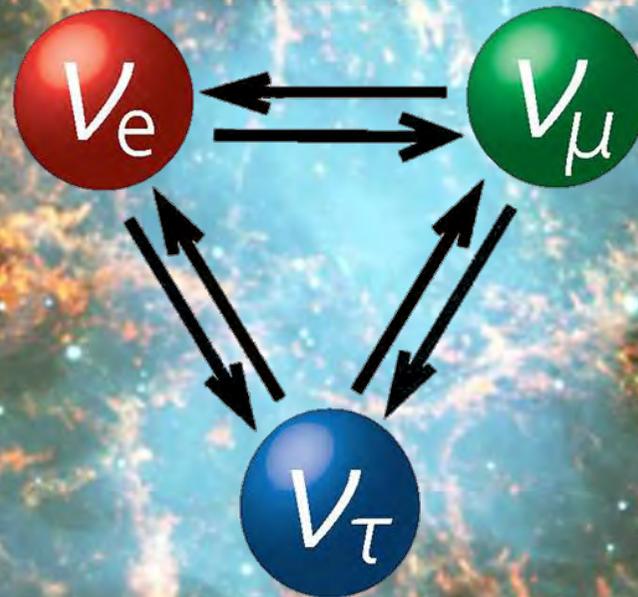


Neutrino Sources in the Universe

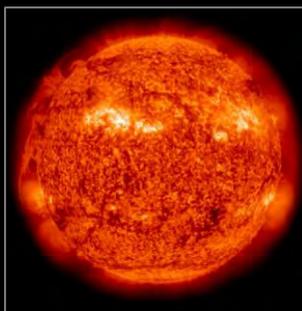


Georg G. Raffelt
Max-Planck-Institut für Physik, München



Where do Neutrinos Appear in Nature?

✓ Nuclear Reactors



Sun



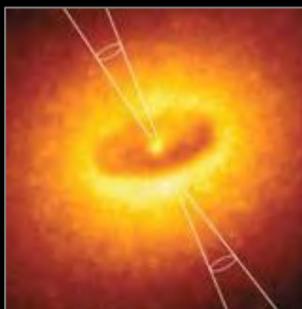
✓ Particle Accelerators



Supernovae
(Stellar Collapse)

SN 1987A ✓

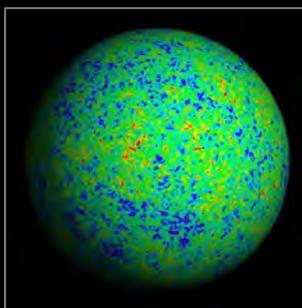
✓ Earth Atmosphere
(Cosmic Rays)



Astrophysical
Accelerators



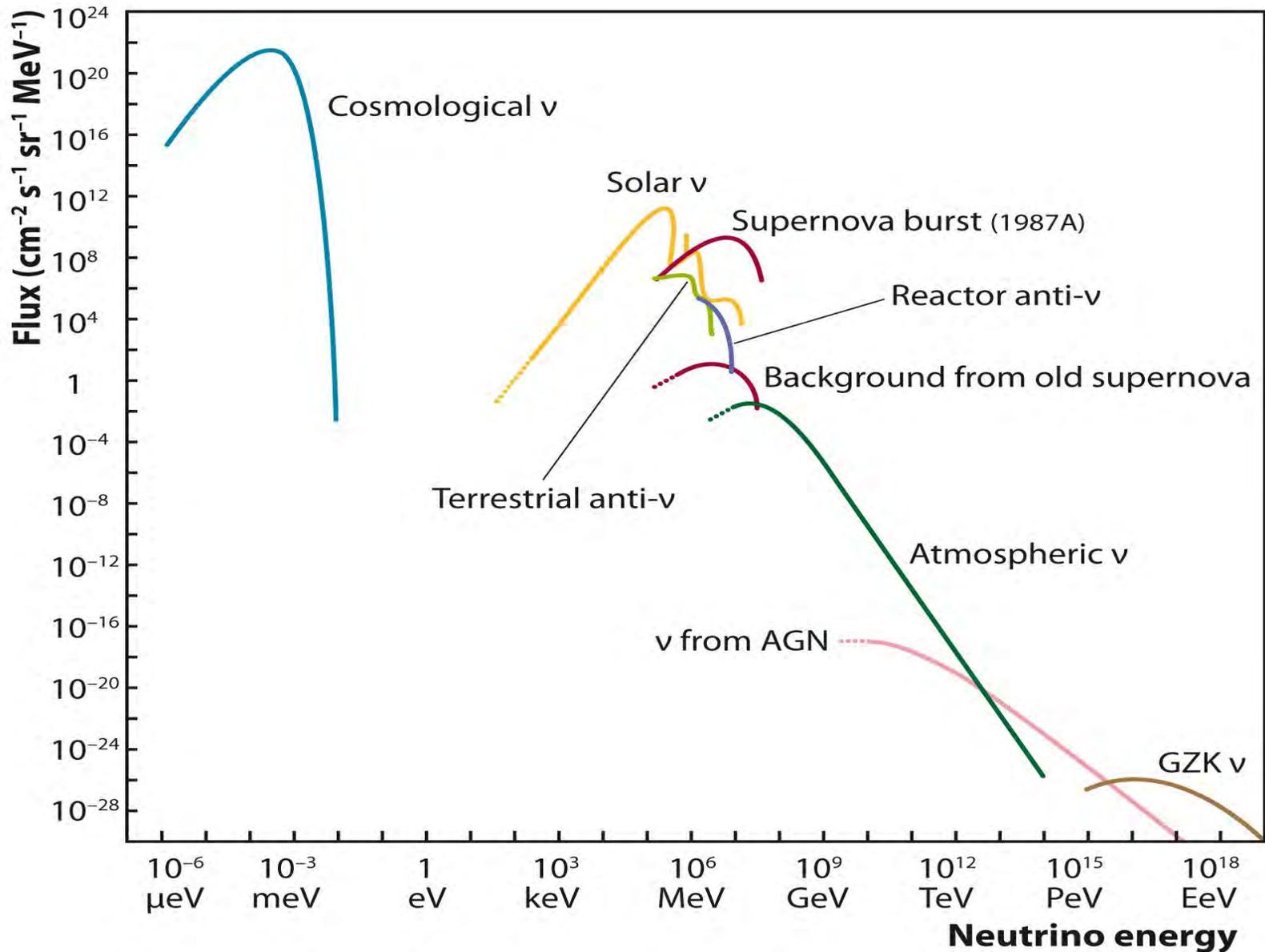
✓ Earth Crust
(Natural Radioactivity)



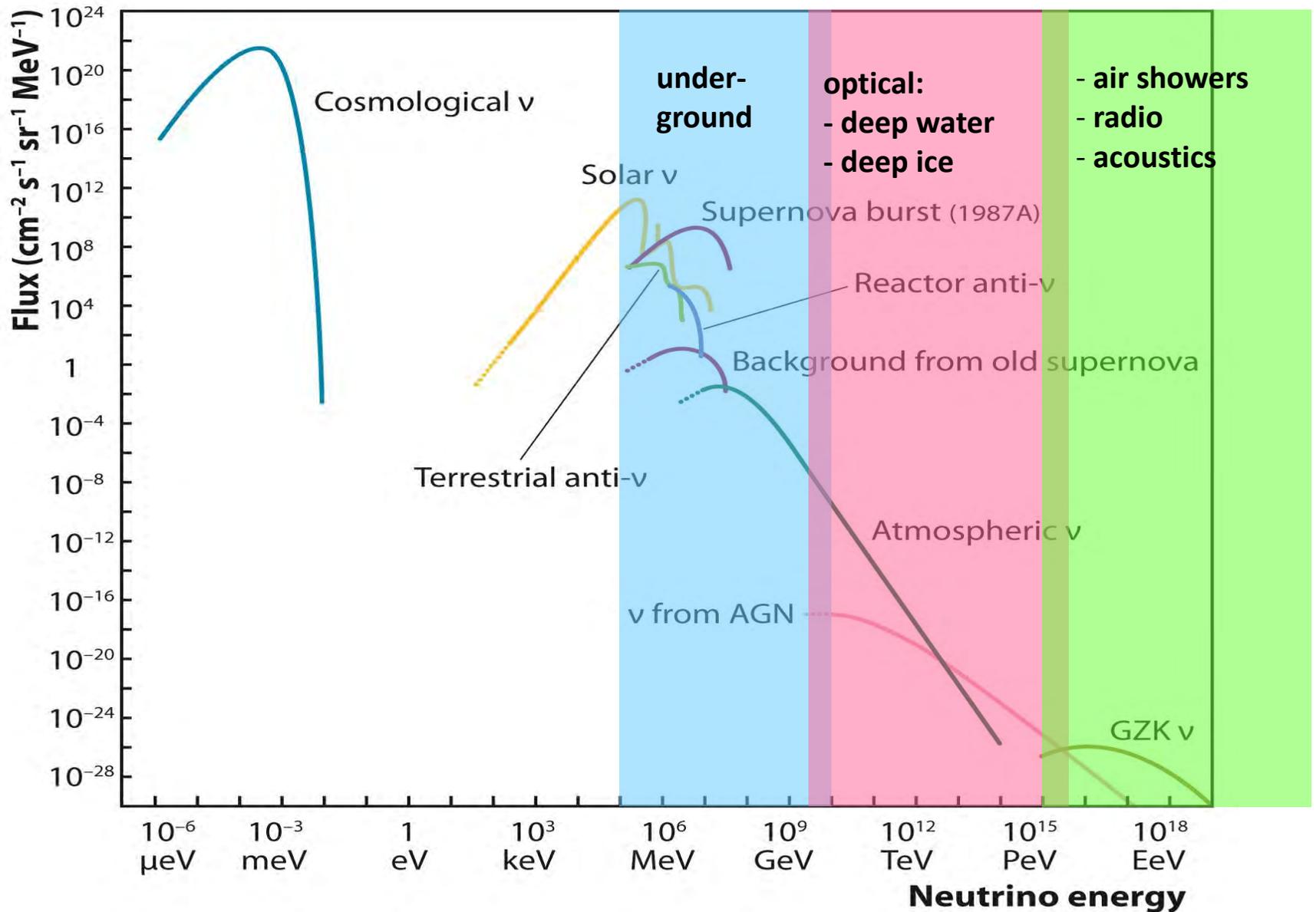
Cosmic Big Bang
(Today $330 \nu/\text{cm}^3$)

Indirect Evidence

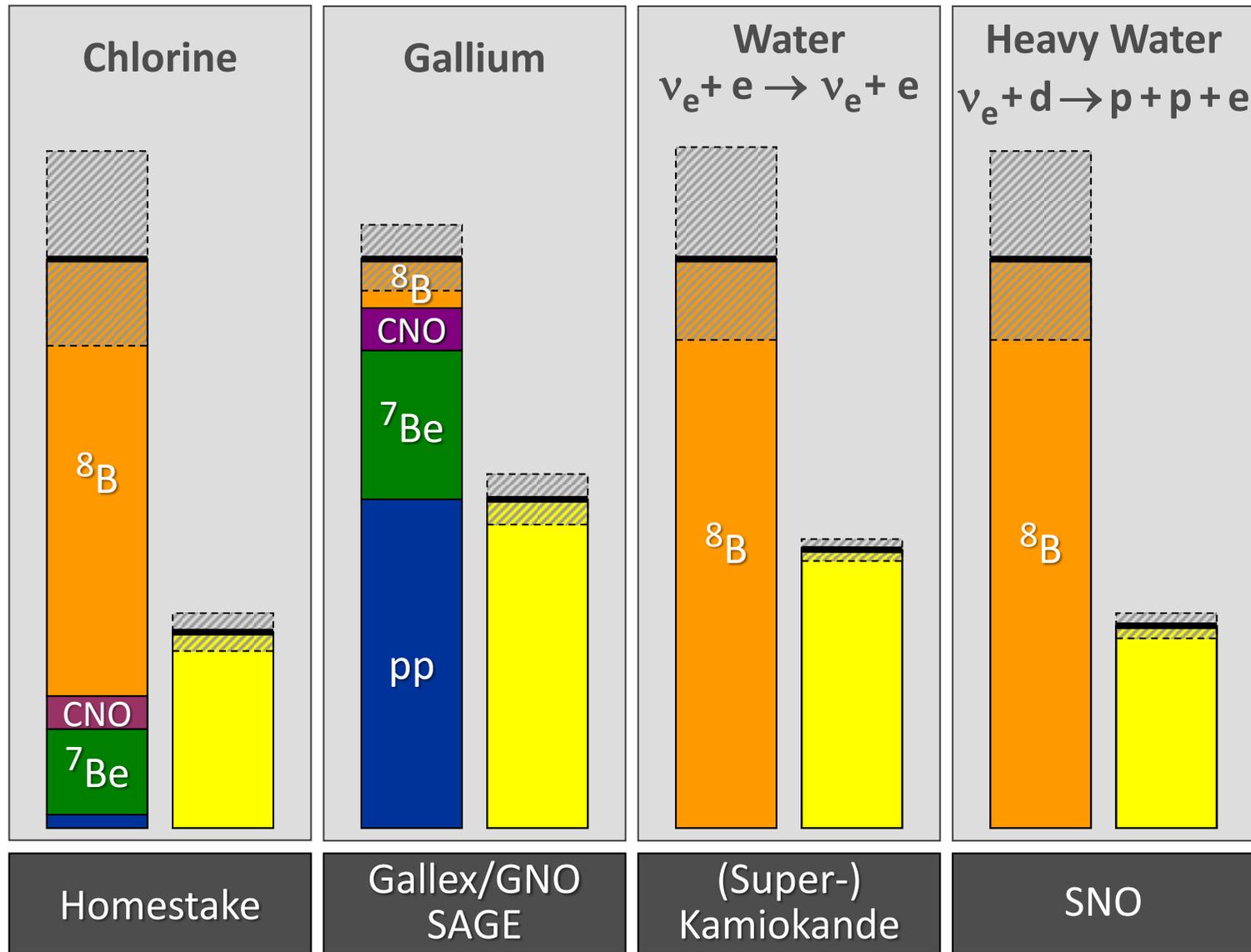
Grand Unified Neutrino Spectrum



Grand Unified Neutrino Spectrum



„Missing Solar Neutrinos“ in Many Experiments



Neutrino Flavor Oscillations

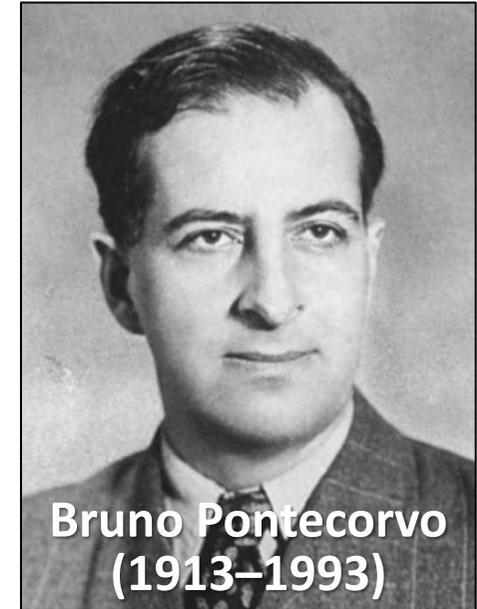
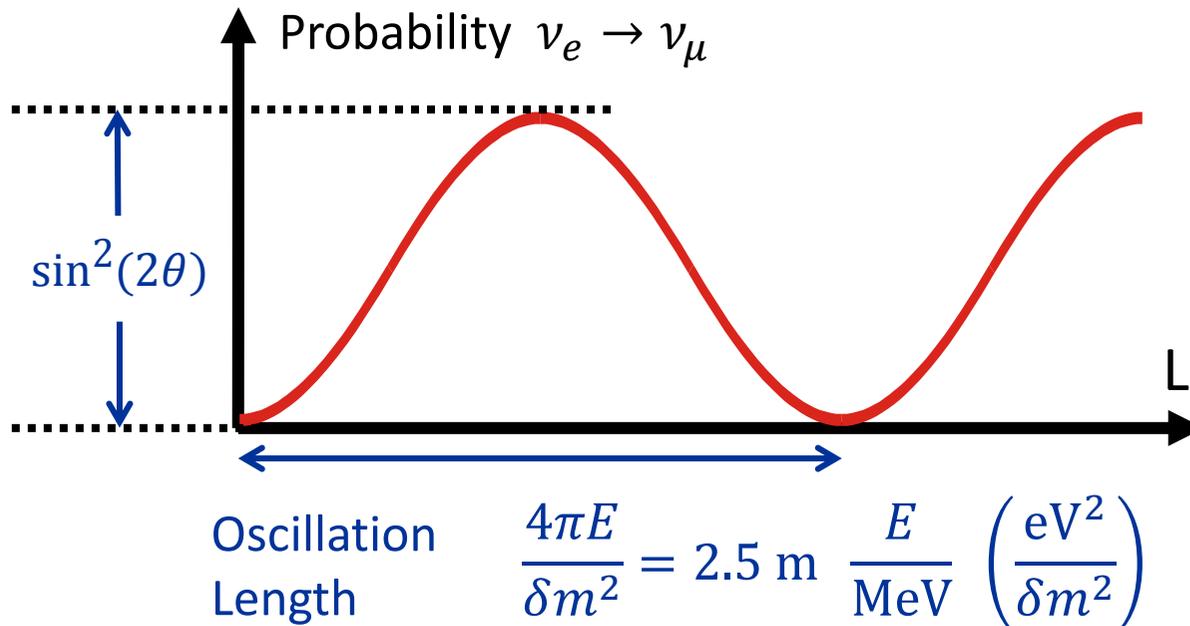
Pontecorvo & Gribov (1968) on the “Solar Neutrino Problem”

