Neutrino signals of the next galactic supernova

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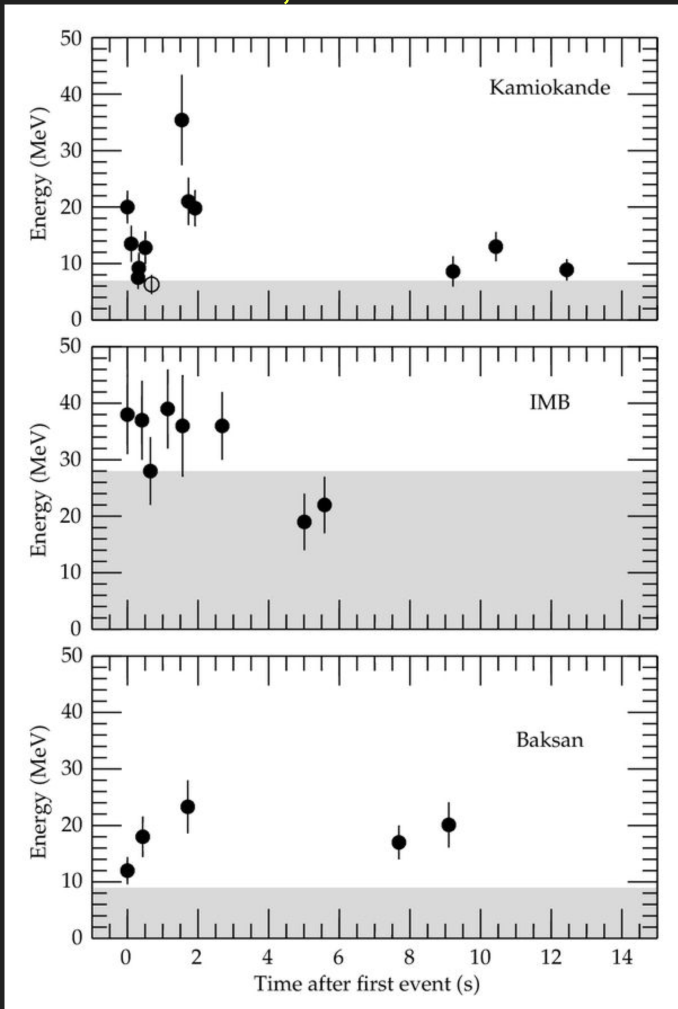
Supernova neutrino signal detection: SN1987a

23 Feb 1987, 7:35 UTC



A burst of **25** neutrino events within **13** seconds observed in three underground neutrino experiments.

Light signal appeared 2-3 hours later: a supernova explosion in the Large Magellanic cloud (51 kpc away)

Low-background neutrino experiments: they were able to look back at the data in the region of interest.

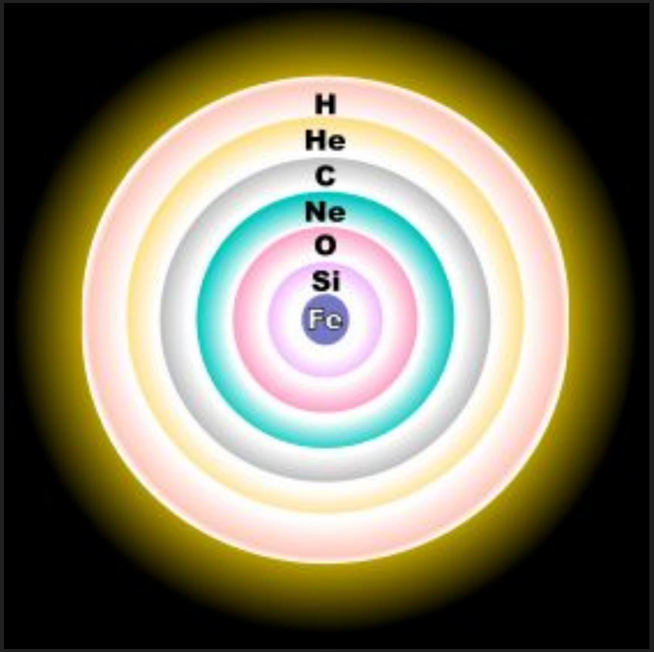
Stellar evolution

In the beginning, star is composed mostly from hydrogen

Nuclear fusion reactions, transforming fuel into heavier elements:

Process	Main fuel	Main products	Temperature (K)	Density (g/cm^3)	Duration
hydrogen burning	hydrogen	helium	7×10^7	10	10^7 years
triple-alpha process	helium	carbon, oxygen	2×10^8	2000	10^6 years
carbon burning process	carbon	Ne, Na, Mg, Al	8×10^8	10^6	1000 years
neon burning process	neon	O, Mg	1.6×10^9	10^7	3 years
oxygen burning process	oxygen	Si, S, Ar, Ca	1.8×10^9	10^7	0.3 years
silicon burning process	silicon	nickel (decays into iron)	2.5×10^9	10^8	5 days

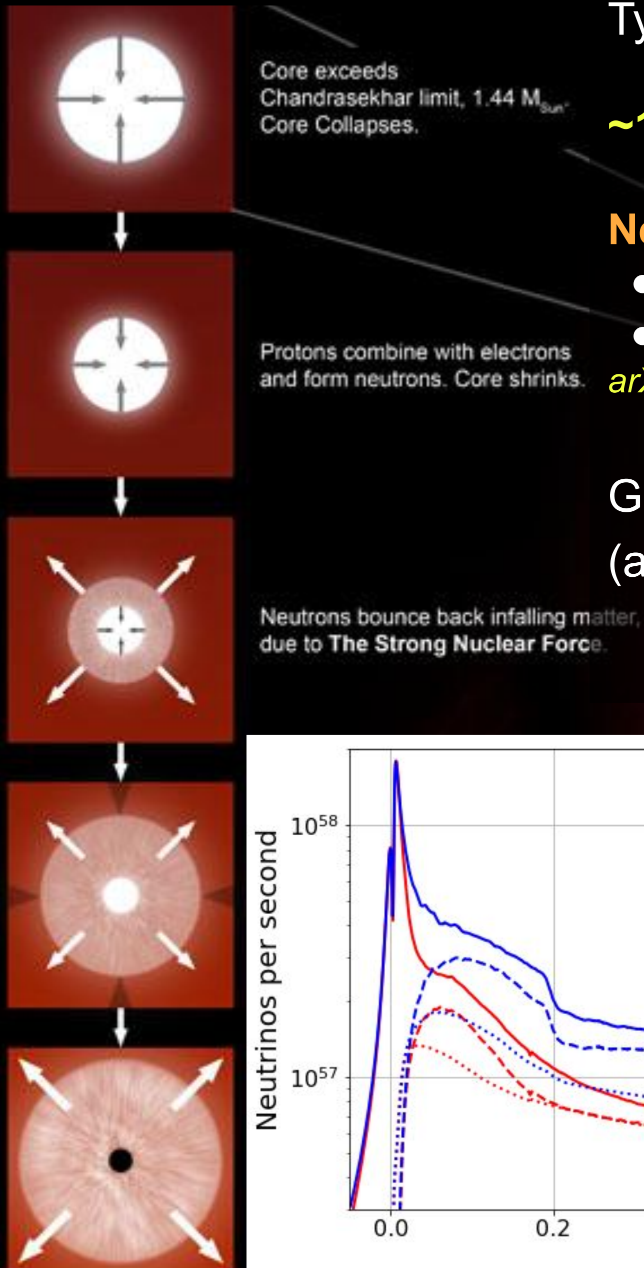
Core-burning nuclear fusion stages for a 25-solar mass star (25 $M_\odot$ star[5])



After Fe, the binding energy of nucleus decreases → fusion in iron core doesn't produce energy.

Gravitational pressure from outer layers is not compensated by fusion energy
⇒ gravitational collapse
⇒ Fe core transformed into proto neutron star

Neutrino signal from the core-collapse supernova



Type II SN radiates ~**99%** of the collapse energy in neutrinos:

~10^{58} neutrinos: **E_ν~10-60 MeV** within **T ~10s**

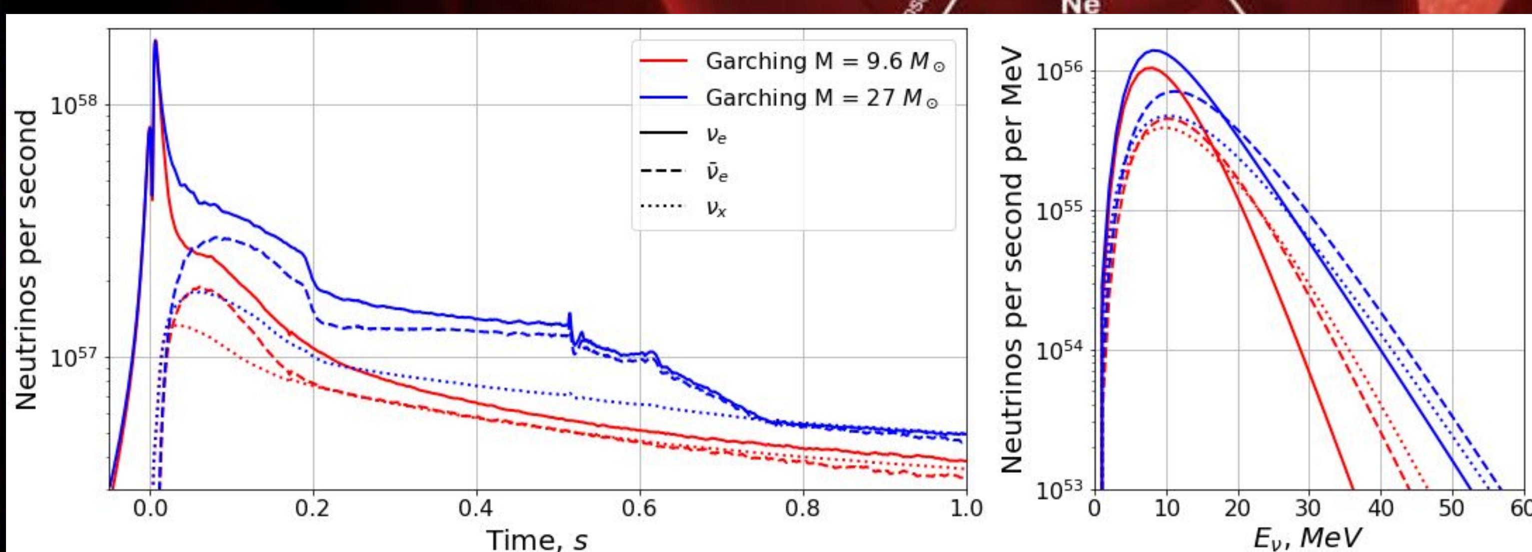
Neutrino signal: probe of

- Neutrino properties
- Supernova properties

arXiv:1508.00785 [astro-ph.HE]

Galactic SN are very rare: **~1-3** per century!

