

# Neutrinos from the Sun and beyond

F. L. Villante – University of L'Aquila and LNGS-INFN

# The (re)search of neutrinos the Sun and beyond ...

- ✓ Solar Neutrinos

in collaboration with A. Serenelli, N. Vinyoles (ICE, BCN) and the Solar ν Borexino WG

- ✓ High-Energy Cosmic Neutrinos

in collaboration with F. Vissani (LNGS and GSSI), A. Palladino (GSSI) and G. Pagliaroli (LNGS,GSSI)

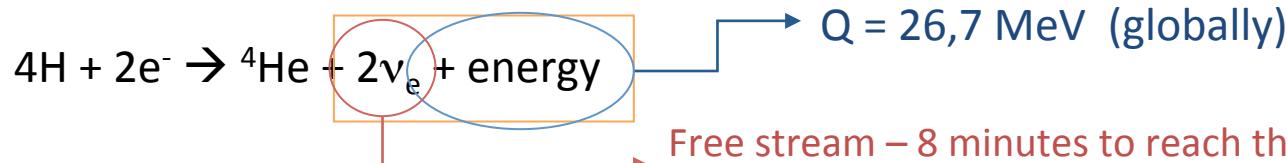
- ✓ keV sterile neutrinos and galactic structure

in collaboration with F. Nesti (Boskovic Inst., Zagreb) and P. Salucci (SISSA) and C. Di Paolo (SISSA)

# Solar neutrinos

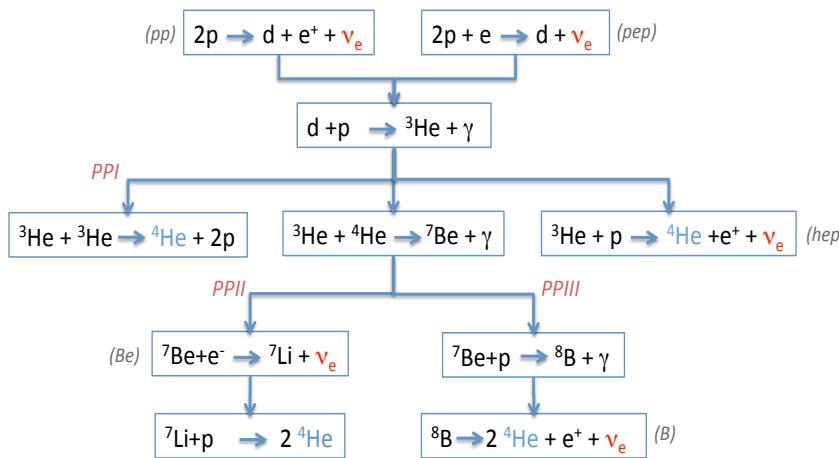
# Hydrogen Burning: PP chain and CNO cycle

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

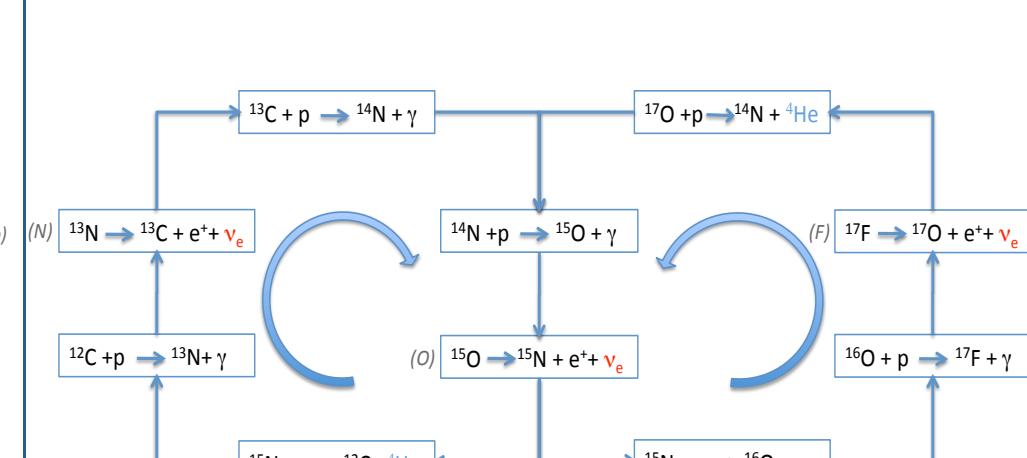


Free stream – 8 minutes to reach the earth  
Direct information on the energy producing region.