- Neutrinos are superposition of “mass eigenstates”

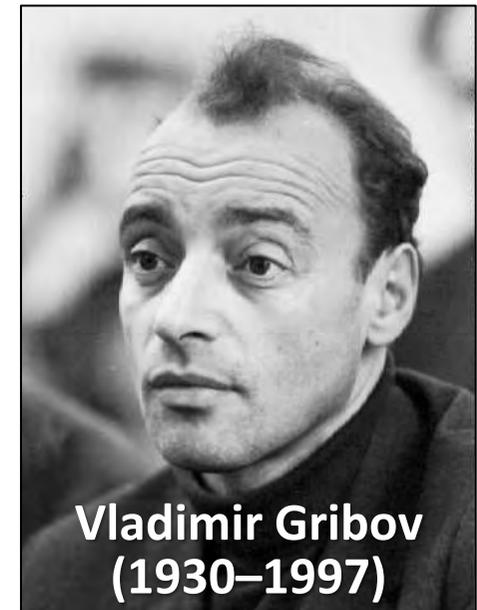
$$\nu_e = +\cos \Theta \nu_1 + \sin \Theta \nu_2$$

$$\nu_\mu = -\sin \Theta \nu_1 + \cos \Theta \nu_2$$

- Different speed of propagation
- Phase difference $\frac{\delta m^2}{2E} L$ causes oscillations
- Similar to “optical activity” in the propagation of light



Bruno Pontecorvo
(1913–1993)



Vladimir Gribov
(1930–1997)

Direct Approach to Resolve the Solar-Neutrino Problem

Herbert H. Chen

Department of Physics, University of California, Irvine, California 92717

(Received 27 June 1985)

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ${}^8\text{B}$ decay via the neutral-current reaction $\nu + d \rightarrow \nu + p + n$ and the charged-current reaction $\nu_e + d \rightarrow e^- + p + p$, is suggested for this purpose.

PACS numbers: 96.60.Kx, 14.60.Gh

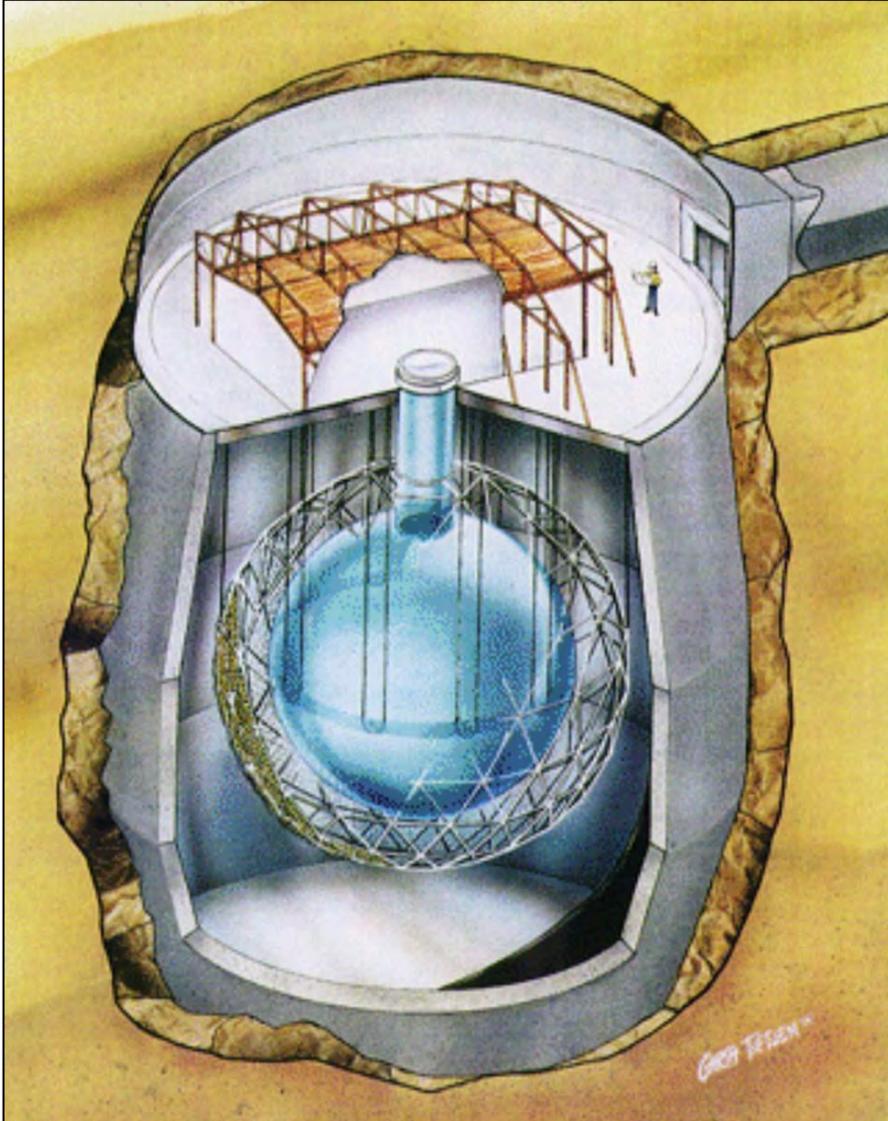


Herbert Hwa Chen
(1942–1987)

- Proposal 1984: Heavy water as target
- Can “see” all neutrino flavors
- Available in Canada as a loan from strategic reserve of CANDU reactor programme
- Formation of Sudbury Neutrino Observatory project (SNO)
- H. Chen passes away on 7. Nov. 1987 and Art McDonald (then Princeton) takes on leadership
- Measurement of the full solar neutrino flux in 2002
- Nobel prize for Art McDonald 2015

Sudbury Neutrino Observatory (SNO) 1999–2006

1000 tons of heavy water



Normal (light) water



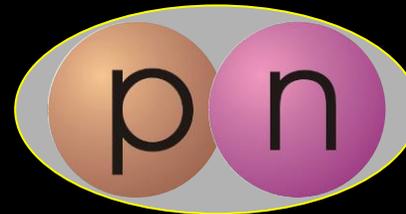
Heavy water



Nucleus of hydrogen (proton)

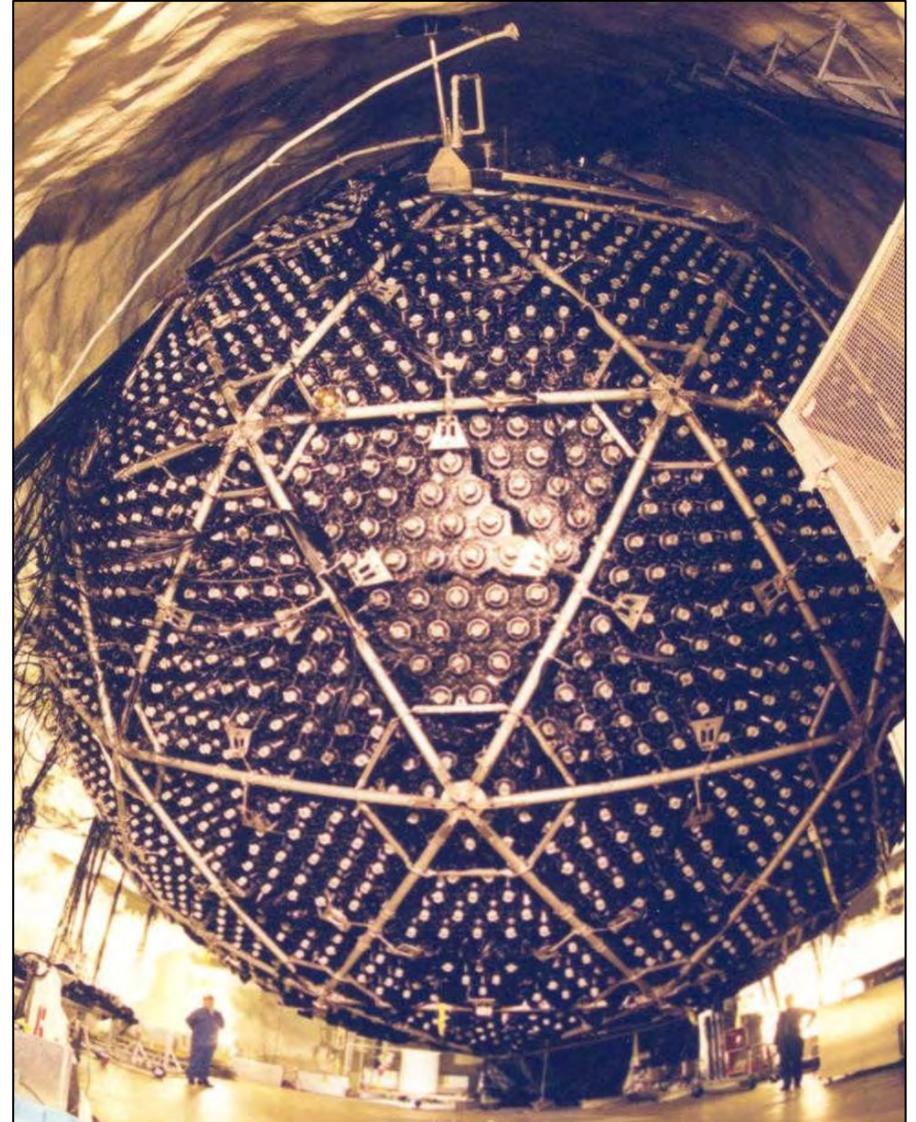
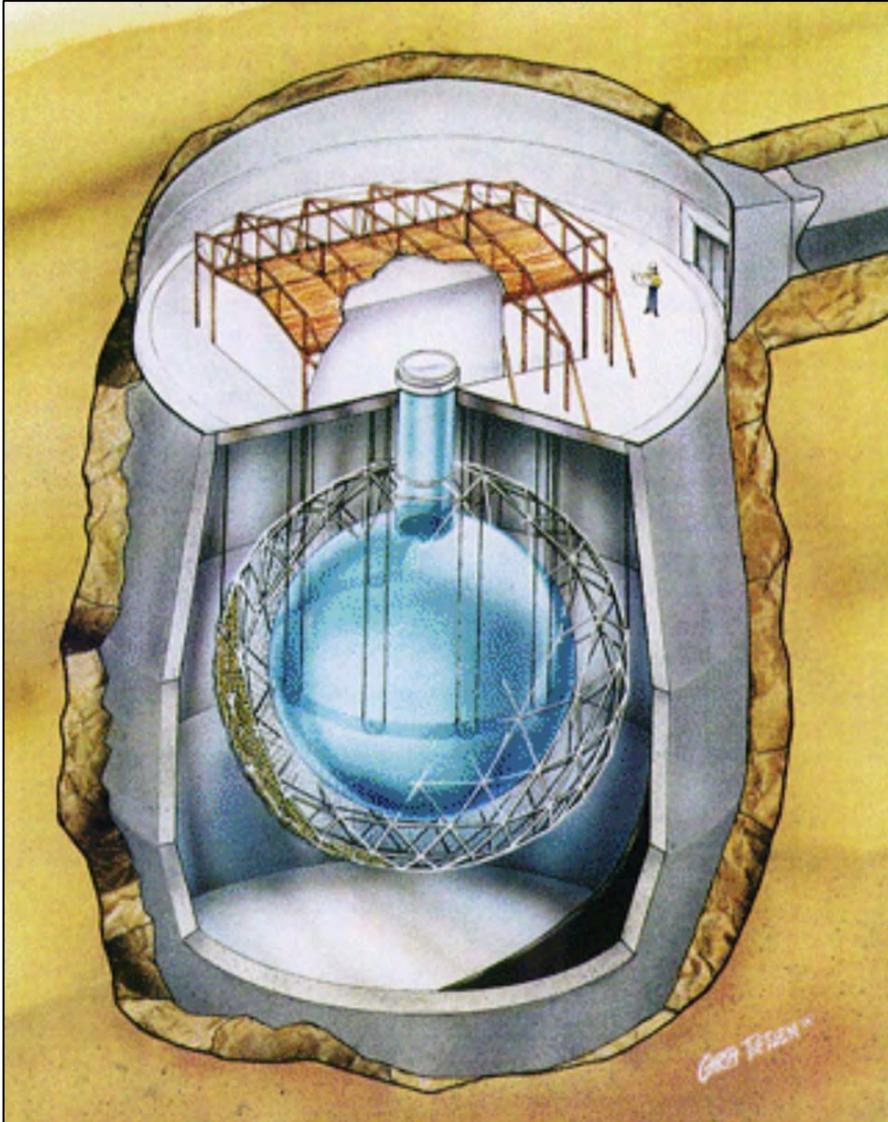


Nucleus of heavy hydrogen
(deuterium)



