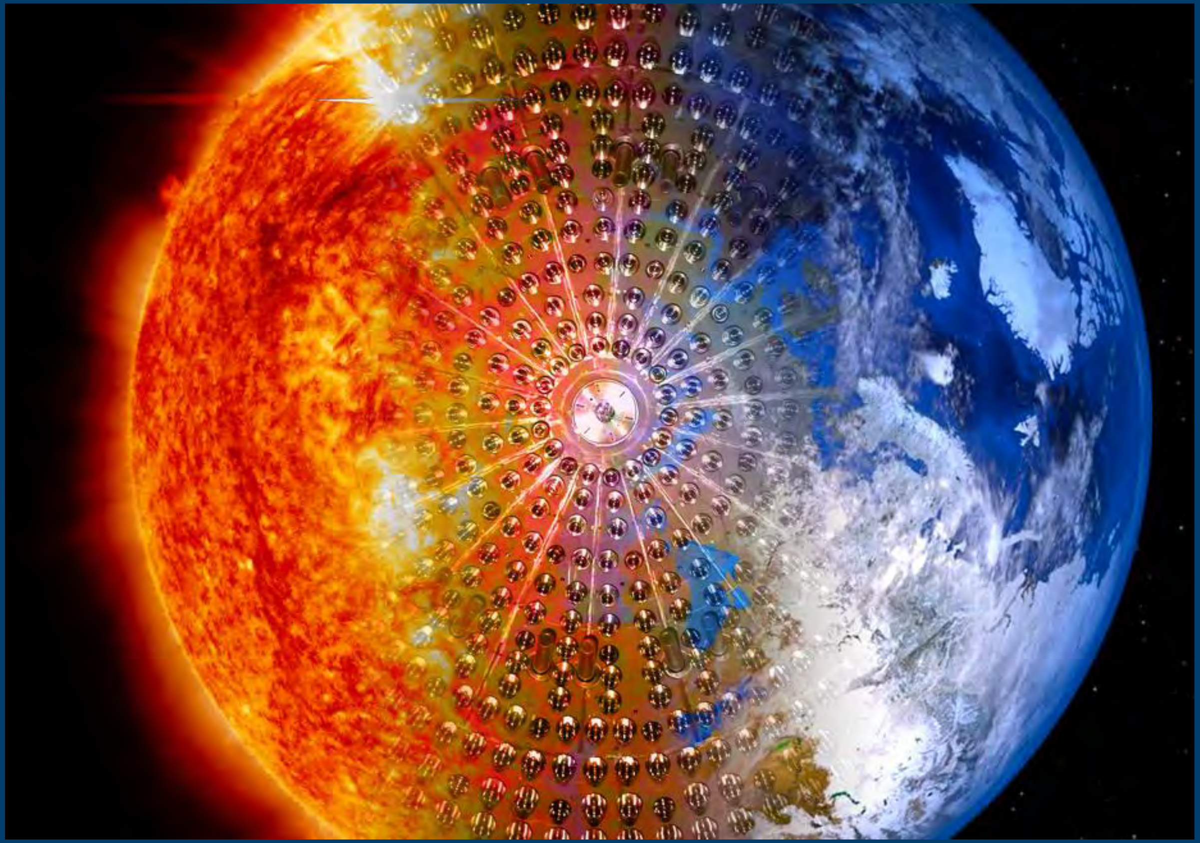
SOLAR AND GEO NEUTRINOS



LIVIA LUDHOVA

GSI DARMSTADT

& JGU MAINZ UNIVERSITY, GERMANY

SEPTEMBER 15-16, 2025, FRAUENINSEL, GERMANY

SUMMER SCHOOL - MAINZ PHYSICS ACADEMY

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!**

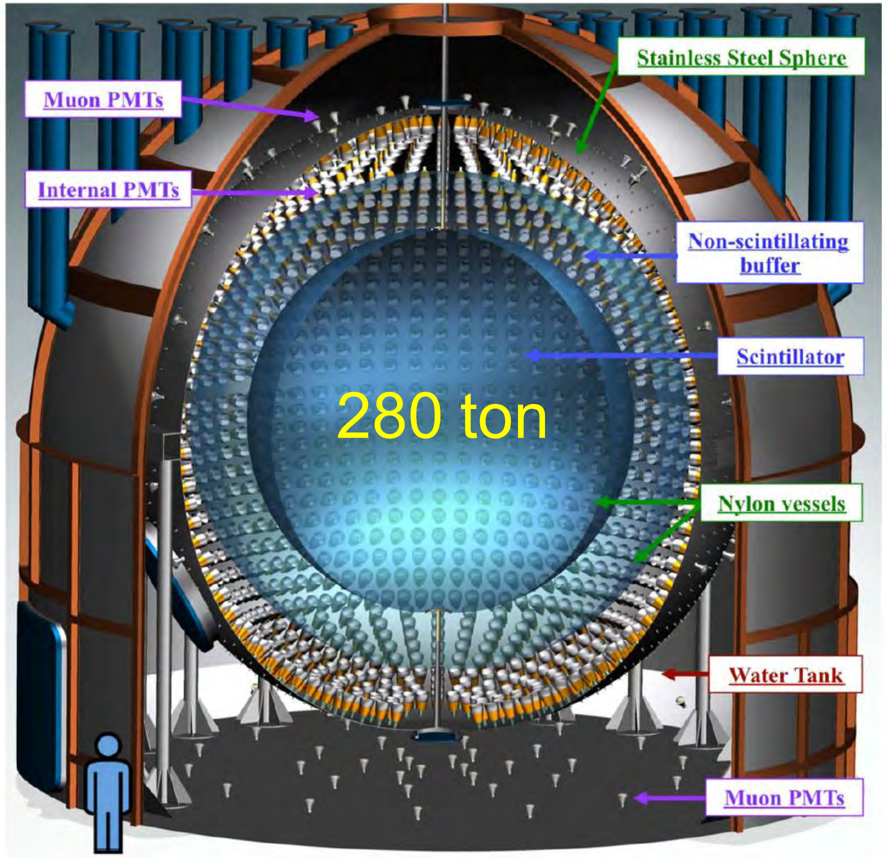
Passion for Physics: at the JUNO site.

Passion for Geology:
Mutnovka Volcano, Kamchatka, Russia.

BOREXINO DETECTOR

Laboratori Nazionali del Gran Sasso, Italy

Operated from 2015 - 2021

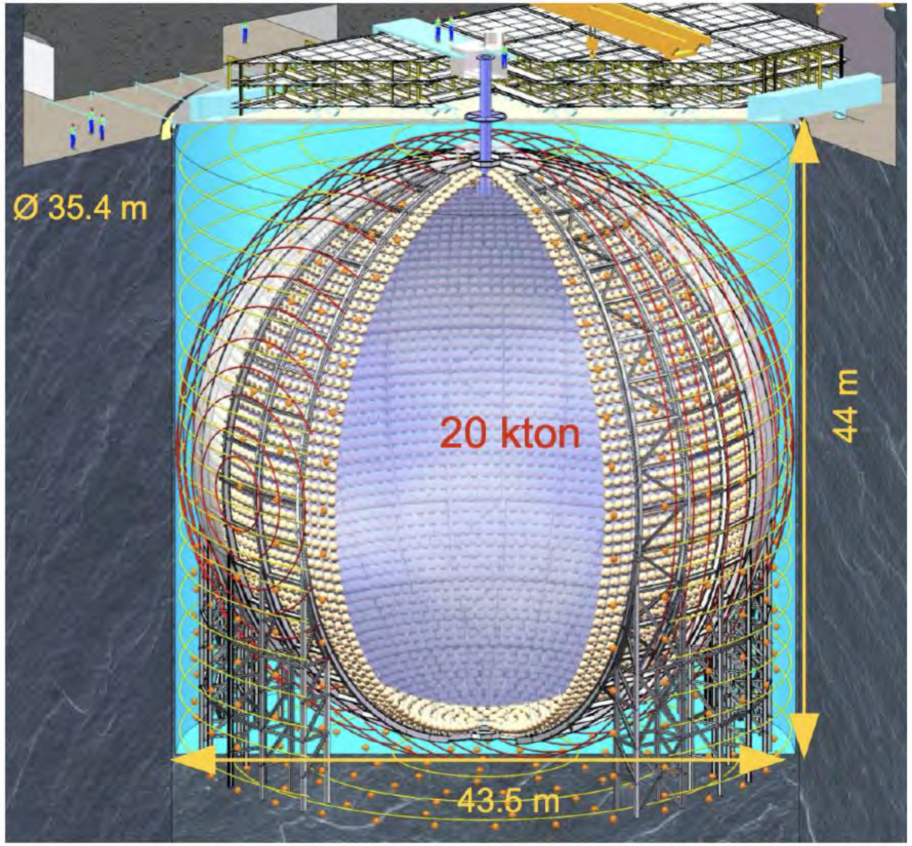


- Underground
- Liquid scintillator
- Large volume
- PMTs
- Muon water veto

JUNO DETECTOR

Jiangmen, south China

Will be completed this year!



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

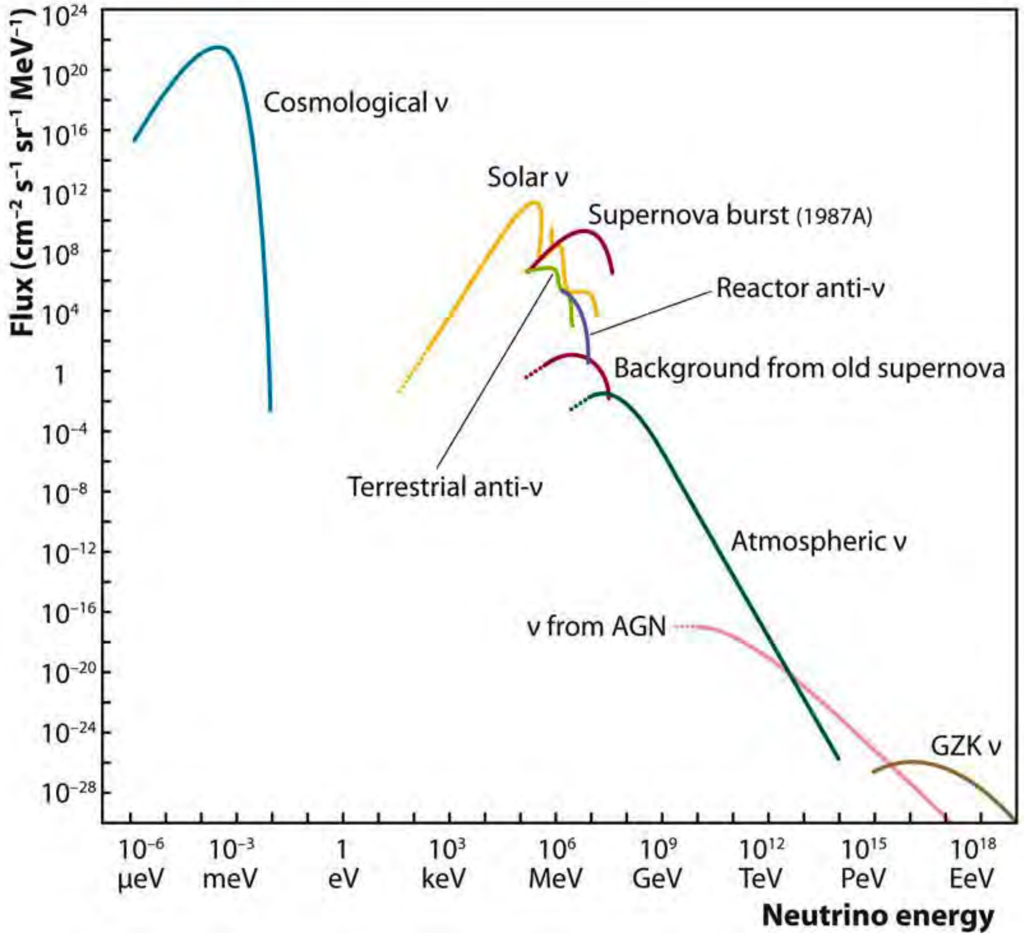
- Historical perspective
- Motivation of the measurements
- Overview of the results
- Outlook

WHAT ARE NEUTRINOS?

Basic constituents of matter:
Standard Model of Elementary Particles

There are 3 flavours for both neutrinos and antineutrinos.

NEUTRINO SOURCES



Spanning throurgh many orders of magnitude both in energy and flux.

NEUTRINO INTERACTIONS

Gravitational — large scales & mases

~~Strong~~

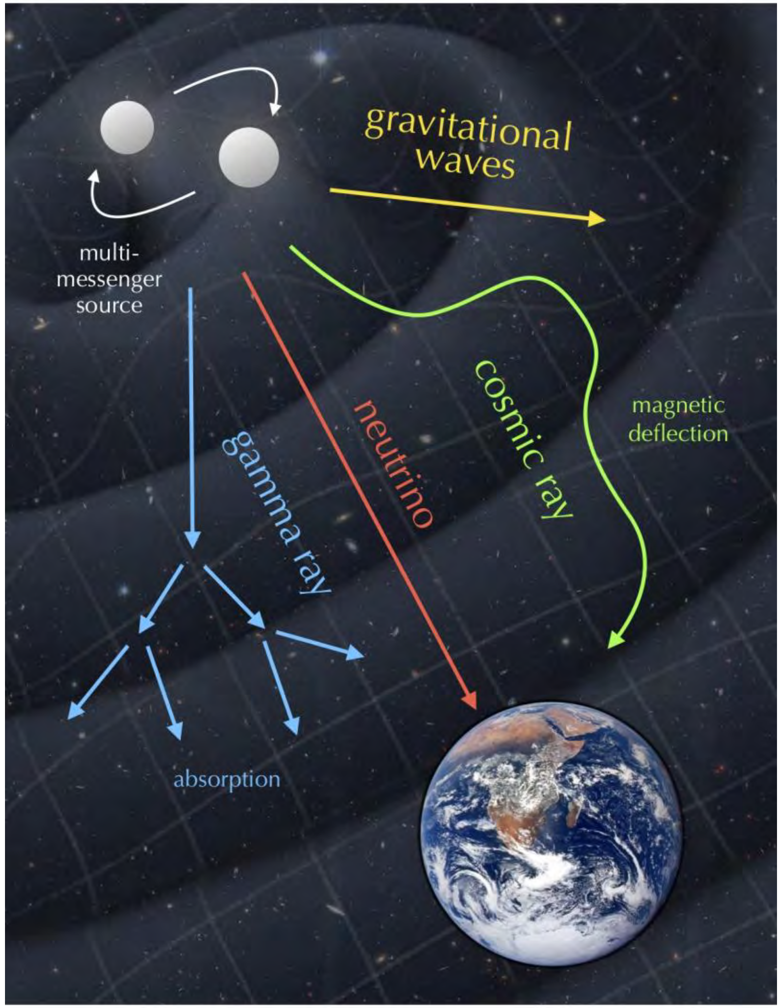
~~Electromgnetic~~

Weak — VERY Weak

Small probability to interact with matter

- (-) **Difficult detection**
- (+) **Bringing unperturbed information**

NEUTRINOS AS MESSENGERS



Taken from https://nbi.ku.dk/english/research/experimental-particle-physics/icecube/astroparticle-physics/

NEUTRINOS ARE SPECIAL

Small interaction cross sections → low rates in the detector!

Imagine……

7 x 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/m^3* ^{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

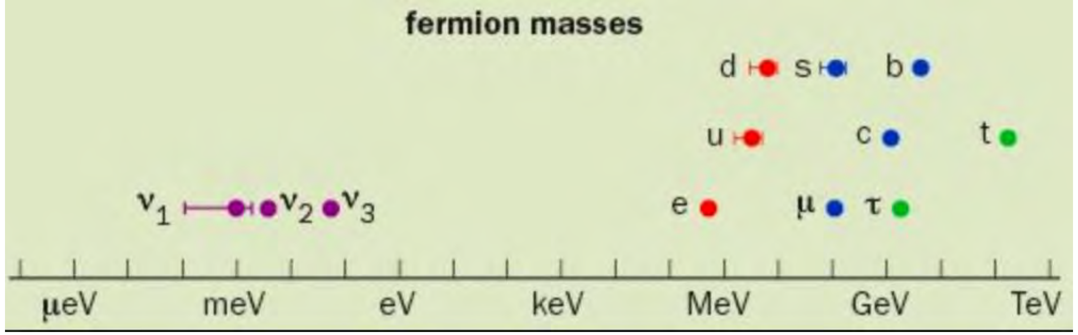
Only weak interactions

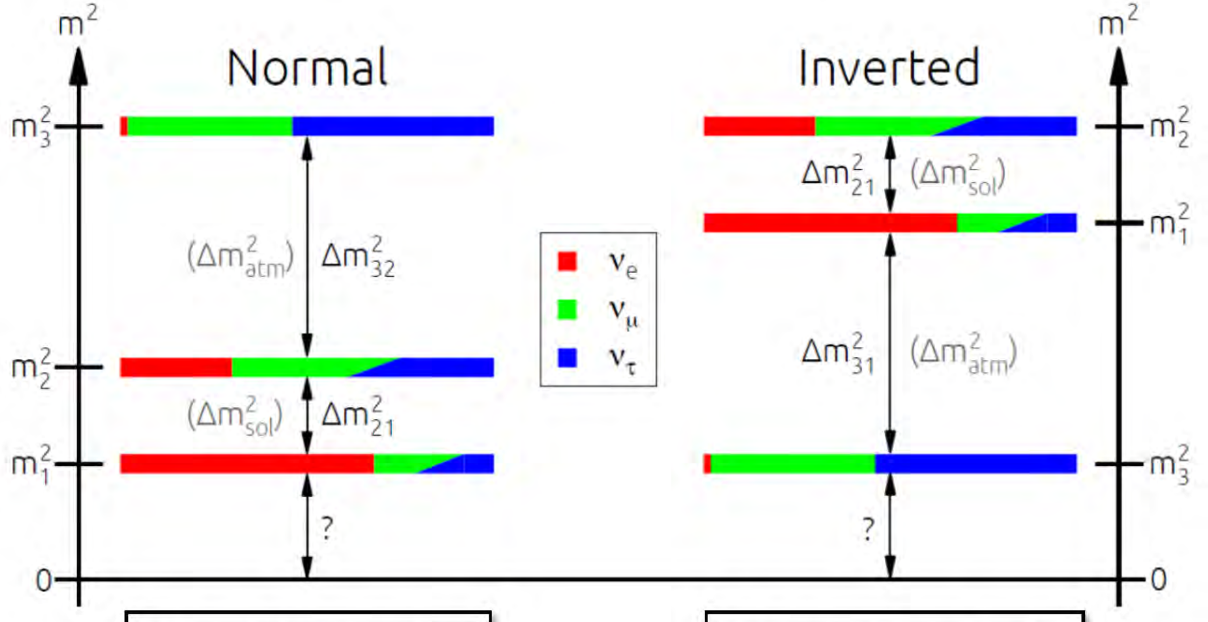
- ✓ **Difficult to detect**
  - o Large detectors
  - o Underground laboratories
  - o Extreme radio-purity
- ✓ **Bring unperturbed information about the source (Sun, Earth,** SN)

Open questions in neutrino physics

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

linked





$m_1 < m_2 < m_3$ $m_3 < m_1 < m_2$

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

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

NEUTRINO MIXING AND OSCILLATIONS

α = e, μ, τ
Flavour eigenstates
INTERACTIONS

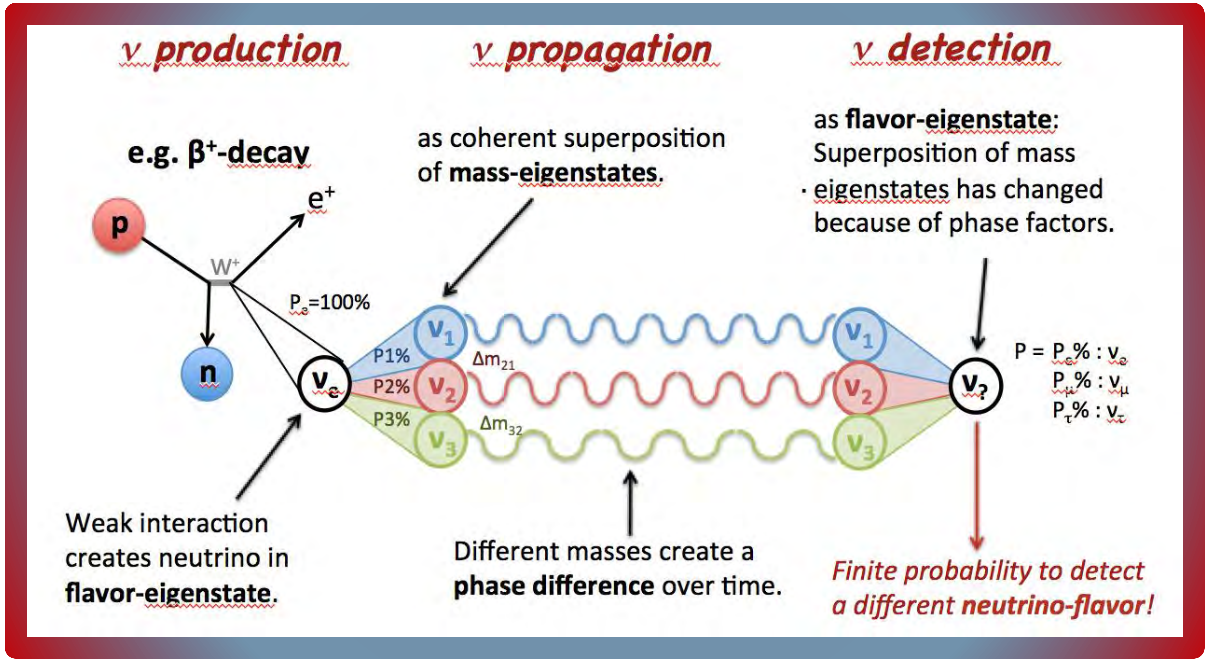
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}\,|\nu_i\rangle$$

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 α1 , α2** 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)

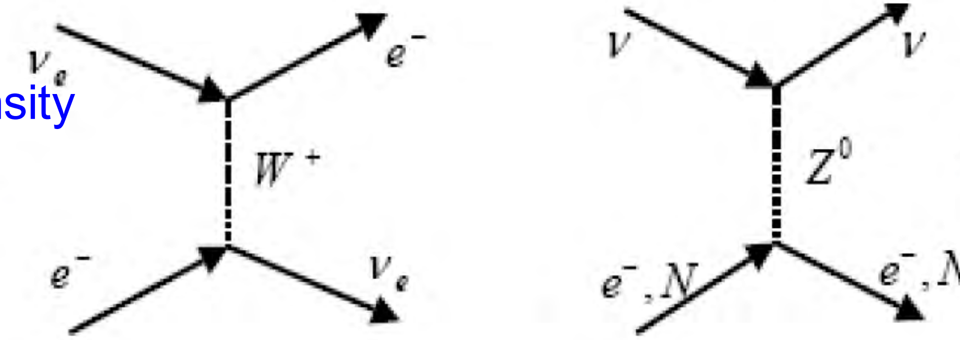
ν-oscillations in matter: MSW effect

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, $\sin^2 2\theta_M$)**

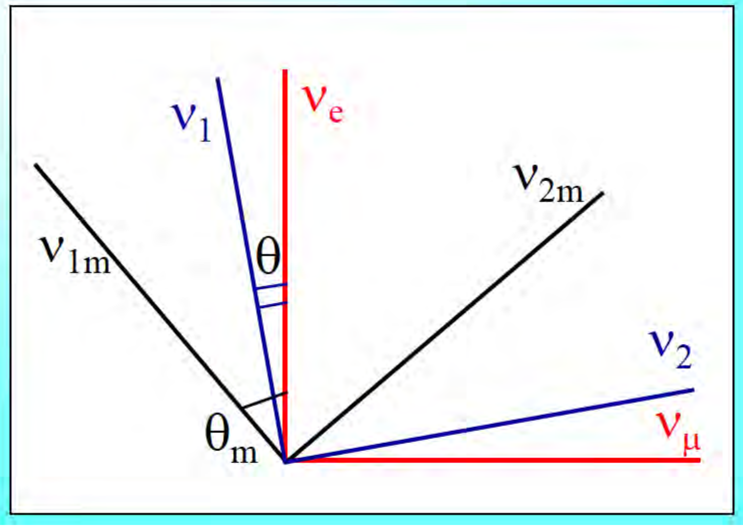
Effective oscillation parameters (Δm^2_M, θ_M) instead of the vacuum ones (Δm^2_V, θ_V)

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

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

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

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**
  <u>**Mikheyev–Smirnov–Wolfenstein effect**</u>

For solar neutrinos

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

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

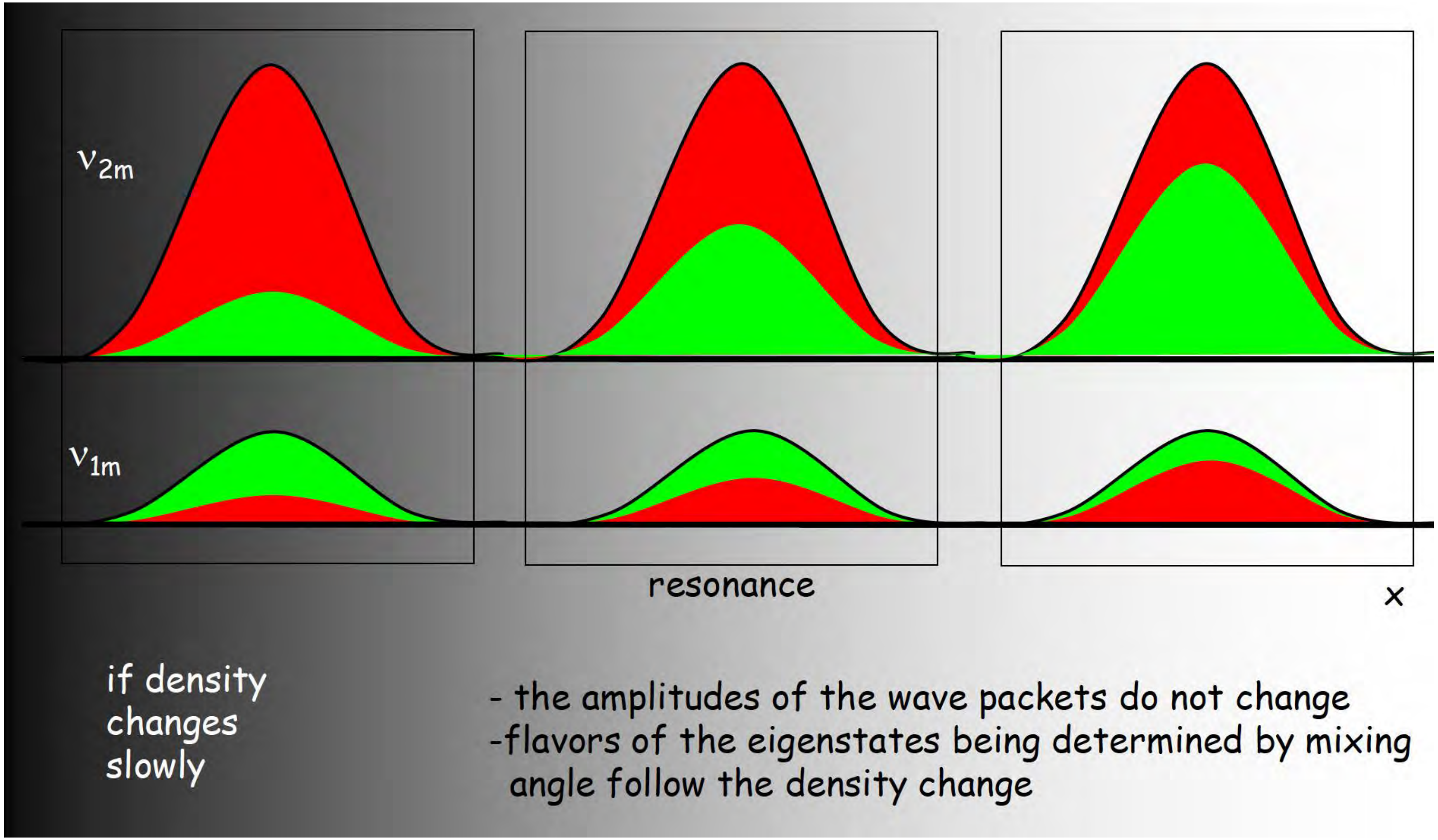
- **There is a combination of electron density N_e and neutrino energies E, for which the effective mixing angle = 1 (even if the vacuum mixing is small)**

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

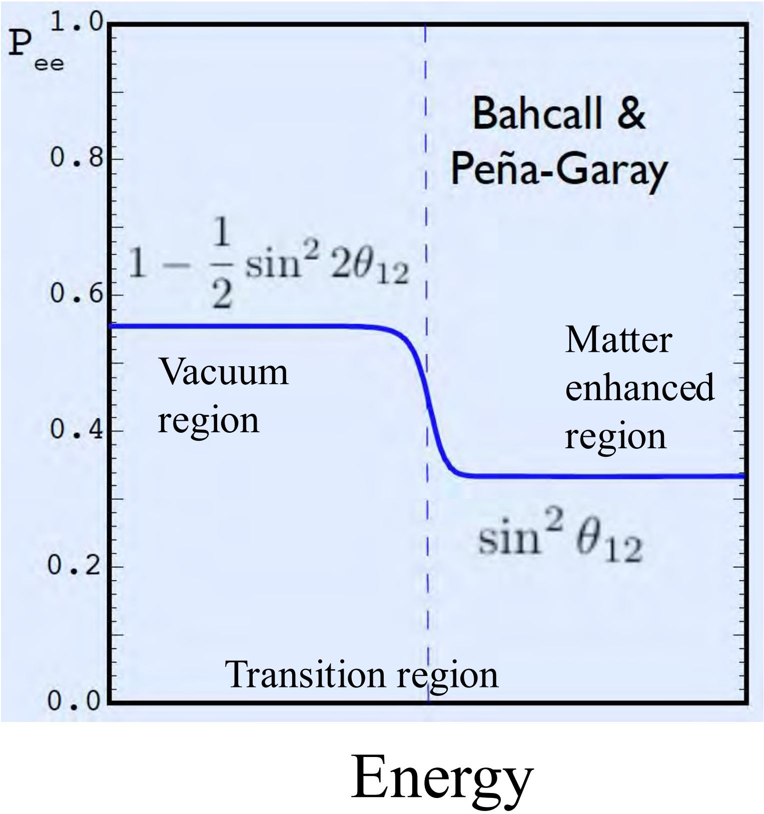
Maximal mixing

- **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%):

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

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

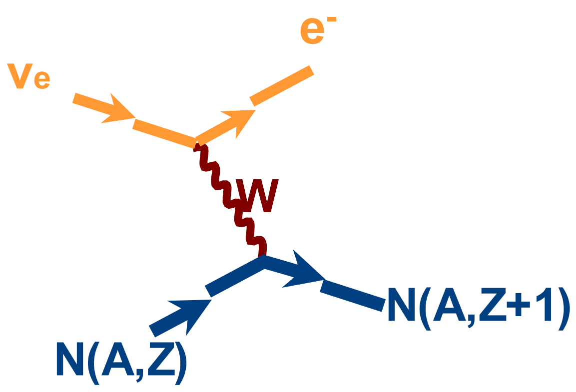
BASIC DETECTION INTERACTIONS

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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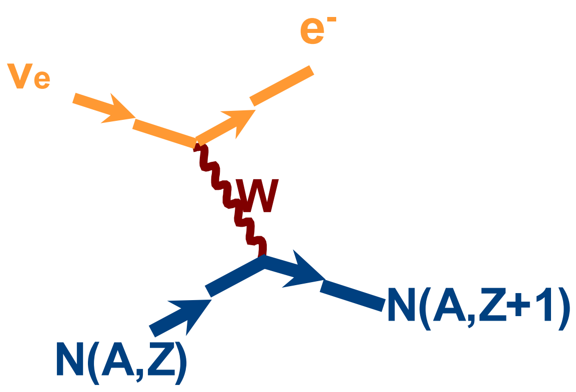
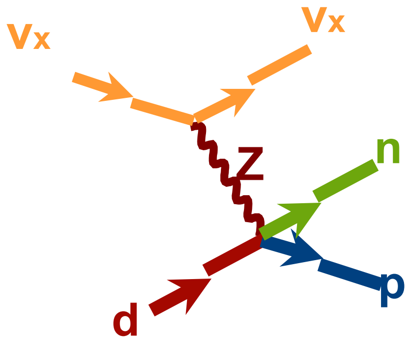


2) Neutral current (NC)

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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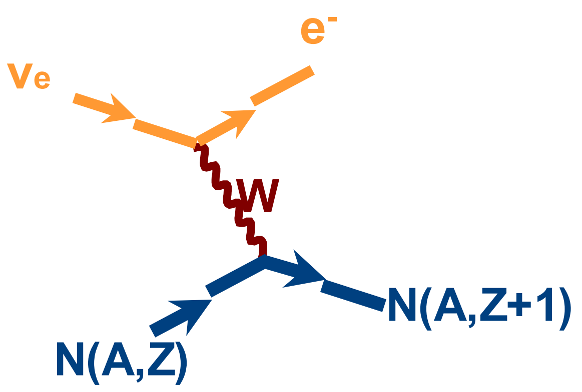

