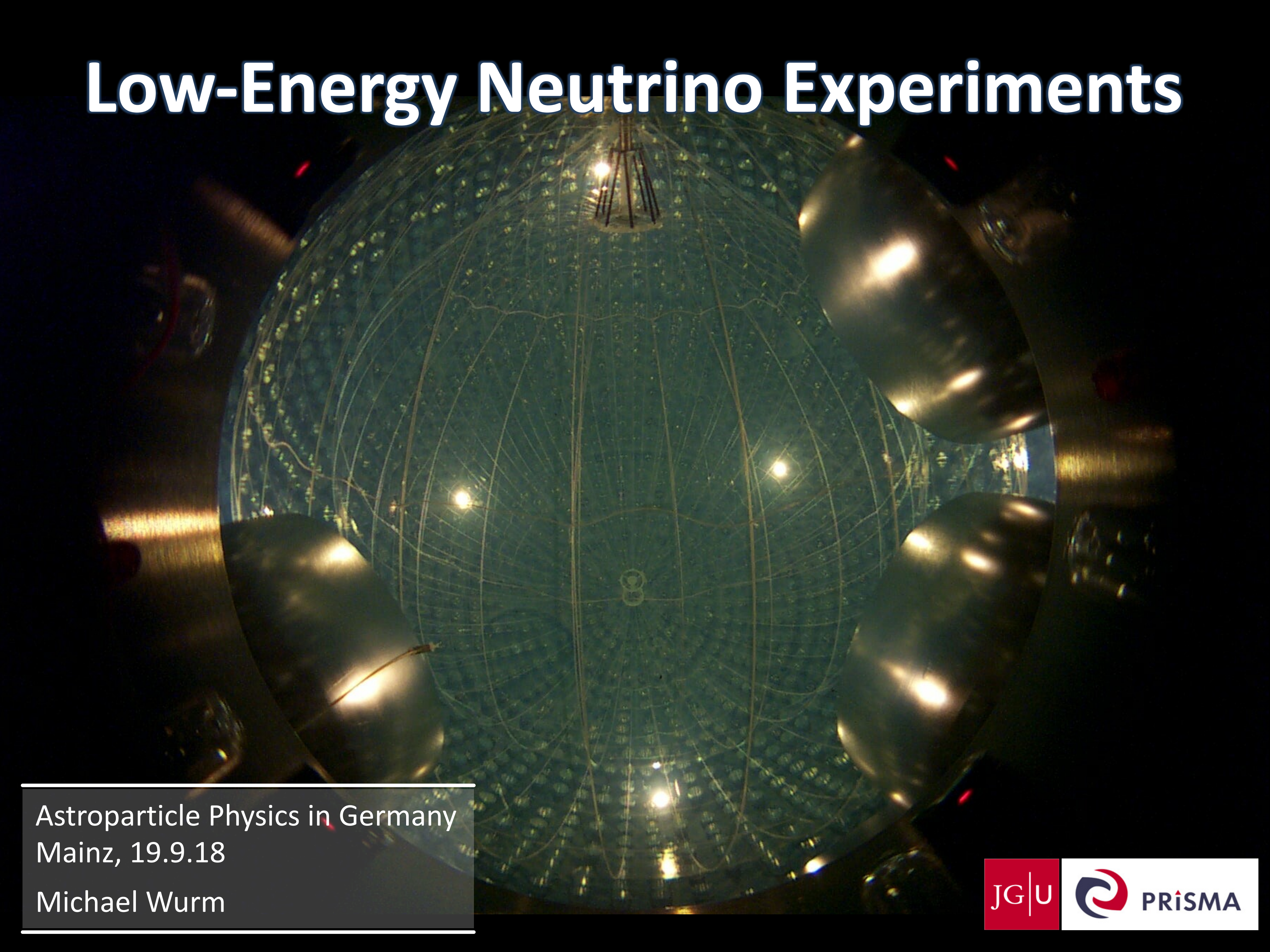
Low-Energy Neutrino Experiments



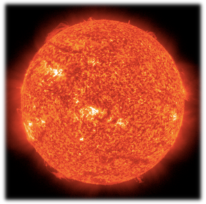
Astroparticle Physics in Germany
Mainz, 19.9.18

Michael Wurm

Low-energy neutrinos in a nut-shell

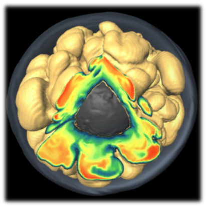
JG|U

natural sources



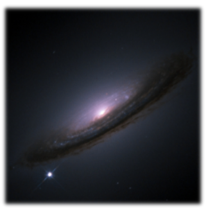
the Sun

solar hydrogen fusion
solar metallicity
oscillations in matter



Supernovae

dynamics of collapse
collective oscillations
gravitational waves



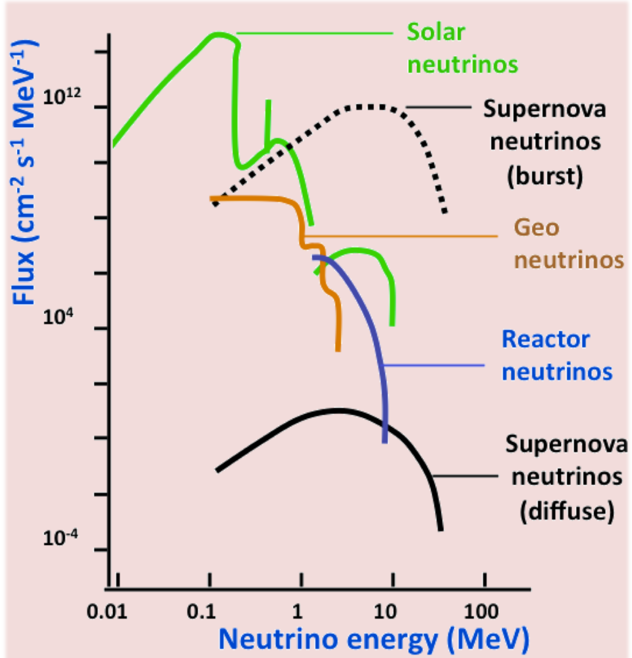
diff. SNν background

DSNB discovery
mean SNν spectrum
(dark) SN rate

the Earth

radiogenic heat
U/Th in crust/mantle
U/Th ratio

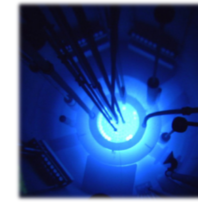
neutrino energy spectrum



man-made sources

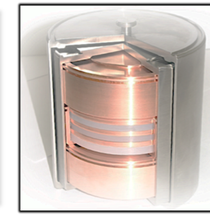
nuclear reactors

mixing angles
mass hierarchy
steriles neutrinos
coherent scattering



radioactive sources

very short-baseline oscillations
sterile neutrinos

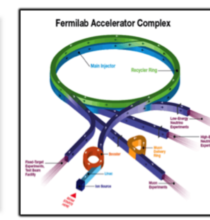


neutron spallation source

coherent neutrino scattering

neutrino beams

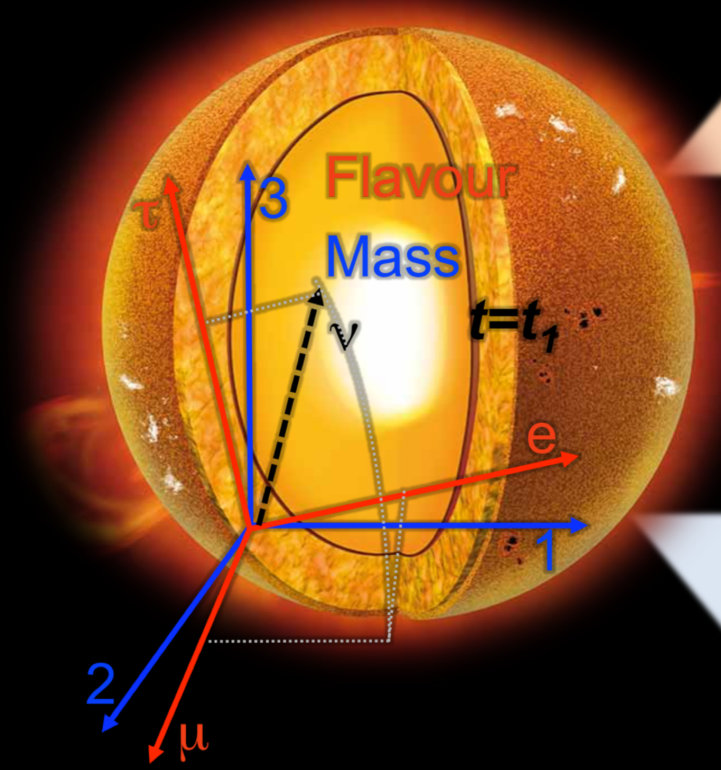
mixing angles
mass hierarchy
leptonic CP phase



Investigate physics of the sources / neutrino properties and oscillations

Significant German participation: Aachen, Dresden, Hamburg, Heidelberg, Jülich, Mainz, München, Tübingen

Solar neutrinos

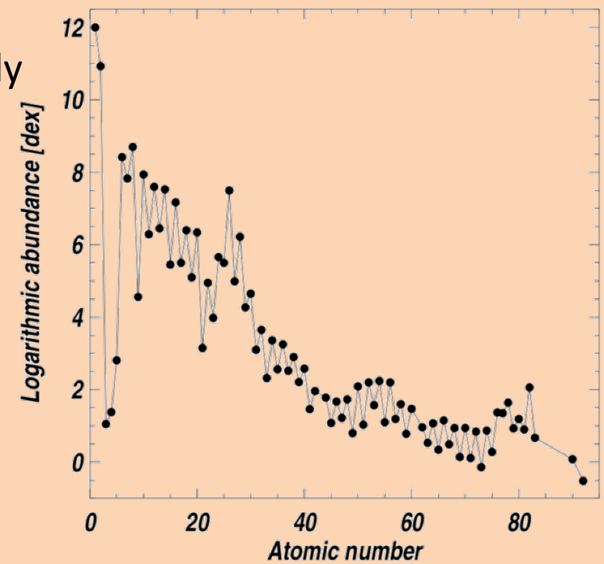


Exploration of the Solar Interior

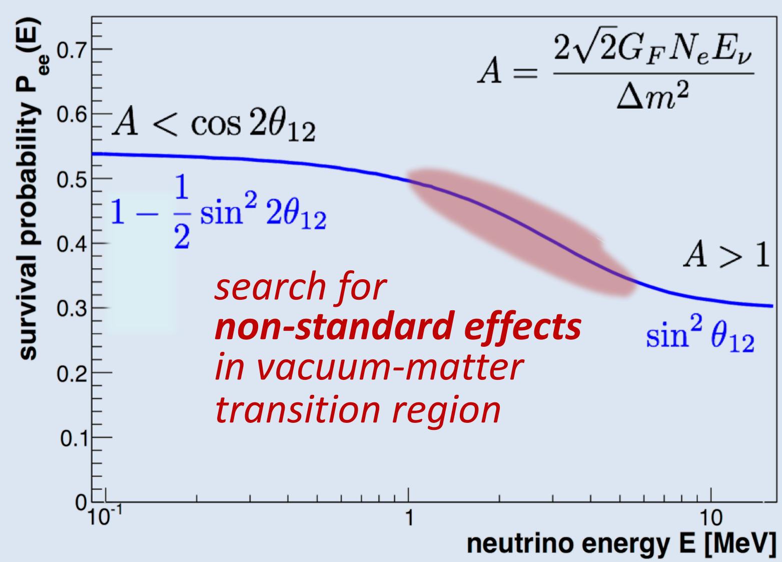
only messengers reaching us directly from solar center

currently most interesting: contribution of CNO cycle to solar fusion

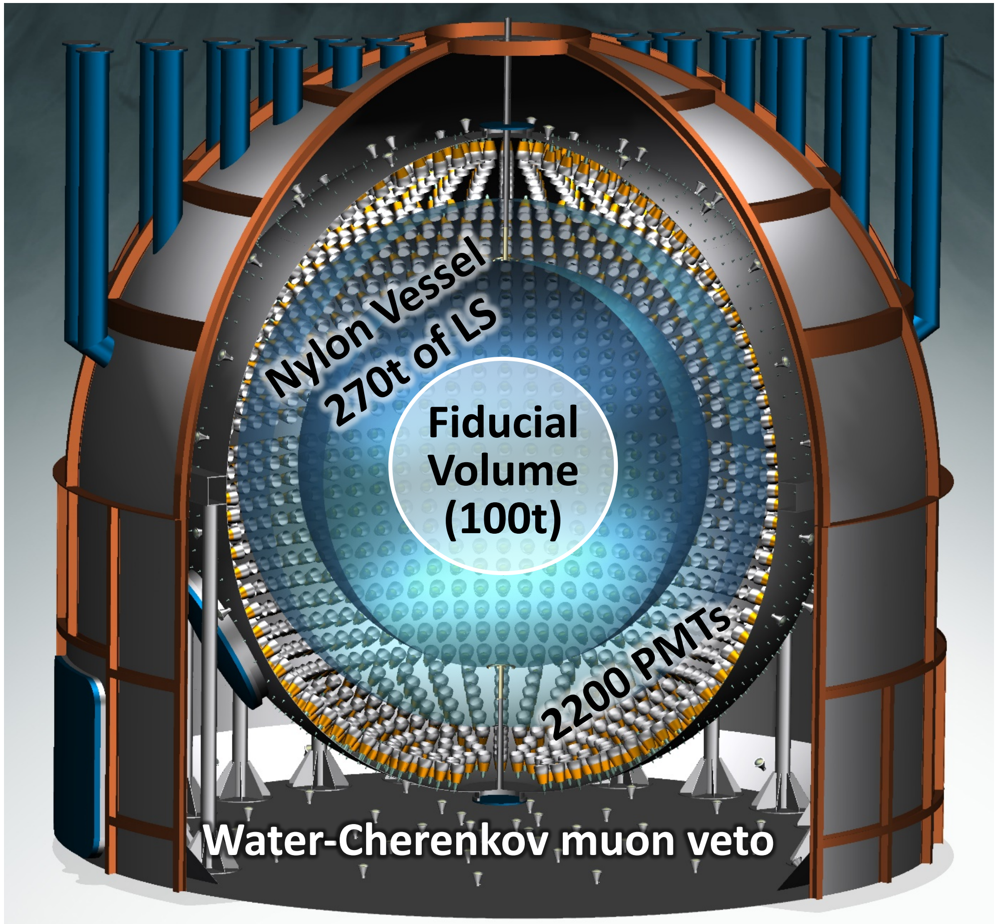
→ elemental abundances (metallicity)

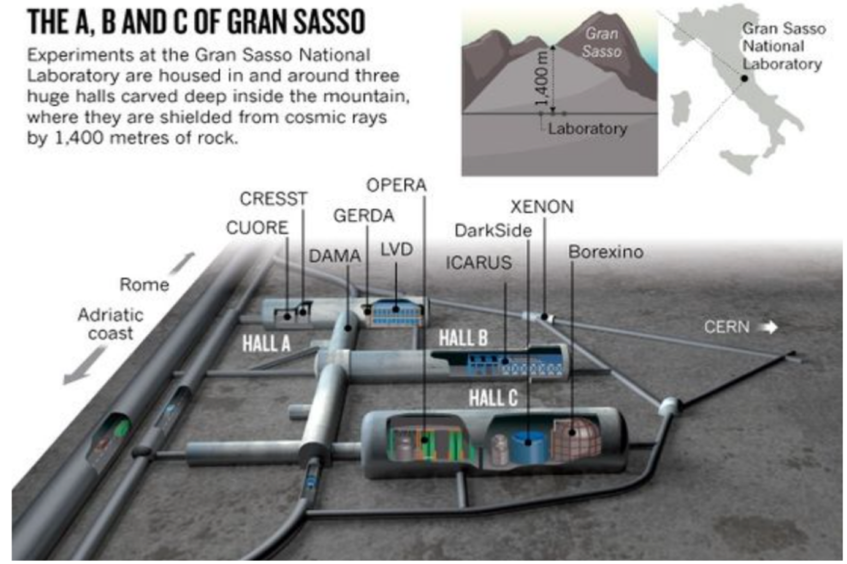


Neutrino Oscillations in Matter



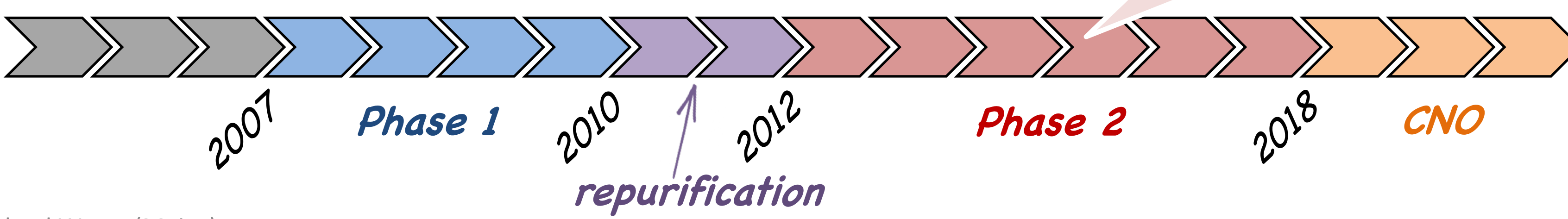
Borexino in a nut-shell





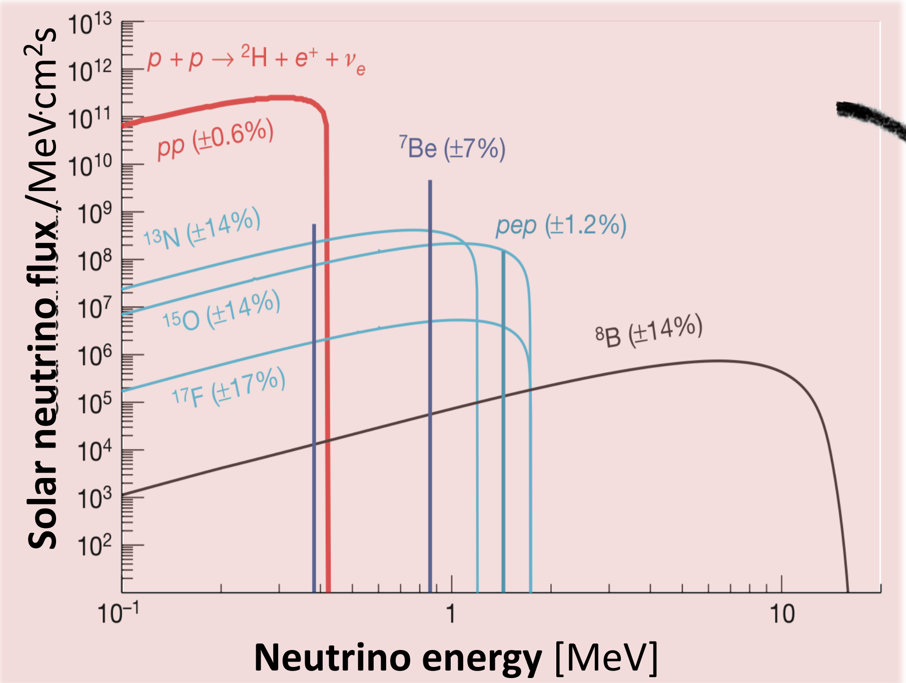
new 4-year data set with

- record radiopurity levels: **$\leq 10^{-18}$ g/g in U/Th**
- improved time stability

