Neutrinos as a Cosmic Messenger

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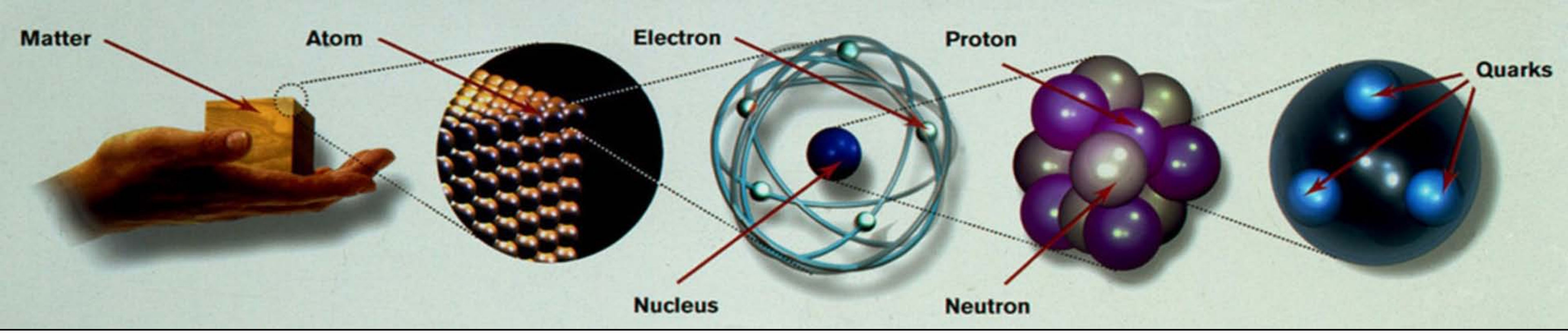
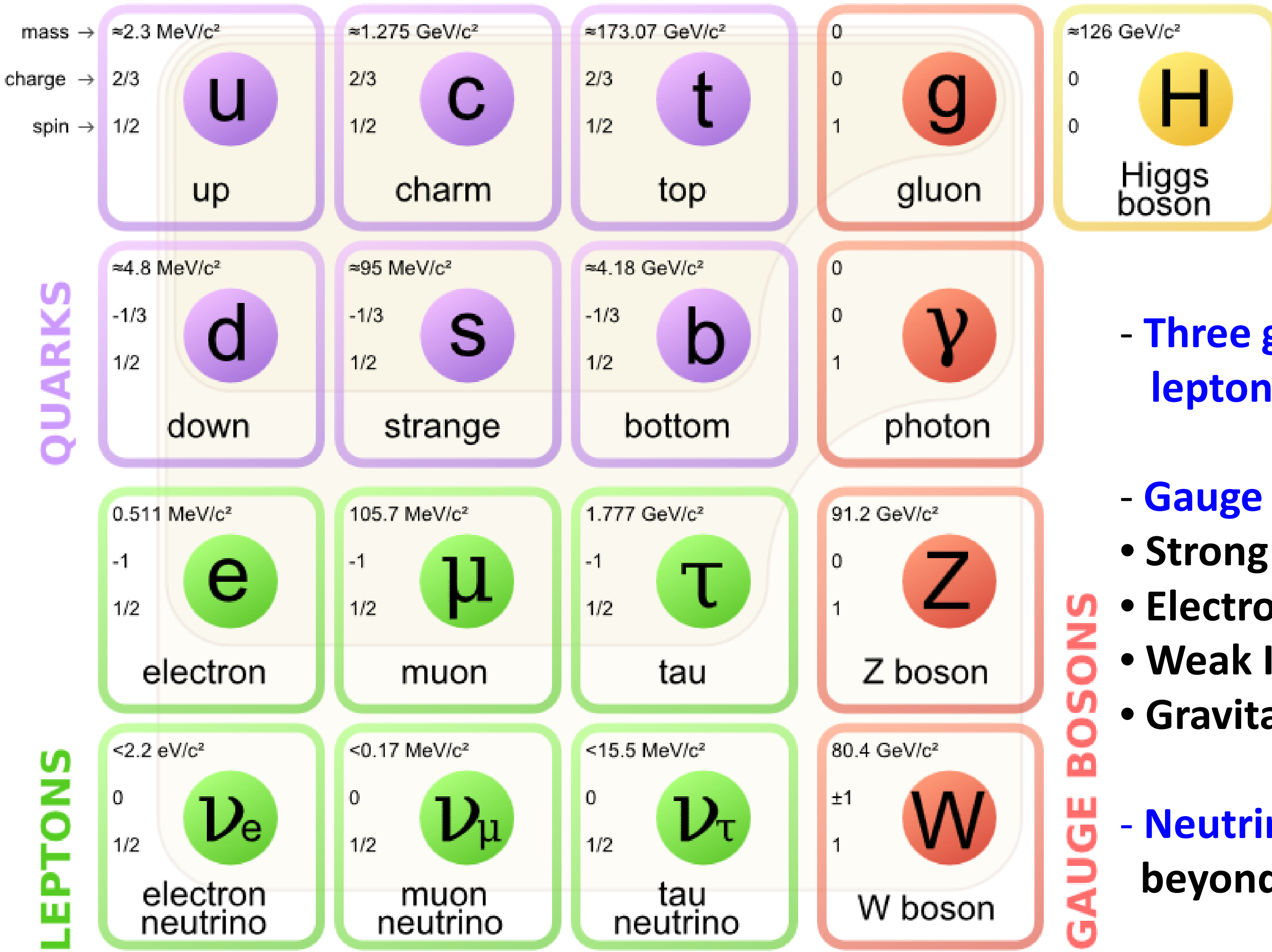




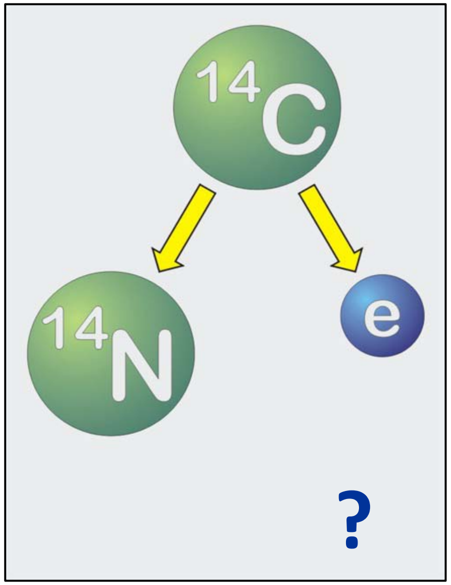
Standard Model of Elementary Particles

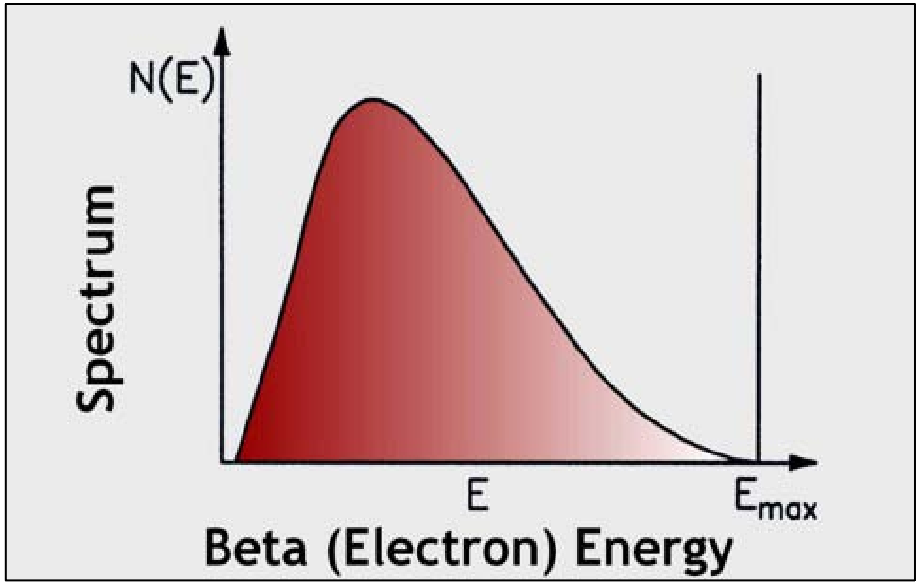
- Three generations of quarks and leptons-building blocks of matter

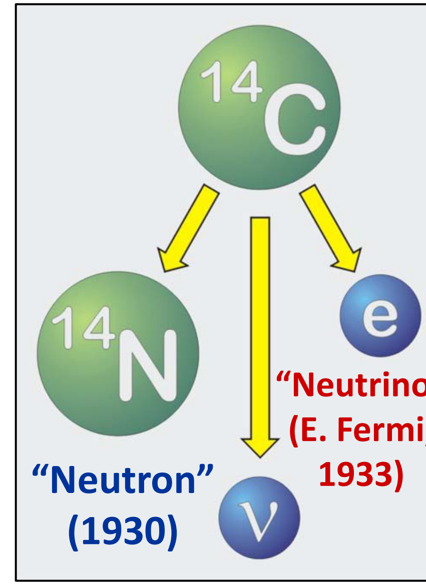
- Gauge bosons as force carriers
  - Strong Interaction (8 gluons)
  - Electromagnetic Interaction (γ)
  - Weak Interaction (W and Z)
  - Gravitation (Graviton?)

- Neutrinos are massive particles- beyond the Standard Model

Pauli's Neutrino Hypothesis







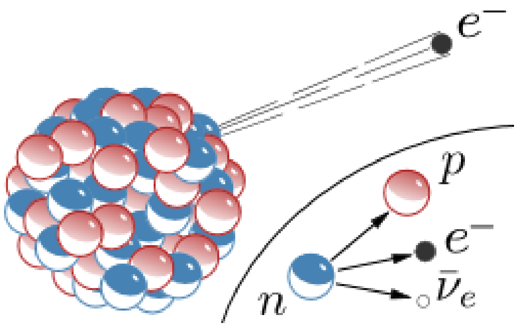
Niels Bohr
(1885-1962)
Nobel Prize 1922

Energy not conserved in the quantum domain?

Wolfgang Pauli
(1900–1958)
Nobel Prize 1945

there exist in the nuclei electrically neutral particles, that I call neutrons

Detecting Neutrinos from Nuclear Explosions?



Bethe and Peierls (1934)

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad \text{Cross section } \sigma < 10^{-44}\ \text{cm}^2$$

"It is therefore absolutely impossible to observe the processes of this kind with the neutrinos created in nuclear transformations."

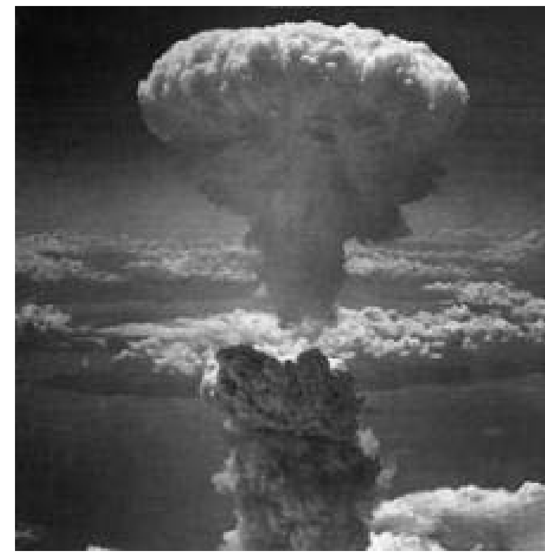
Hans A. Bethe
(1906–2005)
Nobel Prize 1967

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H + H = D + \epsilon^+. \tag{1}$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

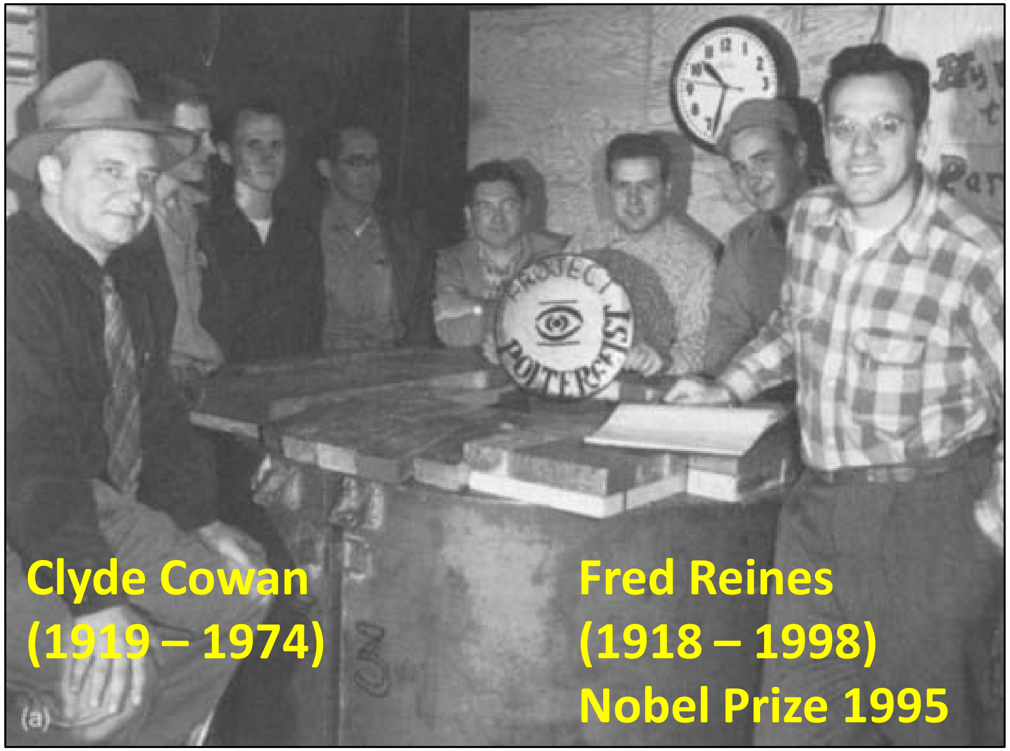
$$\begin{array}{ll} C^{12} + H = N^{13} + \gamma, & N^{13} = C^{13} + \epsilon^+ \\ C^{13} + H = N^{14} + \gamma, & \\ N^{14} + H = O^{15} + \gamma, & O^{15} = N^{15} + \epsilon^+ \\ N^{15} + H = C^{12} + He^4. & \end{array} \tag{2}$$

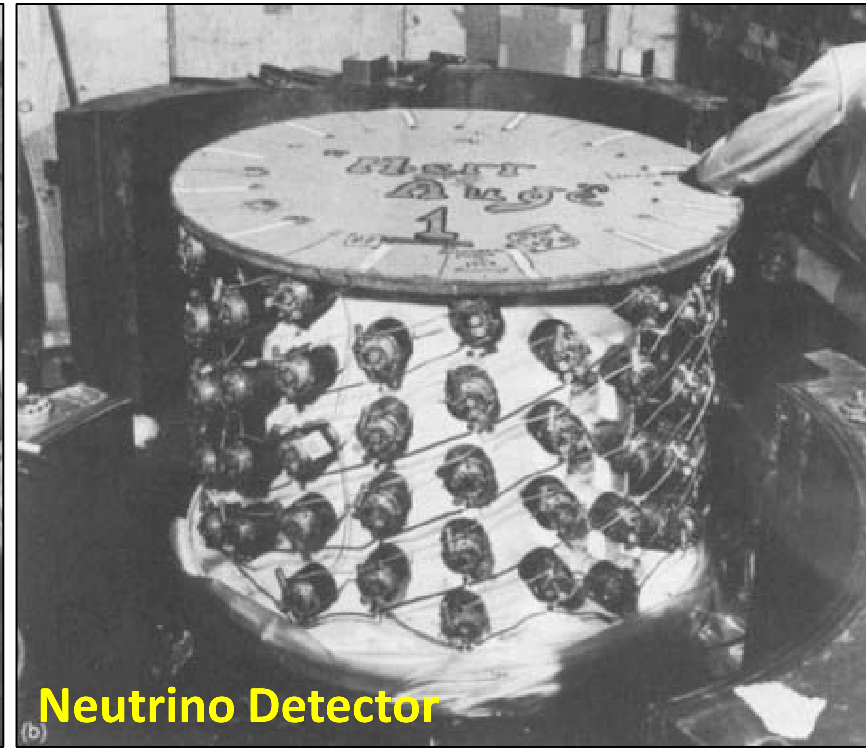


No neutrinos in Bethe's classic paper on nuclear reactions in stars (1939)

Reines to Fermi (1951): neutrino detector near 'A-bombs'?

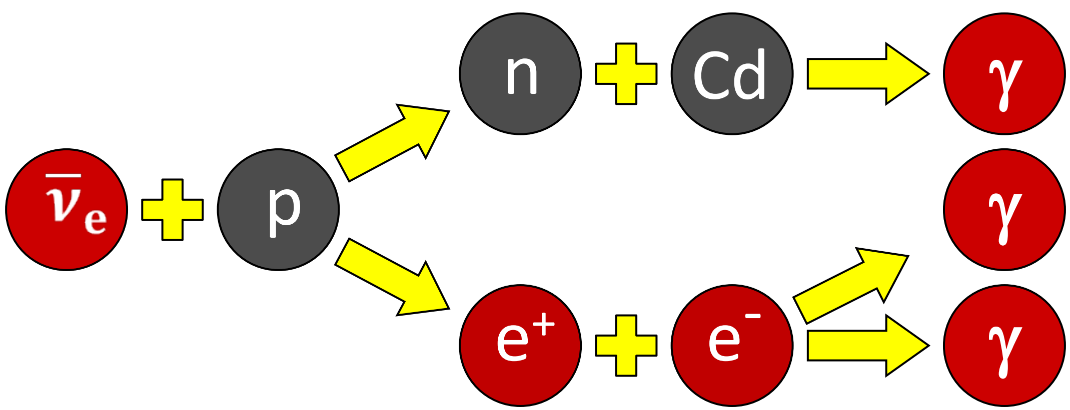
Discovery of Reactor Neutrinos 1954-1956





Gave up 'A-bombs'

Hanford Nuclear Reactor

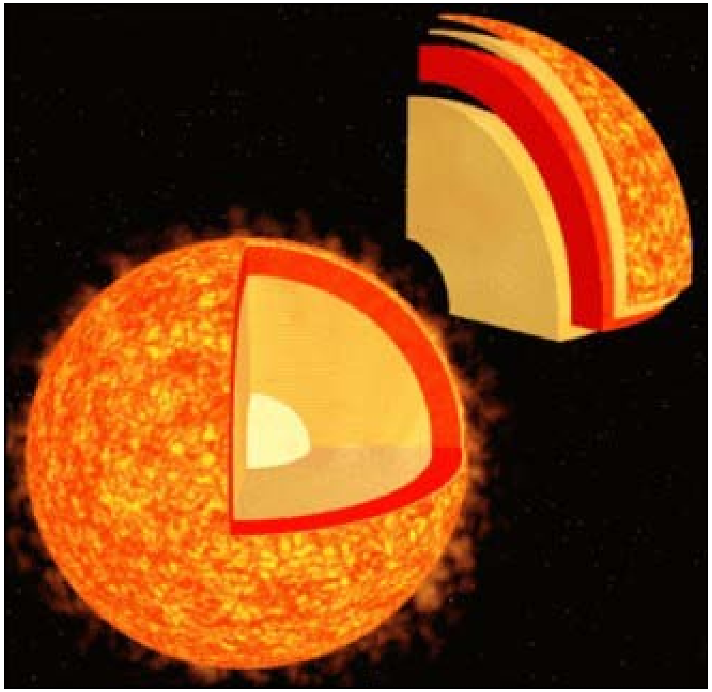


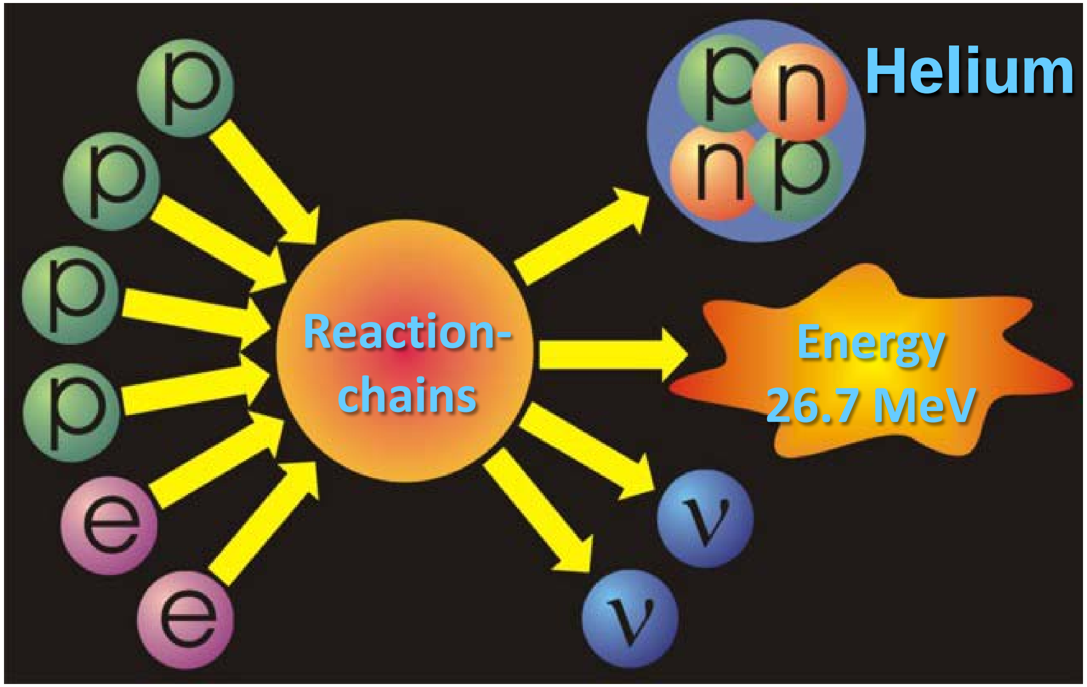
three Gammas

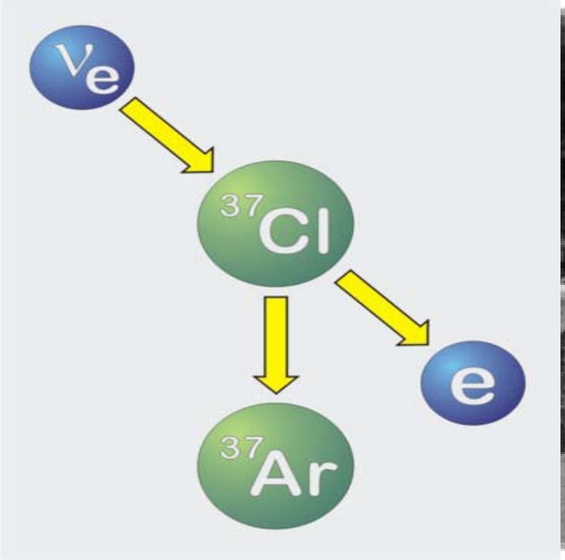
5 μs delay of γ from n capture on Cadmium

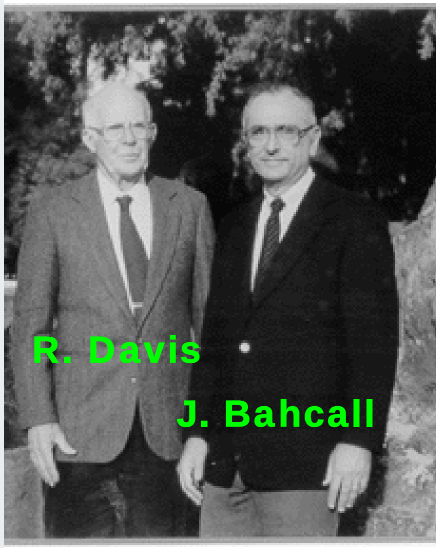
time coincidence

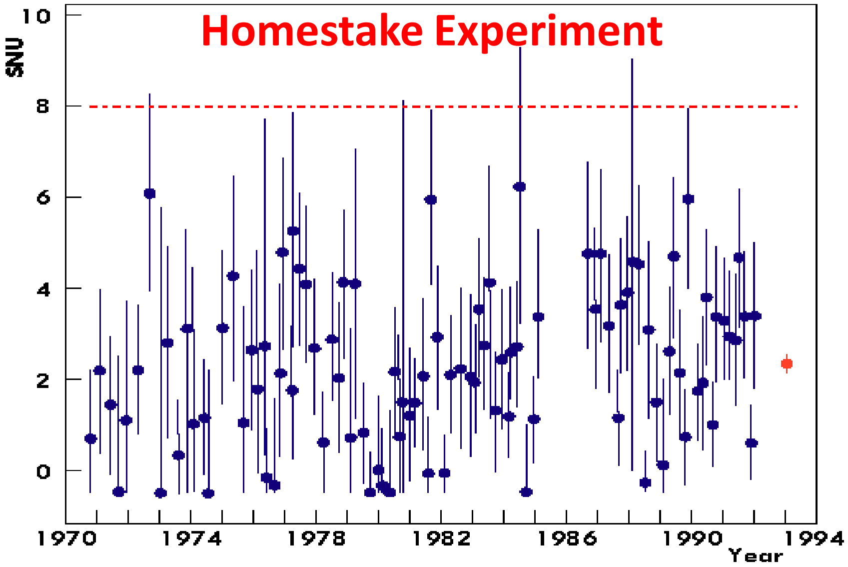
Discovery of Solar Neutrinos (1968)



