The Sun and solar neutrinos

F. L. Villante
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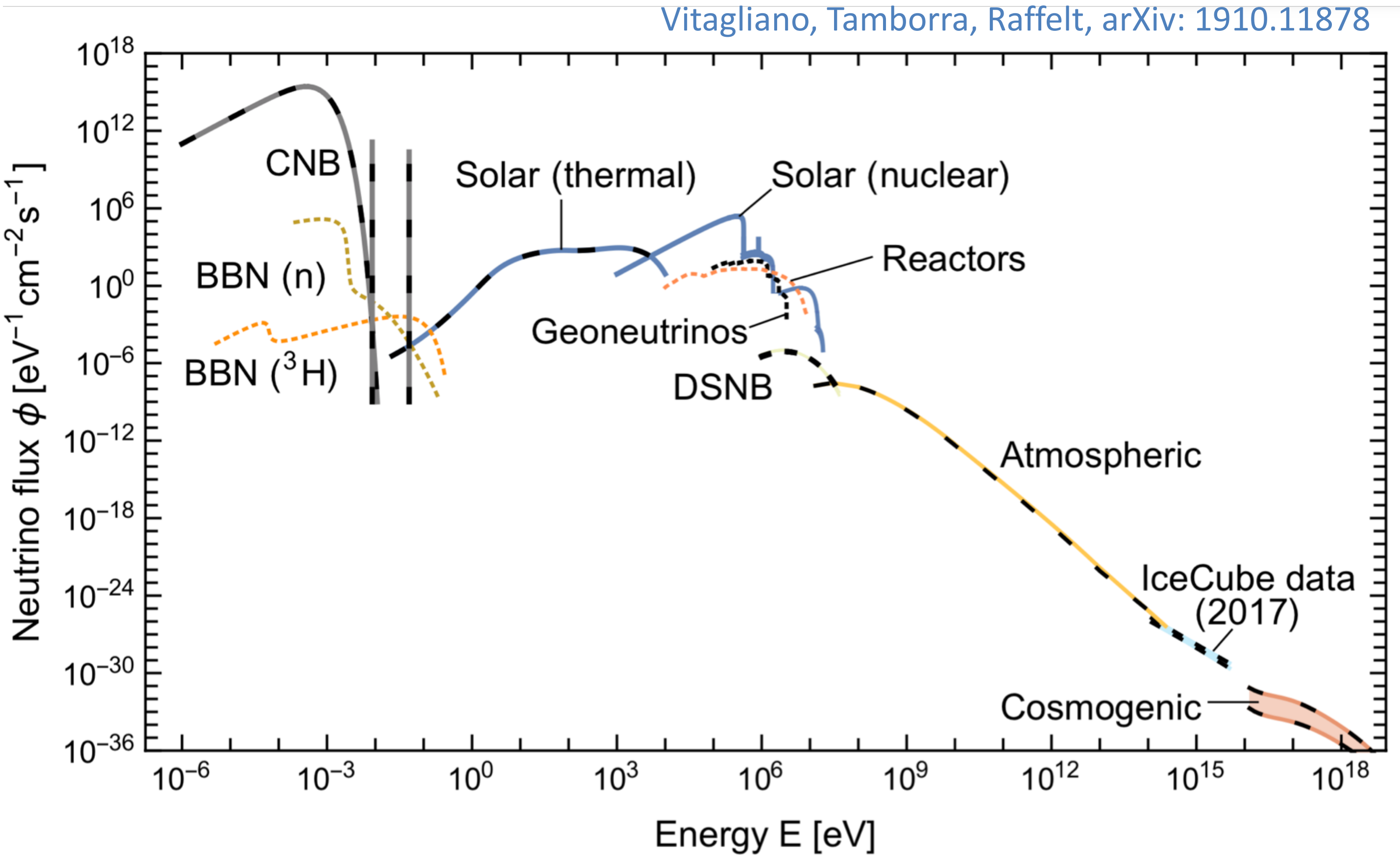
The “grand unified” neutrino spectrum at Earth



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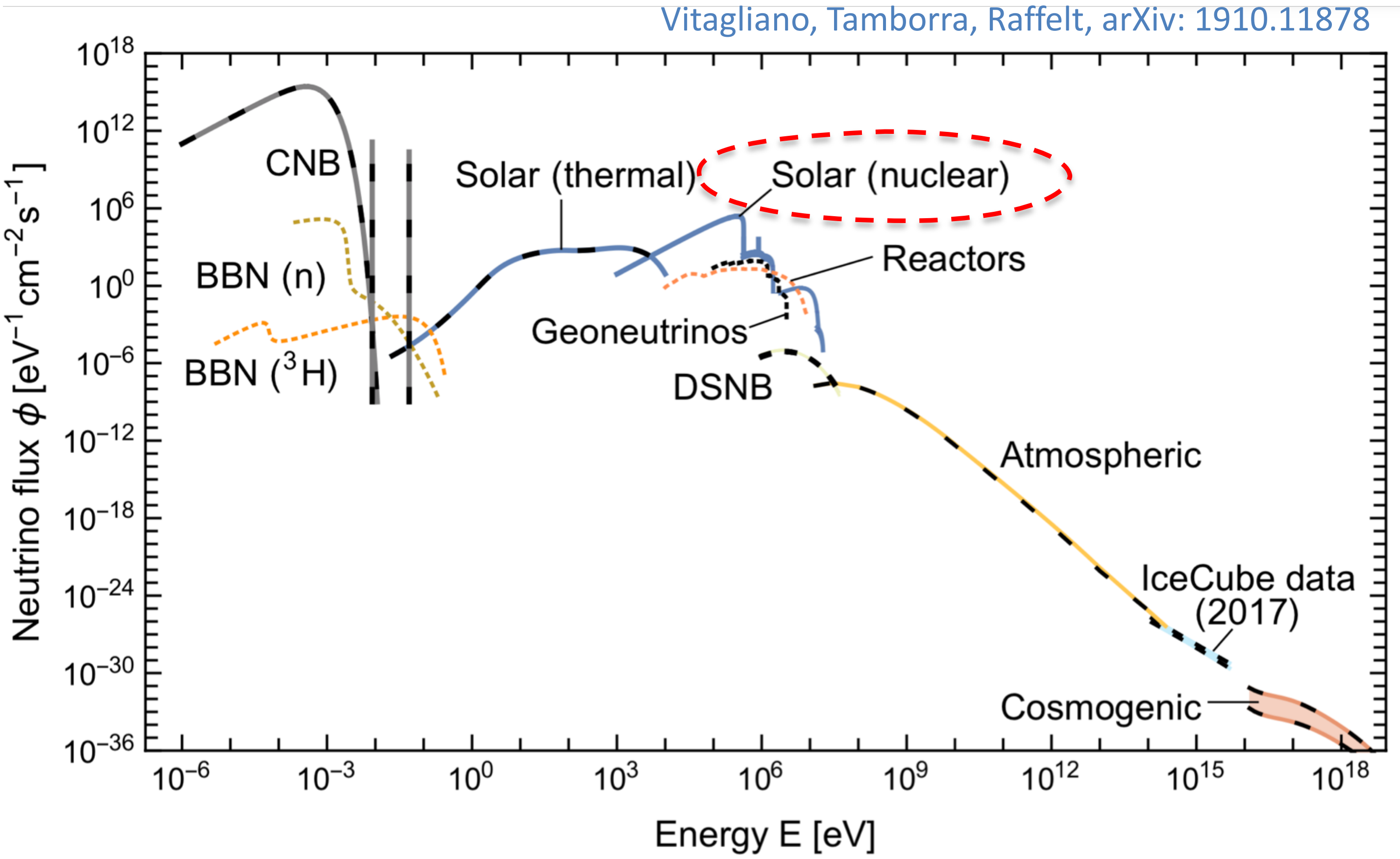


Solar ν flux: $\Phi_\nu \approx 6\times10^{10}\ \mathrm{cm^{-2}\,s^{-1}}$

largely dominant at $E_\nu \approx [0.1,15]$ MeV

Hydrogen Burning

The Sun is powered by nuclear reactions that transform H into ^{4}He:

$$4H + 2e^{-} \rightarrow {}^{4}He + 2\nu_e + \text{energy}$$

Q = 26,7 MeV (globally)

Free stream – 8 minutes to reach the earth
Direct information on the energy producing region.

The Sun observed with:

$$\Phi_{\nu} \approx 2\, K_{\gamma}/Q \approx 6 \times 10^{10} cm^{-2} s^{-1}$$

neutrinos

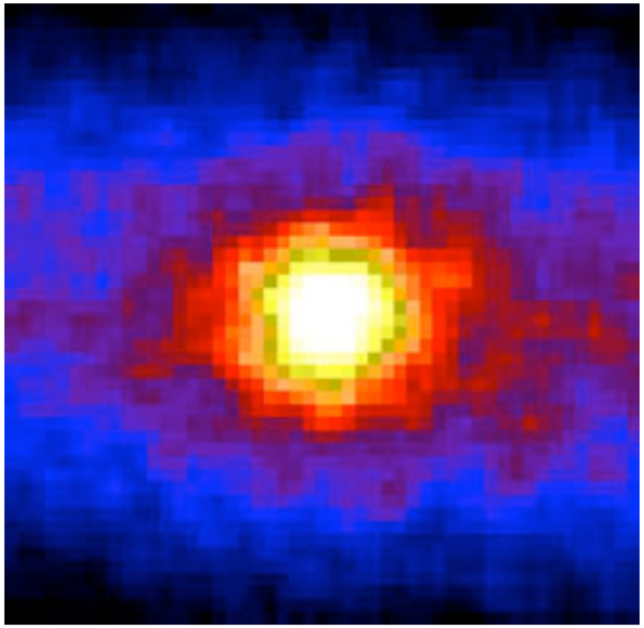
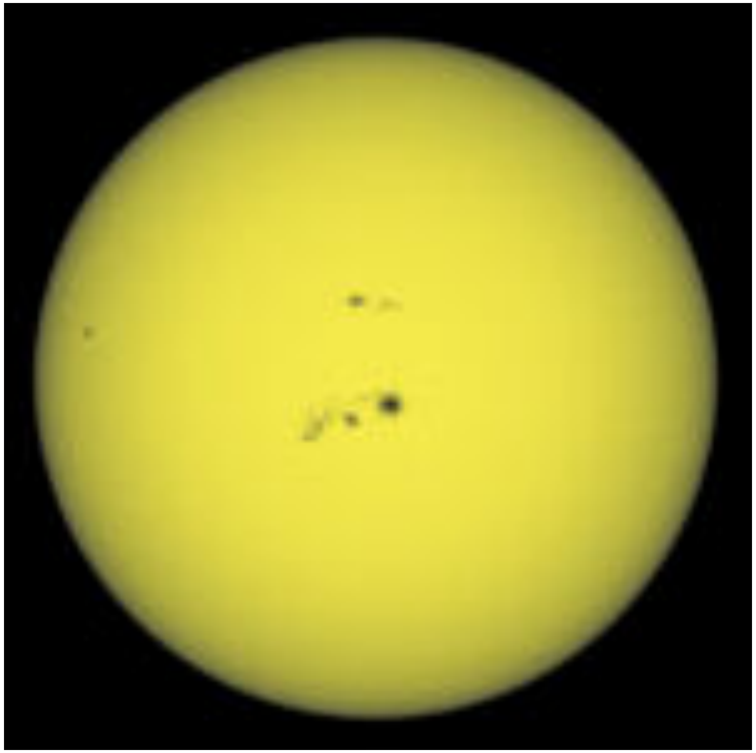


Image credits: Super-Kamiokande Coll.

photons



Neutrinos freely escape from the core of the Sun:
- 8 minutes to reach the earth
- Direct information on the energy producing region.

