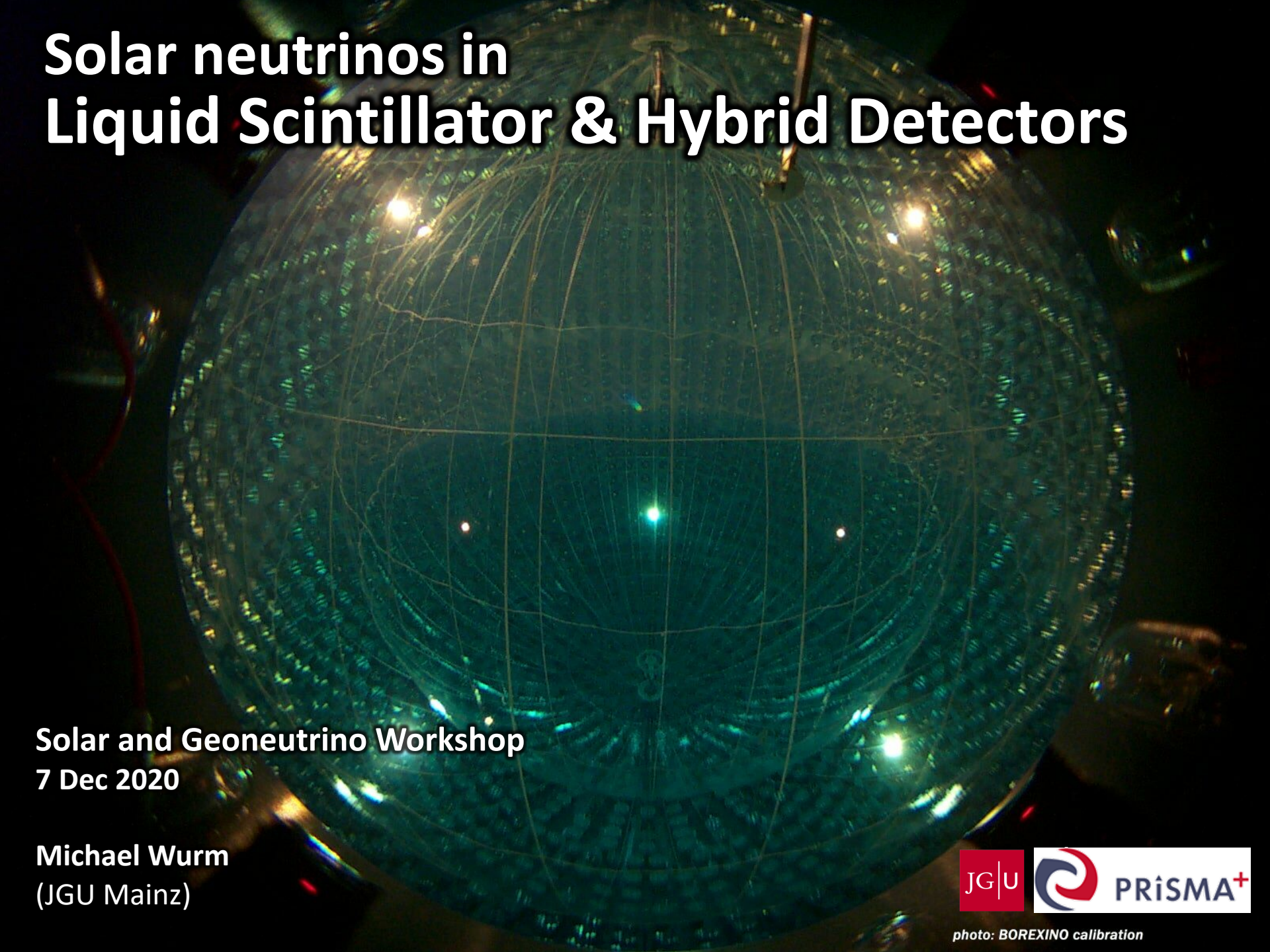
Solar neutrinos in Liquid Scintillator & Hybrid Detectors

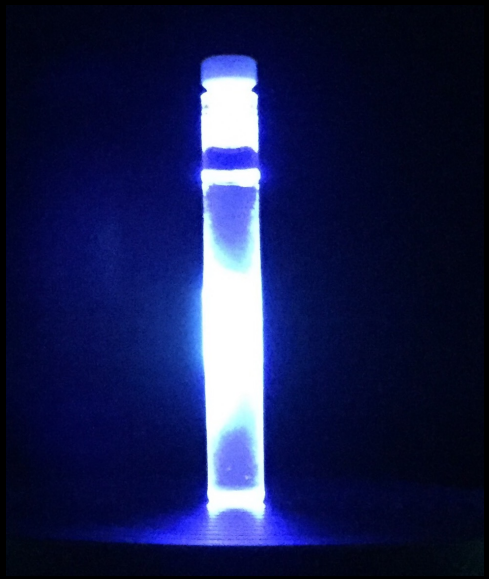


Solar and Geoneutrino Workshop
7 Dec 2020

Michael Wurm
(JGU Mainz)

photo: BOREXINO calibration

Organic Liquid Scintillator Detectors



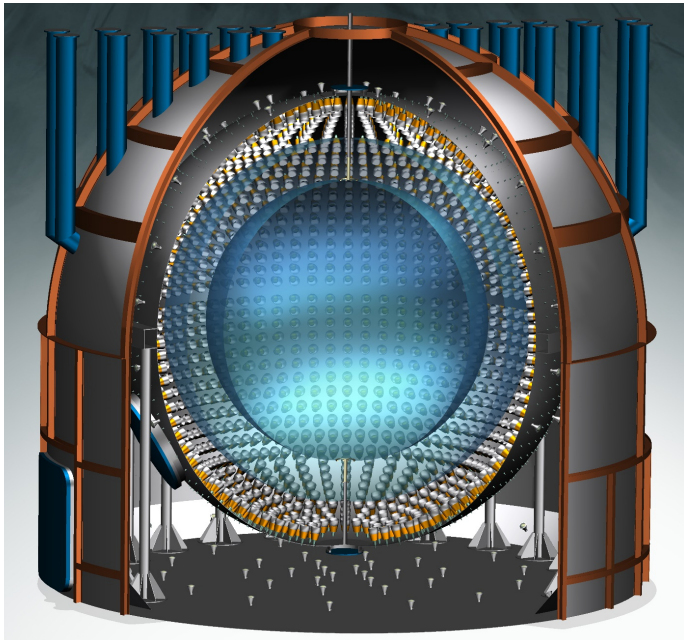
Virtues

- high light yield
  → energy resolution (5% @ 1MeV)
  → very low instrumental threshold (50 keV)
- powerful techniques for radio-purification
  → ultra-low background levels ($\leq 10^{-18}$ U/Th!)
- background discrimination by pulse-shaping
- relatively cheap: $1.5 per liter

Disadvantages

- no (or limited?) directionality
  → no pointing for BG discrimination
- intrinsic ^{14}C (pp) and μ-induced ^{11}C (CNO,pep) BGs

Current State-of-the-Art: Borexino



Borexino key parameters

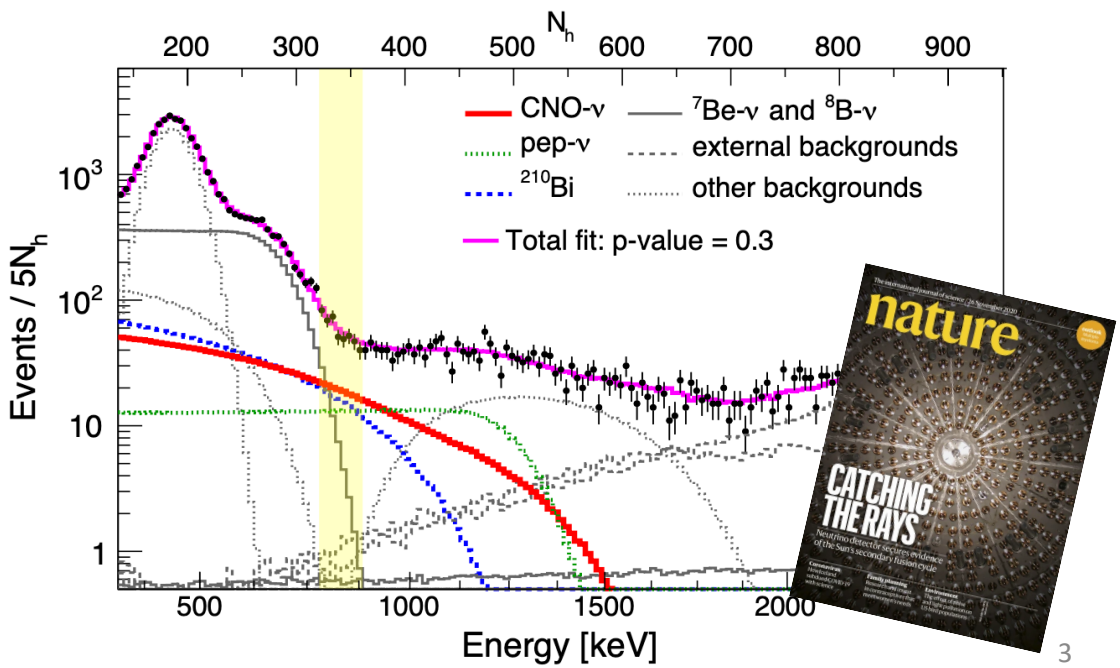
- fiducial mass: <100 tons
- p.e. yield: 550 pe/MeV
- radiopurity: $<10^{-18}$ g/g U/Th
- depth: ~3,500 mwe

long list of successes:

- first spectroscopic measurements of ^{7}Be, pep, pp and finally CNO neutrinos
- lowest energy threshold on ^{8}B neutrinos