(and have never been observed in the neutrinos in our galaxy)



SuperNova Early Warning System v1.0

snews.bnl.gov

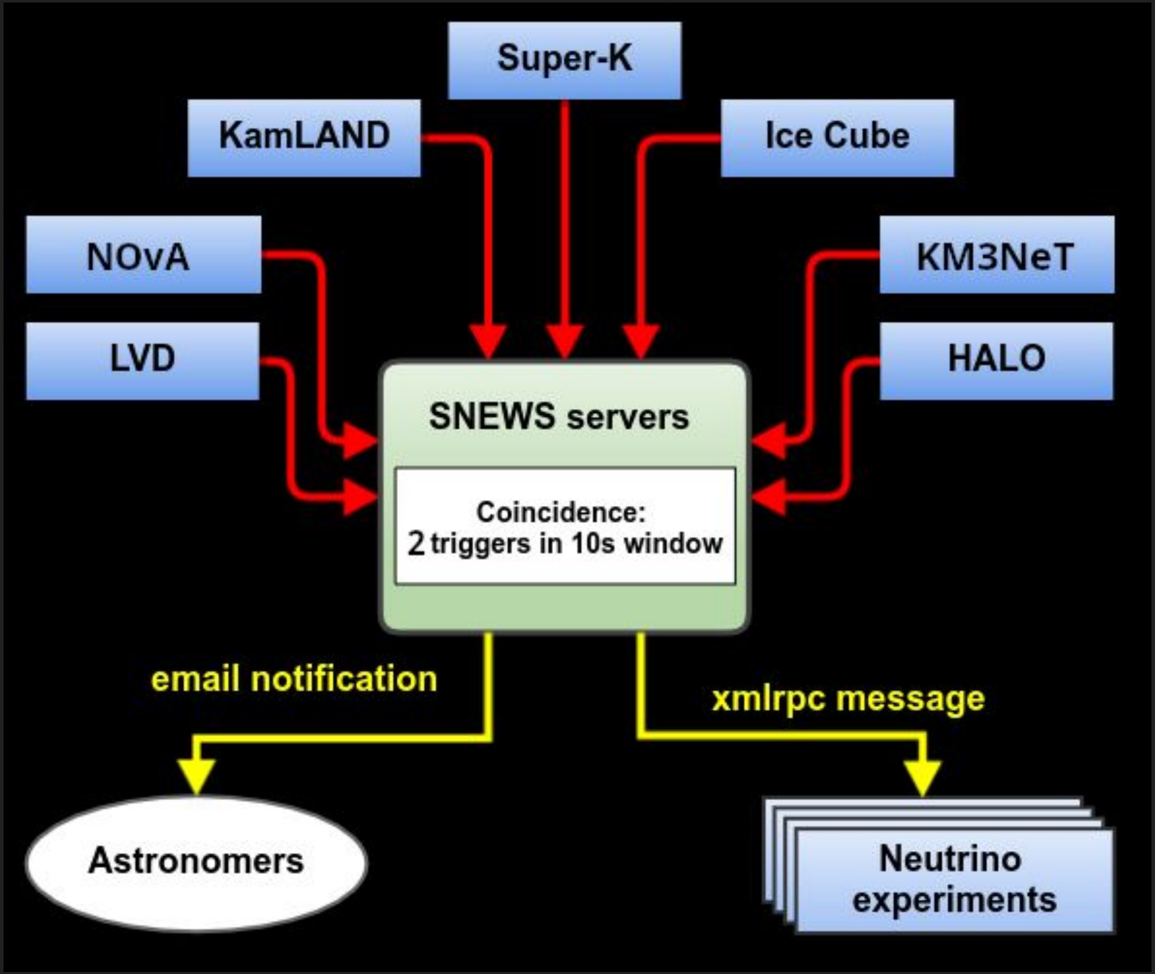
A global network to make sure we don't miss a galactic event.

Neutrinos arrive several minutes to hours prior to optical signal.

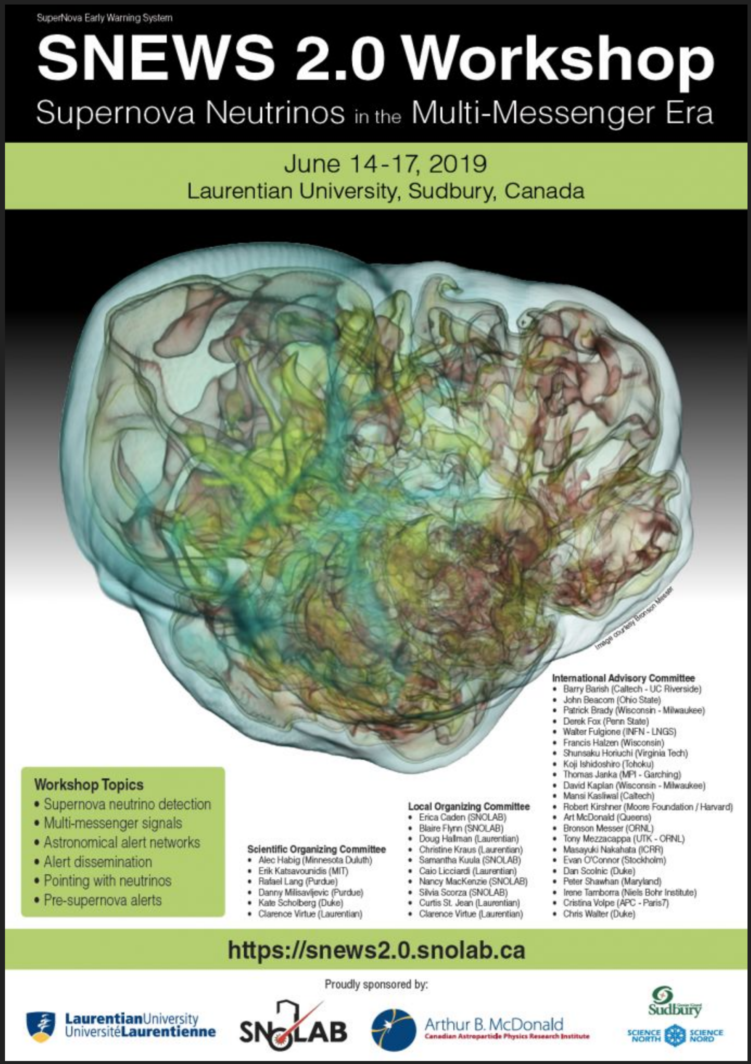
Operational since 1998

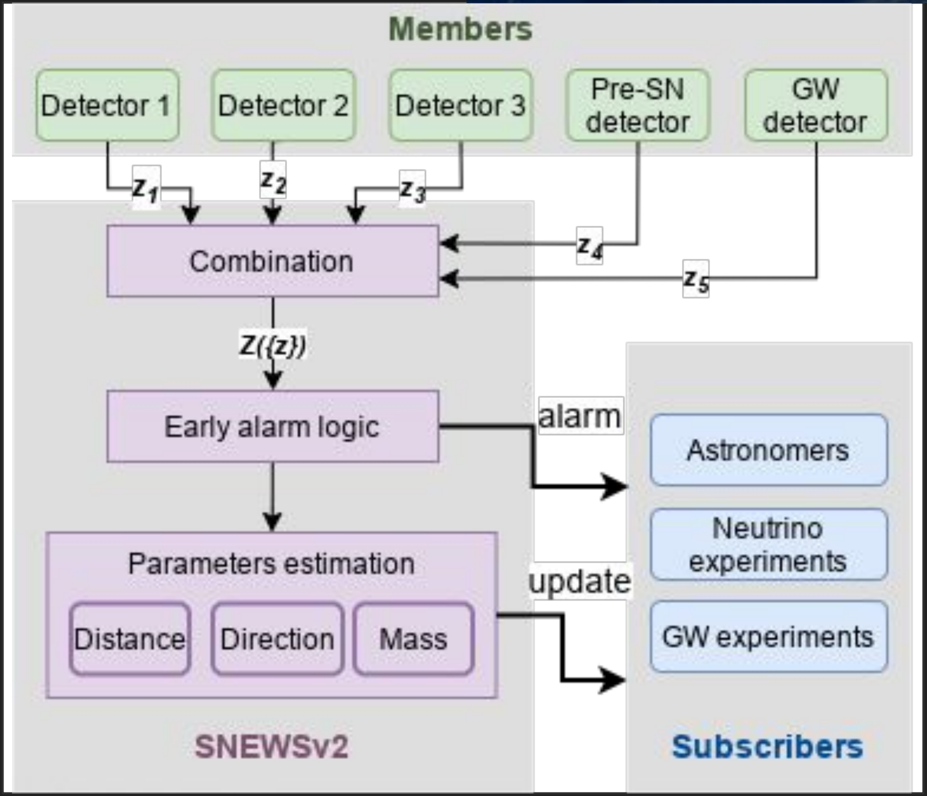
Fully-automated since 2005

Composed of mostly low-background experiments: trigger is just observing N_{events} >Threshold



SuperNova Early Warning system v2.0





https://snews2.org

A joint effort to build a new system, combining significance and parameters estimation measurements in real-time.