Hydrogen Burning: PP chain and CNO cycle

The Sun is powered by nuclear reactions that transform H into ^{4}He:

$$4H + 2e^- \rightarrow {}^4He + 2\nu_e + \text{energy}$$

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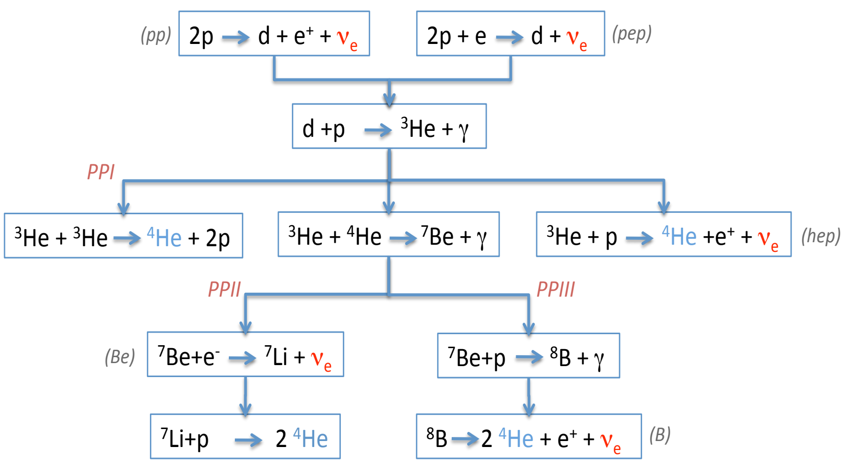
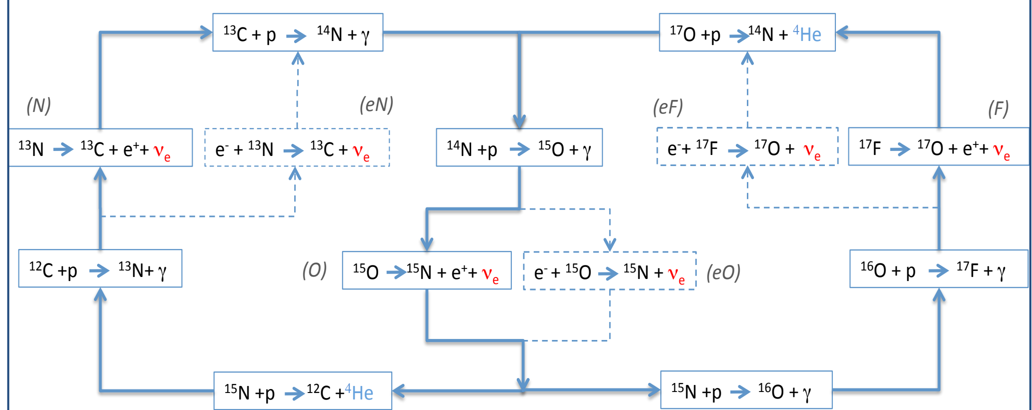
Direct information on the energy producing region.

The PP-chain



The CN-NO (bi-)cycle

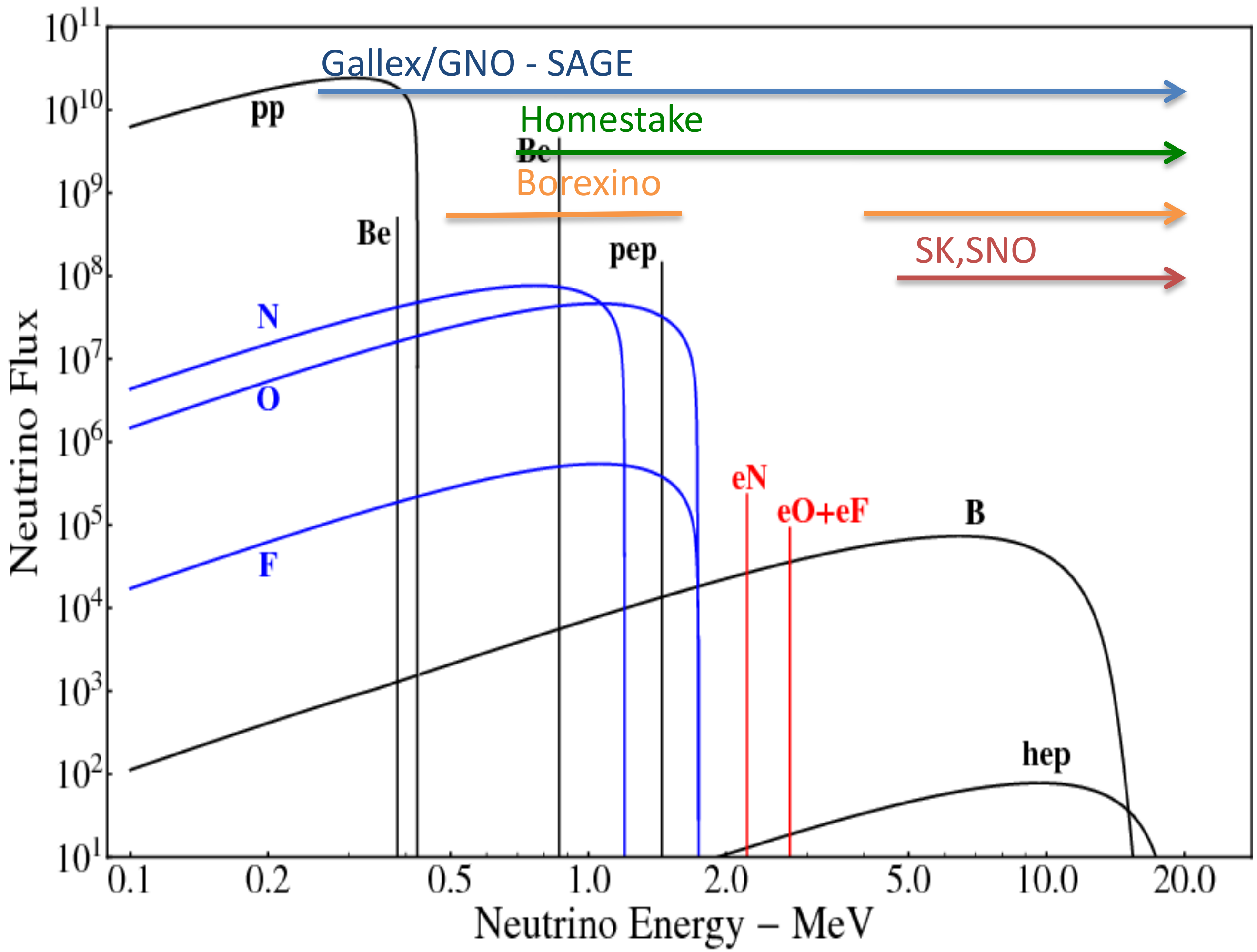


The pp chain is responsible for about 99% of the total energy (and neutrino) production.

C, N and O nuclei are used as catalysts for hydrogen fusion.

CNO (bi-)cycle is responsible for about 1% of the total neutrino (and energy) budget. Important for more advanced evolutionary stages

The solar neutrino spectrum



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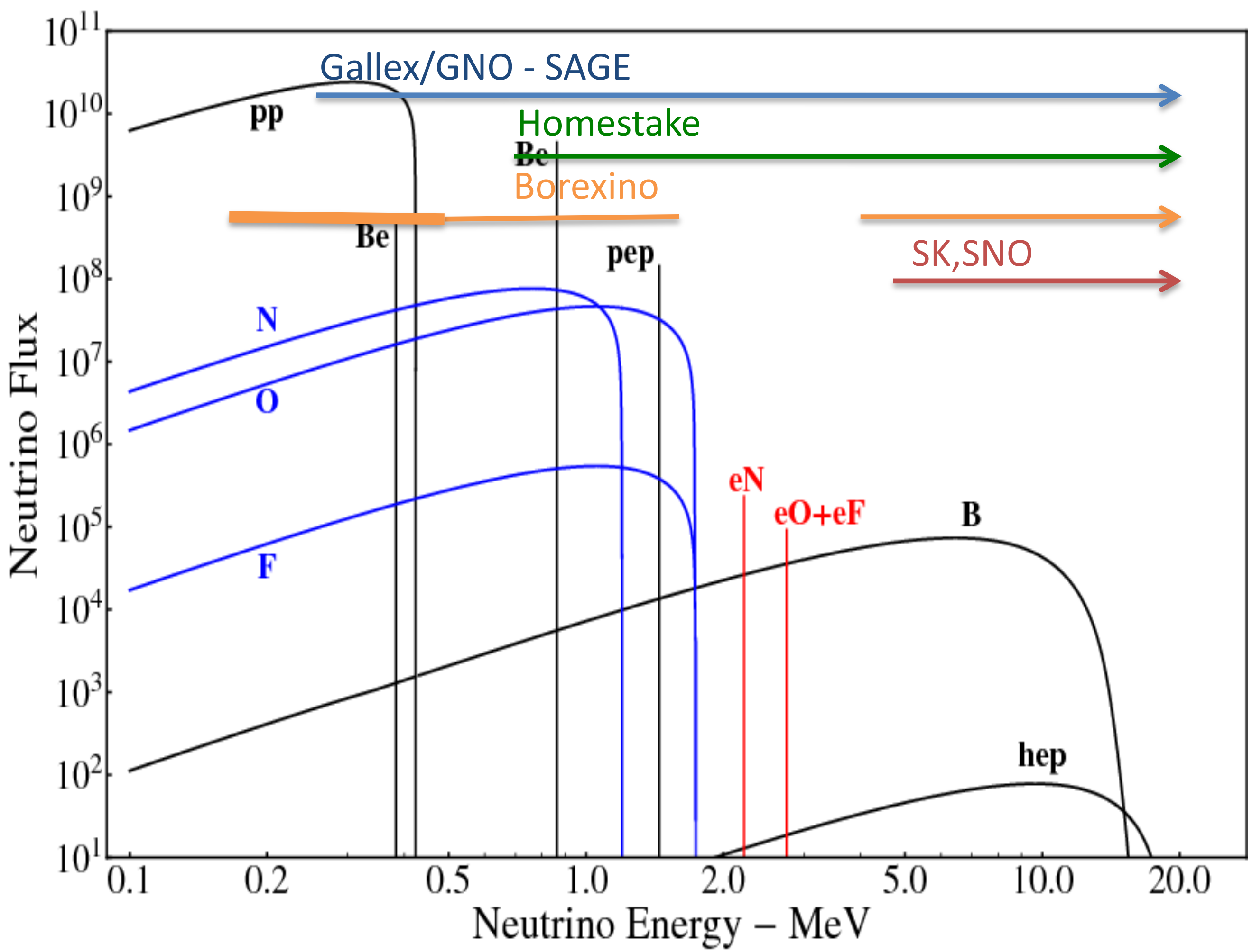

