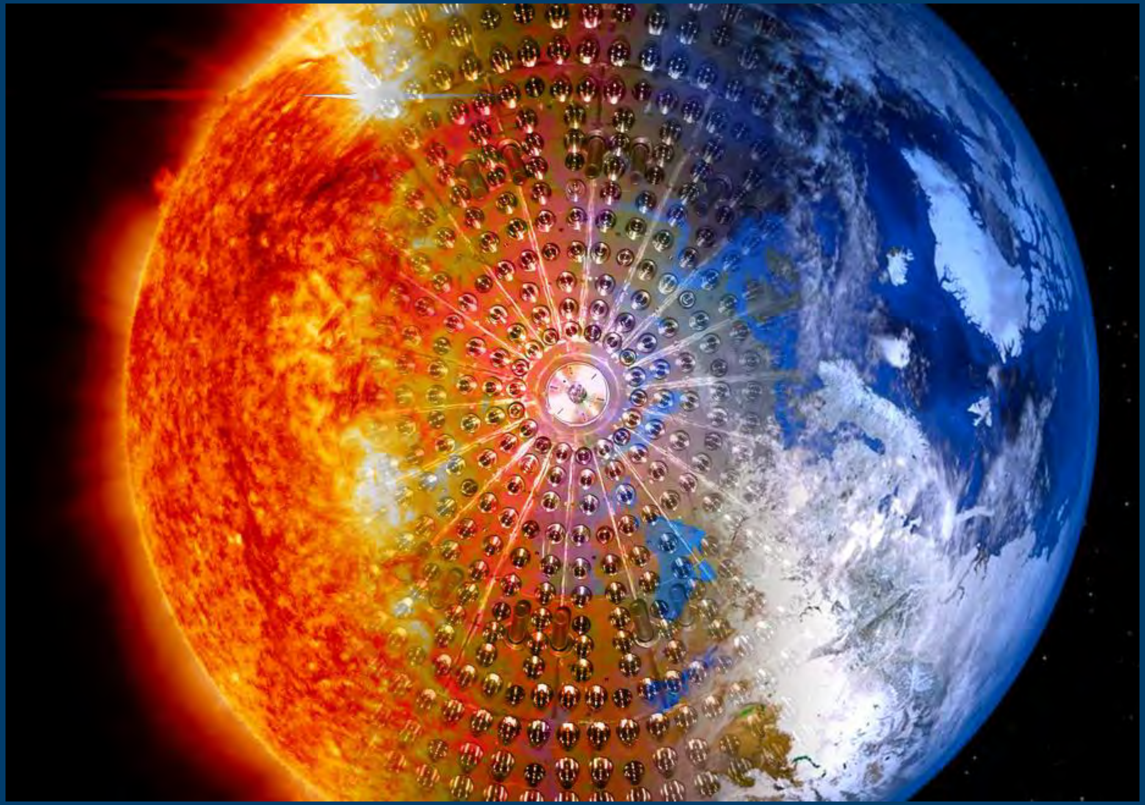
NEUTRINOS AS PROBES OF THE SUN'S CORE AND EARTH'S INTERIOR - I

LIVIA LUDHOVA

GSI DARMSTADT
& JGU MAINZ UNIVERSITY, GERMANY

JUNE 23 & 24, MAYORANA CHOOL, MODICA, SICILY



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.**

Passion for Physics: at the JUNO site.

- ✓ **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.
    - ❖ **my PhD with Randolf Pohl as a postdoc (now Prof. at JGU)!**
- ✓ **Neutrino Physics:**
  - ✓ **Borexino @** LNGS, Italy – data taking 2007 – 2021.
    - solar neutrinos and geoneutrinos.
  - ✓ **JUNO** in Jiangmen, China **- topic of today!**

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 ☺)

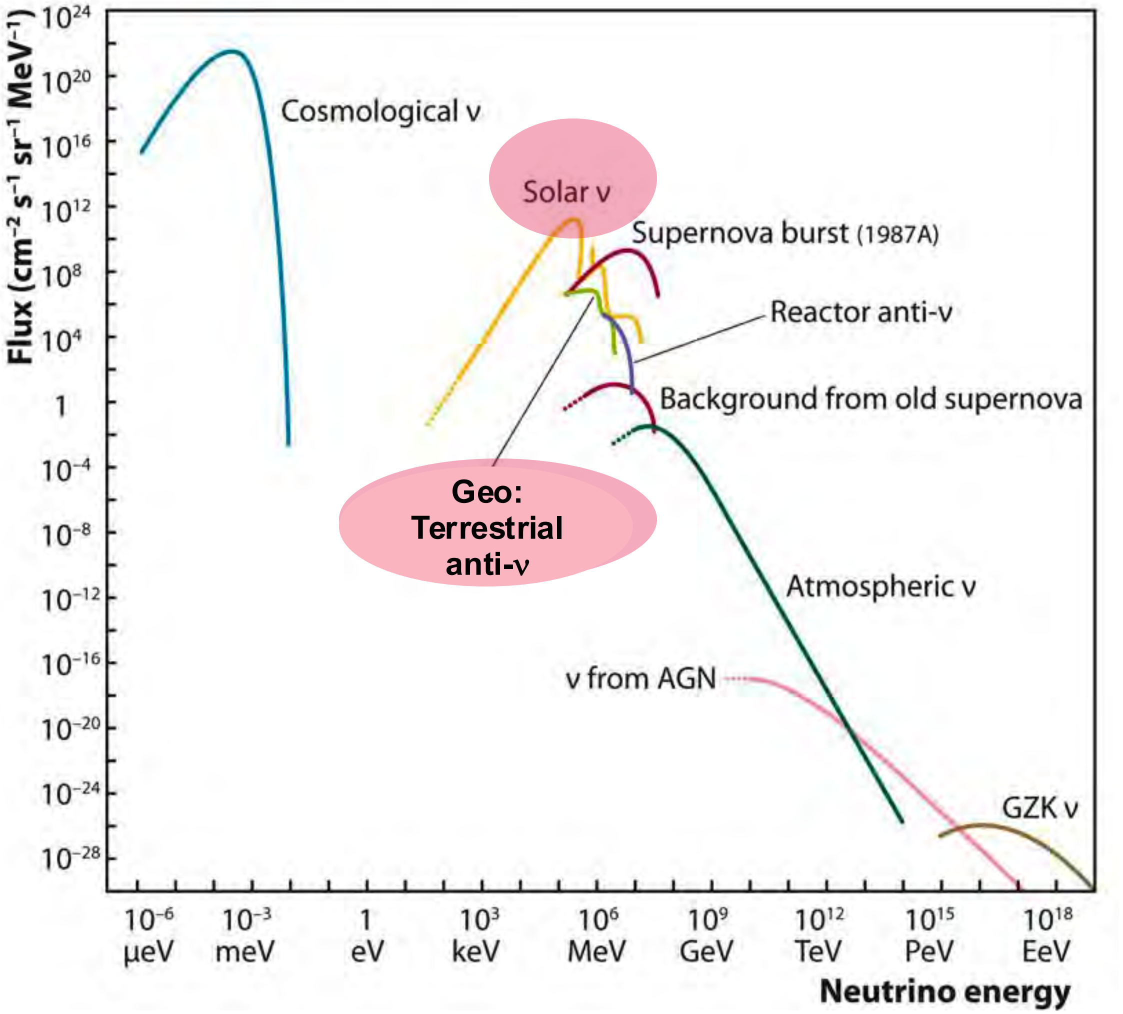
1. Introduction to neutrinos
2. Detection of MeV neutrinos
3. Solar neutrinos
4. Geoneutrinos

- Historical perspective
- Motivation of the measurements
- Overview of the results
- Personal perspective – analysis details from “my” experiments – Borexino and JUNO
- Outlook

WHAT ARE NEUTRINOS?

Basic constituents of matter:
Standard Model of Elementary Particles

NEUTRINO SOURCES



There are 3 neutrino flavours and their antiparticles, so antineutrinos of 3 flavours.

NEUTRINO INTERACTIONS

Gravitational large scales & mases

~~Strong~~

~~Electromgnetic~~

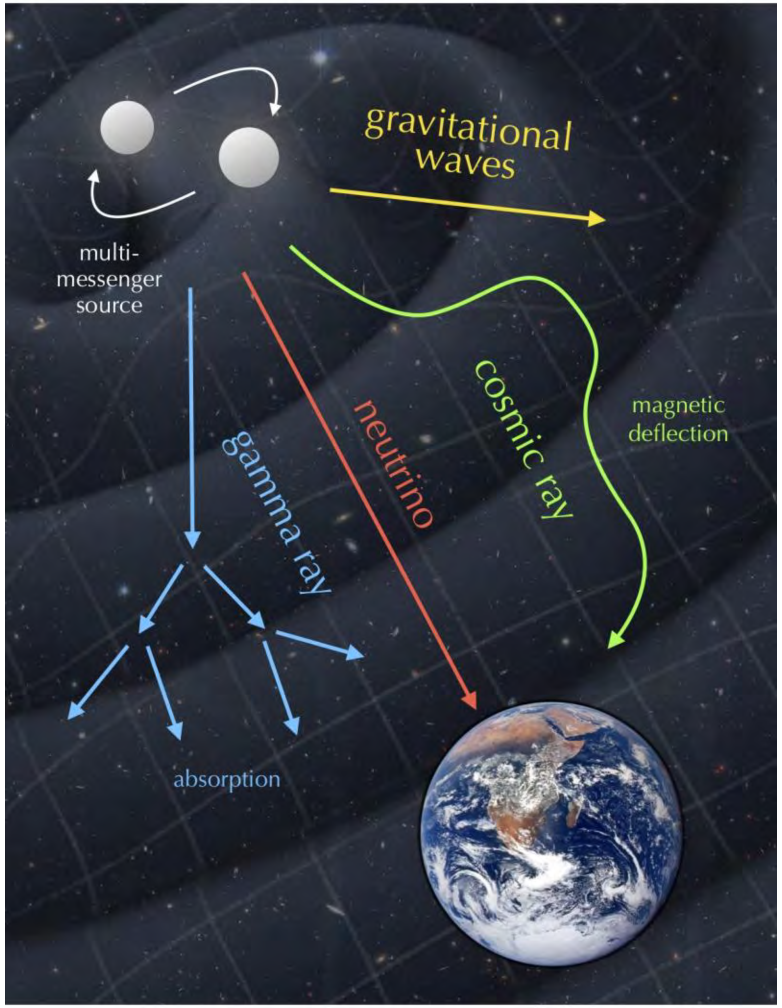
Weak VERY Weak

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

NEUTRINOS ARE SPECIAL

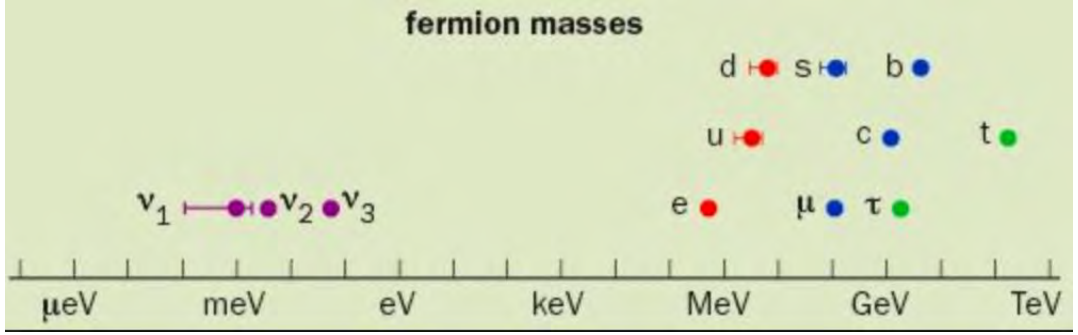
Only weak interactions

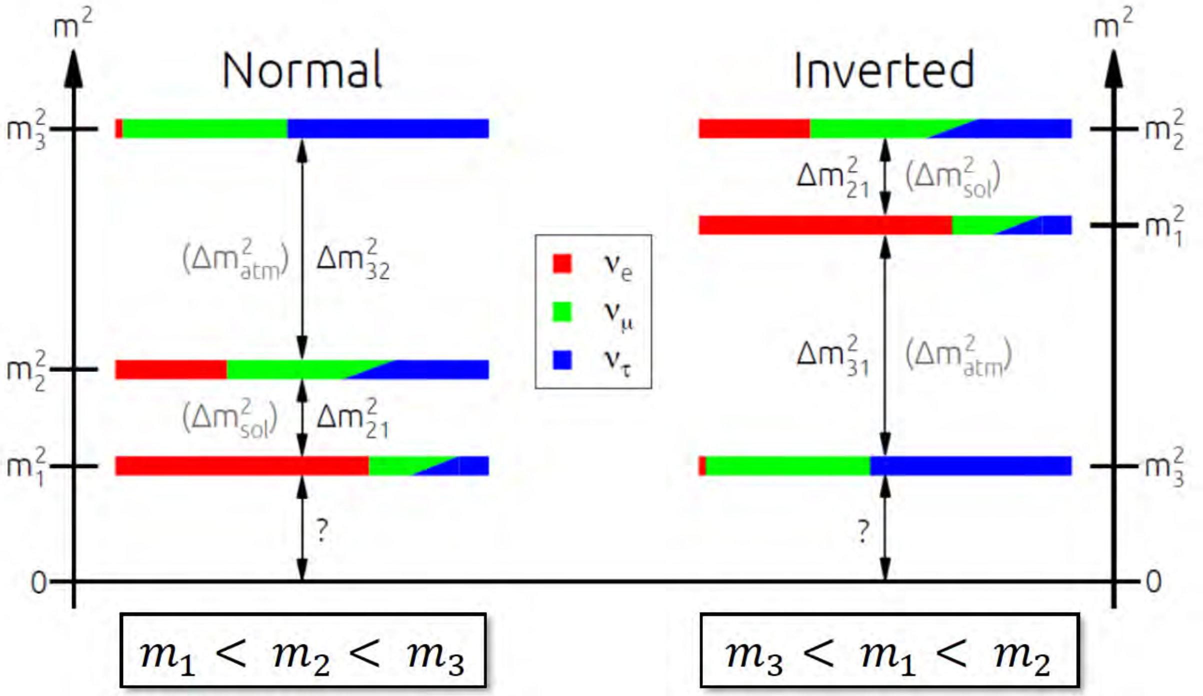
- ✓ **Difficult to detect**
  - Large detectors
  - Underground laboratories
  - Extreme radio-purity
- ✓ **Bring unperturbed information about the source (Sun, Earth,** SN)

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

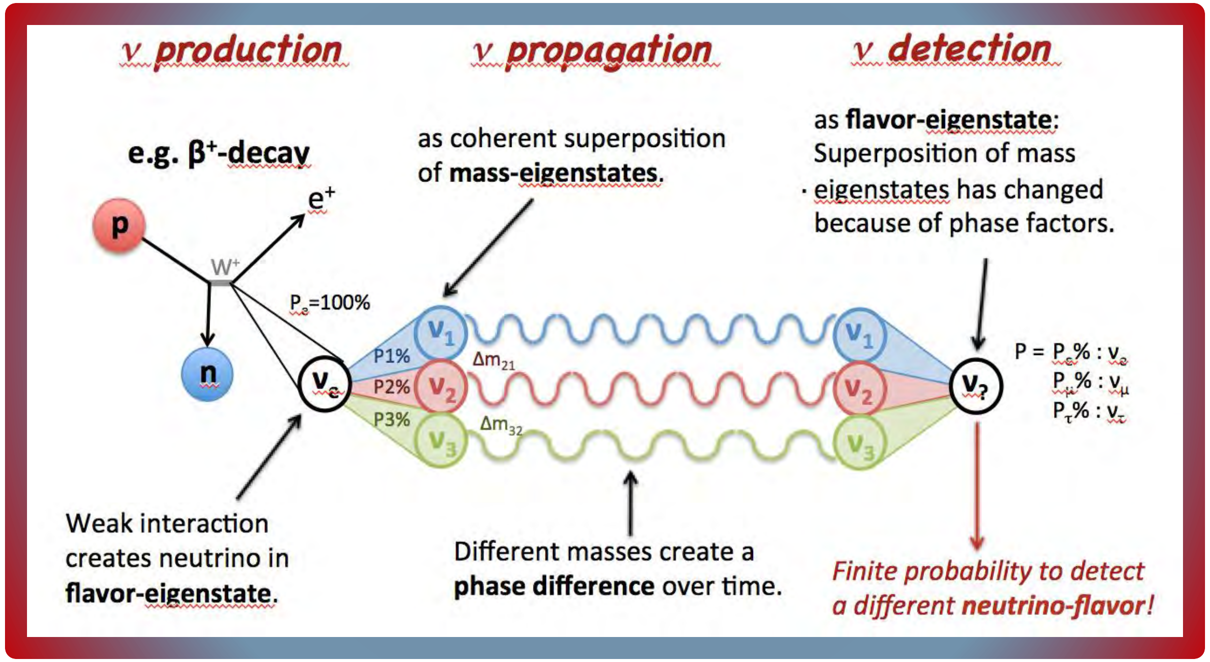
α = e, μ, τ
Flavour eigenstates
INTERACTIONS

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

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



Courtesy M. Wurm

- **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

- **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)
  - Appearance/disappearance experiments
  - **<u>Oscillations in matter</u>** -> effective (θ_{ij}, Δm_{ij}^2) parameters = f(e^- density N_e, E_ν)

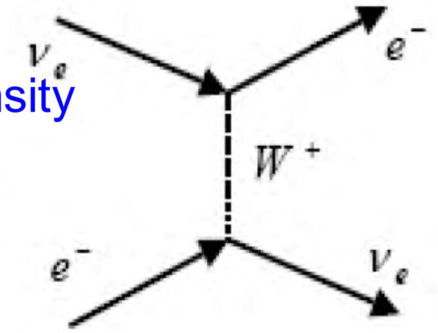
ν-oscillations in matter: MSW effect

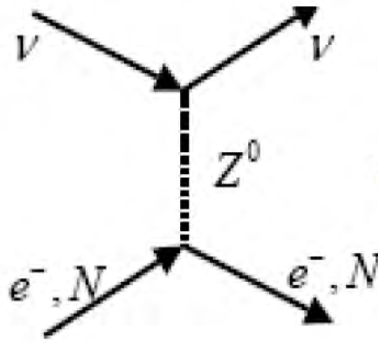
Electrons exist in standard matter –μ, τ do not. Electron neutrinos travelling in matter can experience an extra charged current interaction that other flavours cannot.

N_e = matter electron density

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

Interaction Potential





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

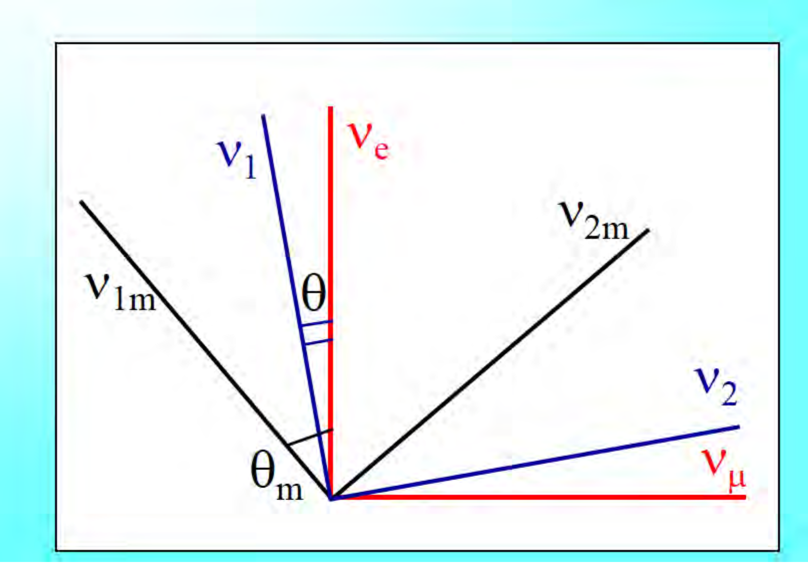
Oscillation probabilites are now function of **$(\Delta m^2_M, \sin^2 2\theta_M)$**

Effective oscillation parameters $(\Delta m^2_M, \theta_M)$ instead of the vacuum ones $(\Delta m^2_V, \theta_V)$

$$\boxed{\begin{aligned} \Delta m^2_M &= \Delta m^2_V \sqrt{\sin^2(2\theta_V) + (\cos 2\theta_V - \zeta)^2} \\ \sin^2 2\theta_M &= \frac{\sin^2 2\theta_V}{\sin^2 2\theta_V + (\cos 2\theta_V - \zeta)^2} \end{aligned}}$$

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

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

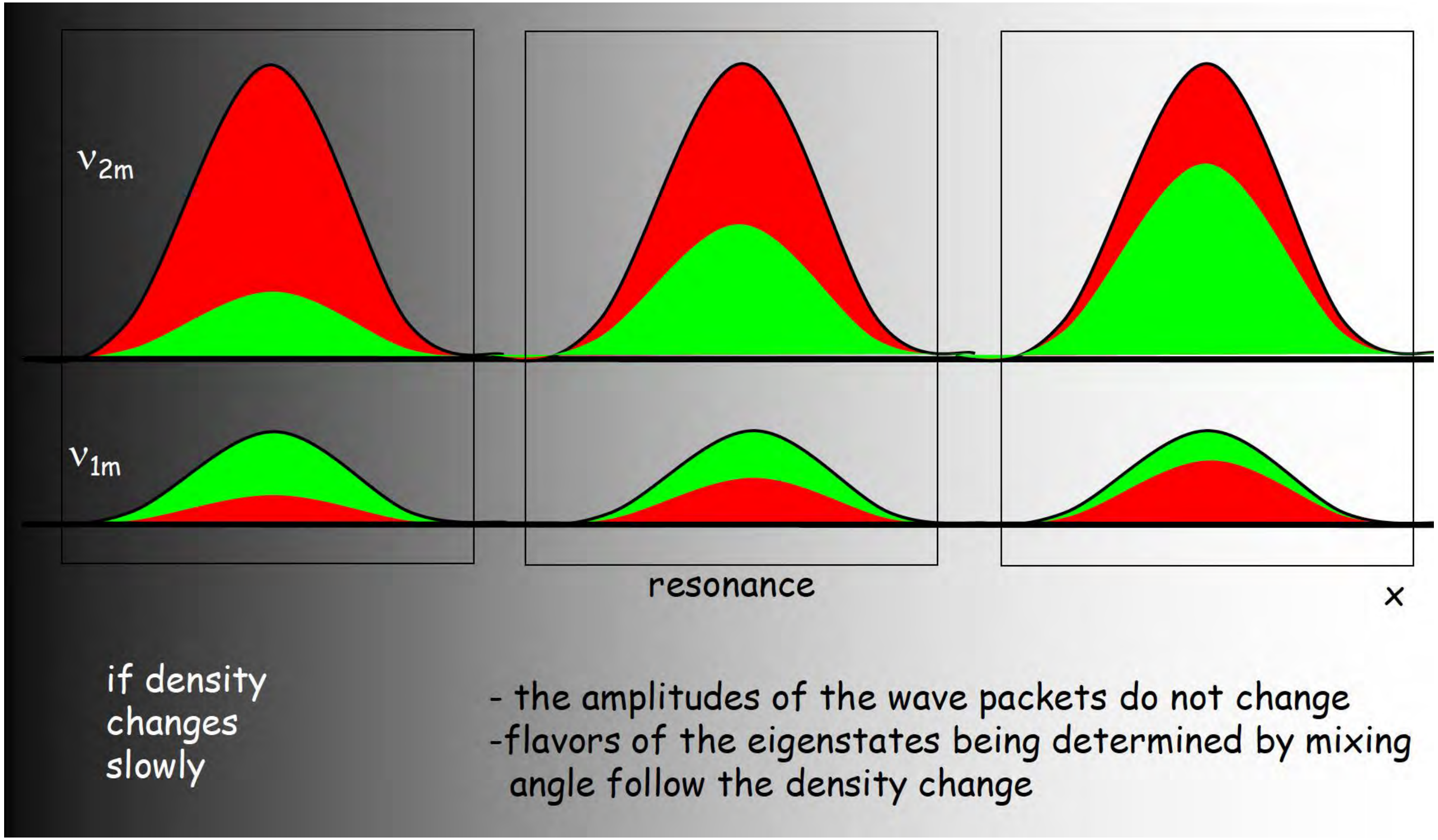
- ✓ **There is a combination of electron density N_e and neutrino energies E, for which the effective mixing angle = 1 (even if the vacuum mixing is small)**

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

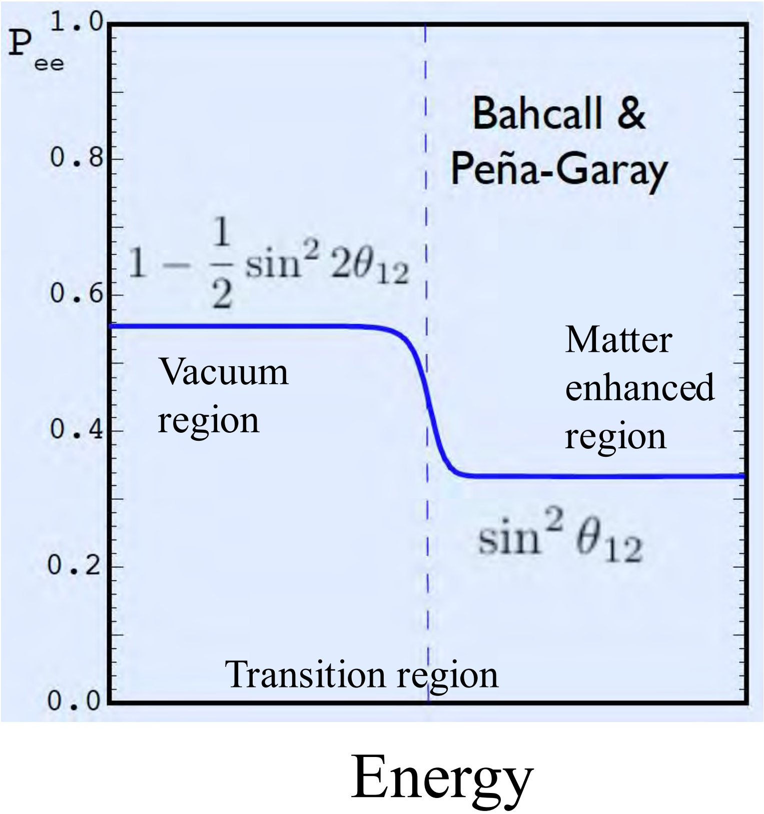
Maximal mixing

- ✓ **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%):

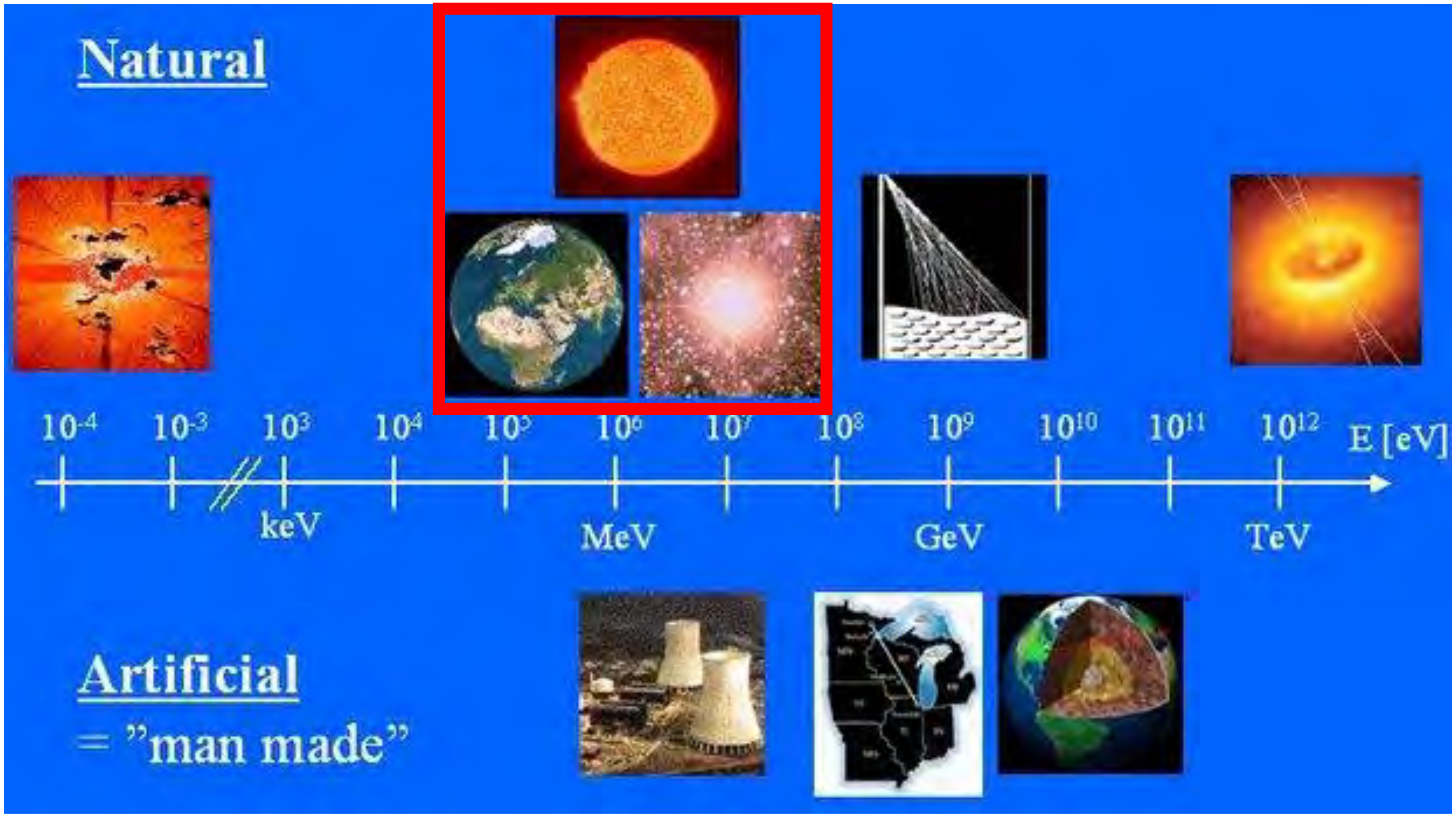
$$P_{ee} = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$\sin^2$ averages to ½.

Matter enhanced oscillation (33%):

$$|\langle \nu_e | \nu_2 \rangle|^2 = \sin^2\theta$$

NEUTRINO SOURCES

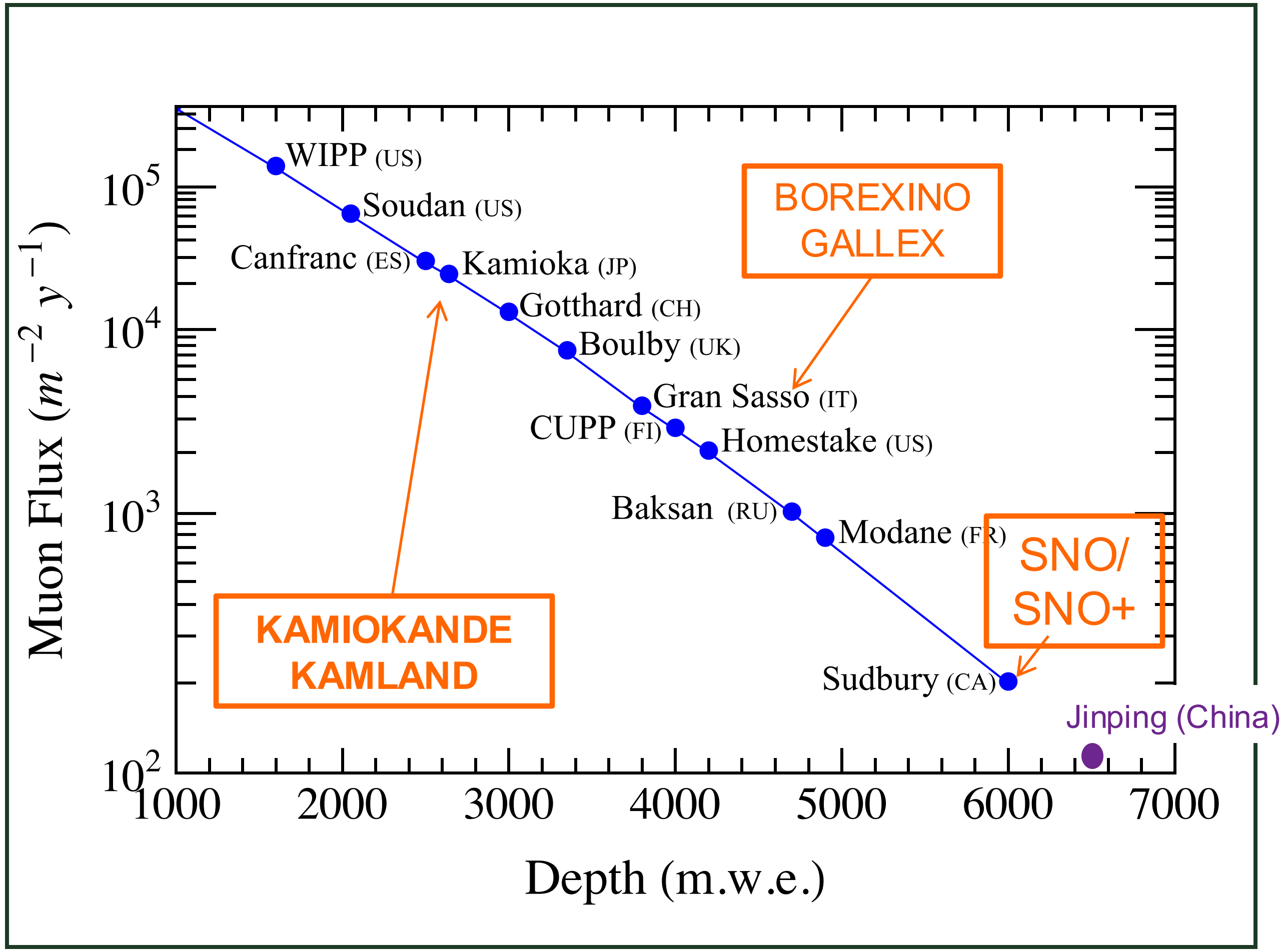


Neutrino detection is special

Cosmogenic background -> underground laboratories

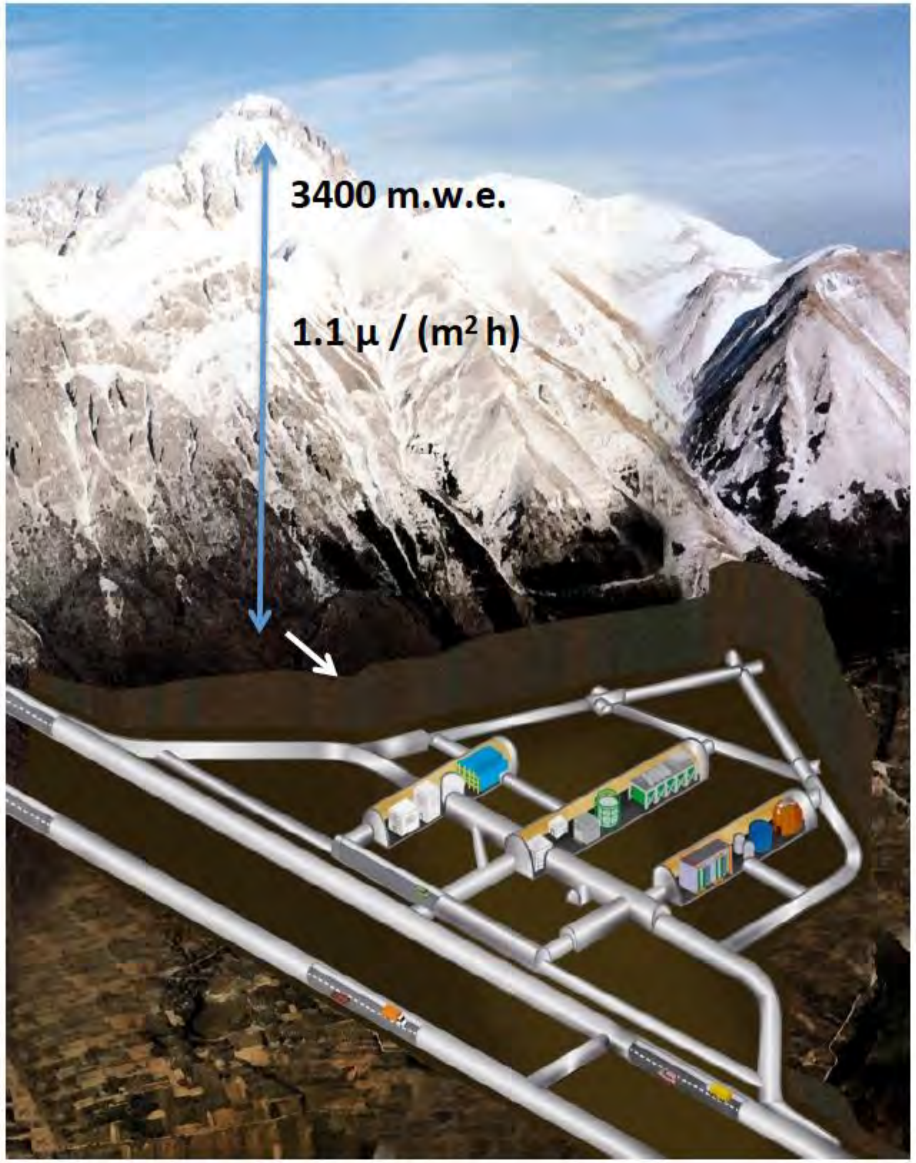
Small neutrino interaction rates → shielding against cosmic rays

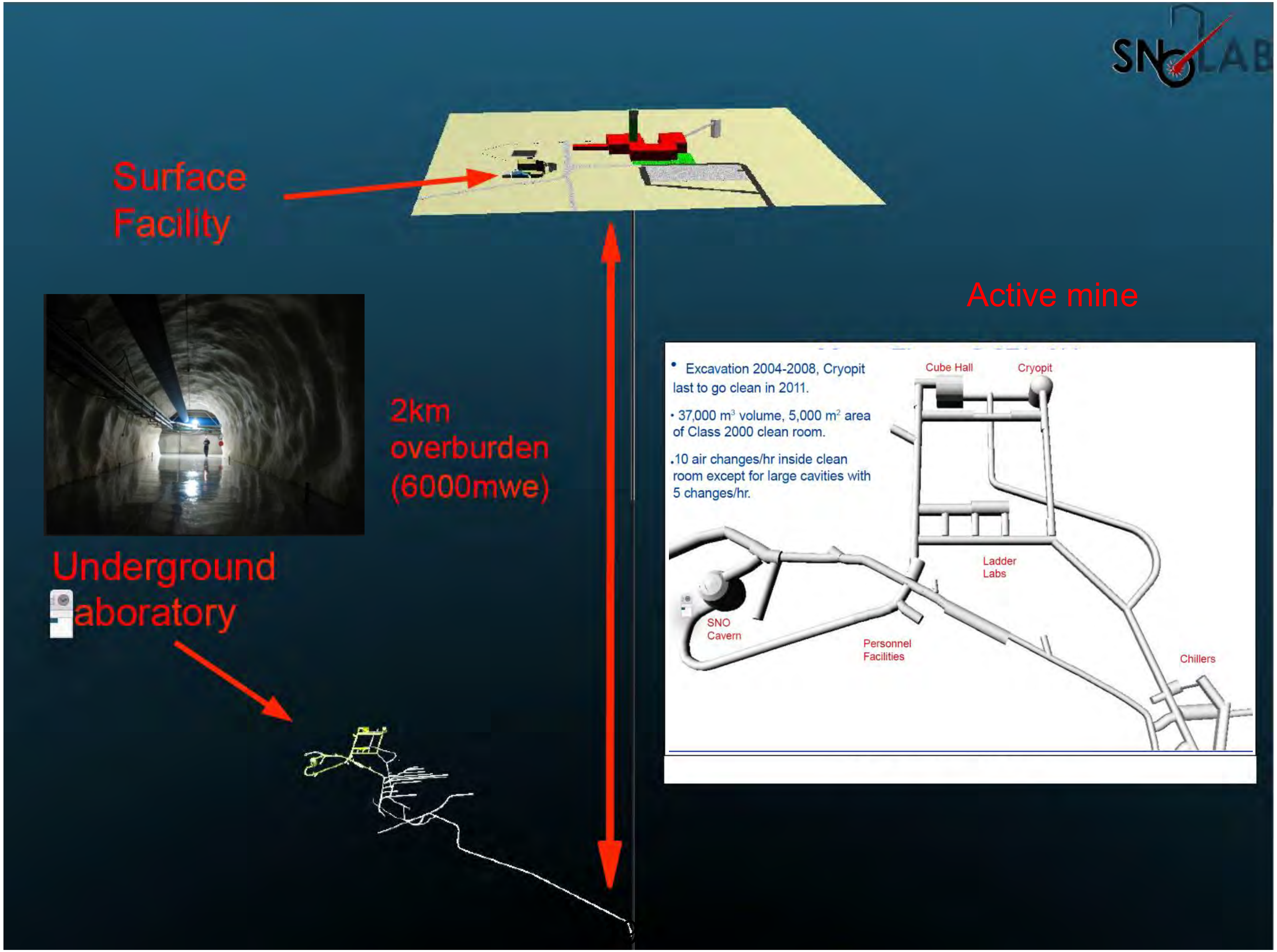
Muon flux in undeground laboratories



Laboratori Nazionali del Gran Sasso

- Muon flux: 3.0 10^{-4} $m^{-2}s^{-1}$
- Neutron flux:
  - 2.92 10^{-6} $cm^{-2}s^{-1}$ (0-1 keV)
  - 0.86 10^{-6} $cm^{-2}s^{-1}$ (> 1 keV)
- Rn in air: 20-80 Bq m^{-3}
- **Surface: 17 800 m^2**
- **Volume: 180 000 m^3**
- Ventilation: 1 vol / 3.5 hours
- **Mechanical Design and Workshop**
- **Electronics Lab & Service**
- **Chemistry Lab & Service**
- **ULB Lab & Service**
- > 900 users from 29 countries
- ~ 100 Staff
- 225 avg. daily presence in 2014
- ~ 8000 visitors/y
- Virtual tour via Street View




Surface
Facility
Active mine
2km
overburden
(6000mwe)
Underground
aboratory
• Excavation 2004-2008, Cryopit last to go clean in 2011.
• 37,000 m³ volume, 5,000 m² area of Class 2000 clean room.
• 10 air changes/hr inside clean room except for large cavities with 5 changes/hr.
Cube Hall
Cryopit
Ladder Labs
SNO Cavern
Personnel Facilities
Chillers

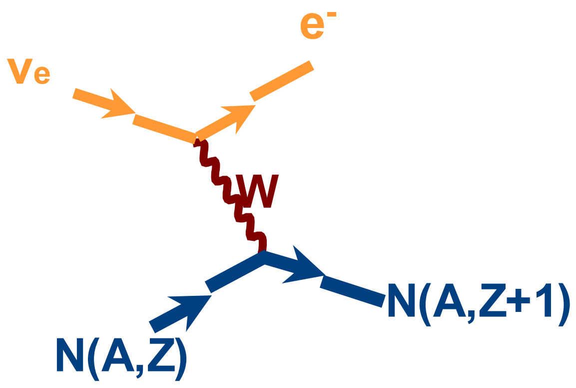
BASIC DETECTION INTERACTIONS

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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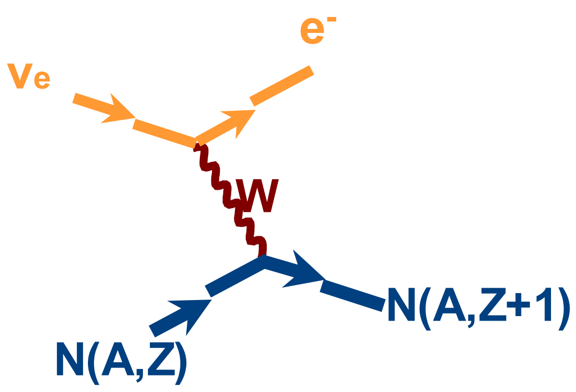
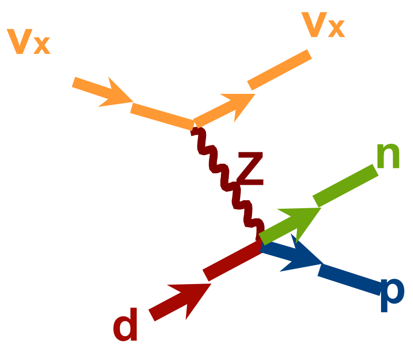


2) Neutral current (NC)

