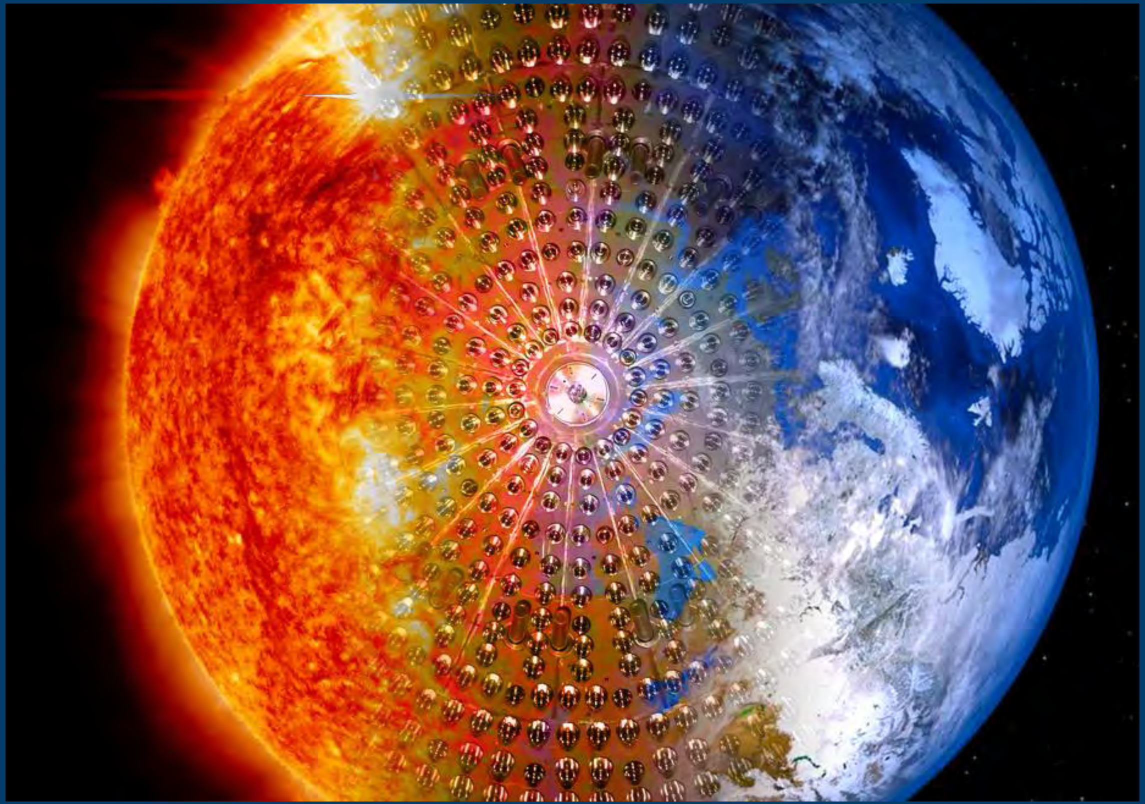
SOLAR & GEO NEUTRINOS



LIVIA LUDHOVA

GSI DARMSTADT

& JGU MAINZ UNIVERSITY, GERMANY

JULY 4, 2025, STRASBOURG, FRANCE

SUMMER SCHOOL ON NEUTRINO PHYSICS BEYOND THE STANDARD MODEL

Mitglied der Helmholtz-Gemeinschaft

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

ABOUT ME

- ✓ **W2 Professor at JGU Mainz and head of the neutrino group at GSI Darmstadt since September 2024.**

- ✓ W2 Professor at **RWTH Aachen** and head of the neutrino group at **IKP-2 FZ Jülich, Germany,** November 2015 – September 2024.
- ✓ Postdoc and researcher @ **INFN Milano, Italy**, 2005 – 2015.
- ✓ Ph.D. in Physics in 2005, Fribourg University, **Fribourg, Switzerland.**
- ✓ Ph.D. (1999) & M.Sc. (1996) in Geology and M.Sc. in Physics (2001), Comenius University, **Bratislava, Slovakia.**

- ✓ **Geology:** evolution of metamorphic rocks in the Tatra Mts., Slovakia
- ✓ **Exotic atoms:**
  - **DAΦNE/DEAR** (Kaonic hydrogen spectroscopy), INFN Frascati, Italy.
  - **CREMA** (μp-Lamb shift), PSI, Switzerland.
- ✓ **Neutrino Physics:**
  - ✓ **Borexino @** LNGS, Italy – data taking 2007 – 2021.
    - solar neutrinos and geoneutrinos.
  - ✓ **JUNO** in Jiangmen, China **- topic of today!**

Passion for Physics: at the JUNO site.

Passion for Geology:
Mutnovka Volcano, Kamchatka, Russia.

ABOUT MY NEUTRINO GROUP

http://neutrino.gsi.de/

14 nationalities passed through the group!

- Focused on experimental neutrino physics with liquid scintillator detectors.
- Dynamic and international group established in November 2015.
- Funded from Helmholtz recruitment initiative and DFG JUNO Research Unit.
- Typically about 10 persons: 2-3 postdocs, 7-8 PhDs, 1-2 Master/Bachelors.

OUTLINE

Ask questions

There are no stupid questions
(and if, it happened to all of us ☺)

1. Introduction to neutrinos
2. Detection of MeV neutrinos
3. Solar neutrinos
4. Geoneutrinos

- Historical perspective
- Motivation of the measurements
- Overview of the results
- Outlook

NEUTRINOS ARE SPECIAL

Small interaction cross sections → low rates in the detector!

Imagine……

7×10^{10} solar neutrinos / cm^2 / s

and about 200 interactions / day / 100 tons of liquid scintillator

IMPORTANCE OF RADIOPURITY

- In **100 ton** of scintillator: ~**200 events/day** from solar ν expected
  (200 / 86400 / 100 000 kg **~ 2 10^{-8} Bq/kg)**
- The scattering of a neutrino on an electron is **intrinsically not distinguishable** from a **β radioactivity** event or from Compton scattering from **γ radioactivity**

- ***Typical natural radioactivity:***
  - ✓ *Good mineral water:* *~10 Bq/kg* ^{40}K, ^{238}U, ^{232}Th
  - ✓ *Air:* *~10 Bq/m³* ^{222}Rn, ^{39}Ar, ^{85}Kr
  - ✓ *Typical rock* *~100-1000 Bq/kg* ^{40}K, ^{238}U, ^{232}Th, *+ many others*

If you want to detect solar neutrinos with liquid scintillator, you must be
9-10 orders of magnitude more radio-pure than anything on Earth!

NEUTRINOS ARE SPECIAL

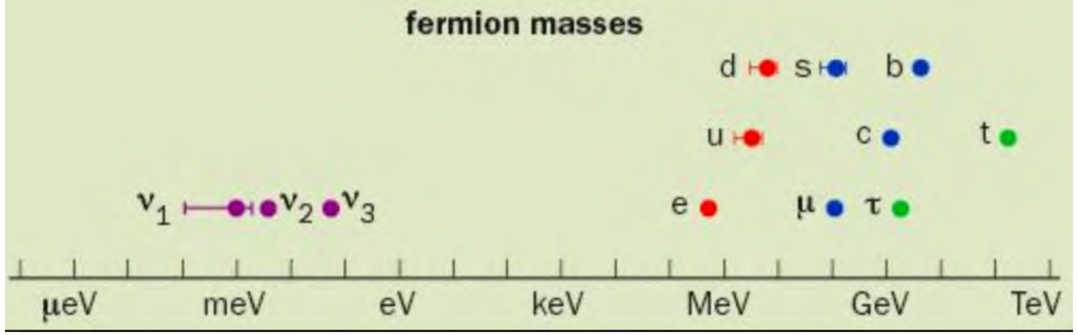
Only weak interactions

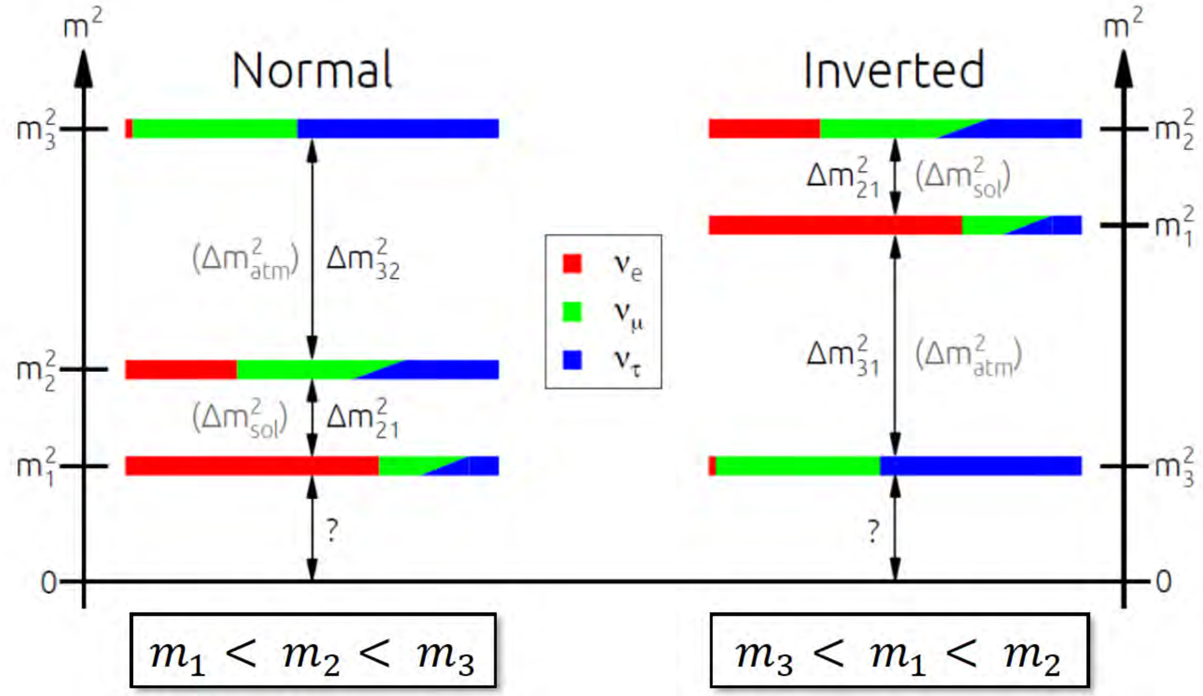
- ✓ **Difficult to detect**
  - Large detectors
  - Underground laboratories
  - Extreme radio-purity
- ✓ **Bring unperturbed information about the source (Sun, Earth,** SN)

Open questions in neutrino physics

- ✓ **Mass Hierarchy** (Normal vs Inverted)
  - CP-violating phase
  - Octant of θ_{23} mixing angle
  - Absolute mass-scale
  - Origin of neutrino mass (Dirac vs Majorana)
- ✓ Existence of sterile neutrino

linked





$$\Delta m^2_{31,\mathrm{normal}} > \Delta m^2_{31,\mathrm{inverted}}$$

Δm^2_{31} = has opposite signs in the two hierarchies!

NEUTRINO MIXING AND OSCILLATIONS

α = e, μ, τ
Flavour eigenstates
INTERACTIONS

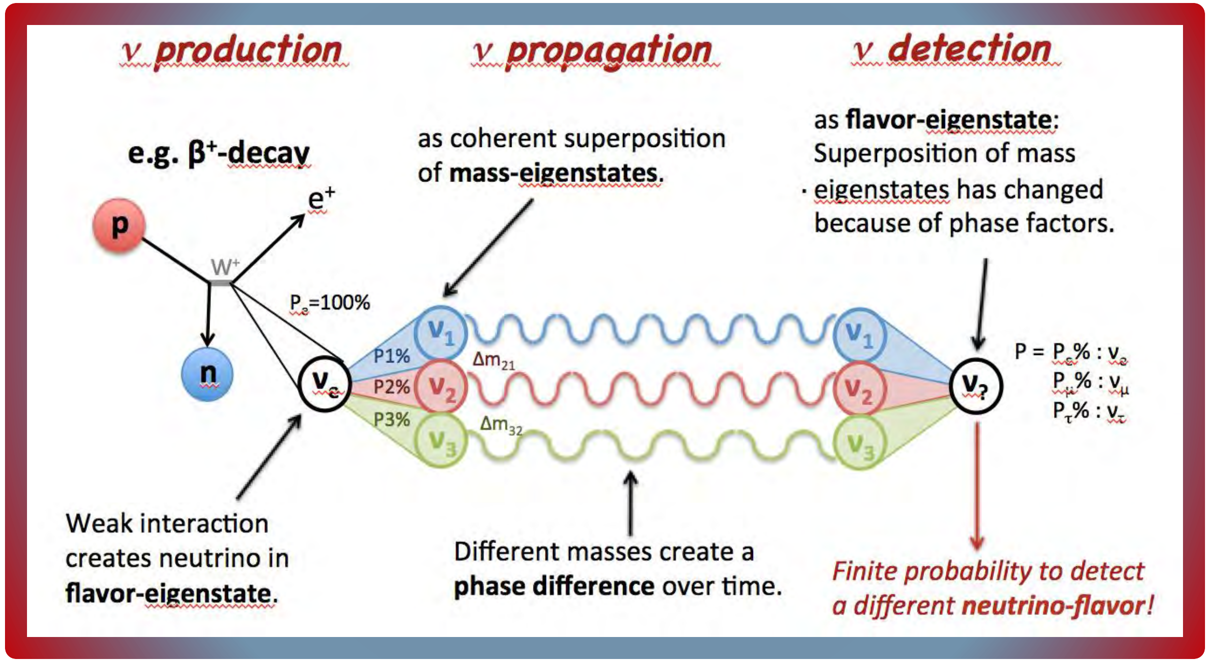
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}\,|\nu_i\rangle$$

i = 1, 2, 3
Mass eigenstates
PROPAGATION

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric | Reactor | Solar | Majorana

- **3 mixing angles θ_{ij}:**
  - θ_{23} H45° (which quadrant?)
  - θ_{13} H9° (non-0 value confirmed in 2012)
  - θ_{12} H33°
- **Majorana phases $\alpha 1$, $\alpha 2$** and **CP-violating phase δ** unknown



Courtesy M. Wurm

- **Neutrino oscillations**
  - Non-0 rest mass (Nobel prize 2015)
  - Survival probability of a certain flavour = f(baseline L, E_ν)
  - Different combination (L, E_ν) => sensitivity to different (θ_{ij}, Δm_{ij}^2)
  - Oscillations in matter -> effective (θ_{ij}, Δm_{ij}^2) parameters = f(e^- density N_e, E_ν)

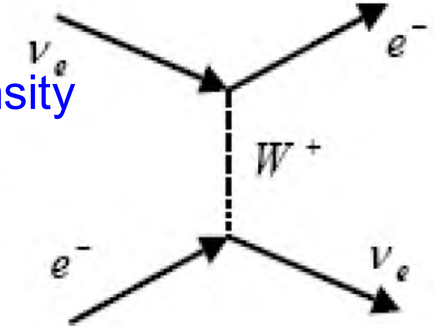
ν-oscillations in matter: MSW effect

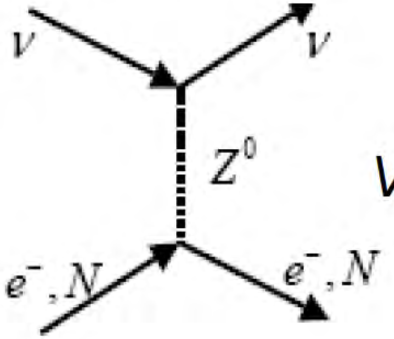
Electrons exist in standard matter – μ, τ do not. Electron neutrinos travelling in matter can experience an extra charged current interaction that other flavours cannot.

N_e = matter electron density

$$V_W = \sqrt{2}\, G_F N_e$$

Interaction Potential





$$V_Z = -\frac{\sqrt{2}}{2} G_F N_n$$

Oscillation probabilites are now function of **(Δm^2_M, $\sin^2 2\theta_M$)**

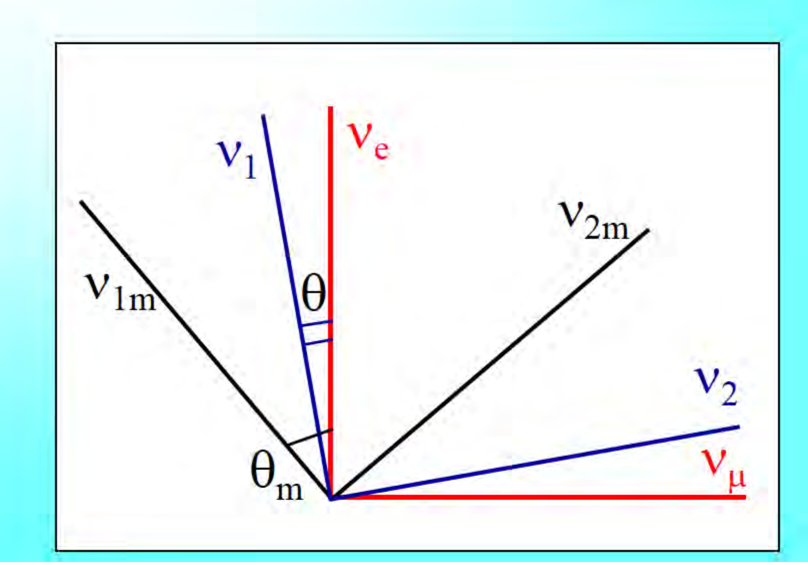
Effective oscillation parameters (Δm^2_M, θ_M) instead of the vacuum ones (Δm^2_V, θ_V)

$$\Delta m^2_M = \Delta m^2_V \sqrt{\sin^2(2\theta_V) + (\cos 2\theta_V - \zeta)^2}$$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta_V}{\sin^2 2\theta_V + (\cos 2\theta_V - \zeta)^2}$$

$$\zeta = \frac{2\sqrt{2}\, G_F N_e E}{\Delta m^2_V}$$

ν-oscillations in matter: MSW effect



Mixing angle determines flavors (flavor content) of eigenstates of propagation

θ_m depends on n_e, E

$$\Delta m_M^2 = \Delta m_V^2 \sqrt{\sin^2(2\theta_V) + (\cos 2\theta_V - \zeta)^2}$$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta_V}{\sin^2 2\theta_V + (\cos 2\theta_V - \zeta)^2}$$

$$\zeta = \frac{2\sqrt{2} G_F N_e E}{\Delta m_V^2}$$

N_e = matter electron density

E= neutrino energy

Flavour content of mass eigenstates changes.

Resonance character of the MSW effect

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta_V}{\sin^2 2\theta_V + (\cos 2\theta_V - \zeta)^2} \qquad \zeta = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{Vac}}$$

- ✓ The effect can be enhanced by a **resonance**
  Mikheyev–Smirnov–Wolfenstein effect

For solar neutrinos

$\Delta m^2 = m_2^2 - m_1^2$

Matter effects on solar neutrinos, we know $m_2 > m_1$.

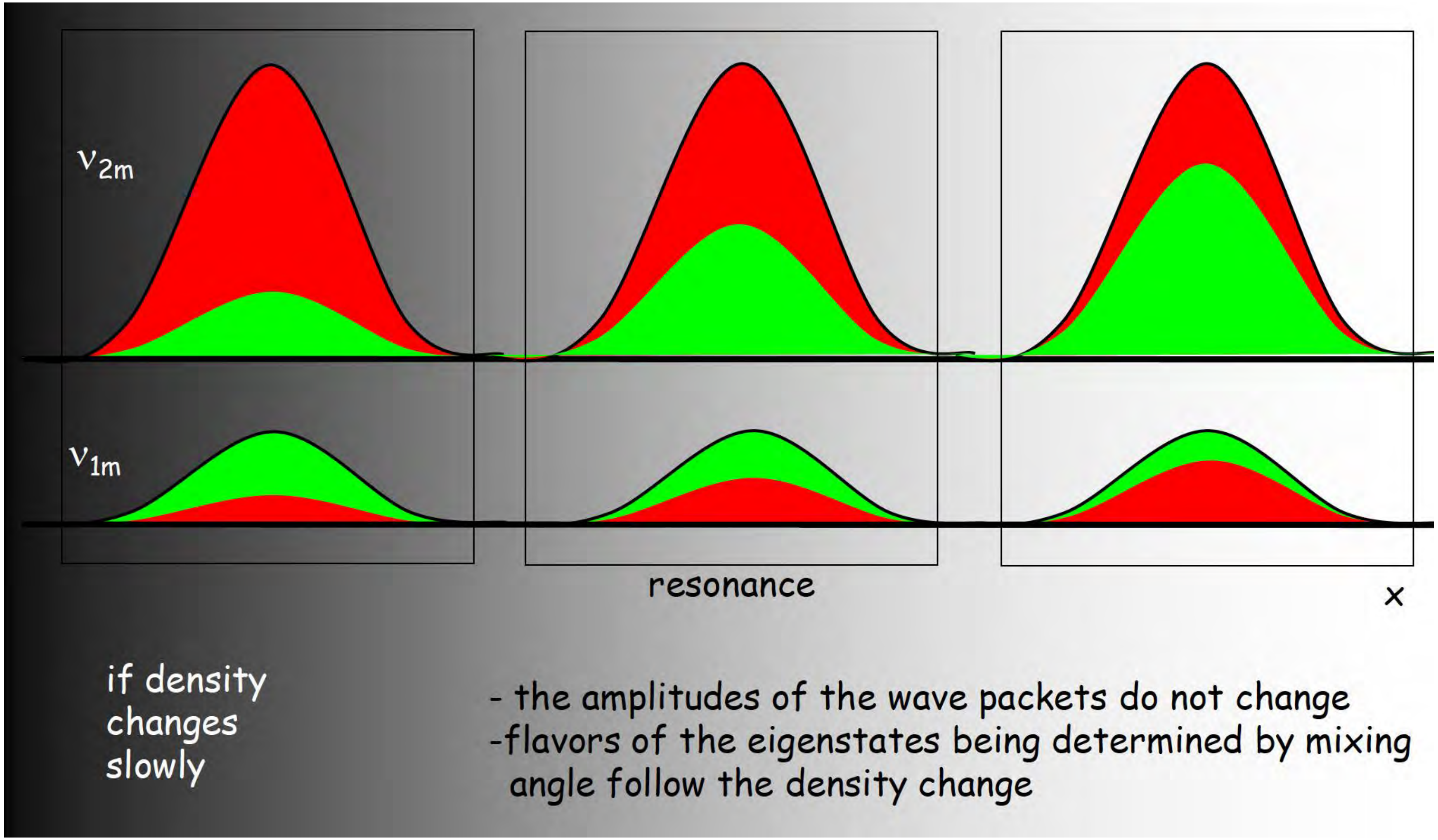
- ✓ **There is a combination of electron density N_e and neutrino energies E, for which the effective mixing angle = 1 (even if the vacuum mixing is small)**

$$\zeta = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2} = \cos 2\theta_V \Rightarrow \sin^2 2\theta_M = 1$$

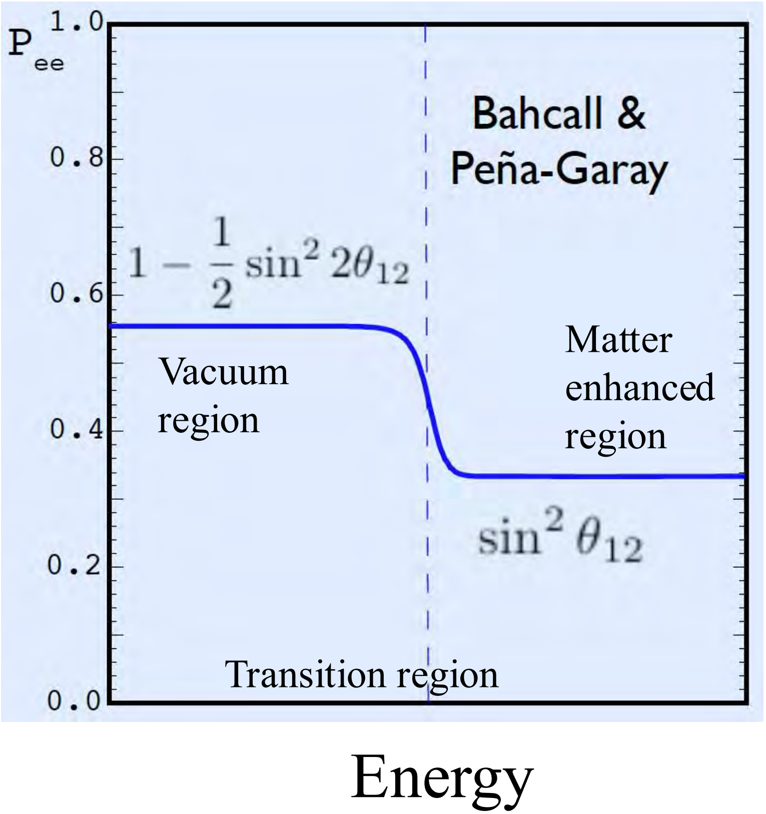
Maximal mixing

- ✓ **This yields the energy dependence of the "survival probability": $P_{ee}(E)$**

Adiabatic conversion in the Sun



MSW for solar neutrinos



Before reaching the Earth:

- **pp neutrinos:** ~15 million oscillation lengths
- **^8B neutrinos:** ~900,000 oscillation lengths

Vacuum oscillation (57%):

$$P_{ee} = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{12}^2 L}{4E_\nu}\right)$$

sin² averages to ½.

Matter enhanced oscillation (33%):

$$|\langle \nu_e | \nu_2 \rangle|^2 = \sin^2\theta_{12}$$

Neutrino detection is special

Cosmogenic background -> underground laboratories

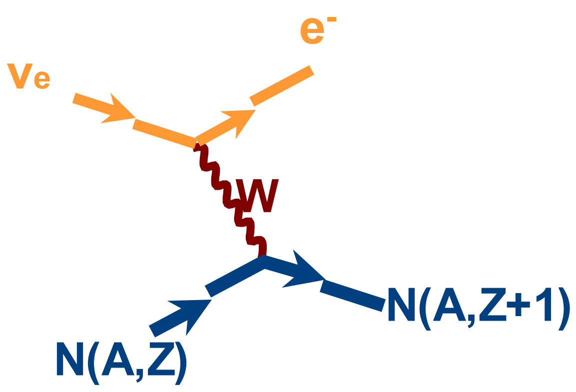
BASIC DETECTION INTERACTIONS

1) Charged current (CC) interaction

Inverse β decay on a proton or a nucleus

ν_e **ONLY** at MeV energies

- Muon and Tau lepton too heavy



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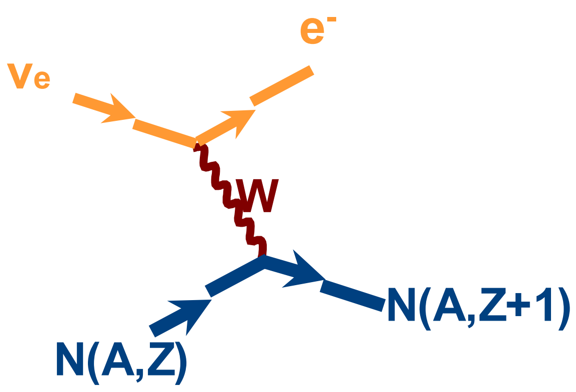

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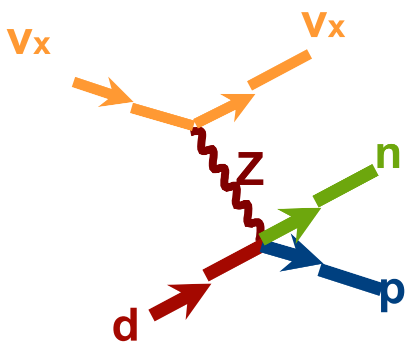

2) Neutral current (NC)

Elastic scattering on a nucleus

- either with the emission of a recoil neutron
- All neutrino flavors have the SAME cross section

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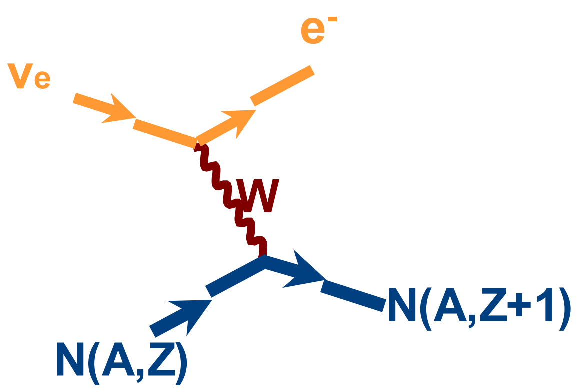

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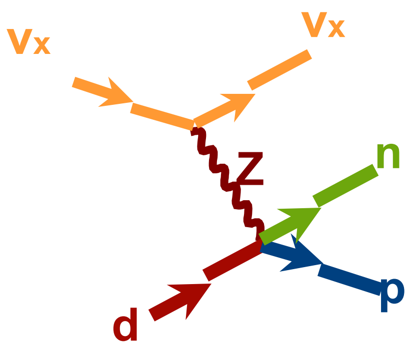
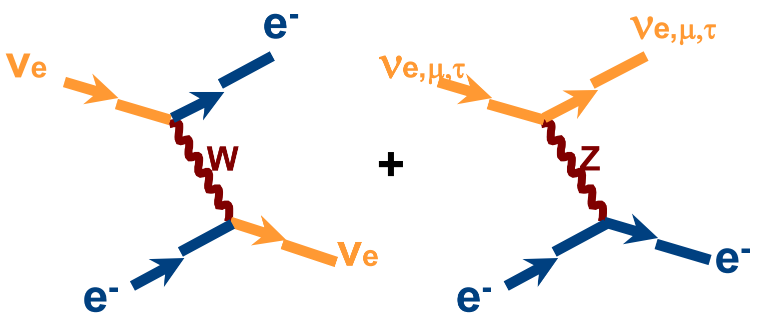


3) Elastic scattering off an electron

(charged current (CC) + neutral current (NC))

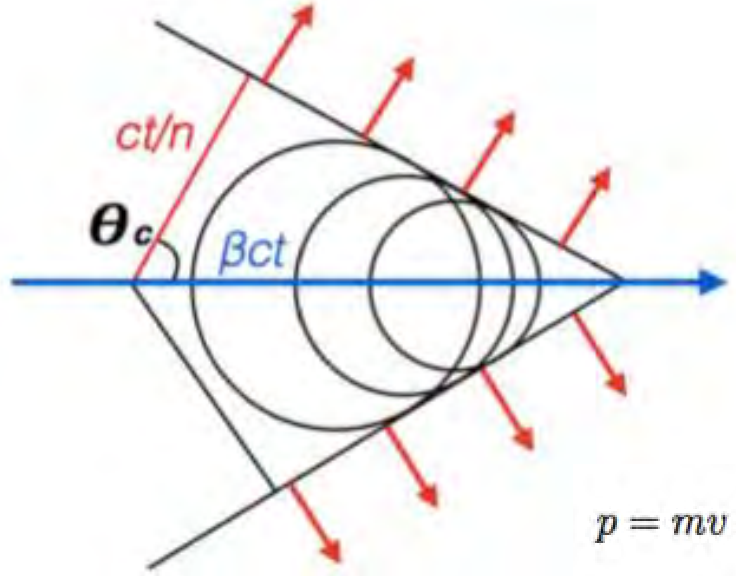
- Cross section for ν_e and $\nu_{\mu,\tau}$ is different
- for $\nu_{\mu,\tau}$ NC only;



The secondary particles are typically detected in :

1) Water – Cherenkov radiation (solars)
2) Liquid scintillator – scintillation light (solars and geoneutrinos)

Cherenkov cone



$$p = mv \geq \frac{mc}{n}$$

The geometry of the emitted photon with speed of c/n, being slower than the charged particle with speed of v = βc, results in a cone-shaped shock wave front

Momentum threshold :

(mβc > mc/n in the figure)

β > 1/n

(with the n~1.34 in the water, the momentum thresholds (MeV/c) are:

e : 0.57

μ : 118

π^{+-} : 156

p : 1051

Energy threshold :

$$\frac{E_s}{m_0 c^2} = \frac{1}{\sqrt{1-\beta_s^2}} = \frac{1}{\sqrt{1-1/n^2}}$$

m_0 : particle mass

Cherenkov angle: $\cos\theta_C = \frac{c/n}{\beta c} = \frac{c}{nv}$

1) maximum angle for a particle with the speed v=c ~ 42° in the water
2) slower particle -> smaller Cherenkov angle

Cherenkov radiation in neutrino detection

Solar neutrinos

Kamiokande (past) /**Superkamiokande (present)** /Hyperkamiokande (future)

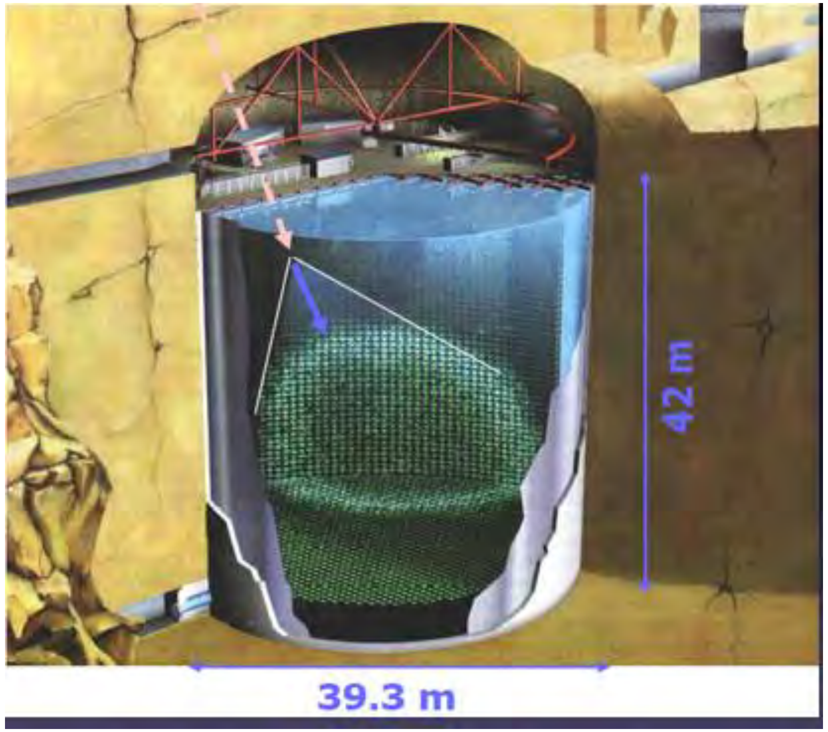
SNO (past) – Nobel Prize for solar detection!

