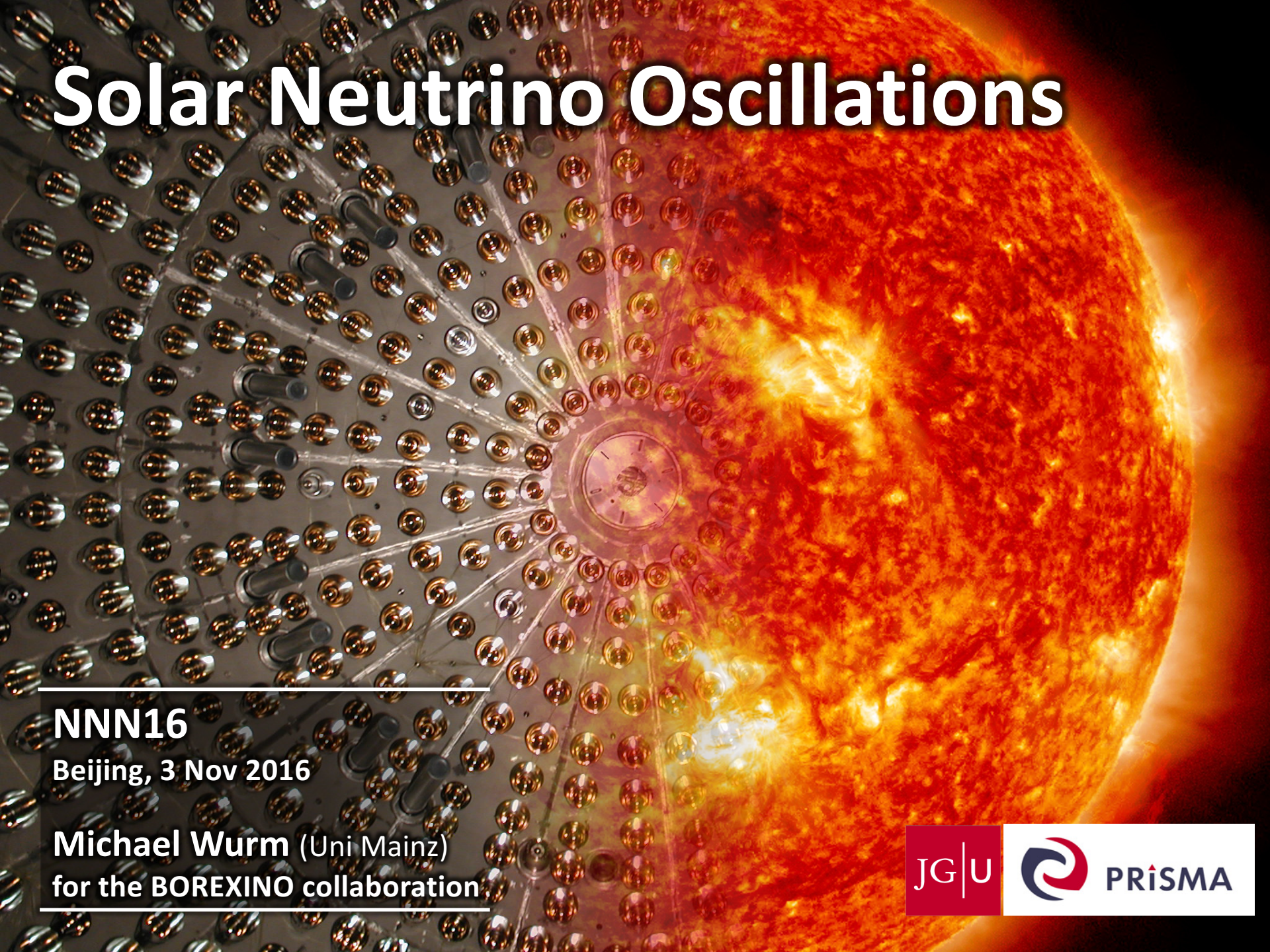
Solar Neutrino Oscillations



NNN16

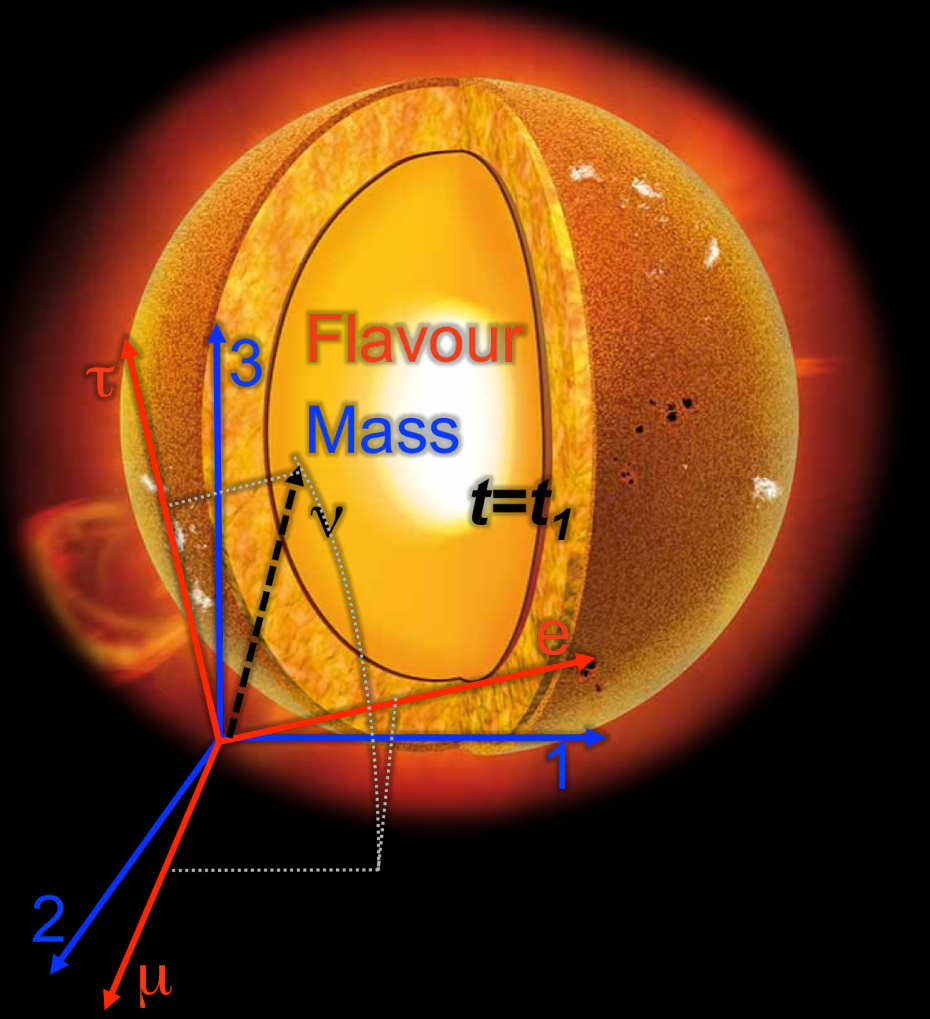
Beijing, 3 Nov 2016

Michael Wurm (Uni Mainz)
for the BOREXINO collaboration

JG|U PRISMA

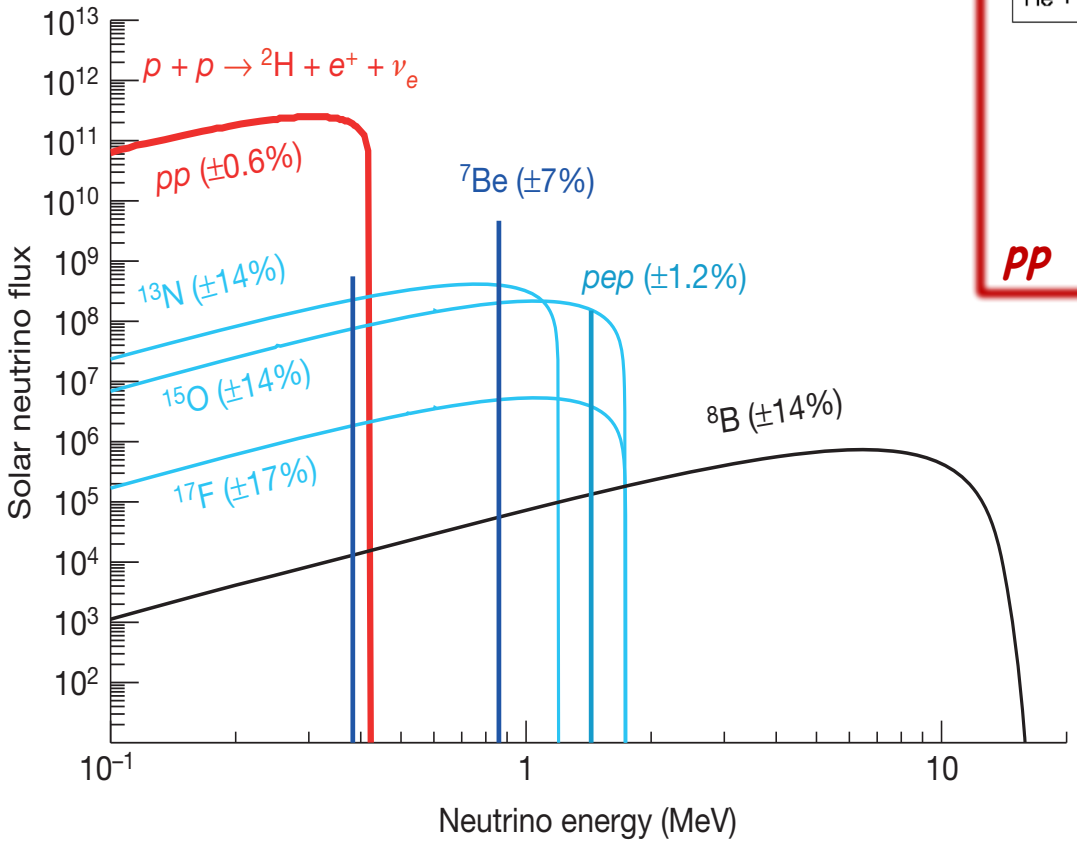
Scientific Motivation

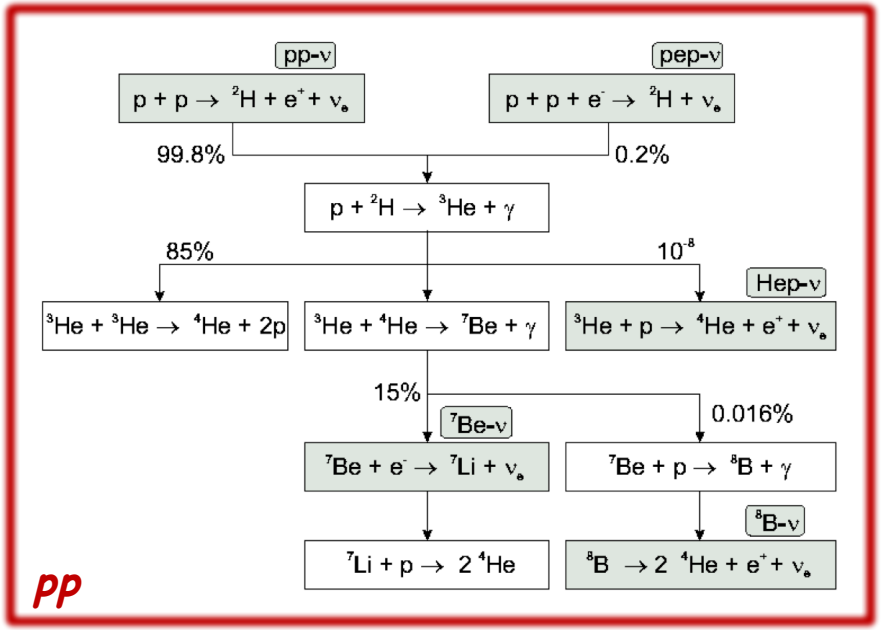
- **Exploration of the solar interior**
  - fusion rates (pp,CNO)
  - solar metallicity
  - …
- **Investigation of neutrino oscillations**
  - 3-flavor oscillations
  - matter effects
  - non-standard phenomena

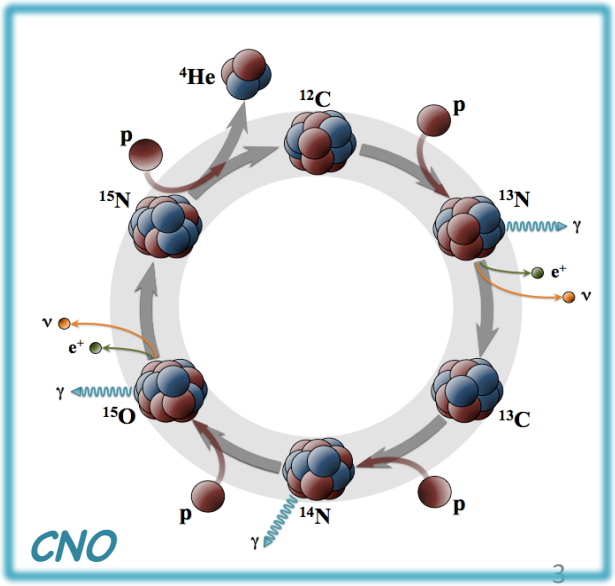


Solar neutrino spectrum

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



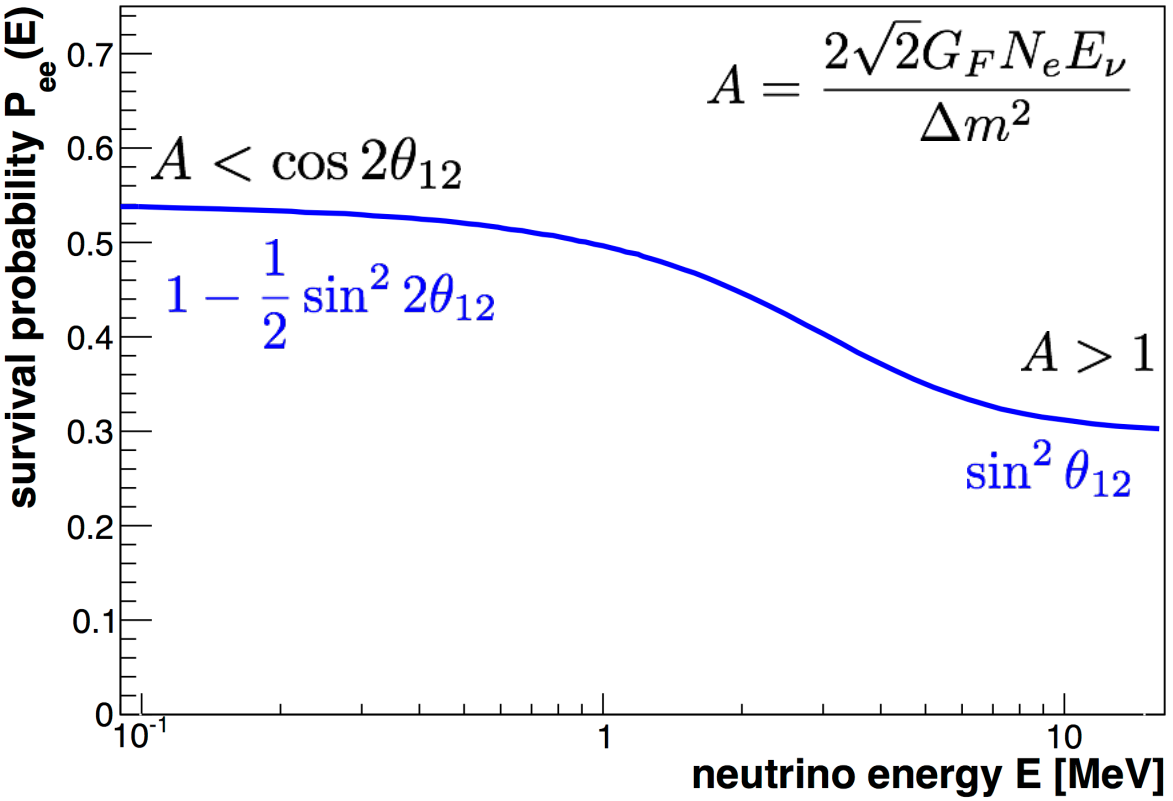




Solar neutrino oscillations: MSW-LMA

Solar neutrino oscillations are observed via ν_e survival probability:

vacuum oscillations
E<1MeV

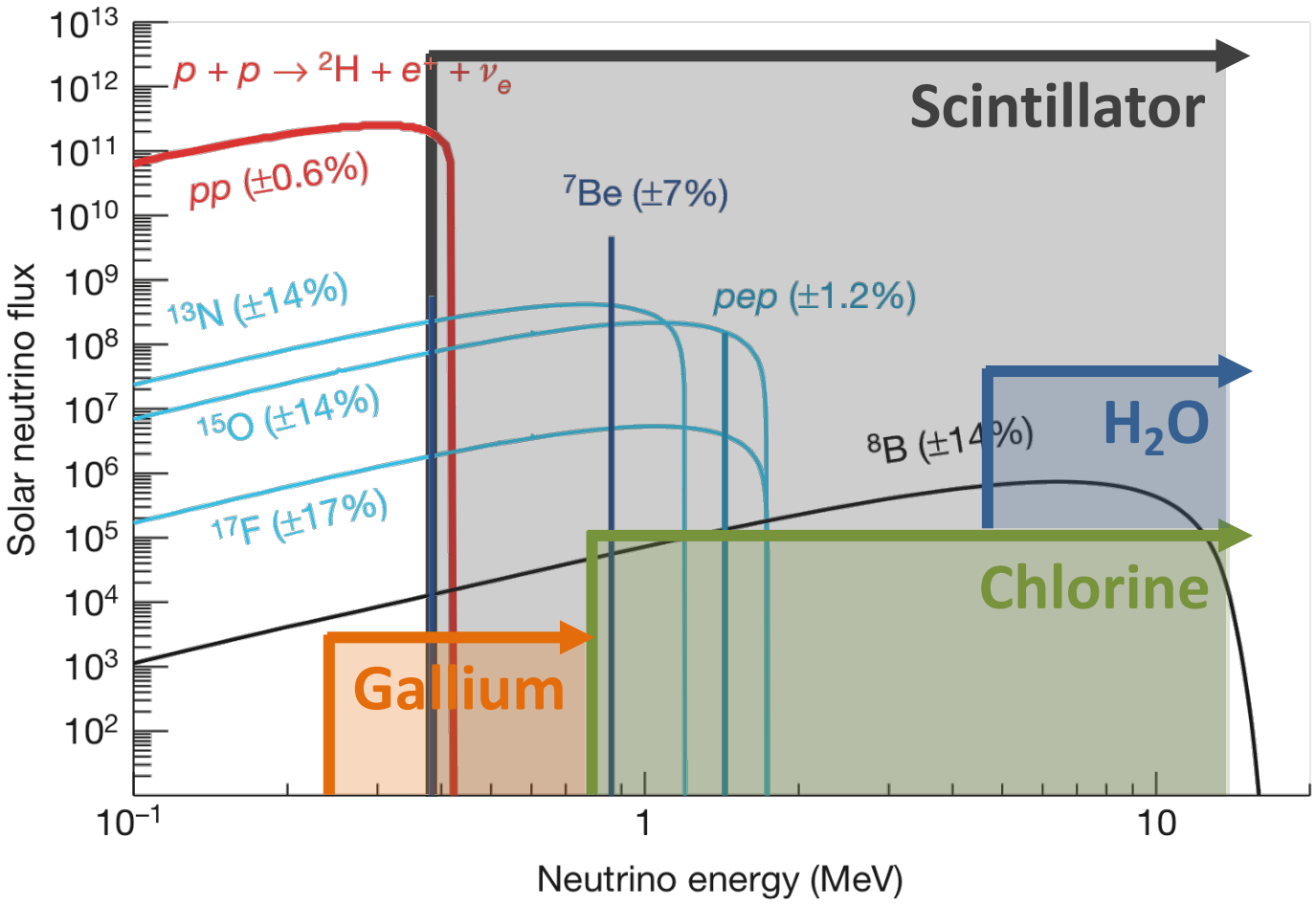


matter oscillations
E>5MeV

→ **Three distinctive regions:**

vacuum oscillations, **transition region**, **matter-dominated** oscillations

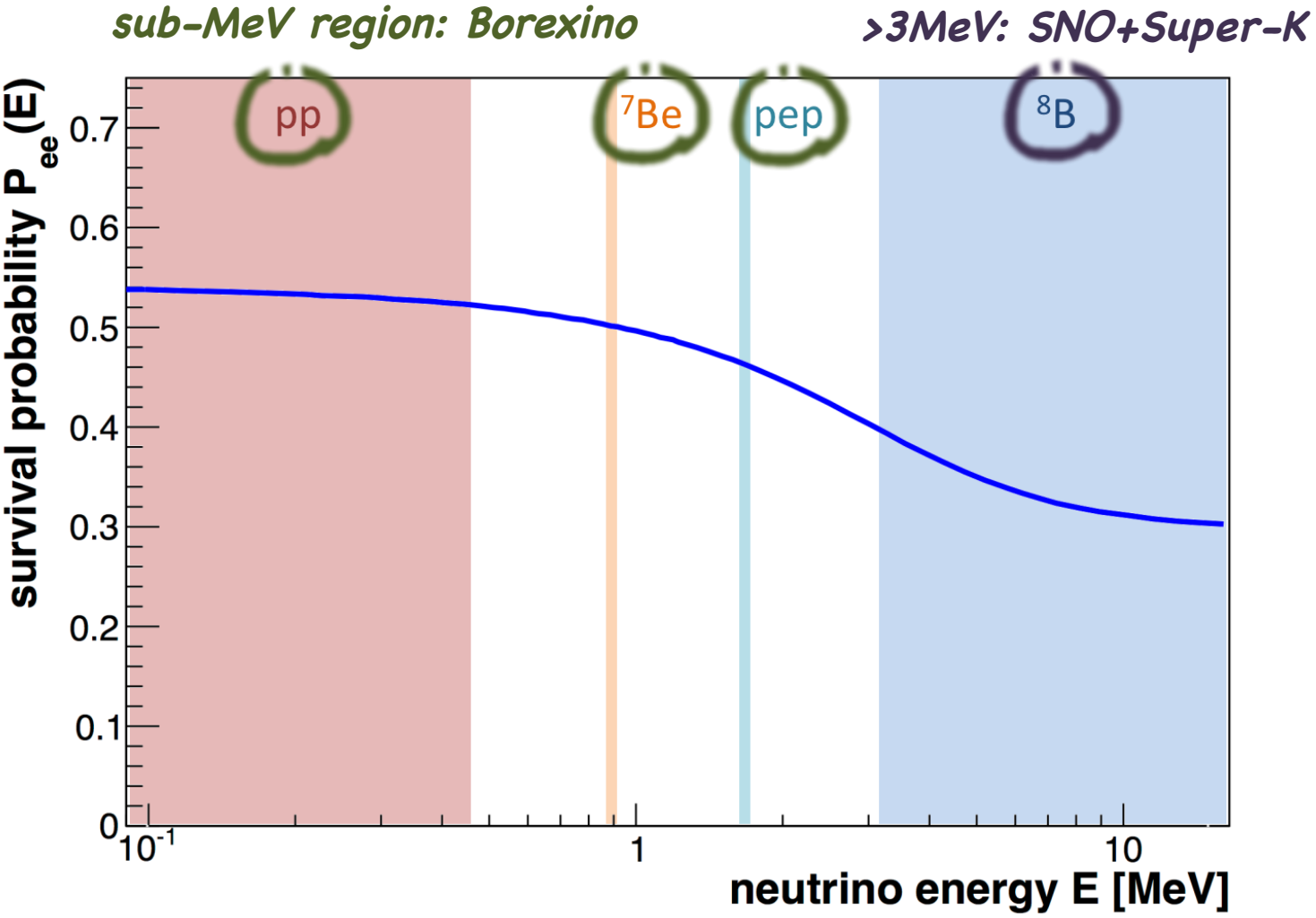
Solar ν experiments: Observational windows



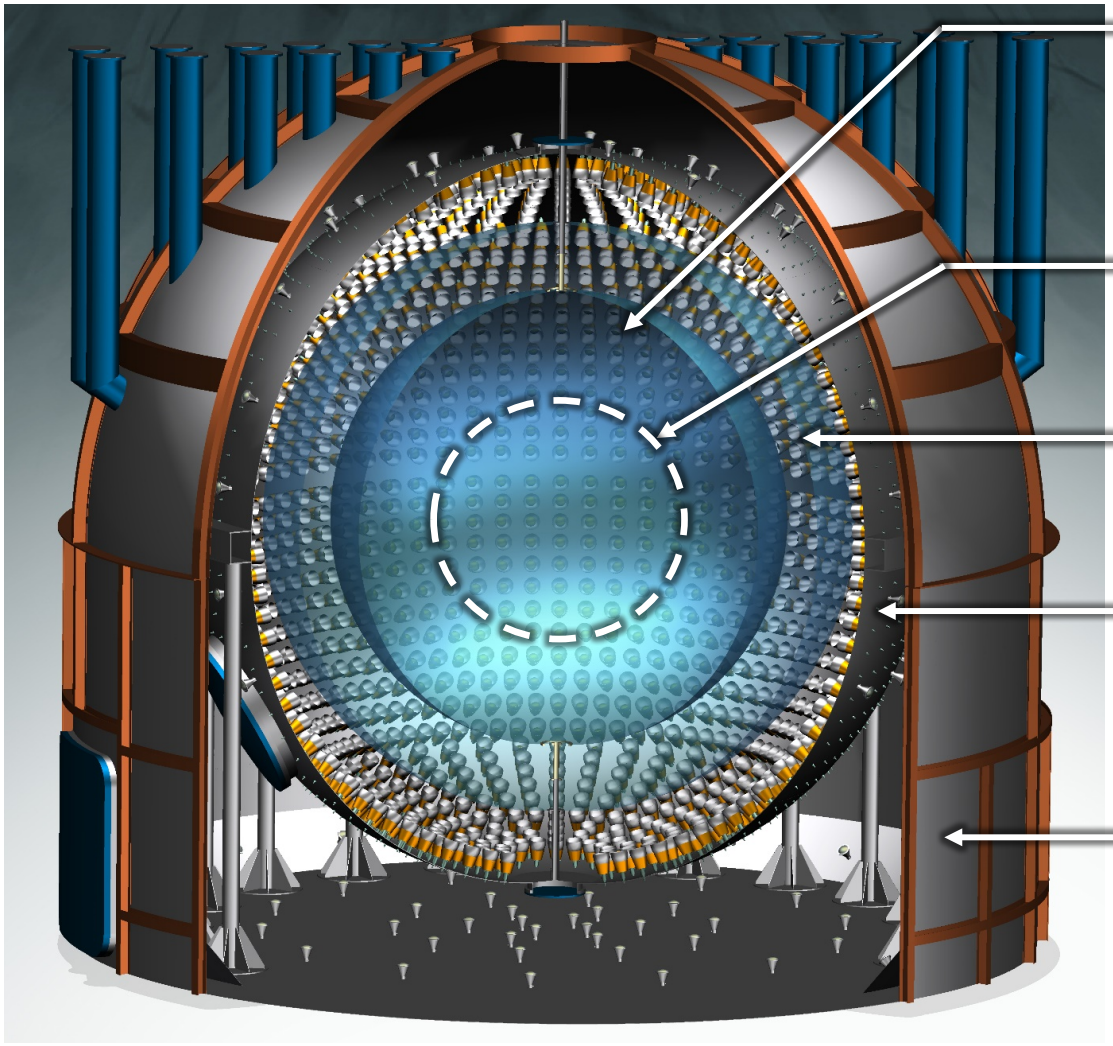
- **radiochemical: Gallium, Chlorine** → integral measurements
- **Water Cherenkov** → directionality, high threshold
- **Liquid Scintillator** → sub-MeV threshold, lower target mass

Spectroscopic measurement of $P_{ee}(E)$

ν_e flux measurement of spectral components allows to map out $P_{ee}(E)$:



BOREXINO detector layout



Active volume
270t of liquid scintillator (PC)
in nylon vessel of R=4.25 m

Fiducial volume: 100t
defined by software cut

Inactive buffer volume
shielding of external γ-rays

Stainless steel sphere
radius: 6.85 m
2212 inward-facing PMTs

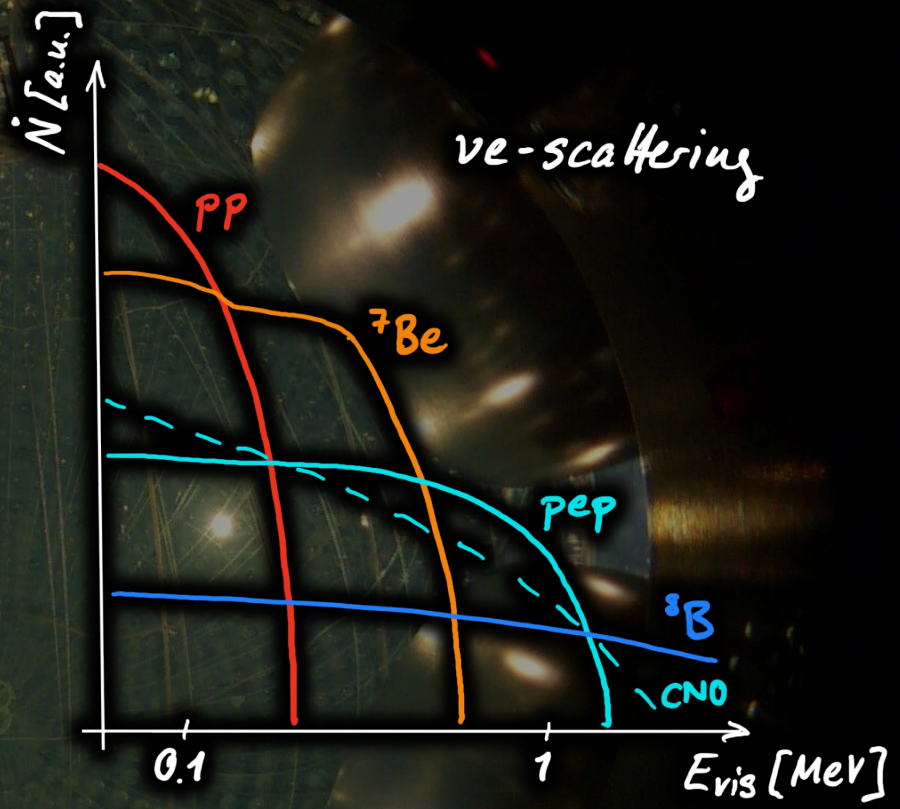
Inner Detector

Outer muon veto
2.1 kt of water, R=9m
208 PMTs
muon-Cherenkov veto

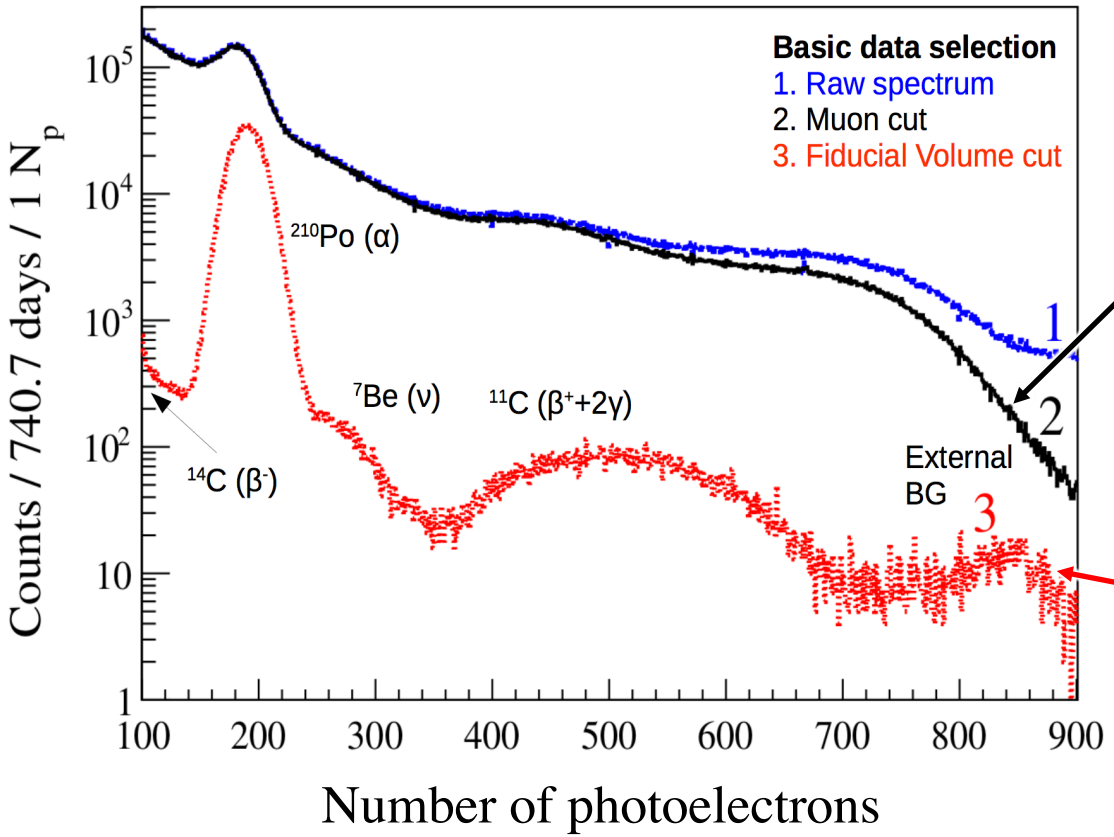
Outer Detector

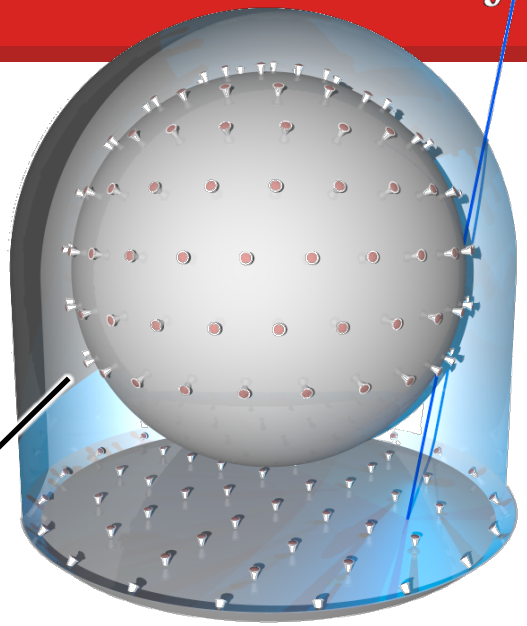
BOREXINO detector specifications

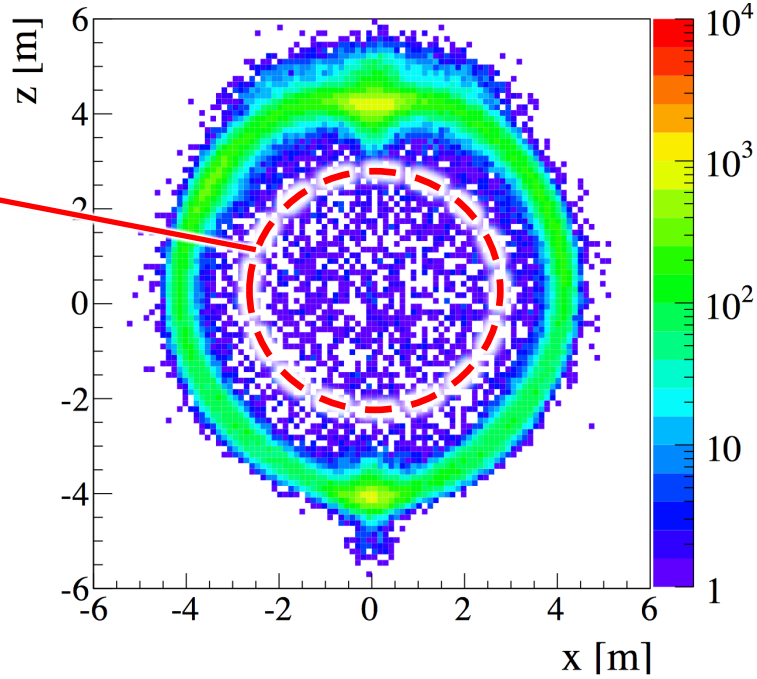
- **Solar neutrino detection**
  elastic νe-scattering
- **Energy resolution**
  ~500 p.e. per MeV
  → **ΔE/E ~ 5% @ 1 MeV**
- **Energy threshold**
  instrumental: ~50 keV
  analysis: **~150 keV**
- **Spatial reconstruction**
  from photon time-of-flight
  → **Δx ~ 10 cm @ 1 MeV**
  → **fiducial volume cut**



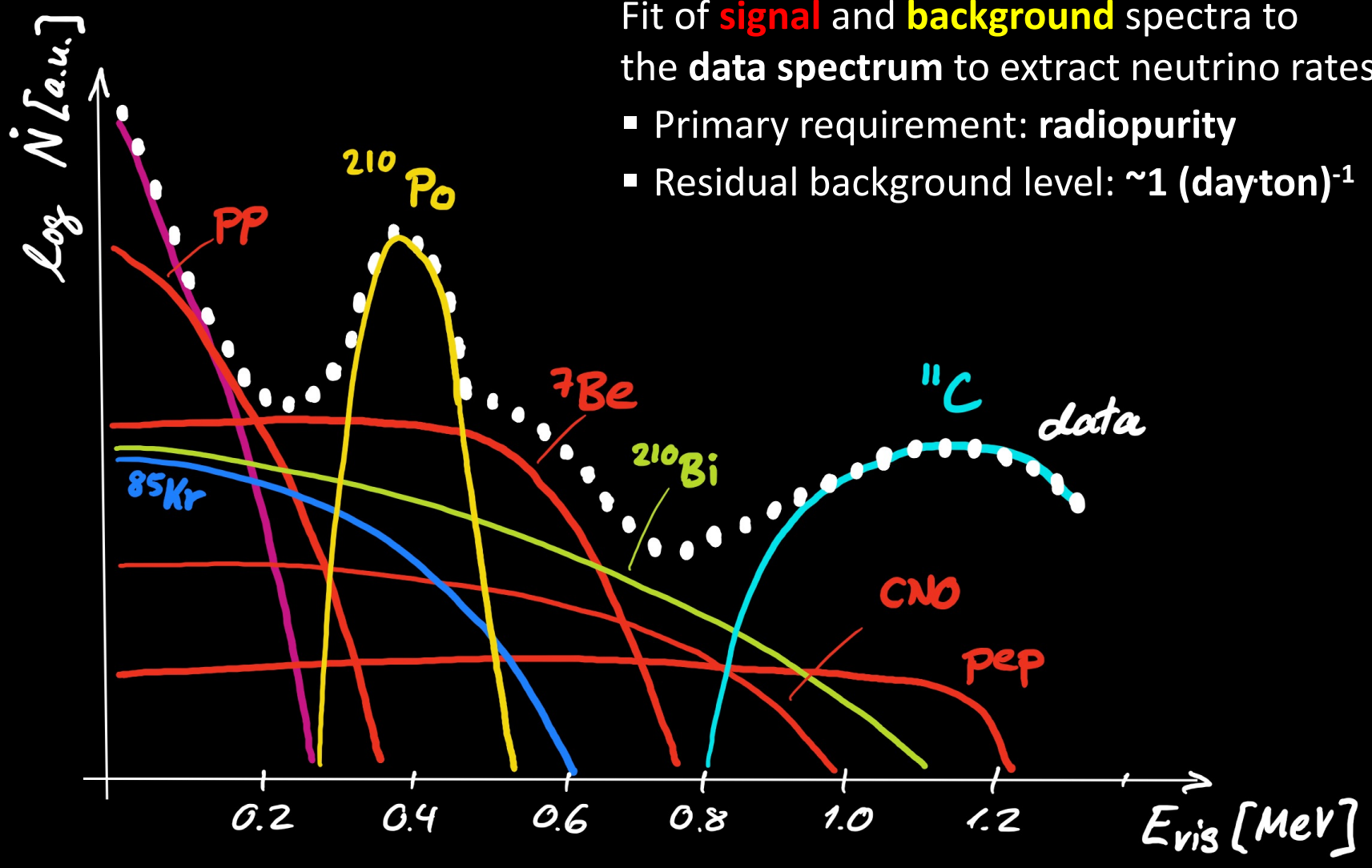
Background reduction







Solar neutrino rates from spectral fit

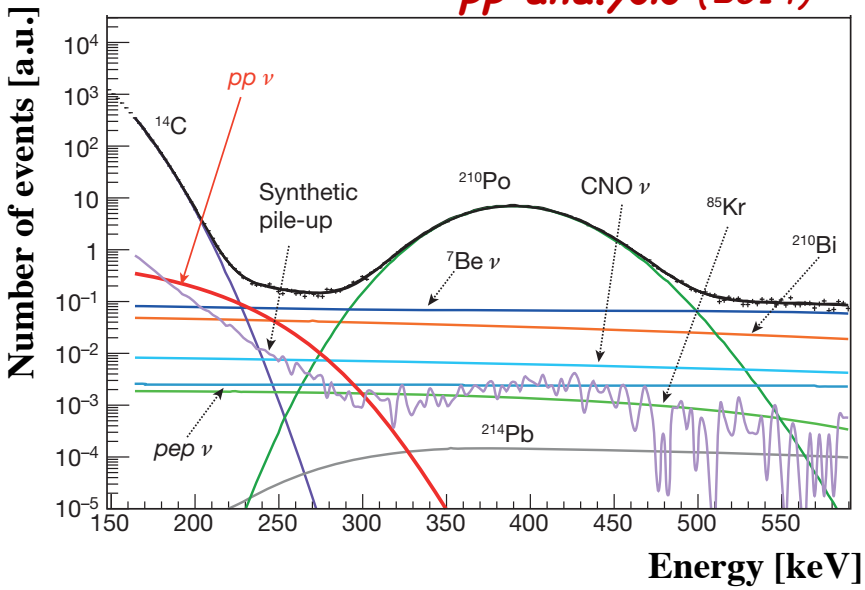


Fit of **signal** and **background** spectra to the **data spectrum** to extract neutrino rates

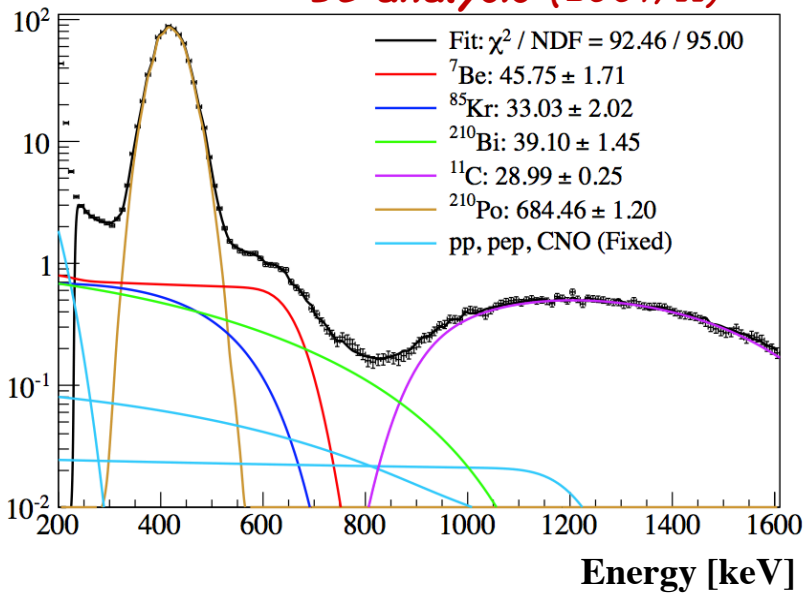
- Primary requirement: **radiopurity**
- Residual background level: **~1 (day·ton)$^{-1}$**

BOREXINO low-energy results

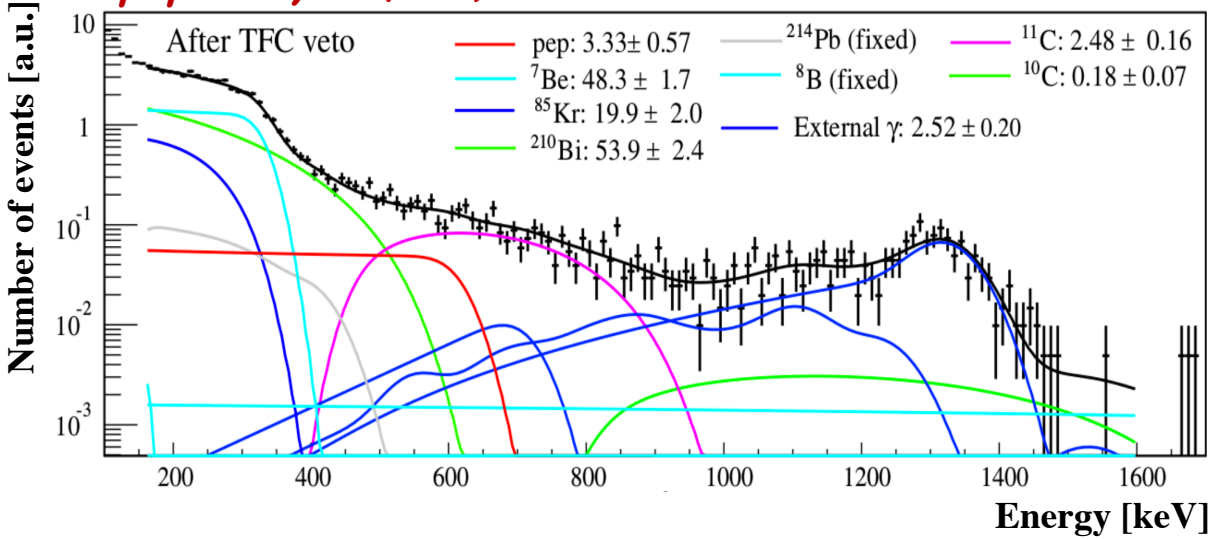
pp analysis (2014)



^{7}Be analysis (2007/11)

