Reactor electron antineutrino

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Baikal School
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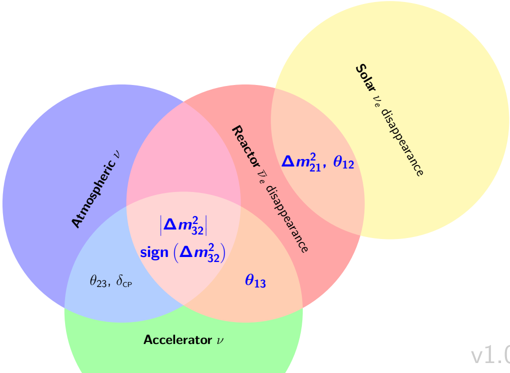
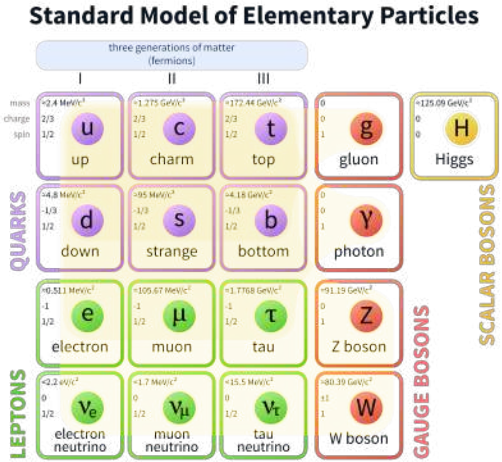


v1.0.0

Elementary particles



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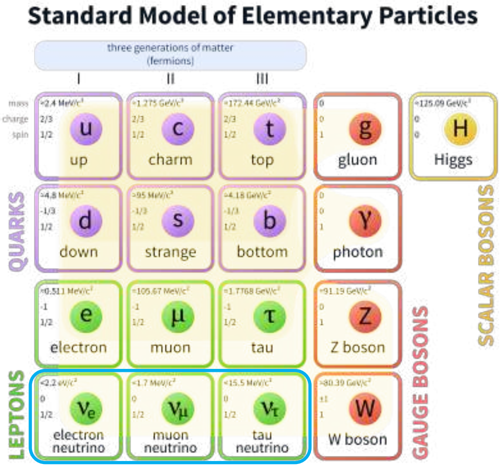
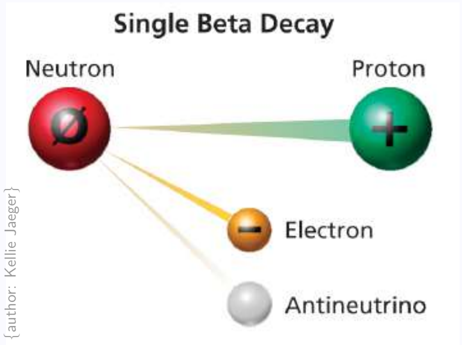


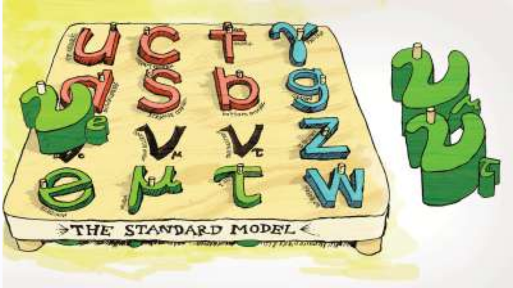
Neutrino



- Neutrino production (example): beta decay
- Neutrino flavor: neutrino interaction state

Elementary particles

Standard Model of Elementary Particles



Neutrino

- Mass state $\neq$ interaction state.
- Flavor: how neutrino interacts.

Massive and flavored neutrinos

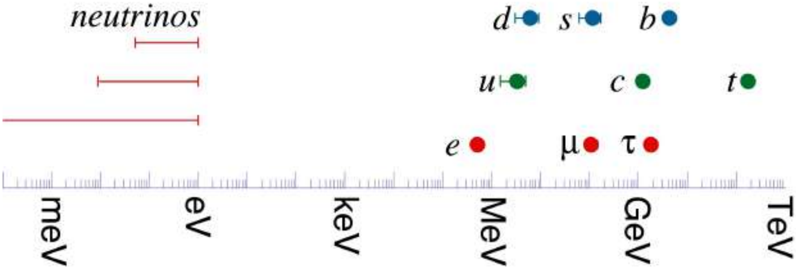
Neutrino properties

Properties

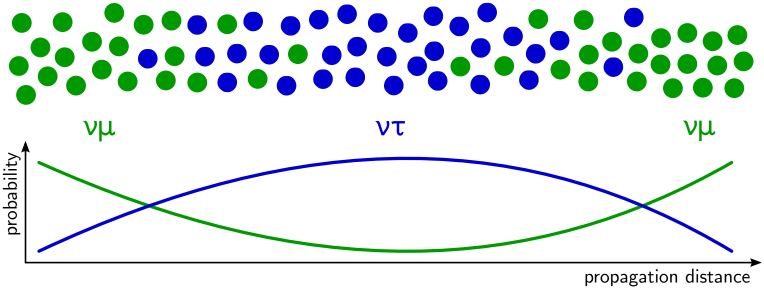
- Neutral, spin 1/2
- Almost massless: $0 \lesssim m_\nu \lesssim 10^{-6} m_e$
- Interact only weakly

  $\sim$ 1′000′000 suns before interaction (1 MeV)
- Strongly mixes
- Oscillates (in an observable way)
- May be it's own antiparticle

  only possible for neutrino



Neutrino mixing and oscillations



Mixing

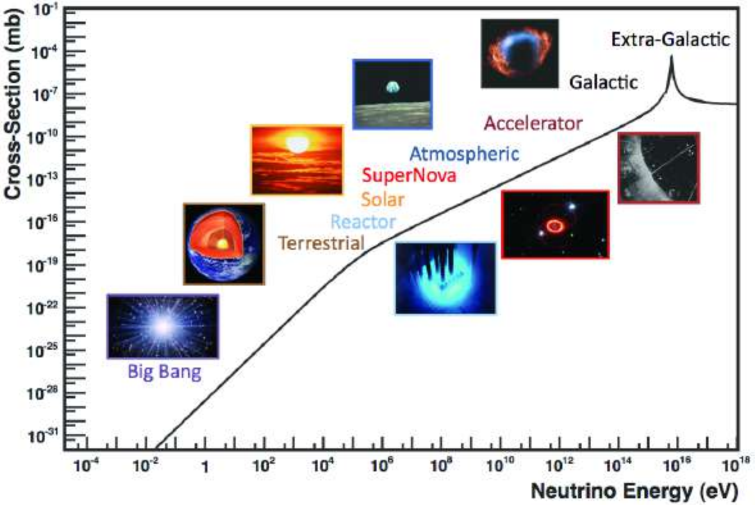
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\text{3D rotation matrix}\\ \text{with 3 angles}^*:\\ \theta_{e2}, \theta_{e3}, \theta_{\mu 3},\ \ i\delta_{\text{CP}}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata (PMNS)

Oscillations

- Mixing angles θ_{12}, θ_{23}, θ_{13}: flavor composition
- Mass splitting Δm^2_{32}, Δm^2_{21}: location of maximum
- At least two neutrinos have nonzero mass
- δ_{CP} differences neutrino/antineutrino

Neutrino sources



10^{14} neutrinos are passing you per second at any given time at the speed of light.

($\sim$ 100′000′000′000′000 particles/second)

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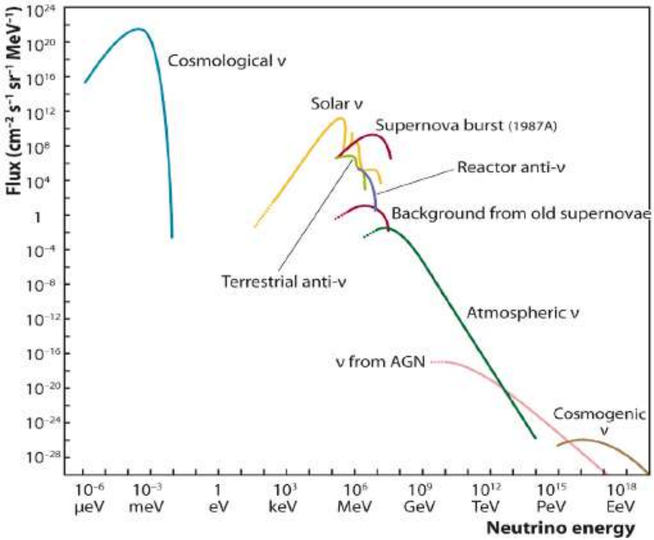

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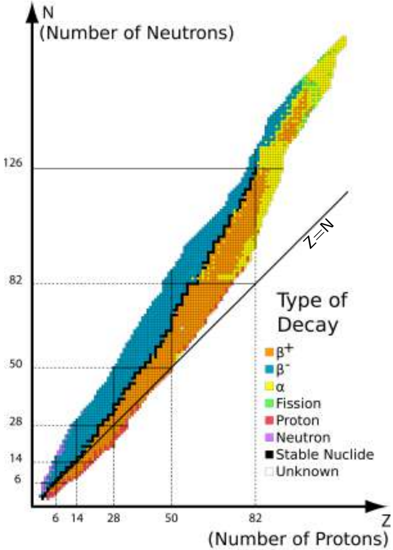

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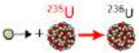

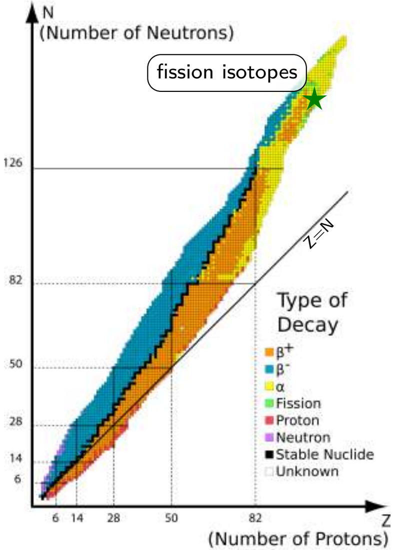

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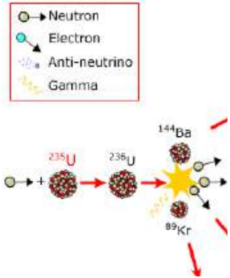

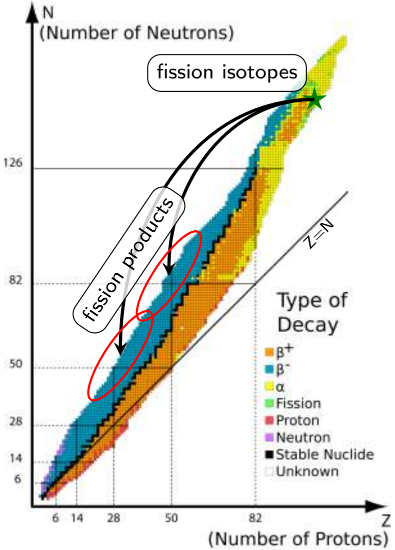

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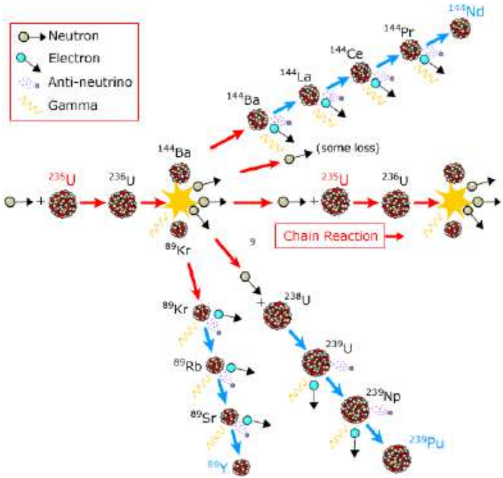
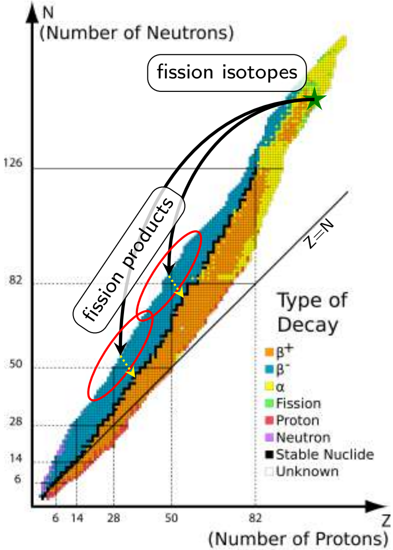


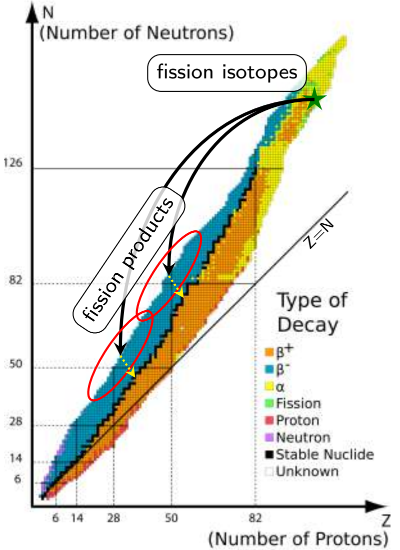


Reactor $\overline{\nu}_e$ production and detection

Reactor $\overline{\nu}_e$ production

in beta decays of fission products of

- ^{235}U, ^{239}Pu and ^{241}Pu (slow *n*)
- ^{238}U (fast *n*)



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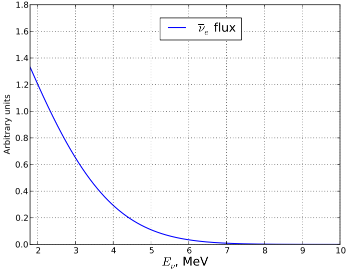
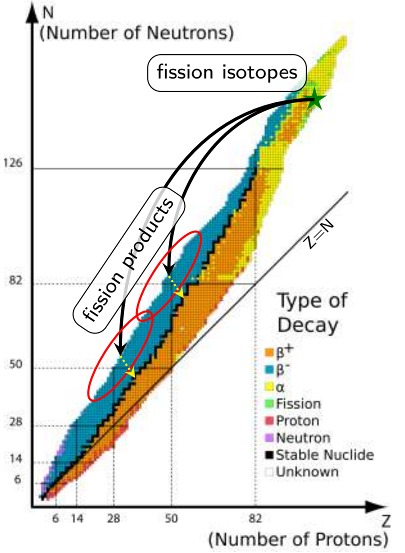
- $E_\nu \lesssim 10$ MeV





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$\overline{\nu}_e$ detection

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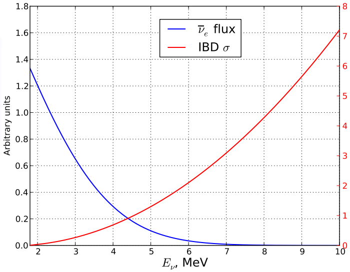
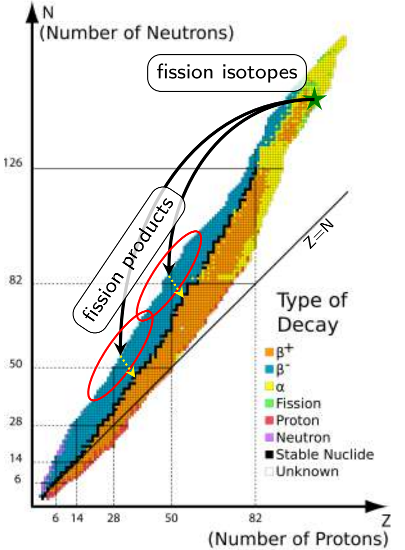
$$\overline{\nu}_e + p \longrightarrow e^+ + n$$





Reactor $\overline{\nu}_e$ production and detection

Reactor $\overline{\nu}_e$ production

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- ^{238}U (fast n)
- $\sim 6\ \overline{\nu}_e$/fission (+ 200 MeV of heat)
- $E_\nu \lesssim 10$ MeV

$\overline{\nu}_e$ detection

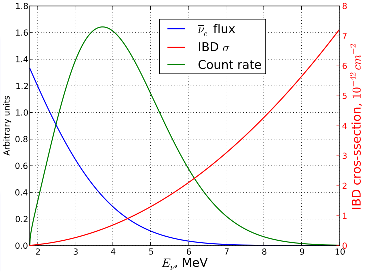
- Inverse beta decay:

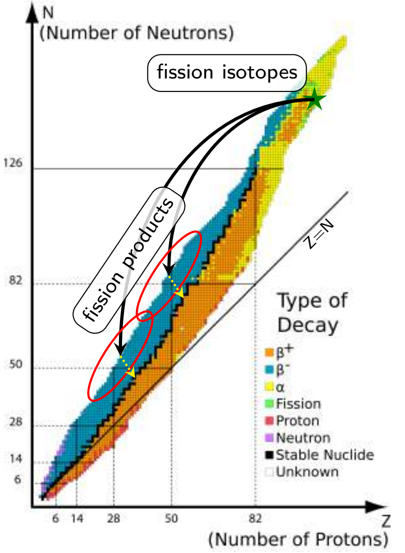
$$\overline{\nu}_e + p \longrightarrow e^+ + n$$

- Threshold: 1.8 MeV

Not covered

- $\overline{\nu}_e + e$ elastic scattering
- $\overline{\nu}_e$+nucleus coherent scattering

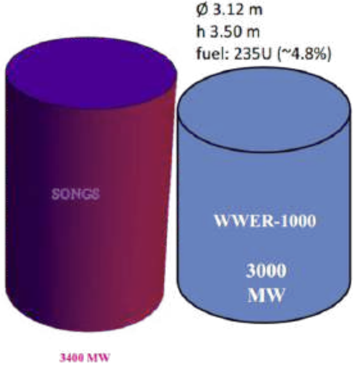




Nuclear reactor types

Industrial reactors

- Size: $\sim 3\,\mathrm{m}$
- ✓ Thermal power: $\sim 3\,\mathrm{GW}$
- Fuel: composite
- Spectrum: complex, time dependant
- "Free" to use for science
- Safety restrictions



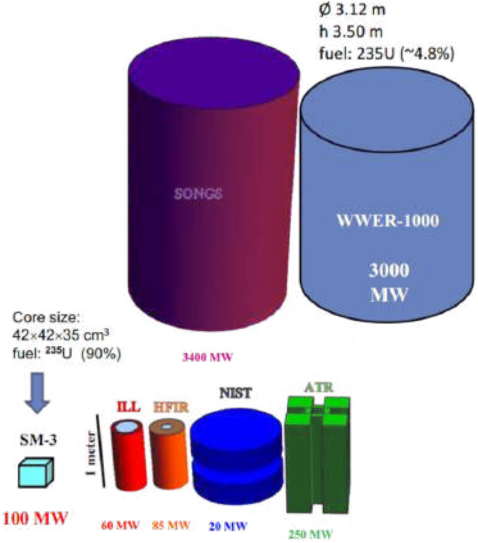
Nuclear reactor types

Industrial reactors

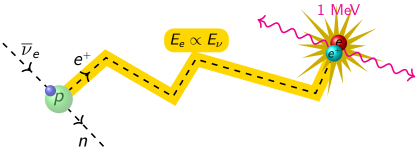
- Size: ~ 3 m
- ✓ Thermal power: ~ 3 GW
- Fuel: composite
- Spectrum: complex, time dependant
- "Free" to use for science
- Safety restrictions

Research reactors

- Size: < 1 m
- Thermal power: < 100 MW
- Fuel: pure ^{235}U
- ✓ Spectrum: simple



Inverse beta decay and selection criteria



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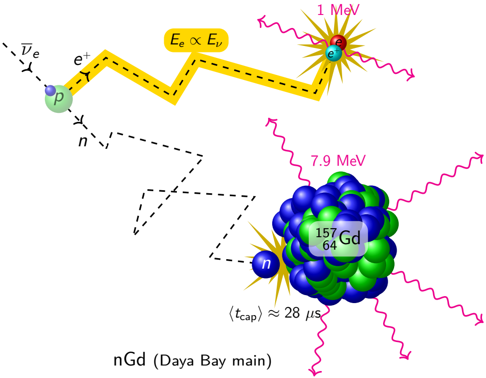

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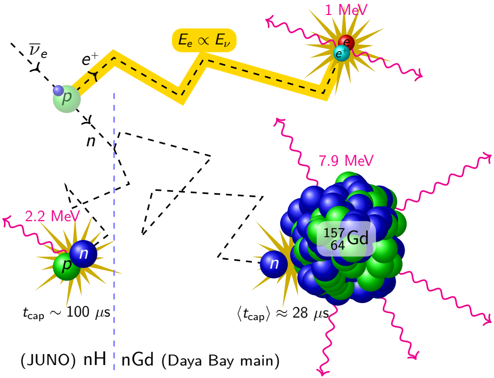
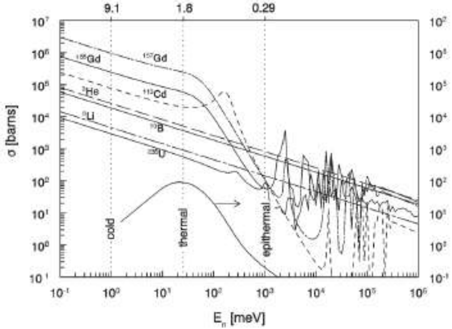
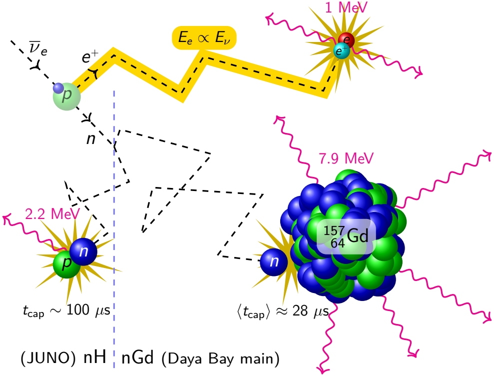


Inverse beta decay and selection criteria

Commonly used capture targets

^{157}Gd	γ(8 MeV)	huge σ_n, large energy	complex chemistry
^{1}H	γ(2.2 MeV)	abundant in LS	long capture time
^{6}Li	α, T	capture point	quenched scintillation
^{113}Cd	γ(9 MeV)	σ_n, large energy	





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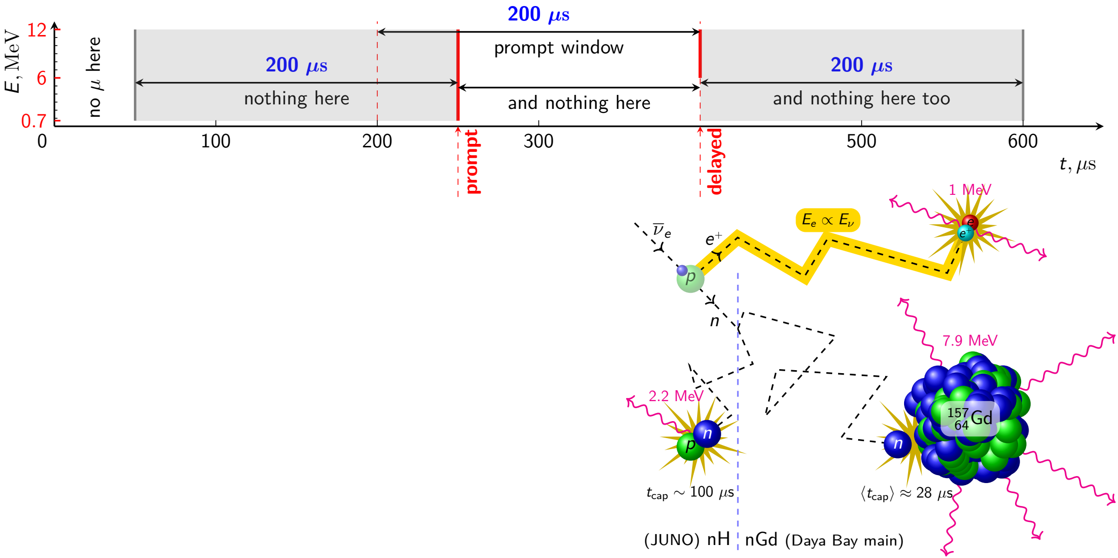
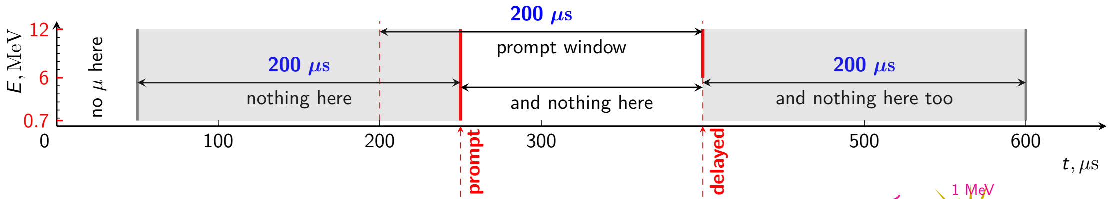


