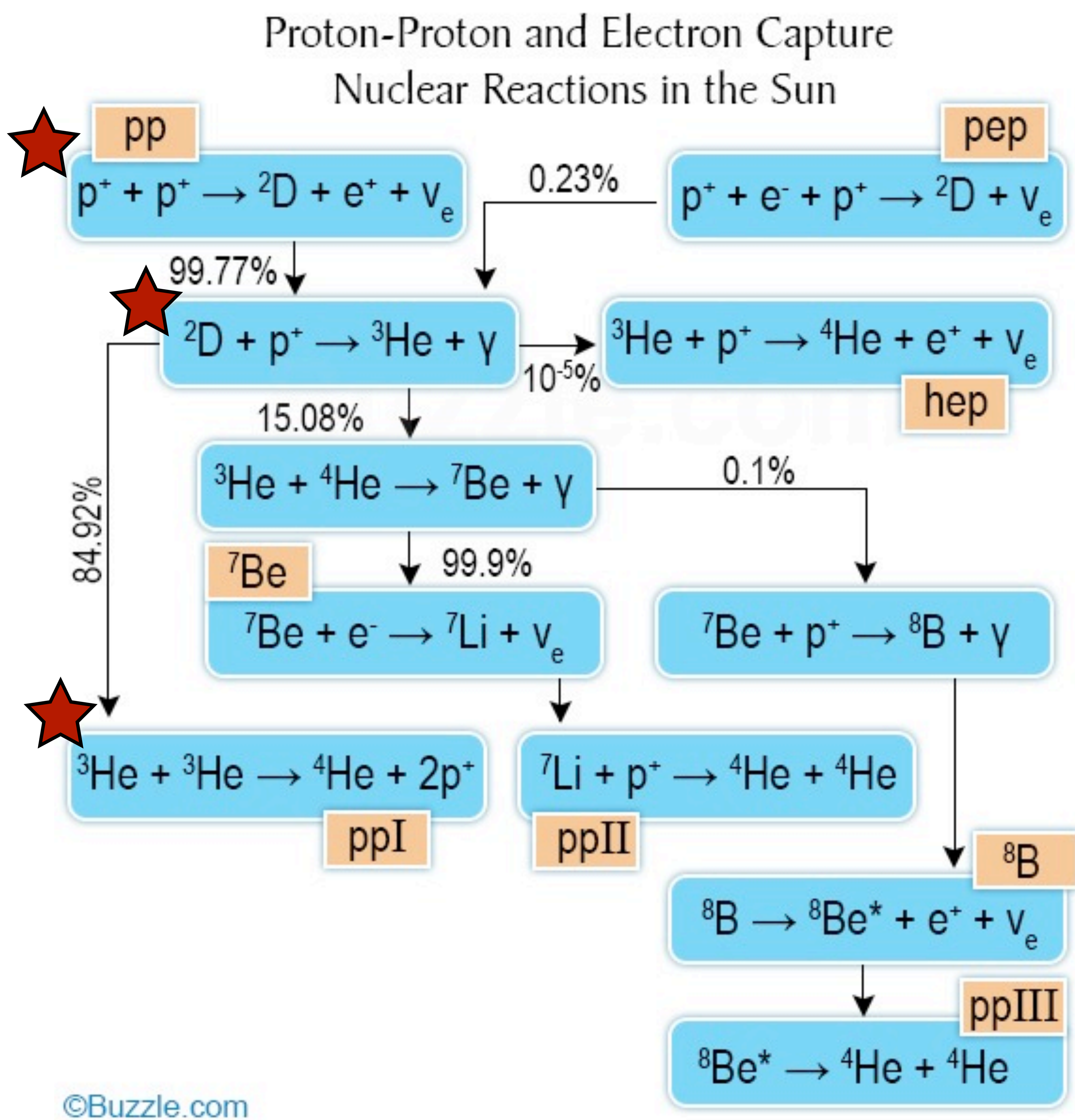
Lecture 3: solar neutrinos

PhD Cycle XXXIV

Suggested textbook: "Neutrino astrophysics", J.Bahcall
Solar models: arXiv:1611.09867v4

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⁺ → ²D + e⁺ + νe
pep
p⁺ + e⁻ + p⁺ → ²D + νe
0.23%
99.77%
²D + p⁺ → ³He + γ
10⁻⁵%
³He + p⁺ → ⁴He + e⁺ + νe
hep
15.08%
84.92%
³He + ⁴He → ⁷Be + γ
0.1%
99.9%
⁷Be
⁷Be + e⁻ → ⁷Li + νe
⁷Be + p⁺ → ⁸B + γ
³He + ³He → ⁴He + 2p⁺
ppI
⁷Li + p⁺ → ⁴He + ⁴He
ppII
⁸B
⁸B → ⁸Be* + e⁺ + νe
ppIII
⁸Be* → 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

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

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

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

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

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

Remarks on pp-I chain : pp neutrinos

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

- Note that the first step is a weak interaction process,
- It transforms the *p*'s into *n*'s necessary to form ^4He; 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 $\langle E \rangle$=0.2 MeV

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

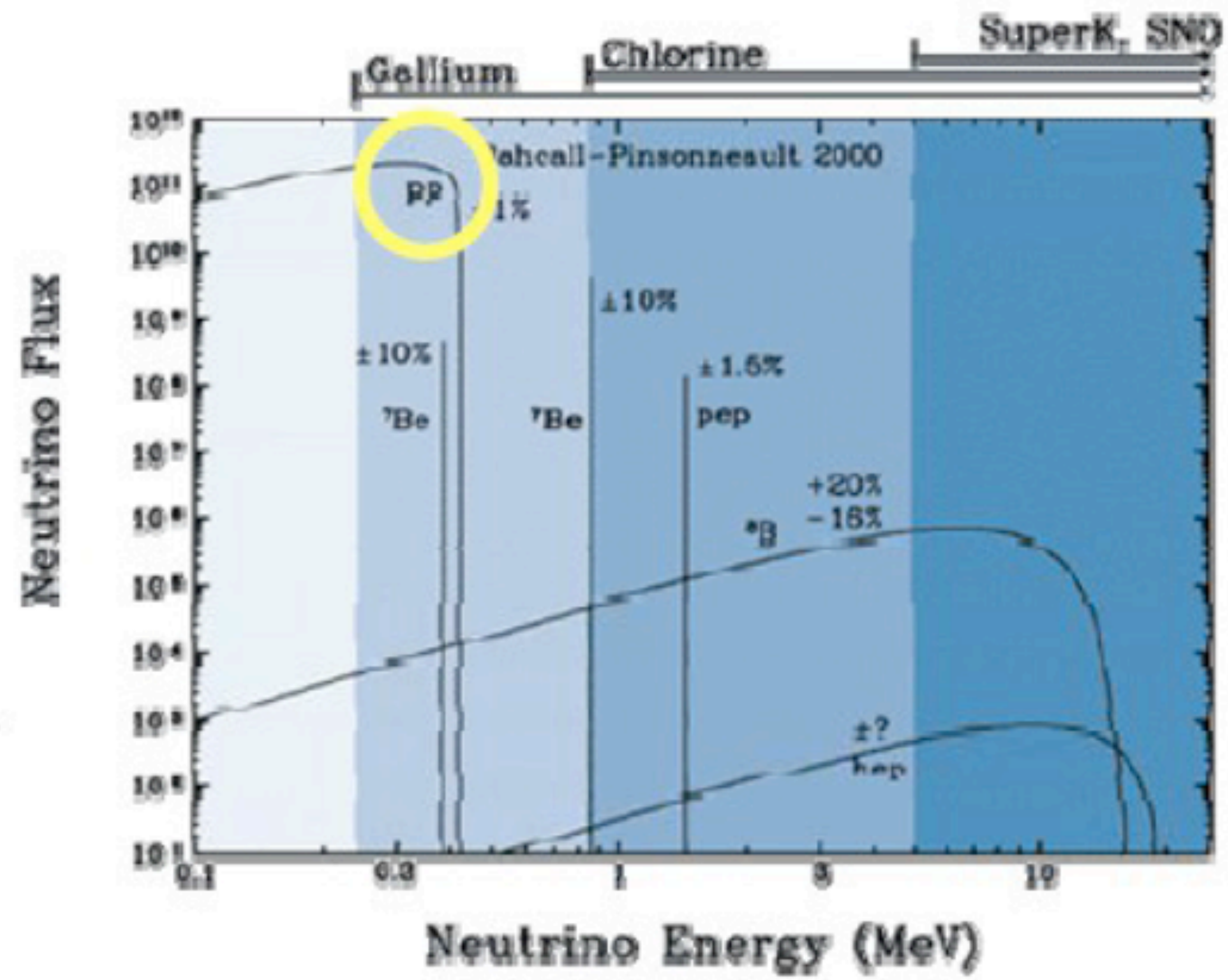
- This is an e.m process, which destroys *d*. This is generally the fate of *d* in stars and the reason why it is rare. It is formed by weak process where Hydrogen is present, and is destroyed by an e. m process which requires Hydrogen

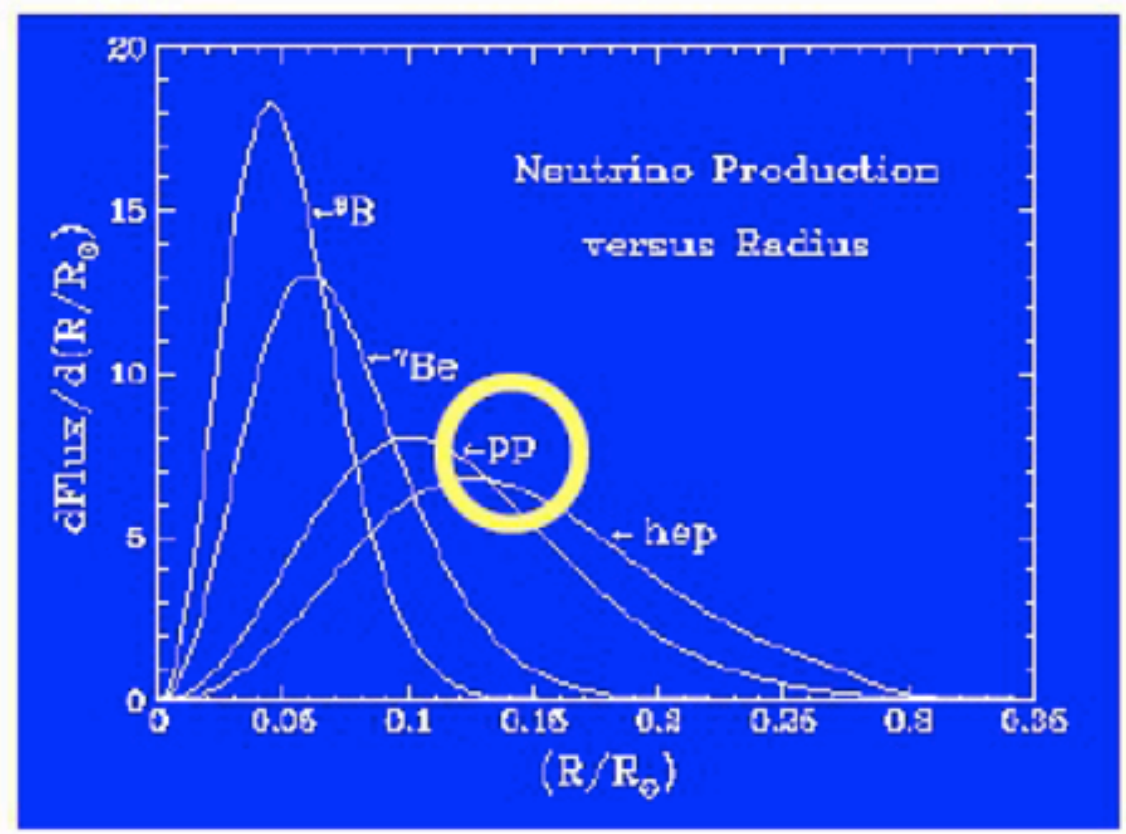
$${}^3He + {}^3He \longrightarrow {}^4He + 2p$$

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

$$^3He$$

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

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

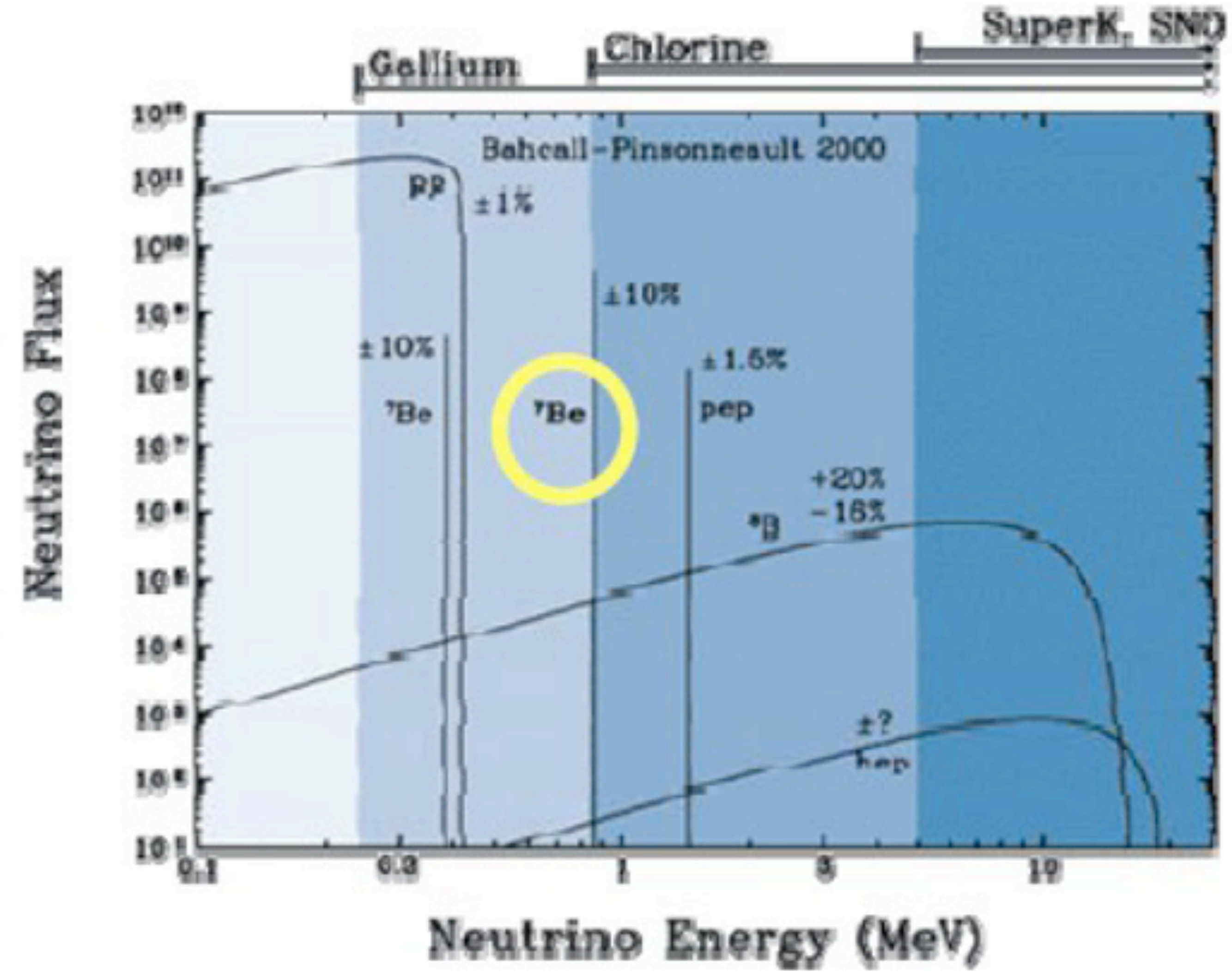
$$e + {^7Be} \rightarrow {^7Li} + \nu_e$$

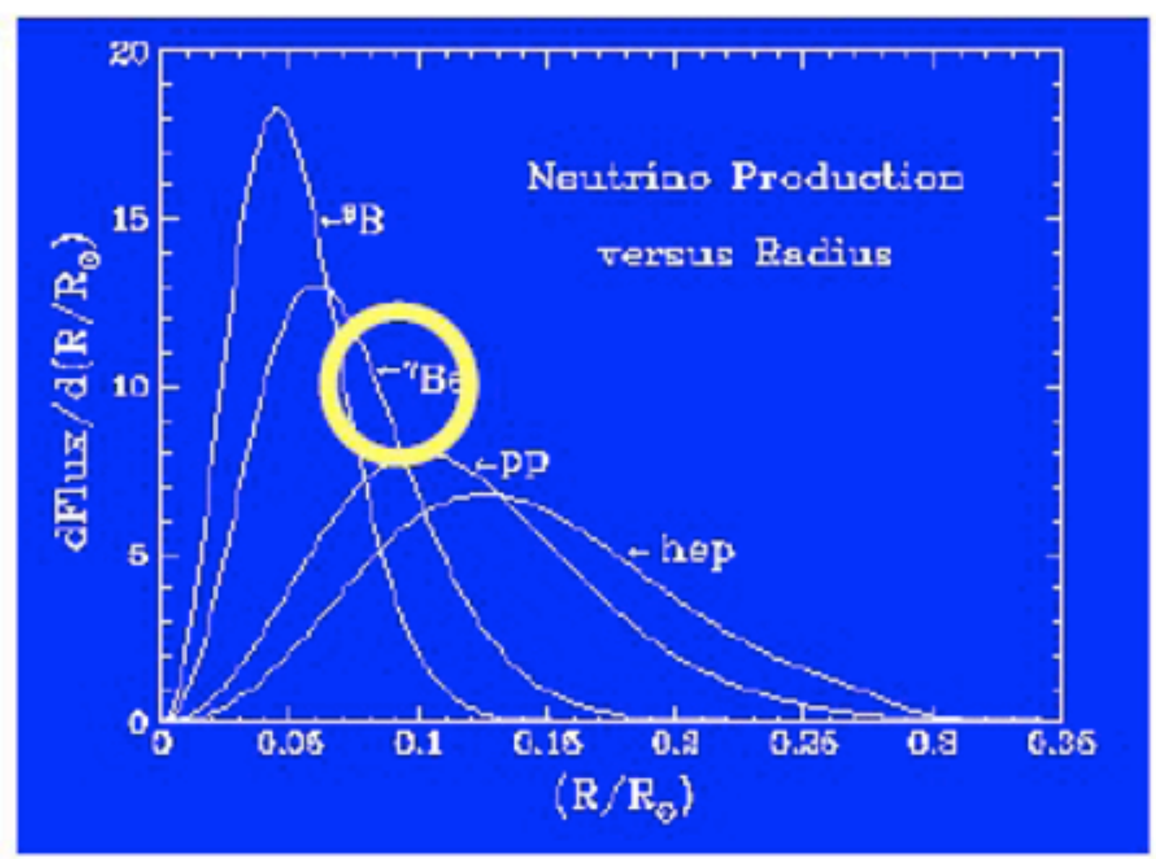
$$p + {^7Li} \rightarrow 2\,{^4He}$$

- Collisions with ^4He are less likely, since an e.m process is involved and more massive particles are involved in the tunneling.
- A (bare) nucleus of ^7Be, 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,