The PP-chain



The CN-NO bi-cycle

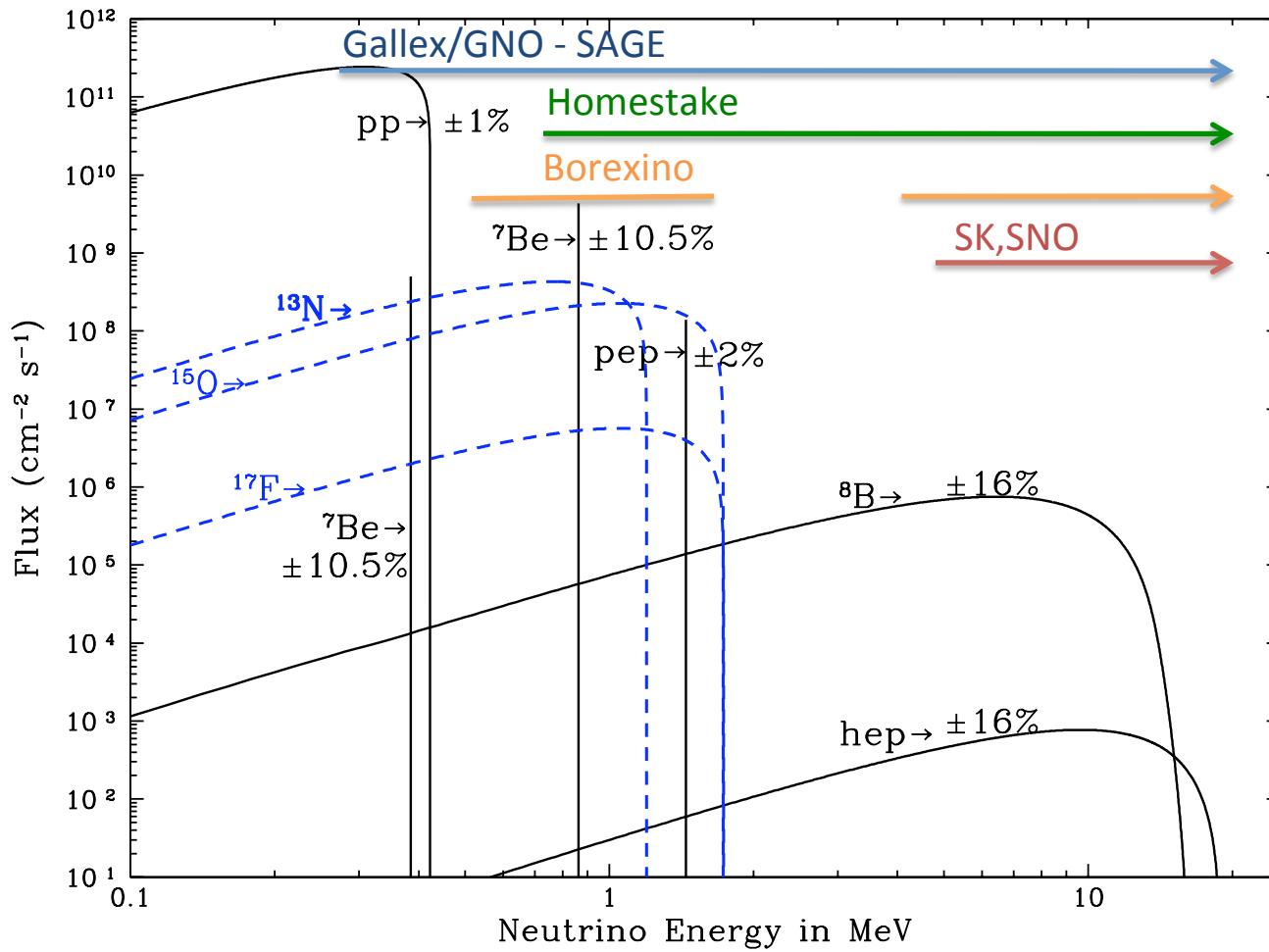


The **pp chain** is responsible for about 99% of the total energy (and neutrino) production.

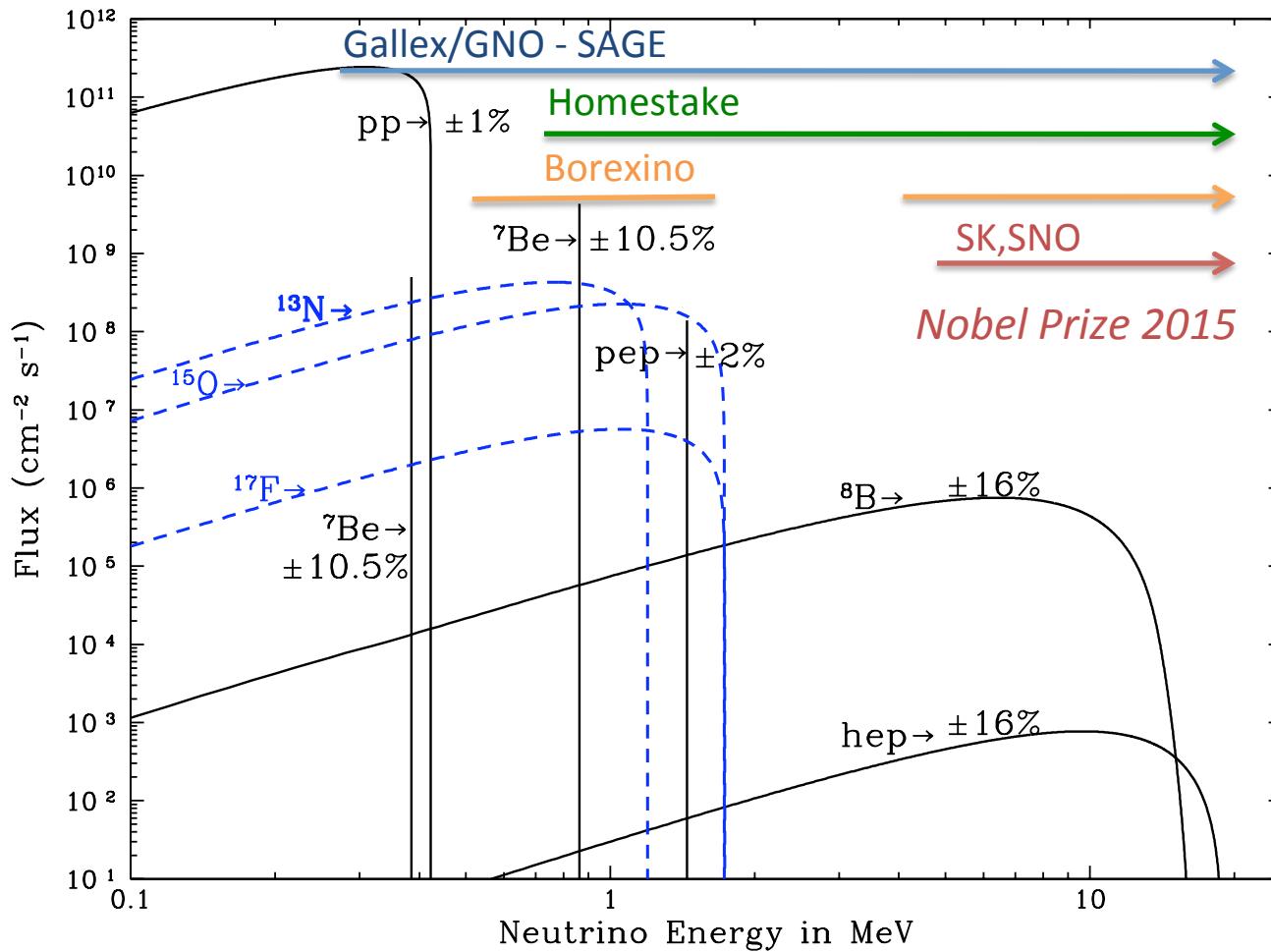
C, N and O nuclei are used as catalysts for hydrogen fusion.

