NEUTRINO LINES AND THE TEMPERATURE OF THE SUN

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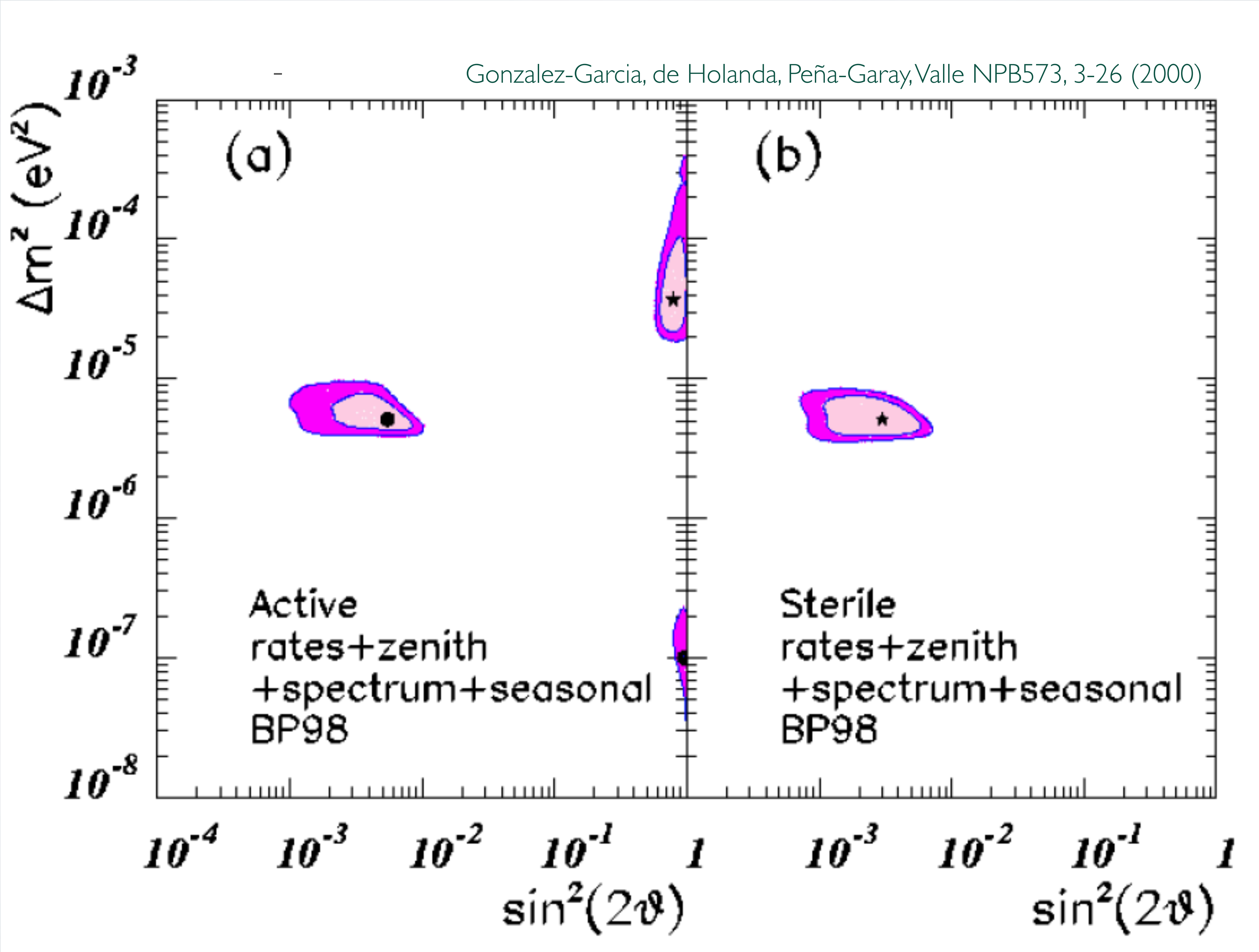
SolarNu18, Dresde

