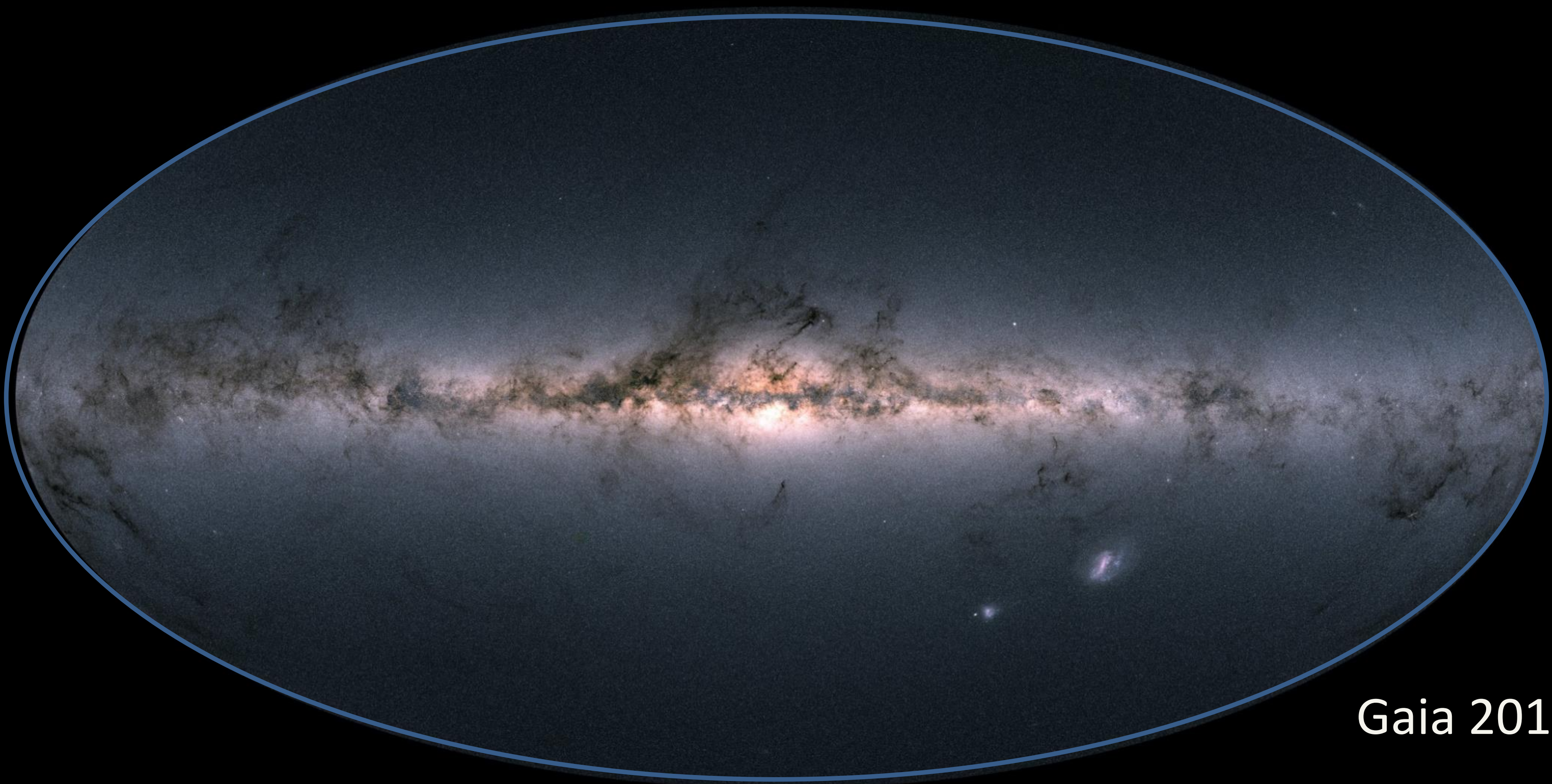
Astrophysical neutrinos with

Lutz Köpke, Bolshie Koty, July, 2019

Radio Infrared **visible** x-ray Gamma

(0.3μm)

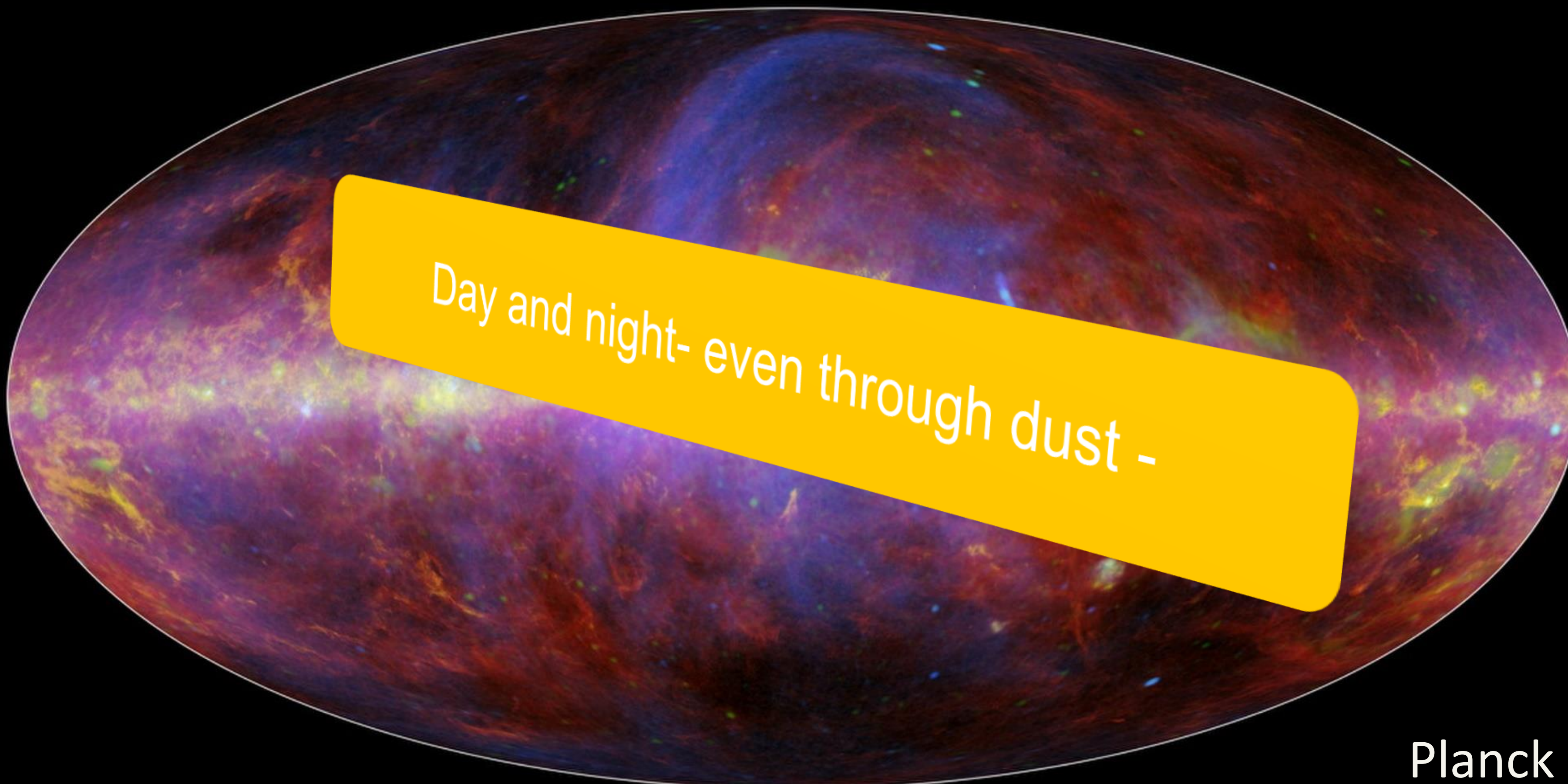


Gaia 2018

15 Oktaves

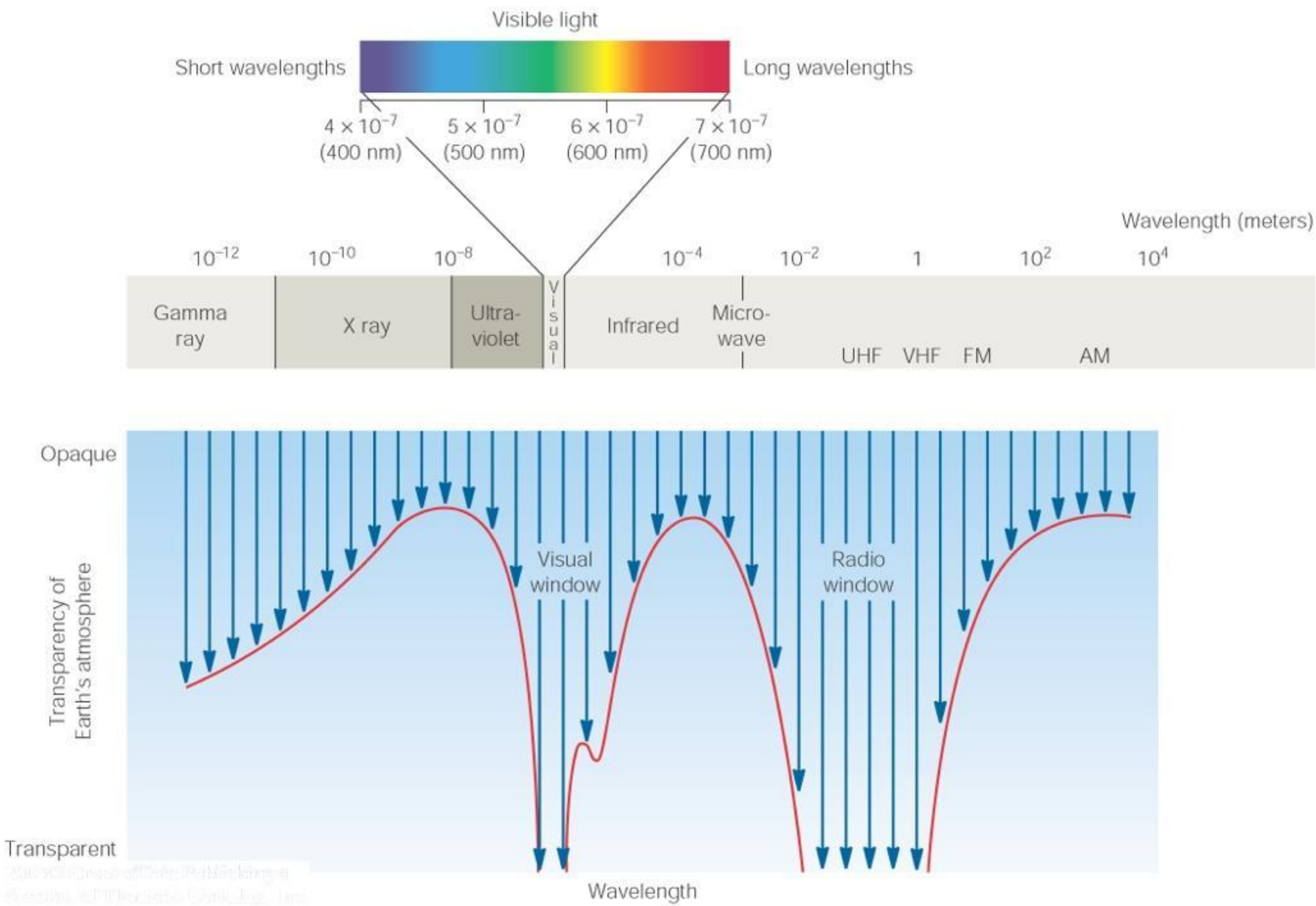
Idea Werner Hoffmann

Radio (mm) infrared visible X-ray Gamma

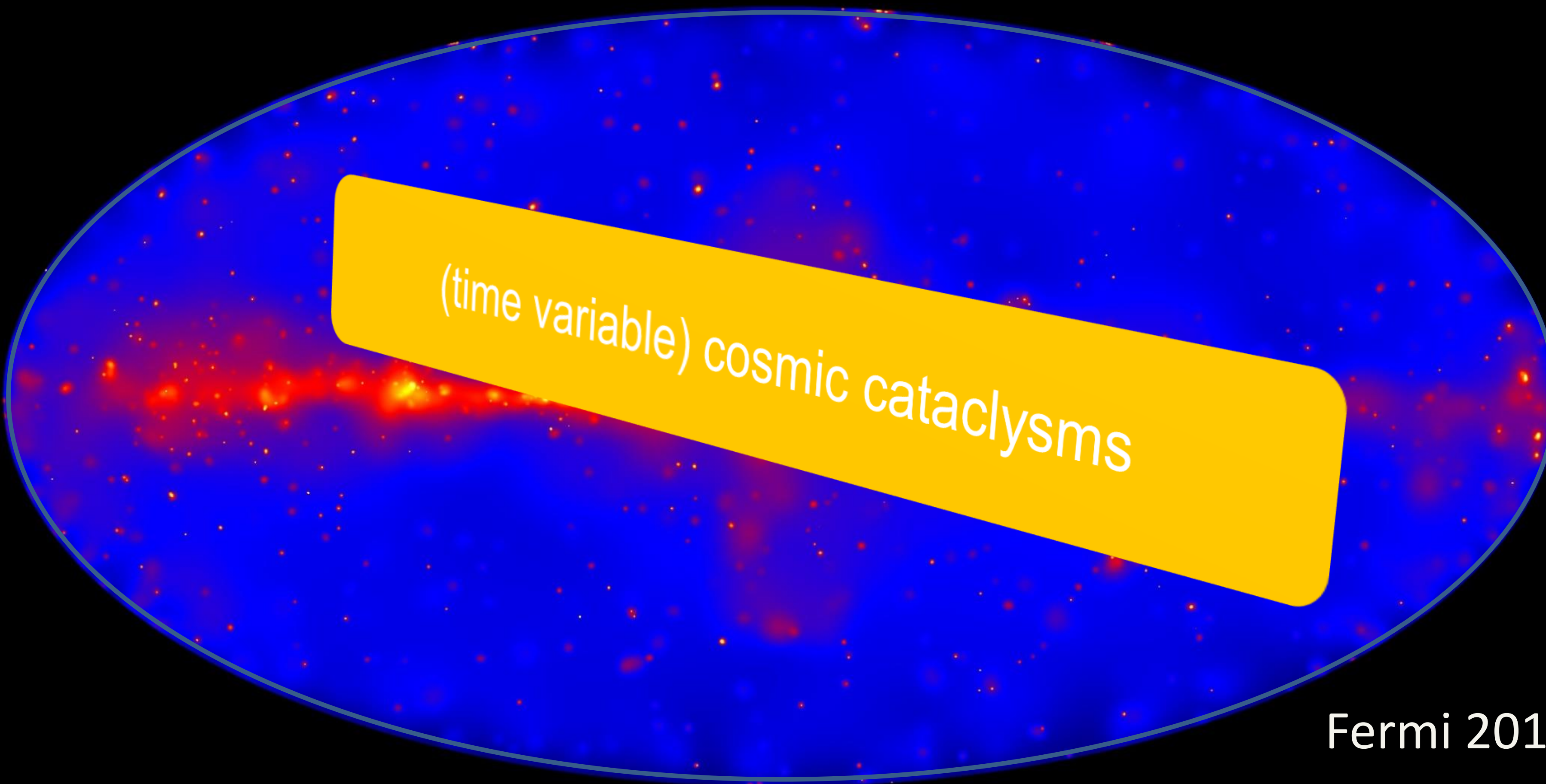


Planck

Transparency of atmosphere



Radio infrared visible X-ray **Gamma**



Fermi 2016

See 60 Watt „light bulbs“ with speed of light in 40 km distance

Table of content: Part 1

Goal of astroparticle physics: Explore sky outside of visible electromagnetic band

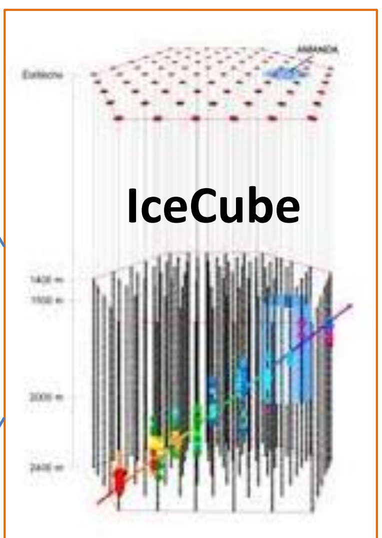
Messengers and their limitations ...

Exploring the Sky with Particles

… sensitivity determined by energy range, effective area …

Type	Experiment	$E_{typical}$ [eV]	Effective area
Satellite based	Fermi-LAT	10^6-10^9	1 m^2
	Hubble	1	5 m^2
Neutrino telescope	**IceCube**	**10^{10}-10^{15}**	**5 m^2**
Cherenkov telescope array	CTA	10^{10}-10^{13}	10^6 m^2
Cosmic air shower array	AUGER	10^{18}-10^{20}	3×10^9 m^2

1 km



~

similar effective area
but signal flux $\propto 1/E^2$

for a serious comparison, other parameters matter …

- angular coverage
- obstruction by matter
- magnetic field sensitivity
- backgrounds

Transparency of the Universe

photons of all energies abound in universe (3K $\rightarrow$ visible)

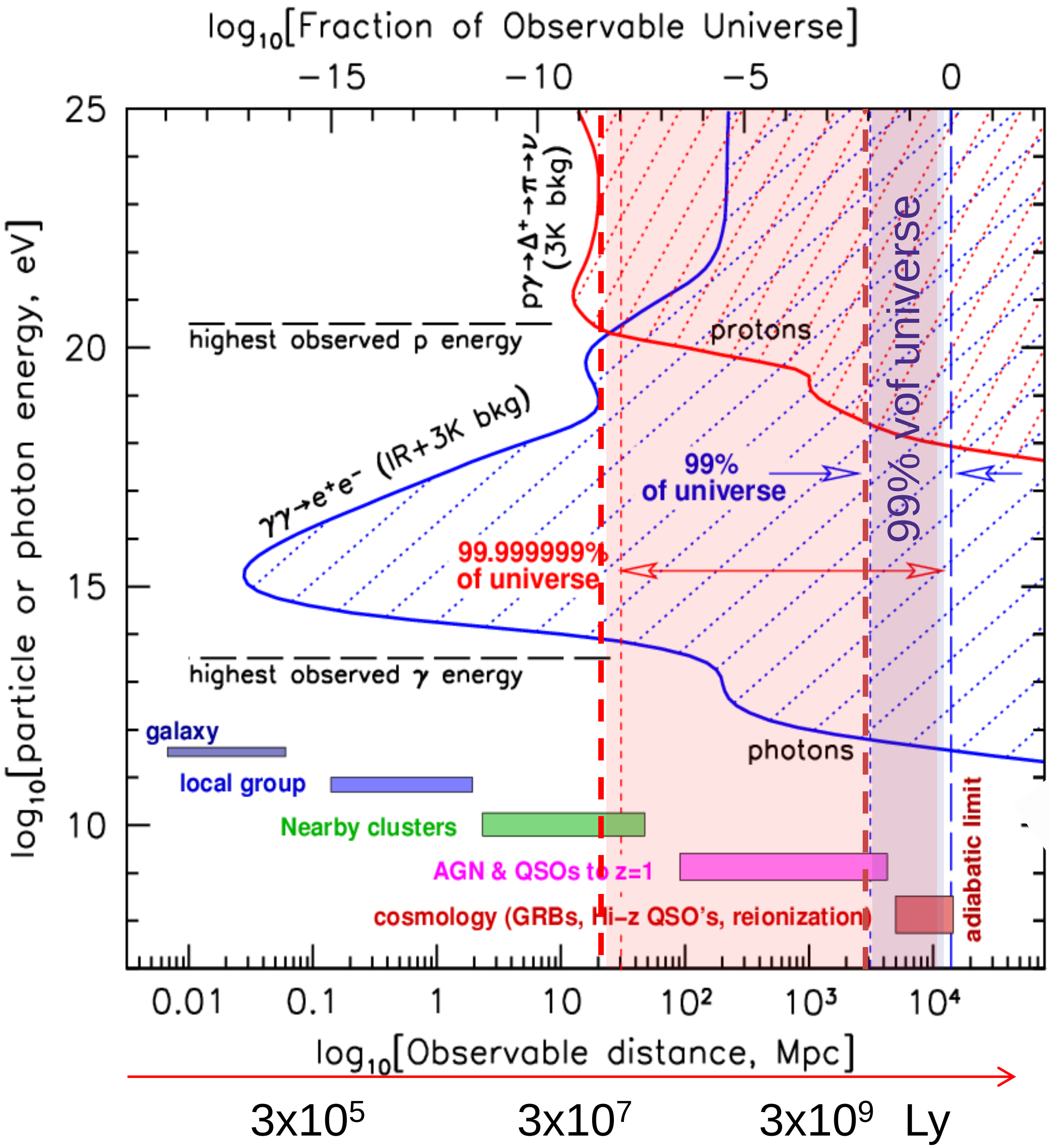
interactions with p and γ:

$p + \gamma(3K) \rightarrow \Delta(1232) \rightarrow p + \pi$

$\gamma + \gamma(IR + 3K) \rightarrow e^+ e^-$

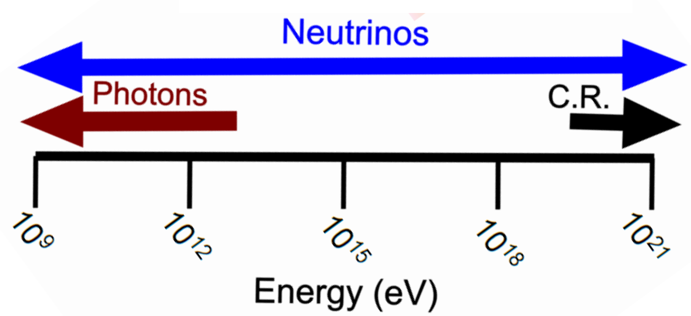
limits „seeing“ range …

…transparency of the Universe

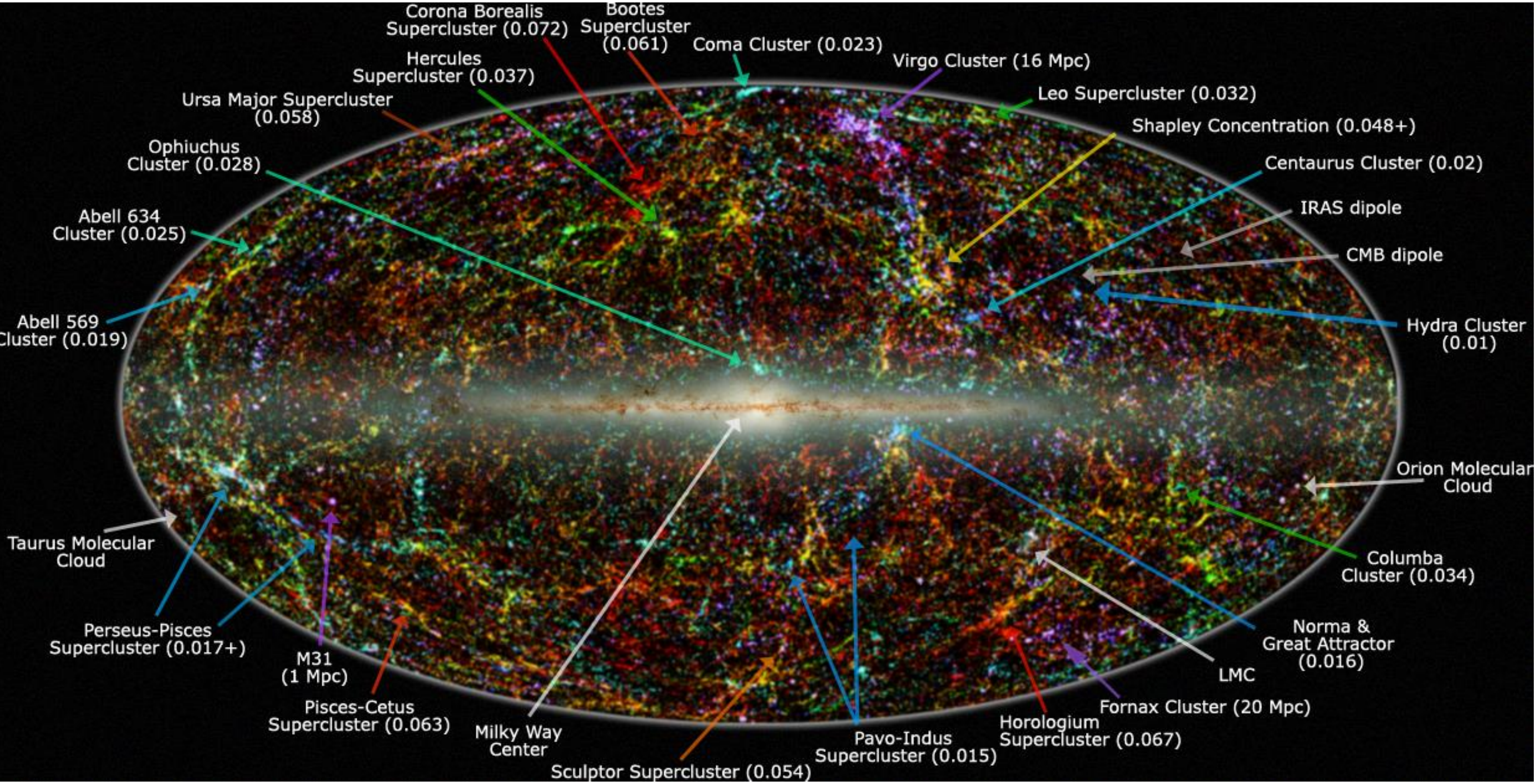


- Only ν's and GW's can "see" beyond local Universe above 100 TeV
- Only ν's and GW's can escape from dense environments
- Only ν's can unambiguously prove hadronic acceleration

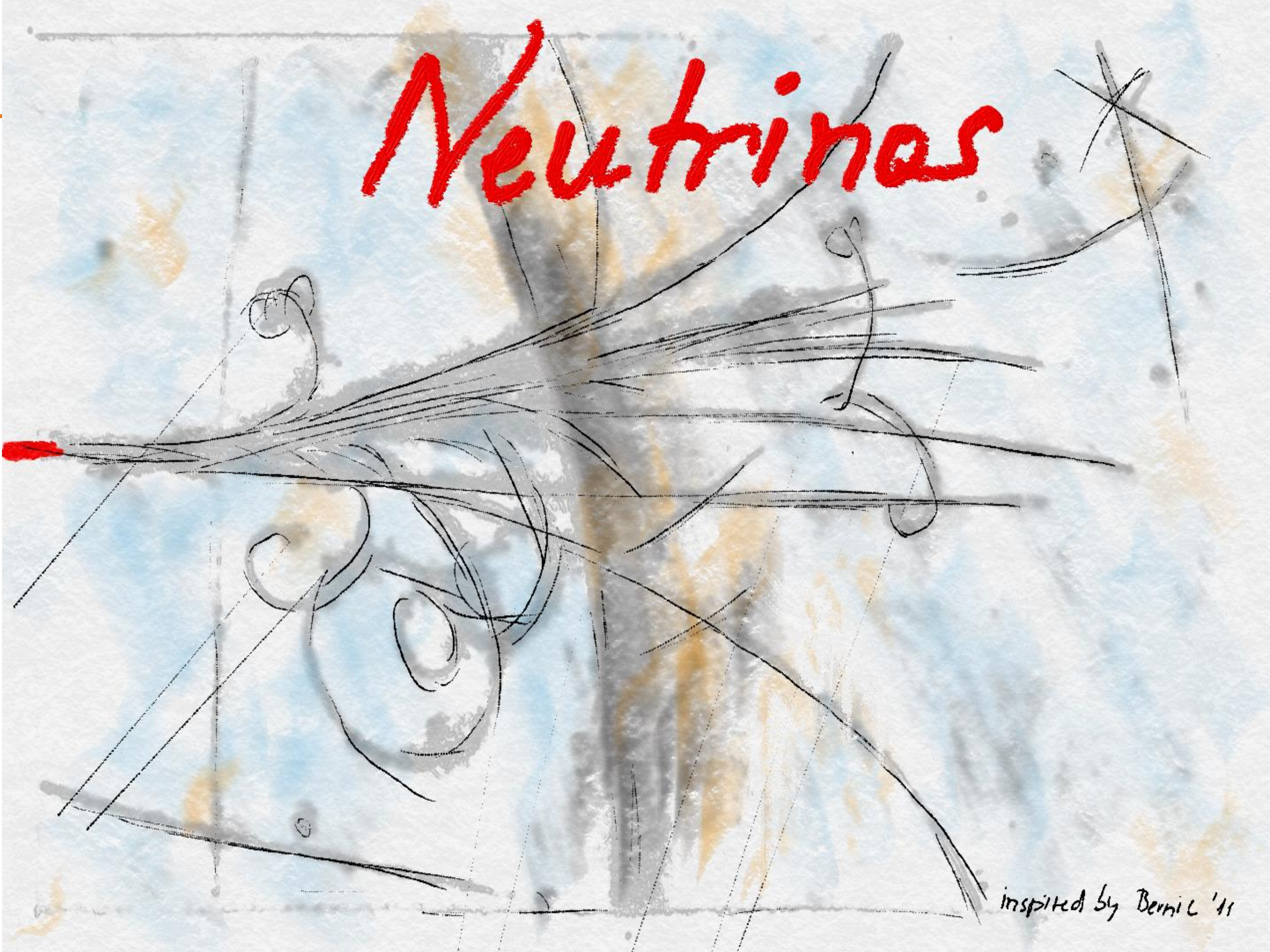
useful range for point searches:



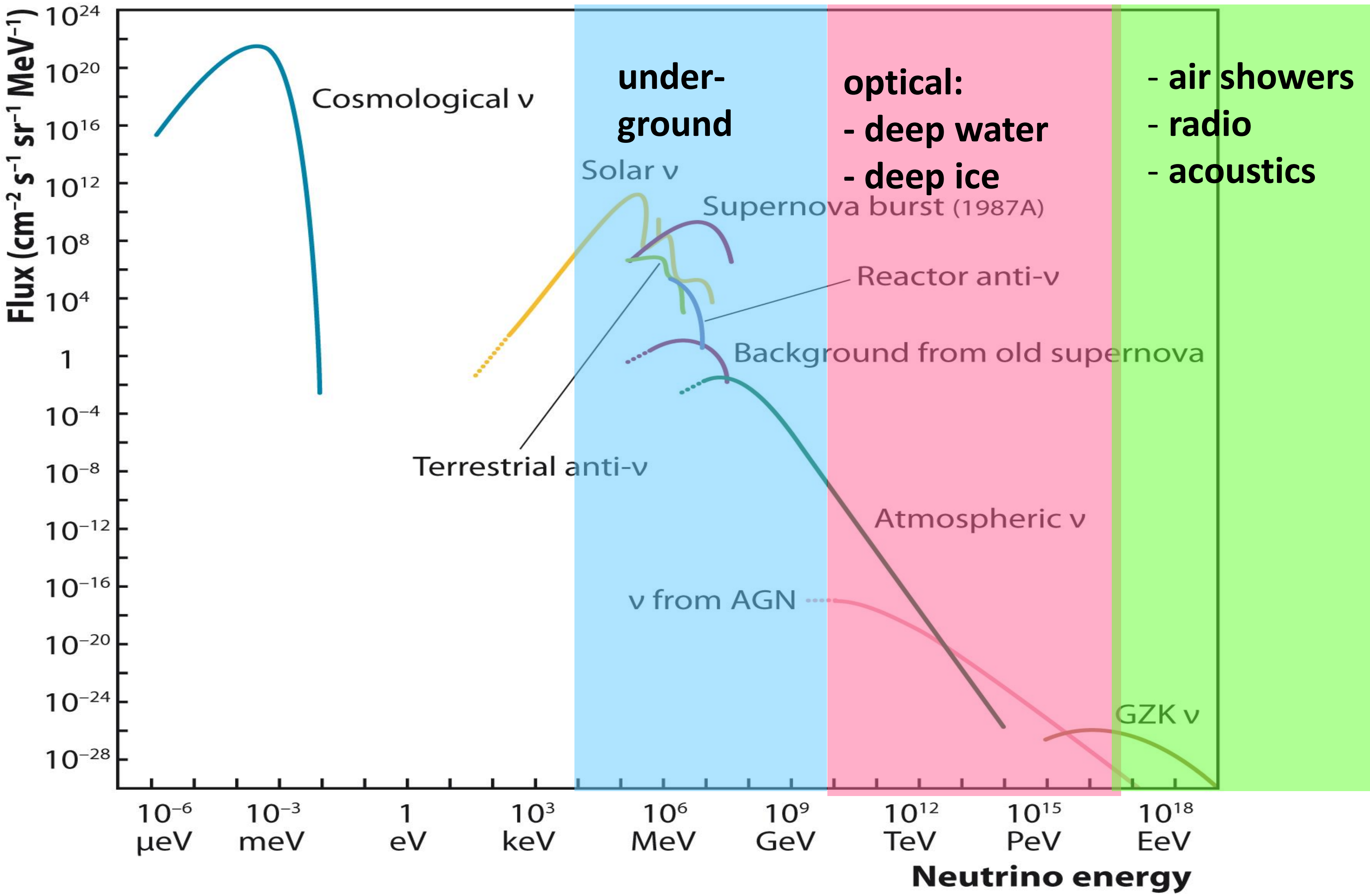
Galaxies and stars within 60 MLy



10^{20} eV p, 100 TeV γ : seeing range 60 million light years


Neutrinos
inspired by Bernie '11

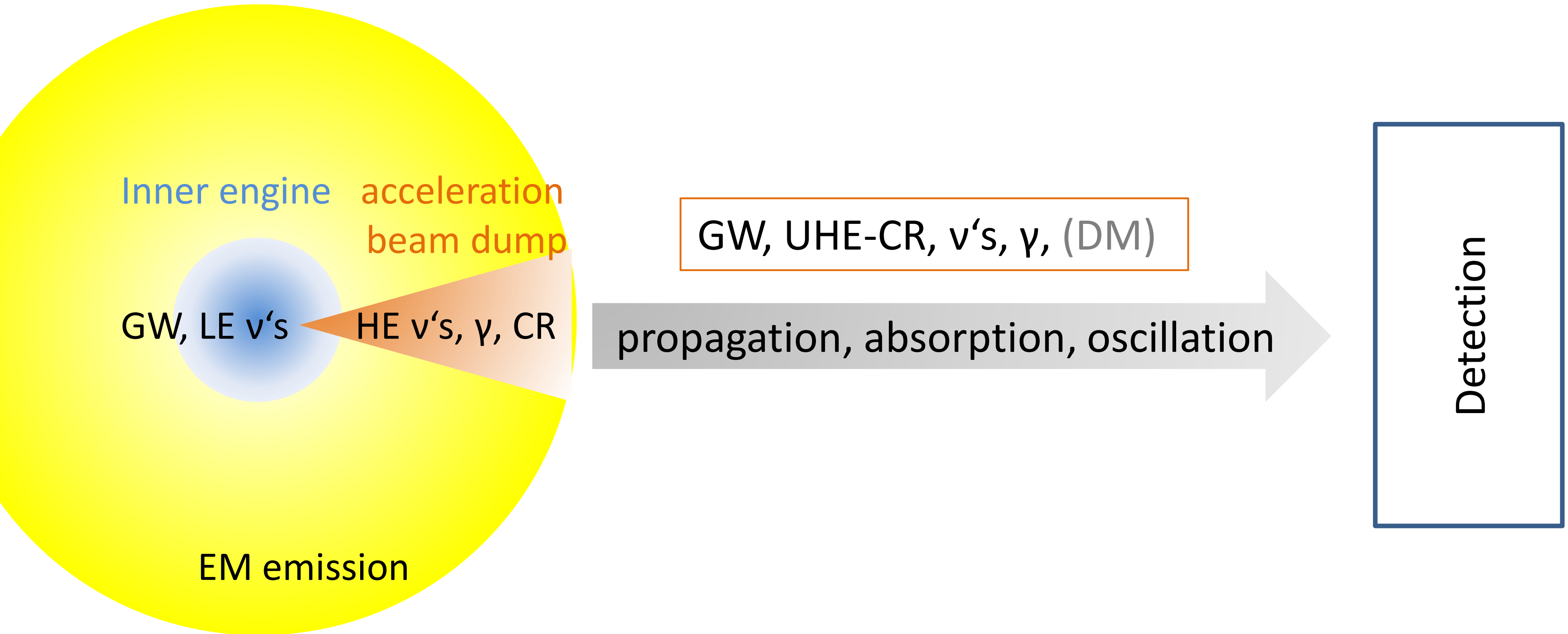
Fluxes of cosmic neutrinos



Kamiokande also uses neutrinos from accelerator beams (e.g. T2K)

Production, propagation, detection

… is a complex picture



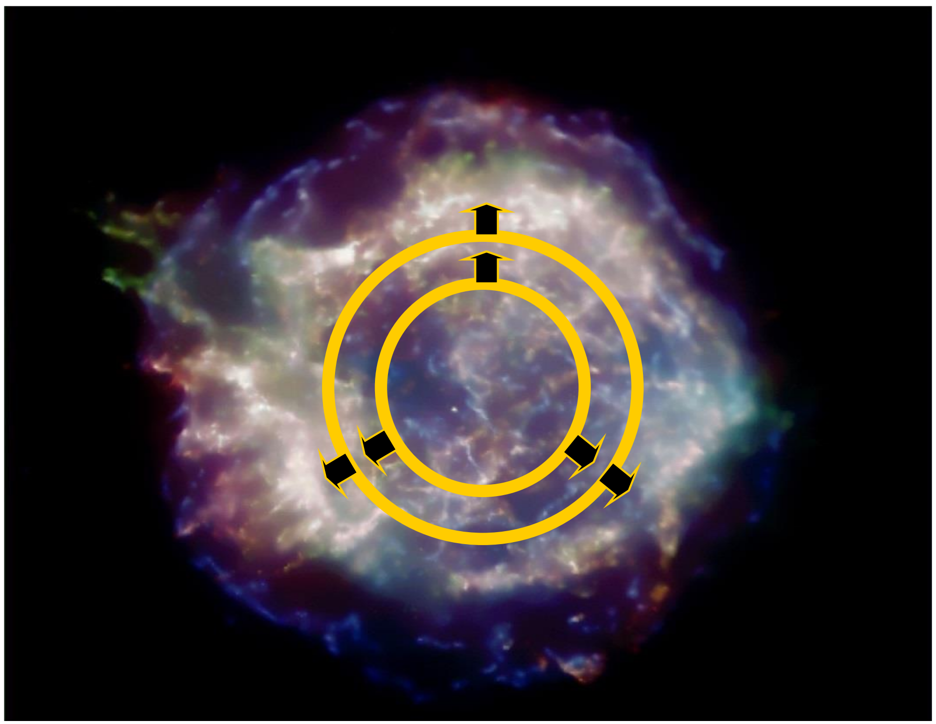
Theory: source distribution, production (L_γ/L_ν ; $\nu_e/\nu_\mu/\nu_\tau$; escapes), radiation and acceleration model, 3d magnetic fields, infrared backgrounds …

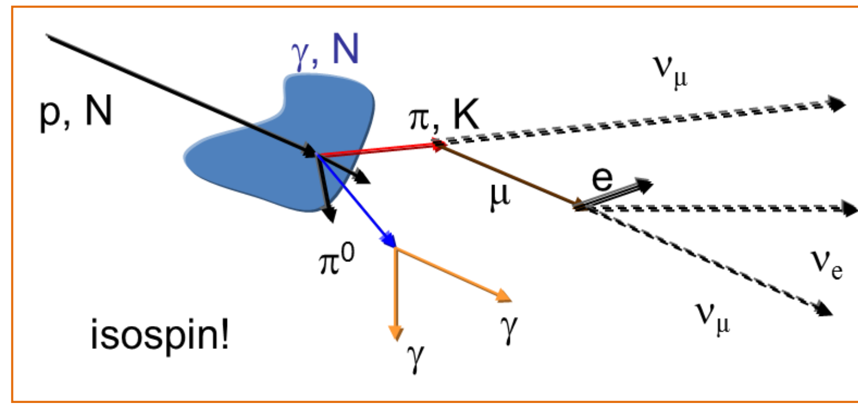
Detection: cross sections, oscillations in matter, observation in natural media ….

