Neutrinos and Astrophysics: An Experimental Overview

Workshop on Astro-particles and Gravity, 20-22 Sept 2022, Cairo University, Egypt

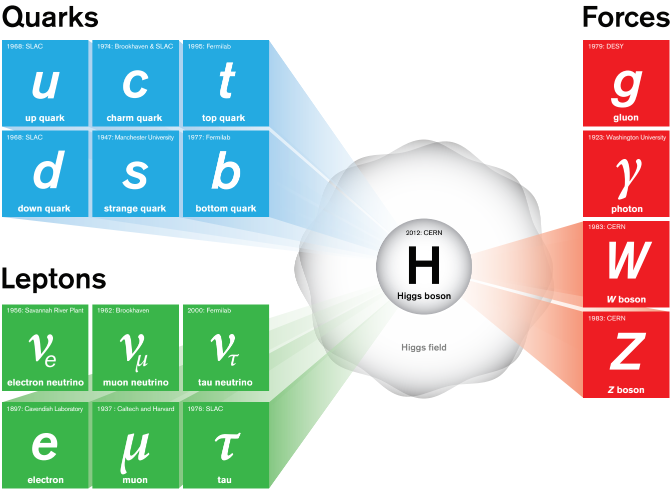
Mary Bishai

Brookhaven National Laboratory

Sep 22^{nd}, 2022

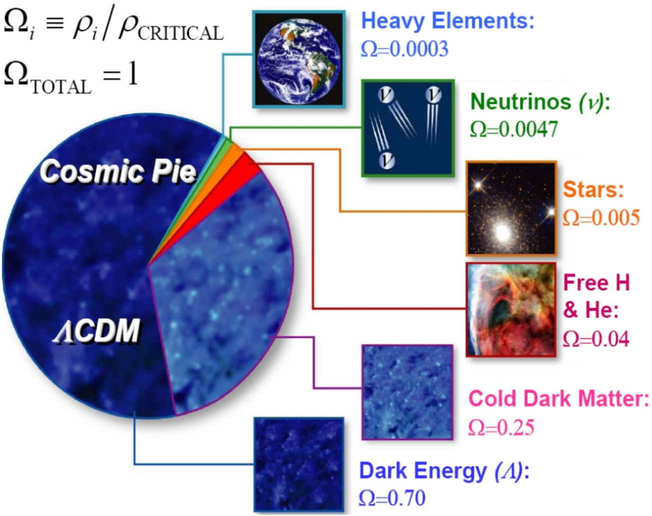
Introduction to Astro-physical Neutrinos

The Particle Zoo

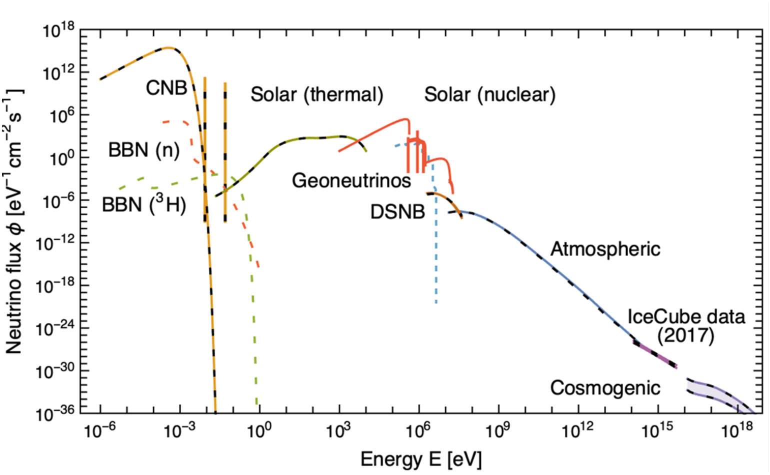


Neutrinos and Todays Universe

Neutrino mass $<$ 1 eV (beta-decay limits)



Spectrum of Neutrinos on Earth



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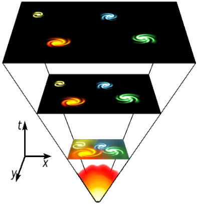
Introduction to Astro-physical Neutrinos and Experimental Survey

The Current Neutrino Experimental Landscape

Sources of Neutrinos

Big Bang

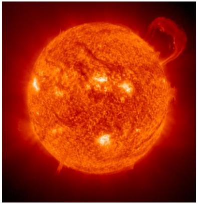


10^{-4} **eV**
300/cm^3

Reactors

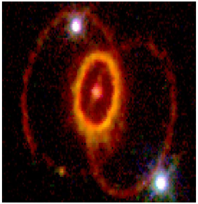
few MeV
10^{21}**/GW$_{th}$/s**

Sun



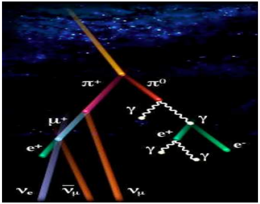
0.1-14 MeV
10^{10}**/cm^2/s**

SuperNova



$\sim$ 10 **MeV**
10^{9}**/cm^2/s**

Atmosphere

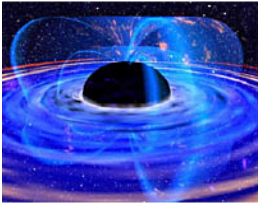


$\sim$ 1 **GeV**
few/cm^2/s

Accelerators

1-20 GeV
10^{6}**/cm^2/s/MW (at 1km)**

Extragalactic

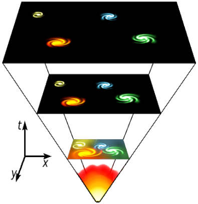


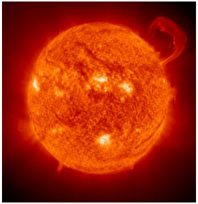
TeV-PeV
varies

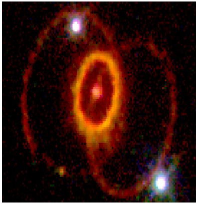
The Current Neutrino Experimental Landscape

Examples of Neutrino Experiments (current, future)