Atmospheric and accelerator neutrinos:
Kamiokande/Superkamiokand /Hyperkamiokande

String detectors for atmospheric and Ultra High-Energy neutrinos

Ice-Cube
KM3NET – ORCA & ARCA
Baikal

Super-Kamiokande
Kamioka, Japan
50 kton water

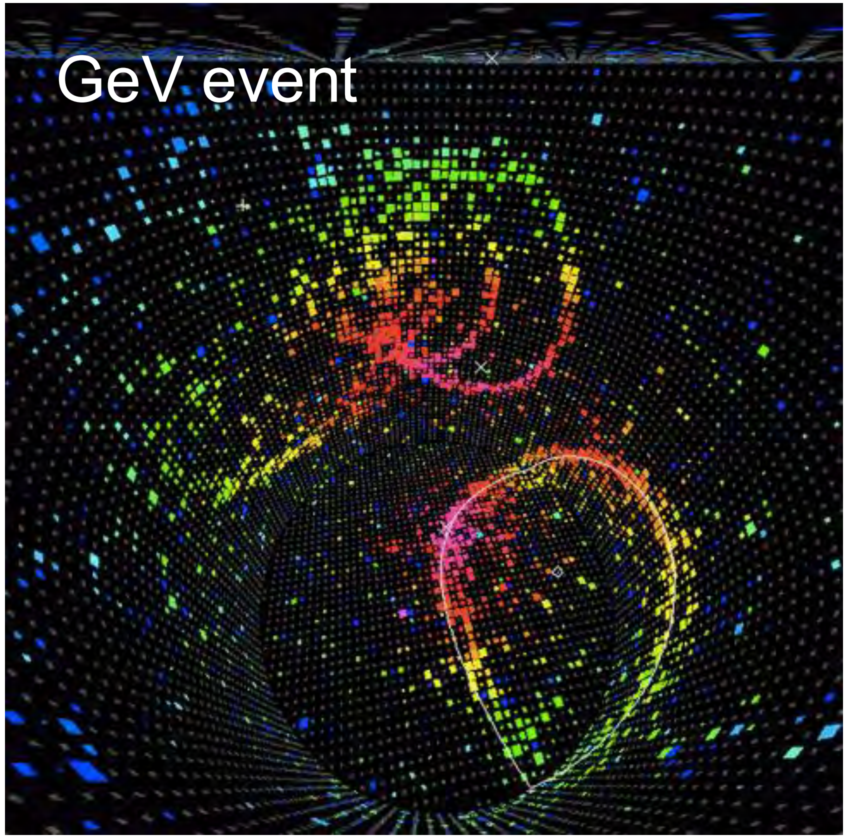


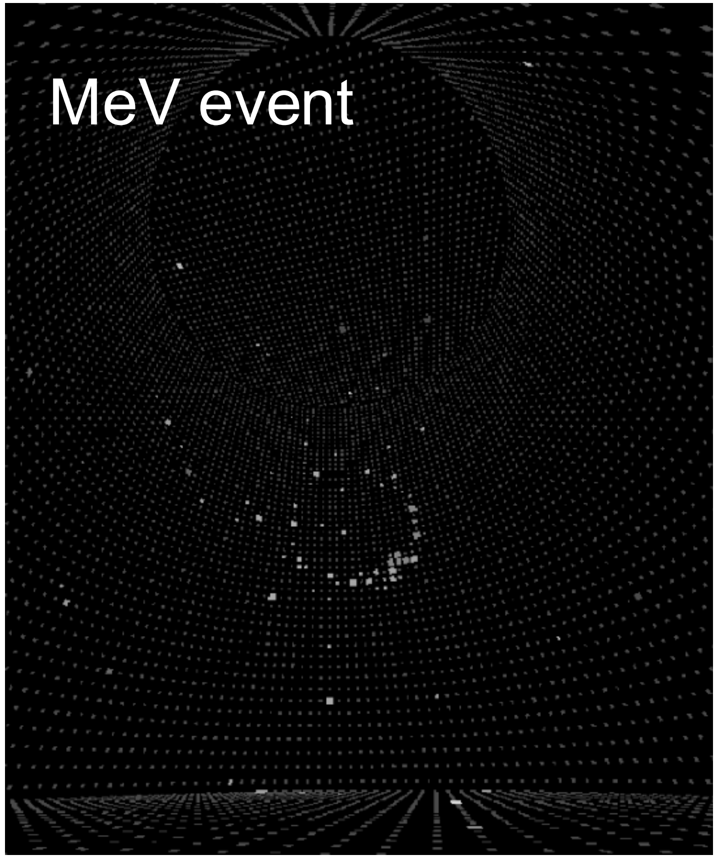
SNO
Sudbury, Canada
1 kton water

Cherenkov cone in SuperK

By reconstruction of timing & spacial pattern of Cherenkov ring, one can learn

→ vertex position, direction,





Liquid-scintillator based detection

Scintillation based neutrino detection

Detection of ionizing radiation through the scintillation light induced in special organic liquid materials = scintillators

Important characteristics:

- High scintillation efficiency and high light yield.
- Good energy and position resolution.
- Low energy threshold.
- No directionality.
- Real time measurement (energy of single events).
- Quenching: non-linearities between energy deposit and produced light.
- Pulse shape discrimination (alpha/beta, positron/electron).
- High transparency.
- Fast pulses (short decay time of the scintillation light production).
- Refractive index similar to the glass (phototube matching).

Liquid scintillators in neutrino detection

Solar neutrinos

Borexino (ended in 2021), SNO+ (first data), JUNO – (about to start)

Geoneutrinos

Borexino, KamLAND (present), SNO+, JUNO

Reactor antineutrinos

KamLAND

Daya Bay, RENO, Double Chooz (just ended)

JUNO

0-ββ decay

KamLAND – Zen (present)

SNO+ (present)

Sterile neutrino search with reactor antineutrinos

NEOS, Stereo, Neutrino-4, Prospect (present)

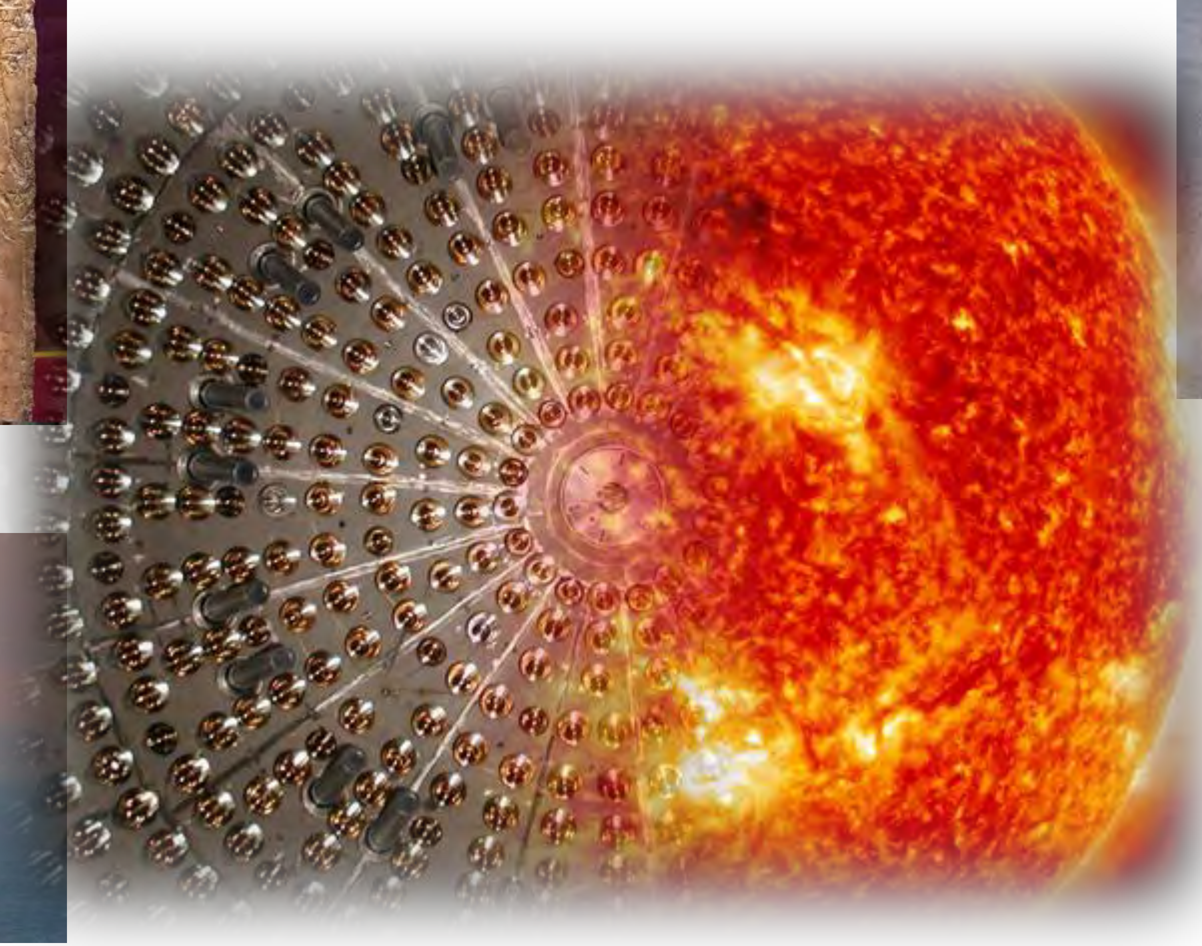
Supernovae neutrinos

LVD (past)

Accelerator neutrinos

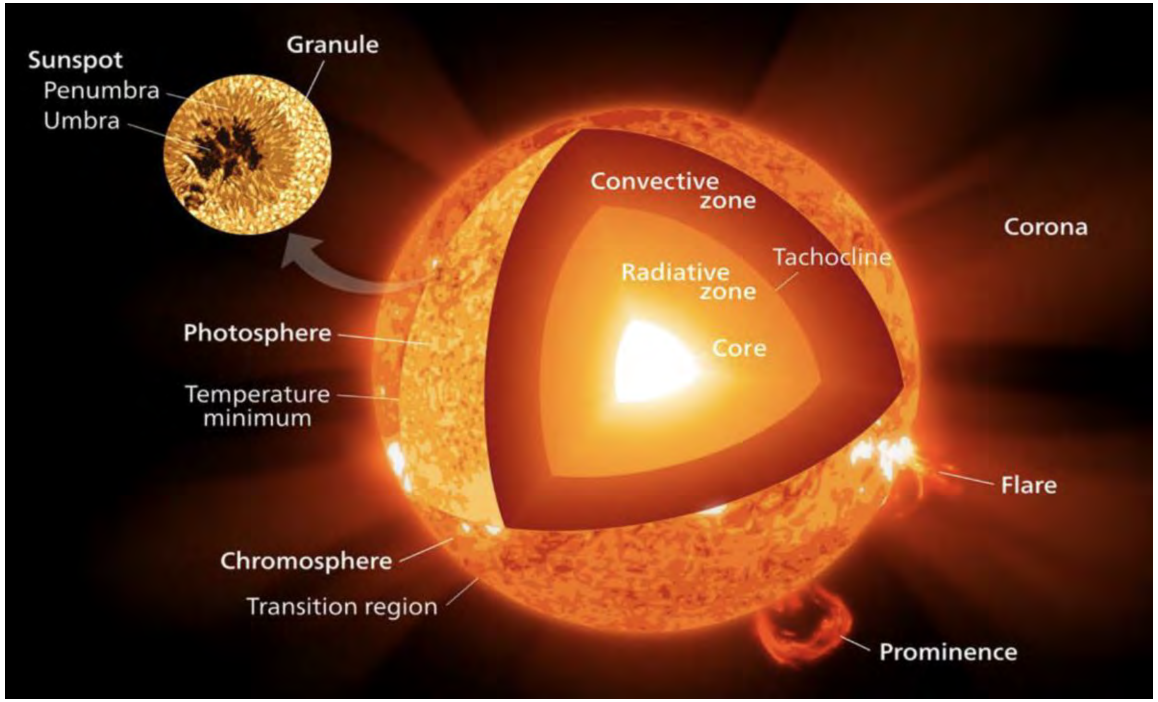
LSND (past)

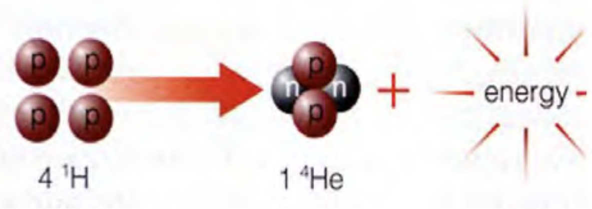
Solar neutrinos



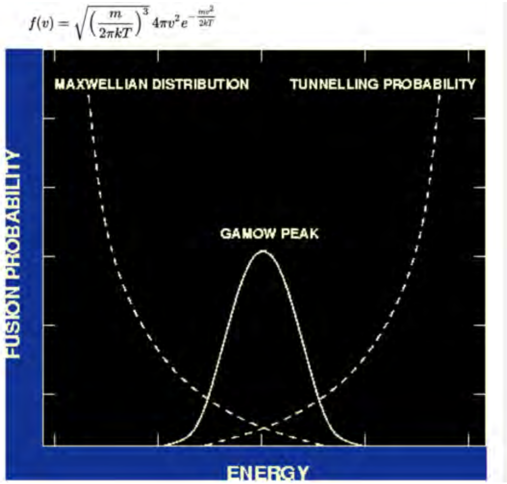
Millennia of fascination continued.

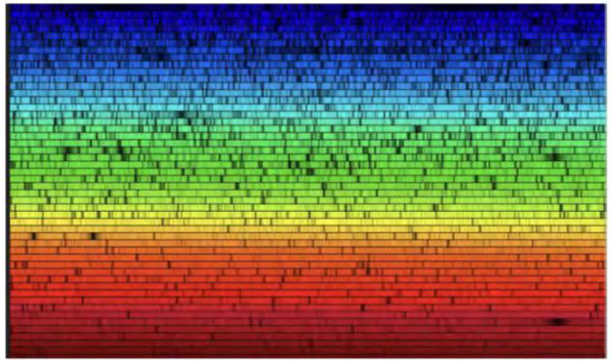
THE SUN





(26.7 MeV) + 2 ν





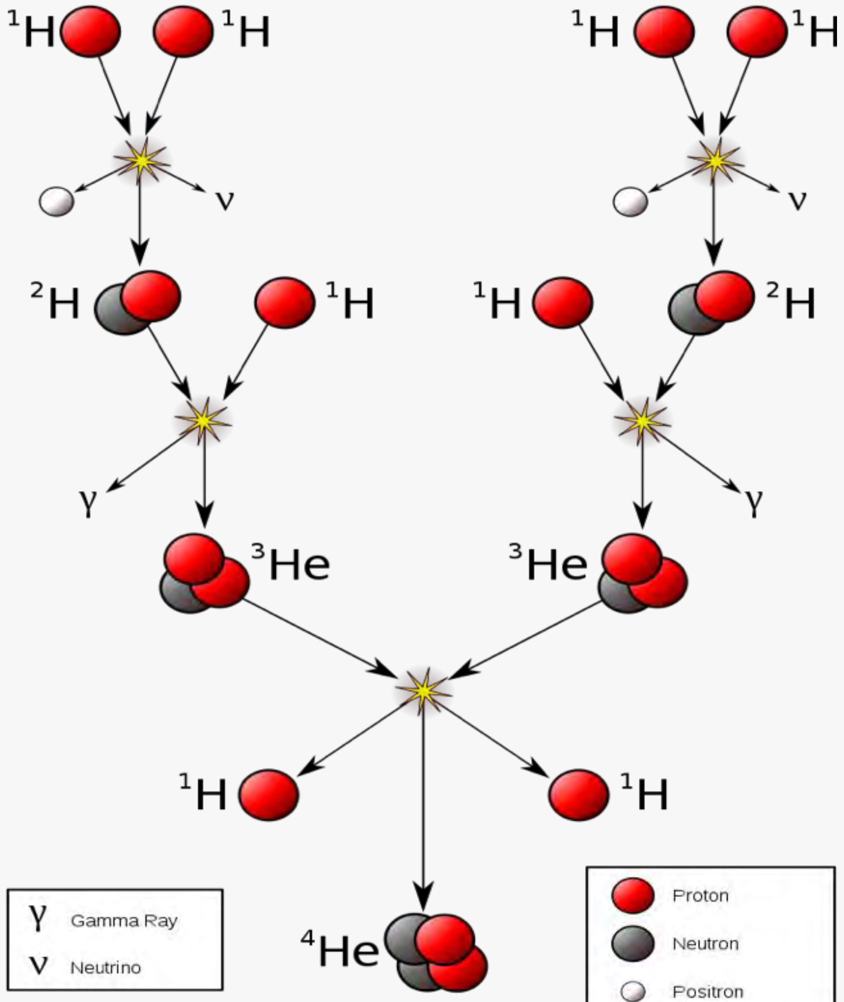
- Luminosity (3.8418.10^{33} erg/s (± 0.35%) (1 erg = 10^{-7} J)
- Age (~4.6.10^{9} years - old meteorites)
- Mass M = 1.989·10^{30} kg (± 0.02%)
- Radius R = 6.9598 ·10^{8}m (± 0.01%)

- Nucleosynthesis occurs only in the core.
- Neutrinos reach the Earth in ~ 8 minutes.
- Photons take order of 100,000 years to reach the photosphere.

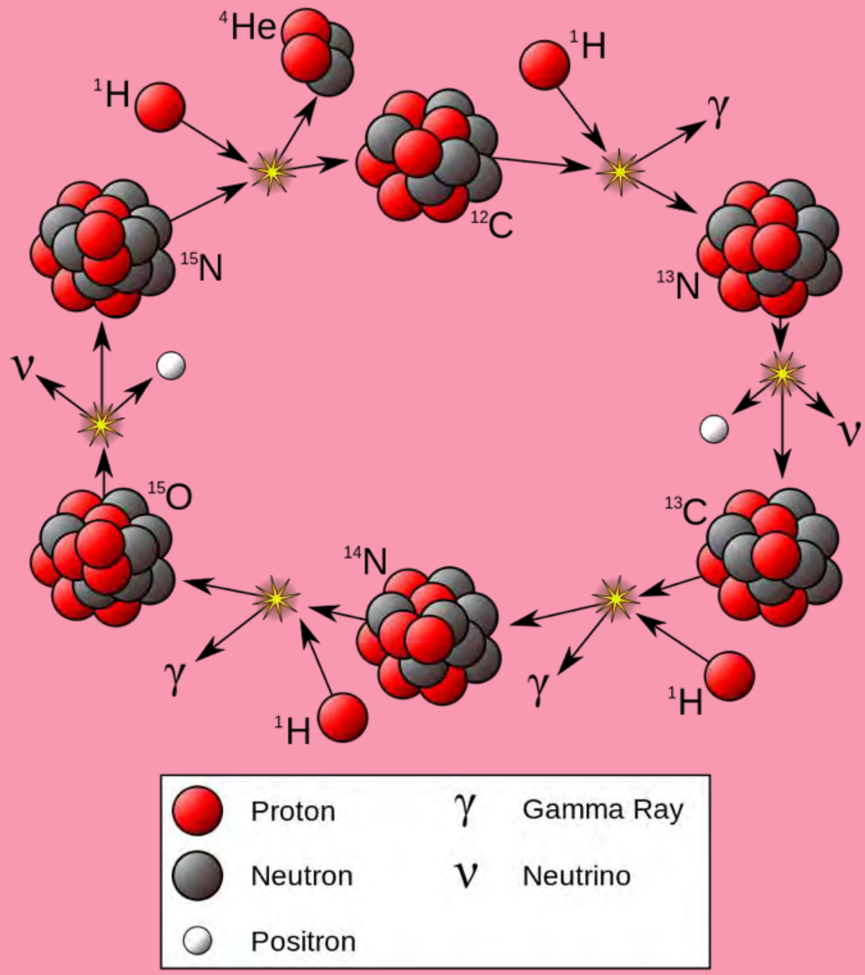
HYDROGEN-TO-HELIUM FUSION

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e \qquad Q \approx 26.7 MeV$$

pp-chain: ~99% solar energy



CNO-cycle: < 1% solar energy



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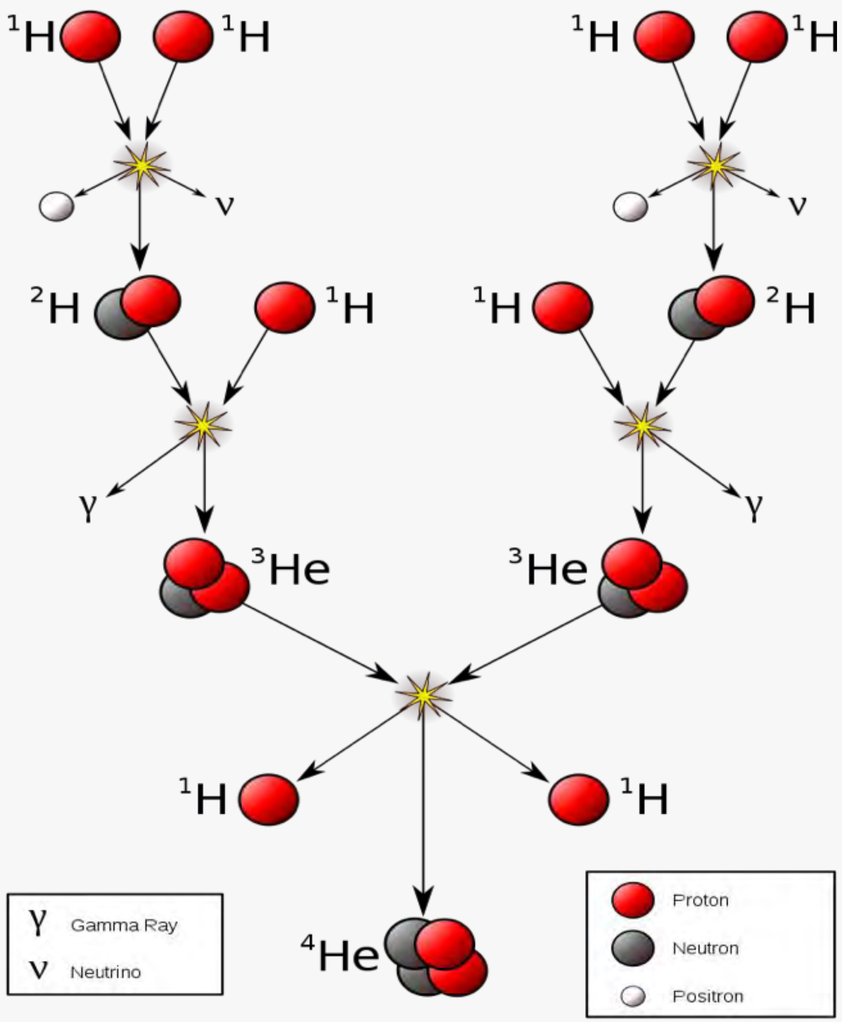
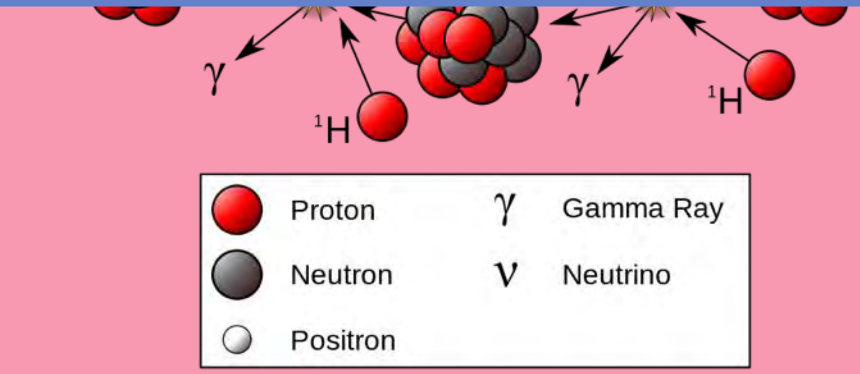


CNO-cycle: < 1% solar energy

In stars with M > 1.3 solar mass, the CNO cycle is the dominant energy source.

That makes
the CNO fusion cycle
the main Hydrogen-to-Helium
conversion process in the stars.



STANDARD SOLAR MODELS (SSM)

Inputs:

- **Basic properties of the Sun:**
  - luminosity
  - age, mass, radius
- **Nuclear parameters**
  - cross sections
  - Q-values…
- **Radiation opacity**
- **Surface abundance of metals** (C, N, O, Ne, Mg, Si, Ar, Fe) – to - hydrogen ratio **(Z/X = metallicity)**
- **Elemental physics laws**
  - Equations of state
  - Energy-transport equations
  - Conservation laws

Outputs:

to be compared with independent data

- **Helioseismology** (sound-waves speed profiles)
- **Neutrino fluxes**

Metallicity influences **the solar neutrino fluxes** in two ways:

- **Indirect for all neutrinos:** opacity -> temperature -> cross sections -> flux
- **Direct for the CNO neutrinos:** **influence through C, N, O catalyzing the fusion**

SOLAR METALLICITY PROBLEM

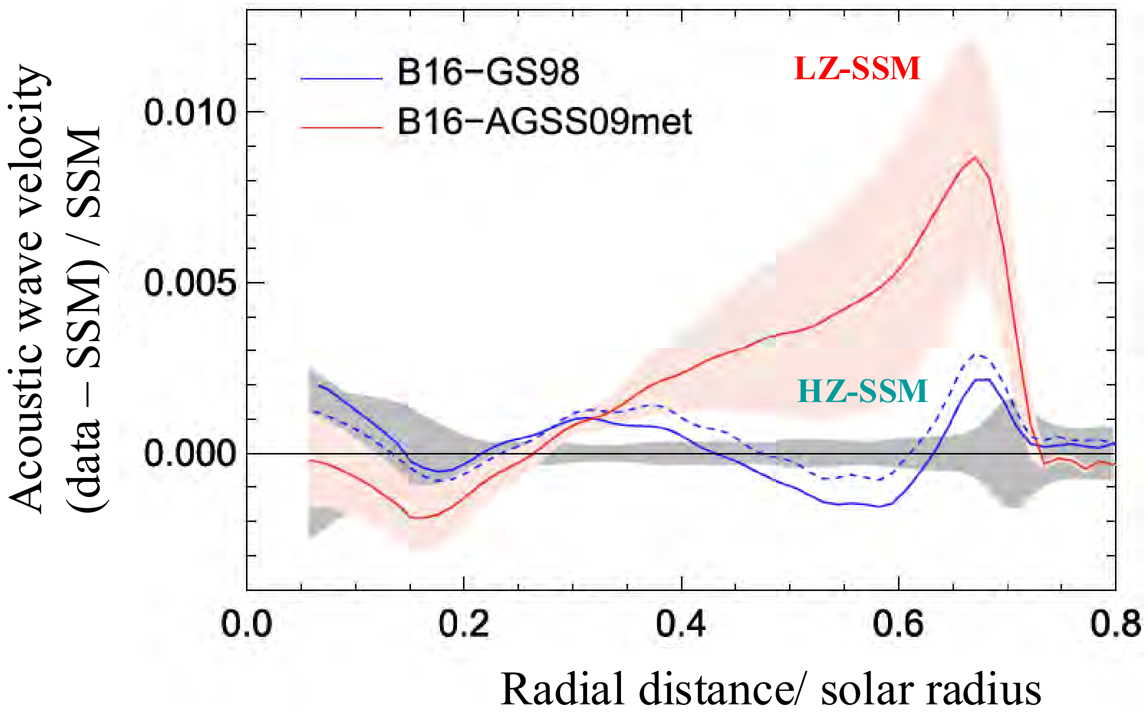
B16 Standard Solar Model with different metallicity inputs:

High-Metallicity HZ-SSM: older GS98 metallicity input: Z/X = 0.0229

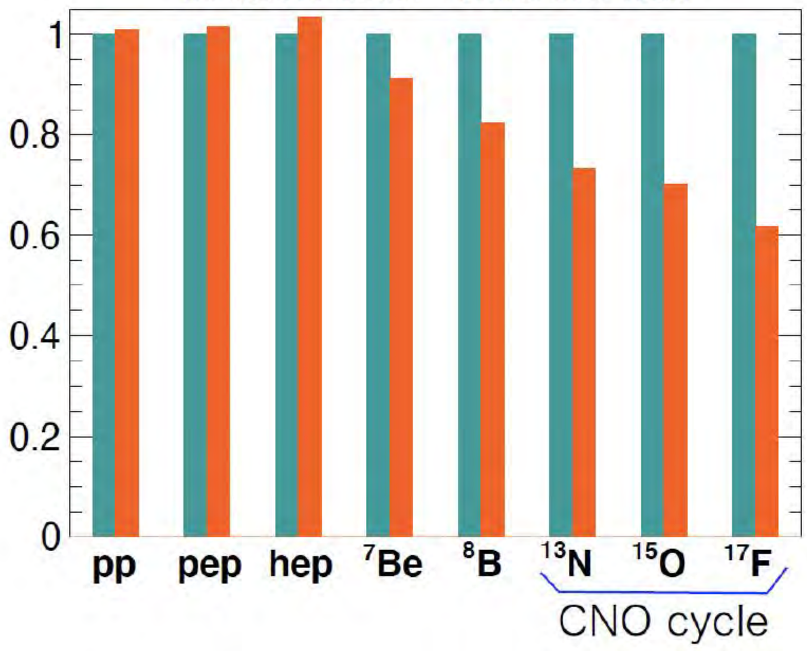
Low-Metallicity LZ SSM: newer AGSS09 metallicity input: Z/X = 0.0178

Low metallicity inputs, based on the new spectroscopic analysis and 3D models of solar atmosphere, spoil the agreement of the **HZ-SSM (using older metallicity)** with the helio-seismological data. The **LZ-SSM** in contrast with the helio-seismological data.