Closer look: neutrino production

example: proton acceleration in supernova remnant shock fronts v= O(10^6 m/s)

- *“lucky” particles pass shock fronts frequently, experiencing accelerating “kicks”*
- neutrinos (and gammas) created in beam dump made of gas or photon fields





Expect: $\nu_\mu : \nu_e : \gamma = 2:1:1$
energy distributions different

1 PeV $\upsilon \approx$ 2 PeV $\gamma \approx$ 20 PeV cosmic ray

Electrons: produce bremsstrahlung and synchroton radiation
Protons: interact with γ‘s or protons to produce pions and kaons → Waxman-Bahcall limit

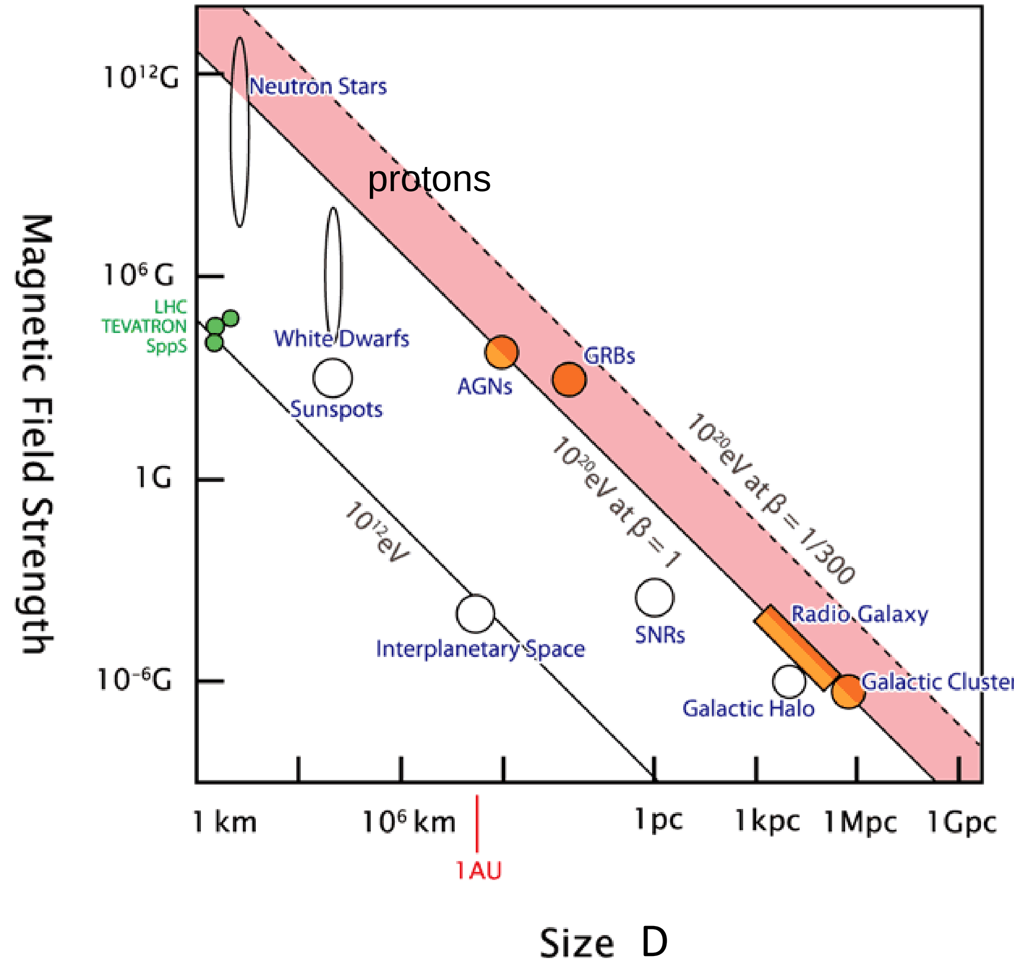
Potential sources of astrophysical neutrinos

- Which object accelerates to what energies?
- Difficult to explain energies >~10^{21} eV for protons
- Easier for heavy nuclei

$$R_{gyro}(=\frac{p}{ZqB}) \ \leq \ \beta\frac{D}{2}$$

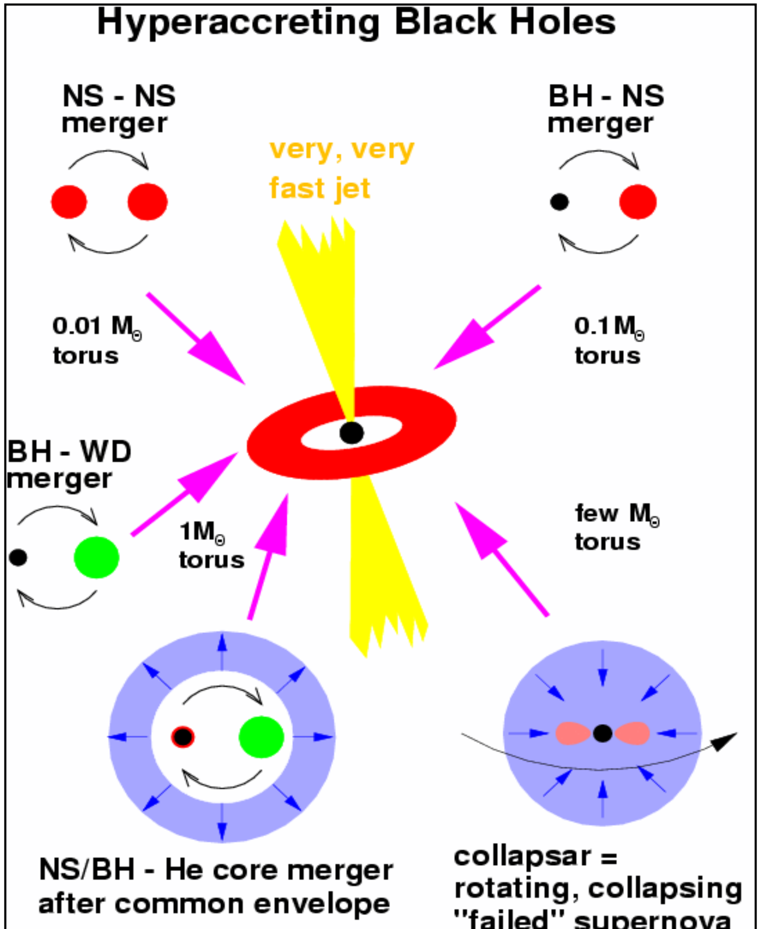
$$p \ \leq \ \frac{1}{2}\beta ZqBD$$

$$E \ \leq \ \frac{1}{2}c\beta ZqBD$$

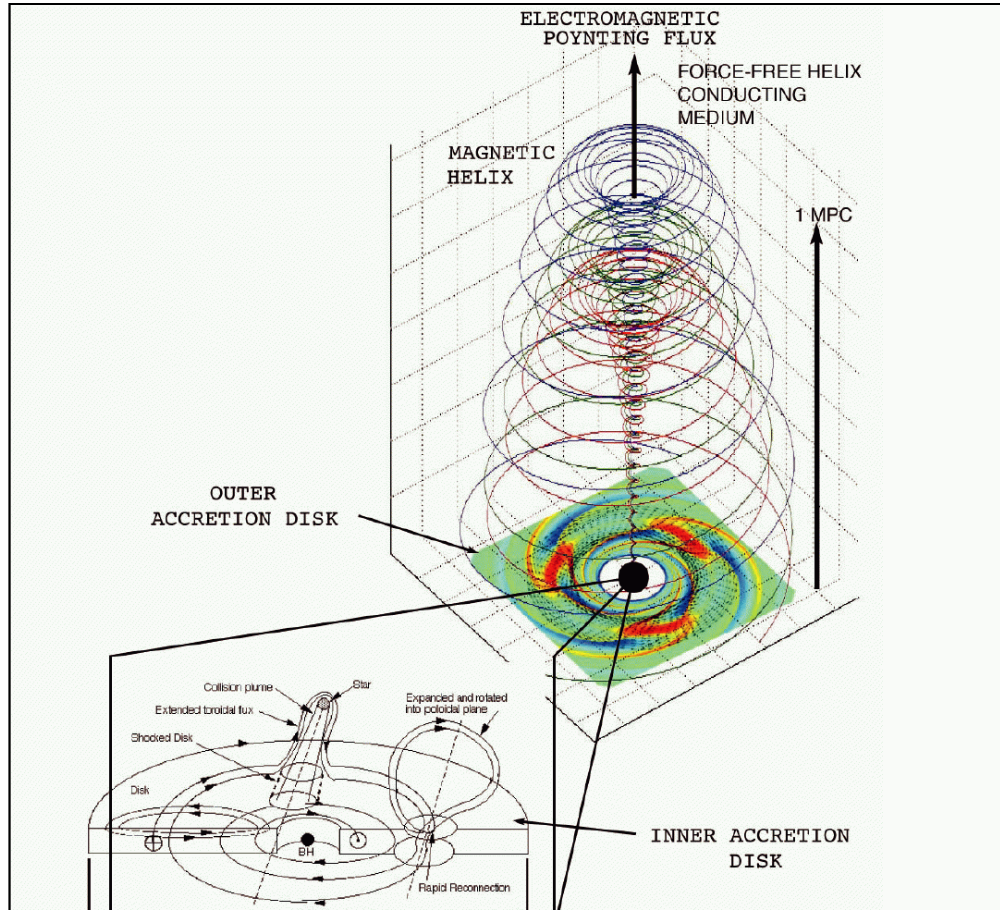


βc: velocity of scattering centers $\rightarrow$ transforms D< $2R_{gyro}$ $\rightarrow$D< $2R_{gyro}/\beta$

Example: Gamma-Ray bursts



S. Woosley, Ringberg, 1997

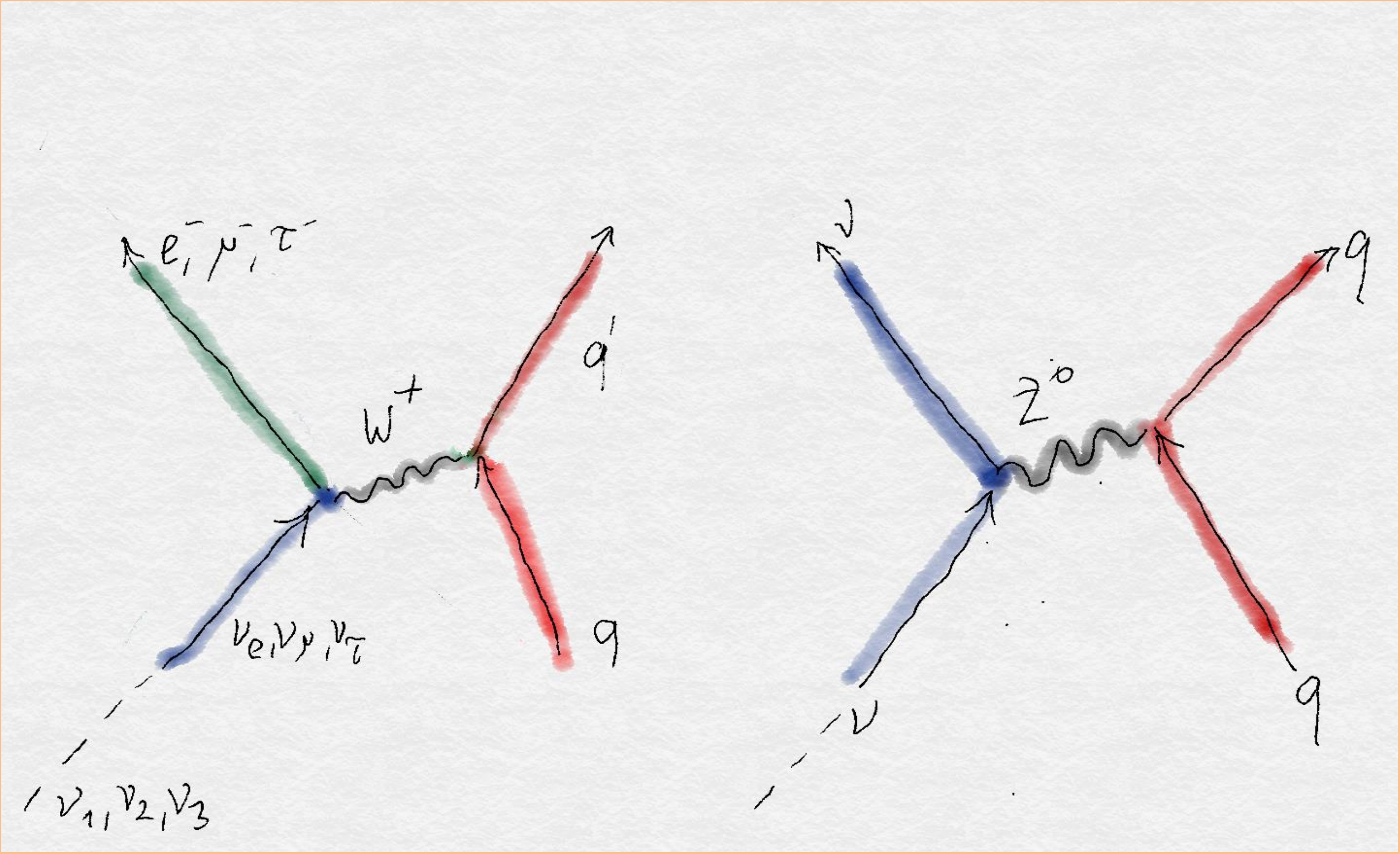


Li, Colgate, Kronberg

~ 80% of stars in Milky Way multiple!

Source of magnetic field – "dynamo" in accretion disk
Source of jet energy - accretion disk + black hole spin

ν progagation and interaction



Inspired by Nick Berger, Mainz

ν oscillations & decoherence

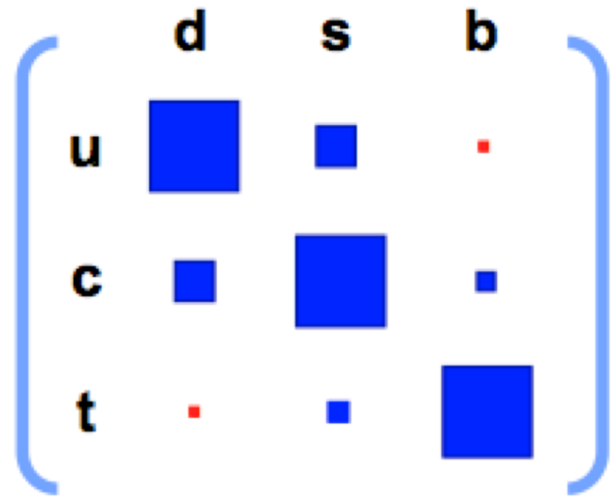
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

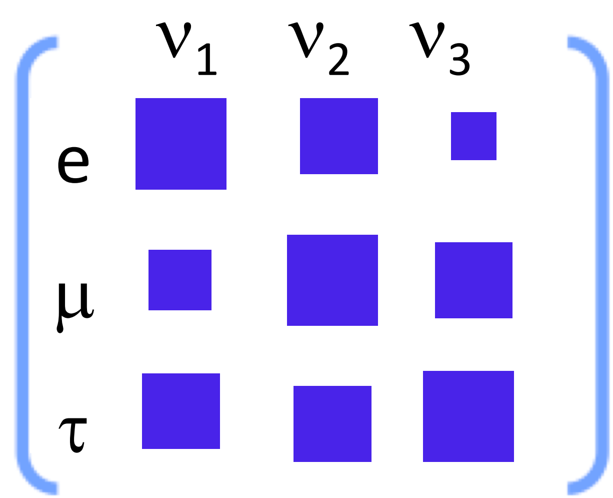
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

weak eigen-states

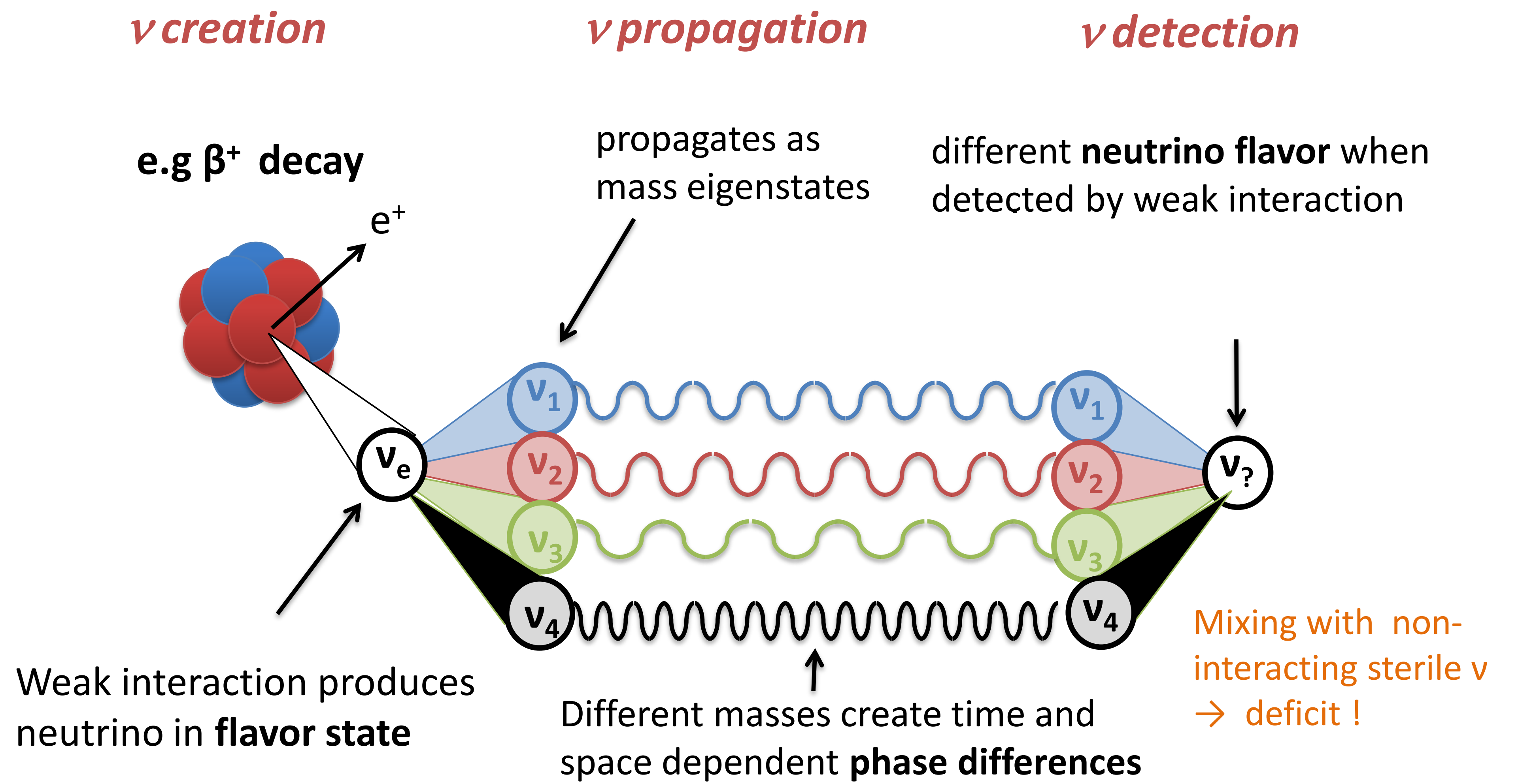
CKM or PMNS matrix

mass eigen-states





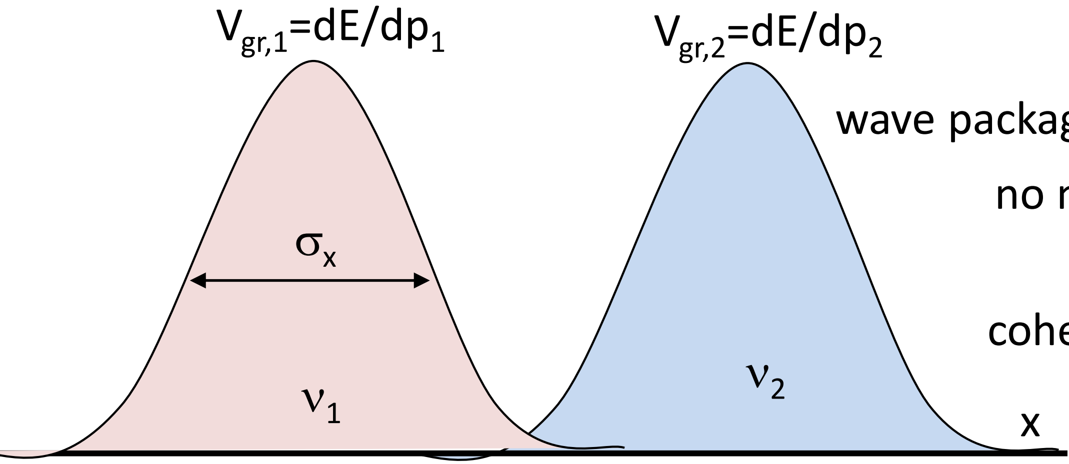
Neutrino oscillations



$$P_{\alpha\to\beta} = \left|\langle \nu_\beta | \nu_\alpha(t)\rangle\right|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i}\, e^{-im_i^2 L/2E}\right|^2 = f(\theta_{ji}, (m_j^2 - m_i^2)\frac{L}{E_j})$$