Big Bang | **Reactors** | **Sun** | **SuperNova**







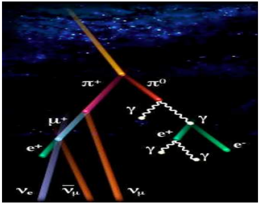
Big Bang: PTOLEMY

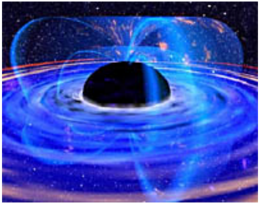
Reactors: Daya Bay / JUNO

Sun: BOREXINO / SNO+/JUNO

SuperNova: SuperK-GD / DUNE/HK/JUNO

Atmosphere | **Accelerators** | **Extragalactic**





Atmosphere: SuperK/IC-DeepCore / HyperK/KM3NeT/ORCA

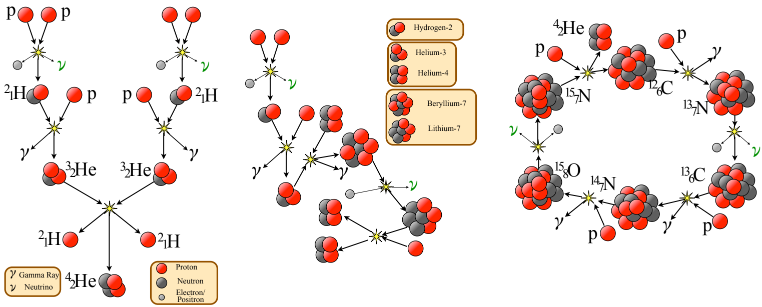
Accelerators: T2K/NoVA / T2HK/DUNE/ESSνSB

Extragalactic: IceCUBE / IceCUBE-Gen2

Solar Neutrinos

Solar Neutrinos

Fusion of nuclei in the Sun produces solar energy and neutrinos



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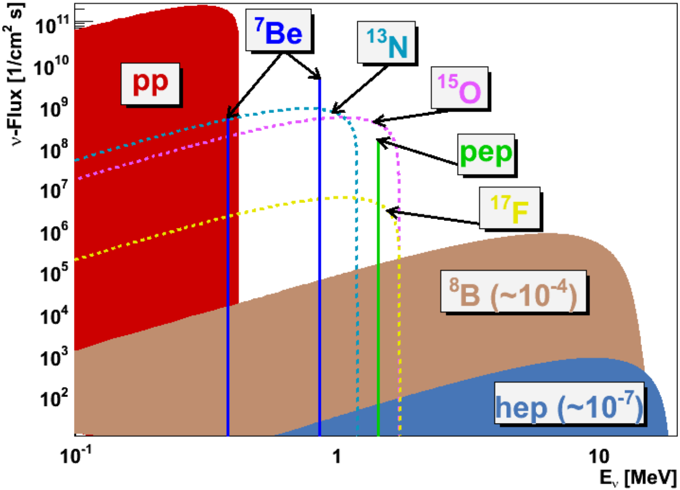


The Homestake Experiment

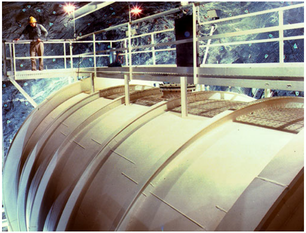
Neutrinos and Astrophysics: An Experimental Overview

Mary Bishai

1967: Ray Davis from BNL installs a large detector, containing 615 tons of tetrachloroethylene (cleaning fluid), 1.6km underground in Homestake mine, SD.

1. $\nu_e^{sun} + ^{37}\text{CL} \rightarrow e^- + ^{37}\text{Ar}, \ \tau(^{37}\text{Ar}) = 35$ **days.**
2. **Number of** Ar **atoms** $\approx$ **number of** ν_e^{sun} **interactions.**

Ray Davis



Results: 1969 - 1993 Measured 2.5 $\pm$ 0.2 SNU (1 SNU = 1 neutrino interaction per second for 10^{36} target atoms) while theory predicts 8 SNU. This is a ν_e^{sun} deficit of 69%.

Where did the suns ν_e's go?

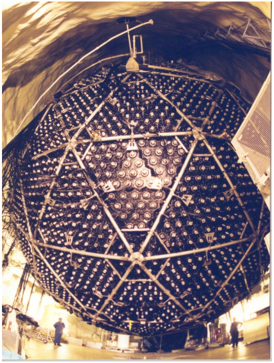
RAY DAVIS SHARES 2002 NOBEL PRIZE

SNO Experiment: Solar ν Measurments

$1 \leftrightarrow 2$ mixing

2001-02: Sudbury Neutrino Observatory. Water Čerenkov detector with 1 kT heavy water (0.5 B$ worth on loan from Atomic Energy of Canada Ltd.) located 2Km below ground in INCO's Creighton nickel mine near Sudbury, Ontario. Can detect the following $\nu^{\rm sun}$ interactions:

1) $\nu_e + d \rightarrow e^- + p + p$ **(CC).**
2) $\nu_{e,x} + e^- \rightarrow e^- + \nu_x, \quad \nu_e : \nu_x = 6 : 1$ **(ES)**
3) $\nu_x + d \rightarrow p + n + \nu_x, \quad x = e, \mu, \tau$ **(NC).**



SNO measured:

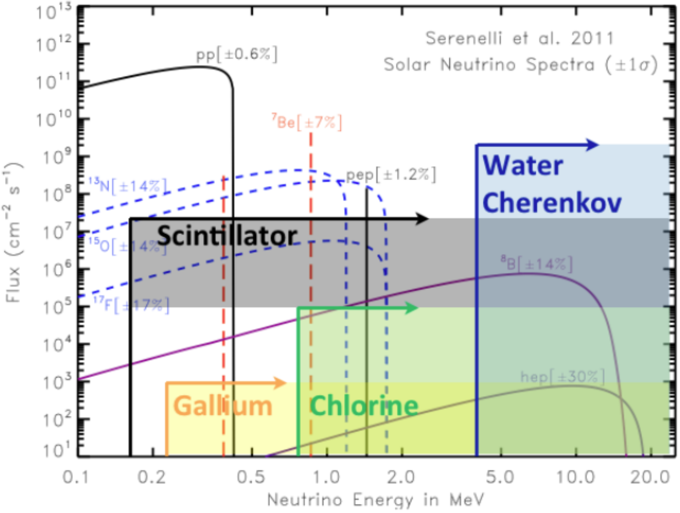
$\phi^{CC}_{SNO}(\nu_e) = 1.75 \pm 0.07(\mathrm{stat})^{+0.12}_{-0.11}(\mathrm{sys.}) \pm 0.05(\mathrm{theor}) \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$

$\phi^{ES}_{SNO}(\nu_x) = 2.39 \pm 0.34(\mathrm{stat})^{+0.16}_{-0.14}(\mathrm{sys.}) \pm \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$

$\phi^{NC}_{SNO}(\nu_x) = 5.09 \pm 0.44(\mathrm{stat})^{+0.46}_{-0.43}(\mathrm{sys.}) \pm \times 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$

All the solar ν's are there but ν_e appears as ν_x!