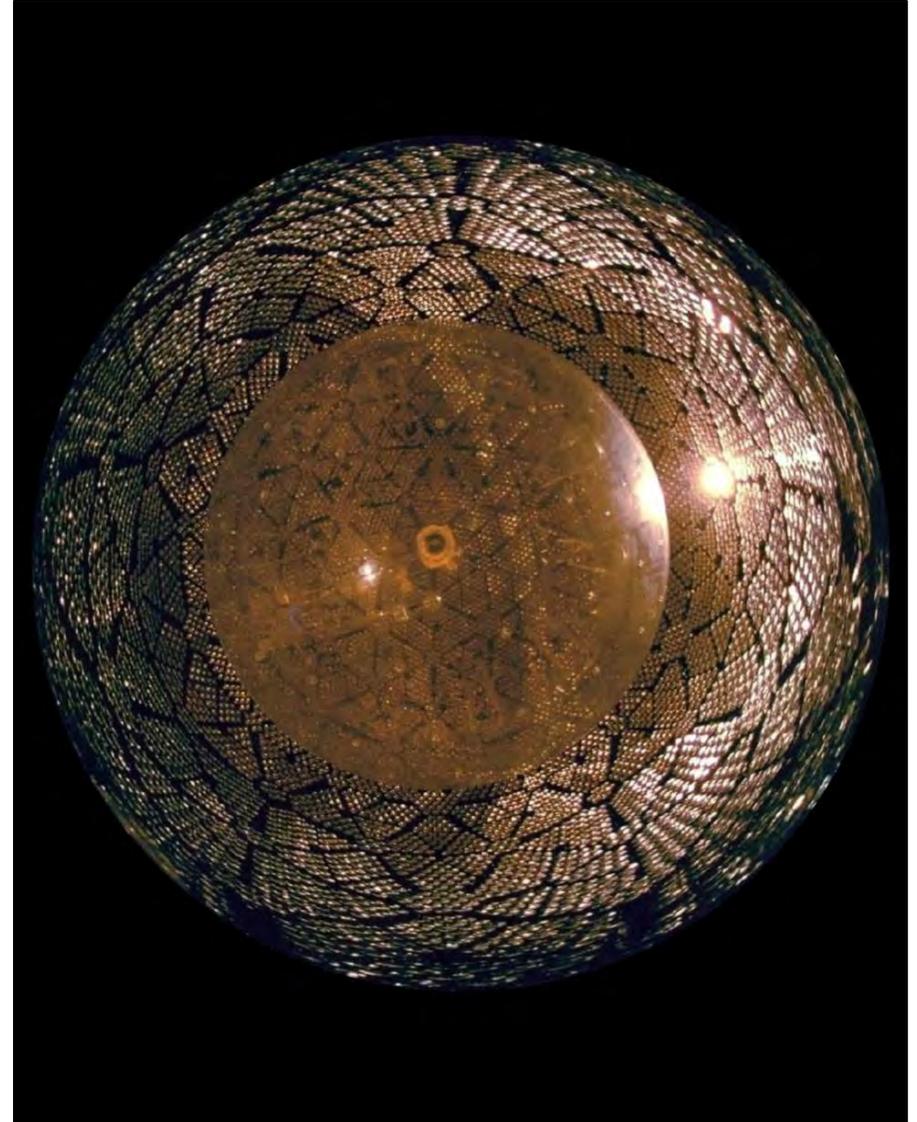
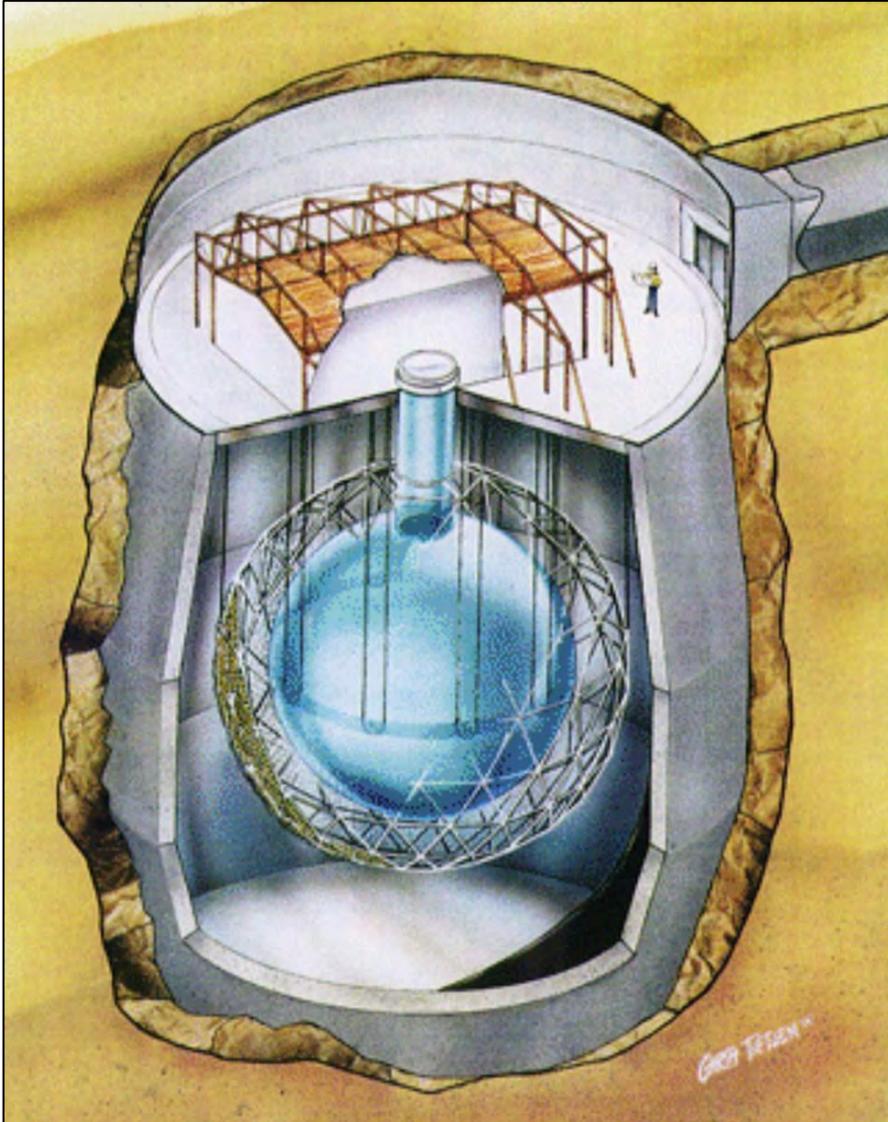
Sudbury Neutrino Observatory (SNO) 1999–2006

1000 tons of heavy water

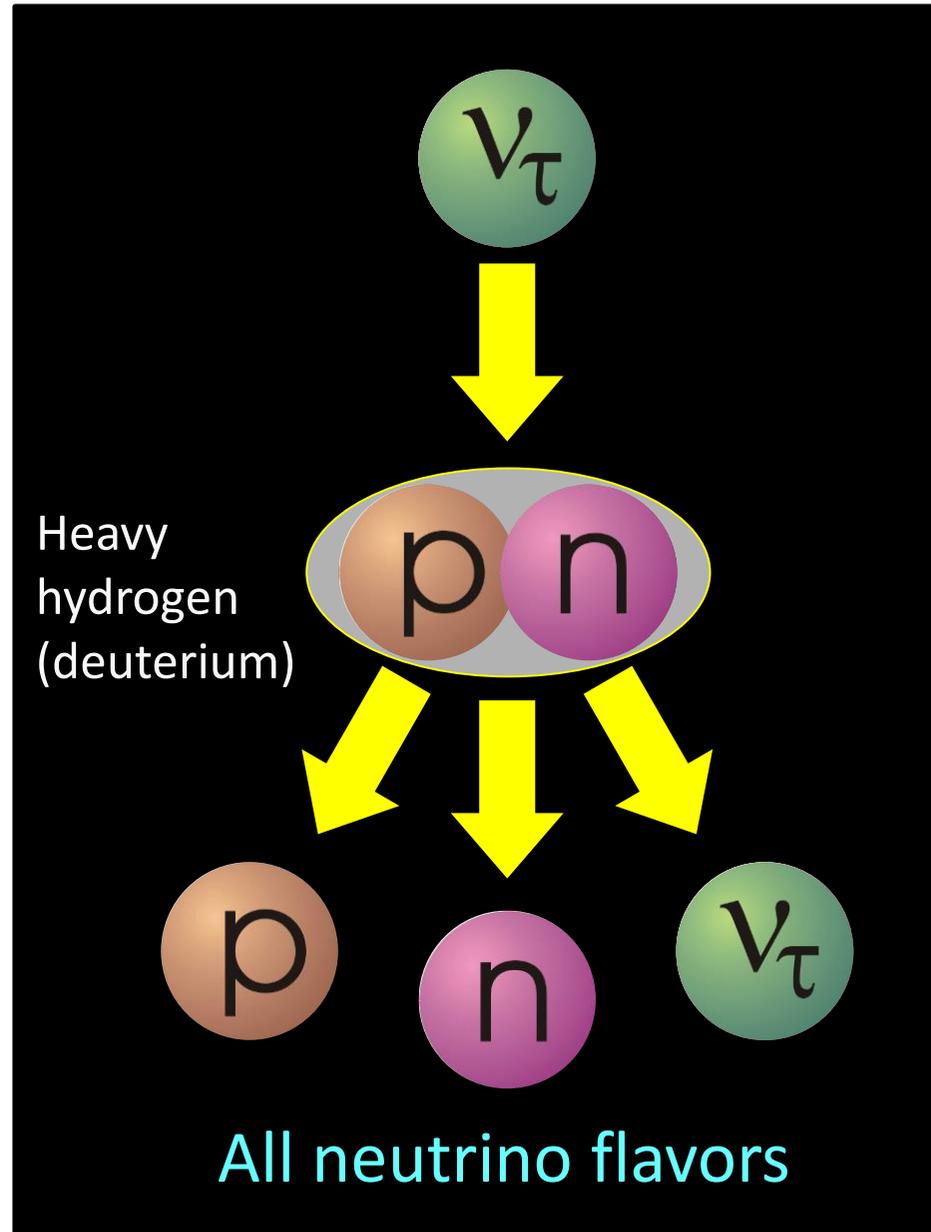
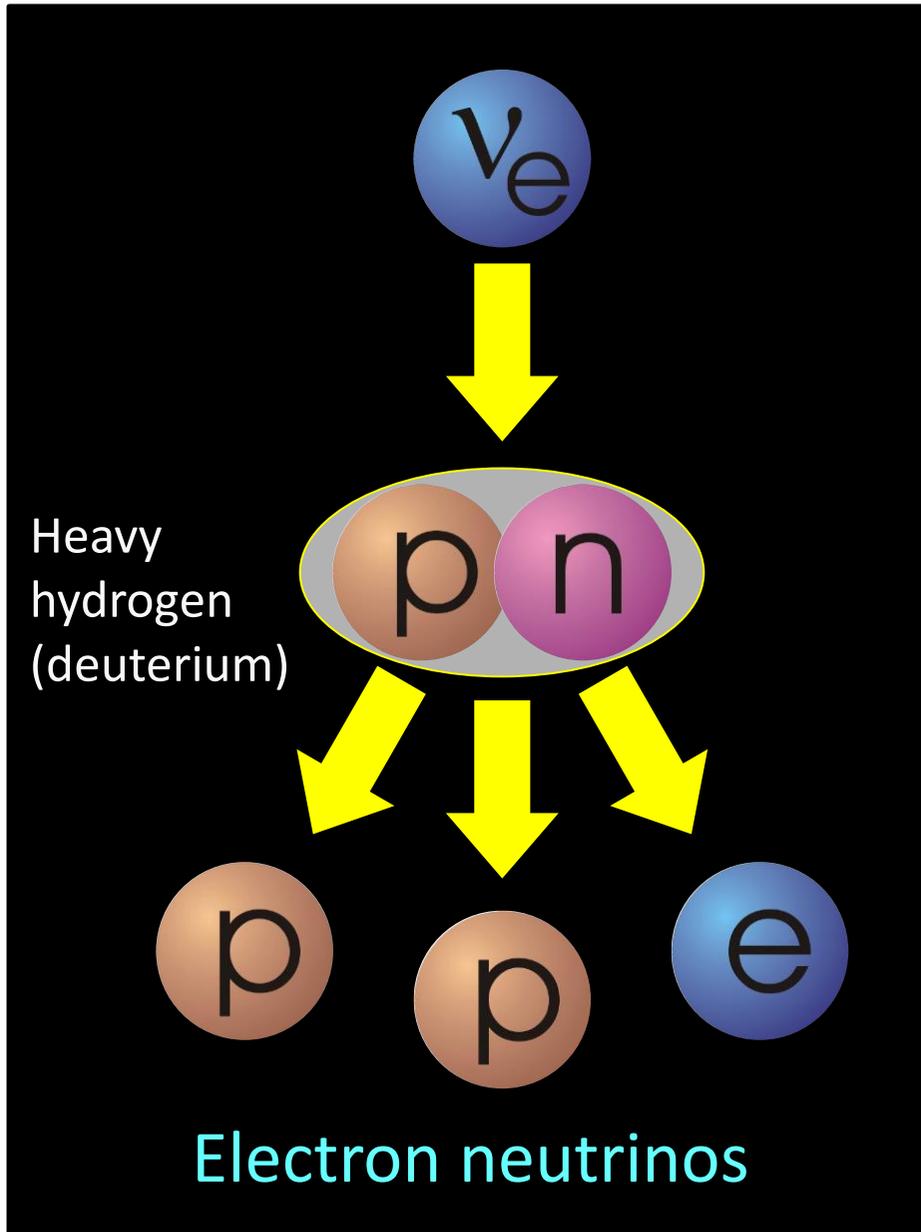


