Detection techniques
Lecture 2: neutrinos

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Detectors for neutrinos

- Physics goals:
  - Understanding of astrophysical objects (ν-sources)
  - Learning about neutrino particle properties

  → Many detectors are multi-purpose

- Neutrinos have low cross sections (weak interaction)

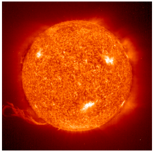
  → Large detector masses required

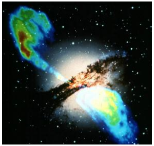
- Main detection principle:

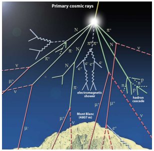
  Cherenkov effect or scintillation in liquid media are used

Neutrino-sources: natural or man-made


Supernova

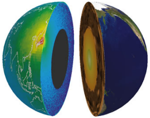

The Sun


Galaxies



Atmosphere


Radioactivity


The Earth


Reactors


Accelerators

Neutrino spectra

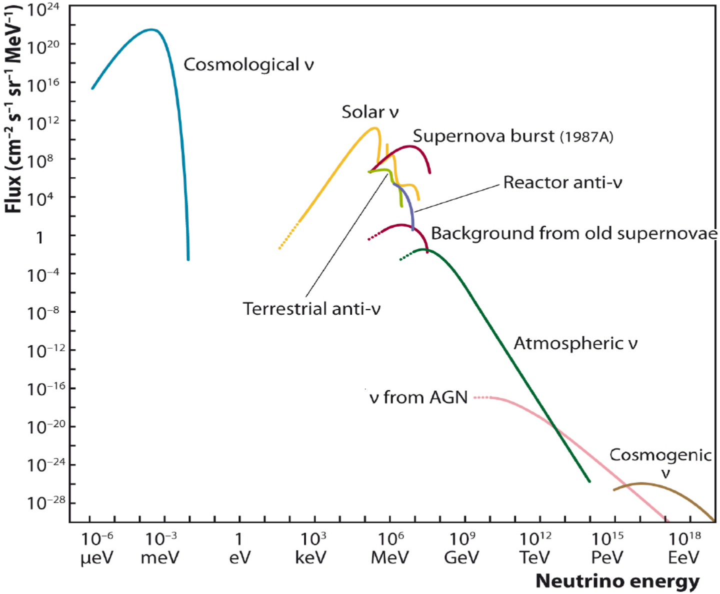


Figure from IceCube homepage

Cherenkov effect

- Charged particles which move faster than the speed of light in the medium $v > \frac{c}{n}$ emit Cherenkov light
- Cherenkov angle: $\cos\theta = \frac{1}{\beta n}$
- Threshold for different particles: $E_{thr} = \frac{n}{\sqrt{n^2-1}} m_0 c^2$

  $\rightarrow$ In water ($n = 1.3$):

Particle	Threshold [MeV]
$e^{\pm}$	0.77
$\mu^{\pm}$	159
$\pi^{\pm}$	210

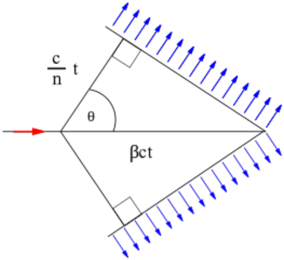
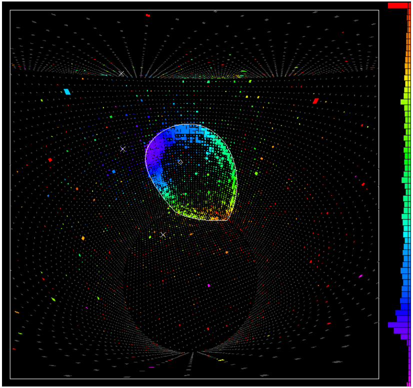
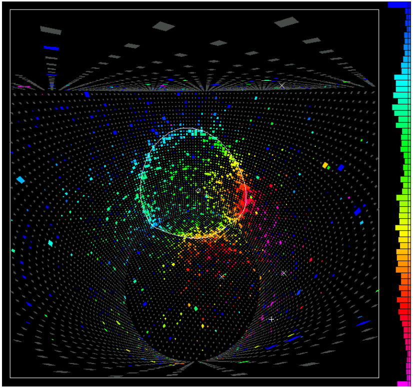


Figure from wikipedia

- Reconstruction of the particle direction

Cherenkov ring examples in Superkamiokande





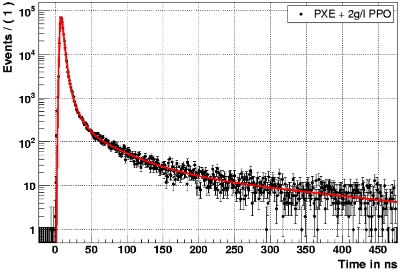
- 1 GeV muon
- 600 MeV electron

Scintillation

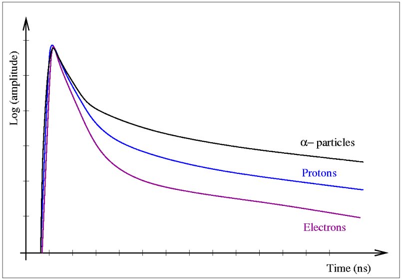
- Energy deposition by charged particles

→ excited states in the medium, relaxation producing photons

- Typically organic liquids with a solvent and a wavelength-shifter
  - Good linearity for most of the energies
  - High light yield → energy resolution
  - Pulse shape for particle discrimination

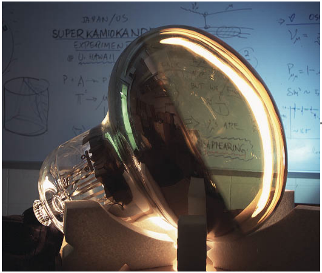


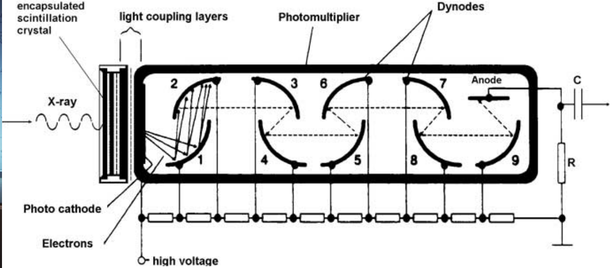
Measurement of an electron signal
Figure from Rev. Sci. Instrum. 80 (2009) 043301



Scheme of the pulse shape for different particles types

Photomultipliers

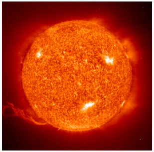




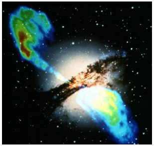
- Key ingredients:
  - Large size: good photo-coverage
  - Wavelength sensitivity: window and cathode material
  - Single photoelectron resolution and noise
  - Timing: allow for position reconstruction or pulse shape

Neutrino sources

Supernova



The Sun



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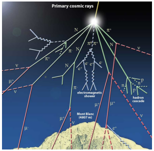
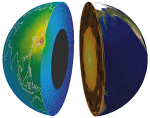


Atmosphere

Radioactivity

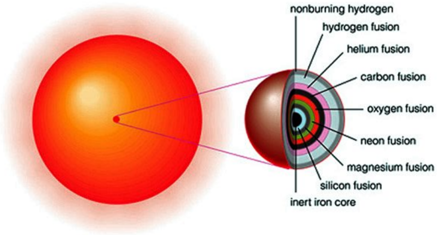


The Earth

Reactors

Accelerators

Stellar evolution

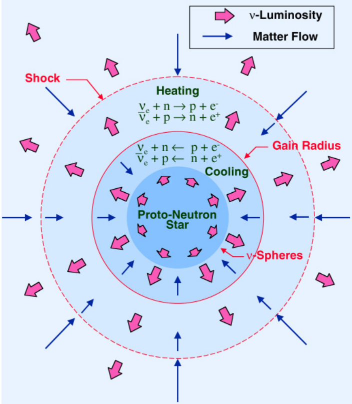


→ Burning processes in stars produce energy to compensate gravitation

- Longest phase: Hydrogen burning
- After this, star contracts increasing the temperature
- Burning of helium can start
- Similarly: carbon, neon, oxygen and silicon burning (for stars with $> 8M_\odot$)
- Further energy gain from fusion no longer possible

  → collapse

Supernova explosion



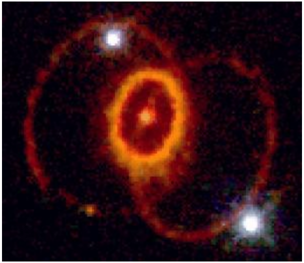
- Electrons cannot hold gravitational pressure → collapse occurs
- Disintegration of nuclei of the iron group and electron capture

→ ν_e emission: neutronization

- neutrino trapping (coherent neutrino nucleus scattering)
- Shock wave
- Further collapse adiabatically

- Thermal emission of all ν and $\bar{\nu}$ flavours
- Neutrinos carry away 99% of the gravitational energy!
- Time duration: $\sim 10\,\mathrm{s}$ → clear signature in a detector

Supernova 1987A

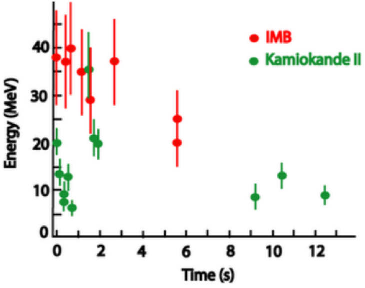


- Explosion on 23rd of February 1987
- Distance of 50 kpc (150 000 light years)
- Located in the Magellanic cloud
- Progenitor: blue supergiant of $\sim 20\,M_\odot$

→ first SN detected in neutrinos!