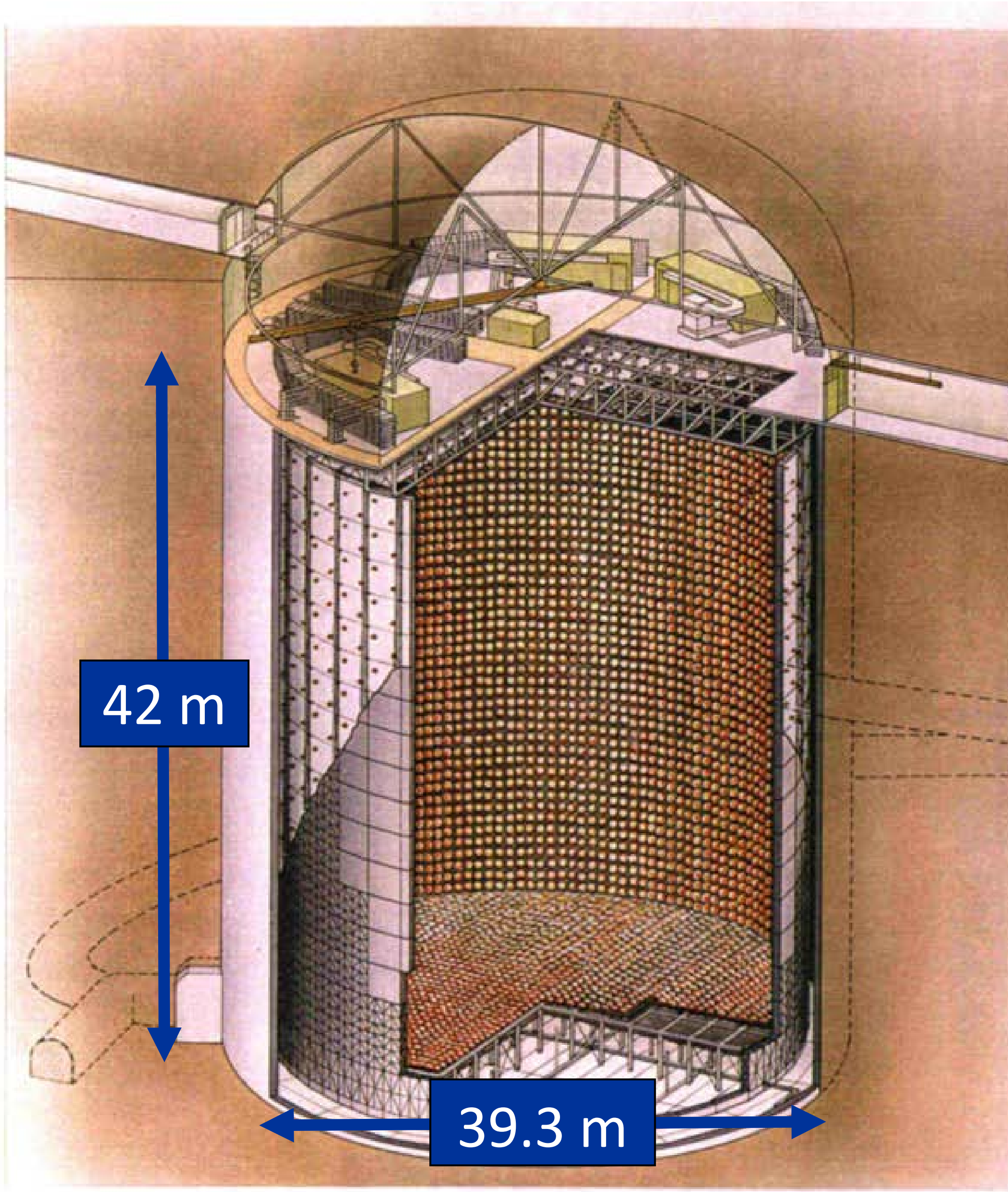


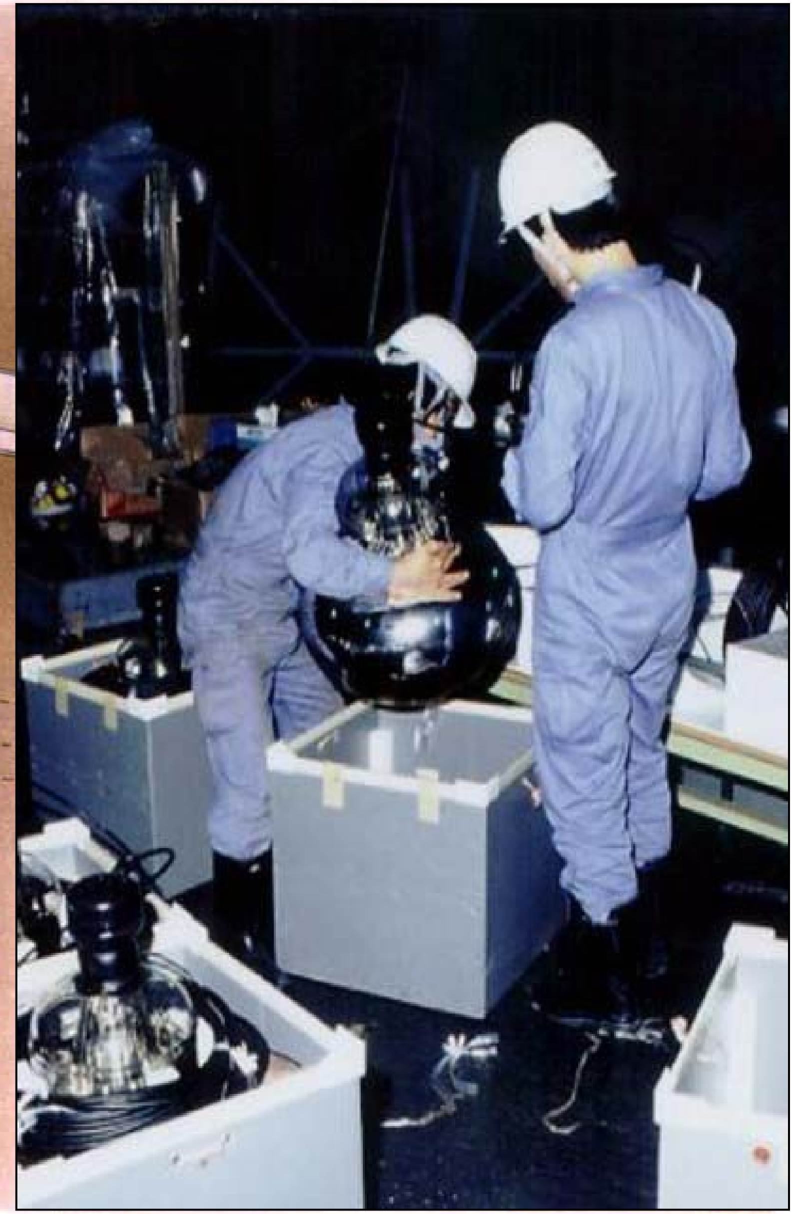




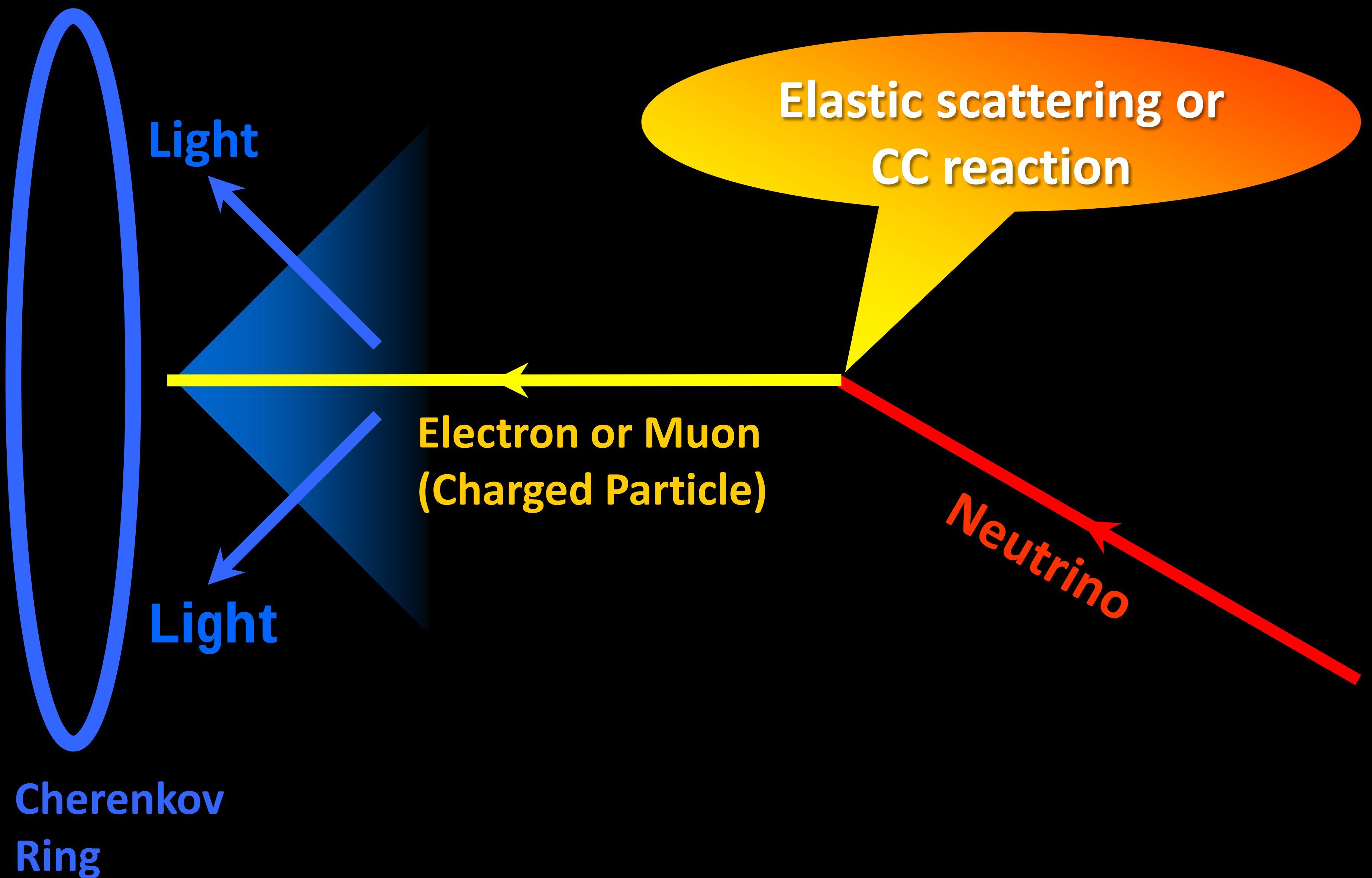


Super-Kamiokande Neutrino Detector (since 1996)

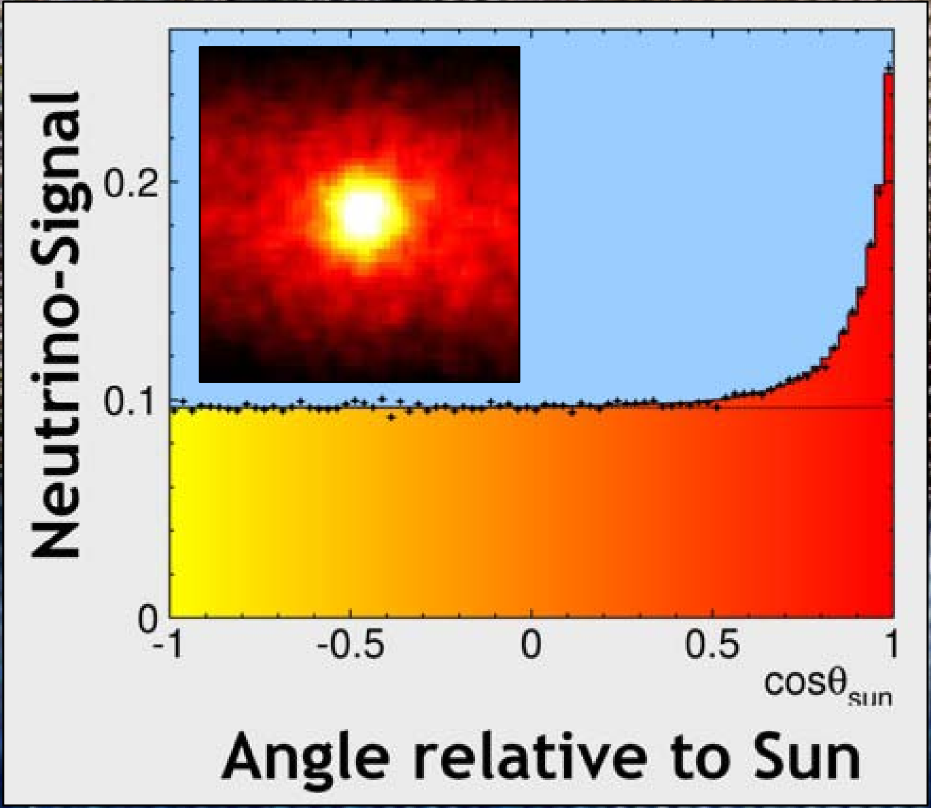


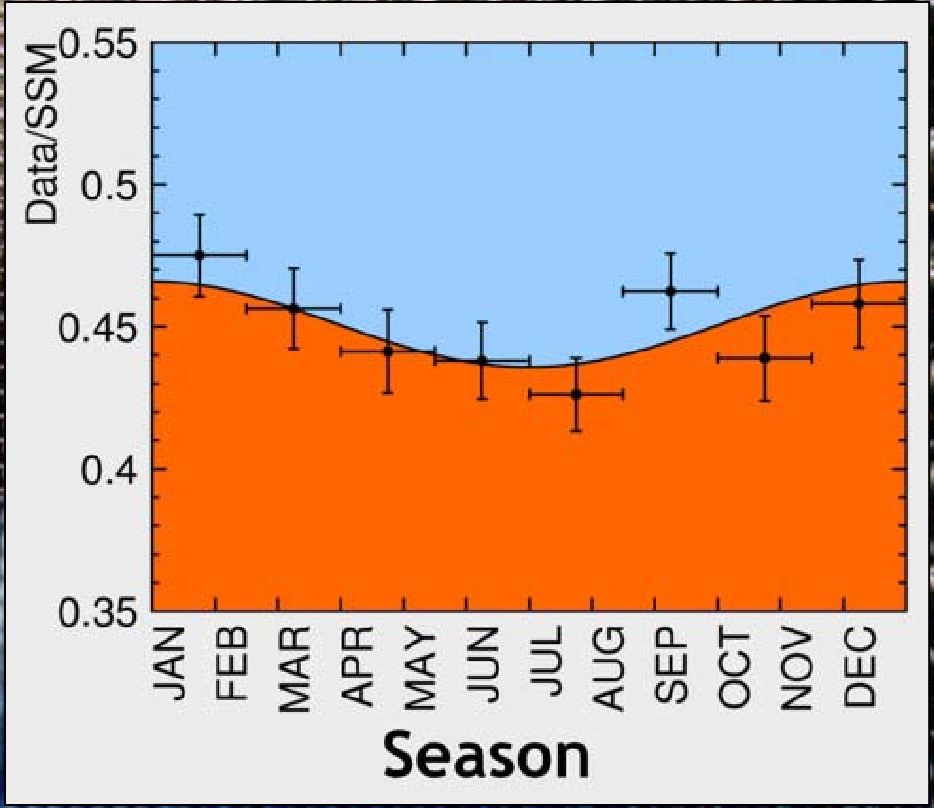


Cherenkov Detectors



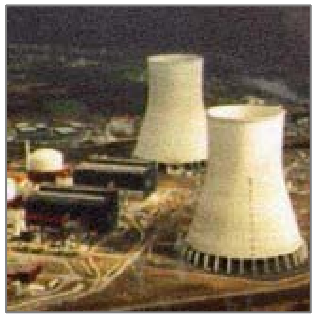
Super-Kamiokande : Image of the Sun in Neutrino Light



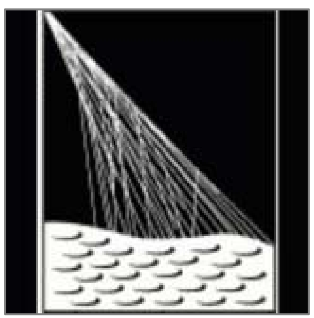


Neutrino Sources in Nature

Particle Accelerators

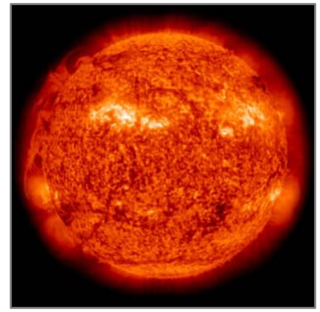


Nuclear Reactors

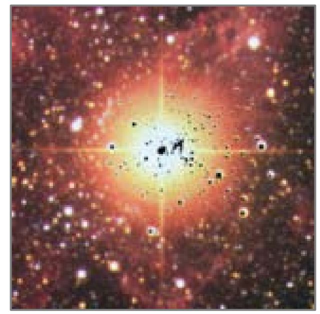


Cosmic rays
@ the Earth
Atmosphere

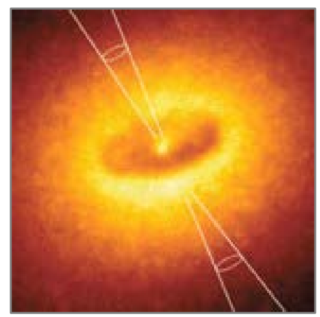
Natural radioactivity
in the Earth Crust



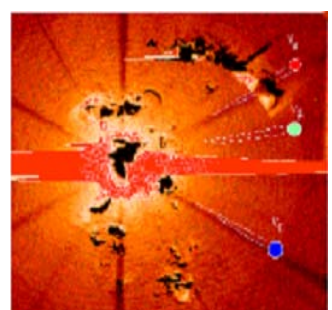
Nuclear Fusion
in the Sun

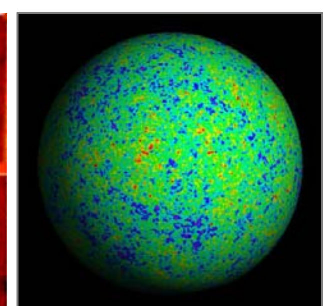


Supernova Explosion
SN 1987A



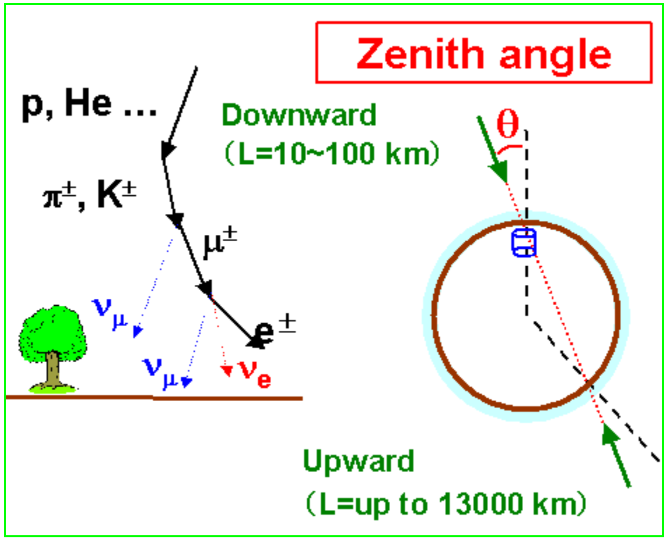
Cosmic Accelerators ?
3 UHE neutrino events
@ IceCube



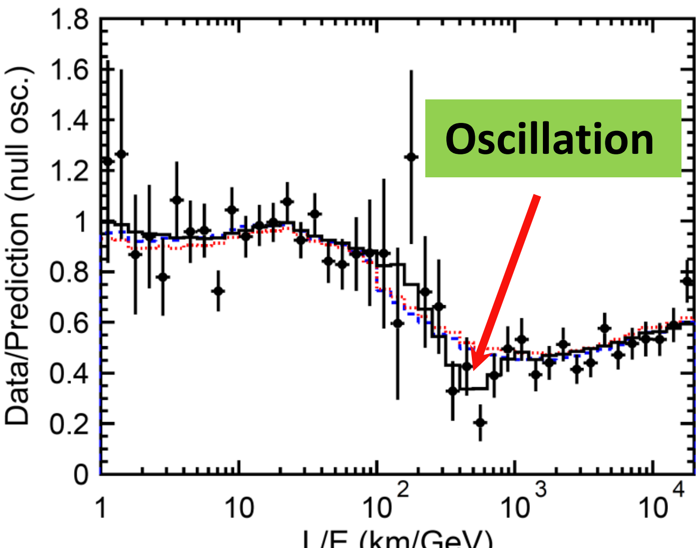


Big Bang
(Indirect
Evidence)

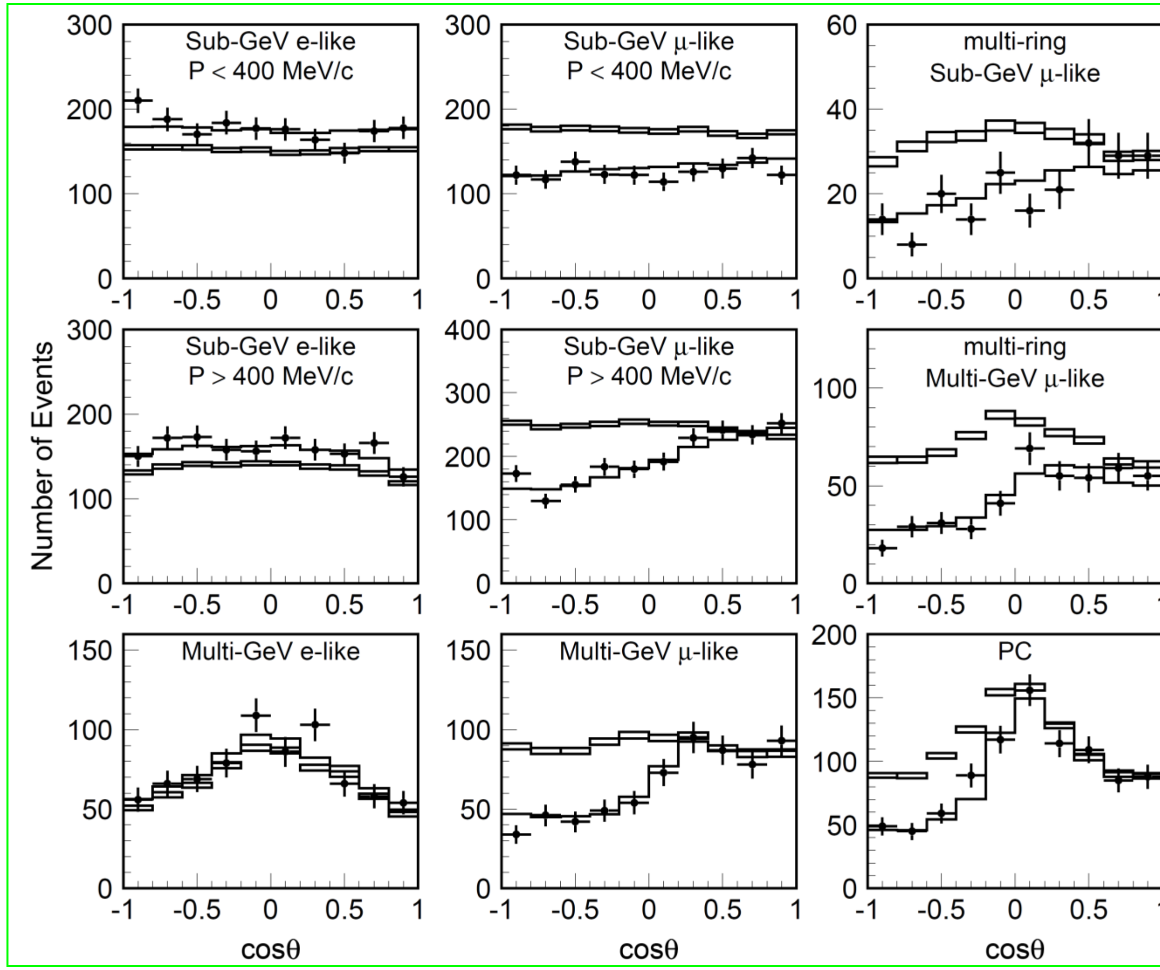
Discovery of Neutrino Oscillations



L/E Significance



Angular Distribution of Events



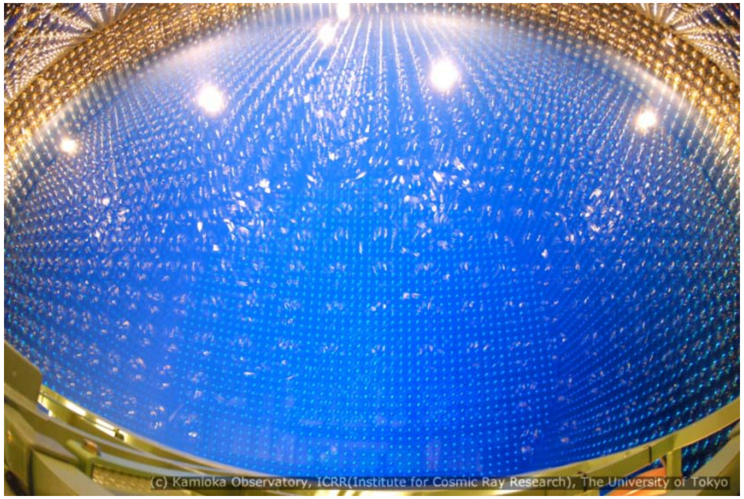
~13000 km ~500 km ~15 km

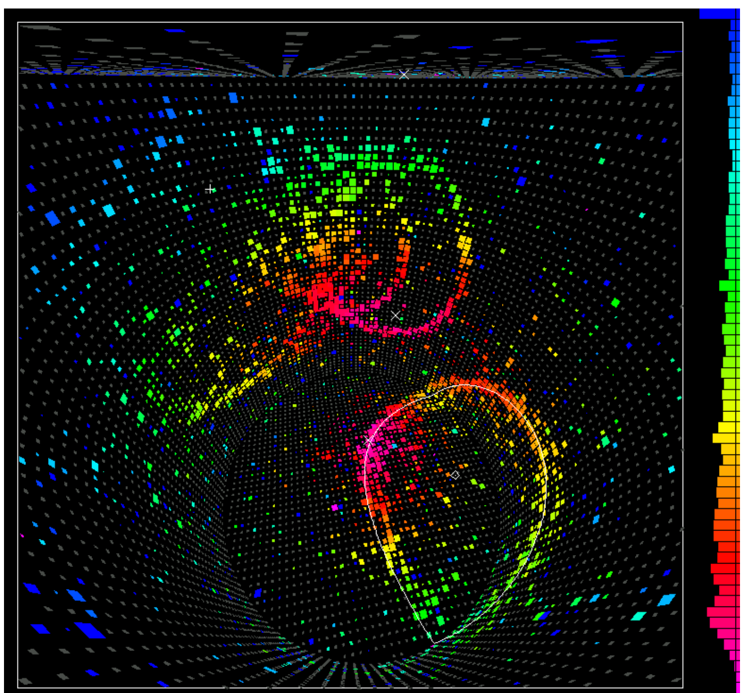
Super-Kamiokande 1998, 2005

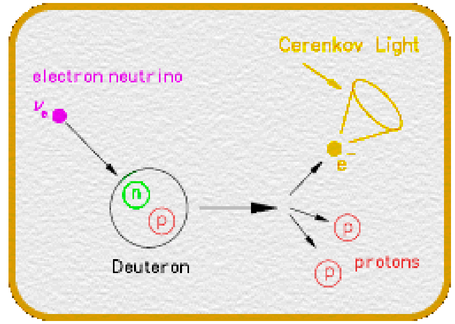
Discovery of Neutrino Oscillations

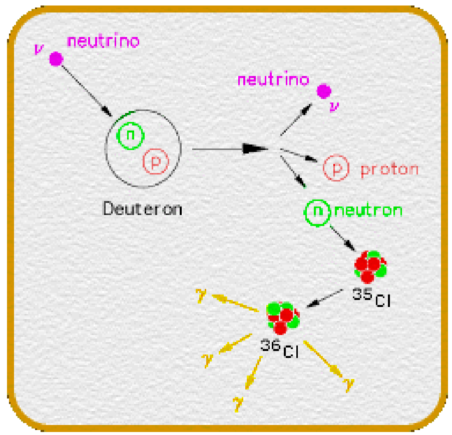
Super-Kamiokande Experiment

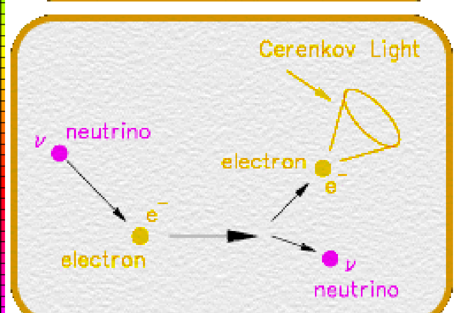
$$\nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$$









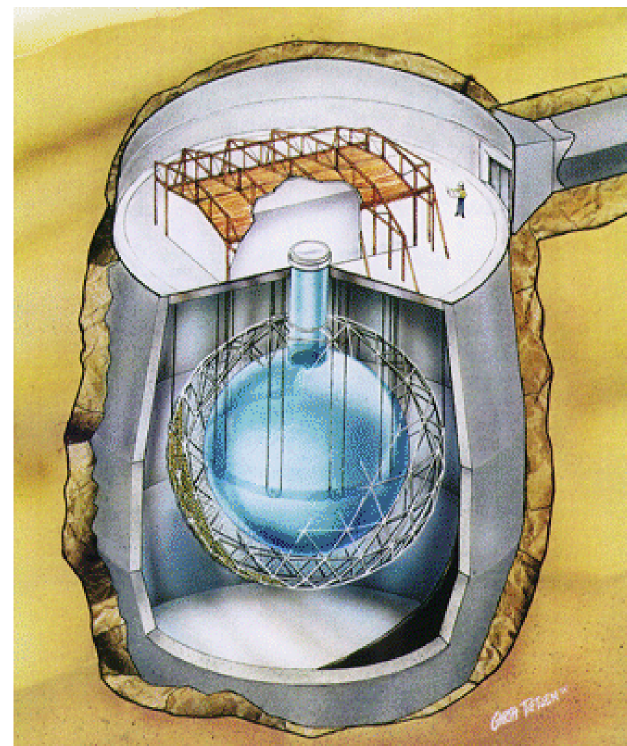


SNO Experiment

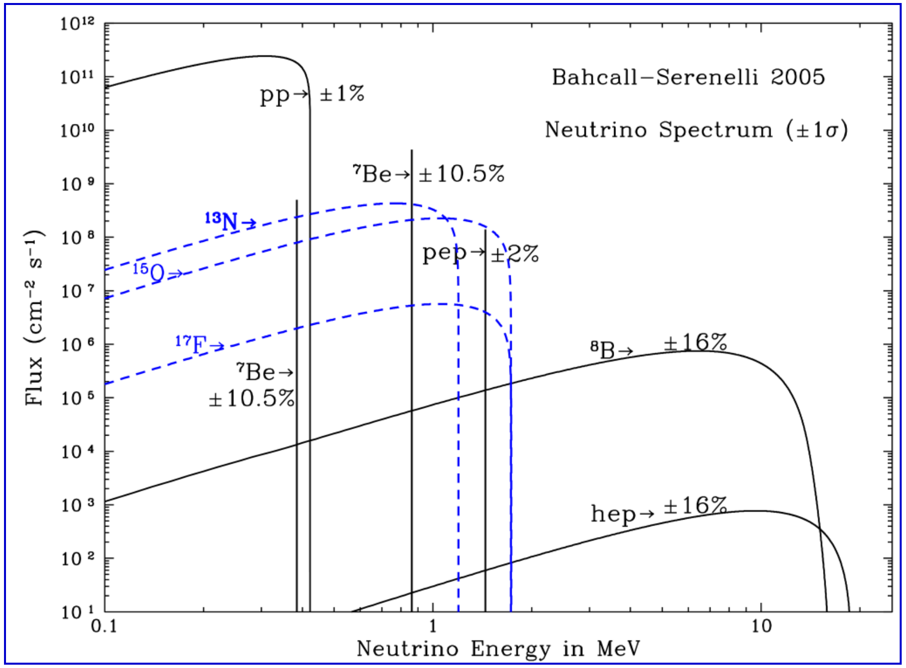
$$\text{CC}: \quad \nu_e + d \rightarrow p + p + e^-$$