SOLAR NEUTRINO HEROES

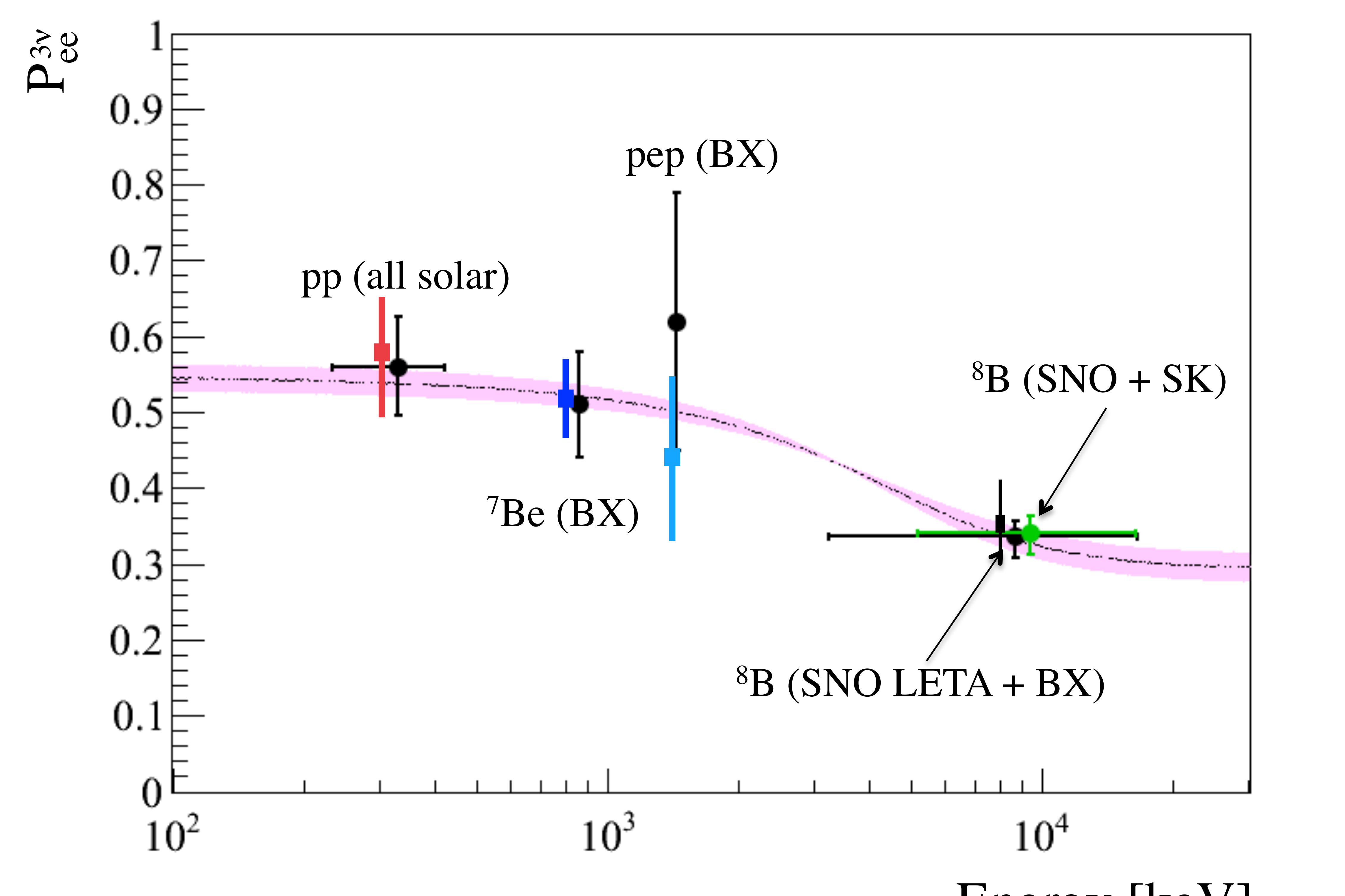
[Congratulations to the SolarNu2018 Organizers]
(British Dictionary) Distinguished by exceptional courage,…
Pictures and selection from sns.ias.edu/~jnb/

Reminder: A global community effort contributing to answer the question How does the Sun shine? (verify nuclear reactions source the Sun power), which muted into the solar neutrino problem(s).