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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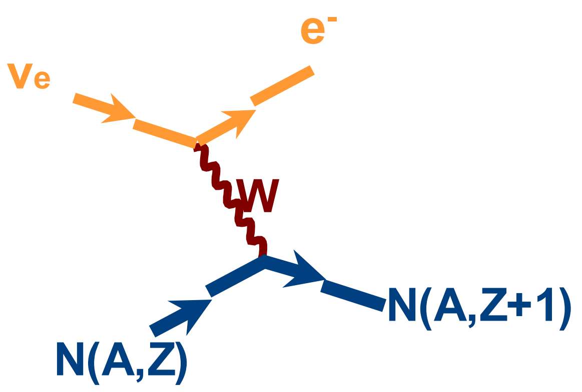

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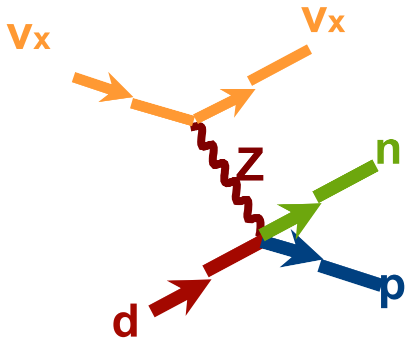
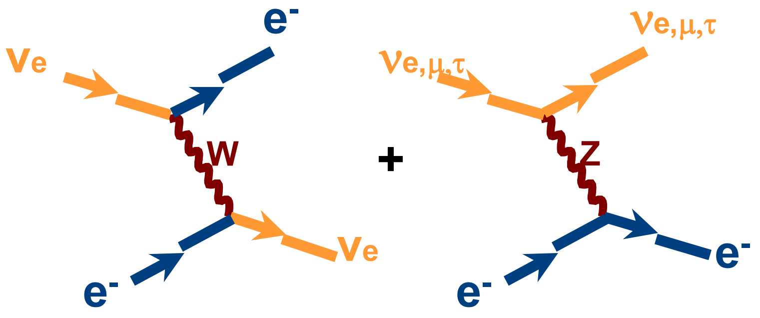


3) Elastic scattering off an electron

(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)

Water Cherenkov detection

Pavel Cherenkov

Physicist

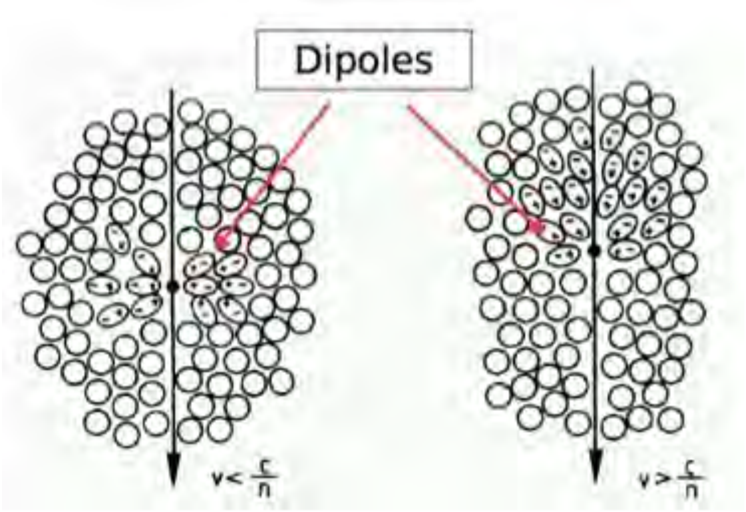
Pavel Alekseyevich Cherenkov was a Soviet physicist who shared the Nobel Prize in physics in 1958 with Ilya Frank and Igor Tamm for the discovery of Cherenkov radiation, made in 1934. Wikipedia

Born: July 28, 1904, Novaya Chigla, Russia

Died: January 6, 1990, Moscow, Russia

Cherenkov radiation

When a charged particle moves in the dielectric medium, it polarises the material



Katharina Muller (UZH)

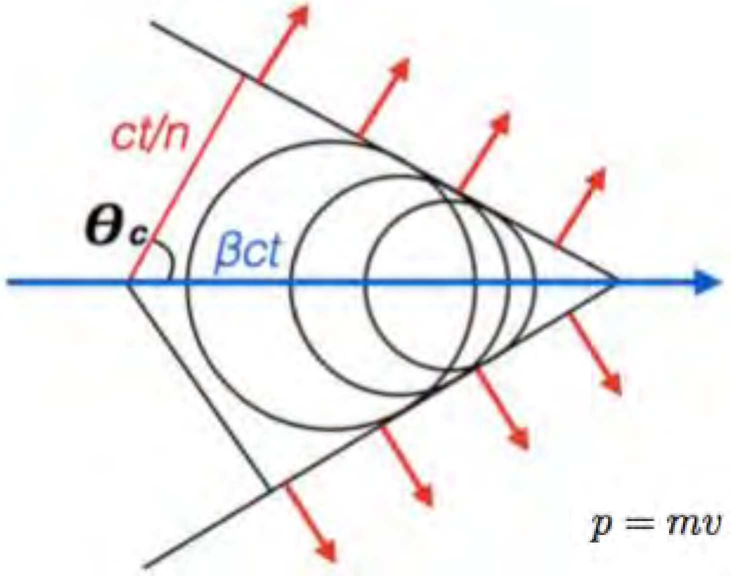
n : refraction index

time dependent dipole field → dipole radiation

v<c/n dipoles symmetric → no net radiation
v>c/n asymmetric → Cherenkov radiation

When a charged particle travels faster than the speed of the light in that medium (= c/n): de-excitation gives rise to a coherent radiation "Cherenkov radiation"

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 :

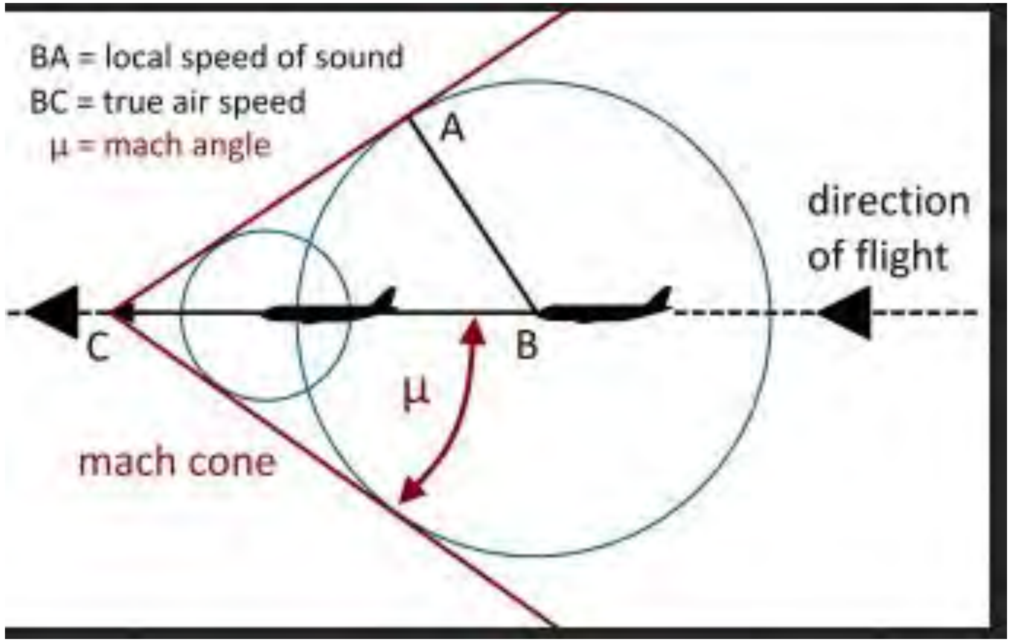
$$\frac{E_s}{m_0 c^2} = \frac{1}{\sqrt{1-\beta_s^2}} = \frac{1}{\sqrt{1-1/n^2}}$$

m_0 : particle mass

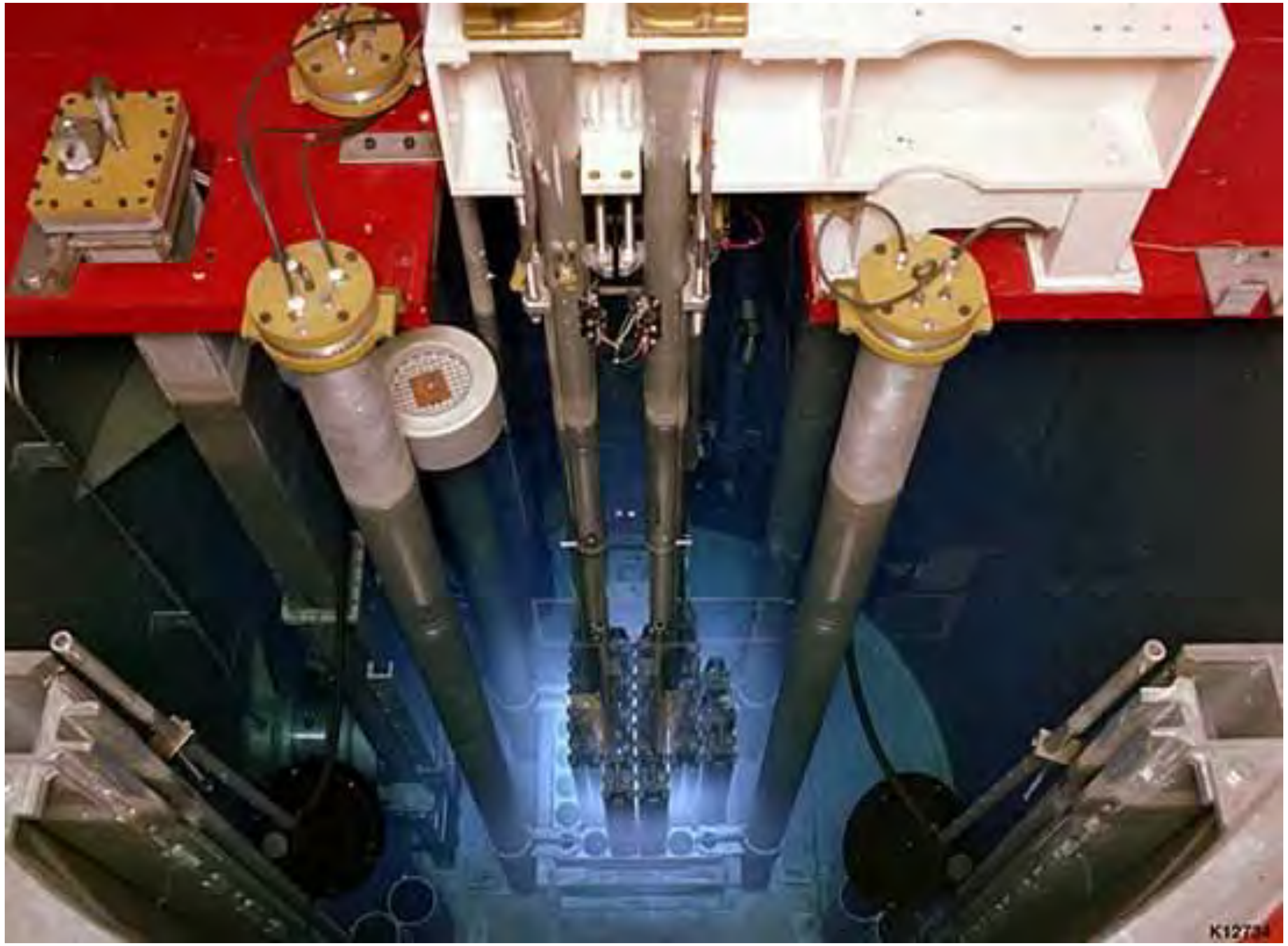
Cherenkov angle: $\cos\theta_C = \frac{c/n}{\beta c} = \frac{c}{nv}$

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

Mach cone


BA = local speed of sound
BC = true air speed
μ = mach angle
A
direction
of flight
C
B
μ
mach cone

Cherenkov light is produced in a reactor water pool, into which the core is submerged.



In water, light is travelling at 0.75 x the speed in vaccum.

Cherenkov light spectrum

The number of photons emitted by a charged particle of charge ze per unit path length $\boldsymbol{x}$ per wavelength $\boldsymbol{\lambda}$ is, travelling with velocity v:

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{c^2}{n(\lambda)^2 v^2}\right)$$

The spectrum has a $\frac{1}{\lambda^2}$ dependence.

Refractive index n depends on wavelength!

Cherenkov radiation in neutrino detection

Solar neutrinos

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

SNO (past) – Nobel Prize for solar detection!

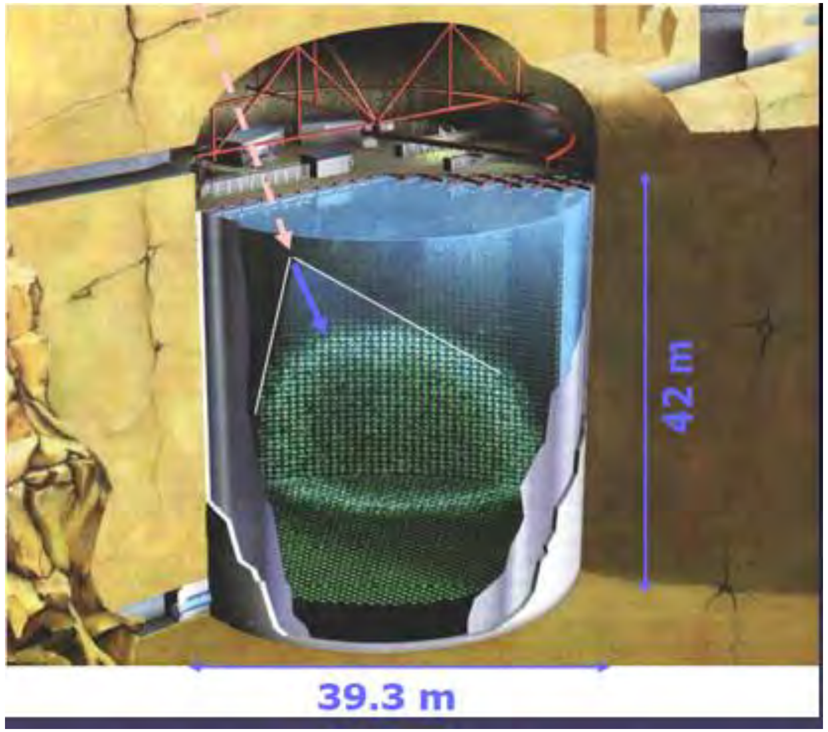
Atmospheric and accelerator neutrinos:

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

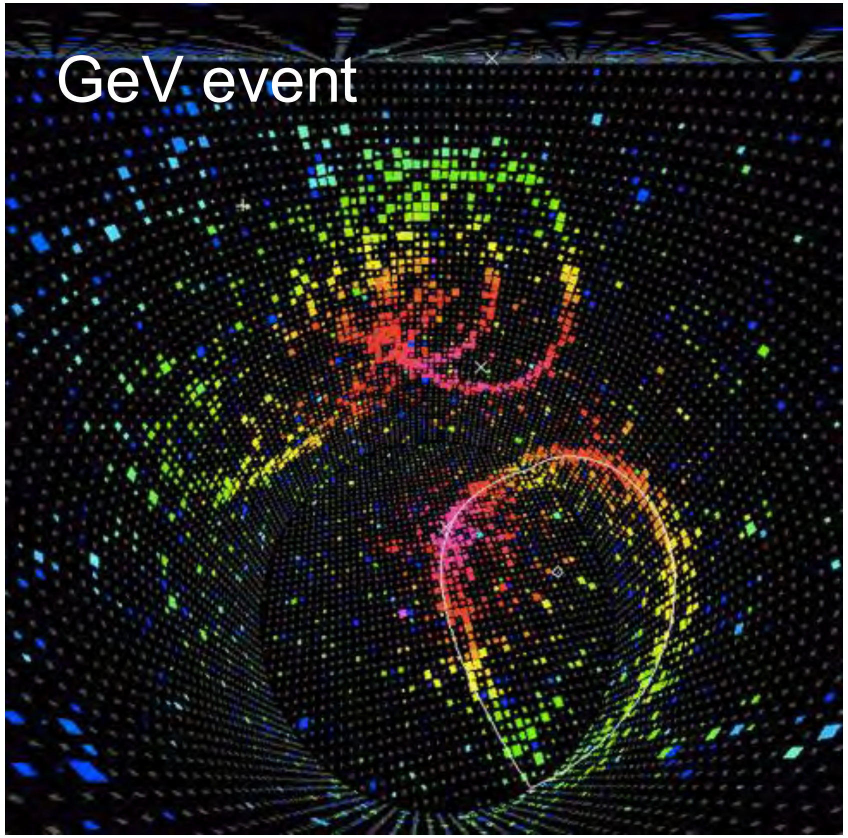


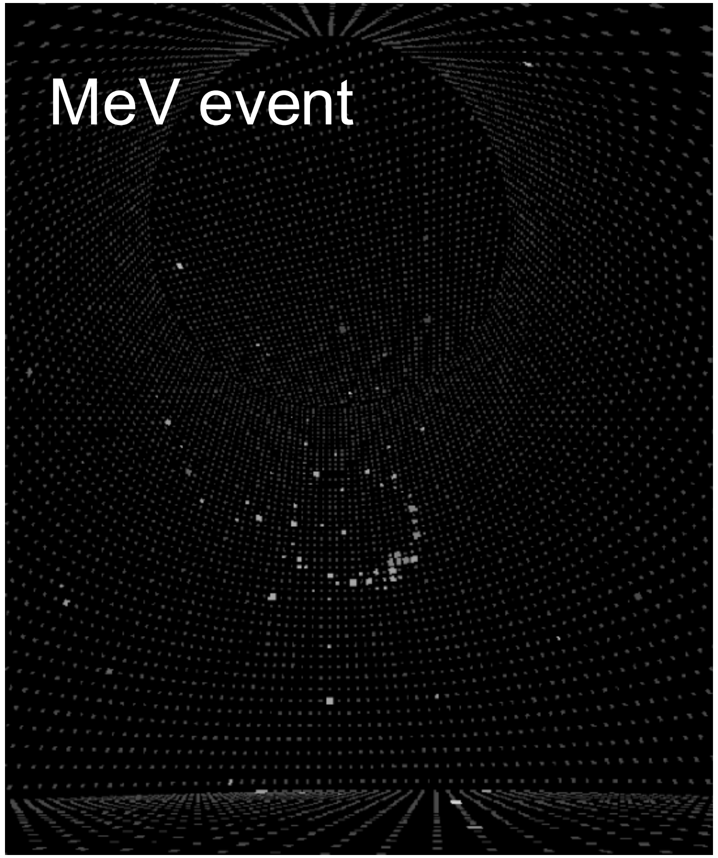
SNO
Sudbury, Canada
1 kton water

Cherenkov cone in SuperK

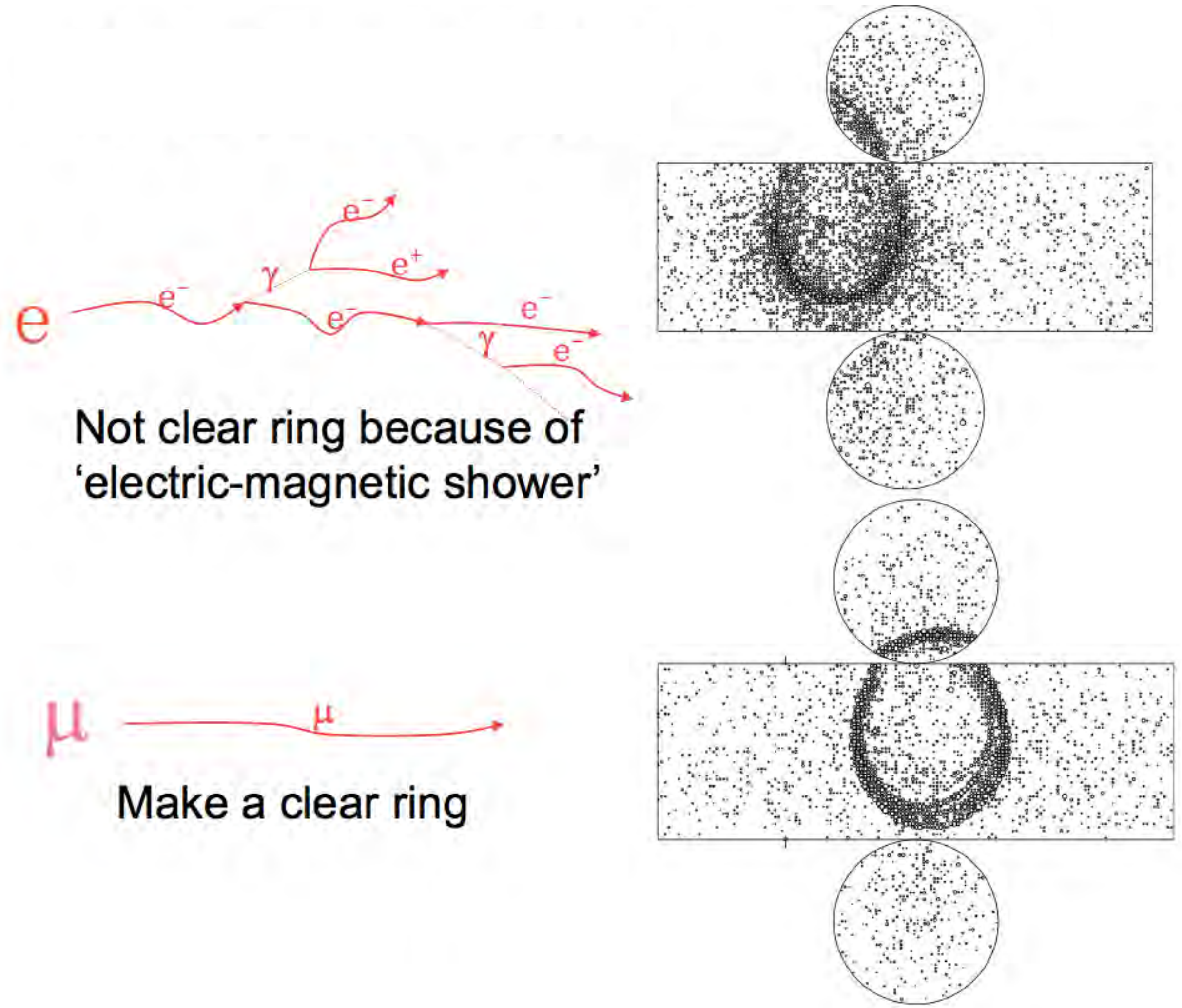
By reconstruction of timing & spacial pattern of Cherenkov ring, one can learn

→ vertex position, direction,





Particle ID (PID): rings are identified as e-like or μ-like, based on the geometry of the Cherenkov ring



Liquid-scintillator based detection

Scintillation based neutrino detection

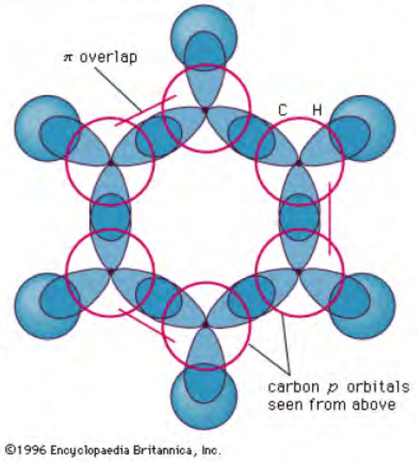
Detection of ionizing radiation through the scintillation light induced in special organic liquid materials = scintillators

Important characteristics:

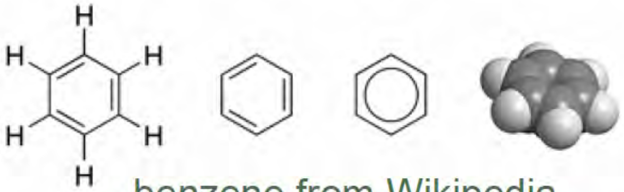
- High scintillation efficiency and high light yield.
- Good energy and position resolution.
- Low energy threshold.
- No directionality.
- Real time measurement (energy of single events).
- Quenching: non-linearities between energy deposit and produced light.
- Pulse shape discrimination (alpha/beta,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

σ-Bonds and π-Bonds

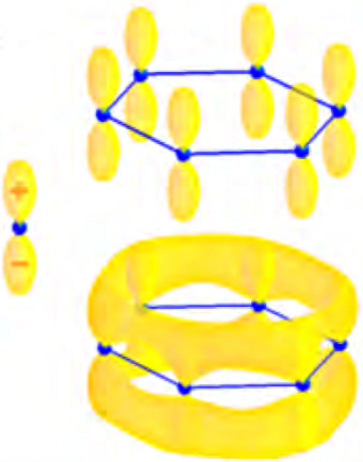
from Encyclopedia Brittanica web



- σ-bonds are in the plane, bond angle 120°, from sp^2 hybridization
- π-orbitals are out of the plane
  - in the benzene ring (and other carbon double bonds) they overlap each other
  - result is the π-electrons are completely delocalized

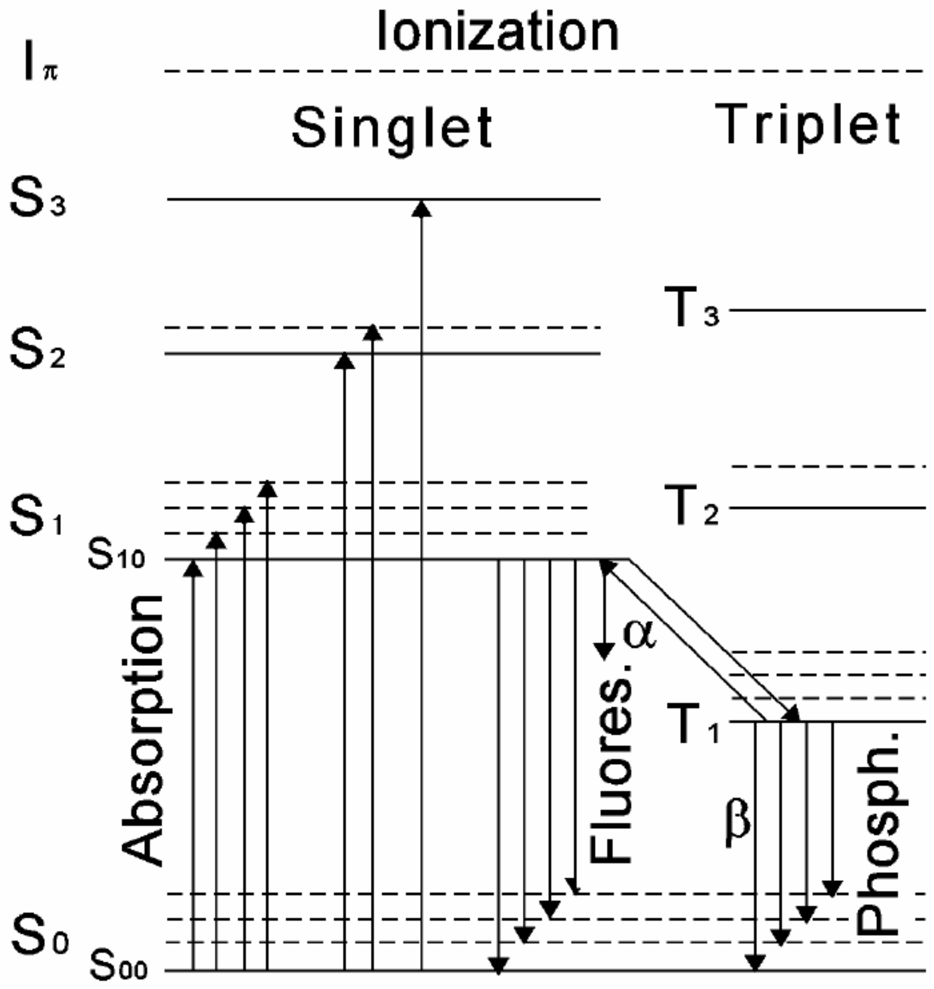


benzene from Wikipedia



from http://www.monos.leidenuniv.nl/smo/index.html?basics/photophysics.htm

Molecular states in aromatic hydrocarbons: π bonds



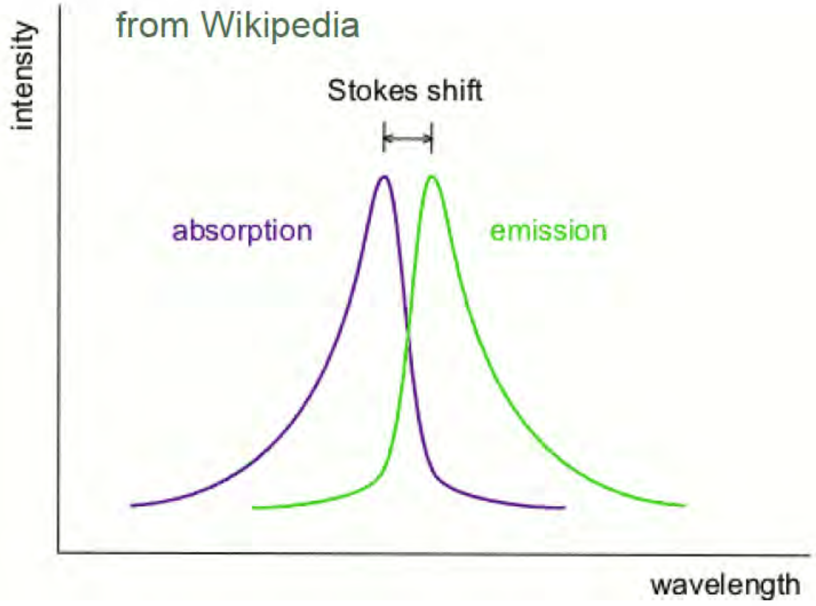
Absorption higher frequencies and smaller wavelengths than emission.

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

Stokes shift

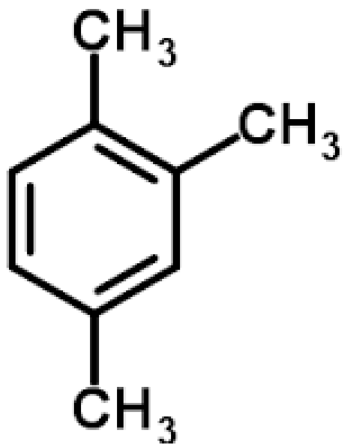
an important, general concept to keep in mind for all scintillators

- emitted photons are at longer wavelengths (smaller energies) than the energy gap of the excitation
- the processes that produce this “Stokes shift” are different in different scintillating materials
- this allows the scintillation light to propagate through the material
  - emitted photons can’t be self-absorbed by exciting the material again

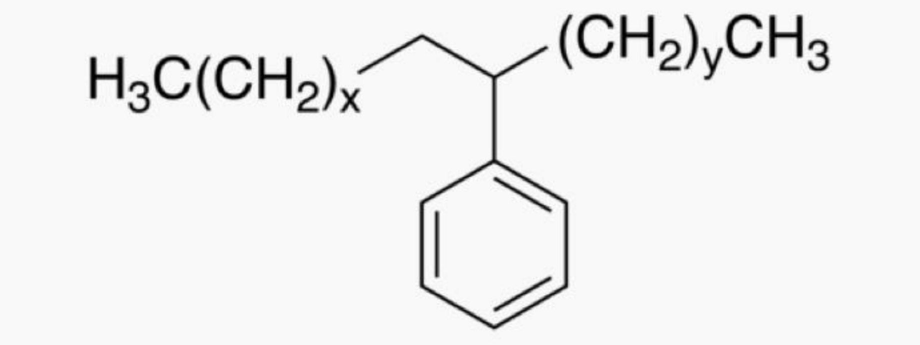


Scintillator cocktails - SOLVENTS

Pseudocumene (PC) as a solvent
1,2,4-trimethylbenzene



LAB
linear-alkylbenzene

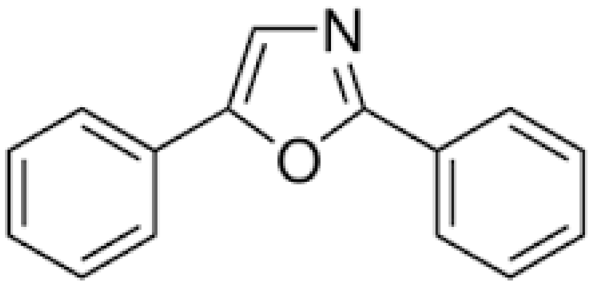


LAB is used in new detectors (SNO+, JUNO), as compared to pseudocumene, it is:

- Non toxic and safer (high flash point).
- Cheaper – we need always larger detectors.
- Compatible with acrylic vessels holding LS (SNO+, JUNO).
- Excellent transparency.
- Drawback: worse particle discrimination.

Scintillator cocktails: additions

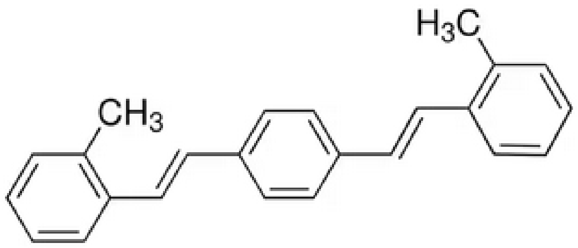
Called fluor / solute
Added at the level of g/l
2,5-diphenyloxazol: PPO



Addition of this fluorescence dye serves as:
- ✓ Efficient non-radiative transfer of excitation energy from the solvent to fluor.
- ✓ Fast decay times.
- ✓ Wavelength shift.

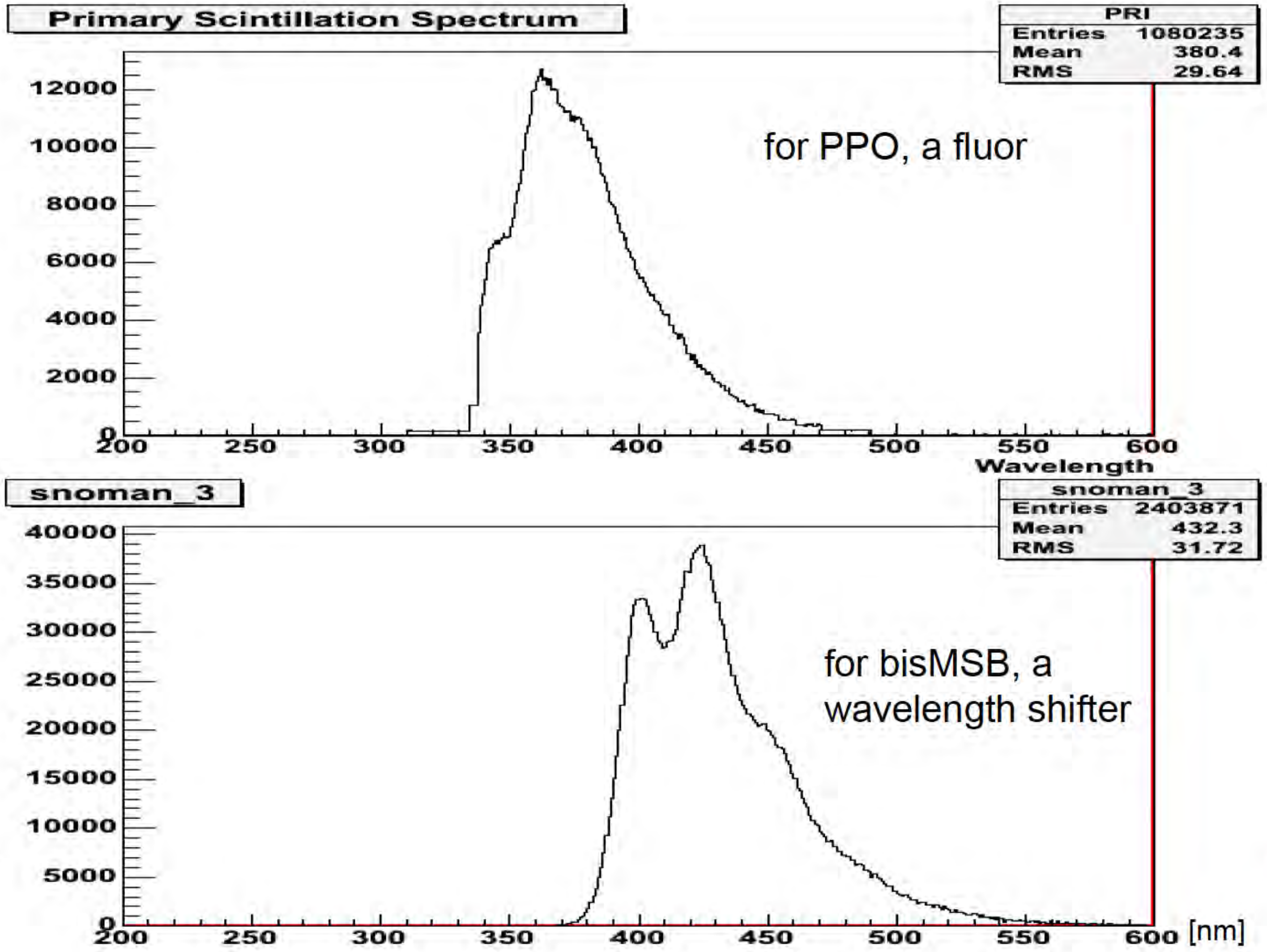
Wavelength shifter (secondary fluor)
Added at the level of mg/l

1,4-Bis(2-methylstyryl)benzene: bisMSB



Shifts wavelength to longer values to match quantum efficiency of the phototubes and decrease self-absorption in LS.

Emission spectra



Quenching

- Quenching is an external process that de-excites the scintillator without fluorescence.
- Impurity quenching: Oxygen!
- Ionisation quenching: high ionization density quenches the excited π-electrons

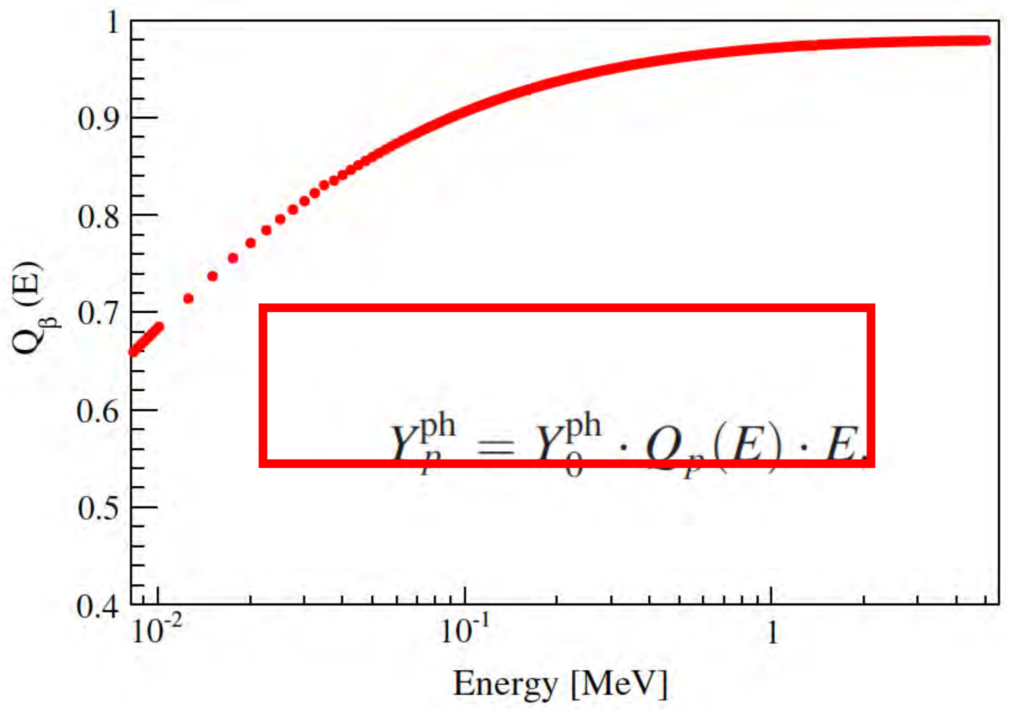
Important consequences:

1) Non-linearity in the energy response
heavy particles with **higher dE/dx (e.g. α, protons) produce less light** for the same energy deposit (by a factor of >10 for α's)

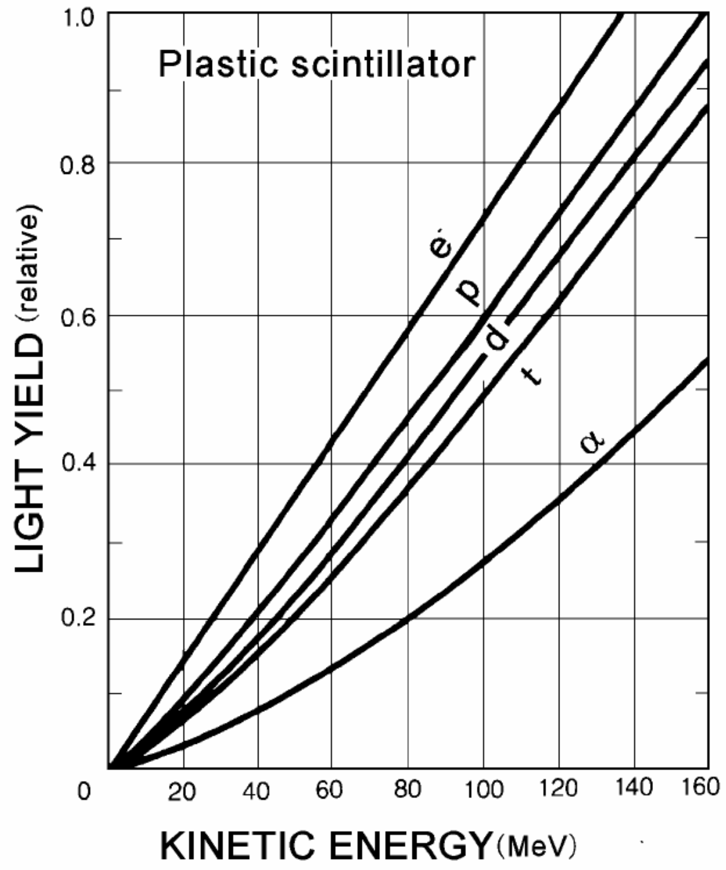
2) Particle discrimination:
the scintillation **pulse shape (fast/slow components) is different**

Quenching

For electrons in Borexino



from Gooding and Pugh



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-$\beta\beta$ decay

KamLAND – Zen (present)

SNO+ (present)

Sterile neutrino search with reactor antineutrinos

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

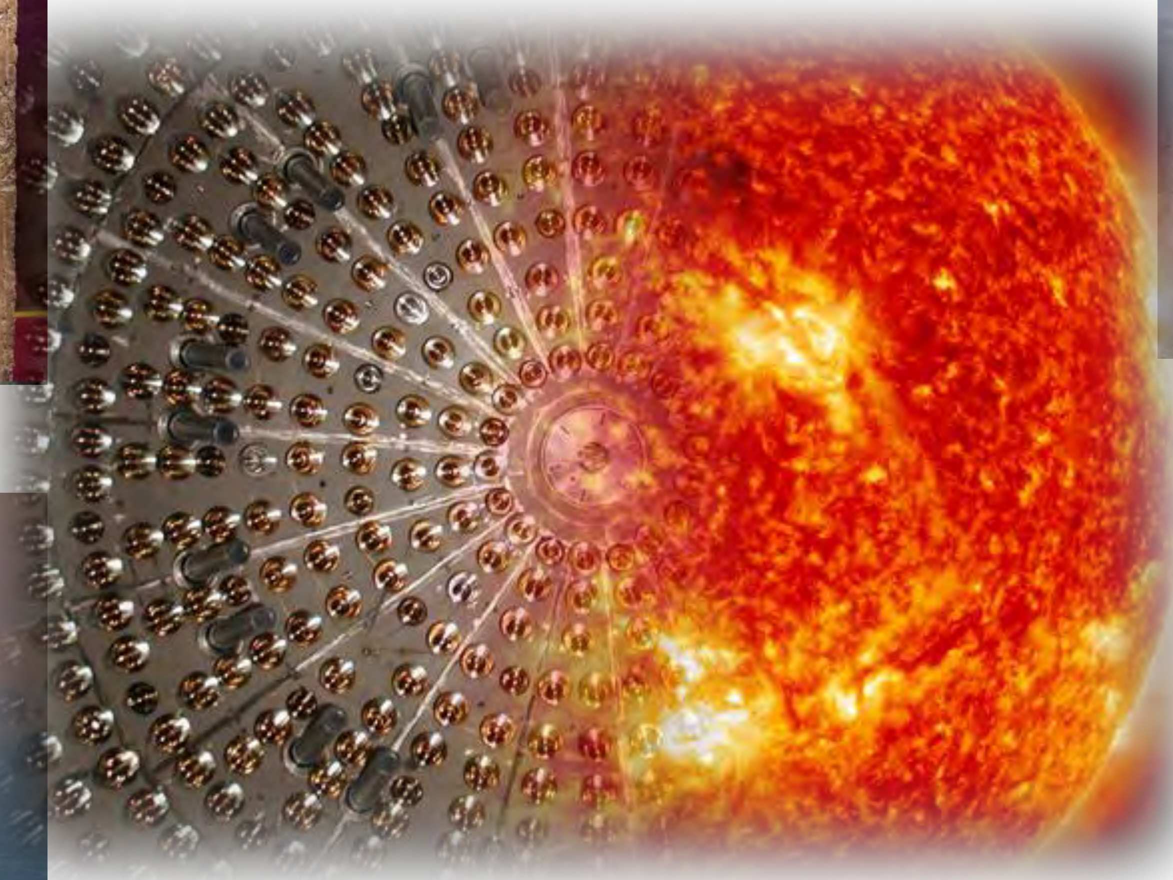
Supernovae neutrinos

LVD (past)