Sudbury Neutrino Observatory (SNO) 1999–2006

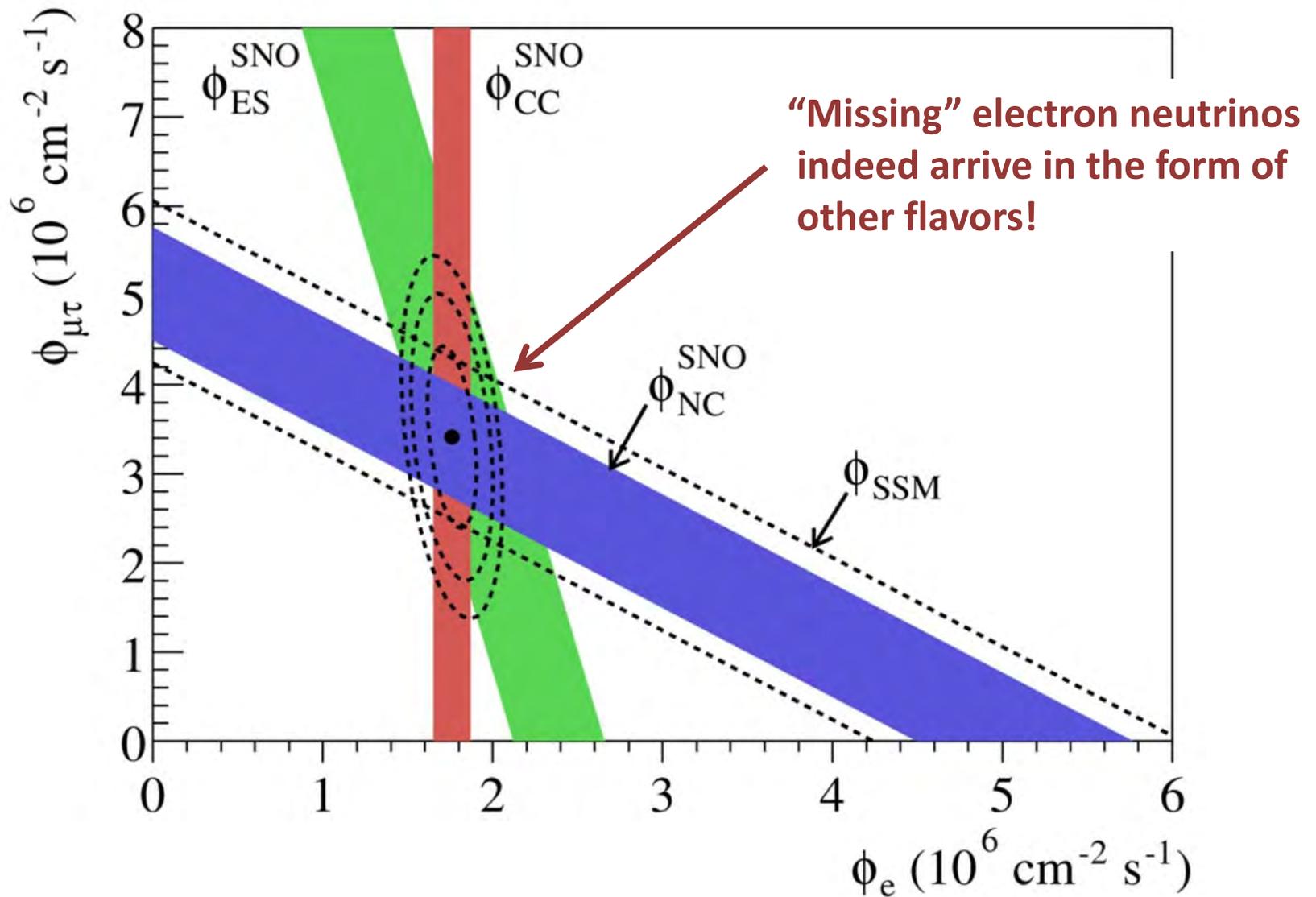
1000 tons of heavy water



Sudbury Neutrino Observatory (SNO) 1999–2006

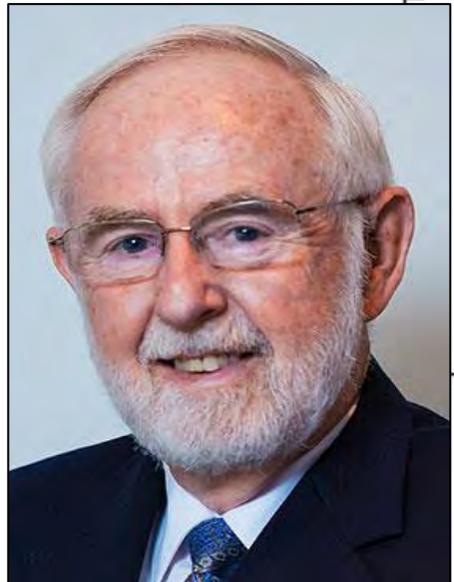
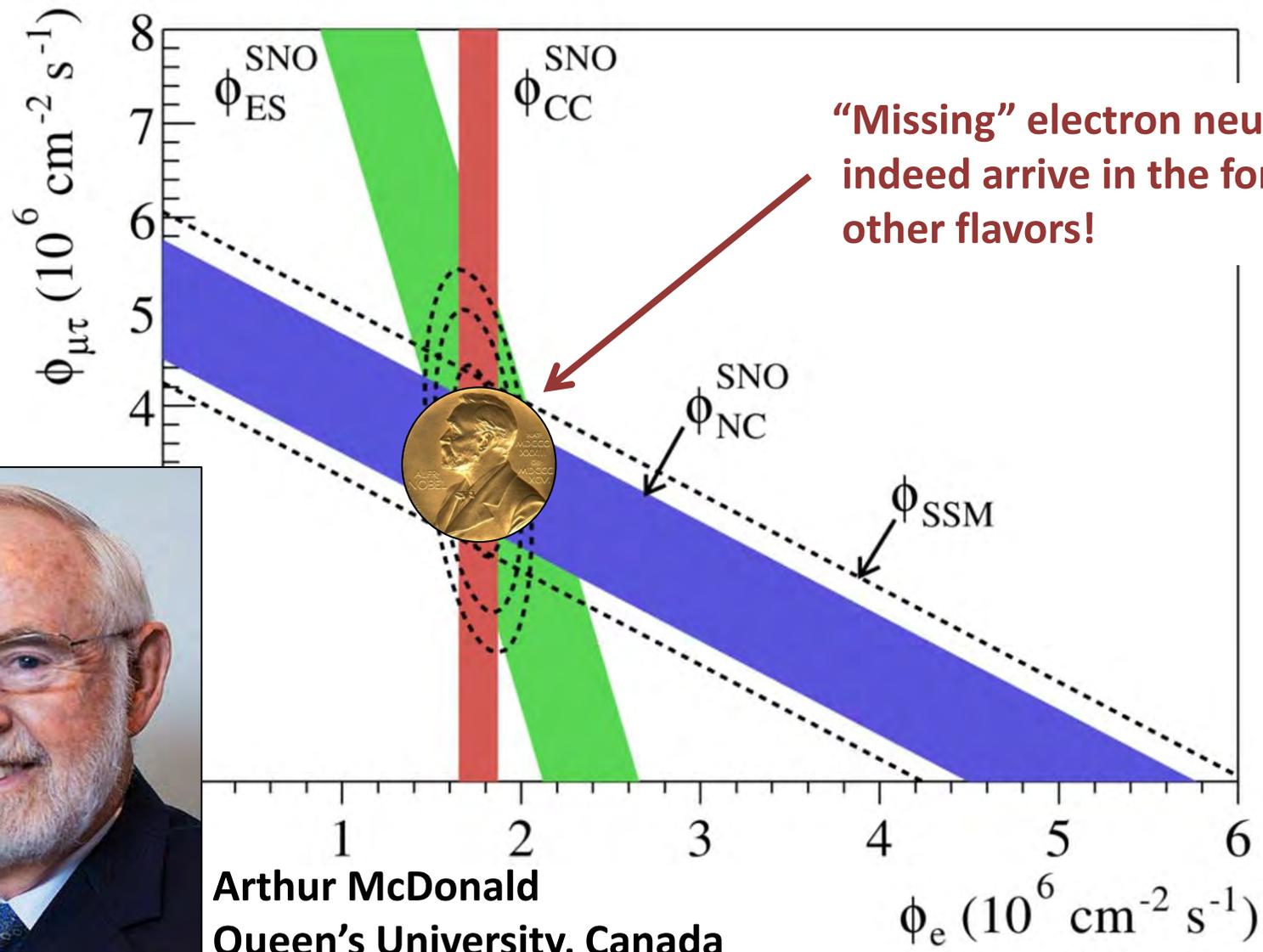


SNO Results (2002)



Phys. Rev. Lett. 89:011301, 2002 (<http://arXiv.org/abs/nucl-ex/0204008>)

SNO Results (2002)

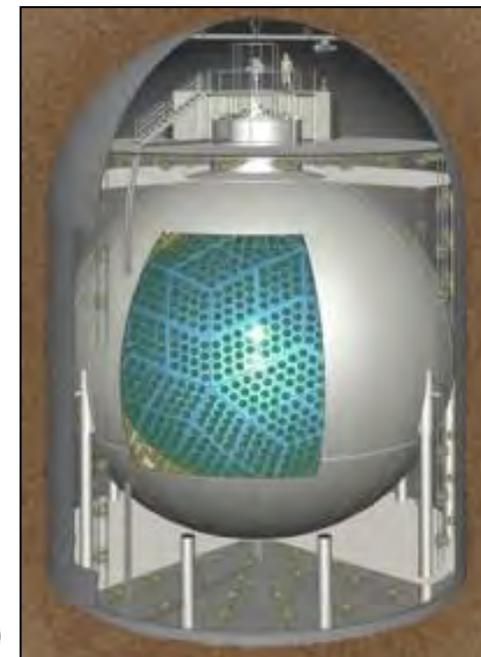
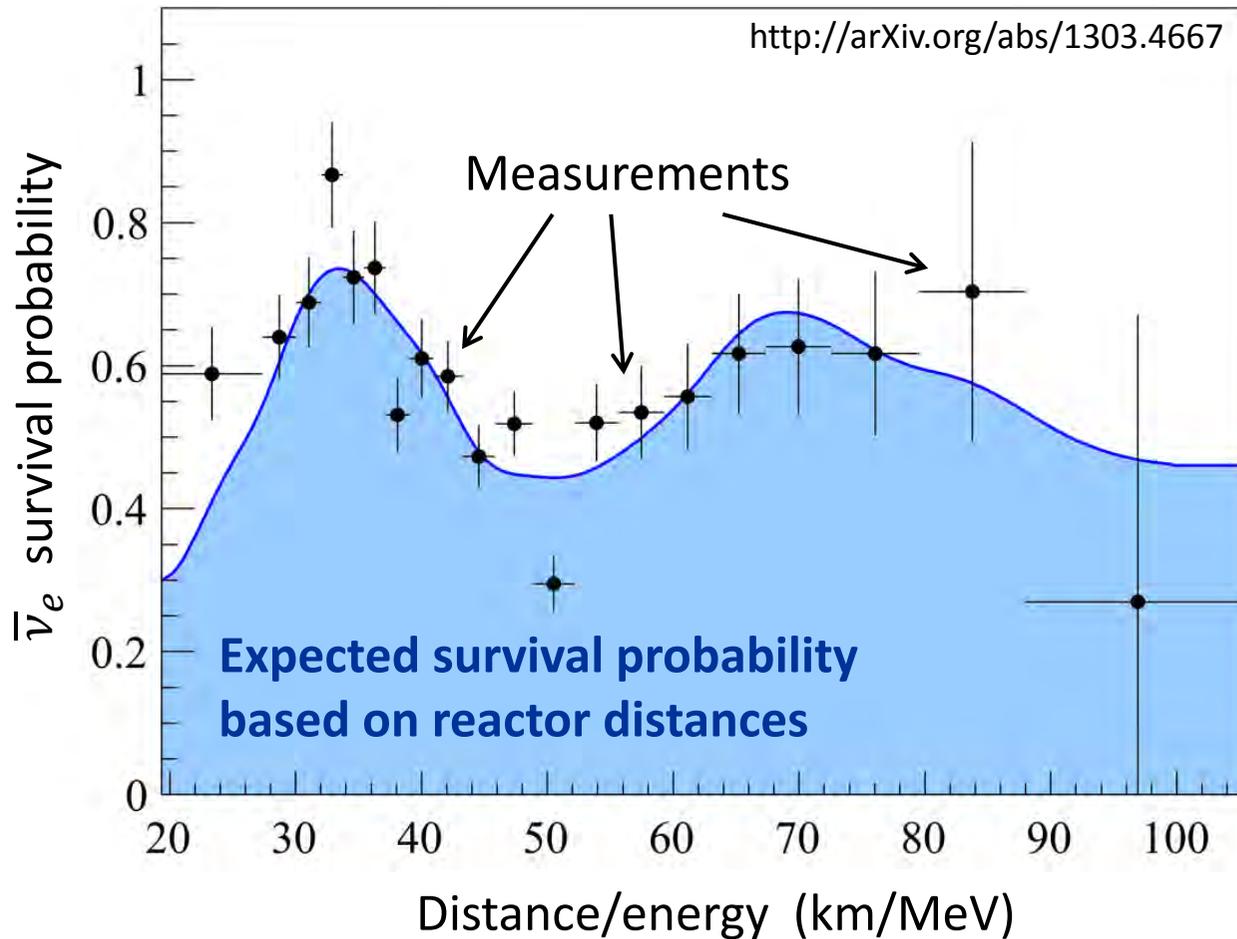


Arthur McDonald
Queen's University, Canada

Phys. Rev. Lett. 89:011301, 2002 (<http://arXiv.org/abs/nucl-ex/0204008>)

Reactor Neutrino Oscillations (KamLAND, Japan)

Oscillation pattern for anti-electron-neutrinos as a function of energy at fixed distance (ca 180 km)

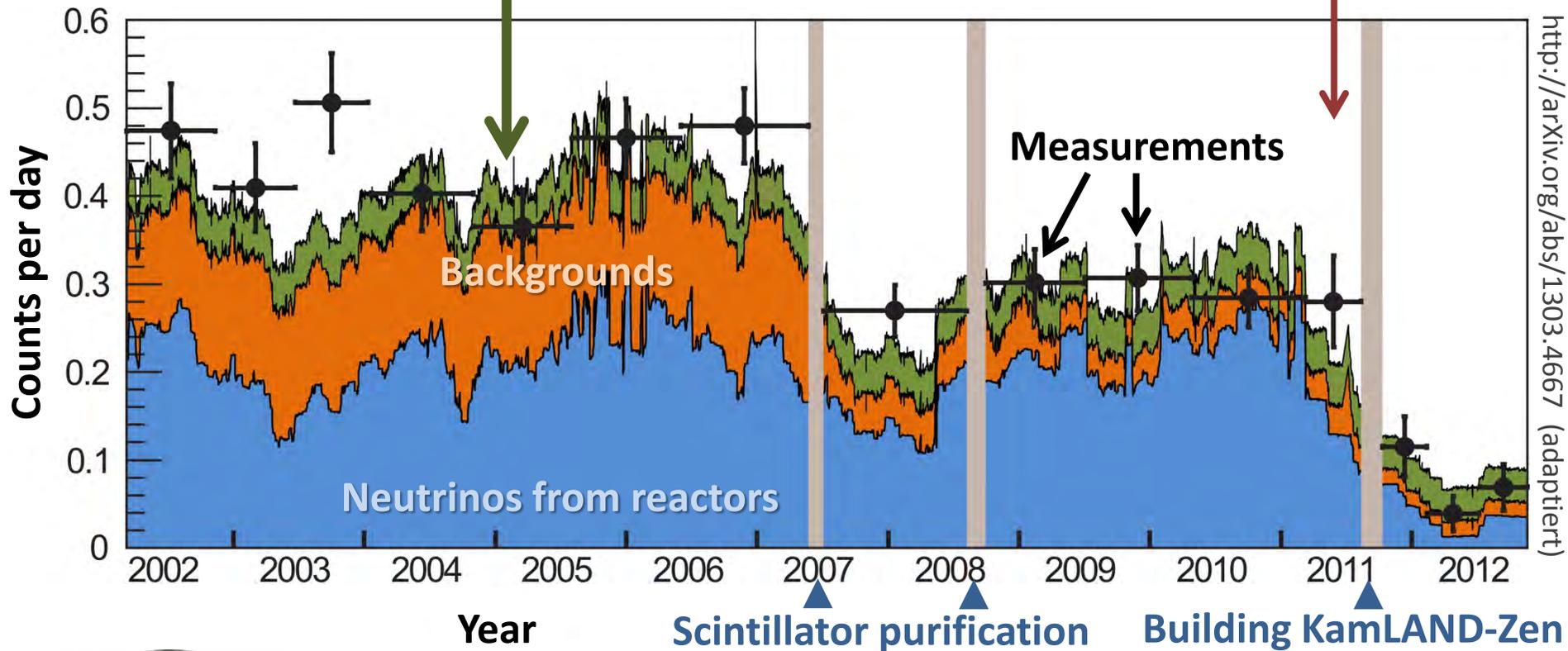


KamLAND Scintillator-Detector (1000 t)

Reactor- and Geo-Neutrinos in KamLAND (Japan)

Overall 116_{-27}^{+28} Geo-neutrinos
(plus 24_{-6}^{+7} in Borexino)

Earthquake & Tsunami (2011)
All reactors switched off

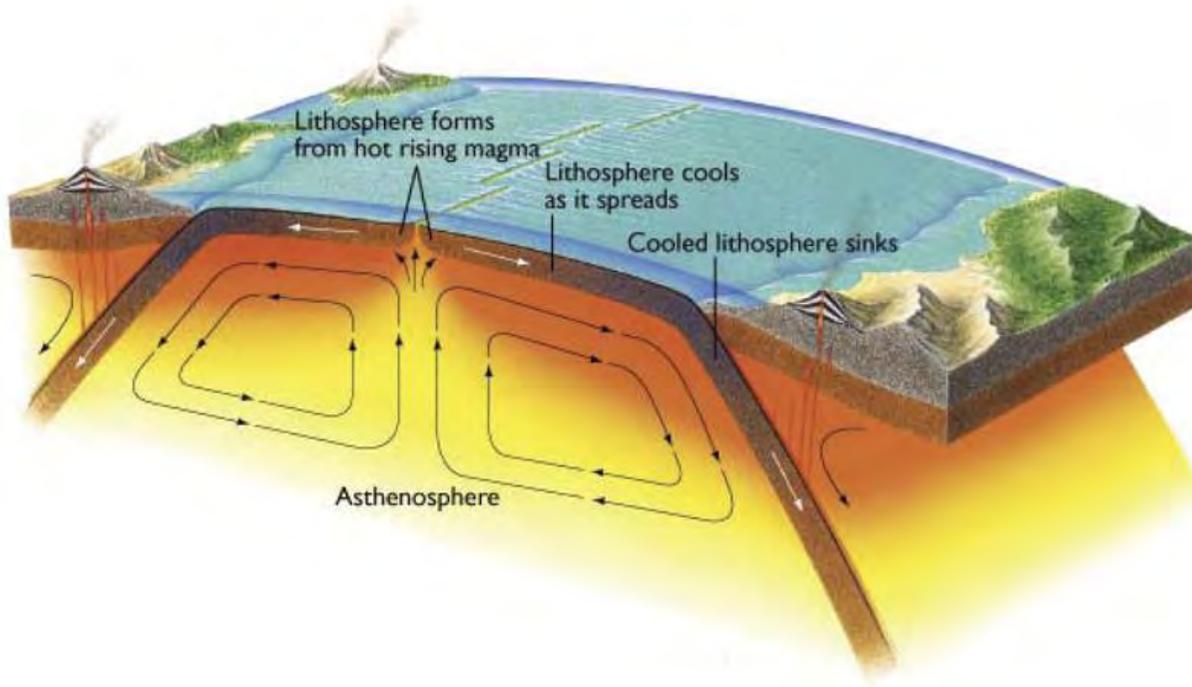


Beginning of geophysics with neutrinos!