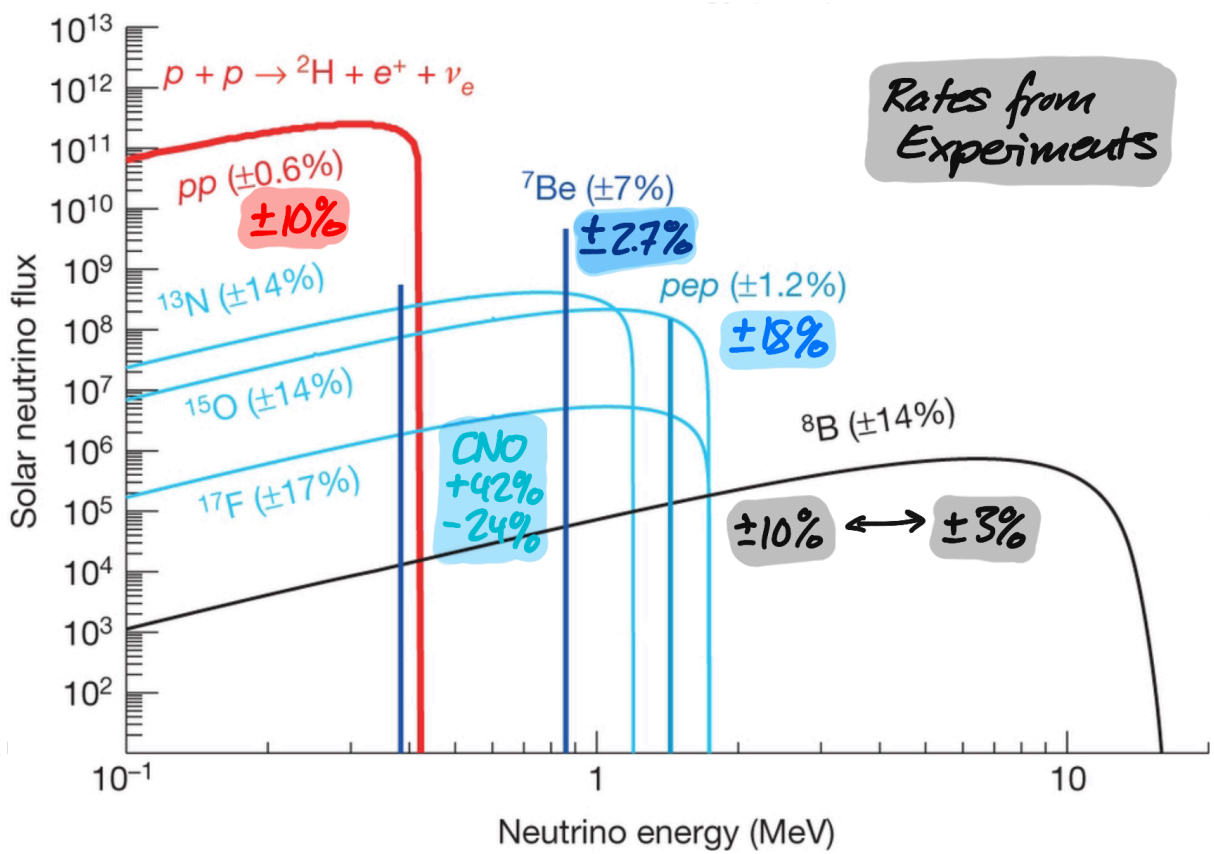
take-away lessons:

- low radioactive background levels and stable detector conditions are the key
- patience (or stubborness) can be helpful



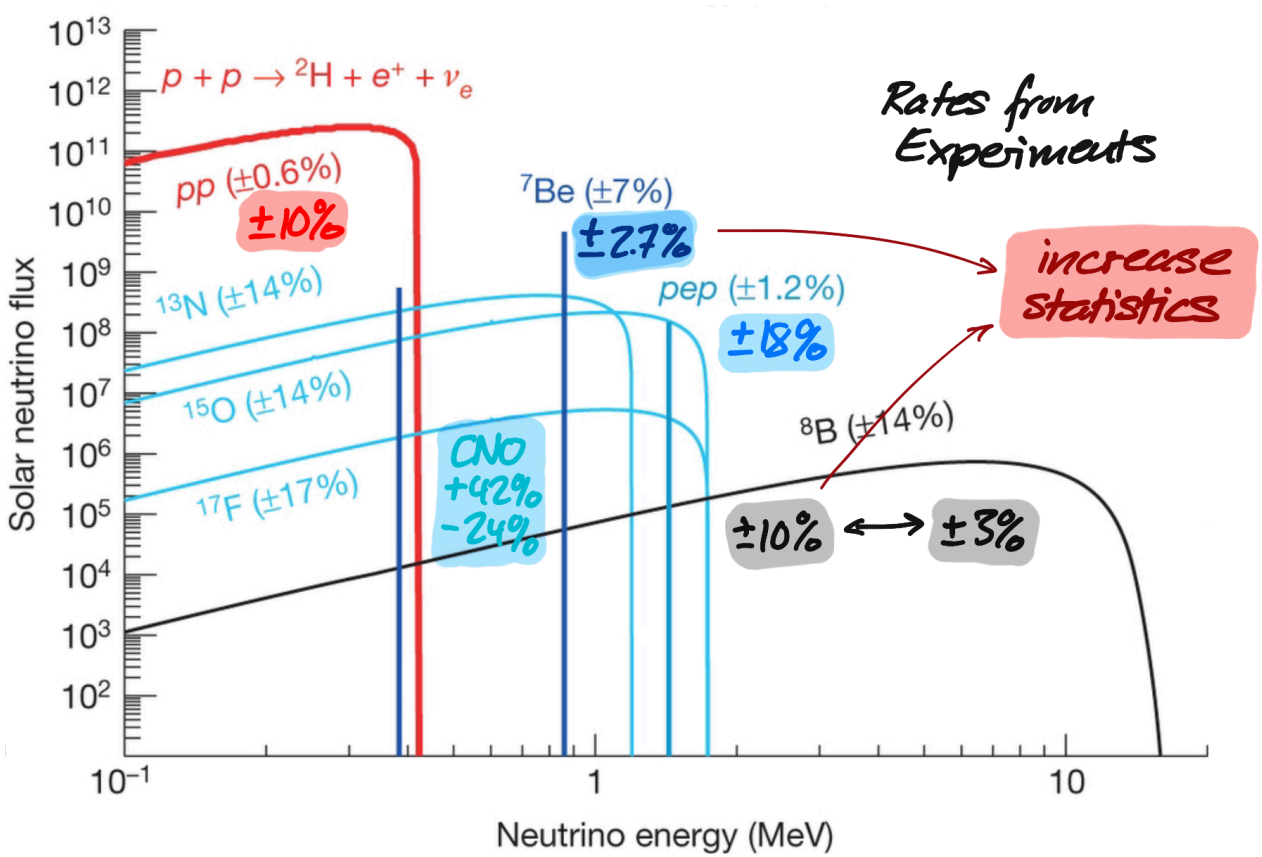
Where we are …

SSM vs. experimental uncertainties



How to improve ^{7}Be+^{8}B measurements?

SSM vs. experimental uncertainties



JUNO

JUNO key parameters

- total mass: 20,000 tons
- p.e. yield: >1100 pe/MeV
- radiopurity: $<10^{-(16\div17)}$ U/Th
- depth: ~1,800 mwe

