Neutrinos

Ghost Particles of the Universe

Georg G. Raffelt
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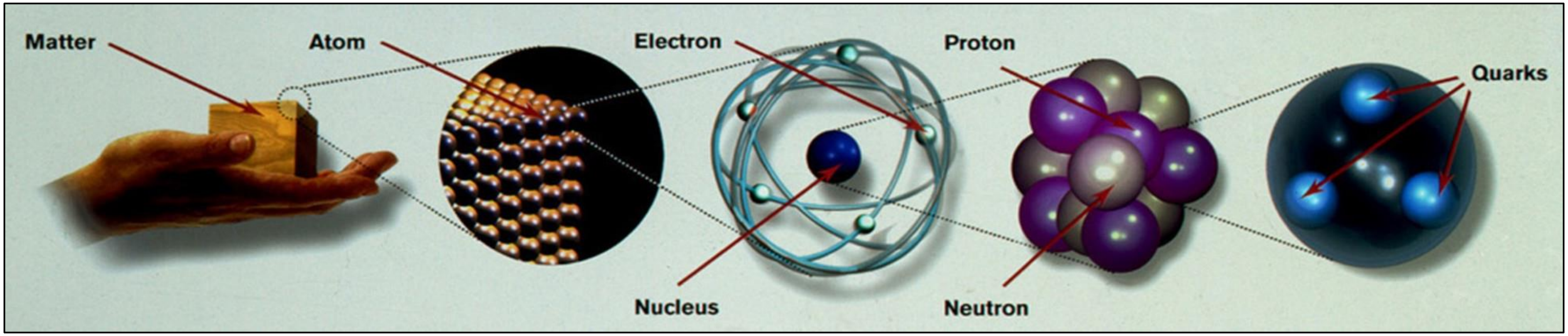
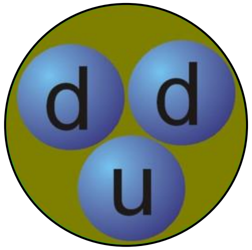
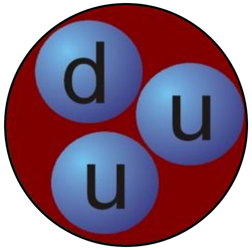
Periodic System of Elementary Particles



Quarks		Leptons	
Charge −1/3	Charge +2/3	Charge −1	Charge 0
Down d	Up u	Electron e	e-Neutrino ν_e

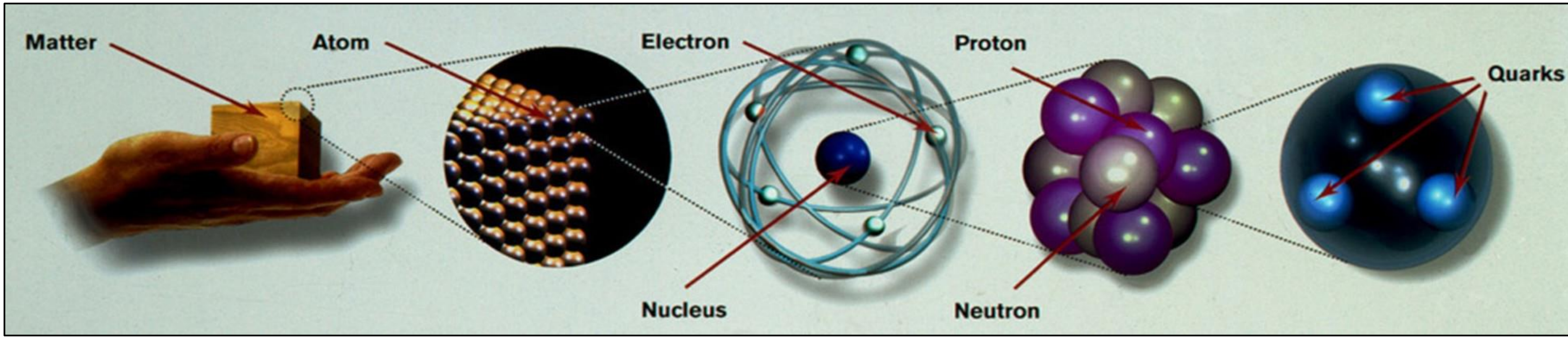


Neutron



Proton

Periodic System of Elementary Particles



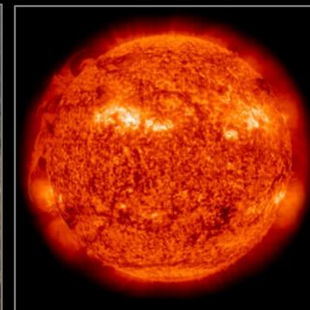
	Quarks		Leptons	
	Charge −1/3	Charge +2/3	Charge −1	Charge 0
1st Family	Down d	Up u	Electron e	e-Neutrino ν_e
2nd Family	Strange s	Charm c	Muon μ	μ-Neutrino ν_μ
3rd Family	Bottom b	Top t	Tau τ	τ-Neutrino ν_τ

Higgs

- Strong Interaction (8 Gluons)
- Electromagnetic Interaction (Photon)
- Weak Interaction (W and Z Bosons)
- Gravitation (Gravitons?)

Where do Neutrinos Appear in Nature?

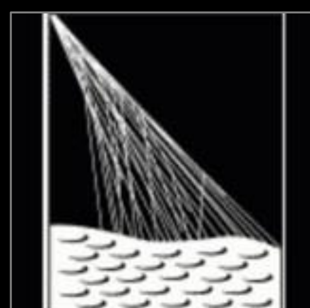
✓ Nuclear Reactors



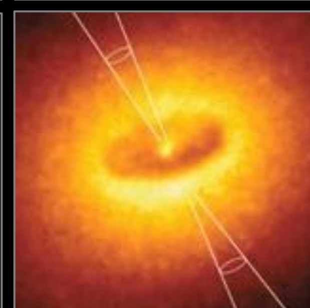
Sun ✓

✓ Particle Accelerators

Supernovae
(Stellar Collapse)
SN 1987A ✓

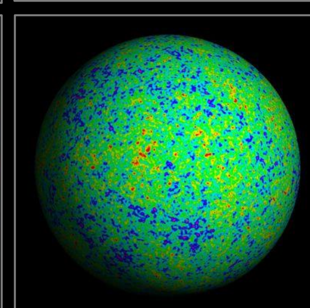


✓ Earth Atmosphere
(Cosmic Rays)



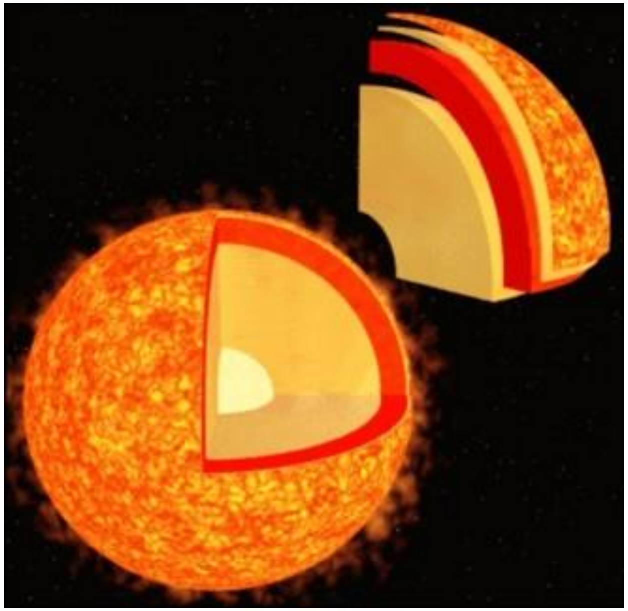
Astrophysical
Accelerators ✓

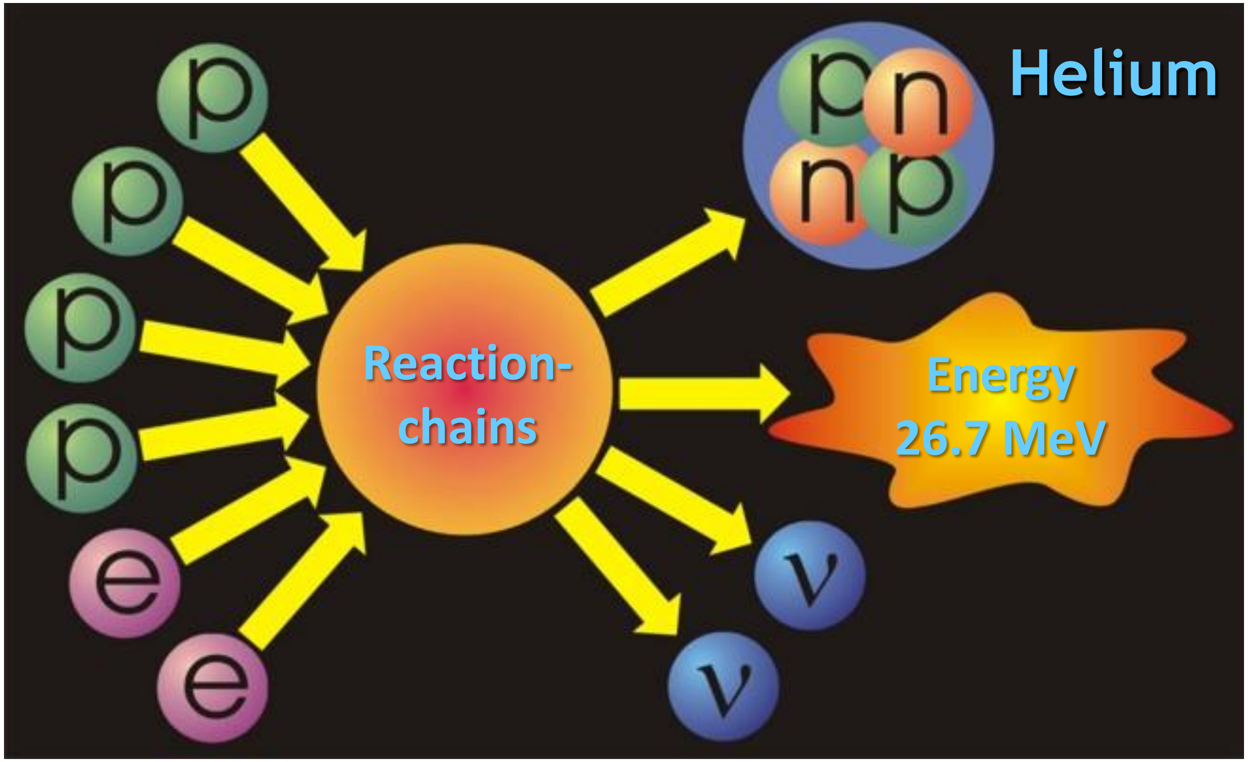
✓ Earth Crust
(Natural Radioactivity)



Cosmic Big Bang
(Today 330 ν/cm^3)
Indirect Evidence

Neutrinos from the Sun

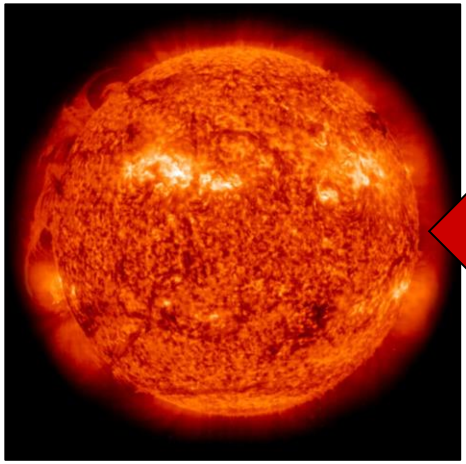




Solar radiation: 98 % light (photons)
2 % neutrinos
At Earth 66 billion neutrinos/cm^2 sec

Hans Bethe (1906–2005, Nobel prize 1967)
Thermonuclear reaction chains (1938)

Sun Glasses for Neutrinos?

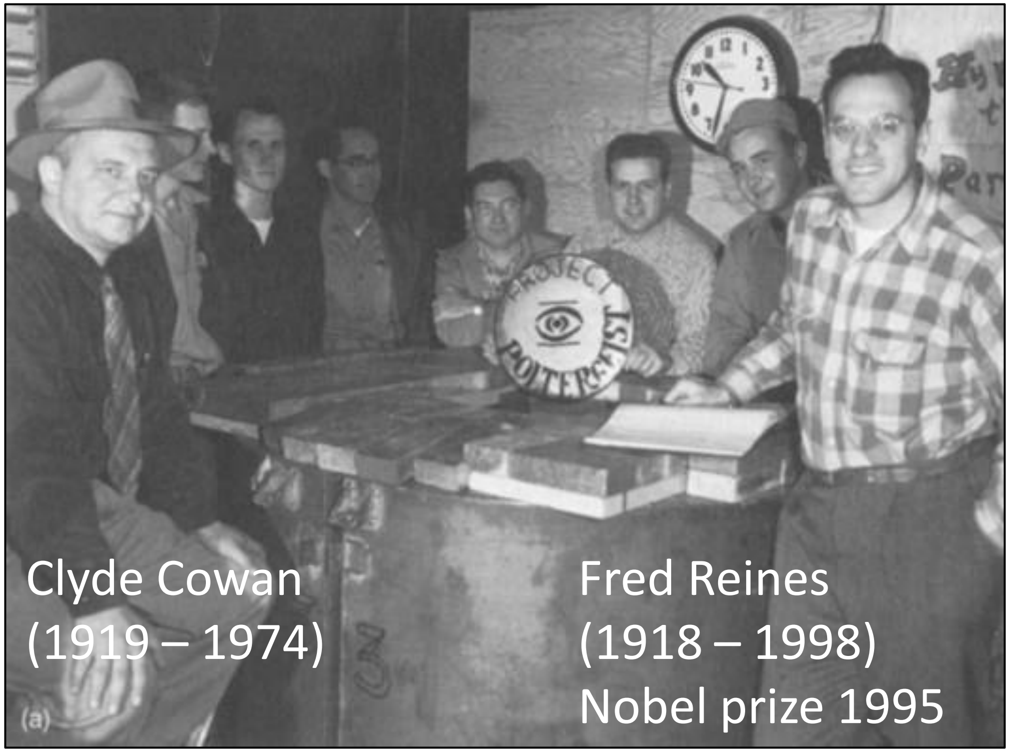


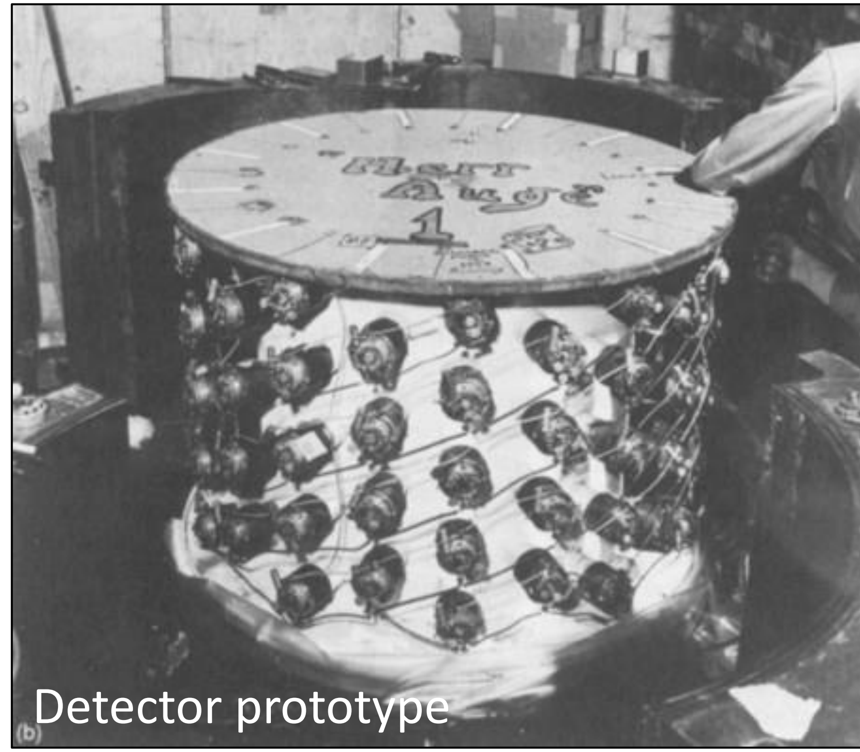
8.3 light minutes

Several light years of lead needed to shield solar neutrinos

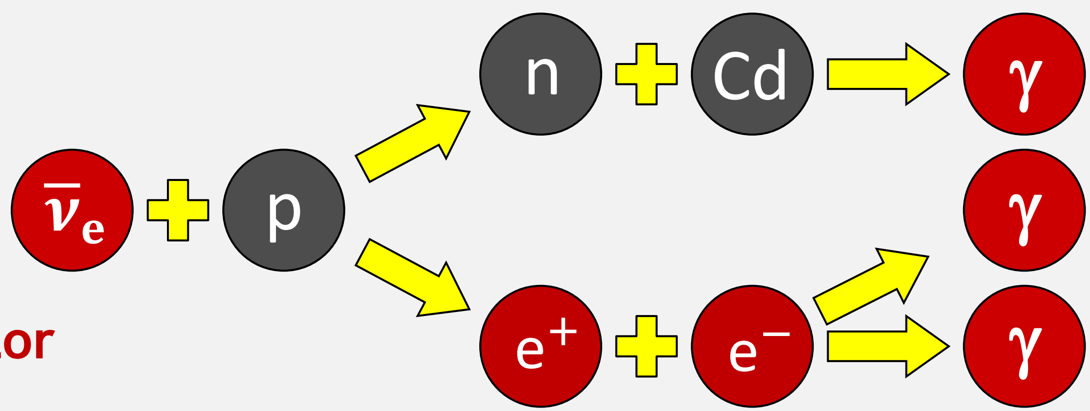
Bethe & Peierls 1934:
… this evidently means that one will never be able to observe a neutrino.

First Detection (1954 – 1956)



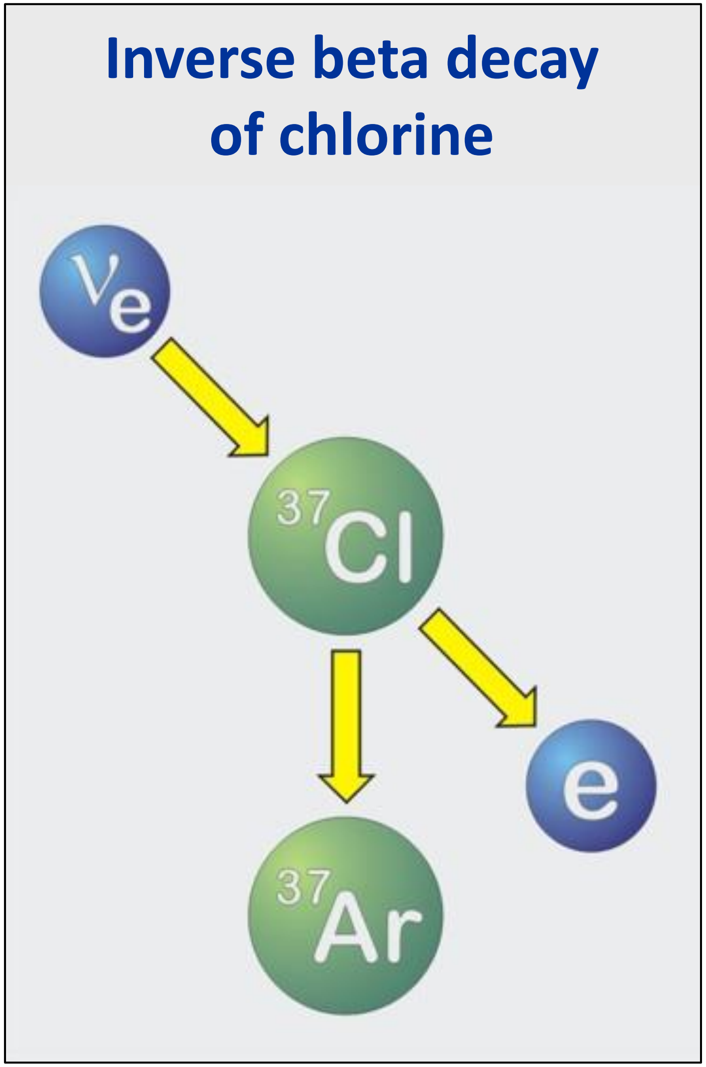


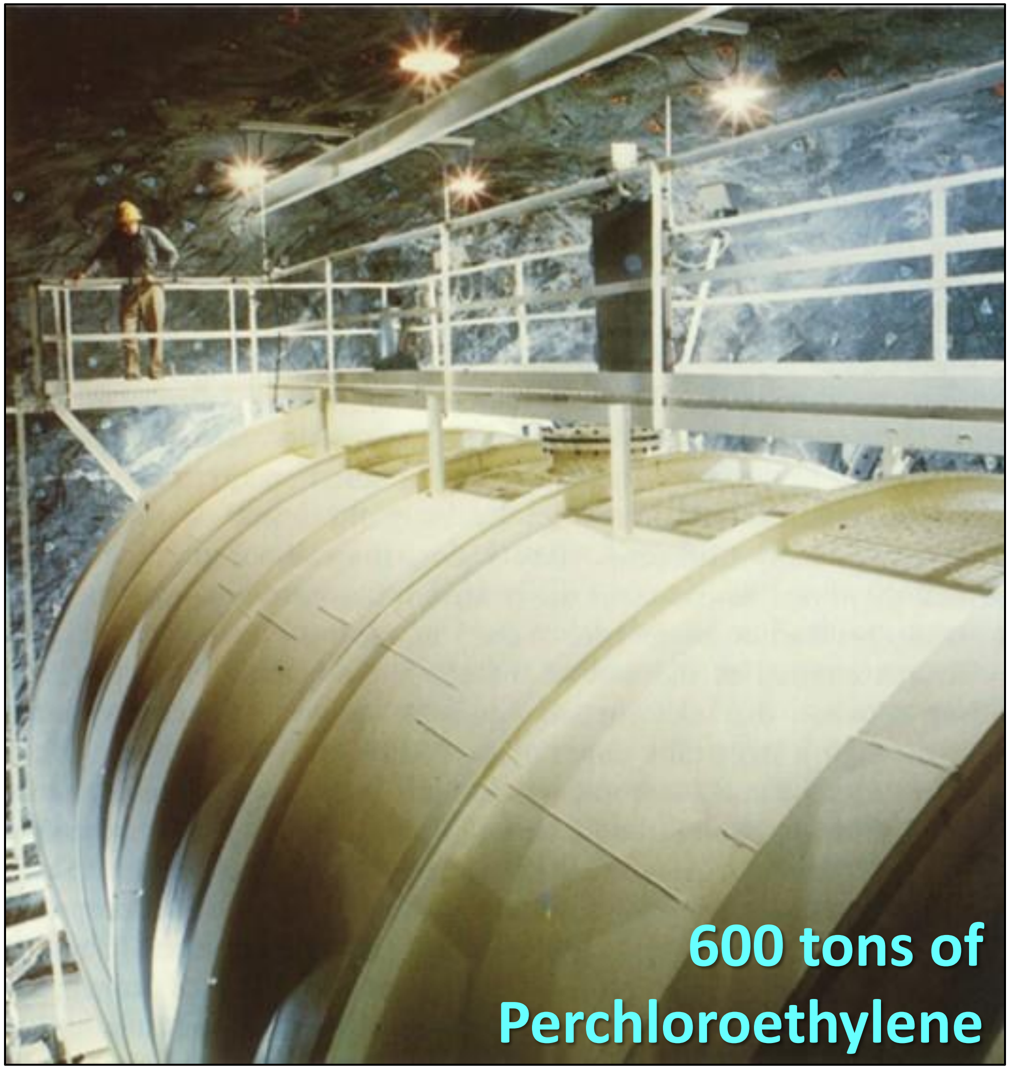
Anti-Electron Neutrinos from Hanford Nuclear Reactor



3 Gammas in coincidence

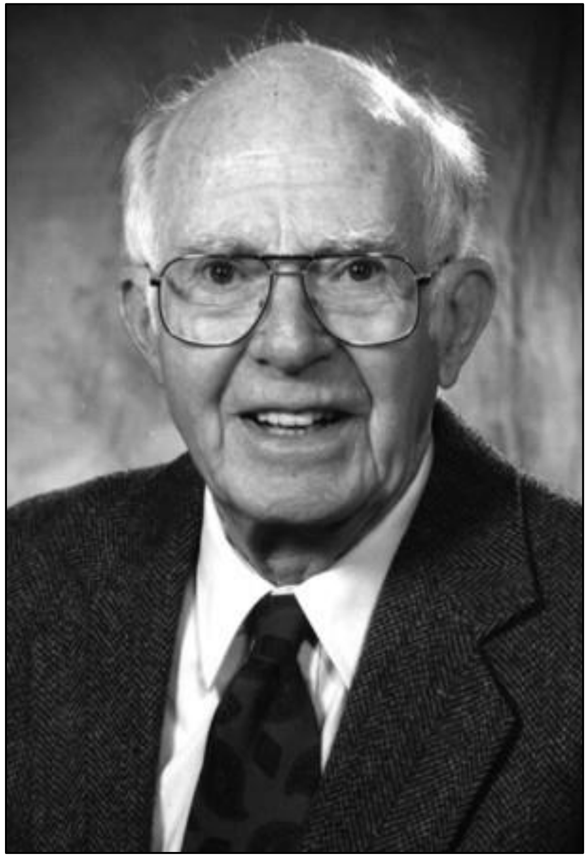
First Measurement of Solar Neutrinos





Homestake solar neutrino observatory (1967–2002)

2002 Physics Nobel Prize for Neutrino Astronomy

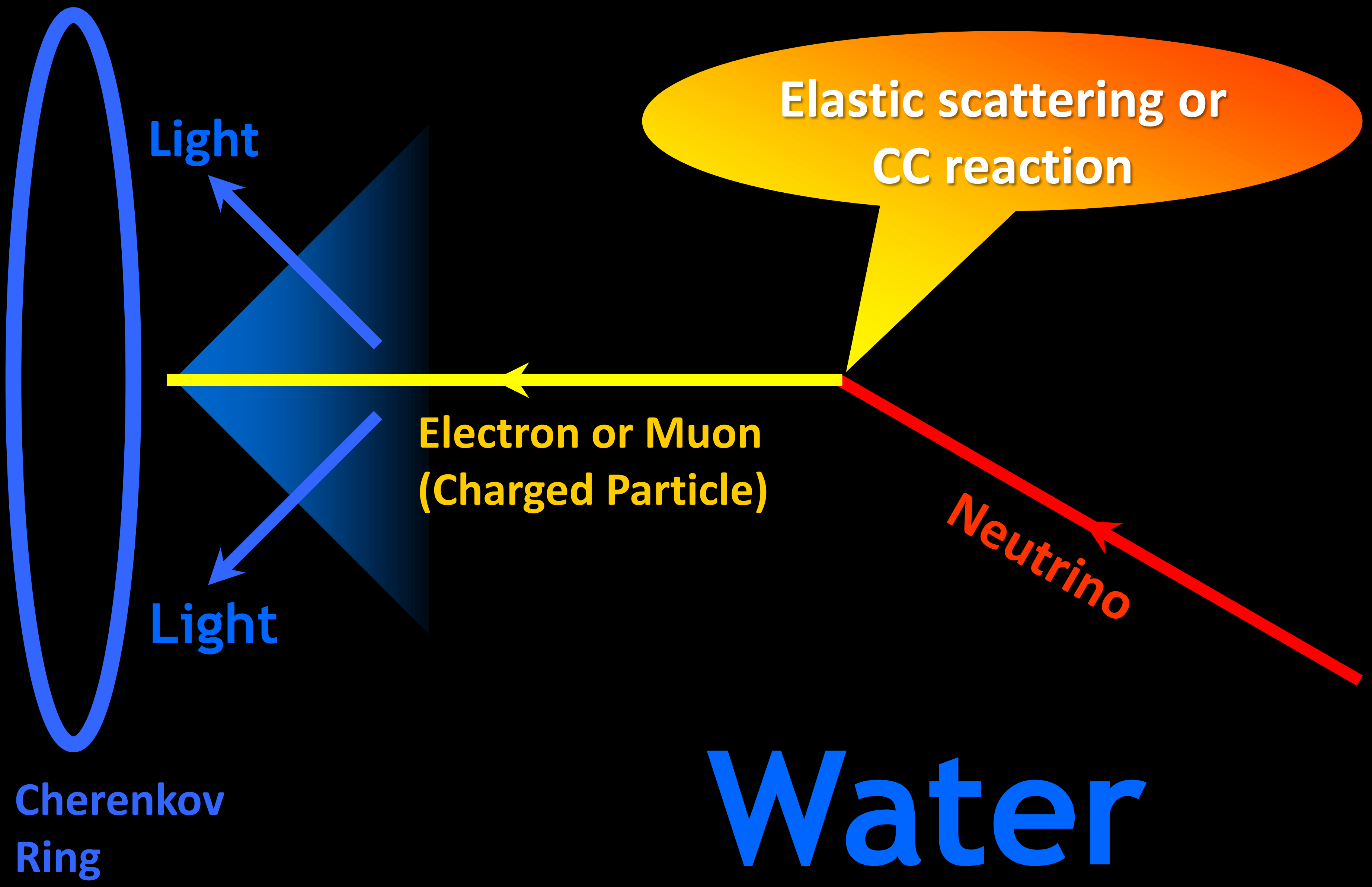


Ray Davis Jr.
(1914–2006)