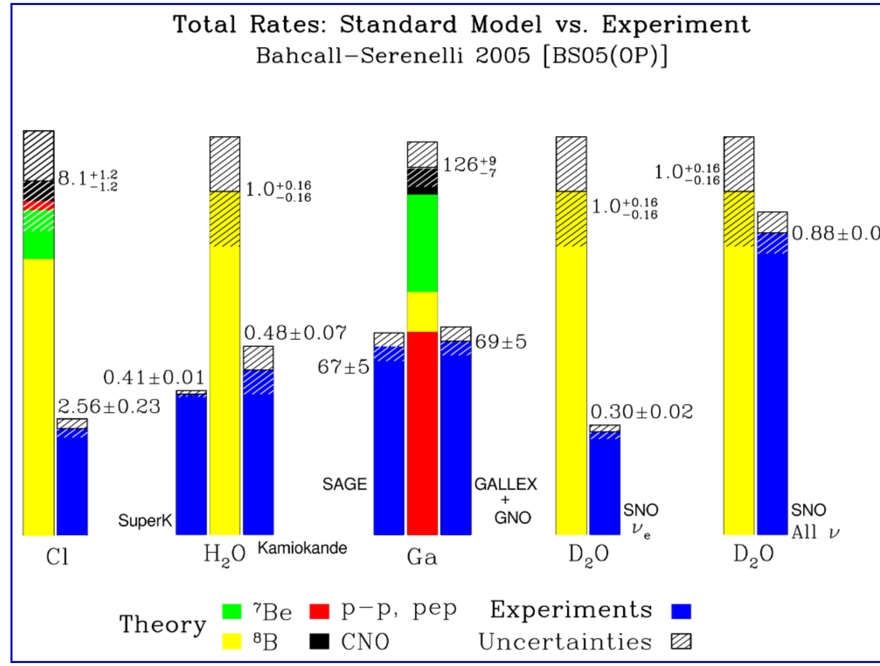
$$\text{NC}: \quad \nu_\alpha + d \rightarrow p + n + \nu_\alpha$$

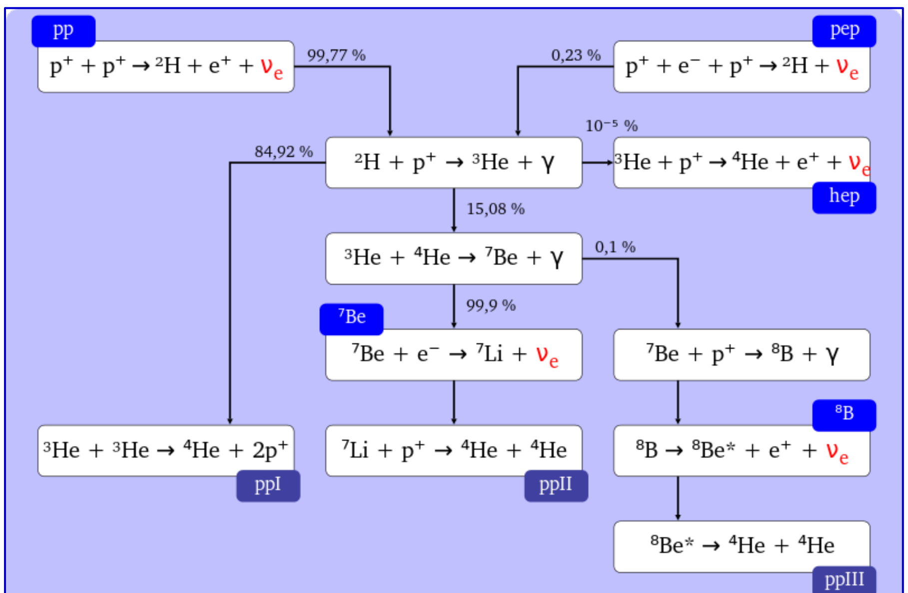
$$\text{ES}: \quad \nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$$

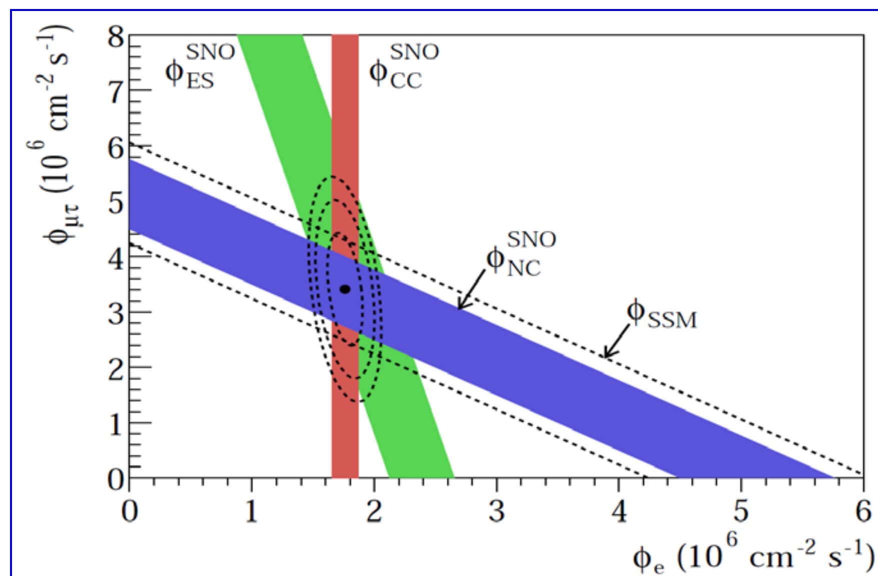


Solar Neutrino Experiments



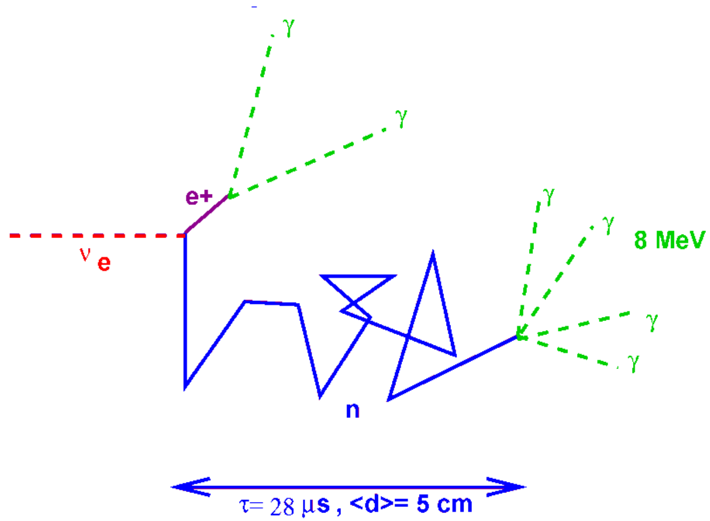


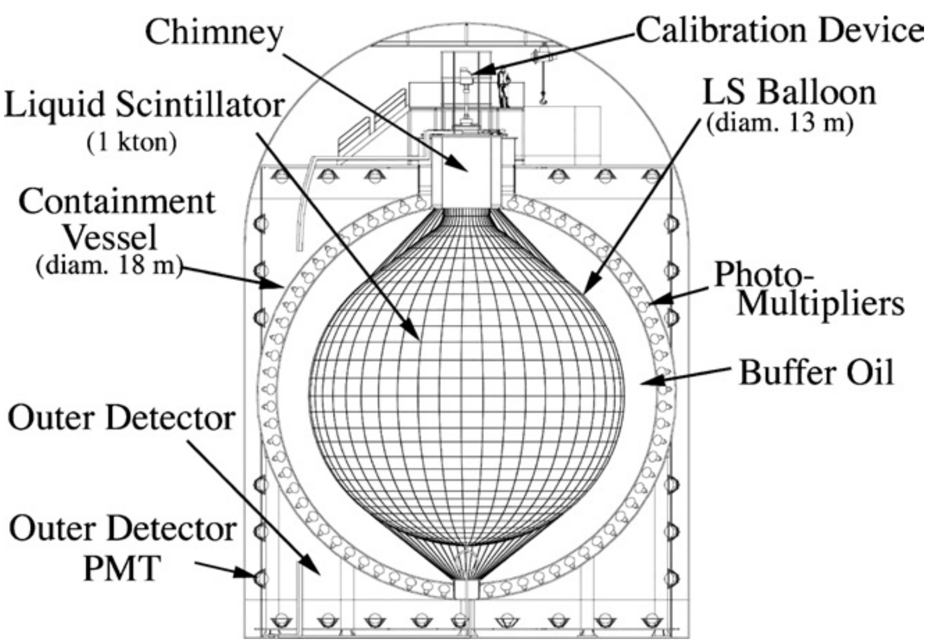


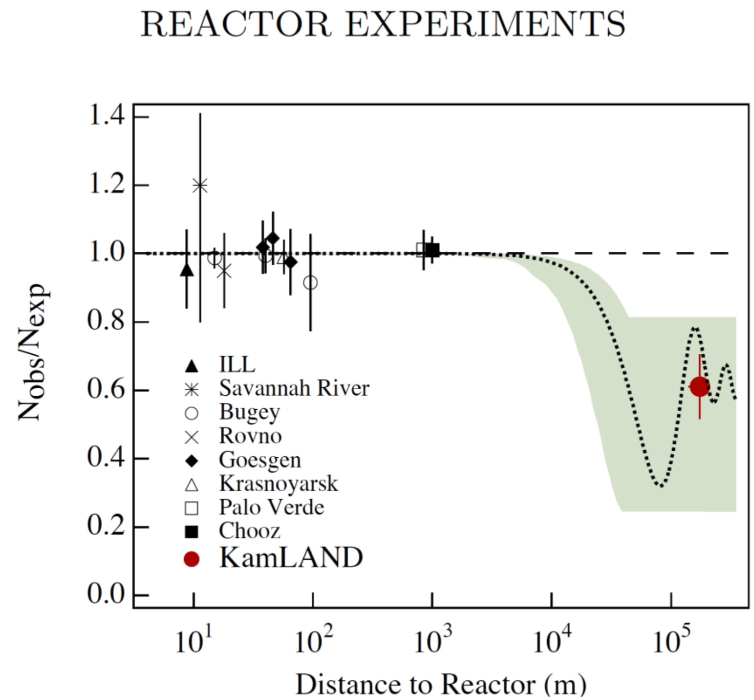


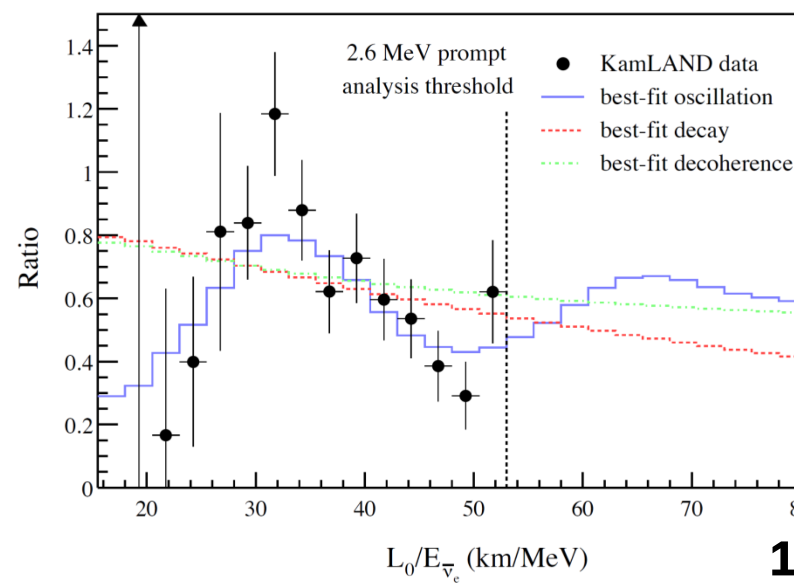
Reactor Neutrino Experiments

$$\overline{\nu_e} + p \rightarrow e^+ + n$$

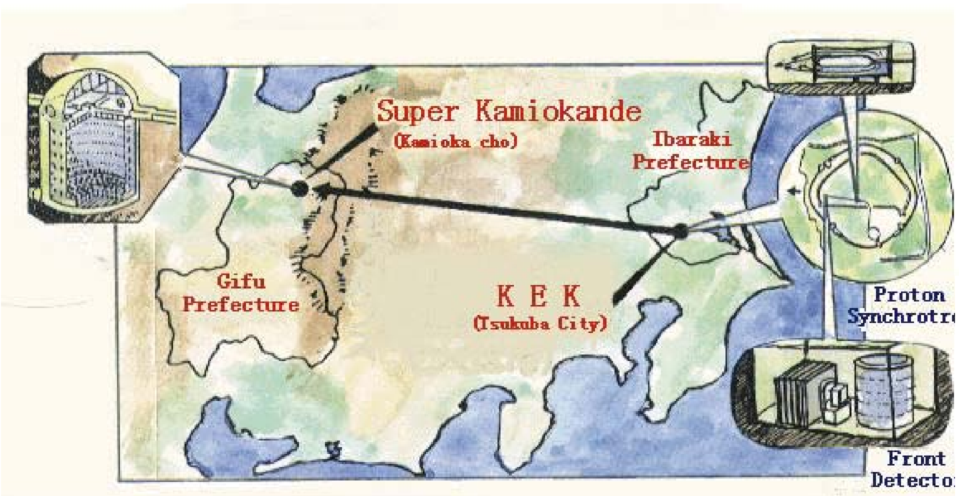


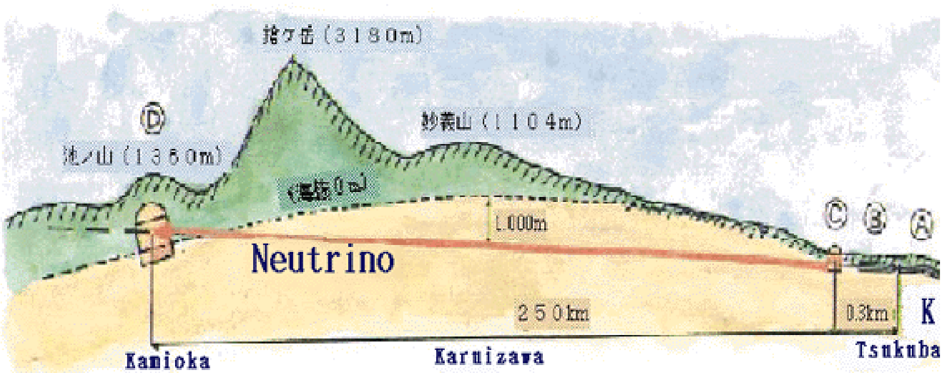






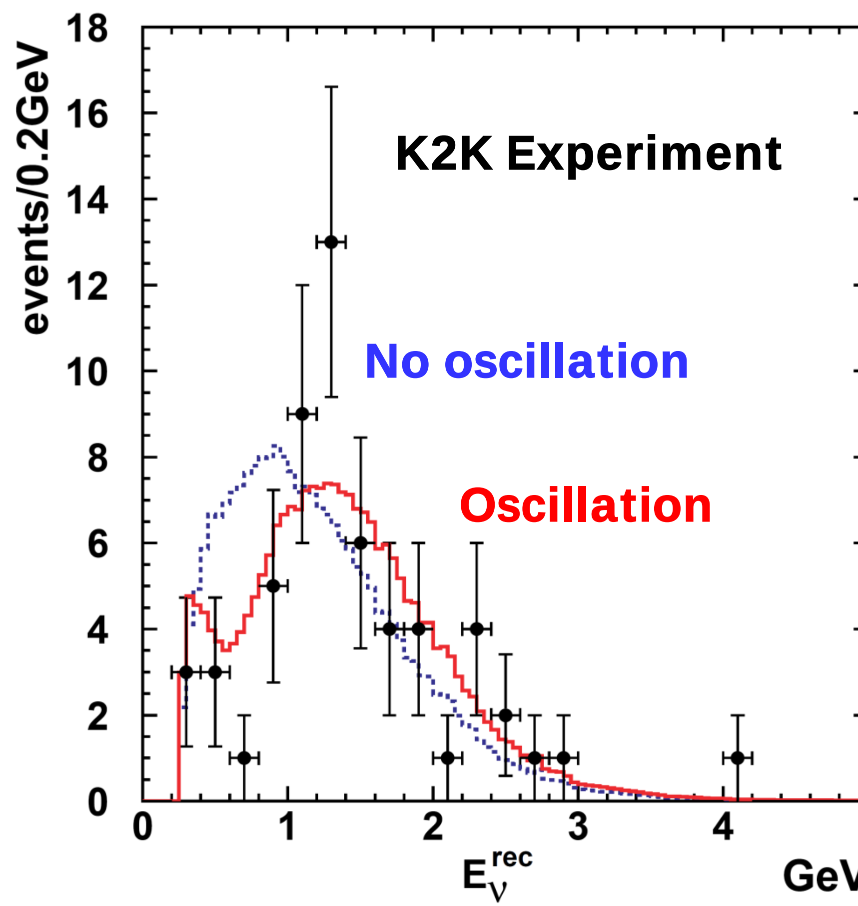
Accelerator Neutrino Experiments





From KEK to Super-Kamiokande

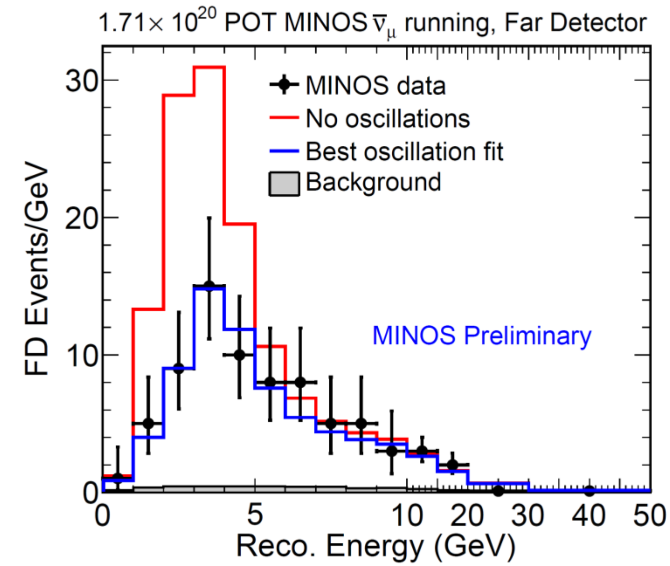
E ~ 1.3 GeV, L ~ 250 km

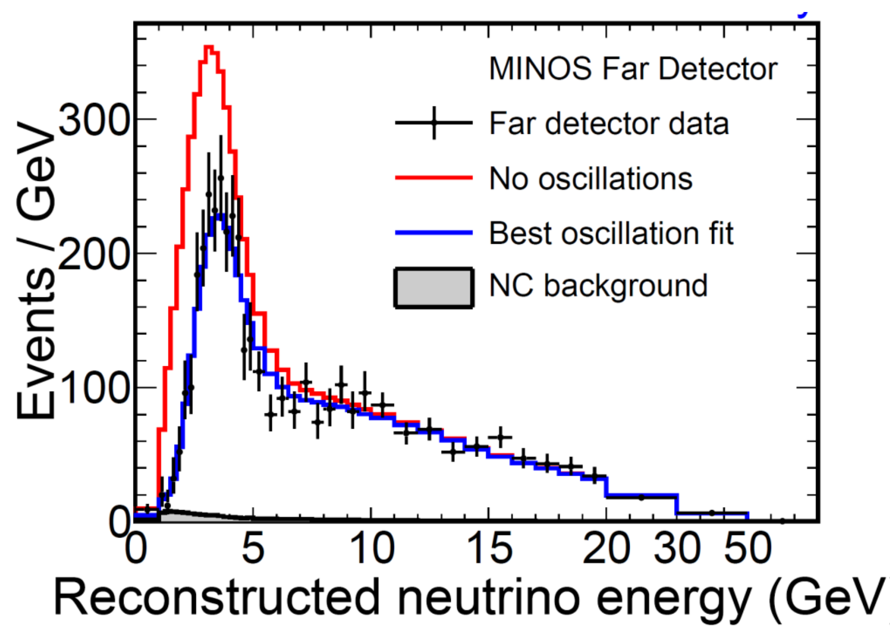


Accelerator Neutrino Experiments

MINOS Experiment

E ~ 3 GeV, L ~ 735 km



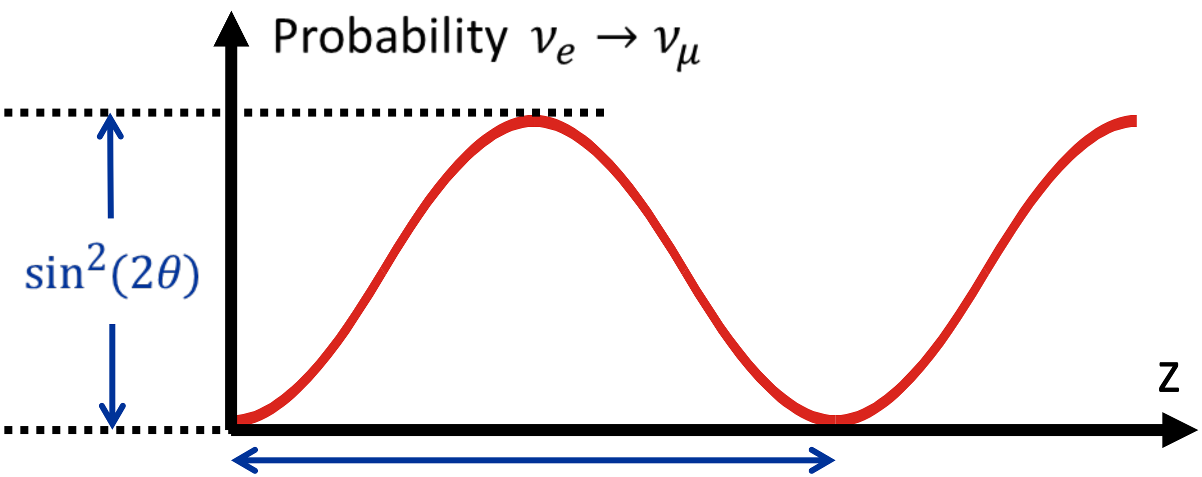


Neutrino Flavor Oscillations

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

Pontecorvo, 1957; Maki, Nakagawa, Sakata, 1962

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

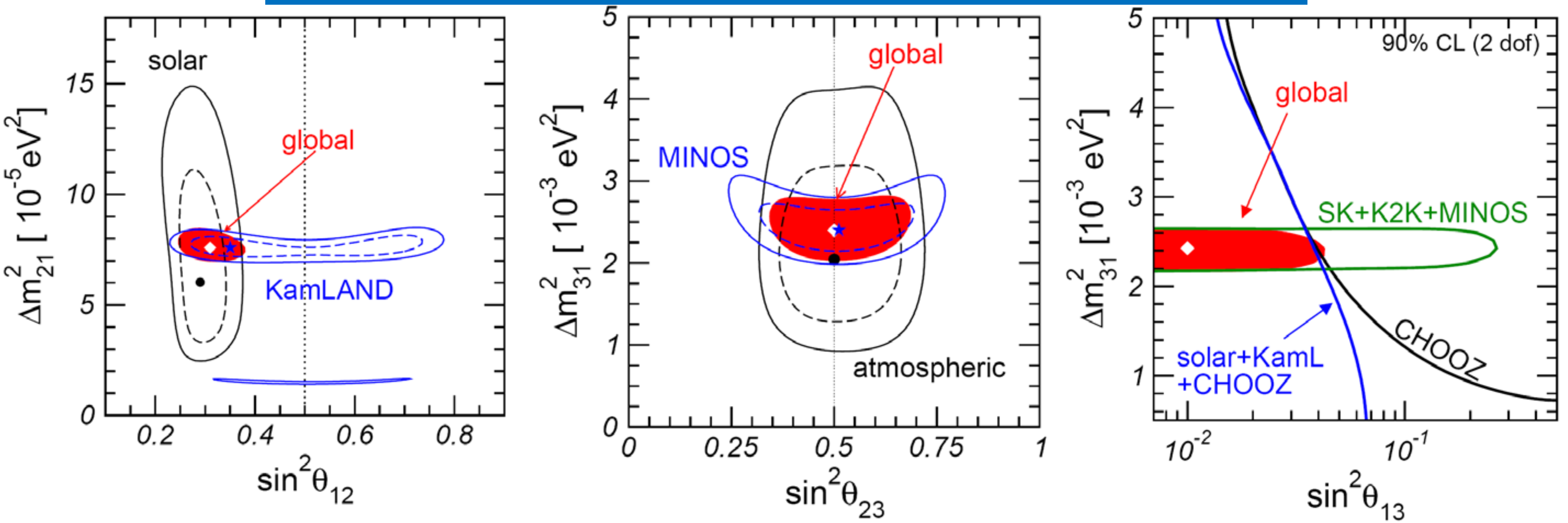


Oscillation Length $\dfrac{4\pi E}{\delta m^2} = 2.5\ \mathrm{m}\ \dfrac{E}{\mathrm{MeV}}\left(\dfrac{\mathrm{eV}}{\delta m}\right)^2$

Neutrino Oscillations: quantum phenomena of massive neutrinos at the macroscopic distances

What we have learned about neutrinos

Global Analysis of Neutrino Oscillation Experiments



Schwetz et al., NJP 2008

No direct evidence for a nonzero ϑ_{13}

parameter	best fit	2σ	3σ
Δm^2_{21} [10^{-5}eV^2]	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2]	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

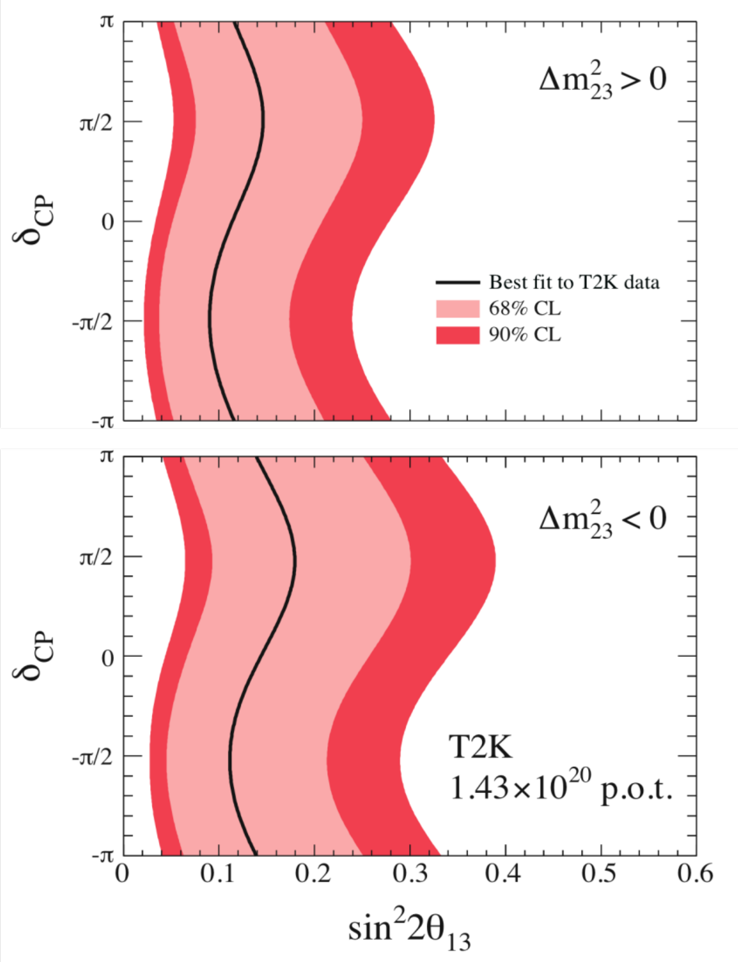
0.9σ

θ_{12}=33.5º, θ_{23}=45º, θ_{13}=5.7º

What we have learned about neutrinos

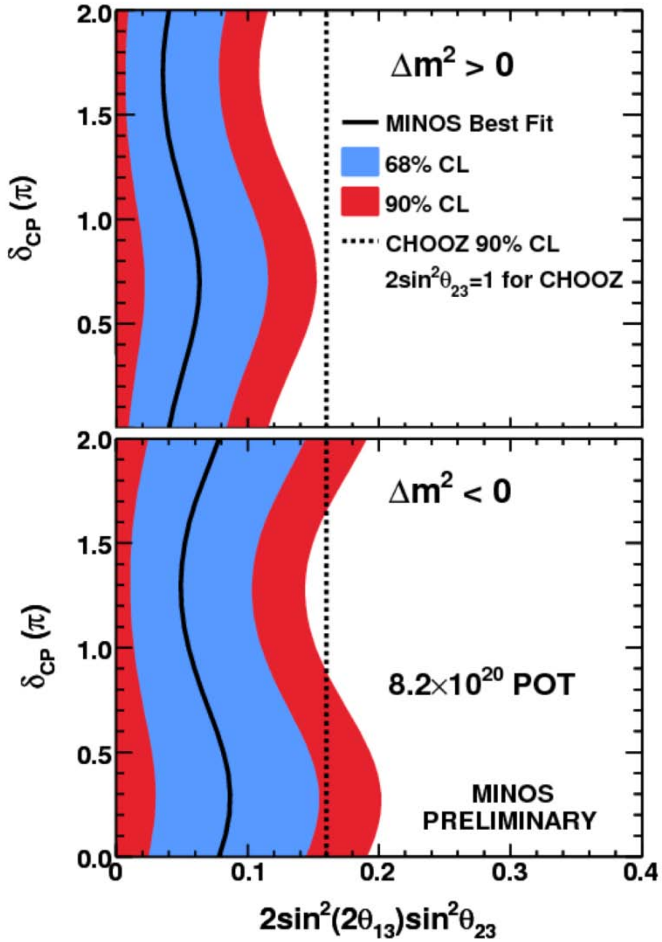
June 2011 breakthrough: Appearance results from T2K and MINOS