- Reactions in water:
  - $\overline{\nu}_e\, p \rightarrow n\, e^+$ → highest cross section
  - $\overline{\nu}_e\, {}^{16}\mathrm{O} \rightarrow {}^{16}\mathrm{N}\, e^+$
  - $\nu_e\, {}^{16}\mathrm{O} \rightarrow {}^{16}\mathrm{F}\, e^-$
  - $\nu_x\, (\overline{\nu}_x)\, e^- \rightarrow \nu_x\, (\overline{\nu}_x)\, e^-$ with $x = e, \mu, \tau$

Neutrinos from SN 1987A



Events from water Cherenkov detectors setting $t_0 = 0$

- 11 events in Kamiokande within 12 s
- 8 events in IMB within 6 s
- 5 events in Baksan within 9 s

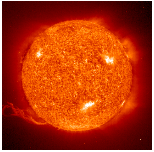
→ all simultaneous (considering respective time resolutions)

- What did we learn?
  - $>$ 90% SN binding energy into ν's
  - Neutrino lifetime $\tau_{\overline{\nu}_e} > 5 \times 10^{12}$ s
  - Neutrino mass $m_{\overline{\nu}_e} < 30$ eV

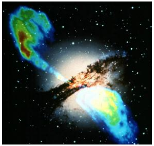
- SN explosion today: 100s to 1000s events expected
  → Superkamiokande: $\sim 15\times$ larger than Kamiokande
  → Large liquid scintillator detectors + dark matter detectors
  → Large neutrino observatories (Ice Cube)
- Nowadays: SNEWS – SuperNova Early Warning System

Neutrino sources

Supernova



The Sun



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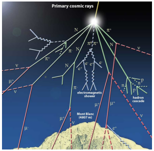
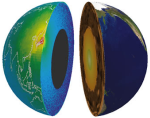


Atmosphere

Radioactivity



The Earth

Reactors

Accelerators

Sun burning process

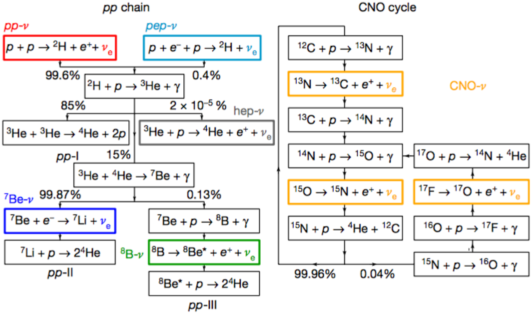


Figure from Borexino Collaboration, Nature 562 (2018) 505

$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + 26.73\,\mathrm{MeV}$

ν_e emitted in all reactions!

- ~keV thermal energies in stars

  several MeV Coulomb barriers

  → tunnelling for nuclear reactions

- Primary energy production in the Sun: pp-cycle (H burning)
- ~ 2% CNO-cycle

Prediction of the solar neutrino spectrum

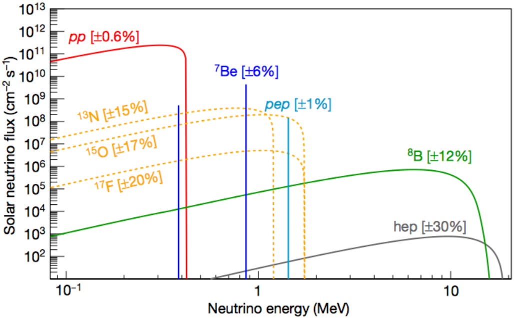


Figure from Borexino Collaboration, Nature 562 (2018) 505

- Input parameters:
  - Solar age and luminosity
  - equation of state
  - nuclear parameters
  - chemical abundances
  - opacities

→ Solar models predict fluxes of ~ 10^{10} cm^{-2} s^{-1} with % precision

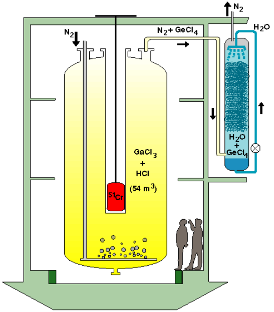
Solar neutrinos on Earth: 100 Billion (10^{11})/cm^2/s

Radiochemical experiments

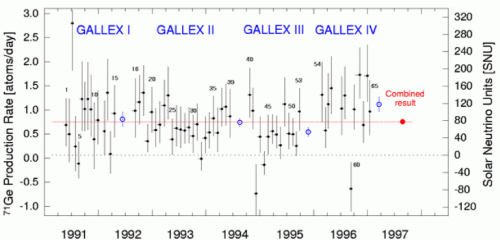
- General reaction: $^{A}_{N}Z + \nu_e \rightarrow {}^{A}_{N-1}(Z+1) + e^-$
- Integrated rate down to the threshold
- Tracing of the daughter nuclei
- Reasonable exposure and half-life

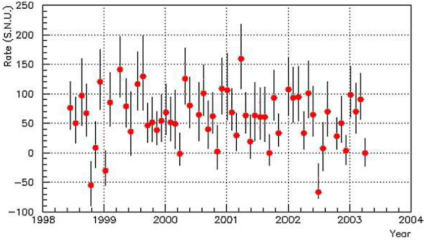
- First experiment: Homestake experiment (chlorine)
  - Measurements from 1970 - 1994
  - $\sim$800 keV threshold and daughter nucleus ^{37}Ar 35 days half-life

- GALLEX/GNO: (30 tons of gallium)
  - Located at Gran Sasso
  - Measurements from 1991 - 1997
  - 233 keV threshold
  - Daughter: ^{71}Ge 11.4 days half-life
  - ^{71}Ge detection with miniaturized proportional counters



Results from radiochemical experiments





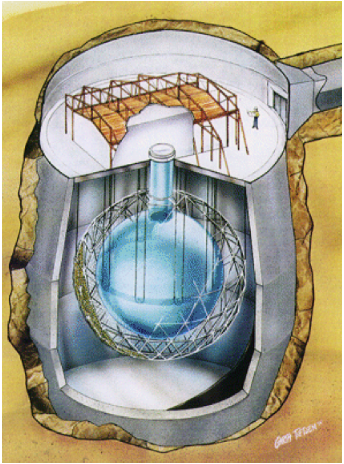
Figures from GALLEX, Phys. Lett. B447 (1999) 127 and GNO, Phys. Lett. B 616 (2005) 174

'Solar neutrino problem' → where are the neutrinos?

- Chlorine: (2.23 ± 0.22) SNU (expected 9.3±1.4)
- GALLEX/GNO: (66.9 ± 5.0) SNU (expected 132±20)

1 SNU = 1 ν reaction per second in 10^{36} target atoms

SNO experiment



- Sudbury Neutrino Observatory (Canada)
- Target: 1 kt heavy water D_2O
- Detection: Cherenkov effect

- Charge current reaction for ν_e

$$\nu_e + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{p} + e^- \qquad \text{(CC)}$$

- Reactions for all ν_x

$$\nu_x + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{n} + \nu_x \qquad \text{(NC)}$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \qquad \text{(ES)}$$

SNO Results

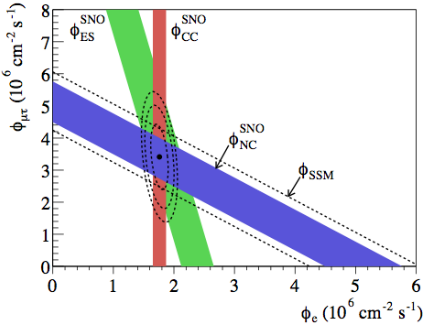


Figure from SNO, Phys. Rev. Lett. 89 (2002) 011301

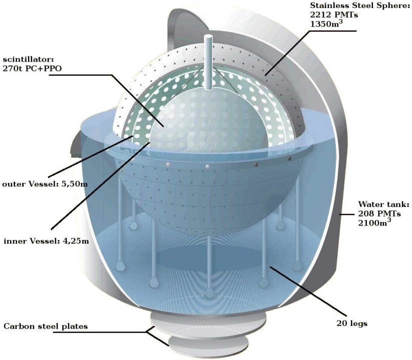
Normalized integrated rates above threshold (5 MeV)

- Sensitive to ^{8}B neutrinos
- Fluxes for electron and non-electron components:

- $\phi_e = (1.76 \pm 0.14) \cdot 10^6\,\mathrm{cm^{-2}s^{-1}}$
- $\phi_{\mu\tau} = (3.41 \pm 0.9) \cdot 10^6\,\mathrm{cm^{-2}s^{-1}}$

- Evidence for neutrino flavour transformation!