Solar Neutrino Spectrum

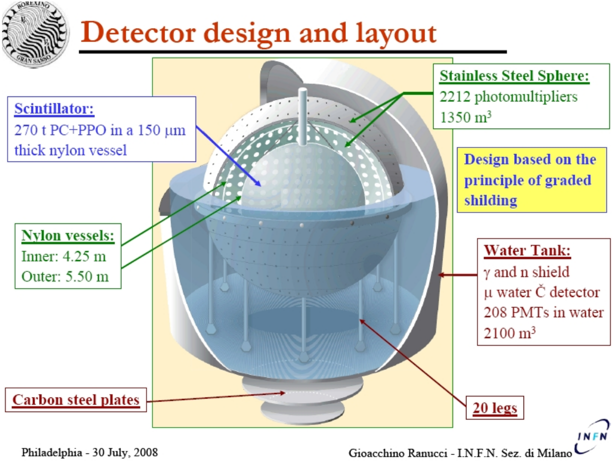


from G. Orebi Gann

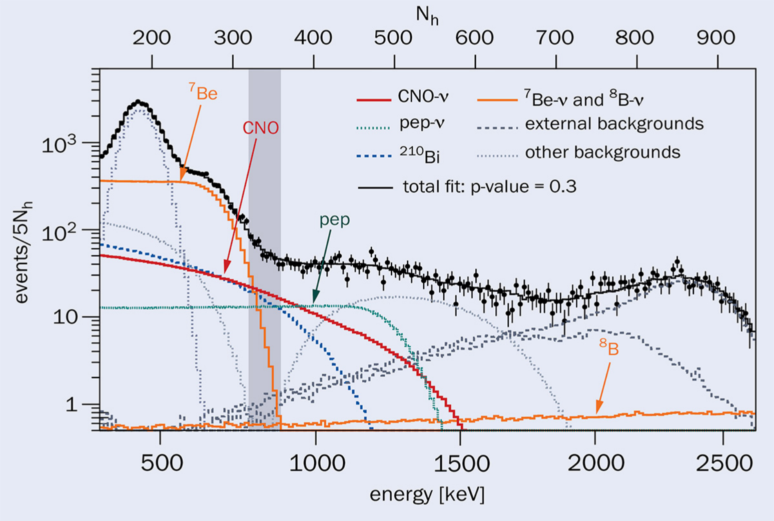
Borexino

GOAL: Direct determination of the low energy neutrino fluxes: ^{7}Be (monoenergetic) , CNO ($<$ 1% in our sun), pep, pp

TECHNIQUE: $\nu_x + e \rightarrow \nu_x + e$ elastic scattering in high radio-purity scintillator.



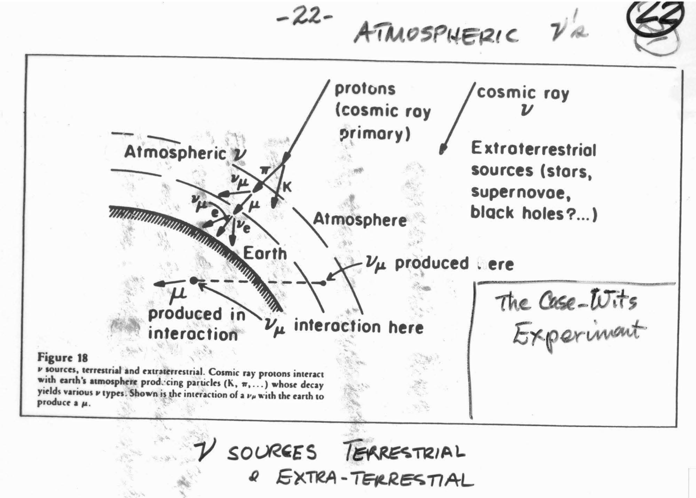
Borexino solar data - 2021



Atmospheric Neutrinos

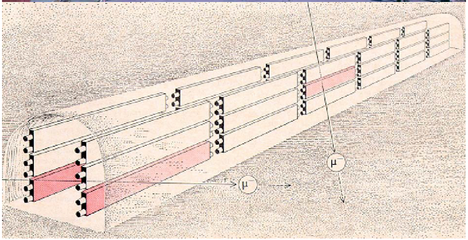
Proposal to find Atmospheric Neutrinos

Slide to find atmospheri neutrinos by Fred Reines (Case Western Institute):



The CWI-SAND Experiment

1964: The Case Western Institute-South Africa Neutrino Detector (CWI-SAND) and a search for atmospheric ν_μ at the East Rand gold mine in South Africa at 3585m depth



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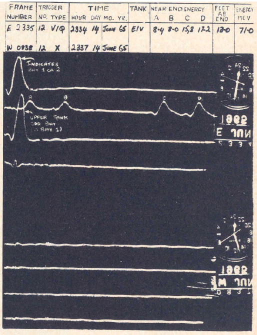
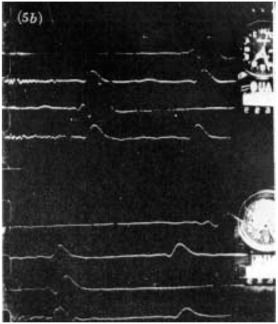


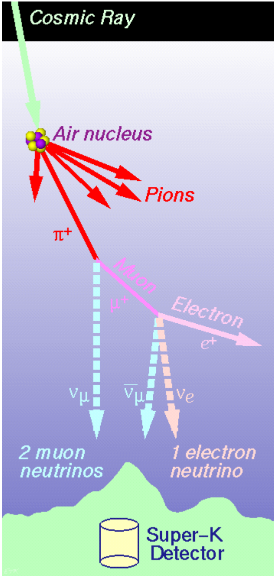
Downward-going Muon (background)

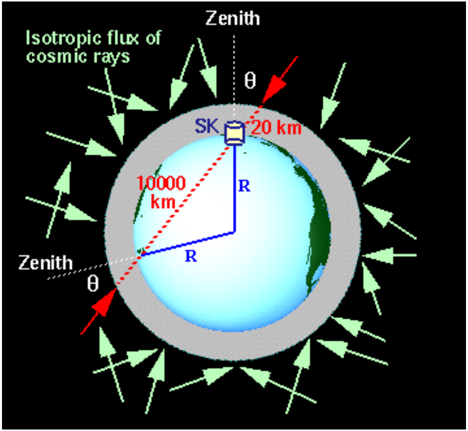


Horizontal Muon (neutrino signal)

Detection of the first neutrino in nature!

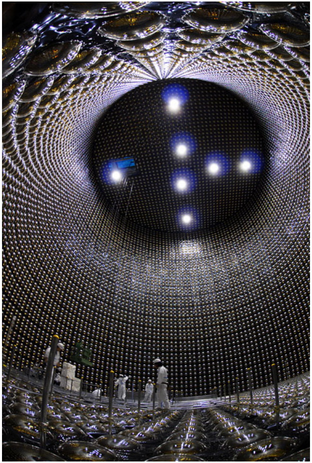
Neutrinos from our Atmosphere: $\nu_\mu, \nu_e, \bar{\nu}$





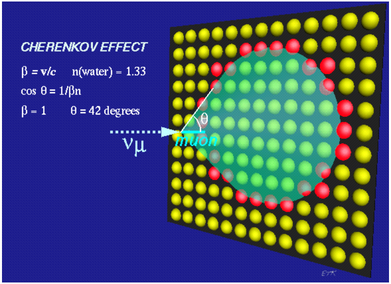
L = 0 to 13,000 km

The Super-Kamiokande Experiment. Kamioka Mine, Japan



50kT double layered tank of ultra pure water surrounded by 11,146 20" diameter photomultiplier tubes.

