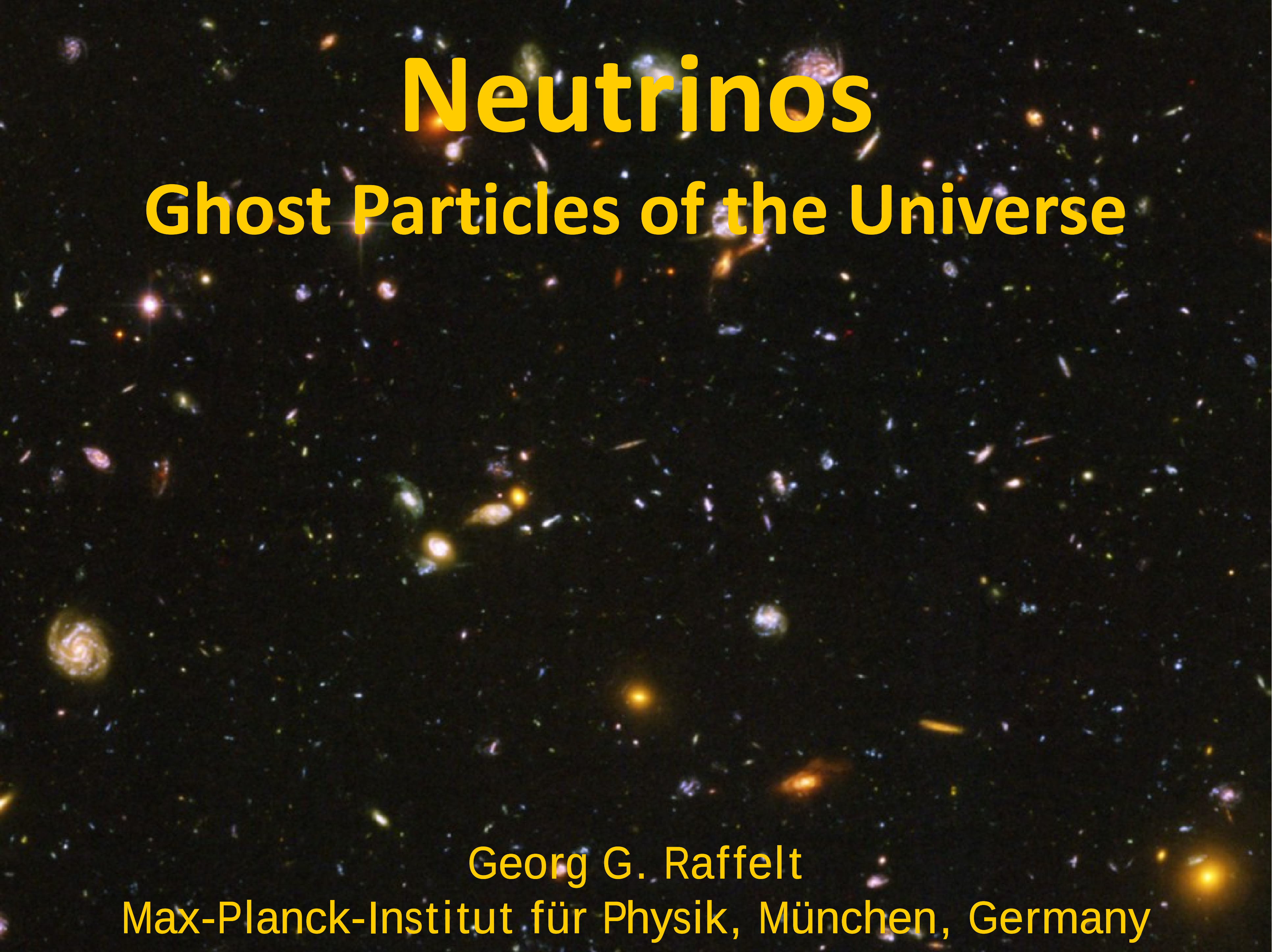

Neutrinos

Ghost Particles of the Universe

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

Neutrinos

Ghost Particles of the Universe

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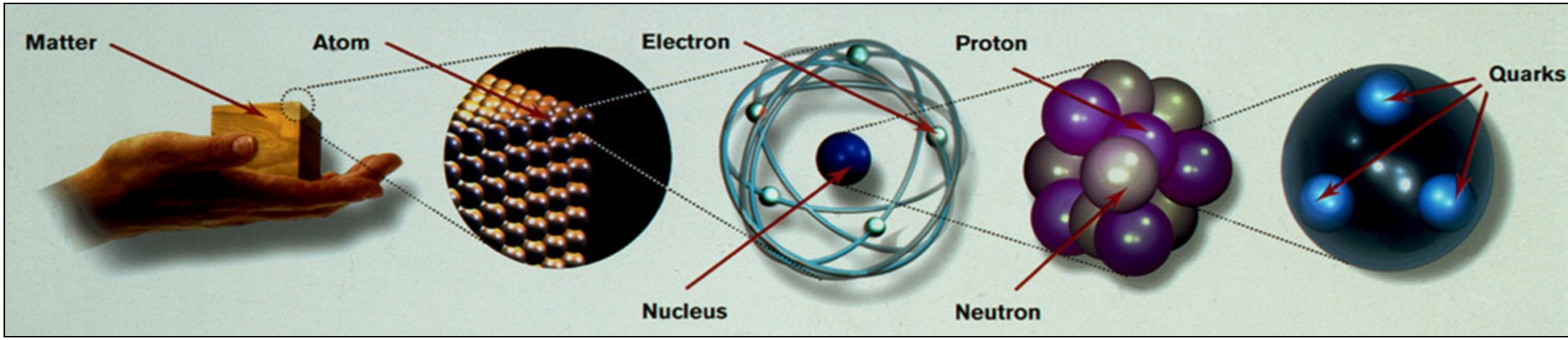
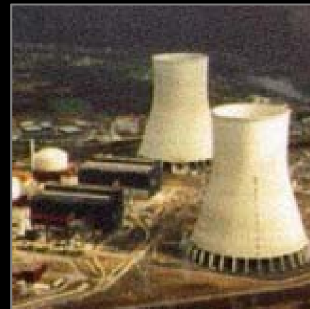
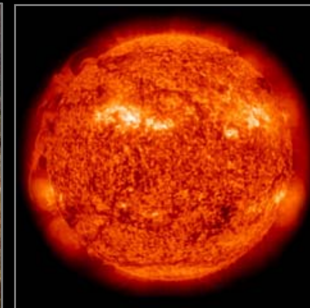
Periodic System of Elementary Particles



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

Where do Neutrinos Appear in Nature?

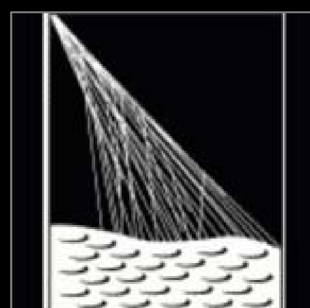
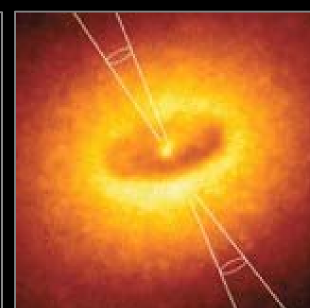



✓ Nuclear Reactors

Sun ✓

✓ Particle Accelerators

Supernovae
(Stellar Collapse)
SN 1987A ✓

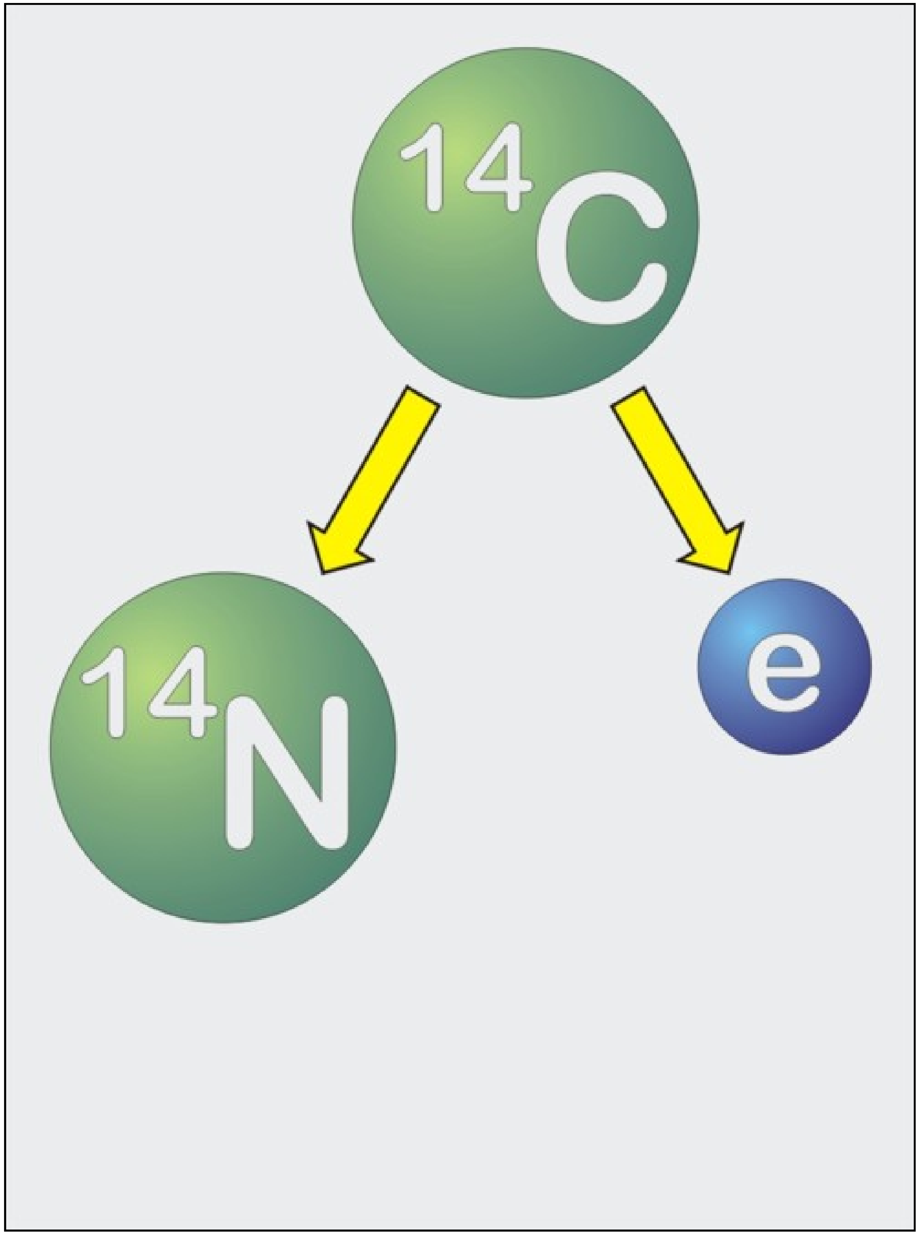
✓ Earth Atmosphere
(Cosmic Rays)

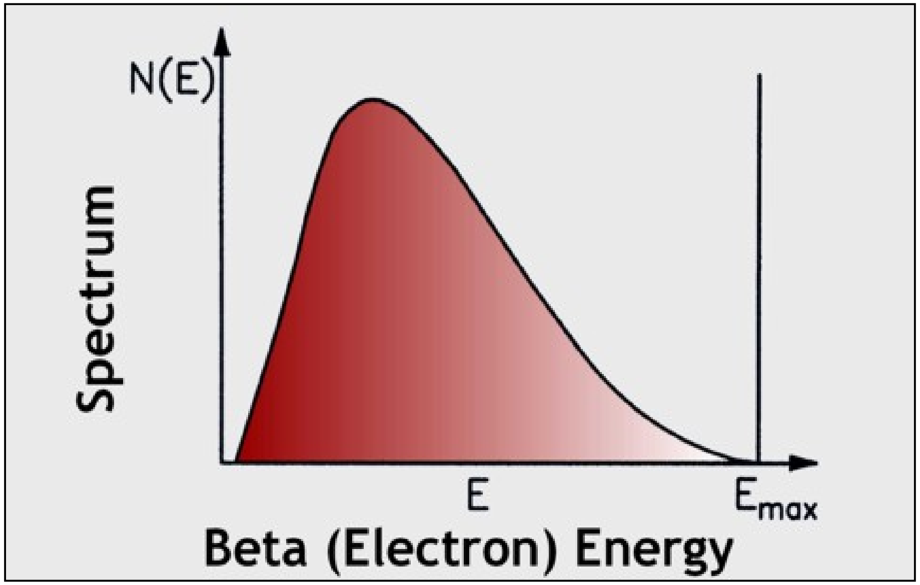
Astrophysical
Accelerators Soon ?


✓ Earth Crust
(Natural Radioactivity)

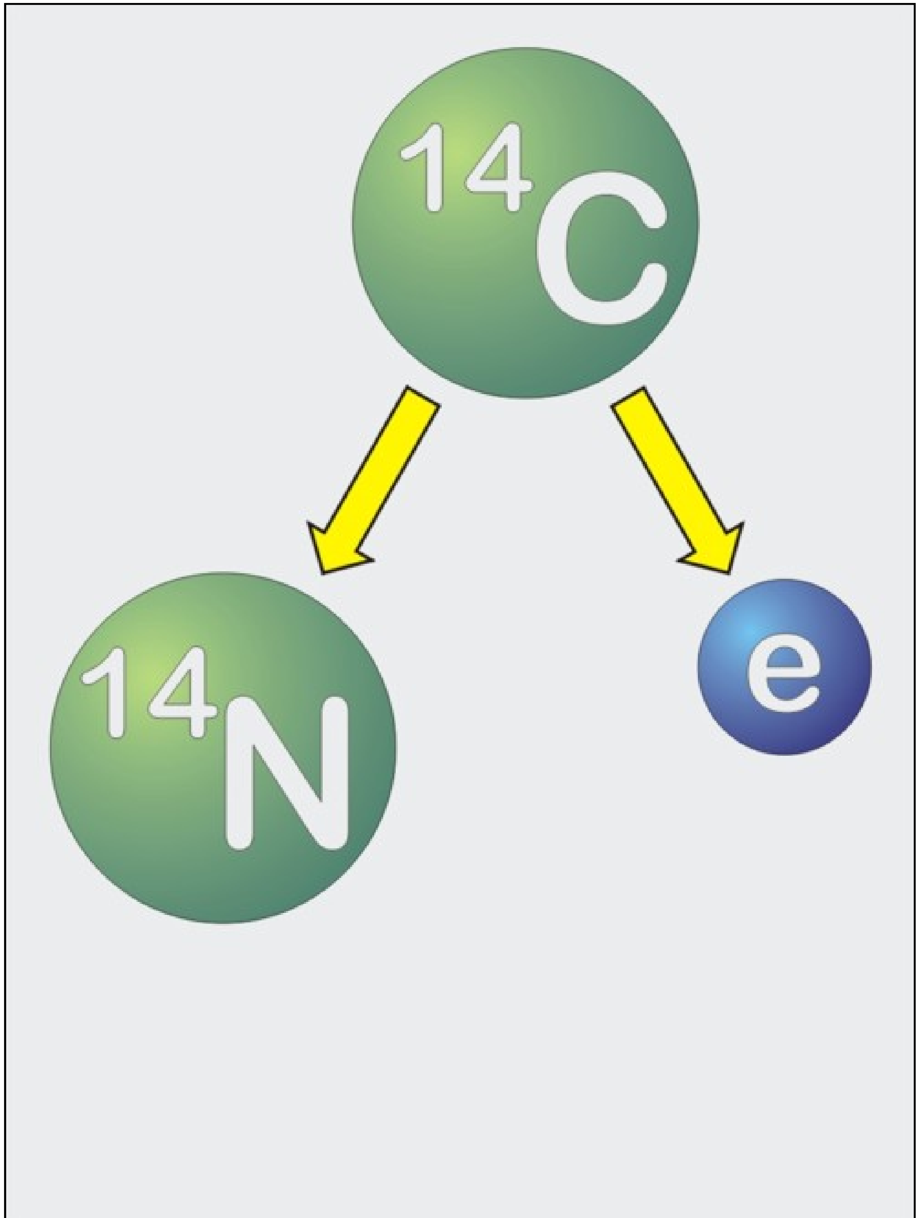
Cosmic Big Bang
(Today 330 ν/cm^3)
Indirect Evidence

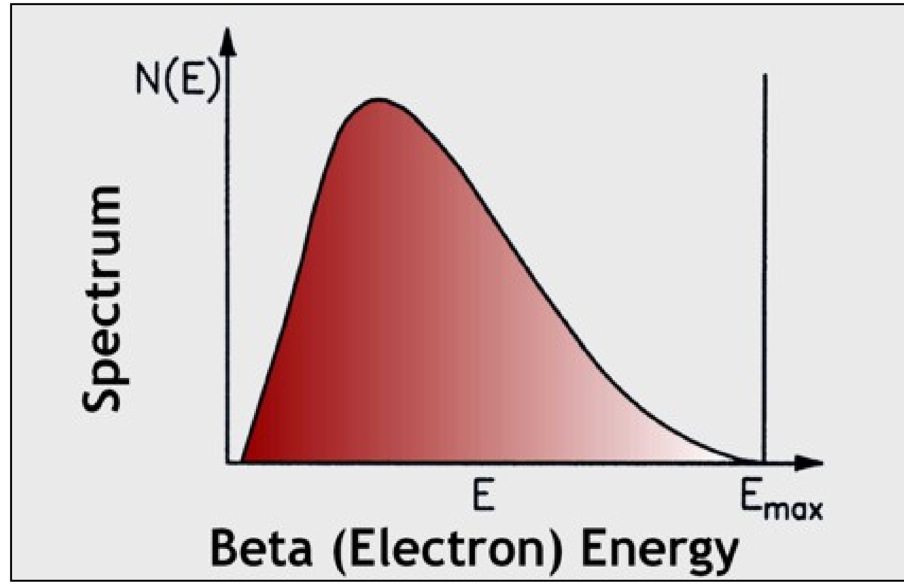
Pauli's Explanation of the Beta Decay Spectrum (1930)





Pauli's Explanation of the Beta Decay Spectrum (1930)

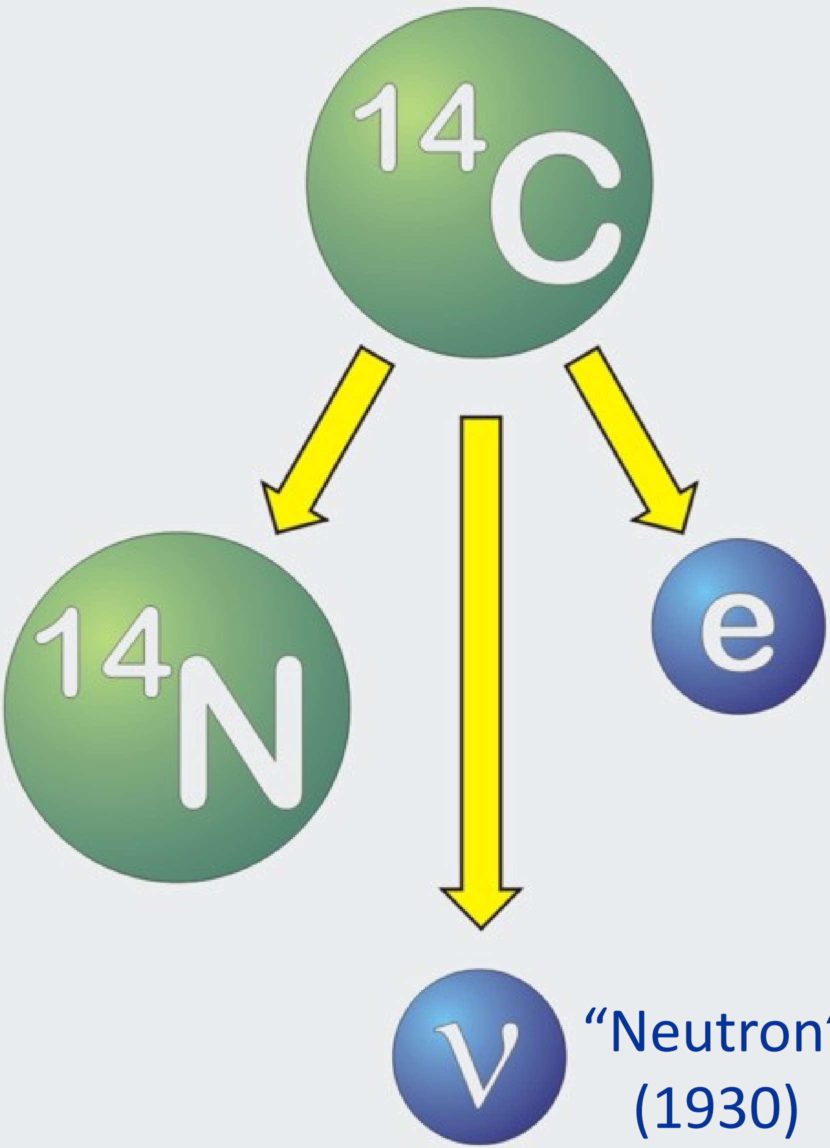




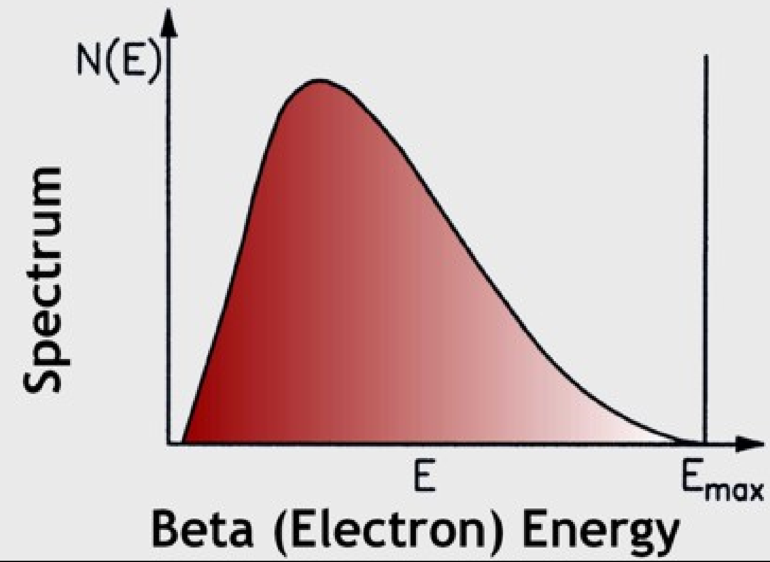
Niels Bohr:

Energy not conserved in the quantum domain?

Pauli's Explanation of the Beta Decay Spectrum (1930)

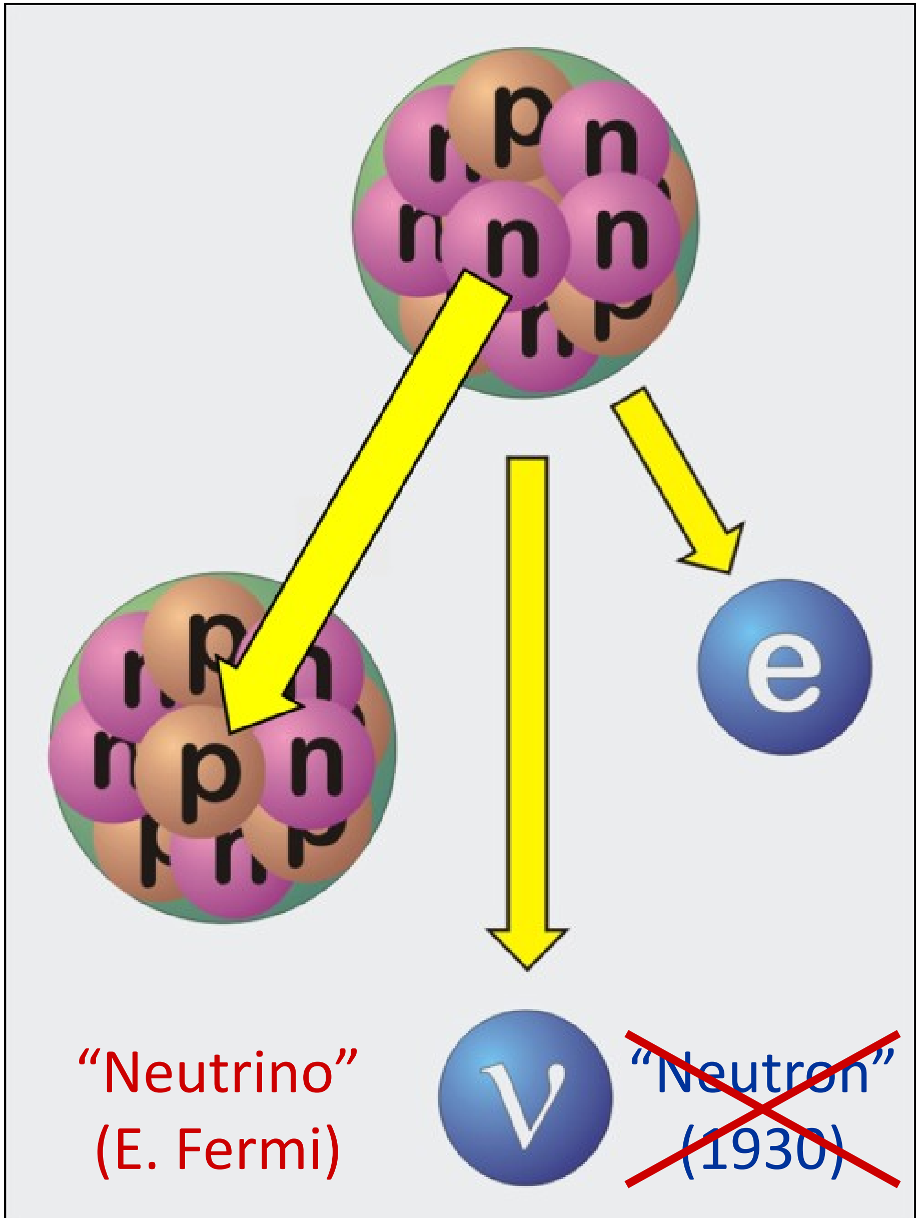


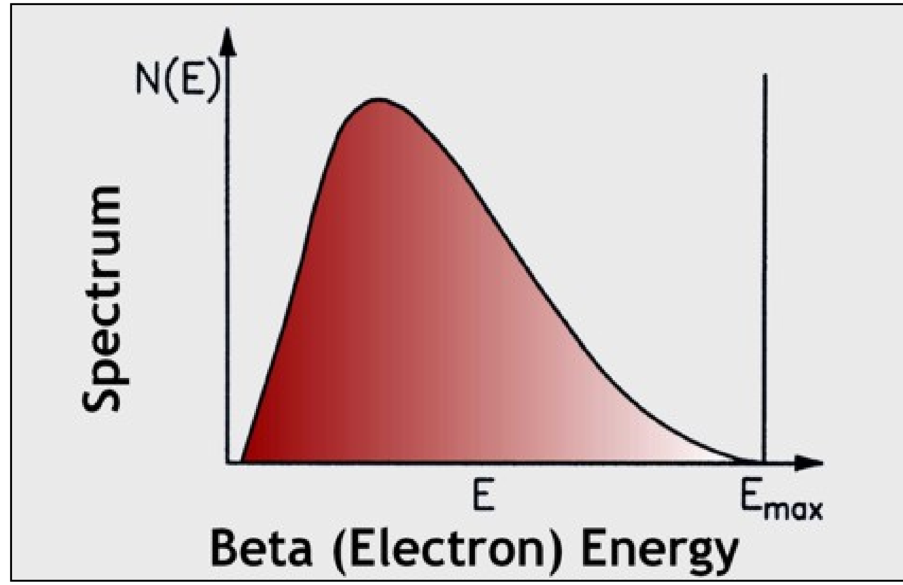
"Neutron"
(1930)



Wolfgang Pauli
(1900–1958)
Nobel Prize 1945

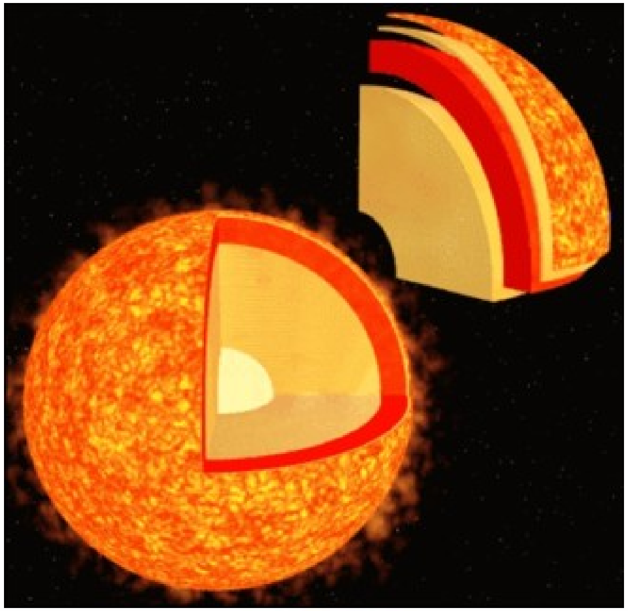
Pauli's Explanation of the Beta Decay Spectrum (1930)

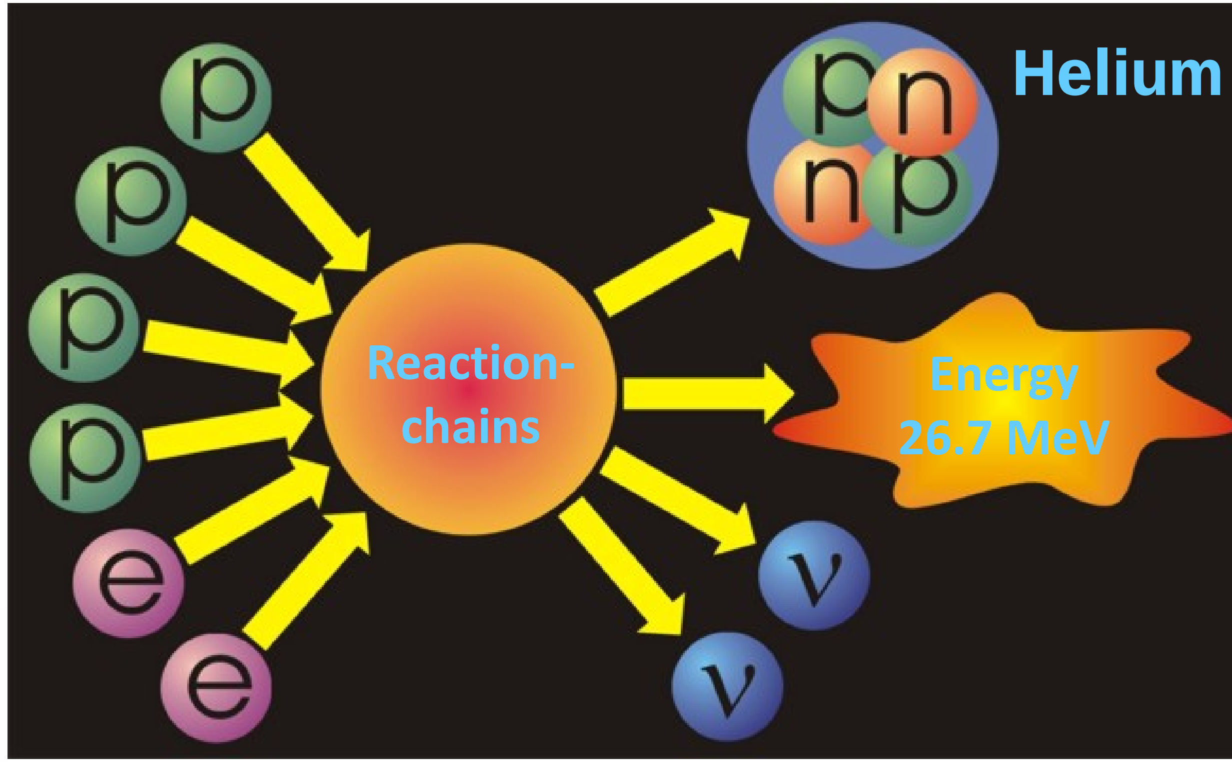




Wolfgang Pauli
(1900–1958)
Nobel Prize 1945

Neutrinos from the Sun





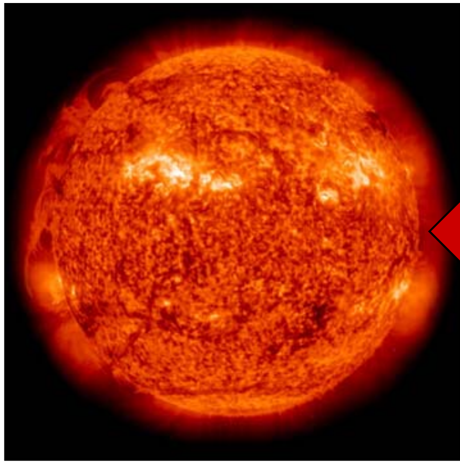
Solar radiation: 98 % light

2 % neutrinos

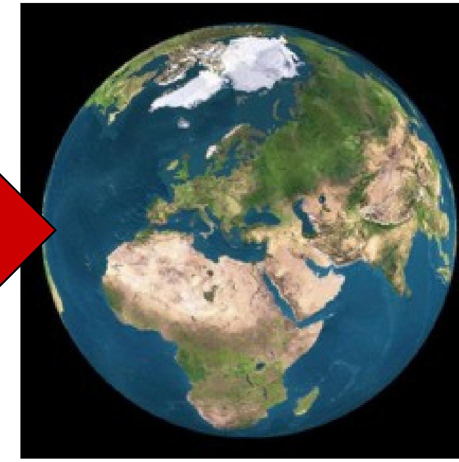
At Earth 66 billion neutrinos/cm^2 sec

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

Sun Glasses for Neutrinos?



