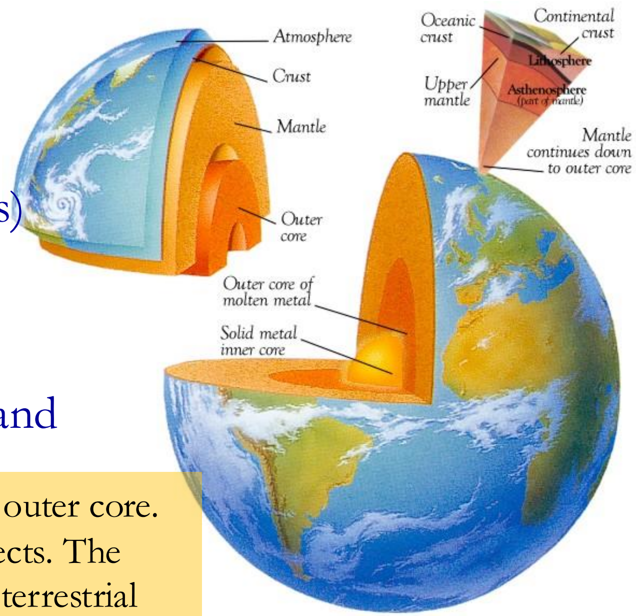
Geo Neutrinos

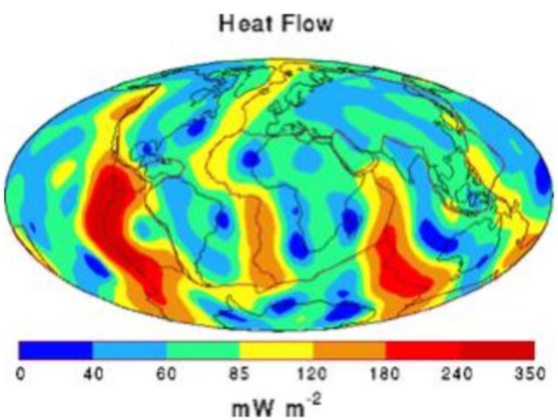
Geo Neutrinos: What is it all about?

We know surprisingly a little about the Earth's interior

- Deepest drill hole about 12 km
- Samples of crust for chemical analysis available (e.g. vulcanos)
- Reconstructed density profile from seismic measurements
- Heat flux from measured temperature gradient 30-44 TW (Expectation from canonical BSE model 19 TW from crust and mantle, nothing from core)



All these regions are solid except for the outer core. Even though the mantle is solid, it convects. The mantle convection is responsible for the terrestrial phenomena such as plate tectonics and earthquakes.



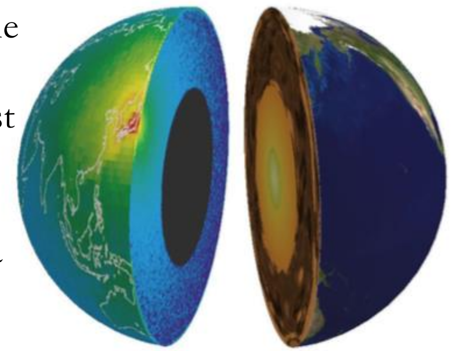
- The **Bulk-Silikate Earth (BSE)** model predicts the origin and size of radiogenic heat released in the Earth's interior and which coincides with the averaged value at surface by integrating over worldwide 40,000 deep bore-holes measurements. The heat is generated by **decays of mainly U/Th.**
  - The Earth's conductive heat flow has been evaluated to be **44 TW** (or **31 TW**, with an assumption of lower hydrothermal heat flow near mid-ocean ridges).
  - These evaluations use borehole temperature gradient and conductivity measurements.
  - These borehole measurements are concentrated in the US, Europe, and Japan. The deepest borehole is ~12km, 1/500 of the Earth's radius. So, **we know very a few** about the Earth structure and properties.

- Neutrinos escape unscathed
- Carry information about chemical composition, radioactive energy production or even a hypothetical reactor in the Earth's core

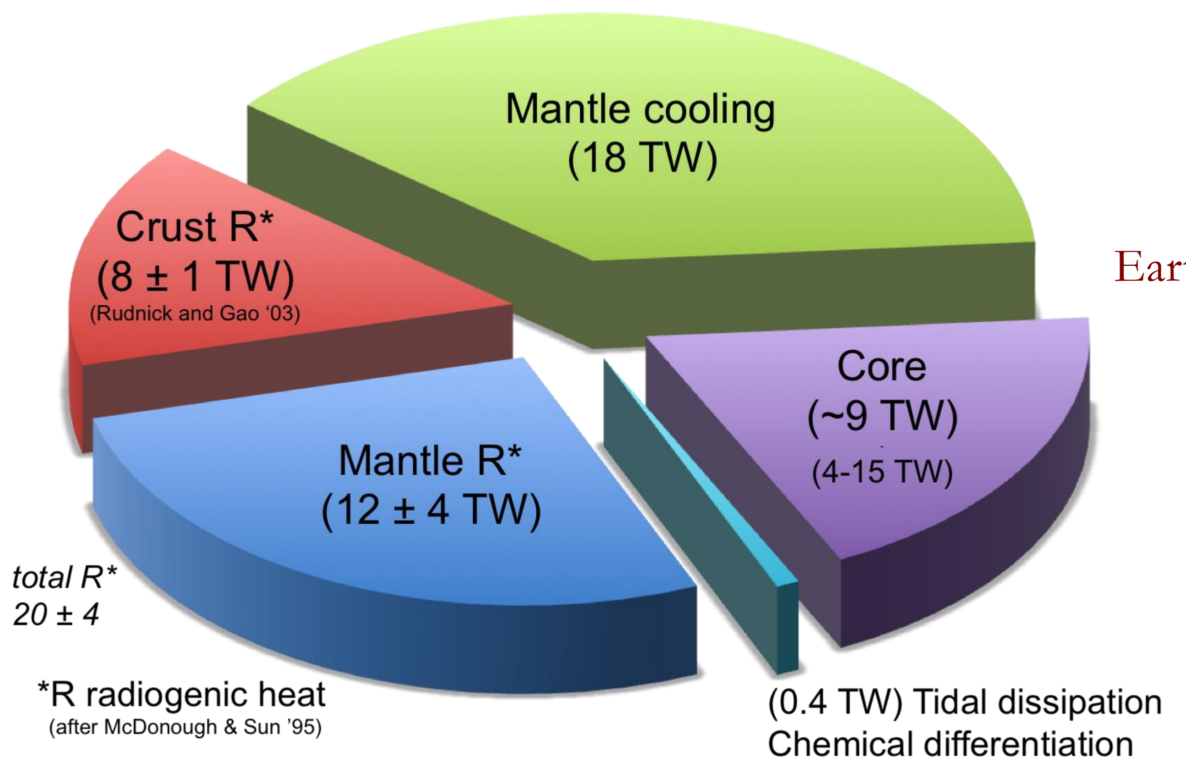
Neutrino from Earth

^{238}U and ^{232}Th are the main sources of Geo-neutrino

- "Geoneutrinos" are electron antineutrinos produced by beta-decays of the nuclei in the decay chains of ^{238}U, ^{232}Th and ^{40}K.
- Decays of the daughter nuclei in the decay chains of ^{238}U, ^{232}Th and ^{40}K generate most of the radiogenic heat produced. According to the estimated concentrations of these isotopes, the radiogenic heat production rates are **8.0, 8.3, and 3 TW** for ^{238}U series, ^{232}Th series, and ^{40}K decays, respectively. Measuring these antineutrinos may serve as a crosscheck of the radiogenic heat production-rate.



The left half shows the simulated production distribution for the geoneutrinos detectable with KamLAND, and the right half shows the Earth structure.



after Jaupart et al 2008 Treatise of Geophysics

Earth's surface heat flow 46±3 TW

Neutrinos from the Earth

- The Earth emits about 44TW of energy (sum of all man-made reactors ~1TW).
- About half is supposed to come from radioactivity of ^{238}U, ^{232}Th, and ^{40}K which produce $\bar{\nu}_e$'s.
- Geo-neutrinos are produced by:

$$^{238}U \rightarrow {}^{206}Pb + 8\,{}^{4}He + 6\,e^{-} + 6\,\bar{\nu}_e$$

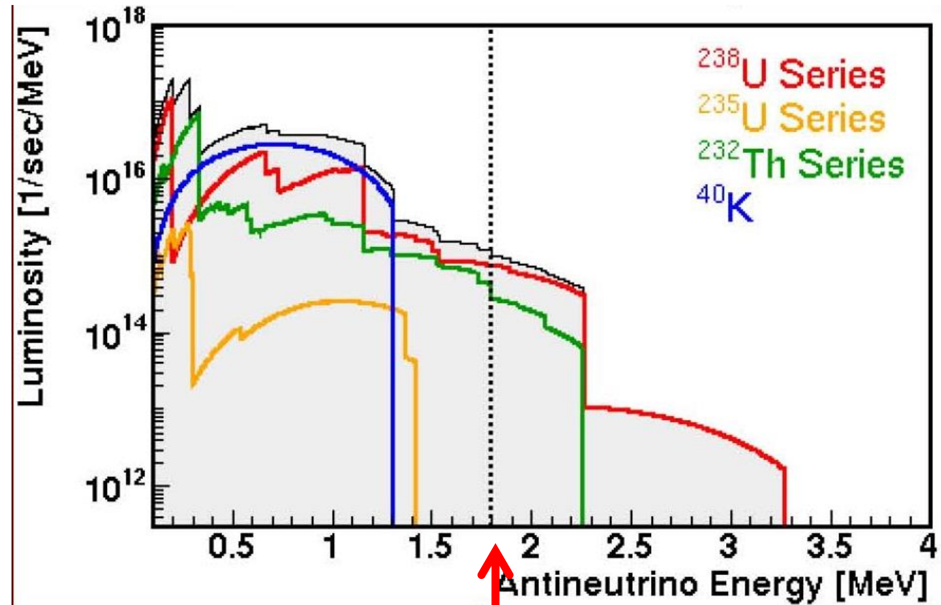
$$^{232}Th \rightarrow {}^{208}Pb + 6\,{}^{4}He + 4\,e^{-} + 4\,\bar{\nu}_e$$

$$^{40}K \rightarrow {}^{40}Ca + e^{-} + \bar{\nu}_e$$

- Geo-neutrinos are detected by:

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

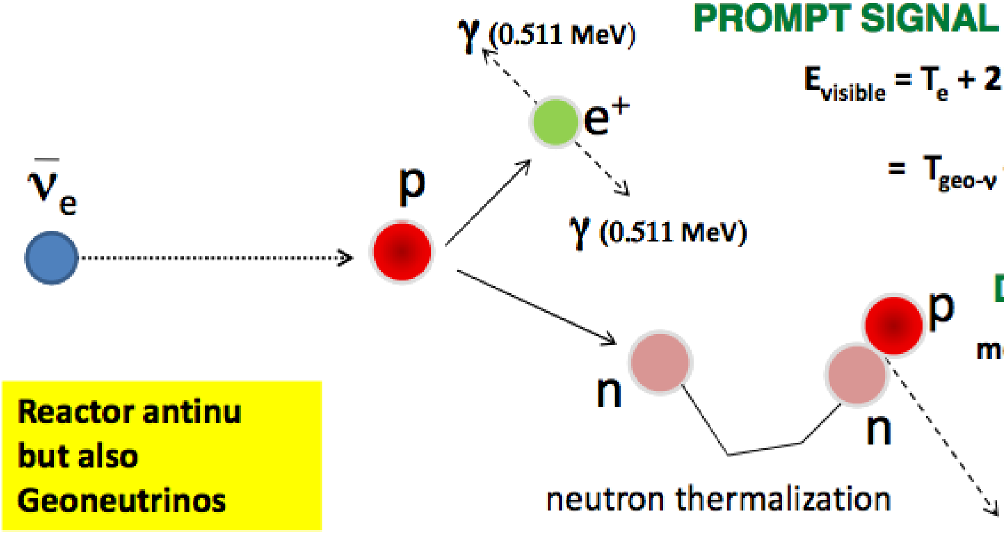
$$\Phi_{\bar{\nu}} \sim 10^{6}\,cm^{-2}s^{-1}$$



Threshold 1.8 MeV

Decay	$T_{1/2}$ [10^9 yr]	E_{max} [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$kg^{-1}s^{-1}$]	ε_H [W/kg]
$^{238}U \rightarrow {}^{206}Pb + 8\,{}^{4}He + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}Th \rightarrow {}^{208}Pb + 6\,{}^{4}He + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}K \rightarrow {}^{40}Ca + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}

Detecting anti-ν: inverse β-decay



PROMPT SIGNAL

$E_{visible} = T_e + 2*0.511$ MeV =

= $T_{geo\text{-}\nu} - 0.78$ MeV

DELAYED SIGNAL

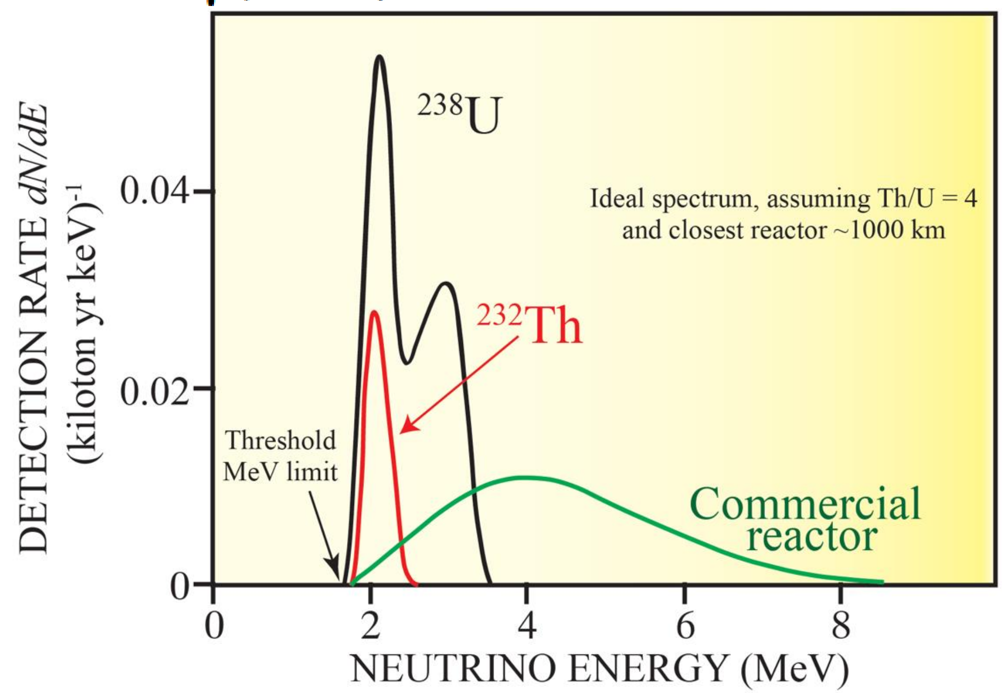
mean n-capture time on p
256 μs

Reactor antinu
but also
Geoneutrinos

Energy threshold of $T_{geo\text{-}\nu}$ = 1.8 MeV

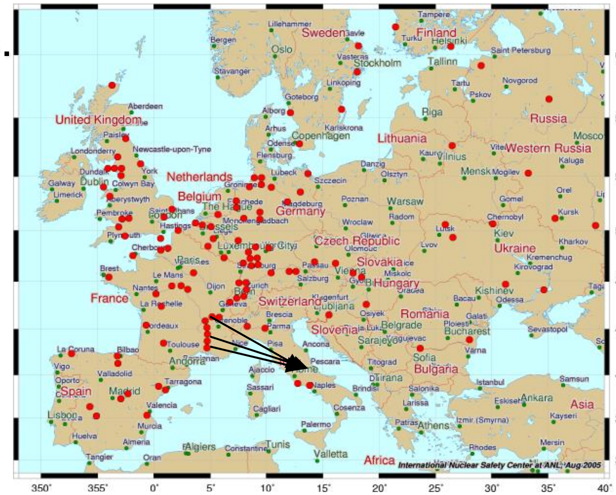
i.e. $E_{visibile} \approx 1$ MeV

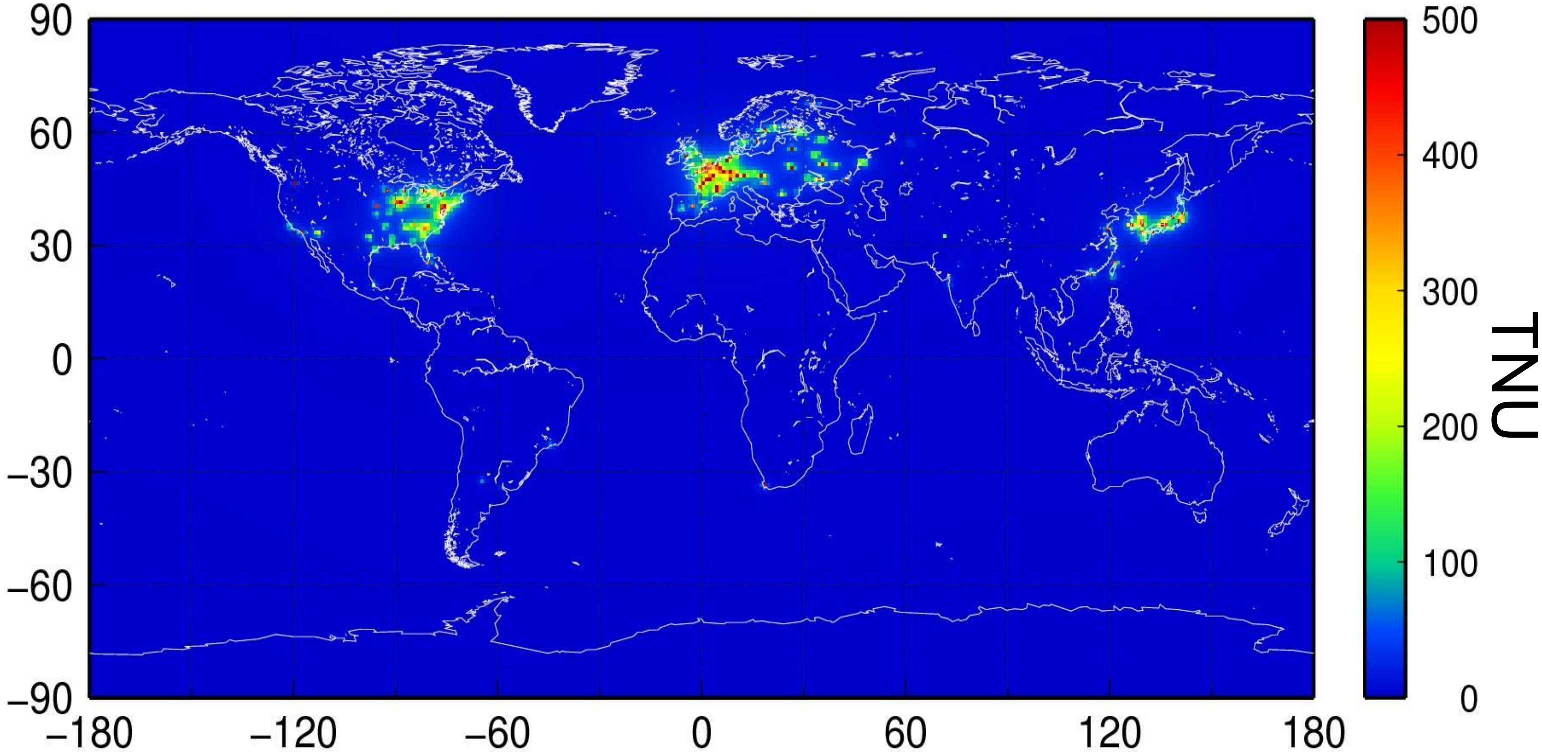
The coincidence technique makes the background requirements much less challenging!