T2K



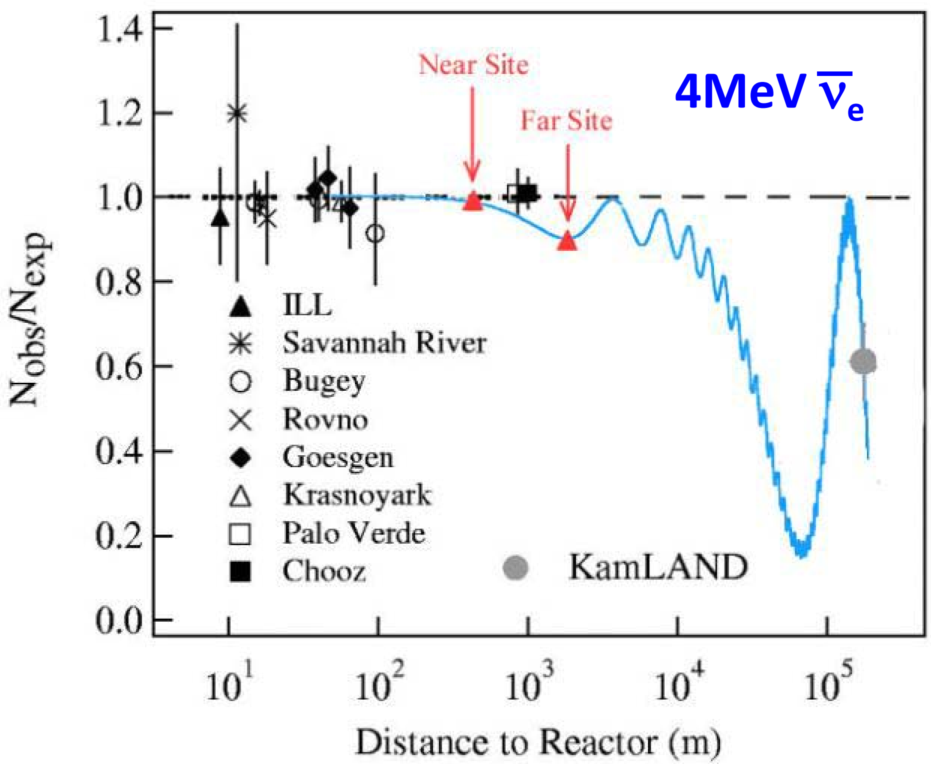
2.5σ

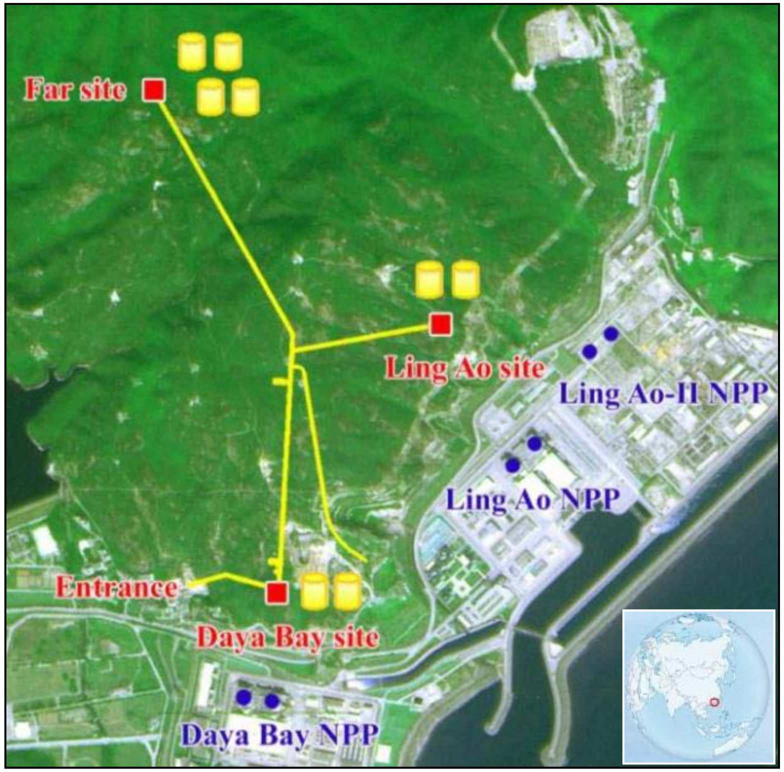
MINOS



1.7σ

What we have learned about neutrinos





Dec. 2011	**Double Chooz (far detector):**	$\sin^2\theta_{13} = 0.022 \pm 0.013$	**1.7σ**
Mar. 2012	**Daya Bay (near + far detectors):**	$\sin^2\theta_{13} = 0.024 \pm 0.004$	**5.2σ**
Apr. 2012	**RENO (near + far detectors):**	$\sin^2\theta_{13} = 0.029 \pm 0.006$	**4.9σ**

What we have learned about neutrinos

θ_{13} = 0 is now excluded at 8σ ! Forero et al., 1205.4018

parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.62 ± 0.19	7.27–8.01	7.12–8.20
Δm^2_{31} $[10^{-3}\text{eV}^2]$	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$	$2.34 - 2.69$ $-(2.25 - 2.59)$	$2.26 - 2.77$ $-(2.15 - 2.68)$
$\sin^2\theta_{12}$	$0.320^{+0.015}_{-0.017}$	0.29–0.35	0.27–0.37
$\sin^2\theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.05}_{-0.07}$	0.41–0.62 0.42–0.62	0.39–0.64
$\sin^2\theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$	0.019–0.033 0.020–0.034	0.015–0.036 0.016–0.037
δ	$\left(0.83^{+0.54}_{-0.64}\right)\pi$ 0.07π [a]	$0 - 2\pi$	$0 - 2\pi$

θ_{12}=34°, θ_{23}=44° (46°), θ_{13}=9°

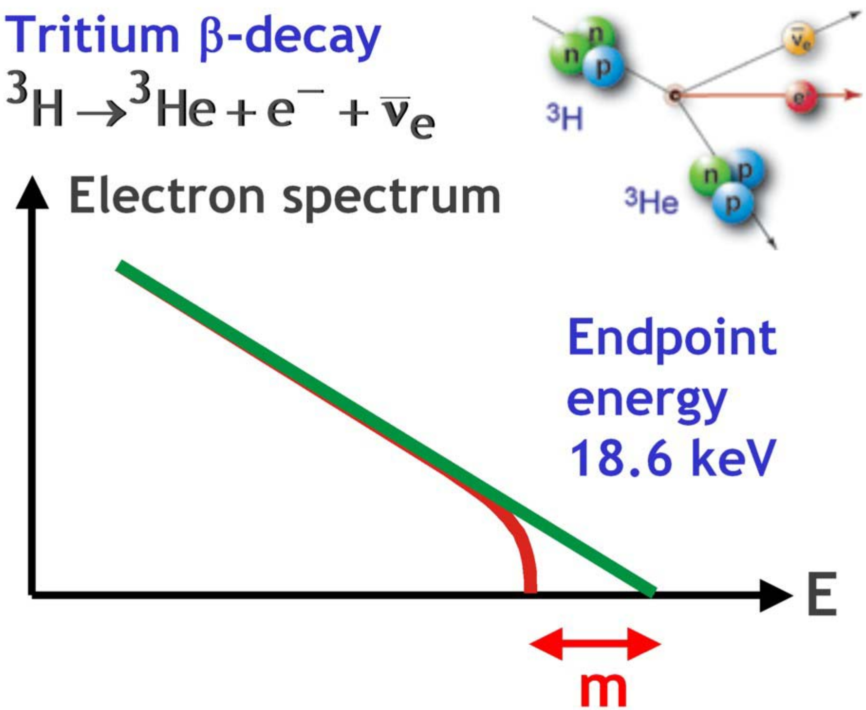
To know more about ν's

- ★ Absolute Neutrino Masses?
- ★ Majorana or Dirac Particles?
- ★ More Neutrino Species?
- ★ Origin of Neutrino Masses?
- ★ Origin of Large Flavor Mixing?
- ★ Origin of CP Violation?

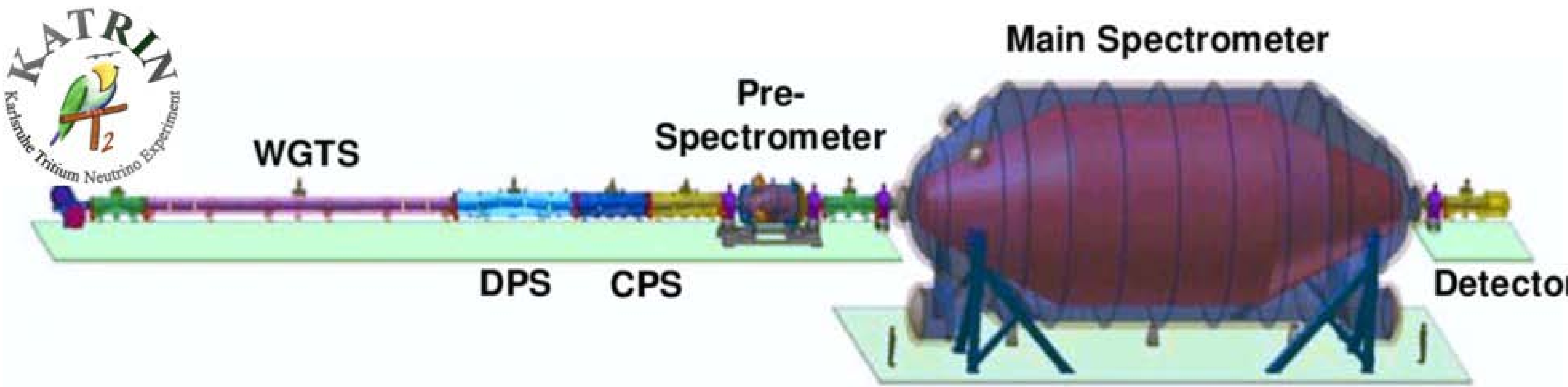
Now that θ_{13} is relatively large, what's next ?

1. **Mass Ordering: $\Delta m^2_{31} > 0$ (Normal) or $\Delta m^2_{31} < 0$ (Inverted)?**
2. **Leptonic CP Violation: What is the value of CP Phase δ ?**

Tritium Beta Decay: Absolute Neutrino Masses



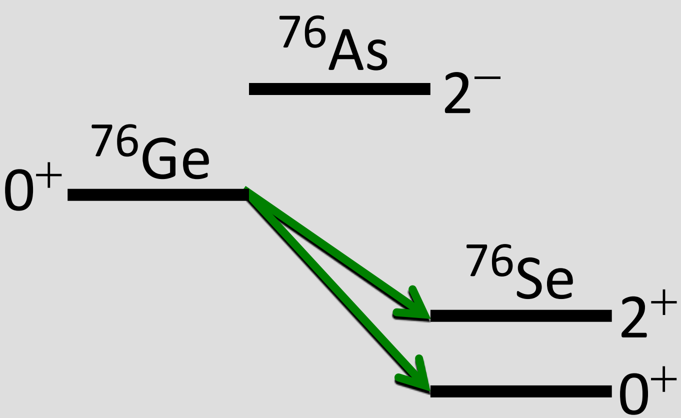
- Sensitive to common mass scale m for all flavors because of small mass differences from oscillations
- Best limit from Mainz and Troitsk
  m < 2.2 eV (95% CL)
- KATRIN can reach 0.2 eV
- Under construction
- Data taking to begin 2015/16
- http://www.katrin.kit.edu



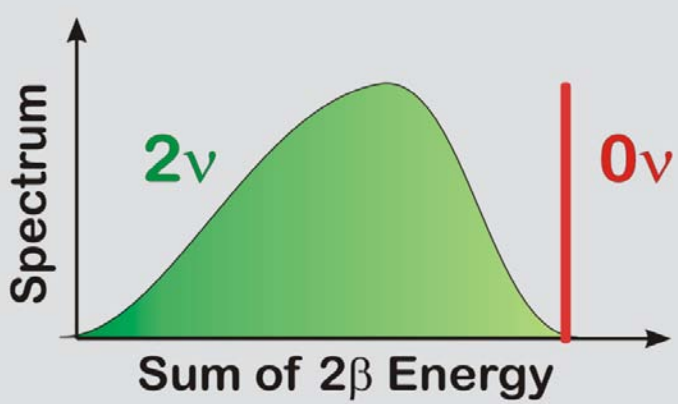
KATRIN: So Near, and Yet So Far

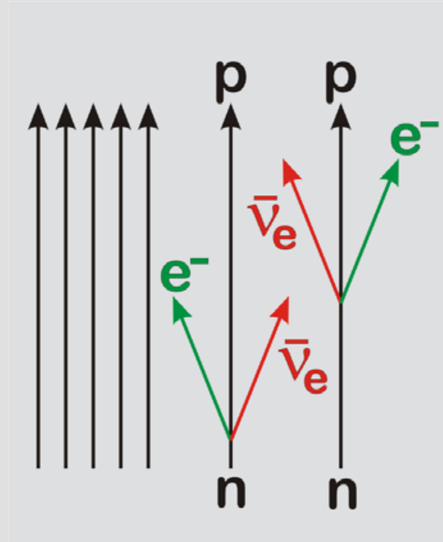
Neutrinoless Double-Beta Decay: Majorana vs. Dirac

Some nuclei decay only by the ββ mode, e.g. Ge-76

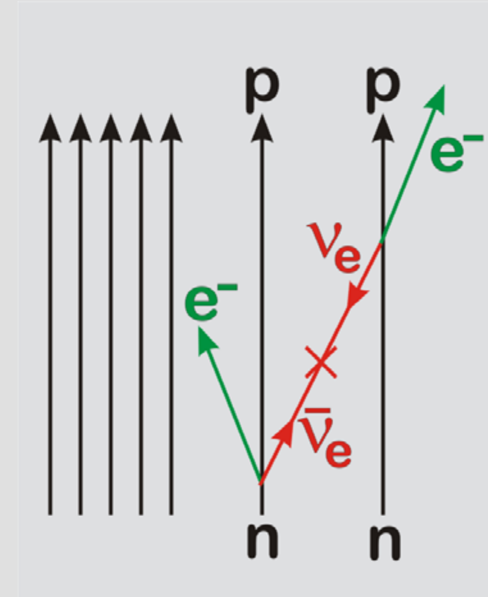


Half life ~ 10^{21} yr





Standard 2ν mode



0ν mode, enabled by Majorana mass

Measured quantity

$$|m_{ee}| = \left|\sum_{i=1}^{N} \lambda_i |U_{ei}|^2 m_i\right|$$

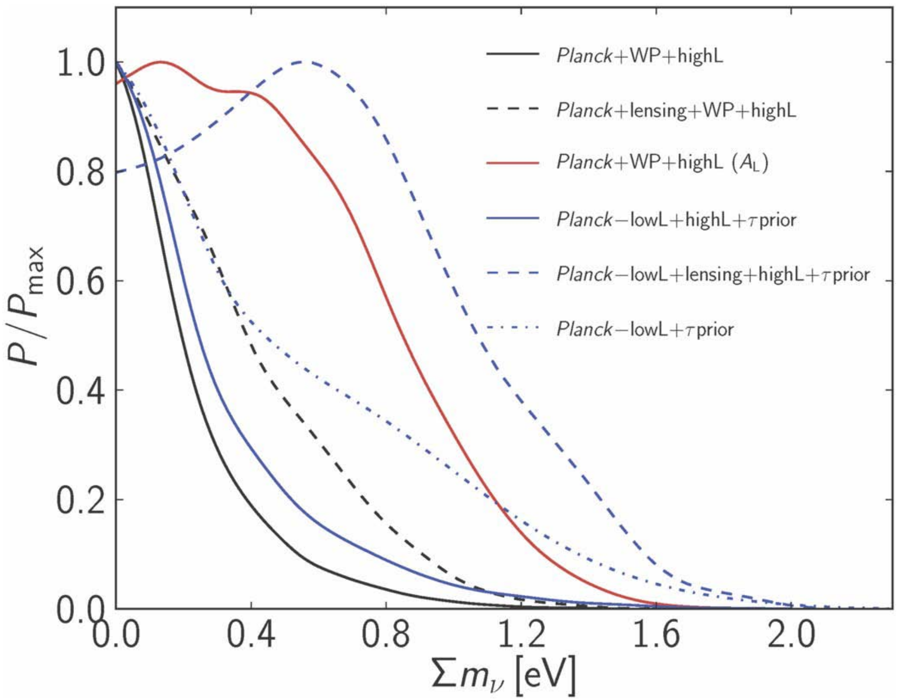
Best limit from ^{76}Ge

$$|m_{ee}| < 0.35\ \text{eV}$$

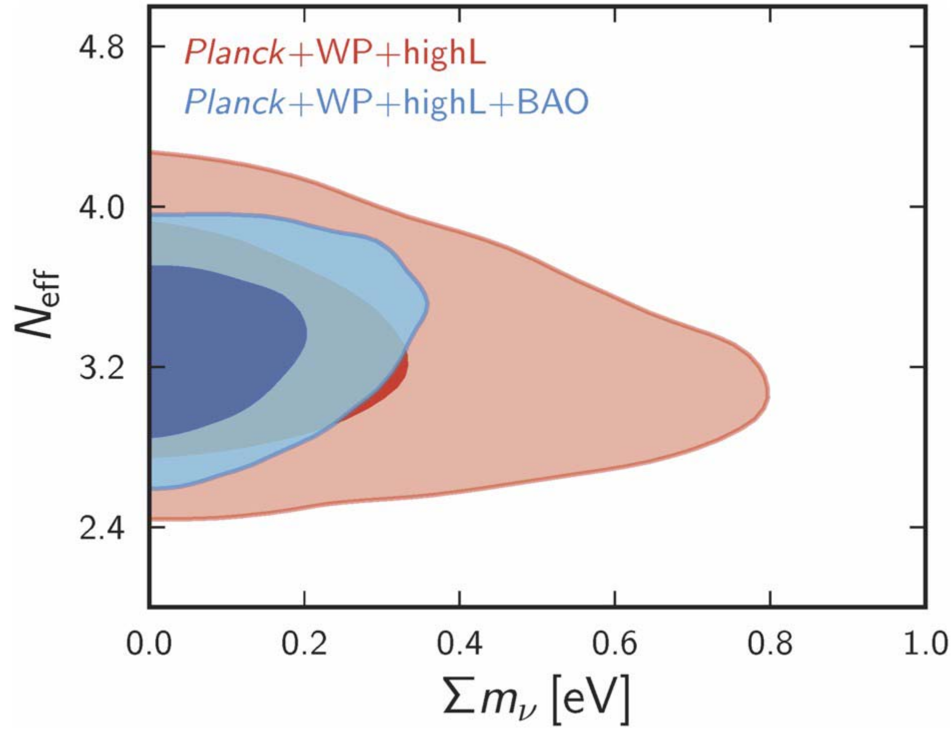
Cosmological Limit on Neutrino Masses

Cosmic background neutrinos: 112 neutrinos and anti-neutrinos per flavor per cubic centimeter, next to relic photons from the Big Bang

CMB alone constraining Σm_ν



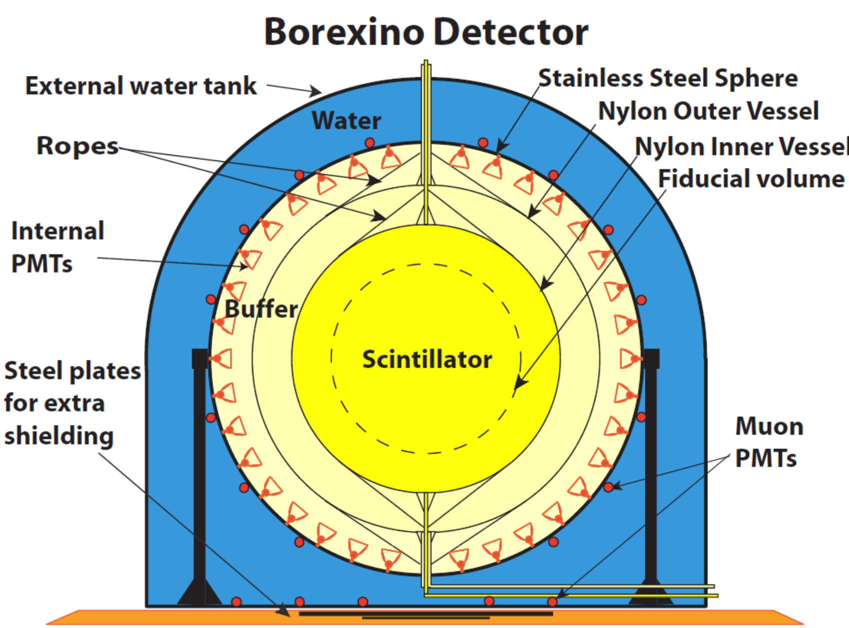
CMB + BAO constraining $\Sigma m_\nu + N_{eff}$



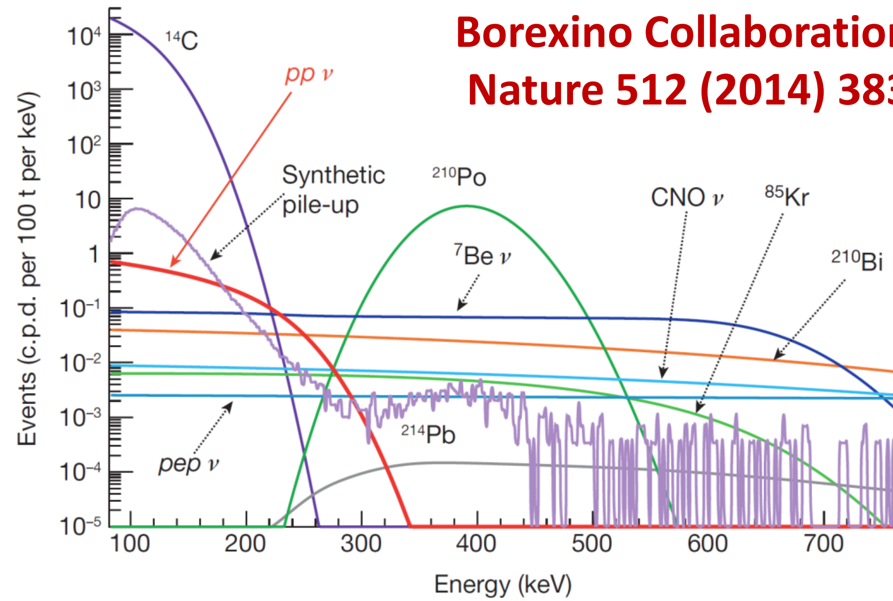
CMB + BAO limit: $\Sigma m_\nu < 0.23$ eV (95% CL)

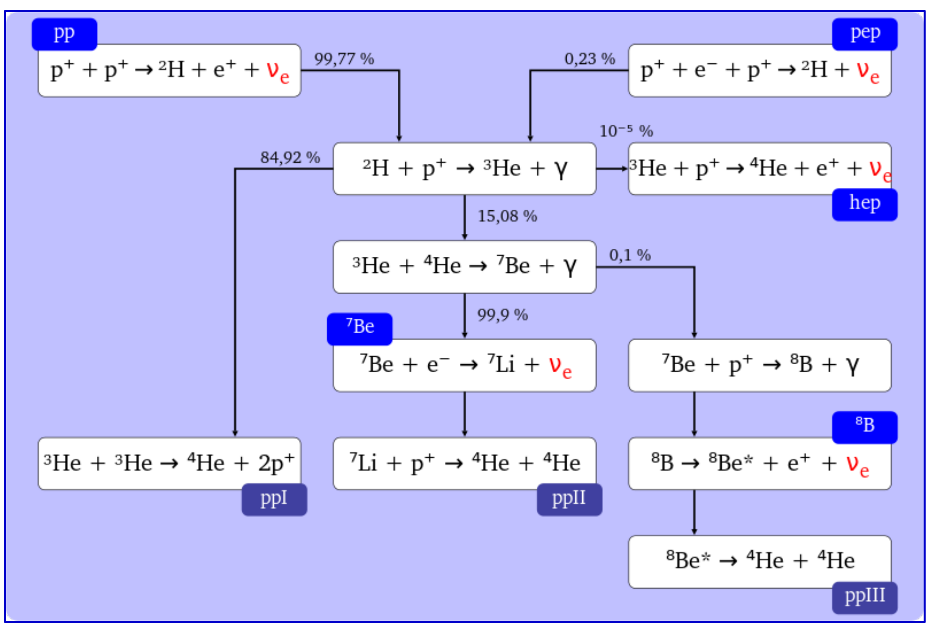
Ade et al. (Planck Collaboration), arXiv:1303.5076

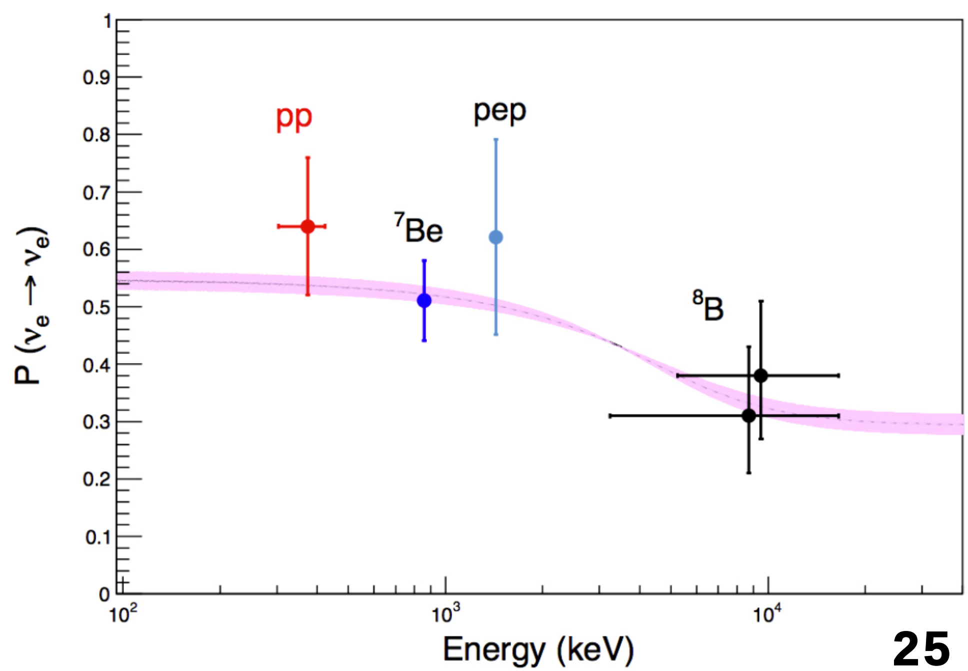
Detection of pp Neutrinos from the Sun

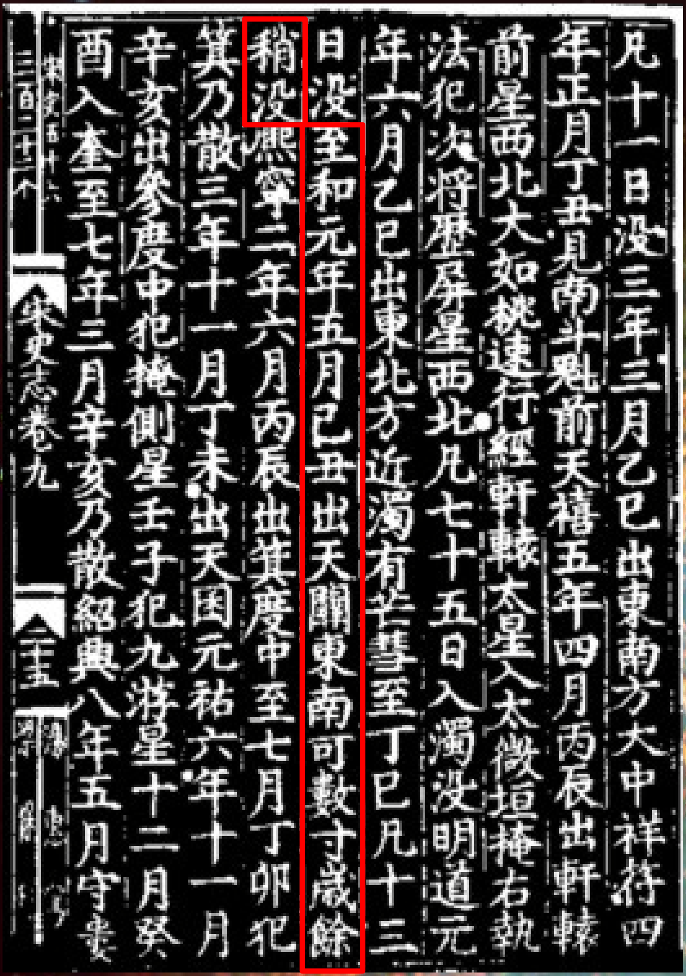


Borexino Collaboration Nature 512 (2014) 383







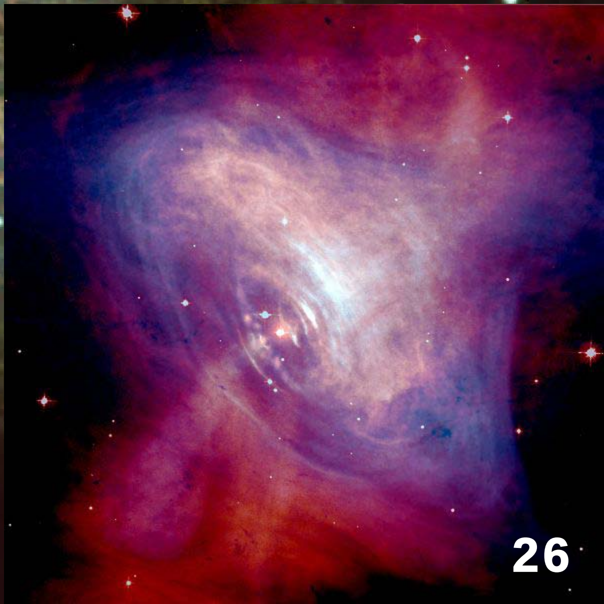


凡十一日沒三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅太星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁沒明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日沒至和元年五月己丑出天關東南可數寸歲餘稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