Plot: Daya Bay

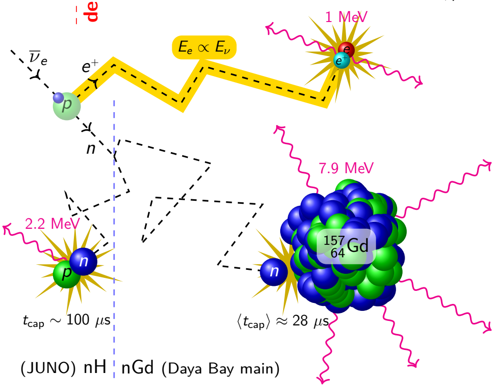
Cherenkov: < 5%

Inverse beta decay and selection criteria



Plot: Daya Bay

Cut	Daya Bay nGd	JUNO nH
Instrumental	Flashers	
Fiducial volume	natural	$R < 17$ m
Time	200 μs	1 ms
Prompt E, MeV	0.7 – 12	
Delayed E, MeV	6 – 12	1.9 – 2.5
Distance, m	no	1.5
Muon veto	0.6 ms – 1 s	TBD
Multiplicity veto, us	±200	TBD



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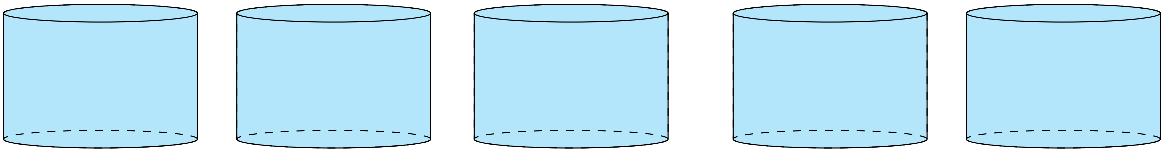
•	IBD	events/AD	635	75		45	
•	Geo ν	%	negligible	negligible	negligible	2.4	30
•	Accidentals	%	1.3	1.6	1	2.0	negligible
•	^{8}He/^{9}Li	%	**0.3**	**0.2**	**30**	3.6	20
•	Fast neutrons	%	0.08	0.07	17	0.3	100
•	^{241}Am-^{13}C	%	0.03	0.07	45	no	no
•	^{13}C$(\alpha, n)^{16}$O	%	0.01	0.07	50	0.1	50
•	Total bkg	%	1.72	2.01		8.6	

Accidentals | β-n isotopes | Fast neutrons | ACU | ^{13}C$(\alpha, n)^{16}$O



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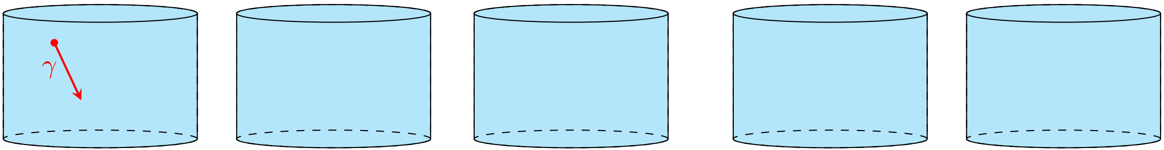

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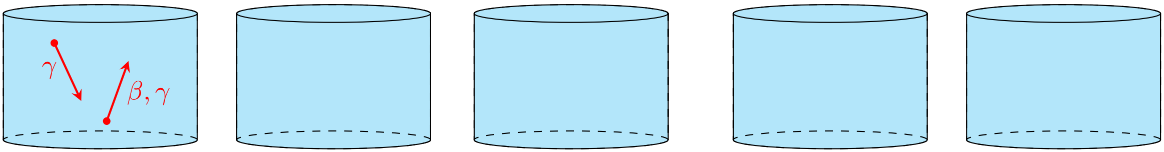

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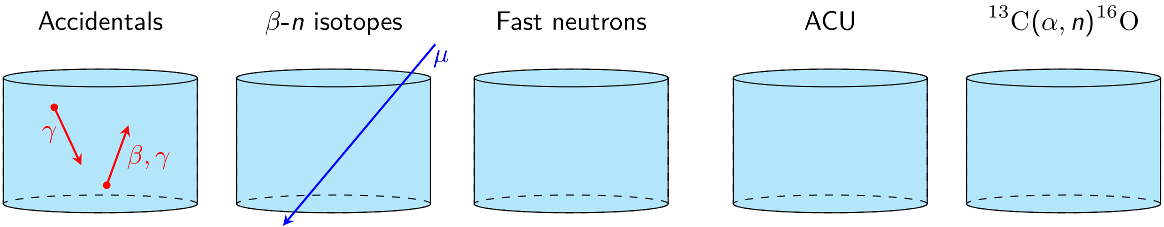

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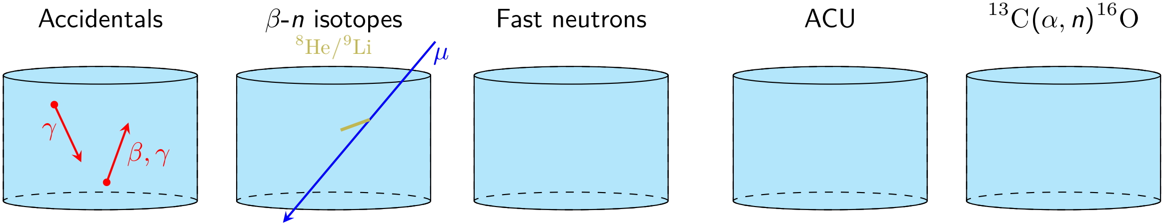

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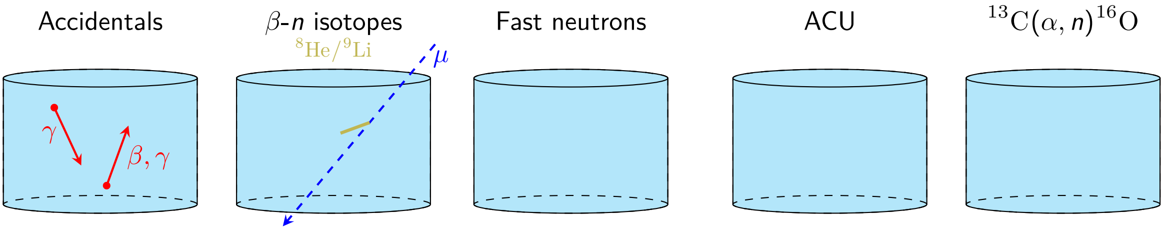

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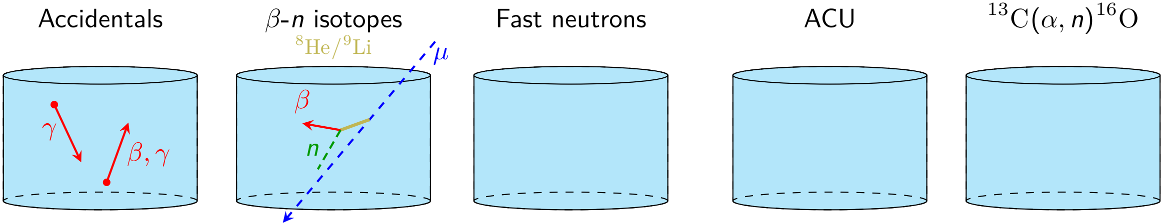

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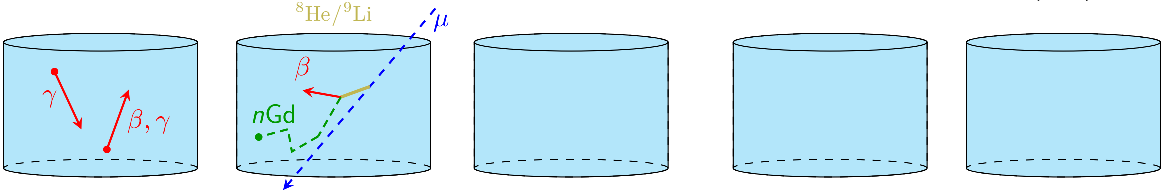

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•	^{241}Am-^{13}C	%	0.03	0.07	45	no	no
•	^{13}C$(\alpha, n)^{16}$O	%	0.01	0.07	50	0.1	50
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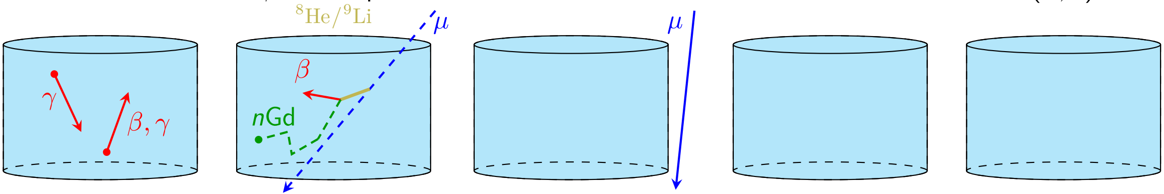
Accidentals β-n isotopes Fast neutrons ACU ^{13}C$(\alpha, n)^{16}$O



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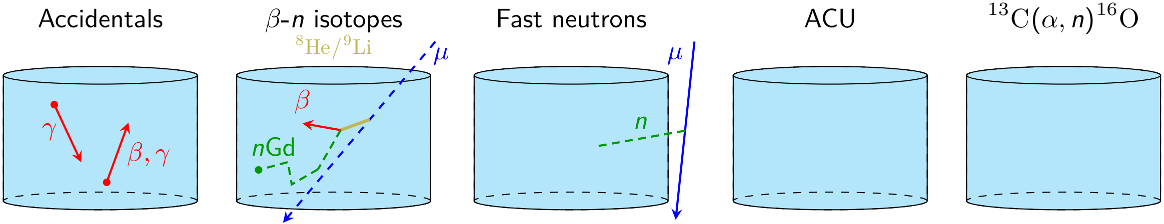

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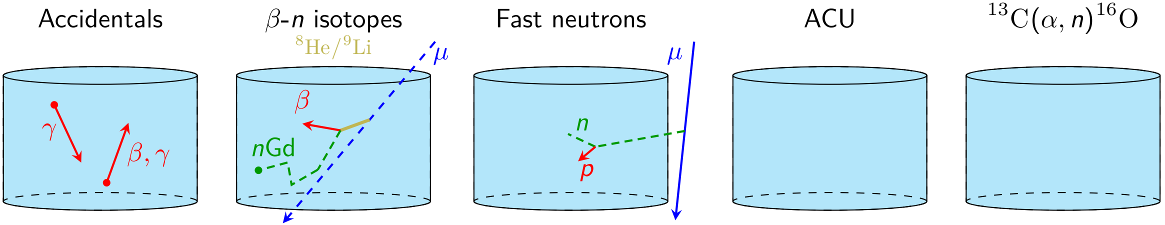

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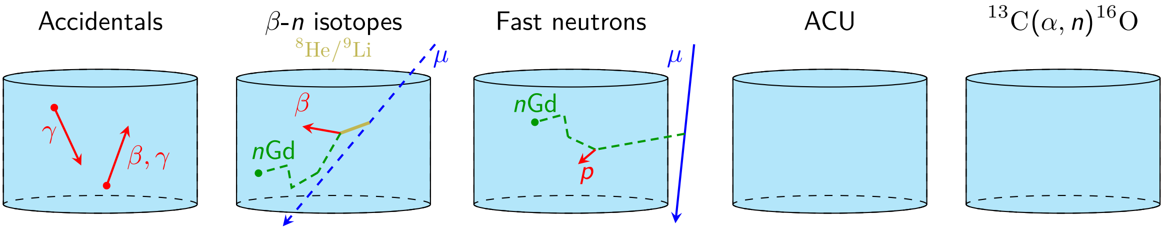

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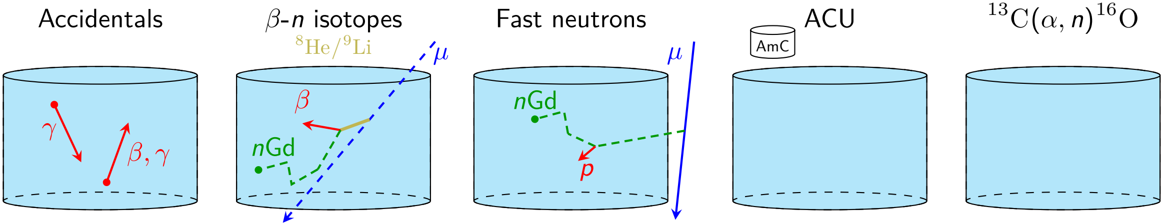

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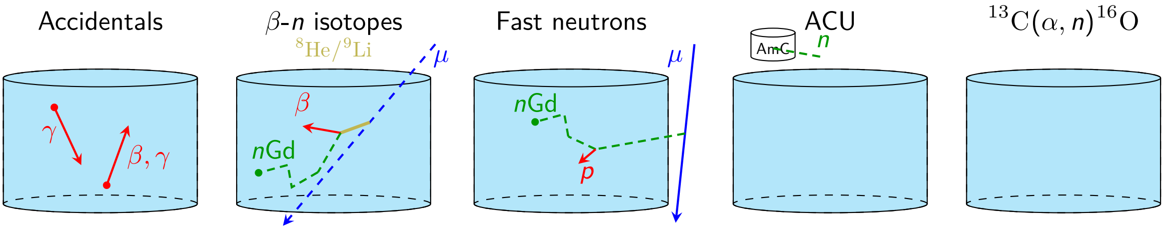

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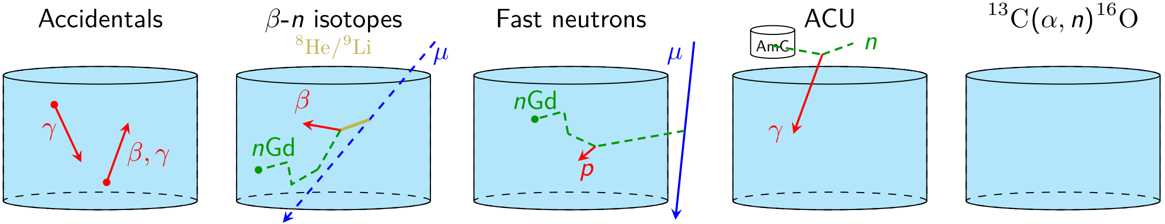

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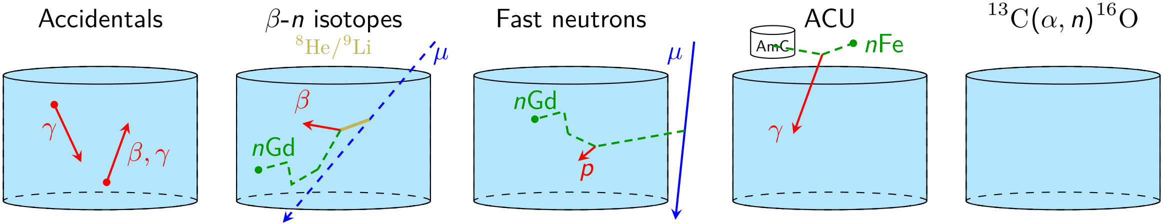

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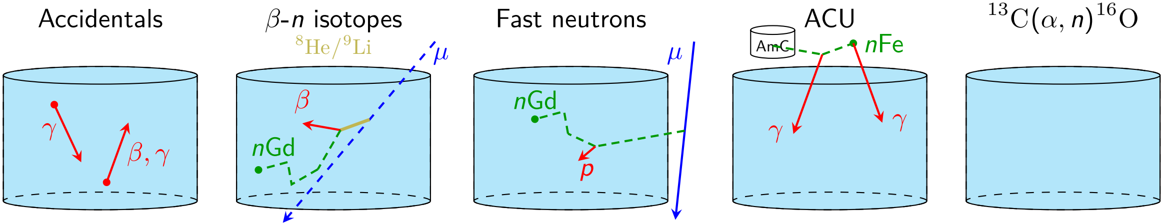

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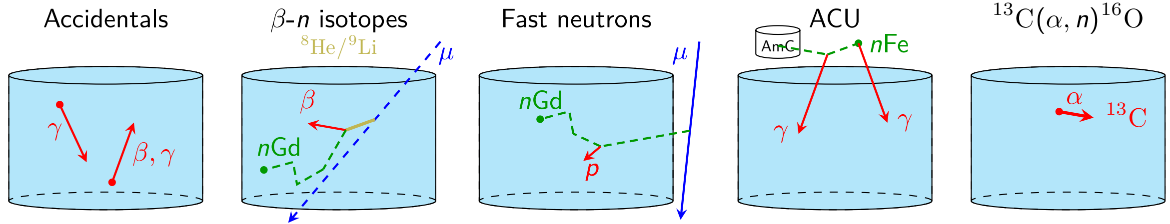

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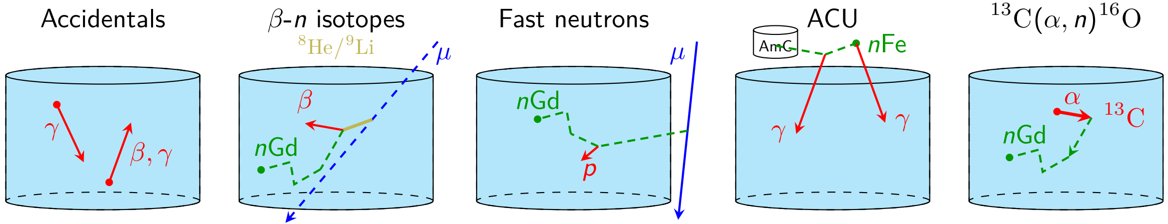

Scintillation and Cherenkov light

- Common scenario: neutrino interaction produces a single charged particle in a large volume

Scintillation and Cherenkov light

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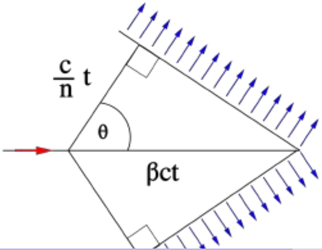
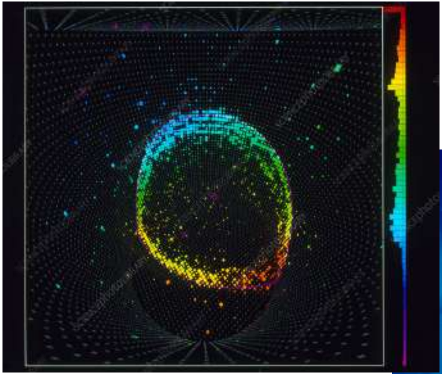
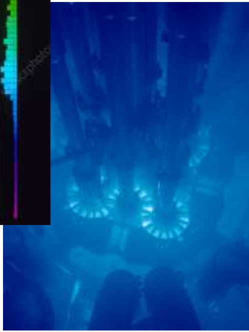
Cherenkov light

- Any transparent material
- Particle velocity > light velocity in matter
- Cherenkov cone
- Time distribution: 'immediate'





△ Super Kamiokande muon event.



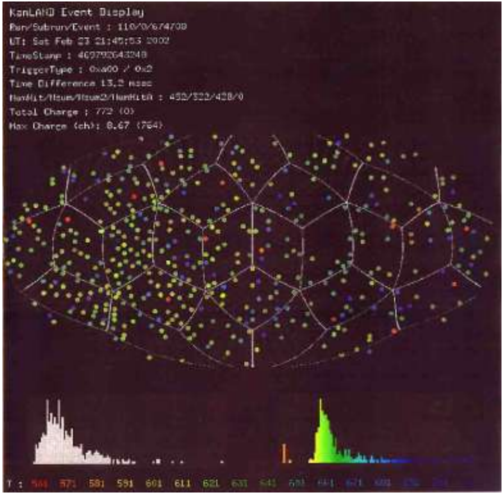
ATR reactor Cherenkov light ▷

Scintillation and Cherenkov light

- Common scenario: neutrino interaction produces a single charged particle in a large volume

Scintillation light

- Special material: scintillator
- Energy: any
- Light direction: isotropic
- Time distribution: exponential decay
  scintillator (de)excitation takes some time $\sim$ ns



Reactor neutrino questions

✓ Covered in this talk

- *Not* covered

Nuclear reactors

✓ Reactor $\overline{\nu}_e$ spectrum

- Reactor monitoring:

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Related questions

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Absolutely unrelated questions

- ✗ θ_{23} and its octant
- ✗ δ_{CP} and CP violation in leptonic sector
- ✗ Absolute neutrino mass
- ✗ Nature of neutrino mass: Dirac or Majorana

Past:

Reactor $\overline{\nu}_e$ observation

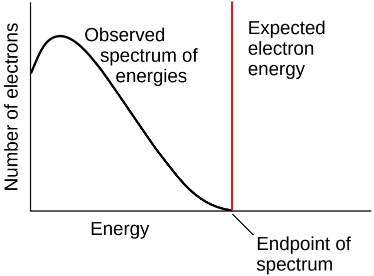
Reines and Cowan: neutrino detection experiment

Neutrino proposal

✗ Problem: in tritium (three body) decay

$$^3\mathrm{T} \longrightarrow {}^3\mathrm{He} + e^-$$

e^- should have definite energy.



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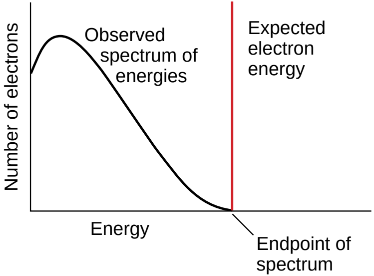

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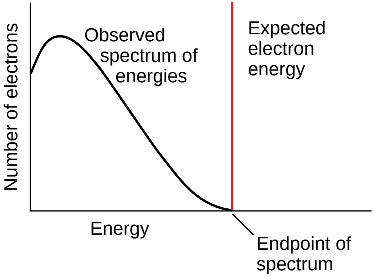

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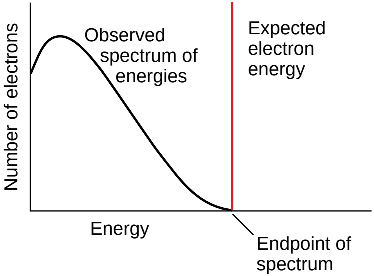
  ↪ impossible to detect



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First proposal by Reines and Cowan

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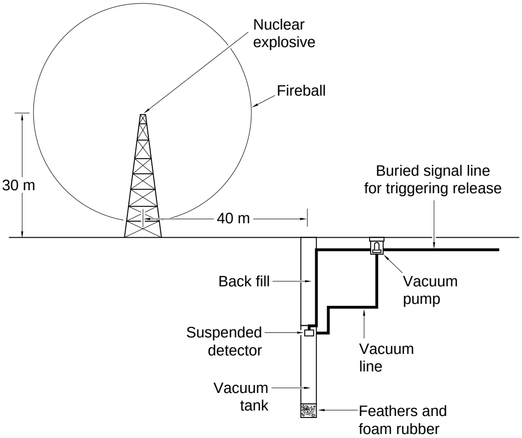

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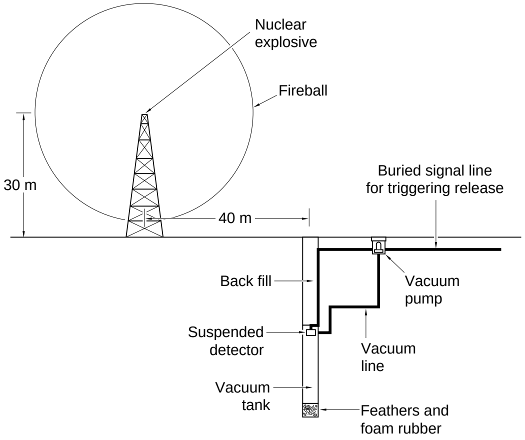

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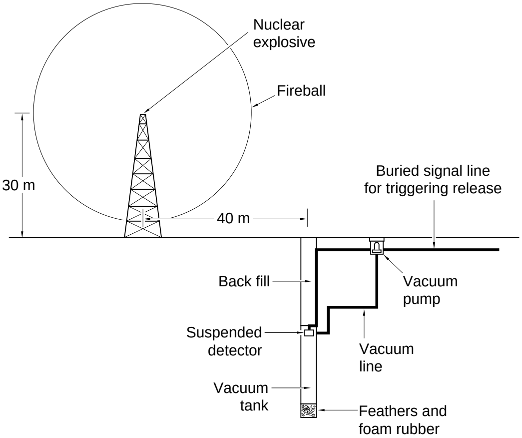

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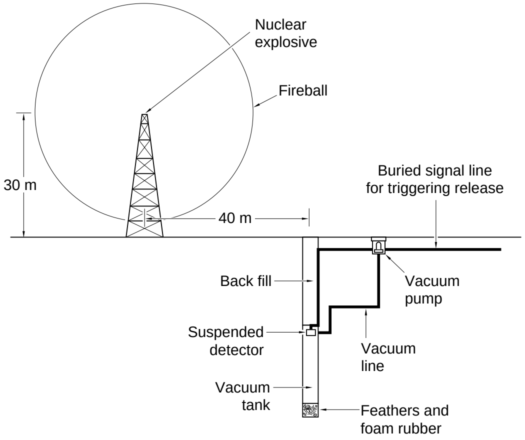

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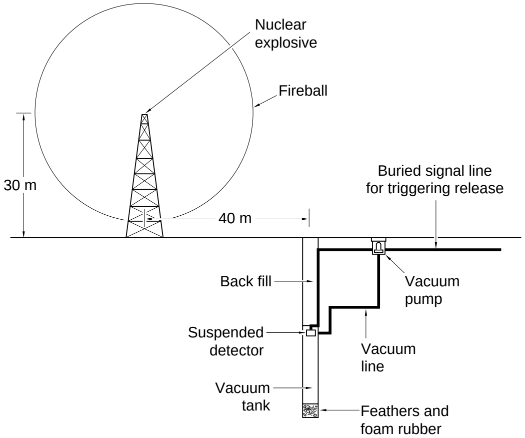
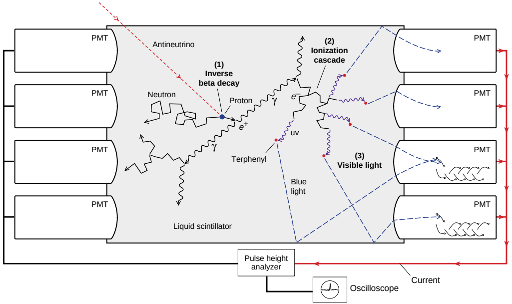
- ✓ With double signal: no need to use explosion.