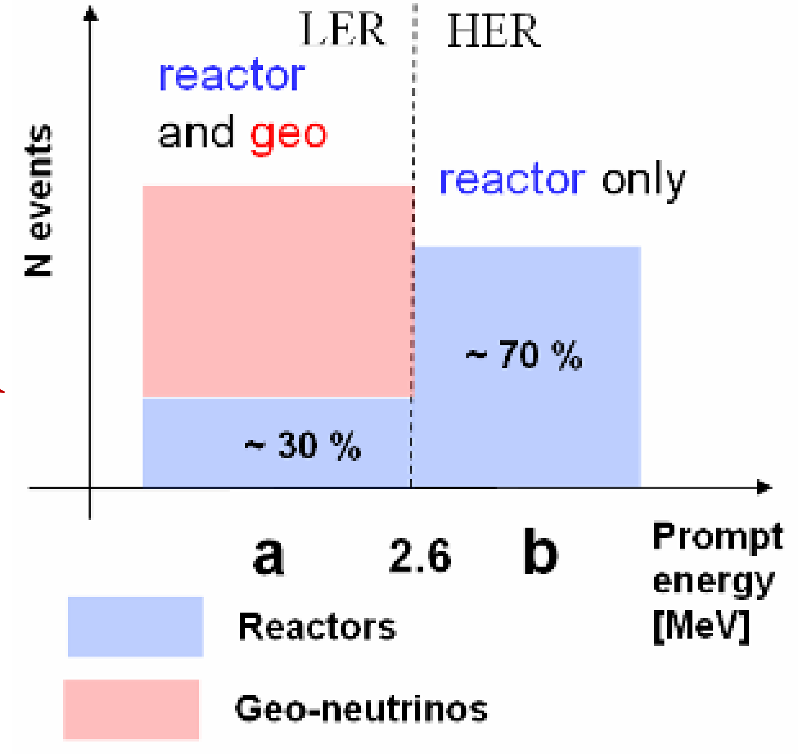
Sources of background

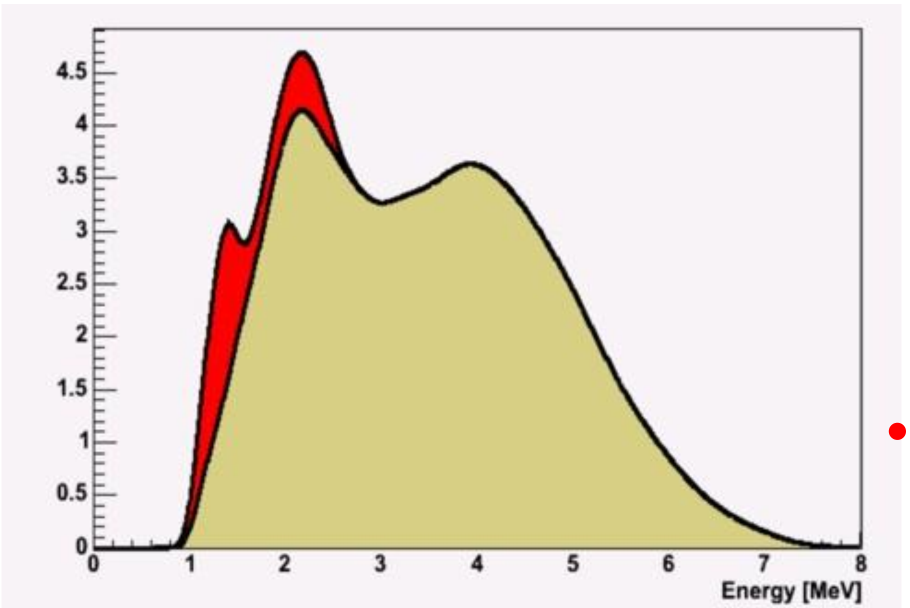
- Main contribution comes from 194 European nuclear plants.
- Other 245 plants around the world contribute only 2.5% of the total reactor signal.
- Mean base line: 1000 km (~60% of total flux)
- Spent fuel contributes at the level of 1.5% [V.I. Kopeikin *et al*., Phys. Atom. Nucl. **69**, 185 (2006)]
- Nominal thermal power and monthly load factor for each European reactor originates from IAEA and EDF.





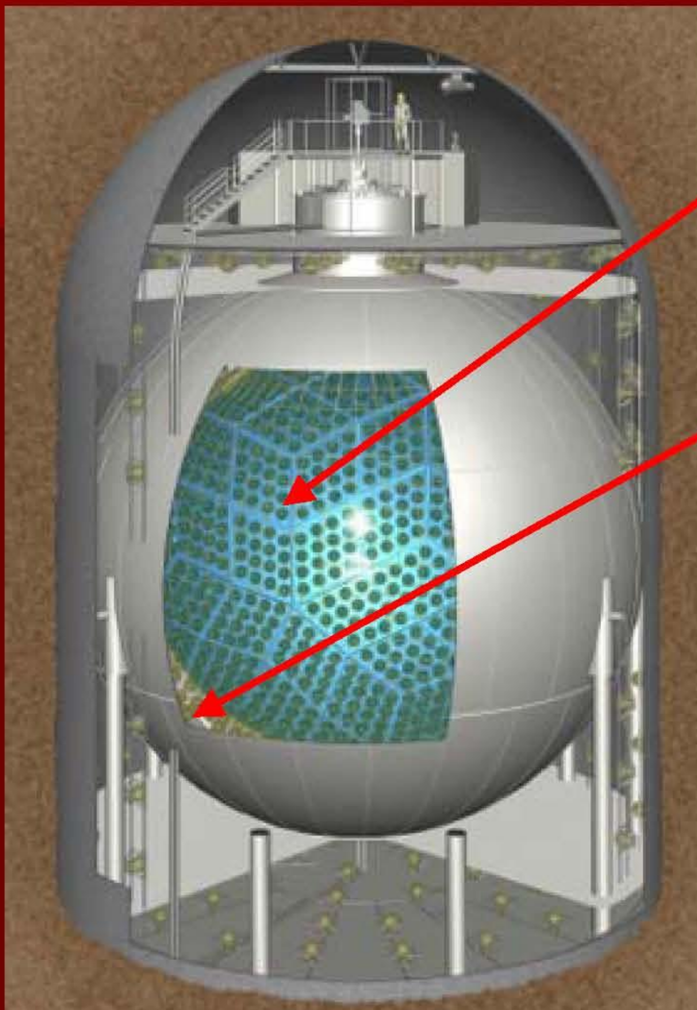
- For a geo-neutrino experiment, reactors are important since:
  - ✓ One can calibrate the experiment with reactor in the **HER**
  - ✓ One has to subtract their contribution in **LER**





- How many $\bar{\nu}_e$ in Japan? Reactors have been switched on/off in Japan in the last few years:
  - Reactor/geo-events was about **10** in 2006
  - Some reactors were shut down due to the earthquake in 2007, but in 2009 started again
  - After the 2011 tsunami/earthquake 80% of reactors have shut down…
  - Reactor/geo-events became about **2**

KamLAND: The First Detector Sensitive to Geoneutrinos



20m

Detector Center

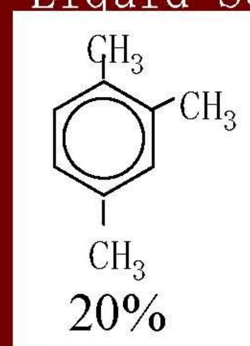
Liquid Scintillator 1000 ton
Contained in plastic balloon

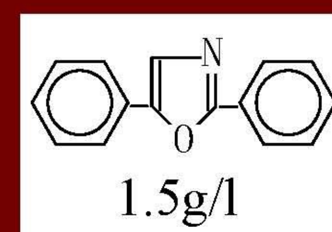
Surrounded by

17-inch PMT 1325
20-inch 554

(PMT : Photo Multiplier Tube, a photo sensor)

Liquid Scintillator



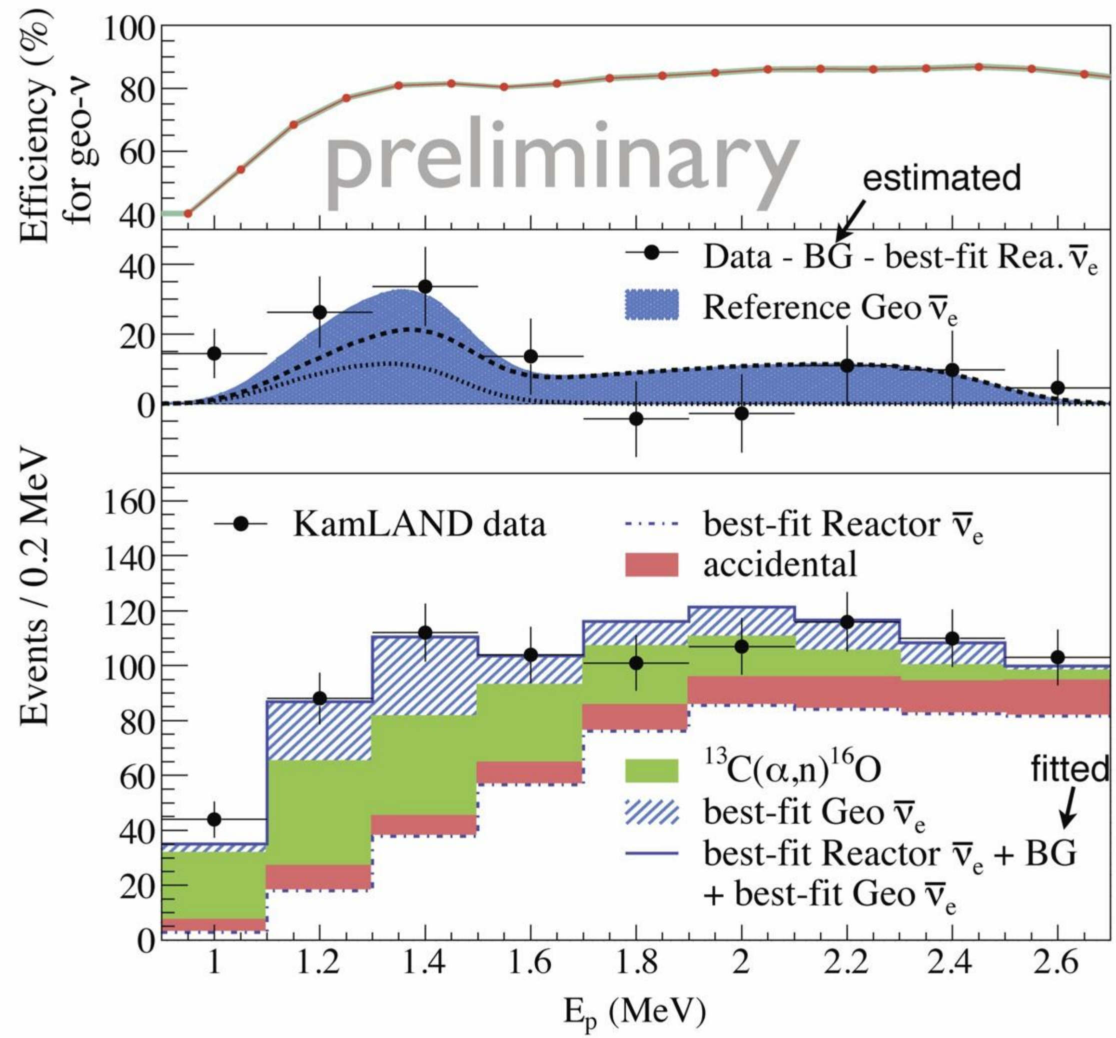


- Yields light on ionization (8000 photons/MeV)
- Mainly consists of only C and H

KamLAND Measurements of Geo Neutrinos

Period: March 9, 2002 ~ November 4, 2009
Total exposure: 3.49 x 10^{32} target-proton-years

K. Inoue at Neutrino 2010



841 candidates in 0.9-2.6 MeV

BG summary

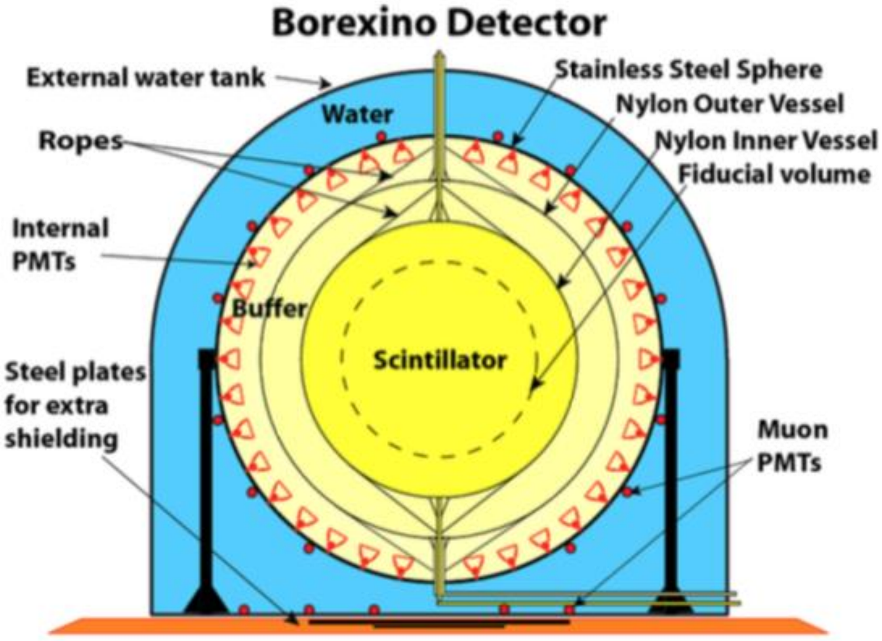
reactor $\bar{\nu}_e$	484.7±26.5
$^{13}C(\alpha,n)^{16}O$	165.3±18.2
accidental	77.4±0.1
^{9}Li	2.0±0.1
atm.ν+fast n	<2.8
Total	729.4±32.3

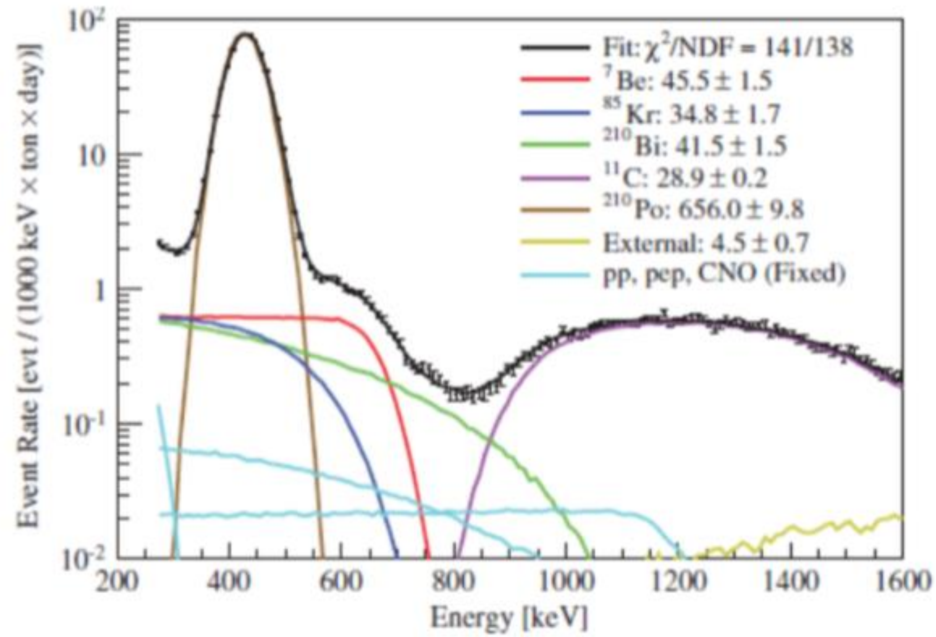
rate-only analysis 111^{+45}_{-43} events

Null signal exclusion 99.55% CL.
(rate-only hypothesis test)

Neutrino from Earth

Detection of Geo-ν by Borexino





Borexino background spectrum and its fit

Same principle of $\bar{\nu}_e$ detection in liquid-scintillator via the inverse neutron β decay,

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

Background: cosmic-ray induced backgrounds, anti-neutrinos from European reactor plants, U/Th daughter nuclides (mainly ^{210}Po).