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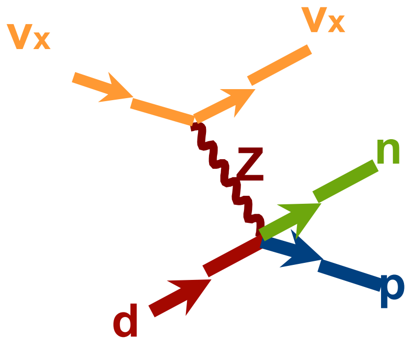
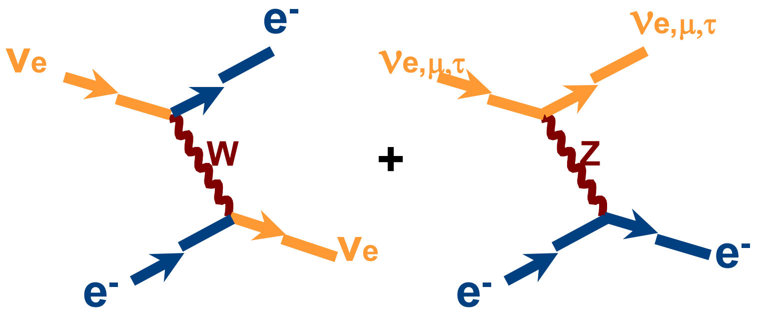


3) Elastic scattering off an electron

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

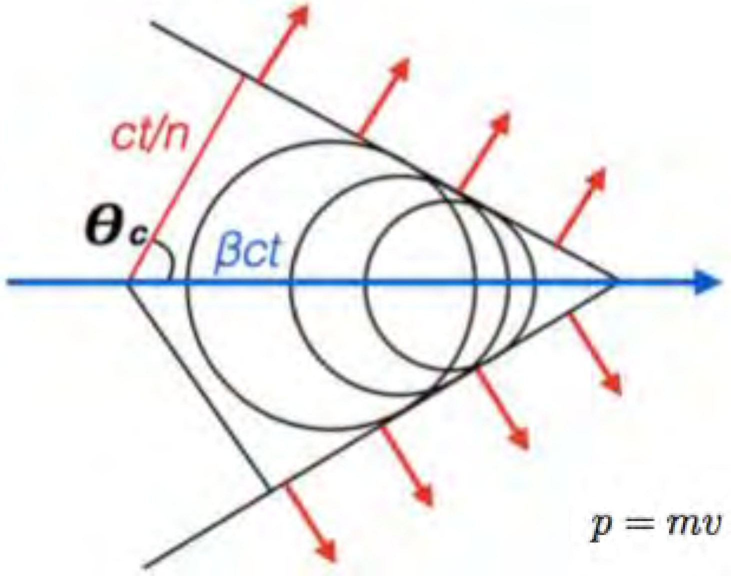
- Cross section for ν_e and $\nu_{\mu,\tau}$ is different
- for $\nu_{\mu,\tau}$ NC only;



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)

$\beta > 1/n$

(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

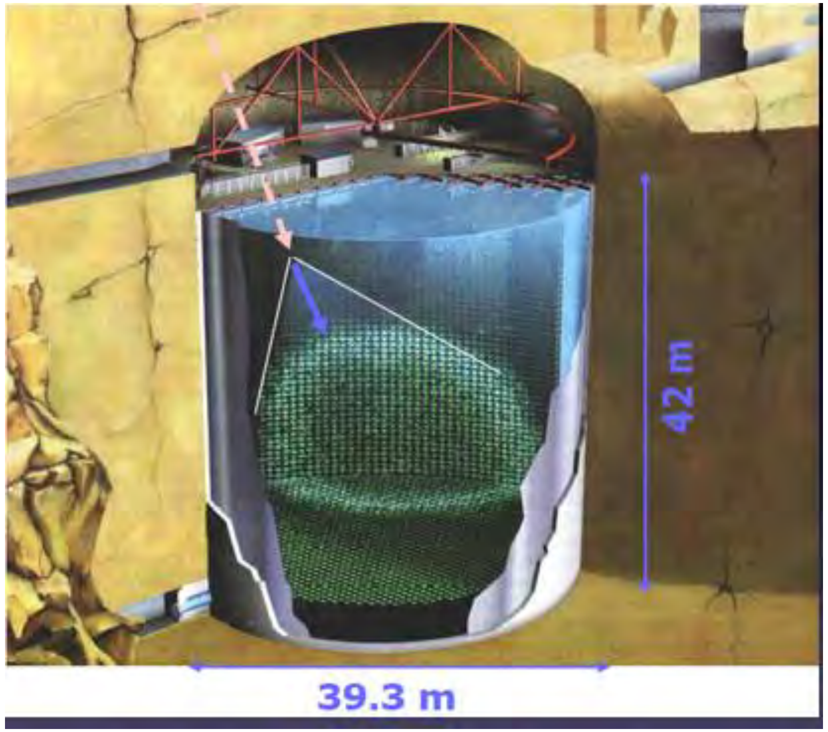
Ice-Cube

KM3NET – ORCA & ARCA

Baikal

Super-Kamiokande
Kamioka, Japan
50 kton water

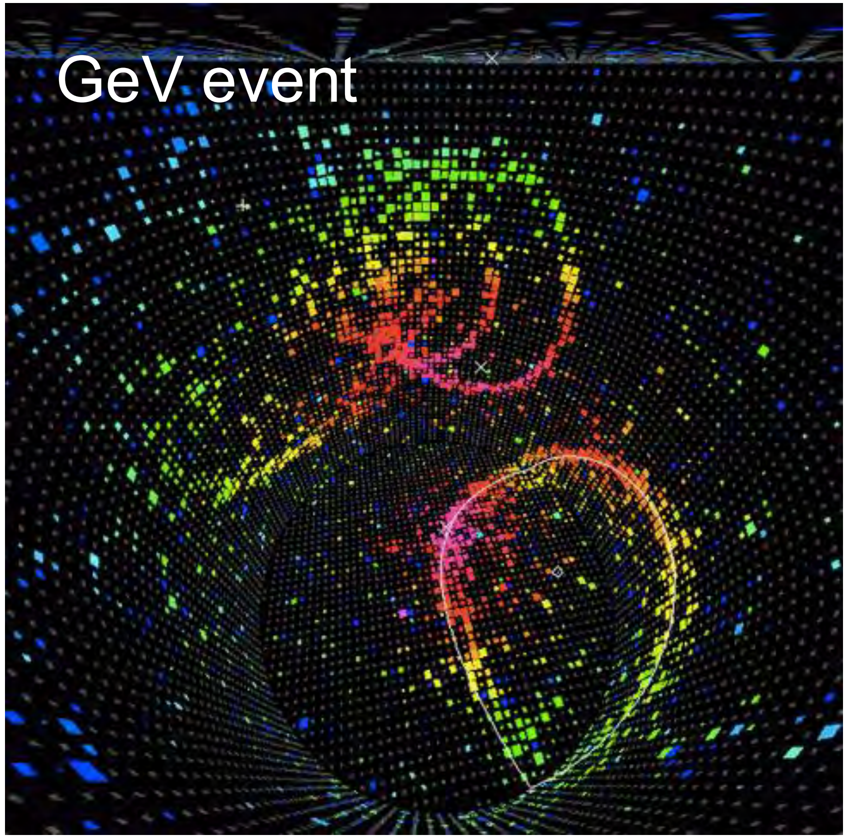
SNO
Sudbury, Canada
1 kton water

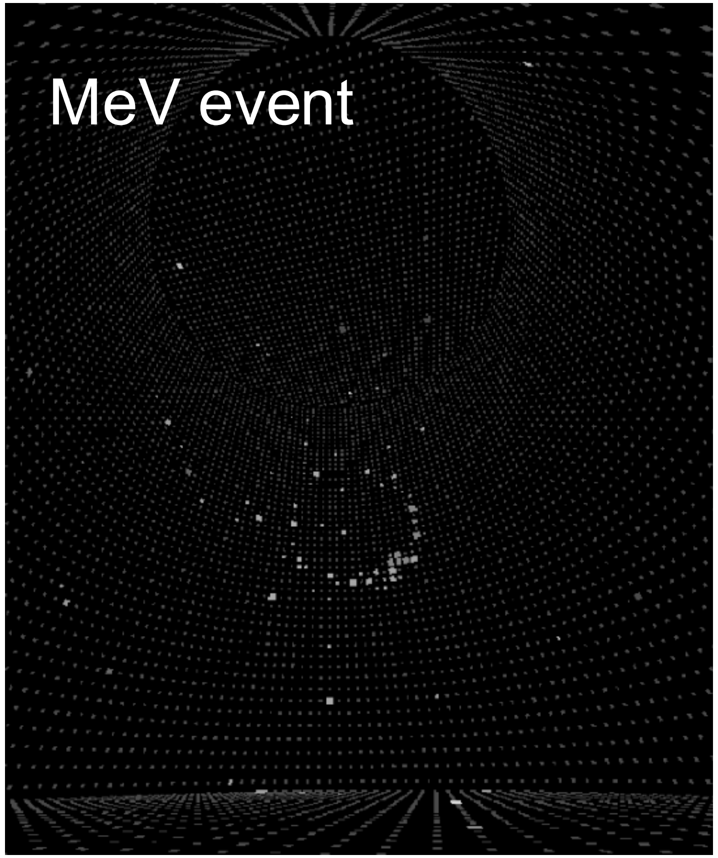


Cherenkov cone in SuperK

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

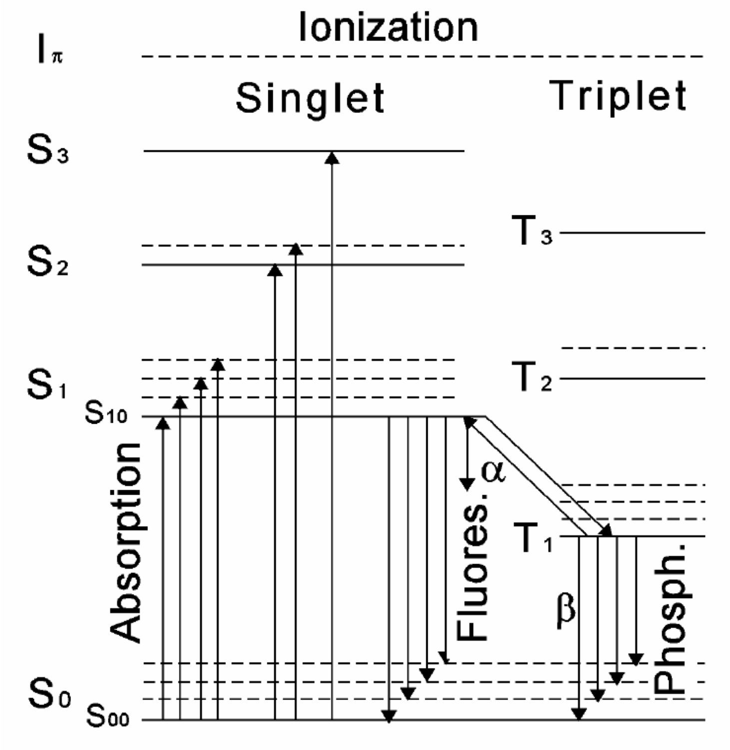
→ vertex position, direction,





Liquid-scintillator based detection

MOLECULAR STATES IN AROMATIC CARBOHYDRATES

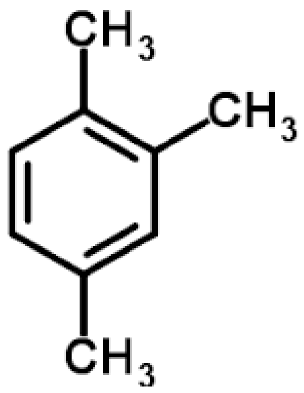


Absorption higher frequencies and smaller wavelengths than emission

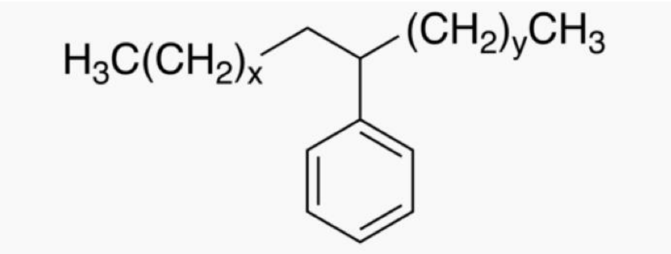
Fast fluorescence has higher frequencies and smaller wavelengths than **slower phosphorescence**

Used by Borexino

Pseudocumene (PC)
1,2,4-trimethylbensene

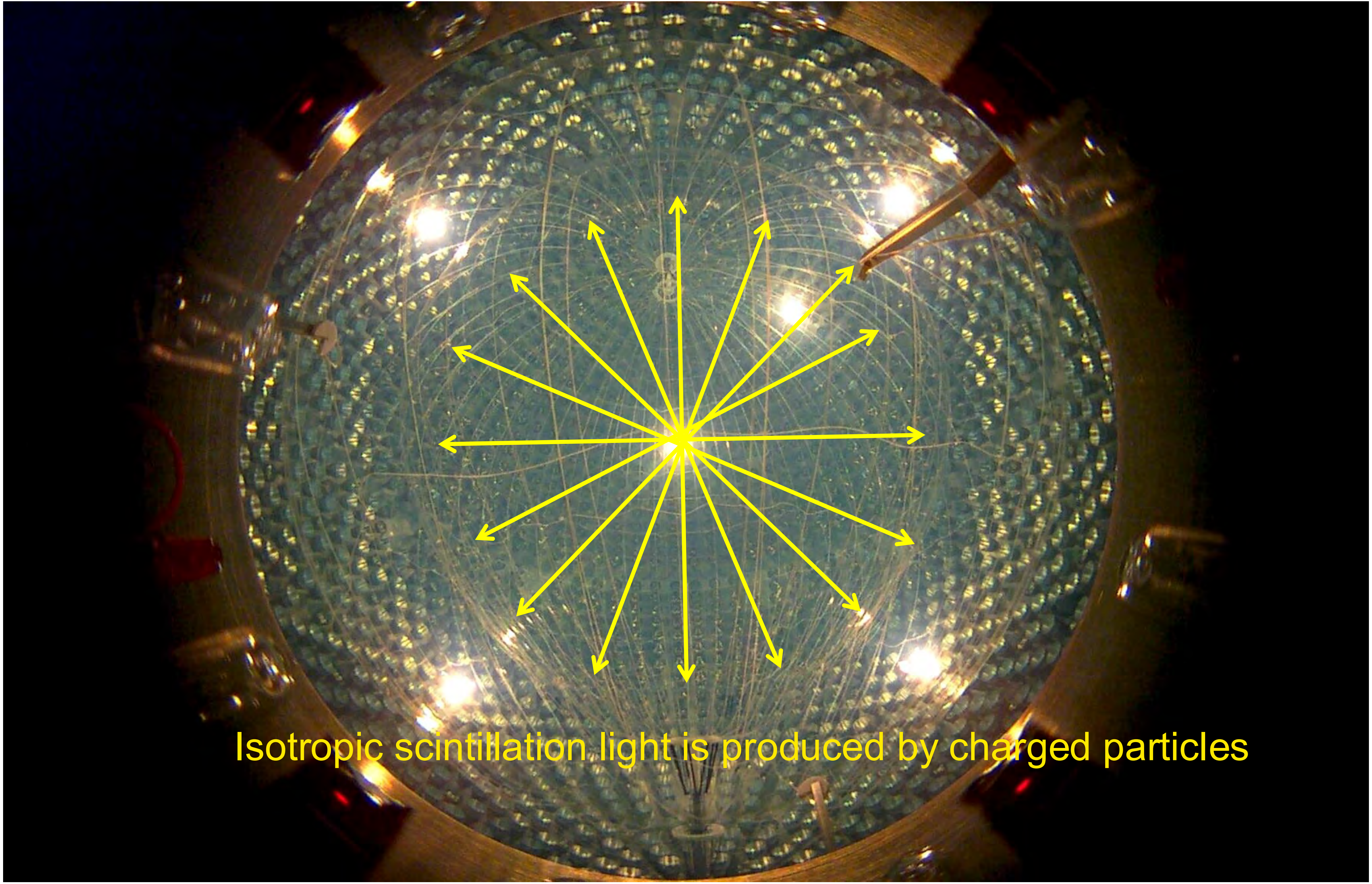


Used by JUNO
LAB: inear-alkylbenzene



- Aromatic carbohydrates
- Stokes shift
- Fluor (PPO)
- Wavelength shifter (MPC)

Liquid scintillator (LS) cocktail


Isotropic scintillation light is produced by charged particles

FROM SCINTILLATION LIGHT TO MEASURED VARIABLES

- **Charged particles** produce scintillation light;
- **Gamma rays** are neutral particles but in the scintillator they interact mostly via Compton scattering producing electrons = charged particles;
- Scintillation light is detected by an array of **phototubes (PMTs)** converting optical signal to electrical signal;
- Number of hit PMTs = function (energy deposit) = energy estimator
- Hit PMTs time pattern = position reconstruction of the event
- Each trigger has its GPS time = absolute time

MAIN CHARACTERSTICS OF THE LS BASED NEUTRINO DETECTION

- High scintillation efficiency and high light yield
- Good energy and position **resolution**
- Low energy **threshold**
- **No directionality** – scintillation light is isotropic
- **Real time** measurement (energy of single events)
- **Quenching:** intrinsic **non-linearity** between energy deposit and produced light
- **Pulse shape** discrimination (alpha/beta, positron/electron)
- High transparency – needed for large detectors
- 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 – started physics data taking in August! – LECTURE TOMORROW

0-ββ decay

KamLAND – Zen (present)

SNO+ (present)

Sterile neutrino search with reactor antineutrinos

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

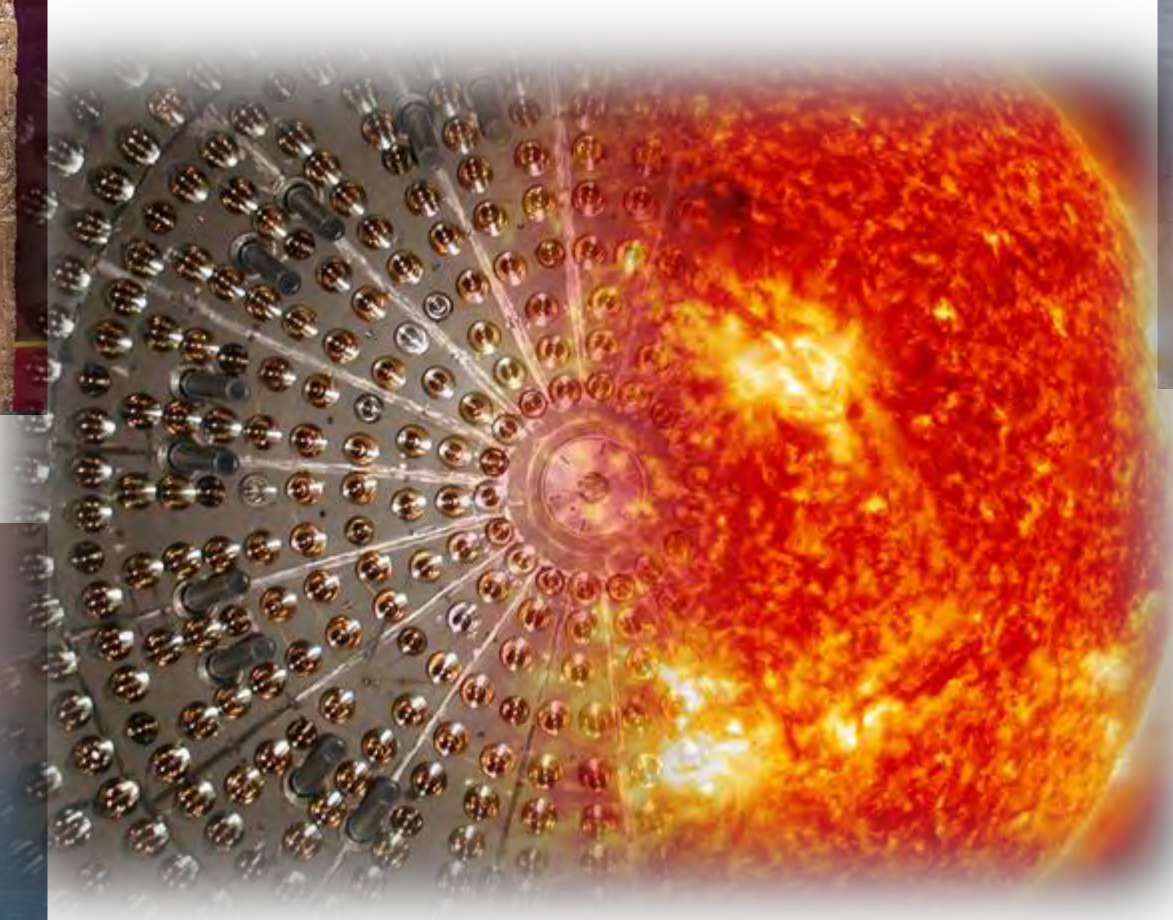
Supernovae neutrinos

LVD (past)

Accelerator neutrinos

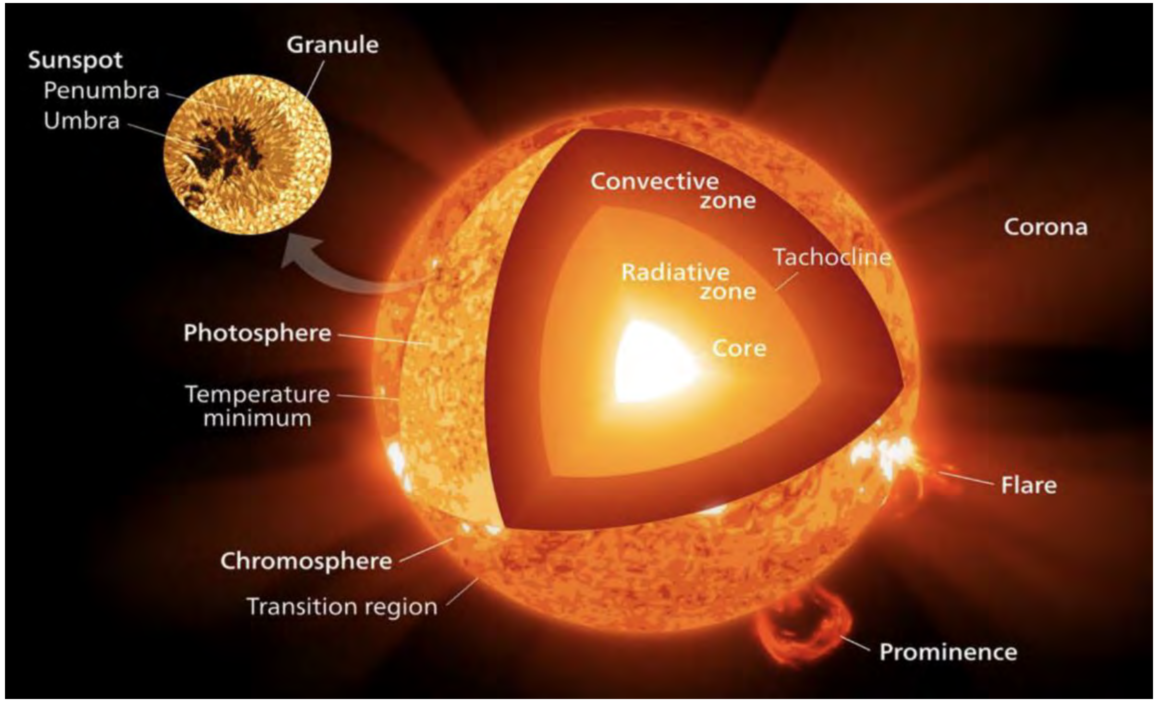
LSND (past)

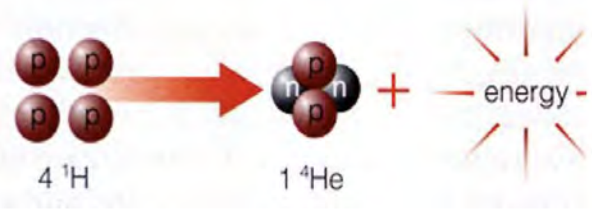
Solar neutrinos



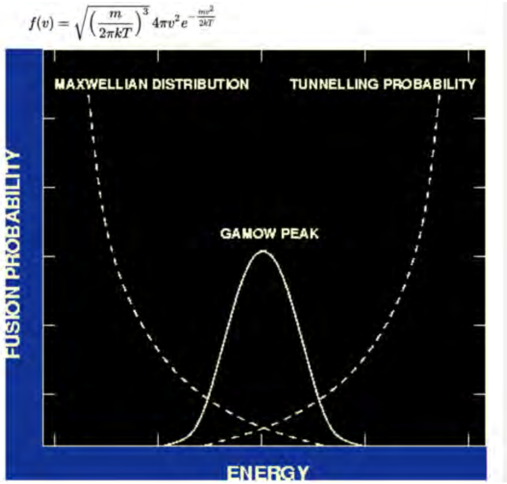
Millennia of fascination continued.

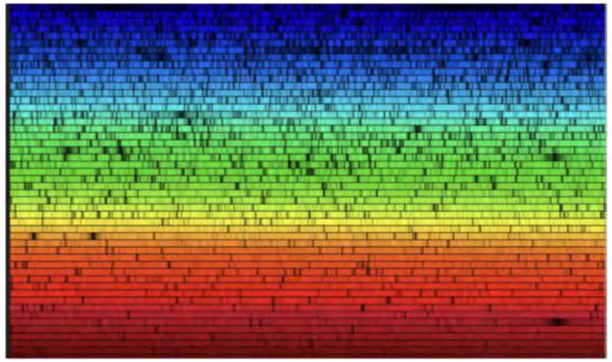
THE SUN





(26.7 MeV) + 2 v





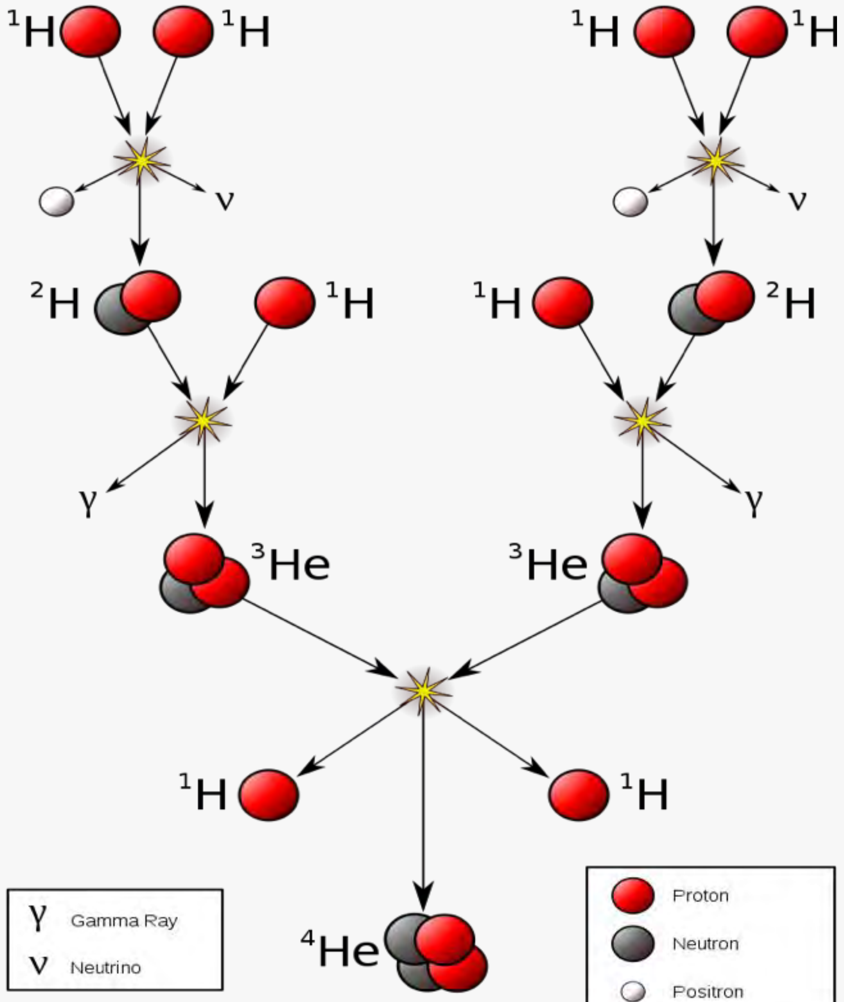
- Luminosity (3.8418.10^{33} erg/s (± 0.35%) (1 erg = 10^{-7} J)
- Age (~4.6.10^{9} years - old meteorites)
- Mass M = 1.989·10^{30} kg (± 0.02%)
- Radius R = 6.9598 ·10^{8}m (± 0.01%)

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

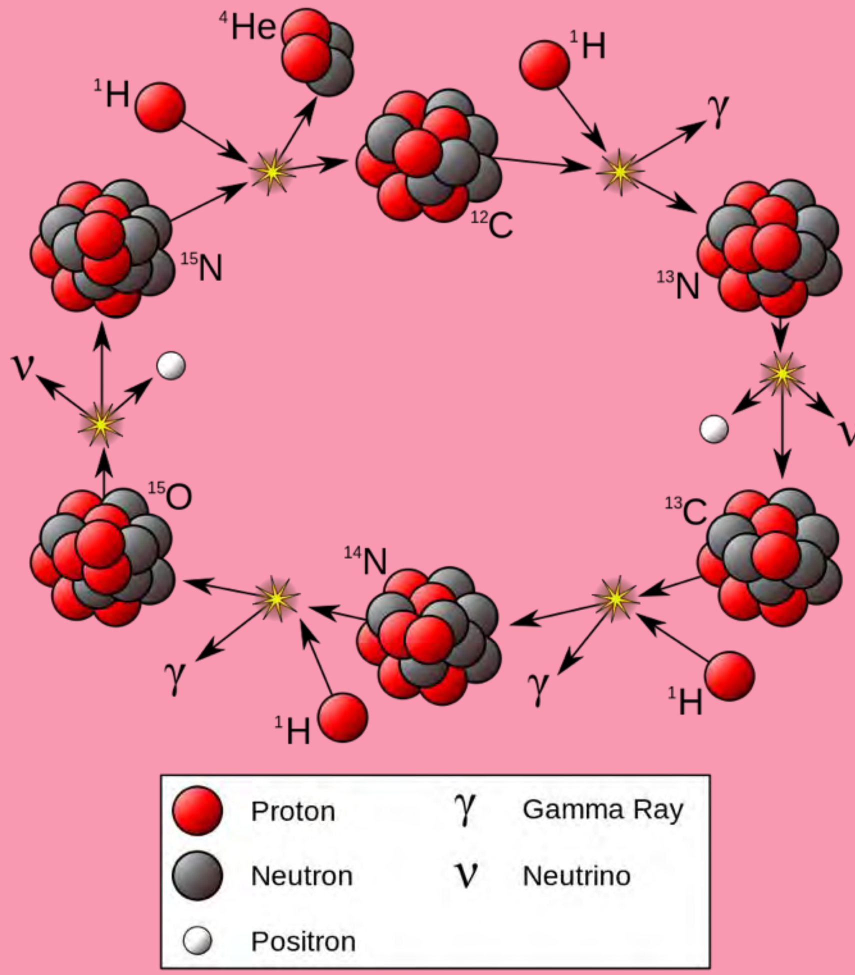
HYDROGEN-TO-HELIUM FUSION

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

pp-chain: ~99% solar energy



CNO-cycle: < 1% solar energy



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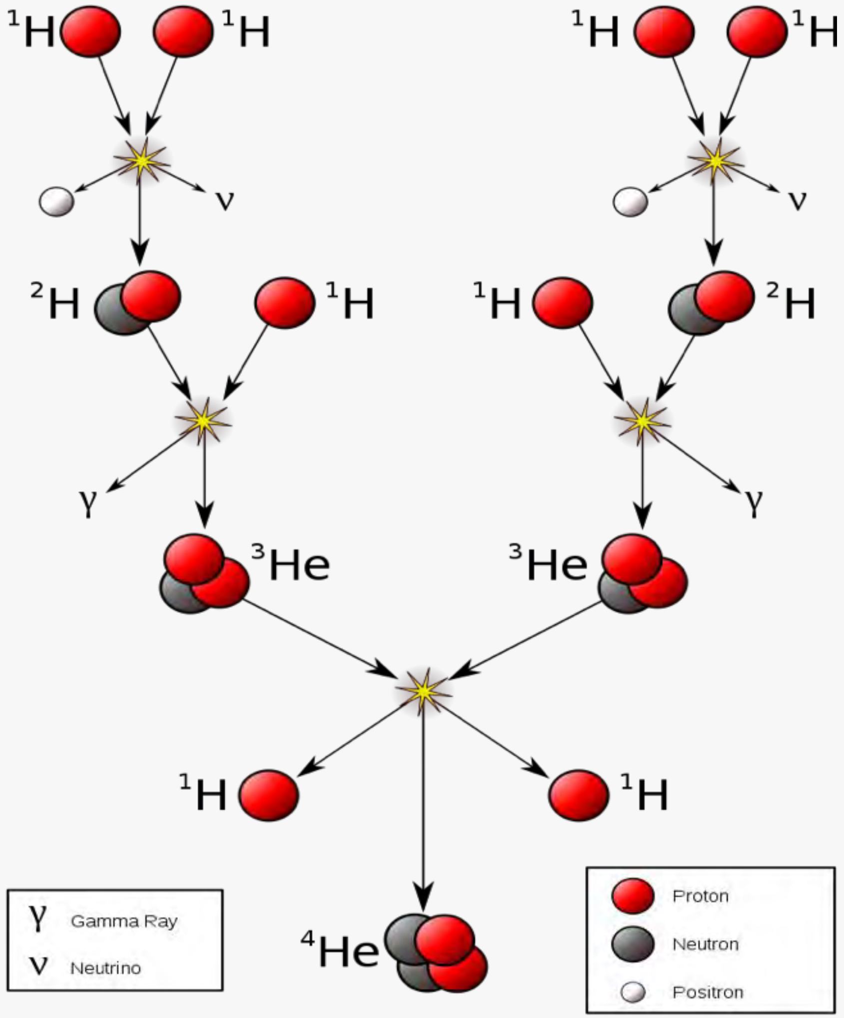
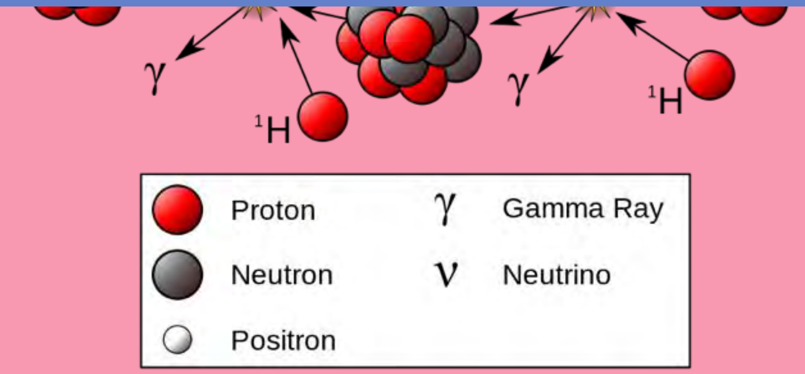