The Borexino experiment



- Detection reaction: $\nu_e e^- \rightarrow \nu_e e^-$
- Sphere of 14 m $\varnothing$
- 300 tons of liquid scintillator

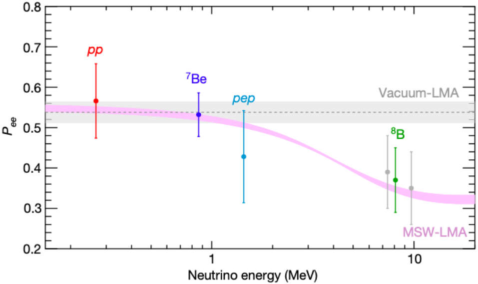


Figure from Borexino Collaboration, Nature 562 (2018) 505

- Measurement of the pp-, ^{7}Be, pep- and ^{8}B neutrinos
- Study of neutrino oscillations in matter within one detector

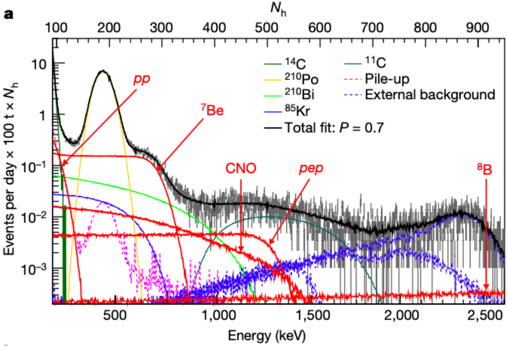


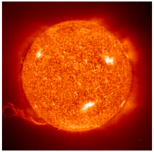
Figure from Borexino Collaboration, Nature 562 (2018) 505

- Red curves: solar neutrino components
- Coloured curves: backgrounds

- ^{14}C at low energies
  → clean scintillator
  + careful handling
- ^{222}Rn
  parent of ^{210}Po & ^{210}Bi
  $[^{238}\mathrm{U}] = 5.3 \times 10^{-18}$ g/g
  → clean radon barrier
- ^{85}Kr from the air
  → nitrogen purge

Neutrino sources

Supernova



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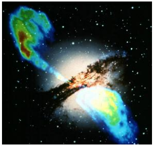

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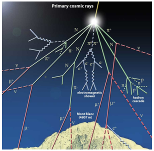

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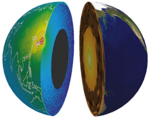
Radioactivity



The Earth

Reactors

Accelerators

High energy neutrino production

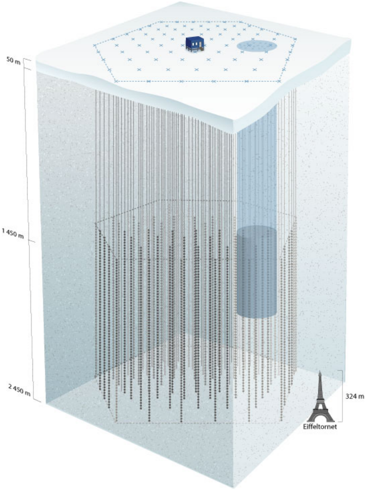
- Neutrinos: no charge
  → not affected by magnetic fields

- Weak interaction
  → no absorption during propagation

- Scientific questions:
  - Cosmic ray sources
  - Acceleration/propagation processes
  - Neutrino particle properties

→ Results can be correlated with other signals: multi-messenger approach (e.g. with radio, optical, X-ray ...)

The Ice Cube detector

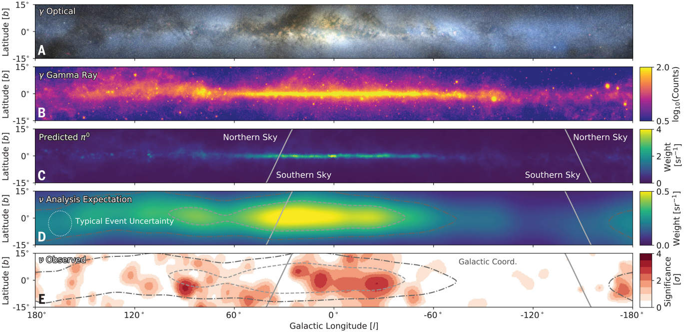


- Location: South pole
- km^3 of ice $\rightarrow$ Cherenkov effect
- Neutrino detection using timing to identify the ν−direction and signal size for energy reconstruction
- Largest neutrino telescope!
- 25 cm $\varnothing$ PMTs for light readout
- Physics goals:
  - Point like sources (AGNs)
  - Supernova neutrinos
  - Indirect dark matter search

Also Antares and KM3Net in the mediterranean see (Cherenkov effect in seawater)

Ice Cube sky map

- Observation of high-energy neutrinos from the Galactic plane
  → 4.5 σ significance, consistent with diffuse emission or point sources

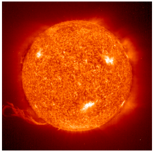


IceCube, Science 380 (2023) 1338

- Experimental challenges:
  - Operation in a remote place
  - Drilling holes in ice (engineer challenge)
  - Understanding the ice as a 'particle detector'

Neutrino sources

Supernova



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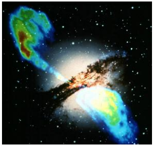

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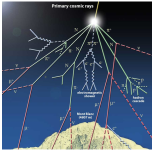

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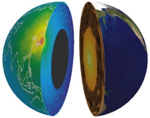
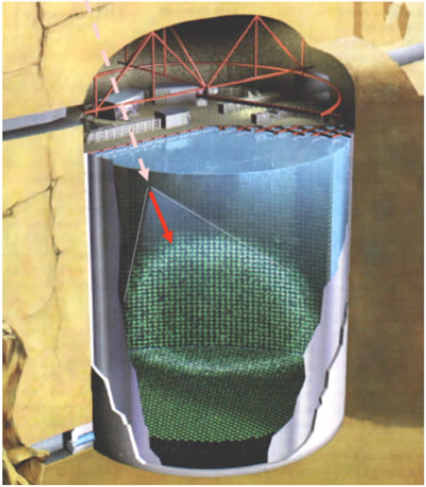


The Earth

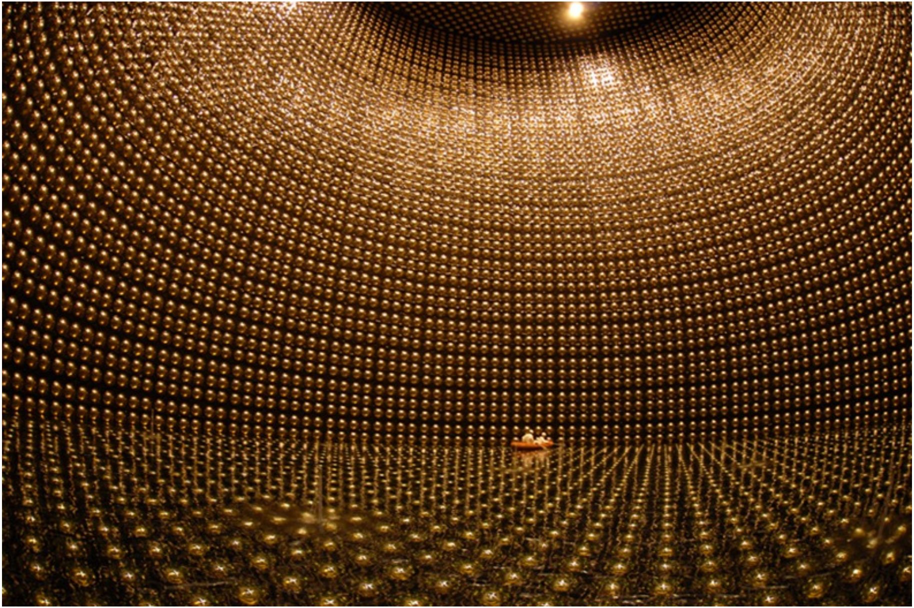
Reactors

Accelerators

スーパーカミオカンデ
Super-Kamiokande



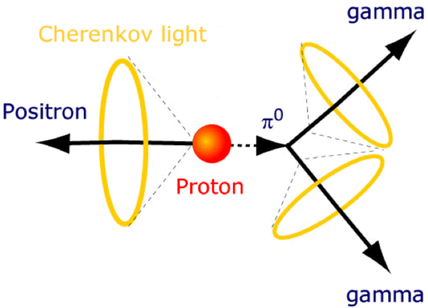
- Size: 41 m height and 39 m ∅
- Mass: 50 ktons of pure water
- 22 kton fiducial mass
- ~11 000 photosensors of 0.5 m ∅
- 1 000 m underground
- Kamioka mine (Japan)
- Challenges:
  - Optical instrumentation of a huge volume
- Key feature:
  - Directionality of the signal → pointing possible



