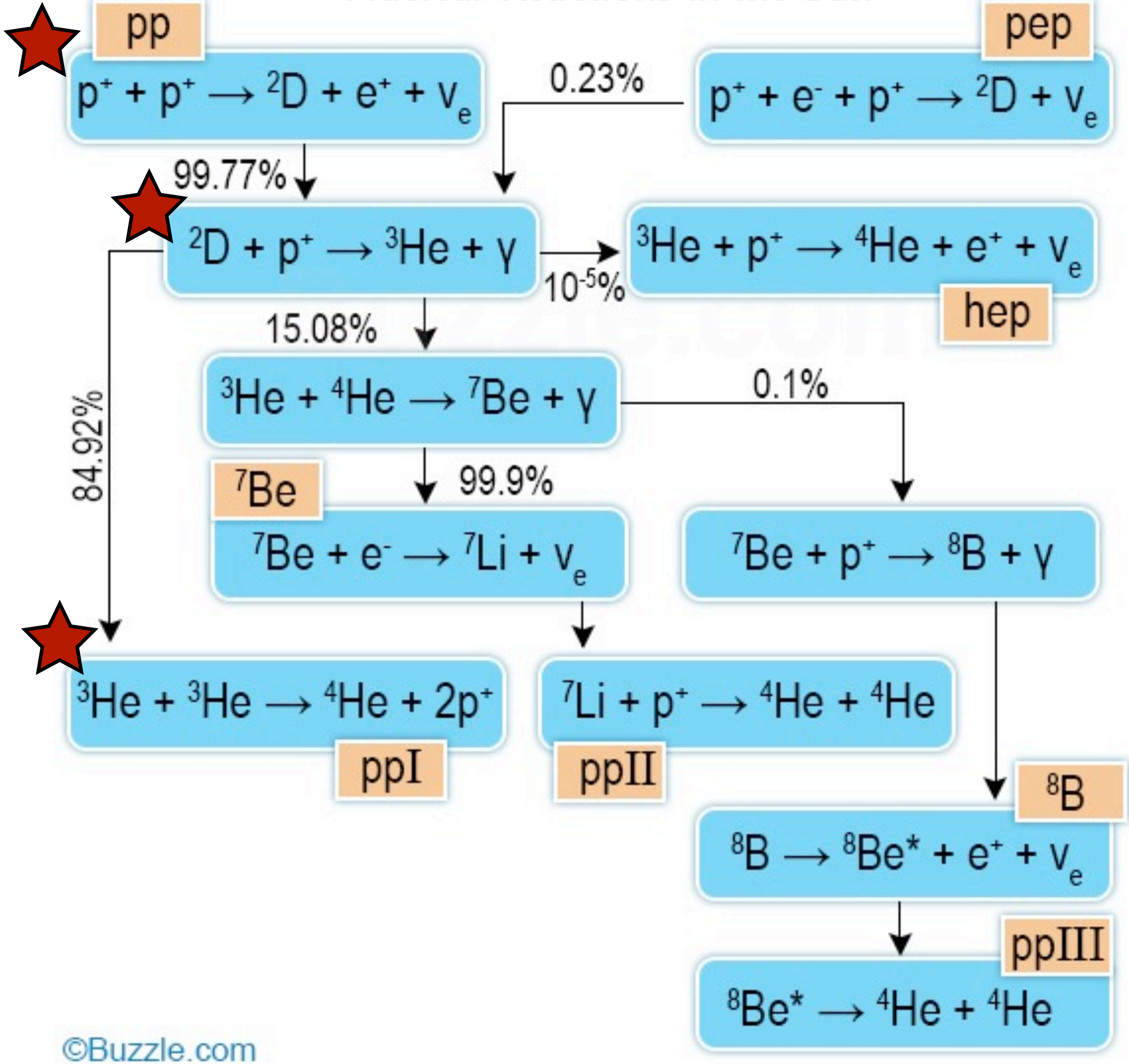
Lecture 3:
solar neutrinos

PhD Cycle XXXIII

Solar neutrinos

- The proof that the Sun is powered by nuclear reactions has to come from the observation of the reaction products
- Among them only the neutrinos can escape unaffected the production region
- Their detection allows the study of the production region which is the innermost one, unobservable by other techniques

Proton-Proton and Electron Capture Nuclear Reactions in the Sun



pp

$p^+ + p^+ \rightarrow {}^2D + e^+ + \nu_e$

0.23%

pep

$p^+ + e^- + p^+ \rightarrow {}^2D + \nu_e$

99.77%

${}^2D + p^+ \rightarrow {}^3He + \gamma$

$10^{-5}\%$

${}^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

hep

15.08%

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

0.1%

84.92%

99.9%

${}^7Be$

${}^7Be + e^- \rightarrow {}^7Li + \nu_e$

${}^7Be + p^+ \rightarrow {}^8B + \gamma$

${}^3He + {}^3He \rightarrow {}^4He + 2p^+$

ppI

${}^7Li + p^+ \rightarrow {}^4He + {}^4He$

ppII

${}^8B$

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

ppIII

${}^8Be^* \rightarrow {}^4He + {}^4He$

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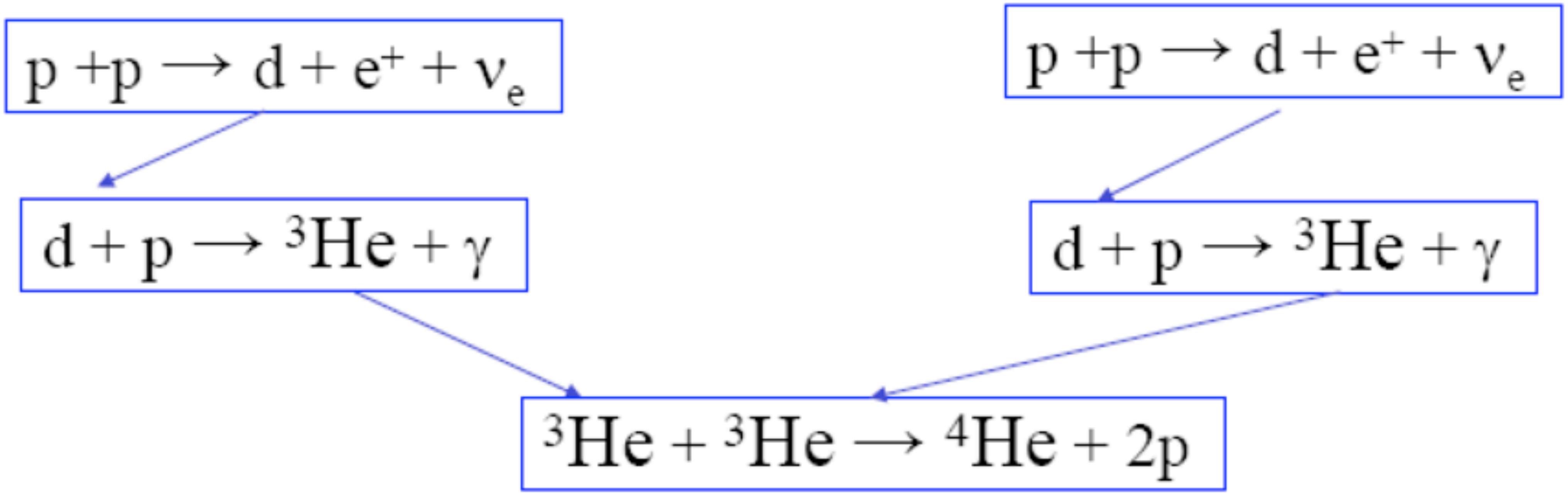
The pp-I chain

- Reactions involving nuclei with the smallest charges are favoured, due to smaller Coulomb barrier. This is the reason why in the Sun we believe that pp-I is the dominant energy production mechanism, accounting for some 90% of the total energy production.
- It proceeds along the following steps



$p + p \longrightarrow d + e^+ + \nu_e$ $\qquad$ $p + p \longrightarrow d + e^+ + \nu_e$

$d + p \longrightarrow {}^3He + \gamma$ $\qquad$ $d + p \longrightarrow {}^3He + \gamma$

$${}^3He + {}^3He \longrightarrow {}^4He + 2p$$

- Each e^+ will annhilate against e^- in the plasma
- The full result is

$$4p + 2e^- \longrightarrow {}^4He + 2\nu_e$$

Remarks on pp-I chain : pp neutrinos

$$\boxed{p + p \longrightarrow d + e^+ + \nu_e}$$

- Note that the first step is a weak interaction process,
- It transforms the *p*'s into *n*'s necessary to form ^{4}He; this is different from BBN, where free neutrons were available.
- The produced neutrinos (called pp-ν) have a continuous spectrum, with E_{max}=0.4 MeV and <E>=0.2 MeV

$$\boxed{d + p \longrightarrow {}^3\mathrm{He} + \gamma}$$

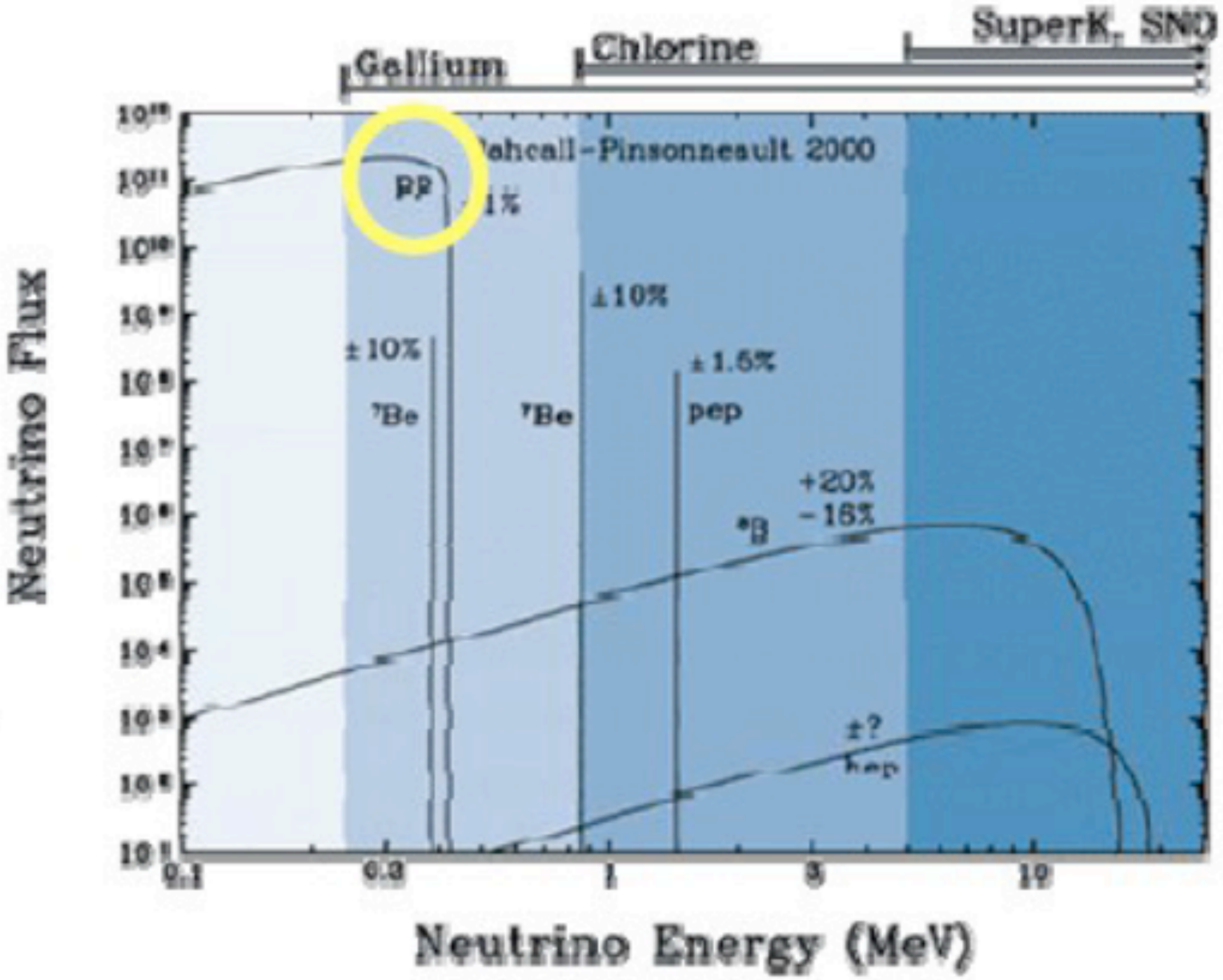
- This is an e.m process, which destroys *d*. This is generally the fate of *d* in stars and the reason why it is rare. It is formed by weak process where Hydrogen is present, and is destroyed by an e. m process which requires Hydrogen

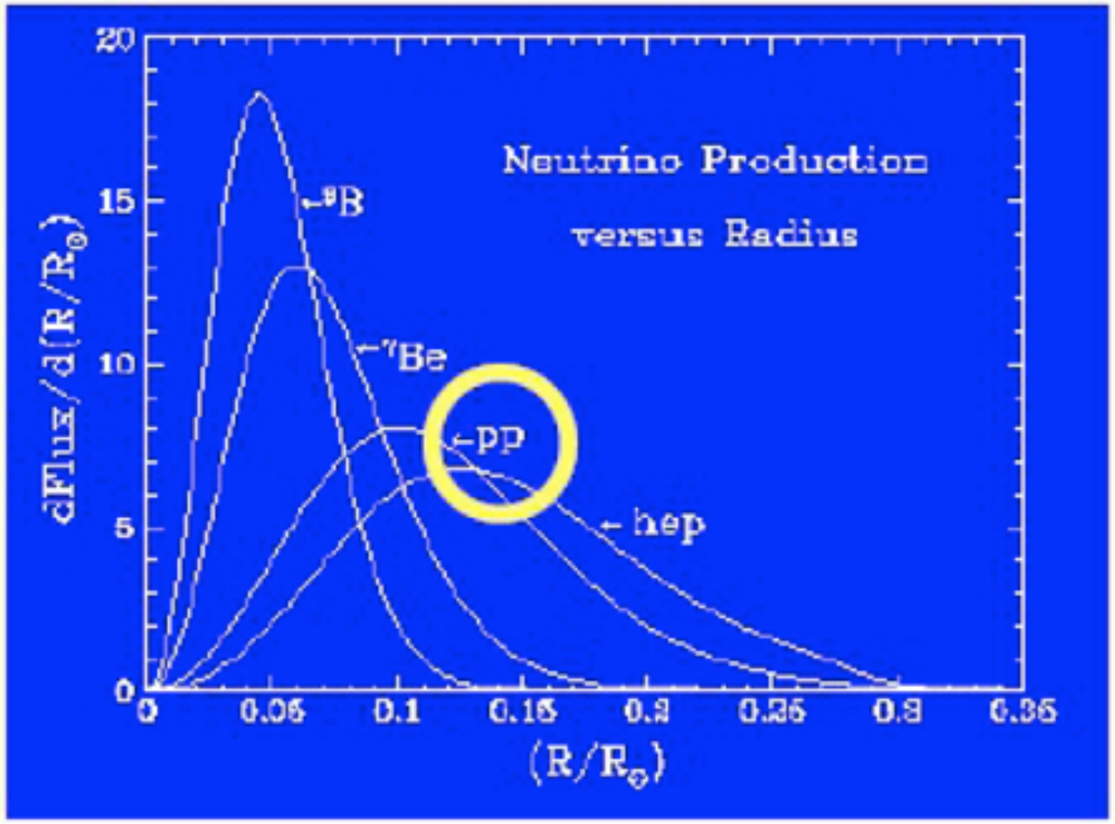
$$\boxed{{}^3\mathrm{He} + {}^3\mathrm{He} \longrightarrow {}^4\mathrm{He} + 2p}$$

- It is a strong interaction process, which completes the chain.

pp neutrinos

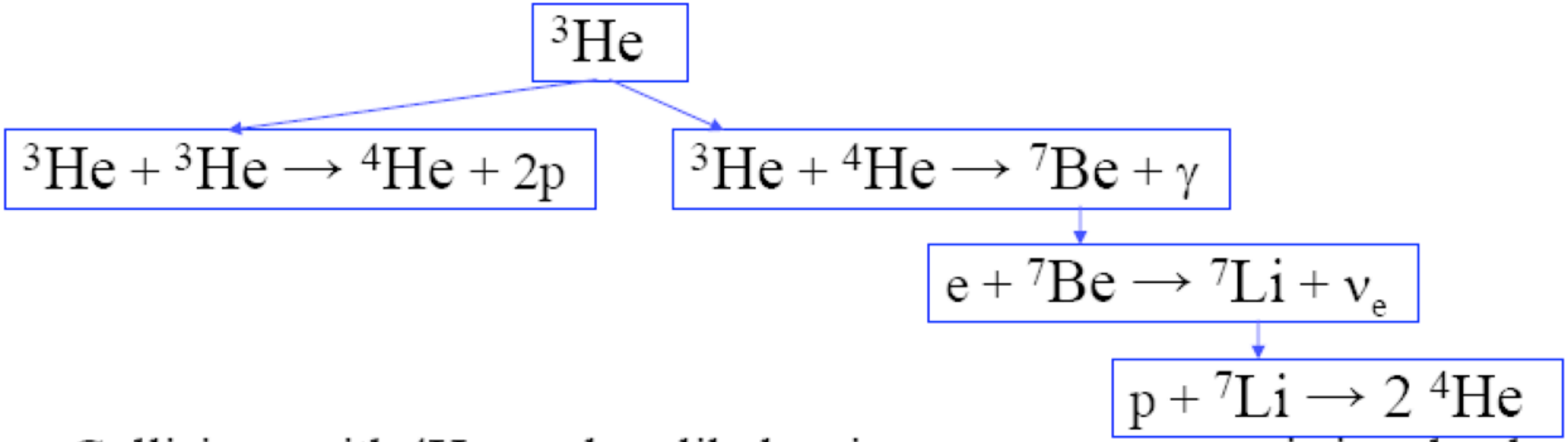
- Energy spectra and production region is shown for pp neutrinos.
- pp neutrinos are :
  - the dominant component in number
  - the component with smallest energy
  - The component which is produced in a more extended area of the Sun, concentrated however within 1/3 of the solar radius and with a maximun at 1/10 of R_o