Neutrinos are identified by using CC interaction $\nu_{\mu,e} \rightarrow e^{\pm}, \mu^{\pm}X$. The lepton produces Cherenkov light as it goes through the detector:



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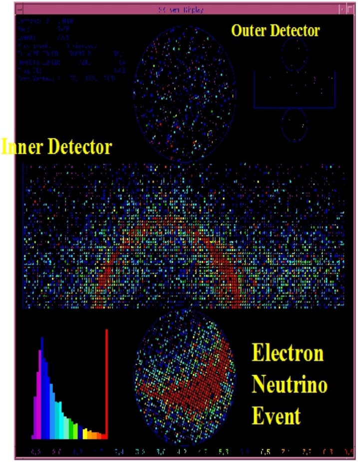
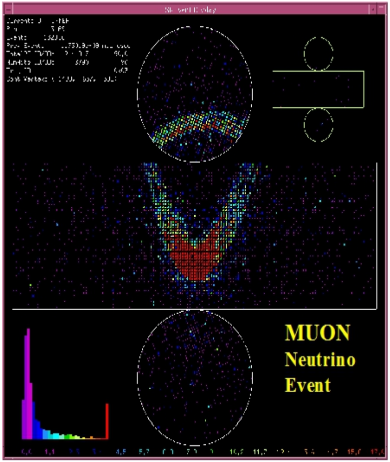
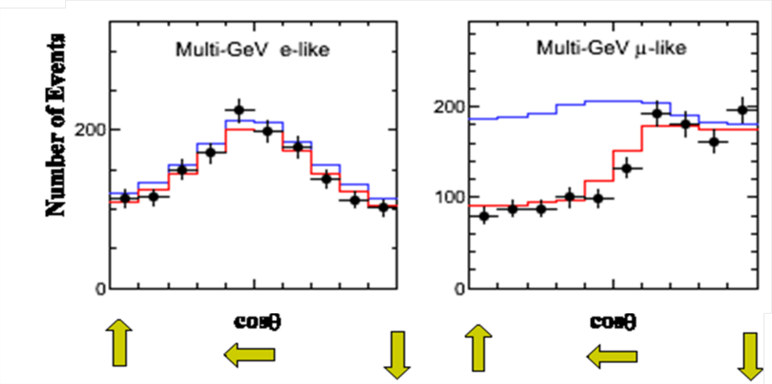




More Disappearing Neutrinos!!



All the ν_e are there! But what happened to the ν_μ ??

Neutrino Mixing

Neutrino Mixing ⇒ Oscillations

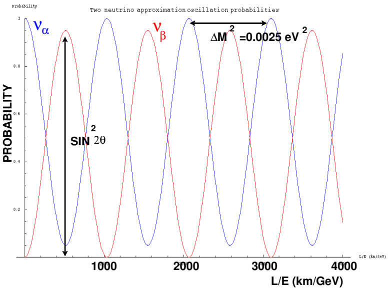
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\begin{aligned} \nu_a(t) &= \cos(\theta)\nu_1(t) + \sin(\theta)\nu_2(t) \\ P(\nu_a \rightarrow \nu_b) &= |<\nu_b|\nu_a(t)>|^2 \\ &= \sin^2(\theta)\cos^2(\theta)|e^{-iE_2 t} - e^{-iE_1 t}|^2 \end{aligned}$$

$$P(\nu_a \rightarrow \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27\Delta m^2_{21} L}{E}$$

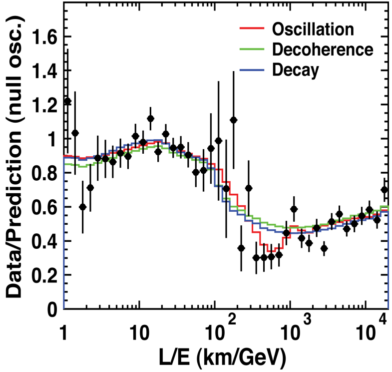
where $\Delta m^2_{21} = (m^2_2 - m^2_1)$ **in** eV^2**, L (km) and E (GeV).**

Observation of oscillations implies non-zero mass eigenstates

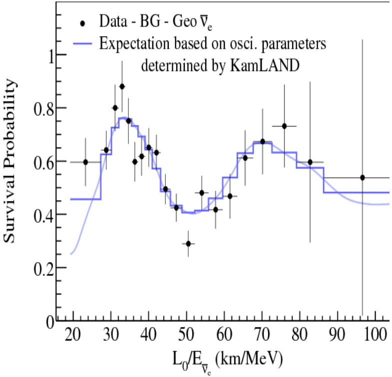


Neutrino Oscillations: Atmospheric and Solar

Super-K, atmospheric ν_μ



KamLAND, reactor $\bar{\nu}_e$



Global fit 2013:

$$\Delta m^2_{\rm atm} = 2.43^{+0.06}_{-0.10} \times 10^{-3}\ \mathbf{eV^2}$$

$$\sin^2\theta_{\rm atm} = 0.386^{+0.24}_{-0.21}$$

Atmospheric L/E $\sim$ 500 km/GeV

Global fit 2013:

$$\Delta m^2_{\rm solar} = 7.54^{+0.26}_{-0.22} \times 10^{-5}\ \mathbf{eV^2}$$

$$\sin^2\theta_{\rm solar} = 0.307^{+0.18}_{-0.16}$$

Solar L/E $\sim$ 15,000 km/GeV

Supernova Neutrinos

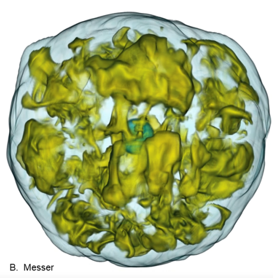
Supernova Neutrinos

Neutrinos from core-collapse supernovae

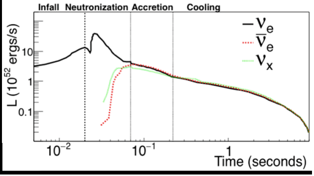
When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of ***all flavors*** with ~tens-of-MeV energies

(Energy *can* escape via ν's)

Mostly ν-νbar pairs from proto-nstar cooling



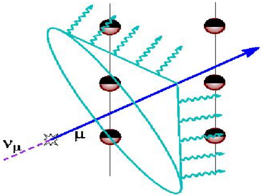
Timescale: *prompt* after core collapse, overall Δt~10's of seconds