Coherence in propagation

Neutrinos travel as wave package that loose overlap due to group velocity differences Δv_{gr} :



wave package separation: Δv_{gr} L/c

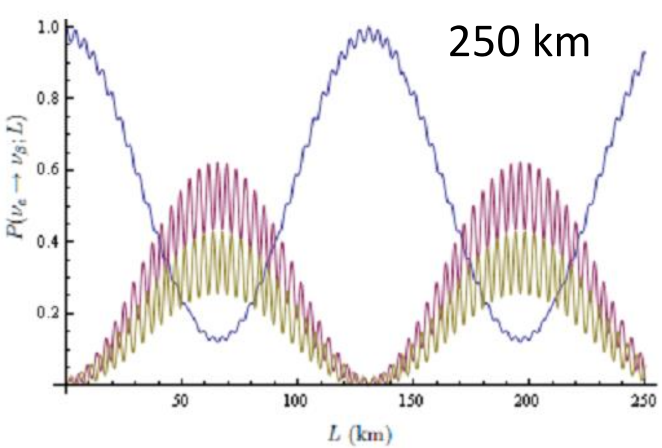
no more overlap: Δv_{gr} L/c ≈> σ_x

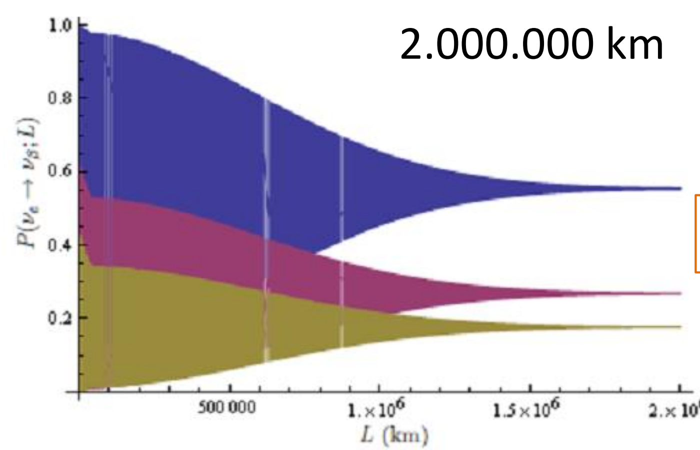
coherence length: $L_{coh} = 2\sigma_x\ E^2/(\Delta m^2 c^4)$

… coherence also determined by conditions of creation and detection …

Example 4 MeV neutrinos

http://users.jyu.fi/~jojapeil/thesis/coherence_in_neutrino_oscillations_040211.pdf





decoherent!!

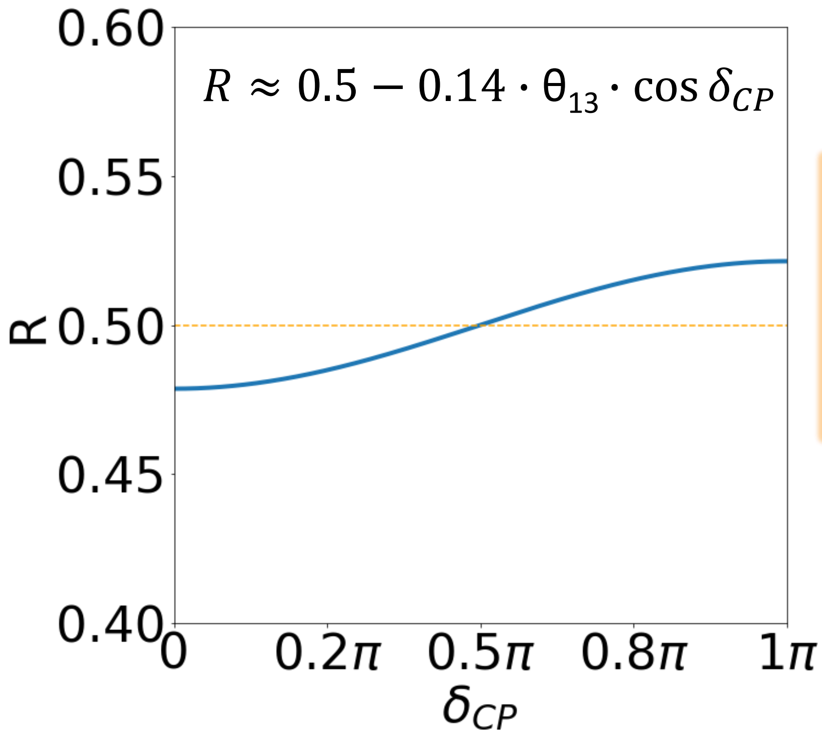
Neutrinos from far away sources

If coherence lost, averaged effect:

$$\overline{P}_{\alpha\rightarrow\beta} = \sum_i |U_{\beta i}|^2 |U_{\alpha i}|^2$$

if $\nu_e : \nu_\mu : \nu_\tau$ = 1 : 2 : 0 ($\pi^{+/-}$ decay): **flux at Earth = 1 : 1 : 1**

To be exact, there is some dependence on θ_{13} , θ_{23} and $\boldsymbol{\delta_{CP}}$:



In principle: flavor ratio could be used for CP violation studies!

... if production process were exactly known !!

$$R^{\text{Pion beam}} = \frac{2P_{\mu\mu} + P_{e\mu}}{2P_{\mu e} + P_{ee} + 2P_{\mu\tau} + P_{e\tau}}$$

Neutrino cross sections

s < 10⁴ GeV²:

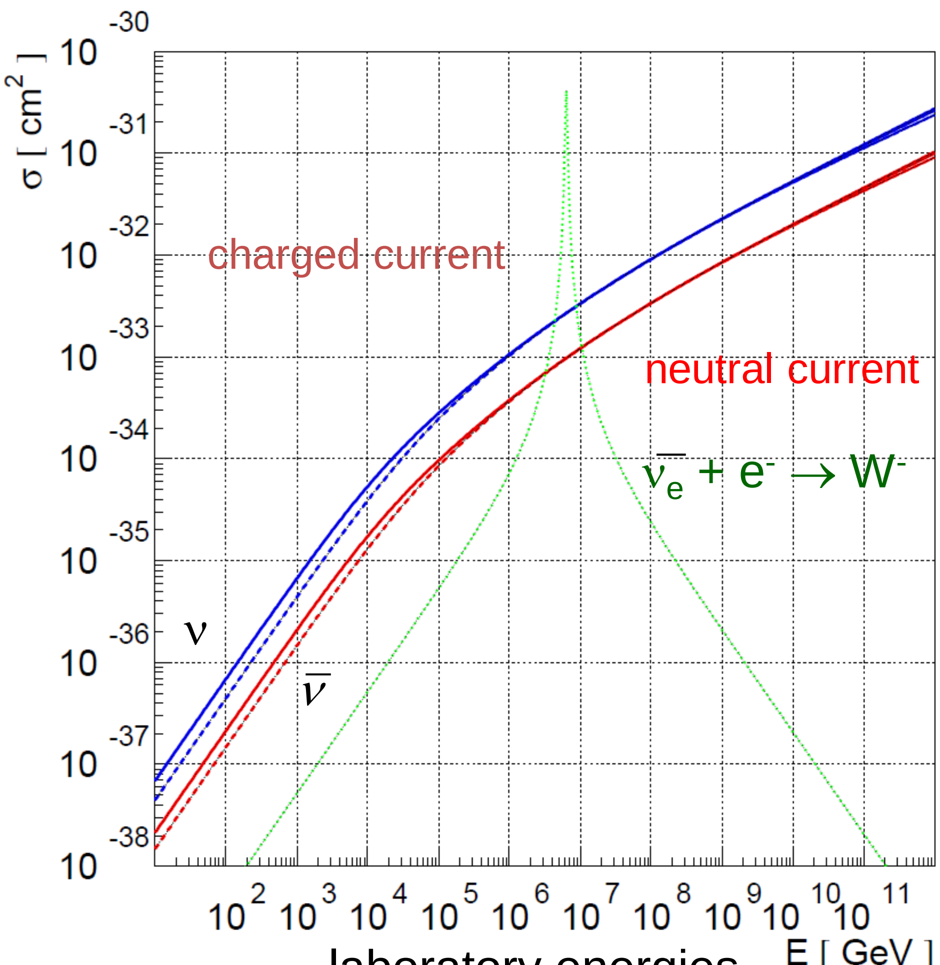
$$\frac{d^2\sigma}{dx\,dy} = \frac{G_F^2}{\pi} s \left[x d(x) + (1-y)^2 x \overline{u}(x) \right]$$

x : fraction nucleon momentum carried by q

y : fraction E_ν transferred to hadronic state

xd(x) = momentum distribution of d-type quarks

xu(x) = momentum distribution of u-type anti-quarks



laboratory energies

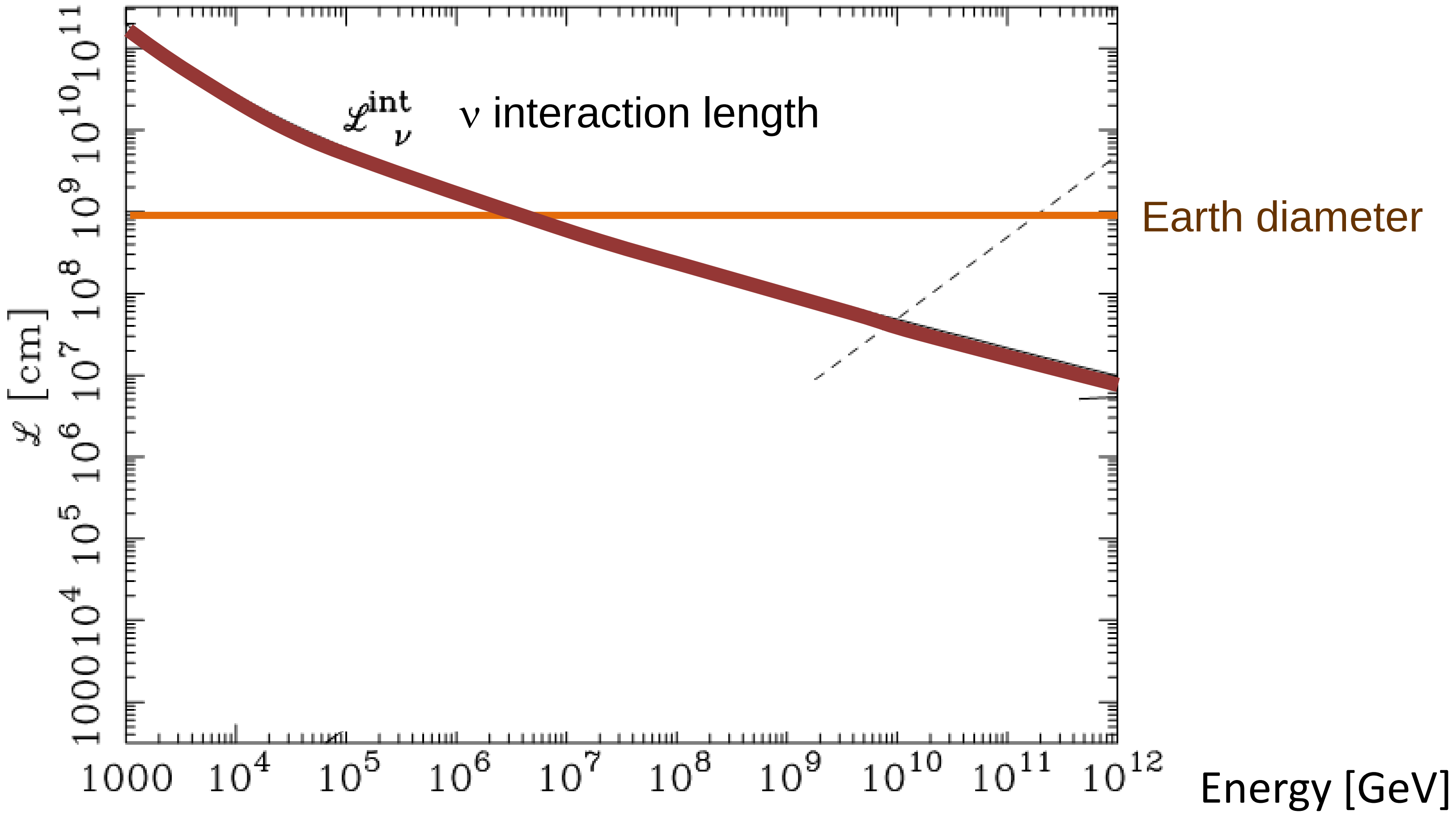
Obvious questions:

- Why is there a kink?
- Why σ(anti-ν) lower?
- Why is there a resonance?

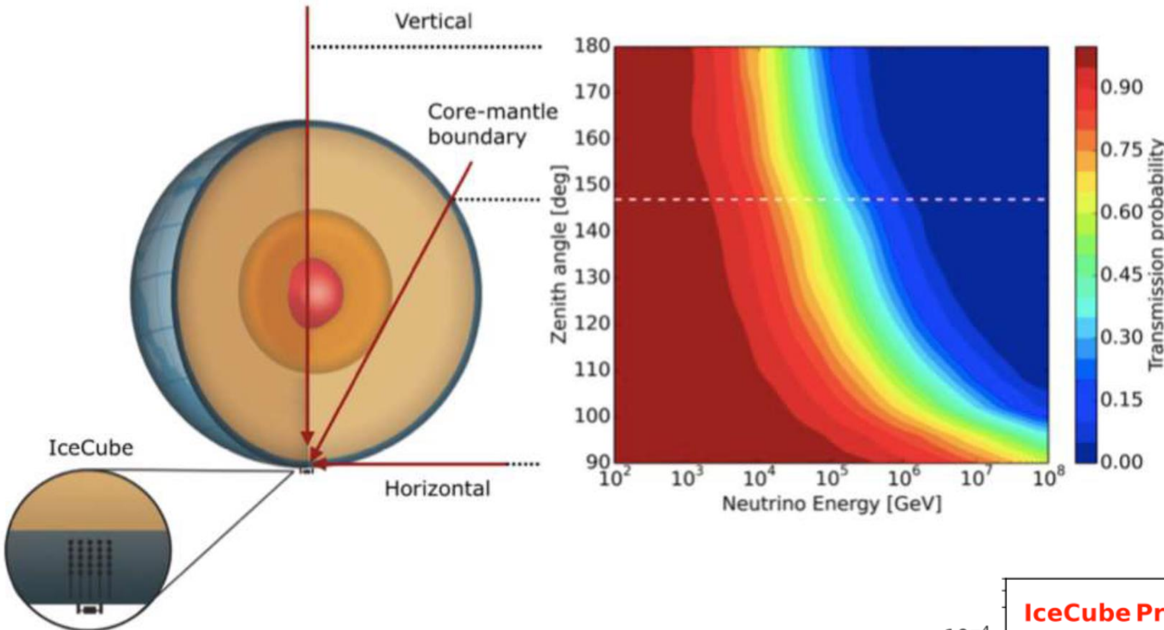
ν interaction length in Earth

path length L_A forA travelling through medium with B with number density ρ_B :

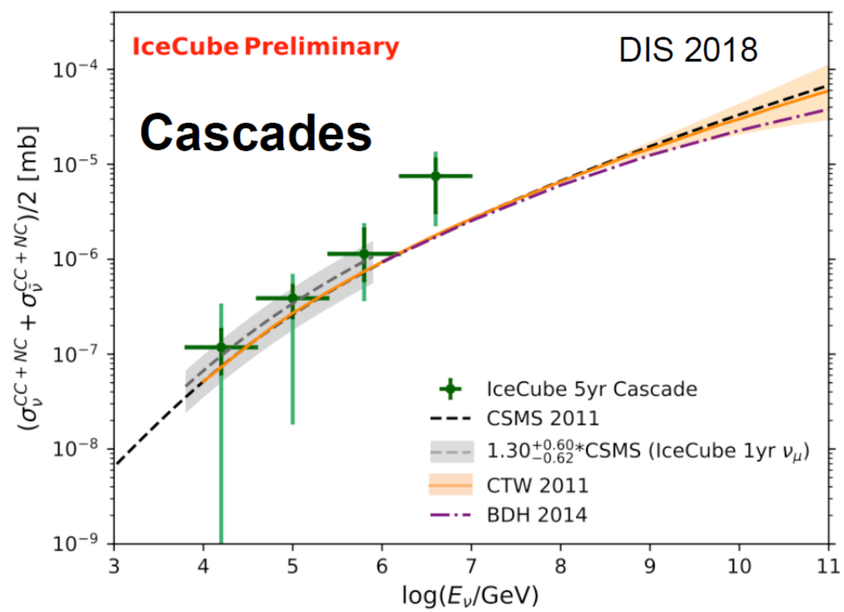
$L_A = 1 / (\rho_B \, \sigma_{A \to B})$ → larger than universe for $\sigma_\nu(1\text{ TeV}) = 10^{-39}\text{ m}^2$, $\rho = 0.4/\text{cm}^3$