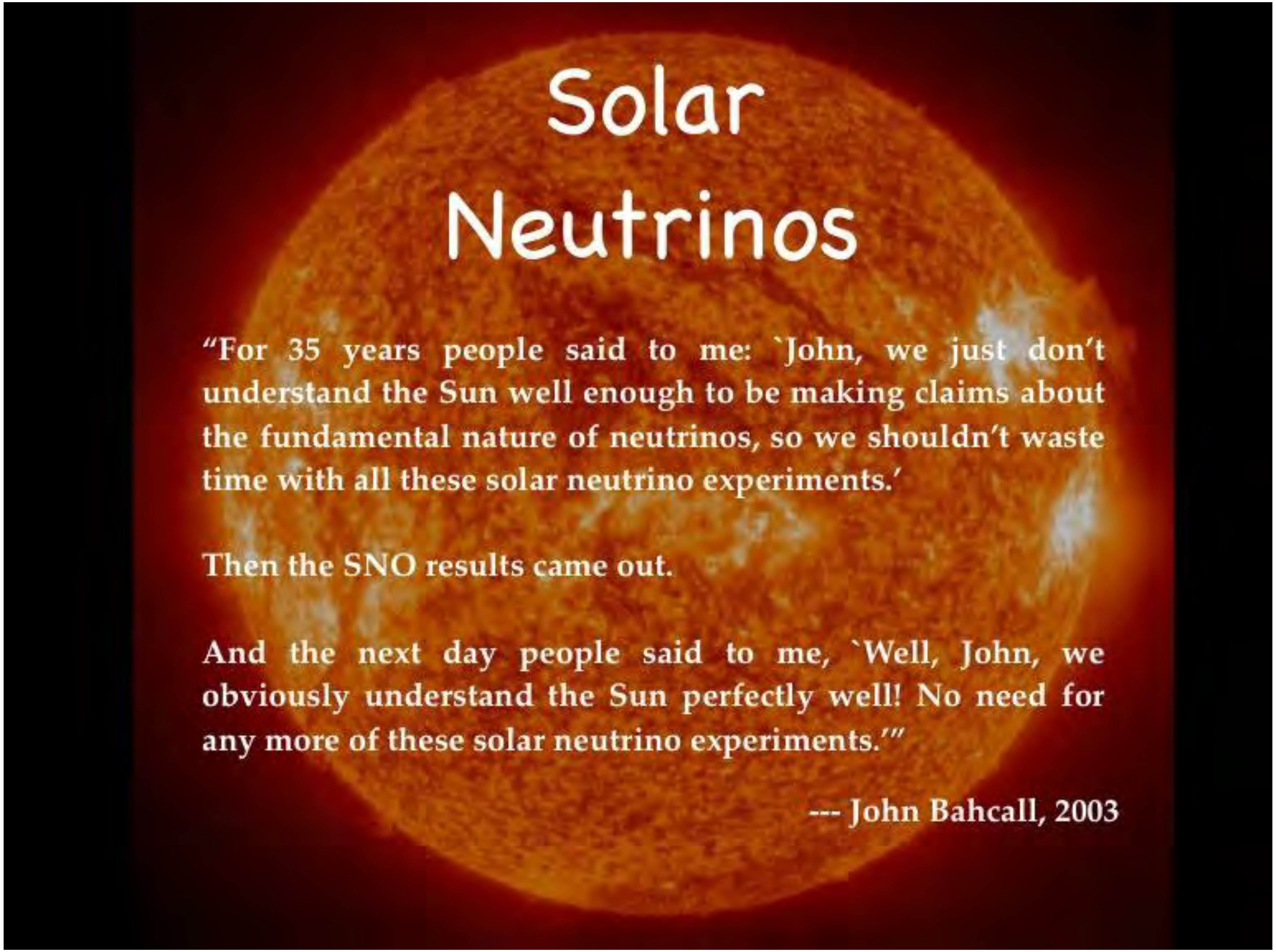
Accelerator neutrinos

LSND (past)

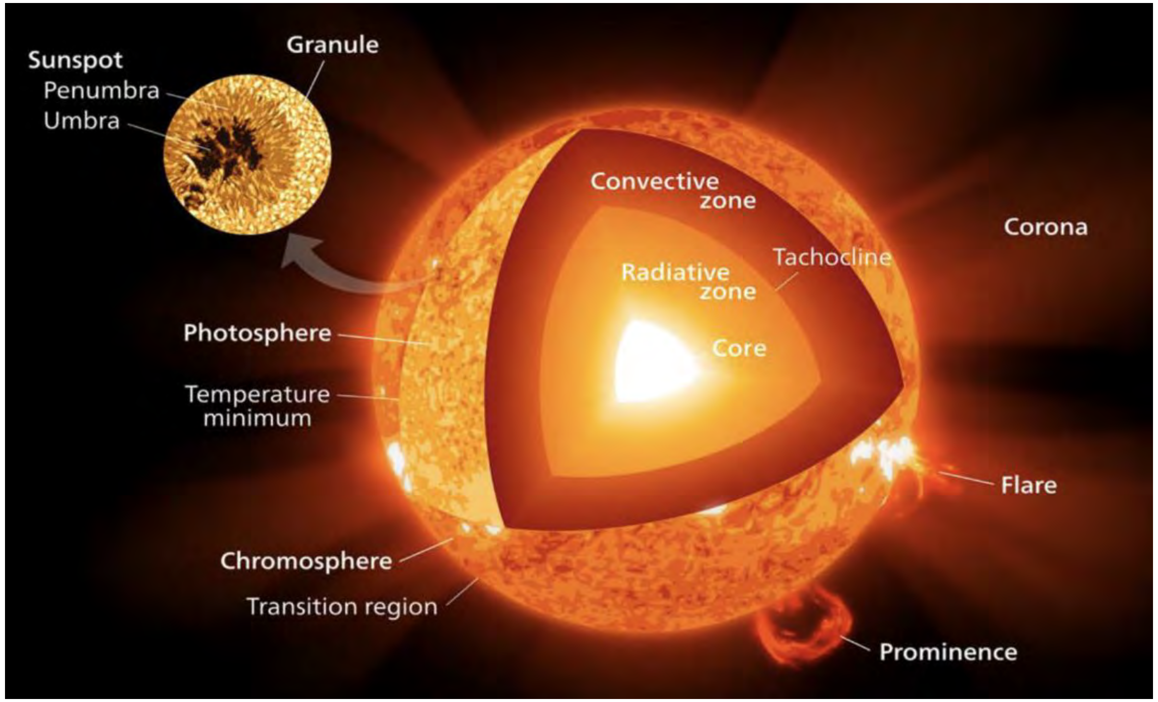
Solar neutrinos

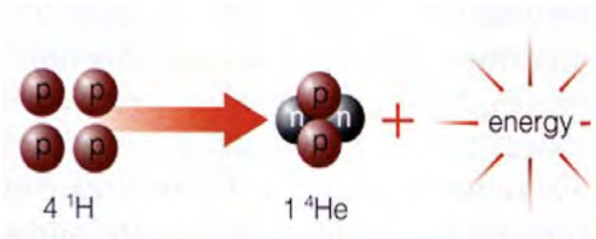


Millennia of fascination continued.

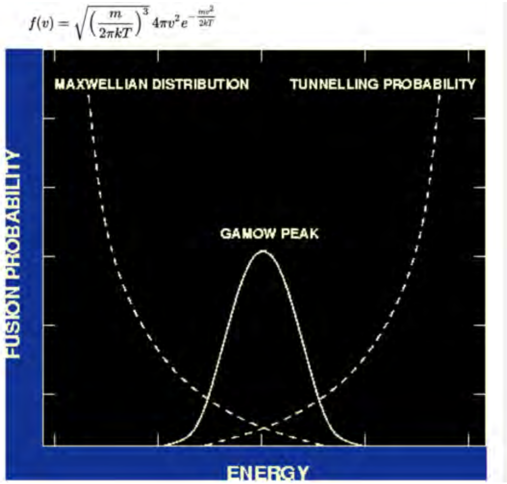

Solar
Neutrinos
"For 35 years people said to me: `John, we just don't understand the Sun well enough to be making claims about the fundamental nature of neutrinos, so we shouldn't waste time with all these solar neutrino experiments.'
Then the SNO results came out.
And the next day people said to me, `Well, John, we obviously understand the Sun perfectly well! No need for any more of these solar neutrino experiments.'"
--- John Bahcall, 2003

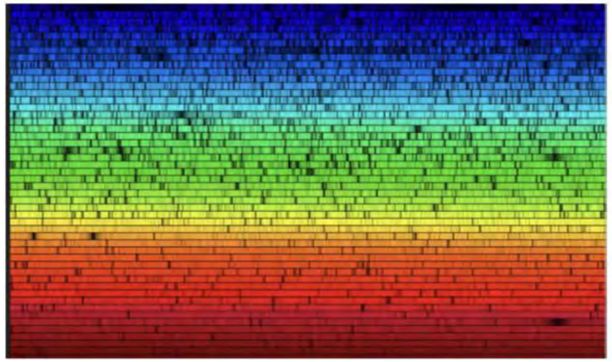
THE SUN





(26.7 MeV) + 2 ν





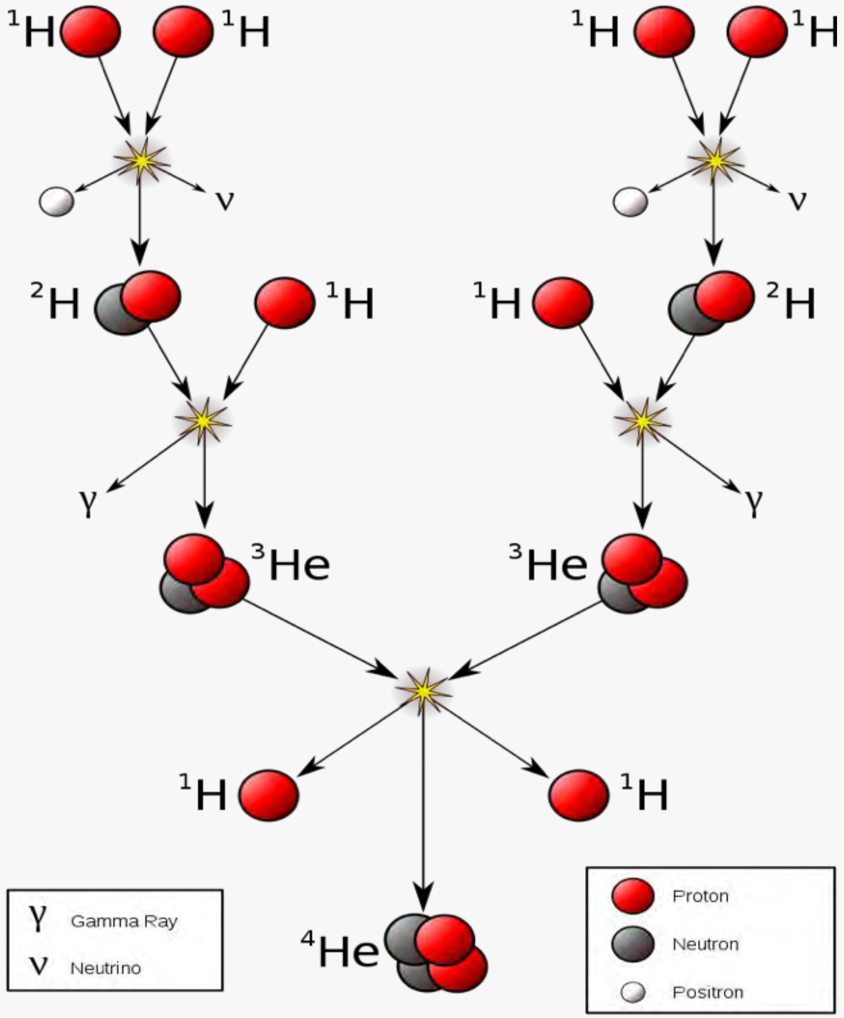
- Luminosity ($3.8418.10^{33}$ erg/s ($\pm$ 0.35%) (1 erg = 10^{-7} J)
- Age (~$4.6.10^9$ years - old meteorites)
- Mass M = $1.989 \cdot 10^{30}$ kg ($\pm$ 0.02%)
- Radius R = $6.9598 \cdot 10^8$m ($\pm$ 0.01%)

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

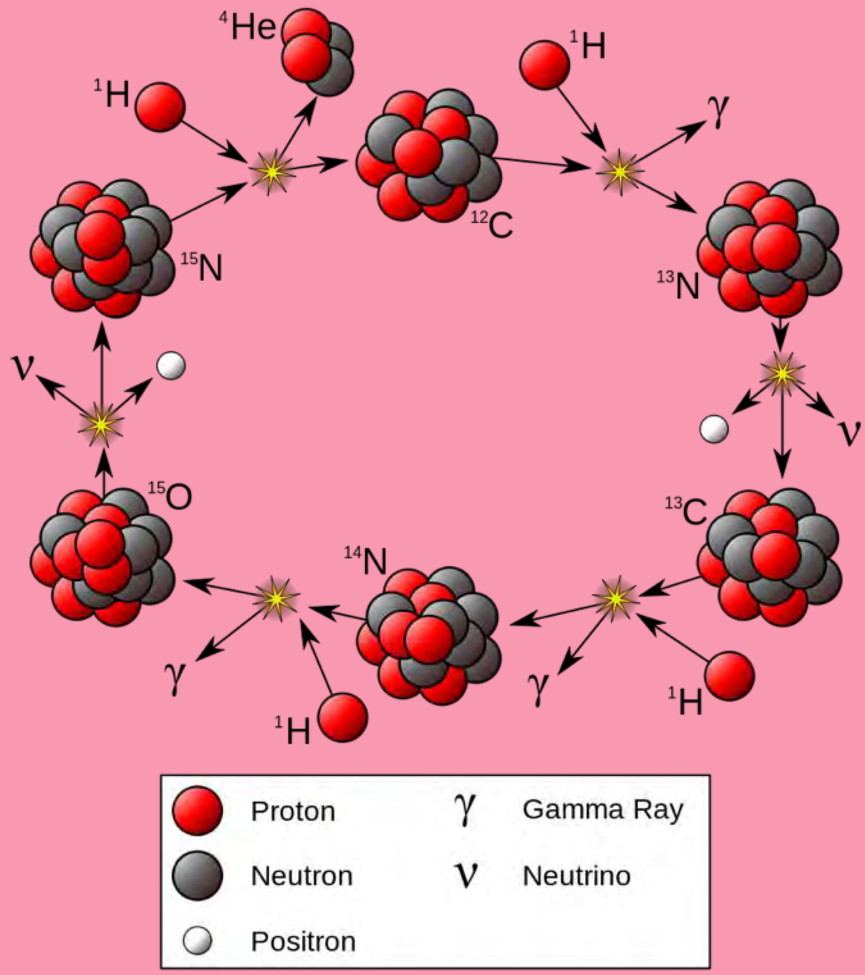
HYDROGEN-TO-HELIUM FUSION

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

pp-chain: ~99% solar energy



CNO-cycle: < 1% solar energy



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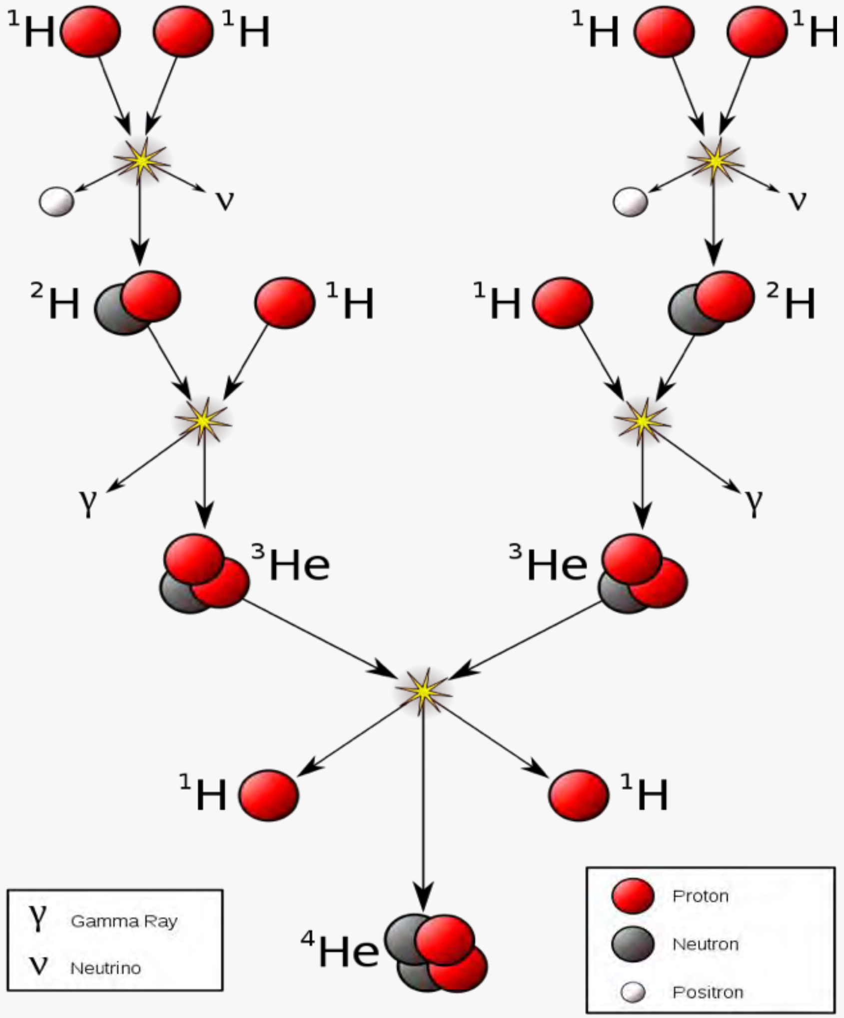
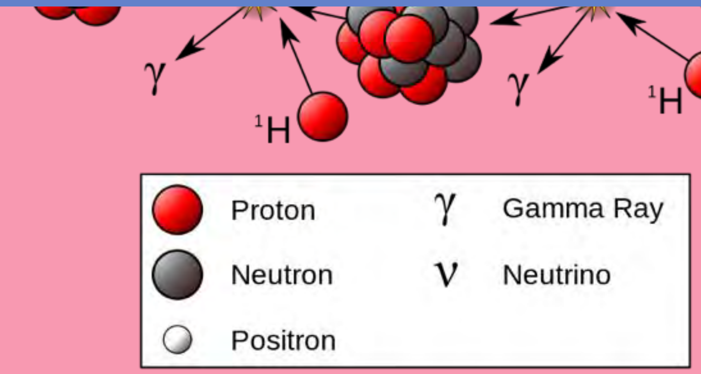


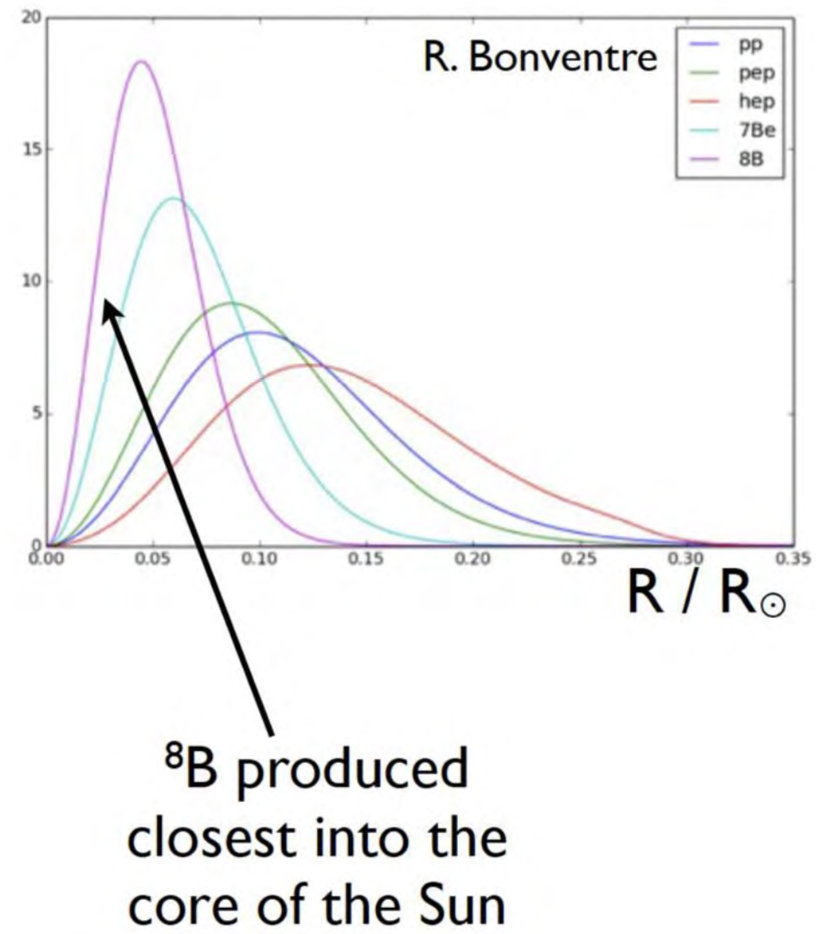
CNO-cycle: < 1% solar energy

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.



WHERE DOES THE FUSION OCCUR



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

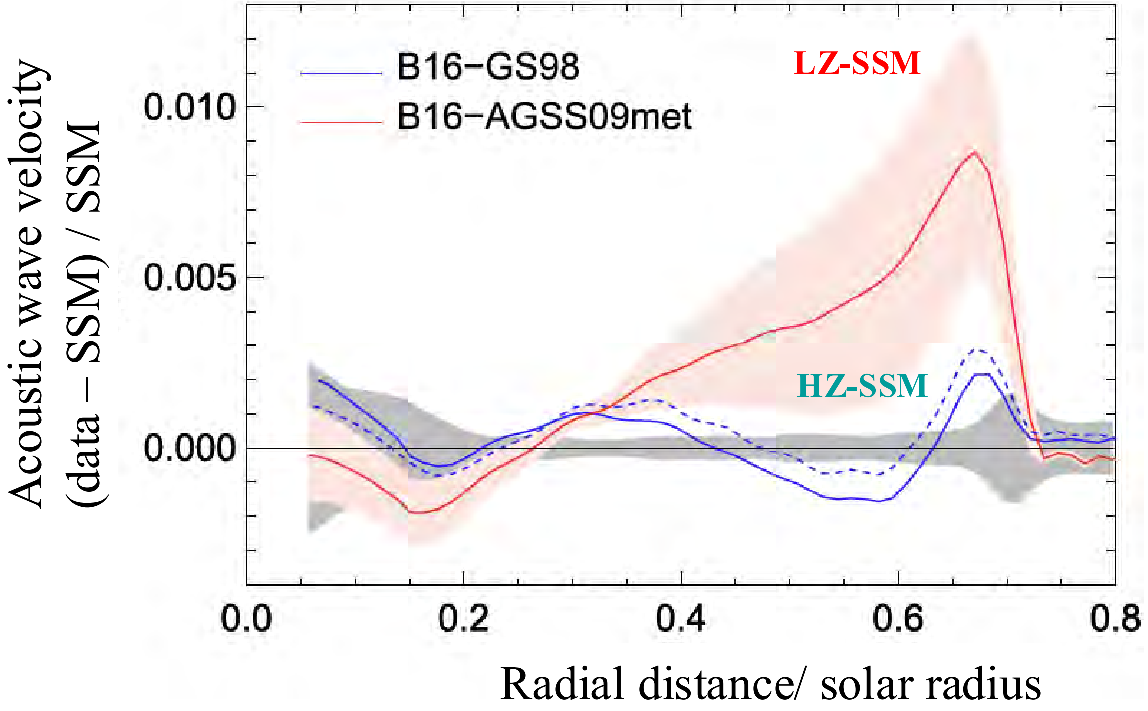
B16 Standard Solar Model with different metallicity inputs:

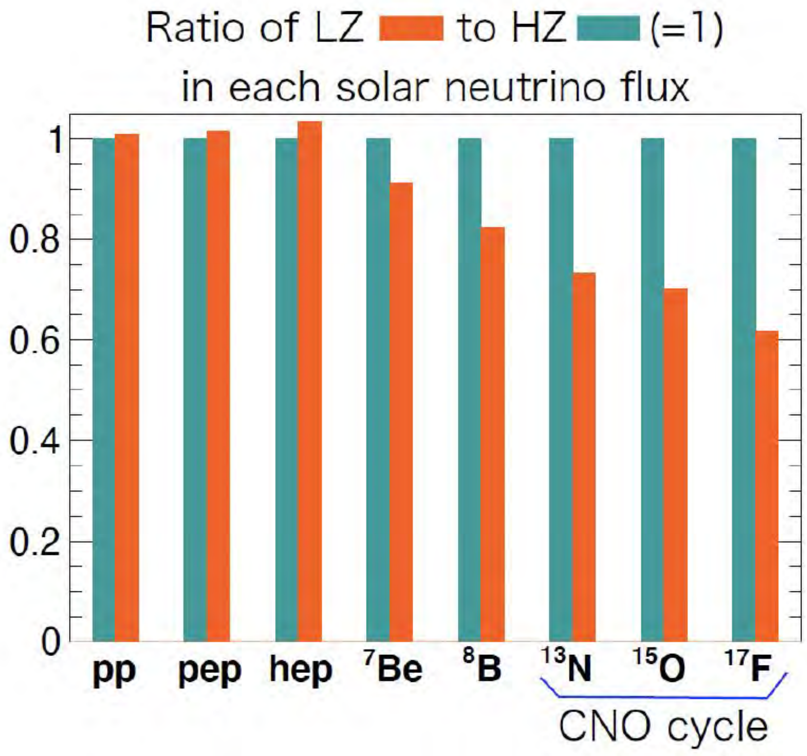
High-Metallicity HZ-SSM: older GS98 metallicity input: Z/X = 0.0229

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

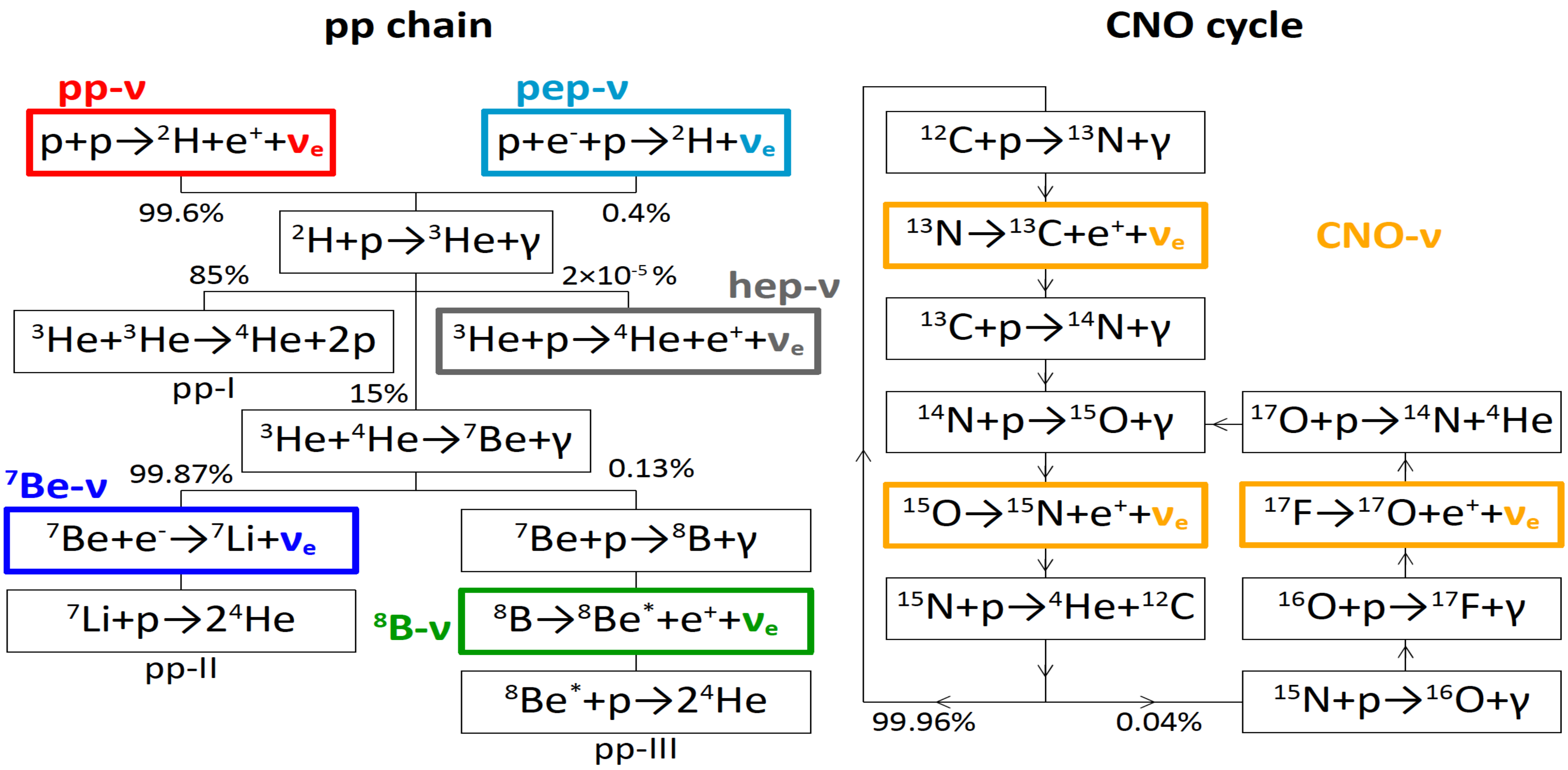
Neutrino physics

- **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

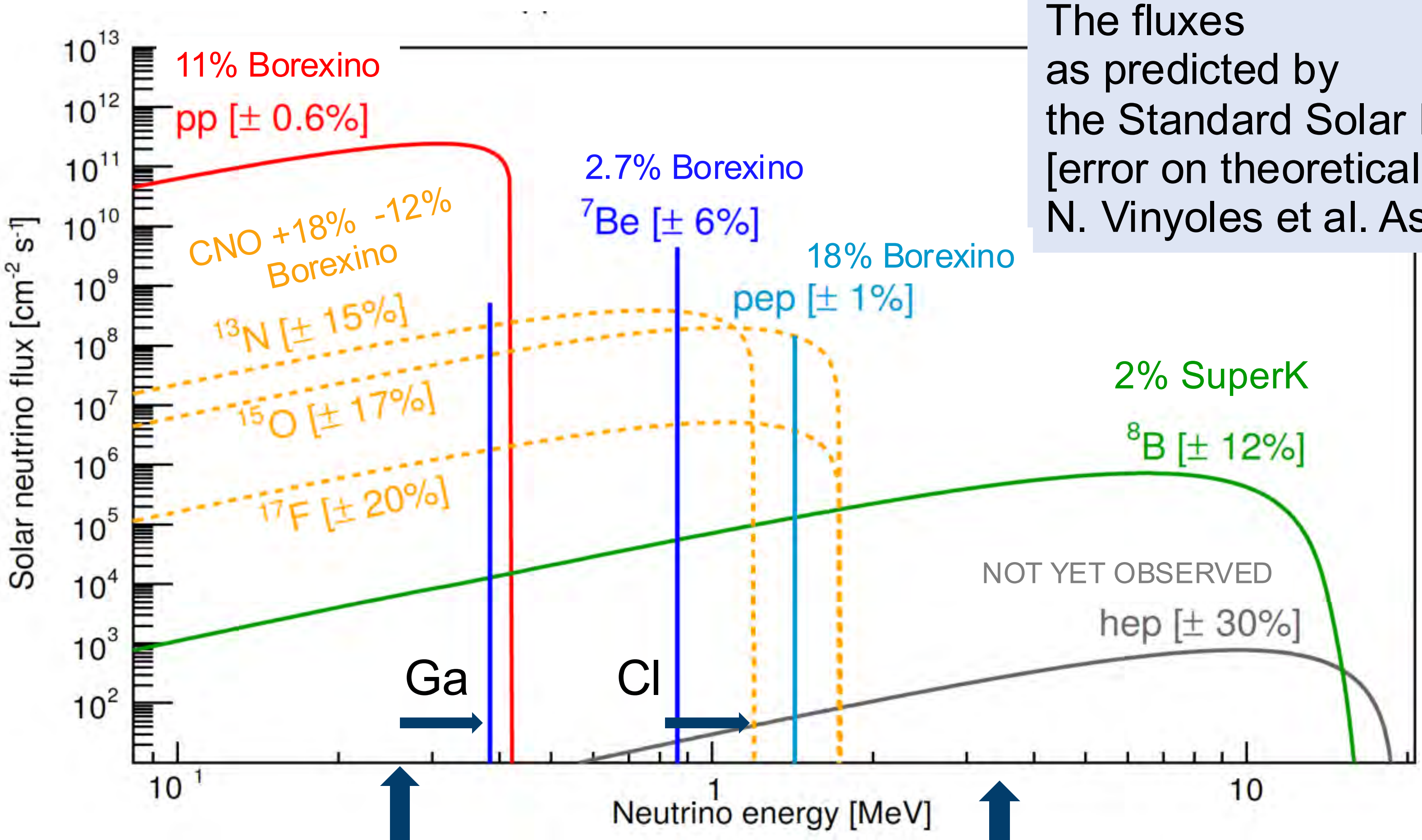
- Direct probe of **nuclear fusion.**
- Photon vs neutrino luminosity: testing **thermo-dynamical stability** of the Sun.
- **Standard Solar Models:**
  - ✓ Metallicity problem.

SOLAR NEUTRINOS FROM THE PP AND CNO



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



John N. Bahcall
1934 - 2005

Borexino threshold
with liquid scintillator

Super-Kamiokande threshold
with water Cherenkov

Experimental techniques in a nutshell

1) Radiochemical

- ✓ CC: **ν_e only**
- ✓ $^{A}X + \nu_e \rightarrow {}^{A}Y + e^-$ W-exchange
- ✓ **only integral flux above the threshold T**
- ✓ T (Ga) = 233 keV,
- ✓ $T(C_2Cl_4)$ = 814 keV
- ✓ Homestake, Gallex/GNO, SAGE

2) Water Cherenkov

- ✓ Elastic Scattering ES
- ✓ In heavy water: also NC & CC.
- ✓ **Real- time technique: E_ν spectrum!**
- ✓ ~3 to 5 MeV threshold.
- ✓ Directionality.
- ✓ (Super)-Kamiokande, SNO/

3) Liquid scintillator

- ✓ Elastic scattering: T ~200 keV for neutrino.
- ✓ IBD: T = 1.8 keV for antineutrino.
- ✓ **Real- time technique: E_ν spectrum!**
- ✓ High light yield (Borexino: 500 pe/MeV)
- ✓ No directionality.
- ✓ Extreme radio-purity needed.
- ✓ Particle identification (α/β, e^+/e^- separation).
- ✓ Borexino, KamLAND, SNO+, JUNO.

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 ^8B-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 ^7Be, pep, pp neutrinos
- ✓Observation of CNO
- ✓Low-energy ^8B neuttrinos (> 3 MeV recoiled e^-)

SNO+ - first ^8B data & JUNO in commissioning phase

<u>First detection</u>

Solar-neutrino puzzle

Solution:
Neutrino oscillations!

Real-time
precision spectroscopy

Radiochemical methods in detection of solar neutrinos (^{37}Cl)

- **Pioneering Chlorine-based Homestake Experiment**

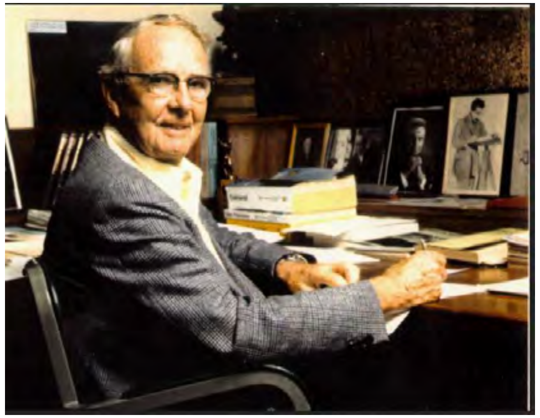
$\nu_e + {}^{37}Cl \dashrightarrow e^- + {}^{37}Ar$ (threshold 0.814 MeV)

EC (electron capture) back to ^{37}Cl (32 days)

Method proposed by Bruno Pontecorvo (1946) and Luis Alvarez (1949)

Bruno Pontecorvo

Bruno Pontecorvo in the 1950s



Luis Alvarez

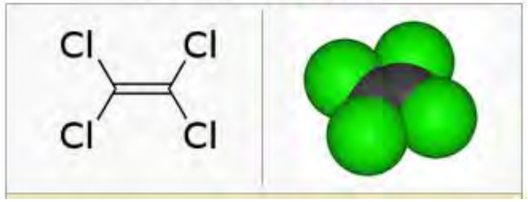
HOMESTAKE - NOBEL PRIZE 2002

- In Homestake Gold Mine, South Dakota, USA
- 1438 m underground

Target: a tank with 614 ton of liquid soap (C_2Cl_4)

Ray Davis
(1914 – 2006)

Tetrachloroethylene



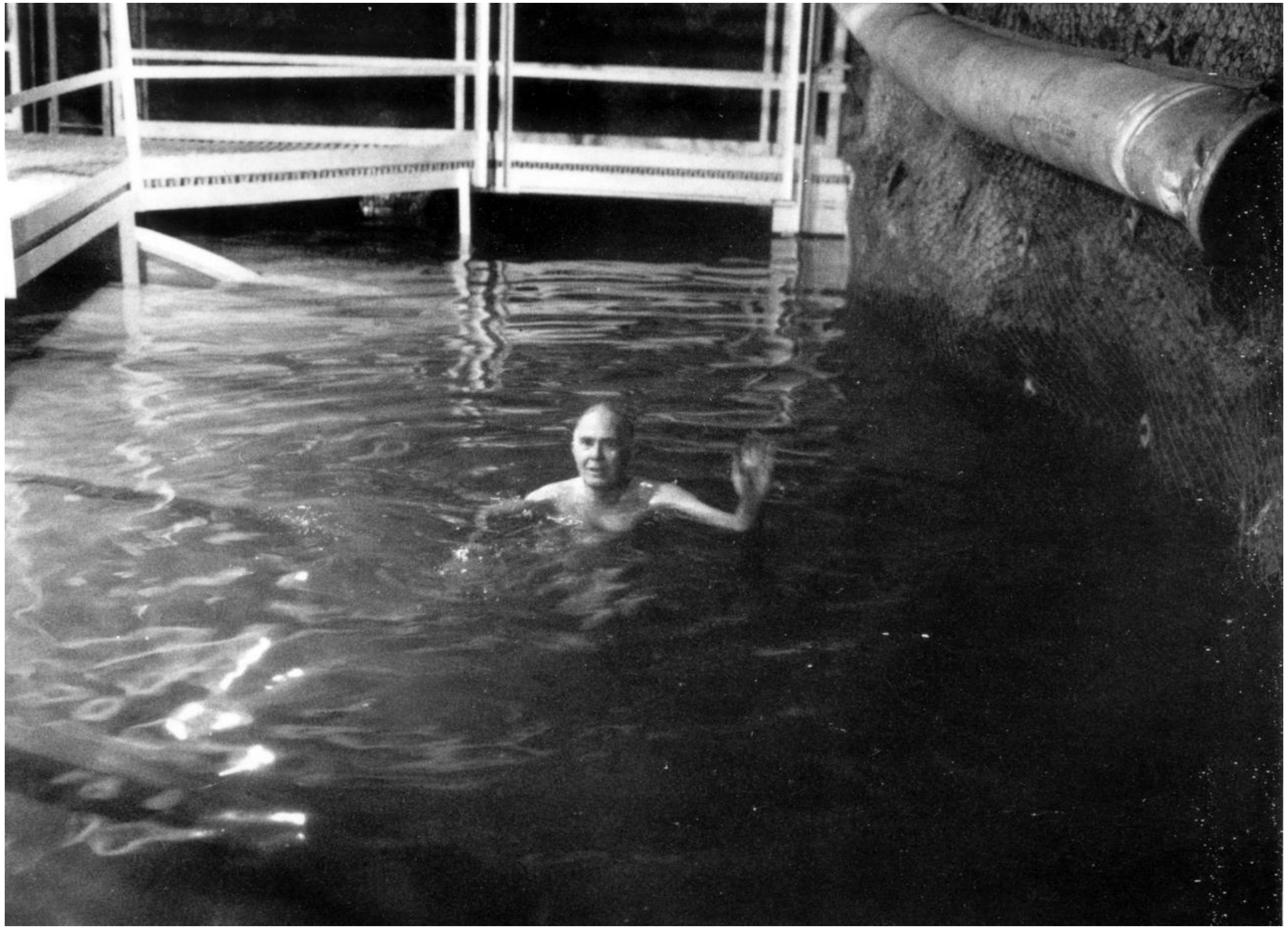
Perchlorethylen

Cross section for ^{8}B-ν
~1.1 x 10^{-41} cm^2

$\nu_e + {}^{37}Cl \dashrightarrow e^- + {}^{37}Ar$ (threshold 0.814 MeV)

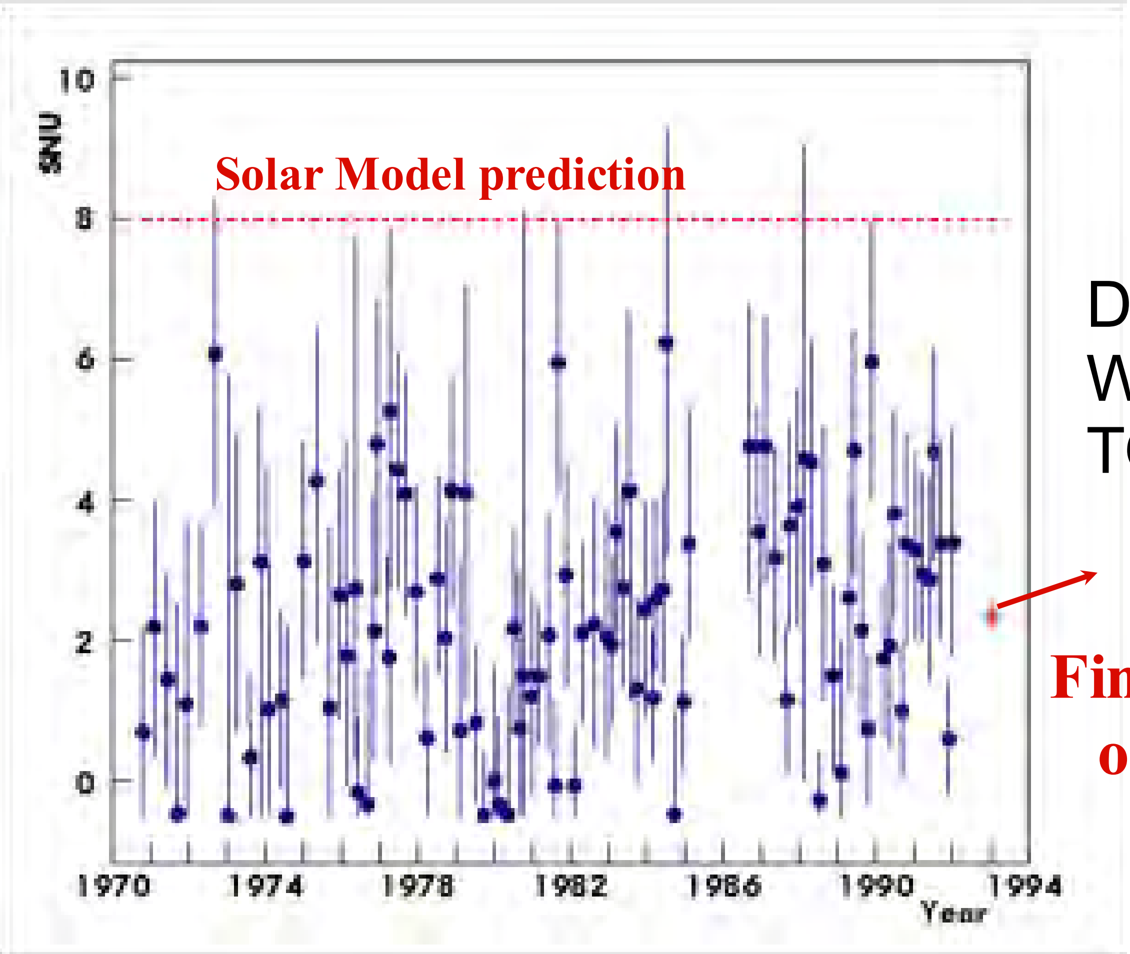
Only 2200 atoms of ^{37}Ar counted in 25 years (1970 - 1994).