20 YEARS AGO … THERE WERE MANY POSSIBLE SOLUTIONS

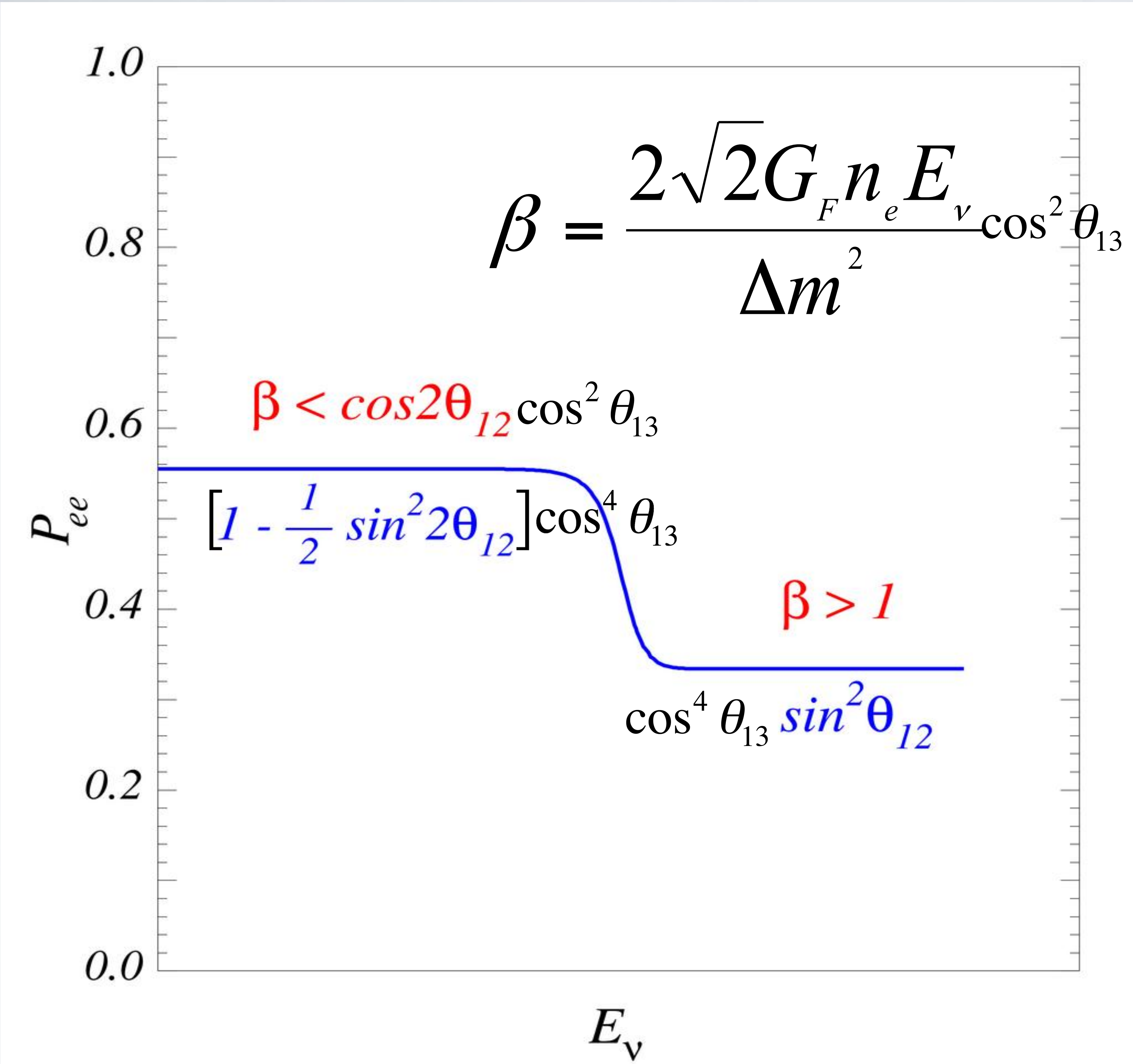


TOTAL RATES BY ALL SOLAR NEUTRINO EXPERIMENTS



Latest Borexino rates in color

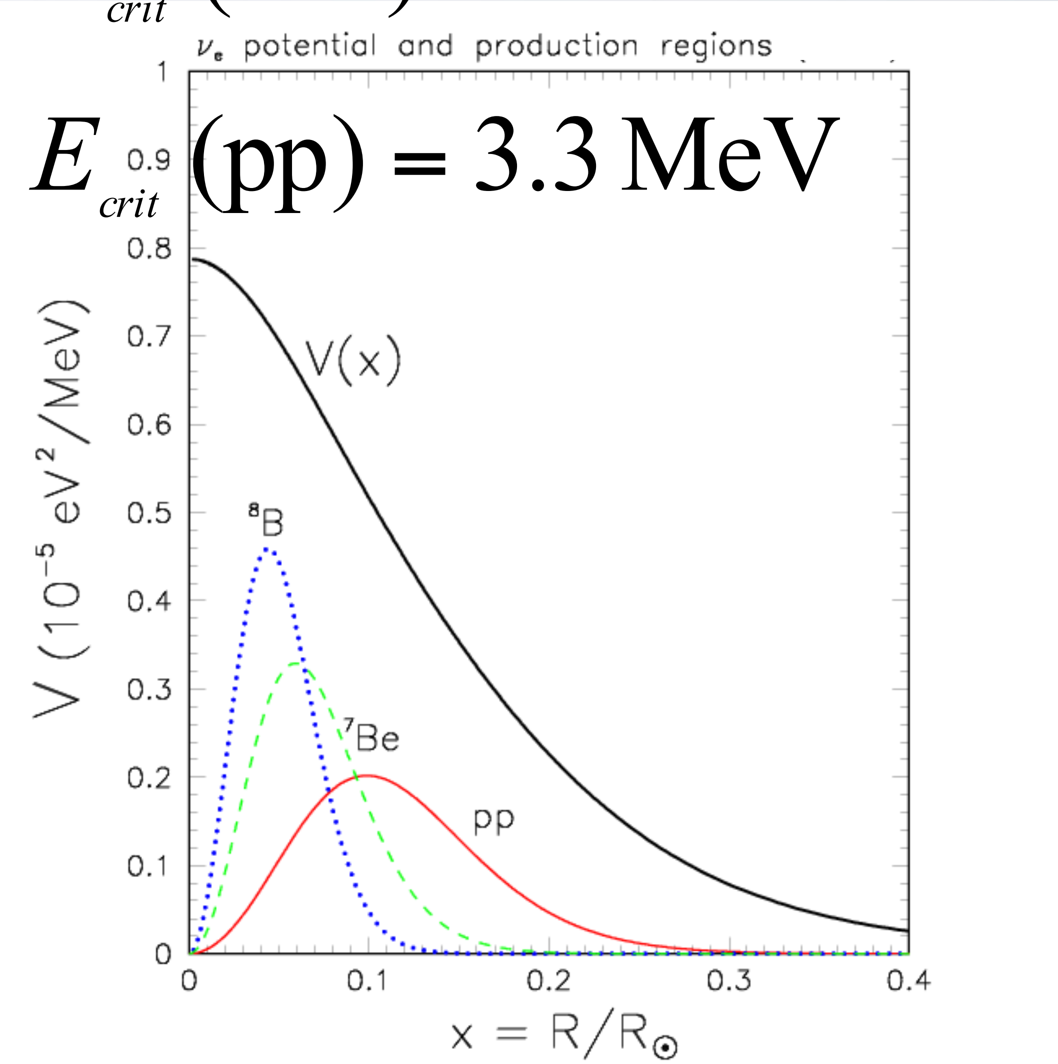
LMA : Vacuum to adiabatic transition



$E_{crit}\,(^8B) = 1.8$ MeV