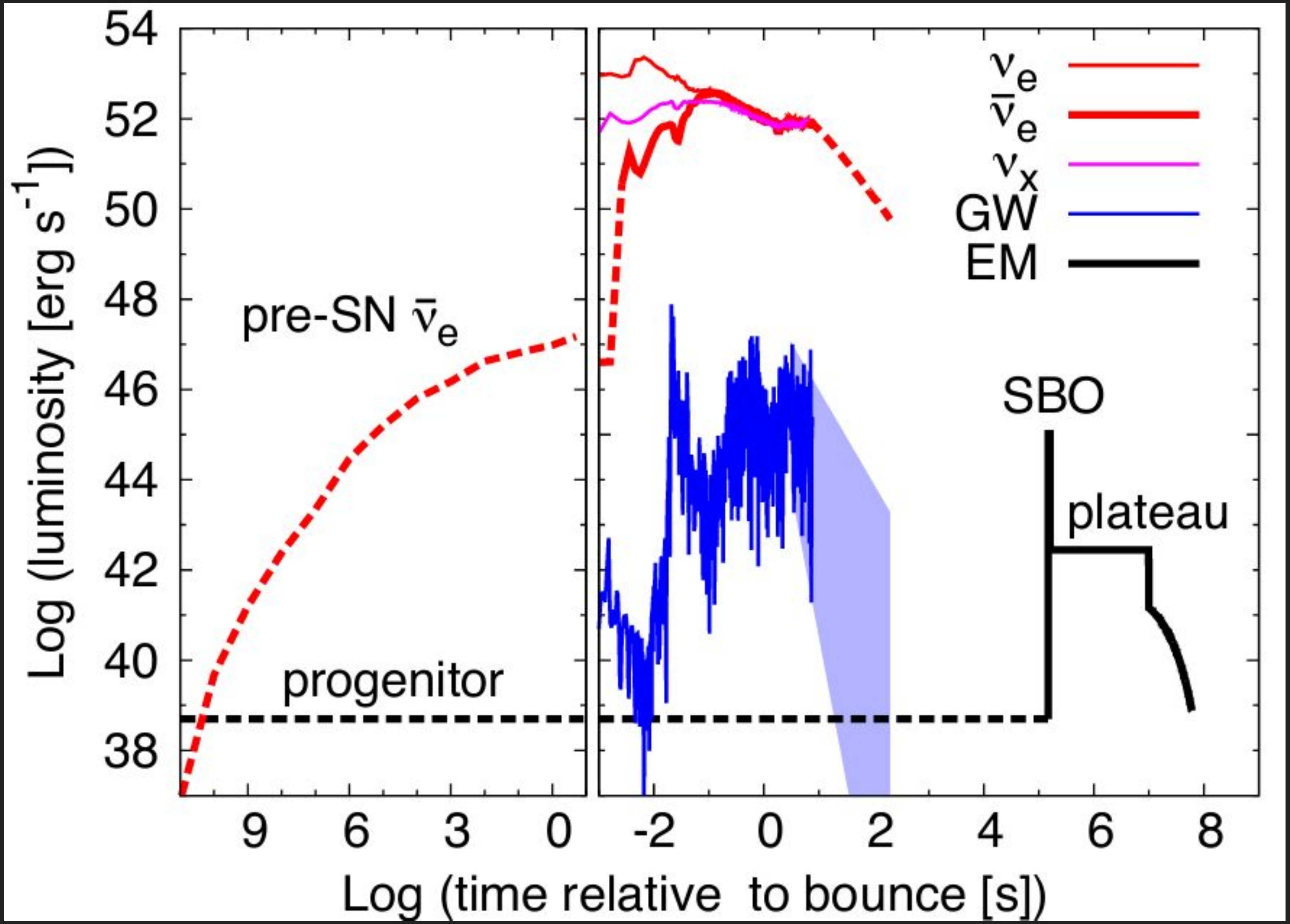
Status: development and testing.

Many exciting tasks ahead!

SNEWSv2.0 features: detectors capabilities

Experiment	Type	Mass [kt]	Location	$11.2\,M_\odot$	$27.0\,M_\odot$	$40.0\,M_\odot$
Super-K	$H_2O/\bar{\nu}_e$	32	Japan	4000/4100	7800/7600	7600/4900
Hyper-K	$H_2O/\bar{\nu}_e$	220	Japan	28K/28K	53K/52K	52K/34K
IceCube	String/$\bar{\nu}_e$	2500*	South Pole	320K/330K	660K/660K	820K/630K
KM3NeT	String/$\bar{\nu}_e$	150*	Italy/France	17K/18K	37K/38K	47K/38K
LVD	$C_nH_{2n}/\bar{\nu}_e$	1	Italy	190/190	360/350	340/240
KamLAND	$C_nH_{2n}/\bar{\nu}_e$	1	Japan	190/190	360/350	340/240
Borexino	$C_nH_{2n}/\bar{\nu}_e$	0.278	Italy	52/52	100/97	96/65
JUNO	$C_nH_{2n}/\bar{\nu}_e$	20	China	3800/3800	7200/7000	6900/4700
SNO+	$C_nH_{2n}/\bar{\nu}_e$	0.78	Canada	150/150	280/270	270/180
NOνA	$C_nH_{2n}/\bar{\nu}_e$	14	USA	1900/2000	3700/3600	3600/2500
Baksan	$C_nH_{2n}/\bar{\nu}_e$	0.24	Russia	45/45	86/84	82/56
HALO	Lead/ν_e	0.079	Canada	4/3	9/8	9/9
HALO-1kT	Lead/ν_e	1	Italy	53/47	120/100	120/120
DUNE	Ar/ν_e	40	USA	2700/2500	5500/5200	5800/6000
MicroBooNe	Ar/ν_e	0.09	USA	6/5	12/11	13/13
SBND	Ar/ν_e	0.12	USA	8/7	16/15	17/18
DarkSide-20k	Ar/any ν	0.0386	Italy	-	250	-
XENONnT	Xe/any ν	0.006	Italy	56	106	-
LZ	Xe/any ν	0.007	USA	65	123	-
PandaX-4T	Xe/any ν	0.004	China	37	70	-

Supernova: a multi-messenger event



Pre-supernova neutrinos

Core-burning nuclear fusion stages for a 25-solar mass star

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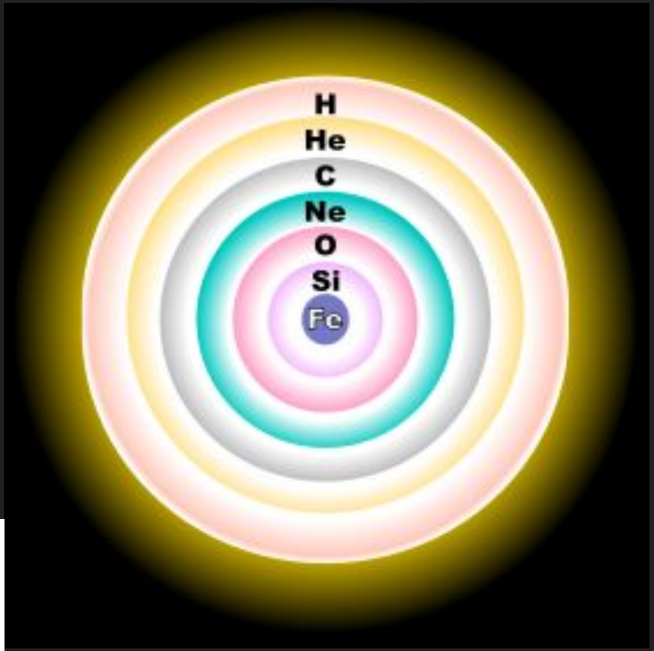
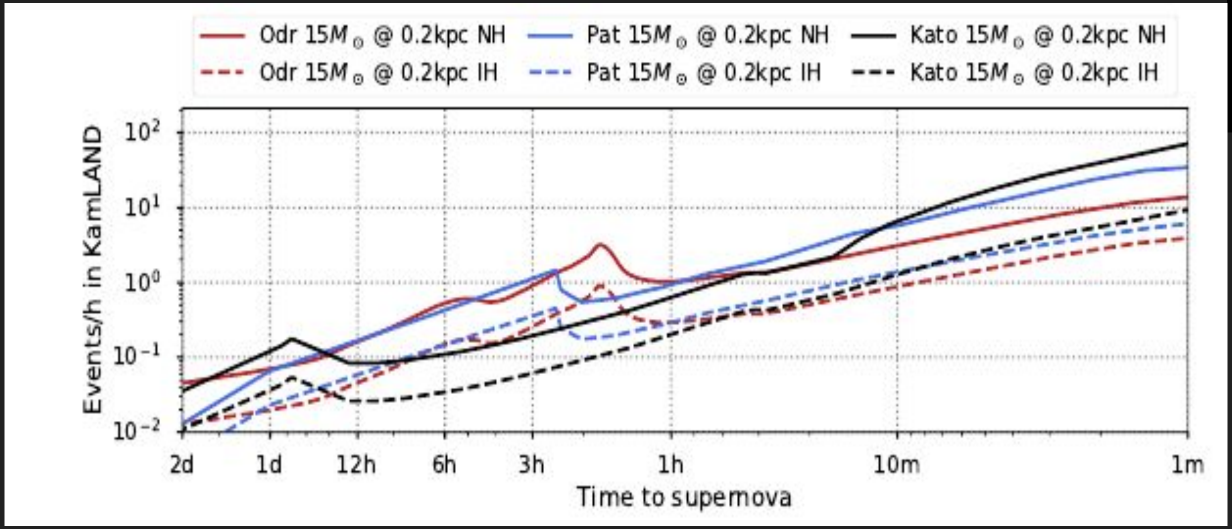