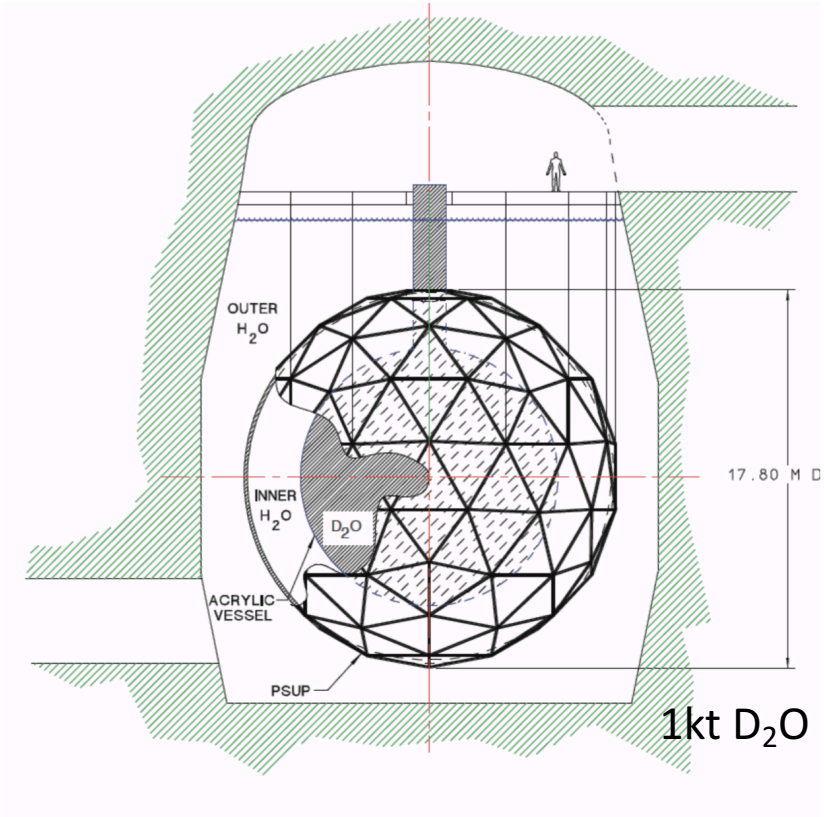


pep analysis (2011)

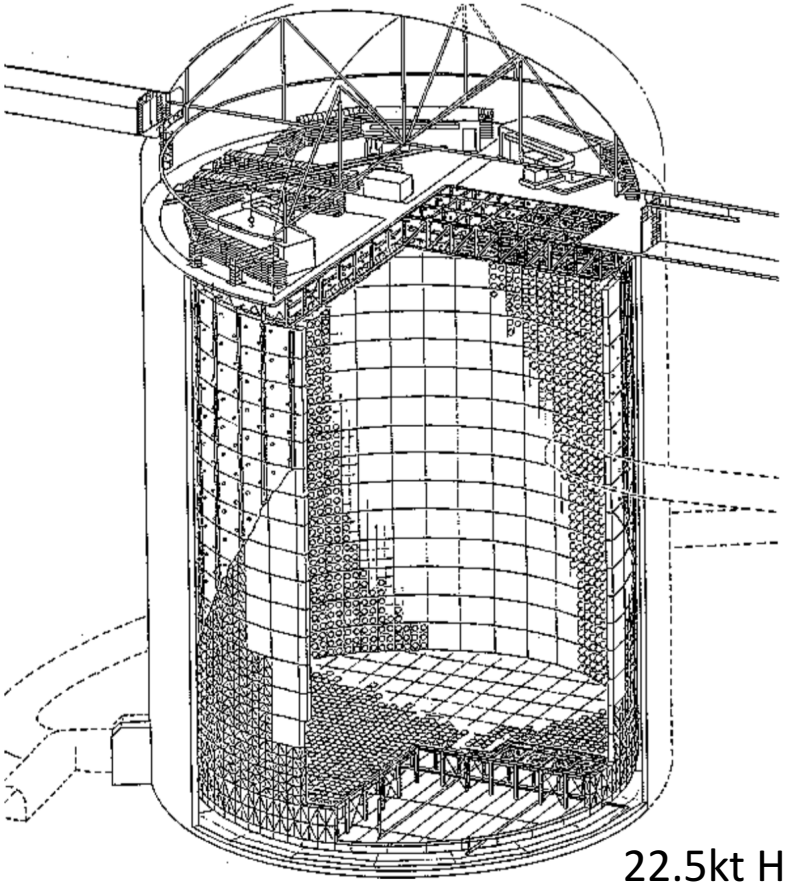


flux	$P_{ee,vac}$
pp	0.62±0.11
^{7}Be	0.51±0.07
pep	0.62±0.17

SNO and Super-Kamiokande

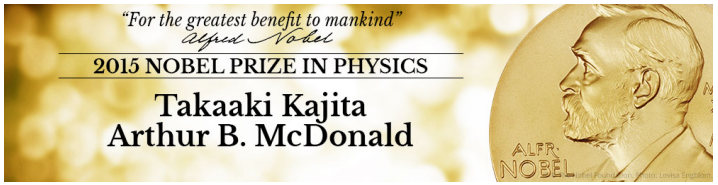


1kt D_2O

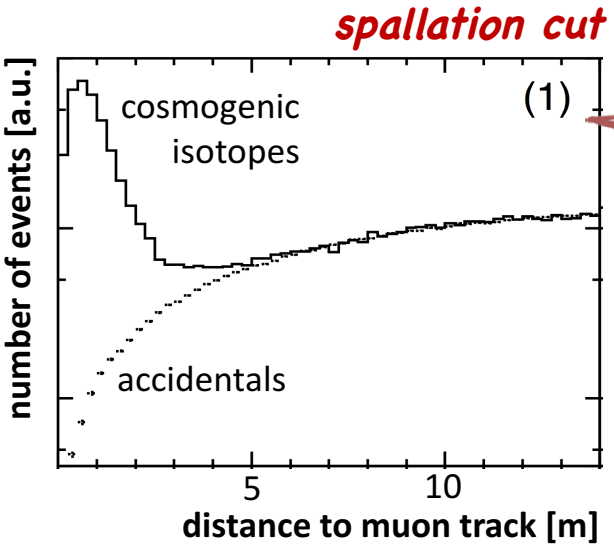


22.5kt H_2O

$$
\begin{aligned}
&(\mathrm{ES}) \quad \nu_x + e^- \rightarrow \nu_x + e^- \\
&(\mathrm{CC}) \quad \nu_e + d \rightarrow p + p + e^- \\
&(\mathrm{NC}) \quad \nu_x + d \rightarrow p + n + \nu_e
\end{aligned}
$$



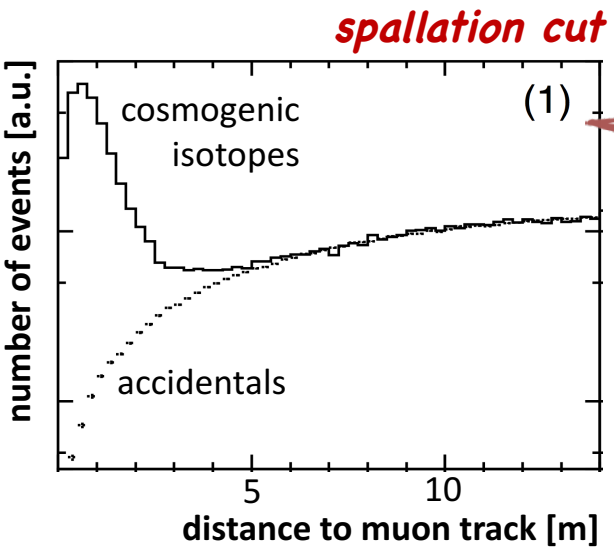
New SK-IV analysis

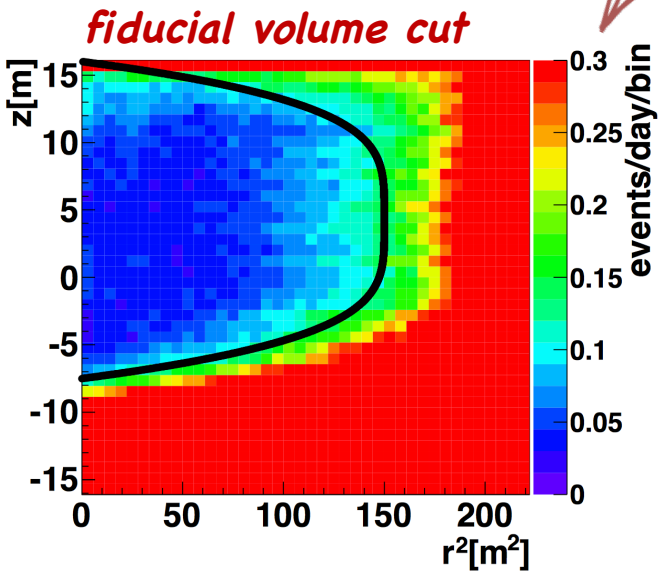


Solar neutrino event selection

- **Spallation cut:** correlation to parent muons

New SK-IV analysis

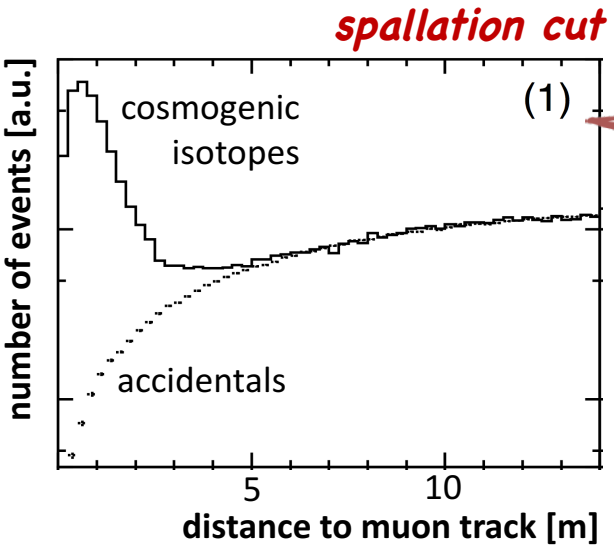


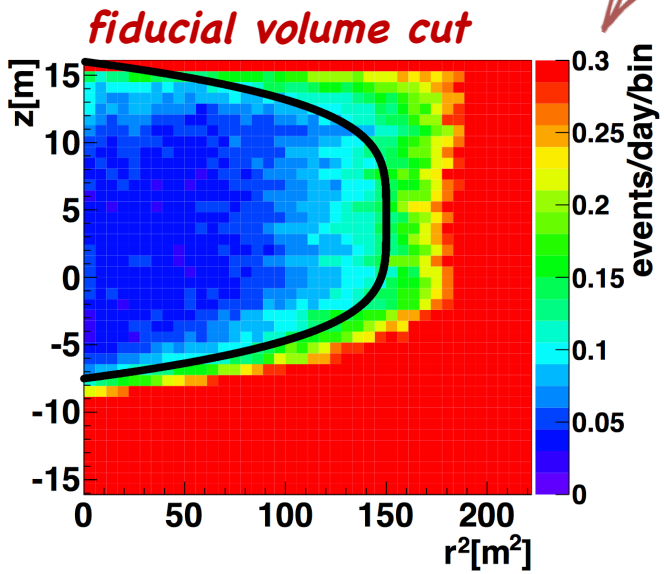


Solar neutrino event selection

- **Spallation cut:** correlation to parent muons
- **Fiducial volume cut**

New SK-IV analysis

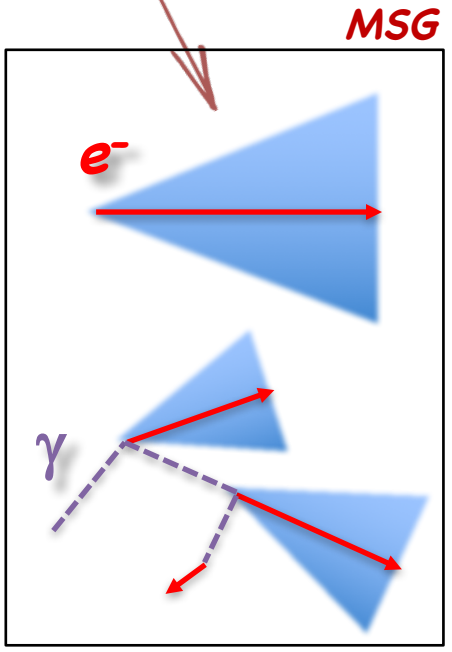




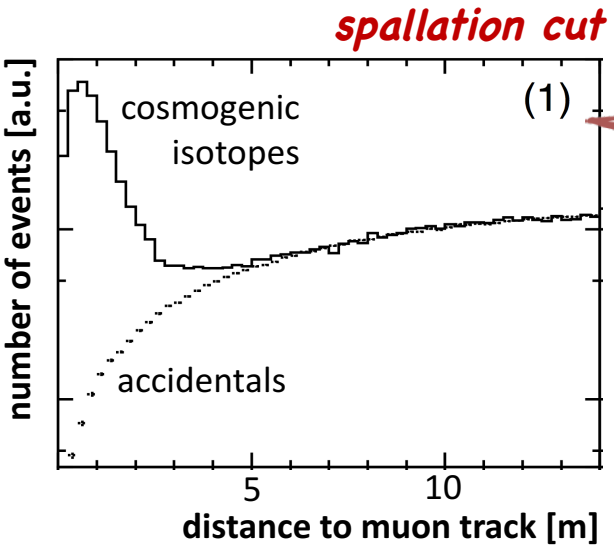
Solar neutrino event selection

- **Spallation cut:** correlation to parent muons
- **Fiducial volume cut**
- **Multiple Scattering Goodness (MSG)** for low-energy gamma BG rejection

NEW!



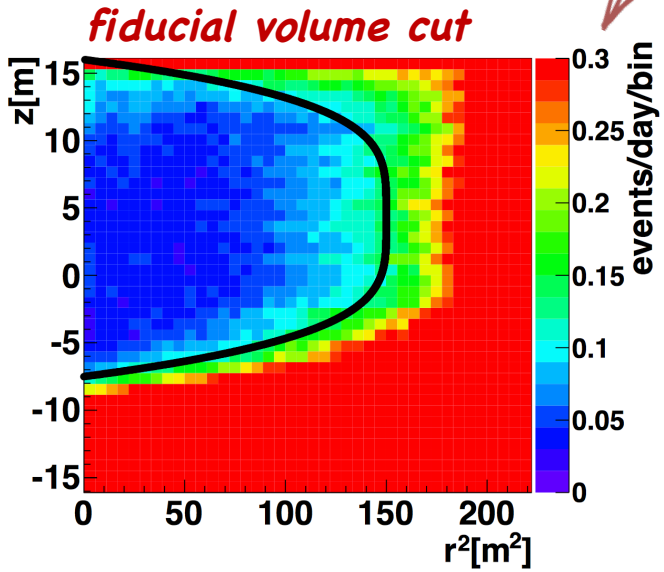
New SK-IV analysis

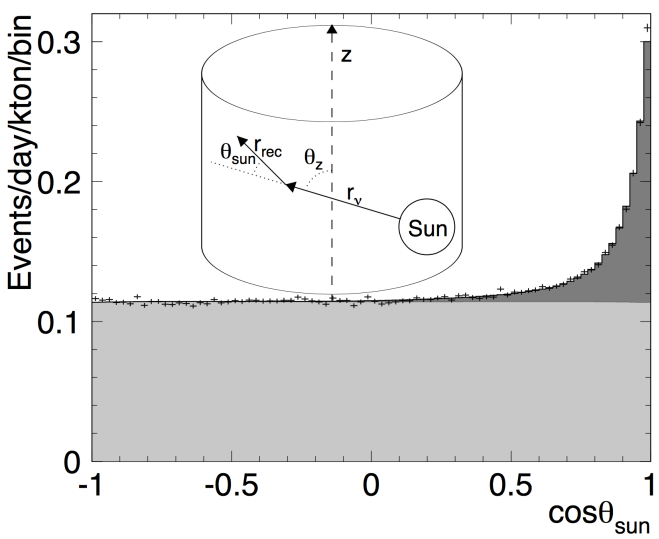


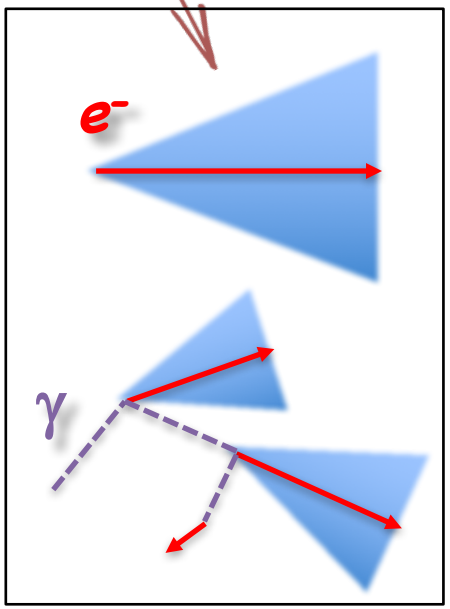
Solar neutrino event selection

- **Spallation cut:** correlation to parent muons
- **Fiducial volume cut**
- **Multiple Scattering Goodness (MSG)** for low-energy gamma BG rejection
- **Directional fit**

NEW!