Borexino: expectations and results (2010)*

- Predicts a total of **20.0** events ir 24 months

(R=14.0 ; G=5.6 ; **Bk**=0.4)

- The HER can be used to test the experiment sensitivity to reactors

- In the LER one expects comparable number of geo-ν and reactor-ν

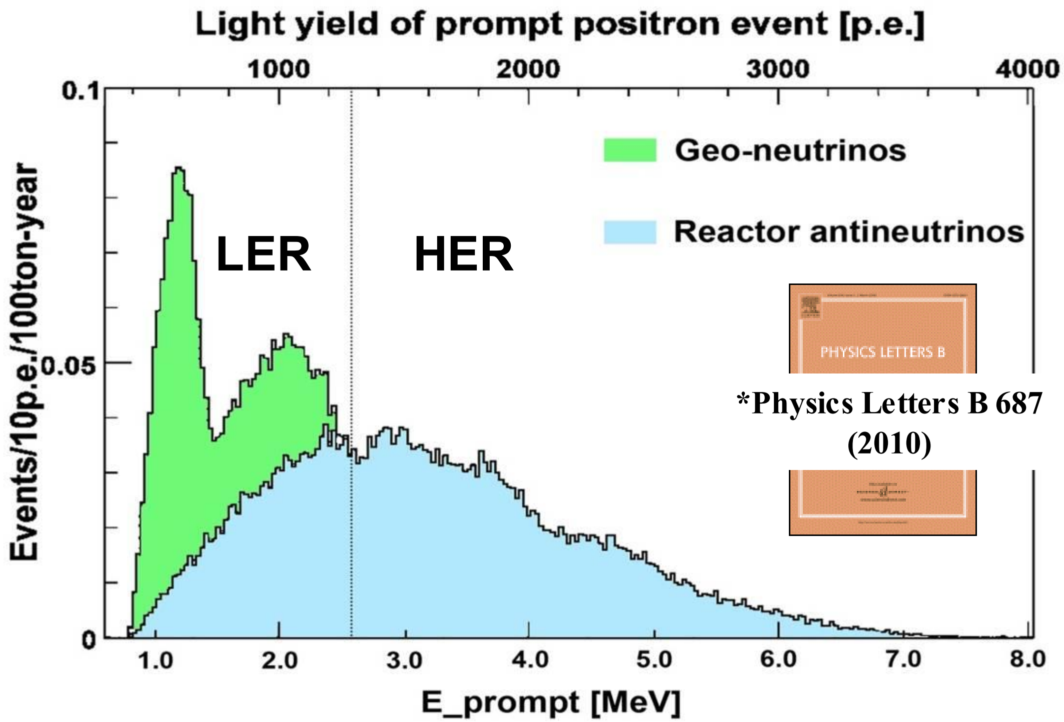
- Observe **21** events in 24 months, attributed to

R=10.7 $_{-3.4}^{+4.3}$

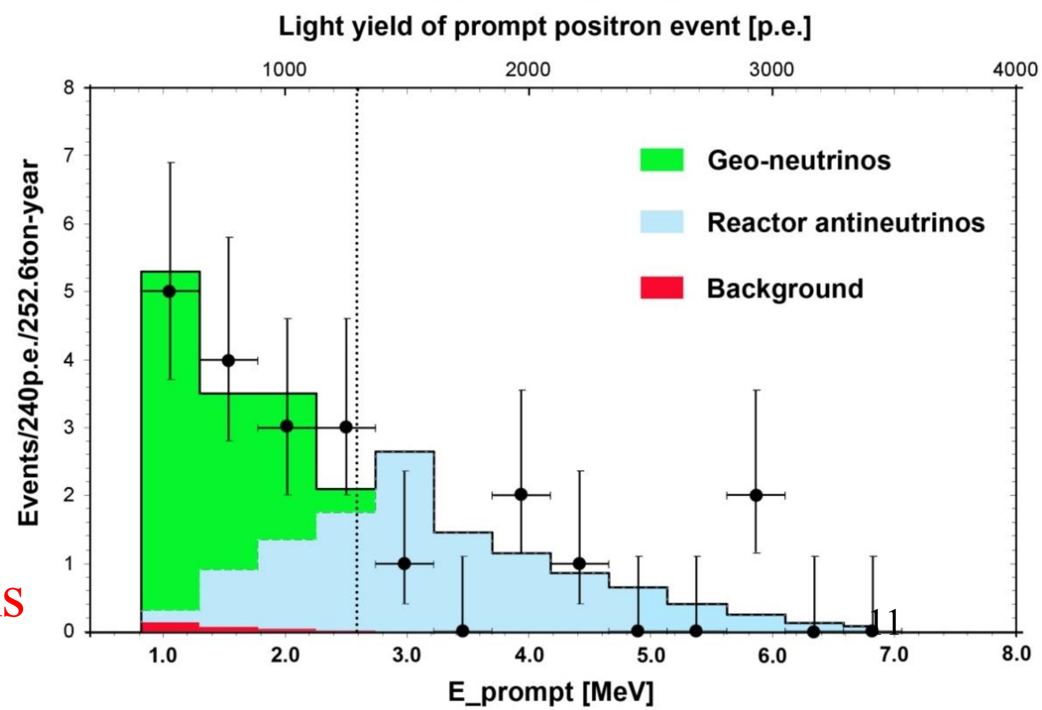
G= 9.9 $_{-3.4}^{+4.1}$

BK=0.4

- One geo-ν event each two months experiment!



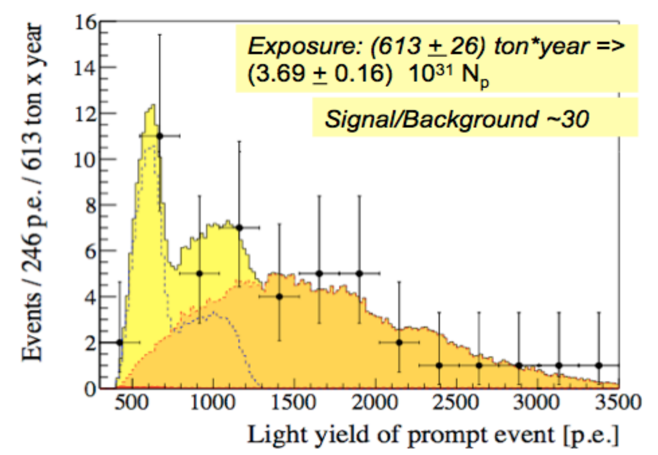
*Physics Letters B 687 (2010)



46 golden anti-neutrino candidates

(in 1198.9 days from Dec. 2007 to Aug.2012)

- ✓An unbinned maximal likelihood fit of the energy spectrum of the 46 prompt candidates has been performed;
- ✓U/Th mass ratio fixed to the chondritic value of 3.9;



Free fit parameters:

- N_{geo}
- N_{rea} (no dependence of the result on the reactor flux normalisation)
- Backgrounds constrained at their ±1σ expectation values

N_{geo} =(14.3 ± 4.4)

N_{rea} = $(31.2\ ^{+7.0}_{-6.1})$

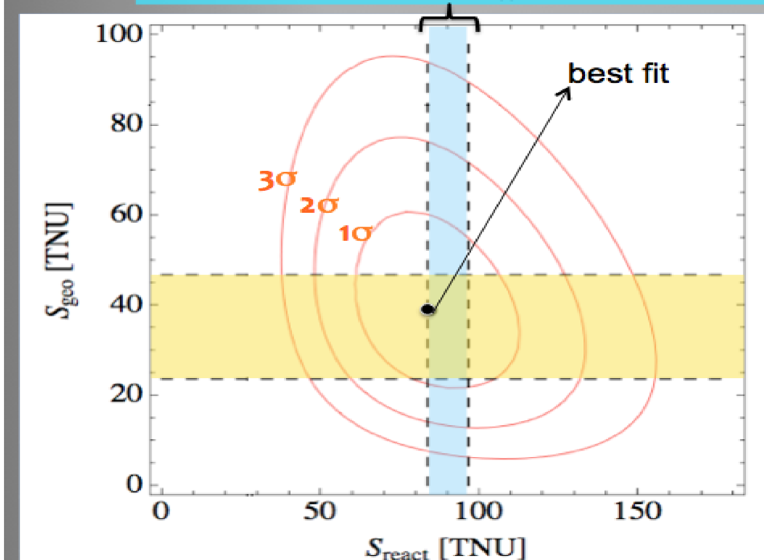
S_{geo}= 0: probability of 6 10^{-6}

Evidence for geo-ν at 4.5σ C.L.

Latest BOREXINO results

Contour plot for geo-ν and reactor antineutrino signal rate

1σ expectation band of S_{rea}: (83.2-97.3) TNU



Observed number of reactor antineutrinos is consistent with expectations

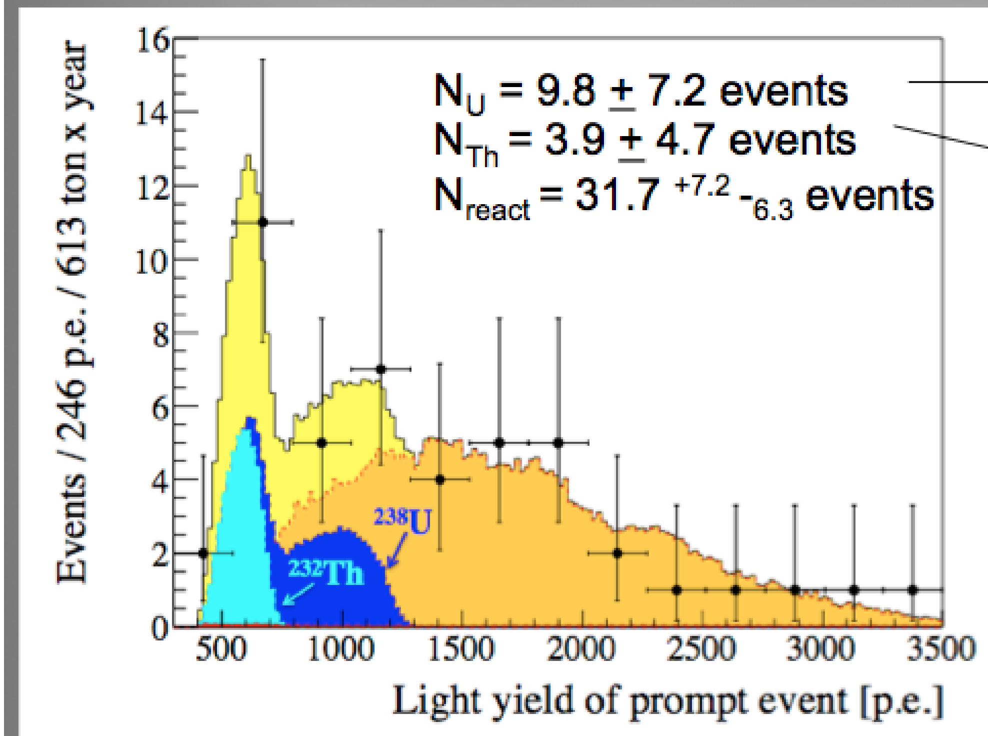
Observed number of geo-neutrinos falls within the range expected by geological models

1σ expectation band of S_{geo}=(26.3-46.6)TNU for different geo-models

1 TNU =
1 Terrestrial Neutrino Unit =
1 event/year /10^{32} protons.

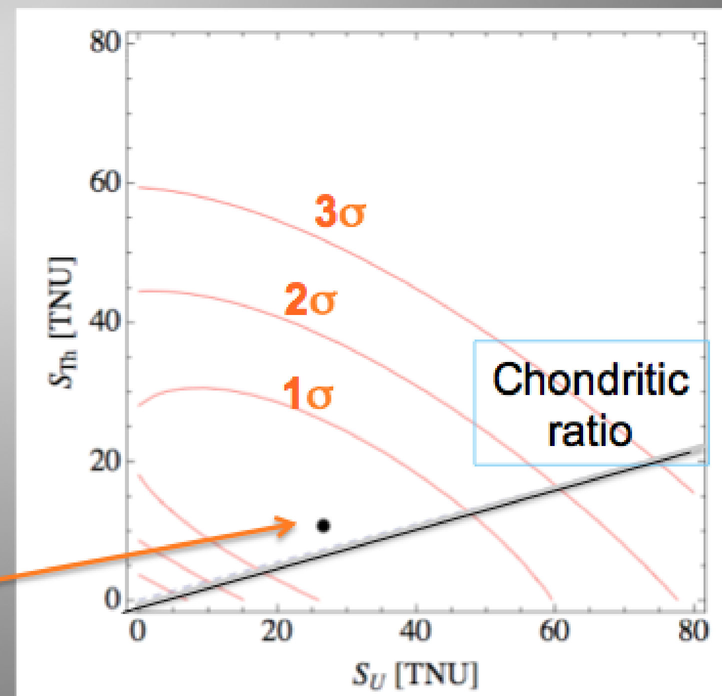
Fit with free U/Th ratio

U and Th spectra have been fit as two independent PDF's.



S_U = (26.5 ± 19.5) TNU

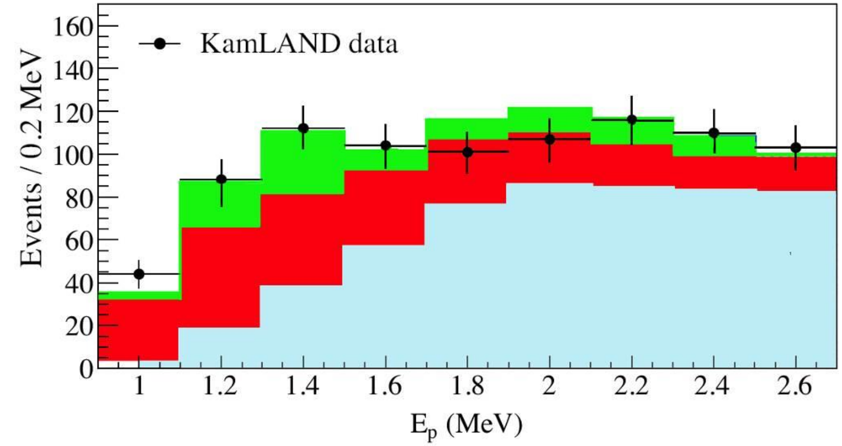
S_{Th} = (10.6 ±12.7) TNU

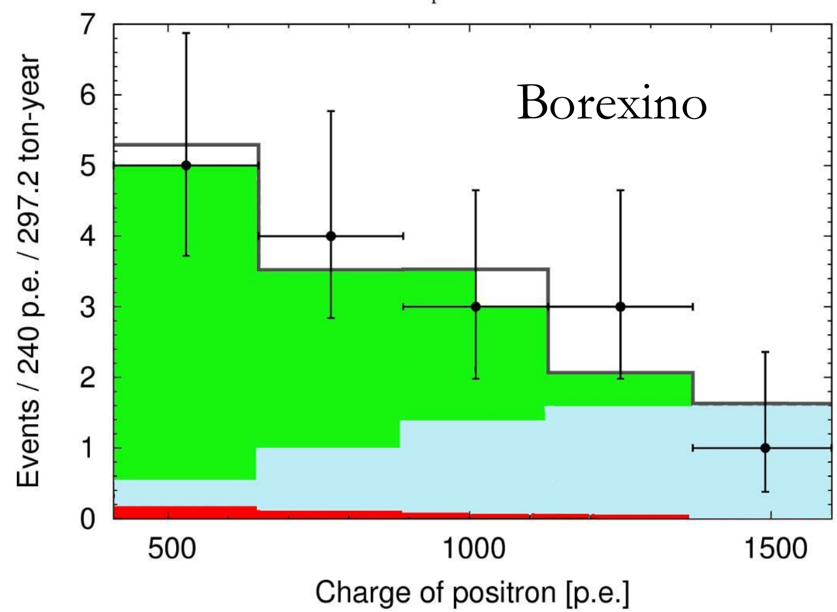


Best fit result (black point) in good agreement with chondritic value

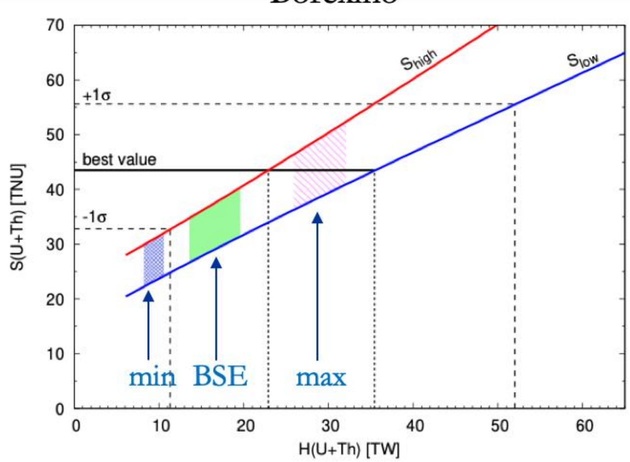
Borexino and Kamland

- Borexino has a mass and exposure time smaller than Kamland
- It benefits from:
  - ✓ much higher purity
  - ✓ absence of nearby reactors