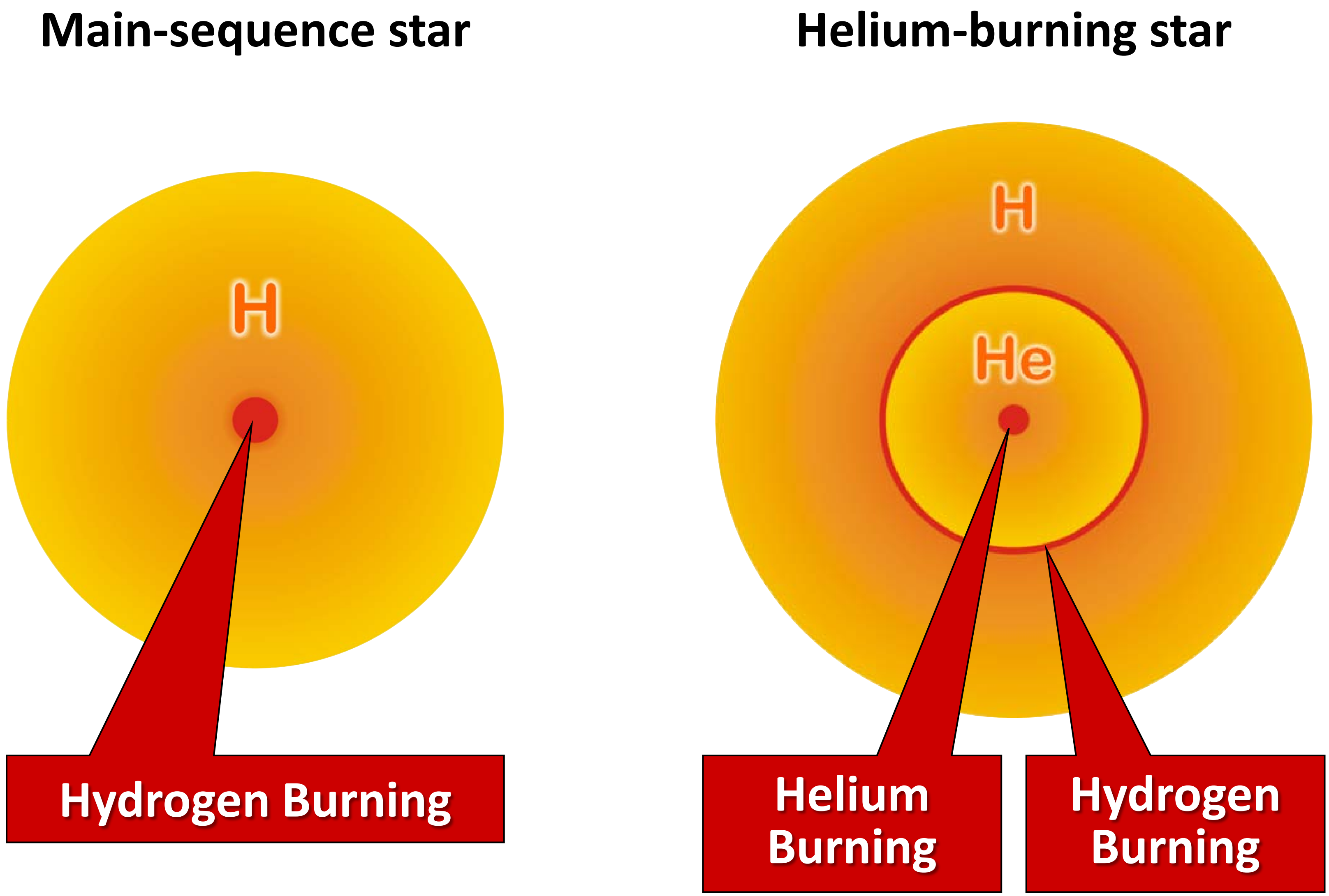
Galactic SN 1054

Distance: 6500 light years (2 kpc)
Center: Neutron Star (R~30 km)
Progenitor : M ~ 10 solar masses



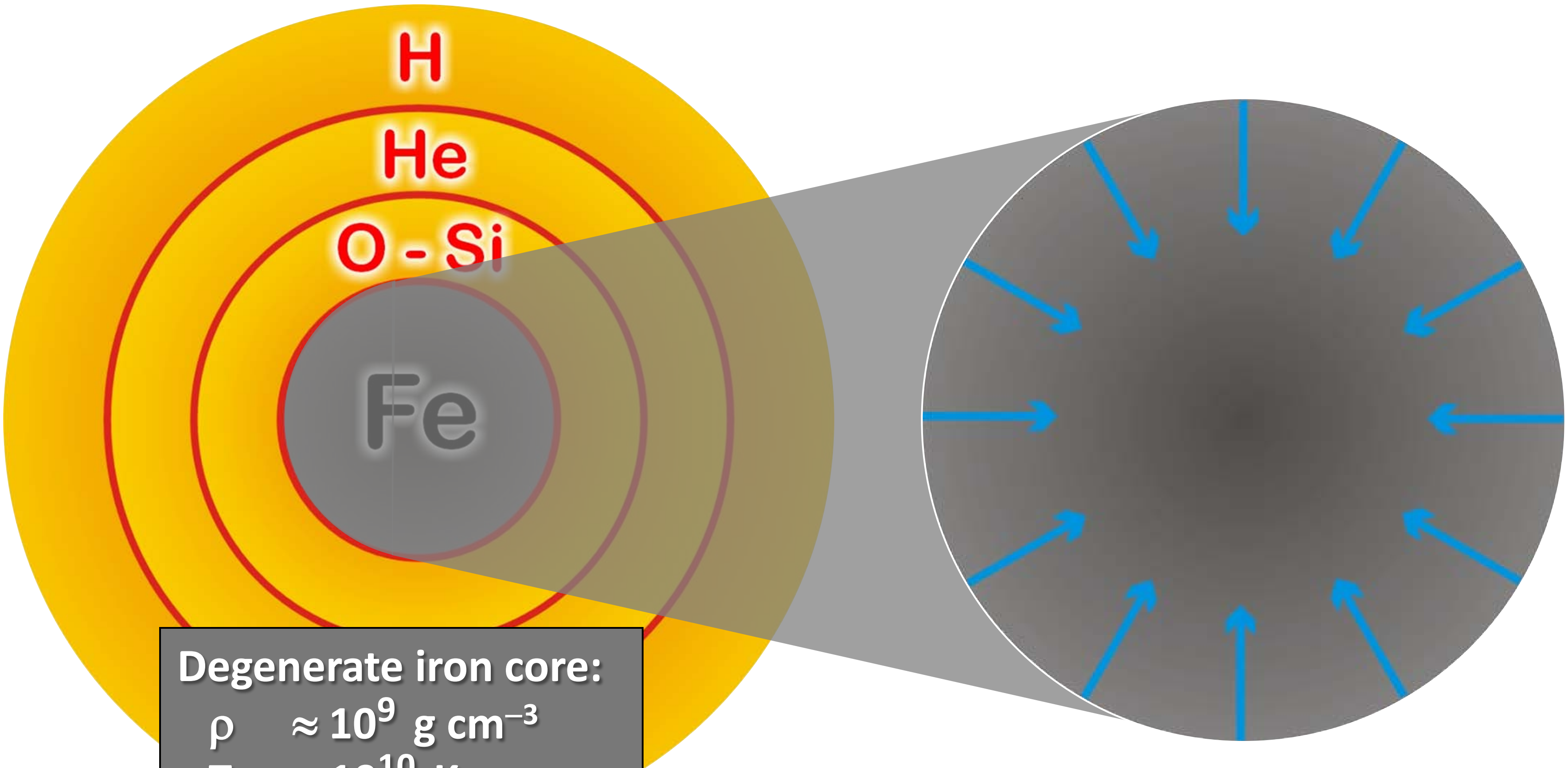
Red：Optical (Hubble)
Blue：X-Ray (Chandra)

Stellar Collapse and SN Explosion



Stellar Collapse and SN Explosion

Onion structure | **Collapse (implosion)**



Degenerate iron core:

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

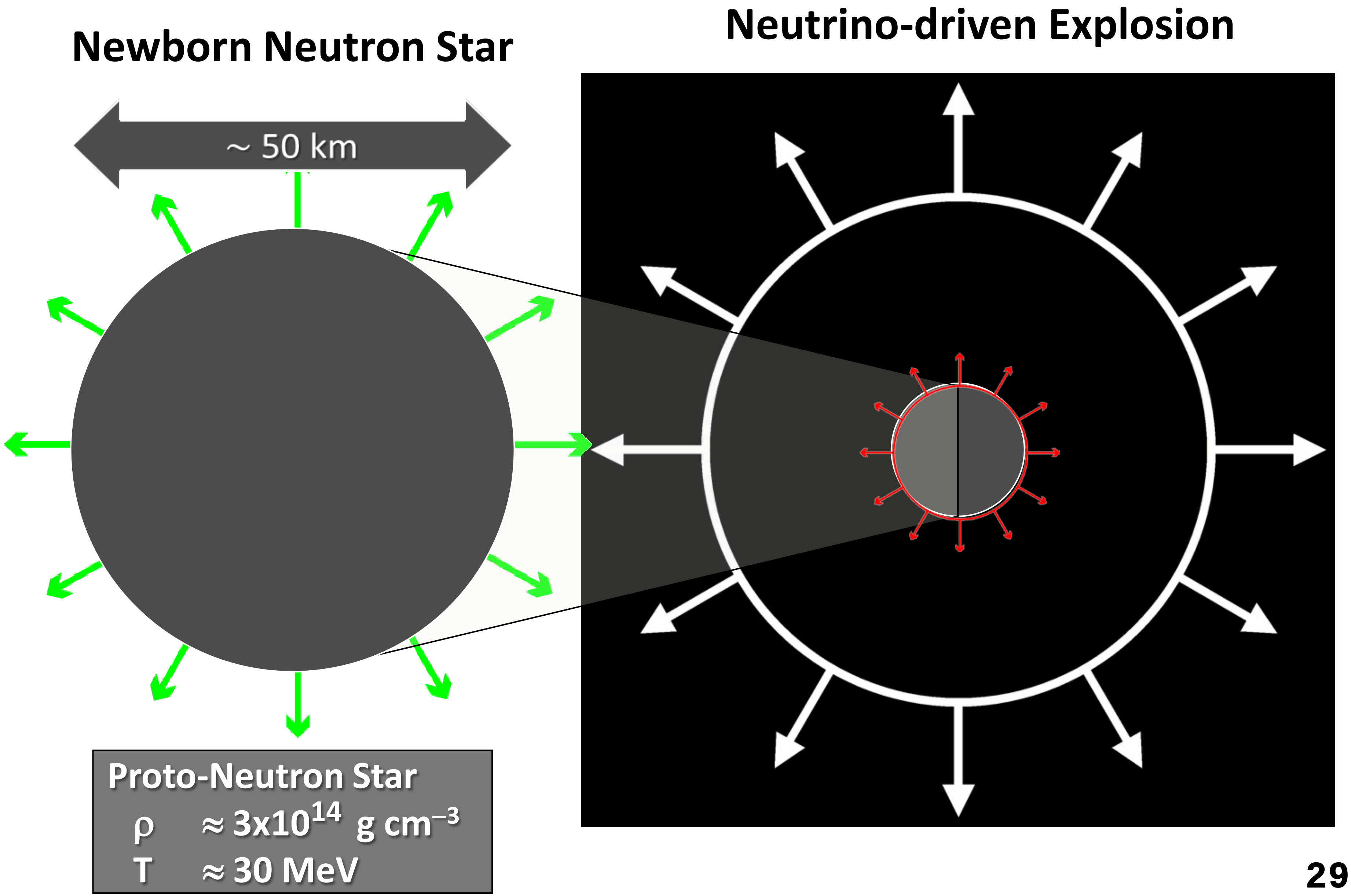
$T \approx 10^{10}\ \mathrm{K}$

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

$R_{Fe} \approx 8000\ \mathrm{km}$

Stellar Collapse and SN Explosion

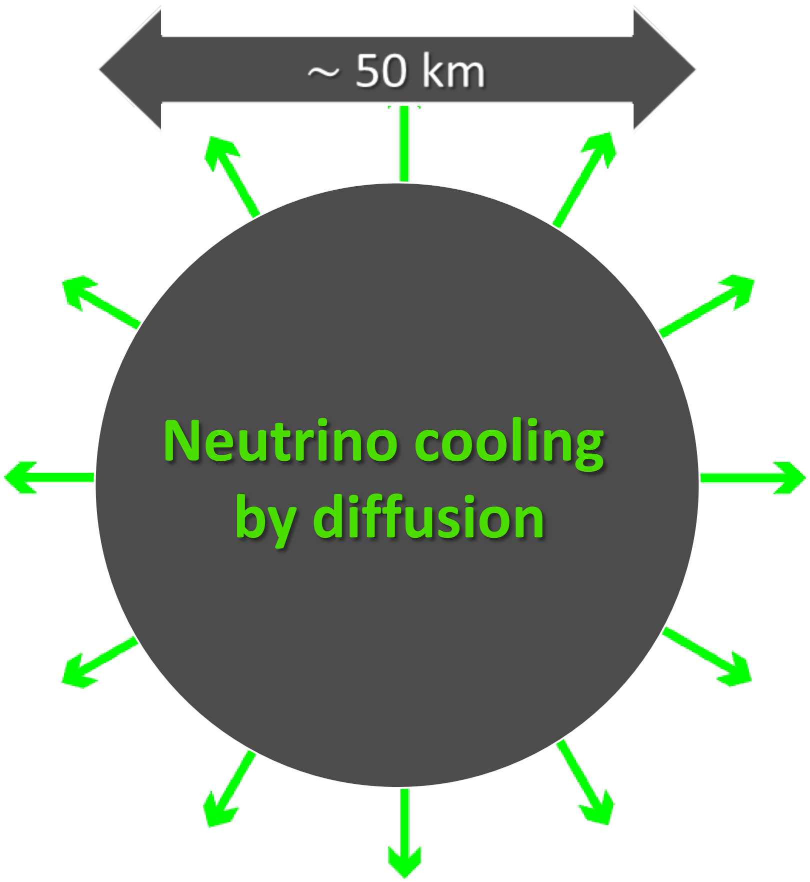
© Raffelt



Stellar Collapse and SN Explosion

© Raffelt

Newborn Neutron Star



Proto-Neutron Star

$\rho \approx 3\text{x}10^{14}\ \text{g cm}^{-3}$

$T \approx 30$ MeV

Gravitational binding energy

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

This shows up as

- 99% Neutrinos
- 1% Kinetic energy of explosion (1% of this into cosmic rays)
- 0.01% Photons, outshine host galaxy

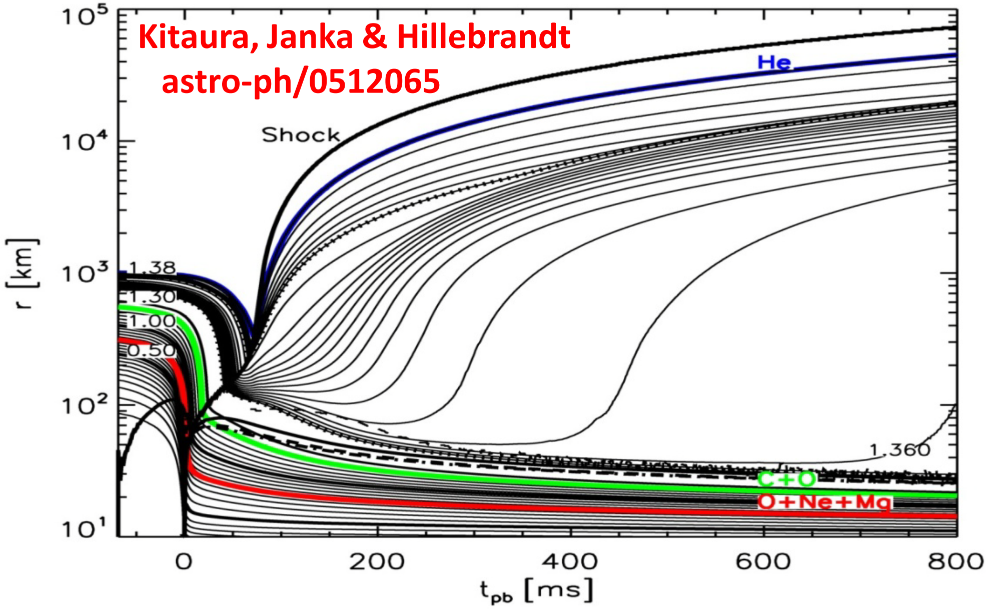
Neutrino luminosity

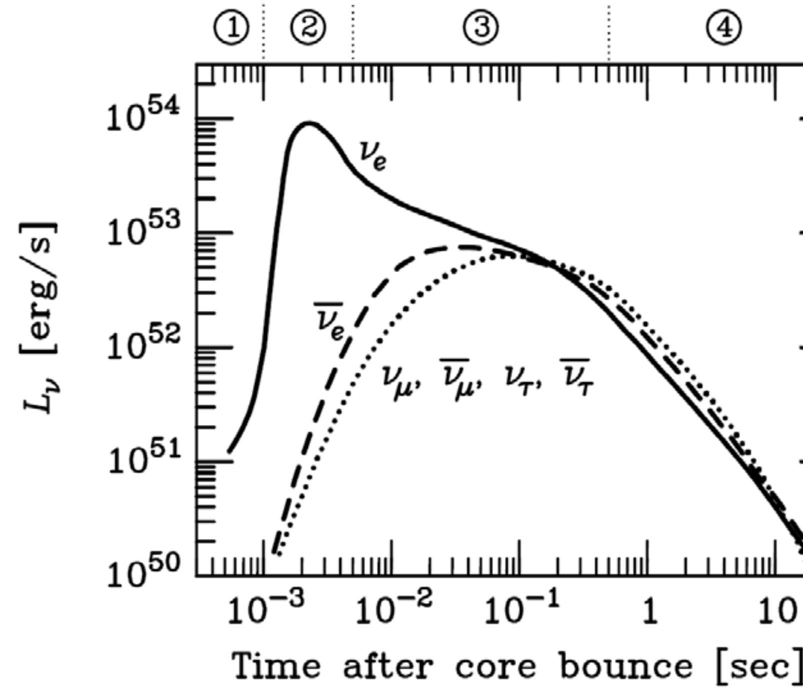
$L_\nu \approx 3 \times 10^{53}$ erg / 3 sec

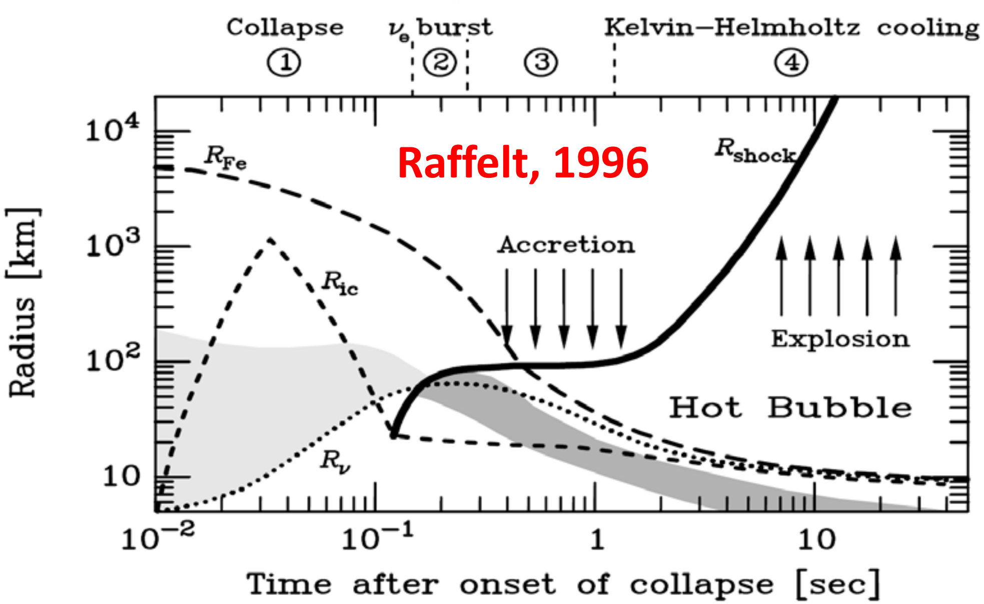
$\approx 3 \times 10^{19}\ L_{SUN}$

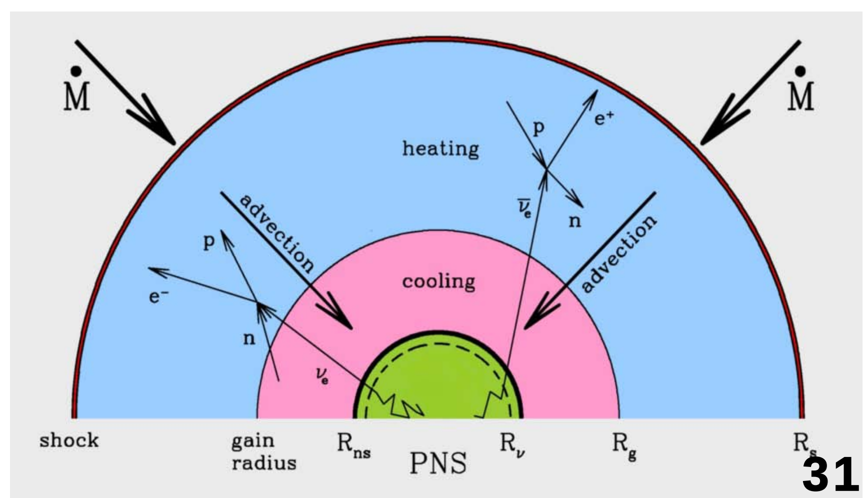
While it lasts, outshines the entire visible universe