Fractional sound speed difference as a function of radius



Ratio of LZ to HZ (=1) in each solar neutrino flux



From J. Maneira @ Neutrino 2024

EVOLUTION OF THE METALLICITY PREDICTIONS

Recent studies still discrepant

1998

GS98*: **high metallicity**

Uses 1D hydrodynamical model of solar atmosphere

Z/X= 0.023

Helioseismology: ok

Grevesse et al.,Space Sci.Rev. (1998**)85]*

2009

AGS09met*: **low metallicity**

Uses 3D hydrodynamical model of solar atmosphere

Z/X= 0.018

Helioseismology: ko

**A. Serenelli er al., Astr. J. 743,(2011)24*

2011

Caffau11*: **low metallicity**

Uses 3D hydrodynamical model of solar atmosphere

Z/X= 0.0209

Helioseismology: ko

**E.Caffau et al., Sol.Phys. (2011) 268*

2021

AGG21*: **low metallicity**

Uses 3D hydrodynamical model of solar atmosphere

Z/X= 0.0187

Helioseismology: ko

**Asplund et al .Rev.Astr.Astr A&A (2021) 653*

2022

MB22*: **high metallicity**

Uses 3D hydrodynamical model of solar atmosphere

Z/X= 0.0225

Helioseismology: ok

Magg et al., arXiV:2203.02255

SOLAR NEUTRINOS AND WHY TO STUDY THEM

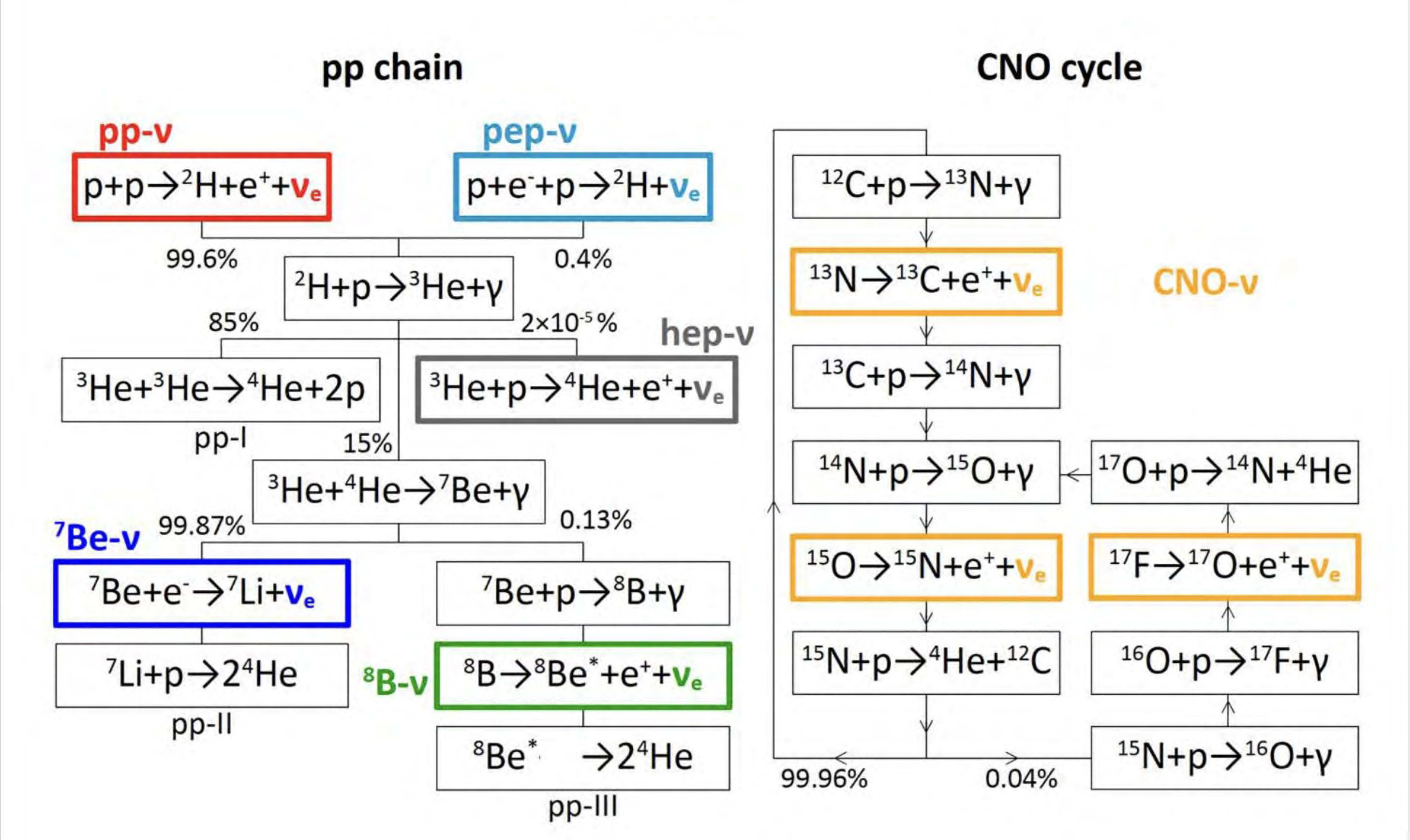
Neutrino physics

- **Neutrino oscillation parameters:** solar sector ($\theta_{12,}\ \Delta m^2{}_{12}$) and global fits.
- **Survival probability P_{ee} as f(E_ν):** matter effects, testing LMA-MSW prediction and its upturn.
- Searches for **Non-standard Neutrino Interactions.**

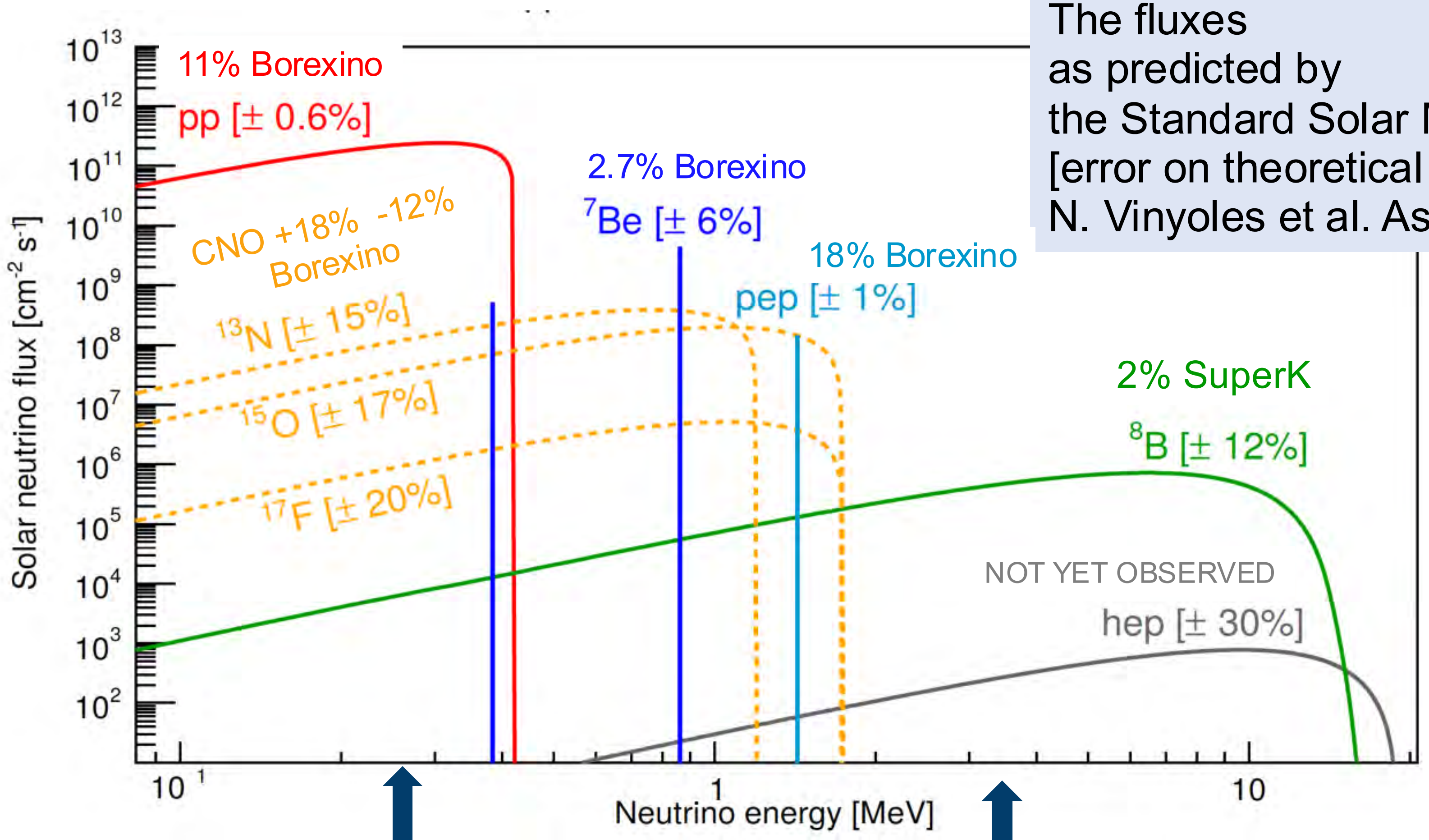
Solar and stellar physics

- Direct probe of **nuclear fusion.**
- Photon vs neutrino luminosity: testing **thermo-dynamical stability** of the Sun.
- **Standard Solar Models:**
  - ✓ Metallicity problem.

SOLAR NEUTRINOS FROM PP CHAIN AND CNO CYCLE



ENERGY SPECTRUM OF SOLAR NEUTRINOS



The fluxes
as predicted by
the Standard Solar Model
[error on theoretical predictions].
N. Vinyoles et al. Astrop. J 836 (2017) 202

Borexino threshold
with liquid scintillator

Super-Kamiokande threshold
with water Cherenkov

Short history of solar ν experiments in 1 slide

70's-80's: Homestake (R. Davies): Radiochemistry: $E_\nu > 814$ keV
- ✓ $^{37}Cl + \nu \dashrightarrow {}^{37}Ar + e^-$
- ✓**THE FIRST DETECTION!** deficit in the observed flux, skepticism
- ✓final triumph, **Nobel prize 2002**
- ✓**J. Bahcall** continues the development of the Standard Solar Model

80's-90's: (super)Kamiokande: Water Cherenkov: $E_\nu > 5$ MeV
- ✓confirms deficit on ^{8}B-ν and with a real-time technique
- ✓first neutrino picture of the Sun (directionality)
- ✓neutrinos from other stars observed (supernova SN1987-A)

90's: Gallex (GNO) and Sage: Radiochemistry: $E_\nu > 233$ keV
- ✓ $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
- ✓deficit observed also at low energy, but is energy dependent!

2001: SNO: Water Cherenkov: $E_\nu > 5$ MeV
- ✓**flavour transformation of solar neutrinos proved**
- ✓CC (electron flavor) and NC (all flavors) interactions separately in **D_2O**
- ✓total flux agrees with Standard Solar Model !

2002: KamLAND: Liquid scintillator
- ✓observes and measures oscillations of electron anti-neutrinos from reactors

2007 - 2021: Borexino: Liquid scintillator of extreme radiopurity: : $E_\nu > 300$ keV
- ✓First real-time observation of ^{7}Be, pep, pp neutrinos
- ✓Observation of CNO
- ✓Low-energy ^{8}B neuttrinos (> 3 MeV recoiled e^-)

First detection

Solar-neutrino puzzle

Solution: Neutrino oscillations!

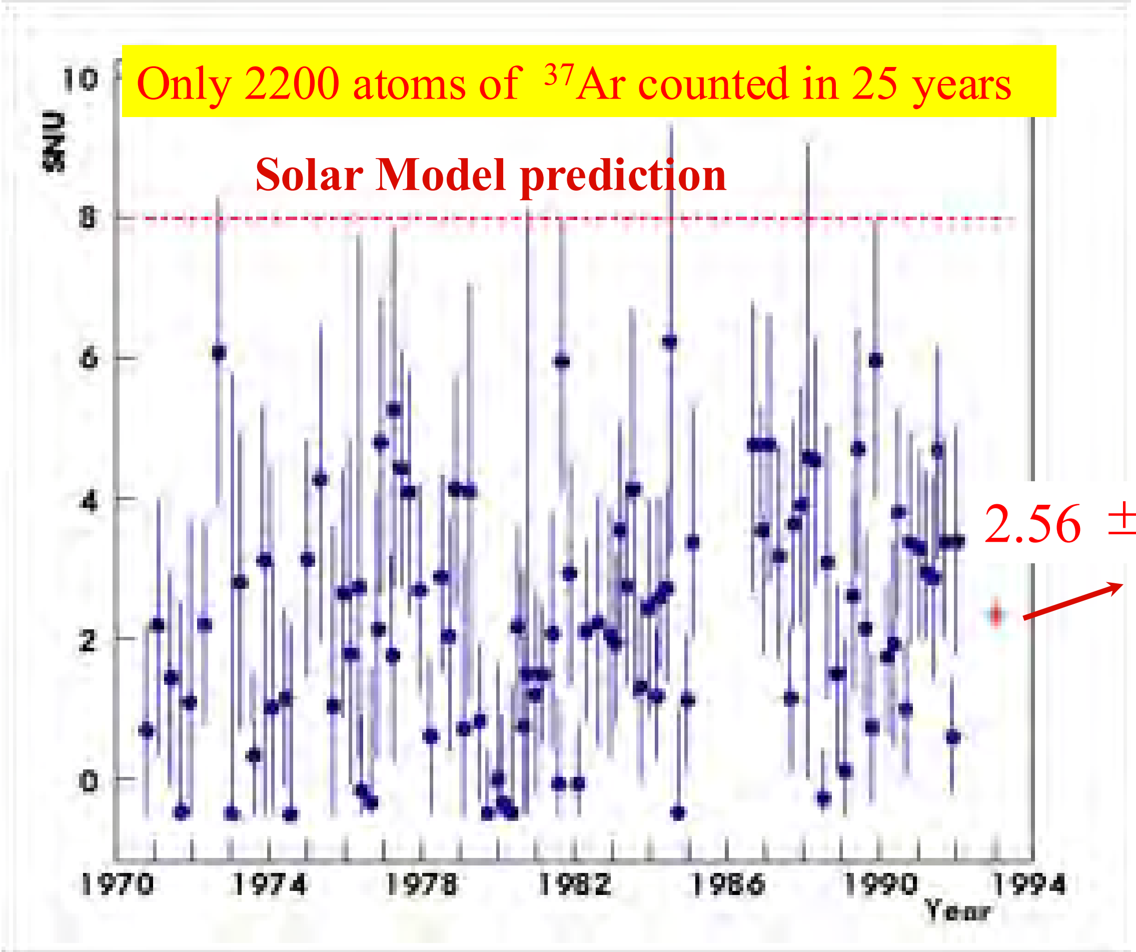
Real-time precision spectroscopy

Super/HyperK & SNO+ - first ^{8}B data & JUNO in commissioning phase

FIRST DETECTION: HOMESTAKE - NOBEL 2002

- collect ~1 atom/day out of 10^{31}
- Charged current interaction, but no detection of the electron

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

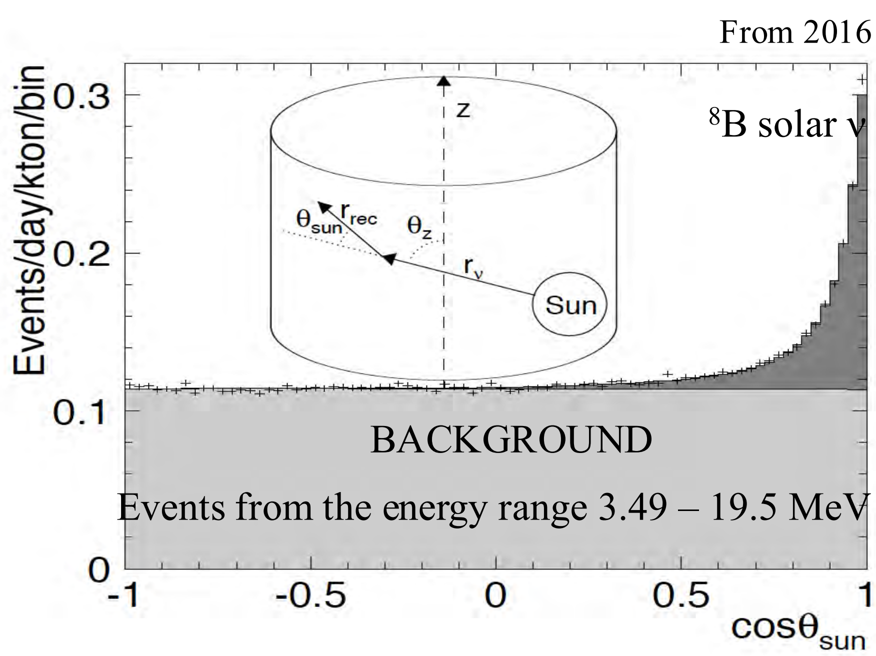


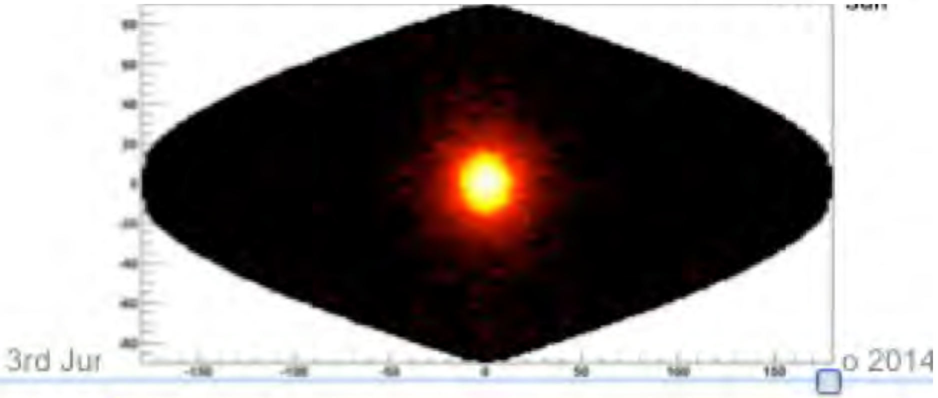
Ray Davis

1 SNU (Solar Neutrino Unit) = 10^{-36} interactions on target nuclei per second

SUPER-KAMIOKANDE: START IN 1986, NOBEL IN 2002, STILL ONLINE!

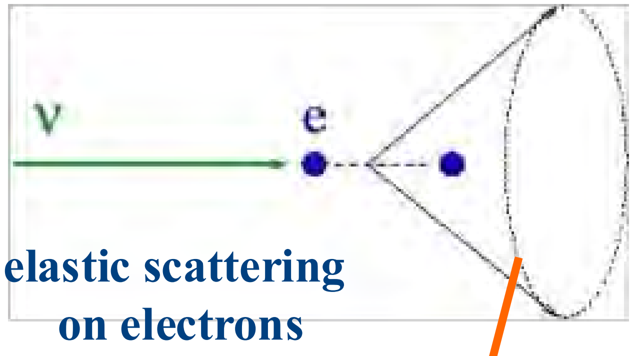
THE FIRST REAL-TIME SOLAR NEUTRINO DETECTION

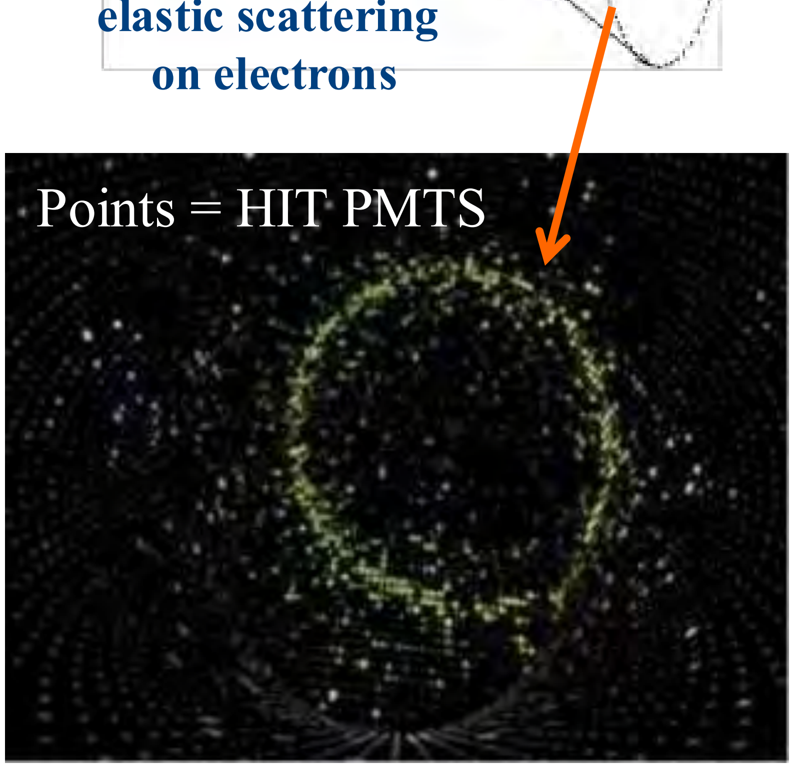




The Sun's picture in neutrinos!

Detection in Water



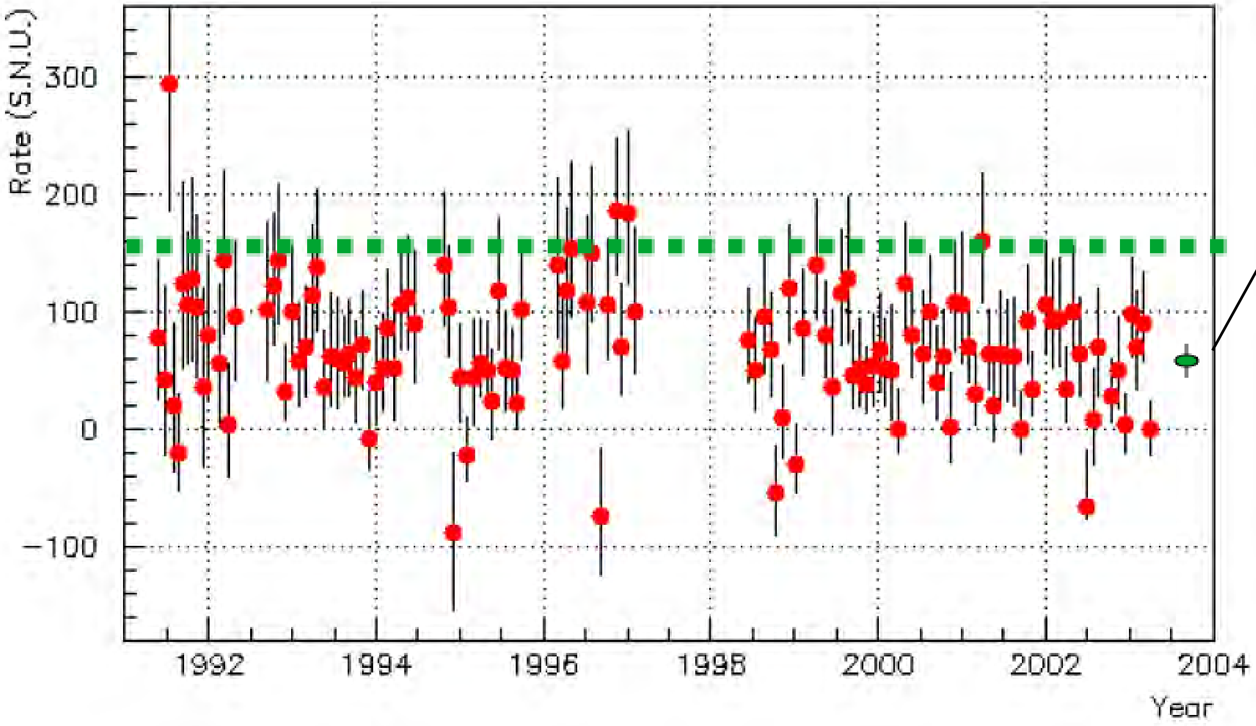


1991-2003 GALLEX-GNO @ LNGS, ITALY RADIOCHEMICAL EXPERIMENT

Charged current interaction:

$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

Till Kirsten
(MPI
Germany)



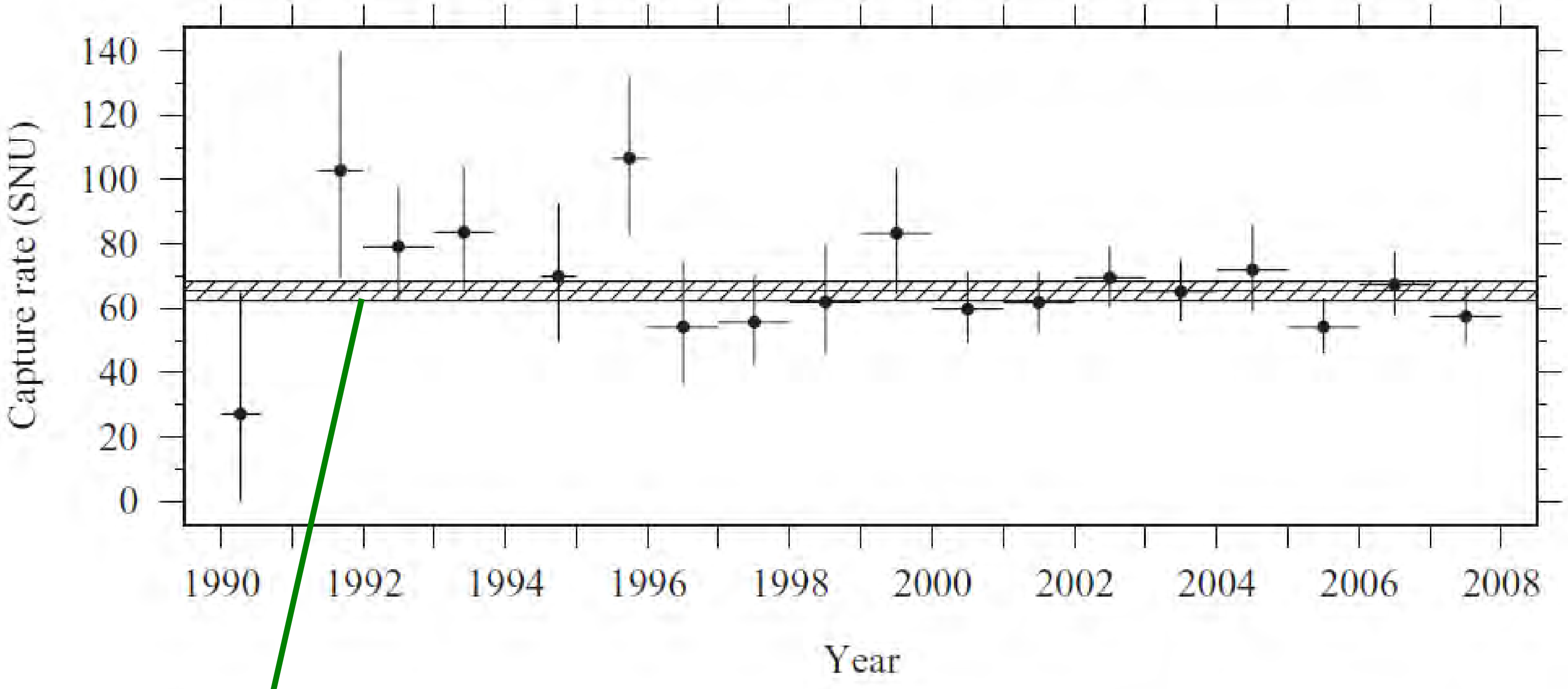
Final result:

67.6 ± 5.1 SNU

0.541 ± 0.081

as a fraction
of the SSM prediction

1990-2011 SAGE EXPERIMENTAL RESULTS BAKSAN, RUSSIA



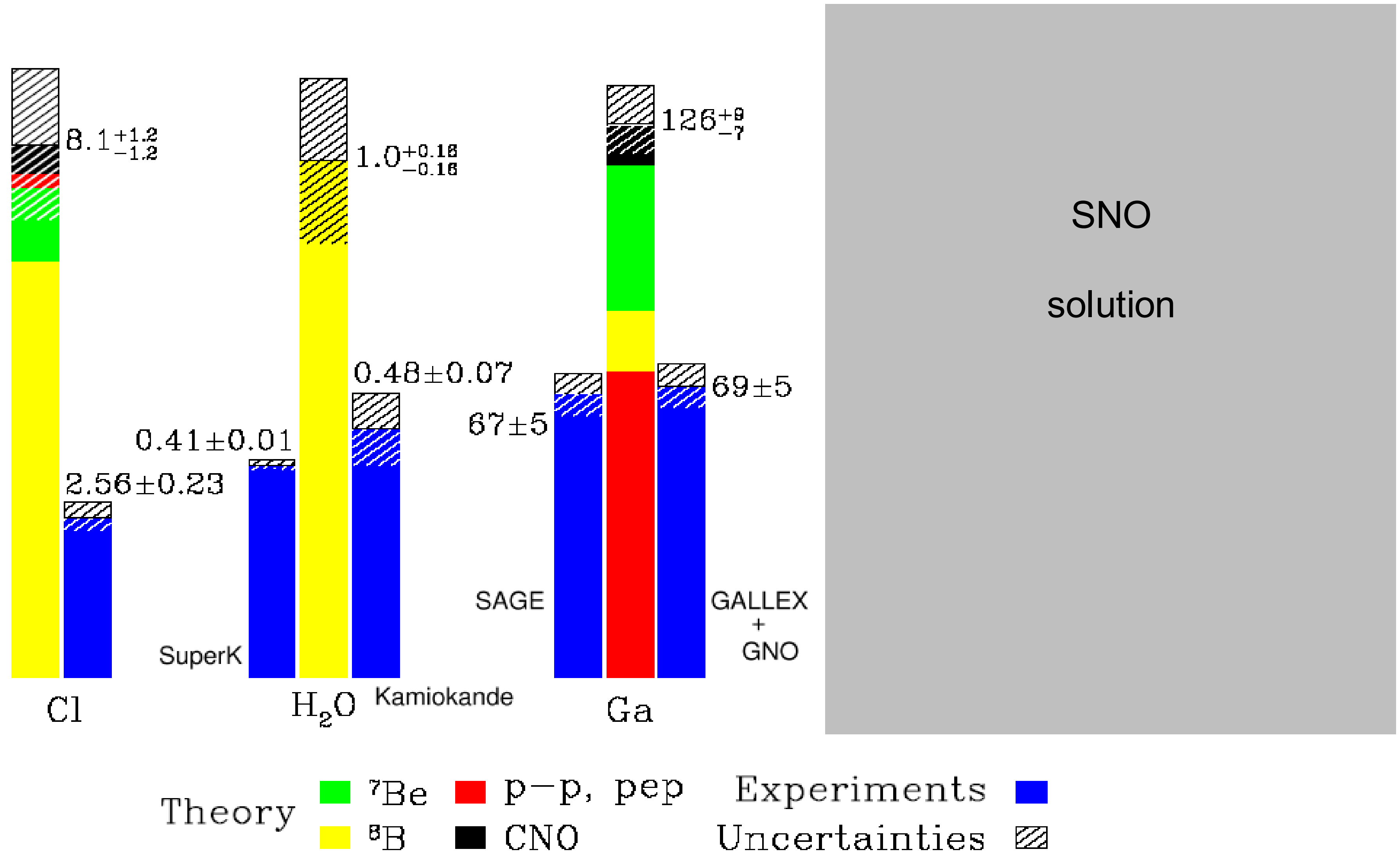
Vladimir Gavrin (Russia)

