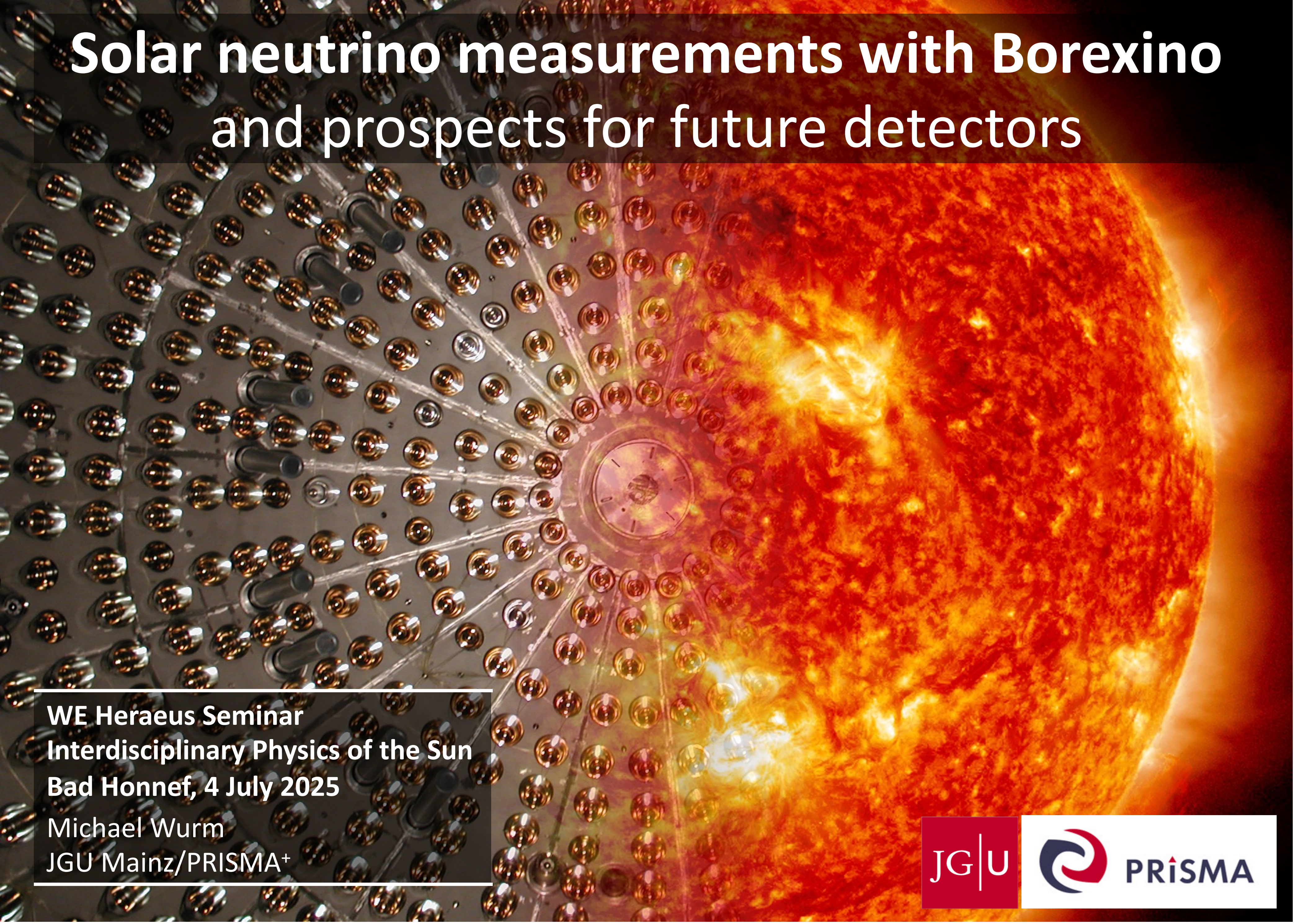


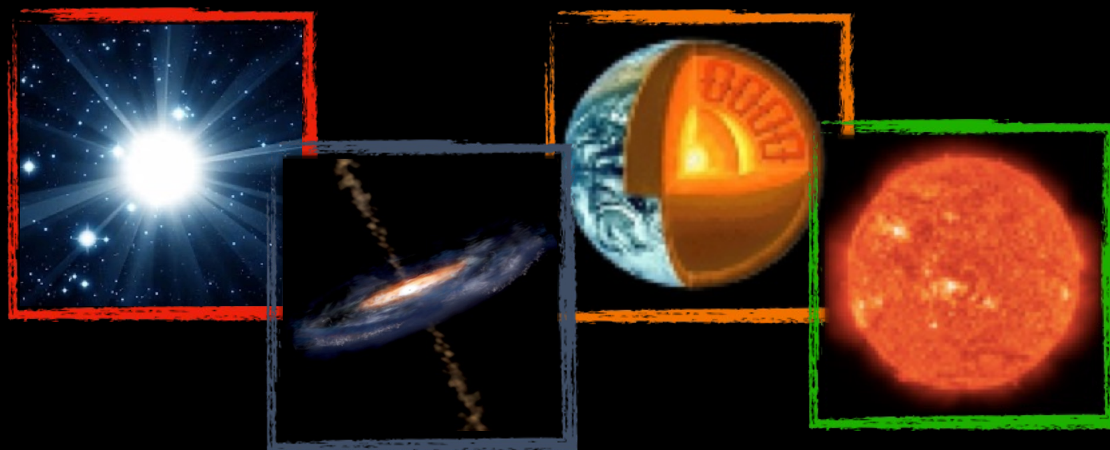
Solar neutrino measurements with Borexino
and prospects for future detectors

WE Heraeus Seminar
Interdisciplinary Physics of the Sun
Bad Honnef, 4 July 2025

Michael Wurm
JGU Mainz/PRISMA+

Neutrinos as astrophyiscal probes

- **pro:** neutrinos are (nearly) mass-less, charge-less elementary particles that only interact extremely weakly with matter
  → ideal probes to investigate the interior of astrophysical objects like
  - Supernova explosions
  - cosmic accelerators
  - the Earth‘s interior
  - our Sun



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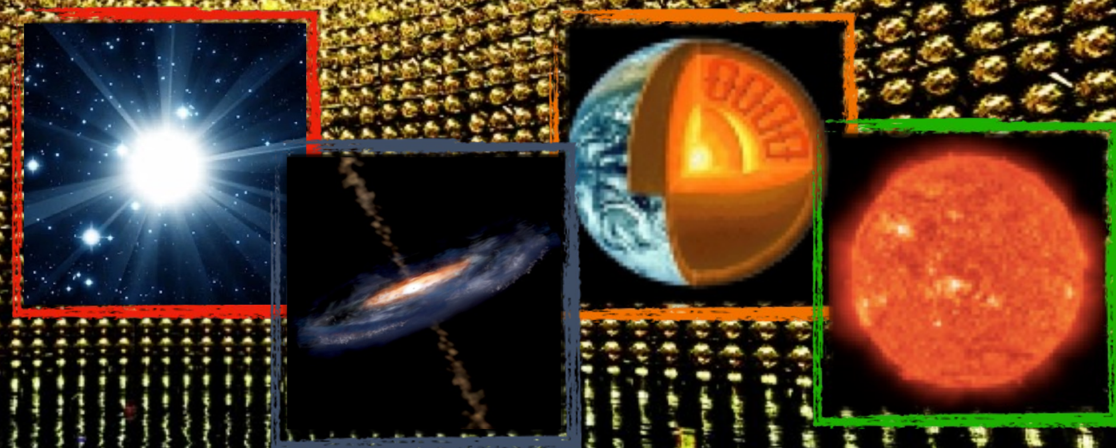


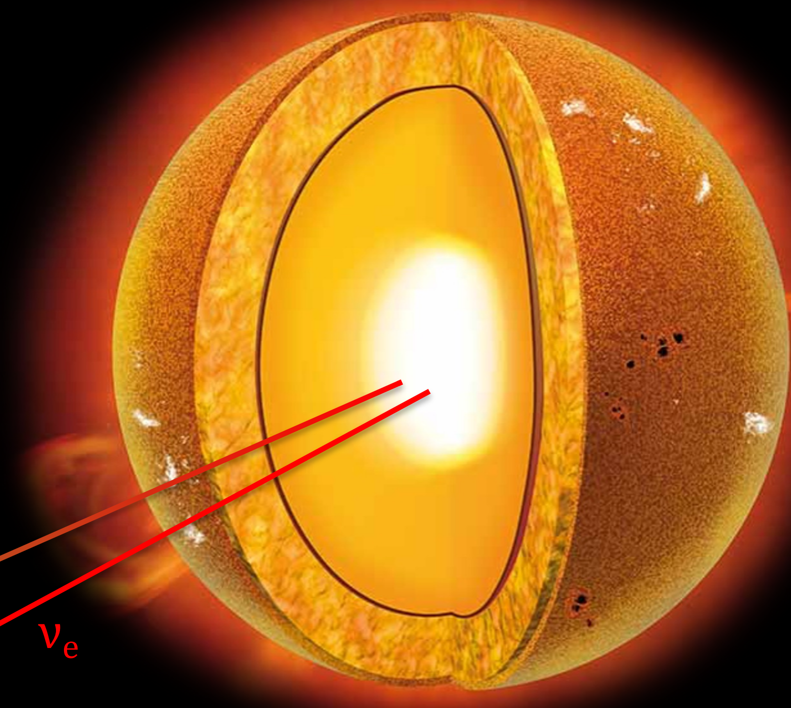
- **con:** neutrinos are (nearly) mass-less, charge-less elementary particles that only interact extremely weakly with matter
  - detection is notoriously difficult and requires vast underground detectors with excellent radiopurity

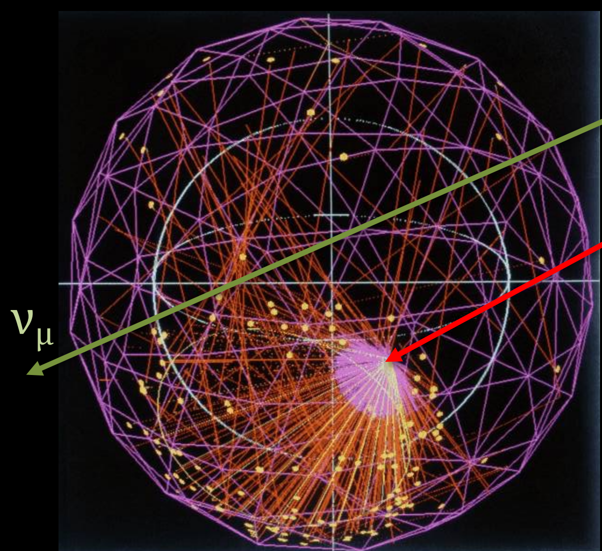
Solar neutrino spectroscopy

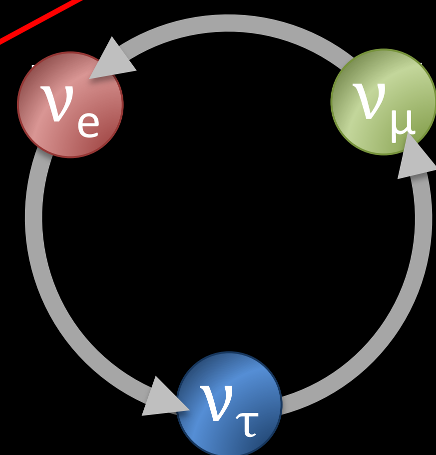
→ What can we learn?

>> Inside view of a main sequence star

- hydrogen burning
- conditions of solar interior: elemental composition, temperatures, opacities
  …







>> Investigate neutrino oscillations

- 3-flavor oscillations
- matter effects
- non-standard phenomena

Back-of-the-envelope solar neutrino flux

Net fusion reaction: $4p \rightarrow {}^4He + 2e^+ + \mathbf{2\nu_e}$ [+26.7 MeV]

electromagnetic luminosity

$L_\odot = 3.85 \times 10^{26}$ W

$\longrightarrow \gamma$

$\sim\sim\sim \nu$

neutrino luminosity

$L_\nu \approx 2\% \, L_\odot$

flux at Earth

$\Phi_\gamma \approx 4 \times 10^{21}$ /m²s

$\rightarrow S_\gamma = 1367$ W/m²

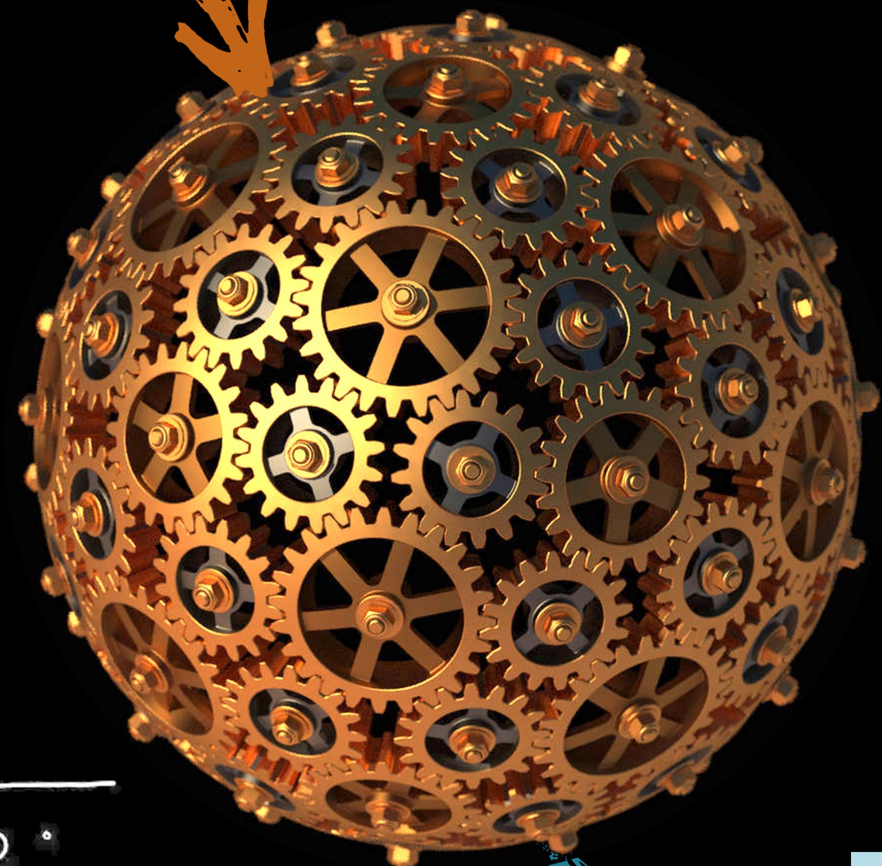
$$\Phi_\nu = \frac{S_\gamma}{Q_{4p\rightarrow\mathrm{He}}} \times 2$$

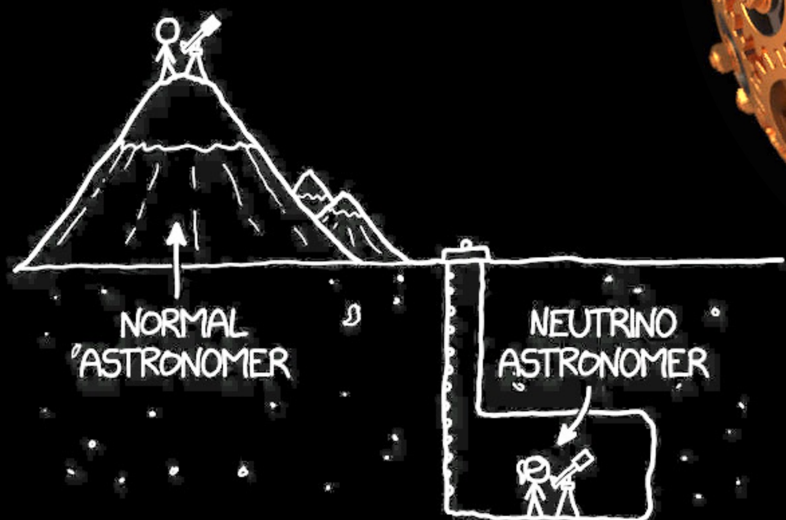
$\approx \mathbf{6.6 \times 10^{14}}$ **/m²s**

Standard Solar Model (SSM)

INPUTS

- Stellar structure equations
- Equation of state, plasma physics
- Nuclear physics
- Elemental abundances, opacity of solar matter
- Surface observations
- ...



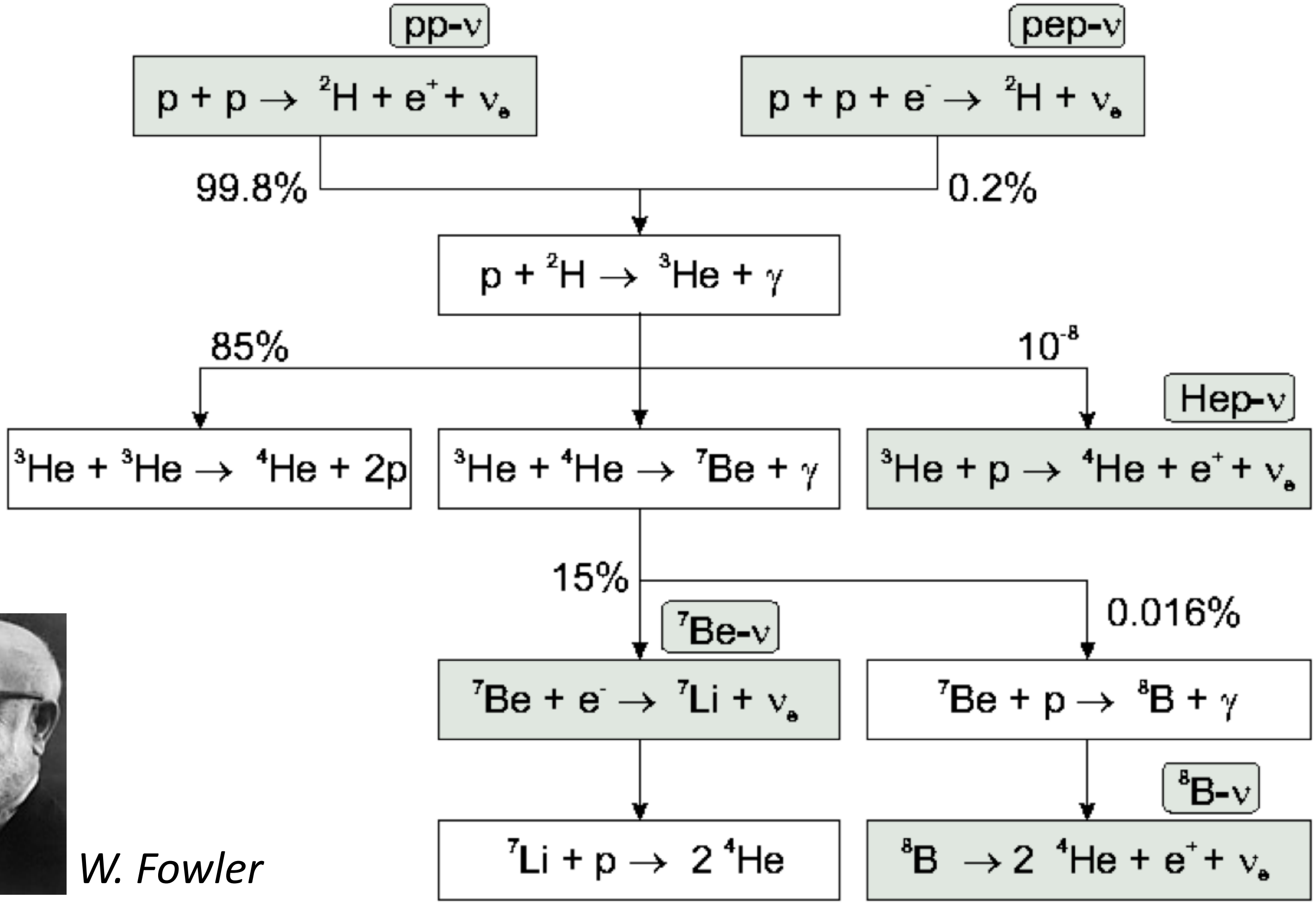


→ see talks by Francesco Villante Aldo Serenelli

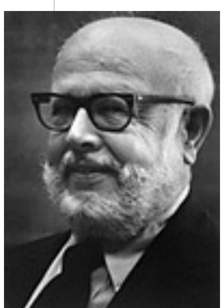
precise prediction of fusion rates and thus **neutrino fluxes**

Overview of the solar pp-chain

Net fusion reaction: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e$ [+26.7 MeV]



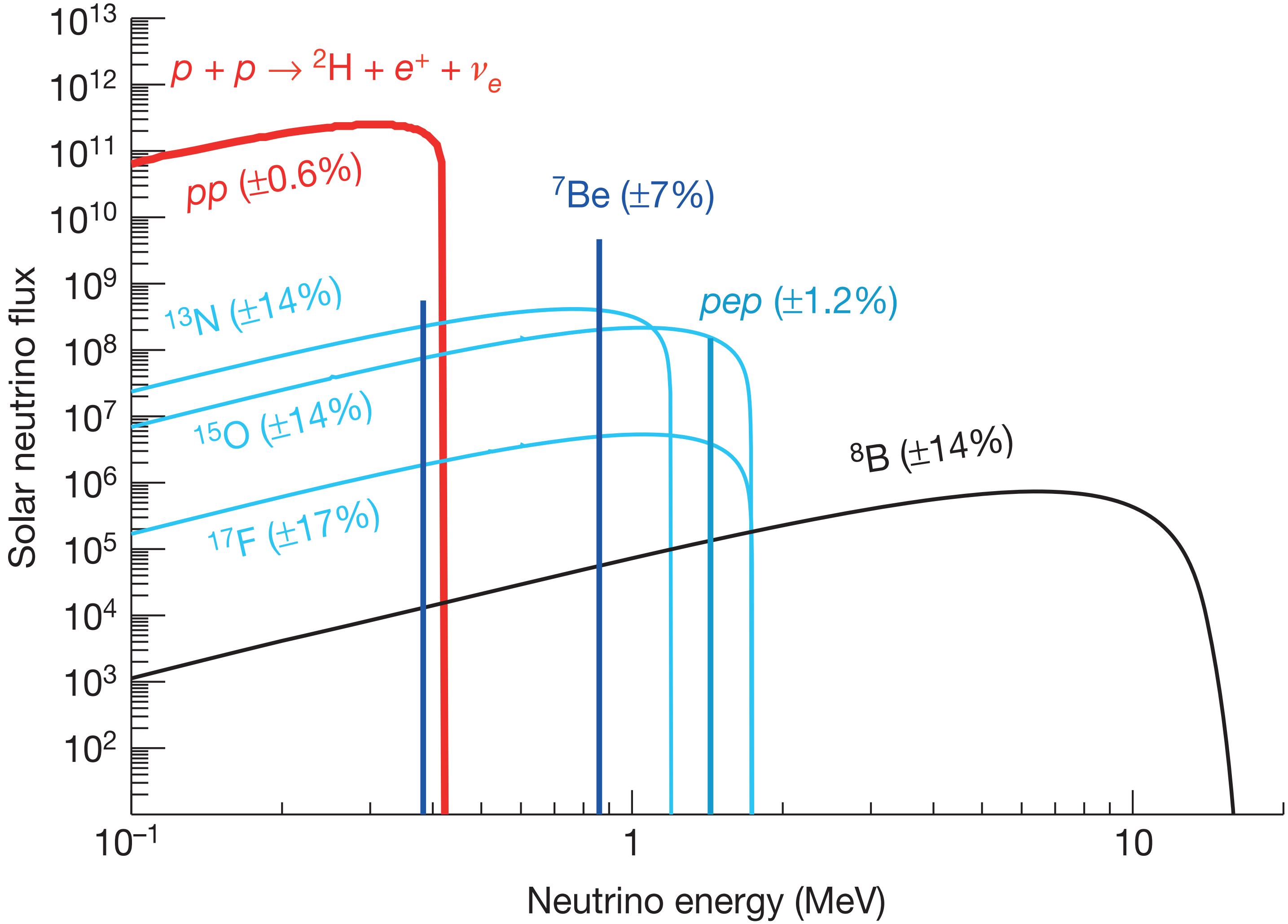
H. Bethe



W. Fowler

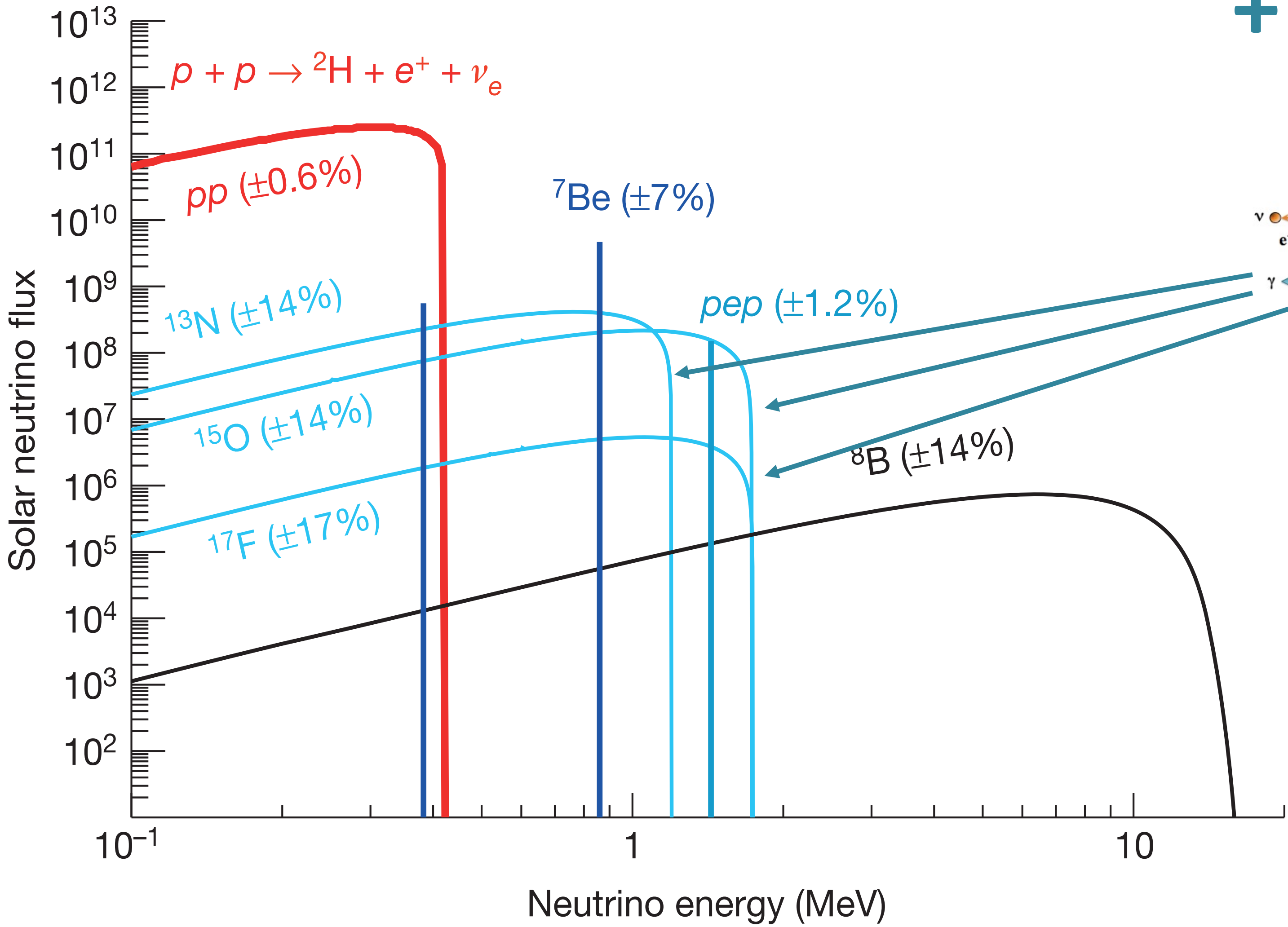
Solar neutrino spectrum : pp-neutrinos

- flux predictions based on **Standard Solar Model (SSM)**
- energy spectra based on **nuclear physics/weak interaction**



Solar neutrino spectrum : CNO cycle

- flux predictions based on **Standard Solar Model (SSM)**
- energy spectra based on **nuclear physics/weak interaction**