Proton decay in Superkamiokande

→ Original motivation to build Kamiokande

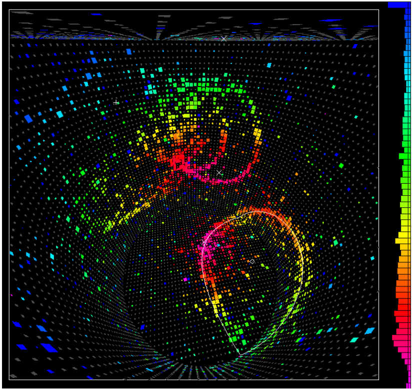
- Process predicted by **GUT** : Grand Unified Theories
- Clear identification of the decay $p \rightarrow e^{+}\pi^{0}$

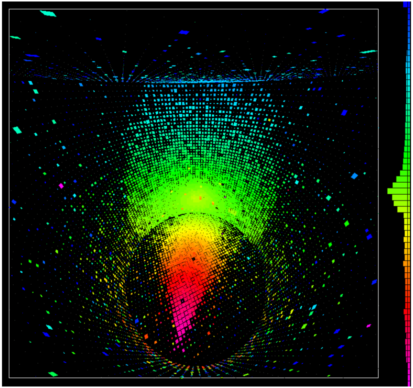


- Limit on the lifetime: $\tau(p \rightarrow e^{+}\pi^{0}) \gtrsim 1.6 \cdot 10^{34}$ y (90% C.L.)

Super-Kamiokande, Phys. Rev. D95 (2017) no.1, 012004

Cherenkov rings in Superkamiokande II





- Multi-ring event
- Through-going muon

Atmospheric neutrinos: the 'background'

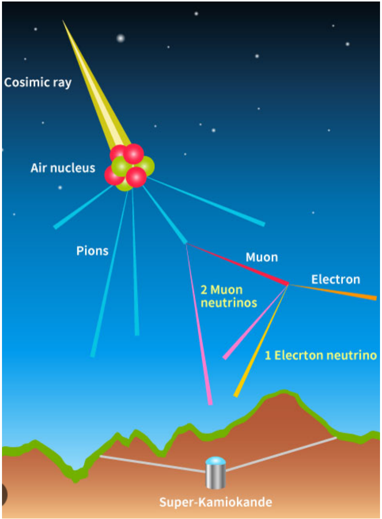


Figure from Superkamiokande homepage

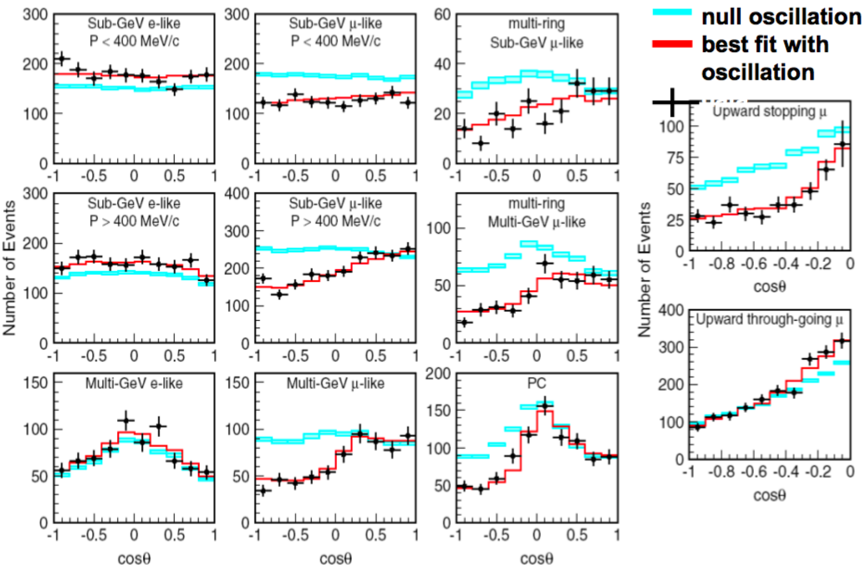
- Neutrino production:

  $\pi^- \rightarrow \mu^- \overline{\nu}_\mu$

  $\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$

- Detection with neutral current reactions:
  - $\nu_x (\overline{\nu}_x)\ e^- \rightarrow \nu_x (\overline{\nu}_x)\ e^-$
    with $x = e, \mu, \tau$

- Detection with charged current reactions:
  - $\overline{\nu}_e\ p \rightarrow n\ e^+$
  - $\nu_e\ ^{16}\mathrm{O} \rightarrow ^{16}\mathrm{F}\ e^-$
  - $\overline{\nu}_e\ ^{16}\mathrm{O} \rightarrow ^{16}\mathrm{N}\ e^+$
  - \+ ν_μ and ν_τ CC reactions



Super-Kamiokande, Phys. Rev. D71 (2005) 112005

Neutrino oscillations

- ν_e, ν_μ and ν_τ: flavour eigenstates
- ν_1, ν_2 and ν_3: mass eigenstates

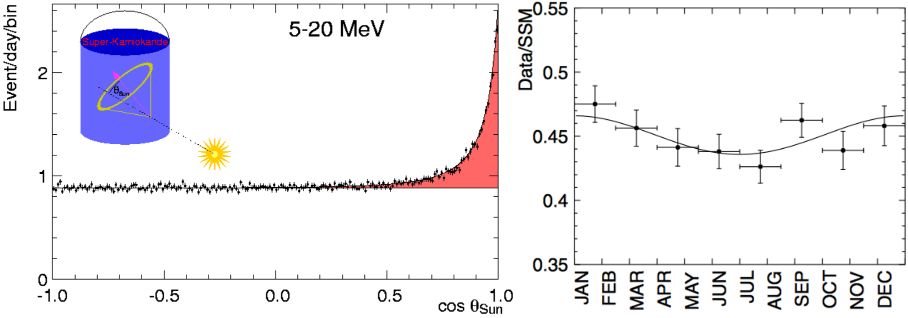
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Survival probability: $P_{e\rightarrow\mu} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$
  - $\sin^2 2\theta$: mixing of neutrino flavours
  - Δm^2: splitting of neutrino mass eigenstates
  - L: propagation distance
  - E: neutrino energy

→ the amount of neutrinos expected depends on their angle (length of the path through the atmosphere) and on their energy

* Nobel prize to Takaaki Kajita (Super-Kamiokande) and Arthur B. McDonald (SNO) in 2015 *for the discovery of neutrino oscillations, which shows that neutrinos have mass*

SK solar neutrino results

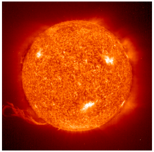


Super-Kamiokande, Phys. Rev. Lett. 86 (2001) 5651

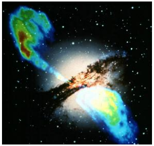
- Measurement of the angle dependence of the rate
- Solar neutrino energy region of interest
- Unique feature of Cherenkov detectors → directionality

Neutrino sources

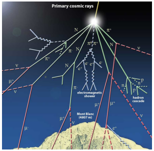
Supernova



The Sun

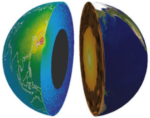


Stars



Atmosphere

Radioactivity



The Earth

Reactors

Accelerators

What can we learn?

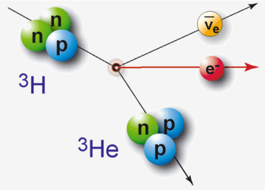
- Neutrino mass
  - Precision measurement of tritium decay spectrum
- Nature of neutrinos: Dirac or Majorana particles
  - Search for neutrinoless double beta decay

! In none of these cases neutrinos are measured ☺

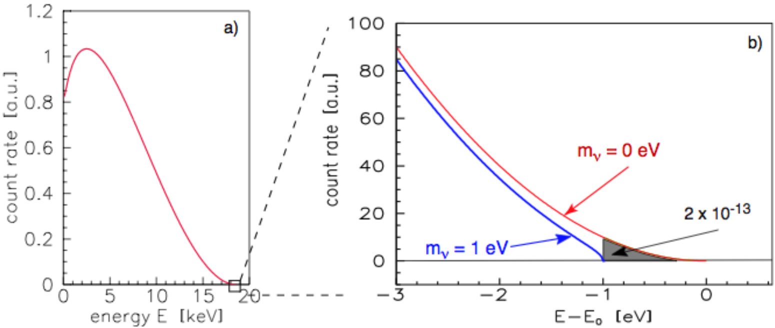
Neutrino mass

- Limits on the neutrino mass:
  - Pion decay: $m_{\nu_\mu} < 170\,\text{keV}$ (at PSI)
  - SN1987: $m_{\overline{\nu}_e} < 30\,\text{eV}$
  - Cosmology: $\sum \nu_i < 1\,\text{eV}$ (model dependent)
- Direct measurements from tritium decay
  - The Mainz experiment $m_{\nu_e} < 2.2\,\text{eV}$ (95% C.L.)
  - Running: KATRIN experiment $m_{\nu_e} < 0.8\,\text{eV}$ (90% C.L.)