Liquid metallic Ga

Final result: $65.4^{+3.1}_{-3.0}{}^{+2.6}_{-2.8}$ SNU

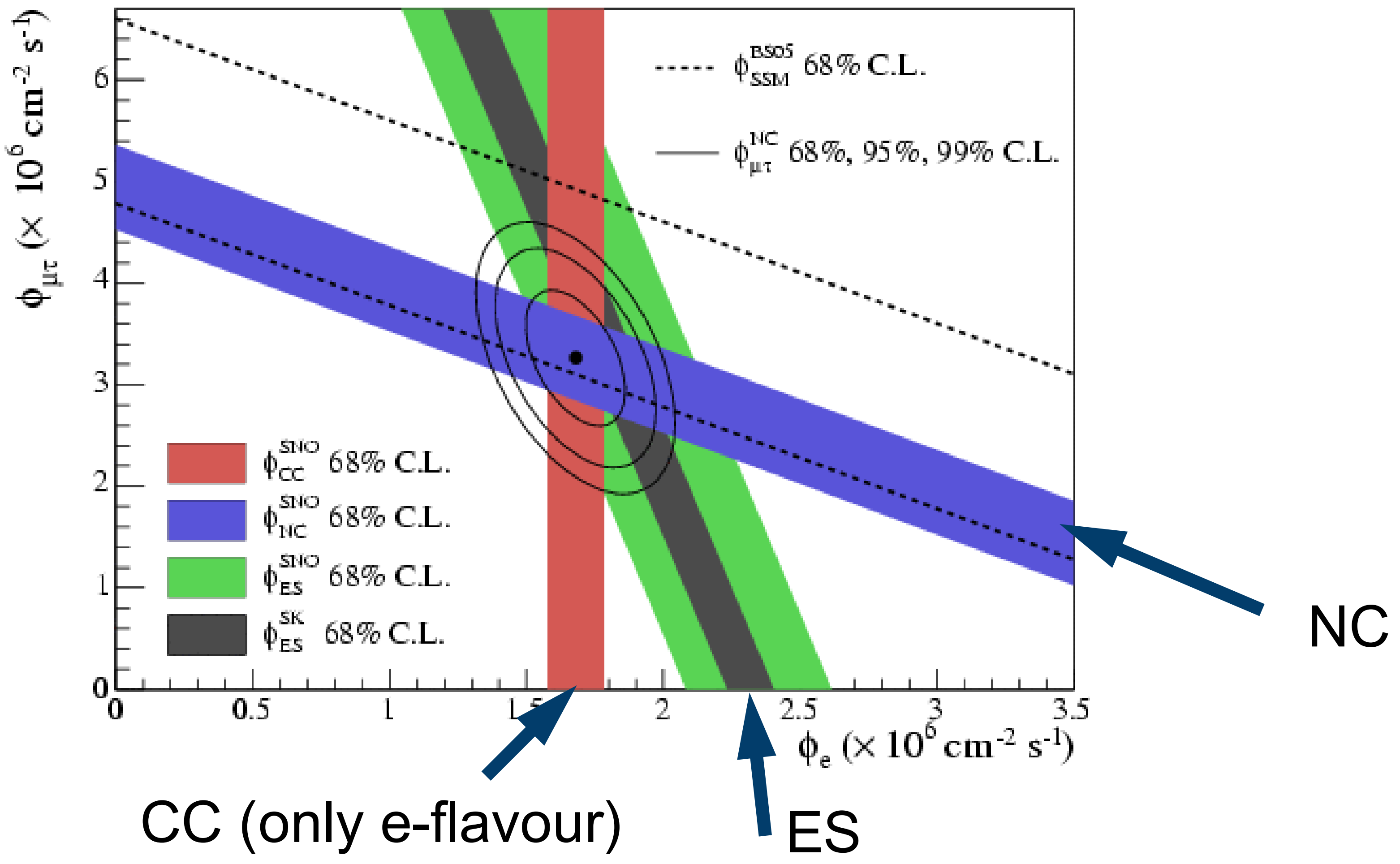
Total Rates: Standard Model vs. Experiment

Bahcall–Serenelli 2005 [BS05(OP)]



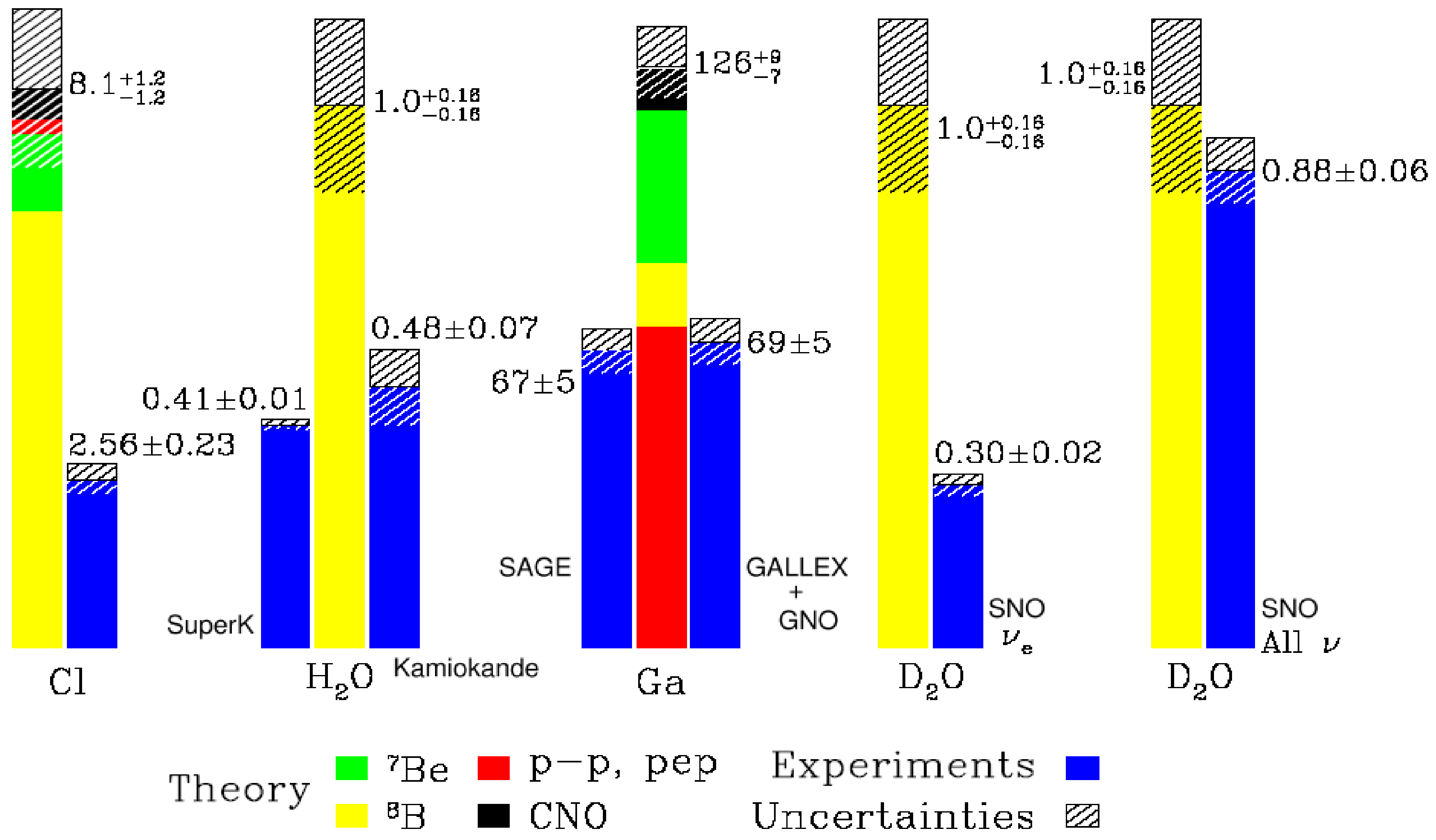
SNO 2001: DISCOVERY OF SOLAR NEUTRINO OSCILLATIONS

- Prove that $\Phi(\nu_e)$ is DIFFERENT from $\Phi(\nu_\mu, \nu_\tau)$.
- Prove that the TOTAL neutrino flux is consistent with the Standard Solar Model.
- Big success for SNO, neutrino oscillations, and solar model theoreticians.



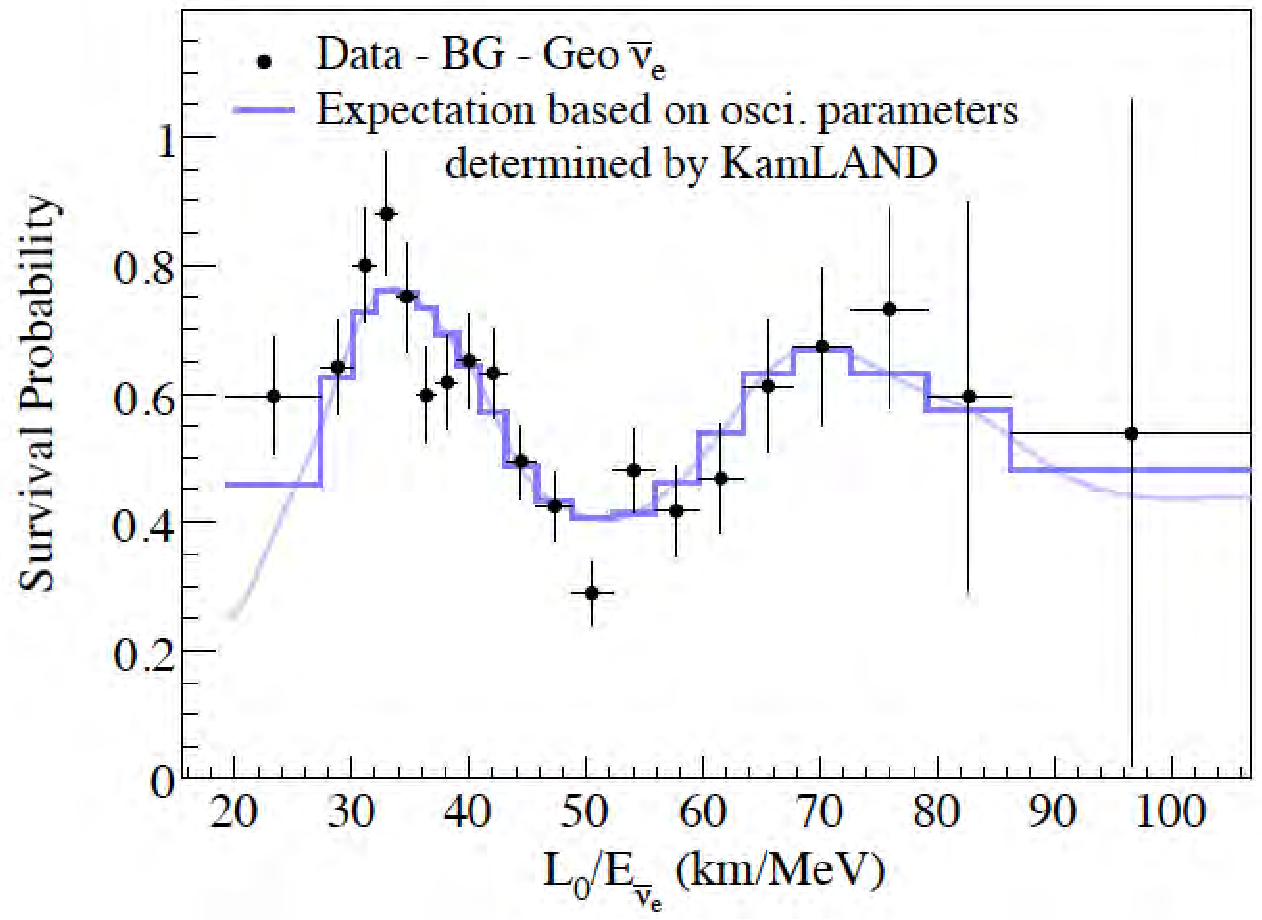
Total Rates: Standard Model vs. Experiment

Bahcall-Serenelli 2005 [BS05(OP)]

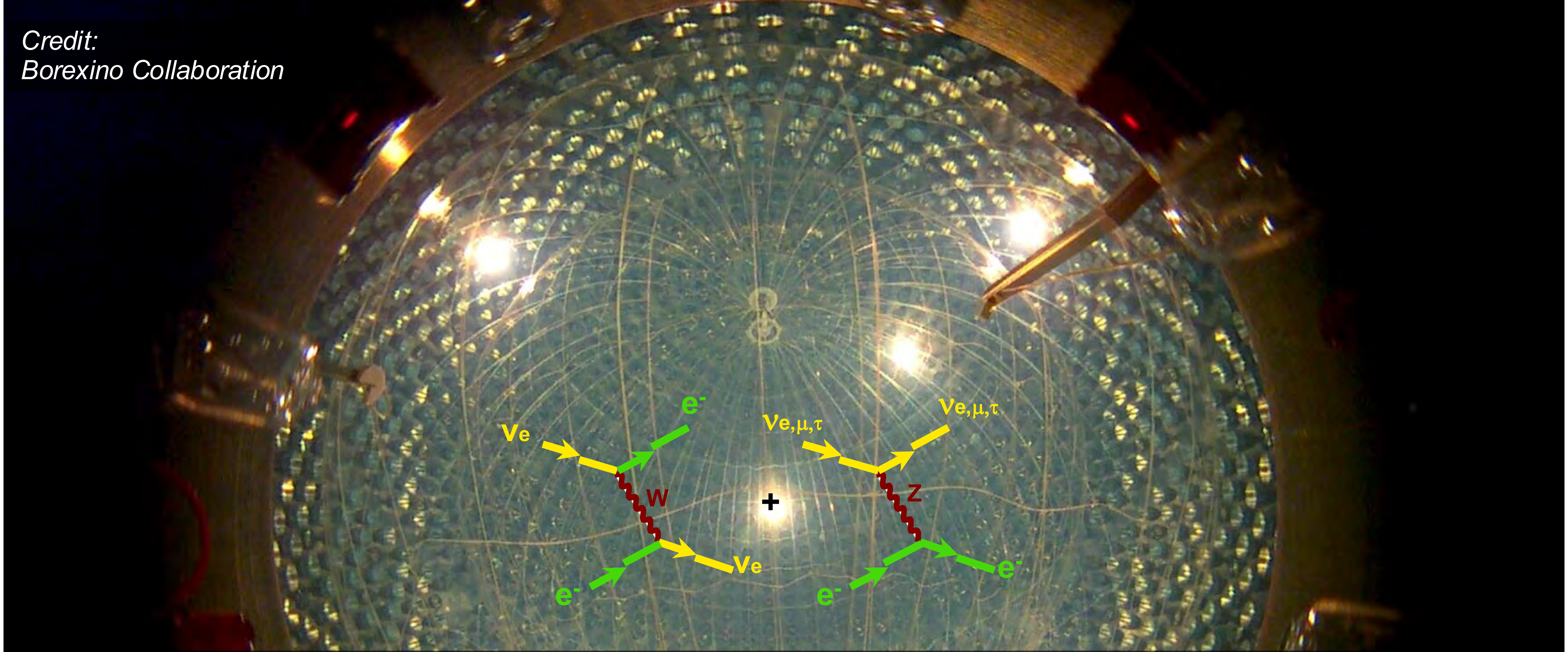


PRECISE MEASUREMENT OF Δm^2_{12} AND FINAL PROOF OF OSCILLATIONS (ON ANTI-NEUTRINOS FROM REACTOR!)

KamLAND, 2002



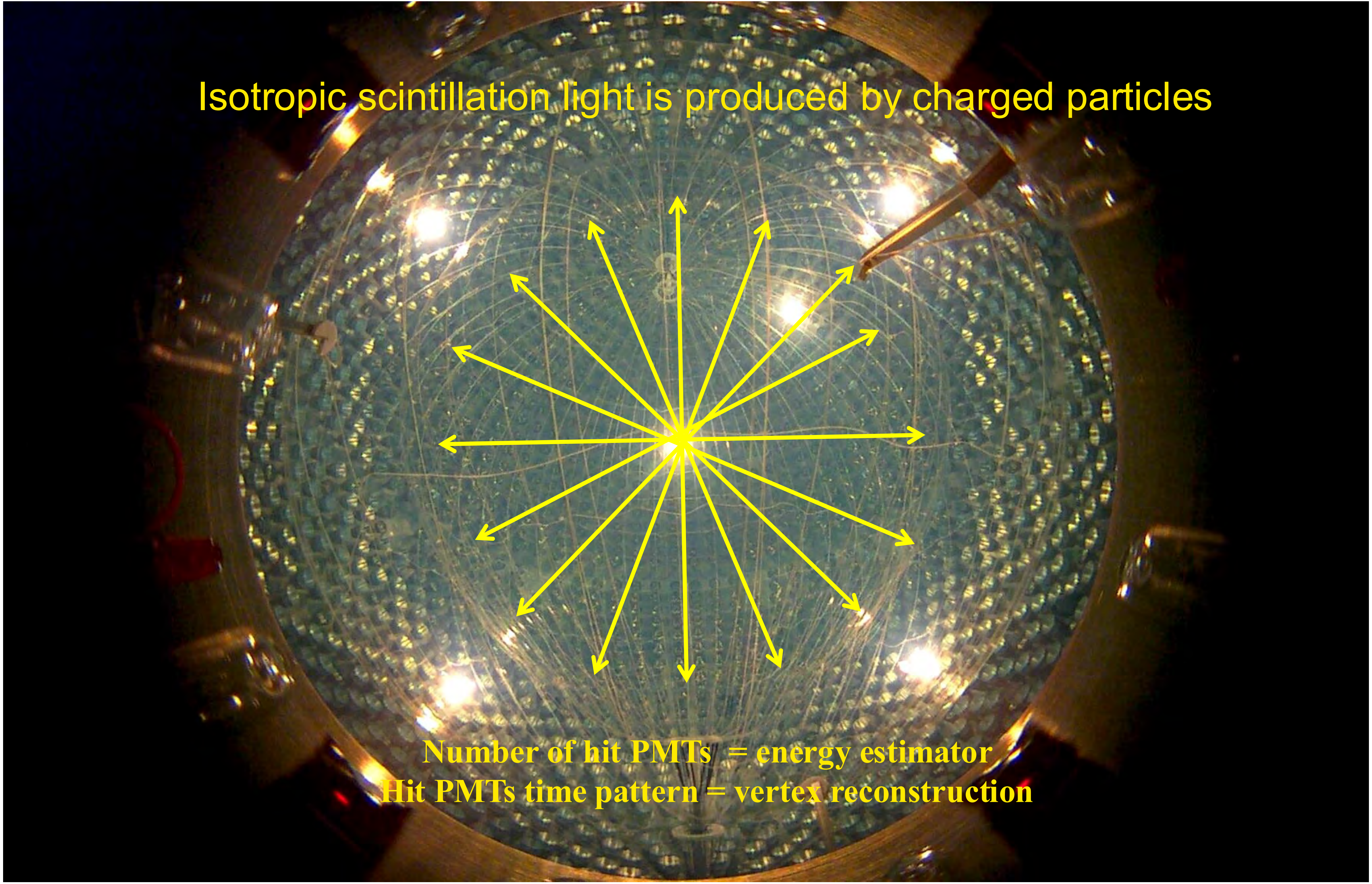
OSCILLATION PATTERN WAS SEEN!



Credit:
Borexino Collaboration

Precision solar neutrino detection: SINGLES

- **Elastic scattering** off electrons both in liquid scintillator (Borexino, SNO+) and water Cherenkov (SNO, Super-Kamiokande) based detectors.
- No threshold.
- All flavours (cross section for ν_e ~6x higher) – MEASURED RATE DEPENDS ON P_{ee}.
- Even mono-energetic neutrinos – continuous spectrum with a Compton-like edge.
- Undistinguishable from normal radioactivity.

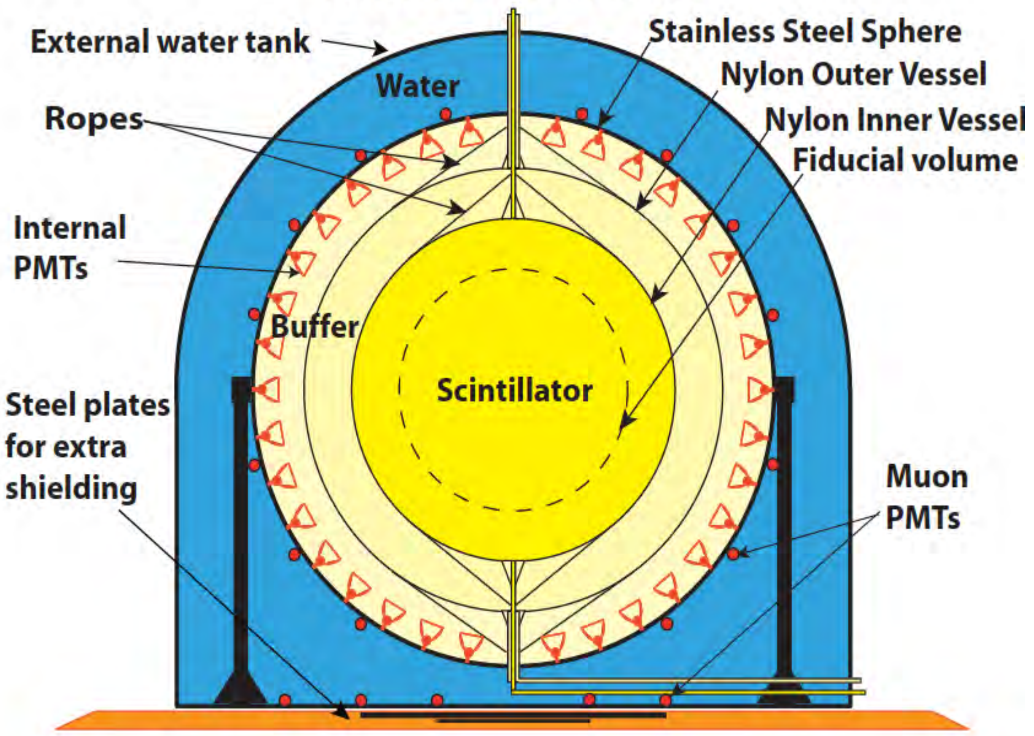

Isotropic scintillation light is produced by charged particles
Number of hit PMTs = energy estimator
Hit PMTs time pattern = vertex reconstruction

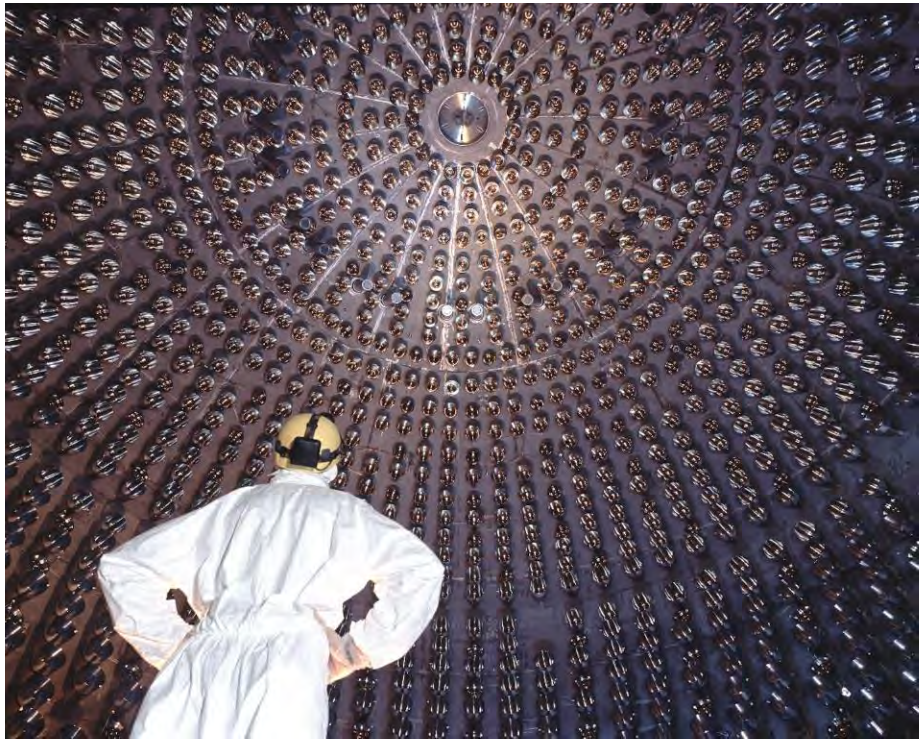
BOREXINO @ LNGS, ITALY

- Data taking: 2007 – 2021;
- PC based LS: 280 tons;
- Depth: 3800 m.w.e.

Main goal: solar neutrinos below 2 MeV

Unprecedented radio-purity
was the key to the success of the experiment.





BOREXINO TIMELINE AND SOLAR NEUTRINO RESULTS

2007 | 2010 | 2012 | 2016 | 2017 | 2020 | Oct 2021

Phase I
Source Calibration

LS Purification

Phase II

Phase III

The end

First observation
^{7}Be
pep
^{8}B > 3MeV

Directional detection of sub-MeV solar neutrinos & ^{7}Be rate (CID method)

First observation
pp reaction
NATURE 28/08/2014

Full pp chain spectroscopy
NATURE 25/10/2018

CNO
1st observation
NATURE 25/11/2020

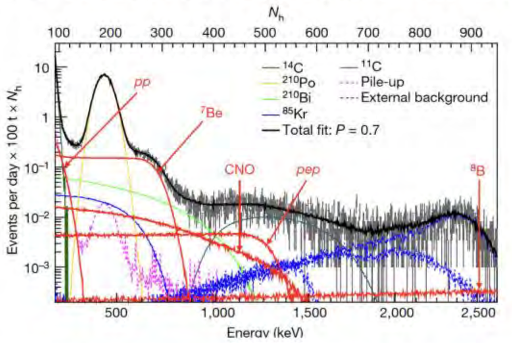
CNO improved and final
PRL 12/12/2022
PRD 108 (2023) 102005,

CNO observation with the Correlated Integrated Directionalty (CID) using Cherenkov photons
PRD 108 (2023) 102005,

BOREXINO SOLAR RESULTS IN 1 SLIDE

pp (10.5%), **^{7}Be** (2.7%), ***pep*** (>5σ, 17%)

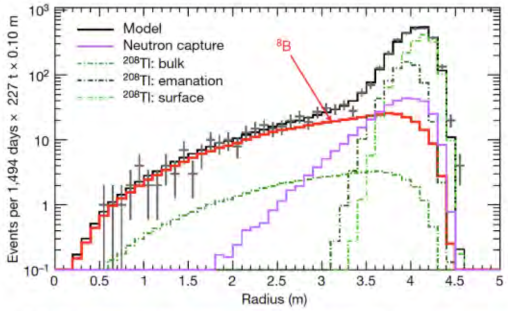
Low Energy Range (LER) [0.19 – 2.93 MeV]



Fit of **energy spectra** – spectral shape rather independent on oscillation in matter

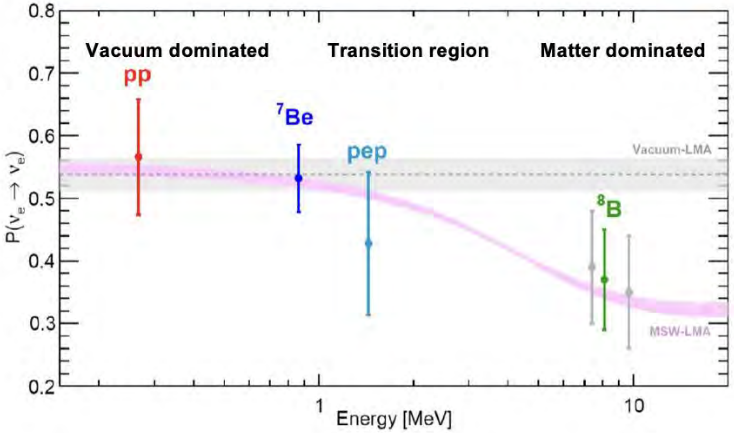
^{8}B with 3 MeV threshold (8%)

High Energy Range (HER) [3.2 – 16.0 MeV]

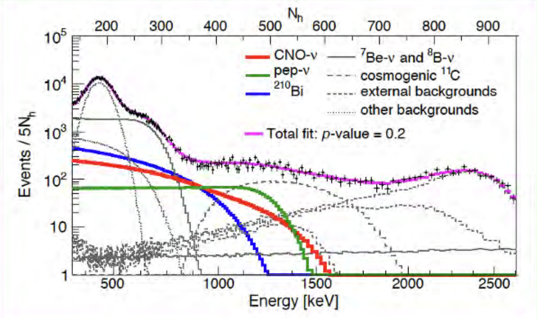


Fit of **radial distribution** – no assumption on oscillation mechanism in solar matter.
Matter effect is important at these energies.

P$_{ee}$ survival probability at different energies
Vacuum-LMA model excluded at 98.2% CL

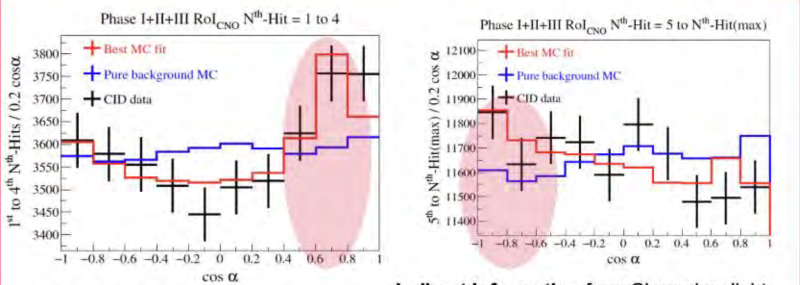


CNO Phase III spectral fit



(> 8σ, +18% -12% precision)

CNO Phase I+II+III CID directional analysis

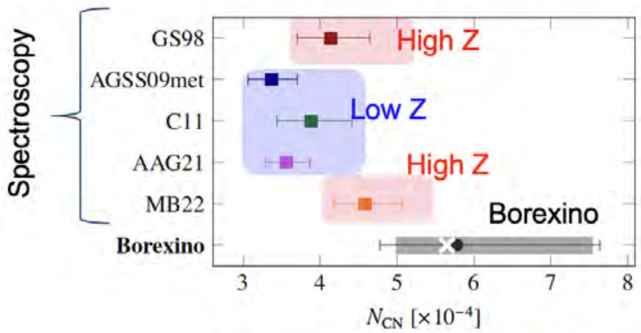


Direct information from Cherenkov light

Indirect information from Cherenkov light (vertex reco bias in Cherenkov cone direction)

Exploiting sub-dominant Cherenkov light in LS detector!