The pp-II chain and Beryllium neutrinos

- Indeed, ^{3}He can be destroyed also in collisions with ^{4}He,



$^3\mathrm{He}$

$^3\mathrm{He} + {}^3\mathrm{He} \longrightarrow {}^4\mathrm{He} + 2p$

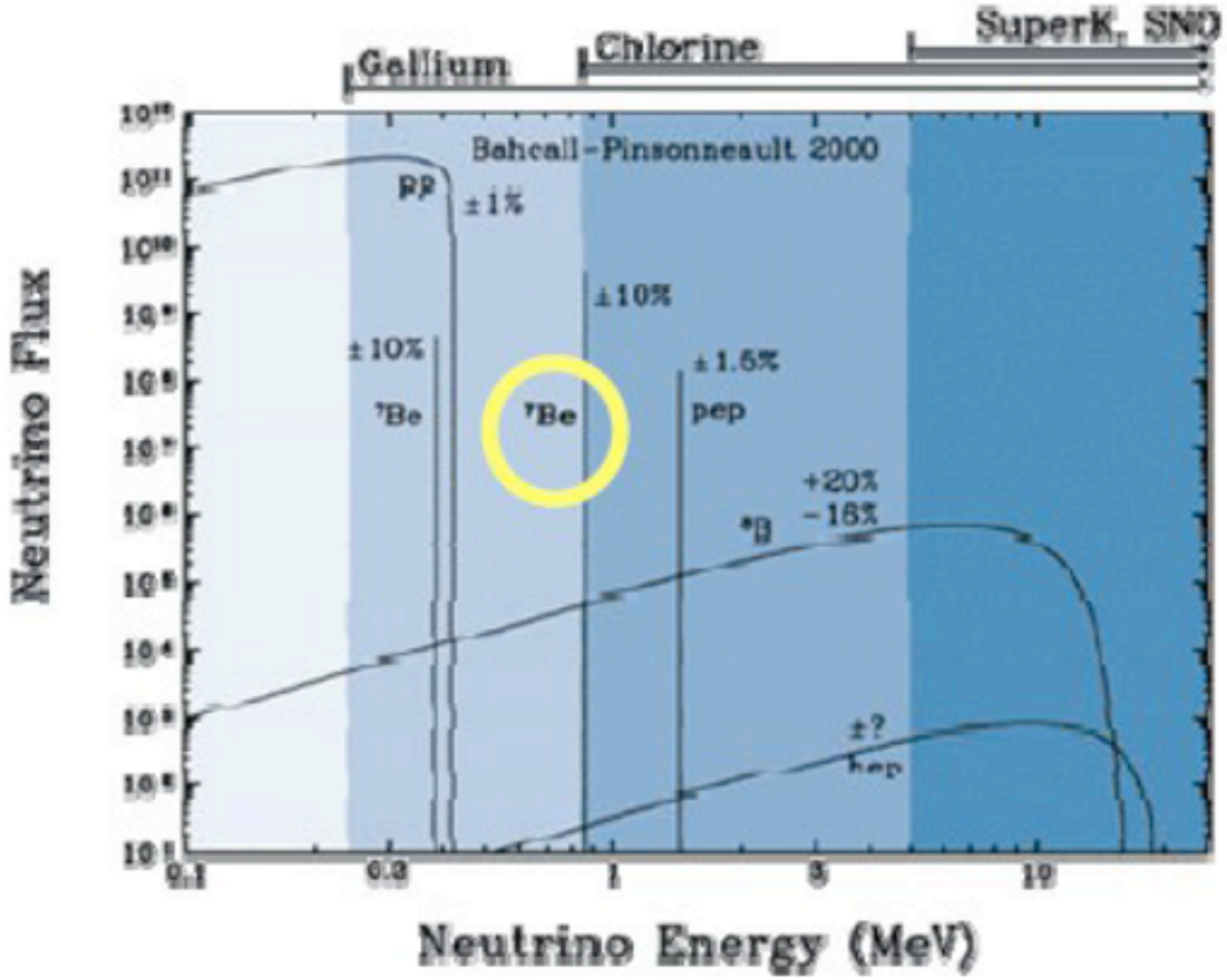
$^3\mathrm{He} + {}^4\mathrm{He} \longrightarrow {}^7\mathrm{Be} + \gamma$

$e + {}^7\mathrm{Be} \longrightarrow {}^7\mathrm{Li} + \nu_e$

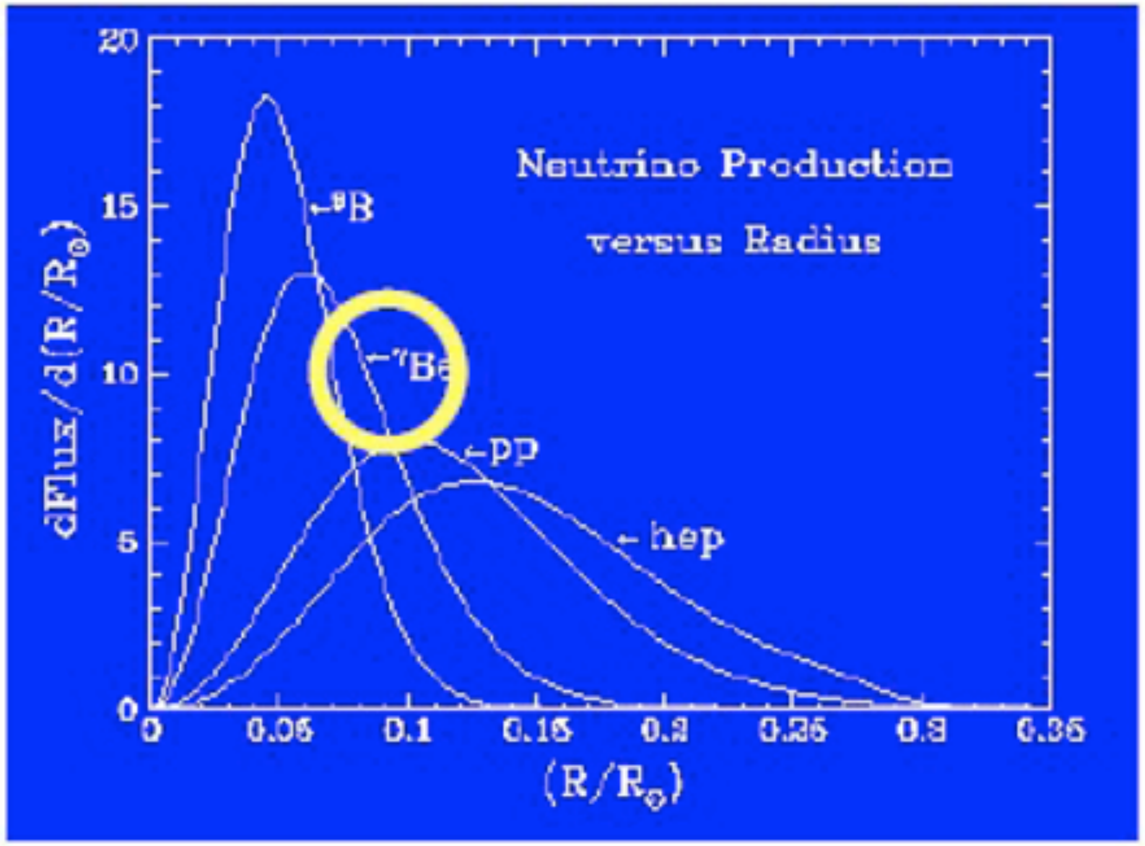
$p + {}^7\mathrm{Li} \longrightarrow 2\,{}^4\mathrm{He}$

- Collisions with ^{4}He are less likely, since an e.m process is involved and more massive particles are involved in the tunneling.
- A (bare) nucleus of ^{7}Be, in vacuum is stable* but in the plasma an electron can be captured, with emission of a monochromatic Be-neutrino** with E=0.8 MeV.
- Be neutrinos are 10% with respect to pp neutrinos.

Be neutrinos

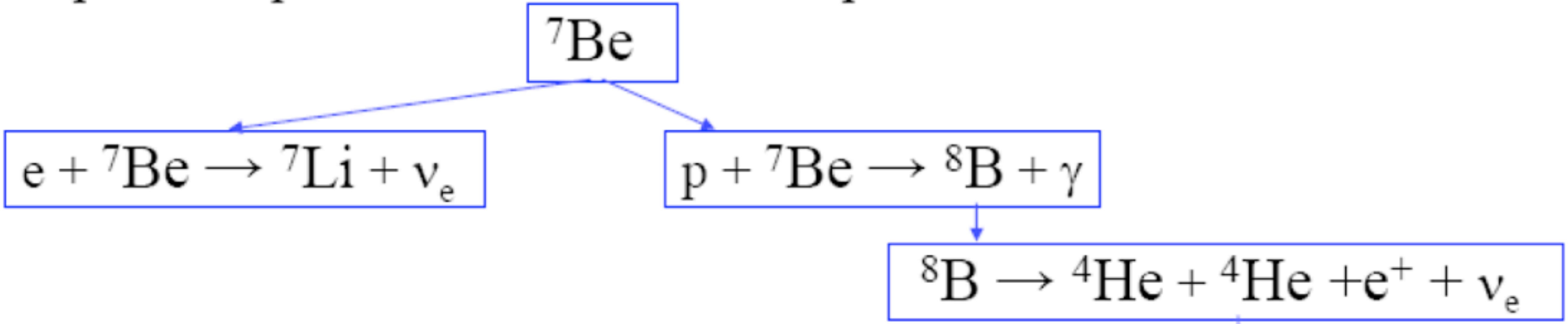


- Shape and production region are shown in the figures
- Be neutrinos are:
  - the second source in intensity, after pp
  - They are “intermediate energy neutrinos”, in that their energy is in between that of pp and B.
  - They are produced in a more central region, where reaction with ^{4}He is more likely due to higher temperature.



The pp-III chain and Boron neutrinos

- Indeed, ^{7} Be can be destroyed also in collisions with protons, i.e proton capture instead of electron capture,



$^7\mathrm{Be}$

$e + {}^7\mathrm{Be} \longrightarrow {}^7\mathrm{Li} + \nu_e$

$p + {}^7\mathrm{Be} \longrightarrow {}^8\mathrm{B} + \gamma$

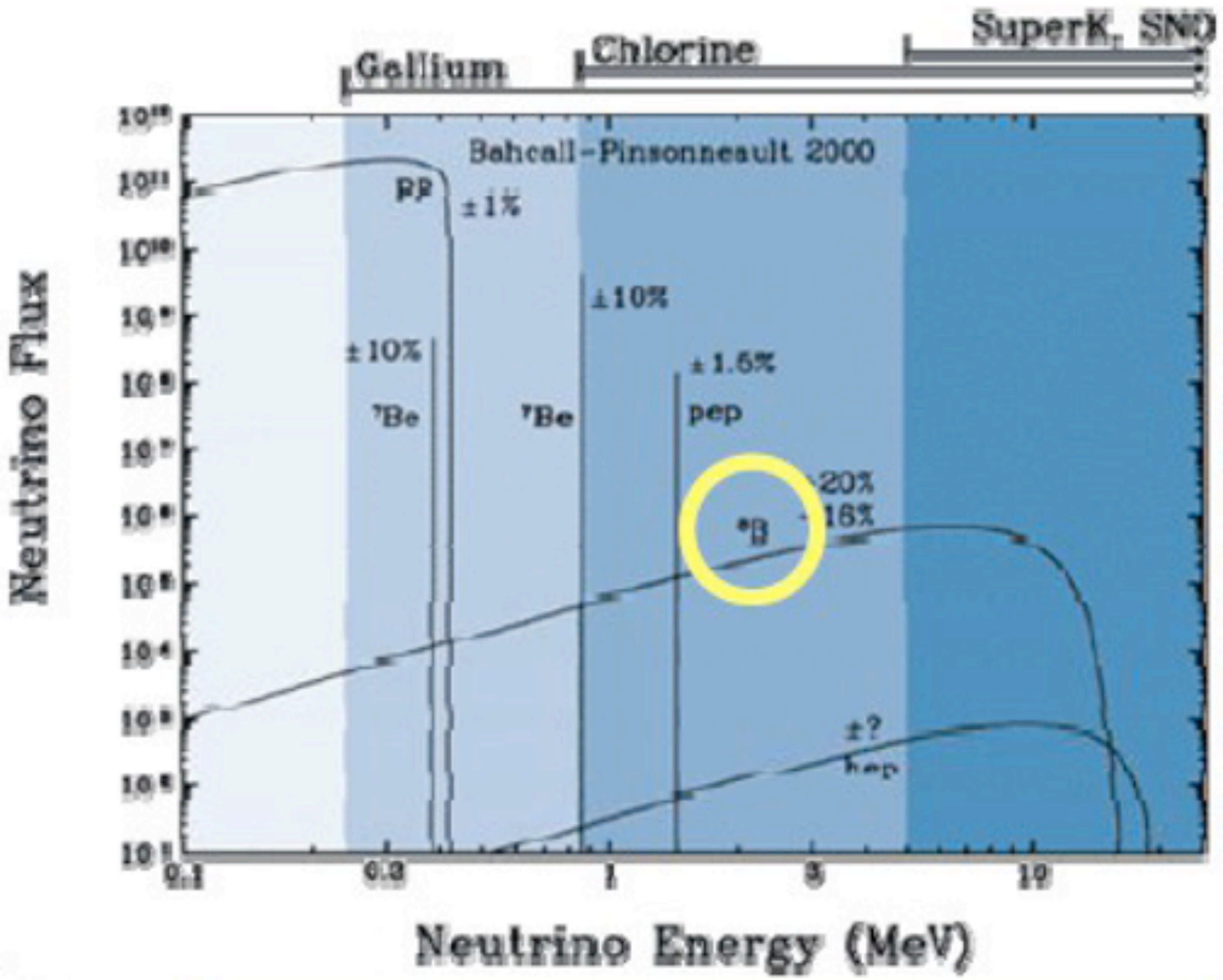
$^8\mathrm{B} \longrightarrow {}^4\mathrm{He} + {}^4\mathrm{He} + e^+ + \nu_e$

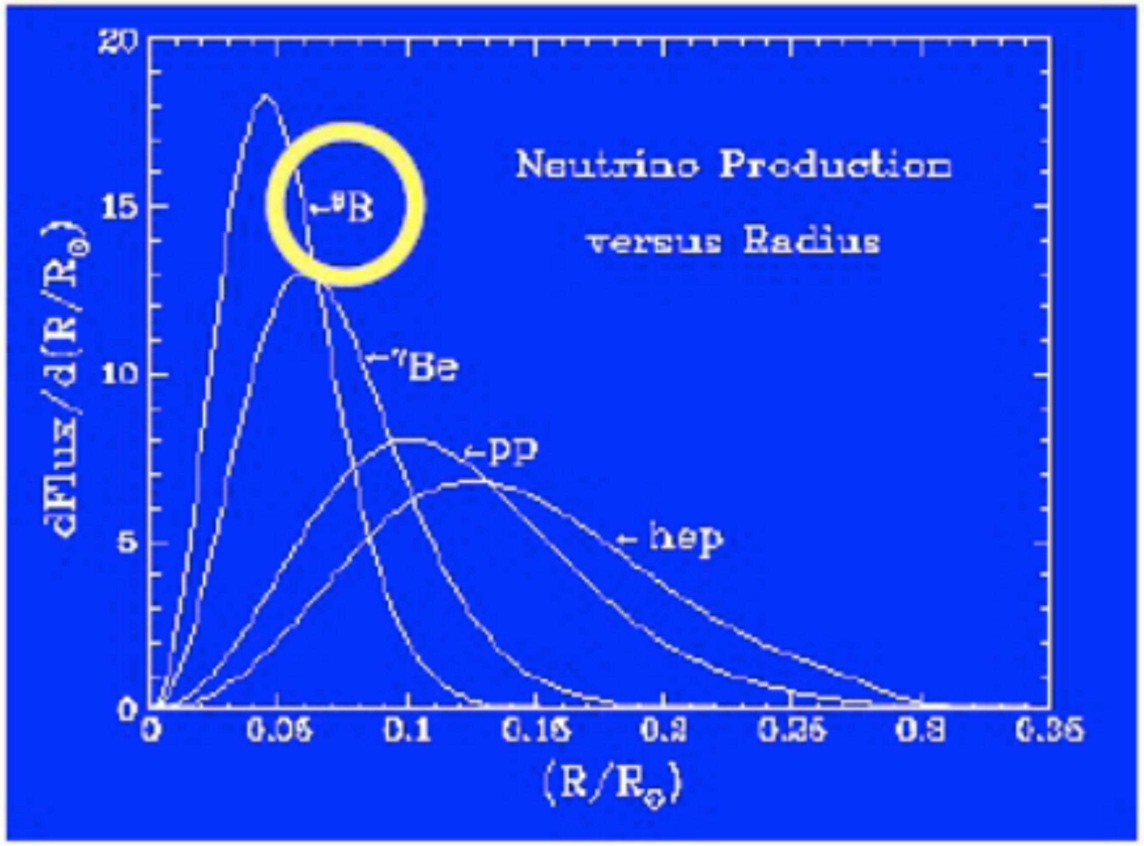
- *p* capture is disfavoured with respect to *e* capture due to Coulomb repulsion, although the instrinsic strength of an e.m. process is larger than that of a weak process.
- Boron neutrinos have a continuous spectrum, extending to 14 MeV.
- Their intensity is about 10^{-4} with respect to pp
- Predictions on B neutrinos are affected by larger errors, due to the several branching involved an to marked temperature dependence.

