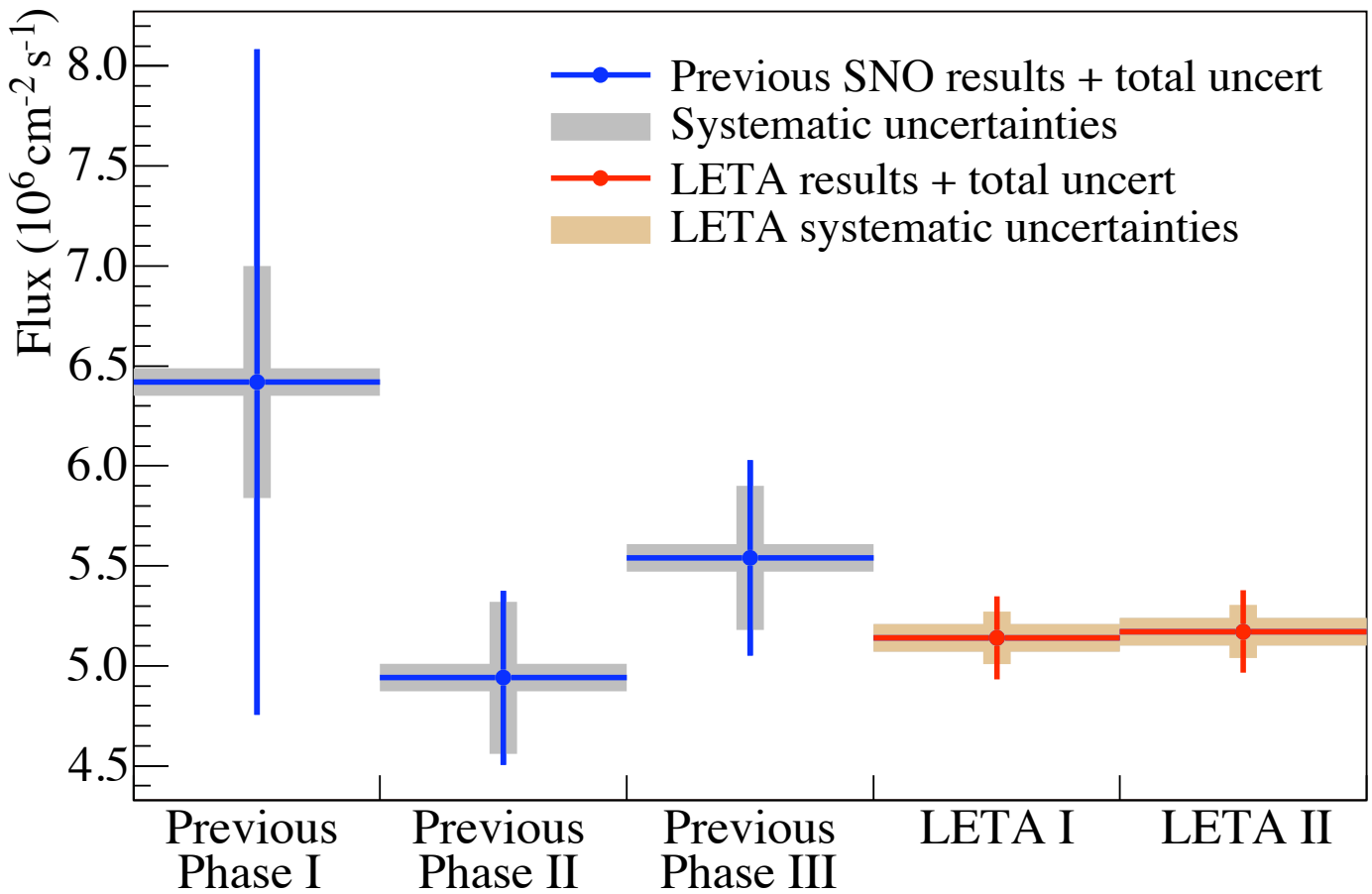
Solar Neutrinos III: Unresolved Issues

- SNO: the low-energy and three-flavor analyses
- Borexino
- Metals and helioseismology
- What remains to be done

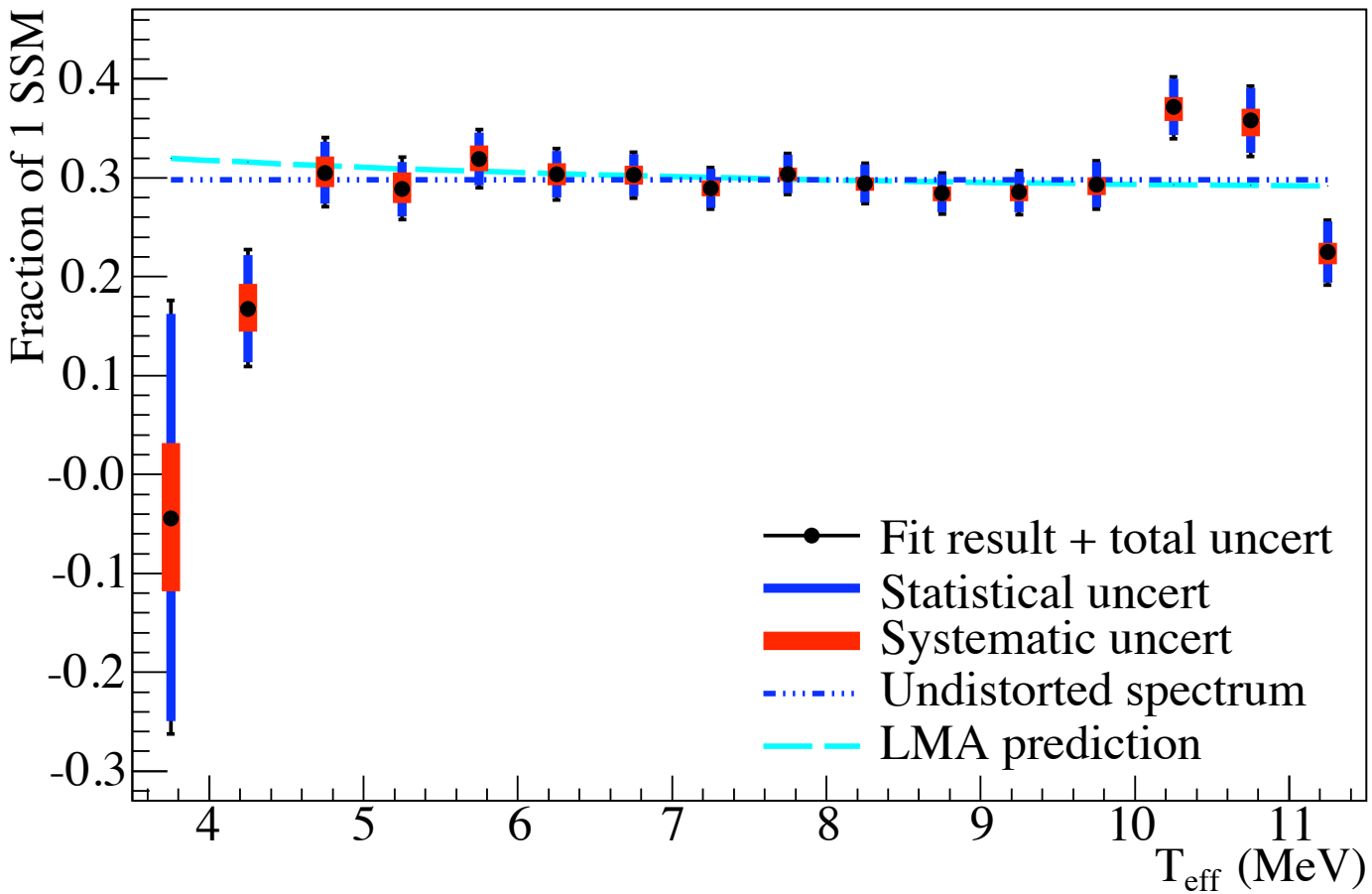
Wick Haxton, UC Berkeley and LBL

SSI 2010, August 2-10

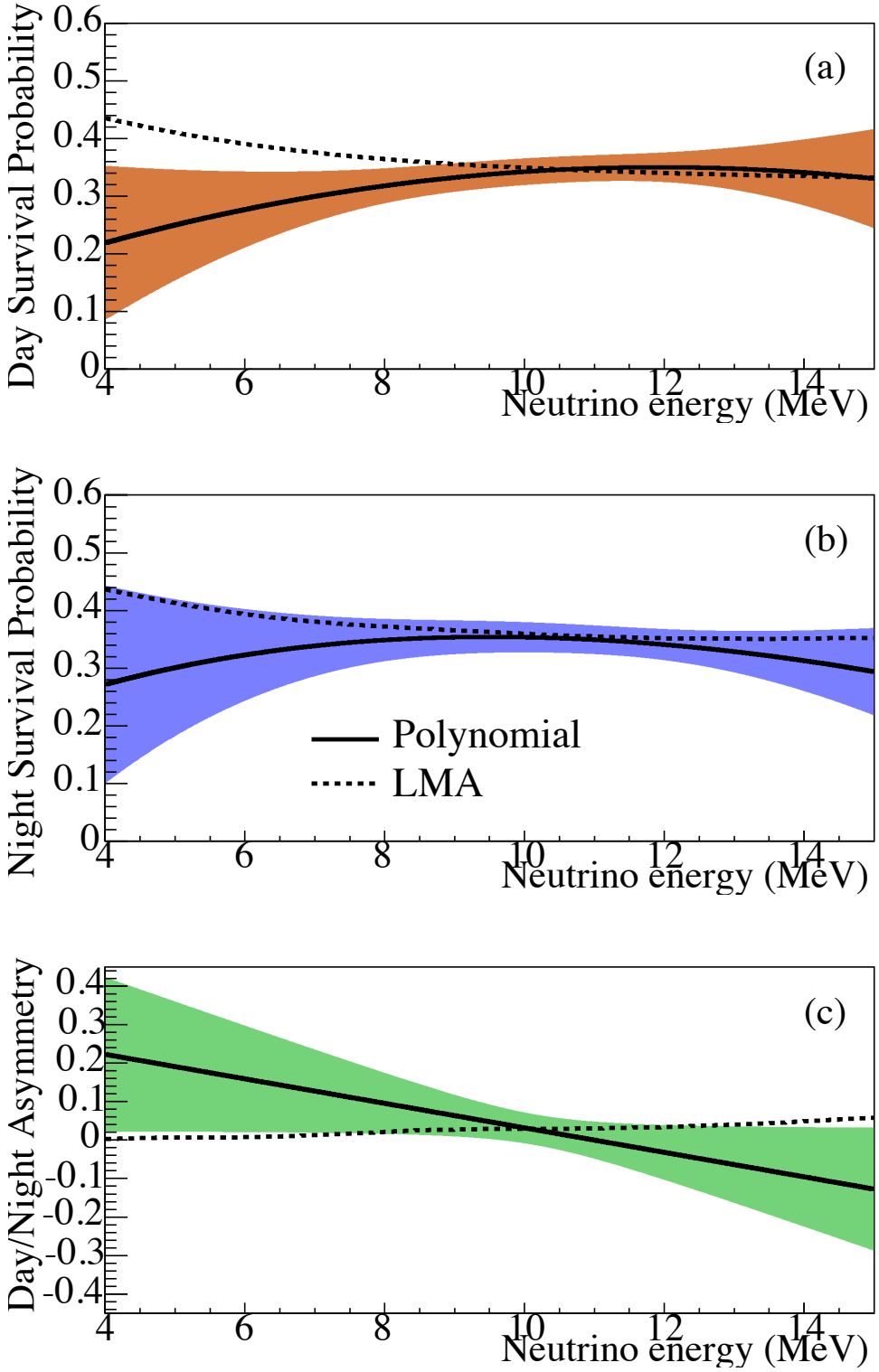
SNO low-energy analysis: 3.5 MeV



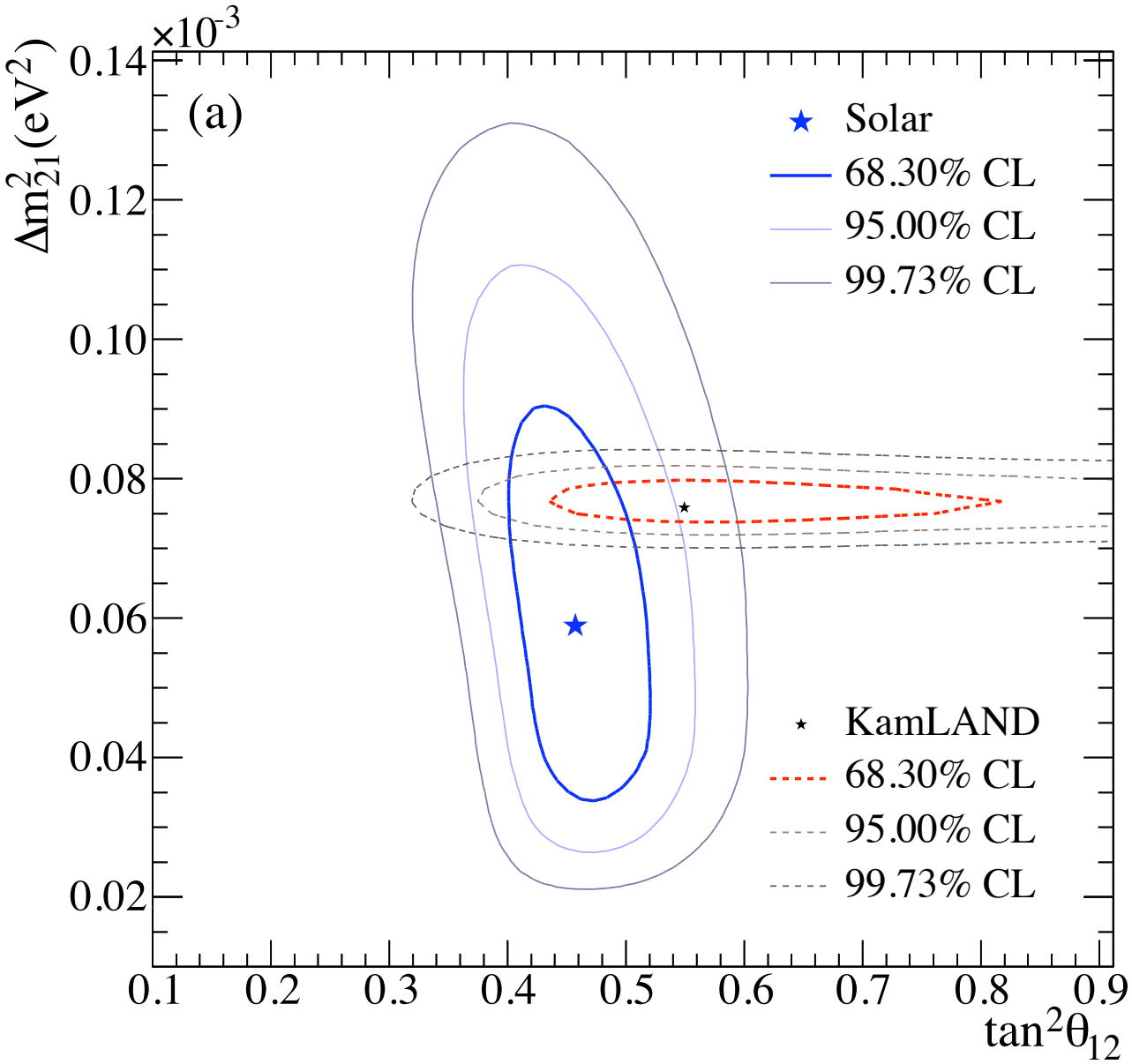
$$\phi(^8\mathrm{B}) = \left(5.046^{+0.169}_{-0.152}(\mathrm{stat})^{+0.107}_{-0.123}(\mathrm{syst})\right) \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$