Hanford experiment: detector Herr Auge

First attempt 1953

- Cylindrical detector: $\varnothing$71 cm, $\updownarrow$ 76 cm, 300 l
- Target: liquid scintillator (LS) + $^{113}\mathrm{Cd}$
- 90 2" PMTs



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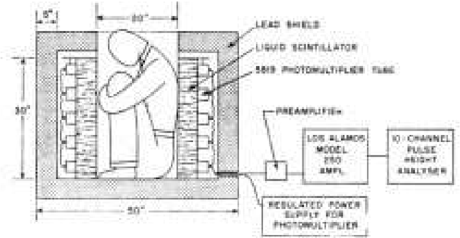

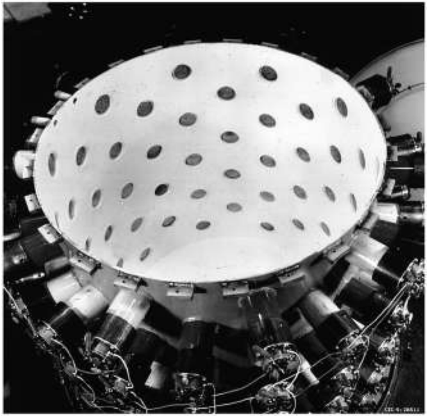

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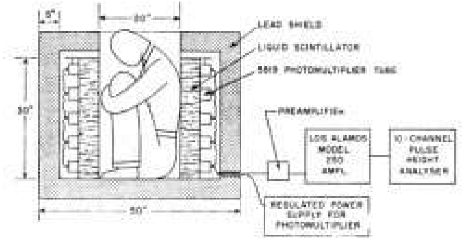
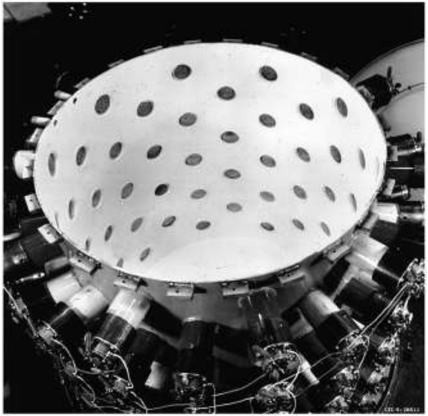
- Expected count rate: $0.3\,\text{min}^{-1}$
- Observed count rate: $5\,\text{min}^{-1}$



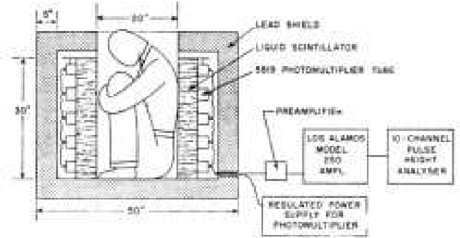


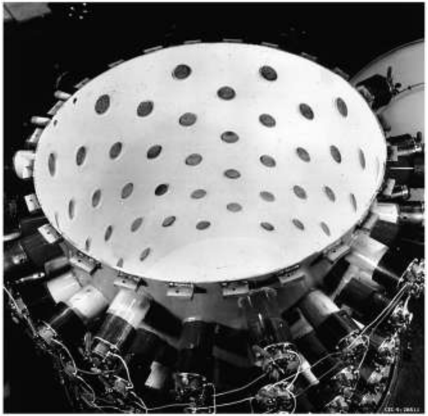
Hanford experiment: detector Herr Auge

First attempt 1953

- Cylindrical detector: $\varnothing$71 cm, $\updownarrow$ 76 cm, 300 l
- Target: liquid scintillator (LS) + ^{113}Cd
- 90 2" PMTs
- Expected count rate: 0.3 min^{-1}
- Observed count rate: 5 min^{-1}

✗ Found cosmogenic background

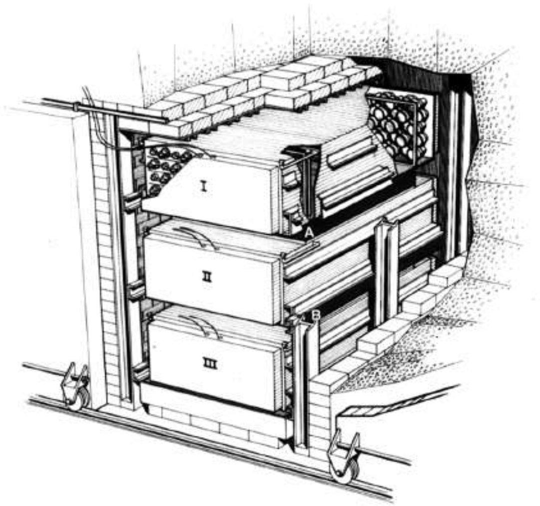




Savannah River experiment: observation

Second attempt 1955

- Sandwich detector: 3×1400 l LS
- Target: 2×200 l, $H_2O/D_2O + {}^{113}Cd$
- Depth: 12 m
- 3×110 5" PMTs



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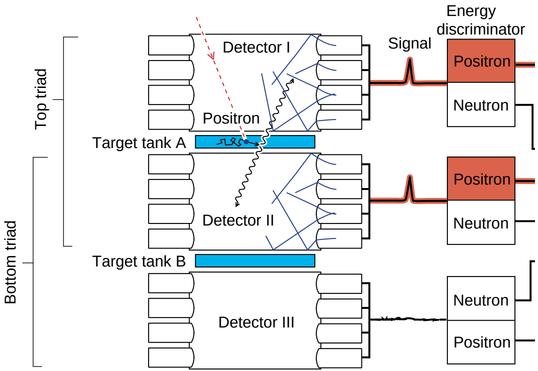
- Select coincidences



Savannah River experiment: observation

Second attempt 1955

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- Target: $2 \times 200\,\mathrm{l}$, $H_2O/D_2O + {}^{113}\mathrm{Cd}$
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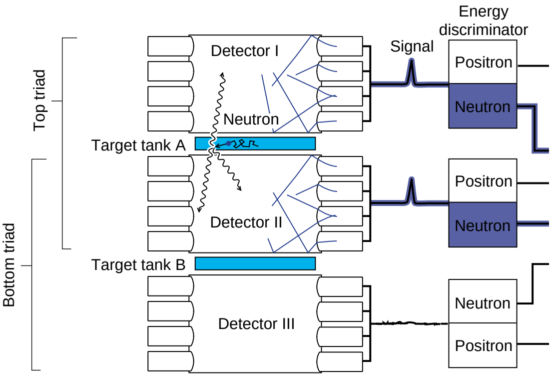

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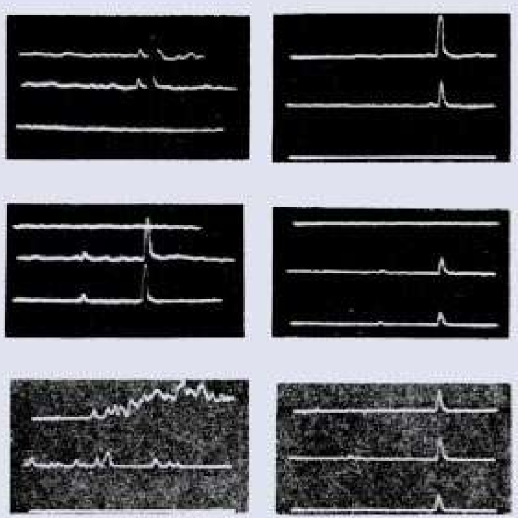
Results

- Observed rate: $3\,h^{-1}$
- S/N ratio: 3/1



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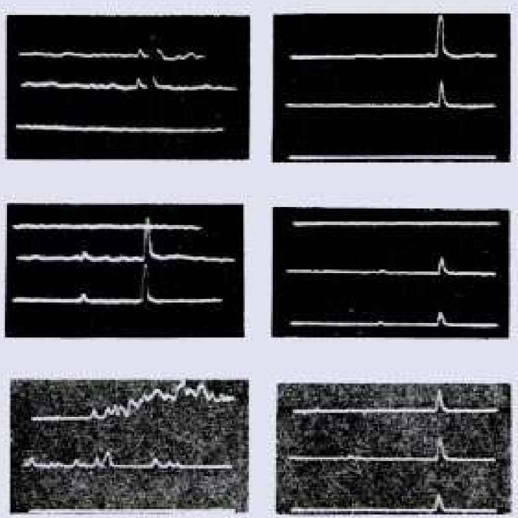

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- Signal *does not* depend on shielding

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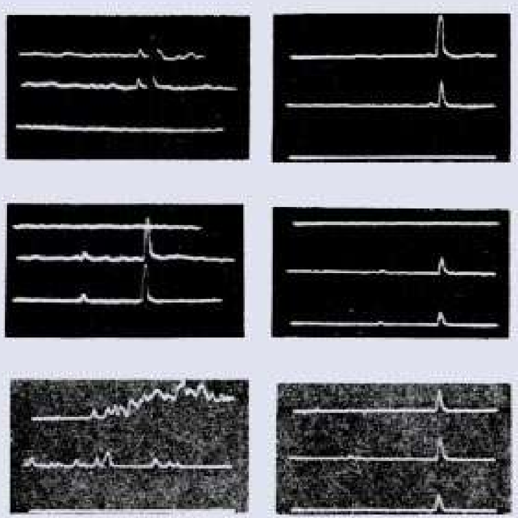
- Nobel Prise 1974 (Reines)



Past:

Reactor $\overline{\nu}_e$ spectrum

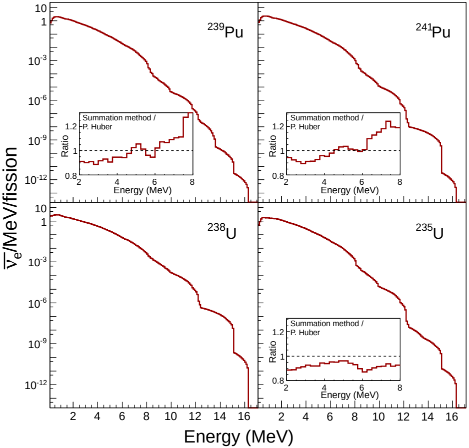
Summation method

- Alternative names: *ab initio*
- Examples: Vogel et al. (PRC24, '81), Mueller et al. [1101.2663], Estienne et al. [1904.09358]
- Variable: number of $\overline{\nu}_e$ per fission per MeV

Summation method

The method

- Combine contributions from:

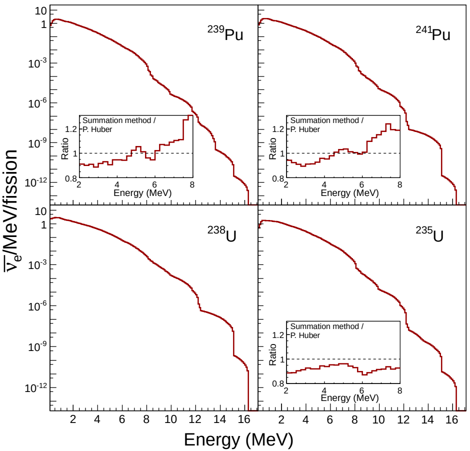


Fallot et al. [1208.3877]

Summation method

The method

- Combine contributions from:
- 4 fission isotopes ×

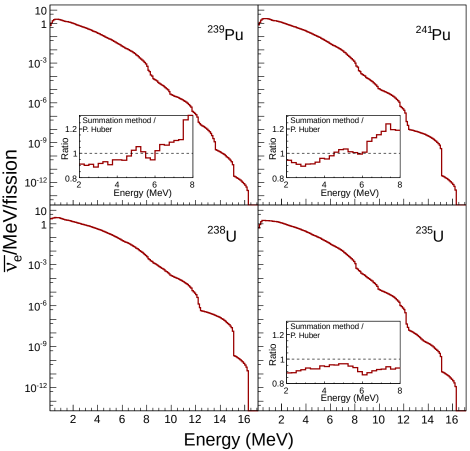


Fallot et al. [1208.3877]

Summation method

The method

- Combine contributions from:
- 4 fission isotopes ×
- Tens of fission states ×



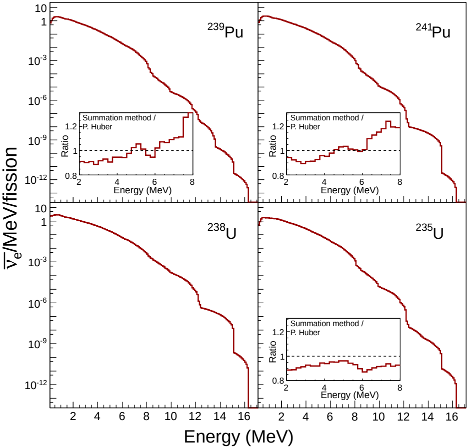
Fallot et al. [1208.3877]

Summation method

The method

- Combine contributions from:
- 4 fission isotopes ×
- Tens of fission states ×
- Hundreds of beta decay branches ×

$\hookrightarrow$ thousands of components



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Summation method

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- Combine contributions from:
- 4 fission isotopes ×
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- Hundreds of beta decay branches ×
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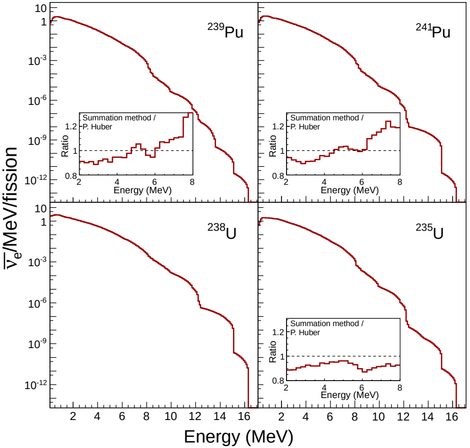
- Databases: ENDF/B, JEFF



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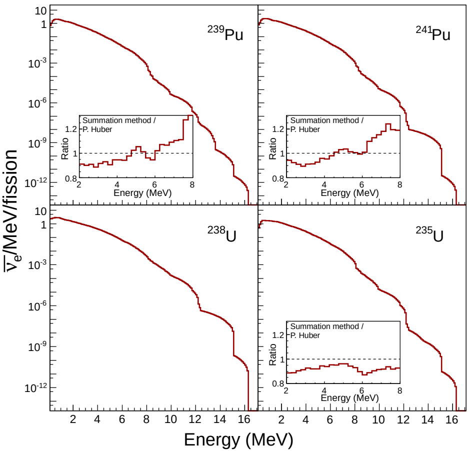

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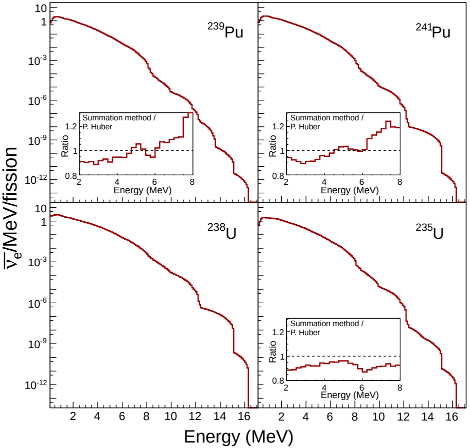
Problems

✗ Missing data: branches, forbiddennes, …



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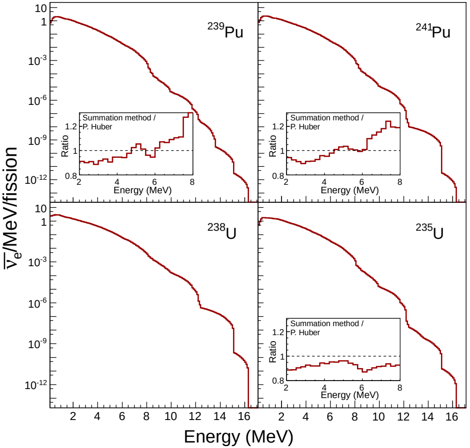
✗ Biased data: pandemonium effect



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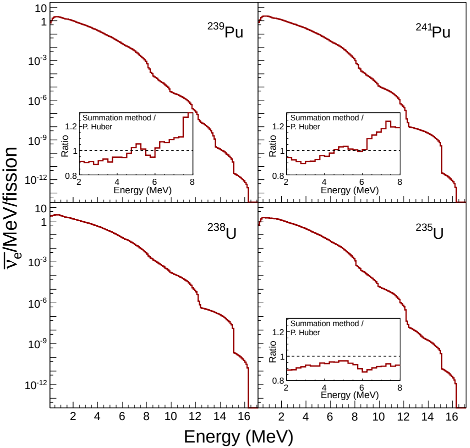
- ✗ Biased data: pandemonium effect
- ✗ Does not agree with experiment



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Problems

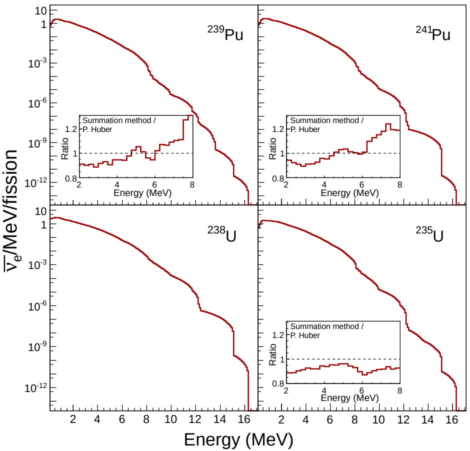
✗ Missing data: branches, forbiddennes, ...

✗ Biased data: pandemonium effect

✗ Does not agree with experiment

✗ Overall: difficult to account systematics

conservatively estimated in $\sim 10\,\%$



Fallot et al. [1208.3877]

Conversion method

- Notable publications:

  Shreckenbach et al (PLB160, 1985)

  Hahn et al (PLB218, 1989)

  Mueller et al [1101.2663]

  Haag et al [1312.5601]

  Haag et al [1405.3501]

- Variable: number of $\overline{\nu}_e$ per fission per MeV

Conversion method

The method

- Irradiate thin foil:

  $^{235}\mathrm{U}/^{239}\mathrm{Pu}/^{241}\mathrm{Pu}$ with slow neutrons

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Conversion method

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- Irradiate thin foil:
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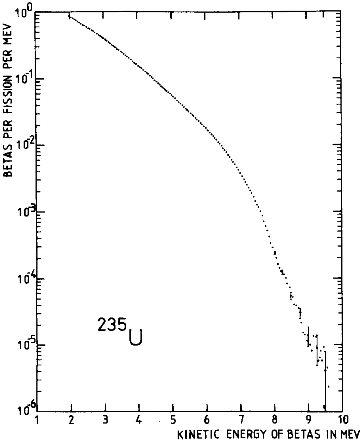

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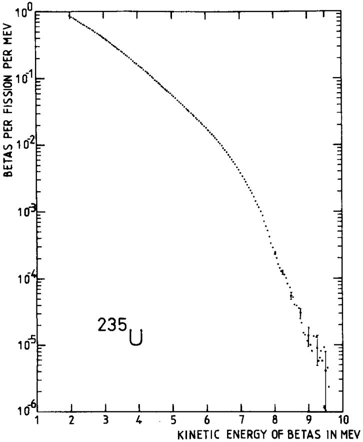

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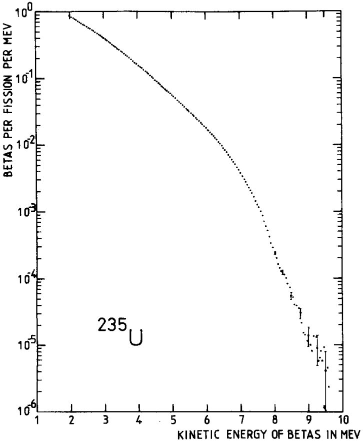

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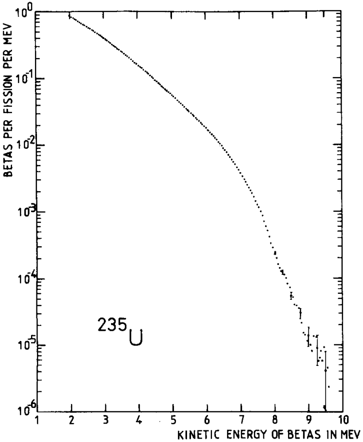

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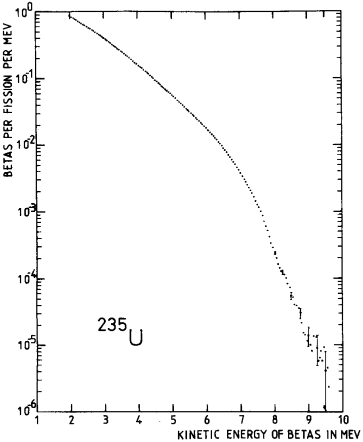
Conversion (example)

- Introduce 30 virtual decay branches



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Conversion (example)

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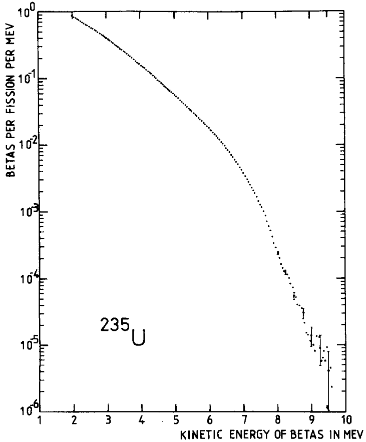
- Fit parameters to match beta-decay data



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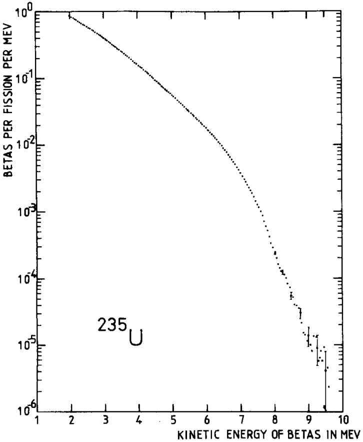

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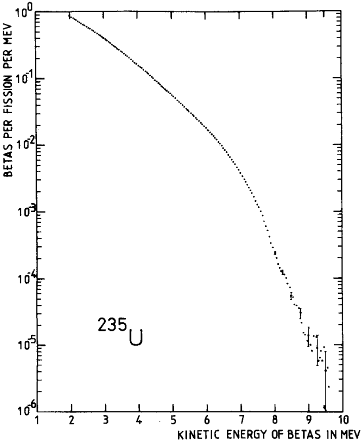
✗ Does not agree with experiment



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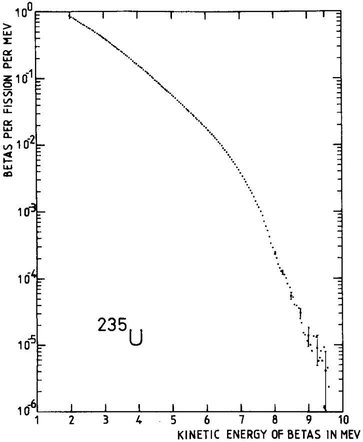
✗ Systematics: conservatively estimated in $\sim 10\,\%$



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Huber+Mueller spectra and reactor anomaly

- In 2011 Patrick Huber and Mueller et al. independently recalculated ILL spectra (conversion).

Huber+Mueller spectra and reactor anomaly

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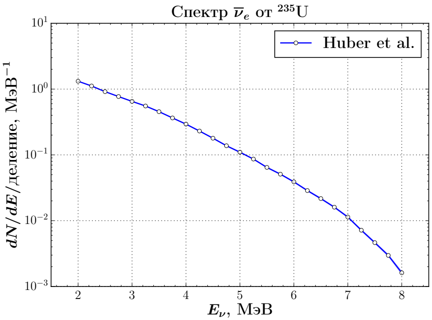
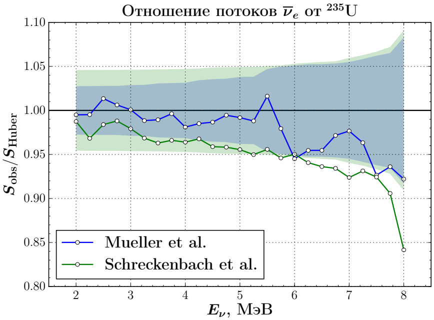
- The predicted spectrum increased by 3 %.