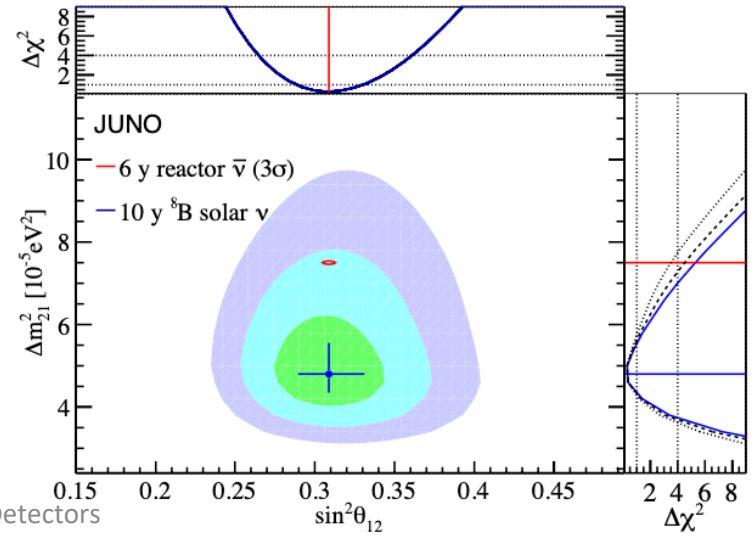
Expected performance

+ great energy resolution and statistics

– (cosmogenic) background levels, threshold

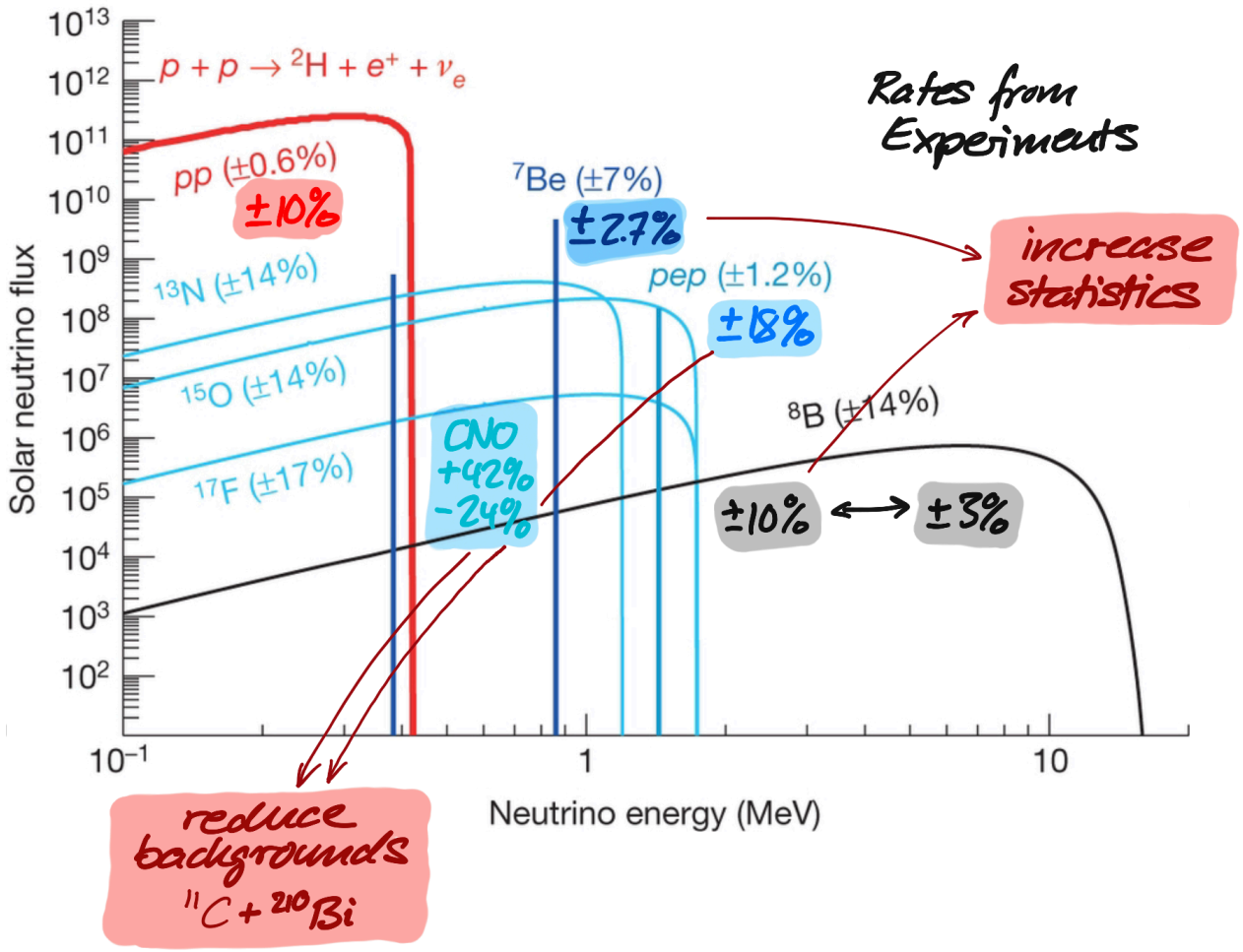
Measuring program

- low-energy ^{8}B neutrino spectrum:
  2 MeV threshold for eES, CC on ^{13}C
  → spectral upturn and day/night asymmetry
- high-statistics on ^{7}Be neutrinos: ~10^4/day
  → search for time varations
- pep, pp, CNO depending on BG levels/discrim.

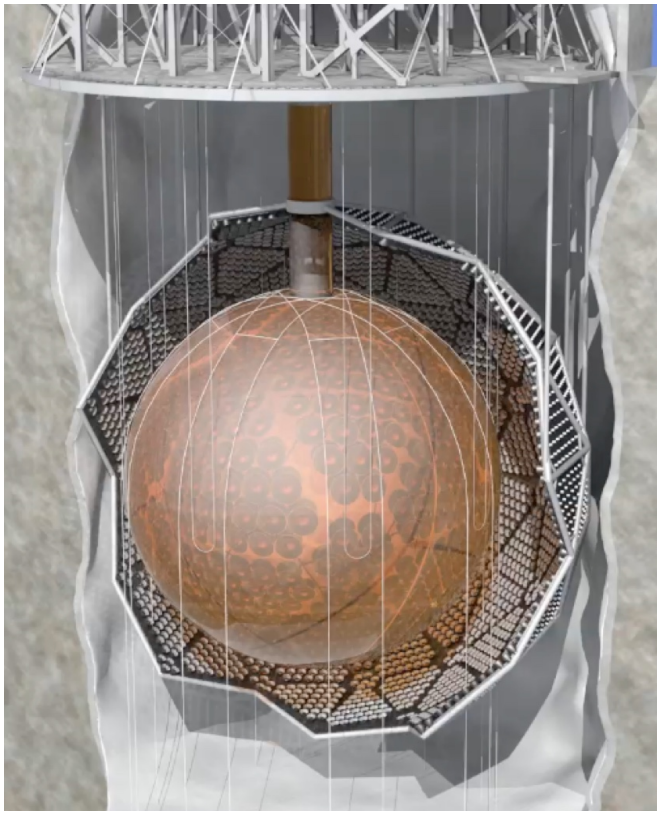


How to improve pep and CNO?

SSM vs. experimental uncertainties



SNO+



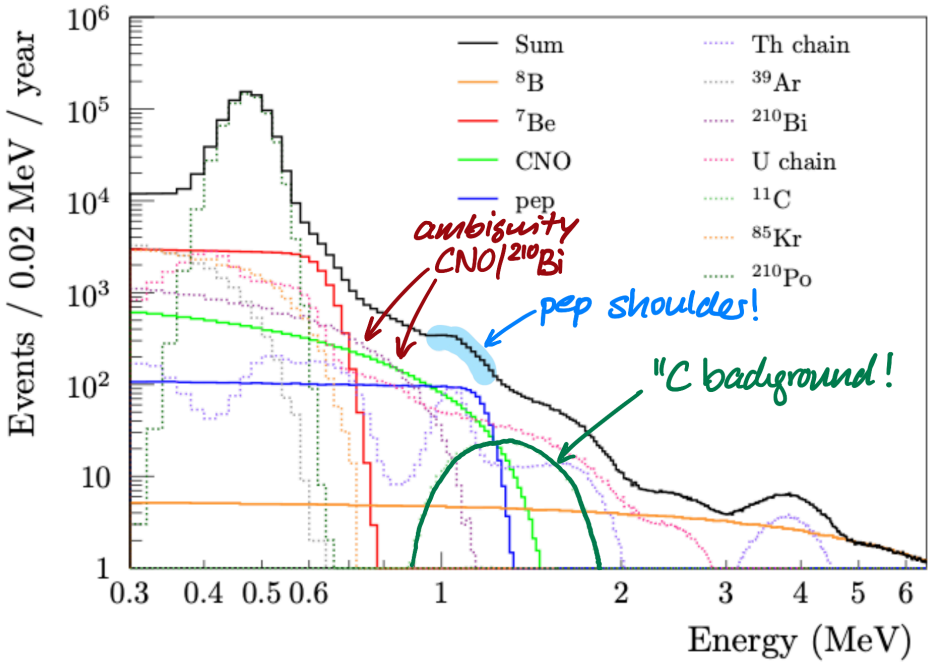
SNO+ key parameters

- total mass: 900 tons
- p.e. yield: 520 pe/MeV
- radiopurity: $<10^{-17}$ U/Th
- depth: ~6,000 mwe

Expected performance

+ larger target mass and cosmic shielding cf. Borexino

o background levels?

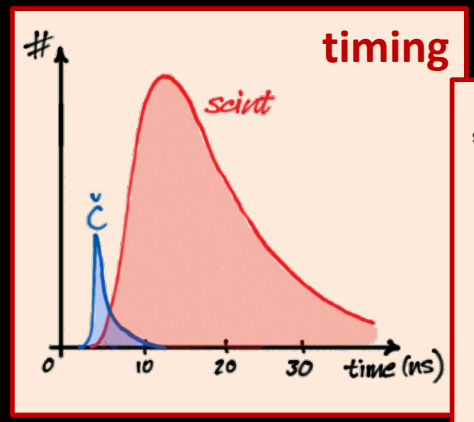


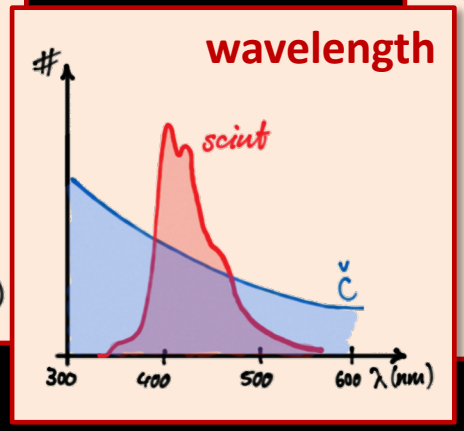
Solar neutrino program (after 0νßß)

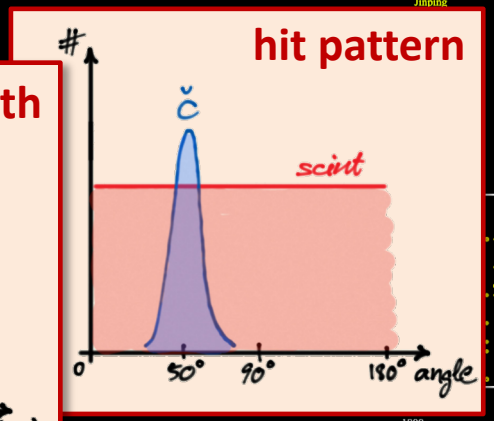
if initial Borexino radiopurity levels will be achieved:

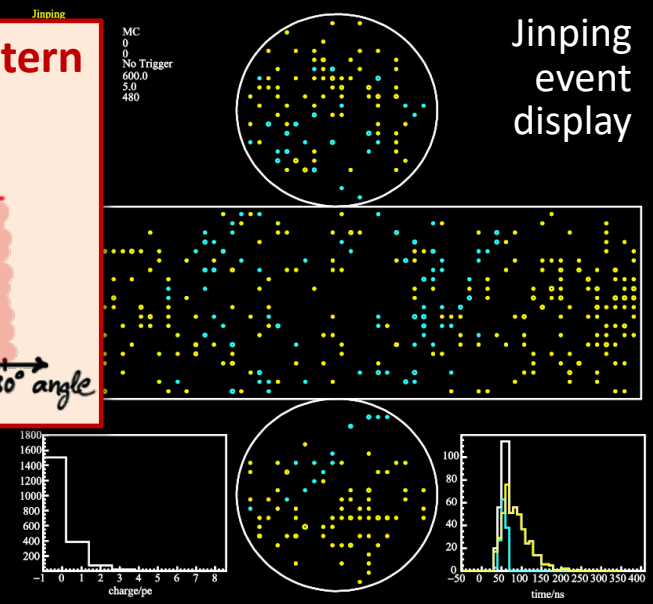
- pep neutrinos at 10% level
- CNO neutrinos at 15% level