"Observing" the Sun with neutrinos: the present situation

Experimental results agree with Standard Solar Models (SSM) + flavor oscillations:

Vinyoles et al., ApJ 2017

Flux	B16-GS98	B16-AGSS09met	Solar
$\Phi(\mathrm{pp})$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.971^{(1+0.006)}_{(1-0.005)}$
$\Phi(\mathrm{pep})$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.448(1 \pm 0.009)$
$\Phi(\mathrm{hep})$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$19^{(1+0.63)}_{(1-0.47)}$
$\Phi(^{7}\mathrm{Be})$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$
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Units:
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$\Phi_{Be} = 4.99\ (1 \pm 0.03)$ Borexino

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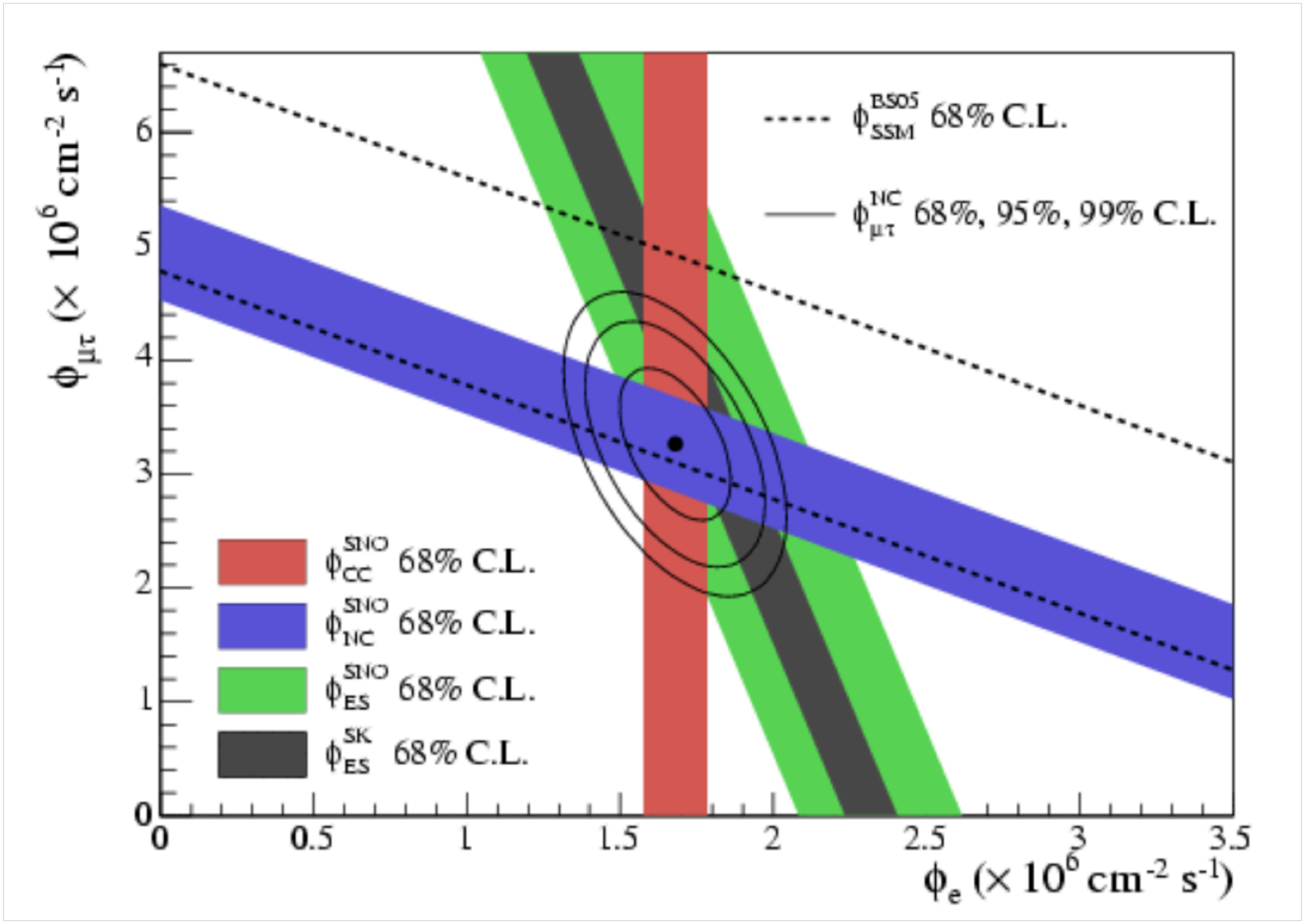
^{8}B @ 2% (SNO & SK) and ^{7}Be @ 3% (Borexino)

2001-2002: the solution of the solar neutrino puzzle

The Boron neutrino flux measured by SK (ES) and SNO (ES,CC,NC):
[N.B: The plot describes the situation at the end of SNO-phaseII]



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CNO neutrinos essentially not constrained

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otherwise solar luminosity matched @ 15% (Maltoni et al. 2010)

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→ Φ_{pp} = 6.1 (1 ± 0.10) Borexino

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Direct measurement of pp by Borexino now to 10%

L_ν(8 minutes) ≈ L_γ (10^5 year) – test of solar stability
Still not accurate enough to test SSMs (≈ few % accuracy required)

Solar neutrino oscillations

Neutrino propagation is described in the flavor basis by:

$$i\frac{\partial}{\partial t}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

$$H = H_{free} + V$$

Neutrino matter potentials:
$V \approx G_F\, N_{target}$

ν are ultra-relativistic:
$H_{free} = (P^2 + m^2)^{1/2} \approx P + m^2/2E$

ν-oscillations are consequence of ν-mixing:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \cdots\end{pmatrix} = U \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \cdots\end{pmatrix}$$

U = unitary matrix

N_ν larger than 3 ↔ $\nu_{sterile}$

$$H = P + U\frac{M^2}{2E}U^+ + V$$

$$M^2 = \mathrm{diag}(m_1^2, m_2^2, m_3^2, \ldots)$$

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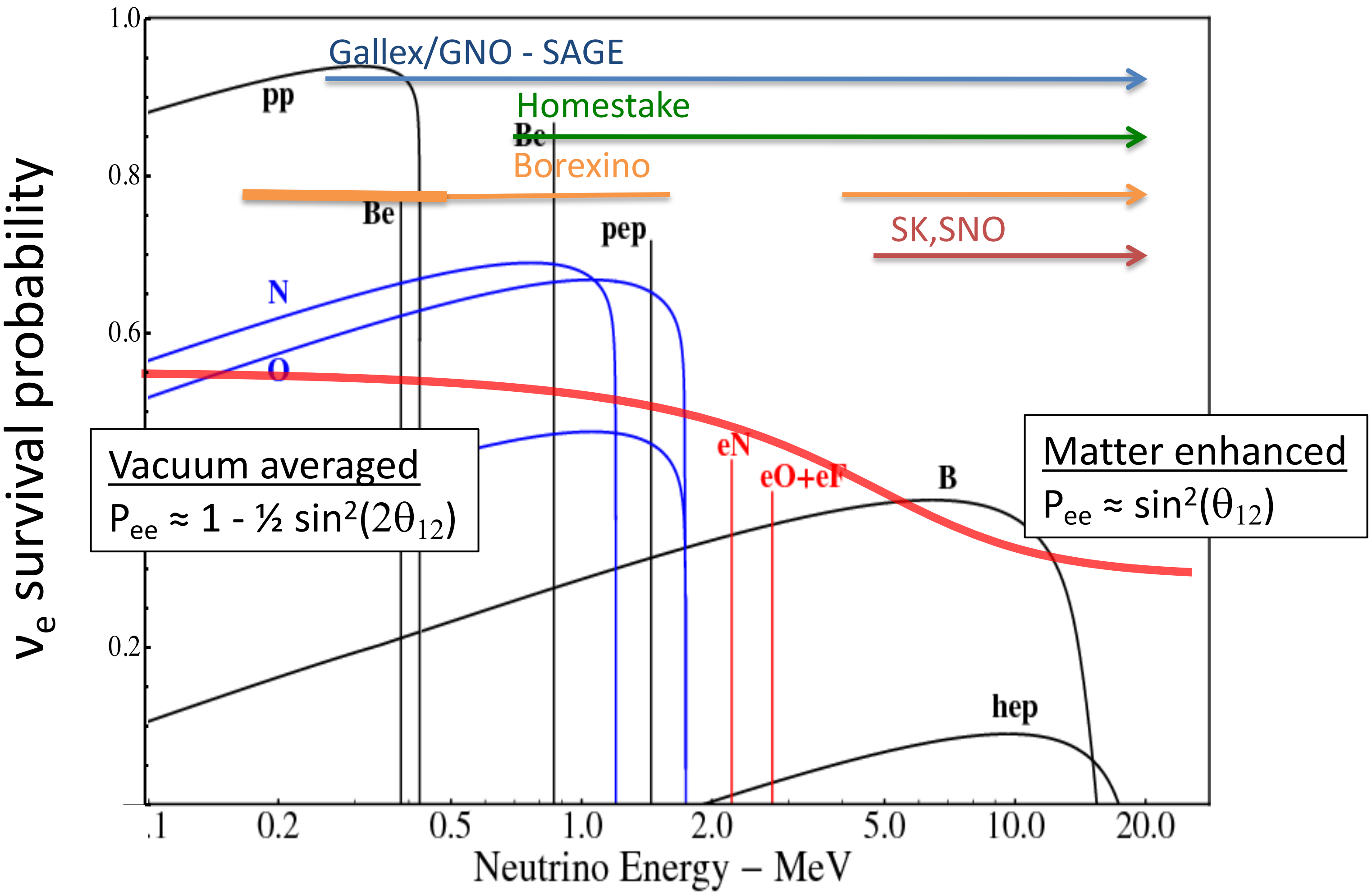
Different regimes for solar neutrinos - *2 ν mixing, $L_{osc} \ll Min[1UA, (d\ln n_e/dr)^{-1}]$*:

$$\frac{\Delta m^2 \cos(2\theta)}{2E} \gg \sqrt{2}G_F\, n_{e,\odot} \qquad P_{ee} = \sum_i |U_{ei}|^2\, |U_{ei}|^2 = 1 - (1/2)\sin^2(2\theta)$$