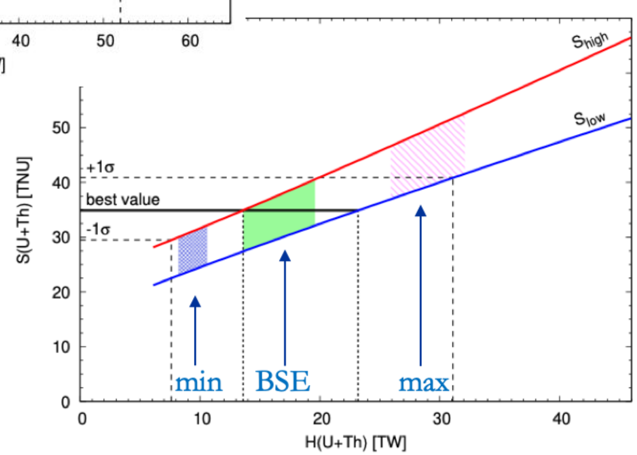




Borexino

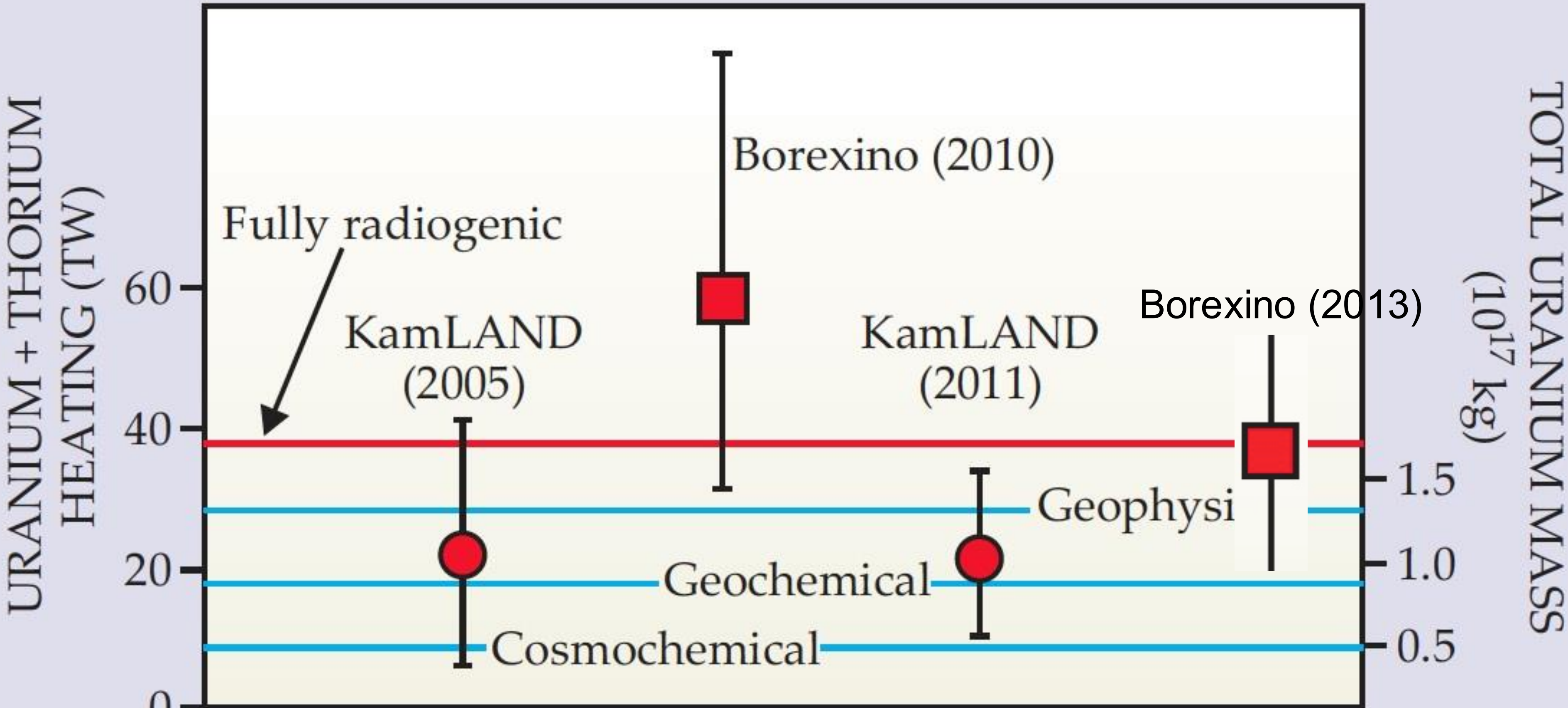


Kamland



1 TNU = one event per 10^{32} free protons per year

Summary of geoneutrino results



McDonough, Learned, Dye (2012) Physics Today

MODELS

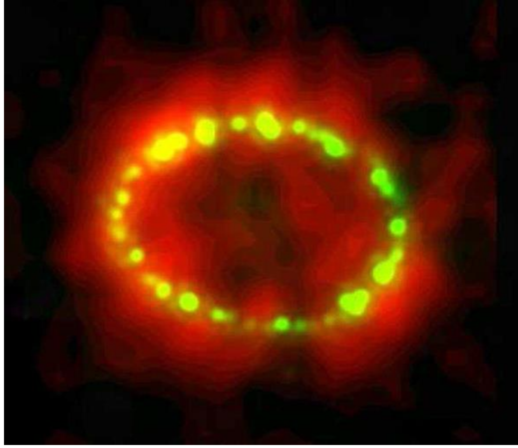
Cosmochemical: uses meteorites – *O'Neill & Palme ('08); Javoy et al ('10); Warren ('11)*

Geochemical: uses terrestrial rocks – *McD & Sun '95; Allegre et al '95; Palme O'Neil '03*

Geophysical: parameterized convection – *Schubert et al; Davies; Turcotte et al; Anderson*

Supernova neutrinos

ν's produced in a stellar collapse



When a massive star at the end of its life collapses to a neutron star, it radiates almost all of its binding energy in the form of ν's, most of which have energies in the range 10-30 MeV.

- Gravitational collapse (implosion)
- Neutronization ($e^- + p \rightarrow n + \nu_e$) lasts for few millisec.
- Explosion, with mantle being thrown off.
- End up as neutron star (or black hole) → neutrinosphere from $e^+e^- \rightarrow \nu's$ (this lasts about 1-10 sec).

❑ The ν's come in all flavours, and are emitted over a timescale of several tens of secs.

❑ The ν's luminosity of a gravitational collapse-driven supernova is typically 100 times its optical luminosity.

❑ During the collapse of a star, about 10^{57} ν's are produced.

❑ The ν signal emerges from the core of a star promptly after core collapse, whereas the photon signal may take hours or days to emerge from the stellar envelope.

→ The ν's signal can give information about the very early stages of core collapse

- Supernovae have been observed since the 1002 A.D. observation recorded by Chinese astronomers in our Galaxy; as neutron star since 1967
- Neutrinos from SN not seen until Feb. 28, 1987: SN1987A!
- None since!

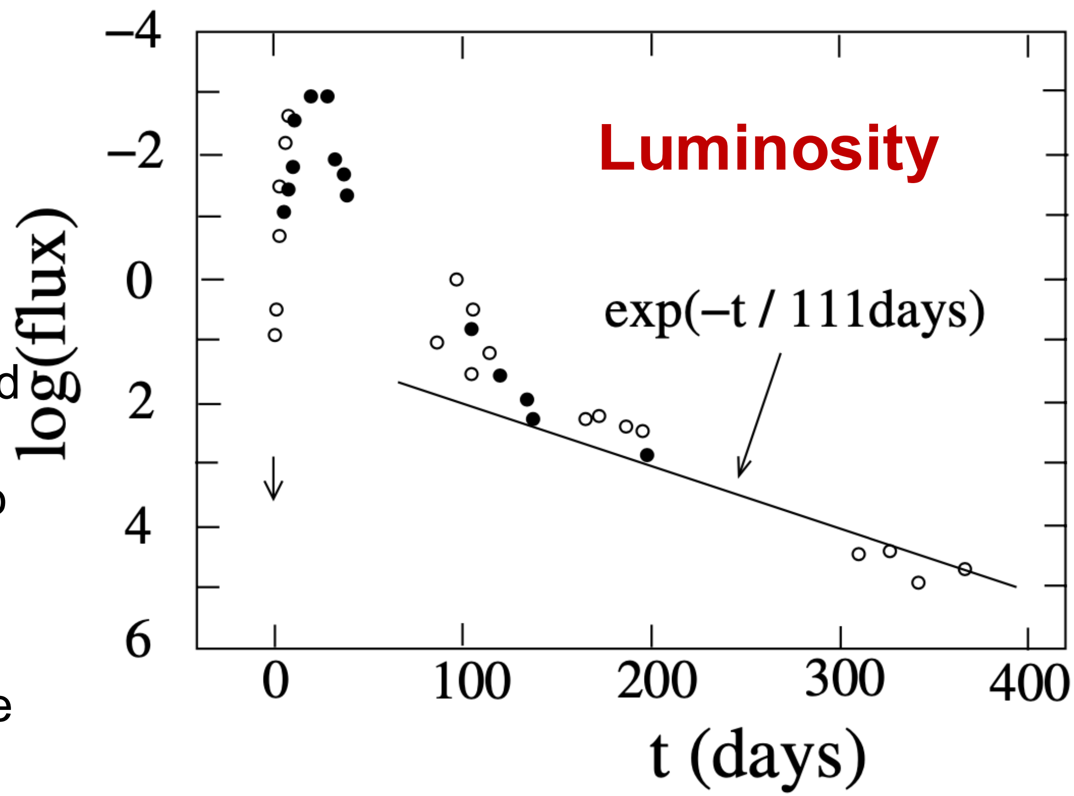
Types of Supernovae

- **Type I** – no hydrogen absorption lines
  - Ia – no hydrogen lines, no helium lines, but does have strong absorption line of ionized Silicon (Si II)
  - Ib – strong helium lines, still no hydrogen
  - Ic – no helium lines, still no hydrogen
- **Type II** – hydrogen absorption lines

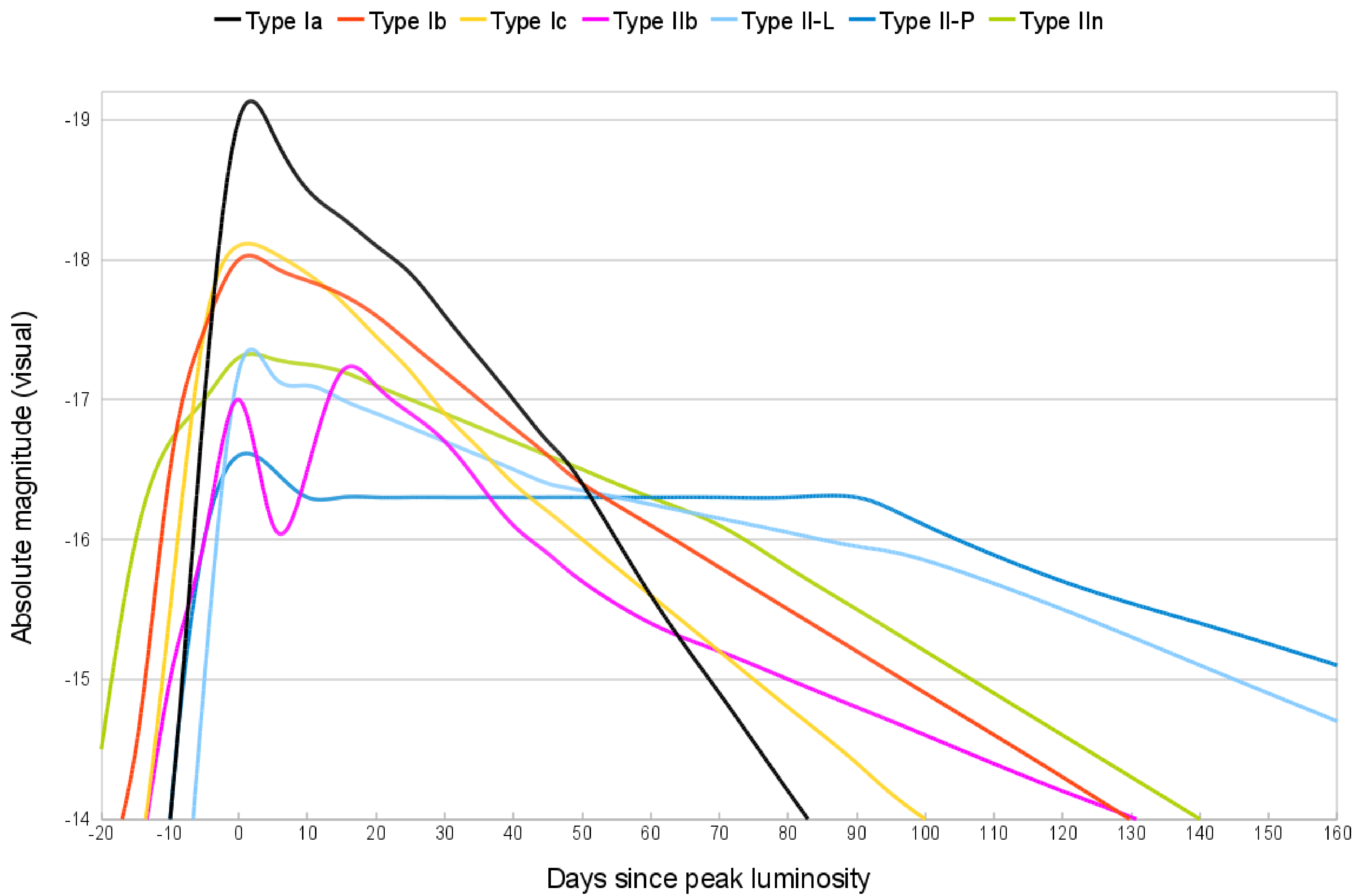
- Collapse of massive stars leads to type II and Ib, only difference is whether star sheds outer hydrogen layer before exploding

Kepler's supernova

- Open circles are European measurements and filled circles are Korean measurements.
- Astronomers at the time measured the evolution of the luminosity of the supernovae by comparing it to known stars and planets.
- It has been possible to determine the positions of planets at the time when they were observed, and, with the notebooks, to reconstruct the luminosity curves.



- The superimposed curve shows the rate of ^{56}Co decay using the laboratory-measured half-life.
- The vertical scale gives the visual magnitude V of the star, proportional to the logarithm of the photon flux.
- V = 0 corresponds to a bright star, while V = 5 is the dimmest star that can be observed with the naked eye.



Type Ia
Type Ib
Type Ic
Type IIb
Type II-L
Type II-P
Type IIn
Absolute magnitude (visual)
-19
-18
-17
-16
-15
-14
-20
-10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
Days since peak luminosity

What determines the time scale?

Main neutrino reactions

$$\nu_e + n \to p + e^-, \ \bar{\nu}_e + p \to n + e^+, \ \nu + N \to N + \nu$$

Neutral-current scattering cross section

$$\sigma(\nu N \to N\nu) \approx 2 \times 10^{-40} \mathrm{cm}^2 \left(\frac{E_\nu}{100 \text{ MeV}}\right)$$

Nucleon density

$$n_B = \frac{\rho_{\mathrm{nuc}}}{m_N} \approx 1.8 \times 10^{38} \text{ cm}^{-3}$$

Scattering rate

$$\Gamma = \sigma n_B \approx 1.1 \times 10^9 \text{ s}^{-1} \left(\frac{E_\nu}{100 \text{ MeV}}\right)$$

Mean free path

$$\lambda = (\sigma n_B)^{-1} \approx 28 \text{ cm} \left(\frac{100 \text{ MeV}}{E_\nu}\right)$$

Diffusion time

$$t_{\mathrm{diff}} \approx \frac{R^2}{\lambda} \approx 1.2 \text{ s} \left(\frac{R}{10 \text{ km}}\right)^2 \left(\frac{E_\nu}{100 \text{ MeV}}\right)$$

Random walk. Simple case with N steps of constant $\lambda = ct_s$. The walked distance R is:

$$R = \sqrt{N}\lambda = \sqrt{\frac{t_{diff}}{t_s}}\lambda = \sqrt{\frac{t_{diff}\,\lambda^2}{\lambda/c}}$$

$$t_{diff} \approx \frac{R^2}{\lambda}$$

What Determines the Neutrino Energies?