Hybrid Cherenkov/Scintillation Detectors









Jinping event display

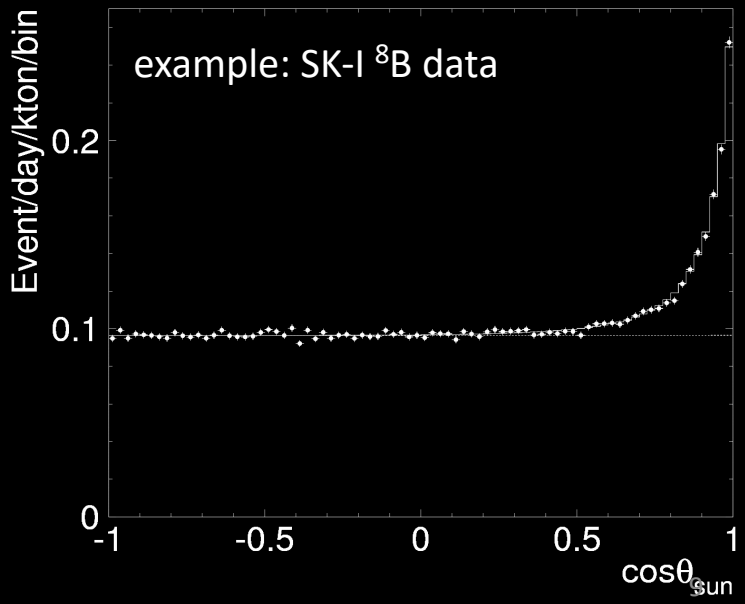
Basic ingredients for hybrid C/S detection:

- scintillator sufficiently transparent to let the Cherenkov light reach the light sensors
- light sensors permitting C/S discrimination (ns-PMTs, LAPPDs, dichroicons)

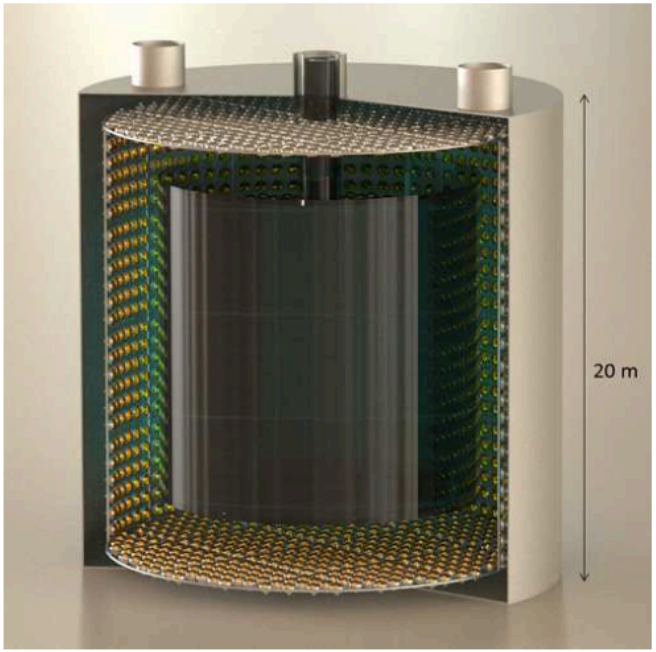
Advantages:

- good light yield, i.e. threshold & resolution
- background discrimination by directionality

→ ideally, the best of both worlds!

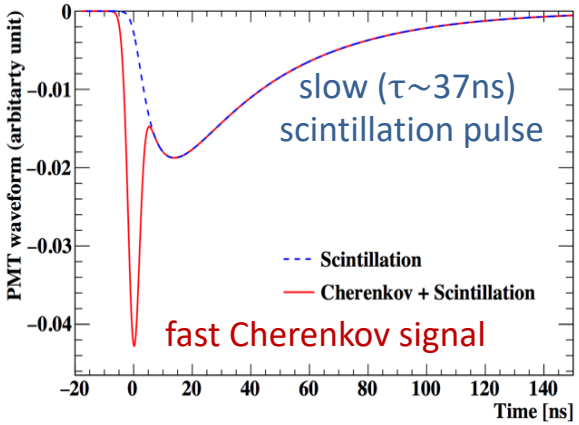


Jinping Neutrino Experiment



Slow scintillator:
e.g. LAB + 0.1 g/l PPO

+ easy separation of C/S components
+ radiopurity
– worse vertex reco



Solar neutrino program

- very low BG levels and excellent discrimination
- high statistics

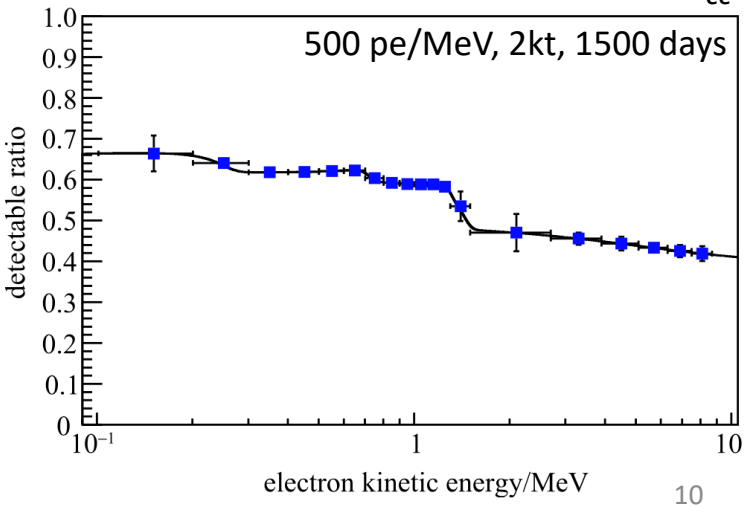
Jinping NE key parameters

- fiducial mass: 2,000 tons
- p.e. yield: 500 pe/MeV
- radiopurity: Bx level
- depth: ~8,000 mwe

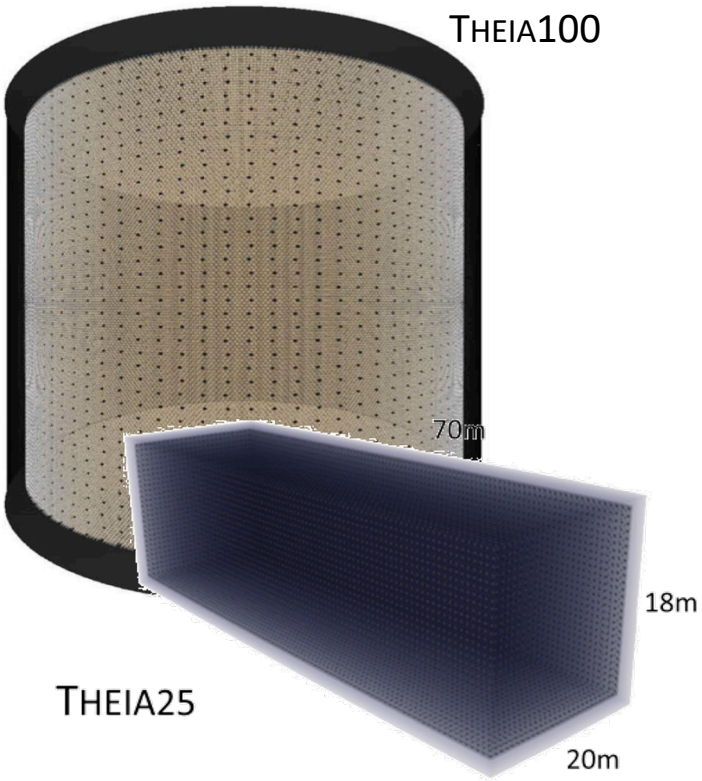
Projected uncertainties

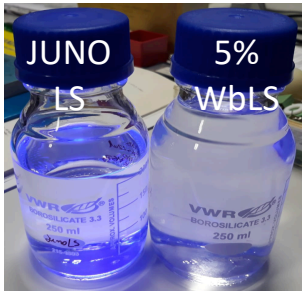
- ^{13}N: 30%
- ^{15}O: 10%
- pep: 3%

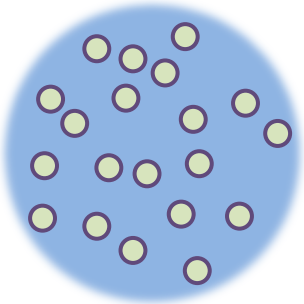
binned measurement of P_{ee}

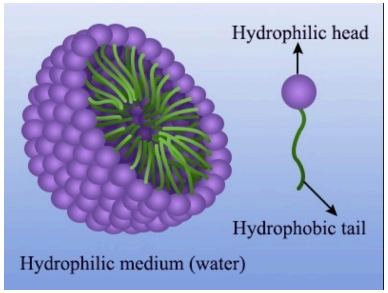


Theia









WbLS mycels (nm-scale)

Water-based Liquid Scintillator
water + surfactant + LAB (5%) + fluor

+ great transparency, cheap → large detector
o fast scintillation → sub-ns photo sensors
– radiopurity limited by water phase, light yield