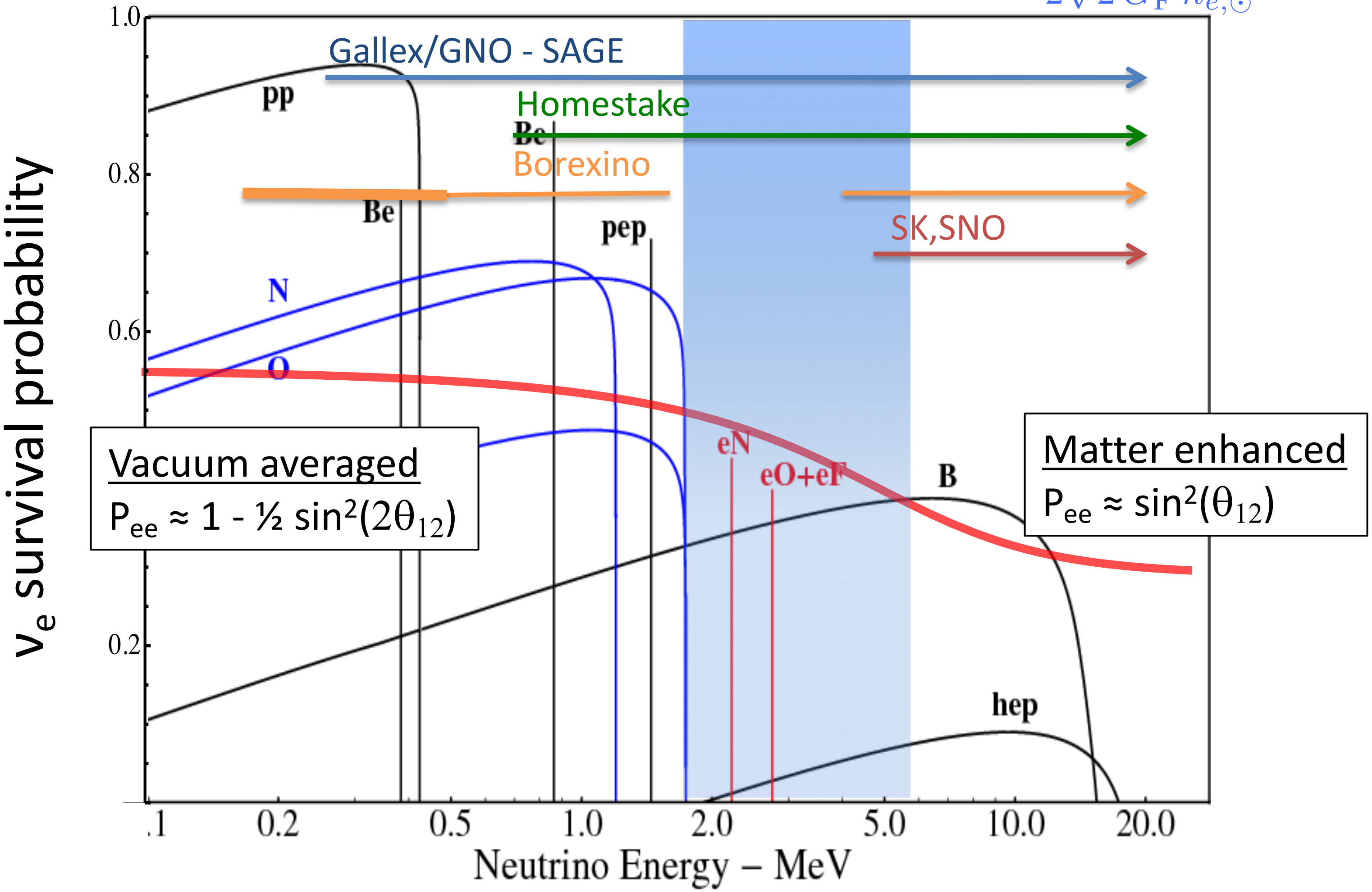
$$\frac{\Delta m^2 \cos(2\theta)}{2E} \ll \sqrt{2}G_F\, n_{e,\odot} \qquad P_{ee} = \sum_i \left|\tilde{U}_{ei}(x_p)\right|^2\, \left|\tilde{U}_{ei}(x_d)\right|^2 = \sin^2(\theta)$$

The solar neutrino survival probability



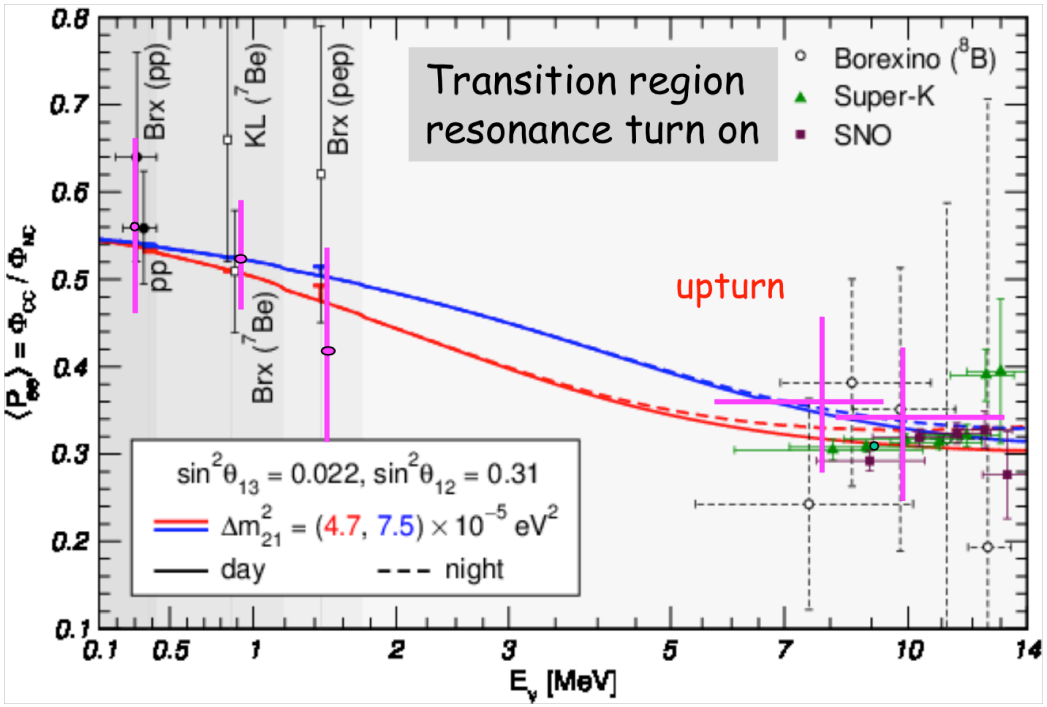
The solar neutrino survival probability

“Transition” at: $E^* = \frac{\Delta m^2_{21} \cos(2\theta_{12})}{2\sqrt{2}\, G_F\, n_{e,\odot}}$

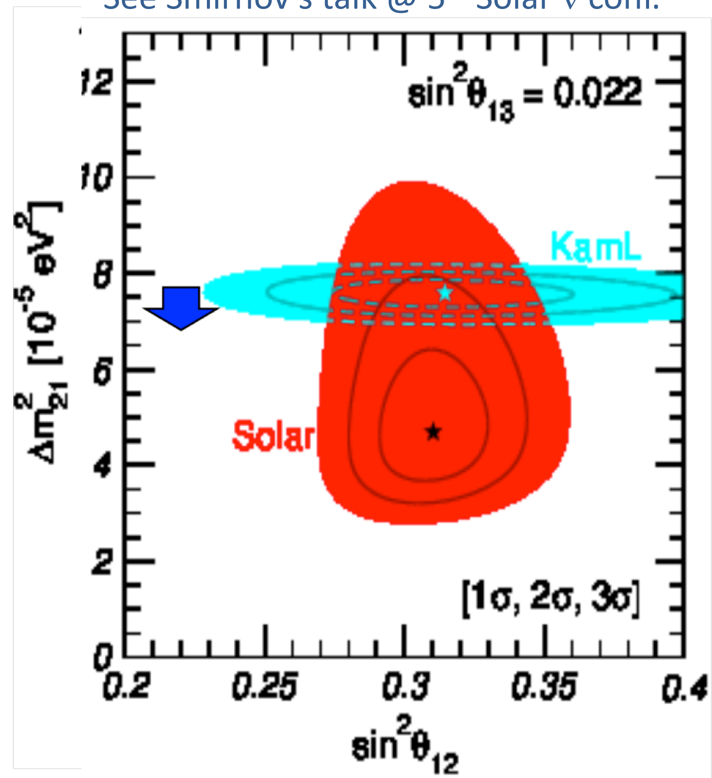


The solar neutrino survival probability

Maltoni & Smirnov, Eur. Phys. J. 2016



See Smirnov's talk @ 5th Solar ν conf.