T^{18}!!

Boron neutrinos

- Shape and production region are shown in the figures
- B- neutrinos are:
  - 10^{-4} in intensity with respect to pp
  - They are “high energy neutrinos”, in that their energy is higher than that of pp and of Be
  - They are produced in a more central region, where p capture on 7Be is more likely due to higher temperature.





Most studied solar neutrinos

name:	pp	^{7}Be	^{8}B
reaction:	$p+p \rightarrow d+e^++\nu_e$	$^7Be+e^- \rightarrow {}^7Li+\nu_e$	$^8B \rightarrow {}^8Be+e^++\nu_e$
energy: [MeV]	≤ 0.42	0.861 (90%) 0.383 (10%)	≤ 15
abundance: [cm $^{-2}$ s^{-1}]	$5.96 \cdot 10^{10}$	$4.82 \cdot 10^9$	$5.15 \cdot 10^6$
uncertainty: (1σ)	1%	10%	18%
production zone:	$0.1\ R_o$	$0.06\ R_o$	$0.05\ R_o$

More neutrinos from the Sun: pep neutrinos , a variant of pp-I chain :

- Whenever a β^+ decay is possible, $(Z,A) \longrightarrow (Z-1,A) + e^+ + \nu_e$ also Electron Capture is possibile, $e + (Z,A) \longrightarrow (Z-1,A) + \nu_e$, since $Q(EC) = Q(\beta^+) + 2m_e$, so if $Q(\beta^+) > 0$ then also $Q(EC) > 0$

- Thus *d* can be formed also through:

$$\boxed{e^- + p + p \longrightarrow d + \nu_e}$$

- This reaction is less likely (≈1%) , then $p + p \longrightarrow d + e^+ + \nu_e$ since having three particles on a region with nuclear dimension is more difficult than two.
- The reaction produces monochromatic neutrinos, with

$$E = E_{max} + 2m_e = 1.4 \text{ MeV}$$

Hydrogen Burning: PP chain and CNO cycle

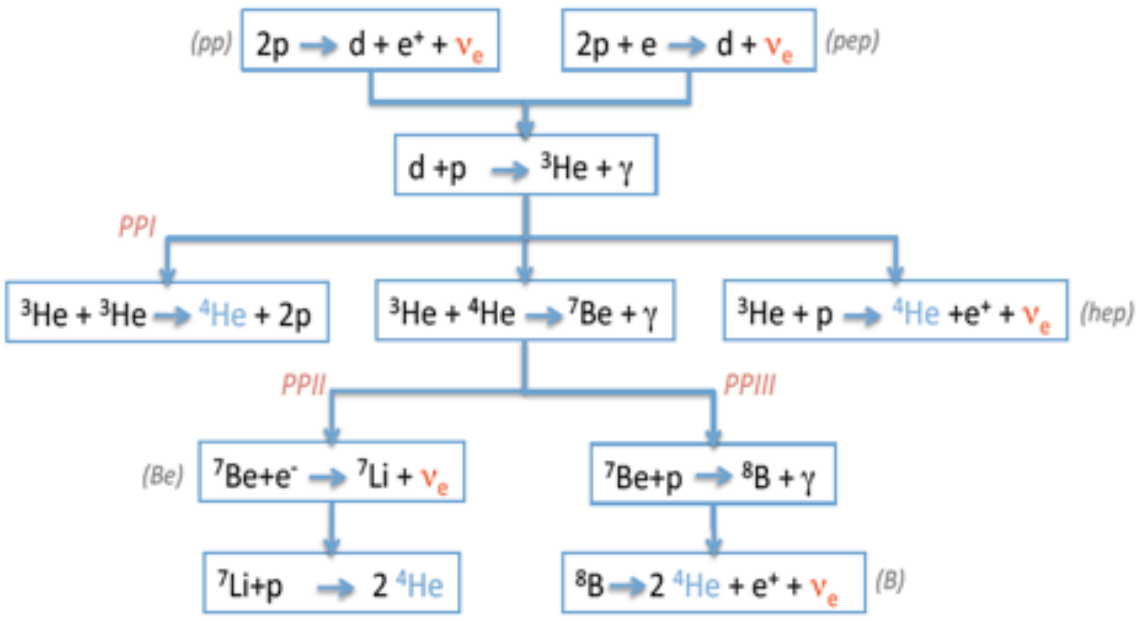
The Sun is powered by nuclear reactions that transform H into ^{4}He:

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

Q = 26,7 MeV (globally)

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

The PP-chain



(pp) $2p \rightarrow d + e^+ + \nu_e$

$2p + e \rightarrow d + \nu_e$ (pep)

$d + p \rightarrow {}^3He + \gamma$

PPI

$^3He + {}^3He \rightarrow {}^4He + 2p$

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

$^3He + p \rightarrow {}^4He + e^+ + \nu_e$ (hep)

PPII

(Be) $^7Be + e^- \rightarrow {}^7Li + \nu_e$

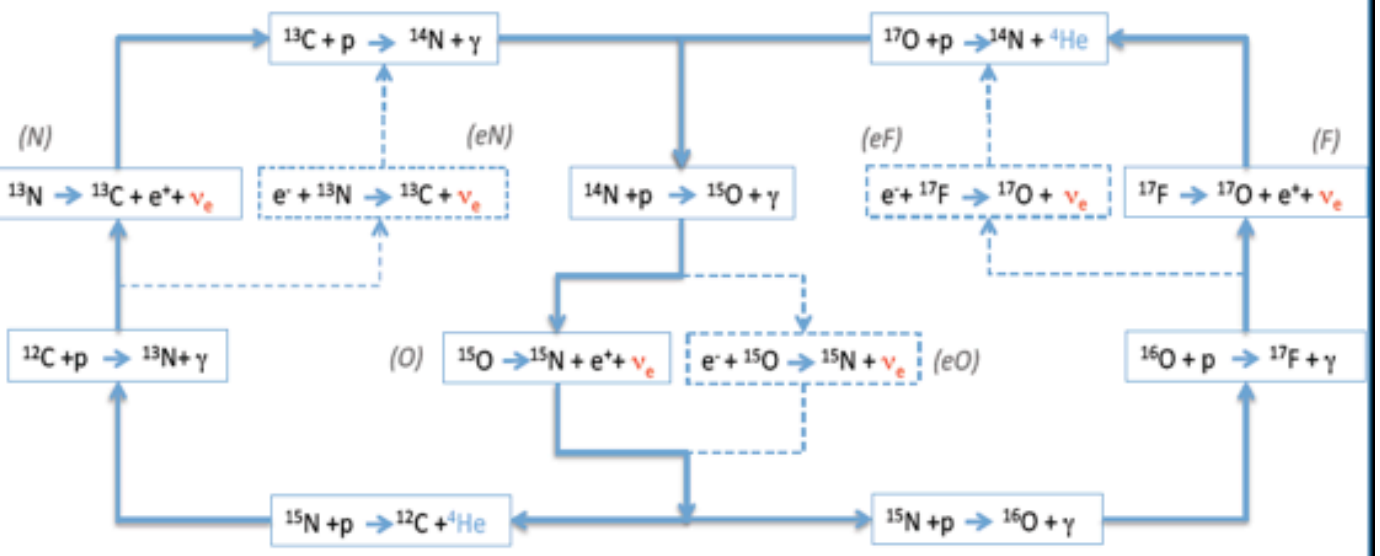
$^7Li + p \rightarrow 2\,{}^4He$

PPIII

$^7Be + p \rightarrow {}^8B + \gamma$

$^8B \rightarrow 2\,{}^4He + e^+ + \nu_e$ (B)

The CN-NO (bi-)cycle



$^{13}C + p \rightarrow {}^{14}N + \gamma$

$^{17}O + p \rightarrow {}^{14}N + {}^4He$

(N) $^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$

(eN) $e^- + {}^{13}N \rightarrow {}^{13}C + \nu_e$

$^{14}N + p \rightarrow {}^{15}O + \gamma$

(eF) $e^- + {}^{17}F \rightarrow {}^{17}O + \nu_e$

(F) $^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$

$^{12}C + p \rightarrow {}^{13}N + \gamma$

(O) $^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$

$e^- + {}^{15}O \rightarrow {}^{15}N + \nu_e$ (eO)

$^{16}O + p \rightarrow {}^{17}F + \gamma$

$^{15}N + p \rightarrow {}^{12}C + {}^4He$

$^{15}N + p \rightarrow {}^{16}O + \gamma$

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

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

Metalicity problem

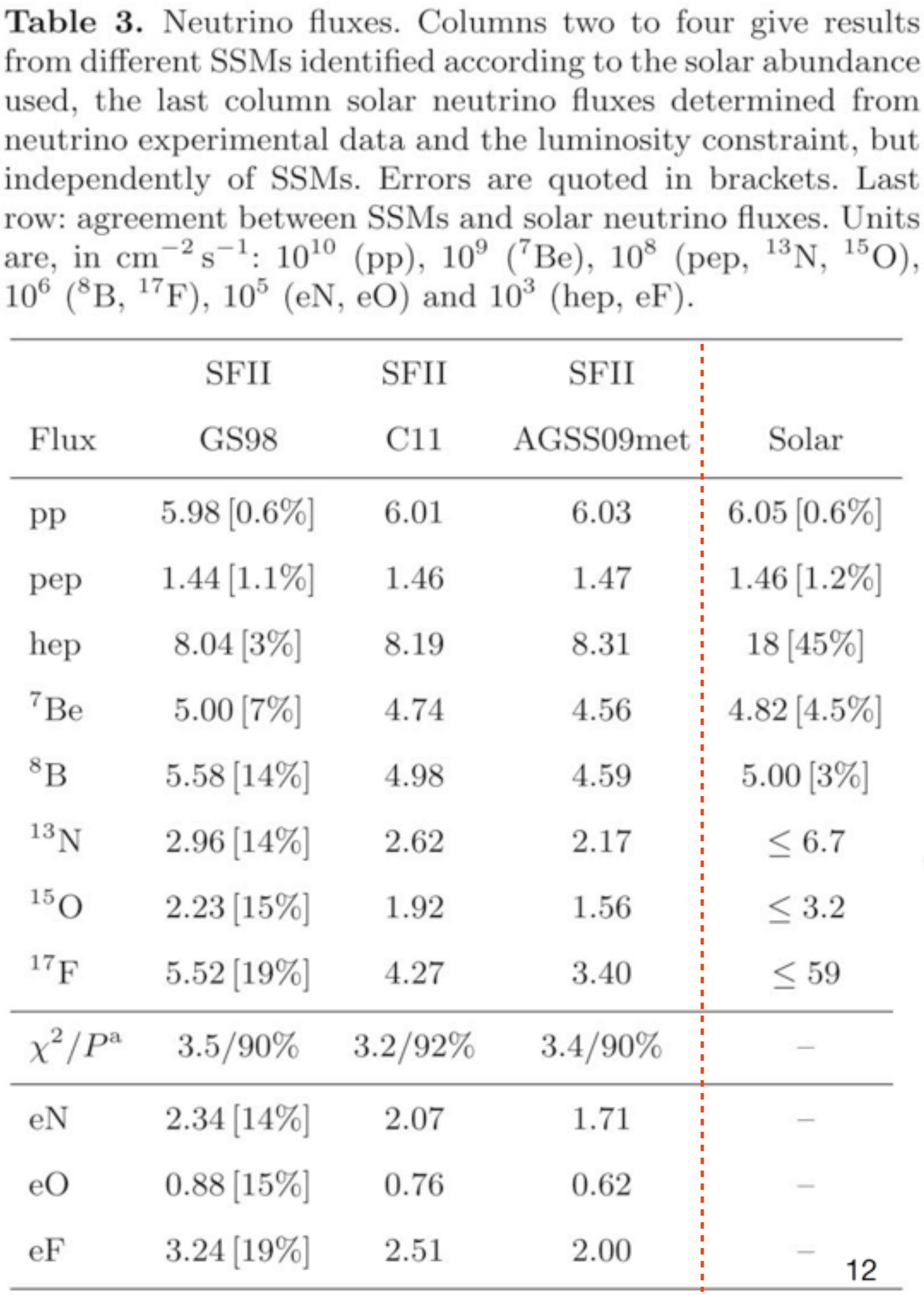
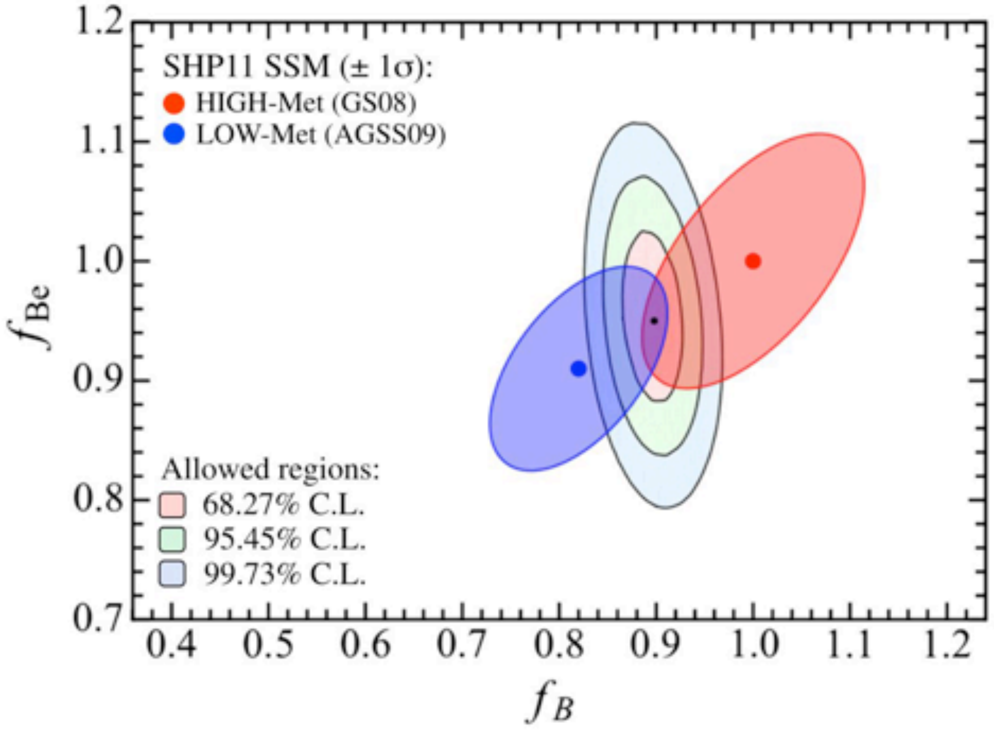


Table 3. Neutrino fluxes. Columns two to four give results from different SSMs identified according to the solar abundance used, the last column solar neutrino fluxes determined from neutrino experimental data and the luminosity constraint, but independently of SSMs. Errors are quoted in brackets. Last row: agreement between SSMs and solar neutrino fluxes. Units are, in $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$: 10^{10} (pp), 10^{9} (^{7}Be), 10^{8} (pep, ^{13}N, ^{15}O), 10^{6} (^{8}B, ^{17}F), 10^{5} (eN, eO) and 10^{3} (hep, eF).