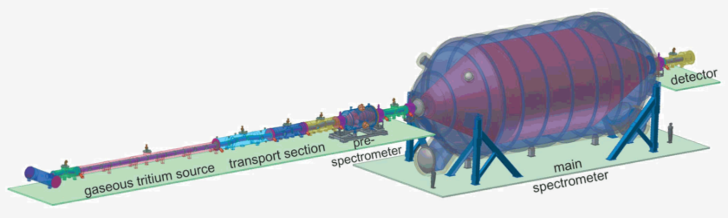
Tritium decay

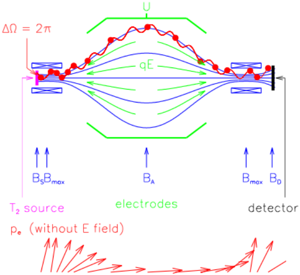


- Superallowed transition:
  $^3\mathrm{H} \rightarrow ^3\mathrm{He} + e^- + \overline{\nu}_e$
- Endpoint at E_0 = 18.57 keV
- Half-life $t_{1/2}$ = 12.32 y



KATRIN experiment





- Karlsruhe Tritium Neutrino Experiment
- MAC-E filter to select region of interest
- Data taking ongoing
- Experimental challenges:
  - Source intensity/stability
  - energy analysis & low background!

KATRIN results

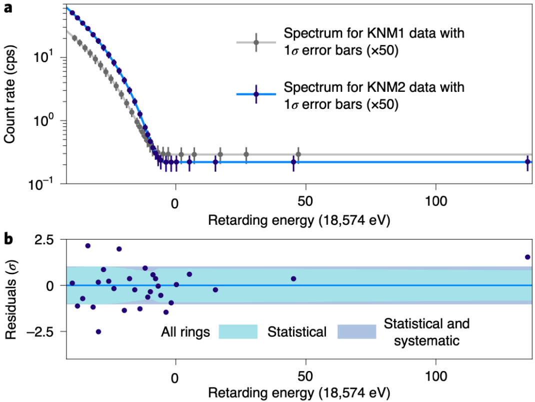
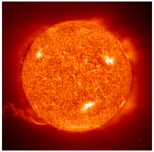


Figure from KATRIN collaboration, Nature physics 18 (2022) 160

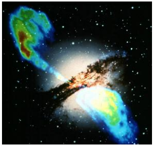
- Two runs released KNM1 & KNM2
- Combined result: $m_{\nu_e} < 0.8\,\mathrm{eV}/c^2$ at 90 % C.L.
- Final goal: determine the neutrino mass with a sensitivity close to $m_{\nu_e} < 0.2\,\mathrm{eV}/c^2$

Neutrino sources

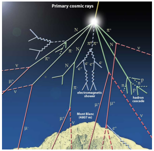
Supernova



The Sun

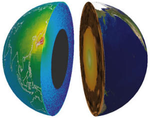


Stars



Atmosphere

Radioactivity



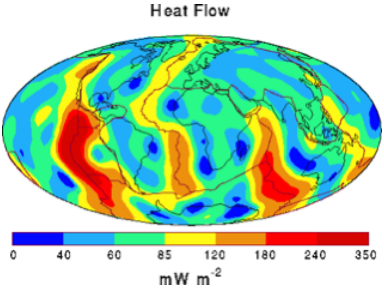
The Earth

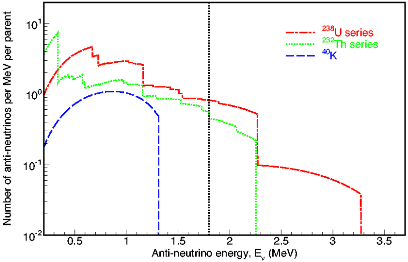
Reactors

Accelerators

Studying the Earth with geoneutrinos

- Unexplained source of heat flow from Earth
- Unknown contribution of natural radioactivity
- How are ^{238}U, ^{232}Th distributed in core, mantle and crust?
- Is it possible to have a nuclear reactor in the center of the Earth?





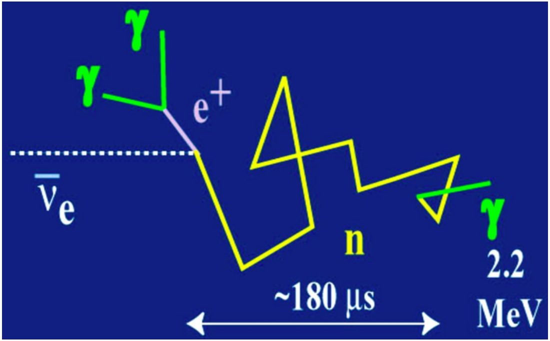
Expected anti-neutrino spectrum from KAMLAND, Nature 436 (2015)

Detection of $\overline{\nu}_e$

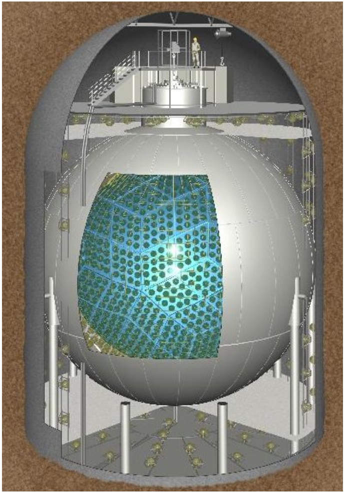
In water or liquid scintillator (free protons necessary):

$\overline{\nu}_e + p \rightarrow n + e^+$ $\qquad$ $n + p \rightarrow d + \gamma$

Delayed coincidence: e^+ signal + 2.2 MeV signal from n capture



The KamLAND experiment

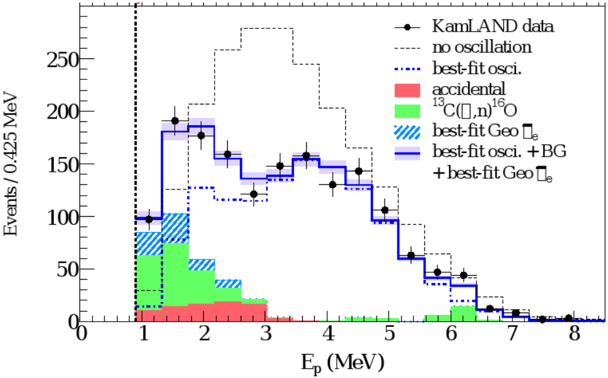


- Location: old Kamiokande cavity in Japan
- Surrounded by 55 nuclear power reactors
- Sphere of 18 m ∅
- 1 kton of liquid scintillator
- ~ 2 100 photomultipliers

o Built to measure precisely the solar mixing parameters θ_{12} and Δm^2_{12}

KamLAND geoneutrino results

... from background to signal

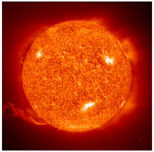


KAMLAND, Phys. Rev. Lett. 100 (2008) 221803

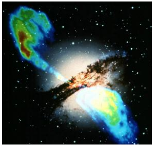
- 73 ± 27 events in agreement with the reference model
- Upper limit of 6.2 TW for a $\overline{\nu}_e$ reactor at the Earth's center