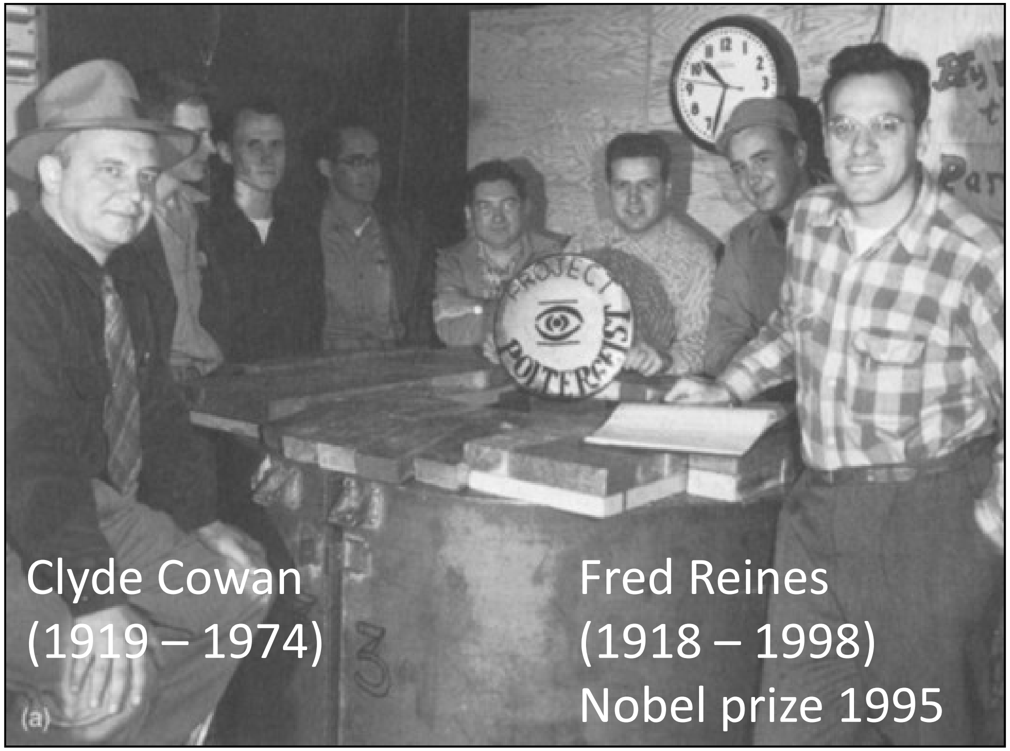
8.3 light minutes

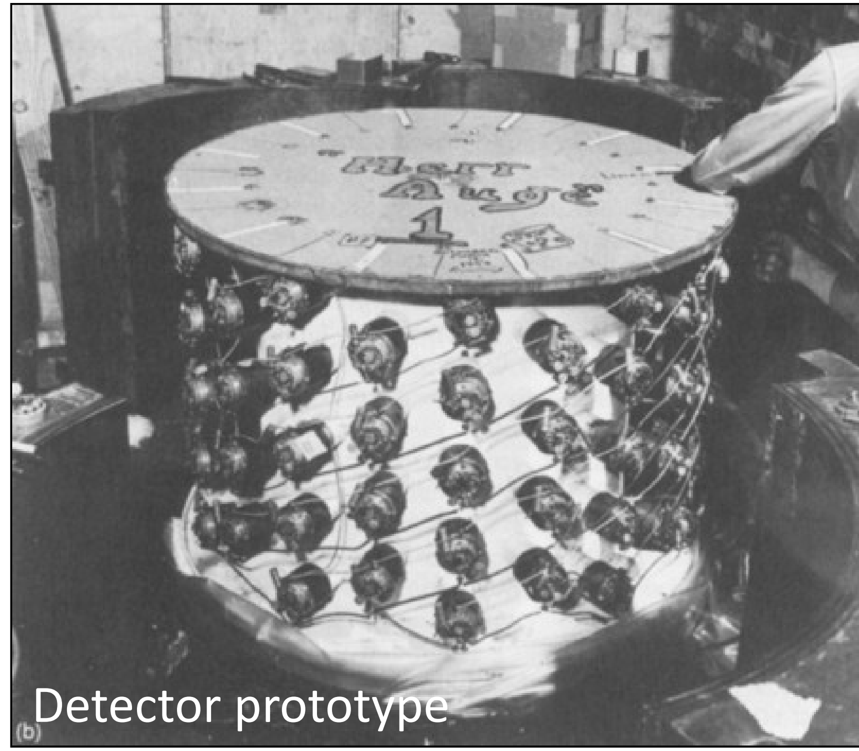


Several light years of lead needed to shield solar neutrinos

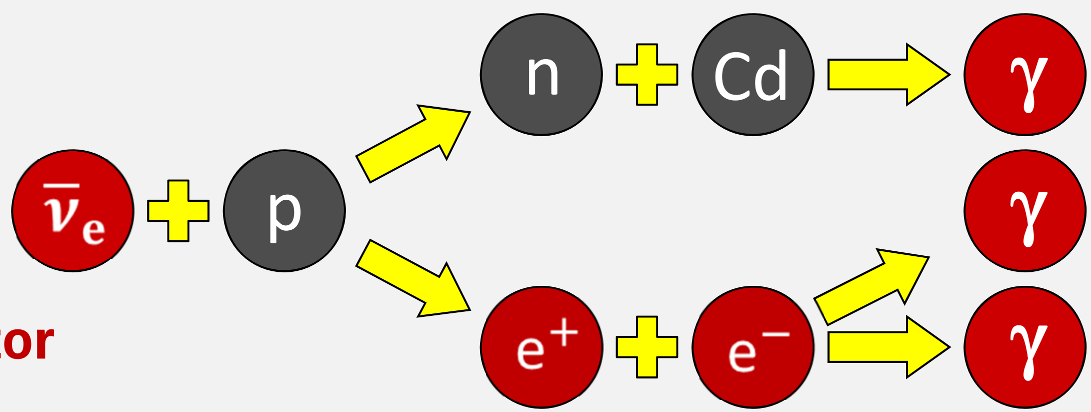
Bethe & Peierls 1934:
… this evidently means that one will never be able to observe a neutrino.

First Detection (1954 – 1956)



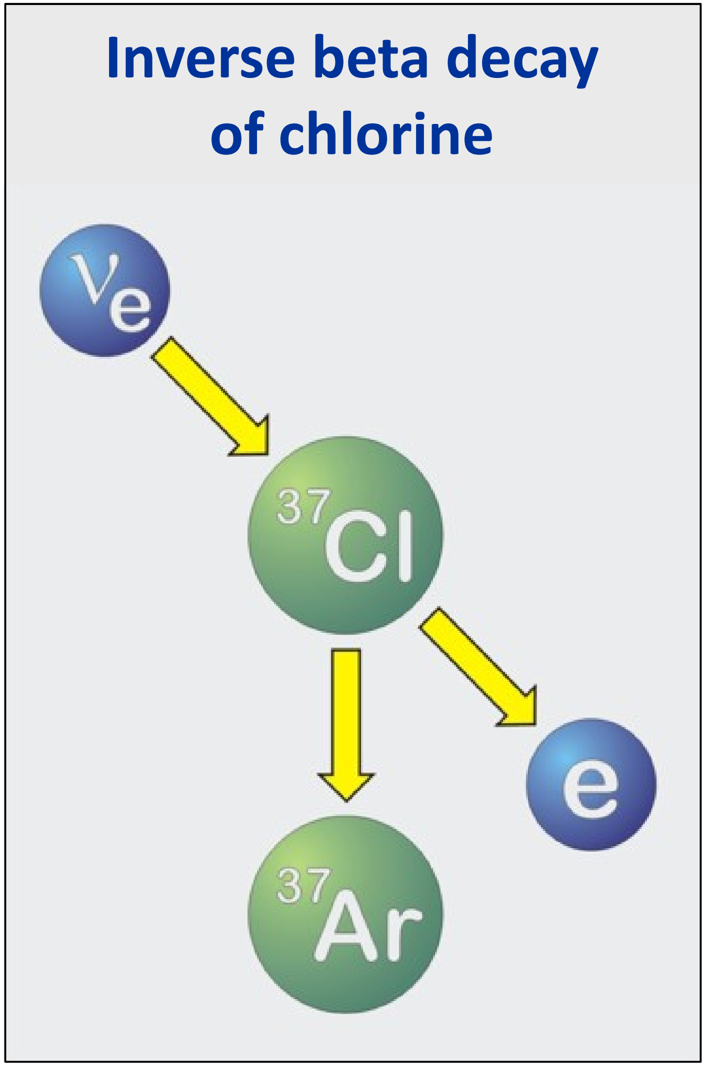


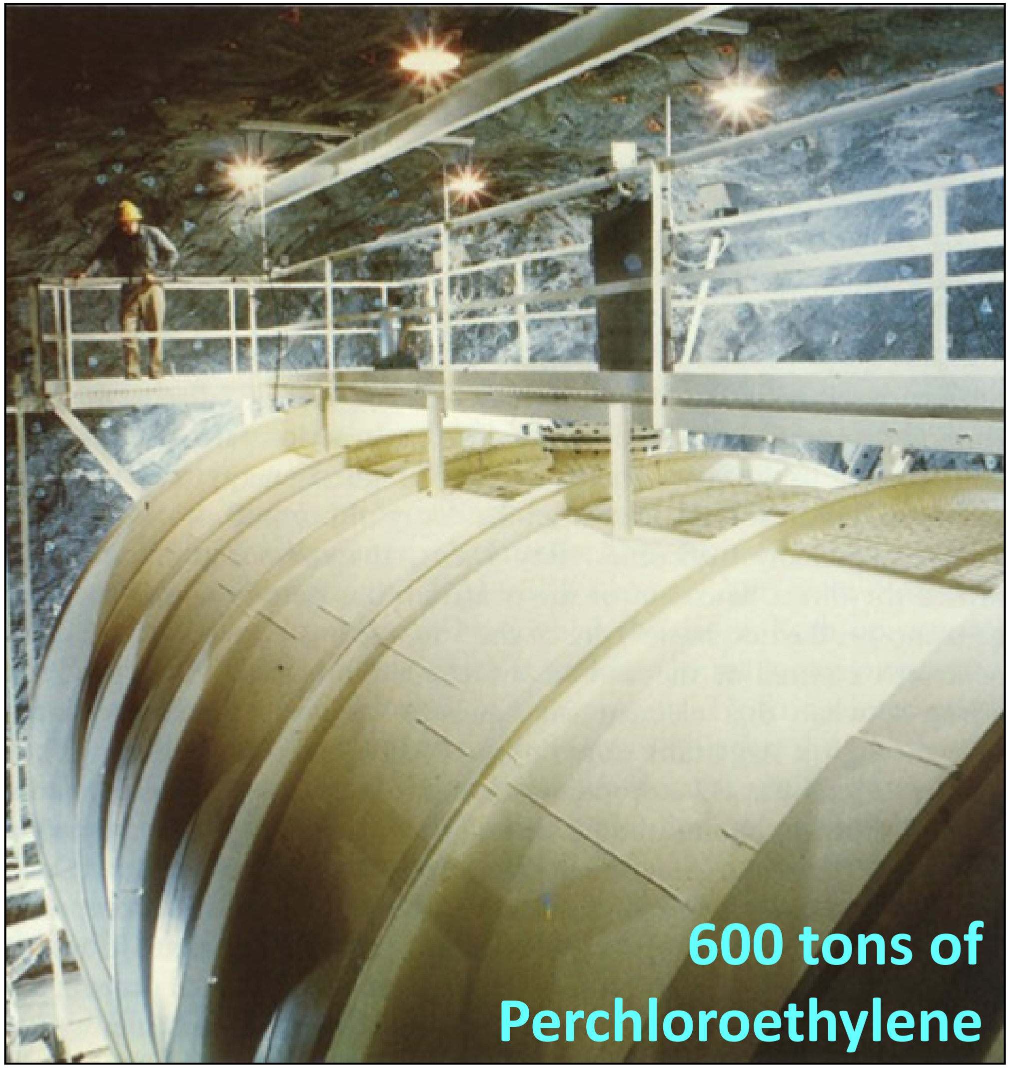
Anti-Electron Neutrinos from Hanford Nuclear Reactor



3 Gammas in coincidence

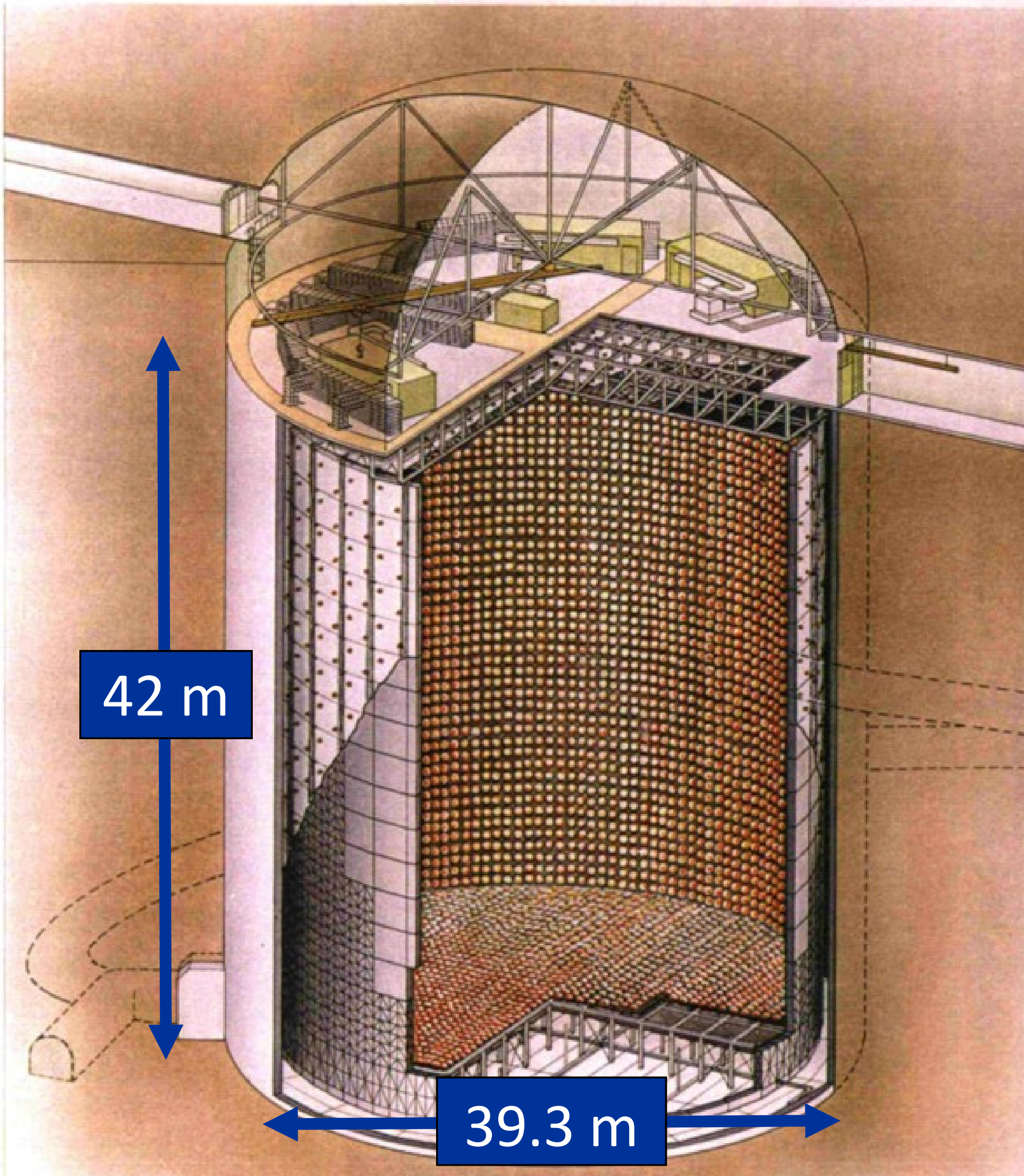
First Measurement of Solar Neutrinos



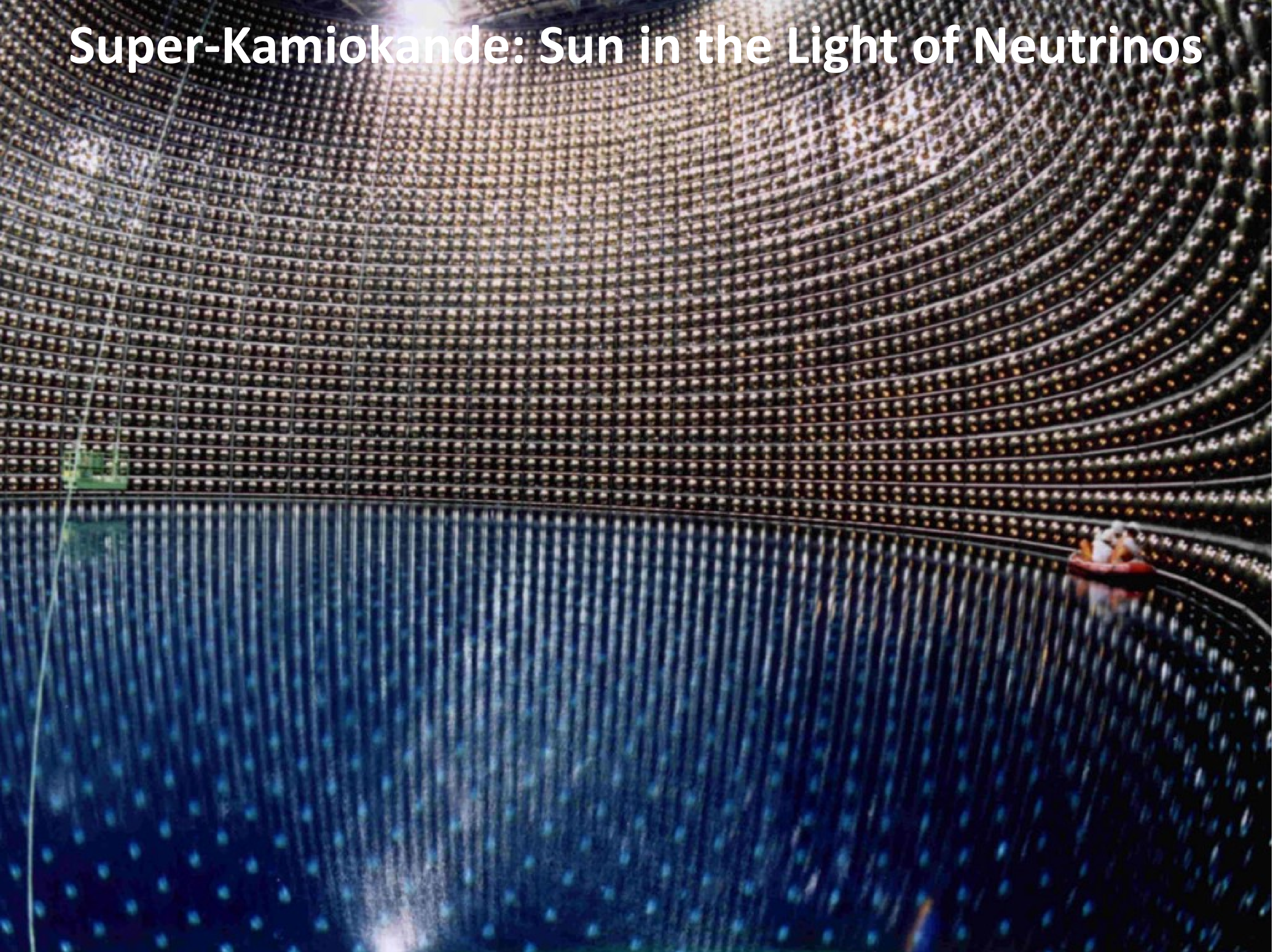


Homestake solar neutrino observatory (1967–2002)

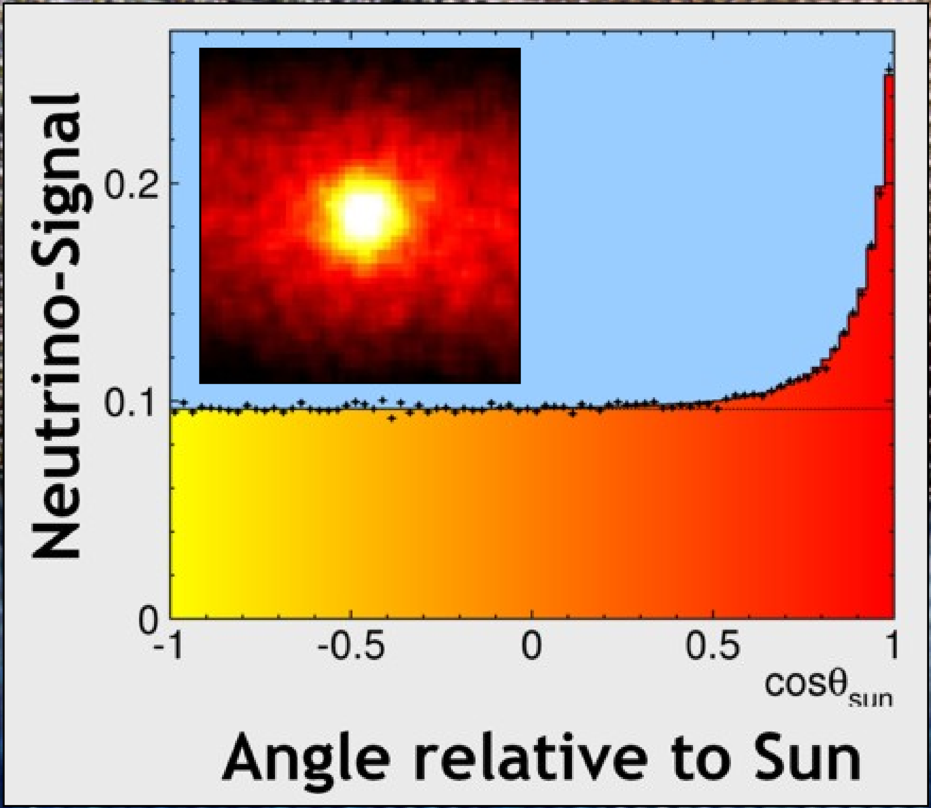
Super-Kamiokande Neutrino Detector (Since 1996)

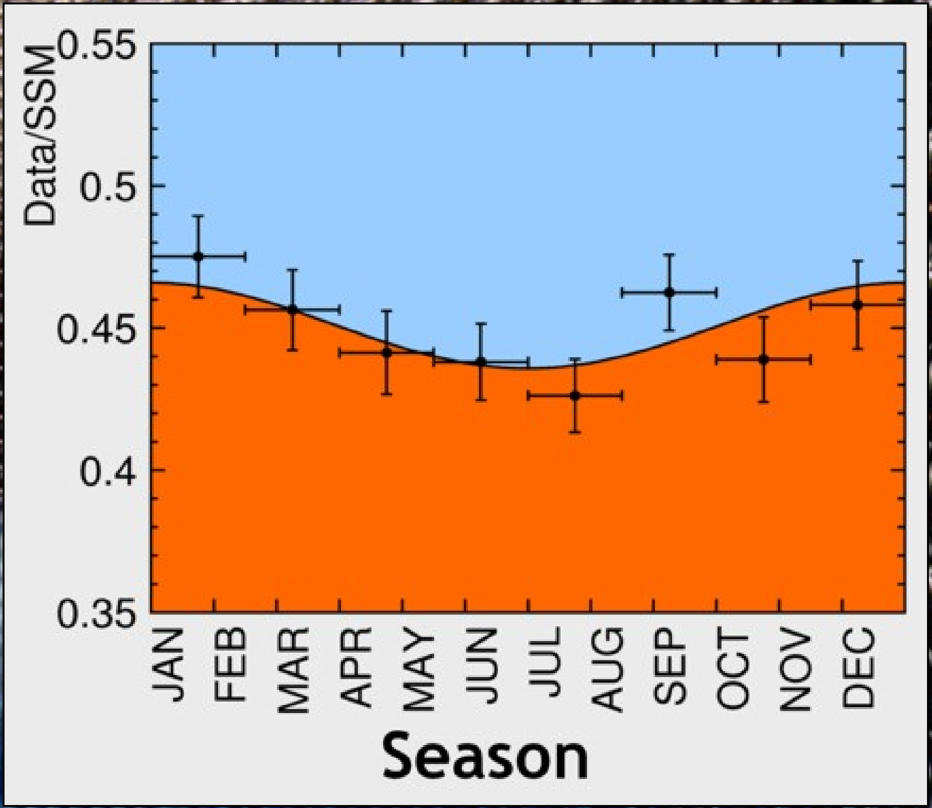


Super-Kamiokande: Sun in the Light of Neutrinos



Super-Kamiokande: Sun in the Light of Neutrinos





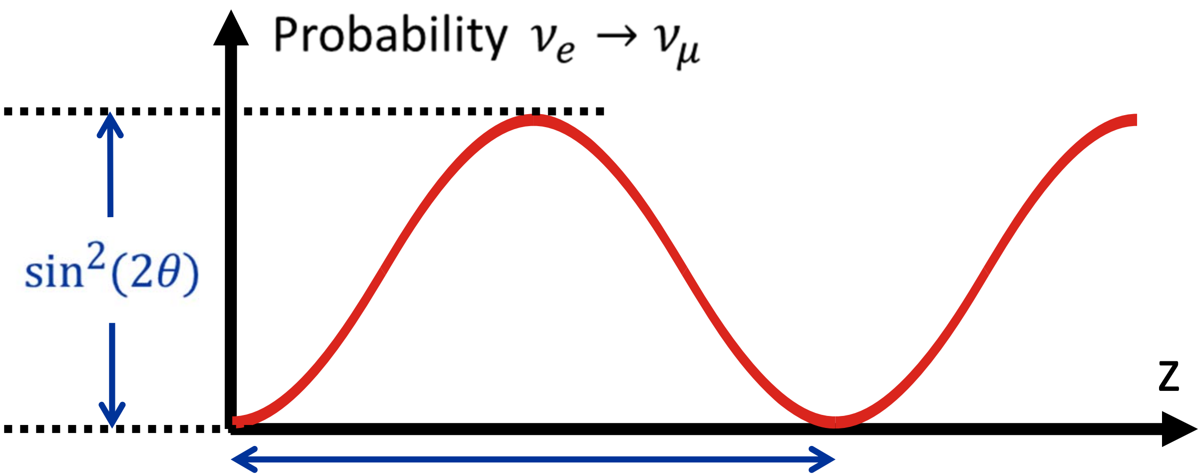
Neutrino Flavor Oscillations

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

Each mass eigenstate propagates as e^{ipz}

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

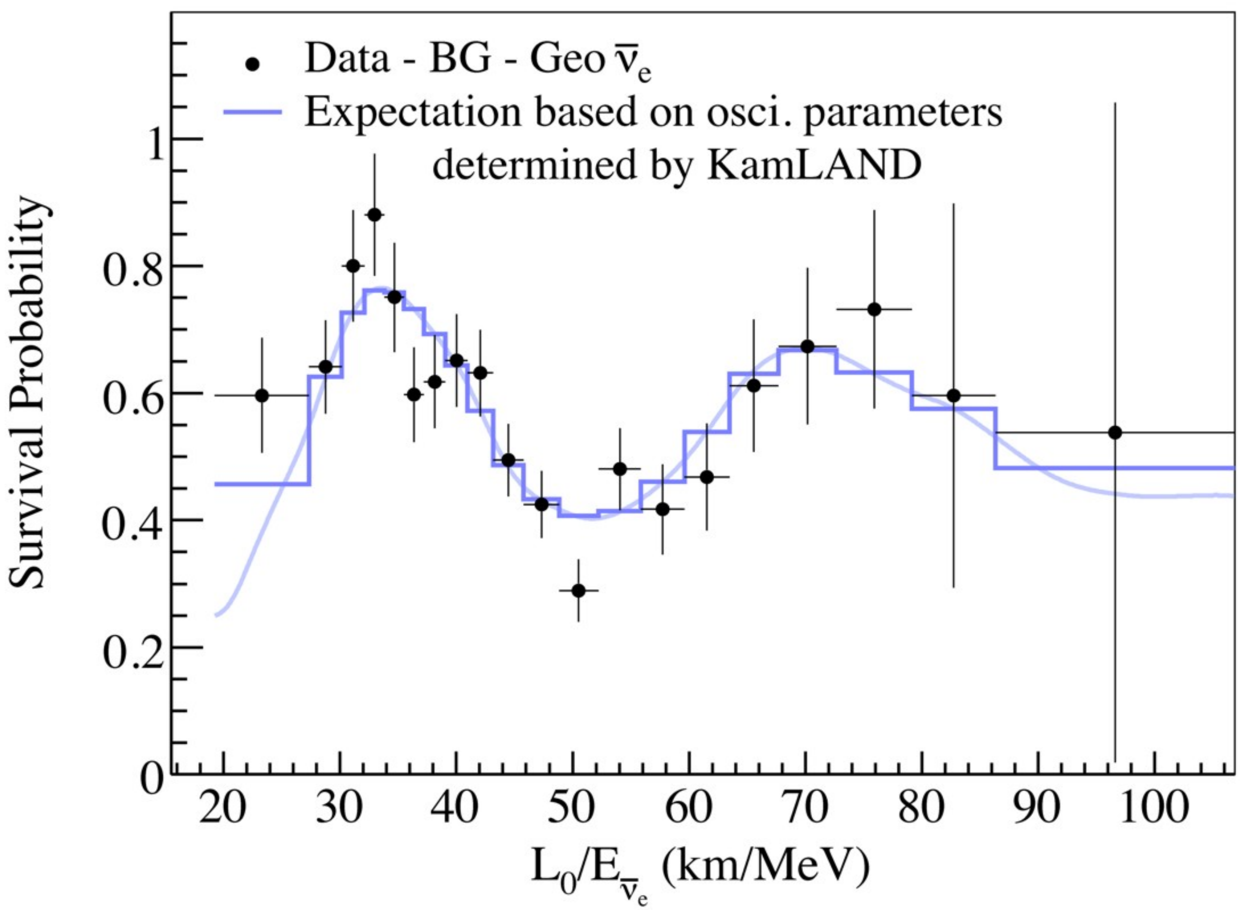
Phase difference $\frac{\delta m^2}{2E} z$ implies flavor oscillations