$E_{crit}\,(^7Be) = 2.2$ MeV

$E_{crit}\,(pp) = 3.3$ MeV



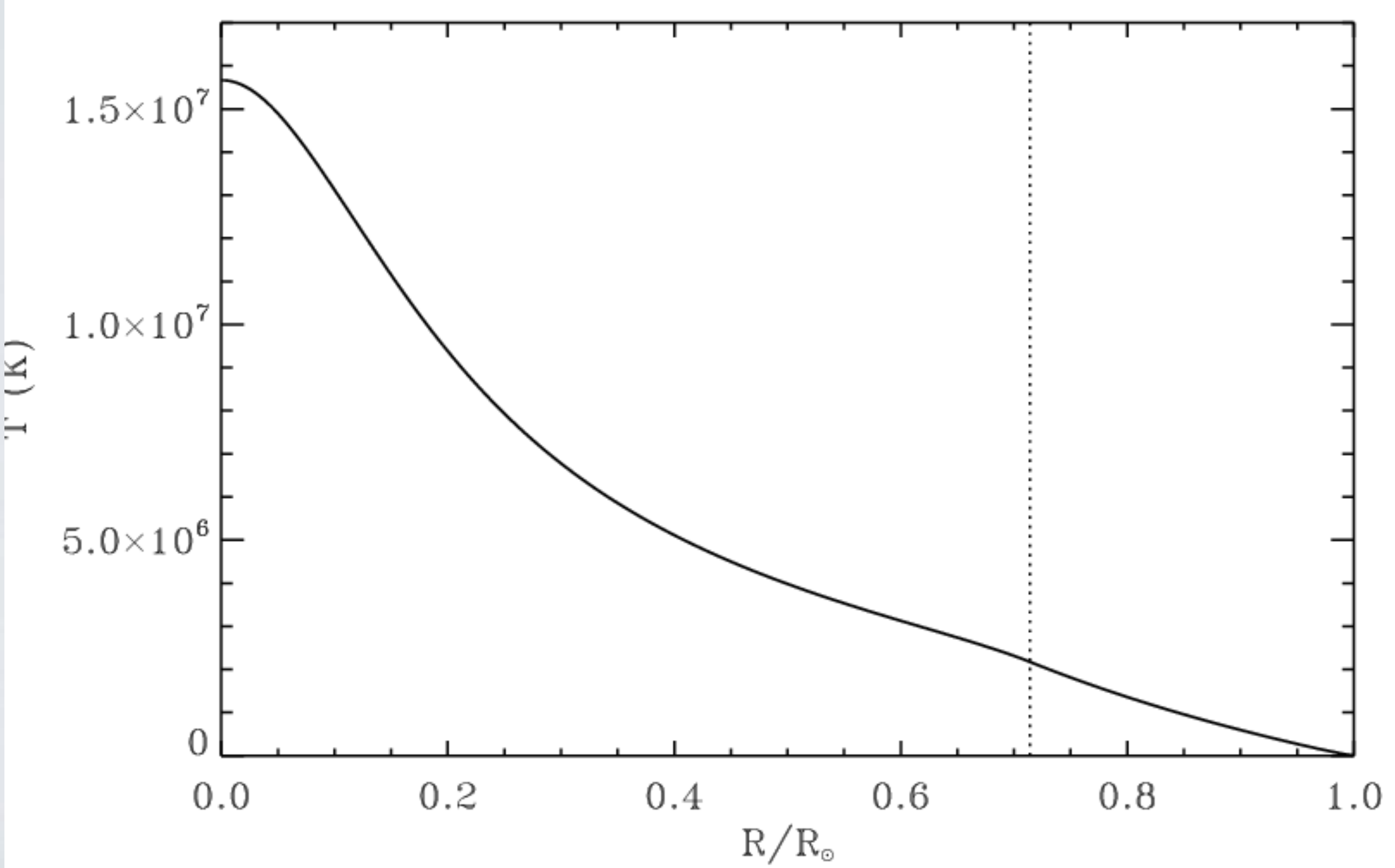
THE CENTRAL TEMPERATURE OF THE SUN

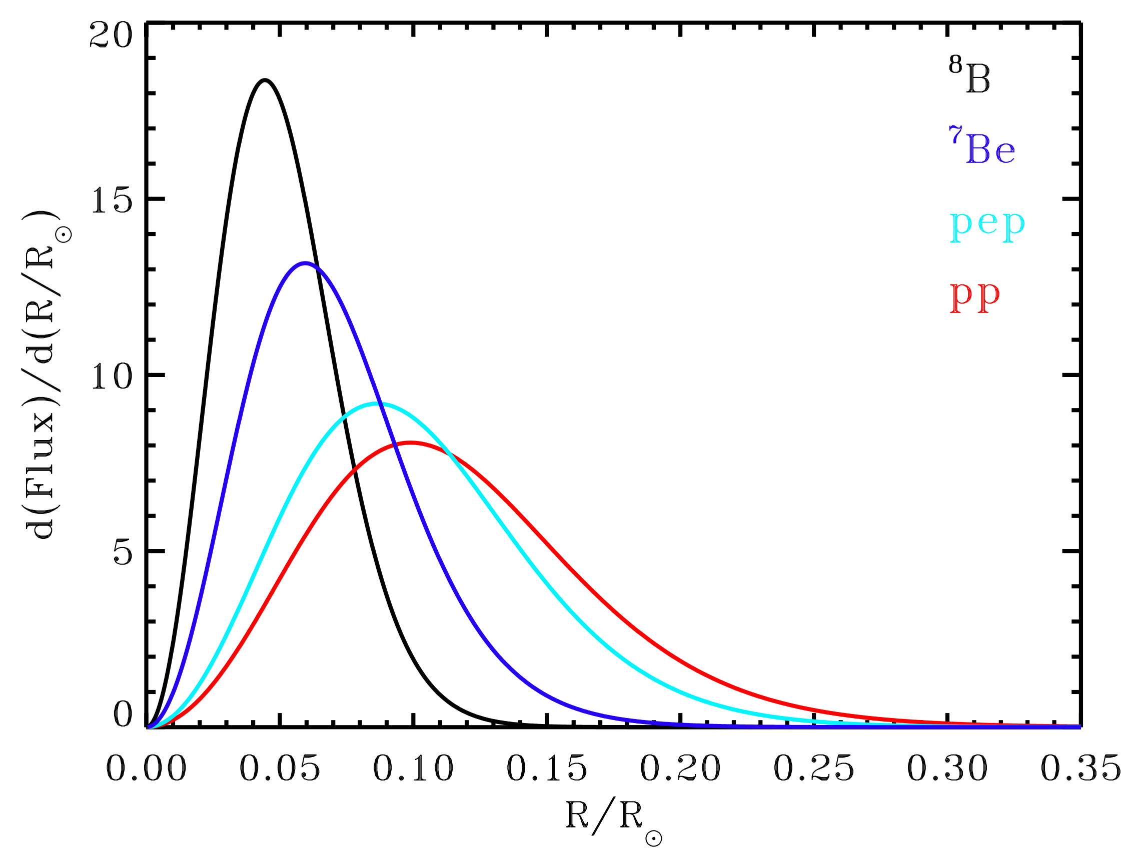
SSM output. Decreasing function from 15.7 MK. Indirectly verified by observations.