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- Previously consistent experiments became inconsistent: ↪ observed deficit ∼ 5 %
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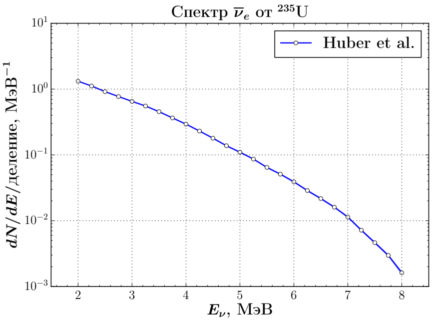

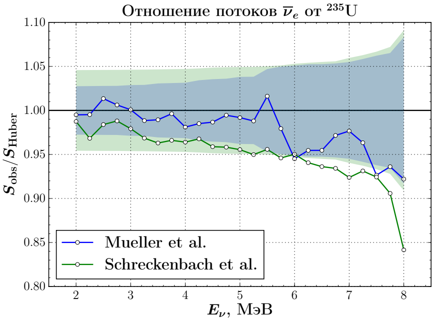

Huber+Mueller spectra and reactor anomaly

- In 2011 Patrick Huber and Mueller et al. independently recalculated ILL spectra (conversion).
- The predicted spectrum increased by 3 %.
- Previously consistent experiments became inconsistent: ↪ observed deficit ∼ 5 %
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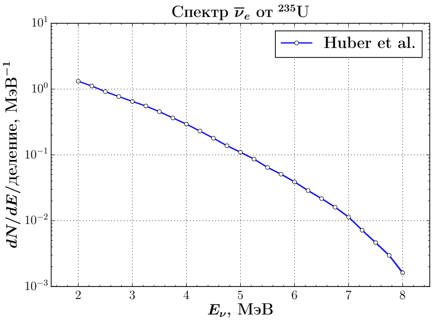
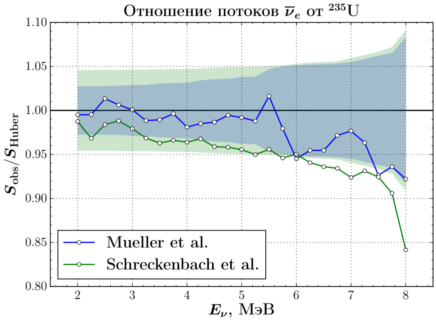
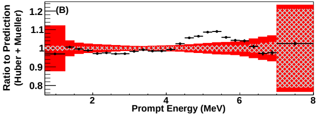
- Combination $^{235}U/^{239}Pu/^{241}Pu$ by Huber and ^{238}U by Mueller et al. often used as reference.



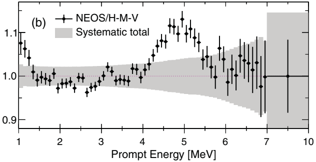


Reactor antineutrino spectrum: current status

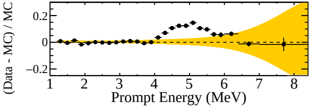
Daya Bay [1607.05378]



NEOS [1610.05134]

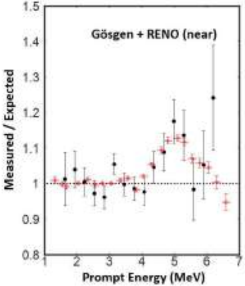


RENO [1911.04601]

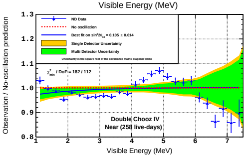


also: Stereo [2010.01876]

Gösgen [1807.01810]



Double Chooz [1901.09445]



Current status

Experiments are consistent in observation:

- Overall deficit of $\sim 5\,\%$
- Bump/excess at $4\,\mathrm{MeV} - 6\,\mathrm{MeV}$

Reactor antineutrino spectrum: current status

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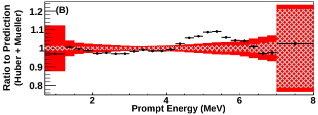

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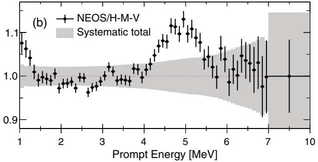

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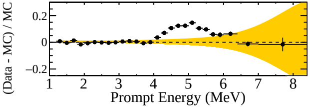

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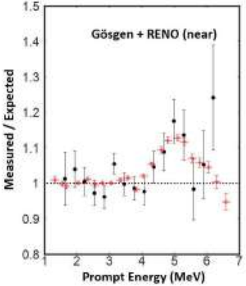
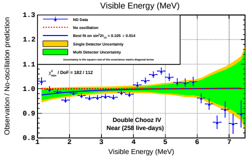


Double Chooz [1901.094



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Experiments are consistent in observation:

- Overall deficit of $\sim 5\,\%$
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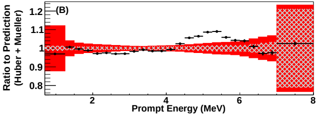
Possible reasons

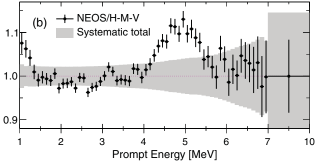
- $^{86}\mathrm{Ge}$ fission yields (NDSF/B)
- Incorrect $^{238}\mathrm{U}$ contribution
- Incorrect $^{235}\mathrm{U}$ contribution

Reactor antineutrino spectrum: current status

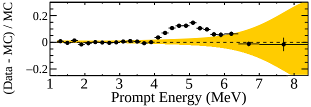
Daya Bay [1607.05378]



NEOS [1610.05134]

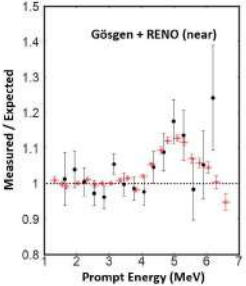


RENO [1911.04601]

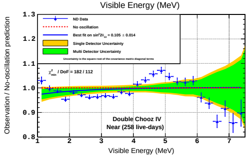


also: Stereo [2010.01876]

Gösgen [1807.01810]



Double Chooz [1901.094



Current status

Experiments are consistent in observation:

- Overall deficit of $\sim 5\,\%$
- Bump/excess at $4\,\mathrm{MeV} - 6\,\mathrm{MeV}$

Possible reasons

- $^{86}\mathrm{Ge}$ fission yields (NDSF/B)
- Incorrect $^{238}\mathrm{U}$ contribution
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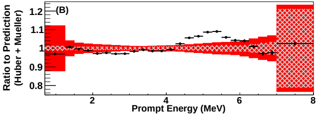

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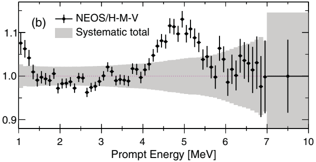

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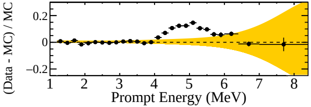

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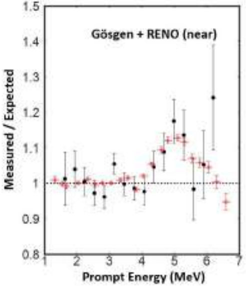

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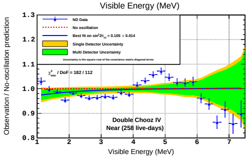

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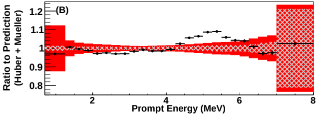

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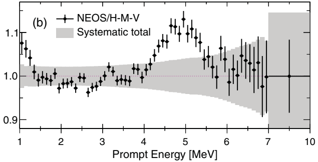

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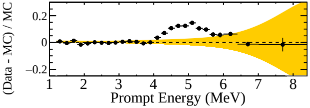

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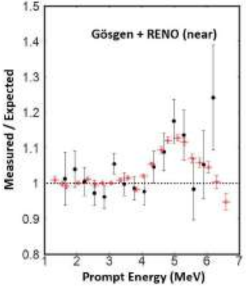

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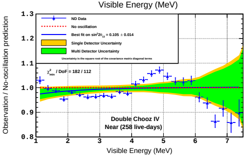

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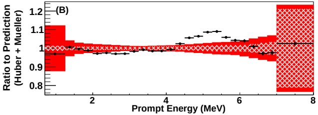

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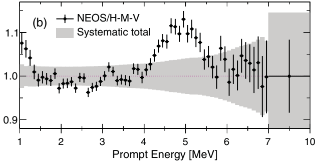

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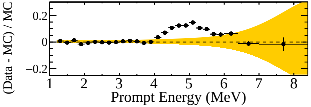

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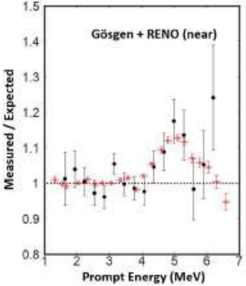

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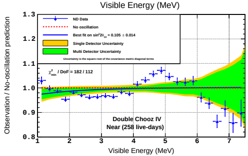

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no clear resolution yet...

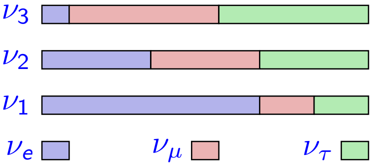
Reactor $\overline{\nu}_e$ spectrum

Summary

- Reactor antineutrino is complex
- No satisfactory spectrum model is present
- Reasons for discrepancies are not understood
- Should be properly treated in reactor neutrino experiments
- A lot of work to be done...

Neutrino oscillations

Mandatory slide I: Neutrino mixing



Weak and mass eigenstates differ:

$$|\nu_\alpha\rangle = \sum U^*_{\alpha i}|\nu_i\rangle$$

α – flavor states

i – mass states

Mixing parametrized by:

- three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$,
- CP-violating phase: δ_{CP}.

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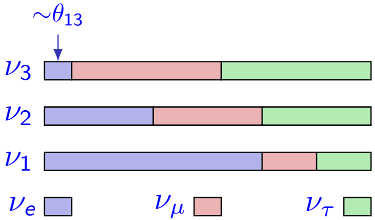

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Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

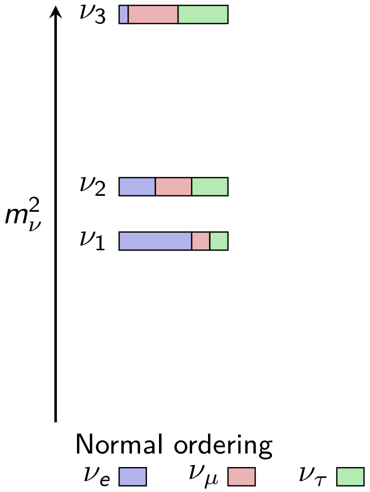
✓ $\theta_{23} \approx 45°$ established through atmospheric and accelerator experiments: possibly maximal.

✓ $\theta_{12} \approx 34°$ established through solar experiments and KamLAND: large, but not maximal.

✓ $\theta_{13} \approx 8°$ established by reactor: **Daya Bay**, RENO, Double Chooz, T2K and MINOS.

- δ_{CP} unknown: NOvA and T2K.

Mandatory slide II: Neutrino mass and ordering



Neutrino mass

- Mass limits, meV:

$m_2,\ m_3 >$	0	oscillations	
$\sum m_\nu \gtrsim$	60		
$\sum m_\nu \lesssim$	120	cosmology	Planck
$m_{\nu_e} <$	1100	direct	KATRIN
$\langle m_{\beta\beta} \rangle <$	160		
		$0\nu\beta\beta$	GERDA
$m_{\text{light}} <$	440		

Numbers updated: 2020.04.17

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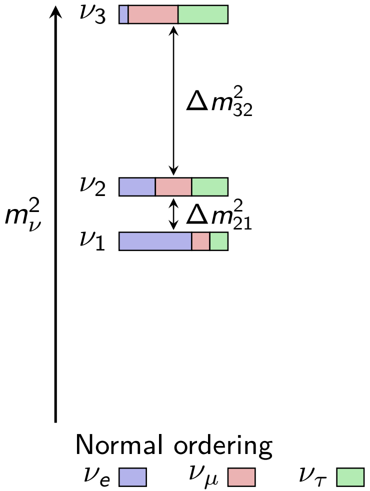

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Mass splitting from oscillations

- $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \text{eV}^2$
- $\left|\Delta m^2_{32}\right| = (2.42 \pm 0.06) \times 10^{-3}\ \text{eV}^2$
- $\left|\Delta m^2_{32}\right| / \Delta m^2_{21} \sim 32$

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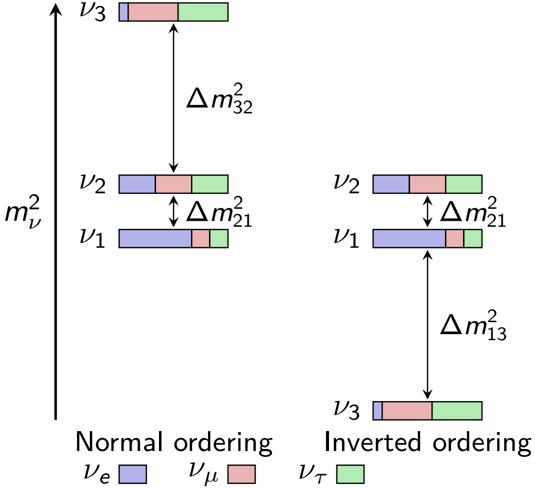

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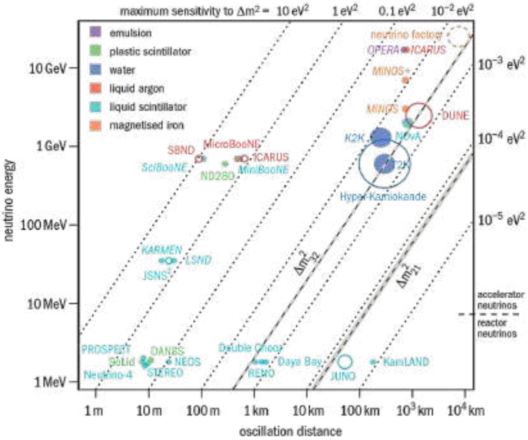
- Mass ordering: is ν_1 lighter than ν_3?

Numbers updated: 2020.04.17

Neutrino oscillation global picture



$$P_{\text{osc}} \propto f\left(\frac{\Delta m^2 L}{E}\right)$$

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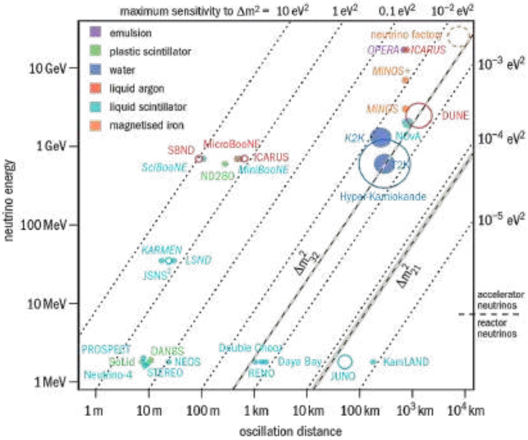
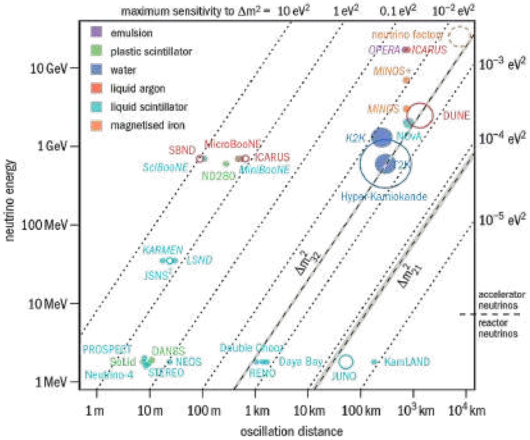


$$P_{osc} \propto f\left(\frac{\Delta m^2 L}{E}\right)$$

Reactor baselines

- SBL — small < 100 m
- MBL — medium ~ 1 km
- LBL — large $\gtrsim 50$ km

Neutrino oscillation global picture



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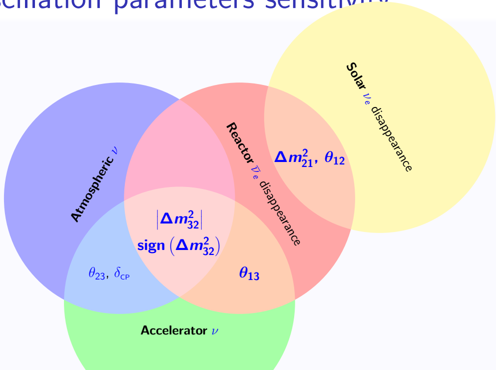
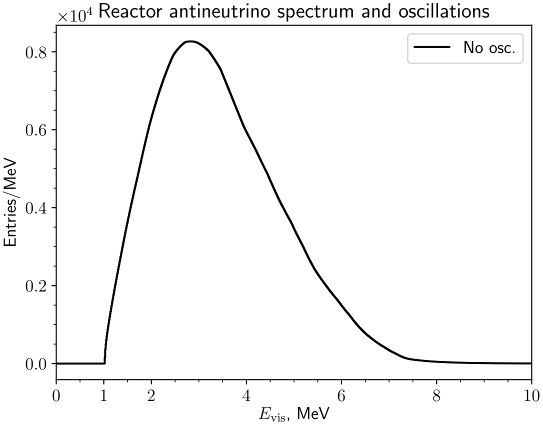
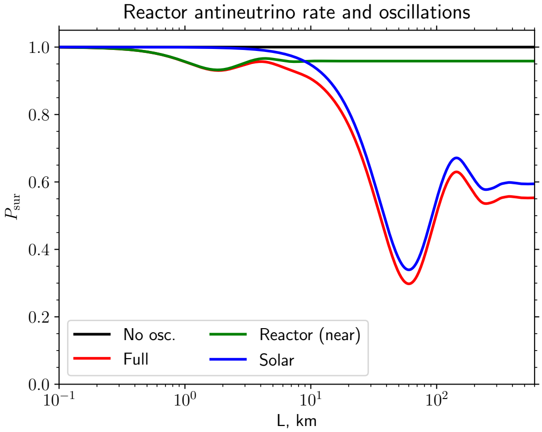
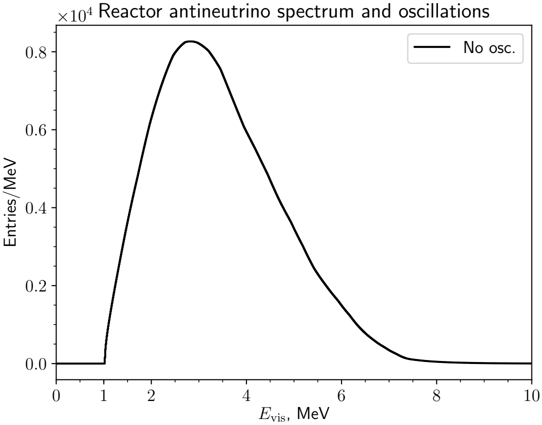
Oscillation parameters sensitivity





$E_{\mathrm{vis}} \approx E_\nu - 0.78\,\mathrm{MeV}$





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~~$\delta_{\rm CP}$, θ_{23}~~

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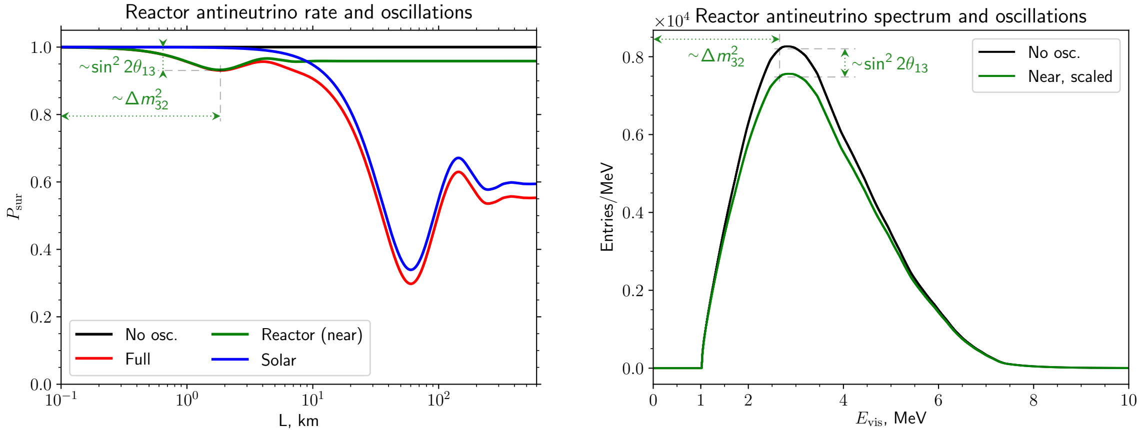

deficit value

minimum location

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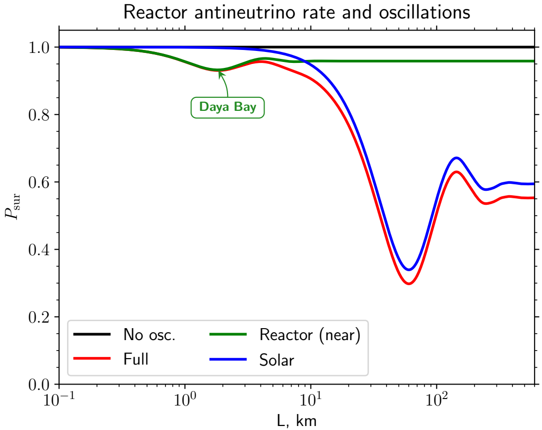

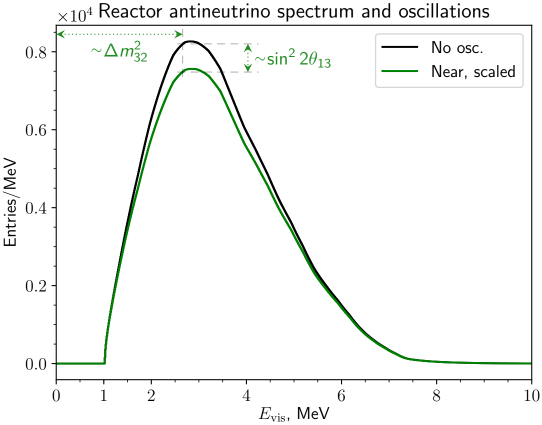

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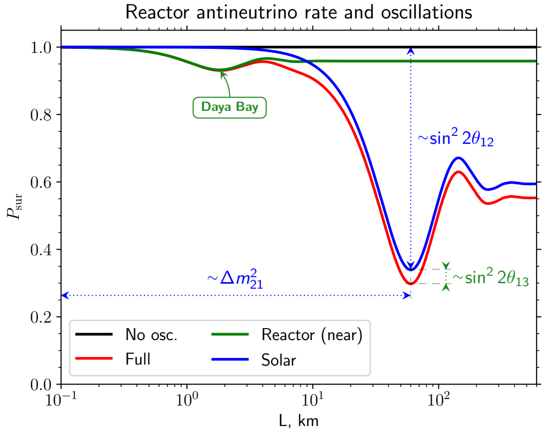

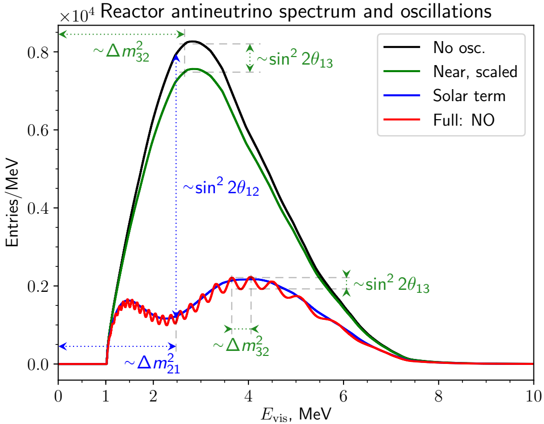

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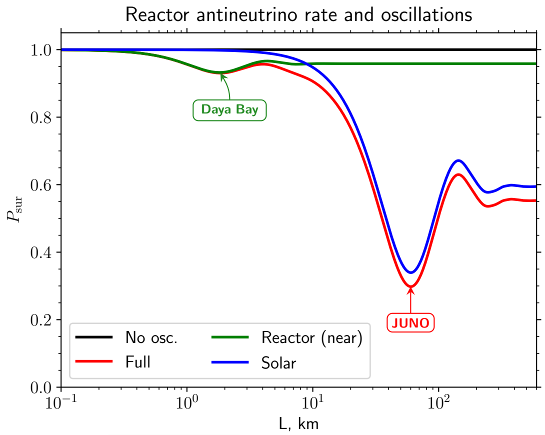

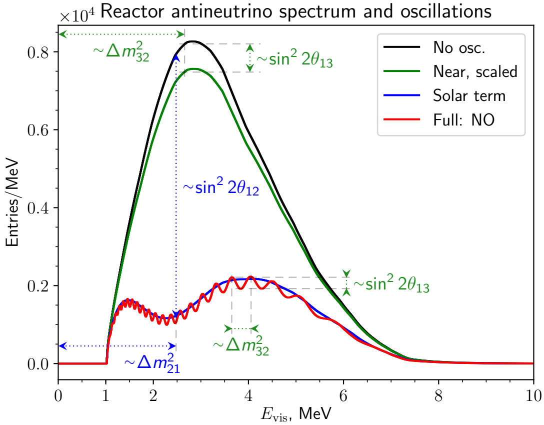

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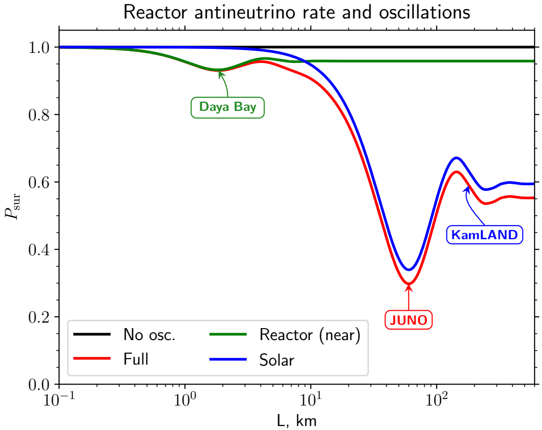