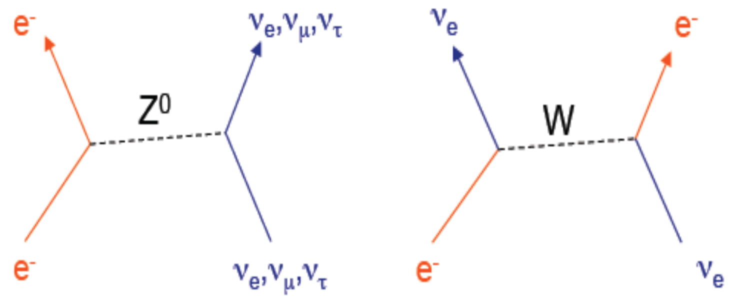


Expected neutrino signal in Borexino

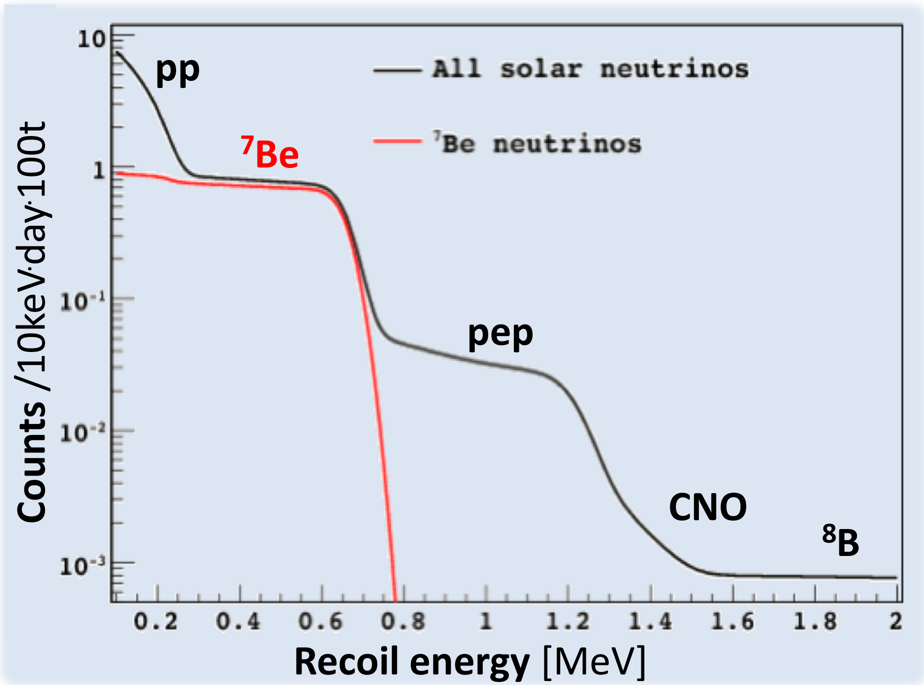
Solar neutrino spectrum



weak elastic ν-electron scattering



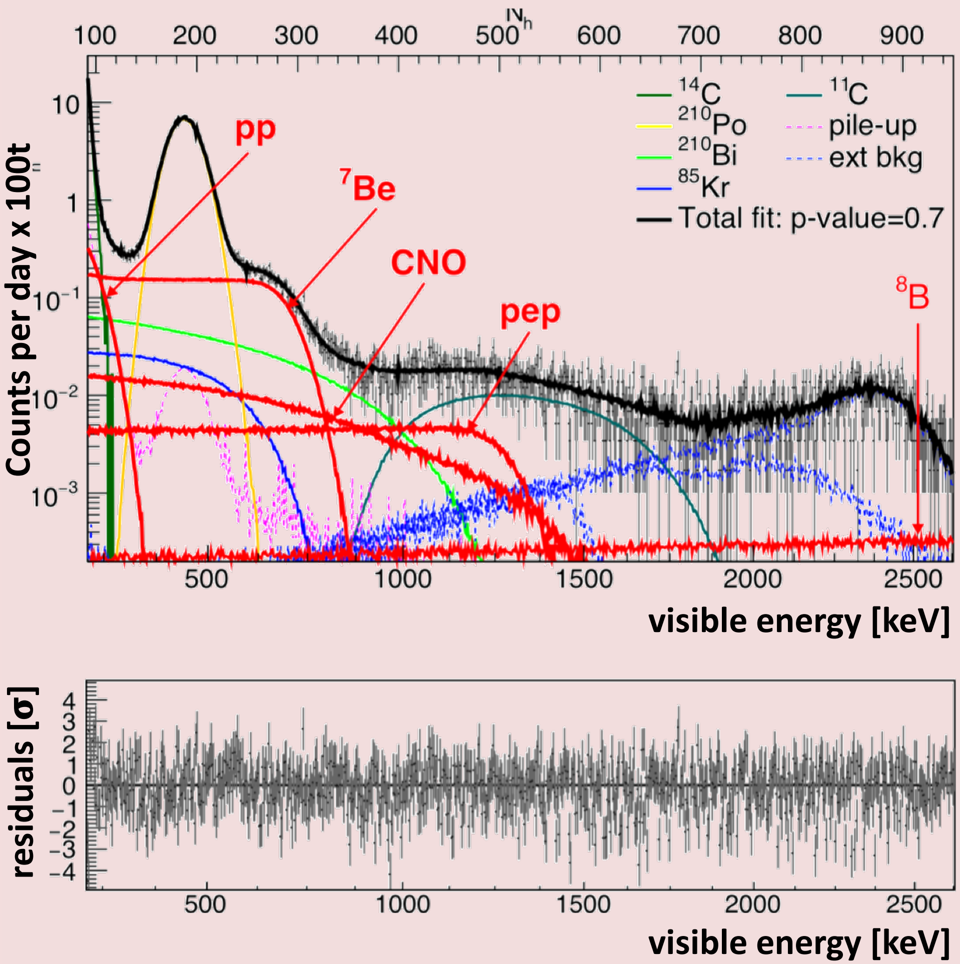
Electron recoil spectrum in Borexino



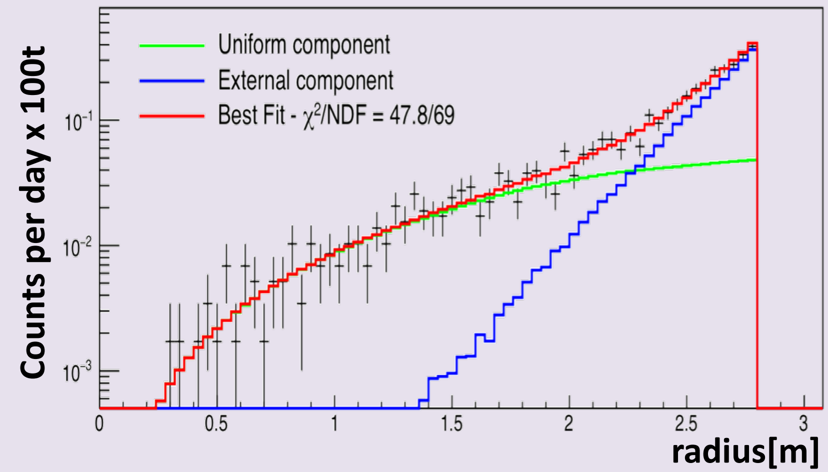
Multivariate fit to Borexino data

Energy spectrum

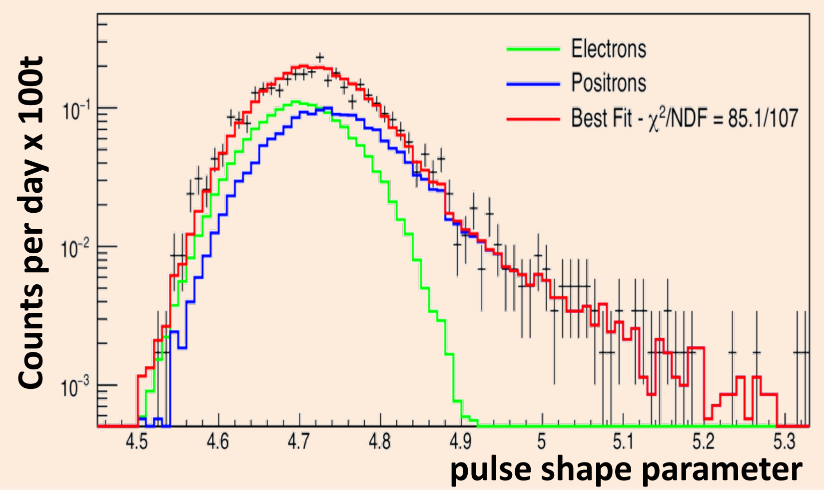
after **fiducial volume cut + cosmogenic ^{11}C cut**



+ radial fit (external γ-background)



+ e⁺/e⁻ pulse shape discrimination (^{11}C)



Phase-2 results: Neutrinos from pp-chain

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Results on pp-chain neutrino rates

	Earlier result	NEW (cpd/100t)
pp	$144 \pm 13 \pm 10$ (11%)	$134 \pm 10^{+6}_{-10}$ (11%)
^{7}Be	$46.0 \pm 1.5^{+1.6}_{-1.5}$ (4.7%)	$46.3 \pm 1.1^{+0.4}_{-0.7}$ (2.7%)
pep	$3.1 \pm 0.6 \pm 0.3$ (22%)	$2.43 \pm 0.36^{+0.15}_{-0.22}$ (16%, HZ)
^{8}B	$0.22 \pm 0.4 \pm 0.1$ (19%)	$0.220^{+0.015}_{-0.016} \pm 0.006$ (7.7%)

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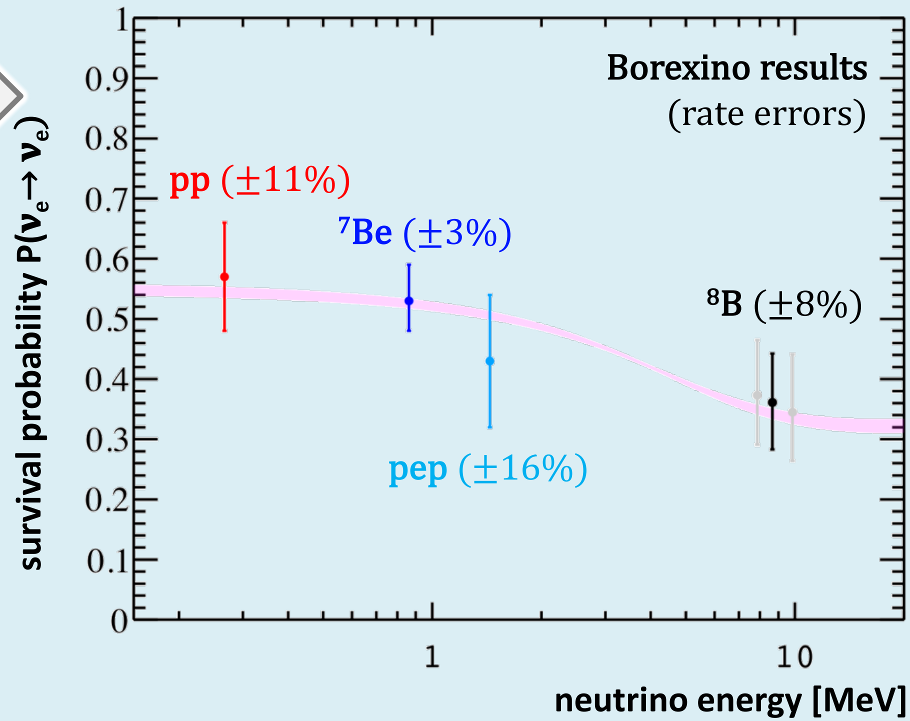
Tracking solar oscillation probabilities

- assuming high-metallicity SSM (GS98)
- including Phase-2 ^{8}B neutrino results



→ confirmation of MSW-LMA solution in vacuum and matter regions

→ transition region to be explored further

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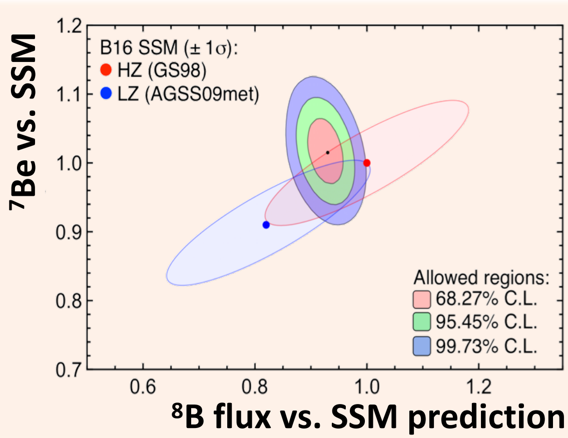
Solar metallicity



→ GS98 high-metal-licity model slightly favored

Tracking solar oscillation probabilities

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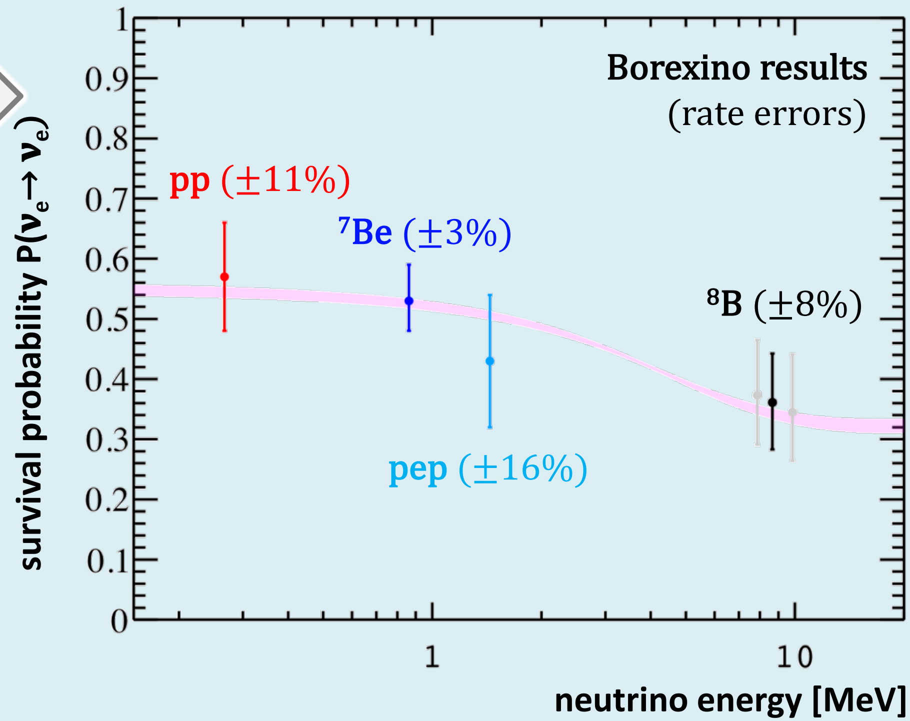

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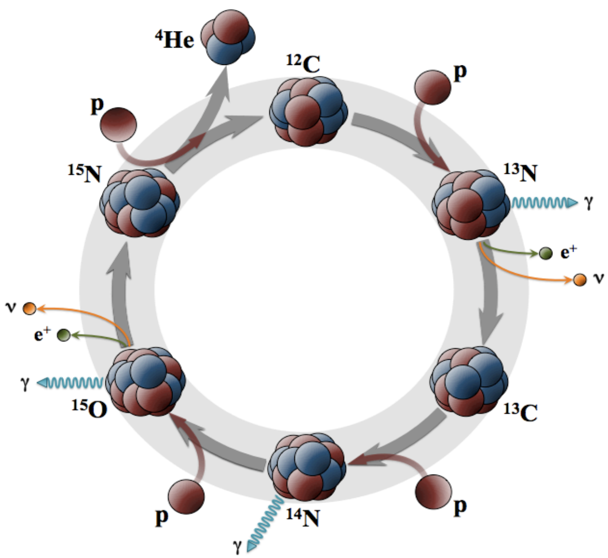
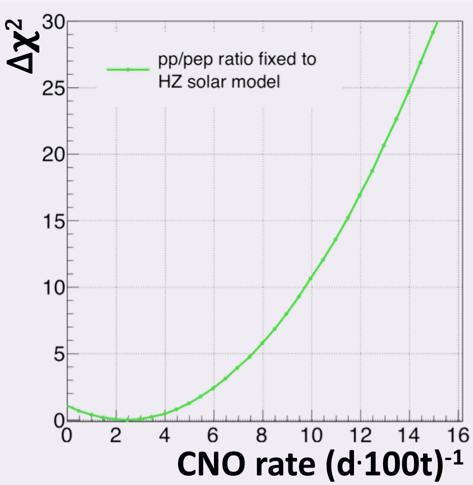
Outlook: Quest for CNO neutrinos



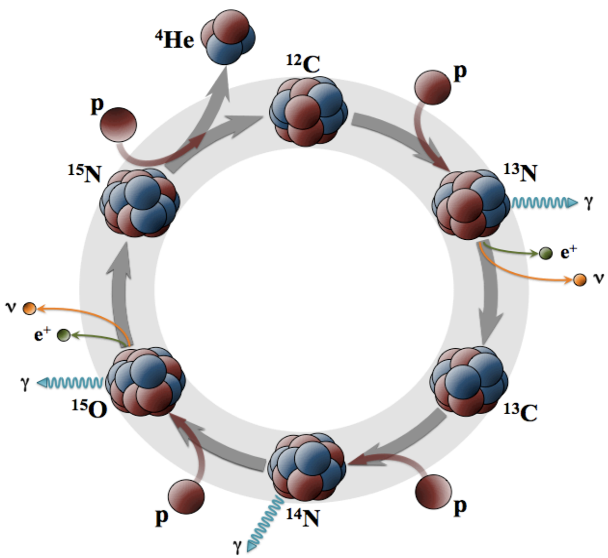
- **CNO cycle** subdominant in the Sun (~1%), but dominant in more massive and older stars
- very sensitive to the solar metallicity (abundance of C, N direct impact on rate)
- up to now: only upper limits for the Sun

CNO signal in Phase 2 data set



→ new upper limit on CNO contribution to ν spectrum, but no positive detection yet

Outlook: Quest for CNO neutrinos



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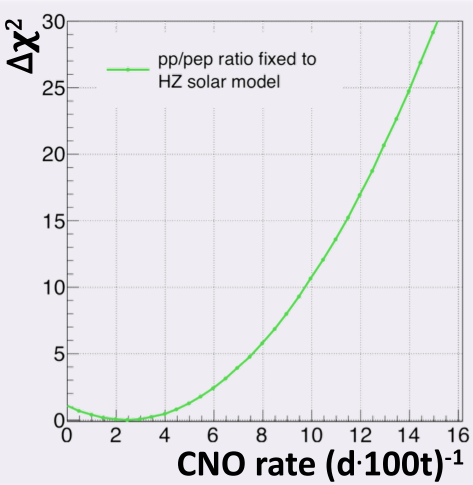

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Future effort on CNO neutrinos

- an additional 3+ years of data taking
- **main background: ^{210}Bi** beta-decays with very similar spectral shape to CNO

→ evaluate ^{210}Bi rate in central region of the detector by using the decay of ^{210}Po in secular equilibrium

→ further stabilize the detector temperature gradient to mitigate entry of new ^{210}Bi/Po from convective currents