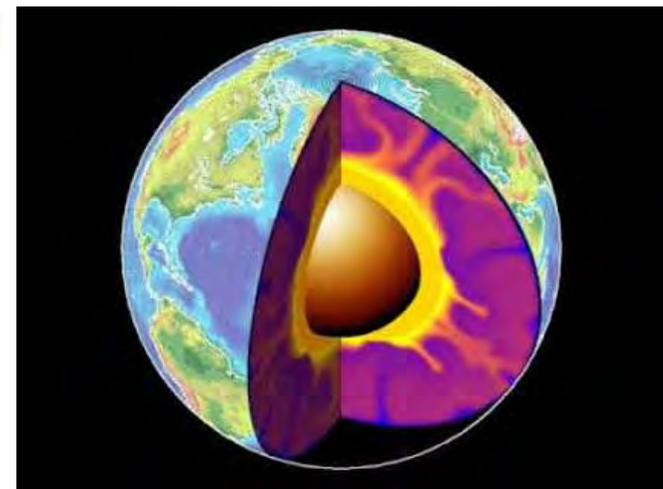
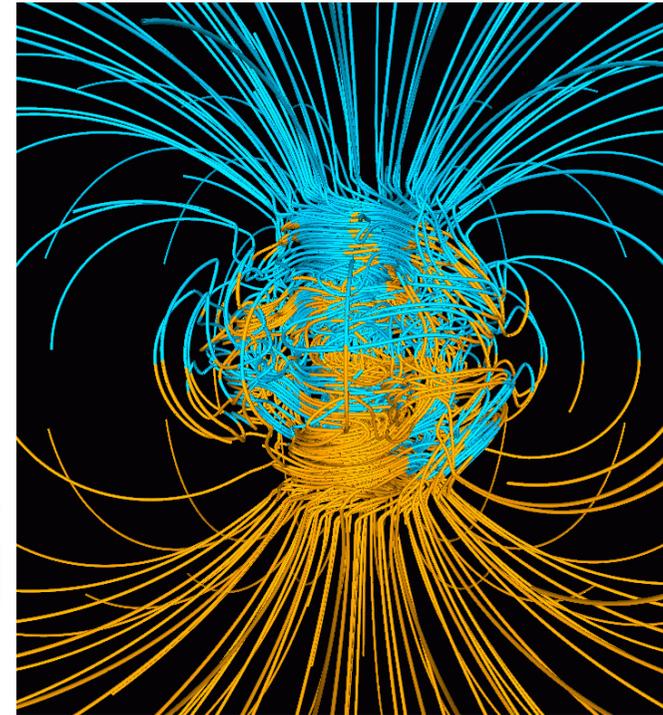
<http://www.ipgp.fr/fr/evenements/neutrino-geoscience-2015-conference>

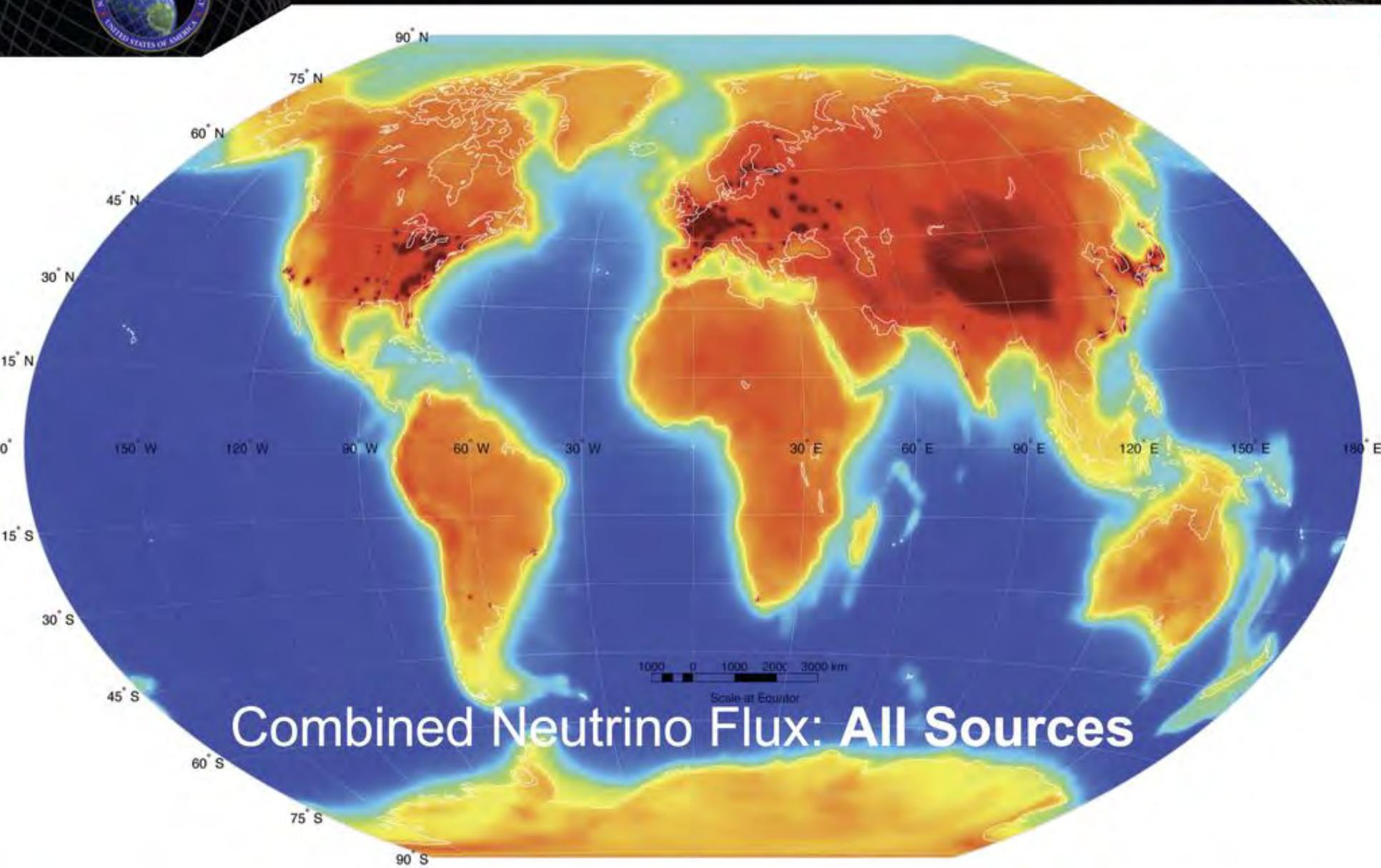
Plate Tectonics, Convection, Geo-Dynamo

- Potassium-40 (Half life 1.25 billion years)
- Thorium-232 (14 billion years)
- Uranium-238 (4.5 billion years)



**Radioactive decays
are the driving force!**

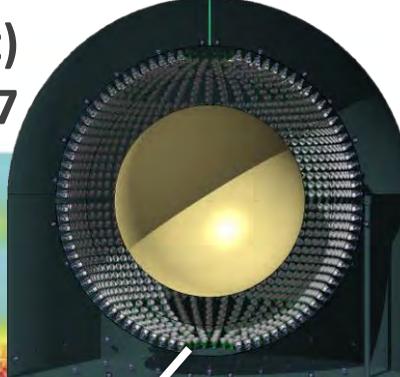




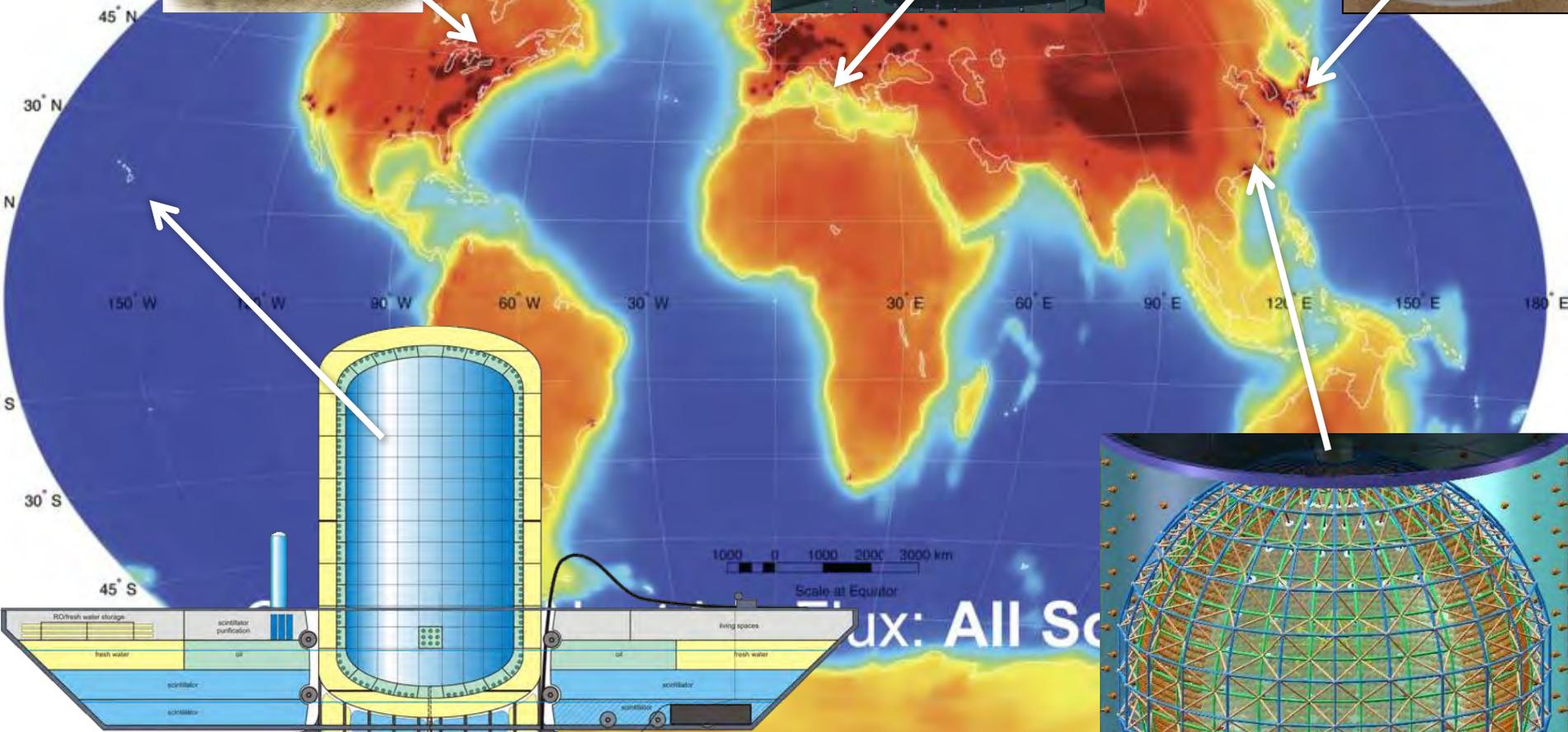
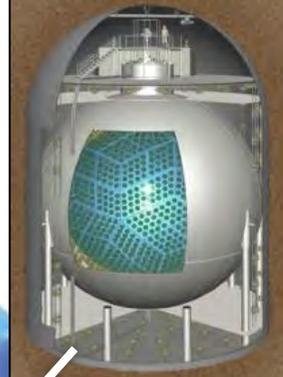
**SNO+
(800 t)
to begin
2016**



**Borexino (300 t)
since 2007**

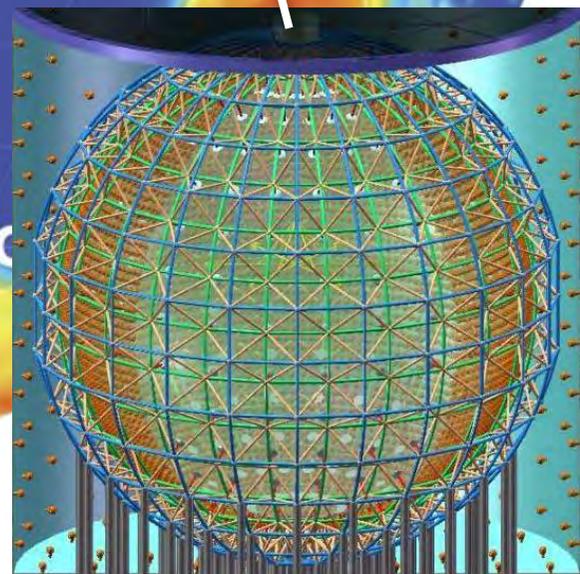


**KamLAND
(1000 t)
since 2002**



**Hanohano (10 000 t)
For oceanic crust
(Idea of principle, not a project)**

**JUNO (20 000 t)
to begin 2020**

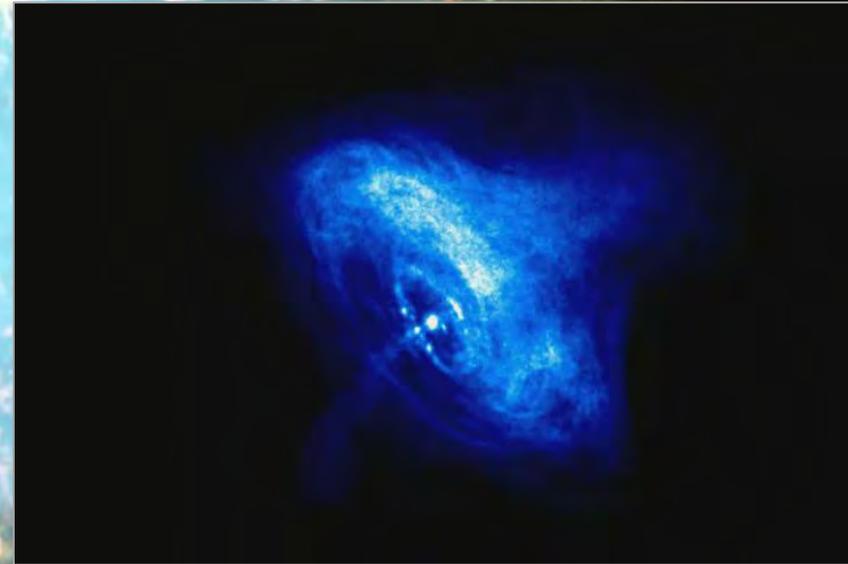


Crab Nebula – Remnant of SN 1054

凡十一日没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棗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没明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日没至和元年五月己丑出天關東南可數寸歲餘稍没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

“Chinese Supernova”