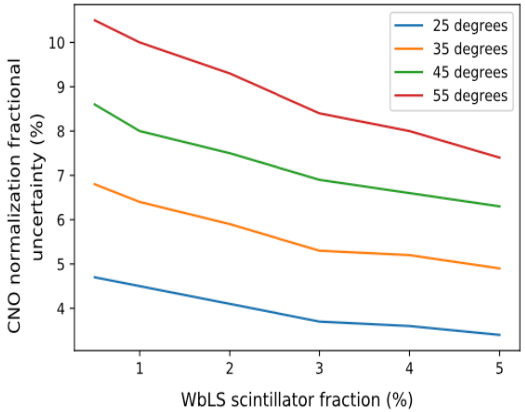
Theia25 key parameters

- fiducial mass: 12,000 tons
- p.e. yield: ~30 pe/MeV
- radiopurity: 10^{-15} g/g U/Th
- depth: 4,800 mwe

Solar neutrino program

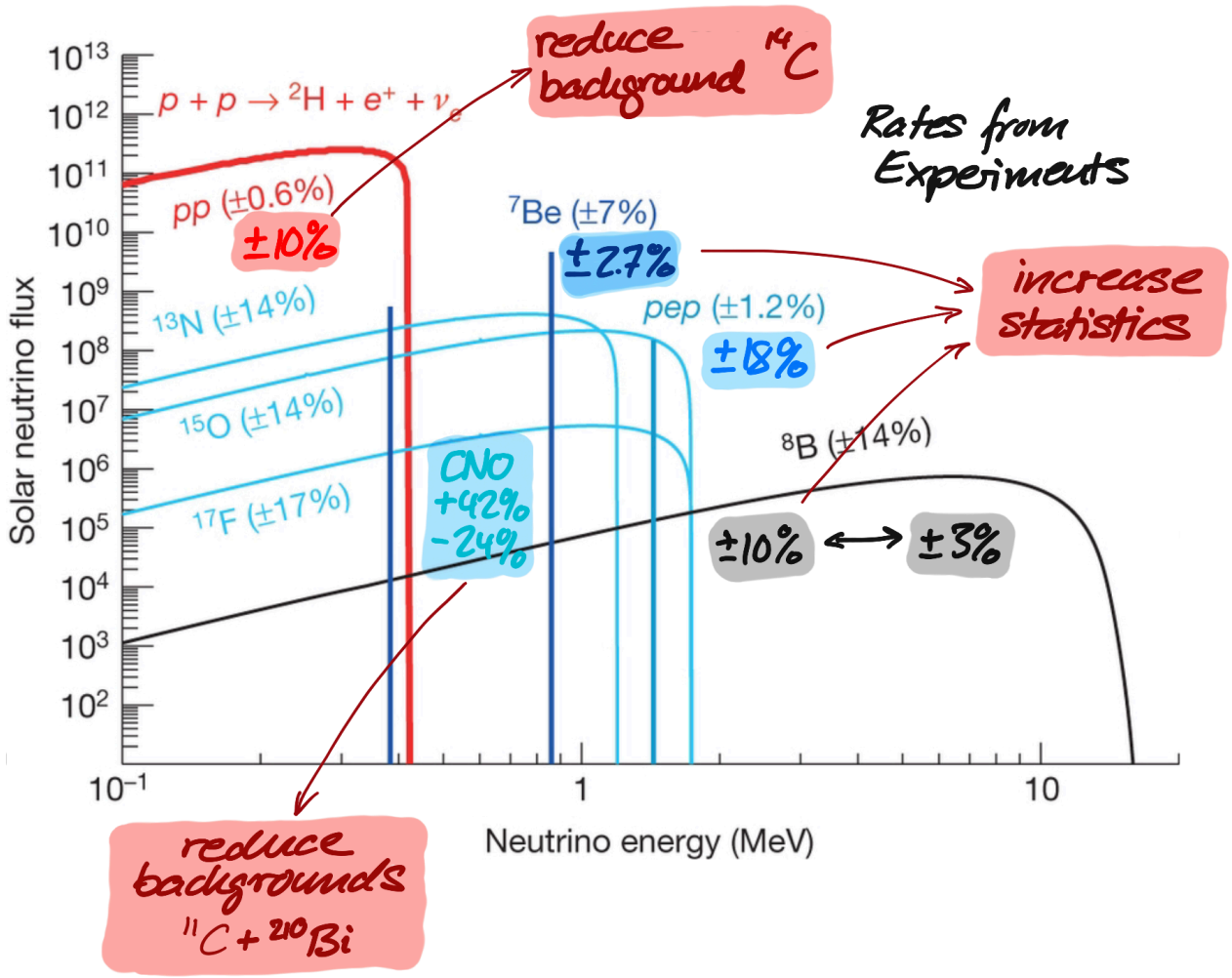
- profits from directional discrimination & statistics
  → CNO to ~5% level
- possibility for Li loading
  → CC spectral measurem.

CNO sensitivity



What can be done on pp neutrinos?

SSM vs. experimental uncertainties



pp neutrinos vs. ^{14}C background

Borexino measurement at **10% level**, main obstacle is intrinsic ^{14}C (2.5×10^{-18})

1) how to improve using organic LS?

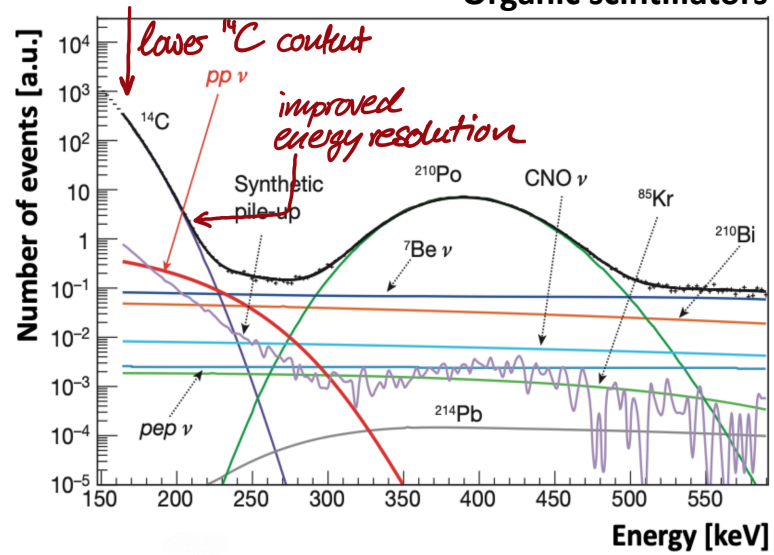
- improve energy resolution/threshold
- low-^{14}C scintillator? requires $\leq 10^{-20}$
- relatively small detector (20t) with >1500 pe/MeV: $\leq$5% accuracy

2) inorganic (carbon-free) scintillators

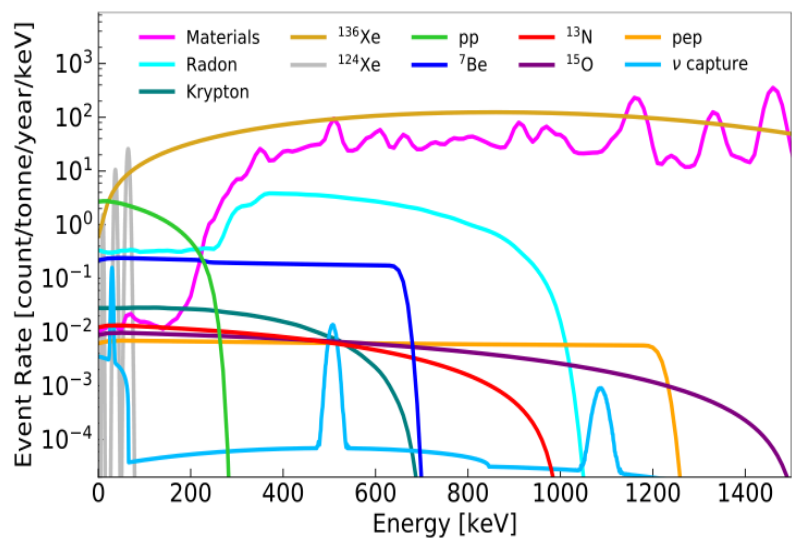
- studies performed for LXe TPCs → pp neutrino window at low energies
- in DARWIN: ~5% accuracy
- main background ^{136}Xe → depletion ...

