New Puzzles in Low Energy Neutrino Astronomy

LEXI Cluster Meeting
Hamburg, 10 Oct 2011

Michael Wurm
FG Neutrinophysik
Universität Hamburg

photo: BOREXINO calibration

81 years of neutrino physics

1930

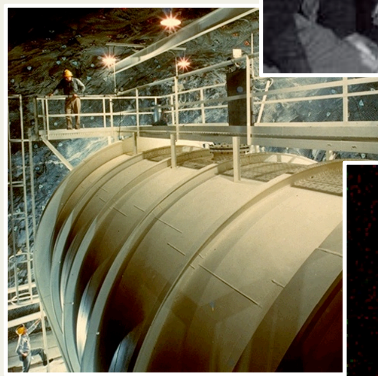
Postulate of the neutrino

Theory of Majorana neutrinos

1940

1950

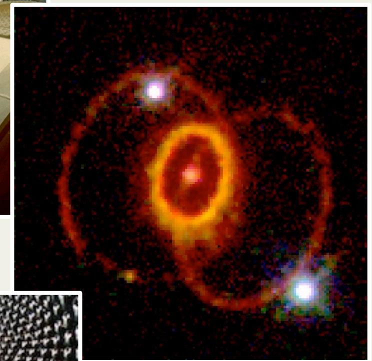
First detection of the neutrino



1960

Distinction of muon from electron neutrinos

Distinction of antineutrinos from neutrinos



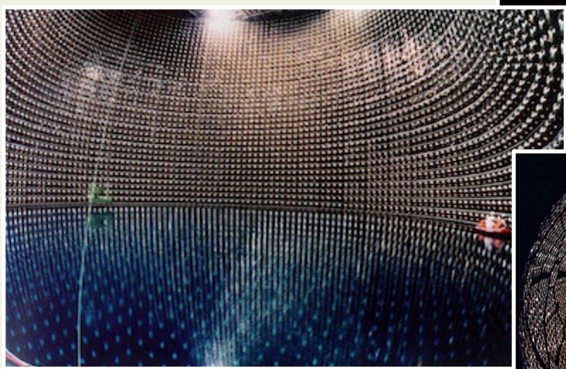
1970

First detection of solar neutrinos

and the **solar neutrino deficit**

1980

First detection of **Supernova neutrinos**

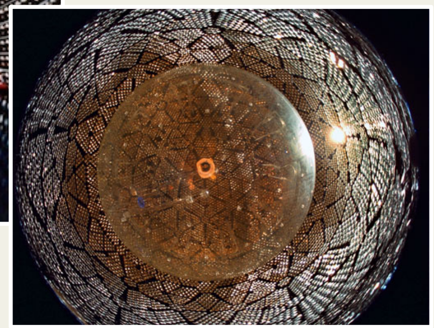


1990

2000

First detection of tau neutrinos

Discovery of neutrino oscillations



2010

Top 10 of wanted neutrino properties 2011

θ_{13}	*What is the size of the last unknown neutrino mixing angle?*
δ_{CP}	*Is there CP-violation in the leptonic sector?*
NH IH	*Is the neutrino mass hierarchy normal or inverted?*
m_ν	*What is the absolute neutrino mass scale?*
$\nu=\bar{\nu}$	*Are neutrinos their own antiparticles?*
ν_s	*Are there sterile neutrinos?*
μ_ν	*Has the neutrino a non-vanishing magnetic moment?*
NSI	*Are there non-standard neutrino interactions with matter?*
$\nu\nu$ osc	*Are there collective neutrino oscillations at large neutrino densities?*
$v_\nu > c$	*Are neutrinos faster than light?*

Order and contents depend of course on the viewer

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PMNS neutrino mixing matrix

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

$$\text{mixing angles} : c_{ij} = \cos\theta_{ij}, \; s_{ij} = \sin\theta_{ij}$$

$$\text{CP violating phase} : \delta$$

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flavor eigenstates — *atmospheric mixing* — *reactor mixing & CP violation* — *solar mixing* — *mass eigenstates*

atmospheric mixing: $\theta_{23} \approx 45°$

reactor mixing & CP violation: $\theta_{13} < 14°$, $\delta_{CP} = ?$

solar mixing: $\theta_{12} \approx 33°$

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flavor eigenstates	atmospheric mixing	reactor mixing & CP violation	solar mixing	mass eigenstates
	$\theta_{23}\approx 45°$	$\theta_{13}<14°$, $\delta_{CP}=?$	$\theta_{12}\approx 33°$	

Two alternatives for measuring θ_{13}:

- ***Disappearance of reactor neutrinos***

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13})\sin^2(\Delta_{13})$$

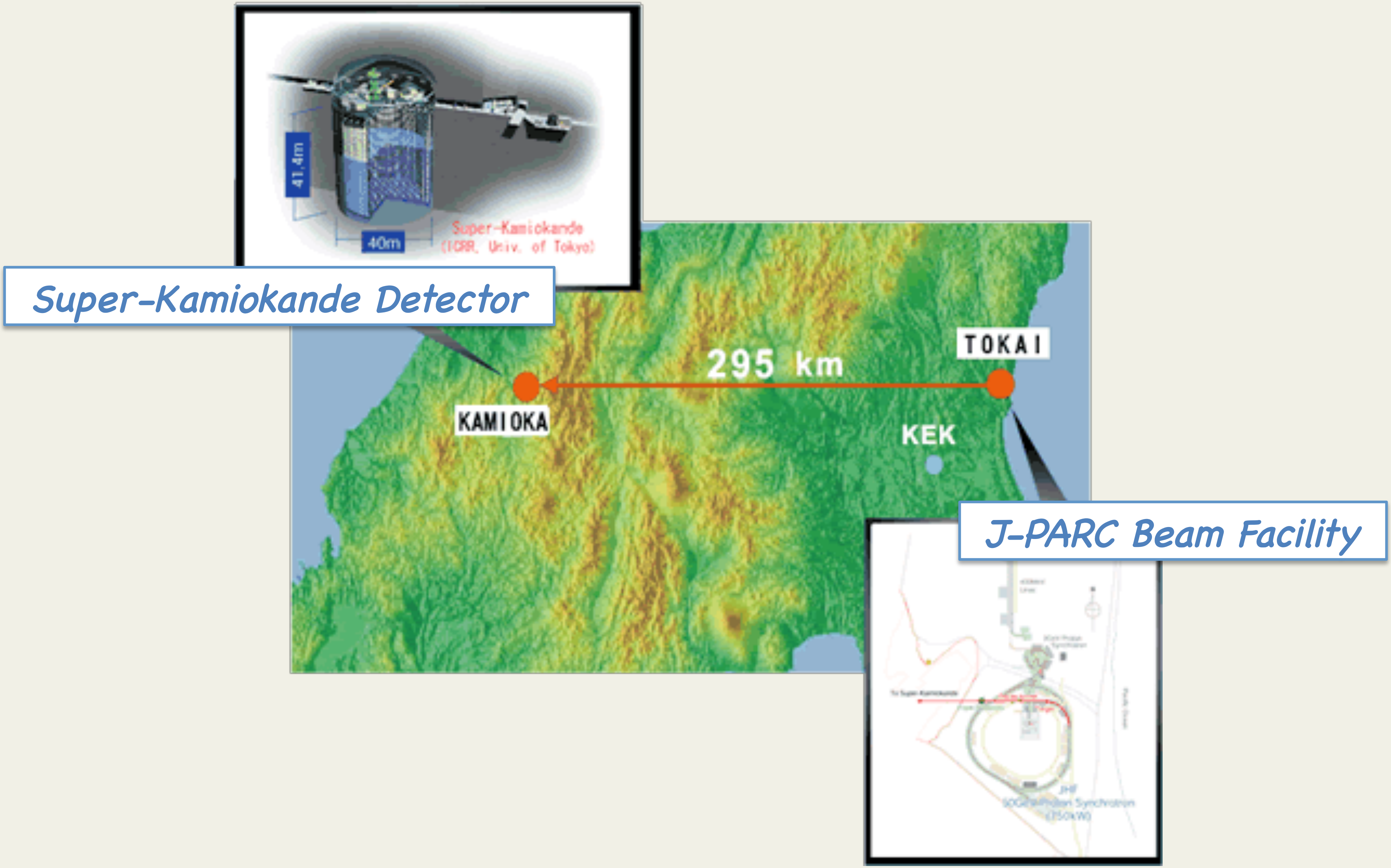
- ***Appearance of beam neutrinos***

$$P(\nu_\mu \to \nu_e) \approx \cos^2(\theta_{23})\sin^2(2\theta_{13})\sin^2(\Delta_{13}) + \sin(2\theta_{12})\sin(2\theta_{13})\sin(\Delta_{13})\cos(\delta - \Delta_{13})$$

$$\Delta_{13} = \frac{\Delta m_{13} L}{4E}$$

Hunting θ_{13}

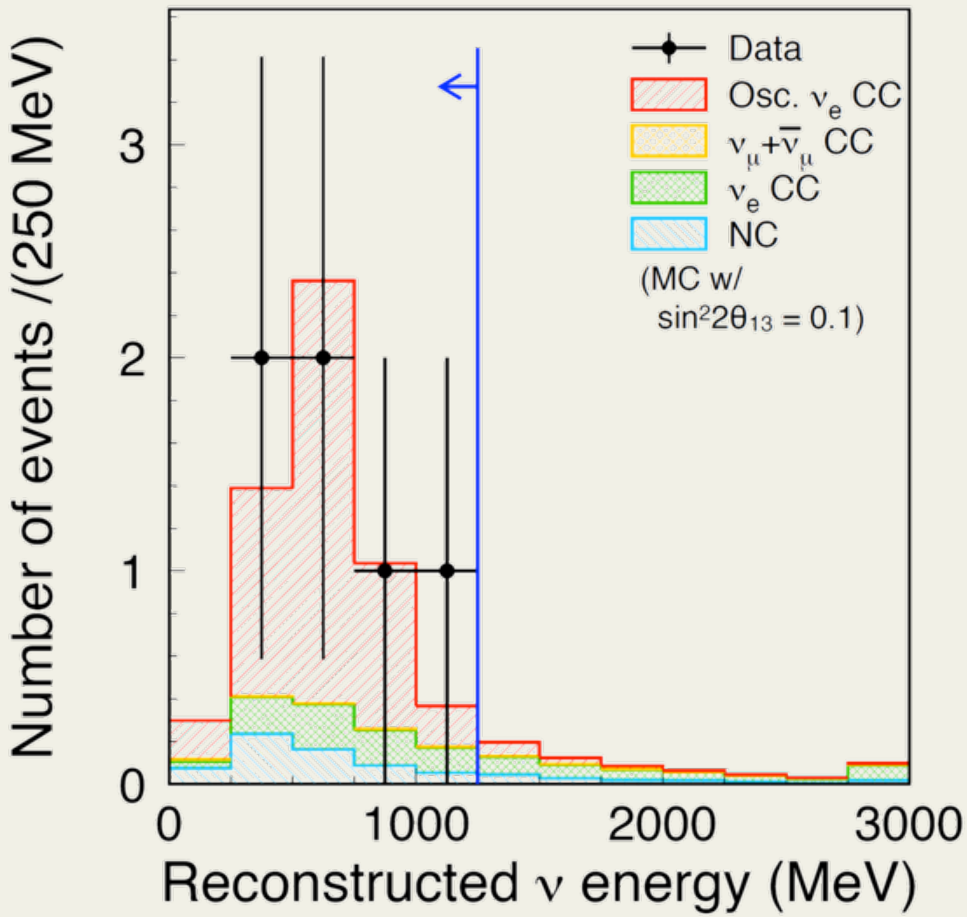
Tokai 2 Kamioka Beam Experiment



First T2K result – ν_e appearance

T2K, arXiv:1106.2822

ν_e-like events in Super-Kamiokande



1 expected, 6 events found!
Significance of excess: 2.5σ

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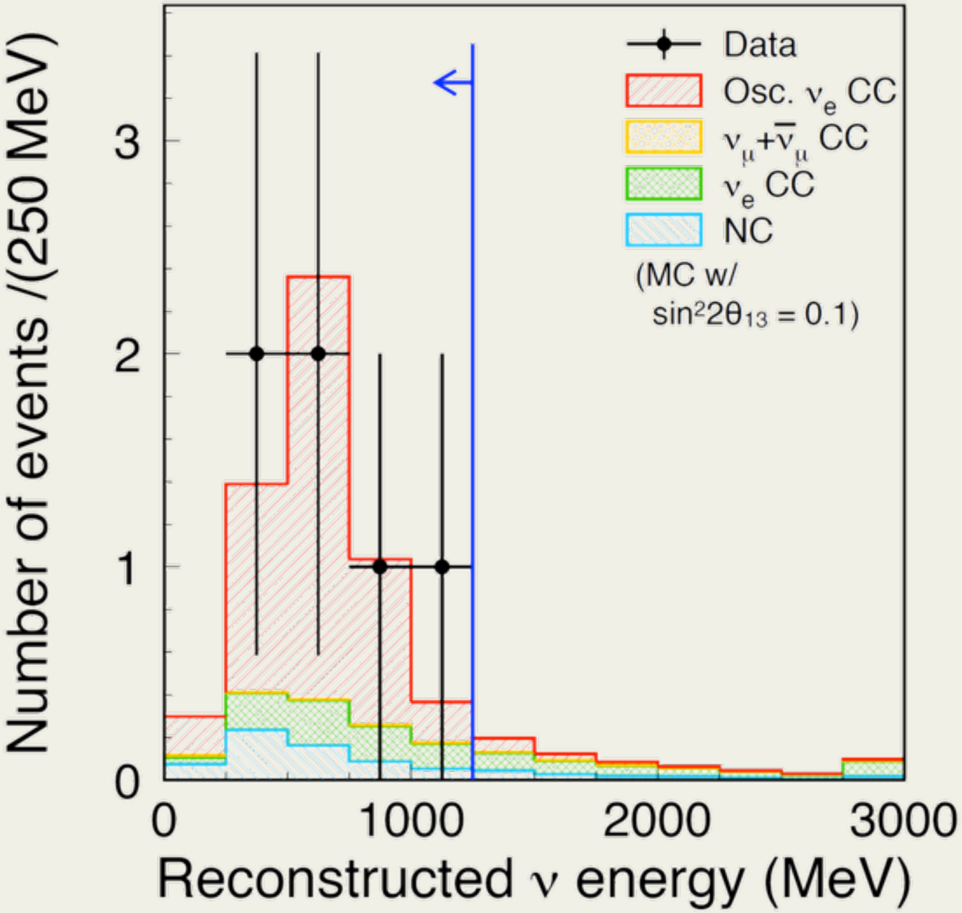