Could we directly verify the Solar temperature in the central region?

Neutrino experiments can potentially probe the Temperature in the production region

First and second momentum of the temperature at different radii can be probed with different neutrino fluxes.

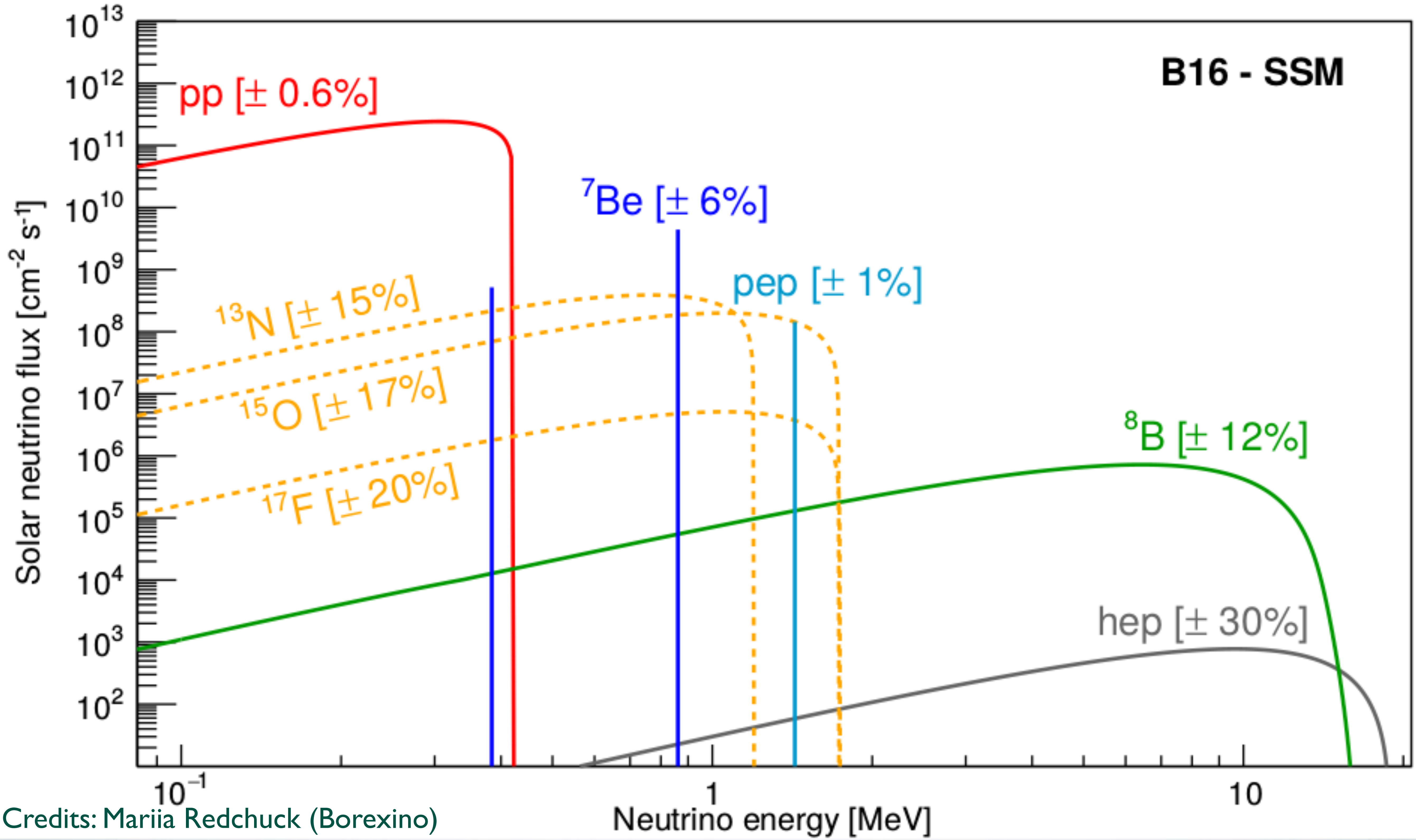




The neutrinos observed experience a Doppler shift because of the motion in the line-of-sight of the center of mass relative to the laboratory frame: $q_{obs} = q_{cm}(p)(1 - V_{z,cm})$