→ extensive simulation of fluid mechanics

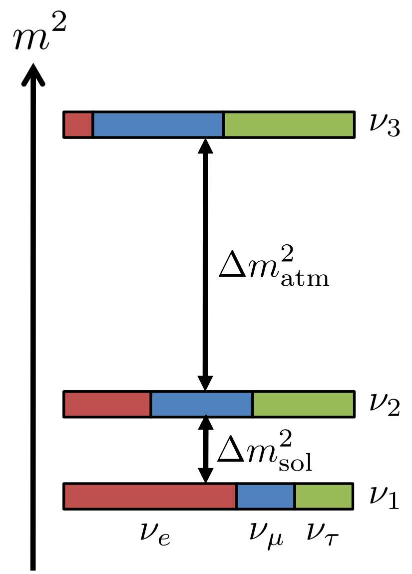
Neutrino oscillations : what we know

PMNS mixing matrix $U_{3\times3}$ → oscillation amplitudes

flavor states / mass states

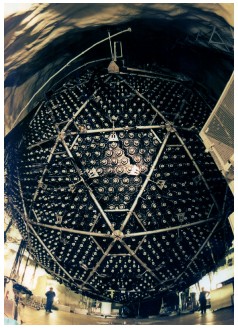
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

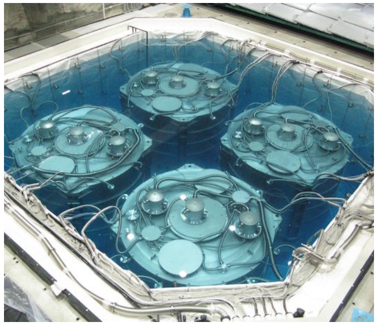
Super-Kamiokande	Daya Bay, RENO, DC	SK,SNO [KL,Bx]
atmospheric: $\theta_{23}\approx45°$?	reactors: $\theta_{13}\approx9°$, $\delta=-\pi$?	solar: $\theta_{12}\approx33°$



mass squared differences → oscillation frequencies

- $\Delta m^2_{\mathrm{sol}} = \Delta m^2_{21}$ → KamLAND+solar: $+8\times10^{-5}$ eV^2
- $\Delta m^2_{\mathrm{atm}} = \Delta m^2_{32} \approx \Delta m^2_{31}$ → SK+acc+reactor: $\pm2.5\times10^{-3}$ eV^2



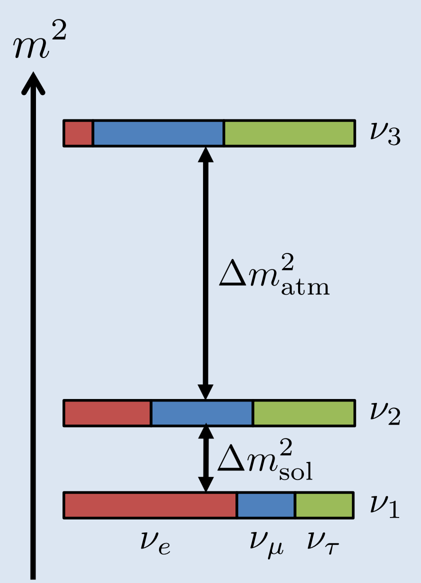



Neutrino oscillations : what we lack

PMNS mixing matrix $U_{3\times3}$ → oscillation amplitudes

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \overbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

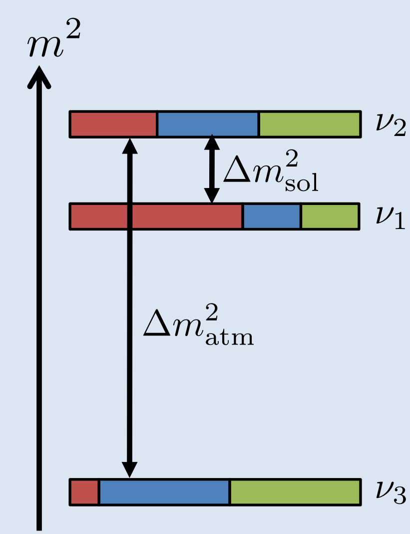
normal ordering



What is the

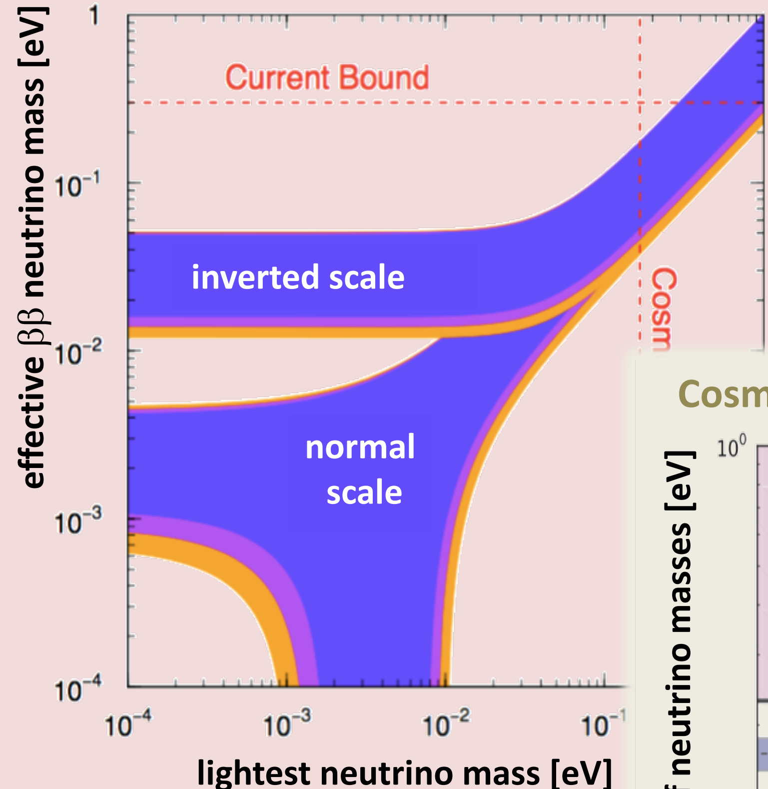
- **octant of θ_{23} ($\gtrsim 45°$)?**
- **leptonic CP-phase?**
- **mass hierarchy?** (sign of $\Delta m^2_{\mathrm{atm}}$)
- PMNS unitarity: **sterile neutrinos?**
- other non-standard effects/interactions?

inverted ordering

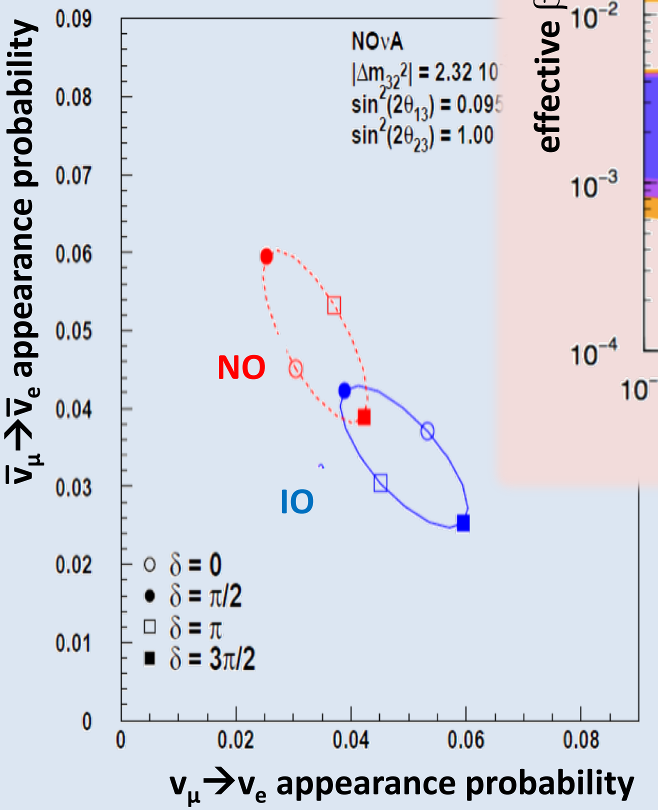


Implications of neutrino mass hierarchy

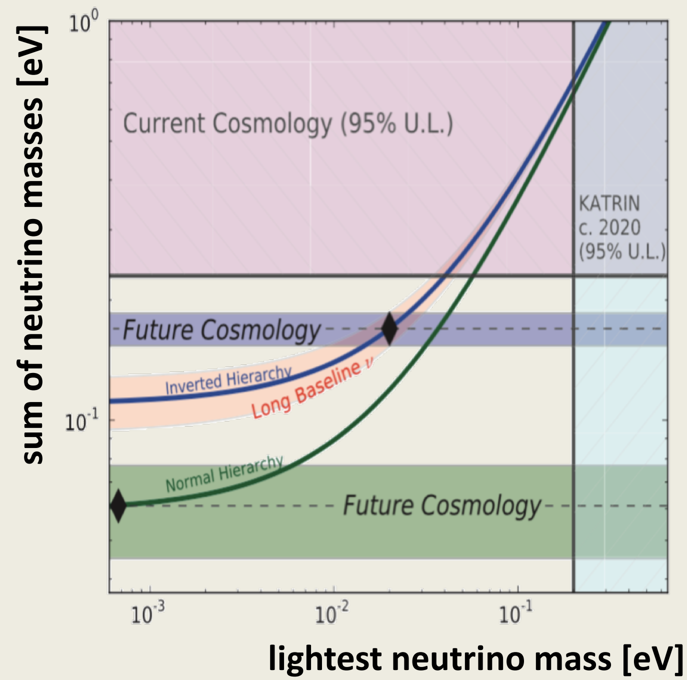
Lightest vs. effective $\beta\beta$ neutrino mass



Degeneracy of MO & δ_{CP}

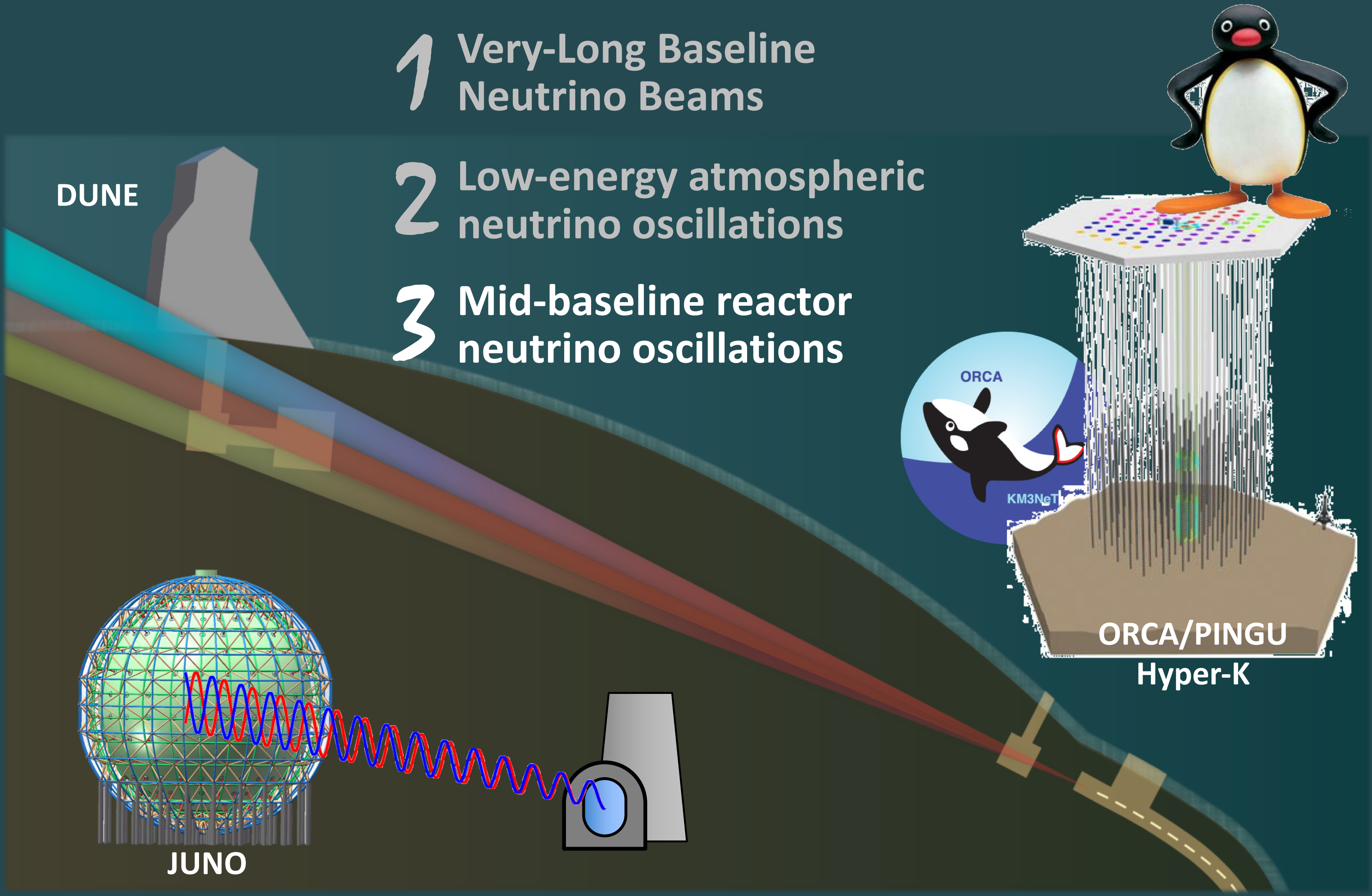


Cosmological neutrino mass vs. MO

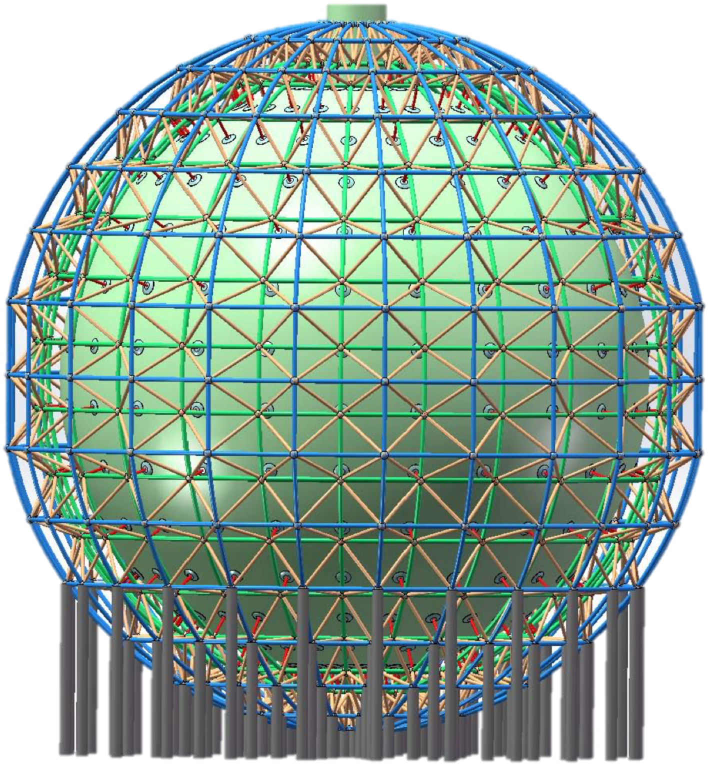


Concepts for MO measurement

1. Very-Long Baseline Neutrino Beams
2. Low-energy atmospheric neutrino oscillations
3. Mid-baseline reactor neutrino oscillations



JUNO in a nutshell



Physics objectives

- neutrino mass hierarchy
- sub-% measurement of solar oscillation parameters
- astrophysical neutrinos
- nucleon decay
- eV-scale sterile neutrinos

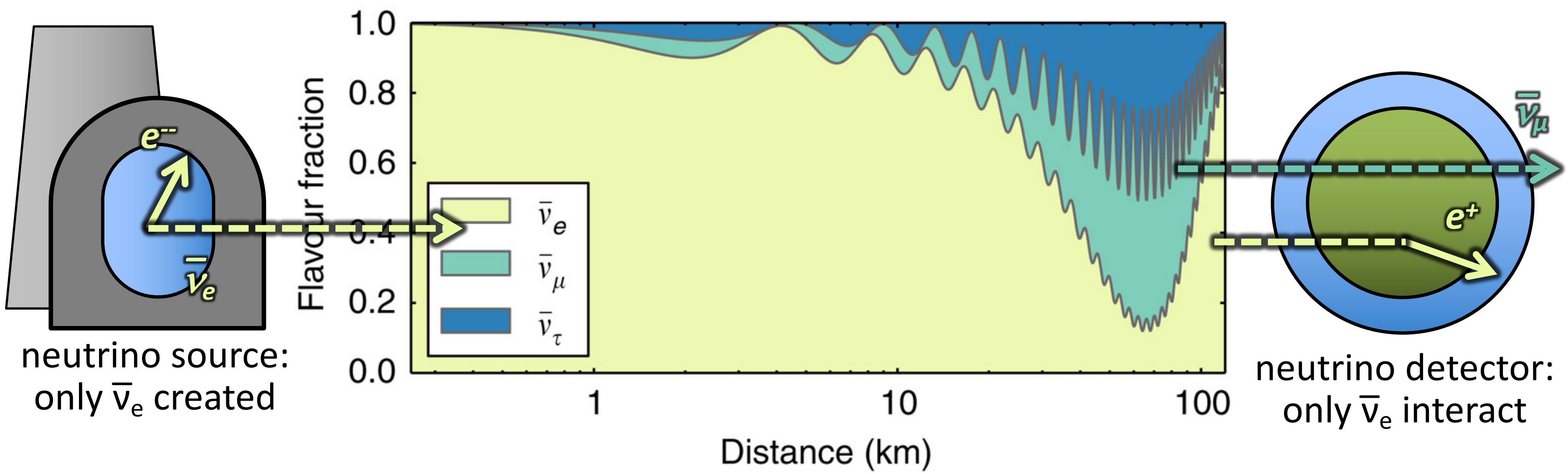
JUNO characteristics

- liquid scintillator detector: 20ktons
- number of PMTs: 17,000 (20'')
- energy resolution: 3% at 1MeV
- rock overburden: 700m
- distance to reactors: 53km

Reactor antineutrino oscillations

Common three-flavor reactor electron-antineutrino survival probability:

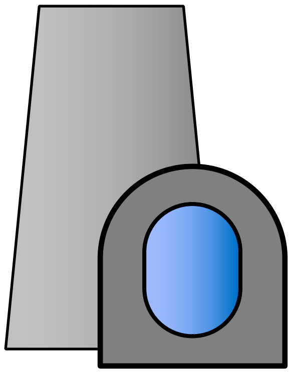
$$P_{ee} = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}}{4E}\right) - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}}{4E}\right)$$



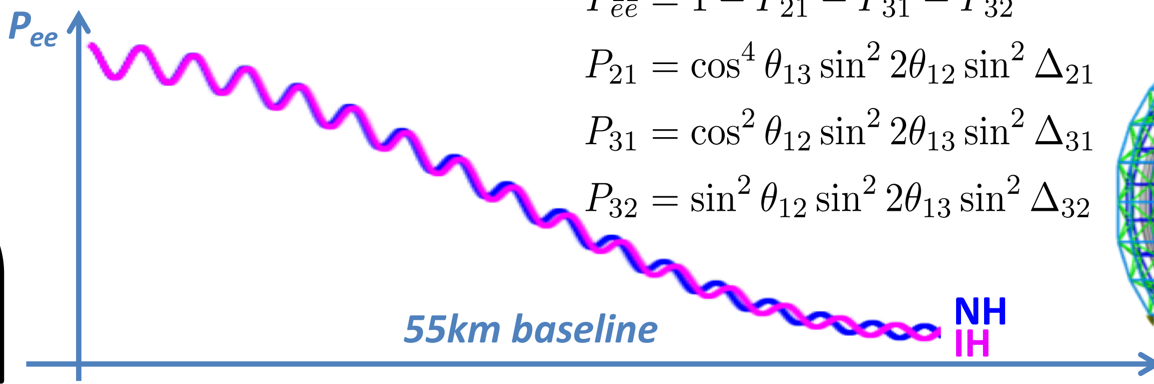
→ oscillation parameters are extracted from **$\bar{\nu}_e$ disappearance pattern**