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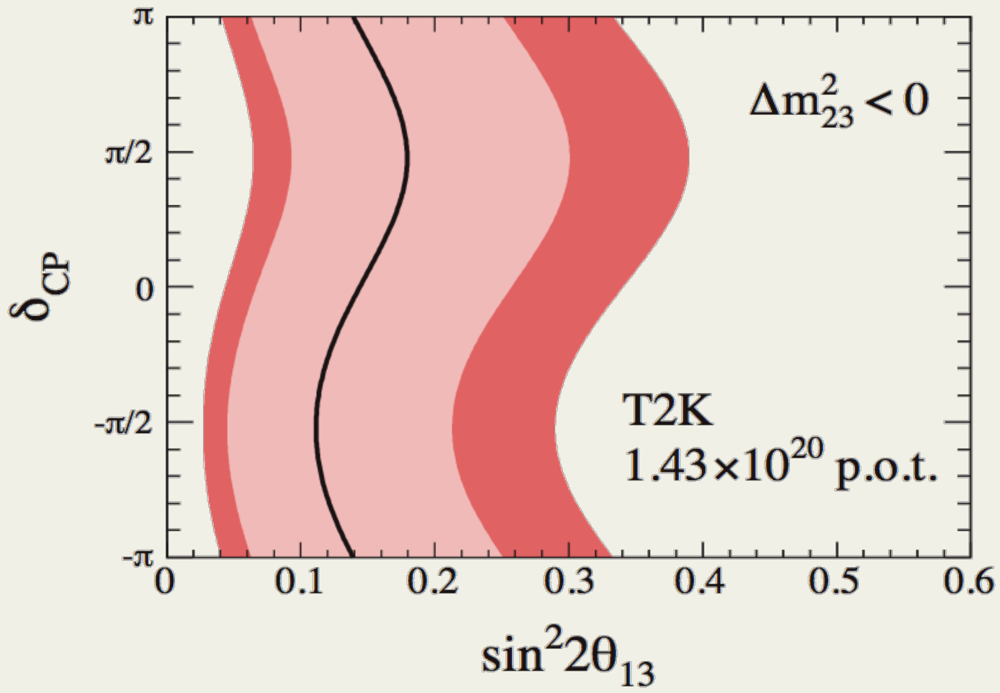
Allowed range for θ_{13}

For δ_{CP}=0, normal hierarchy:

$0.03 < \sin^2 2\theta_{13} < 0.28$ (90% C.L.)



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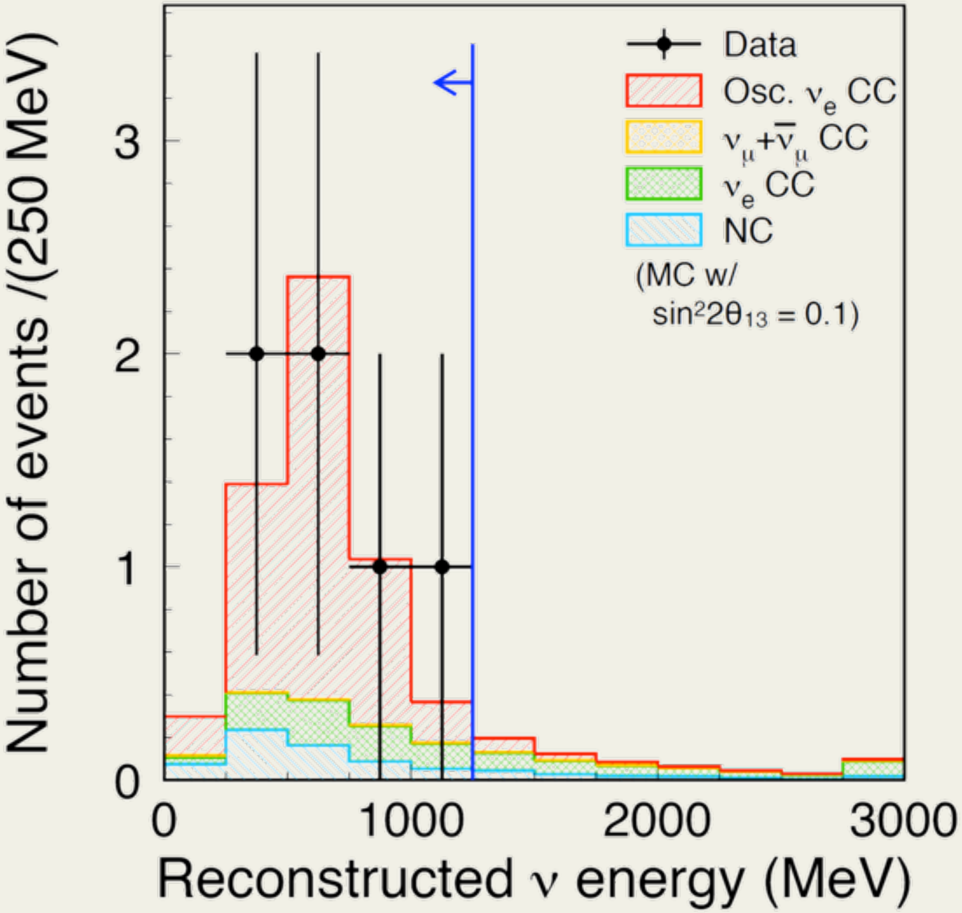

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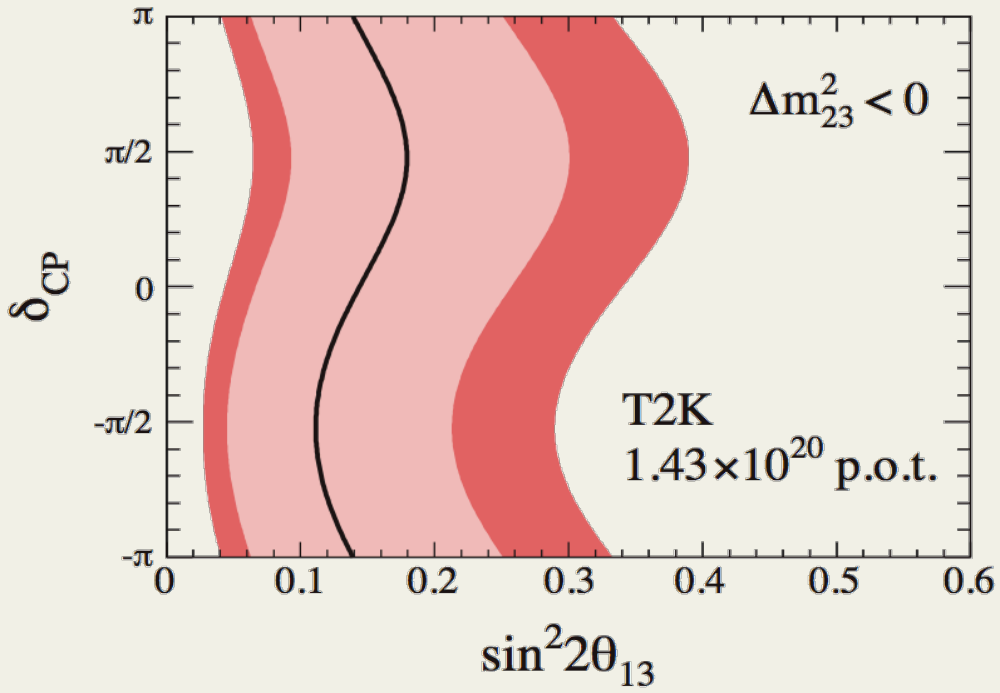


From global analysis

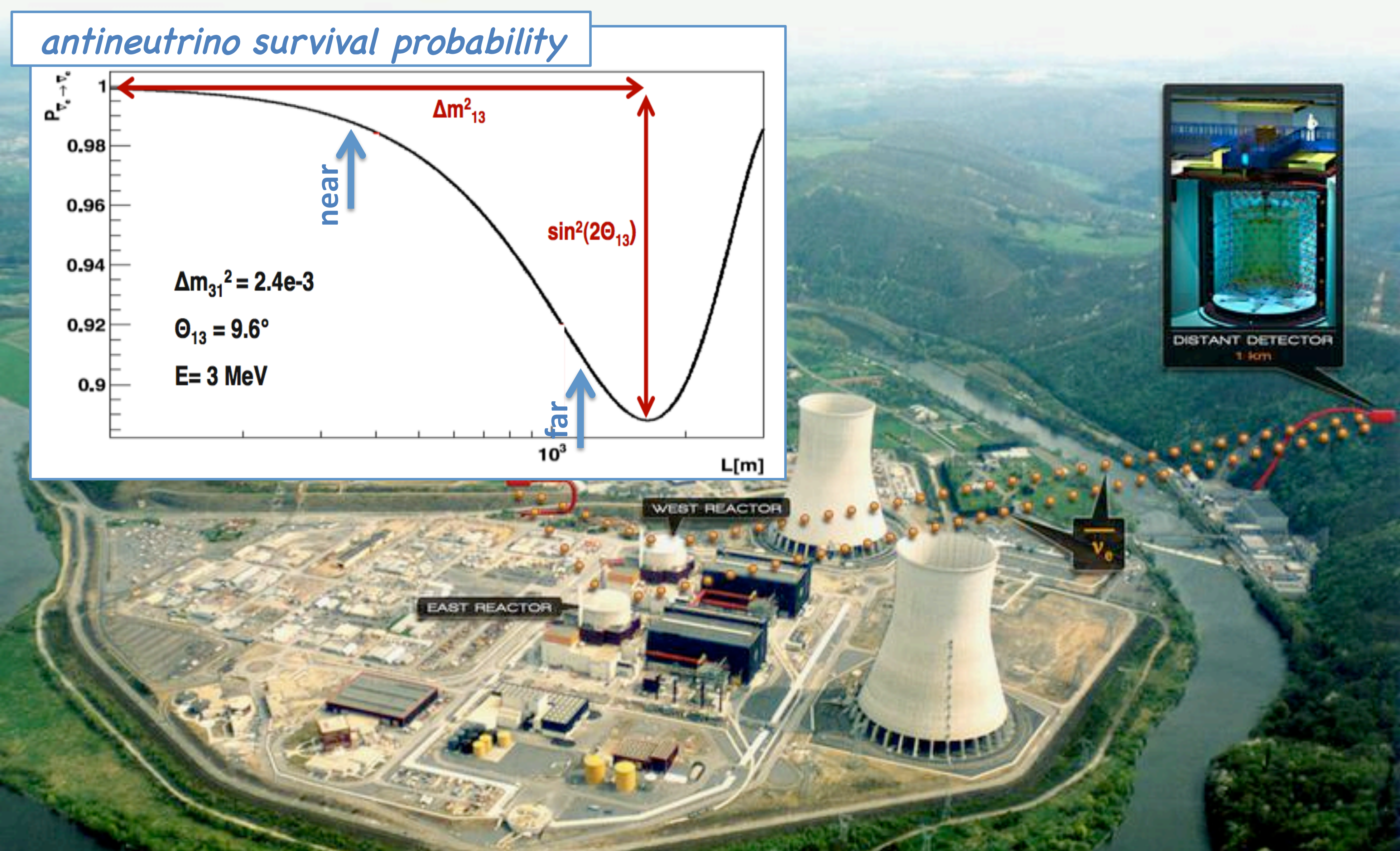
including MINOS, reactor & solar data

$\sin^2 2\theta_{13} = 0.080 \pm 0.027$ (1σ)