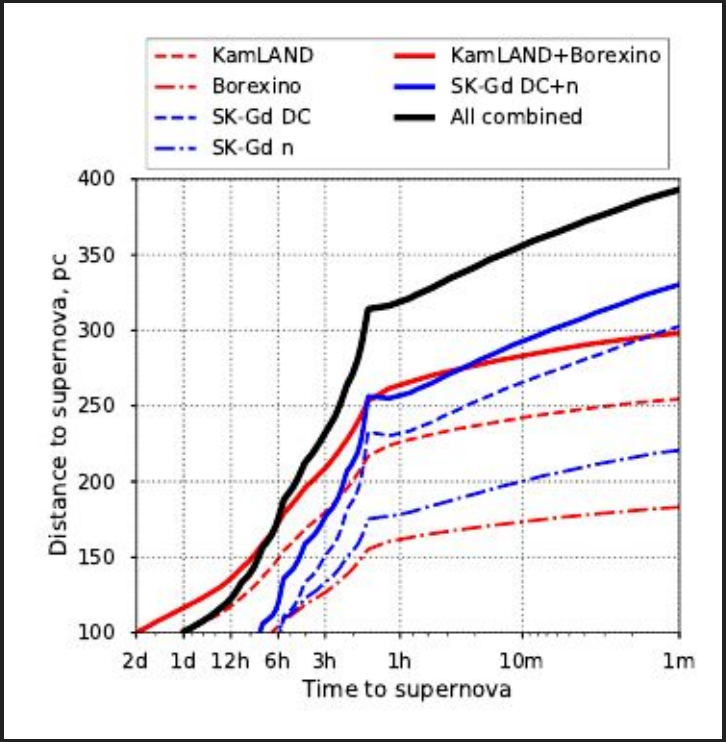


Neutrinos from burning of O, Si shells: ~days before collapse

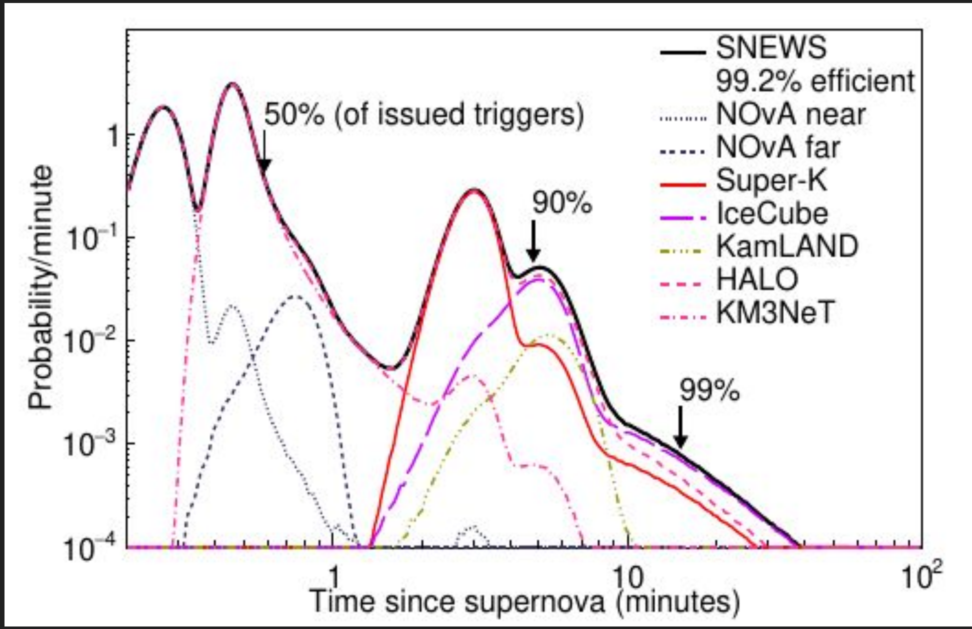
Gradually increasing flux and energy (~several MeV)

SNEWSv2.0 features: early SN alert

Presupernova alert - hours before collapse! But limited distance



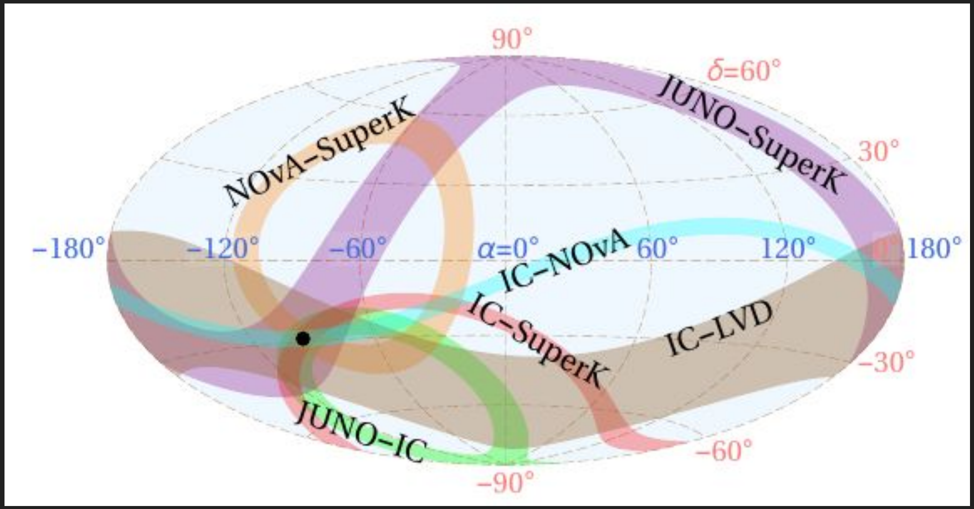
Low-latency core-collapse detection: still hours before the explosion

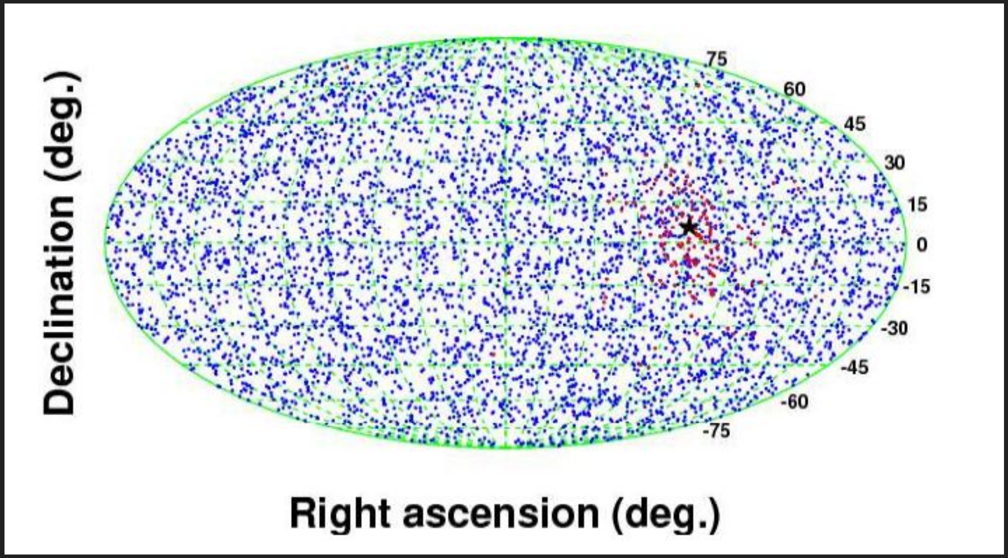


SNEWSv2.0 features: pointing to the SN

Triangulation using time shifts between detectors:

Depend on bg level, time precision, SN model





Direction reconstruction event-by event in SuperK

- blue: IBD,
- red: nu-e elastic scattering
- star: SN direction

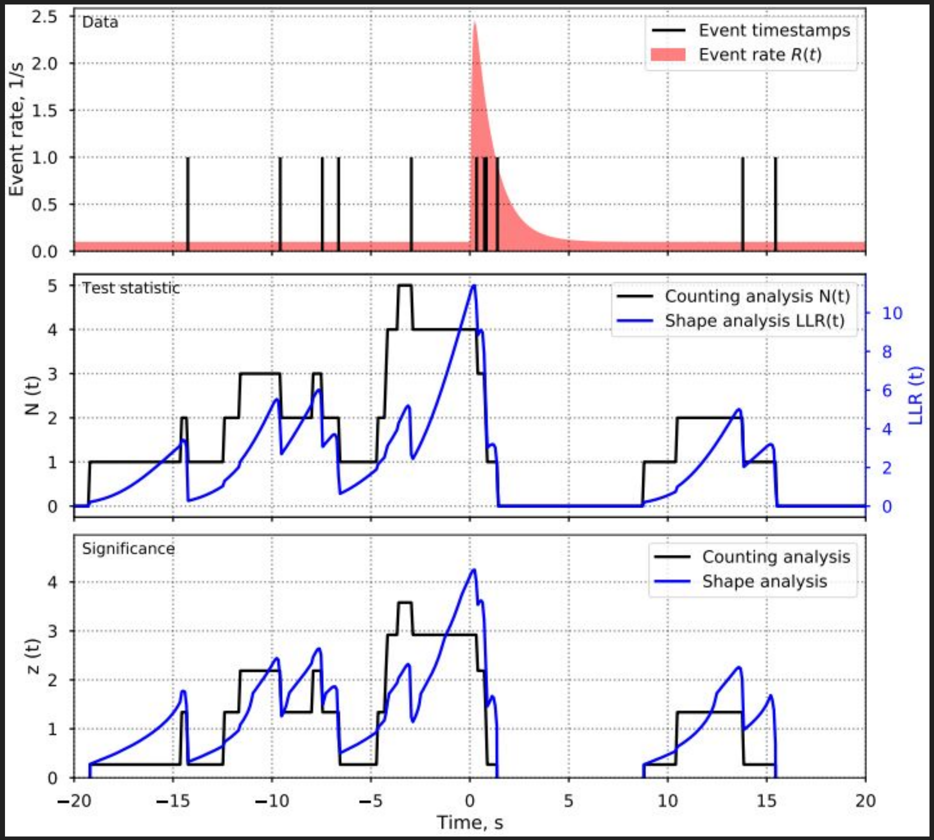
Work In Progress

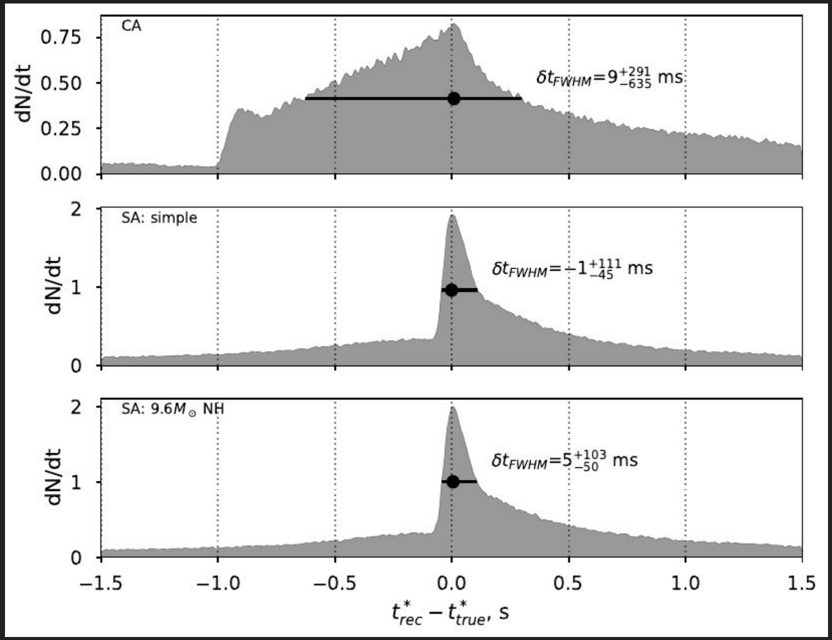
Finding SN signal in data

Counting analysis: Poissonian analysis of event numbers *N(t)* within fixed time window.