spectral distortion

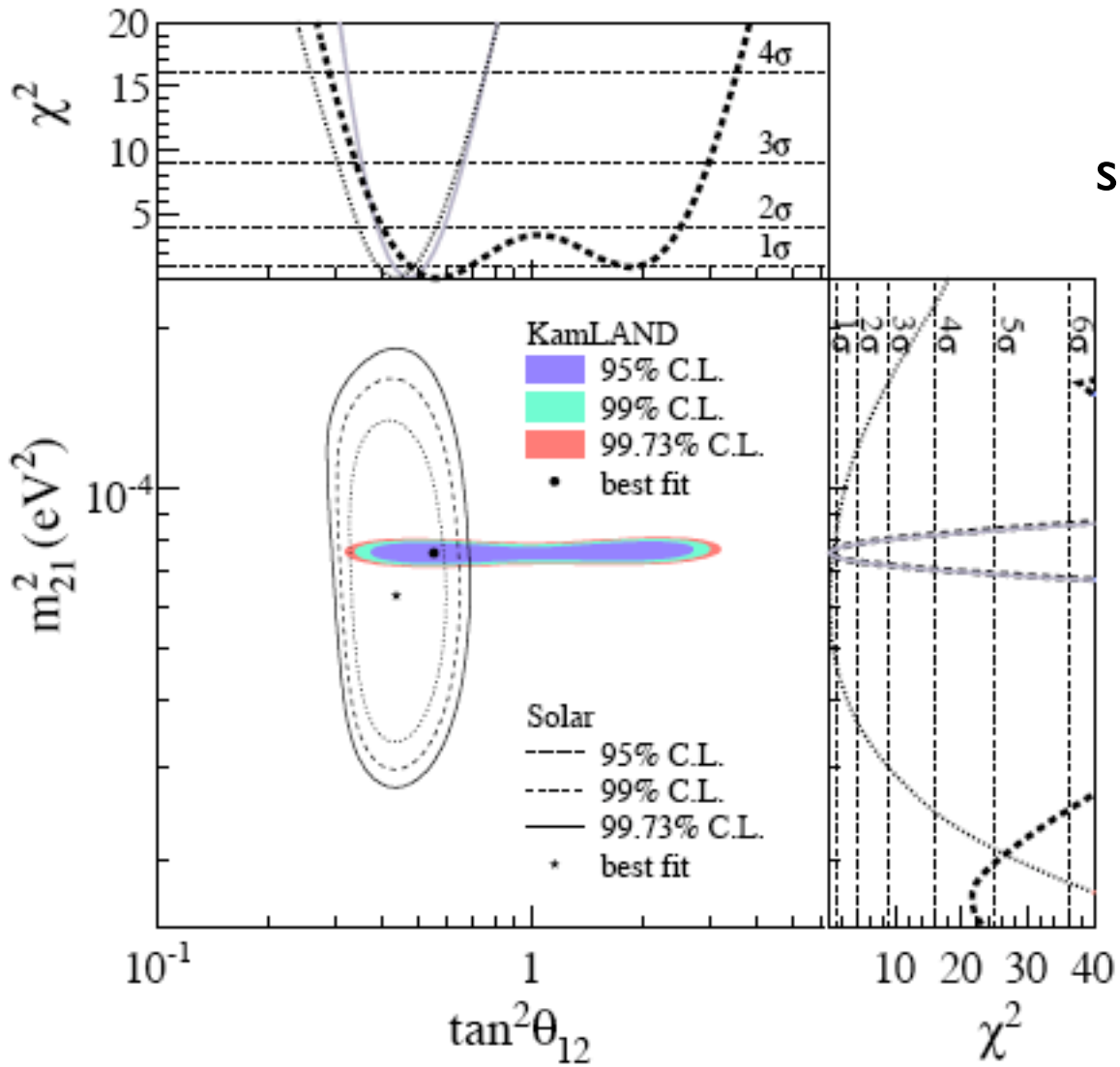


SNO day-night signal

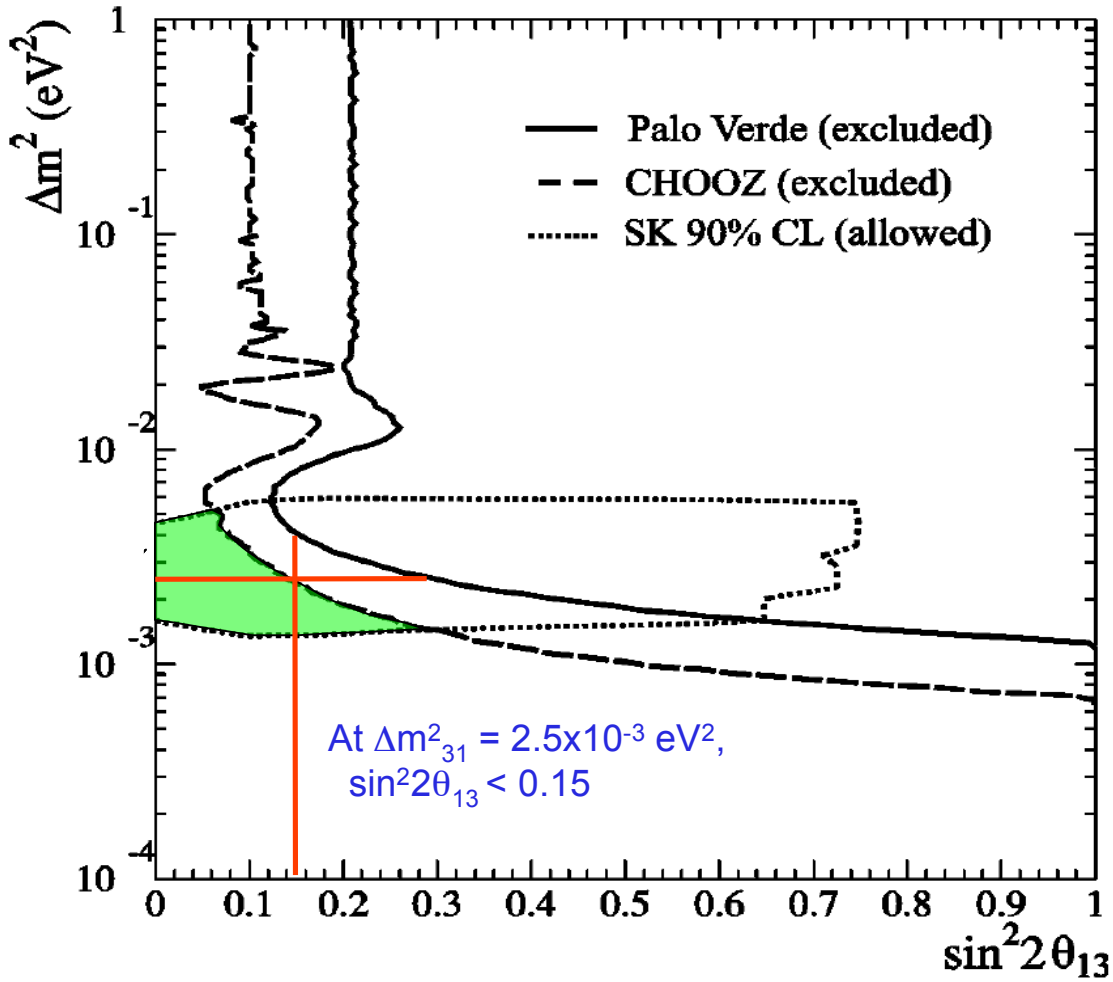


global two-flavor solar neutrino analysis (SNO, SK, Cl, SAGE, Gallex/GNO, Borexino) combined with KamLAND

the large-angle solution



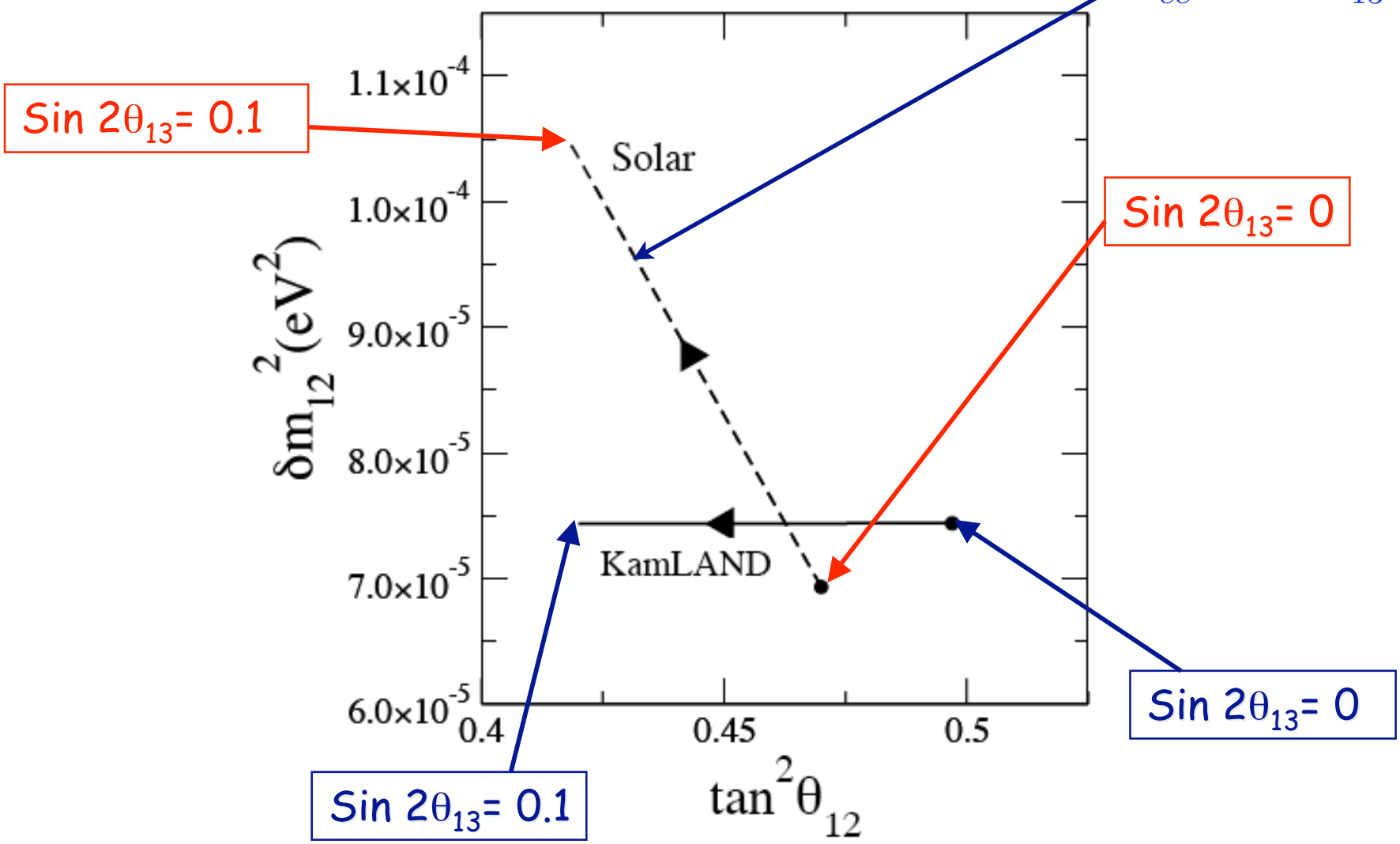
two-flavor
some tension?



critically important to the CP-violation signal in future LB studies: $J_{CP} \sim 0.2 \sin 2\theta_{13} \sin\delta$

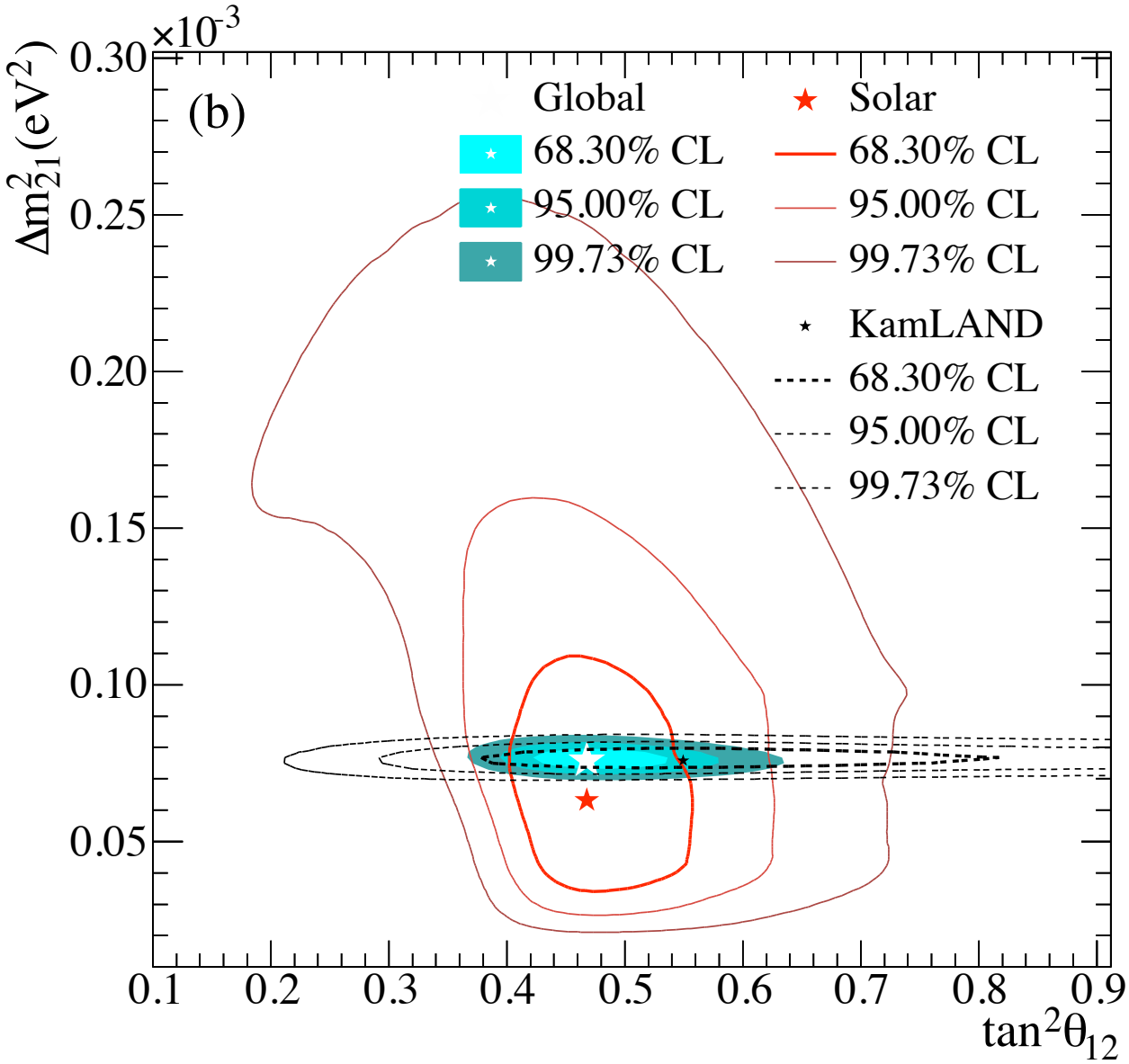
....or is it simply ignoring θ_{13} ?