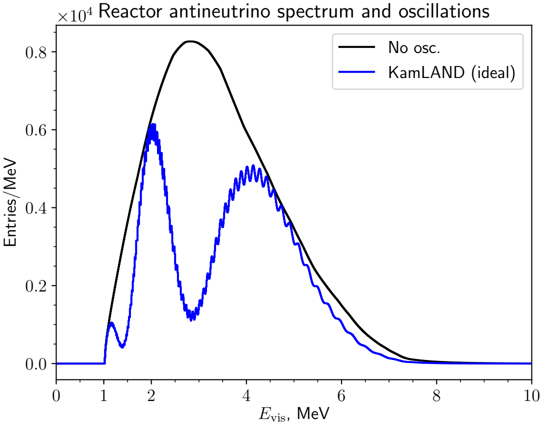

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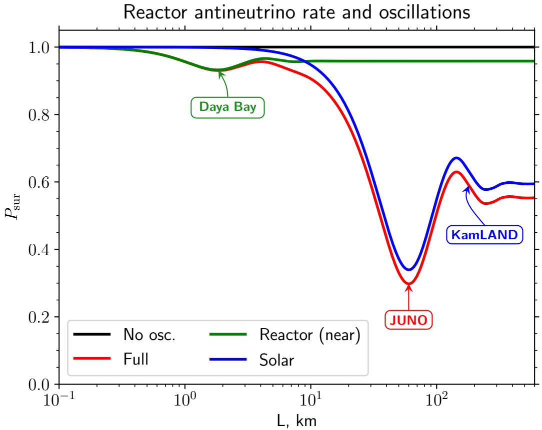

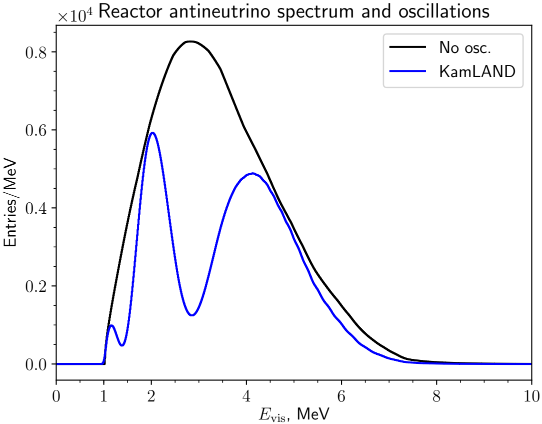

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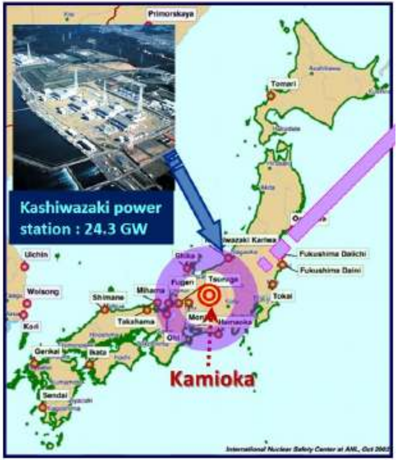
Past:

Δm^2_{21} and θ_{12}

Kamioka Liquid Scintillator Antineutrino Detector

Goals

- 2002 – 2011: Δm^2_{21} and θ_{12}



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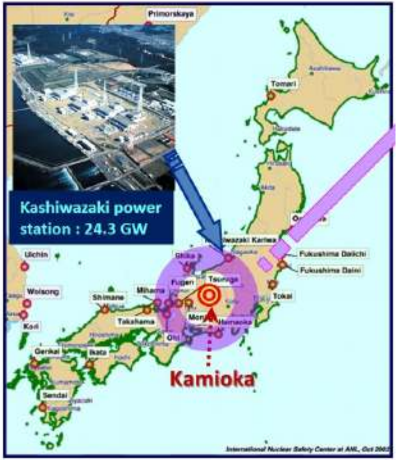
  $\hookrightarrow$ NPP shutdown



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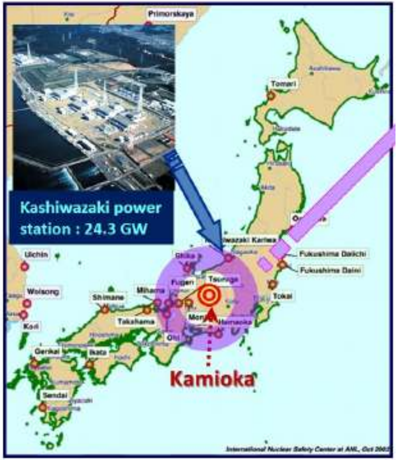
  $\hookrightarrow$ NPP shutdown
- 2013–: geo-ν and 0νββ decay



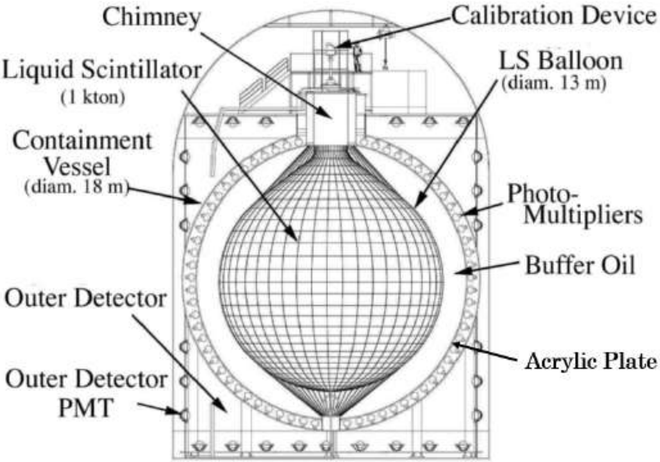
Kamioka Liquid Scintillator Antineutrino Detector

Goals

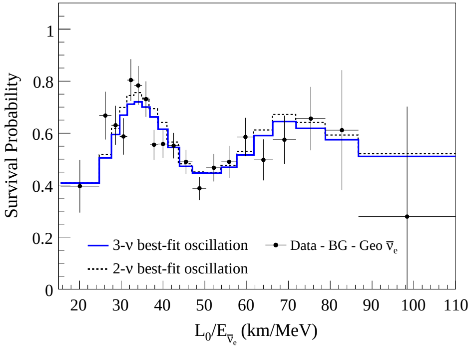
- 2002 – 2011: Δm^2_{21} and θ_{12}
- ✗ 2012: Fukusima disaster
  $\hookrightarrow$ NPP shutdown
- 2013–: geo-ν and 0νββ decay

Summary

- Detector: ⌀13 m balloon
- Target: 1 kt LS
- 1879 17”/20” PMTs
- Average baseline: 180 km



KamLAND results



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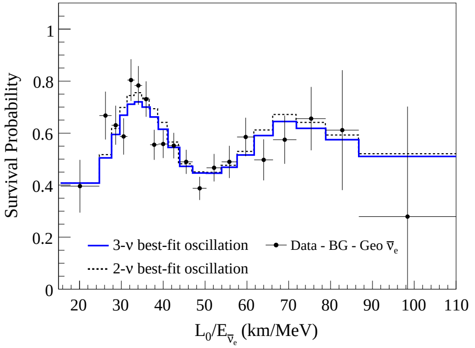
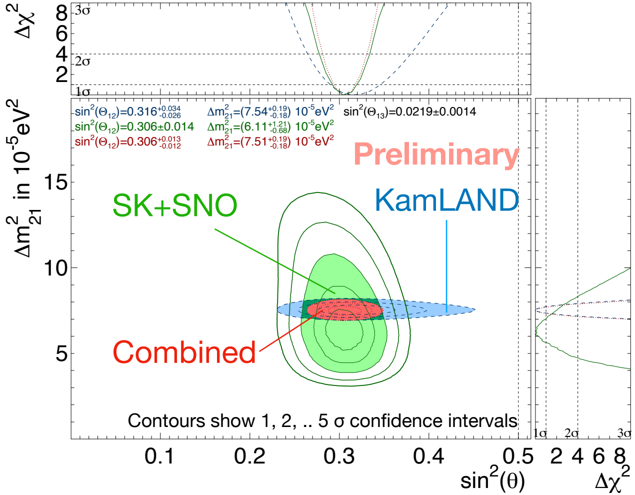
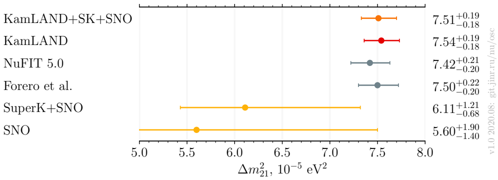
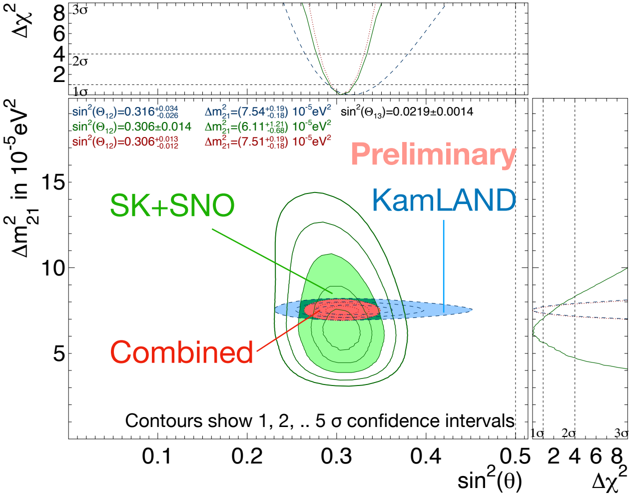




KamLAND results

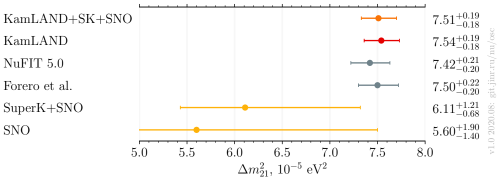
✓ Most precise Δm^2_{21} measurement

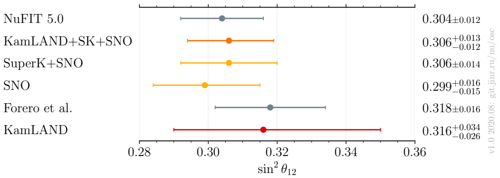


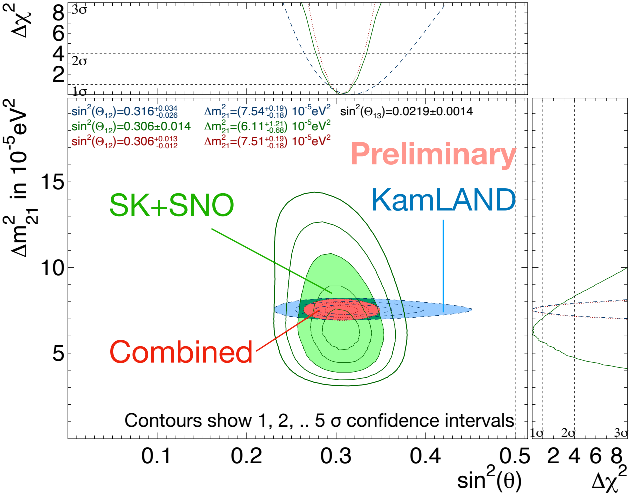


KamLAND results

- ✓ Most precise Δm^2_{21} measurement
- ✓ One of three θ_{12} measurements

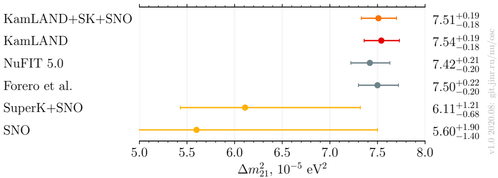


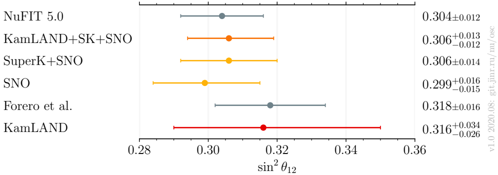


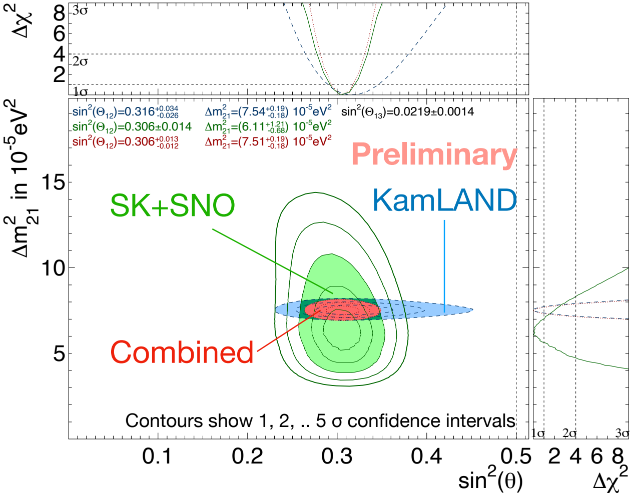


KamLAND results

- ✓ Most precise Δm^2_{21} measurement
- ✓ One of three θ_{12} measurements
- ✗ 1.5σ tension with SuperK
  ↪ solar discrepancy

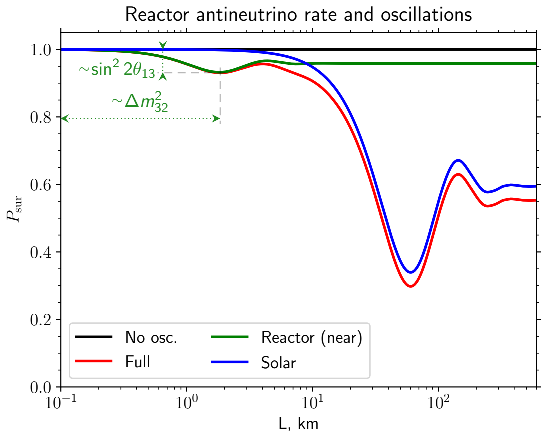


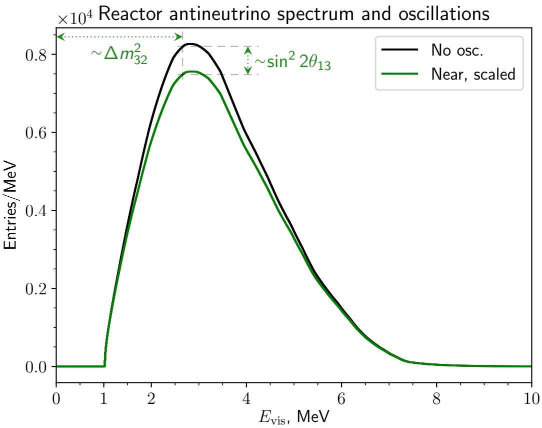




PRESENT:

θ_{13} and Δm^2_{32}





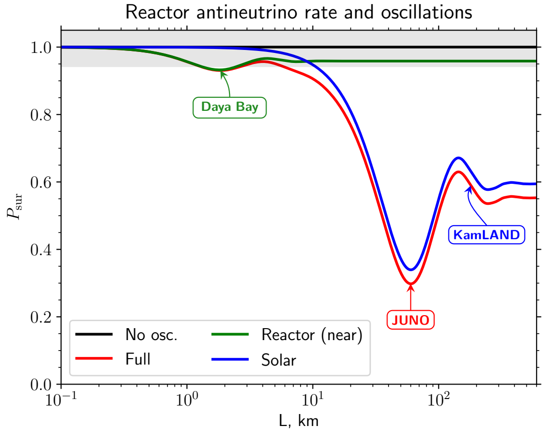
deficit value

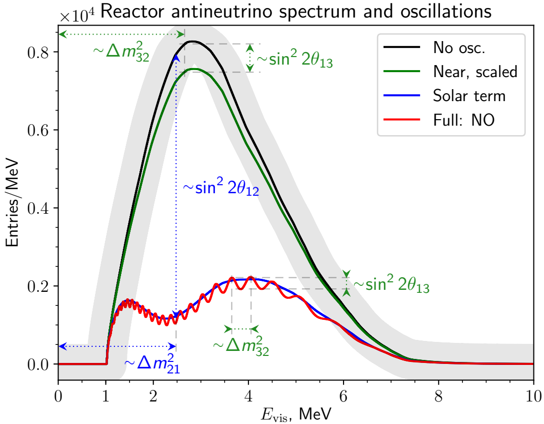
minimum location

$$1 - P_{\nu_e\to\nu_e} = \sin^2 2\theta_{13} \underbrace{\left(\sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E} + \cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E}\right)}_{\stackrel{\text{def}}{=}\sin^2\Delta m^2_{ee}L/(4E)} + \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

~~$\delta_{\rm CP}$, θ_{23}~~

$E_{\rm vis} \approx E_\nu - 0.78\,{\rm MeV}$





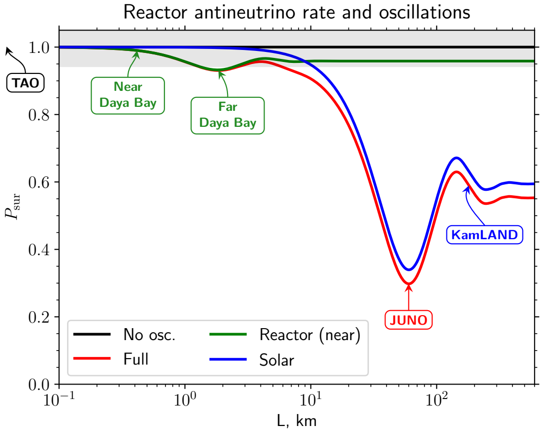
Challenges:

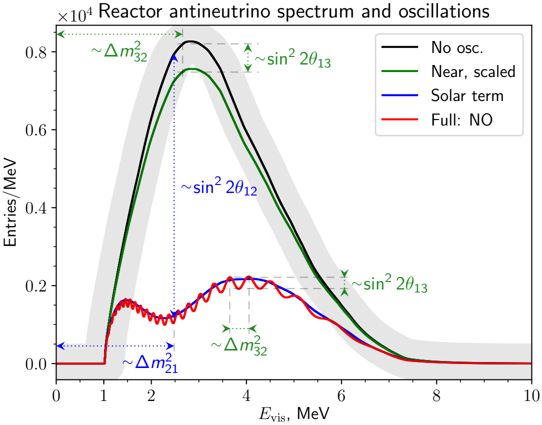
- Unreliable spectrum model

Daya Bay
total flux, spectrum shape

JUNO
fine structure?

$E_{\rm vis} \approx E_\nu - 0.78\,\text{MeV}$





Challenges:

- Unreliable spectrum model
- Efficiency uncertainty
- Energy scale uncertainty
- Energy resolution σ_E

Daya Bay

total flux, spectrum shape

$\lesssim 0.2\%$ uncorrelated

JUNO

fine structure?

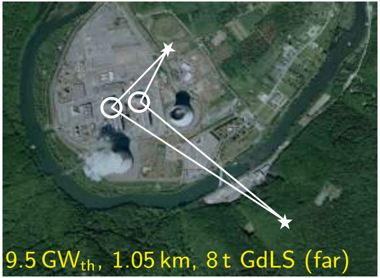
$<1\%$

$<3\%$ at 1 MeV

$E_{\rm vis} \approx E_\nu - 0.78\,\text{MeV}$

Medium baseline reactor experiments: 2011 $\rightsquigarrow$ 2020

Double CHOOZ, France



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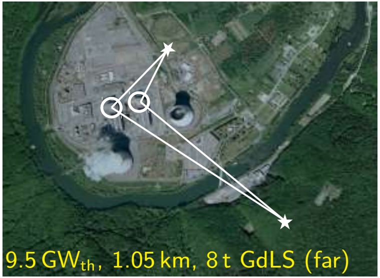

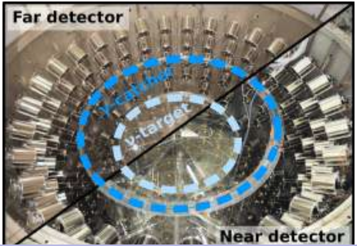

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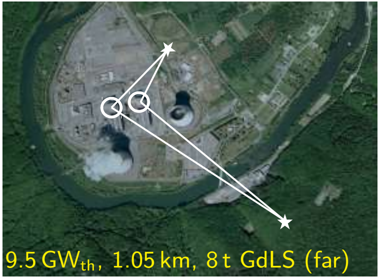
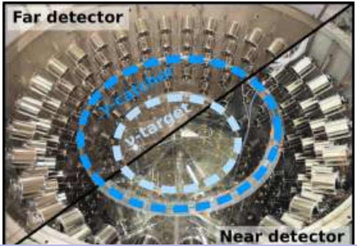


Reno, South Korea



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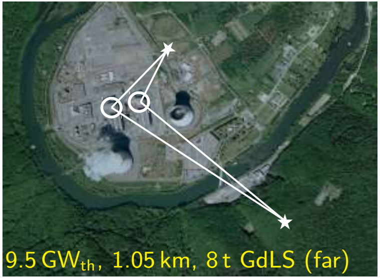

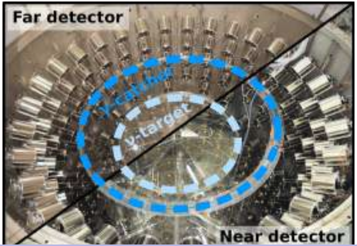

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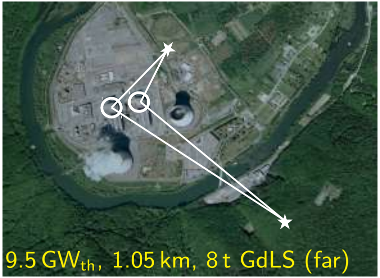

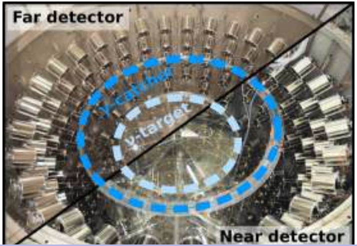

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Daya Bay, China

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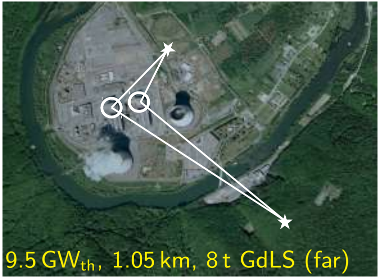

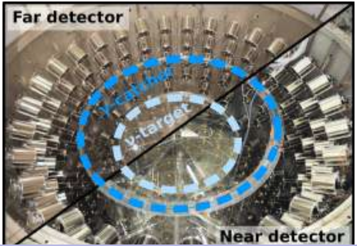

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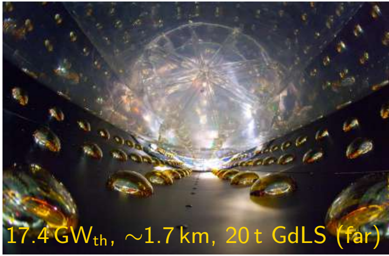
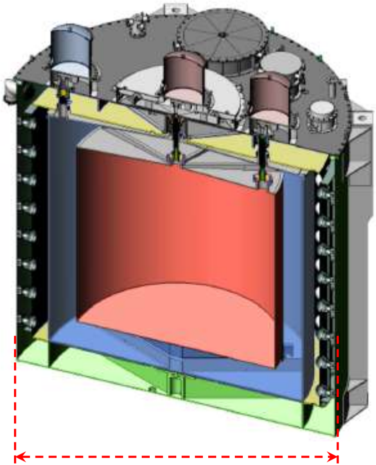
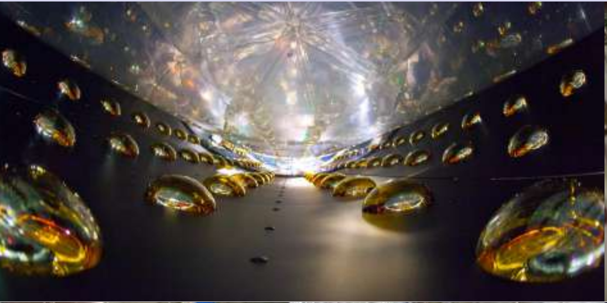
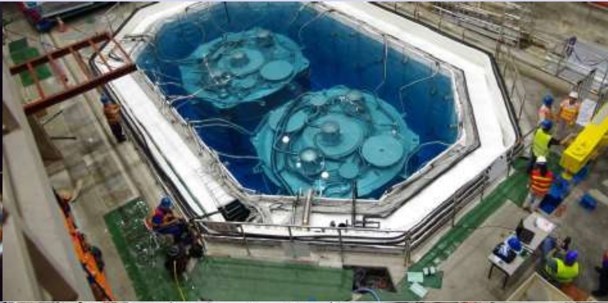