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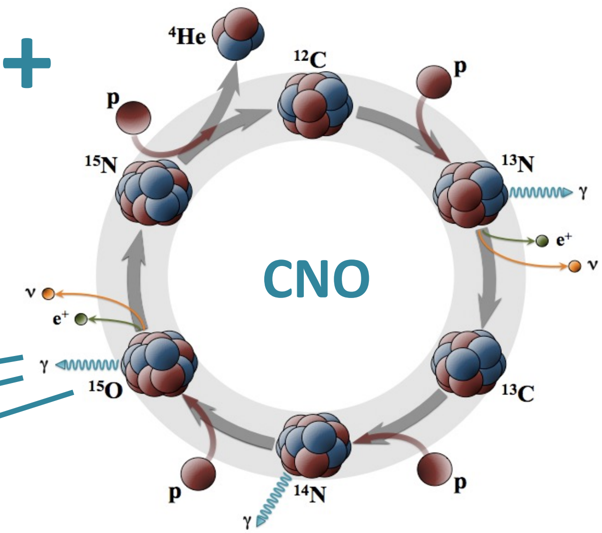
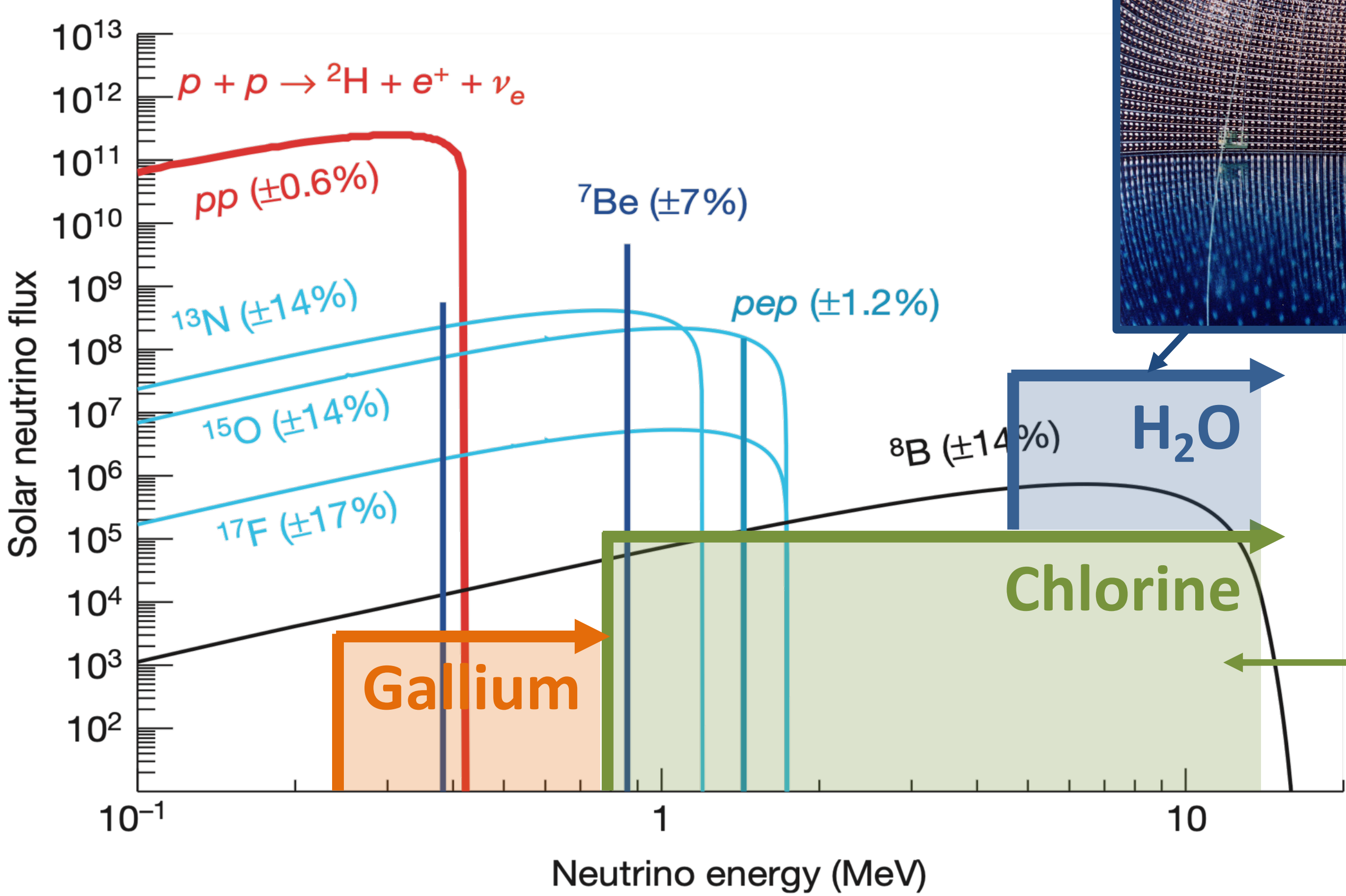
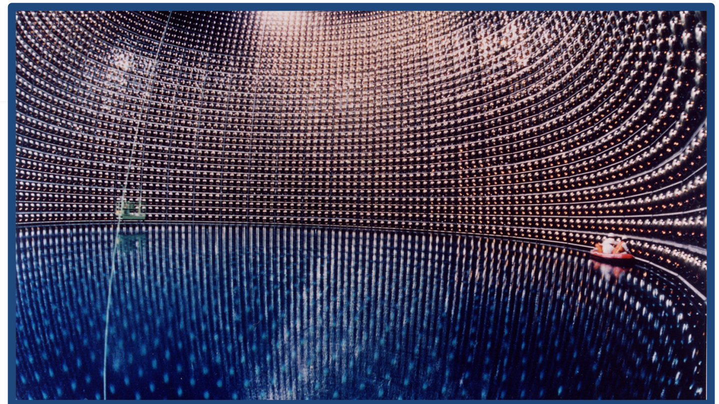


- subdominant flux (~1% of total)
- difficult energy range to detect

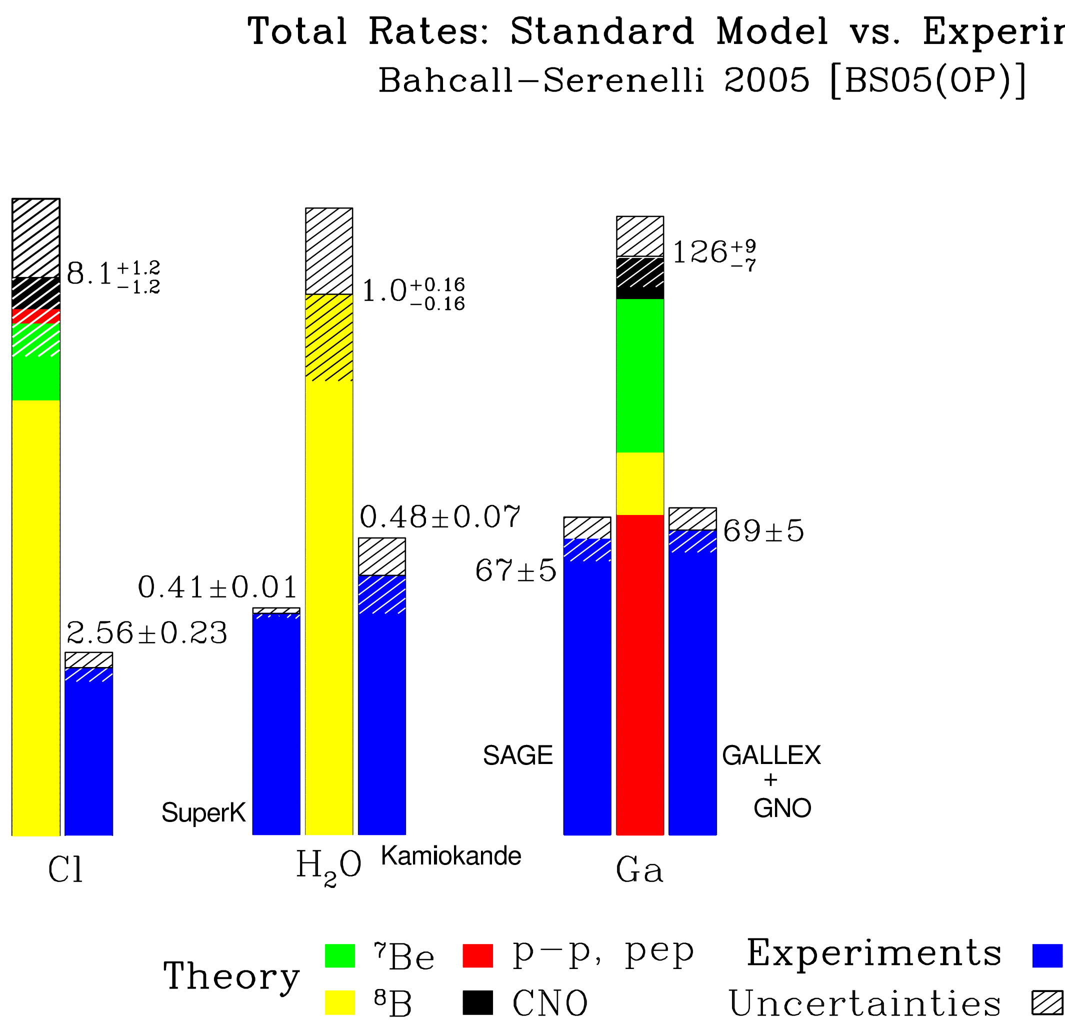
Spectral ranges of early solar neutrino experiments

- **radiochemical: Gallium, Chlorine** → integral measurements
- **Water Cherenkov:** Kamiokande → spectral measurement, high threshold

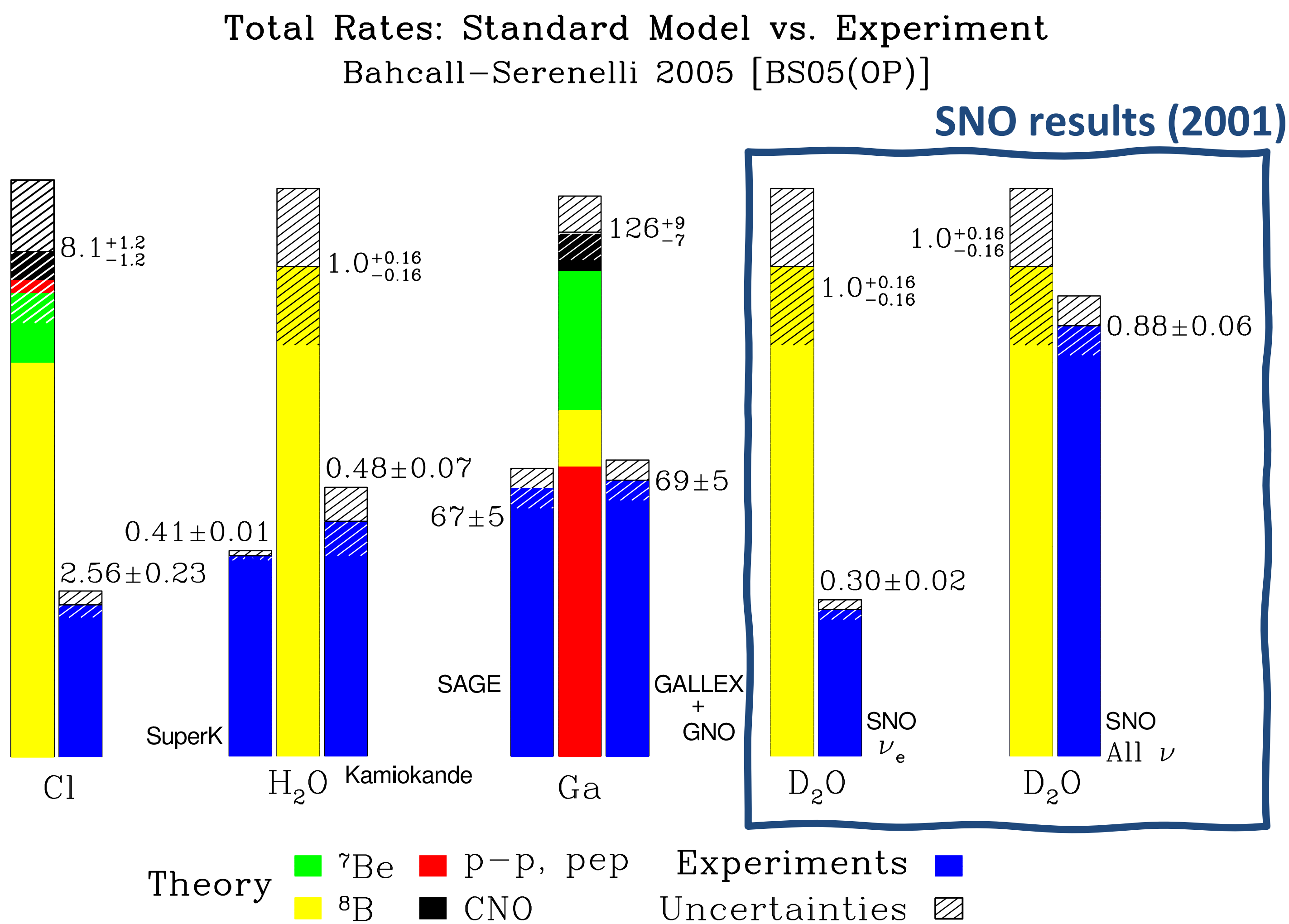




Predicted vs. observed solar neutrino rates

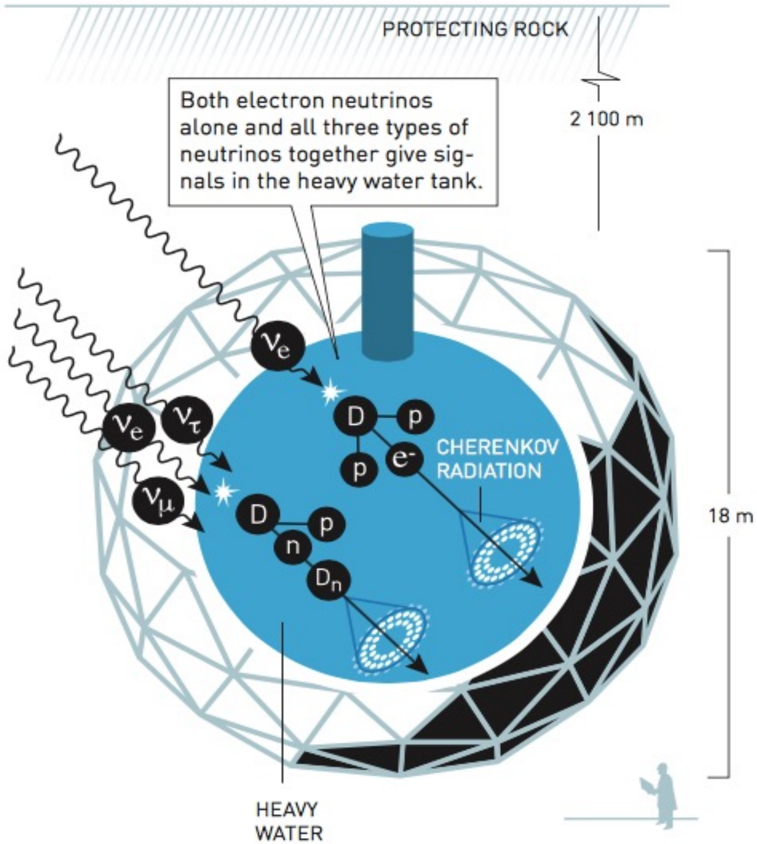


Predicted vs. observed solar neutrino rates

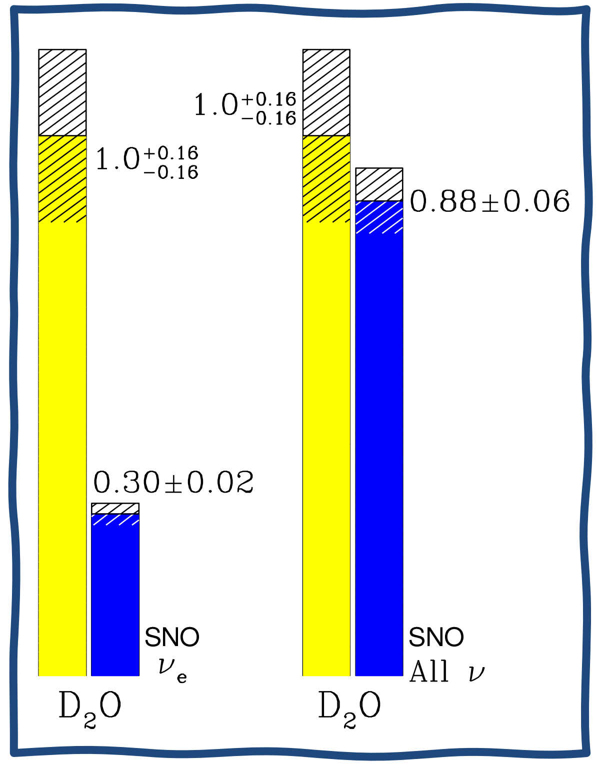


Predicted vs. observed solar neutrino rates

Sudbury Neutrino Observatory (SNO)
Heavy Water (D_2O) Cherenkov detector



SNO results (2001)



Charged Current: $\nu_e + d \rightarrow p + p + e^-$
Neutral Current: $\nu_x + d \rightarrow p + n + \nu_x$

→ **solar neutrinos change flavor!**
$\nu_e \rightarrow \nu_{\mu/\tau}$

Neutrino masses and mixing

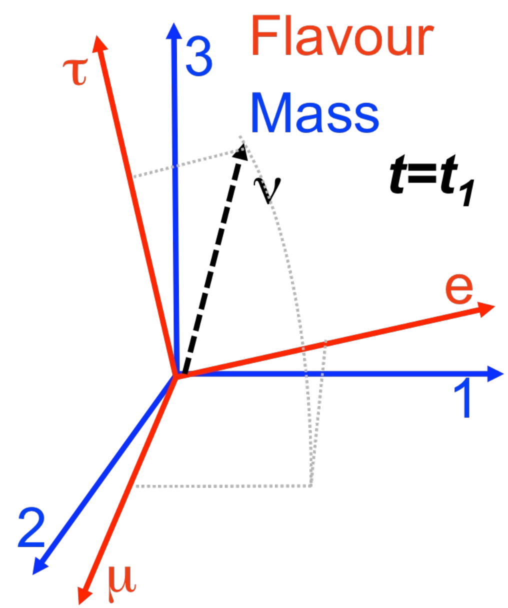
QM: For massive neutrinos ($m_\nu \lesssim 0.2$eV) with differing masses,

- the three neutrino **flavor-eigenstates**
  (taking part in weak interactions)

can be a **superposition** of

- the three **mass-eigenstates**
  (propagating through space)

- The relative fractions of mass in flavor states (and vice versa) are described by a **3x3-mixing matrix**



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

flavor-states ***mass-states***

PMNS-mixing matrix *corresponds to a 3D-rotation between flavor and mass eigenspaces*

→ cf. CKM-matrix in quark-sector

Solar neutrinos: two-flavor approximation

2x2 mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

flavor states *mass states*

Oscillation probability:

$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

baseline-over-energy

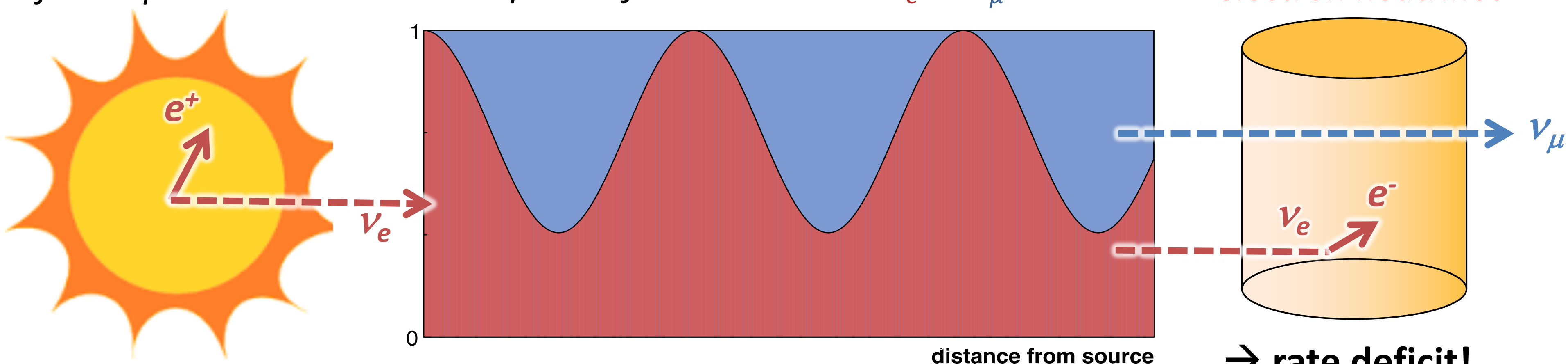
oscillation amplitude

oscillation frequency/length

electron neutrinos created in solar fusion processes

neutrinos propagate → oscillate partial flavor transition $\nu_e \to \nu_\mu$

conventional detector mostly sensitive to electron neutrinos



→ **rate deficit!**

Solar neutrinos: two-flavor approximation

2x2 mixing:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

flavor states — *mass states*

Oscillation probability:

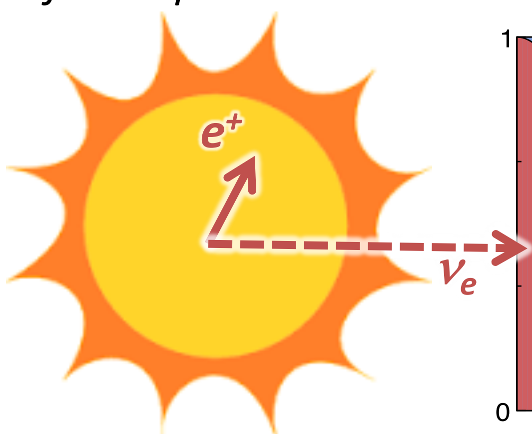
$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

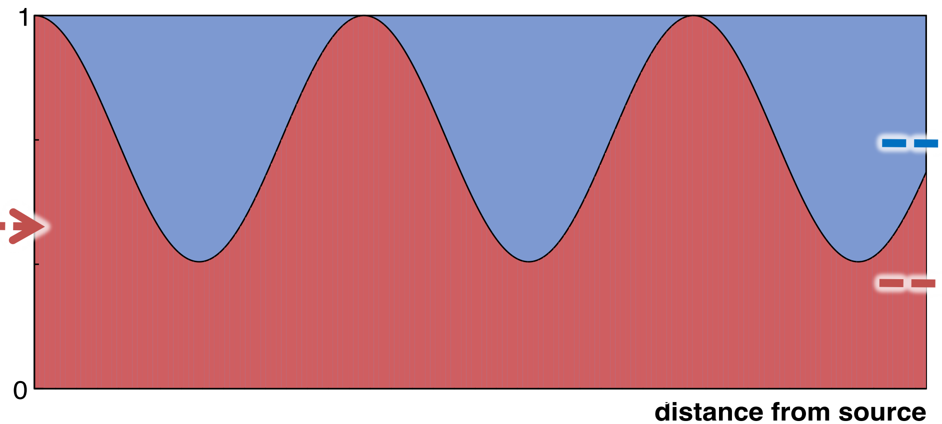
oscillation amplitude — *oscillation frequency/length* — *baseline-over-energy*

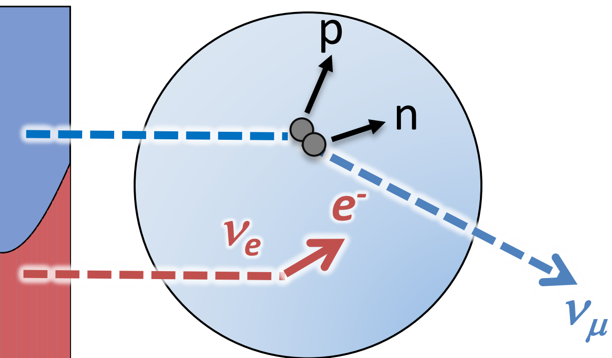
electron neutrinos created in solar fusion processes

neutrinos propagate → oscillate
partial flavor transition $\nu_e \to \nu_\mu$

SNO detector with heavy water
all neutrino flavors

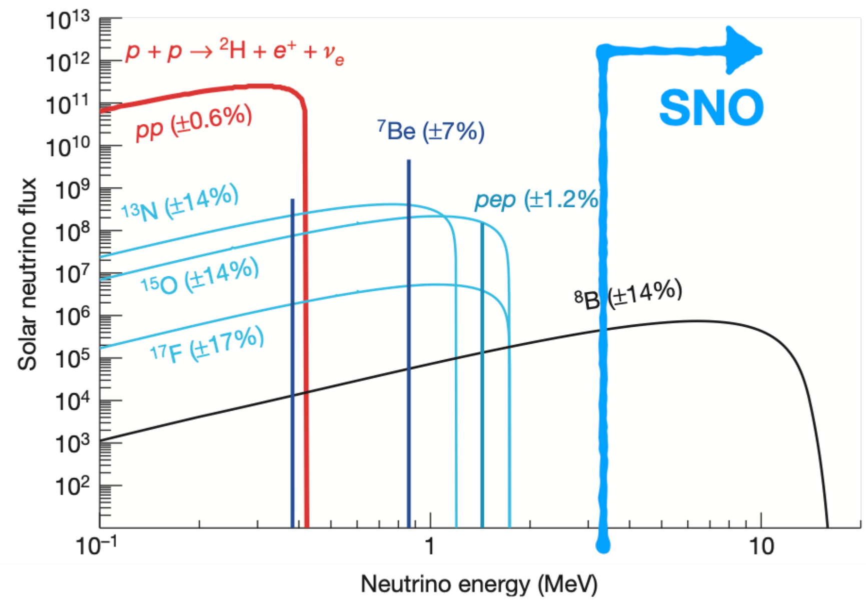






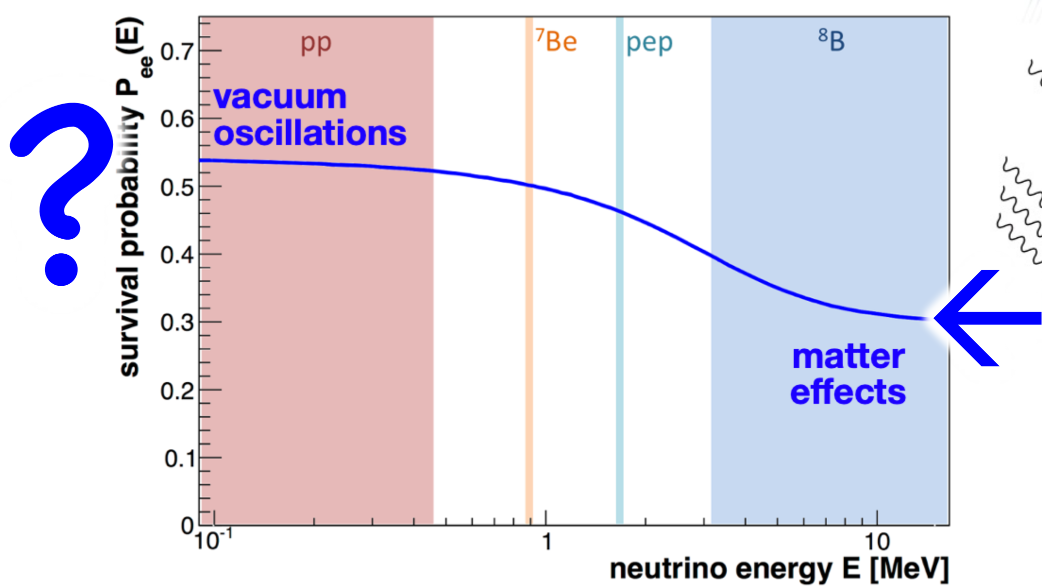
→ full rate observed!