$$P_{ee} \sim \cos^4\theta_{13}\sin^2\theta_{12}$$



$$P_{ee} \sim \cos^4\theta_{13}\left(1-\sin^2 2\theta_{12}\sin^2\frac{\delta m^2_{12}L}{4E}\right)$$

from Balantekin

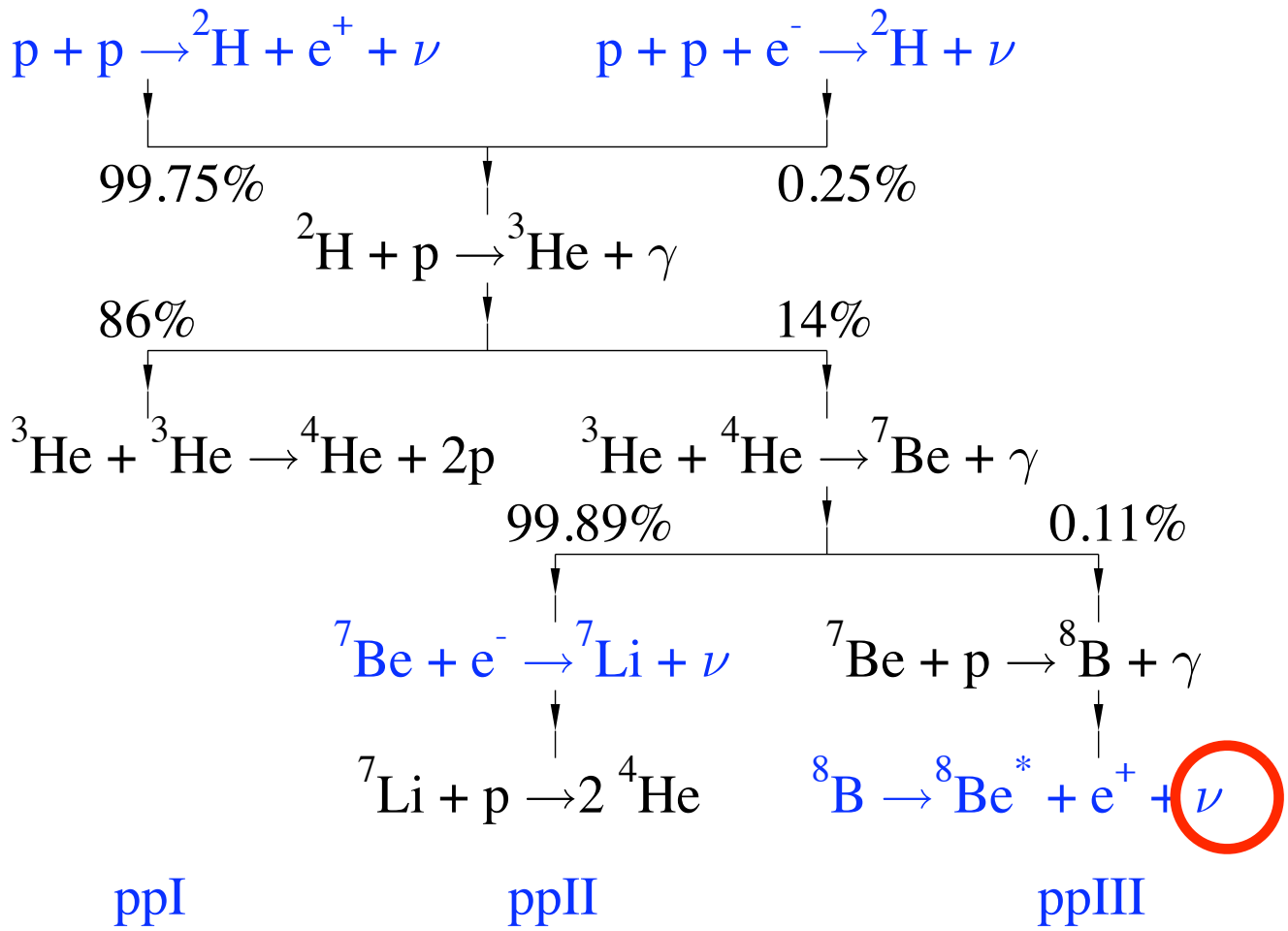


$$\sin^2\theta_{13} < 0.057\ (95\%)$$

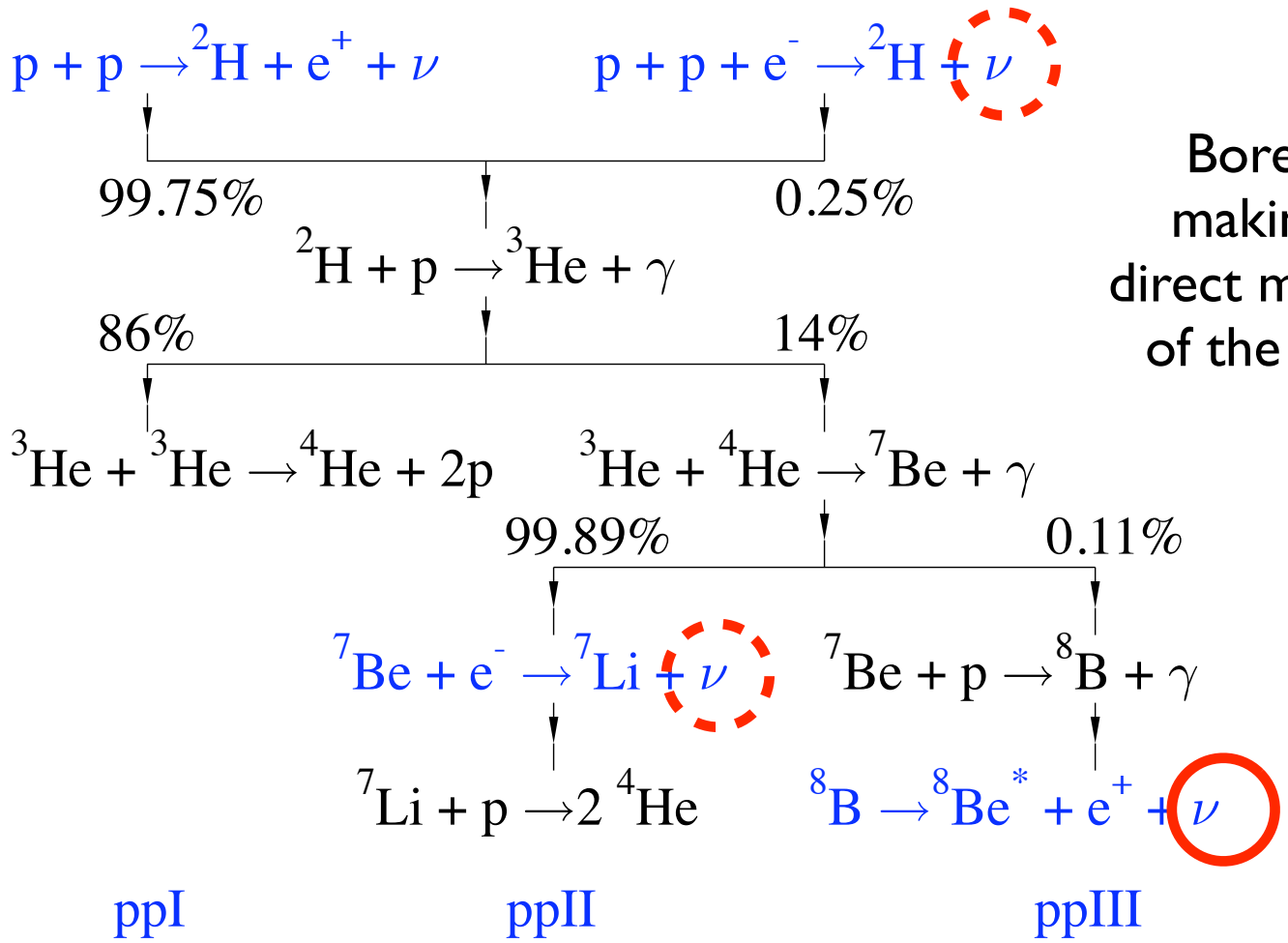
$$\sin^2\theta_{13} = 2.00^{+2.09}_{-1.63} \times 10^{-2}$$

a hint of an effect

SNO 3-flavor global analysis

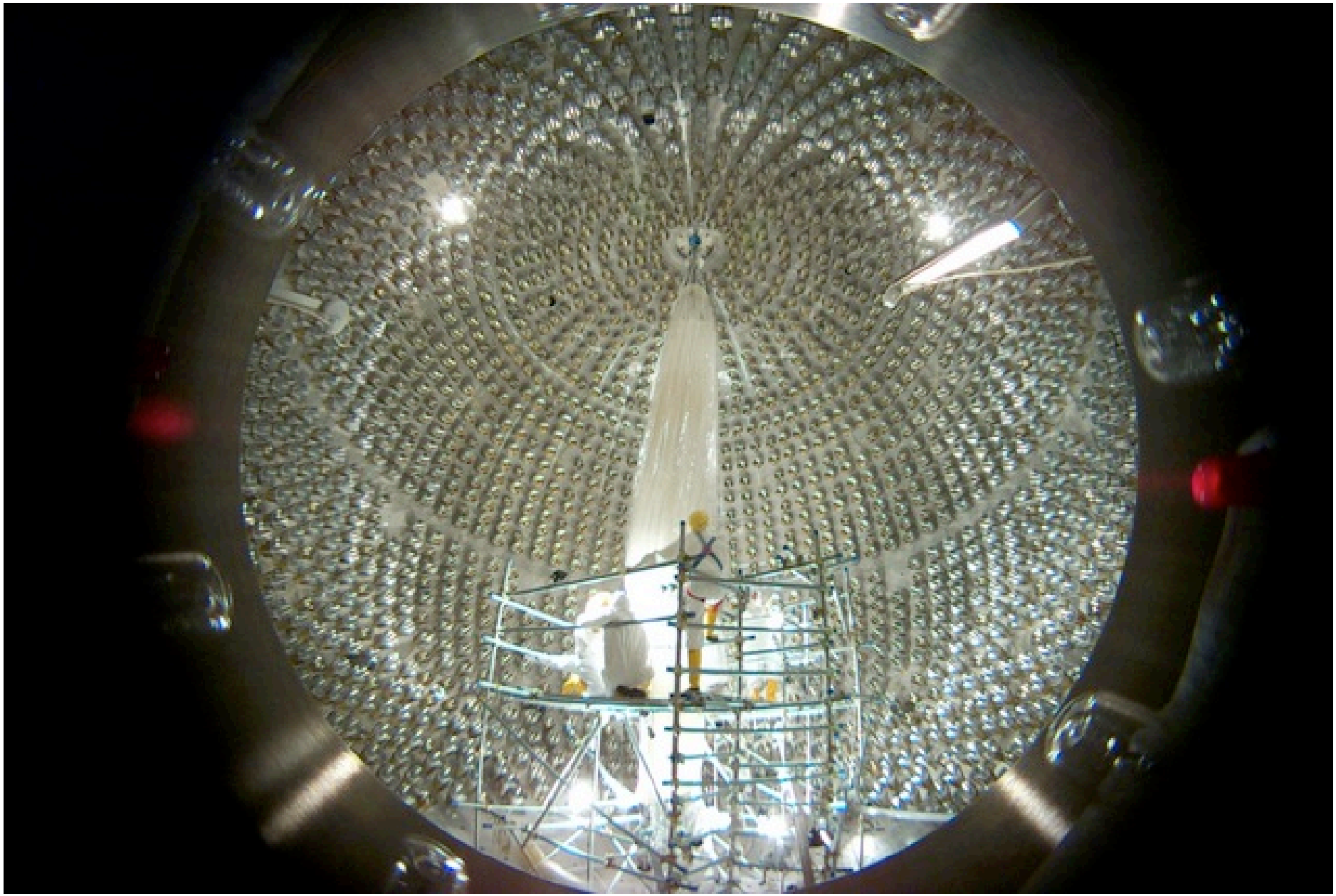


SNO, Super-K physics has been extracted from 0.01% of the available flux



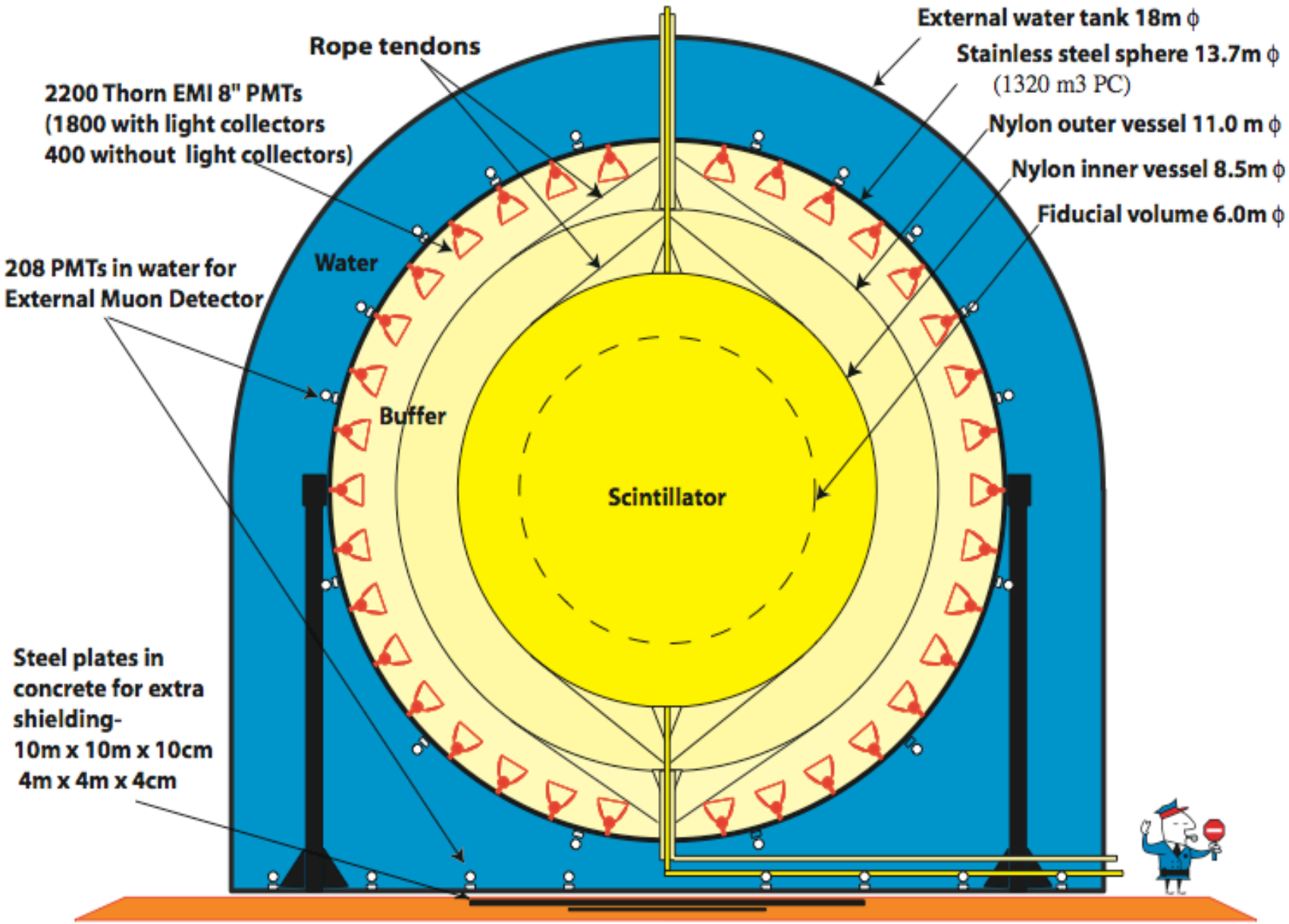
Borexino now making the first direct measurements of the low-energy flux