IceCube Measurement

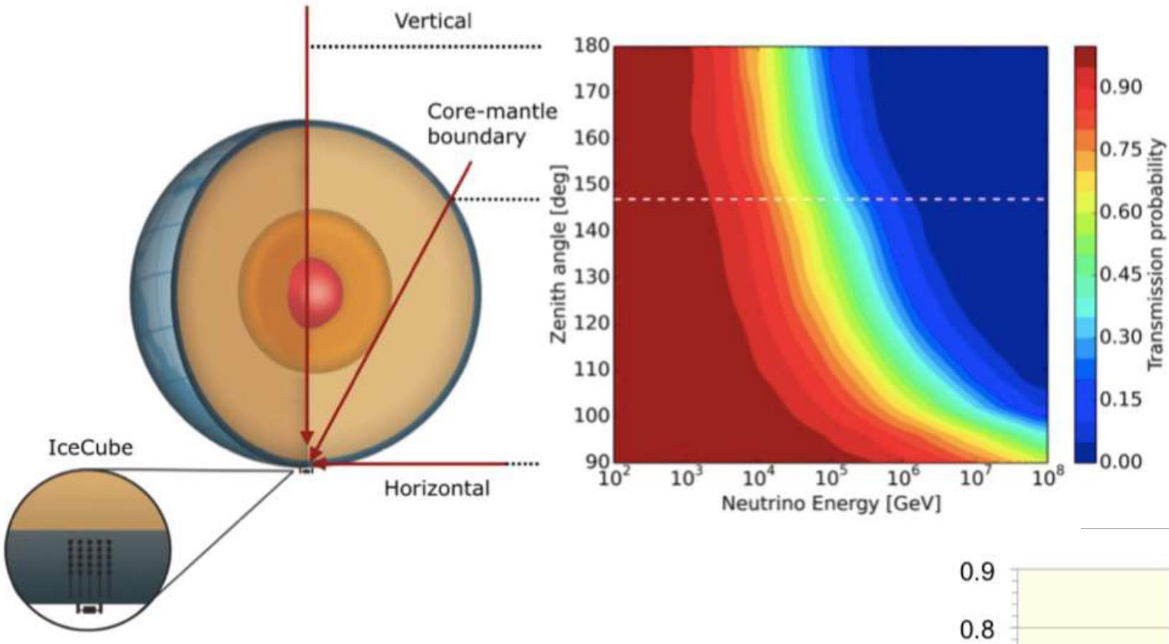


Nature 551 (2017) 596

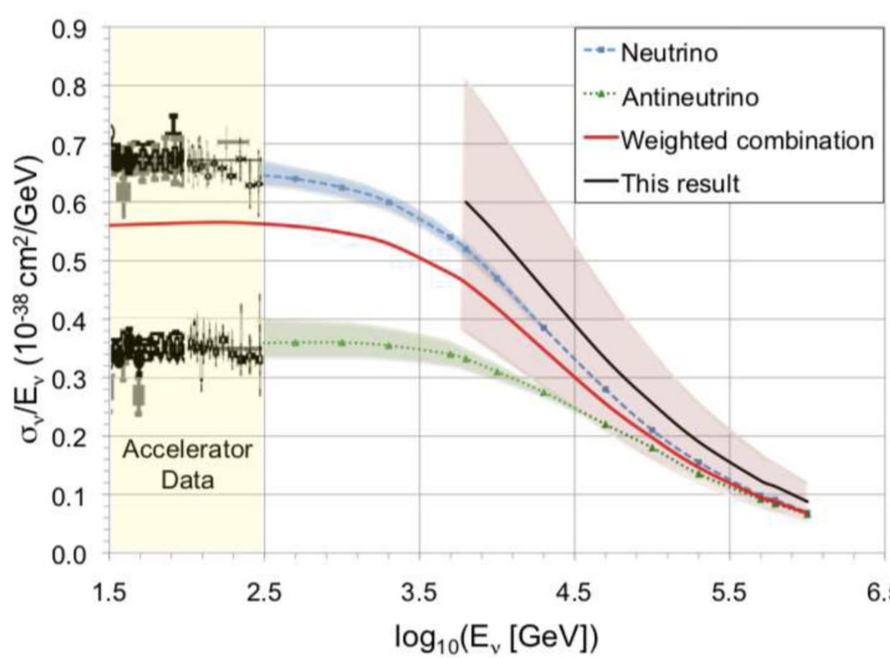


- Effect of W propagator clearly seen
- Uncertainties still rather high

IceCube Measurement

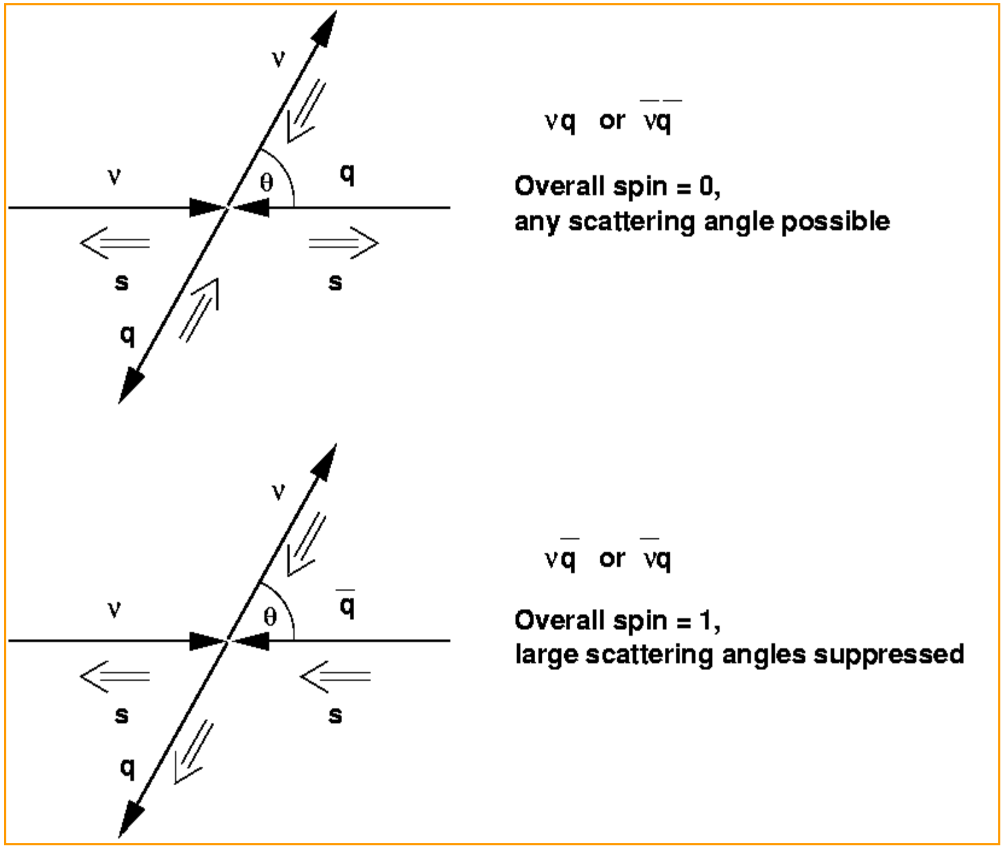


Nature 551 (2017) 596



- Effect of W propagator clearly seen
- Uncertainties still rather high

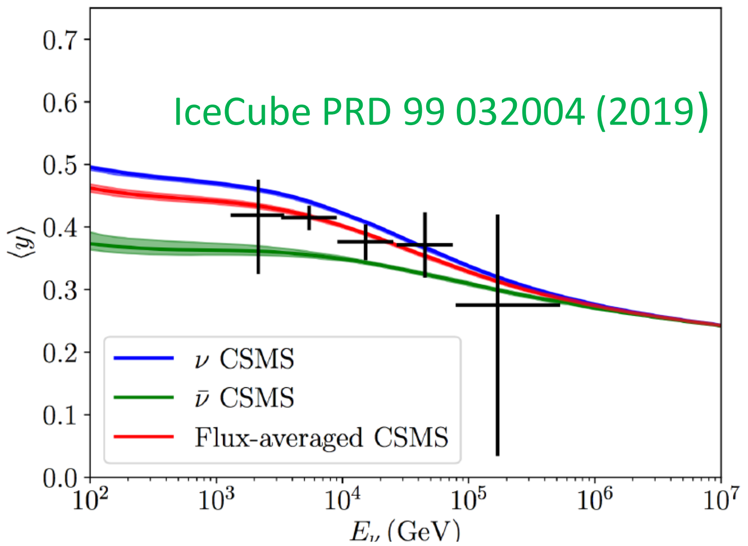
Why are $\sigma(\nu q)$ & $\sigma(\bar{\nu} q)$ different?



- neutrino has helicity -½
- quark prefers helicity -½

- spin 0 system has no directional preference

- conservation of spin gives $y=E_{had}/E_\nu$-dependence for s=1



weak interaction couples to left-handed fermions only ...

Effect of the W propagator

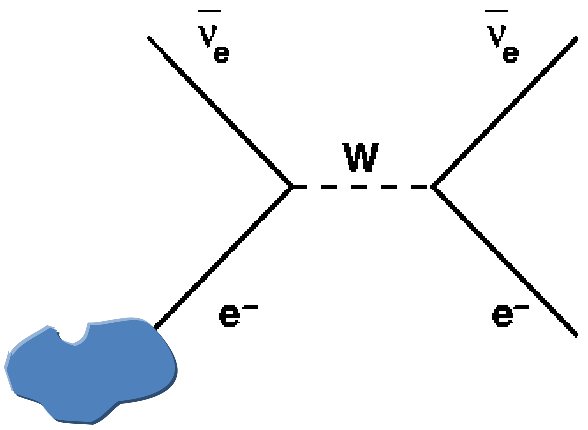
Exchange of massive real W needs to be accounted for energies > 40 TeV

reasonable cross section approximation above W threshold:

$$\sigma_{tot} = 1.2 \times 10^{-32} cm^2 (E_\nu / 10^{18} eV)^{0.40}$$

... no longer ~ E_ν

Glashow resonance: resonant production of real W^- from $\bar{\nu}_e$ hitting ambient electrons



Resonance paramters:

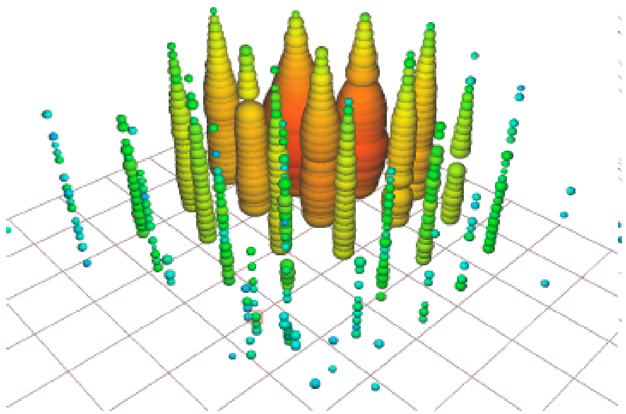
neutrino laboratory energy:	6.7 PeV
resonance width:	±130 TeV
peak cross section:	5 x 10^{-35} m^2

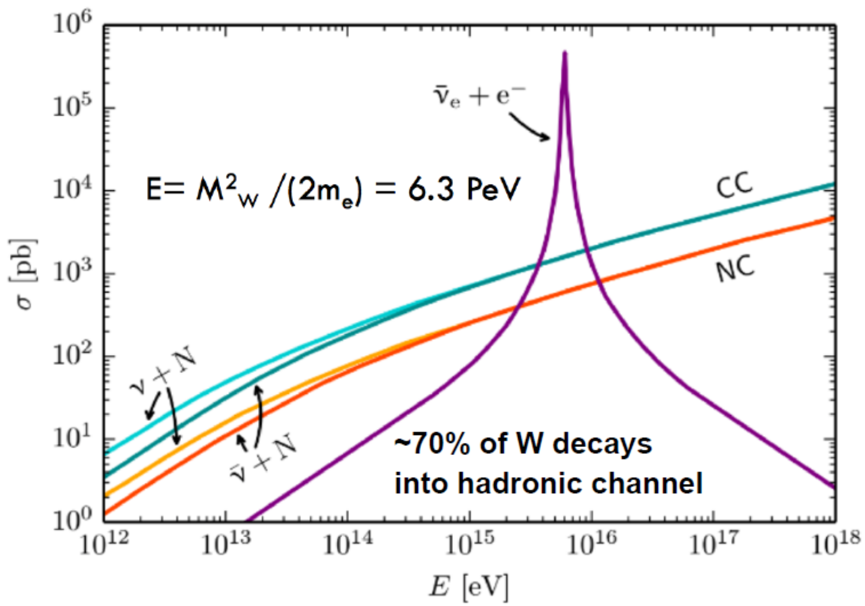
„Amplifier“ at very high energies!

Candidate event?

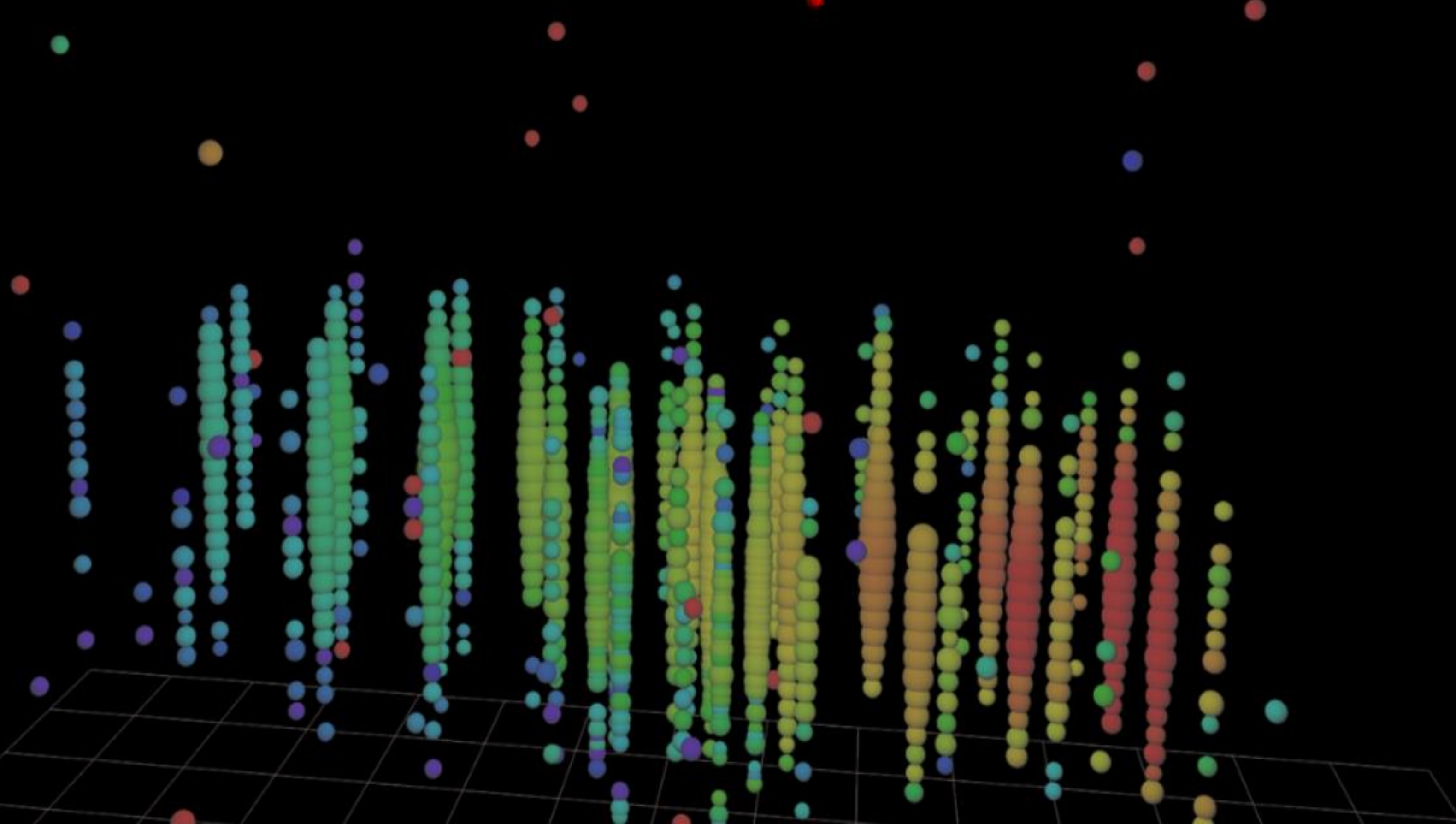
A new high(est) energy cascade interaction with atomic electron?

- Partly contained event
- Likely neutrino energy $6.35^{+0.30}_{-0.23}$ PeV PoS (ICRC2017) 1002
- Consistent with shower containing hadrons („muon tag“)





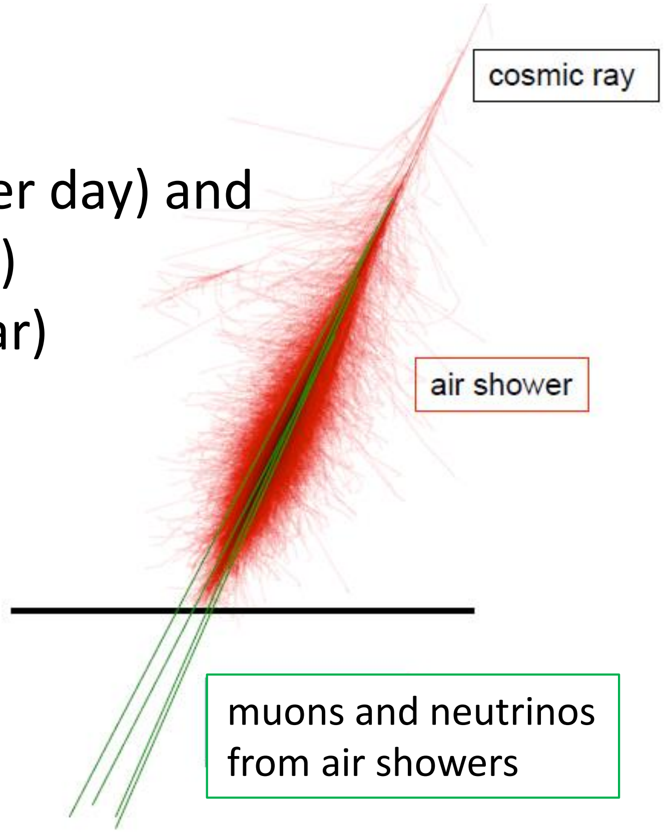
Detection principle



Main Goals of 1km^3 ν telescopes

Measure fluxes of

- atmospheric muons (250 million per day) and
- atmospheric neutrinos (> 200 per day)
- astrophysical neutrinos (~ 100 per year)



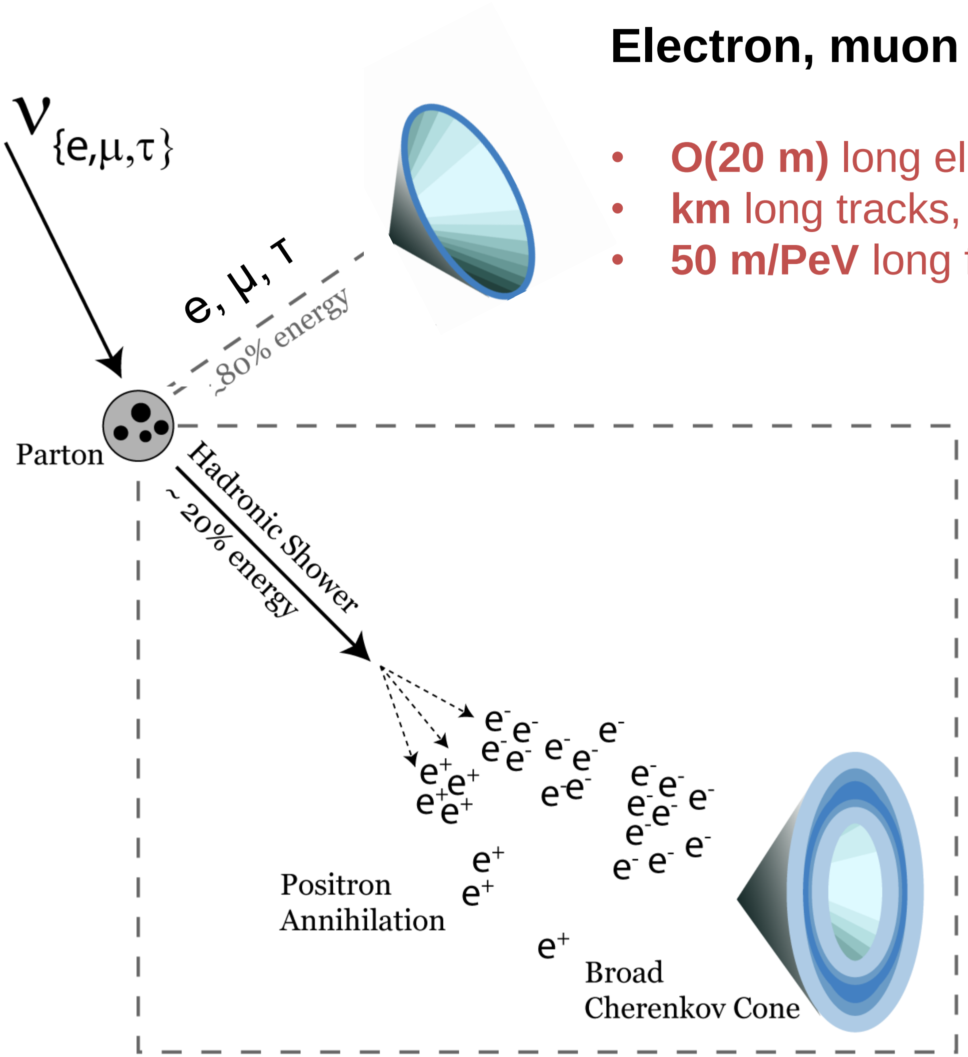
at higher energies & with better statistics than previous experiments

Any deviations from what is expected is new

- neutrino physics or
- new astrophysics

Realistic: Understand more about origin, composition and cosmic ray interactions
Dream: Dark matter, new, rare particle interactions, galactic supernovae, etc.