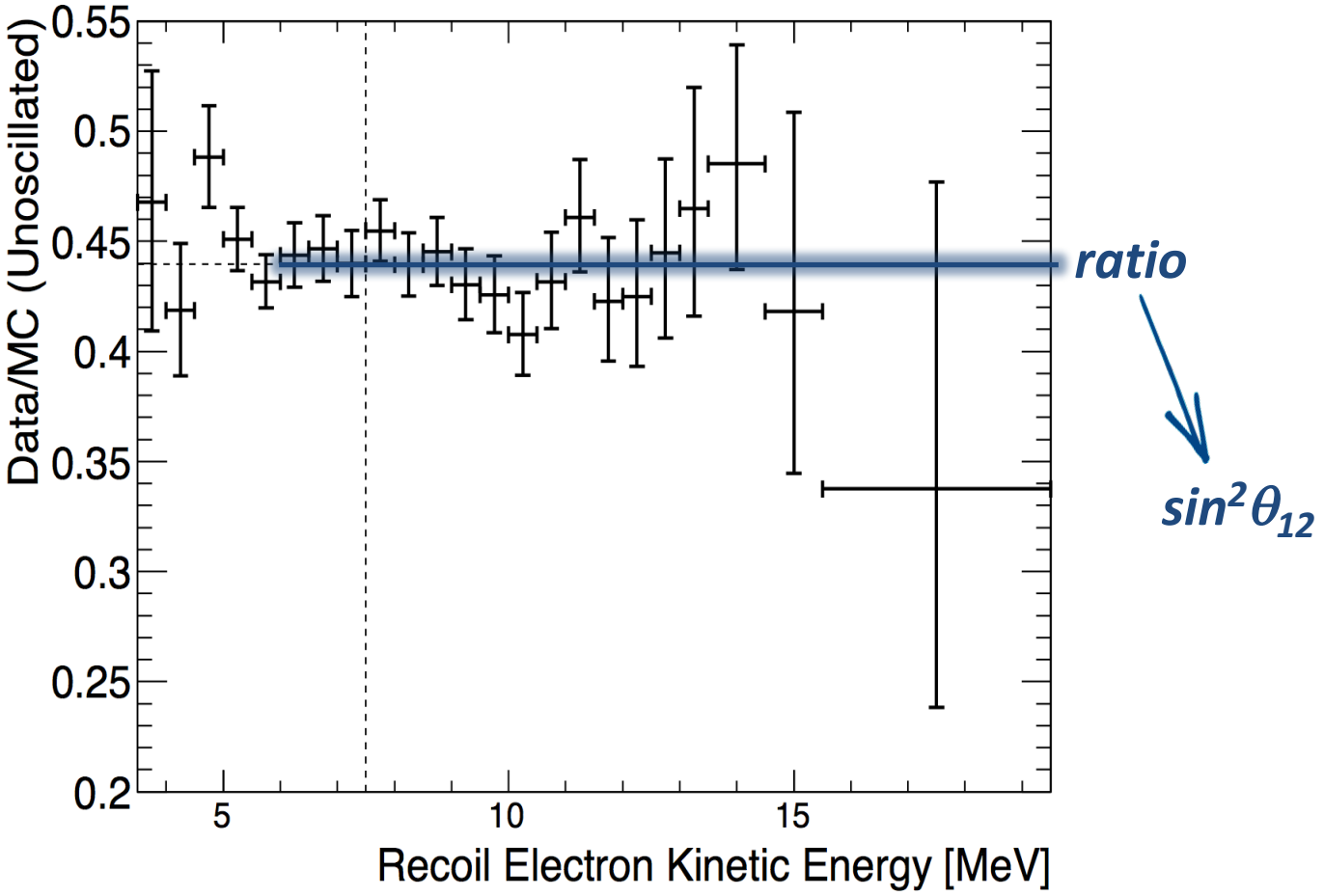






SK-IV electron recoil spectrum

ES data spectrum divided by SSM predicted shape for ^{8}B-ν's → **sensitive to $P_{ee}(E)$**



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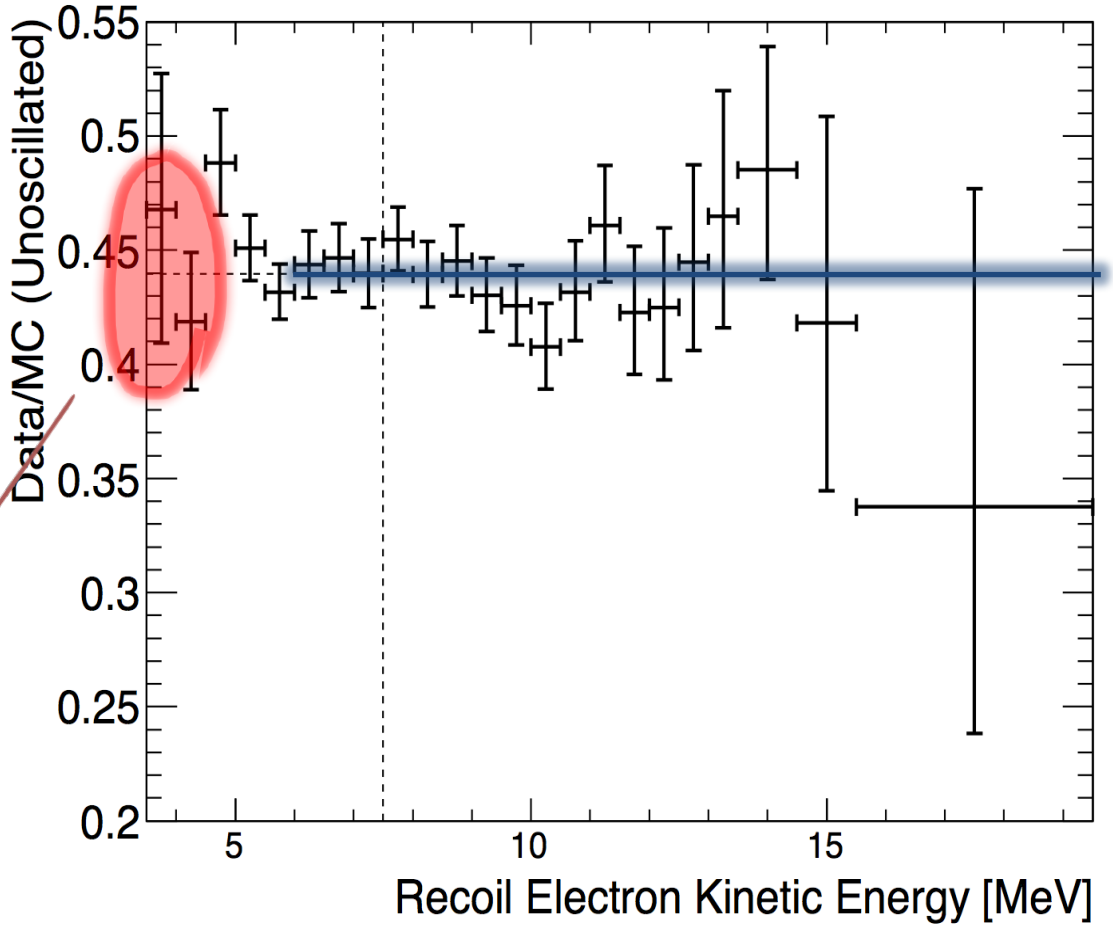