CNO-cycle: < 1% solar energy

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

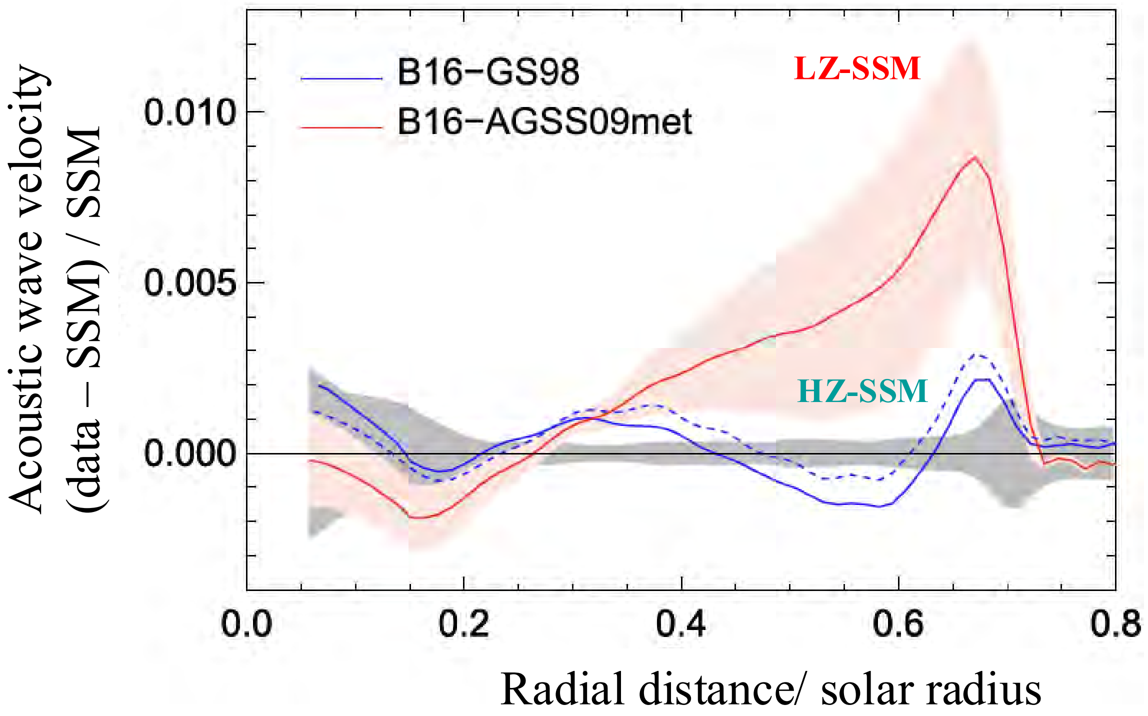
B16 Standard Solar Model with different metallicity inputs:

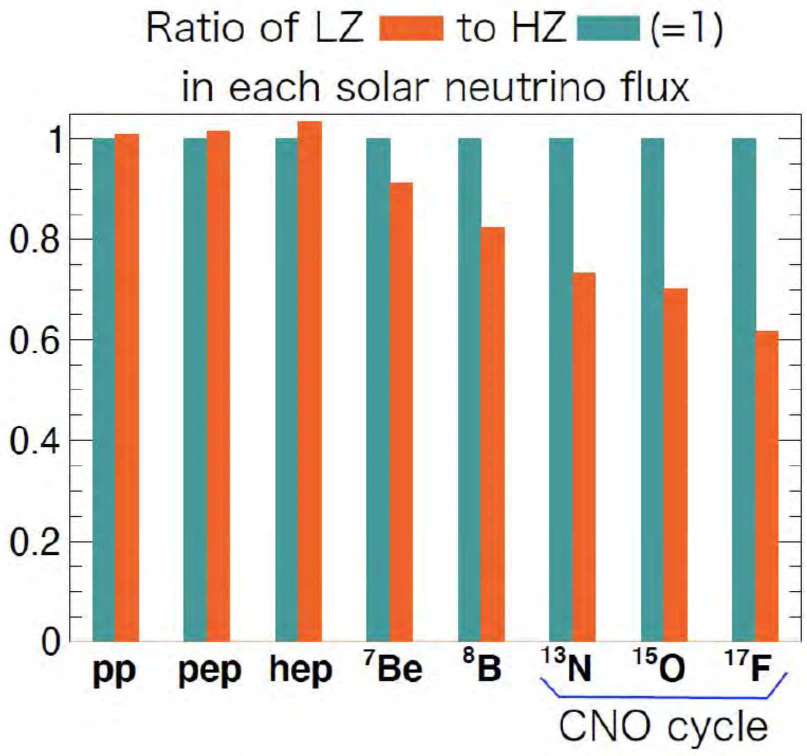
High-Metallicity HZ-SSM: older GS98 metallicity input: Z/X = 0.0229

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





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

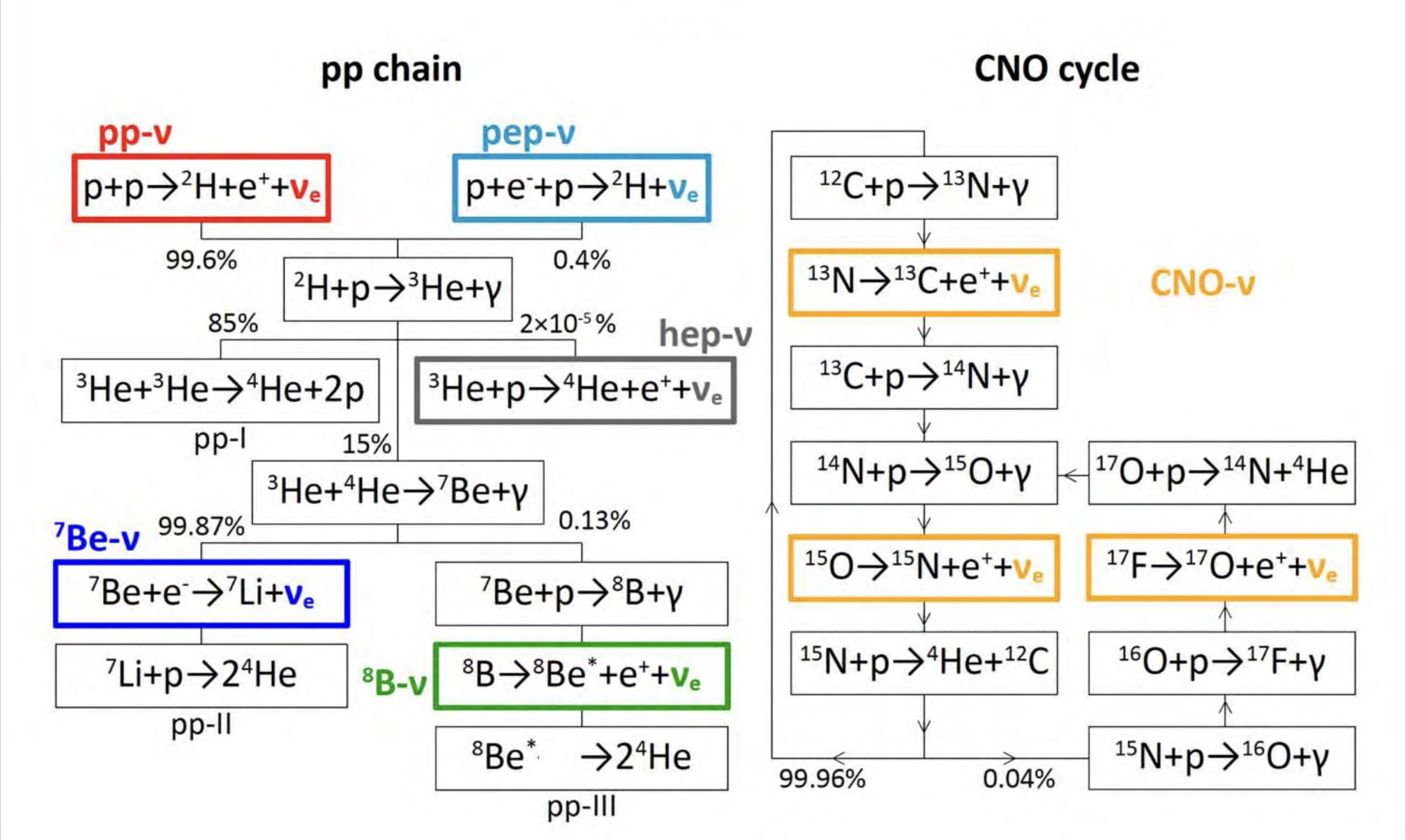
Neutrino physics

- **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

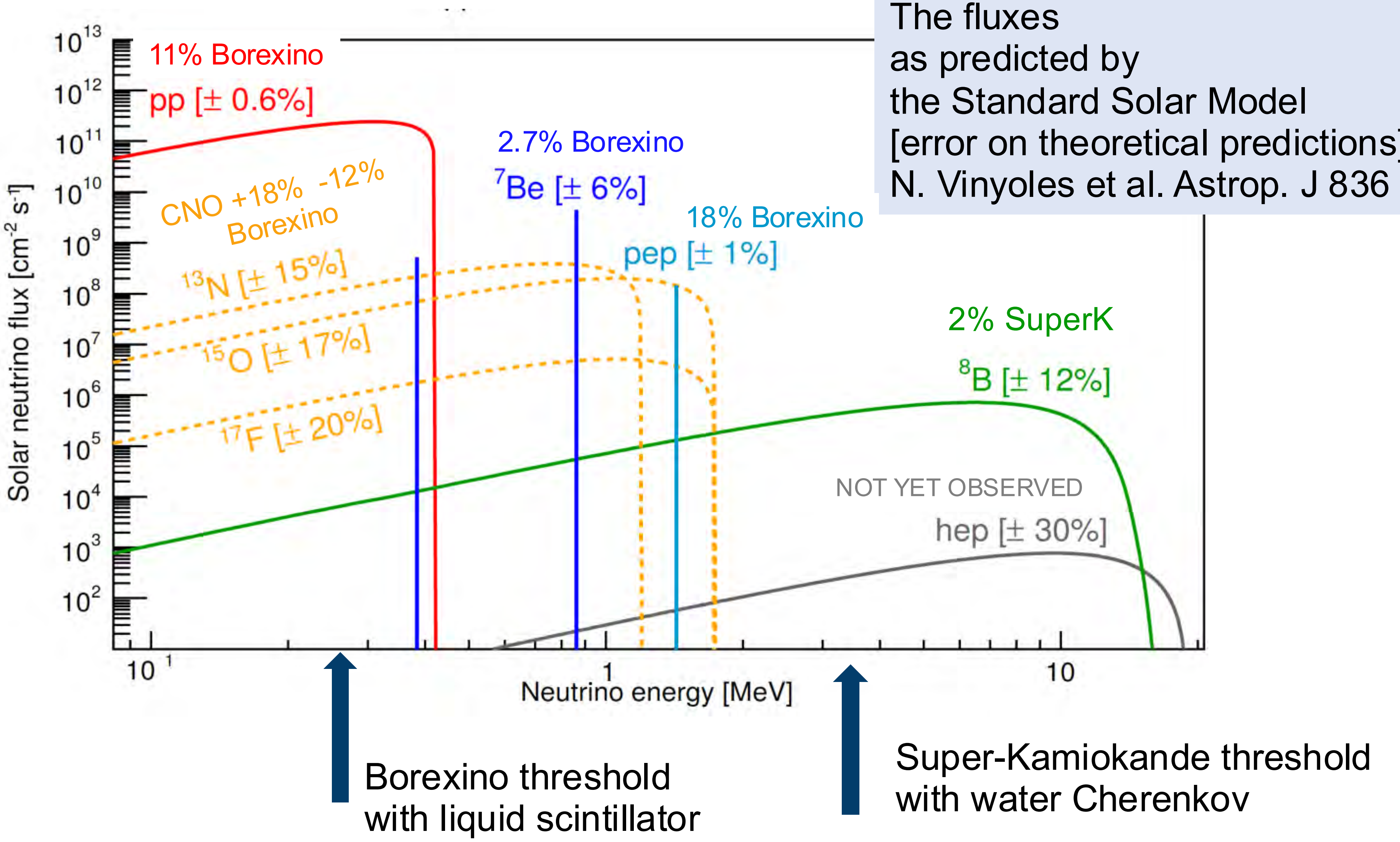
- Direct probe of **nuclear fusion.**
- Photon vs neutrino luminosity: testing **thermo-dynamical stability** of the Sun.
- **Standard Solar Models:**
  - ✓ Metallicity problem.

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



Short history of solar ν experiments in 1 slide

70's-80's: Homestake (R. Davies): Radiochemistry: $E_\nu > 814$ keV
- ✓ $^{37}Cl + \nu \rightarrow ^{37}Ar + e^-$
- ✓**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!

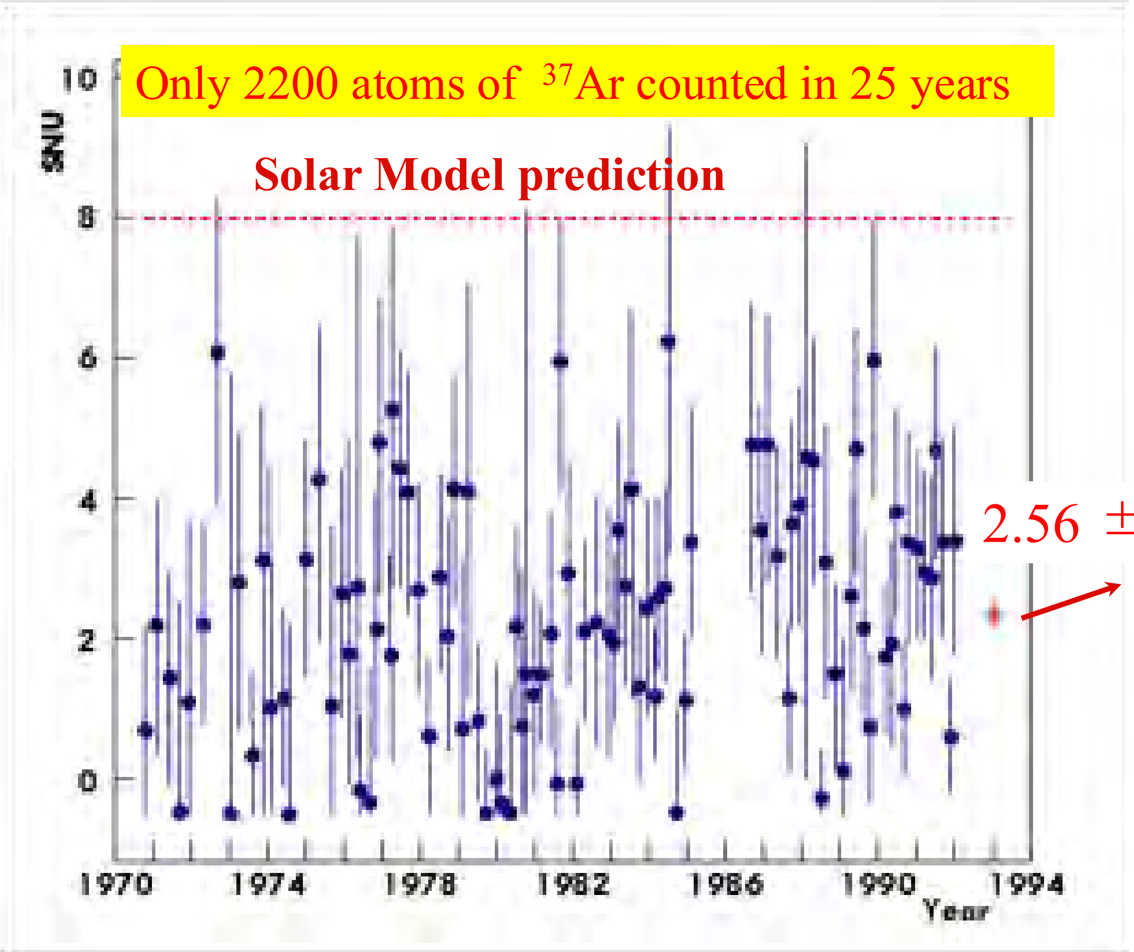
Real-time precision spectroscopy

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

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



2.56 ± 0.16 ± 0.16 SNU

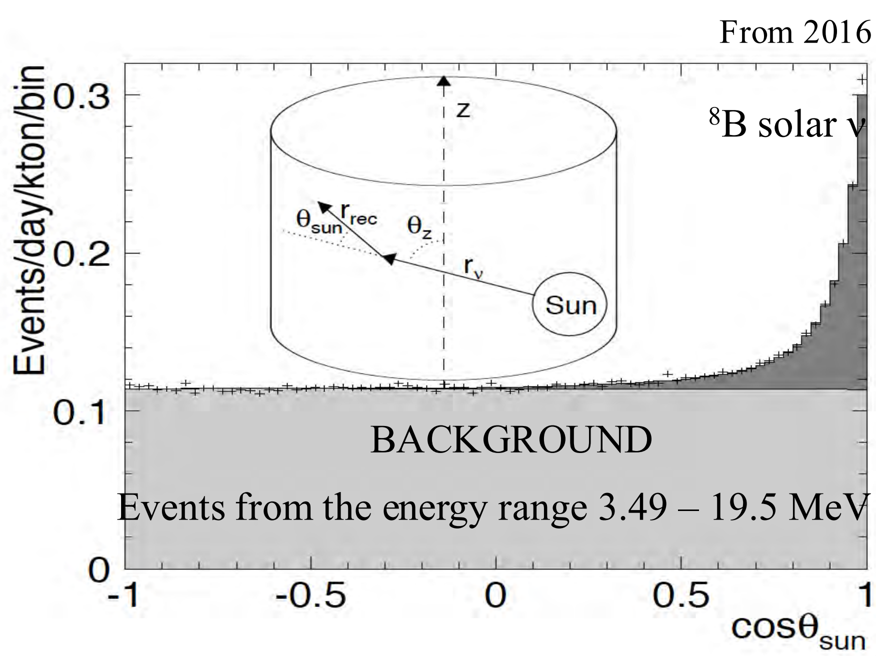
Final Result

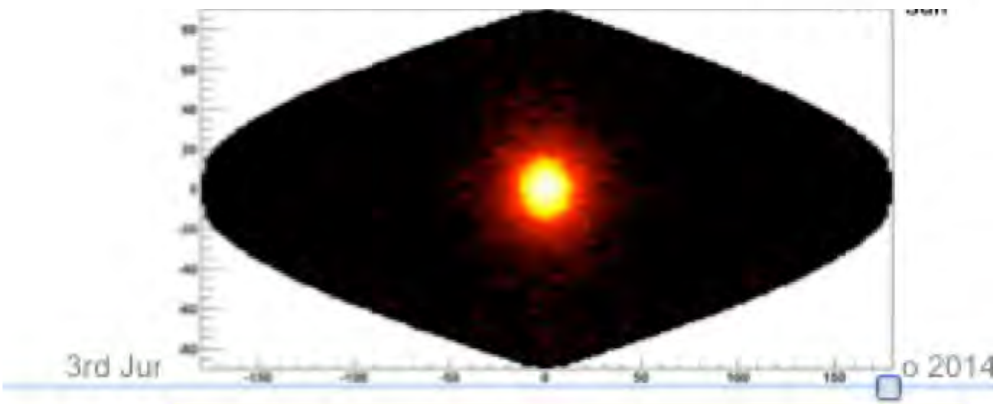
Ray Davis

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

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

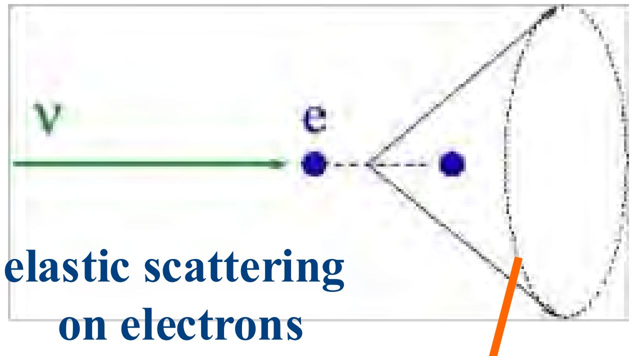
THE FIRST REAL-TIME SOLAR NEUTRINO DETECTION

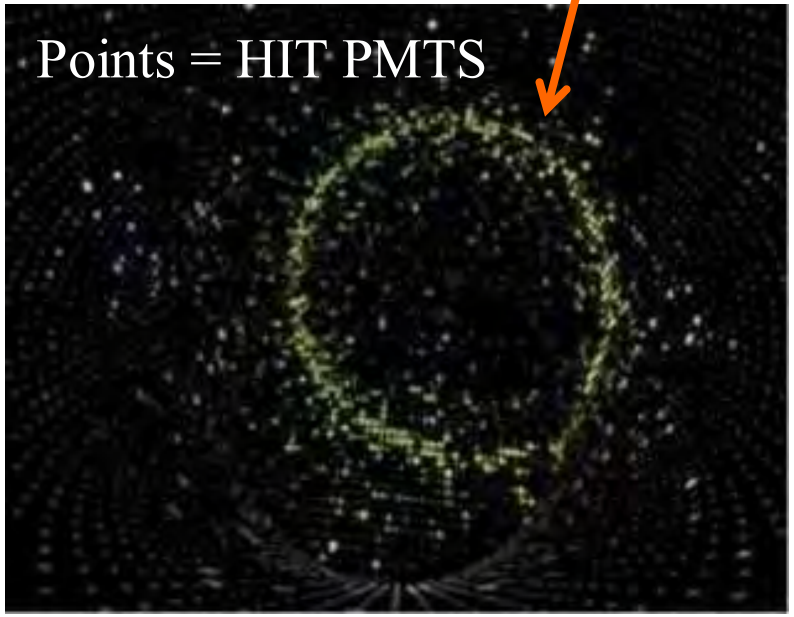




The Sun's picture in neutrinos!

Detection in Water



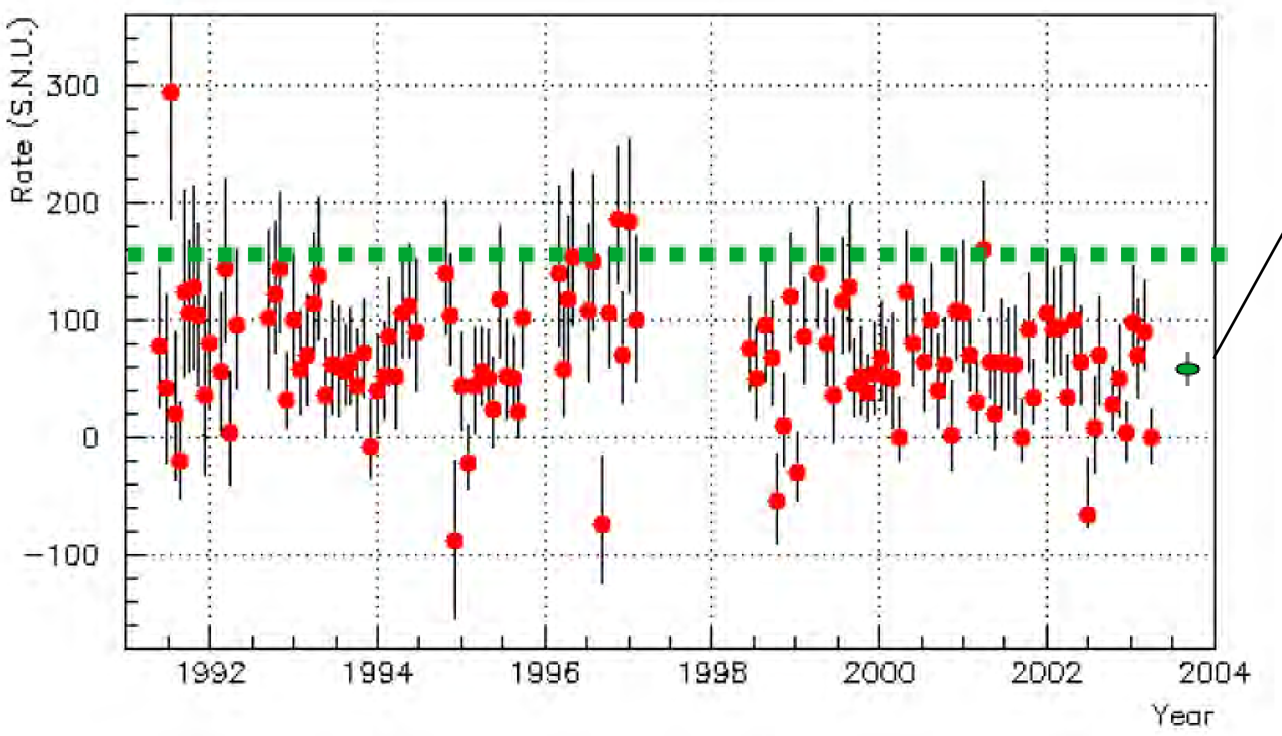


1991-2003 GALLEX-GNO @ LNGS, ITALY RADIOCHEMICAL EXPERIMENT

Till Kirsten (MPI Germany)

Charged current interaction:

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



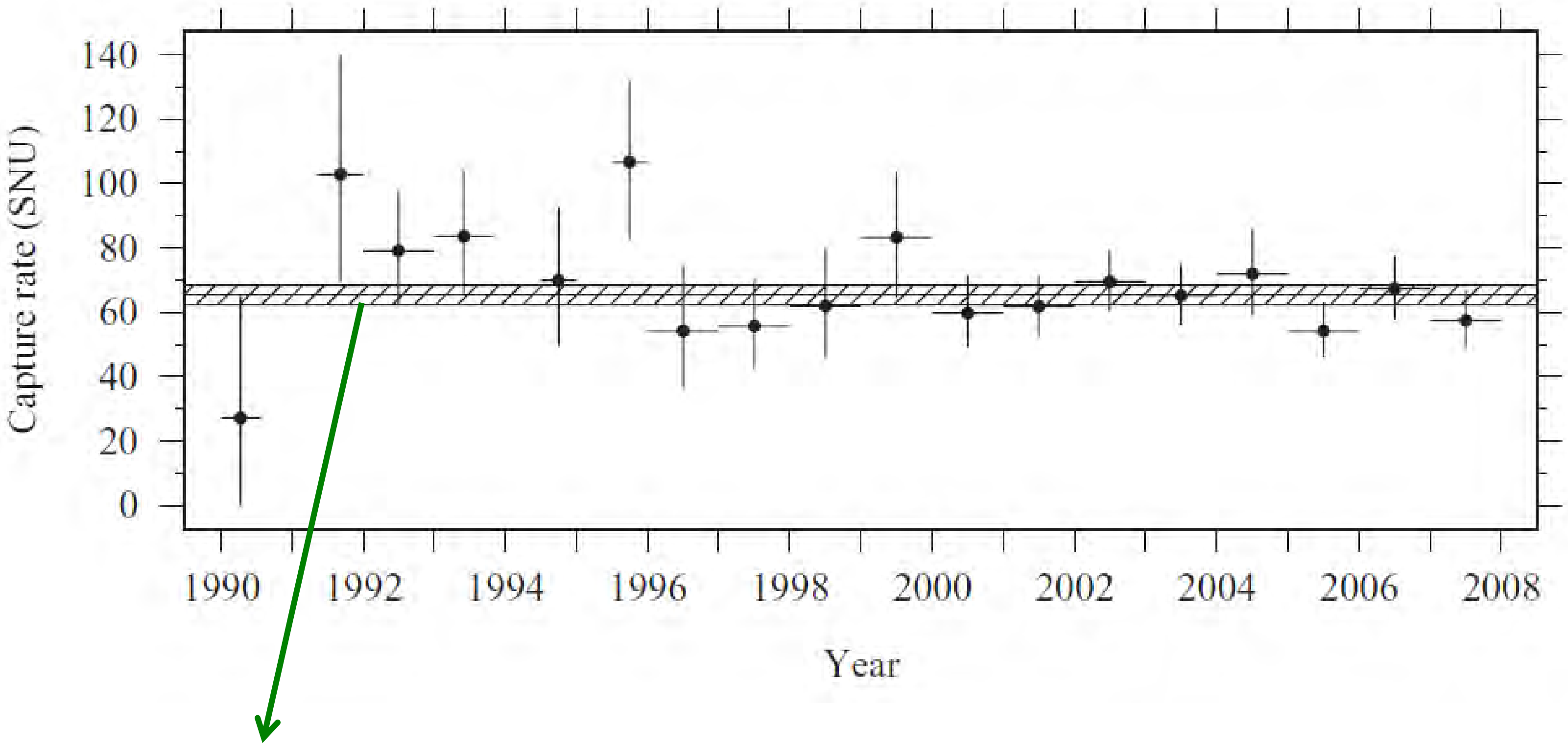
Final result:

67.6 ± 5.1 SNU

0.541 ± 0.081

as a fraction of the SSM prediction

1990-2011 SAGE EXPERIMENTAL RESULTS BAKSAN, RUSSIA



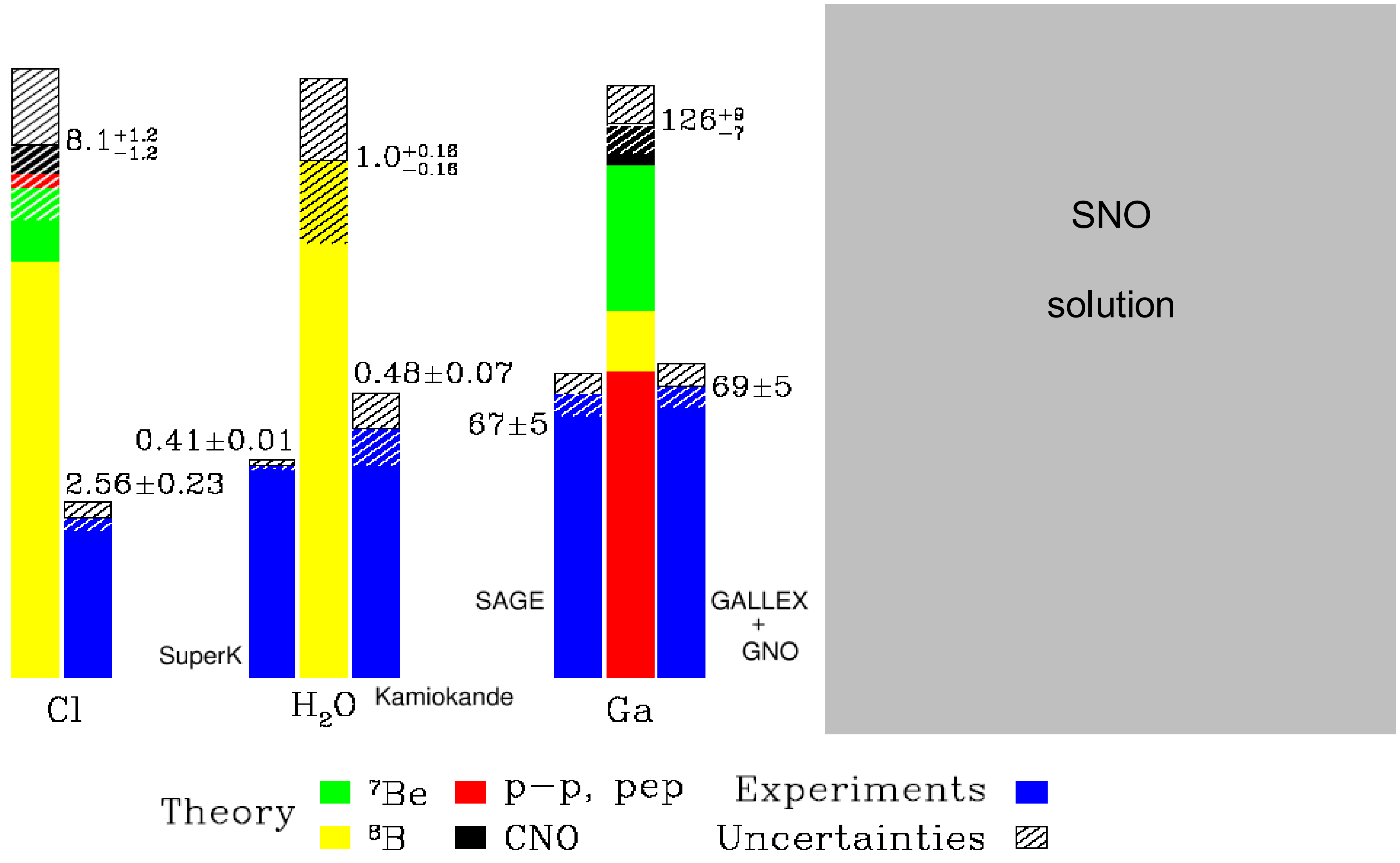
Final result: $65.4^{+3.1}_{-3.0}{}^{+2.6}_{-2.8}$ SNU