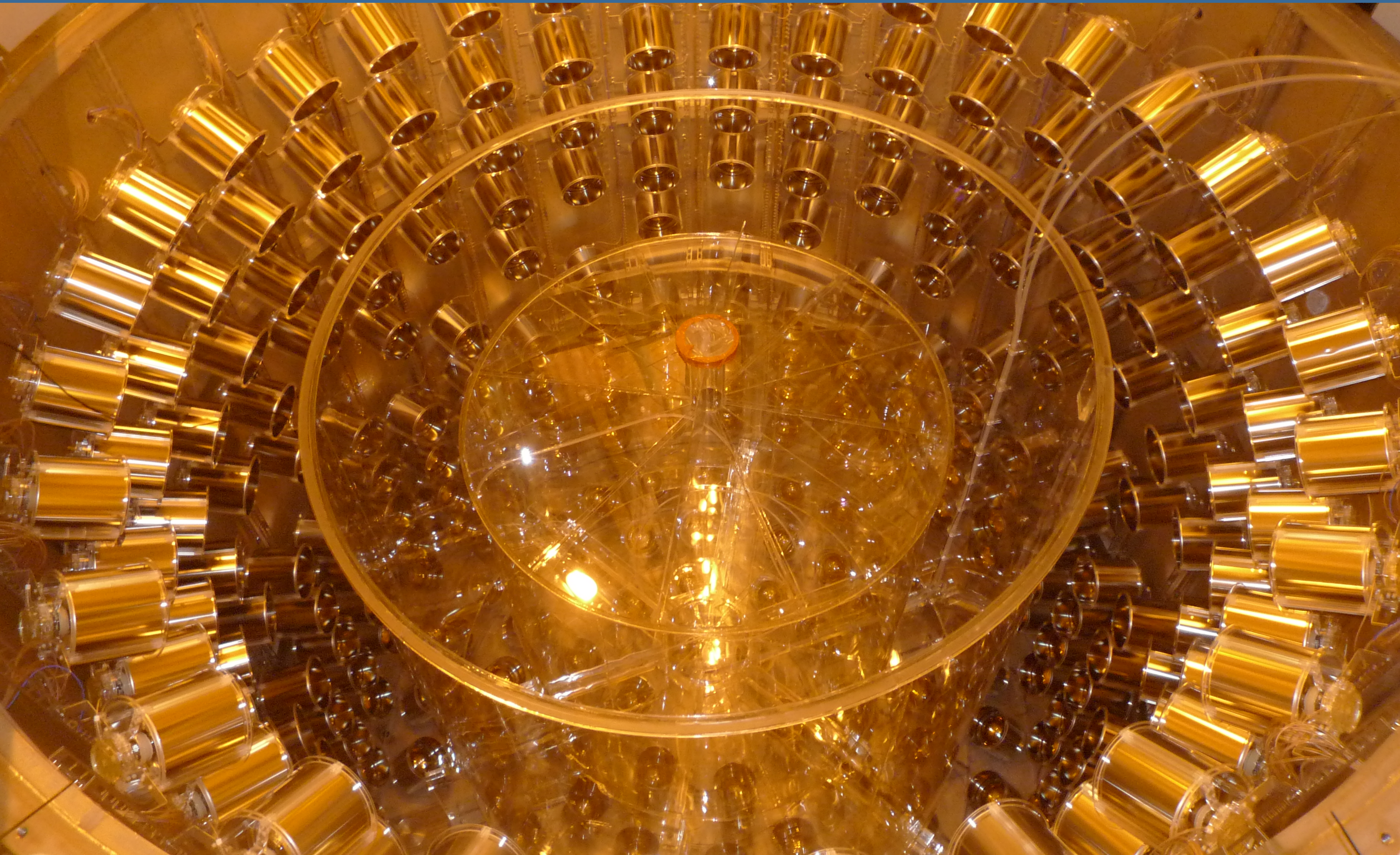
Fogli et al., arXiv:1106.6028

The Double-Chooz Experiment

The Double-Chooz Experiment



Double-Chooz Far Detector



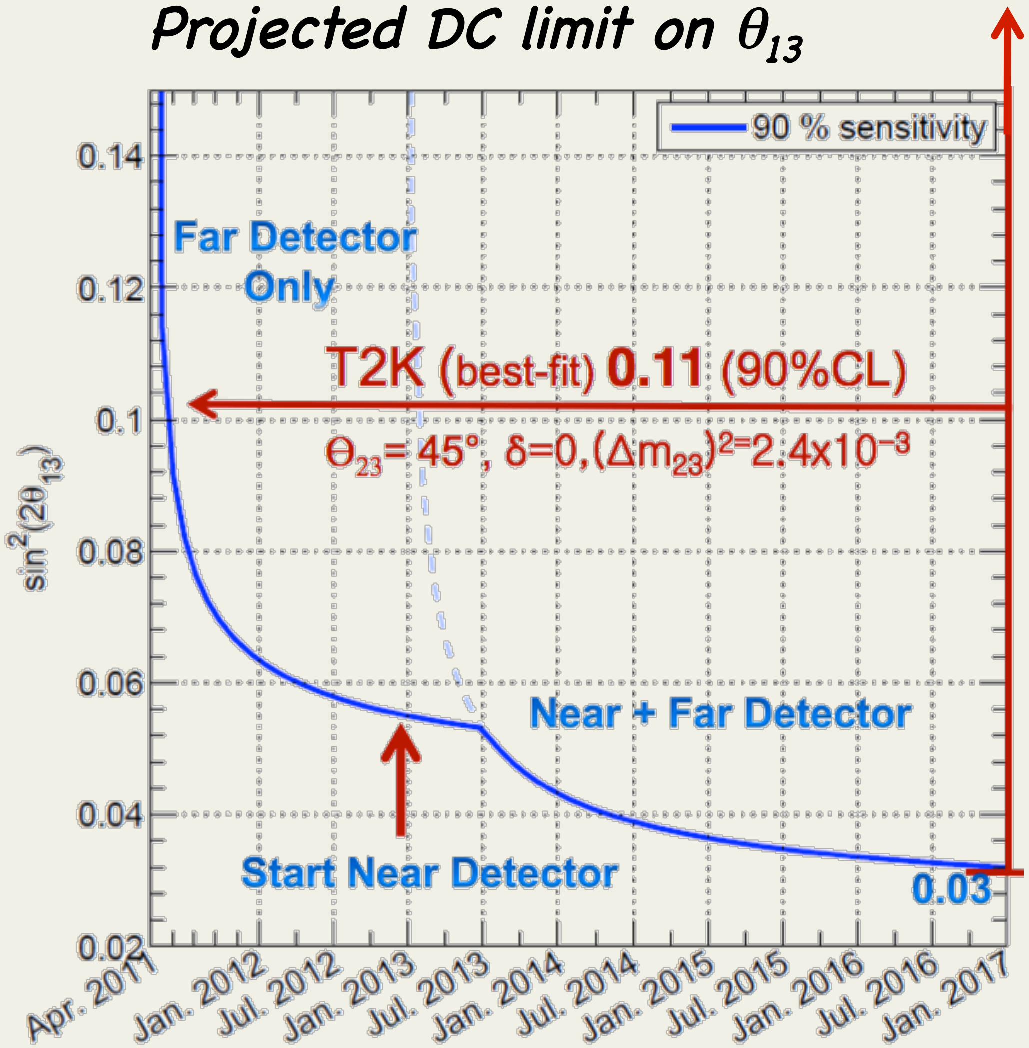
Prospects of Double-Chooz

- ***Far Detector***
  - completed and filled in 2010
  - data taking started in April 2011
  - more than 4000 events collected

→ **sufficient to test old CHOOZ limit and the T2K best-fit value**

- ***Near Detector***
  - lab construction started
  - start of data taking foreseen for January 2013

Projected DC limit on θ_{13}



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Reactor antineutrino anomaly

G. Mention et al., arXiv:1101.2755

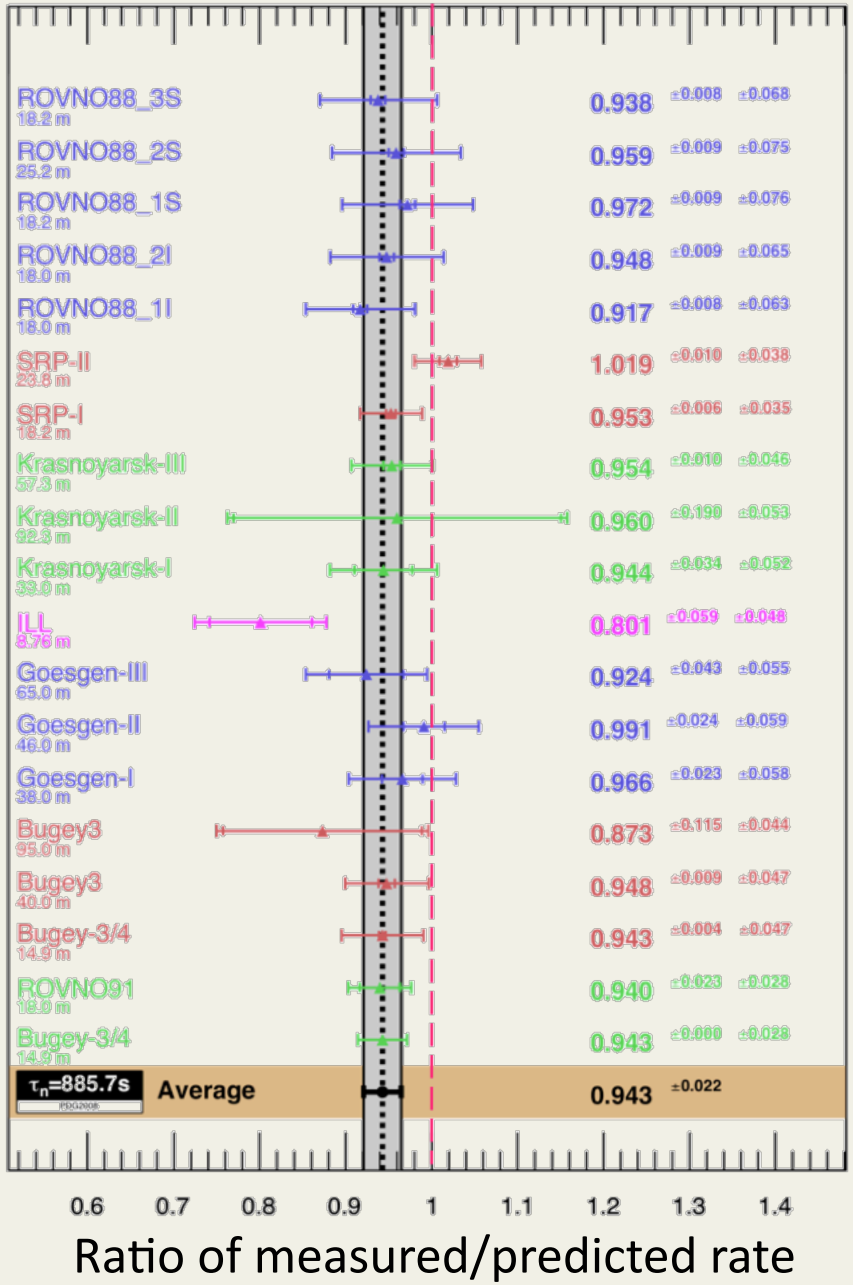
Re-Evaluation of the reactor $\bar{\nu}_e$ spectrum:

- ILL integral β-spectra of fission products from ^{235}U, ^{239}Pu, ^{241}Pu + ^{238}U predictions
- *new:* full available data on fission yields for spectral inversion to ν spectra
- *updated:* weak magnetism corrections and neutron life time (IBD cross section)

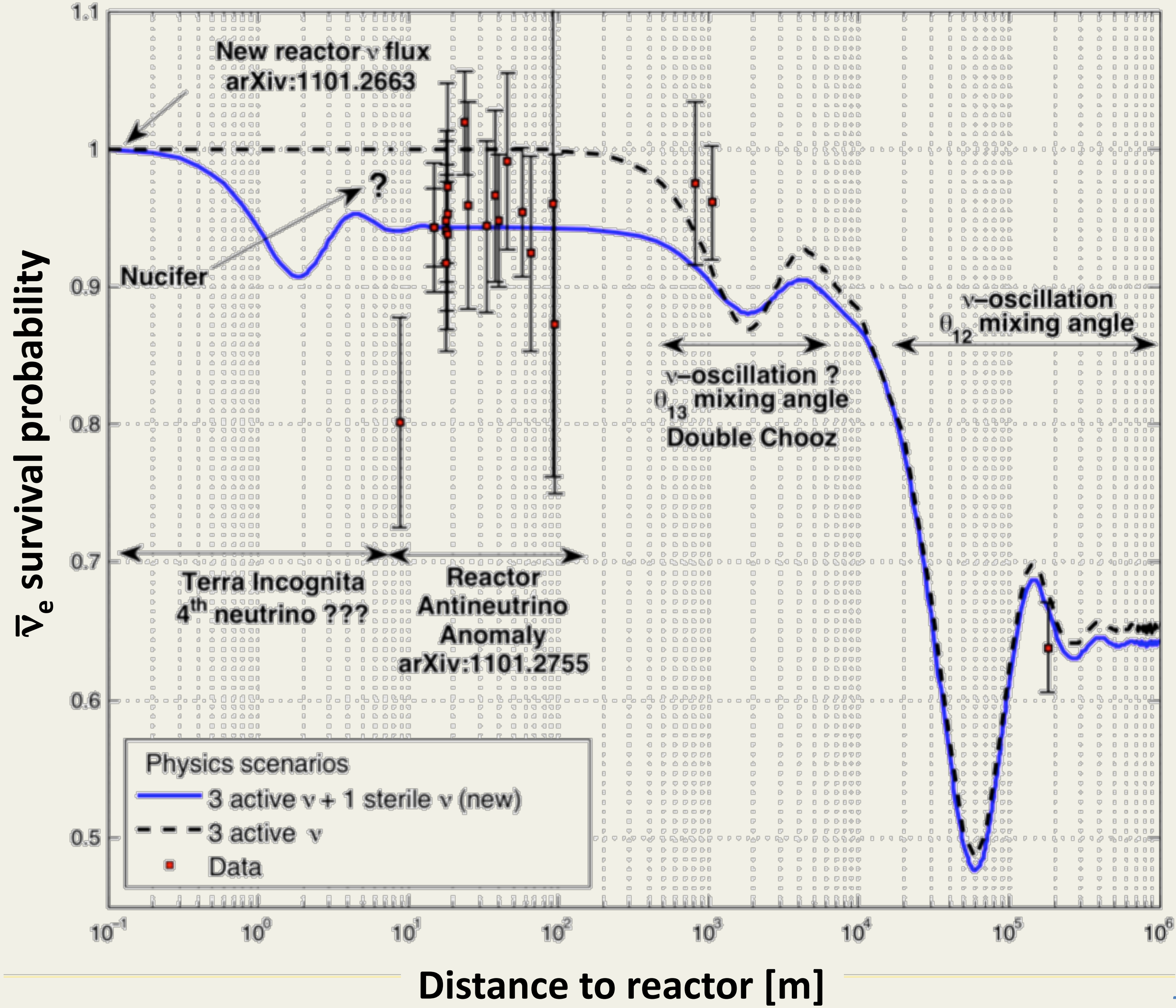
➔ **Predicted experimental rates effectively increase by 3.5%**