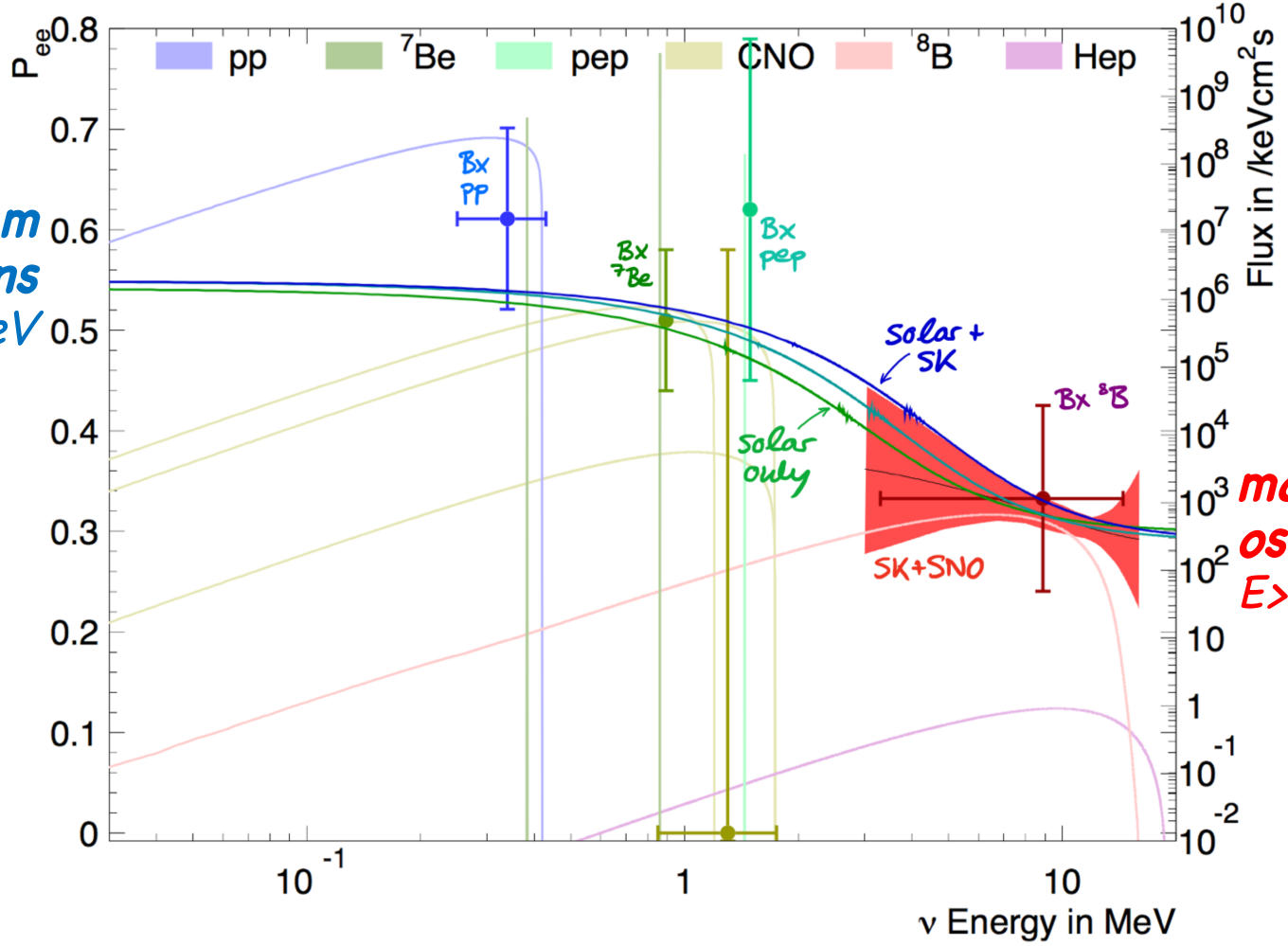
MSG! *new low-energy data points*

spectral upturn *sensitive to* Δm^2_{21}

ratio

$\sin^2\theta_{12}$

Current status of $P_{ee}(E)$ from solar data



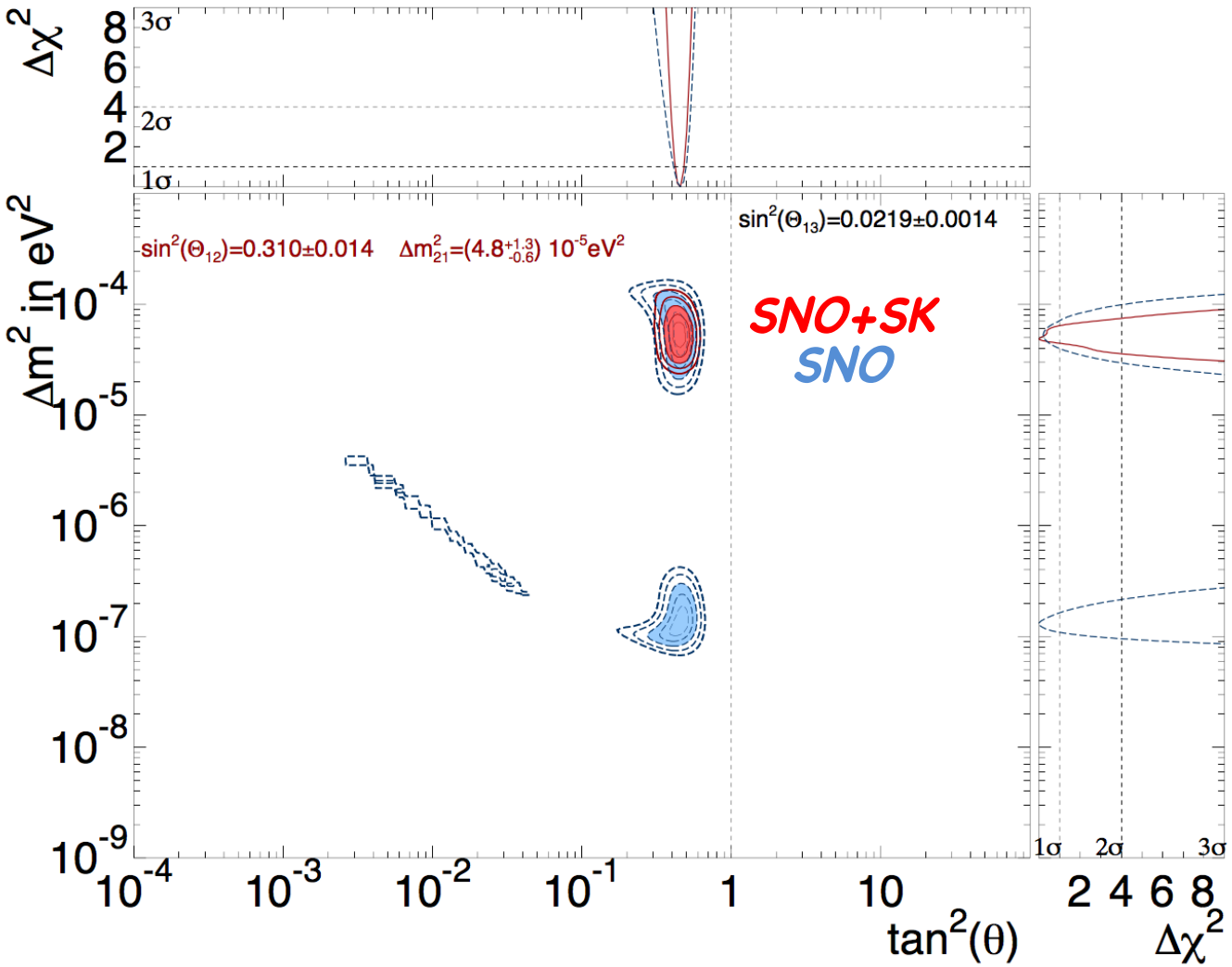
vacuum oscillations *E<1MeV*

matter oscillations *E>5MeV*

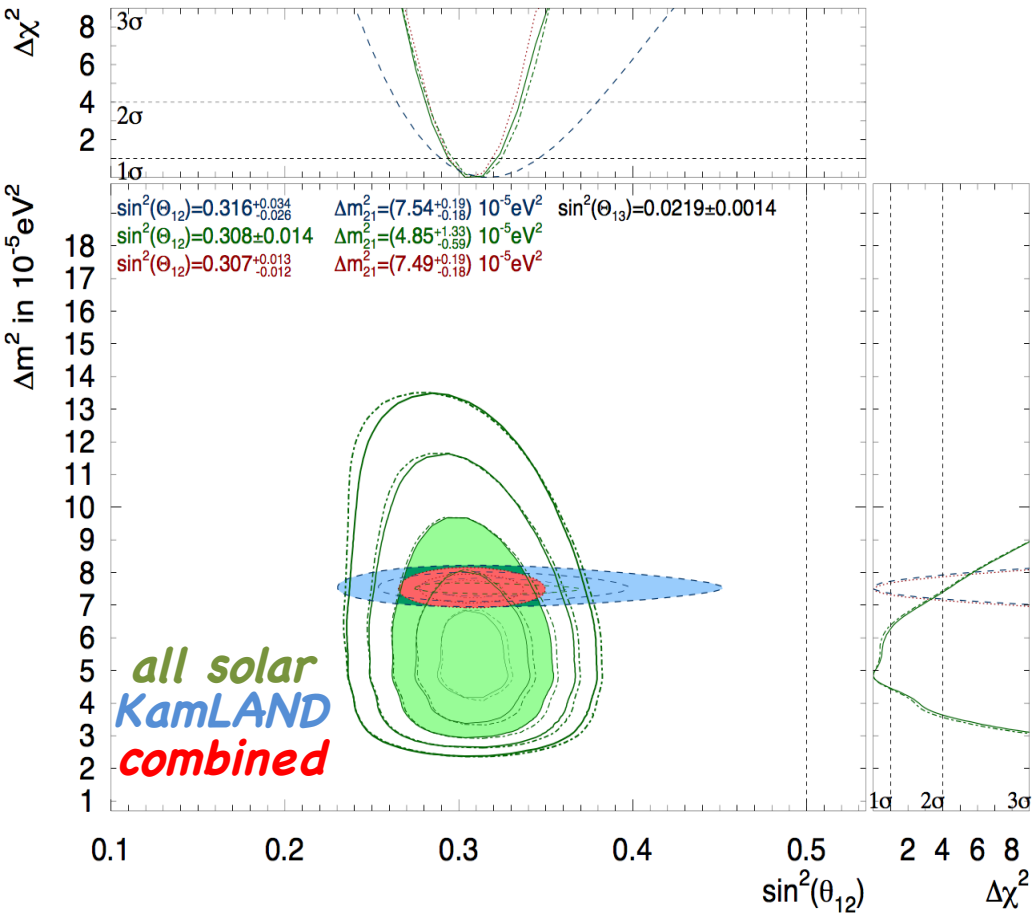
→ ***full agreement with basic MSW-LMA scenario***

Results on solar mixing parameters (1)

→ oscillation fit driven by P_{ee} measurement of high-energy ^{8}B neutrinos



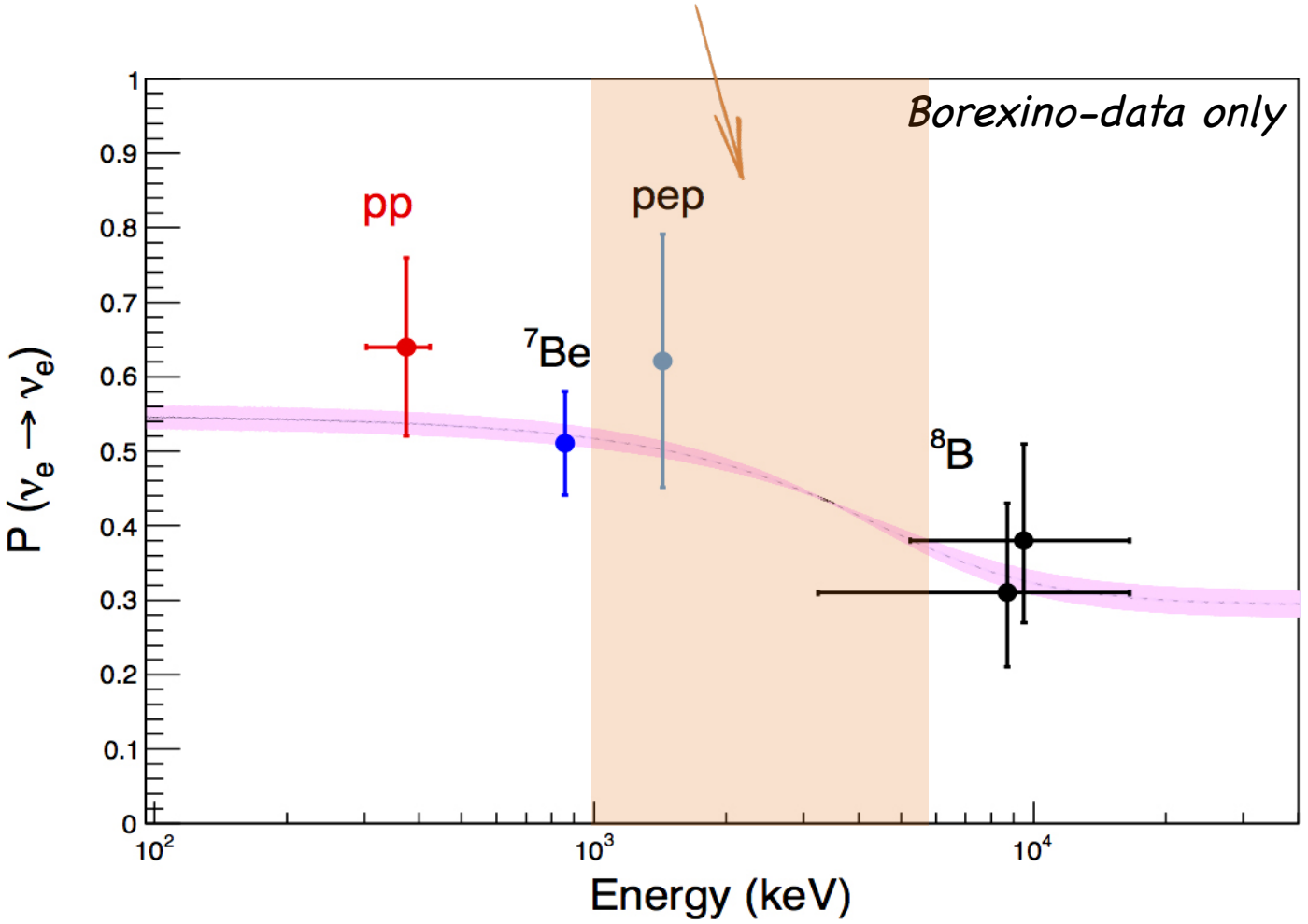
Results on solar mixing parameters (2)



- → **Solar results** still dominate θ_{12}, **KamLAND results** Δm^2_{21}
- → **Solar data:** mixing parameters still dominated by SK+SNO
- → **+KamLAND:** tension in the best-fit value for Δm^2_{21}: 5×10^{-5} vs. 7×10^{-5} eV^2

Motivations to improve on $P_{ee}(E)$

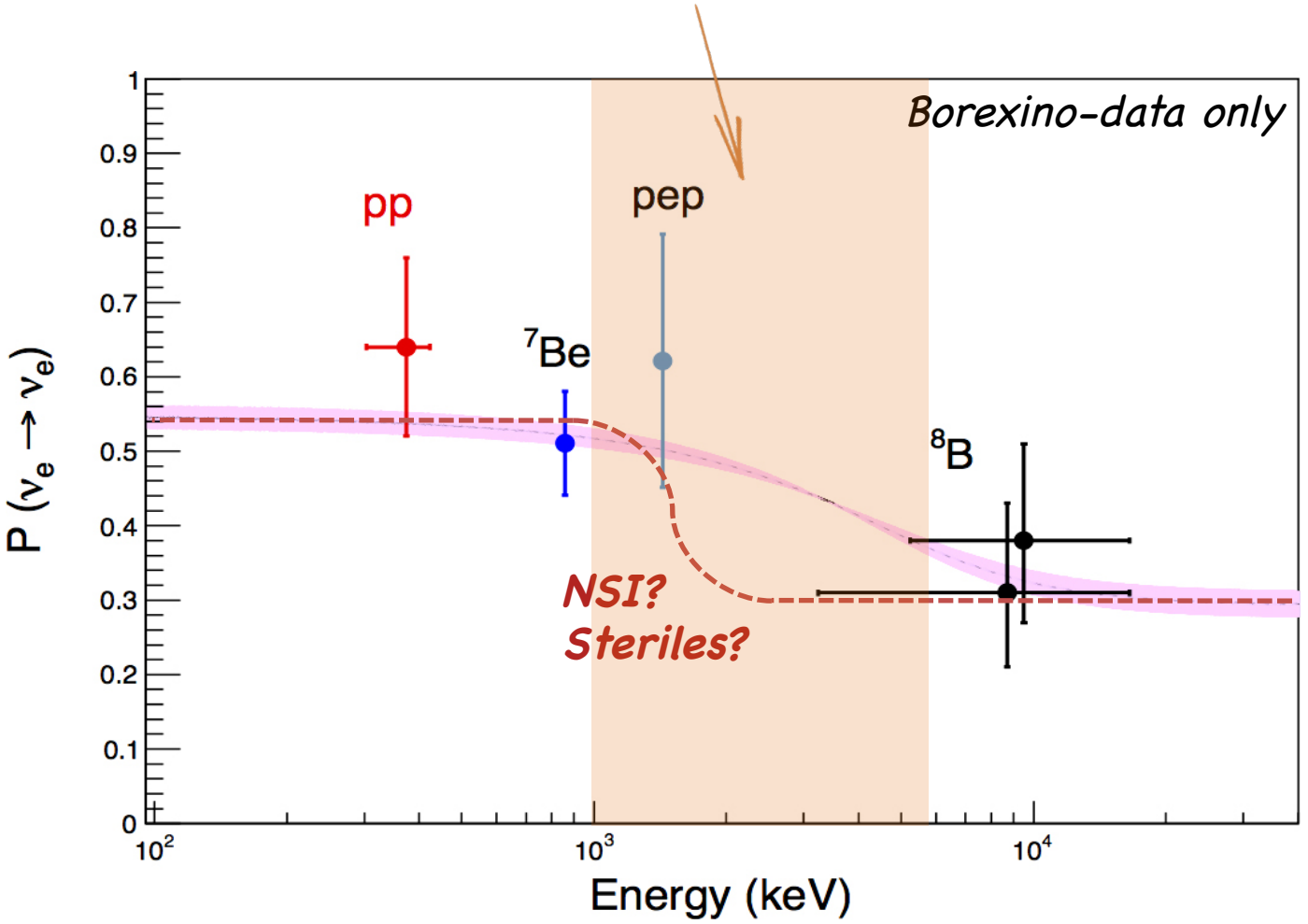
- Resolve Δm^2_{21} inconsistency between solar and KamLAND data
- Better constrain $P_{ee}(E)$ in **transition region**



MSW-LMA expectation

Motivations to improve on $P_{ee}(E)$

- Resolve Δm^2_{21} inconsistency between solar and KamLAND data
- Better constrain $P_{ee}(E)$ in **transition region → sensitivity to new physics?**



MSW-LMA expectation

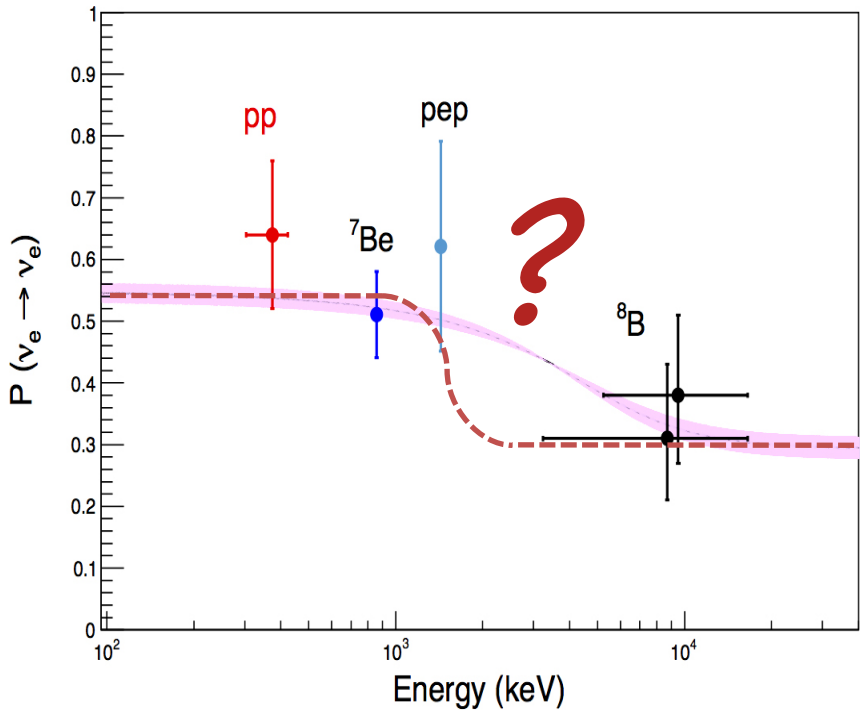
How to improve?