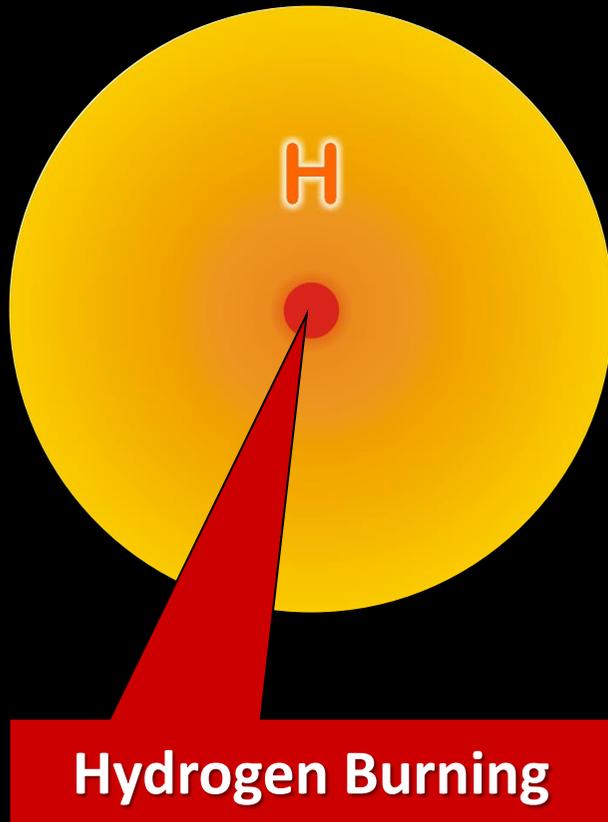


Crab Pulsar

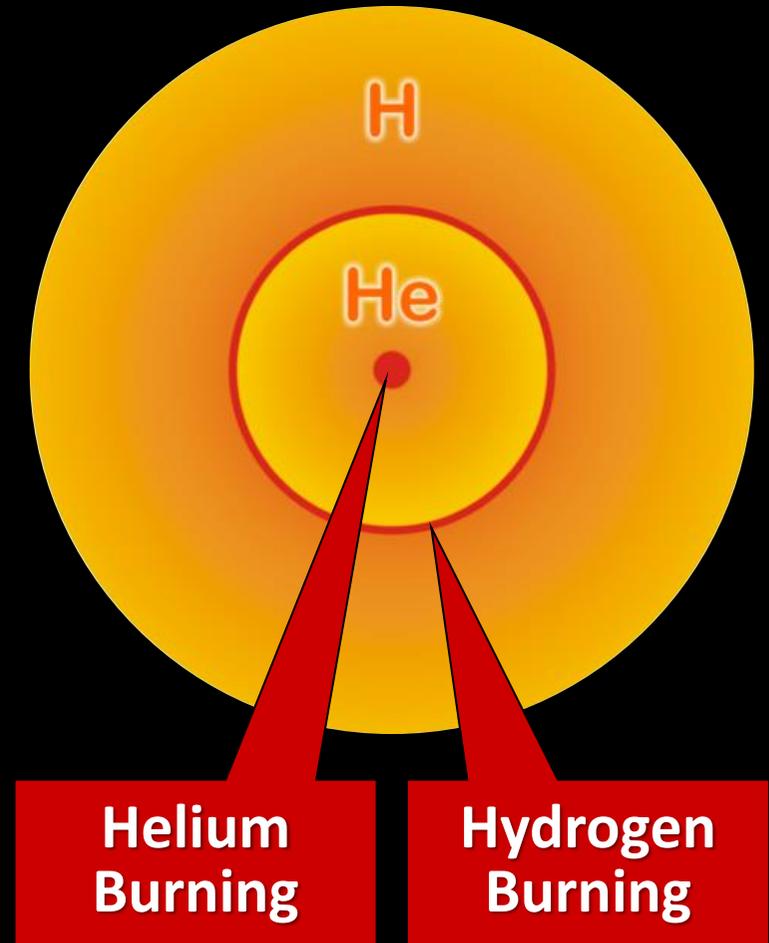
Chandra x-ray images

Stellar Collapse and Supernova Explosion

Main-sequence star

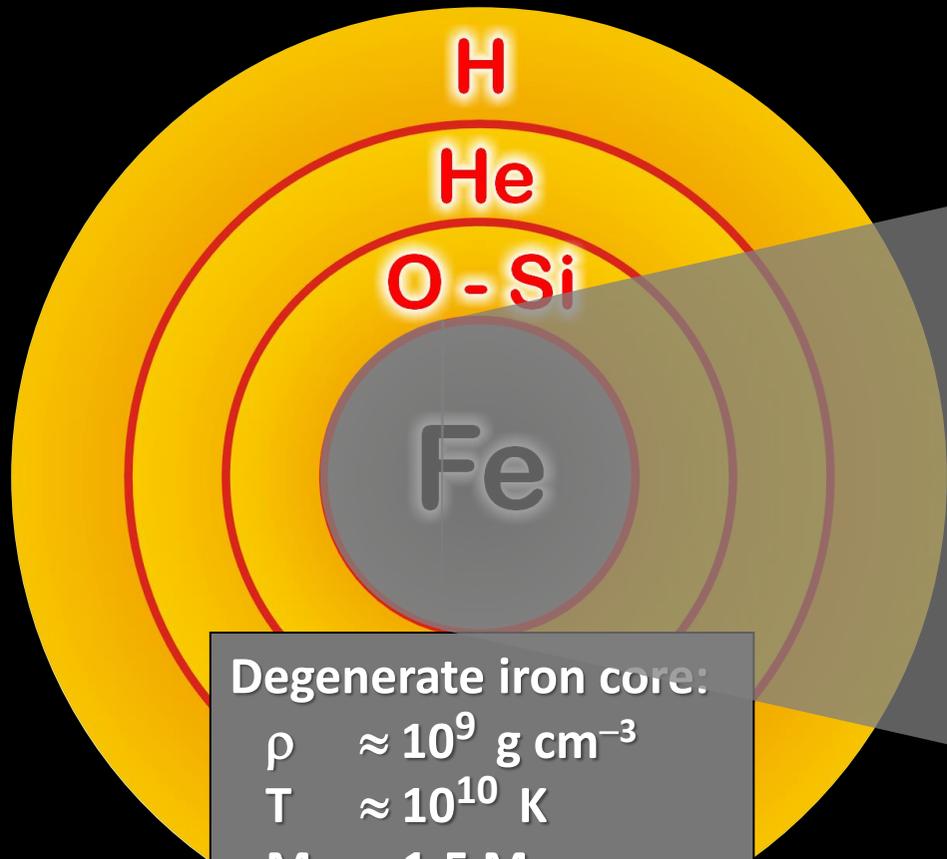


Helium-burning star

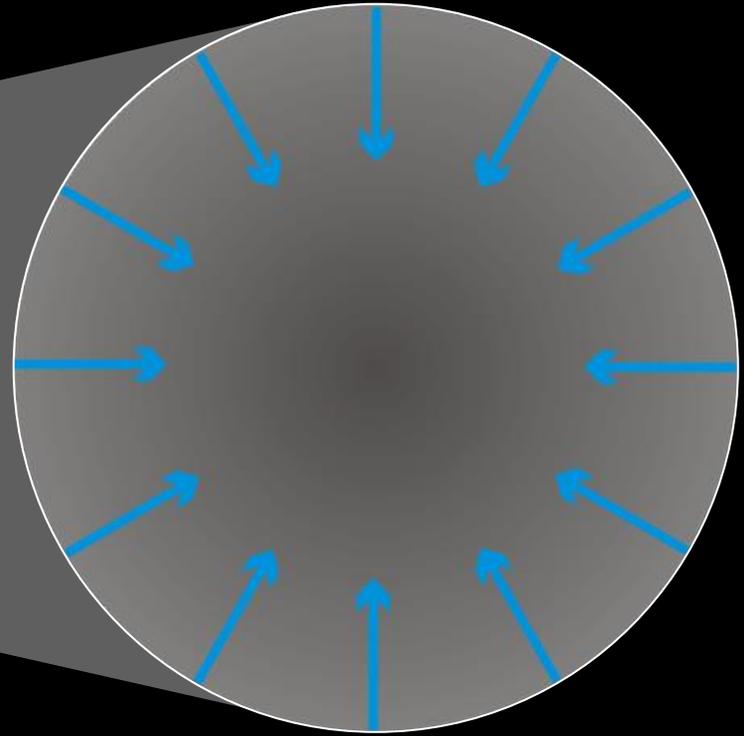


Stellar Collapse and Supernova Explosion

Onion structure



Collapse (implosion)



Degenerate iron core:

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

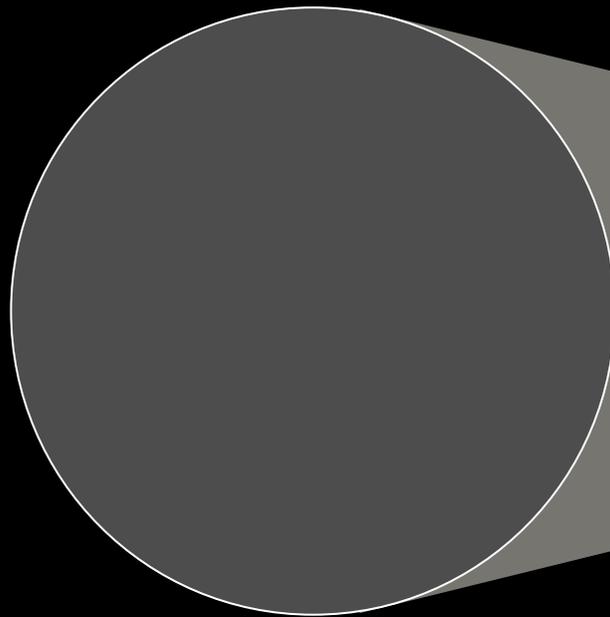
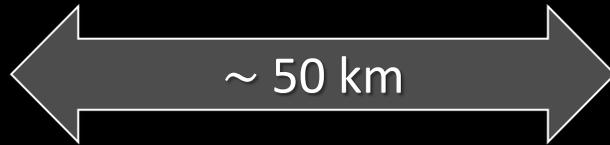
$$T \approx 10^{10} \text{ K}$$