→ however, the formula above implicitly assumes $\Delta m^2_{31} = \Delta m^2_{32}$

Reactor neutrino oscillations and MH

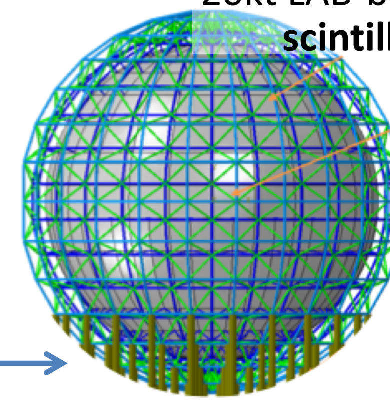


Nuclear reactor(s)
ΣP~30GW

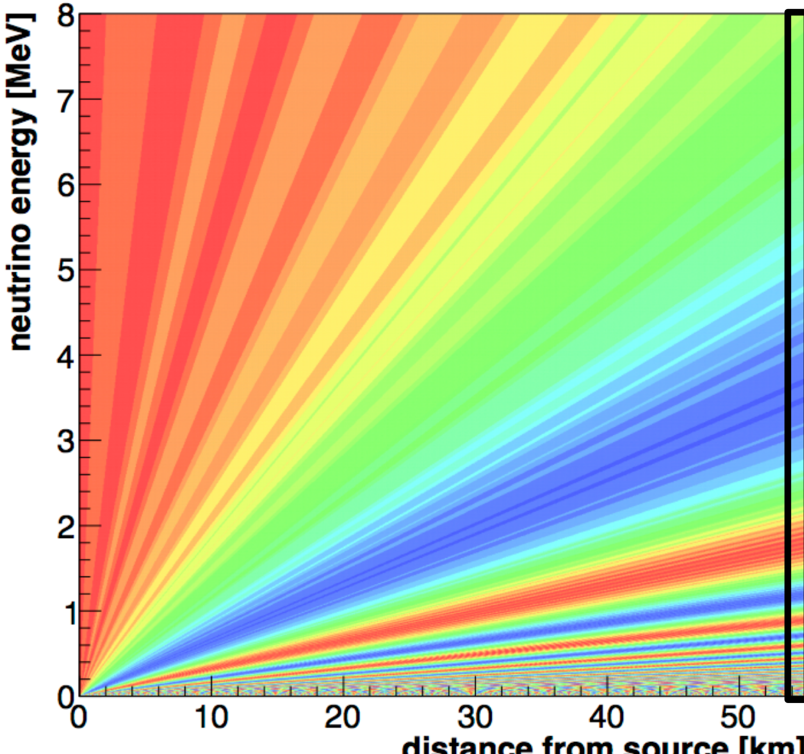


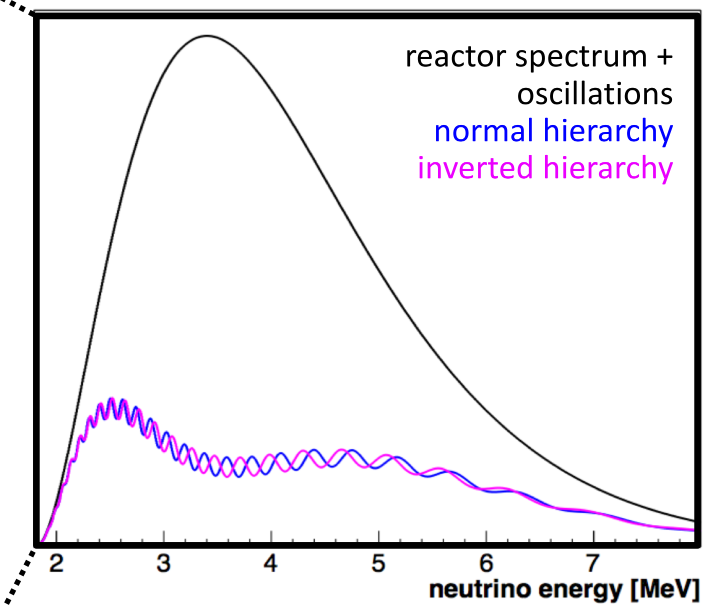
$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$
$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

20kt LAB-based **scintillator**



energy range of reactor spectrum

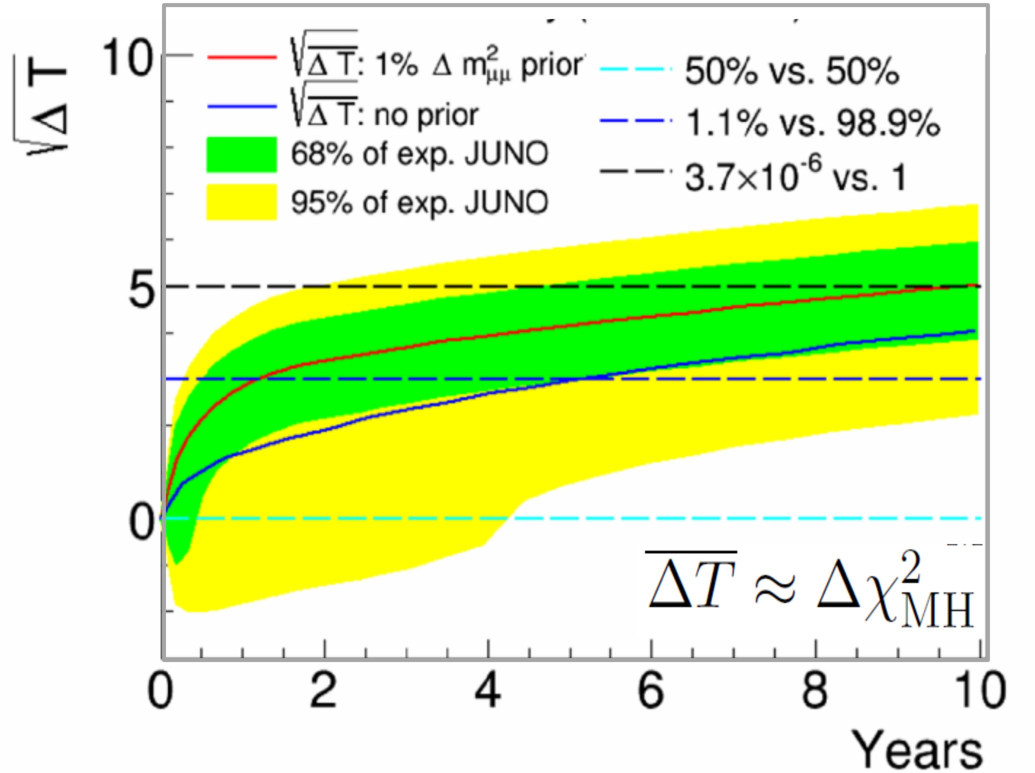




→ MH from position of spectral wiggles
→ **energy resolution (~3%) decisive!**

JUNO sensitivity to mass ordering

JUNO, arXiv:1507.05613



Experimental conditions:

- E resolution: 3% at 1MeV
- statistics: 100,000 ev

Sensitivity budget	$\Delta\chi^2$
Statistics only	+16
different core distances	-3
reactor background	-1.7
spectral shape	-1
S/B ratio (rate)	-0.6
S/B ratio (shape)	-0.1
information on $\Delta m^2_{\mu\mu}$	**+8**

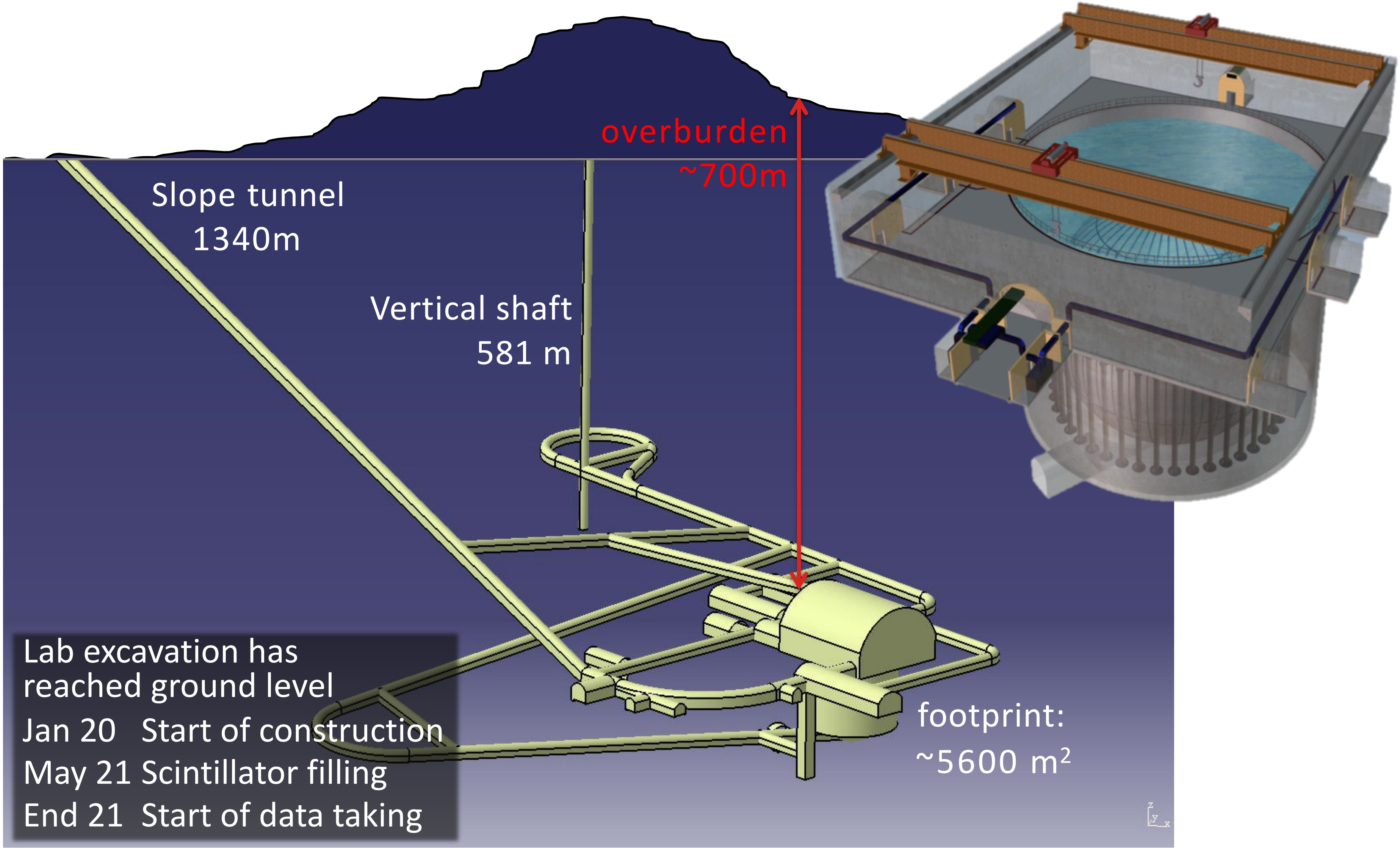
JUNO's expected sensitivity level

(assuming 3% energy resolution)

JUNO alone based on 6 years: ~3σ

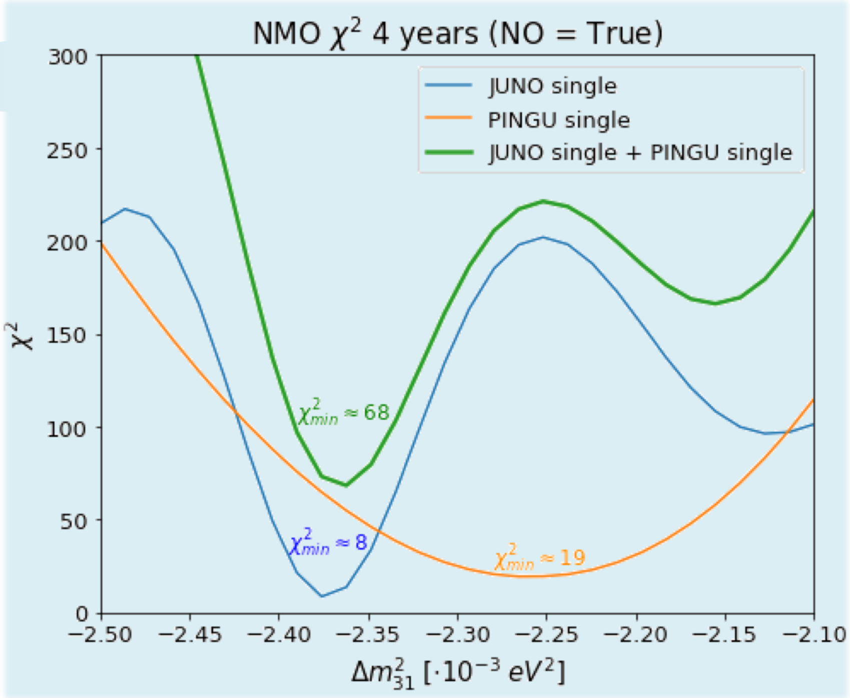
+ precise data by T2K/NOvA on $\Delta m^2_{\mu\mu}$: **4σ**

JUNO progress



German contribution to JUNO

- Physics studies: Mass hierarchy & astrophysical neutrino sources
- Novel reconstruction methods for complex event topologies (muons) and particle ID
- liquid scintillator characterization and radiopurity monitoring in OSIRIS
- PMT quality control for large 20’’ PMTs: more than 7,500 PMTs already tested
- detector electronics, intelligent PMTs



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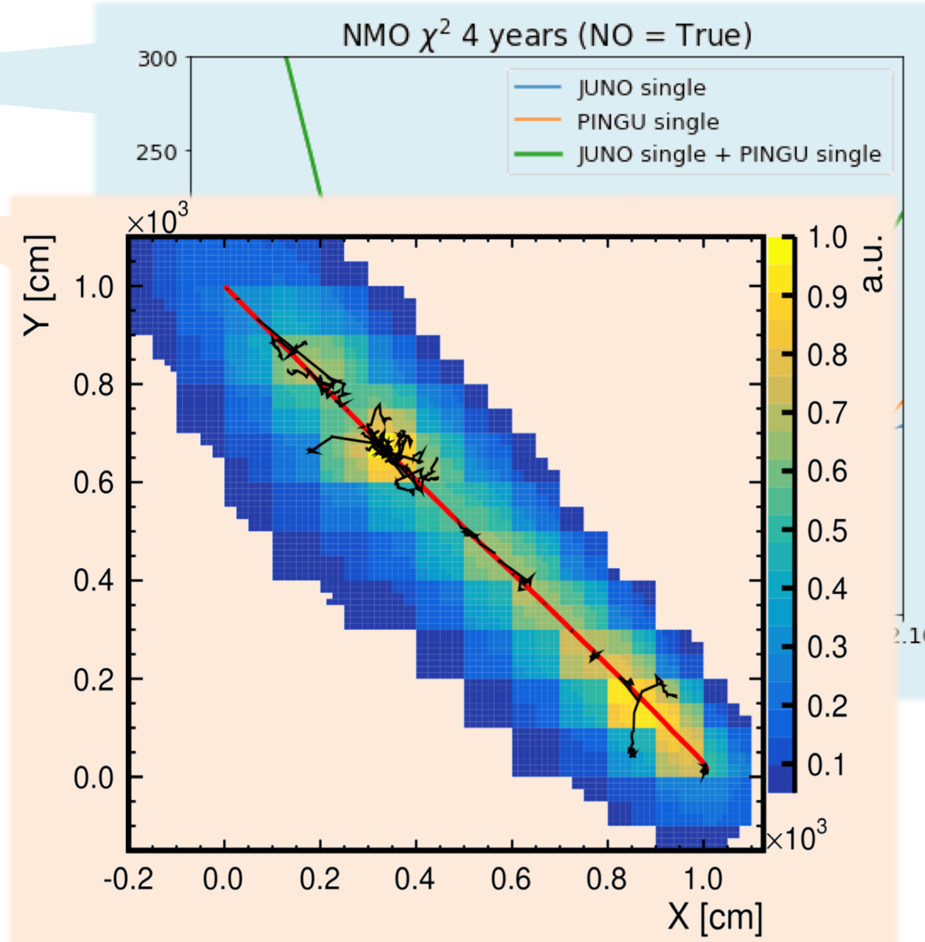

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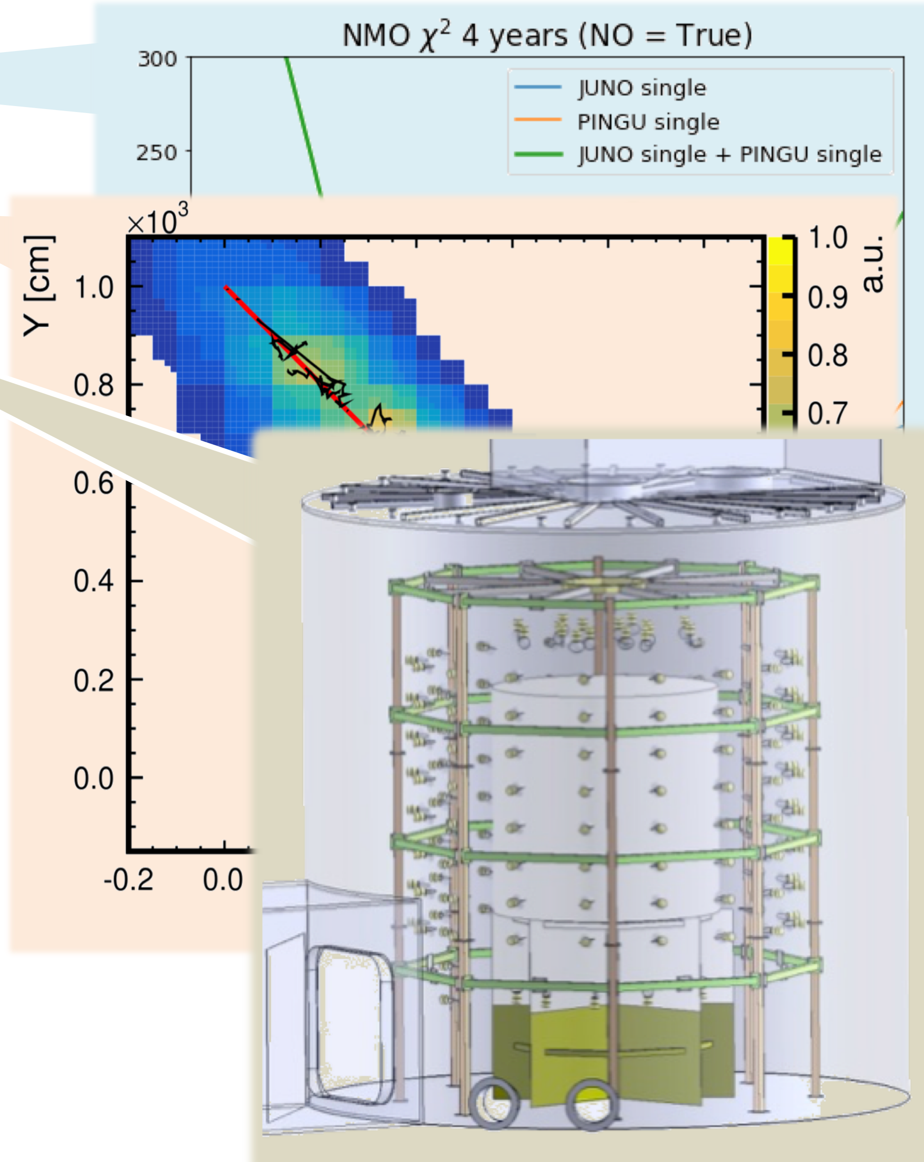
- PMT quality control for large 20'' PMTs: more than 7,500 PMTs already tested
- detector electronics, intelligent PMTs