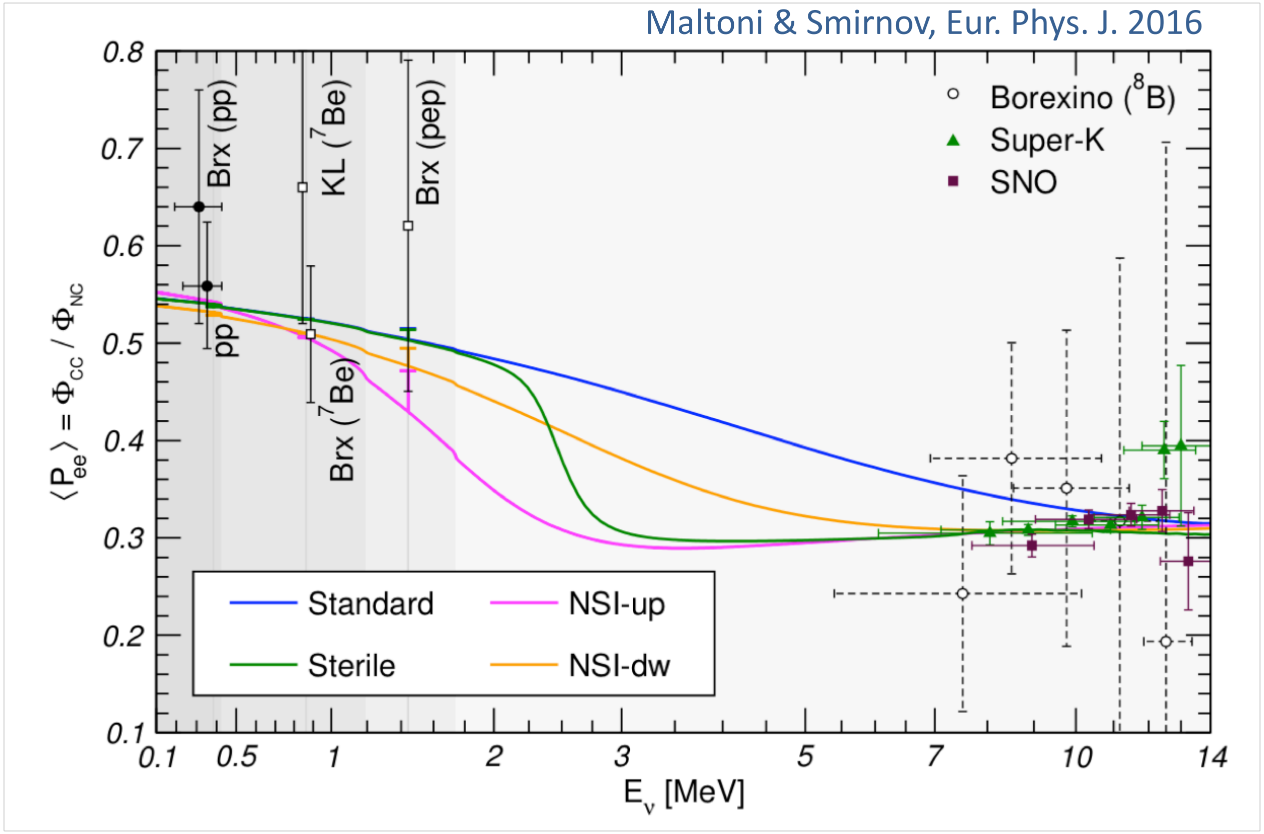


SK-IV provides evidence for D/N effect. $A_{DN} = -3.3 \pm 1.1\%$
[$A_{DN} = -1.8\%$ *expected from global analysis]*

The transition region:

- Final confirmation of LMA-MSW paradigm
- ≈ 2σ tension between Kamland and solar Δm^2

The solar neutrino survival probability



The transition region:

- Final confirmation of LMA-MSW paradigm
- Constraints on new physics beyond the standard 3ν paradigm: see e.g. Maltoni & Smirnov, Eur. Phys. J. 2016

The Standard Solar Model (SSM)

Our comprehension of the Sun is based on the **Standard Solar Model (SSM).**
This implies:

✓ Stellar structure equations;
(α = mixing length)

✓ Chemical evolution paradigm:
ZAMS homogenous model (Y_{ini} , Z_{ini})
Nuclear reactions + elemental diffusion

✓ Knowledge of the properties of solar plasma
(i.e. opacity, equation of state, nuc. cross sections);

No free parameters
The unknown quantities
- α, Y_{ini} , Z_{ini} ,
are fixed by requiring that the present Sun (t_{sun}=4.57 Gyr) reproduces its observational properties
- R_{sun} , L_{sun} , $(Z/X)_{Surf}$

Note that:
*The Sun provides the **benchmark** for stellar evolution. If there is something wrong in solar models, then this is wrong for all the stars ...*

Latest (improved) SSM calculations

N.Vinyoles et al. ApJ 2017 [arXiv:1611.09867v1]

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- Improved EOS;
- Updated astrophysical factors (S_{11}, S_{17}, S_{114});
- Different treatment of opacity uncertainties.

Heavy elements photospheric abundances → **inputs for SSM calculations**

Grevesse et al. 98 (**GS98**): 1D atm. model (old) – High metallicity

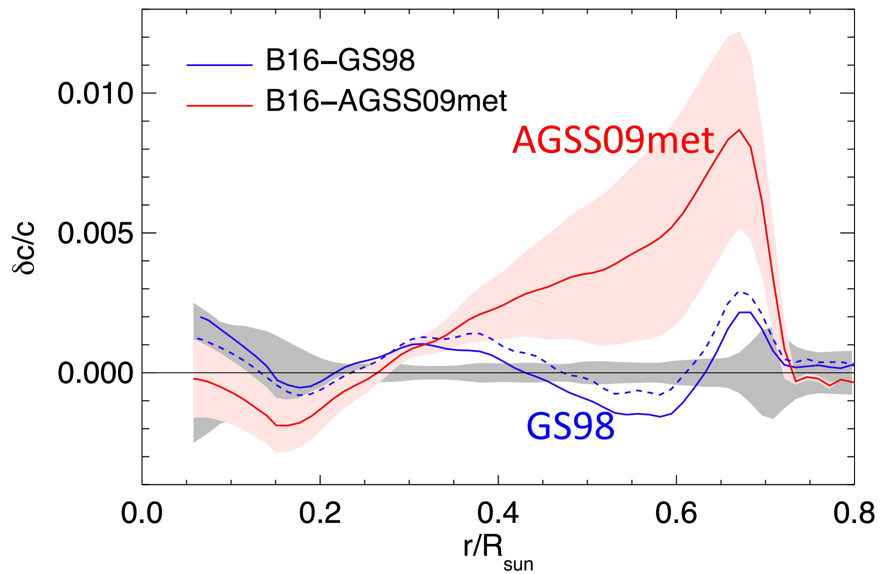
Asplund et al. 09 (**AGSS09**): 3D + NLT model (new) – Low metallicity
(20% for C,N; 40% for O,Ne; 12% Fe,Si, S,Mg)

Note: GS98 and AGSS09 are used as references but do not exhaust the list of possible values.
See e.g.: CO^{5}BOLD (Caffau et al, 2011)
Solar wind abundances (von Steiger & Zurbuchen, 2016) and rel. criticisms (Serenelli et al., 2016).

The solar composition problem

The **downward revision** of heavy elements photospheric abundances leads to SSMs which **do not correctly reproduce helioseismic observables**

Vinyoles et al, ApJ 835 (2017) no.2, 202



$$\delta c \equiv (c_{\rm obs} - c_{\rm mod})/c_{\rm mod}$$

High-Z models are preferred by helioseismology.

Flux	B16-GS98	B16-AGSS09met	Solar
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{cz}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
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(≈ 2-3σ discrepancies)

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The solar composition problem

There is something **wrong** or **unaccounted** in solar models

- Are the new abundances (i.e. the atmospheric model) **wrong**?

  see e.g. Villante et al., ApJ 2014
  Song et al., arXiv:1710.02147

- Are properties of the solar matter (e.g. **opacity**) correctly described?

  see e.g. Song et al., arXiv:1710.02147
  Villante, ApJ 2011
  Christensen-Dalsgaard et al, A&A 2009
  Bailey et al, Nature 2015; Krief et al, arXiv:1603.01153

- Non standard effects (e.g. DM accumulation in the solar core)?

  see e.g. Vincent et al. – arxiv:1411.6626 / 1504.04378 / 1605.06502

- Is the **chemical evolution** not understood (extra mixing?) or peculiar (accretion?) with respect to other stars?

  see e.g. Serenelli et al. – ApJ 2011

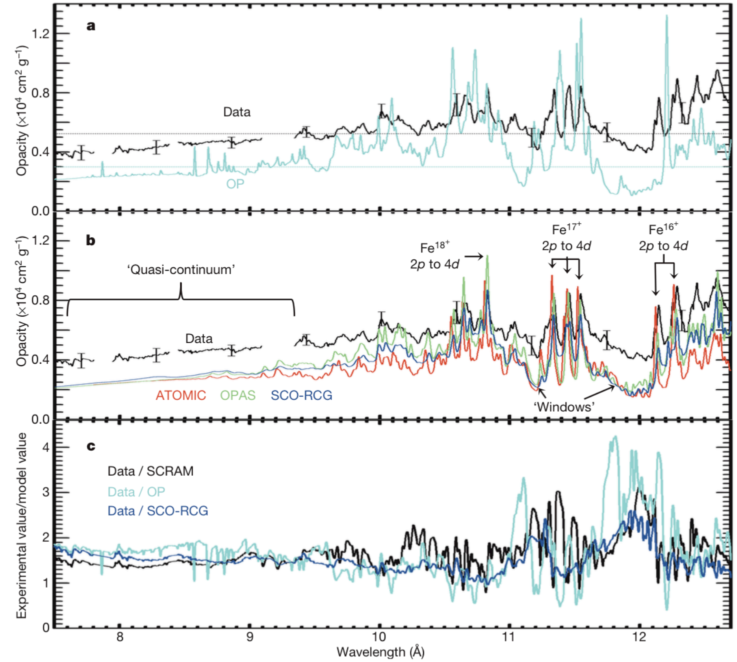
Note that:

It is not just the problem of deciding between AGSS09 (new) and GS98 (old and presumably wrong) abundances

Wrong opacity?