3) **loaded LS**, e.g. ^{115}In

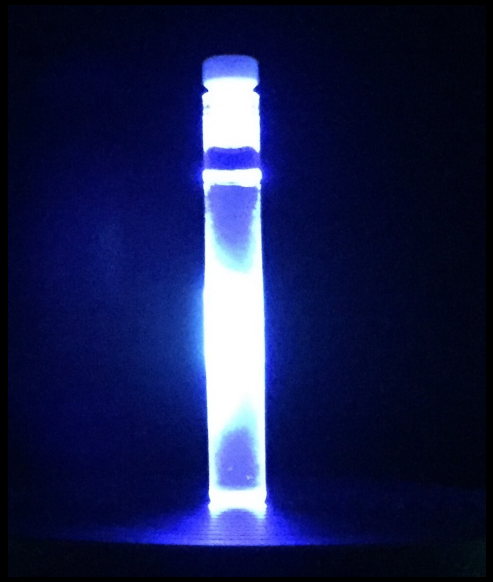
Organic scintillators



LXe – DARWIN



Conclusions

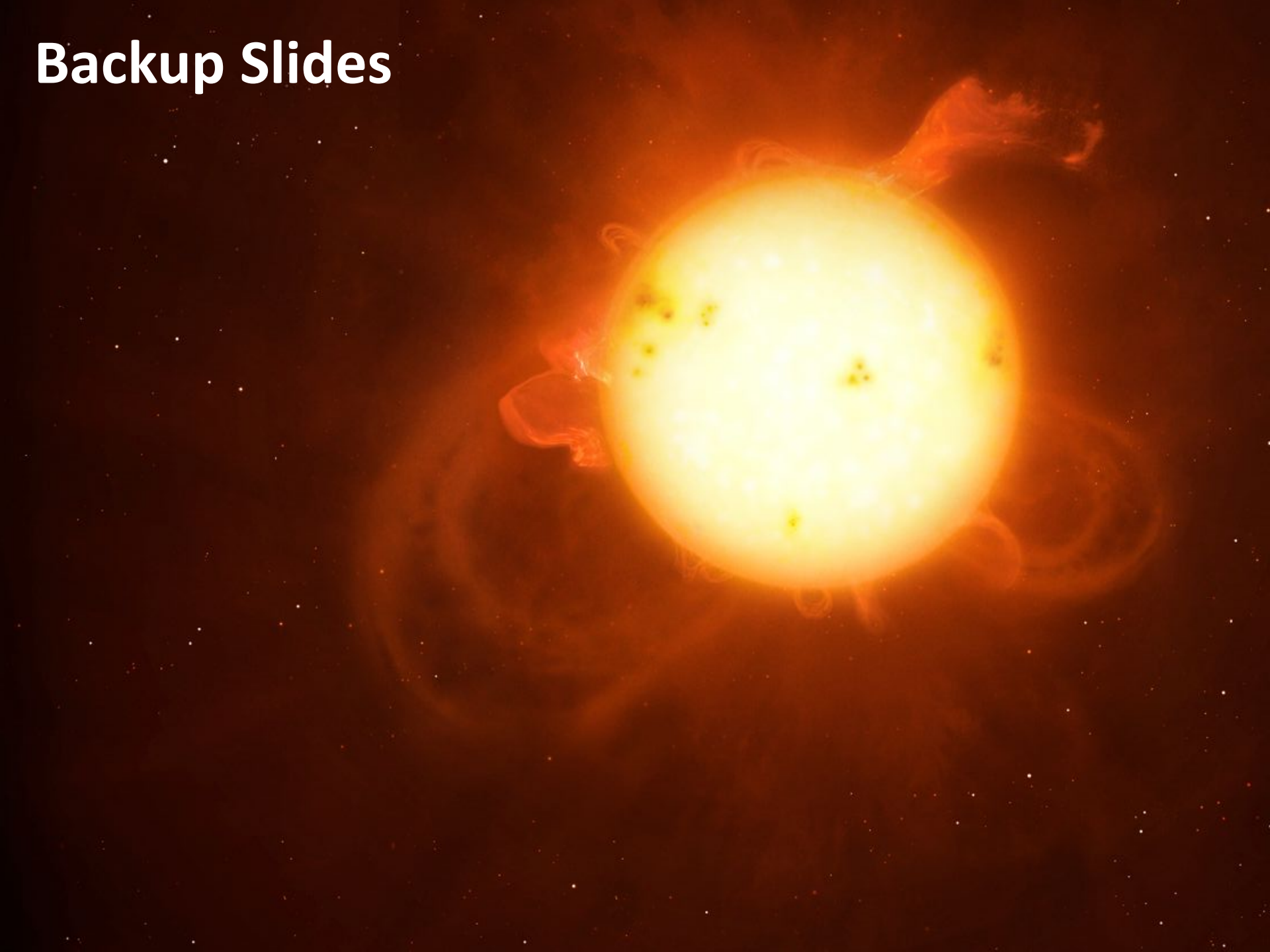


- with Borexino and KamLAND, organic liquid scintillators have played an important role in solar neutrino physics
- ``conventional´´ detectors still in a very good position to contribute:
  JUNO → ^{7}Be, ^{8}B
  SNO+ → pep, CNO
- hybrid detectors offer considerable potential! Jinping, Theia: 5%-level measurement of CNO
- best chance for pp neutrinos: low-^{14}C LS or large LXe TPC (DARWIN)
- isotope loading would permit direct neutrino energy measurement via CC reations

Thank you!

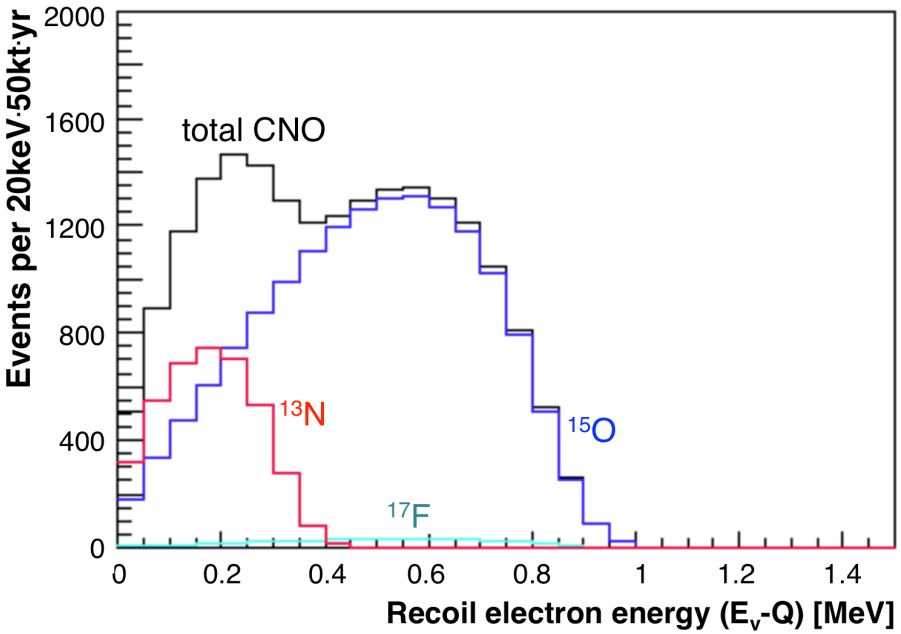
- Borexino Coll., E*xperimental evidence of neutrinos produced in the CNO fusion cycle in the Sun*, Nature 587 (2020) 577-582, arXiv:2006.15115
- JUNO Coll., *Neutrino Physics with JUNO*, J.Phys.G 43 (2016) 3, 030401, arXiv:1507.05613
- JUNO Coll., *Feasibility and physics potential of detecting ^{8}B solar neutrinos at JUNO*, arXiv:2006.11760
- M. Wurm et al., *Search for modulations of the solar Be-7 flux in the next-generation neutrino observatory LENA*, Phys.Rev.D 83 (2011) 032010, arXiv:1012.3021
- SNO+ Coll., *Current Status and Future Prospects of the SNO+ Experiment*, Adv. High Energy Phys. 2016 (2016) 6194250, arXiv:1508.05759
- B.J. Land et al., *MeV-scale performance of water-based and slow liquid scintillators*, arXiv:2007.14999
- J. Beacom et al., *Physics Prospects of the Jinping neutrino experiment*, Chinese Physics C, 41 (2017) 2, 023002, arXiv:1602.01733
- M. Askins et al., *THEIA: an advanced optical neutrino detector*, Eur. Phys. J. C 80 (2020) 5, 416, arXiv:1911.03501
- O. Smirnov et al., *Search for Solar pp neutrinos with an upgrade of the CTF detector, Physics of Atomic Nuclei*, Vol. 66, No. 4, 2003, pp. 712–723.
- DARWIN Coll., *Solar Neutrino Detection Sensitivity in DARWIN via Electron Scattering*, arXiv:2006.03114
- M. Wurm, *Solar neutrino spectroscopy*, Phys.Rept. 685 (2017) 1-52 arXiv:1704.06331

Backup Slides

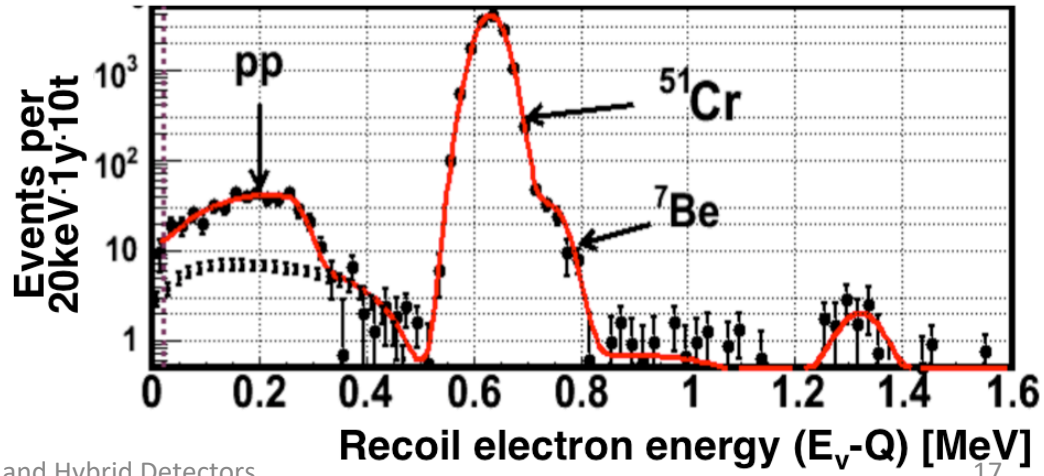


Isotope Loading?