German contribution to JUNO

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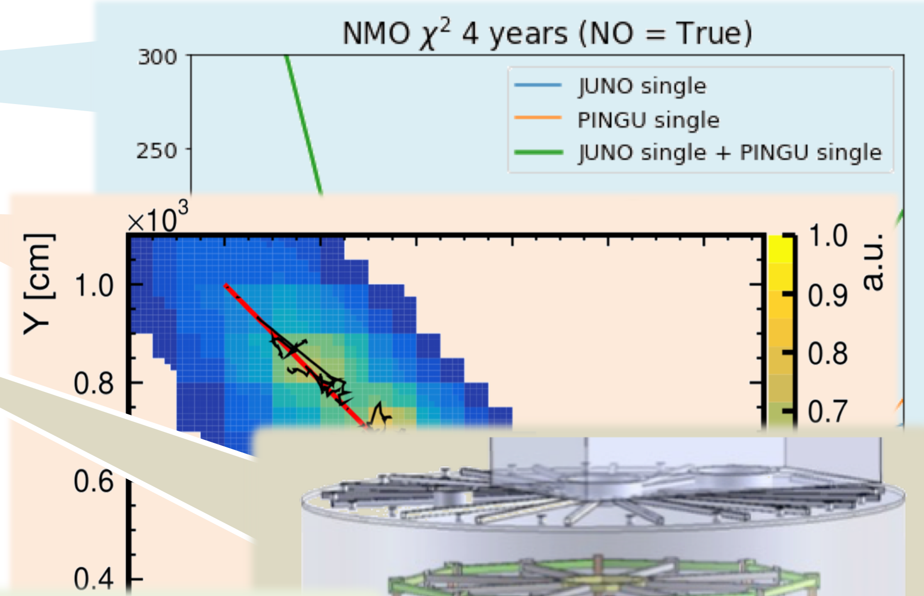

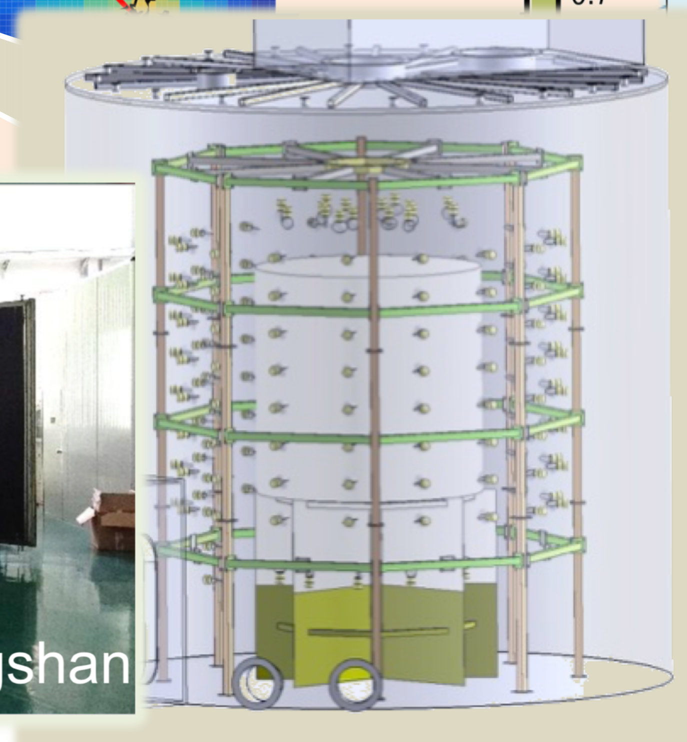

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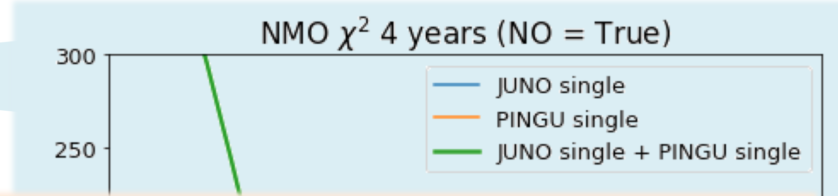
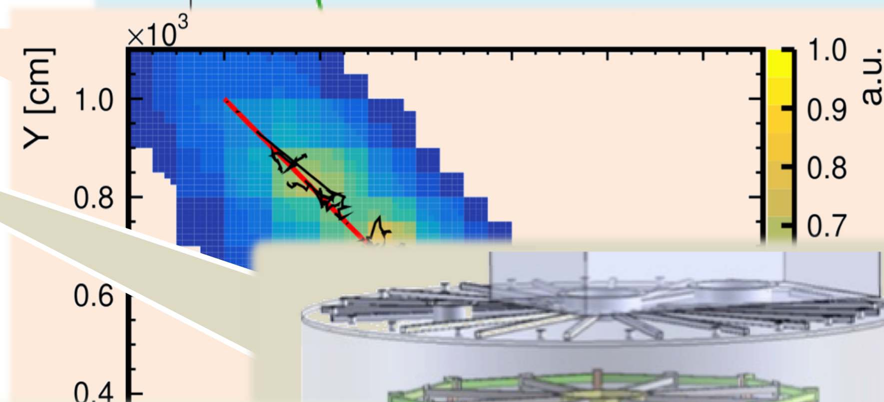
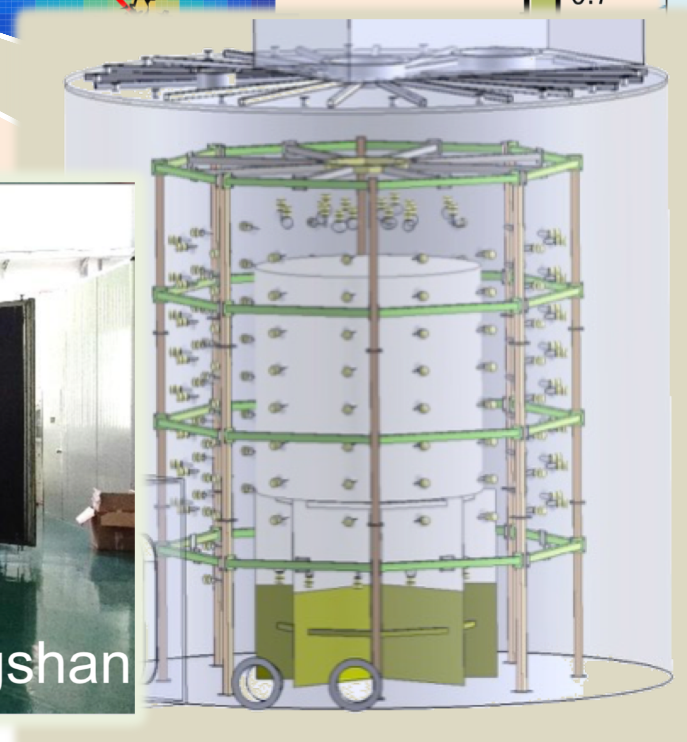
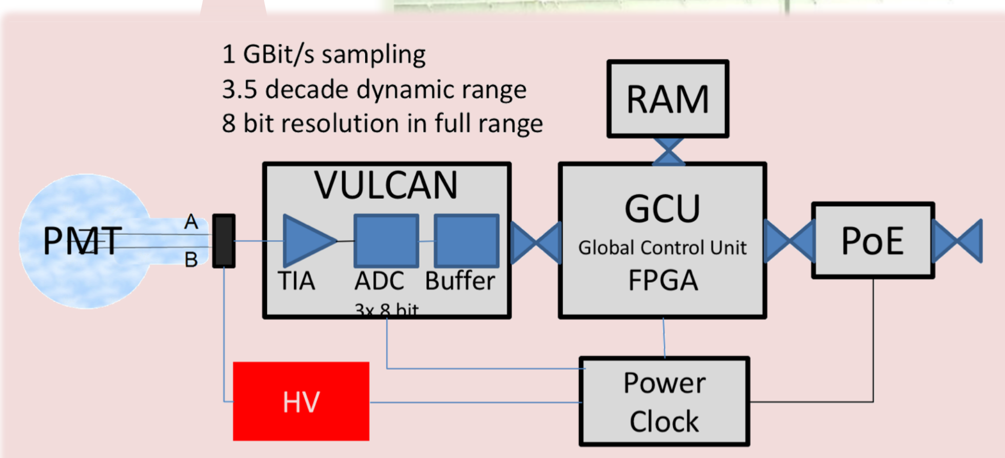




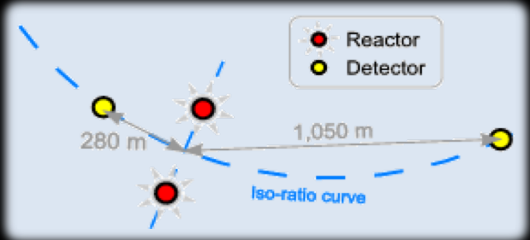




Outlook : low-energy ν projects

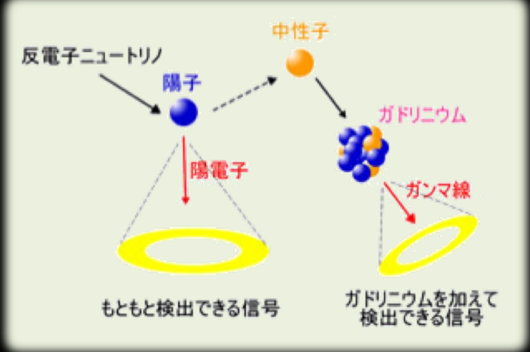
Borexino : Phase 2 results released last year, now entering final phase aiming to detect the CNO neutrino signal

JUNO : civil construction of underground laboratory is on-going, more than half of the PMTs received



further projects that could not be covered in this talk:

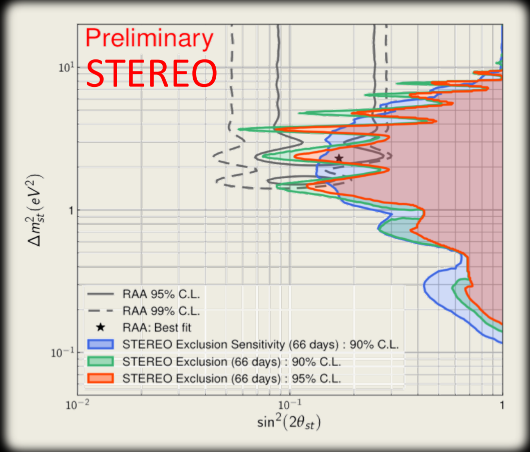
Double-Chooz : end of physics data taking in 2017 publication of two-detector result on θ_{13} imminent



Super-Kamiokande : detector is drained this summer in preparation of new phase with gadolinium-loading

→ **enhanced sensitivity for diffuse SNν's + proton decay**

SNO+ : will come online with Te-loaded scintillator this year there might be a short ν observation phase beforehand

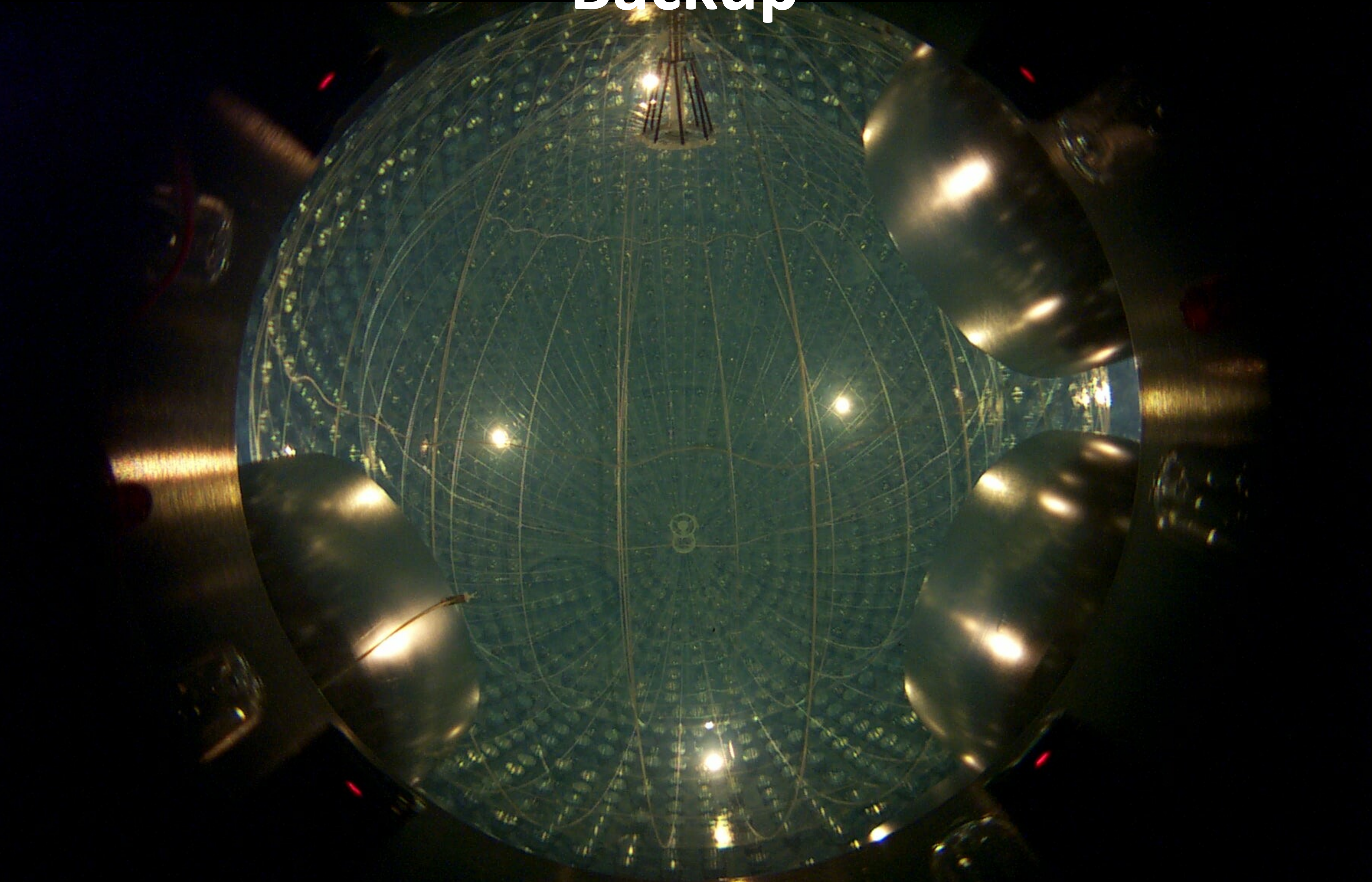


eV-mass sterile neutrinos : most of the short-baseline reactor experiments now running, first results coming in

→ **initital anomalies under pressure but still inconclusive**

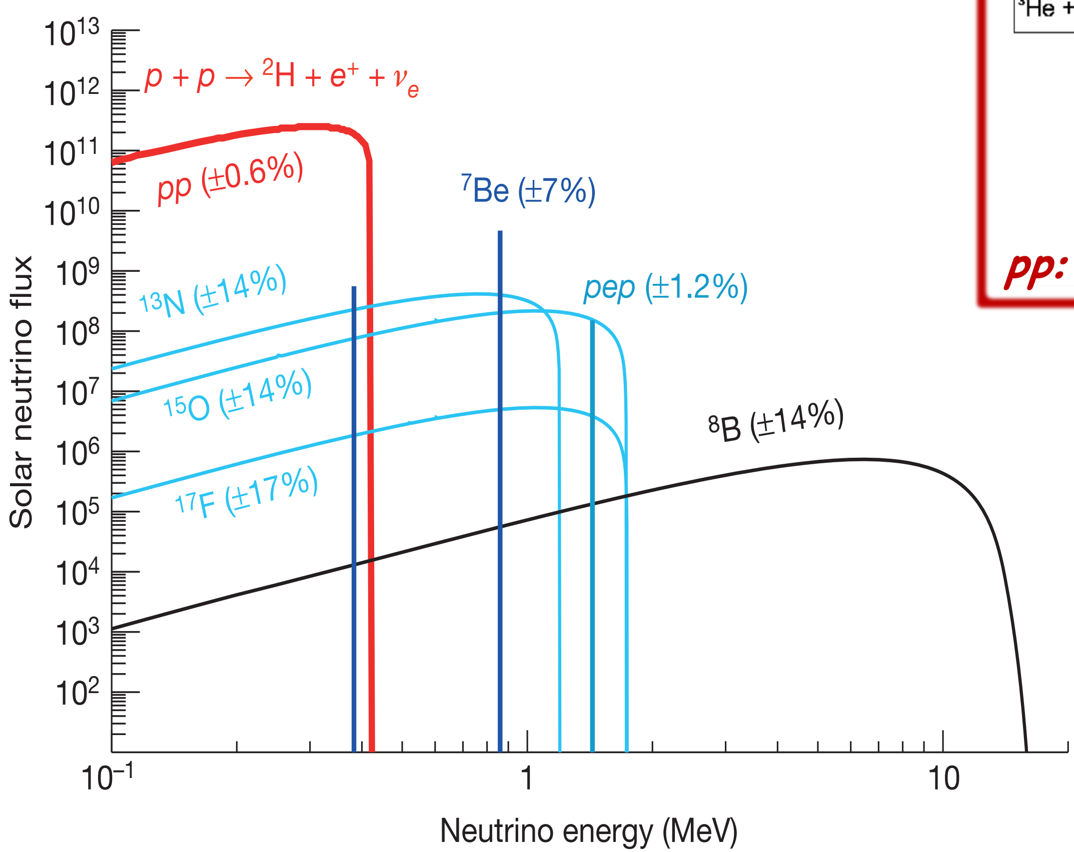
→ **many exiting results on ν oscillations and observations to come!**