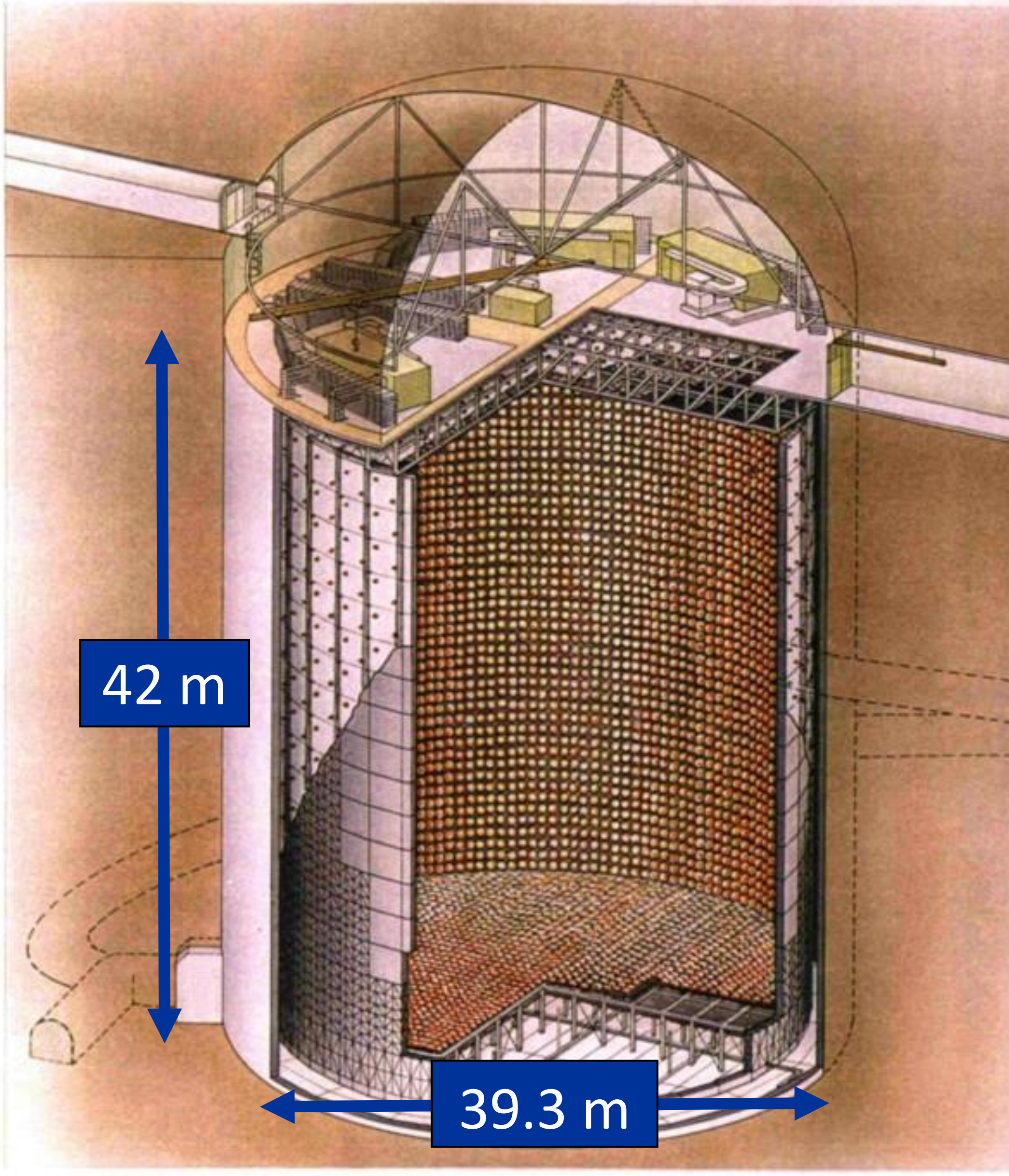
Masatoshi Koshiba
(*1926)

“for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos”

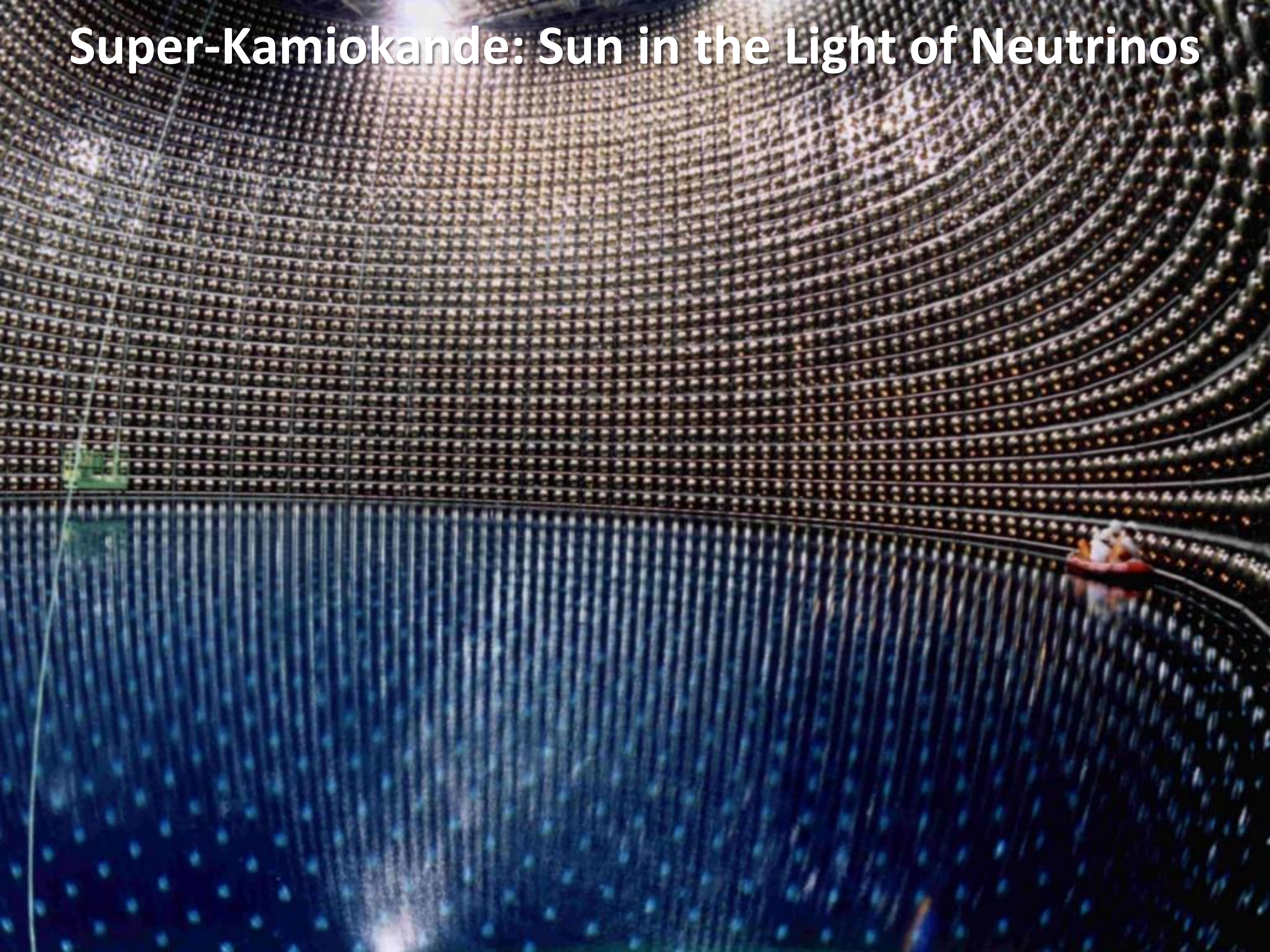
Cherenkov Effect



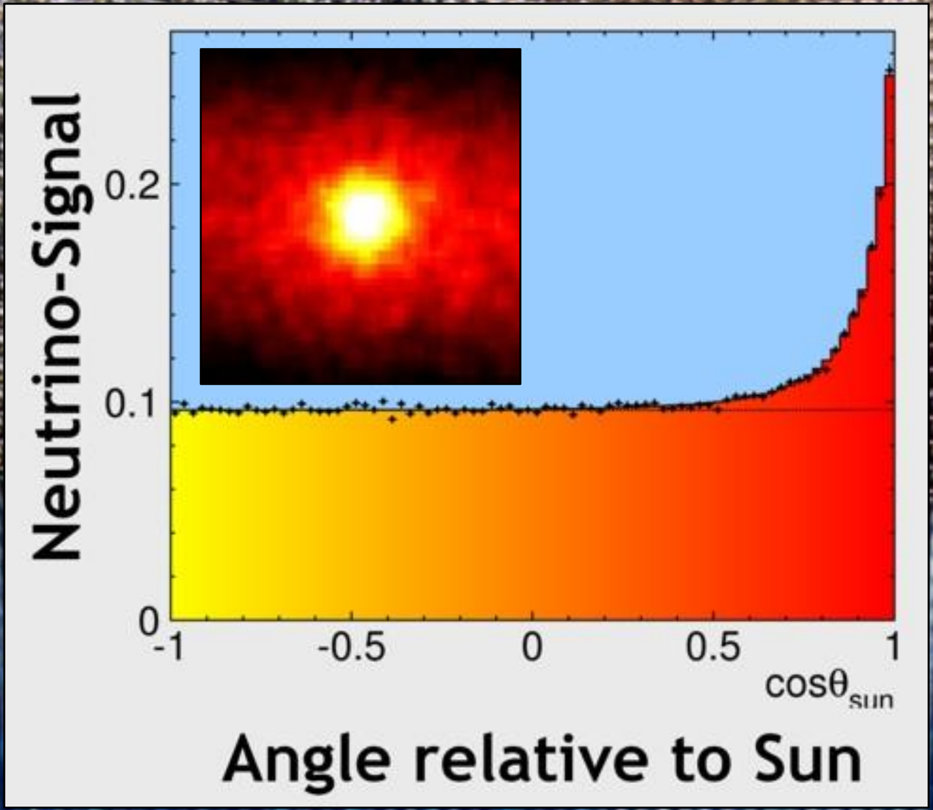
Super-Kamiokande Neutrino Detector (Since 1996)

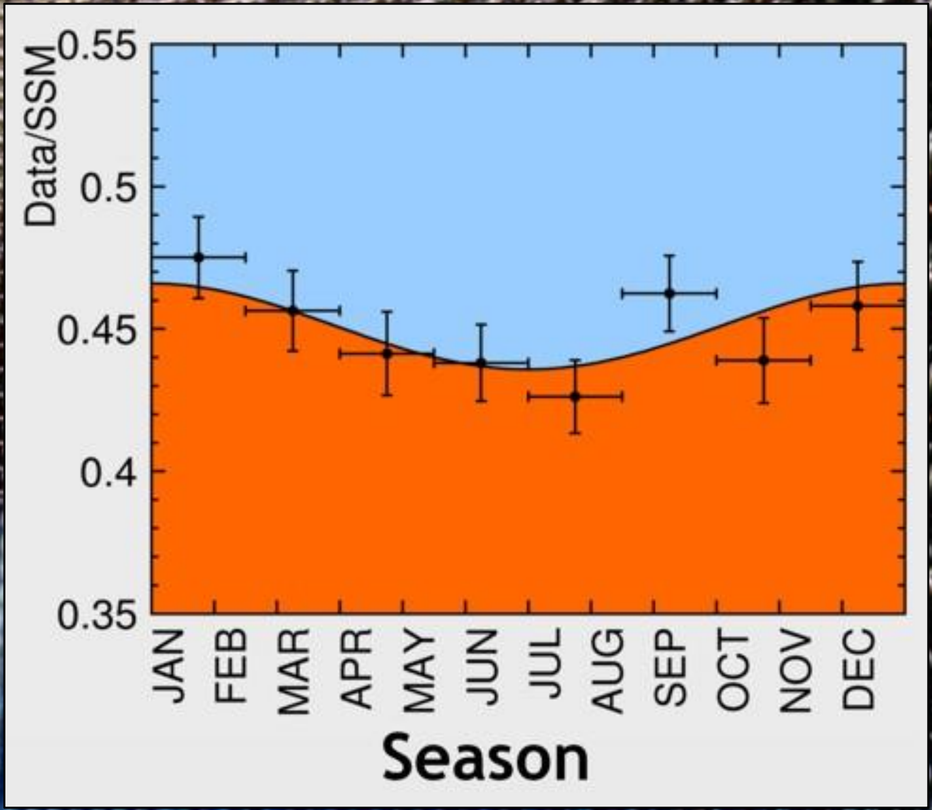


Super-Kamiokande: Sun in the Light of Neutrinos



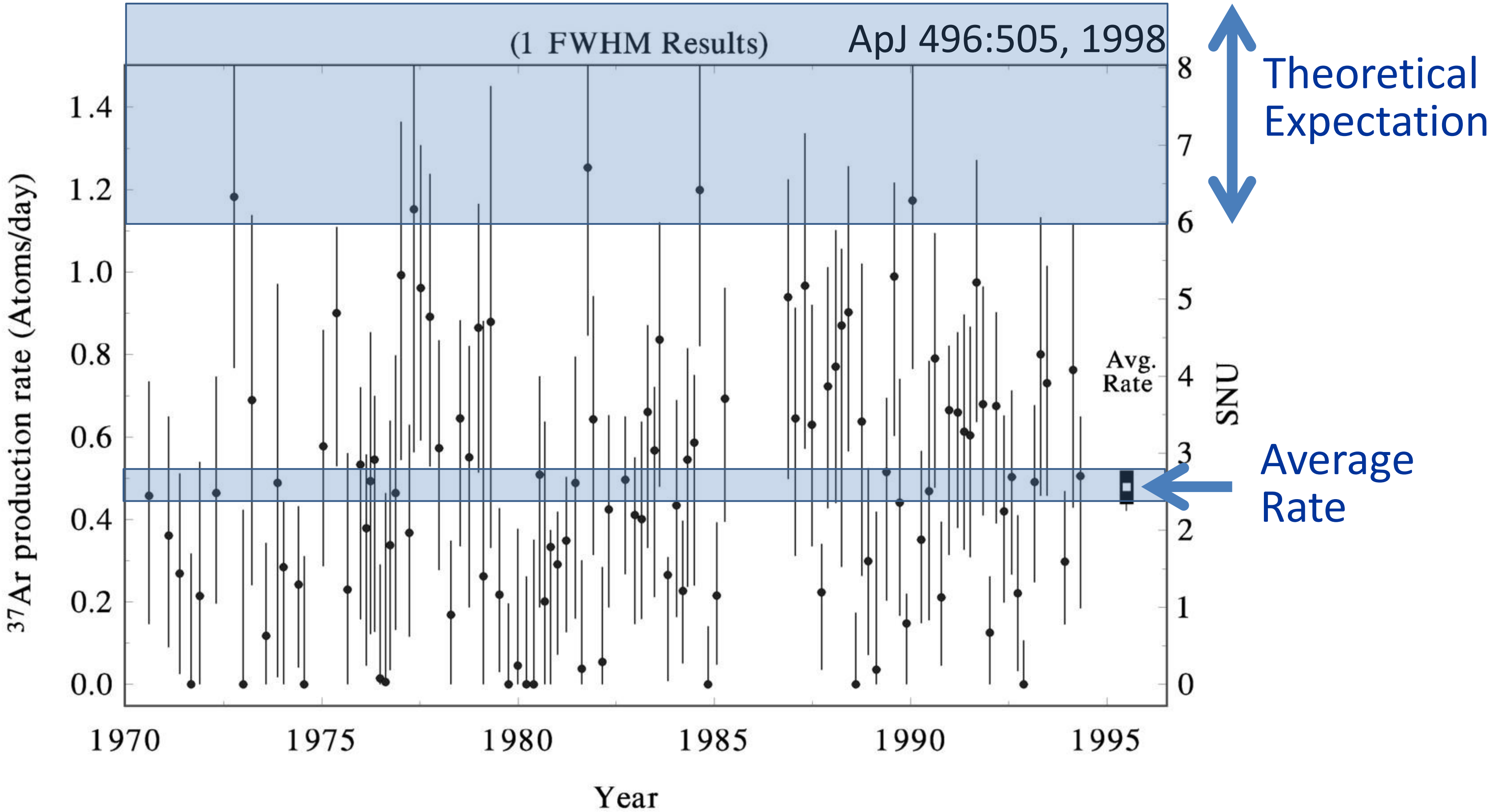
Super-Kamiokande: Sun in the Light of Neutrinos





ca. 60,000 solar neutrinos measured in Super-K (1996–2012)

Results of Chlorine Experiment (Homestake)



Average (1970–1994) $2.56 \pm 0.16_{stat} \pm 0.16_{sys}$ SNU

(SNU = Solar Neutrino Unit = 1 Absorption / sec / 10^{36} Atoms)

Theoretical Prediction 6–9 SNU

"Solar Neutrino Problem" since 1968

Neutrino Flavor Oscillations

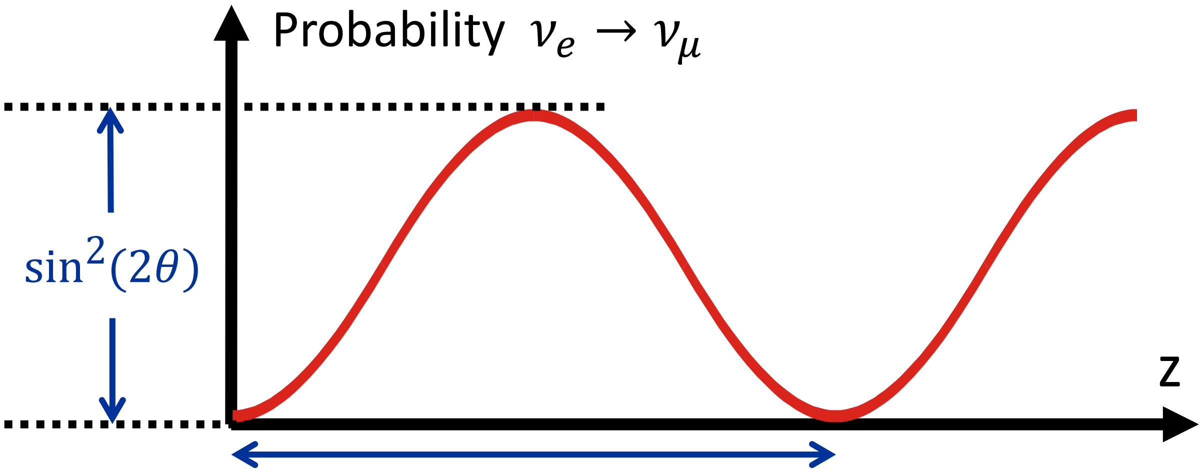
Two-flavor mixing $\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta \\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1 \\ \nu_2\end{pmatrix}$

Bruno Pontecorvo
(1913–1993)
Invented nu oscillations

Each mass eigenstate propagates as e^{ipz}

with $p = \sqrt{E^2 - m^2} \approx E - m^2/2E$

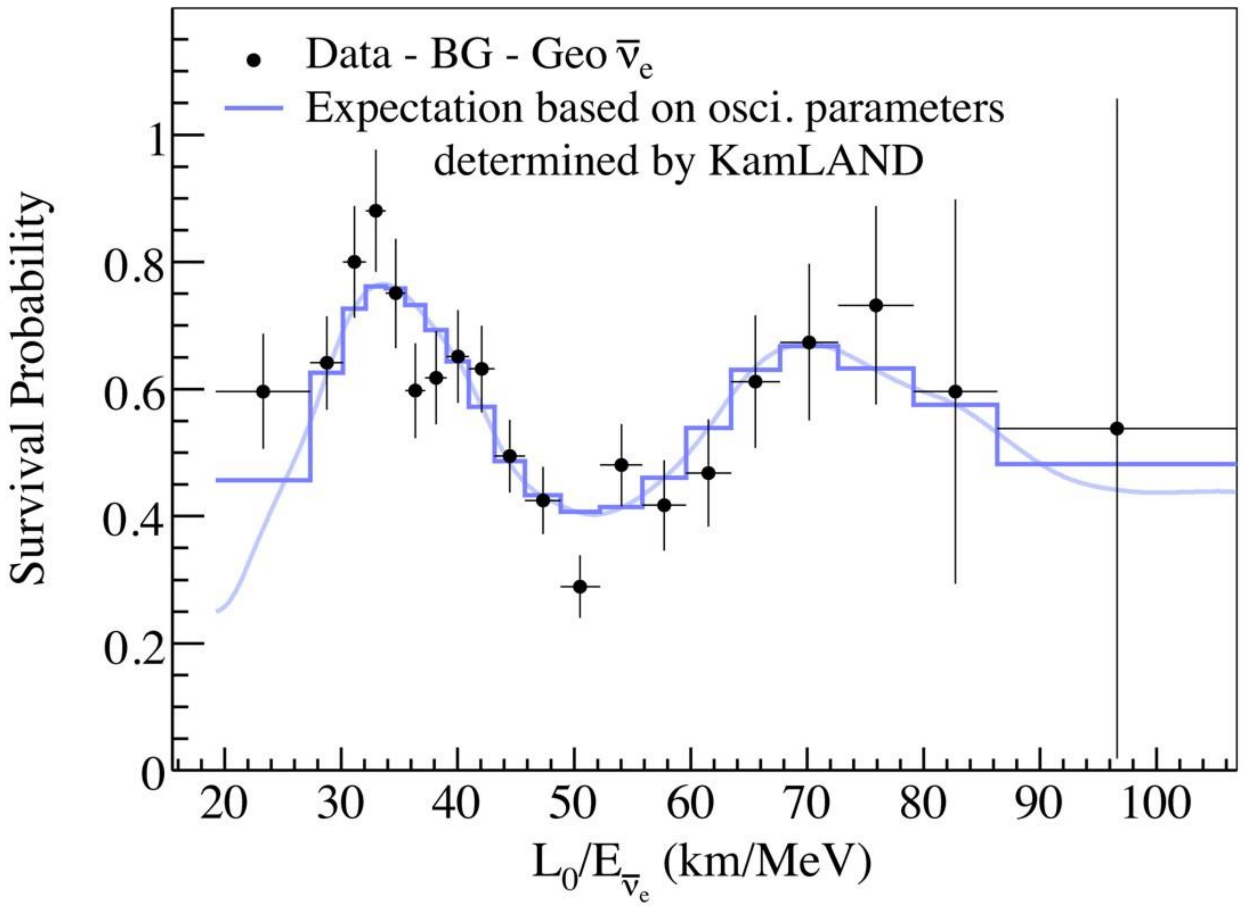
Phase difference $\frac{\delta m^2}{2E} z$ implies flavor oscillations

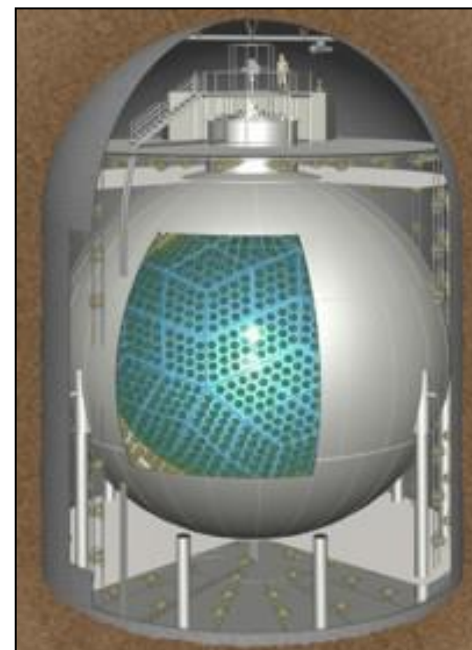


Oscillation Length $\frac{4\pi E}{\delta m^2} = 2.5\ \mathrm{m}\ \frac{E}{\mathrm{MeV}} \left(\frac{\mathrm{eV}}{\delta m}\right)^2$

Oscillation of Reactor Neutrinos at KamLAND (Japan)

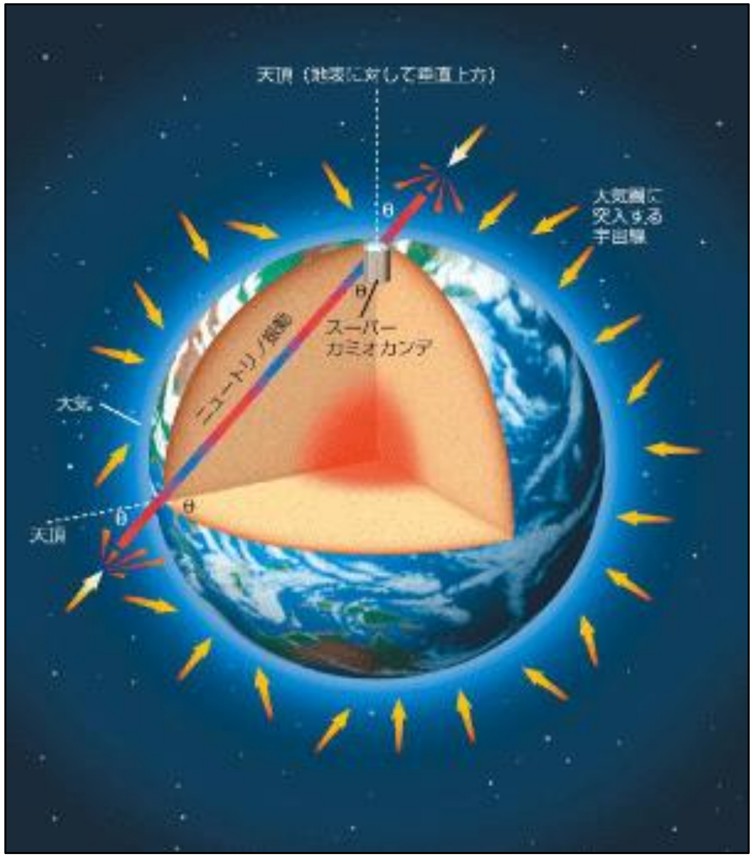
Oscillation pattern for anti-electron neutrinos from Japanese power reactors as a function of L/E