Tank construction in Homestake (1966).



Ray Davis swimming in water shield around perchlorethylen tanks (1971).

FIRST SOLAR NEURINO DETECTION: HOMESTAKE



Nobel 2002 to Ray Davis

DEFICIT
WITH RESPECT
TO SSM EXPECTATIONS

2.56 $\pm$0.16 $\pm$0.16 SNU

Final Result
only about 32% of the expectation!

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

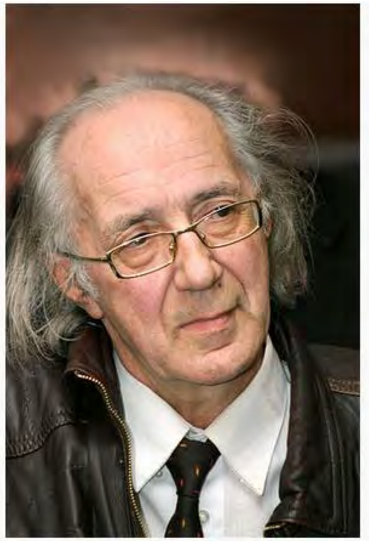
Radiochemical methods in detection of solar neutrinos (^{71}Ga)

- **Gallium experiments (Gallex/GNO, SAGE)**

$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$ (threshold **0.233 MeV**)

EC (electron capture) back to ^{71}Ga (16 days)

Method proposed by V. Kuzmin (1965) and R. J. Raghavan (1978)



Vadim Kuzmin
(1937 – 2015)

Raju Raghavan
(1937 – 2011)

Gallium experiments

$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$ (threshold 233.2 MeV)

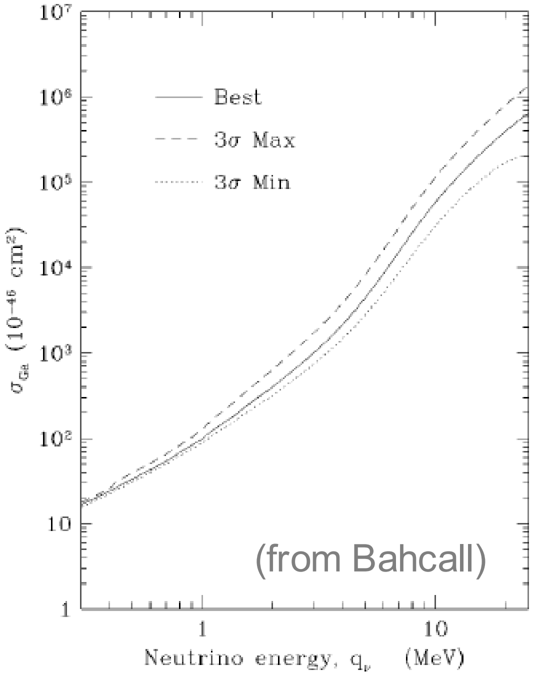
Detection of **low energy pp-chain neutrinos**

(pp – 53%, ^{7}Be – 27%, ^{8}B – 12%, CNO ? – 8%)

GALLEX/GNO@LNGS, Italy

SAGE @ Baksan, Russia

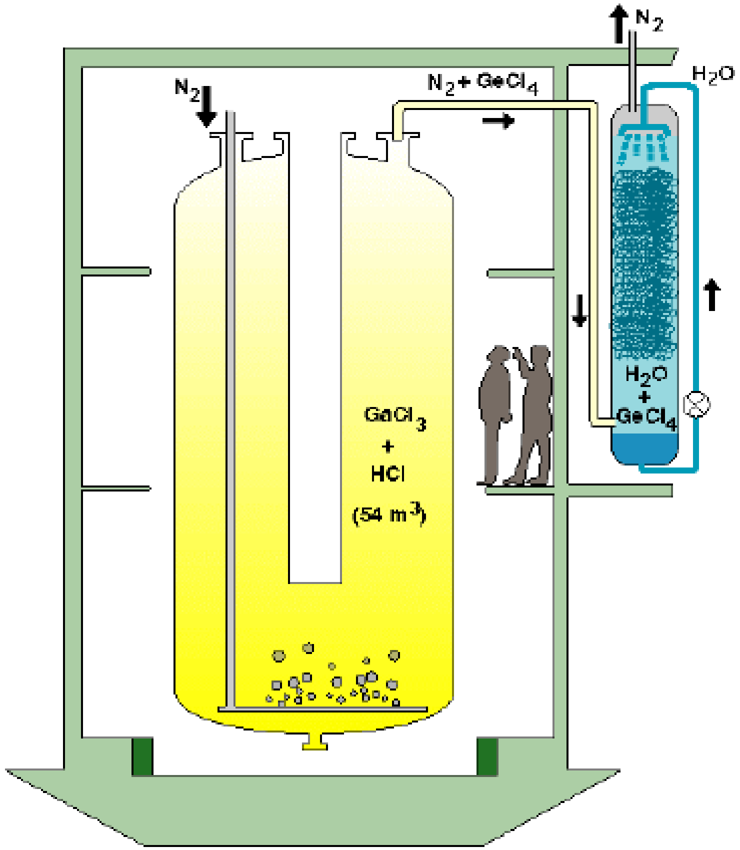
Till Kirsten
MPI Germany



Vladimir Gavrin
Russia

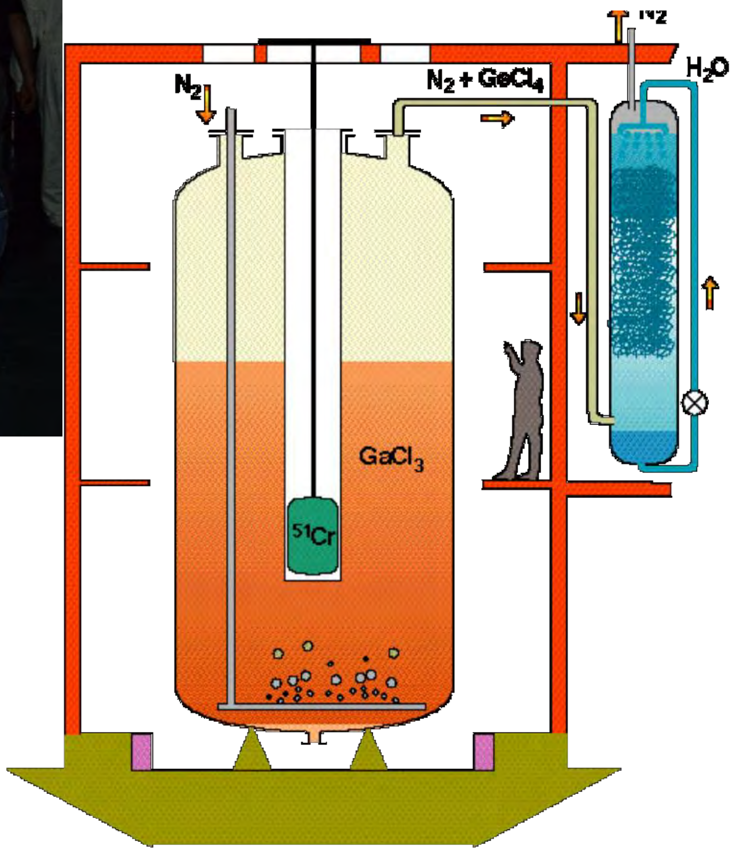
Gallex (1991-1997)/GNO (1998- 2003) at LNGS, Italy

- 101 ton of GaCI3 solution in water and HCl containing 30.3 ton of natural Gallium.
- When equilibrium between the production and the decay rates is reached, there are about 10 ^{71}Ge atoms among ~10^{29} atoms of ^{71}Ga.



- Extraction of ^{71}Ge every 4 weeks
- ^{71}Ge is present as a volatile $GeCl_4$, which is extracted by purging with 3000 m^3 of Nitrogen.
- ^{71}Ge is converted to GeH_4 (German gas) and inserted to proportional counters filled with Xe and observed for 6 month: ^{71}Ge completely decays and the background can be determined.

Important part of the overall methodology: global calibration with a ^{51}Cr neutrino source

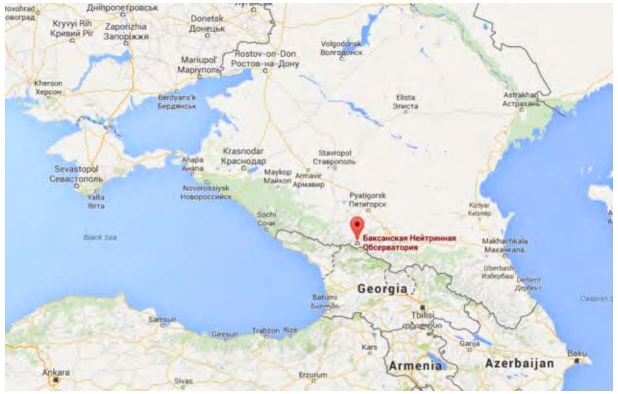


^{51}Cr decays via EC into ^{51}V,
Emitting two neutrino (electron flavour) lines:
750 keV (90%)
430 keV (10%),

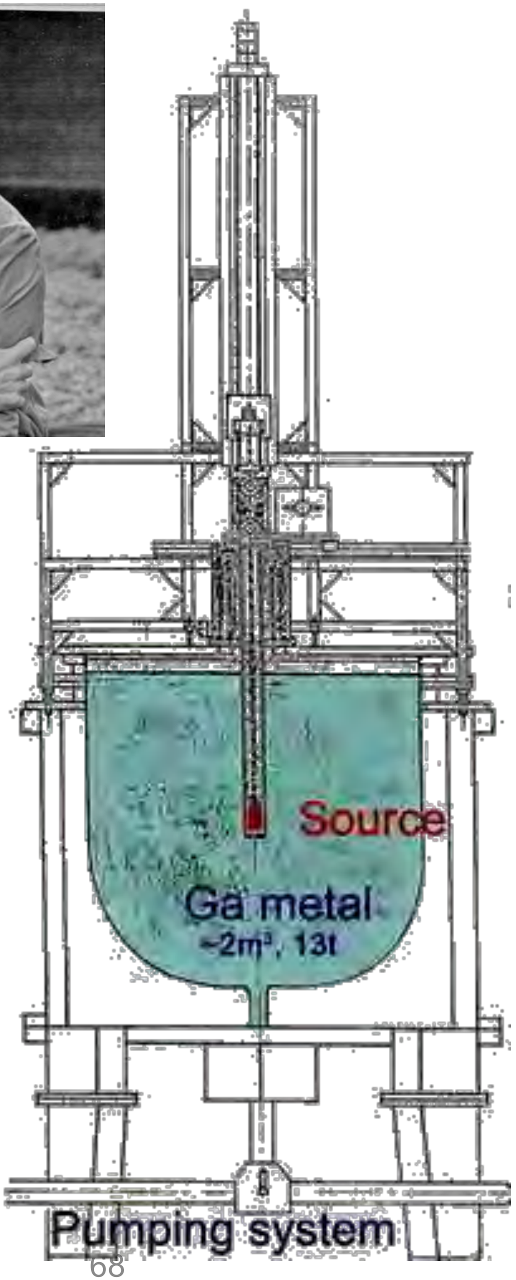
SAGE, Baksan

(1989 – 2007)

Soviet–American Gallium Experiment



Gavrin & Bahcall



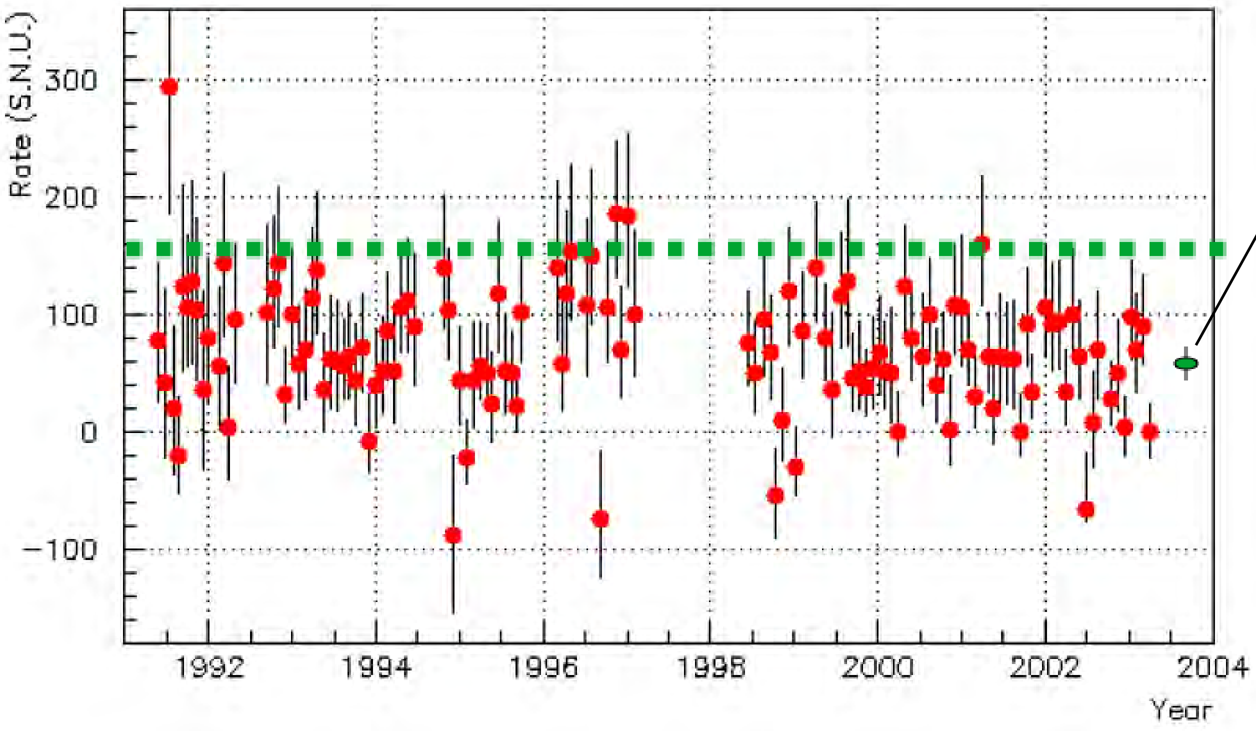
Calibration with ^{37}Ar and ^{51}Cr neutrino sources

Liquid metallic Ga in the window of chemical reactor

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

Till Kirsten (MPI Germany)

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



Final result:

67.6 ± 5.1 SNU

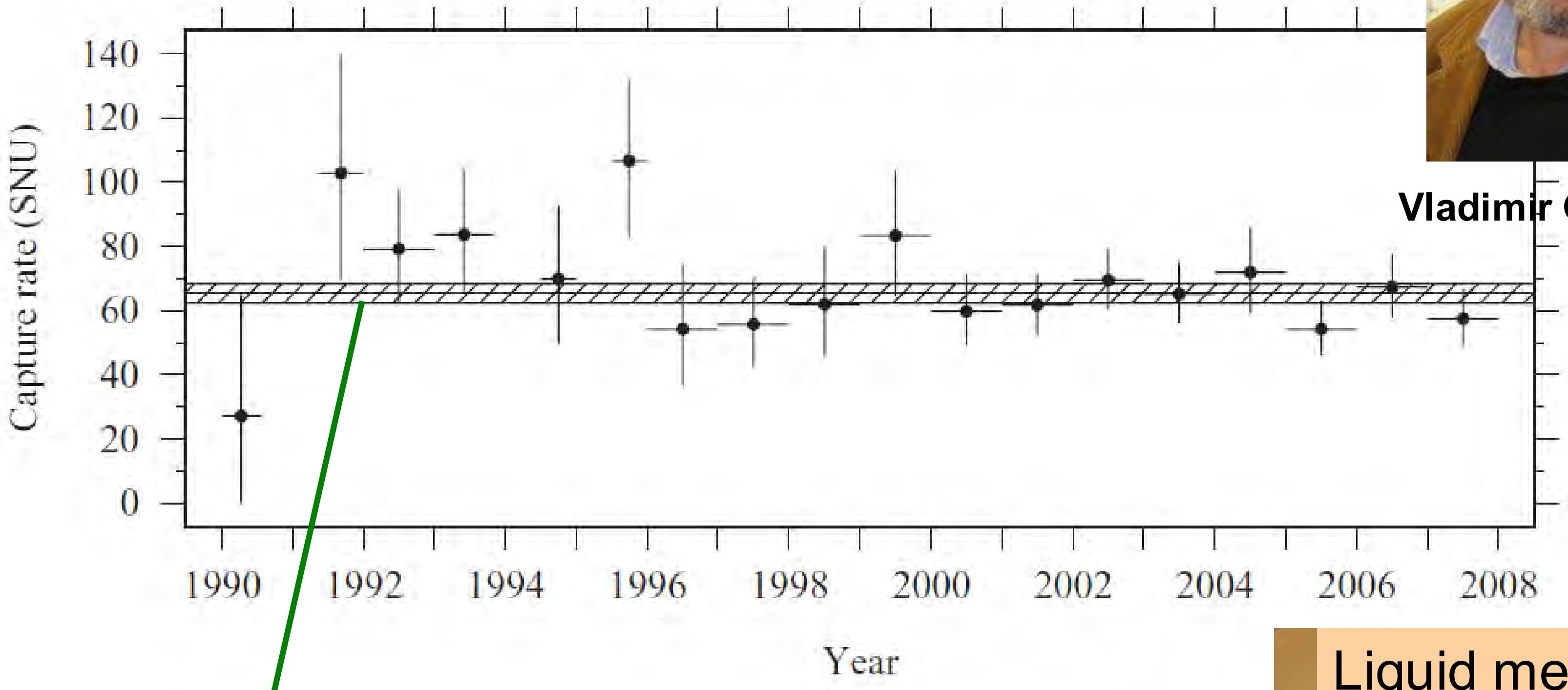
0.541 ± 0.081

as a fraction

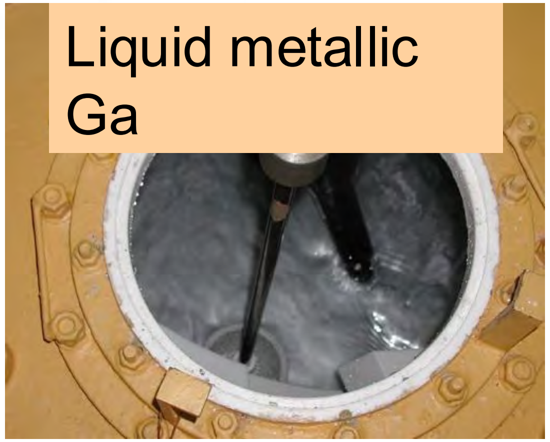
of the SSM prediction

(difference wrt to Homestake)

1990-2011 SAGE EXPERIMENTAL RESULTS, BAKSAN, RUSSIA



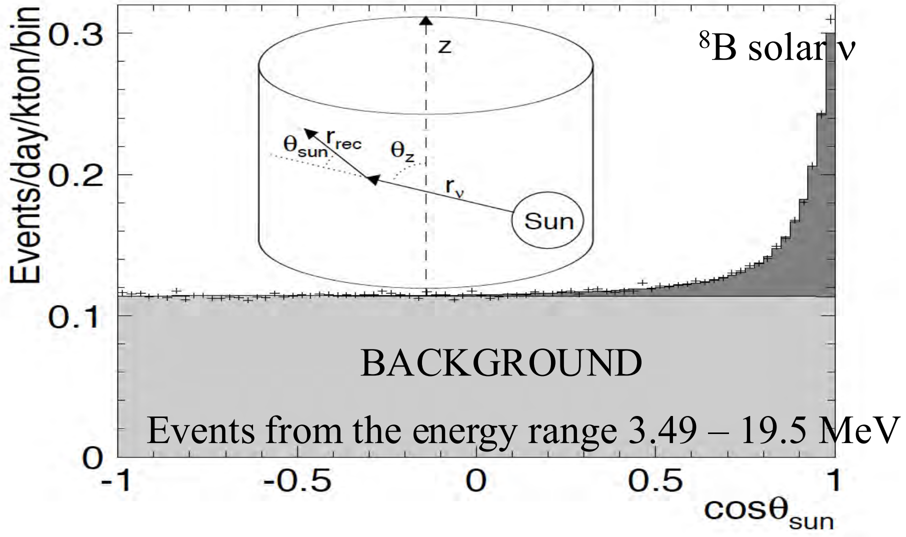
Vladimir Gavrin (Russia)

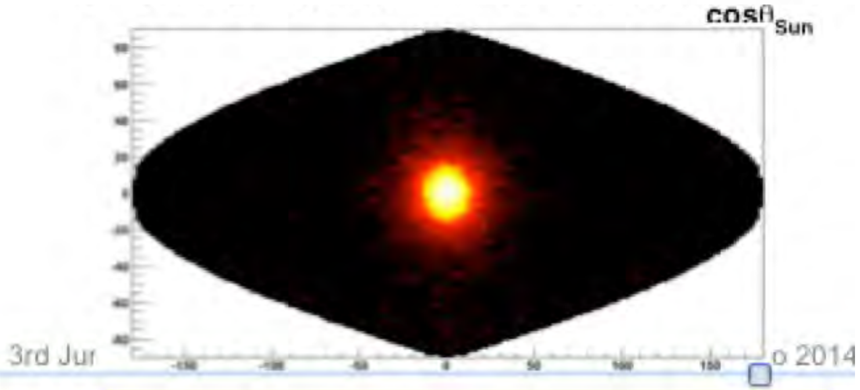


Final result: $65.4^{+3.1}_{-3.0}{}^{+2.6}_{-2.8}$ SNU

SUPER-KAMIOKANDE: START IN 1986, NOBEL IN 2002, STILL ONLINE! THE FIRST REAL-TIME SOLAR NEUTRINO DETECTION

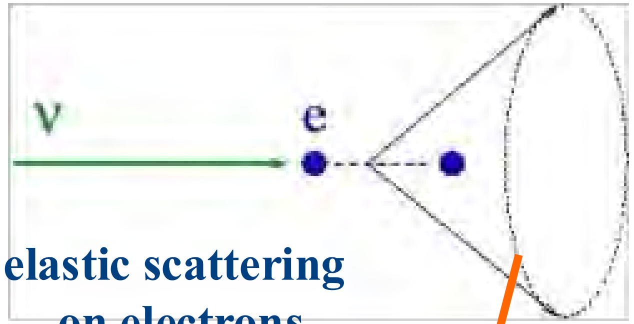
From 2016



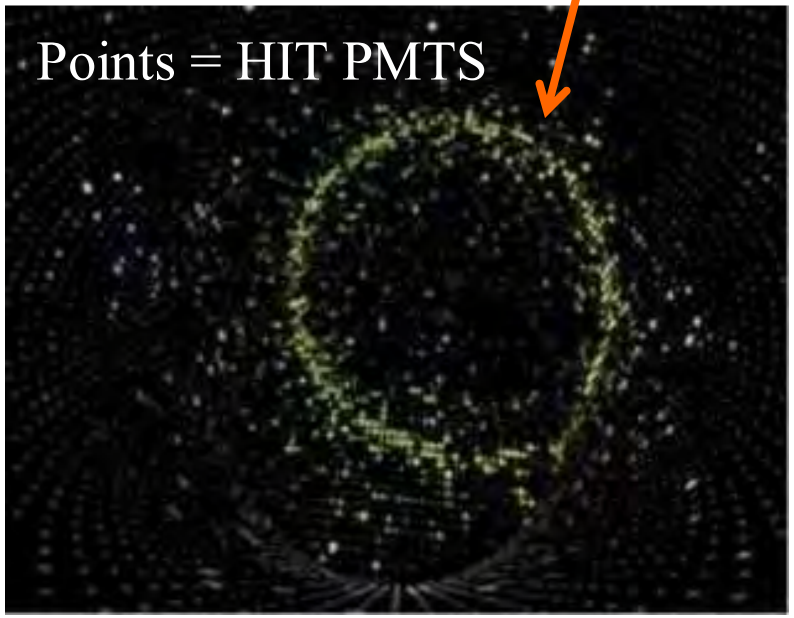


The Sun's picture in neutrinos!

Detection in



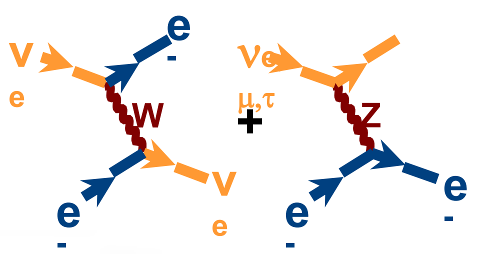
elastic scattering on electrons

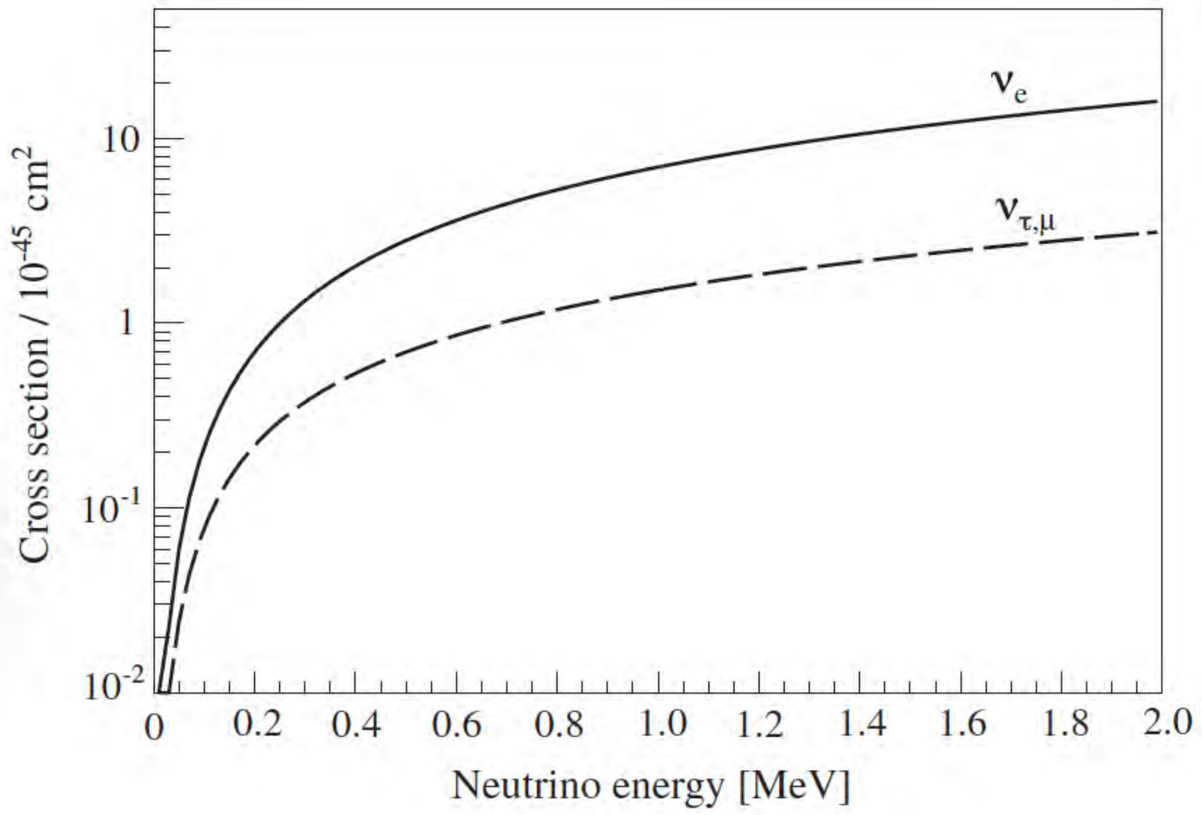


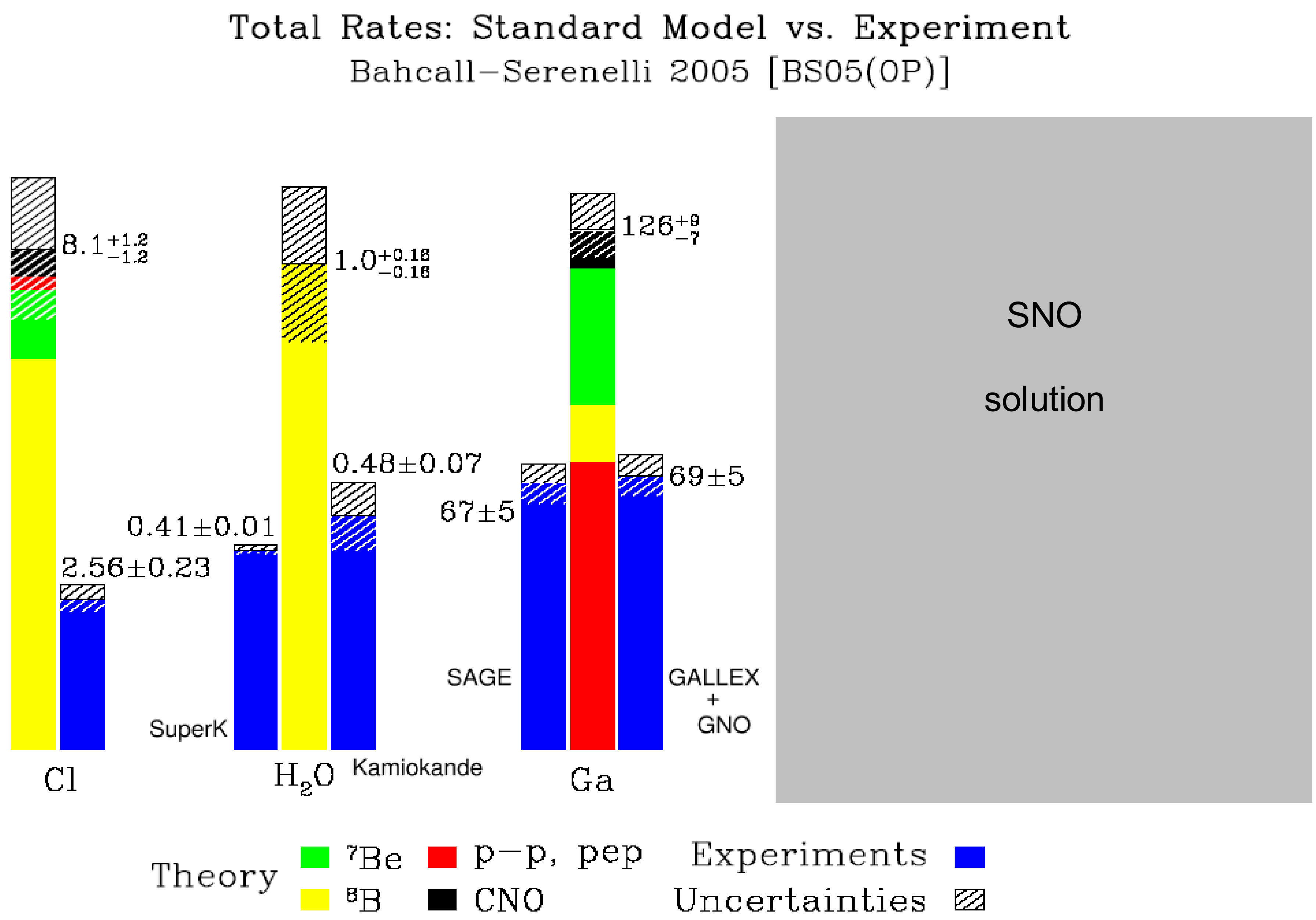
Neutrinos detected through elastic scattering: singles

@ 1-2 MeV for electron flavour: ~10^{-44} cm^2

for μ,τ flavours about 6 x smaller cross section

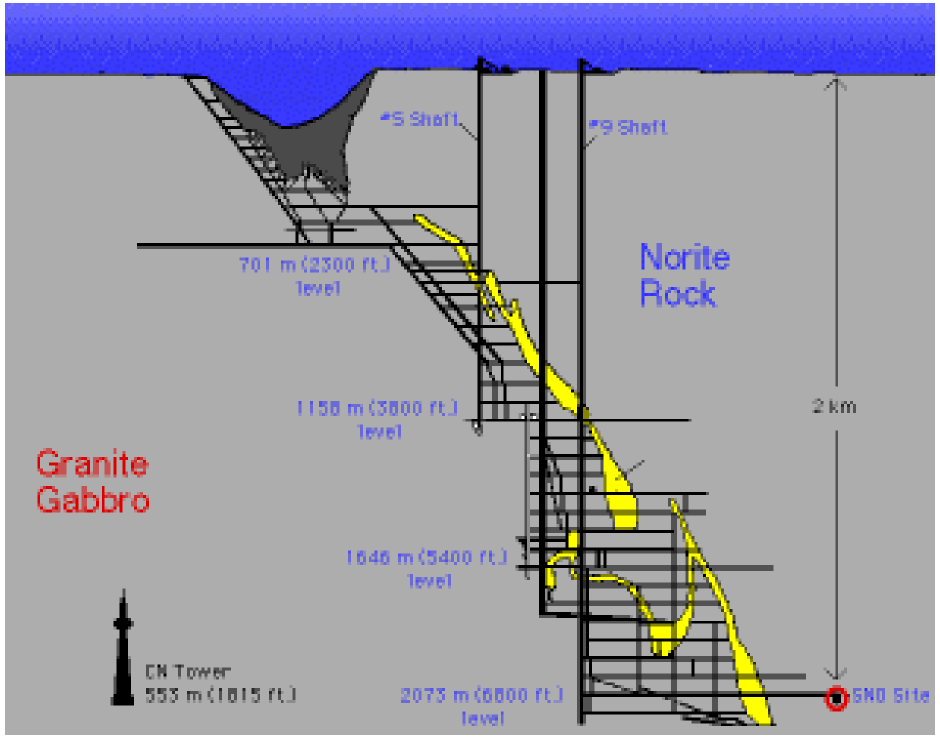


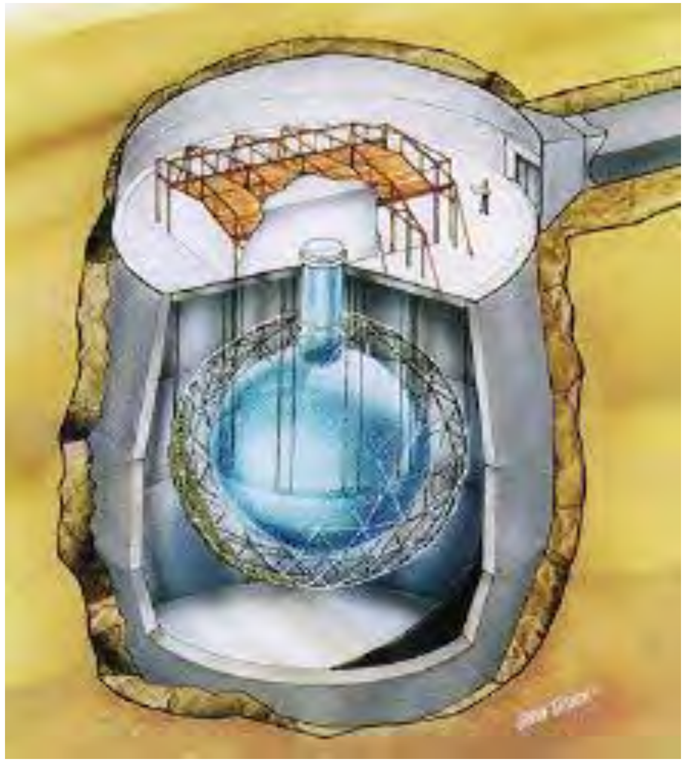



Total Rates: Standard Model vs. Experiment
Bahcall−Serenelli 2005 [BS05(OP)]
8.1 +1.2 −1.2
2.56±0.23
Cl
0.41±0.01
SuperK
1.0 +0.16 −0.16
0.48±0.07
H2O
Kamiokande
126 +9 −7
67±5
SAGE
69±5
GALLEX + GNO
Ga
SNO
solution
Theory
7Be
8B
p−p, pep
CNO
Experiments
Uncertainties

SNO- HEAVY WATER CHERENKOV DETECTOR

- Sudbury Neutrino Observatory (SNO), Ontario, Canada, at 2070 m depth.
- SNO - 1000 tones of ultra-pure heavy water(D_2O) in ultrapure acrylic vessel, 12 m diameter.
- Cherenkov light detected with 9600 PMTs, mounted at the geodesic sphere, 17 m diameter.
- Detector was immersed in the ultrapure water, contained in the barrel-shaped cavern 22 m in diameter and 34 m in heights.
- 10 neutrino events/day.



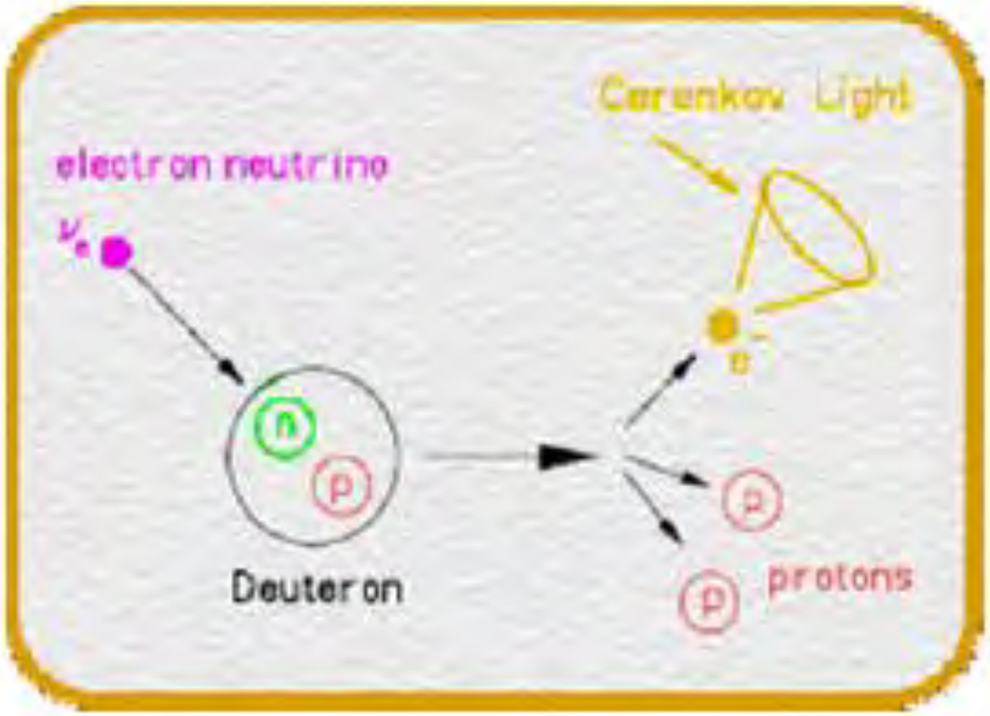


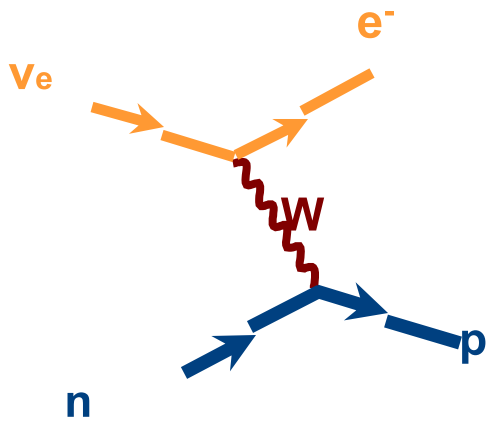
SNO Charge Current measurement

E_{thresh} = 1.4 MeV $\quad \nu_e + d \rightarrow p + p + e^- \qquad$ (CC),

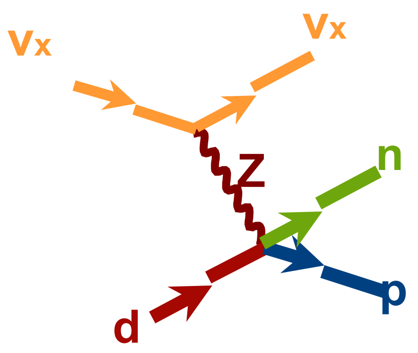
$$\nu_x + d \rightarrow p + n + \nu_x \qquad \text{(NC)},$$

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





SNO Neutral Current measurement

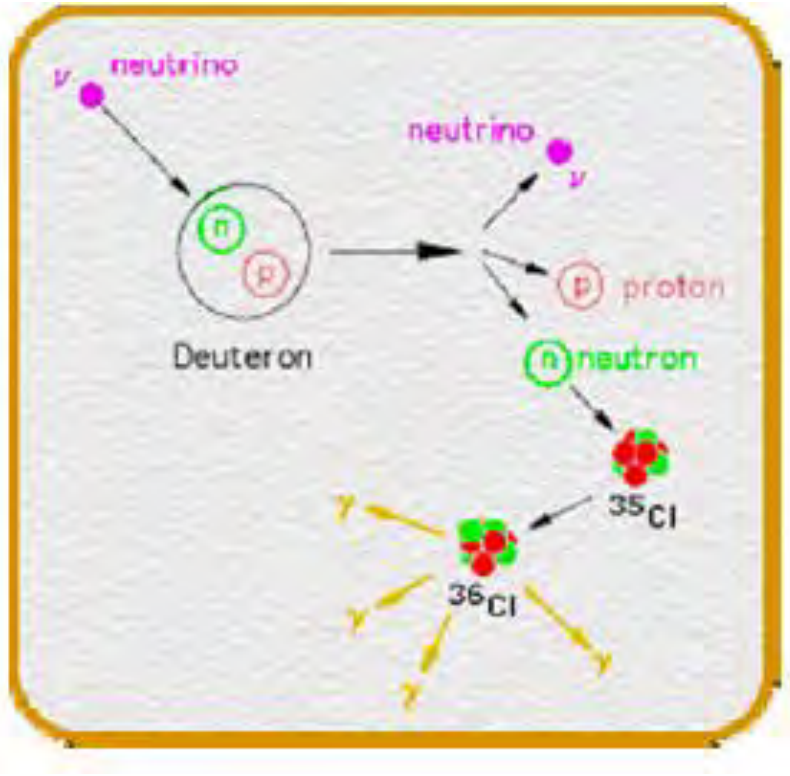


$$\nu_e + d \rightarrow p + p + e^- \qquad \text{(CC)},$$

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

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

Neutron detection is critical!