Supernova Neutrinos: Theoretical Predictions

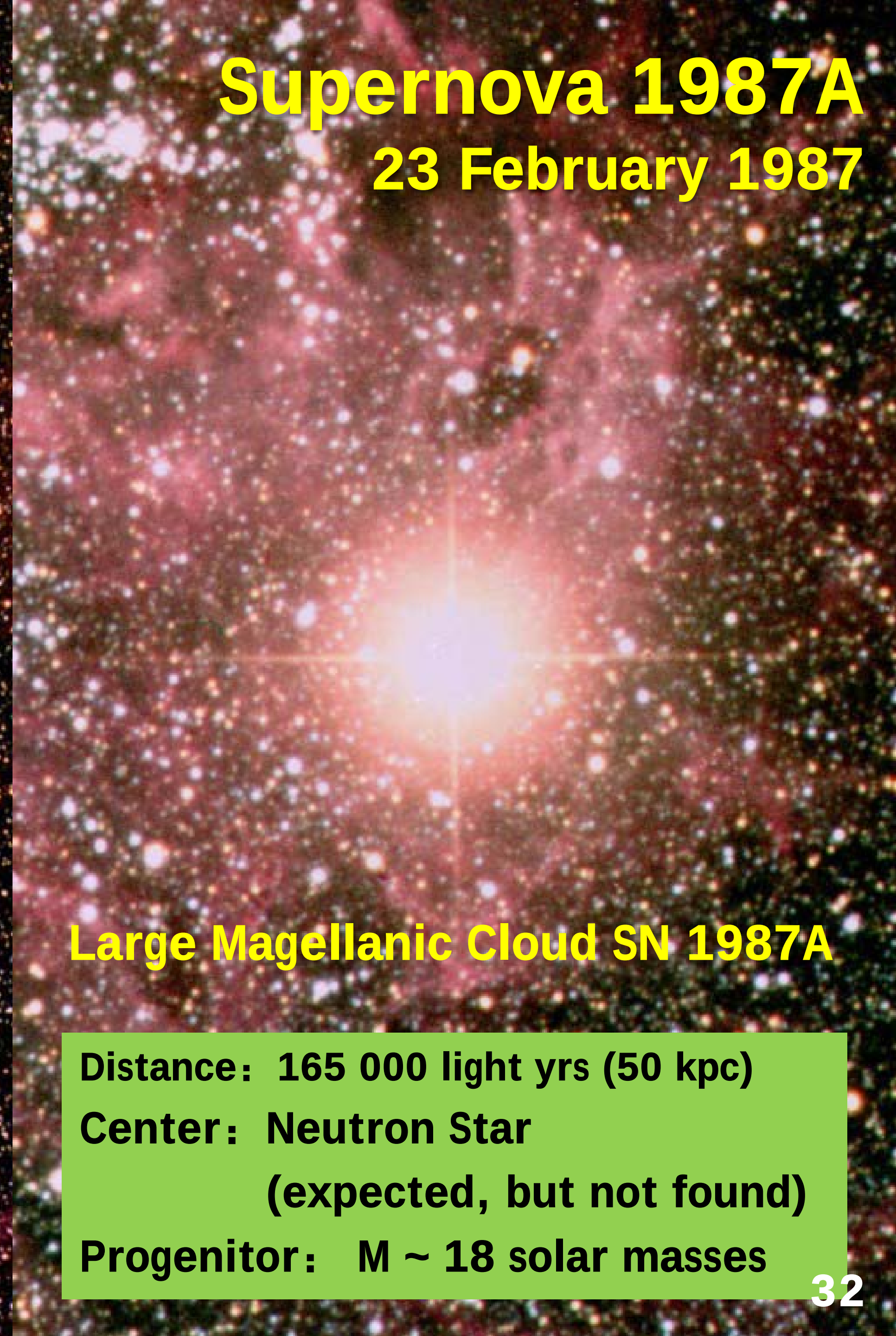




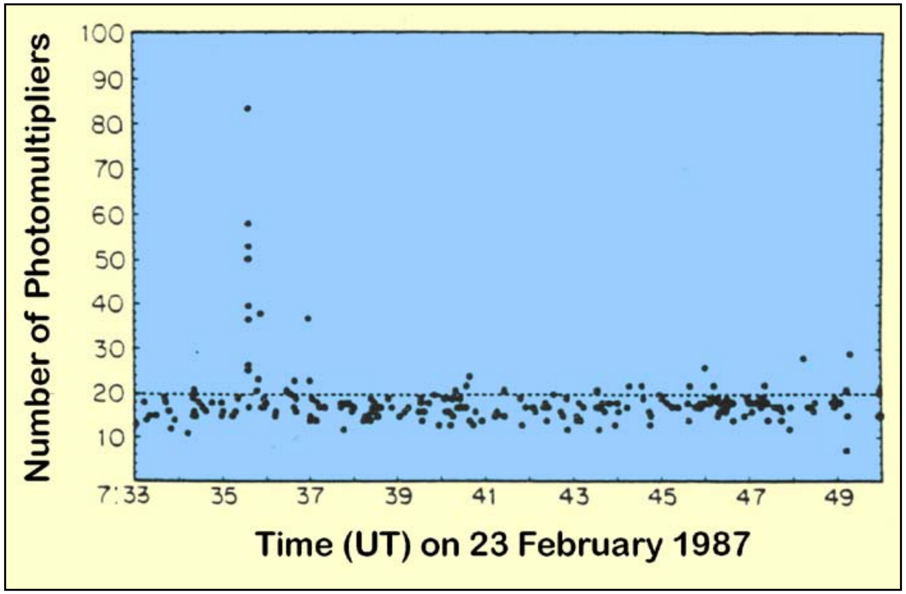


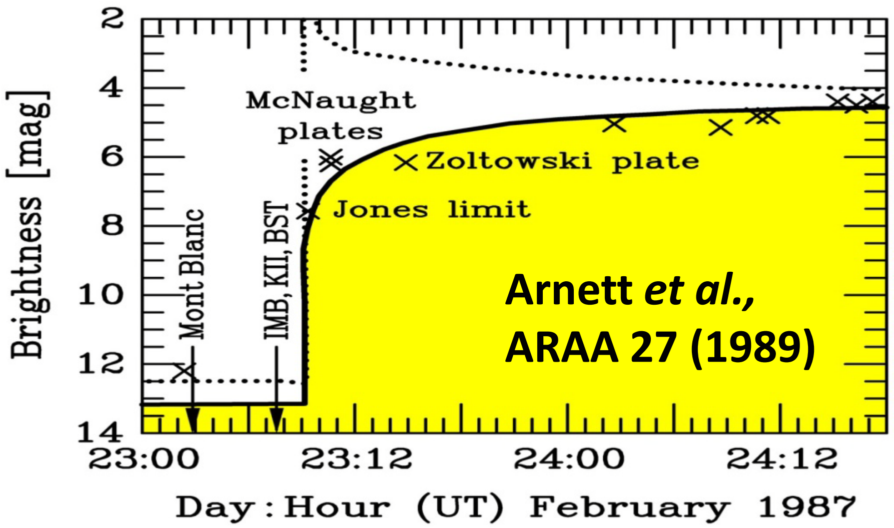



Sanduleak - 69 202

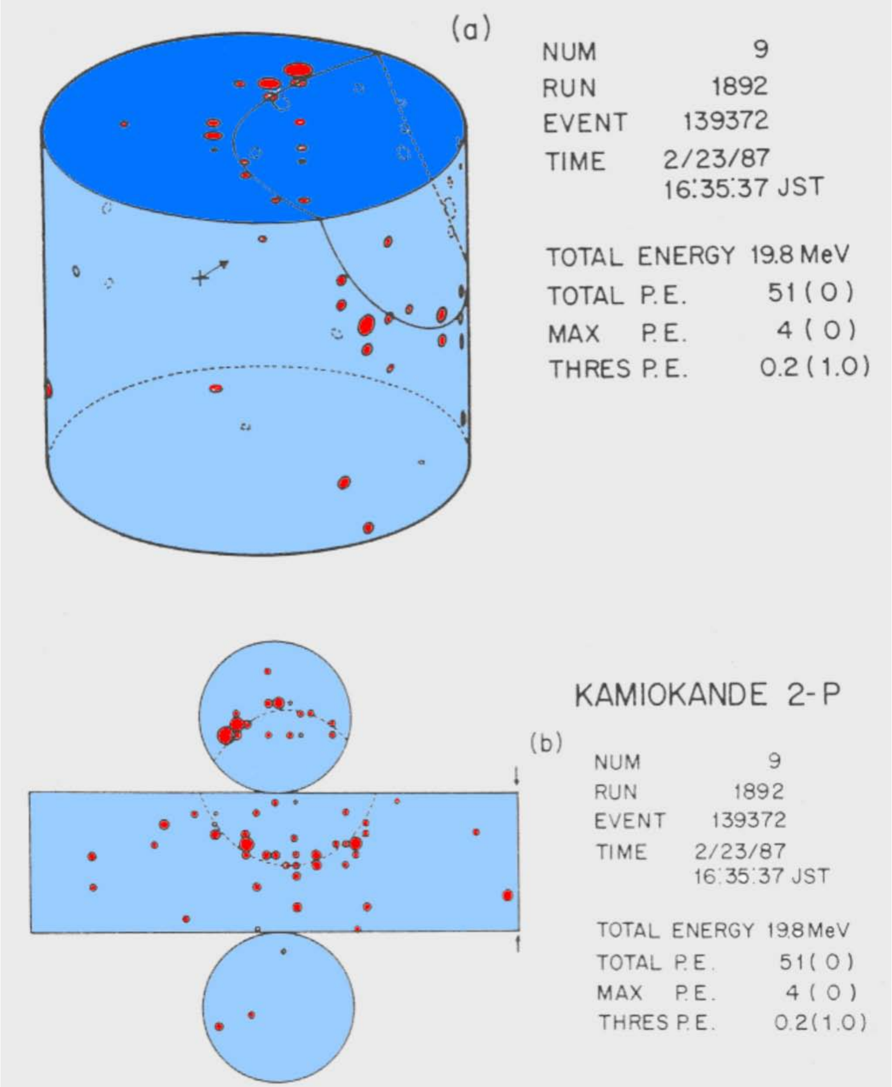

Supernova 1987A
23 February 1987
Large Magellanic Cloud SN 1987A
Distance：165 000 light yrs (50 kpc)
Center：Neutron Star
(expected, but not found)
Progenitor：M ~ 18 solar masses

Supernova Neutrinos: SN 1987A





Arnett *et al.*, ARAA 27 (1989)



Hirata et al., PRD 38 (1988) 448

Supernova Neutrinos: SN 1987A

Kamiokande-II (Japan):

- Water Cherenkov (2,140 ton)
- Clock Uncertainty ± 1 min

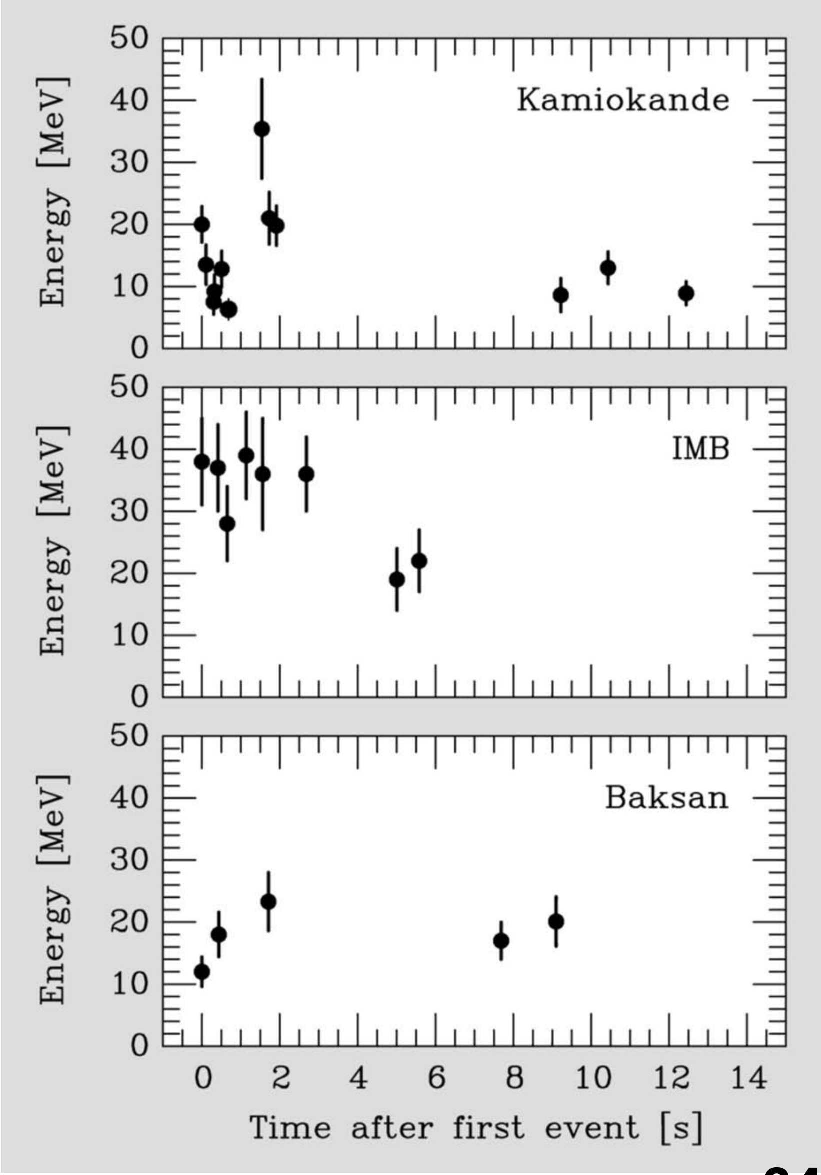
Irvine-Michigan-Brookhaven (US):

- Water Cherenkov (6,800 ton)
- Clock Uncertainty ±50 ms

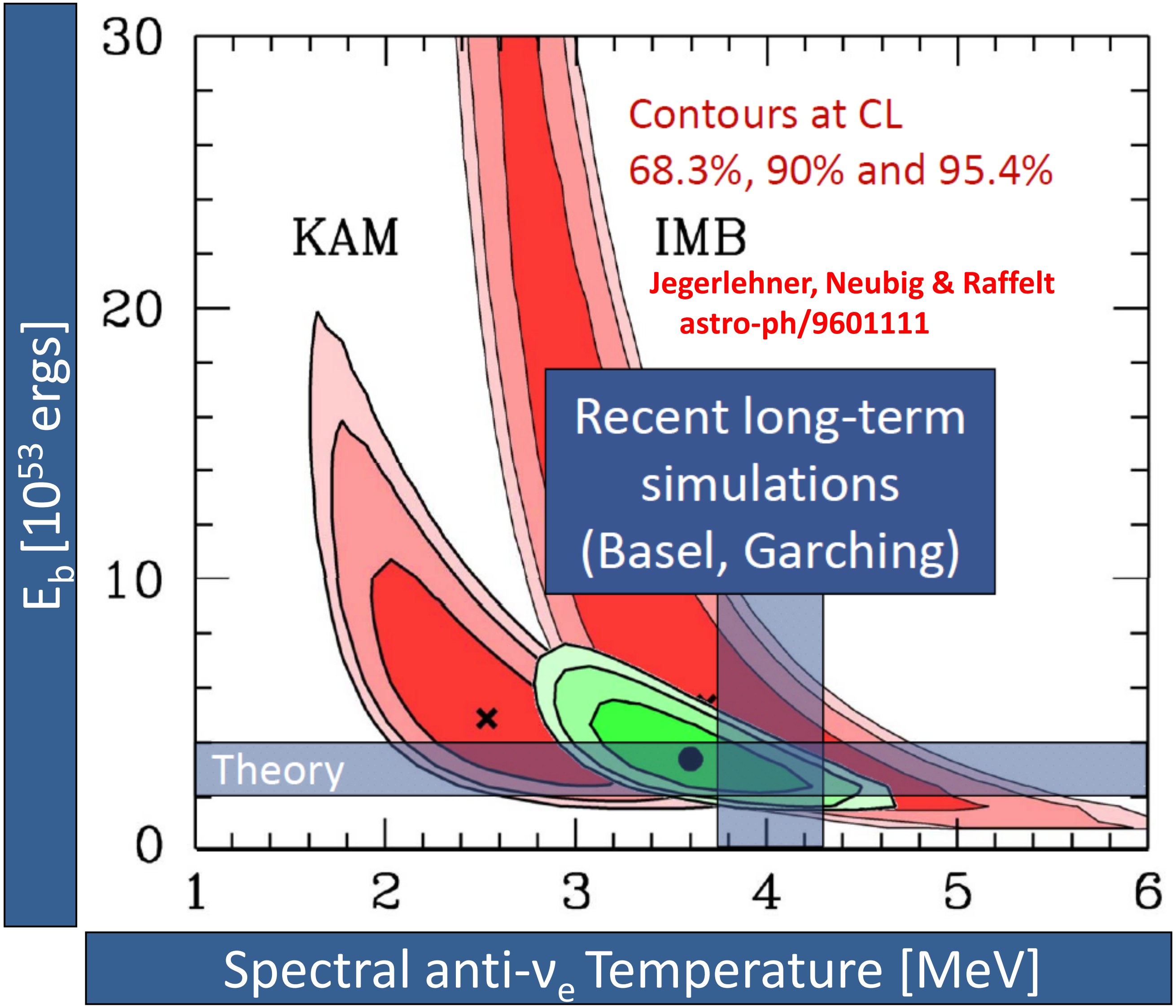
Baksan LST (Soviet Union):

- Liquid Scintillator (200 ton)
- Clock Uncertainty +2/-54 s

Mont Blanc: 5 events, 5 h earlier



Supernova Neutrinos: SN 1987A



Assumptions:
- ☐ Thermal
- ☐ Equipart.

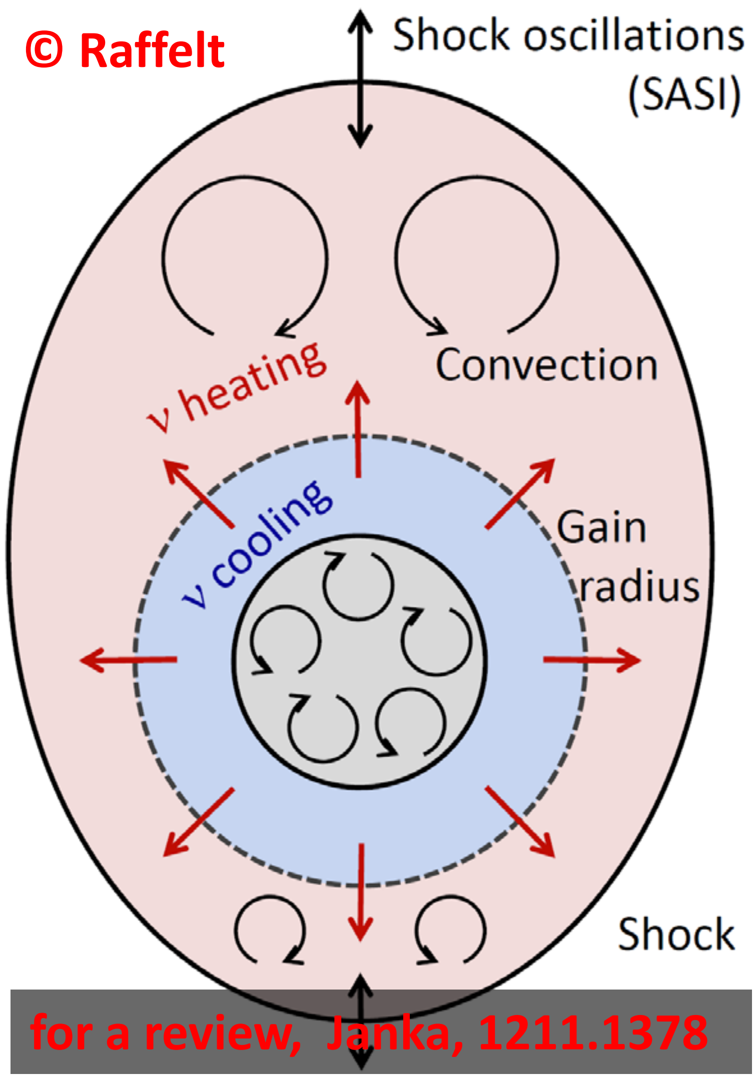
Conclusions:
- ■ Collapse
- ■ Ave.Ener.
- ■ Duration

Problems:
- ☐ 24 events
- ☐ by chance

Supernova Neutrinos: Astrophysics & Astronomy

■ Explosion Mechanism: Neutrino-driven Explosion

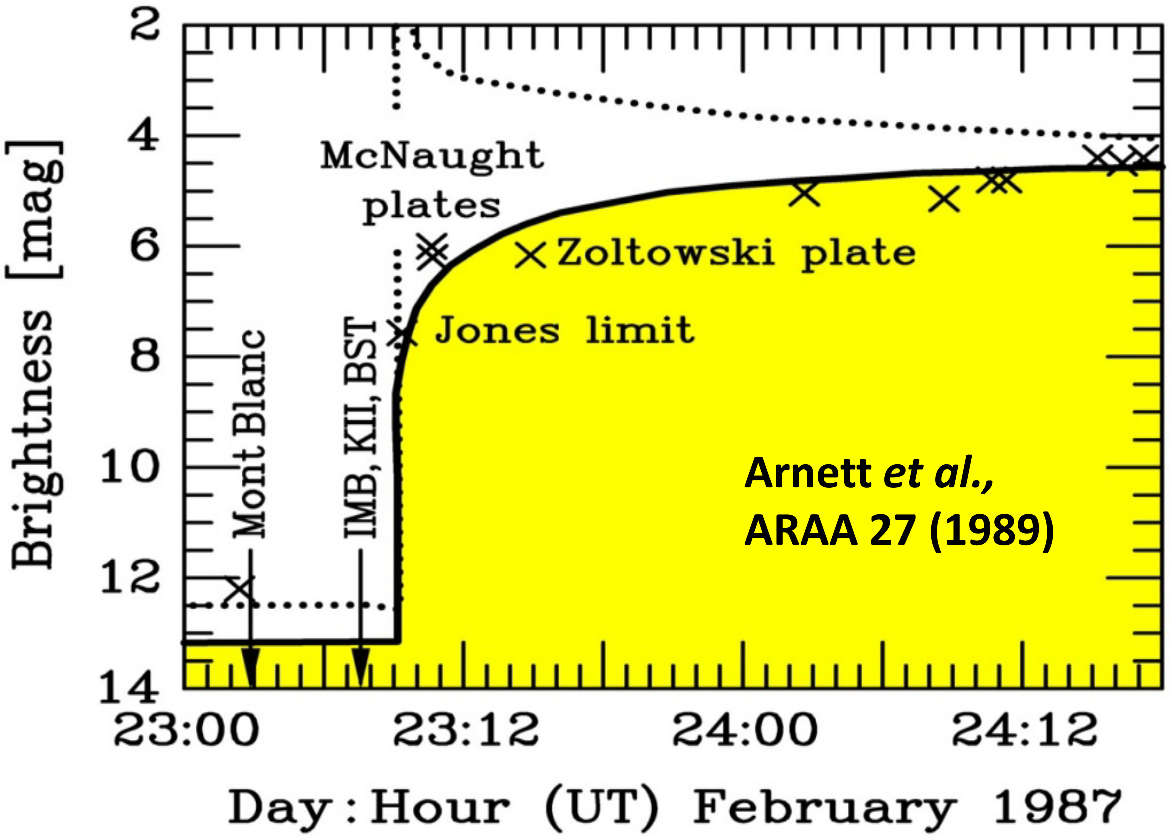
- The prompt shock halted at 150 km, by disintegrating heavy nuclei
- Neutrinos deposit their energies via interaction with matter; 1 % neutrino energy leads to successful explosion
- Simulations in 1D & 2D for different progenitor masses observe explosions
- 3D simulation has just begun; but no clear picture (resolution, progenitors)



for a review, Janka, 1211.1378

Supernova Neutrinos: Astrophysics & Astronomy

■ **For Optical Observations: SuperNova Early Warning System (SNEWS)**



Neutrinos arrive several hours before photons

To alert astronomers several hours in advance

Super-K | **IceCube** | **LVD** | **Borexino**

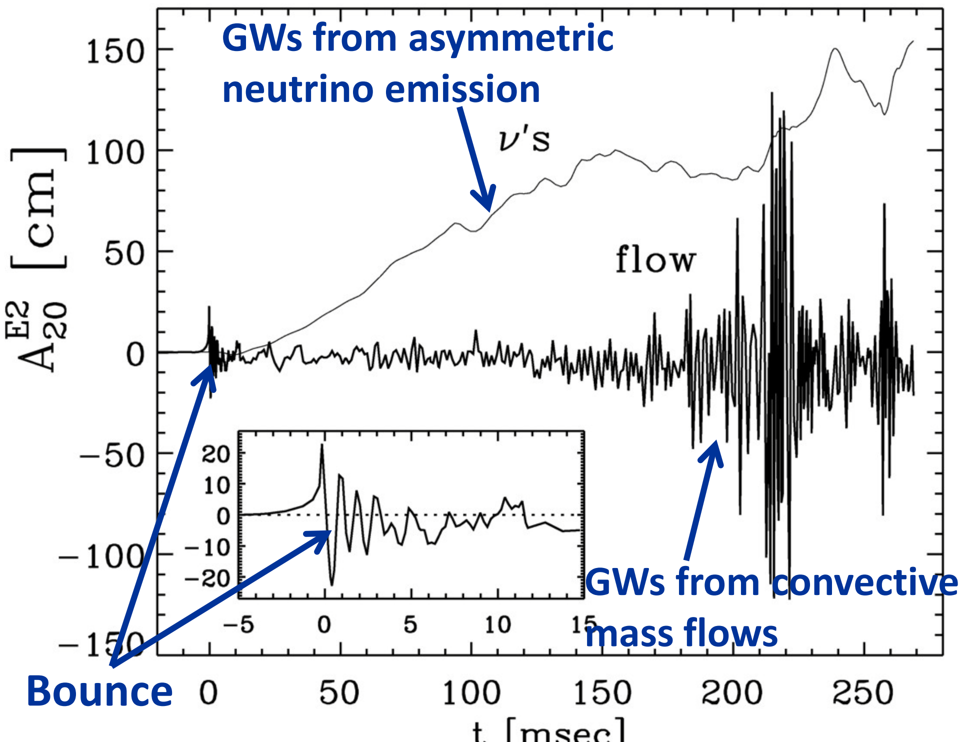
→ **Alert @BNL**

Supernova Neutrinos: Astrophysics & Astronomy

■ Gravitational waves from SN Explosions

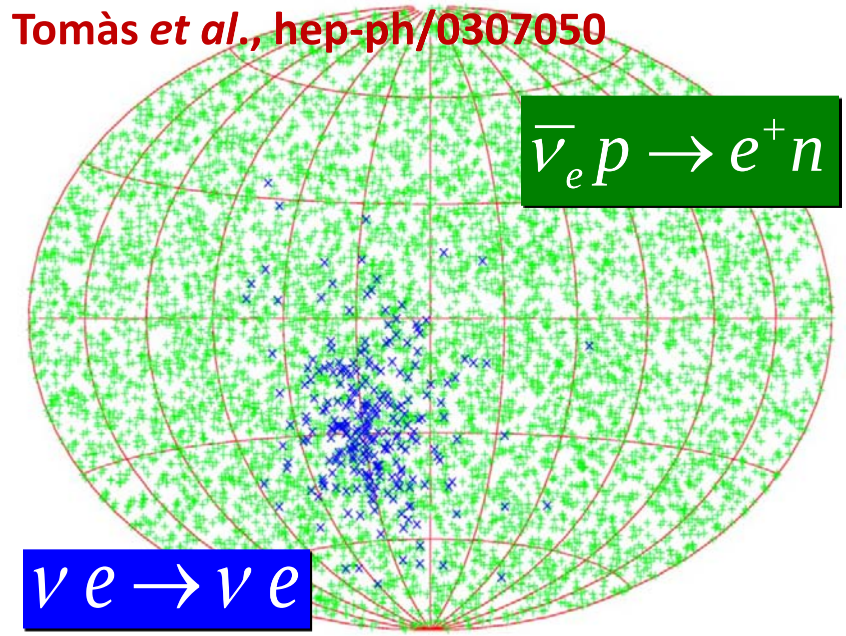
Müller, Rampp, Buras, Janka,& Shoemaker, astro-ph/0309833

"Towards gravitational wave signals from realistic core collapse supernova models"



■ Locate the SN via neutrinos

Tomàs *et al.*, hep-ph/0307050



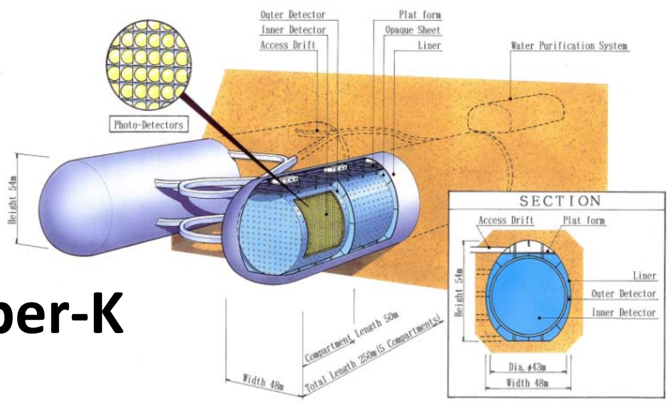
Beacom & Vogel, astro-ph/9811350

n-tagging efficiency		95% CL half-cone opening angle
None	90 %	
7.8°	3.2°	SK
1.4°	0.6°	SK × 30

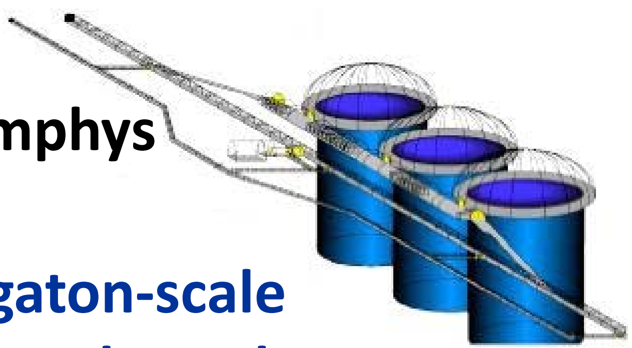
Supernova Neutrinos: Next-Generation Detectors