Neutrino sources

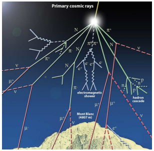
Supernova



The Sun

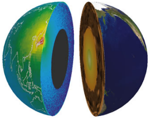


Stars



Atmosphere

Radioactivity

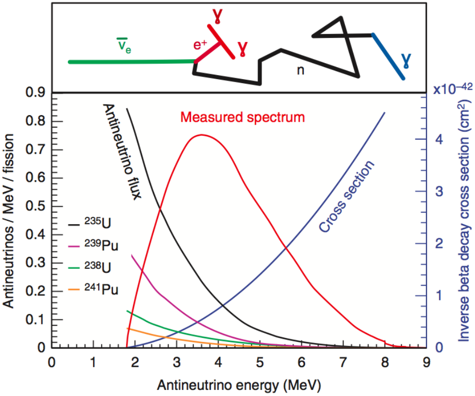


The Earth

Reactors

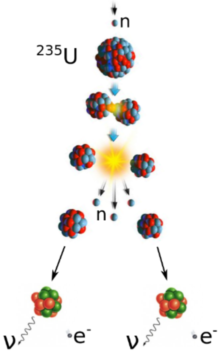
Accelerators

Neutrino production in reactors



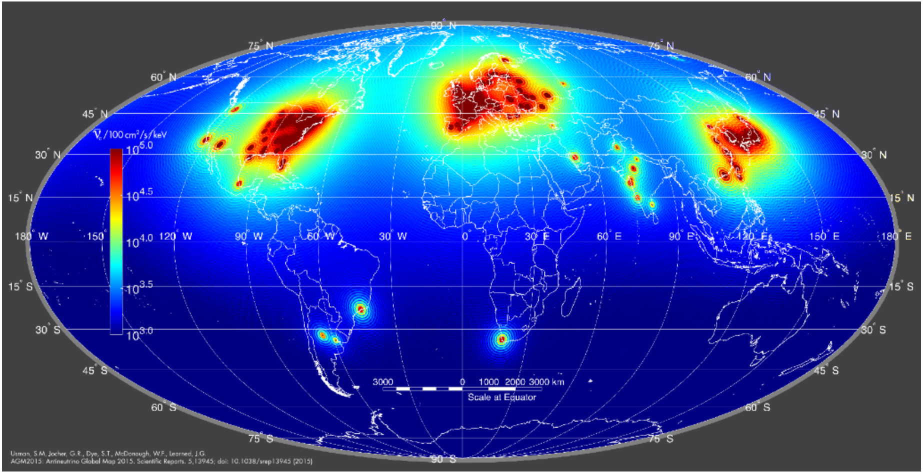
P. Vogel *et al.*, Nature Commun. 6 (2015) 6935

Nuclear reactors:
high intensity $\overline{\nu}_e$ sources



- β^- decay of neutron rich fragments of U and Pu fission
- $^{235}\mathrm{U} + n \rightarrow X_1 + X_2 + 2n \quad \rightarrow \quad 6\,\overline{\nu}_e$ per fission in average
- $3\,\mathrm{GW}_{th}$ reactor power produces $6 \times 10^{20}\,\overline{\nu}_e/\mathrm{s}$

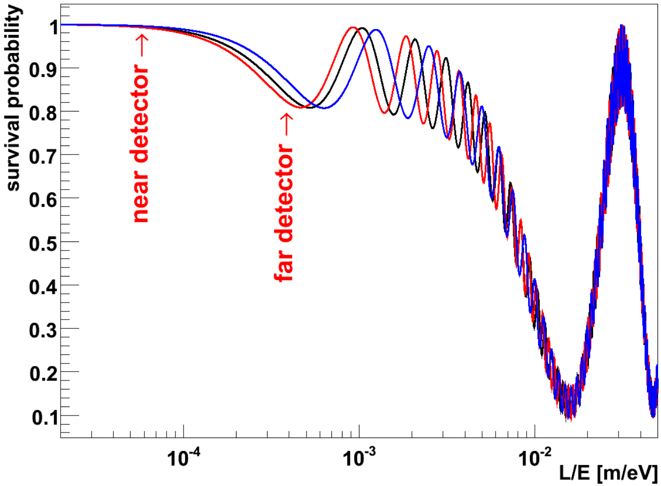
Reactor neutrino flux worldwide



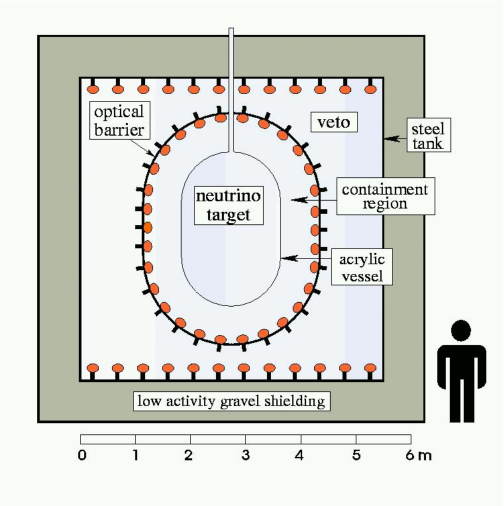
Antineutrino Global Map 2015, S.M. Usman et al., Sci. Rep. Vol. 5 (2015) 13945.

L/E oscillation plot

$$P(\nu_\alpha \rightarrow \nu_\beta) \propto \sin^2 2\theta_{ij} \cdot \sin^2\left(1.27\frac{\Delta m^2_{ij}(\mathrm{eV}^2)L(\mathrm{m})}{E(\mathrm{MeV})}\right)$$



CHOOZ experiment: a metal loaded scintillator

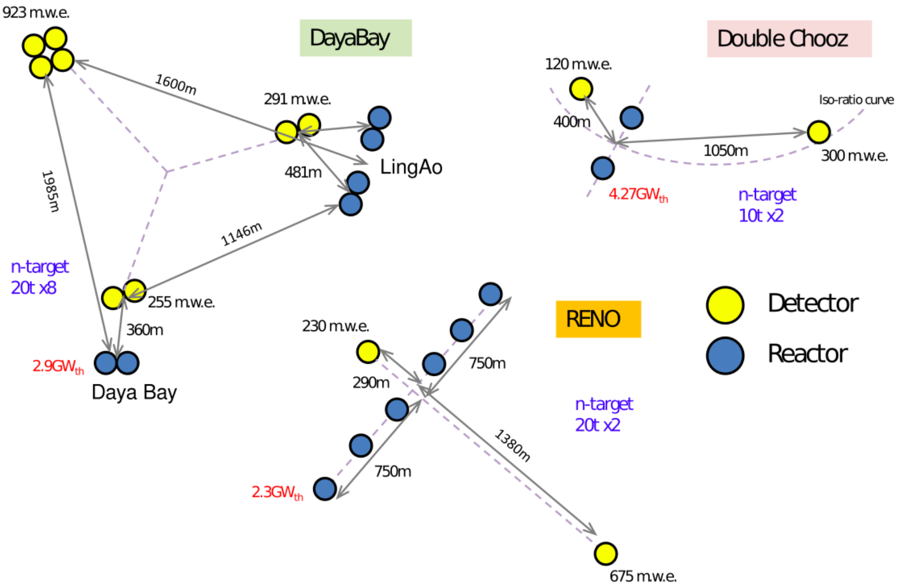


- Scintillator loaded with Gadolinium
- Detection reaction:
  $\overline{\nu}_e + p \rightarrow n + e^+$

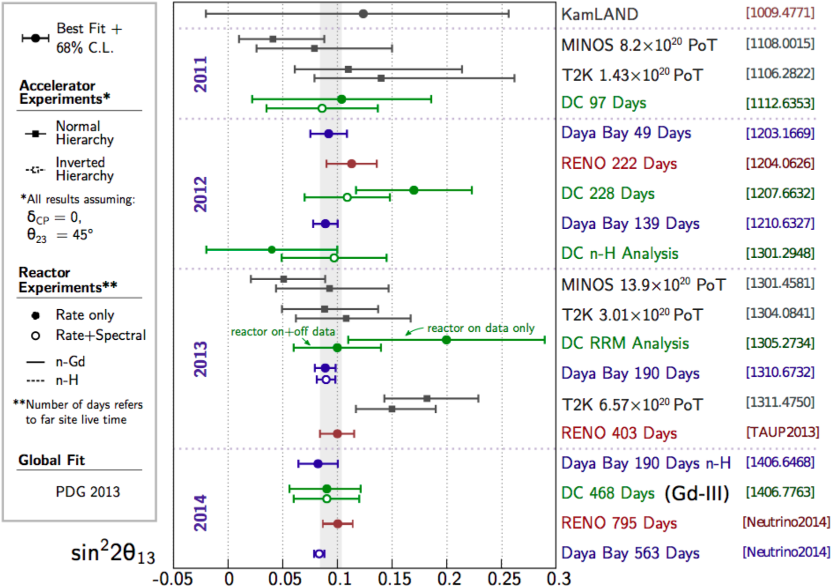
  $\mathrm{Gd} + n \rightarrow \gamma$'s (8 MeV)
- No evidence for neutrino oscillation