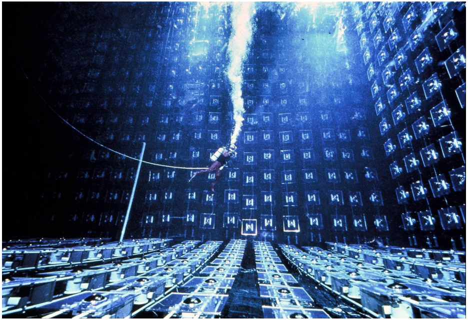
K. Scholberg

The Irvine-Michigan-Brookhaven (IMB) Detector

A relativistic charged particle going through water, produces a ring of light

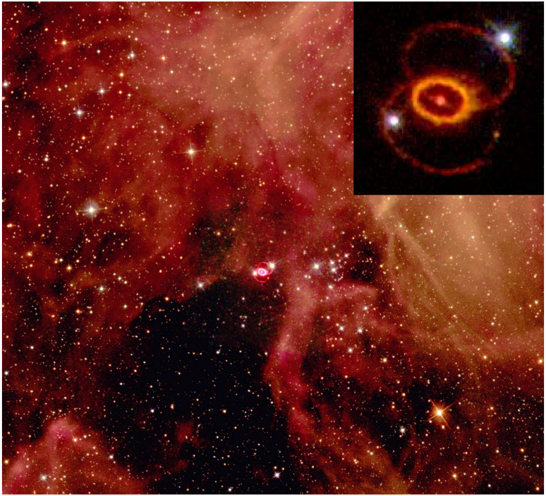


The Irvine-Michigan-Brookhaven Detector



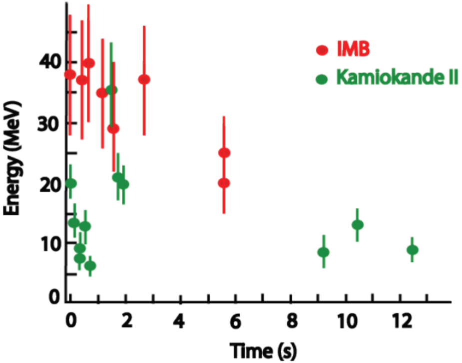
IMB consisted of a roughly cubical tank about 17 × 17.5 × 23 meters, filled with 2.5 million gallons of ultrapure water in Morton Salt Fariport Mine, Ohio. Tank surrounded by 2,048 photomultiplier tubes. IMB detected fast moving particles produced by proton decay or neutrino interactions

IMB/Kamioka Detect First Supernova Neutrinos!



1987: Supernova in large Magellanic Cloud (168,000 light years)

IMB/Kamioka Detect First Supernova Neutrinos!



2-3 hrs earlier: IMB detects 8 neutrinos

AND Kamioka detector (Japan) detects 11 neutrinos

Masatoshi Koshiba (Kamiokande, SuperKamiokande) shares 2002 Nobel Prize with Ray Davis for detection of Cosmic Neutrinos

Neutrinos and Astrophysics: An Experimental Overview

Mary Bishai

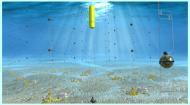
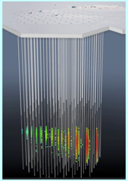
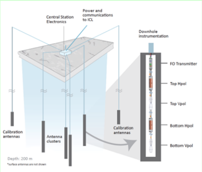
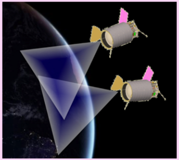
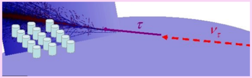
2015 Nobel Prize

Takaaki Kajita
University of Tokyo, Japan
(SuperKamiokande)

Arthur B. MacDonald
Queens University, Canada
(SNO)

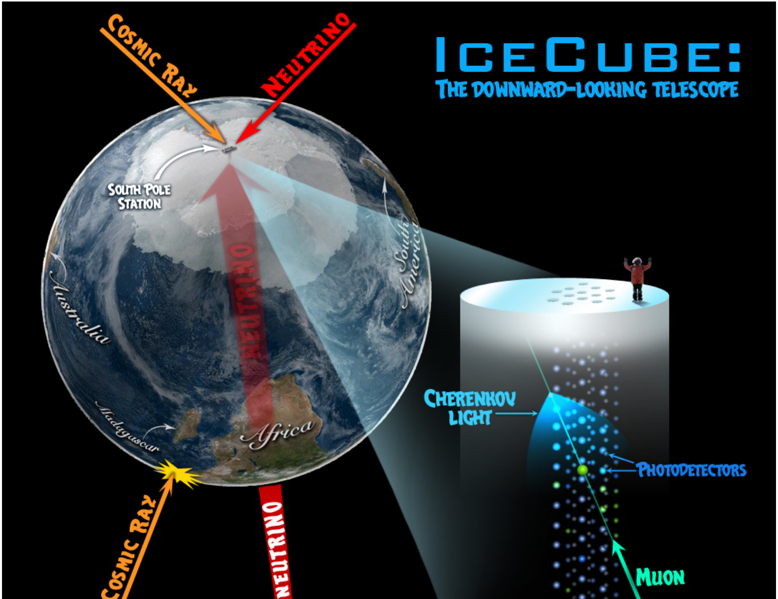
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

Detectors for Ultra High Energy Neutrinos (> 1 TeV)

Long-string Water Cherenkov	Antenna-based detectors	Cosmic-ray shower detectors
  Water and ice	  Balloon or in-ice	  Ground-based or space-based