What happens in the detector?



Electron, muon or tauon

- **O(20 m)** long electron showers (except for highest energies)
- **km** long tracks, narrow Cherenkov cone for muons
- **50 m/PeV** long faint tau tracks, as Bremsstrahlung ~1/mass

for neutral current interactions:

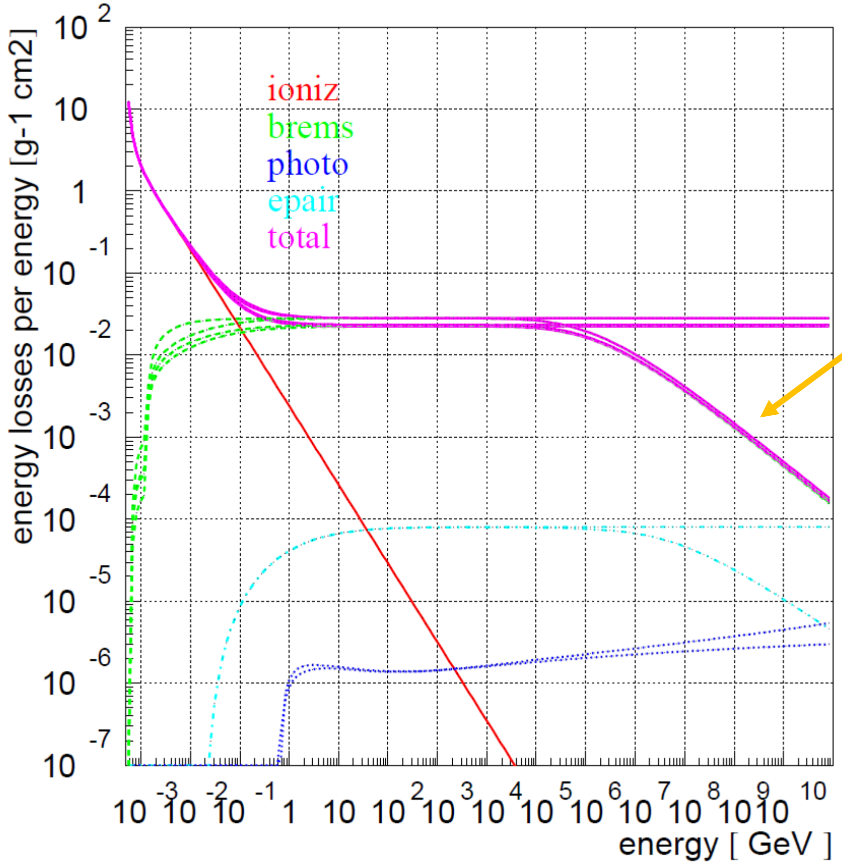
only hadronic cascade visible!

Let‘s look at the propagation of electrons and muons …

Electron interactions and propagation

Processes leading to energy loss of electrons:

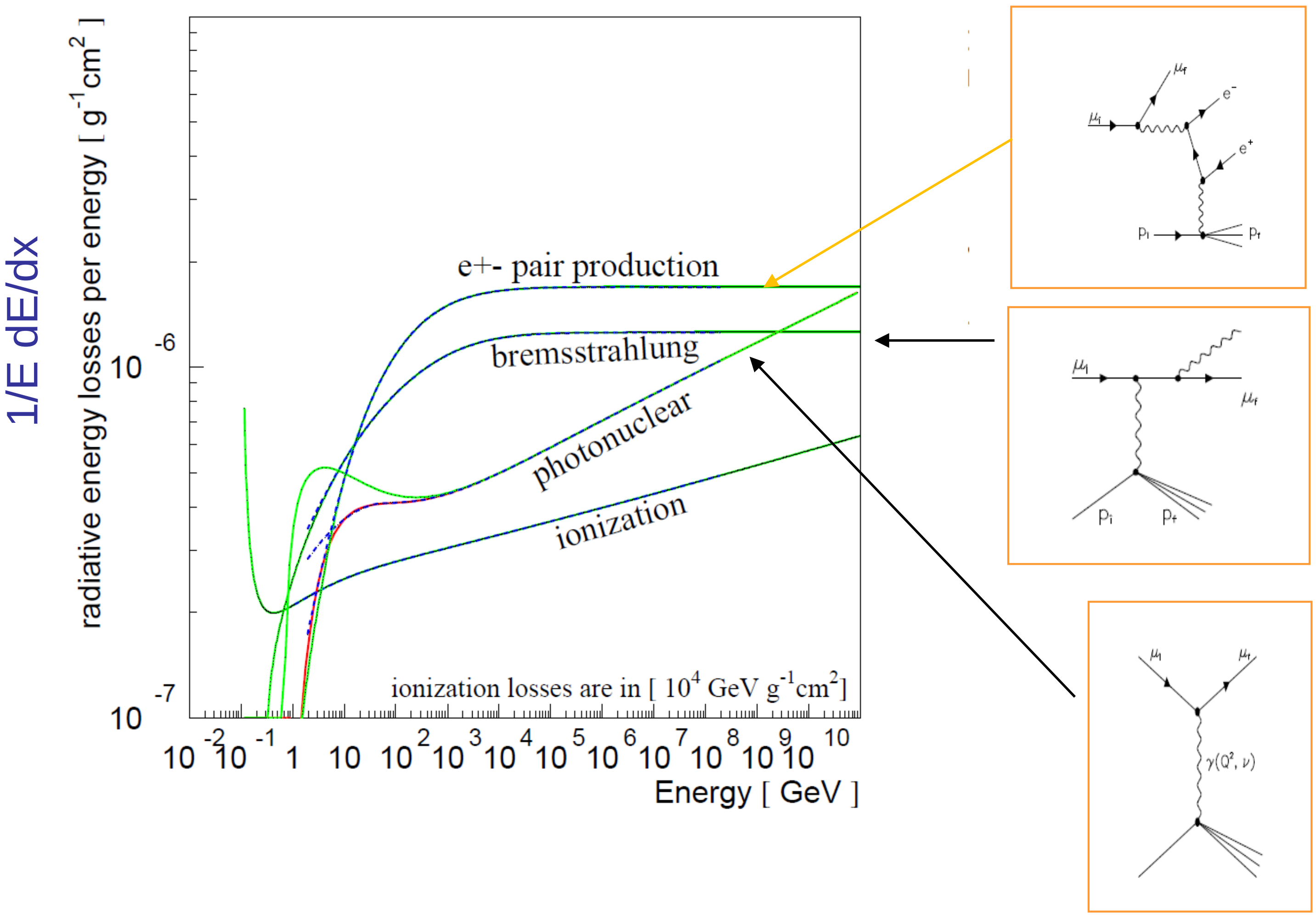
1/E dE/dx



LPM suppression

Lev Landau, Isaak Pomeranchuk and Arkady Migdal

muon energy loss



pair creation dominant!

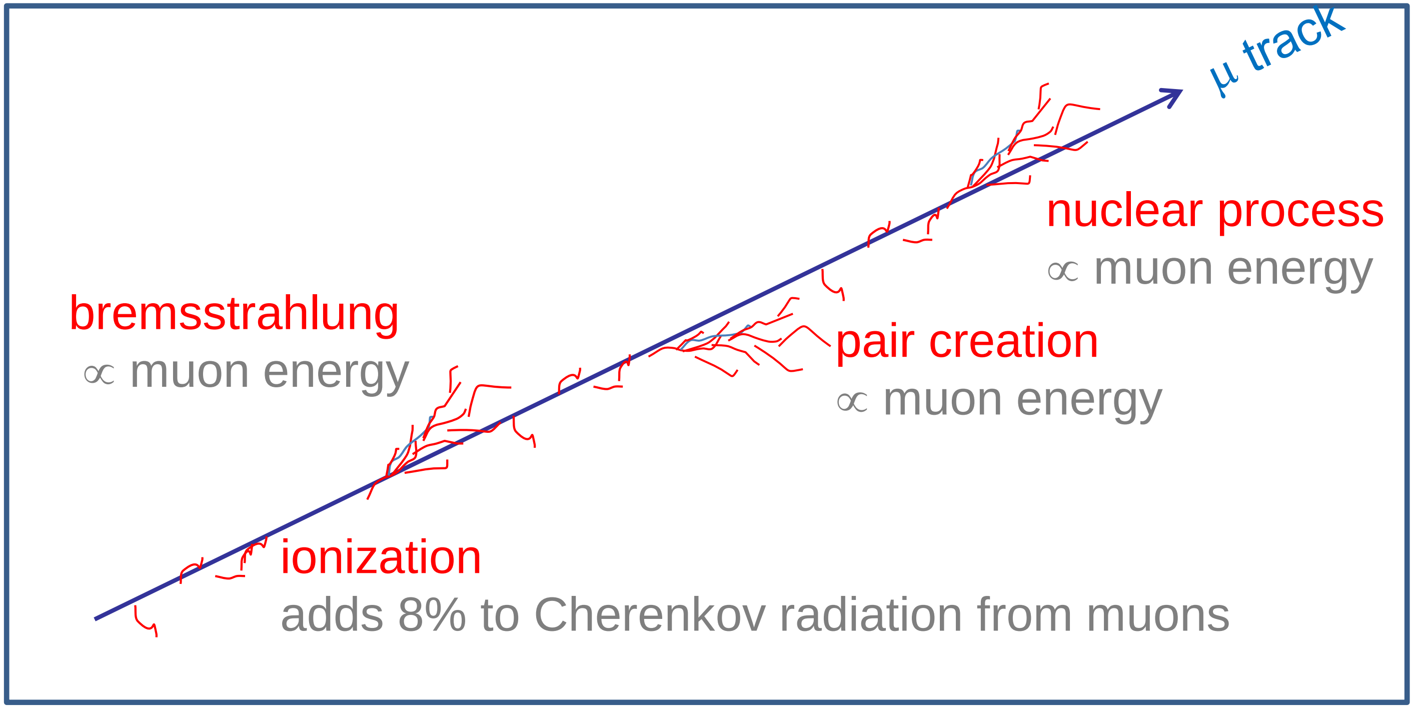
bremsstrahlung

photonuclear

… effect on Cherenkov radiation

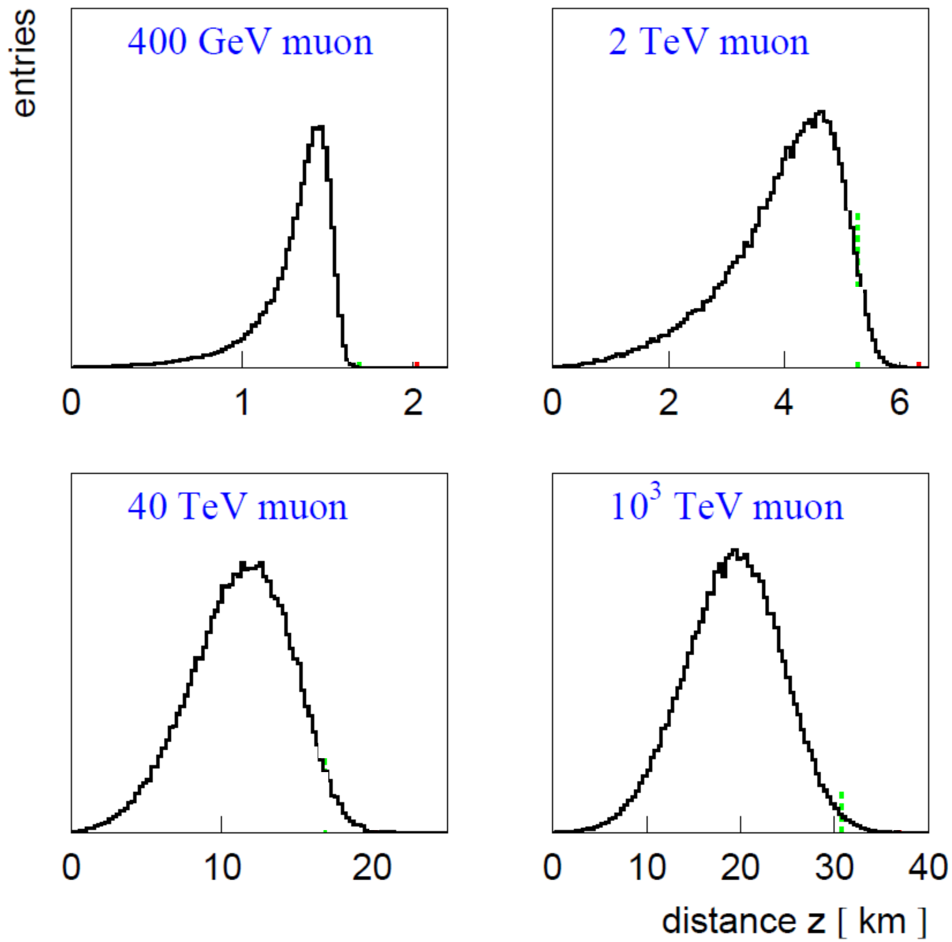
Number of Cherenkov photons: $$\frac{dN_\gamma}{d\lambda dx} = \frac{2\pi\alpha^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n_p^{\ 2}}\right) \overset{\int_{300\,nm}^{600\,nm}}{\approx} 335/\text{cm}$$

Cherenkov angle: $$\cos\theta_C = \frac{1}{\beta \cdot n_p}$$



While muon Cherenkov radiation is at fixed angle, widening by showers/ionization

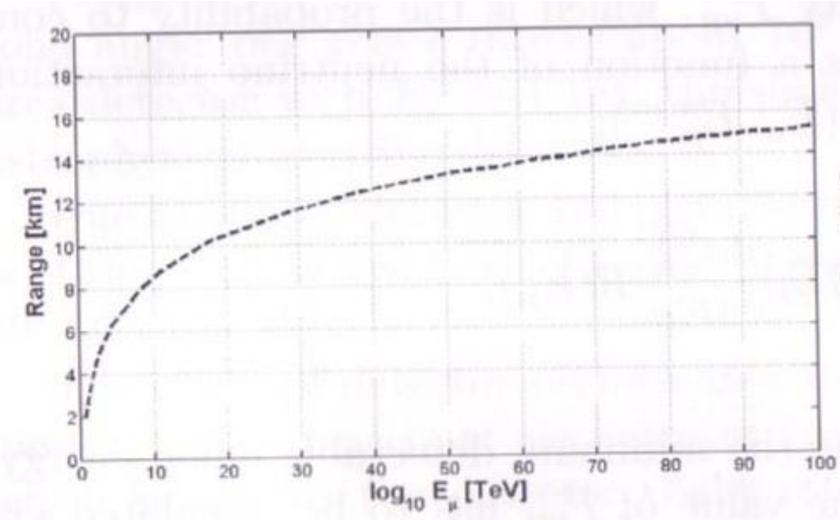
muon range



average range R in ice:

$$R = \int_{E_\mu^{\min}}^{E_\mu} \frac{1}{\langle dE/dX \rangle} dE = -\int_{E_\mu^{\min}}^{E_\mu} \frac{1}{a + b \cdot E}$$

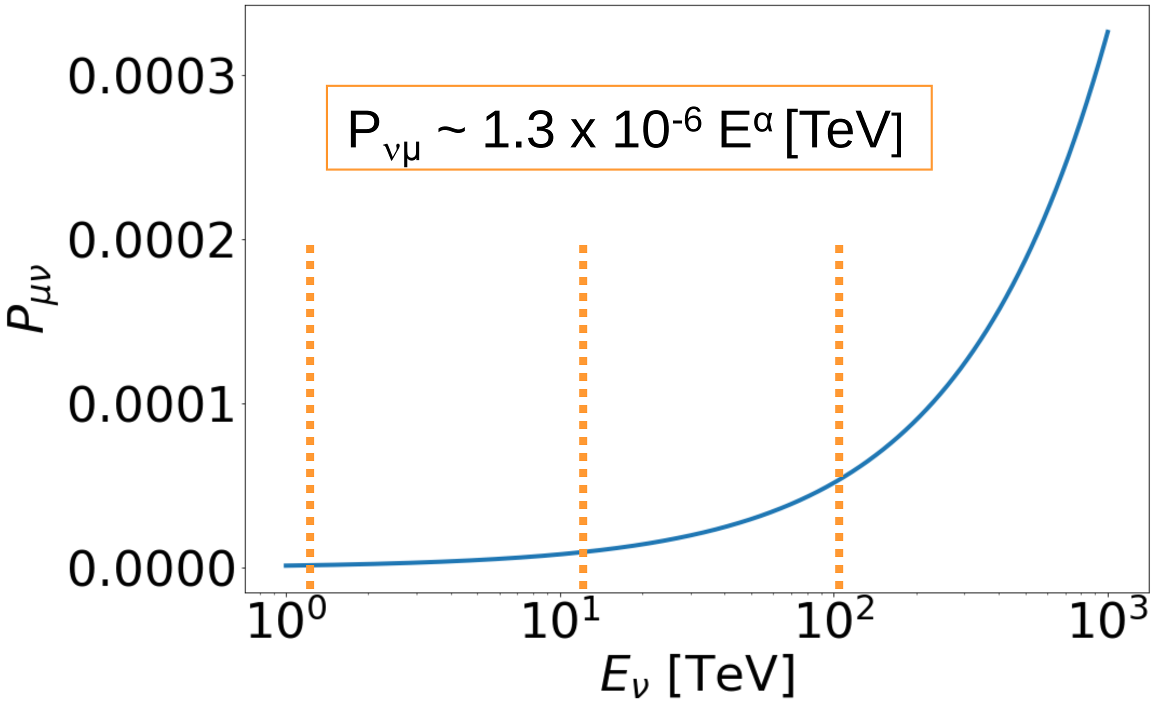
$$= \frac{1}{b} \log \frac{a/b + E_\mu}{a/b + E_\mu^{\min}} .$$



Probability to convert ν into μ

$$P_{\nu\mu} = N_A\, \rho_N \int_{E_\mu^{\min}}^{E_\nu} \frac{d\sigma}{dE_{\mu_\mu}}\, dE_\mu\, R(E_\mu)$$

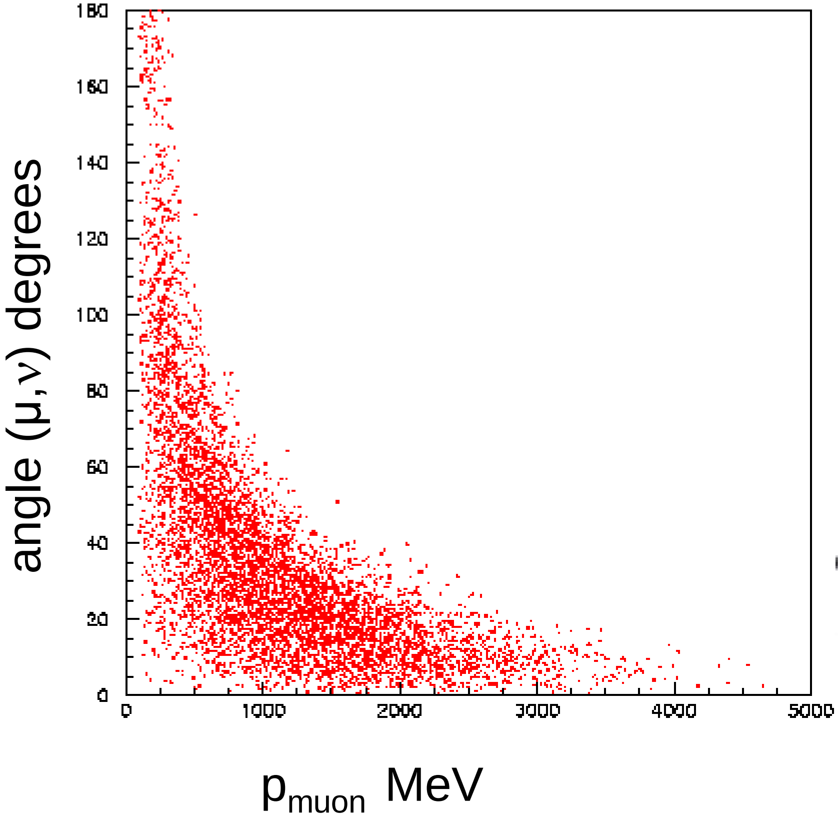
$R_{E\mu}$: average muon range
E^{min}: minimal detectable muon energy
ρ_N : number density