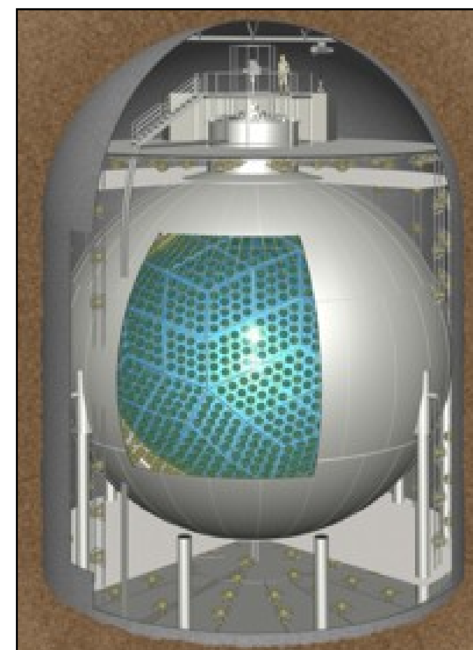


Oscillation Length $\frac{4\pi E}{\delta m^2} = 2.5\ \mathrm{m}\ \frac{E}{\mathrm{MeV}} \left(\frac{\mathrm{eV}^2}{\delta m}\right)$

Oscillation of Reactor Neutrinos at KamLAND (Japan)

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



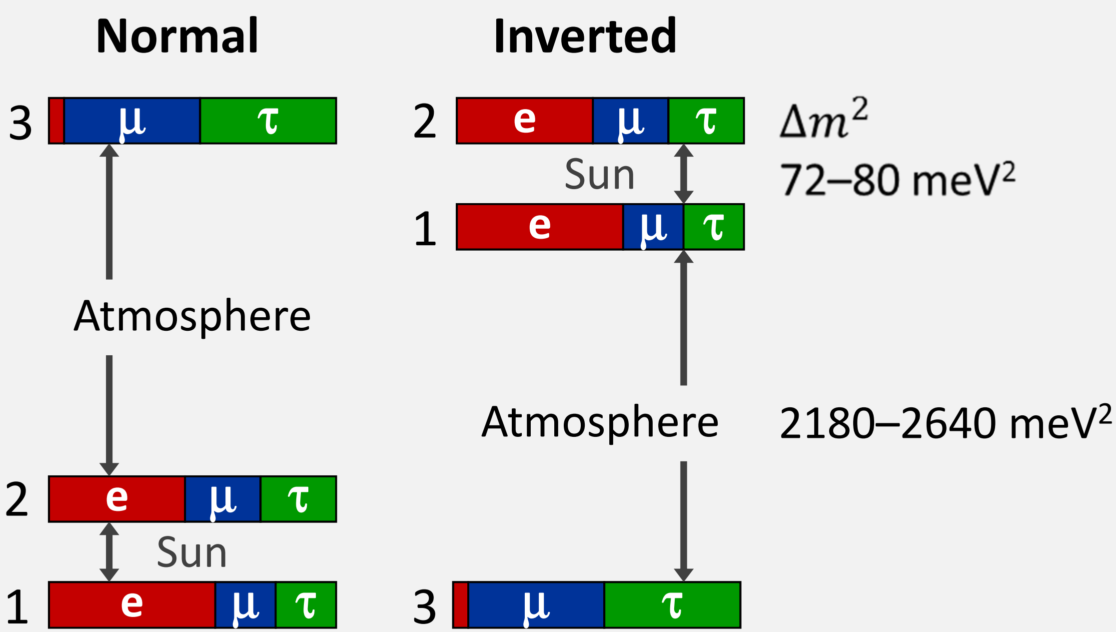


KamLAND Scintillator detector (1000 t)

Three-Flavor Neutrino Parameters

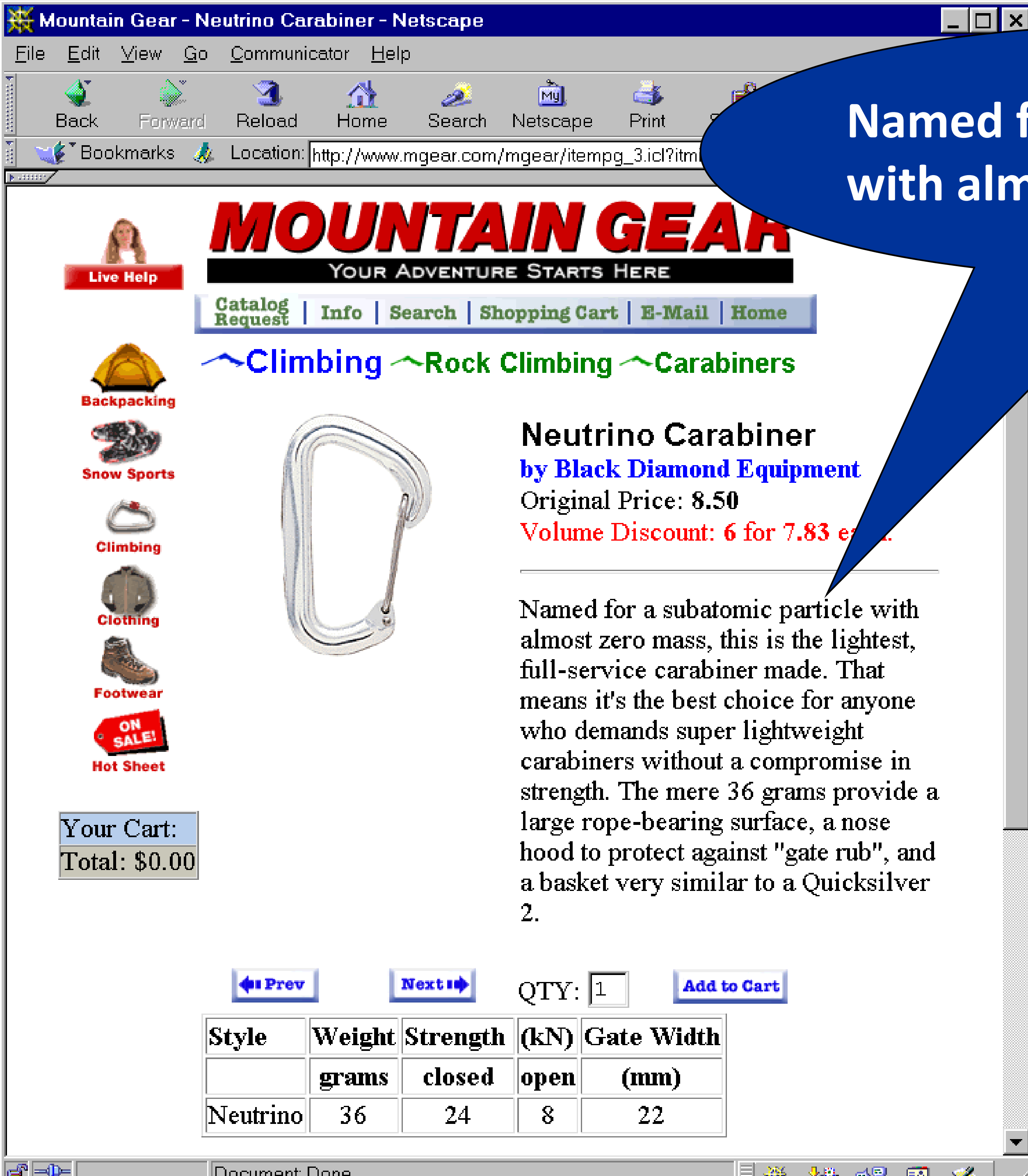
Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ (Euler angles for 3D rotation), $c_{ij} = \cos\theta_{ij}$, a CP-violating "Dirac phase" δ, and two "Majorana phases" α_2 and α_3

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



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 ?

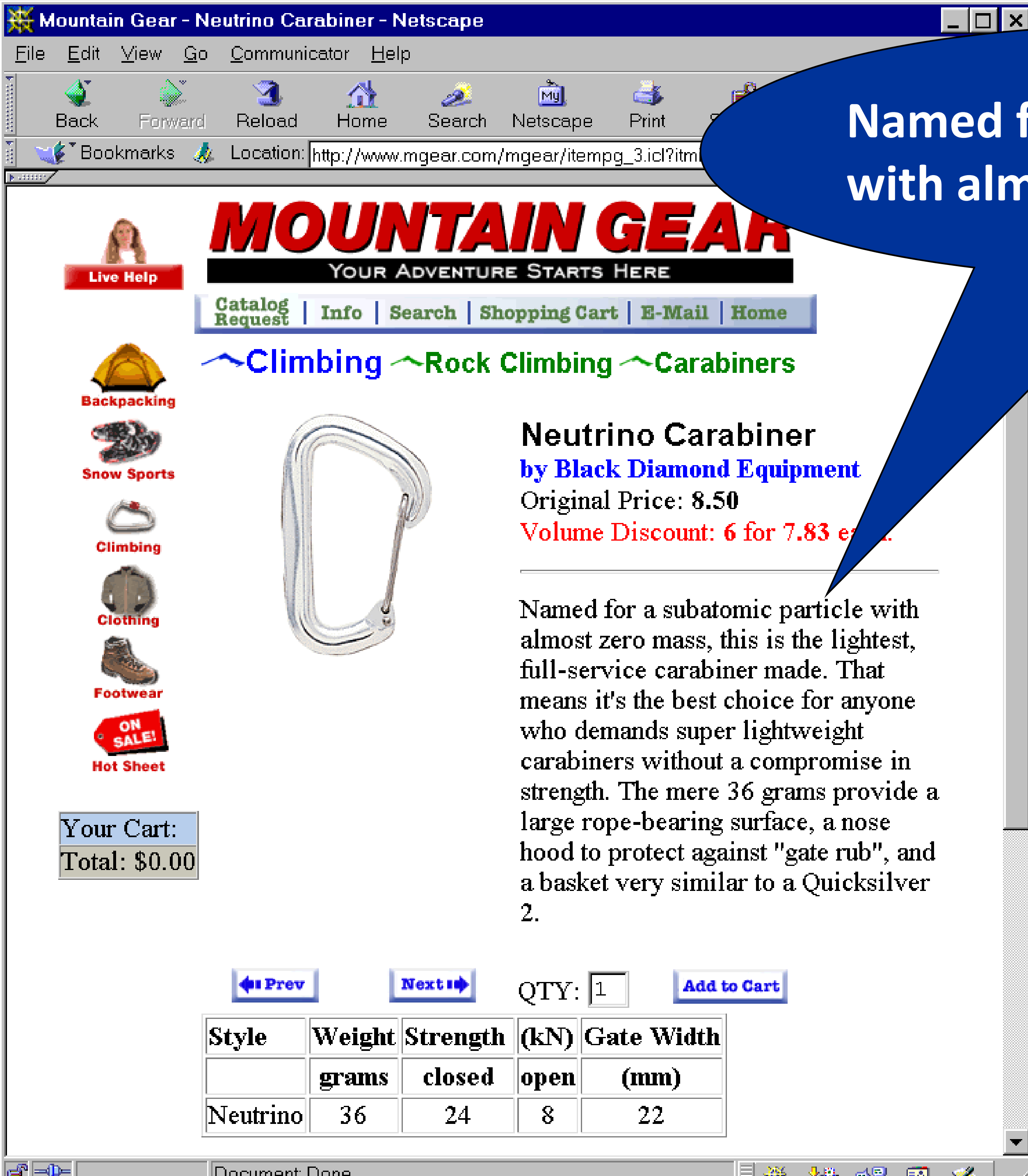


Named for a subatomic particle with almost zero mass, …

Greek “nu”

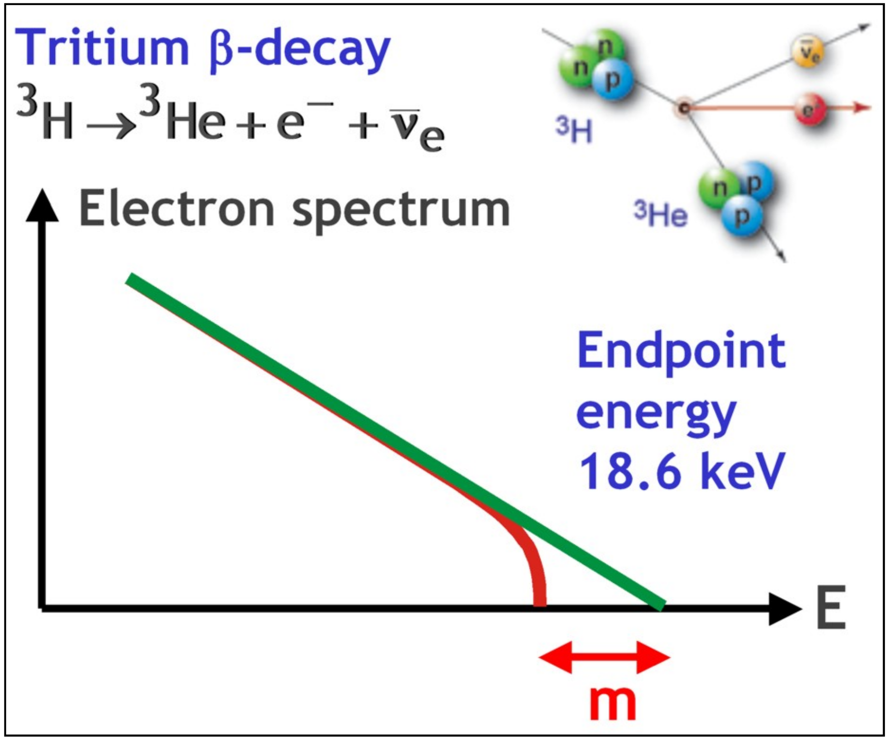
ν

Named for a subatomic particle with almost zero mass, …



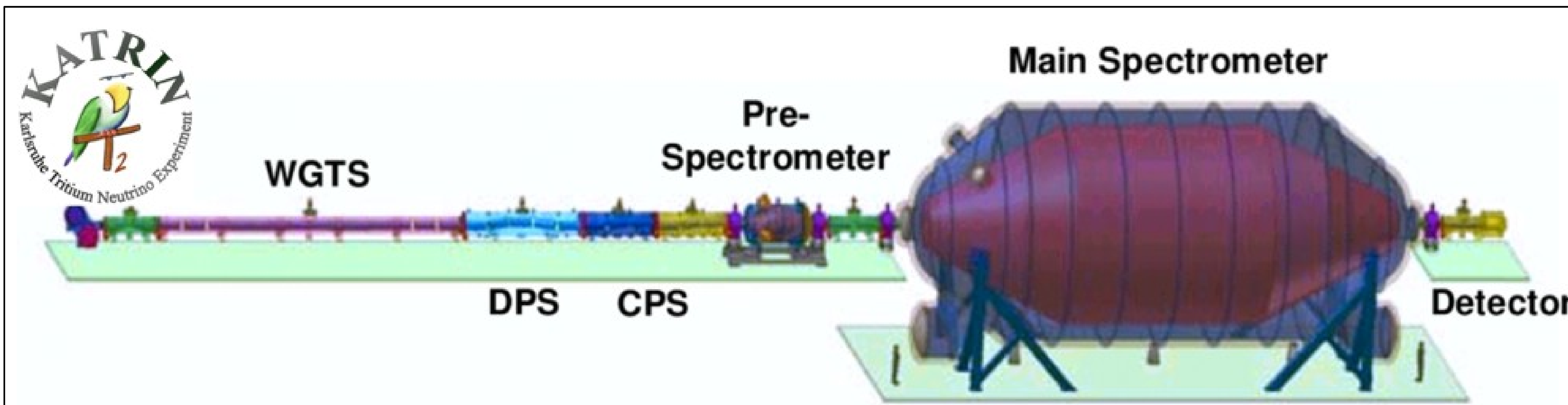
Now also in color

“Weighing” Neutrinos with KATRIN

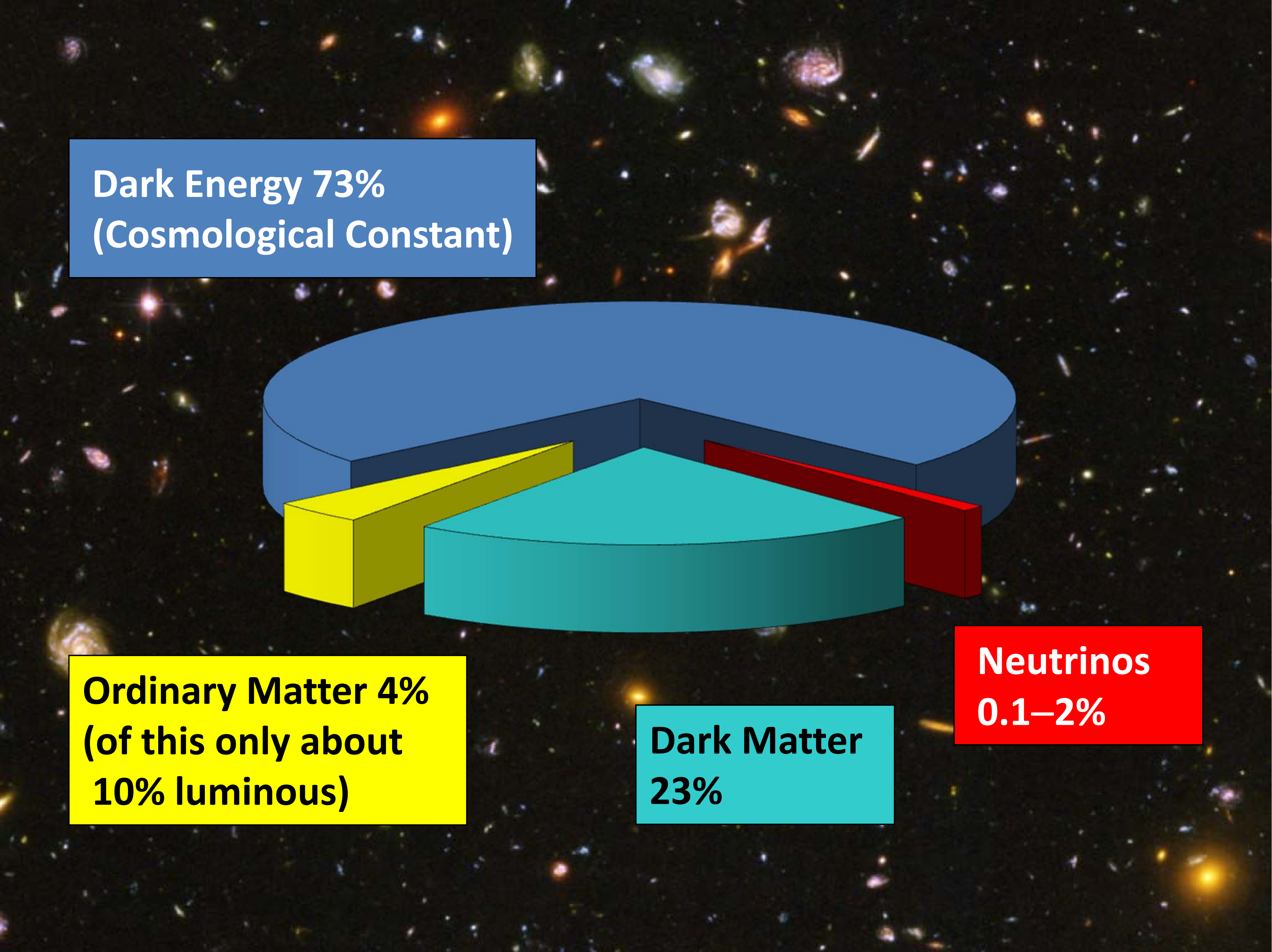


- Sensitive to common mass scale m for all flavors because of small mass differences from oscillations
- Best limit from Mainz und Troitsk
  $m < 2.2$ eV (95% CL)
- KATRIN can reach 0.2 eV
- Under construction
- Data taking to begin soon?

http://www-ik.fzk.de/katrin/



"KATRIN Coming" (25 Nov 2006)


Dark Energy 73%
(Cosmological Constant)
Ordinary Matter 4%
(of this only about
10% luminous)
Dark Matter
23%
Neutrinos
0.1–2%

Cosmological Limit on Neutrino Masses

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

$$\Omega_\nu h^2 = \sum \frac{m_\nu}{93~\text{eV}} < 0.23$$

$$\sum m_\nu \lesssim 20~\text{eV}$$

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 $m(\nu_e) < 200$ eV/c^2 for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^6$ 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)

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

Weakly Interacting Particles as Dark Matter

THE ASTROPHYSICAL JOURNAL, 180: 7–10, 1973 February 15

GRAVITY OF NEUTRINOS OF NONZERO MASS IN ASTROPHYSICS

R. COWSIK* AND J. MCCLELLAND
Department of Physics, University of California, Berkeley
Received 1972 July 24

ABSTRACT

If neutrinos have a rest mass of a few eV/c^2, then they would dominate the gravitational dynamics of the large clusters of galaxies and of the Universe. A simple model to understand the virial mass discrepancy in the Coma cluster on this basis is outlined.

Subject headings: cosmology — galaxies, clusters of — neutrinos

The possibility of a finite rest mass for the neutrinos has fascinated astrophysicists (Kuchowicz 1969). A recent discussion of such a possibility has been in the context of the solar-neutrino experiments (Bahcall, Cabibbo, and Yahil 1972). Here we wish to point out some interesting consequences of the gravitational interactions of such neutrinos. These considerations become particularly relevant in the framework of big-bang cosmologies which we assume to be valid in our discussion here.

In the early phase of such a Universe when the temperature was ~1 MeV, several processes of neutrino production (Ruderman 1969) would have led to copious production of neutrinos and antineutrinos (Steigman 1972; Cowsik and McClelland 1972). Conditions of thermal equilibrium allow an easy estimate of their number densities (Landau and Lifshitz 1969):

$$n_{\nu i} = \frac{1}{\pi^2 \hbar^3} \int_0^\infty \frac{p^2 dp}{\exp[E/kT(z_{eq})] + 1} \, . \qquad (1)$$

Here $n_{\nu i}$ = number density of neutrinos of the ith kind (notice that in writing this expression we have assumed that both the helicity states are allowed for the neutrinos because of finite rest mass); $E = c(p^2 + m^2c^2)^{1/2}$; k = Boltzmann's constant; $T(z_{eq}) = T_r(z_{eq}) = T_\nu(z_{eq}) = T_e(z_{eq}) \cdots =$ the common temperature of radiation, neutrinos, electrons, etc., at the latest epoch characterized by redshift z_{eq} when they may be assumed to have been in thermal equilibrium; $kT(z_{eq}) \simeq 1$ MeV.

Since the masses of the neutrinos are expected to be small, $kT(z_{eq}) \gg m_{\nu i}c^2$, in the extreme-relativistic limit equation (1) reduces to

$$n_{\nu i}(z_{eq}) \simeq 0.183[T(z_{eq})/hc]^3 \, . \qquad (2)$$

As the Universe expands, only the neutrinos (in contrast to all other known particles) survive annihilation because of extremely low cross-sections (deGraff and Tolhock 1966), and their number density decreases with increasing volume of the Universe, simply as $\sim V(z_{eq})/V(z) = [(1 + z)/(1 + z_{eq})]^3$. Noting that $(1 + z_{eq})/(1 + z) = T_r(z_{eq})/T_r(z)$, the number density at the present epoch ($z = 0$) is given by

$$n_{\nu i}(0) = n_{\nu i}(z_{eq})/(1 + z_{eq})^3 \simeq 0.183[T_r(0)/hc]^3 \simeq 300 \text{ cm}^{-3} \, , \qquad (3)$$

* On leave from the Tata Institute of Fundamental Research, Bombay, India.

7

- Almost 40 years ago, beginnings of the idea of weakly interacting particles (neutrinos) as dark matter
- Massive neutrinos are no longer a good candidate (hot dark matter)
- However, the idea of weakly interacting massive particles (WIMPs) as dark matter is now standard

What is wrong with neutrino dark matter?