Antineutrino Detectors (AD)

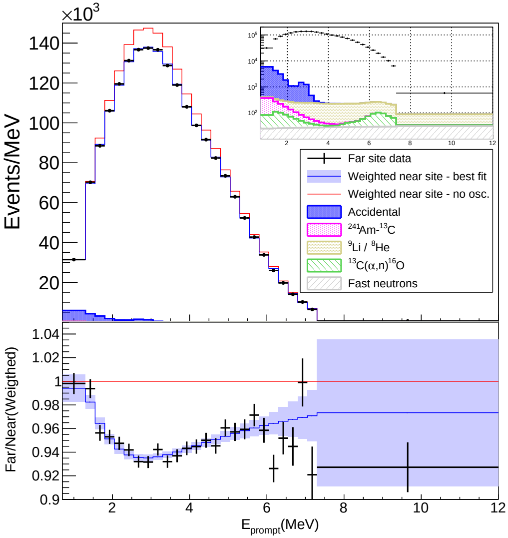


	Daya Bay
Attention	**Uncorr. ε unc.**
Method	**Identical ADs** **3 zones**
Scintillator	**GdLS/LS**
PMTs	**192 8"**
Coverage, %	**12**
Light col. p.e./MeV	**160**
σ_E at 1 MeV, %	**8.7**
Detectors	**4/4** far near
Thermal power, GW	**17.4**
Baseline	**0.5 km—2 km**
IBD/day/AD	**75/635** far near

Daya Bay detectors

Daya Bay oscillation result: 500K/4M events



1958 days, arXiv:1809.02261, PRL

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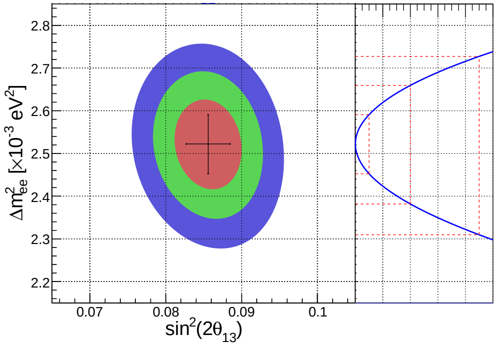
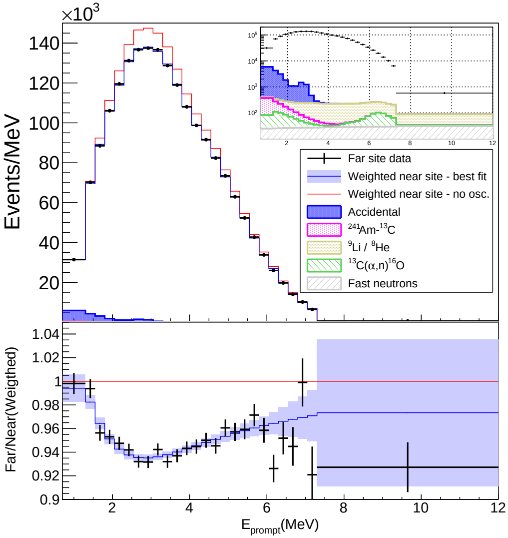




1958 days, arXiv:1809.02261, PRL

$$\sin^2 2\theta_{13} = 8.56 \pm 0.29 \quad \times 10^{-2} \qquad 3.4\%$$

$$|\Delta m^2_{ee}| = 2.522^{+0.068}_{-0.070} \quad \times 10^{-3}\ \text{eV}^2 \qquad 2.8\%$$

$$\chi^2/\text{NDF} = 148.0/154 \qquad \text{precision}$$

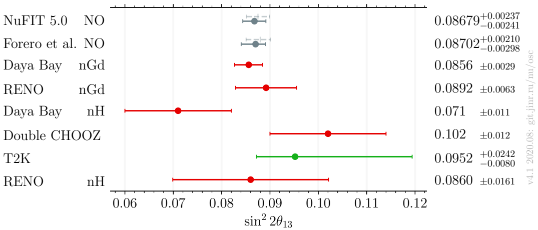
✓ Consistent with 3ν oscillations

Daya Bay oscillation result

nH, 621 days, arXiv:1603.03549, PRD

nGd, 1958 days, arXiv:1809.02261, PRL

- Most precise $\sin^2 2\theta_{13}$ measurement.
- $\sin^2 2\theta_{13} = 0$ is excluded at almost 30σ.
- nH $\sin^2 2\theta_{13}$ measurement is world's third in precision.



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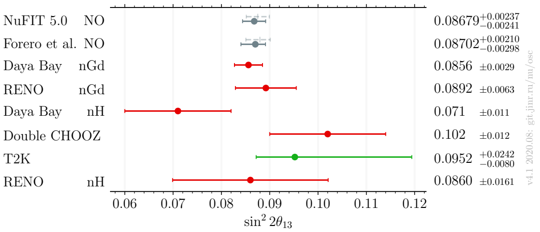
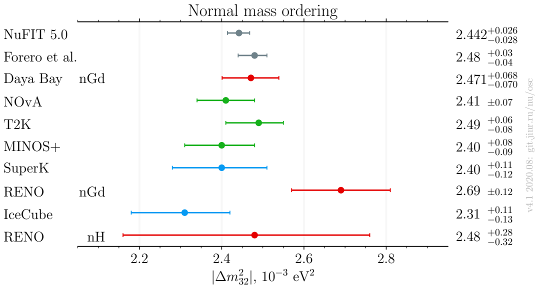
- nH $\sin^2 2\theta_{13}$ measurement is world's third in precision.
- First world's measurement of Δm^2_{32}.
- Δm^2_{32} is consistent with and complementary to accelerator measurements.
- Negligible correlation between $\sin^2 2\theta_{13}$ and Δm^2_{ee}.





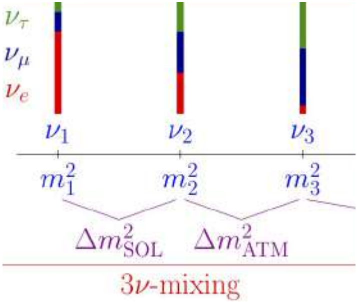
Present:

$\overline{\mathcal{V}}_s$

Why sterile neutrino?

General problem

- Are there any other neutrino flavors?
- Why do not we see them?



What if 3ν mixing is not a complete picture?

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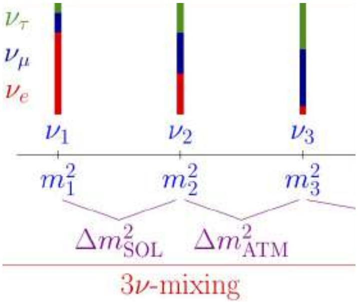
Particular problems

- Events deficit observed
- Spectrum distortion observed



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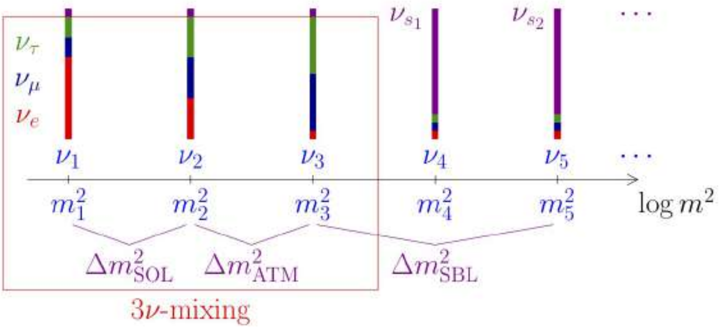

Possible solution

- Introduce new neutrino flavor ν_s
- Make it "undetectable"
- Oscillations to ν_s introduce rate deficit and spectrum distortion
- OR fix spectrum/cross-section/etc calculation

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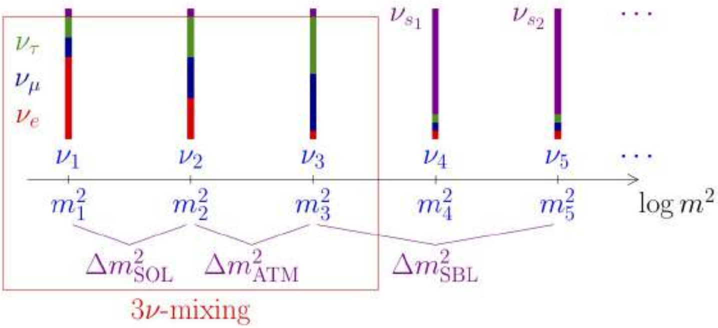

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- ✓ Solar neutrino anomaly Solved! (NP2015)
- Reactor neutrino anomaly
- Accelerator neutrino anomaly
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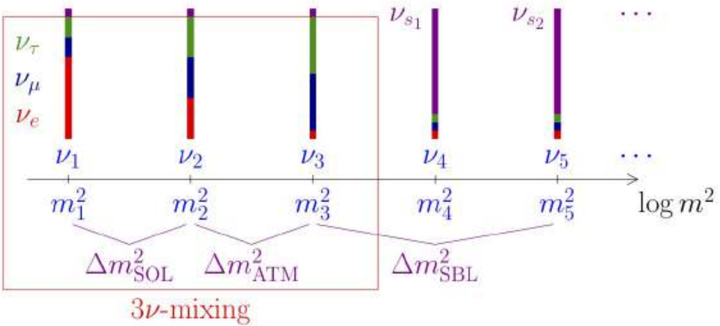

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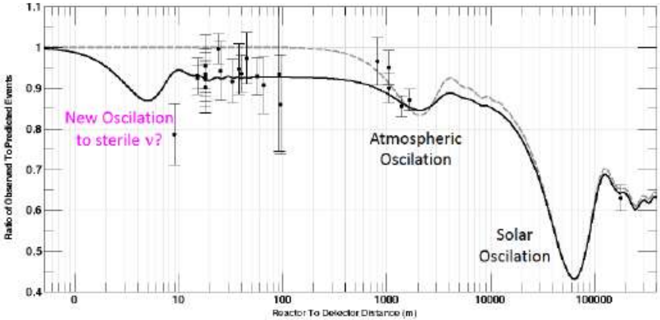
Short baseline neutrino oscillations



- Rate deficit at MBL may be explained as
- Oscillations to ν_s with $\Delta m^2_{41} > 1.5\,\mathrm{eV}^2$

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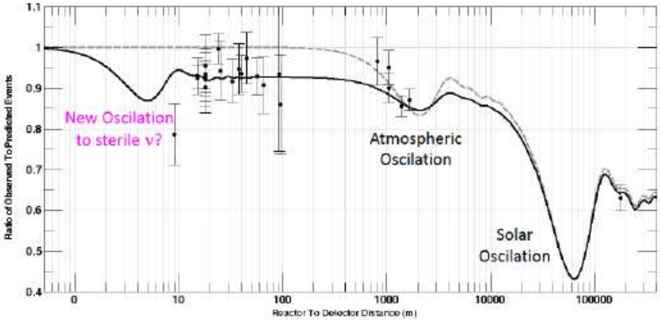

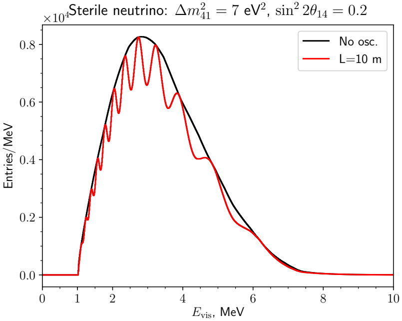

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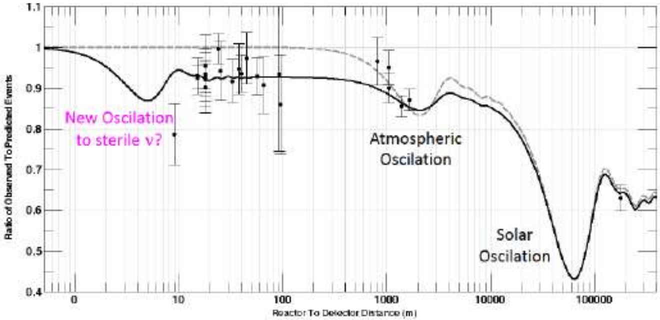

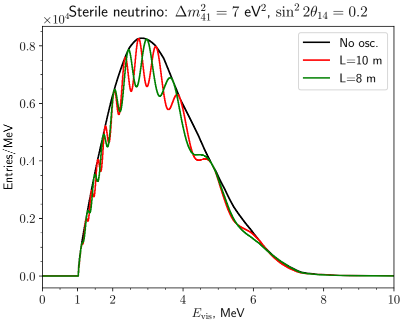

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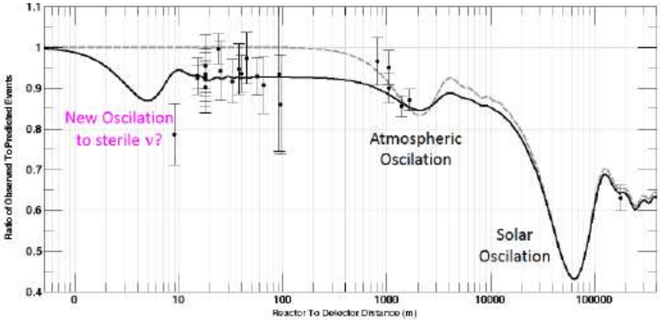

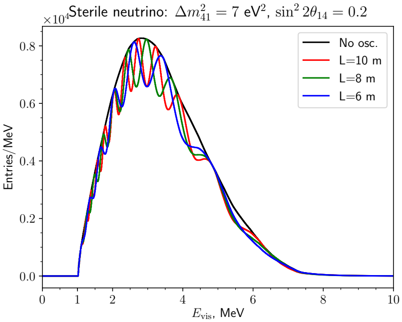

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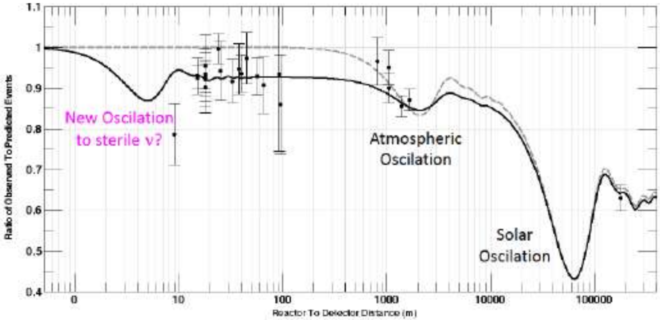

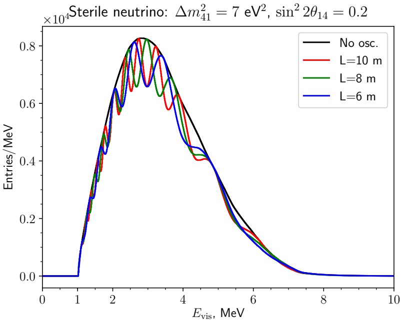

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- ✗ Inconsistent with cosmology

Sterile neutrino experiments

Detector \ Reactor	Segmented movable $L \lesssim 10$ m	Segmented	Whole GdLS	Multiple detectors Multiple reactors GdLS, $L > 100$ m
Research $W_{\mathrm{th}} < 100$ MW $L \lesssim 10$ m			Nucifer 7 m	
Industrial $W_{\mathrm{th}} \sim 3$ GW				

- Status: R&D, running, stopping soon, stopped
- Labels: Liquid scintillator, LS; Plastic scintillator, PS
- Reactor monitoring experiments not included: Angra, Chandler, Panda, Watchman

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Sterile neutrino experiments

Reactor \ Detector	Segmented movable $L \lesssim 10$ m	Segmented	Whole GdLS	Multiple detectors Multiple reactors GdLS, $L > 100$ m
Research $W_{\rm th} < 100$ MW $L \lesssim 10$ m		Stereo GdLS Prospect LiLS Solid LiPS NuLat LiPS	Nucifer 7 m	
Industrial $W_{\rm th} \sim 3$ GW			NEOS 25 m TAO 30 m	

- Status: R&D, running, stopping soon, stopped
- Labels: Liquid scintillator, LS; Plastic scintillator, PS
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Reactor \ Detector	Segmented movable $L \lesssim 10$ m	Segmented	Whole GdLS	Multiple detectors Multiple reactors GdLS, $L > 100$ m
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Sterile neutrino experiments

Reactor \ Detector	Segmented movable $L \lesssim 10$ m		Segmented		Whole GdLS		Multiple detectors Multiple reactors GdLS, $L > 100$ m
Research $W_{\rm th} < 100$ MW $L \lesssim 10$ m	Neutrino-4	GdLS	Stereo	GdLS	Nucifer	7 m	
	Neutrino-5	GdLS	Prospect	LiLS			
			Solid	LiPS			
			NuLat	LiPS			
Industrial $W_{\rm th} \sim 3$ GW	DANSS	GdPS			NEOS	25 m	
	MONUMENT				TAO	30 m	

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Sterile neutrino experiments

Detector / Reactor	Segmented movable, $L \lesssim 10$ m	Segmented	Whole, GdLS	Multiple detectors, Multiple reactors, GdLS, $L > 100$ m
Research, $W_{\rm th} < 100$ MW, $L \lesssim 10$ m	Neutrino-4 GdLS Neutrino-5 GdLS	Stereo GdLS Prospect LiLS Solid LiPS NuLat LiPS	Nucifer 7 m	
Industrial, $W_{\rm th} \sim 3$ GW	DANSS GdPS MONUMENT		NEOS 25 m TAO 30 m	Daya Bay RENO Double CHOOZ

- Status: R&D, running, stopping soon, stopped
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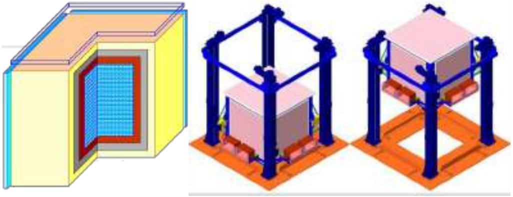
SBL sterile neutrino experiments

DANSS (Kalinin, 16–)



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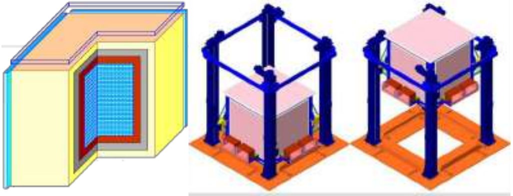
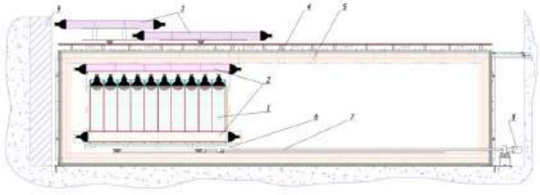


Neutrino 4 (Dimitrovgrad, 13 – 18)



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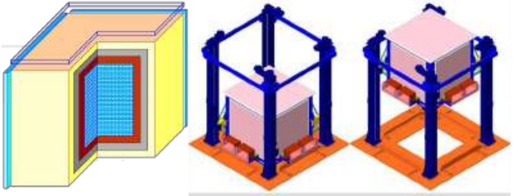

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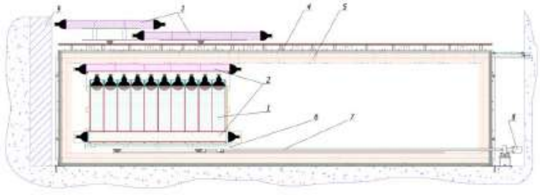
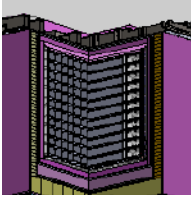
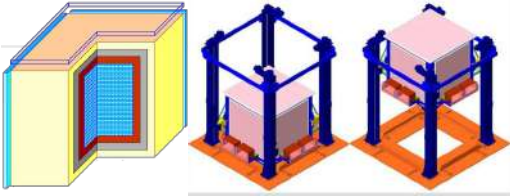


Prospect (US,16–)



SBL STERILE NEUTRINO EXPERIMENTS

DANSS (Kalinin, 16–)



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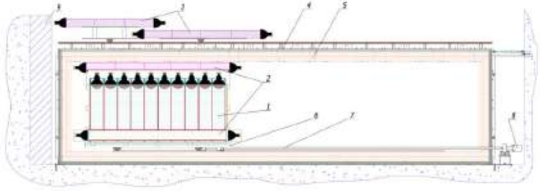

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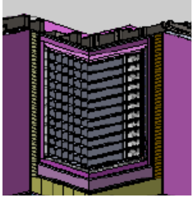
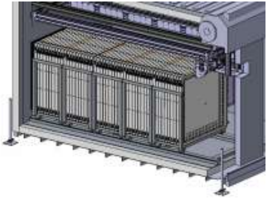


Solid (Belgium, 17–)



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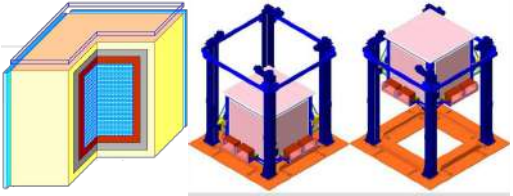

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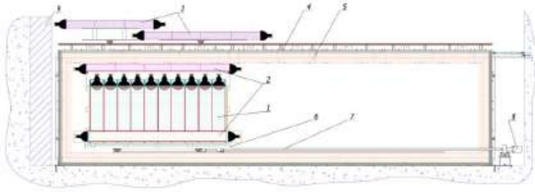

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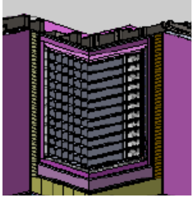

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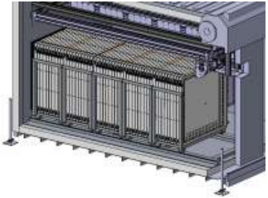
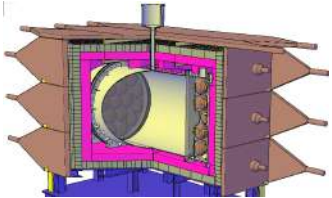


NEOS (Korea, 15 – 17)



SBL sterile neutrino experiments

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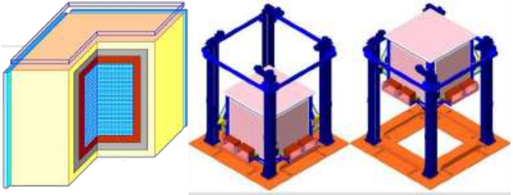

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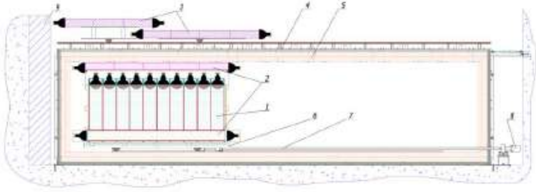

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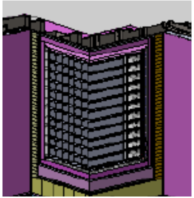

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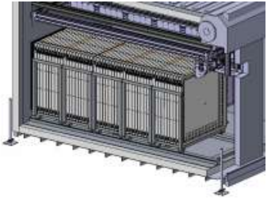

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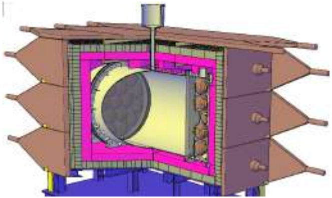
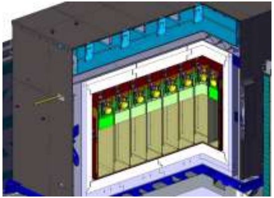


Stereo (France, 15 – 17)



Sterile neutrino SBL results 2020

- Recently Neutrino-4 claims sterile neutrino observation
- $\Delta m^2_{41} = (7.25 \pm 1.09)\,\mathrm{eV}^2$ and $\sin^2 2\theta_{14} = 0.26 \pm 09$.