SNO, Super-K physics has been extracted from 0.01% of the available flux



Borexino

Borexino Experiment



- Detection reaction is $\nu_x + e \rightarrow \nu_x' + e'$

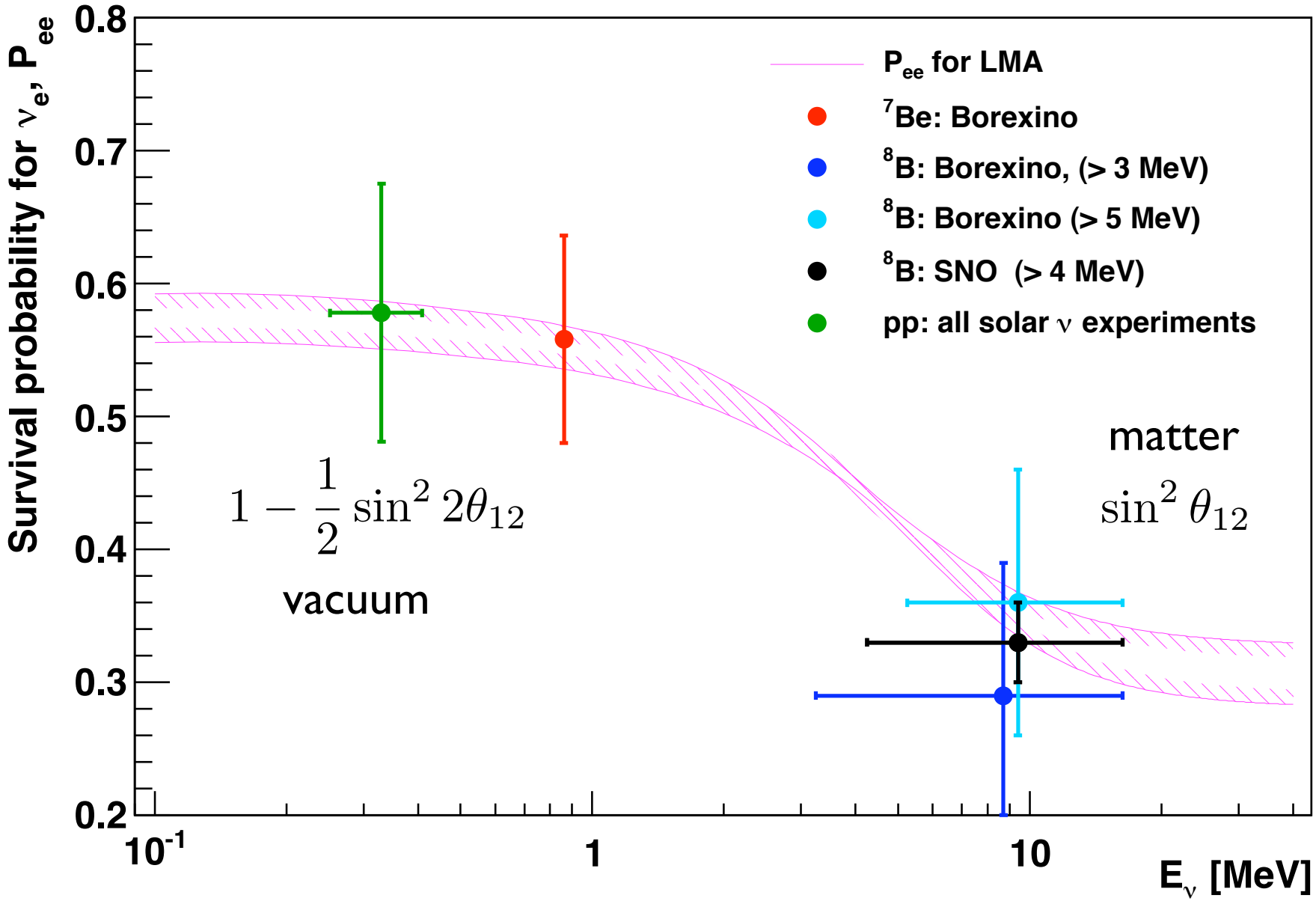
- Use of scintillator allows one to see low energy events: 7Be neutrinos produce scattered electrons with kinetic energy < 0.668 MeV

- Resolution is good, $\sigma(T) \sim 0.8 \text{ MeV } \sqrt{T/\text{MeV}}$, or 8-9% near 0.7 MeV

- Can trigger on events with energy above ~ 250 keV

Thus in principal such detectors can do spectroscopy of the low-energy neutrino spectrum.

In practice this requires great care to reduce ambient backgrounds, which grow rapidly as the energy is lowered. This includes radon-associated (environmental) backgrounds as well long-lived activities produced by cosmic ray muons, e.g., ^{11}C -- a 20.4 minute beta source, 1.47 MeV kinetic energy release


Survival probability for ν_e, P_{ee}
0.8
0.7
0.6
0.5
0.4
0.3
0.2
10^{-1}
1
10
E_ν [MeV]
P_{ee} for LMA
^{7}Be: Borexino
^{8}B: Borexino, (> 3 MeV)
^{8}B: Borexino (> 5 MeV)
^{8}B: SNO (> 4 MeV)
pp: all solar ν experiments
$1 - \frac{1}{2}\sin^2 2\theta_{12}$
vacuum
matter
$\sin^2\theta_{12}$

- Borexino volume is limited, ~300 tons

- Just entering its calibration phase

- Thus substantial improvement in precision is likely

an interesting technology that will be taken to the next level
by SNO+ ... which has the reach to make a very new kind of neutrino
check of the Sun

Recent Re-evaluations of Photospheric Abundances

- SSM requires as input an estimate of core metalicity at t=0

- Taken from meteoritic abundances or from photospheric absorption lines: the latter are the only practical way to determine the abundances of volatile heavy elements, such as C, N, O, Ne, Ar
  - SSM then assumes a homogeneous zero-age sun characterized by these abundances, for reasons previously described

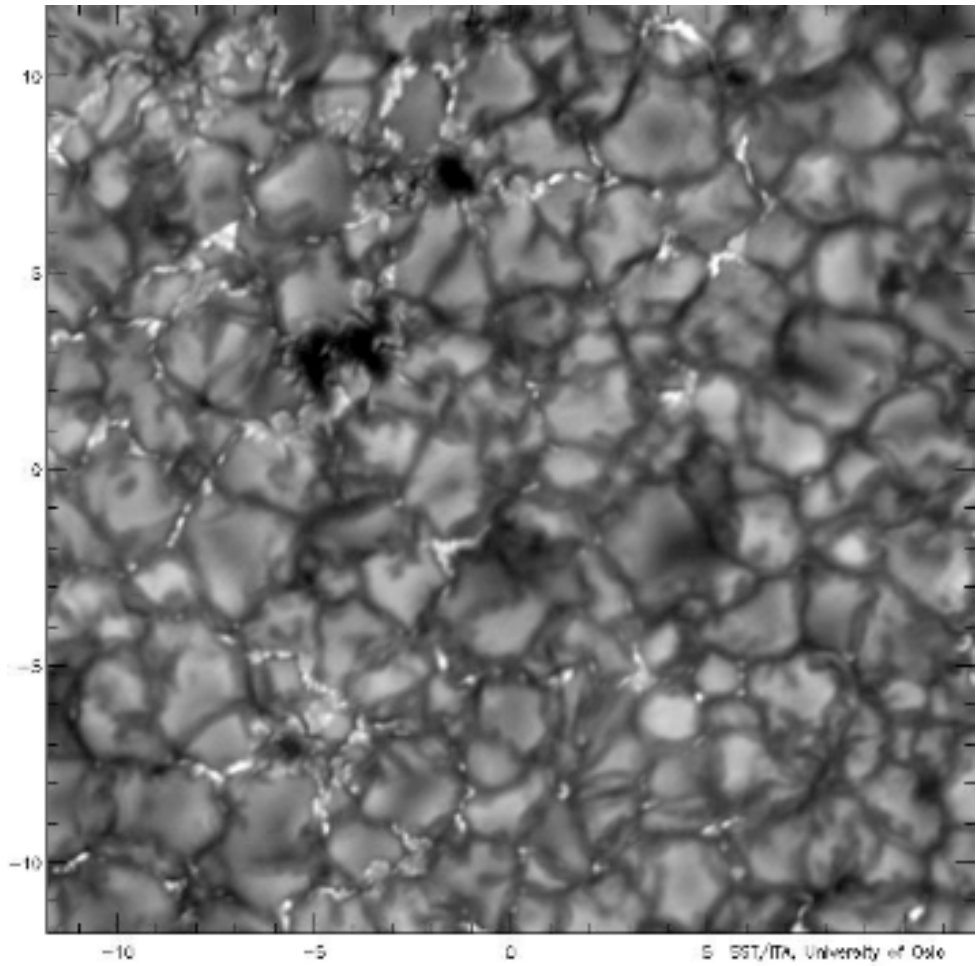
- These metals influence solar dynamics: free-bound transitions important to opacity, influencing local sound speed: different metals dominate in different solar regions

- The once excellent agreement between SSM and helioseismology due in part to this input (Grevesse & Sauval 1998)

- The classic analyses modeled the photosphere in 1D, despite stratification, velocities, inhomogenieties

- But new 3D, parameter-free methods have been introduced, significantly improving consistency of line analyses

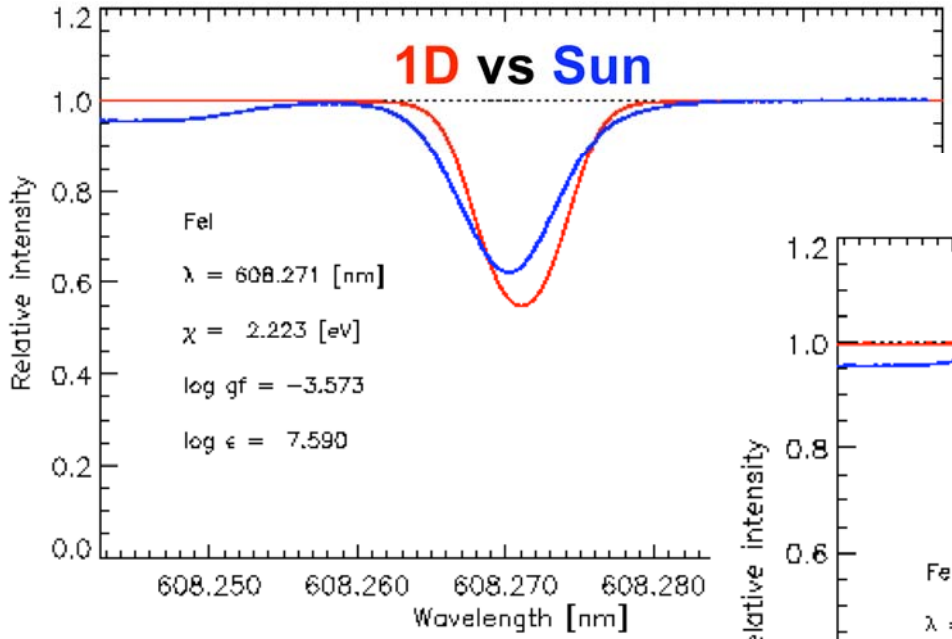
Dynamic and 3D due to convection

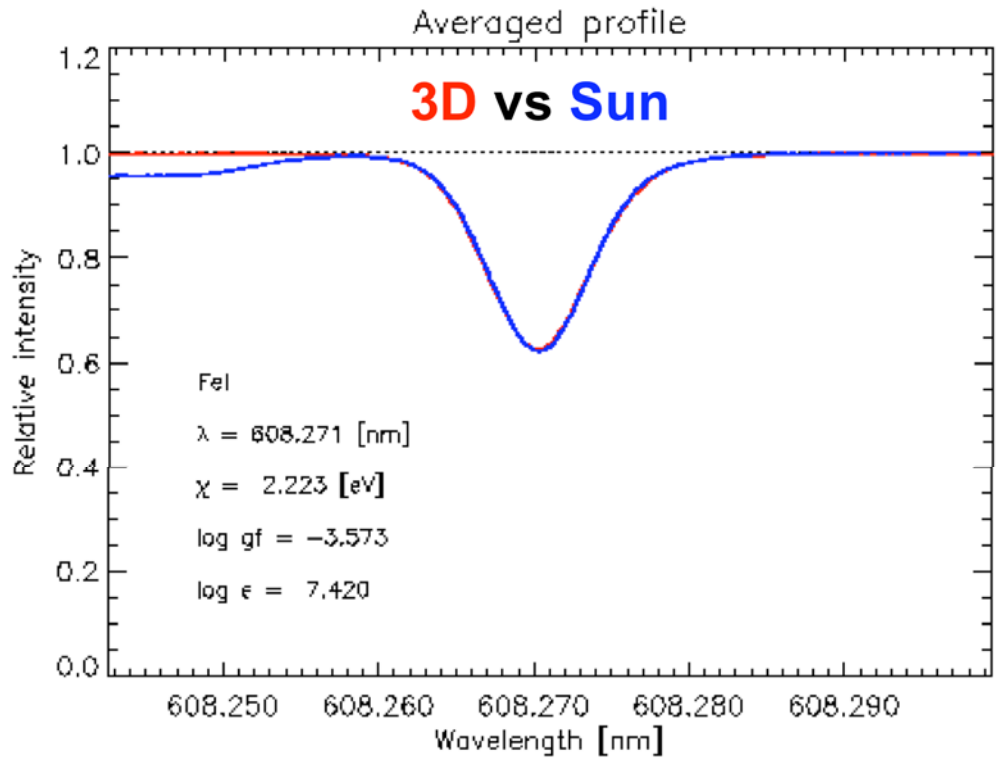


Mats Carlsson (Oslo)