➔ **now 6% deficit in rate for all reactor neutrino experiments @ 2.2σ**

➔ ***Possible explanation: a 4^th^ sterile neutrino!***

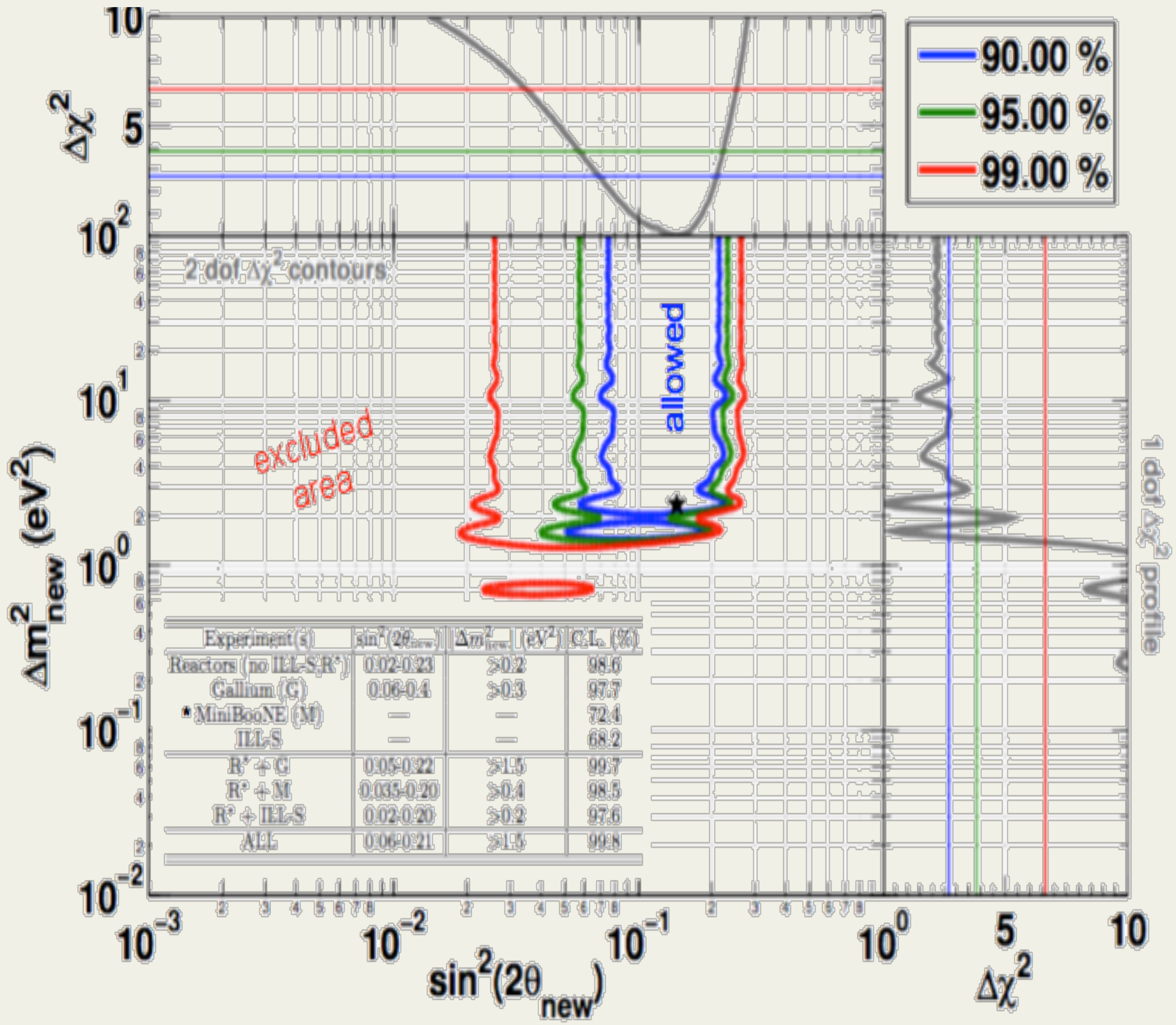


Sterile neutrino oscillations



Th. Lasserre, AAP 2011

Sterile neutrino oscillations parameters



There are further experimental hints

- rate deficit in solar ν Gallium experiments
- MiniBooNE anomaly

Combined best fit for (3+1) scenario

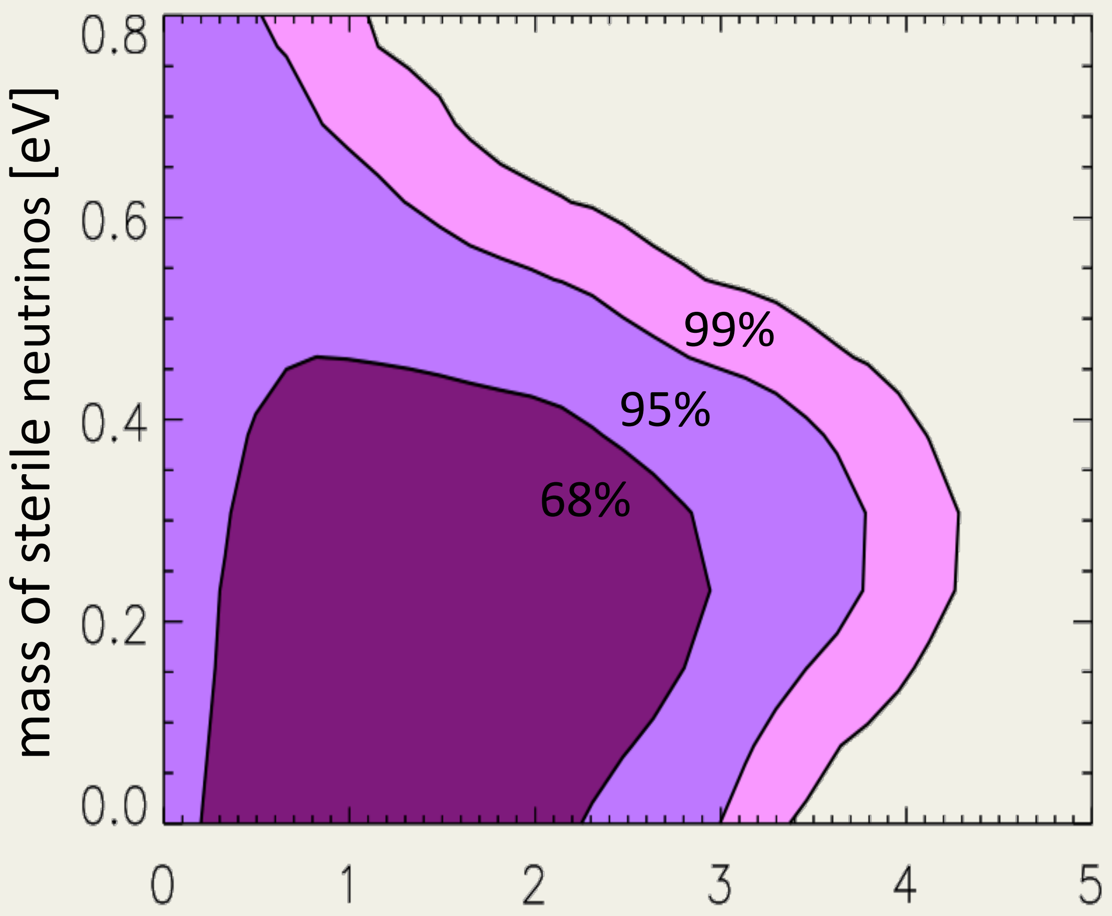
- $\sin^2 2\theta_{14} = 0.16$
- $\Delta m_{14}^2 = 2\ \mathrm{eV}^2$

no oscillation scenario disfavored at 99.8%

Th. Lasserre, AAP 2011

Cosmological bounds on extra-neutrinos

CMB expectation



Hints for sterile neutrinos

- Cosmic Microwave Background (WMAP data): additional degrees of freedom from radiation
- Big Bang Nucleosynthesis: dependence of primordial ^{4}He yield on extraradiation

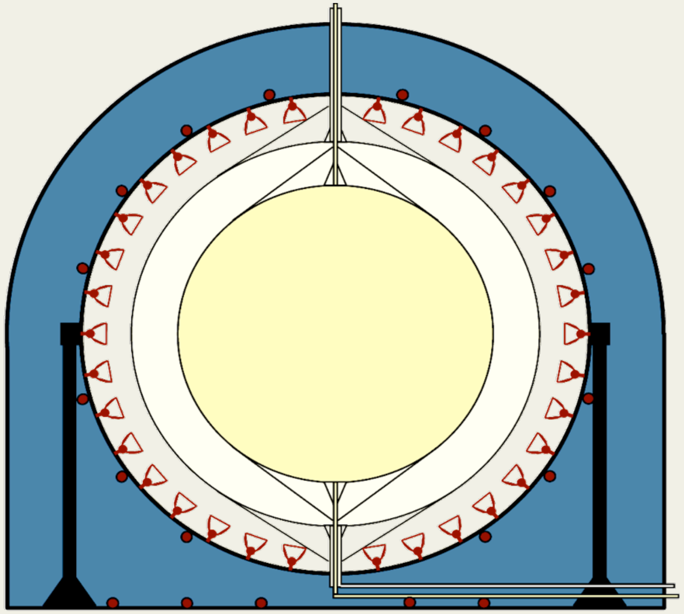
From Cosmology:

- 1-2 sterile neutrinos favored
- $\Delta m_{14}^2 = 2\ eV^2$ is disfavored

→ new Planck data (2012) will set very stringent limits

J. Hamann et al., arXiv:1006.5276

Proposed experimental searches

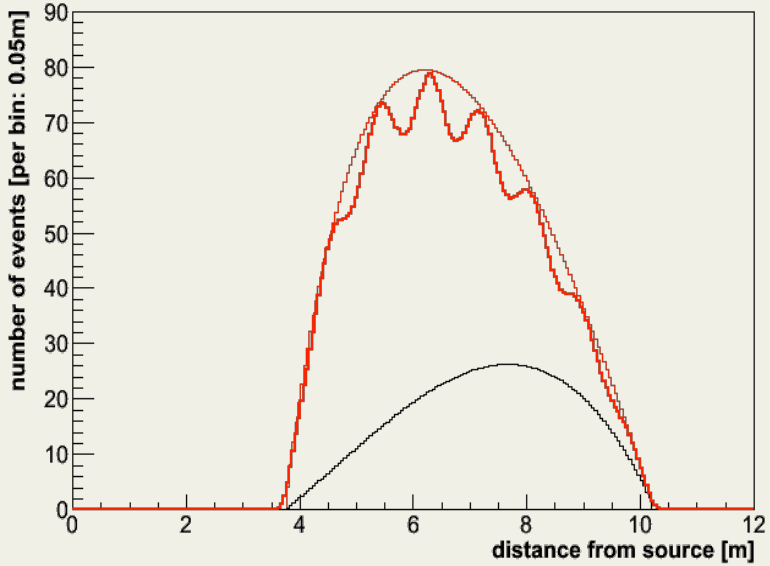


Borexino

- place MCi $\nu_e/\bar{\nu}_e$-source close to or inside detector
- look for spatial oscillation pattern contained inside the scintillator volume