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

Maximum mass density of a degenerate Fermi gas

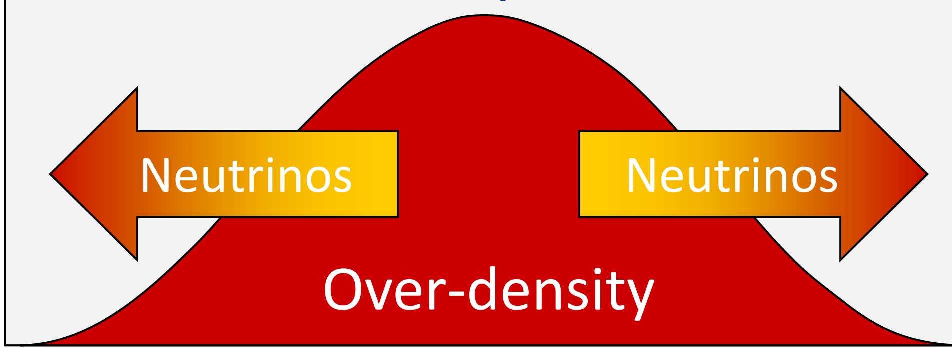
$$\rho_{\max} = m_\nu \underbrace{\frac{p_{\max}^3}{3\pi^2}}_{n_{\max}} = \frac{m_\nu \left(m_\nu v_{\rm escape}\right)^3}{3\pi^2}$$

Spiral galaxies
$m_\nu > 20$–40 eV

Dwarf galaxies
$m_\nu > 100$–200 eV

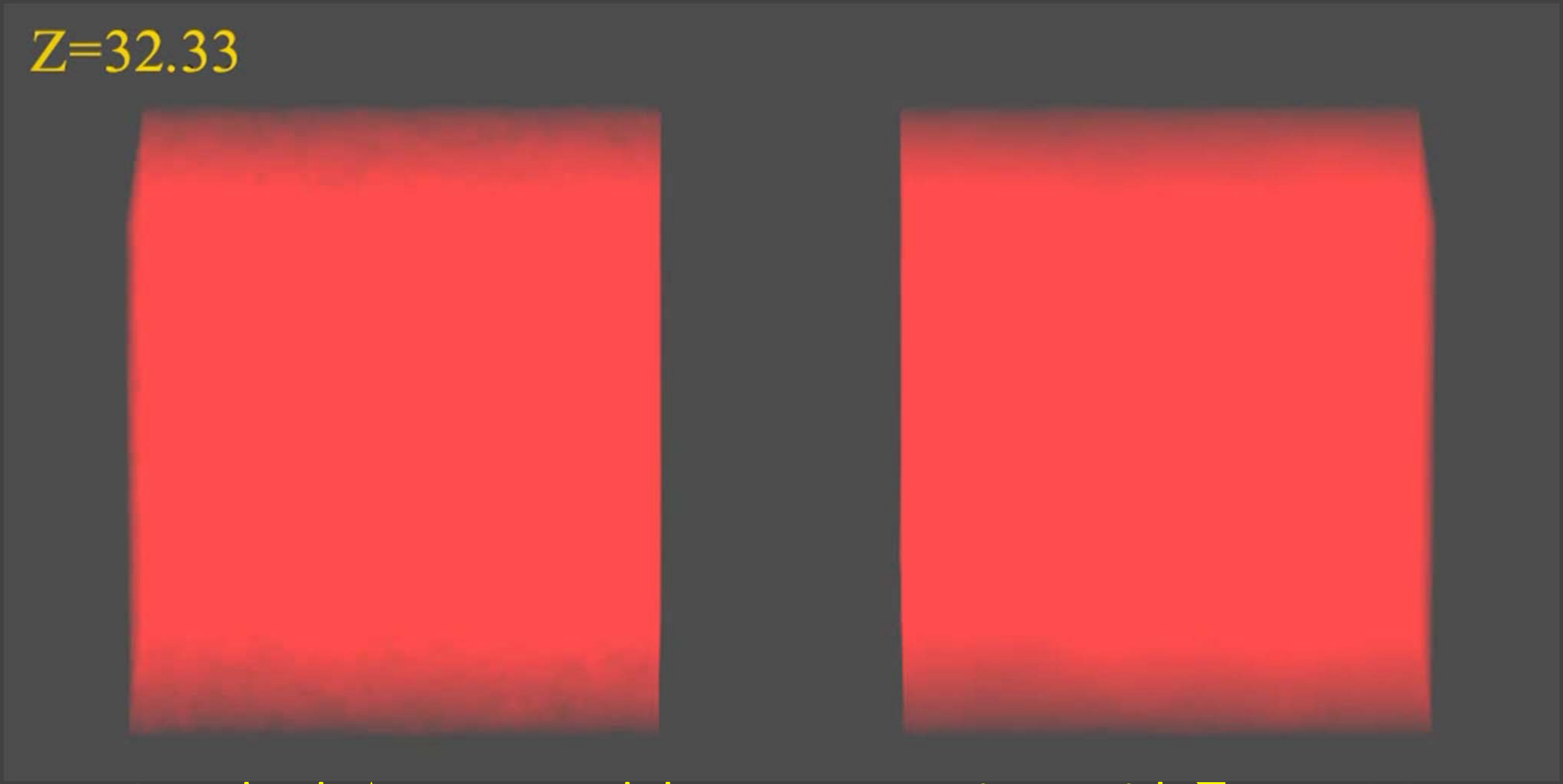
Neutrino Free Streaming (Collisionless Phase Mixing)

- At $T < 1\,\mathrm{MeV}$ 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

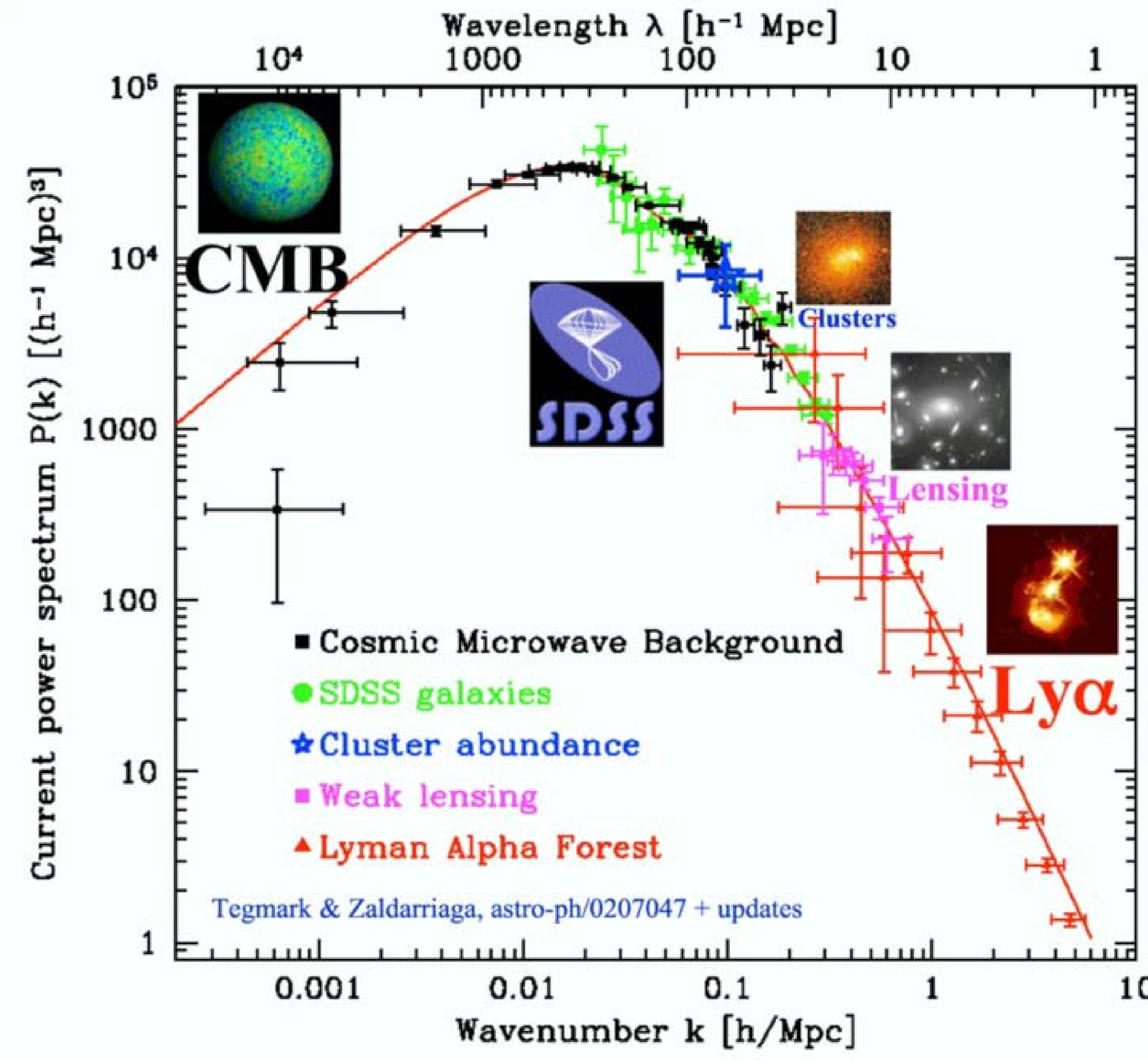
Structure Formation with Hot Dark Matter



Standard ΛCDM Model — Neutrinos with $\Sigma m_\nu = 6.9$ eV

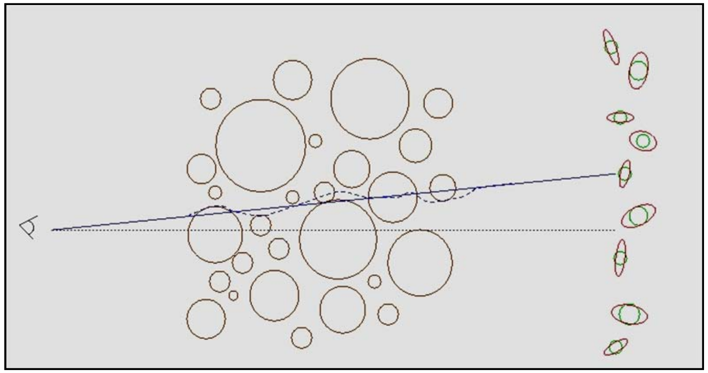
Structure fromation simulated with Gadget code
Cube size 256 Mpc at zero redshift
Troels Haugbølle, http://users-phys.au.dk/haugboel

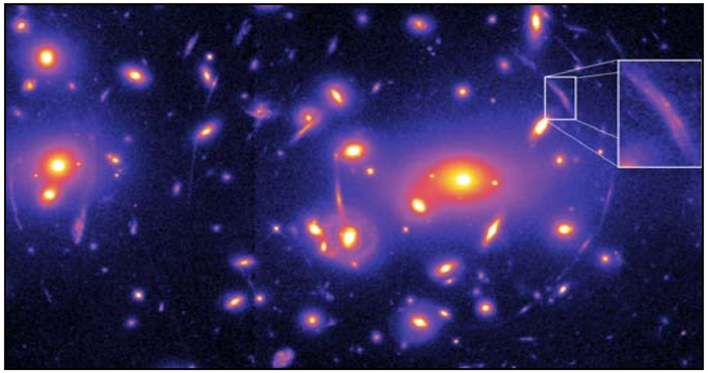
Power Spectrum of Cosmic Density Fluctuations



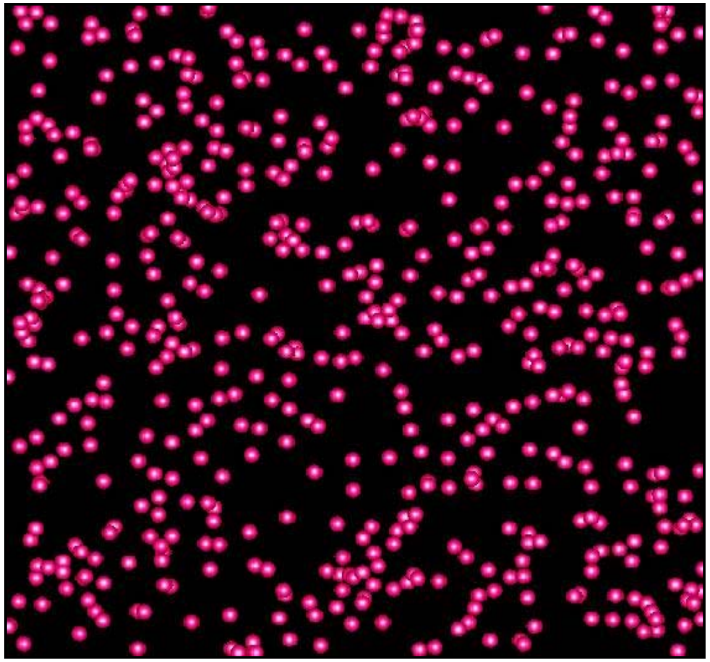
Tegmark, TAUP 2003

Weak Lensing – A Powerful Probe for the Future

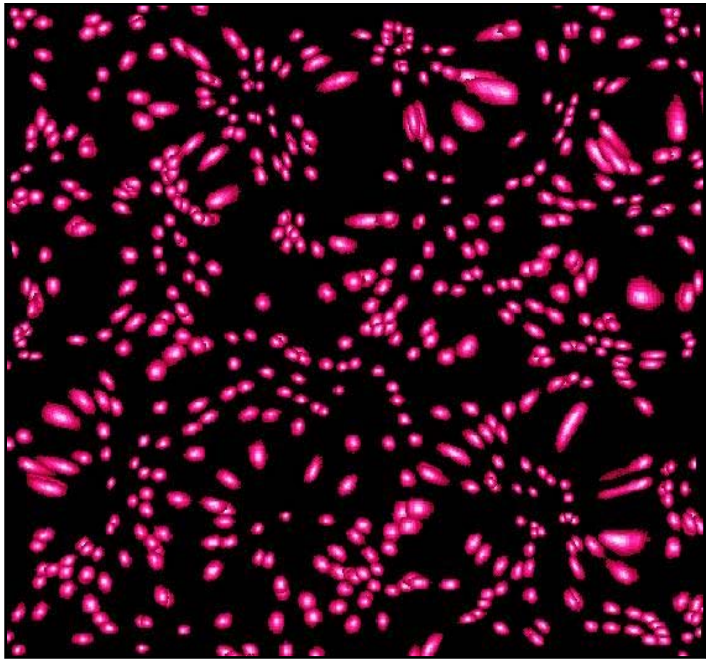




Distortion of background images by foreground matter

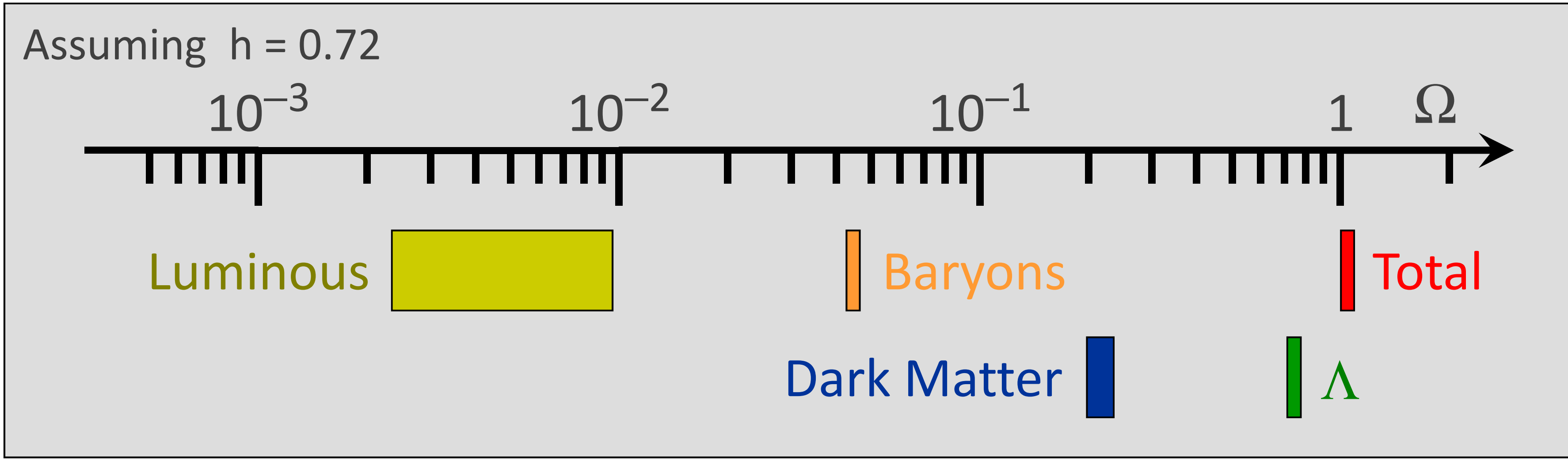


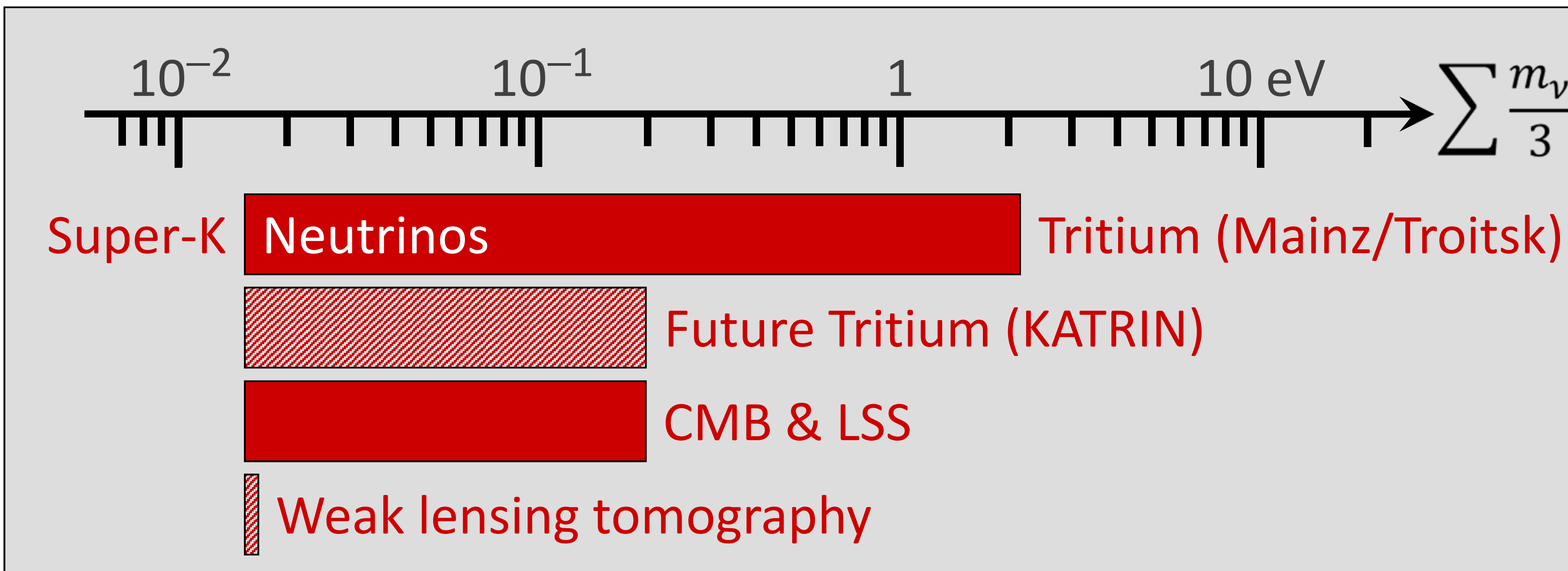
Unlensed



Lensed

Mass-Energy-Inventory of the Universe

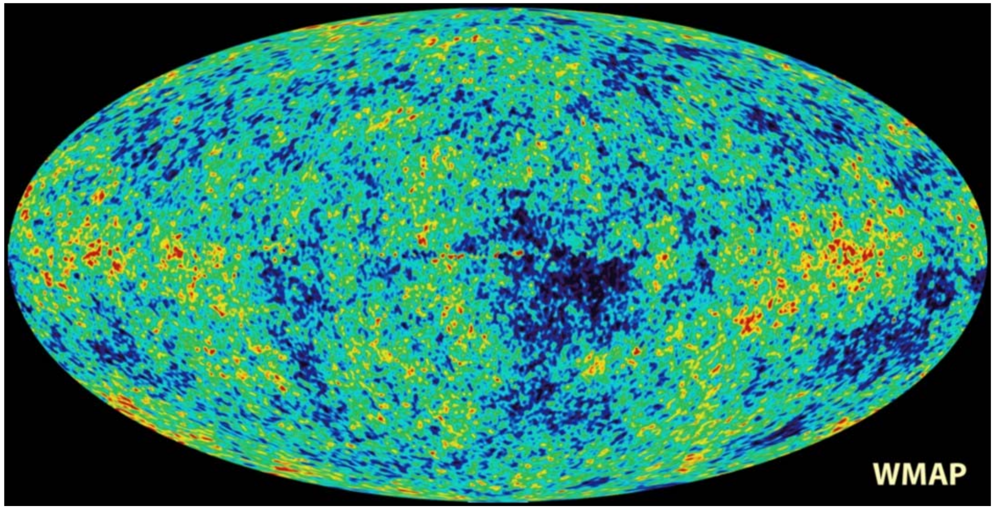




Power Spectrum of CMB Temperature Fluctuations

Sky map of CMBR temperature fluctuations

$$\Delta(\theta,\varphi)=\frac{T(\theta,\varphi)-\langle T\rangle}{\langle T\rangle}$$

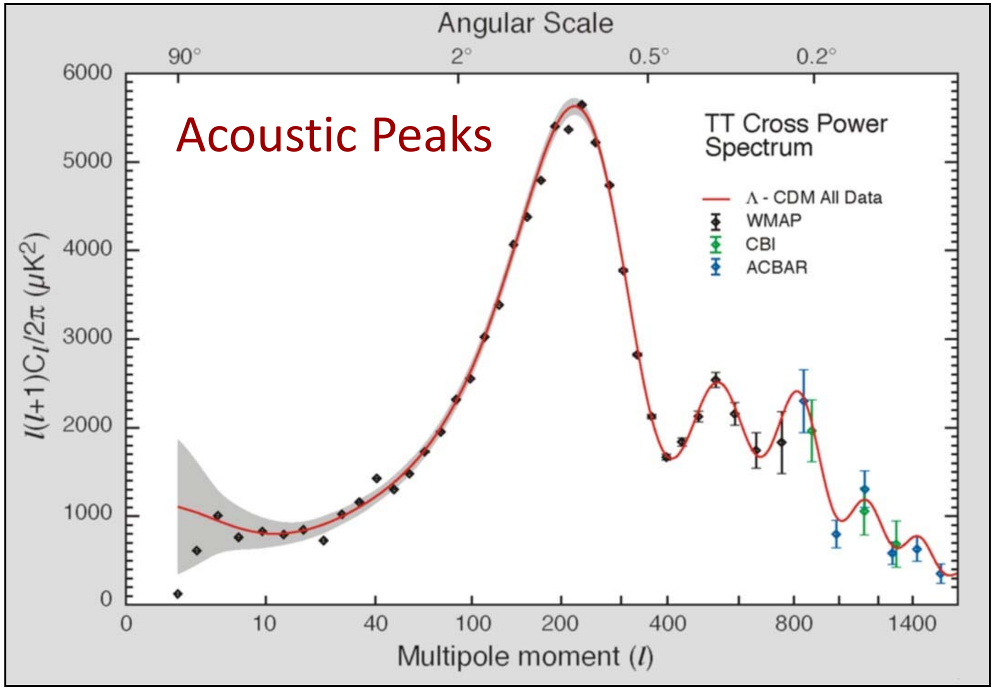


Multipole expansion

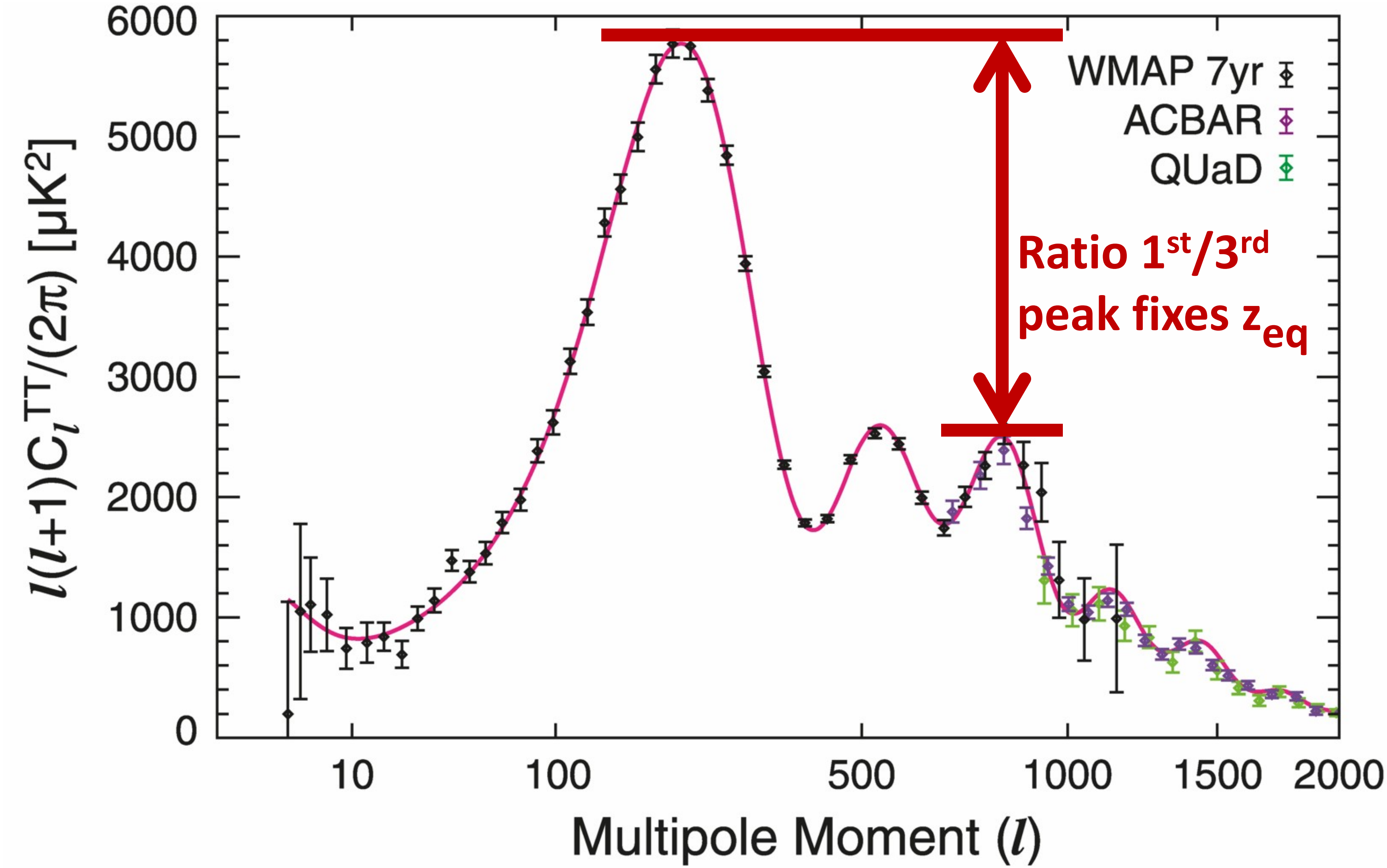
$$\Delta(\theta,\varphi)=\sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell}a_{\ell m}Y_{\ell m}(\theta,\varphi)$$

Angular power spectrum

$$C_\ell=\langle a_{\ell m}^* a_{\ell m}\rangle=\frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell}a_{\ell m}^* a_{\ell m}$$

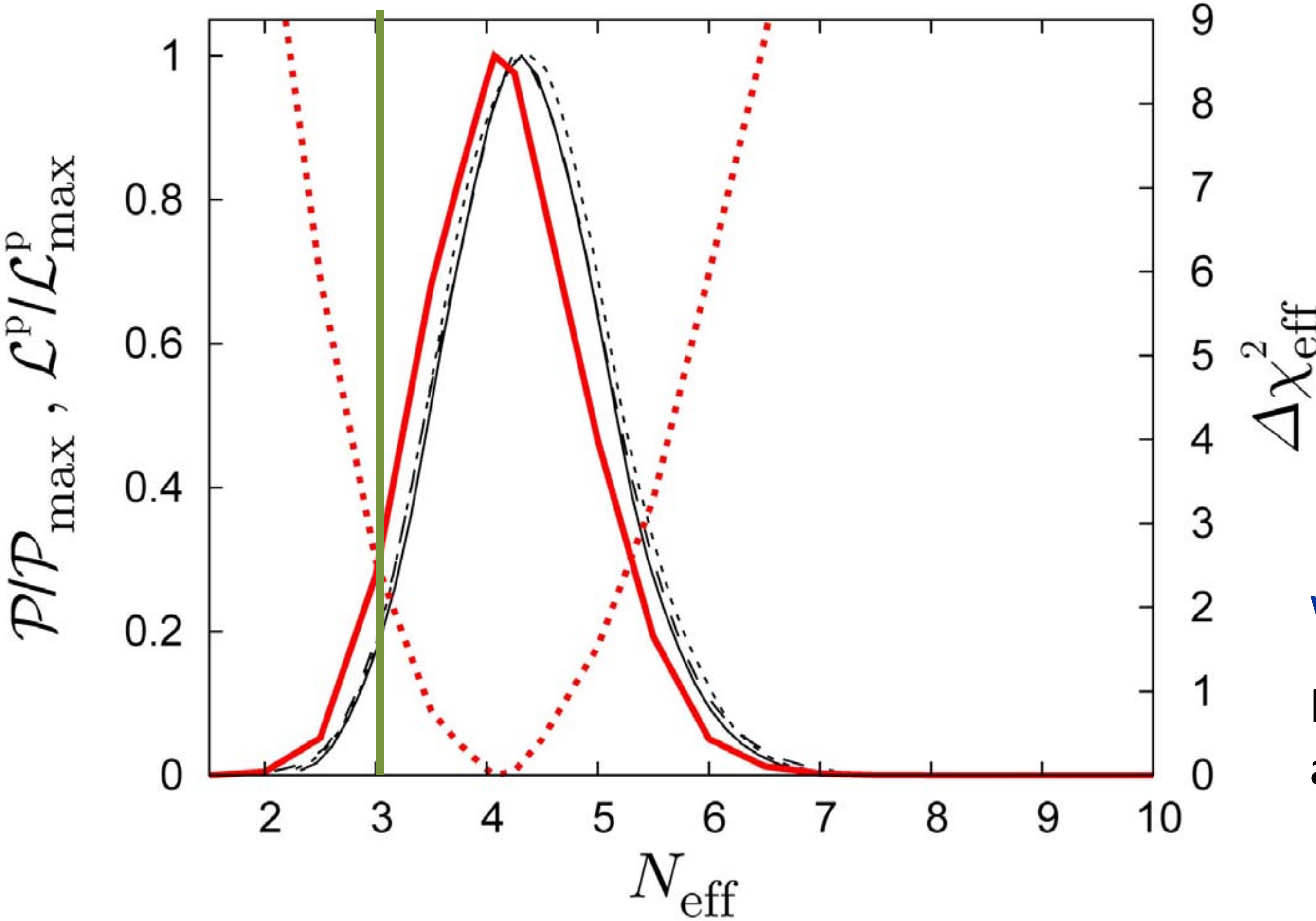


Latest Angular Power Spectrum (WMAP 7 years)



Komatsu et al. (WMAP Collaboration), arXiv:1001.4538

Radiation Content at CMB Decoupling

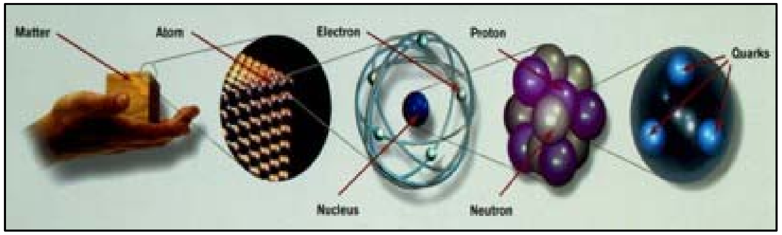


WMAP, LLS and H_0

Hamann, arXiv:1110.4271

- Existence of cosmic neutrino sea clearly confirmed by precision cosmology
- All analyses find tentative indication for excess radiation
- Planck data will fix N_{eff} to ±0.26 (68% CL) or better (January 2013 ?)

Are Neutrinos their own Antiparticles?

Matter	Anti-Matter
	Much less anti-matter in the universe: Baryon asymmetry of the Universe (BAU)

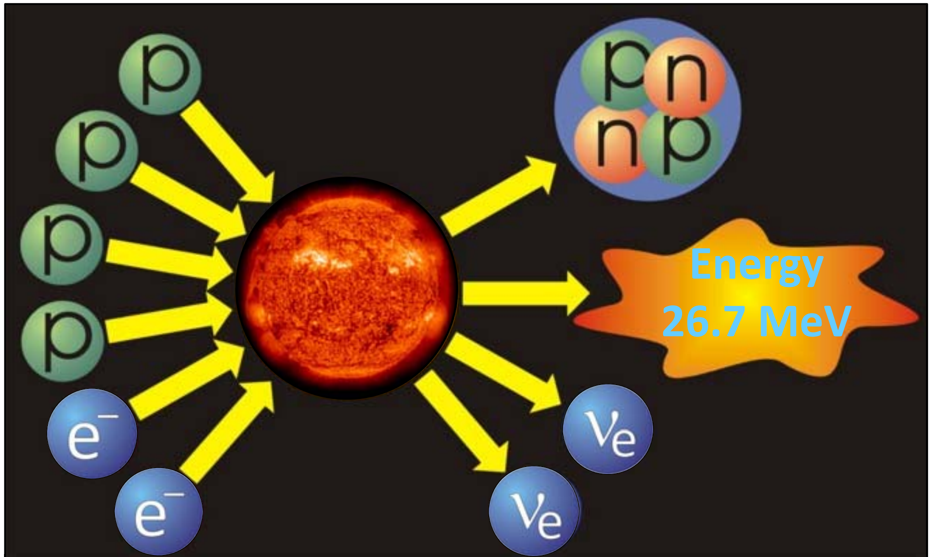
	Quarks		Leptons		Anti-Leptons		Anti-Quarks	
Charge	−1/3	+2/3	−1	0	0	+1	−2/3	+1/3
1st Family	d	u	e	ν_e	$\overline{\nu}_e$	e^+	$\overline{u}$	$\overline{d}$
2nd Family	s	c	μ	ν_μ	$\overline{\nu}_\mu$	μ^+	$\overline{c}$	$\overline{s}$
3rd Family	b	t	τ	ν_τ	$\overline{\nu}_\tau$	τ^+	$\overline{t}$	$\overline{b}$
Strong Int'n	✓	✓					✓	✓
Electromagnetic Int'n	✓	✓	✓			✓	✓	✓
Weak Interaction	✓	✓	✓	✓	✓	✓	✓	✓
Gravitation	✓	✓	✓	✓	✓	✓	✓	✓

Are Neutrinos their own Antiparticles?