$n + d \rightarrow {}^3H + \gamma$

$(E_\gamma = 6.25\ \text{MeV})$

Phase 1

(1999 – 2001)

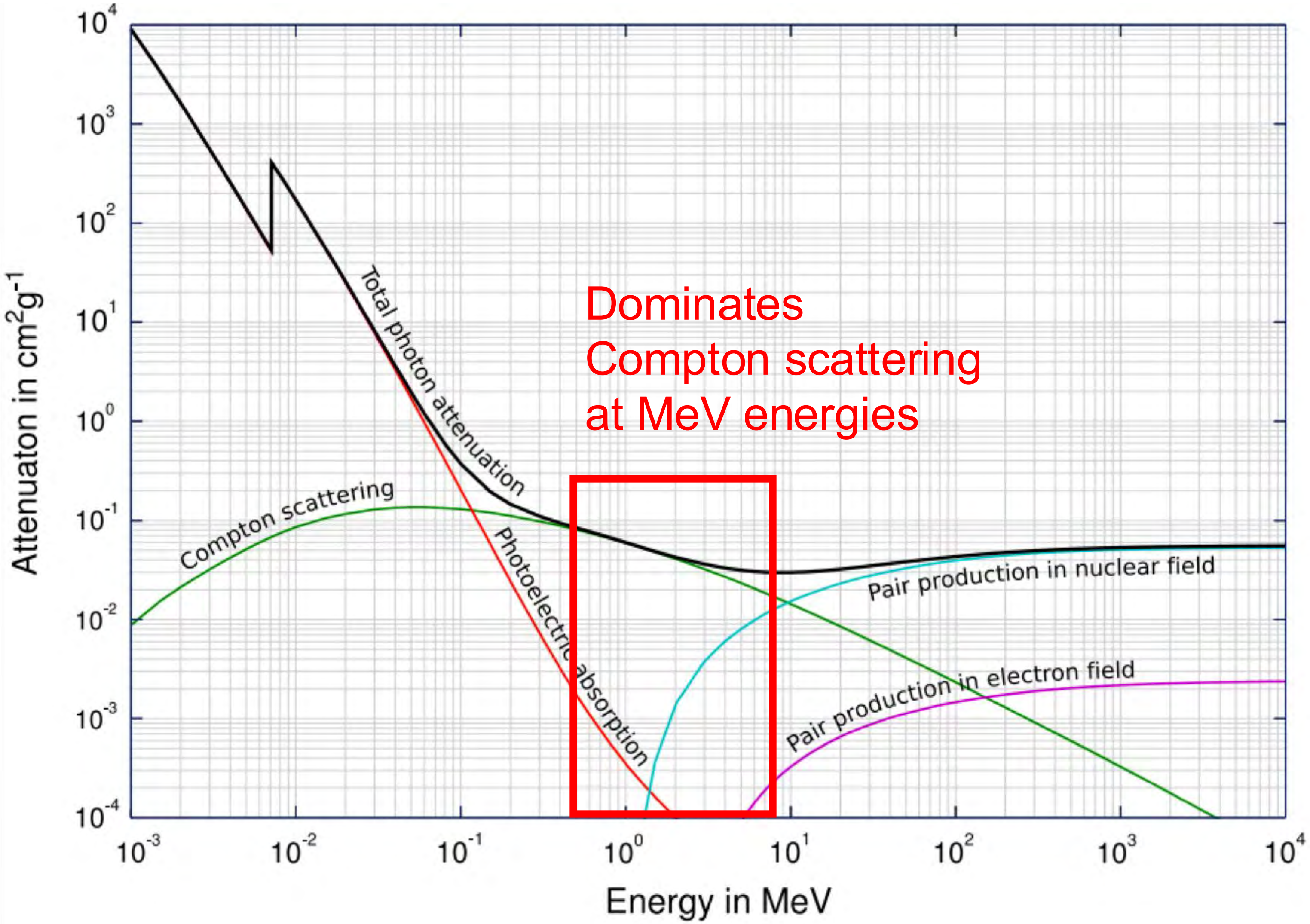
$n + {}^{35}Cl \rightarrow {}^{36}Cl + \Sigma\gamma$

$(E_{\Sigma\gamma} = 8.6\ \text{MeV})$

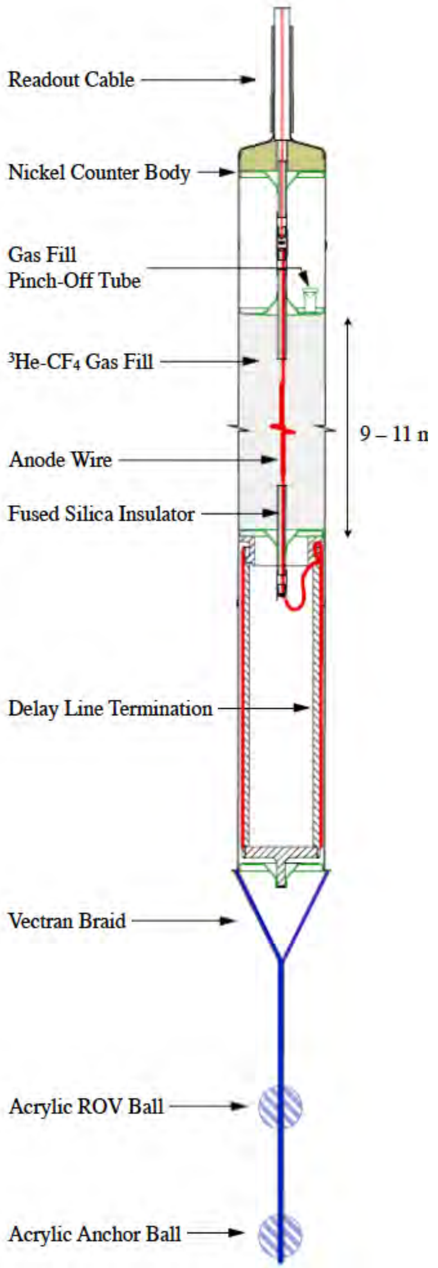
Salt Phase 2
dissolved 2000 t
NaCl (2001-2003)

Gammas are detected through the detection of Compton electrons.

Cross section of gamma rays interactions



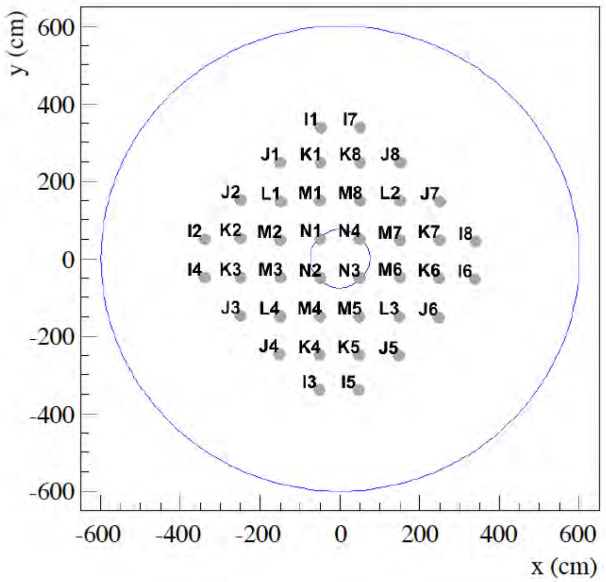
SNO Phase 3 NC measurement (2004 – 2006)



- **to increase neutron detection efficiency**
- 36 strings of Ni proportional counters filled with ^{3}He gas

$$^3\text{He} + n \rightarrow {}^3\text{H} + p$$

- ^{3}H + p have total kinetic energy of 0.76 MeV and travel in opposite directions and were detected by the proportional counter itself

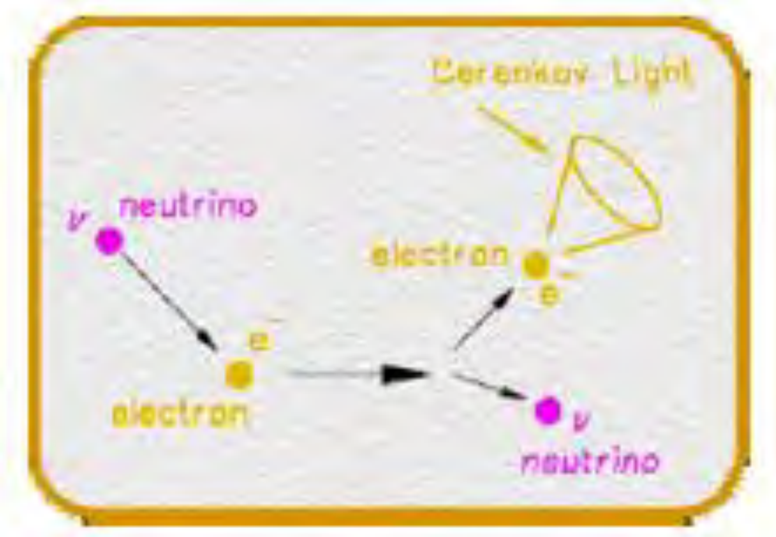


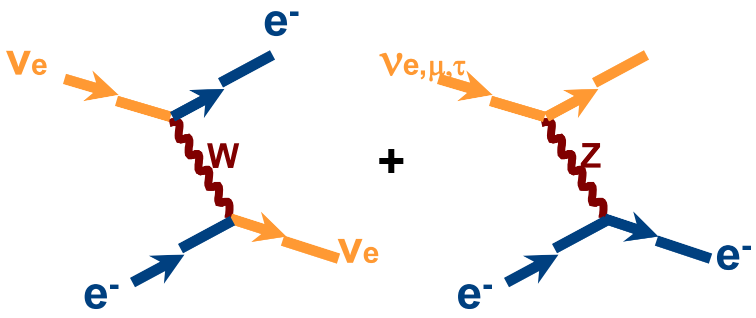
SNO Elastic Scattering measurement

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

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

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

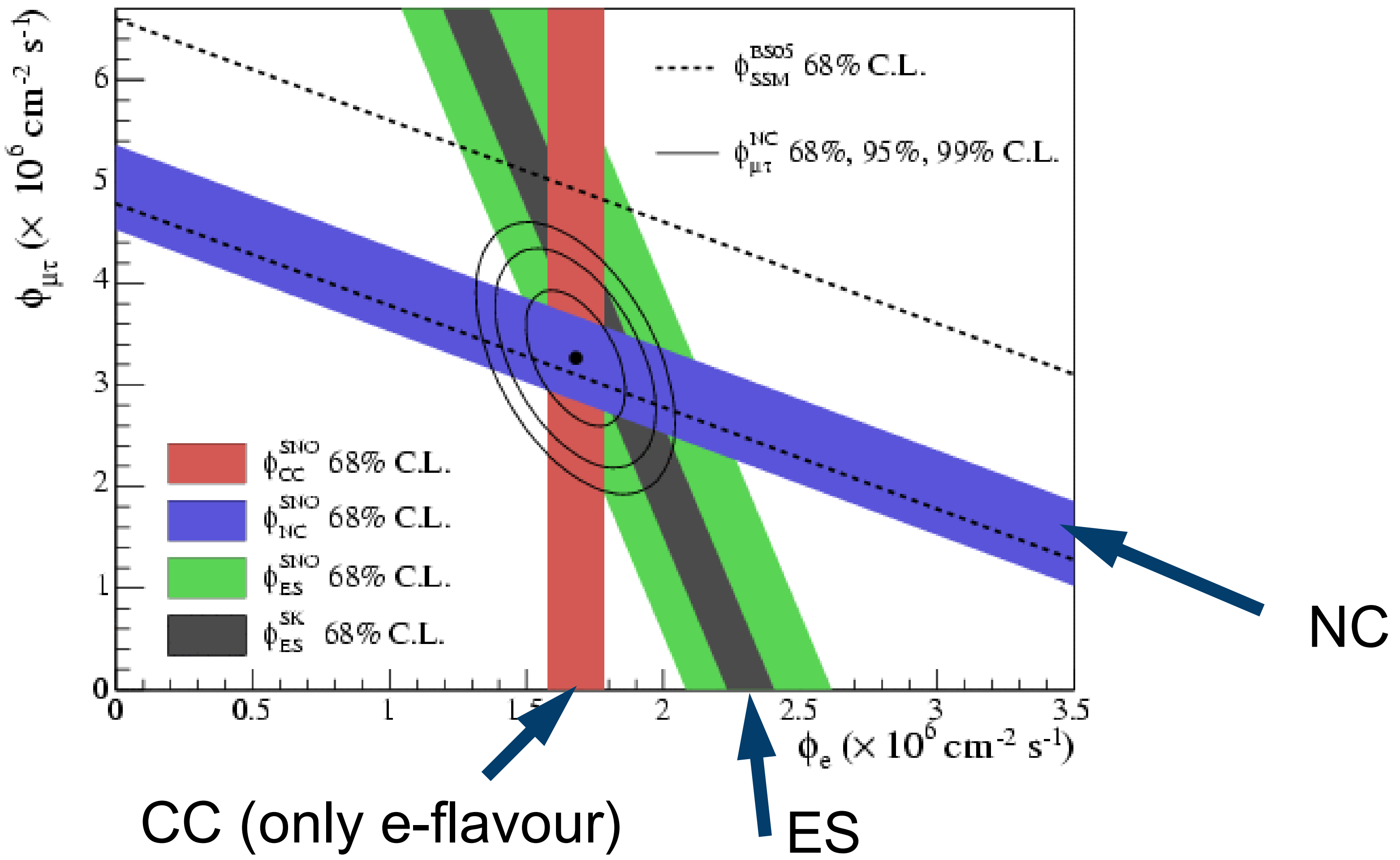


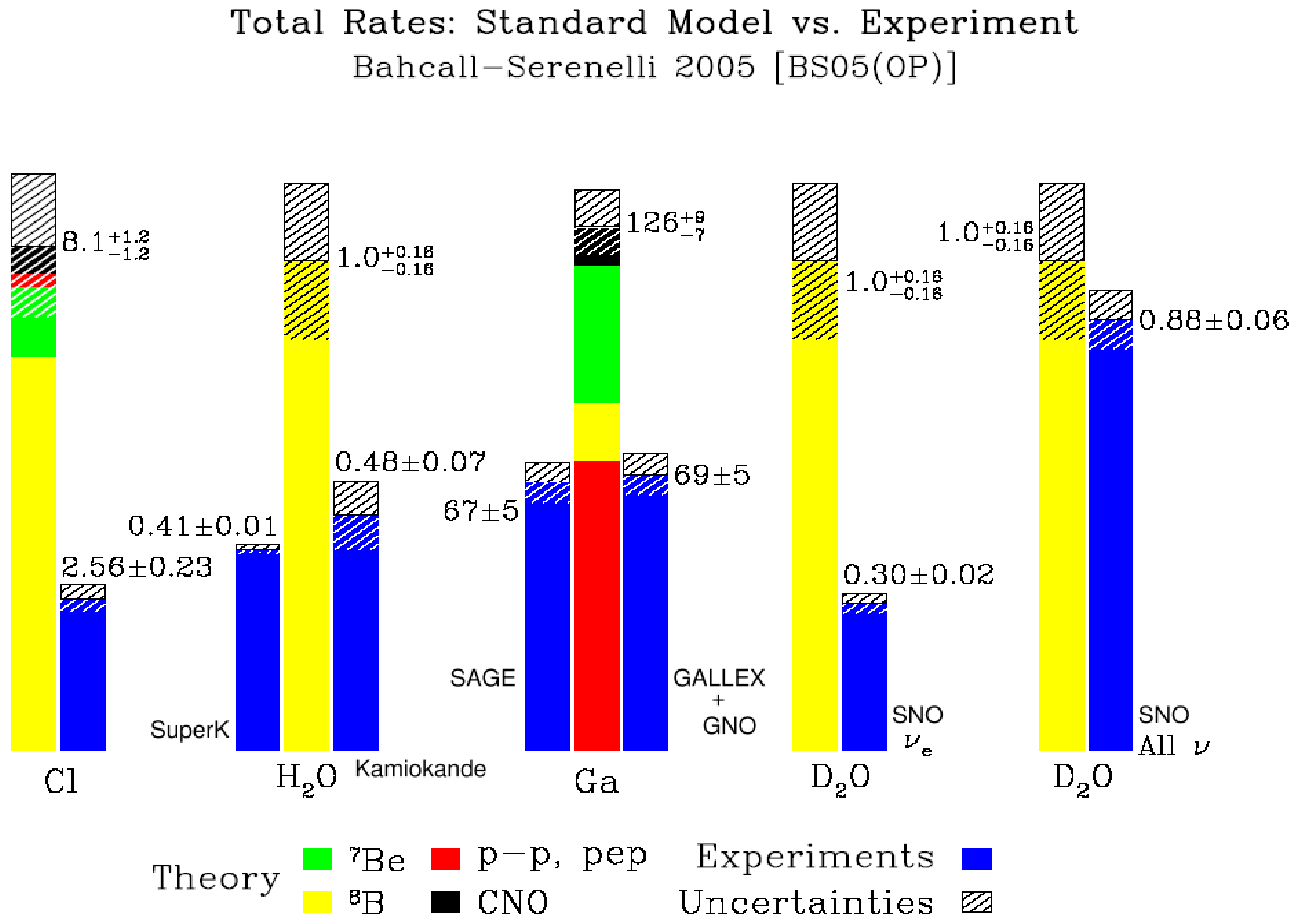


The best directionality measurement!

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.

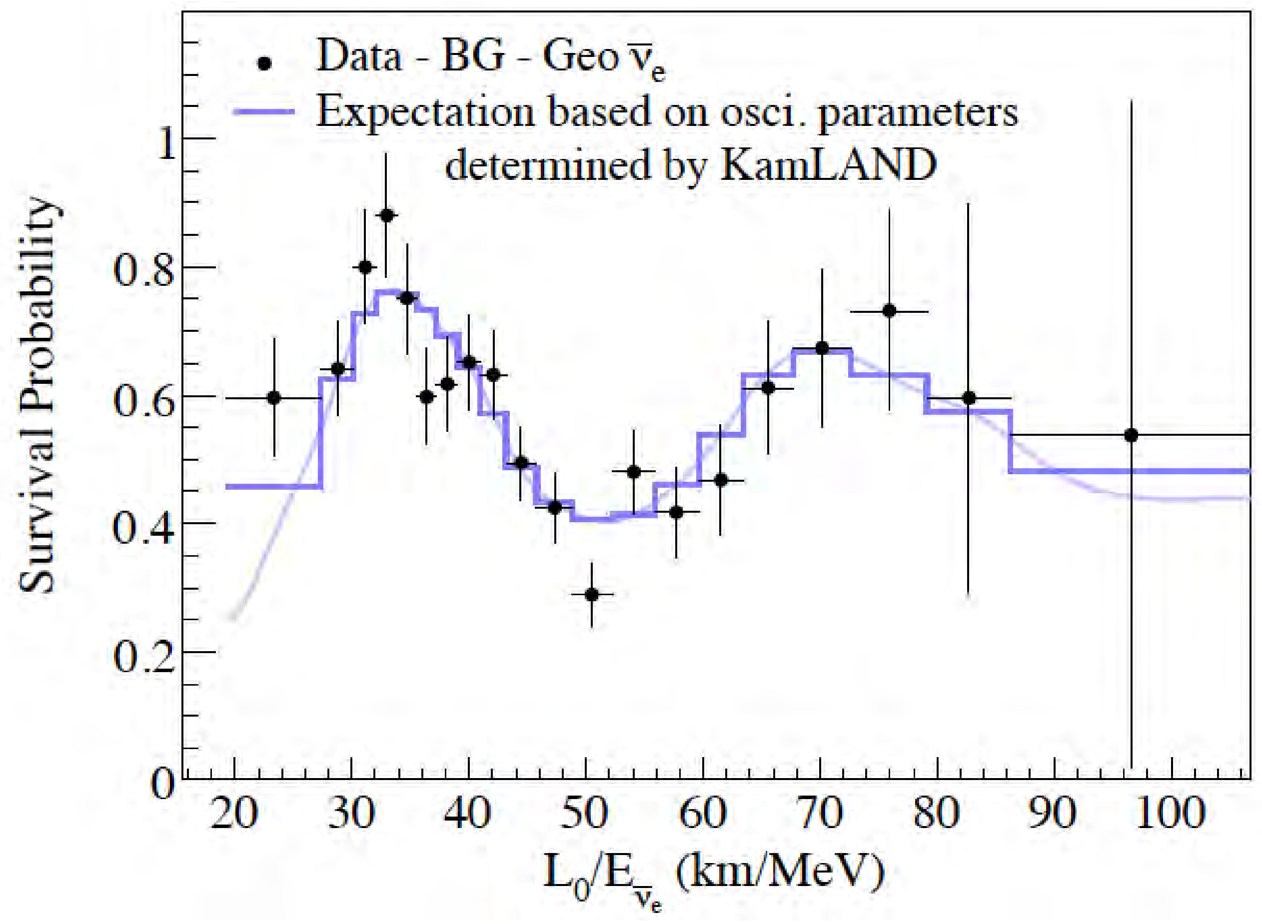




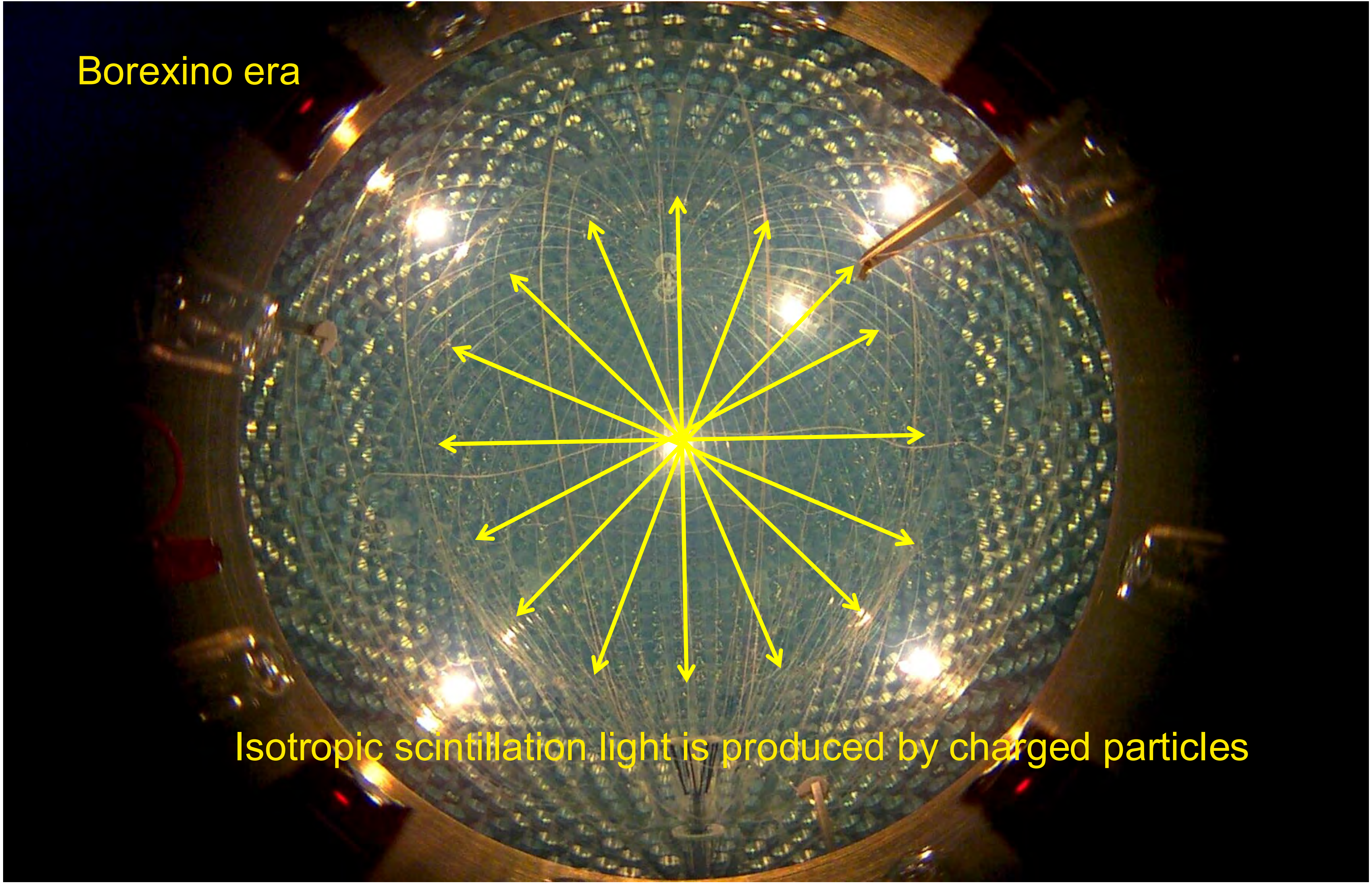
Total Rates: Standard Model vs. Experiment
Bahcall−Serenelli 2005 [BS05(OP)]
$8.1^{+1.2}_{-1.2}$
2.56 ± 0.23
Cl
0.41 ± 0.01
SuperK
$1.0^{+0.16}_{-0.16}$
0.48 ± 0.07
H_2O
Kamiokande
126^{+9}_{-7}
67 ± 5
SAGE
69 ± 5
GALLEX + GNO
Ga
$1.0^{+0.16}_{-0.16}$
0.30 ± 0.02
SNO ν_e
D_2O
$1.0^{+0.16}_{-0.16}$
0.88 ± 0.06
SNO All ν
D_2O
Theory
^{7}Be
^{8}B
p−p, pep
CNO
Experiments
Uncertainties

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

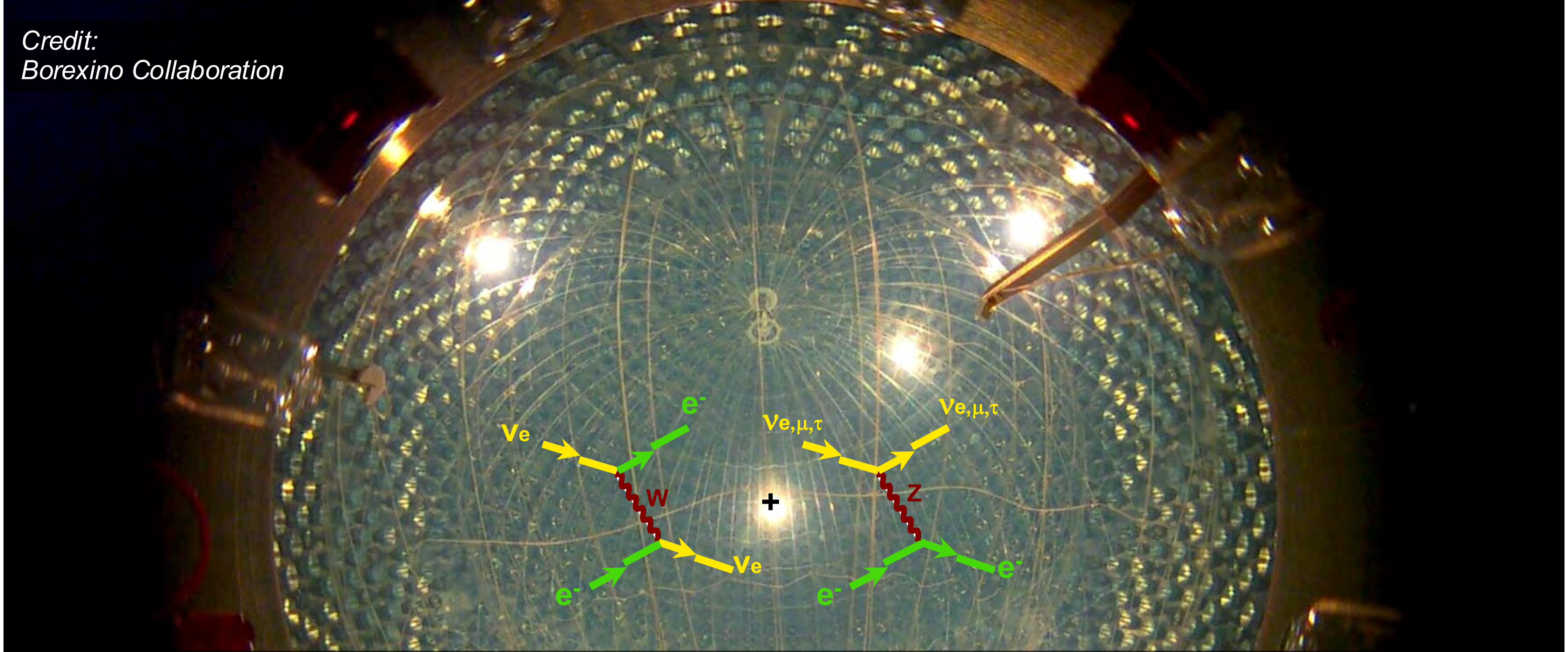
KamLAND, 2002



OSCILLATION PATTERN WAS SEEN!


Borexino era
Isotropic scintillation light is produced by charged particles

Credit:
Borexino Collaboration



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.

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!**

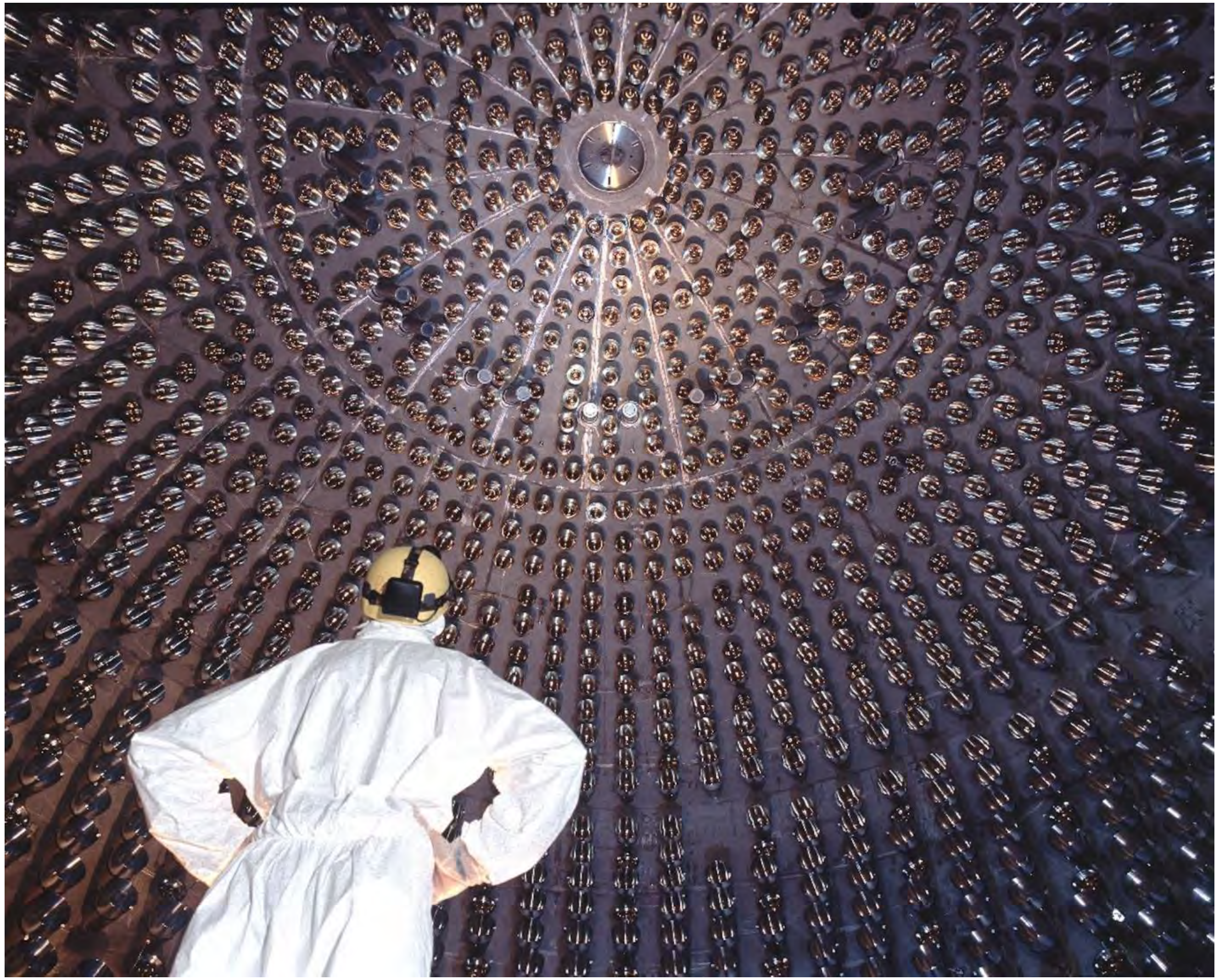
BOREXINO @ LNGS, ITALY

- 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: UNPRECEDENTED RADIOPURITY LEVELS

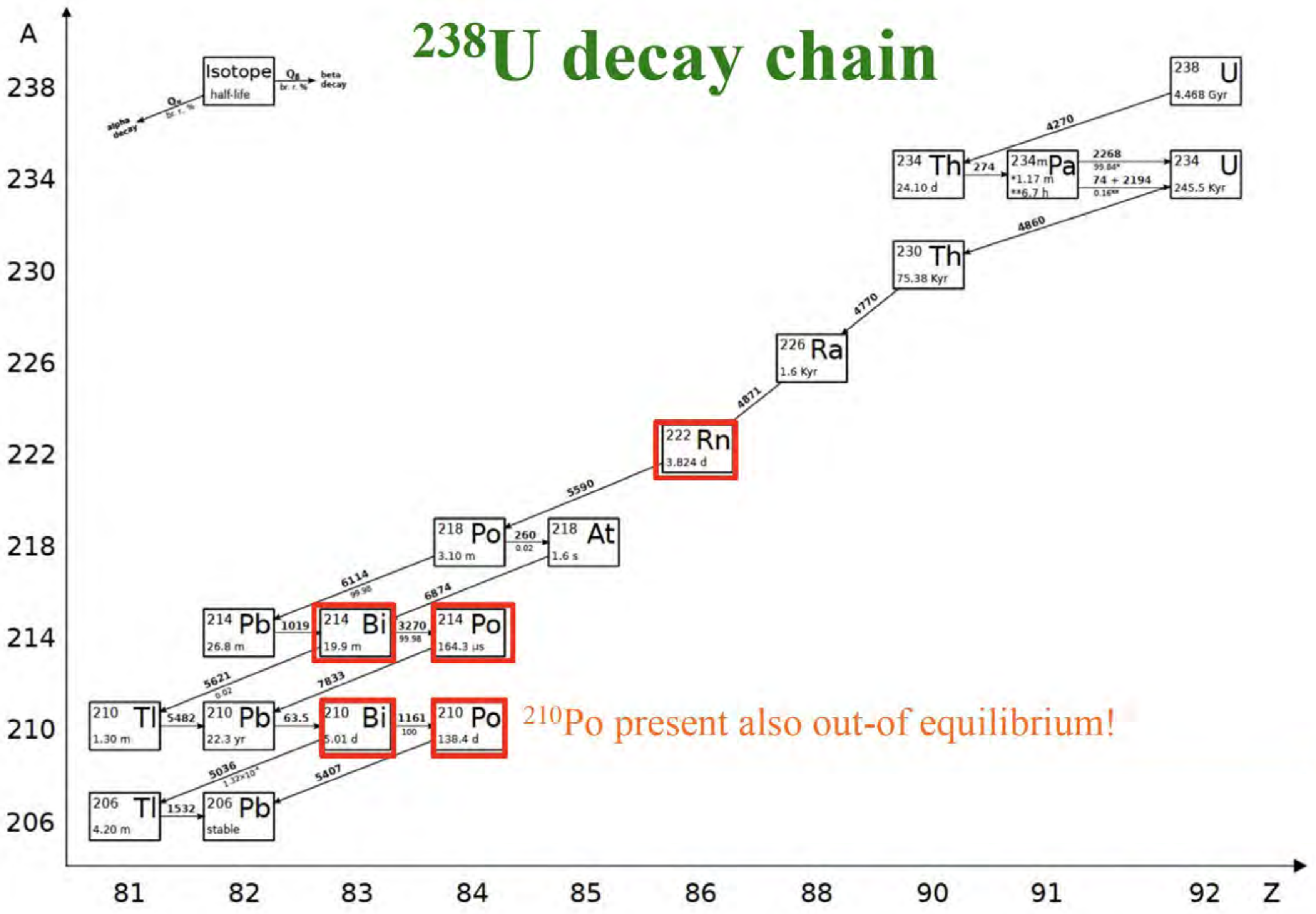
- ☑ **1990**: Start of R&D for innovative radiopurity methods
- ☑ **1995**: Counting Test Facility (CTF) testing the radiopurity
- ☑ **1997**: Approval of the experiment
- ☑ **2007**: Begin of data taking

G. Bellini

- Purification of the scintillation (distillation, vacuum stripping with low Ar/Kr N2);
- Detector design: concentric shells to shield the inner scintillator from external background
- Material selection and surface treatment, clean construction and handling;

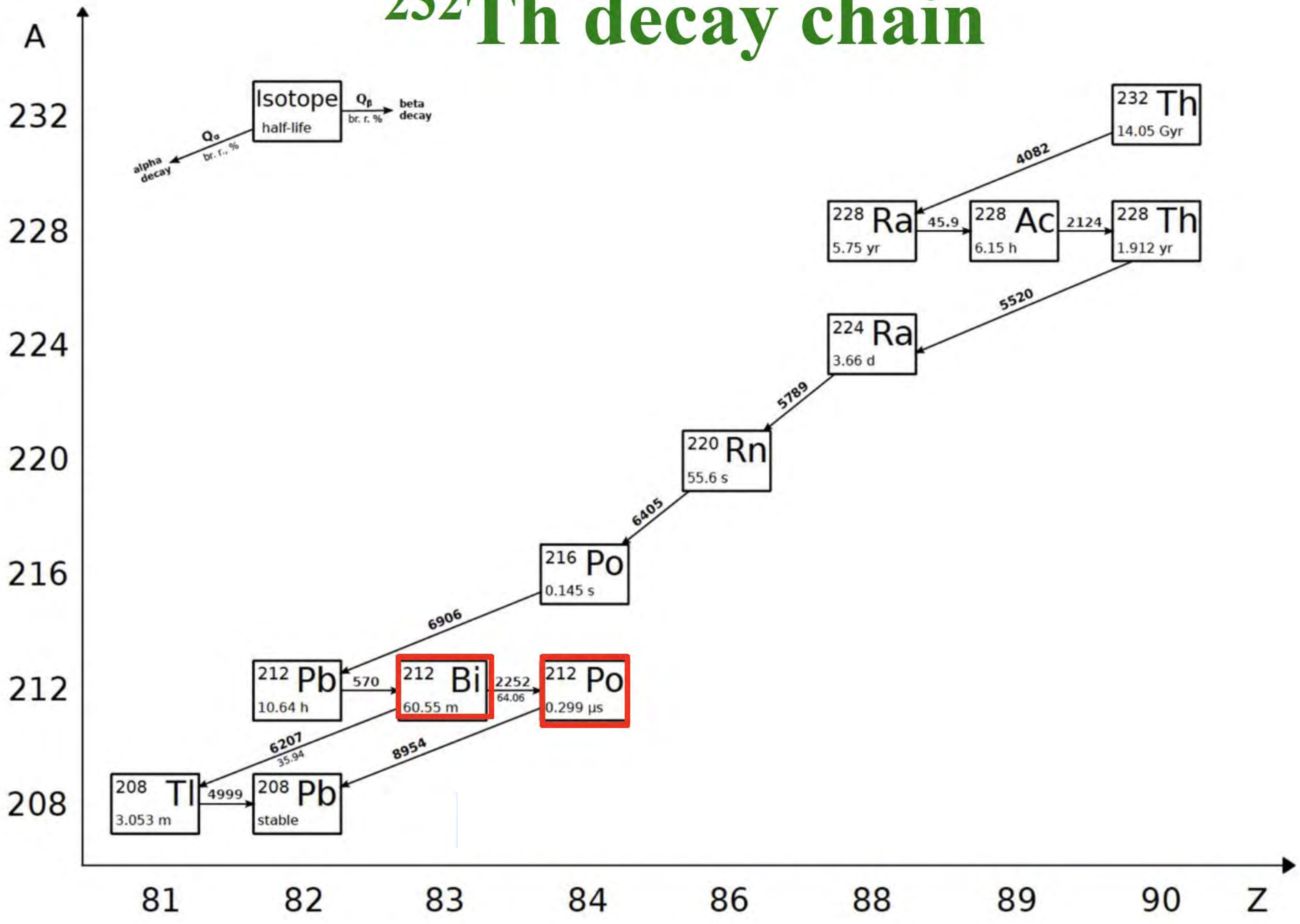
- Radiopurity even exceed design goals in some cases ^{238}U chain $<9.4\text{x}10^{-20}$ g/g and ^{232}Th chain $<5.7\text{x}\times10^{-19}$ g/g;
- Some background out of specifications (^{210}Po, ^{85}Kr, ^{210}Bi)

^{238}U decay chain



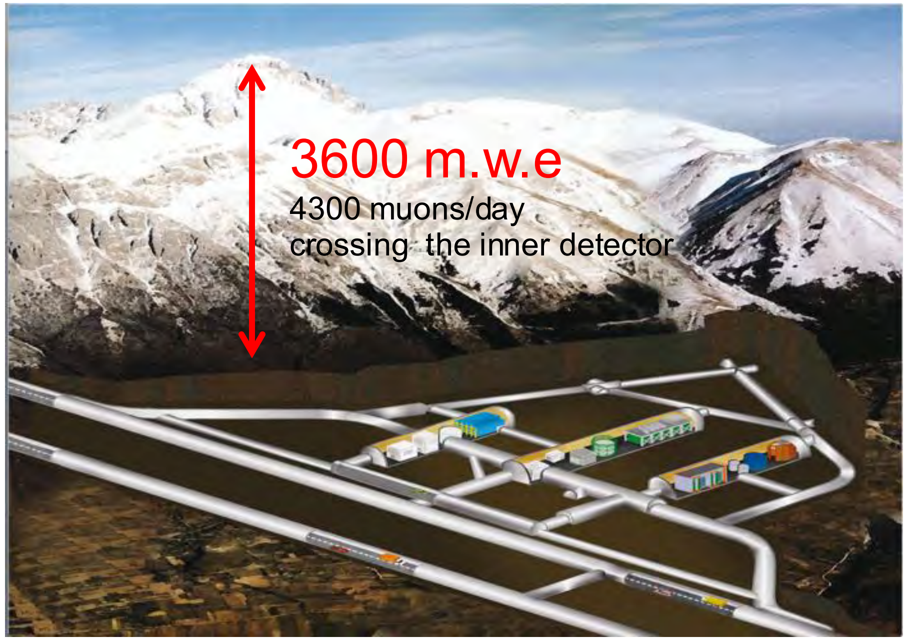
^{210}Po present also out-of equilibrium!