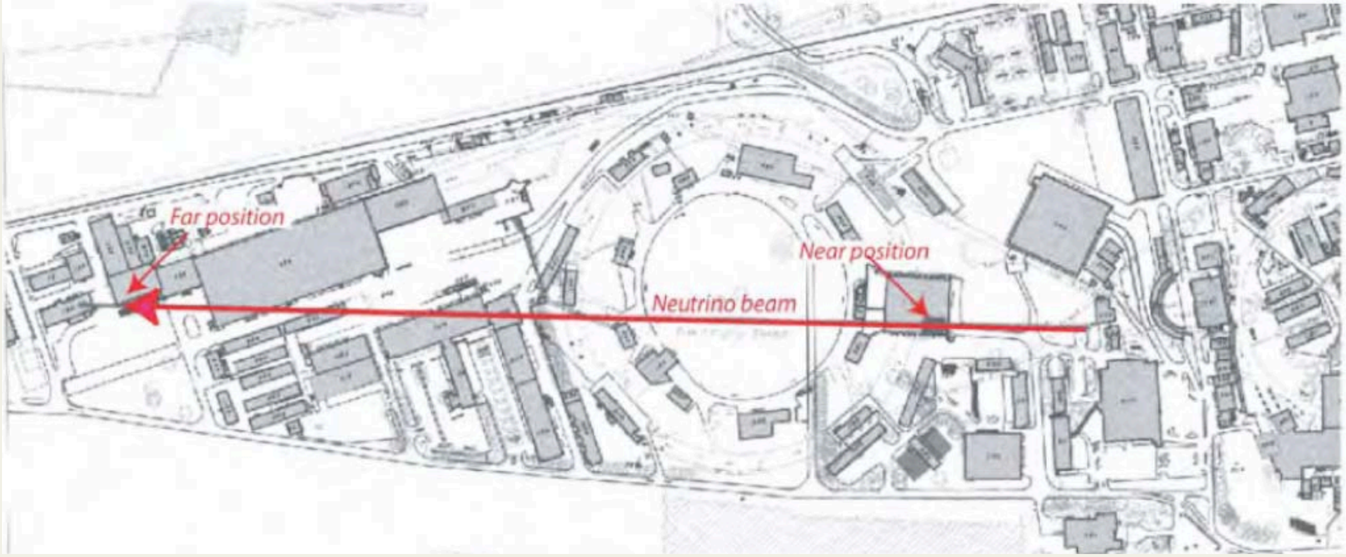
$L_{osc} \approx 1m$ @ $E_\nu \approx 1MeV$

$$P_{ee}(r) = 1 - \sin^2 2\theta \sin^2(\pi \cdot r/\ell)$$



Double-LAr

- placing ICARUS as far & new LAr near detector close to a new PS ν-beam line at CERN
- look for distortion of far detector energy spectrum caused by oscillations



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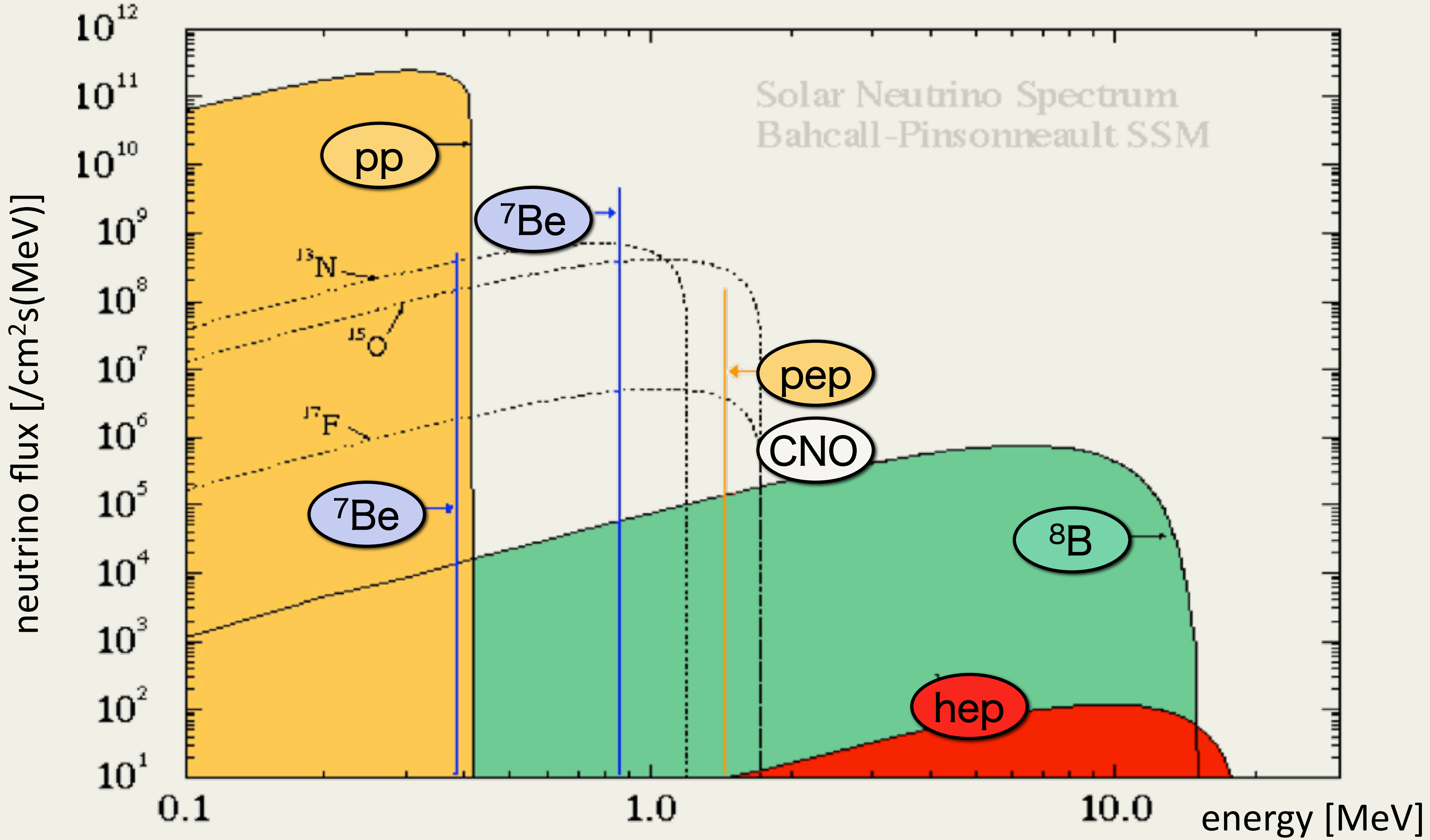
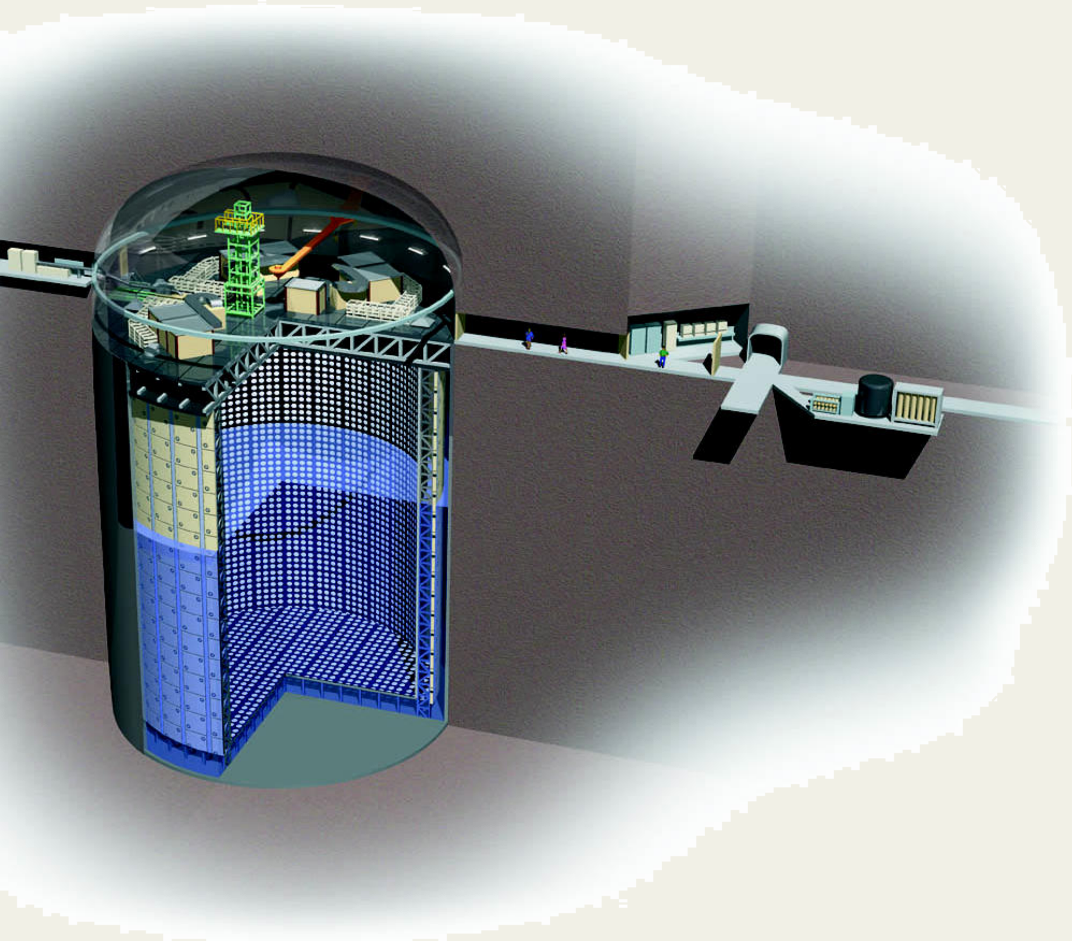
Solar neutrino spectrum



Solar fusion net reaction:

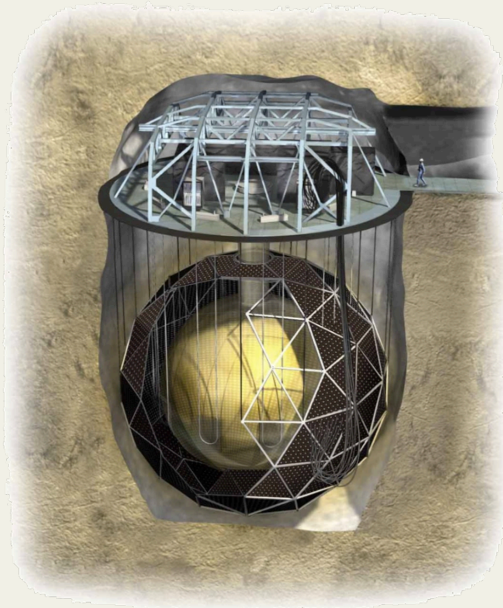
$$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_e + 26.7\ MeV$$

Solar neutrino experiments



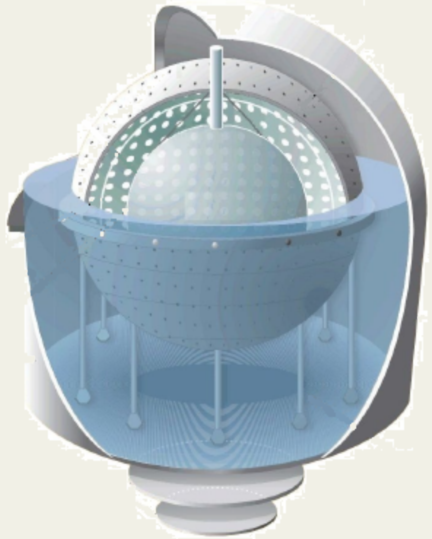
Super-Kamiokande (H_2O, 22.5kt)

- elastic νe-scattering: mostly ν_e
- precise measurement of ^{8}B-ν's above E_{thr}>5 MeV



SNO
(D_2O, 1kt)

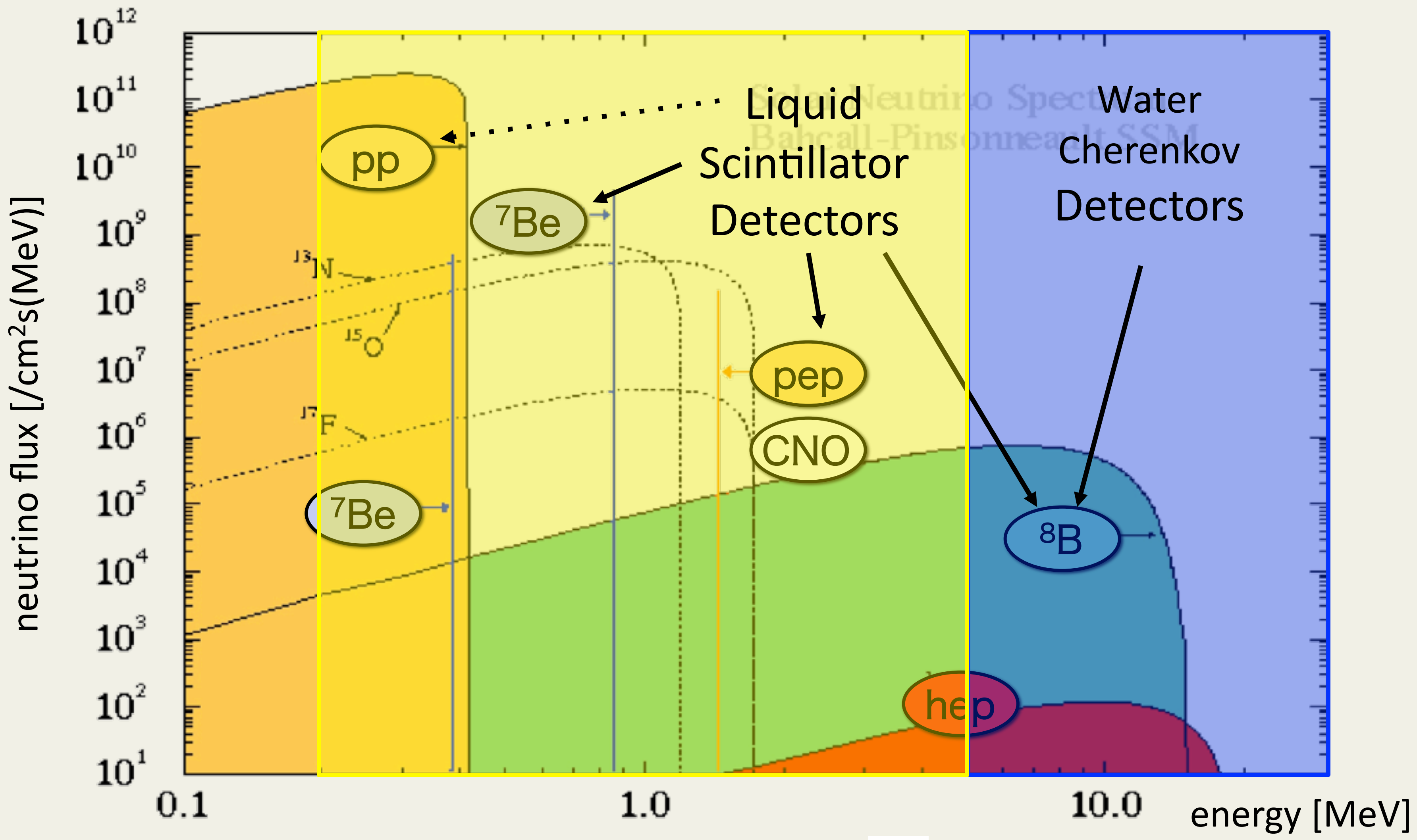
- reactions on D: separation $\nu_e/\nu_{\mu,\tau}$
- only ^{8}B, but new LETA analysis: E_{thr}>3.5MeV