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

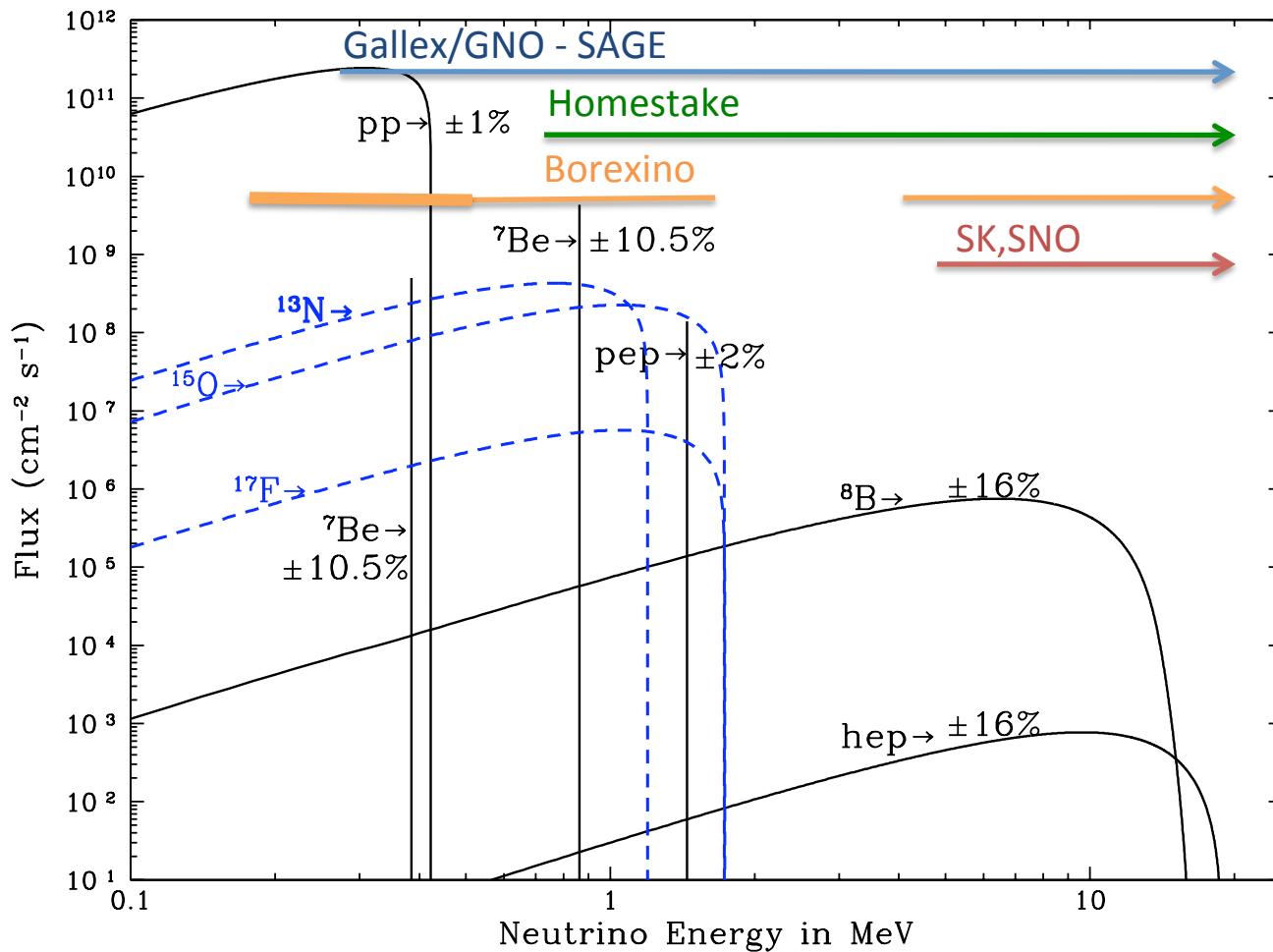
# The solar neutrino spectrum



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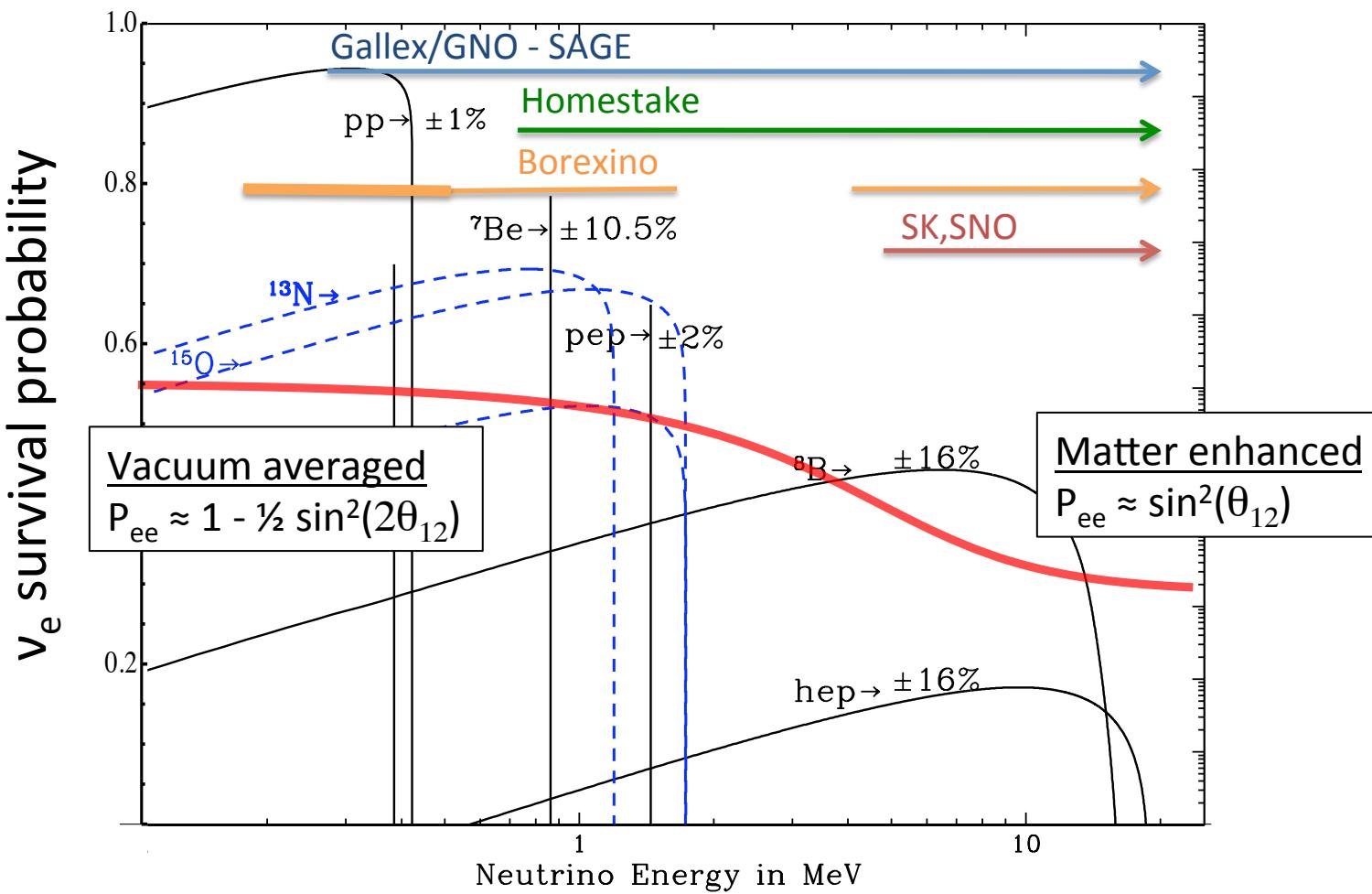
# The solar neutrino spectrum



$$\Phi_{\text{pp}} = (6.6 \pm 0.7) \times 10^{10} \text{ cm}^{-2} \text{s}^{-1}$$