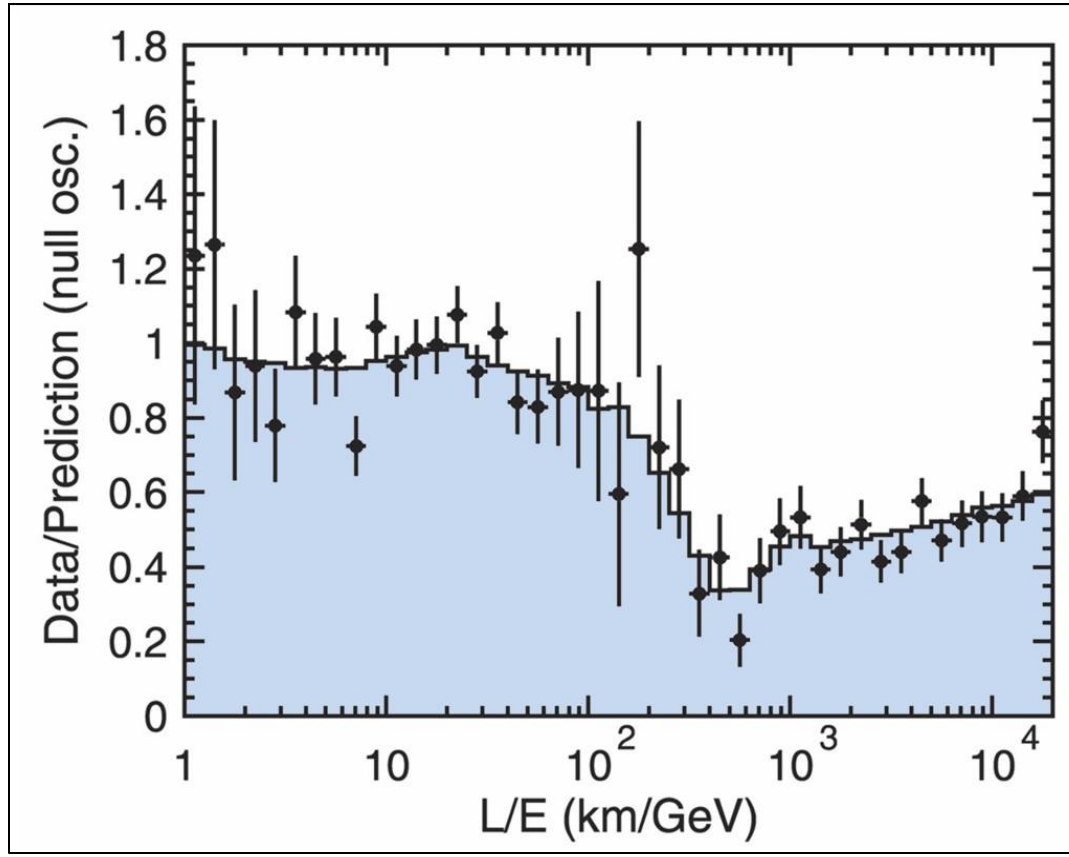




KamLAND Scintillator detector (1000 t)

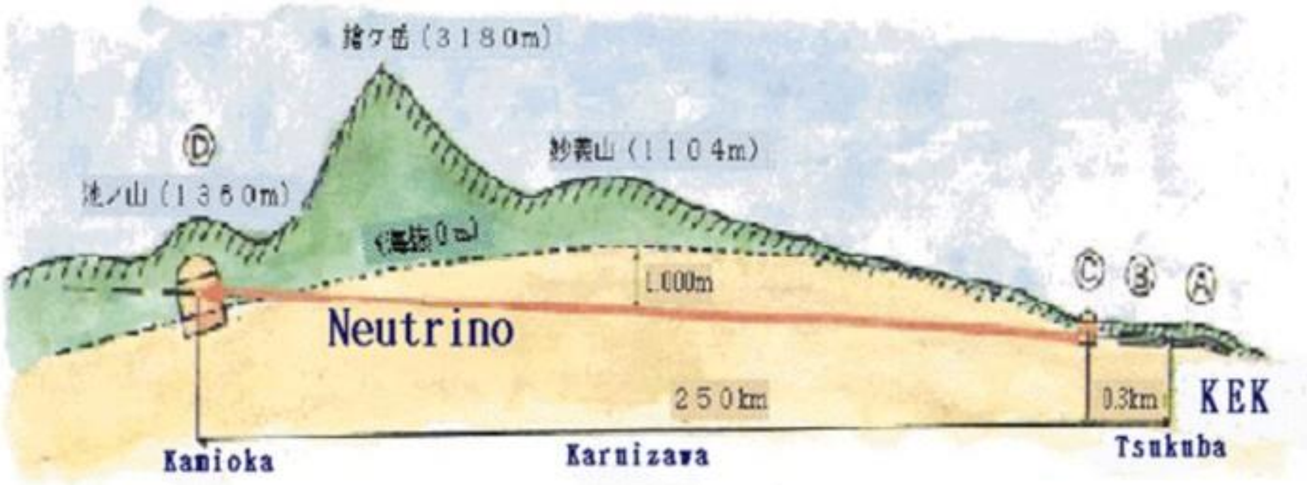
Atmospheric Neutrino Oscillations (since 1998)

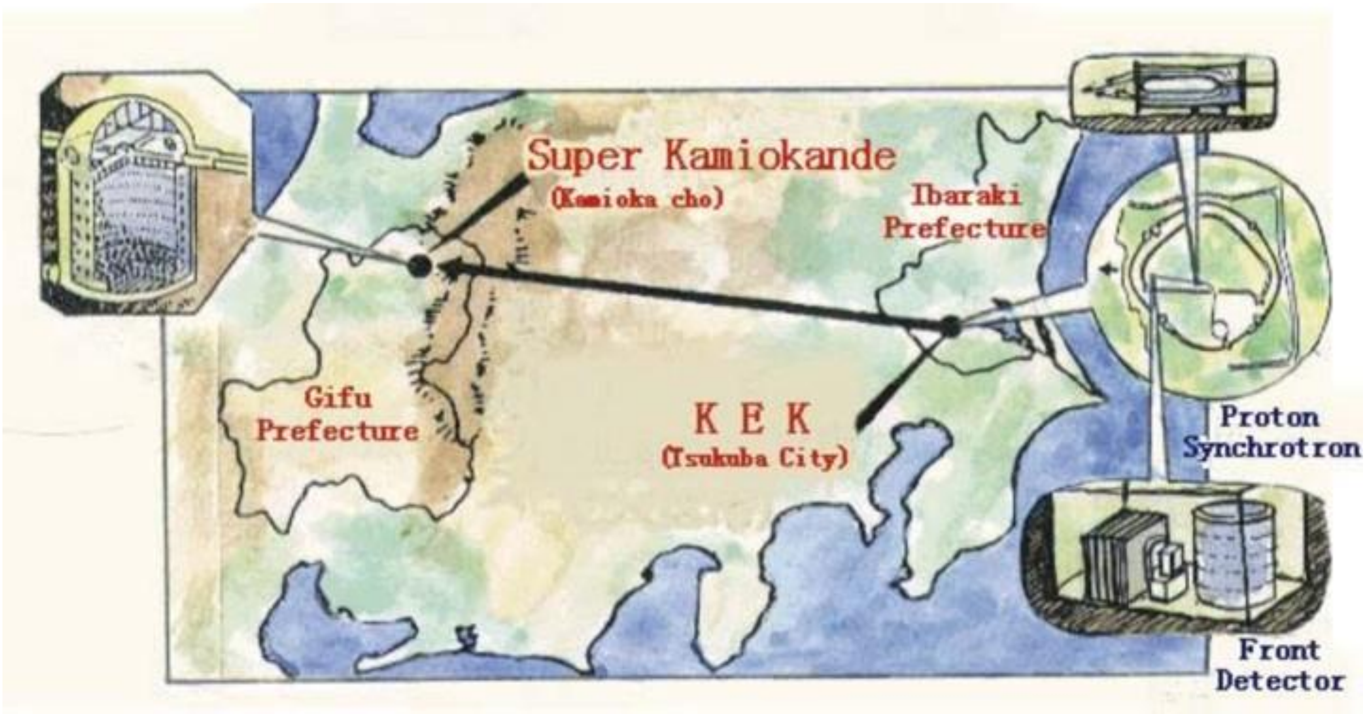




Atmospheric neutrino oscillations show characteristic L/E variation

Long-Baseline (LBL) Experiments



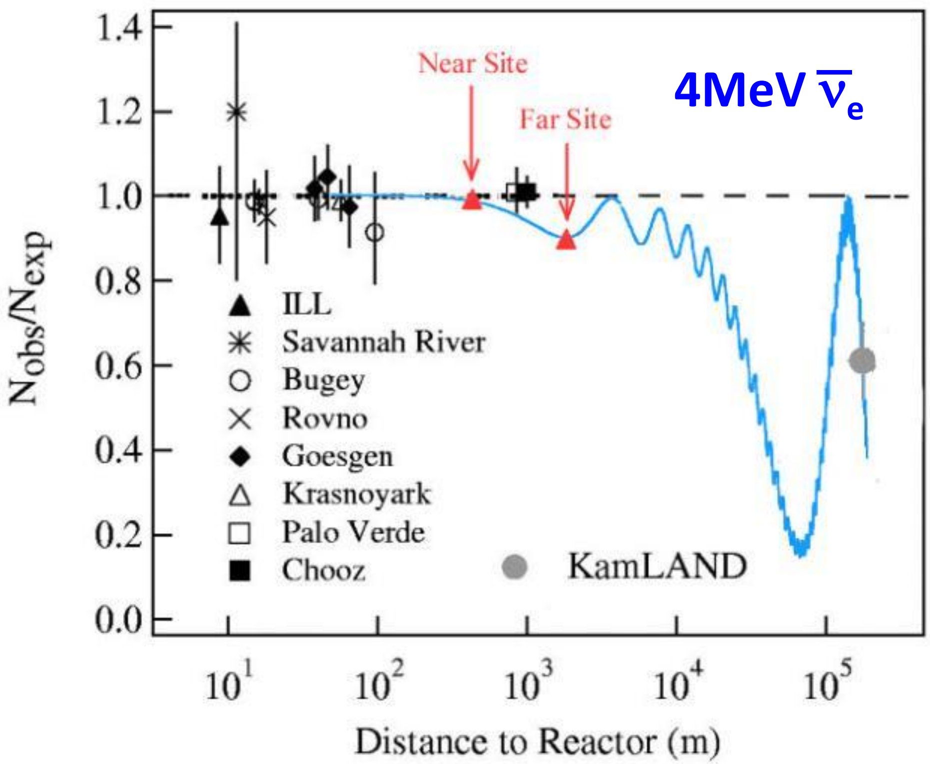


K2K Experiment (KEK to Kamiokande) measures precise neutrino oscillation parameters.

Since then other LBL Experiments:

- Minos (US)
- Opera (Europe)
- T2K (Japan)
- Nova (US)
  - construction
- LBNE/LBNO
  - future projects

Θ_{13} from Reactor Experiments (2012)



$\sin^2 2\theta_{13}$ = 0.089 ± 0.010 (stat) ± 0.005 (syst) Daya Bay (China)

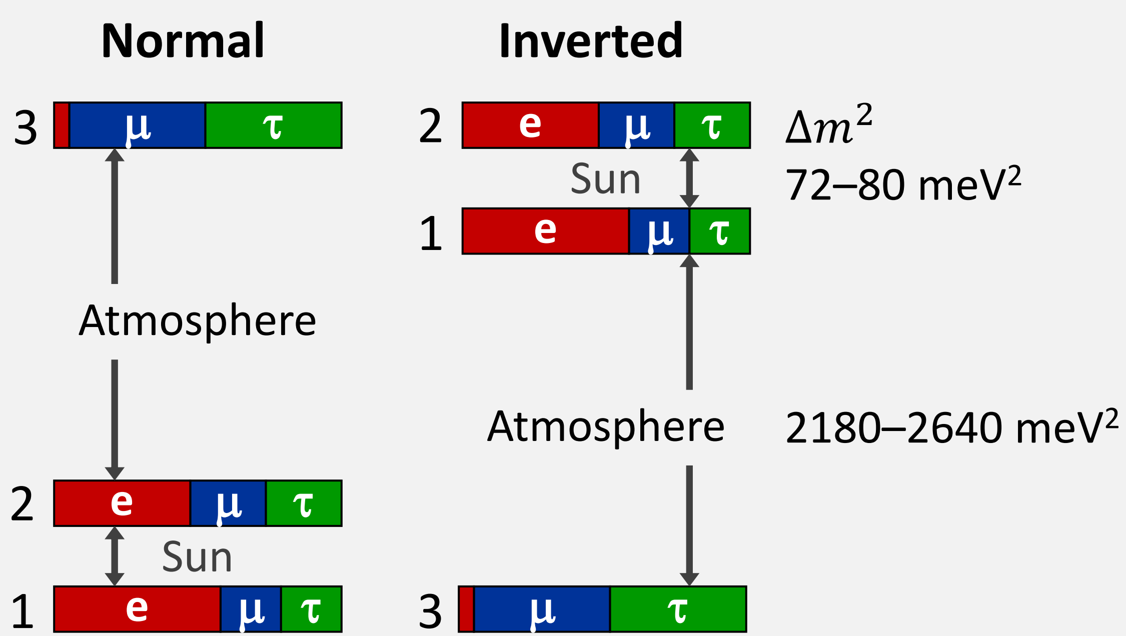
0.113 ± 0.013 (stat) ± 0.019 (syst) Reno (Korea)

0.086 ± 0.041 (stat) ± 0.030 (syst) Double Chooz (Europe)

Three-Flavor Neutrino Parameters

Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ (Euler angles for 3D rotation), $c_{ij} = \cos\theta_{ij}$,
a CP-violating "Dirac phase" δ, and two "Majorana phases" α_2 and α_3

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\substack{39^\circ < \theta_{23} < 53^\circ \\ \text{Atmospheric/LBL-Beams}}} \underbrace{\begin{pmatrix}c_{13} & 0 & e^{-i\delta}s_{13}\\ 0 & 1 & 0\\ -e^{i\delta}s_{13} & 0 & c_{13}\end{pmatrix}}_{\substack{7^\circ < \theta_{13} < 11^\circ \\ \text{Reactor}}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\substack{33^\circ < \theta_{12} < 37^\circ \\ \text{Solar/KamLAND}}} \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\frac{\alpha_2}{2}} & 0\\ 0 & 0 & e^{i\frac{\alpha_3}{2}}\end{pmatrix}}_{\substack{\text{Relevant for} \\ 0\nu2\beta\text{ decay}}} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



Tasks and Open Questions

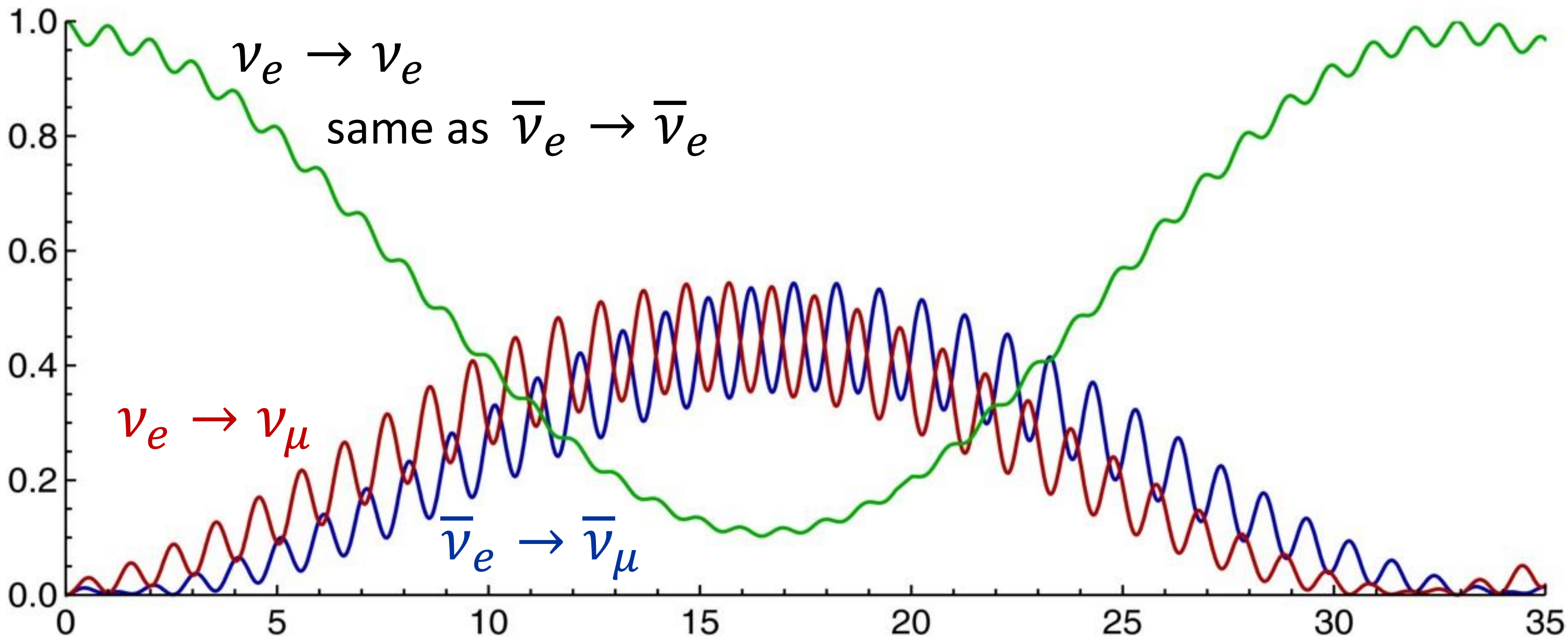
- Precision for all angles
- CP-violating phase δ?
- Mass ordering? (normal vs inverted)
- Absolute masses? (hierarchical vs degenerate)
- Dirac or Majorana?

Antineutrino Oscillations Different from Neutrinos?

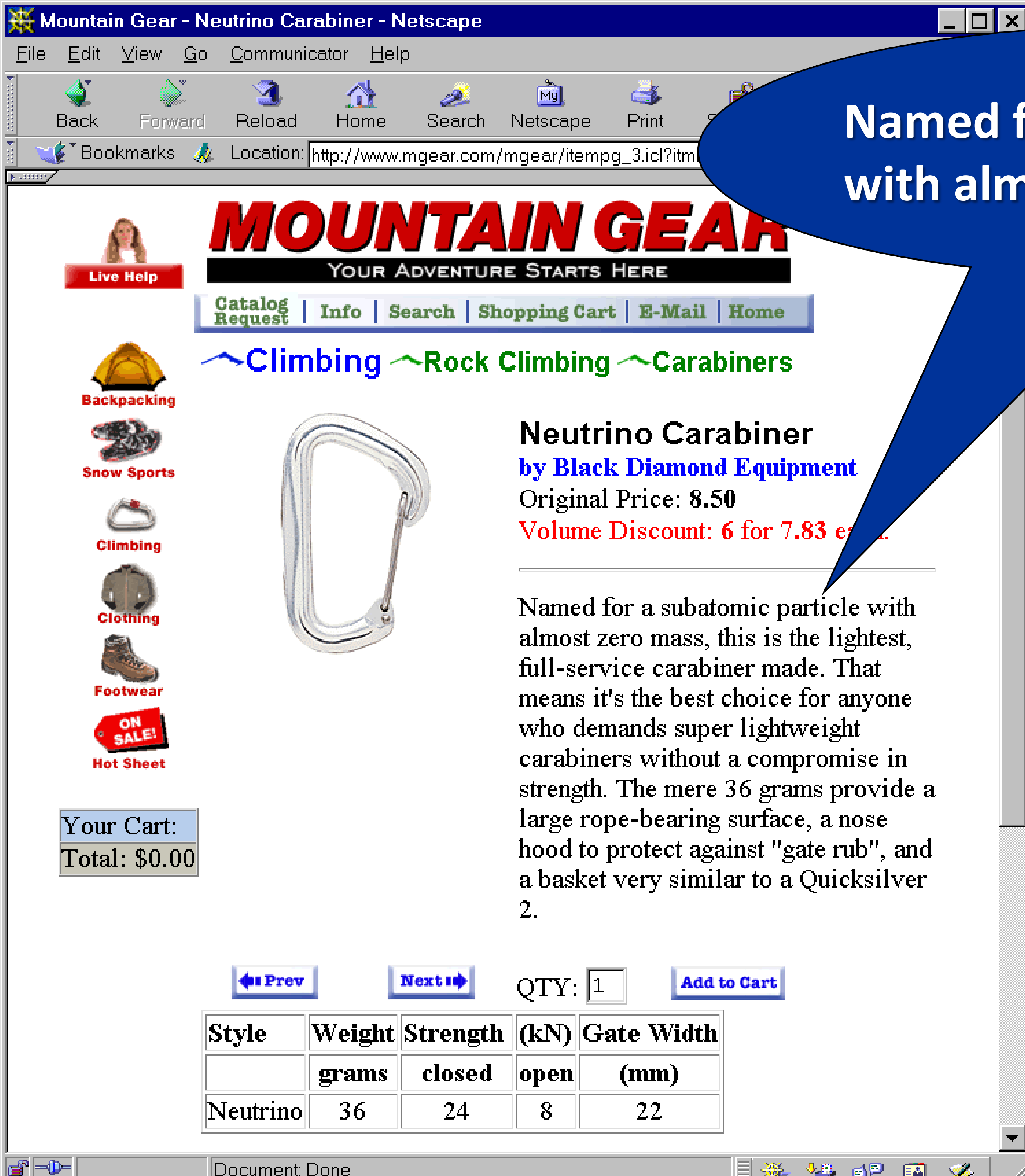
$$\nu_e = c_{12}c_{13}\,\nu_1 + s_{12}c_{13}\,\nu_2 + s_{13}e^{-i\delta}\,\nu_3$$

$$\overline{\nu}_e = c_{12}c_{13}\,\overline{\nu}_1 + s_{12}c_{13}\,\overline{\nu}_2 + s_{13}e^{+i\delta}\,\overline{\nu}_3$$

Dirac phase causes different 3-flavor oscillations for neutrinos and antineutrinos



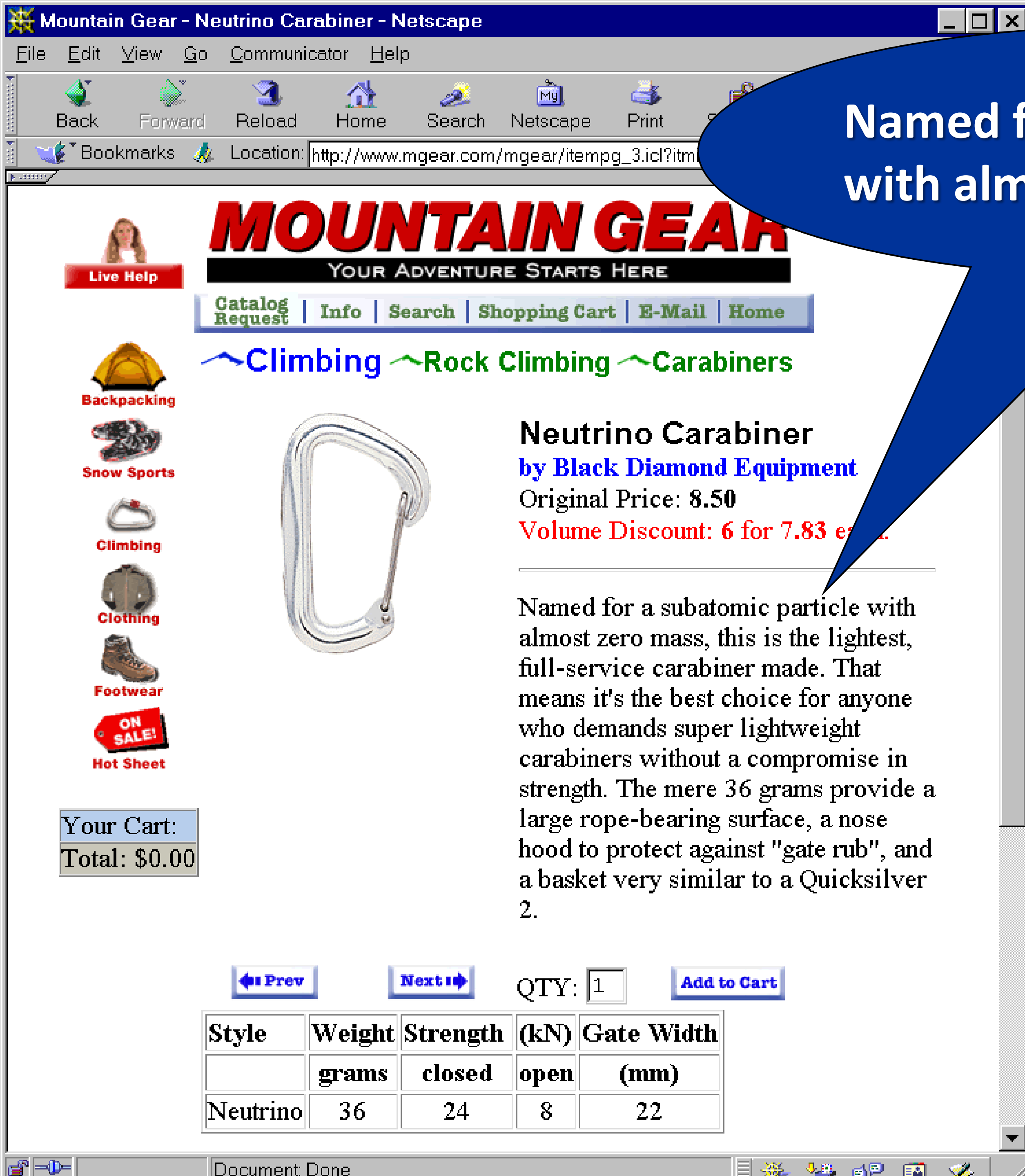
Distance [1000 km] for E = 1 GeV



Named for a subatomic particle with almost zero mass, …

Greek “nu”