^{232}Th decay chain



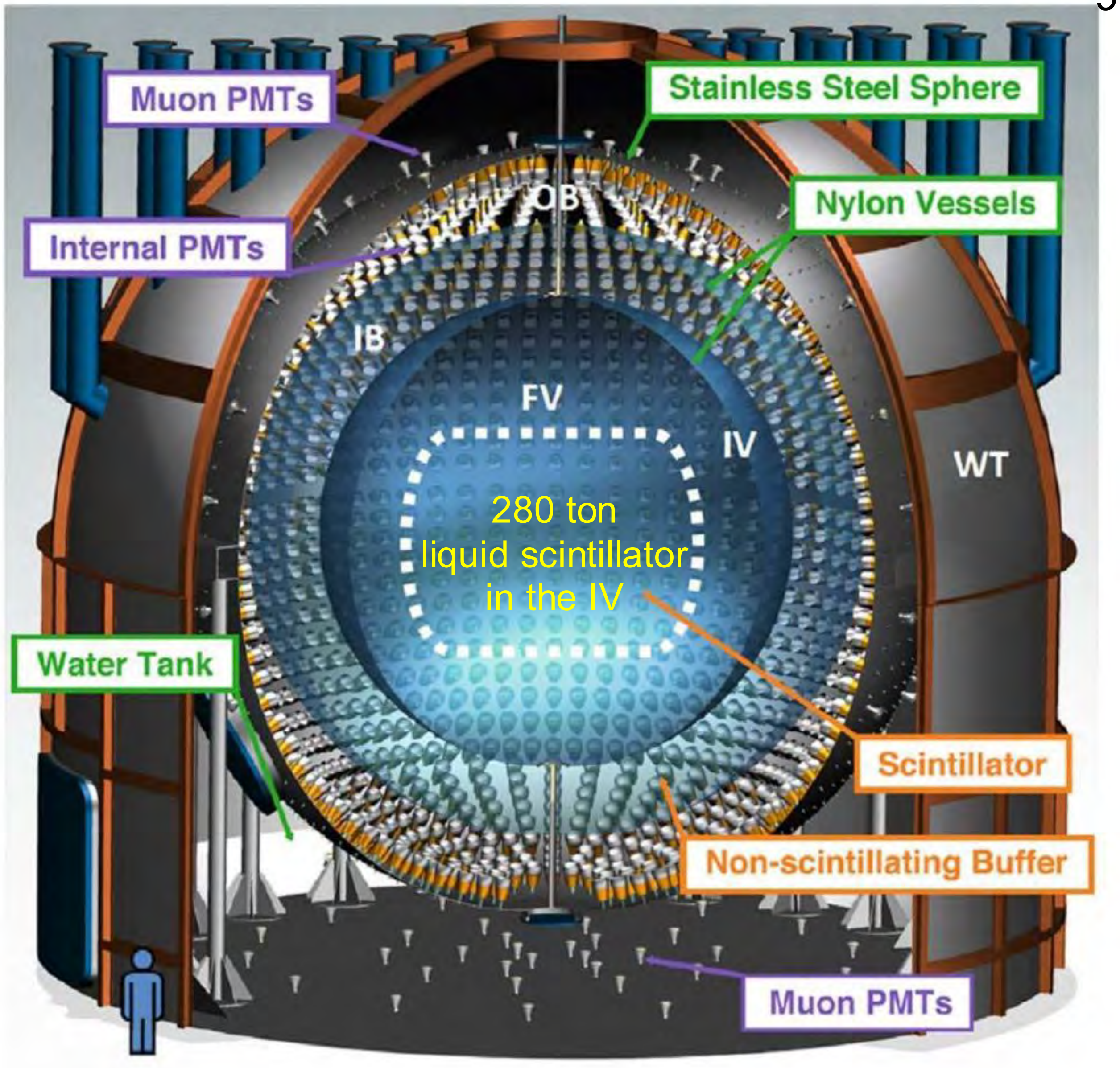
BOREXINO DETECTOR

Laboratori Nazionali del Gran Sasso, Italy



- **the world's radio-purest LS detector**

  < 5.7 × 10^{-19} g(Th)/g , < 9.4 × 10^{-20} g(U)/g
- **~50 keV trigger threshold**
- **effective LY ~500 photoelectrons with 2000 PMTs/ MeV**
- energy reconstruction: 50 keV (5%) @ 1 MeV
- position reconstruction: 10 cm @ 1 MeV
- pulse shape identification (α/β, e^+/e^-)



More about detector in:
NIM A600 (2009) 568

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

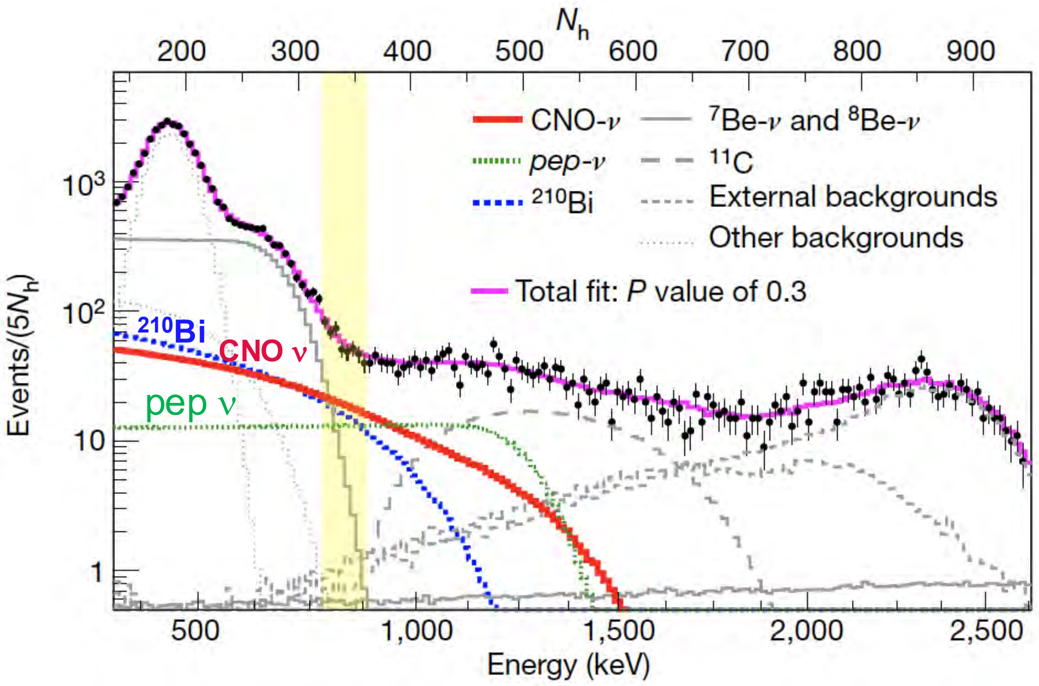
CNO
1st observation
NATURE 25/11/2020

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,

STRATEGY TO EXTRACT SOLAR NEUTRINO SIGNAL

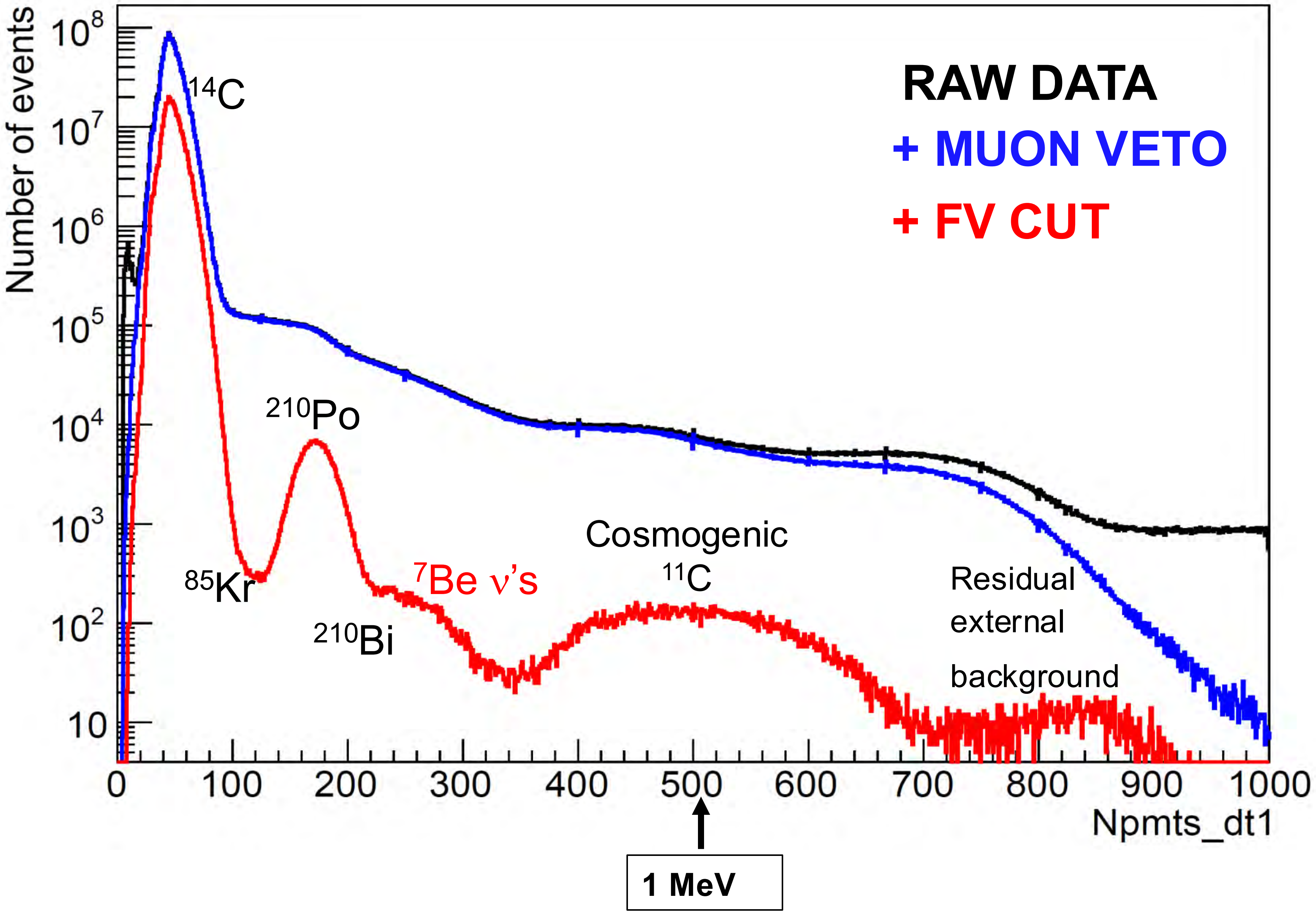
- A fit is performed to the energy distribution of events assumed to be the sum of signal and backgrounds;
- The spectral shapes are those determined with MC simulations;
- We include in the fit also the radial distribution of events to separate external backgrounds;
- **The rates of each species are the only free parameters of the fit;**



CNO discovery: NATURE 25/11/2020

- **Neutrino signal** (pp chain and **CNO**)
- **Backgrounds**
  - ✓ in the LS (^{14}C, ^{210}Po, ^{85}Kr, **^{210}Bi**)
  - ✓ external gammas
  - ✓ cosmogenic (^{11}C)

RAW SPECTRUM AND EVENT SELECTION



THREE-FOLD COINCIDENCE (TFC) TO TAG ^{11}C

Critical for *pep* and CNO neutrinos

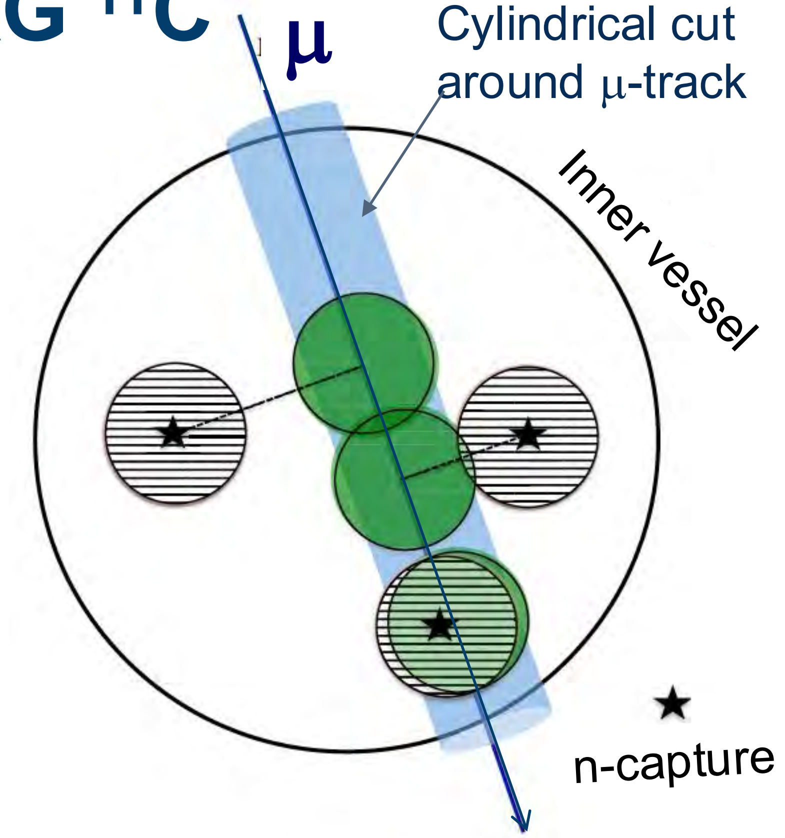
$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

$^{11}C \rightarrow {}^{11}B + e^{+} + \nu_e$
$\tau \sim 30$ min

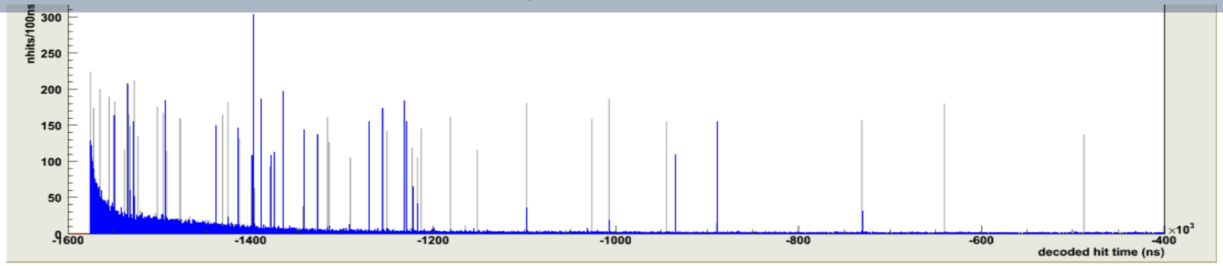
$n + p \rightarrow d + \gamma$ (2.2 MeV)
$\tau \sim 260\ \mu s$

Muon detection ε = 99.992%:

- Outer Detector trigger
- Cluster of hits in Outer Detector data
- Pulse-shape of Inner Detector data



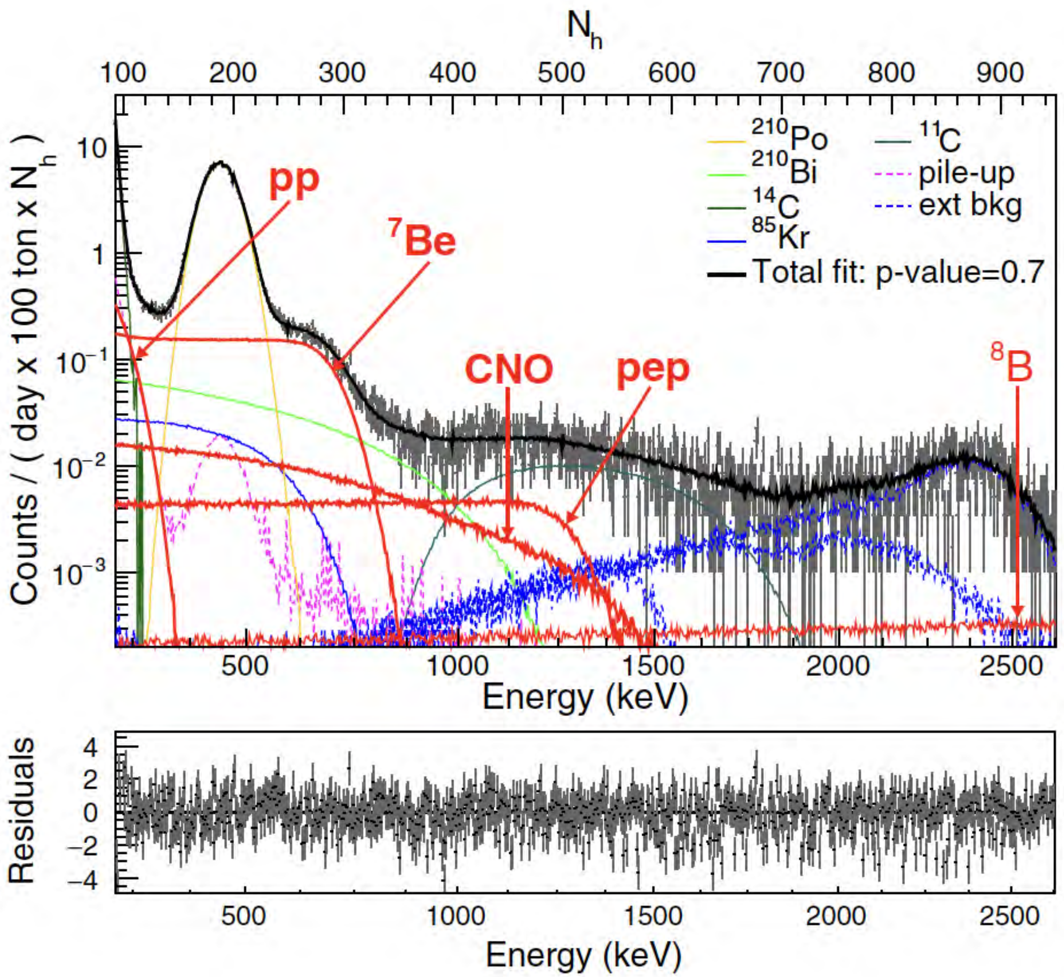
Neutron detection: after each ID μ, 1.6 ms gate is opened to detect neutrons: example with several tens of neutrons.



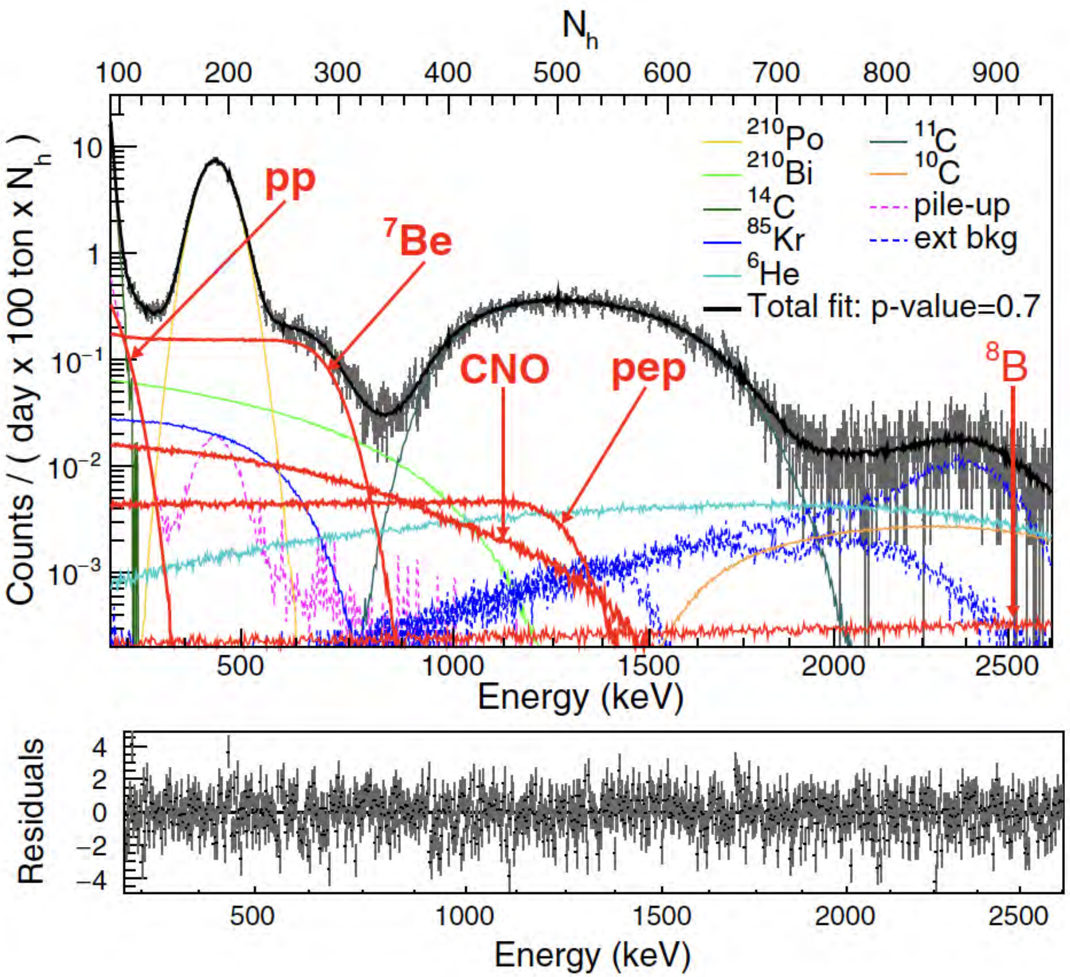
Exposure divided to 2 categories:
TFC-tagged (36% of exposure, 92% of ^{11}C)
TFC-subtracted (64% of exposure, 8% of ^{11}C)

Likelihood that a certain event is ^{11}C uses in input time and space correlations between muons and cosmogenic neutrons.

TFC SUBTRACTED (~10% OF ^{11}C)

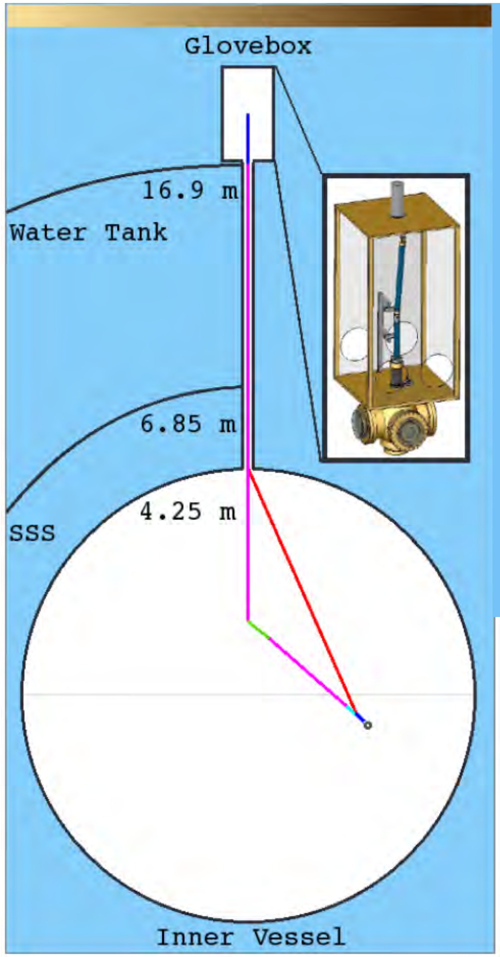


TFC TAGGED (~90% OF ^{11}C)



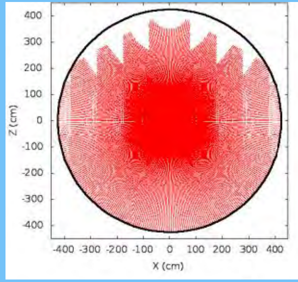
BOREXINO CALIBRATION

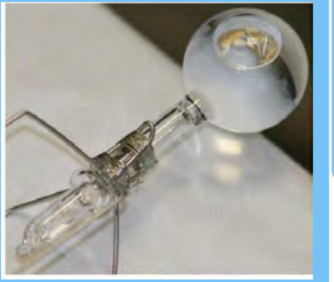
JINST 7 (2012) P10018



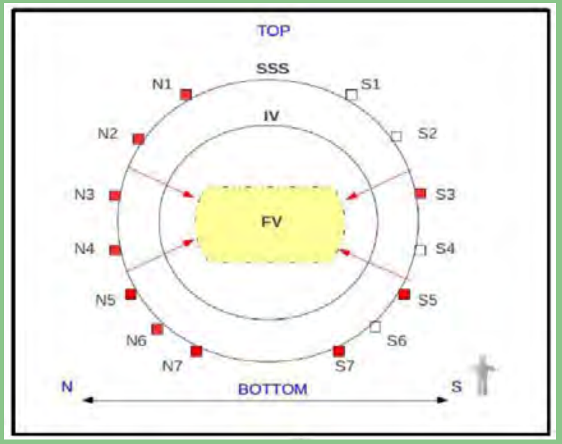
Internal calibration

- ~300 points in the whole scintillator volume
- LED-based source positioning system





Source	Type	E [MeV]	Position	Motivations
^{57}Co	γ	0.122	in IV volume	Energy scale
^{139}Ce	γ	0.165	in IV volume	Energy scale
^{203}Hg	γ	0.279	in IV volume	Energy scale
^{85}Sr	γ	0.514	z-axis + sphere R=3 m	Energy scale + FV
^{54}Mn	γ	0.834	along z-axis	Energy scale
^{65}Zn	γ	1.115	along z-axis	Energy scale
^{60}Co	γ	1.173, 1.332	along z-axis	Energy scale
^{40}K	γ	1.460	along z-axis	Energy scale
^{222}Rn+^{14}C	β,γ	0-3.20	in IV volume	FV+uniformity
	α	5.5, 6.0, 7.4	in IV volume	FV+uniformity
^{241}Am^{9}Be	n	0-9	sphere R=4 m	Energy scale + FV

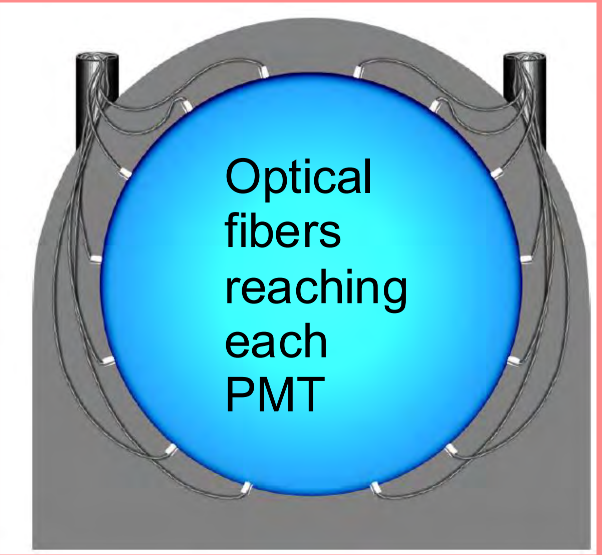


External calibration

9 positions with ^{228}Th source (γ 2.615 MeV)

Laser calibration

- PMT time equalisation
- PMT charge calibration (charge calib. also using ^{14}C)



BOREXINO MONTE CARLO

Better than 1% (1.9%) precision
for all relevant quantities in the solar analysis <2 (>3) MeV

Astrop. Phys. 97 (2018) 136

Geant-4 based

Tracking code

- Full detector geometry
- Energy loss
- Photon production & propagation

C++ Borexino custom

Electronics simulation

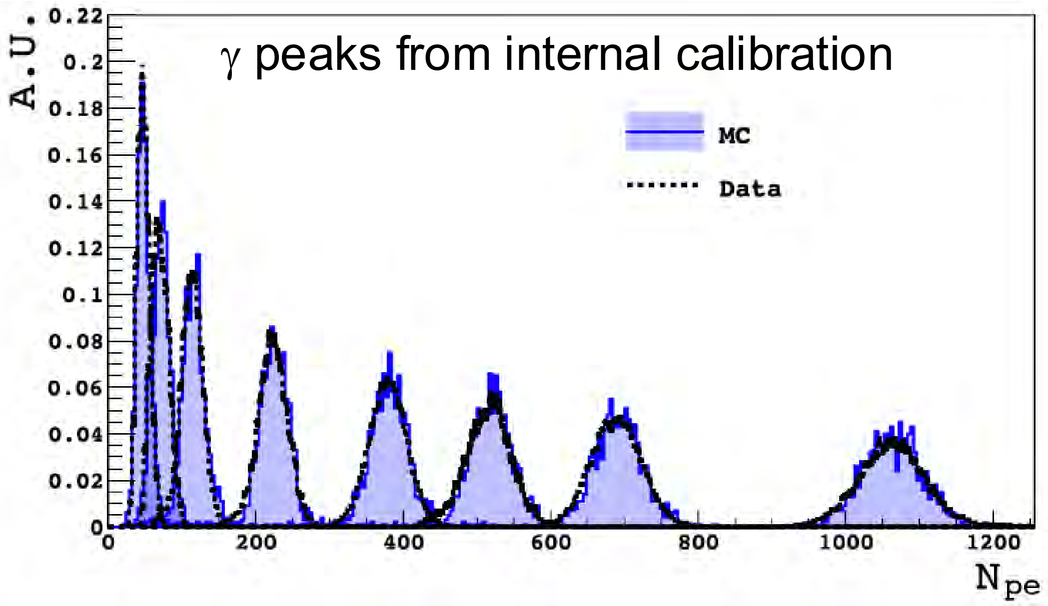
Follows real DAQ conditions

- PMT quality and calibration
- Dark noise
- Trigger condition
- Number of working channels on an event-by-event basis

Echidna: C++ Borexino custom

Reconstruction

- Several energy estimators
- Position reconstruction
- Pulse-shape variables
- Output in the same format as reconstructed data files

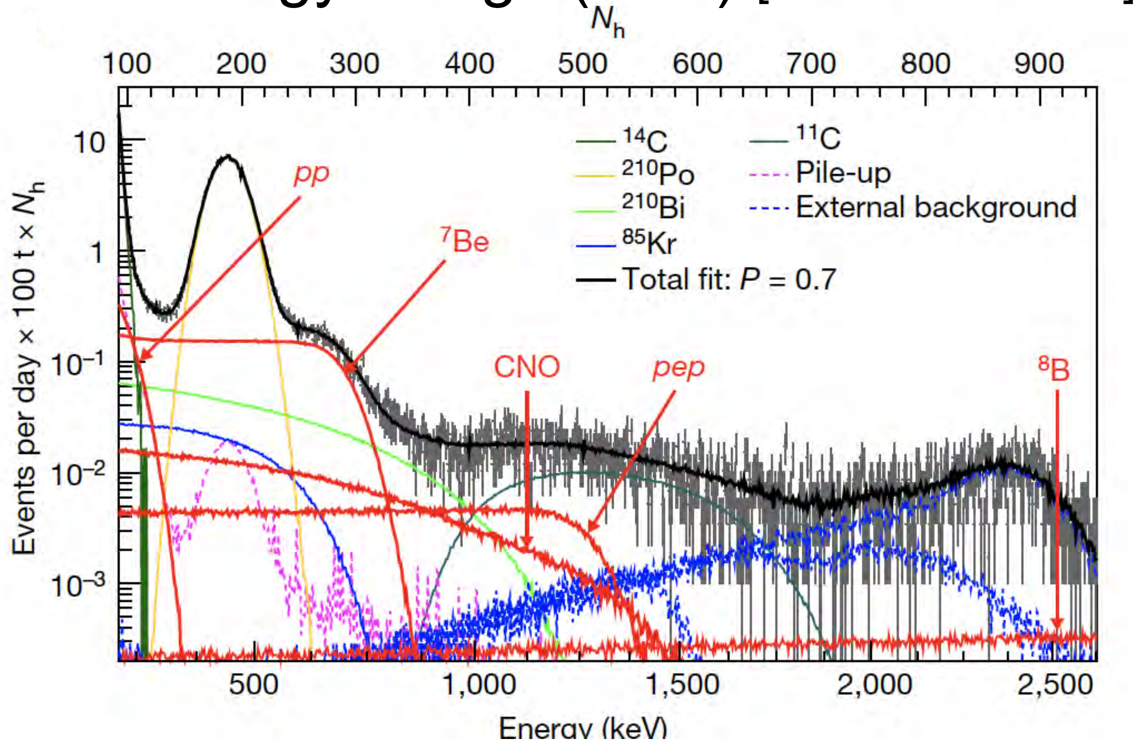


- **Tuning on calibration data.**
- **Independently measured input parameters**: emission spectra, attenuation length, PMT after-pulse, refractive index, effective quantum efficiencies.
- **Biasing technique for external background.**
- **Simulation of pile-up events.**

BOREXINO LATEST PP-CHAIN RESULTS

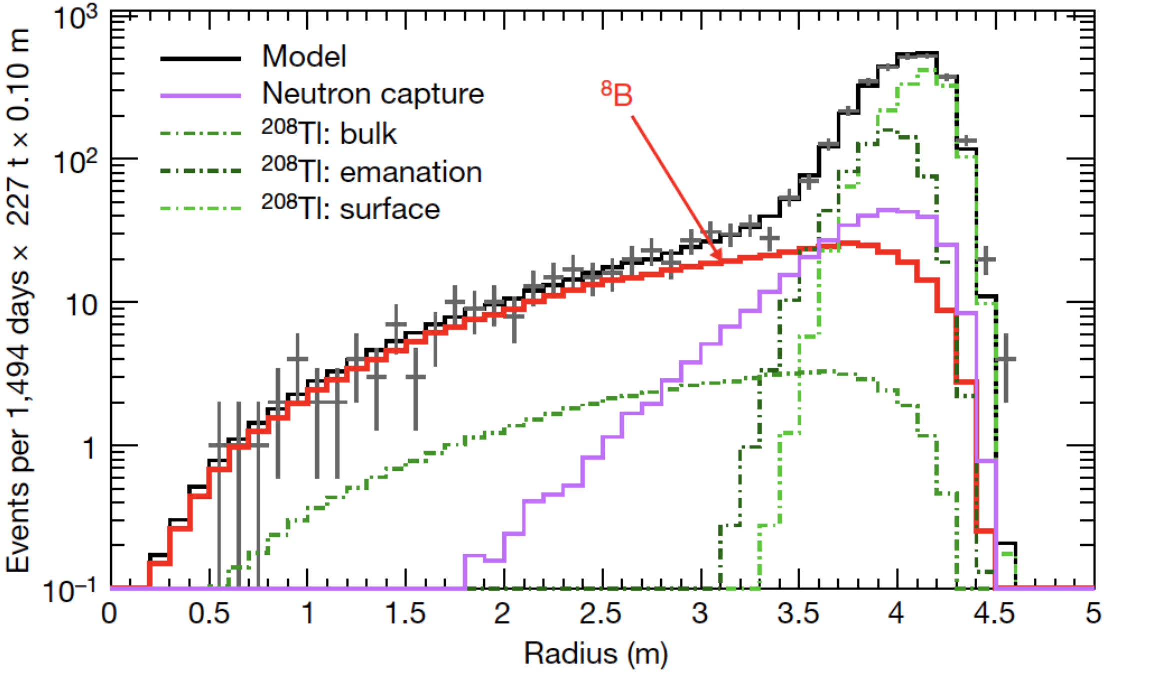
Full pp chain spectroscopy with NATURE 25/10/2018

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 RESULT

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.)

Measurement of the interaction rates:

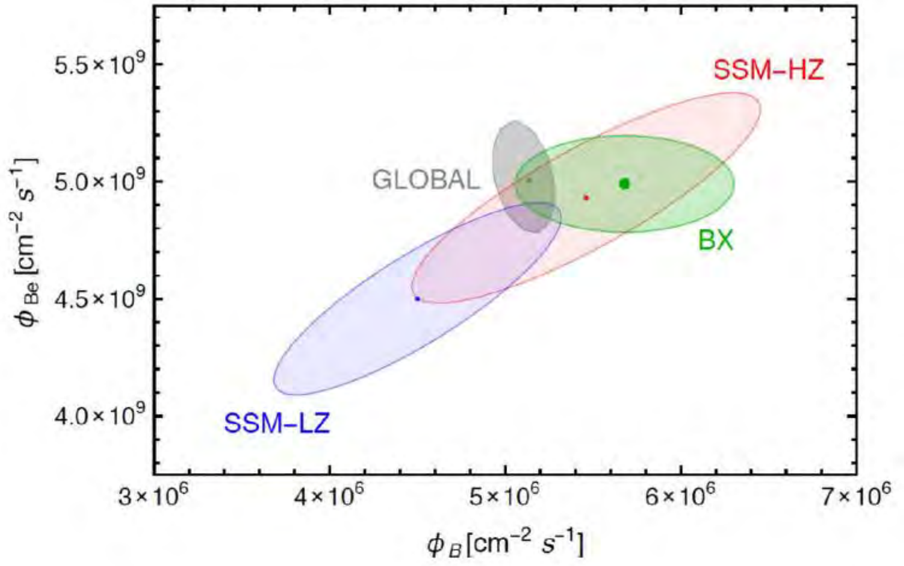
LER: ***pp*** (10.5%), **^{7}Be** (2.7%), ***pep*** (>5σ, 17%)

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

First Borexino limit on **hep** neutrinos

- 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

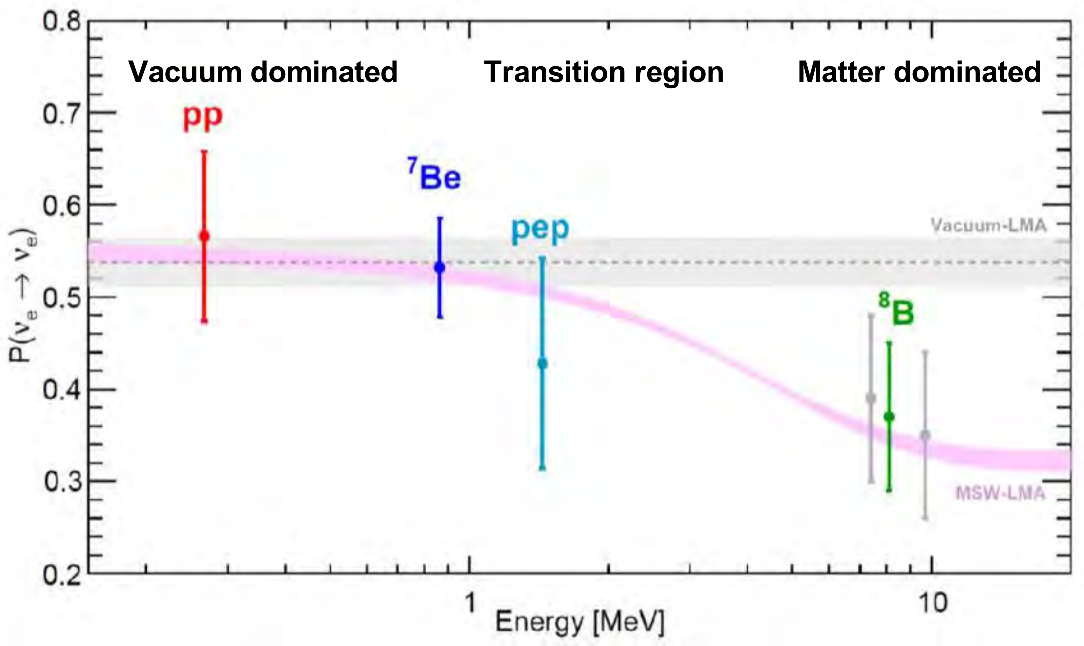
Slight preference towards the HZ SSM



Nature
Oct 25th 2018

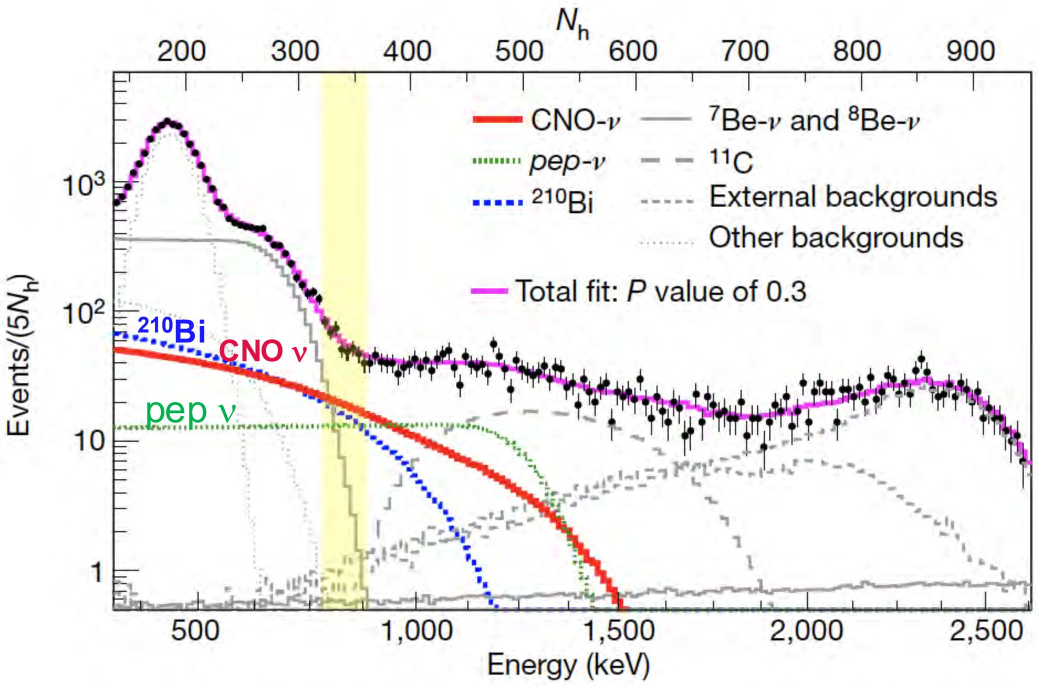
P_{ee} survival probability at different energies

Vacuum-LMA model excluded at 98.2% CL



CHALLENGES TO MEASURE CNO SOLAR NEUTRINO

- Low rate (3-5 counts/day/100 ton of liquid scintillator)
- No prominent spectral features
- Buried under the **cosmogenic ^{11}C background** – **Three Fold Coincidence** & exposure division
- **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: THE CHALLENGE



CNO discovery: NATURE 25/11/2020

- **Neutrino signal** (pp chain and **CNO**)
- **Backgrounds**
  - ✓ in the LS (^{14}C, ^{210}Po, ^{85}Kr, ^{210}**Bi**)
  - ✓ external gammas
  - ✓ cosmogenic (^{11}C)

^{11}C subtracted spectrum

BOREXINO STRATEGY TO CONSTRAIN 210-BISMUTH

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

$$^{210}\mathrm{Pb} \xrightarrow{\beta\ (63\ \mathrm{KeV})} {}^{210}\mathrm{Bi} \xrightarrow{\beta(1160\ \mathrm{keV})} {}^{210}\mathrm{Po} \xrightarrow{\alpha} {}^{206}\mathrm{Pb}$$

^{210}Pb	^{210}Bi	^{210}Po	^{206}Pb
$T_{1/2}$=22y	5 days	138 days	stable

- contaminant of the scintillator
- long-lasting source of ^{210}Bi
- below the analysis threshold

anti-correlated background to CNO

- **event-by-event identification using** MLP α/β pulse shape discriminator

Assuming **secular equilibrium**, all these **rates are the same.**

BOREXINO STRATEGY TO CONSTRAIN 210-BISMUTH

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

$^{210}Pb \xrightarrow{\beta\ (63\ \mathrm{KeV})} {}^{210}Bi \xrightarrow{\beta (1160\ \mathrm{keV})} {}^{210}Po \xrightarrow{\alpha} {}^{206}Pb$

$T_{1/2}$=22y — 5 days — 138 days — stable

- contaminant of the scintillator
- long-lasting source of ^{210}Bi
- below the analysis threshold

anti-correlated background to CNO

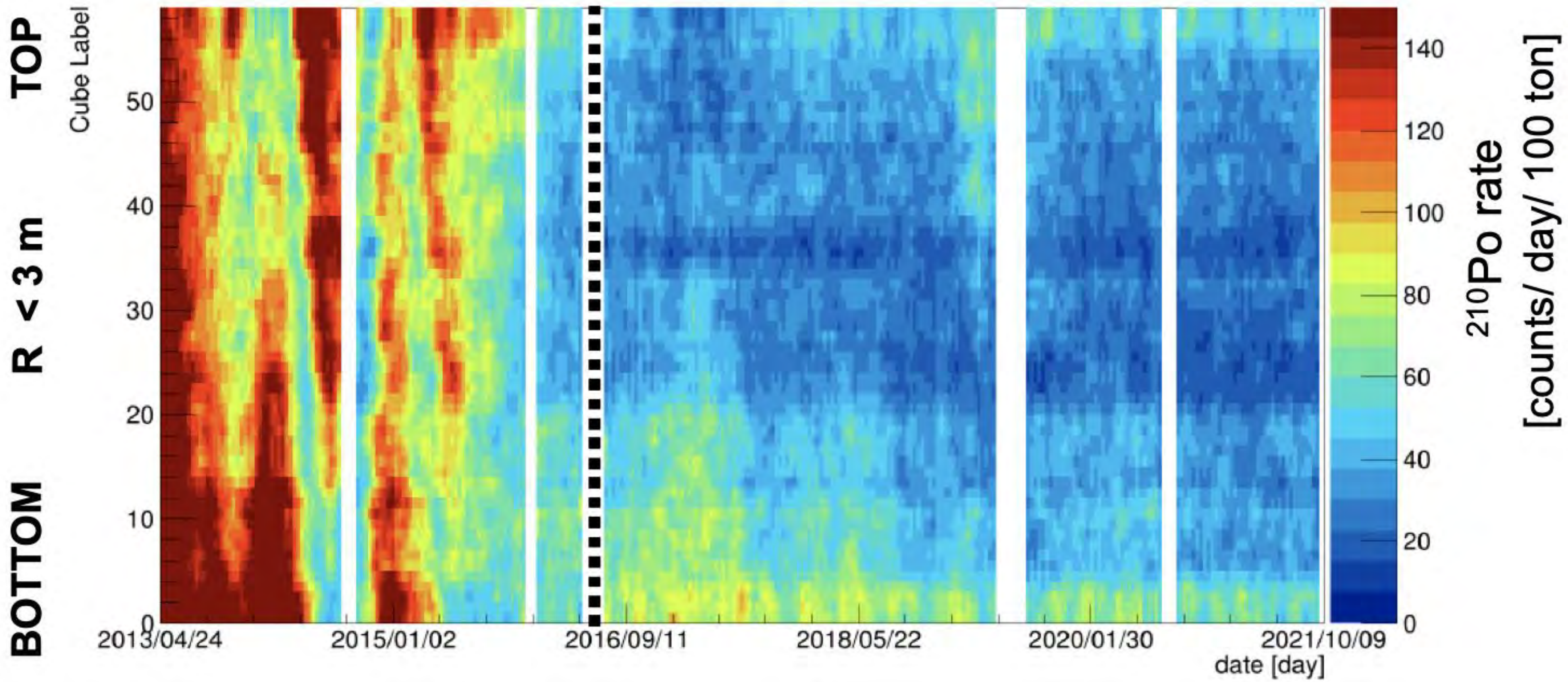
- **event-by-event identification using** MLP α/β pulse shape discriminator

Problem: seasonal convective currents bringing ^{210}Po from the nylon vessel to the fiducial volume of the analysis; **breaking the secular equilibrium**