N_{CN} = (C + N)/H in the Sun: 1st value based on neutrinos
Solar metallicity: ~2σ preference for high - Z

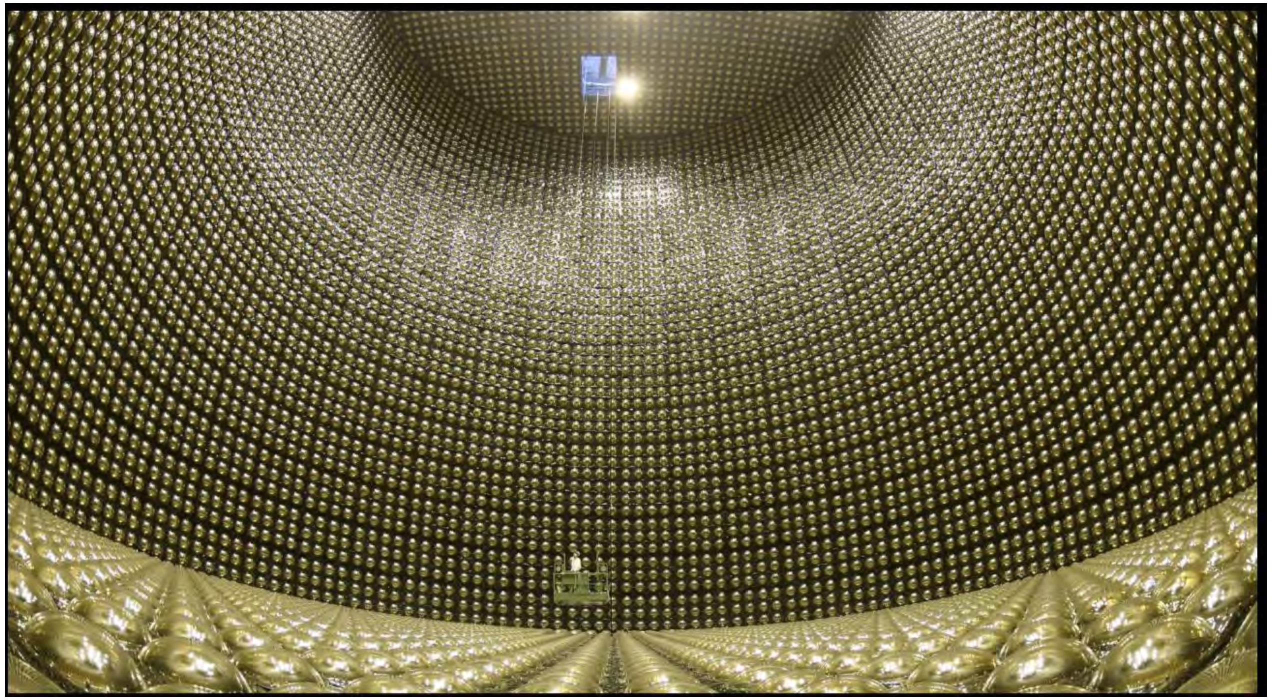


$$N_{CN} = (5.78^{+1.86}_{-1.00}) \cdot 10^{-4}$$

Comprehensive spectroscopy of *pp*-chain and discovery of CNO cycle solar neutrinos.

SUPERKAMIOKANDE

Water Cherenkov detector
Large FV mass of 22.5 kton
> 20 years of ^{8}B solar data in 4 Phases 1996 – 2018



Phase	SK-I	SK-II	SK-III	SK-IV
Period (Start)	April '96	October '02	July '06	September '08
Period (End)	July '01	October '05	August '08	May '18
Livetime [days]	1,496	791	548	2,970
ID PMTs	11,146	5,182	11,129	11,129
OD PMTs	1,885	1,885	1,885	1,885
PMT coverage [%]	40	19	40	40
Energy thr. [MeV]	4.49	6.49	3.99	3.49

Phase IV

- 90% triggering efficiency down to 2.99 MeV;
- Improved analysis techniques and clear ^{8}B measurement above **3.5 MeV;**

Complete analysis of SK phases I – IV

PHYS. REV. D **109,** 092001 (2024)

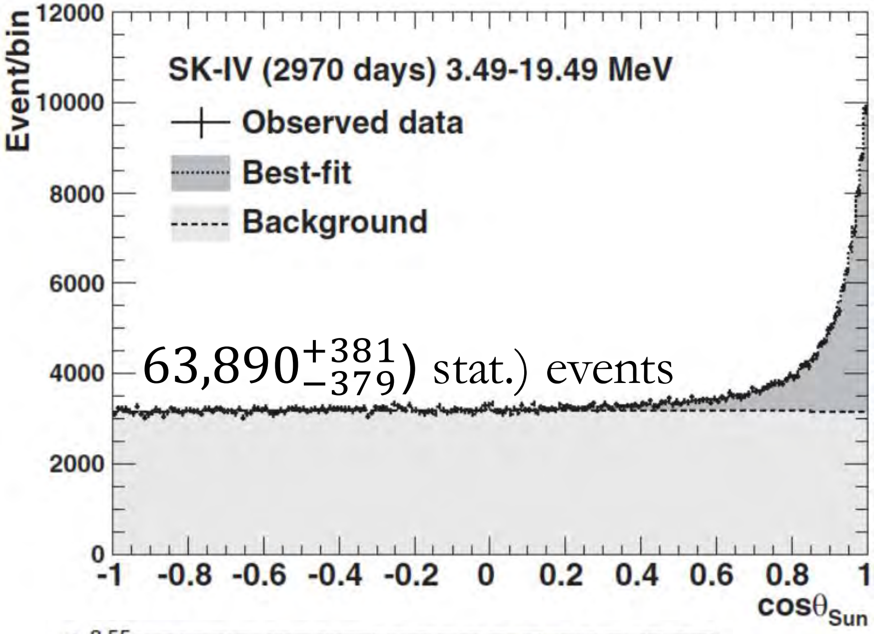
Since 2020: Gd loading of LS for neutron capture to observe DSNB via IBDs.

- SK-V: preparation
- SK-VI (0.01% Gd)
- SK-VII (0.03% Gd)

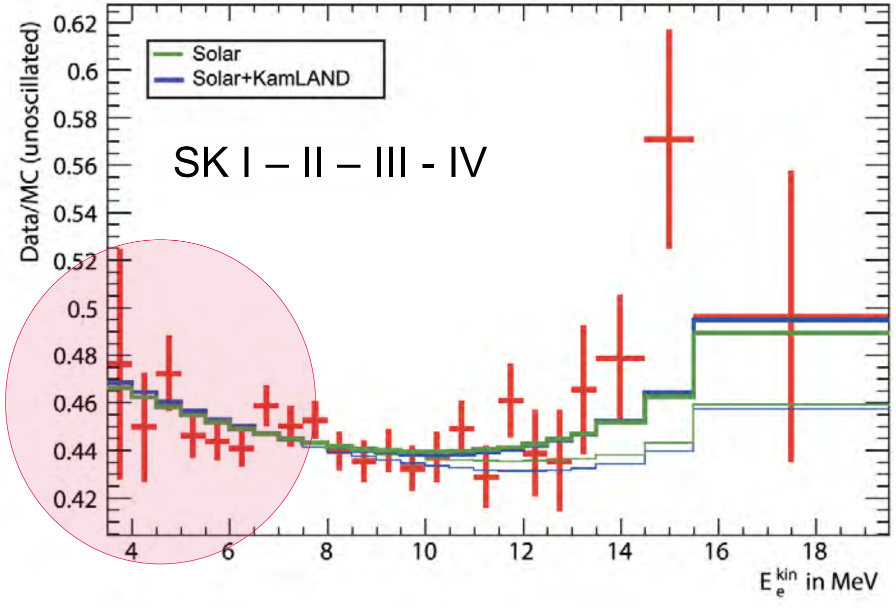
Higher backgrounds as expected, but 4 /4.5 MeV threshold is possible.

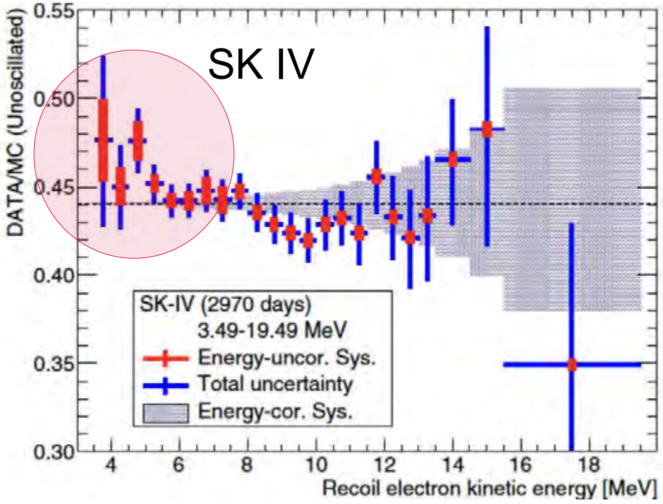
SUPER-KAMIOKANDE LATES RESULTS

PHYS. REV. D **109,** 092001 (2024)



$63{,}890^{+381}_{-379}$) stat.) events

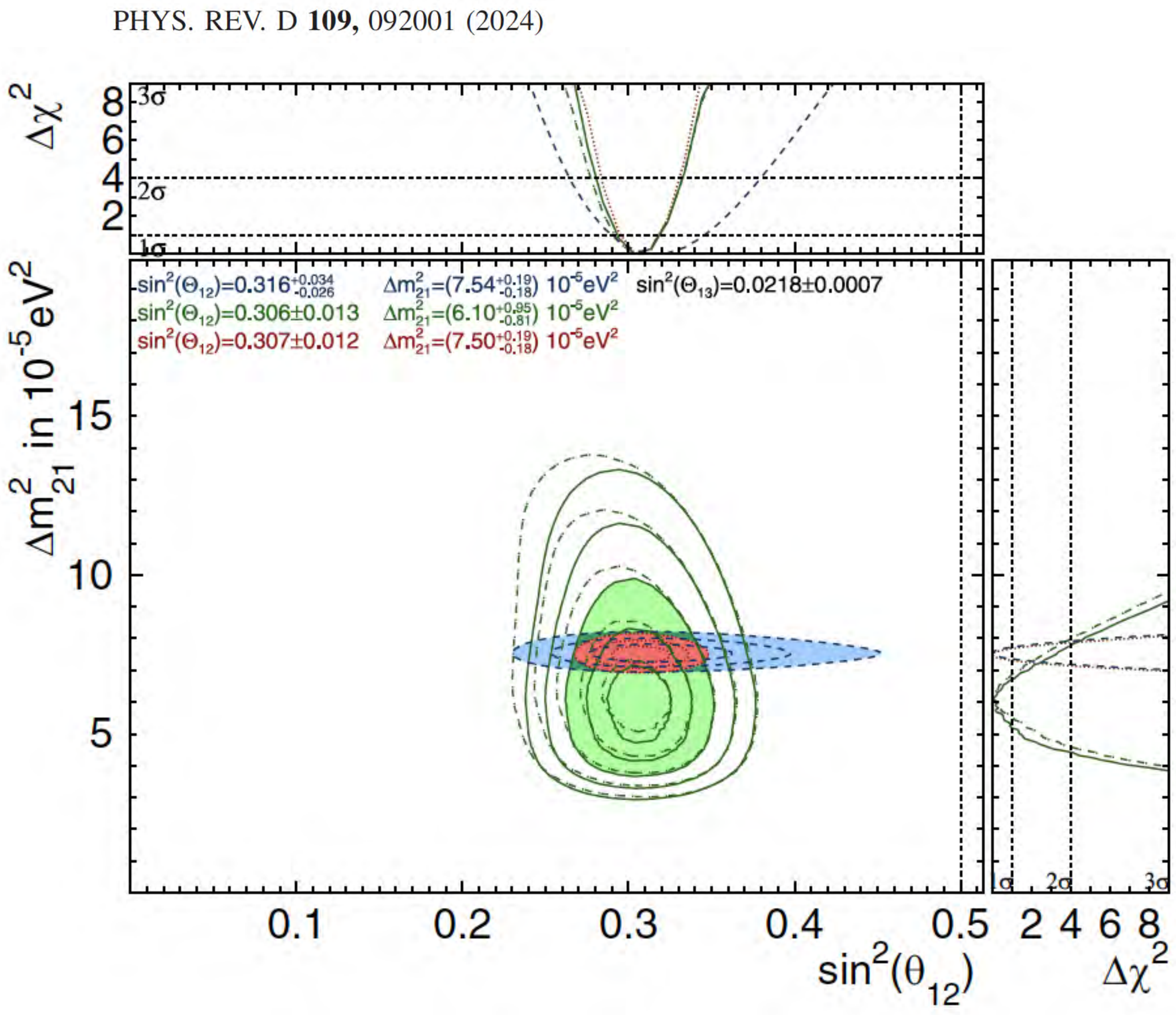




- ^{8}B flux measurement consistent among different phases **– total precision 2%.**
- Spectrum still compatible with flat survival probability, but predicted low energy **MSW upturn is favoured at 1.2 σ** . Jointly with SNO data, at 2.1 σ.
- No time variations except eccentricity and **Day/Night variation** (MSW electron flavour regeneration when crossing the Earth):

$$A_{D/N}^{SK,fit} = -0.0286 \pm 0.0085(\text{stat.}) \pm 0.0032(\text{syst.}).$$

SUPERKAMIOKANDE: SOLAR OSCILLATIONS



Solar best-fit value

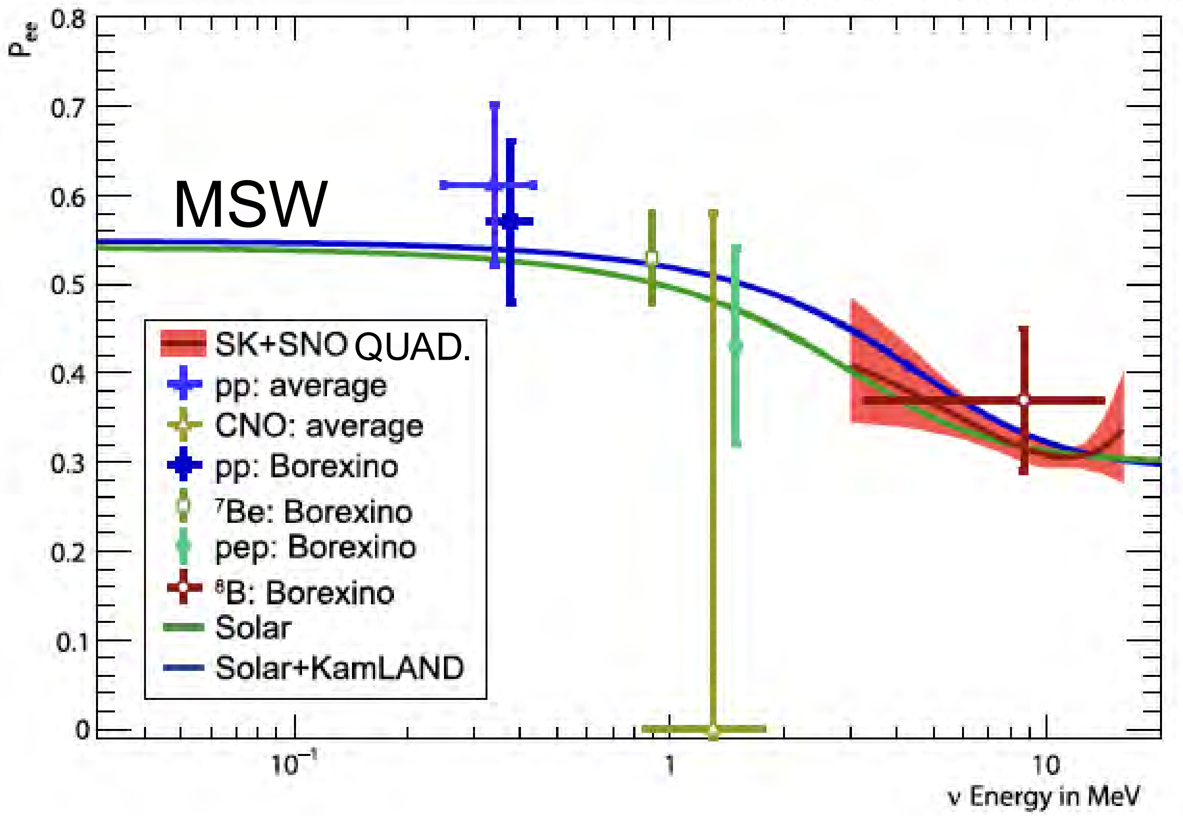
$\Delta m^2_{21} = 6.10^{+0.95}_{-0.81} \times 10^{-5}\, eV^2$

~1.5 σ away from KamLAND

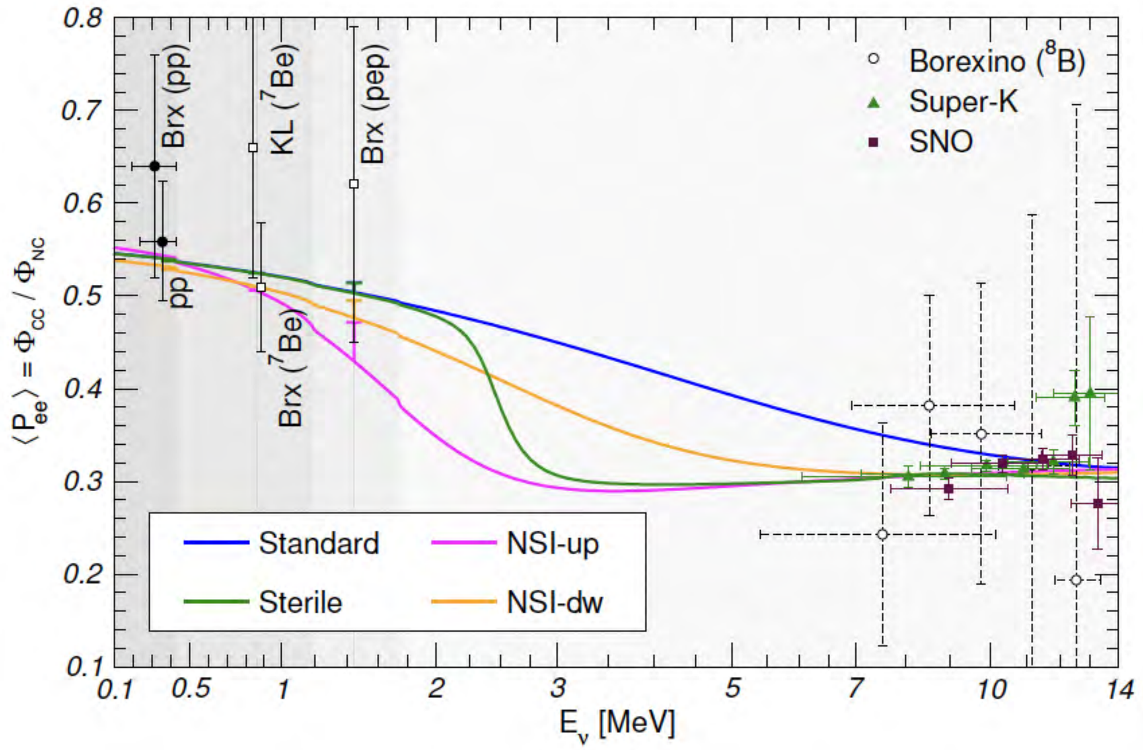
Previously, larger tensions.

P_{ee}: VACUUM TO MATTER TRANSITION

PHYS. REV. D **109**, 092001 (2024)

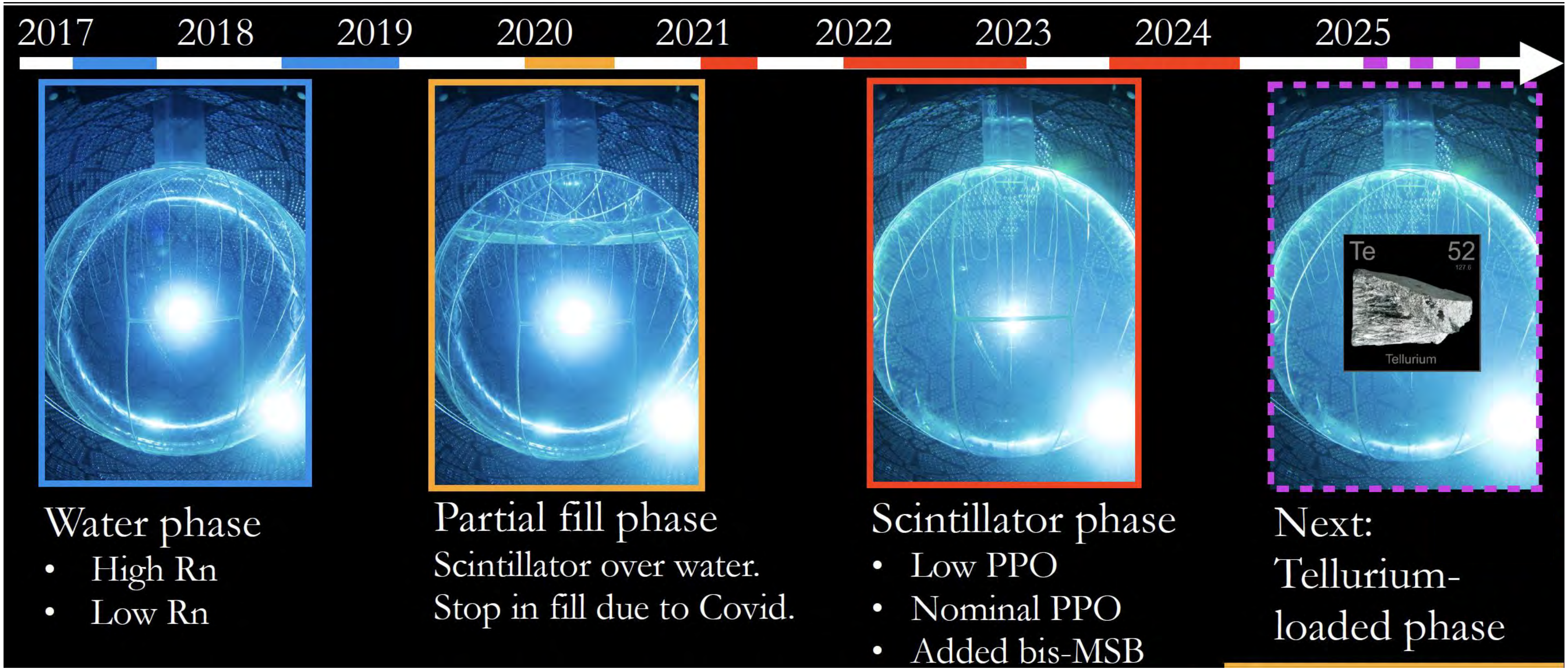


M. Maltoni et al., Eur. Phys. J. A 52 (2016) 87



Transition region crucial for testing BSM ideas.

SNO+ IN SUDBURY, CANADA

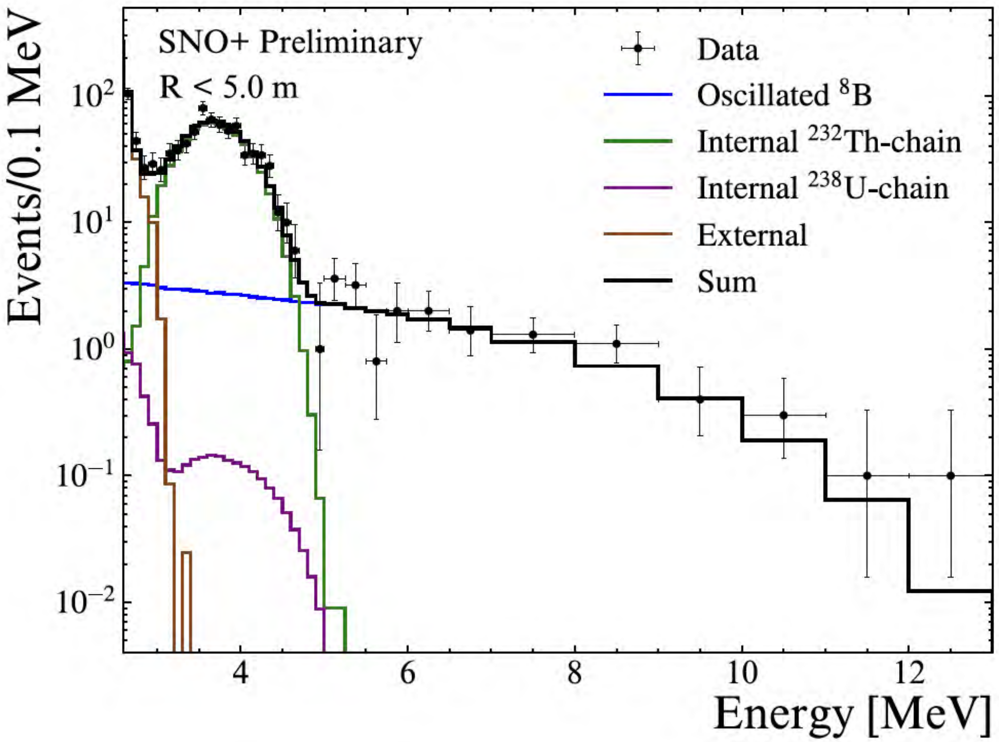


J. Maneira. Neutrino 2024

SNO+ AND 8B SOLAR ANALYSIS

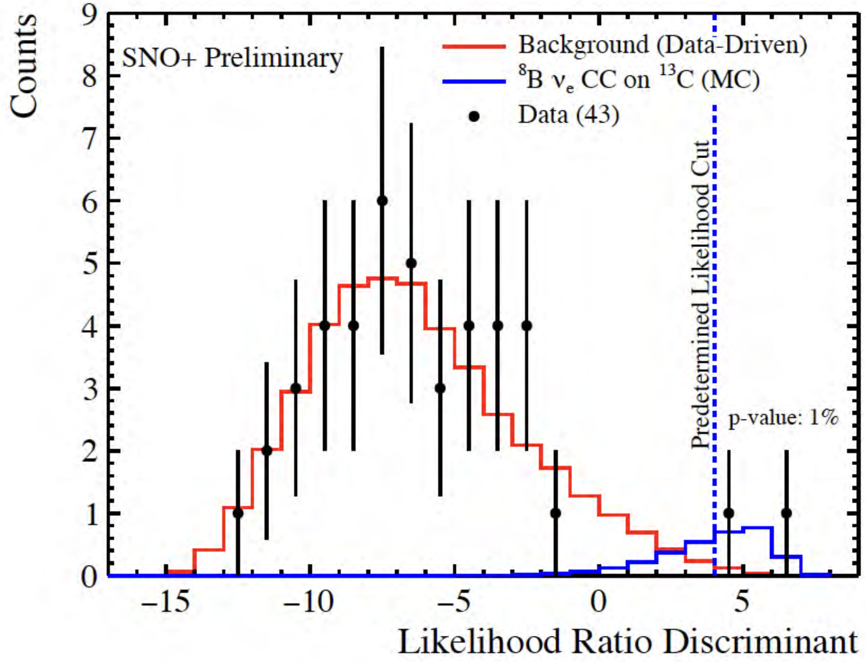
$$\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$$
$$ {}^{13}N \rightarrow e^+ + \nu_e + {}^{13}C$$

Elastic scattering (singles)

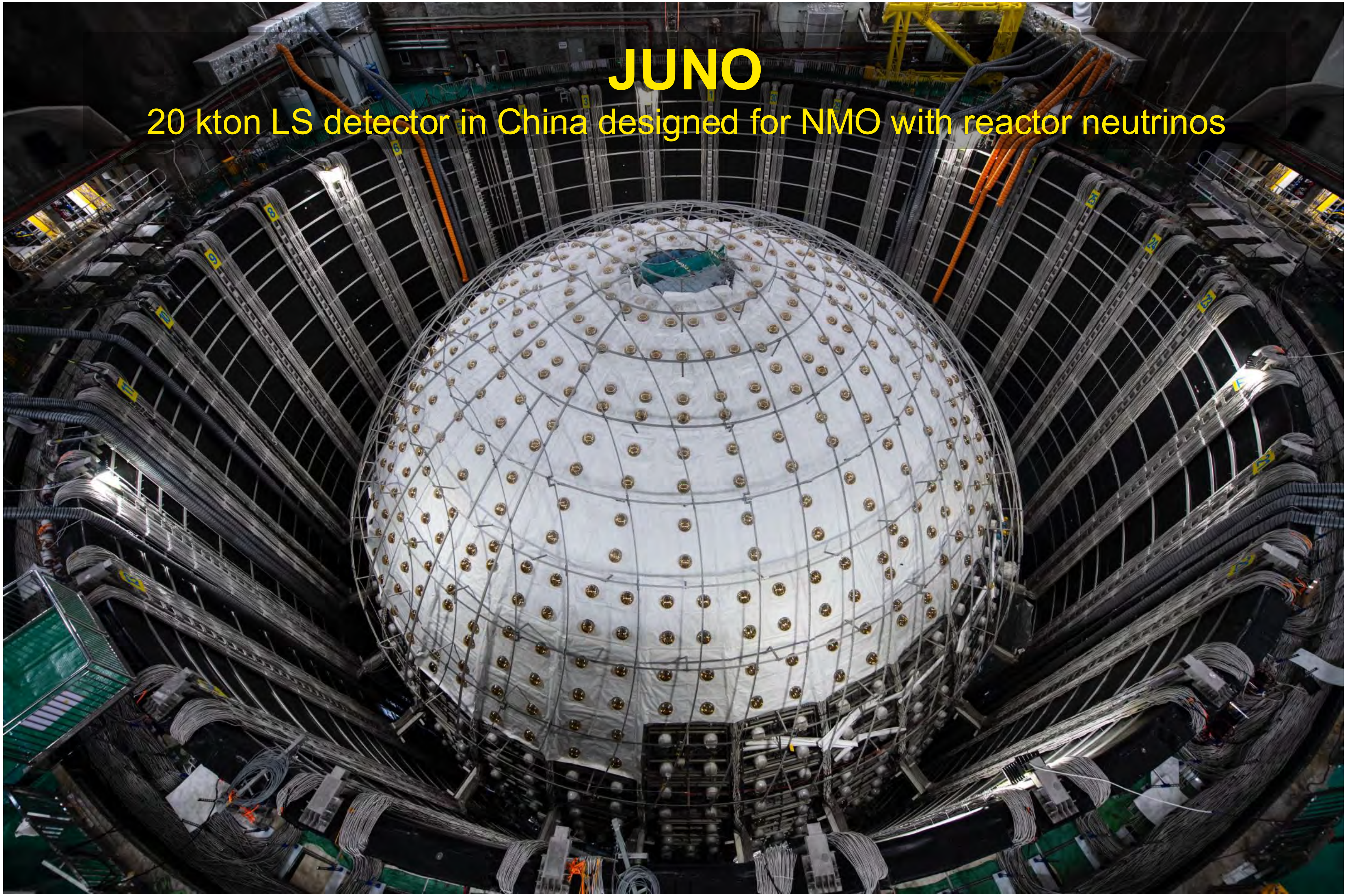


- ES interactions in 138.9 live days of scintillator data.
- Fitted oscillation parameters compatible with global fits.
- Smaller FV opens door towards < 3 MeV.

Charge current on ^{13}C (coincidence)



- 1.1% isotopic abundance, but σ ~12× higher than ES.
- Never observed – 2 events indicative and compatible with expected signal.