Standard Solar Model

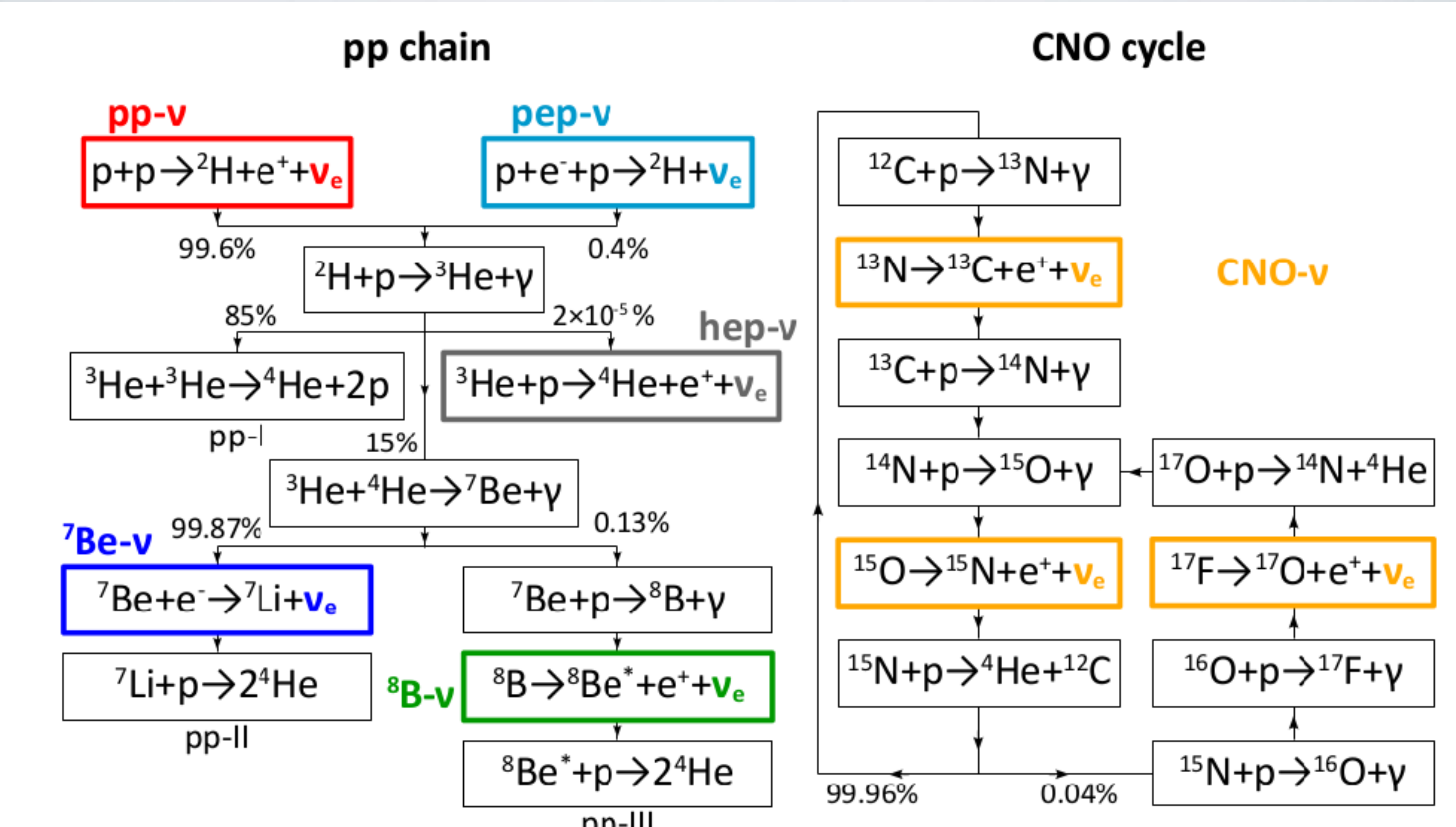
Solar neutrino spectra



Credits: Mariia Redchuck (Borexino)

SOLAR NEUTRINO LINES: ELECTRON CAPTURE

- Solar neutrino lines with the largest fluxes: ^{7}Be and pep lines (measured by Borexino)
- Other lines associated to ß-decays (^{8}B, CNO) Stonehill, Formaggio & Robertson PRC69, 015801(2004)



Credits: Mariia Redchuck (Borexino)

COMPARE FLUXES OF LINES (FACTOR 30-34)

Flux	B16-GS98	B16-AGSS09met	Solar[a]
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.971^{(1+0.006)}_{(1-0.005)}$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.448(1 \pm 0.009)$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$19^{(1+0.63)}_{(1-0.47)}$
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$
$\Phi(^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$
$\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7
$\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8
$\Phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	≤ 85

Table 6. Model and solar neutrino fluxes. Units are: 10^{10} (pp), 10^9 (^{7}Be), 10^8 (pep, ^{13}N, ^{15}O), 10^6 (^{8}B, ^{17}F) and 10^3 (hep) cm^{-2}s^{-1}. [a]Solar values from Bergström et al. (2016).

QUICK TOUR TO CALCULATING THE 1442 keV pep LINE

Considering the electron capture by the pp system, the pep rate can be expressed in terms of the pp rate, with the pep/pp ratio proportional to the ratio of phase space integrals.