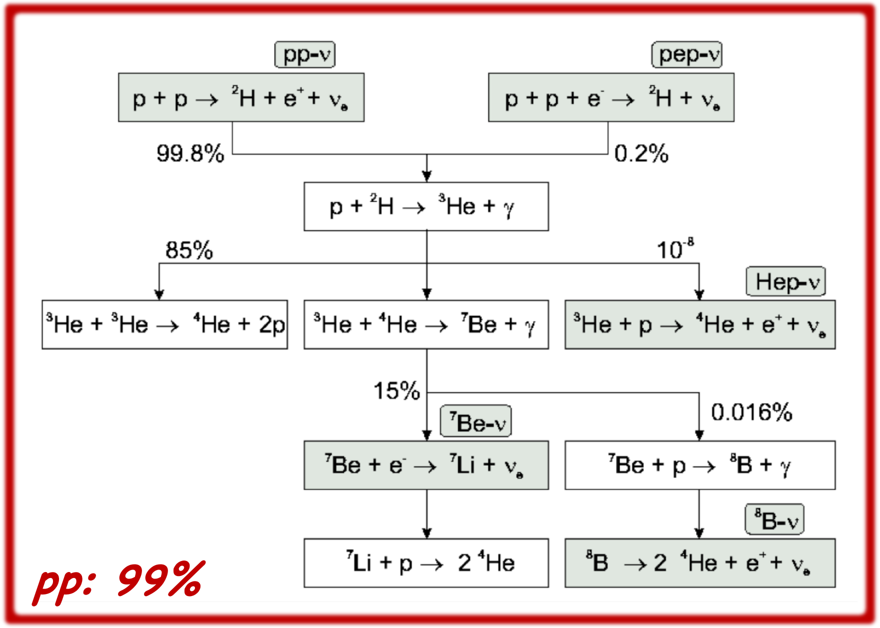
Backup

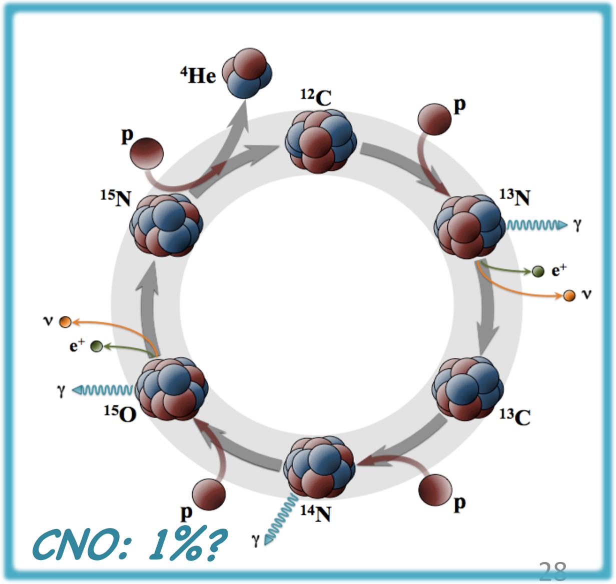


Solar neutrino spectrum

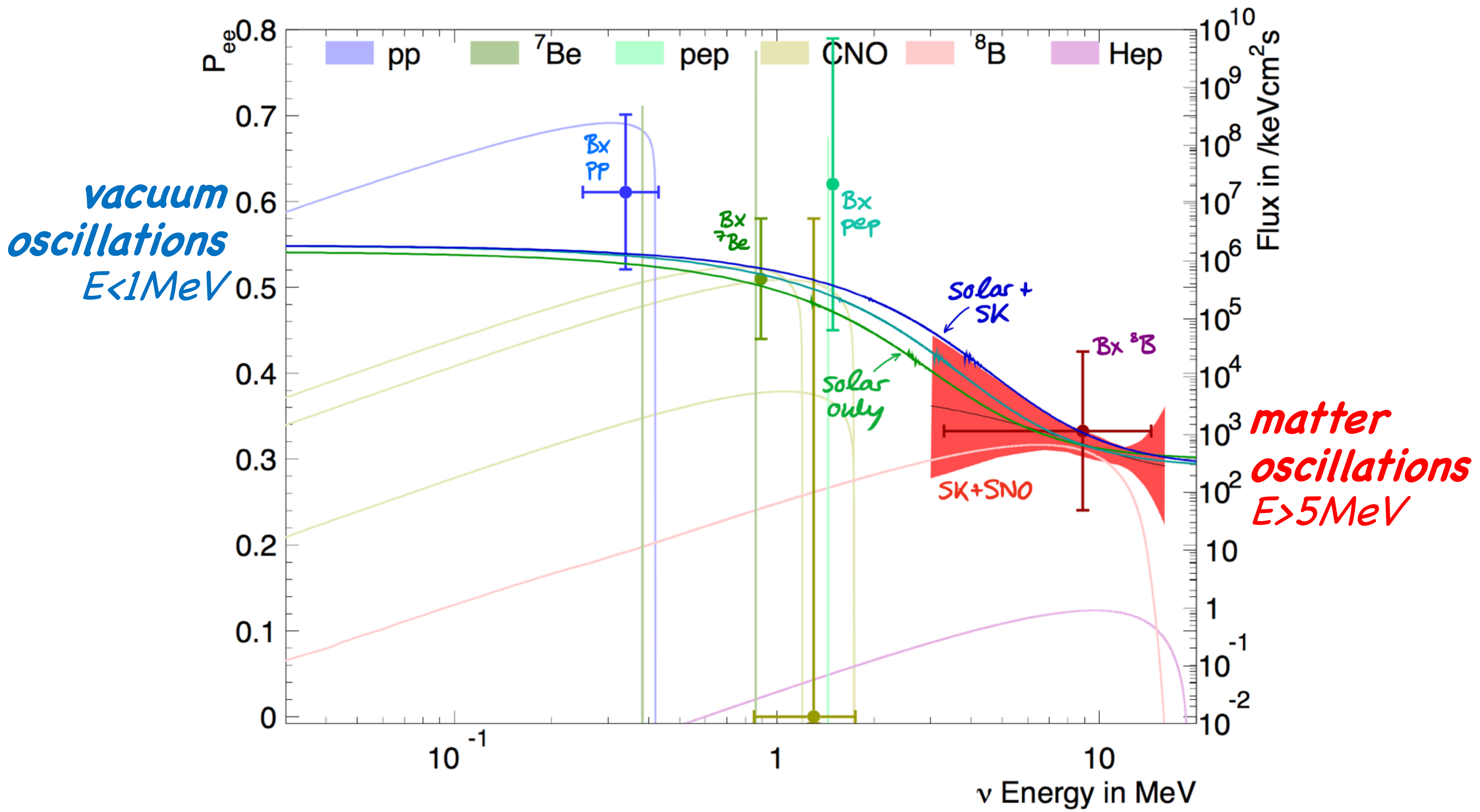
- based on **Standard Solar Model (SSM)** (SSM uncertainties on flux)







Current status of solar oscillation data

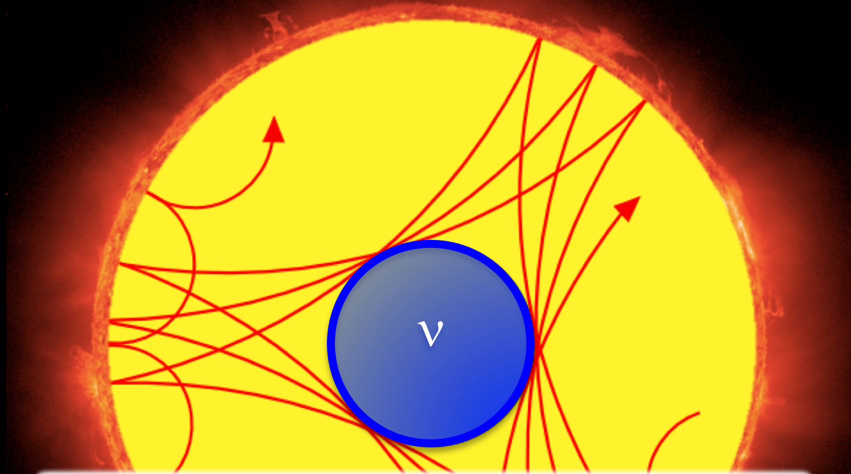


→ *Presence of vacuum and matter-dominated regimes confirmed*

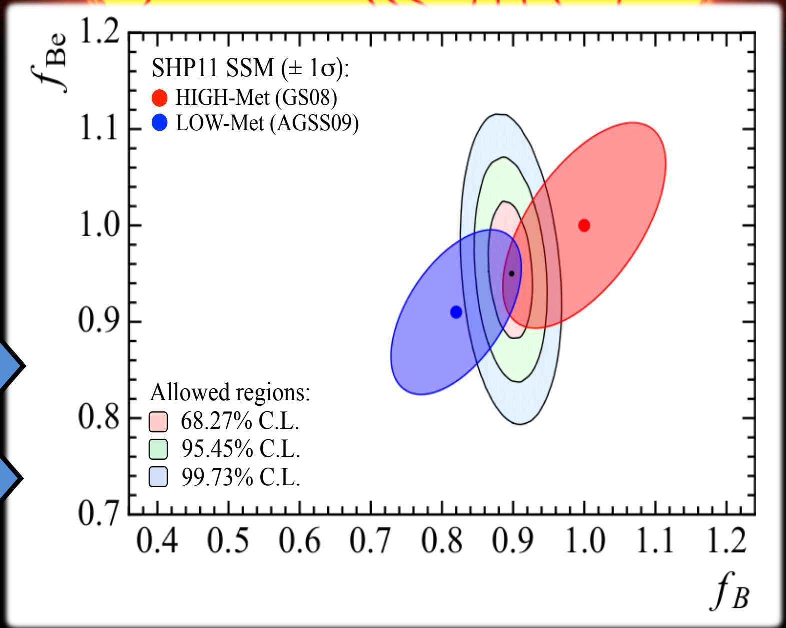
Open issues in solar physics: Metallicity

Metallicity can be derived from
- Optical spectroscopy (Fraunhofer lines)
- Helioseismology (sound speed profiles)

→ **Neutrino production rates**
depend on core metallicity

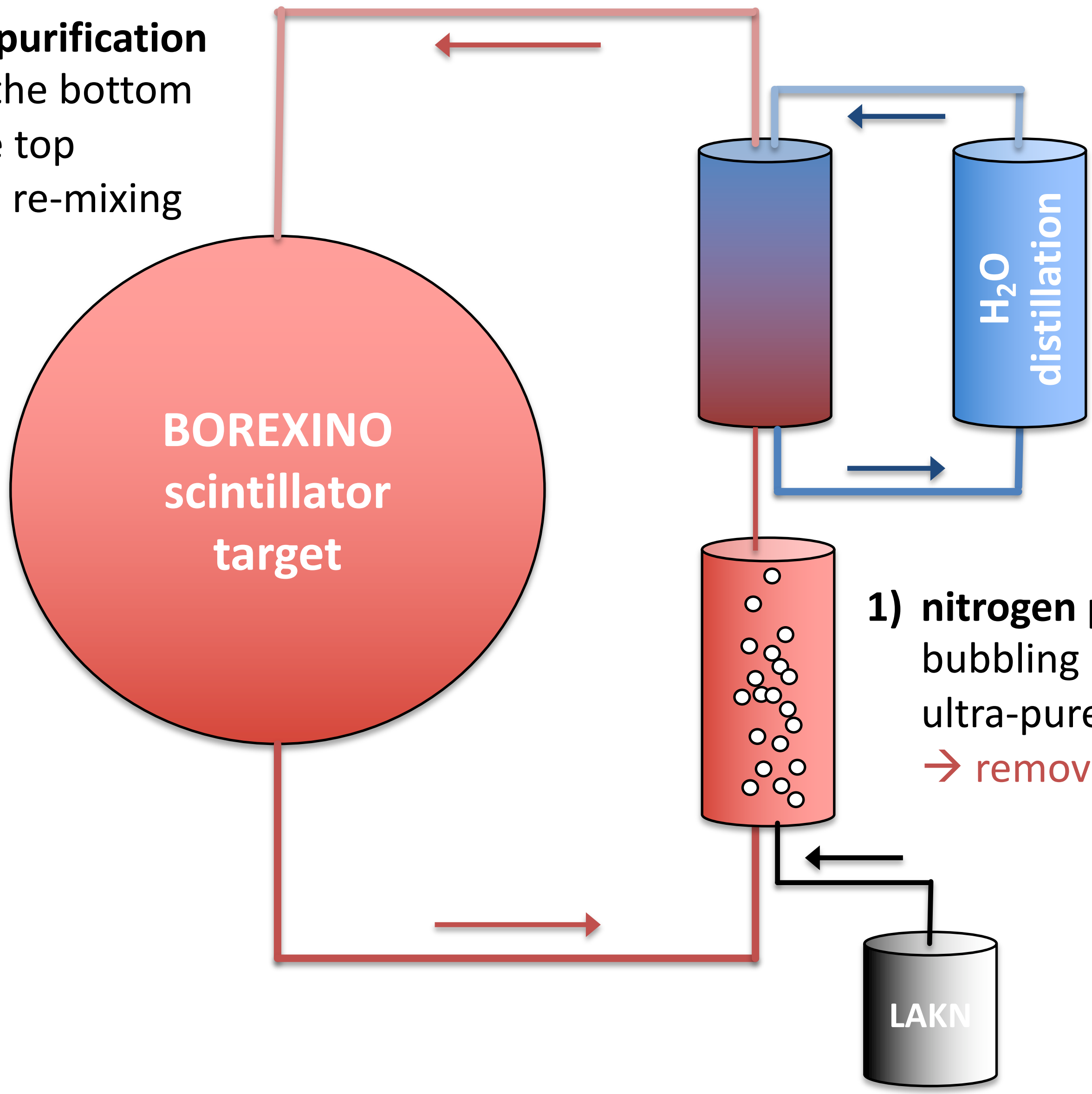


Reaction	$\Delta\Phi_\nu$ (Z)	$\Delta\Phi_{SSM}$	$\Delta\Phi_{exp}$
pp	1.2%	0.6%	–
pep	2.8%	1.1%	20%
^{7}Be	10%	6%	5%
^{8}B	20%	11%	3%
CNO	**38%**	**16%**	–



Borexino purification campaign (2010-12)

loop-mode purification
- extract at the bottom
- refill at the top
- try to keep re-mixing inside low



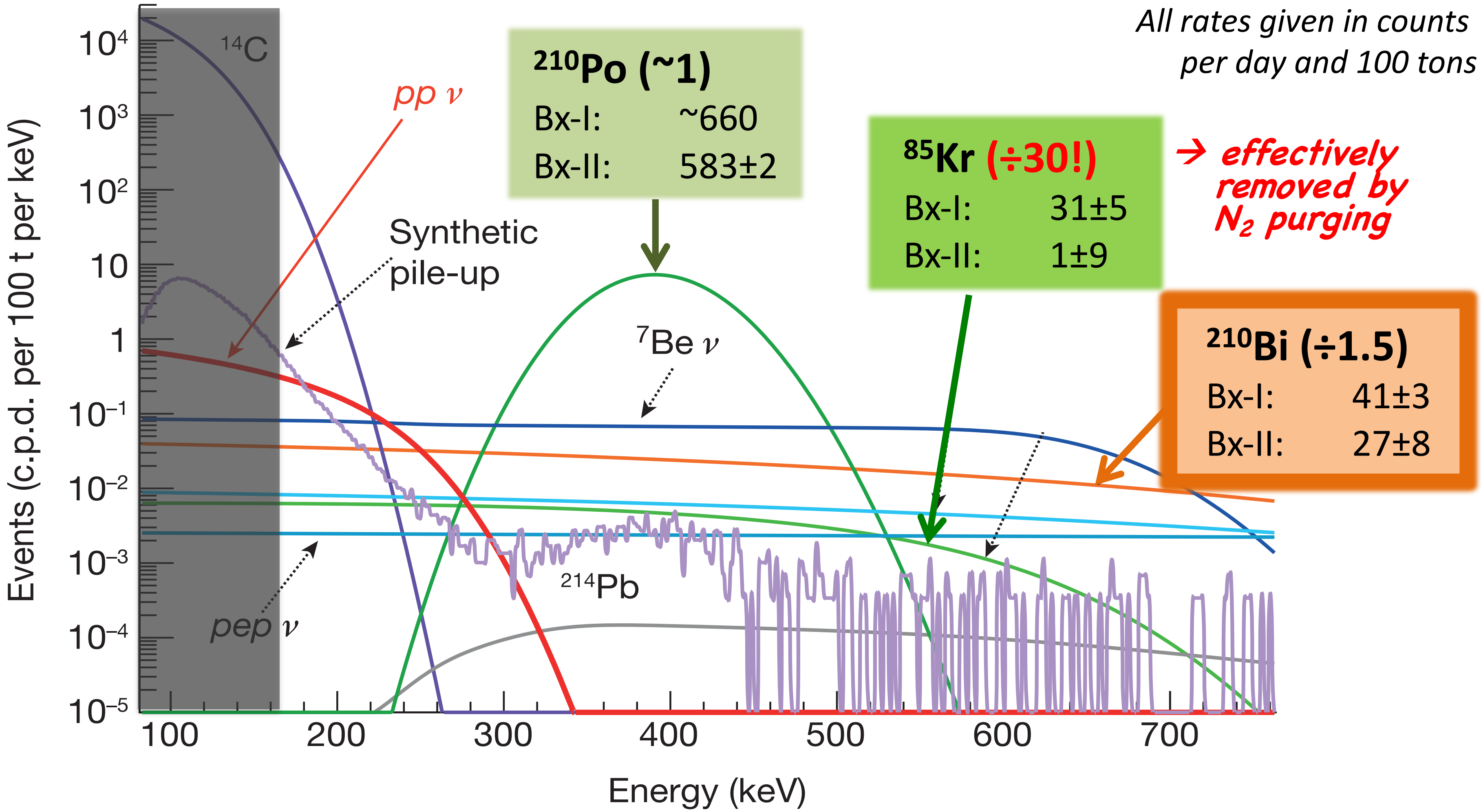
2) water extraction
washing LS with ultrapure water
→ removes ^{210}Pb
→ adds ^{210}Po?