Shape analysis: use log likelihood ratio: *LLR(t)* as test statistic (measure of how observation differs from from background hypothesis)

$$\ell(\vec{n}) \equiv \log \frac{P(\vec{n}|H_1)}{P(\vec{n}|H_0)} = \sum_i n_i \cdot A_i, \quad \text{where } A_i = \log\left(1 + \frac{S_i}{B}\right)$$





- No need to define time window (dependent on Bg conditions)
- Higher signal significance → better sensitivity
- Better determination of signal start time
- Model dependent (not dramatically - using simple analytical approximation for signal model also work)

Summary

- Detecting of the next galactic supernova is a global task
- SNEWSv2.0 is a collaboration to coordinate the effort and automate the analysis:
  - collection of supernova neutrino models, unified interface
  - multimessenger (preSN + ccSN detection + GW followup)
  - directional information reconstruction
  - statistical methods
  - tools for experiments to implement SN trigger systems

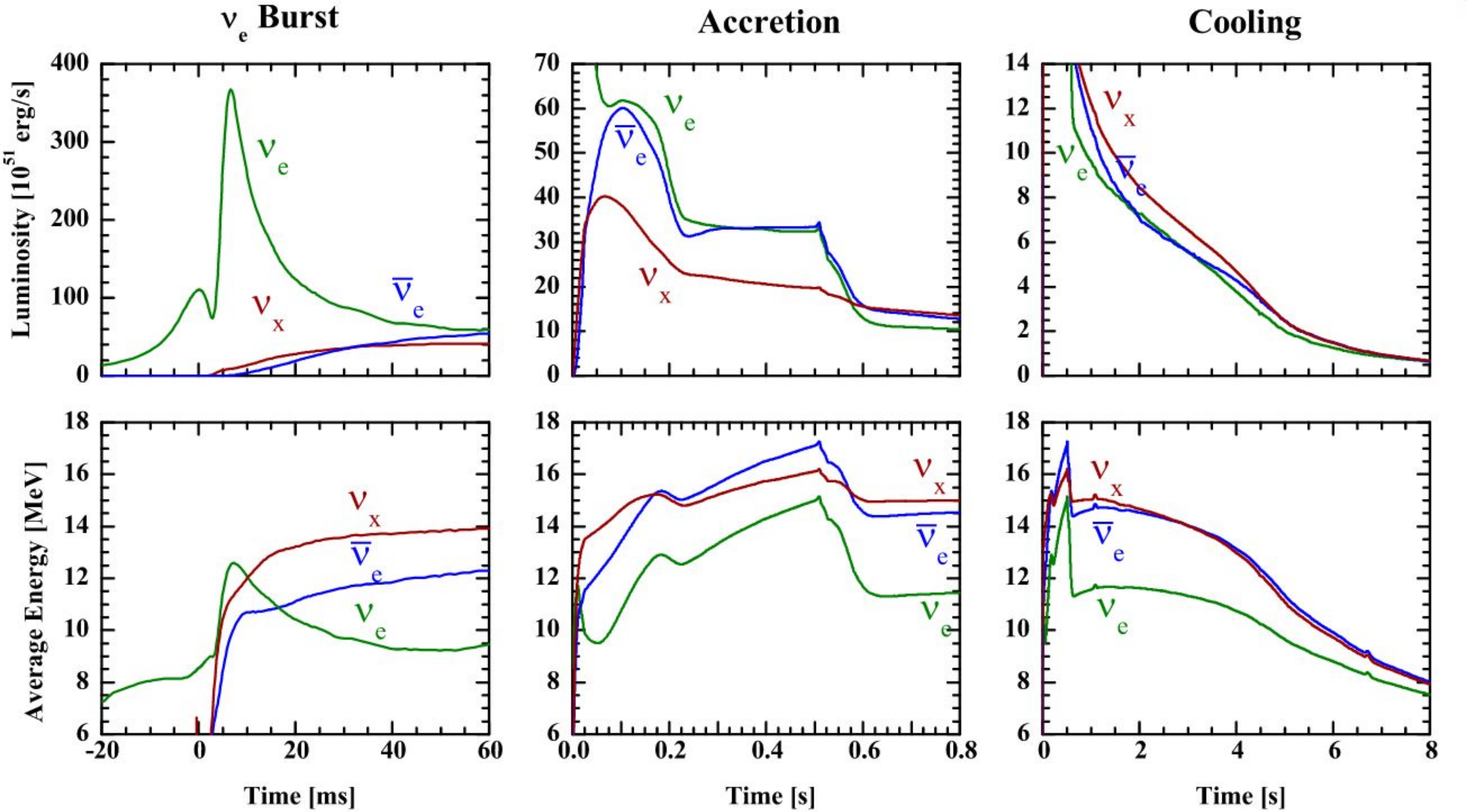
References

- A. Mirizzi *et al.*, "Supernova Neutrinos: Production, Oscillations and Detection" 10.1393/ncr/i2016-10120-8.
- P. Antonioli *et al.*, "SNEWS: the SuperNova Early Warning System" 10.1088/1367-2630/6/1/114.
- S. A. Kharusi *et al.*, "SNEWS 2.0: A Next-Generation SuperNova Early Warning System for Multi-messenger Astronomy," 10.1088/1367-2630/abde33.
- A.Sh., *et al.* "Combined detection of supernova neutrino signals" 10.1088/1475-7516/2021/12/053

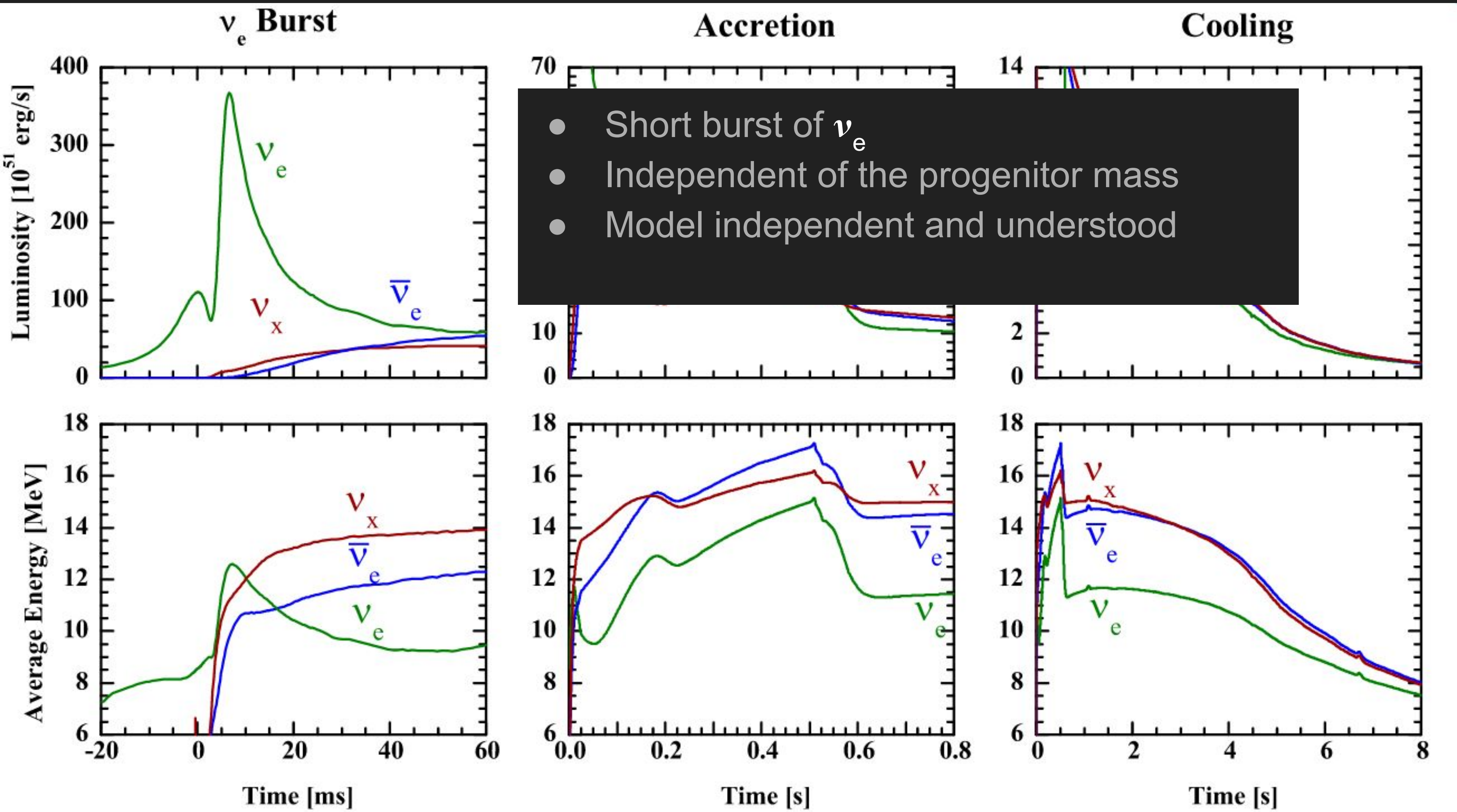
https://snews2.org
If you are interested in being notified about the occurrence of a neutrino burst from SNEWS, please sign up for our alert list.