- **More accurate results on low-E data**
  Borexino Phase-2 data (4++ years)
  - ultra-low background conditions
  - efforts to reduce convection in target

- **Day/night modulation in ^{8}B-ν rate**
  current SK data shows evidence
  → provides sensitivity to Δm^2_{21}

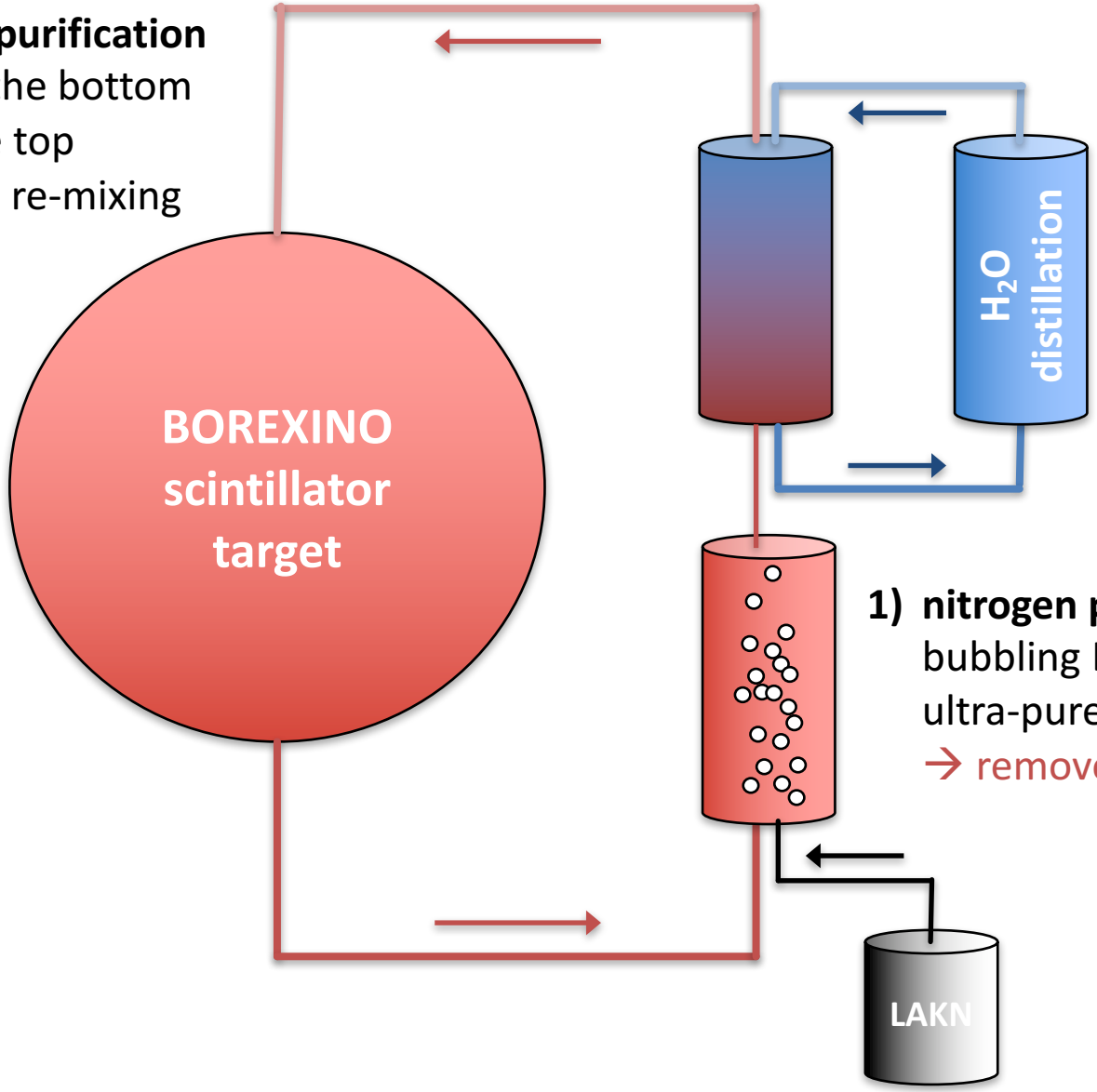
- **Lower threshold on ^{8}B neutrinos**
  in large liquid scintillator detectors
  → elastic scattering data to 2 MeV?

- **Utilize Charged-Current detection**
  for direct measurement of ν energy,
  e.g. via ^{13}C or isotope loading (^{7}Li etc.)
  → **water-based scintillator** talk by Bob Svoboda



Borexino purification campaign (2010-12)

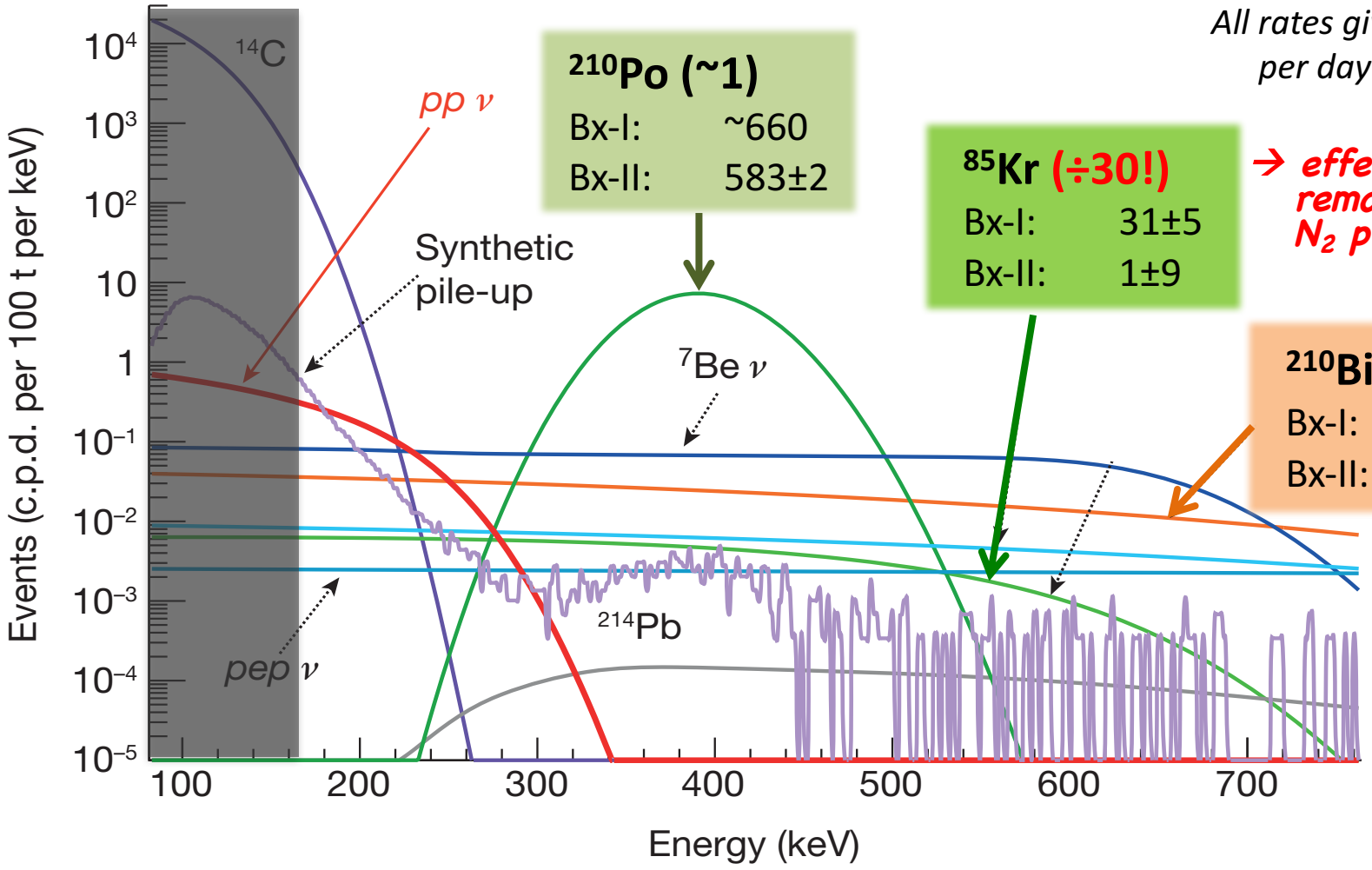
loop-mode purification
- extract at the bottom
- refill at the top
- try to keep re-mixing inside low



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)



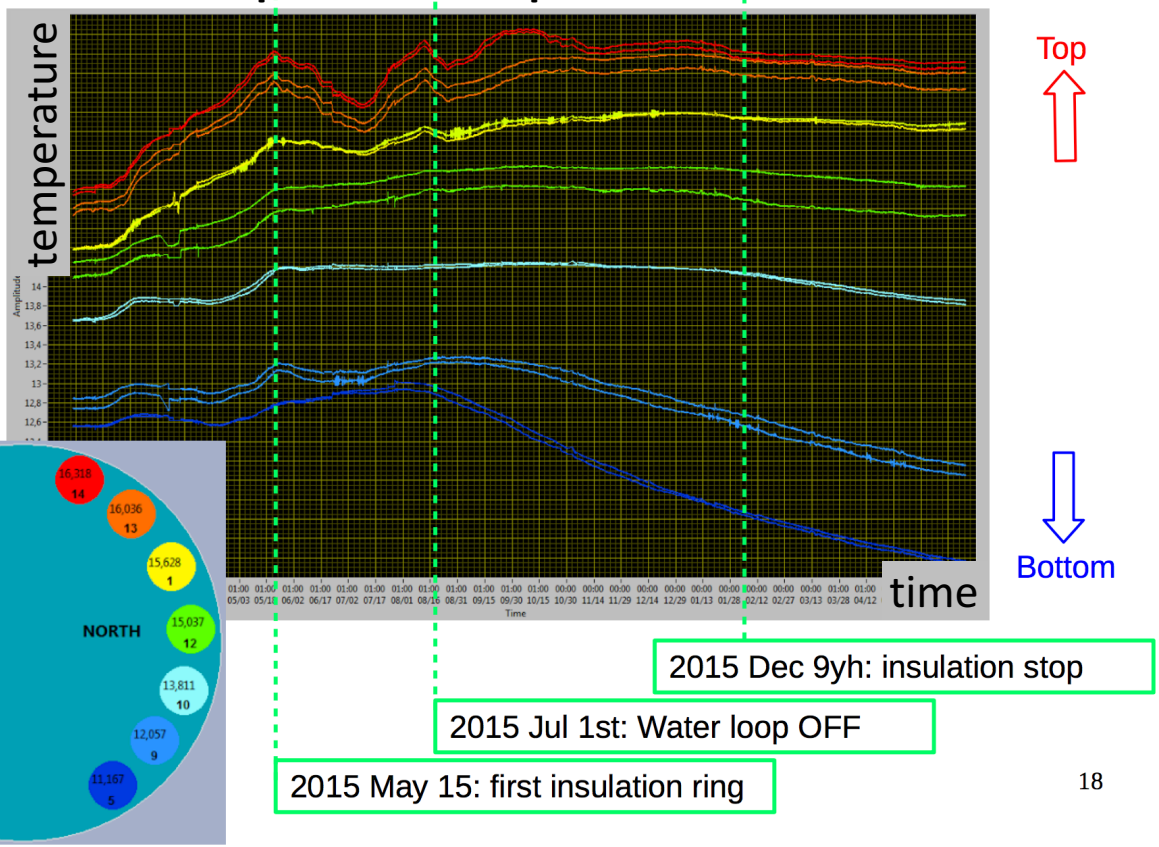
Natural radioactivity: (decay chains broken)

	Bx-I	Bx-II
^{238}U	$(5.3\pm0.5)\times10^{-18}$ g/g	$< 9.7\times10^{-19}$ g/g
^{232}Th	$(3.8\pm0.8)\times10^{-18}$ g/g	$< 2.9\times10^{-18}$ g/g

New thermal insulation for Borexino

slide by N. Rossi

Time development of temperature sensors



18

→ stabilize temperature gradient to stop convection → **BG stabilization** (CNO/pep)

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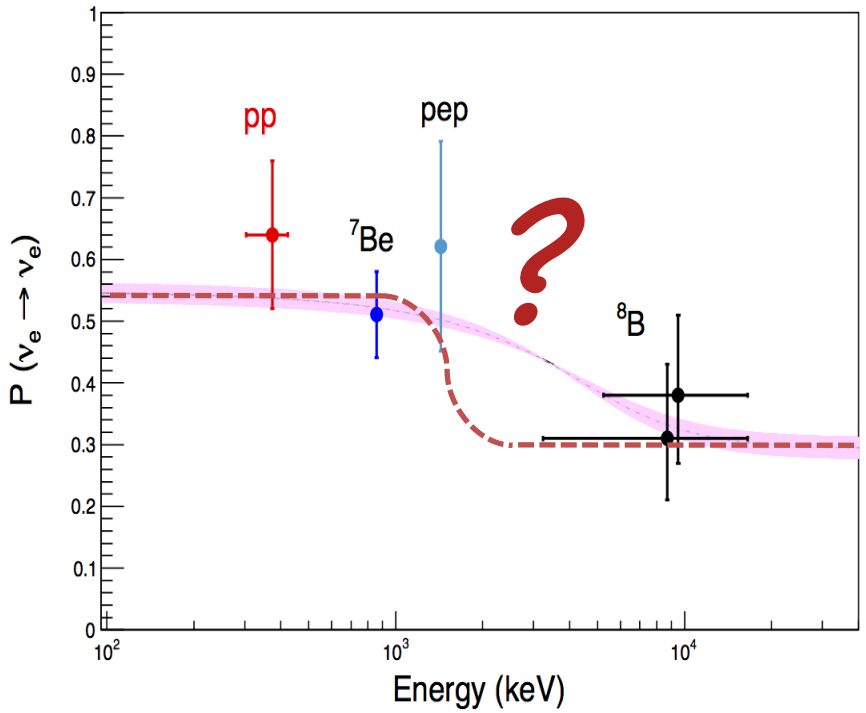
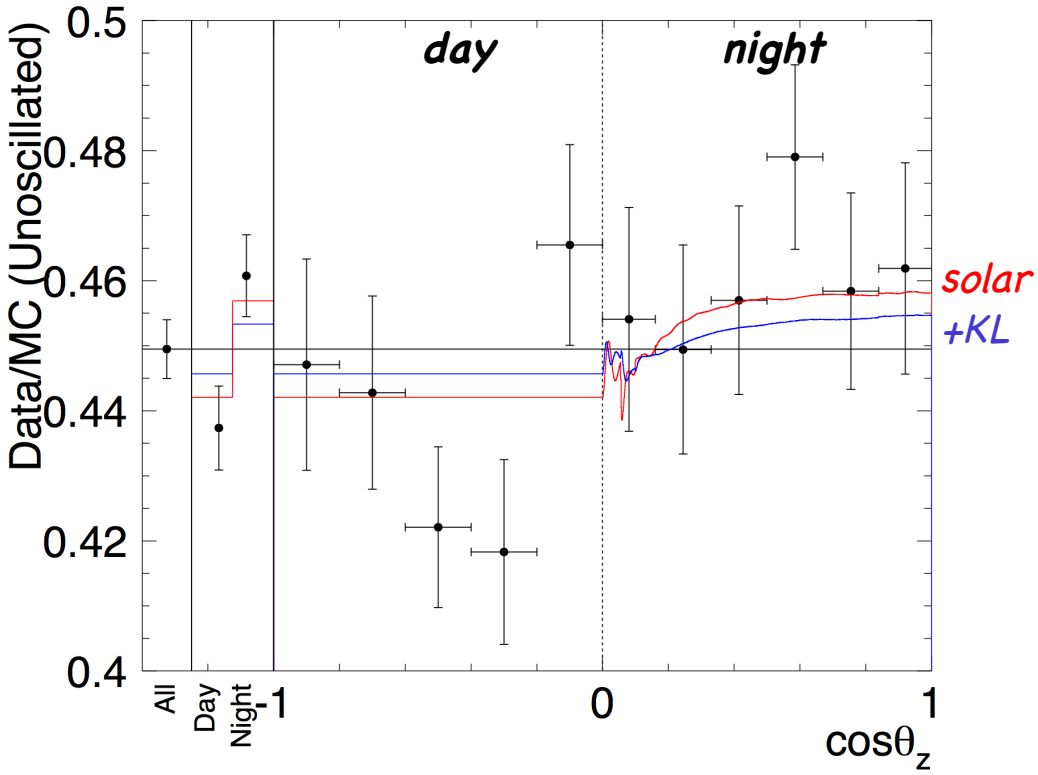
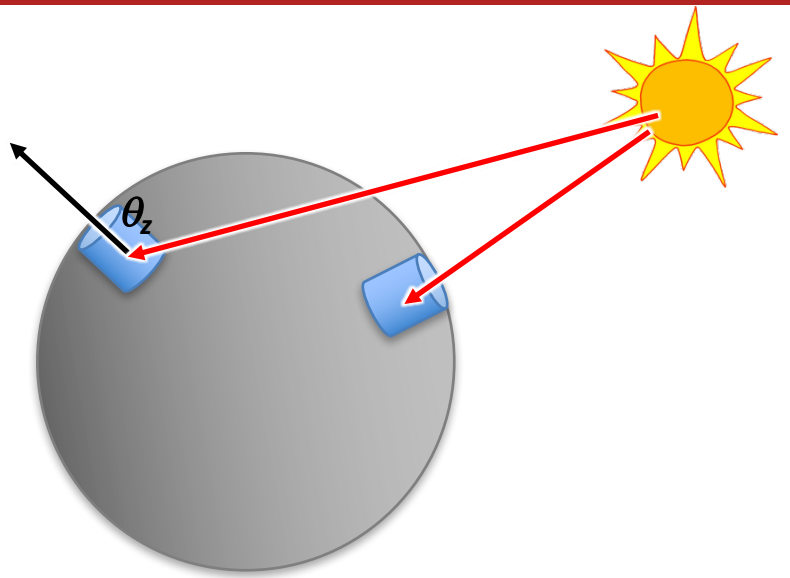