^7Be

$$e + {}^7Be \rightarrow {}^7Li + \nu_e \qquad p + {}^7Be \rightarrow {}^8B + \gamma$$

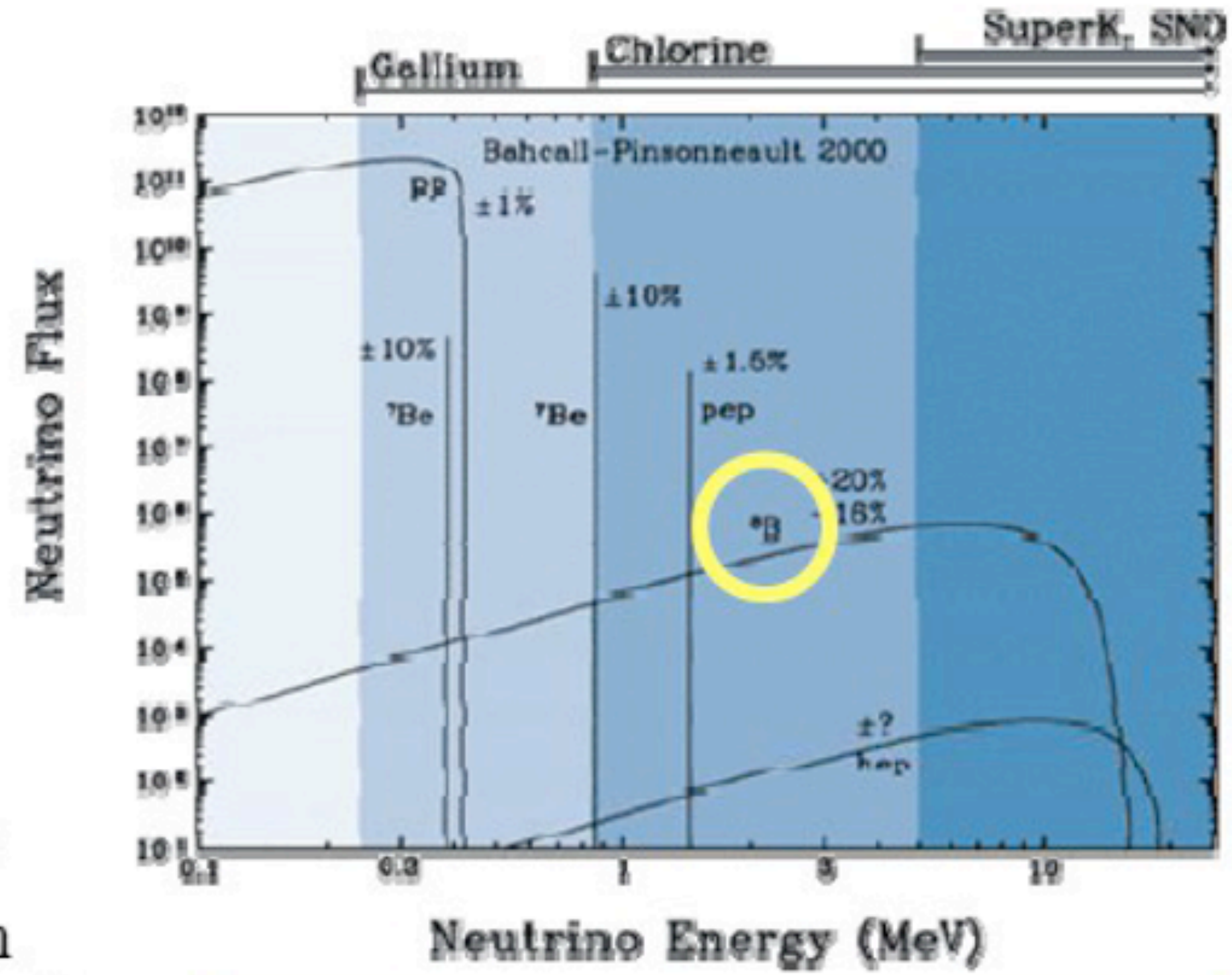
$$^8B \rightarrow {}^4He + {}^4He + e^+ + \nu_e$$

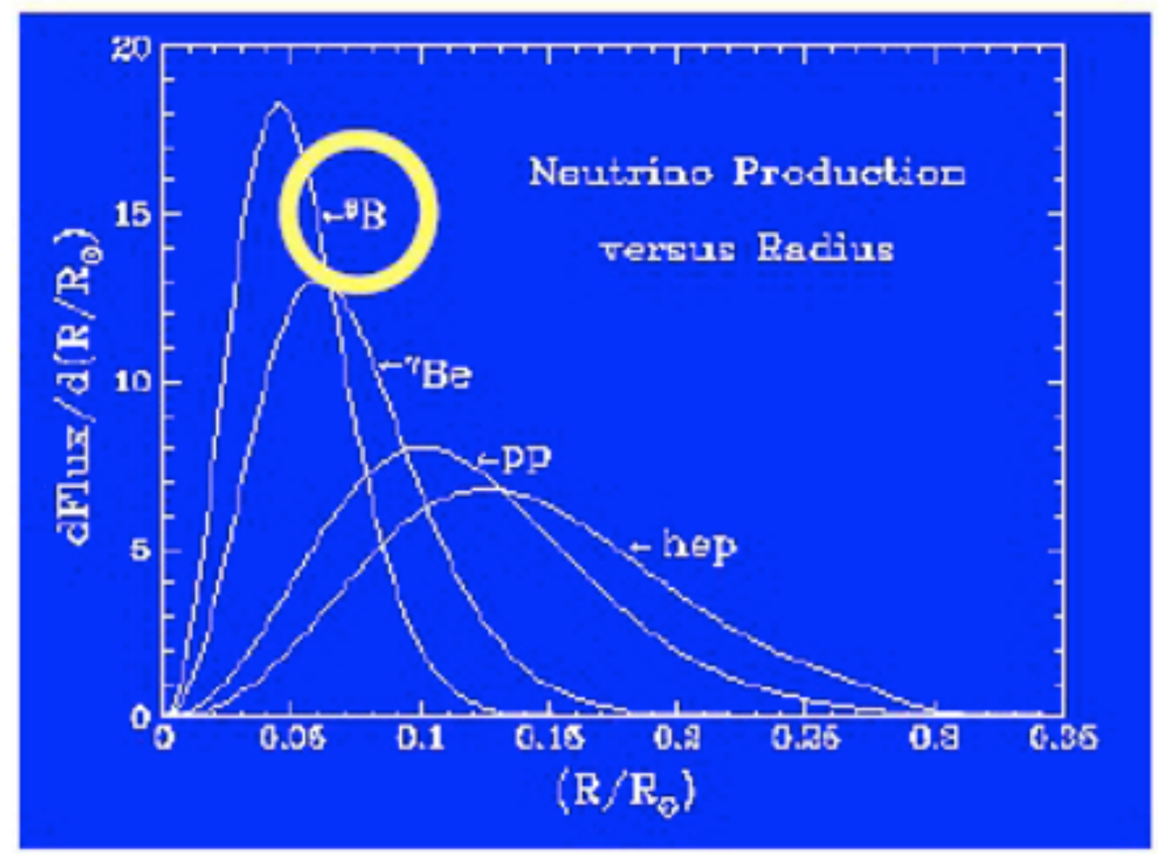
- *p* capture is disfavoured with respect to *e* capture due to Coulomb repulsion, although the instrinsic strength of an e.m. process is larger than that of a weak process.
- Boron neutrinos have a continuous spectrum, extending to 14 MeV.
- Their intensity is about 10^{-4} with respect to pp
- Predictions 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	^7Be	^8B
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:	$0.1\ R_o$	$0.06\ R_o$	$0.05\ R_o$

Hydrogen Burning: PP chain and CNO cycle

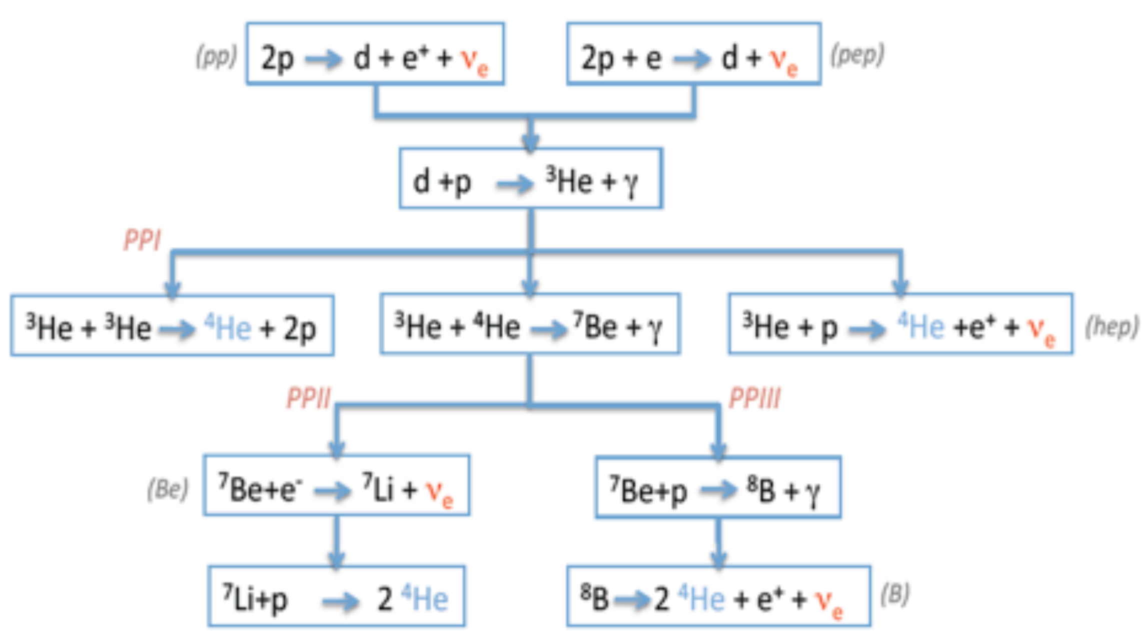
The Sun is powered by nuclear reactions that transform H into ^4He:

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

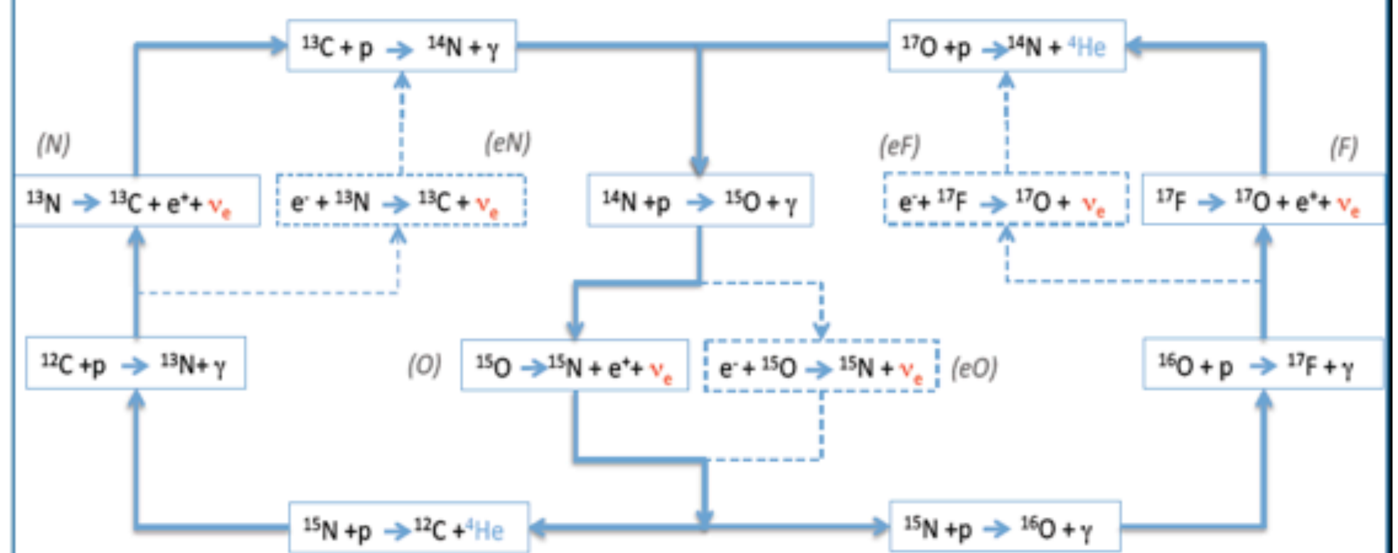
→ Q = 26,7 MeV (globally)

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

The PP-chain



The CN-NO (bi-)cycle



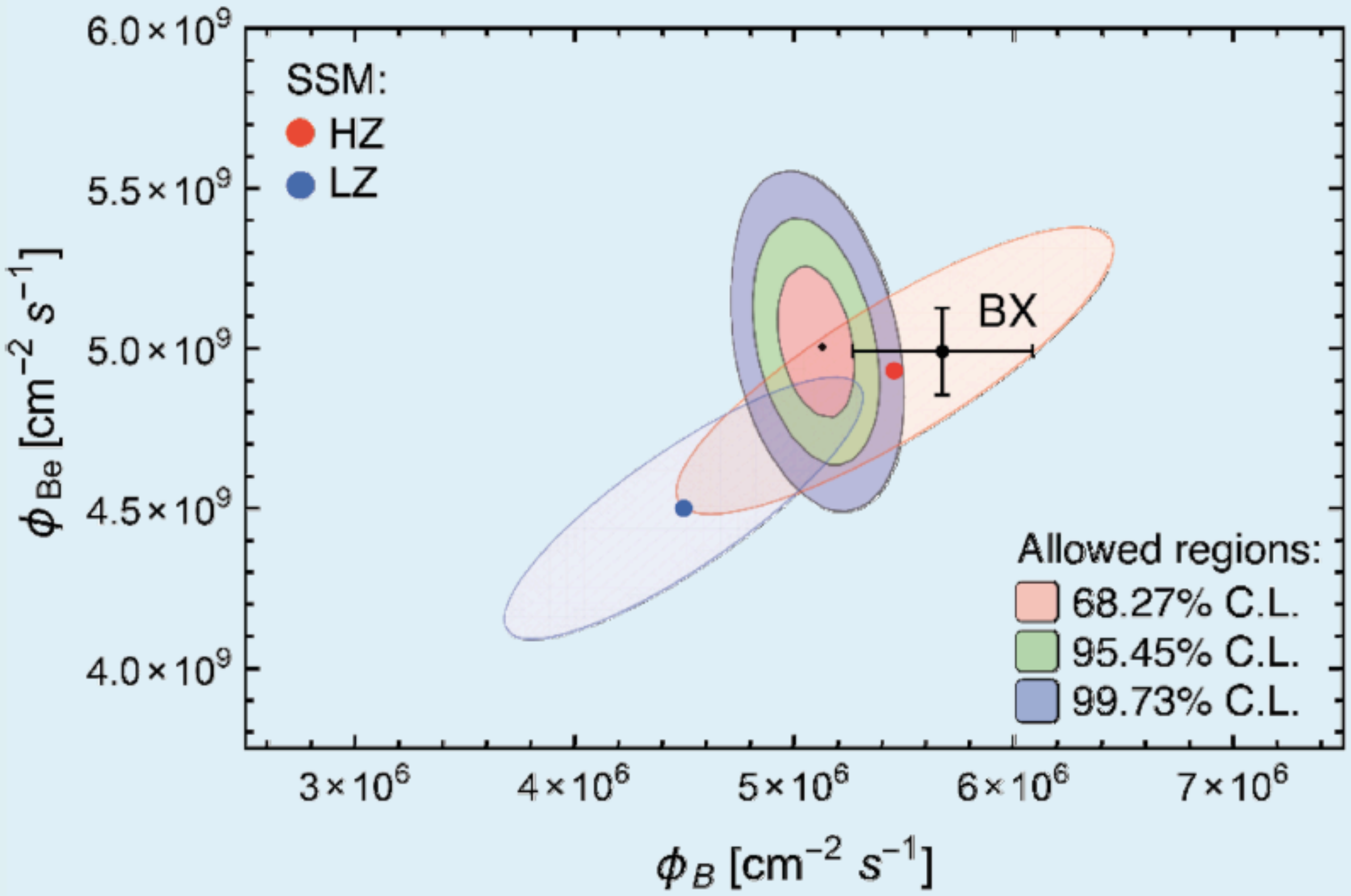
The pp chain is responsible for about 99% of the total energy (and neutrino) production.