Sun

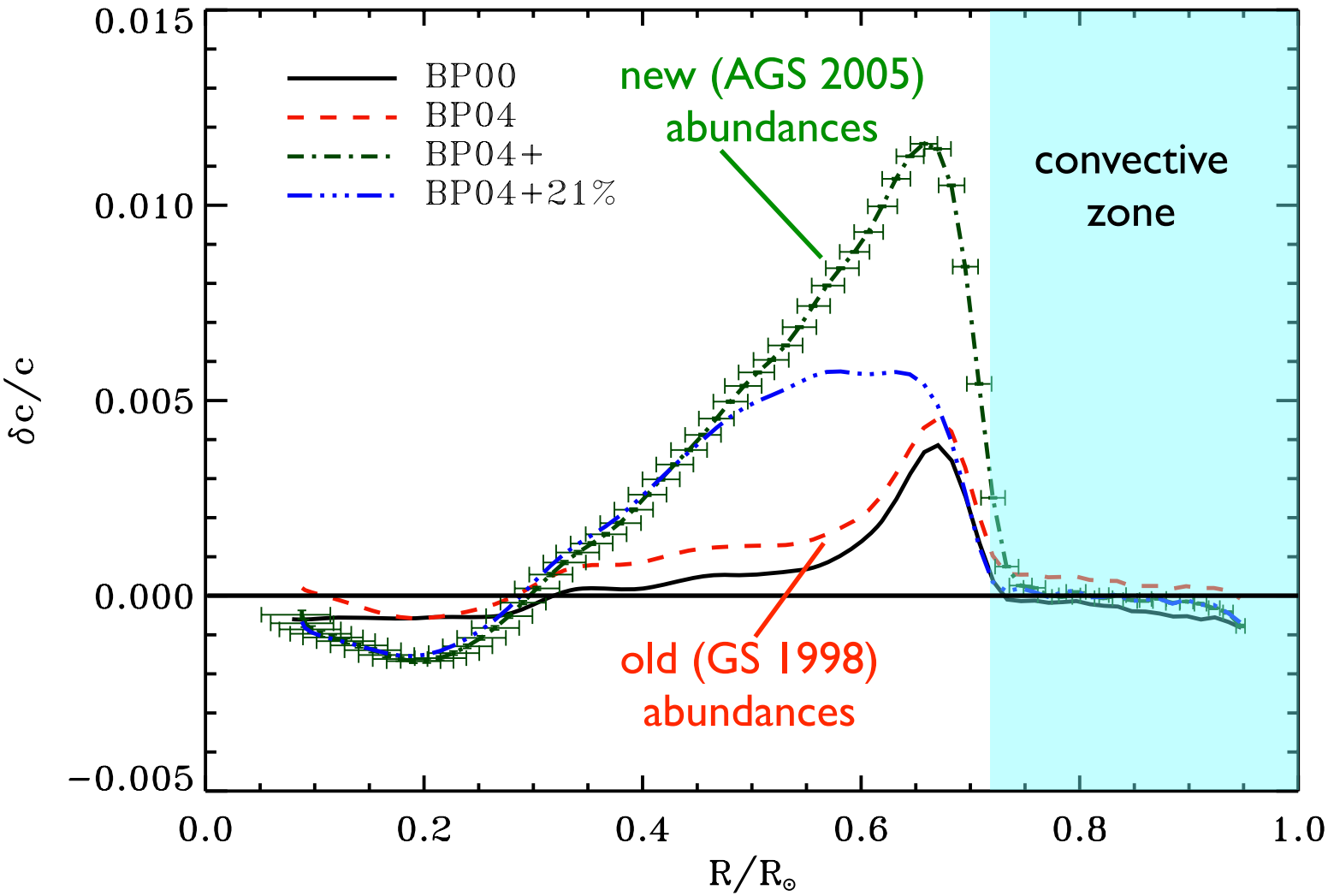
Averaged line profiles (from Asplund 2007)





- Spread in abundances from different C, O lines sources reduced from ~ 40% to 10%
- But abundances significantly reduced Z: 0.0169 ⇒ 0.0122
- Makes sun more consistent with similar stars in local neighborhood
- Lowers SSM ^{8}B flux by 20%

But adverse consequences for helioseismology



Bahcall, Basu, Pinsonneault, Serenelli 2004

- Discrepancy largest for T ~ 2-5 $\times 10^6$ K: C, N, O, Ne, and Ar are partially ionized, with O and Ne particularly important to the opacity

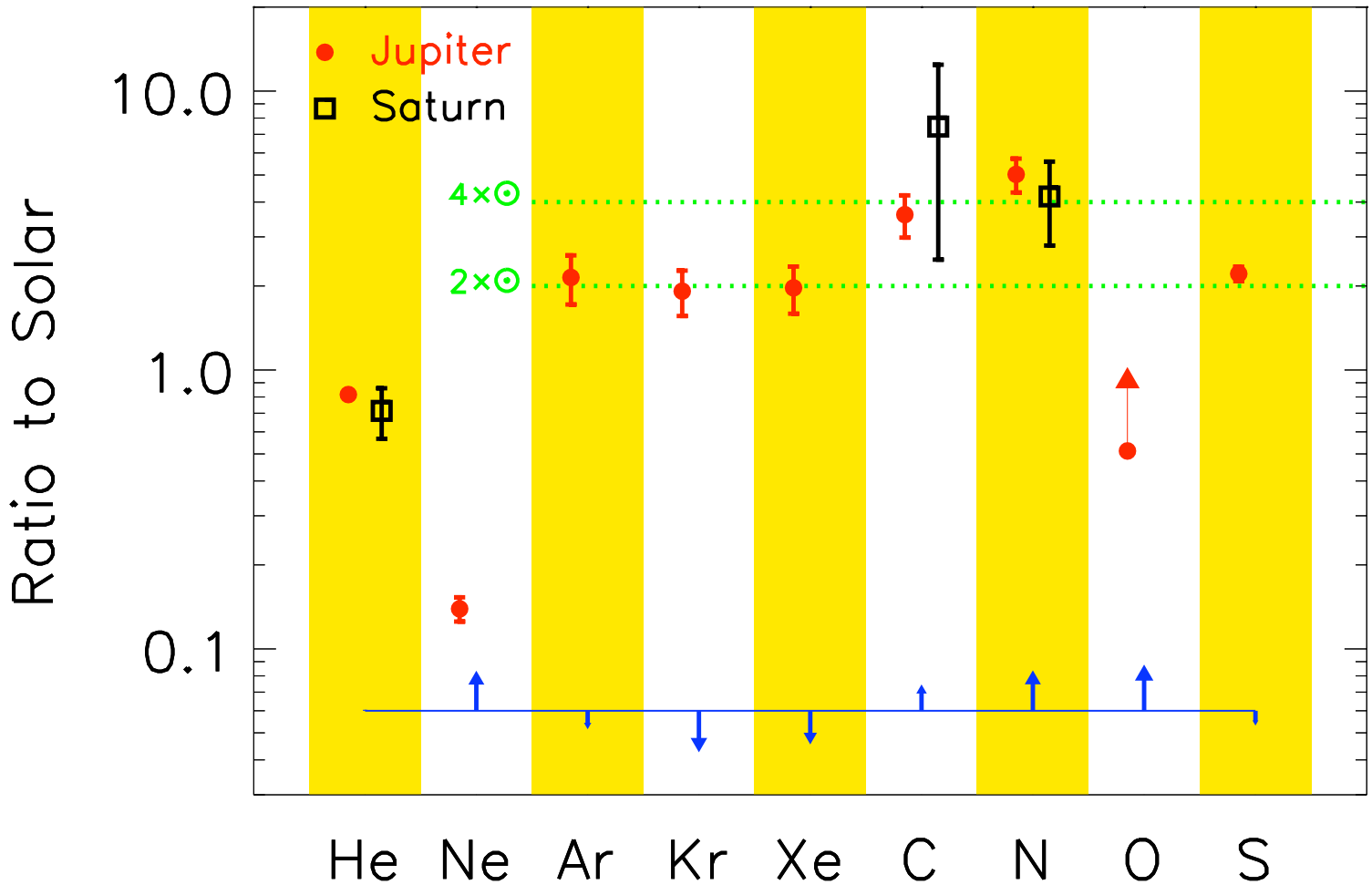
- Troubling because the previous concordance between the SSM and helioseismology helped establish the credibility of the SSM, and thus the plausibility of a neutrino mixing solution to the solar ν problem

Was the primordial Sun really homogeneous?

- Accept the photospheric and helioseismic results at face value: the convective zone (2.6% of the Sun's mass) has ~ 30% fewer metals than the radiative zone: deficit in the convective zone is 50 $M_\oplus$

- Galileo, Cassini, and subsequent planetary modeling show that significant metal differentiation occurred late in the evolution of the solar system, associated with formation of the gaseous giants
  - planets form late, involving the last ~ 5% of the gas
  - angular momentum transfer: that gas is in a thin disk
  - metal-rich grains and ice collect at the disk midplane
  - formation of the 10 $M_\oplus$ rock cores of the giant planet, which scour out this enriched material
  - rapid (1-few My) formation of gaseous envelopes, after the bulk of the nebular gas has already dissipated
  - timing: the sun already has developed its radiative core

- The observed atmospheric enrichments indicate a total metal excess of (40-90) $M_\oplus$, depending on planetary modeling uncertainties

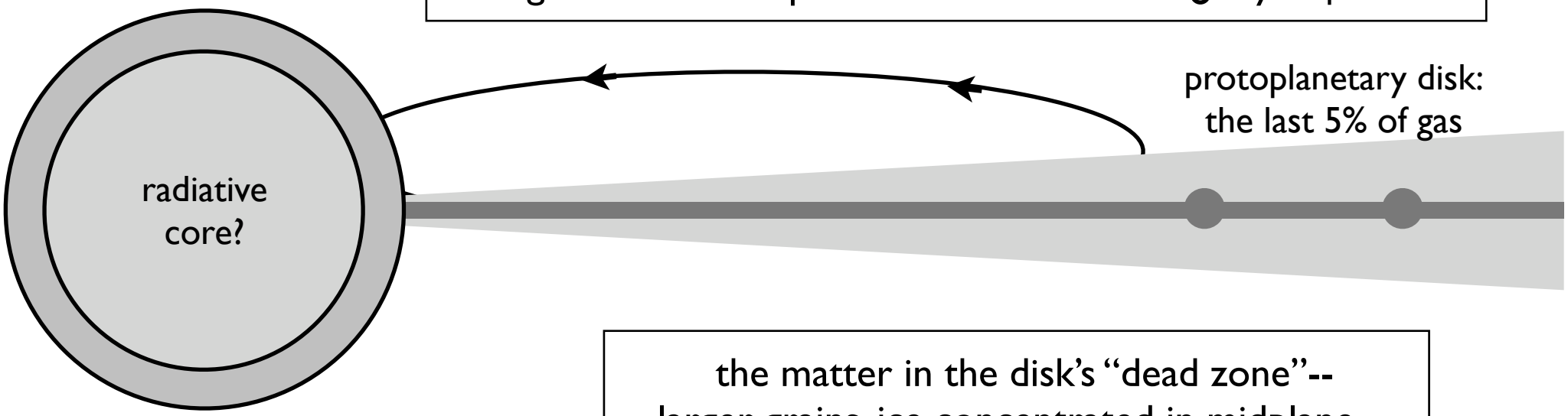


Galileo data, from Guillot AREPS 2005

Standard interpretation: late-stage planetary formation in a chemically evolved disk over ~ 1 m.y. time scale

Could a single mechanism be responsible for both problems?
Did the process of planetary formation perturb and chemically segregate the last few percent of nebular gas, resulting in the enrichment of planetary atmospheres and dilution of the convective zone?

(depleted) active surface of disk ionized by CRs, X-rays
magnetic stellar deposition rates of 0.01 $M_\odot$/My required



convective zone
2.6% of Sun's mass?

the matter in the disk's "dead zone"--
larger grains, ice concentrated in midplane --
preferentially incorporated into the planets,
reservoirs for 40-90 $M_\oplus$ of excess metal

The sun's deep interior would reflect the composition of the primordial gas cloud; the planets and solar surface would be processed

Several requirements

- processed gas remains in the solar system, not expelled
- because of the connection to planetary formation, the associated gas accretion rate would have to be on the order of $10^{-8} \times (1\ \mathrm{My}/\tau_{\mathrm{planets}})$ solar masses/year -- comparable to some observed T Tauri rates
- the Sun must have had a well-developed radiative core at the time of planetary formation (thus an isolated convective zone)

Experimental Possibilities?

- Solar neutrino experiments to date do not have the precision to address this problem. E.g., in the case of SNO

SNO 391-day NCD-phase results:	$(5.54 \pm 0.51) \times 10^6/\mathrm{cm}^2\mathrm{s}$
SNO LET analysis:	$(5.05 \pm 0.20) \times 10^6/\mathrm{cm}^2\mathrm{s}$
SSM, 1998 GS abundances (Z=0.0169):	$5.95 \times 10^6/\mathrm{cm}^2\mathrm{s}$
SSM, 2005 AGS abundances (Z=0.0122):	$4.72 \times 10^6/\mathrm{cm}^2\mathrm{s}$

- Astronomical observations: there have been two recent studies of solar twins -- driven in part by the possibility that if the formation of planets alters a host star's metallicity, a new tool for exo-planet hunting might develop

- New neutrino measurements: there is one possibility for probing solar core metalicity directly

Astronomy

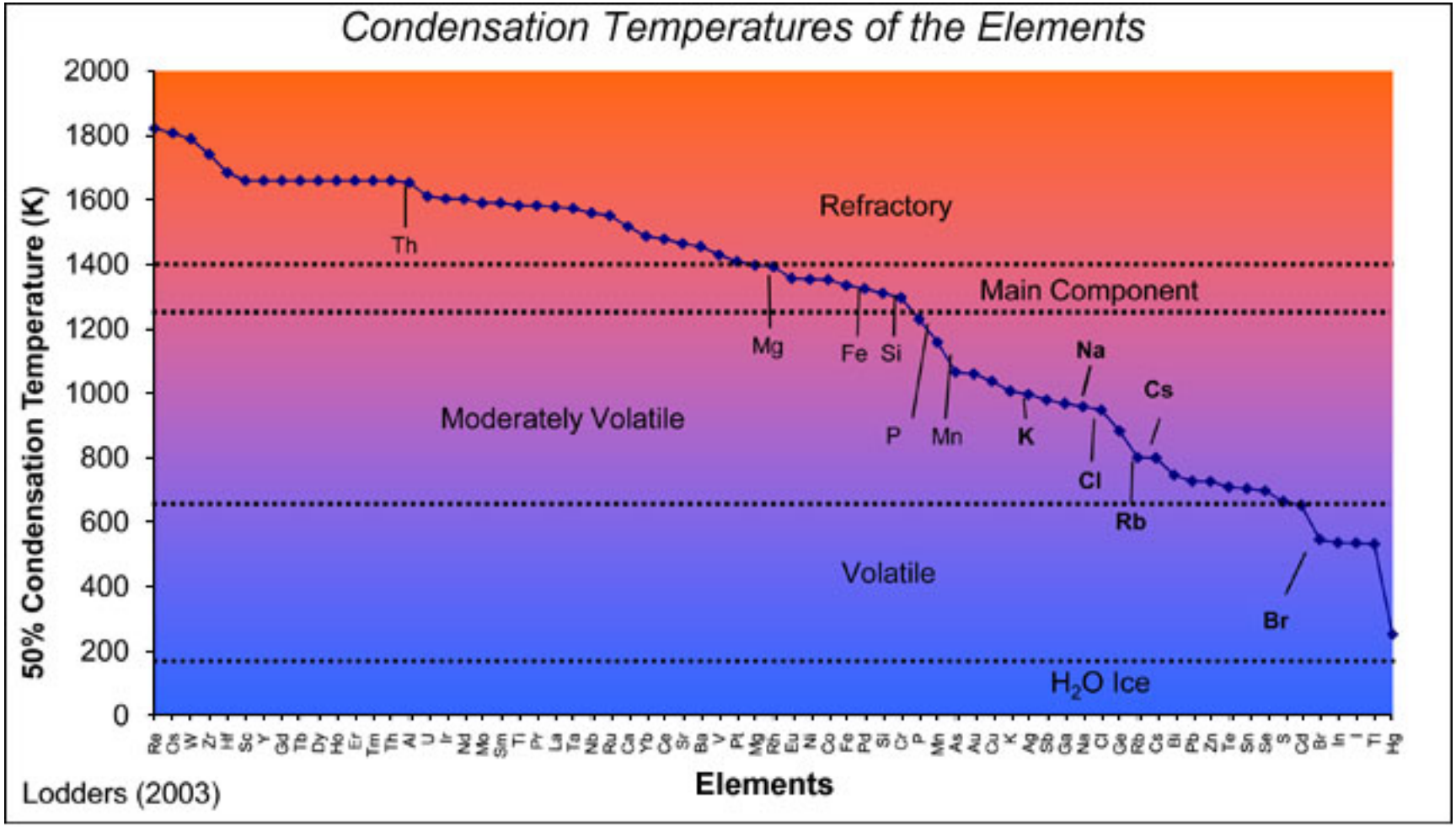
- *Melendez, Asplund, Gustafsson, Young Ap J L 704 (2009) L66*
  Ramirez, Melendez, Asplund A&A 508 (2009) L17

  systematic differences in heavy-element abundances between Sun and nearby solar twins, tightly correlated with the condensation temperature of the elements - so the mechanism is likely chemistry