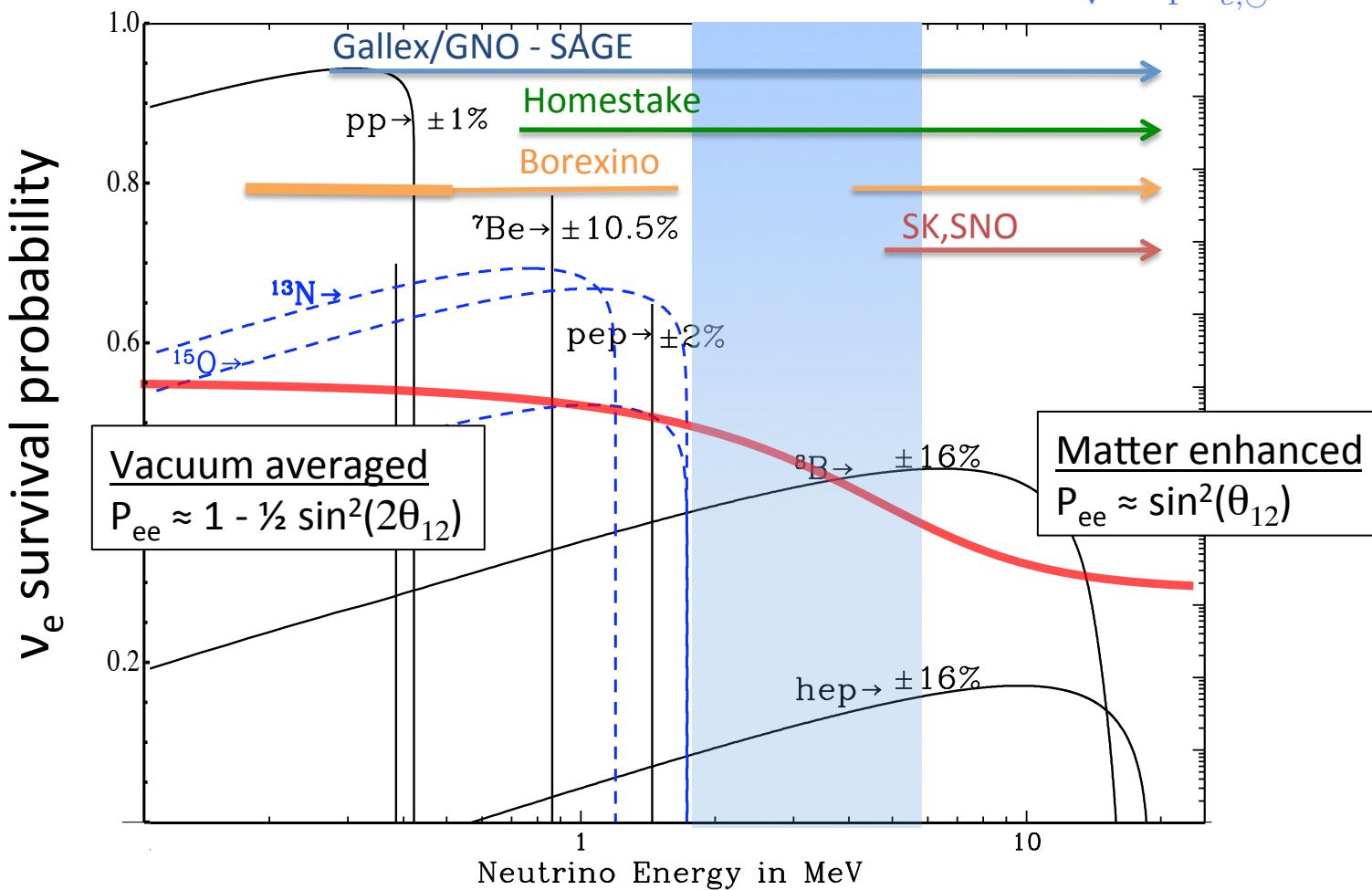
*Borexino, Nature 2014*  
First direct measurement of  
the solar pp-component

# The solar neutrino survival probability



# The solar neutrino survival probability

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



The transition region:

- Final confirmation of LMA-MSW paradigm
- Constraints on new physics beyond the standard 3ν paradigm:

# “Observing” the Sun with neutrinos: the present situation

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

*Serenelli, Haxton, Pena-Garay, ApJ 2011*

$\nu$ flux	AGSS09	GS98	Solar
$\Phi_{pp}$	$6.03 (1 \pm 0.006)$	$5.98 (1 \pm 0.006)$	$6.05(1^{+0.003}_{-0.011})$
$\Phi_{pep}$	$1.47 (1 \pm 0.012)$	$1.44 (1 \pm 0.012)$	$1.46(1^{+0.010}_{-0.014})$
$\Phi_{Be}$	$4.56 (1 \pm 0.07)$	$5.00 (1 \pm 0.07)$	$4.82(1^{+0.05}_{-0.04})$
$\Phi_B$	$4.59 (1 \pm 0.14)$	$5.58 (1 \pm 0.14)$	$5.00(1 \pm 0.03)$
$\Phi_{hep}$	$8.31 (1 \pm 0.30)$	$8.04 (1 \pm 0.30)$	$18(1^{+0.4}_{-0.5})$
$\Phi_N$	$2.17 (1 \pm 0.14)$	$2.96 (1 \pm 0.14)$	$\leq 6.7$
$\Phi_O$	$1.56 (1 \pm 0.15)$	$2.23 (1 \pm 0.15)$	$\leq 3.2$
$\Phi_F$	$3.40 (1 \pm 0.16)$	$5.52 (1 \pm 0.16)$	$\leq 59$

*Units:*

*pp:*  $10^{10} \text{ cm}^2 \text{ s}^{-1}$ ;

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$\Phi_{pp} = 6.6 (1 \pm 0.11)$  Borex. only  
[ $\Phi_{pp} = 6.4 (1 \pm 0.08)$ ] combined

Units:  
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**Direct measurement of pp now to 11% Borexino (90% CL)**

$L_\nu(8 \text{ minutes}) \approx L_\gamma(10^5 \text{ year})$  – test of solar stability

Still not accurate enough to test SSMs ( $\approx$  few % accuracy required)

# Helioseismology

The Sun is a non radial oscillator. The observed oscillation frequencies can be used to determine the properties of the Sun. Linearizing around a known solar model:

$$\frac{\delta\nu_{nl}}{\nu_{nl}} = \int_0^R dr K_{u,Y}^{nl}(r) \frac{\delta u}{u}(r) + \int_0^R dr K_{Y,u}^{nl}(r) \delta Y + \frac{F(\nu_{nl})}{\nu_{nl}}$$

squared isothermal sound speed

Related to temperature stratification in the sun

surface helium abundance

See Basu & Antia 07  
for a review

Impressive agreement with SSM predictions ...