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

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

$^7Be/^8B$ ratios



→ **Bx data alone prefer HZ over LZ at 1.8σ**

- combining data from BX with SK+SNO:

$$f_{Be} = \frac{\Phi(Be)}{\Phi(Be)_{HZ}} = 1.01 \pm 0.03 \qquad f_B = \frac{\Phi(B)}{\Phi(B)_{HZ}} = 0.93 \pm 0.02$$

→ **reduced significance**

- SSM uncertainties dominate

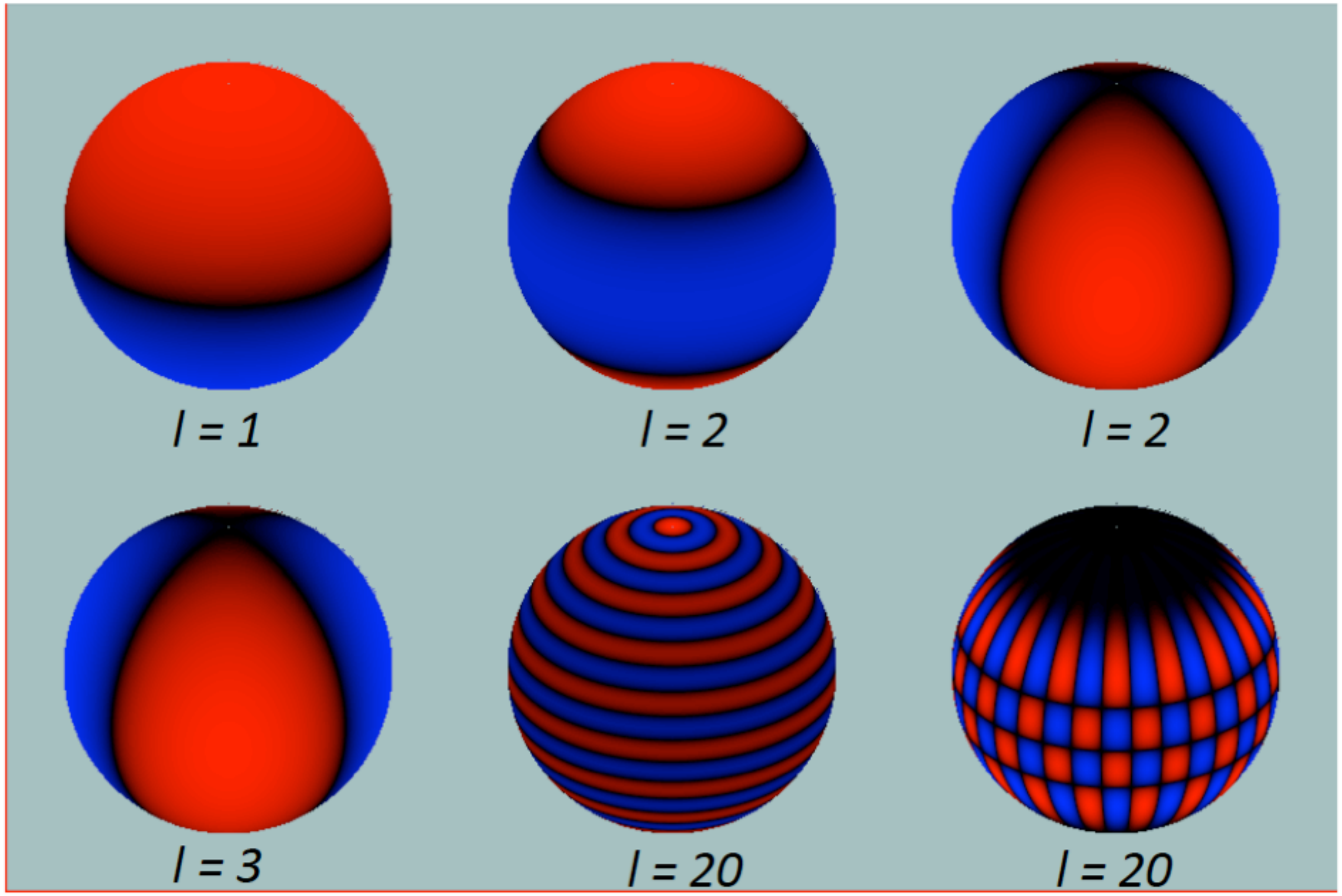
- Spectroscopic observations of the external layers of the sun prefer lower Z than C/N/O

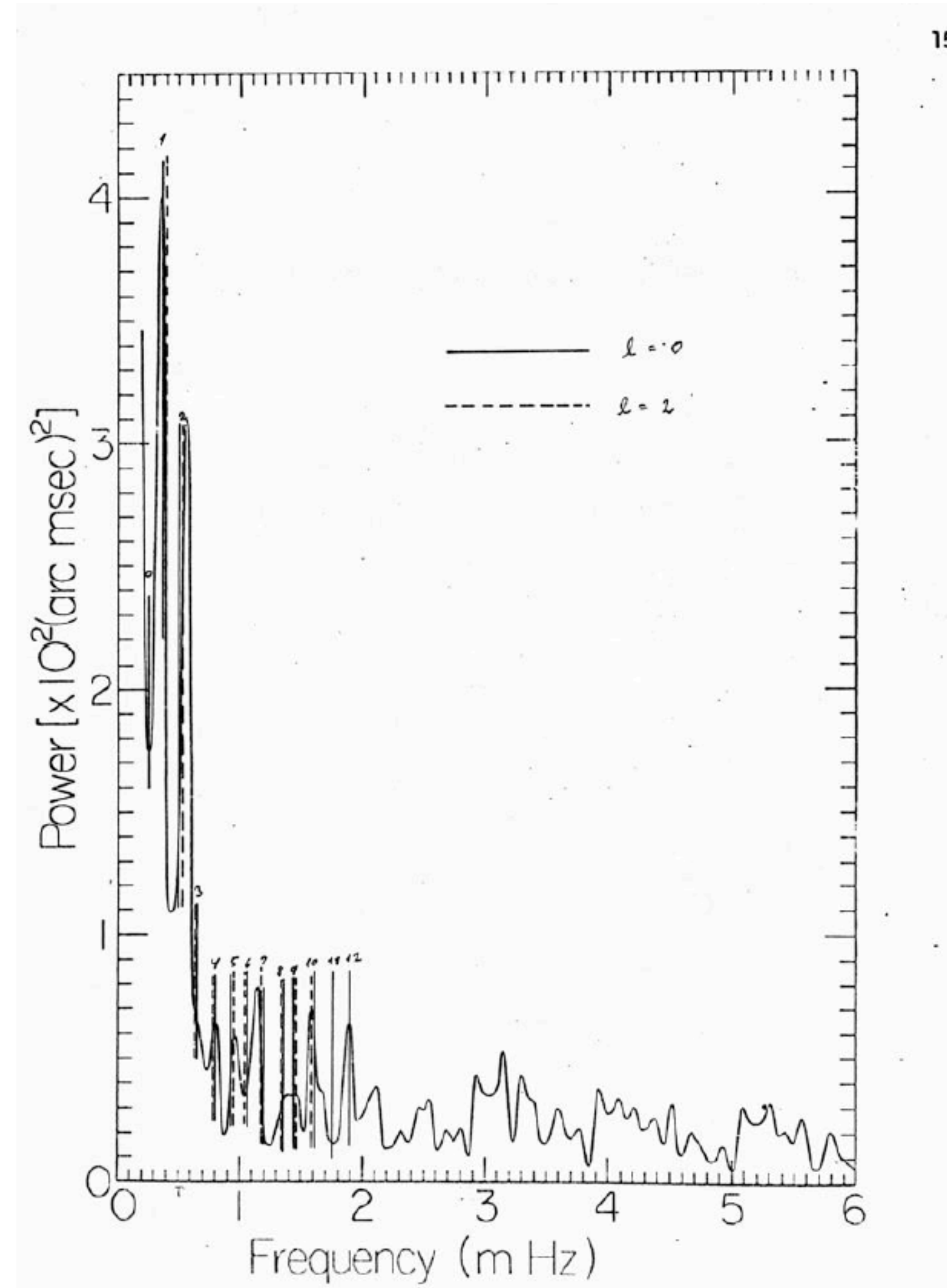
- but neutrino fluxes seem to indicate preference for High Z (HZ) from older models (GS98)

- plus....

Oscillations on the solar surface

aka "helioseismology"





Frequency differences between Sun and model:

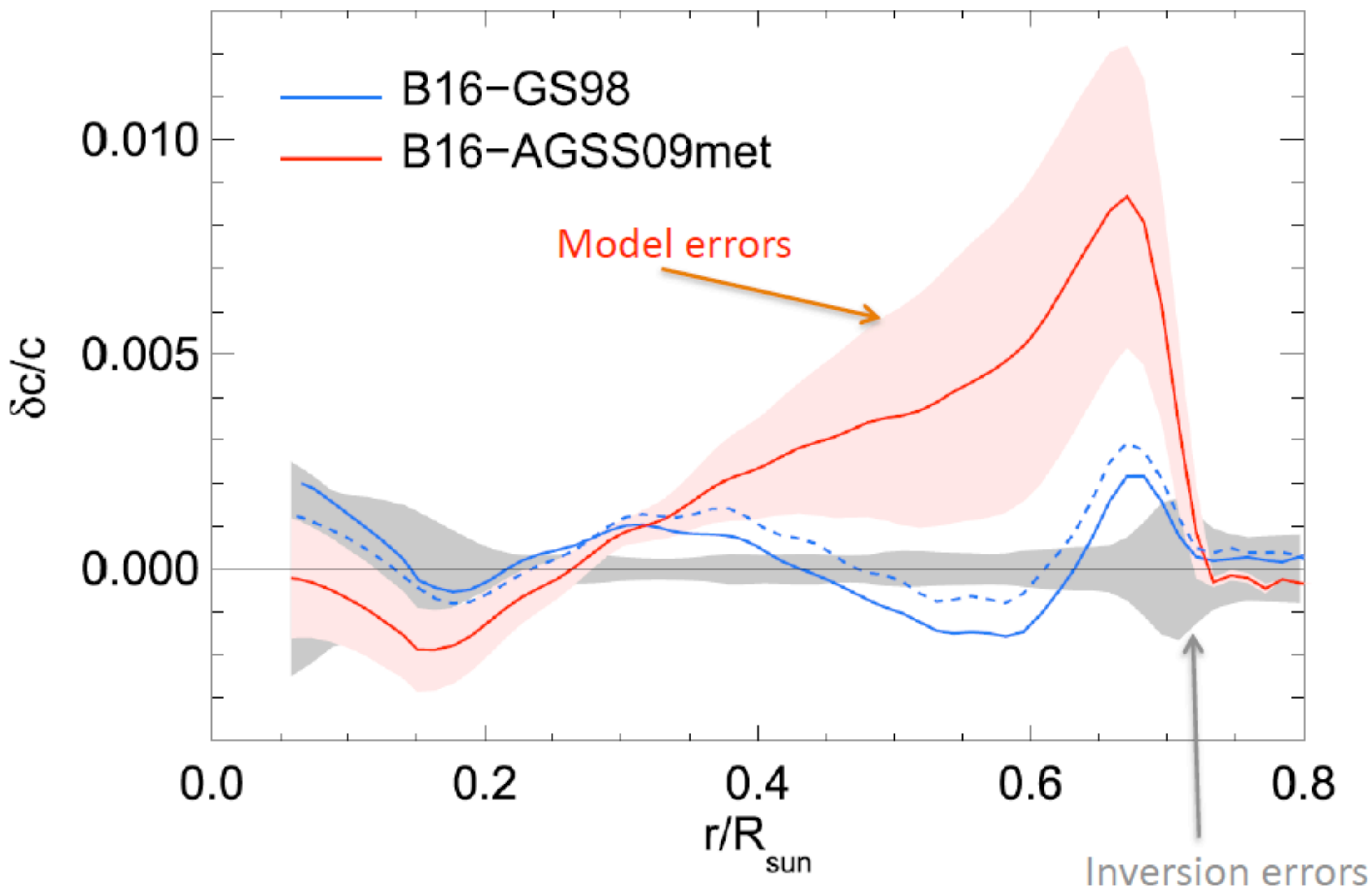
$$\frac{\delta\omega_{nl}}{\omega_{nl}} = \int_0^R \left[K^{nl}_{c^2,\rho}(r)\frac{\delta_r c^2}{c^2}(r) + K^{nl}_{\rho,c^2}(r)\frac{\delta_r \rho}{\rho}(r)\right] \mathrm{d}r + Q^{-1}_{nl}\mathcal{G}(\omega_{nl}) + \epsilon_{nl} \ ,$$

Speed of sound and opacity K probe matter / Z in Sun's core connected to neutrinos

Jørgen Christensen-Dalsgaard
Stellar Astrophysics Centre
Aarhus University

https://indico.desy.de/indico/event/18666/session/3/contribution/1/material/slides/0.pdf

SSM and Helioseismology



Vinyoles et al. (2017; ApJ 835, 202)

c_{obs} = inversion: inference of sound speed from oscillation relations (δν) + opacity (photon scattering in the Sun's core)

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

Fractional sound speed difference

High-Z models are clearly preferred by helioseismology.

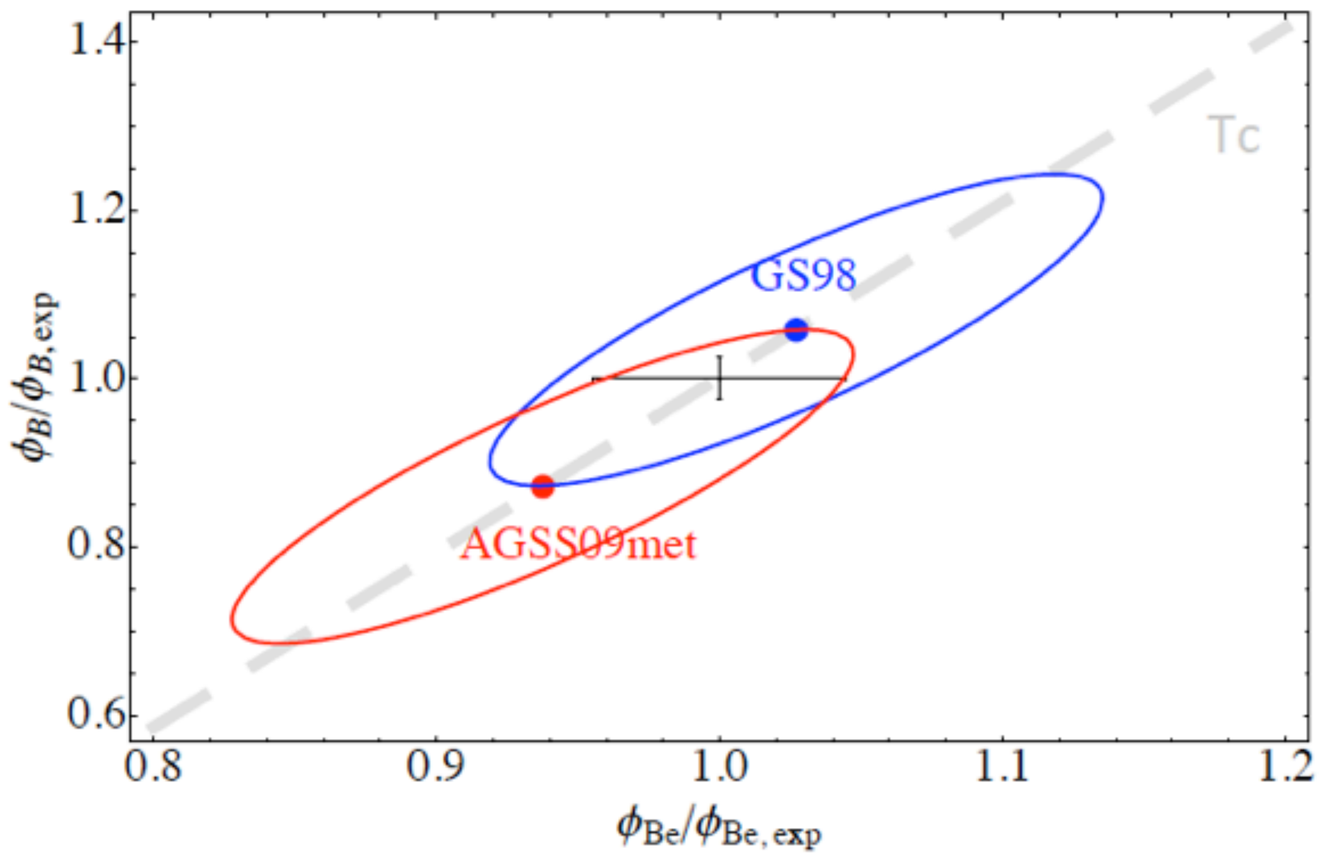
	GS98	AGSS09	Obs
$< \delta c/c >$	$0.0005^{+0.0006}_{-0.0002}$	0.0021 ± 0.001	-
$R_{\rm cz}/R_\odot$	0.7117 ± 0.0048	0.7224 ± 0.0053	0.713 ± 0.001
$Y_{\rm S}$	0.2426 ± 0.0059	0.2316 ± 0.0059	0.2485 ± 0.0035
$Z_{\rm S}$	0.0170 ± 0.0012	0.0134 ± 0.0008	-
$Y_{\rm C}$	0.6320 ± 0.0053	0.6209 ± 0.0062	-
$Z_{\rm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

High Z (more heavy elements than He) — Low Z (less heavy elements than He)

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}.

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

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



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

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

At the moment, **^{7}Be and ^{8}B neutrinos do not determine composition with suff. accuracy**

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?