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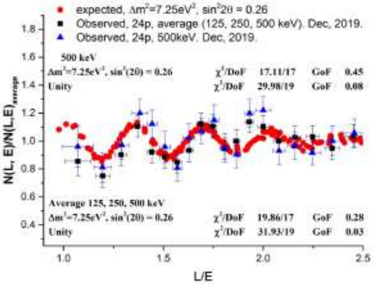

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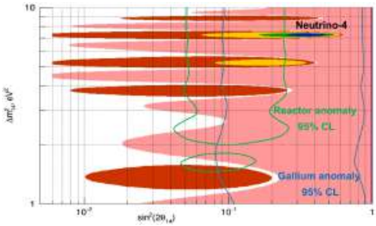

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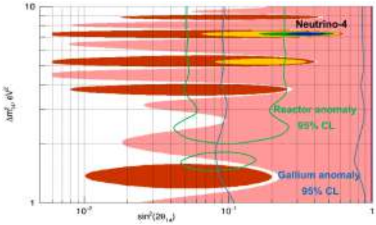
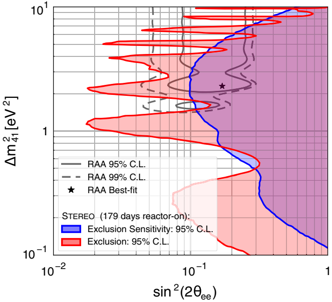


Stereo



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-

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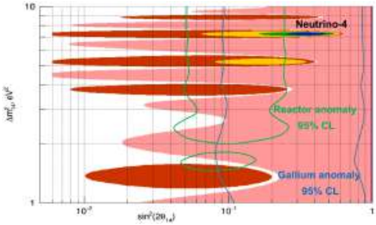

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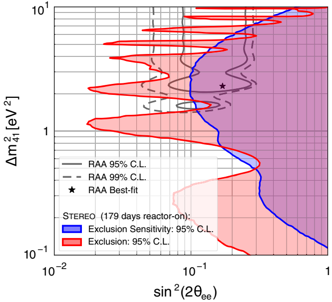

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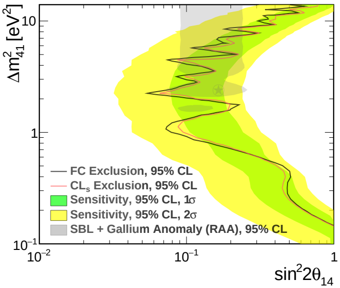
Prospect



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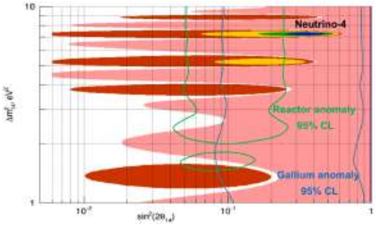
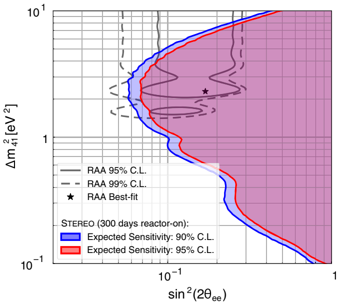
Neutrino-4



Stereo



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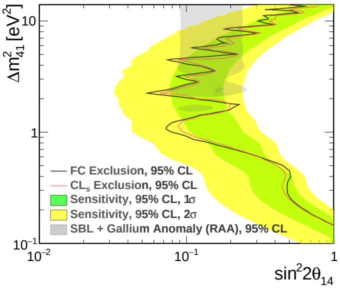

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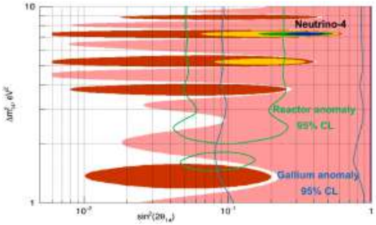
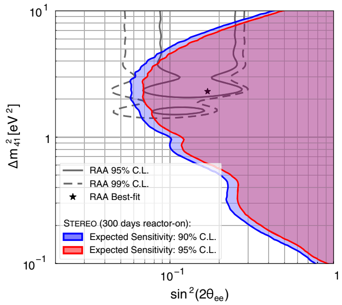
Neutrino-4

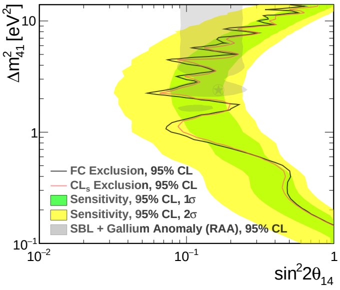


Future Stereo



- Energetic discussion: [2005.05301] started.
- Expect to cover Neutrino-4 on a full dataset.

Prospect



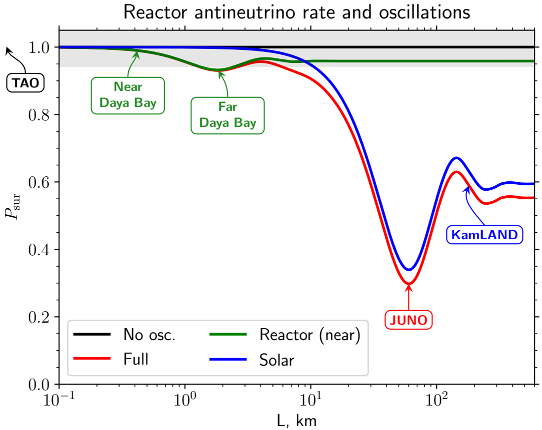
- Prospect not sensitive to Neutrino-4 claim.

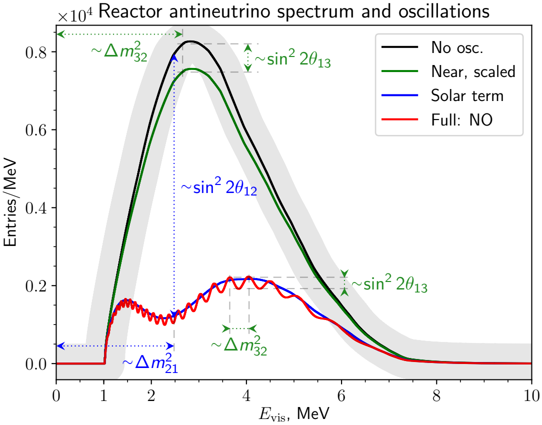
Future:

Neutrino mass ordering

and Δm^2_{32}, Δm^2_{21}, θ_{12},
and reactor $\overline{\nu}_e$ spectrum

and $\overline{\nu}_s$





Challenges:

- Unreliable spectrum model
- Efficiency uncertainty
- Energy scale uncertainty
- Energy resolution σ_E

Daya Bay

total flux, spectrum shape

$\lesssim 0.2\%$ uncorrelated

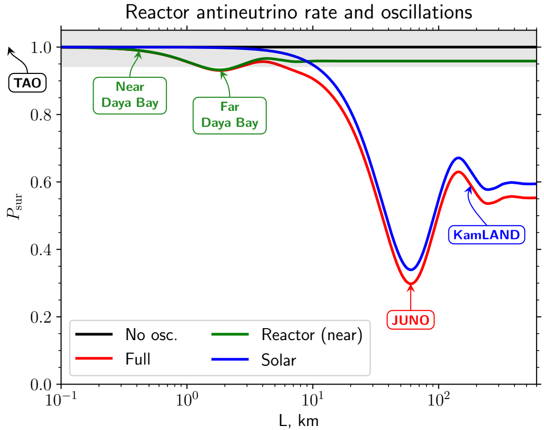
JUNO

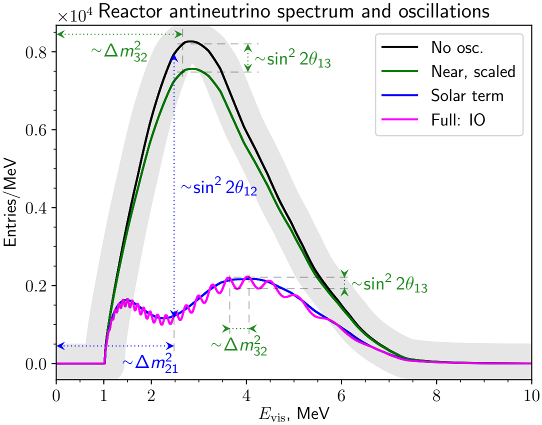
fine structure?

$<1\%$

$<3\%$ at 1 MeV

$E_{\rm vis} \approx E_\nu - 0.78\,\text{MeV}$





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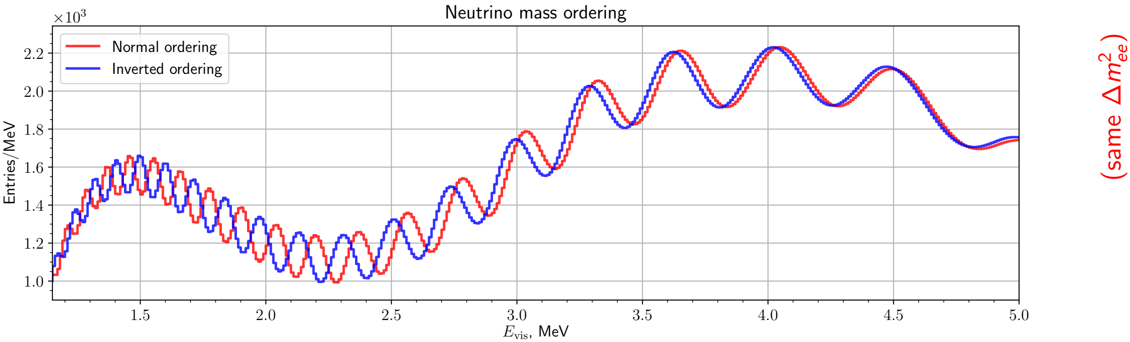

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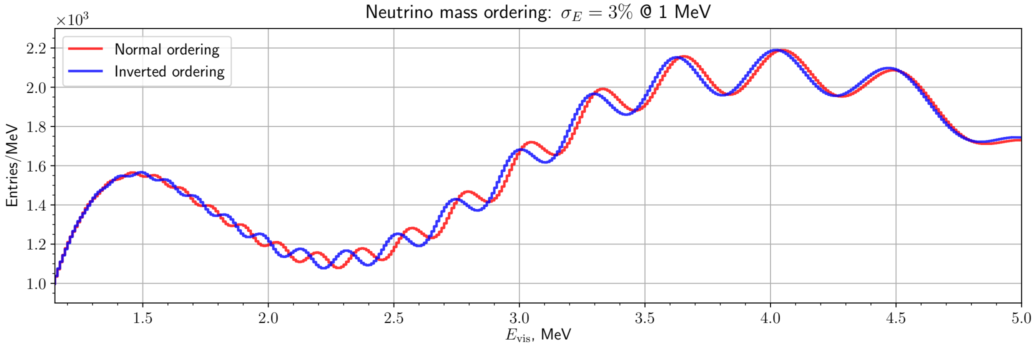

(same Δm^2_{ee})

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Daya Bay, JUNO and TAO location

- JUNO — Jiangmen Underground Neutrino Observatory
- TAO — Taishan Antineutrino Observatory

	Yangjian	Taishan
Thermal power, GW	2.9×6	4.6×~~4~~2
Total, GW	~~35.8~~ 26.6	

Daya Bay, JUNO and TAO location

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	Yangjian	Taishan	Daya Bay	Ling Ao	Ling Ao II
Thermal power, GW	2.9×6	4.6×~~4~~2	2.9×2	2.9×2	2.9×2
Total, GW	~~35.8~~ 26.6			17.4	

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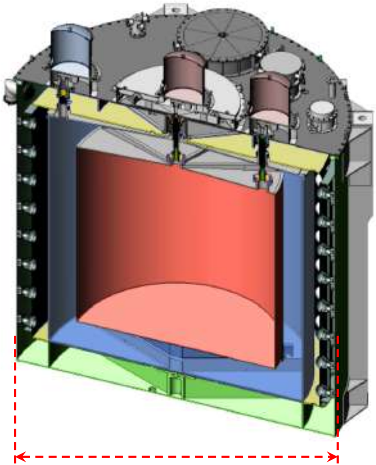
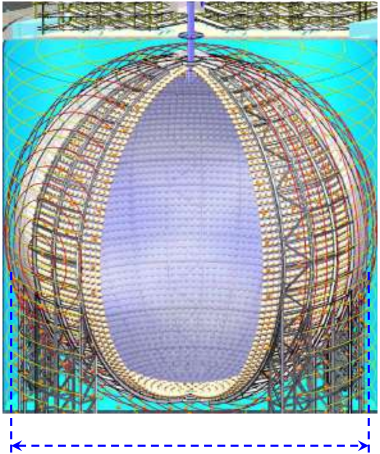
	Yangjian	Taishan	Daya Bay	Ling Ao	Ling Ao II	Huizhou
Thermal power, GW	2.9×6	4.6×~~4~~2	2.9×2	2.9×2	2.9×2	2.9×6
Total, GW	~~35.8~~ 26.6			17.4		17.4 ?

Antineutrino Detectors (AD)



	Daya Bay
Attention	**Uncorr. ε unc.**
Method	**Identical ADs** **3 zones**
Scintillator	**GdLS/LS**
PMTs	**192 8"**
Coverage, %	**12**
Light col. p.e./MeV	**160**
σ_E at 1 MeV, %	**8.7**
Detectors	**4/4** far near
Thermal power, GW	**17.4**
Baseline	**0.5 km—2 km**
IBD/day/AD	**75/635** far near

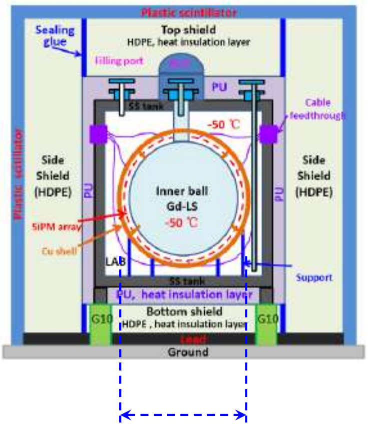
Antineutrino Detectors (AD)



35 m / 20 **k**t LS

	Daya Bay	JUNO
Attention	Uncorr. ε unc.	**Energy resolution**
Method	Identical ADs 3 zones	**Light collection**
Scintillator	GdLS/LS	**LS**
PMTs	192 8"	**18k 20"** **+26k 3"**
Coverage, %	12	**78**
Light col. p.e./MeV	160	~~1200~~ **1350**
σ_E at 1 MeV, %	8.7	**3**
Detectors	4/4 far/near	**1**
Thermal power, GW	17.4	~~35.8~~ **26.6**
Baseline	0.5 km—2 km	**52 km**
IBD/day/AD	75/635 far/near	~~60~~ **45**

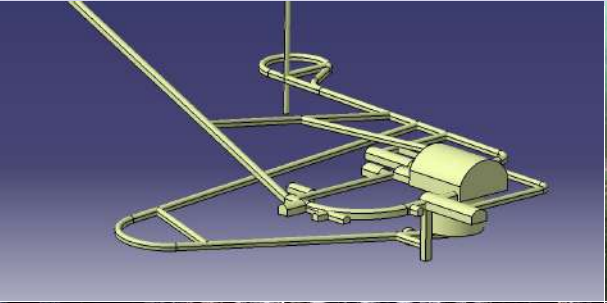
Antineutrino Detectors (AD)



1.7 m / 2.6 t GdLS

	Daya Bay	**TAO**	JUNO
Attention	Uncorr. ε unc.	**Energy resolution**	
Method	Identical ADs 3 zones	**Light collection** **Dark noise**	
Scintillator	GdLS/LS	**GdLS** **@ -50°C**	LS
PMTs	192 8"	**SiPM** **1.5M 5 mm**	18k 20" +26k 3"
Coverage, %	12	**94**	78
Light col. p.e./MeV	160	**4500**	~~1200~~ 1350
σ_E at 1 MeV, %	8.7	**2**	3
Detectors	4/4 far/near	**1**	1
Thermal power, GW	17.4	**4.6**	~~35.8~~ 26.6
Baseline	0.5 km—2 km	**30 m**	52 km
IBD/day/AD	75/635 far/near	**2000**	~~60~~ 45

Civil construction




Neutrino physics at JUNO I

- Neutrino mass ordering (NMO)
  - 3σ NMO sensitivity within ~~6~~ 8 years.
  - 4σ with Δm^2_{32} input from accelerator experiments.
  - $> 5\sigma$ combined analysis with IceCube within 3–7 years or PINGU in 2 years.
  - Combination with accelerator experiments — promising.

JUNO, IceCUBE, PINGU, arXiv:1911.06745

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Physics with TAO

- Precision reactor $\overline{\nu}_e$ spectra:
  - Total spectrum.
  - ${}^{235}\mathrm{U}/{}^{239}\mathrm{Pu}$ spectra.
- Search for sterile neutrino.

JUNO, IceCUBE, PINGU, arXiv:1911.06745

Neutrino physics at JUNO I

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  - Test U_{PMNS} unitarity on $< 1\%$ level $\hookrightarrow$ similar to quark sector.
- Atmospheric neutrinos ▶
  - Measure θ_{23} with 6° precision.
  - Complimentary NMO sensitivity.

Physics with TAO

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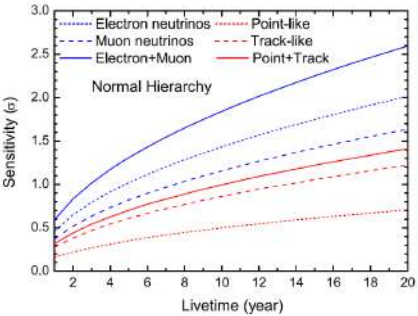

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Neutrino physics at JUNO II

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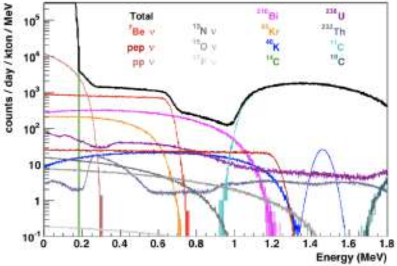

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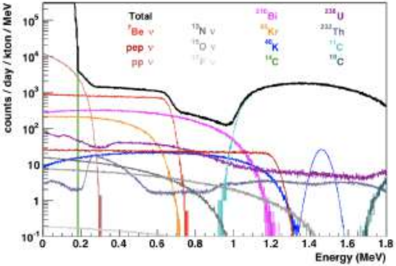
  - Sensitivity: flavor content, energy spectrum, time evolution.
  - 10k events (5k via IBD) for SN @ 10kpc.
- Diffuse SuperNOVA background (DSNB)
  - 3σ sensitivity in 10 years or strongest constraint.



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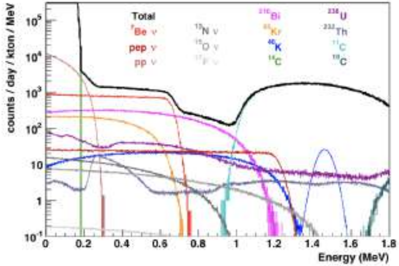
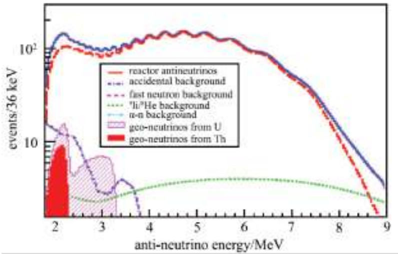
  - 400 – 500 neutrinos per year.
  - Largest statistics. Precision 5% in 10 years.





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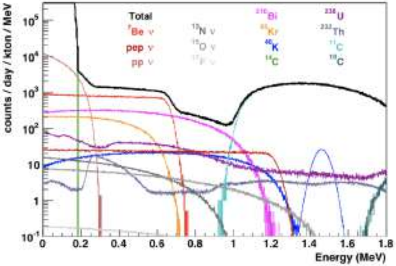
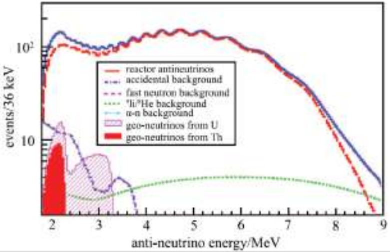
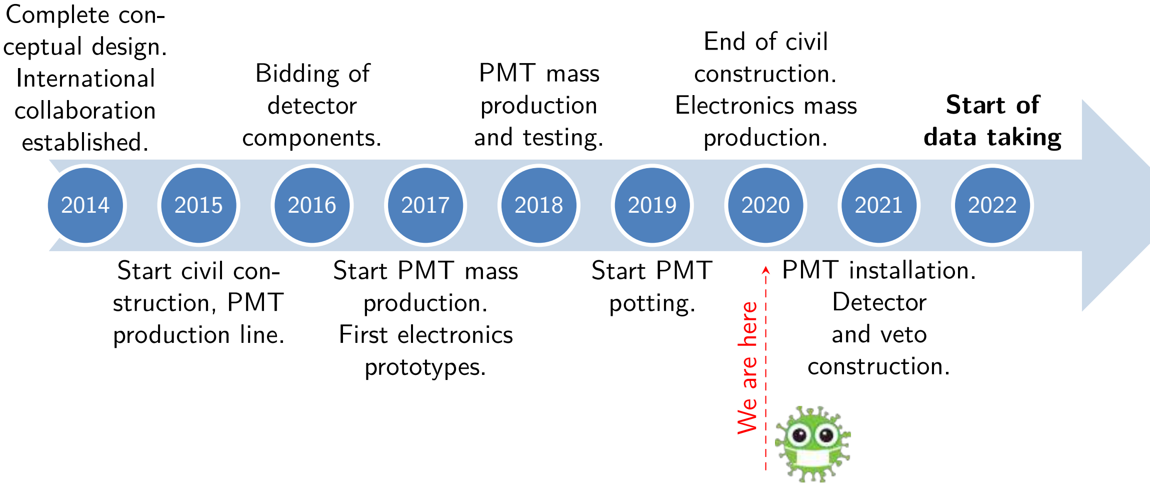
  - Competitive sensitivity via $p \to \overline{\nu} + K^+$.
  - Triple coincidence signal.

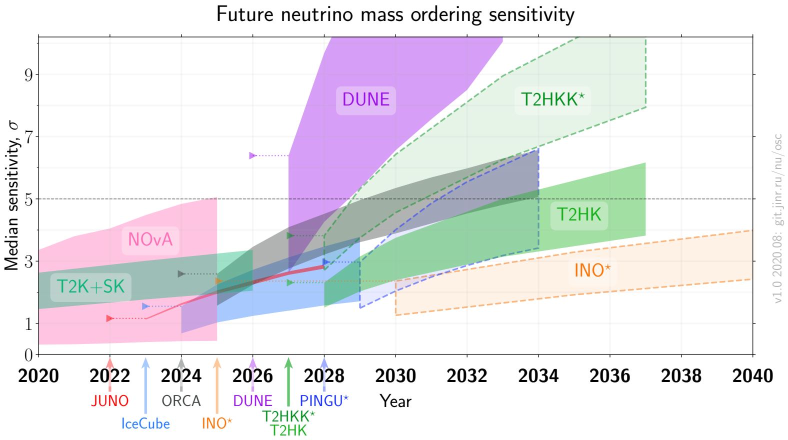




JUNO SCHEDULE



NMO estimation status



✓ JUNO alone: $\sim 3\sigma$

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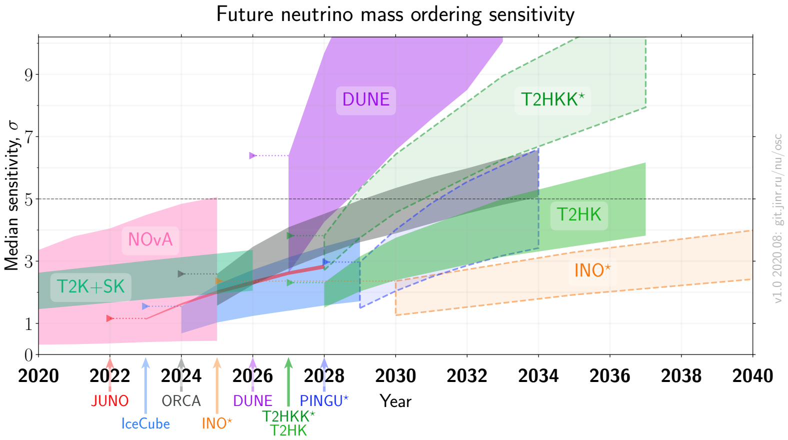

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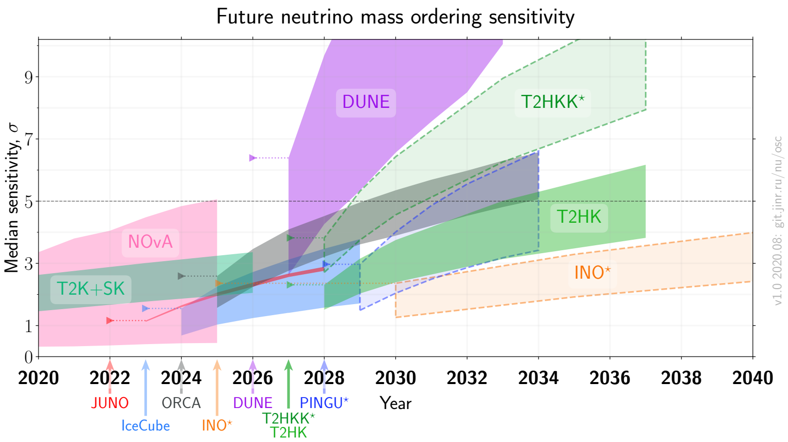

✓ JUNO alone: $\sim 3\sigma$

✓ +external constrain on Δm^2_{32}: $\sim 4\sigma$

✓ Combined with accelerator experiment: $> 5\sigma$

$\hookrightarrow$ sensitivity boost due to tension for wrong NMO

Reactor $\overline{\nu}_e$ summary

Summary

- Reactor $\overline{\nu}_e$ studies have long history

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  - Reactor monitoring: Angra, Chandler, Panda, Watchman

Thank you for your attention!