→ best limit on the mixing angle θ_{13}, $\sin^2 2\theta_{13} < 0.2$

Search strategy for θ_{13}

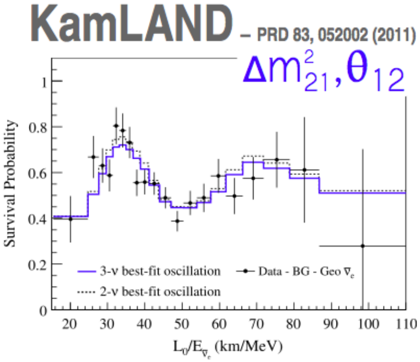


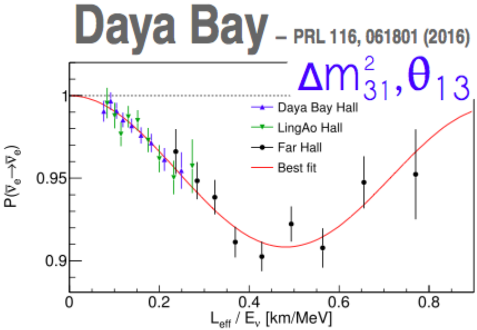
θ_{13} results



Double CHOOZ, JHEP 10 (2014) 086

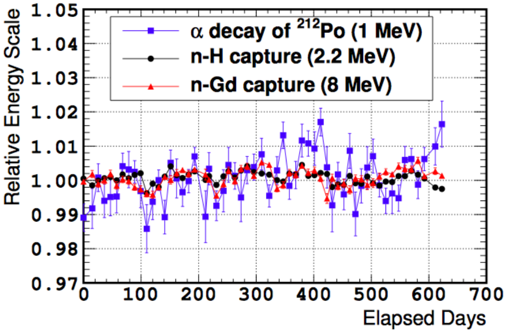
Neutrino oscillations L/E measurements



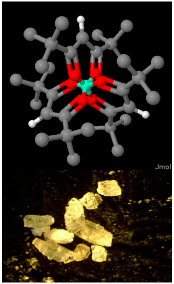


Challenge: metal-loaded scintillator

- Main concerns:
  Chemical stability & Light yield stability (absorption length)
- Metal loaded scintillators:
  - ^{155,157}Gd, ^{6}Li and ^{10}B → neutron capture
  - ^{115}In → solar neutrinos (ν_e capture)
  - ^{176}Yb and ^{150}Nd → neutrinoless double beta decay

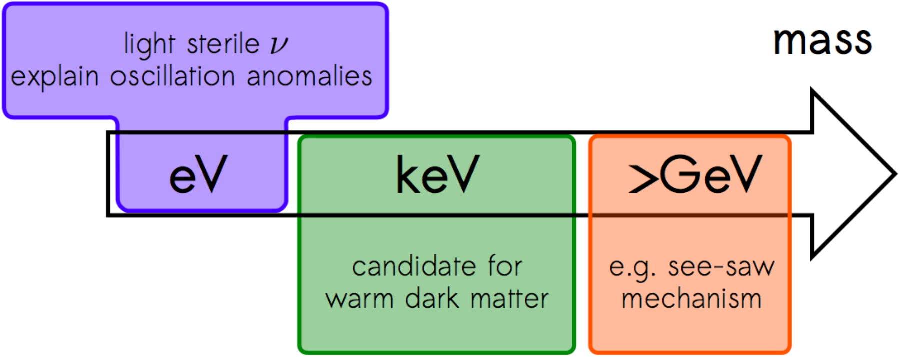


Light yield stability in Double CHOOZ,
figure from J. High Energy Phys. JHEP10 (2014) 086



Gadolinium (β−diketones),
figure from C. Buck

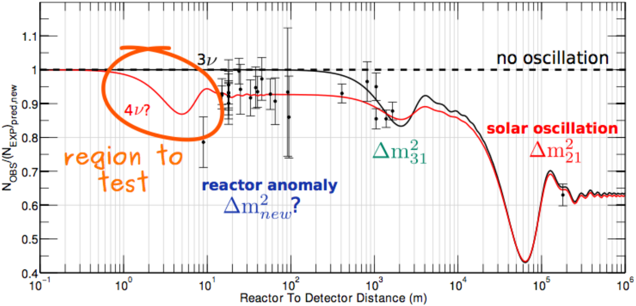
Sterile neutrinos



Scheme from J. Haser

eV sterile neutrinos

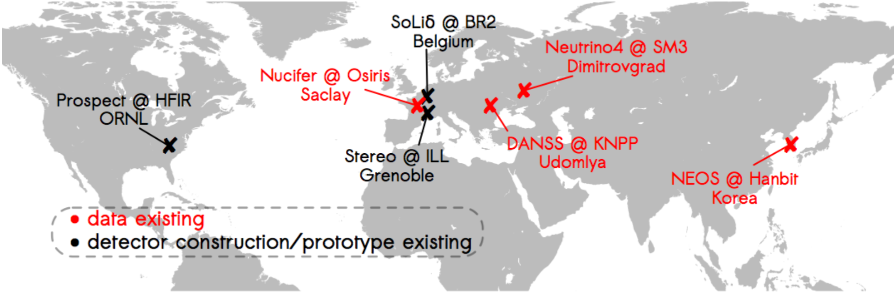
- Experimental hints:
  - Gallex/SAGE ν-source anomalie (1990ies) Giunti, Laveder, PRC83, 065504 (2011)
  - Reactor neutrino anomalie (2011) Mention et al., PRDD83, 073006 (2011)



$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix}$$

- $3+1$ scenario $\rightarrow$ minimal extension
- ν_4 has no direct coupling to W/Z bosons

Sterile neutrinos



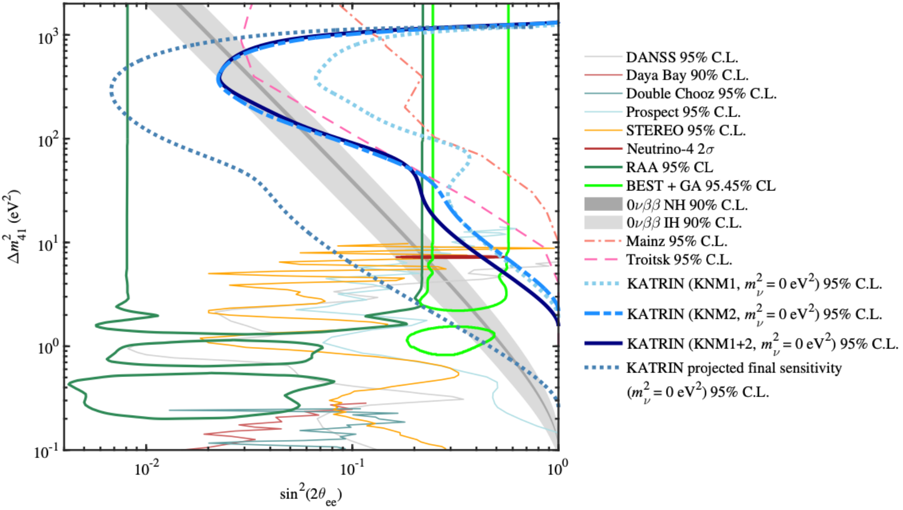
experiment	technology	m_t [t]	P_{th} [MW]	L [m]	S/B	$\sigma_{E,Ph}/E$
DANSS	Gd-PS	0.9	3000	10.7-12.7	100	0.18
NEOS	Gd-LS	1	2800	25	23	0.05
Neutrino4	Gd-LS	0.3	100	7-11	<1	-
Nucifer	Gd-LS	1	70	7	<1	0.1
SoLiδ	^{6}Li-PS	1.6	60-80	5.7	3	0.14
Stereo	Gd-LS	1.8	57	8.9-11.1	1.5	0.05
Prospect I	^{6}Li-PS	1.5	85	7-12	3	0.045

$\sigma_{E,Ph}/E$: photon statistical energy resolution @ 1MeV visible energy

- highly segmented
- highly segmented & inhomogeneous neutron detection
- movable detector

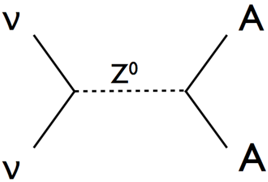
Slide from J. Haser

Results for sterile neutrinos



KATRIN Collaboration, Phys. Rev. D 105 (2022) 072004

Coherent neutrino nucleus scattering

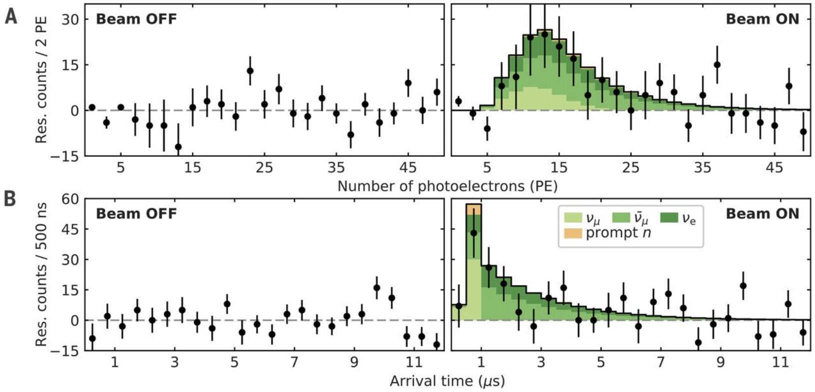


- Standard model process
- Coherence up to $E_\nu \sim 50\,\text{MeV}$
  - → Above ν's can resolve the nucleus structure