K. Scholberg

The IceCUBE Experiment



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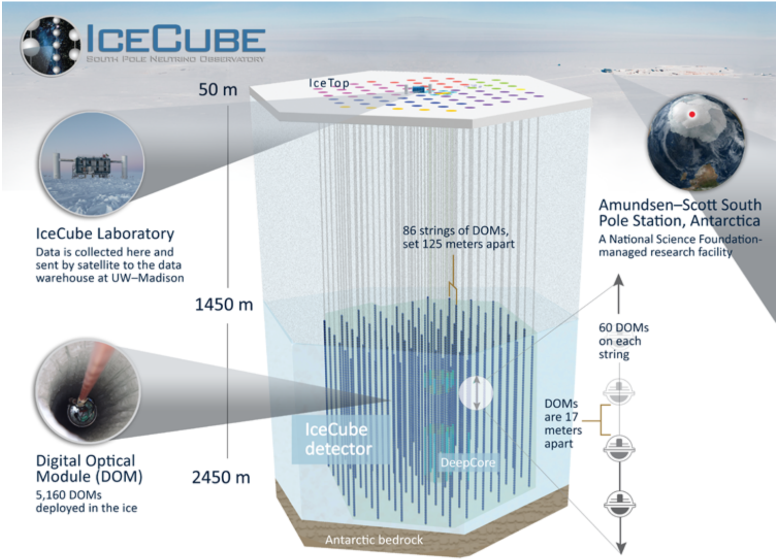
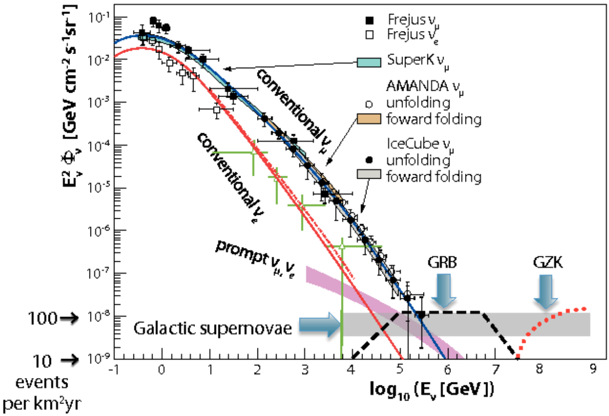
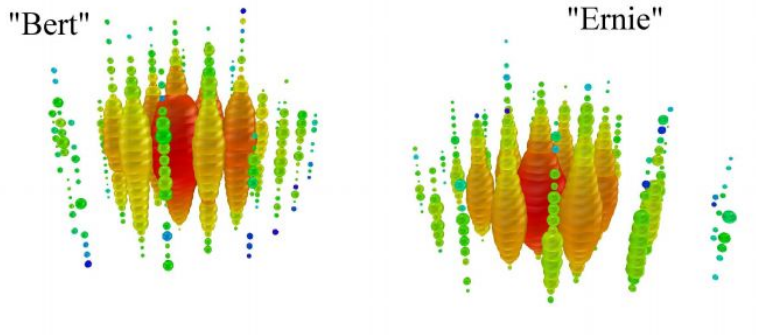


The Highest Energy Neutrinos (Gamma Ray Bursts)



The Highest Energy Neutrinos (Gamma Ray Bursts)

Neutrino events with energies > PeV (10^{15}eV)



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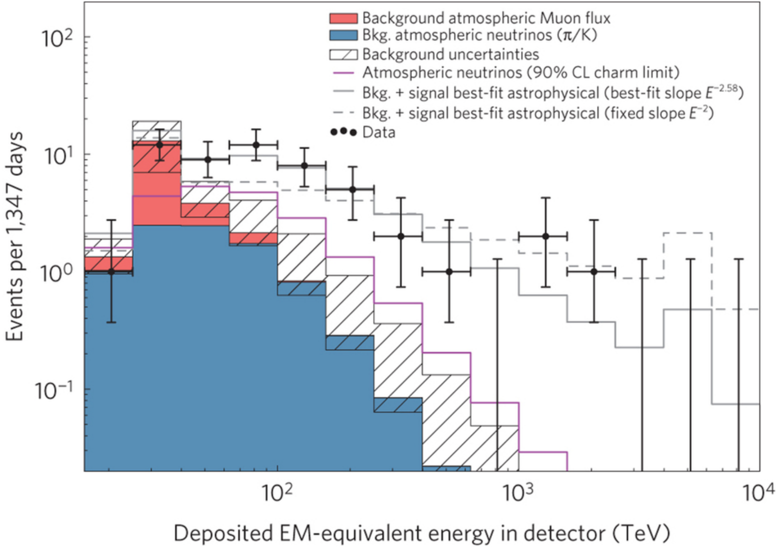


Neutrinos and Cosmology

The Cosmic Neutrino Background

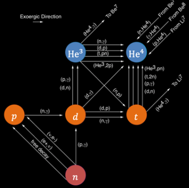
Indirect information about CNB from cosmology

Yvonne Wong, Snowmass Neutrino colloquium

Cosmological observables...

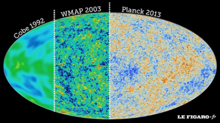
+ Supernova Ia, local H_0, etc.
(No direct neutrino effects)

Light element abundances from primordial nucleosynthesis



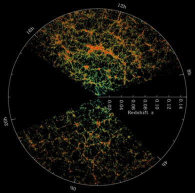
N_{eff} (expansion rate)

Cosmic microwave background anisotropies



N_{eff} (expansion rate)
Interactions (free-streaming)
Lifetime (free-streaming)

Large-scale matter distribution



$\sum m_\nu$ (perturbation growth)

Planck TTTEEE+lowE+lensing+BAO; 7-parameters

$N_{\text{eff}} = 2.99 \pm 0.34$ (95% CL)

Aghanim et al. [Planck] 2021

→ Remarkably consistent with Standard Model prediction $N_{\text{eff}} \approx 3$

Planck TTTEEE+lowE+lensing+BAO; 7-parameters

$\sum m_\nu < 0.12$ eV (95% CL)

Aghanim et al. [Planck] 2021

At face value a factor of 30 tighter than current lab bound from KATRIN, $\sum m$ <2.4 eV (90% C.L.) Aker et al. [KATRIN] 2022

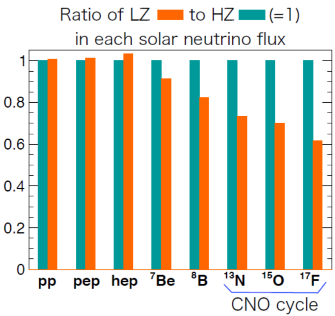
Latest Results and Future Prospects

Solar: The solar metallicity predictions

Previously, two different Standard Solar Models models predicted very different heavy metal abundance. The surface metal to hydrogen abundance ratio (Z/X):

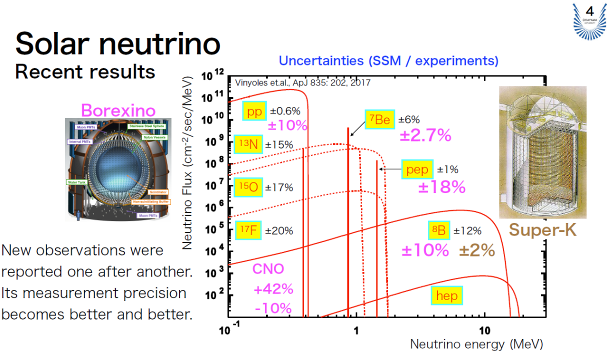
$$Z/X = 0.02292\ \mathbf{GS98} \rightarrow \text{HZModel}$$
$$Z/X = 0.01780\ \mathbf{AGSS09} \rightarrow \text{LZModel}$$

Vinyoles et.al., ApJ 835: 202, 2017



CNO neutrinos now detected!