JUNO
20 kton LS detector in China designed for NMO with reactor neutrinos

MODEL INDEPENDENT MEASUREMENT OF ^{8}B SOLAR NEUTRINOS

Interaction channels of ^{8}B-ν:

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$

- No threshold
- All flavours & $\sigma(\nu_{\mu,\tau}) / \sigma(\nu_e) = 1/6$
- Single events - continuous spectrum

CC: $\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$

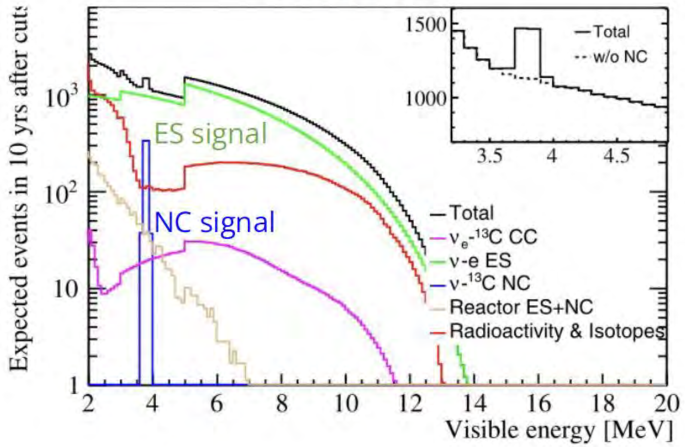
- E_{thr} = 2.2 MeV
- Possible only with ν_e
- Prompt: e^-; Delayed: ^{13}N decay

NC: $\nu_x + {}^{13}C \rightarrow \nu_x + {}^{13}C^*$

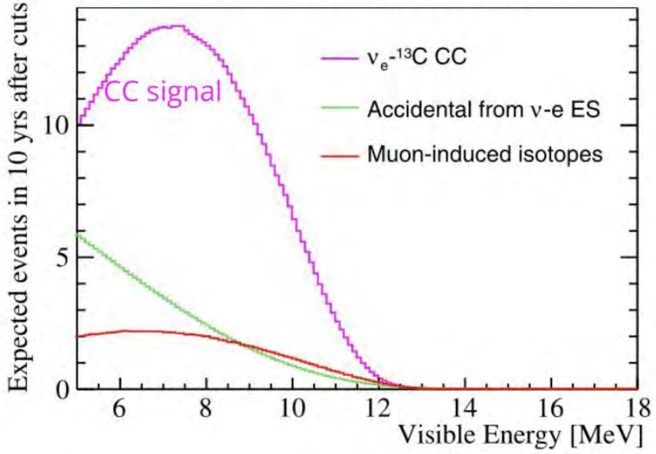
- E_{thr} = 3.685 MeV
- All flavors & equal σ
- Single events - monochromatic γ

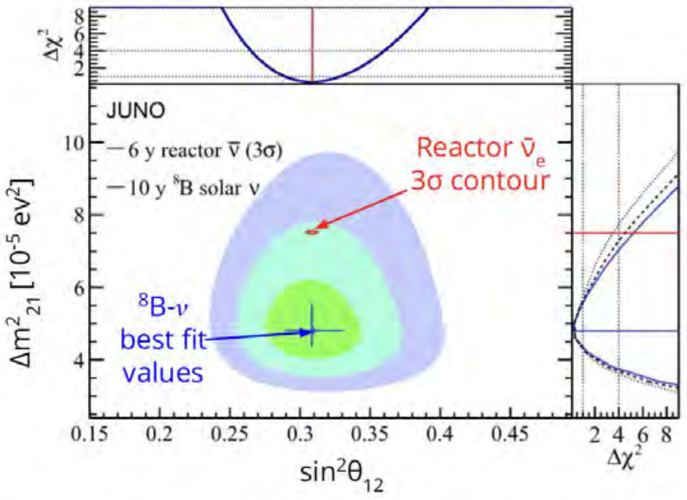
ES: Chinese Phys. C 45 (2021) 1
ES+NC+CC: Ap. J. 965 (2024) 122

10 years, single events after cuts



10 years, correlated prompt events after cuts





Potential to search for possible discrepancies

Expected precision in 10 years:

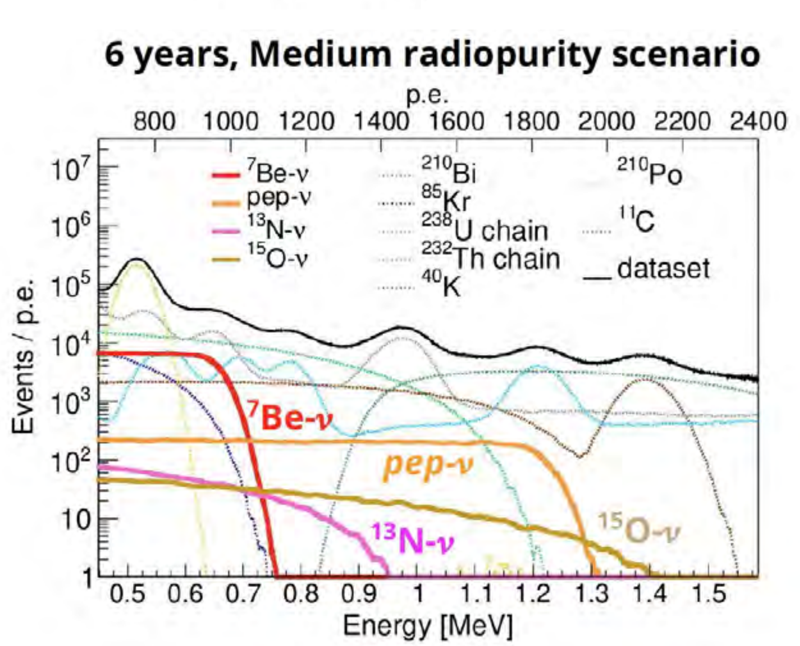
^{8}B flux: 5% JUNO

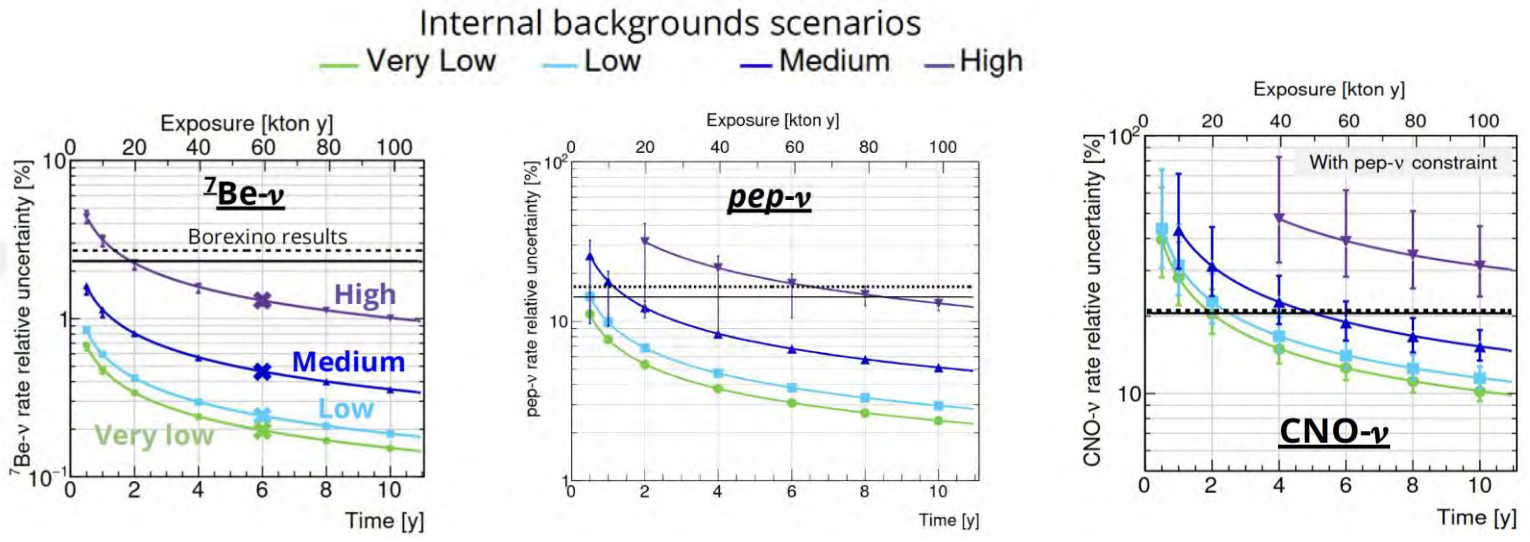
$\sin^2\theta_{12}$: +9% / -8%

Δm^2_{21}: +27% / -17%

SENSITIVITY TO ^{7}Be, pep, CNO SOLAR NEUTRINOS

ES: $\nu_x + e^- \rightarrow \nu_x + e^-$





J. Cos. Astro. Phys. 10 (2023) 022.

- Several radio-purity scenarios: from the Borexino level up to the “IBD” one (minimum required for the NMO)
- JUNO has potential to improve the precision of the existing Borexino measurements
  - ^{7}Be: **in 1-2 years time < 2.7% (current Borexino precision) for all radiopurity scenarios**
  - **pep**: **in 1-2 years time < 17% (current Borexino precision), only in IBD scenario after more than 6 years**
  - **CNO:** constraining *pep* rate is crucial, precision of 20% possible in 2 to 4 years (except for the IBD scenario)
    - constraint of ^{210}Bi radioactive background not needed (applied in Borexino analysis *Nature* 587 (2020) 577–582)
    - Independent measurement of ^{13}N and ^{15}O might be possible for the first time.

Solar neutrino Summary & outlook

- **Borexino** (Italy): comprehensive solar neutrino spectroscopy, CNO discovery, stopped data-taking in October 2021.
- **SuperKamiokande** (Japan): the most precise ^{8}B analysis, data taking with Gd loading ongoing, solar analysis with special analyses possible.
- **SNO+** (Canada): first ^{8}B analyses, CC on ^{13}C seems feasible.
- **JUNO** (China): 20 kton LS & comprehensive solar neutrino program. Fully filled detector in summer 2025.
- **HyperKamiokande** (Japan): 260 kton water, the largest solar detector, upturn & MSW test, precise D/N asymmetry, potential for *hep* discovery. Start expected in 2027.
- **JINPING** (China): deepest lab, 500 m^3 to be filled with water and later LS (slow or loaded), data 2027.
- **DUNE, THEIA, SUPER CHOOZ –** solar also among their goals, further future.

Geoneutrinos

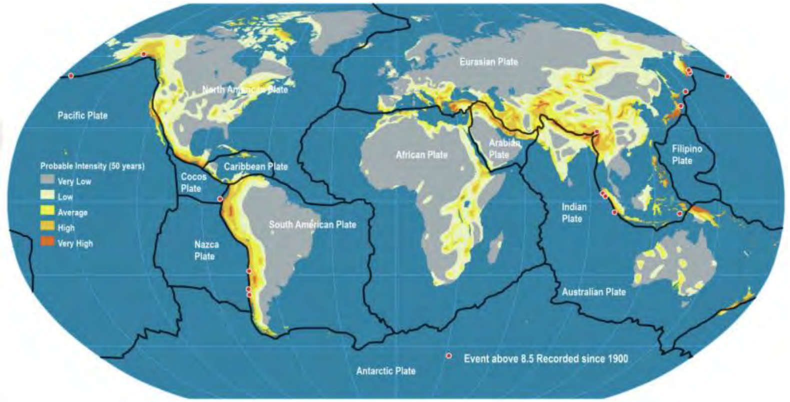
Vulcanism

From where is coming
the energy driving these processes?

How can neutrino physics help us to understand?

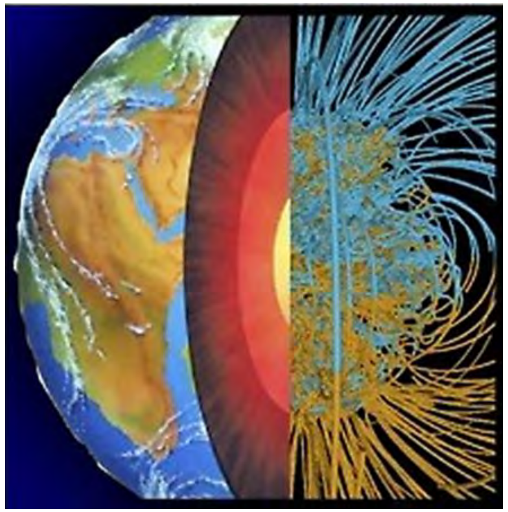
Earth shines in geoneutrinos:
flux ~ 10^6 cm^{-2} s^{-1}

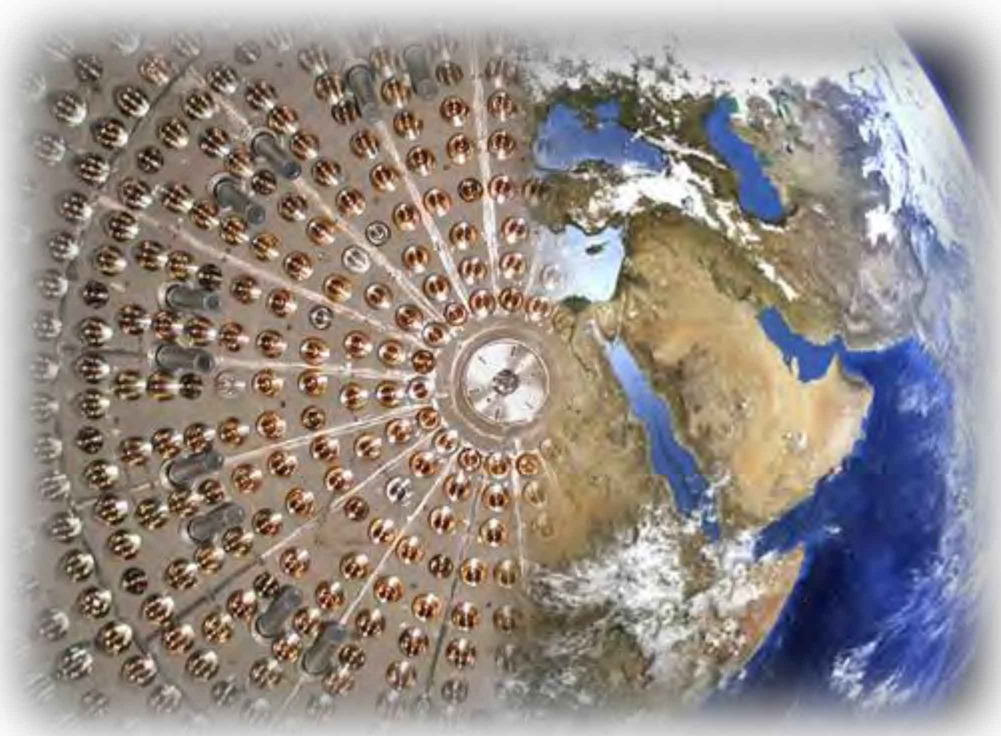
Plate tectonics & mantle convection



https://transportgeography.org

Geo-dynamo





Earthquakes

L'Aquila, Italy, 2009

GEONEUTRINOS AND GEOSCIENCE

Abundances (mass) of radioactive elements

Nuclear physics

$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- +$ 6 anti-neutrinos + 51.7 MeV

$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- +$ 4 anti-neutrinos + 42.8 MeV

$^{40}K \rightarrow {}^{40}Ca + e^- +$ 1 anti-neutrino + 1.32 MeV

Main goal:
Mantle radiogenic heat

- Mantle homogeneity
- U/Th ratio
- Earth formation

Distribution of radioactive elements

Signal prediction

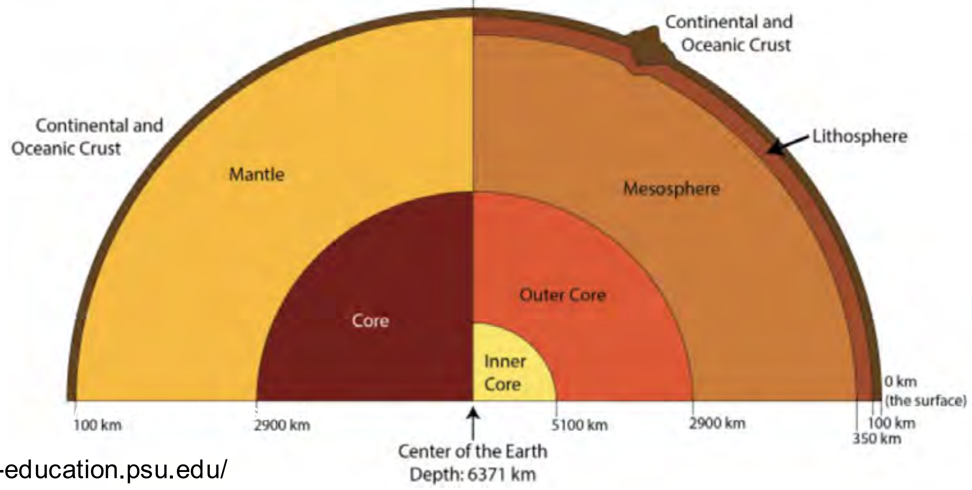
Geoneutrino flux
(signal)

Signal interpretation

Neutrino geoscience: a truly inter-disciplinary field!

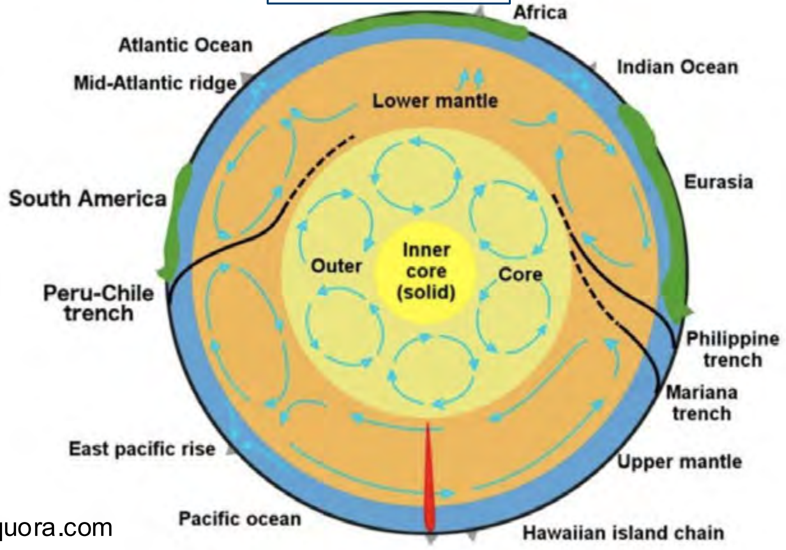
THE EARTH TODAY

Compositional layers | **Mechanical layers**



www.e-education.psu.edu/

Dynamics



www.quora.com

U and Th distribution

Refractory (high condensation T) & **Lithophile** (silicate loving)

Typical concentration for ^{238}U
(Mantovani *et al*. 2004)

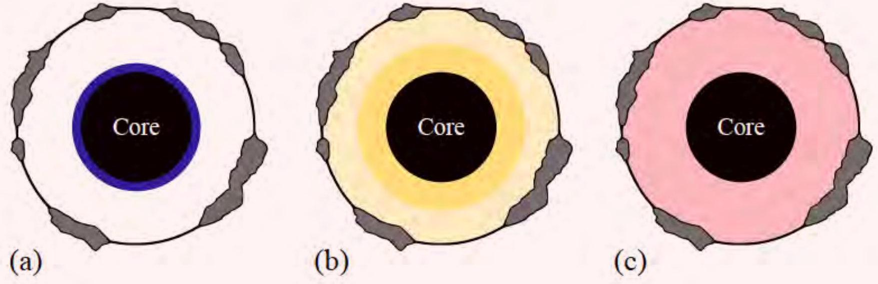
SILICATES	upper continental crust:	2.5 ppm
	middle continental crust:	1.6 ppm
	lower continental crust:	0.63 ppm
	oceanic crust:	0.1 ppm
	upper mantle:	6.5 ppb
	core (**metallic**)	**NOTHING**

Decreases with depth

U/Th distribution in the mantle (3 scenario)

Geoneutrino flux from the mantle

Low | Intermediate | High



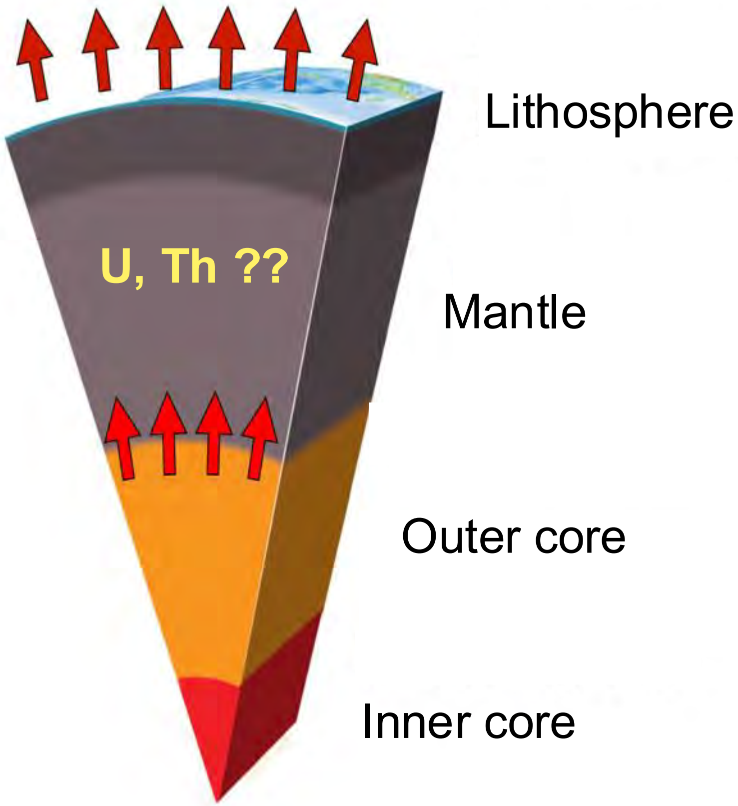
PHYS. REV. D 101, 012009 (2020)

THE EARTH'S HEAT BUDGET

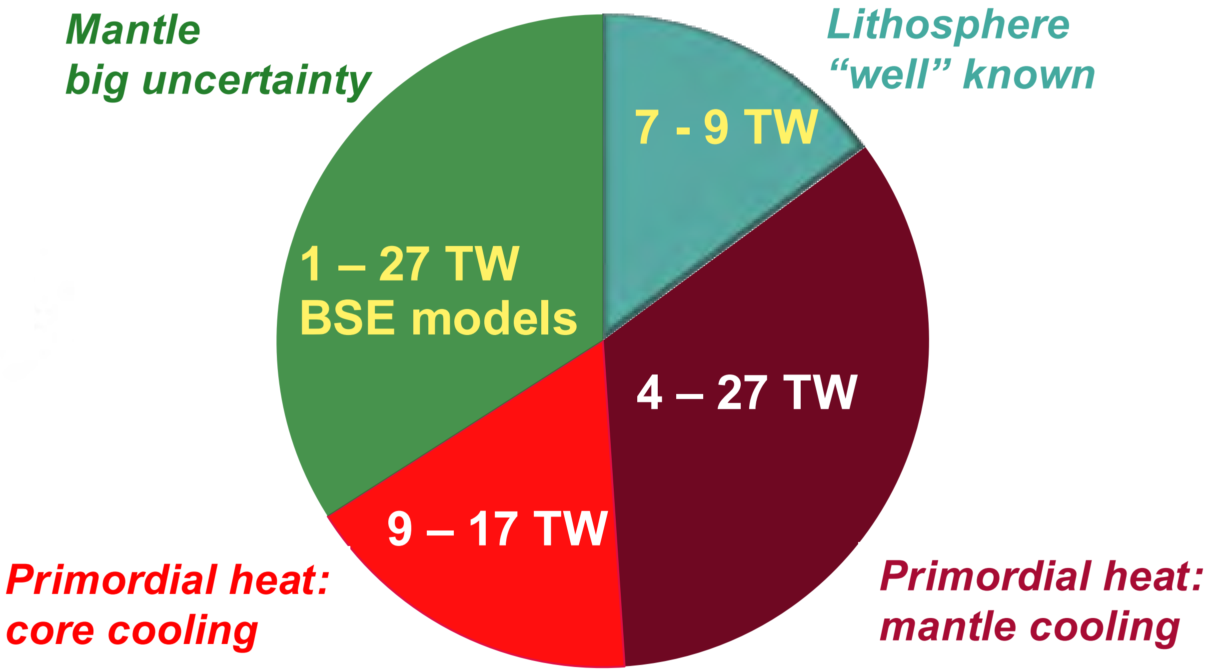
Integrated surface heat flux:

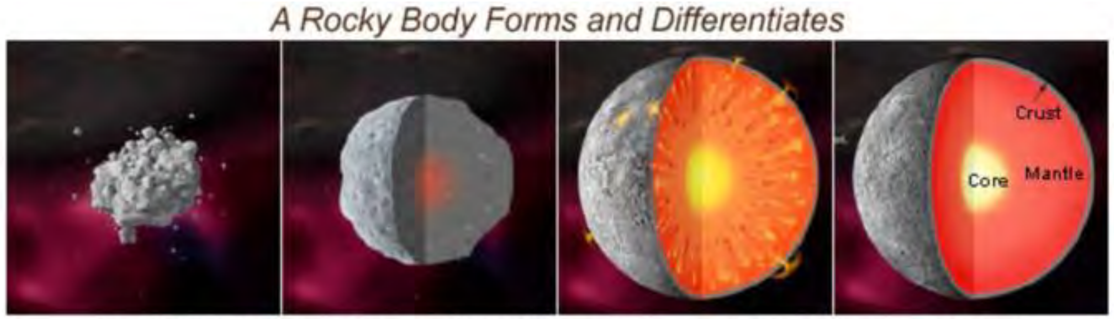
From measured T-gradients along bore-holes

$H_{tot} = 47 \pm 2$ TW



Radiogenic heat & Geoneutrinos





(From Smithsonian National Museum of Natural History - http://www.mnh.si.edu/earth/text/5_1_4_0.html)

BULK SILICATE EARTH (BSE) MODELS

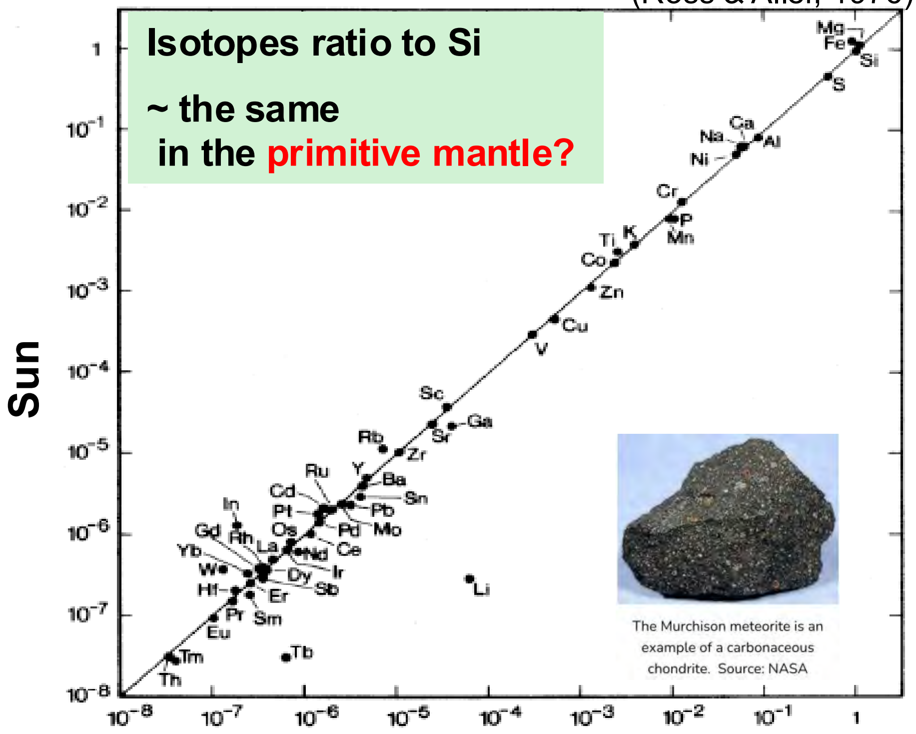
Modeling the composition of the Earth primitive mantle
Various inputs: *composition of the chondritic meteorites, composition of rock samples from the upper mantle and crust, energy needed to run the mantle convection, correlations with the composition of the solar photosphere, …..*

silicate primitive mantle = present-day **crust + mantle**

(Ross & Aller, 1976)

Isotopes ratio to Si

~ the same in the primitive mantle?



The Murchison meteorite is an example of a carbonaceous chondrite. Source: NASA

C1 carbonaceous chondritic meteorites

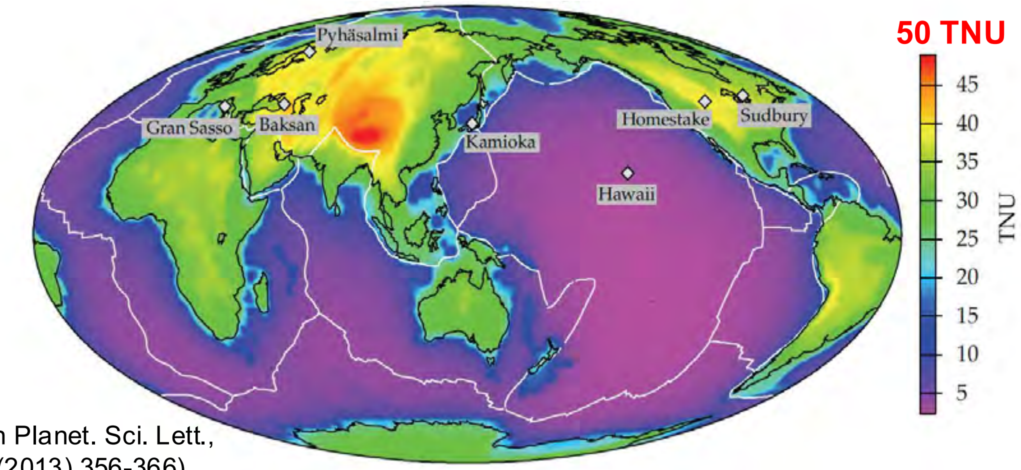
PHYS. REV. D 101, 012009 (2020)

BSE model	M (U) [10^{16} kg]	M (Th) [10^{16} kg]	M (K) [10^{19} kg]	H_{rad} (U+Th+K) [TW]	
Cosmochemical (CC)	5 ± 1	17 ± 2	59 ± 12	**11.3 ± 1.6**	**Low Q**
Geochemical (CC)	8 ± 2	32 ± 5	113 ± 24	**20.2 ± 3.8**	**Middle Q**
Geodynamical (GD)	14 ± 2	57 ± 6	142 ± 14	**33.5 ± 3.6**	**High Q**
„Fully radiogenic" (FR)	20 ± 1	77 ± 3	224 ± 10	47 ± 2	

- Mantle composition is inferred from the BSE models by subtracting the relativly well-known crustal composition
- Ratios of different elements, including U and Th, are much better known than their absolute abundances:
  mass ratio of Th/U = 3.9

GEONEUTRINO SIGNAL WORLDWIDE: from $\phi \sim 10^6$ cm^{-2} s^{-1} to a handful of events

Expected crustal signal: "known and big"



Earth Planet. Sci. Lett., 361 (2013) 356-366)

The signal is small, we need big detectors!