Vladimir Gavrin (Russia)

Liquid metallic Ga

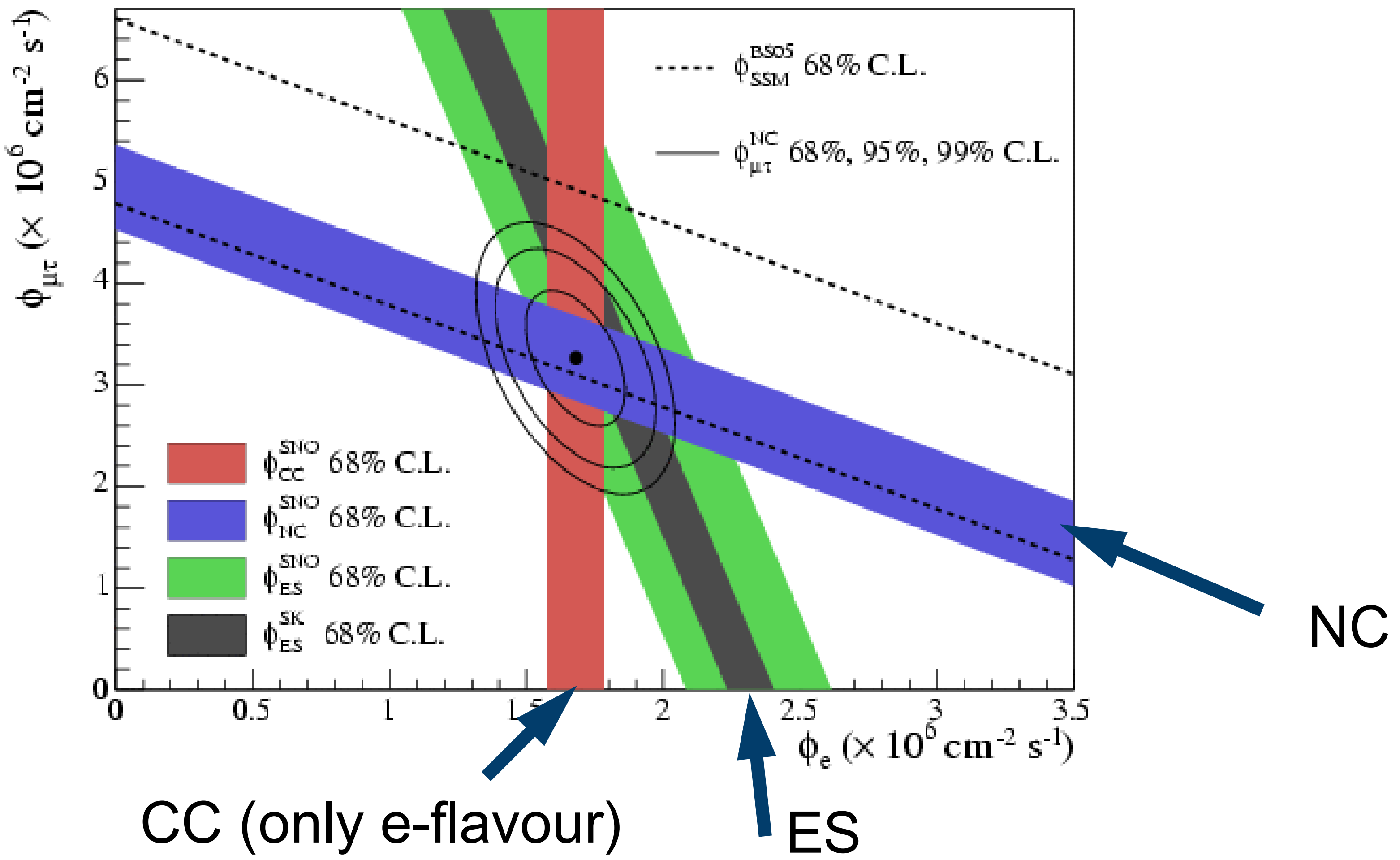
Total Rates: Standard Model vs. Experiment

Bahcall−Serenelli 2005 [BS05(OP)]



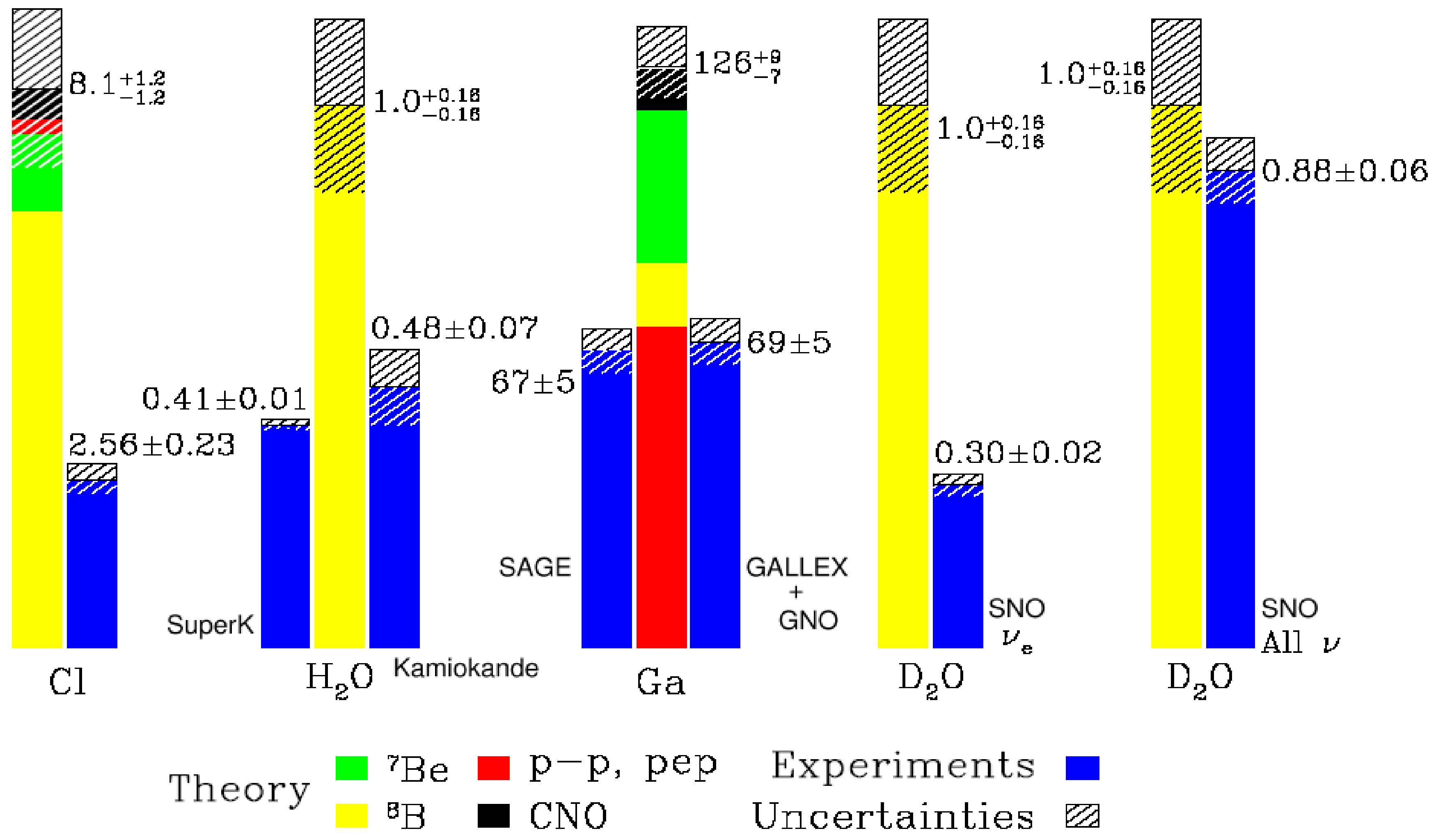
SNO 2001: DISCOVERY OF SOLAR NEUTRINO OSCILLATIONS

- 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.



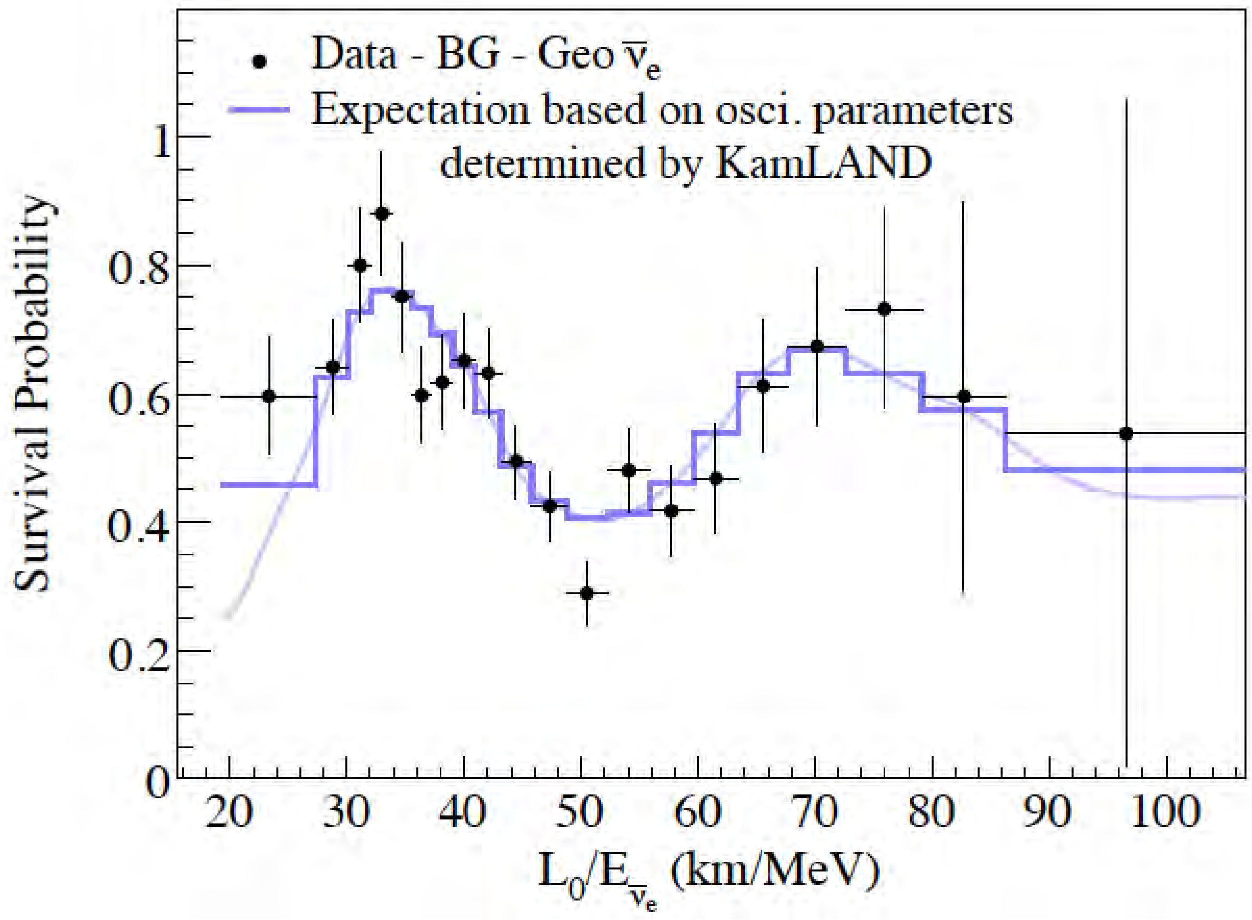
Total Rates: Standard Model vs. Experiment

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!

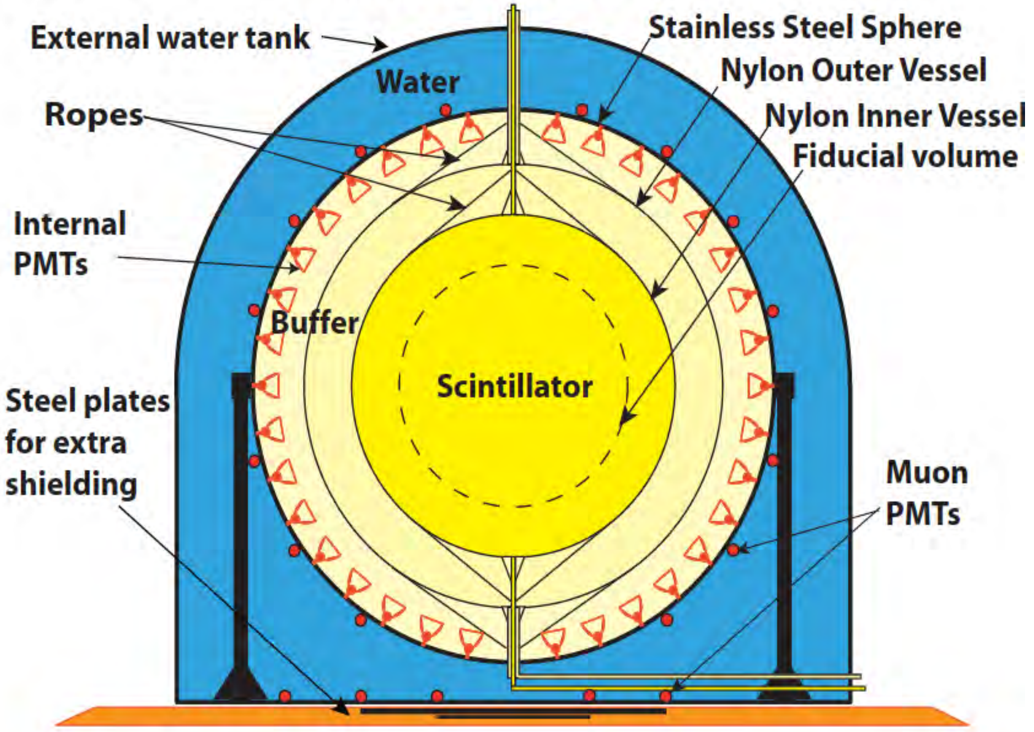
On REACTOR ANTINEUTRINOS!

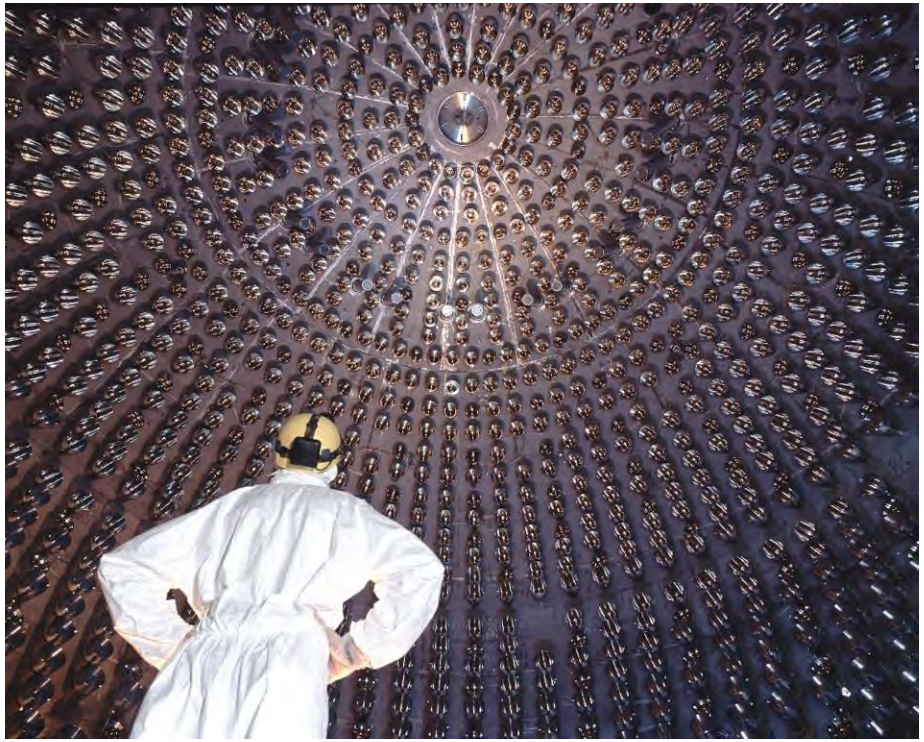
BOREXINO @ LNGS, ITALY

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

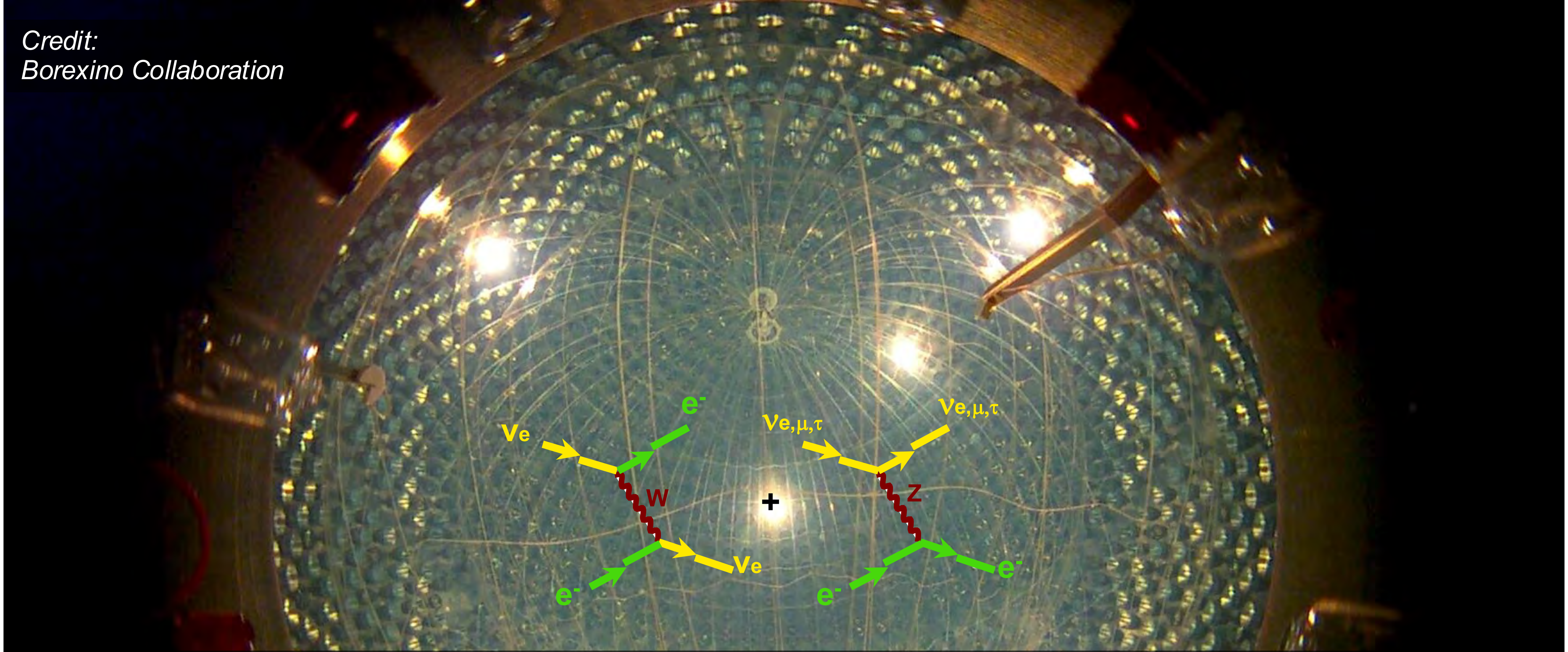
Main goal: solar neutrinos below 2 MeV

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





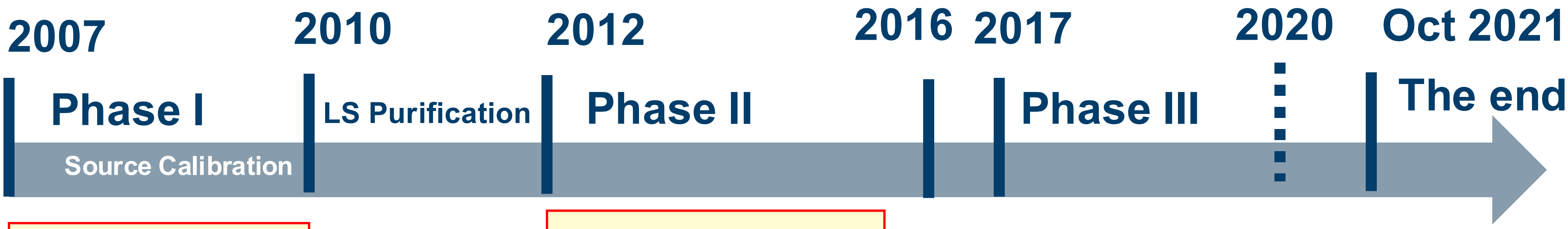
Credit:
Borexino Collaboration



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.

BOREXINO TIMELINE AND SOLAR NEUTRINO RESULTS



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

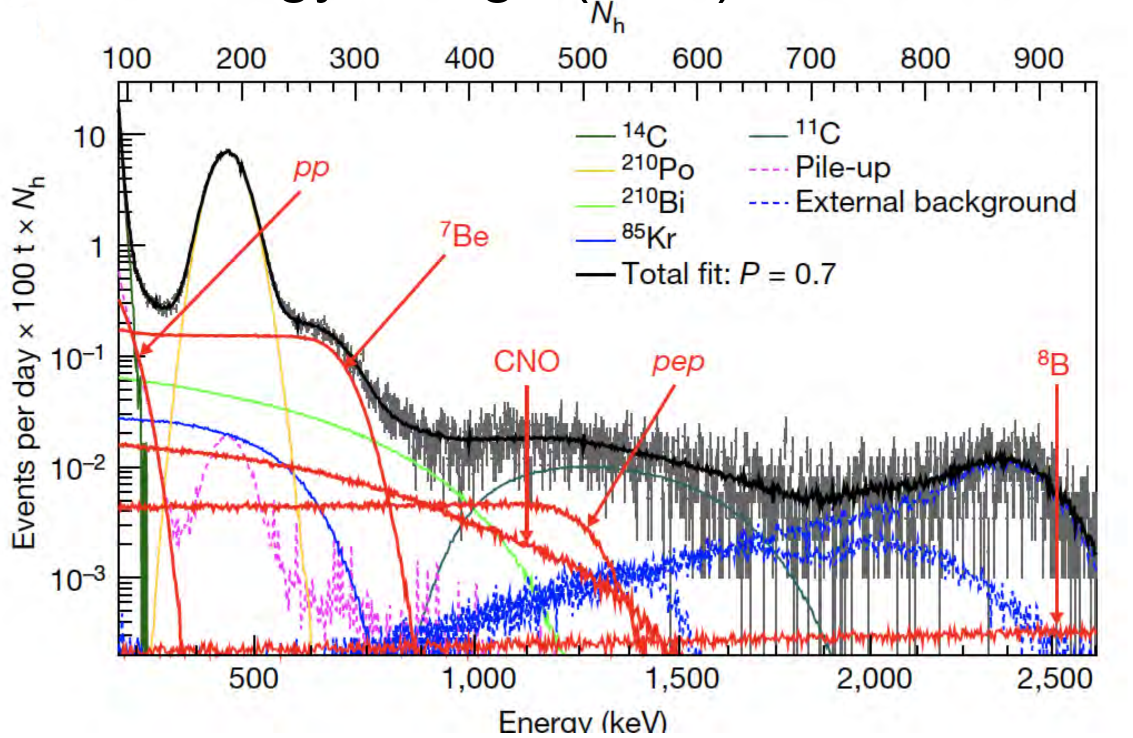
CNO improved and final
PRL 12/12/2022
PRD 108 (2023) 102005,

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

BOREXINO PP-CHAIN RESULTS – I

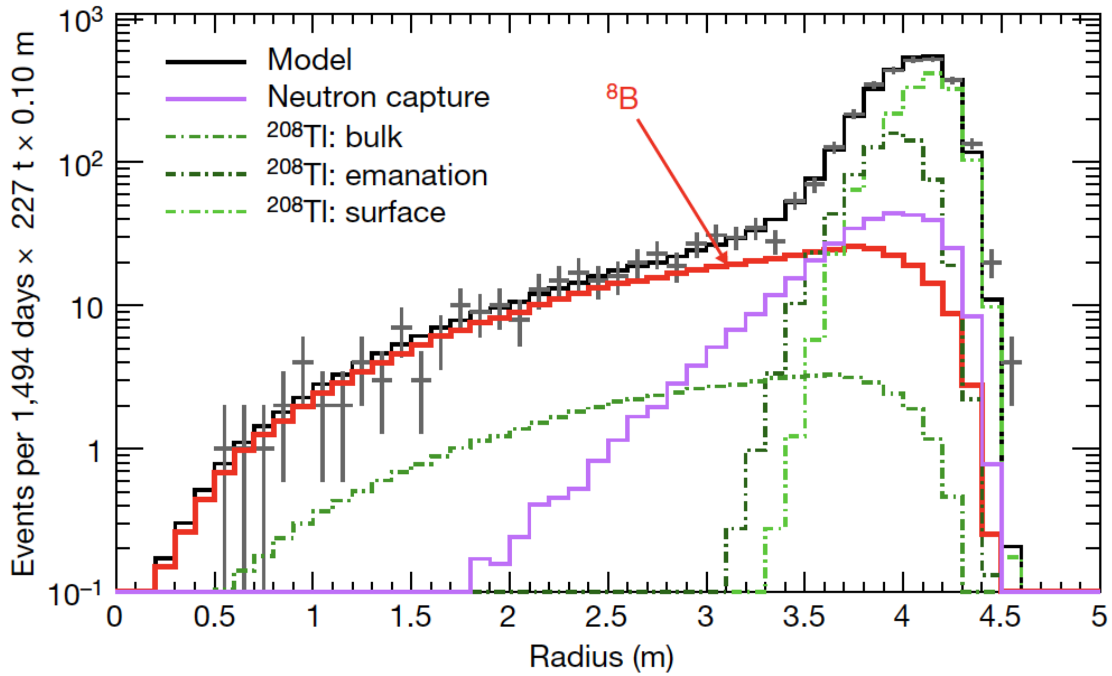
Full pp chain spectroscopy with NATURE 25/10/2018

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



- Multivariate fit of the energy spectra
- Interaction rates of **pp, ^{7}Be, pep neutrinos**

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



- Fit of the radial distribution
- Interaction rate of **^{8}B neutrinos**

BOREXINO PP-CHAIN RESULTS - II

Measurement of the interaction rates:

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

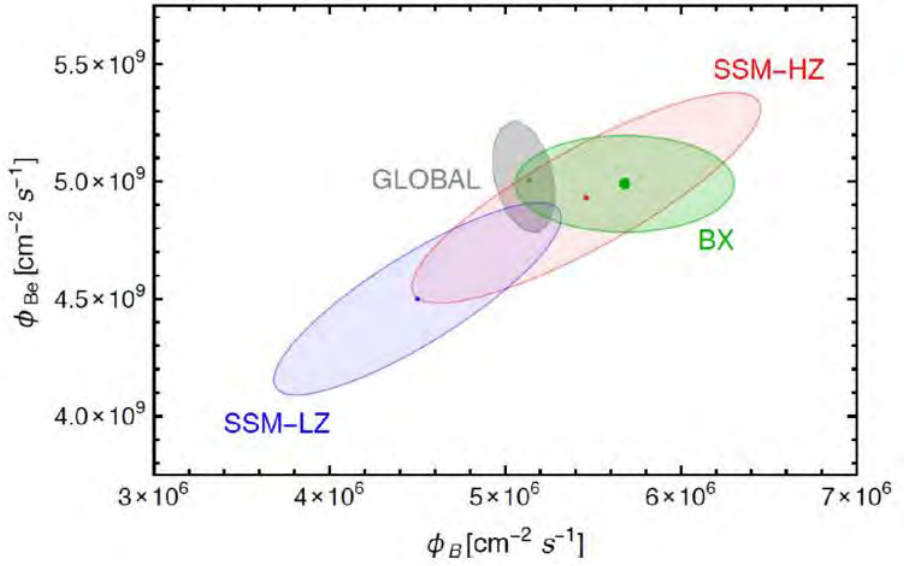
HER: **^{8}B** (3 MeV threshold, 8%)

First Borexino limit on **hep** neutrinos

Solar neutrino	Rate (counts per day per 100 t)
pp	$134 \pm 10^{+6}_{-10}$
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$
$^8B_{HER-I}$	$0.136^{+0.013+0.003}_{-0.013-0.003}$
$^8B_{HER-II}$	$0.087^{+0.080+0.005}_{-0.010-0.005}$
$^8B_{HER}$	$0.223^{+0.015+0.006}_{-0.016-0.006}$
CNO	<8.1 (95% C.L.)
hep	<0.002 (90% C.L.)