The rate of pep neutrinos is proportional, after some algebra, to the integral of the Bolztmann distributions times Coulomb factors:

$$\int d^3p_e d^3p_1 d^3p_2 d^3p_\nu \; f_e f_1 f_2 F\left(2, v_e\right) F\left(-1, v_{12}\right) \delta\left(E_f - E_i\right)$$

After some algebra, the pep spectrum as a function of neutrino energy and temperature is proportional to the integral

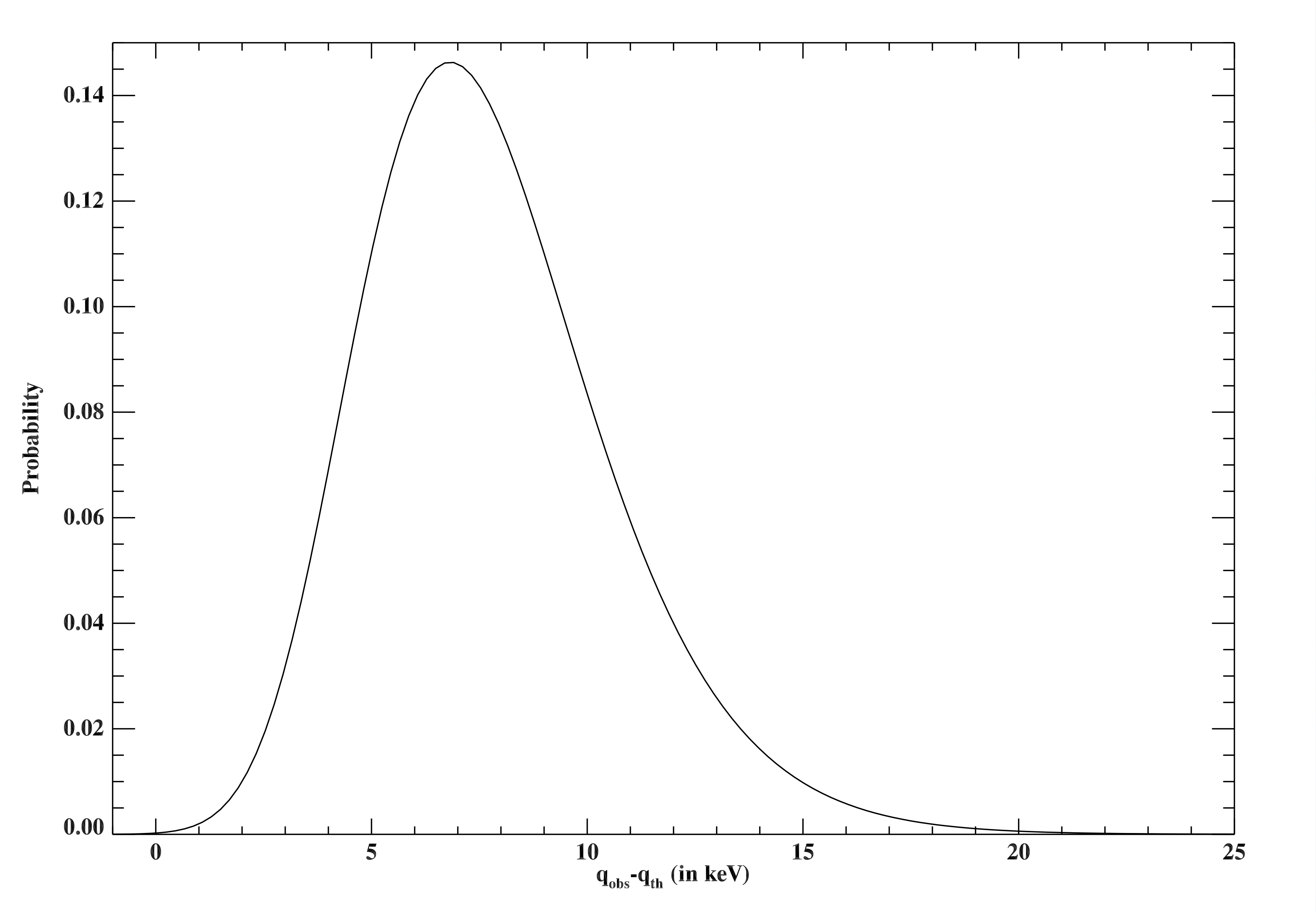
$$\frac{d\Gamma}{dq_{obs}}\left(q_{obs}, T\right) \propto \int dK_e dK_{12} \exp\left(-\frac{K}{T}\right) \exp\left[-\frac{M_p}{\Delta M^2 T}\left(\frac{q_{obs}-\Delta M-K}{1+\frac{K}{\Delta M}}\right)^2\right] \cdot$$

$$\cdot \frac{1}{1-\exp\left(-4\pi\alpha\sqrt{\frac{m_e}{2K_e}}\right)} \frac{1}{1-\exp\left(2\pi\alpha\sqrt{\frac{M_p}{4K_{12}}}\right)} \frac{\Delta M}{1+\frac{\Delta M}{M_D}\left(1+\frac{K}{\Delta M}\right)} \left(1+\frac{K}{\Delta M}\right)$$

Neutrino spectrum as a function of neutrino energy is obtained by integrating the spectrum with the pep production distribution as a function of temperature.