	SFII	SFII	SFII	
Flux	GS98	C11	AGSS09met	Solar
pp	5.98 [0.6%]	6.01	6.03	6.05 [0.6%]
pep	1.44 [1.1%]	1.46	1.47	1.46 [1.2%]
hep	8.04 [3%]	8.19	8.31	18 [45%]
^{7}Be	5.00 [7%]	4.74	4.56	4.82 [4.5%]
^{8}B	5.58 [14%]	4.98	4.59	5.00 [3%]
^{13}N	2.96 [14%]	2.62	2.17	≤ 6.7
^{15}O	2.23 [15%]	1.92	1.56	≤ 3.2
^{17}F	5.52 [19%]	4.27	3.40	≤ 59
χ^2/P^{a}	3.5/90%	3.2/92%	3.4/90%	–
eN	2.34 [14%]	2.07	1.71	–
eO	0.88 [15%]	0.76	0.62	–
eF	3.24 [19%]	2.51	2.00	–

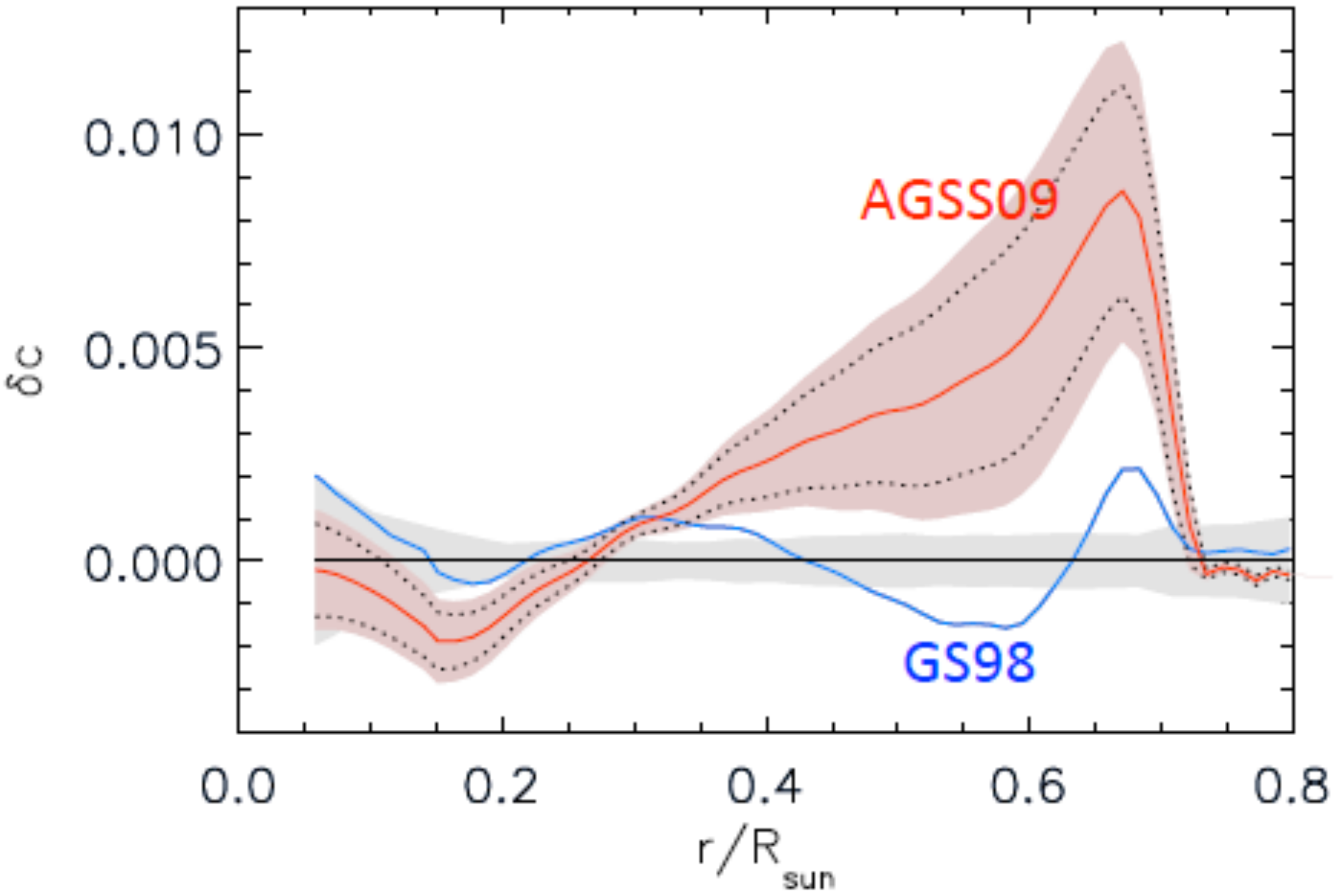


- Spectroscopic observations of the external layers of the sun prefer lower Z, especially C, N, O
- but neutrino fluxes are not conclusively in agreement
- plus....

SSM and Helioseismology

N.Vinyoles et al., 2016 – arXiv:1611.09867v1

$c_{\rm obs}$ = dati di elio-sismologia (propagazione onde all'interno del nucleo solare) + opacita' (dati di scattering dei fotoni)



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

Fractional sound speed difference

High-Z models are clearly preferred by helioseismology.

	GS98	AGSS09	Obs
$<\delta c/c>$	$0.0005^{+0.0006}_{-0.0002}$	0.0021 ± 0.001	-
$R_{\rm cz}/R_\odot$	0.7117 ± 0.0048	0.7224 ± 0.0053	0.713 ± 0.001
$Y_{\rm S}$	0.2426 ± 0.0059	0.2316 ± 0.0059	0.2485 ± 0.0035
$Z_{\rm S}$	0.0170 ± 0.0012	0.0134 ± 0.0008	-
$Y_{\rm C}$	0.6320 ± 0.0053	0.6209 ± 0.0062	-
$Z_{\rm C}$	0.0200 ± 0.0014	0.0159 ± 0.0010	-

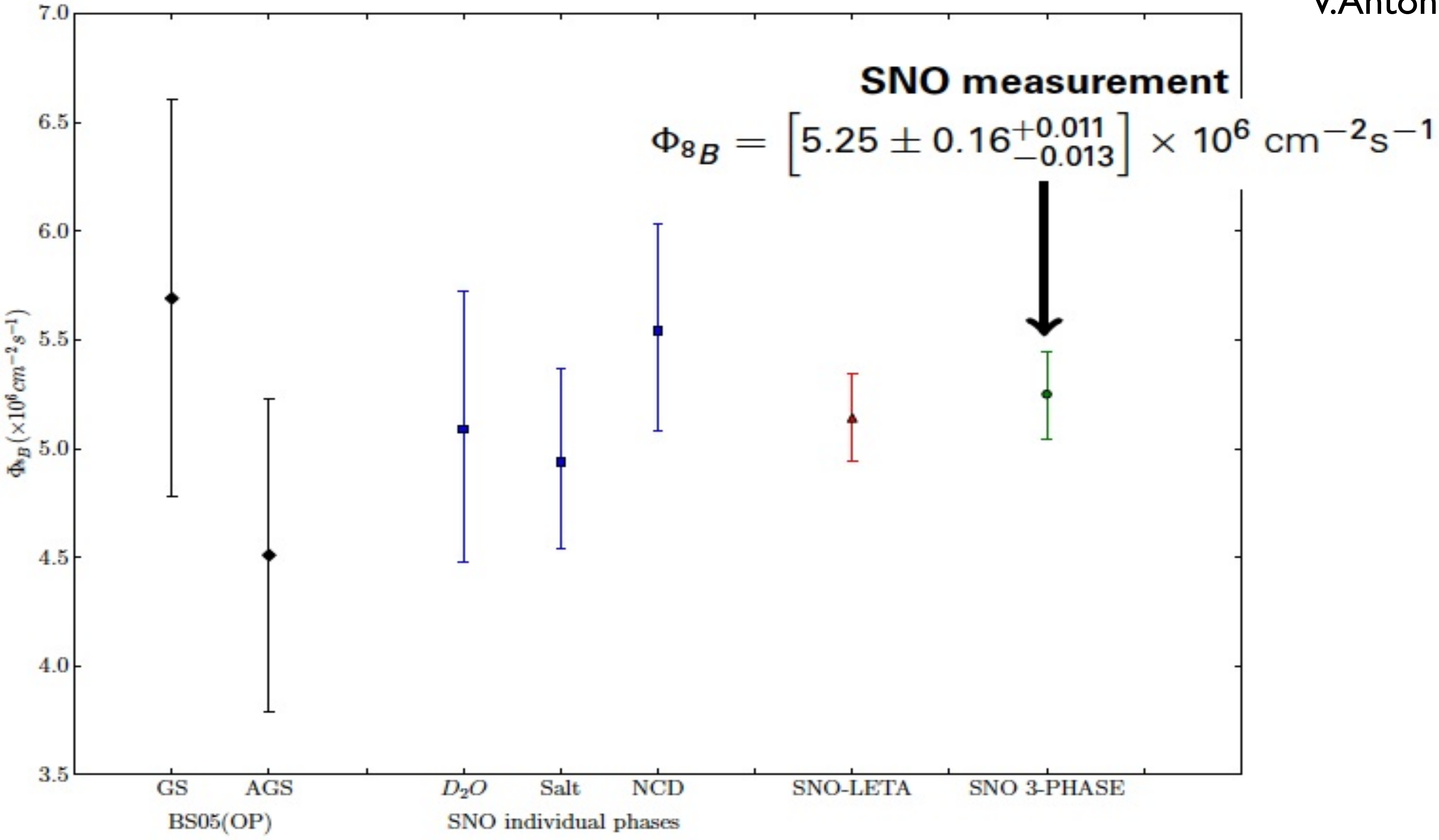
Two helioseismic quantities widely used in assessing the quality of SSMs are the surface helium abundance Y_S and the location of the bottom of the convective envelope R_{CZ} .

High Z (more heavy elements than H)

Low Z (less heavy elements than H)

Progresses in ^{8}B flux experimental determination and comparison with solar models

V.Antonelli



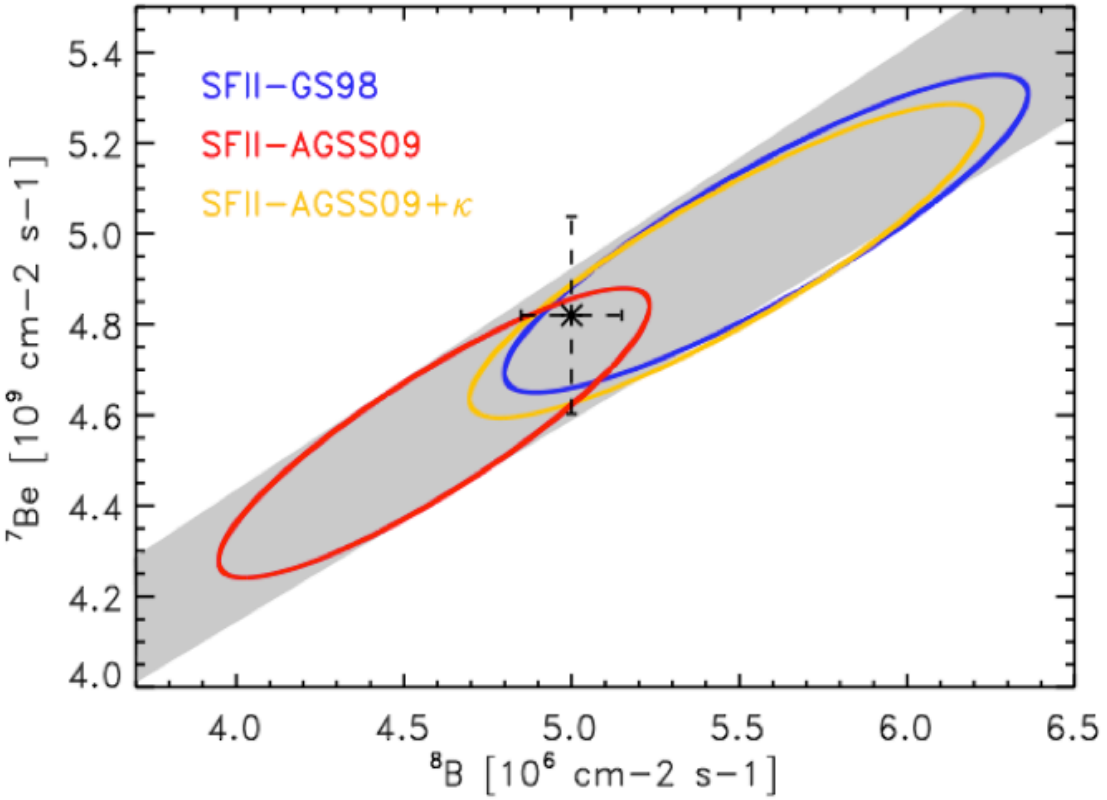
SNO measurement

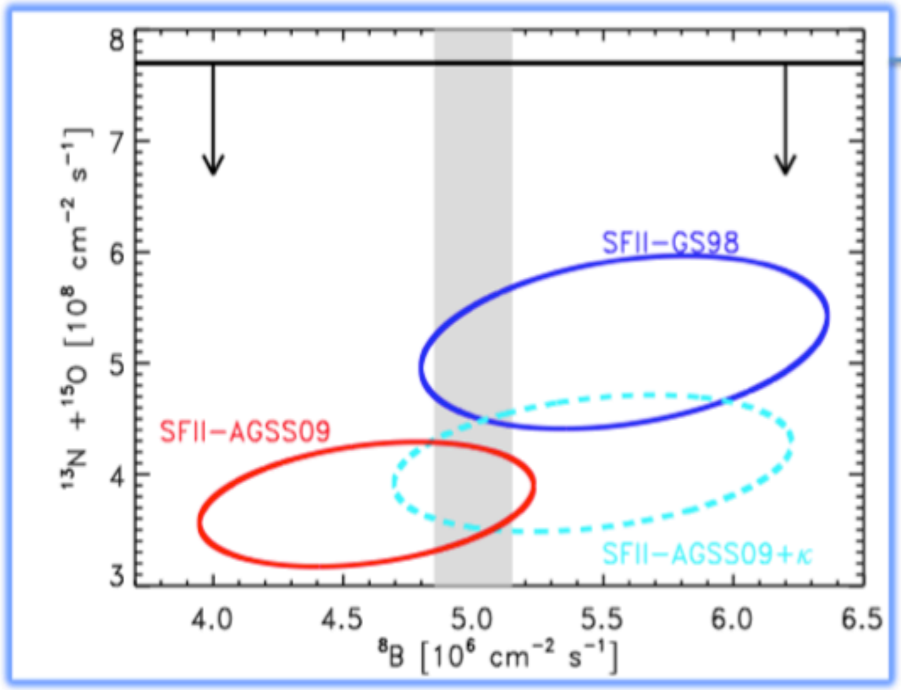
$$\Phi_{^8B} = \left[5.25 \pm 0.16^{+0.011}_{-0.013}\right] \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

^{8}B ν flux: ϕ=5.25±0.16(stat.)±0.12(syst.)×10^6 cm^{-2} s^{-1} , **consistent both with SSMs high-Z** (BPS09 (GS98) ϕ=5.58±0.78×10^6 cm^{-2} s^{-1}) **and low-Z** (BPS09 (AGSS09) (ϕ=4.59±0.64×10^6 cm^{-2} s^{-1}))

The solar metallicity problem

Theoretical predictions, in different SSM versions (high Z, low Z and low Z with increased opacity), and experimental results for the ^{7}Be and ^{8}B ν and the main components of CNO cycle.
Taken from A. M. Serenelli, “A special Borexino event - Borexino Mini-Workshop”, Sept. 5 2014



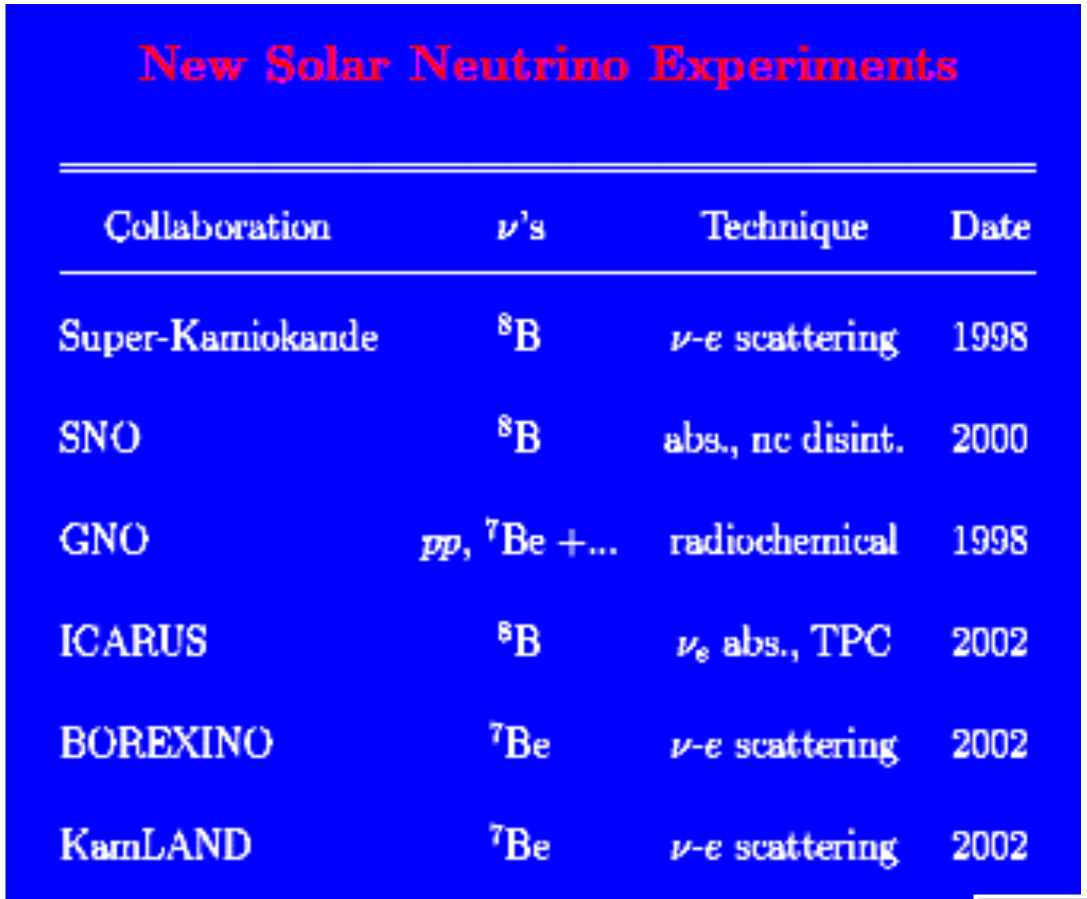


Upper limit by Borexino

V.Antonelli

- Need to **measure CNO neutrinos**, but difficult to extract the very low signal from background, mainly due to ^{210}Bi and ^{11}C.
- Due to the ambiguity metallicity-opacity, important to **complement** also **with the accurate determination of ^{7}Be and/or ^{8}B flux.**
- Difficulty of the measurements and possibilities for present and future experiments (Borexino, SNO+, others).