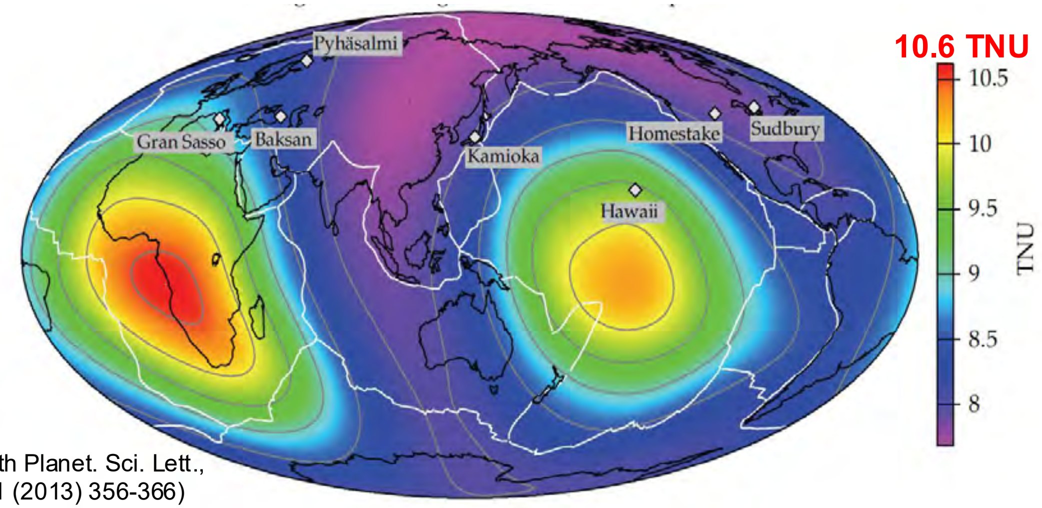
Terrestrial Neutrino Unit

1 TNU = 1 event / 10^{32} target protons / year

cca 1 IBD event /1 kton /1 year, 100% detection efficiency

Expected mantle signal: super-tiny and unknown

Hypothesis of heterogeneous mantle composition motivated by the observed Large Shear Velocity Provinces at the mantle base



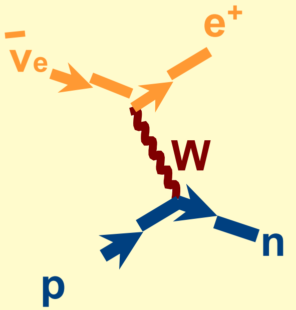
Earth Planet. Sci. Lett., 361 (2013) 356-366)

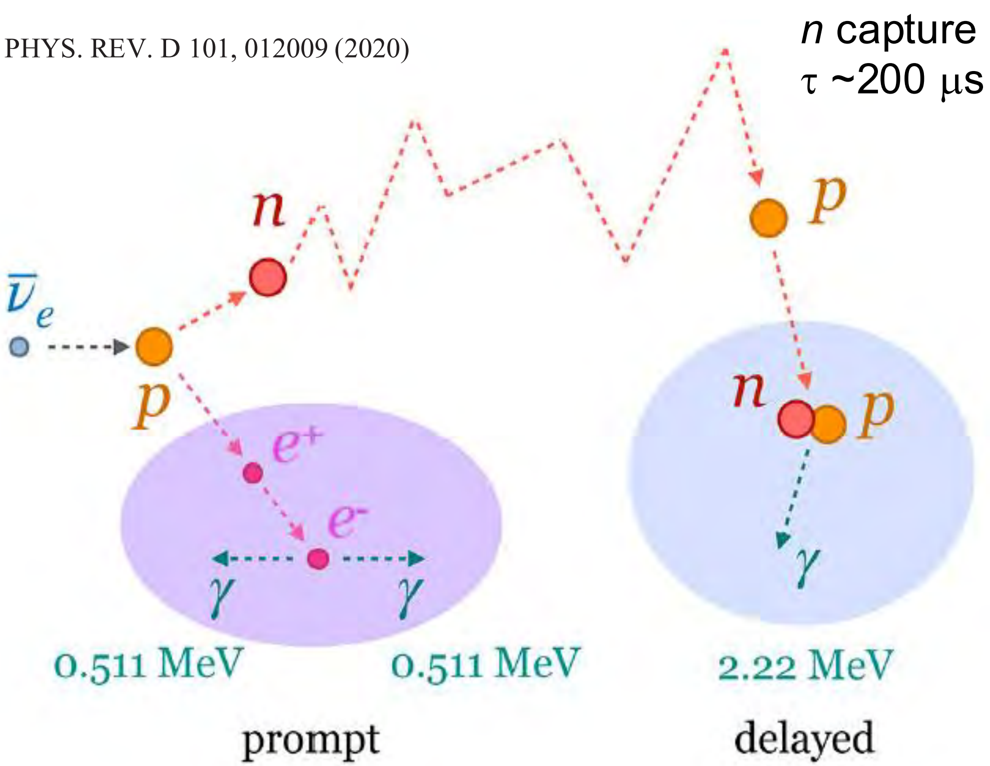
Mantle signal is even more challenging!

GEONEUTRINO DETECTION WITH LIQUID SCINTILLATOR

Electron antineutrino detection: delayed coincidence

- Inverse Beta Decay on proton (IBD)
- Charge current interaction mediated by W bosons
- Sensitive only to **electron flavour antineutrinos**
- Cross section very well known
- Generally, powerful **background suppression** tool
- **Reactor neutrinos – irreducible background** with ~10 MeV end-point, geoneutrinos ~3.3 MeV





Energy threshold = 1.8 MeV

σ @ few MeV: ~10^{-42} cm^2

(~100 x more than elastic scattering on e^-)

Geoneutrino from radioactive decay

$\bar{\nu}_e$

Neutrino oscillation

average P_{ee} ~ **0.55**

$\bar{\nu}_e$ — Detection with IBD

$\bar{\nu}_{\mu,\tau}$ — Invisible to IBD

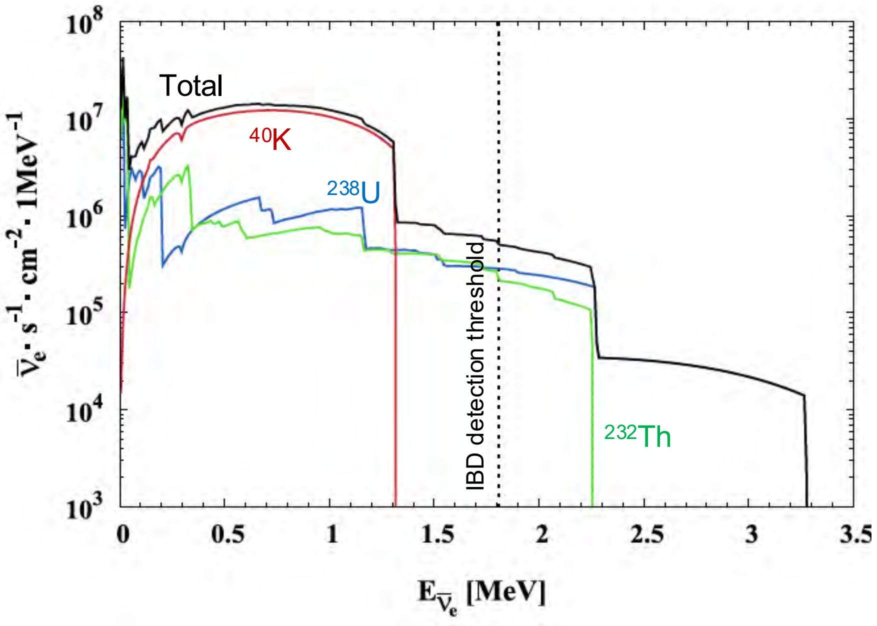
$E_{prompt} = E_{visible}$

$= T_{e+} + 2 \times 511$ keV

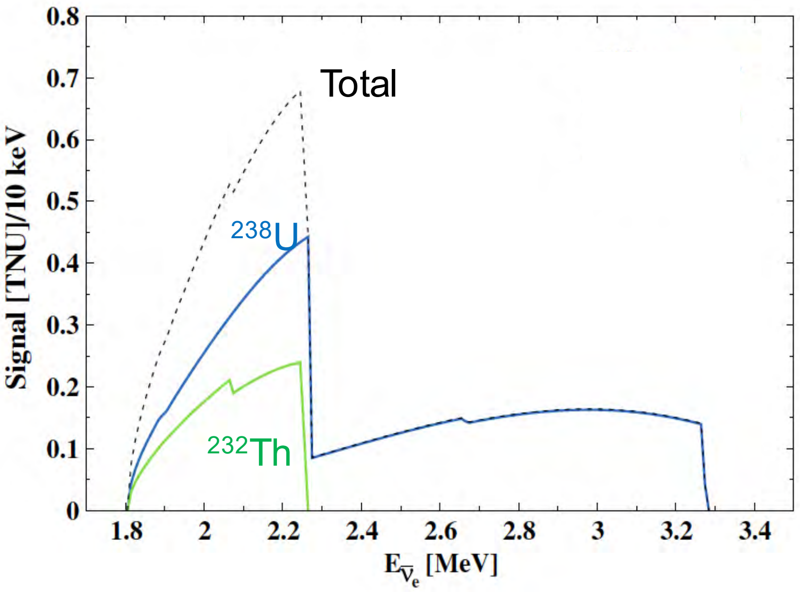
$\sim E_{antinu} - 0.784$ MeV

GEONEUTRINO SPECTRAL SHAPE @ LNGS (BOREXINO SITE)

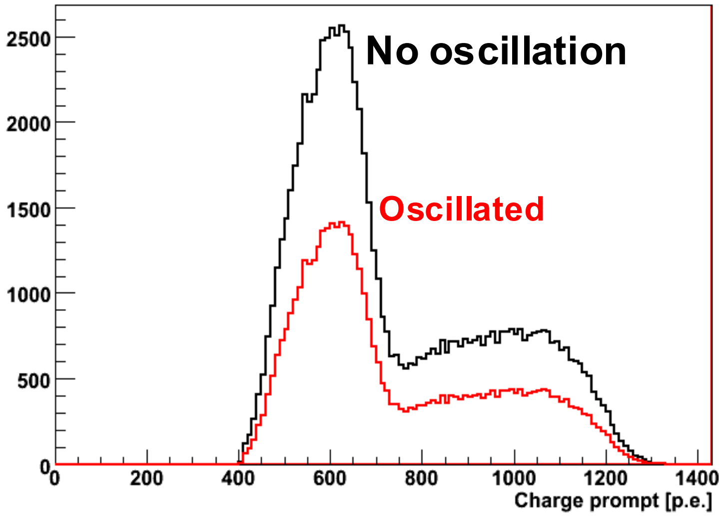
Geoneutrino flux



Geoneutrinos detected via IBD



Effect of neutrino oscillations

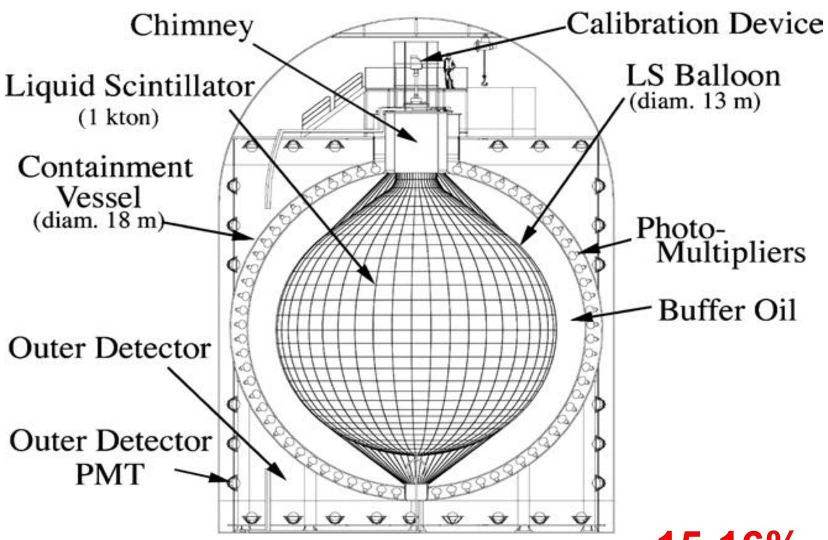


- We are able to **detect geoneutrinos only from the decay chains of ^{238}U and ^{232}Th** above 1.8 MeV energy.
- **^{40}K** geoneutrinos cannot be detected.
- ^{238}U and ^{232}Th have different end points of their spectra: **the key how to distinguish them**.
- **Effect of neutrino oscillations**: for 3 MeV antineutrino, the oscillation length is ~100 km; considering the Earth's dimensions and the continuous distribution of U and Th: for the precision of the current experiments – only suppression of the visible signal without spectral deformation.c

EXPERIMENTS THAT MEASURED GENEUTRINOS

KamLAND, Kamioka, Japan

Border between
OCEANIC / CONTINENTAL CRUST

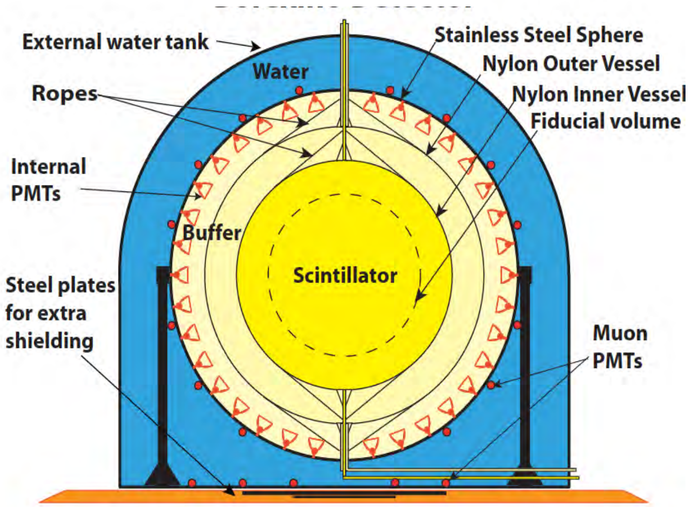


15-16%

- Main goal: reactor neutrinos
- Data taking: since 2022
- LS: 1000 tons;
- Depth: 2700 m.w.e.
- S(reactors)/S(geo) ~ 6.7 (up to 2010)
  ~ 0.4 (from 2011 after Fukushima)

Borexino, LNGS, Italy

CONTINENTAL CRUST

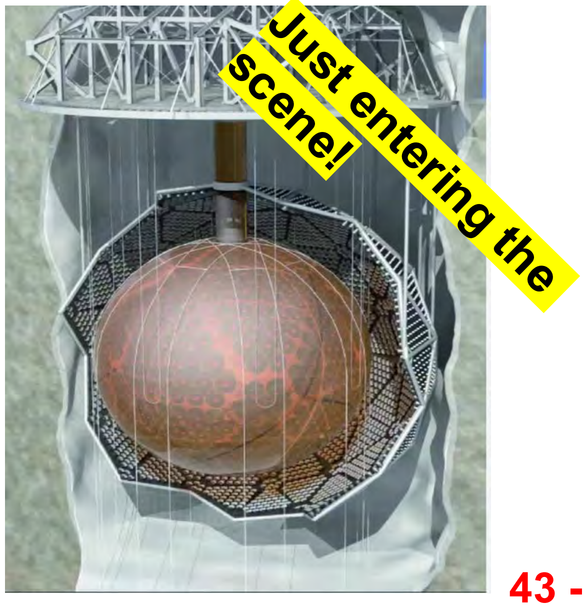


17-18%

- Main goal: solar neutrinos:
  extreme radio-purity needed & achieved;
- Data taking: 2007 - 2021
- LS: 280 tons;
- Depth: 3800 m.w.e.
- S(reactors)/S(geo) ~ 0.3 (2010)

SNO+

CONTINENTAL SHIELD (OLD CRUST)

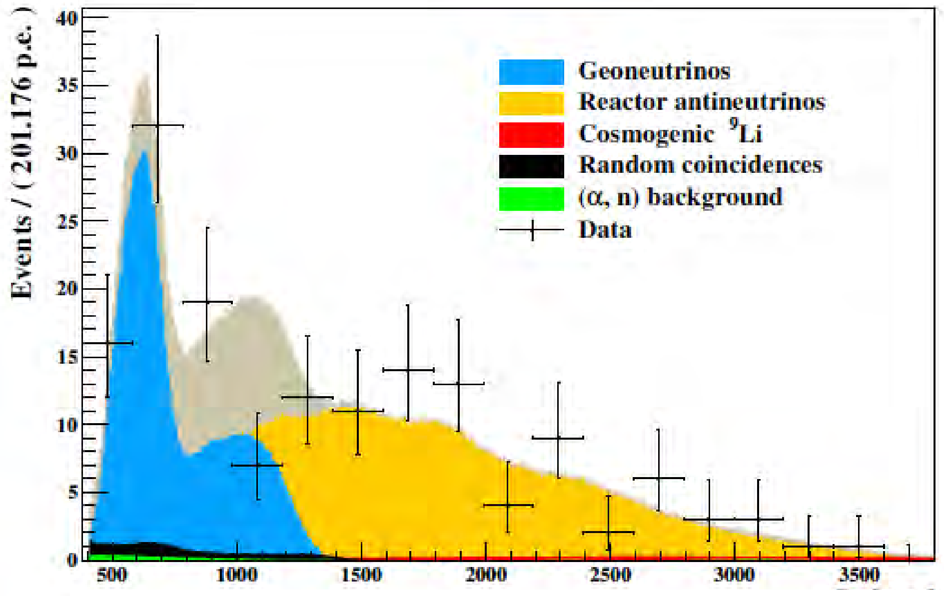


43 - 47%

- Main goal: $0\nu\beta\beta$ decay
- Data taking: since 2022
- LS: 780 tons;
- Depth: 6000 m.w.e.
- Background dominated by (α, n) and not reactors.

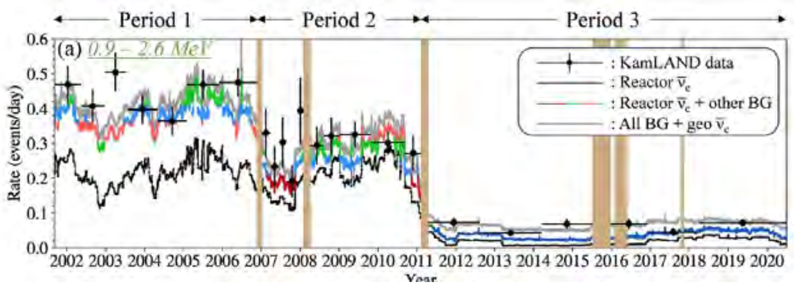
LATES RESULTS: SPECTRAL FIT with chondritic Th/U ratio

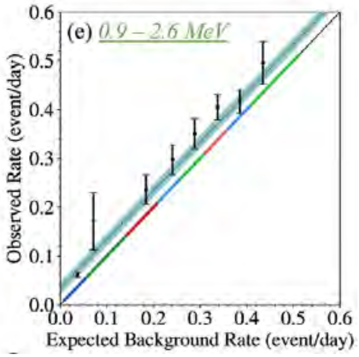
Borexino (PRD101 (2020) 012009)

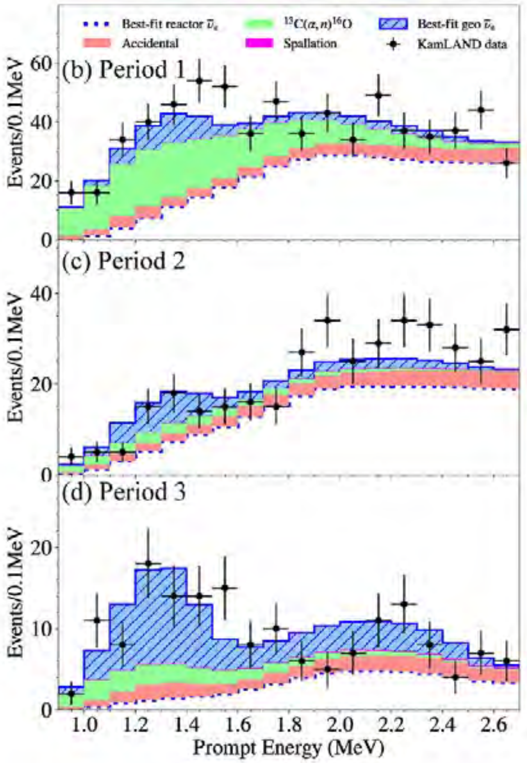


Prompt charge [photoelectrons]: 1 MeV ~500 photoelectrons

KamLAND (Geophys. Res. Lett. 49 e2022GL099566)



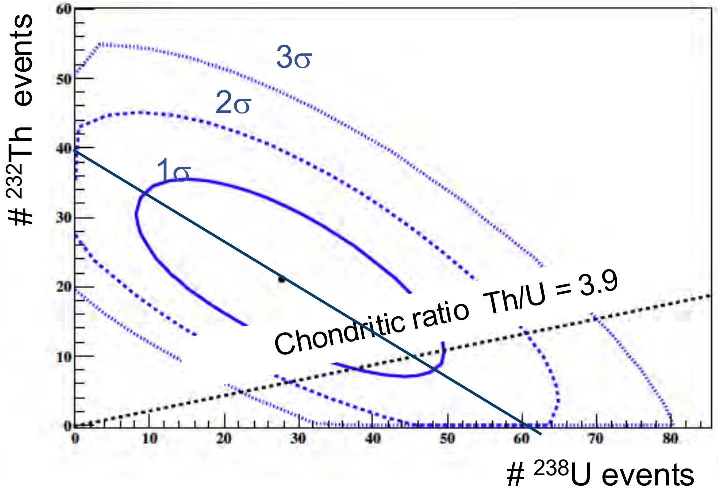




1.29 x 10^{32} proton x years (3262 days, 280 m^3 of FV)	**Exposure [proton x year]**	**6.39 x 10^{32} proton x years** (5227 days, 905 m^3)
154 in total (~90 in the geonu energy window)	**IBD candidates**	**1178** in the geoneutrino energy window
$52.6\ ^{+9.4}_{-8.6}$ *(stat)* $^{+2.7}_{-2.1}(sys)$ $^{+18.3}_{-17.2}\%$	**Geoneutrinos** (mass Th/U fixed to 3.9)	$183\ ^{+29}_{-28}$ *(stat + sys)*: $^{+15.8}_{-15.3}\%$
$47.0\ ^{+8.4}_{-7.7}$ *(stat)* $^{+2.4}_{-1.9}(sys)$ / (39.3 - 55.4)	**Signal [TNU]** / (68% CL interval)	Not provided
Shape only, reactor-ν free – results compatible with prediction	**Analysis with** S(Th)/S(U) = 2.7 (corresponds to chondritic Th/U mass ratio of 3.9)	Rate + shape + time

LATEST RESULTS: SPECTRAL FIT with Th and U free

Borexino (PRD101 (2020) 012009)



$U: 29.0^{+14.1}_{-12.9}$ events

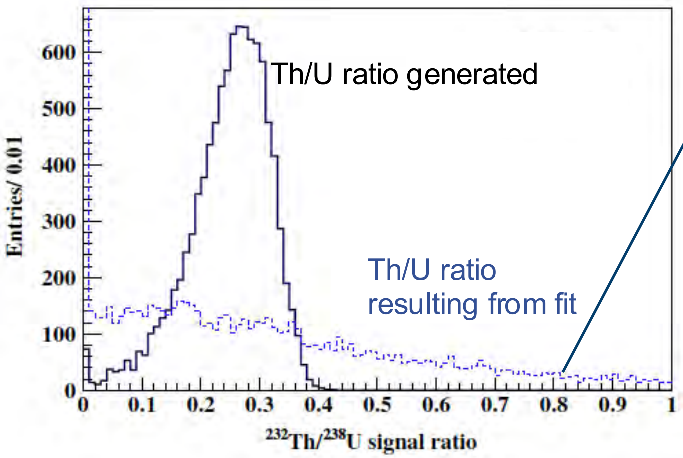
$Th: 21.4^{+9.4}_{-9.1}$ events

$U + Th: 50.4^{+10.1}_{-9.2}$ events

The resulting Th/U ratio is compatible with the chondritic value,

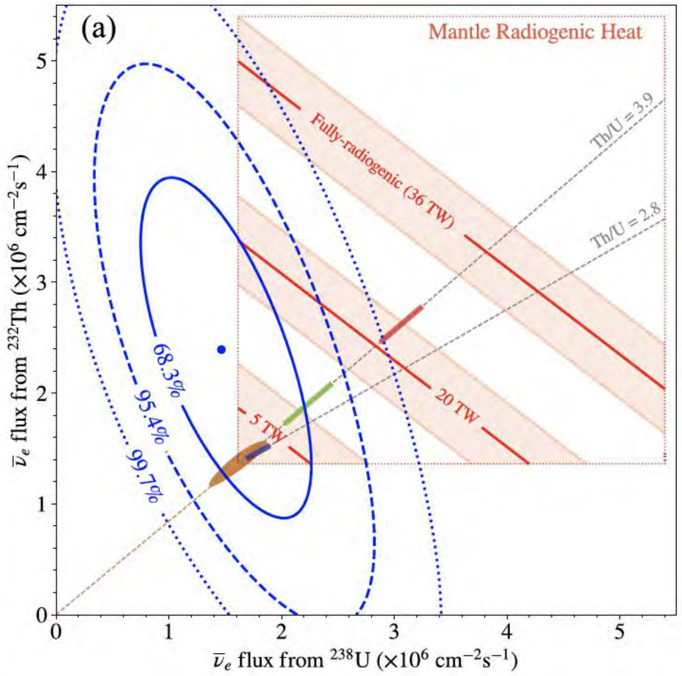
but with the achieved exposure **1.29 x 10^{32} proton x years,** Borexino has no sensitivity to measure the Th/U ratio.

Toy MC study of sensitivity to Th/U ratio



1. Due to the strong anticorrelation of U and Th components, the total geonu signal is very similar in this fit.
2. But to measure the Th/U ratio, large statistics is needed.

KamLAND (Geophys. Res. Lett. 49 e2022GL099566)

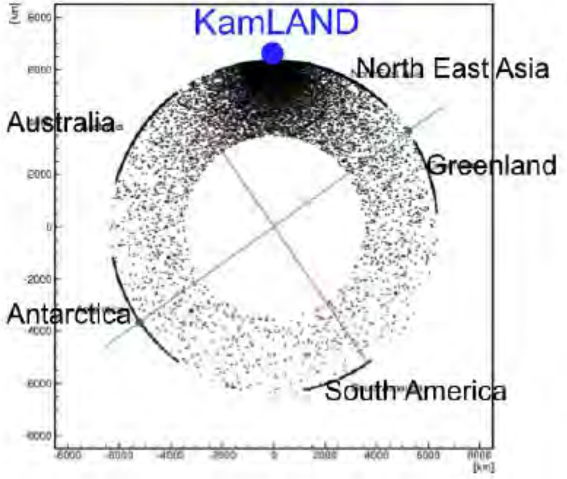


6.39 x 10^{32} proton x year

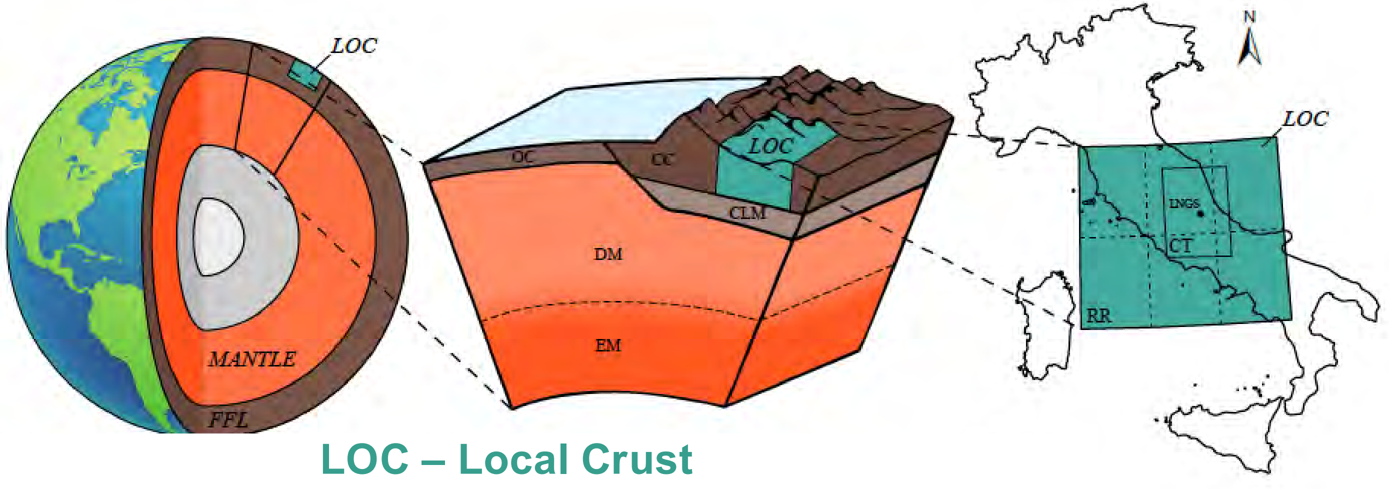
	N of event	0signal rejection
U	117^{+41}_{-39}	3.3σ
Th	58^{+25}_{-24}	2.4σ
U+Th	174^{+31}_{-29}	8.3σ

MANTLE SIGNAL: IMPORTANCE OF LOCAL GEOLOGY

Contribution of different Earth's regions to the total KamLAND signal

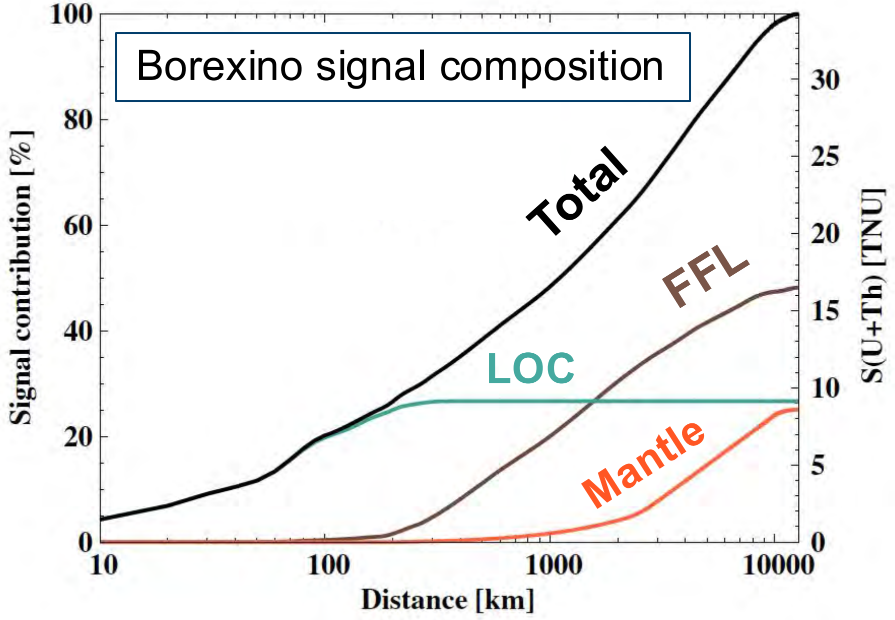


Courtesy: H. Watanabe



LOC – Local Crust
FFL – Far Field Lithosphere
Mantle

PRD101 (2020) 012009

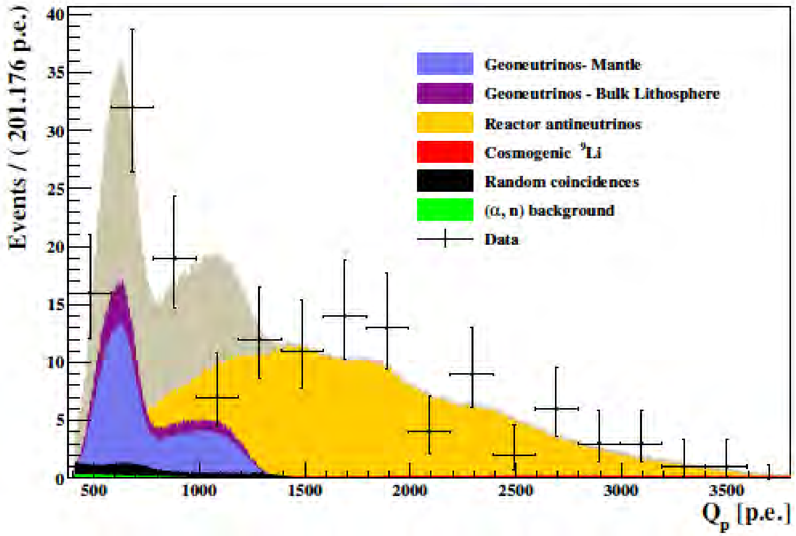


- In order to measure the **Mantle** signal, lithospheric signal must be subtracted.
- **Local Crust (LOC) -** the area of a few hundreds km around the experiment contributes up to 40-50% of the total geoneutrino signal and must be known rather precisely.
- **Far Field Lithosphere (FFL)** – complementary part of the crust to LOC + the continental lithospheric mantle, more approximations are allowed.