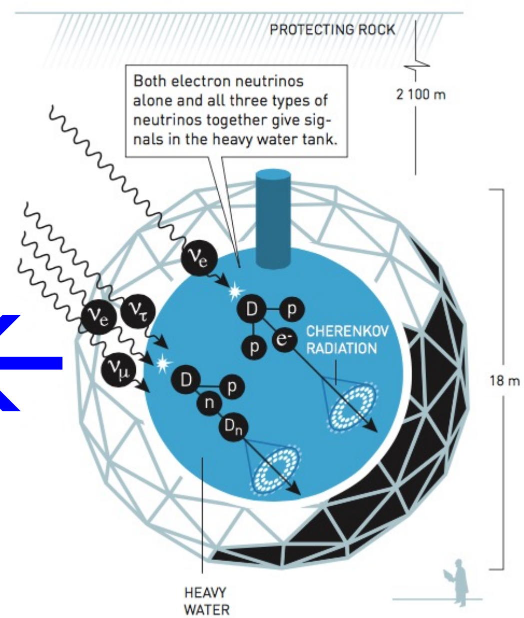
Solar neutrino oscillations in vacuum and matter

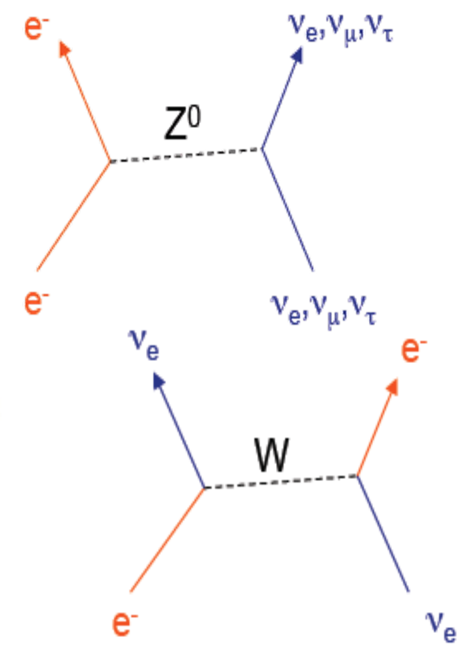


- SNO measured P_{ee} **~ 0.3**
- at high energies, flavor conversion is enhanced by **matter effects** inside the dense solar core region!
- **vacuum oscillations** only at low energy, below detection threshold of SNO

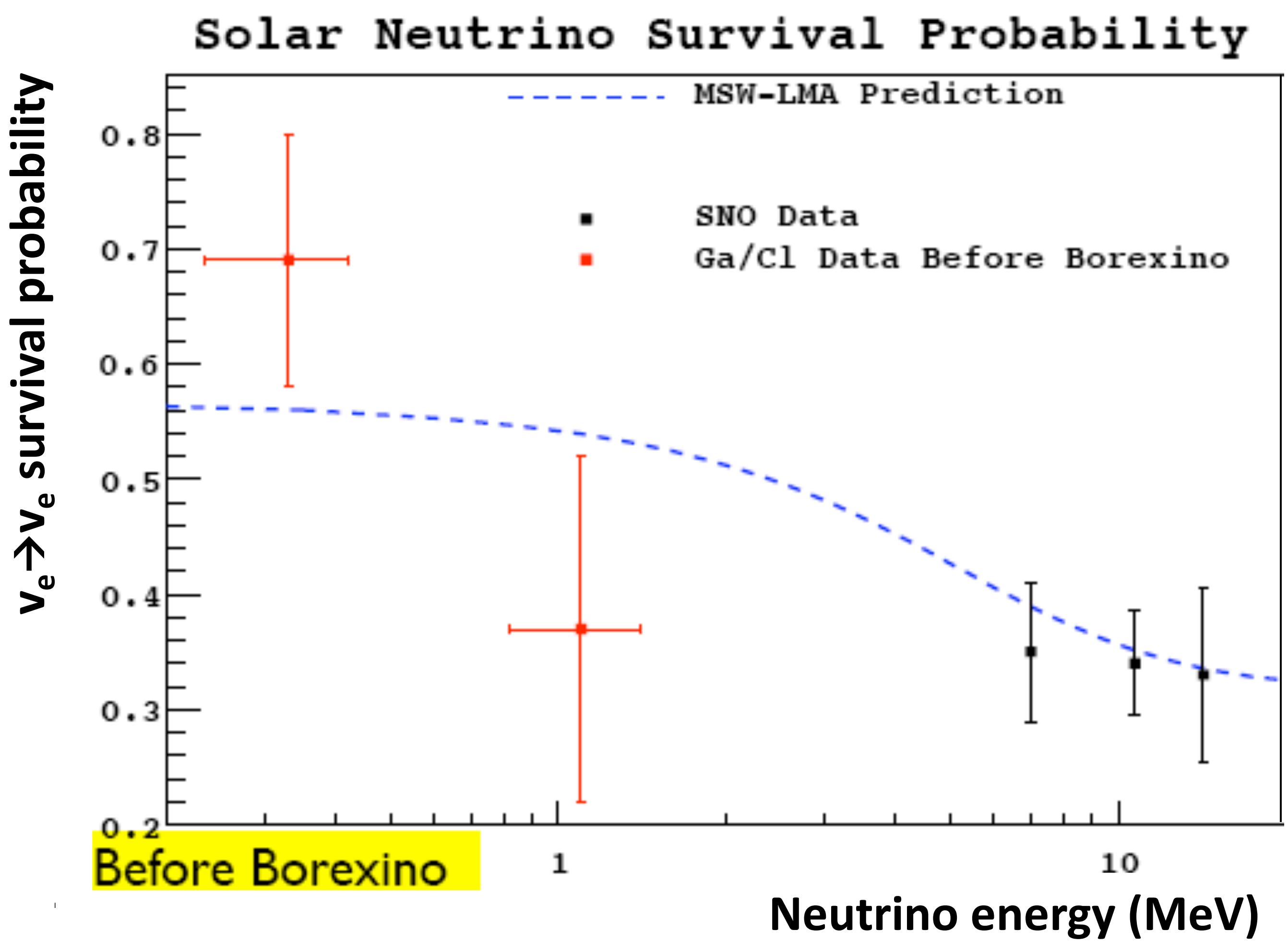
→ needs another detector technology







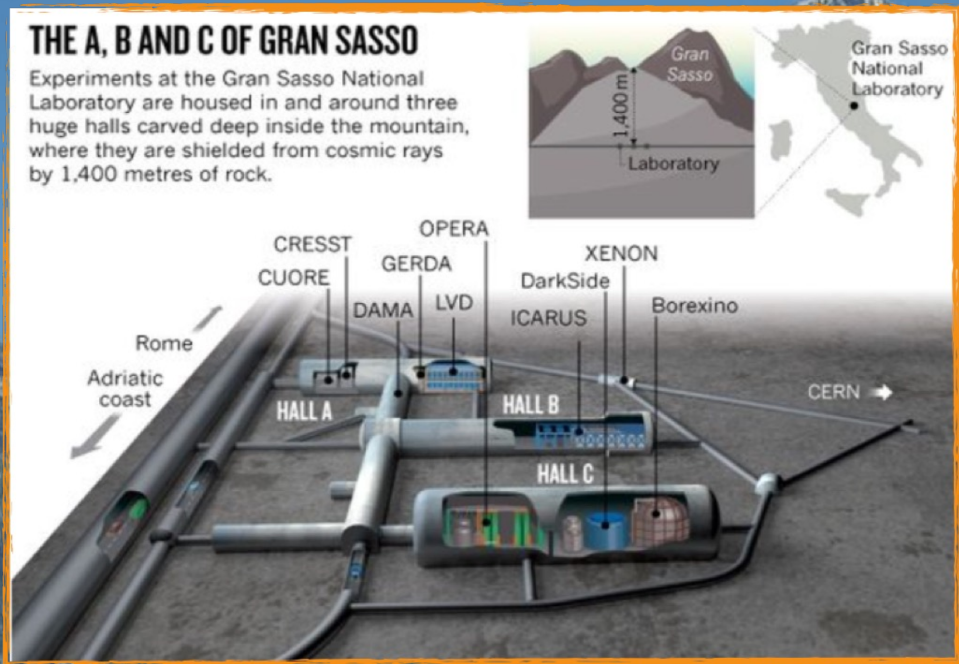
Energy dependence of P_{ee} before Borexino



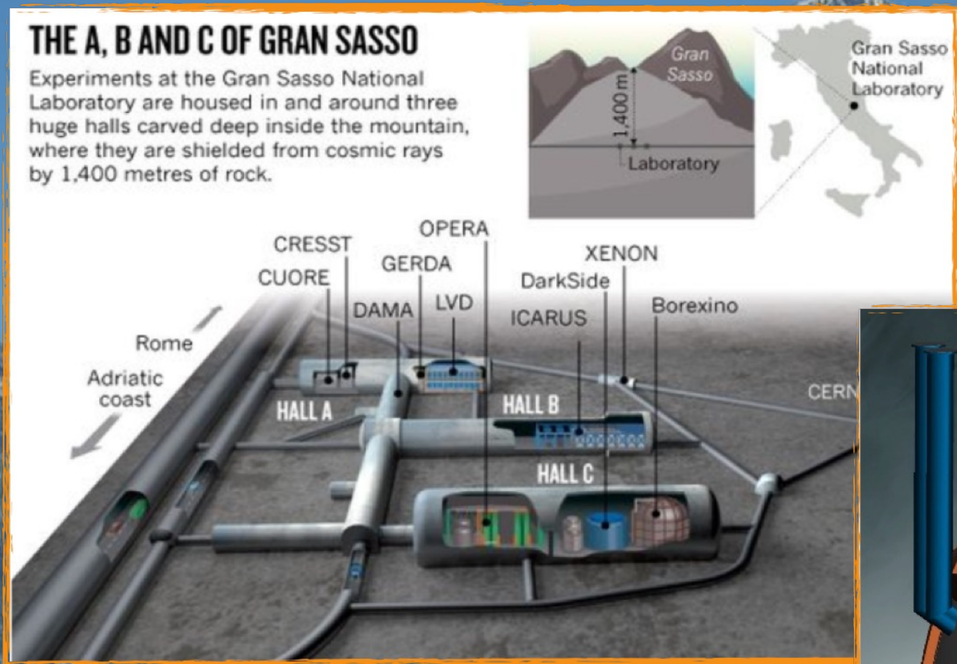
- quite detailed information on the high energy (^{8}B) region of the spectrum
- poor information for the sub-MeV regime

Borexino at Gran Sasso Laboratory

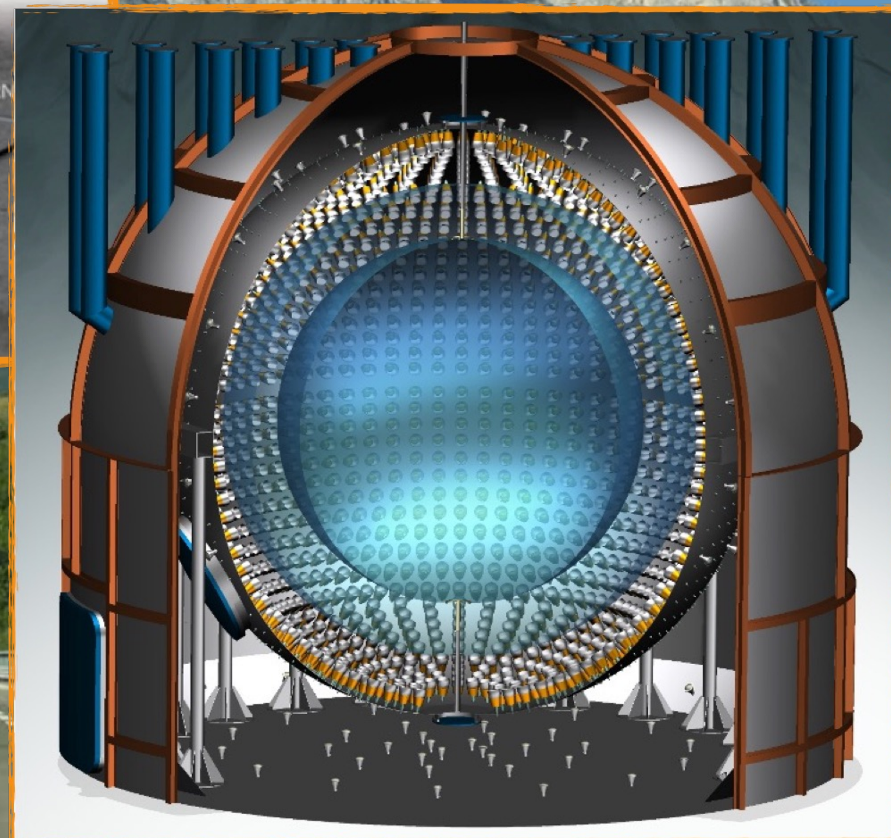
Borexino at Gran Sasso Laboratory



Borexino at Gran Sasso Laboratory



Borexino Detector
Height/Diameter: 18m
Target: Scintillator
Target mass: 270t
Light sensors: 2200 8”-PMTs



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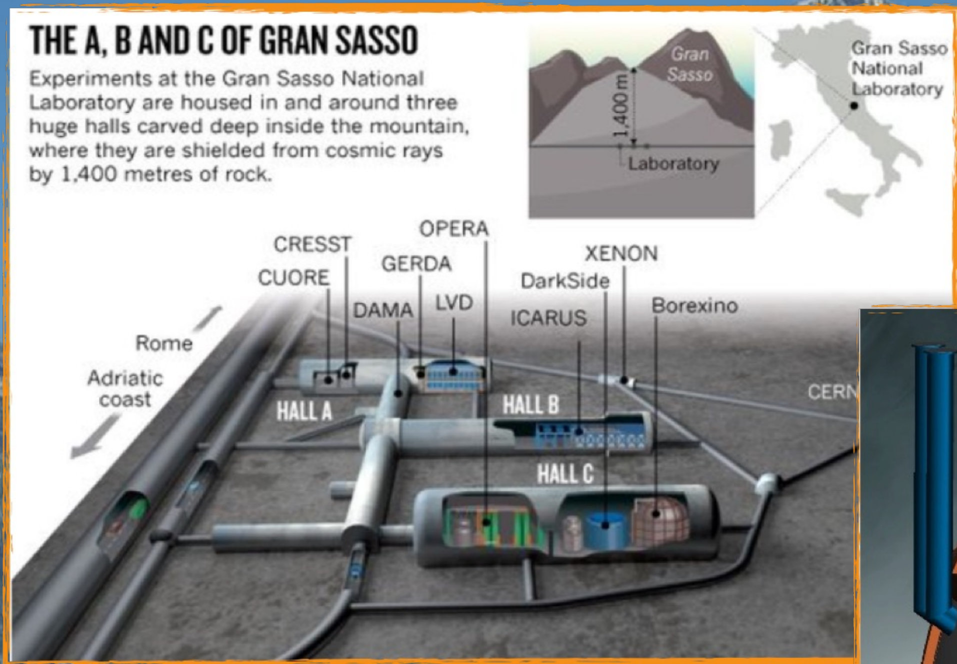

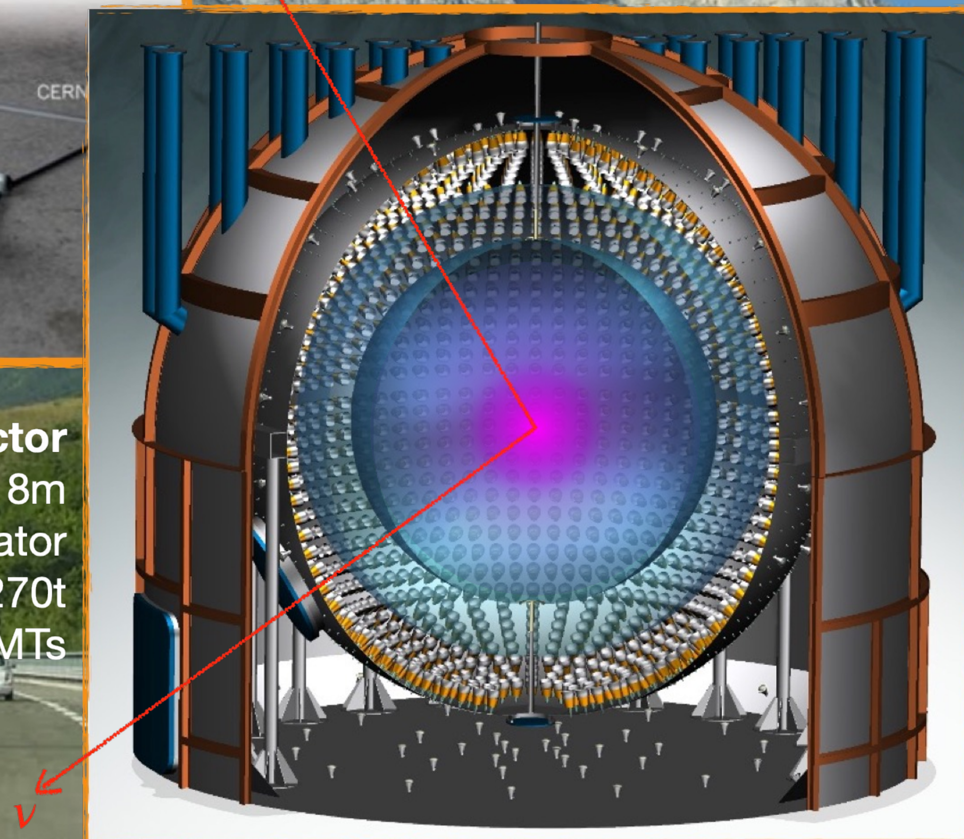

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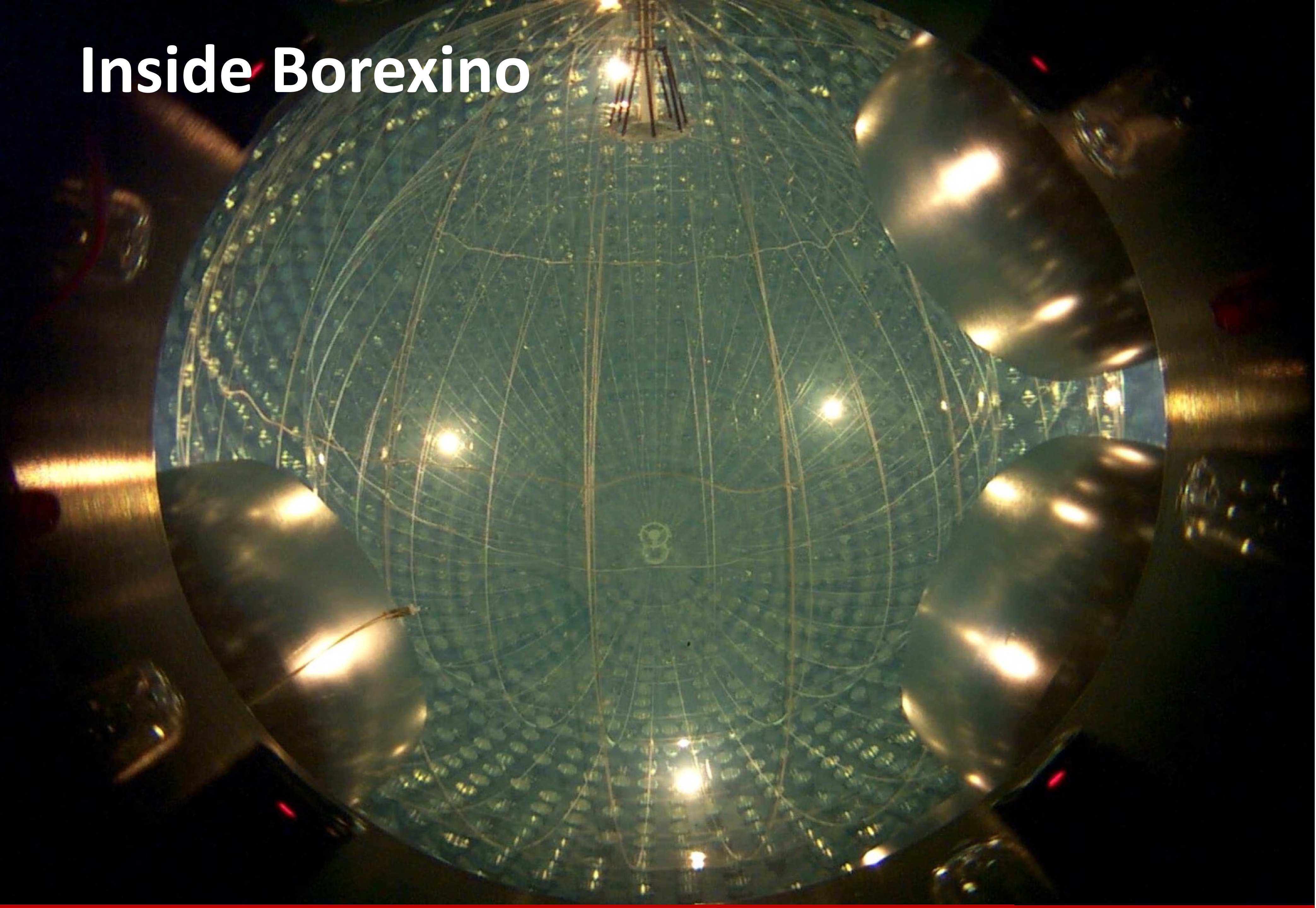
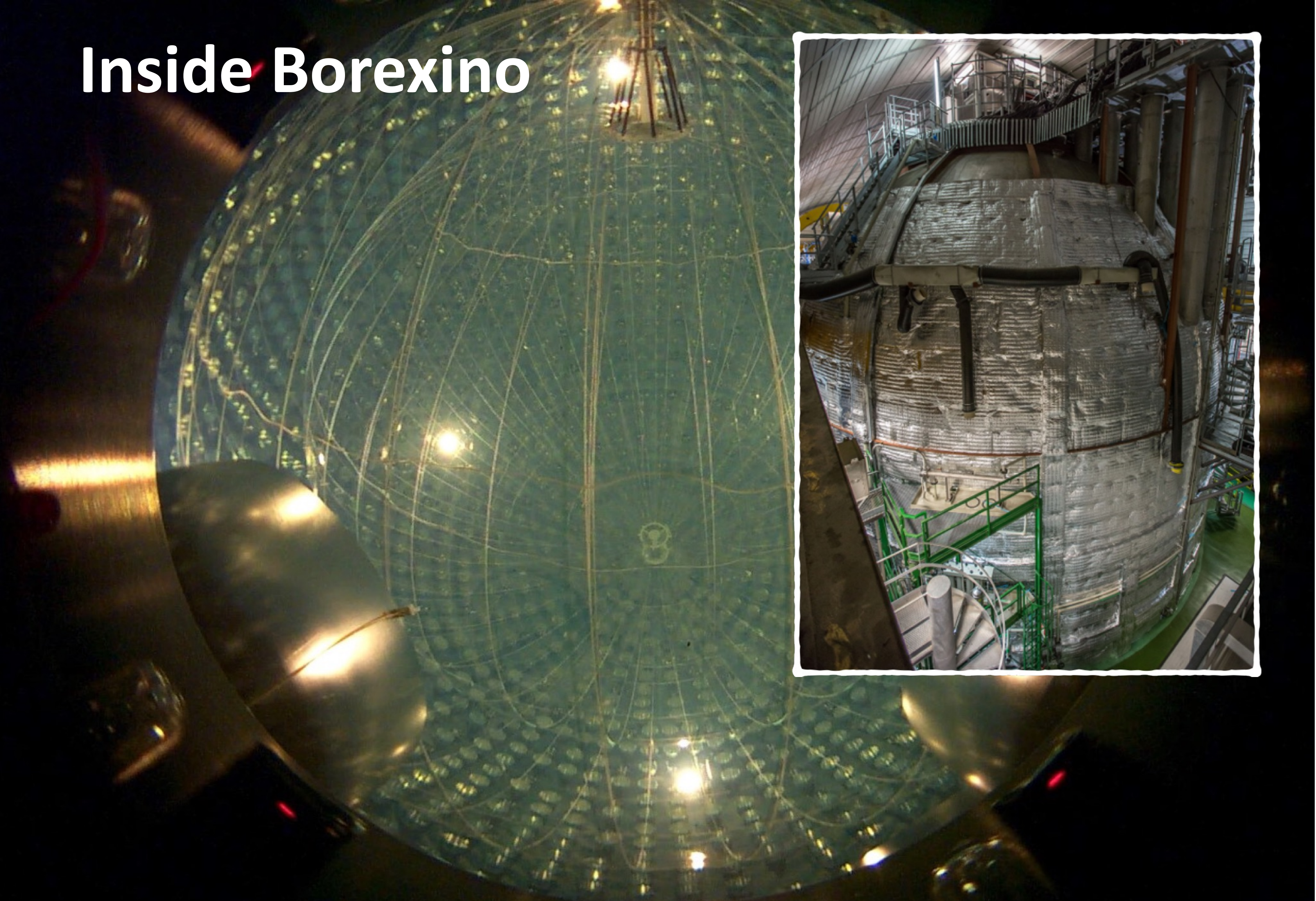
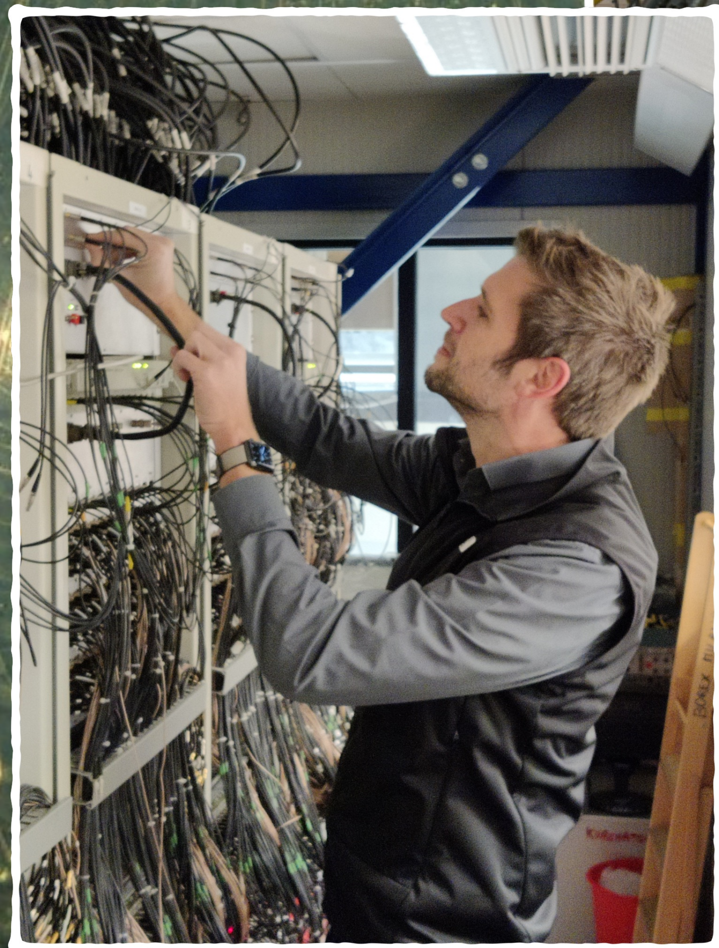
Inside Borexino



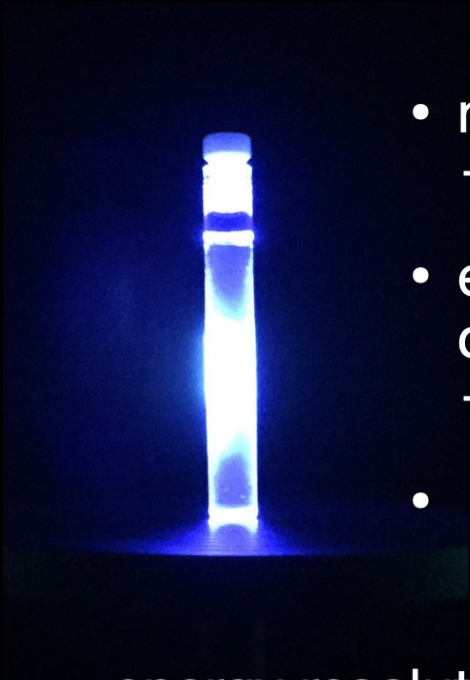
Inside Borexino



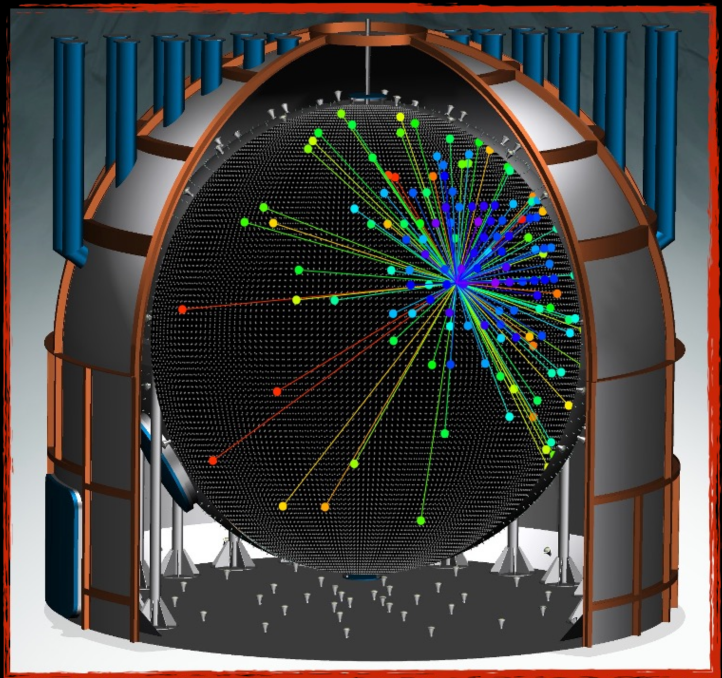
Inside Borexino



Neutrino detection in liquid scintillator

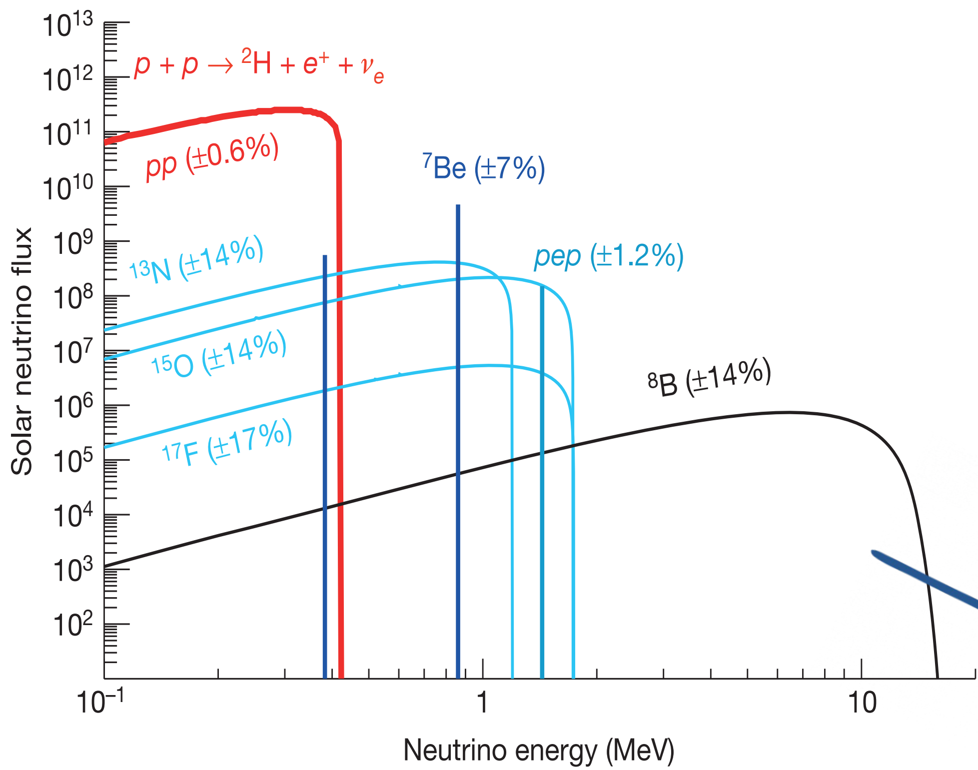


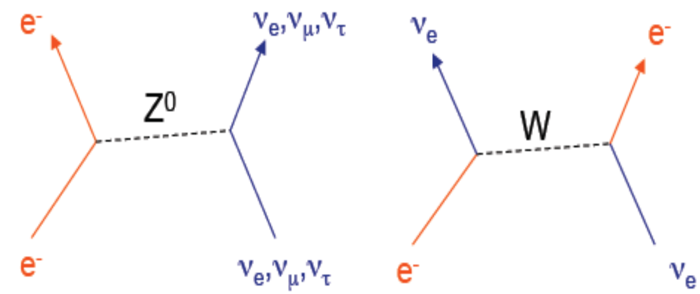
- much greater light yield than Cherenkov effect (x50) → better energy resolution
- efficient purification methods for radioactive contaminants: 10^{-18} g/g uranium/thorium in LS → low energy threshold (pp neutrinos!)
- transparent and cheap → large-scale detectors