Unfortunately reducing the SSM uncertainties is hard (astronomical/hydrodinamical constraints not well controlled)



New Solar Neutrino Experiments

Collaboration	ν's	Technique	Date
Super-Kamiokande	^{8}B	ν-e scattering	1998
SNO	^{8}B	abs., nc disint.	2000
GNO	pp, ^{7}Be +...	radiochemical	1998
ICARUS	^{8}B	ν_e abs., TPC	2002
BOREXINO	^{7}Be	ν-e scattering	2002
KamLAND	^{7}Be	ν-e scattering	2002

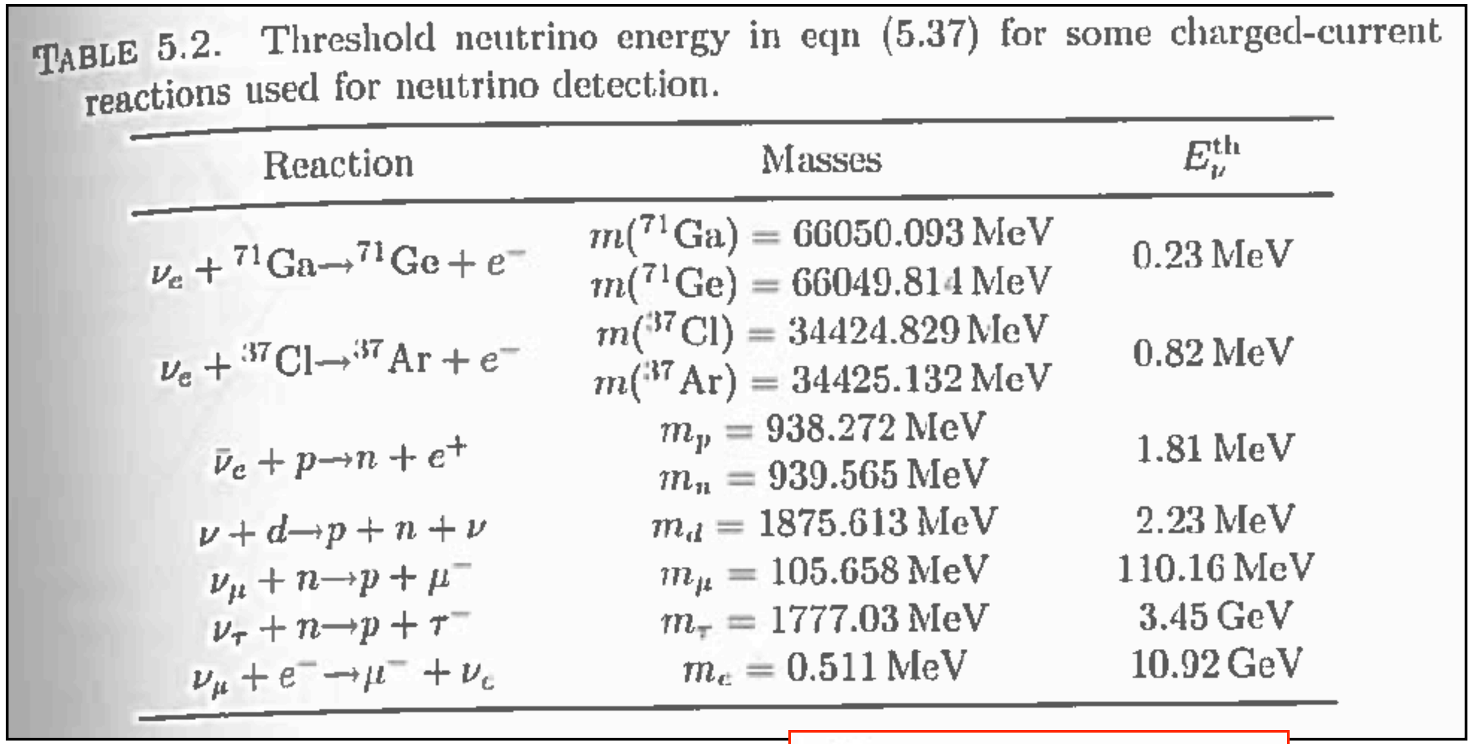
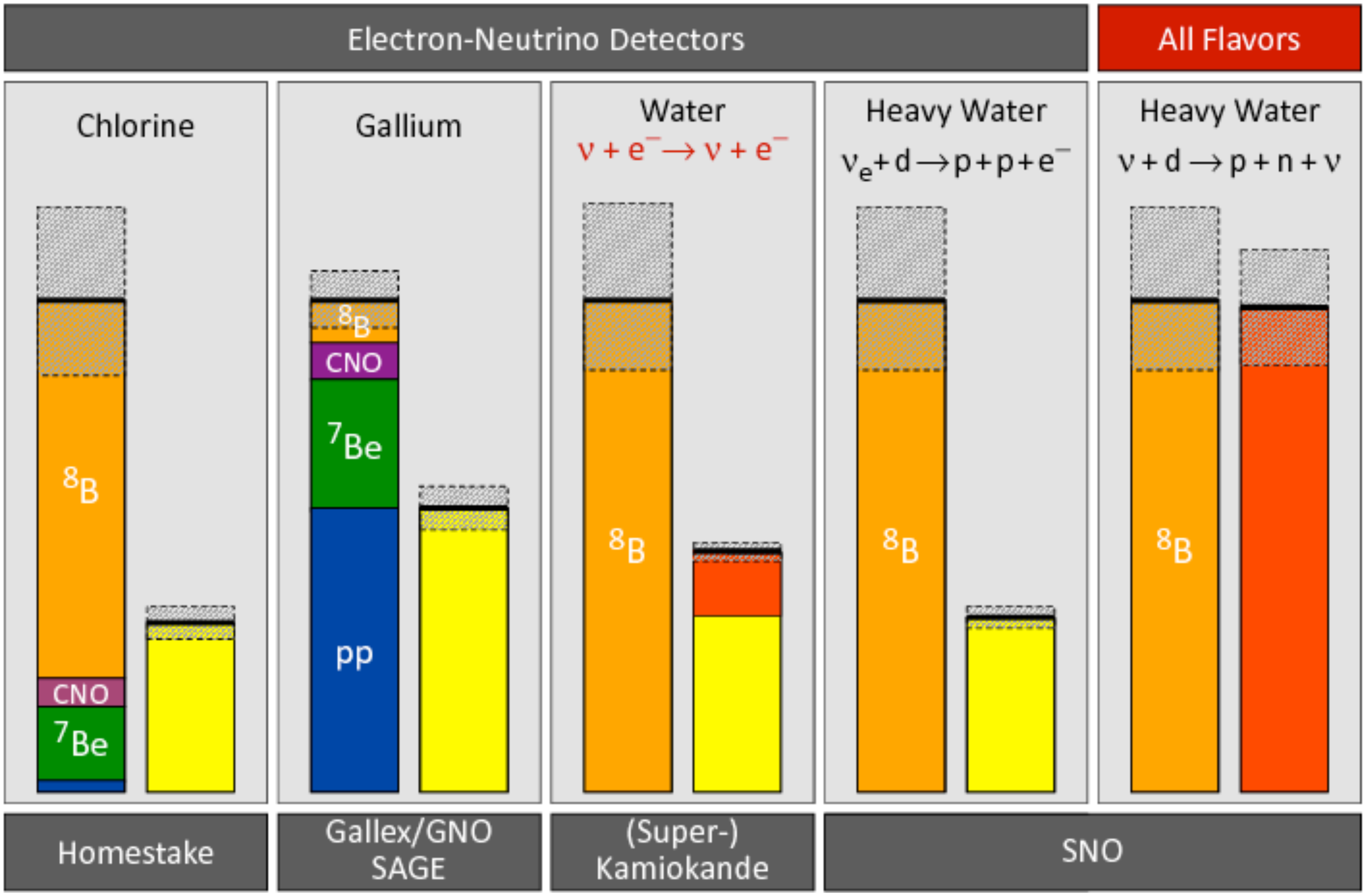


TABLE 5.2. Threshold neutrino energy in eqn (5.37) for some charged-current reactions used for neutrino detection.

Reaction	Masses	$E_\nu^{\rm th}$
$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$	$m({}^{71}\mathrm{Ga}) = 66050.093$ MeV $m({}^{71}\mathrm{Ge}) = 66049.814$ MeV	0.23 MeV
$\nu_e + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + e^-$	$m({}^{37}\mathrm{Cl}) = 34424.829$ MeV $m({}^{37}\mathrm{Ar}) = 34425.132$ MeV	0.82 MeV
$\bar{\nu}_e + p \to n + e^+$	$m_p = 938.272$ MeV $m_n = 939.565$ MeV	1.81 MeV
$\nu + d \to p + n + \nu$	$m_d = 1875.613$ MeV	2.23 MeV
$\nu_\mu + n \to p + \mu^-$	$m_\mu = 105.658$ MeV	110.16 MeV
$\nu_\tau + n \to p + \tau^-$	$m_\tau = 1777.03$ MeV	3.45 GeV
$\nu_\mu + e^- \to \mu^- + \nu_e$	$m_e = 0.511$ MeV	10.92 GeV

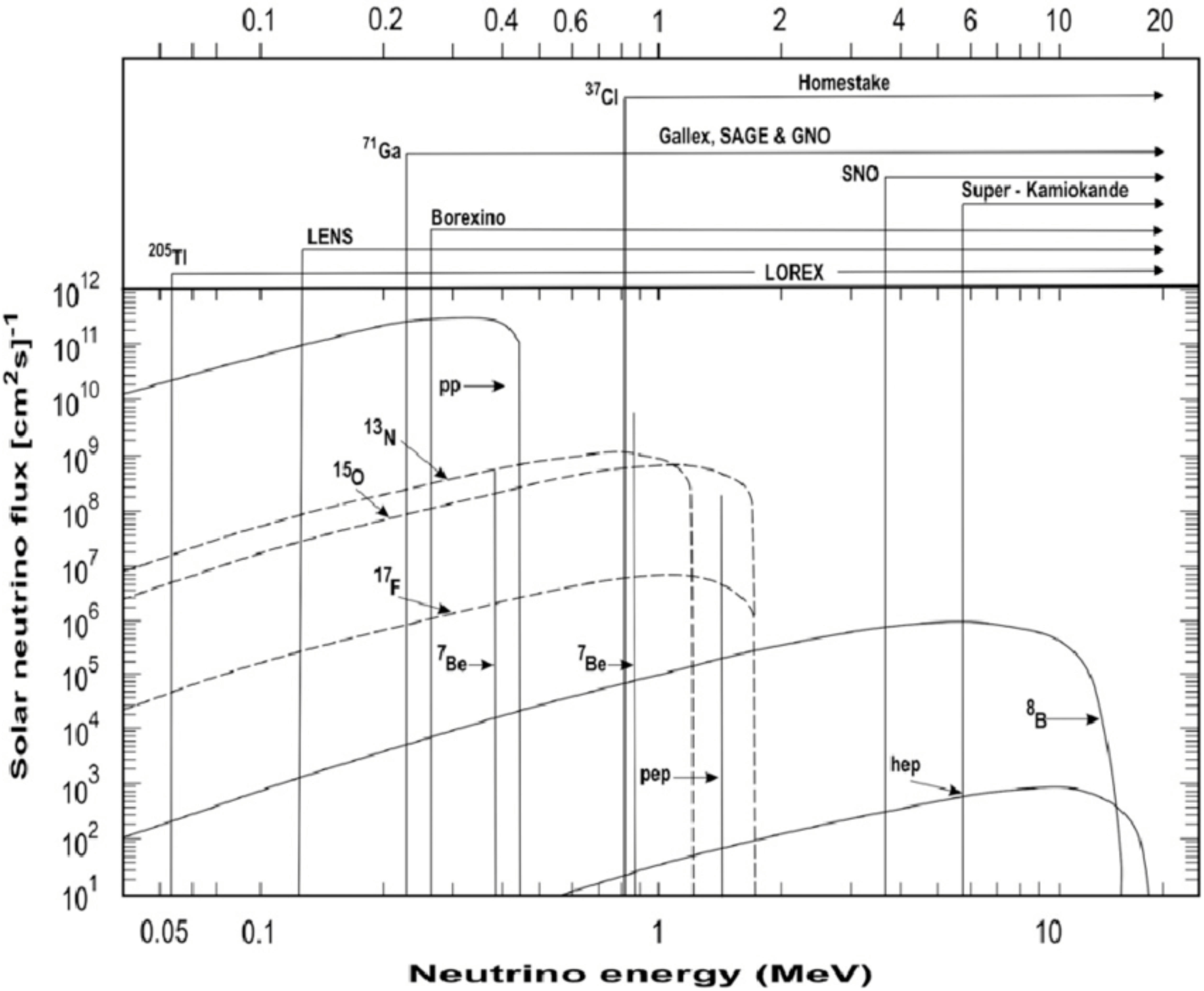
$$\nu + A \to \sum_X X \,.$$

$$E_\nu^{\rm th} = \frac{(\sum_X m_X)^2}{2m_A} - \frac{m_A}{2} \,.$$



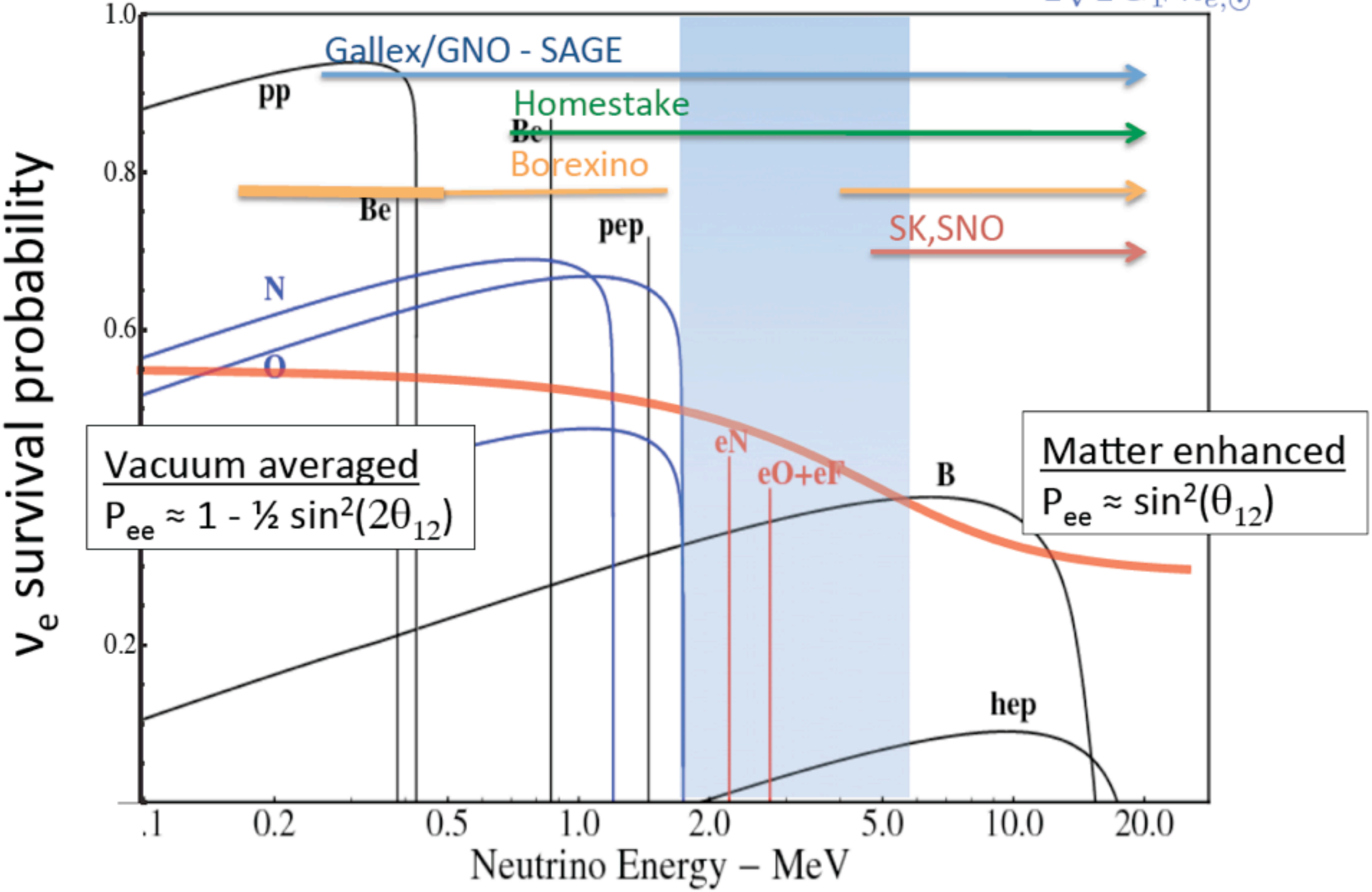
- radio-chemical: counting only, low threshold, but no directional
- water: directional (Cherenkov), cheap, but high threshold because of bkgs
- LS ES: purified, expensive, no directional