BACKUP

Core-collapse supernova neutrino signal

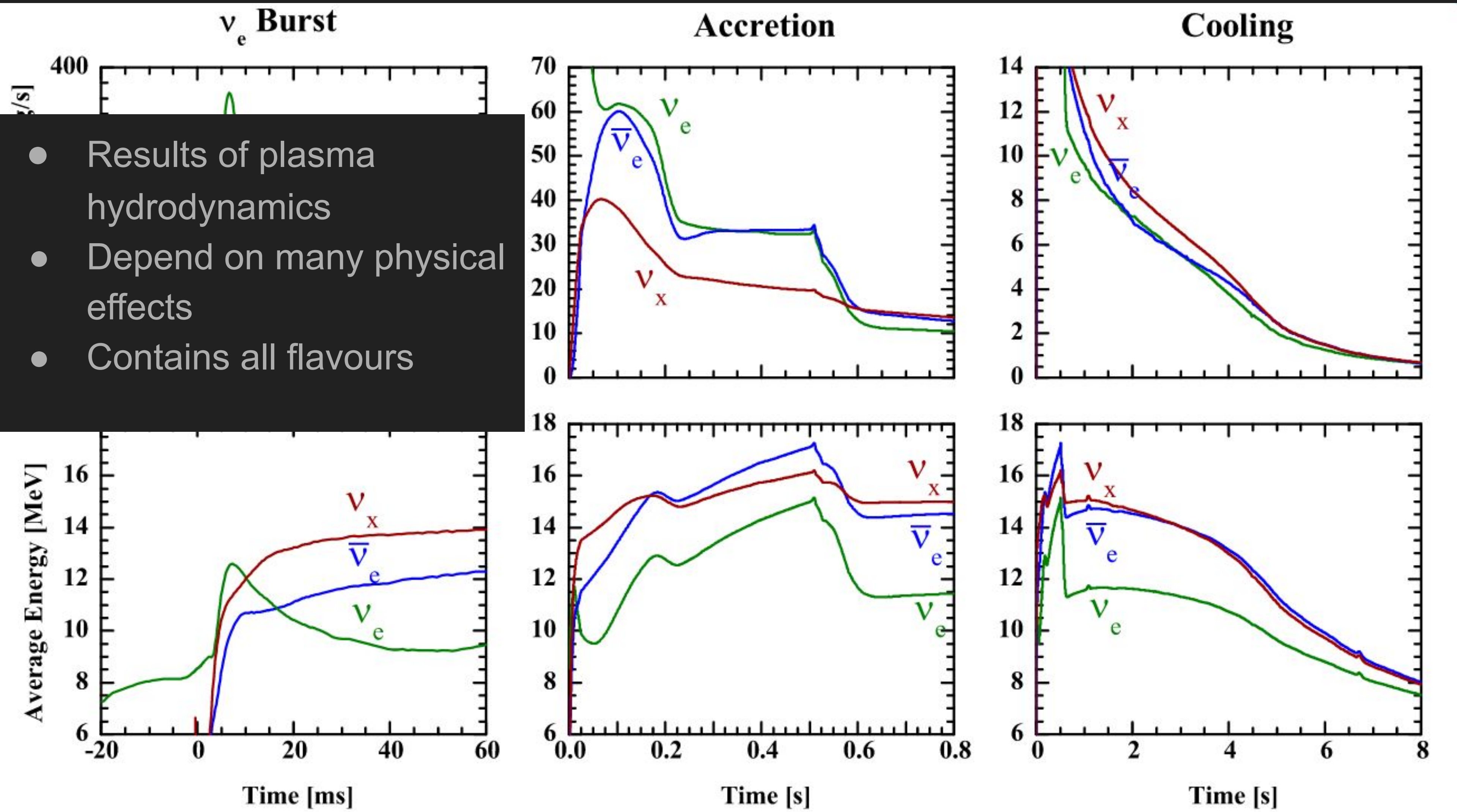


Neutronization phase neutrinos



- Short burst of ν_e
- Independent of the progenitor mass
- Model independent and understood

Accretion and cooling phase neutrinos



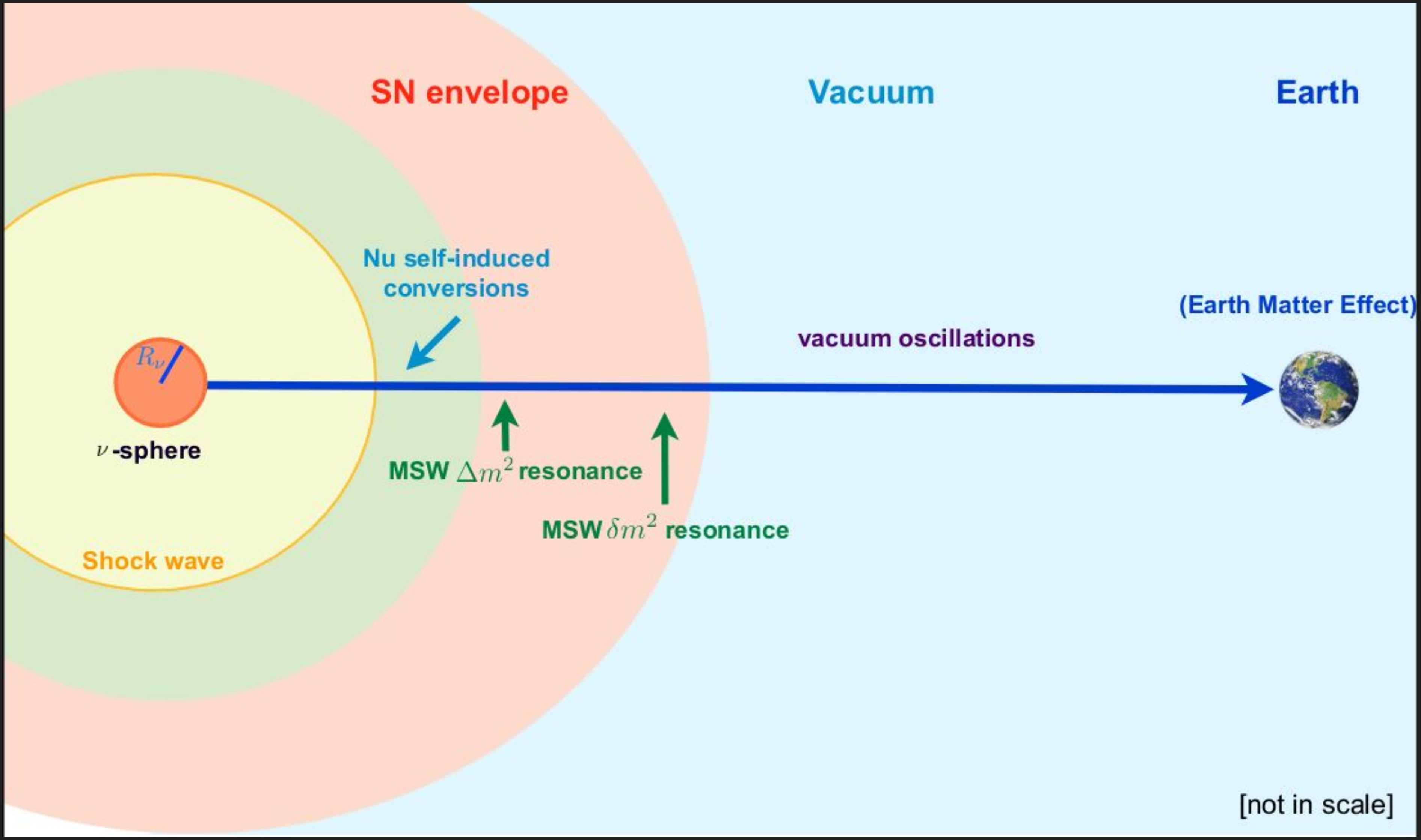
- Results of plasma hydrodynamics
- Depend on many physical effects
- Contains all flavours

Stellar core collapse

- Neutronization phase
  - Iron core grows to ~1.4 $M_\odot$ (Chandrasekhar limit)
    - Electron Fermi gas pressure < Gravitational pressure
  - Electron capture process: $p+e^- \rightarrow n+\nu_e$
    - Forming a proto-neutron star in the center
- Accretion phase
  - Outer matter is still falling to the center
  - Implosion forms a shockwave in the inner core medium
  - Shockwave bounces from the proto-NS
  - Shockwave propagation is stalled
- Neutrinos revive the shockwave
  - ν_e's interact with the stellar media $\nu_e+A \rightarrow \nu_e+A+\nu_x+\nu_x$
  - Shockwave is accelerated and explosion breaks out
  - All neutrino flavors are produced in ~ equal proportions
- Cooling phase
  - SN remnant is a hot dense mess: everything is interacting
  - Only neutrinos can escape

Neutrinos: ~99% $E_{collapse}$ within ~10s immedeately after neutronization
Visible light: <1% $E_{collapse}$ within ~weeks, and delayed by several hours

Neutrino flavor conversions



[Slide from: Irene Tamborra, VII Pontecorvo school, 2017]

Main detection channels

- Inverse beta decay:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Elastic scattering on electrons:

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

- CC interaction on nucleus:

$$\nu_e + (A,Z) \rightarrow e^- + (A,Z+1)$$

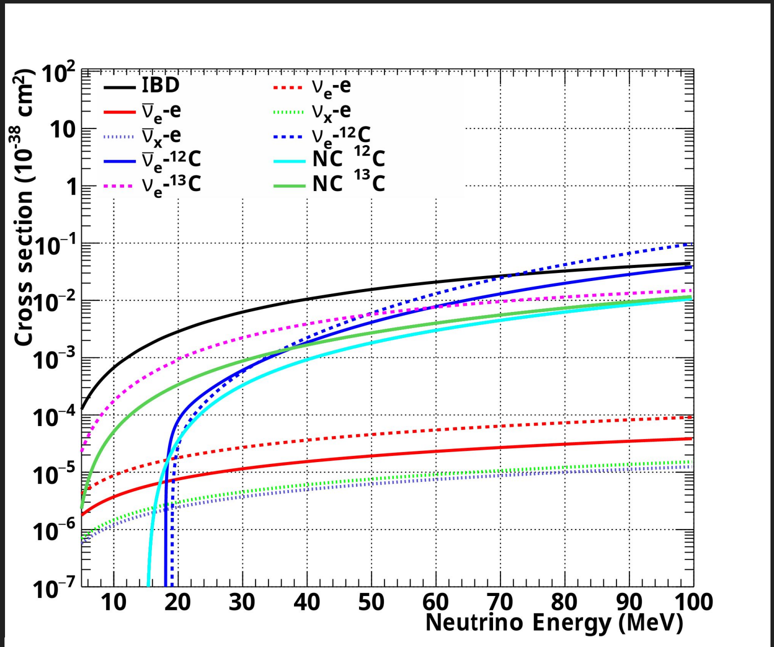
$$\bar{\nu}_e + (A,Z) \rightarrow e^+ + (A,Z-1)$$