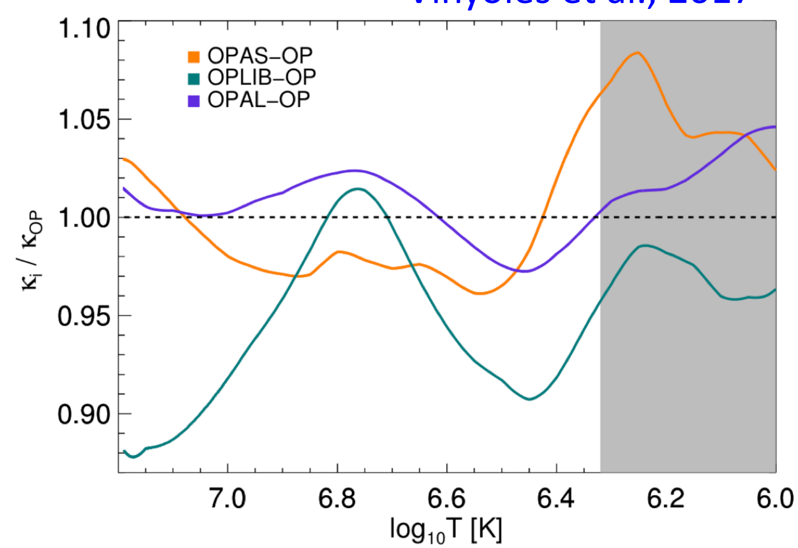
- Opacity is being measured at stellar interiors conditions (Bailey et al., Nature 2015);
- Monochromatic opacity is higher than expected for iron (up to a factor 2);
- Total opacity (integrated over the wavelength and summed over the composition) is increased by about 7%

Bailey et al., Nature 2015



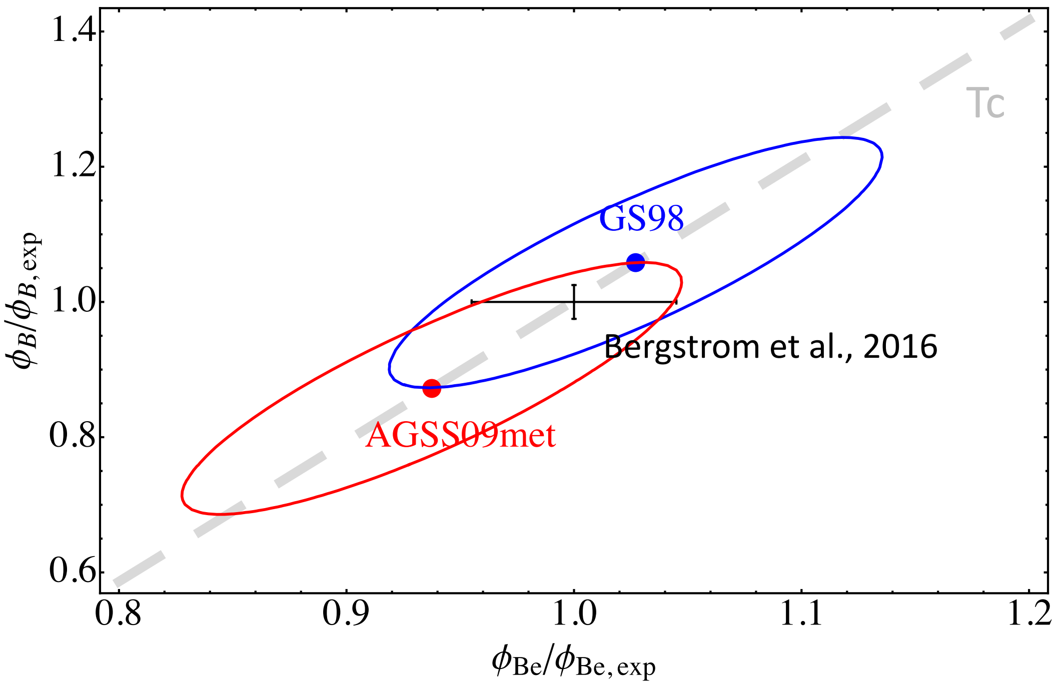
- Different opacity tables may differ "locally" by a large amount (up to 10%) and with a complicated pattern

Vinyoles et al., 2017



The ^{7}Be and ^{8}B neutrino fluxes

N.Vinyoles et al. ApJ 2017 [arXiv:1611.09867v1]



$$\phi_{\mathrm{B}} \propto T_{\mathrm{c}}^{20} \quad \rightarrow \quad (\delta T_{\mathrm{c}})^{\mathrm{GS98}}_{\mathrm{AGSS09}} \leq 1\%$$

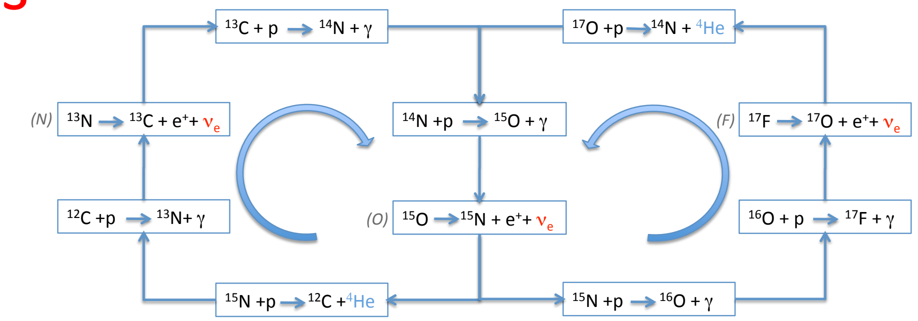
Exp. data are sufficiently accurate to discriminate GS98-AGSS09met central values.
Unfortunately, **theoretical uncertainties dominate the error budget**. These are due to:

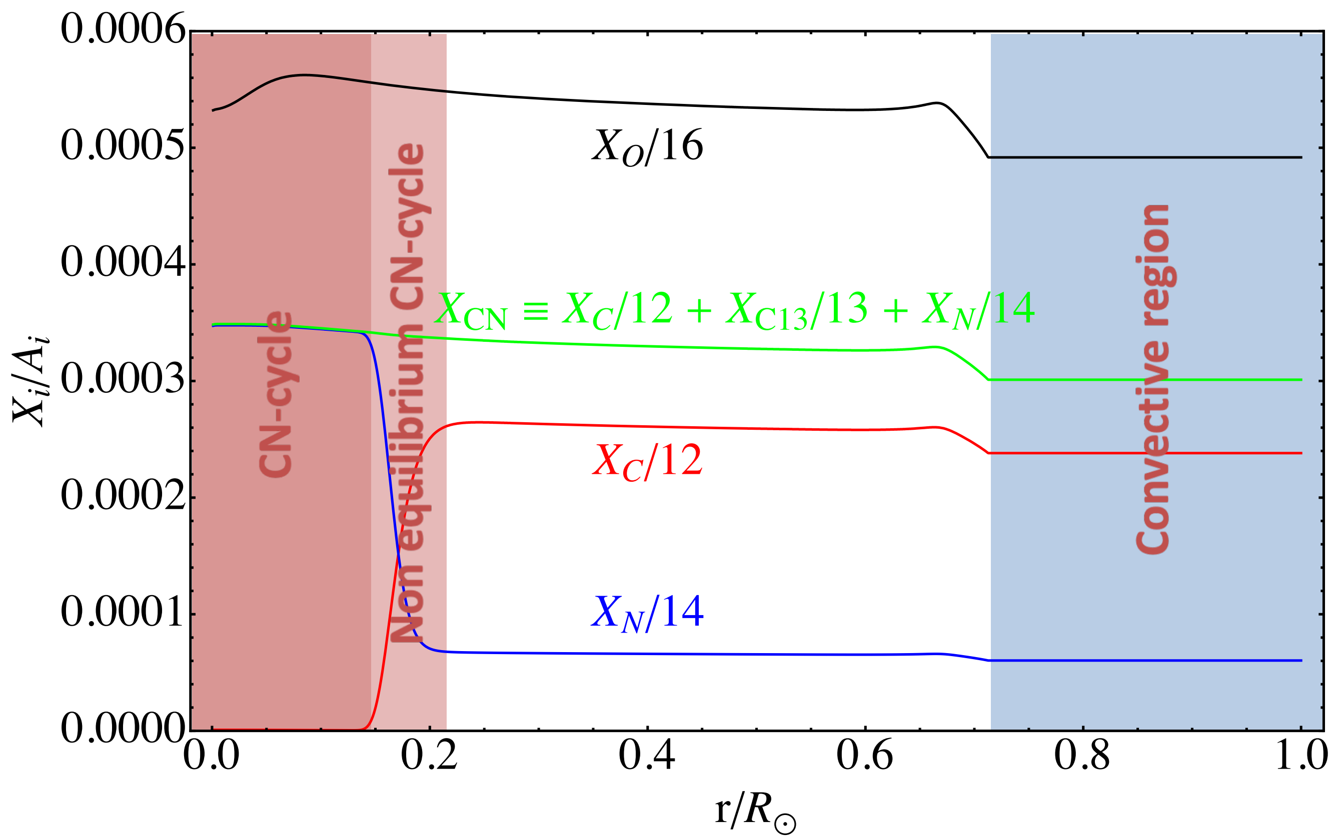
- Surface composition
- Environmental parameters: opacity (few %), diffusion coeff. (15%), etc
- Nuclear cross section: S_{17}(4.7%), S_{33}(5.2%), S_{34}(5.4%) dominant error sources

Note: In order to discriminate composition with **^{7}Be and ^{8}B neutrinos,** we should be able to predict solar central temperature with accuracy δT_c << 1%.

The importance of CNO neutrinos

Neutrinos produced in the CNO-cycle may provide the clues for the solution of solar composition problem because **they directly probe the C+N abundance in the solar core**





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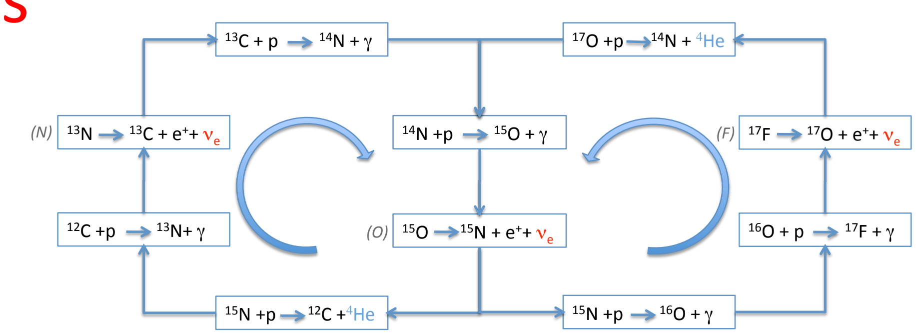