^{8}B day/night-modulation and Δm^2_{21}

MSW-LMA Day-Night-effect
predicts re-generation of ^{8}B **electron ν's**
when crossing the Earth matter potential

→ **size of effect depends on value of Δm^2_{21}**





→ **New SK-IV data**

- first evidence (3σ) for non-zero effect:

$$A_{DN} = (-3.6 \pm 1.6 \pm 0.6)\ \%$$

- amplitude of asymmetry favors lower **solar** Δm^2_{21} over **KamLAND** value

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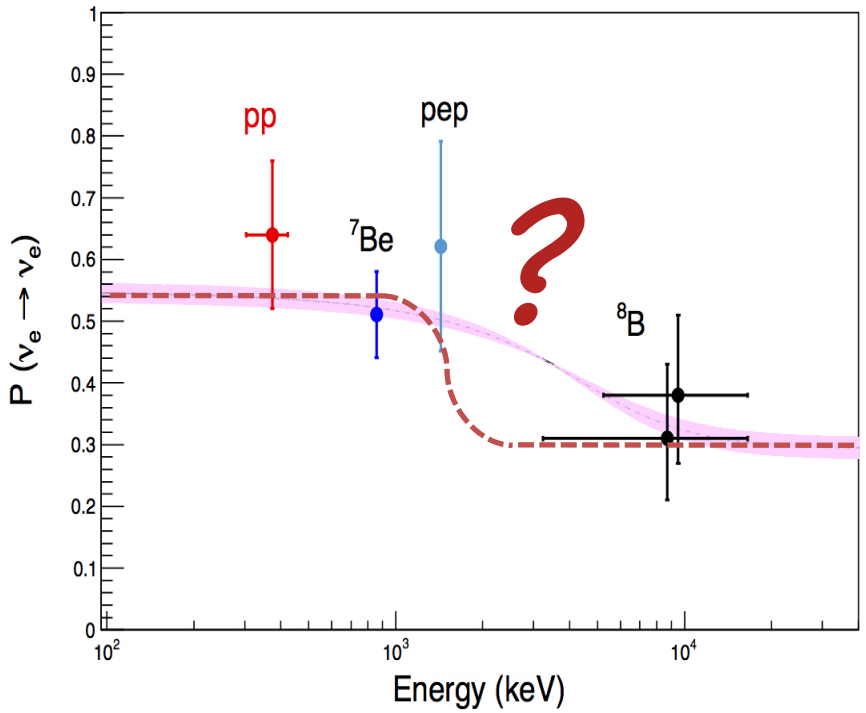
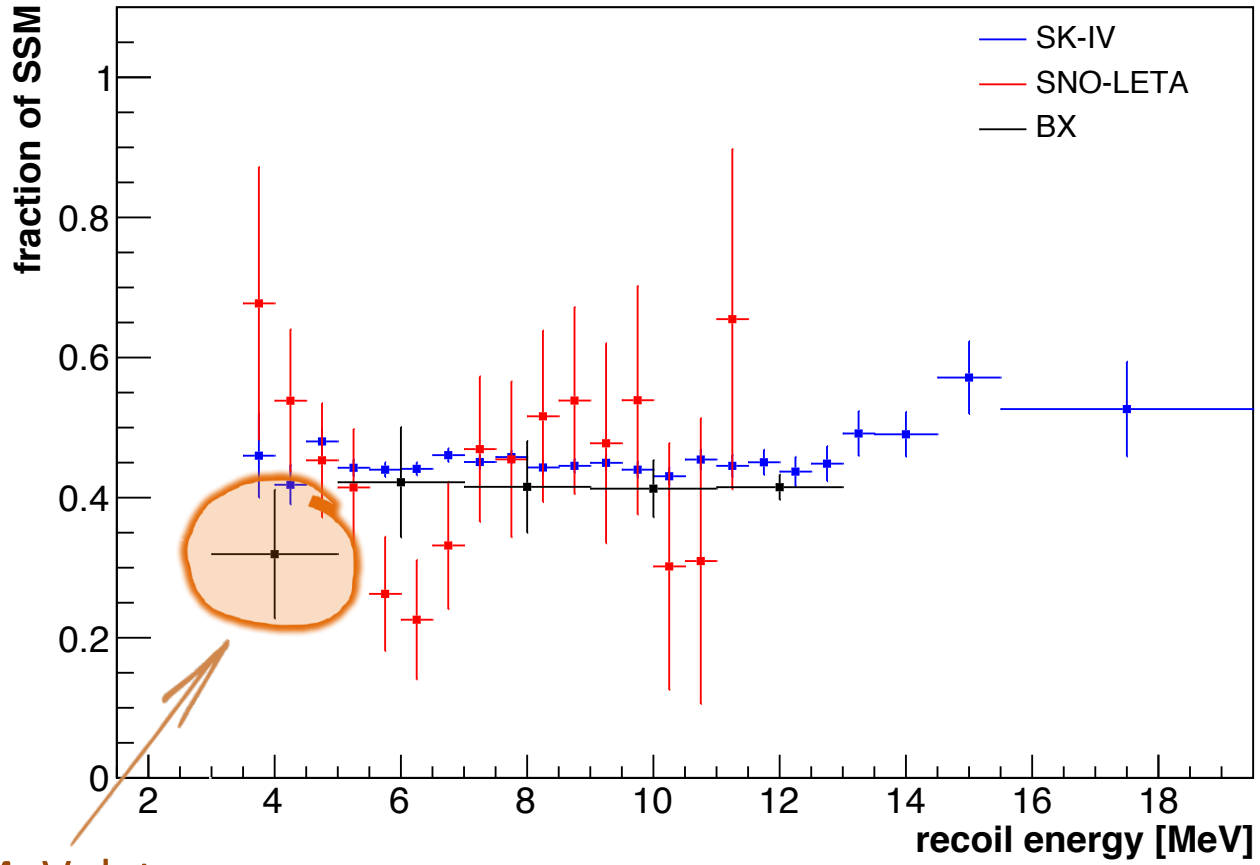


Low-threshold analyses of ^{8}B neutrinos

^{8}B electron recoil (ES) spectra of **SK-IV**, **SNO** and **Borexino**:



[3–5] MeV data point of Borexino: **low statistics (100t)**

→ Upcoming large-scale detectors: SNO+ (1kt), **JUNO (20kt) ,** RENO-50 (18kt) ...

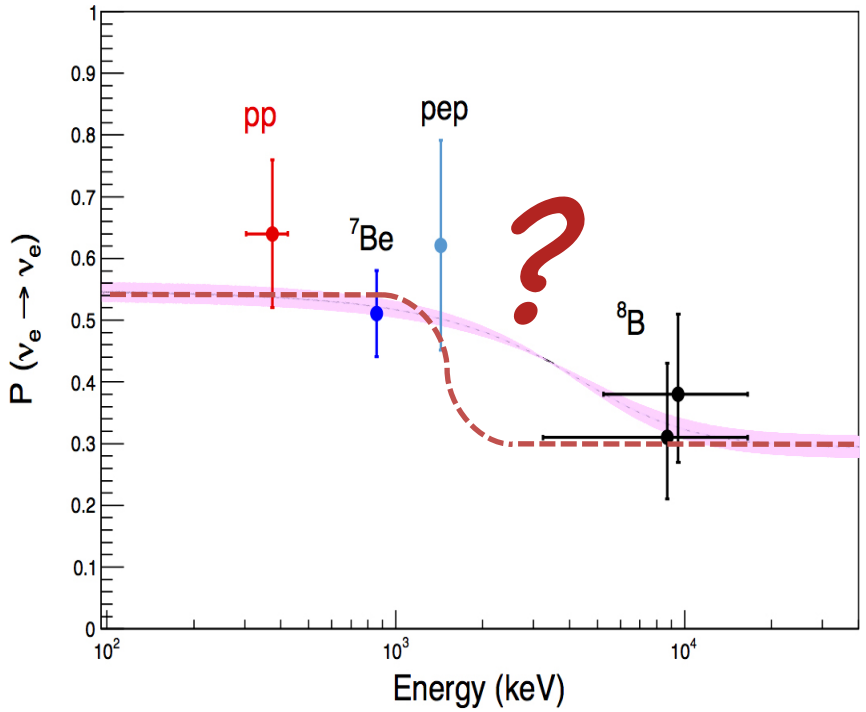
How to improve?

- **More accurate results on low-E data**
  Borexino Phase-2 data (4++ years)
  - ultra-low background conditions
  - efforts to reduce convection in target

- **Day/night modulation in ^{8}B-ν rate**
  current SK data shows evidence
  → provides sensitivity to Δm^2_{21}

- **Lower threshold on ^{8}B neutrinos**
  in large liquid scintillator detectors
  → elastic scattering data to 2 MeV?

- **Utilize Charged-Current detection**
  for direct measurement of ν energy,
  e.g. via ^{13}C or isotope loading (^{7}Li etc.)
  → **water-based scintillator** talk by Bob Svoboda



Conclusions

- **Solar neutrinos** played important role in **discovery of oscillations**
- MSW-LMA vacuum and matter regions well understood,
  but **mild tension with KamLAND** data
- New oscillation/neutrino physics might wait in the **transition region**!
  → several access ways:
  - **low-threshold** (CC?) and **day/night effect in ^{8}B neutrinos**
  - pep-neutrino line
- Running detectors (Borexino, SK) are still able to contribute
- New detectors upcoming: SNO+, JUNO, ...
- **Many new ideas:**
  - doped/directional scintillators: LENS, THEIA ...
  - noble liquids: CLEAN (LNe), DARWIN (LXe), Argo (LAr) ...

Thank you!

Borexino Collaboration

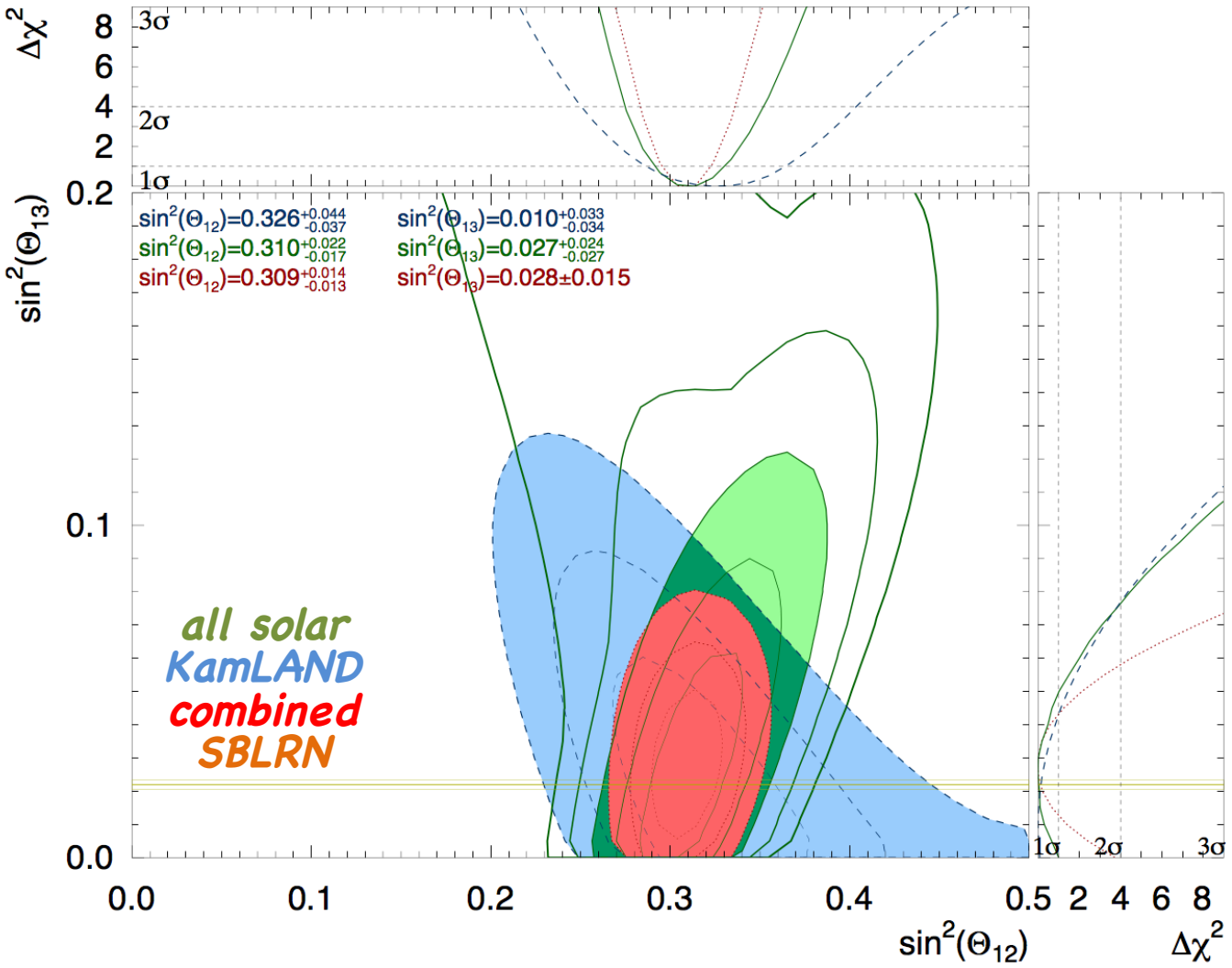
SKOBELTSYN INSTITUTE OF NUCLEAR PHYSICS
LOMONOSOV MOSCOW STATE UNIVERSITY

Joint Institute for
Nuclear Research

TECHNISCHE
UNIVERSITÄT
DRESDEN

Backup slides

New result on θ_{13}



CC detection of ^{8}B on ^{13}C