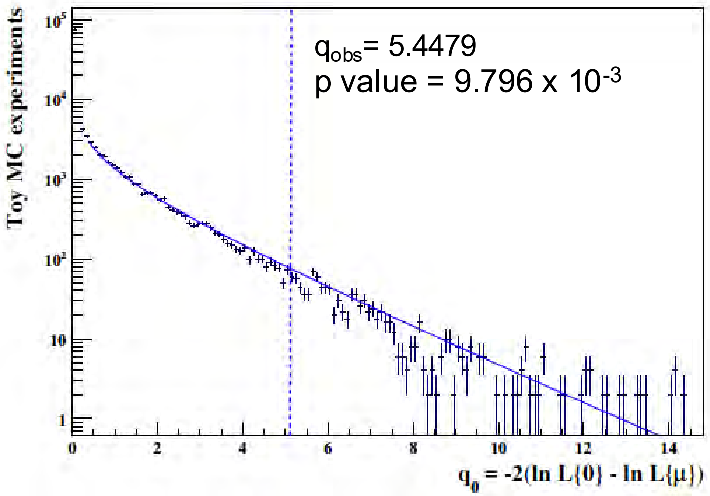
BOREXINO: MANTLE SIGNAL & RADIOGENIC HEAT

PRD101 (2020) 012009

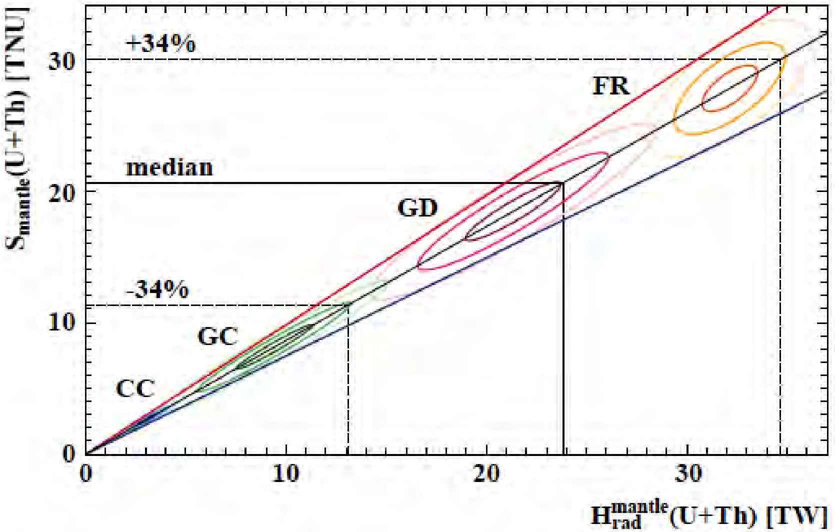
Lithospheric signal: (28.8 ± 5.6) events with S(Th)/S(U) = 0.29
Mantle: S(Th)/S(U) = 0.26
Maintaining for the bulk Earth chondritic Th/U



Sensitivity study using log-likelihood ratio meth



Borexino U+Th mantle signal:



LOC: Coltorti et al. Geochim. Cosmoch. Acta 75 (2011) 2271.
FFL: Y. Huang et al., Geoch. Geoph. Geos. 14 (2013) 2003.

Mantle null hypothesis rejected at 99.0% C.L.

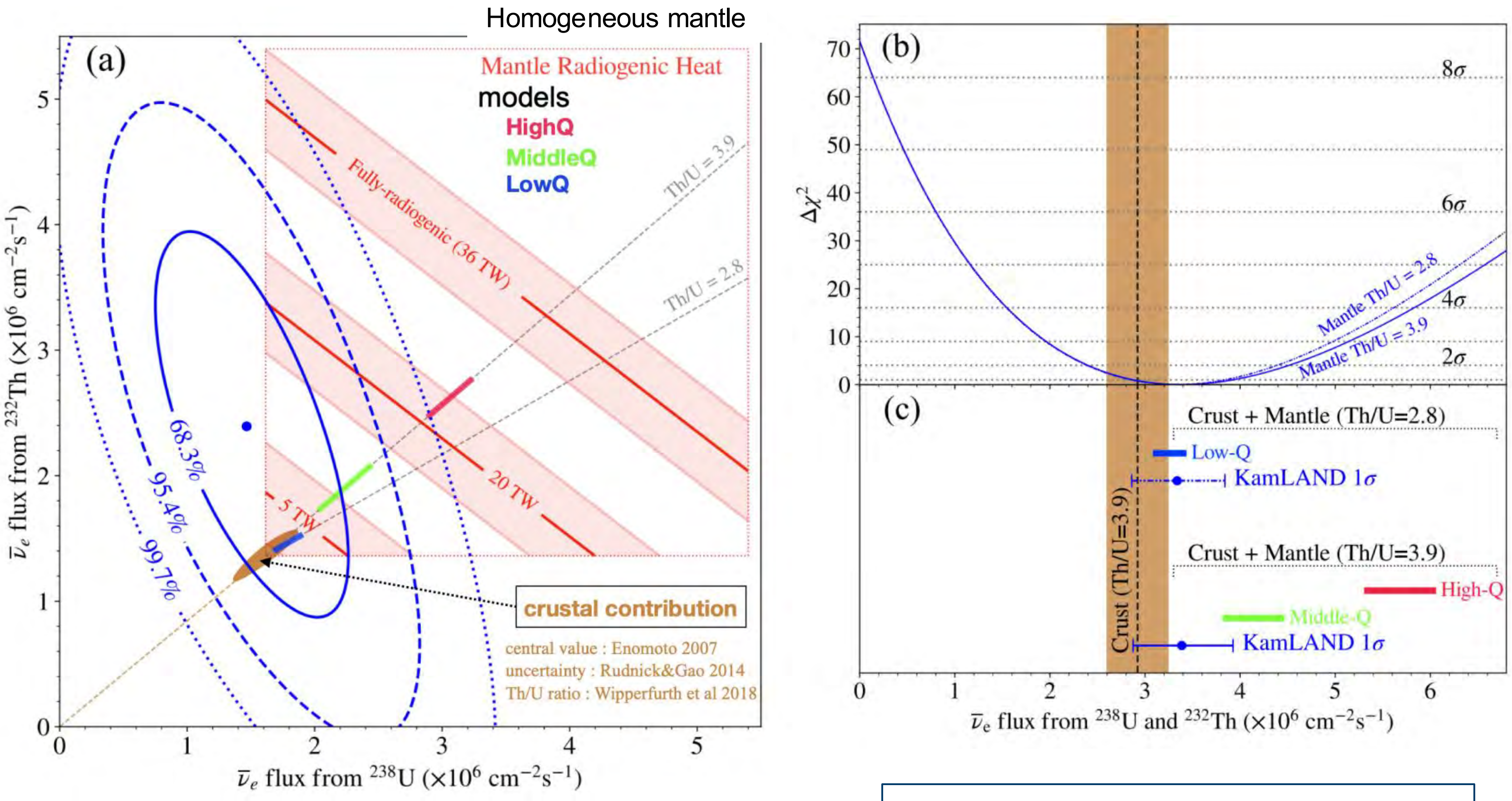
Mantle events	$23.7^{+10.7}_{-10.1}$
Mantle signal U + Th [TNU]	$21.2^{+9.6}_{-9.1}$
Mantle heat U + Th [TW]	$24.6^{+11.1}_{-10.4}$
Earth U + Th + K [TW]	$38.2^{+13.6}_{-12.7}$

Borexino is compatible with geological predictions but least (2.4σ) compatible with the BSE models predicting the lowest U+Th mantle abundances (CC & LowQ BSE).

+ 18% contribution of ^{40}K in the mantle
+ $8.1^{+1.9}_{-1.4}$ TW from lithosphere (U+Th+K)

KAMLAND: RADIOGENIC HEAT

Geophys. Res. Lett. 49 e2022GL099566 & courtesy H. Watanabe



Radiogenic Heat

Th/U free

Adding heat estimate from crust,
^{238}U : 3.4 TW, ^{232}Th : 3.6 TW

Crust + mantle

$$Q^U = 3.3^{+3.2}_{-0.8}\ \mathrm{TW}$$

$$Q^{Th} = 12.1^{+8.3}_{-8.6}\ \mathrm{TW}$$

$$Q^U + Q^{Th} = 15.4^{+8.3}_{-7.9}\ \mathrm{TW}$$

1σ lower limit
allows negative mantle signal.

HighQ model is rejected at

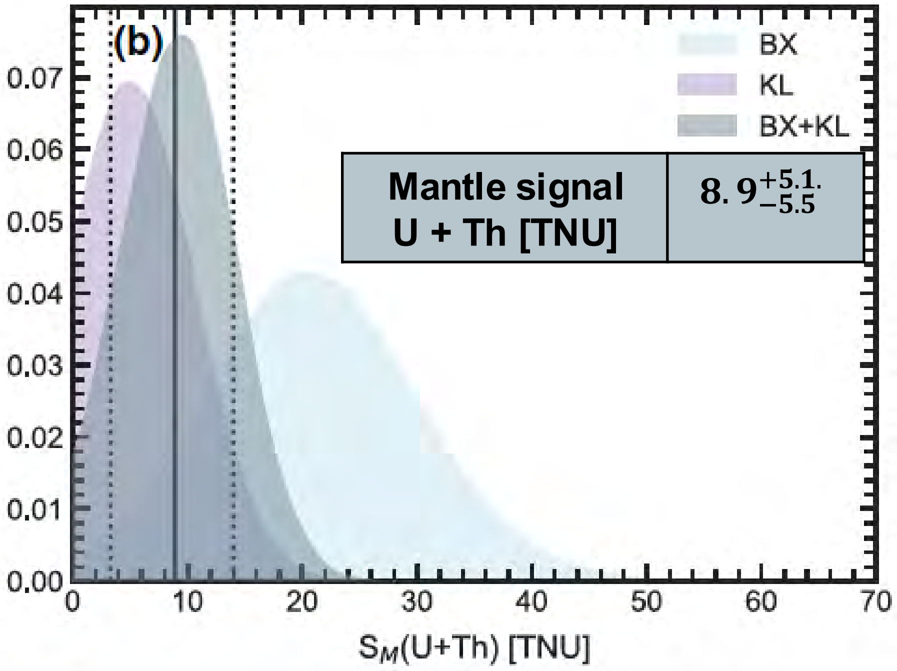
99.76 % C.L. (homogeneous mantle)

97.9% C.L. (concentrated at CMB)

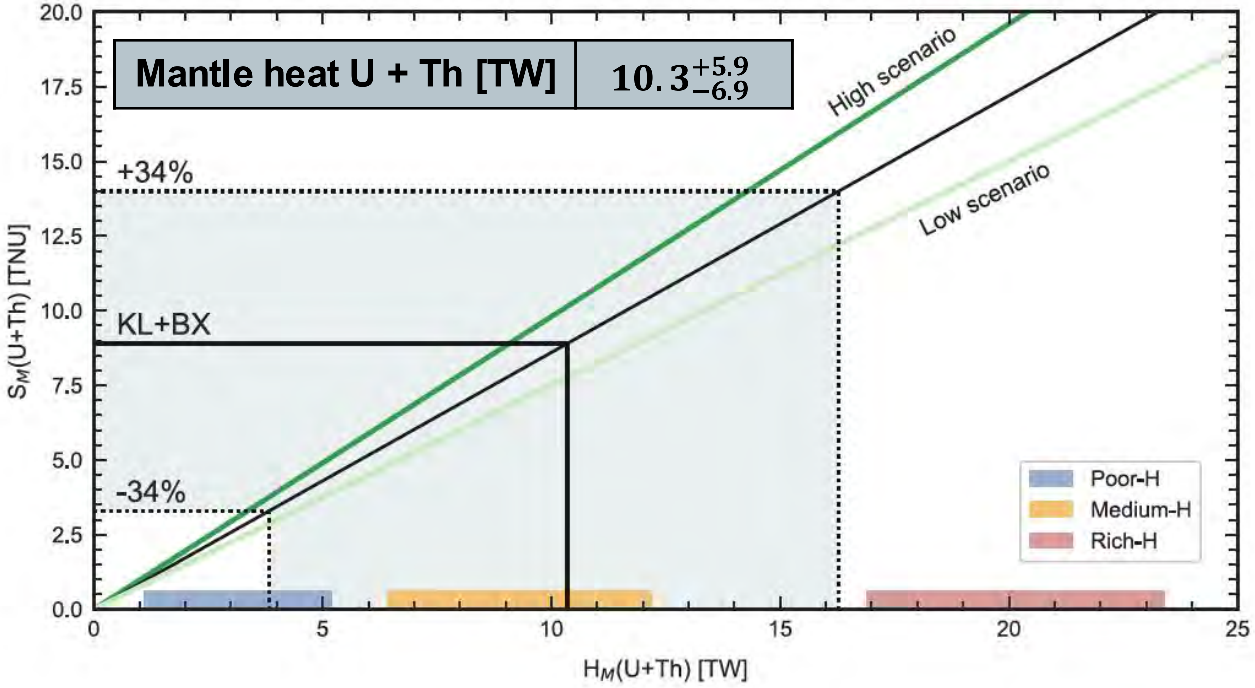
BOREXINO + KAMLAND COMBINED

Bellini at al.: La rivista del Nuovo Cimento 45 (2022) 1

Mantle U + Th signal



Mantle radiogenic heat vs BSE

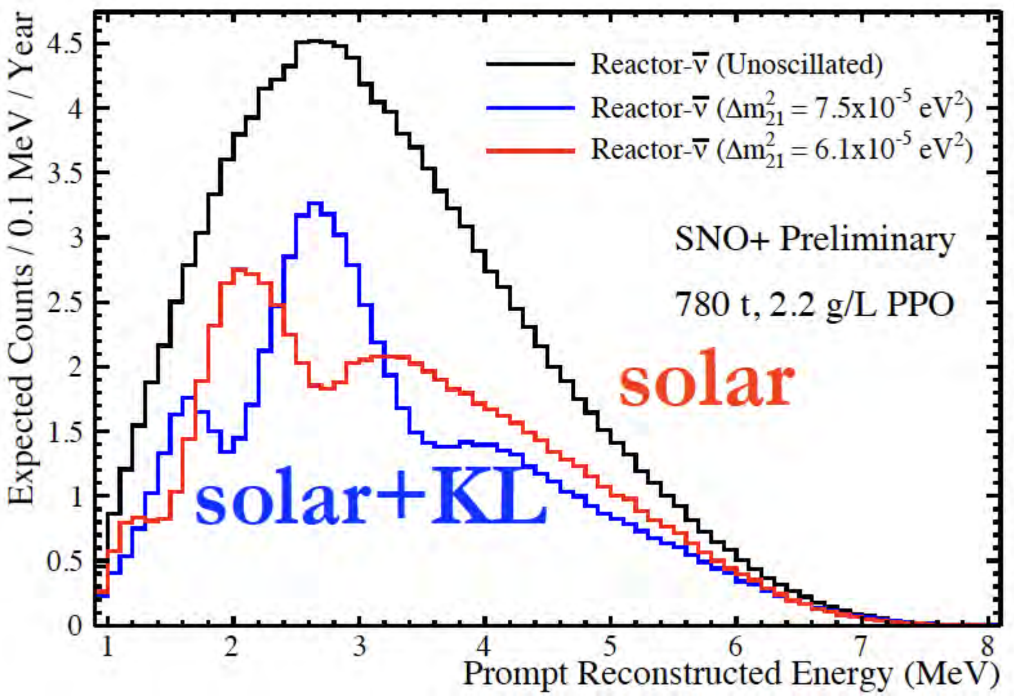


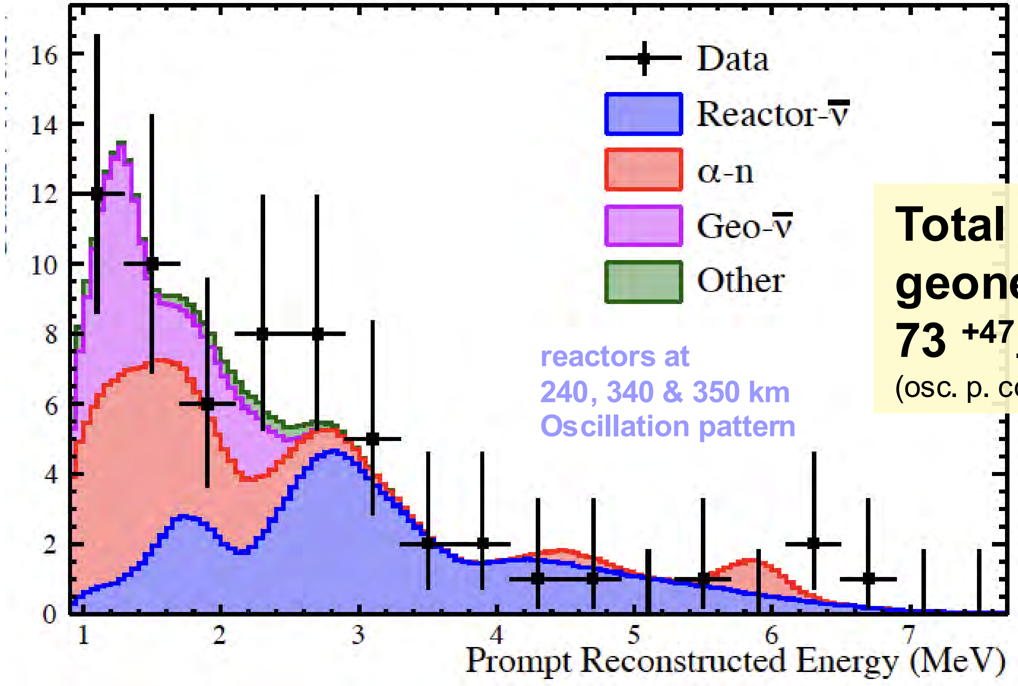
- Analysis assumes laterally homogeneous mantle
- Some level of disagreement between the two experiments
- Combined analysis perfectly compatible with MiddleQ BSE Models

SNO+ EXPERIMENT IN CANADA – LATEST NEWS

The first data: May 7 2025 arXiv: 2505.04469v1

134.4 day data set (May 2022 – March 2023)



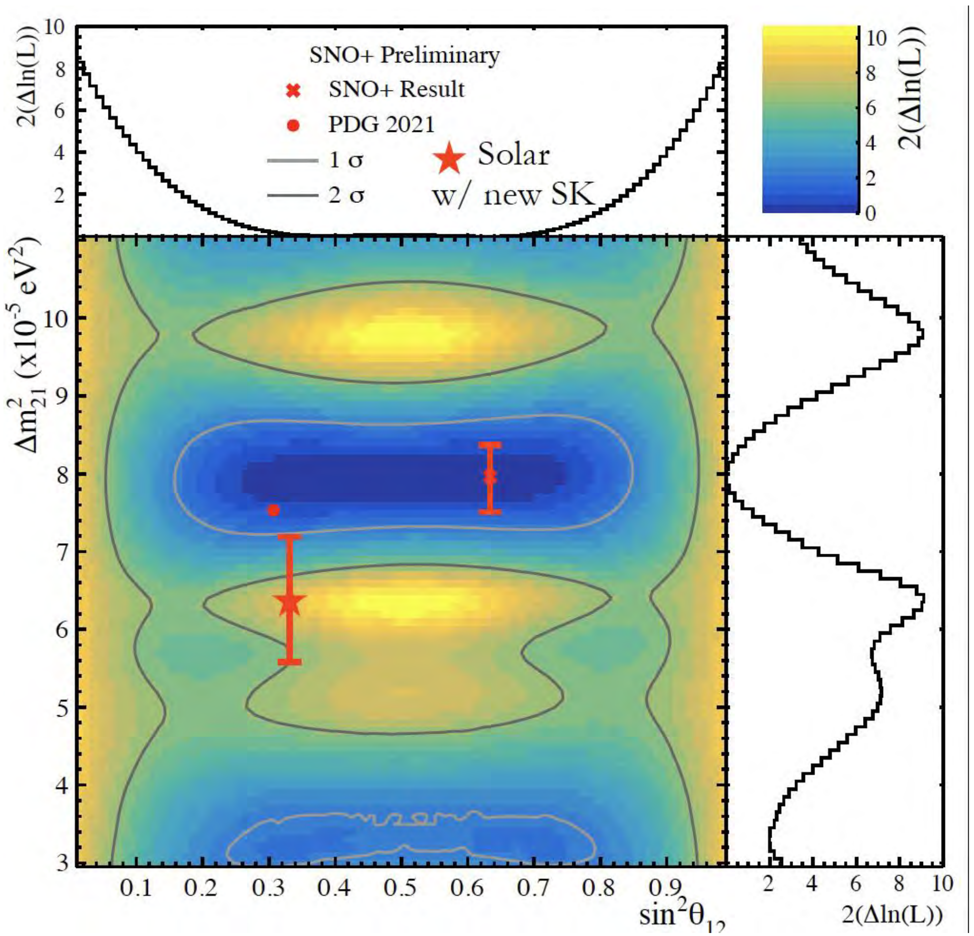


Total measured geoneutrino signal 73^{+47}_{-43} TNU
(osc. p. constrained to PDG 2021)

	Fit (Uncon.)	Fit (Con.)
Δm^2_{21} ($\times 10^{-5}$eV^2)	$7.96^{+0.48}_{-0.42}$	$7.58^{+0.18}_{-0.17}$
$\sin^2\theta_{12}$	$0.62^{+0.16}_{-0.40}$	0.308 ± 0.013
Geo-$\overline{\nu}$ IBD rate (TNU)	79^{+49}_{-44}	73^{+47}_{-43}

SNO+ can measure solar oscillation parameters with reactor neutrinos.

SNO+ EXPERIMENT IN CANADA – LATEST NEWS



SNO+ can measure solar oscillation parameters also with reactor neutrinos.

The first data: May 7 2025 arXiv: 2505.04469v1

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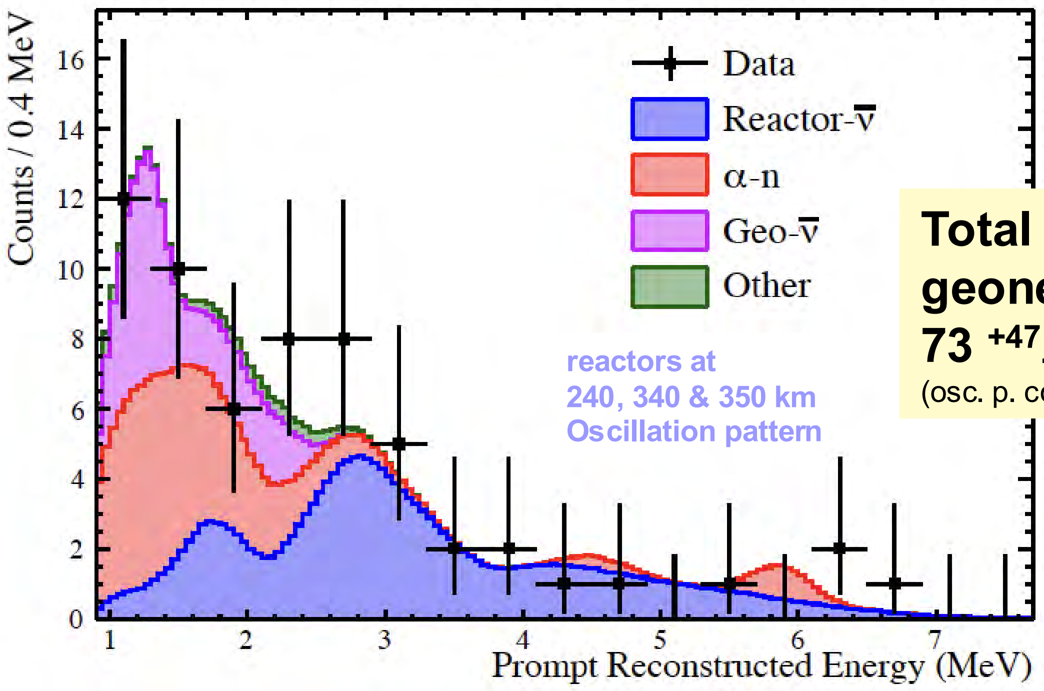

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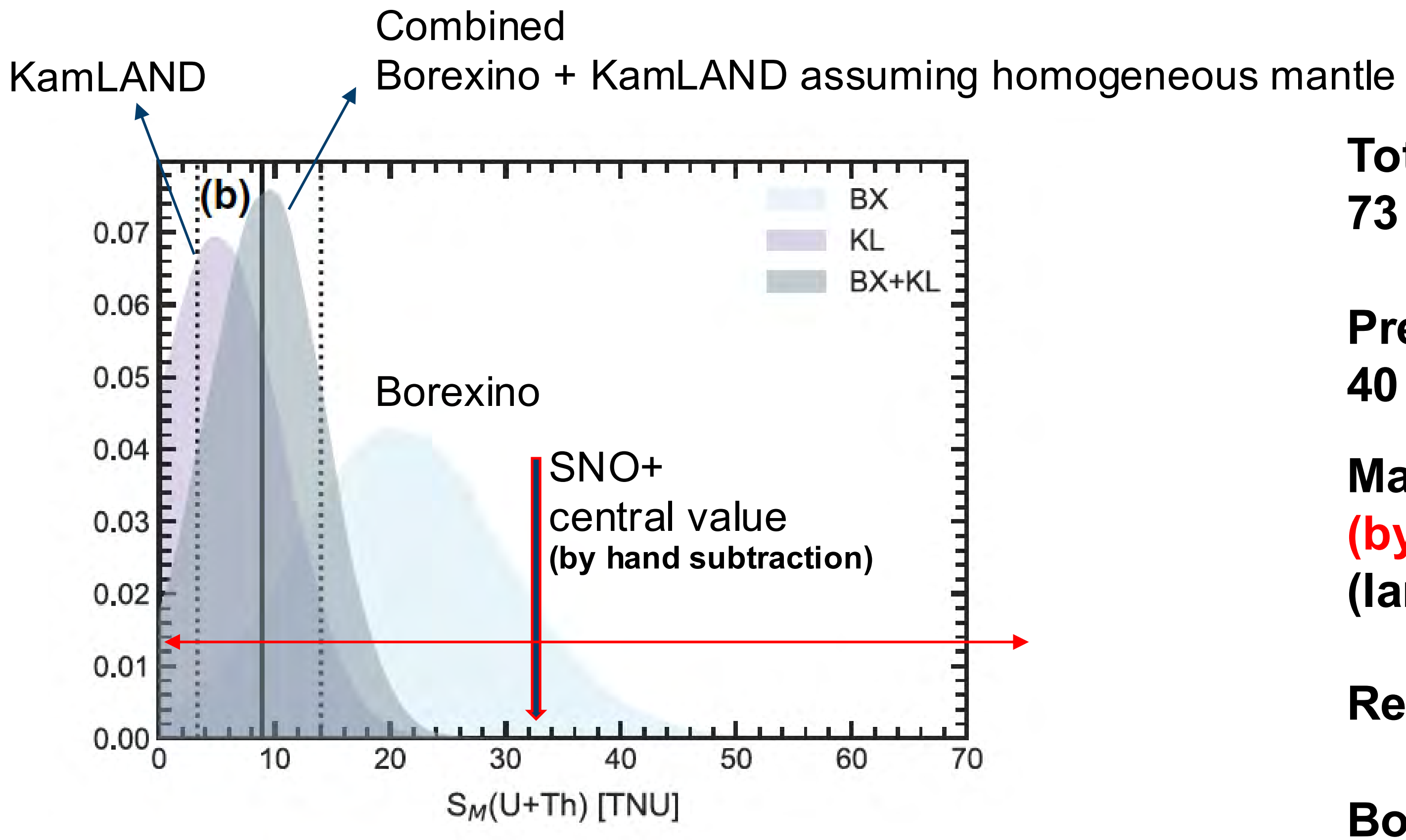
MANTLE SIGNALS COMPARISON



G. Bellini et al. 2021

Intriguing question: is mantle not homogeneous?

Total measured signal by SNO
73 $^{+47}_{-43}$ TNU

Predicted crustal:
40 $^{+6}_{-4}$ TNU **Huang et al. 2014**

Mantle ~ 33 TNU
(by hand subtraction by me)
(large error, 1 sigma touching 0)

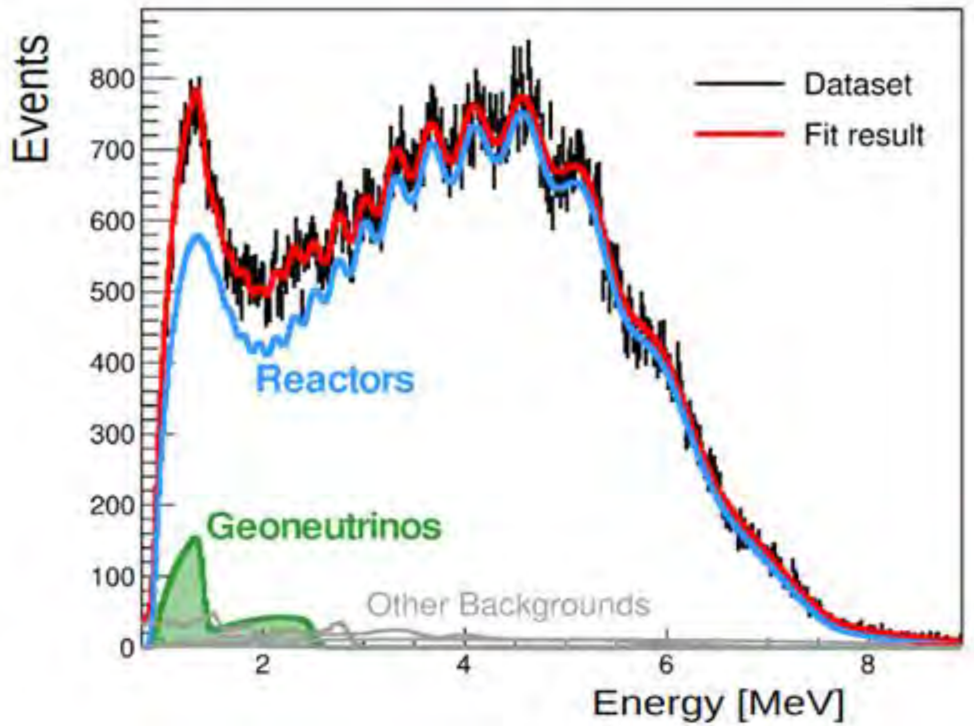
Reminder mantle by

Borexino $21.2^{+9.6}_{-9.1}$ **TNU**

KamLAND ~ 5.4 **TNU**

GEONEUTRINOS IN JUNO

Simulation of 10 years of data



Big advantage:

✓ Large volume and thus high statistics: **400 geoneutrinos / year.**

Main limitations:

✓ Large **reactor neutrino background.**

✓ Relatively shallow depth – cosmogenic background.

- Current (KamLAND and Borexino) precision on measured geoneutrino flux is ~16-18%.
- JUNO can reach this precision in a few years.
- JUNO will provide statistics sufficient to separate with a high significance U and Th.
- **Geological study of the local crust** important in order to separate the mantle contribution and it is ongoing.

- Expected precision of the total geoneutrino signal: **~8% in 10 years** (Th/U mass ratio fixed to 3.9)
- Precision of U and Th individual components **in 10 years:**

^{232}Th ~35% ^{238}U ~30% ^{232}Th + ^{238}U ~15% ^{232}Th/^{238}U ~55%

PRELIMINARY

Geoneutrino summary & outlook

- **Borexino** (Italy): stopped data-taking in October 2021 (last update till April 2019)
- **KamLAND** (Japan): latest update in summer 2022 more data expected to come this year.
- **SNO+** (Canada): 780 ton & DAQ started & 30-40 geonus/year; Low cosmogenics; - first events just detected!
- **JUNO** (China): 20 kton & completion this & 400 geonus/year! - about to start *(J. Phys. G: Nucl. Part. Phys. 43 (2016) 030401);*
- **JINPING** (China): 5 kton; deepest lab, far away from reactors, very thick continental crust at Himalayan region; *(PRD 95 (2017) 053001)*
- **HanoHano** / Ocean Bottom Detector (Hawaii): ~10 kton movable underwater detector with ~80% mantle contribution: **"THE" GEONU DETECTOR**

Solar neutrinos take home message

- *Importance in discovery of neutrino oscillations and neutrino mass.*
- *Evidence for matter effects shaping neutrino transformations.*
- *Detection of neutrinos from pp chain and CNO cycle, key to probing solar metallicity.*
- *Future: precision oscillation studies, new physics searches, deeper understanding of solar fusion and core composition.*

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Geoneutrinos take home message

- *Measurements of geoneutrinos in general agreement with Bulk Silicate Earth (BSE) models.*
- *Slight tension in mantle contributions based on existing measurements.*
- *Key to understanding Earth's heat budget and geodynamics.*
- *Future: precision studies of mantle composition, radioactive element distribution, and thermal evolution of the Earth.*

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Thank you!