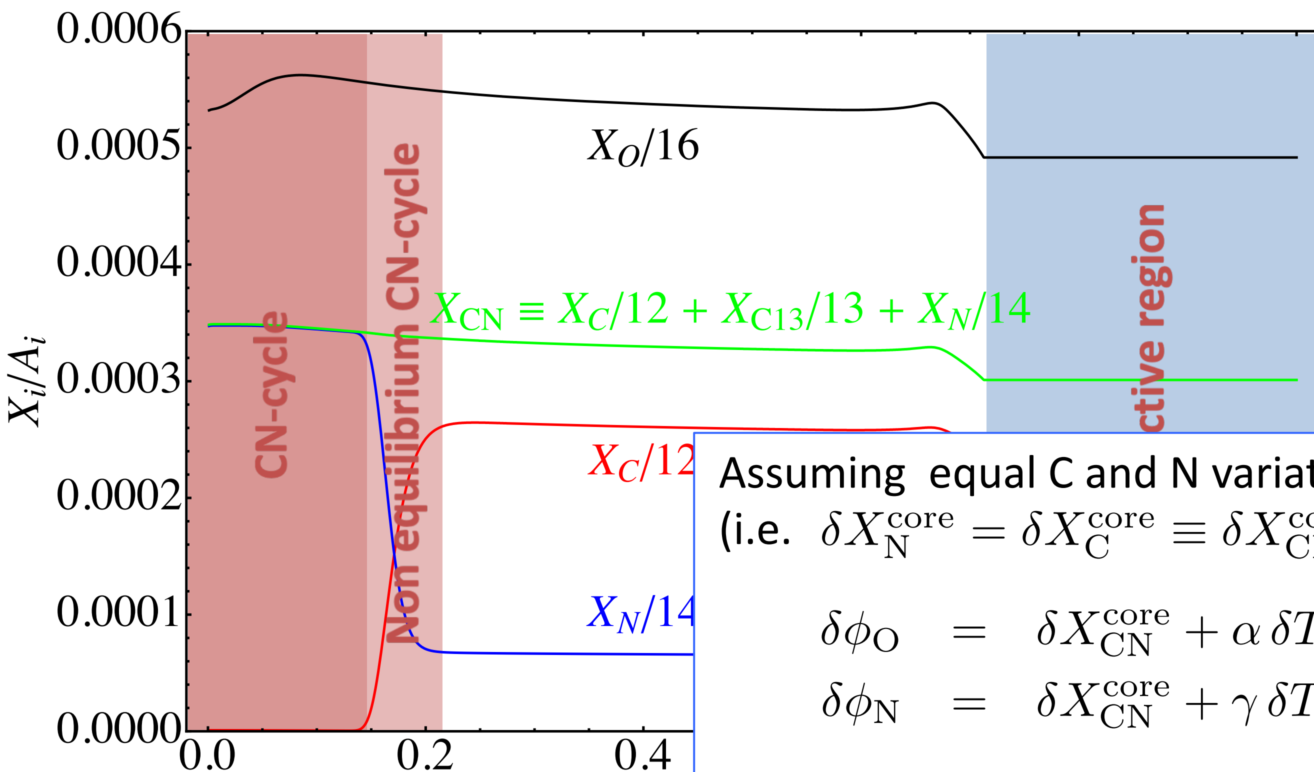

Assuming equal C and N variations

(i.e. $\delta X_{\rm N}^{\rm core} = \delta X_{\rm C}^{\rm core} \equiv \delta X_{\rm CN}^{\rm core}$):

$$\begin{aligned} \delta\phi_{\rm O} &= \delta X_{\rm CN}^{\rm core} + \alpha\,\delta T_{\rm c} + \delta S_{114} \\ \delta\phi_{\rm N} &= \delta X_{\rm CN}^{\rm core} + \gamma\,\delta T_{\rm c} + f\,\delta S_{114} \end{aligned}$$

where $\alpha \simeq \gamma \simeq 20$ and $f \simeq 0.7$

The importance of CNO neutrinos

- Probe the dominant H-burning mechanism in massive and/or evolved stars

- Provide a direct determination of the C+N abundance in the **solar core**:

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indeed, the (strong) dependence on T_c can be eliminated by using **B-neutrinos as solar thermometer**. E.g:

$$\delta\phi_{\rm O} - 0.785\,\delta\phi_{\rm B} = \delta X_{\rm CN}^{\rm core}\ \pm 0.4\%({\rm env})\ \pm 2.6\%({\rm diff})\ \pm 10\%({\rm nuc})$$

Serenelli et al., PRD 2013

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<u>High-Z .vs. Low-Z</u>

$$\delta\phi_{\rm O} = \frac{\phi_{\rm O}^{\rm HZ} - \phi_{\rm O}^{\rm LZ}}{\phi_{\rm O}^{\rm LZ}} \simeq 40\%$$

Beyond solar composition problem (10%):
Using CNO neutrinos to probe for mixing processes in the Sun (and other stars)

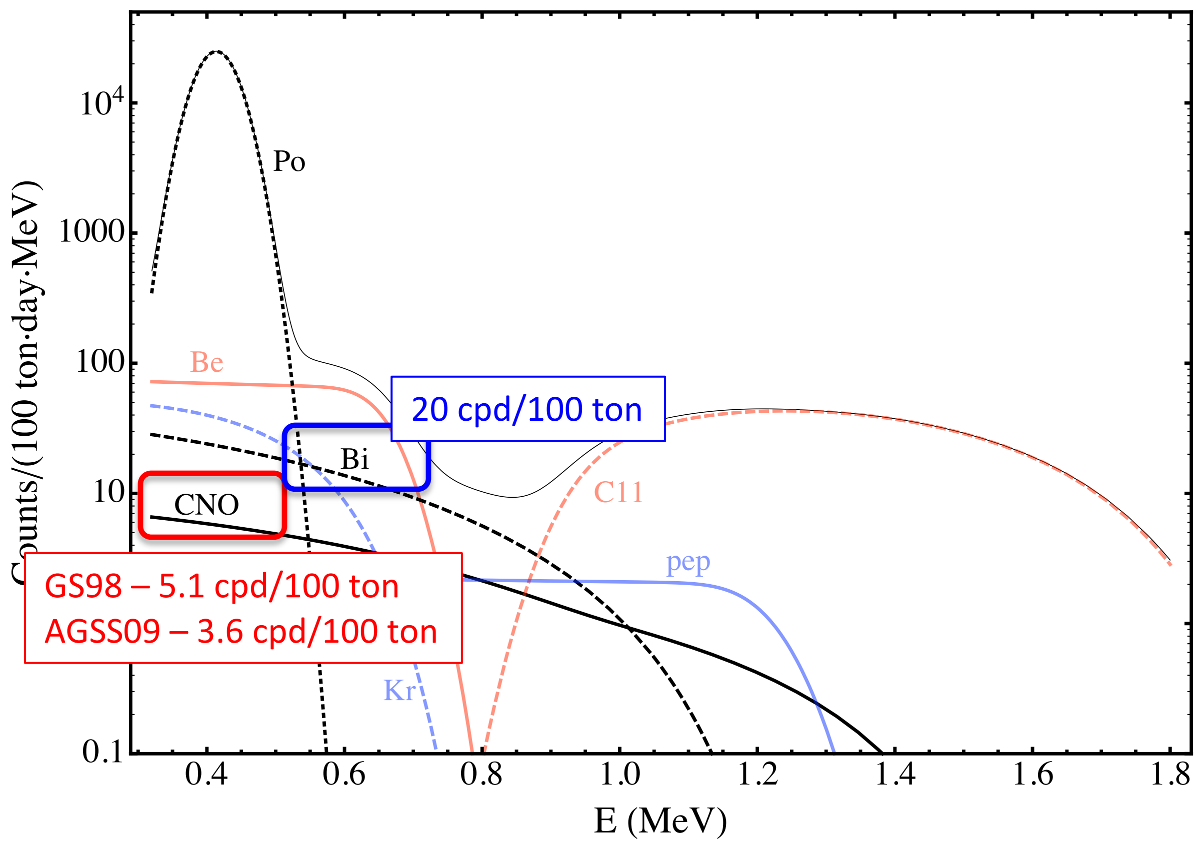
$$\delta X_{\rm CN} = \frac{X_{\rm CN}^{\rm core} - X_{\rm CN}^{\rm surf}}{X_{\rm CN,ini}} \simeq 15\%$$

Is it possible to observe CNO neutrinos in LS?

The detection of CNO neutrinos is very difficult:

- Low energy neutrinos → endpoint at about 1.5 MeV
- Continuos spectra → do not produce recognizable features in the data.
- Limited by the background produced by beta decay of ^{210}Bi.

Event spectrum in ultrapure liquid scintillators (Borexino-like)



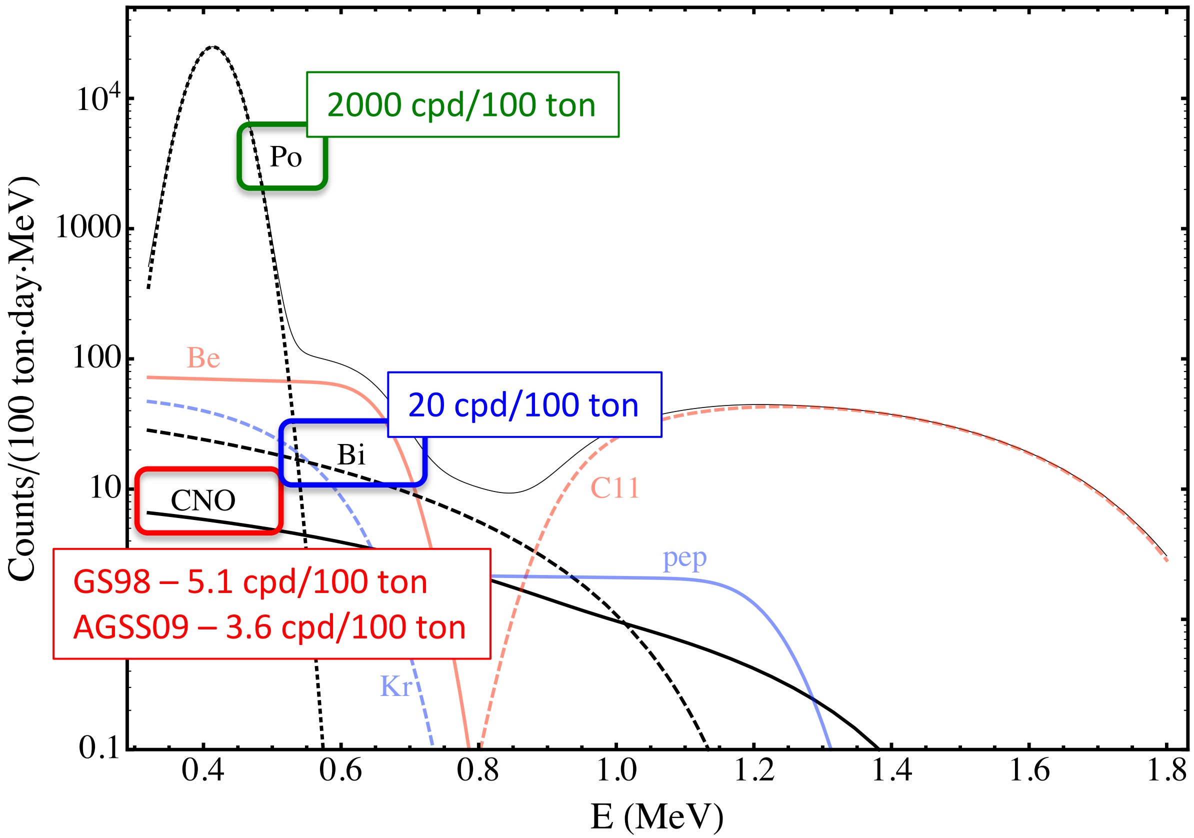
Determining ^{210}Bi with the help of ^{210}Po?