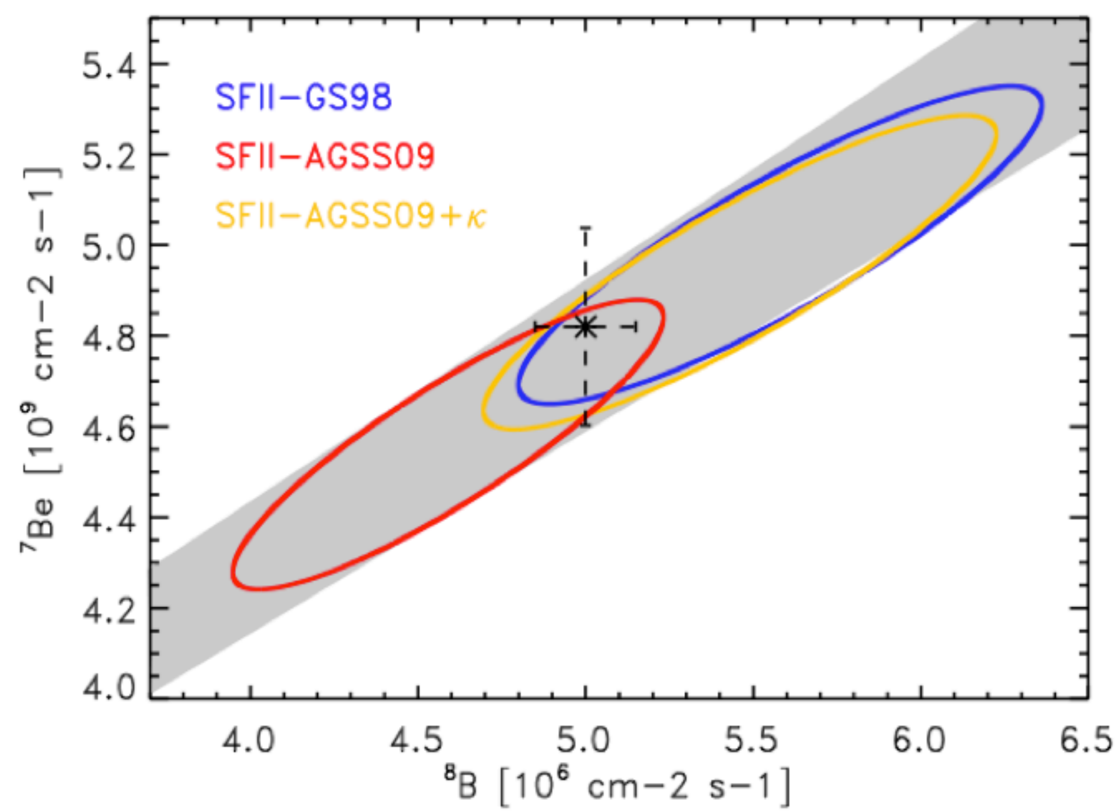
Note that:

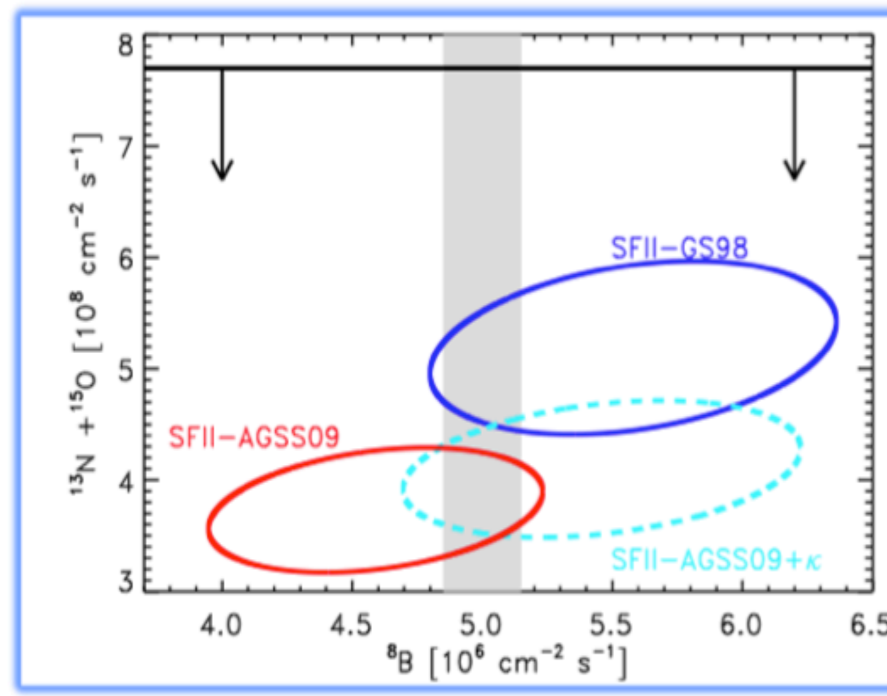
*The Sun provide the **benchmark** for stellar evolution. If there is something wrong in solar models, then this is wrong for all the stars ...*

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

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/hydro-dynamical constraints not well controlled)

Some 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

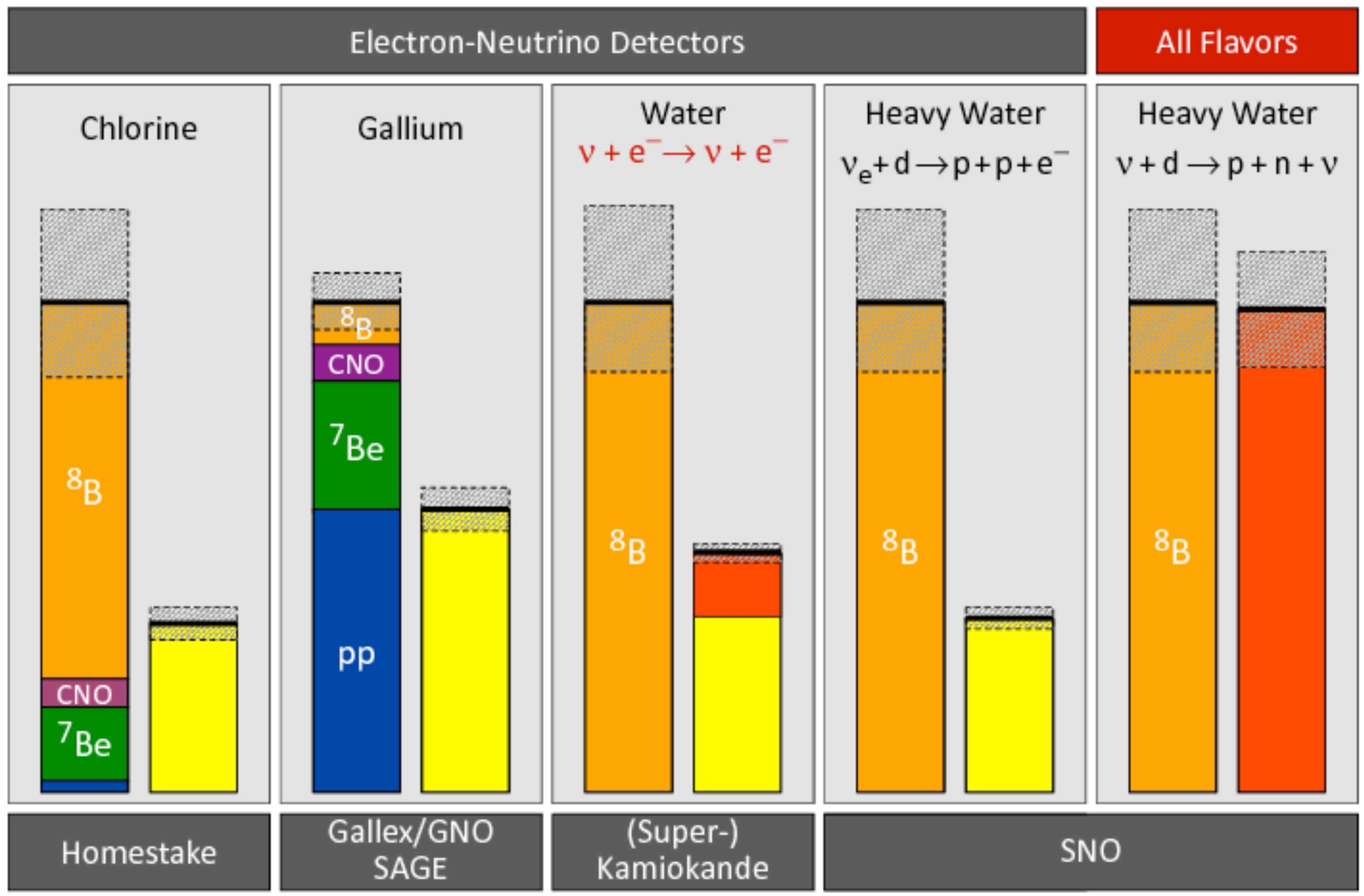
TABLE 5.2. Threshold neutrino energy in eqn (5.37) for some charged-current reactions used for neutrino detection.

Reaction	Masses	E_ν^{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

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

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

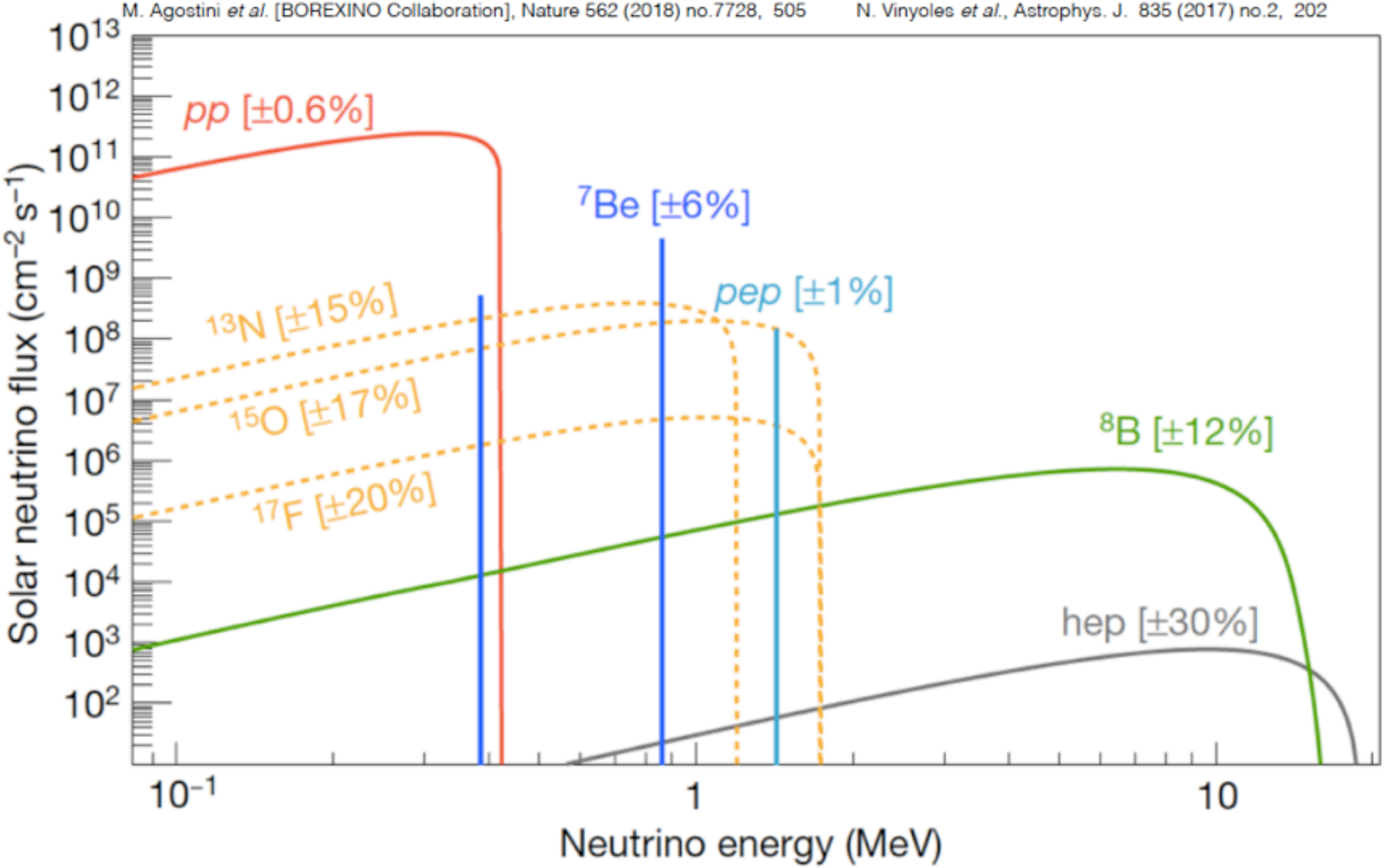
- **radio-chemical**: counting only, low threshold, but no directional
- **water**: directional (Cherenkov), cheap, but high threshold because of bkgs
- **liquid scintillator**: (e^- scattering) purified, expensive, not directional



Solar neutrinos: energy spectrum

SSM predicts the number of neutrinos produced in nuclear reactions

M. Agostini *et al.* [BOREXINO Collaboration], Nature 562 (2018) no.7728, 505 N. Vinyoles *et al.*, Astrophys. J. 835 (2017) no.2, 202



Studying solar neutrinos can confirm our SSM!

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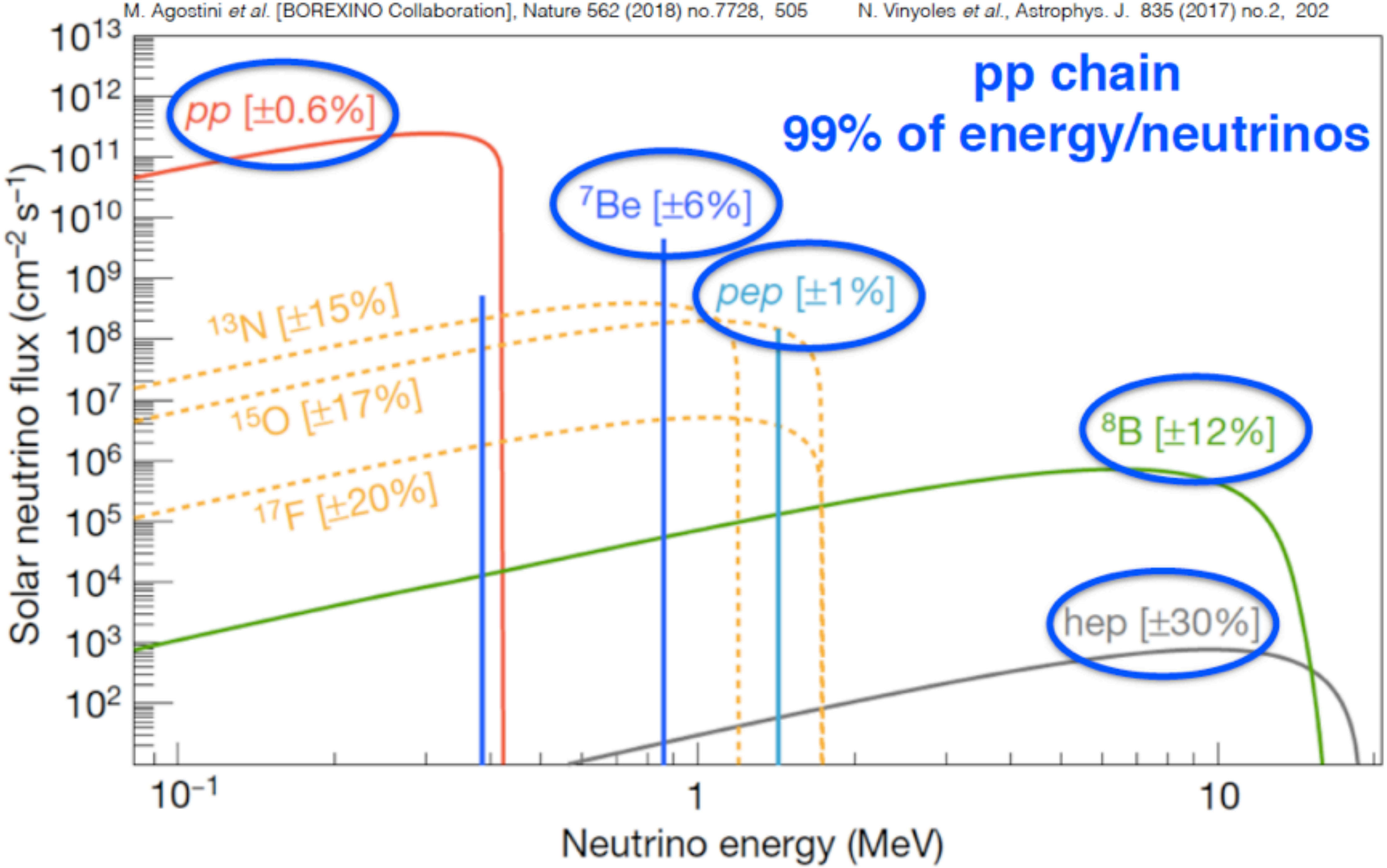