Spare slides:

Open neutrino questions and tasks

- Neutrino oscillation parameters measurement
  - Precision measurement of oscillation parameters
  - Neutrino mass hierarchy determination
  - CP-violation observation and δ_{CP} measurement
  - θ_{23} octant determination
  - Testing the unitarity of neutrino mixing matrix
- Exotic searches
  - Sterile neutrinos
  - Non-standard interactions
  - Lorenz invariance violation
- Neutrino mass
  - Direct neutrino mass measurement
  - Observation of $0\nu\beta\beta$ decay
- Astrophysics and geophysics
  - Solar neutrinos flux measurement
  - Observation of solar CNO neutrinos
  - Geo-neutrino flux measurement
  - Observation of SuperNova neutrinos
  - Observation of diffuse SuperNova neutrinos
  - Observation of relic neutrinos
  - Observation of ultra high-energy neutrinos and their sources
- Other questions:
  - Reactor antineutrino spectrum measurement

Neutrino prizes

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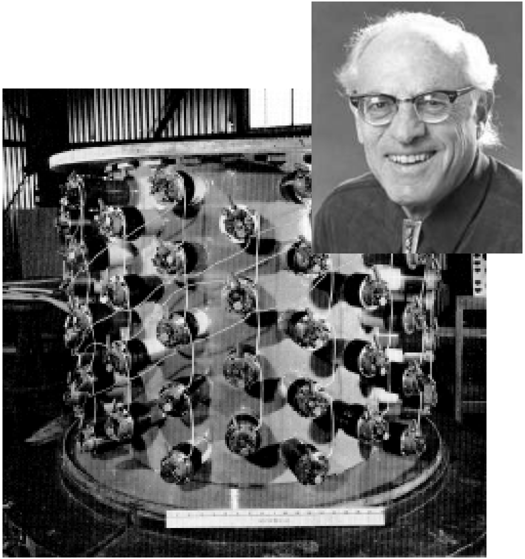

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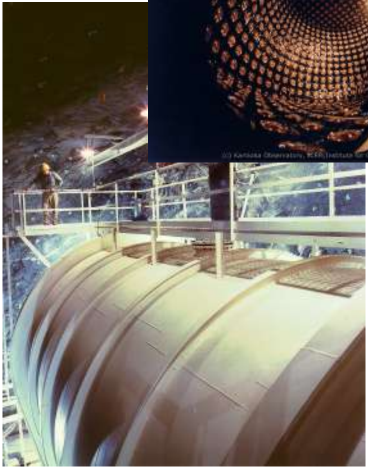

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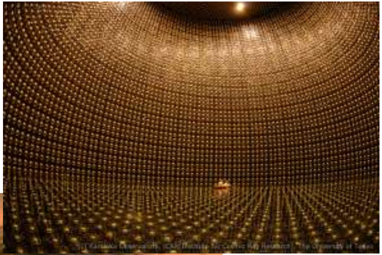

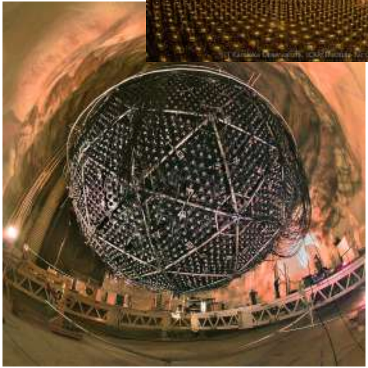

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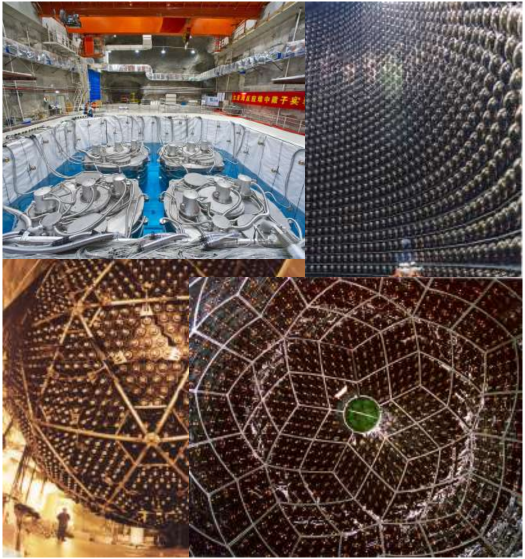


Data set: 1958 DAQ days

	EH1		EH2		EH3			
	AD1	AD2	AD3	AD8	AD4	AD5	AD6	AD7
$\overline{\nu}_e$ candidates	830036	964381	889171	784736	127107	127726	126666	113922
DAQ live time (days)	1536.621	1737.616	1741.235	1554.044	1739.611	1739.611	1739.611	1551.945
$\varepsilon_\mu \times \varepsilon_m$	0.8050	0.8013	0.8369	0.8360	0.9596	0.9595	0.9592	0.9595
Accidentals (day^{-1})	8.27 ± 0.08	8.12 ± 0.08	6.00 ± 0.06	5.86 ± 0.06	1.06 ± 0.01	1.00 ± 0.01	1.03 ± 0.01	0.86 ± 0.01
Fast neutron (AD^{-1} day^{-1})	0.79 ± 0.10		0.57 ± 0.07		0.05 ± 0.01			
^{9}Li/^{8}He (AD^{-1} day^{-1})	2.38 ± 0.66		1.59 ± 0.49		0.19 ± 0.08			
Am-C correlated(day^{-1})	0.17 ± 0.07	0.15 ± 0.07	0.14 ± 0.06	0.13 ± 0.06	0.06 ± 0.03	0.05 ± 0.02	0.05 ± 0.02	0.04 ± 0.02
^{13}C(α, n)^{16}O (day^{-1})	0.08 ± 0.04	0.06 ± 0.03	0.04 ± 0.02	0.06 ± 0.03	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	0.04 ± 0.02
$\overline{\nu}_e$ rate (day^{-1})	659.36 ± 1.00	681.09 ± 0.98	601.83 ± 0.82	595.82 ± 0.85	74.75 ± 0.23	75.19 ± 0.23	74.56 ± 0.23	75.33 ± 0.24

- ✓ 1958 days of DAQ data.
- ✓ Above 3.9M IBD candidates, 0.5M of them are on a far site. (high statistics)
- ✓ Statistical uncertainty in $\overline{\nu}_e$ rates: 0.1% – 0.3%.
- ✓ Background contribution to $\overline{\nu}_e$ rate: 1.5% – 2%. (low background)
- ✓ Background uncertainty in $\overline{\nu}_e$ rates 0.1%. (low systematics)

(+highly redundant)

Systematics: 1958 DAQ days

	Parameters	Uncorr.	Uncertainty	Comment
Free	Oscillation parameters (reactor)	P		
	Oscillation parameters (solar)	P		negligible
Reactor	Thermal power	R	0.5%	
	Fission fractions	RI*	5%	
	Average fission energy	I	0.12% – 0.25%	
	Off-equilibrium correction	RI	30%	
	SNF contribution	R	30%	
	$\overline{\nu}_e$ spectra	IE	2% – 30%	
Detector	**Relative efficiency**	D	**0.13%**	**dominant**
	Relative energy scale	D	**0.2%**	part. correlated
	Energy scale non-linearity	P	<1%	
	Energy resolution	P	30%	negligible
	IAV energy distortion	D	4%	
Background	Accidentals rate	D	0.4%	
	^{8}He/^{9}Li rate	S	30%	**secondary**
	^{9}Li contribution to ^{8}He/^{9}Li		5%	negligible
	Fast neutrons rate	S	10% – 17%	
	^{241}Am-^{13}C rate		40% – 45%	
	^{13}C$(\alpha, n)^{16}$O rate	D	50%	
	Background spectra shape		no	negligible

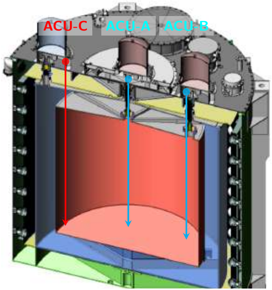
Uncorrelated groups

- **P**arameter
- **R**eactor
- Fissile **I**sotope
- **S**ite
- **D**etector
- **E**nergy bin
- * — part. correlation

Energy response calibration

Automated calibration units (ACU)

- Three ACUs with: ^{60}Co (weekly), ^{68}Ge, ^{241}Am-^{13}C, LED.
- Continuous energy scale calibration with spallation neutrons.



Energy response nonlinearity

- LS nonlinearity (quenching and Cherenkov) + Electronics nonlinearity.

✗ Difficult to disentangle.

Updates

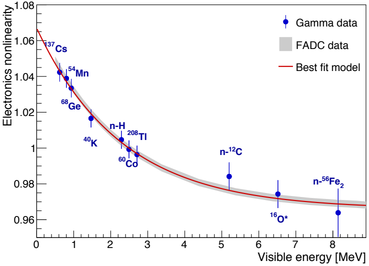
✓ ADC/FADC simultaneous readout in a EH1-AD1 since 2016
$\hookrightarrow$ measurement of electronics nonlinearity.

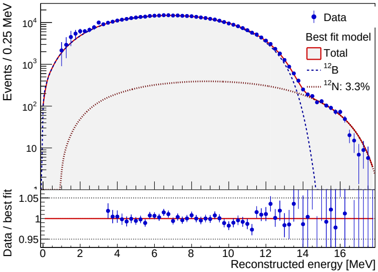
✓ Deployment of ^{60}Co calibration sources with different coating material (early 2017)
$\hookrightarrow$ measurement of shadowing effects.

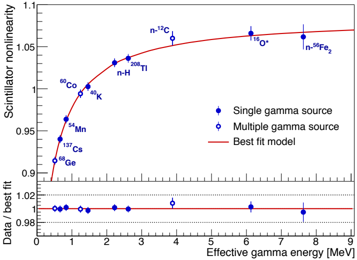
✓ MC simulation of energy loss in ^{60}Co coating material.

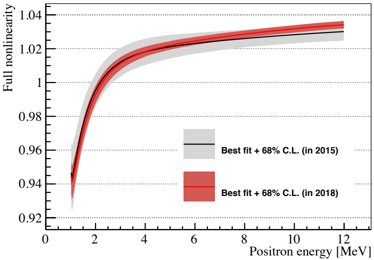
Energy response calibration

arXiv:1902.08241, NIMA





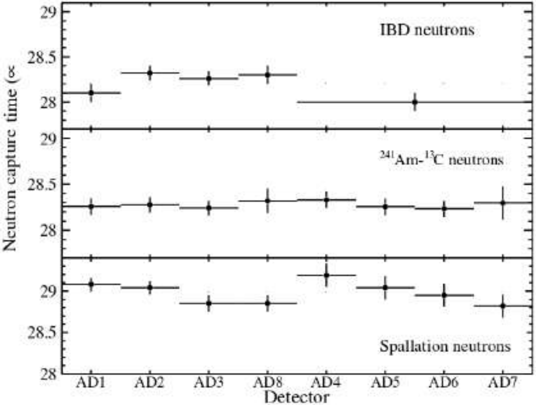




- ✓ Decoupled electronics and scintillator nonlinearity
- ✓ Continuous ^{12}B spectrum
- ✓ Combined positron energy nonlinearity uncertainty: $1\% \to 0.5\%$

Relative efficiency and relative energy scale

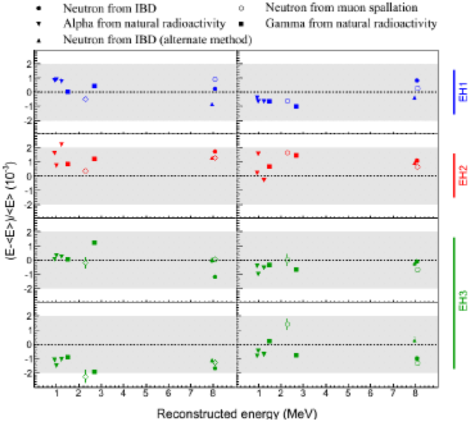
- Relative efficiency $\rightarrow \sin^2 2\theta_{13}$ uncertainty.



✓ Relative Gd capture fraction unc. $< \mathbf{0.10\%}$.

✓ Relative efficiency uncertainty $< \mathbf{0.13\%}$.

- Relative energy scale $\rightarrow \Delta m^2_{32}$ uncertainty.

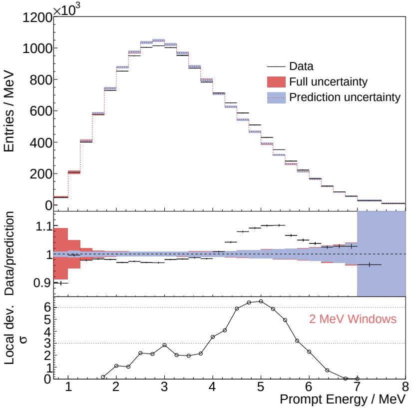


✓ Relative energy scale uncertainty $< \mathbf{0.2\%}$.

INDIVIDUAL SPECTRA OF ^{235}U AND ^{239}Pu

1958 days, arXiv:1904.07812, PRL

Observed positron spectrum



- Disagreement with Huber+Mueller:

  5.3σ global/6.3σ local.

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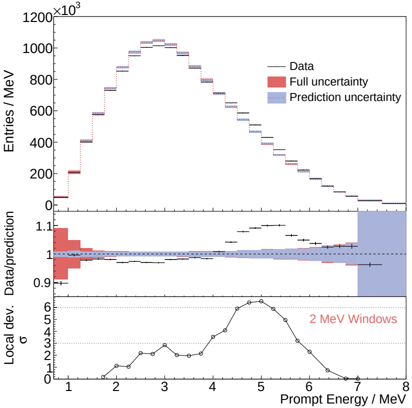
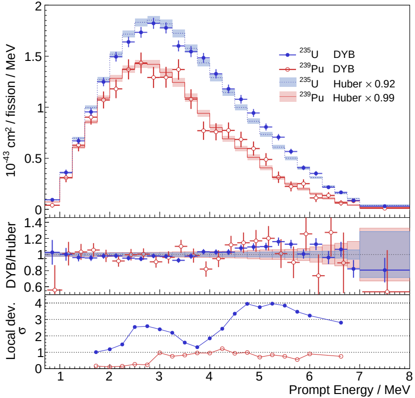


Extracted antineutrino spectra

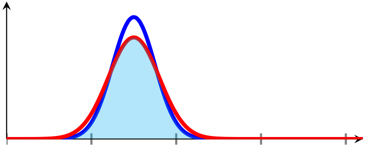


- Disagreement with Huber+Mueller: 5.3σ global/6.3σ local.
- $4-6$ MeV excess: 7% ^{235}U/9% ^{239}Pu.
- ^{235}U shape discrepancy: 4σ.

Wave packet effects

$$\sigma_p = \frac{1}{2\sigma_x}$$

Maximal coherence:
oscillations



- Plane-wave (PW) model of neutrino oscillations is not self-consistent.
- A wave-packet (WP) model modifies the oscillation probability formula.
- New parameter σ_p — effective dispersion of neutrino wave-packet.
- Predicts suppression of oscillations:
  - at distances exceeding the **coherence length** $L^{\text{coh}} = \frac{L^{\text{osc}}}{\sqrt{2\pi}\sigma_{\text{rel}}}$, where $\sigma_{\text{rel}} = \sigma_p/p$.
  - if $\sigma_x \gg L^{\text{osc}}$, where $\sigma_x = 1/(2\sigma_p)$.
- No experimental bounds.

Wave packet effects

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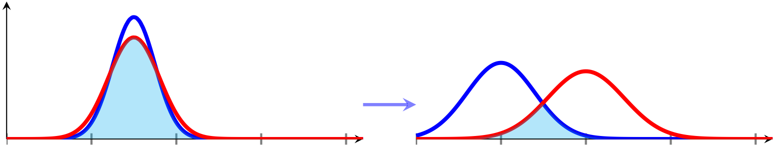
Maximal coherence: oscillations

Partial coherence: oscillations suppressed



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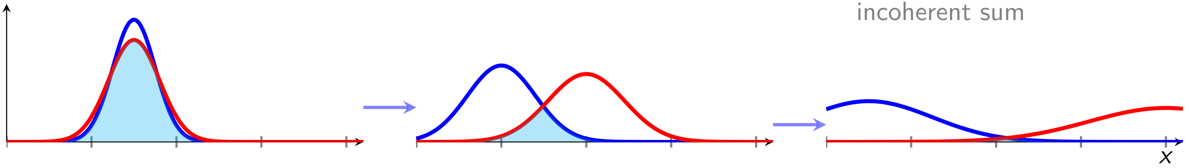
Wave packet effects

Maximal coherence:
oscillations

Partial coherence:
oscillations suppressed

∼No coherence:
no oscillations
incoherent sum

$$\sigma_p = \frac{1}{2\sigma_x}$$

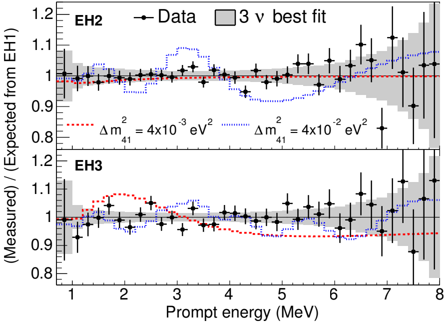


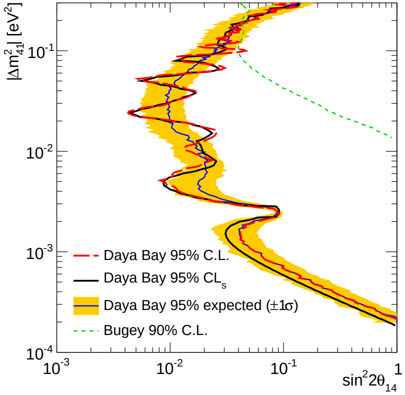
- Plane-wave (PW) model of neutrino oscillations is not self-consistent.
- A wave-packet (WP) model modifies the oscillation probability formula.
- New parameter σ_p — effective dispersion of neutrino wave-packet.
- Predicts suppression of oscillations:
  - at distances exceeding the **coherence length** $L^{\text{coh}} = \dfrac{L^{\text{osc}}}{\sqrt{2}\pi\sigma_{\text{rel}}}$, where $\sigma_{\text{rel}} = \sigma_p/p$.
  - if $\sigma_x \gg L^{\text{osc}}$, where $\sigma_x = 1/(2\sigma_p)$.
- No experimental bounds.

Light sterile neutrino search

621 days, arXiv:1607.01174, PRL

- Sterile neutrino cause spectral distortions, different at the near and far sites.
- ✓ Relative measurement.
- ✓ independent of reactor related systematics.
- **Consistent with 3-flavor oscillations.**





Light sterile neutrino search update

1230 days+MINOS, arXiv:2002.00301

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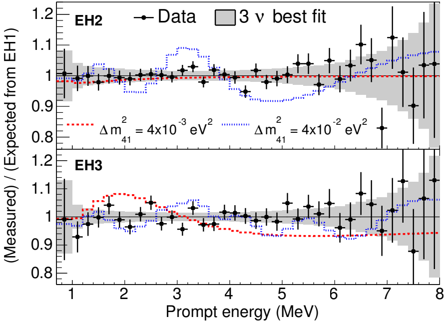
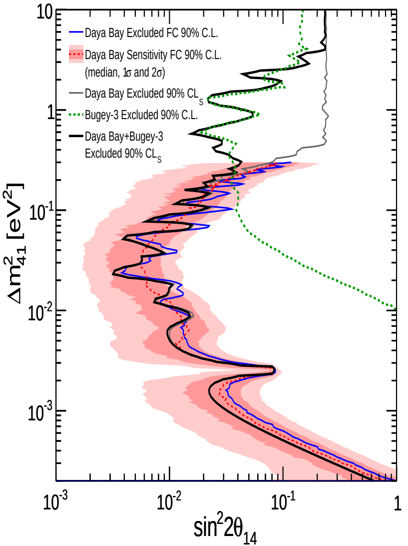




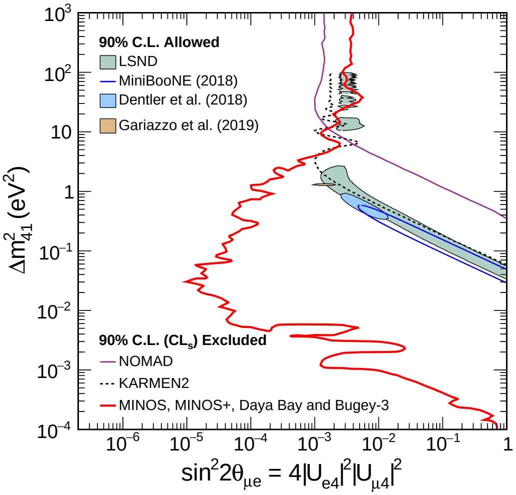
Y-scaled for consistency

Light sterile neutrino search update

1230 days+MINOS, arXiv:2002.00301

- Daya Bay and Bugey-3 strongly constrain Δm^2_{41} and $\sin^2 2\theta_{14}$.
- Daya Bay, Bugey-3 and MINOS data allows to constrain Δm^2_{41} and $\sin^2 2\theta_{14} \sin^2 \theta_{24}$.

✓ LSND and MiniBooNE parameters space is excluded at the 90% C.L.



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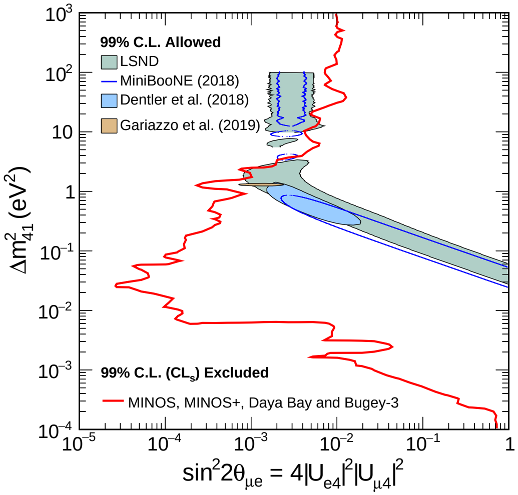
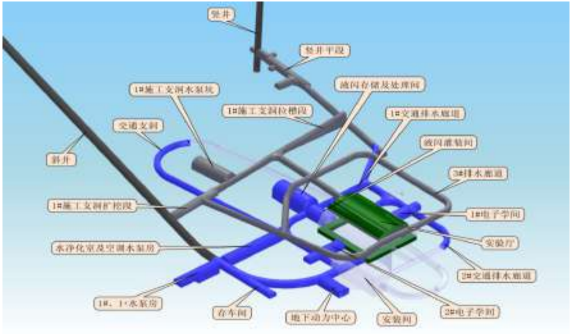
✓ LSND and MiniBooNE parameters space is excluded at the 99% C.L. for $\Delta m^2_{41} < 1.2\,\text{eV}^2$.



JUNO construction status

Civil construction

- Most of the tunnels finished.
- Transportation tunnel 389/506 m.
- Exp hall: above hall almost finished.
- TODO: detector cavern.
- Expect to finish by the end of 2020.



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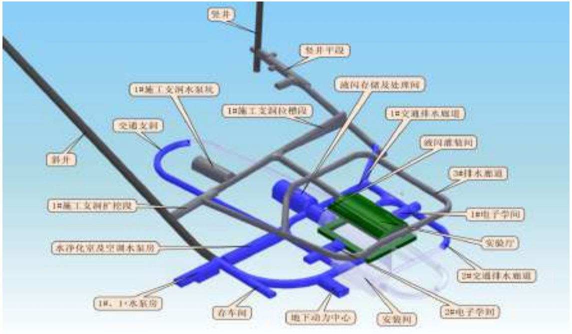
Experiment preparation

- 1:12 prototype at IHEP: 600 tons.
- TAO: CDR coming soon.
- OSIRIS R&D: Online Scintillator Internal Radioactivity Investigation System
  - Sensitivity: 10^{-16} g/g for U/Th within 24 h.



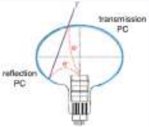
Detector assembly technique:
https://www.youtube.com/watch?v=B_uPQZPgU00

JUNO PMT STATUS

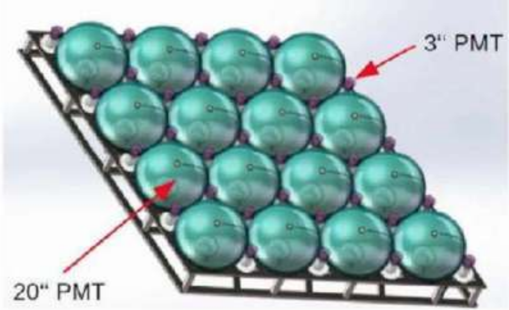
Large 20" PMT system

- 12'768 MCP PMTs by NNVT: delivered.
- 5'000 Dynode PMTs by Hamamatsu: delivered.
- Testing: mostly done.
- Protection cover: production started.

NNVT MCP



Hamamatsu Dynode



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Small 3" PMT system

✓ Complementary PMT system:
  - Increase dynamic range.
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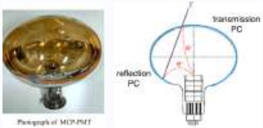
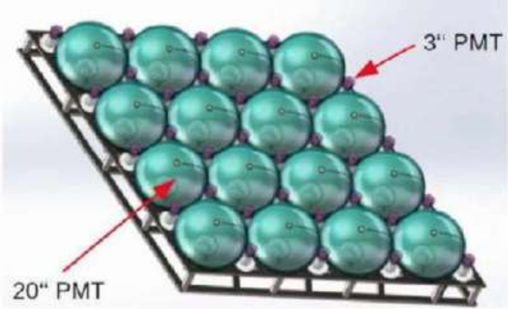
NNVT MCP



Hamamatsu Dynode



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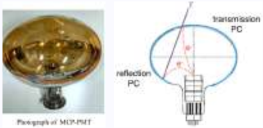
	NNVT	Hamamatsu	HZC
PDE, %	28.3	28.1	24
TTS, ns	12	2.7	1.5

NNVT MCP



Hamamatsu Dynode