Borexino
(C_9H_{12}, 300t)

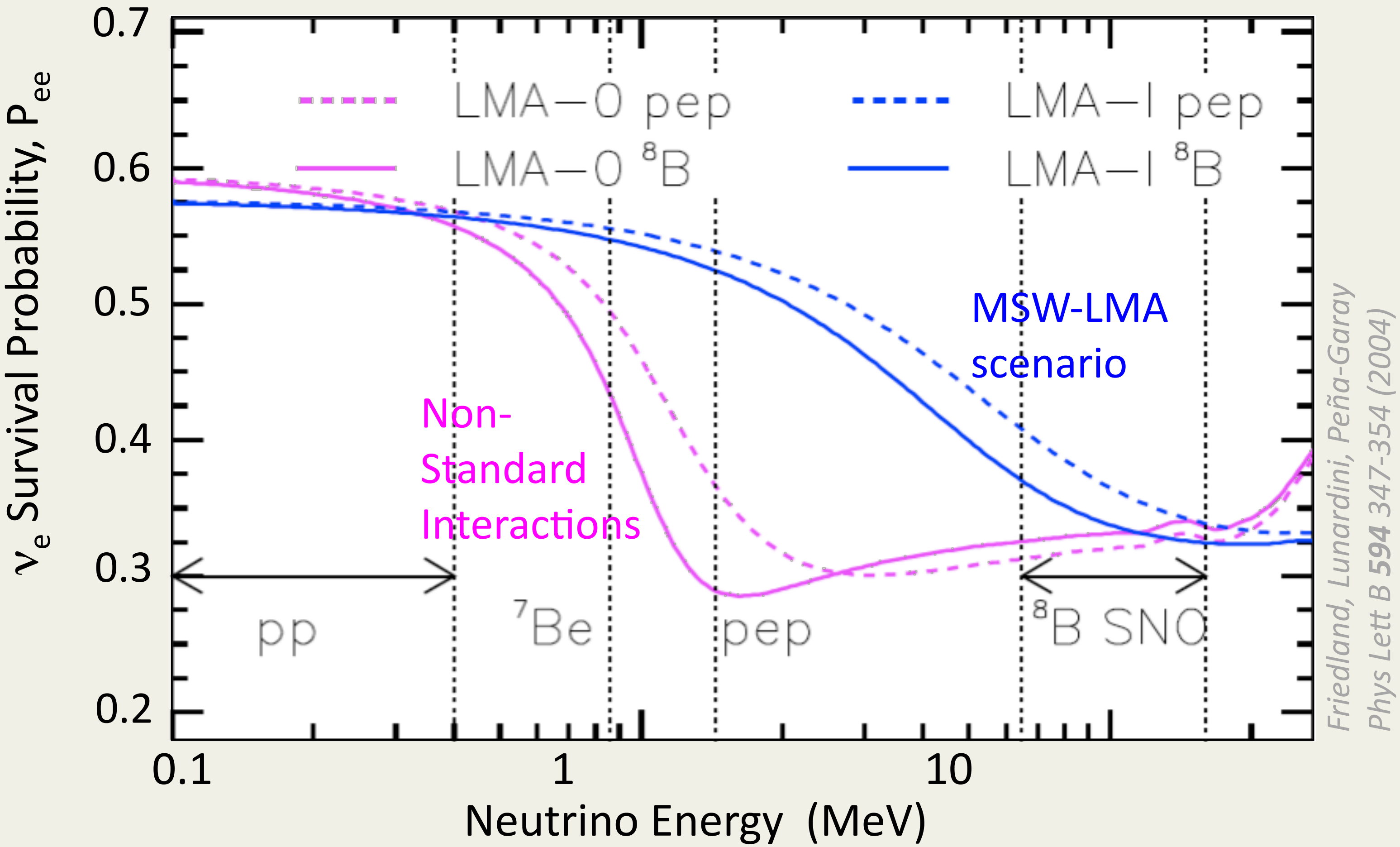
- νe-scattering
- high light yield → low threshold: E_{thr}>200keV
- sensitive to ^{7}Be, pep, low-E ^{8}B

Solar neutrino spectroscopy



- Water Cherenkov Detectors (SNO, Super-K) threshold: 4-5 MeV.
- ***Since 2007: Measurement of low-energy regime by Borexino.***

Solar neutrino survival probability



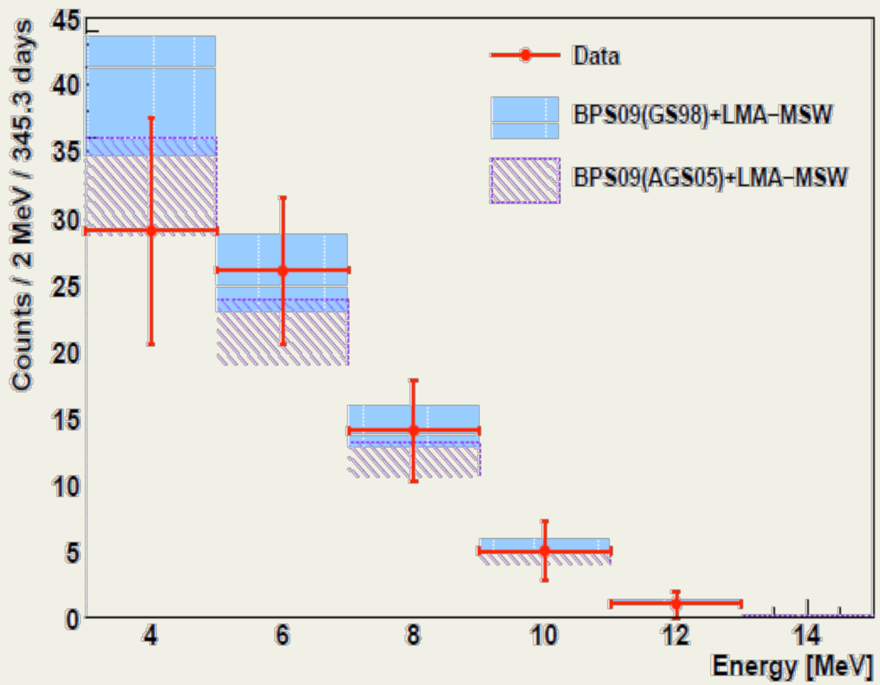
Oscillations in vacuum
probability averages over long distances, $\mathbf{P_{ee}\approx 0.55}$

⇔

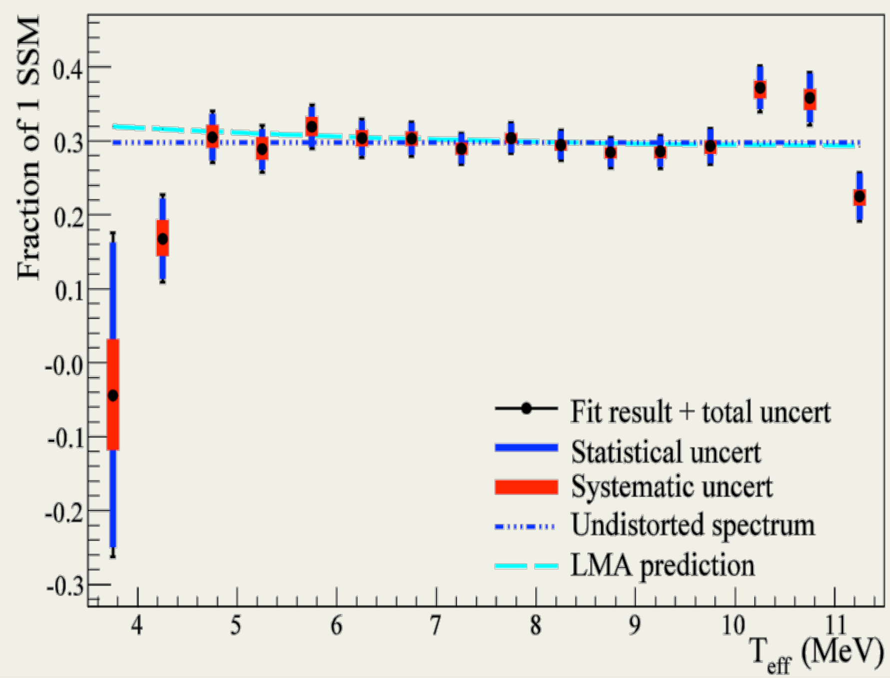
Matter-enhanced oscillations
interaction with solar matter increases osc. probability, $\mathbf{P_{ee}\approx 1/3}$

Hint for non-standard interactions in ^8B data?

BOREXINO (ES)

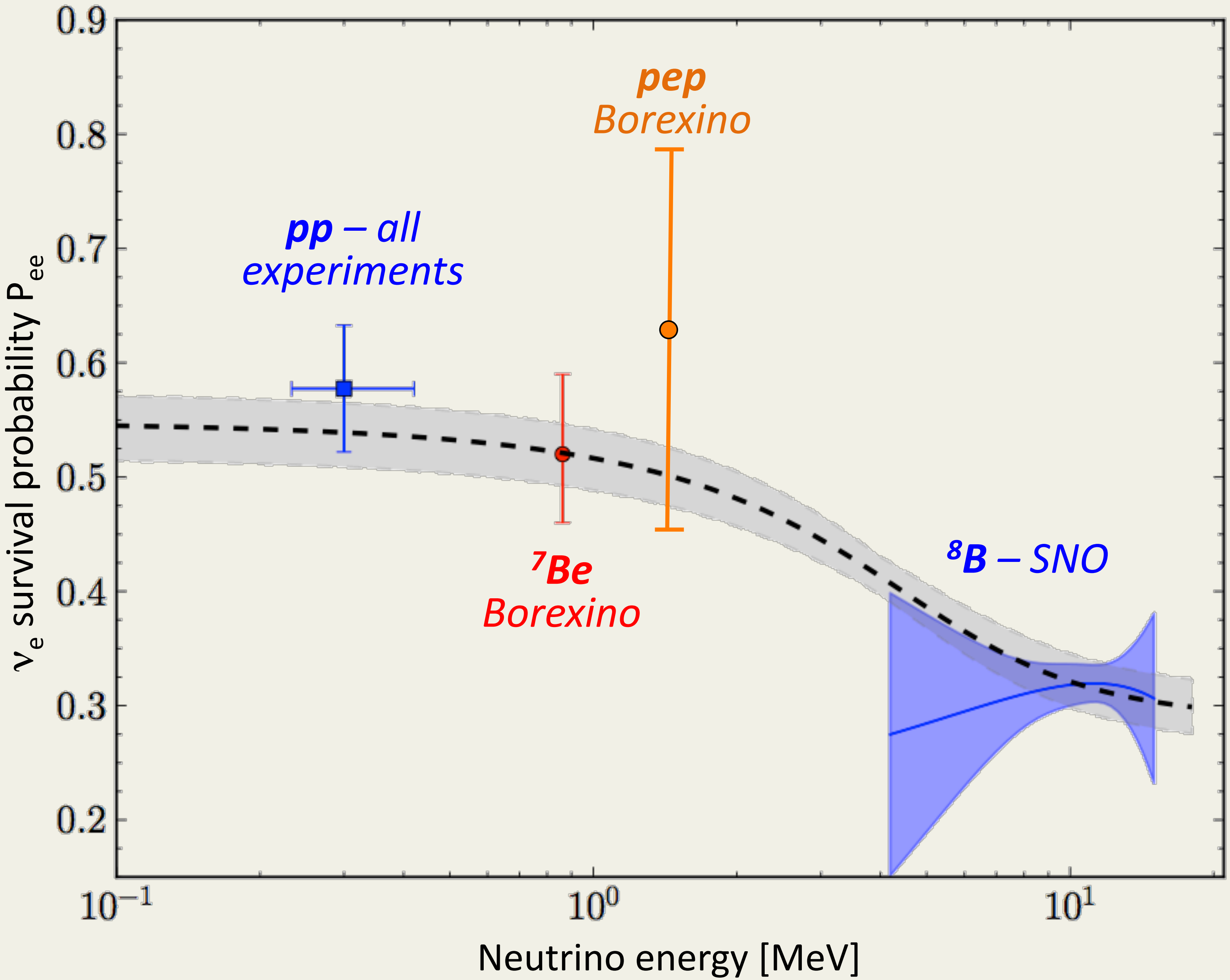


SNO-LETA (CC)



- Borexino and SNO-LETA results are in good agreement
- Rates at low-energies are low compared to prediction.