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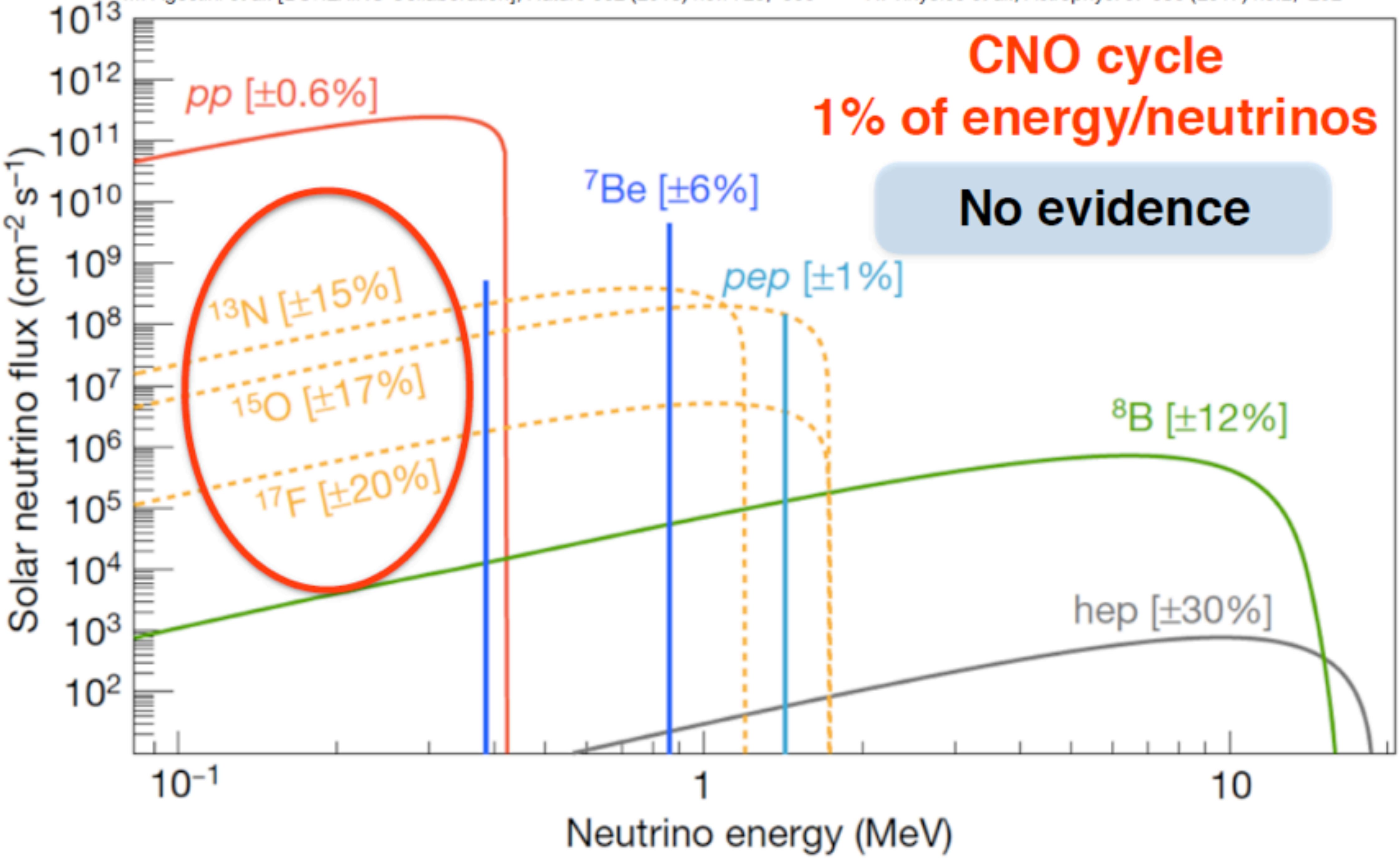

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Solar neutrinos: low energy experiments

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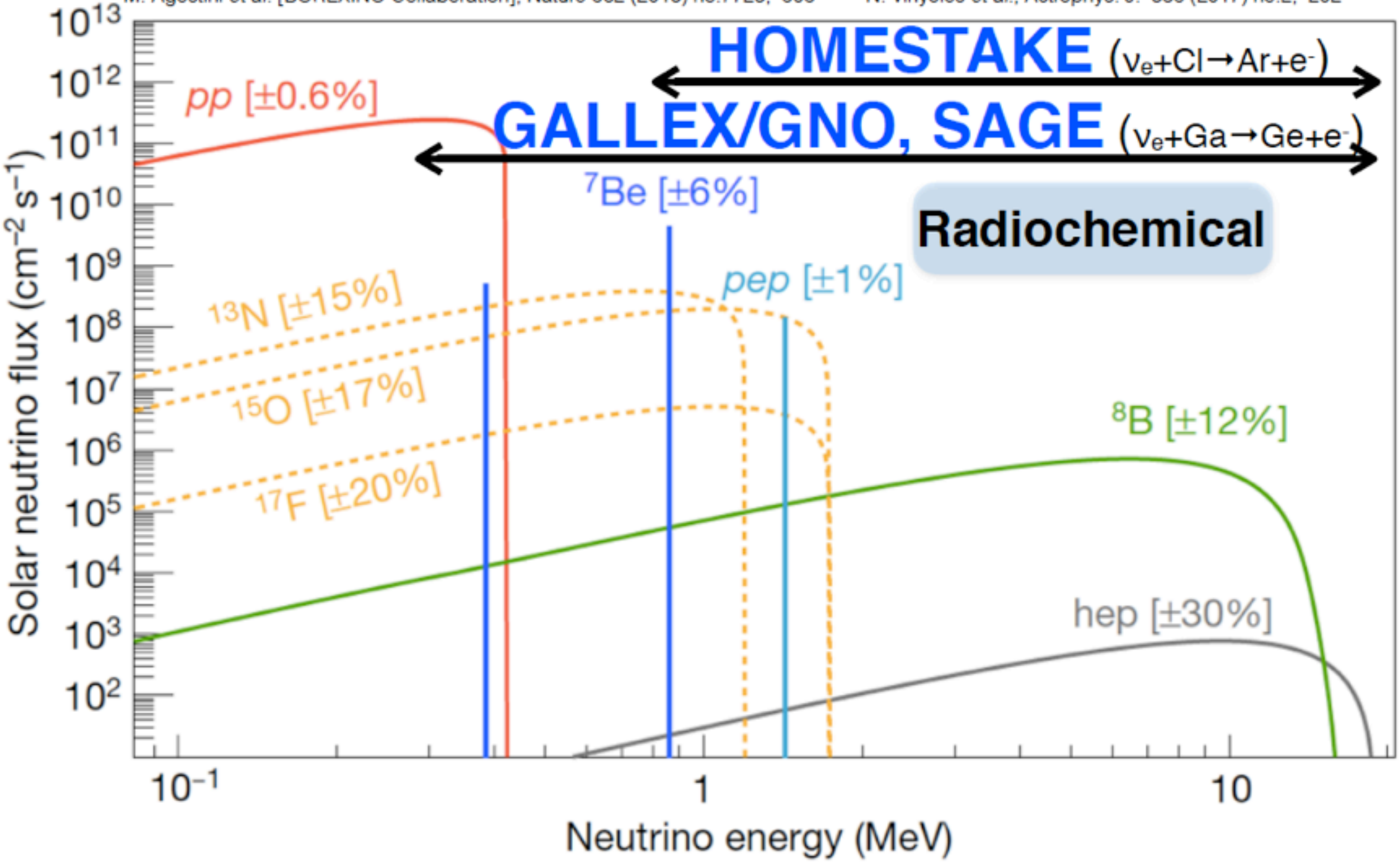

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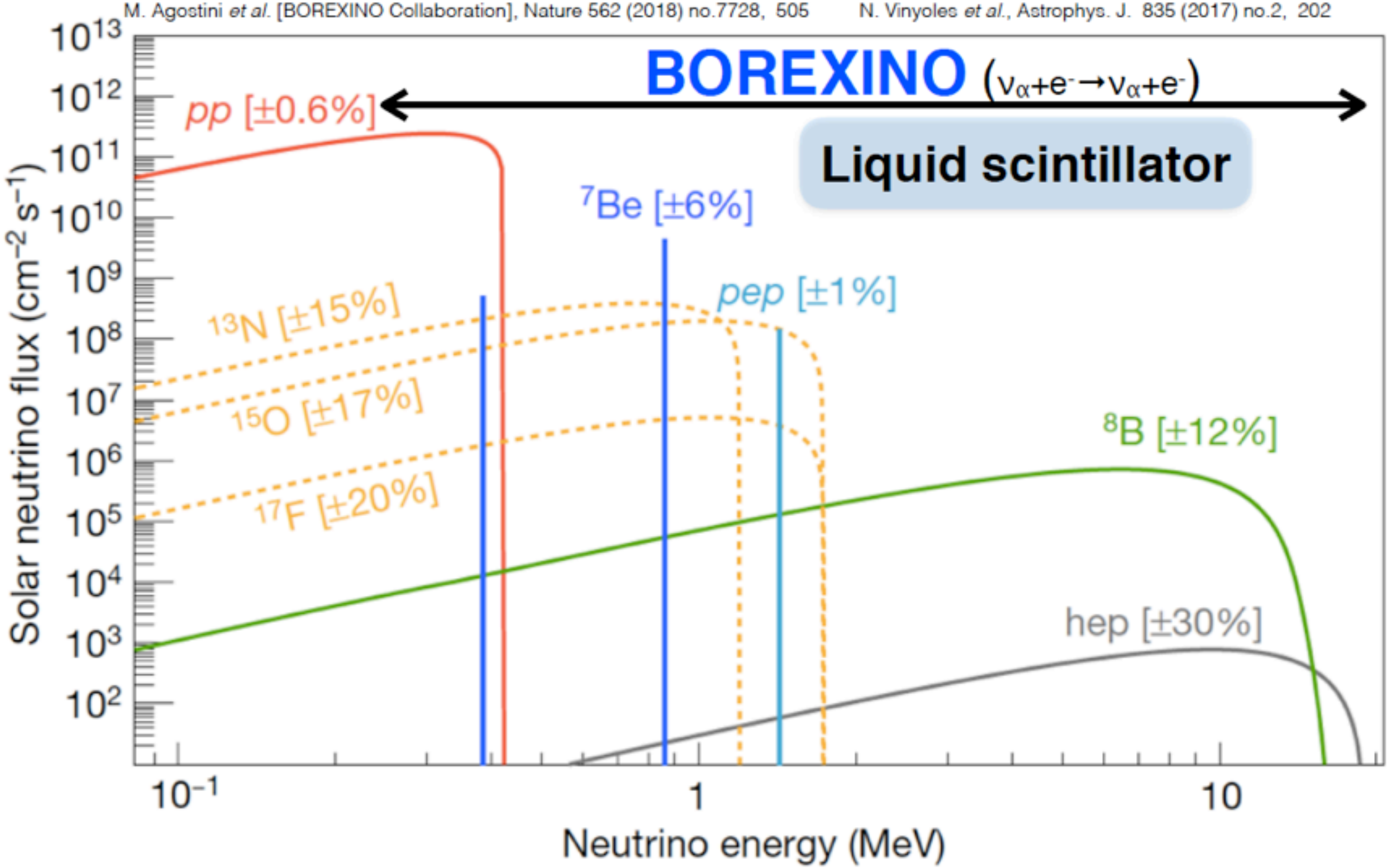
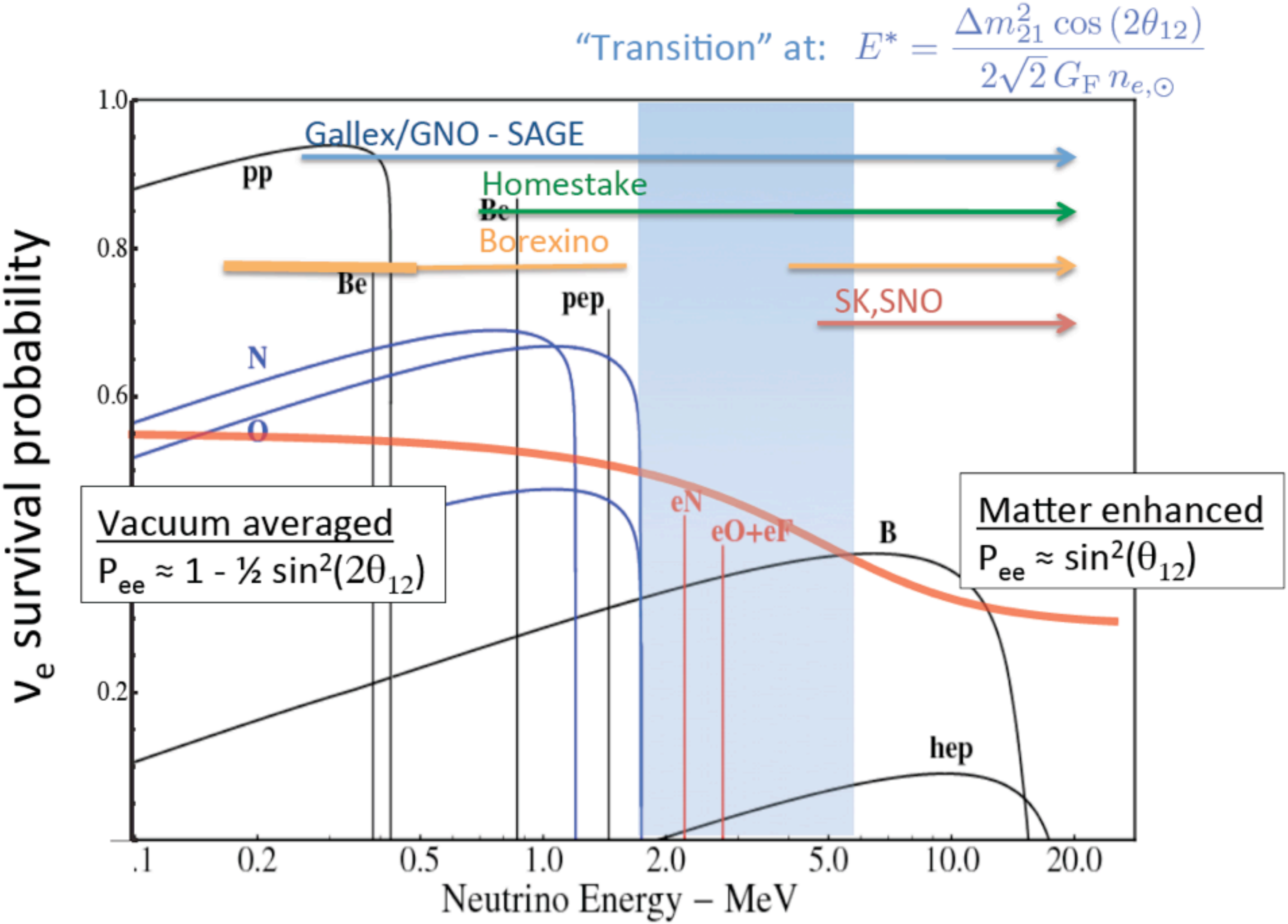


Studying solar neutrinos can confirm our SSM!

The solar neutrino survival probability

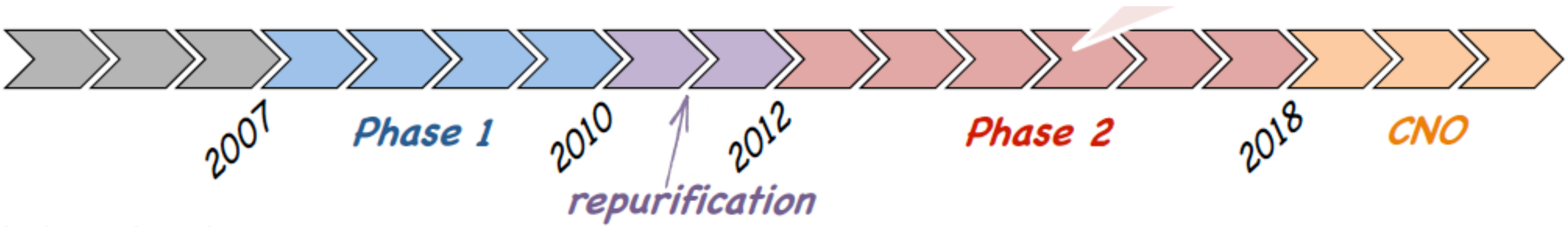


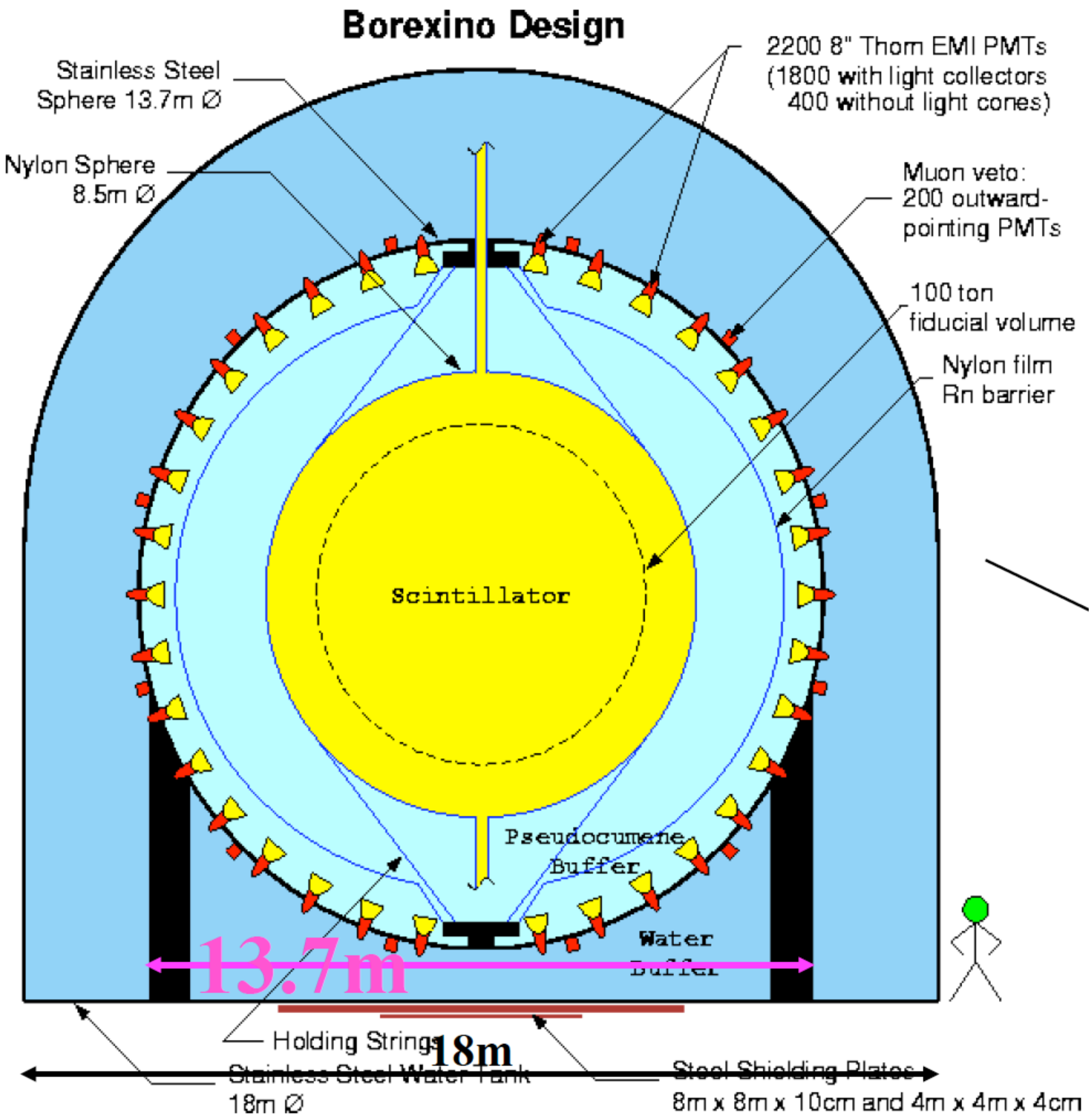
M. Agostini et al. [BOREXINO Collaboration], Nature 562 (2018) no.7728, 505