	Matter				Anti-Matter			
	Quarks		Leptons		Anti-Leptons		Anti-Quarks	
Charge	−1/3	+2/3	−1	0		+1	−2/3	+1/3
1st Family	d	u	e	ν_e		e^+	$\bar{u}$	$\bar{d}$
2nd Family	s	c	μ	ν_μ		μ^+	$\bar{c}$	$\bar{s}$
3rd Family	b	t	τ	ν_τ		τ^+	$\bar{t}$	$\bar{b}$
	Strong Int'n						Strong Int'n	
	Electromagnetic Int'n					Electromagnetic Int'n		
	Weak Interaction							
	Gravitation							

„Majorana Neutrinos”  are their own antiparticles

Solar Neutrinos vs. Reactor Antineutrinos



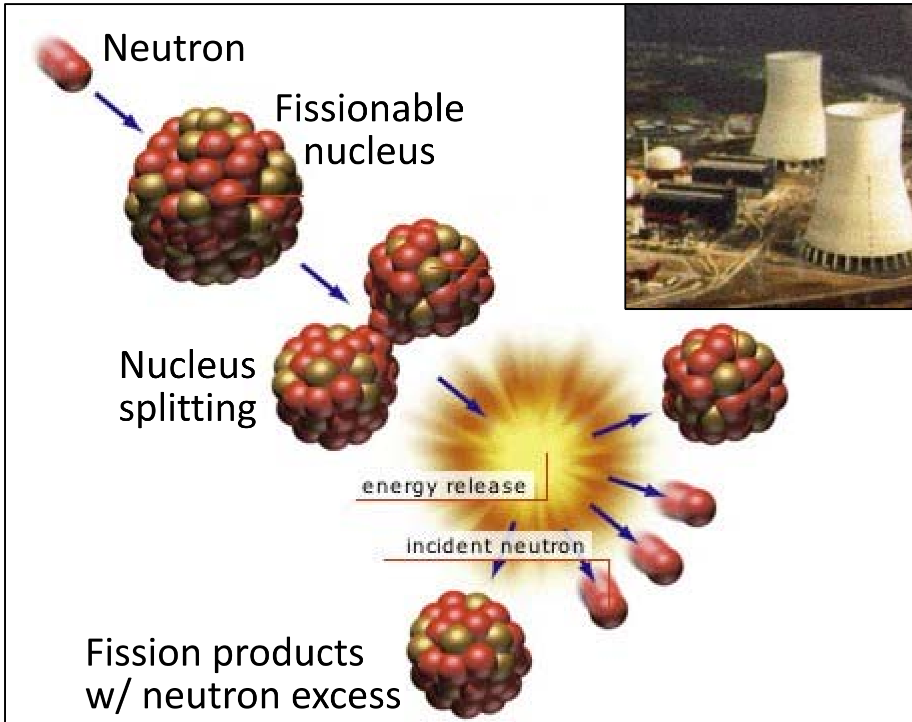
Ray Davis radiochemical detector (1967–1992)

$\nu_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$

Amounts to neutino capture by neutron

$\nu_e + n \to p + e^-$

Does not work for reactor $\overline{\nu}_e$ flux!



β unstable nuclei effectively decay by

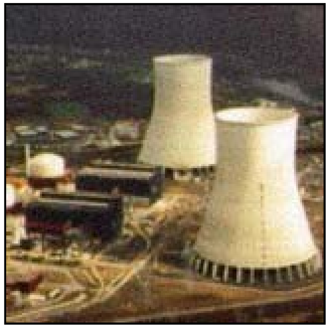
$n \to p + e + \overline{\nu}_e$

Detection by inverse β decay

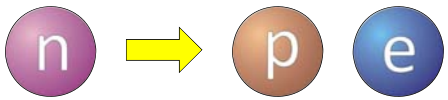
$\overline{\nu}_e + p \to n + e^+$

Reines and Cowan 1954–1956

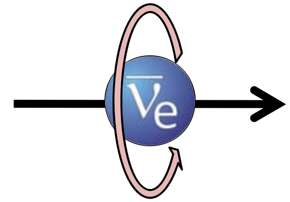
Role of Neutrino Helicity (Handedness)

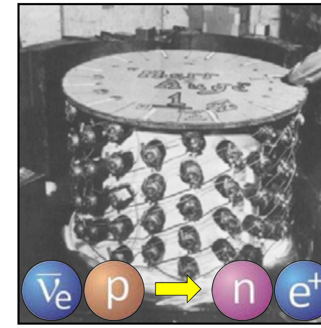


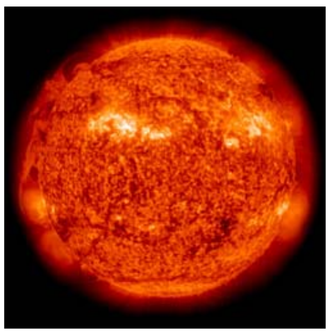
Basic production process in reactors



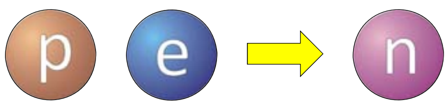
Anti-neutrinos always right-handed helicity



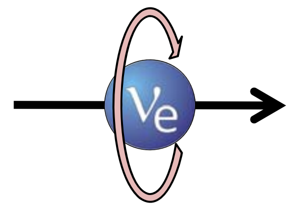


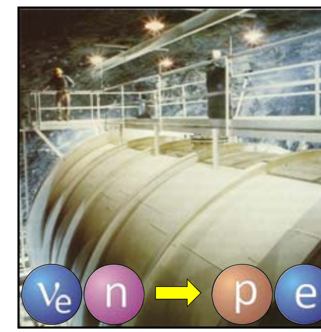


Basic production process in the Sun

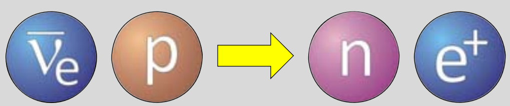


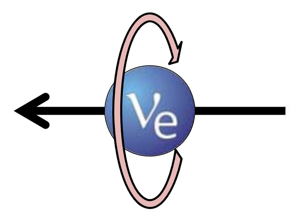
Neutrinos always left-handed helicity





Cowan & Reines $\overline{\nu}_e$ detector in fast-moving rocket, overtakes small-mass solar ν_e

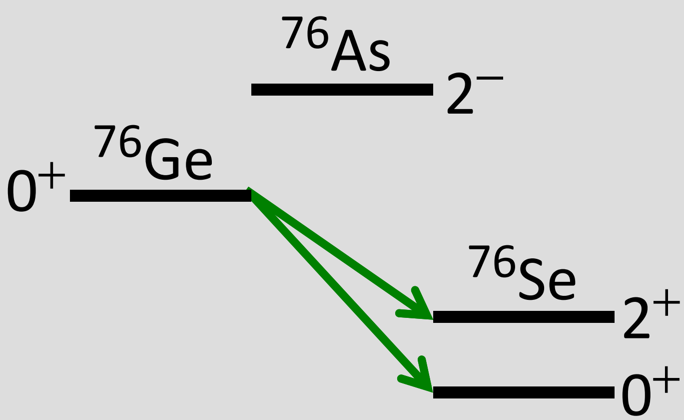




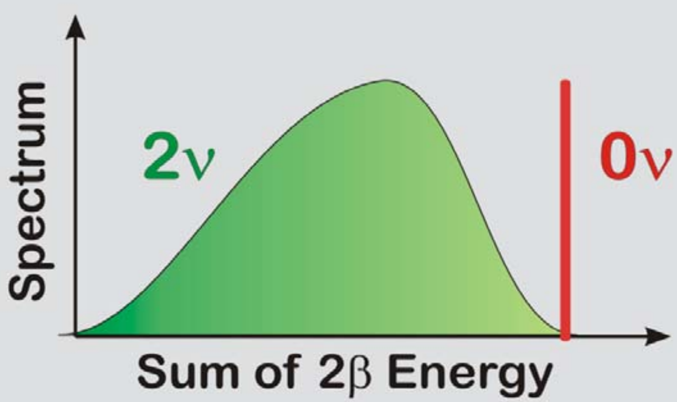
Majorana neutrinos:
Helicity flip → anti-neutrino
$\nu_e/\overline{\nu}_e$ property depends on Lorentz frame

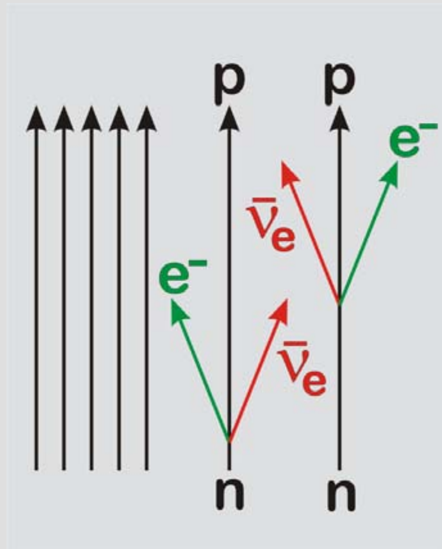
Neutrinoless ββ Decay

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

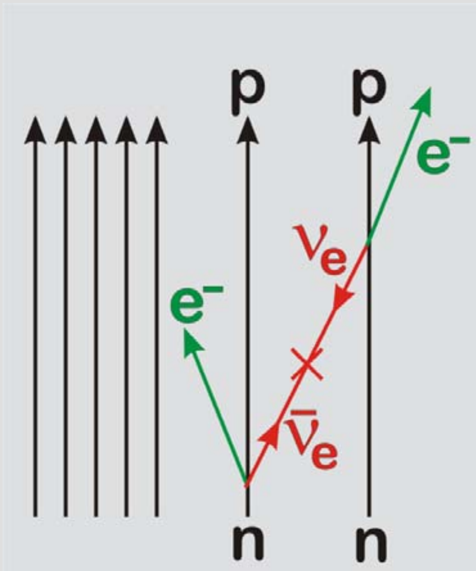


Half life ~ 10^{21} yr





Standard 2ν mode



0ν mode, enabled by Majorana mass

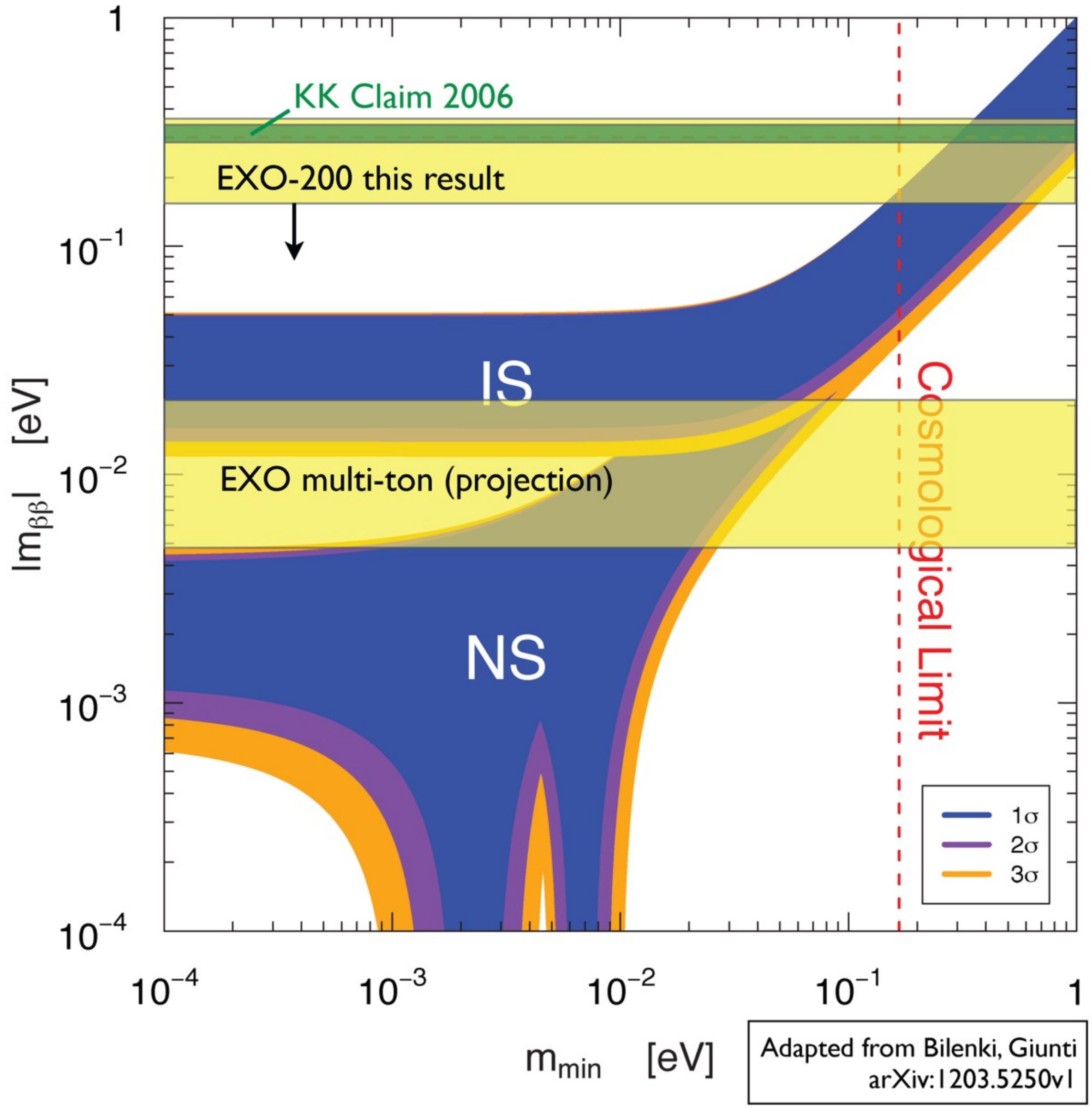
Measured quantity

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

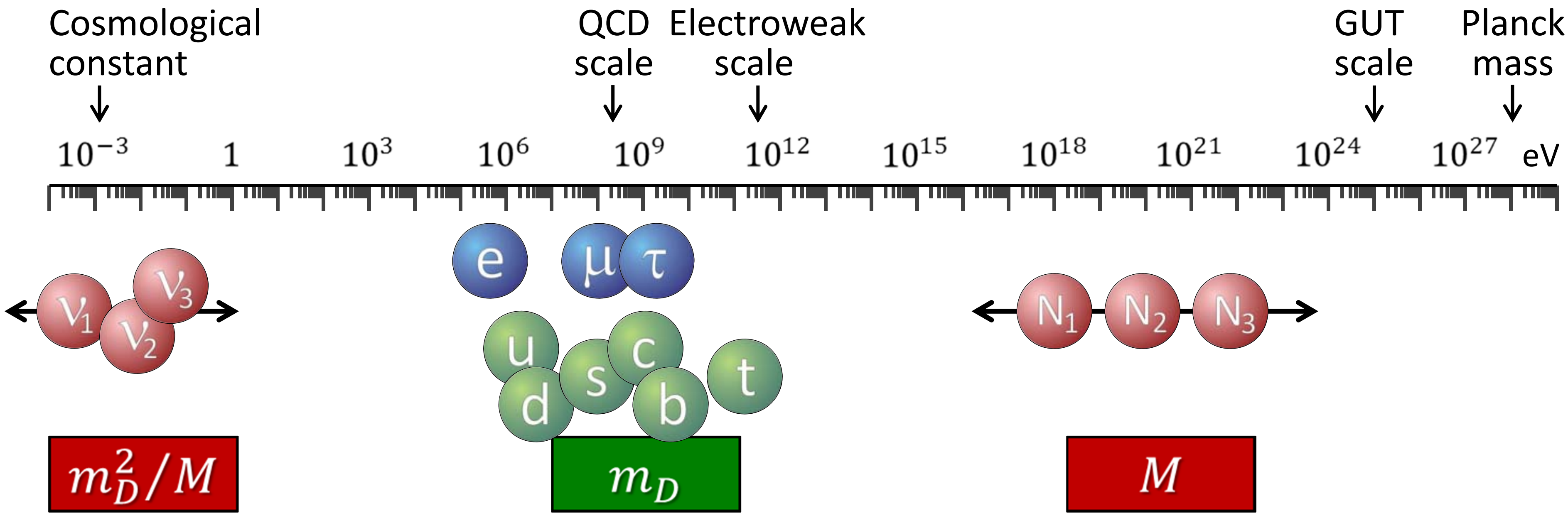
Best limit from ^{76}Ge

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

EXO Limits on Double Beta Decay (Neutrino 2012)



See-Saw Model for Neutrino Masses



Mass matrix for one family of ordinary and heavy r.h. neutrinos

$$(\overline{\nu}_L, \overline{N}_R)\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix}\begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

Diagonalization

$$(\overline{\nu}_L, \overline{N}_R)\begin{pmatrix} m_D^2/M & 0 \\ 0 & M \end{pmatrix}\begin{pmatrix} \nu_L \\ N_R \end{pmatrix}$$

One light and one heavy Majorana neutrino

BARYOGENESIS WITHOUT GRAND UNIFICATION

M. FUKUGITA

Research Institute for Fundamental Physics, Kyoto University, Kyoto 606, Japan

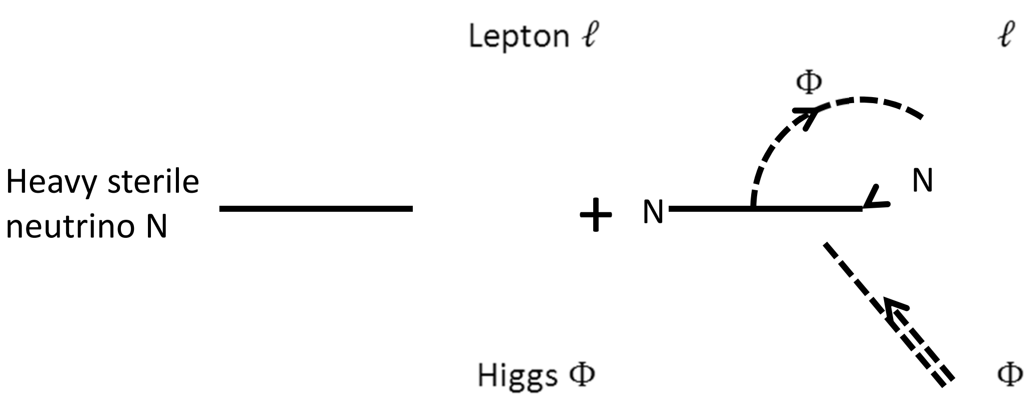
and

T. YANAGIDA

Institute of Physics, College of General Education, Tohoku University, Sendai 980, Japan and Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg, Fed. Rep. Germany

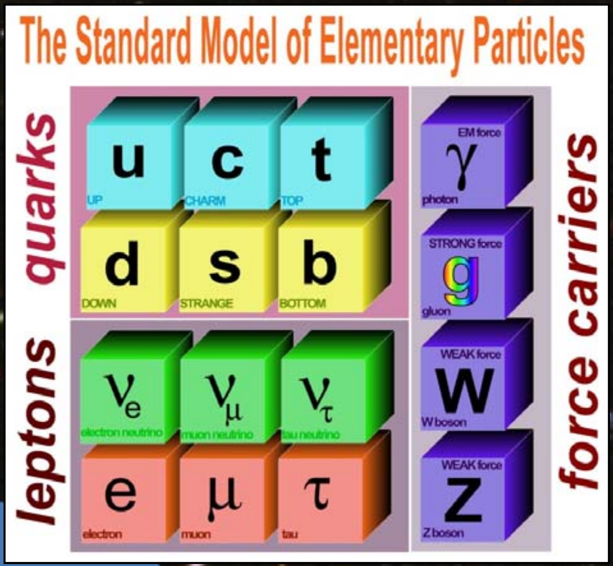
Received 8 March 1986

A mechanism is pointed out to generate cosmological baryon number excess without resorting to grand unified theories. The lepton number excess originating from Majorana mass terms may transform into the baryon number excess through the unsuppressed baryon number violation of electroweak processes at high temperatures.

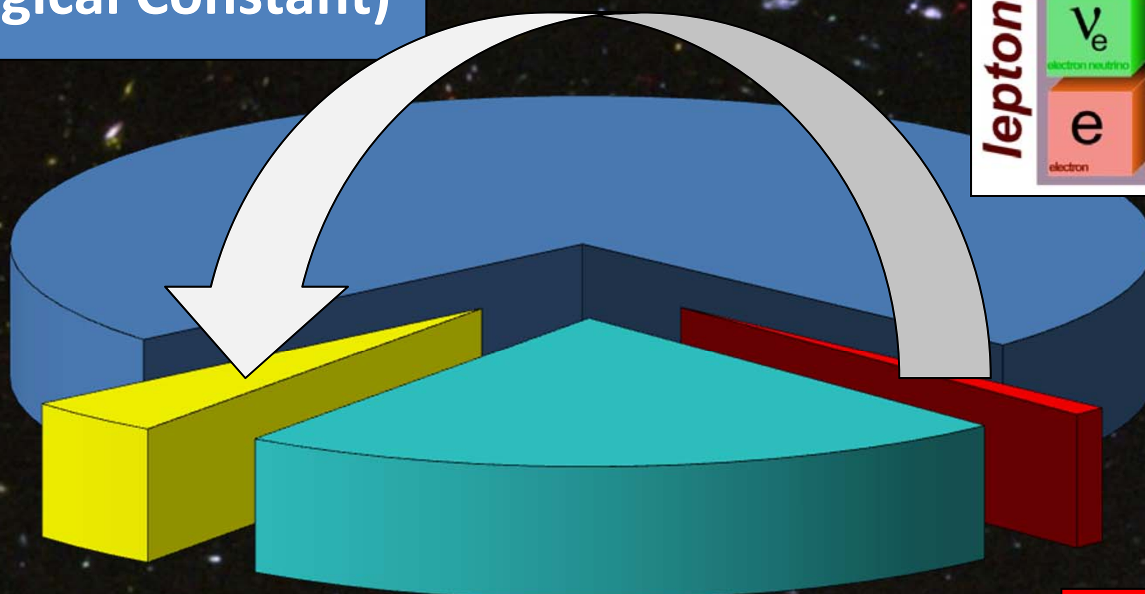


CP-violating decays of heavy sterile neutrinos by interference of tree-level with one-loop diagram

Baryogenesis by Leptogenesis?



Dark Energy 73%
(Cosmological Constant)



Ordinary Matter 4%
(of this only about
10% luminous)

Dark Matter
23%

Neutrinos
0.1–2%

Applied Antineutrino Physics - 13, 14 December 2007
APC, Paris - France

Topics: Geophysics, Non-Proliferation, Reactor Monitoring

AAP 2007

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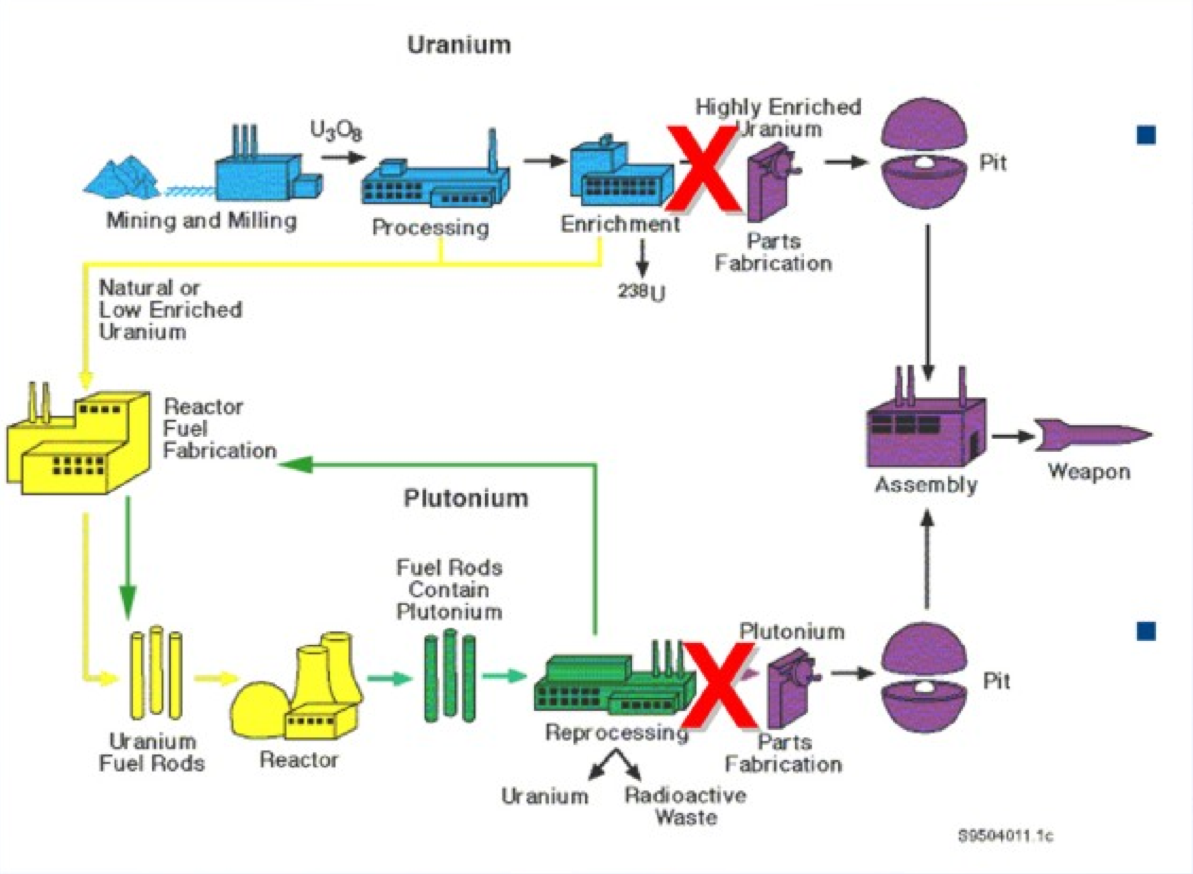
IAEA Monitors Fissile Material in Civil Nuclear Cycles

(under the NPT and Negotiated Safeguards Agreements)



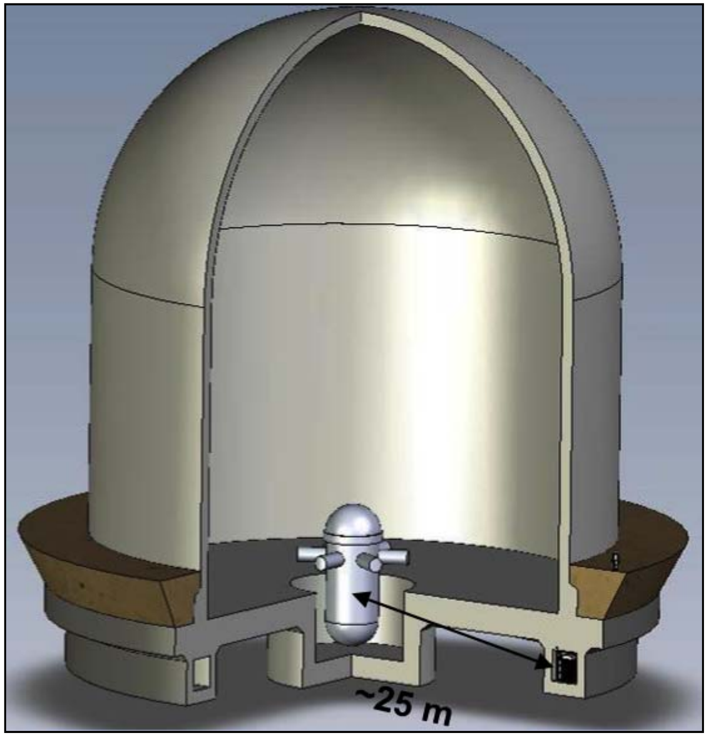
- Current reactor safeguards involve:
  - **Checking Input and Output Declarations**
  - **Item Accountancy**
  - **Containment and Surveillance**
- *No direct Pu production or power measurement made*

- While effective, these techniques consume an increasingly scarce resource – *inspectors*