DUSEL
LBNE

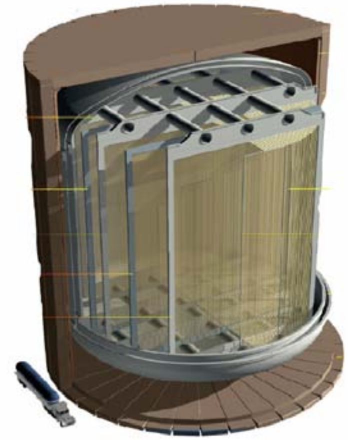
Hyper-K



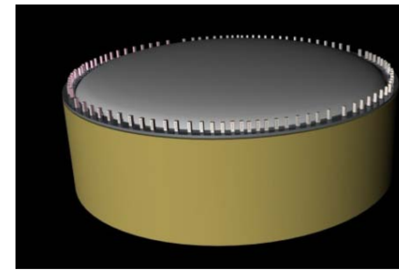
Memphys



Megaton-scale water Cherenkov



5-100 kton liquid Argon

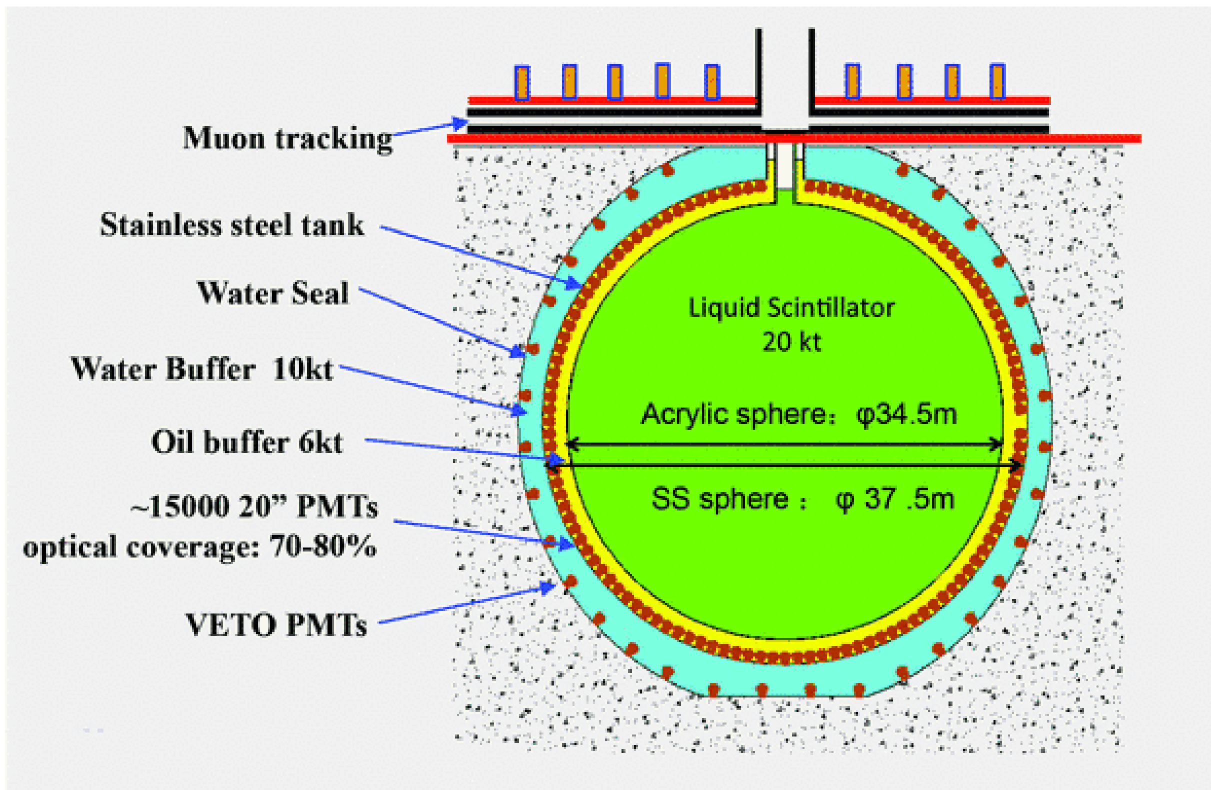


100 kton scale scintillator

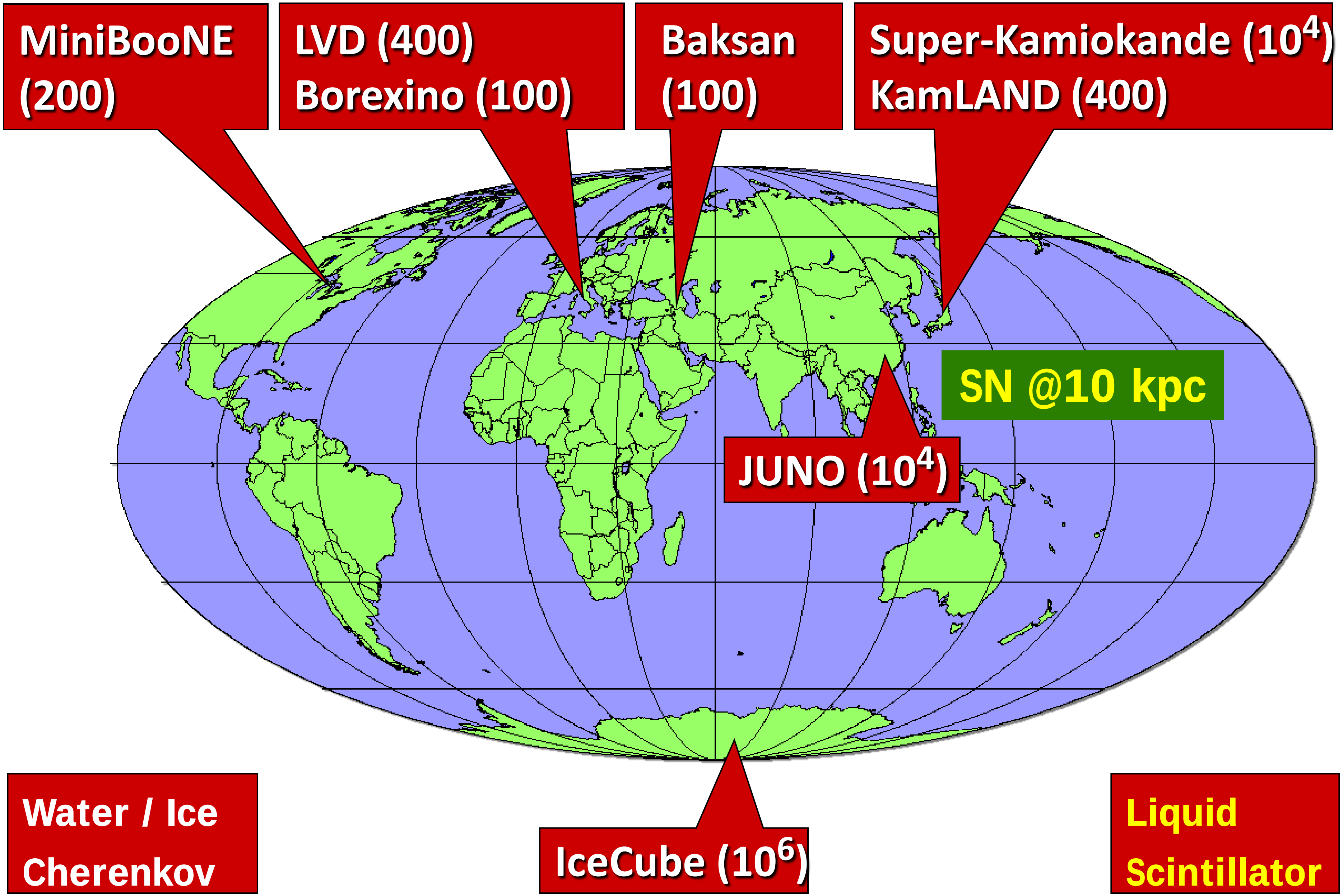
LENA
HanoHano

Supernova Neutrinos: from Dream to Reality

JUNO (Jiangmen Underground Neutrino Observatory), Guangdong, China
Collaboration formed (2014), expected to take data in 2019
20 kt scintillator detector, 3% energy resolution
Determination of neutrino mass hierarchy with reactor neutrinos
Also good for low-energy neutrino astronomy

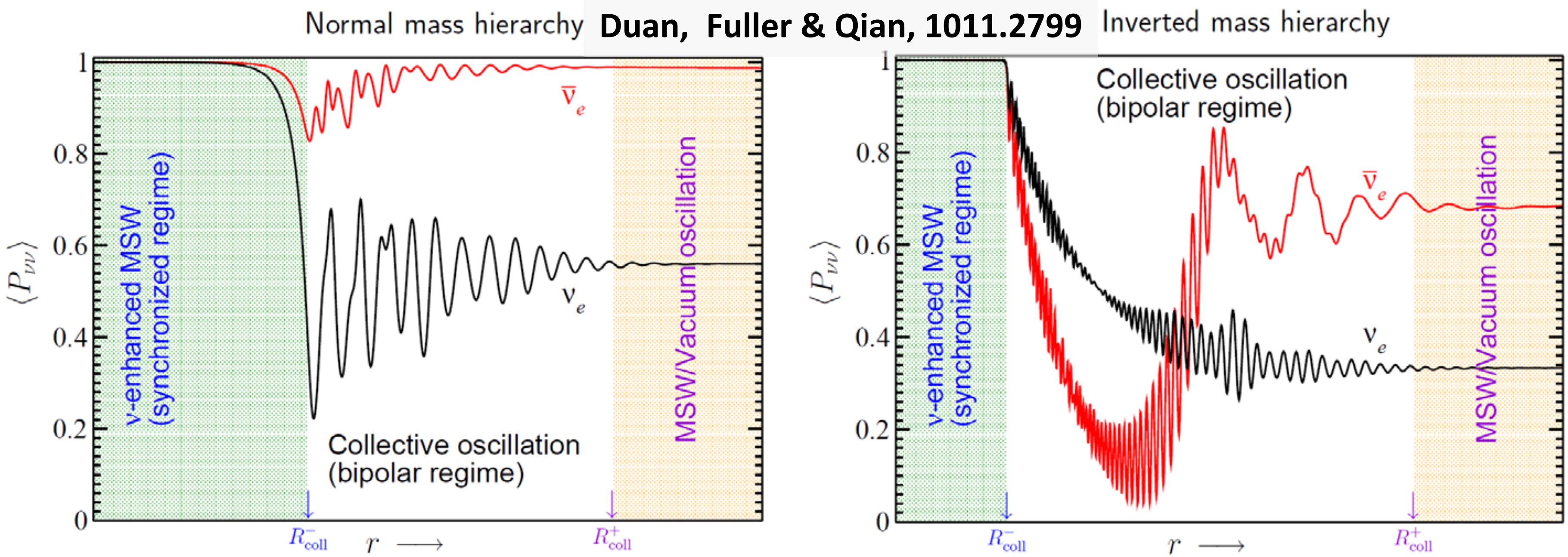


SN ν Detection: ongoing and upcoming experiments



Supernova Neutrinos: Collective Flavor Conversions

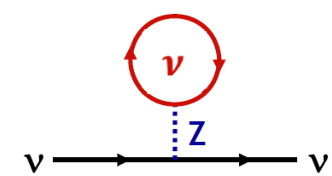
Duan, Fuller & Qian, 1011.2799



Neutrino-neutrino refraction causes a flavor instability, flavor exchange between different parts of spectrum

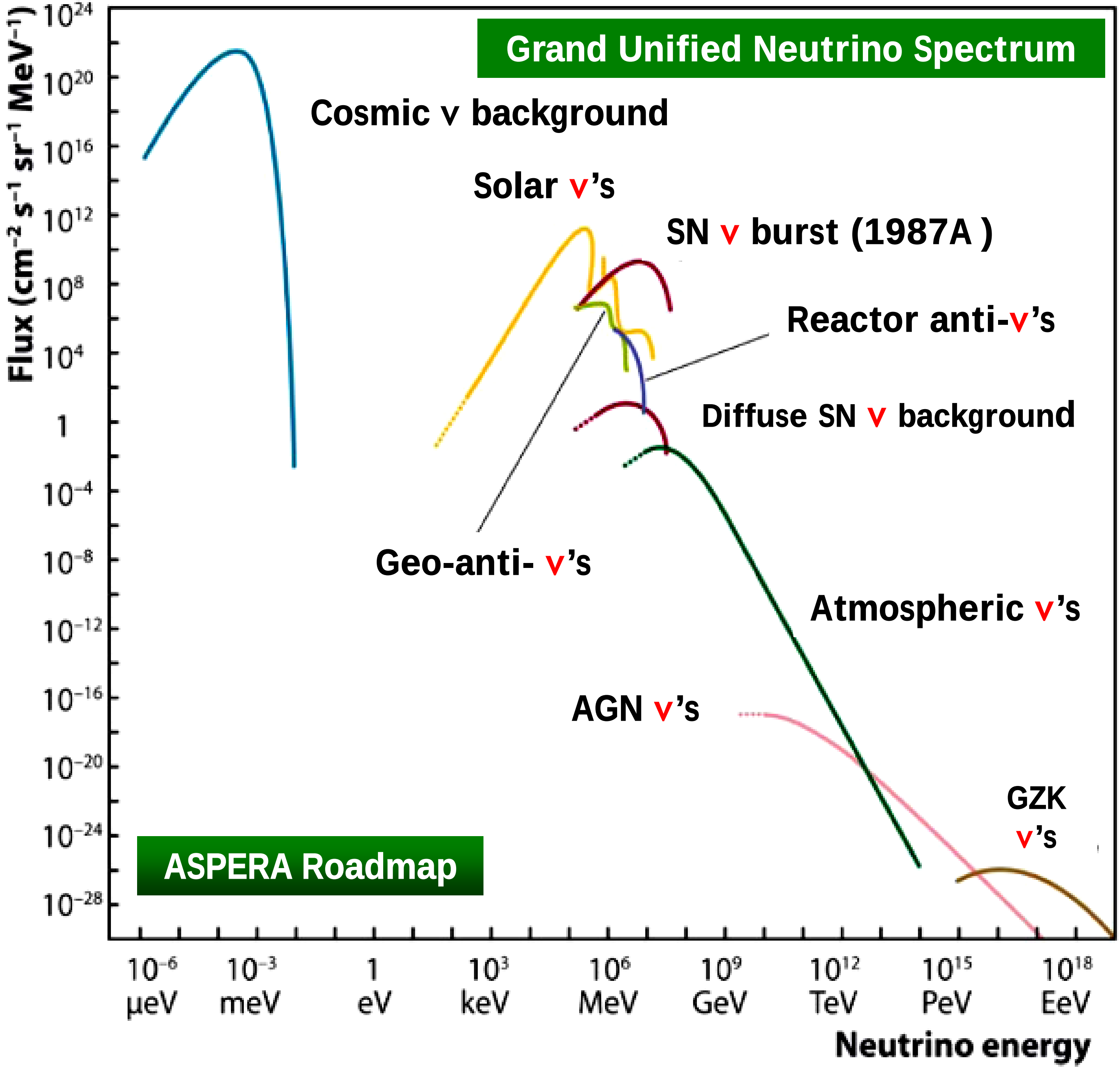
$$\mathrm{i}\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

Effective mixing Hamiltonian

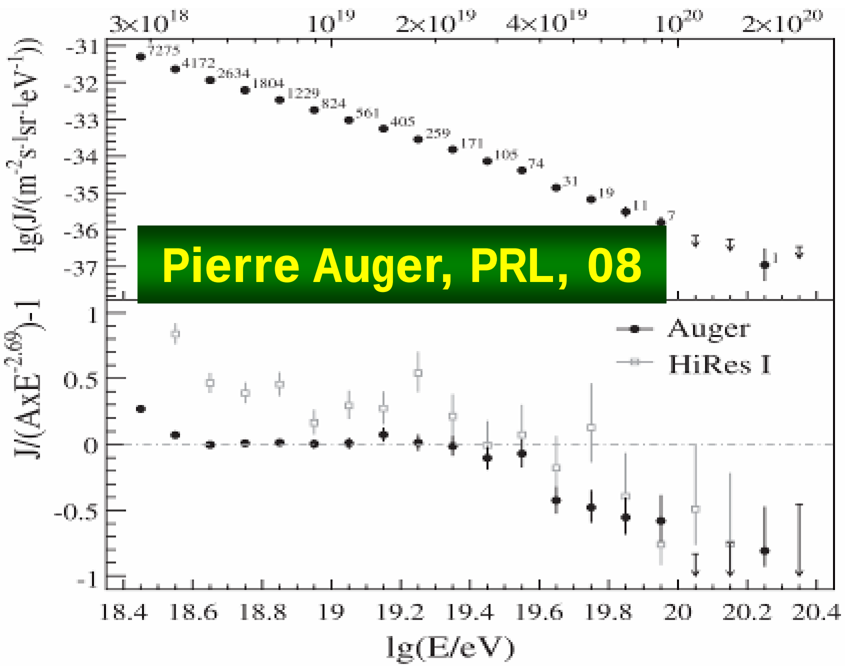


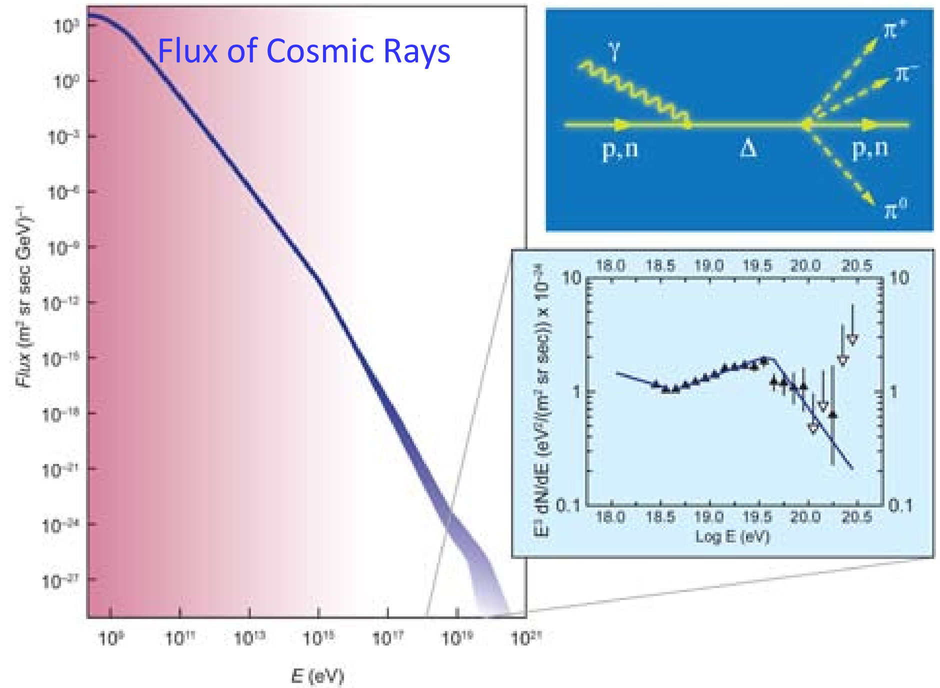
$$H = \frac{M^2}{2E} + \sqrt{2}G_{\rm F}\begin{pmatrix} N_e - \frac{N_n}{2} & 0 \\ 0 & -\frac{N_n}{2}\end{pmatrix} + \sqrt{2}G_{\rm F}\begin{pmatrix} N_{\nu_e} & N_{\langle\nu_e|\nu_\mu\rangle} \\ N_{\langle\nu_\mu|\nu_e\rangle} & N_{\nu_\mu}\end{pmatrix}$$

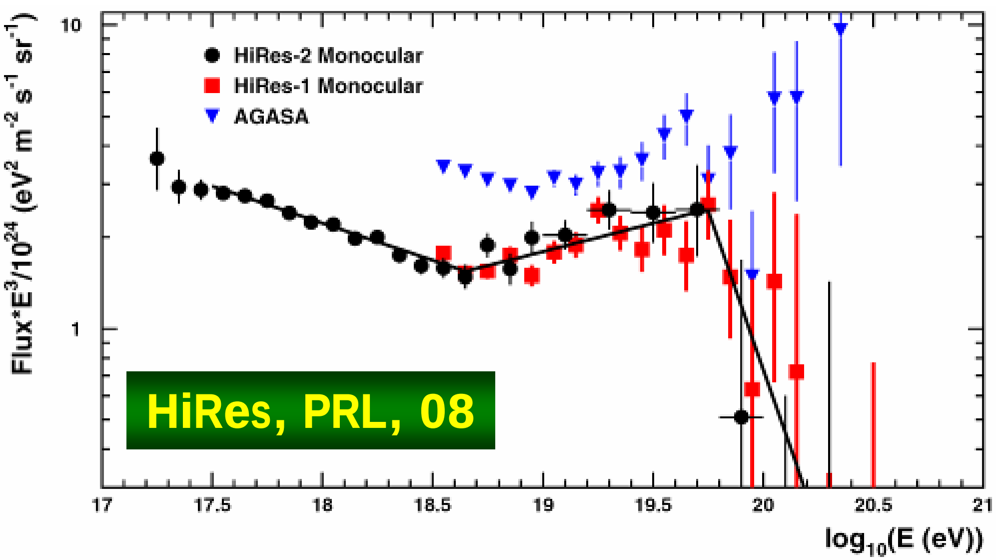
Vacuum **MSW** **Collective**


Grand Unified Neutrino Spectrum
Cosmic ν background
Solar ν's
SN ν burst (1987A)
Reactor anti-ν's
Diffuse SN ν background
Geo-anti- ν's
Atmospheric ν's
AGN ν's
GZK ν's
ASPERA Roadmap
Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10^24
10^20
10^16
10^12
10^8
10^4
1
10^-4
10^-8
10^-12
10^-16
10^-20
10^-24
10^-28
10^-6 μeV
10^-3 meV
1 eV
10^3 keV
10^6 MeV
10^9 GeV
10^12 TeV
10^15 PeV
10^18 EeV
Neutrino energy

Ultrahigh-energy neutrinos: Astrophysical Sources







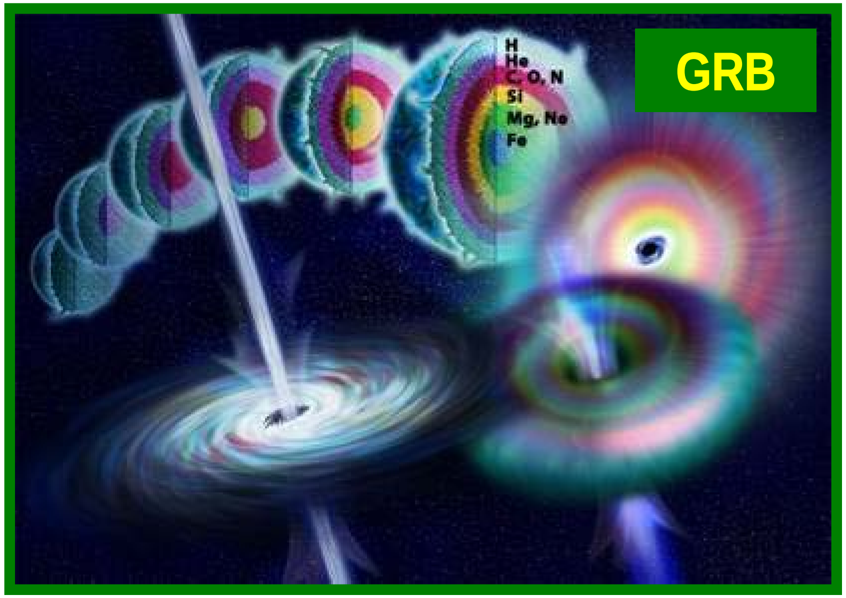
Observation of GZK cutoff ?

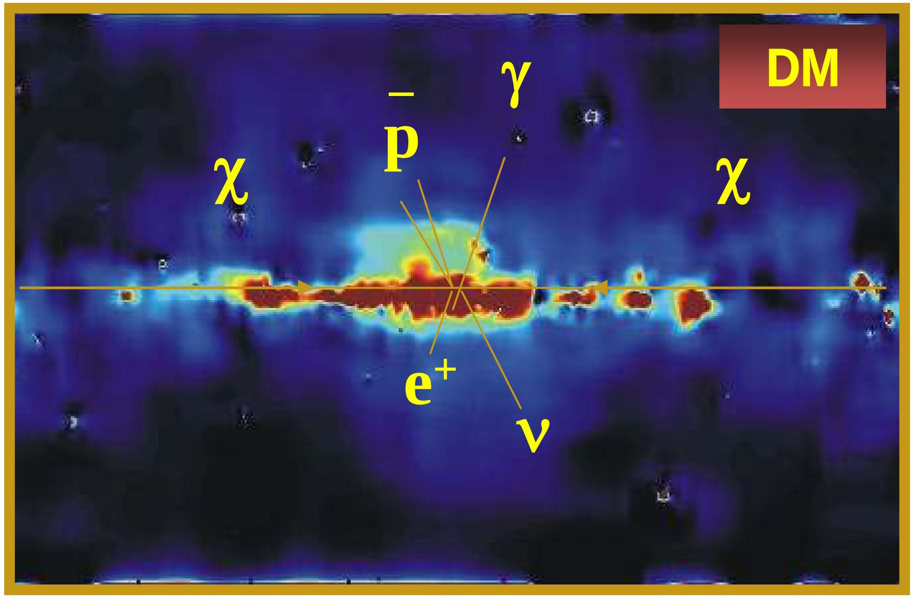
$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

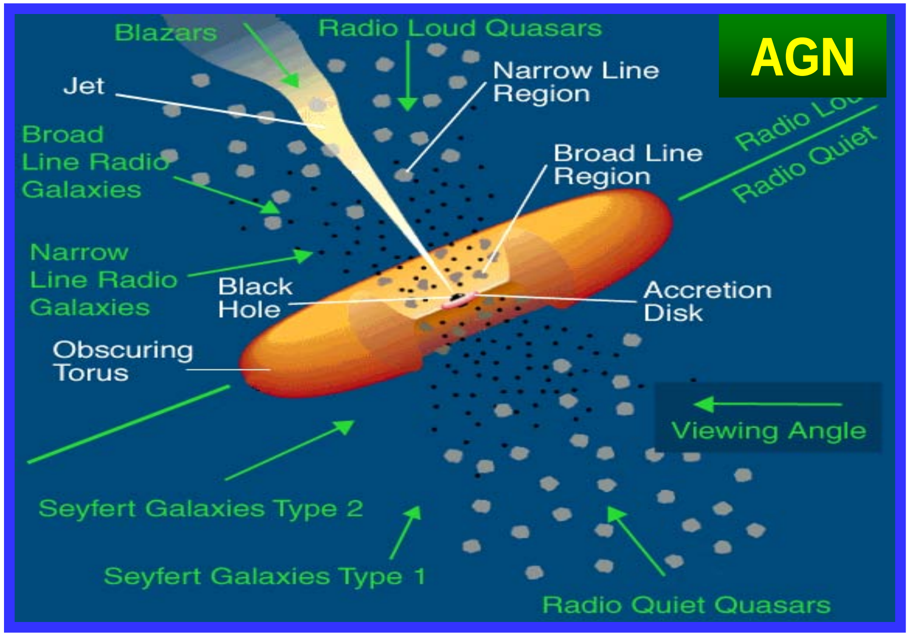
$$\pi^- \longrightarrow \mu^- + \bar{\nu}_\mu$$
$$\quad \hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Existence of UHE Neutrinos?

Ultrahigh-energy neutrinos: Astrophysical Sources

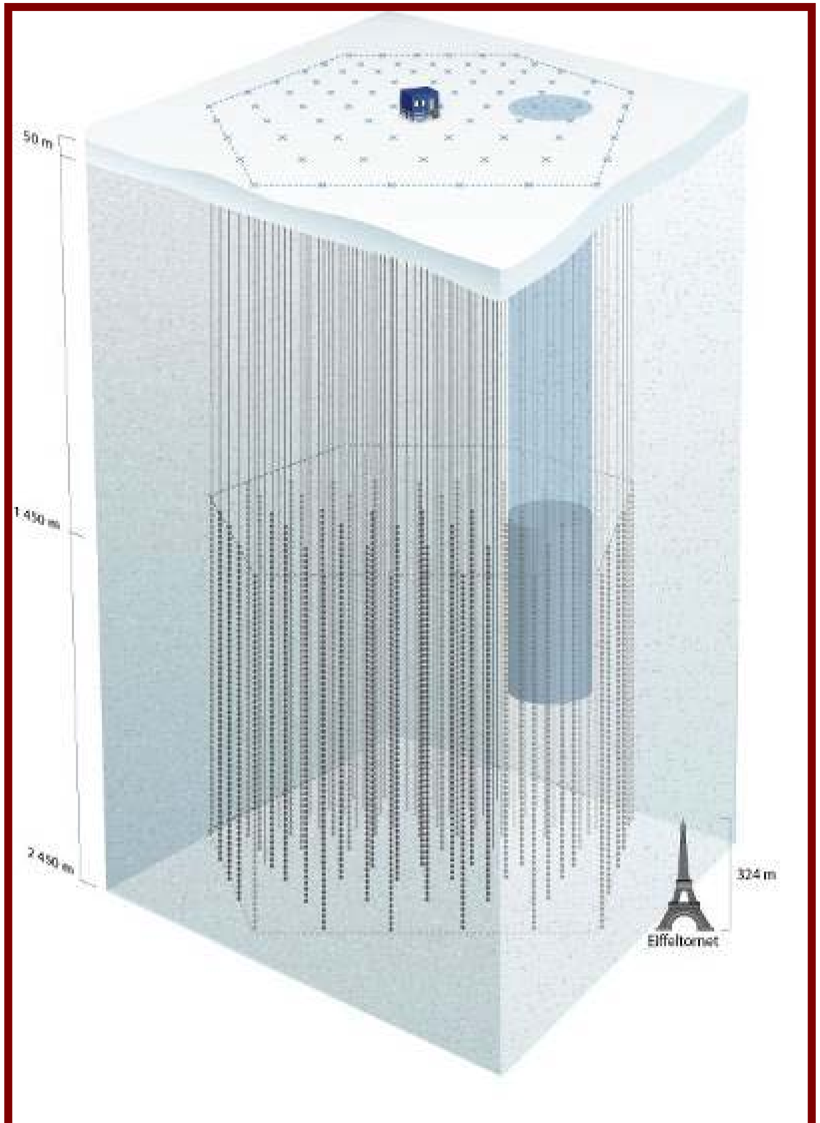




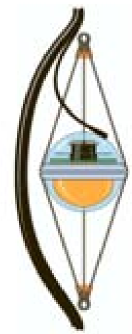


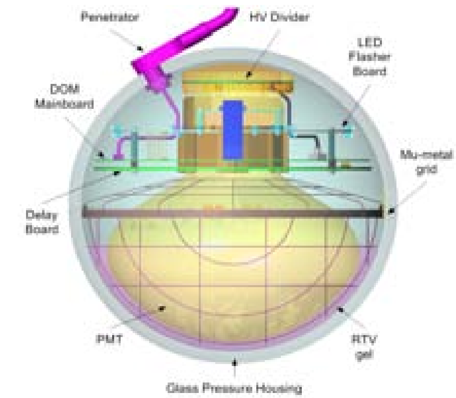
Ultrahigh-energy neutrinos: Challenges and Opportunities

km³-scale NT: IceCube

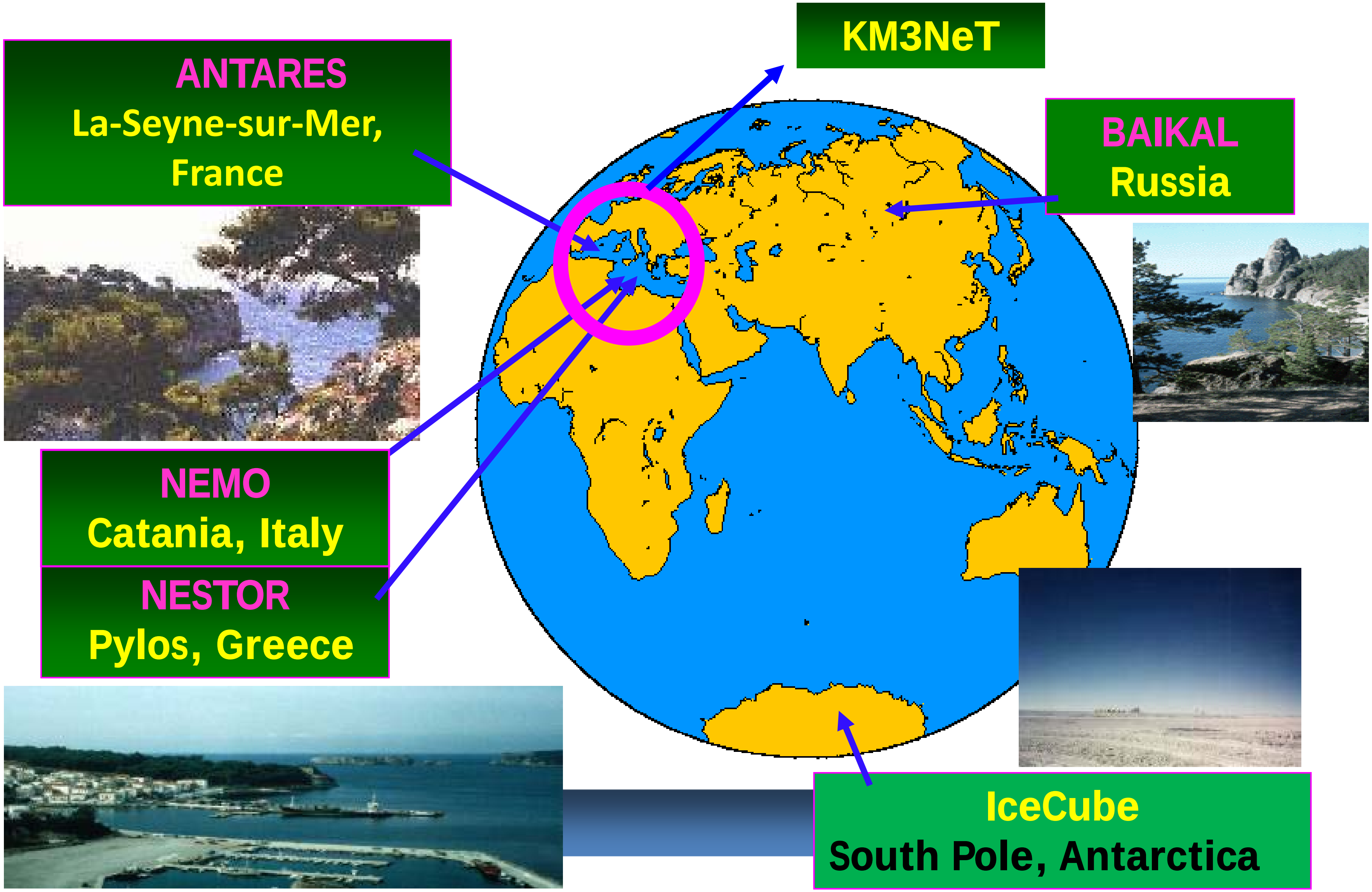


Instrumentation of 1 km³ antarctic ice with ~ 5000 photo multipliers completed December 2010