TEMPORAL EVOLUTION OF 210-POLONIUM RATE

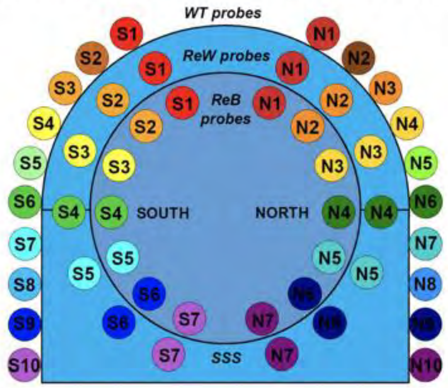
Phase II
Seasonal effect

Phase III
Thermal stabilization of the detector

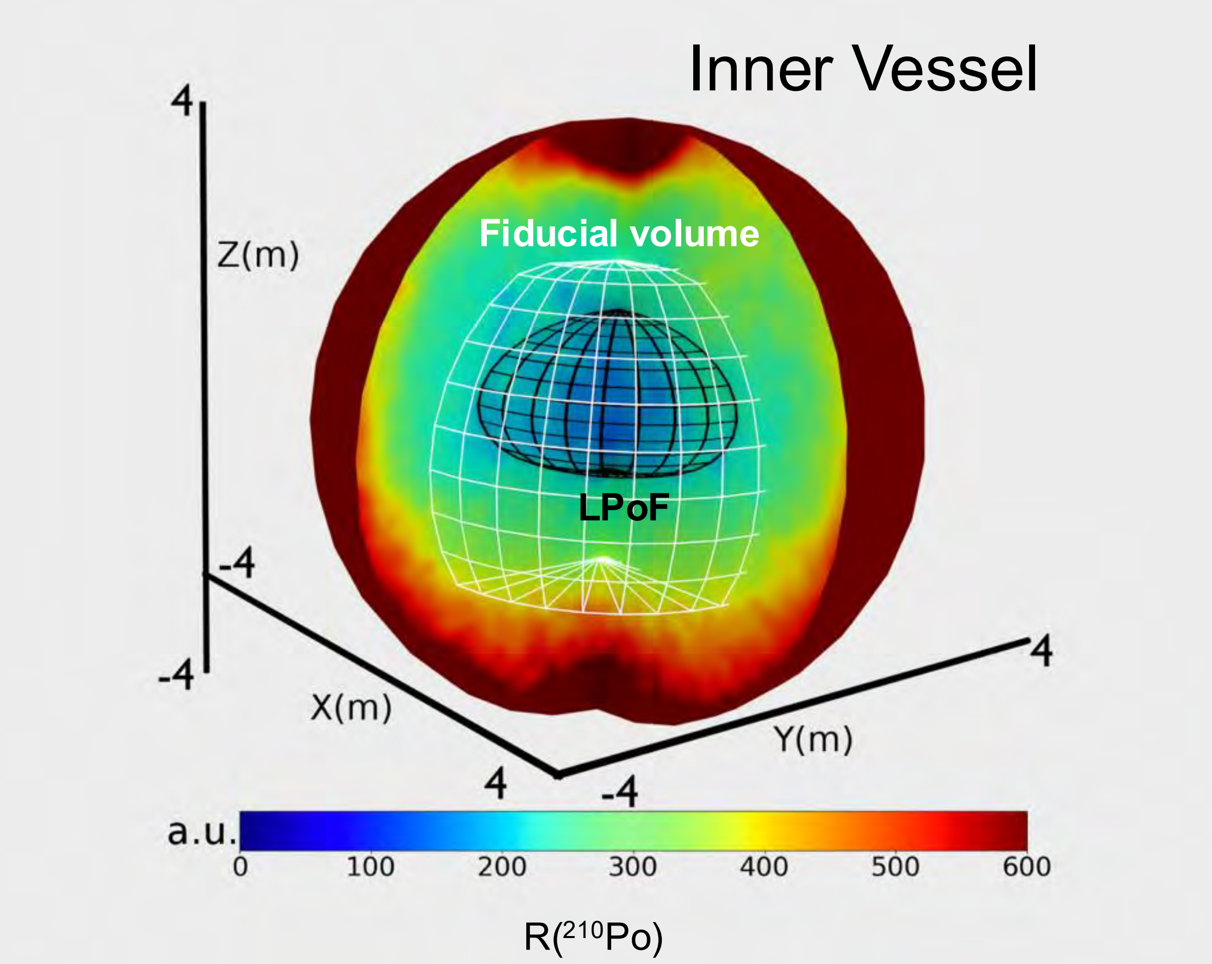


Thermal insulation

Active thermal control



210-BISMUTH UPPER LIMIT CONSTRAINT



Nature 587 (2020) 577

1. LOW POLONIUM FIELD (LPoF): clean region in the core of the detector

2. Fitting LPoF → ^{210}Po minimal rate, that is an upper limit on ^{210}Bi rate

$R(^{210}Bi) < R(^{210}Po_{min}) = R(^{210}Bi) + R(^{210}Po^{vessel})$

3. R(^{210}Bi) is homogeneous in the whole fiducial volume of the analysis within 0.68 cpd/100 ton (major systematics)

4. **Upper limit on R(^{210}Bi) applied** as a half-Gaussian constraint in the spectral fit

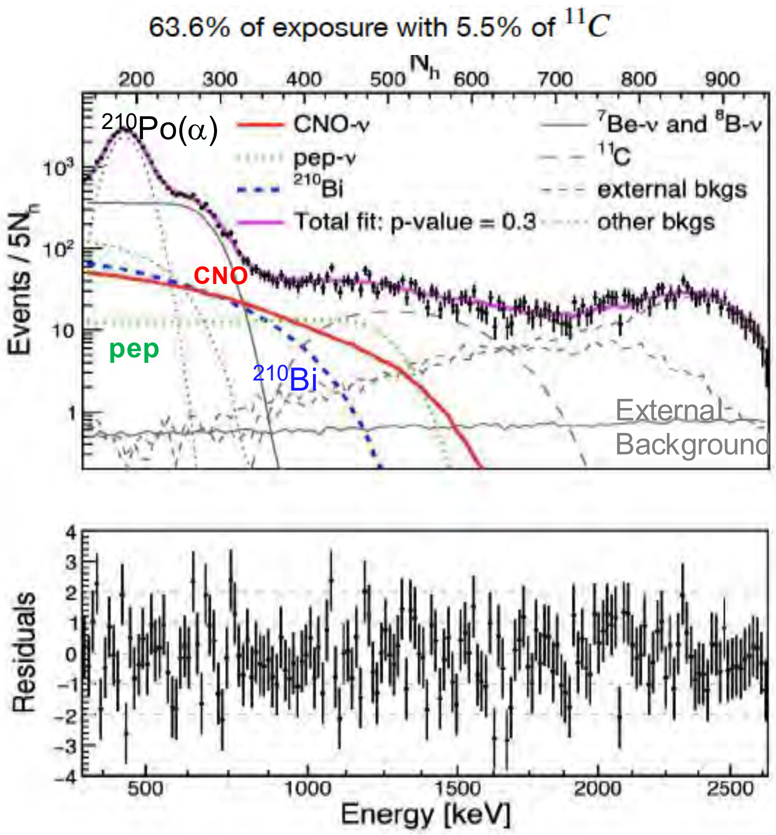
$R(^{210}Bi) \leq (10.8 \pm 1.0)$ counts / day / 100 ton

including all systematic errors

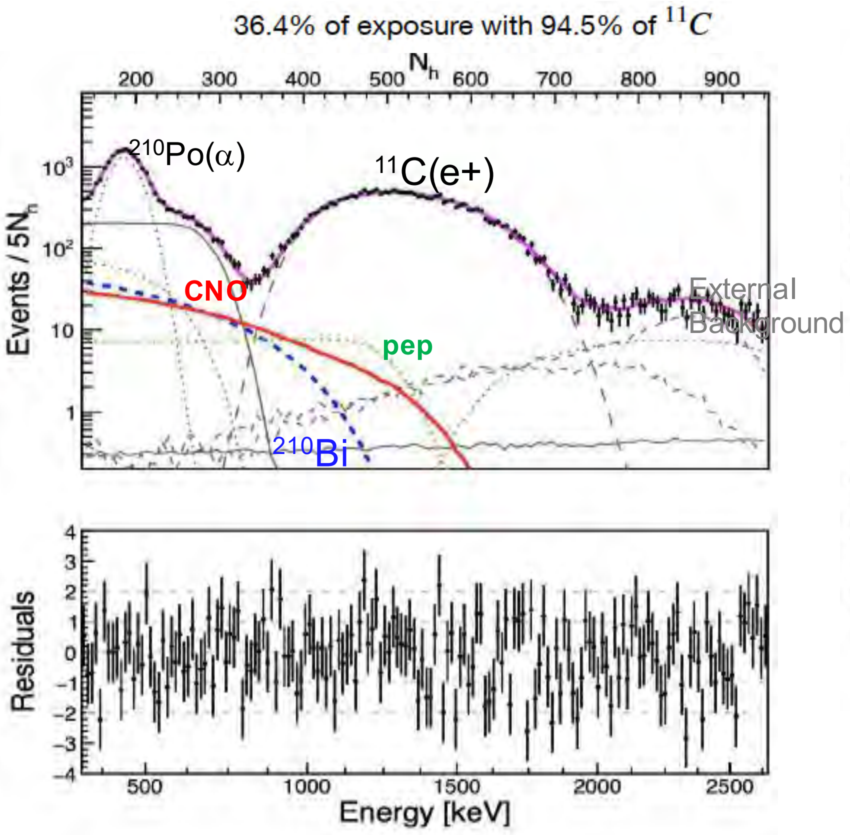
MULTIVARIATE SPECTRAL FIT

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

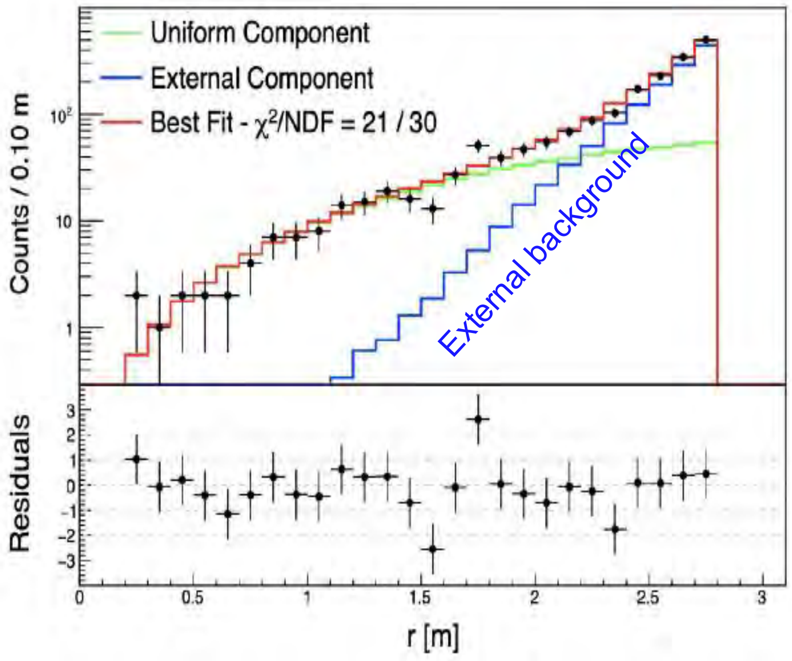
TFC-^{11} C subtracted energy spectrum



TFC-^{11}C tagged energy spectrum



Radial distribution



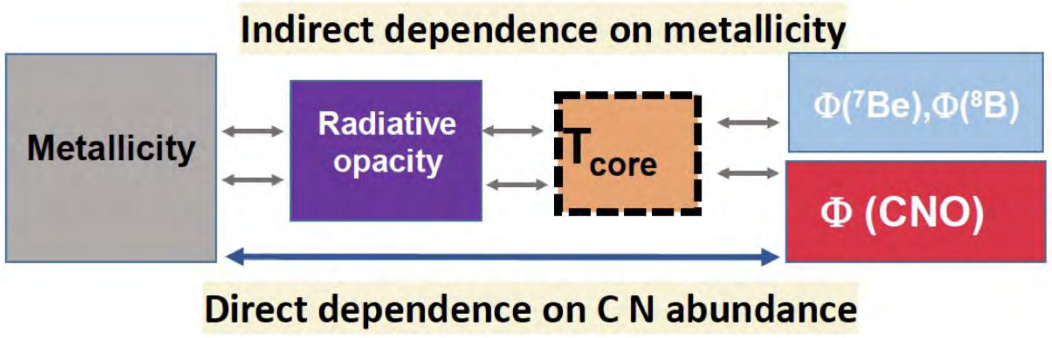
Constraints in the fit:
R(pep) = (2.74 + 0.04) cpd/100 t
R(^{210}Bi) < (10.8 ± 1.0) cpd/100 t

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

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

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

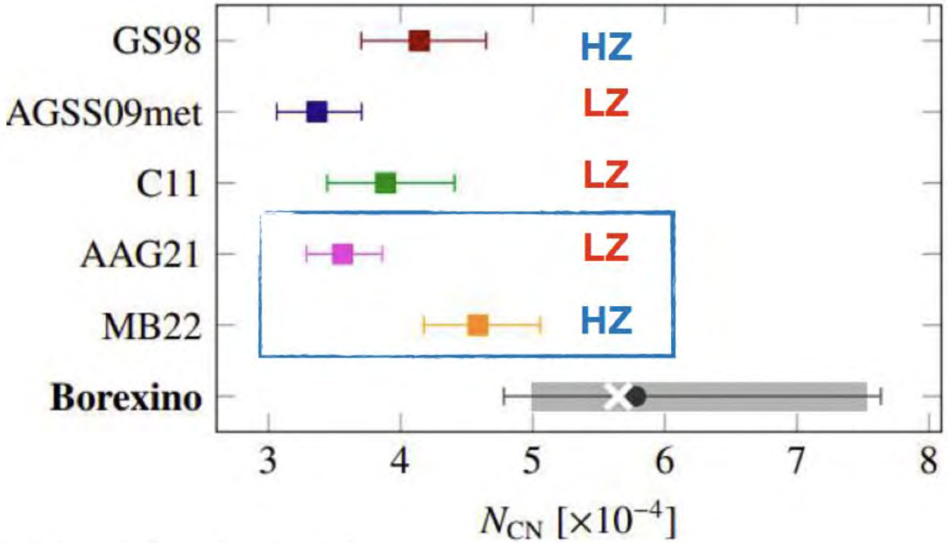
SOLAR IMPLICATIONS: C+N ABUNDANCE



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

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

- 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.

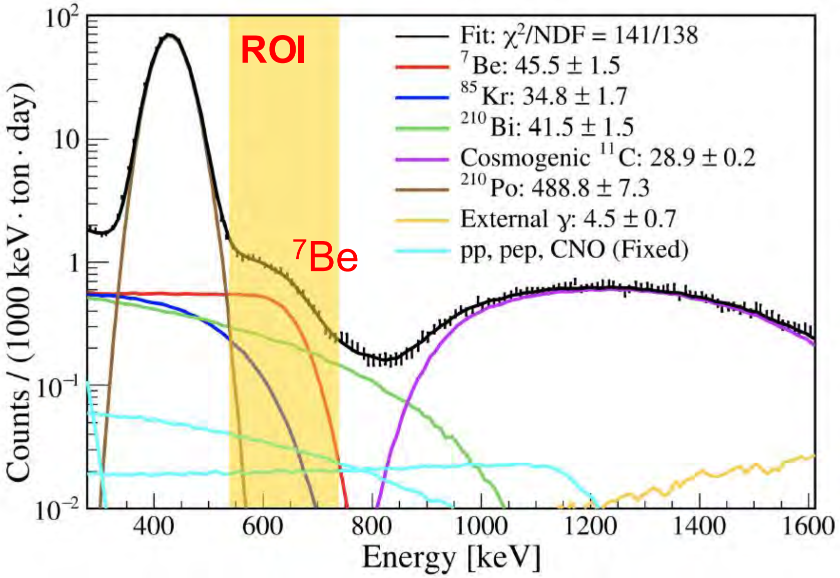
Moderate $\sim 2\sigma$ **tension with SSM-LZ**

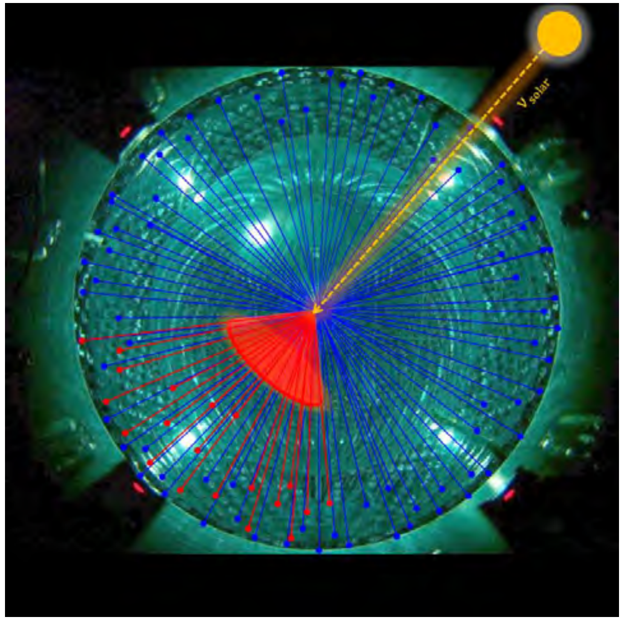
FIRST DIRECTIONAL DETECTION OF SUB-MEV SOLAR NEUTRINOS

BASIC IDEAS

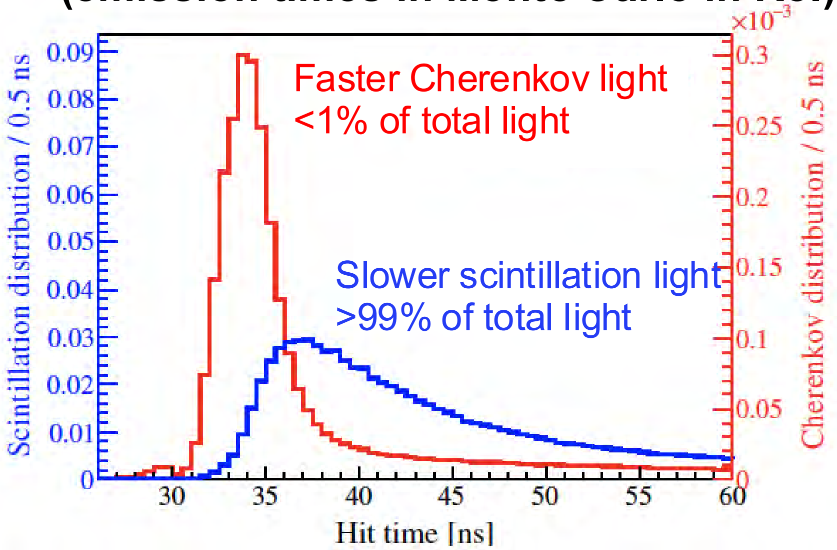
First Directional Measurement of sub-MeV Solar Neutrinos with Borexino, **Phys. Rev. Lett. 128 (2022) 091803.**
Correlated and Integrated Directionality for sub-MeV solar neutrinos in Borexino, **Phys. Rev. D 105 (2022) 052002.**

Phase I spectral fit PRD 89 (2014)112007





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

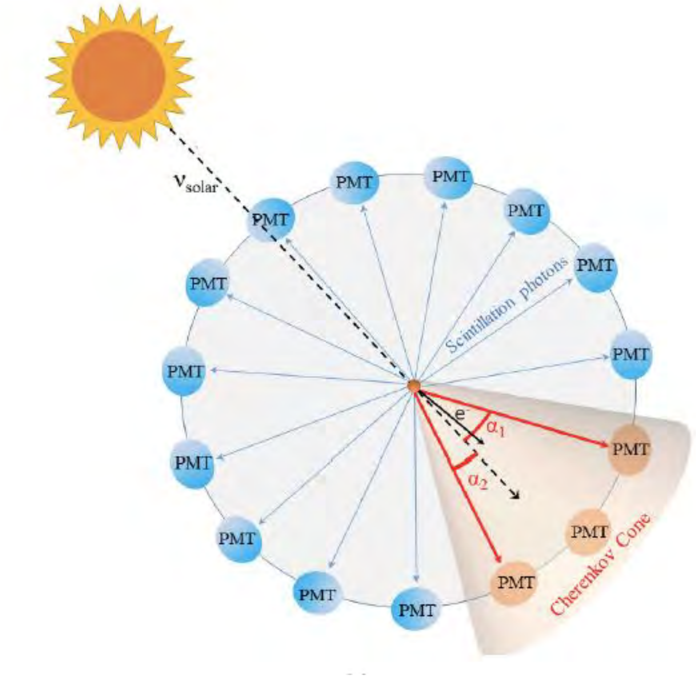


- Selection of the **region of interest** (ROI) using the dominant and **isotropic scintillation light.**
- Using the subdominant **Cherenkov light**, that is fast and directional, to **recognize the solar neutrino signal** correlated with **the known position of the Sun.**
- **Method was eveloped on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

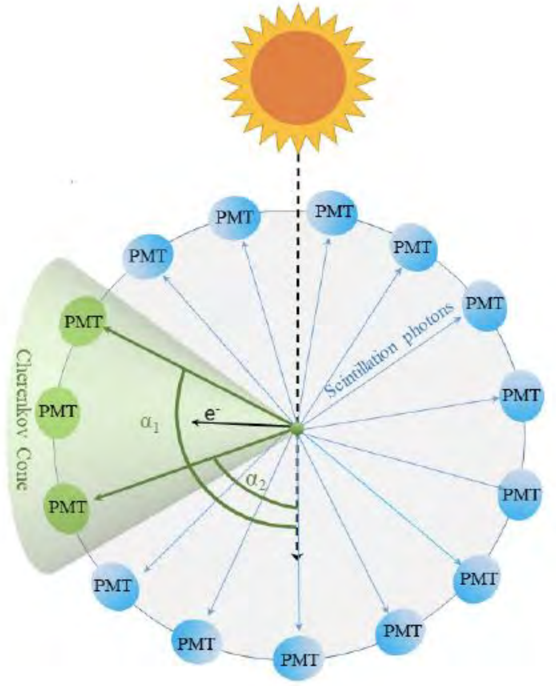
FIRST DIRECTIONAL DETECTION OF SUB-MEV SOLAR NEUTRINOS

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:

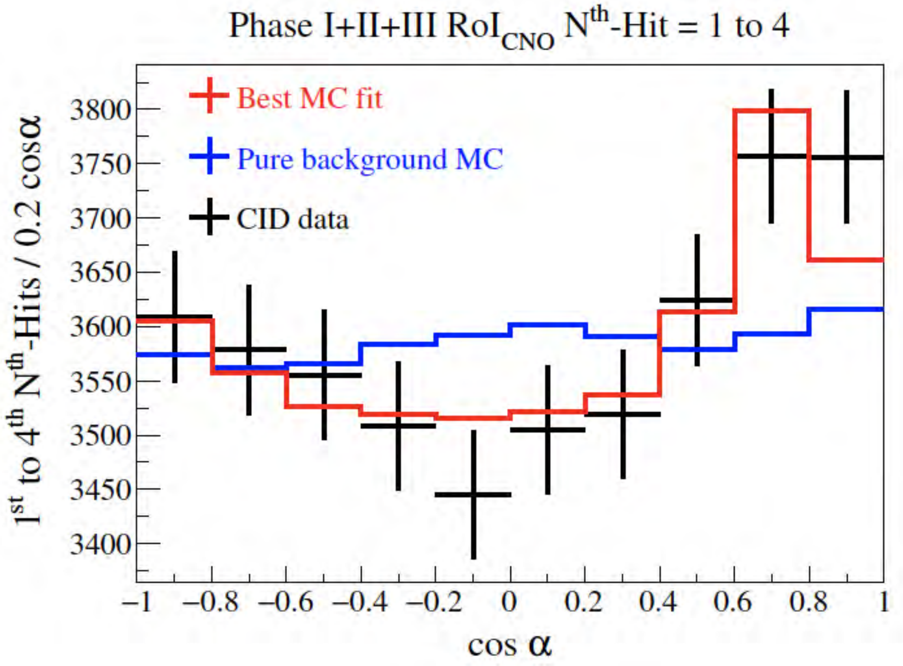
* event-by-event discrimination not possible, we integrate over all events from the RoI

Directionality:

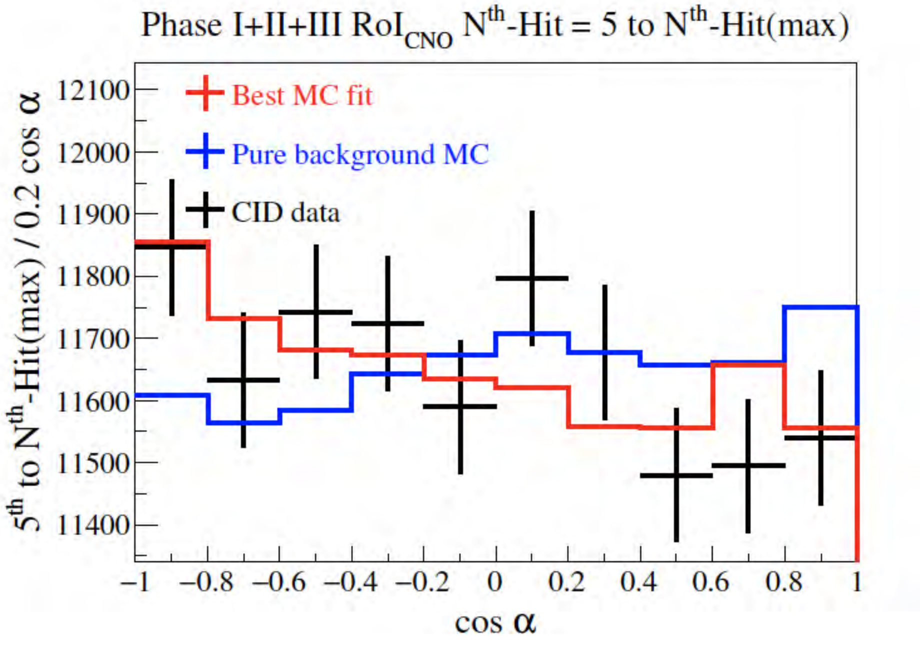
* we exploit directional Cherenkov light

OBSERVATION OF CNO SOLAR NEUTRINOS WITH CID

DATA CID DISTRIBUTIONS AND FIT



Early hits (1 to 4):
<u>Direct information</u>
from the Cherenkov light



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

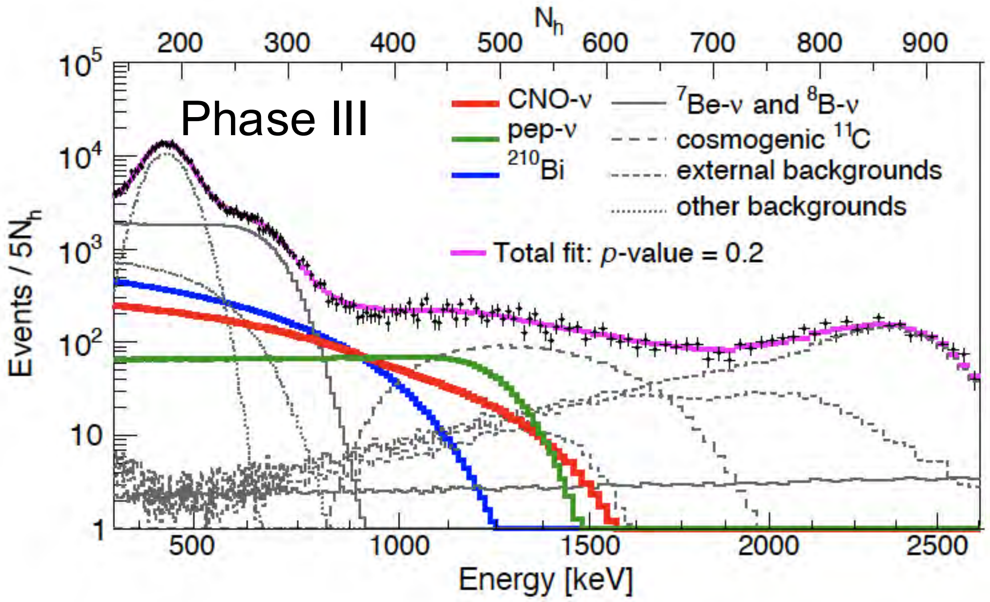
CNO observation with the CID method at 5.3σ CL
No 210Bi constraint needed!

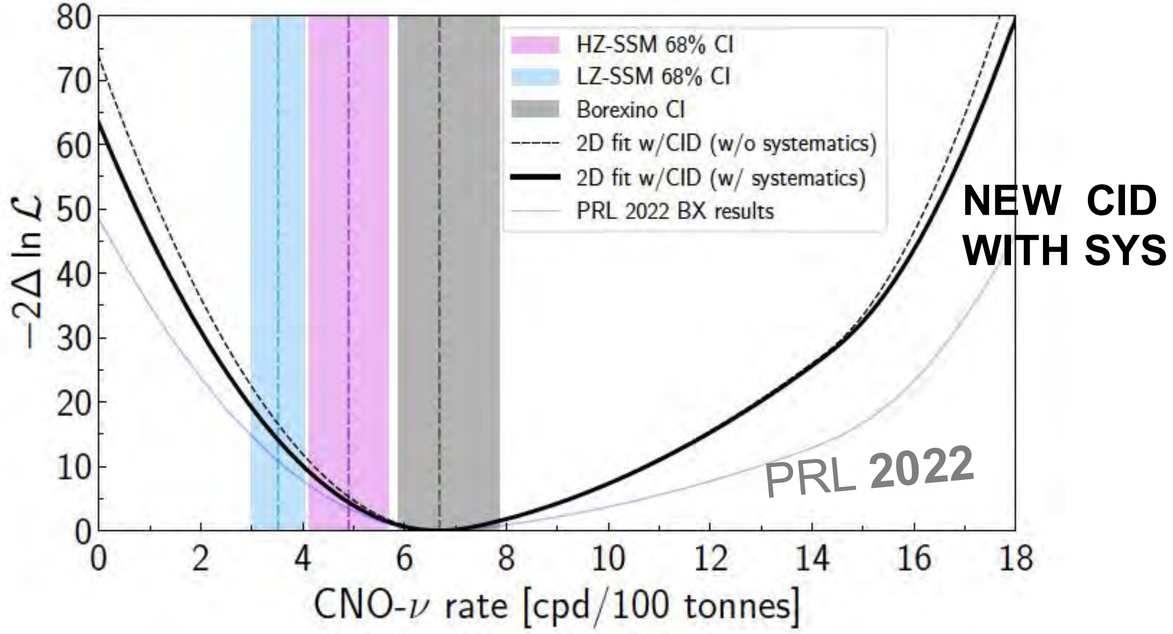
PHYSICAL REVIEW D **108**, 102005 (2023)
Editors' Suggestion

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





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

Standard Multivariate Fit   Pull terms from CID posterior

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

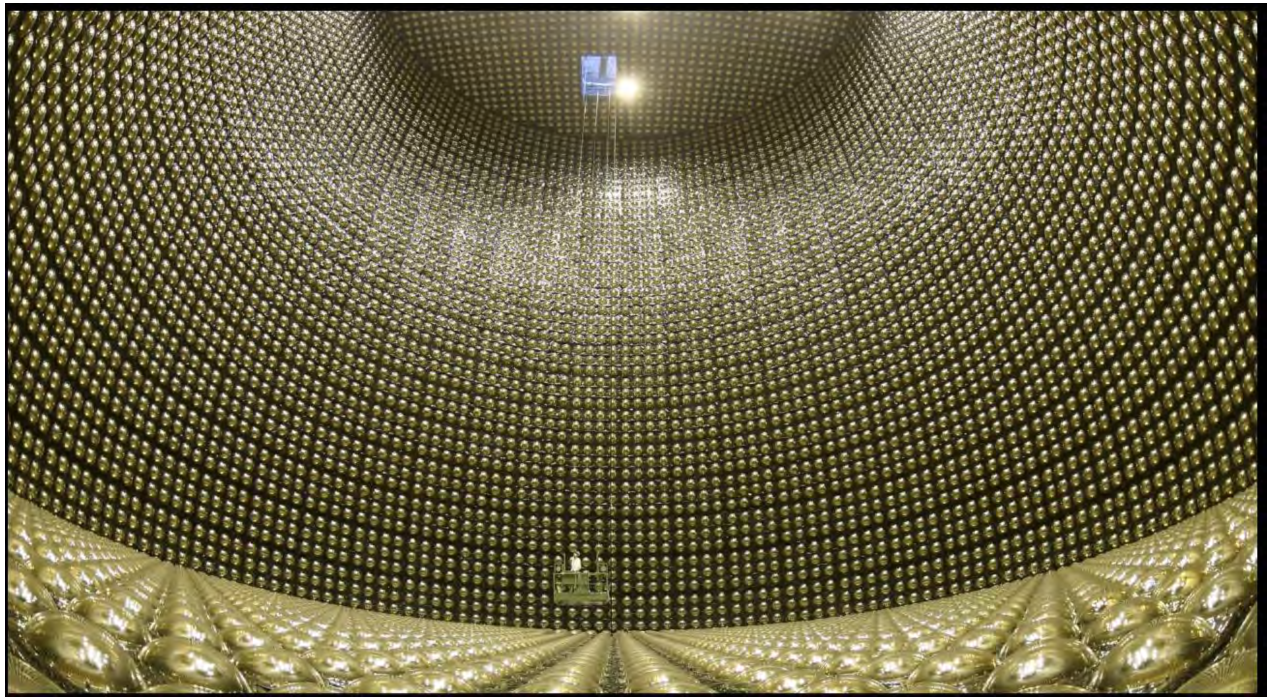
2022 results without CID: $6.7^{+2.0}_{-0.8}$ cpd/100 t

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

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.

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)

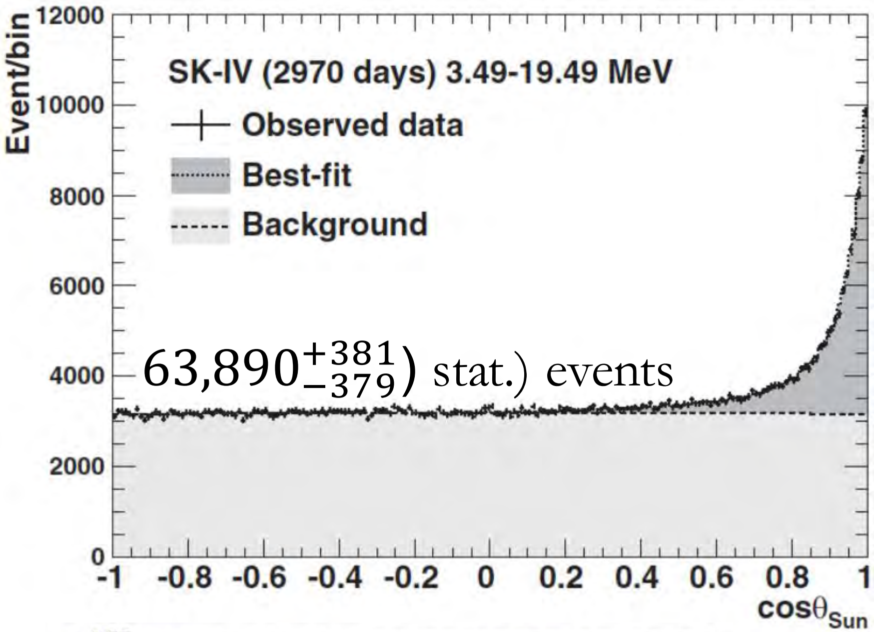
Since 2020: Gd loading of LS for neutron capture to observe DSNB via IBDs.

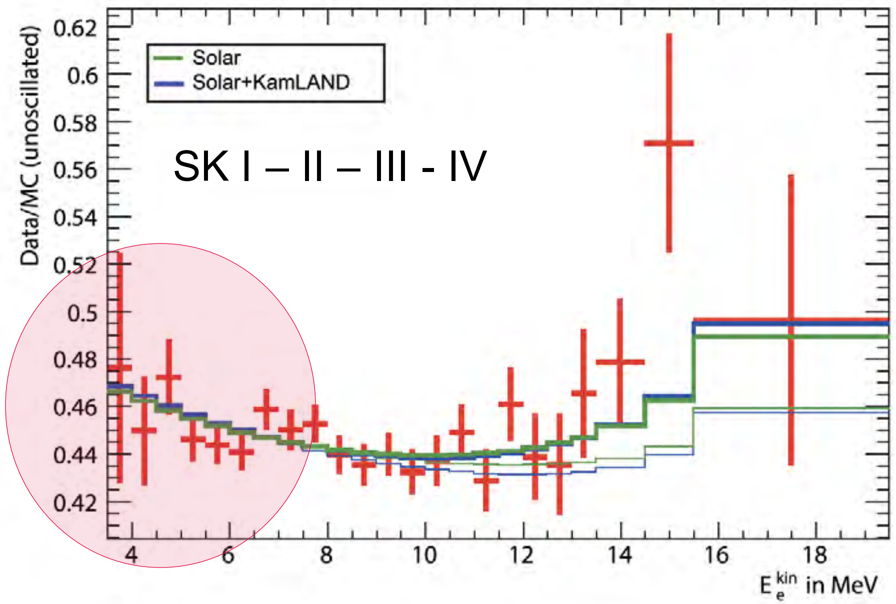
- SK-V: preparation
- SK-VI (0.01% Gd)
- SK-VII (0.03% Gd)

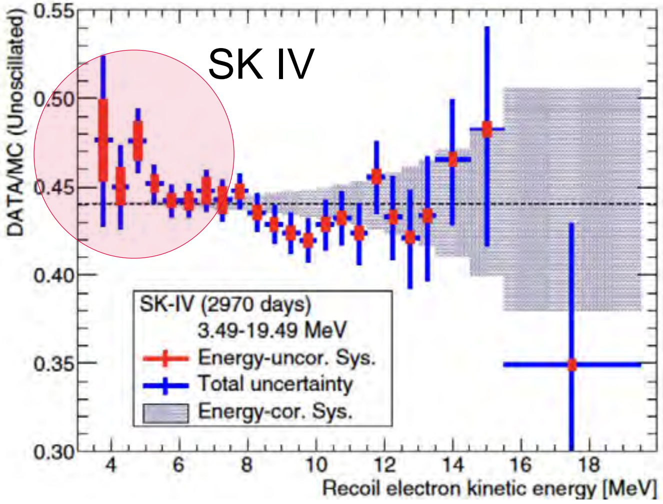
Higher backgrounds as expected, but 4 /4.5 MeV threshold is possible.

SUPER-KAMIOKANDE

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





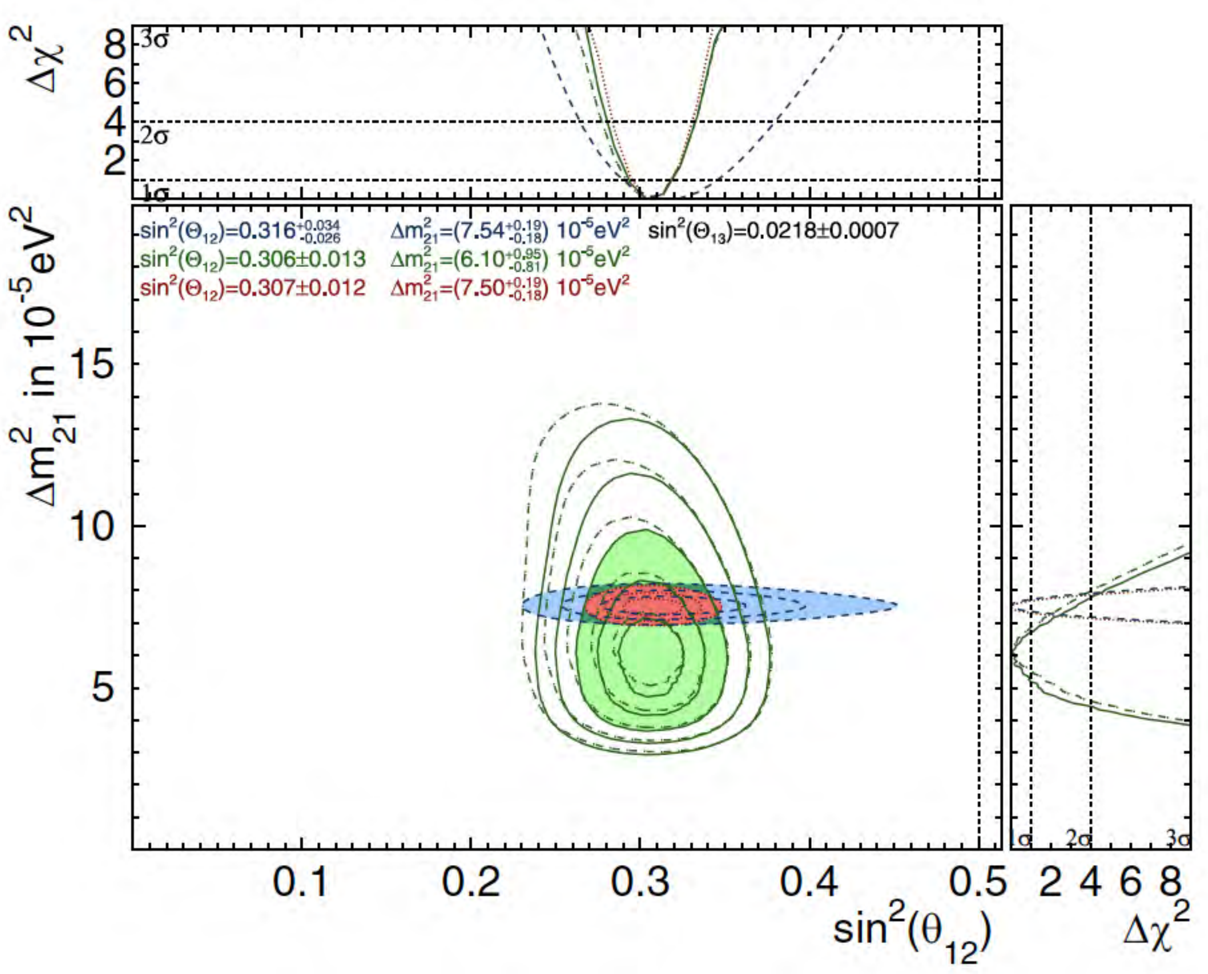


- ^{8}B flux measurement consistent among different phases **– total precision 2%.**
- Spectrum still compatible with flat survival probability, but predicted low energy **MSW upturn is favoured at 1.2 σ** . Jointly with SNO data, at 2.1 σ.
- No time variations except eccentricity and **Day/Night variation**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

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

SUPERKAMIOKANDE: SOLAR OSCILLATIONS

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



Solar best-fit value

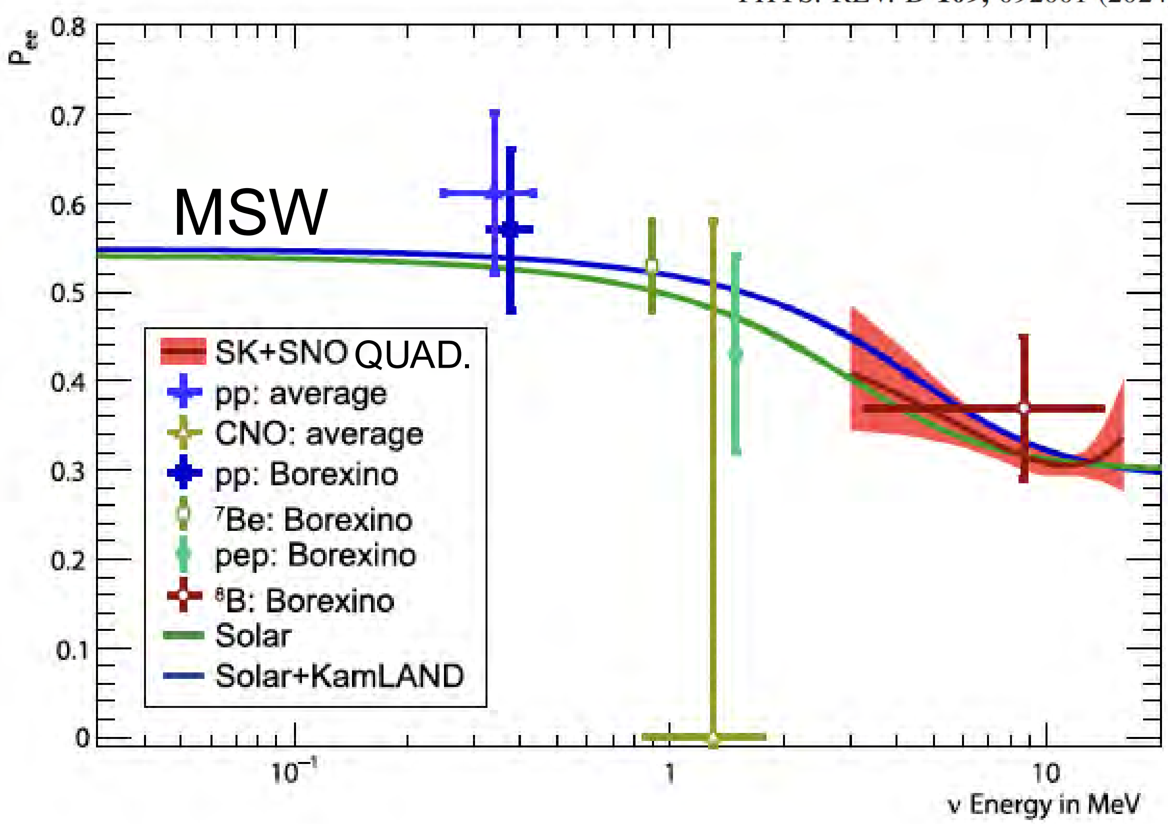
$\Delta m^2_{21} = 6.10^{+0.95}_{-0.81} \times 10^{-5}\ eV^2$

~1.5 σ away from KamLAND

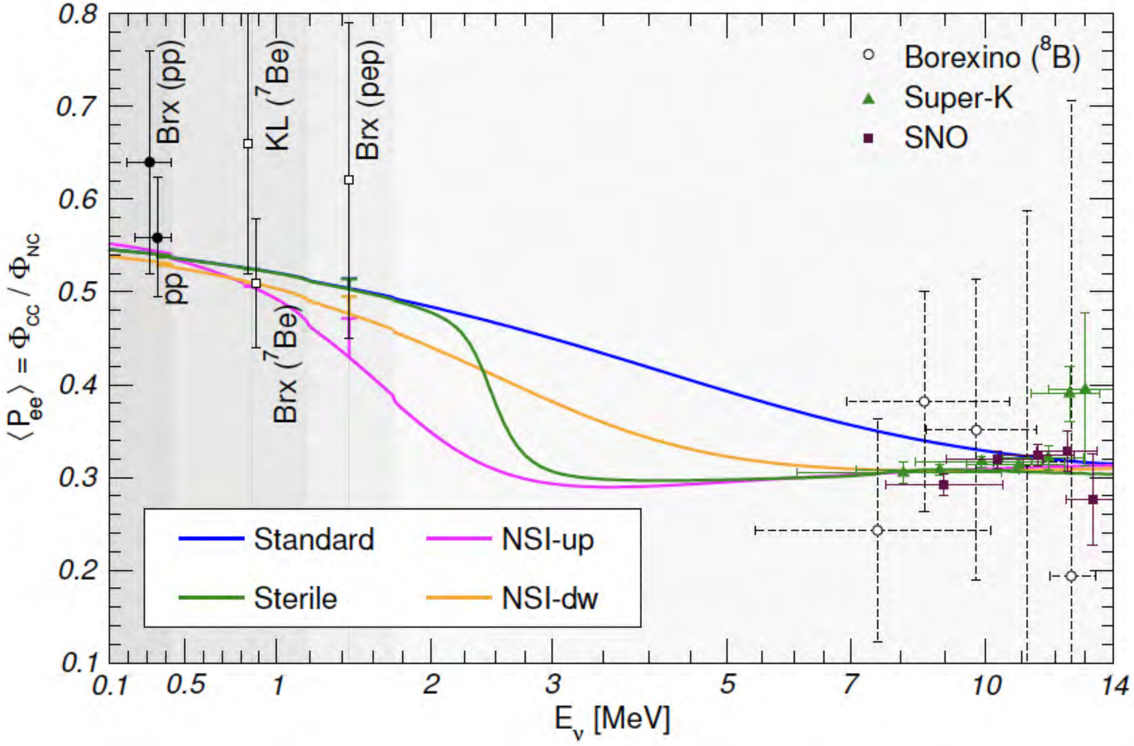
Previously, larger tensions.