Surface helium abundance

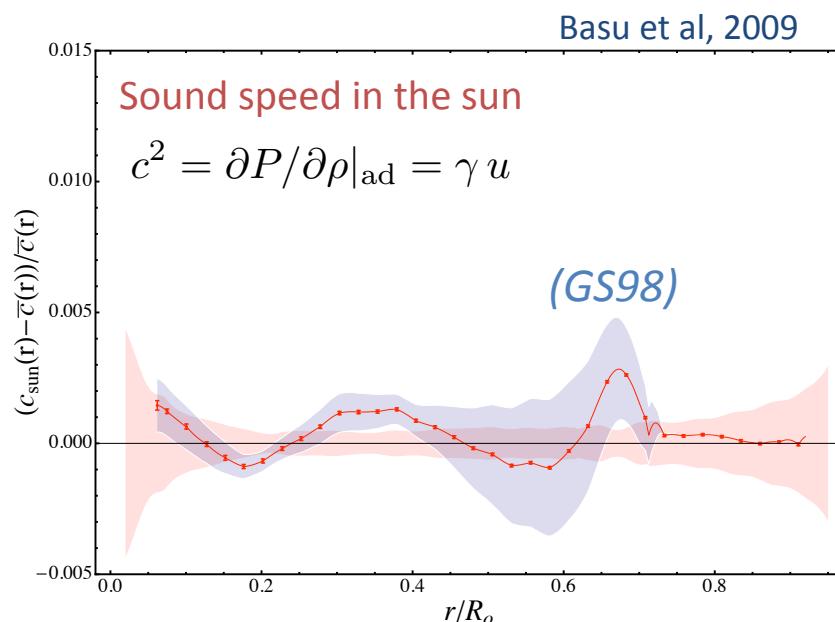
$$Y_b = 0.2485 \pm 0.0035$$

$$Y_b = 0.243 \quad (\text{GS98})$$

Inner radius of the solar convective envelope

$$R_b/R_\odot = 0.713 \pm 0.001$$

$$R_b/R_\odot = 0.712 \quad (\text{GS98})$$



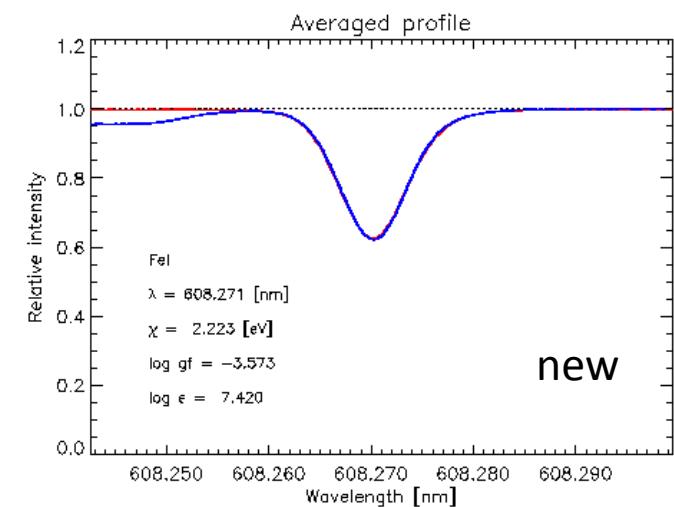
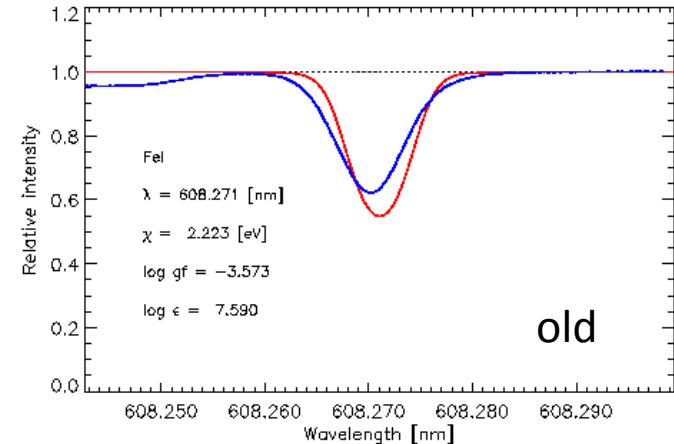
# ... till few years ago

Asplund et al. 05 (AGS05); Asplund et al. 09 (AGSS09)

Re-determination of the photospheric abundances of nearly all available elements (**inputs for SSM calculations**)

Improvements with respect to previous analysis<sup>(\*)</sup>:

- 3D model instead of the classical 1D model of the lower solar atmosphere
- Careful and very demanding selection of the spectral lines... **AVOID blends!!! NOT TRIVIAL!!!**
- Careful choice of the atomic and molecular data **NOT TRIVIAL!!!!**
- NLTE instead of the classical LTE hypothesis... **WHEN POSSIBLE !!!**
- Use of **ALL** indicators (atoms as well as molecules,CNO)



<sup>(\*)</sup>N. Grevesse talk at PHYSUN10

# Less metallic sun ...

AGS05 and AGSS09

Downward revision of heavy elements  
photospheric abundances ...

Element	GS98	AGSS09	$\delta z_i$
C	$8.52 \pm 0.06$	$8.43 \pm 0.05$	0.23
N	$7.92 \pm 0.06$	$7.83 \pm 0.05$	0.23
O	$8.83 \pm 0.06$	$8.69 \pm 0.05$	0.38
Ne	$8.08 \pm 0.06$	$7.93 \pm 0.10$	0.41
Mg	$7.58 \pm 0.01$	$7.53 \pm 0.01$	0.12
Si	$7.56 \pm 0.01$	$7.51 \pm 0.01$	0.12
S	$7.20 \pm 0.06$	$7.15 \pm 0.02$	0.12
Fe	$7.50 \pm 0.01$	$7.45 \pm 0.01$	0.12
$Z/X$	0.0229	0.0178	0.29

$$[I/H] \equiv \log (N_I/N_H) + 12$$

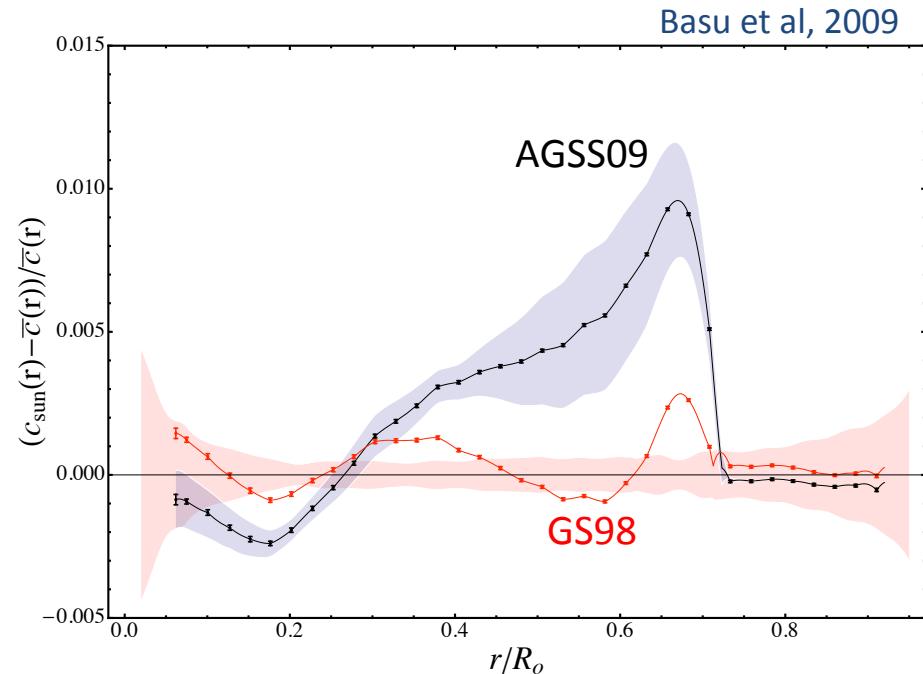
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... leads to SSMs which do not correctly reproduce helioseismic observables