Solar Neutrino Spectrum



The solar neutrino survival probability

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



Vacuum averaged

$P_{ee} \approx 1 - \frac{1}{2}\sin^2(2\theta_{12})$

Matter enhanced

$P_{ee} \approx \sin^2(\theta_{12})$

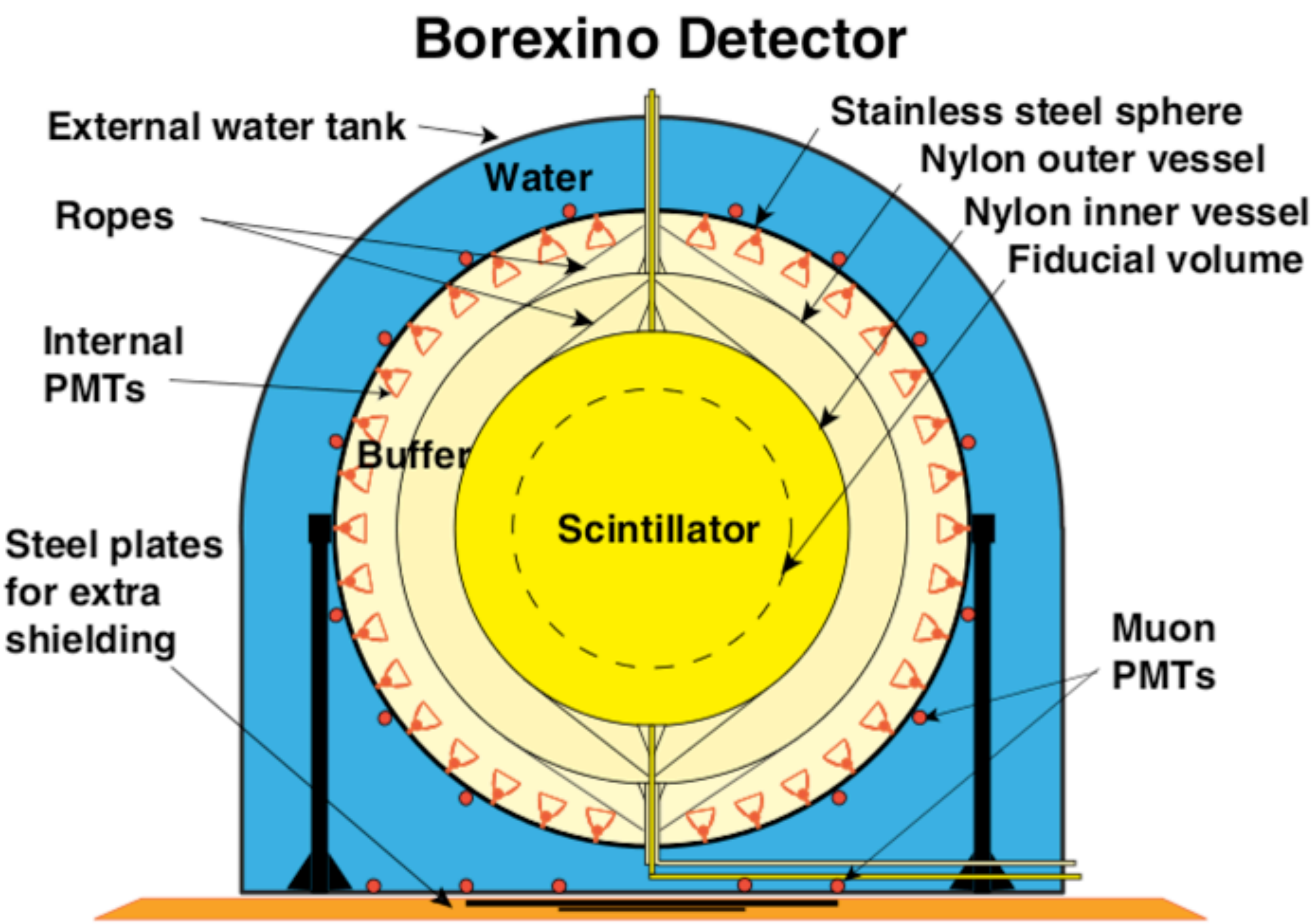
A (but-not-the-most-recent...) Borexino measurement

LS ES: purified, expensive, no directional

G. Bellini *et al.* (Borexino Collaboration)

Phys. Rev. D 89, 112007 – Published 25 June 2014

The experiment set-up



13.7 m stainless sphere
~ 1000 tons of pseudocumene (PC+PPO)
~300 tons Inner Vessel

More than 2000 Photomultiplier tubes (PMTs)

34% Coverage

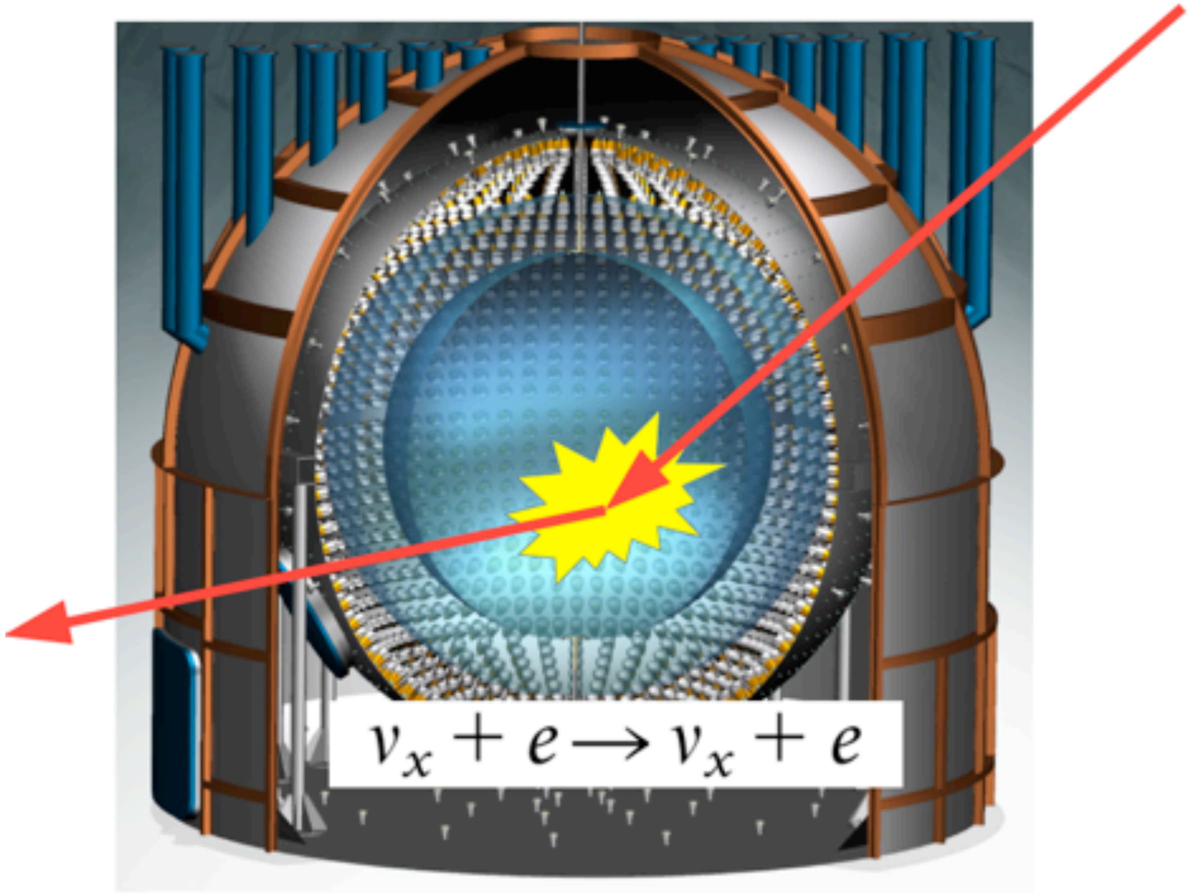
Light Yield = 500 PE/MeV

Cherenkov muon veto (~200 PMTs)

Very (very) low background:

- Nitrogen stripping
- Distillation
- Water Extraction

The Borexino Signal



$$\nu_x + e \rightarrow \nu_x + e$$

The Borexino PMTs detect the scintillation light produced by electrons scattered by neutrinos

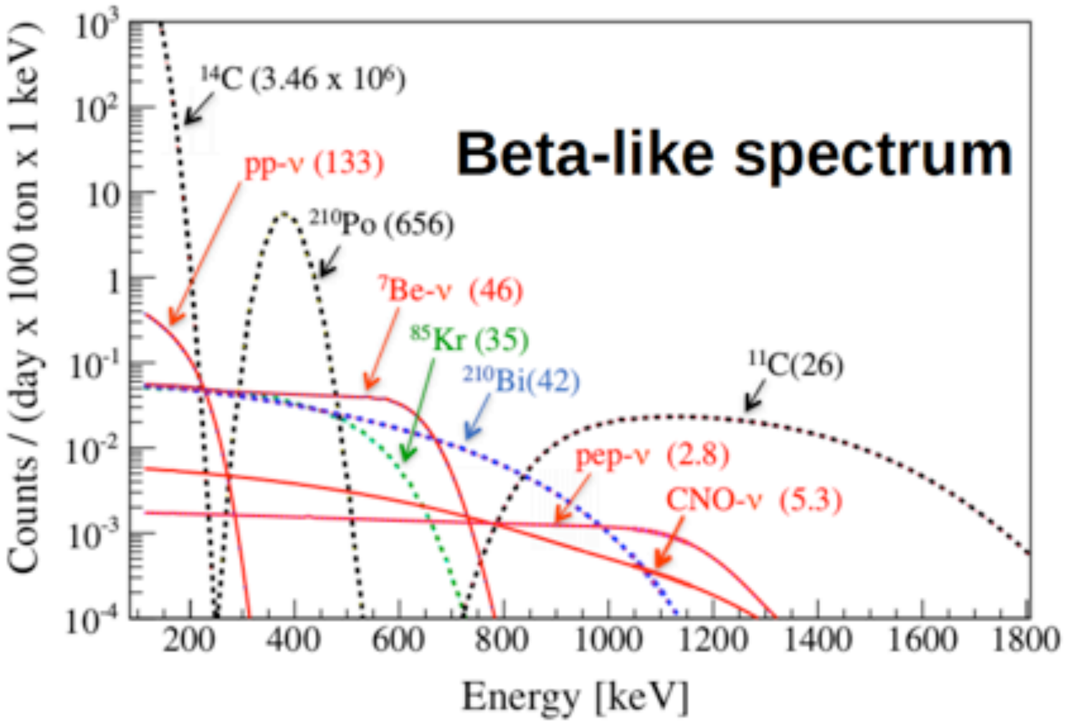
This signal is indistinguishable from the natural radioactivity (β- and γ components)

For α and β+ we can apply the pulse shape discrimination

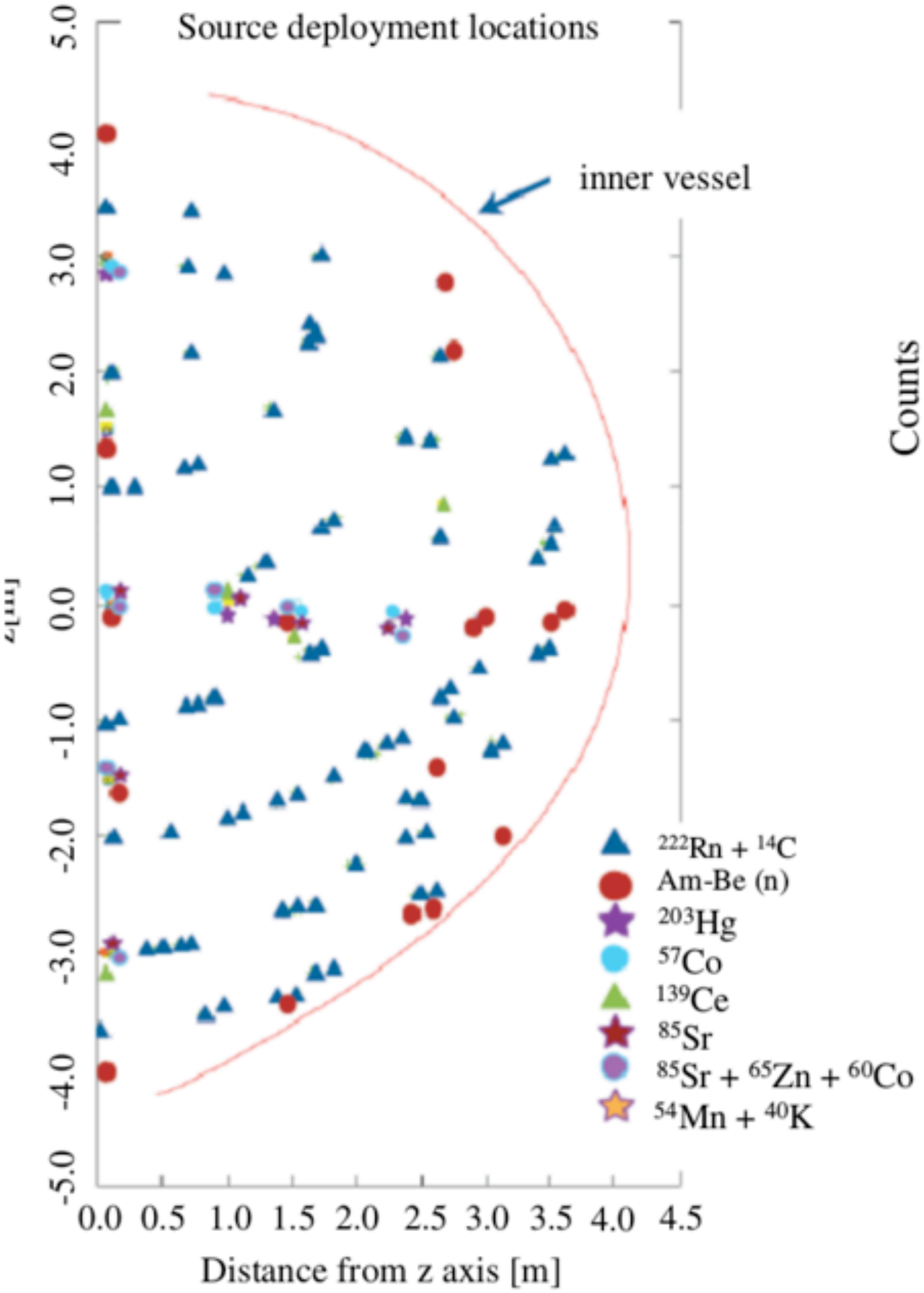
Crucial point:
Extreme low background required!!!