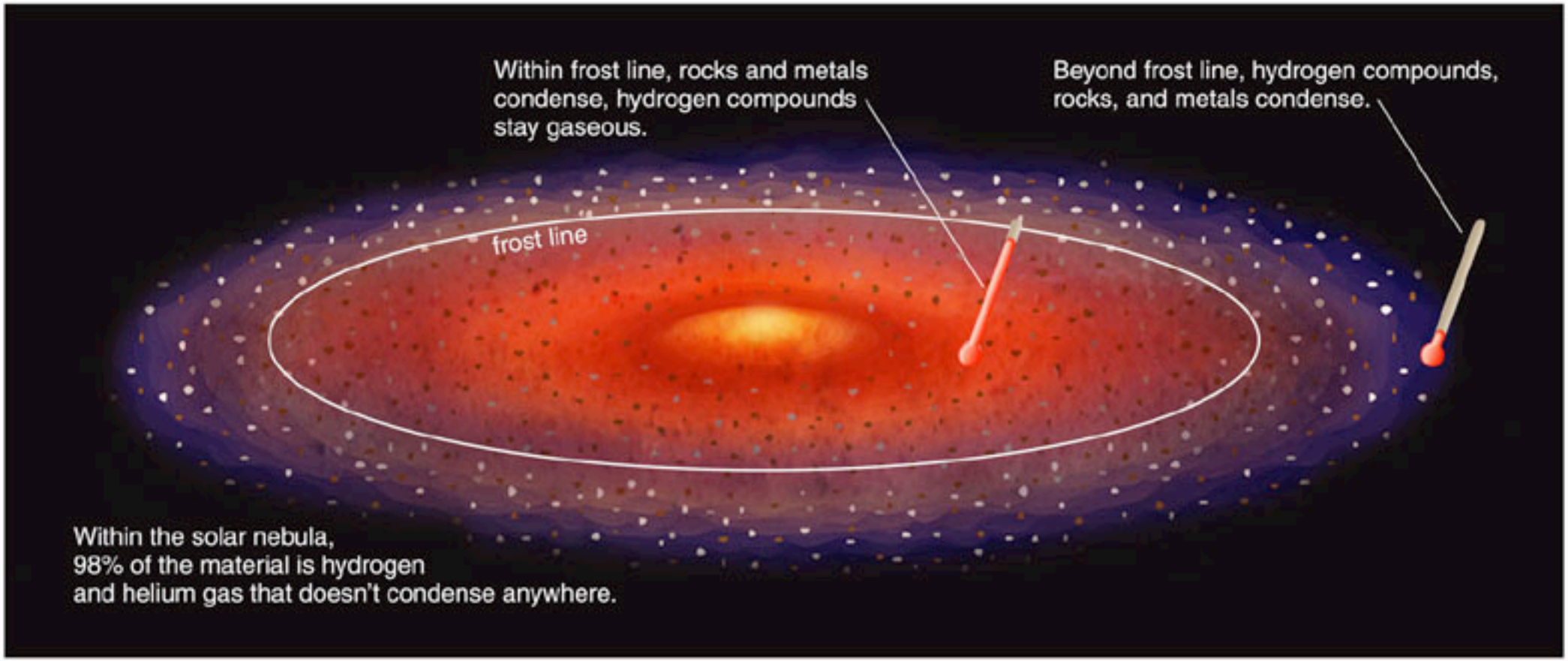
- *Israelian et al., Nature 462 (2009) 189*

  established a direct correlation between solar twin abundance of Li and the presence of planets: otherwise identical systems with planets have roughly 1/10 the Li of those without planets

  - hypothesized a rather exotic "mechanical" explanation



(PSRD graphic based on calculations done by Katarina Lodders, Washington University in St. Louis.)

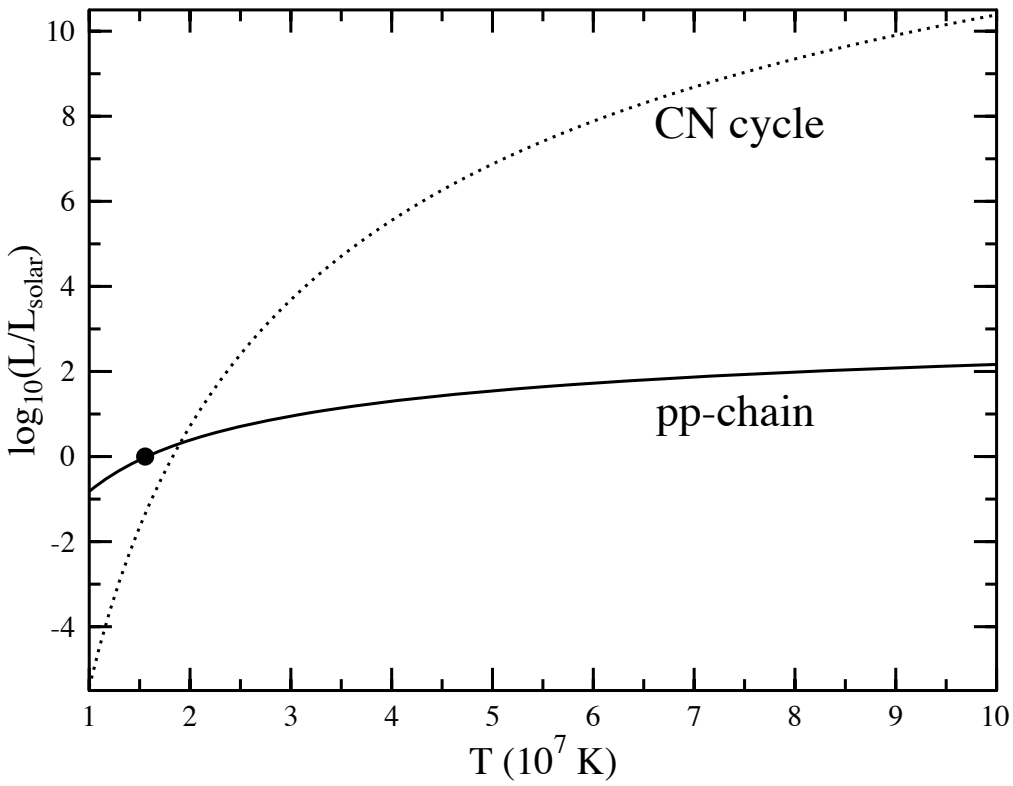


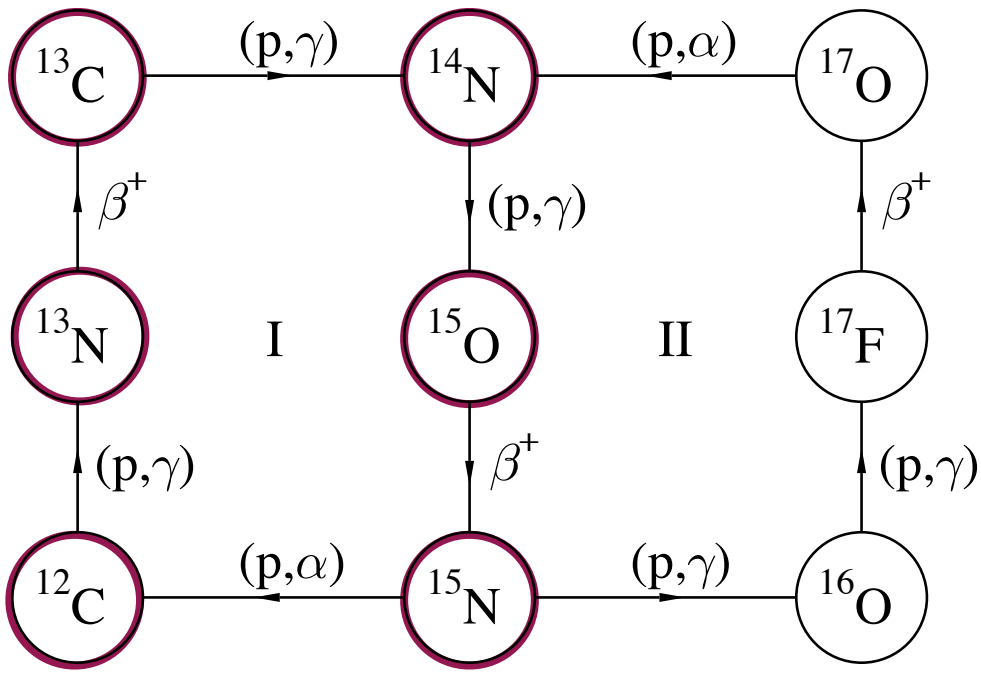
refractory elements condense

H_2O condenses

SNO+ as a possible test of a two-zone Sun

- pp chain (primary) vs CN cycle (secondary): catalysts for CN cycle are pre-existing metals (except ij the interesting case of the first stars)





- the CN-cycle contributes modestly to solar energy generation ~ 1%

- but produces measurable neutrino fluxes

$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \quad E_\nu \lesssim 1.199\ \mathrm{MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

$$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N} \quad E_\nu \lesssim 1.732\ \mathrm{MeV} \quad \phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$$

- these fluxes depend on the core temperature T, but also have an additional linear dependence on the total C+N in the Sun's core

$$\phi_\nu^{\mathrm{CN}} = F[S_{^{14}N+p};\quad T;\quad \theta_{12};\quad CN]$$

↓

what we want to determine

- the CN-cycle contributes modestly to solar energy generation ~ 1%

- but produces measurable neutrino fluxes

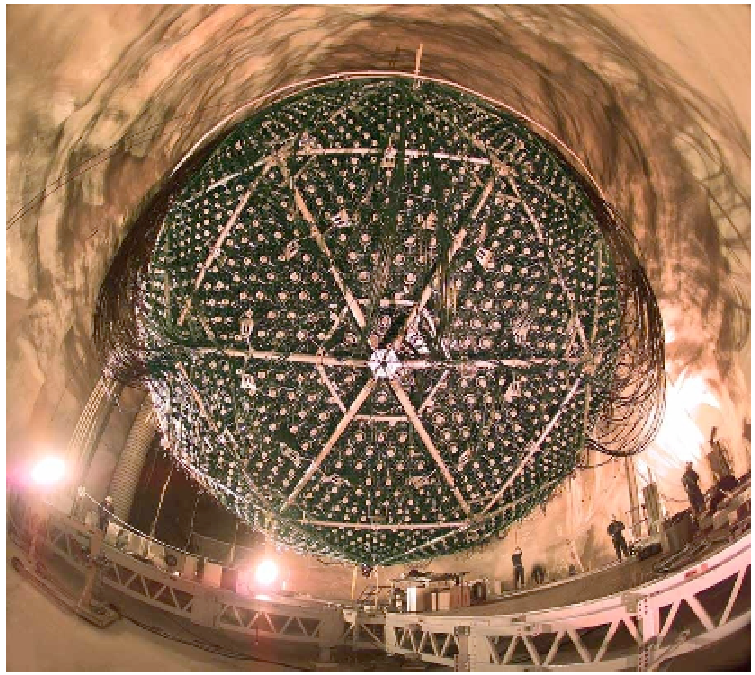
$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \quad E_\nu \lesssim 1.199\ \mathrm{MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

$$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N} \quad E_\nu \lesssim 1.732\ \mathrm{MeV} \quad \phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$$

- these fluxes depend on the core temperature T, but also have an additional linear dependence on the total C+N in the Sun's core

$$\phi_\nu^{\mathrm{CN}} = F[S_{^{14}N+p};\quad T;\quad \theta_{12};\quad CN]$$

well enough measured by SNO and KamLAND



- the CN-cycle contributes modestly to solar energy generation ~ 1%

- but produces measurable neutrino fluxes

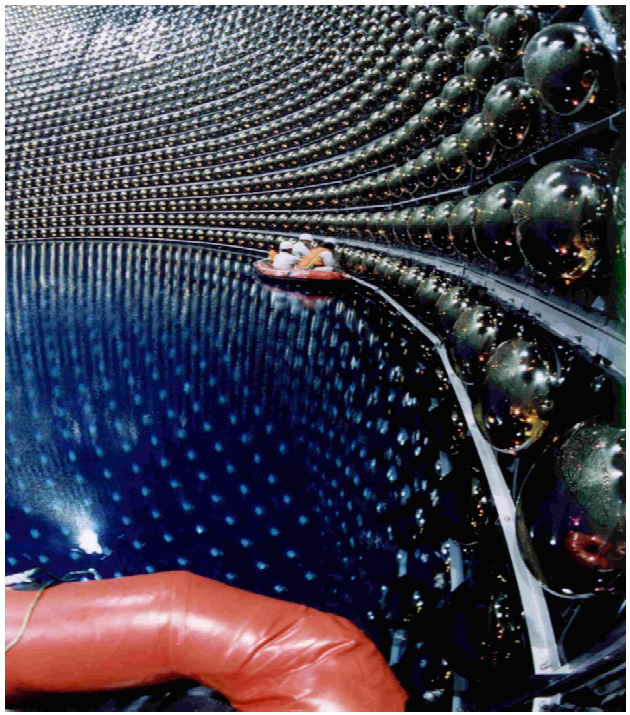
$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \quad E_\nu \lesssim 1.199\ \mathrm{MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

$$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N} \quad E_\nu \lesssim 1.732\ \mathrm{MeV} \quad \phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$$

- these fluxes depend on the core temperature T, but also have an additional linear dependence on the total C+N in the Sun's core

$$\phi_\nu^{\mathrm{CN}} = F[S_{^{14}N+p};\quad T;\quad \theta_{12};\quad CN]$$

a surrogate for 19 SSM parameters: calibrated to 0.5% by Super-Kamiokande



- the CN-cycle contributes modestly to solar energy generation ~ 1%

- but produces measurable neutrino fluxes

$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \quad E_\nu \lesssim 1.199 \text{ MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

$$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N} \quad E_\nu \lesssim 1.732 \text{ MeV} \quad \phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$$

- these fluxes depend on the core temperature T, but also have an additional linear dependence on the total C+N in the Sun's core

$$\phi_\nu^{\mathrm{CN}} = F[S_{^{14}N+p}; \quad T; \quad \theta_{12}; \quad CN]$$

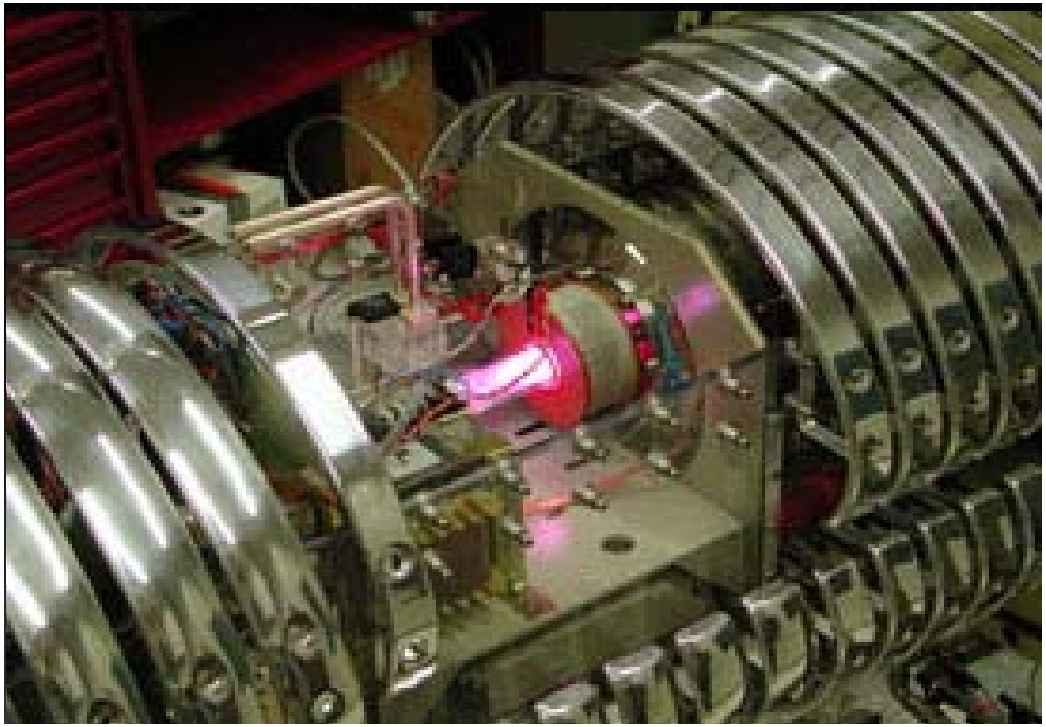
a significant, limiting uncertainty until recently