P_{ee}: VACUUM TO MATTER TRANSITION

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

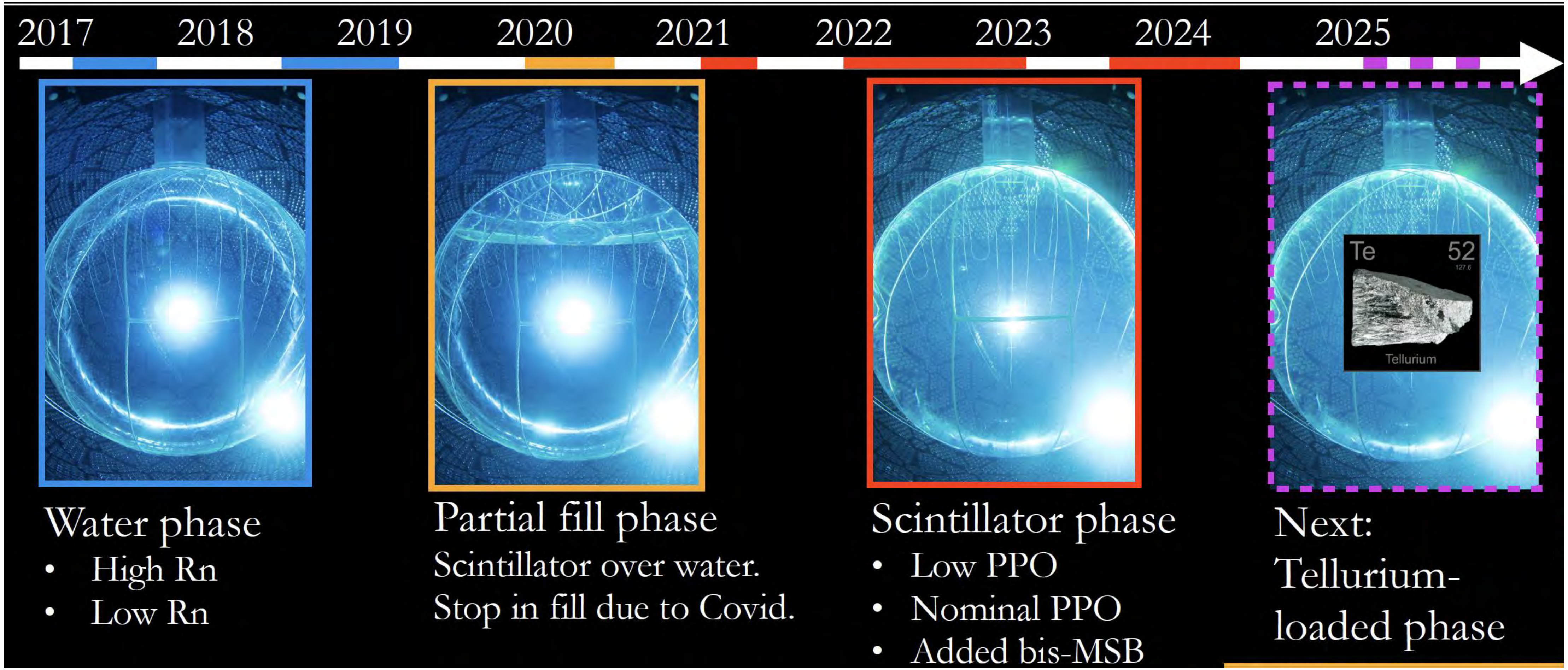


M. Maltoni et al., Eur. Phys. J. A 52 (2016) 87



Transition region crucial for testing BSM ideas.

SNO+ IN SUDBURY, CANADA

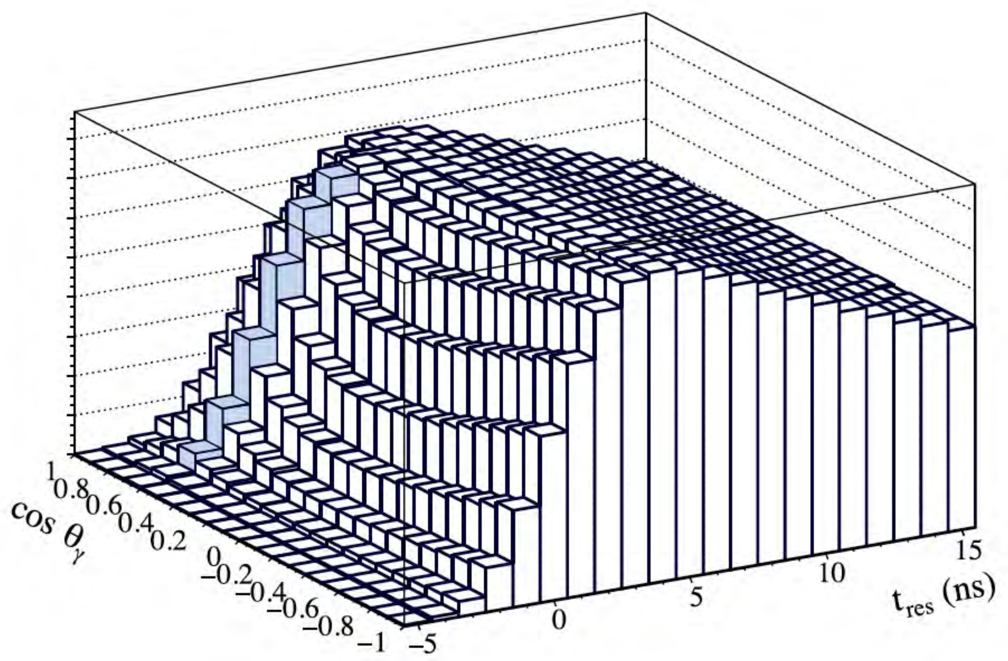


J. Maneira. Neutrino 2024

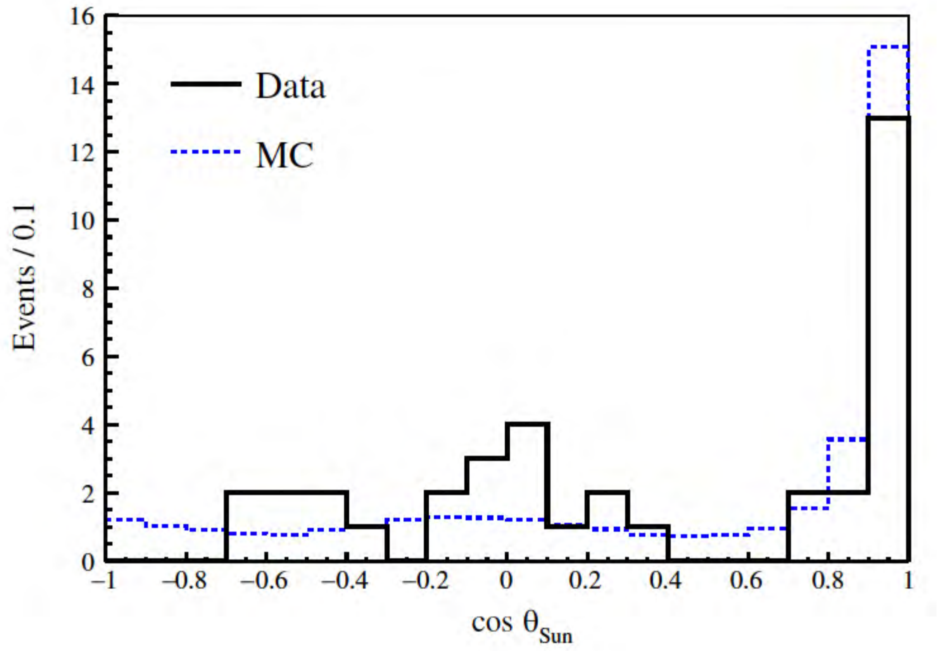
FIRST EVENT-BY-EVENT DIRECTIONALITY IN LS BY SNO+

PRD 109, 072002 (2024)

Data from partial fill & early scint phases, where PPO loading low (0.6 g/L), leading to slow scintillation: good separation with Cherenkov light.



Distribution of photon hits in cos θγ and tres for simulated 6 MeV electrons. A clear peak can be seen at low tres near the expected Cherenkov angle, cos θγ = 0.66, highlighted in blue.

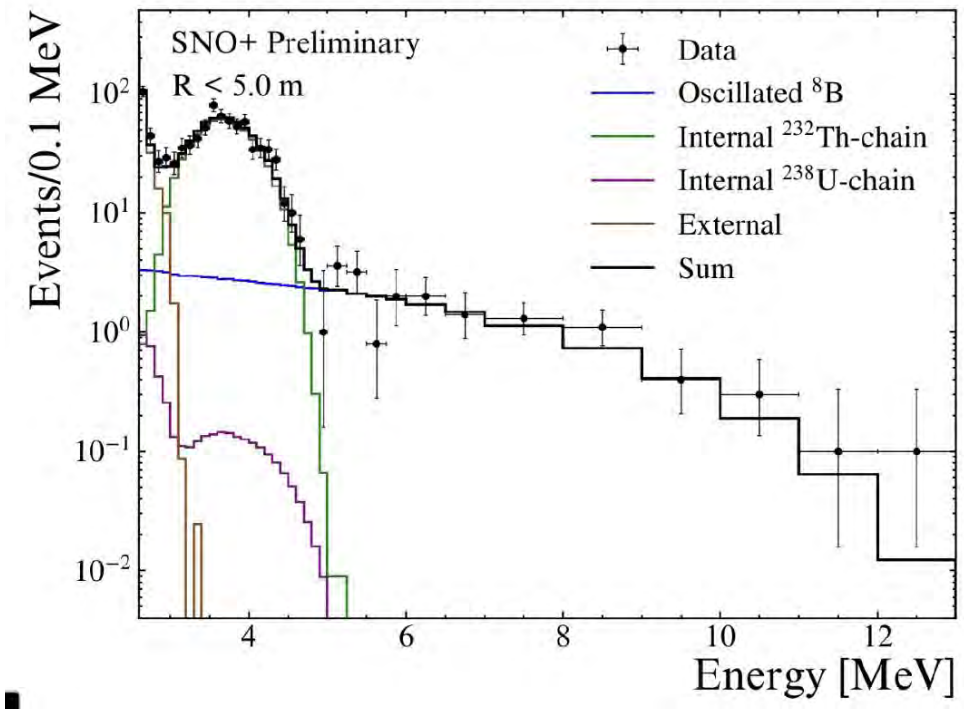


Results of direction reconstruction for measured (solid) and simulated (dashed) ^{8}B solar neutrinos, where simulation sampled from a nominal ^{8}B energy spectrum.

SNO+ AND 8B SOLAR ANALYSIS

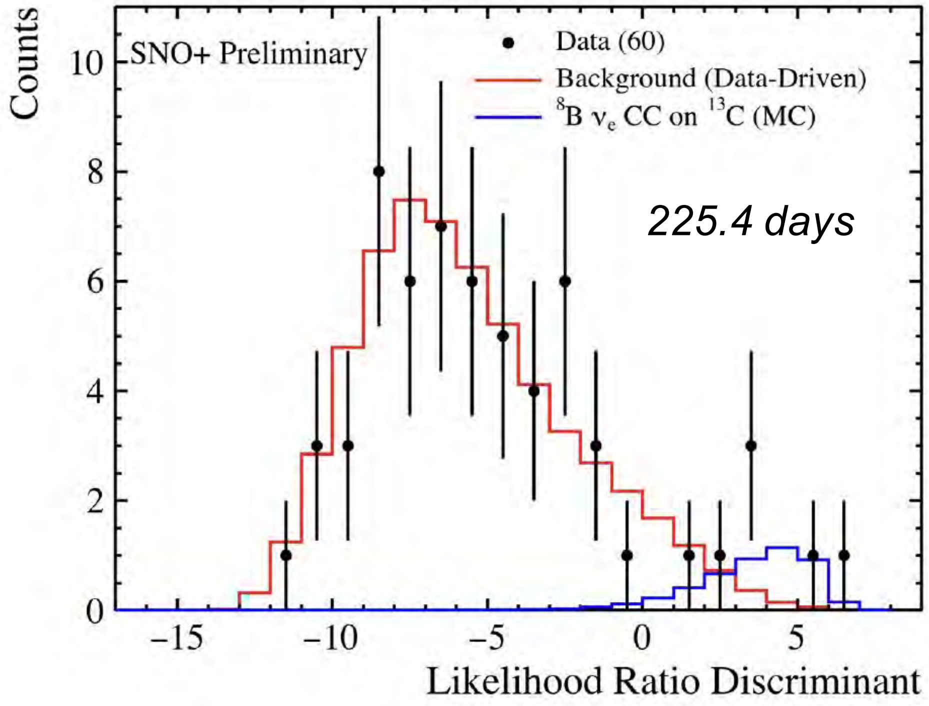
$$\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$$
$$^{13}N \rightarrow e^+ + \nu_e + {}^{13}C$$

Elastic scattering (singles)



- ES interactions in 143.1 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)

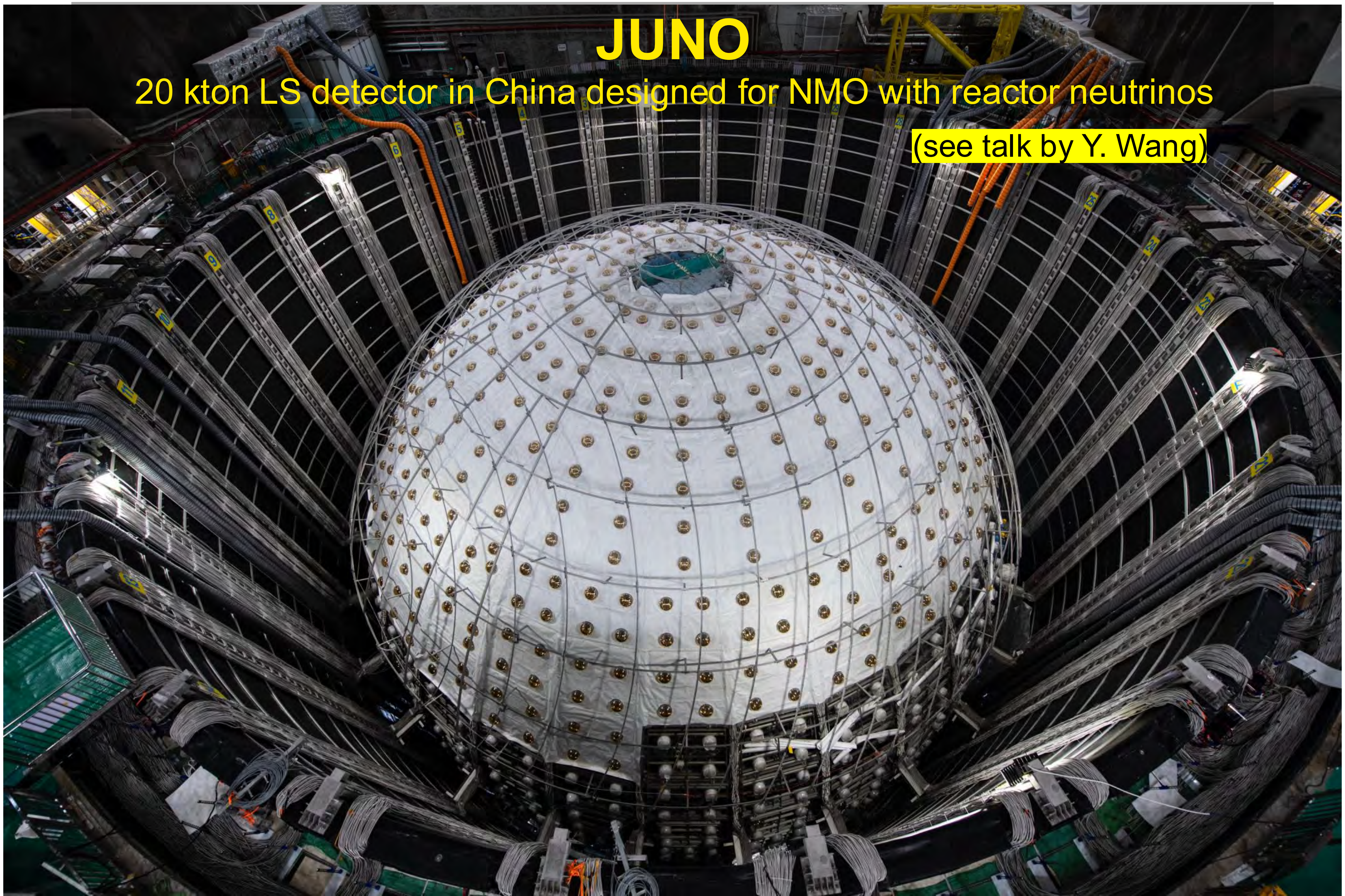


- 1.1% isotopic abundance, but σ ~12× higher than ES.
- 3.8 σ CL – FIRST OBSERVATION of this interaction with solar neutrinos!

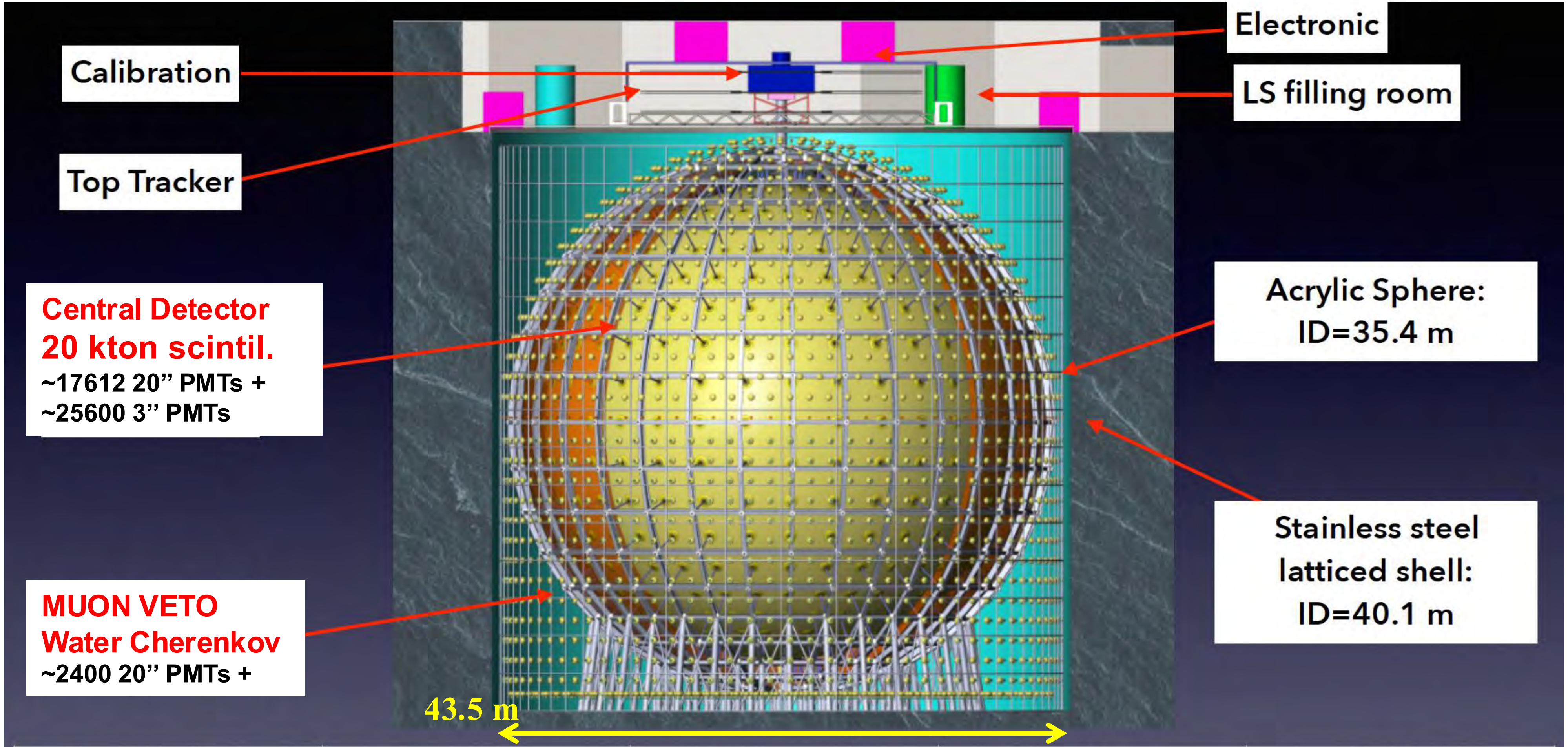
JUNO

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

(see talk by Y. Wang)



JUNO DETECTOR



Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	8x20 ton	~300 ton	~1 kton	20 kton
Coverage	~12%	~34%	~34%	78%
Energy resolution	8.5% / √E MeV	~5%/√E MeV	~6%/√E MeV	~3%/√E MeV
Eff.Light yield	~ 160 p.e. / MeV	~ 500 p.e. / MeV	~ 250 p.e. / MeV	~ 1600 p.e./MeV

A MULTI-PURPOSE OBSERVATORY

Reactor anti-ν

~60 / day

Atmospheric ν

Several / day

Solar ν

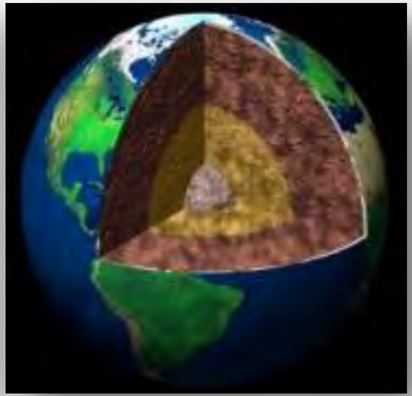
^{8}B: ~50/day
CNO: ~1000/day
^{7}Be: ~10000/day

Supernovae (SN) ν

Core Collapse SN
@ 10 kpc:
thousands in few sec.

Diffuse SN signal:
few / year

Geoneutrinos



~400 / year

+

New physics

Proton decay

Neutrino magnetic moment

Sterile neutrinos

Non-standard interactions

Lorentz invariance violation

Neutrino oscillation & properties

Neutrinos as a probe

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

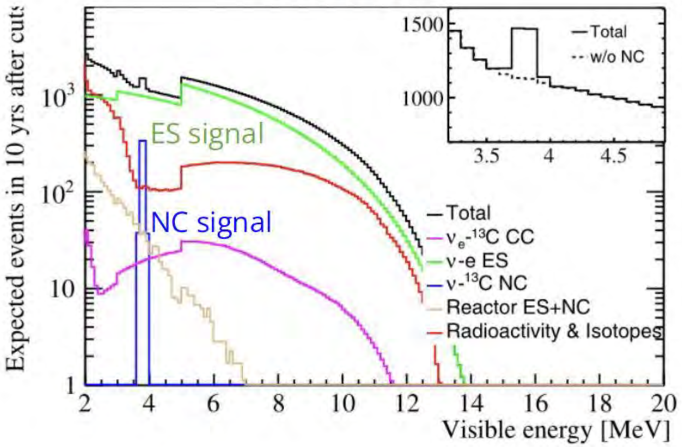
- E_{thr} = 2.2 MeV
- Possible only with ν_e
- Prompt: e^-; Delayed: ^{13}N decay

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

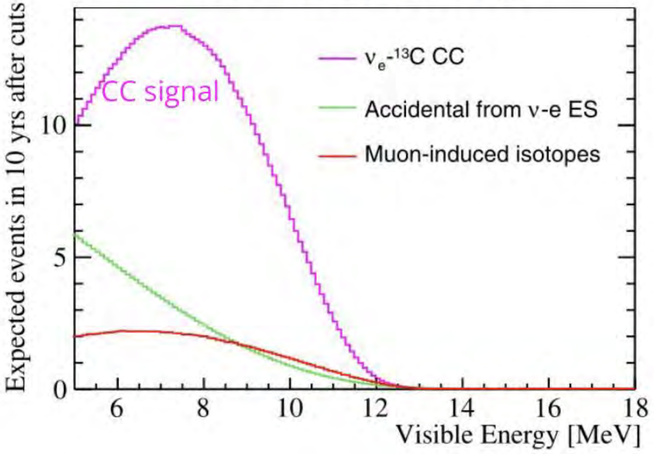
- E_{thr} = 3.685 MeV
- All flavors & equal σ
- Single events - monochromatic γ

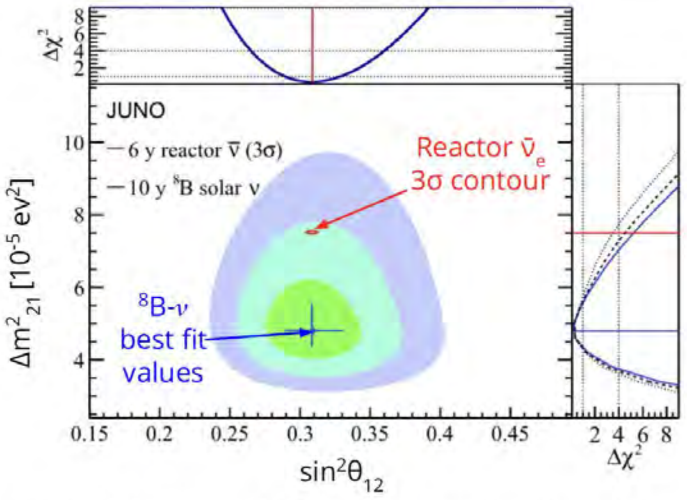
ES: Chinese Phys. C 45 (2021) 1
ES+NC+CC: Ap. J. 965 (2024) 122

10 years, single events after cuts



10 years, correlated prompt events after cuts





Potential to search for possible discrepancies

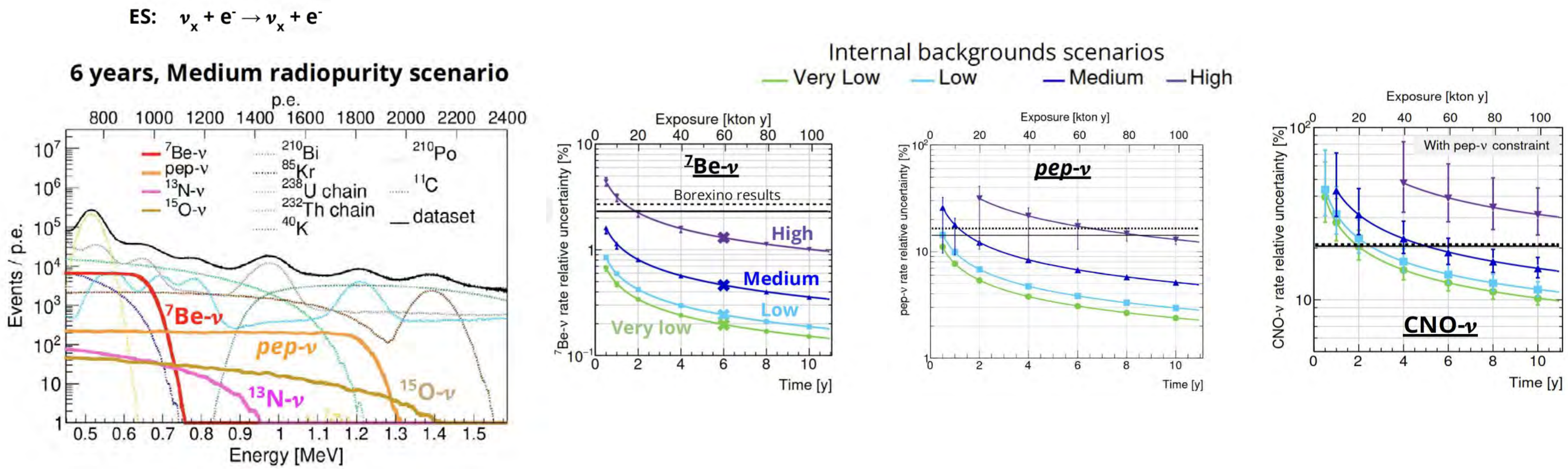
Expected precision in 10 years:

^{8}B flux: 5% JUNO

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

Δm^2_{21}: +27% / -17%

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



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.

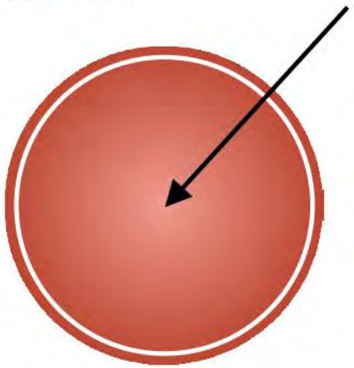
Solar neutrino Summary & outlook

- **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.

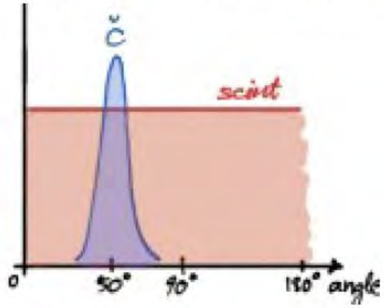
WATER-BASED LS DETECTORS

Cherenkov

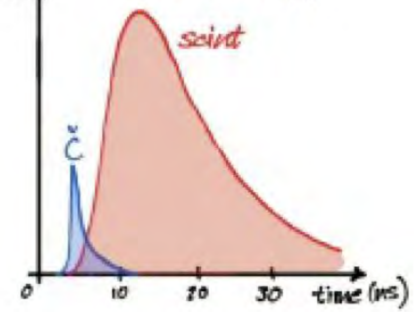
Scintillation



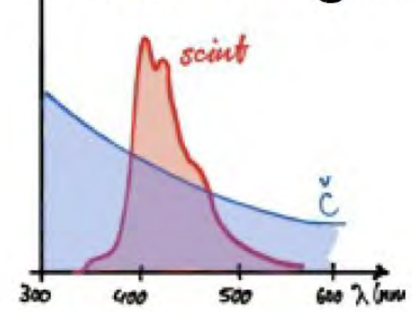
Angular distribution

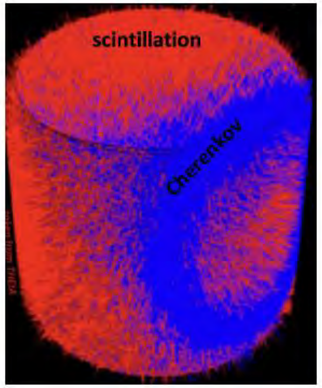


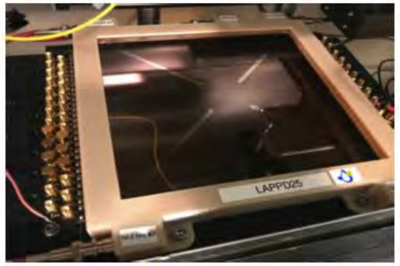
Timing



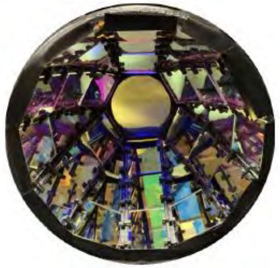
Wavelength







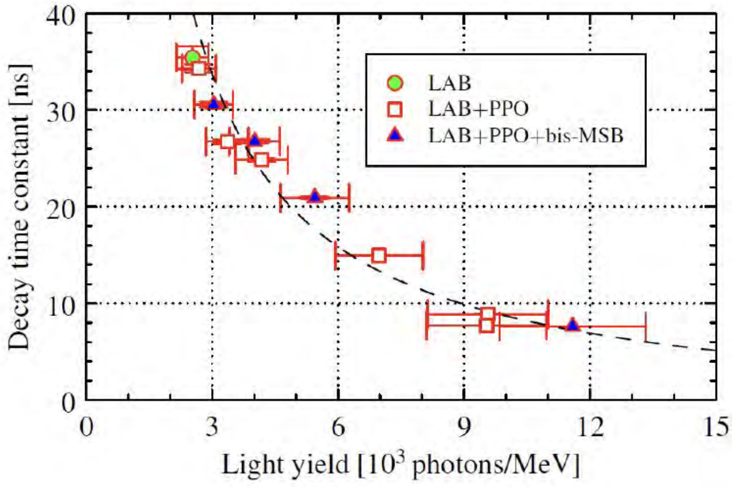
B.W.Adams et al. NIM A Volume 795, 1 (2015)

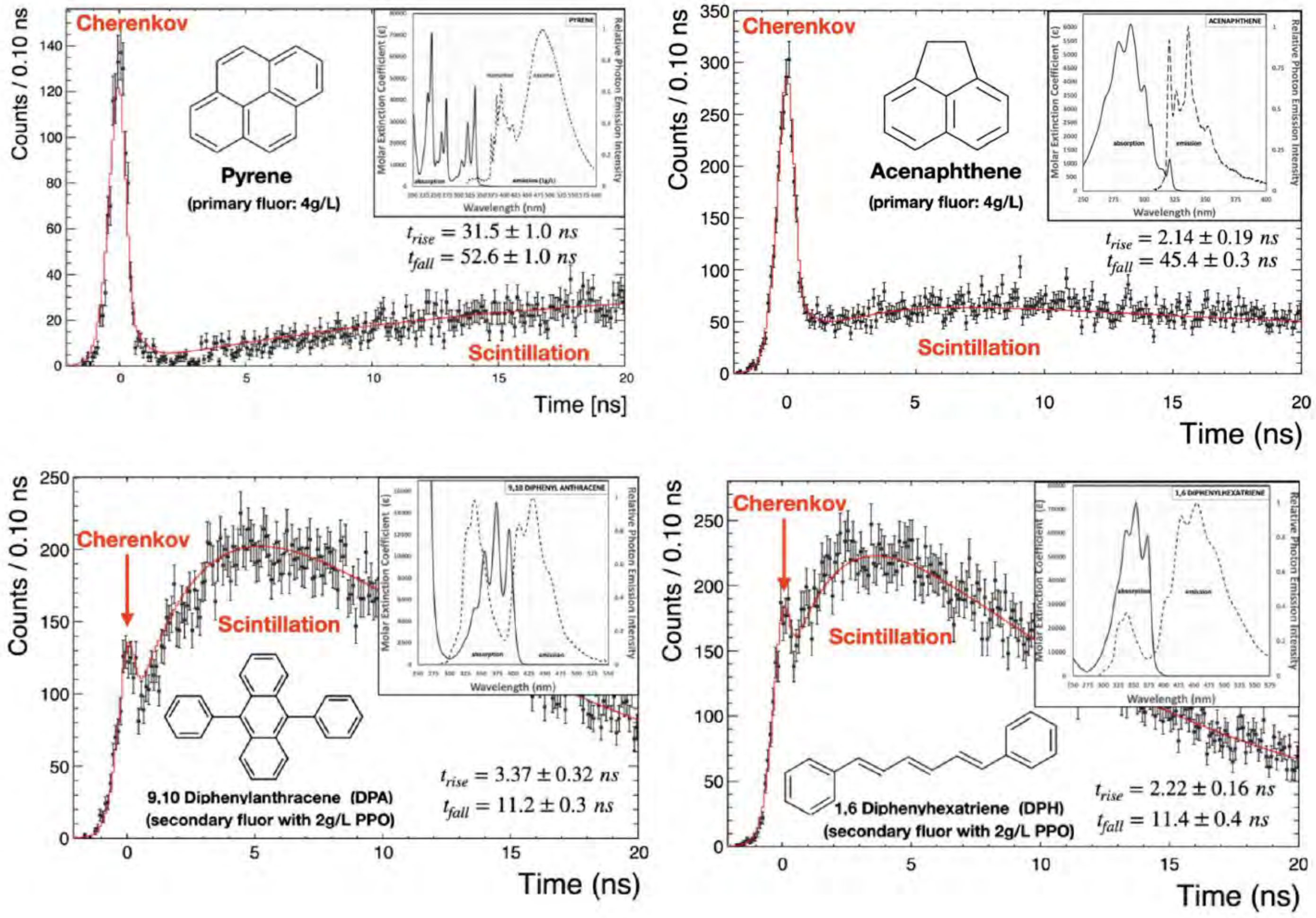


T. Kaptanoglu et al.
Phys. Rev. D 101, 072002 (2020)

Michi Wurm

SLOW SCINTILLATORS





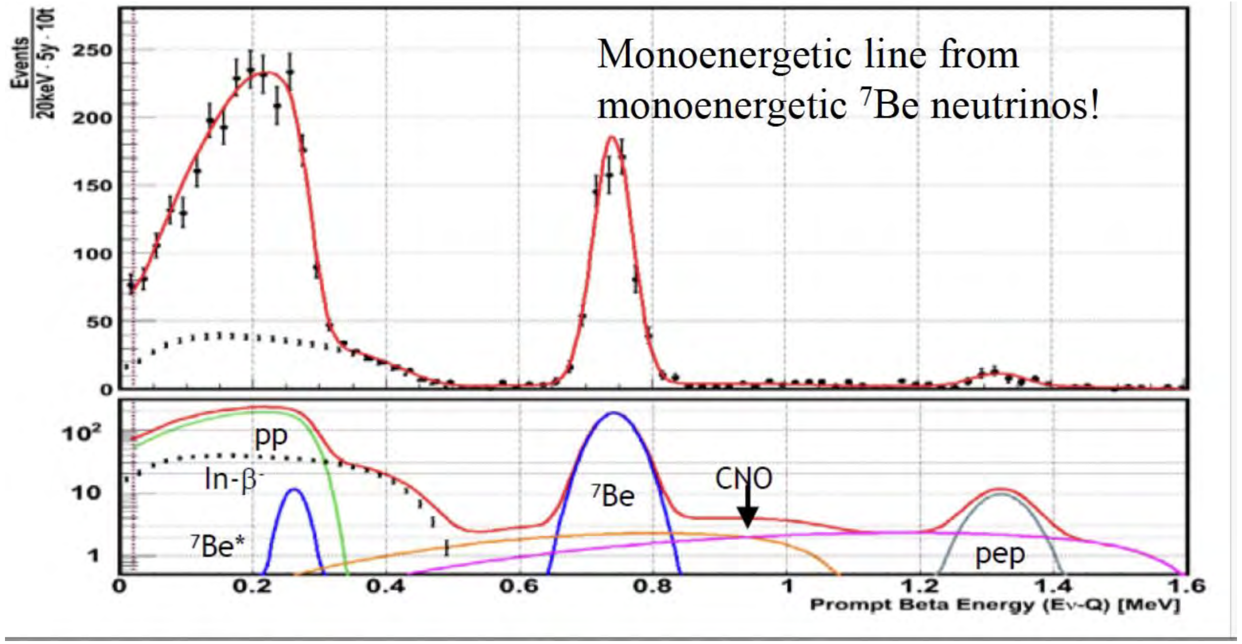
- *Adjust conc. of flour and shifters (Guo et. al., j.astropartphys.2019.02.001)*
- *Utilize slow fluor and WLS (Biller et. al., j.nima.2020.164106)*

METAL LOADED SCINTILLATORS

- Originally proposed by R. Raghavan in ’70s

$$\nu_e + {}^{115}\mathrm{In} \rightarrow {}^{115}\mathrm{Sn}^* + e^- \ (E_{kin}=E_\nu-114\ \mathrm{keV})$$

$$\tau = 4.76\ \mu\mathrm{s} \quad \rightarrow {}^{115}\mathrm{Sn} + \gamma\ (115\ \mathrm{keV}) + \gamma\ (497\ \mathrm{keV})$$



R. Raghavan

(1941 – 2011)

- Pioneering LENS experiment (until ~2015)
- Technical problems & funding issues

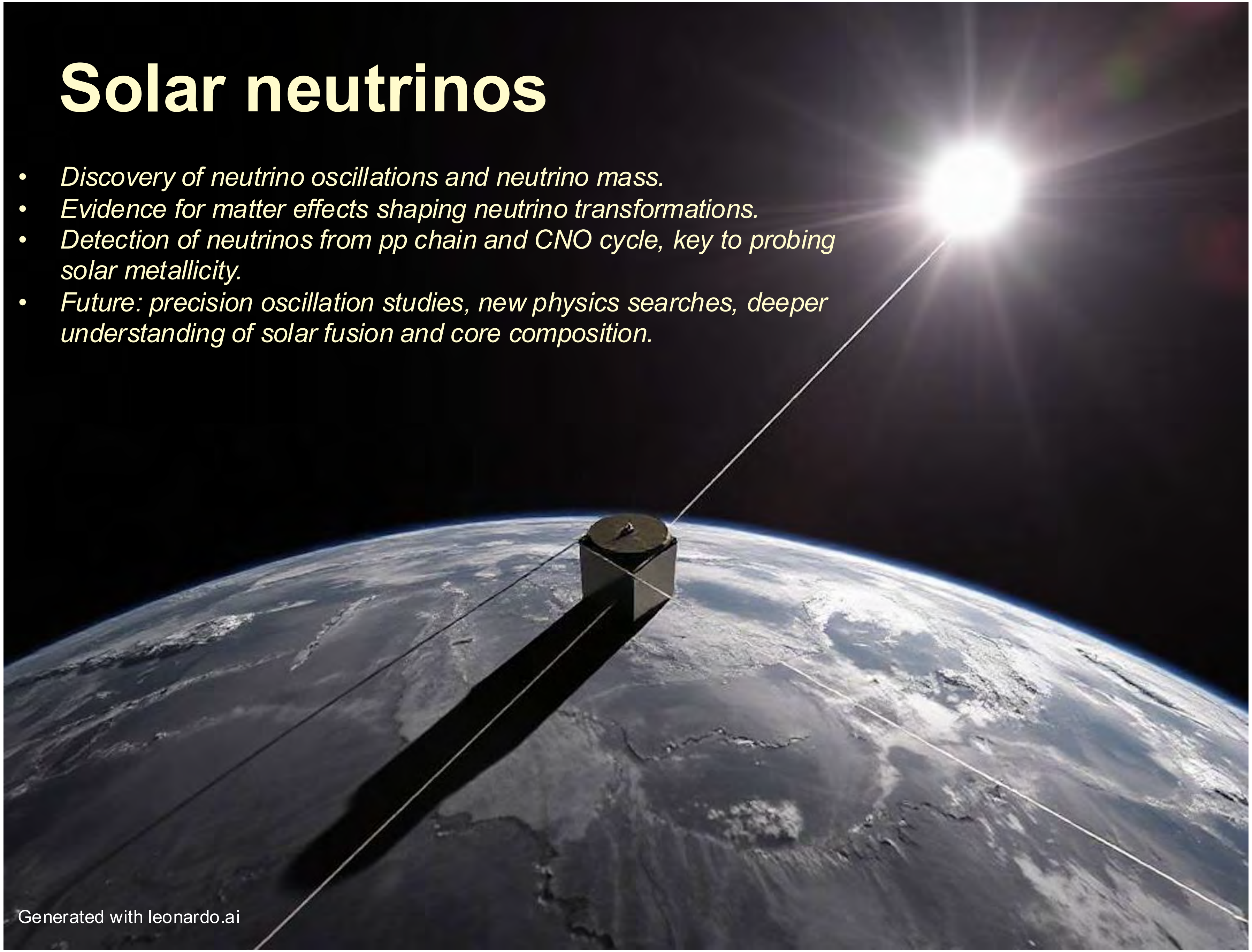
(intrinsic In background, light reduction, scalability)

More candidates of loading: ^{176}Yb, ^{100}Mo, ^{7}Li, ^{209}Bi.

Several ongoing R&D forloaded LS:
THEIA, LiquidO, SNO+, JUNO (Gd R&D), ANNIE (WbLS tests), EOS (WbLS + metal loading studies).

Solar neutrinos

- *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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