Hydrostatic equilibrium (virial equilibrium)

$$-\frac{1}{2}\langle\Phi_{\text{grav}}\rangle = \langle E_{\text{kin}}\rangle = \frac{3}{2}k_{\text{B}}T$$

Assume SN core is homogeneous sphere with

$$M = 1.5\,M_{\odot},\quad \rho = \rho_{\text{nuc}} = 3\times10^{14}\,\text{g/cm}^3,\quad R = 13.4\text{ km}$$

Gravitational potential of nucleon at center

$$\Phi_{\text{grav}} = -\frac{3}{2}\,\frac{G_N M_{\text{core}} m_p}{R} \sim -234\text{ MeV}$$

For non-interacting and non-degenerate nucleons implies

$$T \sim 80\text{ MeV}$$

More realistic, nuclear equation-of-state dependent values

$$T \sim 20\text{–}40\text{ MeV}$$

Energy scale in the multi-10 MeV range set by gravitational potential

Detecting Supernova ν's

- ν's from gravitational collapse can be detected in various ways.
- For water Cerenkov detectors, such as Super-K, the most important detection reaction is the absorption of electron antineutrinos on protons:

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

- The e^+ from this reaction, which retains most of the energy of the incoming $\bar{\nu}_e$, is detected from its Cerenkov light.
- For a gravitational collapse at the center of the Galaxy (8.5 kpc away), Super-K expects to see about 5000 events.
- A few percent of the supernova events observed will be neutrino-electron elastic scattering events,

$$\nu_x(\bar{\nu}_x) + e^- \rightarrow \nu_x(\bar{\nu}_x) + e^-$$

ν_x = a neutrino of any flavour

Detecting Supernova ν's with liquid scintillator

Charged current interactions

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

$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-$

$\bar{\nu}_e + {}^{12}C \rightarrow {}^{12}B + e^+$

Neutral current interactions

$\nu_{(e,\mu,\tau)} + e^- \rightarrow \nu_{(e,\mu,\tau)} + e^-$

$\bar{\nu}_{(e,\mu,\tau)} + e^- \rightarrow \bar{\nu}_{(e,\mu,\tau)} + e^-$

$\nu_{(e,\mu,\tau)} + {}^{12}C \rightarrow {}^{12}C^* + \nu_{(e,\mu,\tau)}$

$\bar{\nu}_{(e,\mu,\tau)} + {}^{12}C \rightarrow {}^{12}C^* + \bar{\nu}_{(e,\mu,\tau)}$

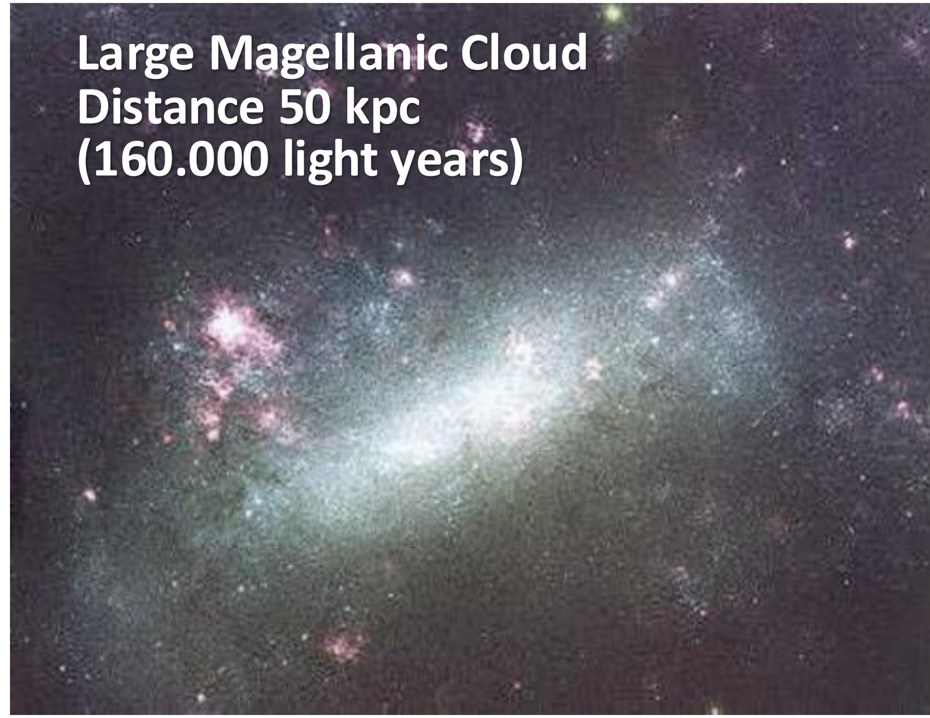
+ gammas from:

$\rightarrow n + p \rightarrow D + \gamma$ $\quad (E_\gamma = 2.23 \text{ MeV})$

$\rightarrow e^+ + e^- \rightarrow 2\gamma$

Borexino, LVD, Kamland, Miniboone …

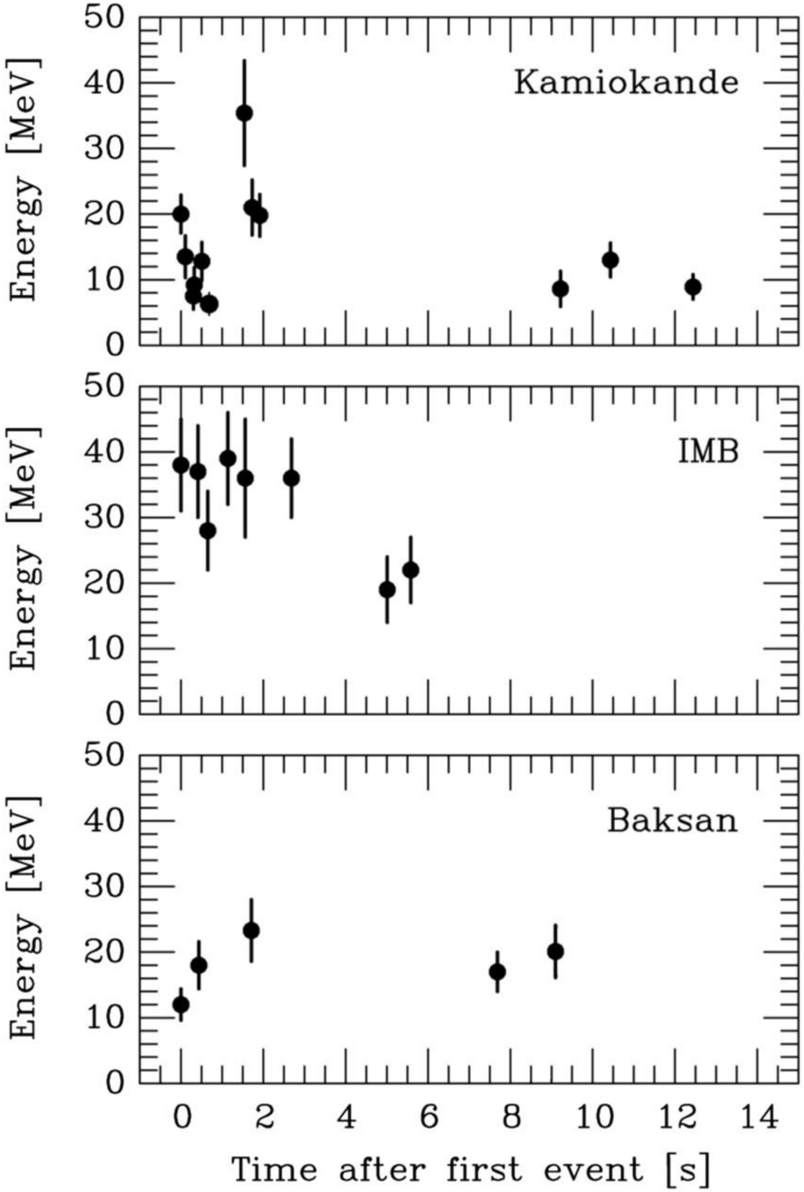
The famous supernova SN1987A (28 February 1987)



- A gravitational collapse event in the Large Magellanic Cloud outside our Galaxy, was the first to have its neutrino signal detected.
- Two water Cerenkov detectors, Kamiokande II and IMB, detected 20 events between them.

- In addition, the Baksan scintillator detector saw 5 events (another scintillator detector, LSD saw 5 events several hours early, but the significance of this signal was controversial.)
- The SN1987A neutrino data, although sparse, was sufficient to confirm the baseline model of gravitational collapse (and put some limits on neutrino properties, such as mass, as well)
- → await a more copious neutrino signal to be able to make distinctions between different theoretical models of core collapse and supernova explosions

Neutrino Signal of Supernova 1987A



Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty $\pm$1 min

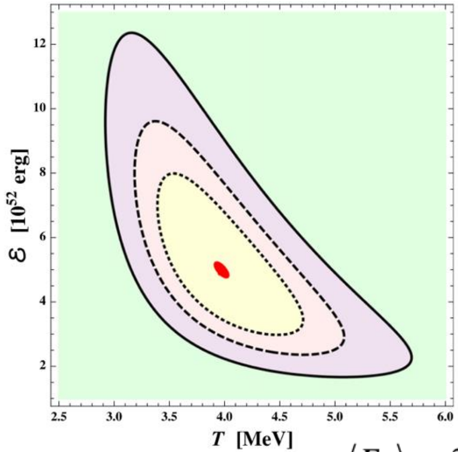
Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty $\pm$50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster 0.7/day
Clock uncertainty +2/–54 s

Within clock uncertainties,
all signals are contemporaneous

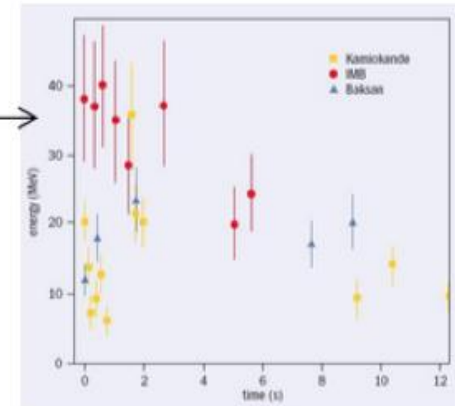
Neutrino from supernova

summary



$\langle E_\nu \rangle = 3T.$

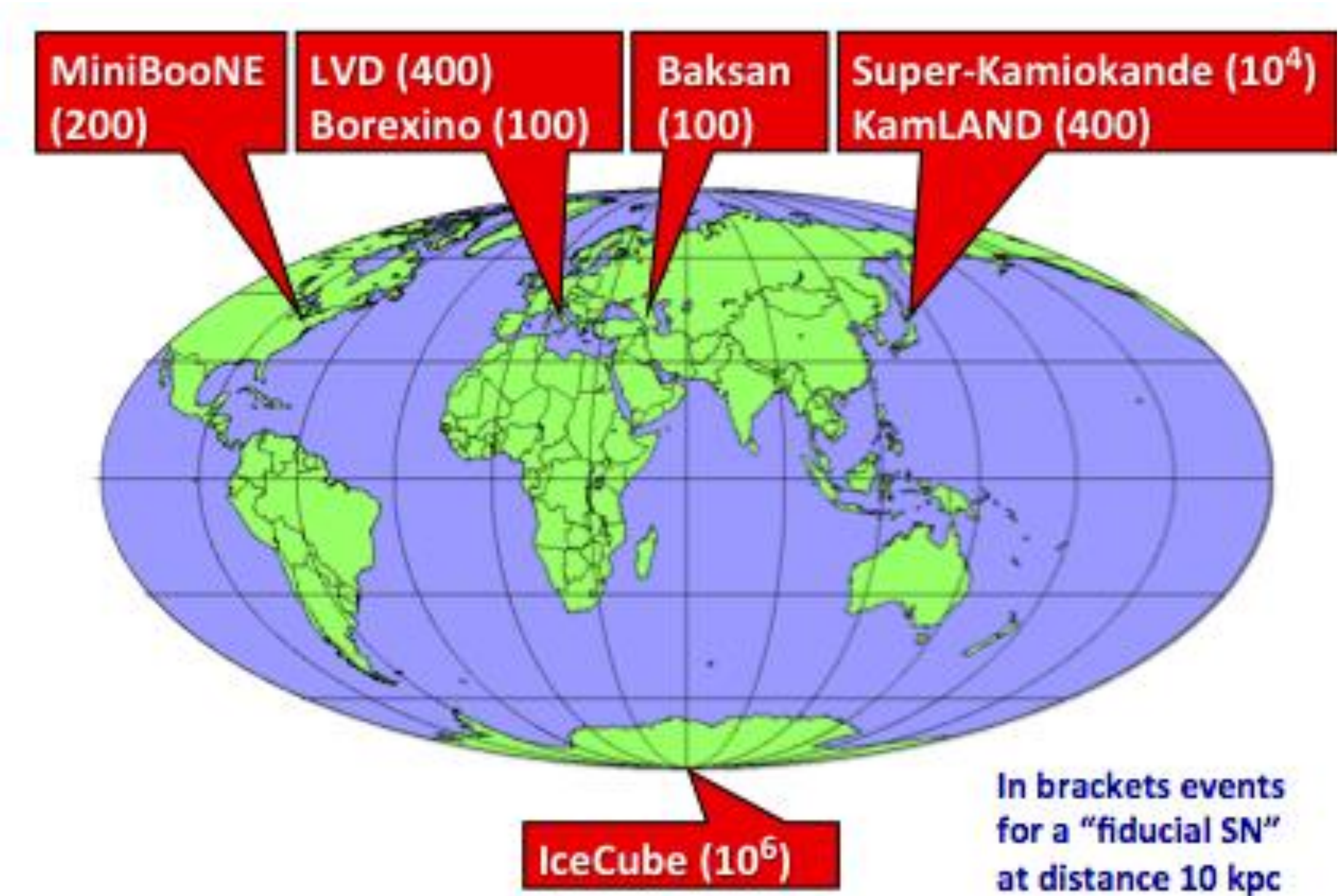
- The events observed by Kamiokande-II, IMB and Baksan few hours before SN1987A are consistent with the hypothesis that the supernova emitted about 5 × 10^{52} erg in electron antineutrinos with an average energy of one dozen of MeV



- There is no clear indication of other physics from the observed energy spectra and that the agreement with the theory is satisfactory even though there are some issues that remain unsolved to date
- it seems fair to conclude that the observations from SN1987A have been a useful benchmark and a precious occasion to test our knowledge of what happens during a gravitational collapse
- The SuperNova Early Warning System (SNEWS) is a network of neutrino detectors (Borexino, Daya Bay, KamLAND, IceCube, LVD, Super-Kamiokande) organized to give early warning to astronomers to study the supernova phenomenon at a very early stage of the collapse by different telescopes (radio, optical, X ray, gamma ray)

Francesco Vissani, Comparative analysis of SN1987A antineutrino fluence, J.Phys. G42 (2015) 013001
M. Koshiba, Observational neutrino astrophysics, Phys. Rep. 220 (1992) 229-381.
D. Denegri, B. Sadoulet, M. Spiro, The number of neutrino species, Rev. Mod. Phys. 62 (1990) 1
V. Trimble, 1987A: The greatest supernova since Kepler, Rev. Mod. Phys. 60 (1988) 859-871

Operational Detectors for Supernova Neutrinos



In brackets events for a "fiducial SN" at distance 10 kpc

La prossima SN: quando e dove?

Raggio efficace per l'osservazione con neutrini: 10 kpc!

Stima del tasso di SNe per collasso gravitazionale:

- Osservazione delle altre galassie e stima della statistica
- Estrapolazione della statistica dalle 5 SNe storiche nella nostra galassia nel millennio passato
- Osservazione dei γ dell' ^{26}Al (circa 10^5 y) prodotto nelle stelle massive

↓

2-3 per secolo!

Dove?

Una SN da collasso gravitazionale è l'ultimo stadio della vita di una stella

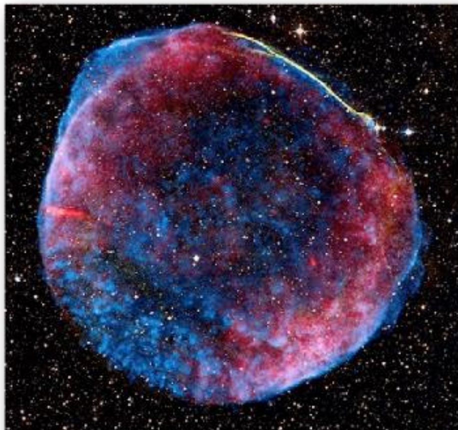
→ Cercare in zone dove le stelle si stanno formando

Stima. Parametri consistenti con il deficit di SNe nella nostra galassia in un raggio tra 3.0 e 5.5 kpc dal centro → studio della distribuzione nella nostra galassia e nelle altre di:

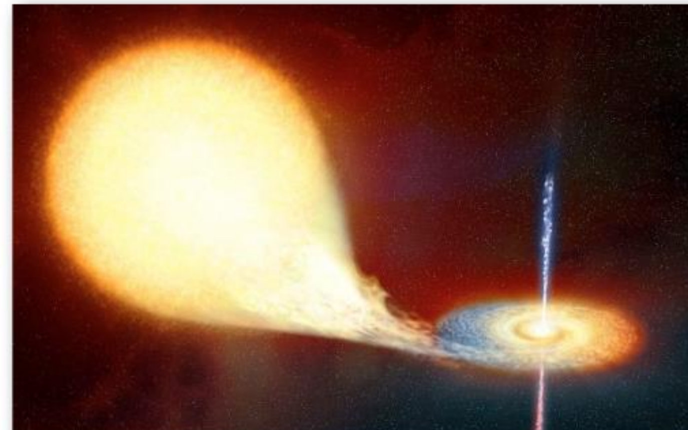
- Pulsar
- SN remnant
- H ionizzato e molecolare

The high-energy universe

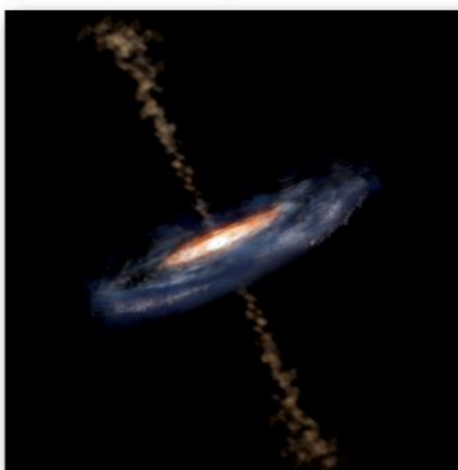
supernova remnants
(SN1006, optical, radio, X-ray)



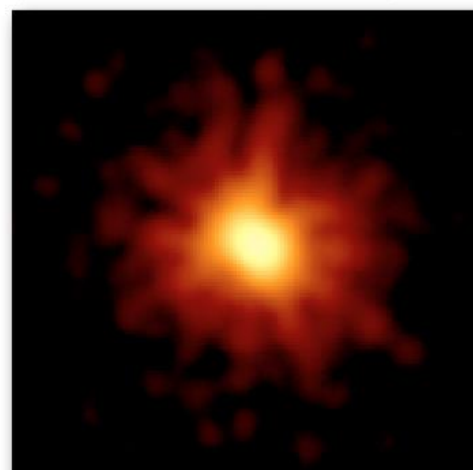
micro-quasars
(artist's view)



active galactic nuclei
(artist's view)



gamma-ray bursts
(GRB 080319B, X-ray, SWIFT)



High-energy particle production in the Universe

Accelerator (source)

- Shock fronts (Fermi acceleration)
- Objects with strong magnetic fields (pulsars, magnetars)

Beam dump (secondary particle production)

- Interaction with photons or matter
- Protons: pion decay

$p + p(\gamma) \rightarrow \pi^{\pm} + X$

$\quad \hookrightarrow \mu + \nu_{\mu}$

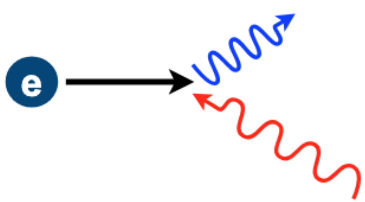
$\quad\quad \hookrightarrow e + \nu_{\mu} + \nu_{e}$

$p + p(\gamma) \rightarrow \pi^{0} + X$

$\quad \hookrightarrow \gamma + \gamma$ (TeV)

- Electrons: inverse Compton-scattering of photons

$e + \gamma \rightarrow e + \gamma$ (TeV)



Why neutrino astronomy?