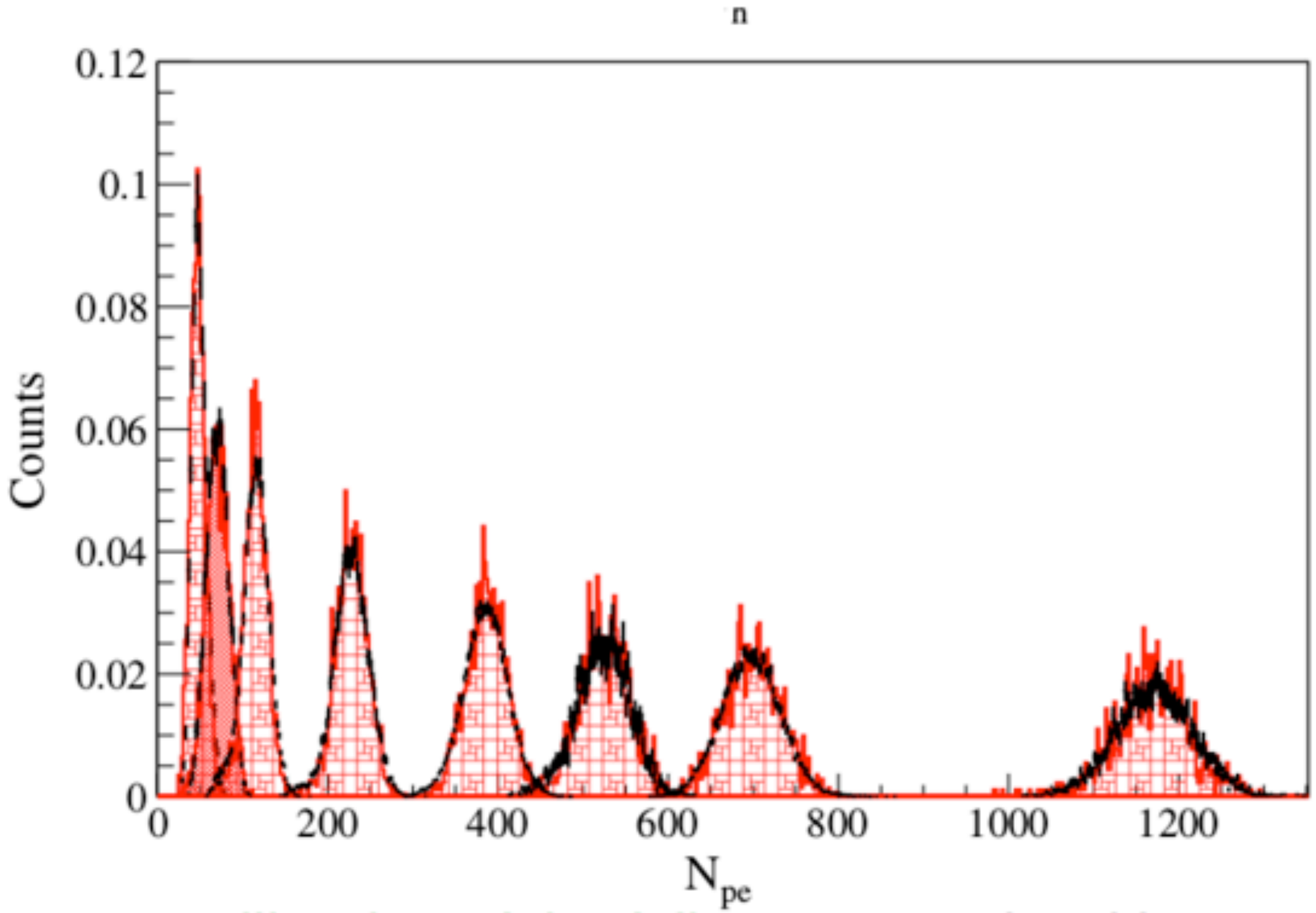
Isotope	Decay Rate [cpd/100 ton]
^{14}C	$(3.46 \pm 0.09) \times 10^6$
^{85}Kr	$(30.4 \pm 5.3 \pm 1.5)^{(a)}$
	$(31.2 \pm 1.7 \pm 4.7)^{(b)}$
^{40}K	< 0.42 (95% C.L.)
^{39}Ar	~ 0.4
^{238}U	(0.57 ± 0.05)
^{222}Rn	(1.72 ± 0.06)
^{210}Bi	$(41.0 \pm 1.5 \pm 2.3)$
^{210}Po	5×10^2–8×10^3
^{232}Th	(0.13 ± 0.03)

Contaminants: Phase-I



Calibration Campaign





Calibration of the full energy scale with different standard sources deployed inside the detector with mechanical arms

Calibration of the position. Position is important for defining the fiducial volume and full reconstruction of the event

Energy resolution: ~5%√E [MeV]

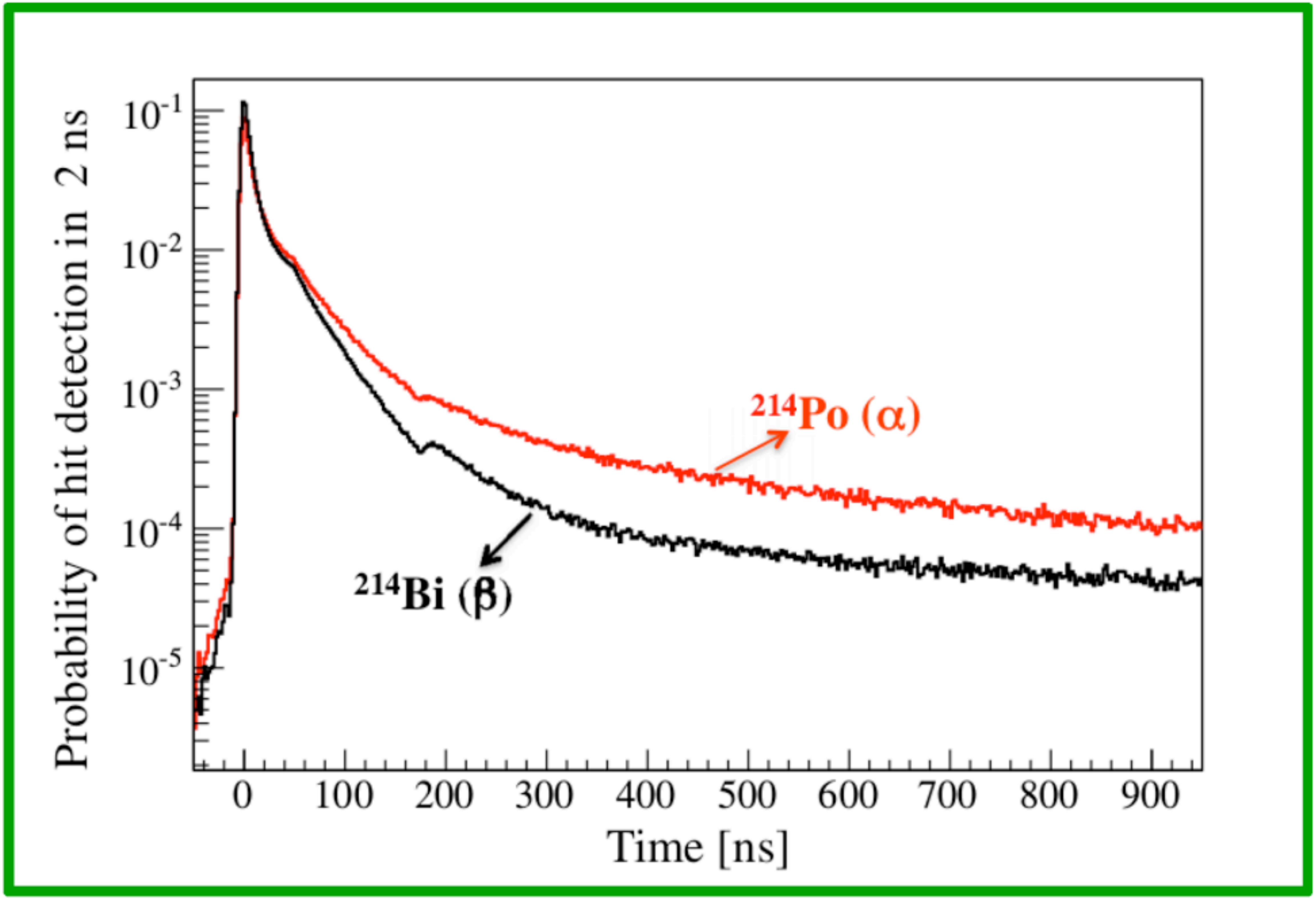
Background levels

Required values of the main backgrounds in Borexino exp., assumed as reference case.

Radio isotope	Source	Typical level	Required level
^{14}C (β) (would be essential for pp ν)	Intrinsic in LAB. E < 156 keV -> fixes the low E threshold	≈ 10^{-12} g/g	< 10^{-17} g/g
^{238}U ^{232}Th	Dust, metallic . Attention to **^{210}Bi (β) from ^{210}Pb out of equilibrium**. Requires spectral shape analysis.	10^{-5}-10^{-6} g/g	< 10^{-16} g/g
^{40}K (β, γ)	Dust, PPO in Liquid Scintillator.	2 x 10^{-6} g/g	< 10^{-17} g/g
^{210} Po (α) (strongly reduced with PSD)	Surface contamination from ^{222}Rn		< 7 cpd/t
^{222}Rn (α)	Materials, rock		< 10 cpd/100 t
^{85}Kr (β)	Air from nuclear weapon. **Spectral shape similar to** e$^-$ recoil spectrum from **^{7}Be** ν.	≈ 1 Bq/m^3	< 30 cpd/100 t
^{39}Ar (β)	Air, cosmogenic	17 mBq/m^3	< 1 cpd/100 t
^{7}Be	Cosmogenic	≈ $3\cdot10^{-2}$ Bq/t	<10^{-6} Bq/t