- Neutrino and photon luminosity in agreement: **thermo-dynamical stability** of the Sun in O(100k) years
- **Testing the pp-chain:** $BR(pp_{II}/pp_{I}) = \langle ^3He + ^4He \rangle / \langle ^3He + ^3He \rangle = 0.18 \pm 0.03$ in agreement with the expectations

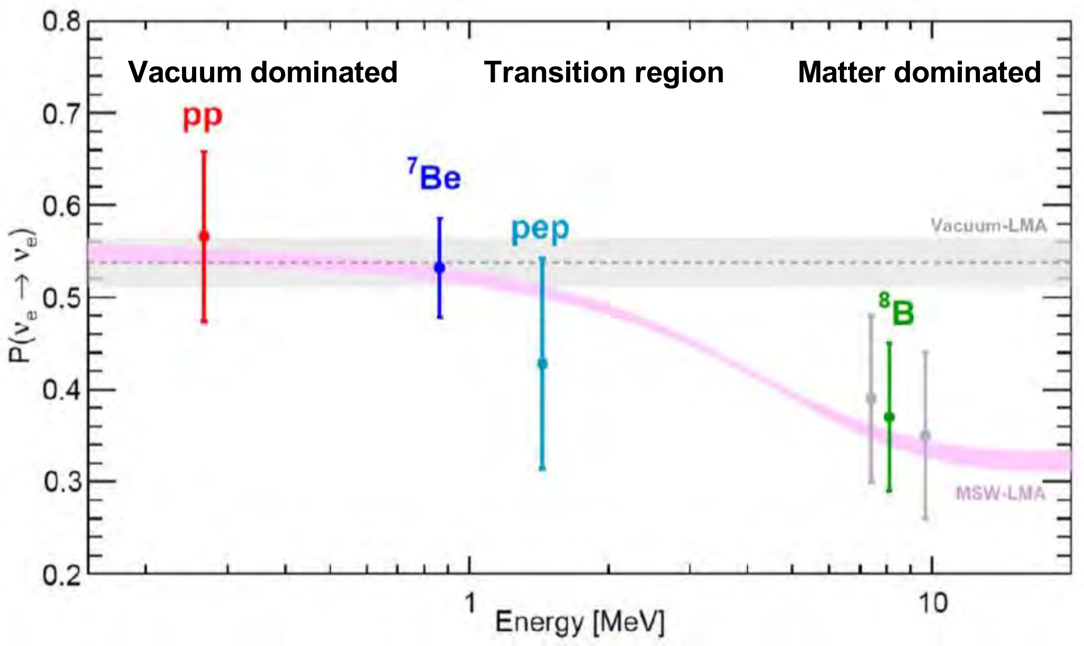
Slight preference towards the HZ SSM



Nature
Oct 25th 2018

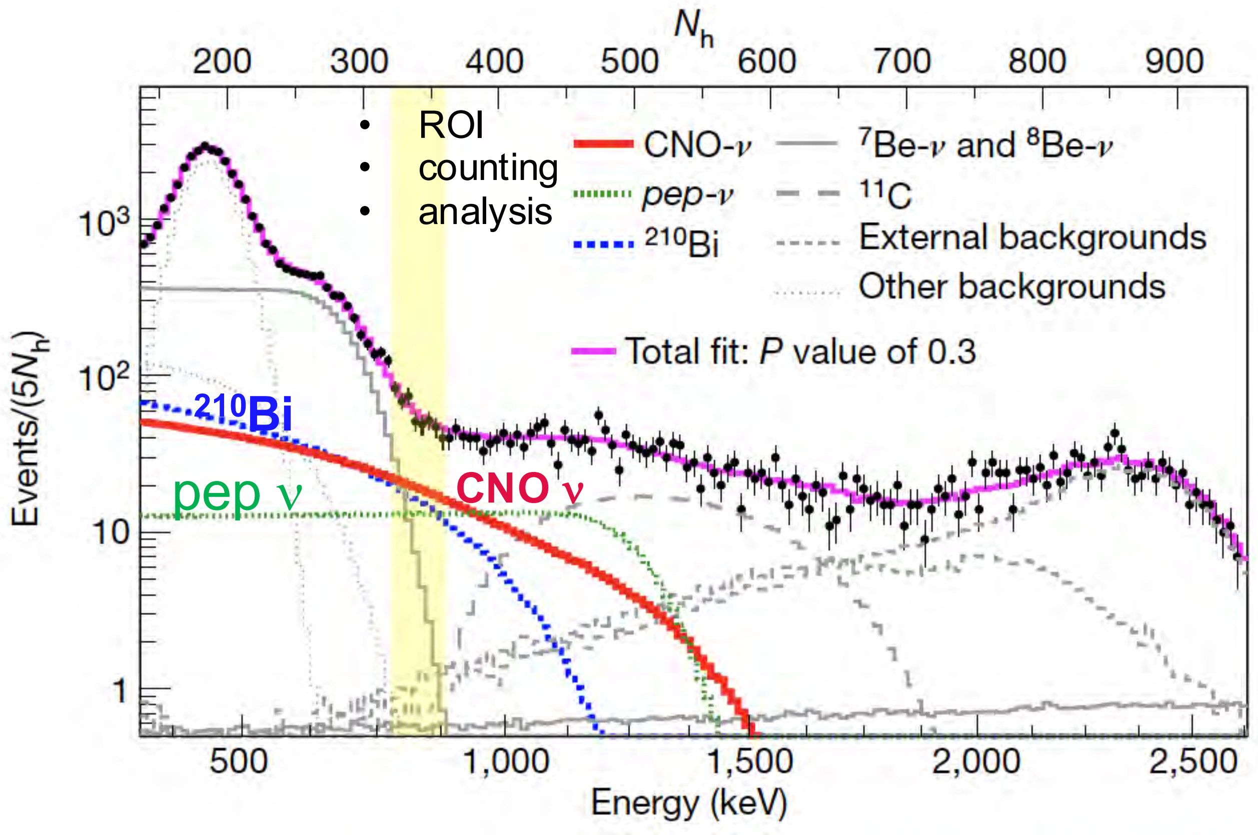
P_{ee} survival probability at different energies

Vacuum-LMA model excluded at 98.2% CL



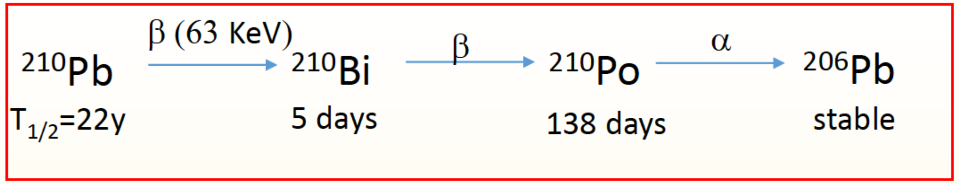
CHALLENGES TO MEASURE CNO NEUTRINOS

- Low rate (3-5 counts/day/100 ton of liquid scintillator)
- No prominent spectral features
- ^{11}C cosmogenic background – Three Fold Coincidence
- **Correlation with**
  - ✓ **pep solar neutrino: 1.4%** constraint from the solar luminosity and global fit of solar data without Bx Phase III
  - ✓ ^{210}Bi contamination of liquid scintillator: CHALLENGE



Nature 587 (2020) 577

F. Villante et al., Phys. Lett. B 701 (2011)



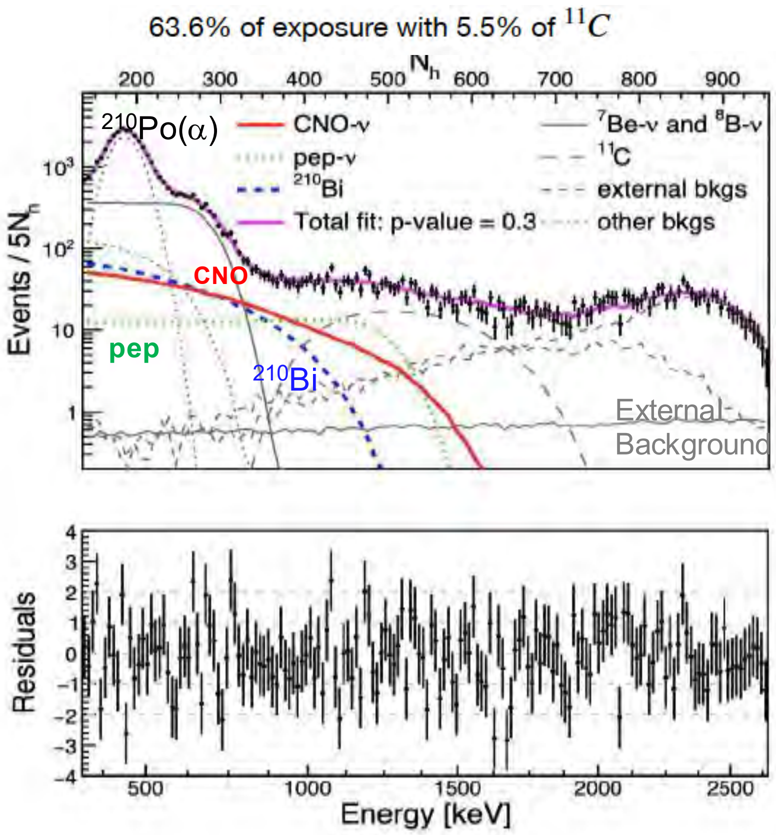
- Thermal insulation of the detector and complicated analysis to evaluate an upper limit on 210Bi

R(^{210}Bi) ≤ (10.8 ± 1.0) counts / day / 100 ton
including all systematic errors

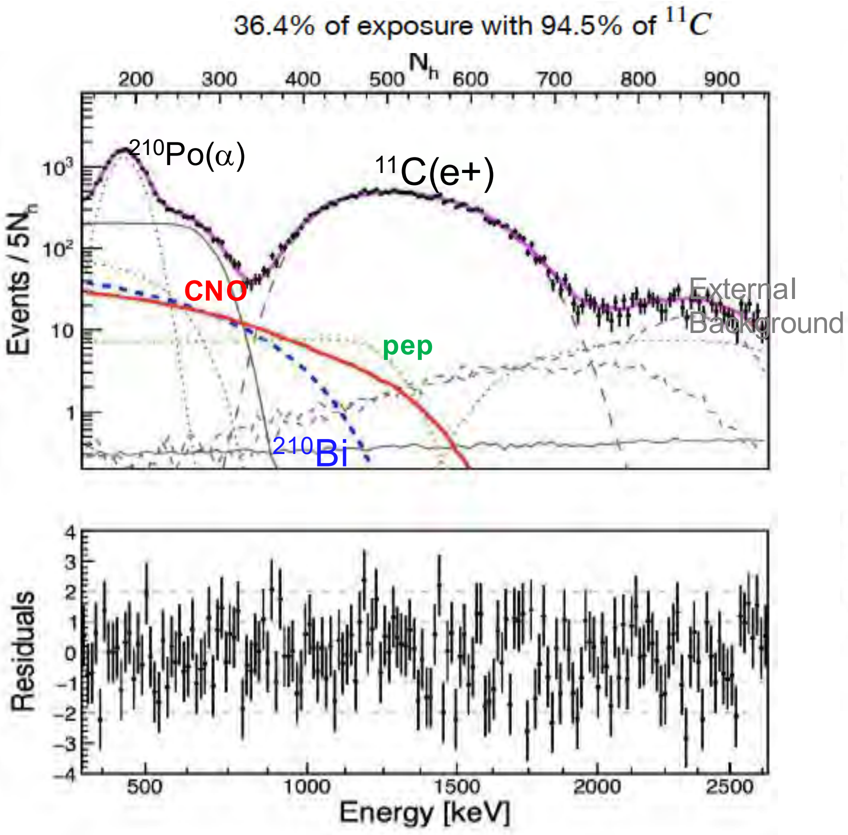
MULTIVARIATE SPECTRAL FIT

Phase III data (Jan 2017 – Oct 2021)
with exposure 1072 days x 71.3 ton

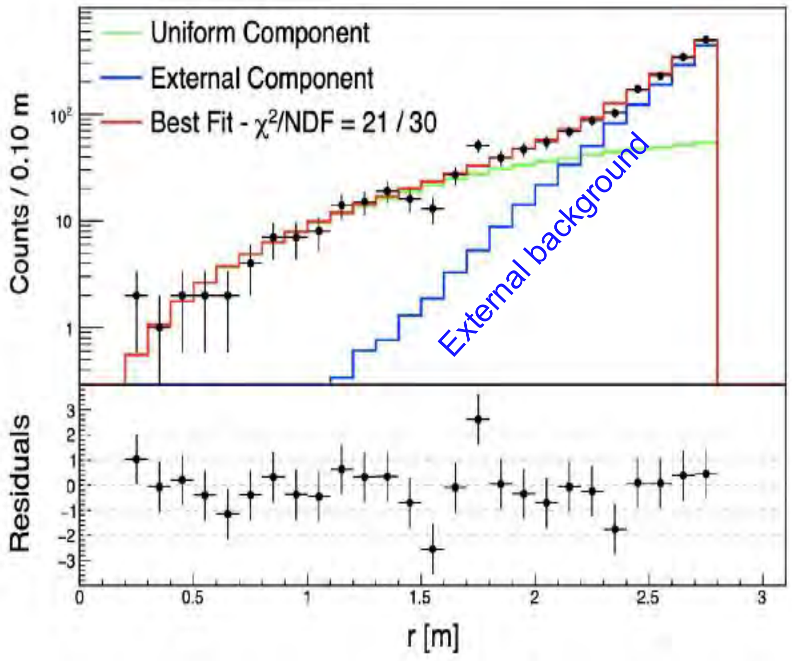
TFC-^{11}C subtracted energy spectrum



TFC-^{11}C tagged energy spectrum



Radial distribution



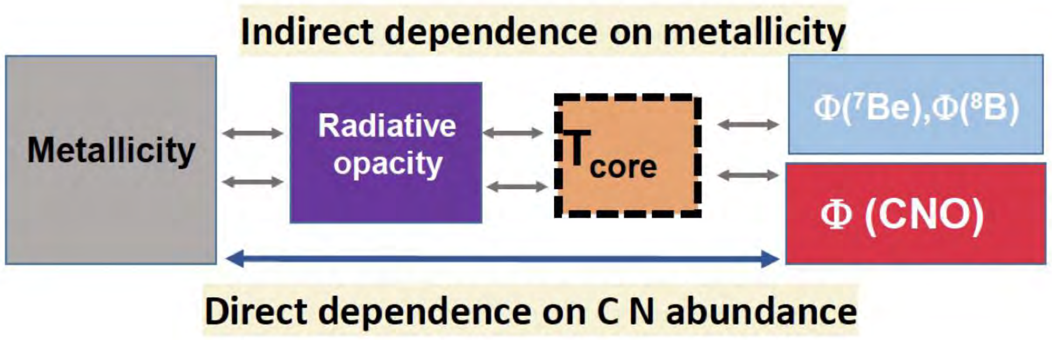
Constraints in the fit:
R(pep) = (2.74 + 0.04) cpd/100 t
R(^{210}Bi) < (10.8 ± 1.0) cpd/100 t

$$\mathcal{L}_{MV}(\vec{\theta}) = \mathcal{L}_{sub}^{TFC}(\vec{\theta})\, \mathcal{L}_{Tag}^{TFC}(\vec{\theta})\, \mathcal{L}_{Radial}(\vec{\theta})$$

Results (statistical errors only)
Rate(CNO)= $6.6^{+2.0}_{-0.7}$ cpd/100t

We disfavor the hypothesis CNO=0 with ~ 7σ significance

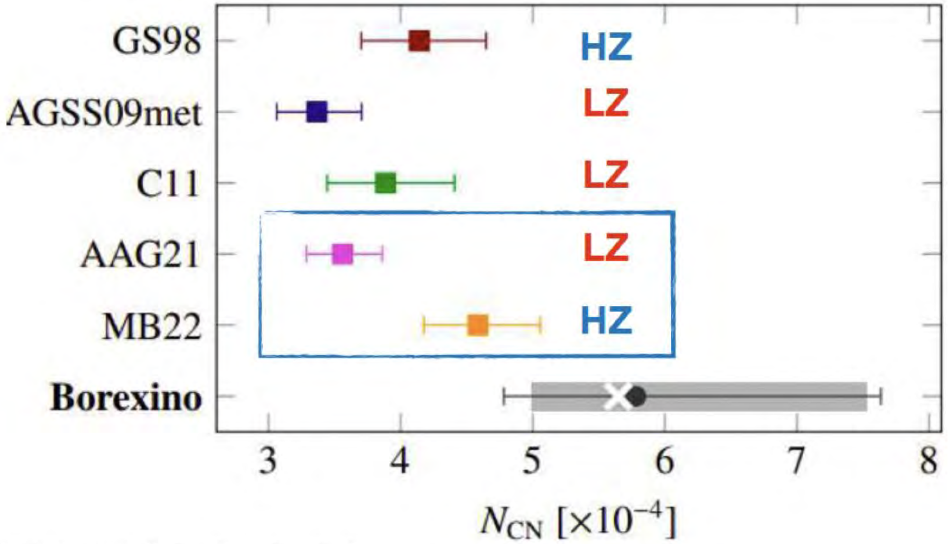
SOLAR IMPLICATIONS: C+N ABUNDANCE



$$\Phi_B/\Phi_B^{SSM} \propto (T_c/T_c^{SSM})^{\tau_B} \qquad \tau_B = 24$$

$$\Phi_O/\Phi_O^{SSM} \propto \frac{n_{CN}}{n_{CN}^{SSM}} \times (T_c/T_c^{SSM})^{\tau_O} \qquad \tau_O = 20$$

- The precise measurement of Φ (^{8}B) can be used as a ``thermometer” of the solar core temperature;



First **determination of C+N abundance** in the Sun using neutrinos
Can be directly compared with measurements from solar photosphere

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

Agreement with SSM-HZ predictions.

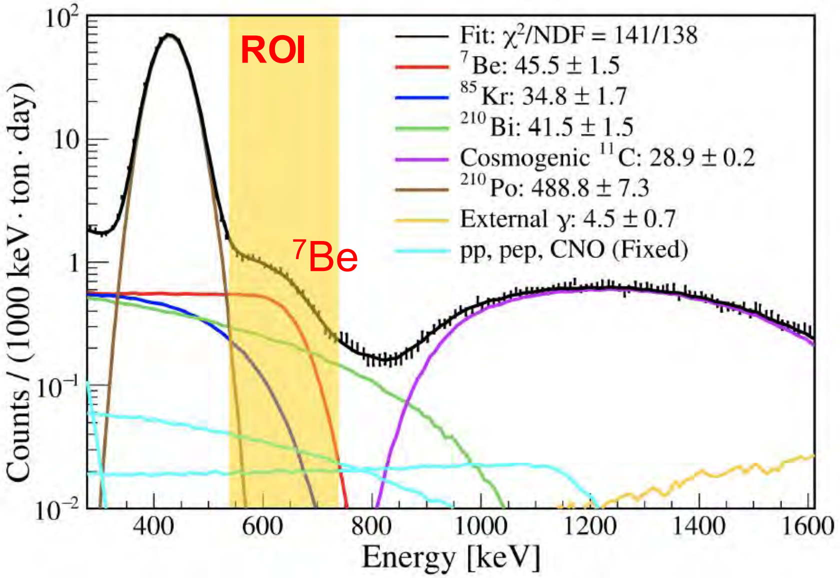
Moderate ~2σ **tension with SSM-LZ**

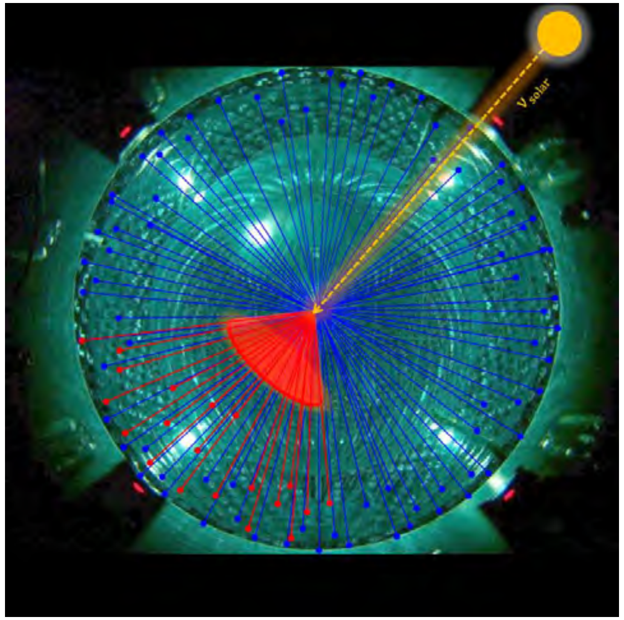
FIRST DIRECTIONAL DETECTION OF SUB-MEV SOLAR NEUTRINOS

BASIC IDEAS

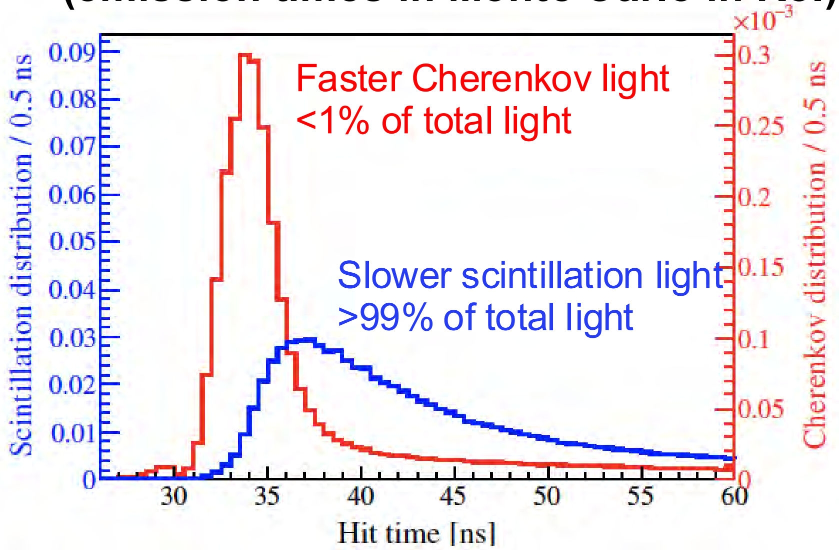
First Directional Measurement of sub-MeV Solar Neutrinos with Borexino, **Phys. Rev. Lett. 128 (2022) 091803.**
Correlated and Integrated Directionality for sub-MeV solar neutrinos in Borexino, **Phys. Rev. D 105 (2022) 052002.**

Phase I spectral fit PRD 89 (2014)112007





Cherenkov and scintillation light (emission times in Monte Carlo in RoI)

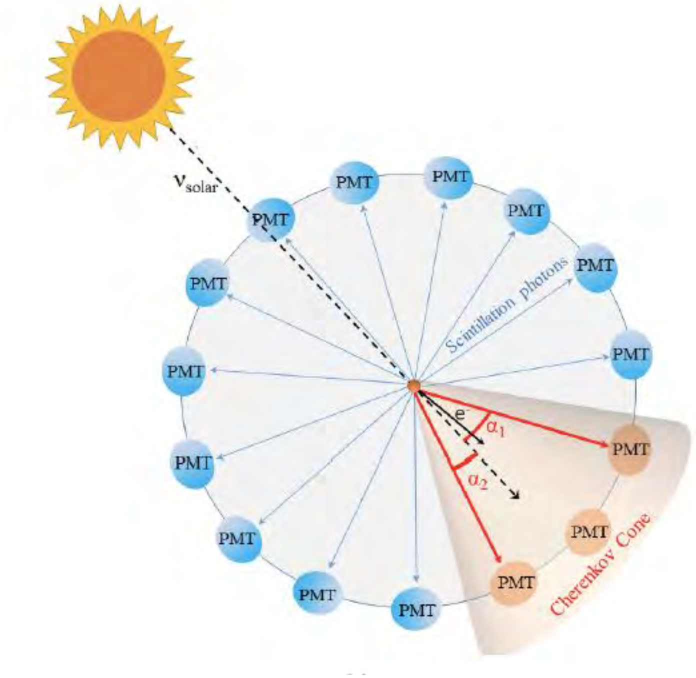


- Selection of the **region of interest** (ROI) using the dominant and **isotropic scintillation light**
- Using the subdominant **Cherenkov light**, that is fast and directional, to **recognize the solar neutrino signal** correlated with **the known position of the Sun.**
- **Method was eveloped on “easy” ^{7}Be and then applied on CNO neutrinos**

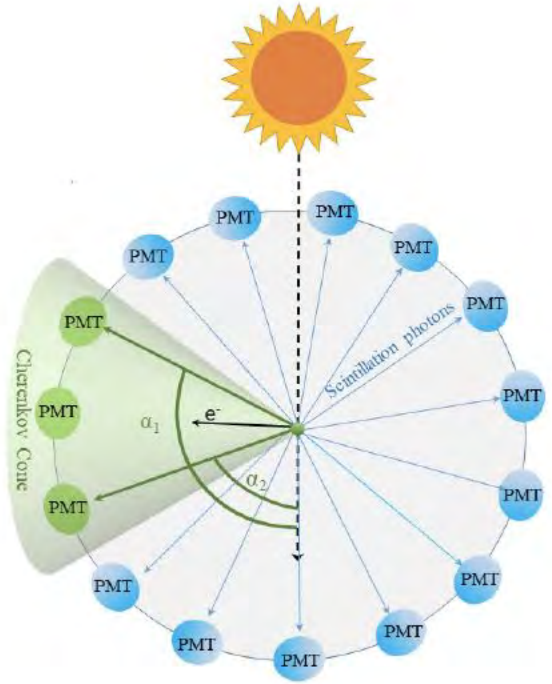
FIRST DIRECTIONAL DETECTION OF SUB-MEV SOLAR NEUTRINOS

NEW METHOD: CORRELATED INTEGRATED DIRECTIONALITY (CID)

Solar neutrino event:
correlated with the Sun



Background event:
UN-correlated with the Sun



Angular analysis of the first hits (after ToF) of each event from the **ROI,** characterized by the highest fraction of the Cherenkov light

Correlated:

* we correlate the reconstructed photon direction (hit-PMT - vertex) with the **known direction from the Sun**

Integrated:

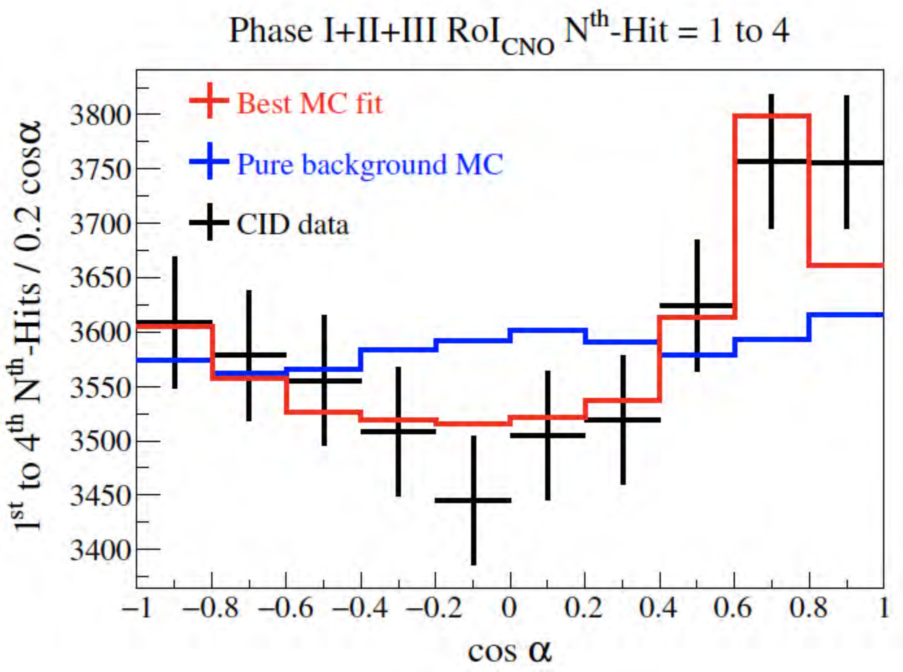
* event-by-event discrimination not possible, we integrate over all events from the RoI

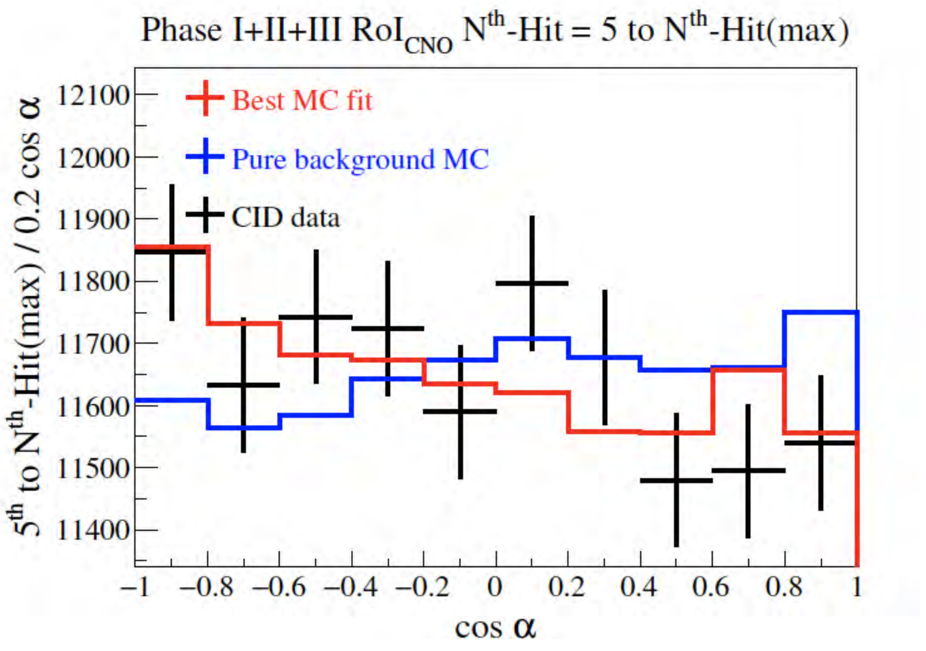
Directionality:

* we exploit directional Cherenkov light

OBSERVATION OF CNO SOLAR NEUTRINOS WITH CID

DATA CID DISTRIBUTIONS AND FIT





Early hits (1 to 4):
Direct information
from the Cherenkov light

Later hits (5 to 15/17):
Indirect information
from the effect of Cherenkov light on the vertex reconstruction (bias)

CNO observation with the CID method at 5.3σ CL
No 210Bi constraint needed!

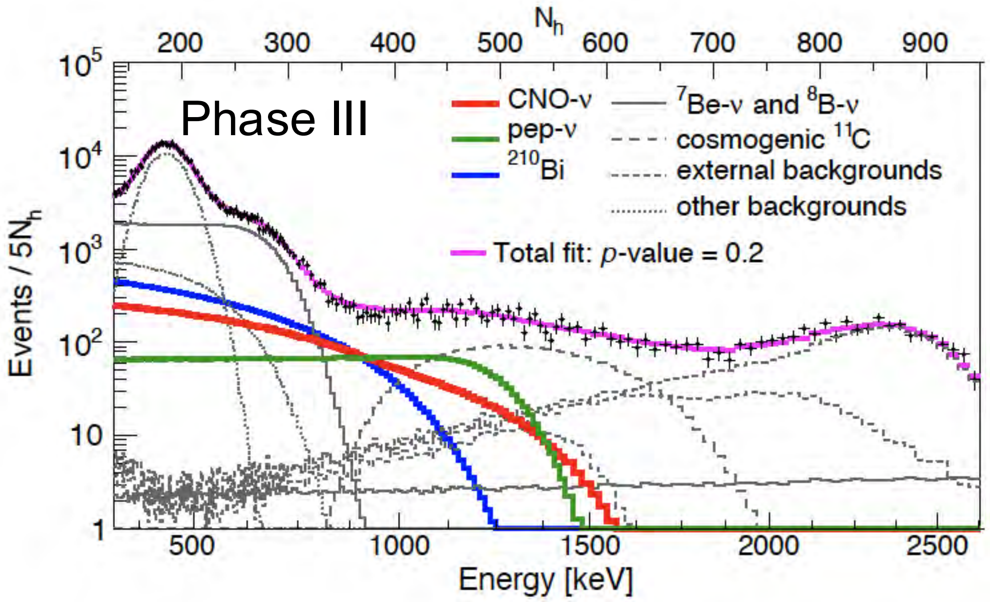
PHYSICAL REVIEW D 108, 102005 (2023)

Editors' Suggestion

Final results of Borexino on CNO solar neutrinos

FINAL BOREXINO RESULT ON CNO

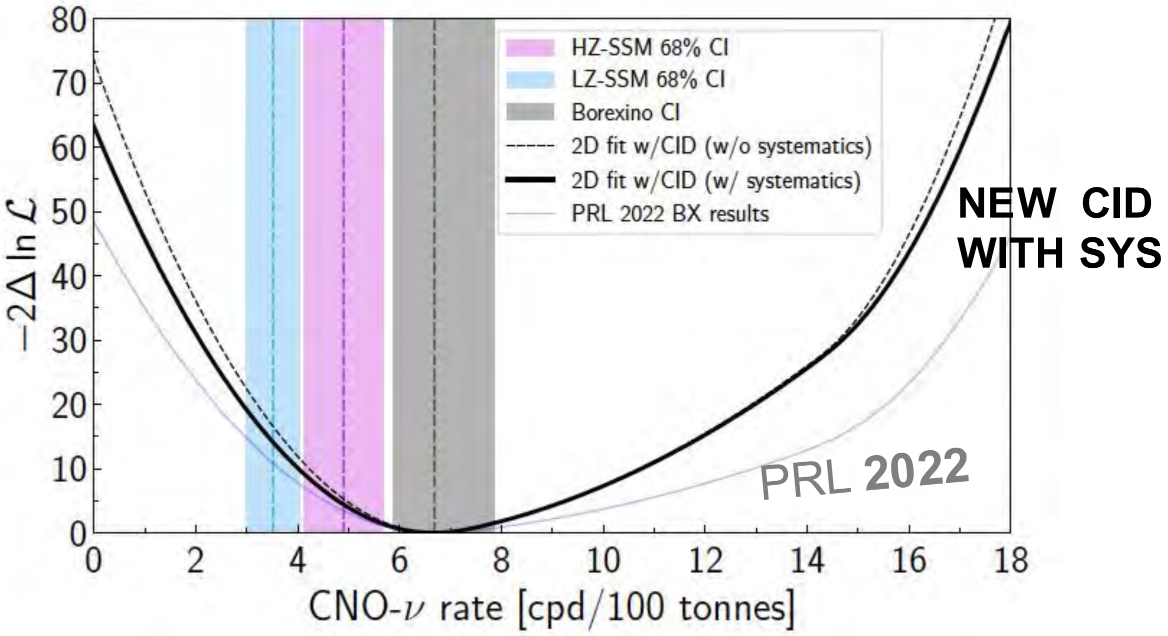
SPECTRAL FIT OF THE PHASE III WITH THE CID (PHASE I+II+III) CONSTRAINT



$$\mathcal{L}_{MV+CID} = \mathcal{L}_{MV} \cdot \mathcal{L}_{pep} \cdot \mathcal{L}_{^{210}Bi} \cdot \mathcal{L}_{CID}^{P-I} \cdot \mathcal{L}_{CID}^{P-II+III}$$

Standard Multivariate Fit | Pull terms from CID posterior

The same spectral analysis
of the Phase III as in PRL **12/12/2022**
with constraints on pep and ^{210}Bi
and additional CID constraint.