- Neutrinos point back to the source
- Neutrinos travel cosmological distances
- Neutrinos escape from optically thick sources
- Neutrinos are a clear sign for hadron acceleration

Neutrinos provide complementary information to gamma-rays and protons

- **High-energy gamma-rays**
  - Can be emitted in hadronic or leptonic processes
  - Partially absorbed in interstellar medium or dense sources
- **Cosmic rays (protons&nuclei)**
  - Signature of acceleration sites
  - Deflected by magnetic fields
- **Gravitational waves**
  - Hint of motion, rotation, or merging of compact objects
- **Neutrinos**
  - Can escape dense environment
  - Not absorbed and not deflected
  - Signature of hadronic processes

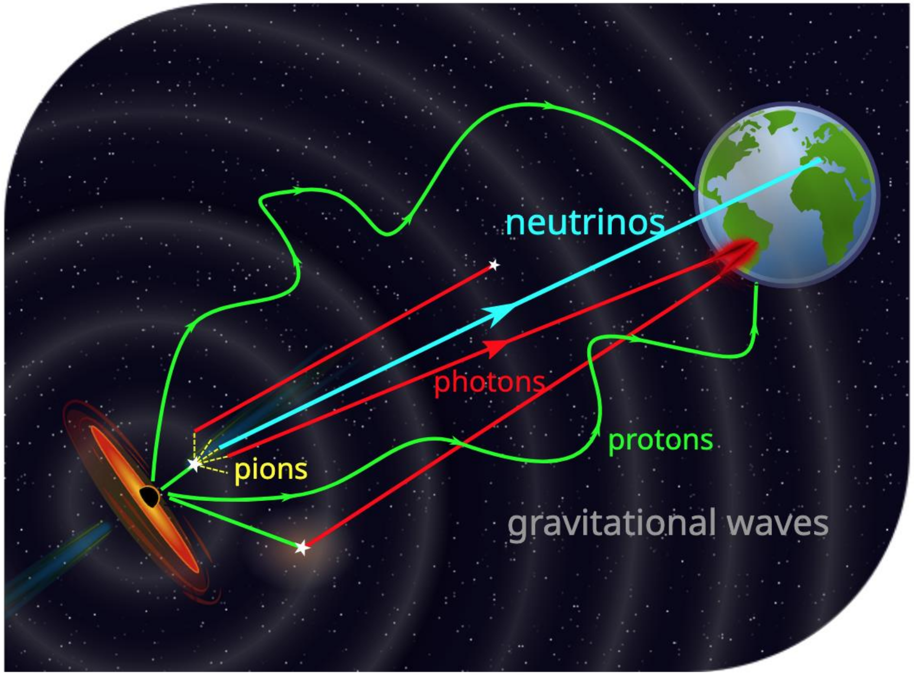
Estimating neutrino fluxes

- Photon ↔ neutrino connection:

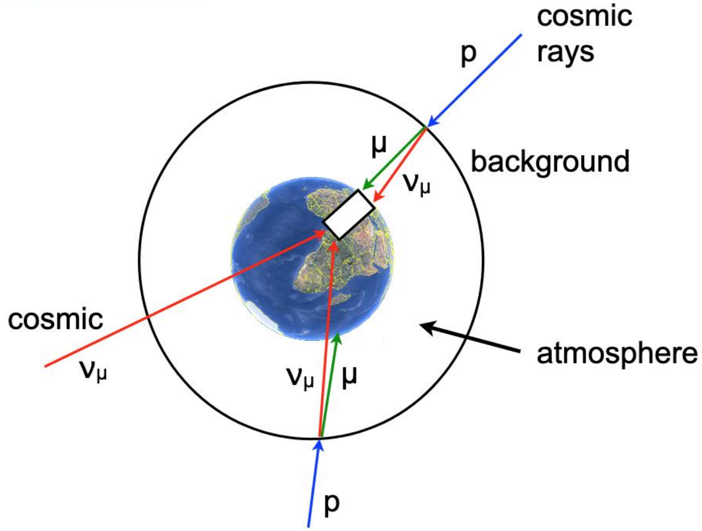
$p + p \rightarrow \pi^0 + X$
↳ $\gamma + \gamma$

$p + p \rightarrow \pi^\pm + X$
↳ $\mu + \nu_\mu$
↳ $e + \nu_\mu + \nu_e$

- Observed from RX J1713.7–3946 (SNR):
  - γ-rays up to several 10 TeV
    → particle acceleration up to 100 TeV and above

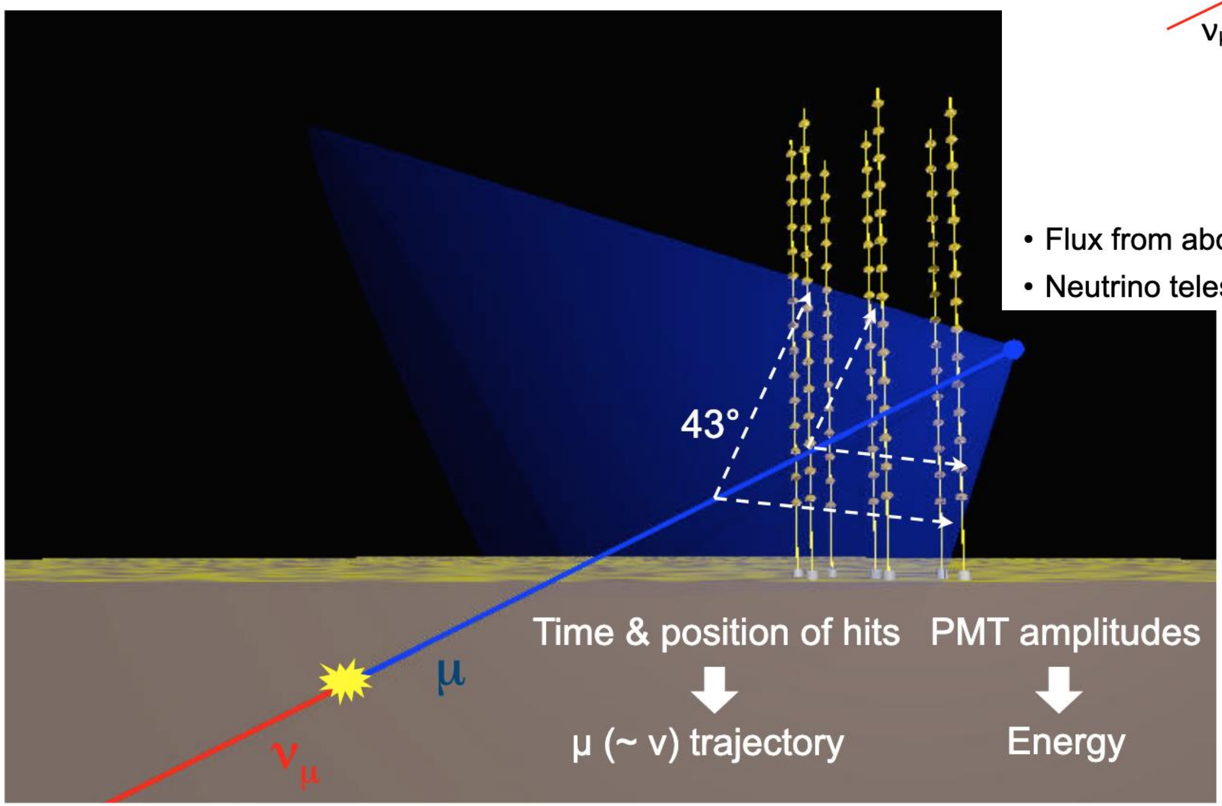


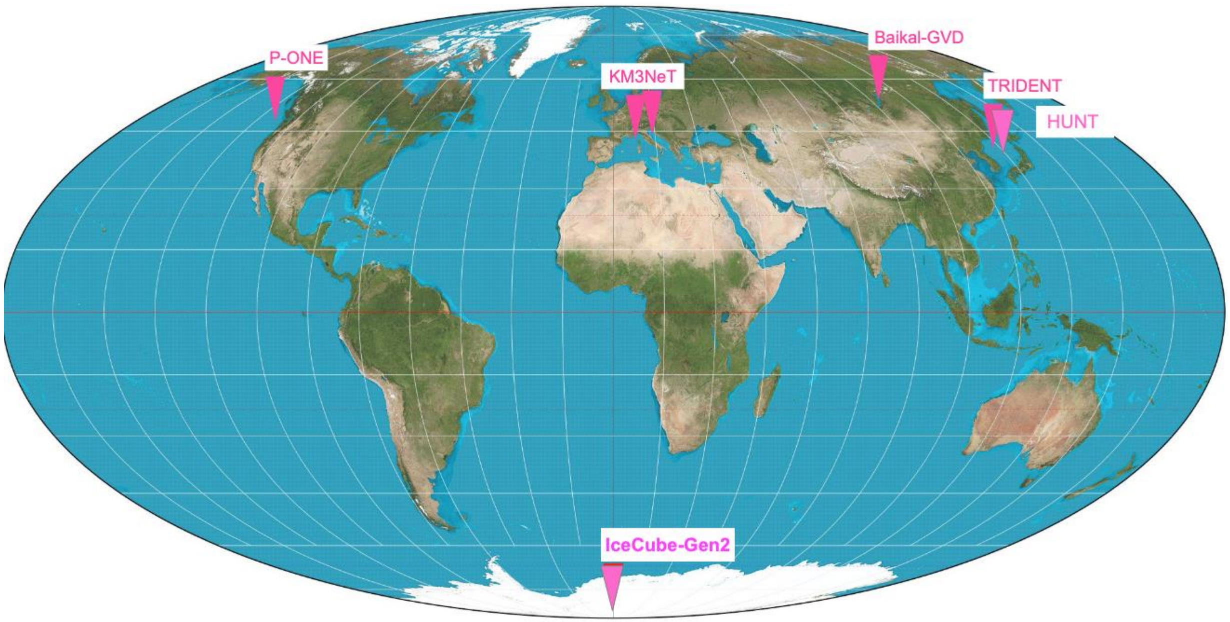
Background: atmospheric muons and neutrinos



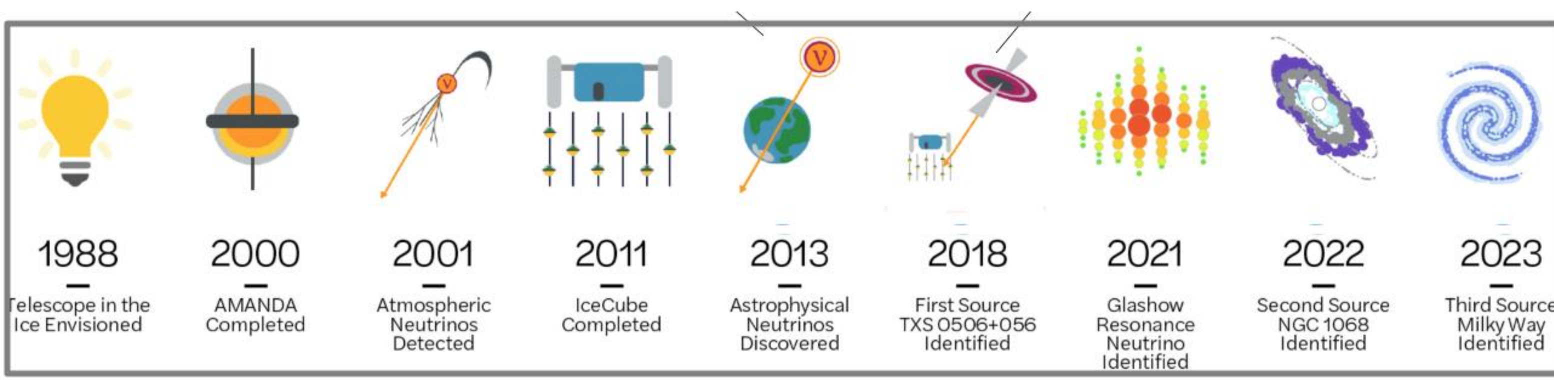
- Flux from above dominated by atmospheric muons
- Neutrino telescopes mainly sensitive to neutrinos from below

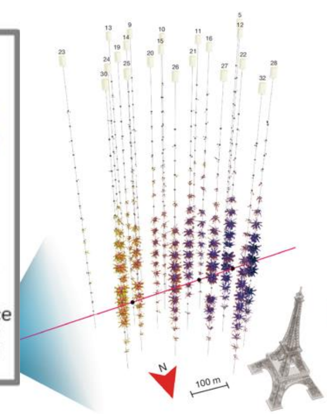
Principle of neutrino detection



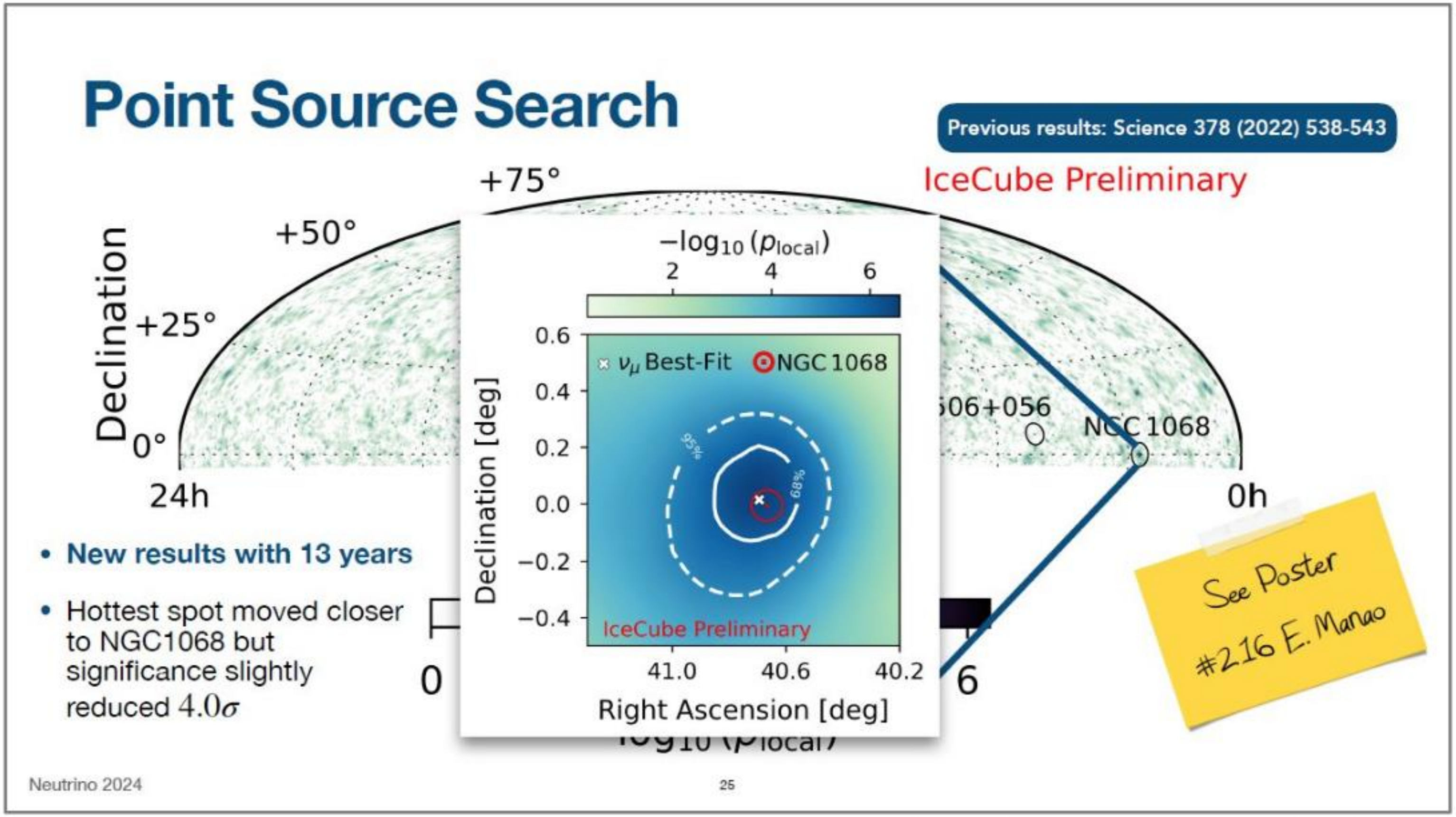


2025 - ultra-high-energy cosmic neutrino with KM3NeT





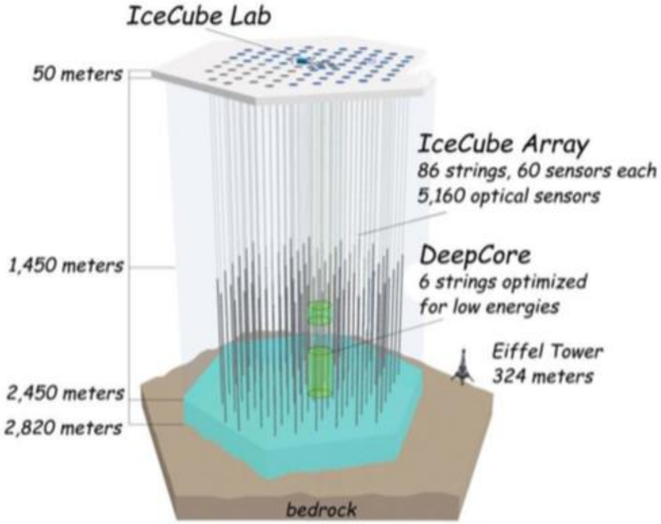
Recent News

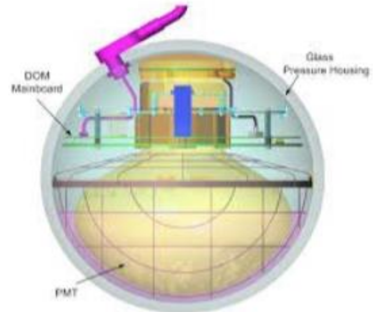


Slide from J. Aguillar (IceCube)