New solar neutrino results in 2011



Borexino
New pep result favors standard MSW-LMA

Borexino
^{7}Be-uncertainty reduced to 5%

SNO
Mild tension to MSW-LMA for low ^{8}B energies

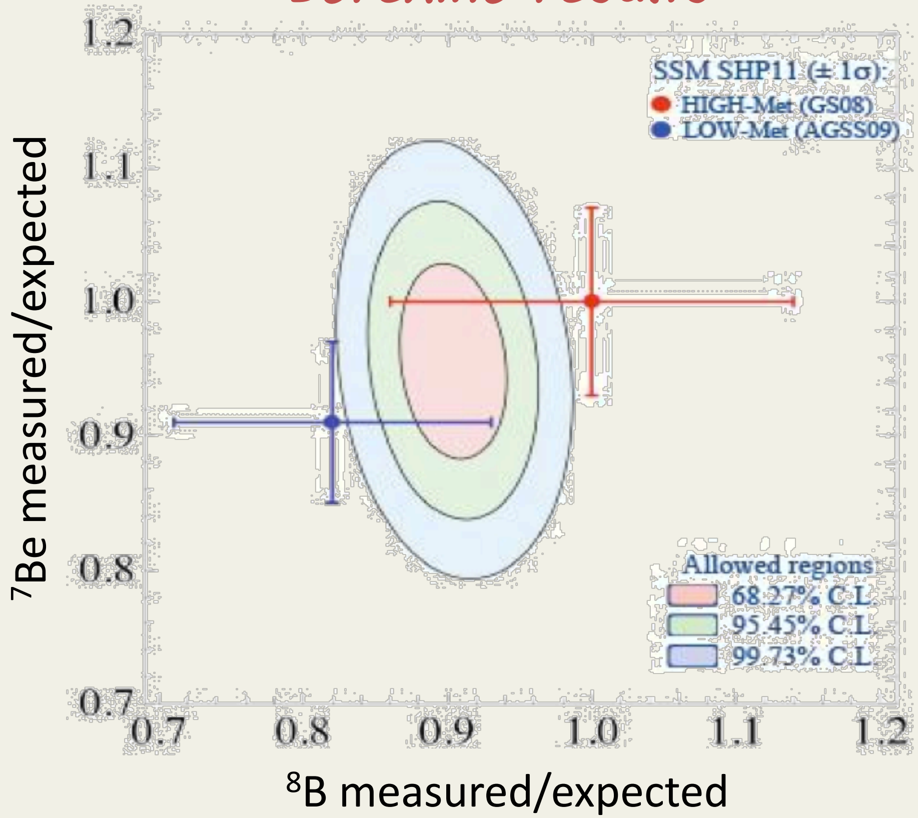
→ NSI ?

Neutrinos and solar metallicity

- new analysis of solar metallicity (3D modelling of Fraunhofer lines) in conflict with helioseismology
- solar neutrino production depends on metallicity Z
- based on SSM and different Z: *[arXiv:0811.2424]*:

Branch	Error	ΔZ		
pp	0.6%	1.2%		
pep	1.1%	2.8%		
^{7}Be	6%	10%	←	Borexino
^{8}B	11%	21%	←	Super-K/SNO
CNO	16%	31-44%	←	Borexino? future liquid scintillators?

Borexino results



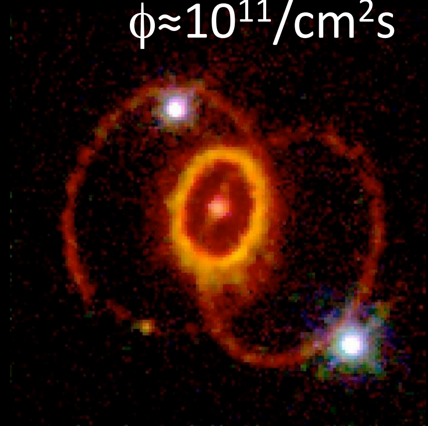
- ***Up to now, solar neutrino data is not sufficient to decide …***

Astronomical neutrino sources

$$\chi\bar{\chi} \rightarrow \nu\bar{\nu}$$

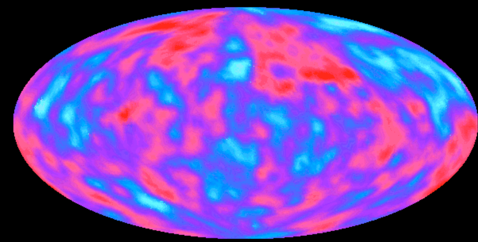
Dark Matter Annihilation

Galactic Supernovae
gravitational collapse
<E>≈15MeV
d≈10kpc
$\phi \approx 10^{11}/cm^2s$



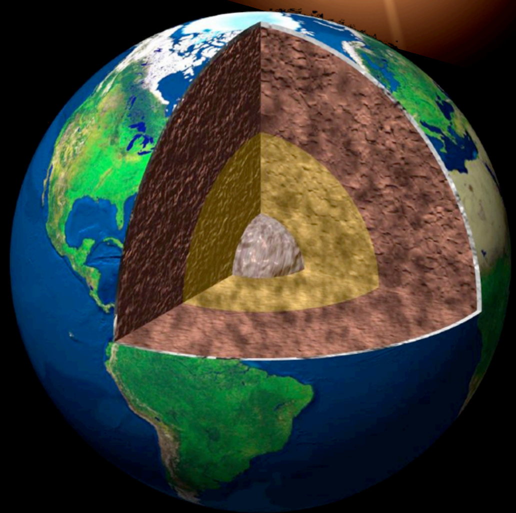
galactic
cosmic

Cosmic ν background
T=1.95K, $\rho = 56/cm^3$



Sun
He burning
E<18MeV
$\phi \approx 10^{10}/cm^2s$

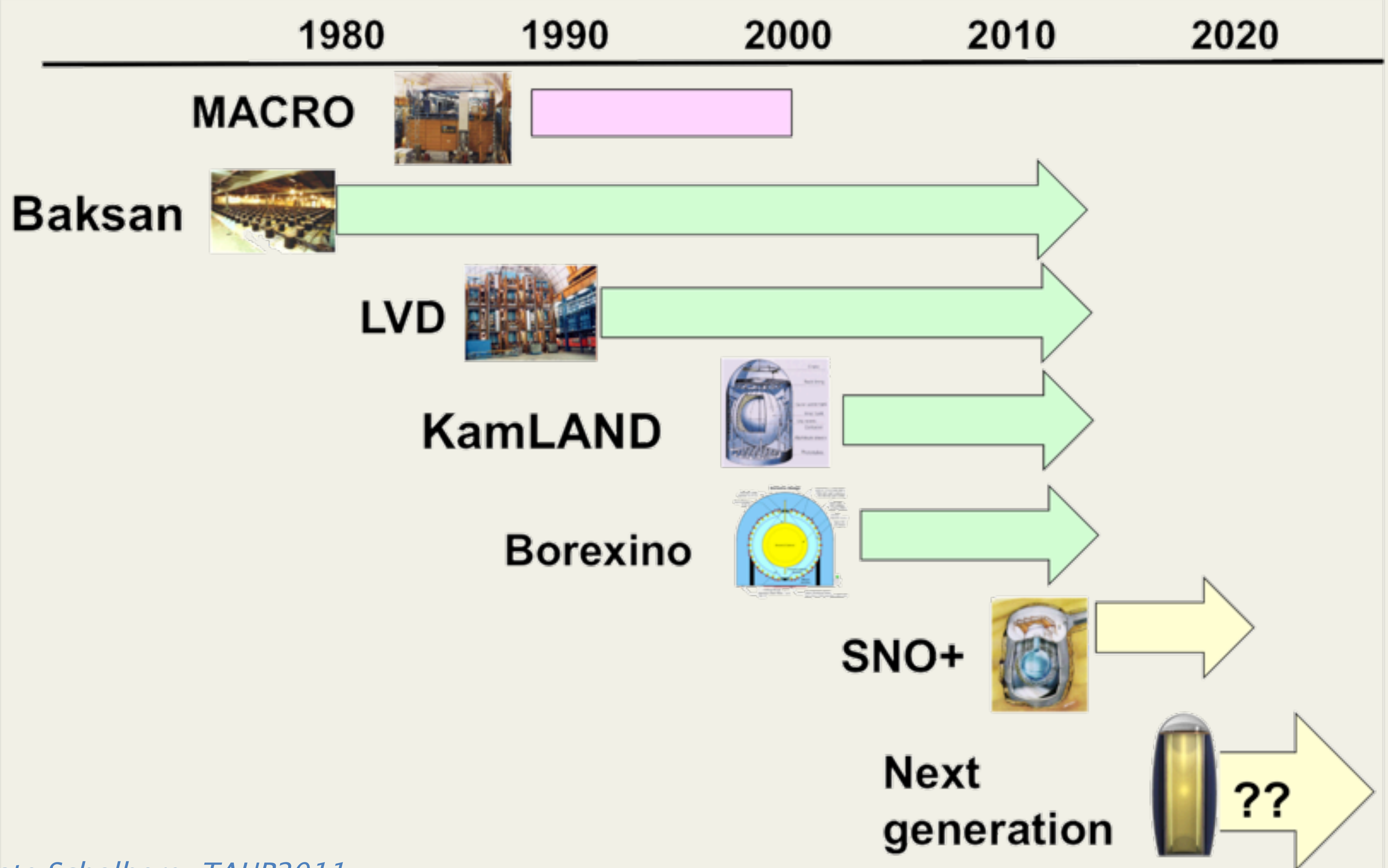
Cosmic Accelerators
AGNs, GRBs ...
E: GeV-EeV
$\phi < 10^{-11}/cm^2s$