R(CNO)= $6.7^{+1.2}_{-0.8}$ cpd/100 t

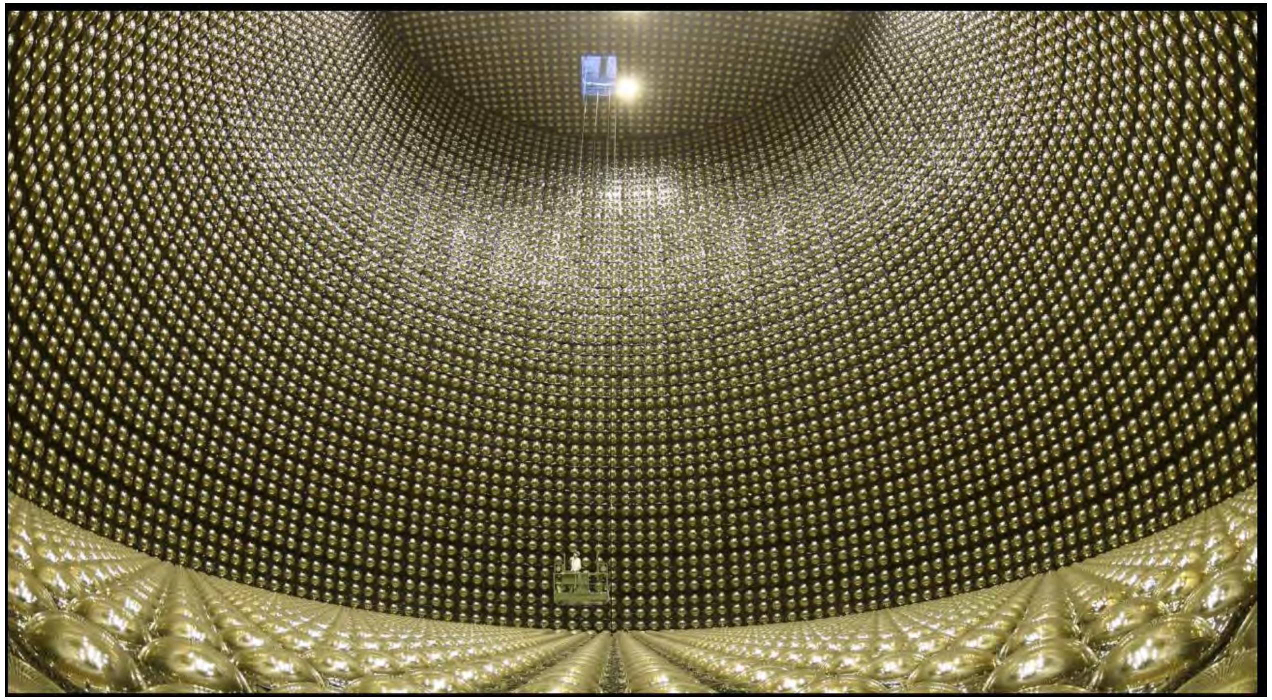
2022 results without CID: $6.7^{+2.0}_{-0.8}$ cpd/100 t

Φ(CNO) = $6.7^{+1.2}_{-0.8}$ x 10^8 cm^{-2} s^{-1}

We disfavour the hypothesis CNO = 0 with ~8σ significance

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)

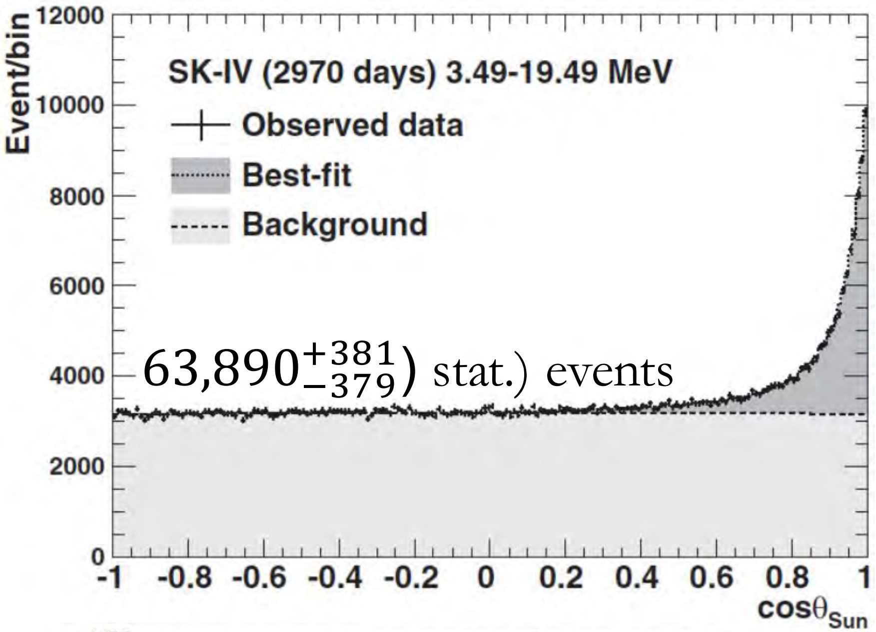
Since 2020: Gd loading of LS for neutron capture to observe DSNB via IBDs.

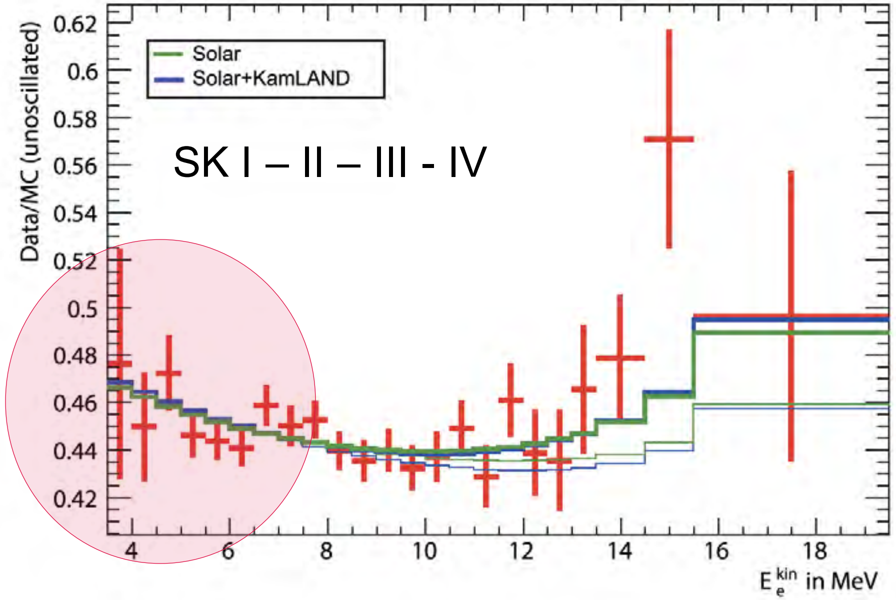
- SK-V: preparation
- SK-VI (0.01% Gd)
- SK-VII (0.03% Gd)

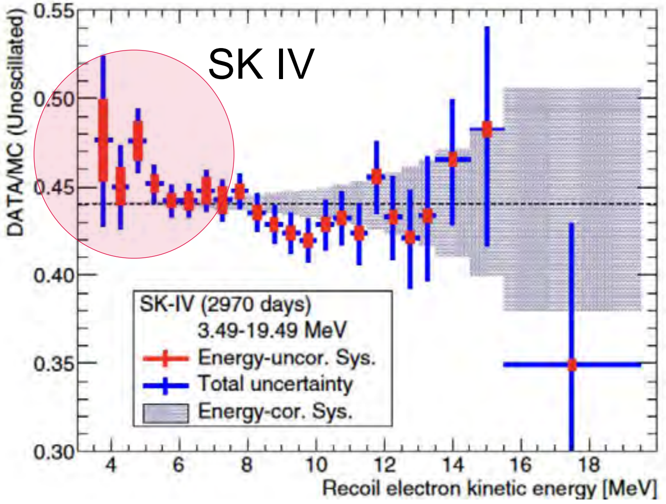
Higher backgrounds as expected, but 4 /4.5 MeV threshold is possible.

SUPER-KAMIOKANDE LATES RESULTS

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





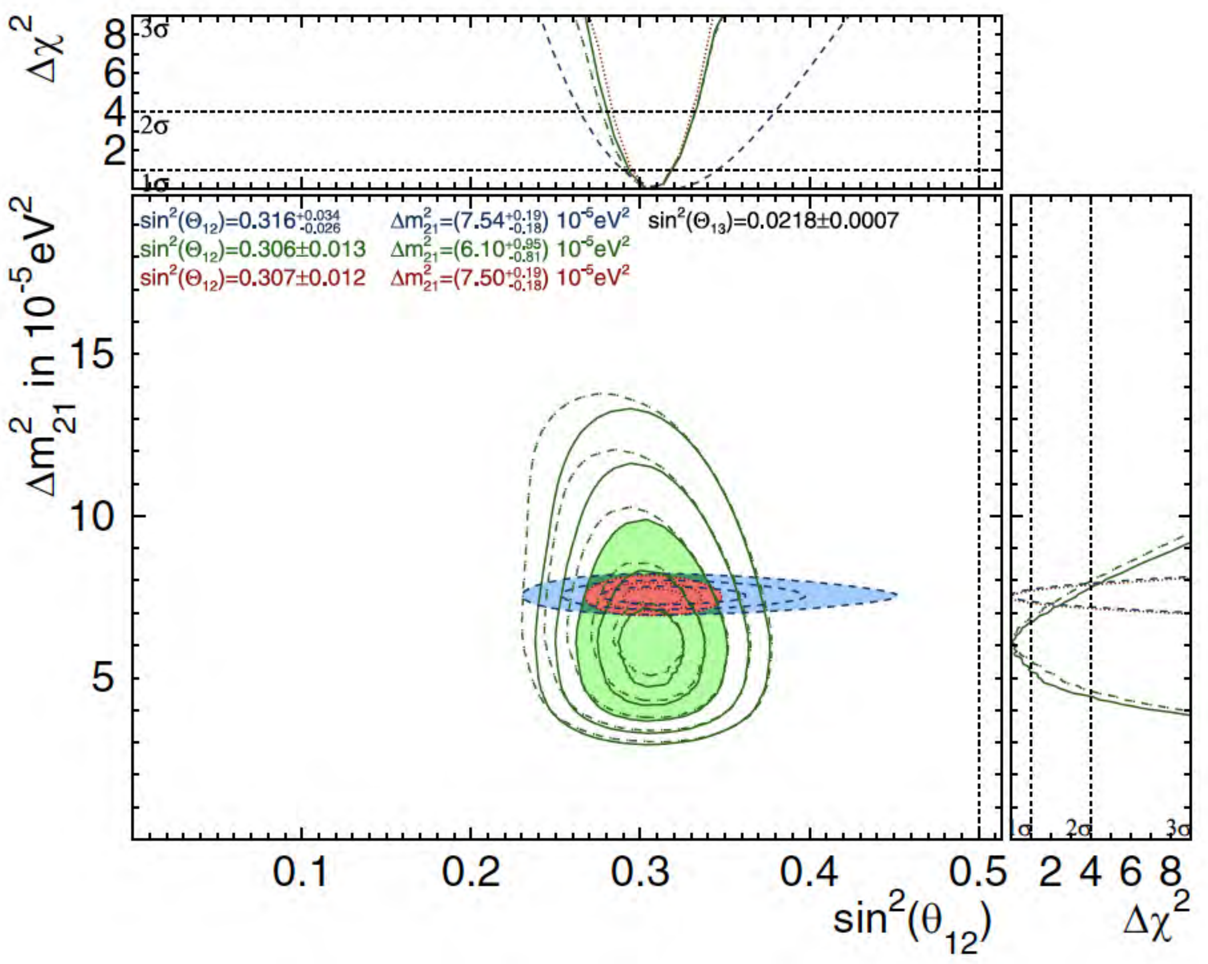


- ^{8}B flux measurement consistent among different phases **– total precision 2%.**
- Spectrum still compatible with flat survival probability, but predicted low energy **MSW upturn is favoured at 1.2 σ** . Jointly with SNO data, at 2.1 σ.
- No time variations except eccentricity and **Day/Night variation**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

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



Solar best-fit value

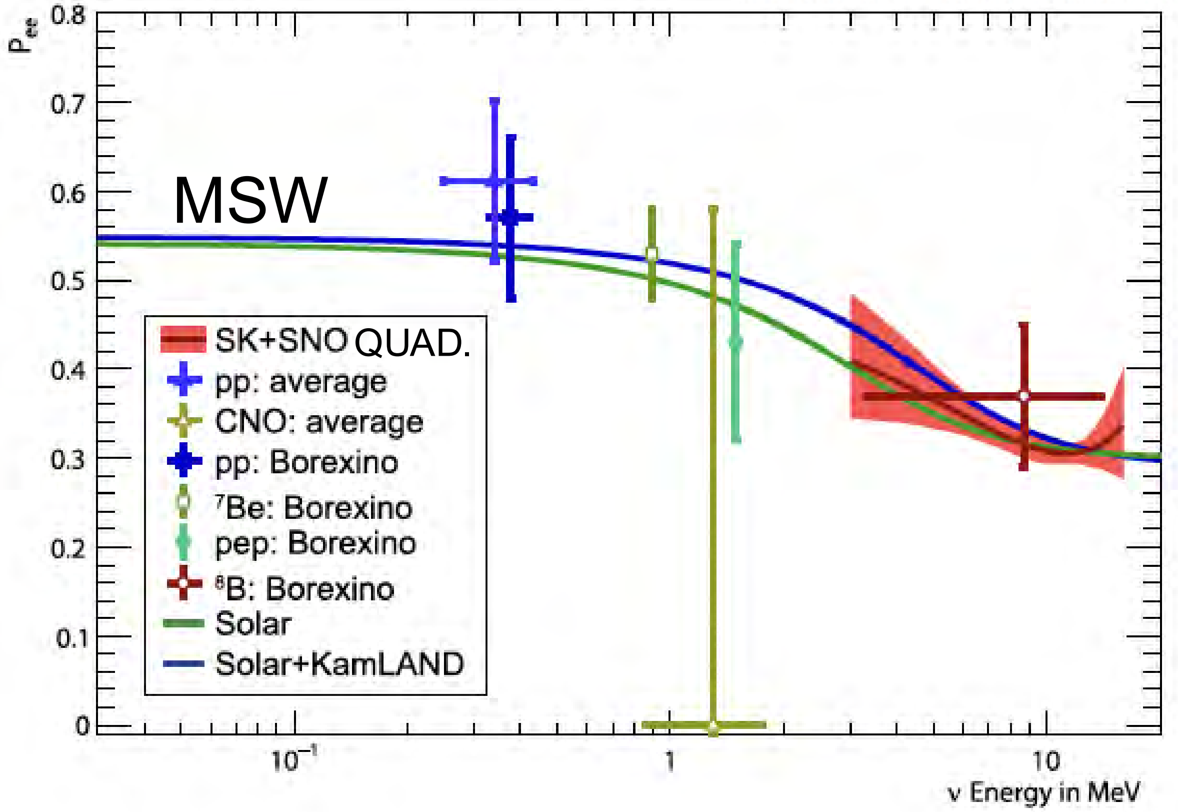
$\Delta m^2_{21} = 6.10^{+0.95}_{-0.81} \times 10^{-5}\ eV^2$

~1.5 σ away from KamLAND

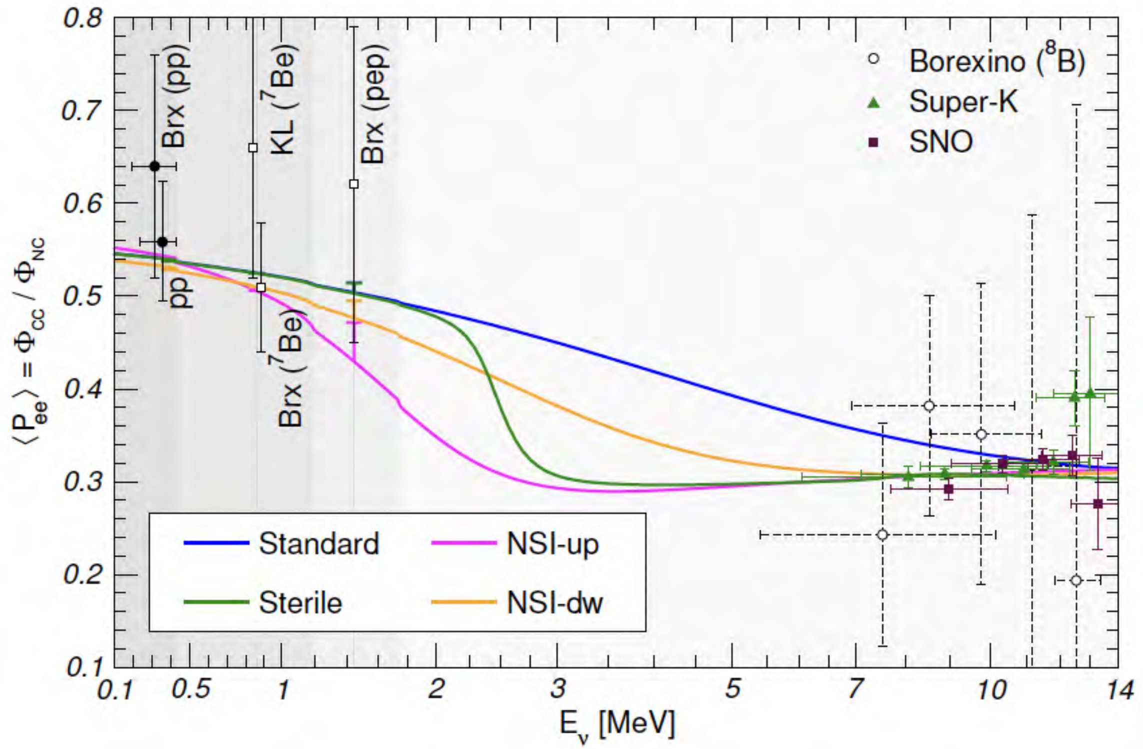
Previously, larger tensions.

P_{ee}: VACUUM TO MATTER TRANSITION

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

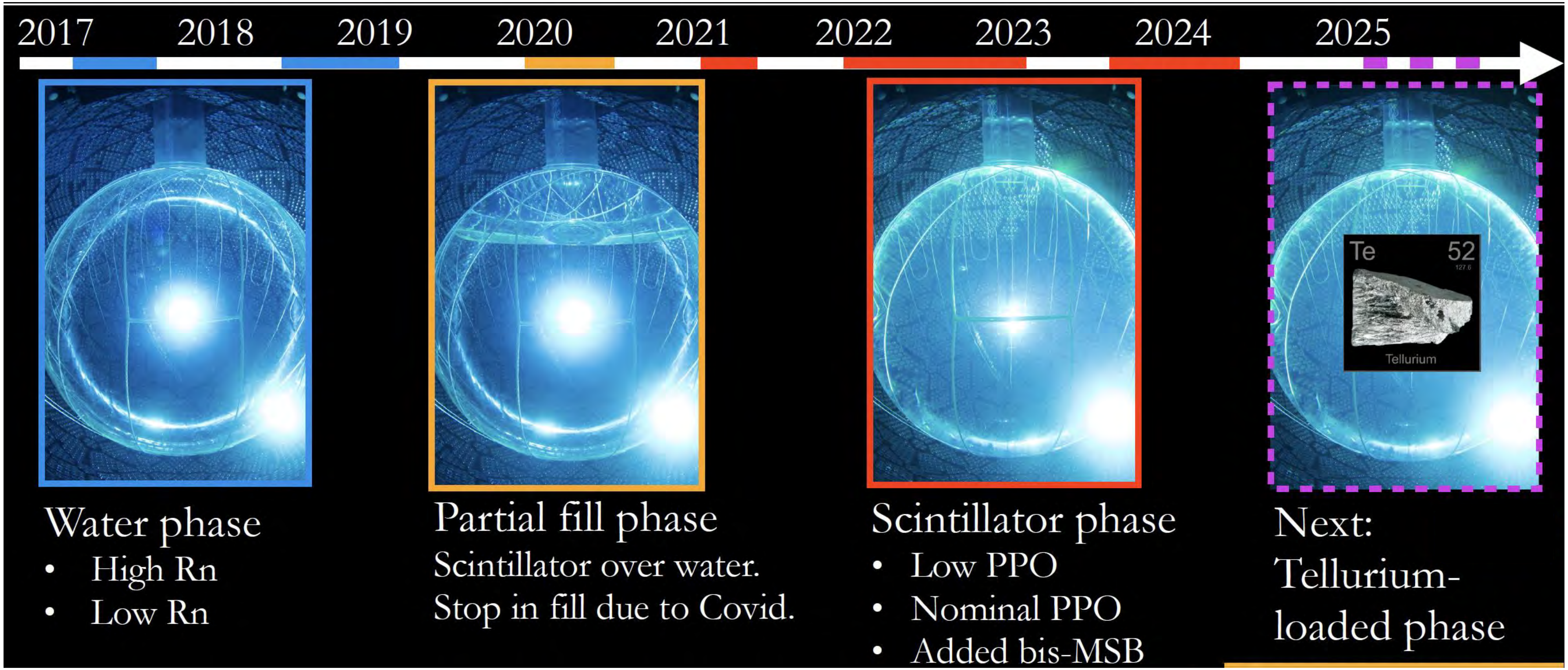


M. Maltoni et al., Eur. Phys. J. A 52 (2016) 87



Transition region crucial for testing BSM ideas.

SNO+ IN SUDBURY, CANADA

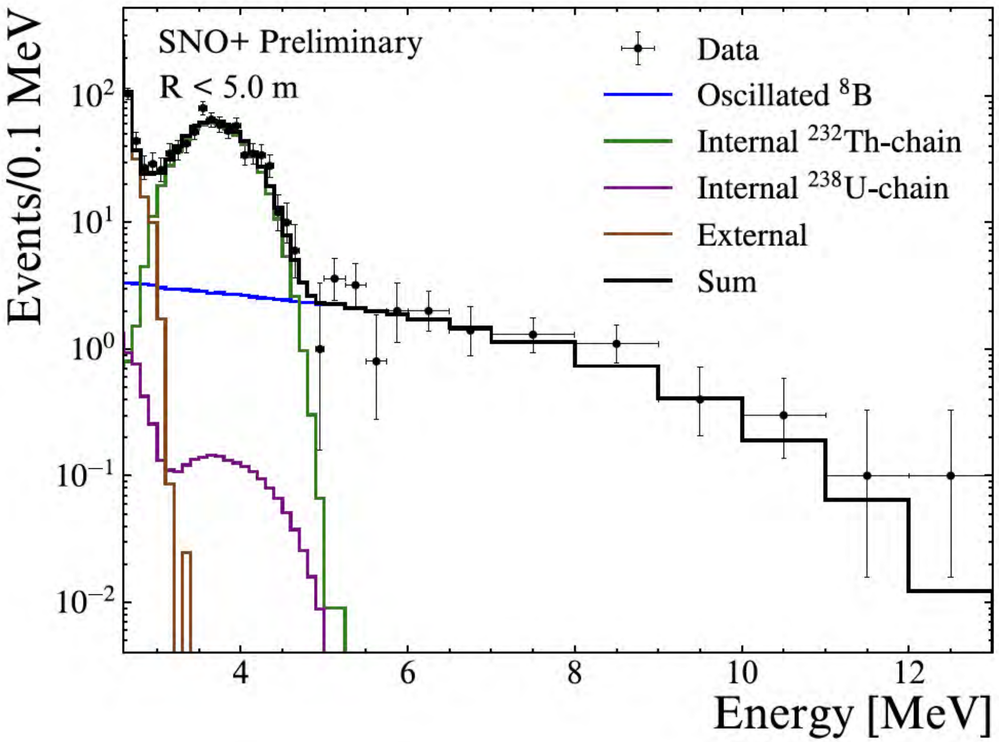


J. Maneira. Neutrino 2024

SNO+ AND 8B SOLAR ANALYSIS

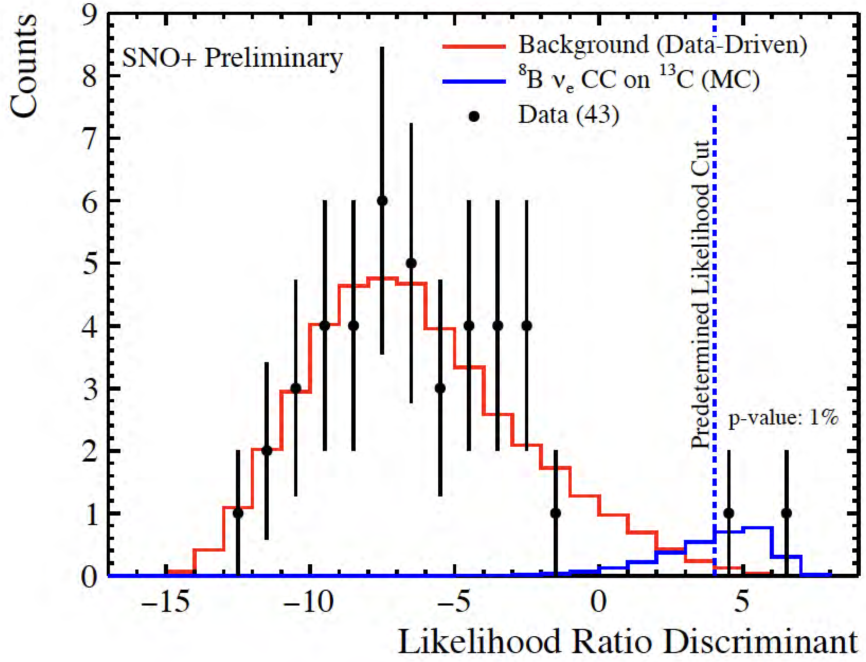
$$\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$$
$$ {}^{13}N \rightarrow e^+ + \nu_e + {}^{13}C$$

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.

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.

Vulcanism

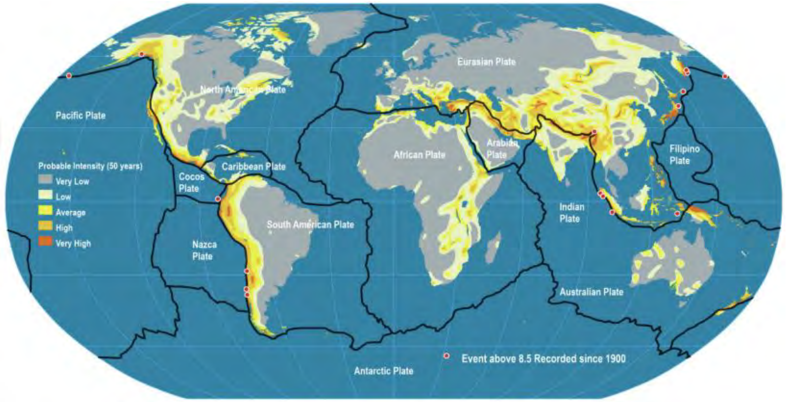
Geoneutrinos

From where is coming
the energy driving these processes?

How can neutrino physics help us to understand?

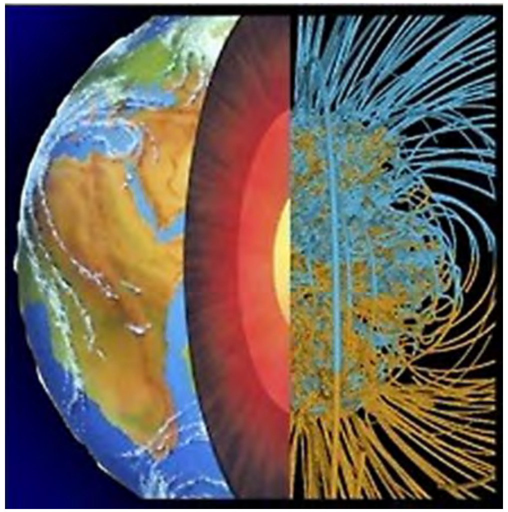
Earth shines in geoneutrinos:
flux ~ 10^6 cm^{-2} s^{-1}

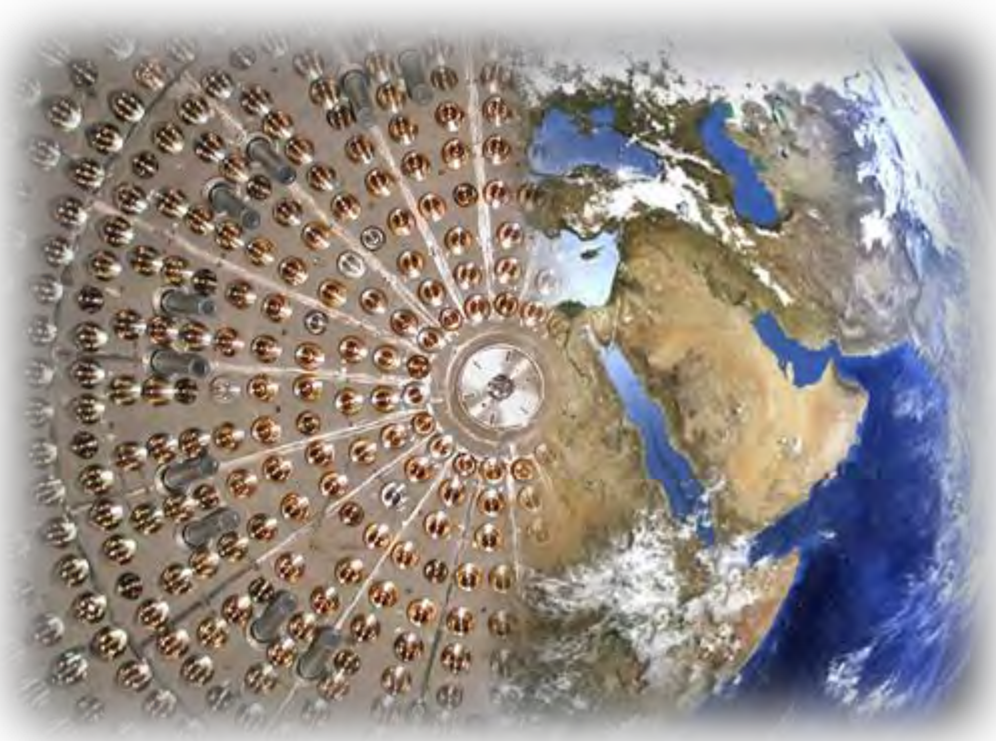
Plate tectonics & mantle convection



https://transportgeography.org

Geo-dynamo





Earthquakes

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

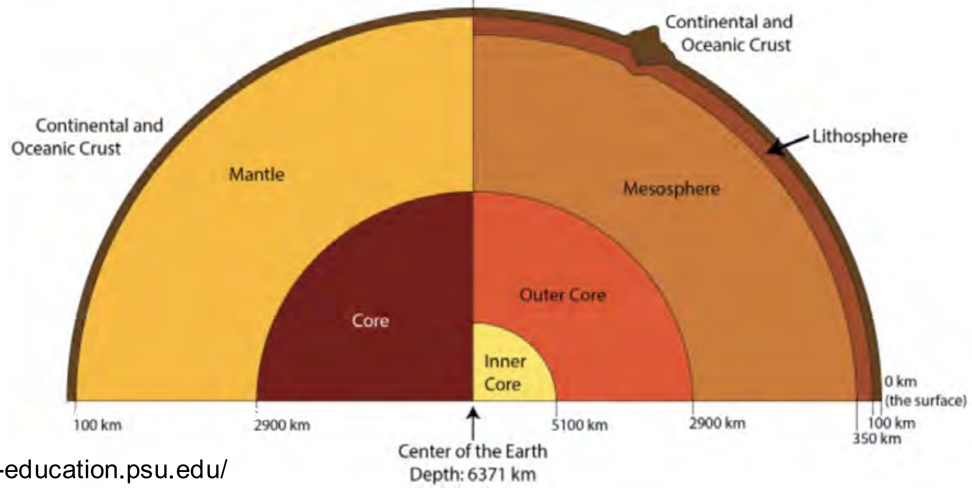
Geoneutrino flux
(signal)

Signal interpretation

Neutrino geoscience: a truly inter-disciplinary field!