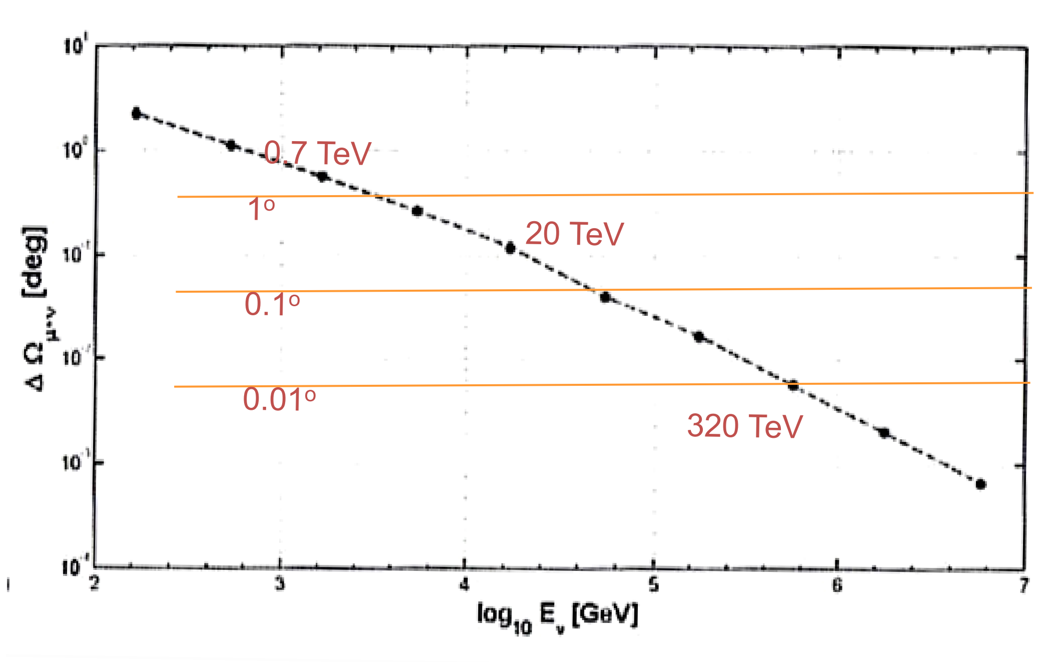


α~0.8 for 1 TeV<E<1 PeV

1 TeV: $P_{\nu\mu}$ ~ 1.3×10^{-6}
10 TeV: $P_{\nu\mu}$ ~ 8.2×10^{-6}
100 TeV: $P_{\nu\mu}$ ~ 52×10^{-6}

muon – neutrino angle





average for high energies:

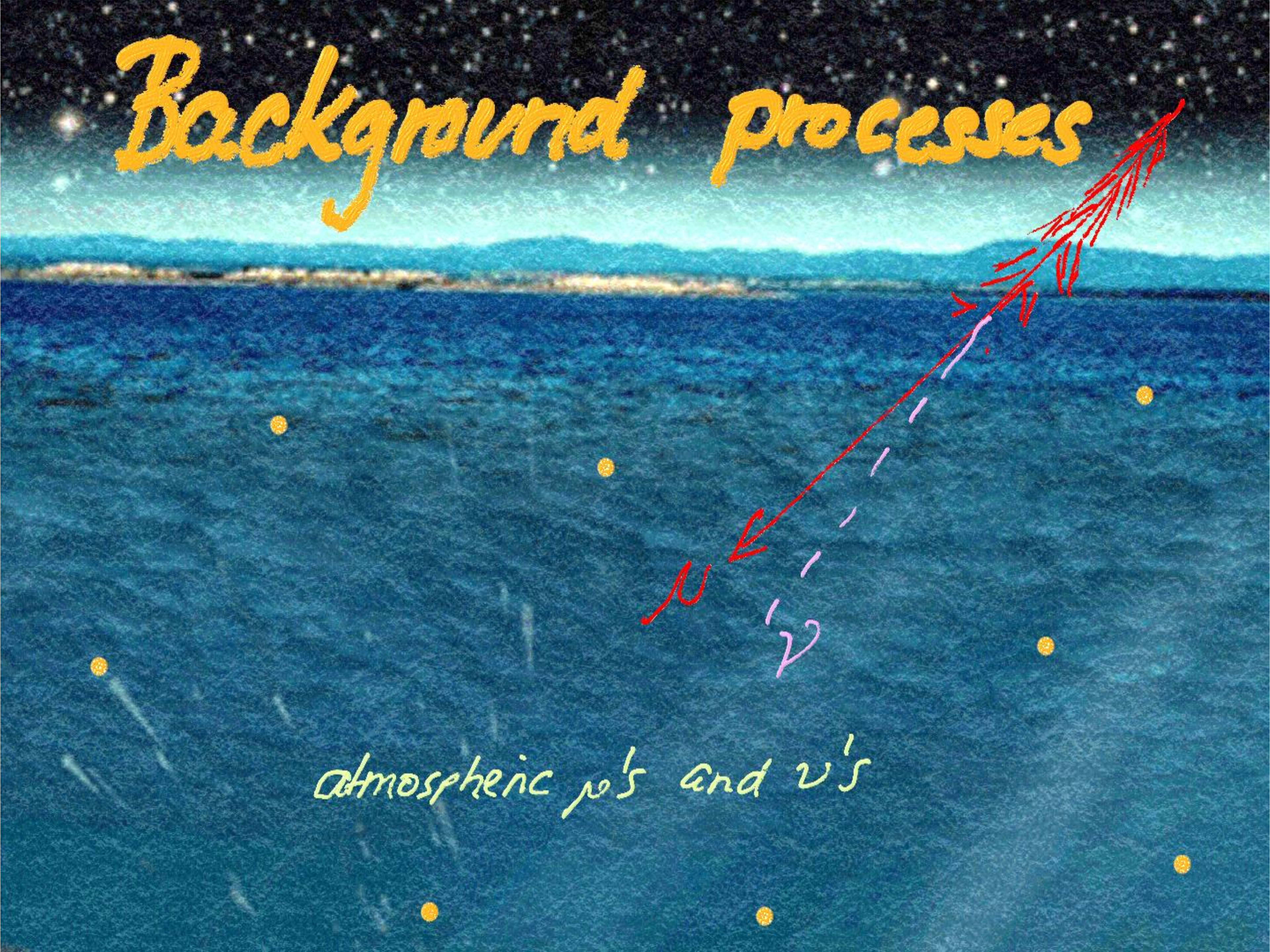
angle= $0.7^\circ / E[\mathrm{TeV}]^{0.6}$

Sub-degree directional resolution makes sense only for E_ν > TeV

Table of content: Part 2

- Background processes
- IceCube and ist experimental challenges
- Point Source searches
- Starting track searches
- Diffuse searches
- Summarizing the results
- The future

Make people trust we see astrophysical ν‘s


Background processes
μ
ν
atmospheric μ's and ν's

Atmospheric ν: π and K decays

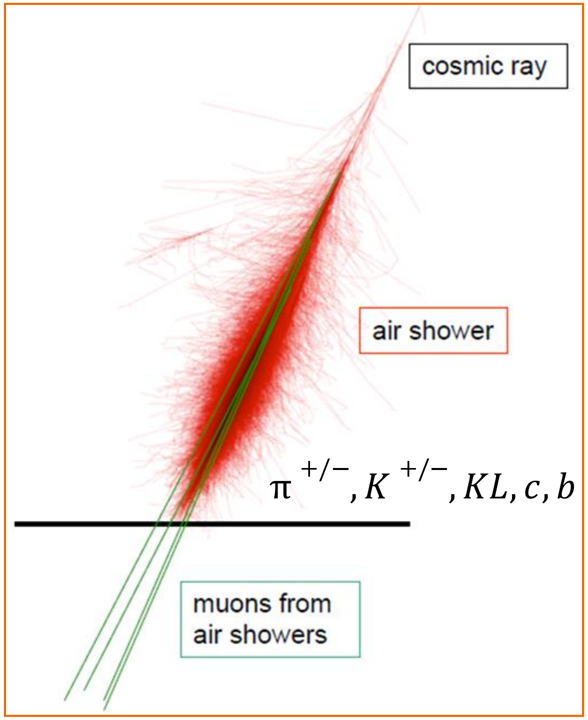
lightest charged mesons only decay via weak interactions:

$\pi^+ = |ud> \rightarrow \mu^+ + \nu_\mu$ + cc (~100%)
$K^+ = |us> \rightarrow \mu^+ + \nu_\mu$ + cc (63%)

Kinematics: $E_\nu(\text{from } \pi) < 0.25 \times E_\pi$
$E_\nu(\text{from K}) < 0.78 \times E_K$

Above ~ 100 GeV, interaction length of π and K in atmosphere shorter than their decay length …

→ ν energy spectrum dN/dE ~ $E^{-3.7}$

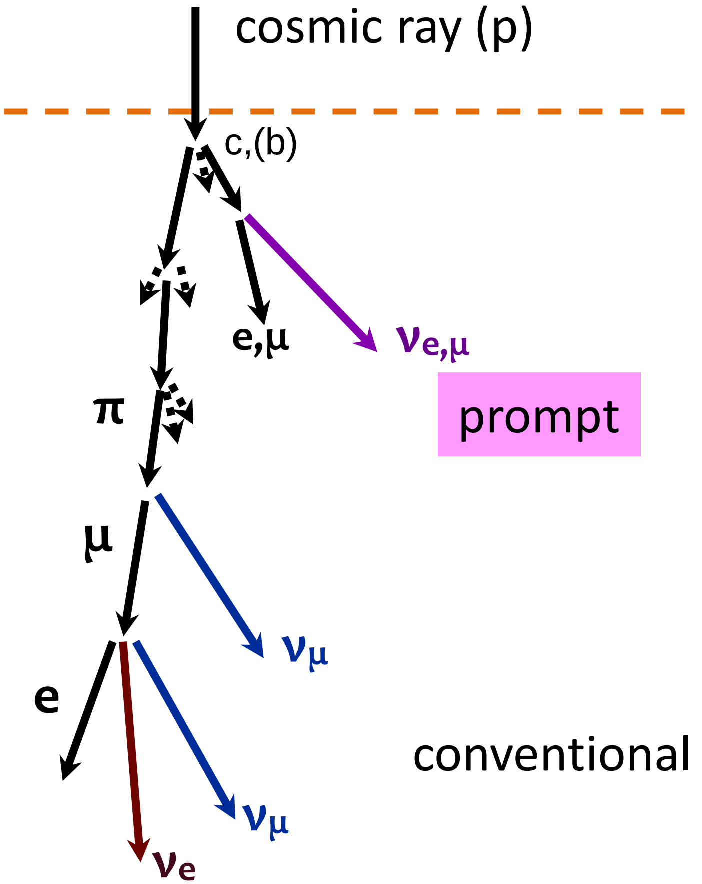


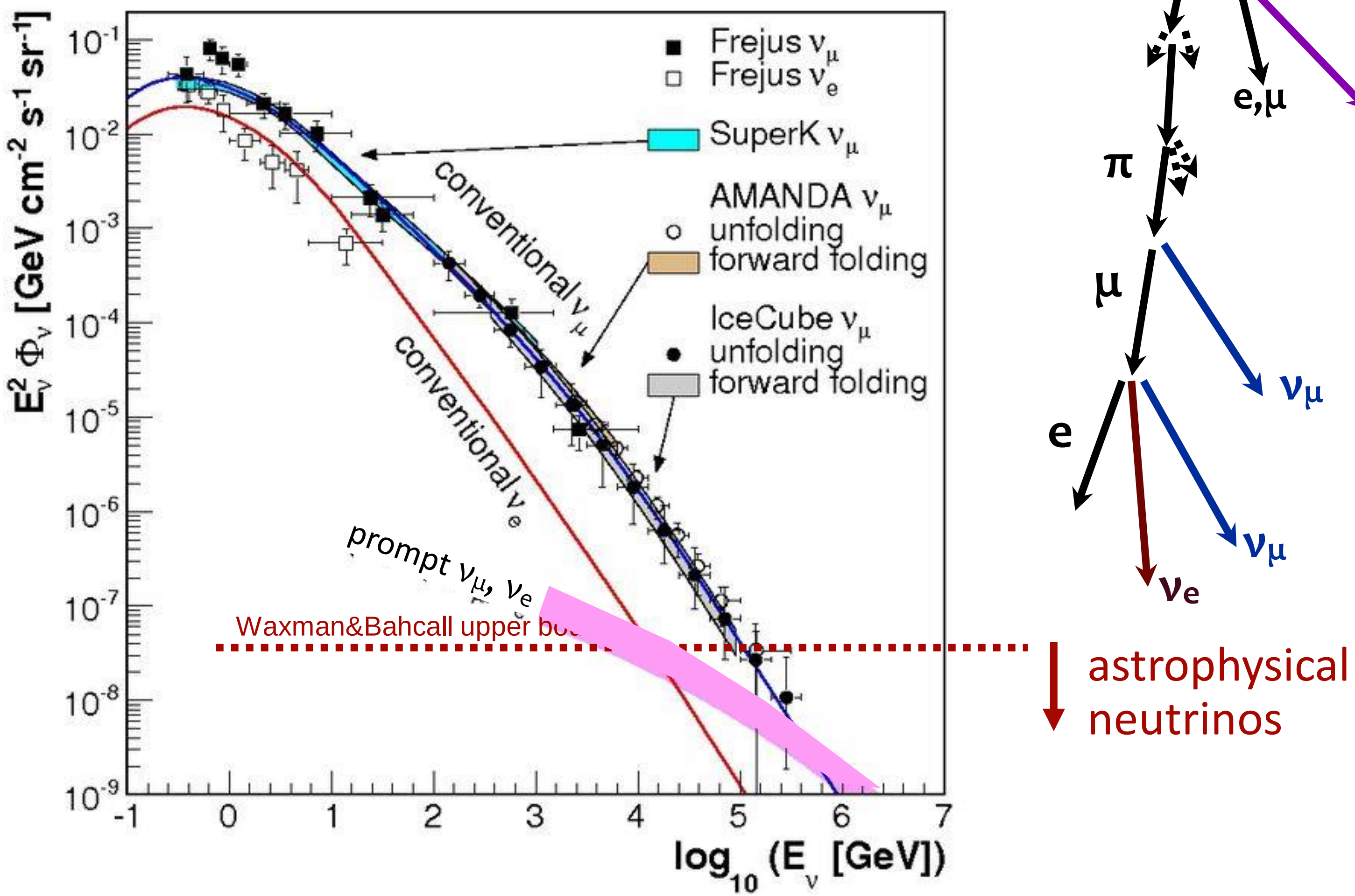
Muons co-produced with neutrinos may decay and produce further neutrinos:

$\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e$ and $\mu^- \rightarrow e^- + \nu_\mu + \nu_e$

at ~ 1TeV the ν_e / ν_μ flux < 0.1, ν_e flux actually dominated by K^0_L decays

Neutrino fluxes

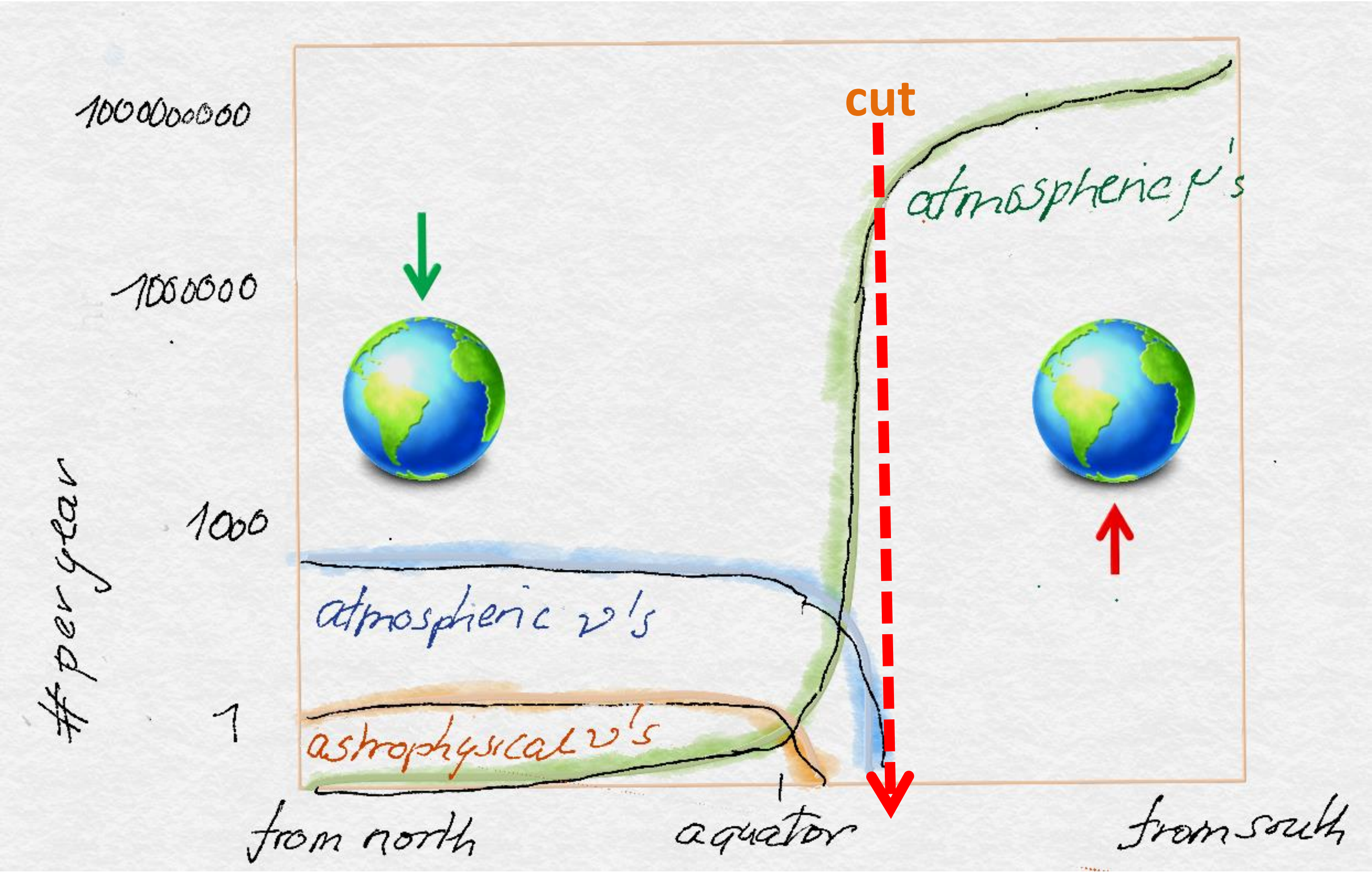




… less background from atmospheric electron neutrinos !!