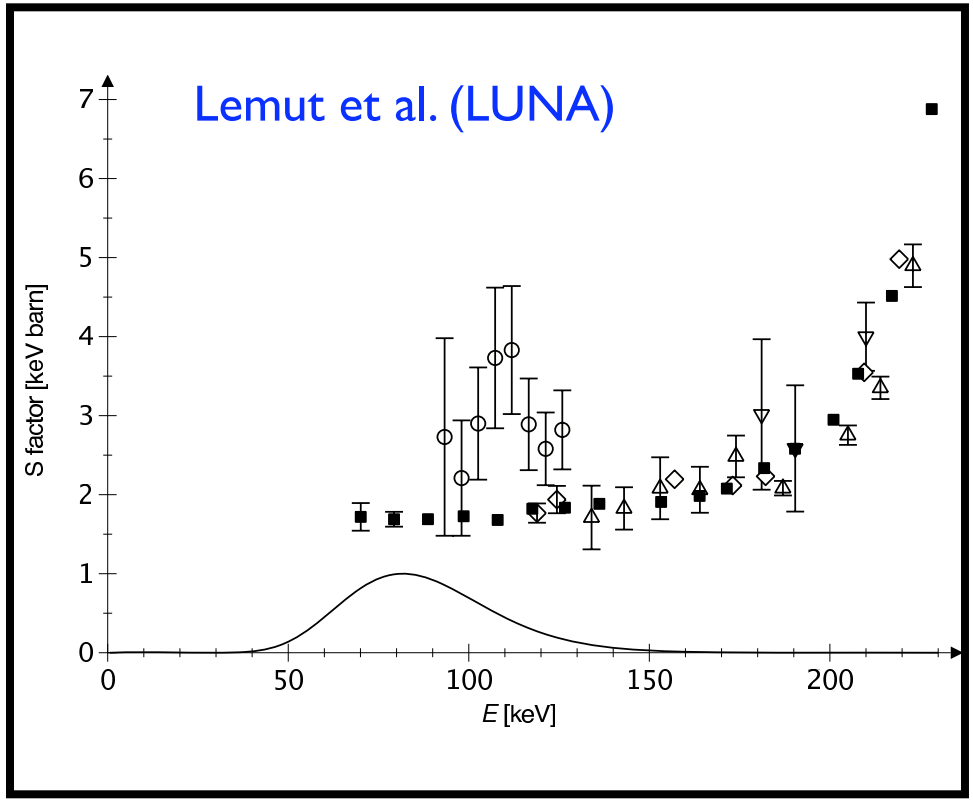
Heroic efforts to make background-free measurements

LUNA and LENA measurements of $^{14}N(p,\gamma)$

Formicola (LUNA) et al. (2004); Imbriani et al. (2005);
Bemmerer et al (2006); Lemut et al. (2006);
Trautvetter et al. (2008); Runkle (TUNL) et al. (2005)

S-factor mapped down to 70 keV ⇒ event rate 1/mo





- the CN-cycle contributes modestly to solar energy generation ~ 1%

- but produces measurable neutrino fluxes

$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \quad E_\nu \lesssim 1.199 \text{ MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

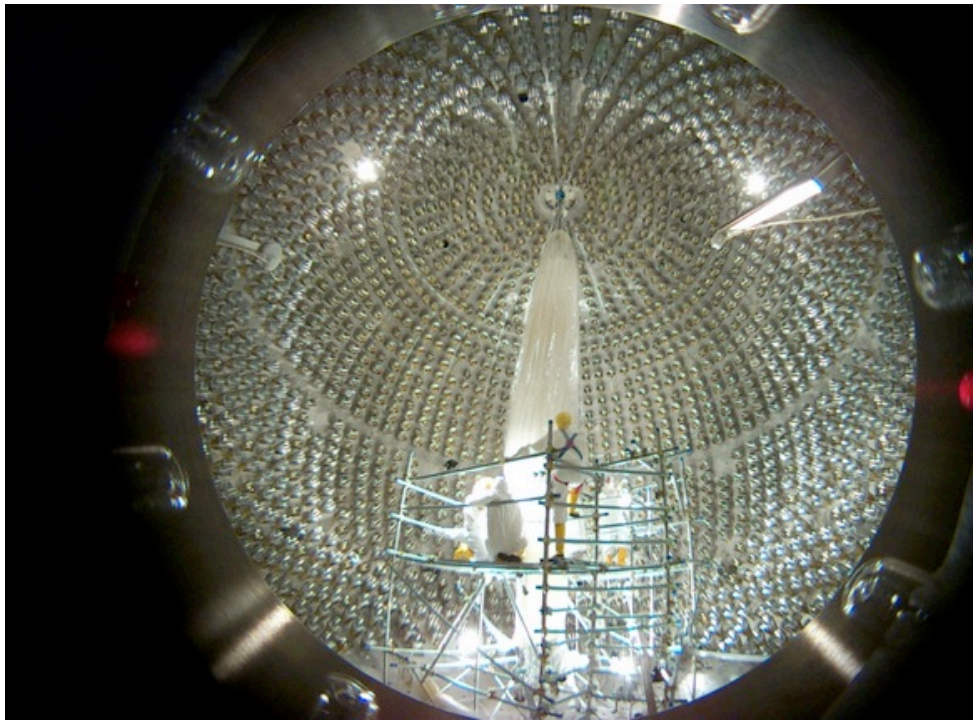
$$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N} \quad E_\nu \lesssim 1.732 \text{ MeV} \quad \phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$$

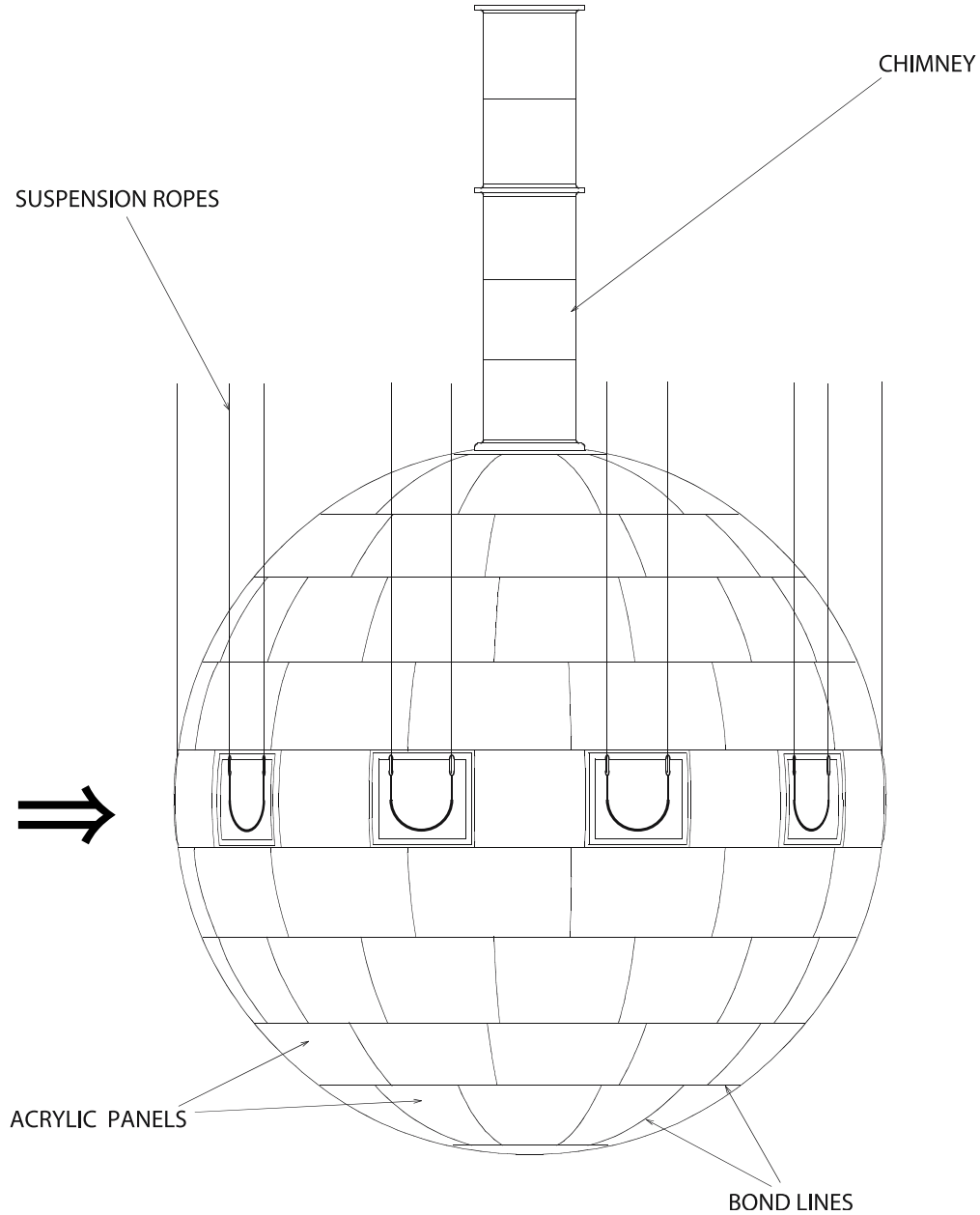
- these fluxes depend on the core temperature T, but also have an additional linear dependence on the total C+N in the Sun's core

$$\phi_\nu^{\mathrm{CN}} = F[S_{^{14}N+p}; \quad T; \quad \theta_{12}; \quad CN]$$

↓

an experiment capable of measuring the fluxes

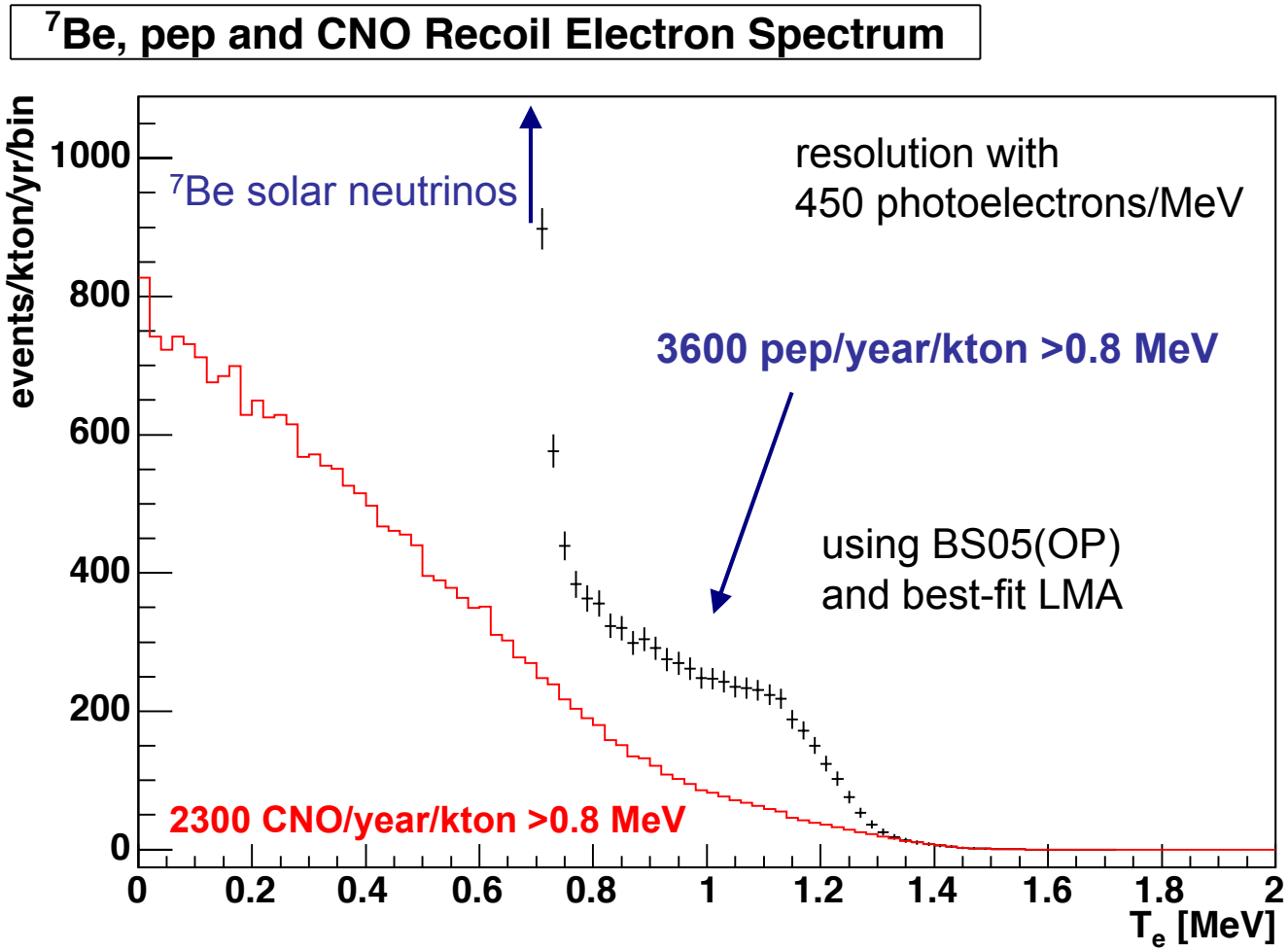




SNO+ will occupy the SNOLab cavity previously occupied by SNO

Three times larger and one kilometer deeper than Borexino

CN spectrum sits between the pep and 7Be line electrons



(from Mark Chen)

SNOLab's 2 kilometer depth: factor-of-70 reduction in long-lived cosmogenic ^{11}C, to 0.1 c/d/100 tons, compared to Borexino

→ 7% CNO flux measurement appears possible

So the next solar neutrino experiment may have a different kind of impact

- It appears SNO+ and analysis could determine the core abundance of C+N to an accuracy of about 11% (with the error nominated by lab astrophysics, which could be improved with a bit of work)
  - this would check a key assumption of the SSM, that the metals are distributed uniformly throughout the Sun

- well motivated, as we have three apparent metalicity problems
  - SSM conflict between helioseismology, photospheric abundances
  - the anomalous abundances of Jupiter, Saturn
  - the systematic chemical anomalies in solar twins