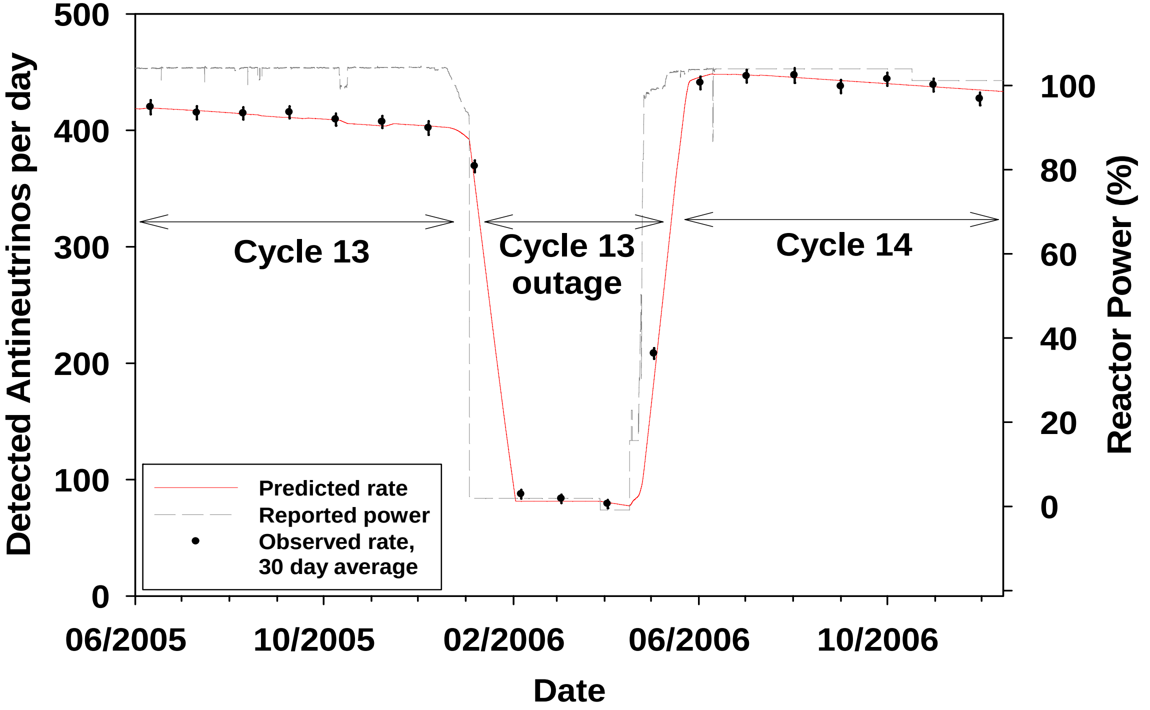
Antineutrino detectors could provide continuous, non-intrusive, unattended *measurements* suitable for IAEA reactor safeguards regimes

Neutrino Monitoring of Nuclear Reactors

San Onofre Nuclear Reactor (California)



Neutrino measurements with SONGS1 detector (1m^3 Scintillator)



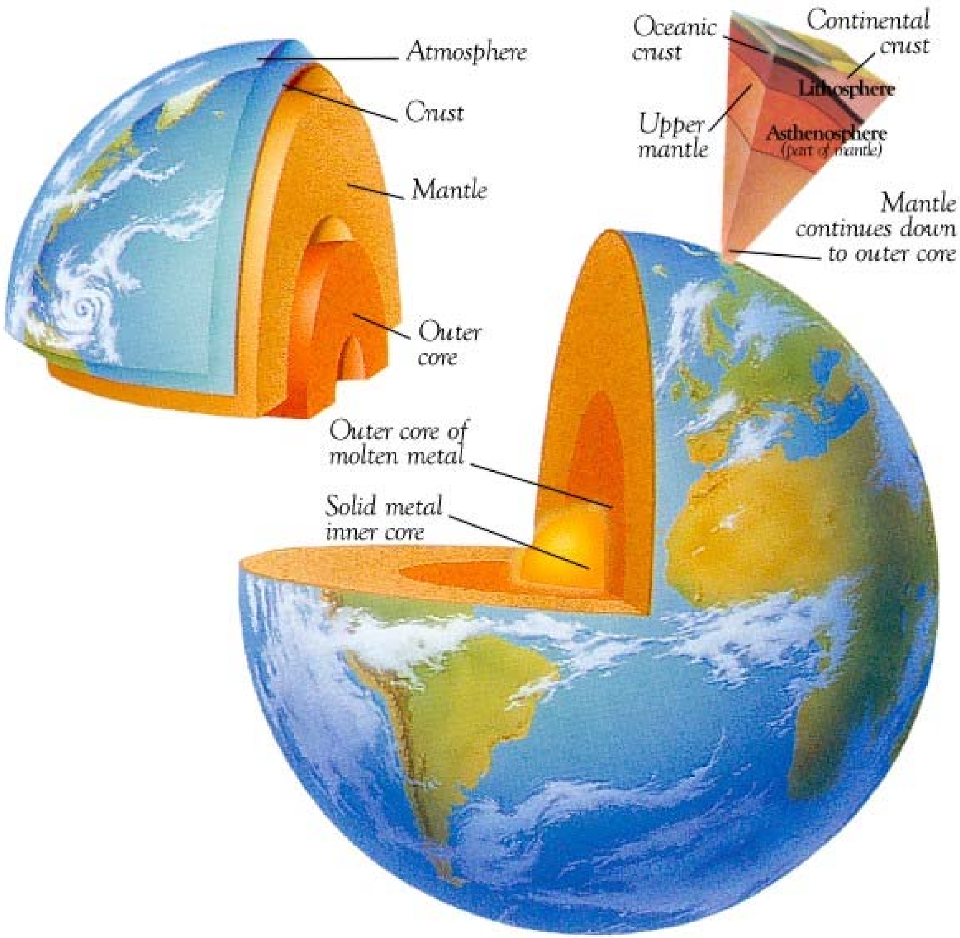
- 3.4 GW thermal power
- Produces $\sim 10^{21}\ \overline{\nu}_e\ s^{-1}$
- 3800 neutrino reactions/day in 1 m^3 liquid scintillator

- Relatively small detectors can measure nuclear activity without intrusion
- Of interest for monitoring by International Atomic Energy Agency (IAEA)

Geo Neutrinos: What is it all about?

We know surprisingly little about the Earth's interior

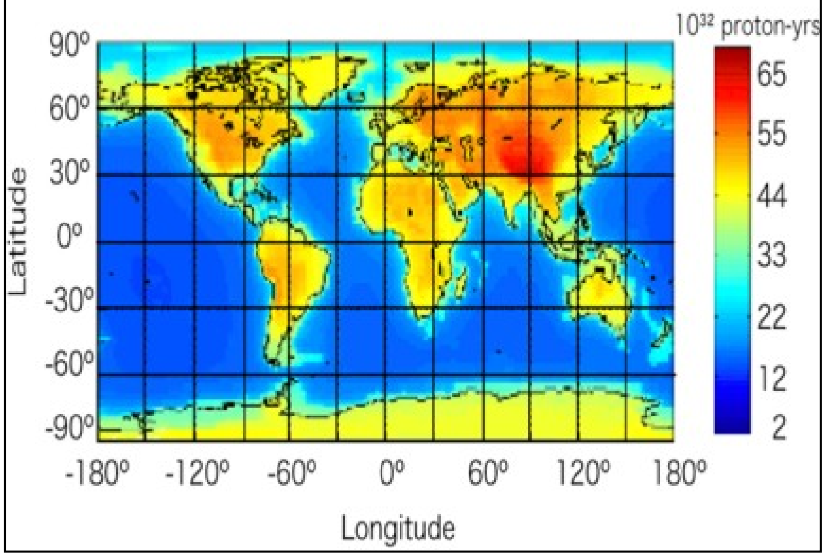
- Deepest drill hole ~ 12 km
- Samples of crust for chemical analysis available (e.g. vulcanoes)
- Reconstructed density profile from seismic measurements
- Heat flux from measured temperature gradient 30–44 TW (Expectation from canonical BSE model ~ 19 TW from crust and mantle, nothing from core)



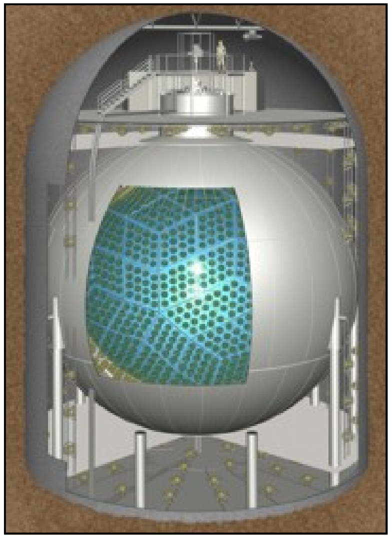
- Neutrinos escape unscathed
- Carry information about chemical composition, radioactive energy production or even a hypothetical reactor in the Earth's core

Geo Neutrinos

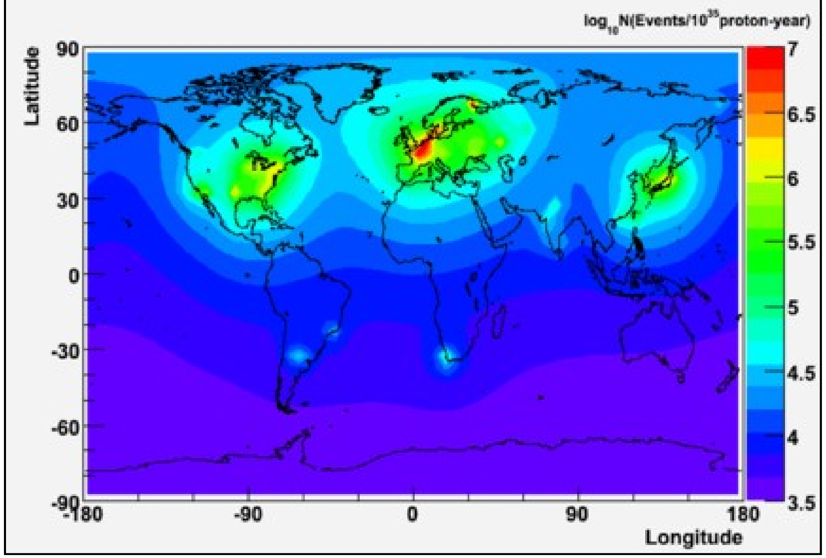
Expected Geoneutrino Flux

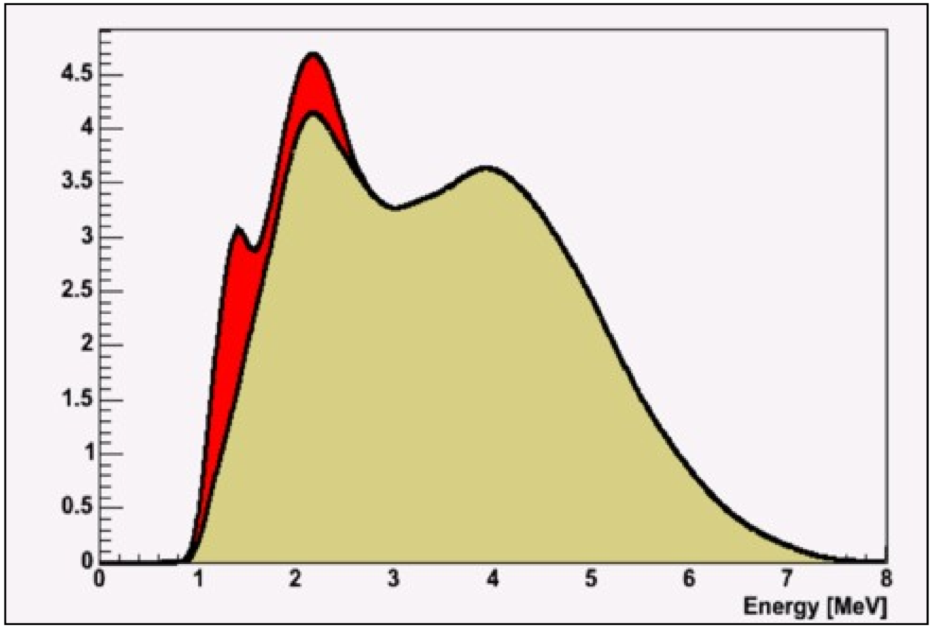


KamLAND Scintillator-Detector (1000 t)



Reactor Background

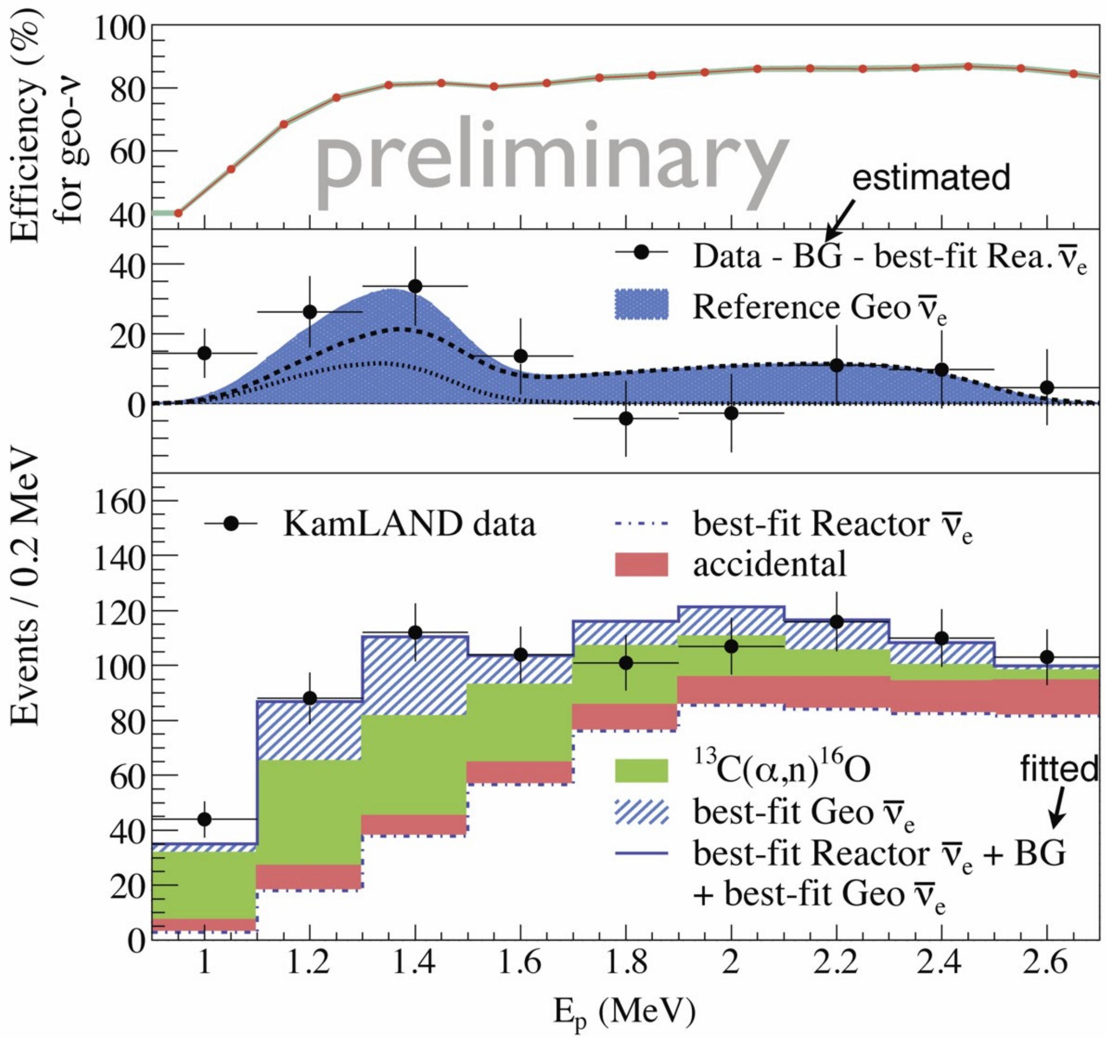




Latest KamLAND Measurements of Geo Neutrinos

K. Inoue at Neutrino 2010

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



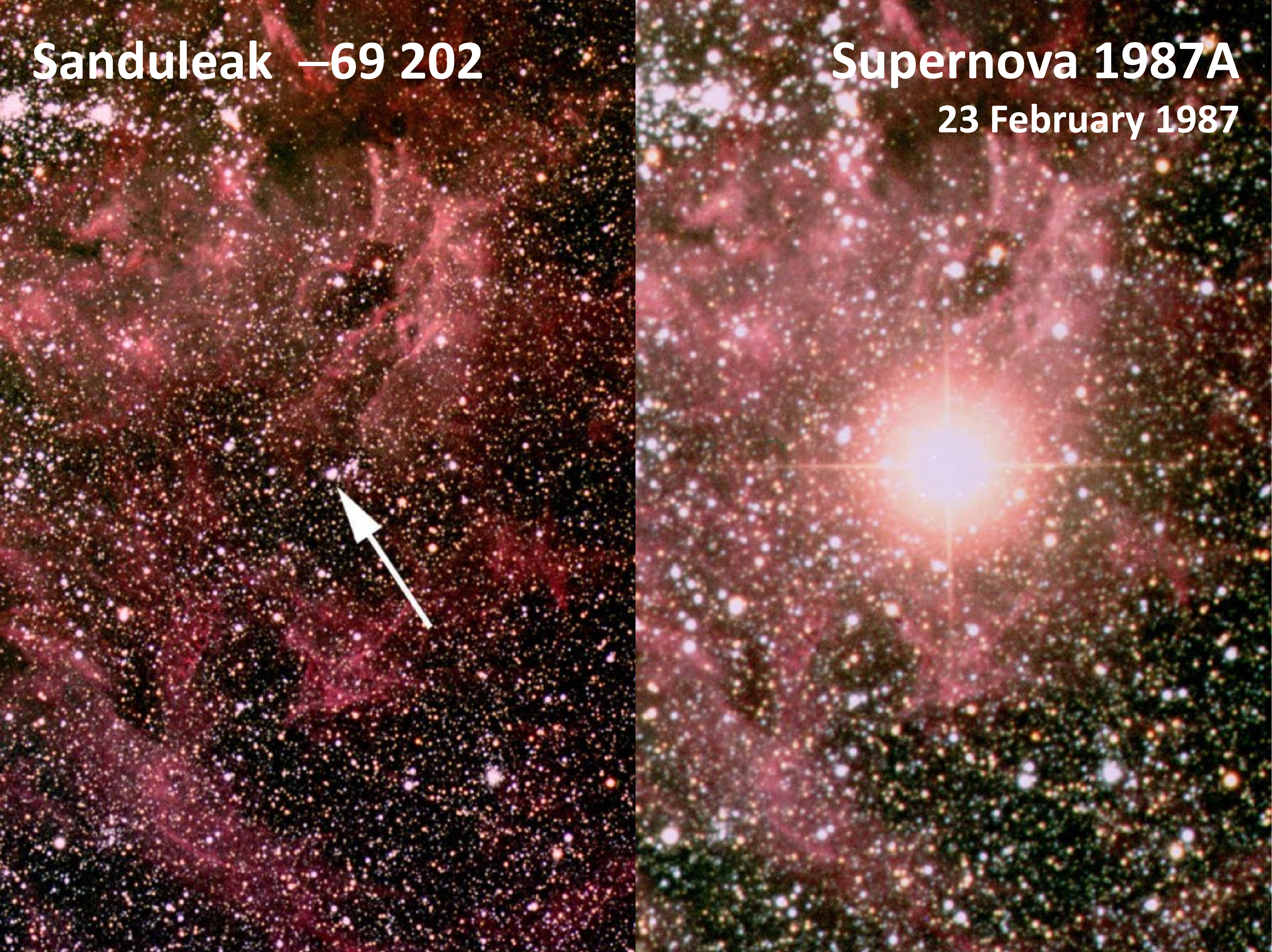
841 candidates in 0.9-2.6 MeV

BG summary

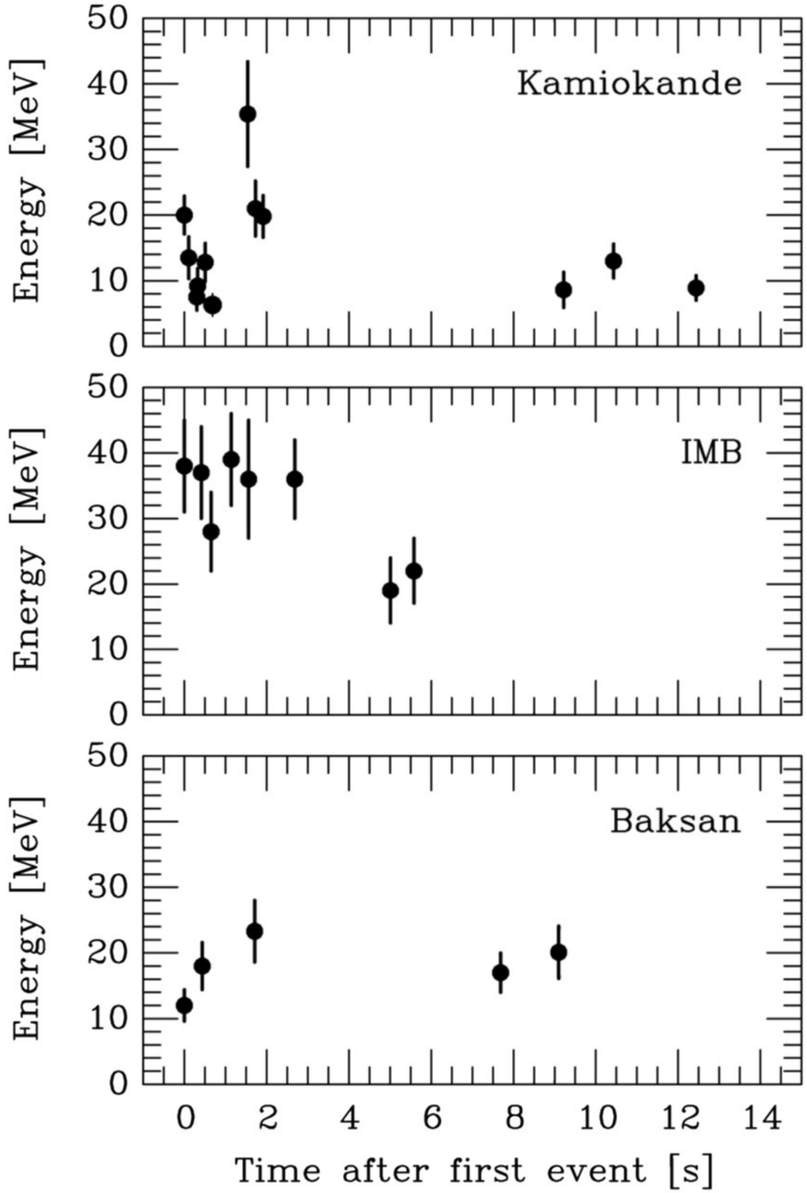
reactor $\bar{\nu}_e$	484.7±26.5
$^{13}C(\alpha,n)^{16}O$	165.3±18.2
accidental	77.4±0.1
^{9}Li	2.0±0.1
atm.ν+fast n	<2.8
Total	729.4±32.3

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

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


Sanduleak –69 202
Supernova 1987A
23 February 1987

Neutrino Signal of Supernova 1987A



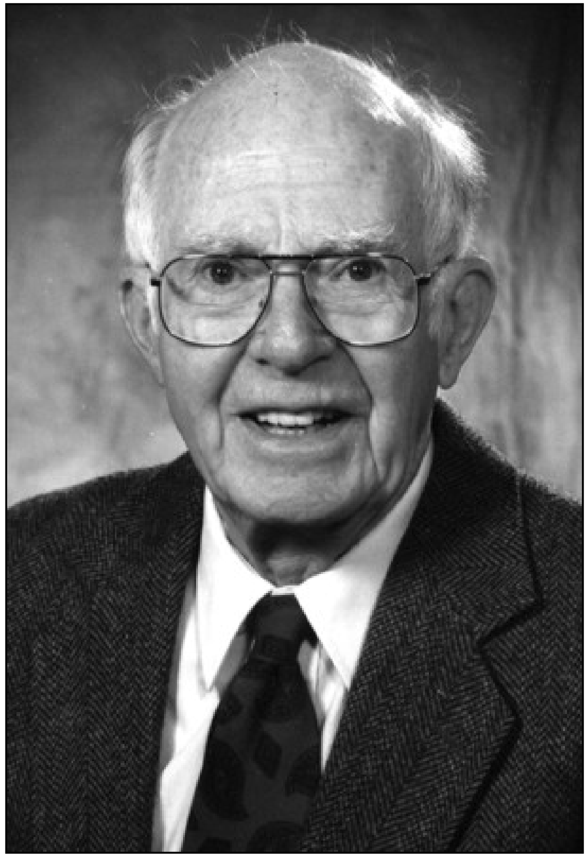
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty $\pm$1 min

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

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

Within clock uncertainties, all signals are contemporaneous

2002 Physics Nobel Prize for Neutrino Astronomy



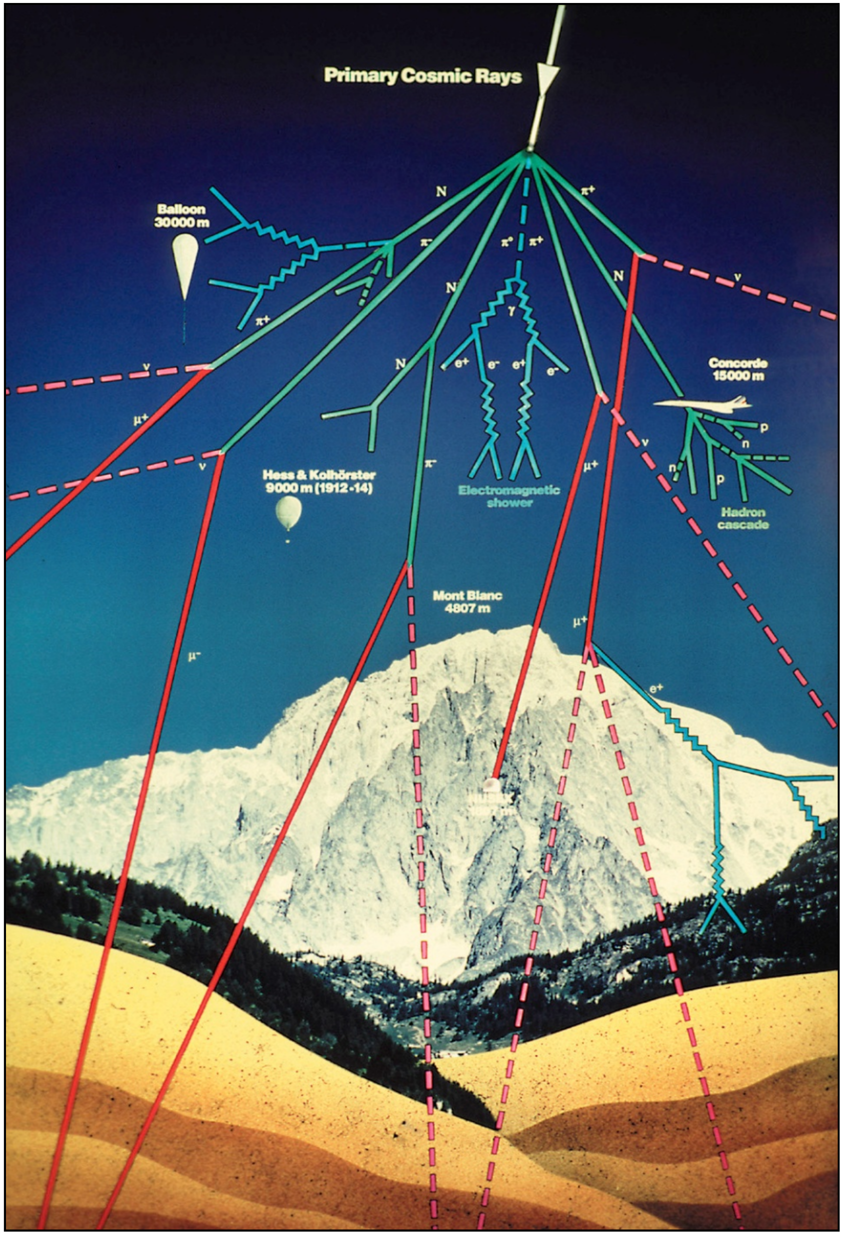
Ray Davis Jr.
(1914–2006)

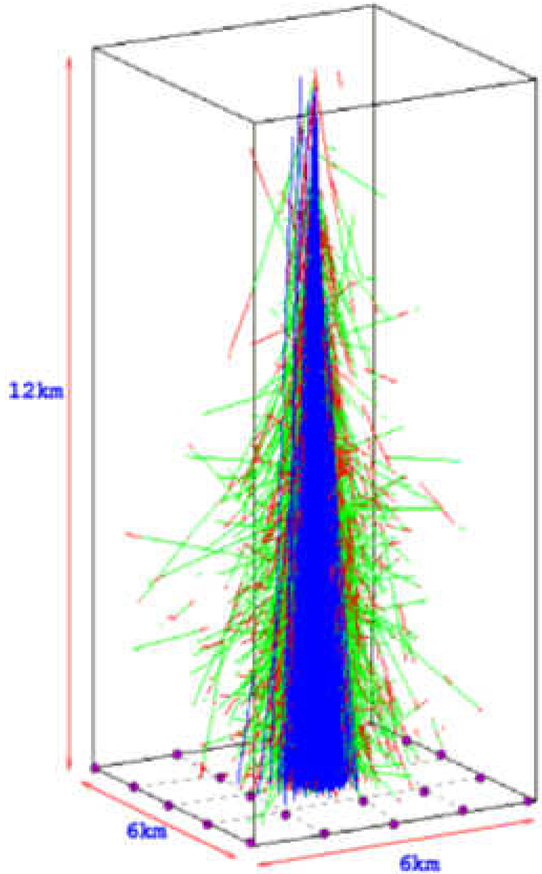
Masatoshi Koshiba
(*1926)