PROPOSALS TO VERIFY T BY USING THE pep LINE

- Energy shift (7.6 keV), first momentum of the central temperature distribution, due to kinetic energies of electrons and protons [q_{LAB}=1442 keV]
- Energy width (6.3 keV FWHM) due to Doppler shifts caused by thermal protons



QUICK COMMENTS ON REQUIREMENTS FOR EXPERIMENTS

- Large detectors

Factor 20 (in electron scattering) more demanding for pep neutrinos
(achieved by Borexino)

- Deep underground

More demanding for pep neutrinos (suppress ^{11}C) in liquid scintillators
(achieved by Borexino)

- Better than 0.1% -1% energy resolution

Factor 3 less demanding for pep neutrinos
Cryogenic detectors or Nobel gas at presume can do it

- Backgrounds

Different energy regions and materials demand different background suppression

See THEIA at Orebi Gan's talk

Remarks:
Different lines measure different temperatures
Differences en matter effects
How close to the goal should the experiment be to get an important insight?

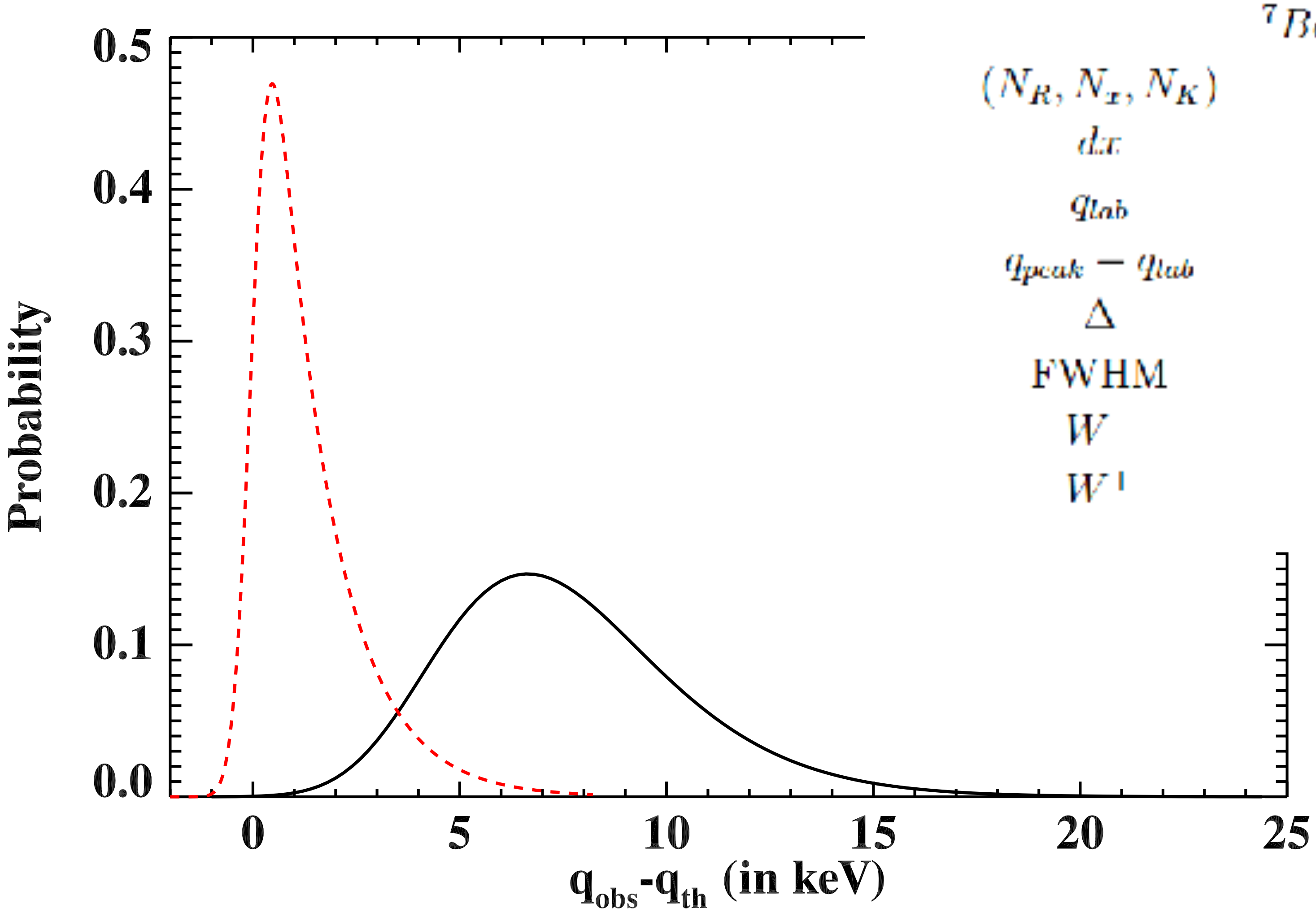
SUMMARY (TAKE HOME MESSAGE)
ADD TEMPERATURE TO THE ROADMAP OF SOLAR NEUTRINOS

Add Test the central temperature of the Sun via neutrino lines to the to-do list (CNO, solar abundances, opacities, upturn, earth matter effects, m^2 splitting,…)

Influence of kinetic energies: shift and widen neutrino lines

Comparison between ^{7}Be and pep lines: pep relaxes a factor three the energy resolution requirement.

Summary results:



	^7Be (Bahcall, 1994)	^7Be	pep
(N_R, N_x, N_K)	-	$(256, 512, 512)$	$(128, 128, 128, 128)$
dx	0.1	0.02	0.2
q_{lab}	861.84	861.84	1442
$q_{peak} - q_{lab}$	0.43	0.46	6.6
Δ	1.29	1.30	7.59
FWHM	1.63	1.72	6.29
W	0.56	0.59	2.71
W^1	1.07	1.13	3.58