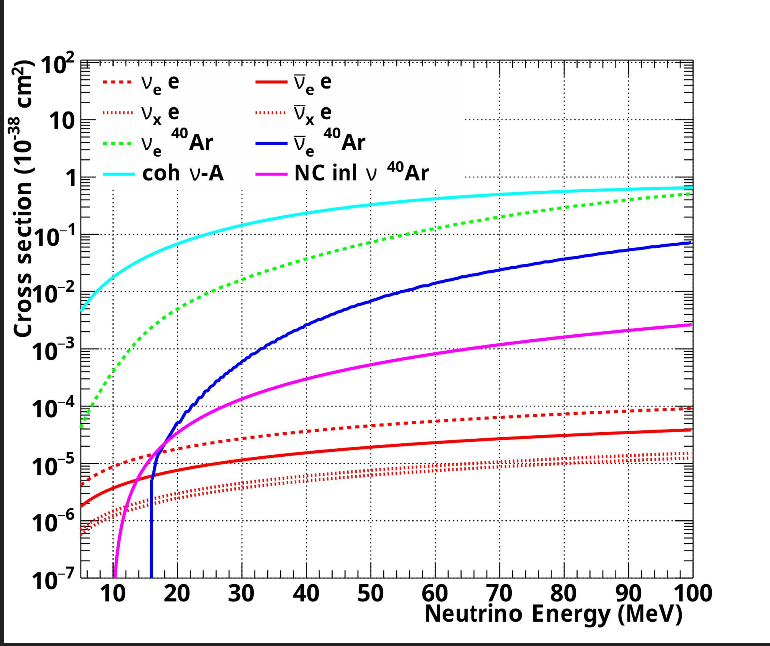
- NC excitation of nucleus:

$$\nu_x + A \rightarrow \nu_x + A^*$$

- Coherent elastic neutrino-nucleus scattering

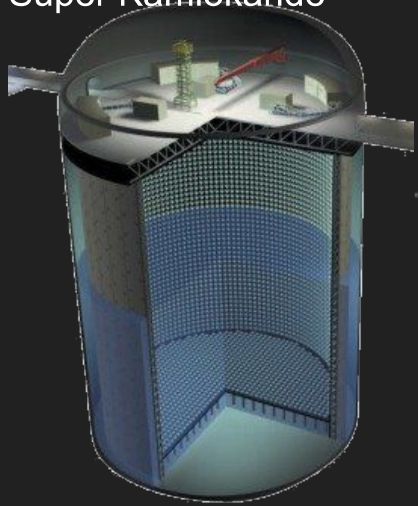
$$\nu_x + A \rightarrow \nu_x + A$$

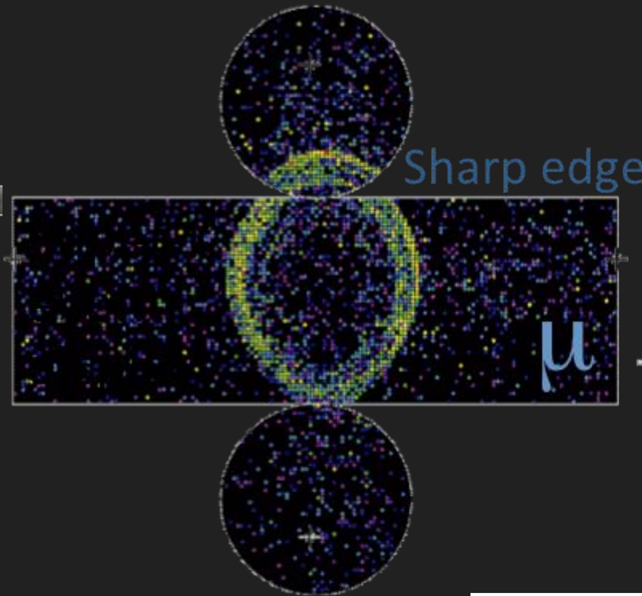


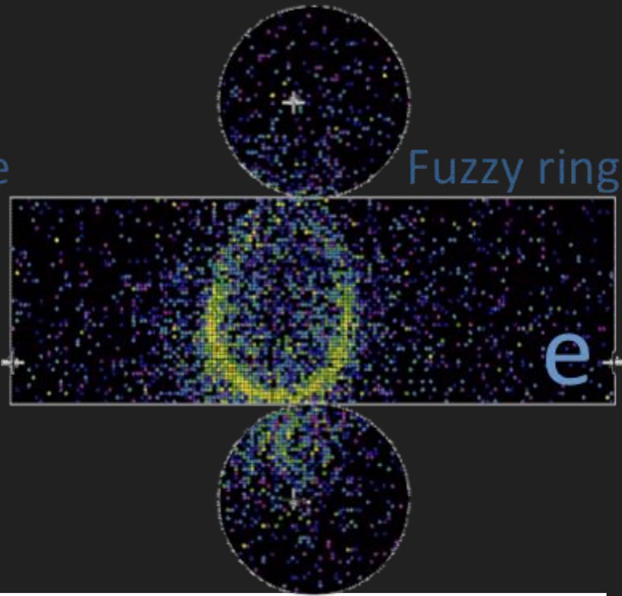


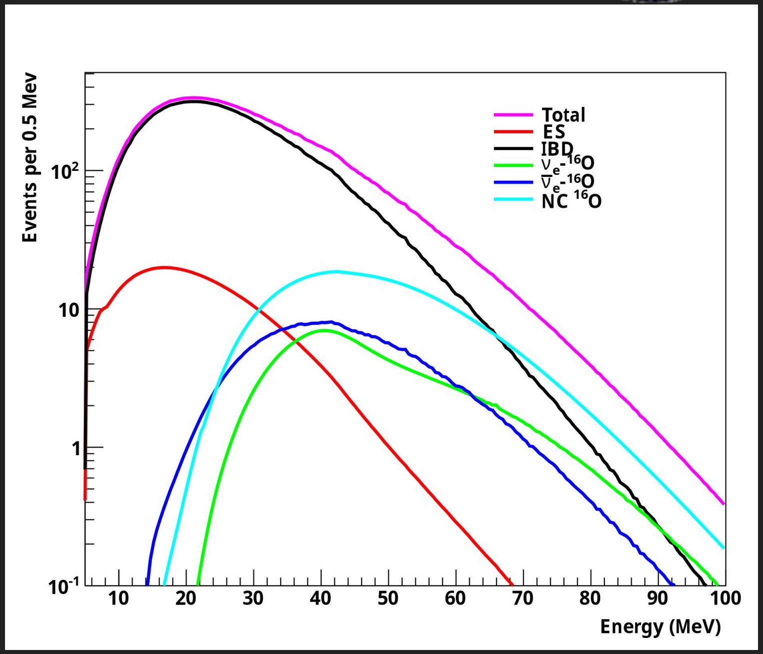
Main detection techniques: Water Cherenkov