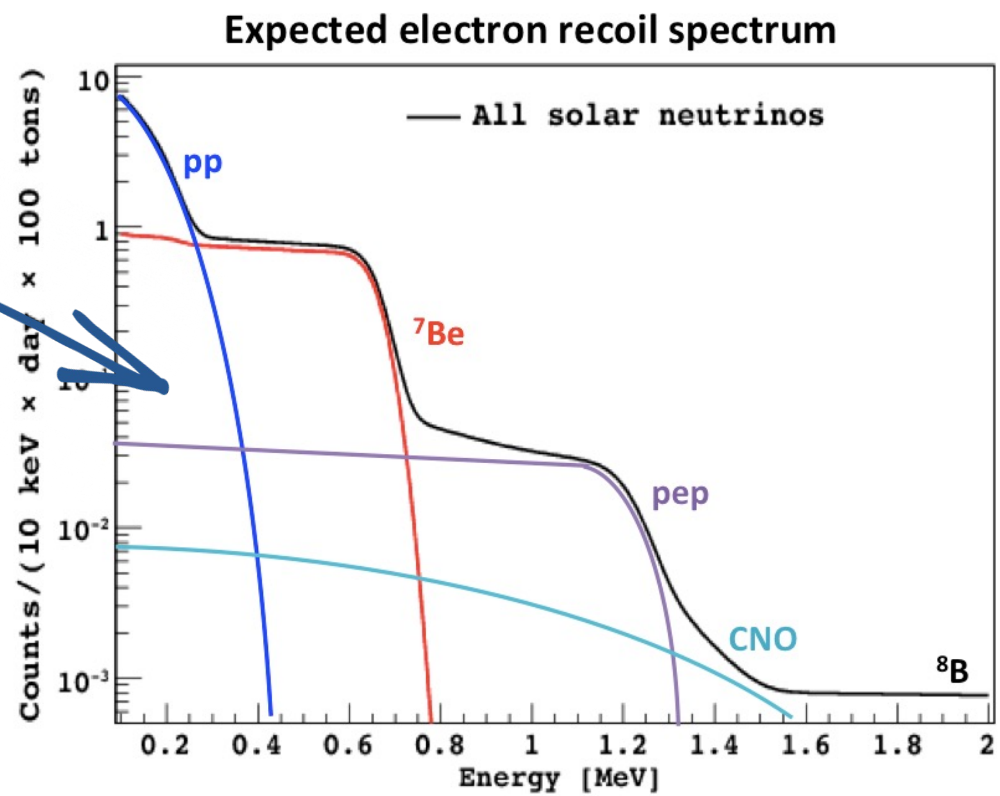


- energy resolution based on number of detected photons:
  isotropic emission: ~10^4/MeV
  detected: Borexino ~500 pe/MeV
  JUNO ~1300 pe/MeV
- vertex reco via photon time-of-flight
- but: no (?) directional resolution

Electron recoil signal in Borexino

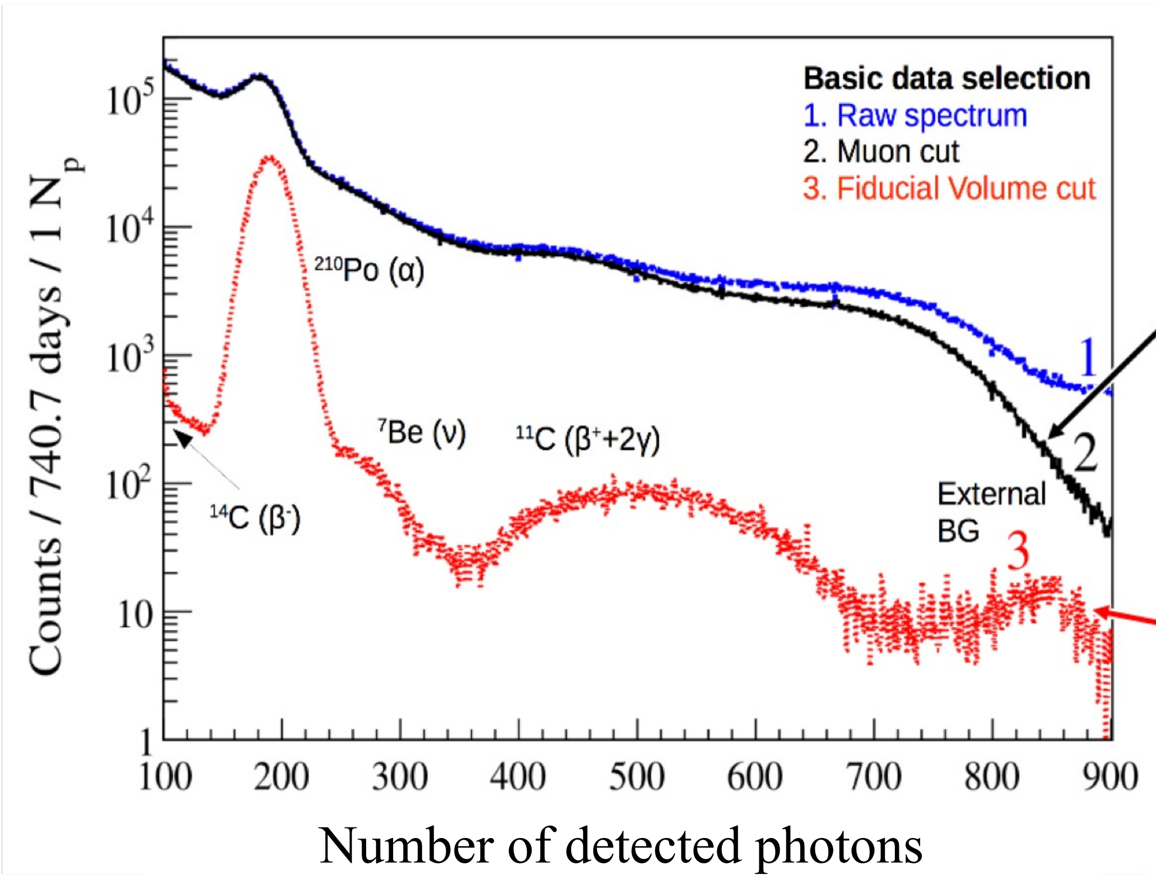


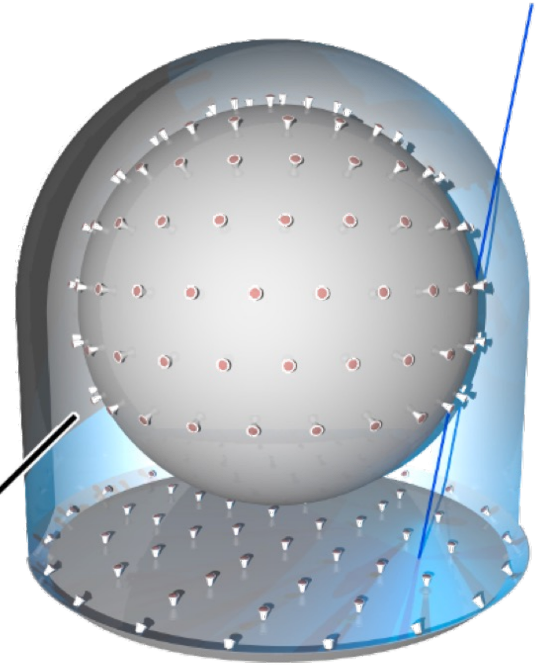


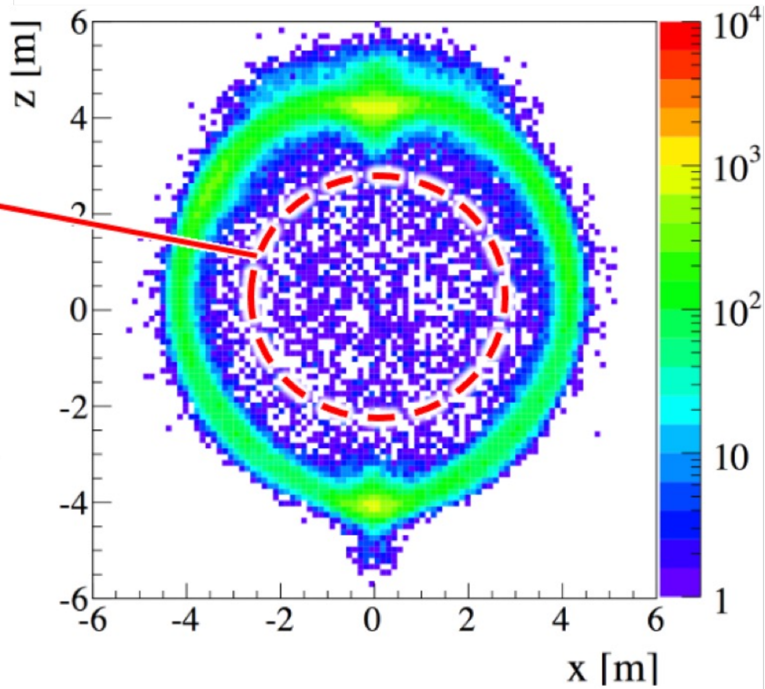


Background reduction

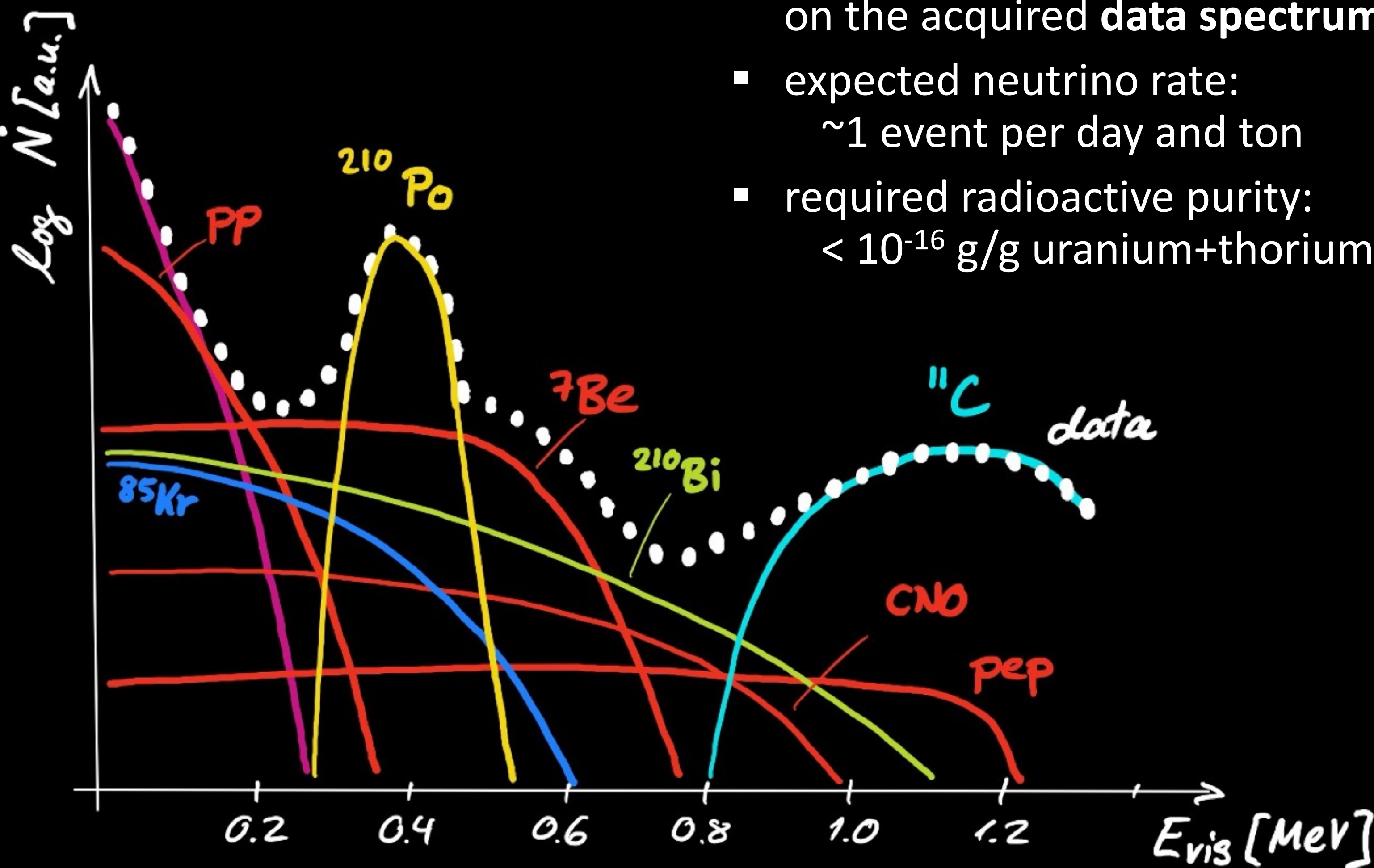
Energy spectrum in raw data







Fit of residual energy spectrum



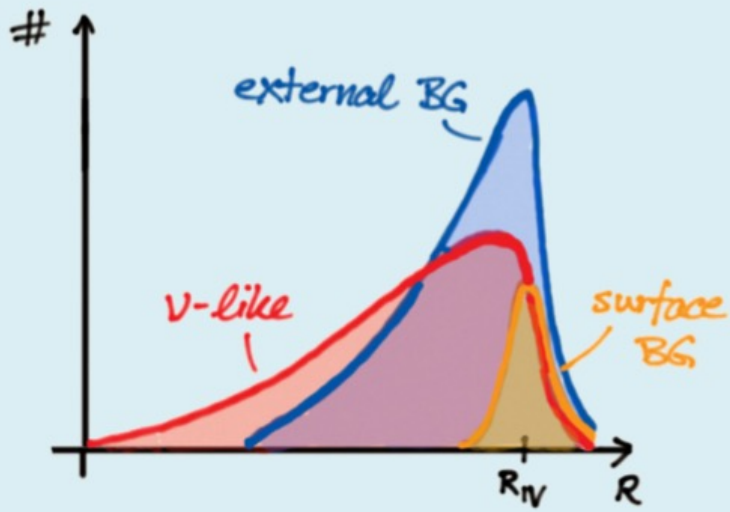
- Fit of known energy spectra of **neutrino signal** and **radioactive backgrounds** on the acquired **data spectrum**
- expected neutrino rate:
  ~1 event per day and ton
- required radioactive purity:
  < 10^{-16} g/g uranium+thorium in LS

Multivariate analysis

- main analysis variable is visible energy → **spectral fit**
- **multivariate analysis** includes further variables in analysis fit (first use for pep-ν's in 2012)

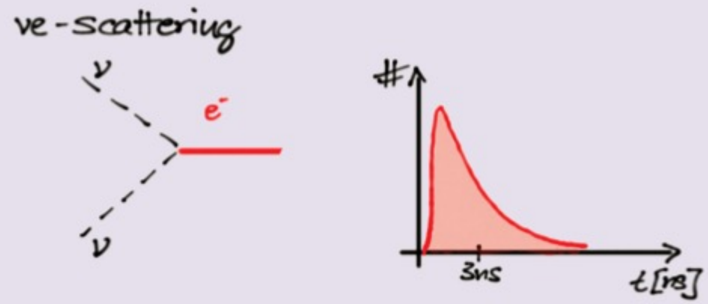
Radial fit

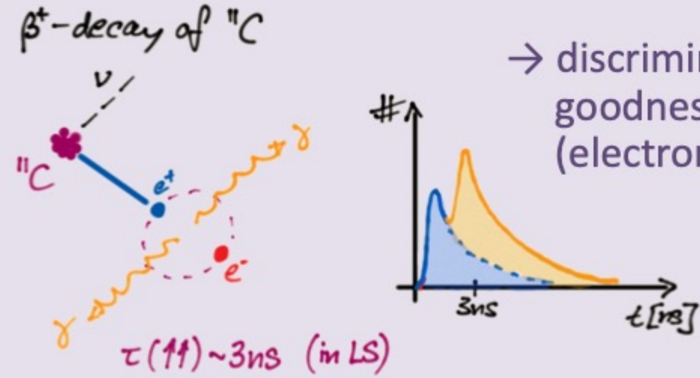
- distribution of neutrinos (and bulk radioactivity) is flat
- external gamma-rays are concentrated at vessel border



Pulse shape discrimination

- recoil electrons: standard scintillation signal
- β^+-emitters like ^{11}C feature elongated signal due to positronium formation in ~50% of the cases





→ discrimination based on goodness of position fit (electron time-PDFs)

Veto for cosmogenic background

Cosmic background levels

- rock shielding: 3500 mwe
- μ rate in Inner Detector: ~3 min^{-1}
- *radioisotopes from ^{12}C spallation are (mainly) produced in hadronic showers*

Main background for pep/CNO ν's: ^{11}C

- $^{12}C \rightarrow {}^{11}C + n$ [$\tau(^{11}C)$~30min]

  $\hookrightarrow {}^{10}C + e^+ + \nu_e$

→ neutron at production [$\tau(nH)$~250μs]

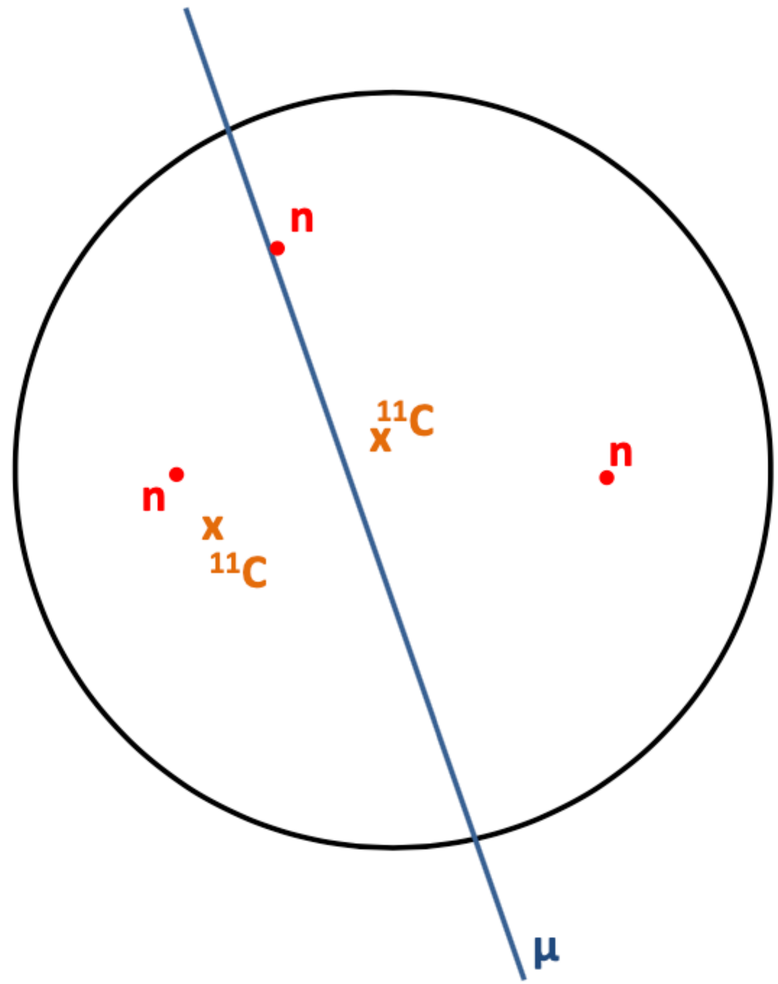
→ delayed β^+ decay signal from ^{11}C

→ visible energy: 1—2 MeV

Expected ^{11}C rate: ~30 d^{-1}

→ signal to background ~1:10 (at best)

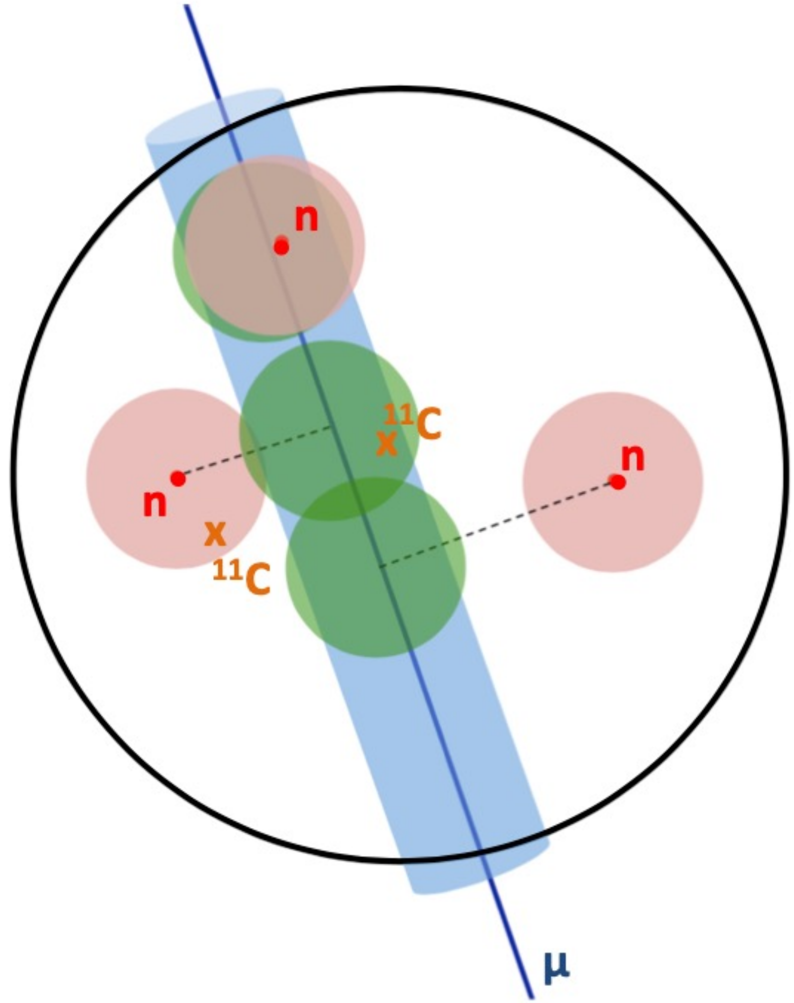
→ veto based on parent μ is mandatory!



Veto for cosmogenic background

Veto strategy

- likelihood approach ascribing each ν/^{11}C candidate with a probability to be a μ-induced radioactive decay
- product of PDFs including
  - visible energy [dE/dx] of the muon
  - neutron multiplicity
  - distance from the muon track
  - distance from next neutron vertex
  - distance from neutron projection point on the muon track



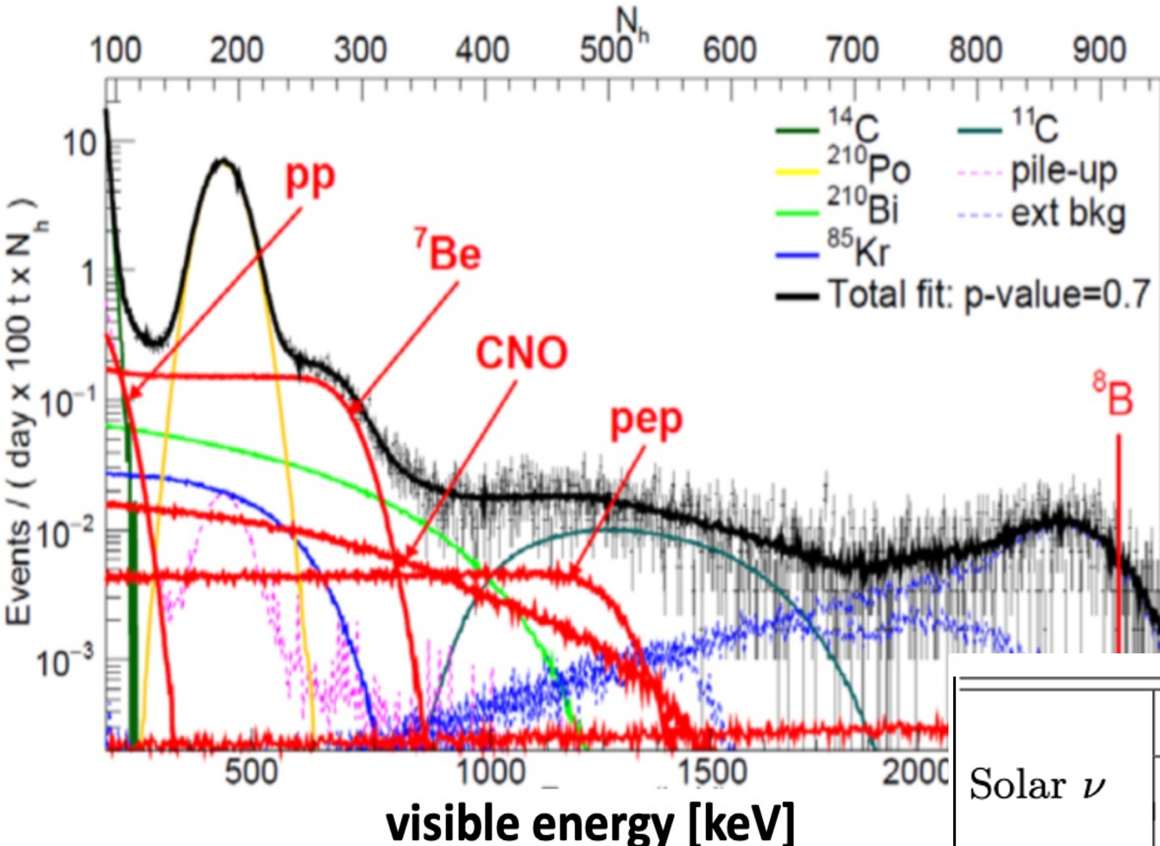
Veto efficiency

→ ^{11}C rejection efficiency: (92 ± 4) %

→ residual life time: (64.28 ± 0.01) %

→ TFC splits data set in a ^{11}C-depleted and a ^{11}C-enriched sample

Borexino low-energy solar neutrino results

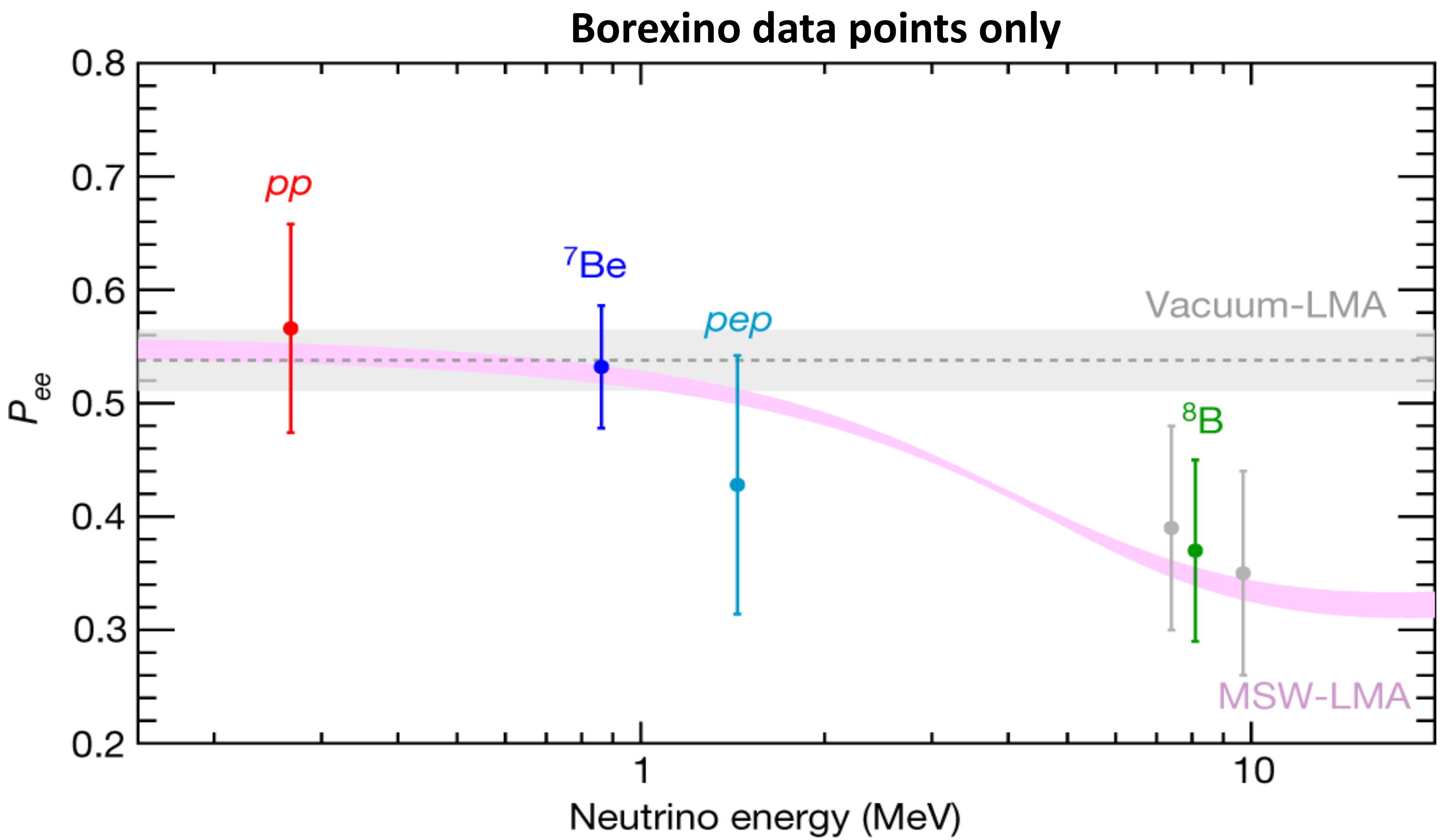


based on Borexino Phase-2
(2012-2017)

- energy spectrum of **data set** depleted in cosmogenic ^{11}C
- fit of **neutrino signals** and **background** spectra
- rate results **consistent with SSM** predictions incl. oscillations

Solar ν	Borexino experimental results	
	Rate [cpd/100 ton]	Flux [cm^{-2}s^{-1}]
pp	$134 \pm 10 \,^{+6}_{-10}$	$(6.1 \pm 0.5 \,^{+0.3}_{-0.5}) \times 10^{10}$
^{7}Be	$48.3 \pm 1.1 \,^{+0.4}_{-0.7}$	$(4.99 \pm 0.11 \,^{+0.06}_{-0.08}) \times 10^9$
pep (HZ)	$2.43 \pm 0.36 \,^{+0.15}_{-0.22}$	$(1.27 \pm 0.19 \,^{+0.08}_{-0.12}) \times 10^8$
pep (LZ)	$2.65 \pm 0.36 \,^{+0.15}_{-0.24}$	$(1.39 \pm 0.19 \,^{+0.08}_{-0.13}) \times 10^8$
CNO	< 8.1 (95% C.L.)	$< 7.9 \times 10^8$ (95% C.L.)