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

More about supernova neutrinos tomorrow …

Cosmic Rays

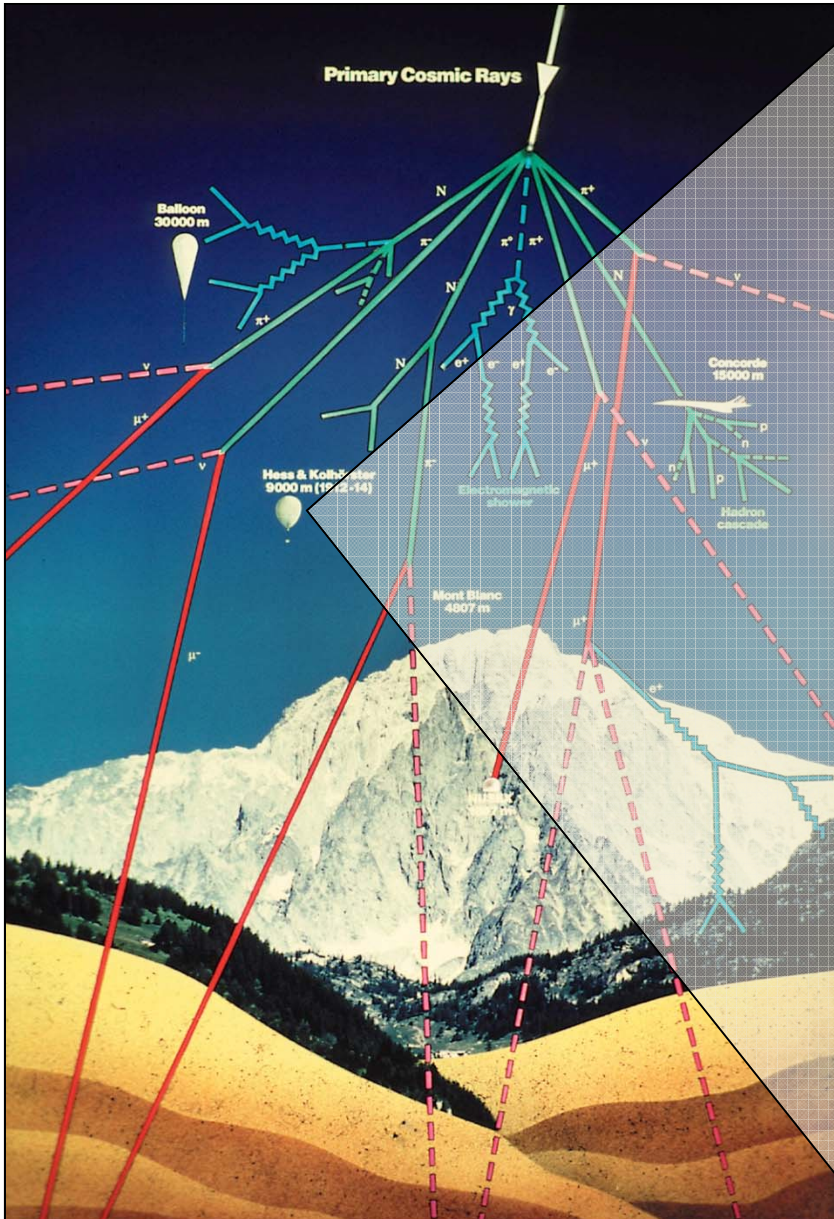


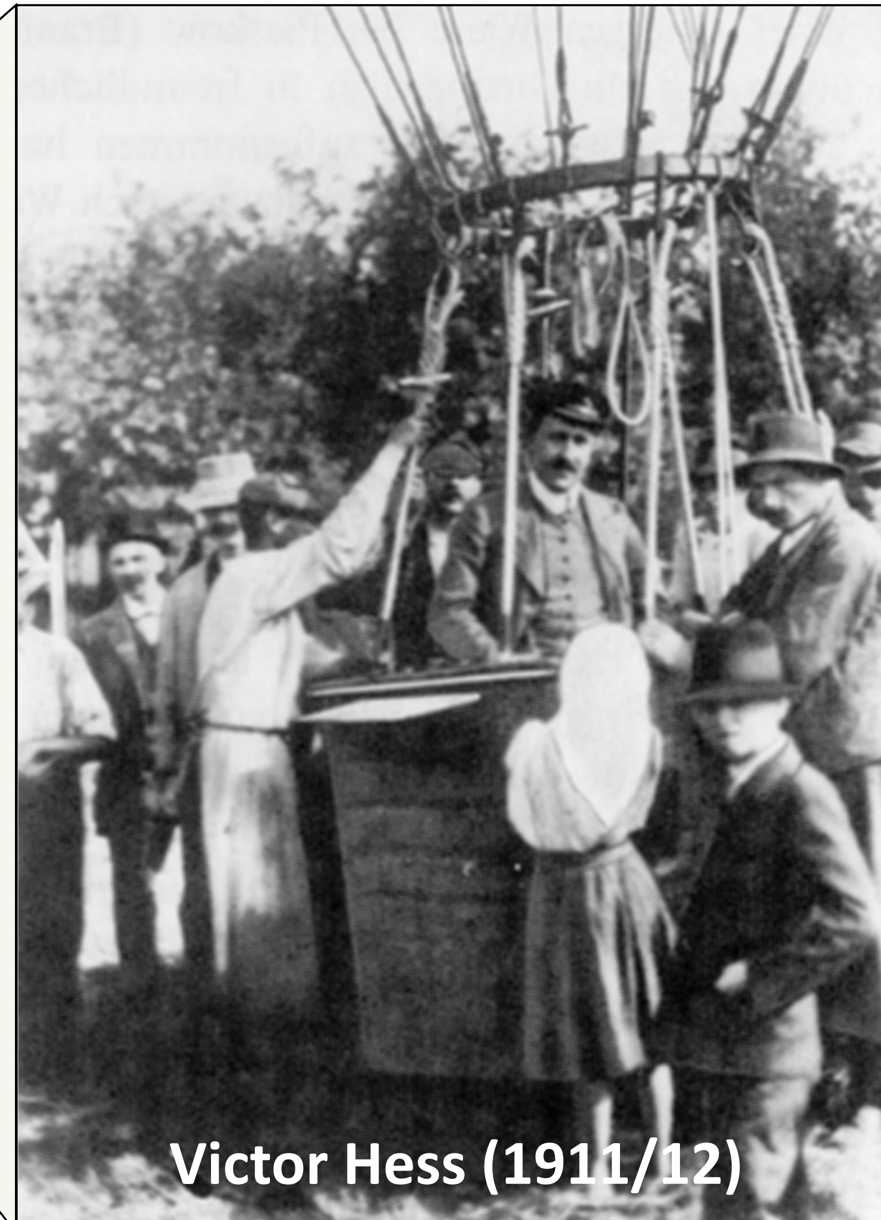


Air Shower:

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

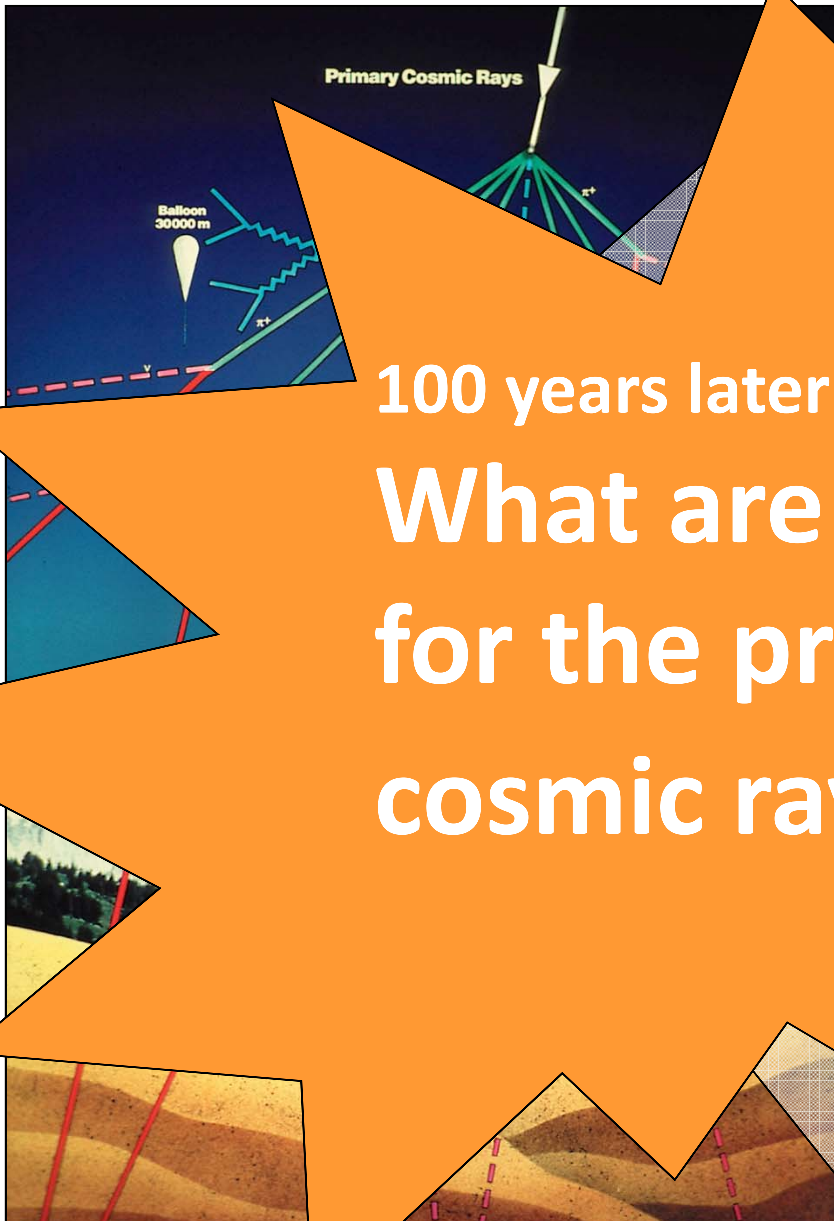
Cosmic Rays





Victor Hess (1911/12)

Cosmic Rays

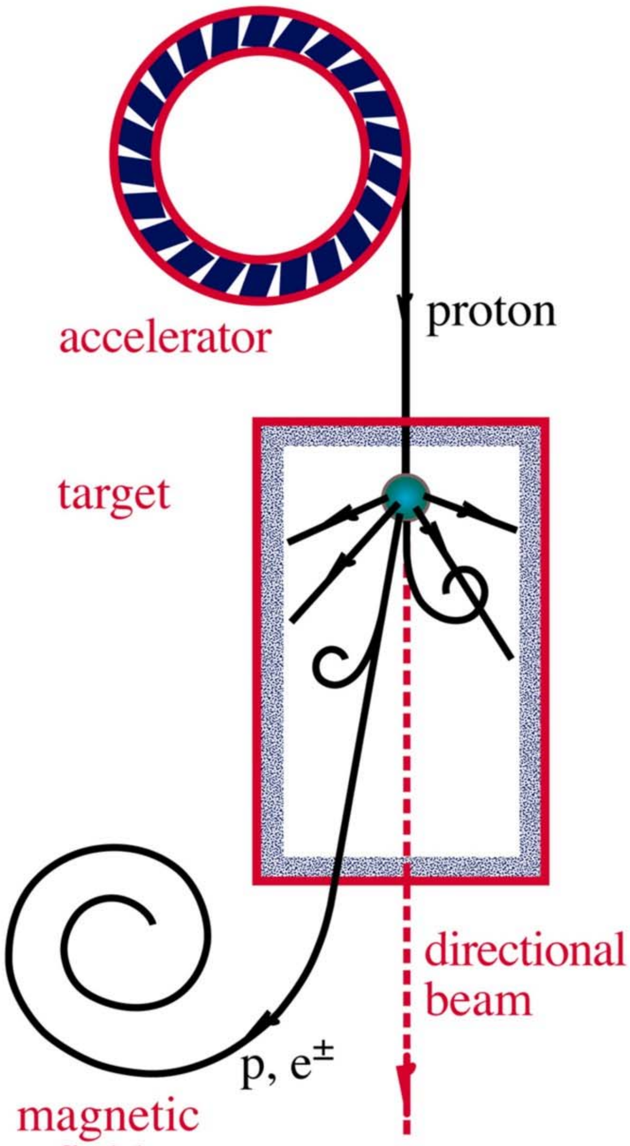


100 years later we are still asking

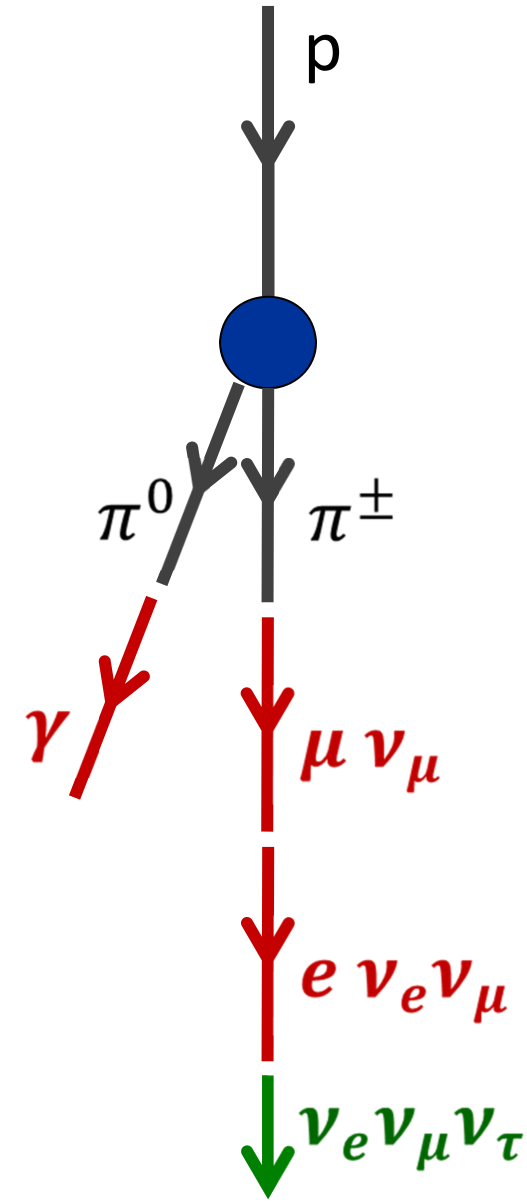
What are the sources for the primary cosmic rays?

Victor Hess (1911/12)

Neutrino Beams: Heaven and Earth



F. Halzen (2002)

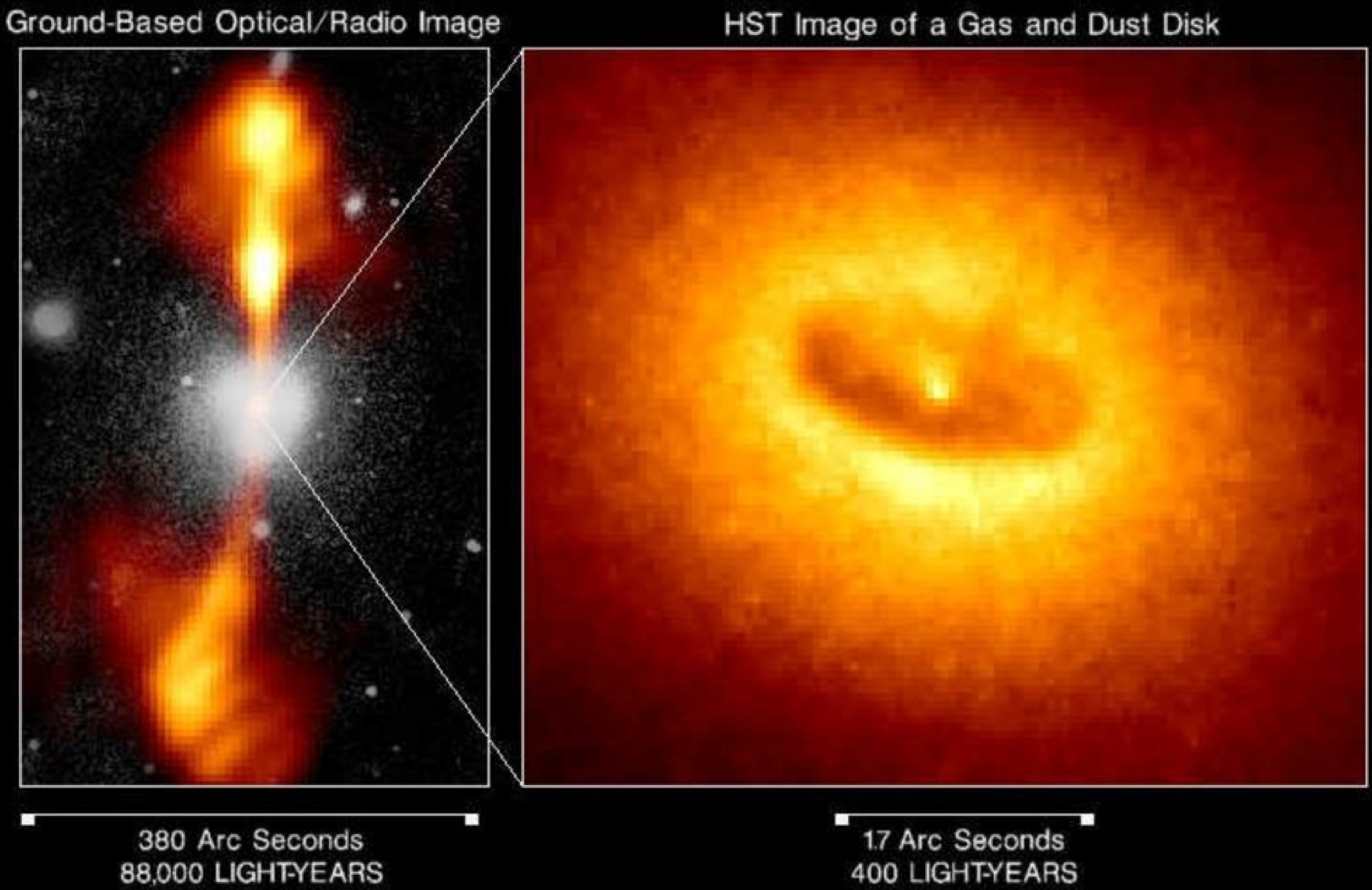


Target:
Protons or Photons

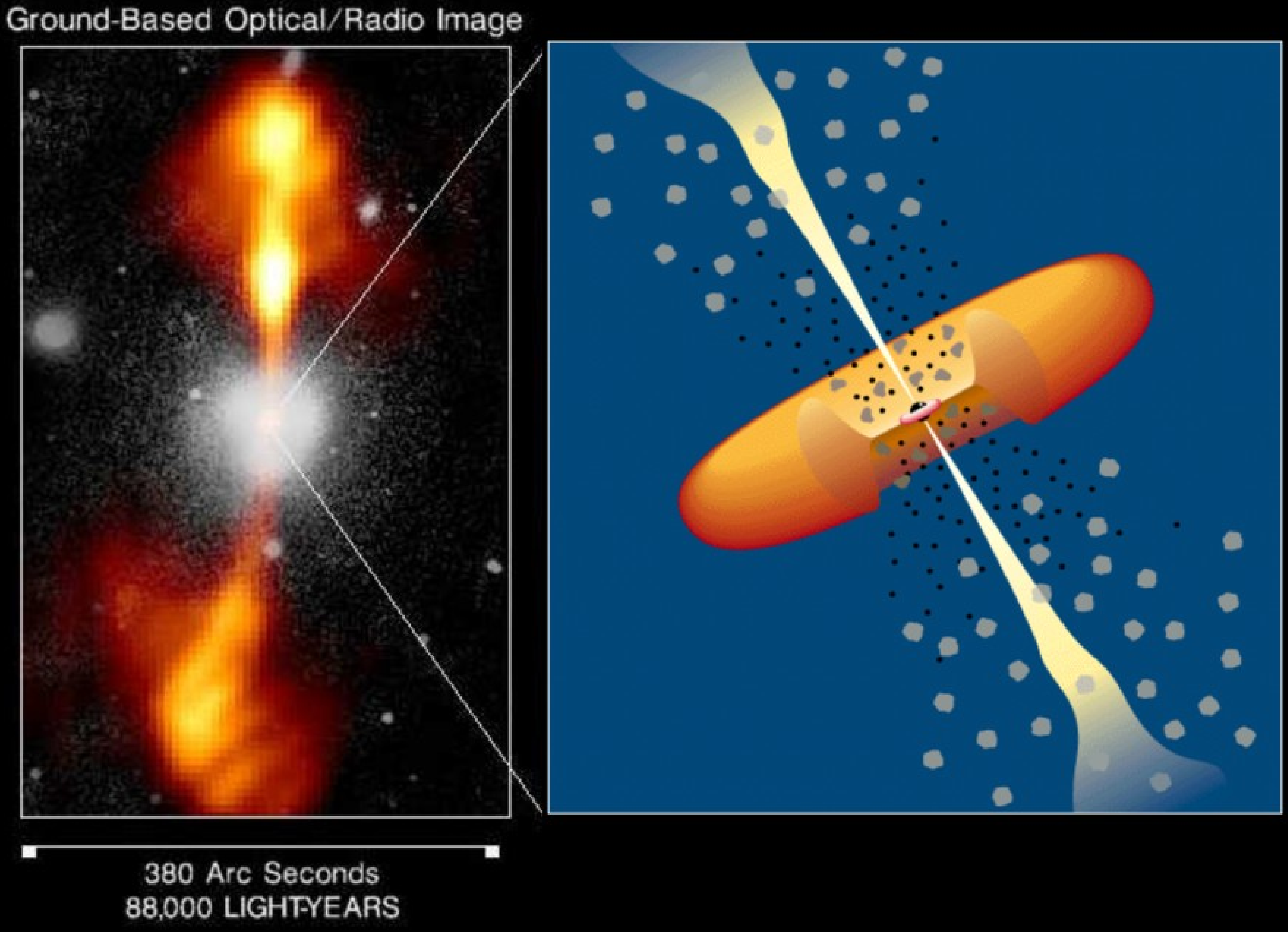
Approx. equal fluxes of photons & neutrinos

Equal neutrino fluxes in all flavors due to oscillations

Nucleus of the Active Galaxy NGC 4261

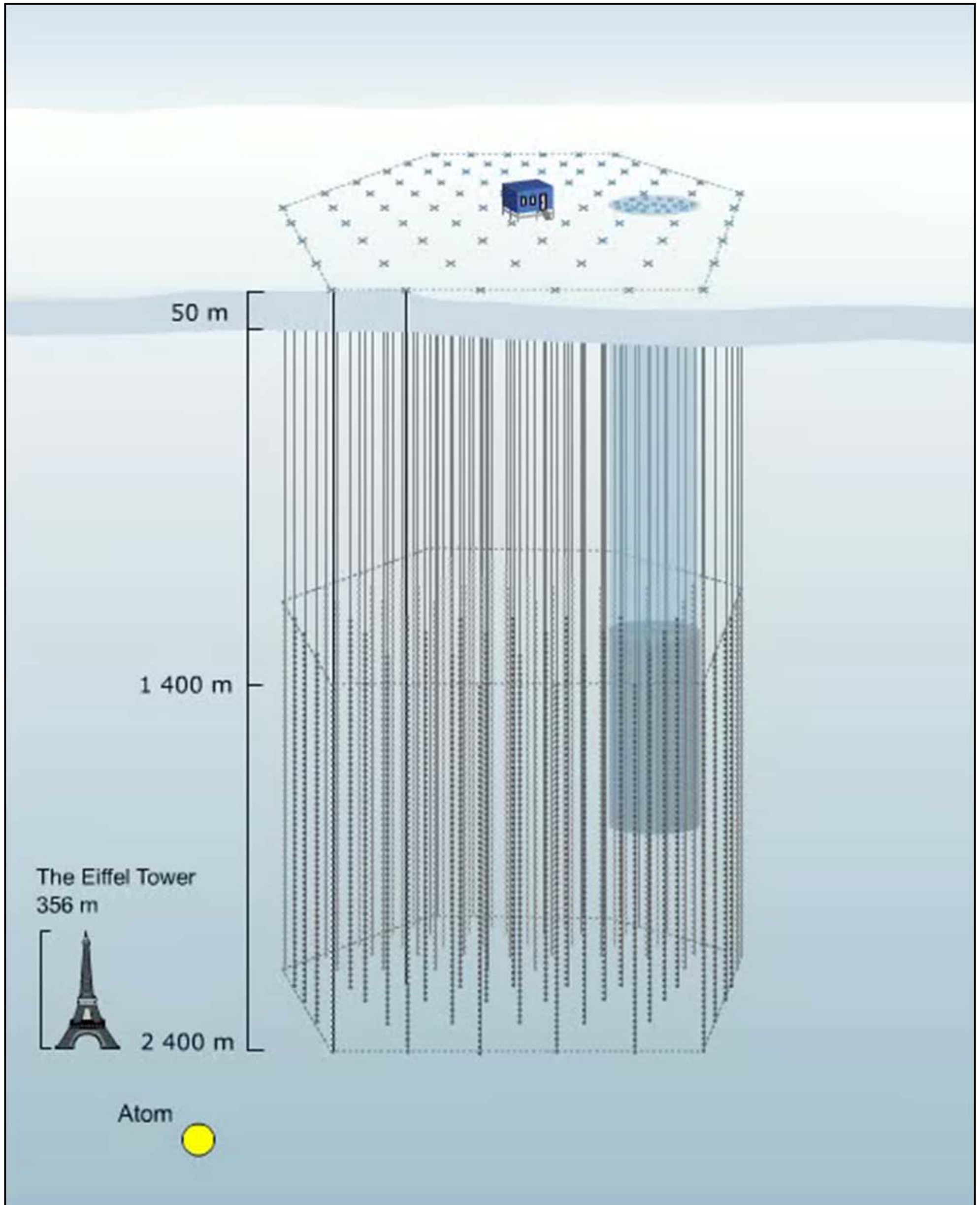


Nucleus of the Active Galaxy NGC 4261

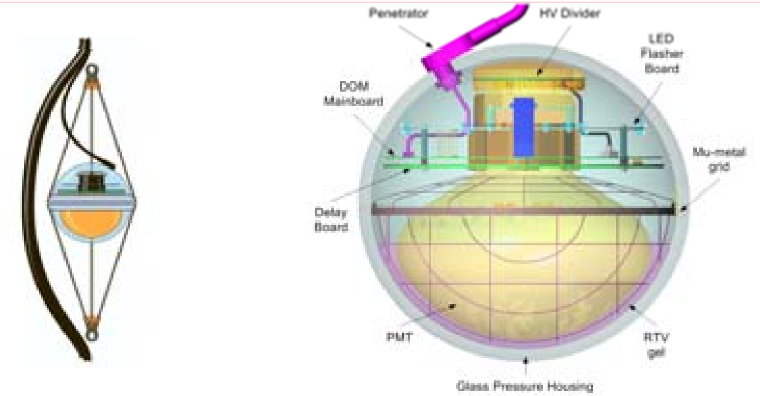


Scott Amundsen Base at the South Pole

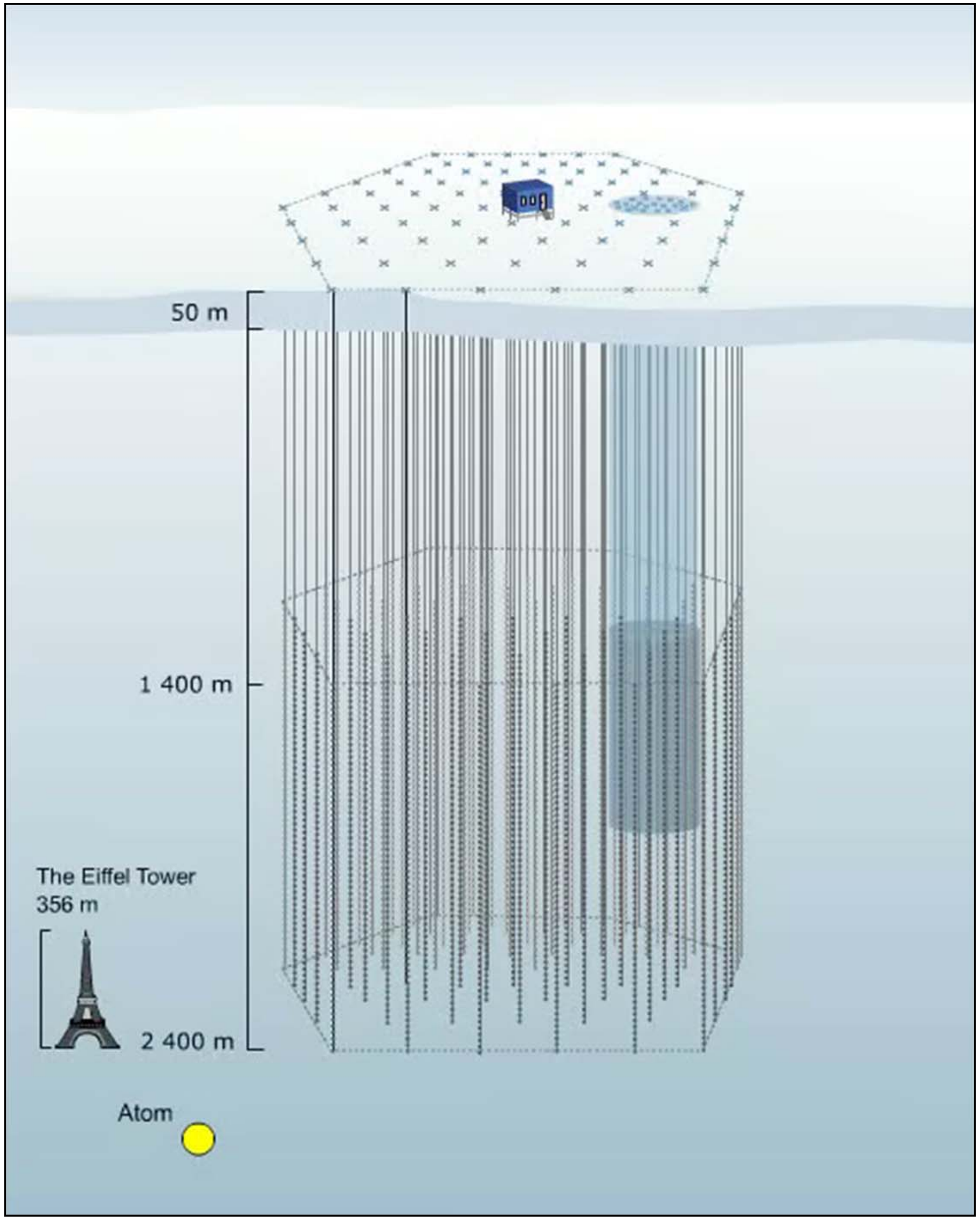
IceCube Neutrino Telescope at the South Pole



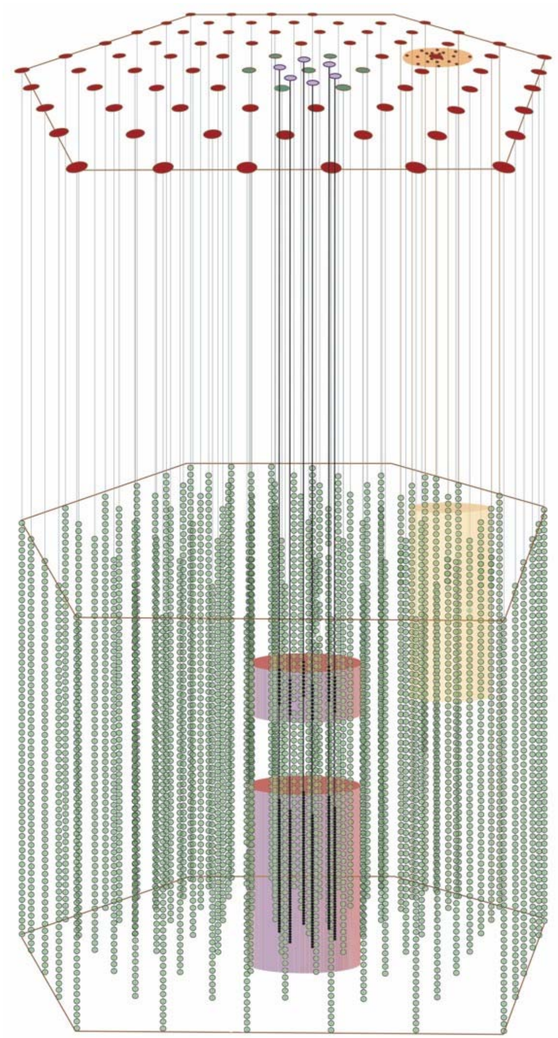
Instrumentation of 1 km^3 antarctic ice with ~ 5000 photo multipliers completed December 2010