The Earth as a shield

40 billion background muons per year …

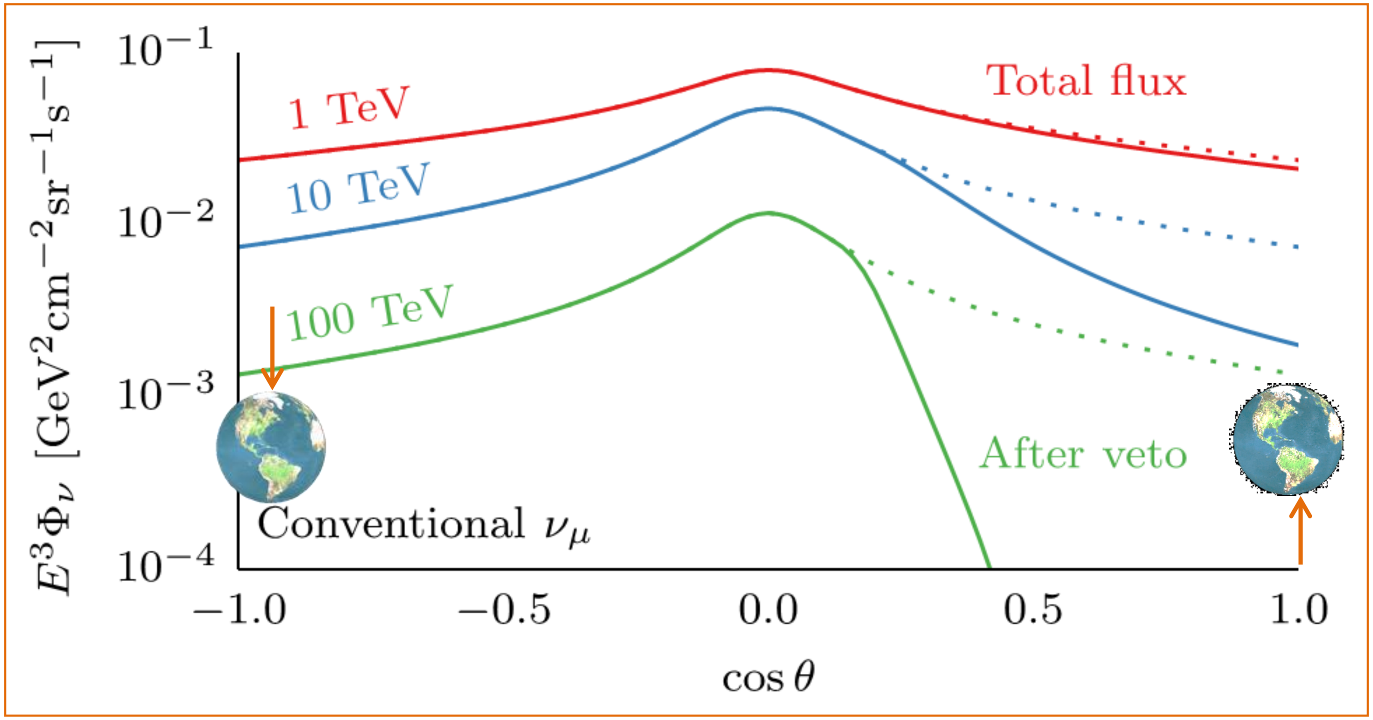


Stupid to see only half of the sky … can one do better?

Can one reduce atmospheric ν's?

Phys. Rev. D.79(4):043009, 2009, Phys. Rev. D 90, 023009, 2014.

atmospheric neutrinos from pion and kaon decays accompanied by muon
Downgoing atmospheric neutrinos can be partly vetoed !!!!



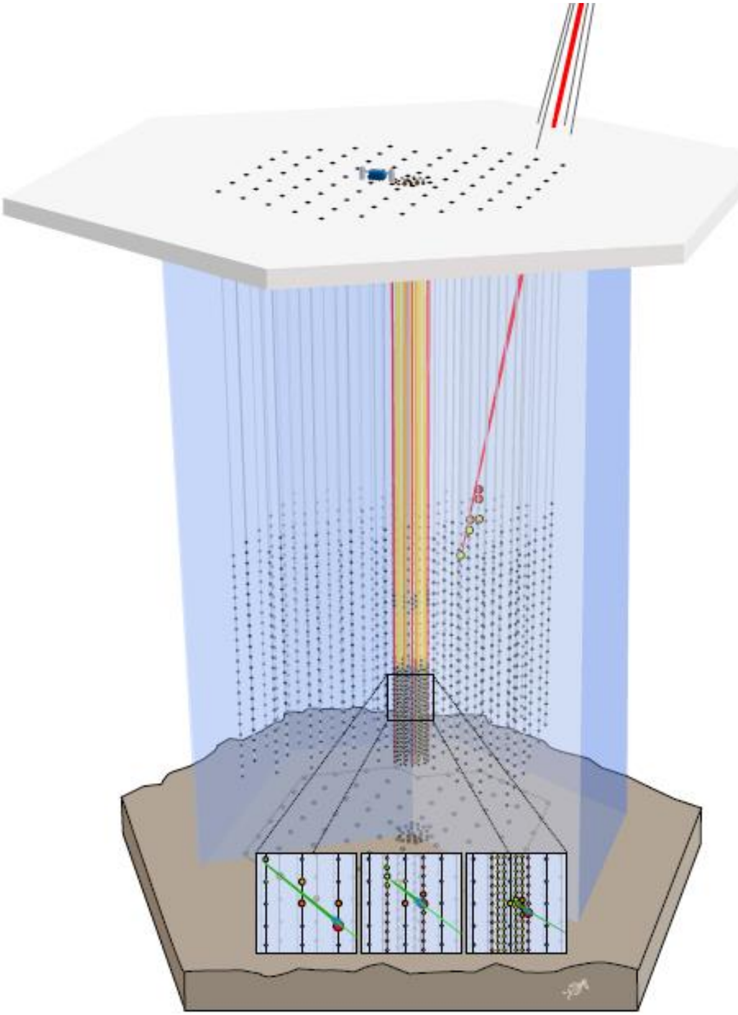
can veto muon with surface detector or in detector boundary

The IceCube observatory

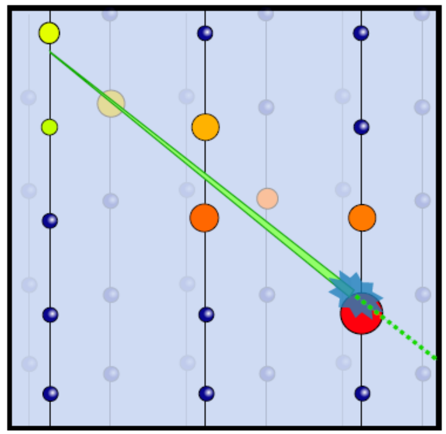
Location: Amundsen-Scott Station
@ geographic South Pole

…data taking with complete detector from May 2011

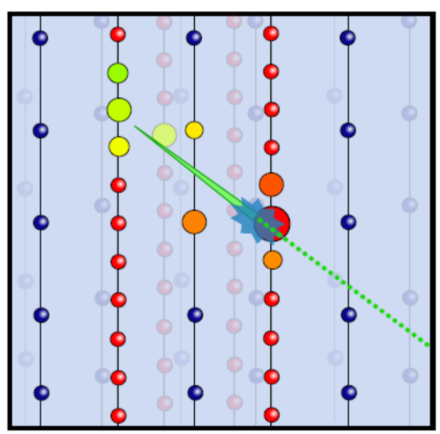
IceCube detector



Plot includes envisaged „Pingu“ low energy extension“



IceCube only



IceCube w/ DeepCore
>few 10 GeV

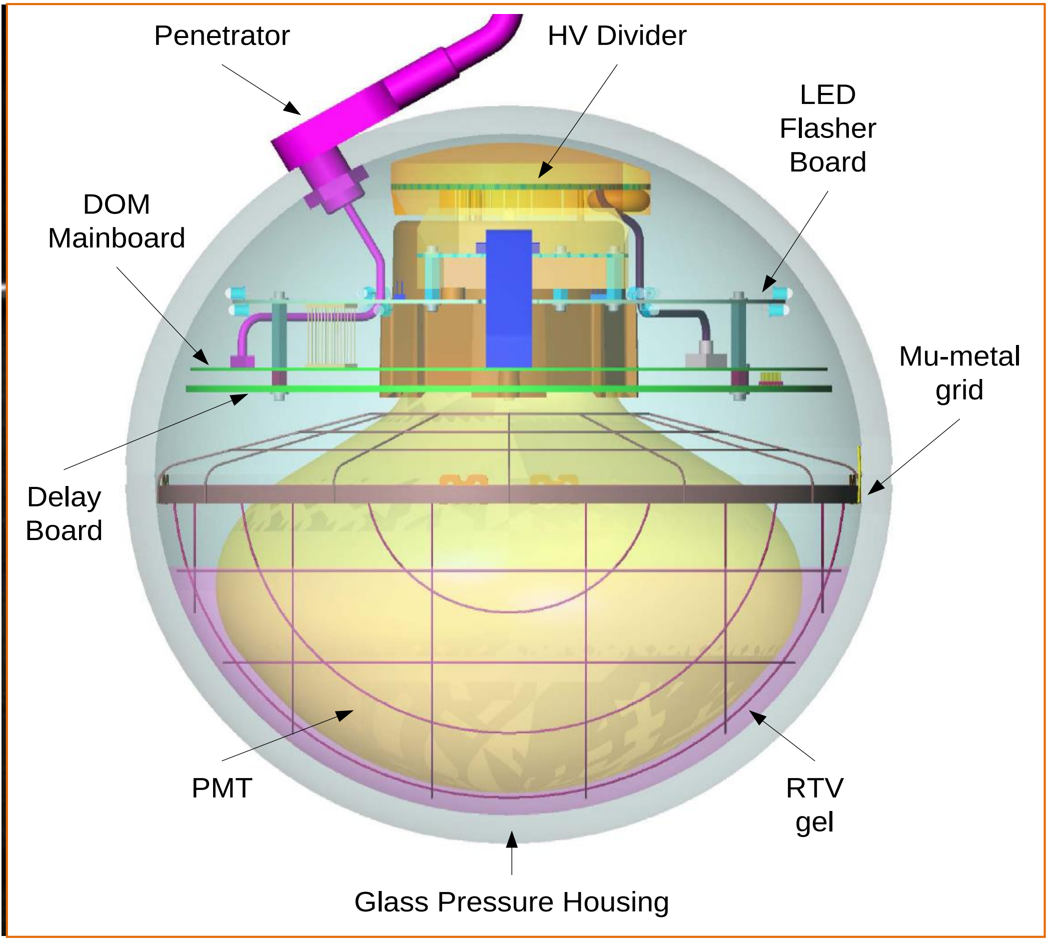
5160 sensors (optical modules) on 86 strings

→ 1 km^3 sensitive volume

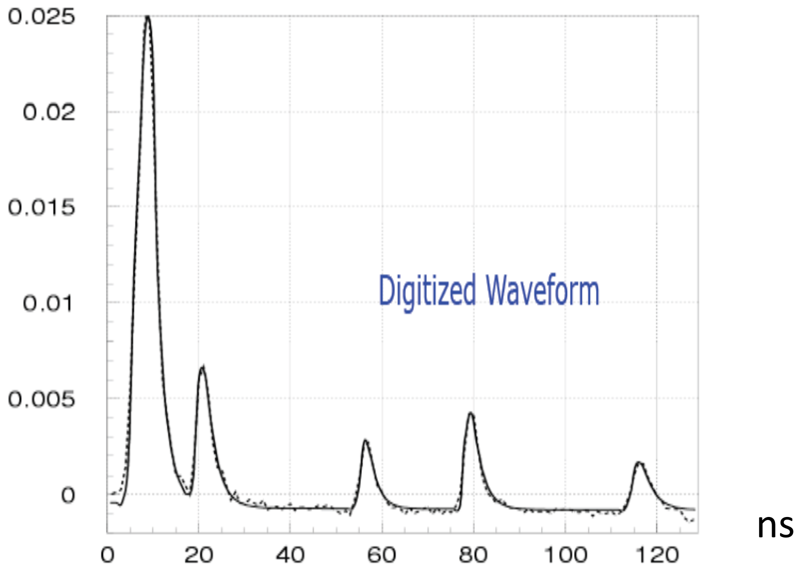
~98% of all sensors working

~99.7% data taking efficiency
.... 365 days of the year

The IceCube Digital Optical Module

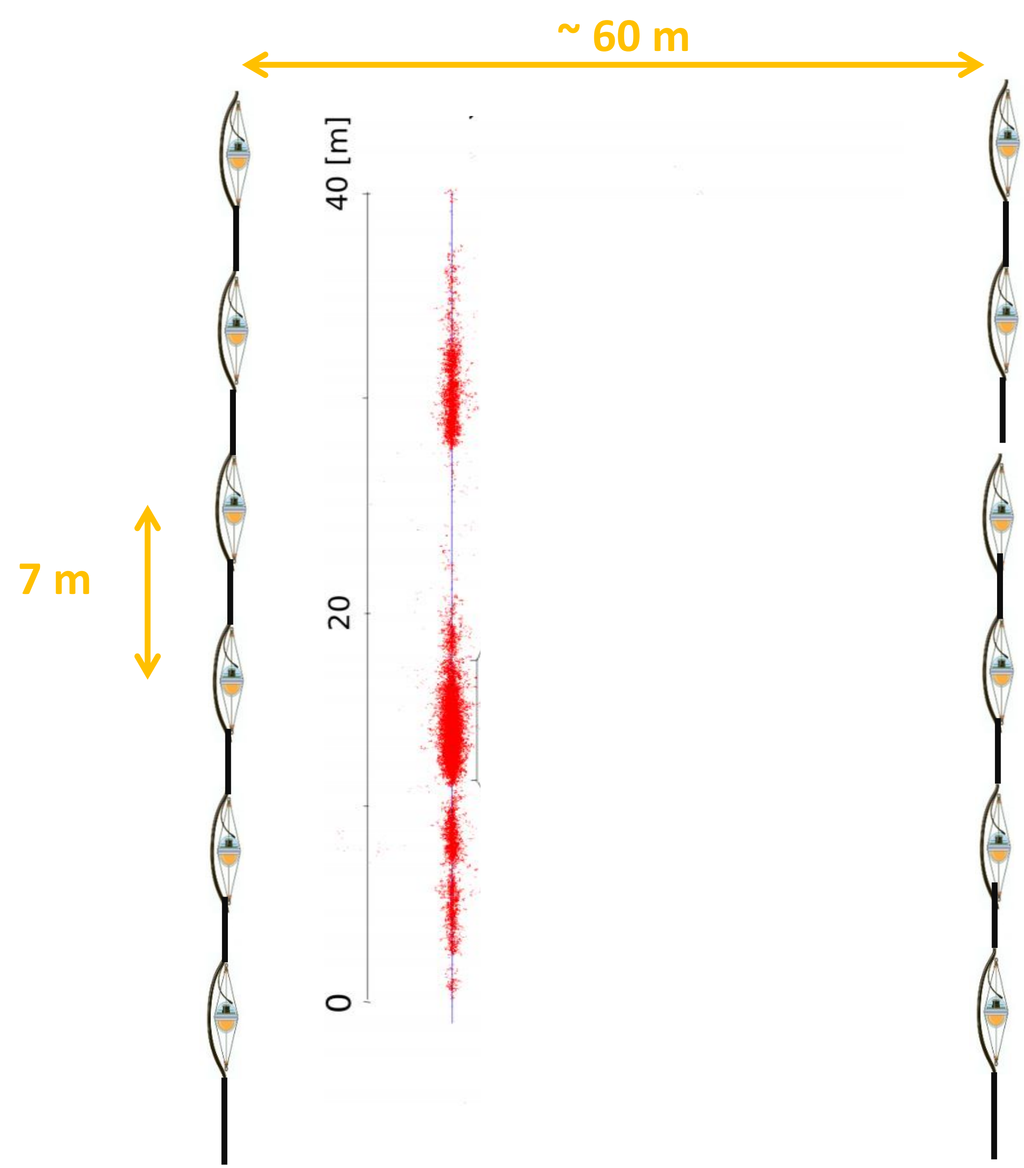


- On board HV, 330 MHz digitization, and rate measurements (1.6ms bins)
- Low power: 3.75 W
- Low noise: ~ 540 Hz
- Fast timing: betw. DOMs: $\Delta t < 5$ ns
- Large dynamic range:
  - 10^3 pe / 10 ns
  - 10^4 pe / 1 µs

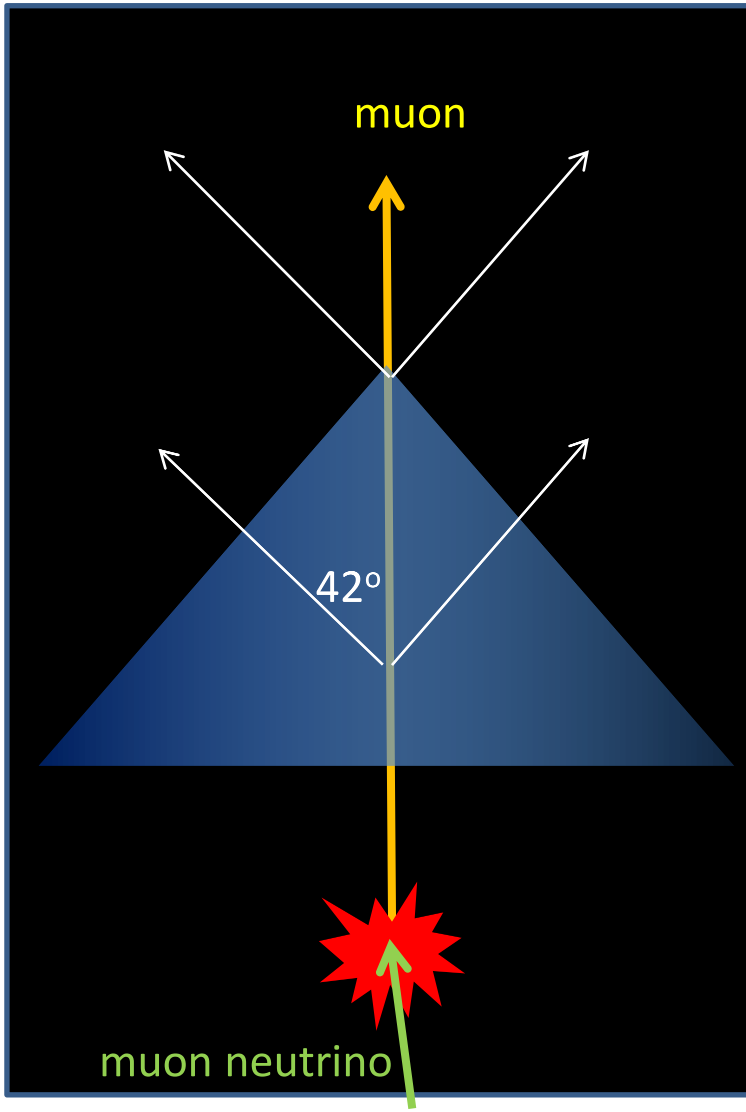


Coarse lattice of DOMs to maximize size
→ essentially no redundance

Coarse detectors to maximize volume



e.g. Antares, DeepCore



Technical and support issues

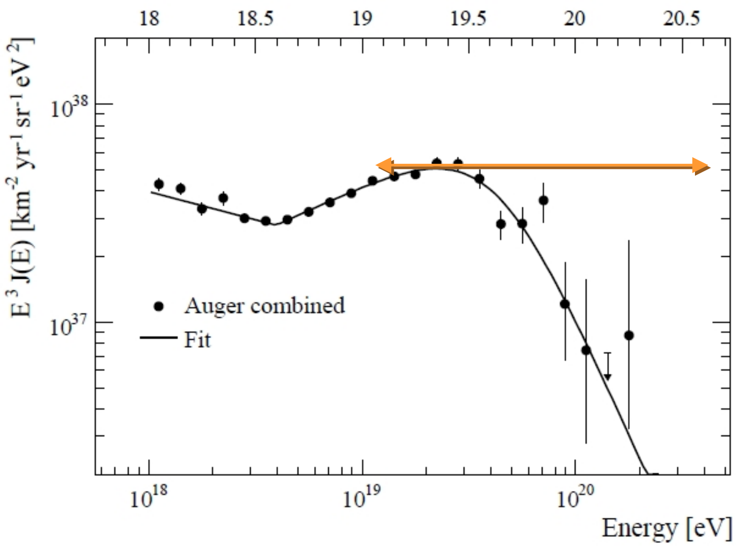
~60 kW power to electronics
90 GB/day filtered out and sent on satellite
2 winterovers
summer population (around 5-7 pop Dec - Jan)

Collaboration map


new station operating at least until 2035

Waxman-Bahcall upper limit

Idea: constrain possible neutrino flux from extragalactic cosmic ray intensity



power required over 10^{10} years to produce measured cosmic ray flux:

$$\dot{\varepsilon} \leq 2x10^{45} \frac{GeV}{MLy^3 year}$$

Nucleons interacting in surrounding material by pγ (and pp, pn) interaction

→ **pions and kaons → neutrinos**

Many assumptions:

- „optically thin sources“
- E^{-2} flux for extrapolation to lower energy …
- Cosmological evolution with maximal rate …

Benchmark for building detector

for $p\gamma \rightarrow \Delta^+ \rightarrow \pi^+ n$: $\phi^{p\gamma}_{\bar{\nu}_\mu + \nu_\mu} < \frac{1.9 \times 10^{-8}}{E_\nu^{\ 2}} \frac{\text{GeV}}{\text{cm}^2 \text{s}^{-1} \text{sr}^{-1}}$