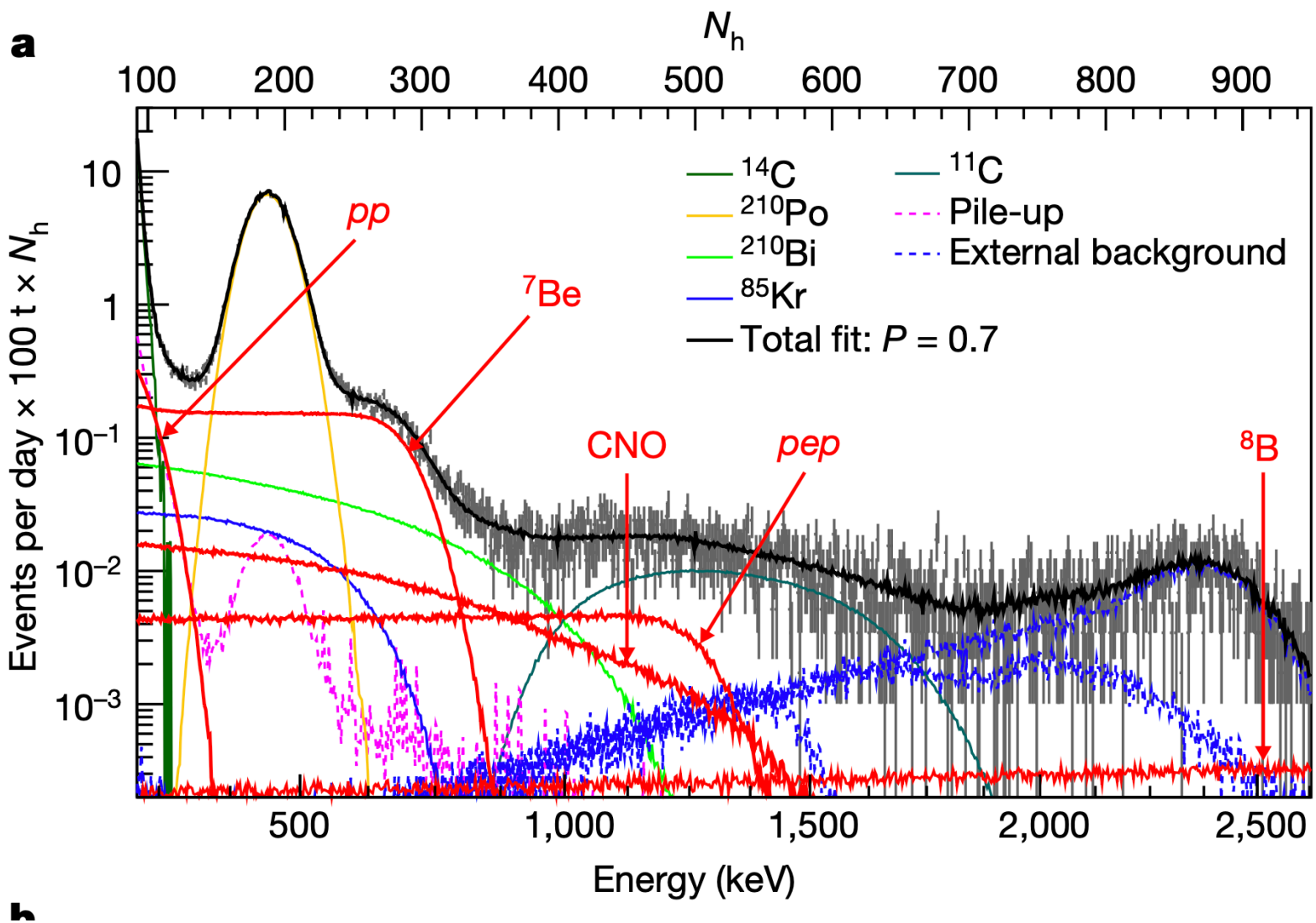
Theia: Li-loading



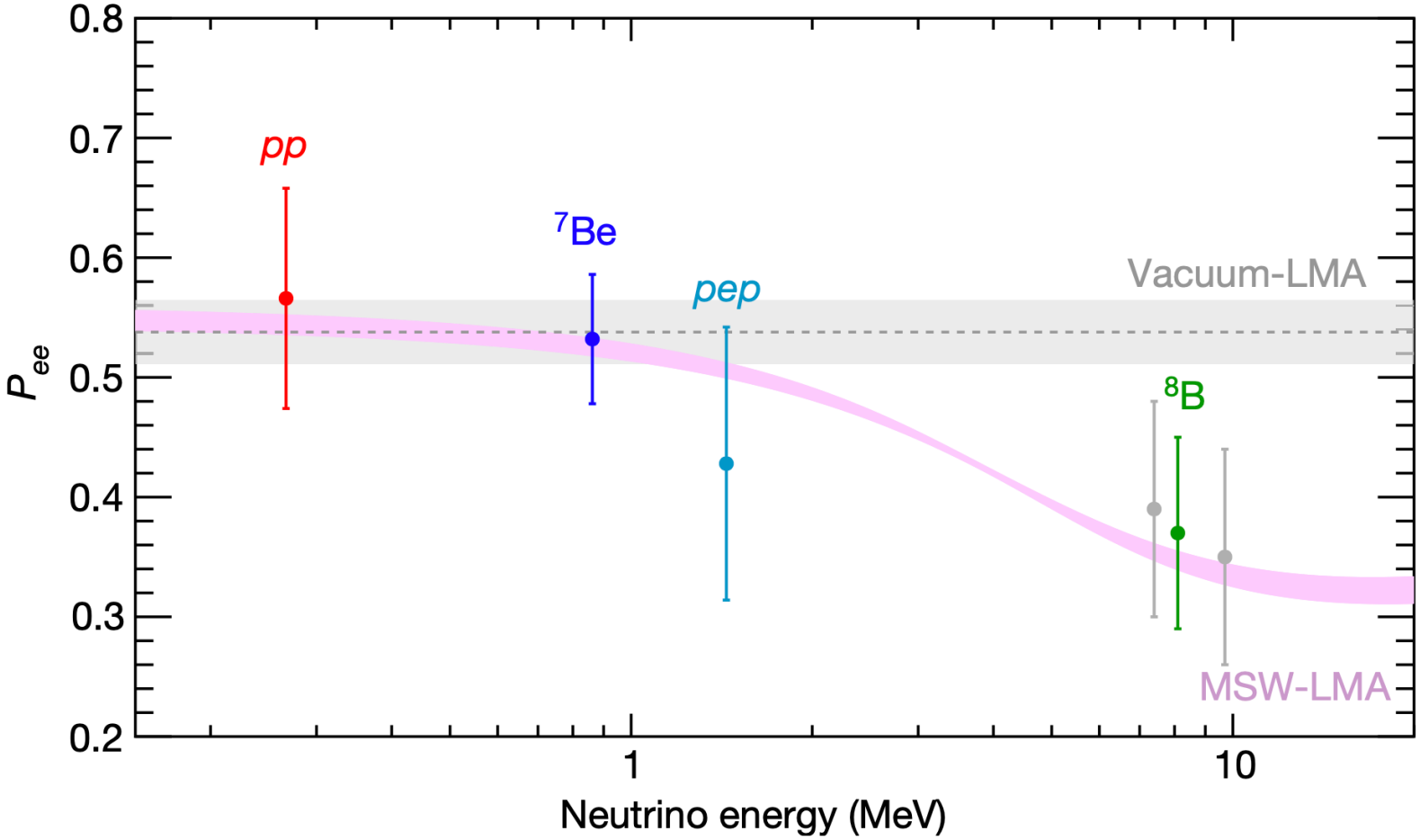
LENS: In-loading



Borexino Comprehensive Fit

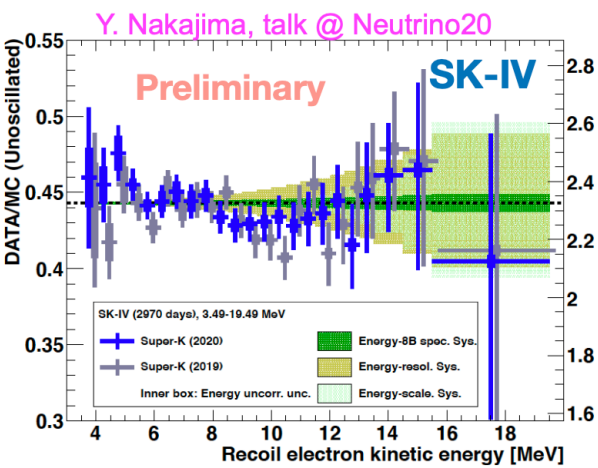


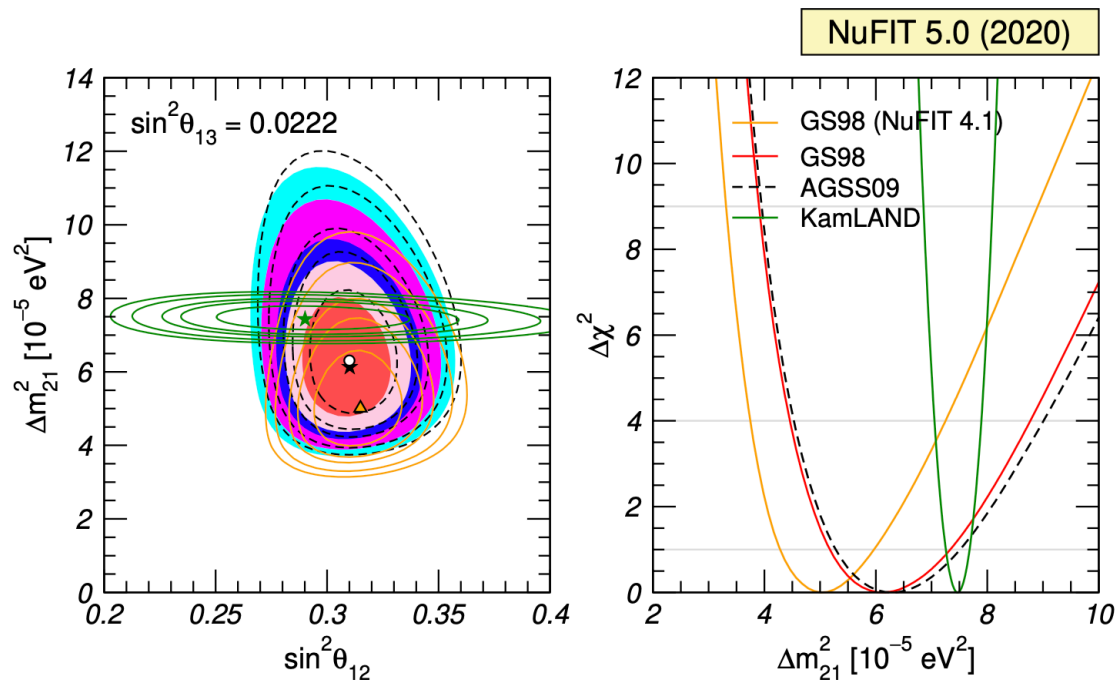
Borexino Pee



^{8}B spectral upturn

Small „tension“ (2σ) in 12 sector: RESOLVED

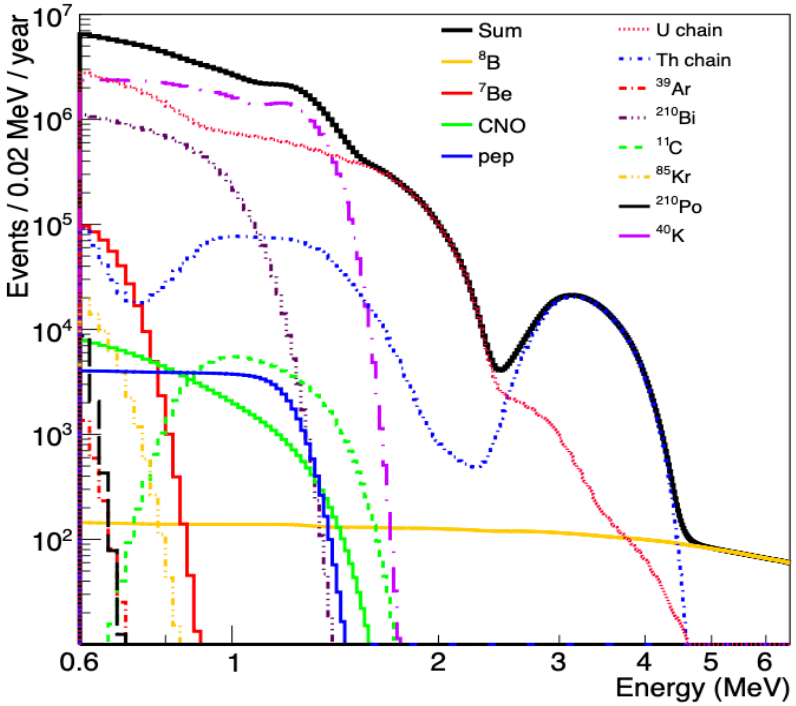




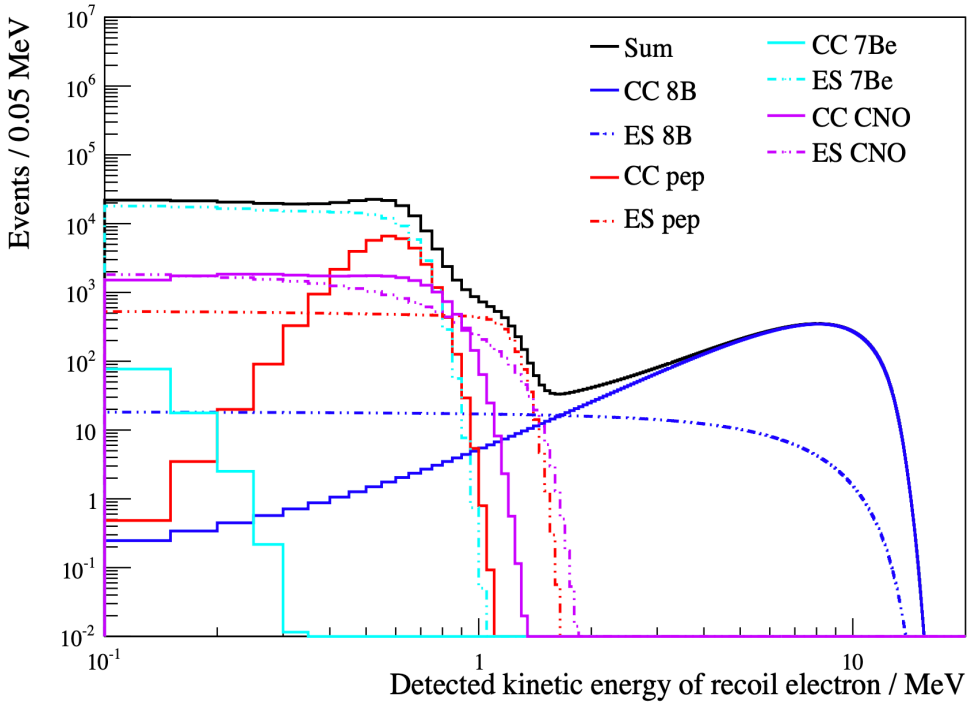
- new SuperK solar neutrino data @ Neutrino20:
  - spectrum better compatible with KamLAND prediction