Named for a subatomic particle with almost zero mass, …

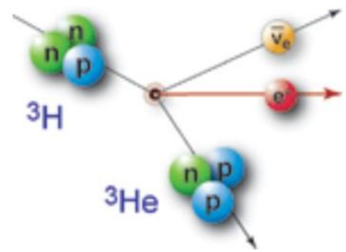


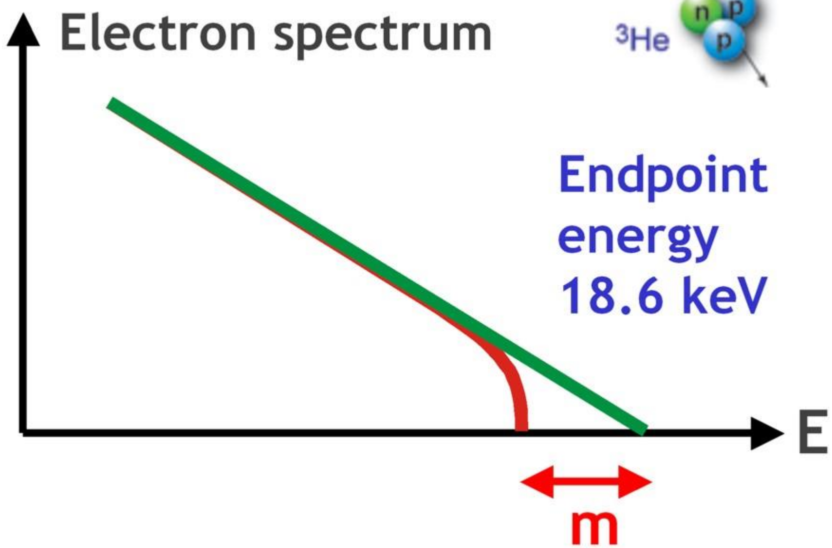
Now also in color

"Weighing" Neutrinos with KATRIN

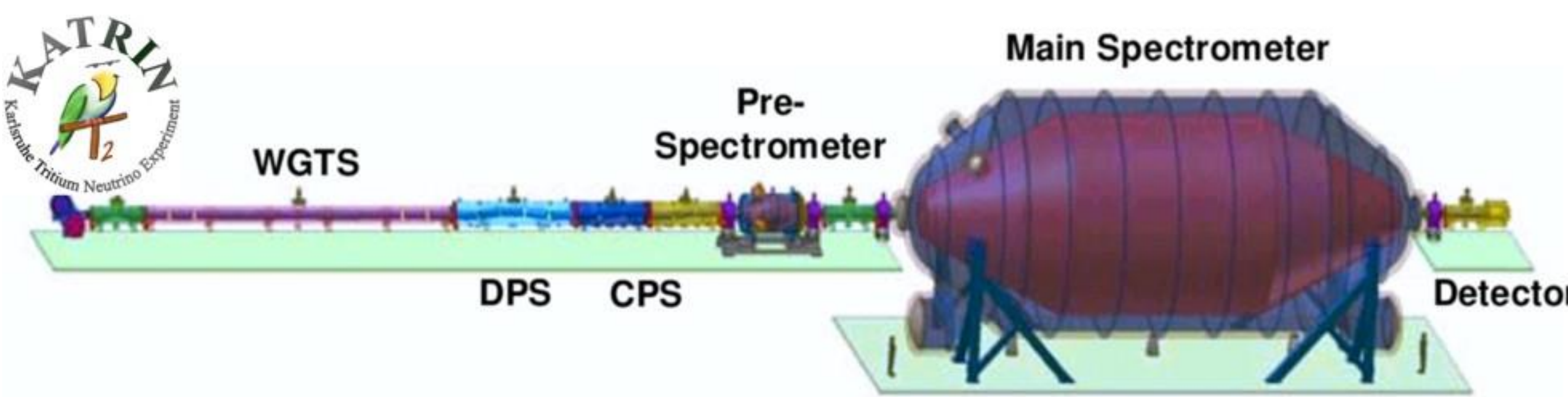
Tritium β-decay

$^3H \rightarrow {}^3He + e^- + \overline{\nu}_e$

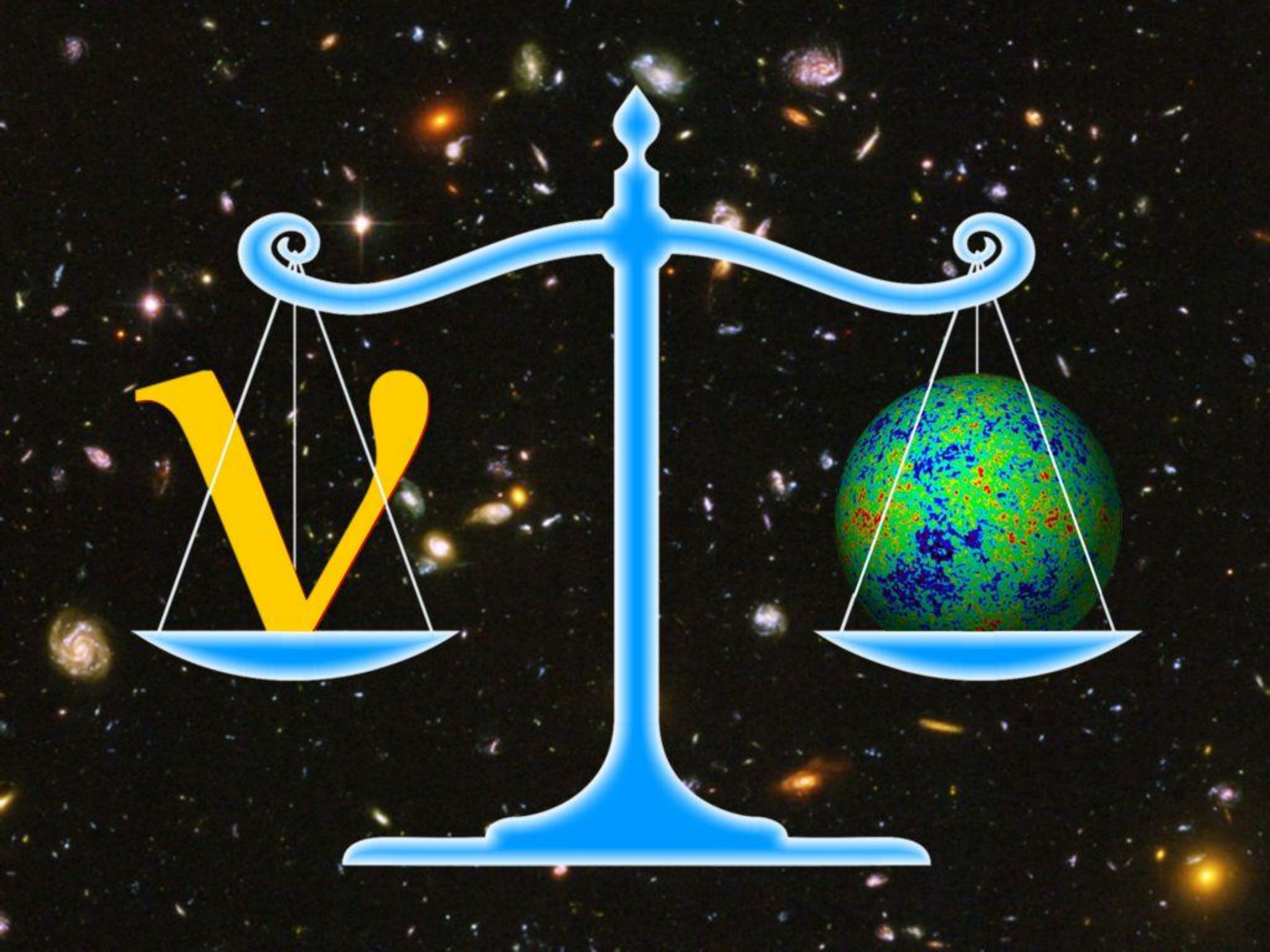




- Sensitive to common mass scale m for all flavors because of small mass differences from oscillations
- Best limit from Mainz und Troitsk
  m < 2.2 eV (95% CL)
- KATRIN can reach 0.2 eV
- Under construction
- Data taking to begin 2015/16
- http://www.katrin.kit.edu



KATRIN Ante Portas (25 Nov 2006)



Cosmological Limit on Neutrino Masses

Cosmic neutrino "sea" ~112 cm^{-3} neutrinos + anti-neutrinos per flavor

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{93\ \mathrm{eV}} < 0.25$$

$\sum m_\nu \lesssim 20\ \mathrm{eV}$ For all stable flavors

JETP Lett. 4 (1966) 120

REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

Low-accuracy experimental estimates of the rest mass of the neutrino [1] yield $m(\nu_e) < 200\ \mathrm{eV/c^2}$ for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6\ \mathrm{eV/c^2}$ for the muonic neutrino.

Cosmological considerations connected with the hot model of the Universe [2] make it possible to strengthen greatly the second inequality. Just as in the paper by Ya. B. Zel'dovich and Ya. A. Smorodinskii [3], let us consider the gravitational effect of the neutrinos on the dynamics of the expanding Universe. The age of the known astronomical objects is not smaller than 5×10^9 years, and Hubble's constant H is not smaller than 75 km/sec-Mparsec $= (13 \times 10^9\ \text{years})^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time [1)]

$$\rho < 2 \times 10^{-28}\ \mathrm{g/cm^3}.$$

What is wrong with neutrino dark matter?

Galactic Phase Space ("Tremaine-Gunn-Limit")

Maximum mass density of a degenerate Fermi gas

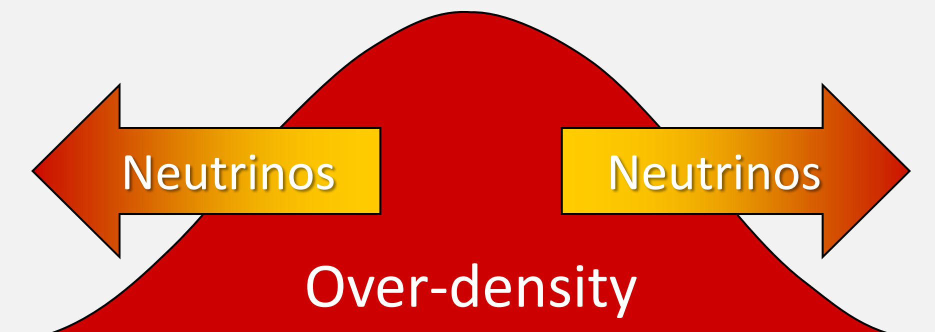
$$\rho_{\max} = m_\nu \underbrace{\frac{p_{\max}^3}{3\pi^2}}_{n_{\max}} = \frac{m_\nu \left(m_\nu v_{\rm escape}\right)^3}{3\pi^2}$$

Spiral galaxies
m_ν > 20–40 eV

Dwarf galaxies
m_ν > 100–200 eV

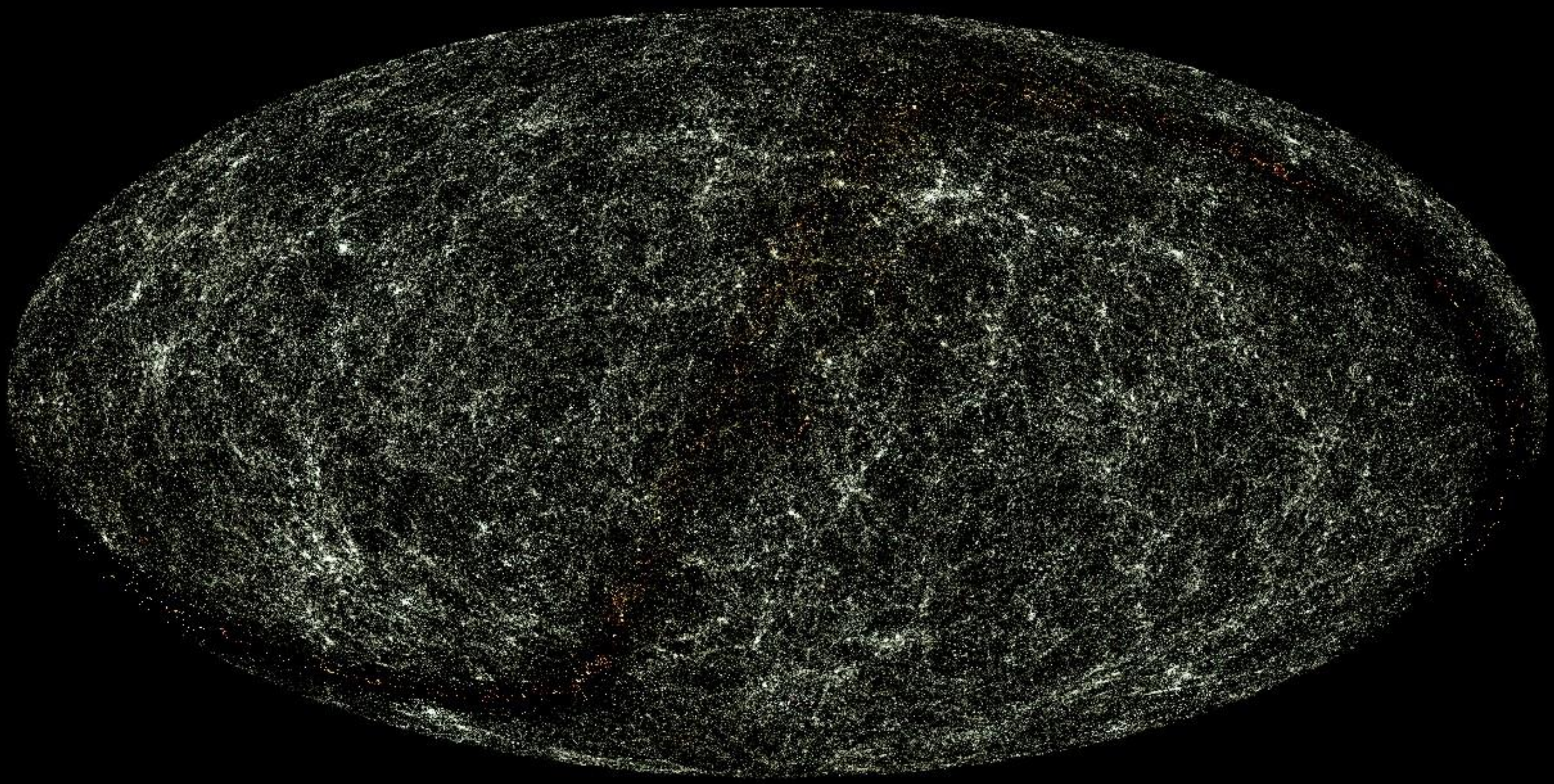
Neutrino Free Streaming (Collisionless Phase Mixing)

- At T < 1 MeV neutrino scattering in early universe is ineffective
- Stream freely until non-relativistic
- Wash out density contrasts on small scales



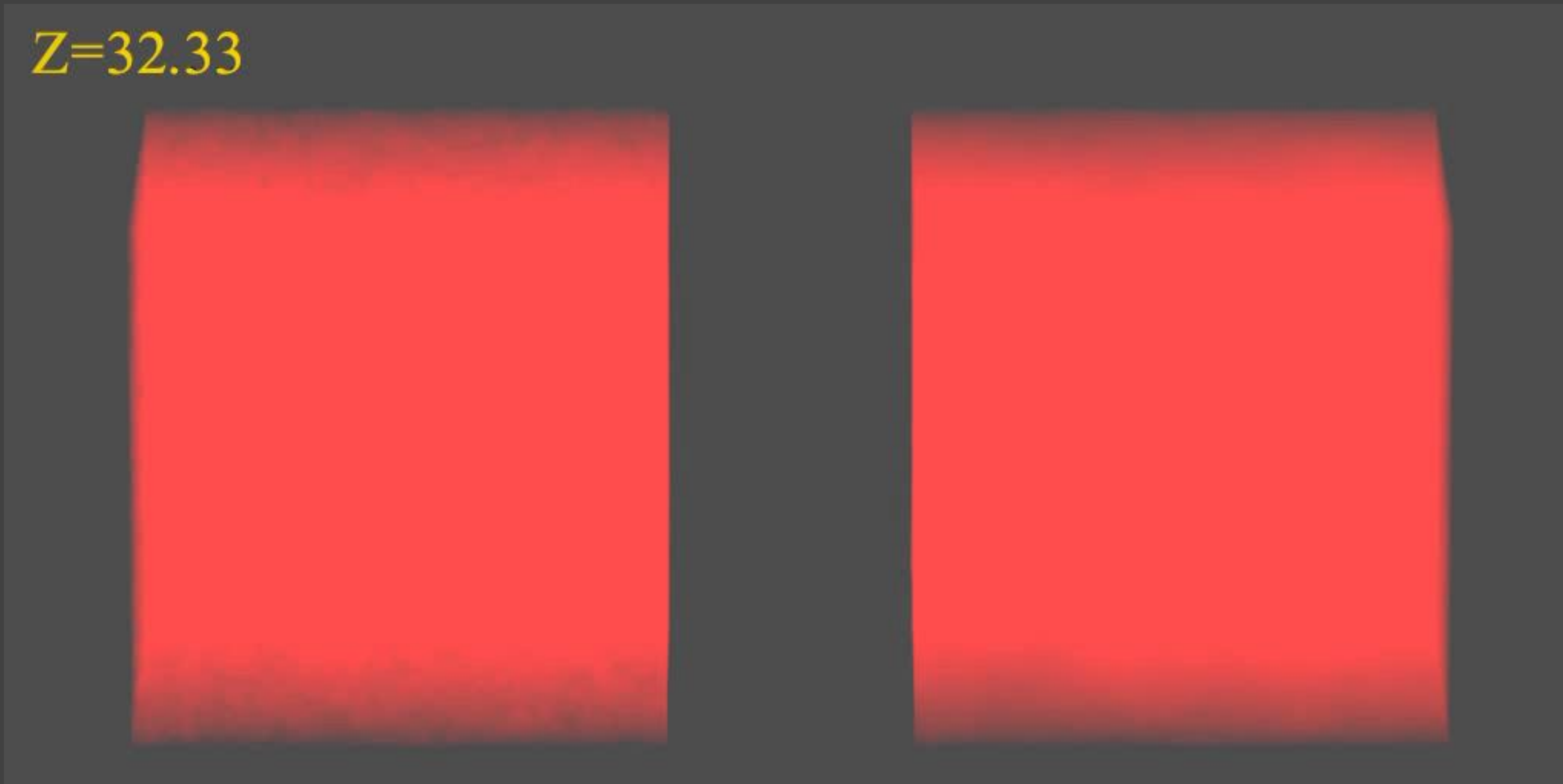
- Neutrinos are "Hot Dark Matter"
- Ruled out by structure formation

Sky Map of Galaxies (XMASS XSC)



http://spider.ipac.caltech.edu/staff/jarrett/2mass/XSC/jarrett_allsky.html

Structure Formation with Hot Dark Matter

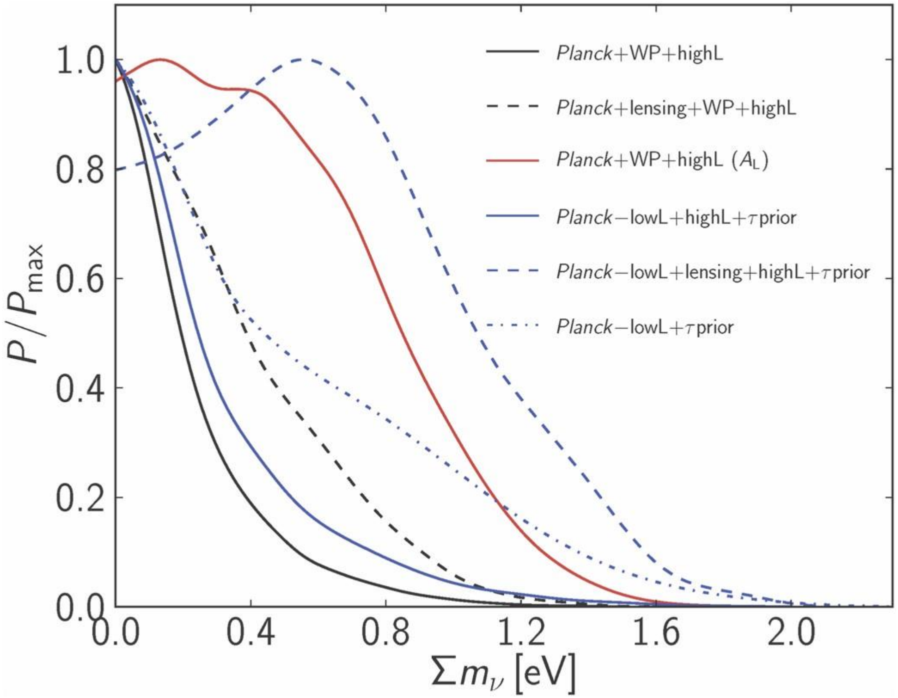


Standard ΛCDM Model Neutrinos with Σm_ν = 6.9 eV

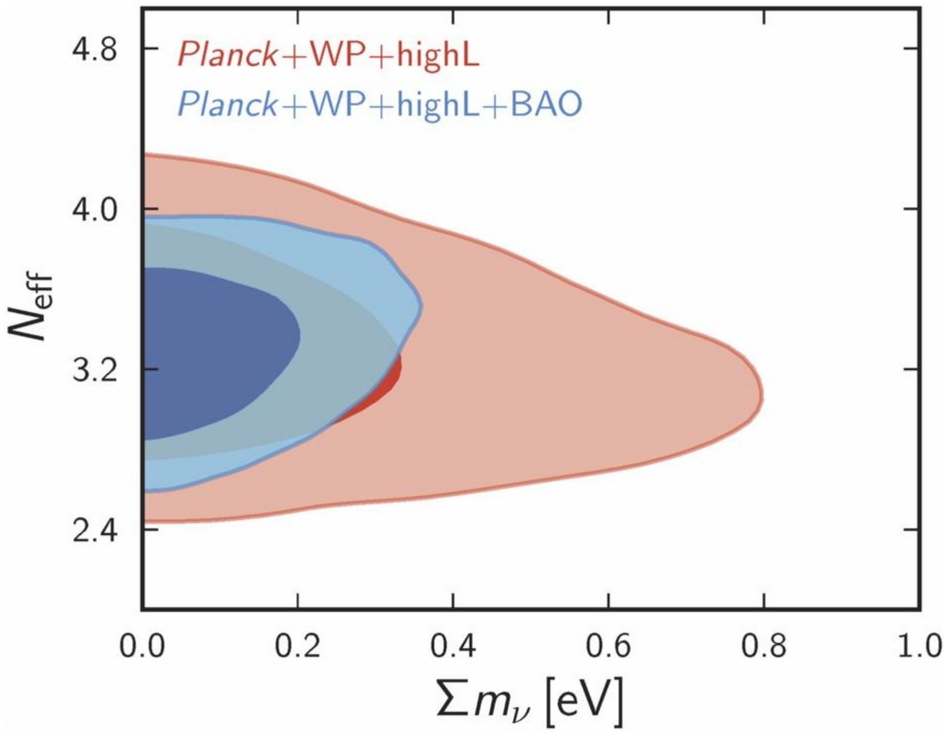
Structure fromation simulated with Gadget code
Cube size 256 Mpc at zero redshift
Troels Haugbølle, http://users-phys.au.dk/haugboel

Neutrino Mass Limits Post Planck (2013)

CMB alone constraining Σm_ν



CMB + BAO constraining Σm_ν + N_{eff}

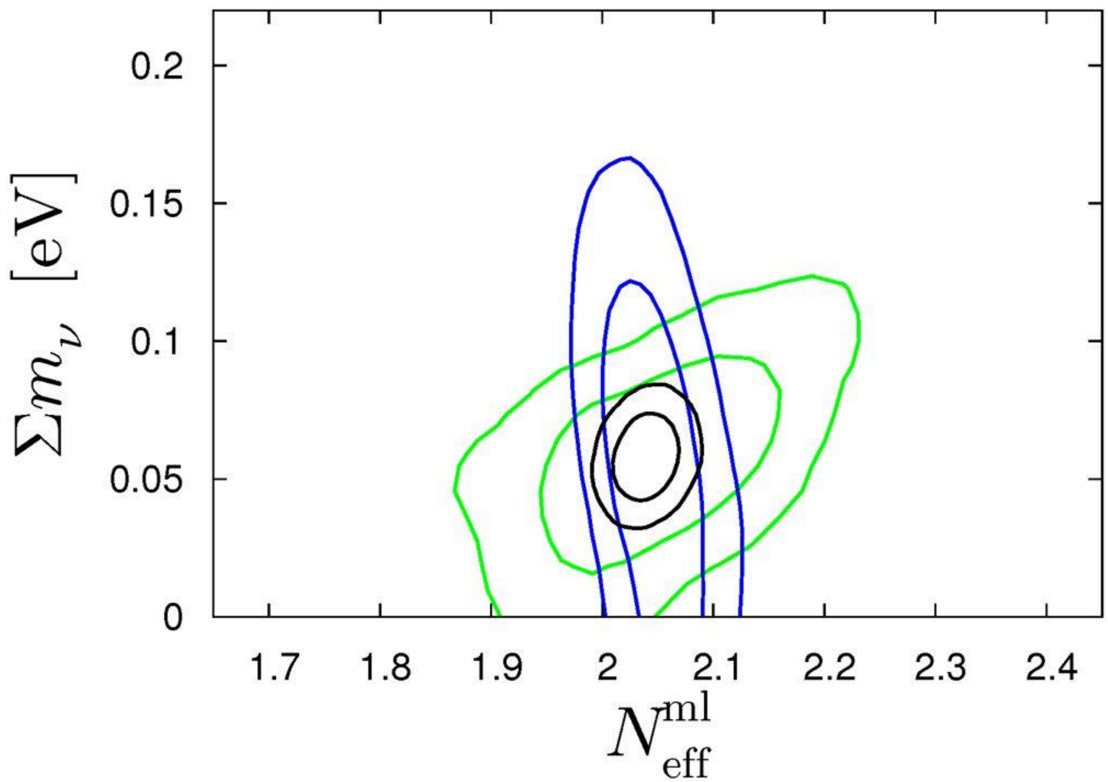


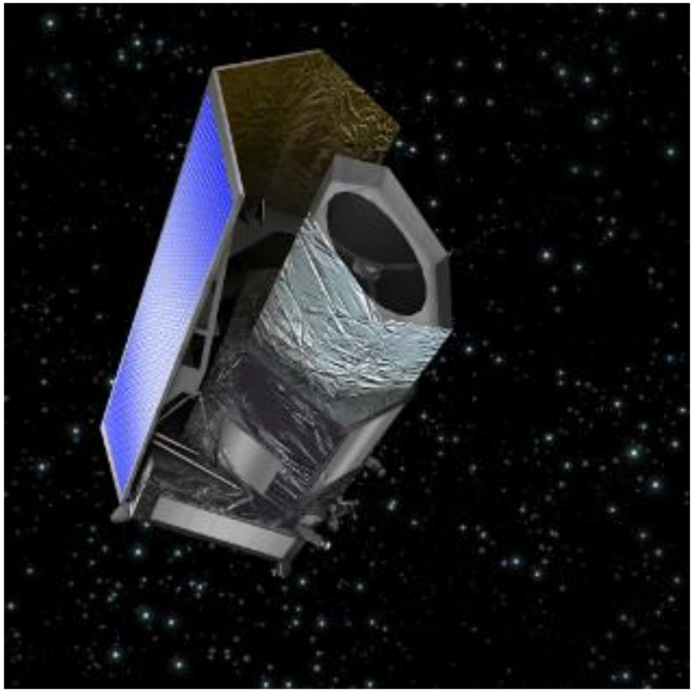
CMB + BAO limit: Σm_ν < 0.23 eV (95% CL)

Ade et al. (Planck Collaboration), arXiv:1303.5076

Future Cosmological Neutrino Mass Sensitivity

Pin down the neutrino mass in the sky!