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

$$R_{\text{Fe}} \approx 3000 \text{ km}$$

Stellar Collapse and Supernova Explosion

Newborn Neutron Star

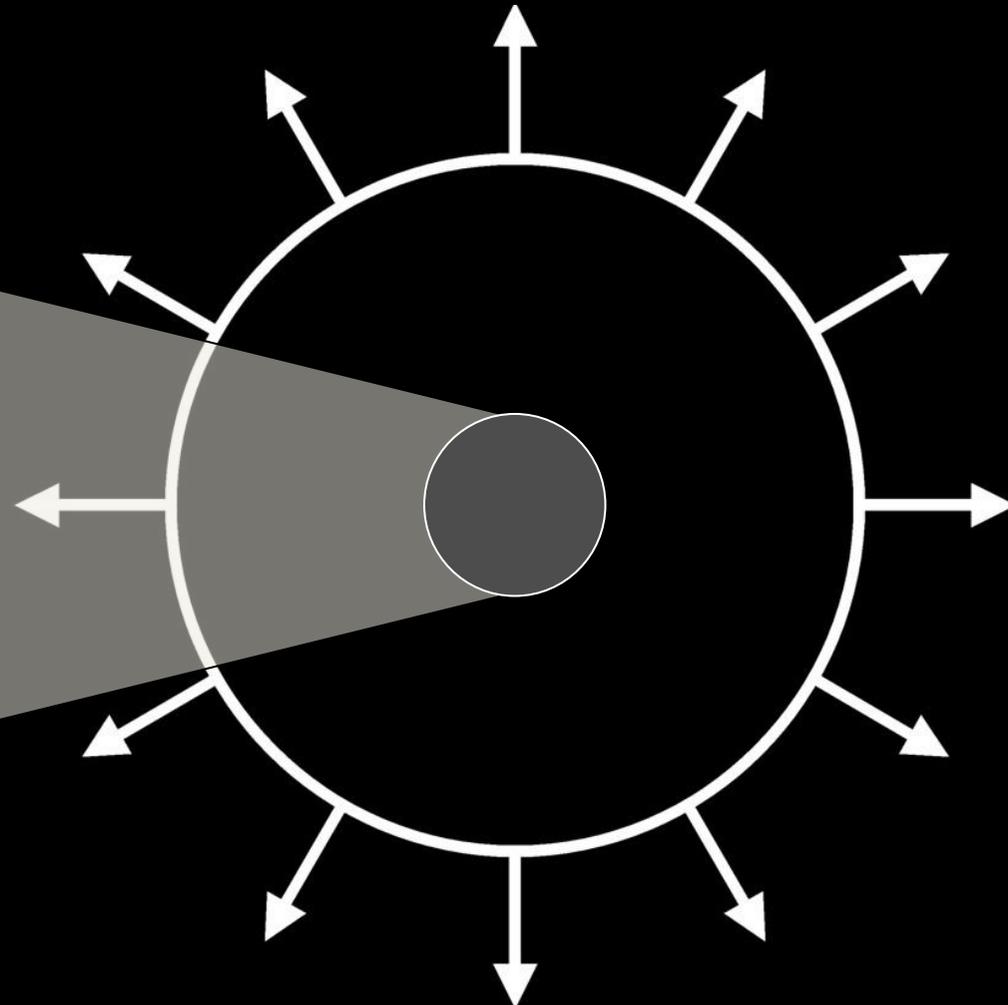


Proto-Neutron Star

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

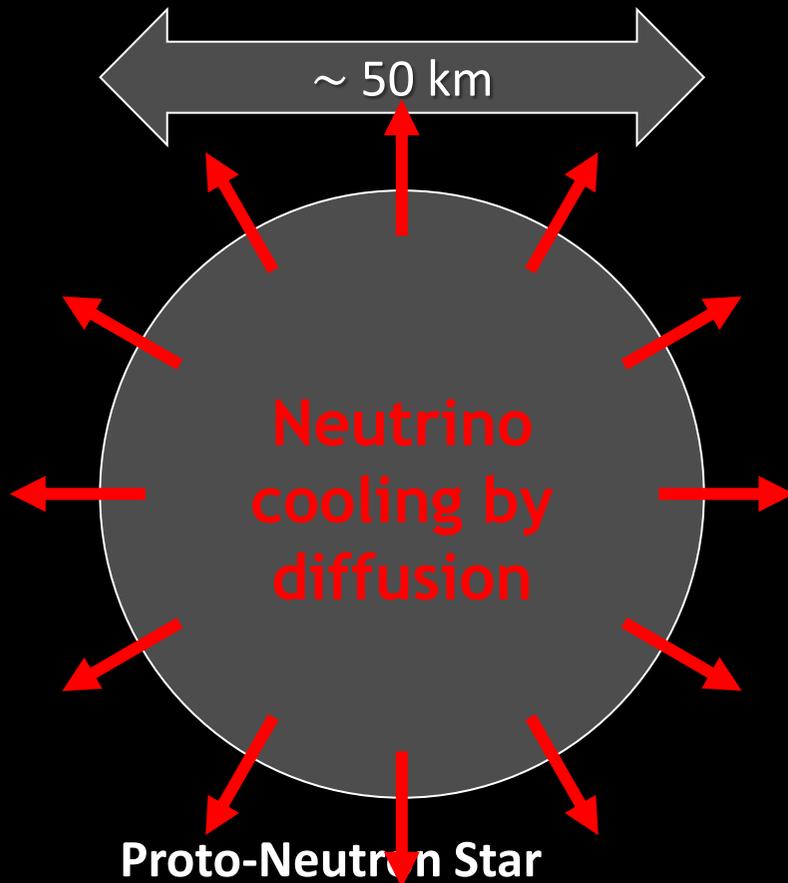
$$T \sim 10 \text{ MeV}$$

Explosion



Stellar Collapse and Supernova Explosion

Newborn Neutron Star



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

Gravitational binding energy

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

This shows up as

99% Neutrinos

1% Kinetic energy of explosion

0.01% Photons, outshine host galaxy

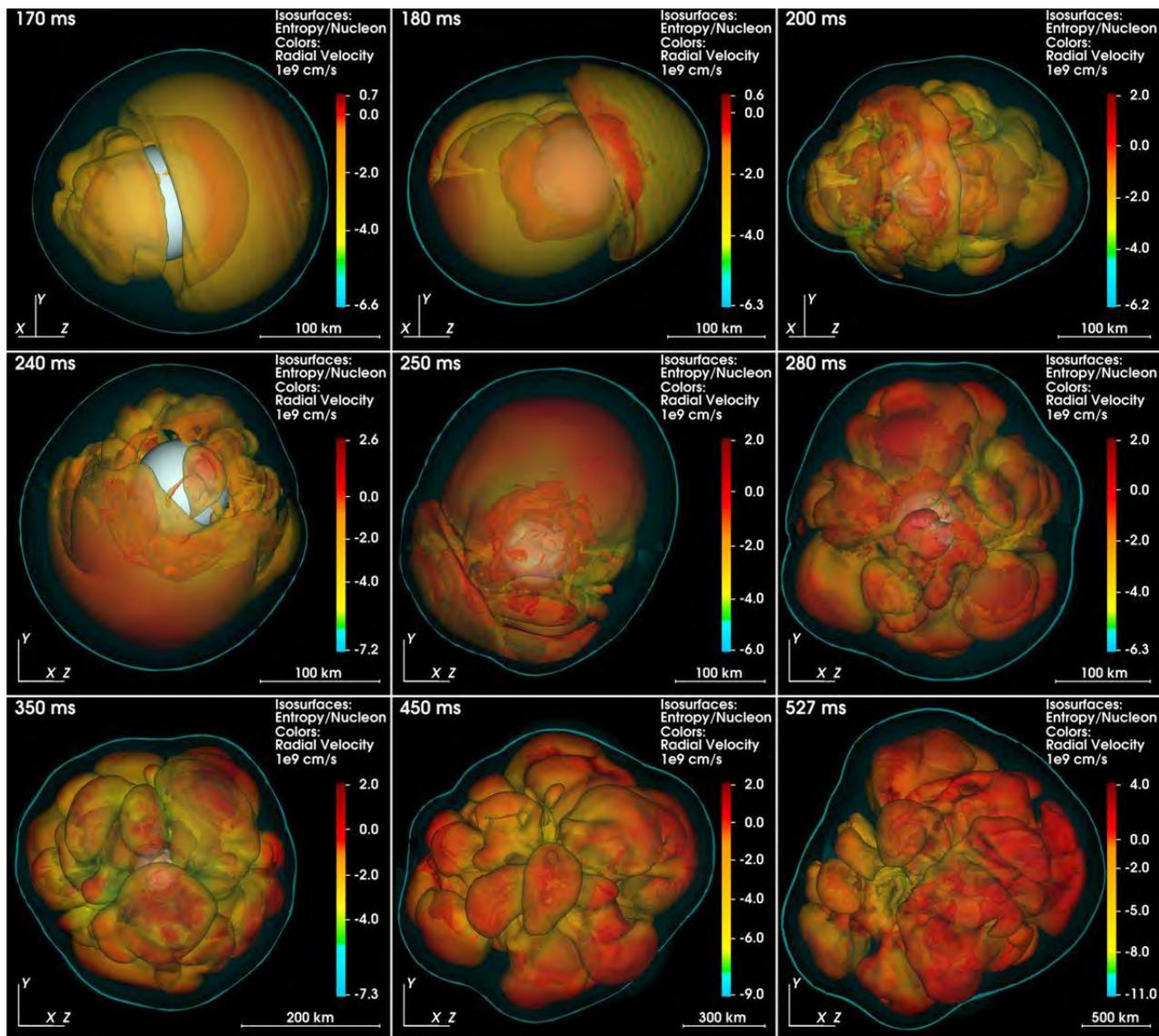
Neutrino luminosity

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

$$\sim 3 \times 10^{19} L_{\text{SUN}}$$

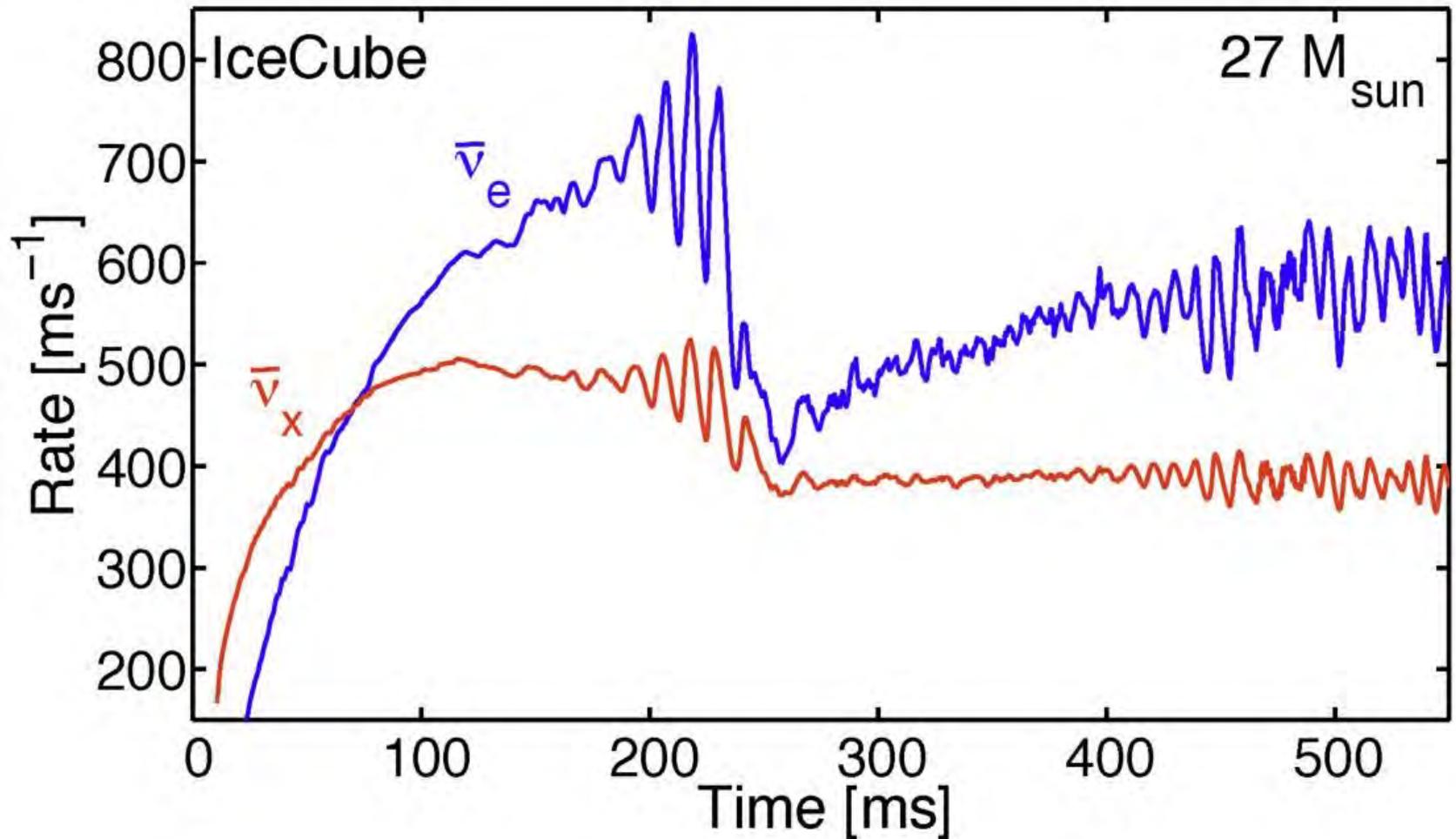
While it lasts, outshines the entire visible universe

Exploding 3D Garching Model (20 M_{SUN})



Melson, Janka, Bollig, Hanke, Marek & Müller, arXiv:1504.07631

Variability to be seen in Neutrinos (3D Model)



Tamborra, Hanke, Müller, Janka & Raffelt, arXiv:1307.7936

See also Lund, Marek, Lunardini, Janka & Raffelt, arXiv:1006.1889

Sanduleak -69 202



Tarantula Nebula

**Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)**



Sanduleak -69 202

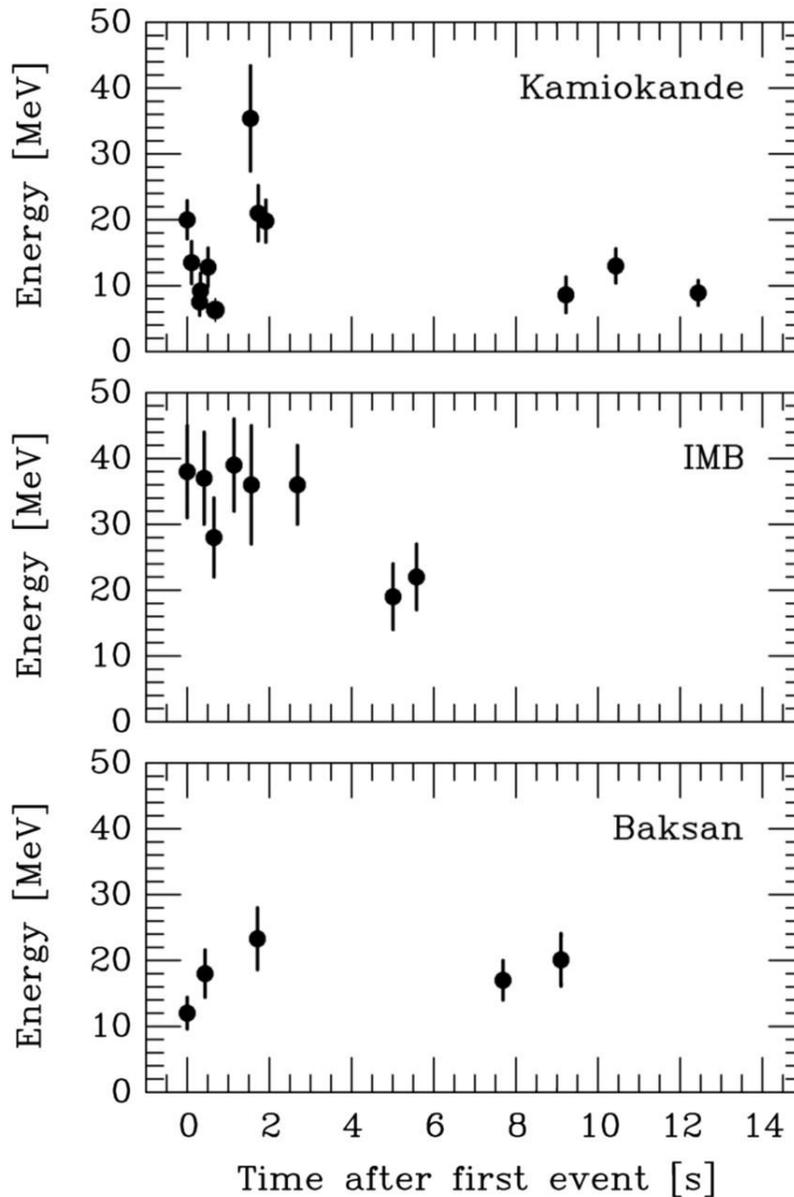


Supernova 1987A

23 February 1987



Neutrino Signal of Supernova 1987A



Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ± 1 min

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

Baksan Scintillator Telescope (Russia)
200 tons
Random event cluster ~ 0.7 /day
Clock uncertainty $+2/-54$ s

**Within clock uncertainties,
all signals are contemporaneous**

Operational Detectors for Supernova Neutrinos

SNO+
(300)

HALO
(tens)

LVD (400)
Borexino (100)

Baksan
(100)

Super-K (10^4)
KamLAND (400)

Daya Bay
(100)

IceCube (10^6)