Phase I: https://arxiv.org/abs/1308.0443v2

The most recent Borexino measurement

LS ES: purified, expensive, no directional





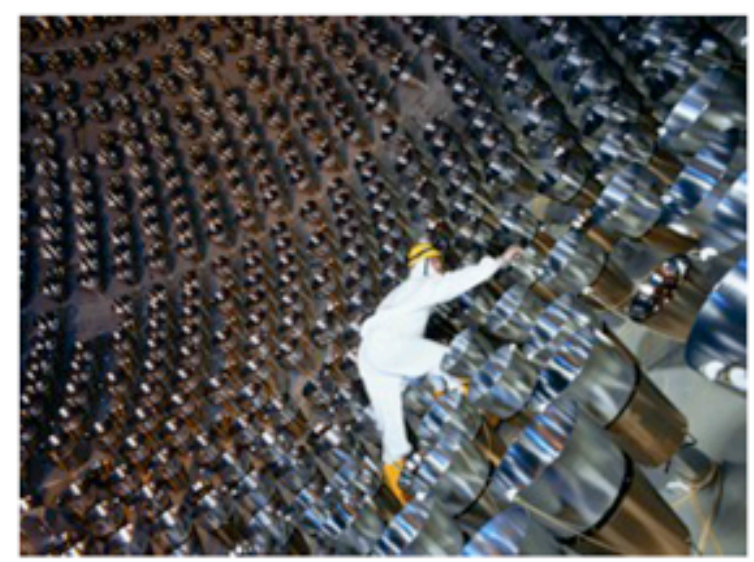
13.7 m stainless sphere
~ 1000 tons of pseudocumene (PC+PPO)
~300 tons Inner Vessel

More than 2000 Photomultiplier tubes (PMTs)

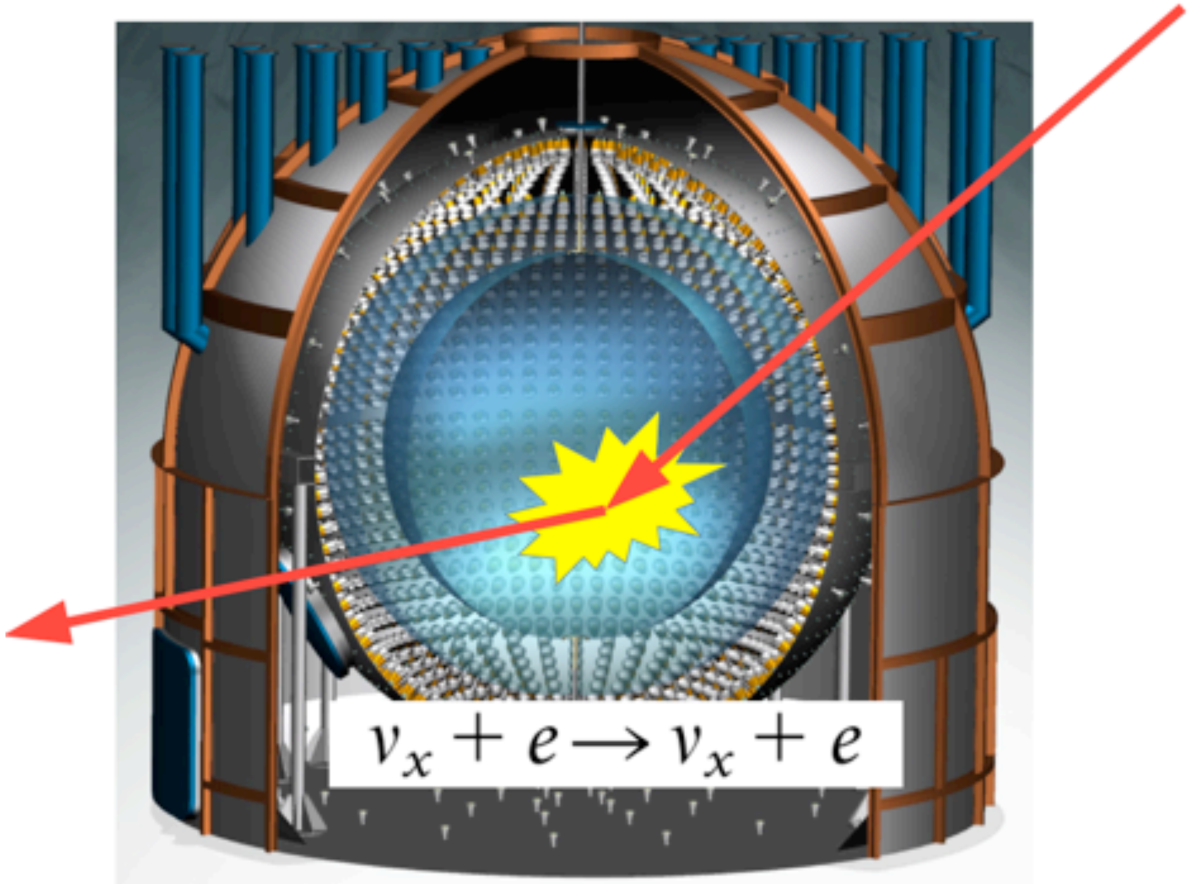
34% Coverage

Light Yield = 500 PE/MeV

Cherenkov muon veto (~200 PMTs)



The Borexino Signal



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

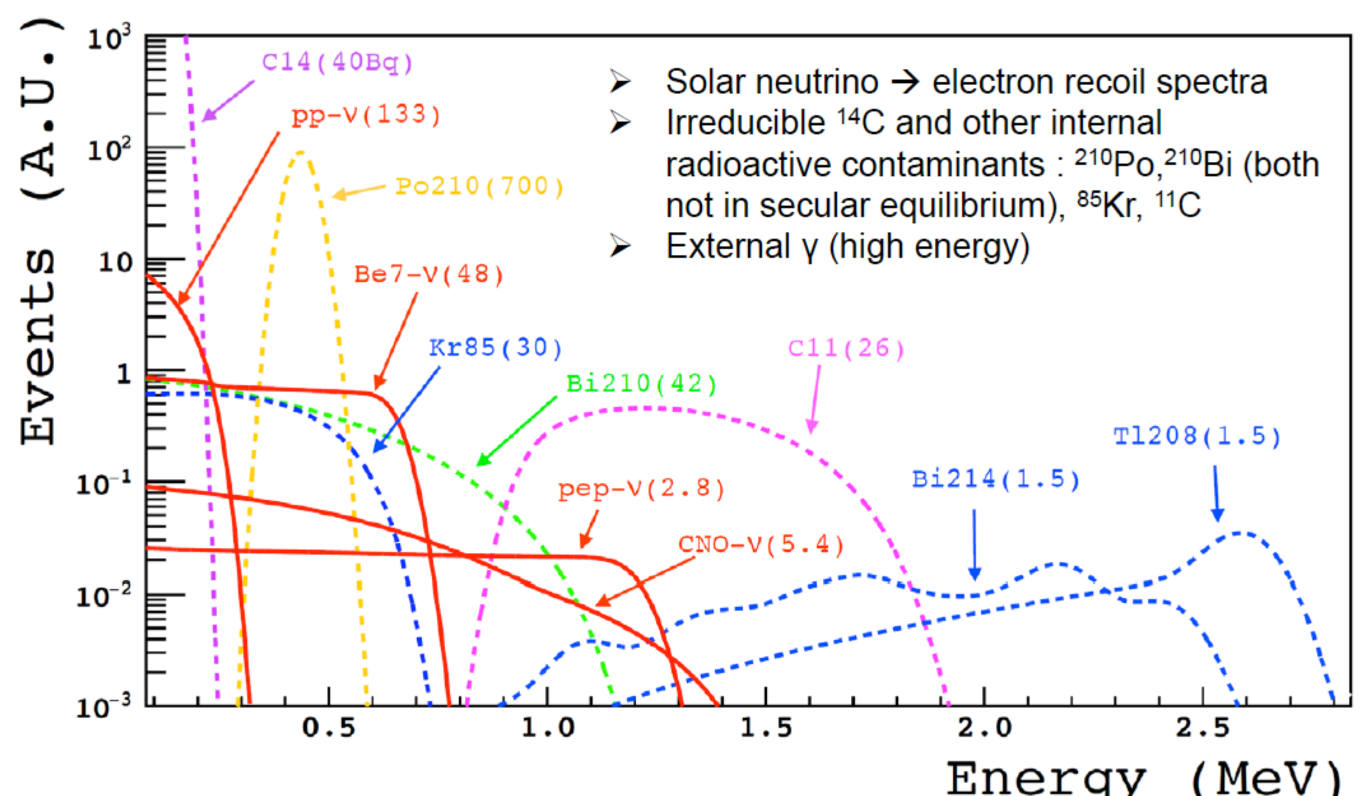
This signal is indistinguishable from the natural radioactivity (β- and γ components)

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

Crucial point:
Extreme low background required!!!

Backgrounds

Background	Rate [cpd/100 t]
^{14}C [Bq/100 t]	40.0 ± 2.0
^{85}Kr	6.8 ± 1.8
^{210}Bi	17.5 ± 1.9
^{11}C	26.8 ± 0.2
^{210}Po	260.0 ± 3.0
Ext. ^{40}K	1.0 ± 0.6
Ext. ^{214}Bi	1.9 ± 0.3
Ext. ^{208}Tl	3.3 ± 0.1



MC input counting rates are quoted in cpd/100 t

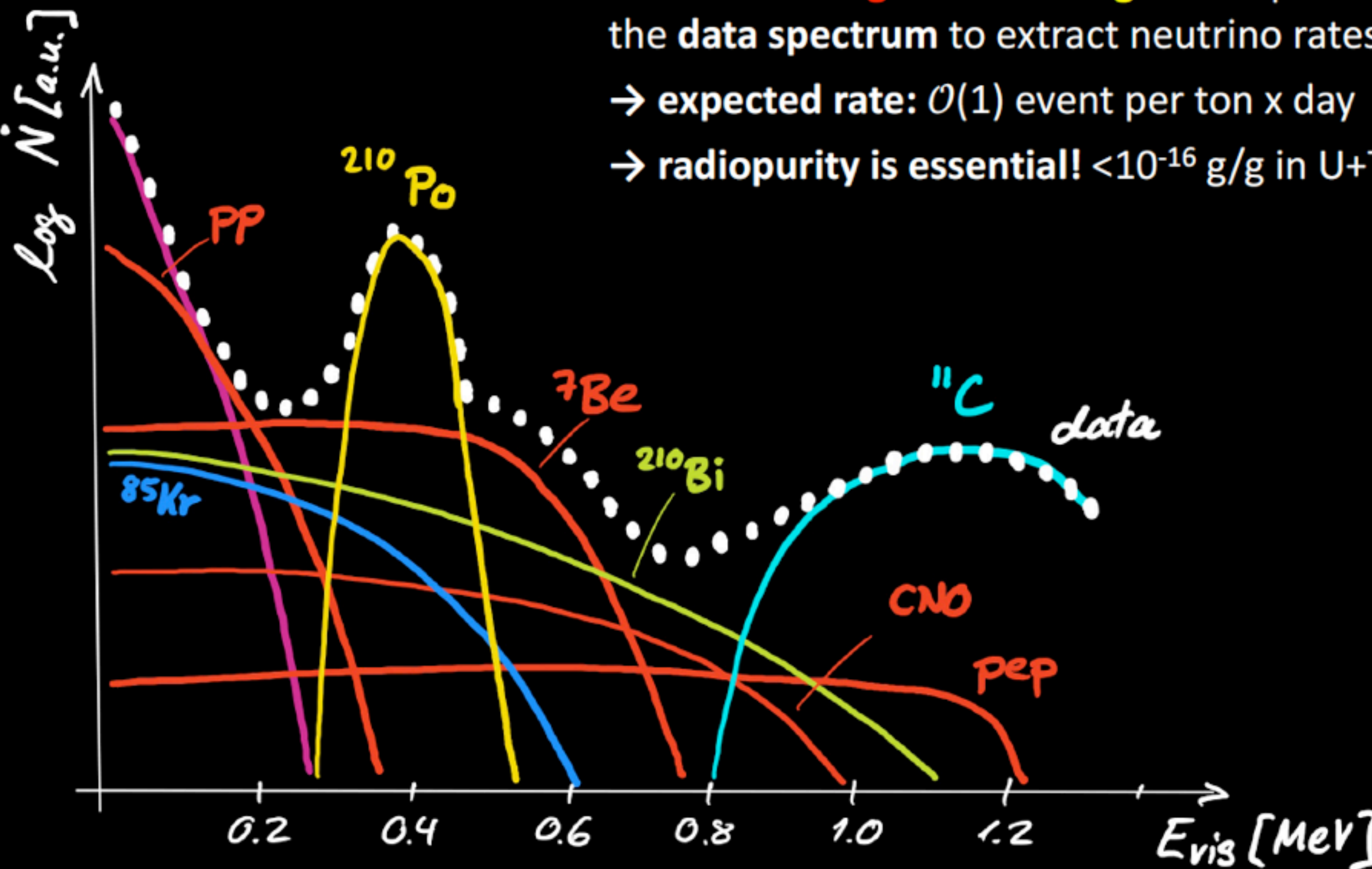
Basic analysis: ν rates from spectral fit

JG|U

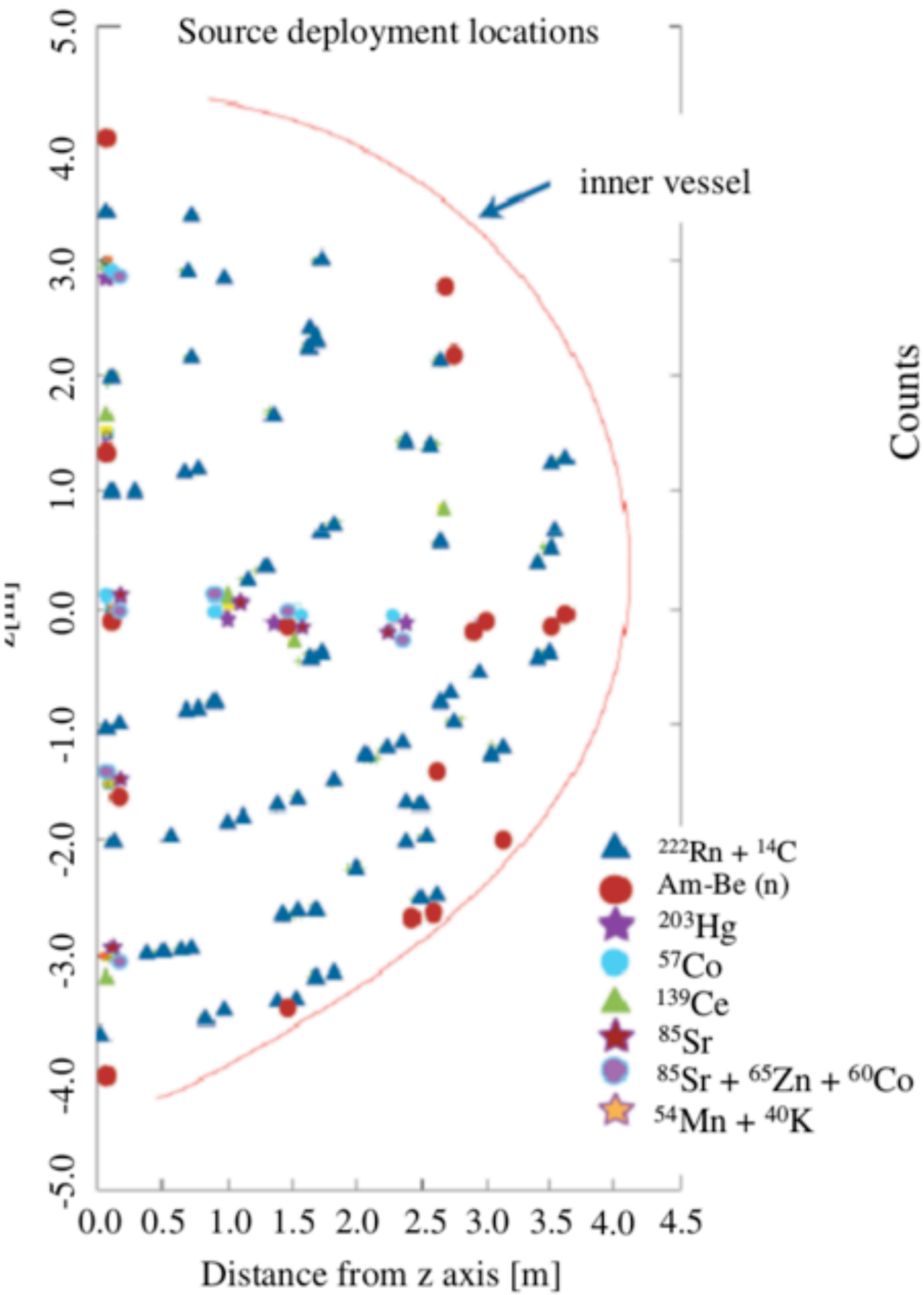
Fit of known **signal** and **background** spectra to the **data spectrum** to extract neutrino rates