$$^{210}\mathrm{Bi} \rightarrow ^{210}\mathrm{Po} + e^- + \overline{\nu}_e$$

$$^{210}\mathrm{Po} \rightarrow ^{206}\mathrm{Pb} + \alpha$$

τ_{Bi} = 7.232 d

τ_{Po} = 199.634 d



F.L. Villante et al. - Phys.Lett. B701 (2011) 336-341

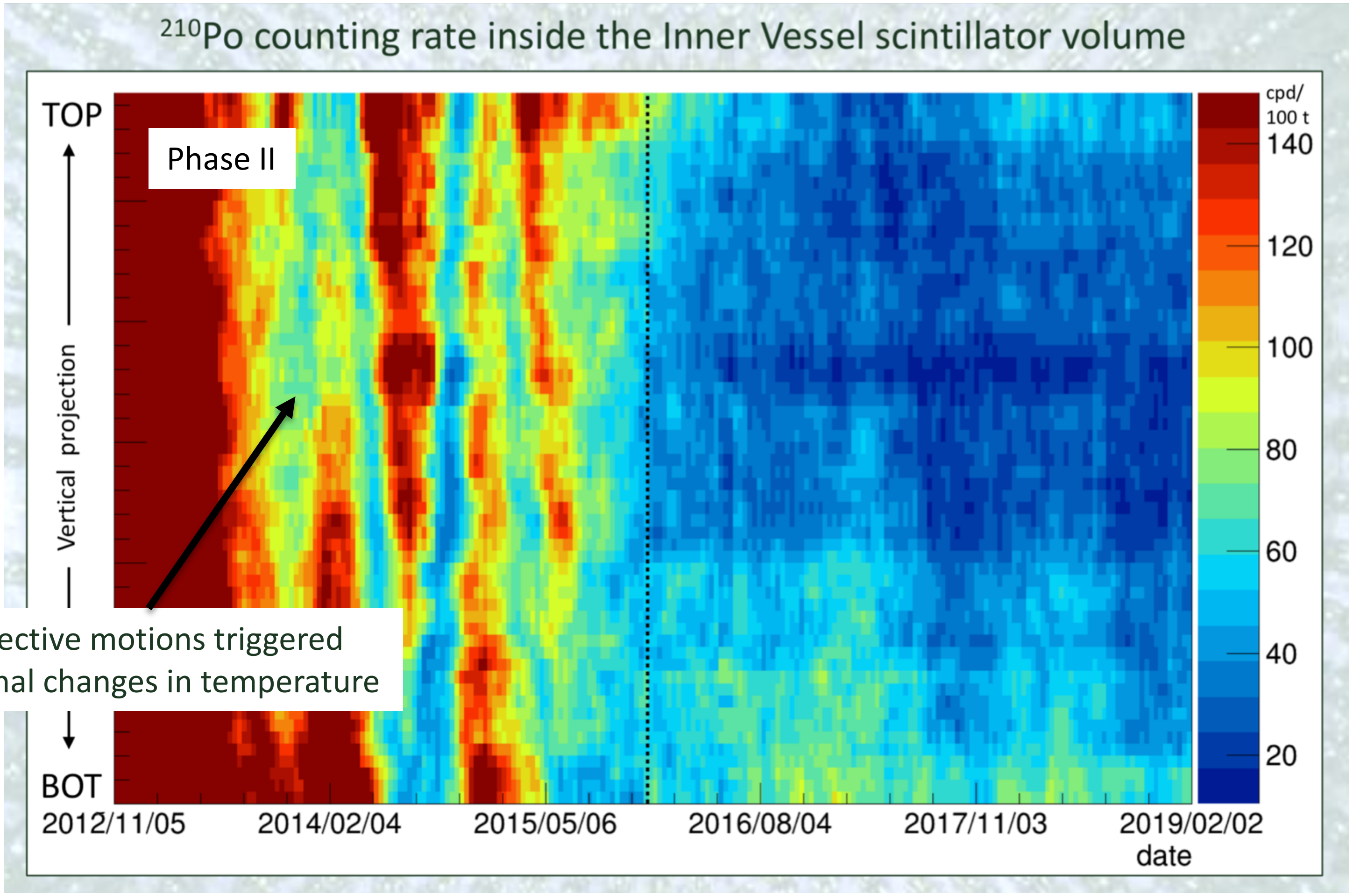
- Deviations from the exponential decay law of ^{210}Po can be used to determine ^{210}Bi

$$n_{\mathrm{Po}}(t) = [n_{\mathrm{Po},0} - n_{\mathrm{Bi}}]\ \exp(-t/\tau_{\mathrm{Po}}) + n_{\mathrm{Bi}}$$

- **Borexino (Phase II) already had the potential to probe the CNO neutrino flux** … but the detector should be stable (no convective motions) over long time scales.

Towards a CNO measurement in Borexino

Alessandra Carlotta Re, talk@ NuPhys2019



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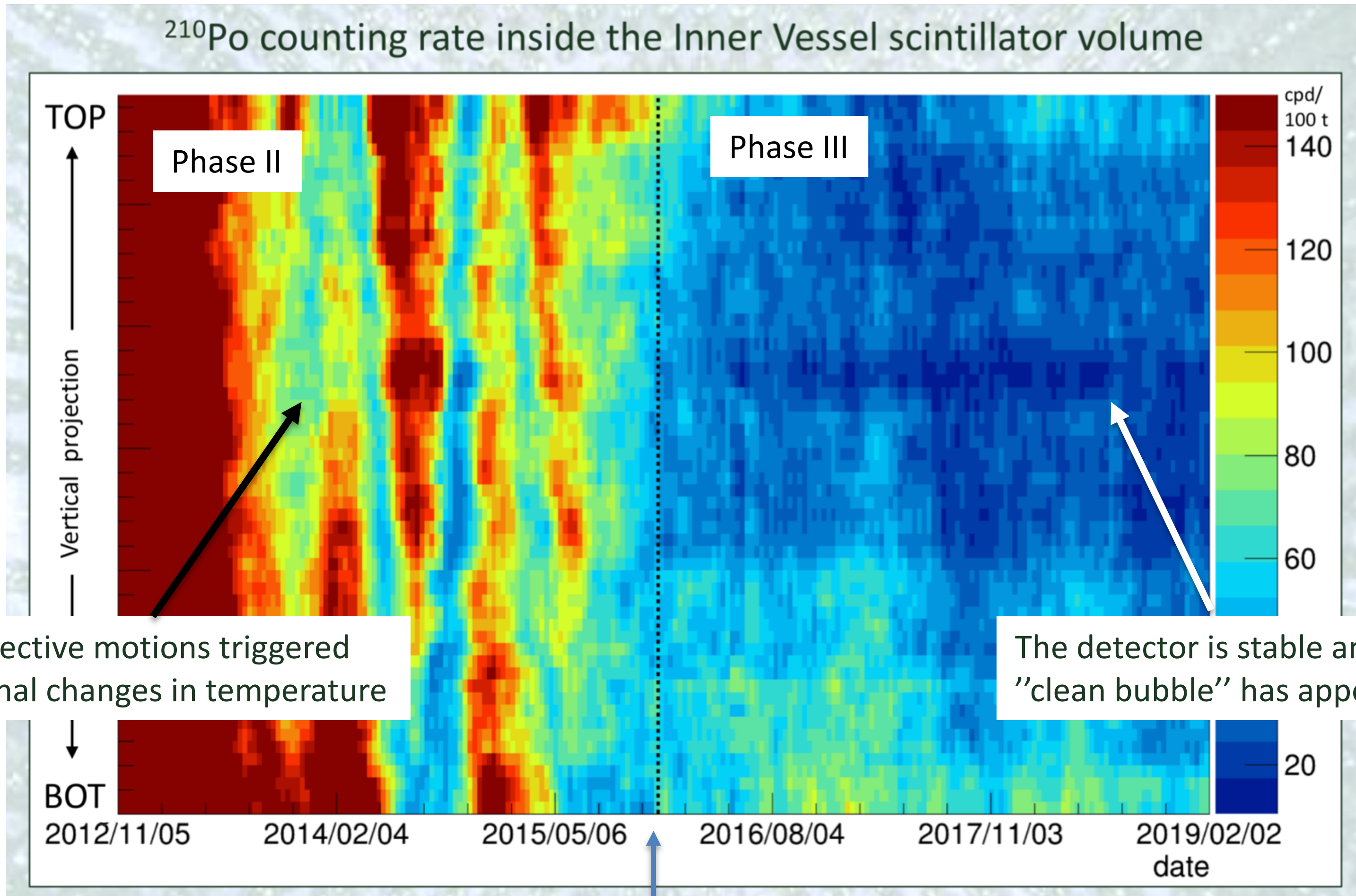

The convective motions triggered by seasonal changes in temperature

The detector is stable and a ''clean bubble'' has appeared

Thermal insulation of the detector

The Borexino experiment has the possibility to get a measurement of CNO neutrino flux between 2σ and 4σ

How to improve?

Increase the detector depth → reduction of cosmogenic ^{11}C background
SNO+: factor 100 lower than BX

Consider larger detectors → Stat. uncertainties scales as $1/M^{1/2}$
SNO+ (1 kton), LENA (50 kton)

The final accuracy depends, however, on the internal background (^{210}Bi)
Borexino: 20cpd/100 ton → 150 nuclei / 100 ton

Future Proposals

- Water based Liquid Scintillators (WbLS)
- "Salty" WbLS → doped (1% by mass) with ^{7}Li (CC detection of ν_e on ^{7}Li)
- Advanced Scintillator Detector Concept discussed in arXiv:1409.5864 (assuming 30-100 kton detector)

See also G. Orebi-Gann talk@Neutrino2014

- G2 DD dark matter experiments will probe solar neutrinos, see e.g.

Cerdeno et al., arXiv:1604.01025;
Franco et al. arXiV:1510.04196 (300 ton Lar-detector@LNGS for solar-ν).

- ecCNO neutrinos: A challenge for gigantic ultra-pure LS detectors (Villante, PLB 2015)
  Expt. requirements: *as clean (and deep) as Borexino;*
  as large as JUNO;

Summary

The **solar composition problem** indicates that there is something **wrong** or **unaccounted** in solar models

- Are properties of the solar matter (e.g. **opacity**) correctly described?
- Are the new abundances (i.e. the atmospheric model) **wrong**?
- Is the **chemical evolution** not understood (extra mixing?) or peculiar (accretion?) with respect to other stars?

Note that:
*The Sun provide the **benchmark** for stellar evolution. If there is something wrong in solar models, then this is wrong for all the stars ...*

CNO and ecCNO neutrinos, besides testing CN-NO cycle, could provide clues for the solution of the puzzle.