ESA's Euclid satellite to be launched in 2020
Precision measurement of the universe out to redshift of 2

Basse, Bjælde, Hamann, Hannestad & Wong, arXiv:1304.2321:
Dark energy and neutrino constraints from a future EUCLID-like survey

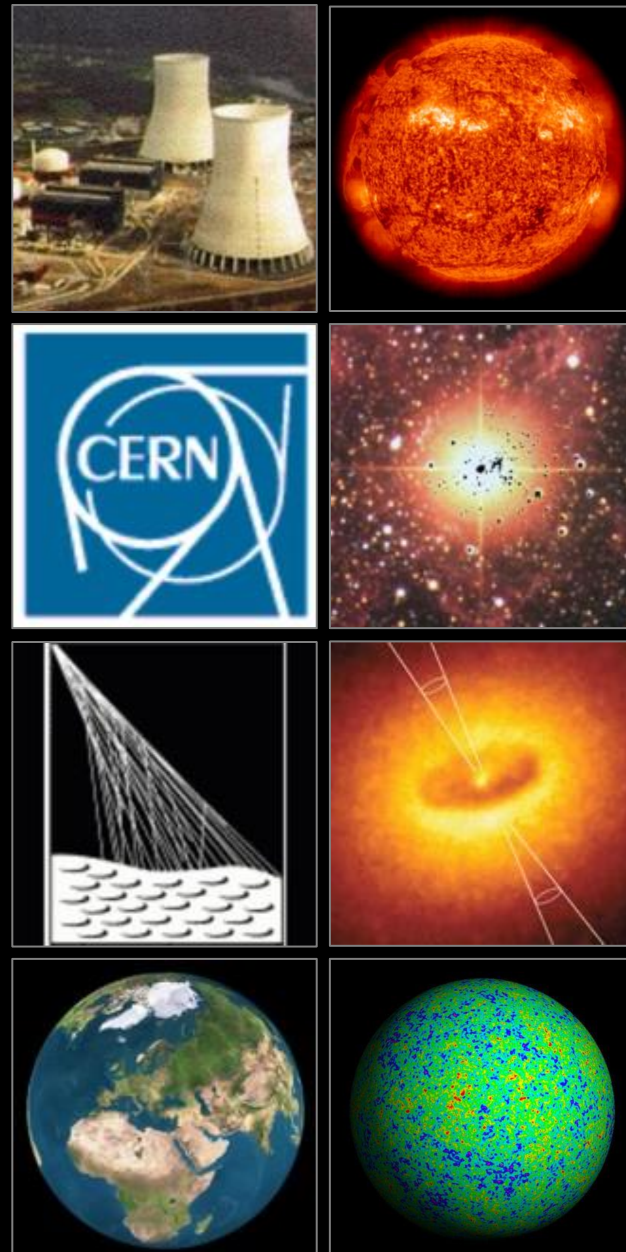
Neutrinos as Astrophysical Messengers

✓ Nuclear Reactors

✓ Particle Accelerators

✓ Earth Atmosphere (Cosmic Rays)

✓ Earth Crust (Natural Radioactivity)



Sun ✓

Supernovae (Stellar Collapse)
SN 1987A ✓

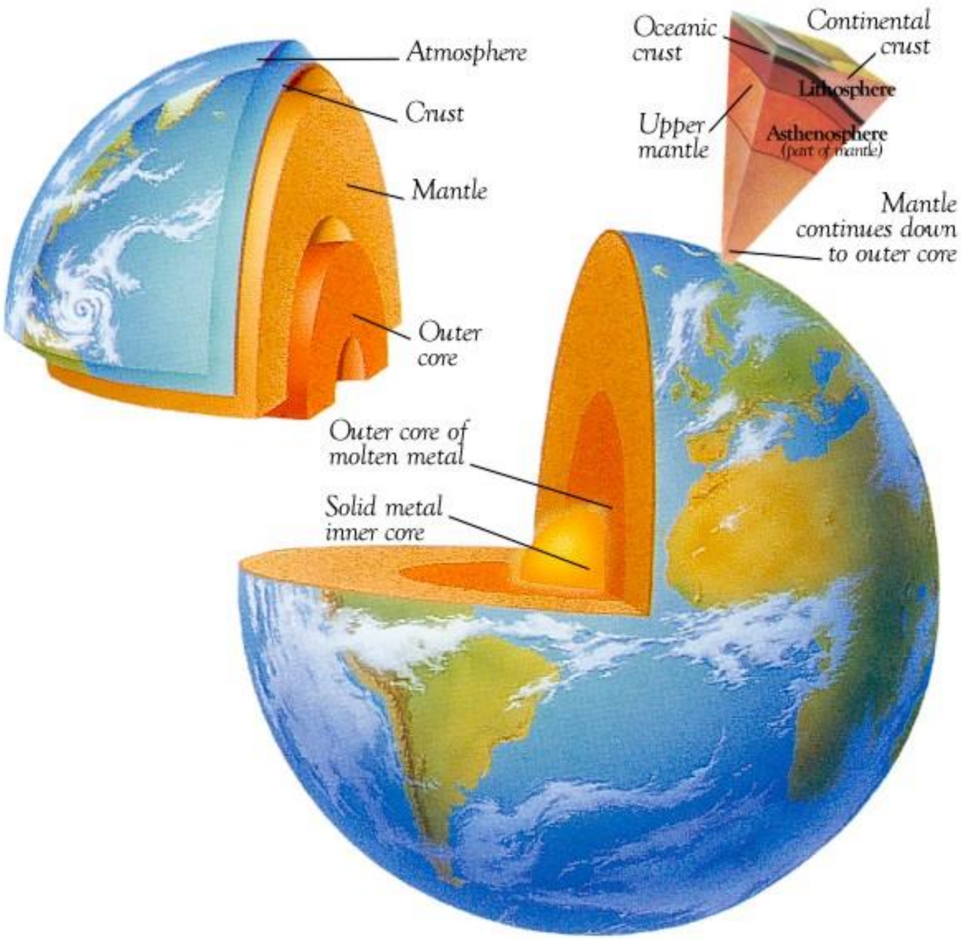
Astrophysical Accelerators ✓

Cosmic Big Bang (Today 330 ν/cm^3)
Indirect Evidence

Geo Neutrinos: What is it all about?

We know surprisingly little about the Earth's interior

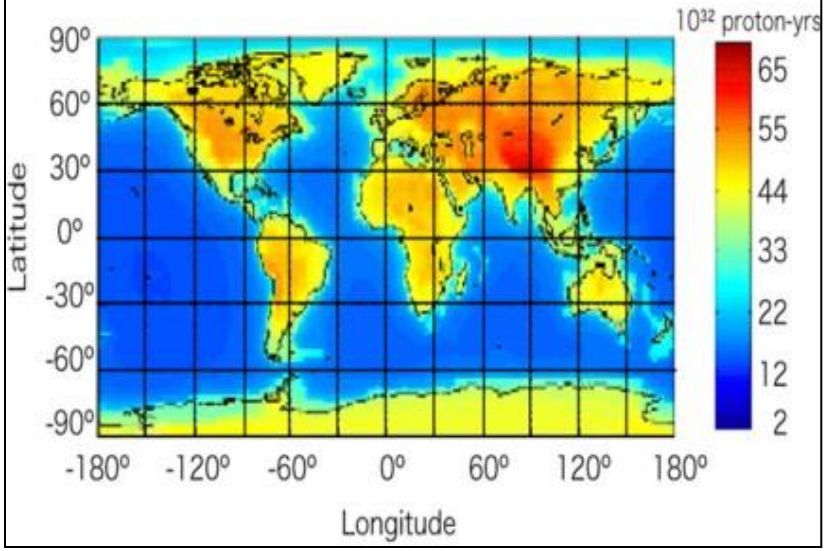
- Deepest drill hole ~ 12 km
- Samples of crust for chemical analysis available (e.g. vulcanoes)
- Reconstructed density profile from seismic measurements
- Heat flux from measured temperature gradient 30–44 TW (Expectation from canonical BSE model ~ 19 TW from crust and mantle, nothing from core)



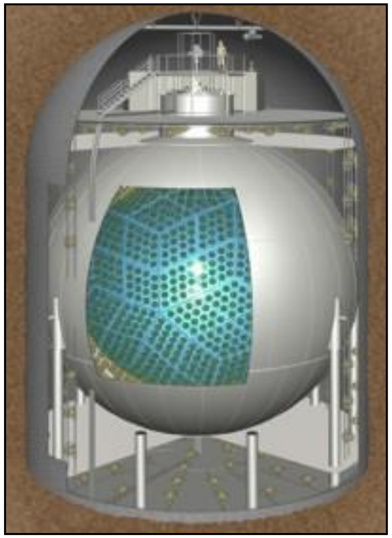
- Neutrinos escape unscathed
- Carry information about chemical composition, radioactive energy production or even a hypothetical reactor in the Earth's core

Geo Neutrinos

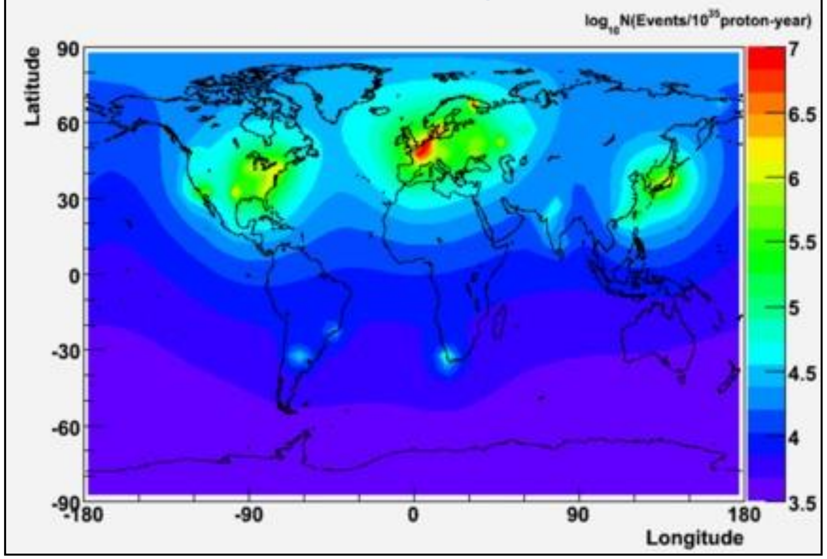
Expected Geoneutrino Flux

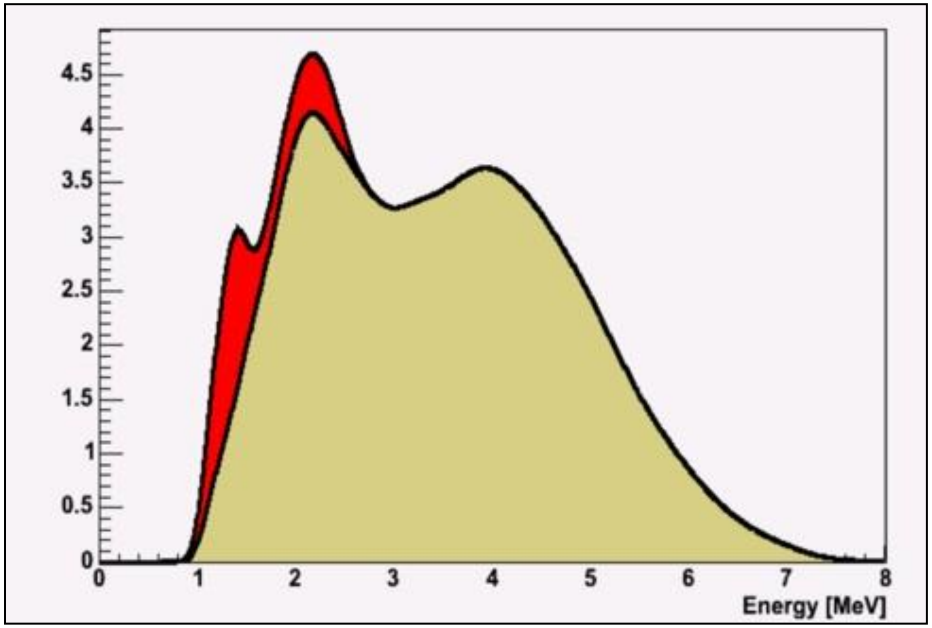


KamLAND Scintillator-Detector (1000 t)

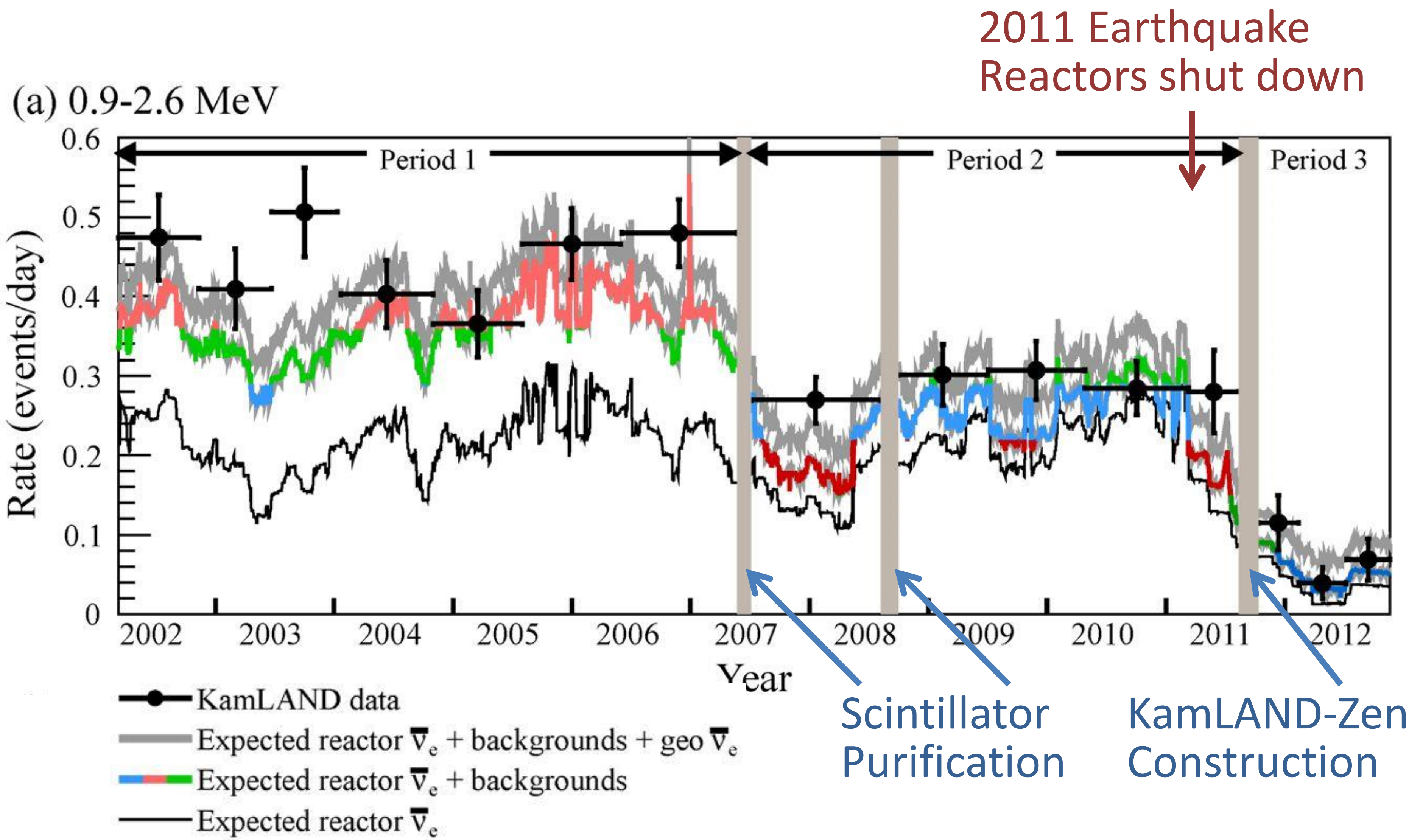


Reactor Background

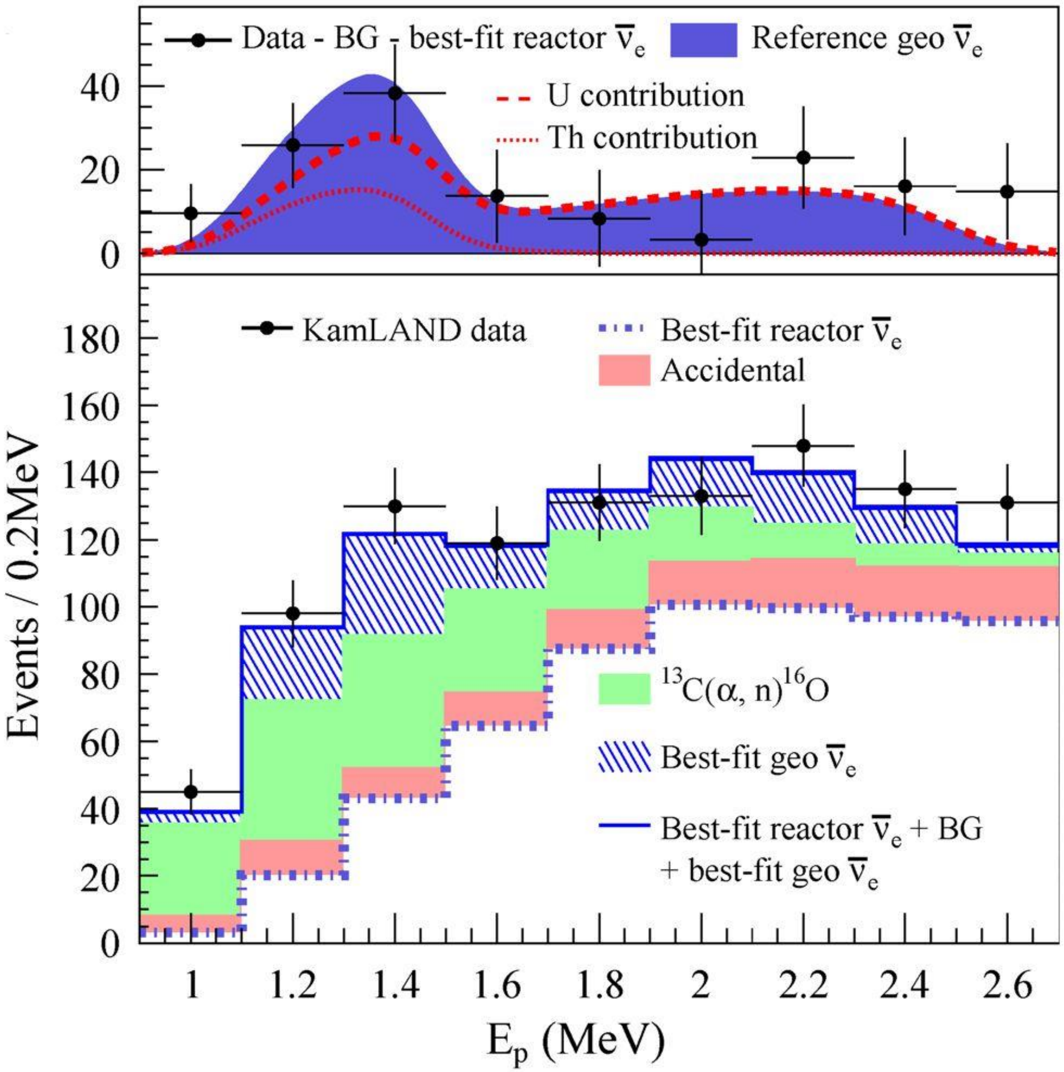




Reactor On-Off KamLAND Data



KamLAND Collaboration, arXiv:1303.4667 (2013)



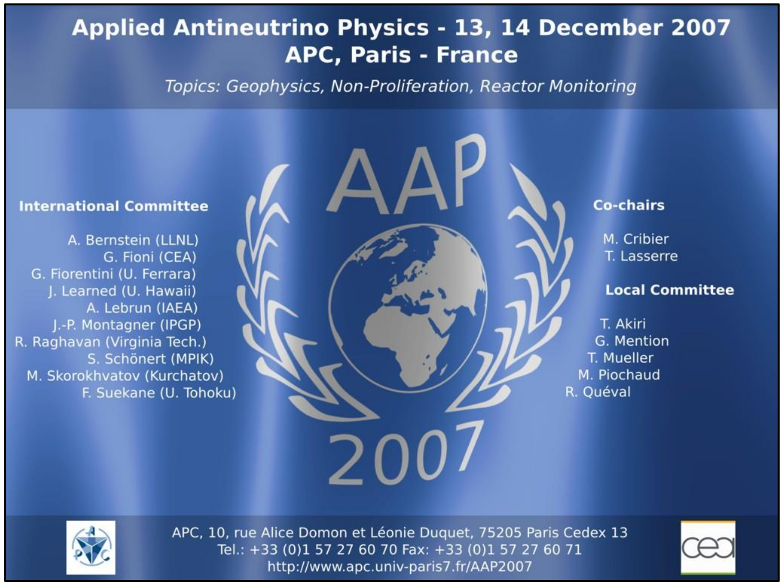
116^{+28}_{-27} Geoneutrino events
(U/Th = 3.9 fixed)

Separately free fitting:
U 116 events
Th 8 events

Beginning of
neutrino geophysics!

KamLAND Collaboration, arXiv:1303.4667 (2013)

Applied Anti-Neutrino Physics (AAP)



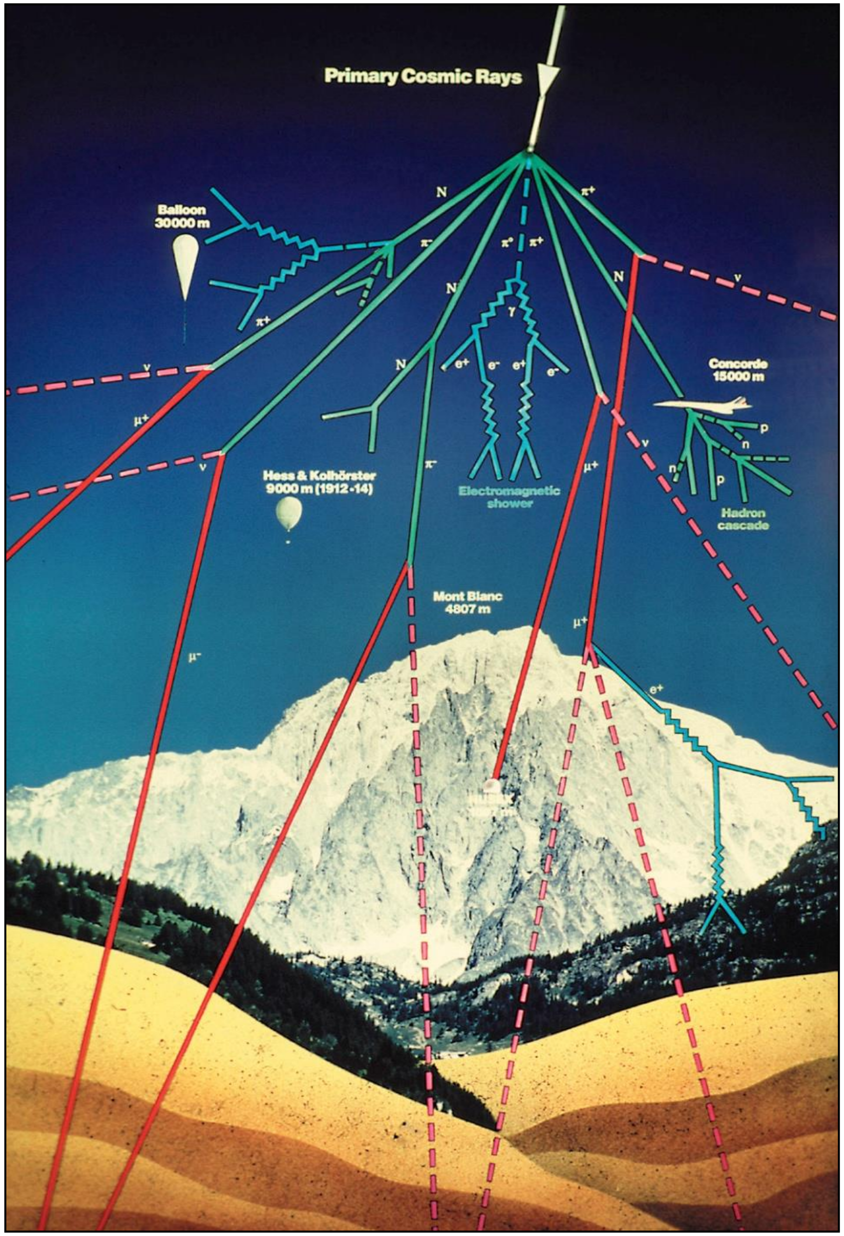
Applied Anti-Neutrino Physics (AAP)
Annual Conference Series since 2004

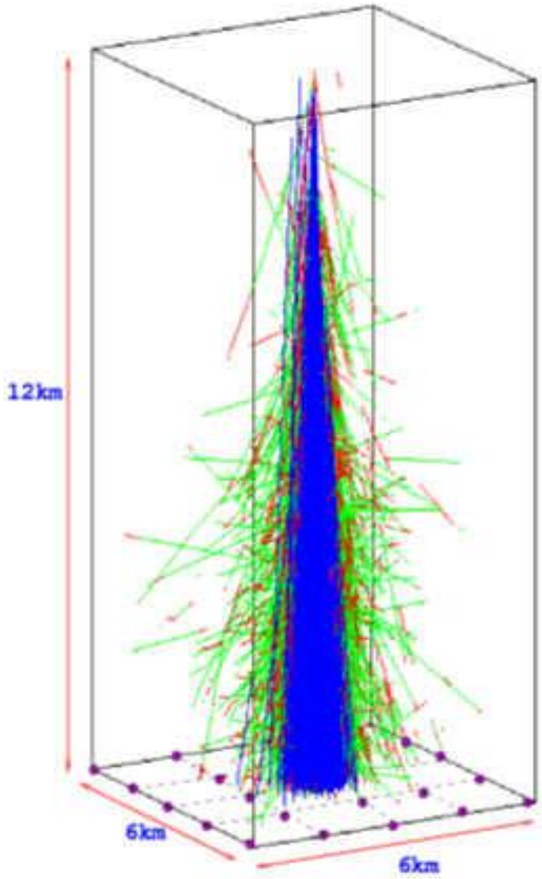
- Neutrino geophysics
- Reactor monitoring ("Neutrinos for Peace")

IAEA
International Atomic Energy Agency
Atoms For Peace

- Relatively small detectors can measure nuclear activity without intrusion
- Of interest for monitoring by International Atomic Energy Agency (Monitors fissile material in civil nuclear cycles)

Cosmic Rays

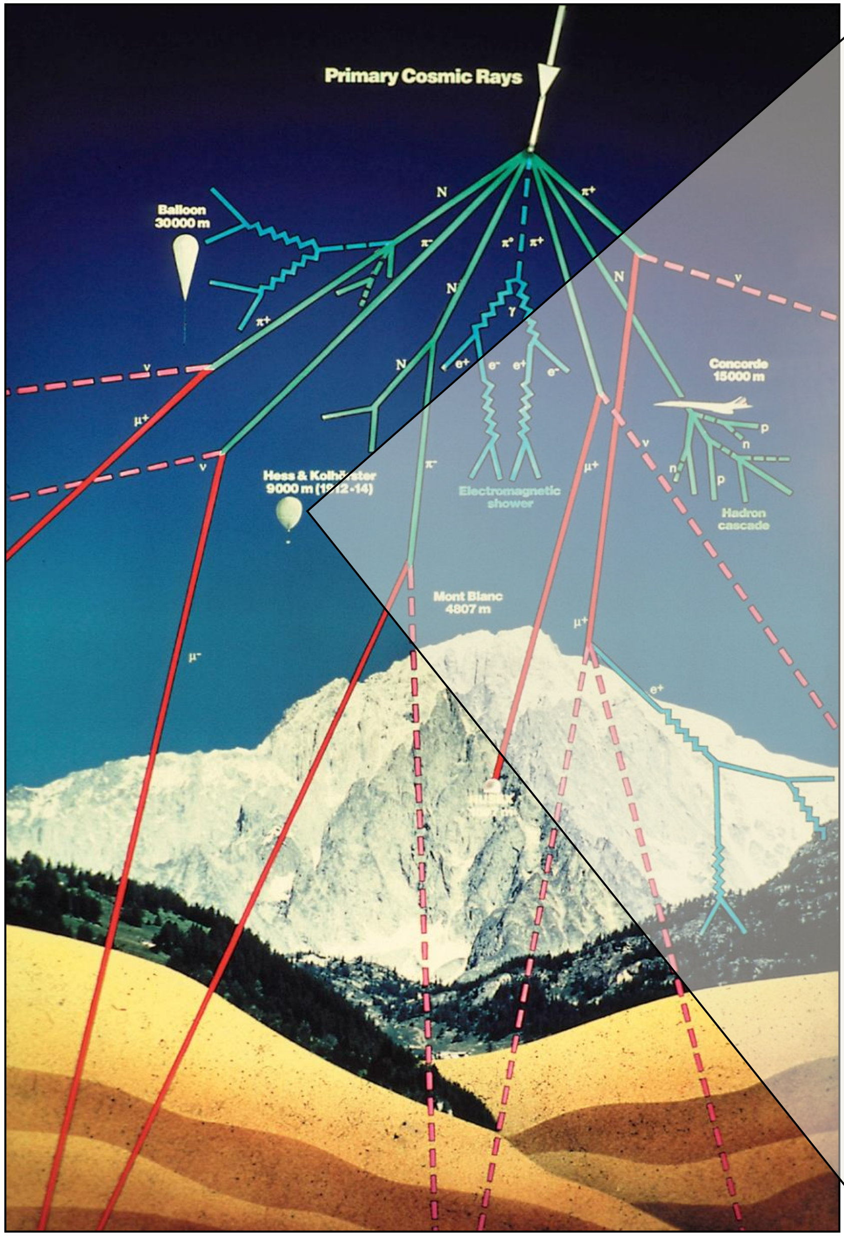




Air Shower:

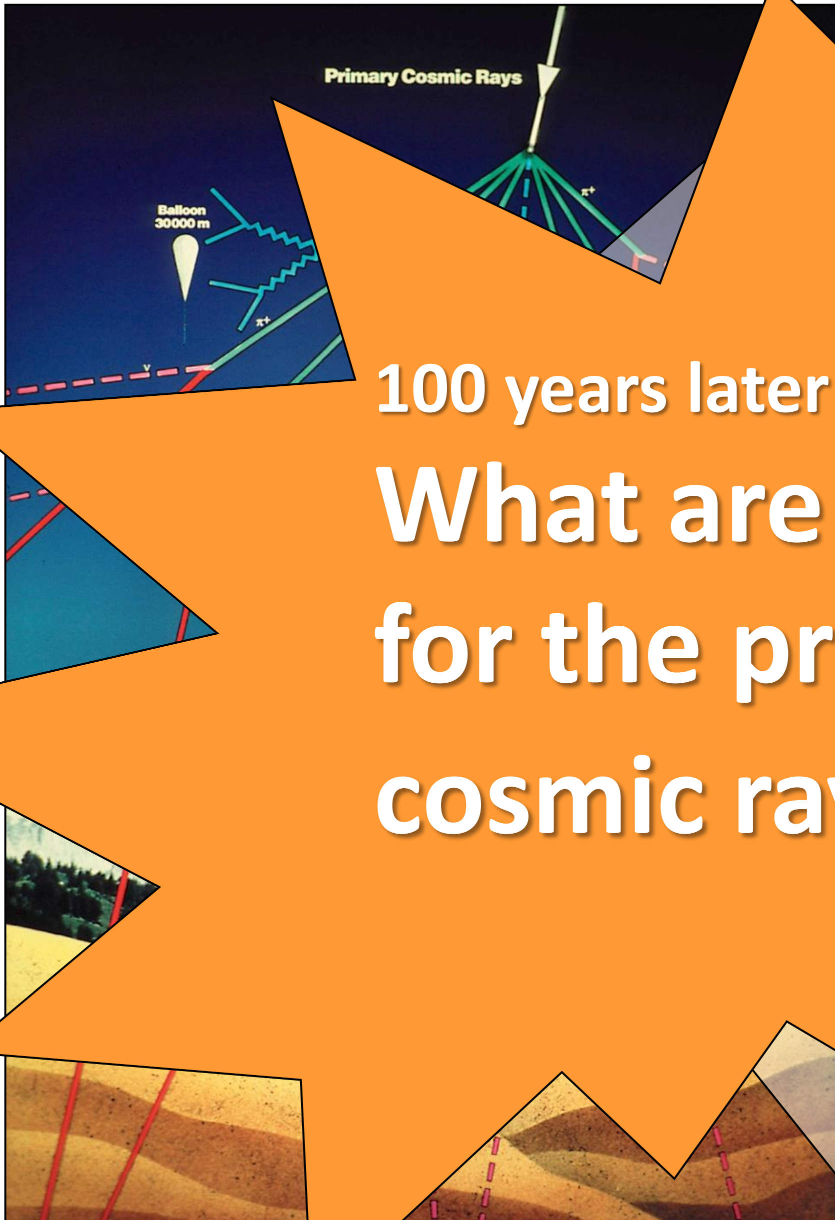
- 10^{19} eV primary particle
- 100 billion secondary particles at sea level

Cosmic Rays


Primary Cosmic Rays
Balloon 30000 m
Concorde 15000 m
Electromagnetic shower
Hadron cascade
Mont Blanc 4807 m


Victor Hess (1911/12)

Cosmic Rays

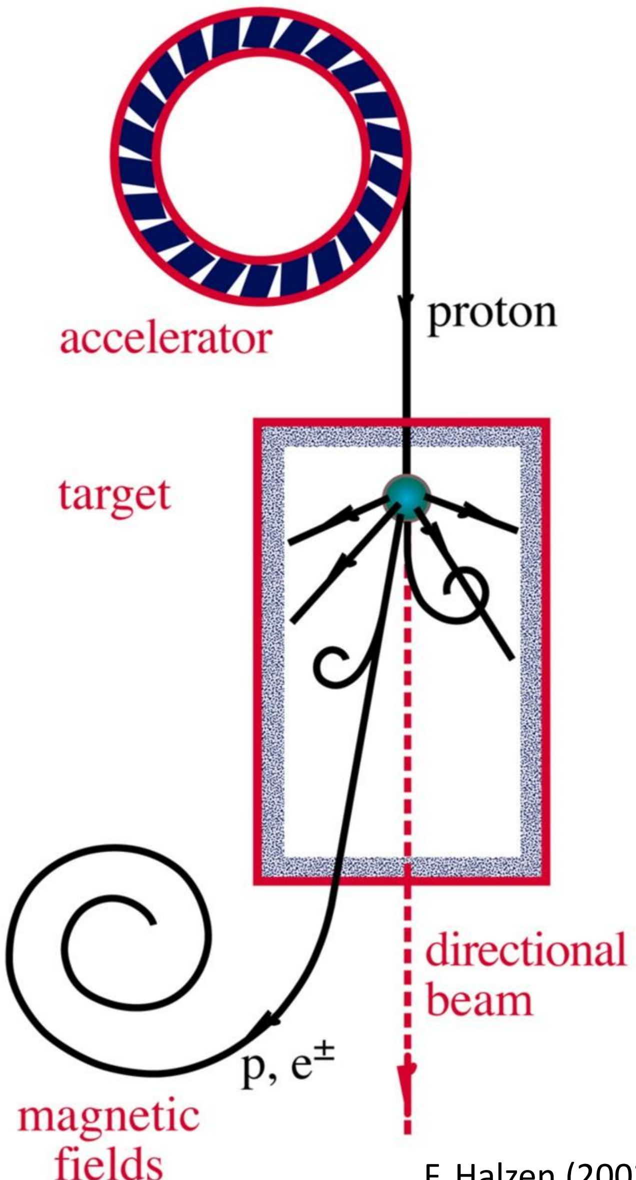


Victor Hess (1911/12)

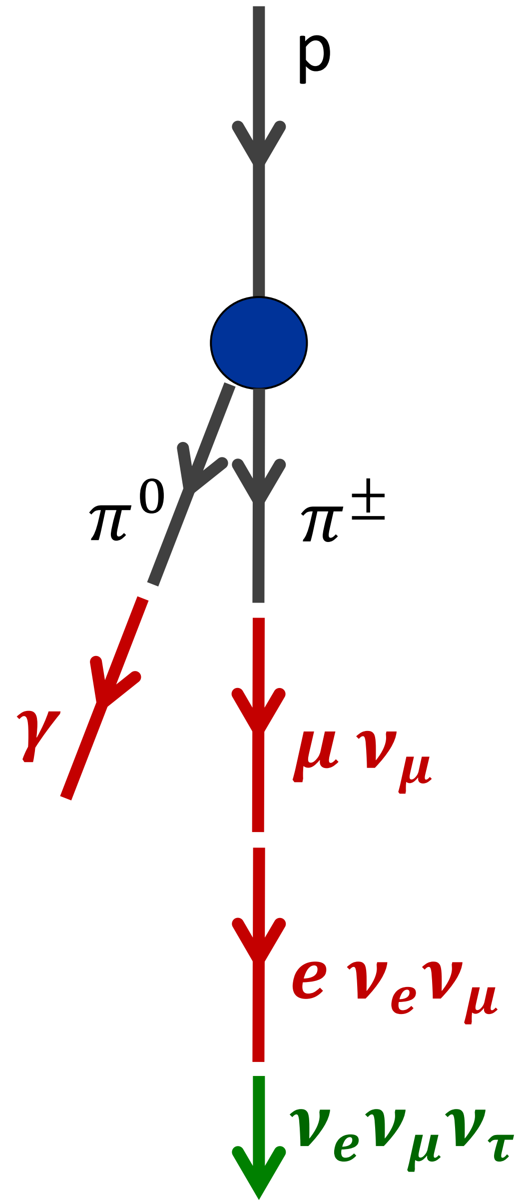
100 years later we are still asking

What are the sources for the primary cosmic rays?

Neutrino Beams: Heaven and Earth



F. Halzen (2002)

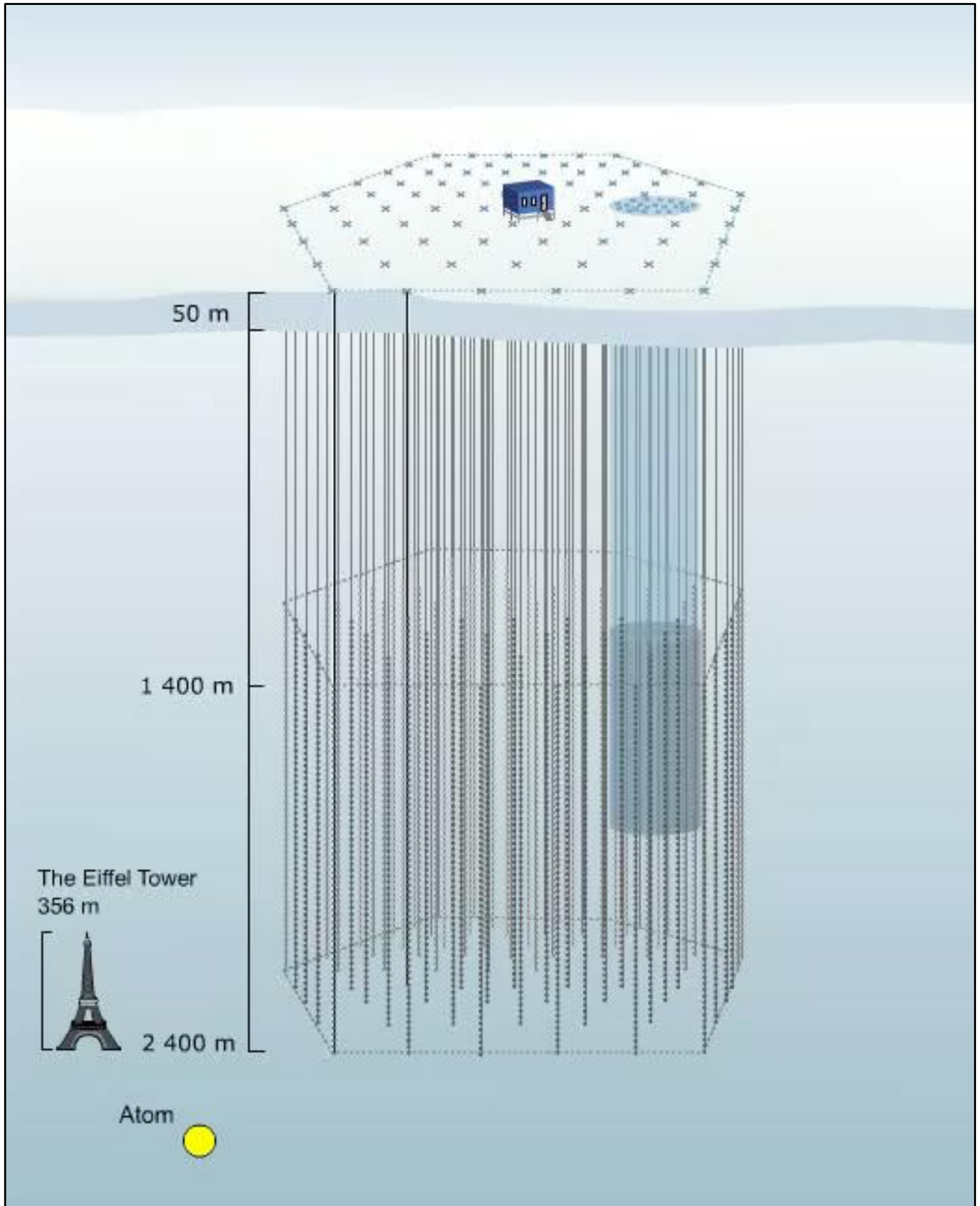


Target:
Protons or Photons

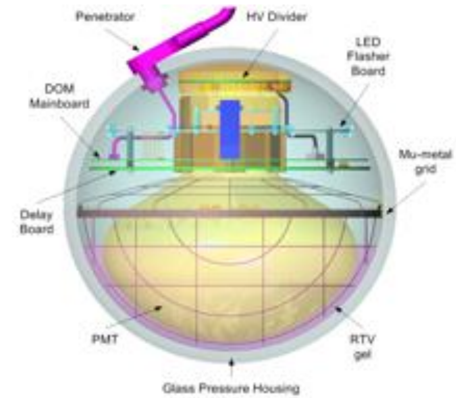
Approx. equal fluxes of photons & neutrinos

Equal neutrino fluxes in all flavors due to oscillations

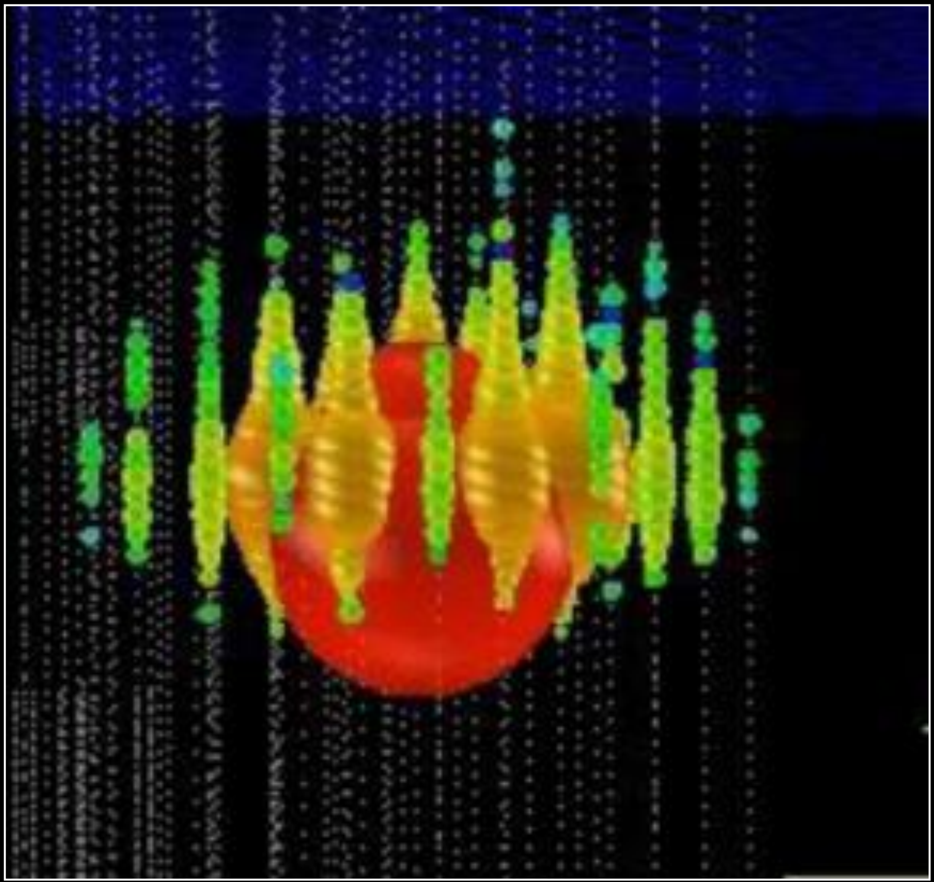
IceCube Neutrino Telescope at the South Pole



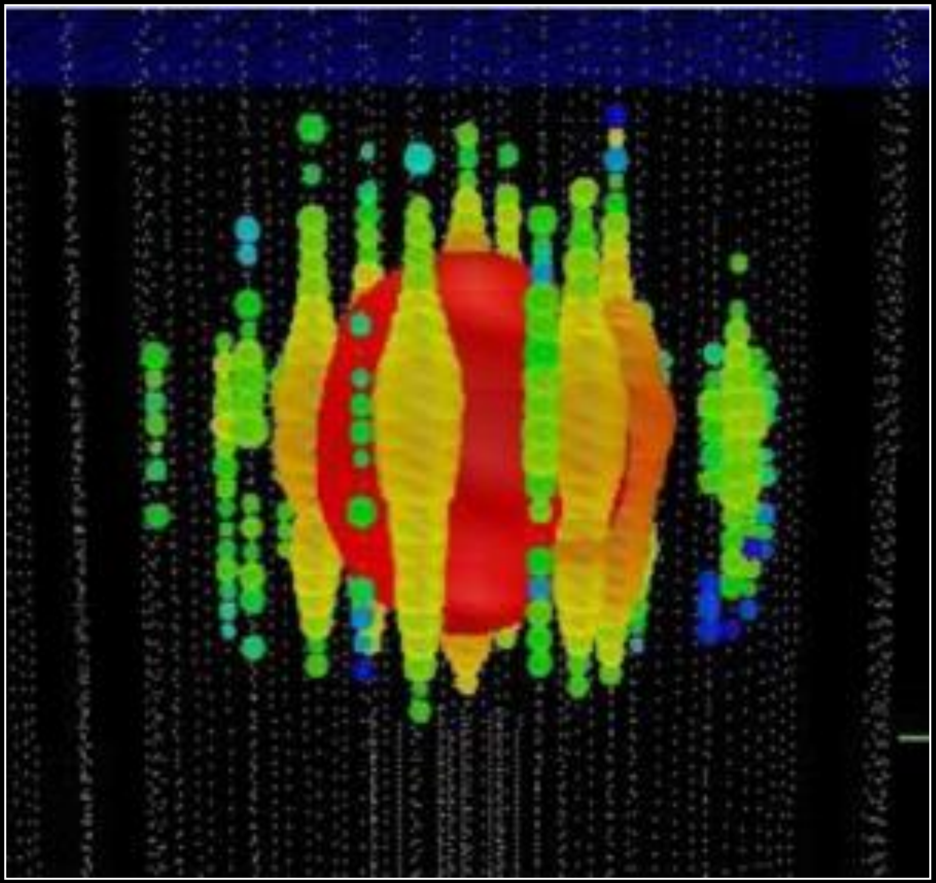
Instrumentation of 1 km^3 antarctic ice with $\sim$ 5000 photo multipliers completed December 2010



Two High-Energy Events in IceCube



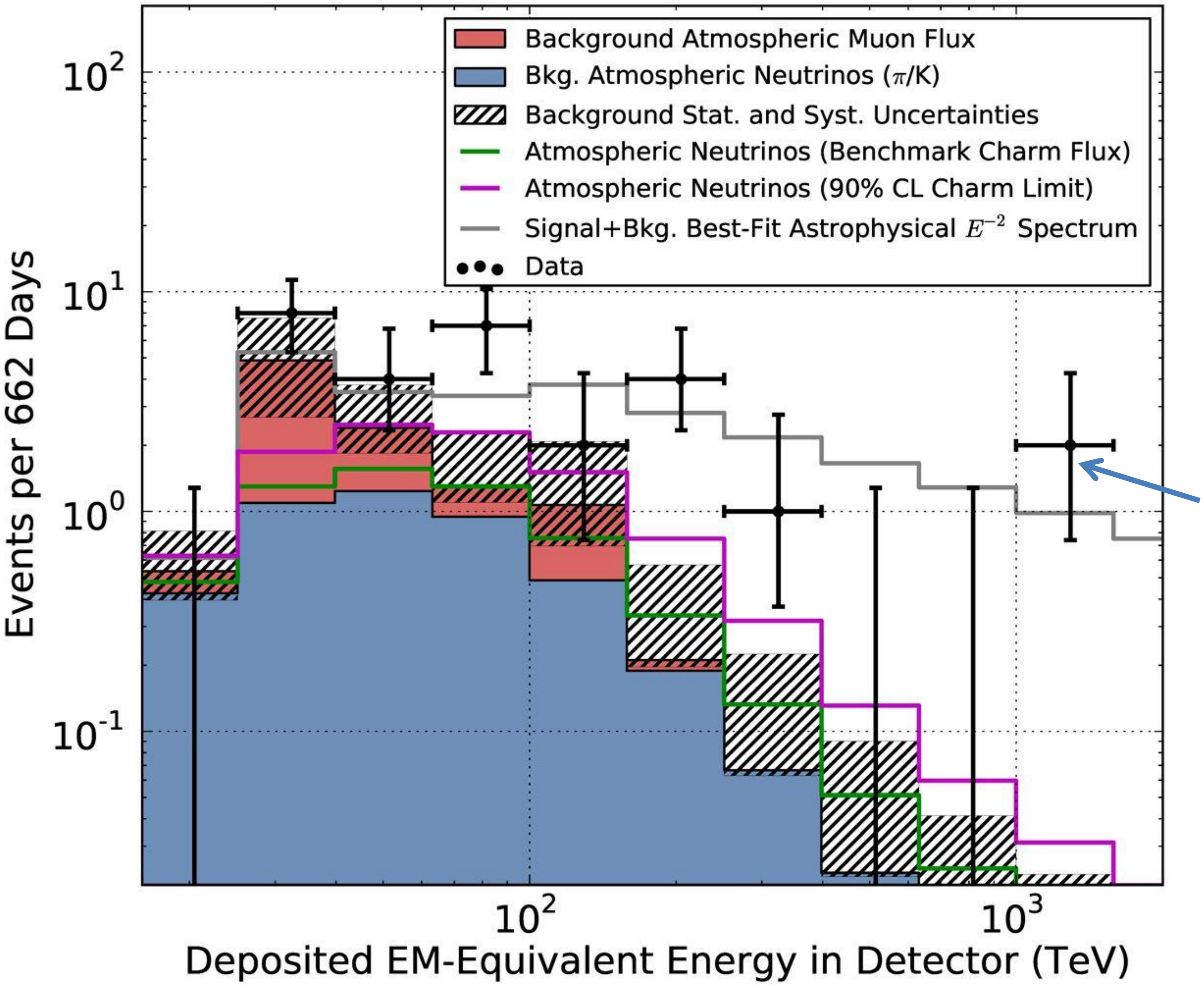
Ernie ~ 1.1 PeV



Bert ~ 1.0 PeV

Ernie & Bert and 26 Additional Events in IceCube

Meanwhile 37 events, including Big Bird (2 PeV), to be published soon



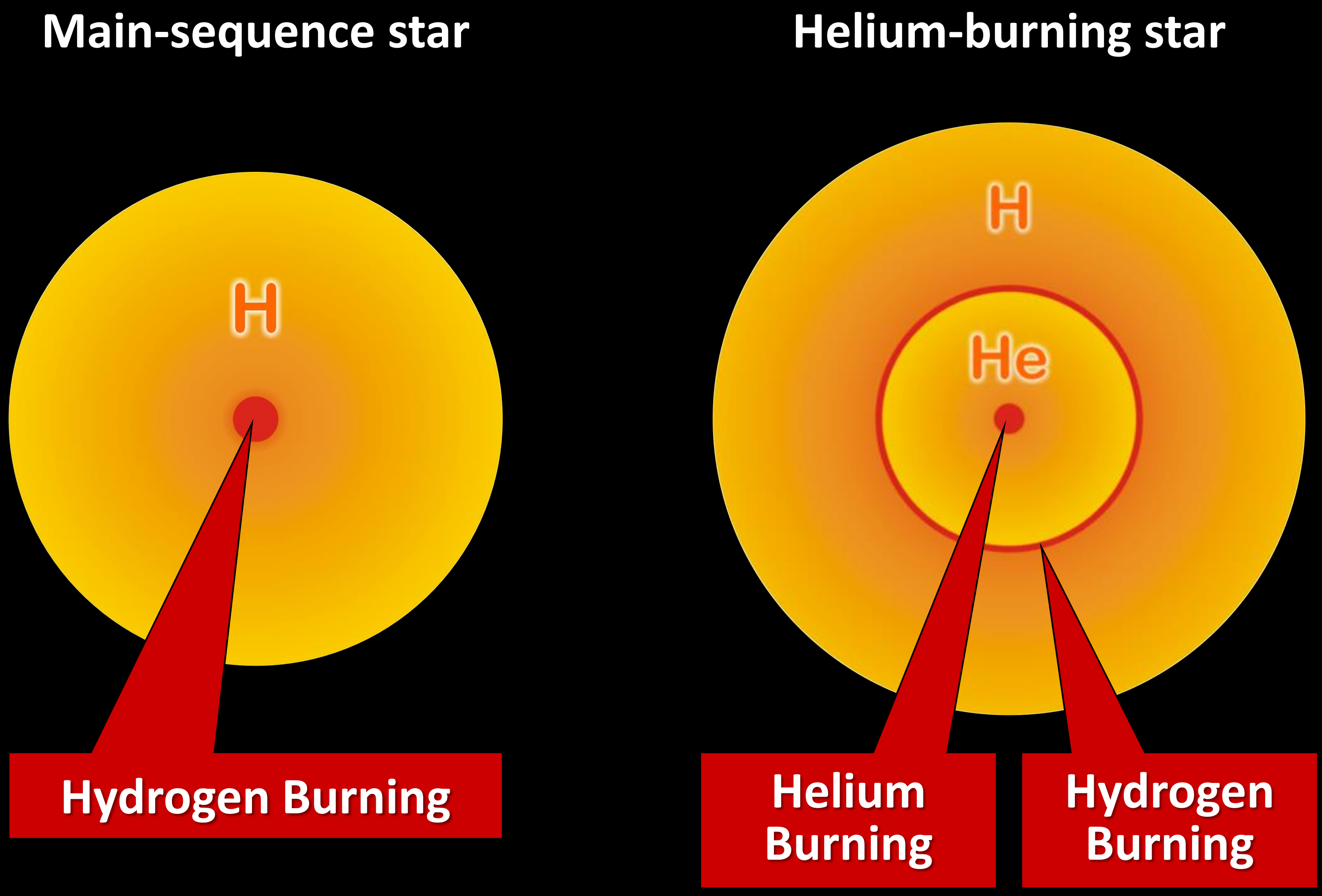
Significance of all 28 events: 4.1σ, Background $10.6^{+5.0}_{-3.6}$

Supernova Neutrinos

Supernova Neutrinos

凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅大星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