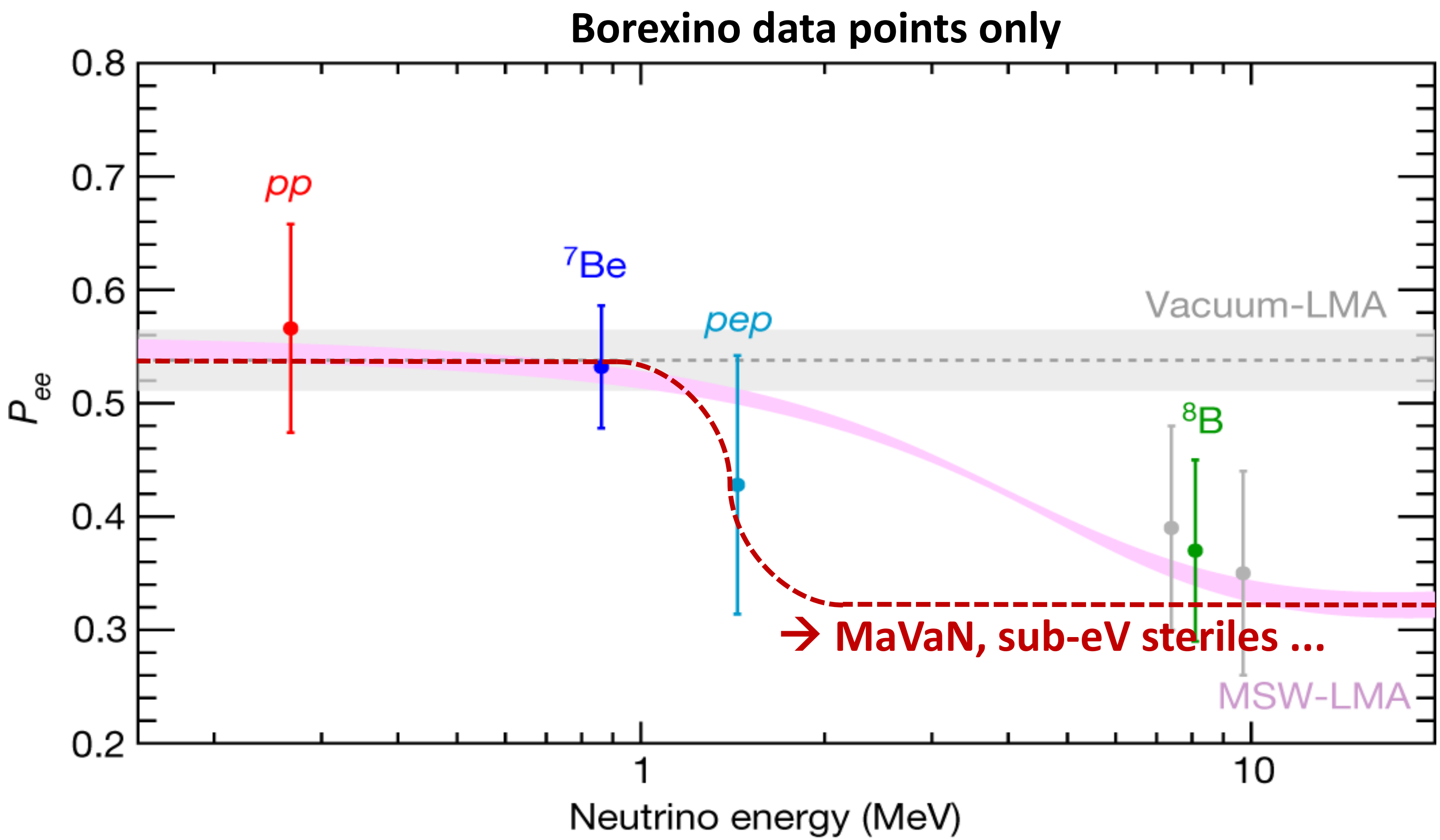
Borexino's measurement of P_{ee}



→ presence of vacuum oscillations at low energies (pp, ^{7}Be, pep)

→ confirms more precise data in high-energy ^{8}B energy range

Borexino's measurement of P_{ee}



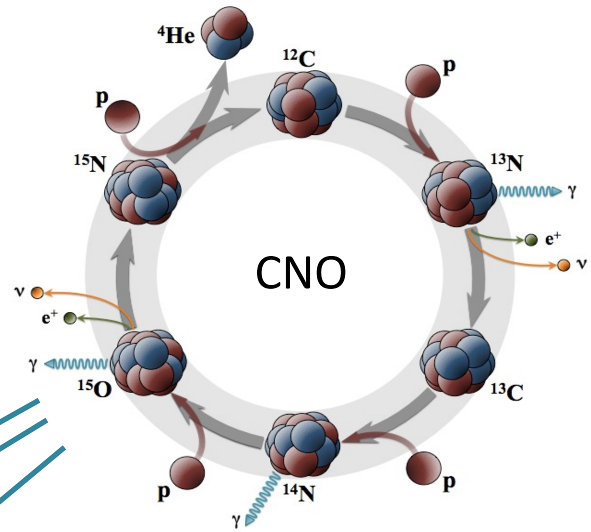
→ presence of vacuum oscillations at low energies (pp, ^{7}Be, pep)

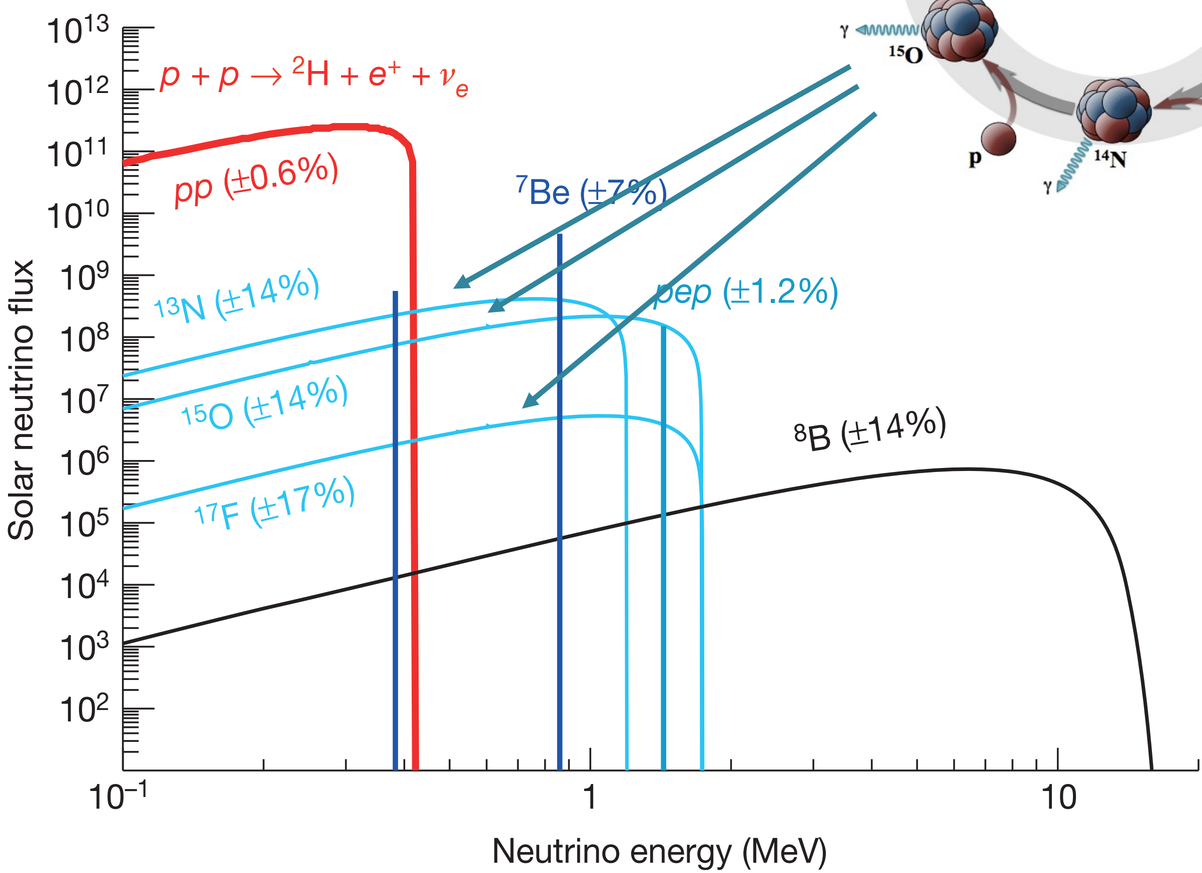
→ confirms more precise data in high-energy ^{8}B energy range

→ more data needed for vacuum-matter transition (1-5 MeV) → **new physics?**

Measurement of CNO neutrinos?

- up to now only results on dominant pp-chain neutrinos
- can a first signal be extracted on the CNO neutrinos?



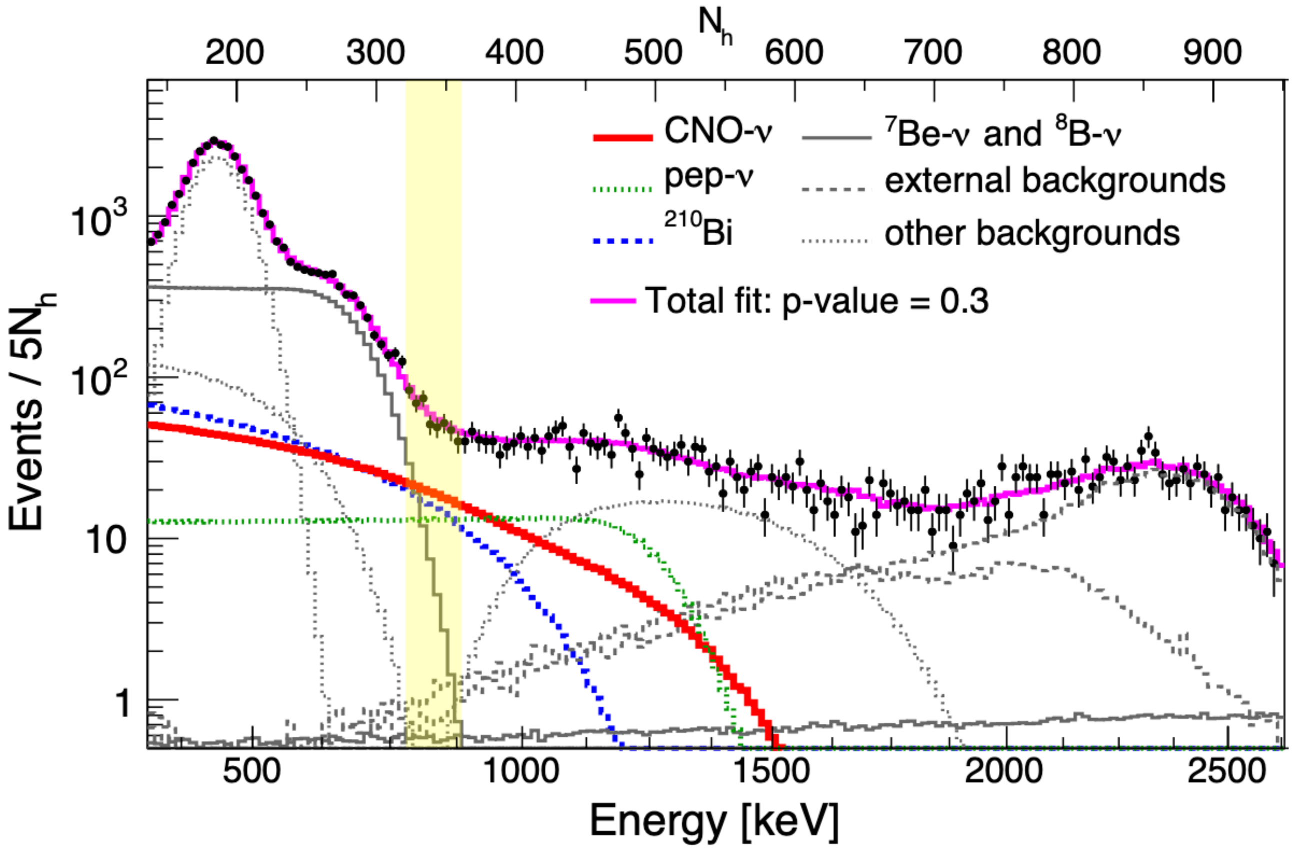


- SSM prediction: relatively large uncertainty due to S-factors
- strong rate dependence on carbon abundance

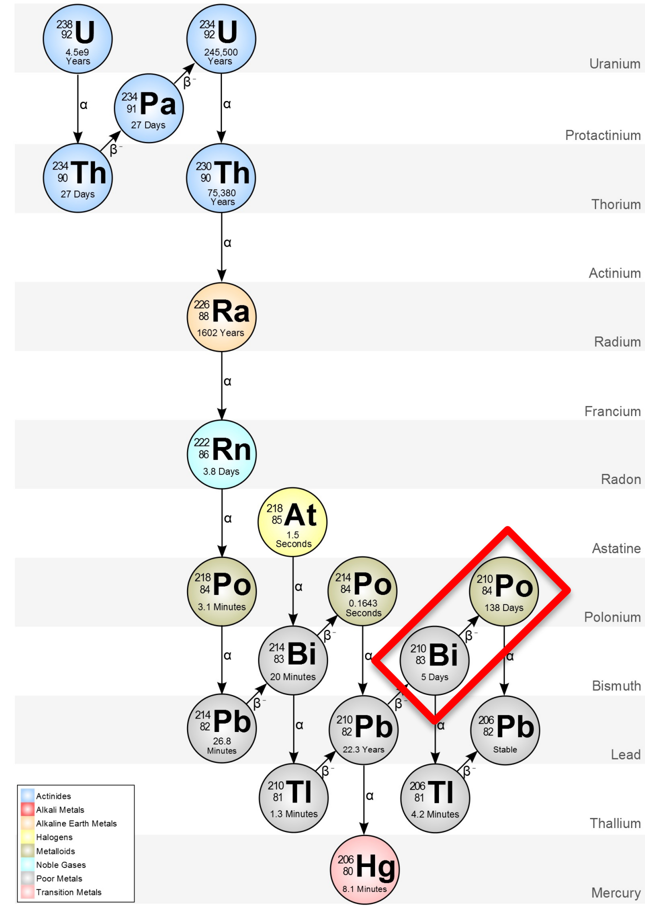
→ measurement interesting to constrain solar metallicity

→ see talks by Francesco Villante Aldo Serenelli

CNO neutrinos in the Borexino spectrum



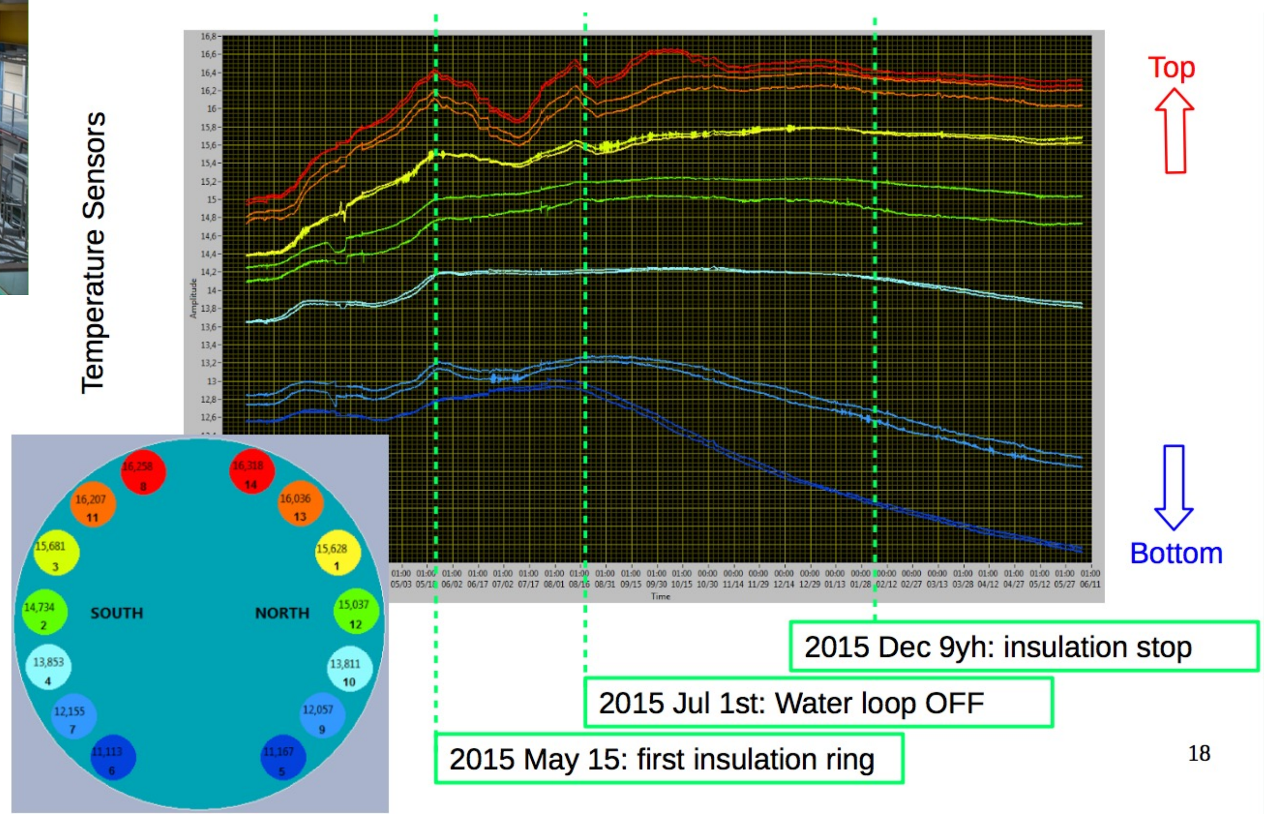
uranium decay chain



- **CNO signal** mostly covered by other neutrino signals
  → define a narrow Region of Interest
- spectral degeneracy with **^{210}Bi β-decays** dissolved in scintillator
  → CNO rate mostly extracted by statistical subtraction
- in the absence of convection, ^{210}Bi rate can be linked to subsequent ^{210}Po decay rate

How to counteract convection in the liquid?

- Thermal insulation of the water tank
- Temperature probes installed
- Active temperature control (i.e. heaters)



→ increase of positive temperature gradient

→ convection mitigated

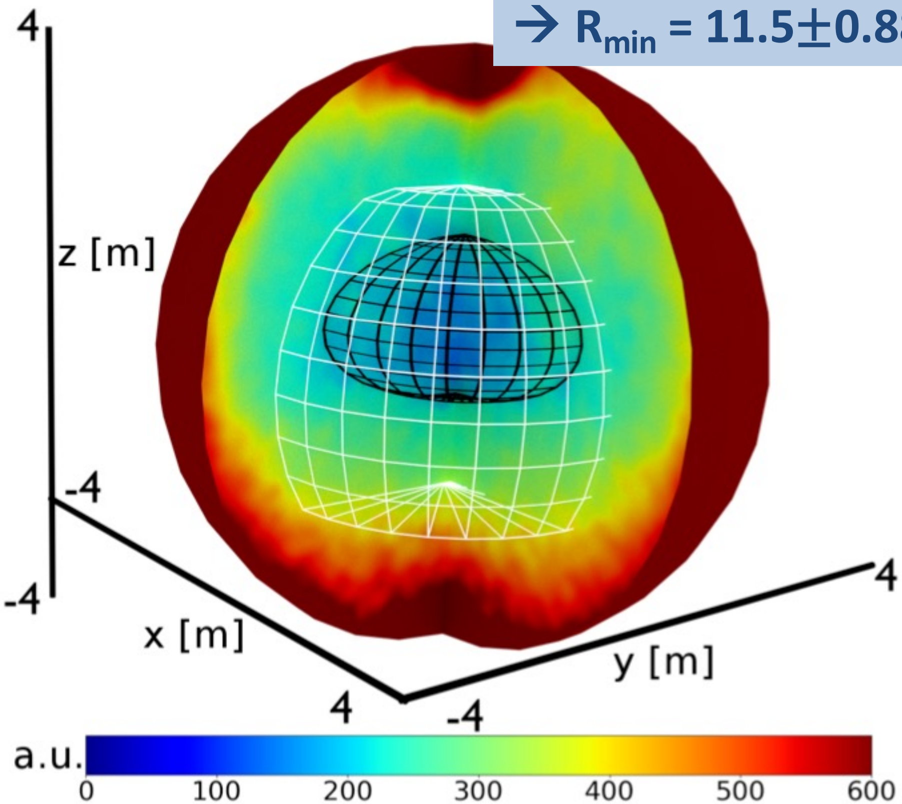
Deriving an upper constraint on ^{210}Bi rate

Find 20-ton low-activity region to extract ^{210}Po rate

→ it is crucial to avoid bias in extracted decay rate!

- 3D paraboloid fit over 2-month periods
- extract z-position of ^{210}Po minimum over time
- align paraboloid using previous month's position

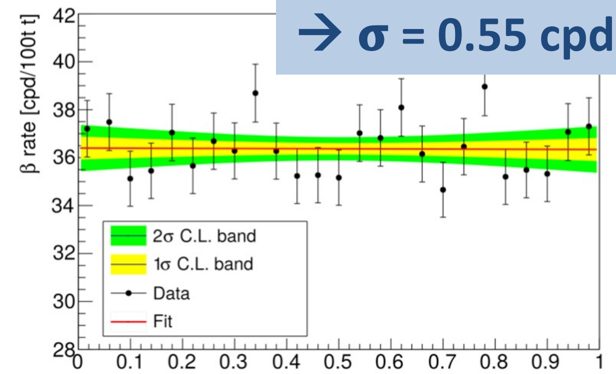
→ R_{min} = 11.5±0.88 cpd

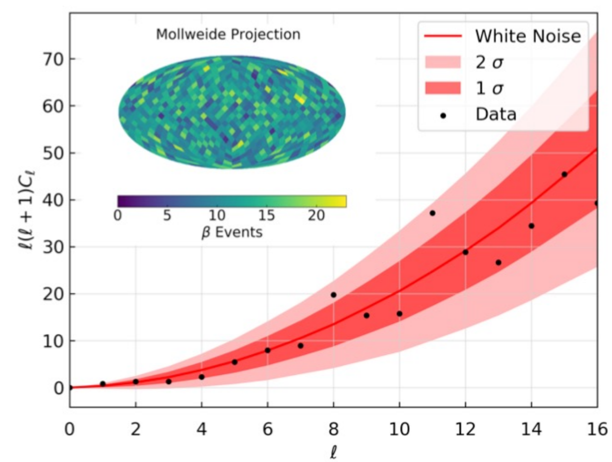


Extrapolate to entire volume

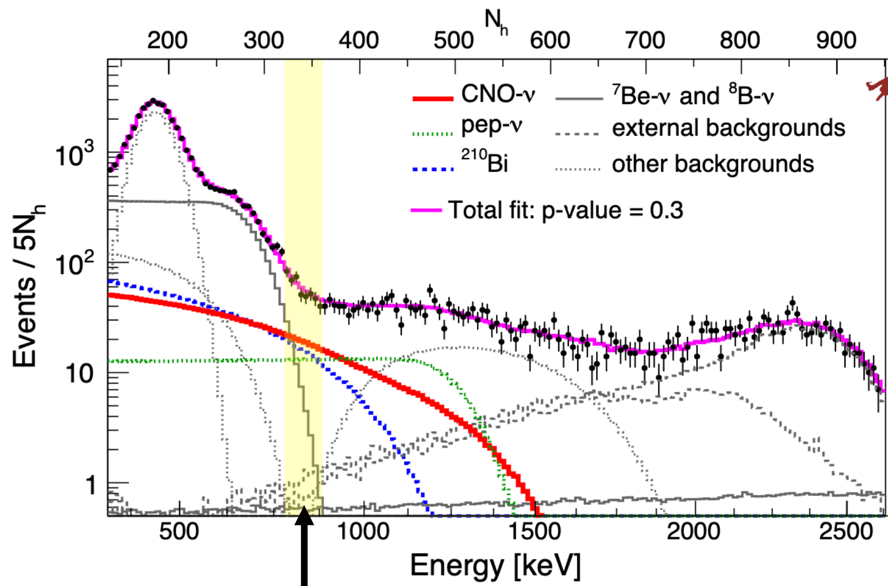
→ it is crucial to make sure ^{210}Bi rate is homogenous!

→ σ = 0.55 cpd





First CNO neutrino rate analysis



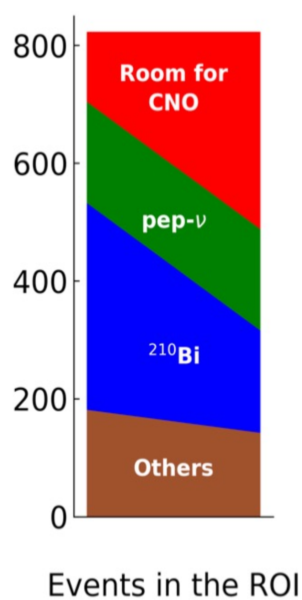
spectral fit

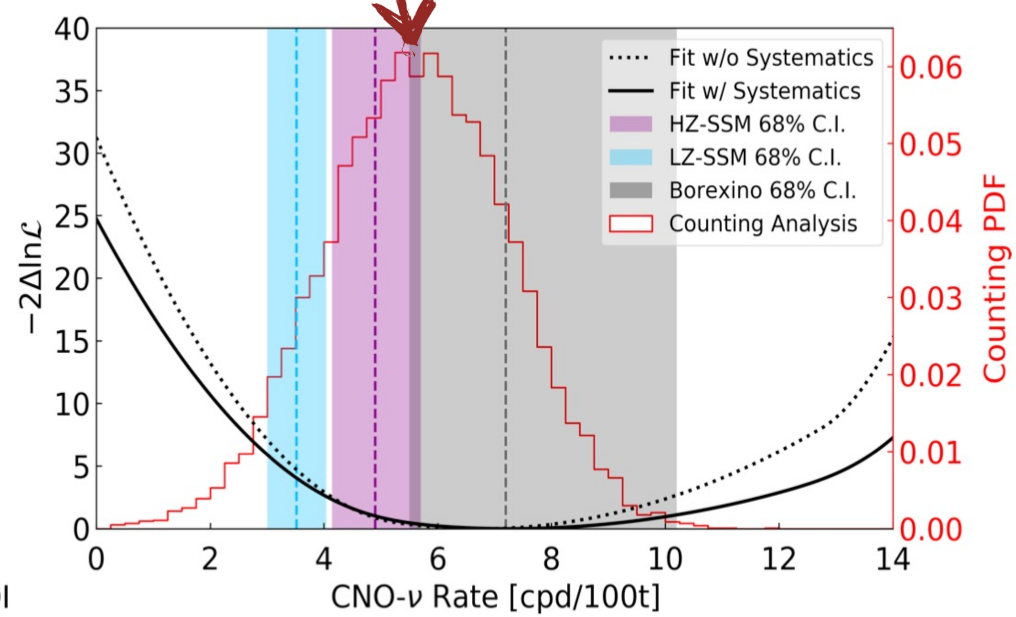
- include ^{210}Bi constraint as prior
- CNO rate fit: $7.2^{+3.0}_{-1.7}$ cpd/100t
- Absence disfavored at 5.0σ

→ **first detection of CNO neutrinos**

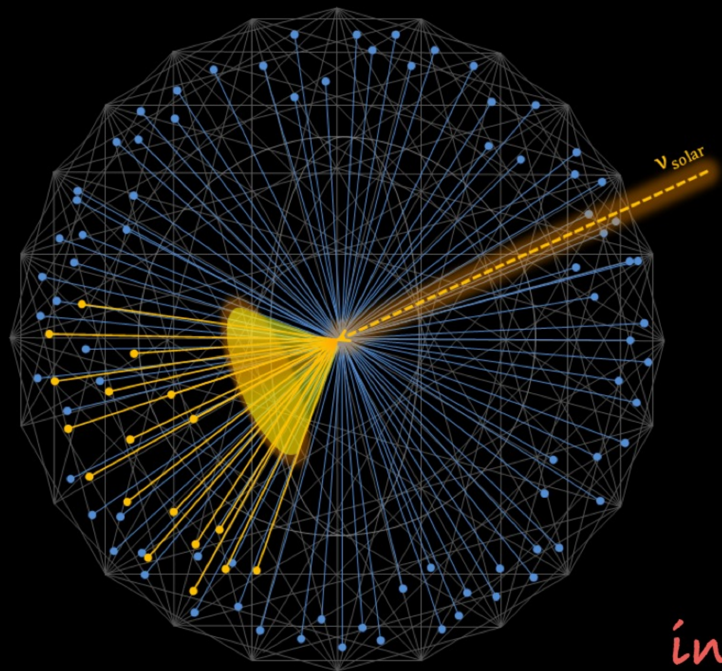
cross check:
counting analysis in ROI

- apply ^{210}Bi constraint
- CNO contribution required at 3.5σ



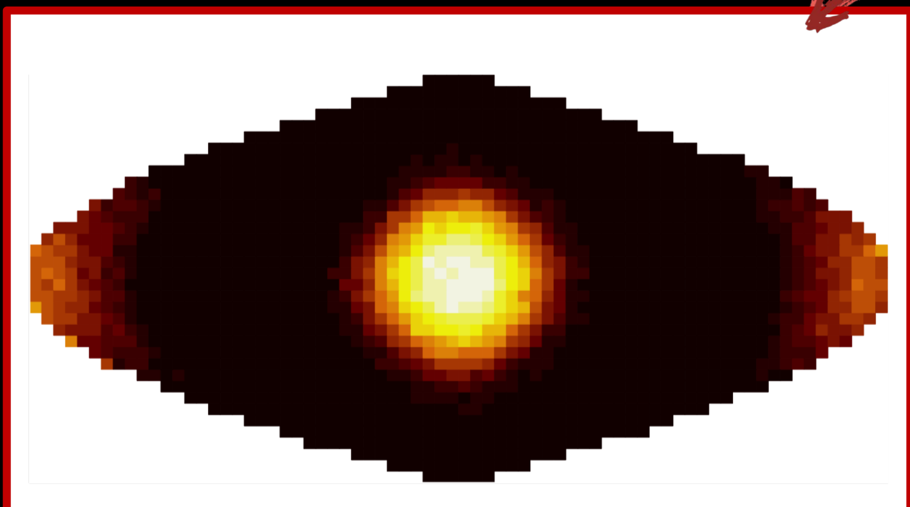


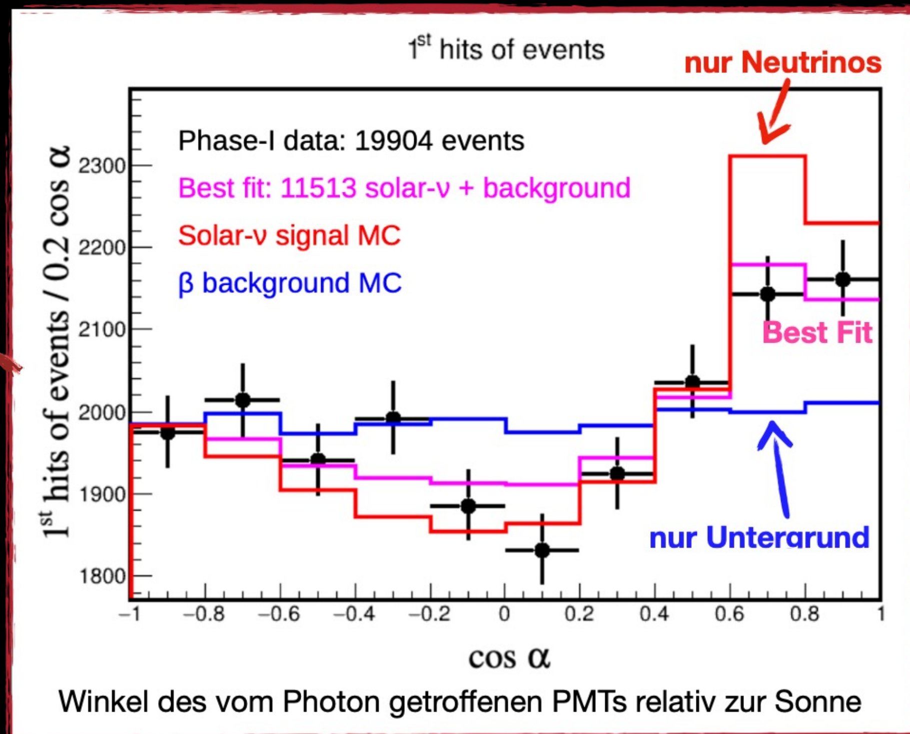
Directional detection (CID) of solar neutrinos