Geoneutrinos
natural U/Th
E<3.4MeV
$\phi \approx 10^6/cm^2s$

SNν background
all SN for z→5
<E>≈10MeV
$\phi \approx 10^2/cm^2s$

Large-volume liquid scintillator detectors



Kate Scholberg, TAUP2011

LENA detector layout

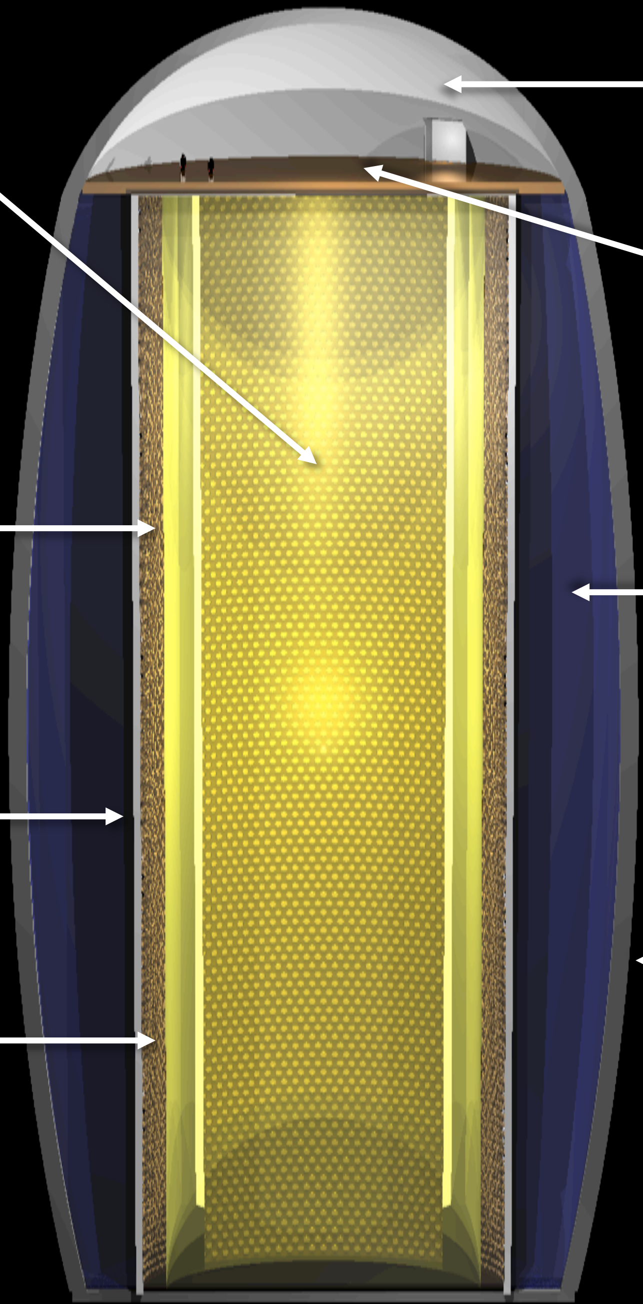
Liquid Scintillator
ca. 50kt LAB

Inner Nylon Vessel
radius: 13m

Buffer Region
inactive, Δr = 2m
ca. 20kt LAB

Steel Tank
r = 15m, h = 100m

50,000 8‘‘-PMTs
Winston cones
optical coverage: 30%



Electronics Hall
dome of 15m height

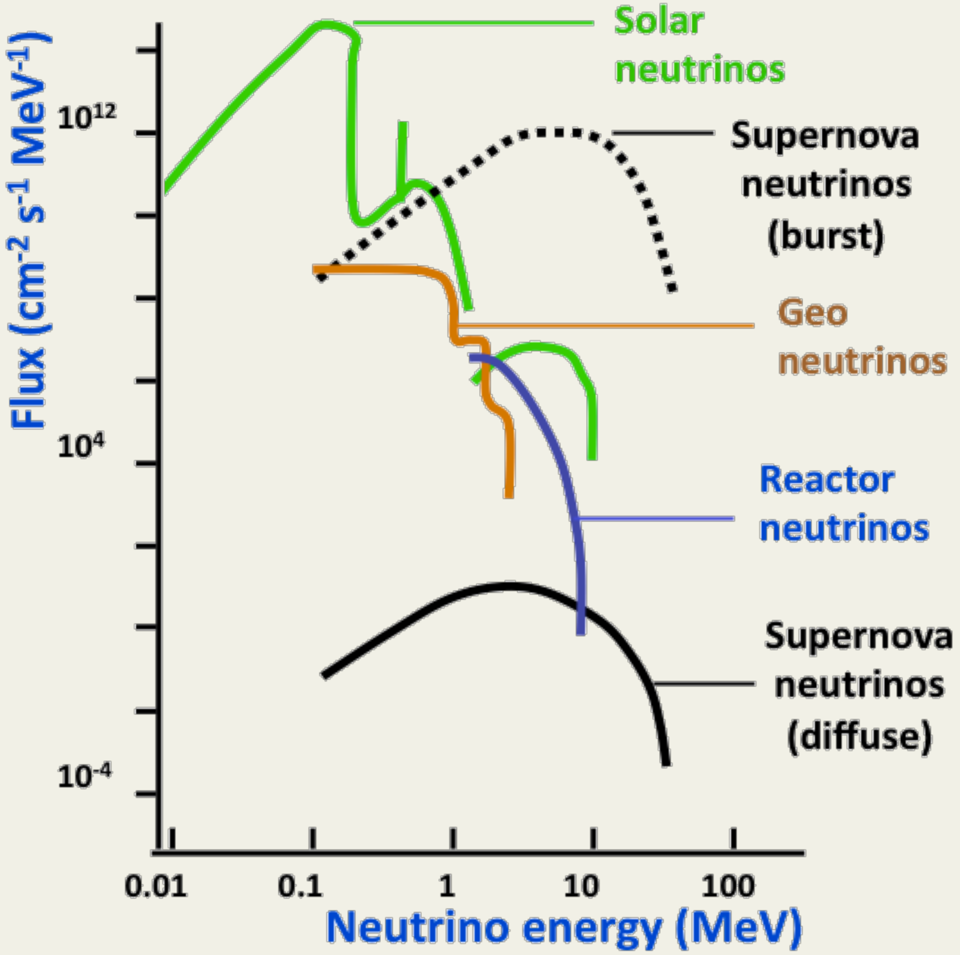
Top Muon Veto
limited streamer tubes
vertical muon tracking

Water Cherenkov Veto
3000 PMTs, Δr > 2m
fast neutron shield
inclined muons

Egg-Shaped Cavern
about 10^5 m^3

Rock Overburden
at least 3500 mwe

LENA: Physics programme



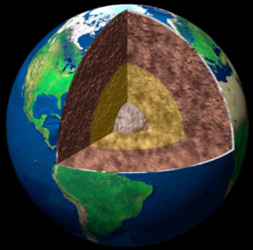
Low Energy Neutrinos

▪ Galactic Supernova neutrinos	10^4/SN
▪ Diffuse Supernova neutrinos	10/yr
▪ Solar neutrinos	10^4/d
▪ Geoneutrinos	10^3/yr
▪ Reactor neutrinos	$10^{3\text{-}4}$/yr
▪ Neutrino oscillometry	10^4/MCi
▪ Pion decay-at-rest beam	
▪ Indirect dark matter search	

GeV energies

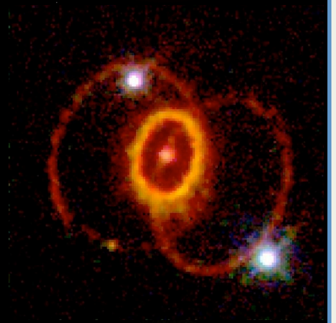
- Atmospheric neutrinos
- Long-baseline neutrino beams
- Proton decay

LENA: A neutrino observatory

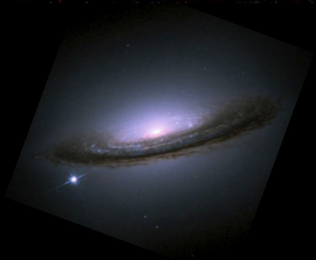


- How large is the U/Th contribution to the total terrestrial heat flux?
- What is the relative abundance of U/Th in crust and mantle?
- Is there a georeactor at the Earth's center?

- What is the correct value for solar metallicity?
- How large is the contribution of the CNO cycle to solar fusion?
- Can we observe helioseismic gravitational modes in the solar core?



- Is there an initial neutrino burst from neutronization?
- Can we monitor the protoneutron star cooling in the light of neutrinos?
- Is the explosion shock wave imprinted in the neutrino signal?
- Might we observe neutrinos from thermonuclear SNe (Type Ia)?



- Can we detect the Diffuse Supernova Neutrino Background?
- What is the neutrino spectrum averaged over all types of SNe?

$\chi\bar{\chi}$

- Are there Dark Matter candidates at masses of 10-100 MeV?

LENA: A particle physics laboratory

θ_{13}	*Long-baseline beam*	*Occurence of resonant flavor conversion* *Supernova: observation of neutronization burst* *SN envelope/Earth matter effeczs*
NH IH	*Long-baseline beam*	*Occurence of resonant flavor conversion* *Supernova: observation of neutronization burst* *SN envelope/Earth matter effeczs*
δ_{CP}	*Long-baseline beam*	*Short-baseline: pion decay-at-rest beam*
ν_s	*Short-baseline oscillation experiments: sources, pion decay at rest*	
μ_ν	*νe-scattering: solar, EC sources*	*$\nu_e \rightarrow \bar{\nu}_e$ conversions by B-fields: solar, SN*
NSI	*Long-baseline beams, solar neutrinos*	
νν osc	*SN neutrinos close to the proto-neutron star: spectral swaps*	
$v_\nu > c$	*Long-baseline beam, 2288 km from CERN to Pyhäsalmi*	

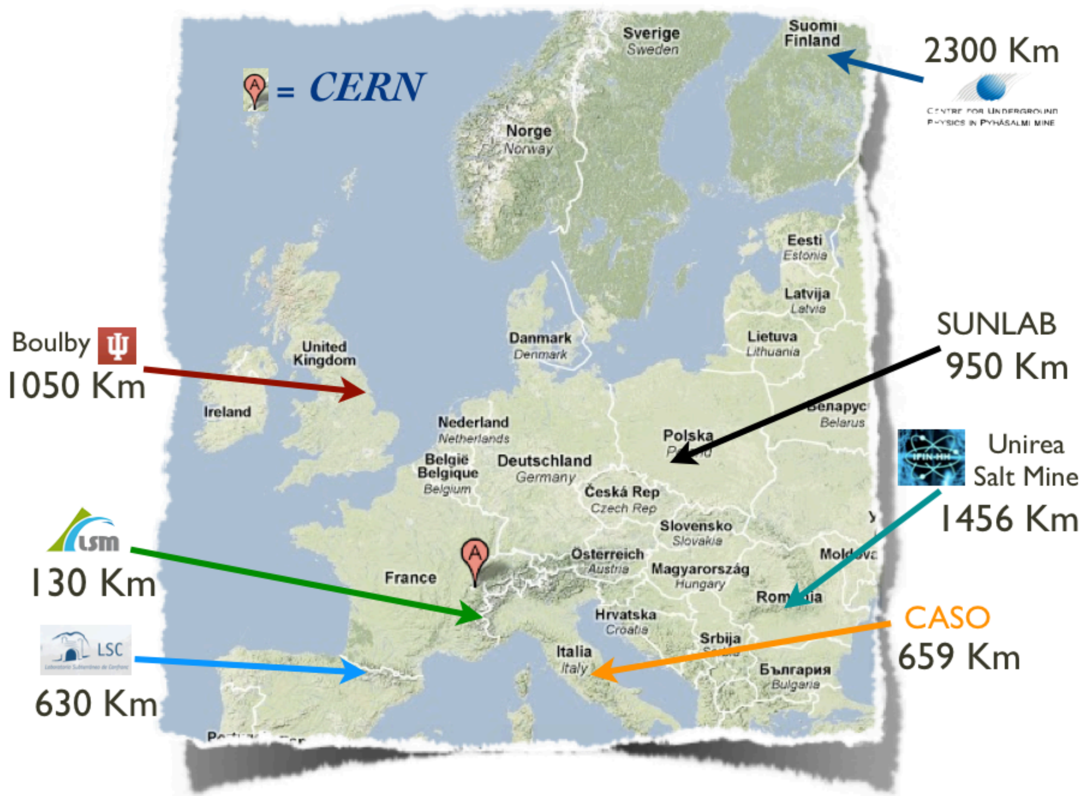
+

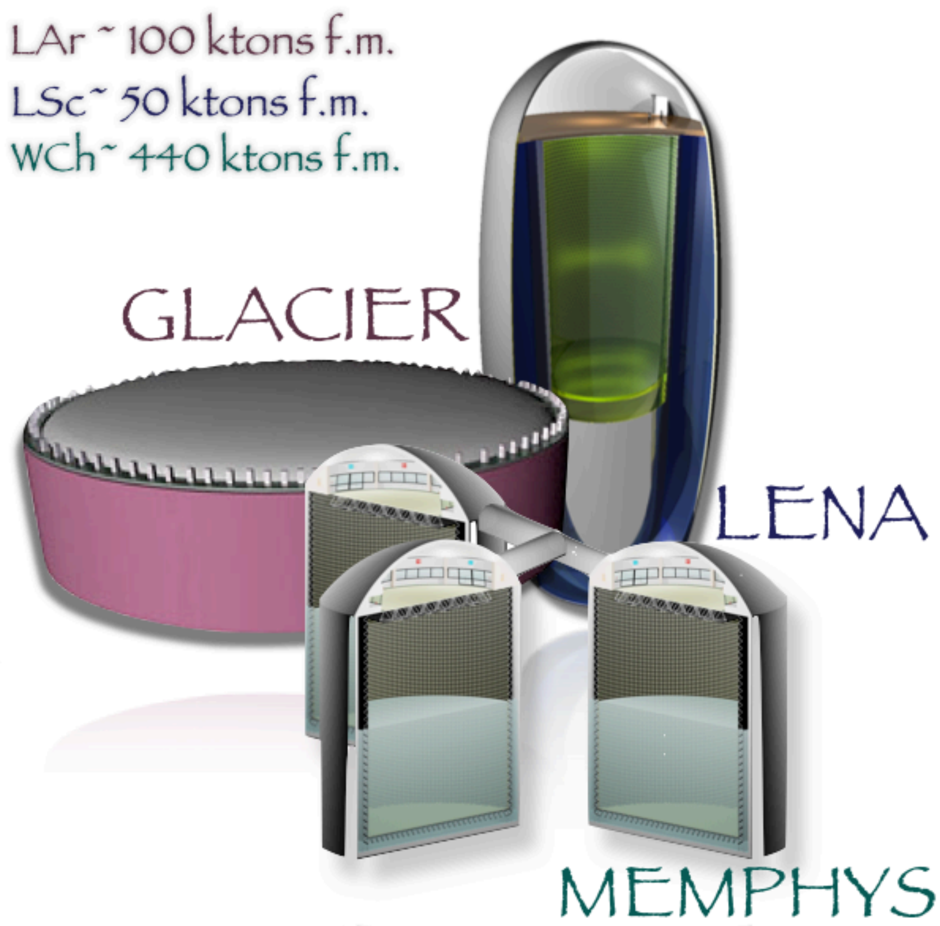
p	*Proton decay into Kaon and antineutrino (SUSY favored)*	

LAGUNA → LAGUNA-LBNO

- Consortium of European science institutions and industry partners
- Design studies funded by the European Community (FP7)
- **LAGUNA:** detector site, cavern, and oscillation baselines (2008-11)
- **LAGUNA-LBNO:** detector tank, instrumentation, and beam source (2011-14)

Seven sites, three detector technologies





Conclusions

- Neutrinos offer a lot of opportunities for the discovery of physics beyond the Standard Model.
- 2011 was an exciting year in terms of neutrinos ... and it is not over yet.
- With underlying neutrino parameters established, neutrinos can be finally used as probes for astronomical observations.
- The next-generation of large-volume neutrino detectors (and especially LENA) offer a broad program both in physics and astronomy.

LENA white paper

arXiv:1104.5620

The next-generation liquid-scintillator neutrino observatory LENA

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