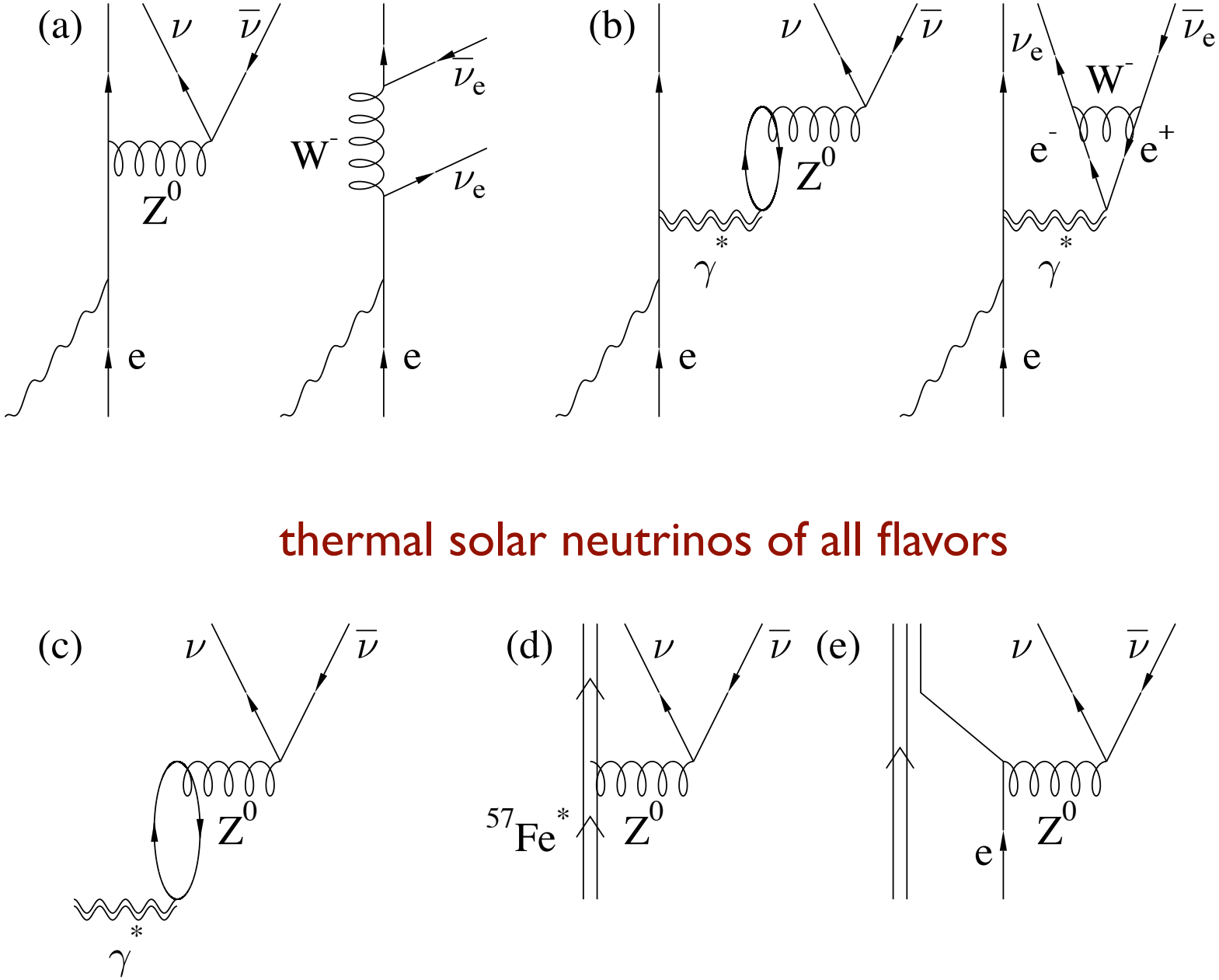
- interesting that the solar neutrino problem has stimulated advances in two of the three available techniques for probing solar system interiors (solar neutrino detection, helioseismology)

- if C+N is anomalous, we will have to reconsider one of the central assumptions of the SSM

When will we be done with solar neutrinos?

When will we be done with solar neutrinos?

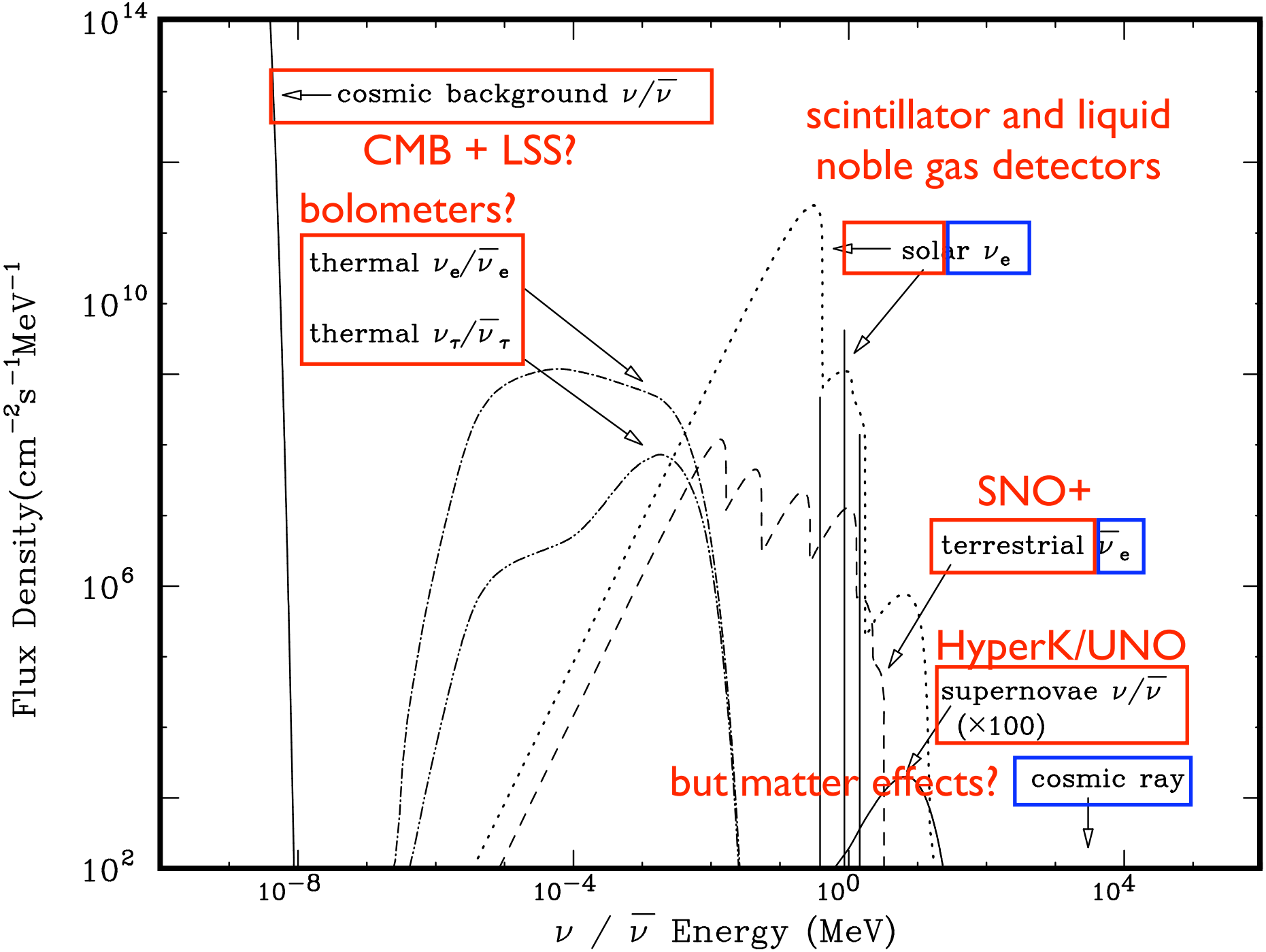
Not soon! ..... for example, there are sources we have not yet even discussed



thermal solar neutrinos of all flavors

FIG. 1. Representative diagrams for the various thermal neutrino pair processes considered here: a) Compton process; b) plasmon pole contribution to the Compton process; c) transverse plasmon decay; d) nuclear Z^0 emission; and e) pair production in free-bound atomic transitions.

As is the case with most sources of astrophysical neutrinos!



supplementary slides

Can one extract from such a measurement the core metalicity?

- There are 19 SSM parameters β_j with significant uncertainties

$$\alpha(i,j) \equiv \frac{\partial \ln\left[\phi_i/\phi_i(0)\right]}{\partial \ln\left[\beta_j/\beta_j(0)\right]} \quad \Rightarrow \quad \phi_i = \phi_i(0) \prod_{j=1}^{N} \left[\frac{\beta_j}{\beta_j(0)}\right]^{\alpha(i,j)}$$

(each β has some estimated SSM uncertainty)

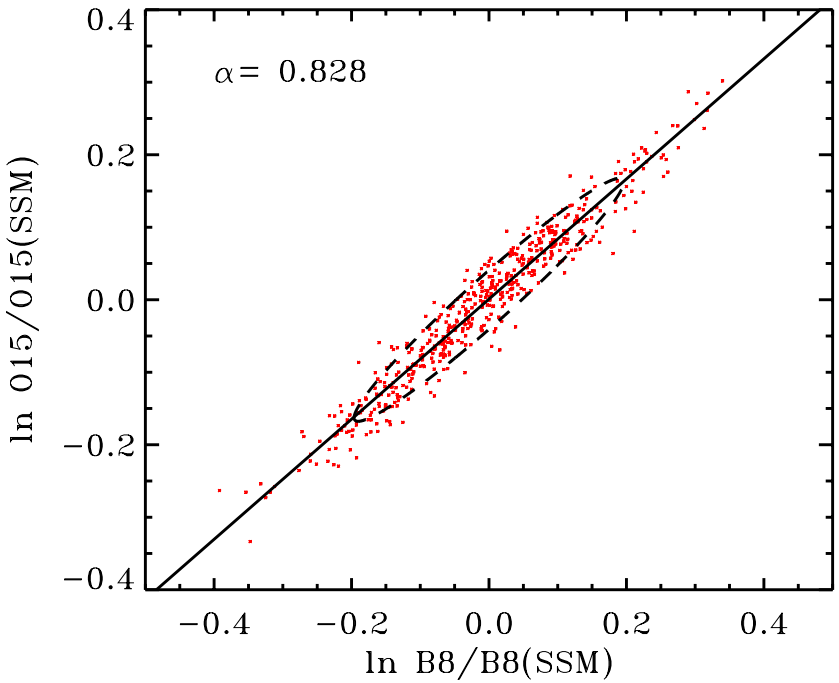
- Divide this dependence into environmental, nuclear, CN terms

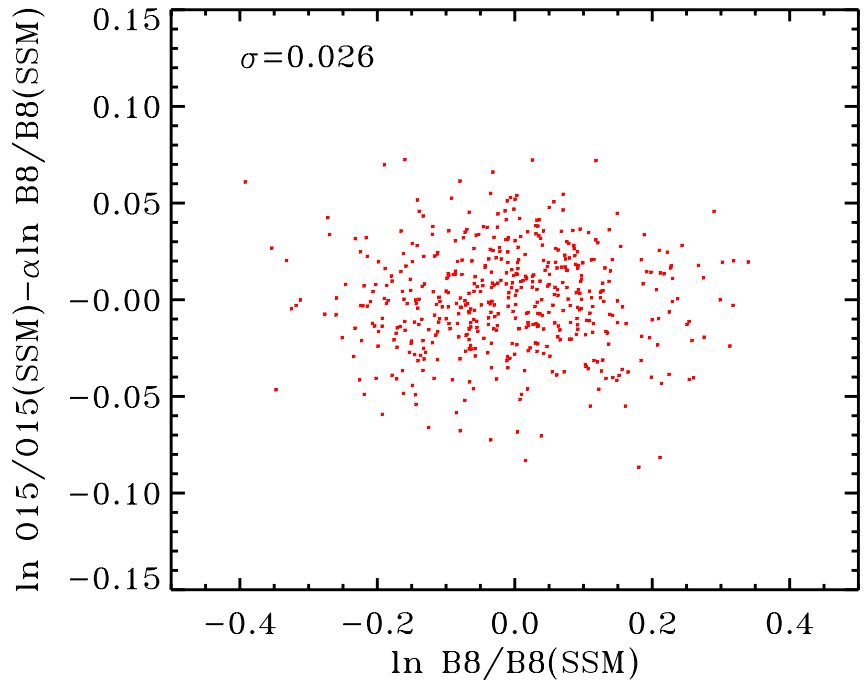
$$\phi_i = \phi_i^{SSM} \left(\prod_{j\in\{\mathrm{Solar}\}} \left[\frac{\beta_j}{\beta_j(0)}\right]^{\alpha(i,j)} \prod_{j\in\{\mathrm{Metals}\neq\mathrm{C,N}\}} \left[\frac{\beta_j}{\beta_j(0)}\right]^{\alpha(i,j)} \right) \prod_{j\in\{\mathrm{Nuclear}\}} \left[\frac{\beta_j}{\beta_j(0)}\right]^{\alpha(i,j)} \prod_{j\in\{\mathrm{C,N}\}} \left[\frac{\beta_j}{\beta_j(0)}\right]^{\alpha(i,j)}$$

- bracketed "environmental" uncertainties: luminosity, radiative opacity, solar age, He and metal diffusion, fractional abundances of O, Ne, Mg, Si, S, Ar, and Fe -- not well controlled by lab constraints, but tend to affect all neutrino fluxes similarly

- what remains is a linear dependence on C, N -- our interest

Monte Carlo SSM studies of ^{8}B, ^{15}O ν correlations





	Environmental β_j				Nuclear β_j					
Source	$L_\odot$	Opacity	Age	Diffusion	S_{11}	S_{33}	S_{34}	S_{17}	S_{e7}	S_{114}
$\phi(^8\mathrm{B})$	7.16	2.70	1.38	0.28	-2.73	-0.43	0.85	1.0	-1.0	-0.020
$\phi(^{13}\mathrm{N})$	4.40	1.43	0.86	0.34	-2.09	0.025	-0.053	0.0	0.0	0.71
$\phi(^{13}\mathrm{N})/\phi(^8\mathrm{B})^{0.599}$	0.11	-0.19	0.03	0.17	-0.45	0.28	-0.56	-0.60	0.60	0.72
$\phi(^{15}\mathrm{O})$	6.00	2.06	1.34	0.39	-2.95	0.018	-0.041	0.0	0.0	1.00
$\phi(^{15}\mathrm{O})/\phi(^8\mathrm{B})^{0.828}$	0.07	-0.18	0.20	0.16	-0.69	0.37	-0.74	-0.83	0.83	1.02

The point: other neutrino measurements (SNO, Superk) have effectively calibrated the environmental uncertainties

The bottom line is a primordial abundances ↔ future experiment relation:

$$\frac{R^{B/S}_{exp}(\mathrm{CN})}{R^{B/S}_{cal}(^{15}\mathrm{O}, \delta m^2_{12}, \theta_{12}))} = \left(\frac{X(^{12}\mathrm{C})}{X(^{12}\mathrm{C})_{SSM}}\right)^{0.805} \left(\frac{X(^{14}\mathrm{N})}{X(^{14}\mathrm{N})_{SSM}}\right)^{0.199}$$

$$\times(1.120 \pm 0.003)[1 \pm 0.03(\mathrm{SK}) \pm 0.026(\mathrm{resid\ env}) \pm 0.049(\mathrm{LMA}) \pm 0.071(\mathrm{nucl})]$$

diffusion: relating today's metals to primordial ones

errors that can be further improved in the laboratory:
nuclear physics
neutrino flavor physics

The net theory "error bar" in relating a SNO+ CN-ν measurement to primordial metallicity is thus about 9%

For details, see WH + Aldo Serenelli, ApJ 687 (2008) 678 (arXiv:0805.2013)