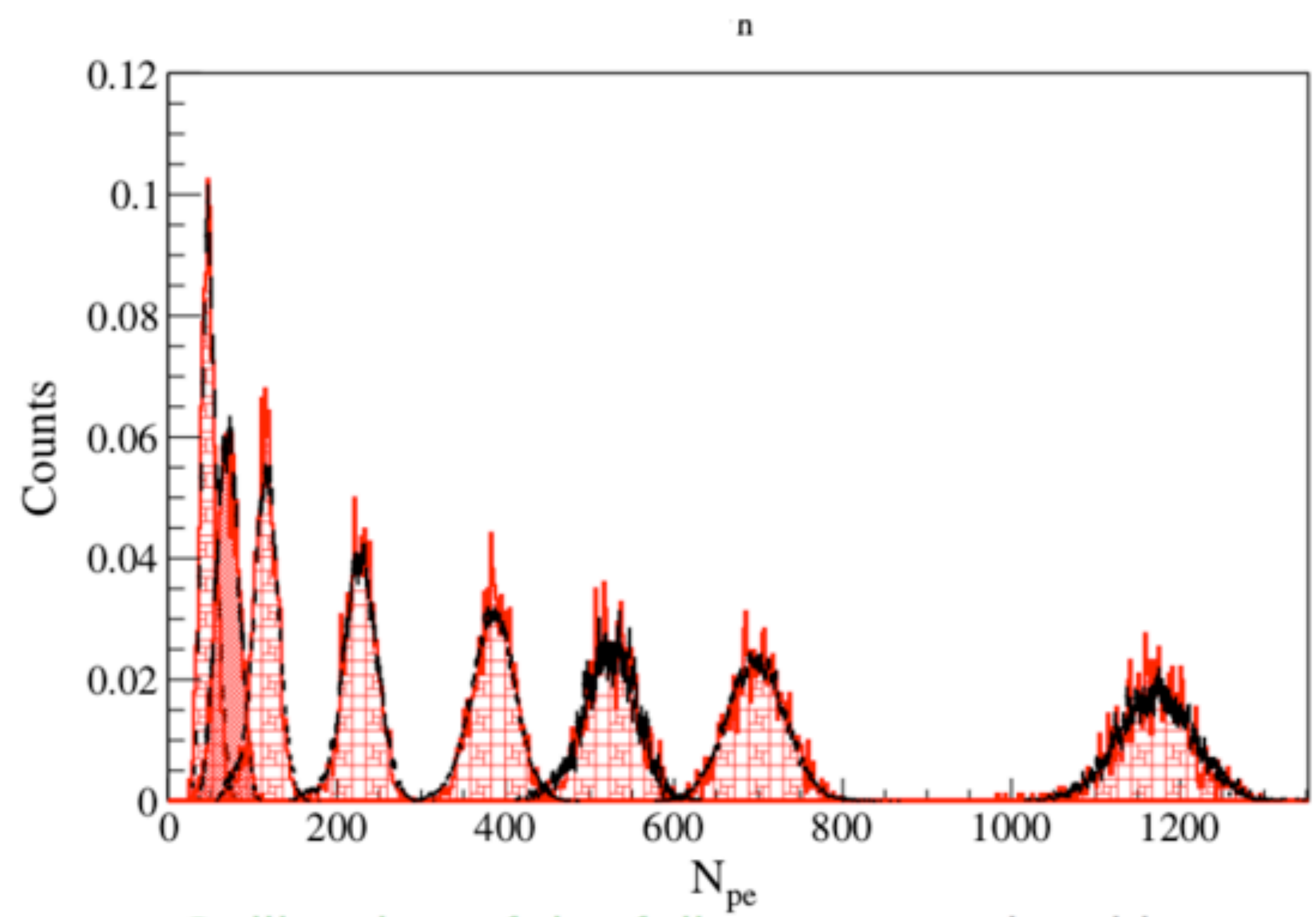
→ **expected rate:** $\mathcal{O}(1)$ event per ton x day

→ **radiopurity is essential!** <10^{-16} g/g in U+Th



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]

Be7

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	$\approx 10^{-12}$ 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 **^7Be** ν.	$\approx$ 1 Bq/m^3	< 30 cpd/100 t
^{39}Ar (β)	Air, cosmogenic	17 mBq/m^3	< 1 cpd/100 t
^7Be	Cosmogenic	$\approx 3 \cdot 10^{-2}$ Bq/t	$<10^{-6}$ Bq/t

Some considerations on ^{14}C

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

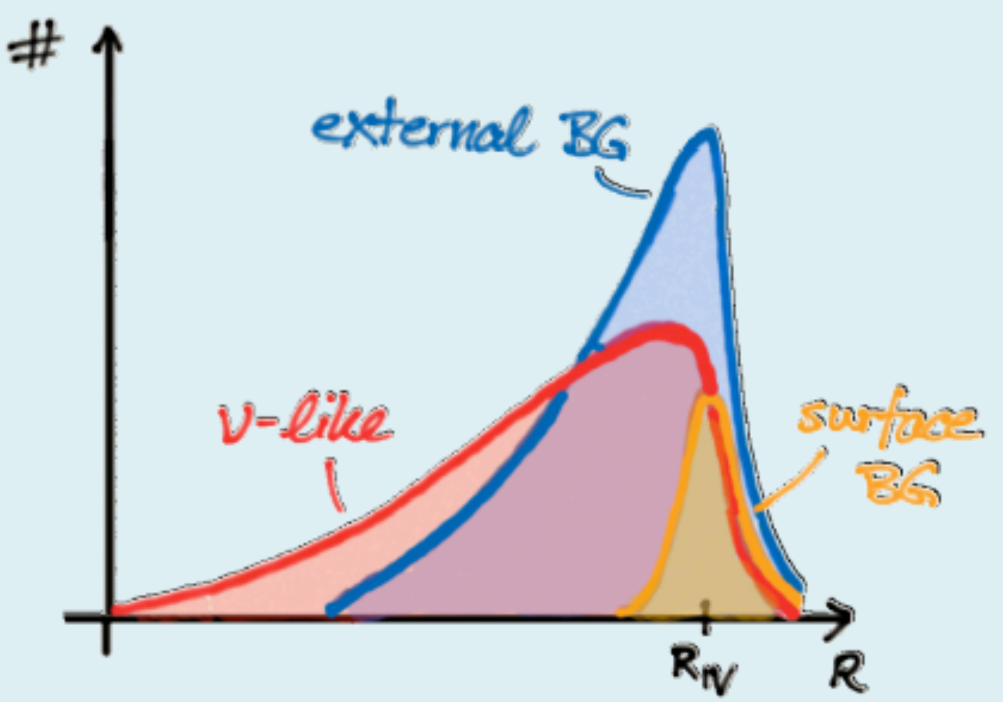
- ^{14}C is produced in atmospheric neutrons interactions with ^{14}N
- it ends up mixed with ^{12}C on the Earth, which the pseudo-cumene (LS) is made of
  - can't be purified out (same chemical composition as ^{12}C)
  - but it has a very small abundance in Bx: $^{14}C / ^{12}C = 10^{-18}$ g/g
  -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

Analysis/fits/PSD

- main analysis variable is visible energy → **spectral fit**
- **multivariate analysis** includes further variables in analysis fit (first use for pep-ν's in 2012)

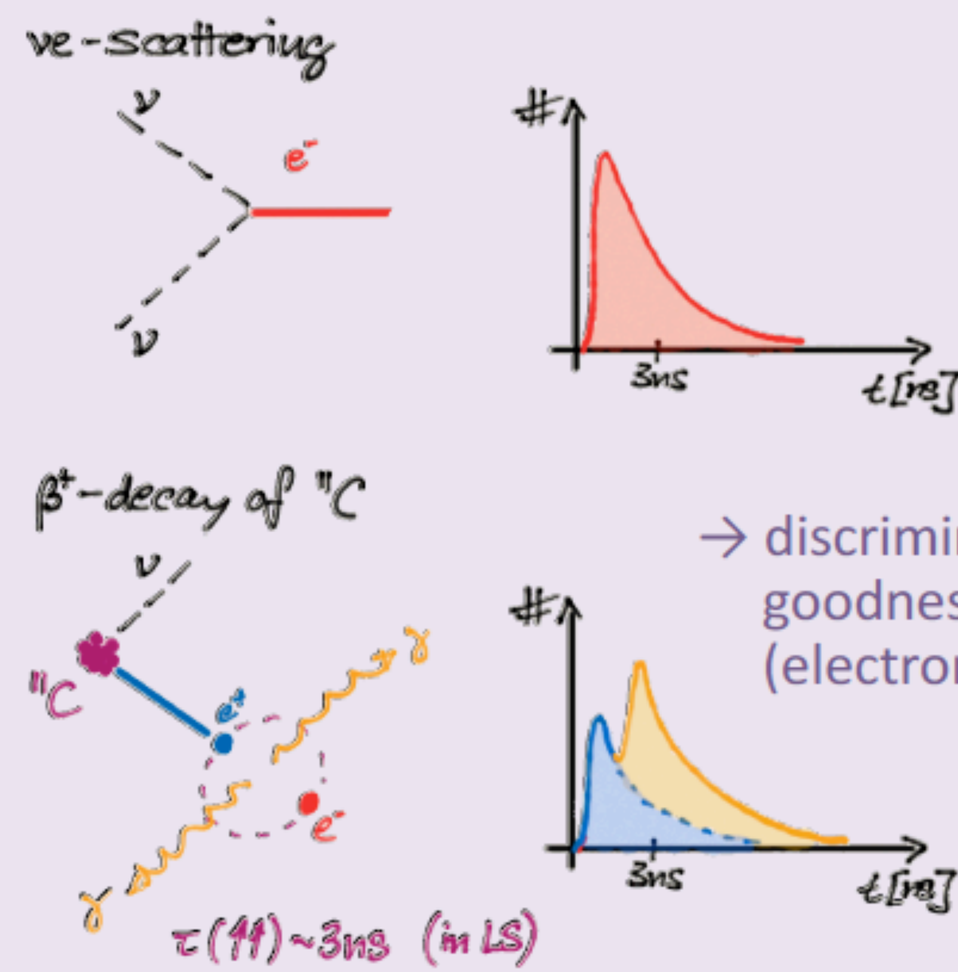
Radial fit

- distribution of neutrinos (and bulk radioactivity) is flat
- external gamma-rays are concentrated at vessel border

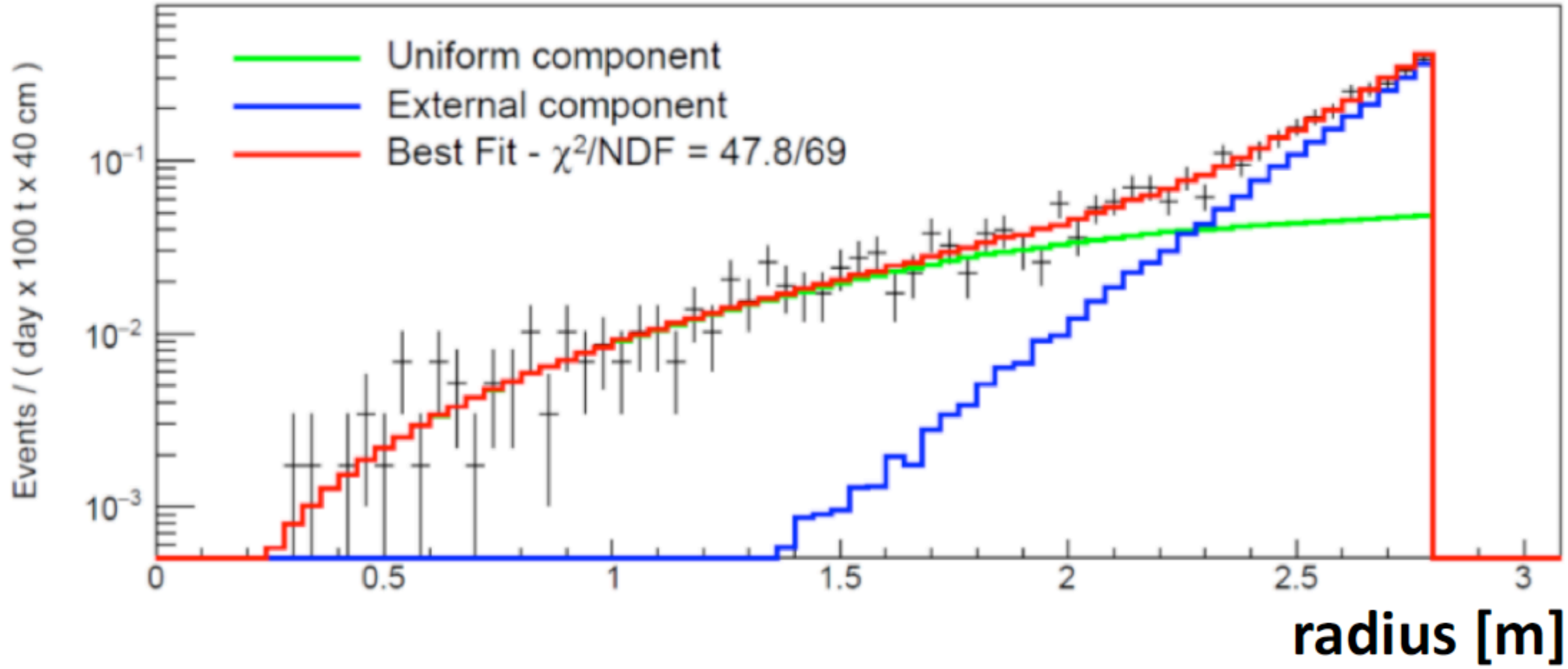


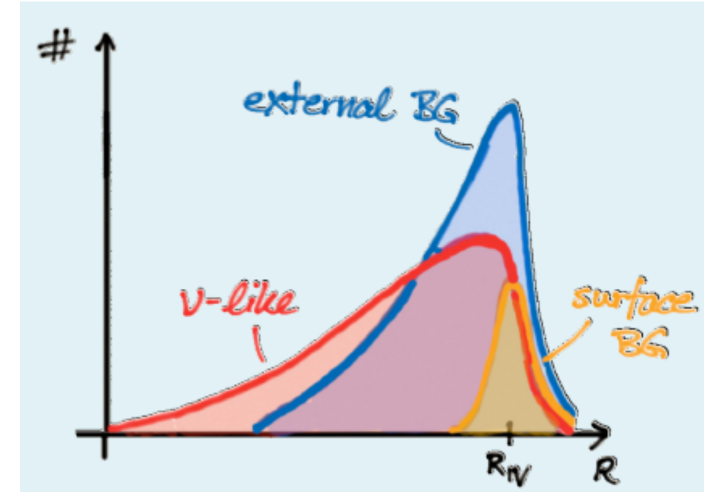
Pulse shape discrimination

- recoil electrons: standard scintillation signal
- β^+-emitters like ^{11}C feature elongated signal due to positronium formation in ~50% of the cases