	AGSS09	GS98	Obs.
$Y_b$	$0.2319 (1 \pm 0.013)$	$0.2429 (1 \pm 0.013)$	$0.2485 \pm 0.0035$
$R_b/R_\odot$	$0.7231 (1 \pm 0.0033)$	$0.7124 (1 \pm 0.0033)$	$0.713 \pm 0.001$
$\Phi_{PP}$	$6.03 (1 \pm 0.005)$	$5.98 (1 \pm 0.005)$	$6.05 (1^{+0.003}_{-0.011})$
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( $\approx 4\sigma$  discrepancies)

# The solar composition problem

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**?
- Non standard effects (e.g. DM accumulation in the solar core)?  
see e.g. Vincent et al. – arxiv:1411.6626 / 1504.04378
- Is the **chemical evolution** not understood (extra mixing?) or peculiar (accretion?) with respect to other stars?  
see A. 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

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

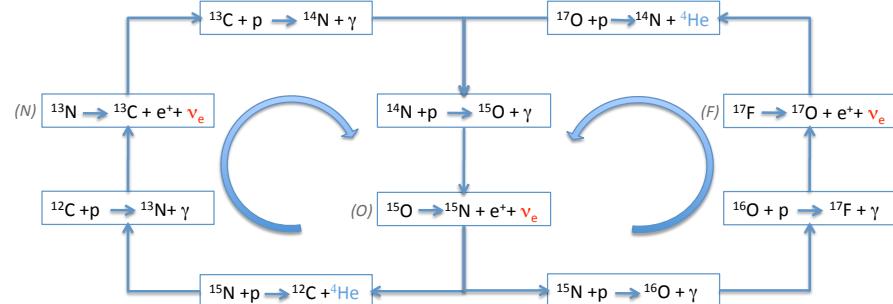
# CNO neutrinos

CNO neutrinos allow us to determine directly the C+N abundance in the solar core:

$$1 + \delta\Phi_\nu = (1 + \delta X_{\text{CN}}) \left[ 1 + \int dr K_\nu(r) \delta\kappa(r) \right]$$

$\downarrow$

$$X_{\text{CN}} \equiv X_{\text{C}}/12 + X_{\text{N}}/14$$



Determines the central temperature  
Constrained by  $\Phi_B$  and  $\Phi_{Be}$

Total number of catalysts for CN-cycle

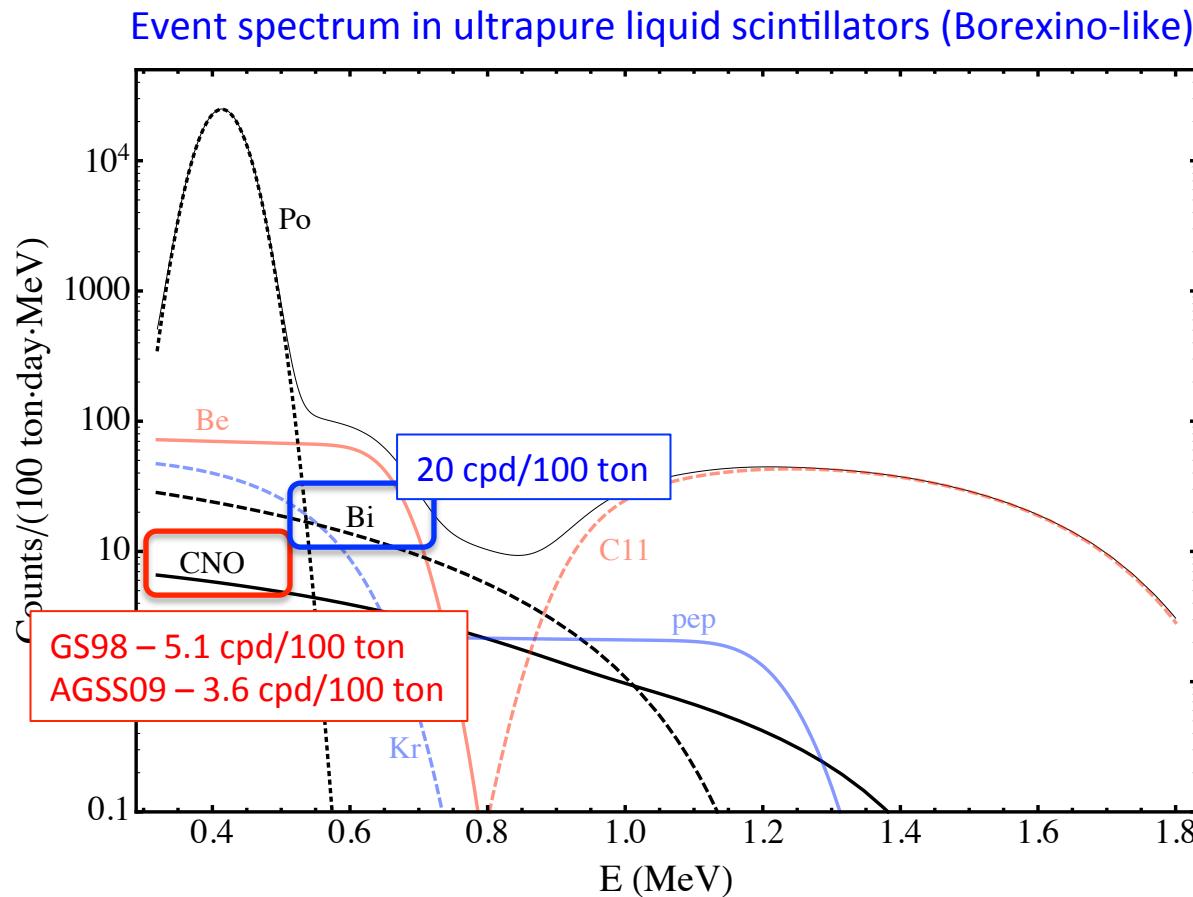
At present, we only have a loose upper limit on CNO neutrino fluxes:

$\nu$ flux	GS98	AGSS09	Solar
$^{13}\text{N}$ ( $10^8 \text{ cm}^{-2} \text{ s}^{-1}$ )	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	$\leq 6.7$
$^{15}\text{O}$ ( $10^8 \text{ cm}^{-2} \text{ s}^{-1}$ )	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	$\leq 3.3$
$^{17}\text{F}$ ( $10^6 \text{ cm}^{-2} \text{ s}^{-1}$ )	$5.52(1 \pm 0.17)$	$3.04(1 \pm 0.16)$	$\leq 59$

# Is it possible to observe CNO neutrinos in LS?

The detection of CNO neutrinos is very difficult:

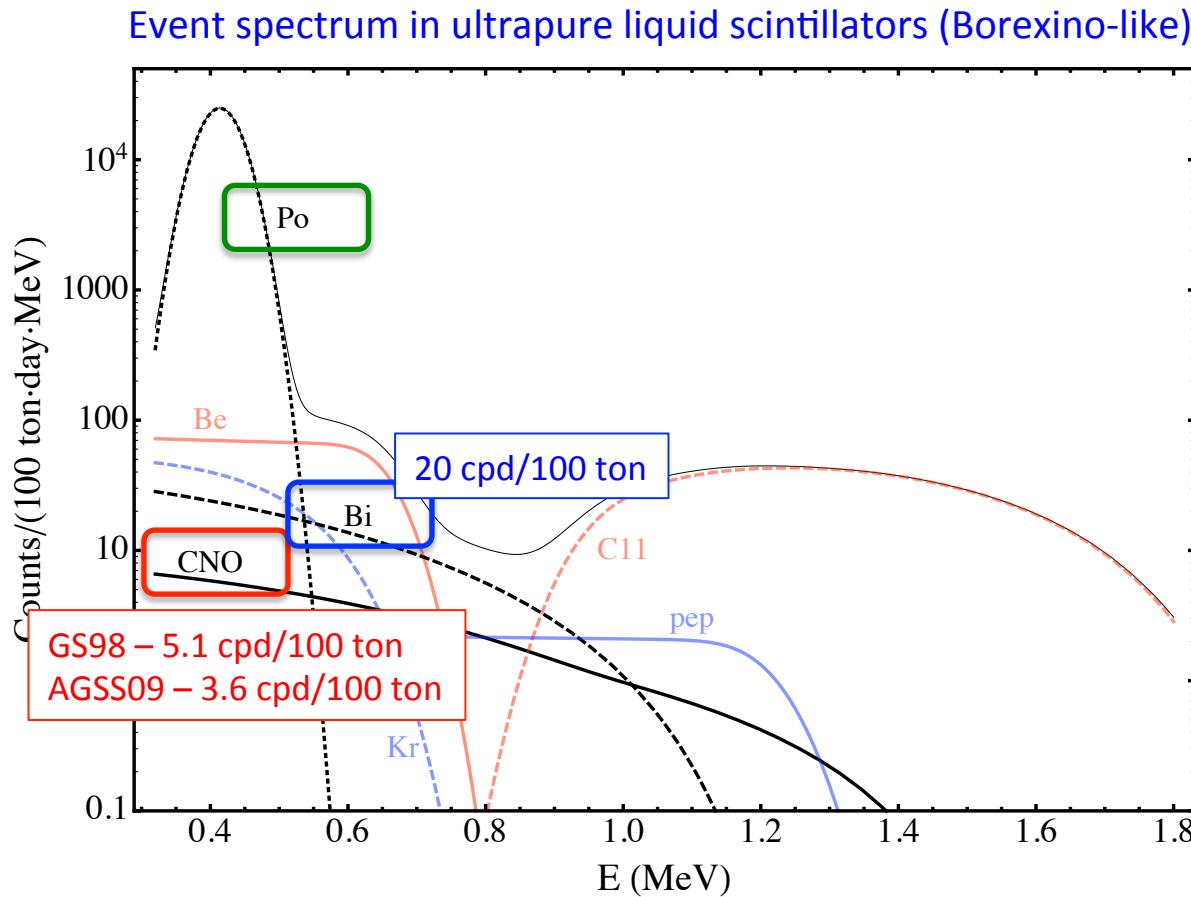
- Low energy neutrinos → endpoint at about 1.5 MeV
- Continuos spectra → do not produce recognizable features in the data.
- Limited by the background produced by beta decay of  $^{210}\text{Bi}$ .



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Determining  $^{210}\text{Bi}$  from  $^{210}\text{Po}$  time evolution?

*Not impossible, in principle. Very difficult, in practice .....*

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

## How to improve?

- |                             |   |
|-----------------------------|---|
| Increase the detector depth | → reduction of cosmogenic $^{11}\text{C}$ background<br><i>SNO+: factor 100 lower than BX</i> |
| Consider larger detectors   | → Stat. uncertainties scales as $1/\text{M}^{1/2}$<br><i>SNO+ (1 kton), LENA (50 kton)</i>    |

**The final accuracy depends, however, on the internal background ( $^{210}\text{Bi}$ )**

**Borexino: 20cpd/100 ton → 150 nuclei / 100 ton**

## Future Proposals

- Water based Liquid Scintillators (WbLS)
- “Salty” WbLS → doped (1% by mass) with  $^7\text{Li}$  (CC detection of  $\nu_e$  on  $^7\text{Li}$ )
- **Advanced Scintillator Detector Concept** discussed in arXiv:1409.5864 (assuming 30-100 kton detector)
- **Liquid argon:** the potential of 300 ton detector@LNGS for solar neutrino studies is discussed in D.Franco et al. arXiV:1510.04196

# High energy cosmic neutrinos

see the talks from G. Pagliaroli and A. Esmaili

# High energy cosmic neutrinos

IceCube has recently opened the era of High Energy neutrino astronomy:

## HESE (High Energy Starting Events)

37 events above 30 TeV in 3 years

Exp. Background:

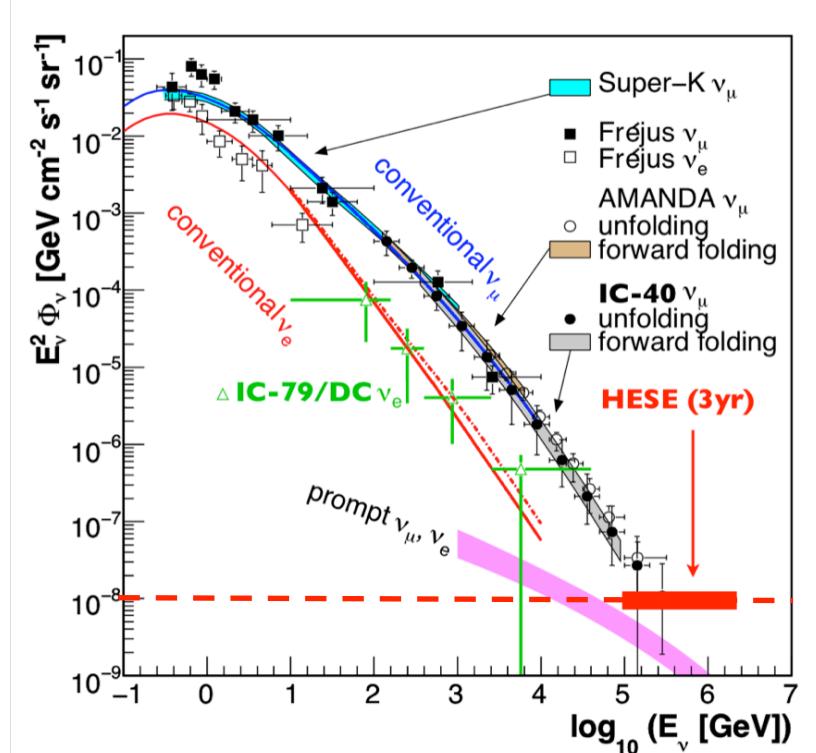
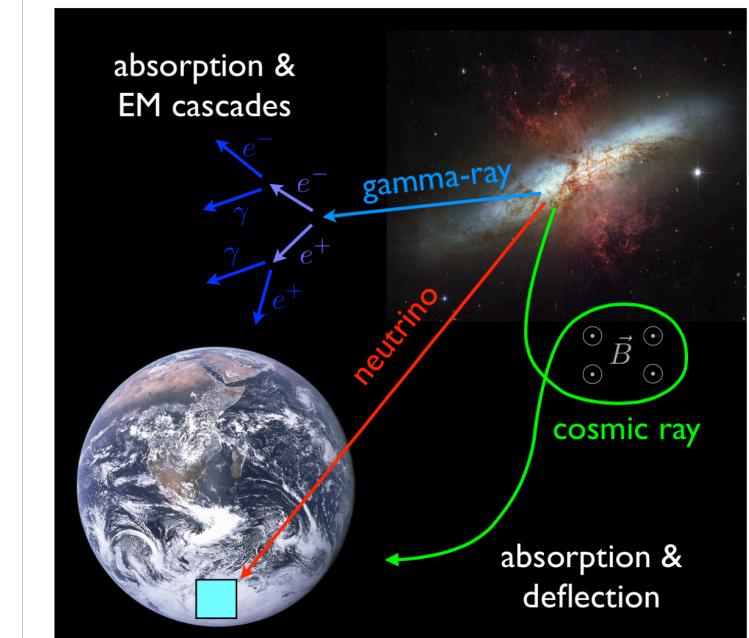
$8.4 \pm 4.2$  [cosmic ray muons]

$6.6 \pm 5.9$  [ $\nu$  atmo]

Energy and arrival angle distributions compatible with cosmic origin

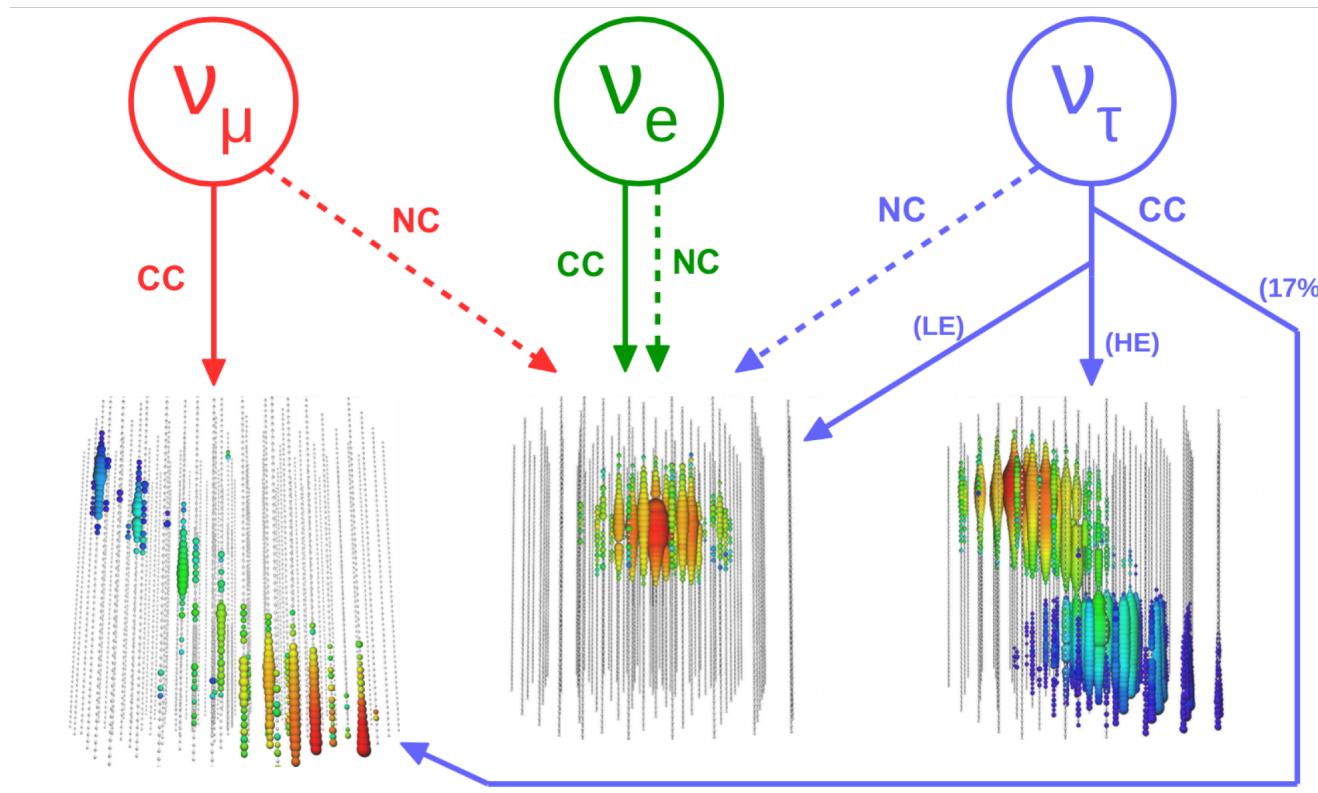
## Upgoing passing muons

High energy excess due to a cosmic population of  $\nu_\mu$  observed at  $2.7\sigma$ .



# Event Topologies and $\nu$ flavor

Figure from L. Mohrmann - TAUP2015



Tracks (8)

Showers (28)

Double-Pulses (0)

(\*) One of the 37 HESE events is not included in analysis

# An (incomplete) list of basic questions ...

- ✓ Are we really seeing a **cosmic  $\nu$  population?**
- ✓ Do  **$\nu$ -oscillations** produce specific signatures for cosmic neutrinos?
- ✓ Can **non standard  $\nu$ -properties** be constrained by cosmic neutrinos?
- ✓ Which is the **mechanism** for cosmic neutrino production?
- ✓ Which are the  **$\nu$  sources?** Galactic? Extra-galactic?
- ✓ .....

... that are waiting for answers