1) nitrogen purging
bubbling LS with ultra-pure nitrogen
→ removes ^{85}Kr

Borexino radiopurity in Phase II (pp-ν)

JG|U

All rates given in counts per day and 100 tons



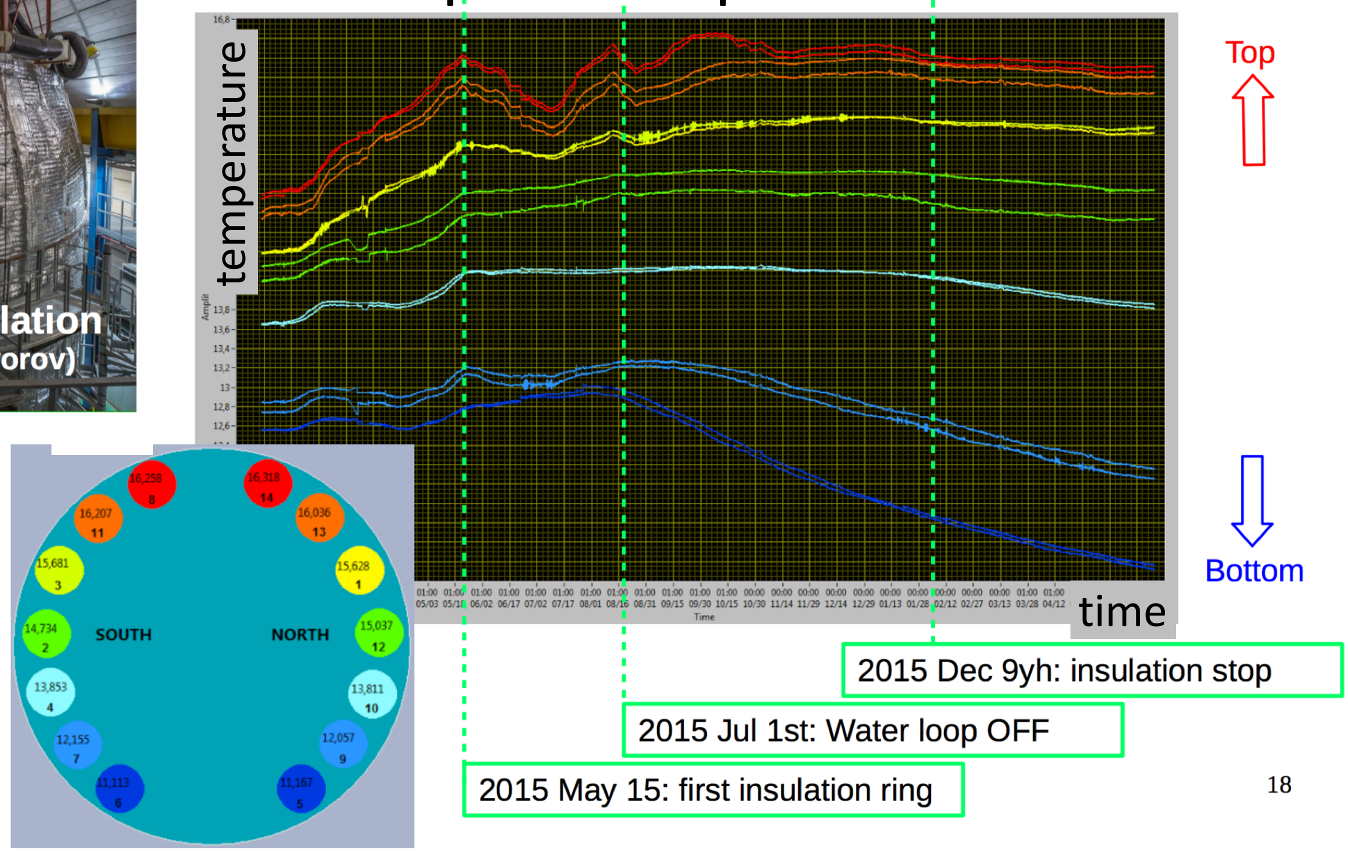
Natural radioactivity: ^{238}**U** Bx-I: $(5.3\pm0.5)\times10^{-18}$ g/g → **Bx-II: < 9.7×10^{-19} g/g**

(decay chains broken) ^{232}**Th** $(3.8\pm0.8)\times10^{-18}$ g/g **< 2.9×10^{-18} g/g**

New thermal insulation for Borexino

slide by N. Rossi

Time development of temperature sensors

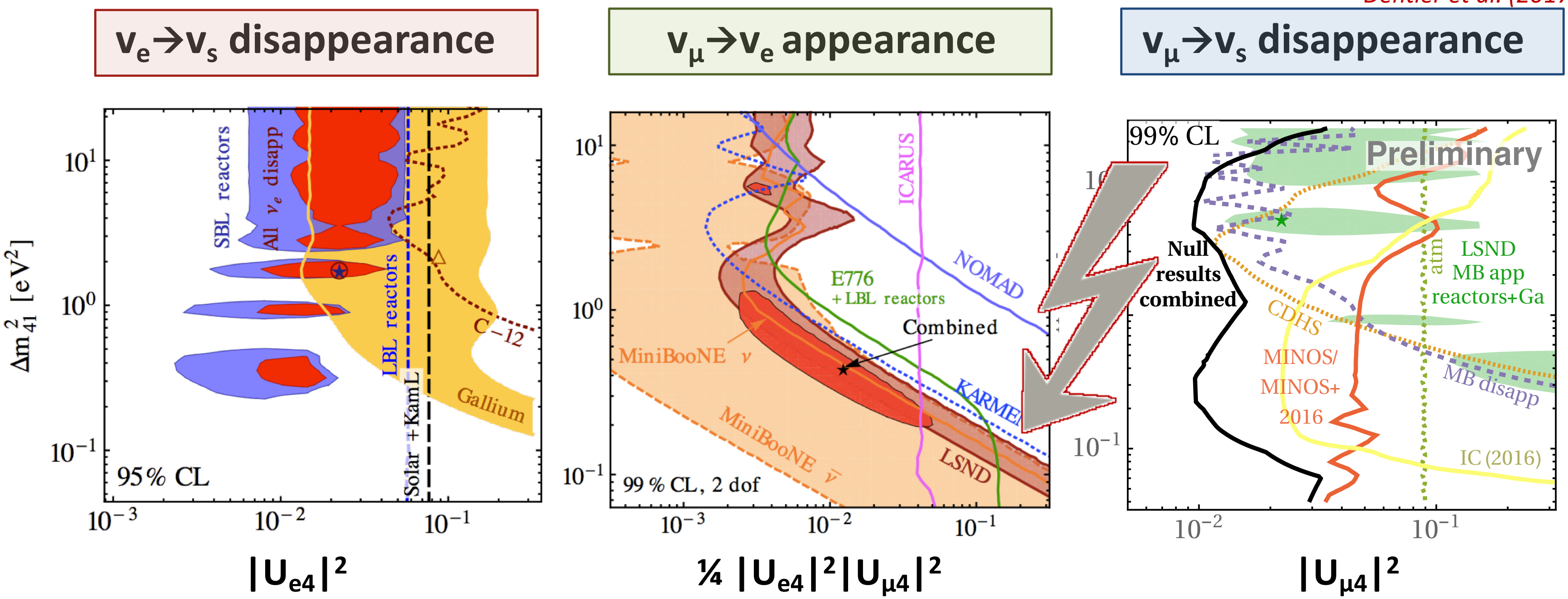


→ inverted temperature gradient established to stop convection of ^{210}Po

→ **indirect determination of ^{210}Bi decay rate** when secular equilibrium is reached

Conflict: No ν_μ disappearance!

Dentler et al. (2017)

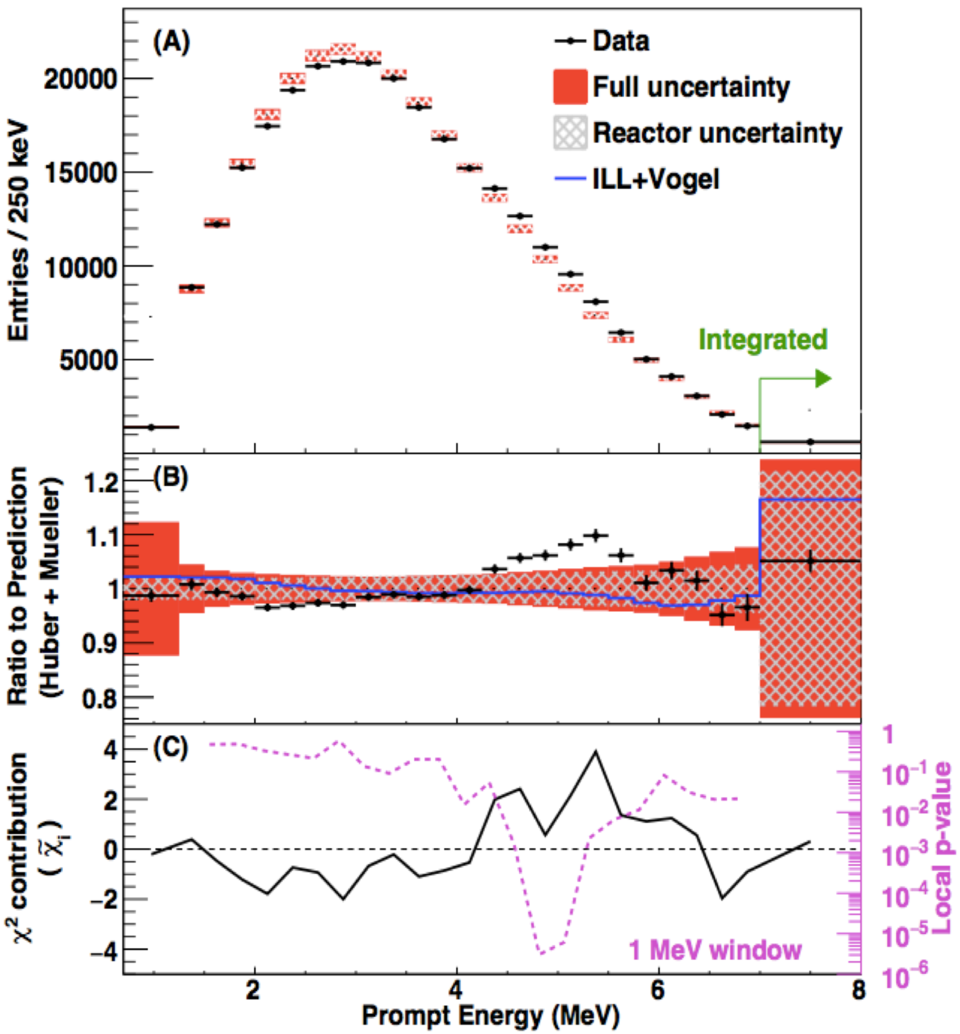


- however, an observation of $\nu_\mu \rightarrow \nu_s$ disappearance is lacking
- no contradiction to $\nu_e \rightarrow \nu_s$ disappearance anomalies,
- but conflict with LSND/MiniBooNE results on $\nu_\mu \rightarrow \nu_e$ appearance

for $\Delta m^2_{41} \approx 1\text{eV}^2$: $|U_{e4}|^2 = \sin^2\theta_{ee} \approx 0.04$, $|U_{\mu4}|^2 = \sin^2\theta_{\mu\mu} \leq 0.03$ $\Big\}$ $\sin^2\theta_{e\mu} \approx ¼\ |U_{e4}|^2|U_{\mu4}|^2 \leq 10^{-3}$

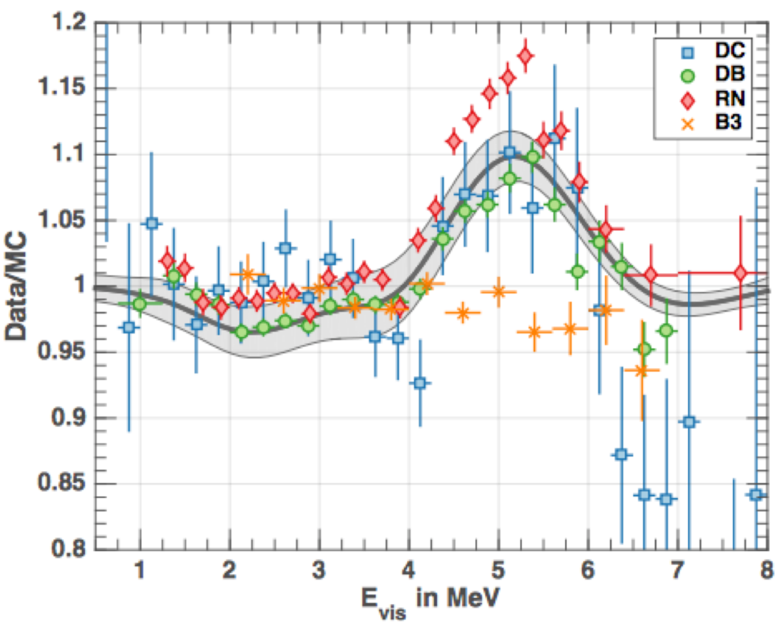
New doubts on understanding of sources 1/2

Daya Bay Near Detector spectrum



- Short-baseline θ_{13} experiments observe a deviation from spectral prediction: „5 MeV bump“
- unknown feature in reactor neutrino spectrum?
- detector calibration issue?

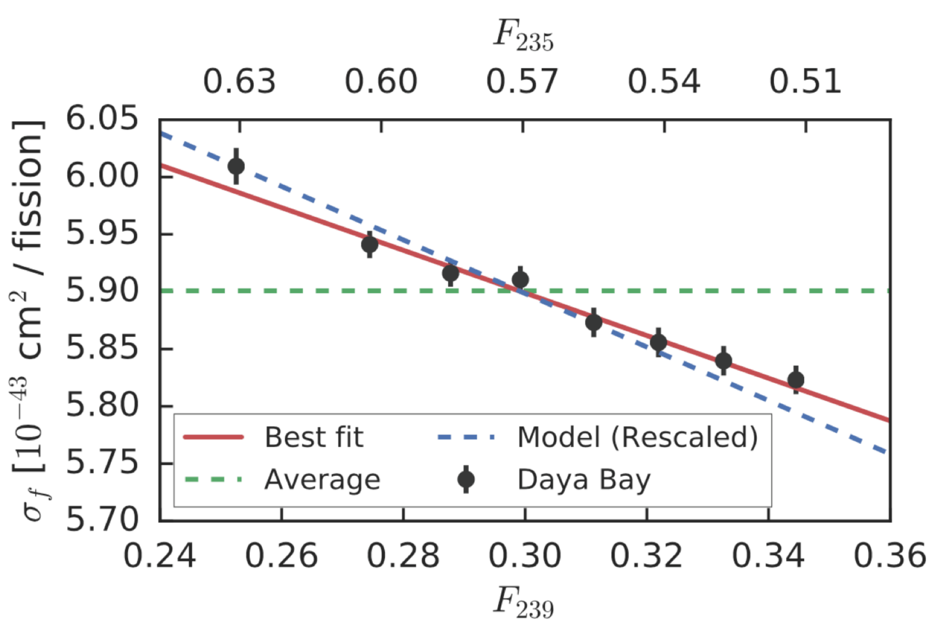
Comparison of experimental spectra

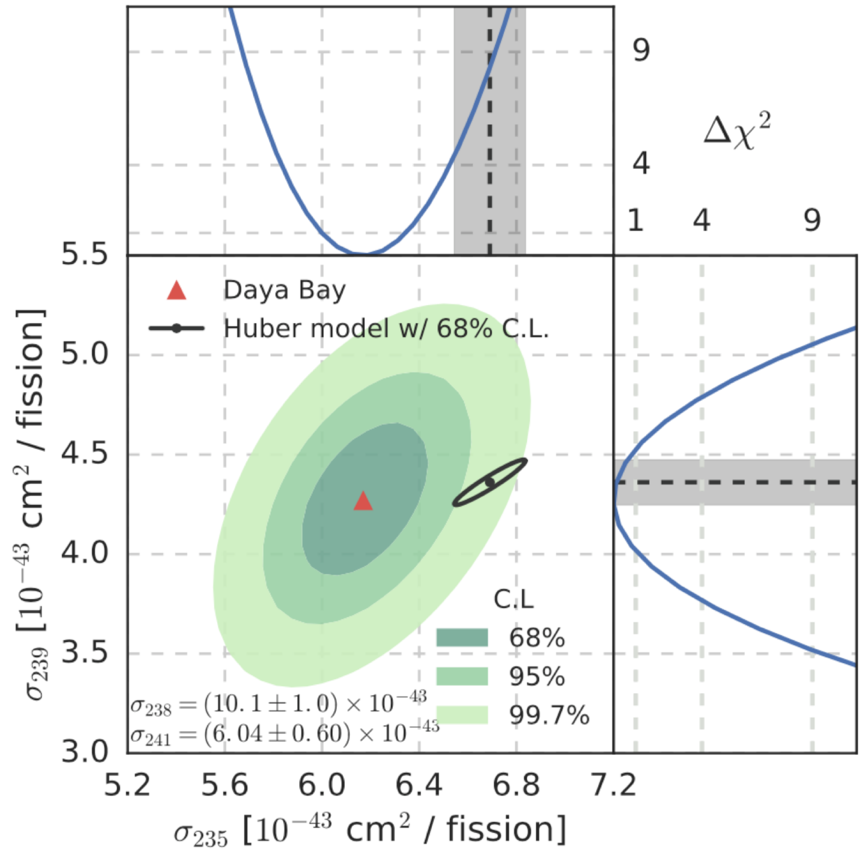


New doubts on understanding of sources 2/2

- **Daya Bay:** dependence of anti-neutrino reaction rates on reactor-burn up shows discrepancy for ^{235}U energy-integrated ν cross-section
- energy-resolved data is inconclusive

IBD rate dependence on core composition





Corresponding energy-integrated X-sections

Cosmological constraints on light steriles

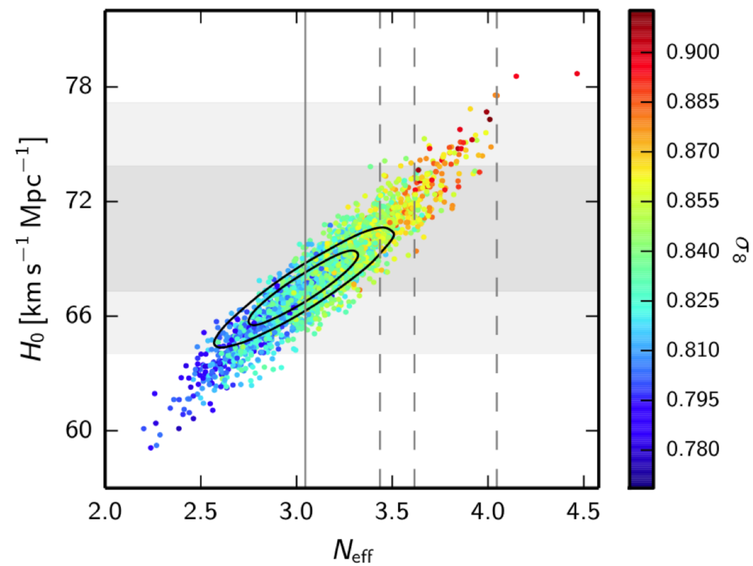
- Cosmological observations able to place stringent bounds on the **number** N_{eff} and **mass sum** Σm_ν of light (i.e. thermalizing) sterile neutrinos

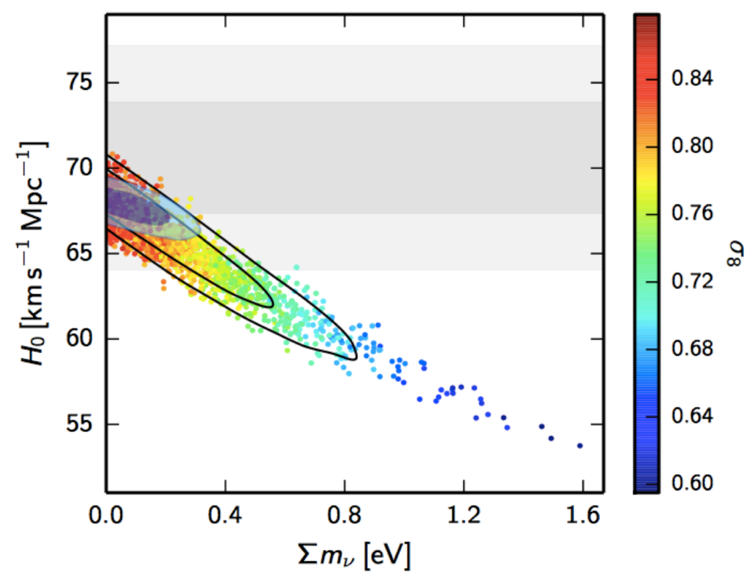
- Most important observables
  - Cosmic Microwave Background
  - Big Bang Nucleosynthesis
  - Large-scale structure

- Bounds from PLANCK (+BAO):
  - $N_{eff} = 2.99 \pm 0.20$
  - $\Sigma m_\nu < 0.49\ (0.17)$ eV (95% C.L.)