IceCube Neutrino Telescope at the South Pole

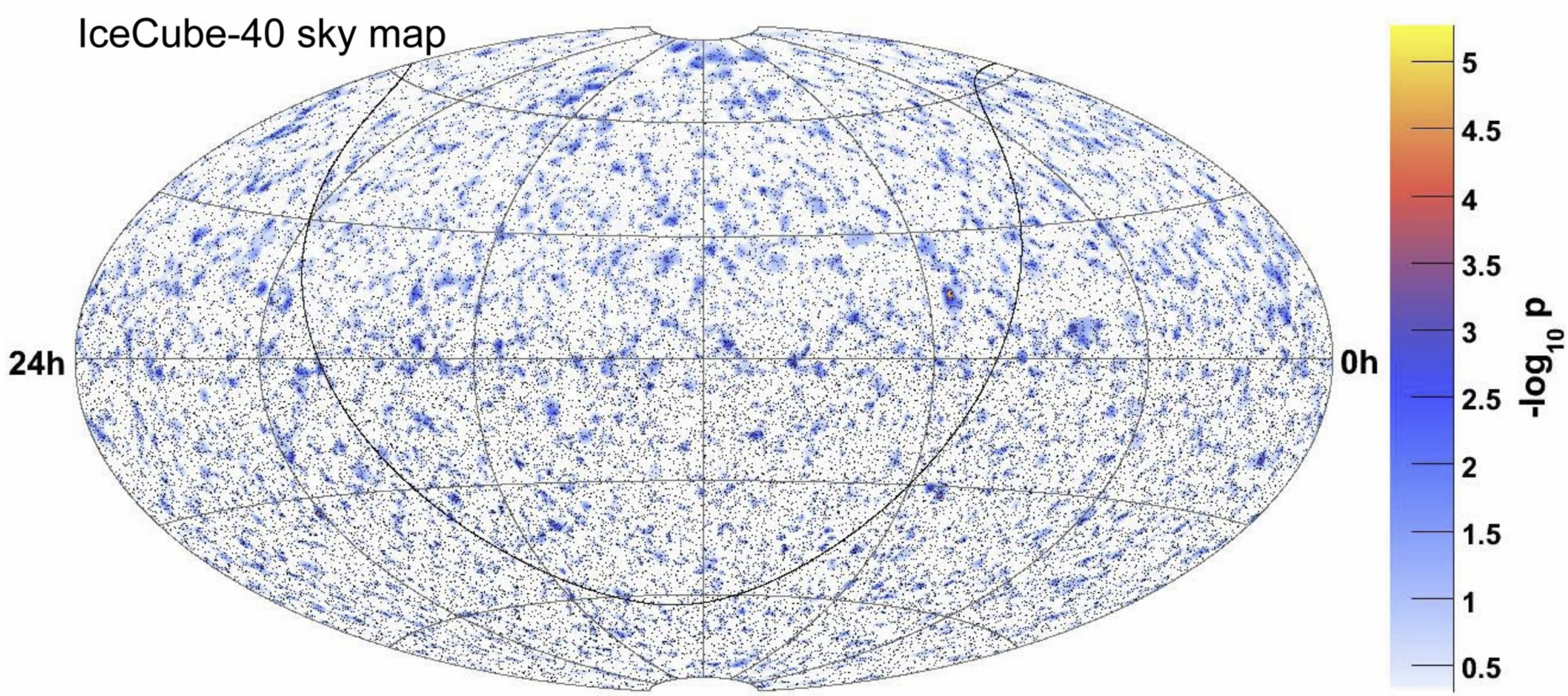


Deep Core installed 2010
Search for dark matter



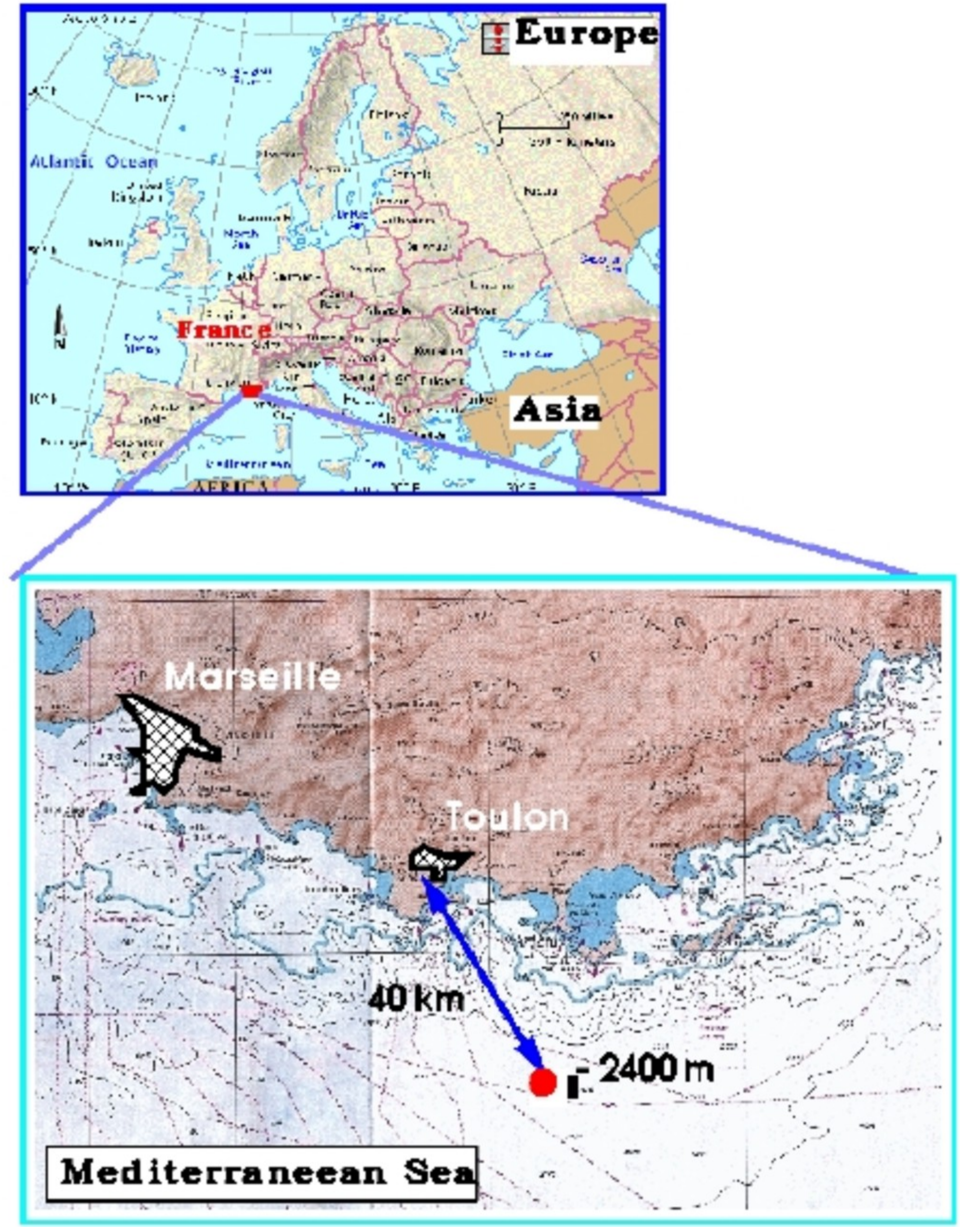
IceCube Neutrino Sky

Full-sky map, based on 40 strings

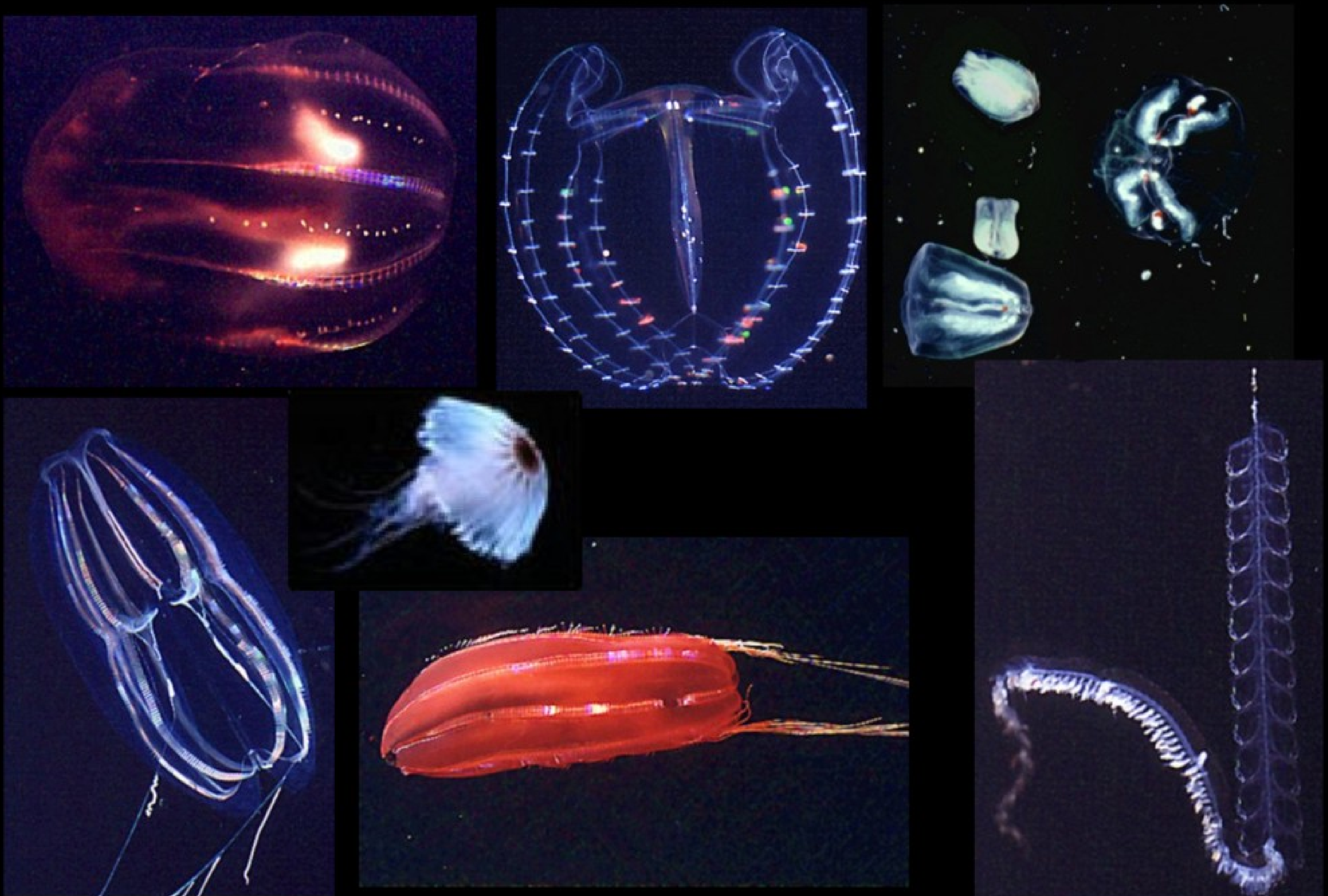


IceCube Collaboration, arXiv:1012.2137 and Gaisser at Neutel 2011

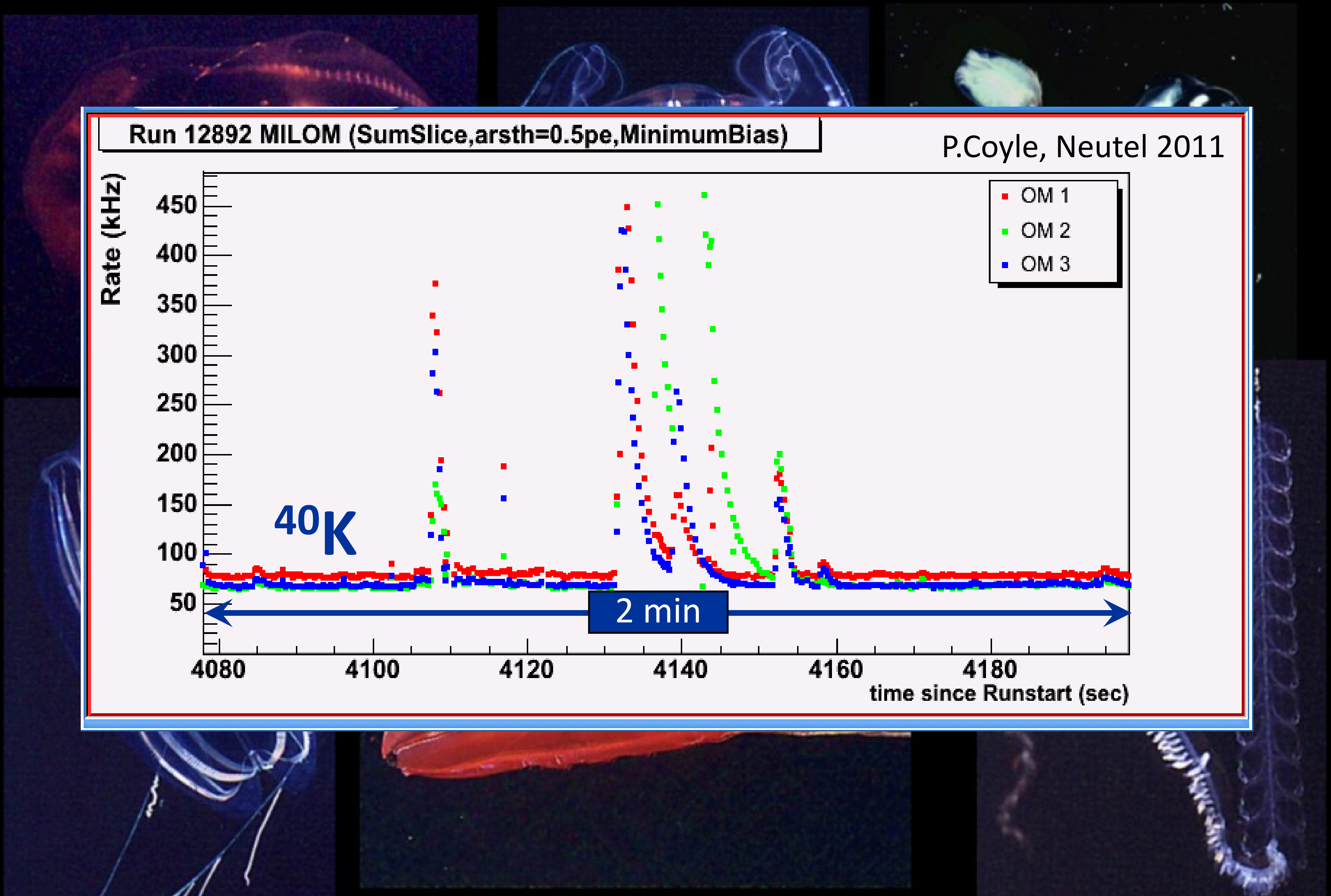
ANTARES – Neutrino Telescope in the Mediterranean



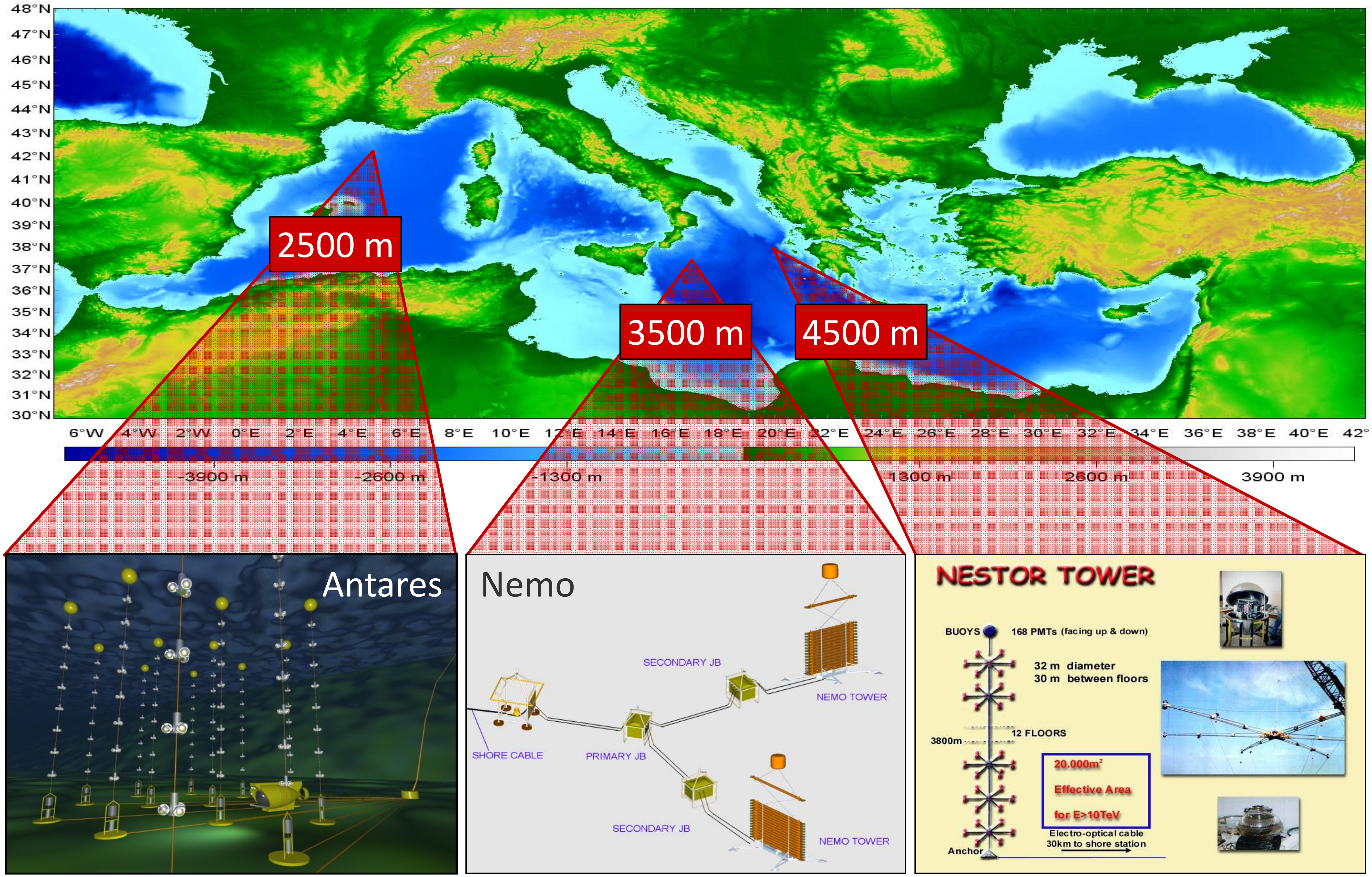
Luminescent Ceatures of the Deep Sea



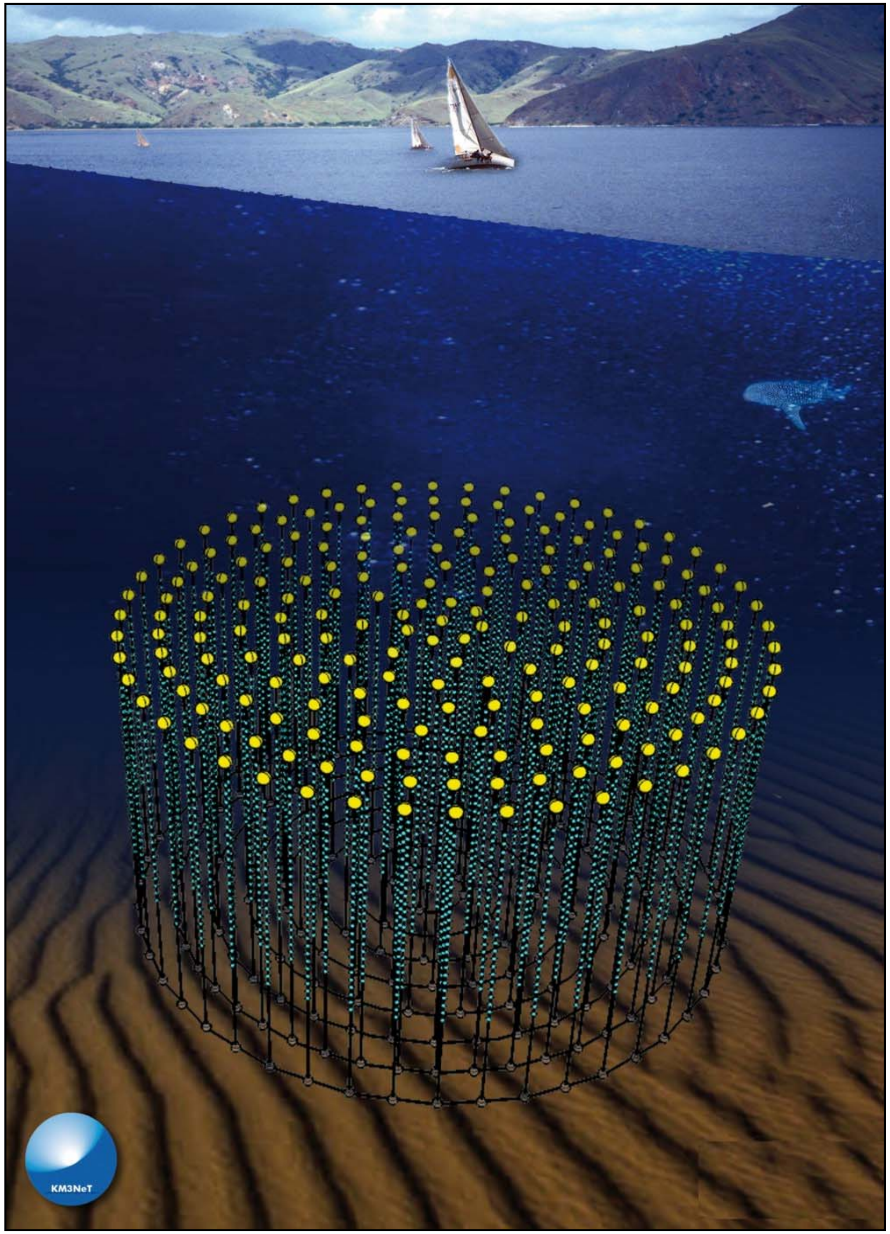
Luminescent Ceatures of the Deep Sea

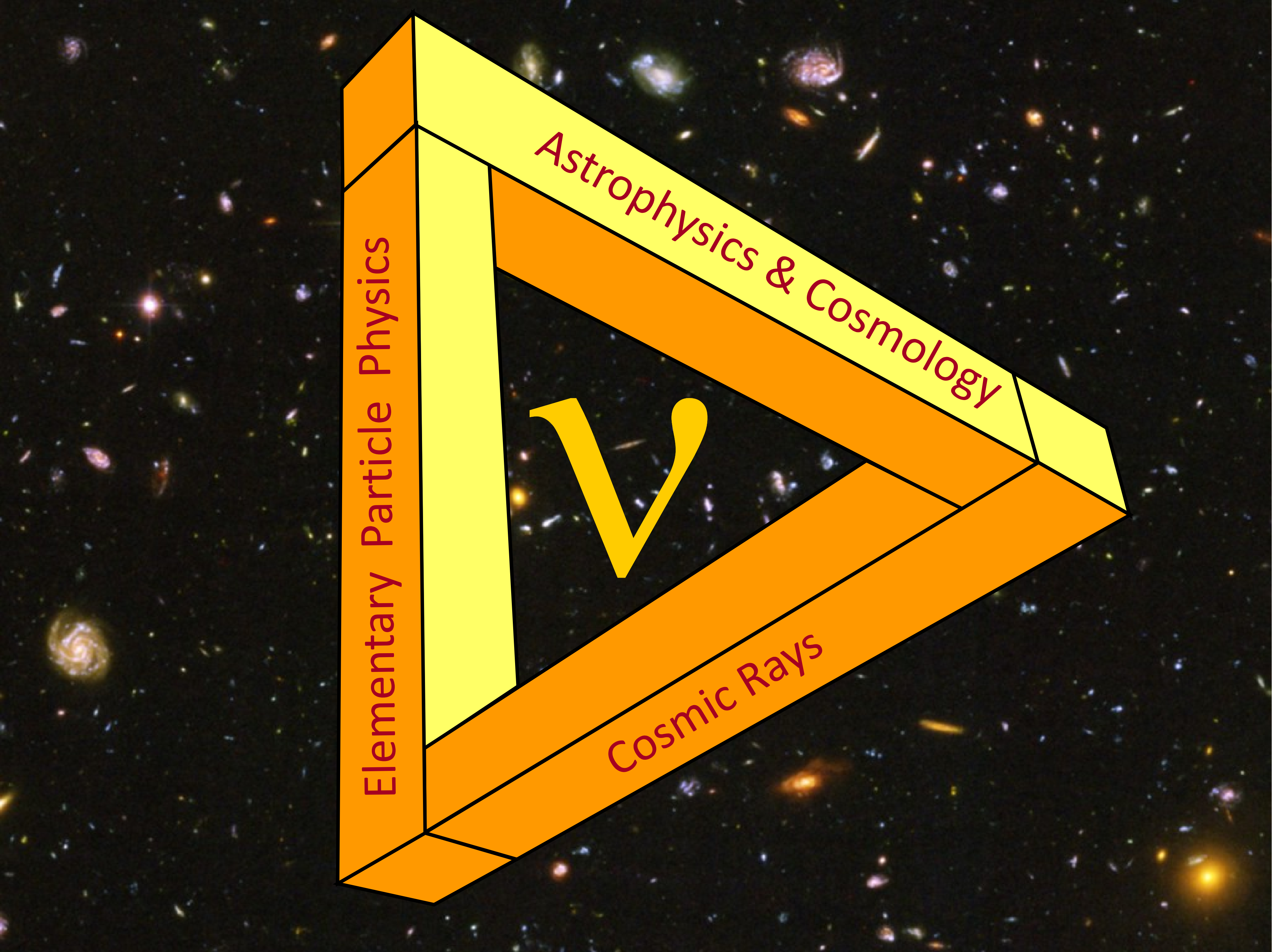


Three Mediterranean Pilot Projects



Towards a km^3 Detector in the Mediterranean

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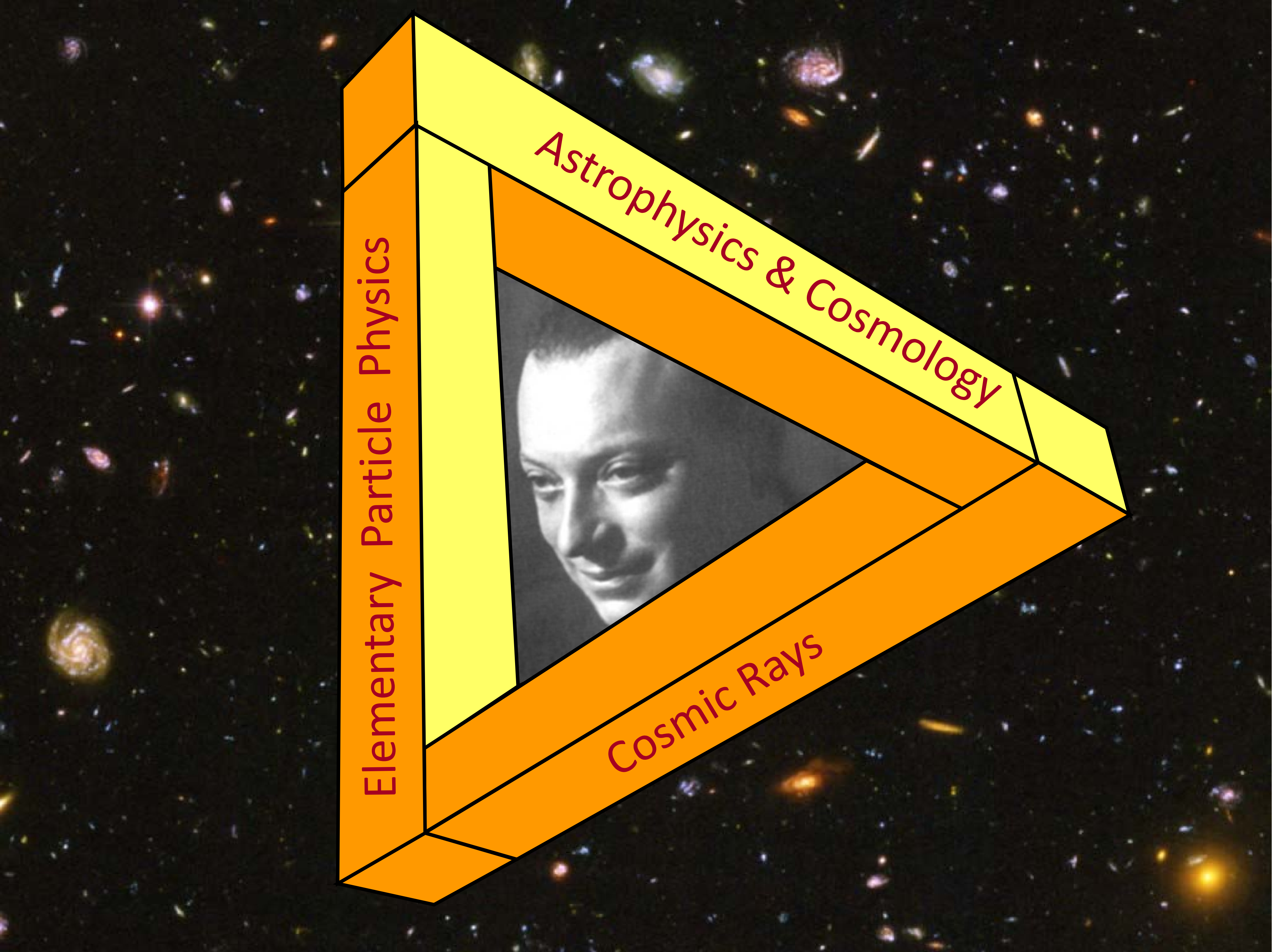
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