High energy ν

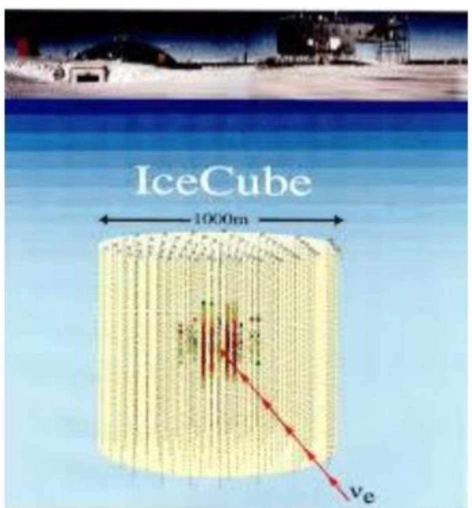
IceCube: largest Cherenkov detector ~ 1 Gt





Photomultiplier in special encapsulation to prevent PMT from high-pressure in the ice

Amundsen–Scott South Pole Station

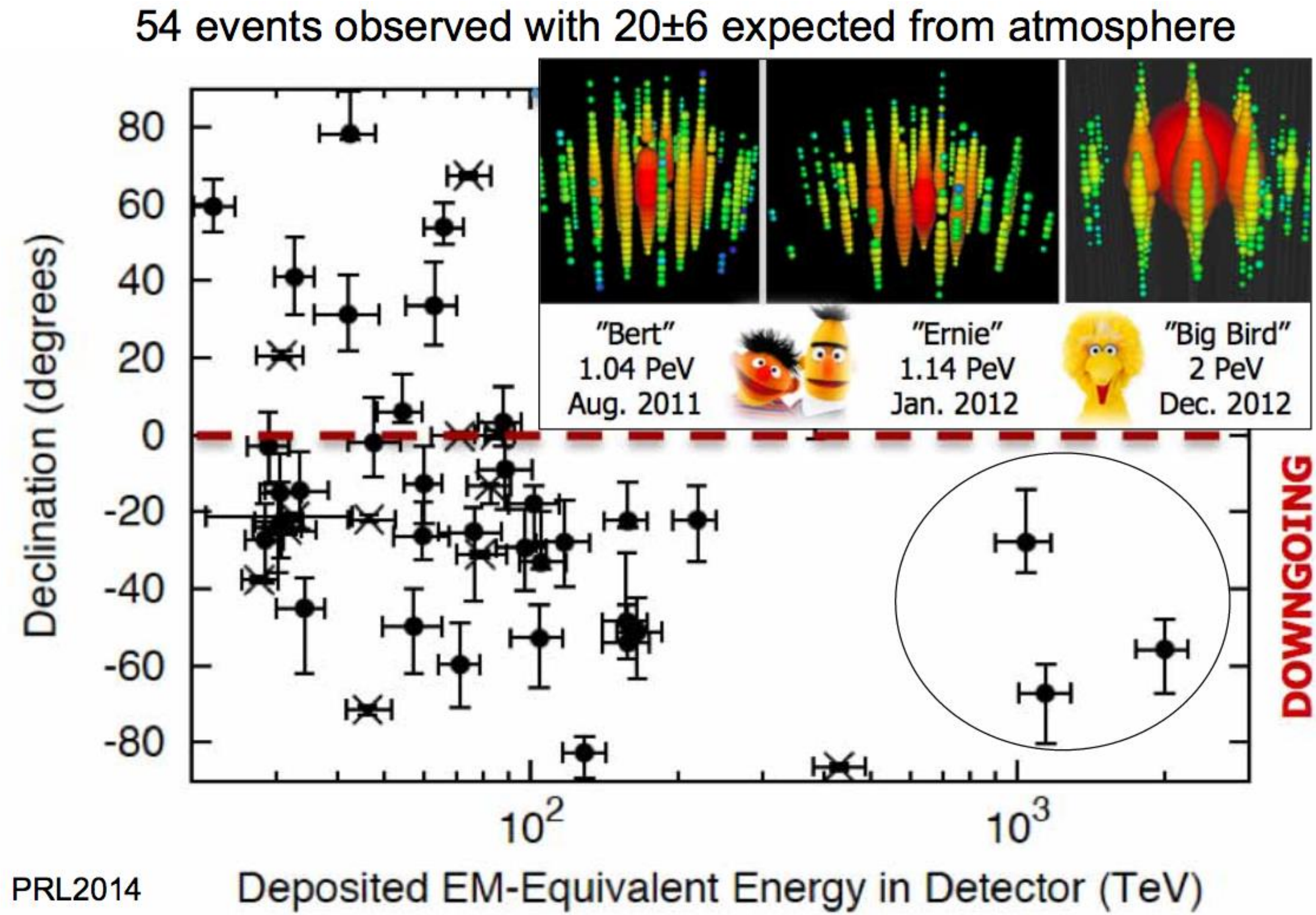


Principle of high energy ν detection

Experimental goals

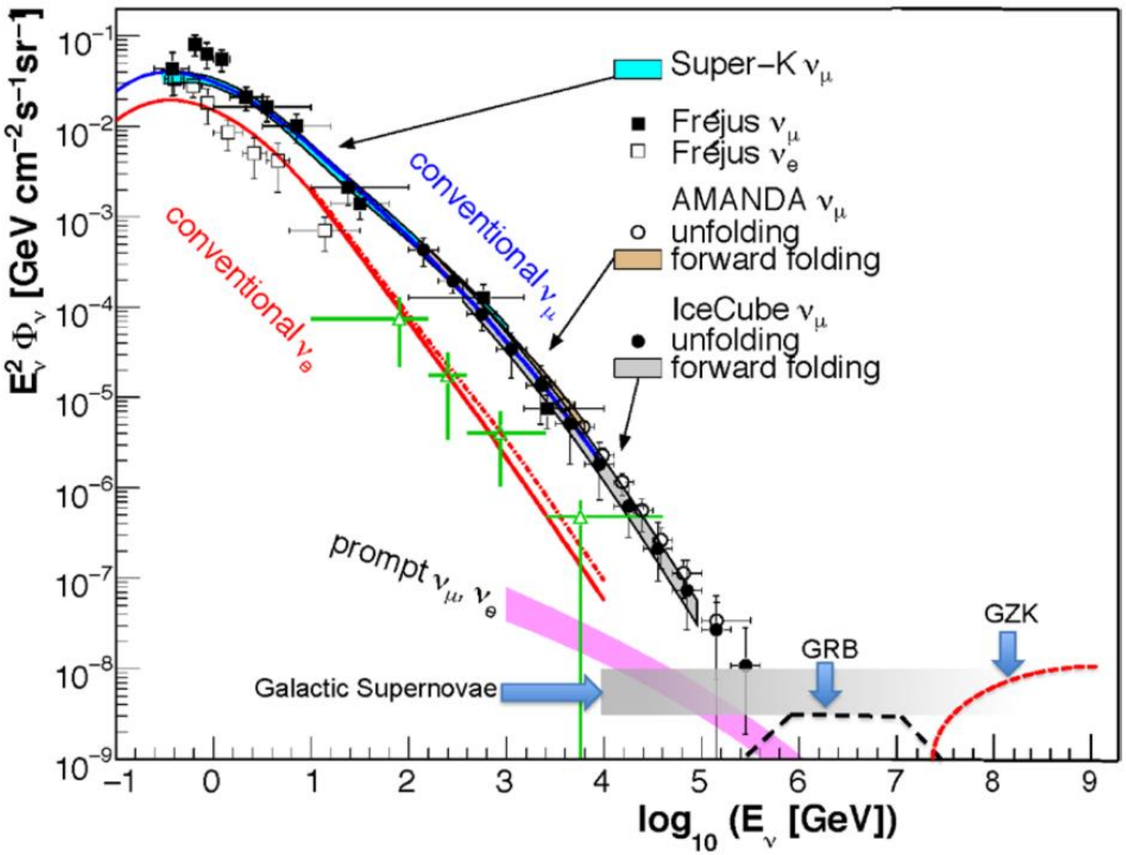
- Point sources of high energy neutrinos
- Gamma ray bursts coincident with neutrinos
- Indirect dark matter searches
- Neutrino oscillations
- Galactic supernovae
- Sterile Neutrinos

High energy ν - IceCube: results



PRL2014

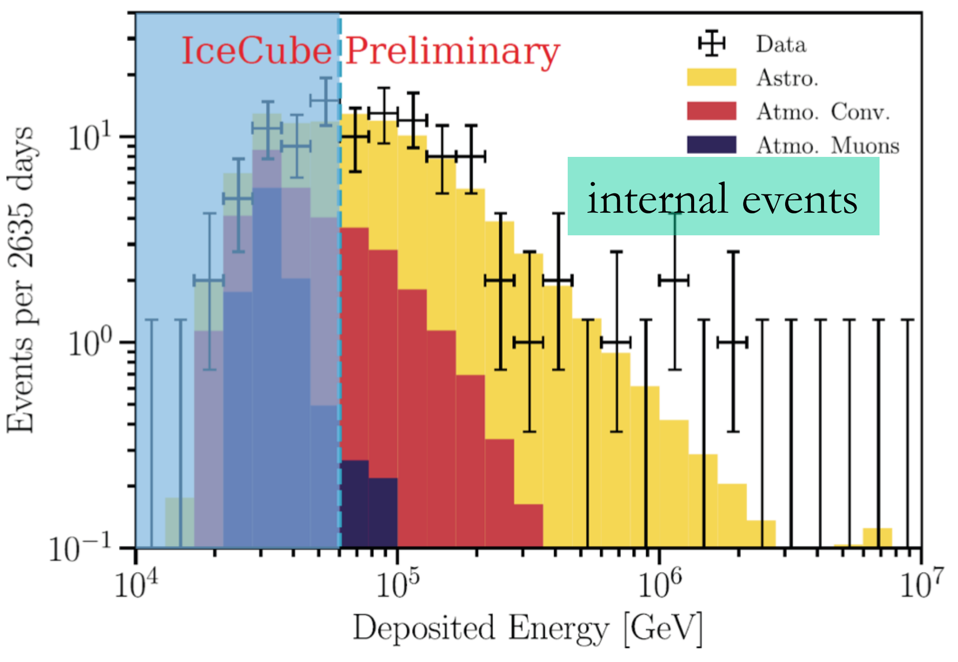
Astrophysical neutrino fluxes

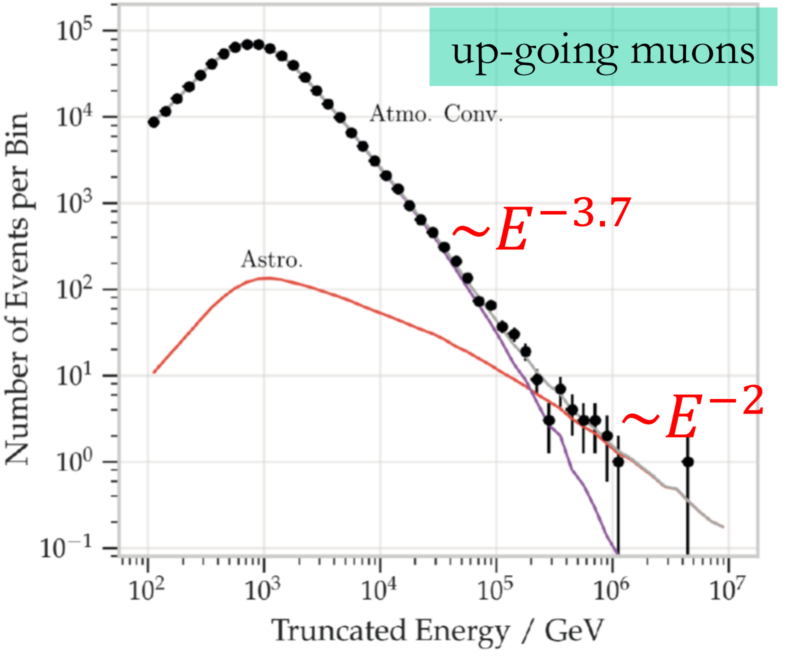


- supernova remnants and GRBs exceed the atmospheric neutrino flux above 100 TeV because of their relatively E^{-2} spectrum
- Simple calculation of the GZK neutrino flux.
- The atmospheric neutrino spectra are shown

ICECUBE

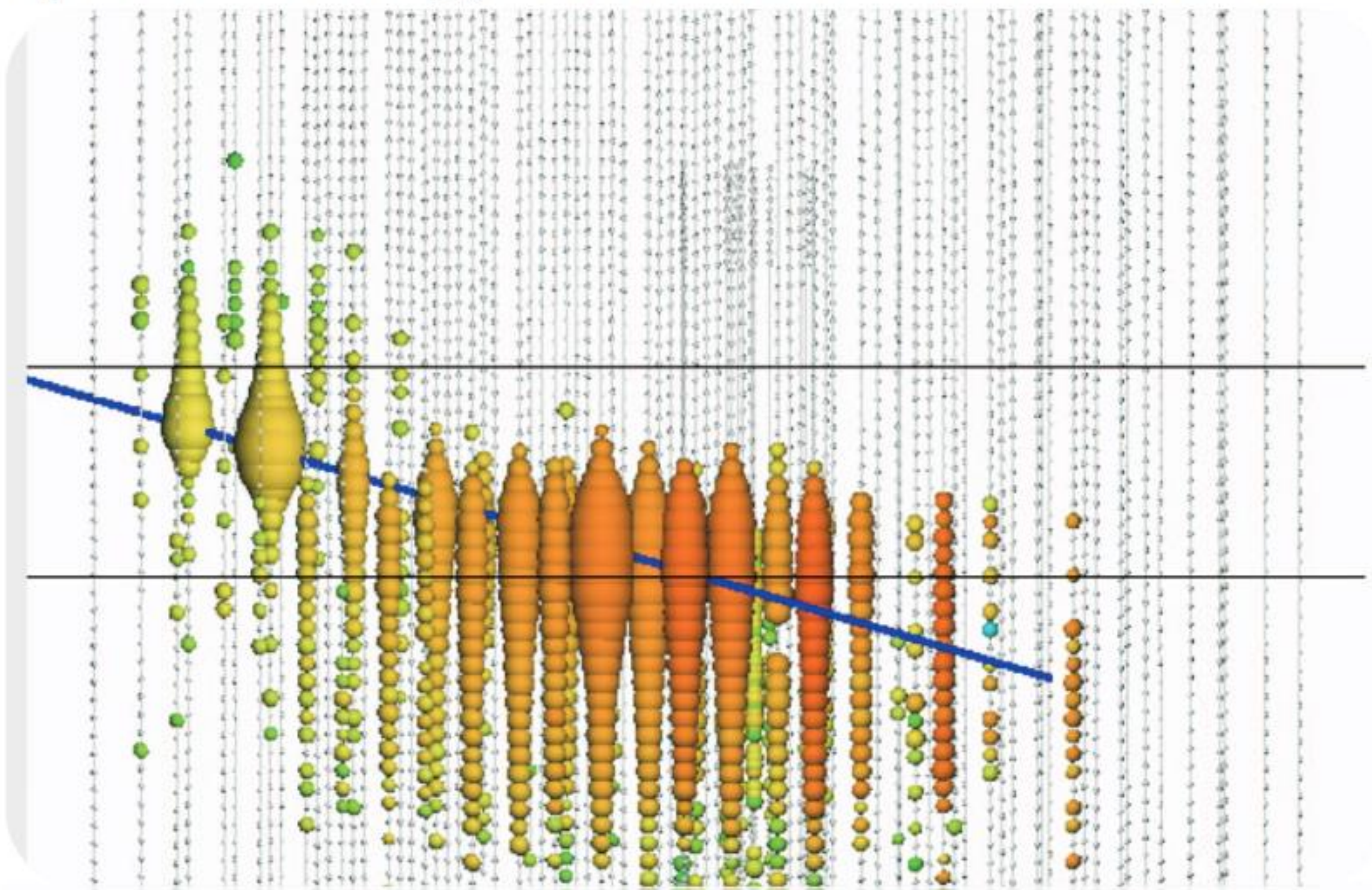
- Atmospheric ν expected $\sim E^{-3.7}$
- Cosmic ν expected $\sim E^{-2}$
- Cosmic ν larger than atm ν for $E_\nu \gtrsim 100\,TeV$
- Found dependence for cosmic ν:
  - internal events: $\sim E^{-2.9}$
  - up-going muons: $\sim E^{-2.2}$
- For up-going muons the angular resolution below 1°
(possible ν astronomy)