From Y. Koshio presentation at Neutrino 2022:



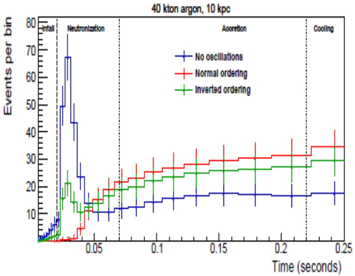
Current generation will continue to push on precision including SNO+. New experiments coming online soon like JUNO and future concepts include THEIA a 100kton scale water-based liquid-scintillator detector.

Supernova Neutrinos: Prospects

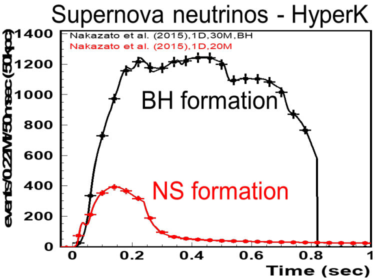
DUNE is uniquely sensitive to the ν_e component of a supernova neutrino burst:

$\nu_e + ^{40}\mathbf{Ar} \rightarrow e^- + ^{40}\mathbf{K}^*$

Expected time-dependent signal in 40 kton of liquid argon for a Supernova at 10 kpc:



HyperK is sensitive to $\bar{\nu}_e$



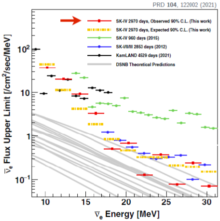
Supernova Neutrinos: Prospects

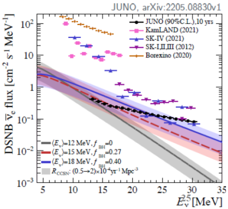
From Yifang Wang summary at neutrino 2020:

Diffused Supernova Neutrinos

- Latest results from SuperK
    - Sensitive to 1.5 $\overline{\nu}_e$/cm²/s, Horiuchi+09 model is 1.9
    - Combined upper limit of 2.6 $\overline{\nu}_e$/cm²/s
        - Most optimistic signals are excluded
    - Best fit is $1.3^{+0.90}_{-0.85}$ $\overline{\nu}_e$/cm²/s
        - 1.5σ excess over background expectation
  - Signal right at the corner ?
- SuperK-Gd successfully operated for 2 years with 0.01% loading. Phase 2 with 0.03% loading just started
- JUNO can significantly improve the sensitivity
- Future experiments: HyperK, DUNE, THEIA, ...
- Shall be discovered in ~15 years from now !

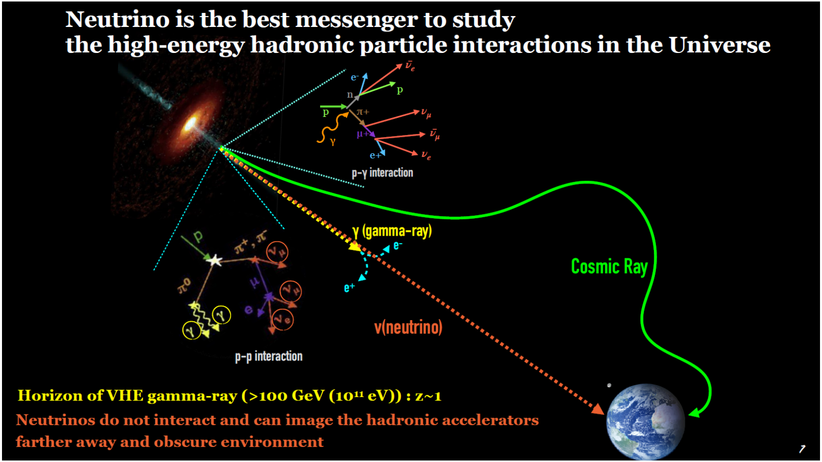
Mastbaum,Vagins,Zhao





UHE: IceCUBE-Gen2

(from N. Park at Nu2022)

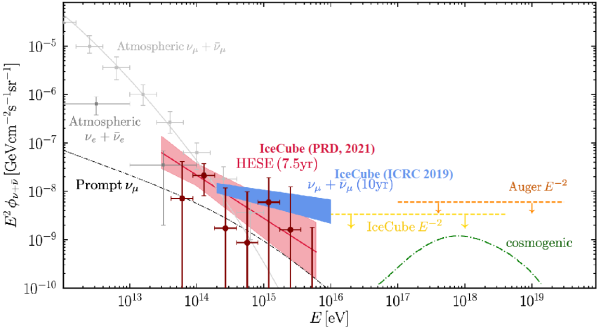


UHE: IceCUBE-Gen2

(from N. Park at Nu2022)

High-Energy Astronomical Neutrinos

IceCube has measured the astrophysical neutrino flux with multiple independent analyses



Neutrino 2022

F. Halzen and A. Kheirandish (arXiv:2202.00694)

9

UHE: IceCUBE-Gen2

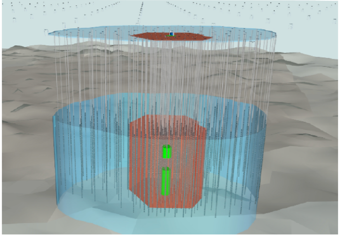
(from N. Park at Nu2022)

ICECUBE GEN2

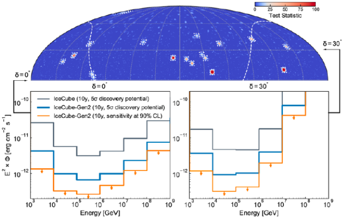
IceCube Gen-2

Designed to achieve five times better sensitivity than IceCube array

- Optical array: Eight times larger active volume compared to IceCube filled with improved optical module based on the R&D studies from IceCube Upgrade
- Surface air shower array: Matching with the optical array throughput, ~40 times higher coincident events
- Radio array: ~ 500 km² area of the antenna array for the detection of EeV neutrinos



"Deep-ice Optical Sensor Array for IceCube-Gen2" - Poster IV-a/5F **MT12-044** by A. Ishihara



IceCube-Gen2 (arXiv: 2008.04323)

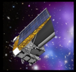
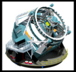
25

Future of CNB Measurements

Indirect information about CNB from cosmology

Yvonne Wong, Snowmass Neutrino colloquium

Future cosmological probes...

			1σ sensitivity to $\sum m_\nu$	1σ sensitivity to N_{eff}
	**ESA Euclid**	2024	0.011 – 0.02 eV	0.05
	**LSST**	2024	0.015 eV	0.05
	**CMB-S4**	2027	0.015 eV	0.02 – 0.04

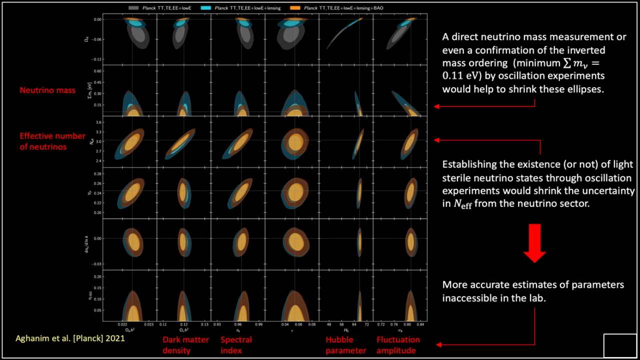
Minimum $\sum m_\nu = 0.06$ eV
From neutrino oscillations (assuming normal mass ordering)

→ Detection of the absolute neutrino mass may be possible!