- Cherenkov and scintillation signals of electron recoils are superimposed in the detector
- Cherenkov signal too weak to be recognized event-by-event, but superimposed angular hit distributions of many events makes surplus Cherenkov ring visible!

in 2D

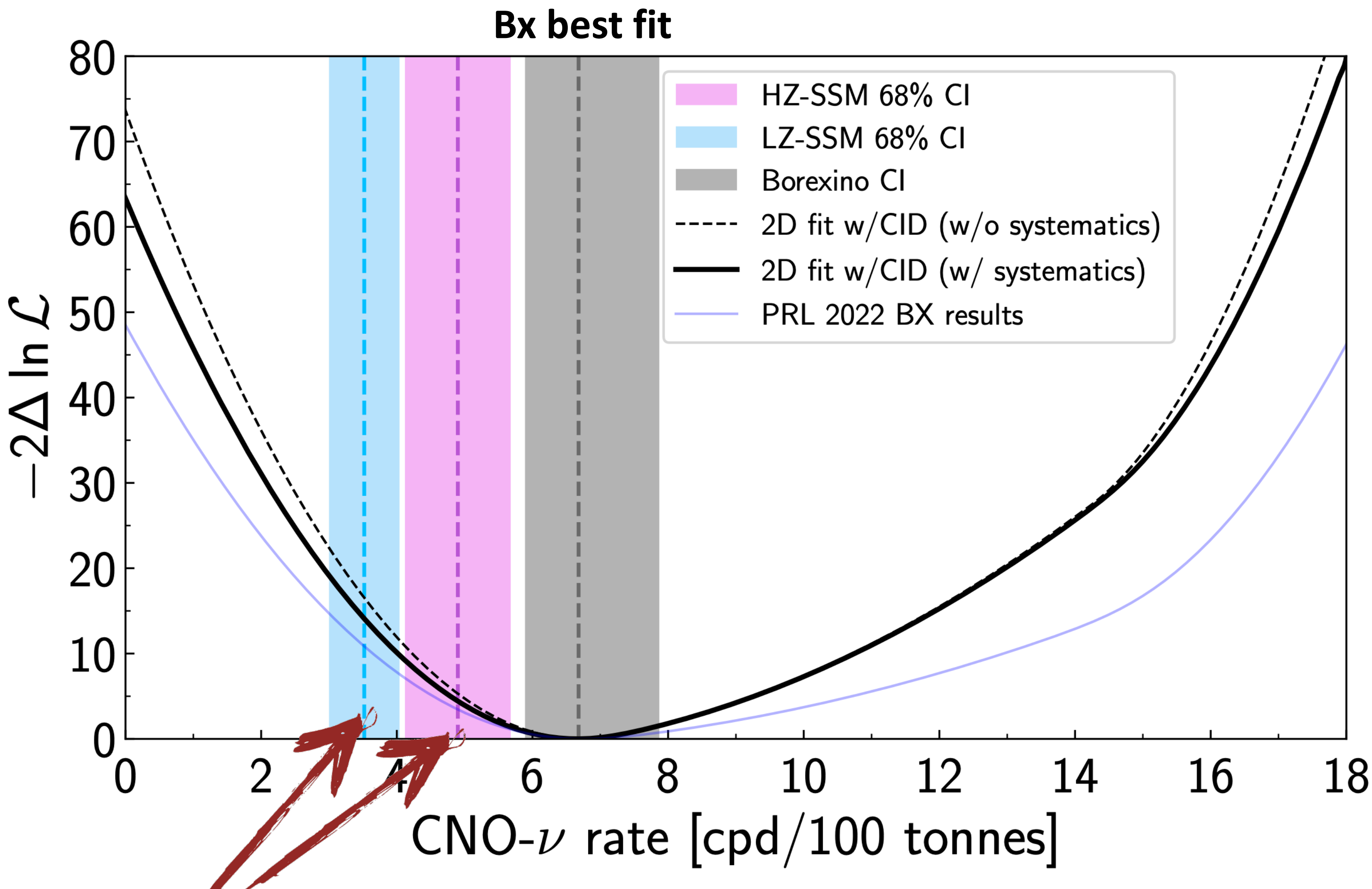




→ used for final CNO ν result of Borexino

[arXiv:2307.14636]

Updated result on CNO rate measurement

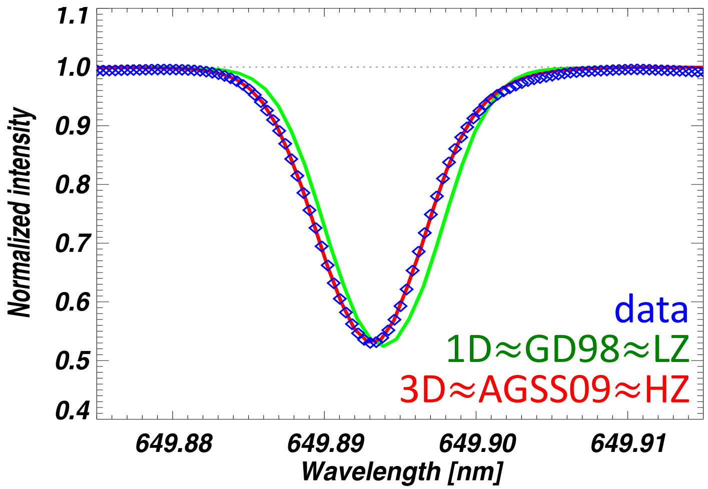


predictions by SSM depend on input metallicity: **LZ=AGSS09** / **HZ=GS98**

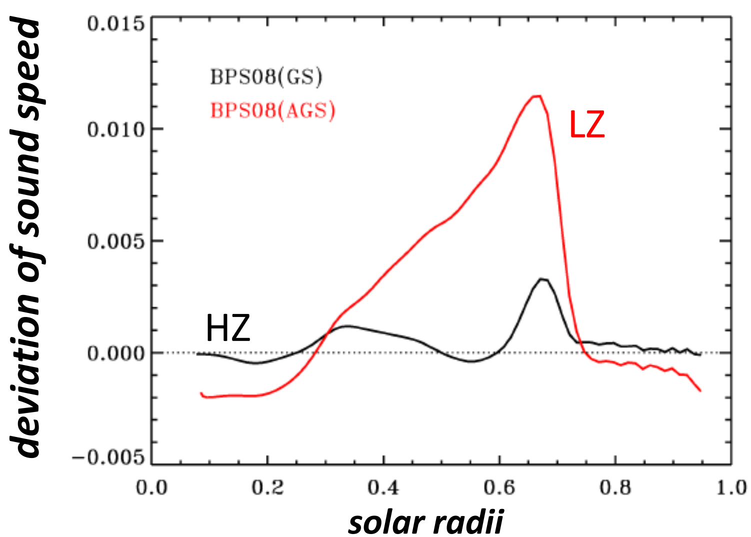
→ **Bx result** favors high values of metallicty

Solar abundances and neutrino rates

modeling of Fraunhofer lines (e.g. Fe-I)
Asplund et al. (2008)



solar spectroscopy vs. helioseismology



Two differing sets of **solar metallicity Z**

- based on analyses of Fraunhofer lines
- cross-checked by helioseismology

→ see talks by
Maria Bergemann
Aldo Serenelli

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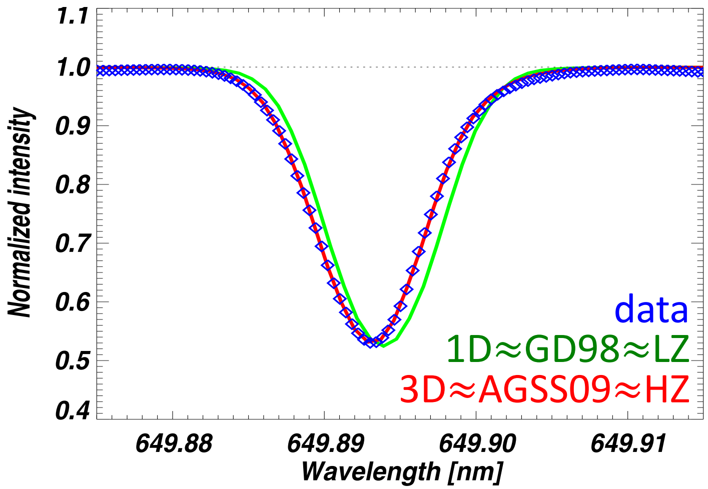

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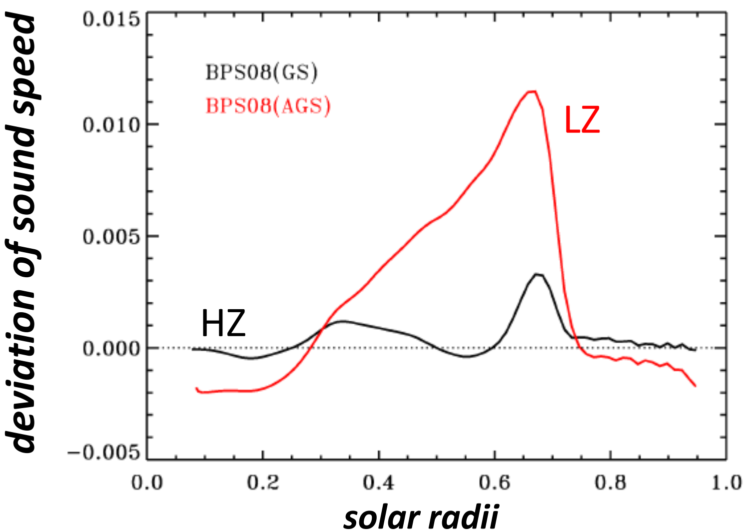


Two differing sets of **solar metallicity Z**

- based on analyses of Fraunhofer lines
- cross-checked by helioseismology

→ **fusion/neutrino rates depend on Z**

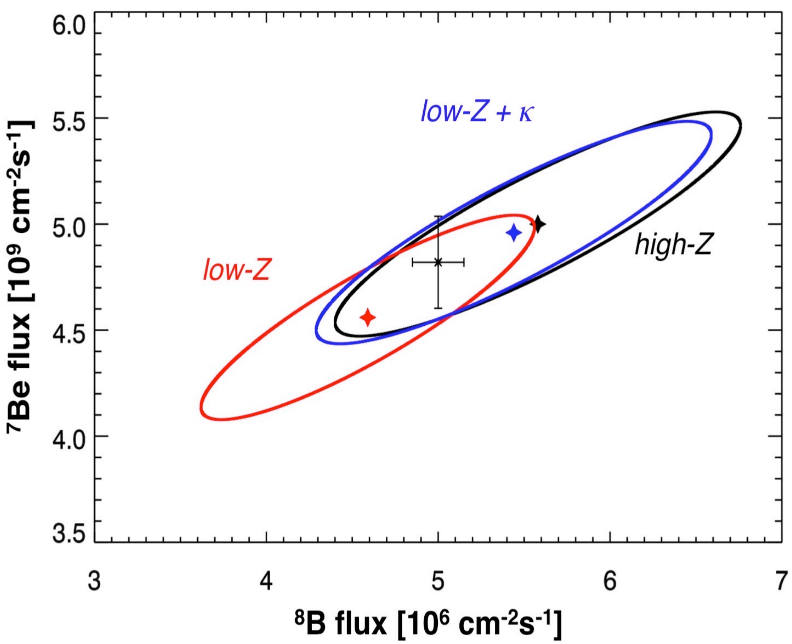
- core metallicity
- radiative opacities

Species	ΔF_n (Z)	ΔF_{SSM}	ΔF_{exp}
pp	1.2%	0.6%	11%
pep	2.8%	1.1%	20%
^{7}Be	10%	6%	5%
^{8}B	20%	11%	3%
CNO	38%	16%	–

Comparison to solar neutrino results I

Two differing sets of **solar metallicity Z**

- based on analyses of Fraunhofer lines
- cross-checked by helioseismology



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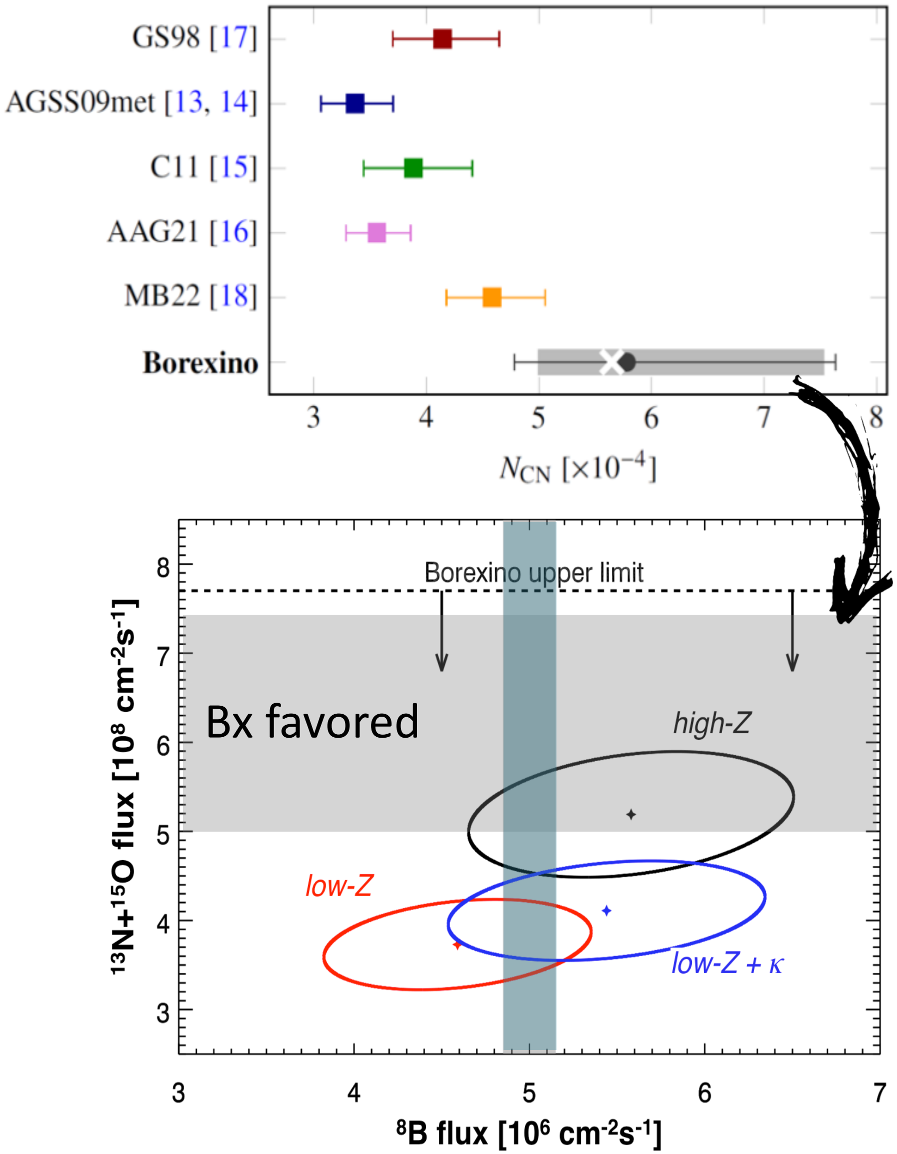
Comparison to solar neutrino results II



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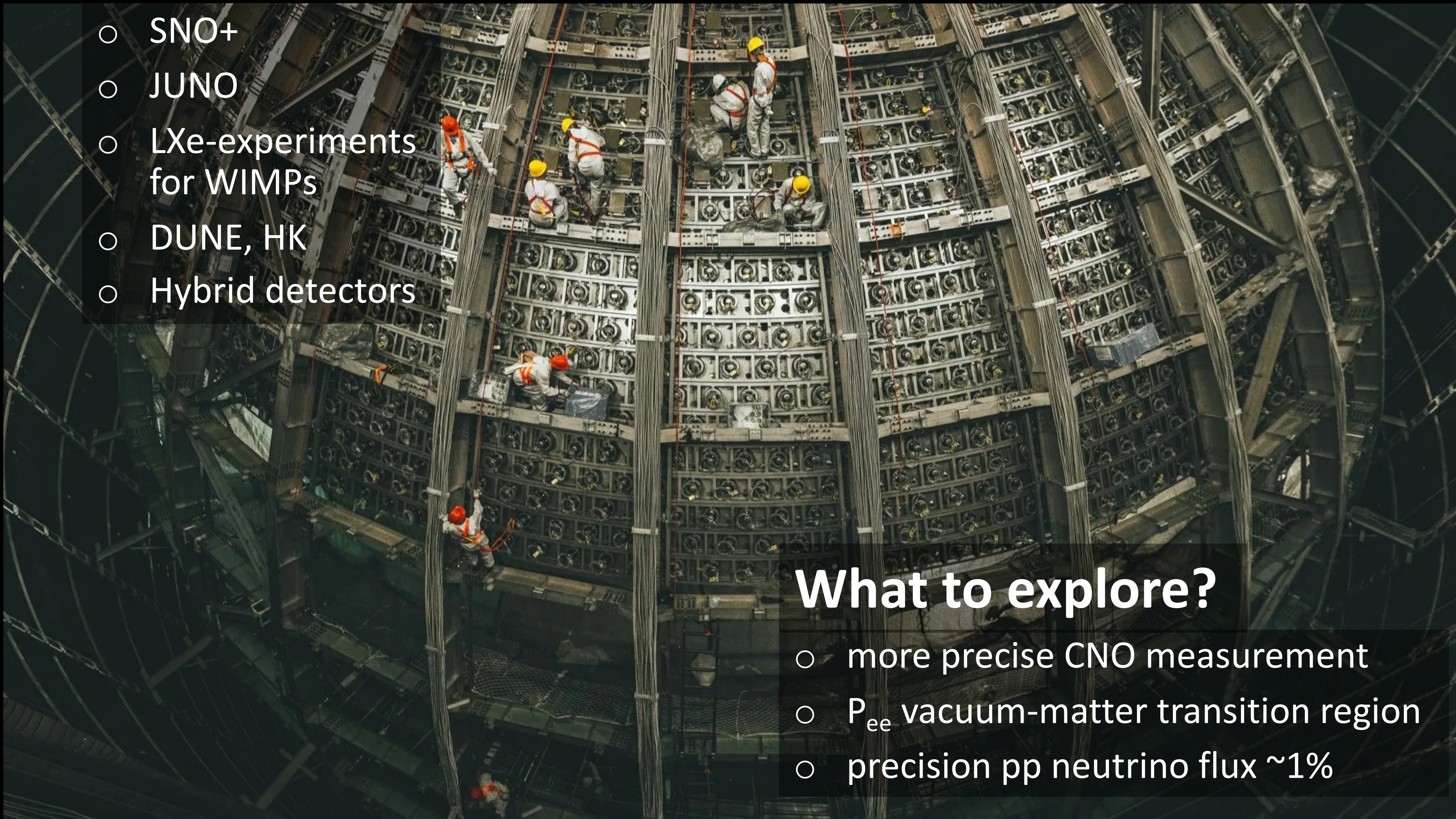
pep	2.8%	1.1%	20%
^{7}Be	10%	%	5%
^{8}B	20%	11%	3%
CNO	38%	16%	$^{+42\%}_{-24\%}$

Future experiments for solar neutrinos?

- Borexino concluded data taking in 2021, no dedicated experiments on the horizon
- but: there are new low-background experiments also sensitive solar neutrinos



  - SNO+
  - JUNO
  - LXe-experiments for WIMPs
  - DUNE, HK
  - Hybrid detectors

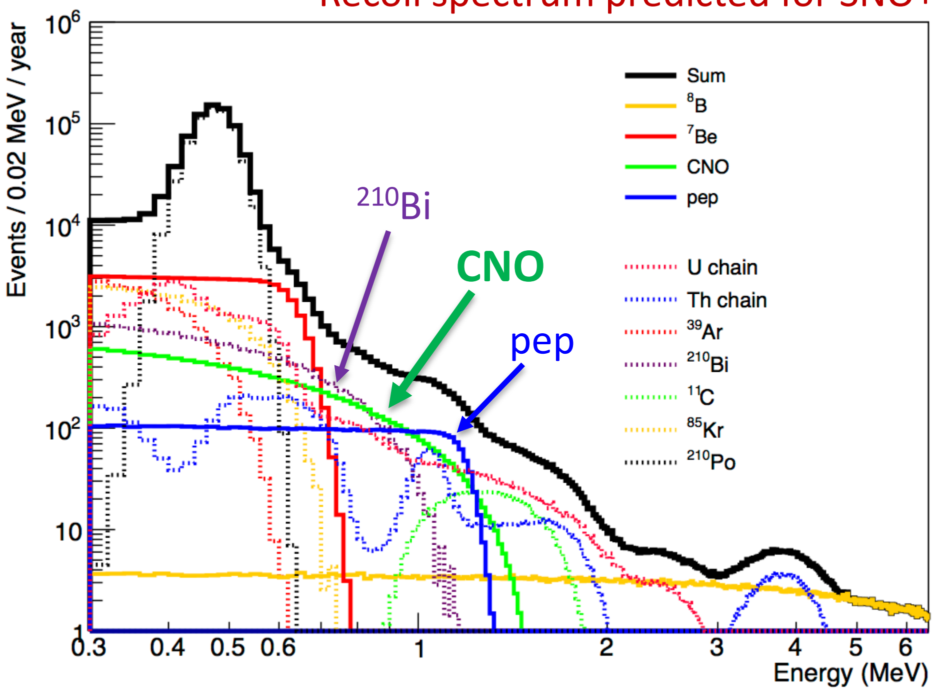
What to explore?

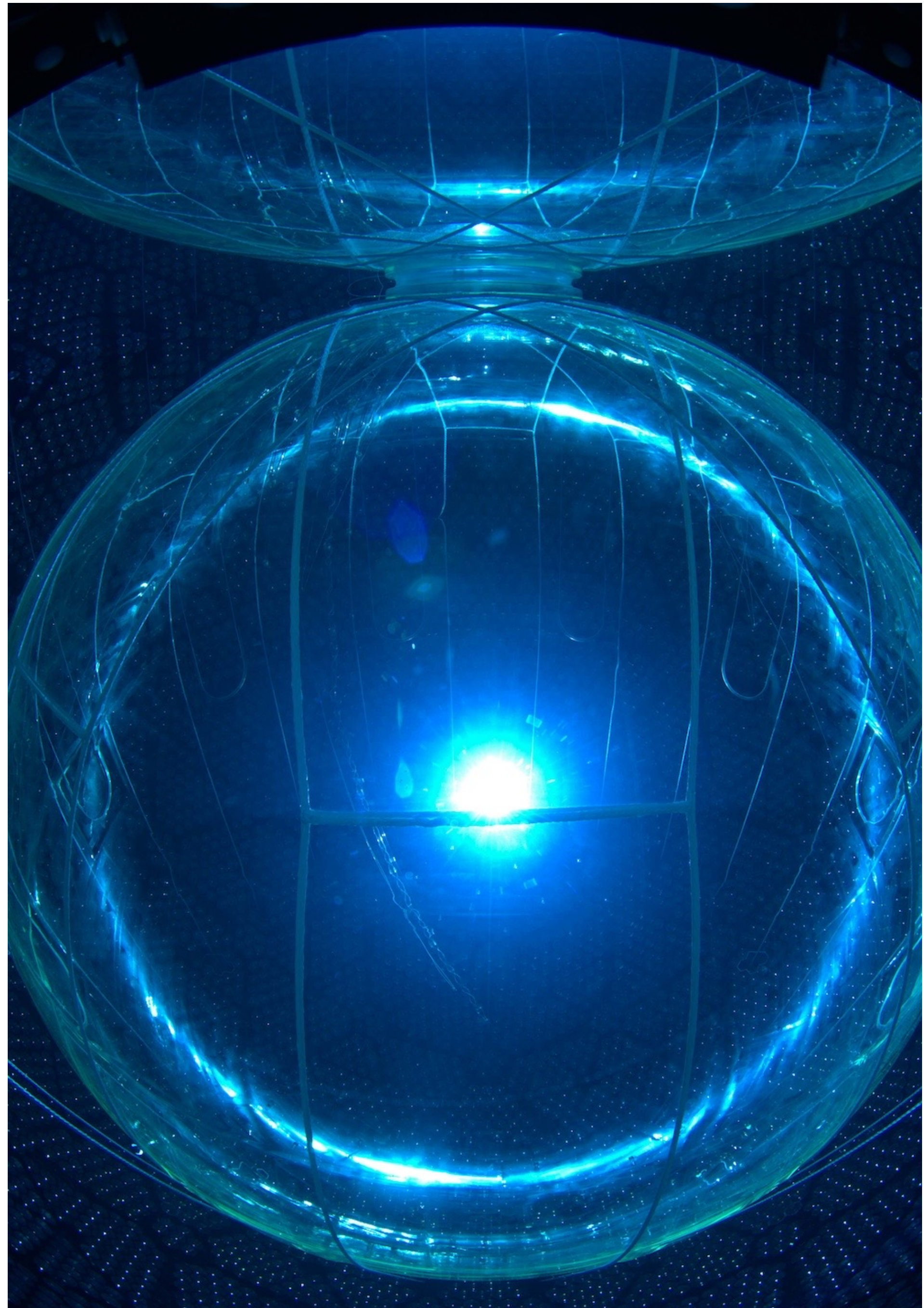
- more precise CNO measurement
- P_{ee} vacuum-matter transition region
- precision pp neutrino flux ~1%

SNO+ Experiment

- upgrade of SNO with (loaded) liquid scintillator to search for neutrino-less double-beta decay
- scintillator filled but not yet tellurium-loaded → potentially excellent sensitivity to CNO-ν's
- SNO site is very deep → low cosmogenic BG → sensitivity depends on radiopurity
- few years of data taken but no results yet

Recoil spectrum predicted for SNO+

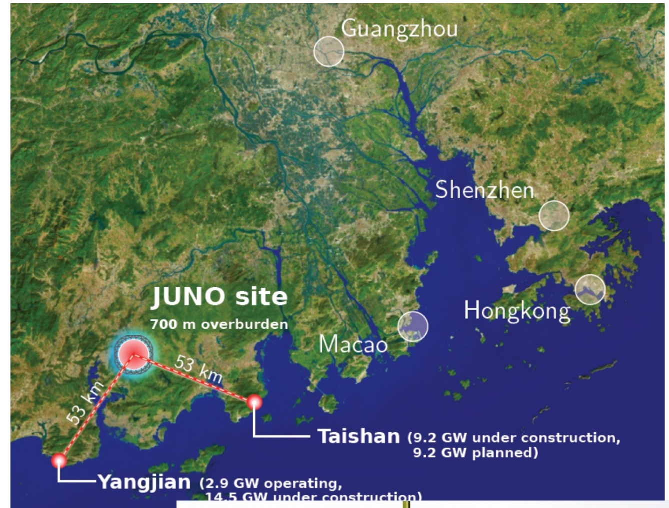


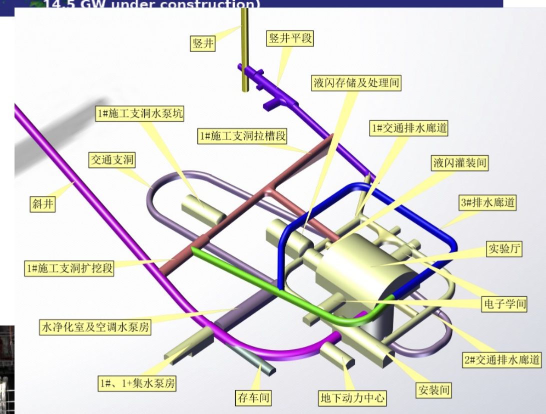


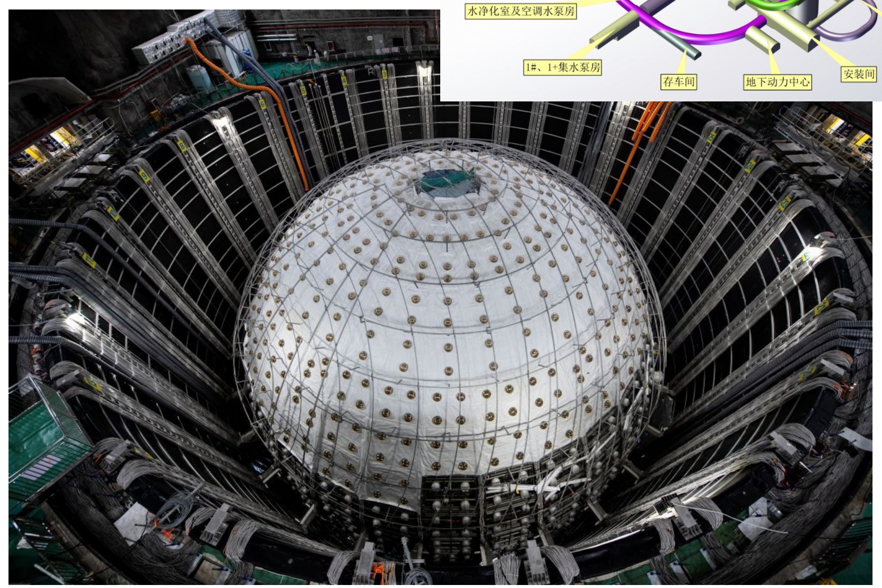
unloaded SNO+ → 900 tons of scintillator