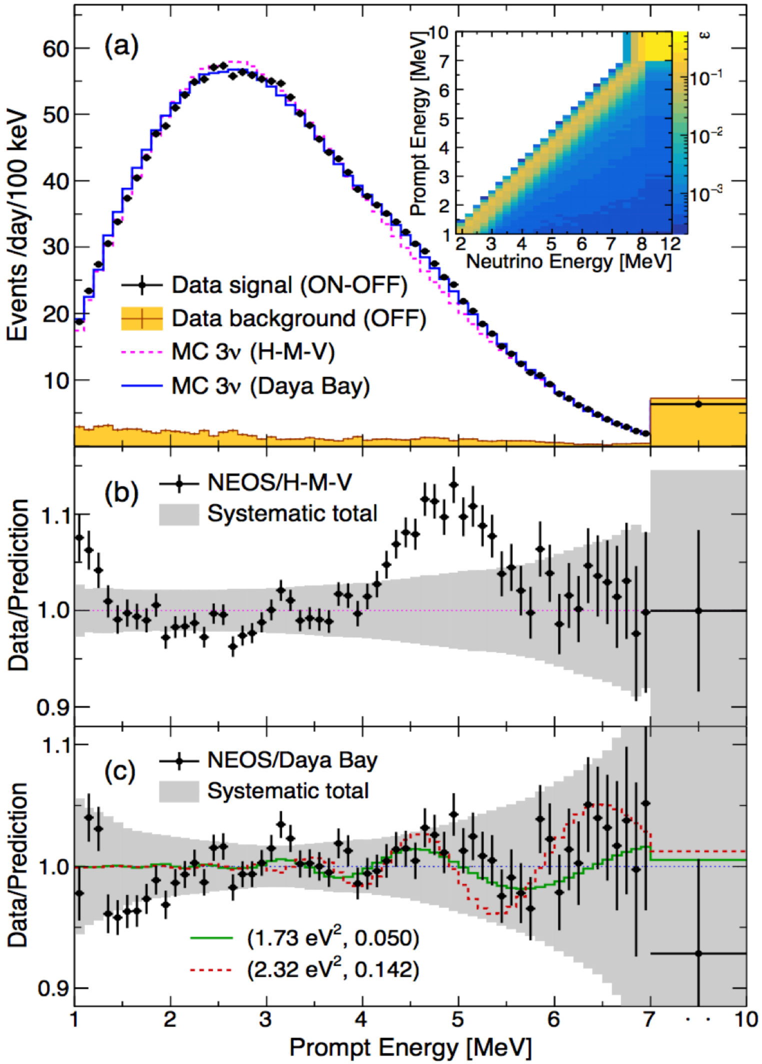
- These limits can be avoided by introducing additional physics, e.g. sterile neutrino self-interactions
  Dasgupta, Kopp [arXiv:1310.6337]

→ still, accommodating sterile ν's needs tuning ...



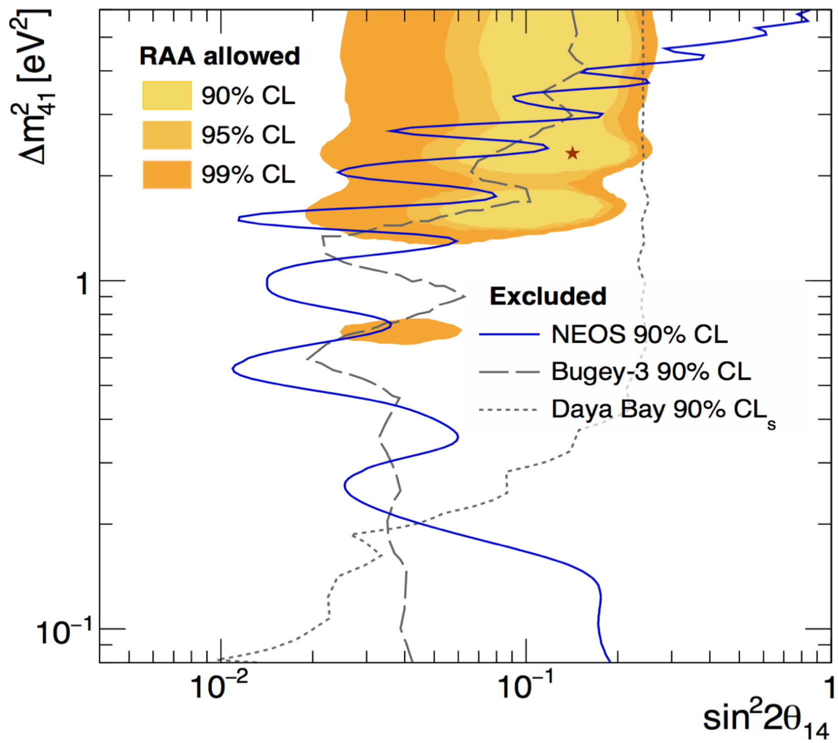


Recent NEOS result



- Experiment at RENO site (South Korea)
- Gd+LS detector (1t) at 28m from reactor
- Shape comparison to Daya Bay spectrum

→ First results in late 2016:
no signs of oscillations found



arXiv:1610.05134

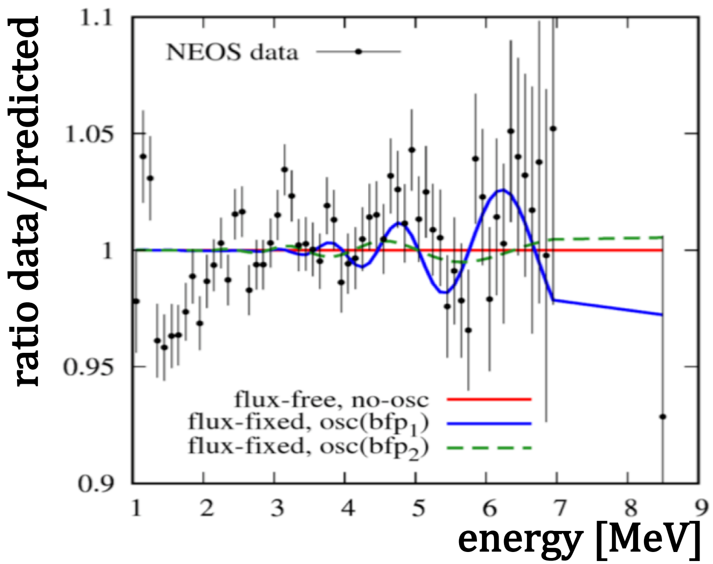
→ **Note:** DANSS (Kalinin NPP) has published very similar (preliminary) results this spring…

Current status of $\nu_e \rightarrow \nu_s$ oscillations

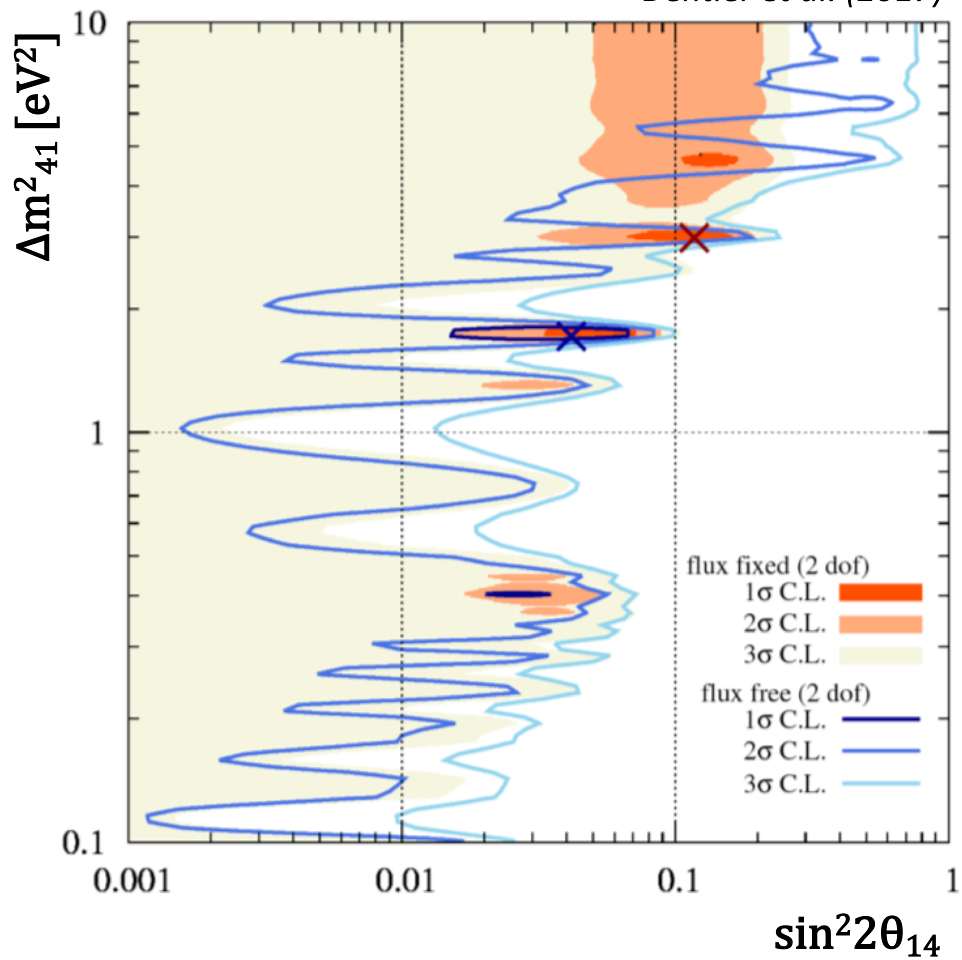
Recent global analysis by Gentler *et al.* (2017) investigates two scenarios:

- fixing reactor neutrino fluxes to model predictions
  → "evidence" for ν_s increases to 2.9σ
- letting reactor fluxes float freely
  → hint weakens somewhat to 1.9σ

<u>Note</u>: $\nu_e \rightarrow \nu_s$ oscillations still favored as they are compatible to spectral data



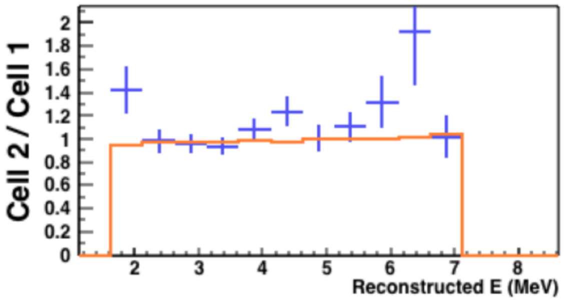
Dentler et al. (2017)

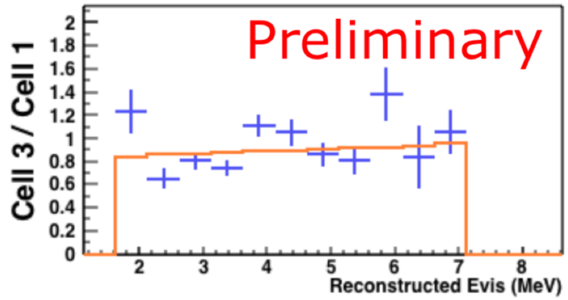


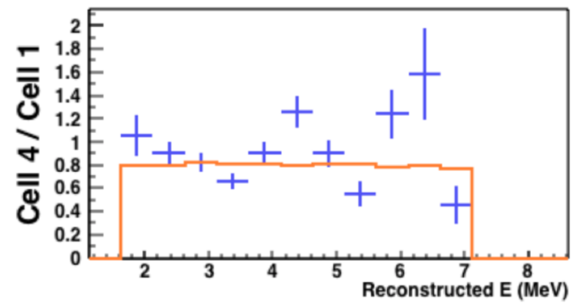
STEREO: First experimental results

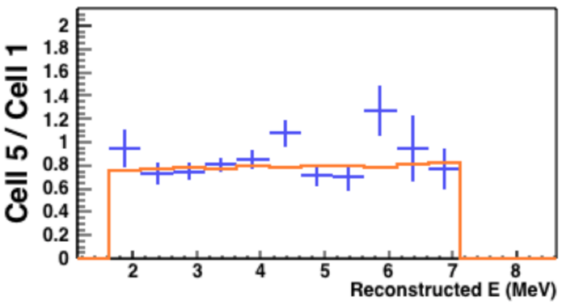
D. Lhullier, Moriond EW 18

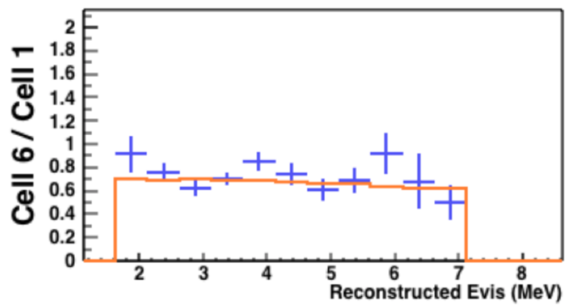
→ test of null-oscillation hypothesis





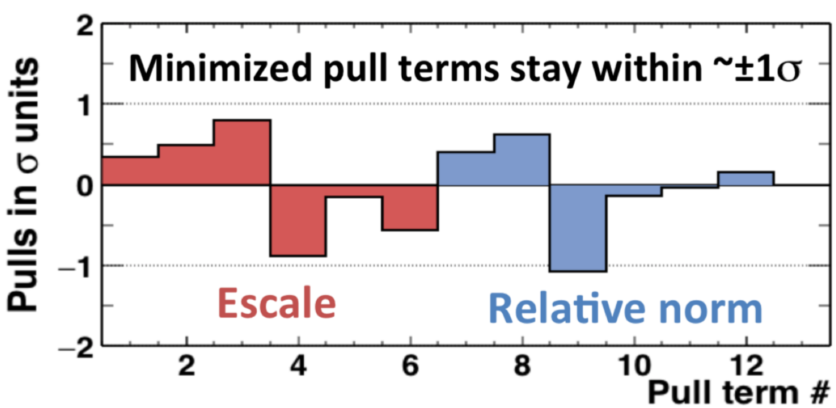




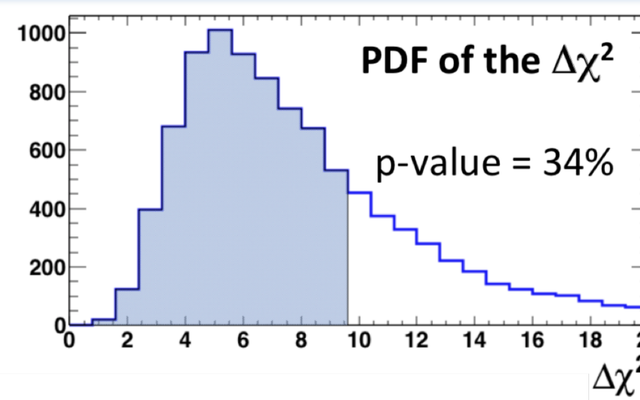


+ Measured ratios

- Non oscillated predictions

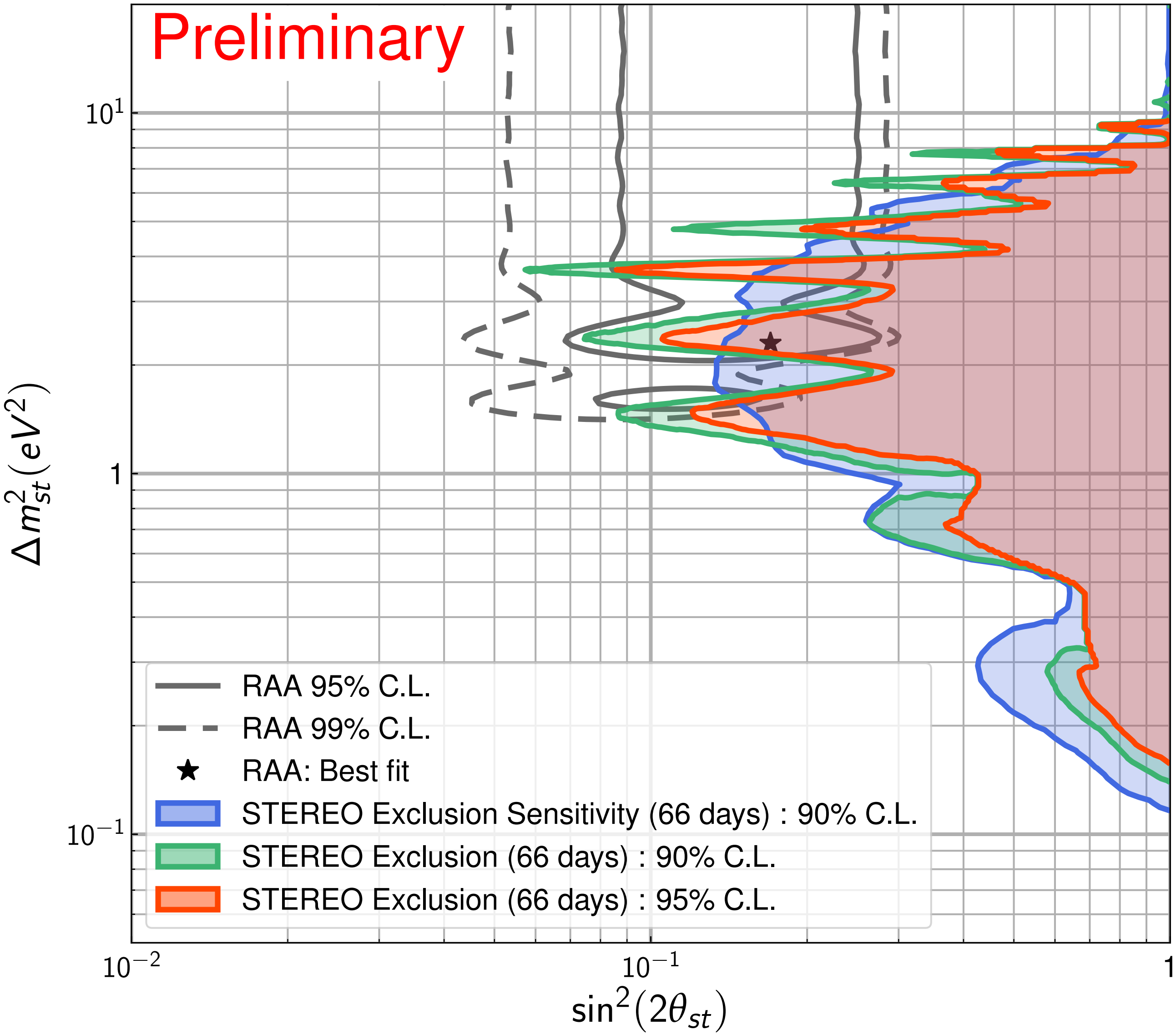


→ no rejection of the null hypothesis



STEREO: Exlusion plot $\nu_e \rightarrow \nu_s$ oscillations

D. Lhullier, Moriond EW 18



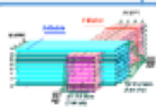
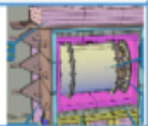
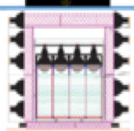
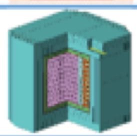
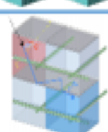
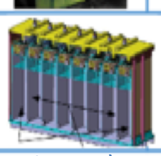
→ exclusion range reaching into the parameter space preferred by the anomalies

→ in agreement with NEOS/DANSS results

→ further results can be expected in 2018 ...

T92.6+7

World-wide efforts at reactors

Experiment		Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability	
DANSS (Russia)		3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only	**first data 2017**
NEOS (South Korea)		2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only	**first data 2017**
nuLat (USA)		40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD	
Neutrino4 (Russia)		100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only	**prototype 2017**
PROSPECT (USA)		85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD	**starting 2018**
SoLid (UK Fr Bel US)		72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD	**started 2017**
Chandler (USA)		72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD	
Stereo (France)		57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD	**first data 2018**

N. Bowden (Neutrino16)