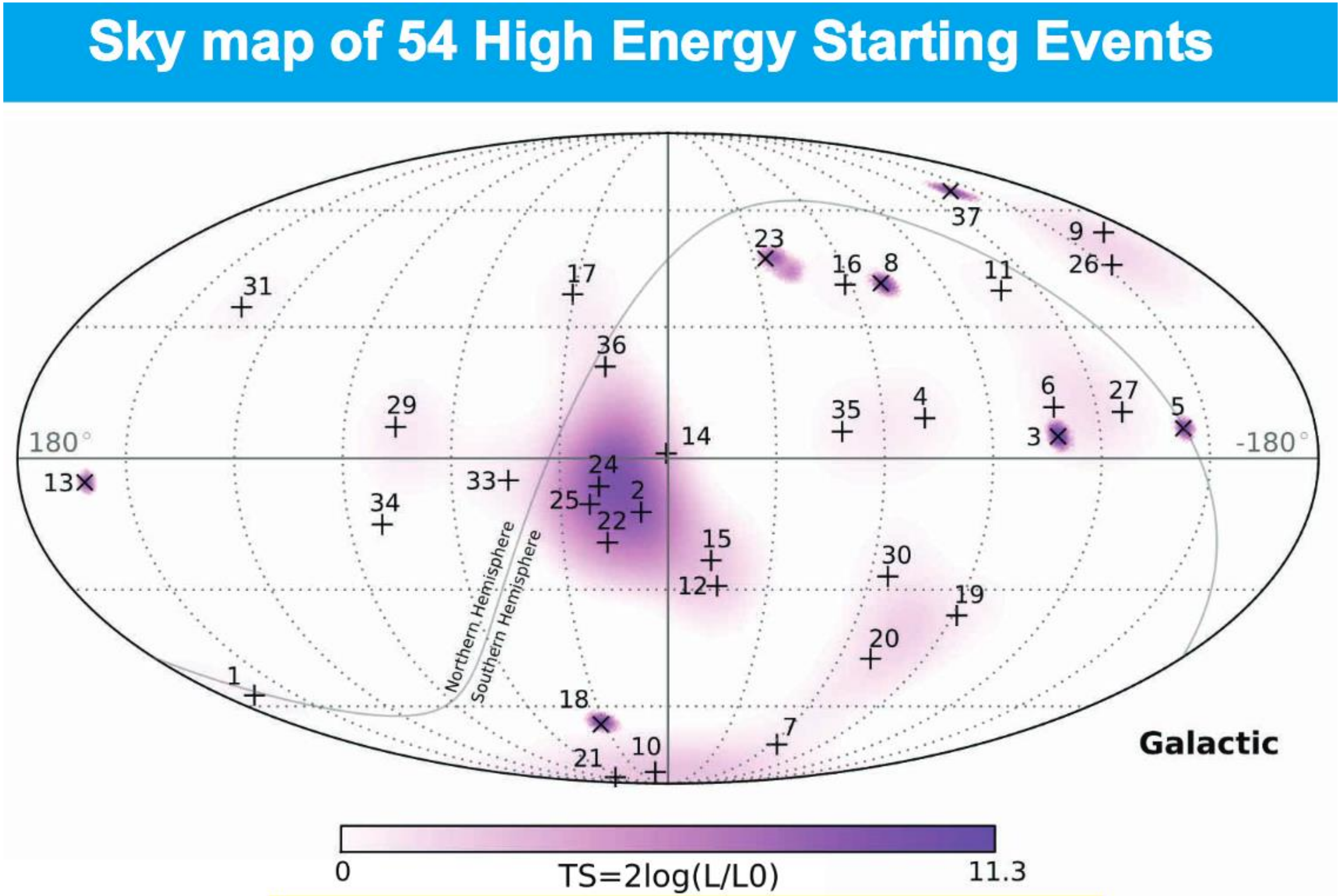
High energy ν - IceCube: results

deposited energy in IceCube: 2.6±0.3 PeV



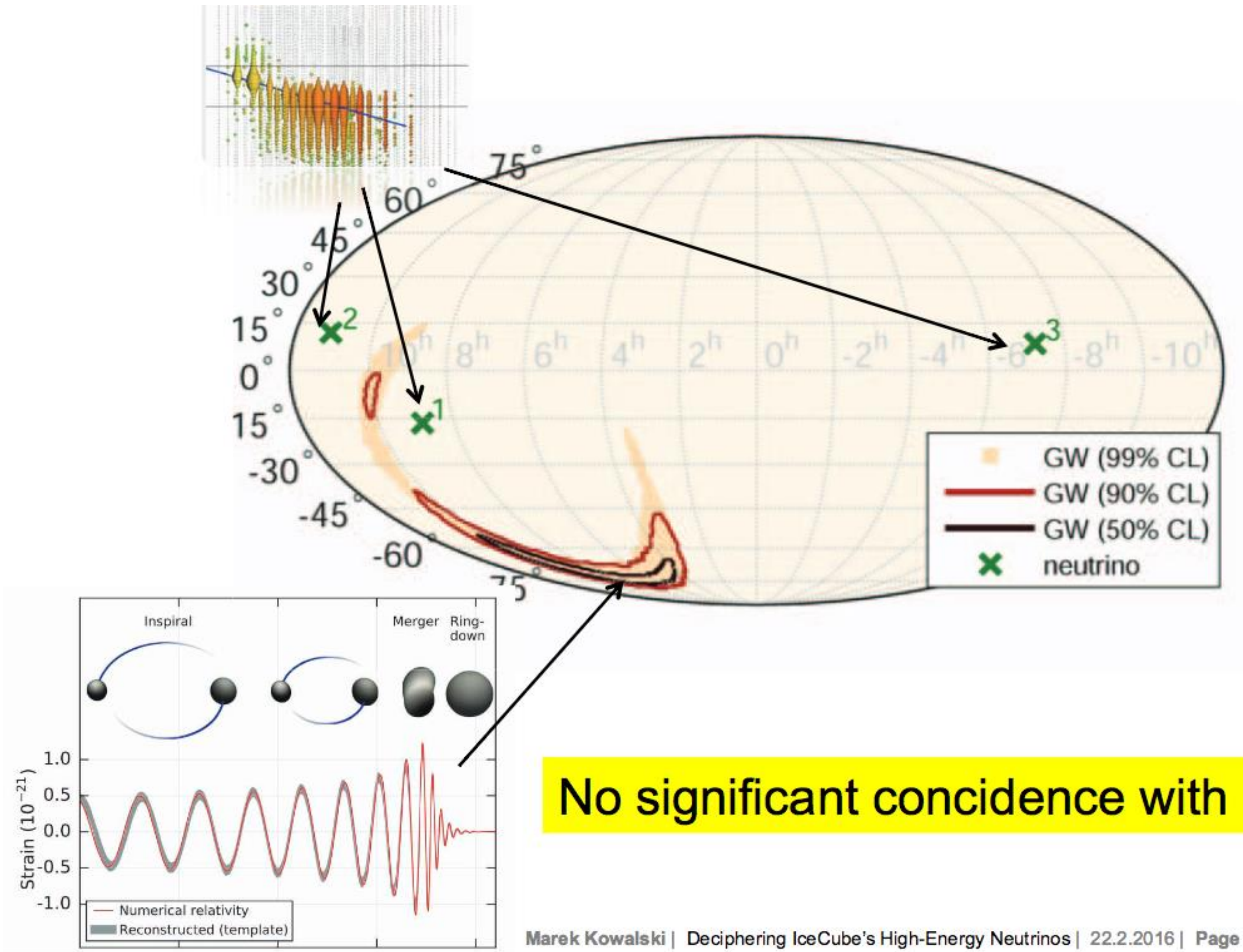
ICRC2015

High energy ν - IceCube: results



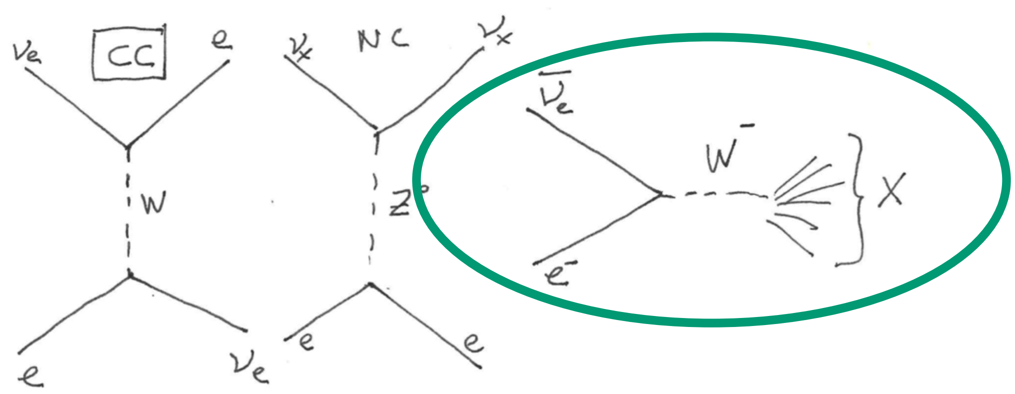
Largely isotropic extragalatic origin!

IceCube: ν follow-up of LIGO event GW150914



No significant concidence with neutrinos

Detection of a particle shower at the Glashow resonance with IceCube



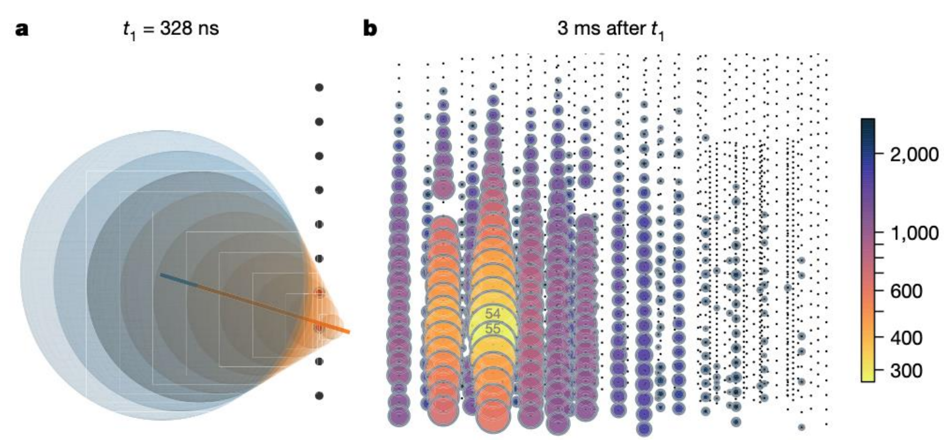
- The Glashow resonance describes the resonant formation of a W boson during the interaction of a high-energy electron antineutrino with an electron, peaking at an antineutrino energy of 6.3 PeV in the rest frame of the electron.
- The cross section is resonant:

$$\sigma(s) = 24\pi\Gamma_W^2 B_{W^-\to\bar{\nu}_e+e^-}\frac{s/M_W^2}{(s-M_W^2)^2+\Gamma_W^2 M_W^2}$$

The cross section is maximal when $s = M_W^2$. In the electron rest frame, the resonance energy is

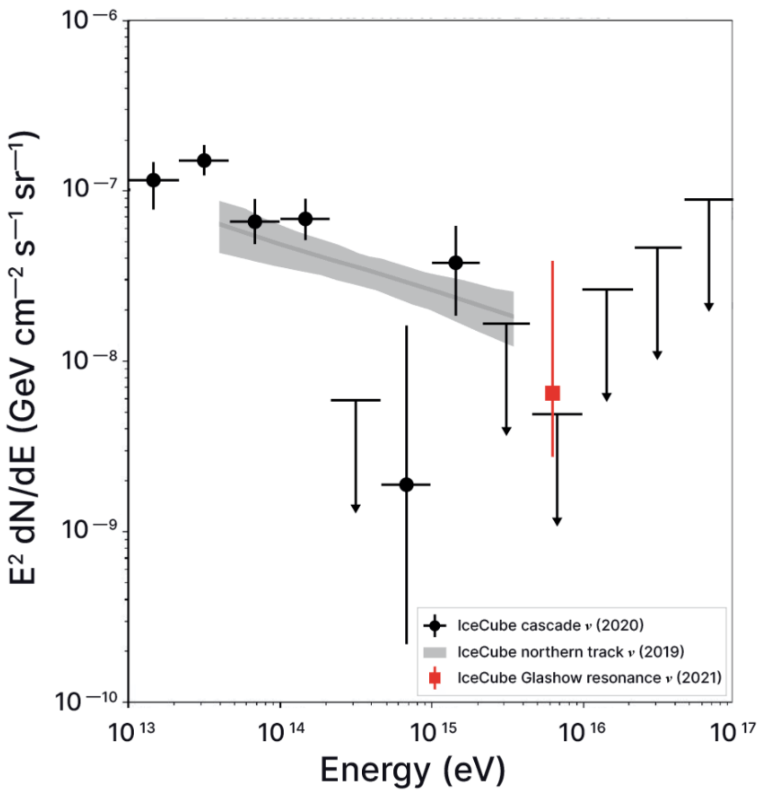
$$E_R = M_W^2/(2m_e) = 6.32 \text{ PeV}$$

- One event was found with a visible energy of 6.05 ± 0.72 PeV.
- Given its energy and direction, it is classified as an astrophysical neutrino at the 5σ level.
- The neutrino energy is inferred to be about 6.3 PeV by correcting the visible energy for shower particles that do not radiate.



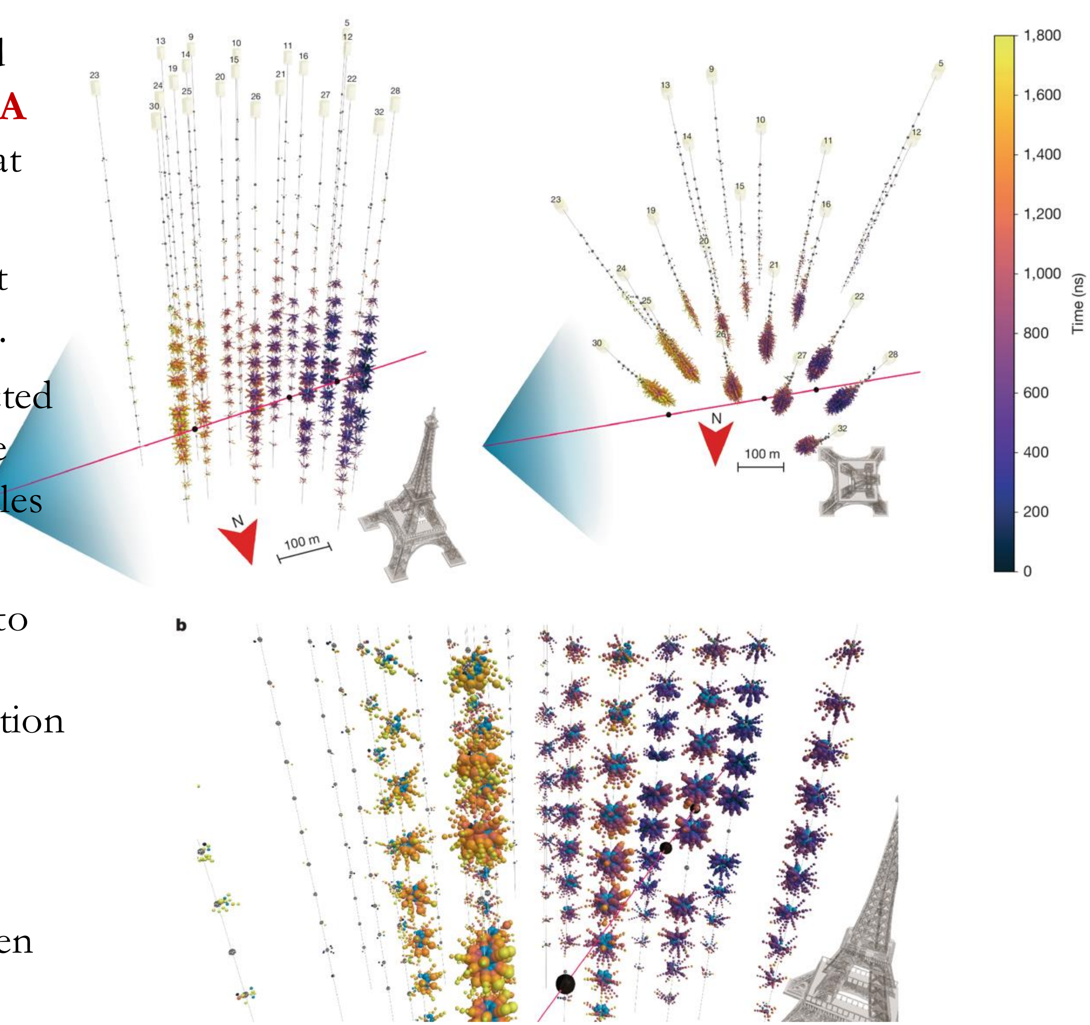
Nature, 591 (2021) 220

Neutrino Astronomy and Multimessenger Astrophysics



- Flux of cosmic muon neutrinos (shaded band)
- Flux of electron and tau neutrinos (data points)
- Both are consistent with the flux derived from the observation of a single Glashow-resonance event (red data point), where an electron anti-neutrino interacts with an atomic electron to produce a charged intermediate boson W

Observation of an ultra-high-energy cosmic neutrino with KM3NeT



- An extremely high-energy μ with an estimated energy of **120^{+110}_{-60} PeV**, traversing the **ARCA** detector was observed on **13 February 2023** at 01:16:47 UTC.
- This event is referred to as KM3-230213A. At that time, 21 detection lines were in operation.
- The direction of KM3-230213A is reconstructed as **near-horizontal**, originating 0.6° above the horizon at an azimuth of 259.8° (azimuth angles increase clockwise, with north at 0°).
- The uncertainty on the direction is estimated to be 1.5° (68% CL), dominated by the present systematic uncertainty on the absolute orientation of the detector.
- In light of its **enormous energy** and near-horizontal direction, the μ most probably originated from **the interaction of a ν** of even higher energy in the vicinity of the detector.
- The cosmic neutrino energy spectrum measured up to now falls steeply with energy.
- However, the energy of this event is **much larger than that of any ν detected so far**.
- This suggests that the ν may have originated in a different cosmic accelerator than the lower-energy neutrinos, or this may be the **first detection of a cosmogenic neutrino**, resulting from the interactions of ultra-high-energy cosmic rays with background photons in the Universe.