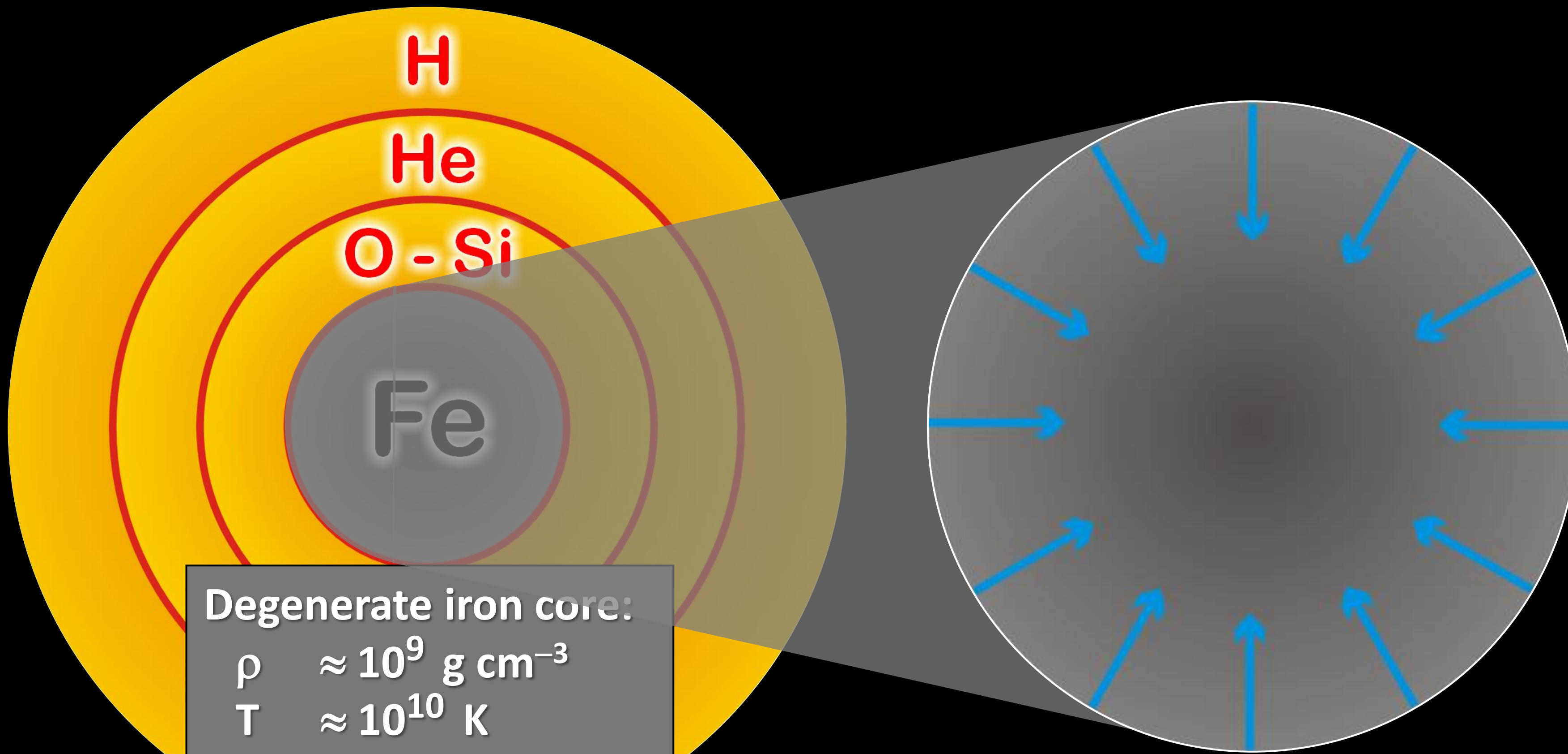
Stellar Collapse and Supernova Explosion



Stellar Collapse and Supernova Explosion

Onion structure

Collapse (implosion)



Degenerate iron core:

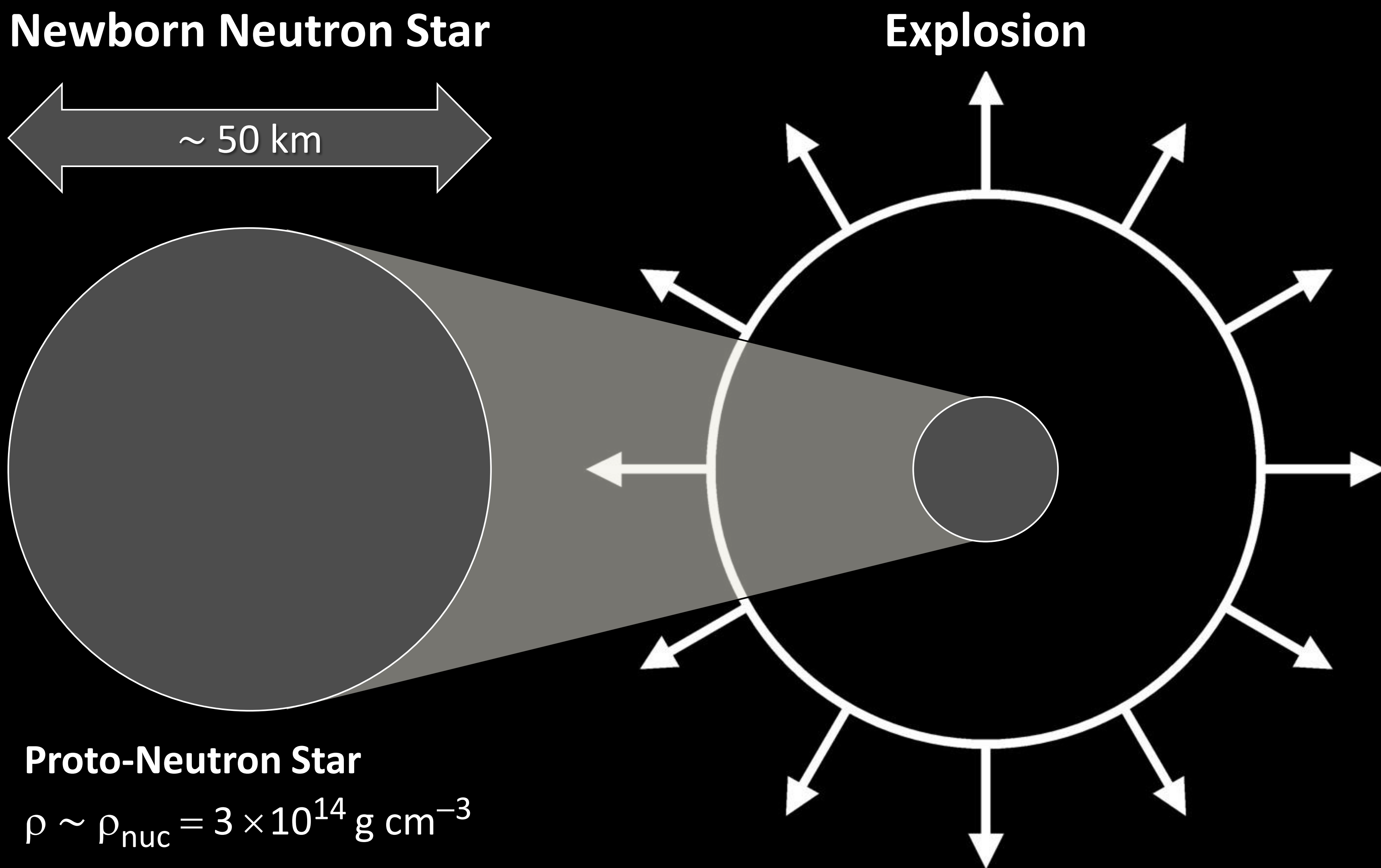
$\rho \approx 10^9$ g cm^{-3}

$T \approx 10^{10}$ K

$M_{Fe} \approx 1.5\ M_{sun}$

$R_{Fe} \approx 3000$ km

Stellar Collapse and Supernova Explosion



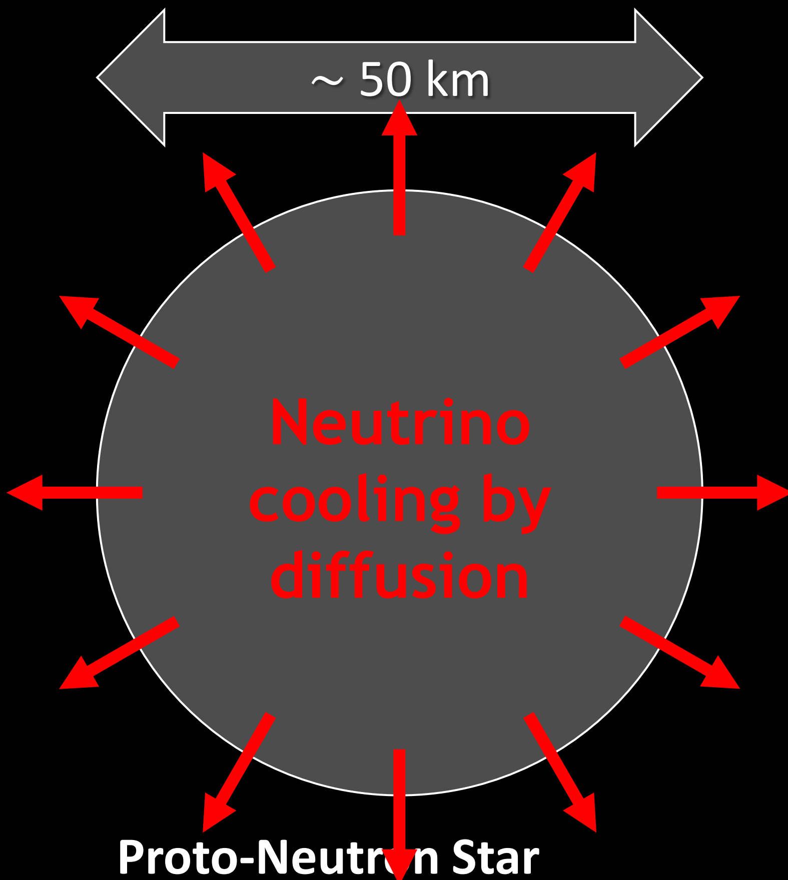
Proto-Neutron Star

$\rho \sim \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \sim 30\ \mathrm{MeV}$

Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

$\rho \sim \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \sim 30\ \mathrm{MeV}$

Gravitational binding energy

$$E_b \approx 3 \times 10^{53}\ \mathrm{erg} \approx 17\%\ M_{SUN}\, c^2$$

This shows up as

99%	Neutrinos
1%	Kinetic energy of explosion
0.01%	Photons, outshine host galaxy

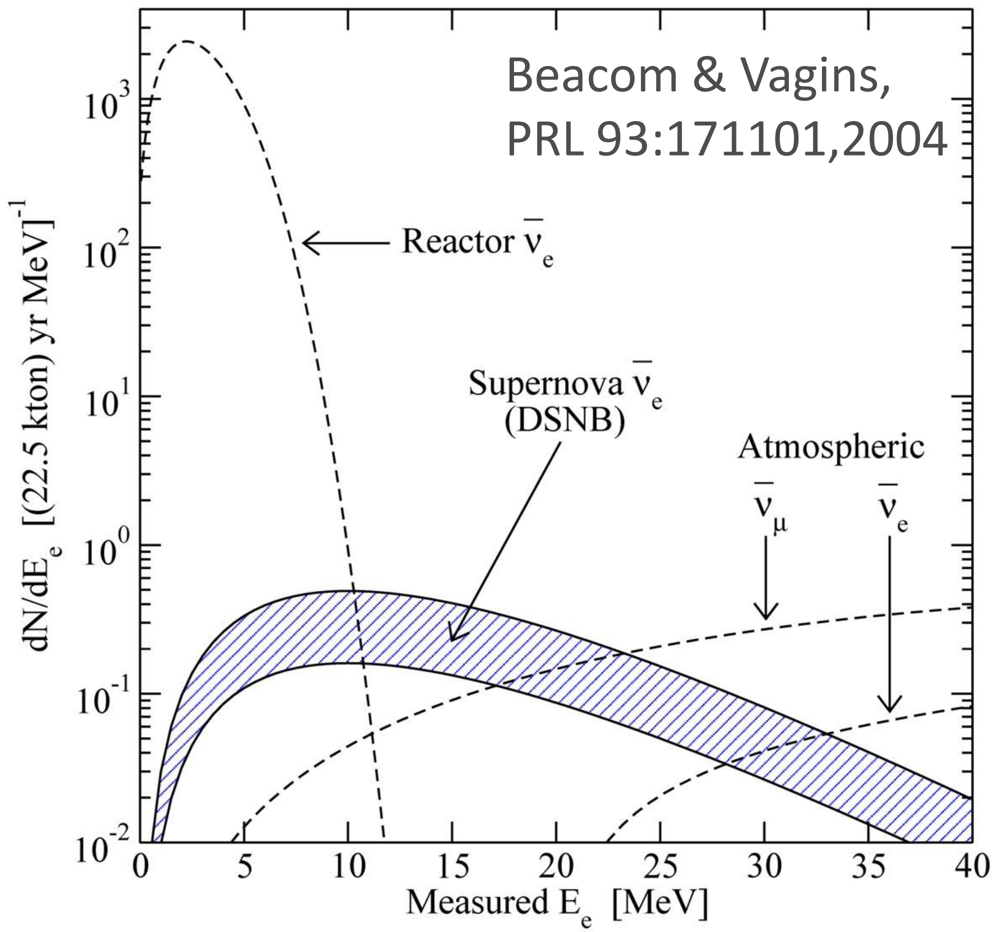
Neutrino luminosity

$$L_\nu \sim 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$$
$$\sim 3 \times 10^{19}\ L_{SUN}$$

While it lasts, outshines the entire visible universe

Diffuse Supernova Neutrino Background (DSNB)

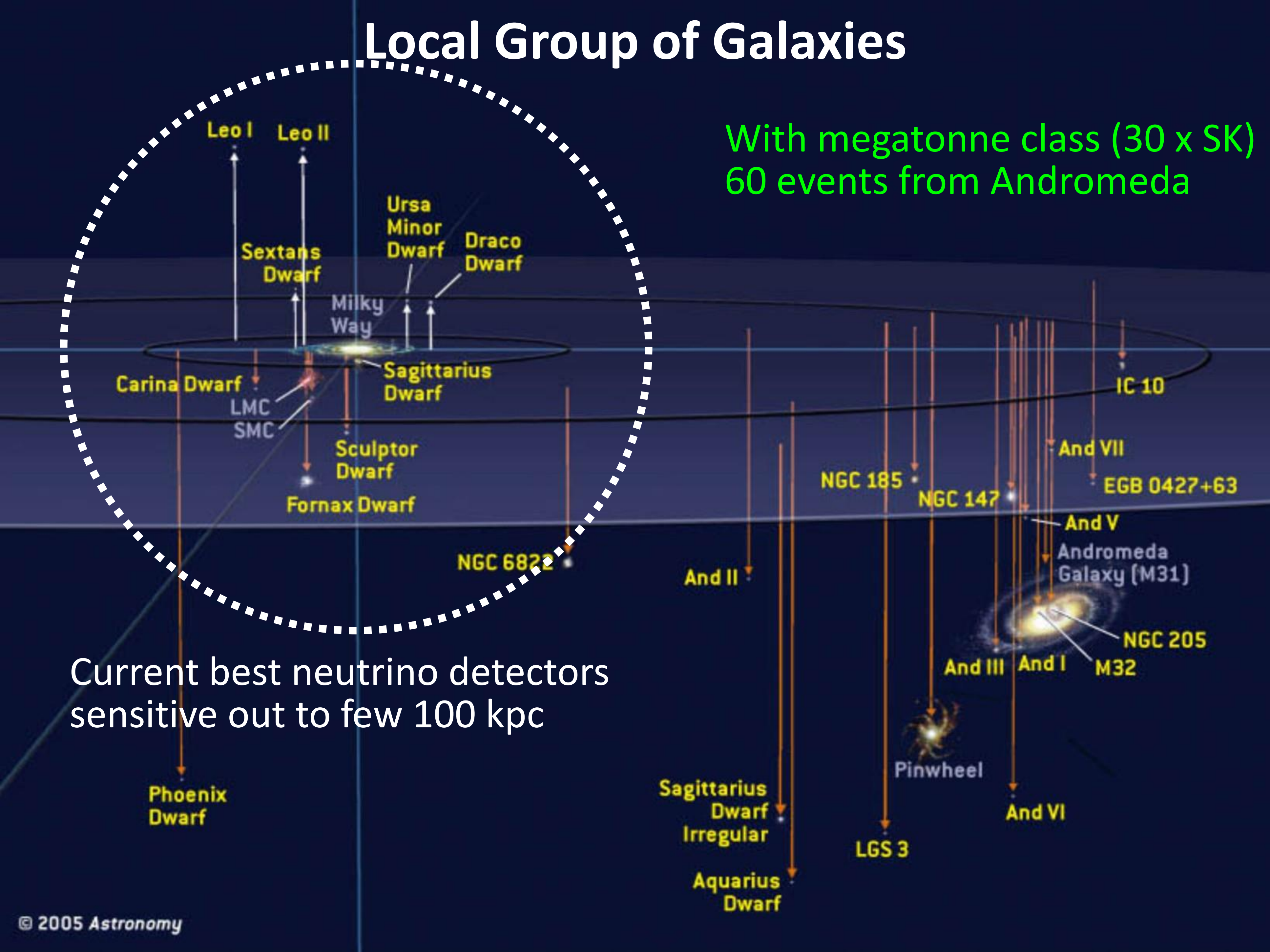
- A few core collapses per second in the visible universe
- Emitted ν energy density
  ~ extra galactic background light
  ~ 10% of CMB density
- Detectable $\overline{\nu}_e$ flux at Earth
  $\sim 10\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
  mostly from redshift $z \sim 1$
- Confirm star-formation rate
- Nu emission from average core collapse & black-hole formation
- Pushing frontiers of neutrino astronomy to cosmic distances!



Window of opportunity between reactor $\overline{\nu}_e$ and atmospheric ν bkg

Local Group of Galaxies

With megatonne class (30 x SK)
60 events from Andromeda

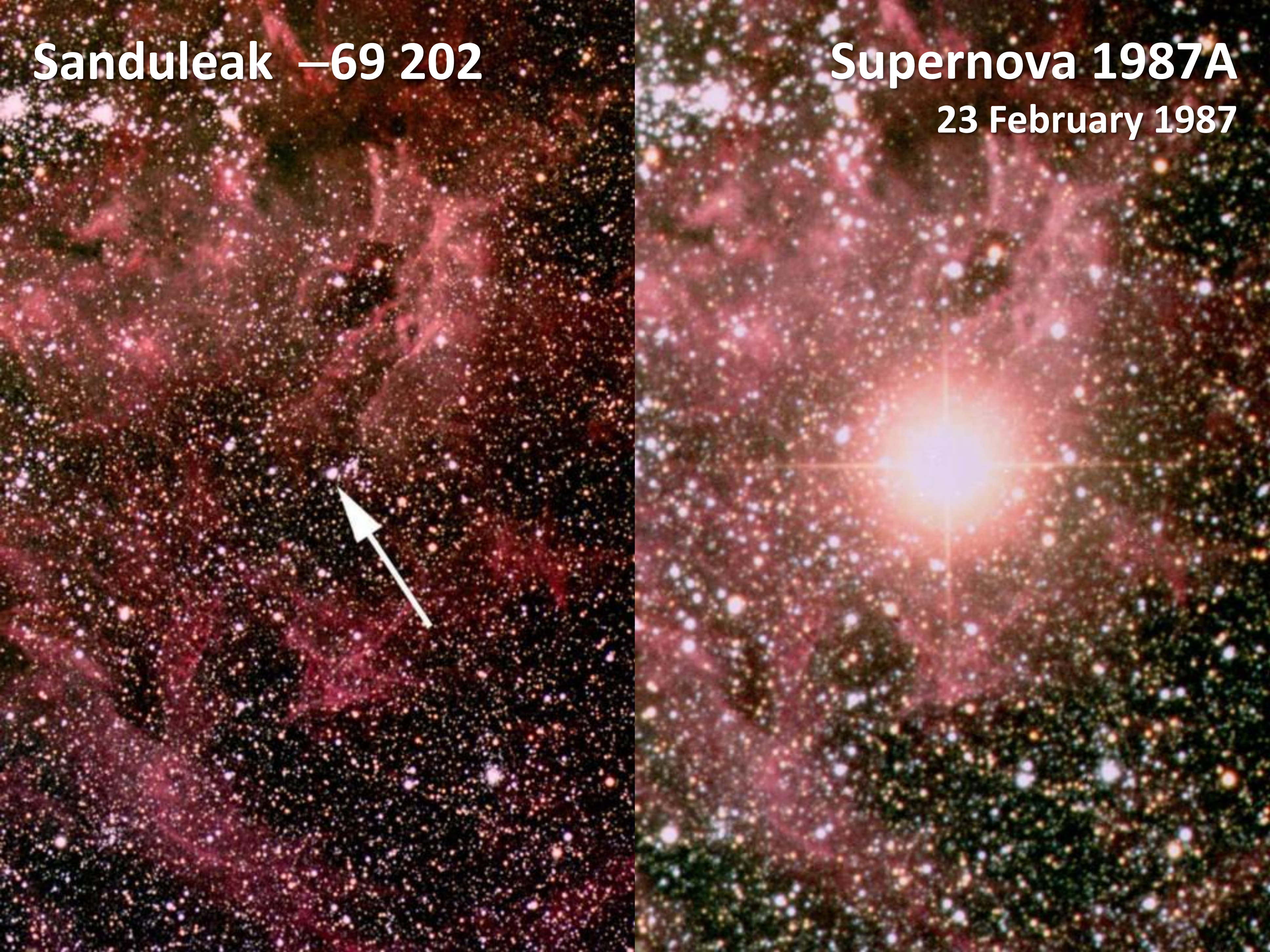


Current best neutrino detectors
sensitive out to few 100 kpc

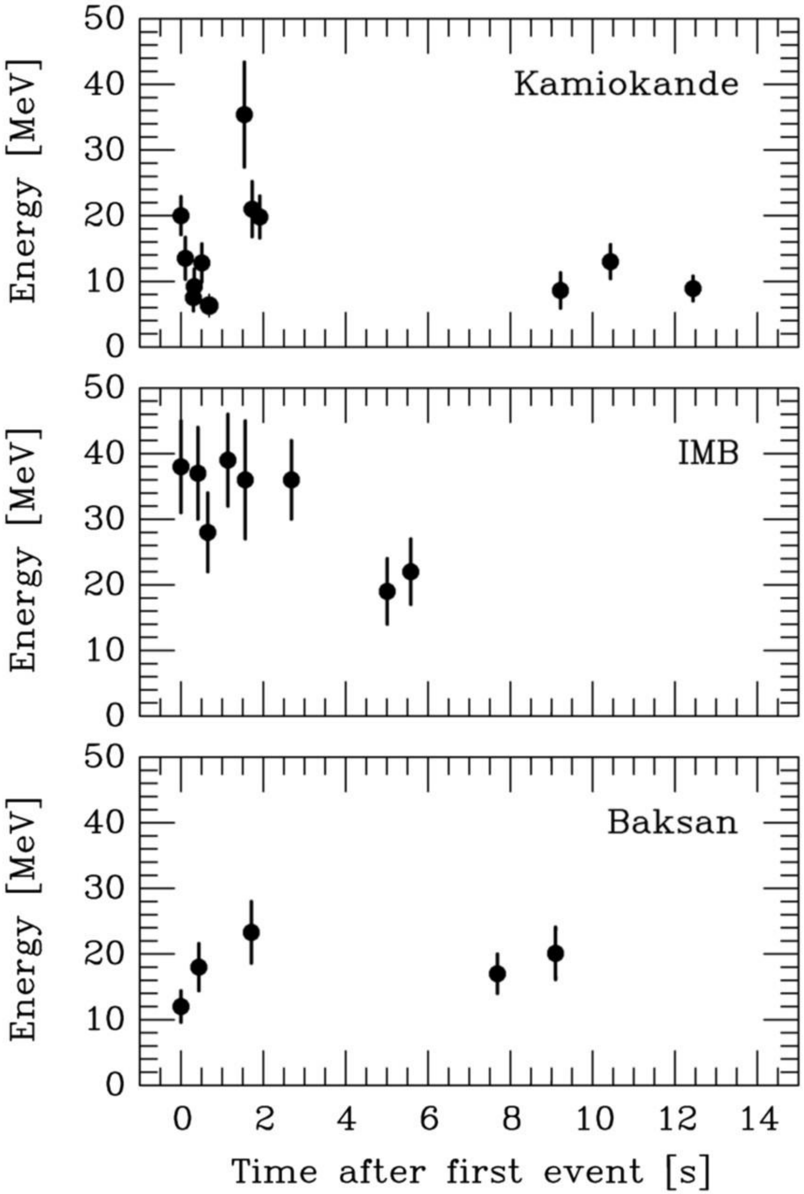

Sanduleak –69 202


Tarantula Nebula


Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)


Sanduleak –69 202
Supernova 1987A
23 February 1987

Neutrino Signal of Supernova 1987A



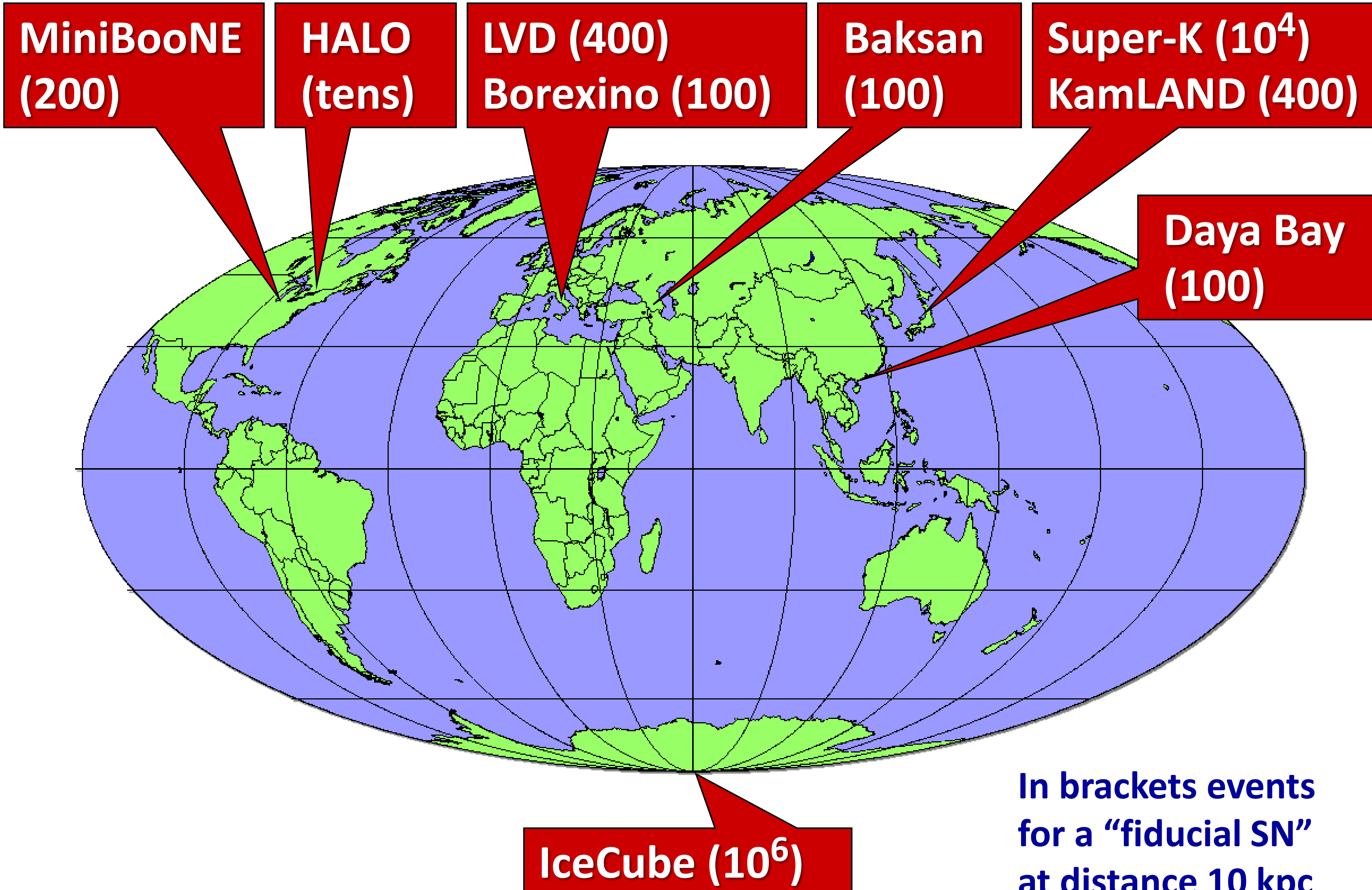
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty $\pm$1 min