Future of CNB Measurements

Neutrinos and Cosmology: indirect CNB

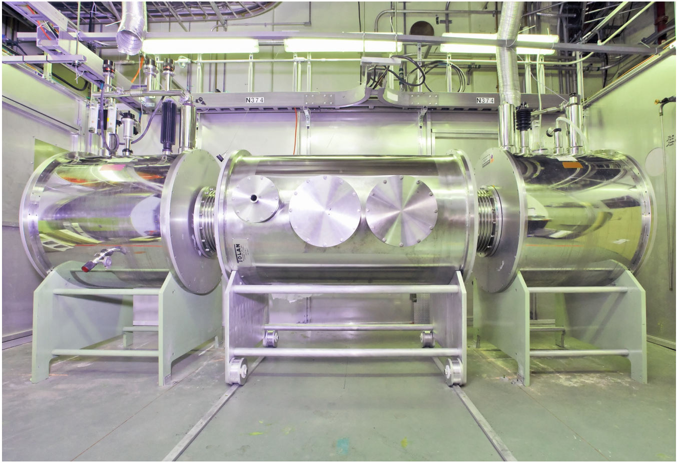
Yvonne Wong, Snowmass Neutrino colloquium



- Cosmological measurements tell us about ν properties
- **Lab experiments help to constrain cosmological fits**

PTOLEMY: Detecting Big Bang Neutrinos

Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield



How to detect Big Bang Neutrinos

From paper by Steven Weinberg in 1962 (Phys. Rev. 128:3 1457]. Detect capture of BB neutrinos on a beta decaying nucleus:

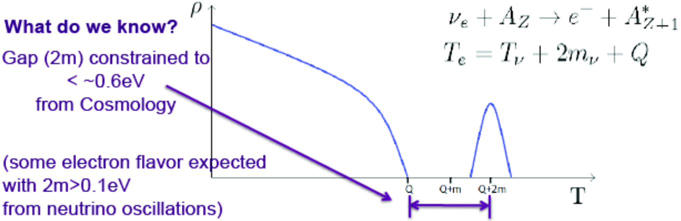
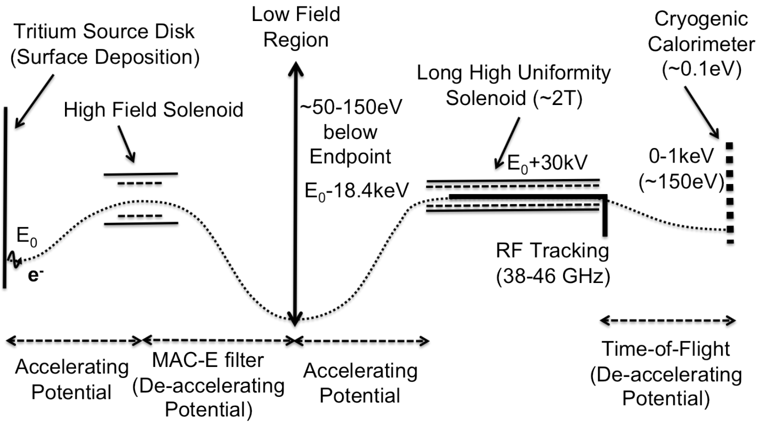


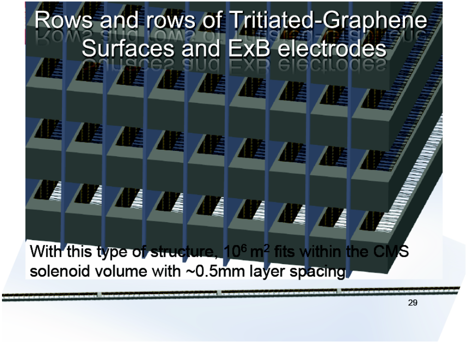
Figure 1: Emitted electron density of states vs kinetic energy for neutrino capture on beta decaying nuclei. The spike at $Q + 2m$ is the CNB signal

Experimental Concept

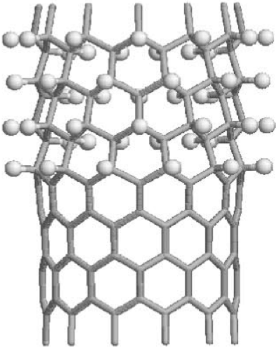


Many techincal challenges!!!

The biggest nearly insurmountable problem for relic neutrino detection using capture on tritium is to provide a large enough surface area to hold at least 100 grams of weakly bound atomic tritium!



Ultra-modern materials science needed: Use tritium trapped in very thin layers of graphene:



Summary and Conclusions

Summary and Conclusions

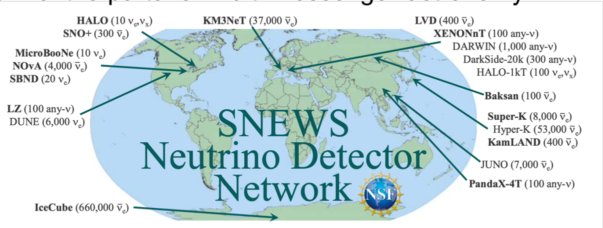
Neutrinos are messengers of astrophysics and cosmology - they tell us what is happening in the Universe, in active galactic cores, inside Supernova and details about our own Sun

Over the past few decades, experiments studying astro-physical neutrinos has primarily enhanced our understanding of the properties of the elementary particle itself such as mixing and oscillations, mass splitting, limits on absolute mass and the number of effective flavors.

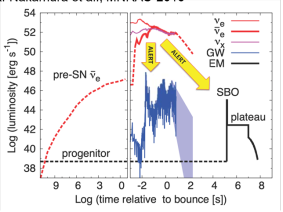
With the past two decades advancement in the understanding of neutrino properties, astro-physical neutrinos are now used as probes to study astrophysical systems: measurement of solar metallicity, UHE neutrinos and study of active galactic nuclei, search for the diffuse Supernova neutrino background, ready to study the mechanics of Supernova explosions should one occur

Summary and Conclusions

In general, the whole is more than the sum of the parts for multi-messenger astronomy



K. Nakamura et al., MNRAS 2016



Neutrinos arrive earlier than the first light from a supernova... combine signals for a high-confidence prompt alert, enabling more physics & astrophysics

K. Scholberg