A. Drukier & L. Stodolsky, Phys. Rev. D 30 (1984) 2295

- Why is it interesting to measure this process?
  - Deviations from the standard model predictions → new physics
  - Important for dark matter detection
  - Important in supernovae neutrino production and detection
- How to measure it?
  - With very low E_{th} detector → germanium detectors or dark matter-like detectors
  - @ A neutrino source → reactors

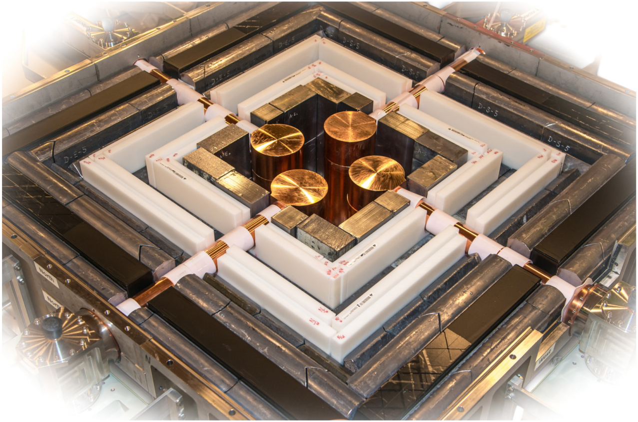
- Multi-target experiment at an spallation neutron source
- Proton collision on mercury: ν's from pion decay ($\sim 30\,\text{MeV}$)
- First detection in 2017!!



COHERENT Collaboration, Science 357 (2017) 6356, 1123

CONUS

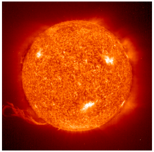
- Germanium detectors at a power reactor
- Neutrinos in the fully coherent regime



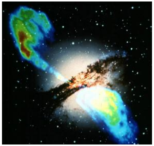
CONUS Collaboration

Neutrino sources

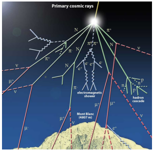
Supernova



The Sun

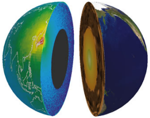


Stars



Atmosphere

Radioactivity



The Earth

Reactors

Accelerators

Physics with neutrino beams

- Discovery of new neutrino types: ν_μ and ν_τ
- Precise determination of mixing parameters
- Determination of the mass ordering
- Search for oscillations to sterile neutrinos
- Search for CP violation

Producing a neutrino beam

- Proton collision on a target (Be, Al, graphite, carbon)
- Pion and kaon production + Focusing system: parabolic horn
- Decaying pipe: pions give 99% of $\overline{\nu}_\mu$

+ decaying muons from kaon decay $\rightarrow \nu_e$ contamination

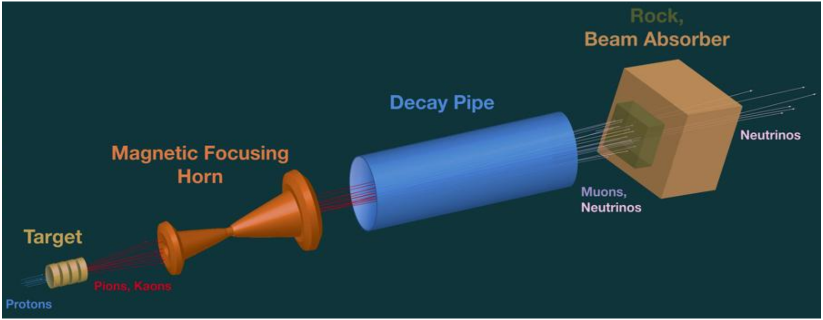
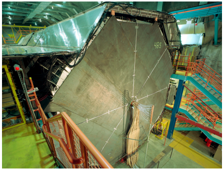


Figure from Fermilab today

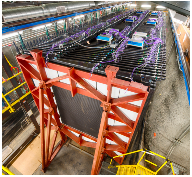
Beams and detectors

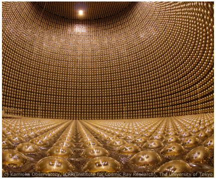
Source	Experiment	Baseline	ν energy	Status
KEK	K2K	L = 250 km	1.4 GeV	finished
Fermilab	MINOS	L = 735 km	(3 – 17) GeV	finished
CNGS	OPERA	L = 732 km	25 GeV	finished
J-PARC	T2K	L = 295 km	0.77 GeV	on-going
Fermilab	NOνA	L = 810 km	2 GeV	on-going
J-PARC	T2HK	L = 295 km	sub GeV	future
Fermilab	DUNE	L = 1 300 km	few GeV	future

Neutrino beam detectors


MINOS
magnetised iron calorimeter


OPERA
Lead + emulsion cloud chambers

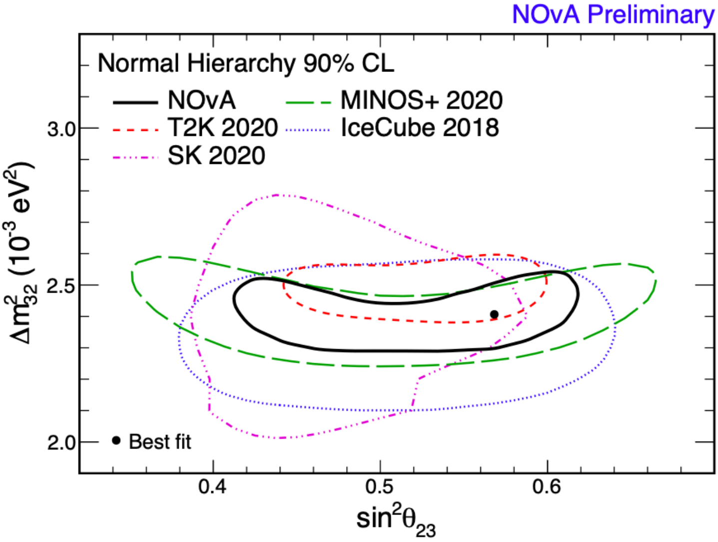

NOvA
cells of liquid scintillator



SuperKamiokande
water Cherenkov detector

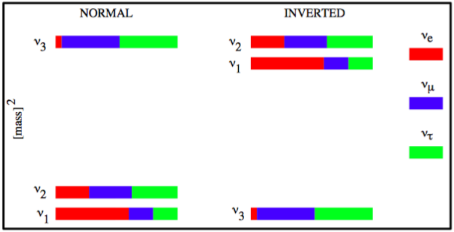
- Main detector types:
  - Homogeneous (liquid scintillator or water)
  - Segmented detectors with heavy element target and detection parts
- Challenges:
  - Large size
  - Reconstruction of neutrino interaction

Summary of oscillation results



NOVA Collaboration, arXiv:2206.03542v1

Open questions: neutrino mass ordering



- **JUNO**: Jiangmen Underground Neutrino Observatory
  - Technology: 20 kt liquid scintillator
  - Source: reactor neutrinos ~ 53 km from the detector
- **PINGU** and **ORCA**
  - Technology: low energy extensions of IceCube and KM3Net
  - Source: atmospheric neutrinos
- Also Hyper-Kamiokande and DUNE detectors (see next slide)

Open questions: Leptonic CP violation

- Leptonic CP violation

  → difference of the vacuum oscillation probabilities for neutrinos and anti-neutrinos

$$P_{\nu_\alpha \to \nu_\beta} \neq P_{\overline{\nu_\alpha} \to \overline{\nu_\beta}}$$

- **HK**: Hyper-Kamiokande detector
  - Main goal: CP violation + mass hierarchy
  - Technology: 2 tanks of 0.37 Mt, water Cherenkov detectors
  - Source: T2HK beam (ν and $\overline{\nu}$ beams)

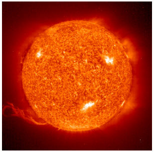
- **DUNE**: Deep Underground Neutrino Experiment
  - Main goal: mass hierarchy + CP violation
  - Technology: 4× LAr TPCs and a near detector
  - Source: beam from Fermilab (distance 1 300 km)

Summary

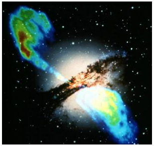
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Solar atmospheric and reactor mixing parameters determined
  → more precise measurements expected in the next years
- Neutrinos from supernova, Sun, astrophysical sources measured
  → Neutrino astronomy: unique opportunity to learn about sources
- δ and the hierarchy not yet known
- Existence of sterile neutrino?
- $\nu = \overline{\nu}$? (Neutrinoless double-beta decay → not discussed in the lecture)

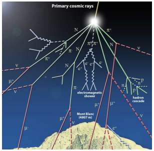
Supernova



The Sun

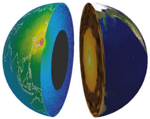


Stars



Atmosphere

Radioactivity



The Earth

Reactors

Accelerators

THE END