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

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

Within clock uncertainties, all signals are contemporaneous

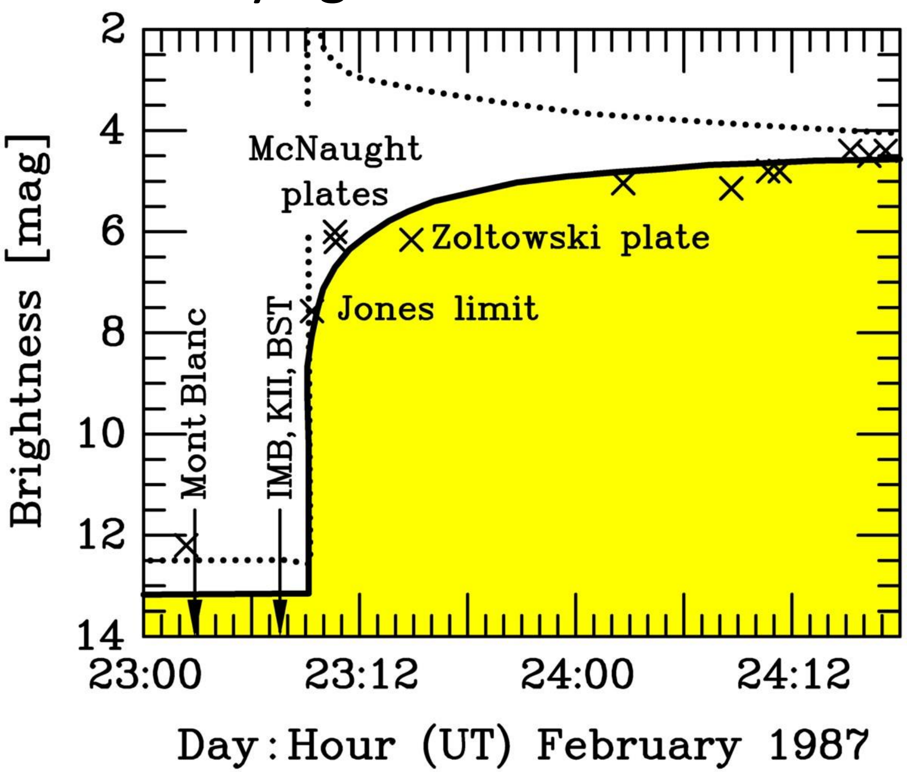
Operational Detectors for Supernova Neutrinos



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

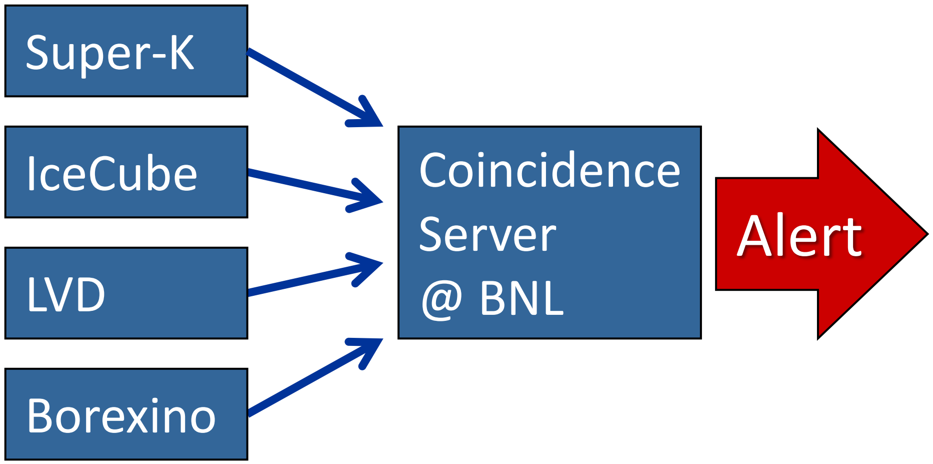
SuperNova Early Warning System (SNEWS)

Early light curve of SN 1987A

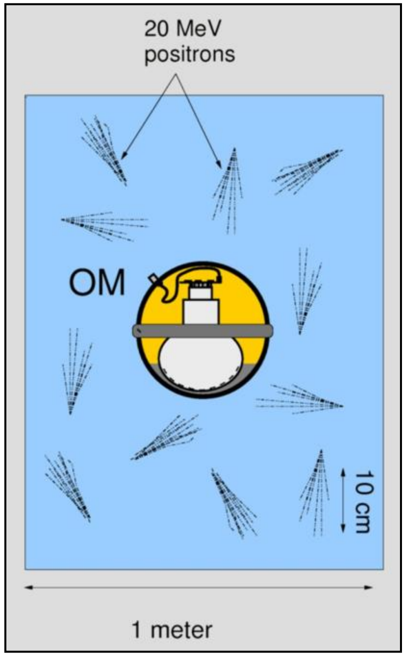


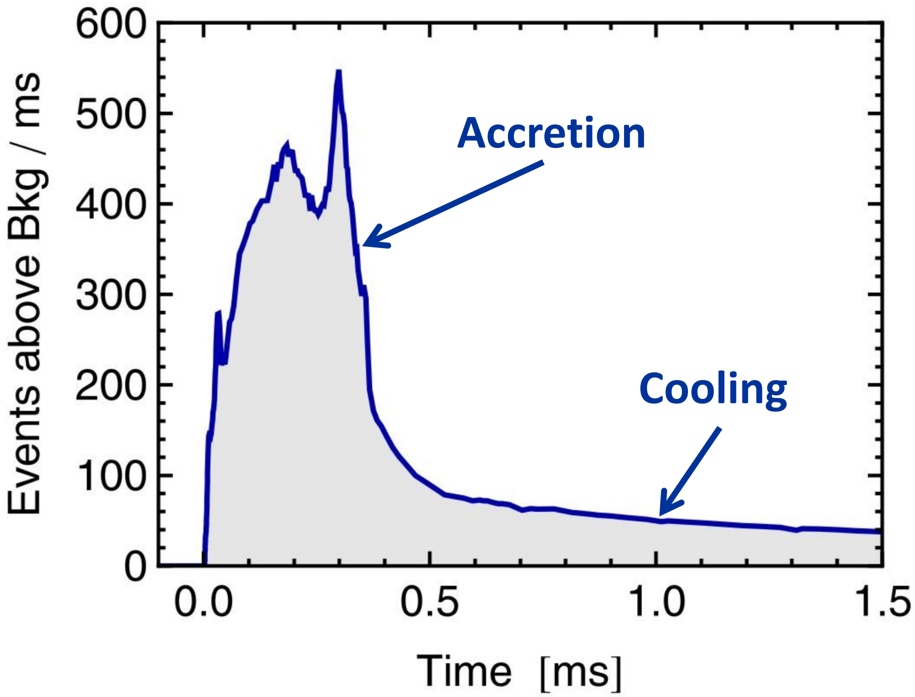
http://snews.bnl.gov

- Neutrinos arrive several hours before photons
- Can alert astronomers several hours in advance



IceCube as a Supernova Neutrino Detector



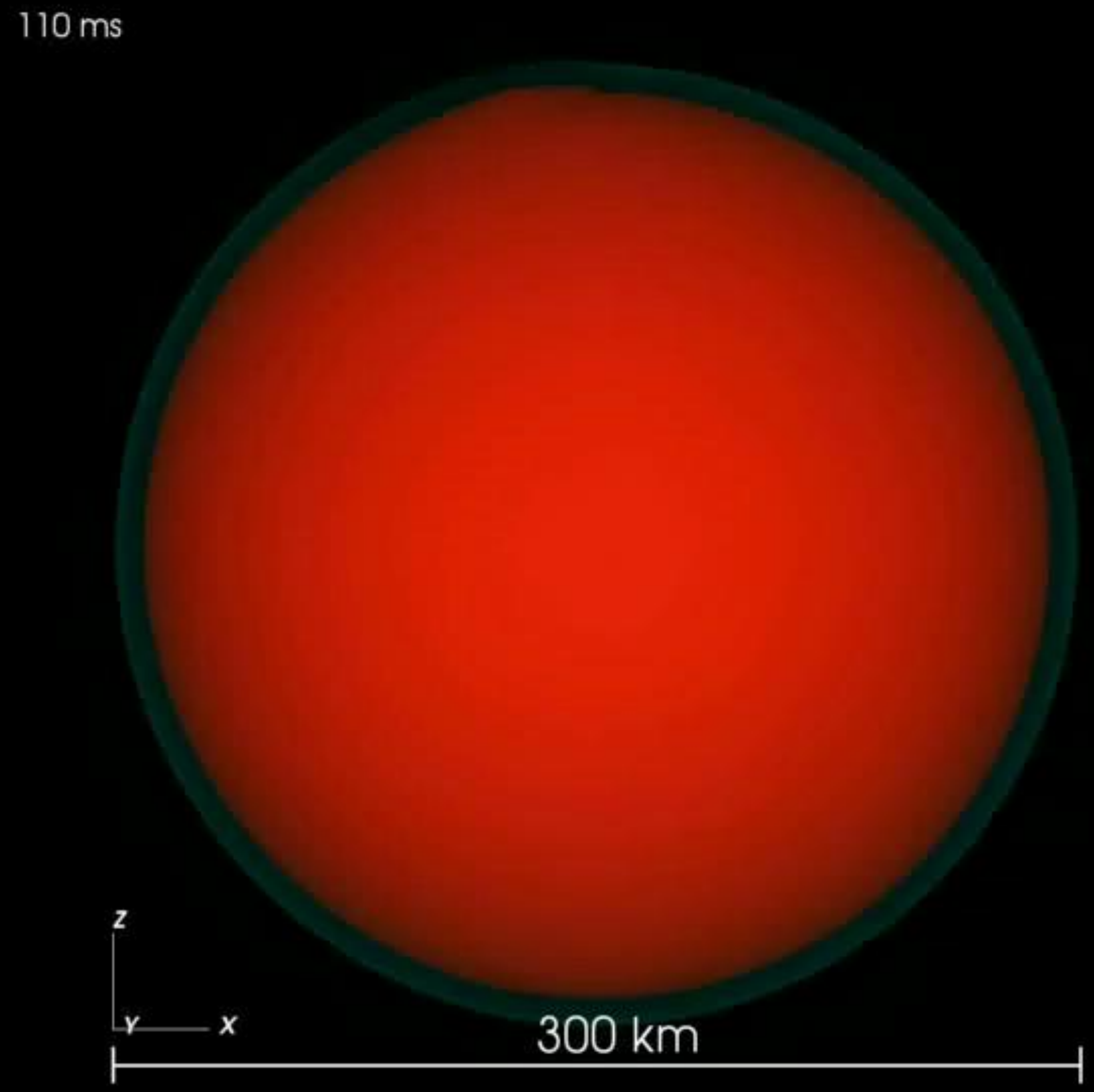


SN signal at 10 kpc
10.8 M_{sun} simulation of Basel group [arXiv:0908.1871]

- Each optical module (OM) picks up Cherenkov light from its neighborhood
- ~ 300 Cherenkov photons per OM from SN at 10 kpc, bkgd rate in one OM < 300 Hz
- SN appears as "correlated noise" in ~ 5000 OMs
- Significant energy information from time-correlated hits

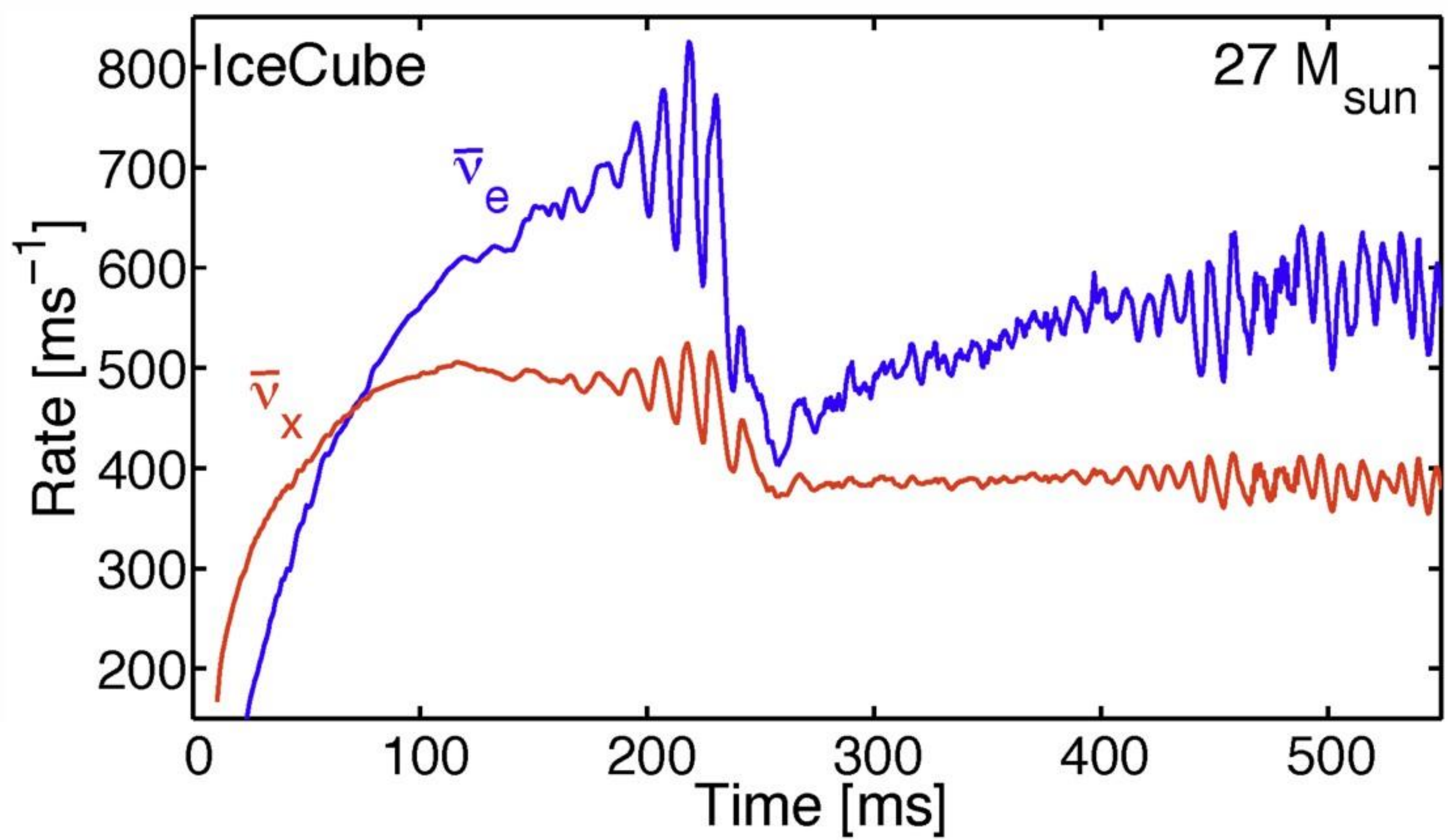
Pryor, Roos & Webster, ApJ 329:355, 1988. Halzen, Jacobsen & Zas, astro-ph/9512080. Demirörs, Ribordy & Salathe, arXiv:1106.1937.

First Realistic 3D Simulation (27 $M_\odot$ Garching Group)



Hanke, Müller, Wongwathanarat, Marek & Janka [arXiv:1303.6269]

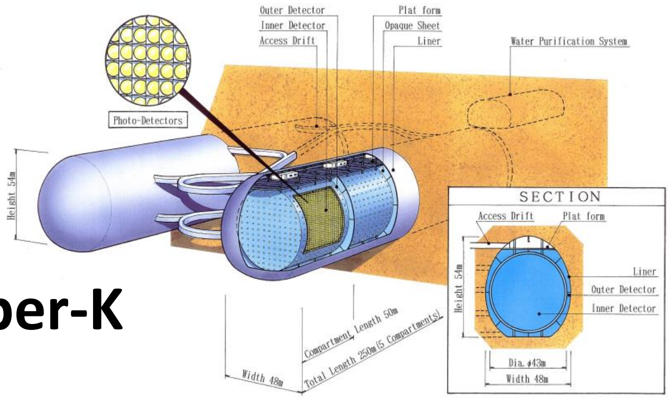
Variability seen in Neutrinos (3D Model)



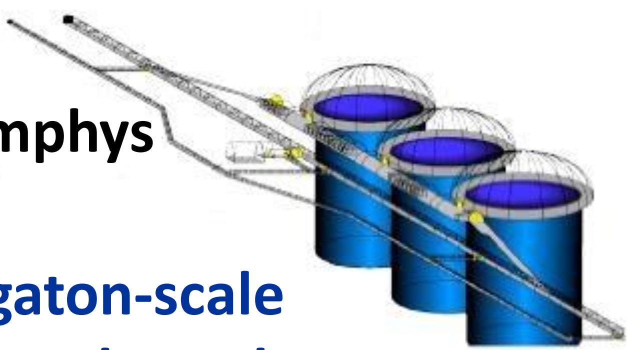
Tamborra, Hanke, Müller, Janka & Raffelt, arXiv:1307.7936
See also Lund, Marek, Lunardini, Janka & Raffelt, arXiv:1006.1889

Next Generation Large-Scale Detector Concepts

DUSEL
LBNE

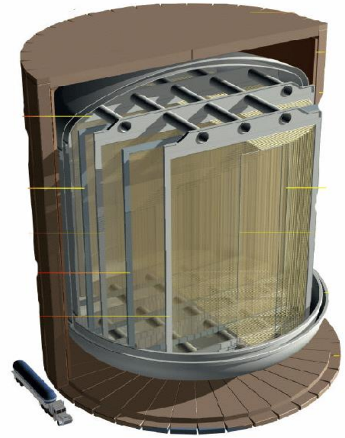


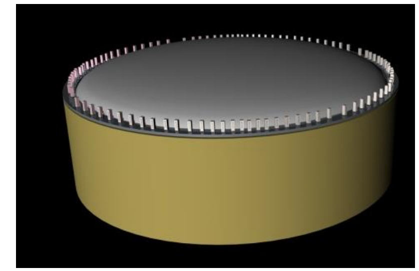
Hyper-K



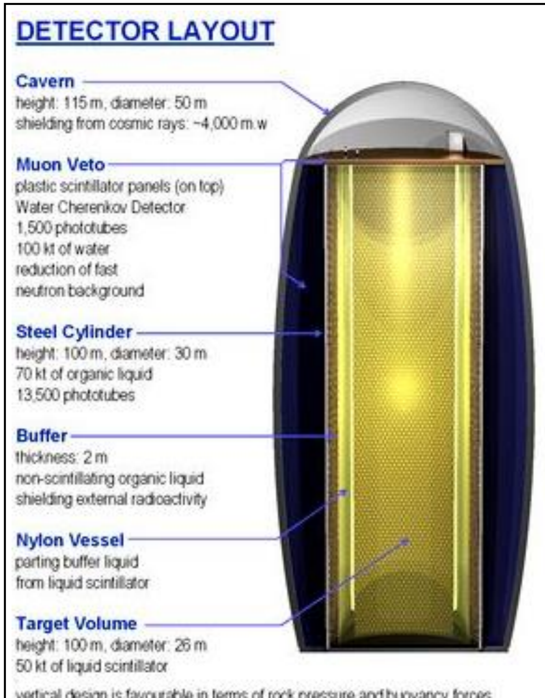
Memphys

Megaton-scale water Cherenkov





5-100 kton liquid Argon



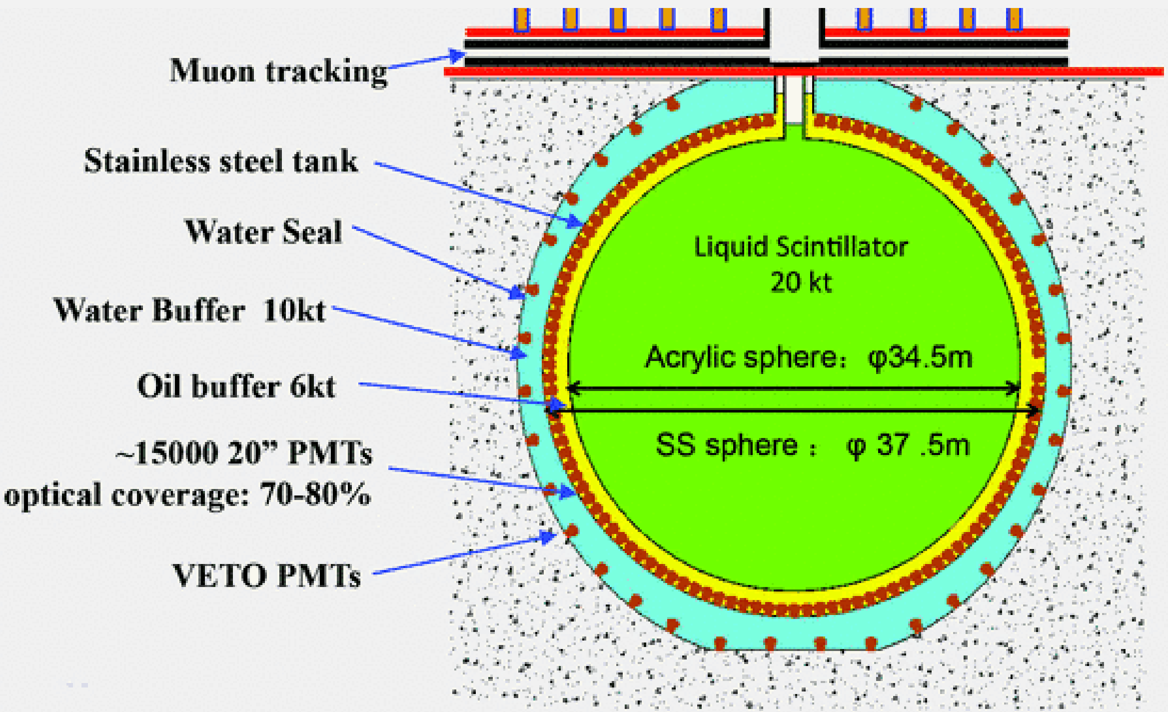
50 kton scale scintillator

LENA
HanoHano

LENA: From Dream to Reality

LENA: From Dream to Reality

JUNO (formerly Daya Bay II) Collaboration formed (2014)
20 kt scintillator detector
Hierarchy determination with reactor neutrinos
Excellent for low-energy neutrino astronomy



Summary

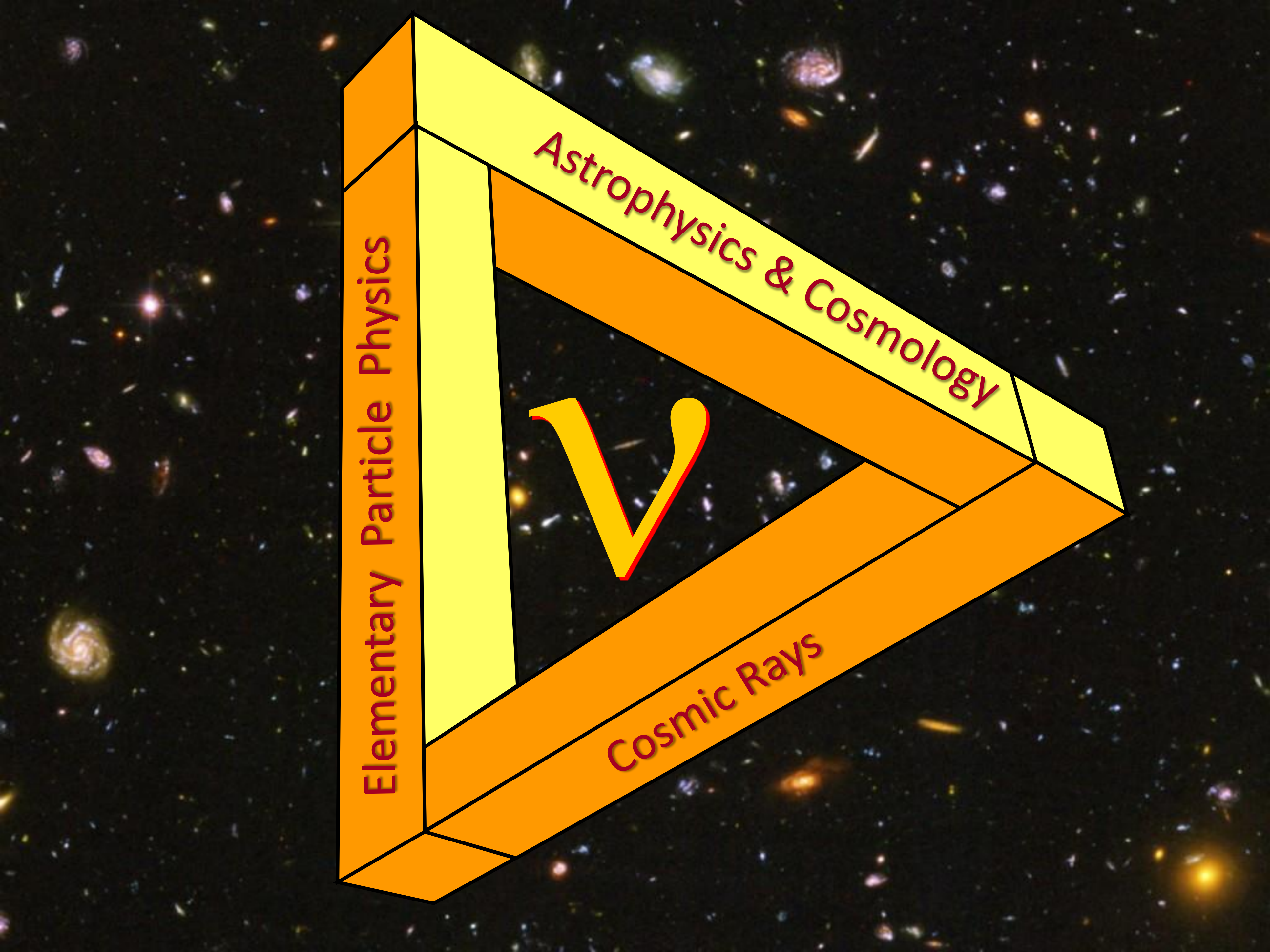
Understanding neutrino internal properties — a mature field

- Neutrino mixing parameters:
  Matrix well known from astro and lab evidence
- New experiments for missing parameters in the making
- Absolute masses yet to be determined (KATRIN, cosmology)
- Majorana nature yet to be found (neutrino-less double beta expts)

Neutrinos as astrophysical messengers — a field in its infancy

- Detailed measurement of solar nus (ca 60,000 events in Super-K)
- First geo-neutrinos (ca 116 events in KamLAND)
- SN 1987A (ca 20 events)
- First high-E events in IceCube (Ernie, Bert, Big Bird and 34 others)

- More statistics needed in most of these areas:
  bigger/better detectors planned or discussed
- Waiting for next nearby supernova



Astrophysics & Cosmology
Elementary Particle Physics
Cosmic Rays
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