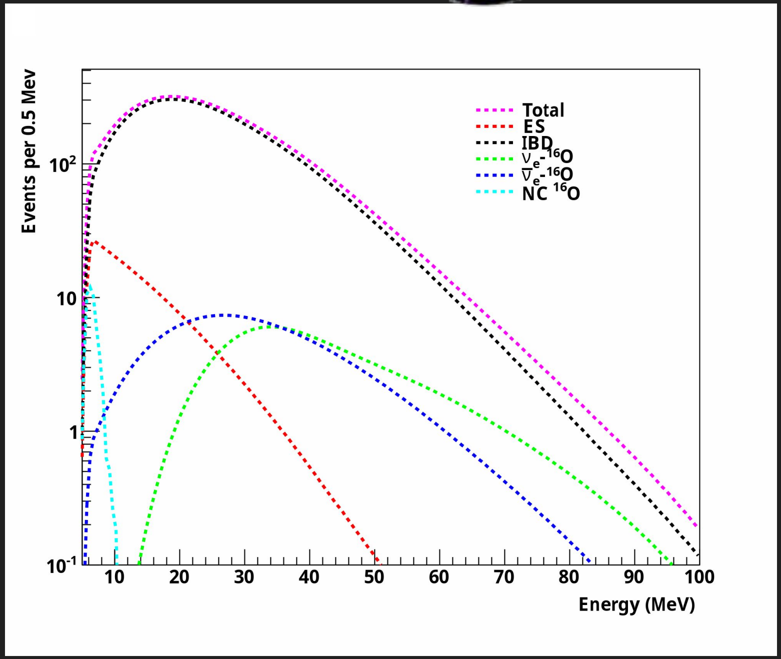
Super Kamiokande



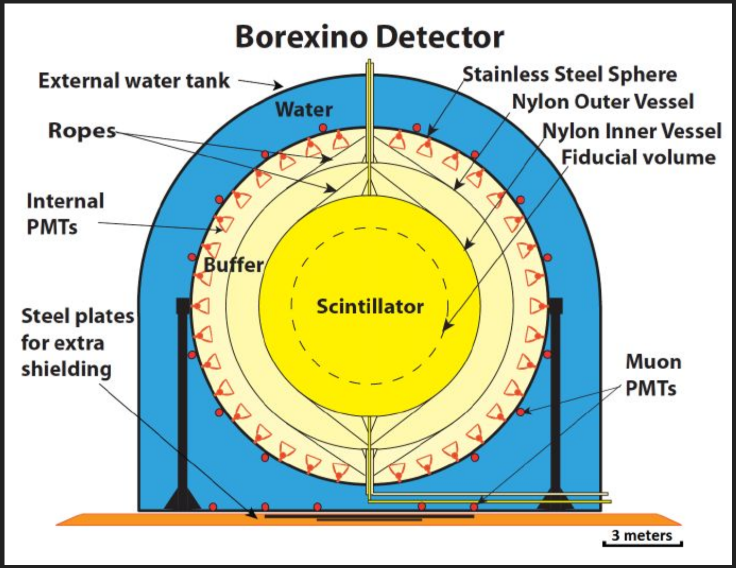


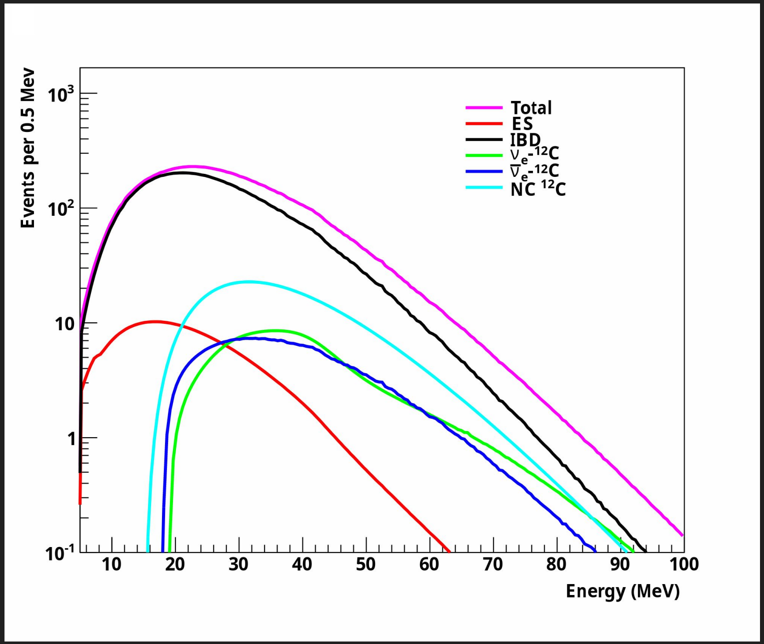


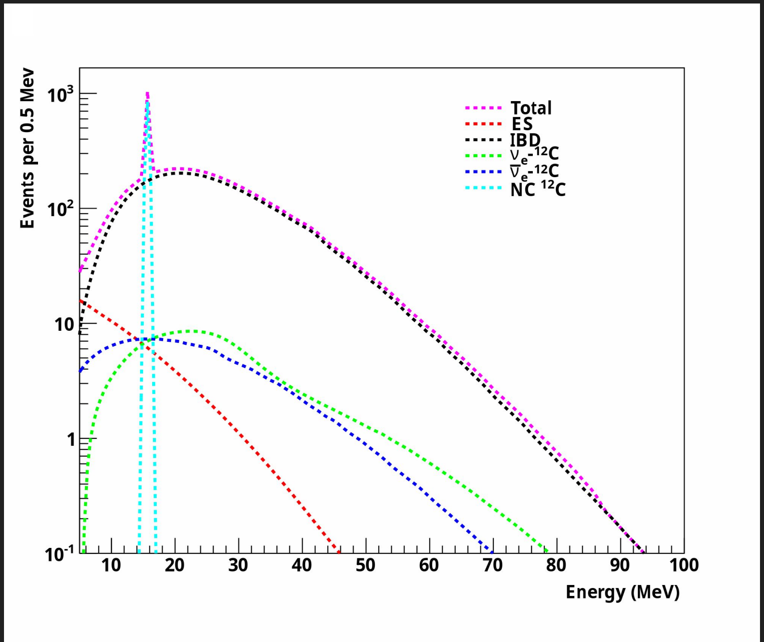




Main detection techniques: Scintillator







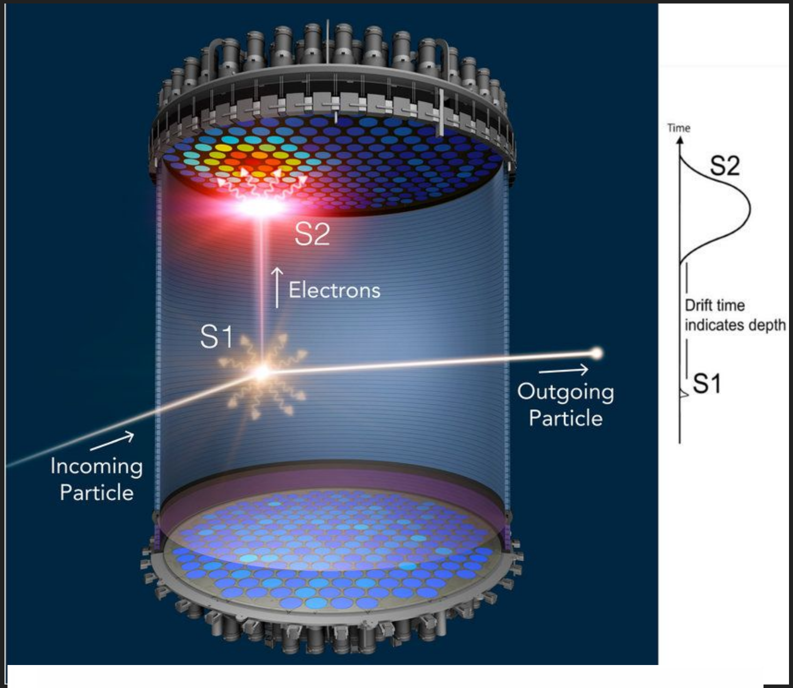
Main detection techniques: Noble Liquids

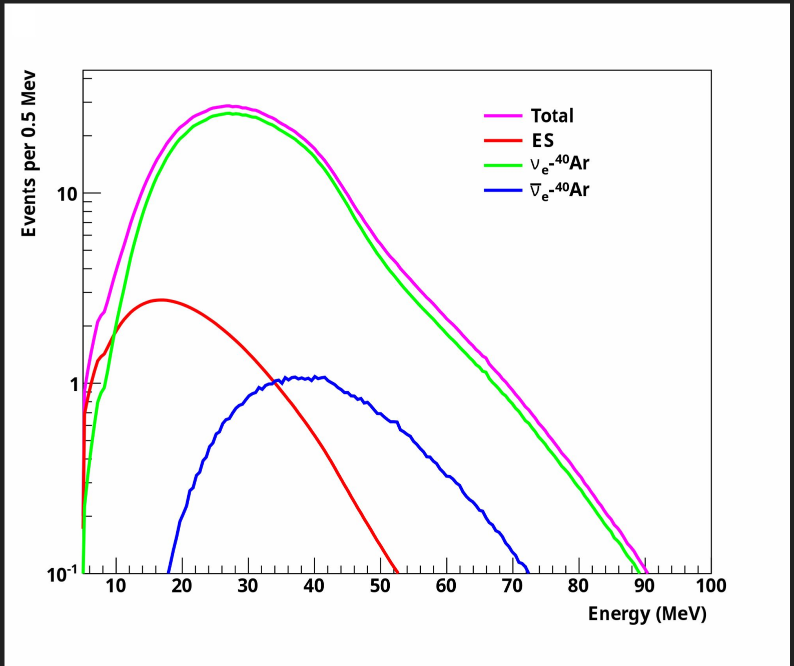
XENON, DarkSide experiments:

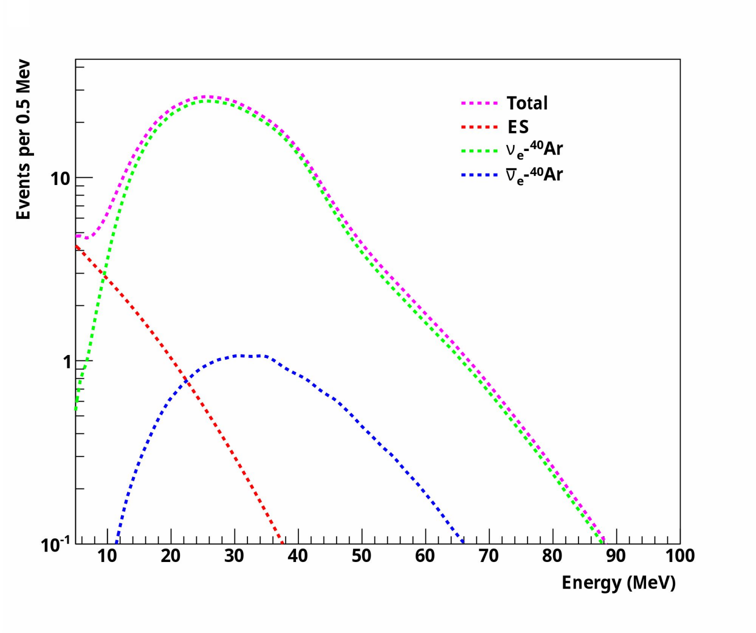
Dark Matter detectors (WIMP)

Designed to see nuclear recoil

Perfectly fit for CEvNS!







Main detection techniques: Lead detector

HALO experiment:

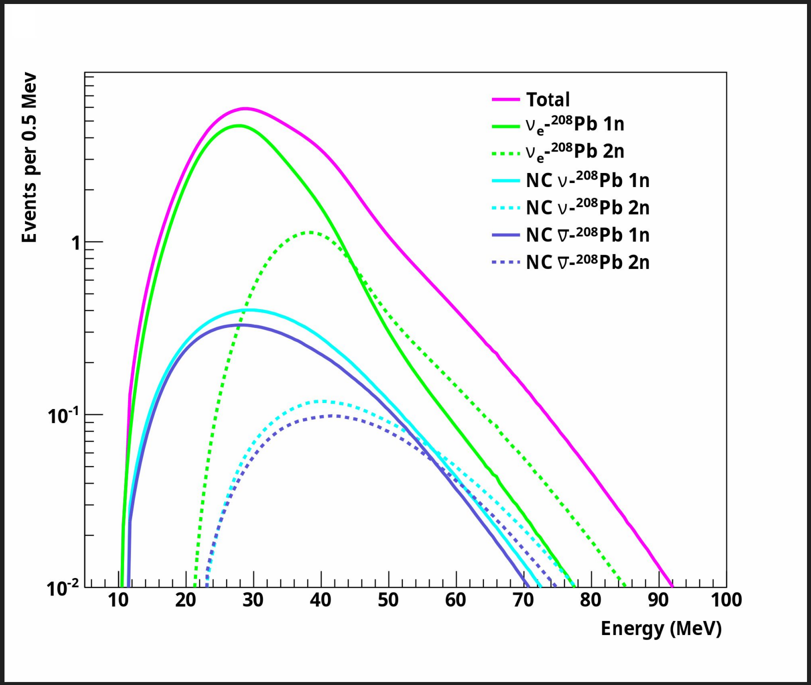
Dedicated to SN neutrinos

Located at SNO lab

Interactions on Pb, producing excited state

Deexitation yields neutrons

Neutrons detected in He3



SNEWSv2.0 unified approach for the SN modelling and statistical processing:

1. SNEWPY (SN Early Warning Models for Python):
   https://github.com/SNEWS2/snewpy
   A collection of CCSN and pre-supernova models with a generalized python interface
2. SNAP (SN Asynchronous Pipeline):
   https://github.com/Sheshuk/snap-base
   a framework for realtime statistical processing and significance combination for multiple detectors
3. SNEWPDAG (SN Early Warning Pointing Directed Acyclic Graph):
   https://github.com/SNEWS2/snewpdag
   And engine for calculating and combining the direction to SN progenitor