In brackets events
for a “fiducial SN”
at distance 10 kpc

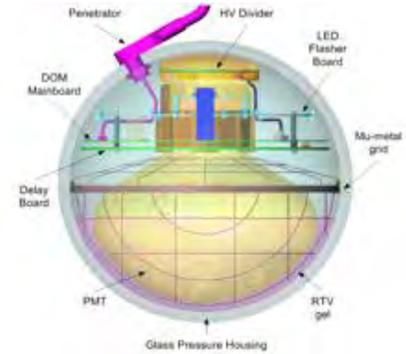
SNEWS

IceCube Neutrino Telescope at the South Pole

IceCube Lab

50 meters

Digital Optical Module



IceCube Array
86 strings, 60 sensors each
5,160 optical sensors

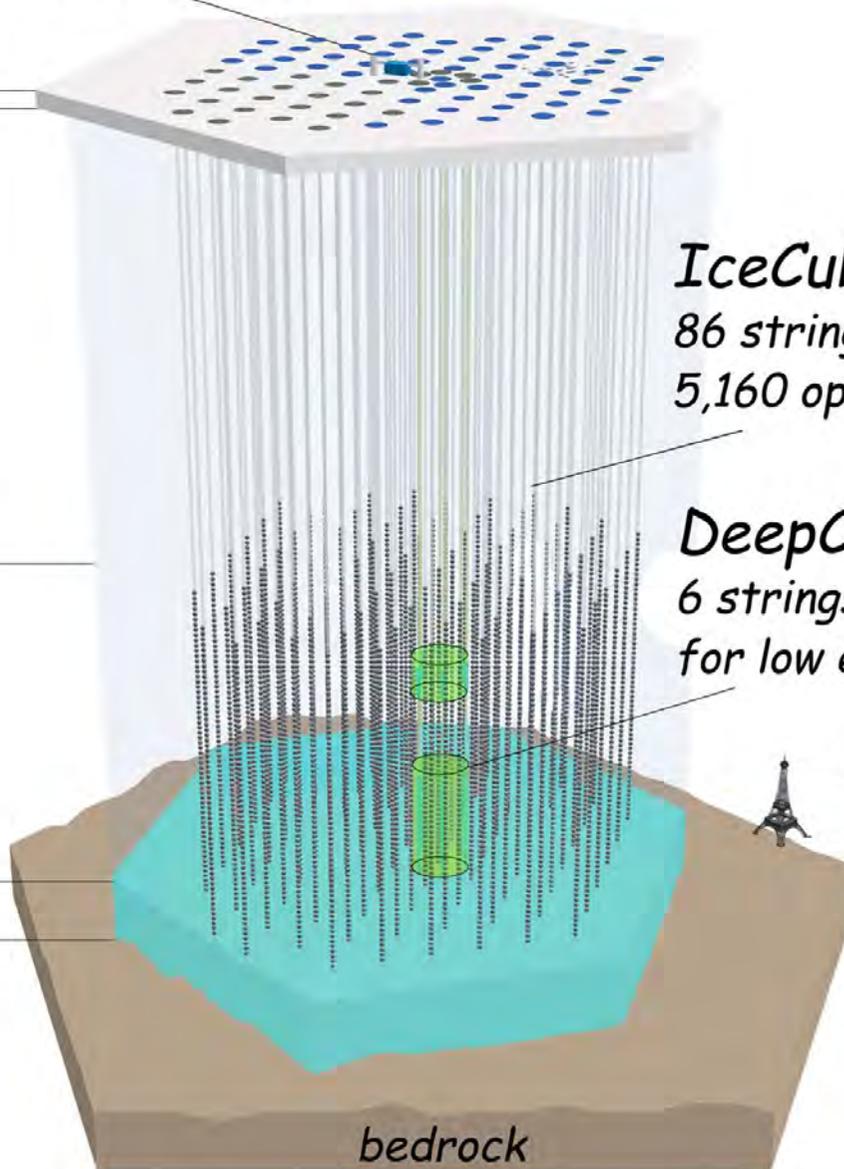
1,450 meters

DeepCore
6 strings optimized
for low energies

2,450 meters

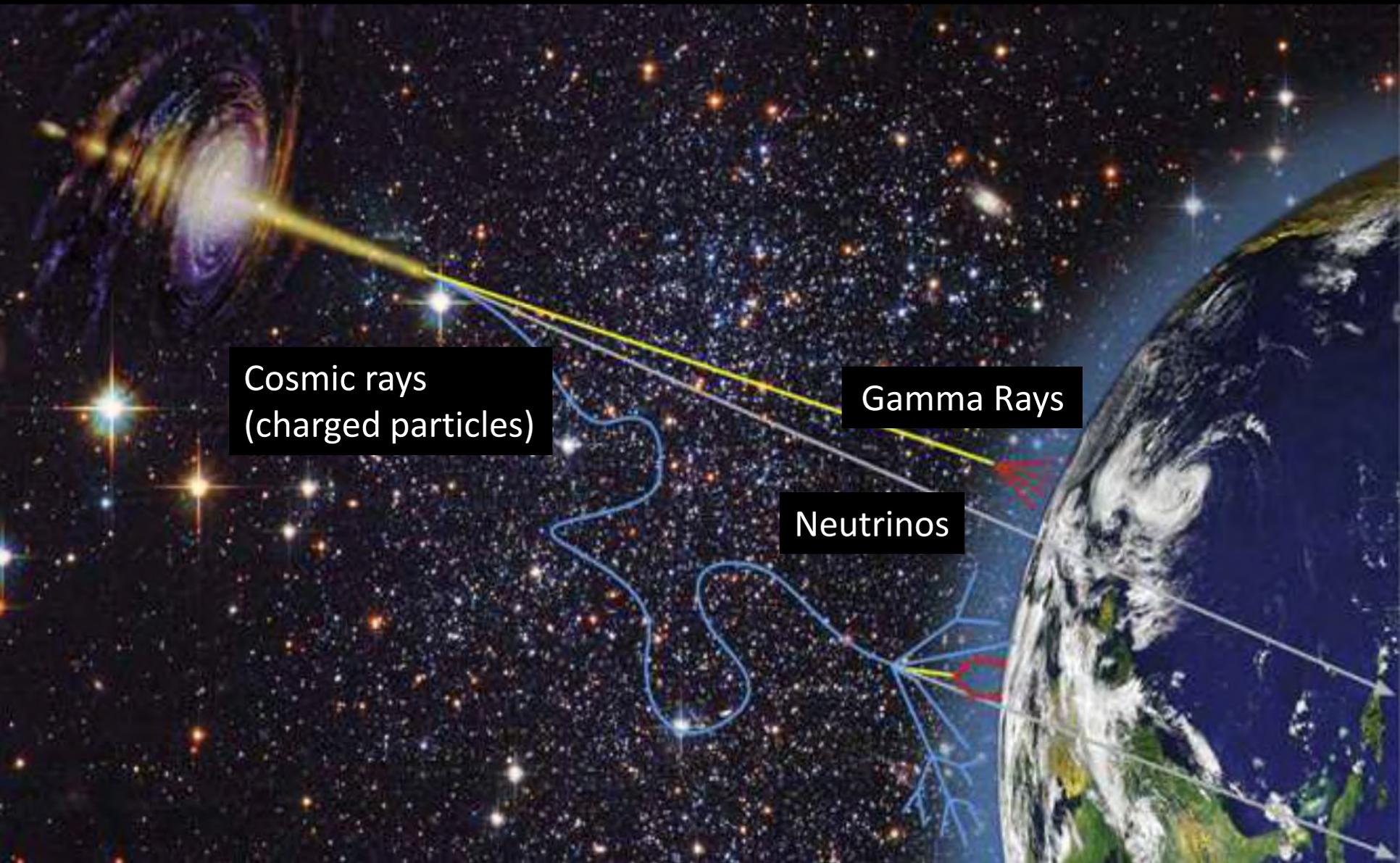
Eiffel Tower
324 meters

2,820 meters

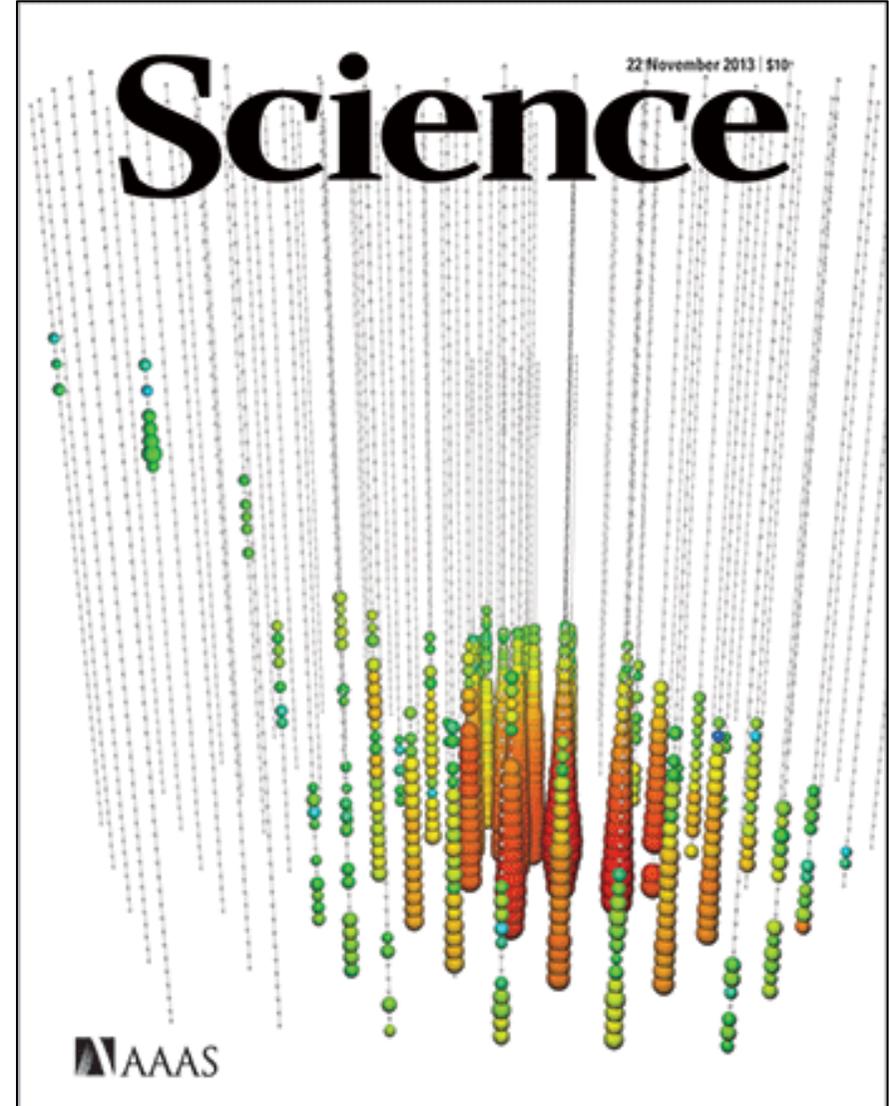
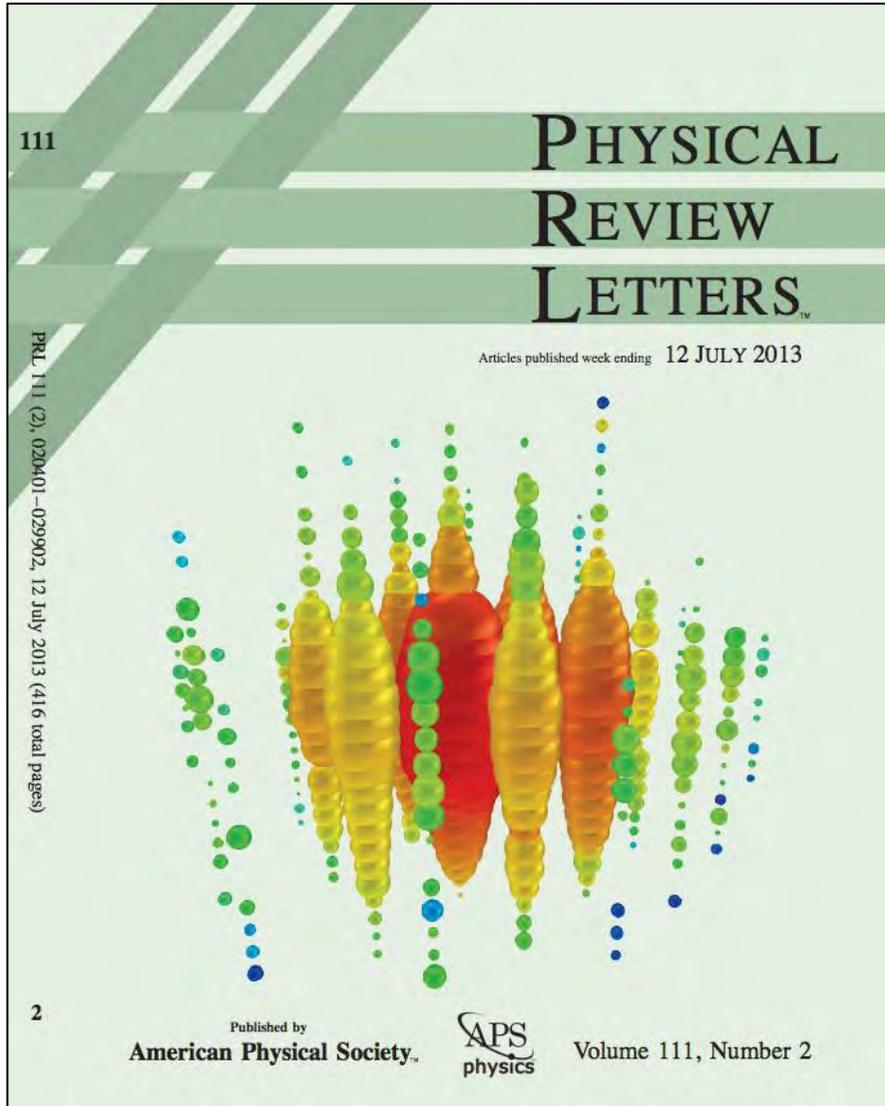


bedrock

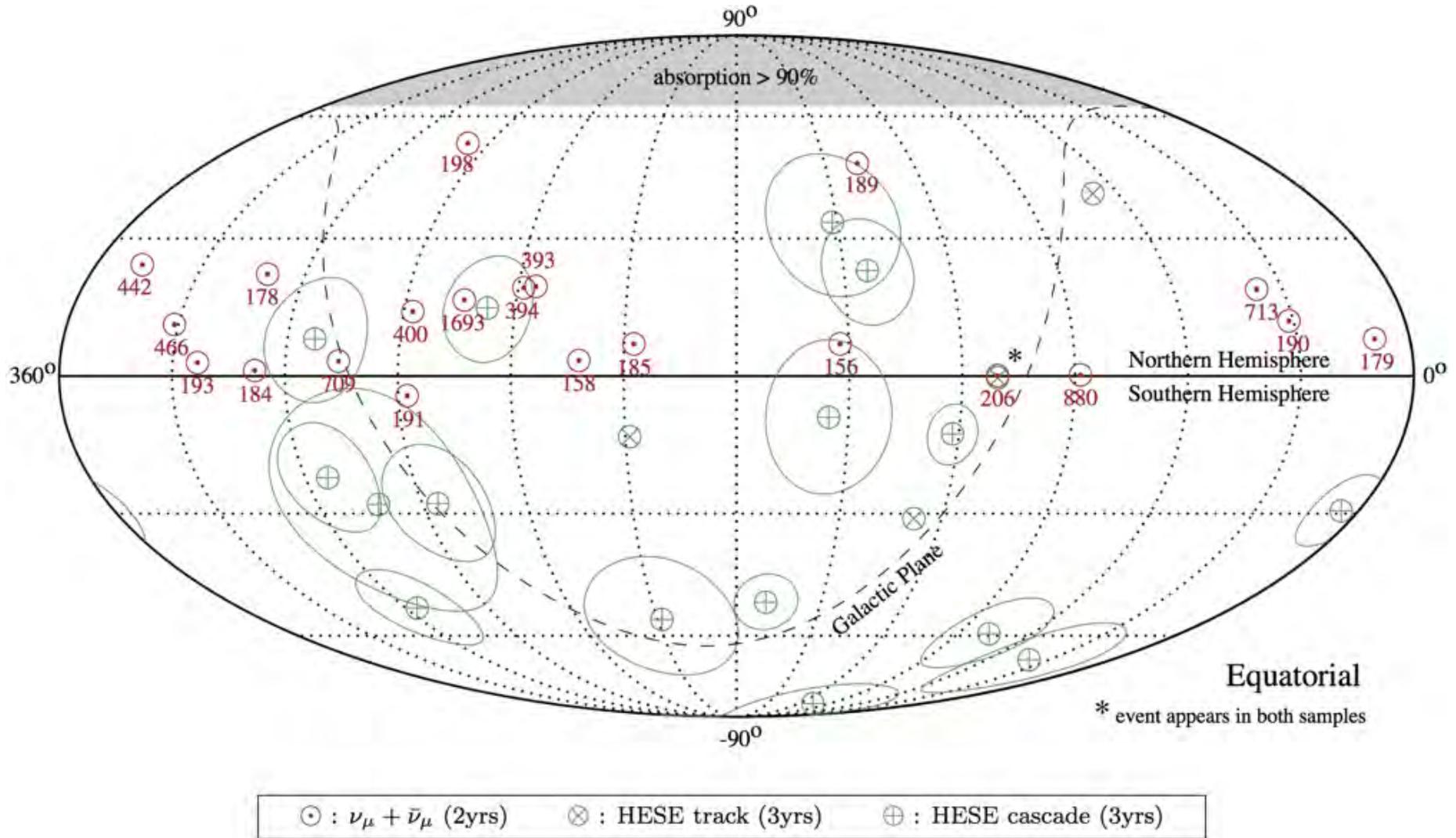
Three Types of High-Energy Messengers



“Discovery of the Year” (2013)

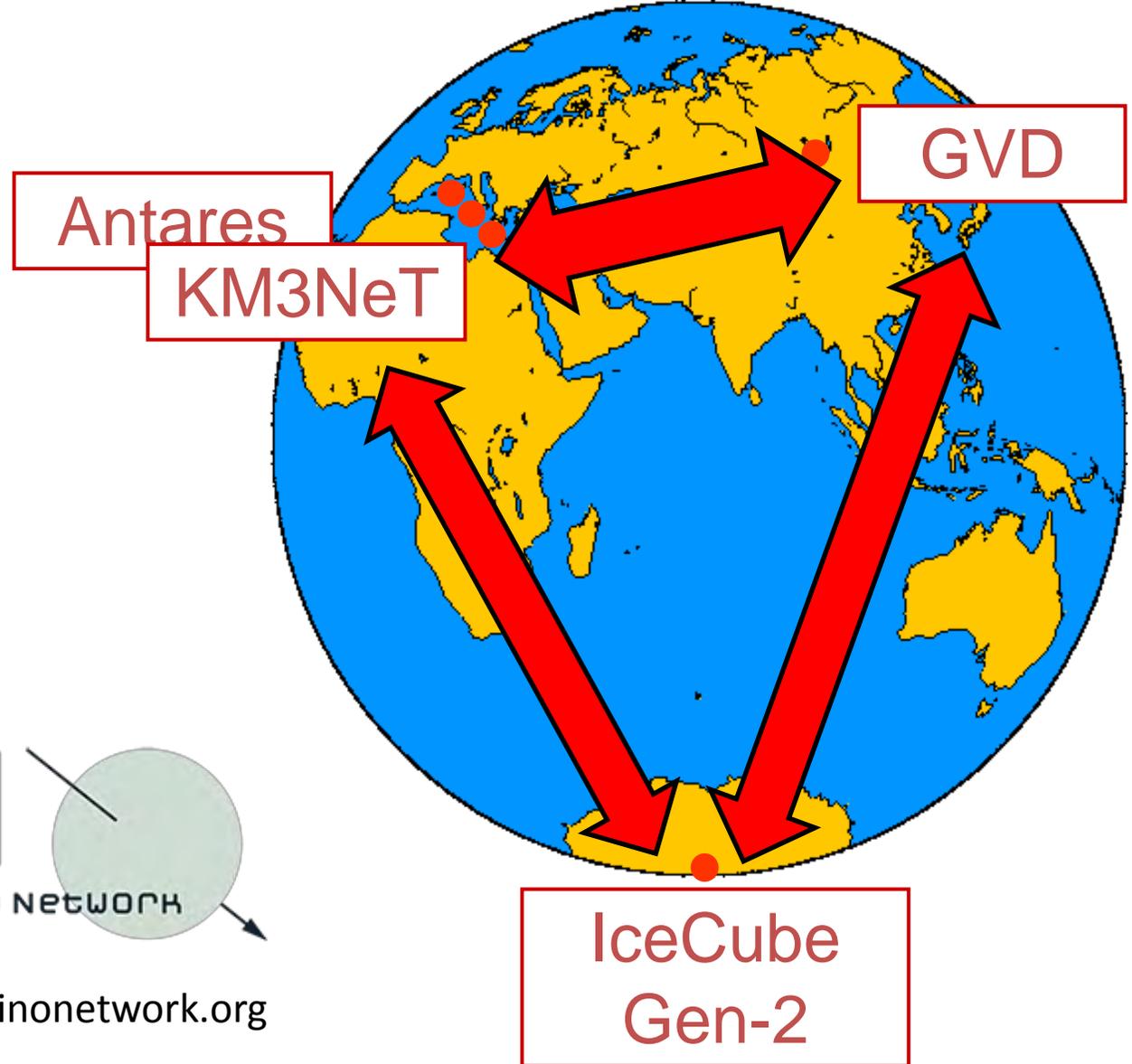


Astrophysical IceCube Neutrinos

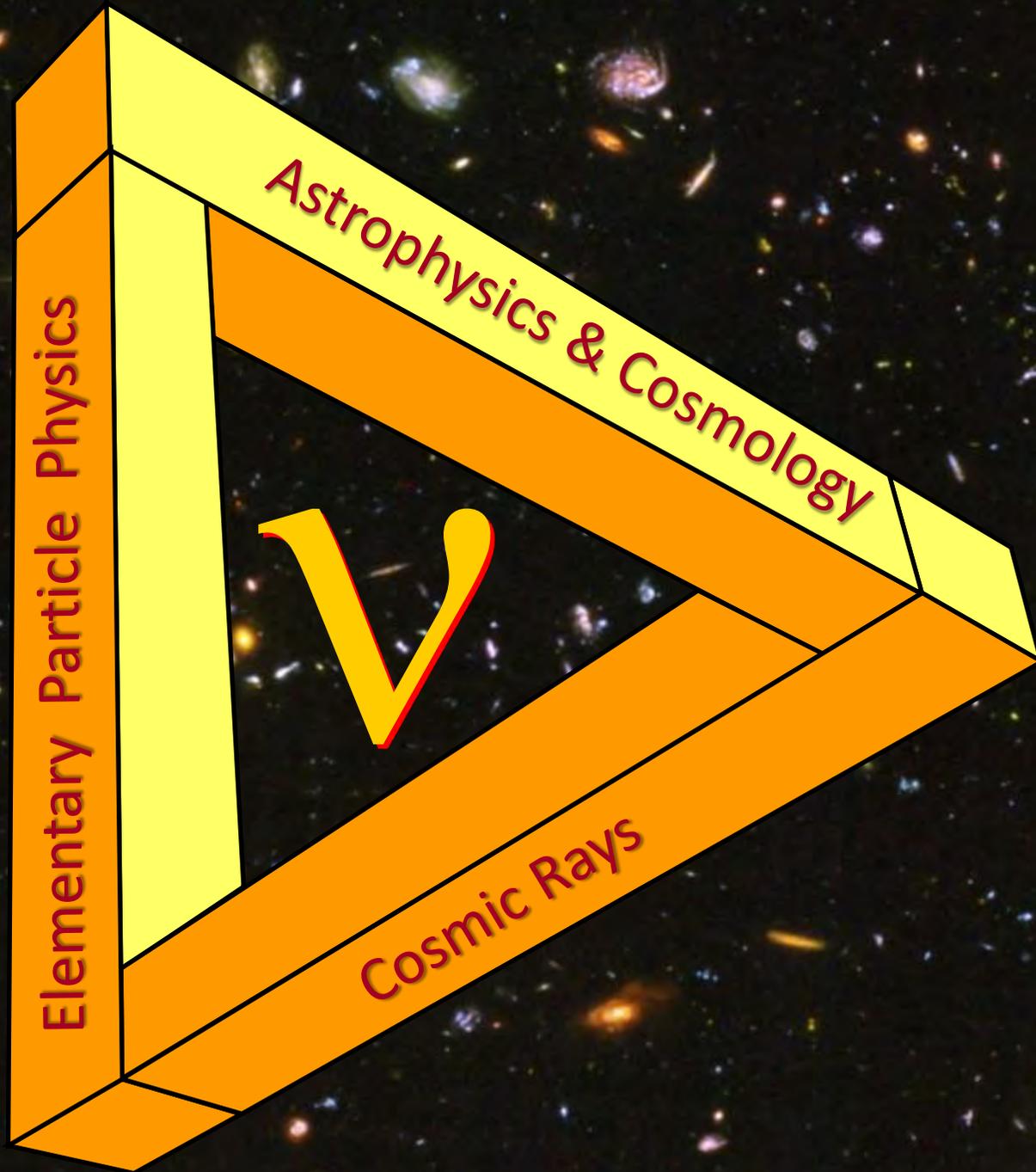


No clear astrophysical sources – more neutrinos needed!

Global Neutrino Network (GNN)



<http://www.globalneutrino.org>



Elementary Particle Physics

Astrophysics & Cosmology

Cosmic Rays

V