JUNO Neutrino Observatory

- located in Jiangmen province, southern China
- large liquid scintillator detector
  scintillator mass : 20,000 t
  sphere diameter : 35 m
  number of 20"-PMTs : 18,000
- construction completed in 2024, currently being filled (60~70%)
- main motivation:
  precision measurement of reactor neutrino oscillations
  → sub-% level on osc. parameters
  → neutrino mass ordering
- **broad astrophysical program**
  - solar neutrinos
  - galactic/diffuse Supernova ν's
  - geo-neutrinos
  - dark matter annihilation







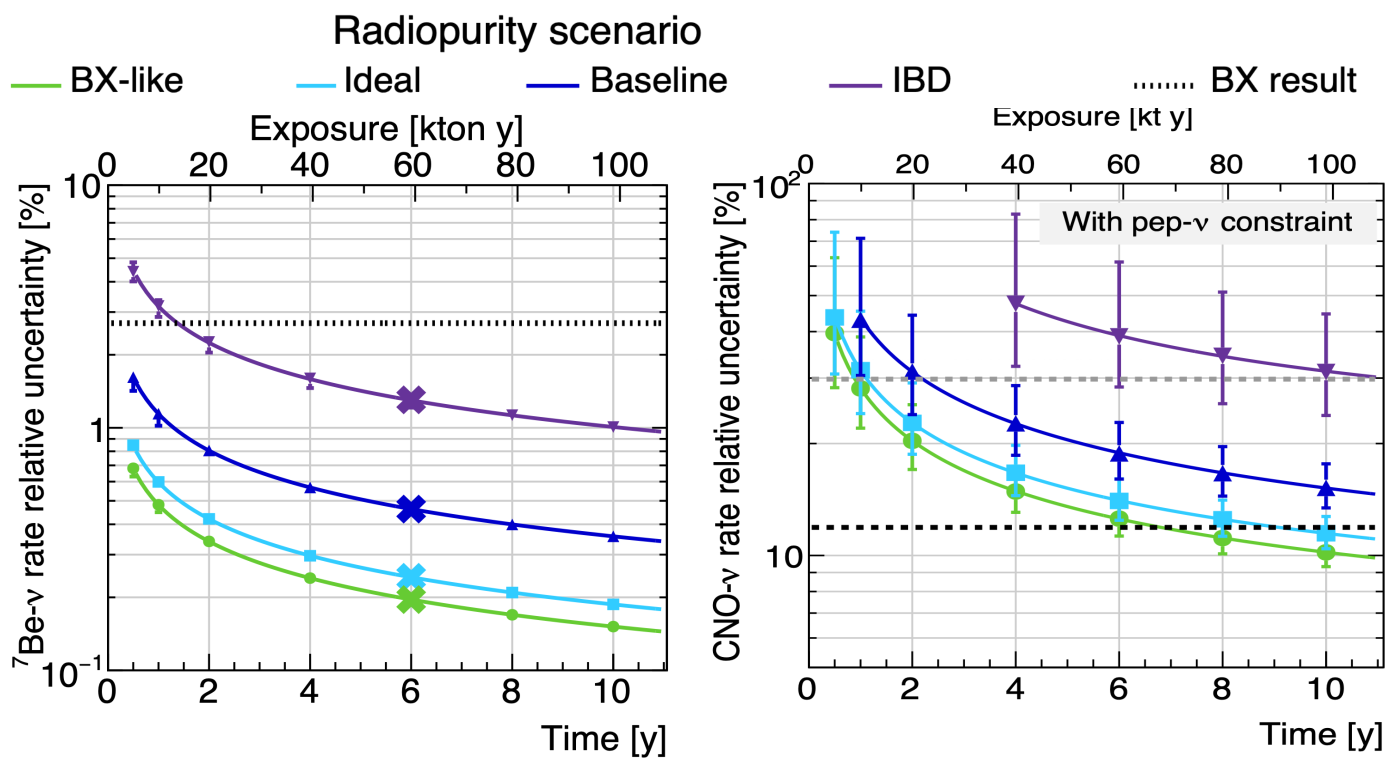
JUNO's solar neutrino sensitivity

- JUNO measures solar neutrinos with the same technique as Borexino
- by comparison, JUNO features x100 larger detection volume and x3 better energy resolution → significant increase in instrumental performance

→ under ideal conditions, precision for e.g. ^{7}Be-ν's ~0.2% and CNO-ν's ~10%

- however, scintillator background levels from radioactivity likely higher and more cosmogenic backgrounds due to reduced depth

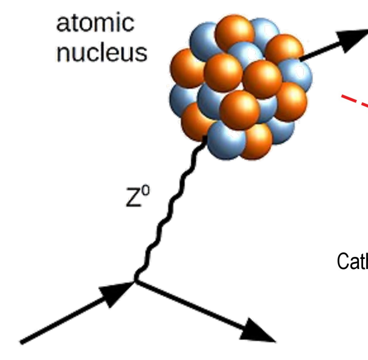
→ stay tuned for first results!

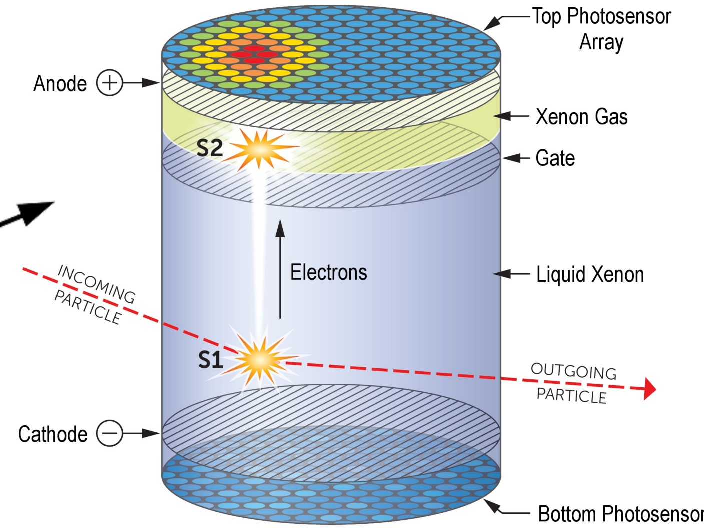


LXe Dark Matter Detectors

- current generation of underground liquid-xenon detectors searches for Dark Matter nuclear recoils (WIMPs)
- in 2024, both XENONnT and Panda-X reported first signs of coherent elastic neutrino-nucleus scattering (CEvNS) from solar ^{8}B neutrinos
- both report low-E rate surplusses of 2-3σ significance over background
- NC reaction → no impact of flavor oscillations on detection rates
- next generation of experiments will feature x10 higher target mass
- in addition, will look for electron scatters at tens of keV energies → great sensitivity for pp neutrinos on the sub-% level

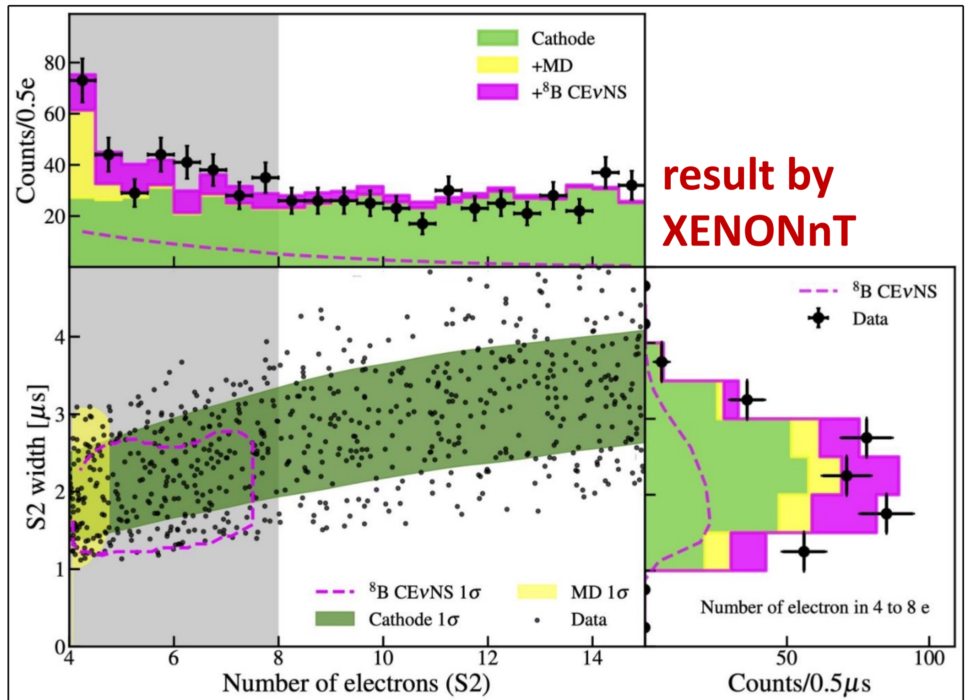
CEvNS





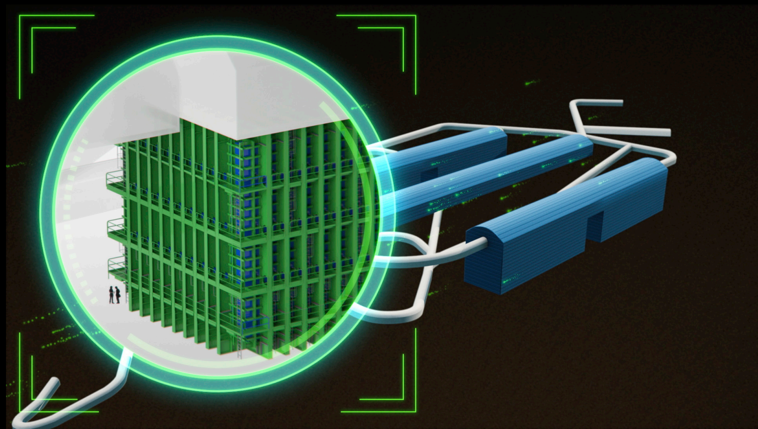
XENONnT TPC

scintillation signal very low → **nuclear recoil**

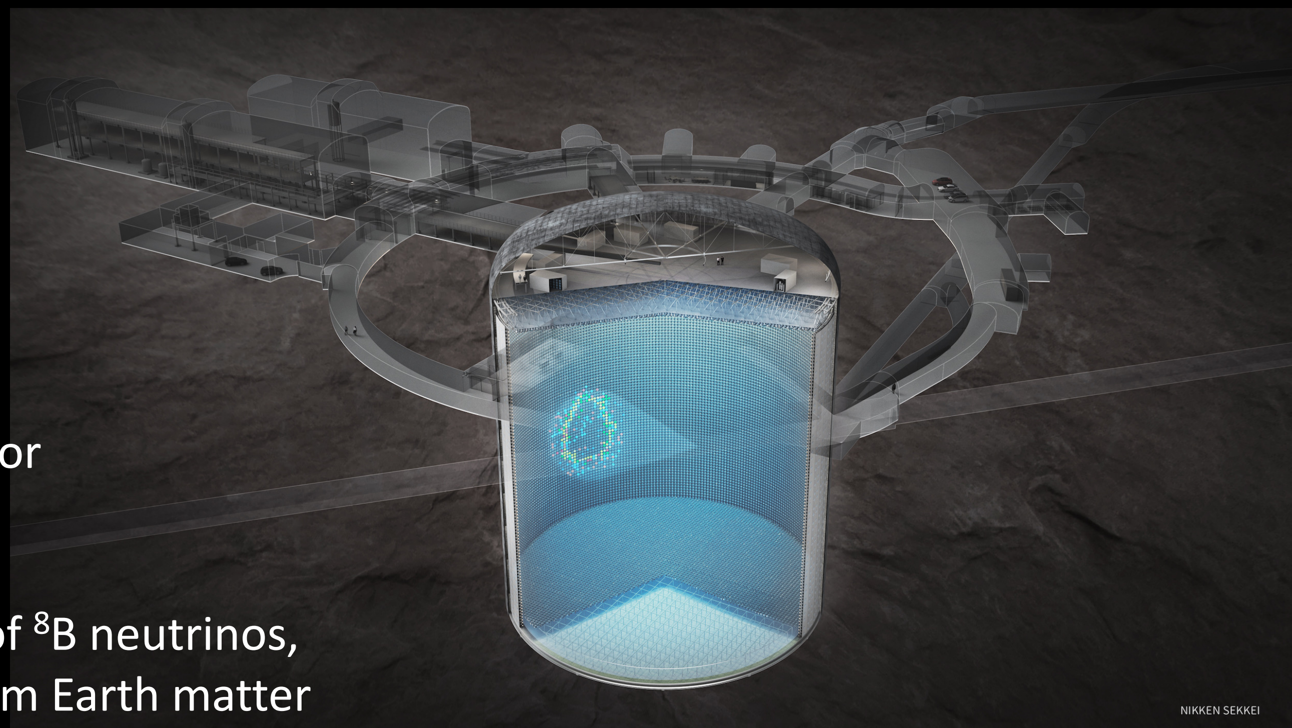


ionization signal low → **low recoil energy**

Upcoming long-baseline neutrino detectors

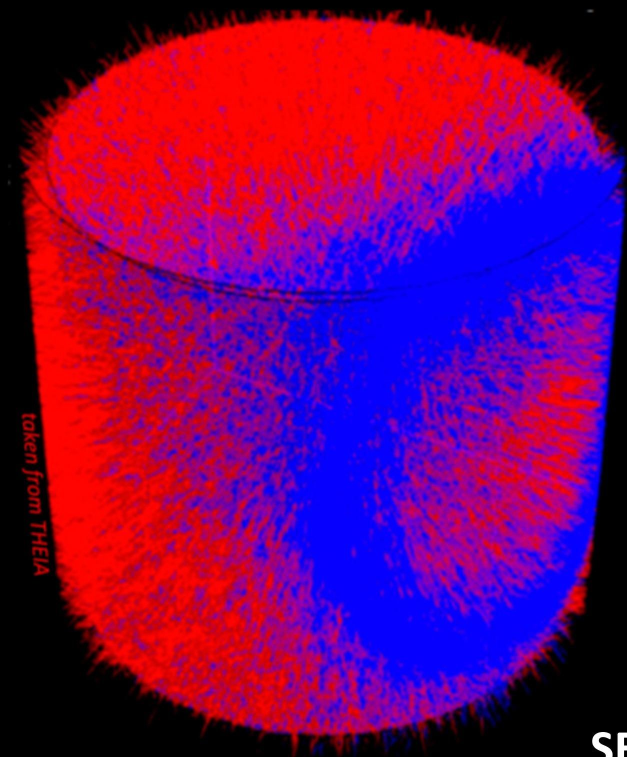


DUNE
→ nominal: 4x 10kt LAr-TPCs
→ optimized for much higher (GeV+) energies
→ but some potential to first detect hep neutrinos



Hyper-Kamiokande
→ giant water-Cherenkov detector
with target mass ~250 kt
→ optimized for higher energies
→ high-statistics measurement of ^{8}B neutrinos,
especially day-night effect from Earth matter

New ideas using advanced scintillators



Organic liquid scintillators can be modified to enhance their sensitivity to solar neutrinos:

THEIA

hybrid detection of Cherenkov and scintillation photons

- transparent/slow scintillator
- fast or wavelength-sensitive light sensors
- Li-loading of scintillator for CC interaction

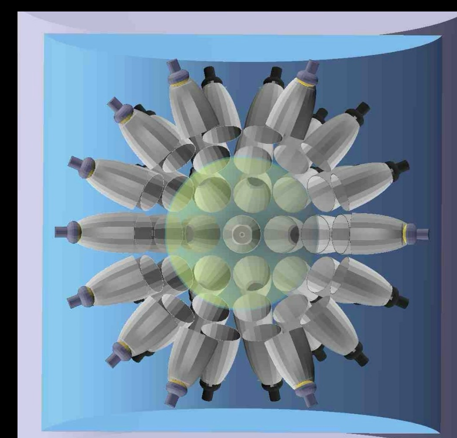
→ substantially improved background discrimination
→ e.g. CNO neutrino flux at better than 10%

SERAPPIS

upgrade of existing small (20t) detector (e.g. JUNO‘s pre-detector OSIRIS) for high light collection and ^{14}C-depleted scintillator

- reduced background levels and better spectral separation for pp neutrinos

→ 1%-level pp measurement to check solar luminosity constraint
→ emission of feebly interacting particles



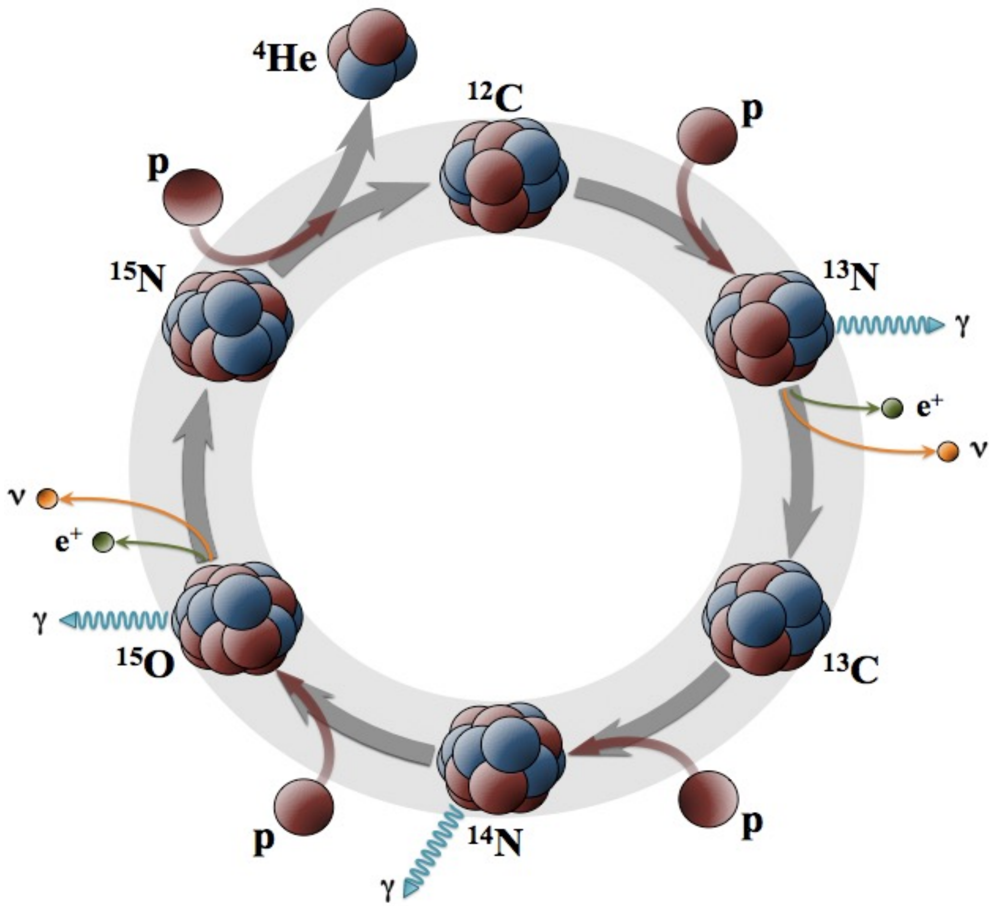
Conclusions

- After discovering neutrino oscillations, solar neutrinos are useful probes of the solar interior
- Measurements of pp-chain and especially CNO neutrinos are sensitive to solar (core) metallicity
- State-of-the-art are liquid-scintillator detectors like Borexino, with SNO+ and JUNO on the horizon
- While there are no dedicated solar neutrino experiments planned, many upcoming experiments potentially offer sensitivity: DUNE, HK, XLZD, …

→ path towards more precise measurements of solar neutrino rates!

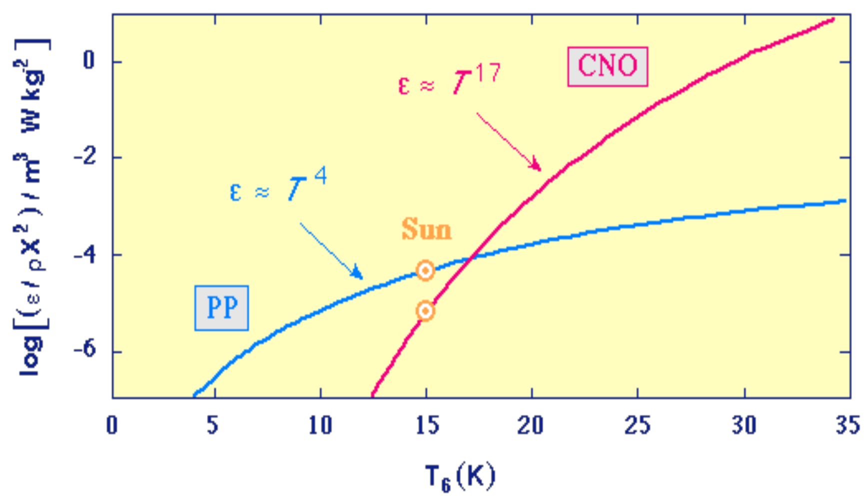
The catalyst CNO cycle

Net fusion reaction: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e$ [+26.7 MeV]



- minor contribution to solar fusion (~1%)
- dominant in heavier and older stars
- relatively large uncertainties in nuclear cross sections

fusion rate vs. solar core temperature

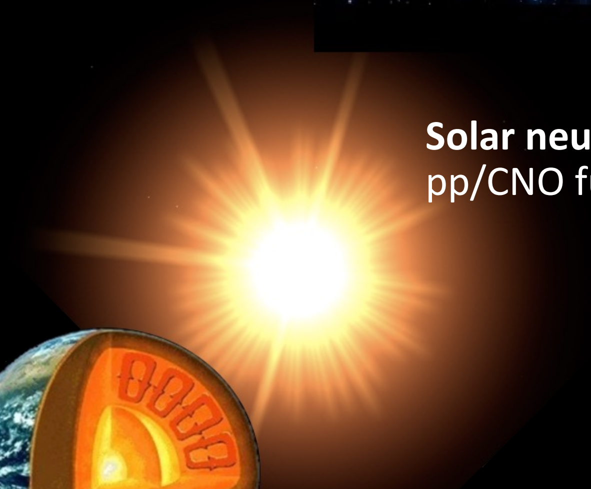


Astrophysical neutrino sources

Supernova neutrinos
collapse of Fe core
of a heavy ($>8M_{\odot}$) star

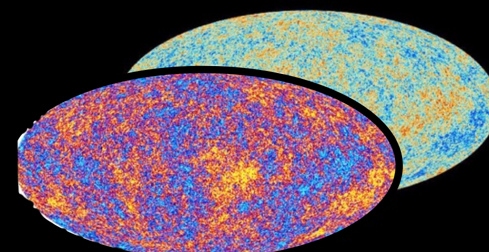
Diffuse Supernova neutrinos
from all core-collapse SNe
throughout the Universe

Extragalactic neutrinos
from cosmic accelerators
(AGNs, GRBs ...?)



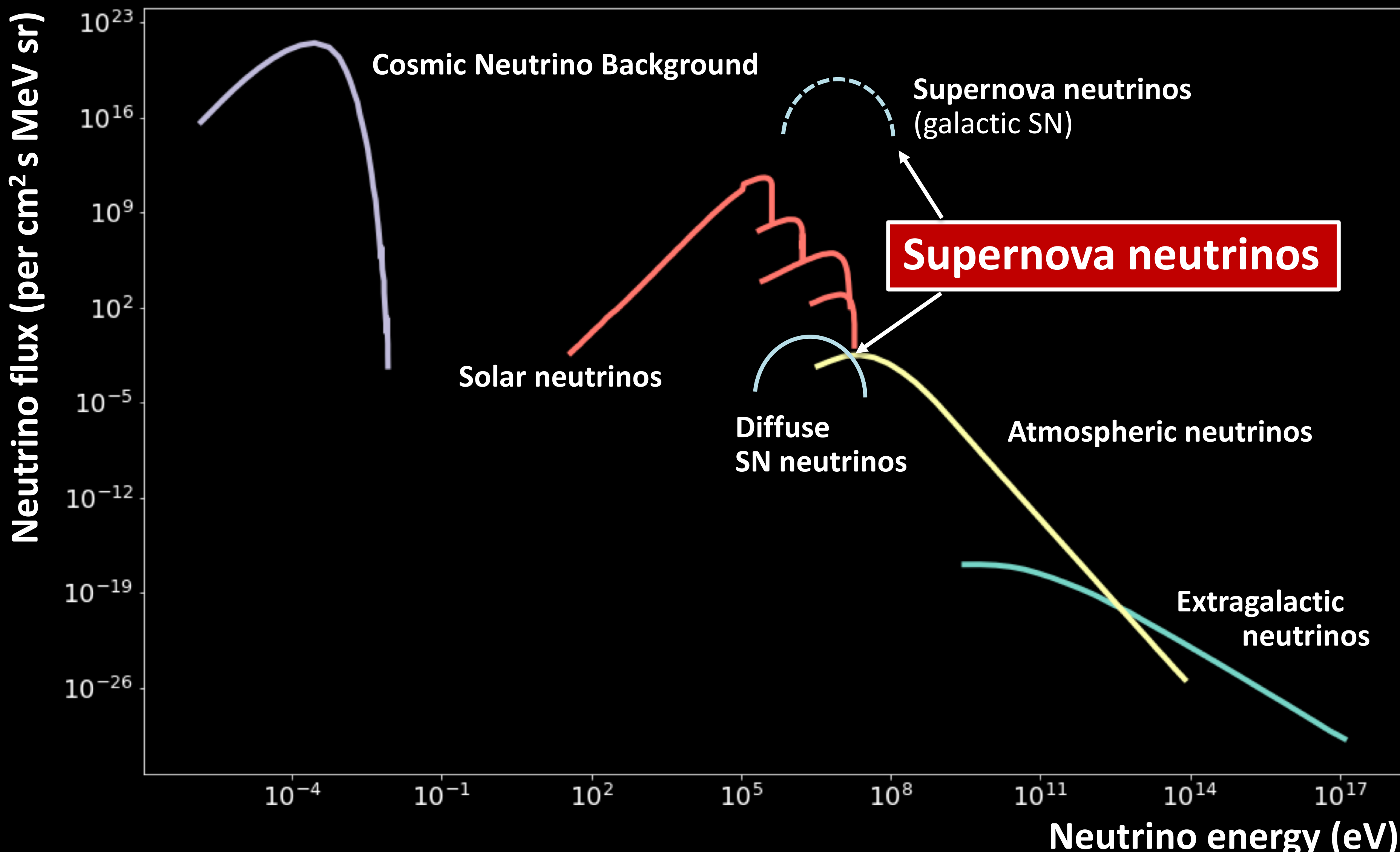
Solar neutrinos
pp/CNO fusion chains

Cosmic Neutrino Background
from the Big Bang (cf. CMB)



Geoneutrinos
radioactive decays of U,Th,K
in Earth crust/mantle

Energy spectrum of astrophysical ν's



Observation of solar neutrinos

- Sun proposed as intense neutrino sources in 1960's
- several solar ν experiments in the 3-4 decades after: Homestake, Gallex/GNO+SAGE, (Super-)Kamiokande, SNO
- ALL found an overall deficit in electron neutrino (**ν**$_e$) flux → Solar Neutrino Problem
- SNO could finally show that the deficit is caused by neutrino flavor transitions $\nu_e \leftrightarrow \nu_{\mu,\tau}$
- the corresponding mechanism is ν flavor oscillations

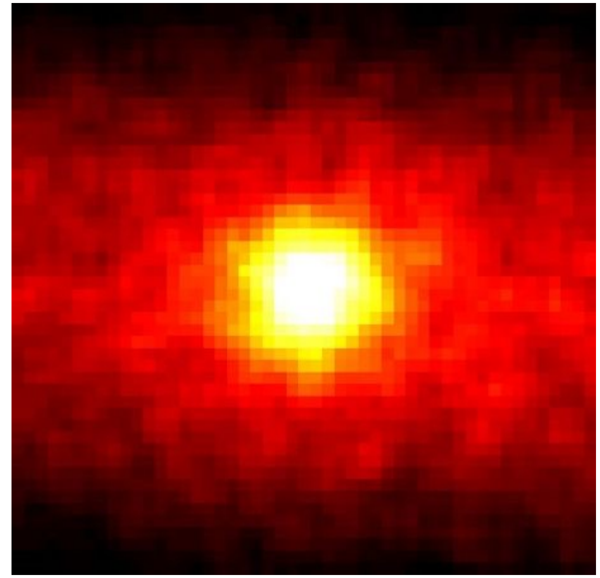
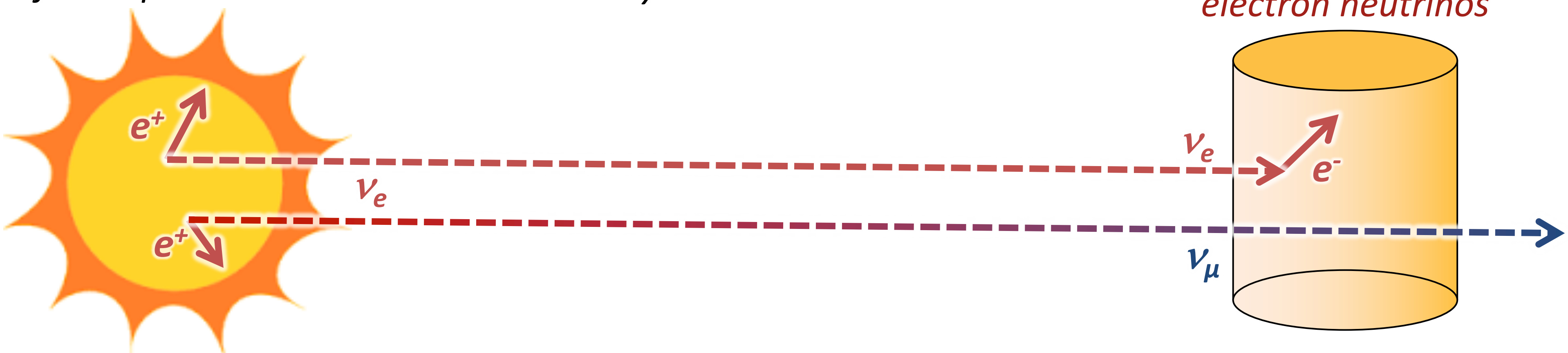


Image of Sun in neutrino light by Super-Kamiokande

electron neutrinos created in solar fusion processes

neutrinos propagate through space some undergo flavor transition $\nu_e \rightarrow \nu_\mu$ caused by neutrino oscillations

standard solar neutrino detector mostly sensitive to electron neutrinos



Neutrino masses and mixing

ν production

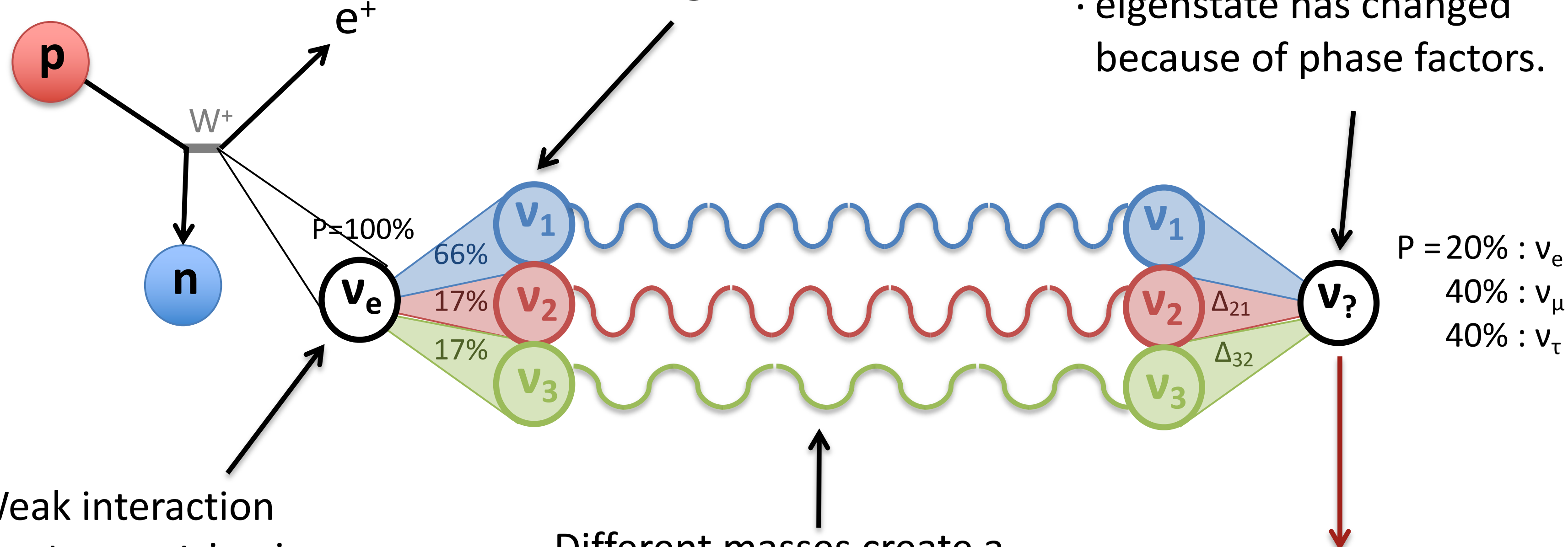
e.g. β⁺-decay

ν propagation

as coherent superposition of **mass-eigenstates**.