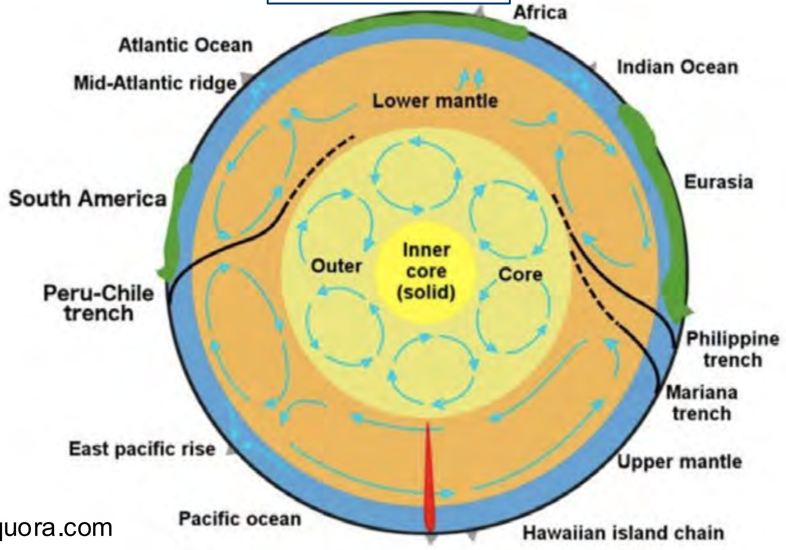
THE EARTH TODAY

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)

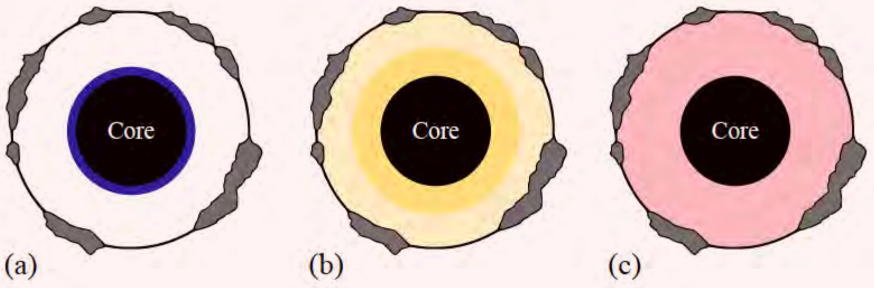
SILICATES	upper continental crust:	2.5 ppm
	middle continental crust:	1.6 ppm
	lower continental crust:	0.63 ppm
	oceanic crust:	0.1 ppm
	upper mantle:	6.5 ppb
	core (**metallic**)	**NOTHING**

Decreases with depth

U/Th distribution in the mantle (3 scenario)

Geoneutrino flux from the mantle

Low | Intermediate | High



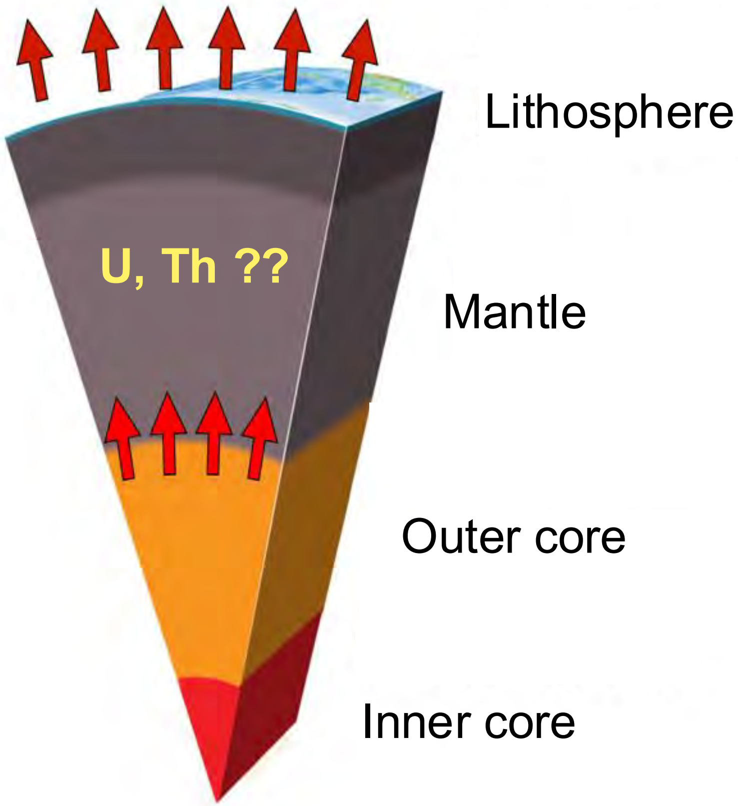
PHYS. REV. D 101, 012009 (2020)

THE EARTH'S HEAT BUDGET

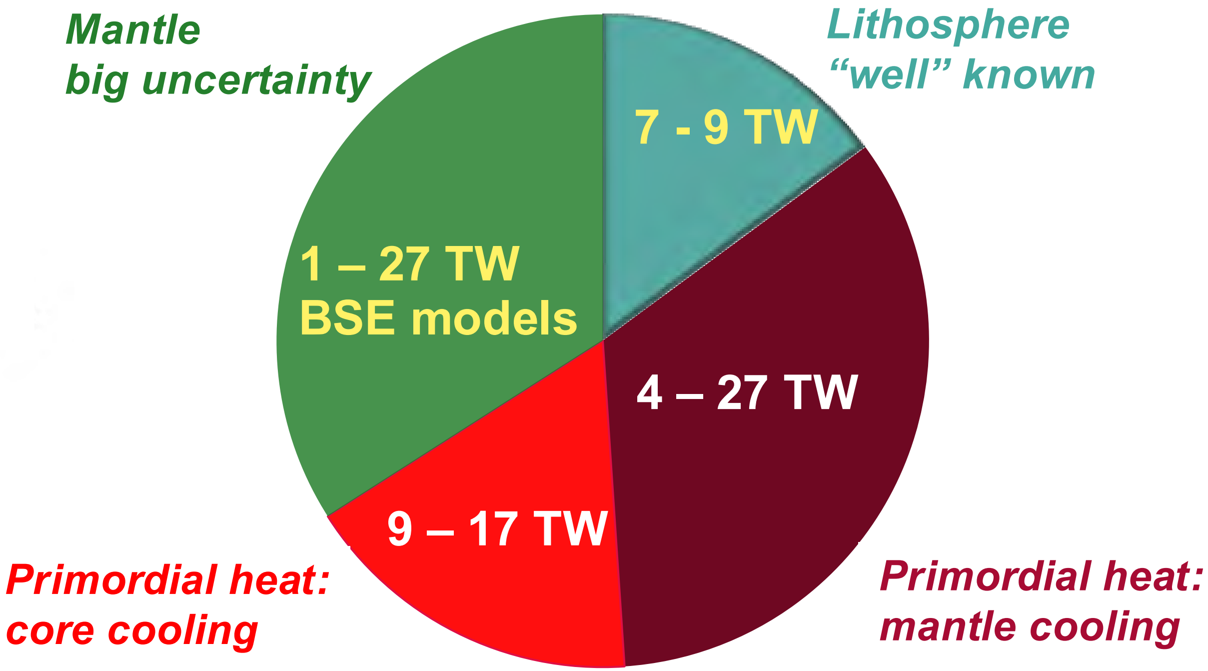
Integrated surface heat flux:

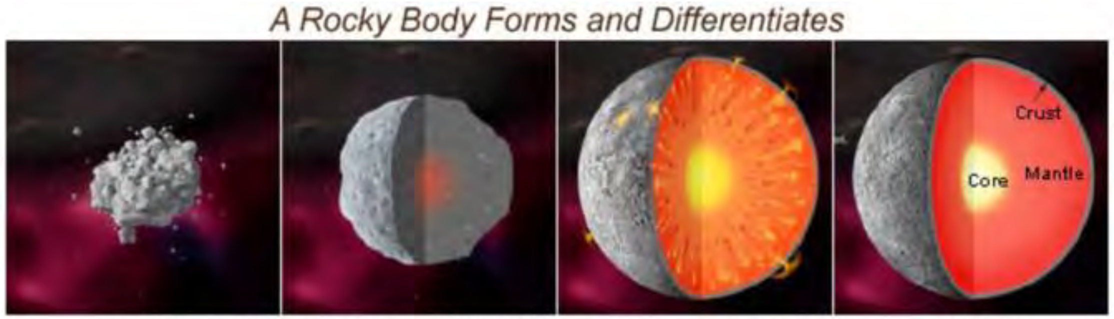
From measured T-gradients along bore-holes

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



Radiogenic heat & Geoneutrinos





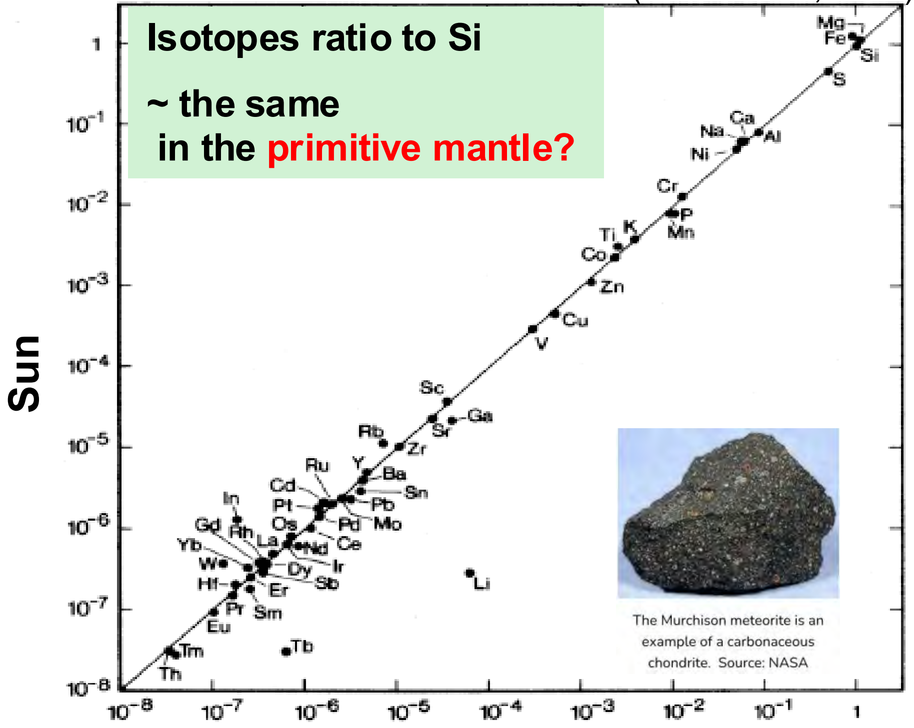
(From Smithsonian National Museum of Natural History - http://www.mnh.si.edu/earth/text/5_1_4_0.html)

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)



C1 carbonaceous chondritic meteorites

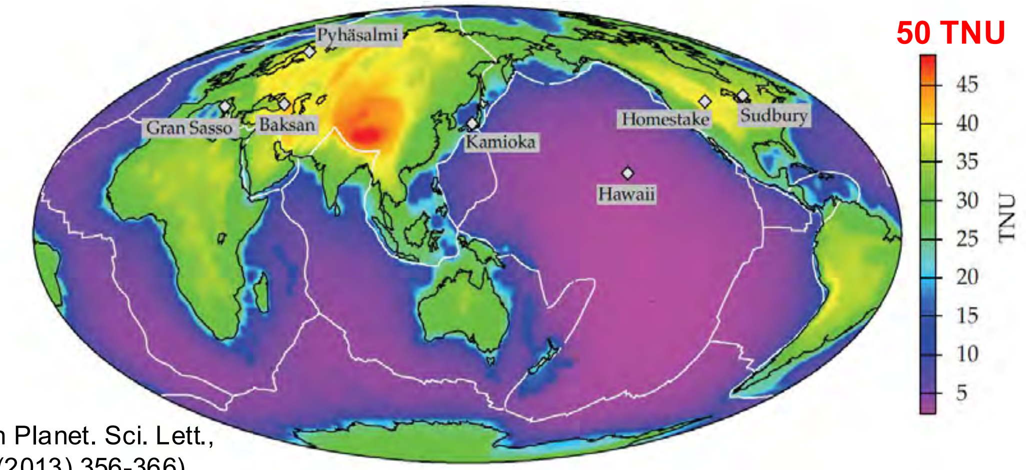
PHYS. REV. D 101, 012009 (2020)

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!

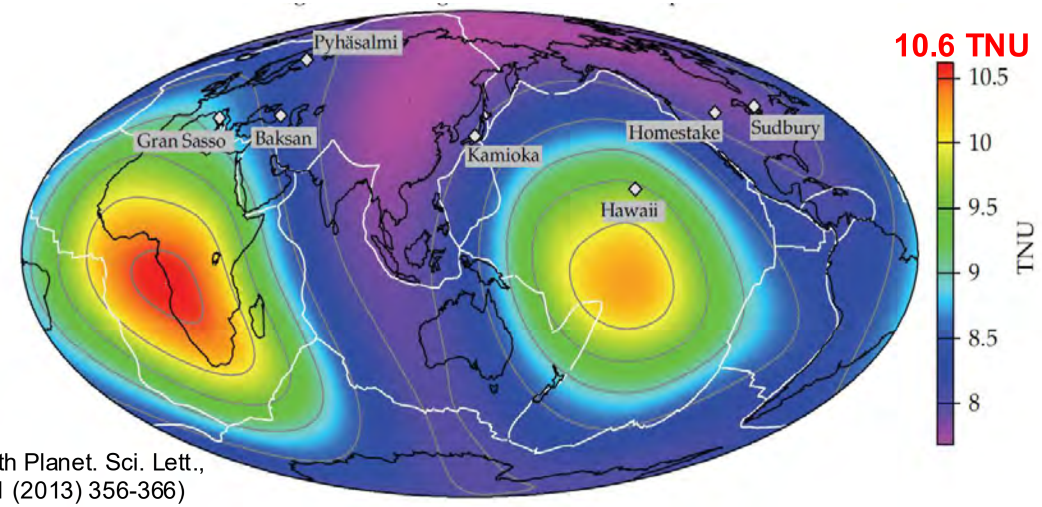
Terrestrial Neutrino Unit

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



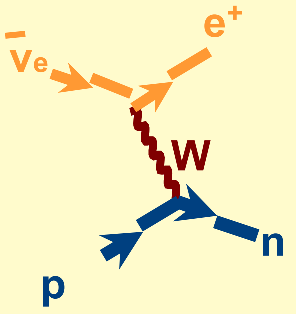
Earth Planet. Sci. Lett., 361 (2013) 356-366)

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

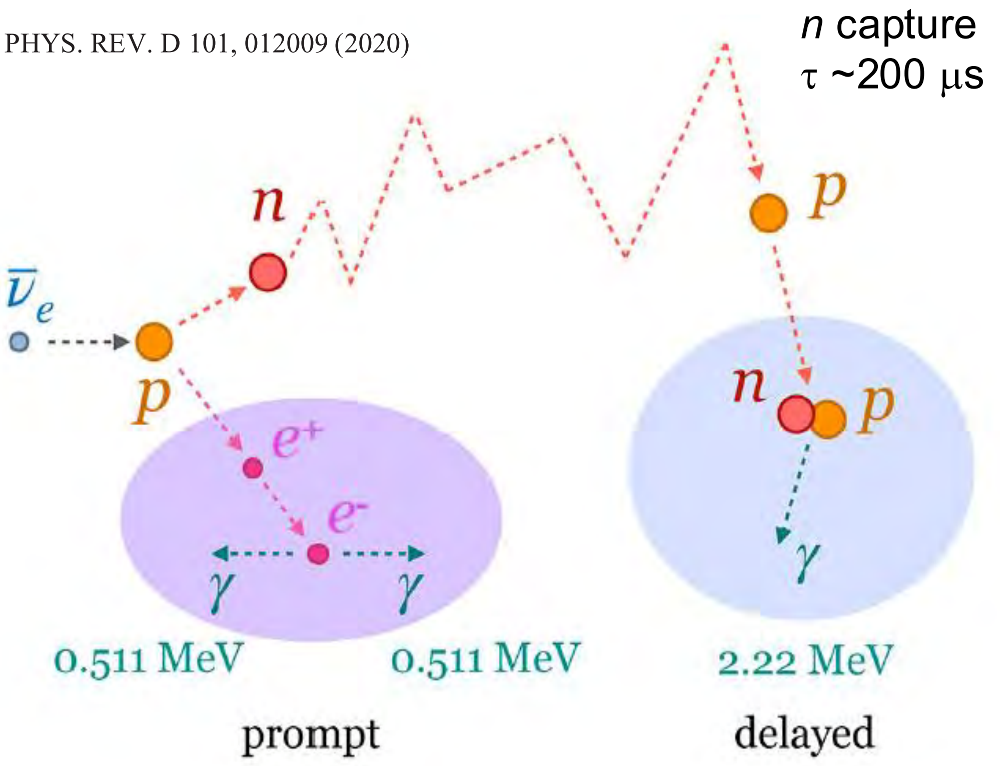


Energy threshold = 1.8 MeV

σ @ few MeV: ~10^{-42} cm^2

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

PHYS. REV. D 101, 012009 (2020)



Geoneutrino from radioactive decay

$\bar{\nu}_e$ → **Neutrino oscillation** (average P_{ee} ~ **0.55**) → $\bar{\nu}_e$ / $\bar{\nu}_{\mu,\tau}$

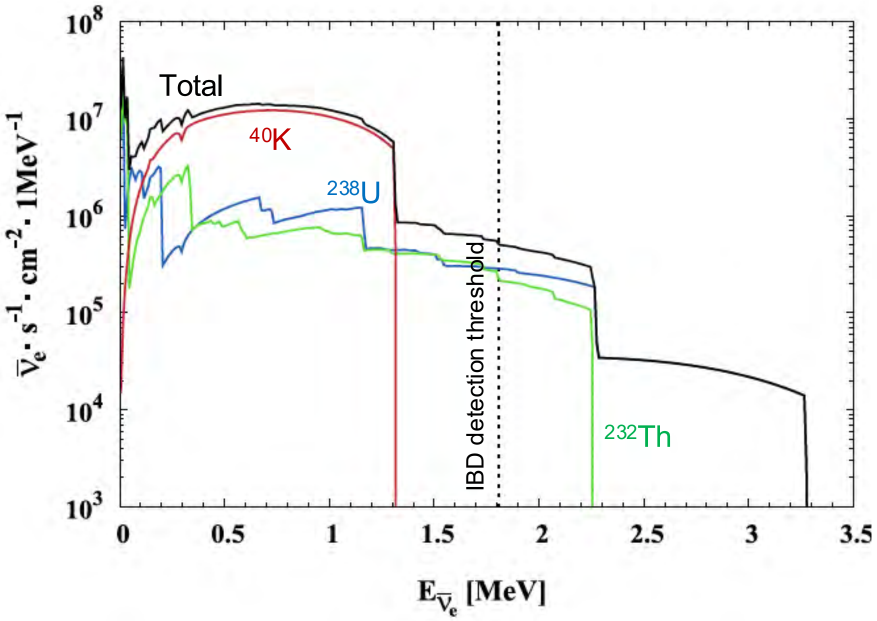
$\bar{\nu}_e$: Detection with IBD

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

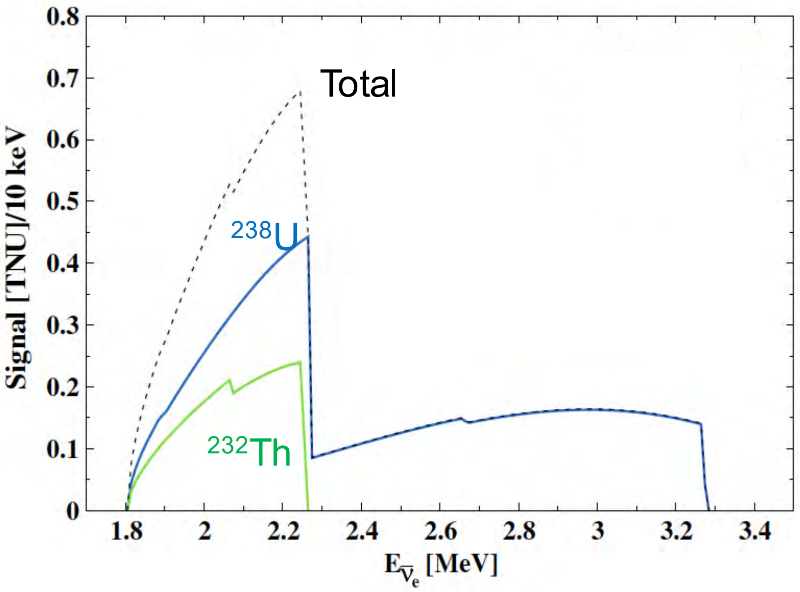
$$E_{prompt} = E_{visible}$$
$$= T_{e+} + 2 \times 511 \text{ keV}$$
$$\sim E_{antinu} - 0.784 \text{ MeV}$$

GEONEUTRINO SPECTRAL SHAPE @ LNGS (BOREXINO SITE)

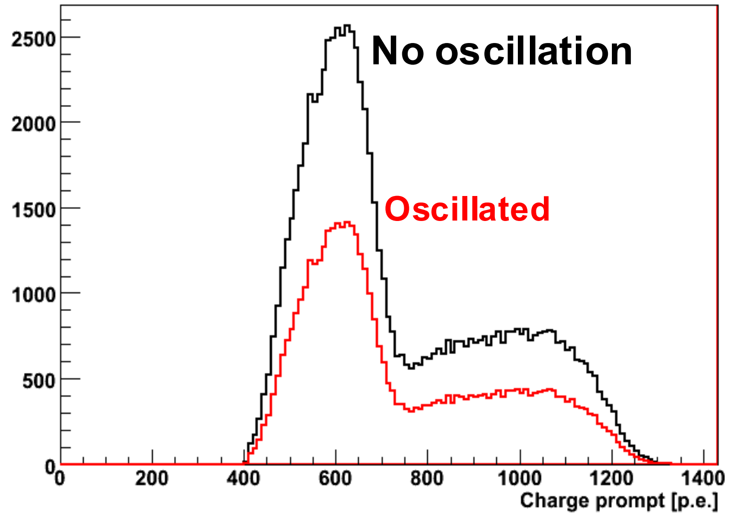
Geoneutrino flux



Geoneutrinos detected via IBD



Effect of neutrino oscillations

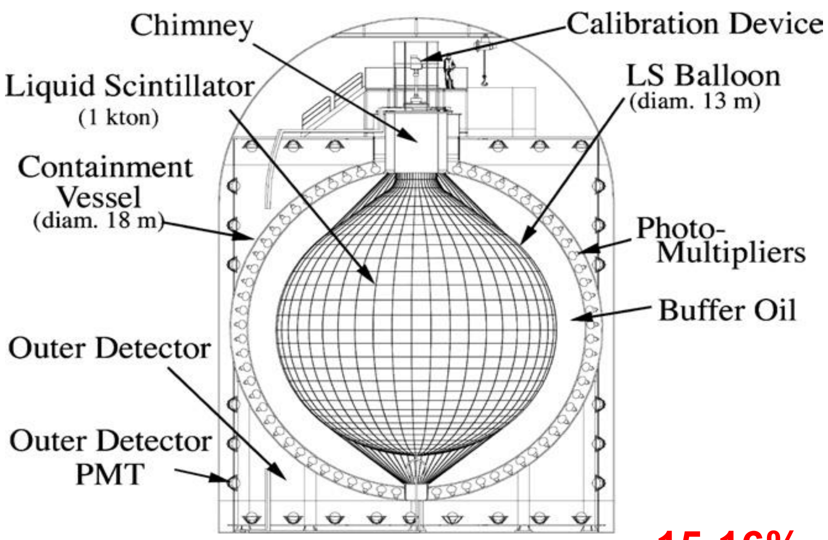


- We are able to **detect geoneutrinos only from the decay chains of ^{238}U and ^{232}Th** above 1.8 MeV energy.
- **^{40}K** geoneutrinos cannot be detected.
- ^{238}U and ^{232}Th have different end points of their spectra: **the key how to distinguish them**.
- **Effect of neutrino oscillations**: 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 GEONEUTRINOS

KamLAND, Kamioka, Japan

Border between
OCEANIC / CONTINENTAL CRUST

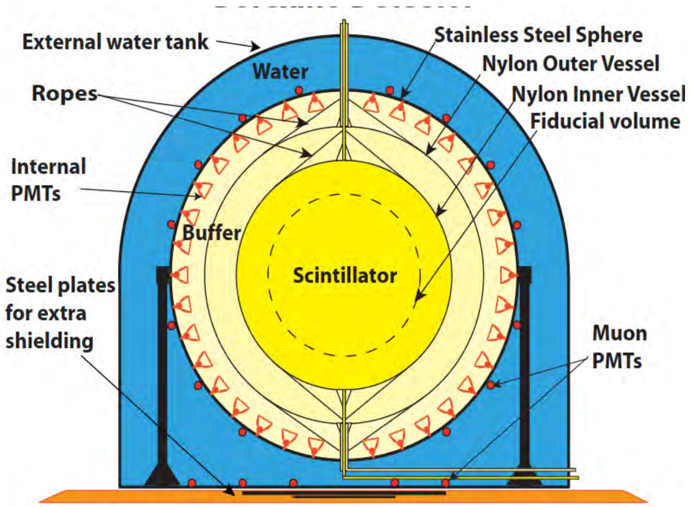


15-16%

- 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

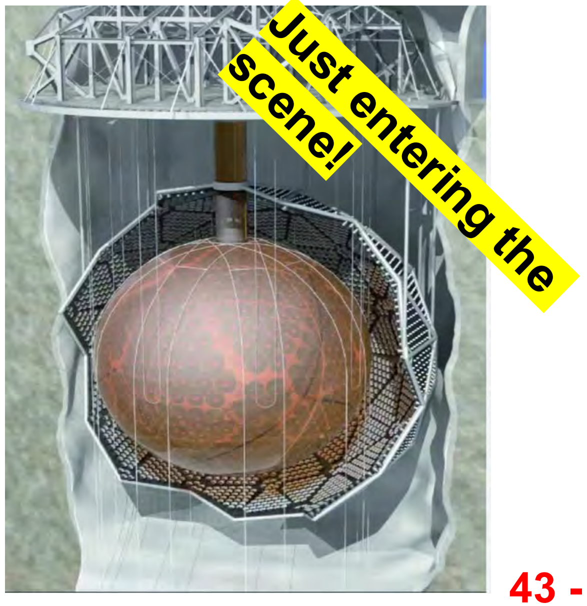


17-18%

- 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)

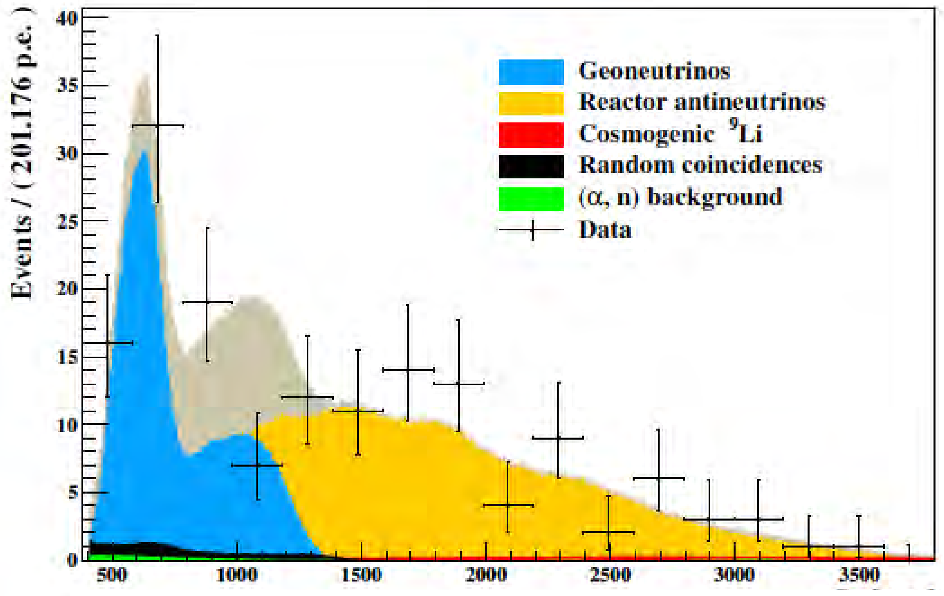


43 - 47%

- 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.

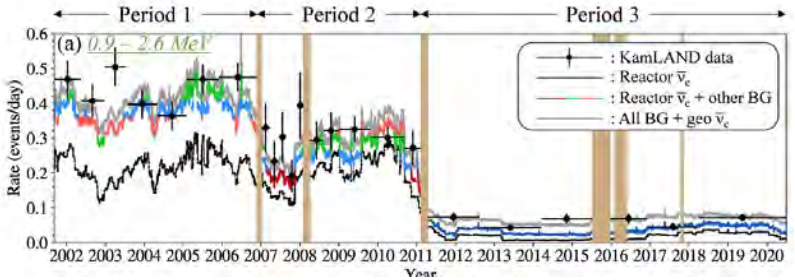
LATES RESULTS: SPECTRAL FIT with chondritic Th/U ratio

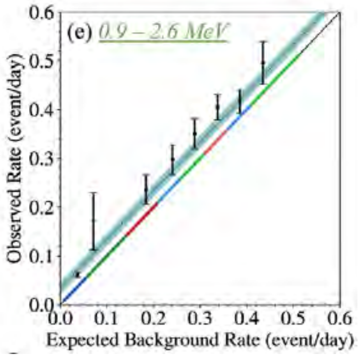
Borexino (PRD101 (2020) 012009)

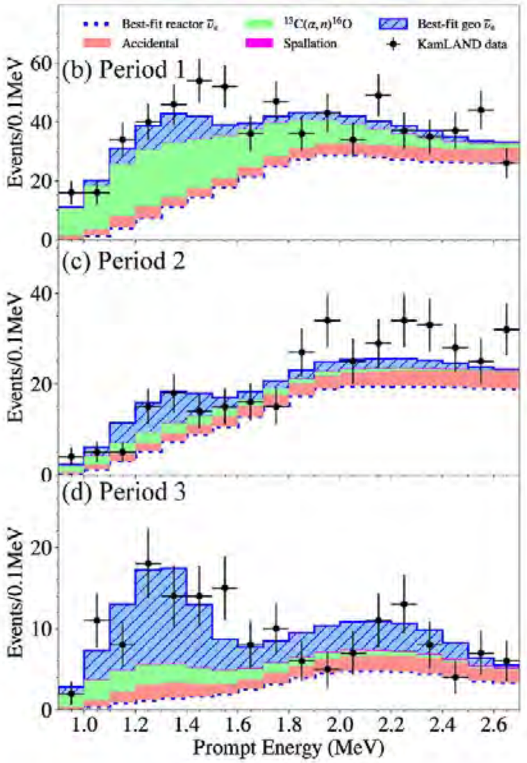


Prompt charge [photoelectrons]: 1 MeV ~500 photoelectrons

KamLAND (Geophys. Res. Lett. 49 e2022GL099566)



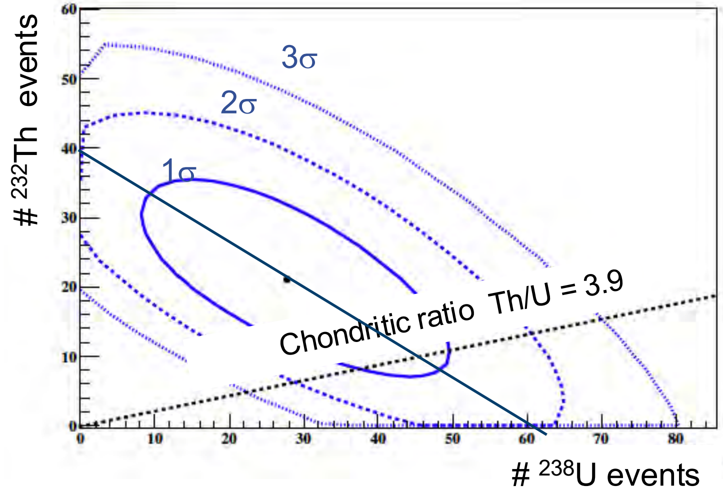




1.29 x 10^{32} proton x years (3262 days, 280 m^3 of FV)	**Exposure [proton x year]**	**6.39 x 10^{32} proton x years** (5227 days, 905 m^3)
154 in total (~90 in the geonu energy window)	**IBD candidates**	**1178** in the geoneutrino energy window
$52.6\ ^{+9.4}_{-8.6}\ (stat)\ ^{+2.7}_{-2.1}(sys)\ \ ^{+18.3}_{-17.2}\%$	**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)



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

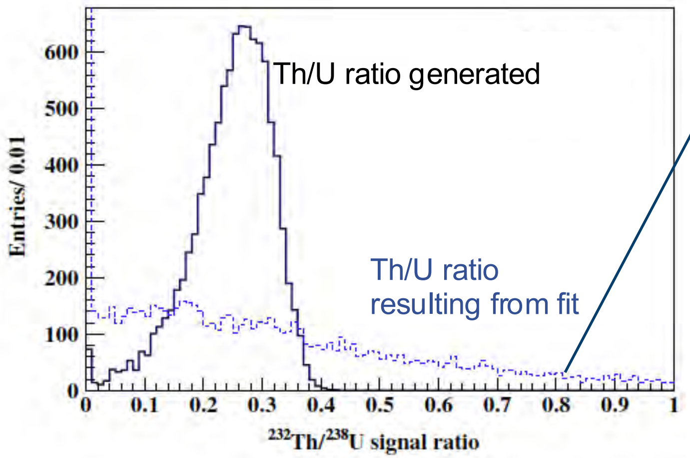
$$Th: 21.4^{+9.4}_{-9.1} \text{ events}$$

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

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

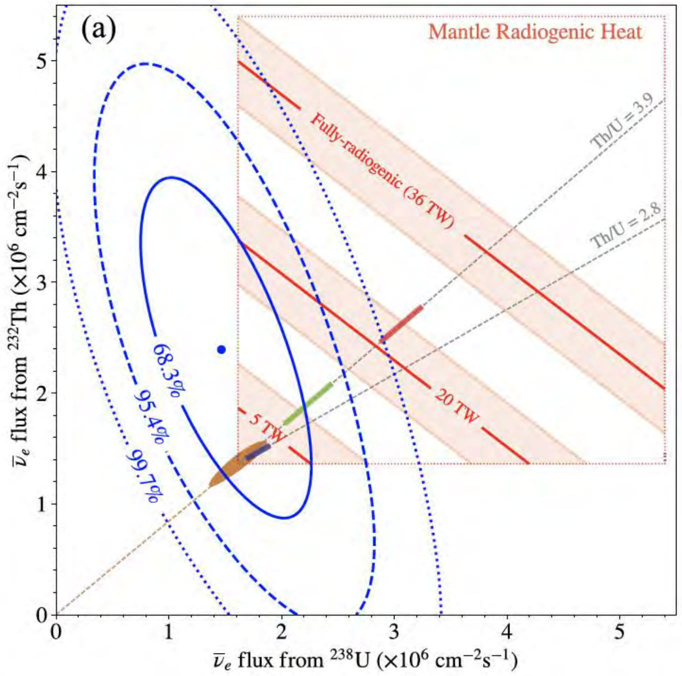
but with the achieved exposure **1.29 x 10^{32} proton x years,** Borexino has no sensitivity to measure the Th/U ratio.