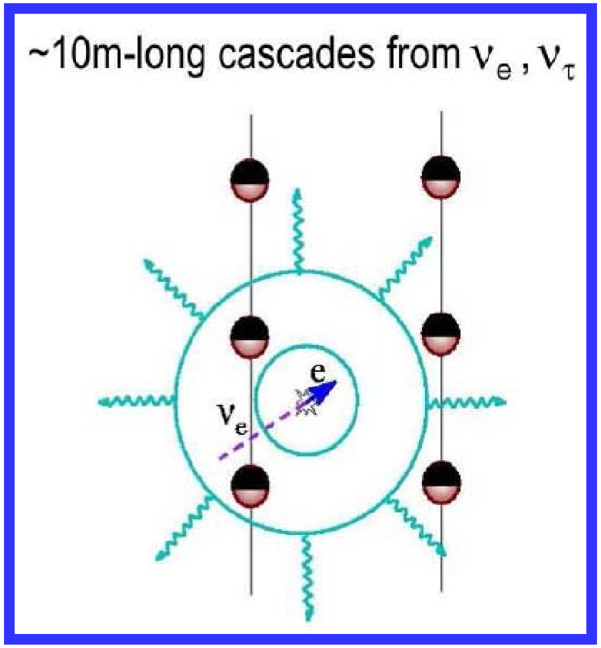


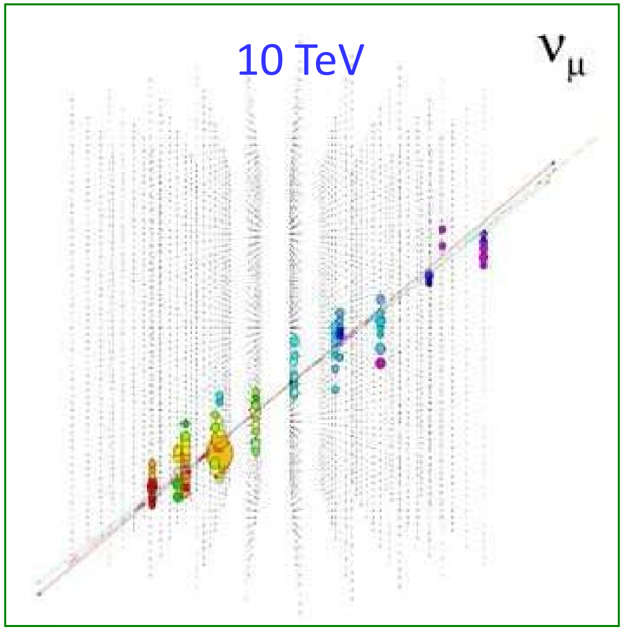


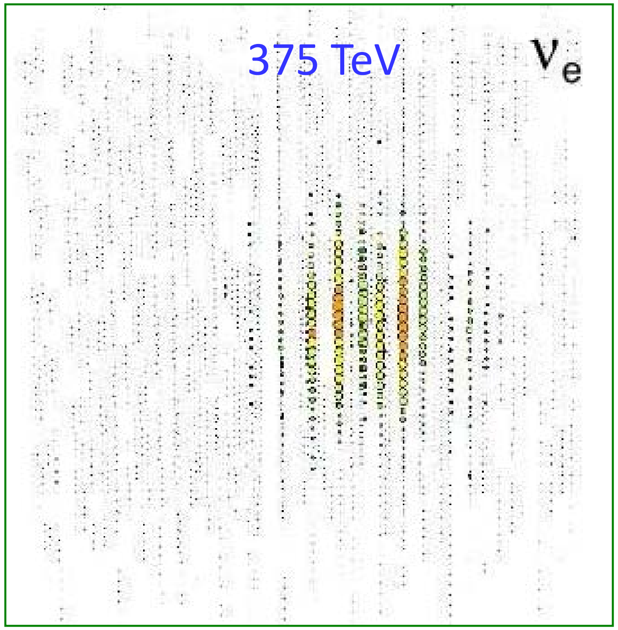
Ultrahigh-energy neutrinos: Challenges and Opportunities

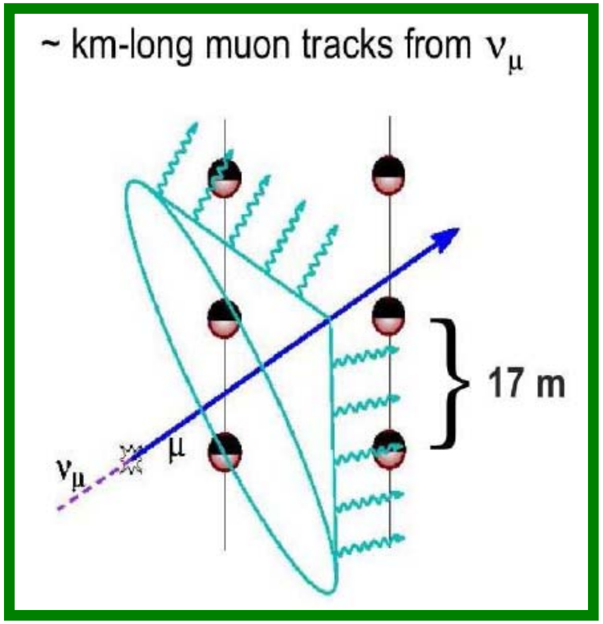


Ultrahigh-energy neutrinos: Challenges and Opportunities





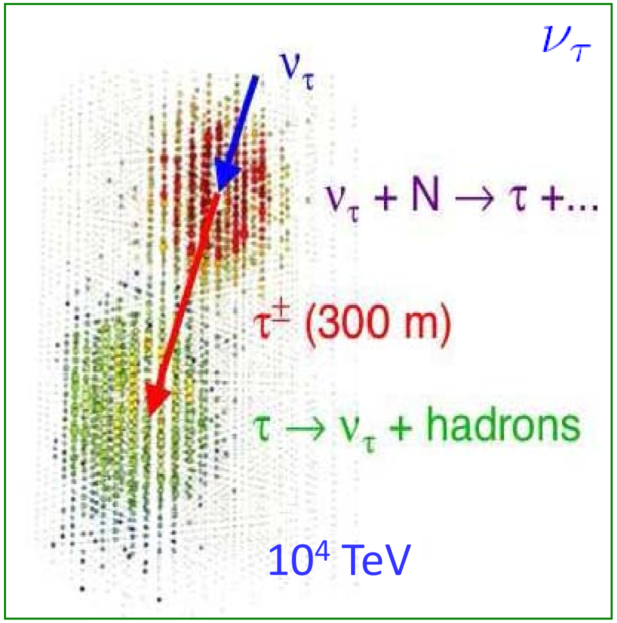




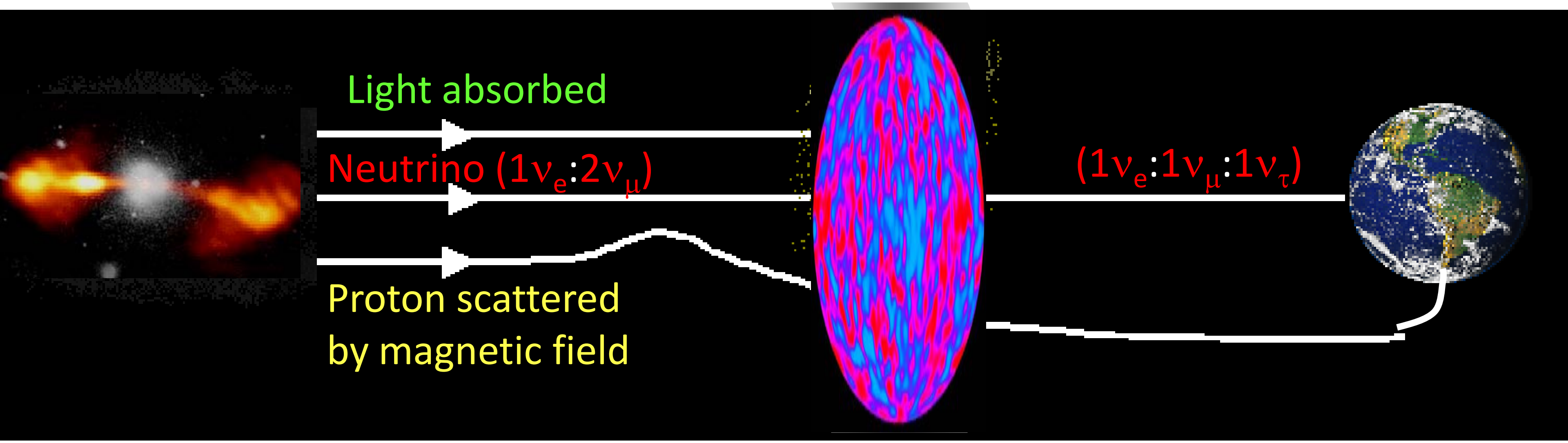
Distinct signals for different flavors:

Particle physics by using the flavors, given the sources

Probe sources by using the flavors, given ν properties



Ultrahigh-energy neutrinos: Unique Opportunity



To explore extremely high energy region

To locate distant astrophysical sources

To study new scenarios in particle physics

$$\phi_e : \phi_\mu : \phi_\tau = 1:2:0$$

$$\phi_e^T : \phi_\mu^T : \phi_\tau^T = 1:1:1$$

$$\pi^+ \to \mu^+ + \nu_\mu, \quad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu, \quad \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

Conventional source: decays of charged π's produced from UHE *p+p* or *p+γ* collisions.

Naïve expectation: ultra-long-baseline UHE cosmic ν-oscillations (Learned, Pakvasa 95).

Incomplete list of relevant works

- ■ Learned, Pakvasa, APP (95)
- ★ Athar et al, PRD (00)
- ★ Bento et al, PLB (00)
- ★ Gounaris, Moultaka, hep-ph/0212110
- ★ Barenboim, Quigg, PRD (03)
- ★ Beacom et al, PRD (03)
- ★ Keraenen et al, PLB (03)
- ★ Beacom et al, PRD (04)
- ★ Hooper et al, PLB (05)
- ★ Serpico, Kachelriess, PRL (05)
- ★ Bhattacharjee, Gupta, hep-ph/0501191
- ★ Serpico, PRD (06)
- ★ Xing, PRD (06)
- ★ Xing, Zhou, PRD (06)
- ★ Winter, PRD (06)
- ★ Athar et al, MPLA (06)

General sources and contaminations

(Parametrization, Xing & Zhou 06)

$$\phi_e : \phi_\mu : \phi_\tau = \sin^2\xi \cos^2\zeta : \cos^2\xi \cos^2\zeta : \sin^2\zeta$$

active-sterile neutrino mixing & oscillation

$$\phi_e^T : \phi_\mu^T : \phi_\tau^T \neq 1:1:1$$

μ-τ symmetry breaking effects and CP phase δ

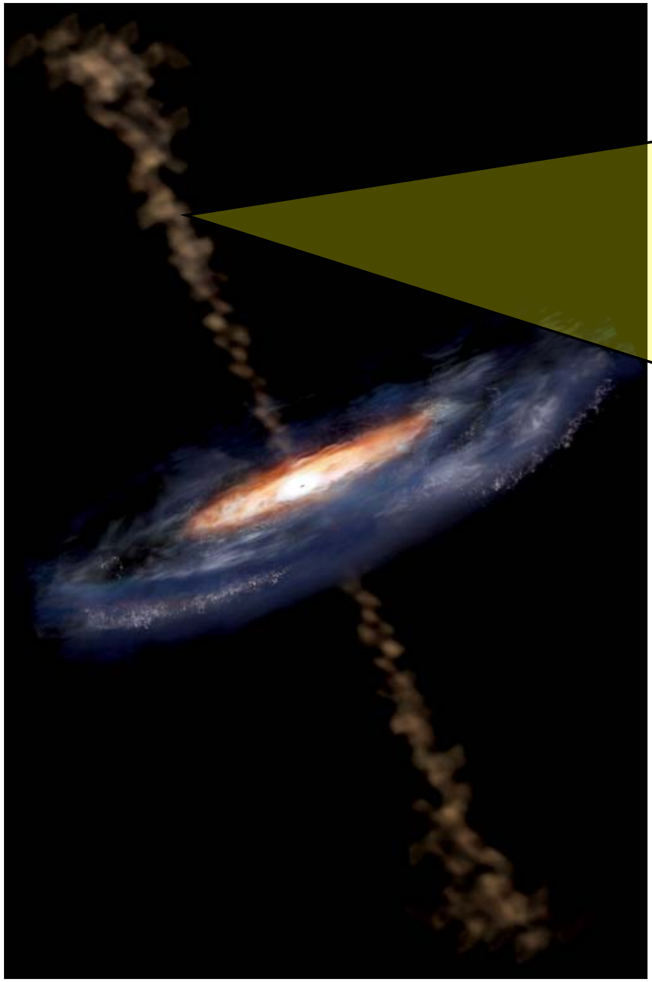
ν-decays

Test of CPT, Q-coherence, unitarity, ...

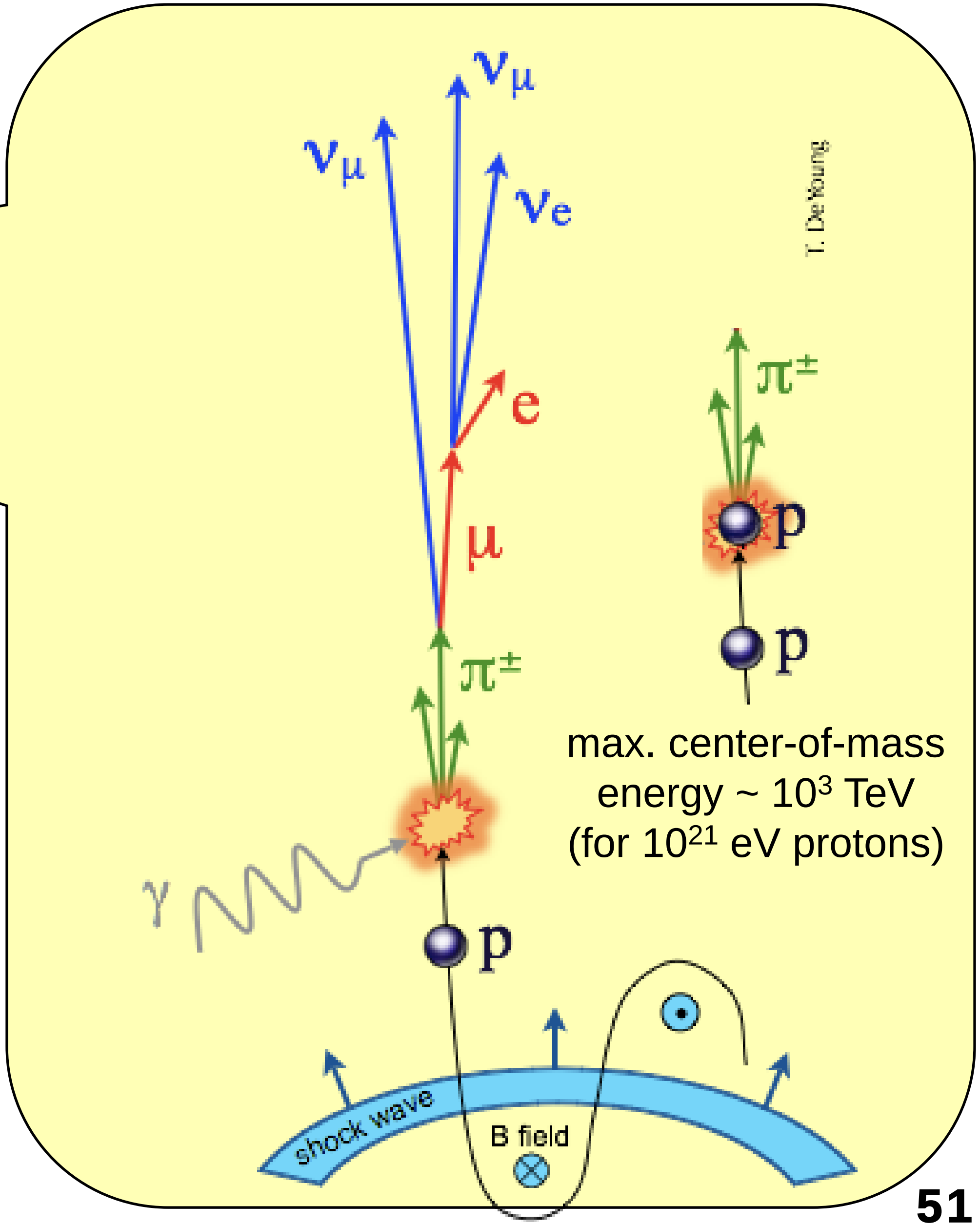
Can ν-telescopes (IceCube, KM3NeT) do ...?

- ★ Rodejohann, JCAP (07)
- ★ Majumdar, Ghosal, PRD (07)
- ★ Xing, NPB (Proc. Suppl.) (07)
- ★ Blum, Nir, Waxman, arXiv:0706.2070
- ★ Lipari et al, PRD (07)
- ★ Meloni, Ohlsson, PRD (07)
- ★ Awasthi, Choubey, PRD (07)
- ★ Hwang, Kim, arXiv:0711.3122
- ★ Xing, NPB (Proc. Suppl.) (08)
- ★ Pakvasa et al, JHEP (08)
- ★ Choubey, Niro, Rodejohann, PRD (08)
- ★ Pakvasa, arXiv:0803.1701
- ★ Maltoni, Winter, JEHP (08)
- ★ Xing, Zhou, PLB (08)
- ★ Xing, Zhou, PRD(11)
- ★ ......

Neutrino Production in Astrophysical Sources



Example: Active galaxy
(Halzen, Venice 2009)



Glashow Resonance as a Discriminator: *pp* vs. *pγ*

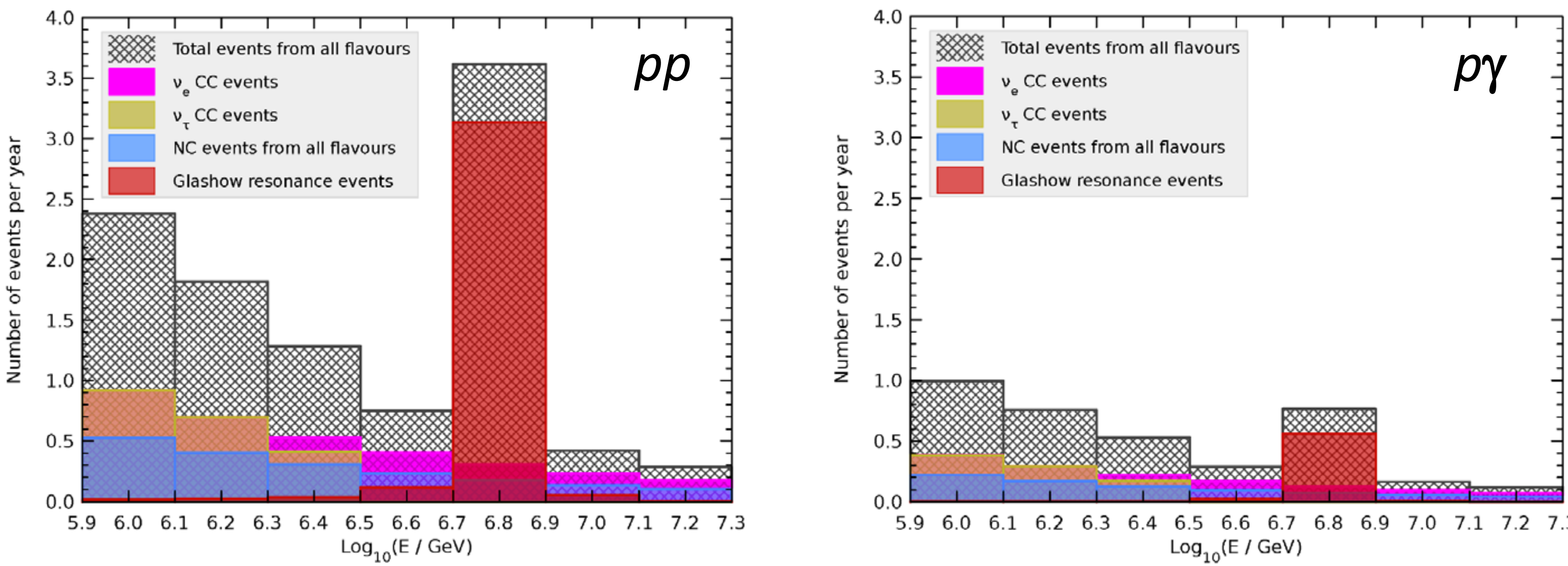
- **unique way to distinguish between neutrinos and antineutrinos**
- **possible way to tell us whether *pp* or *pγ* process is dominant**

Glashow, 1960; Berezinsky , Gazizov, 1977, 1981; Anchordoqui et al., 2004; Winter et al., 2010; Bhattacharya et al., 2005, 2011; Xing, Zhou, 2011

$$\bar{\nu}_e + e^- \to W^- \to \text{anything}$$

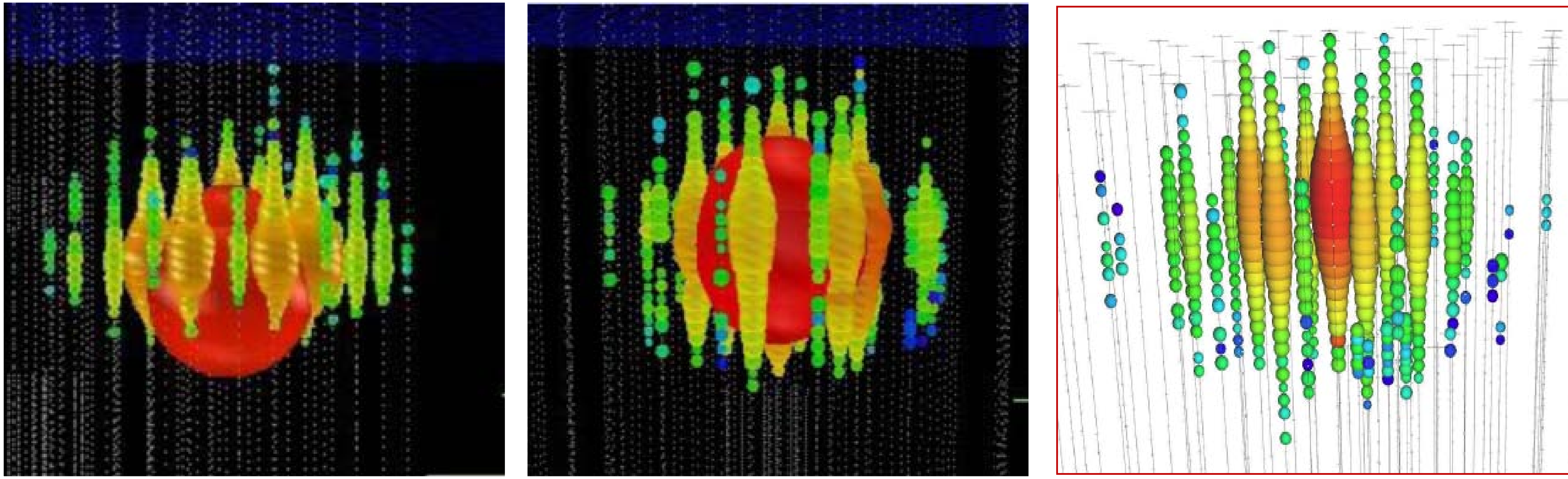
@ E_ν = 6.3 PeV

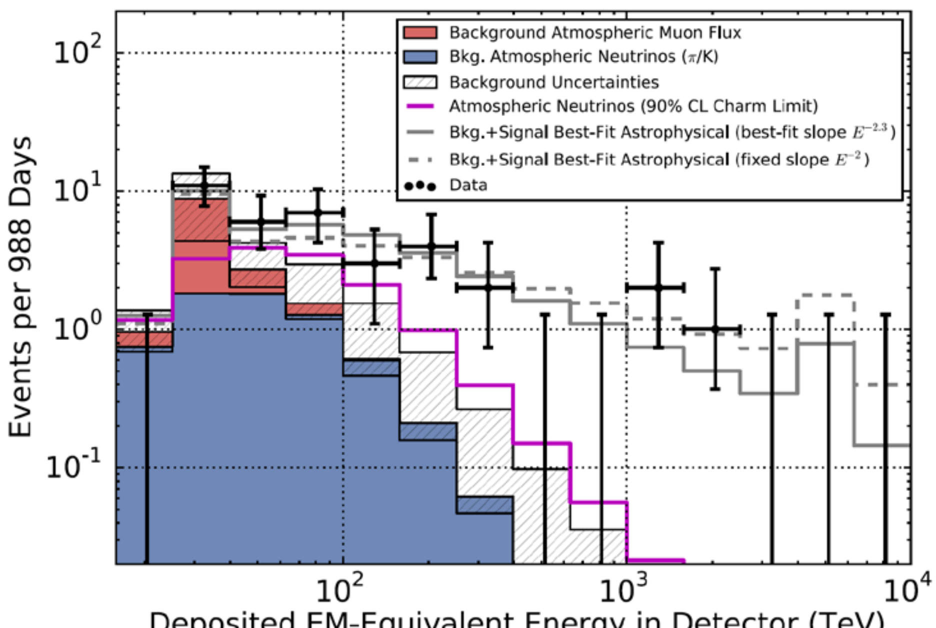
Waxman-Bahcall Bound



Discovery of PeV Cosmic Neutrinos in IceCube

IceCube Collaboration, Science 342 (2013) 947; PRL 113 (2014) 101101





3-year data, 37 events, in the energy range 30 TeV – 2 PeV

Purely atmospheric neutrino explanation excluded @ 5.7σ

Best-fit astrophysical sources with a spectrum $E^{-2.3}$

Summary and Outlook

Understanding intrinsic properties of neutrinos — a mature field

- Neutrino mixing parameters:
  well known from oscillation experiments, precision measurements
- New experiments designed for mass ordering and CP violation
- Absolute masses yet to be determined (KATRIN, cosmology)
- Majorana nature yet to be found (neutrinoless double beta decays)

Neutrinos as a cosmic messenger — a field in its infancy

- Detailed measurement of solar nus (ca 60,000 events in Super-K)
- First detection of solar pp nus (evidence for energy production)
- Geo-neutrinos (ca 116 events in KamLAND, 14 events in Borexino)
- Neutrinos from SN 1987A (ca 20 events)
- UHE nu events in IceCube (1.1 PeV, 1.3 PeV, 2.0 PeV and 34 others)

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