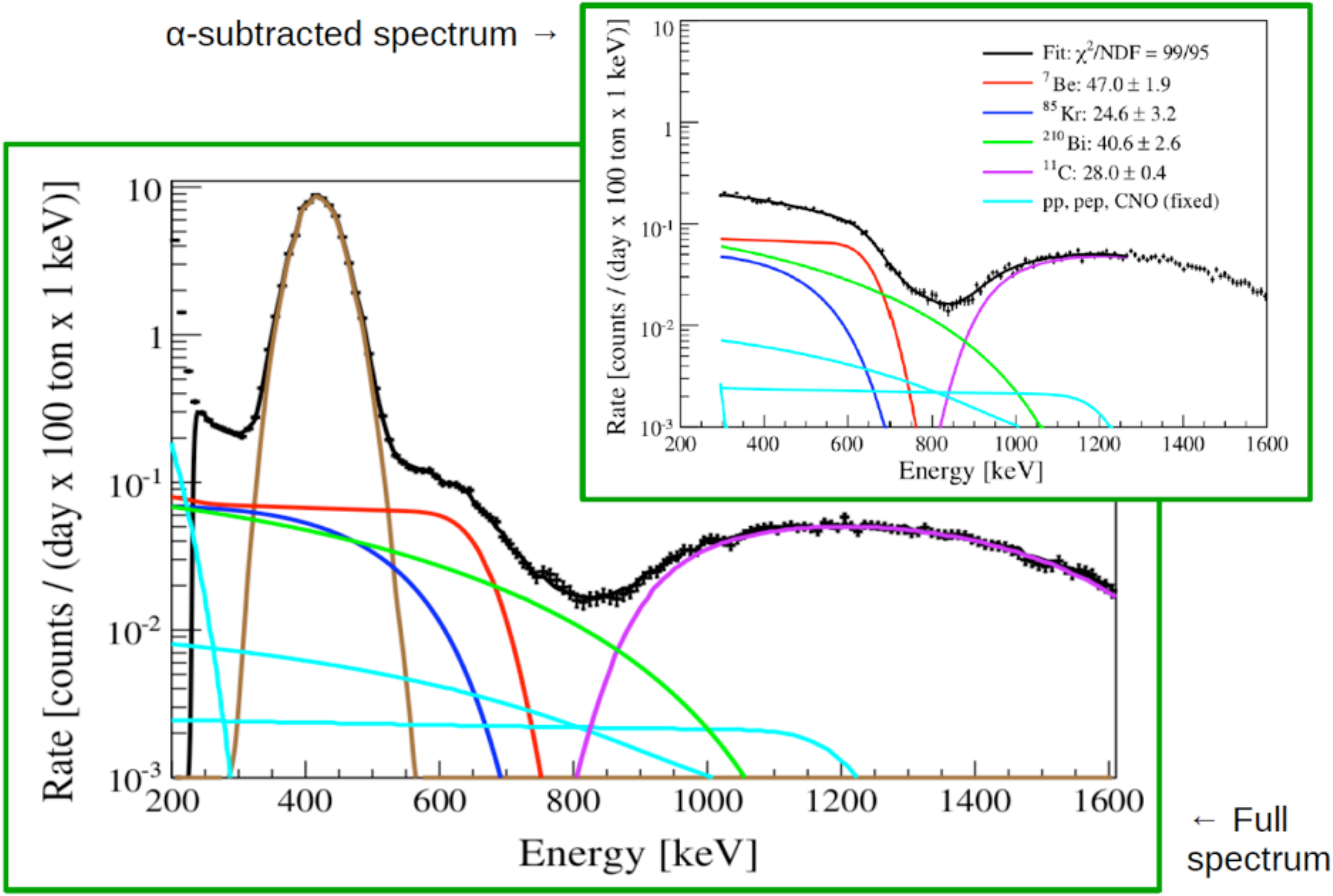
Pulse Shape Discrimination

Scintillation light in time



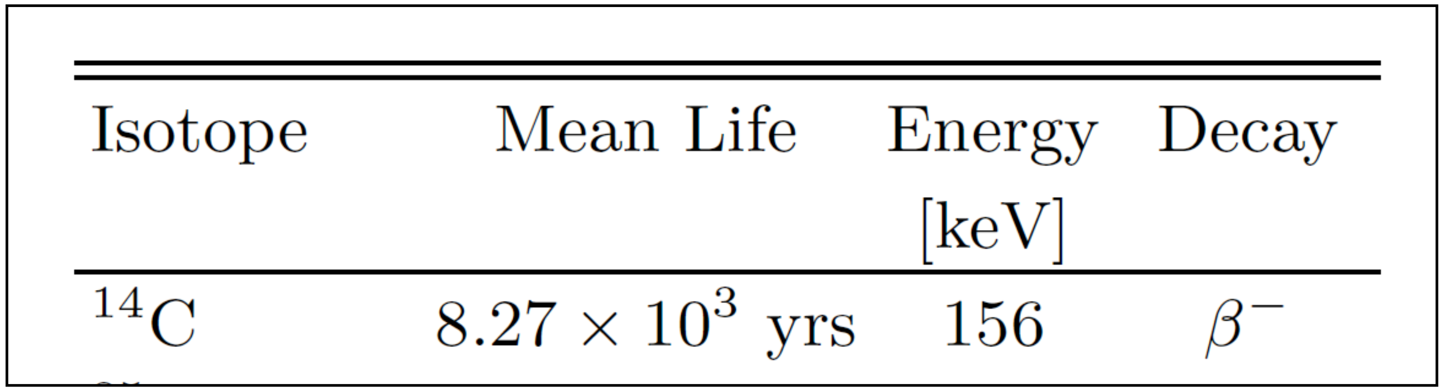
^{7}Be spectrum fit

α-subtracted spectrum →



← Full spectrum

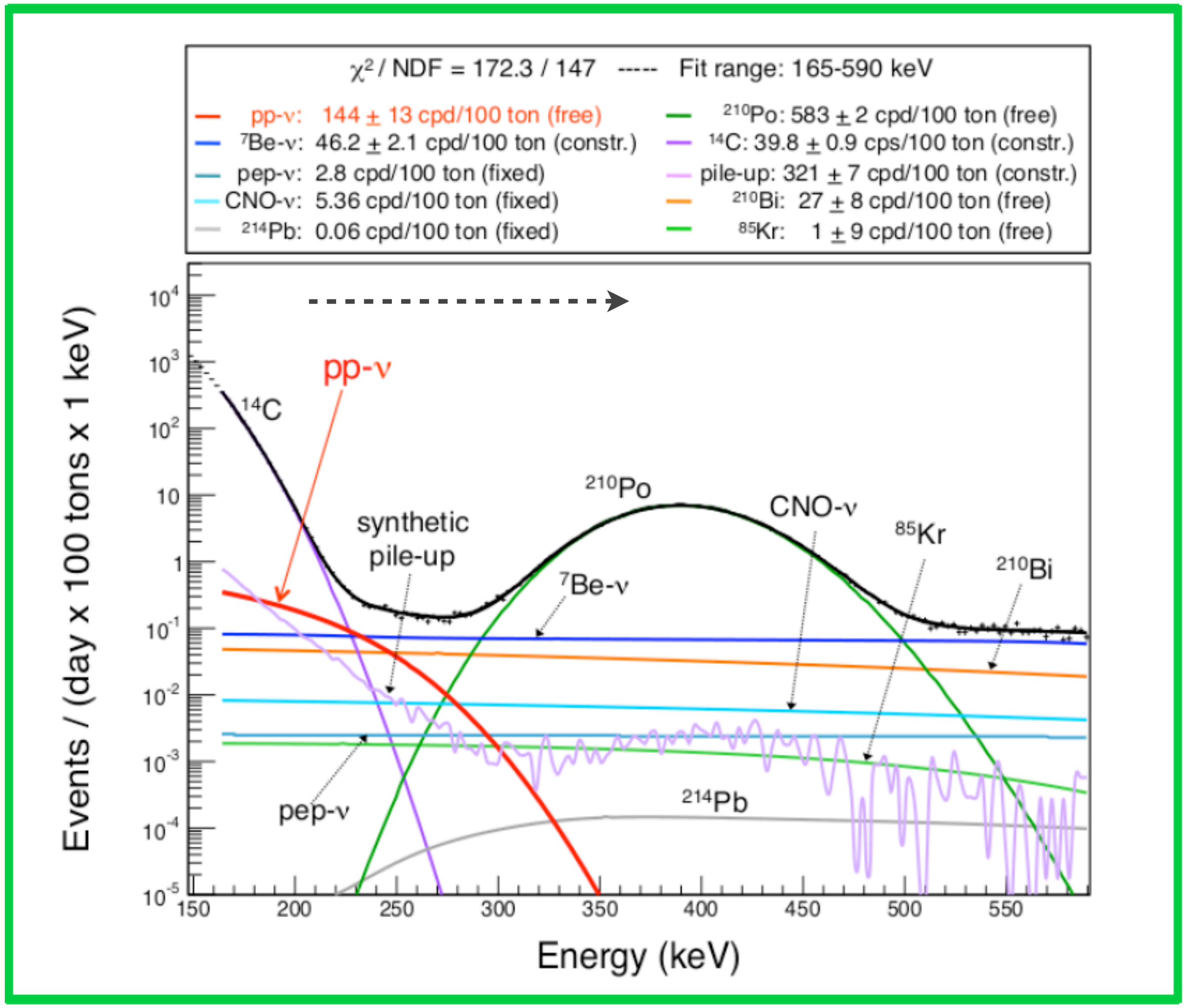
Some considerations on ^{14}C



Isotope	Mean Life	Energy [keV]	Decay
^{14}C	8.27×10^3 yrs	156	β^-

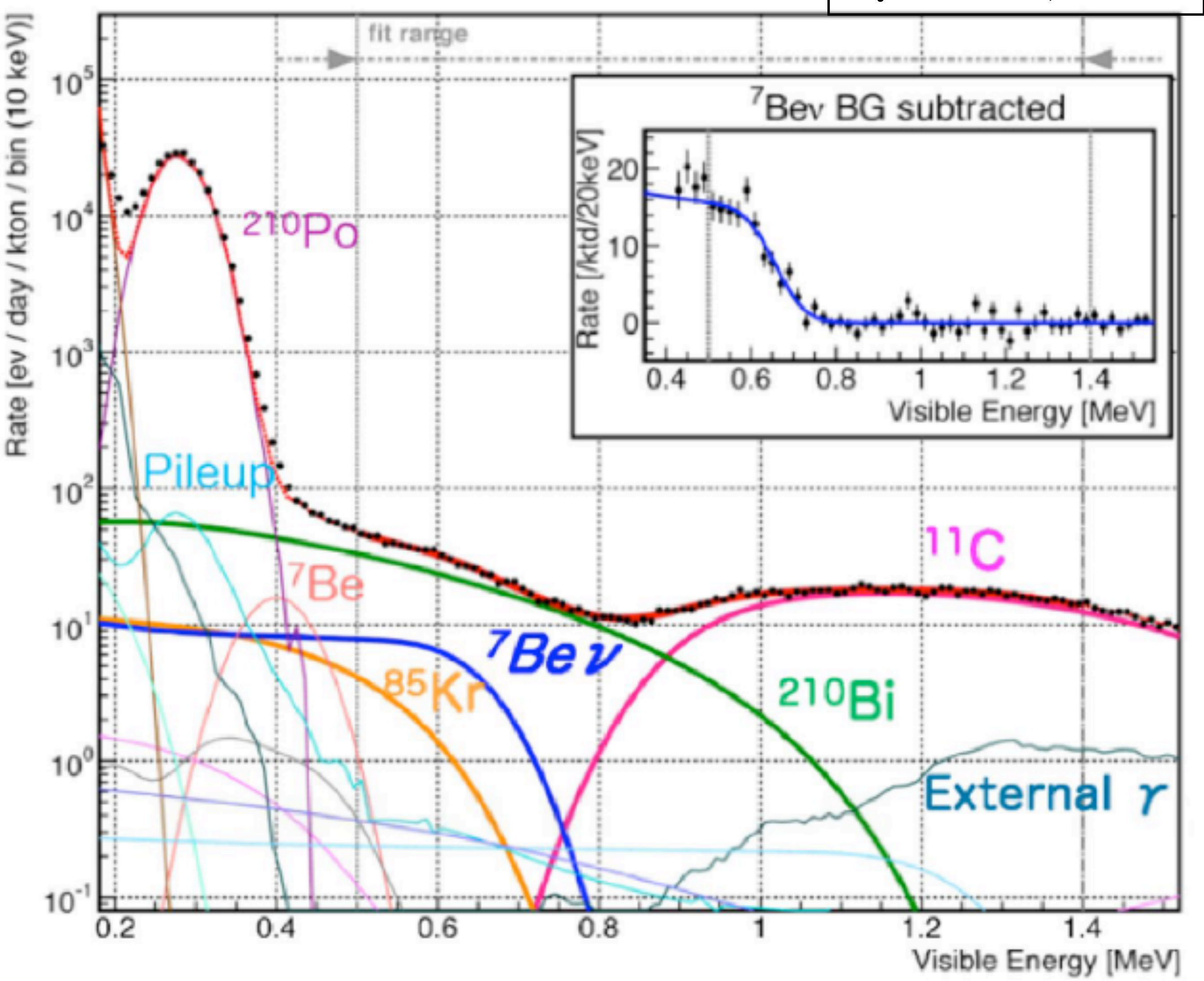
- ^{14}C is produced in atmospheric neutrons interactions with ^{14}N
- it ends up mixed with ^{12}C on the earth, which the pseudo-cumene (LS) is made of
  - can't be purified out (same chemical composition as ^{12}C)
  - but it has a very small abundance in Bx: $^{14}C / ^{12}C = 10^{-18}$ g/g
  - Therefore, one can fit most of ^{7}Be spectrum from 200 keV on without being flooded by ^{14}C electrons

Comparison with Kamland



KamLAND signal[KL2015]

Phys. Rev. C 92, 055808



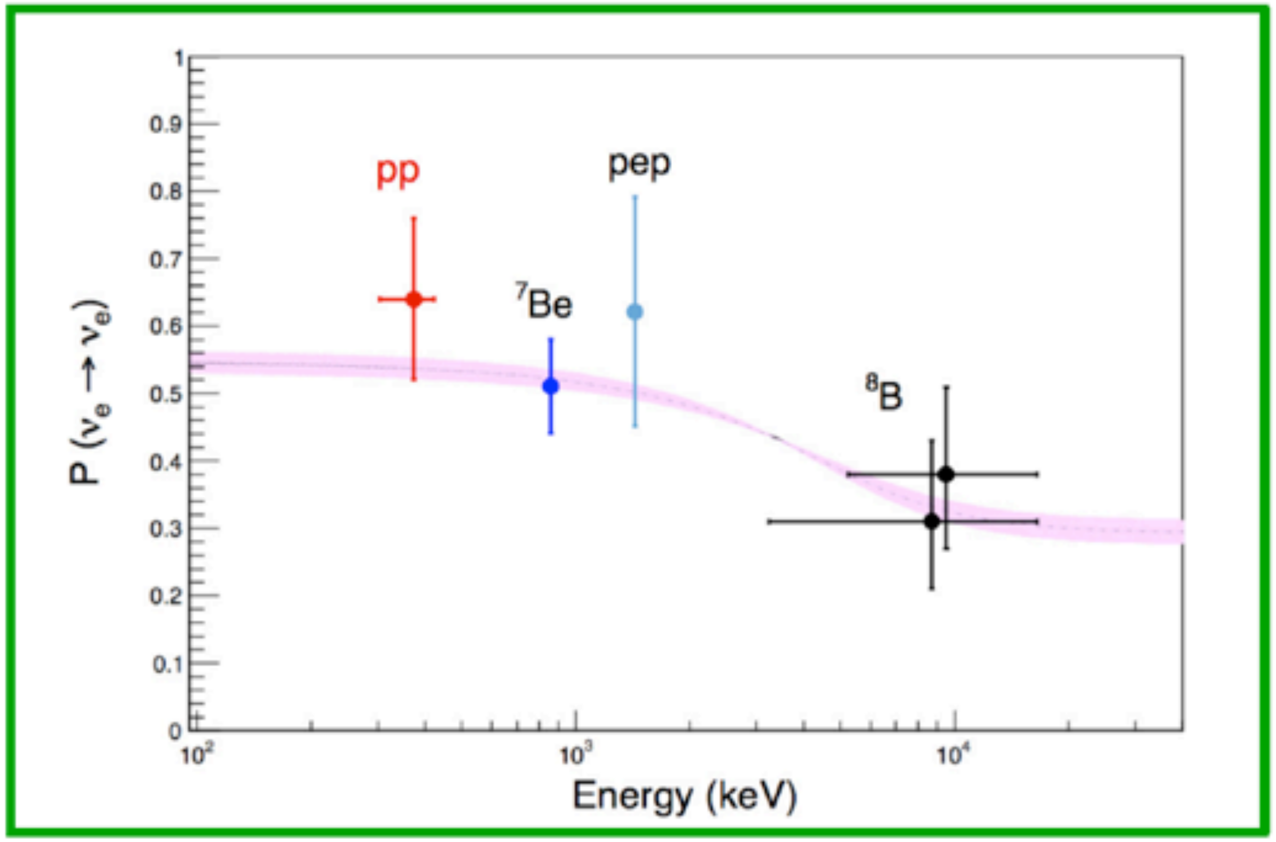
Low level of contamination from ^{14}C allow to gain ^{7}Be statistics in the fit

"Pile-up" of two ^{14}C decays in the same window releasing a high total energy is very suppressed

- was evaluated with special triggers

Solar Neutrino: Published Results

Species	Rate [cpd/100t]	Flux [$cm^{-2}s^{-1}$]
^{7}Be (863 keV)	$46.0 \pm 1.5\ ^{+1.5}_{-1.6}$	$3.1 \pm 0.15 \times 10^9$
pep	$3.1 \pm 0.6 \pm 0.3$	$1.6 \pm 0.6 \times 10^8$
CNO	< 7.9 (95% CL)	7.7×10^8
^{8}B(> 3 MeV)	$0.22 \pm 0.04 \pm 0.01$	$2.4 \pm 0.4 \pm 0.1 \times 10^6$
pp	$144 \pm 13 \pm 10$	$6.6 \pm 0.7 \times 10^{10}$



P_{ee} survival probability in the MSW-LMA scenario with Borexino data only!

G. Bellini *et al.* (Borexino Collaboration)

Phys. Rev. D 89, 112007 – Published 25 June 2014

Borexino Phase II

Major contaminants: comparison

cpd/100t	Phase I	Phase II
^{85}Kr	~30	< 5
^{210}Bi	~40	~20
^{210}Po	>2000	<60

6 cycles of Water Extraction (~1 year) reduced drastically the background contaminants

We have ~5 years of high quality data (Phase-II)!!

^{14}C/^{12}C ~ 2.7 x 10^{-18}

^{238}U (Bi-Po 214)
< 9.7 x 10^{-19} g/g (95% CL)

^{232}Th (Bi-Po 212)
< 1.2 x 10^{-18} g/g (95% CL)

^{40}K no evidence (TBD)

^{39}Ar << ^{85}Kr

1. Solars

- Improvement of the ^{7}Be accurancy (<5%) + annual modulation
- Improvement of the pep evidence (> 3σ)
- New update of the ^{8}B analysis
- Possible update of the pp measurement
- Improvement of CNO sensitivity
  - Thermal insulation (ongoing)
  - Further purification campaign

New Calibration Campaign!

~ Beginning of 2017

Back-up

The sub-MeV analysis: Borexino

- **SK, SNO and KL investigated only the high energy part of solar ν spectrum** (above 4-5 MeV). Up to few years ago the low energy part (main component) of the spectrum studied only by radiochemical exp.
- **Borexino: first real time exp.** exploring the **sub-MeV region** and isolating the monochromatic Berillium line.

•**Measurement of ^{7}Be line** (0.862 MeV) **and ^{8}B spectrum**

No oscill. hypothesis ruled out at 5 σ ;

good agreement with LMA: 48±4 counts/(day·100 tons)

- **2009 Calibration campaign:** reduce systematic uncertainties and tune reconstruction algorithm and MC simulations. Significant reduction of uncertainties on the E scale and fiducial volume: from a 6% for both factors to a global uncertainty of 2.7%.

^{7}Be Interaction Rate: 46.0 ± 1.5(stat)+1.5(-1.6) (syst) counts/(day·100 tons).

Cannot discriminate between high and low Z SSM.

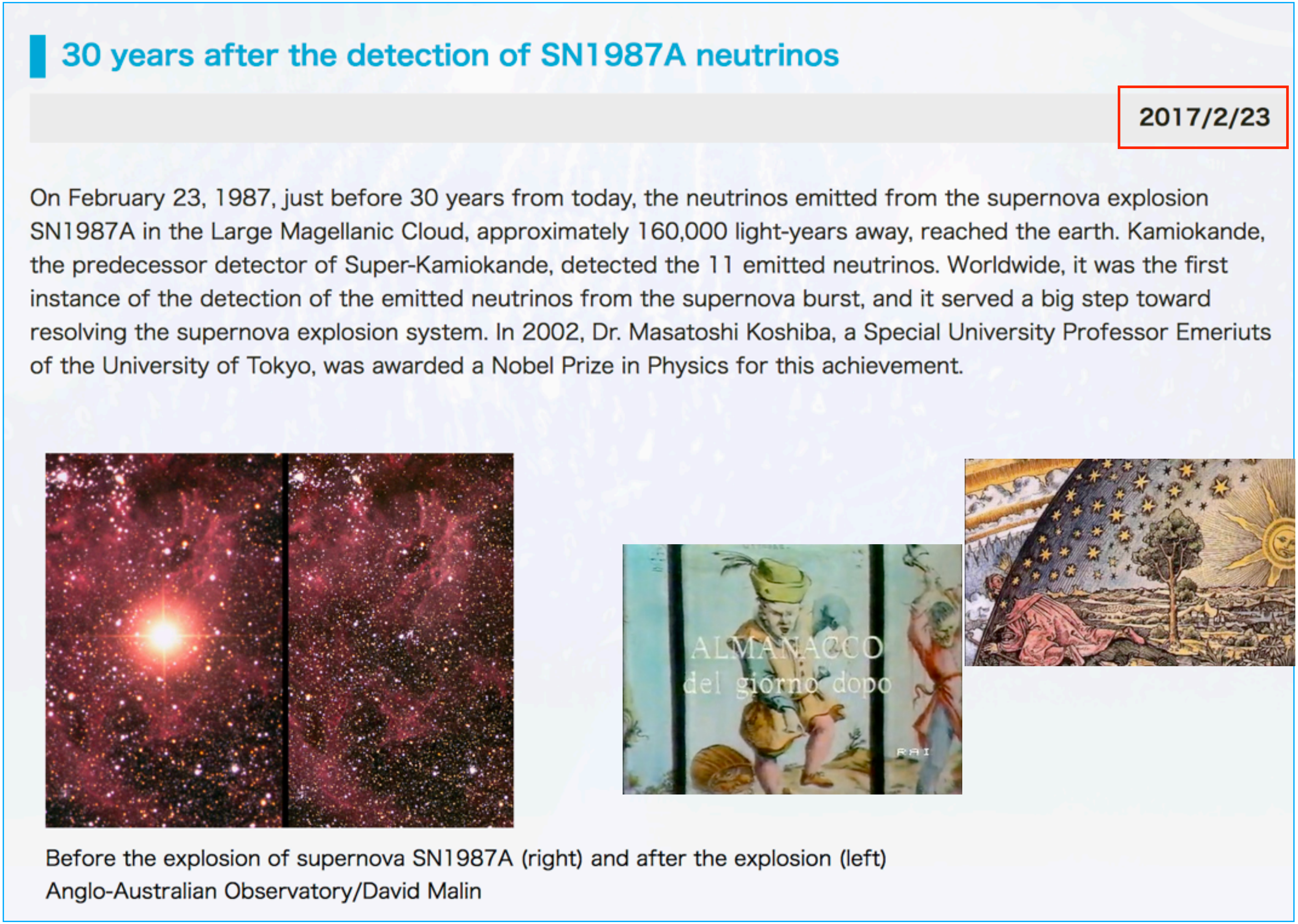
^{8}B , with low E_{thresh}. (T_e > 3 MeV): compatible but less stringent

Dependence on T_c

- By building different solar models, with varied inputs parameters (within their uncertainties) and by using a power law parametrization, one finds (approximately):

$\boxed{\Phi_B \sim T_c^{20}}$ $\boxed{\Phi_{Be} \sim T_c^{10}}$ $\boxed{\Phi_{pp} \sim T_c^{-0.7}}$

- B neutrinos has the strongest dependence, due both to $^3He+^4He$ and (mainly) to ^7Be+p
- Be neutrinos strong depends on T_c, due to Gamow factor in $^3He+^4He$
- For the conservation of total flux, pp neutrinos decrease with increasing T_c



30 years after the detection of SN1987A neutrinos

2017/2/23

On February 23, 1987, just before 30 years from today, the neutrinos emitted from the supernova explosion SN1987A in the Large Magellanic Cloud, approximately 160,000 light-years away, reached the earth. Kamiokande, the predecessor detector of Super-Kamiokande, detected the 11 emitted neutrinos. Worldwide, it was the first instance of the detection of the emitted neutrinos from the supernova burst, and it served a big step toward resolving the supernova explosion system. In 2002, Dr. Masatoshi Koshiba, a Special University Professor Emeriuts of the University of Tokyo, was awarded a Nobel Prize in Physics for this achievement.

Before the explosion of supernova SN1987A (right) and after the explosion (left)
Anglo-Australian Observatory/David Malin