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)

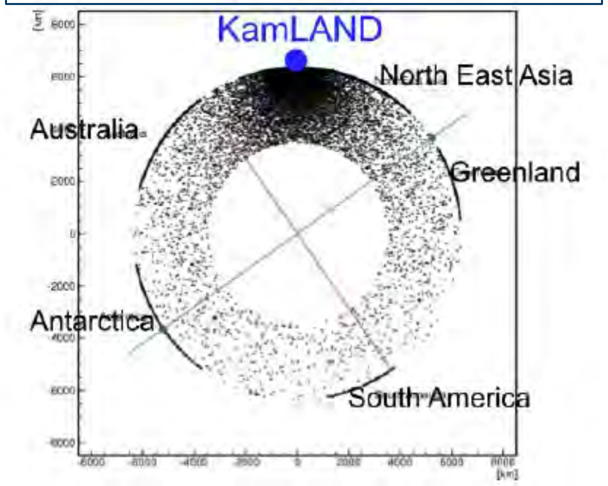


6.39 x 10^{32} proton x year

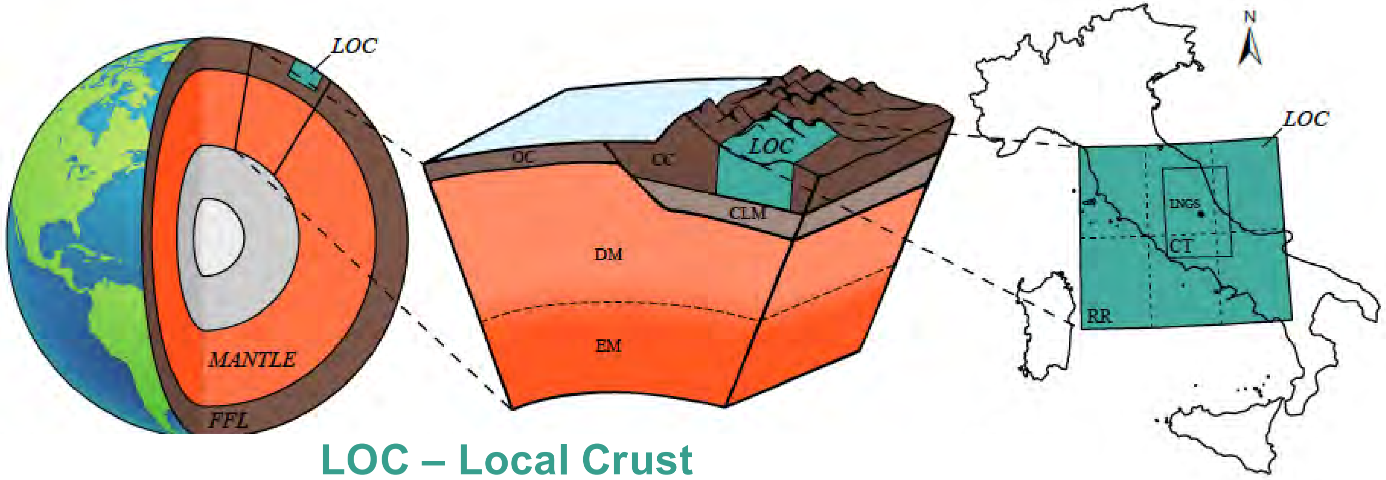
	N of event	0signal rejection
U	117^{+41}_{-39}	3.3σ
Th	58^{+25}_{-24}	2.4σ
U+Th	174^{+31}_{-29}	8.3σ

MANTLE SIGNAL: IMPORTANCE OF LOCAL GEOLOGY

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

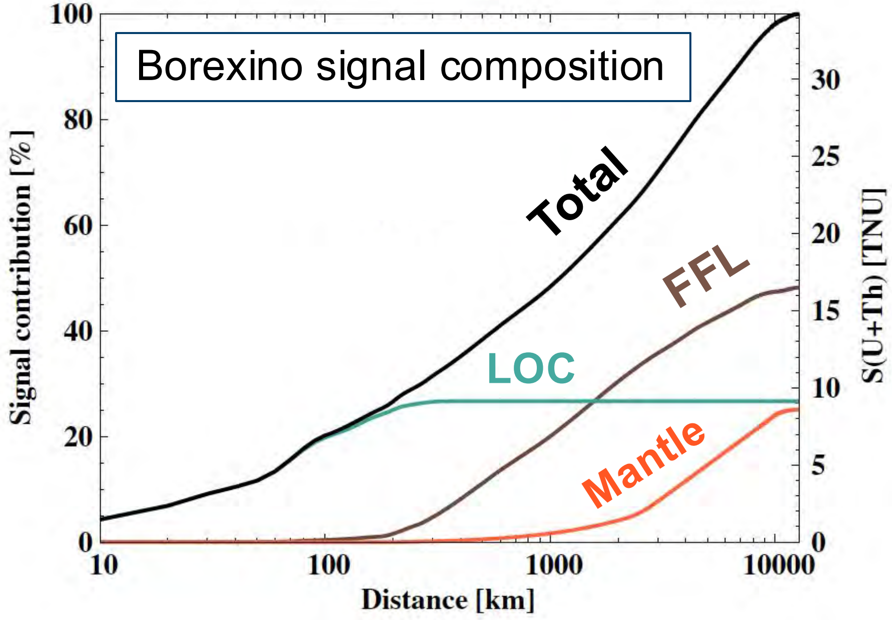


Courtesy: H. Watanabe



LOC – Local Crust
FFL – Far Field Lithosphere
Mantle

PRD101 (2020) 012009

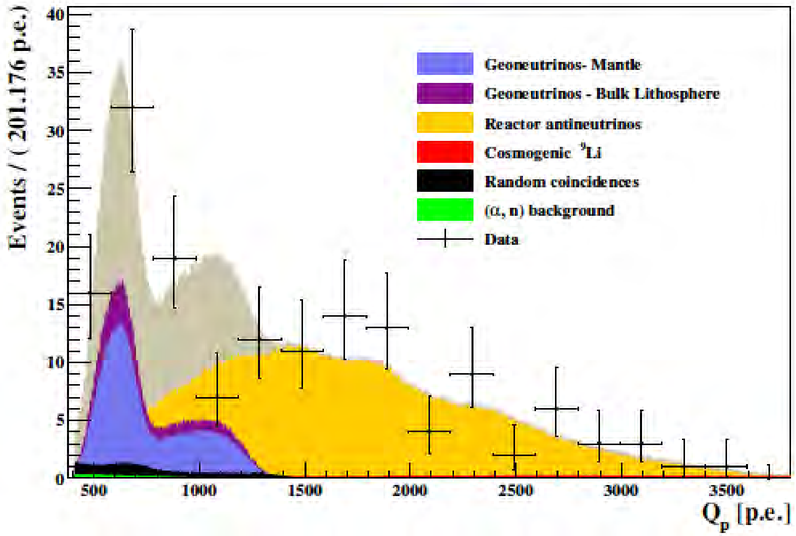


- In order to measure the **Mantle** signal, lithospheric signal must be subtracted.
- **Local Crust (LOC)** - the area of a few hundreds km around the experiment contributes up to 40-50% of the total geoneutrino signal and must be known rather precisely.
- **Far Field Lithosphere (FFL)** – complementary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

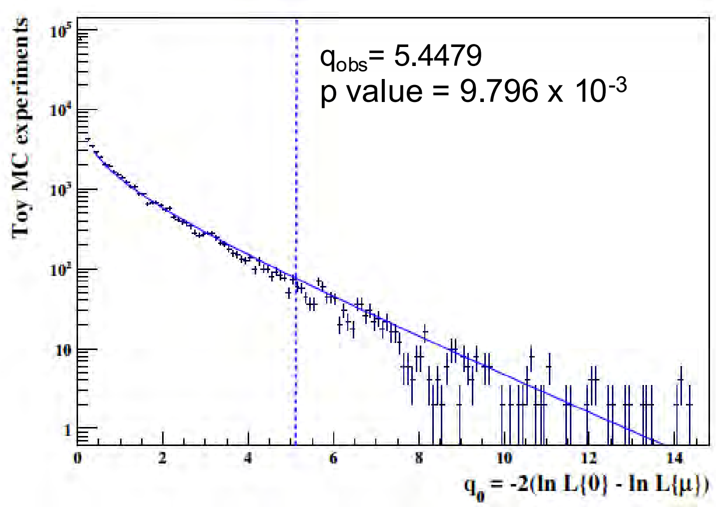
BOREXINO: MANTLE SIGNAL & RADIOGENIC HEAT

PRD101 (2020) 012009

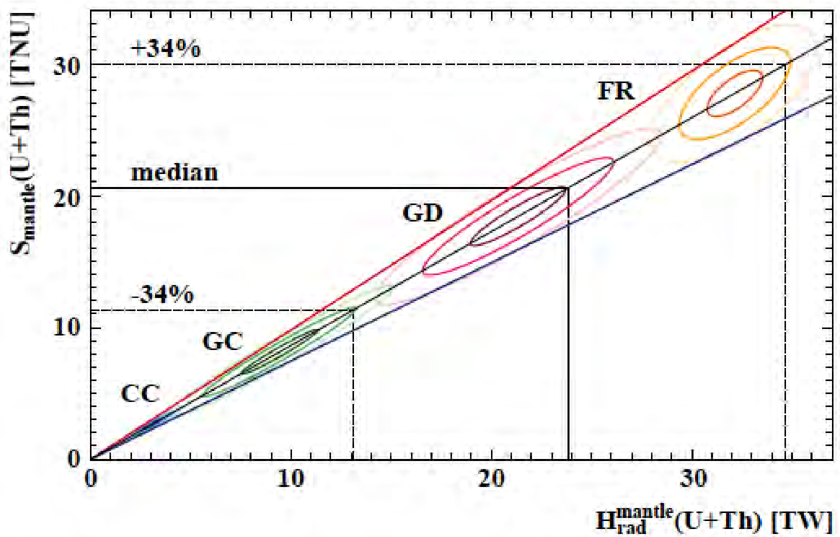
Lithospheric signal: (28.8 ± 5.6) events with S(Th)/S(U) = 0.29
Mantle: S(Th)/S(U) = 0.26
Maintaining for the bulk Earth chondritic Th/U



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.

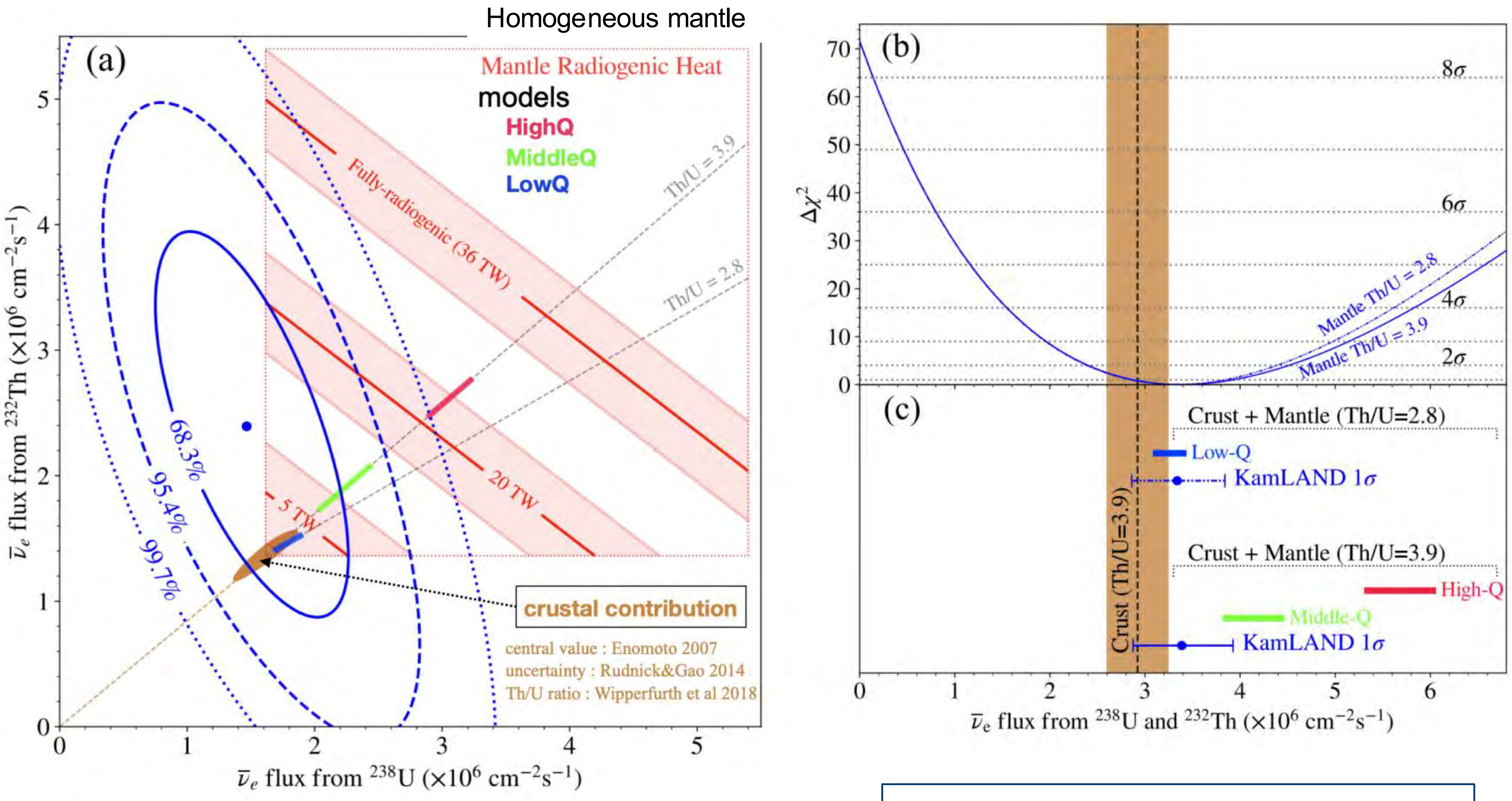
Mantle events	$23.7^{+10.7}_{-10.1}$
Mantle signal U + Th [TNU]	$21.2^{+9.6}_{-9.1}$
Mantle heat U + Th [TW]	$24.6^{+11.1}_{-10.4}$
Earth U + Th + K [TW]	$38.2^{+13.6}_{-12.7}$

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



HighQ model is rejected at

99.76 % C.L. (homogeneous mantle)

97.9% C.L. (concentrated at CMB)

☑ Radiogenic Heat

Th/U free

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

Crust + mantle

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

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

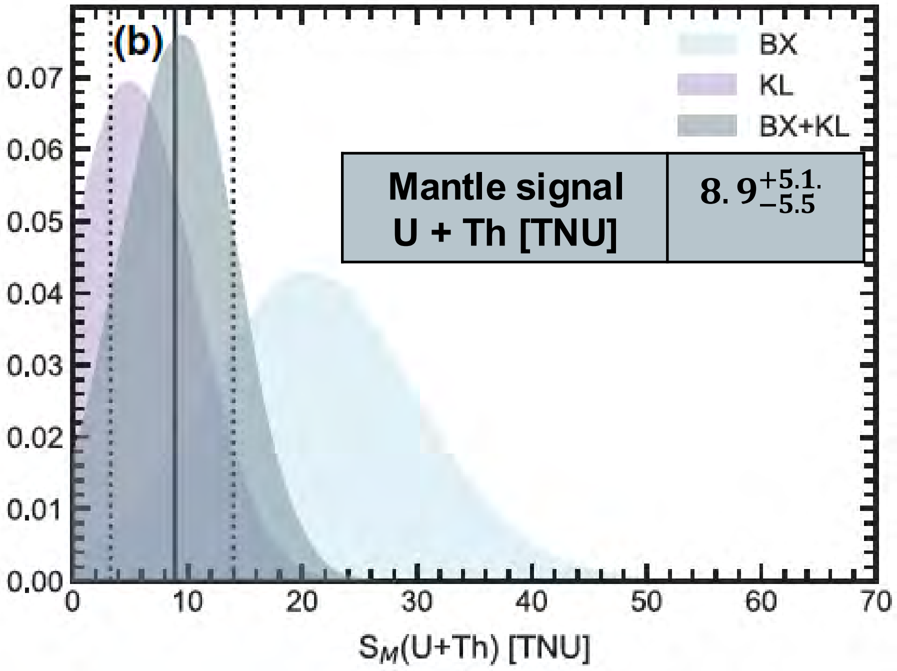
$$Q^U + Q^{Th} = 15.4^{+8.3}_{-7.9}\ \text{TW}$$

1σ lower limit
allows negative mantle signal.

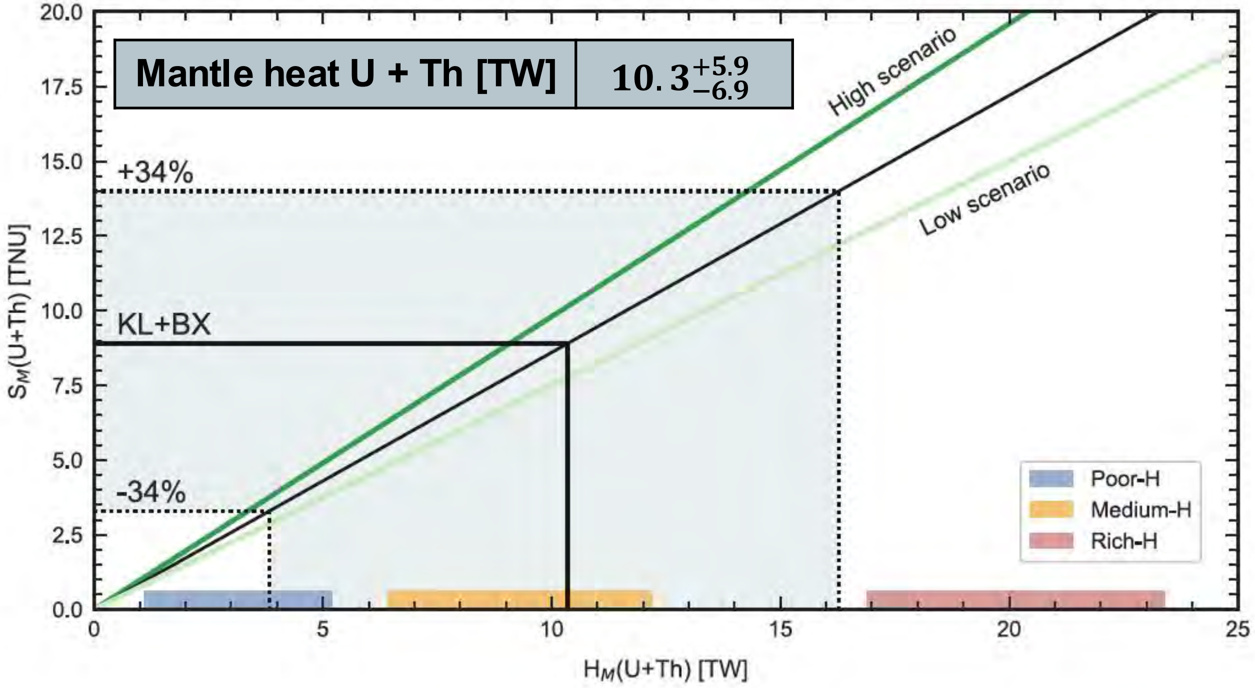
BOREXINO + KAMLAND COMBINED

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

Mantle U + Th signal

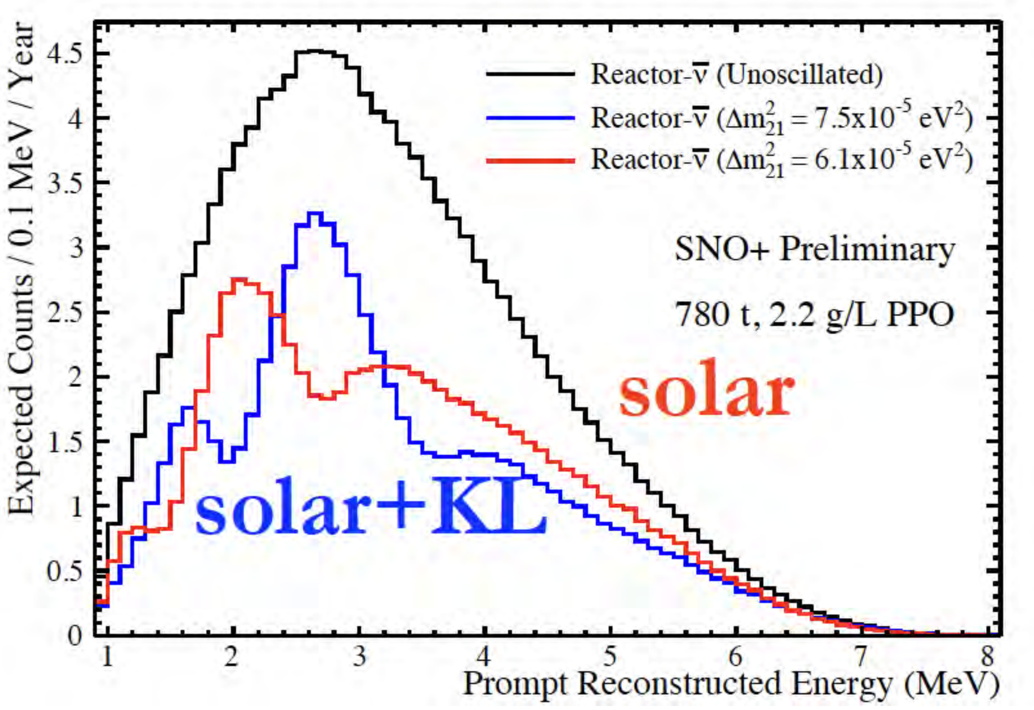


Mantle radiogenic heat vs BSE



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

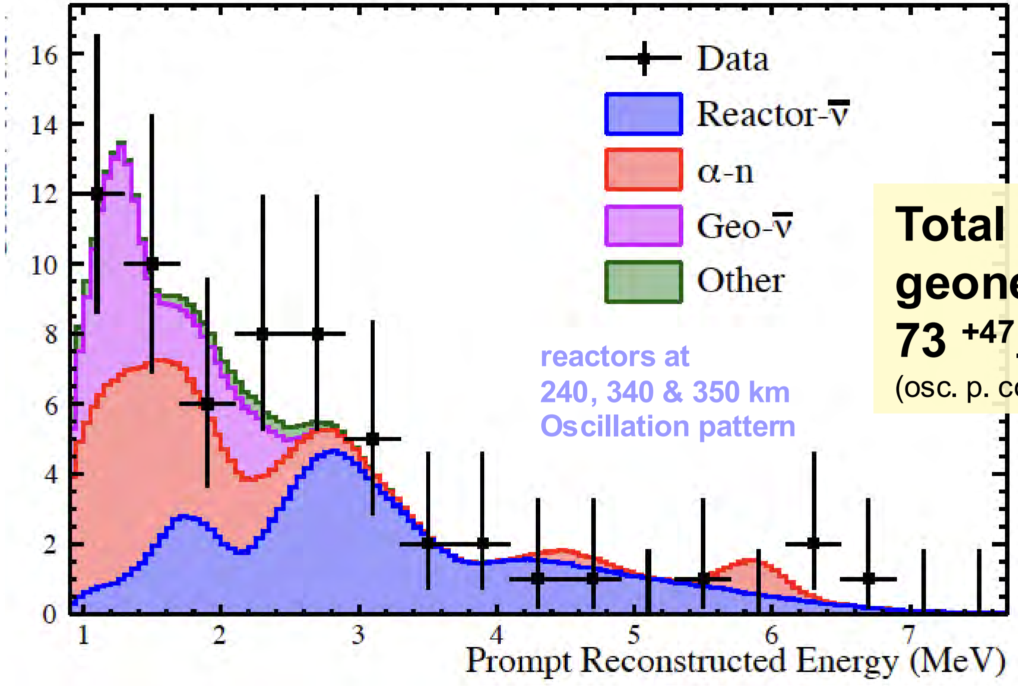
SNO+ EXPERIMENT IN CANADA – LATEST NEWS



SNO+ can measure solar oscillation parameters with reactor neutrinos.

The first data: May 7 2025 arXiv: 2505.04469v1

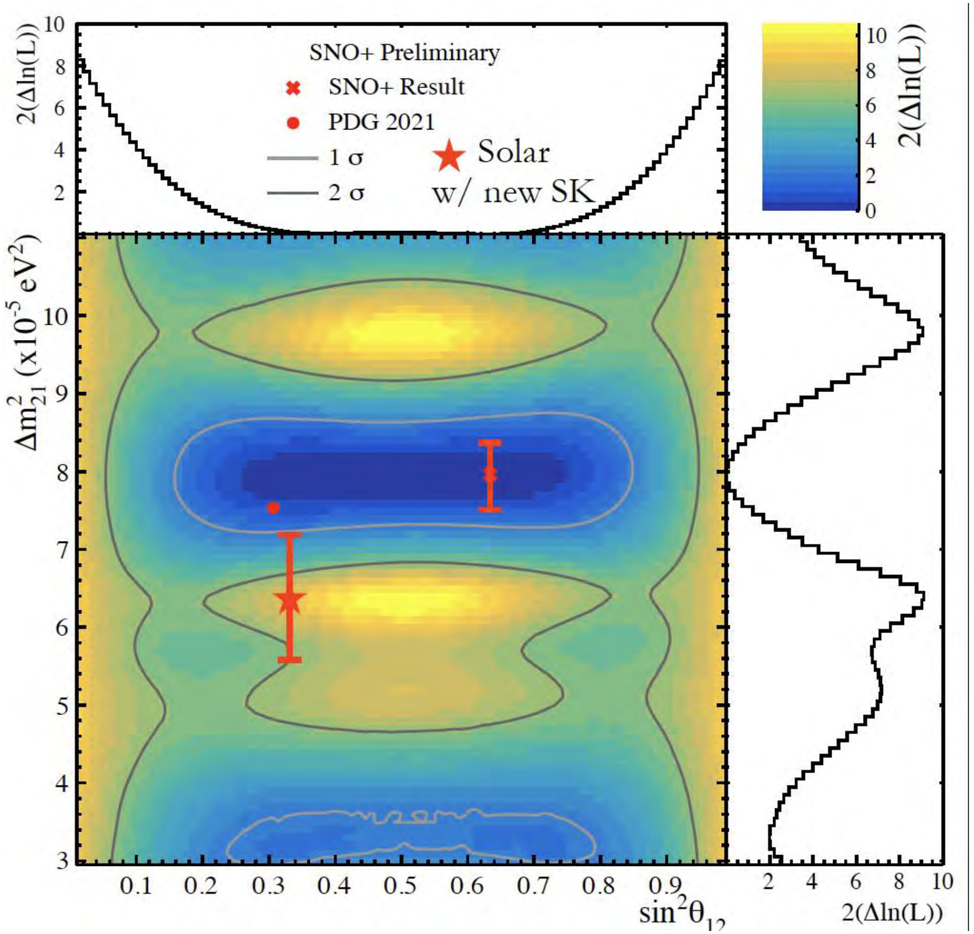
134.4 day data set (May 2022 – March 2023)



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+ 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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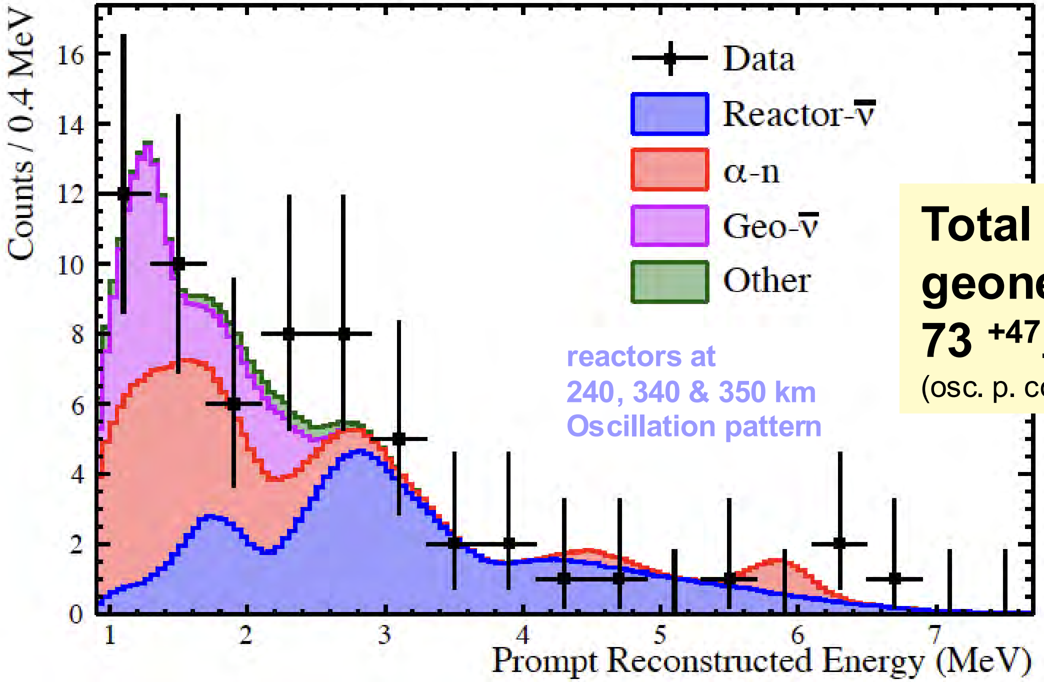

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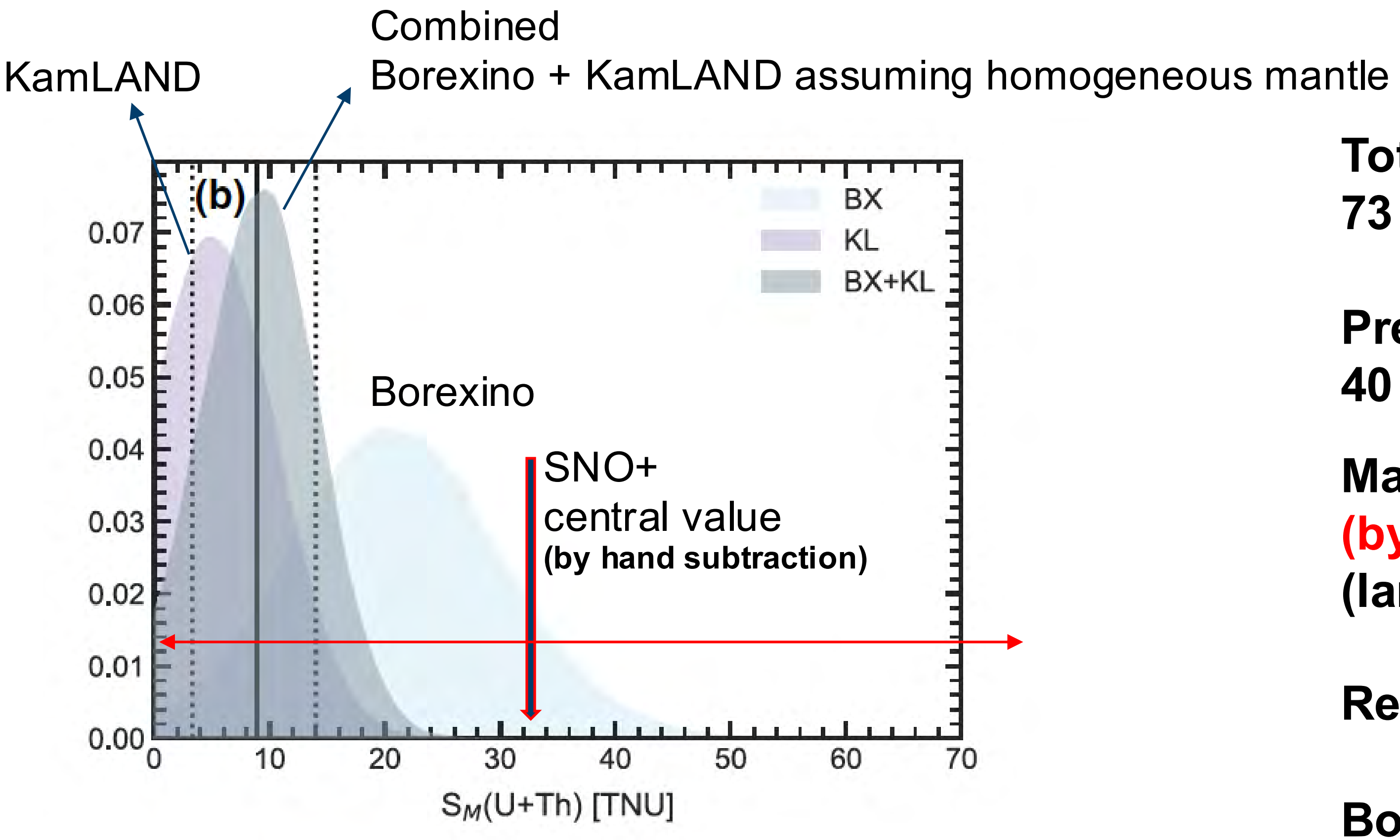
MANTLE SIGNALS COMPARISON



G. Bellini et al. 2021

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**

Intriguing question: is mantle not homogeneous?

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!