  - day/night asym.: $A_{DN}^{Fit} = (-3.6 \pm 1.6(stat) \pm 0.6(syst))\,\%$ → $A_{DN}^{Fit} = (-2.1 \pm 1.1)\,\%$

Theia solar neutrino spectrum

ES+BG

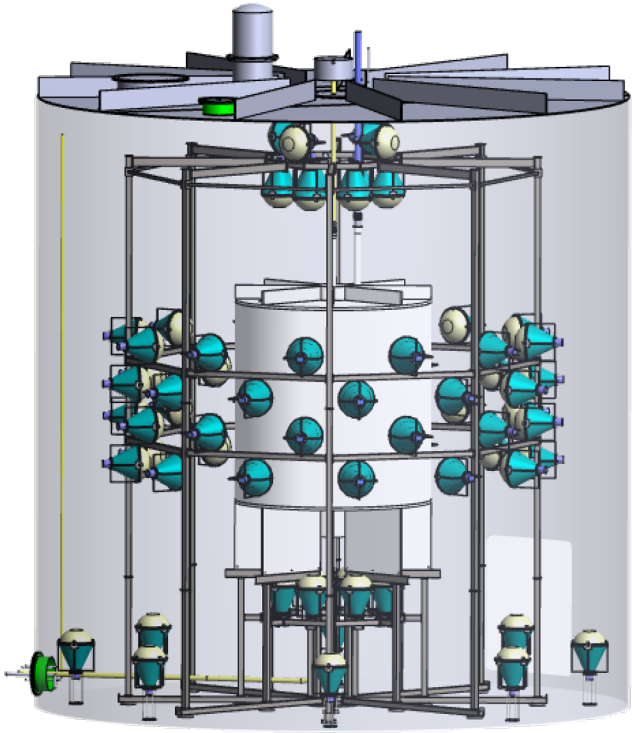
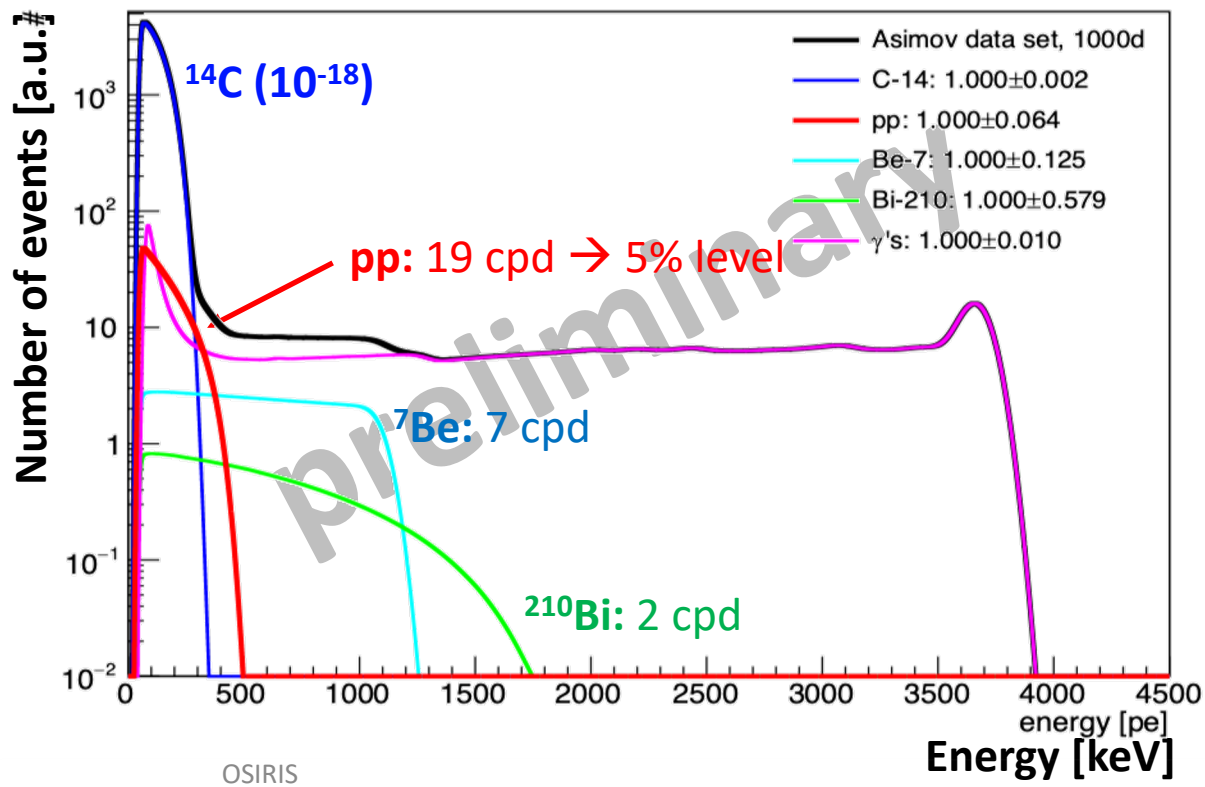


ES+Li



pp neutrino measurement in OSIRIS

OSIRIS = radiopurity monitor for JUNO with target volume of 17t of LS

What changes would be needed?

- low ^{14}C scintillator: 10^{-20} or better
- energy resolution can be improved even beyond JUNO level (light cones!)
- OSIRIS can benefit from the JUNO scintillator purification infrastructure