ν detection

as **flavor-eigenstate**: Superposition of mass eigenstate has changed because of phase factors.

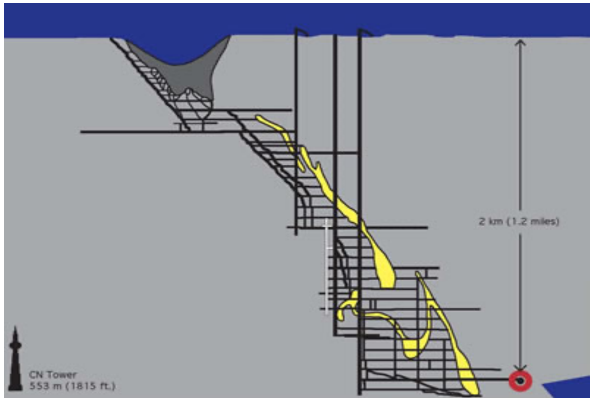


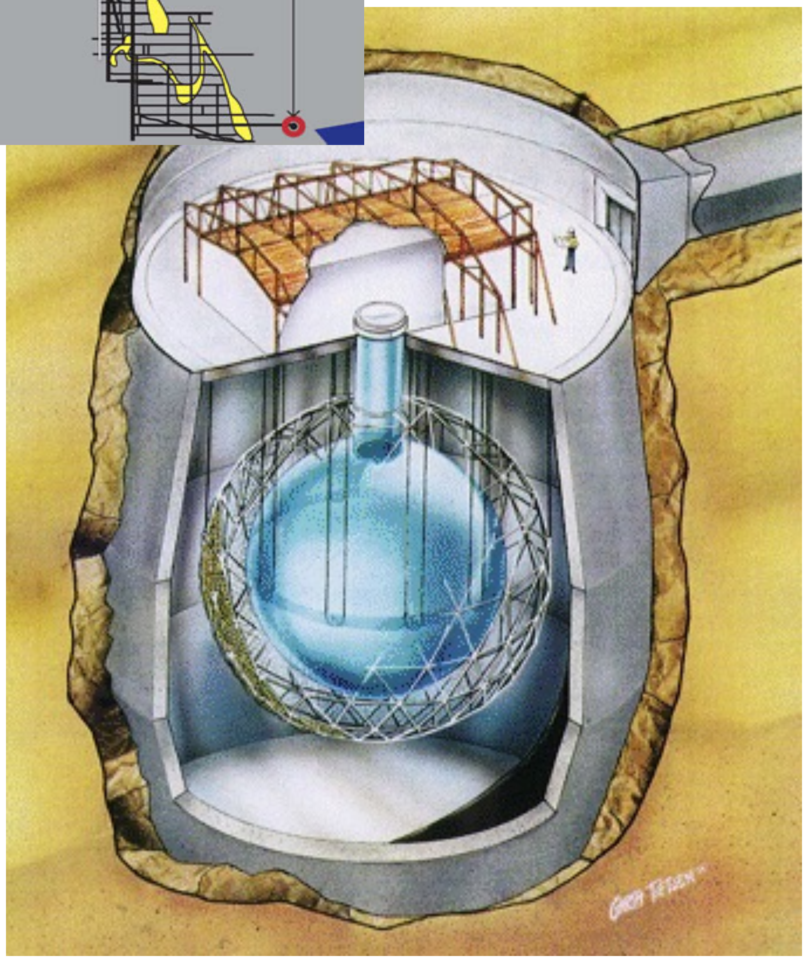
Weak interaction creates neutrino in **flavor-eigenstate**.

Different masses create a **phase difference** over time.

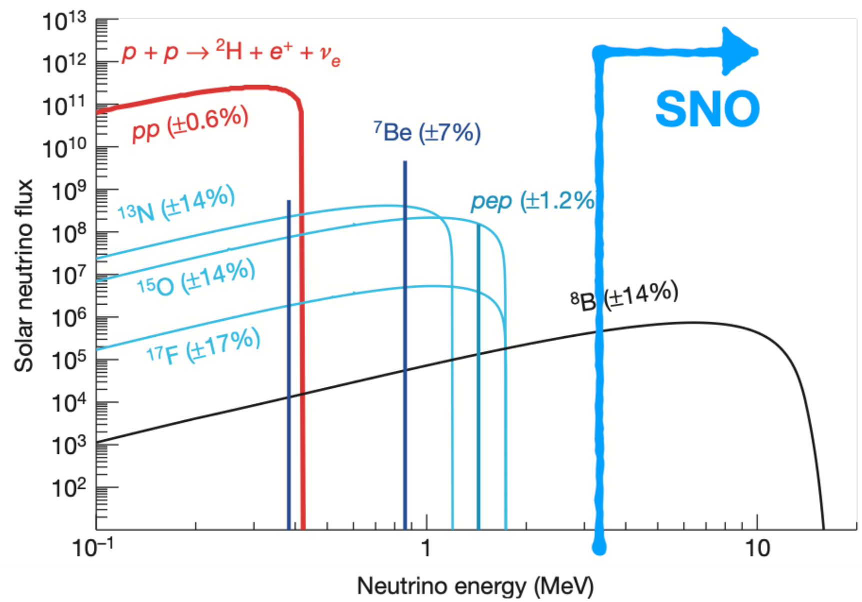
*Finite probability to detect a different **neutrino-flavor**!*

The Sudbury Neutrino Observatory (SNO)

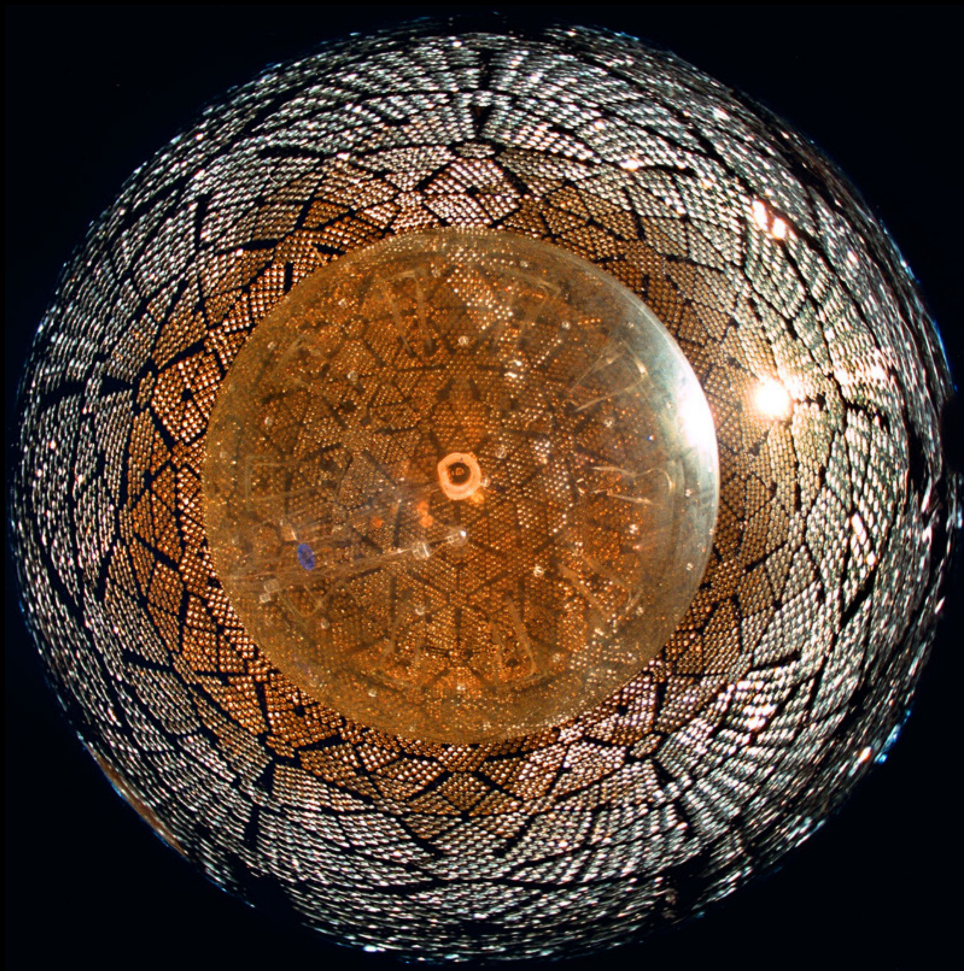




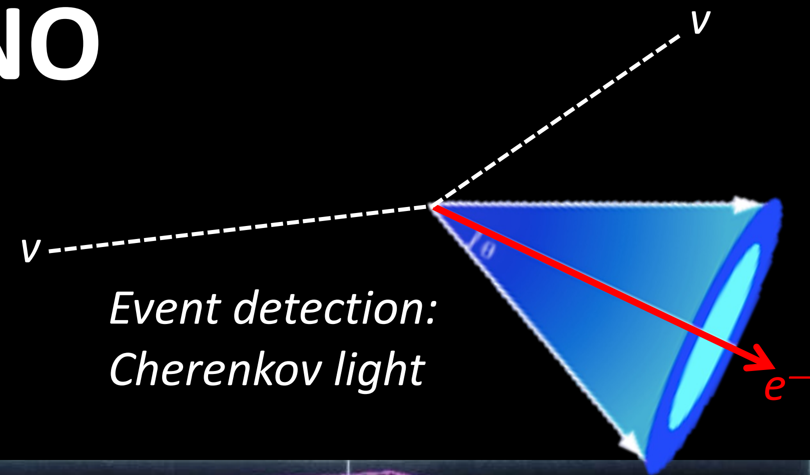
- **Water Cherenkov detector**
  Underground water tank to measure neutrino interactions by final-state charged particles
- **Location:** Sudbury mine
  depth: 2000 m → 6000 mwe
- **Target mass:** 1 kt of D_2O



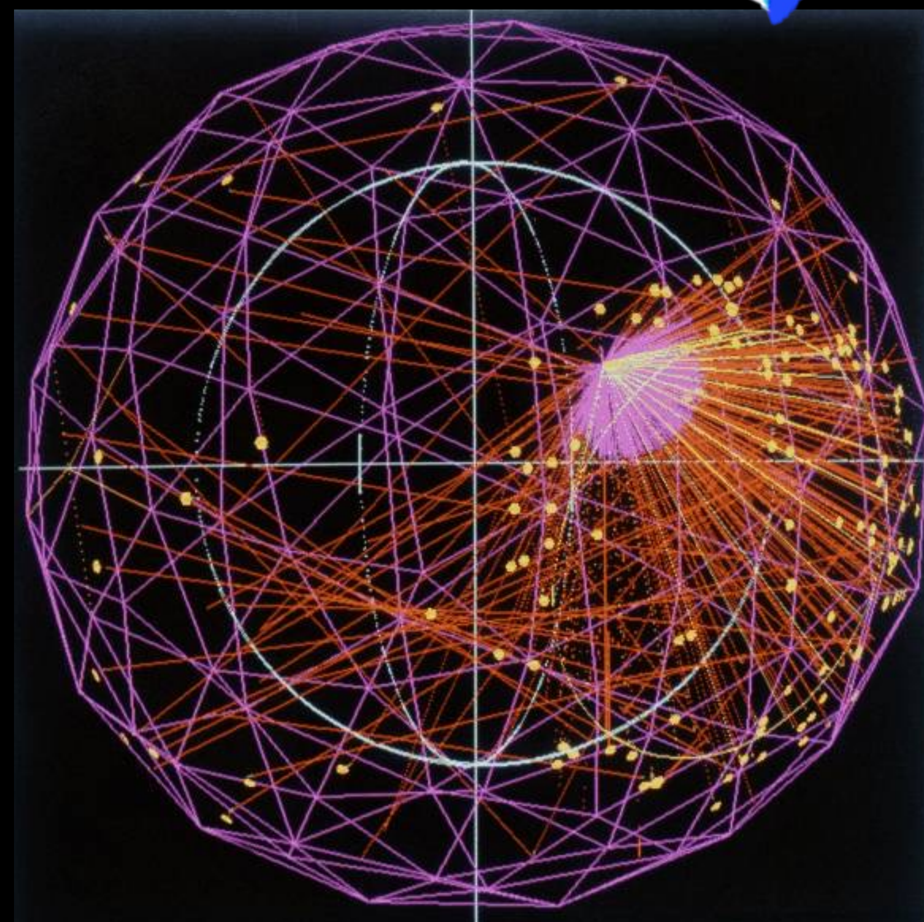
Neutrino detection in SNO



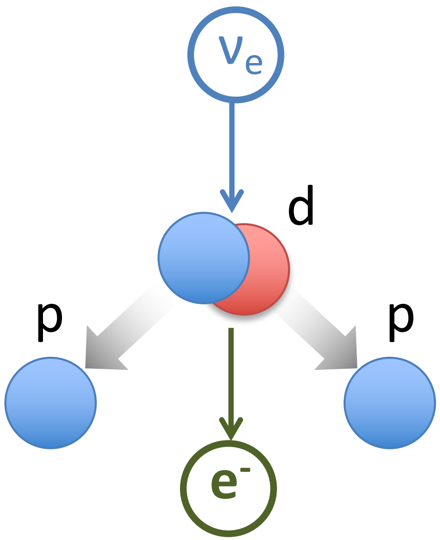
10,000 photomultiplier tubes



Event detection: Cherenkov light



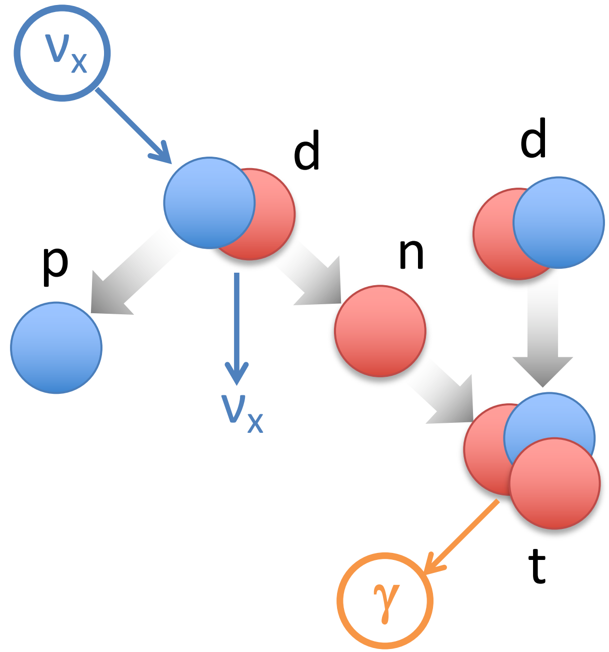
Detection reactions in heavy water



(CC) on deuterons

$$\nu_e + d \rightarrow p + p + e^-$$

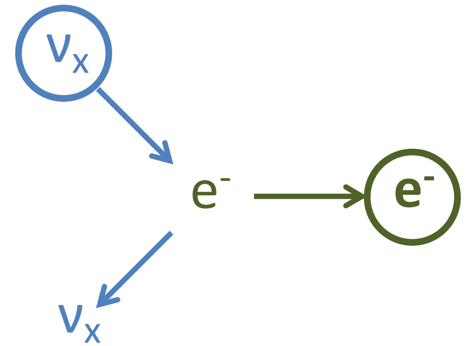
– sensitive only to ν_e



(NC) on deuterons

$$\nu_x + d \rightarrow p + n + \nu_x$$

– sensitive to all flavors



elastic scattering on electrons (ES)

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

– mostly ν_e, but also $\nu_{\mu,\tau}$

→ determine **total neutrino flux (all flavors)** and **ν_e-flux** separately

SNO result: Neutrino flavor conversion

The fluxes measured via the three channels were:

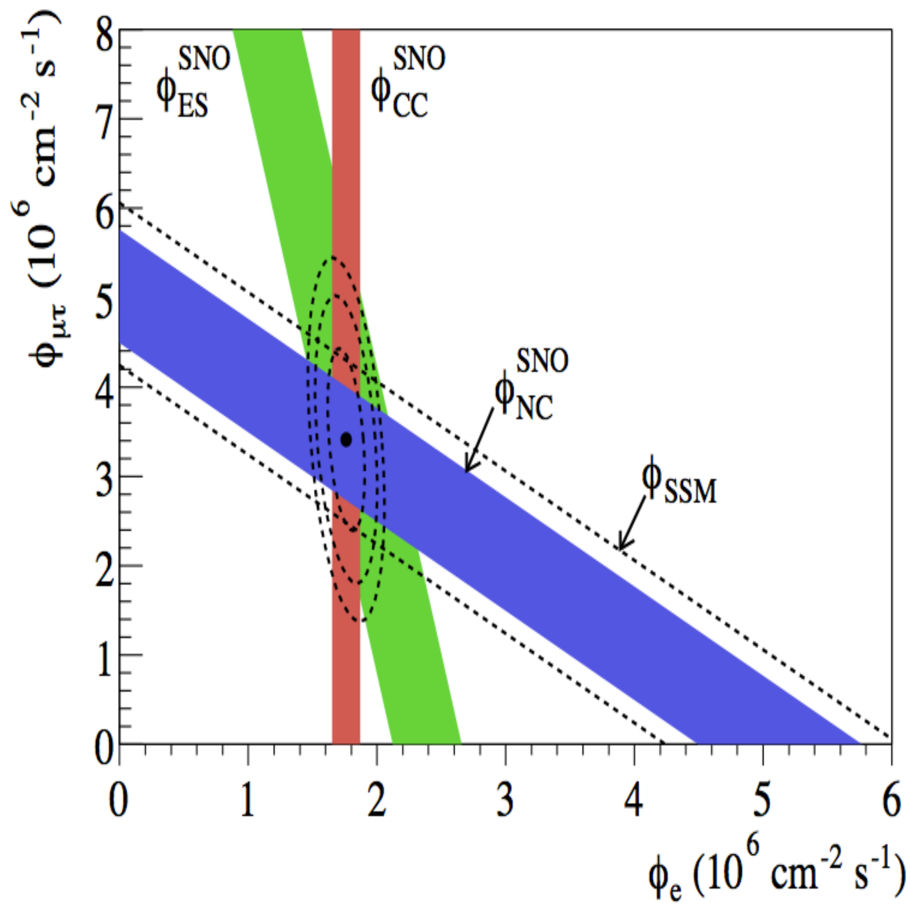
$$\left.\begin{array}{l} \Phi_{\rm CC} = 1.76 \pm 0.11 \\ \Phi_{\rm ES} = 2.39 \pm 0.27 \\ \Phi_{\rm NC} = 5.09 \pm 0.62 \end{array}\right\} \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

The Standard Solar Model prediction for ^{8}B-ν's is:

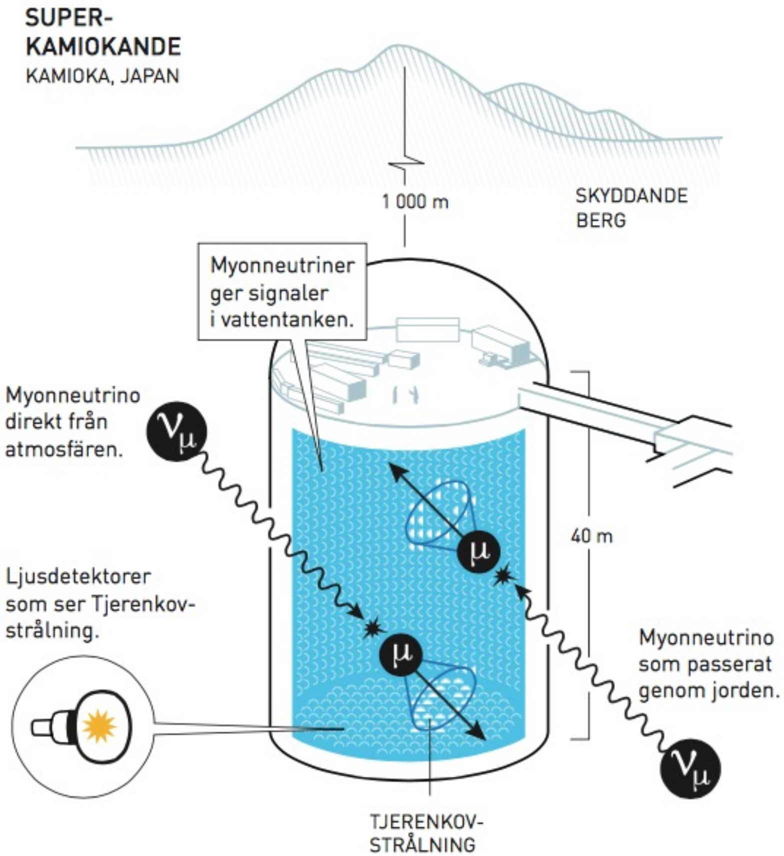
$$\Phi_{\rm SSM} = \left(5.05^{+1.01}_{-0.81}\right) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

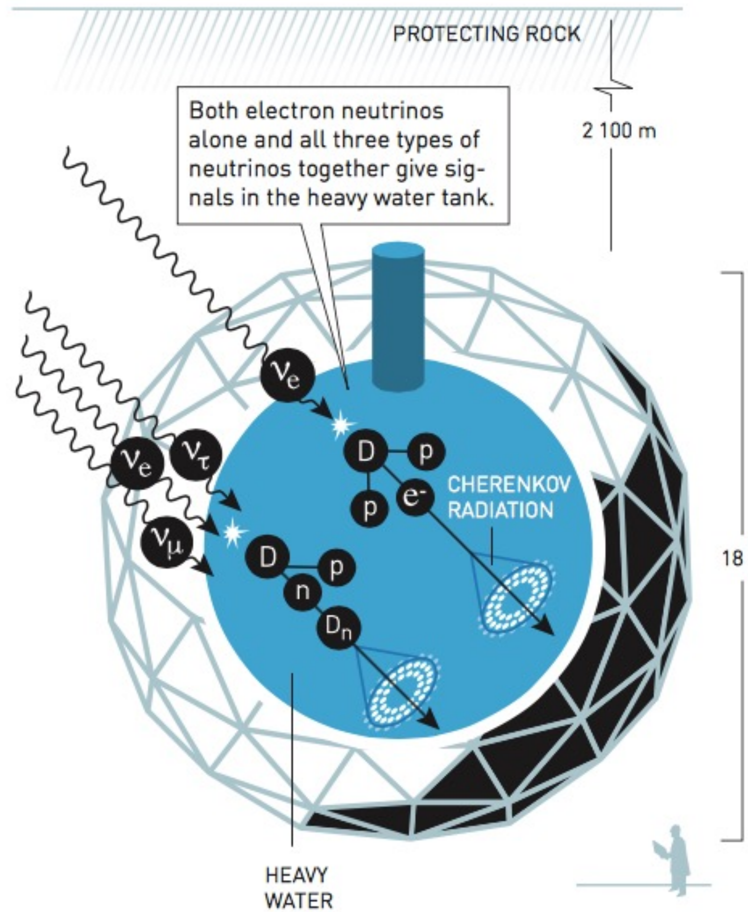
→ The survival probability for ν_e measured in (CC) channel is $P_{ee} \approx 35\,\%$.

→ The overall neutrino flux of (NC) corresponds to the SSM prediction as ν_e converted to $\nu_{\mu,\tau}$ still contribute to the (NC) rate.



Nobel Prize in Physics 2015





→ ν_μ disappear with the correct L/E dependence of oscillations

\+

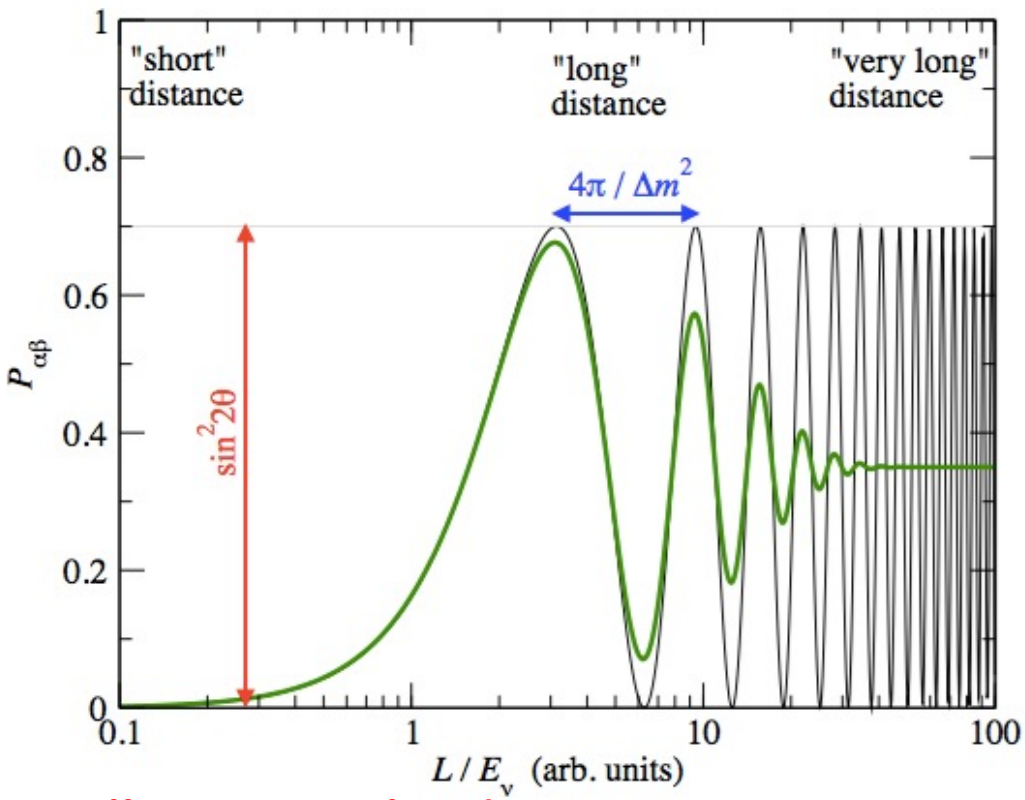
→ ν_e disappear and re-appear as $\nu_{\mu,\tau}$

→ ν's undergo flavor oscillations!

→ at least 2 ν states have mass!

Solar neutrinos: vacuum oscillation pattern

oscillation length
is given by ***4π/Δm²***



oscillation amplitude
depends on ***sin²2ϑ***

oscillation phase *depends on* ***L/E:***

→ $P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$

→ For standard oscillations in vacuum, energy dependence is averaged out:

$$P_{ee} = 1 - \frac{1}{2}\sin^2(2\theta_{12})$$

→ in vacuum, minimum survival probability $\nu_e \to \nu_e$ is P_{ee}~0.5