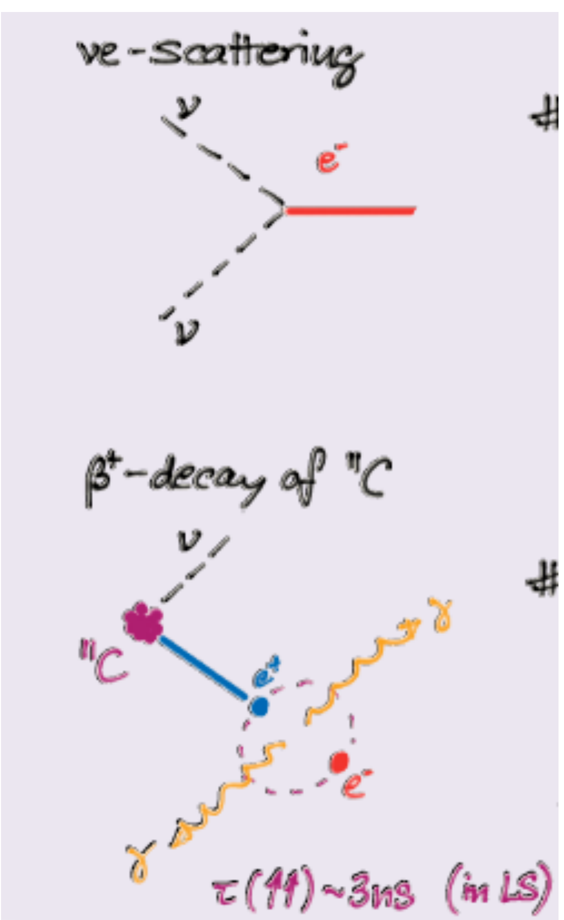


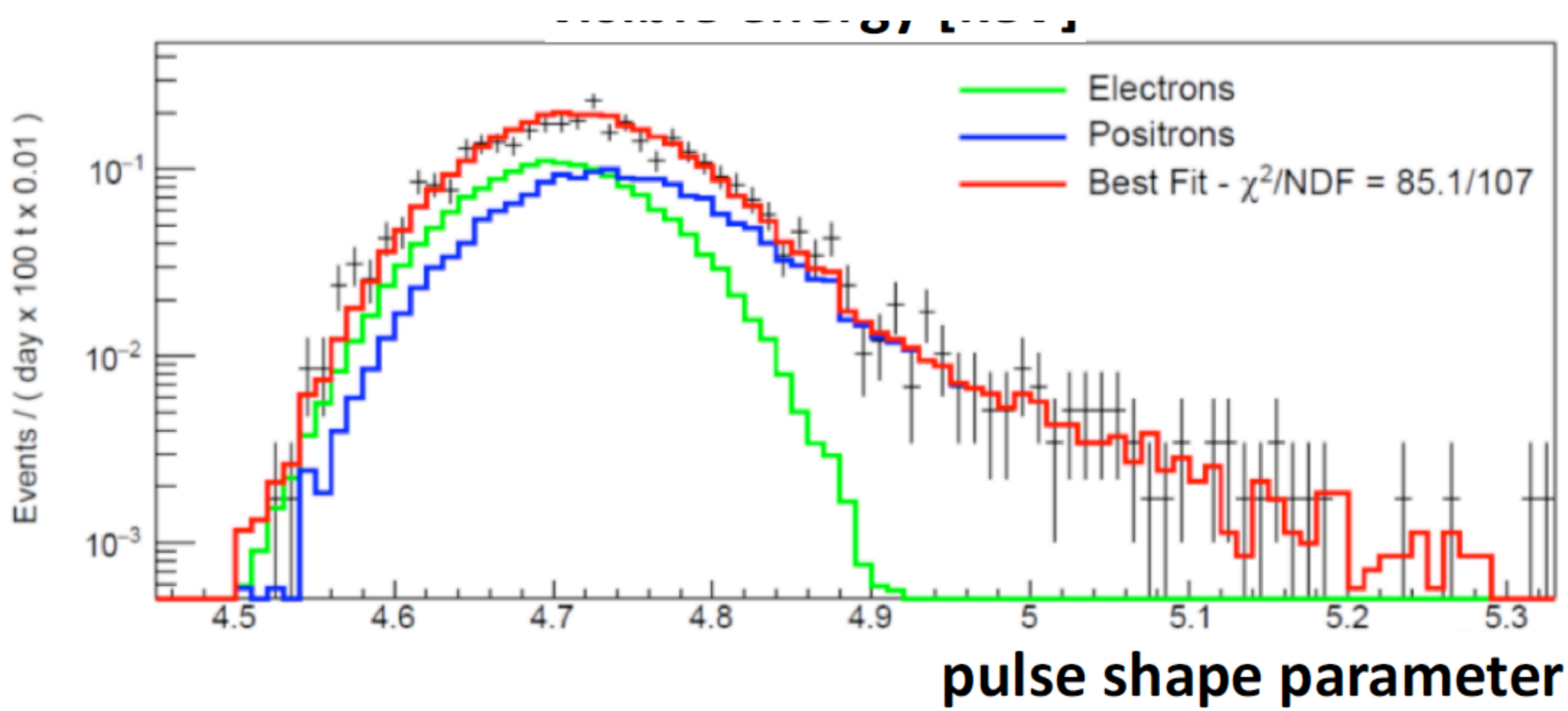
→ discrimination based on goodness of position fit (electron time-PDFs)





radial event distribution





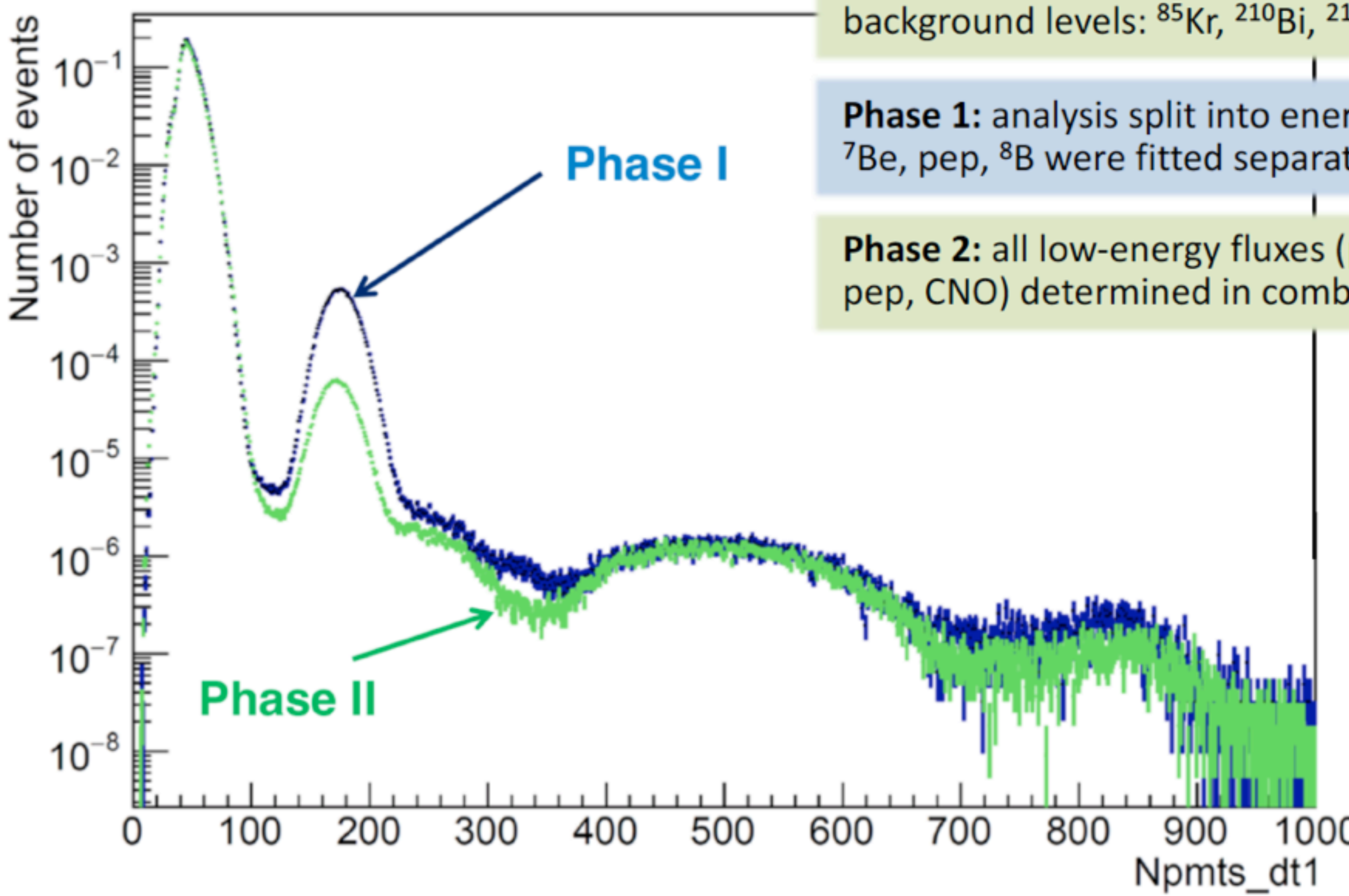
e^+/e^- discrimination

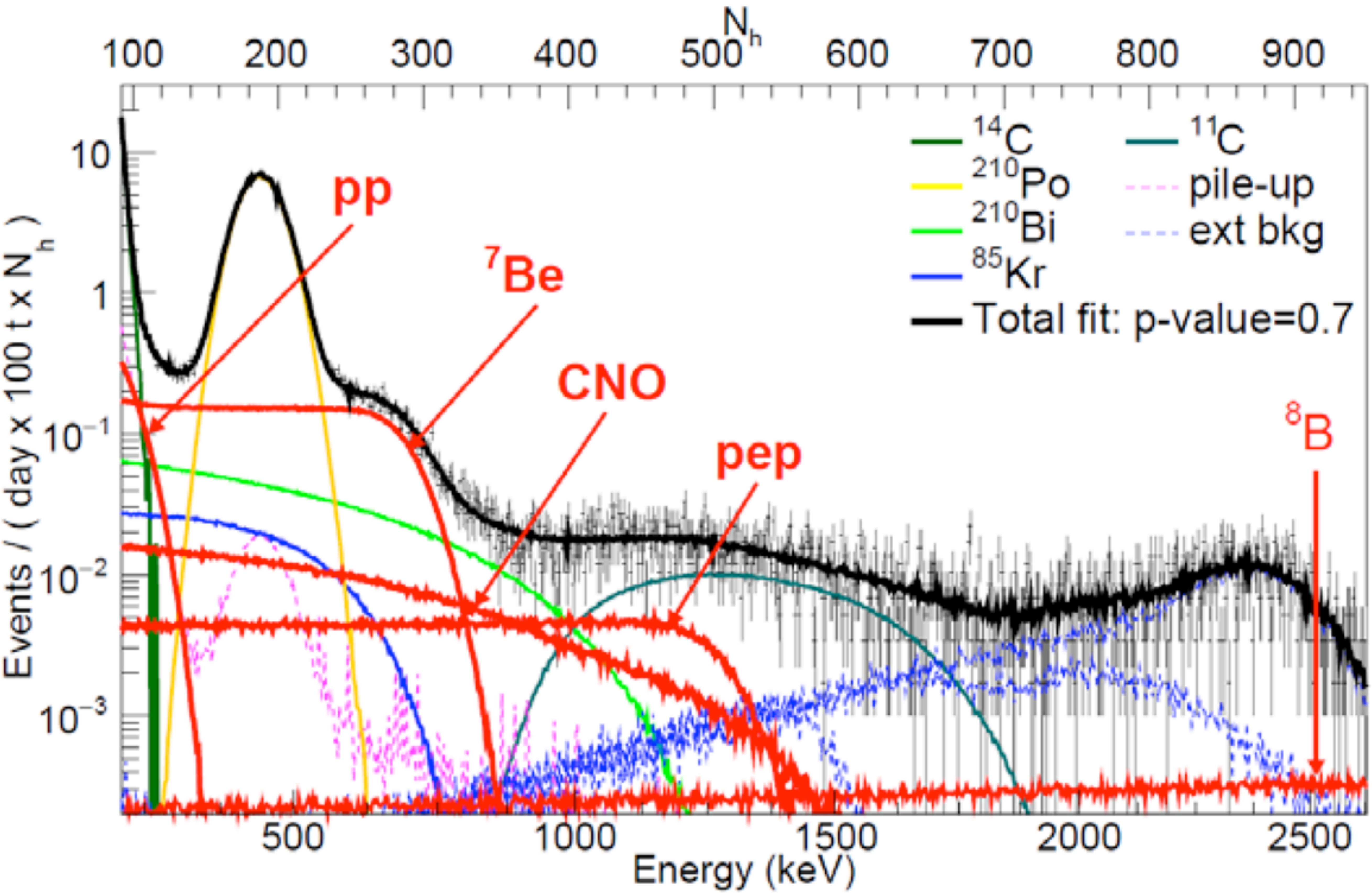
Phase 1 vs. Phase 2

Phase 2 features lower radioactive background levels: ^{85}Kr, ^{210}Bi, ^{210}Po

Phase 1: analysis split into energy ranges, ^{7}Be, pep, ^{8}B were fitted separately

Phase 2: all low-energy fluxes (pp, ^{7}Be, pep, CNO) determined in combined fit





N_h
100
200
300
400
500
600
700
800
900
10
1
10^{-1}
10^{-2}
10^{-3}
Events / (day x 100 t x N_h)
pp
^{7}Be
CNO
pep
^{8}B
^{14}C
^{210}Po
^{210}Bi
^{85}Kr
^{11}C
pile-up
ext bkg
Total fit: p-value=0.7
500
1000
1500
2000
2500
Energy (keV)

Results

arXiv : 1707.09279

- **Data-set:** Dec 14th 2011- May 21st 2016
- **Total exposure**: 1291.51 days x 71.3 tons
- **Fit range**: (0.19-2.93) MeV

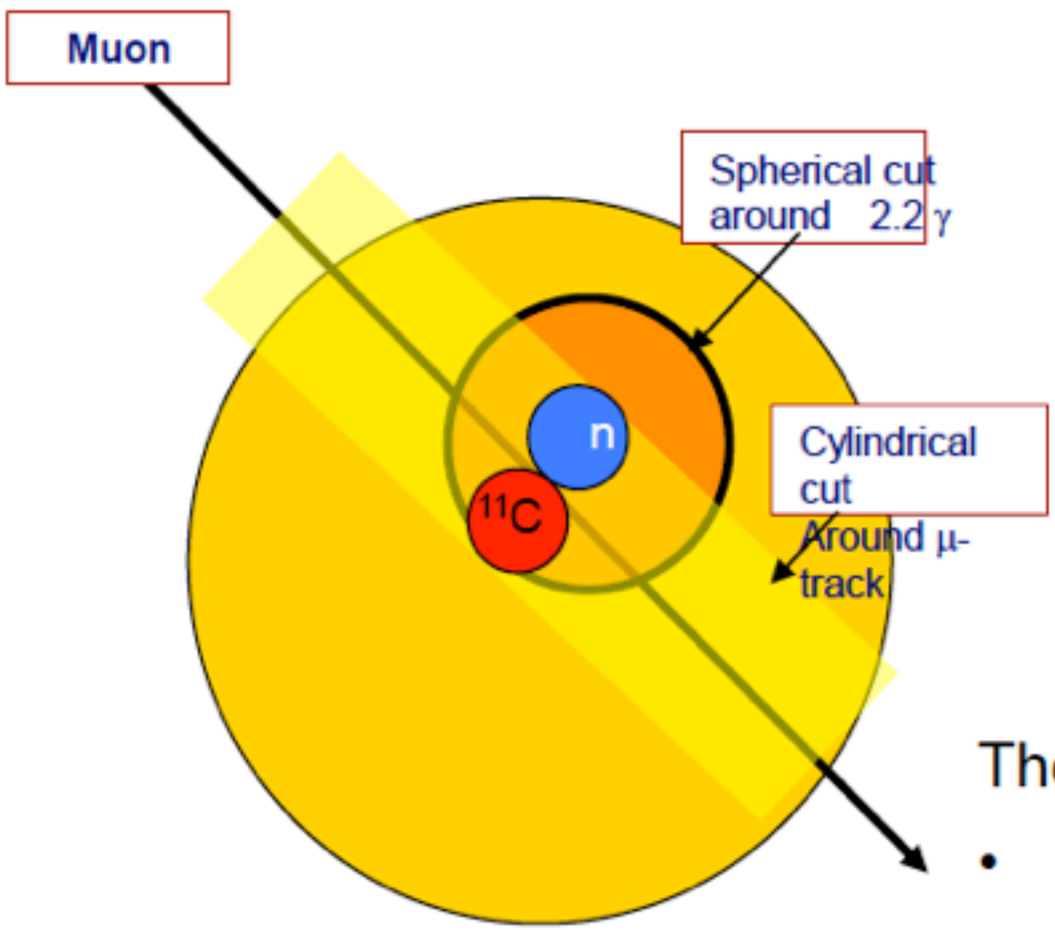
Solar ν	Borexino experimental results		B16(GS98)-HZ		B16(AGSS09)-LZ	
	Rate [cpd/100 t]	Flux [cm^{-2}s^{-1}]	Rate [cpd/100 t]	Flux [cm^{-2}s^{-1}]	Rate [cpd/100 t]	Flux [cm^{-2}s^{-1}]
pp	$134 \pm 10\ ^{+6}_{-10}$	$(6.1 \pm 0.5\ ^{+0.3}_{-0.5}) \times 10^{10}$	131.0 ± 2.4	$5.98\,(1 \pm 0.006) \times 10^{10}$	132.1 ± 2.3	$6.03\,(1 \pm 0.005) \times 10^{10}$
^{7}Be	$48.3 \pm 1.1\ ^{+0.4}_{-0.7}$	$(4.99 \pm 0.13\ ^{+0.07}_{-0.10}) \times 10^{9}$	47.8 ± 2.9	$4.93\,(1 \pm 0.06) \times 10^{9}$	43.7 ± 2.6	$4.50\,(1 \pm 0.06) \times 10^{9}$
pep (HZ)	$2.43 \pm 0.36\ ^{+0.15}_{-0.22}$	$(1.27 \pm 0.19\ ^{+0.08}_{-0.12}) \times 10^{8}$	2.74 ± 0.05	$1.44\,(1 \pm 0.009) \times 10^{8}$	2.78 ± 0.05	$1.46\,(1 \pm 0.009) \times 10^{8}$
pep (LZ)	$2.65 \pm 0.36\ ^{+0.15}_{-0.24}$	$(1.39 \pm 0.19\ ^{+0.08}_{-0.13}) \times 10^{8}$	2.74 ± 0.05	$1.44\,(1 \pm 0.009) \times 10^{8}$	2.78 ± 0.05	$1.46\,(1 \pm 0.009) \times 10^{8}$
CNO	< 8.1 (95% C.L.)	$< 7.9 \times 10^{8}$ (95% C.L.)	4.91 ± 0.56	$4.88\,(1 \pm 0.11) \times 10^{8}$	3.52 ± 0.37	$3.51\,(1 \pm 0.10) \times 10^{8}$

Systematics

Source of uncertainty	pp −%	pp +%	^{7}Be −%	^{7}Be +%	pep −%	pep +%	
Fit method (analytical/MC)	-1.2	1.2	-0.2	0.2	-4.0	4.0	
Choice of energy estimator	-2.5	2.5	-0.1	0.1	-2.4	2.4	
Pile-up modeling	-2.5	0.5	0	0	0	0	
Fit range and binning	-3.0	3.0	-0.1	0.1	1.0	1.0	
Fit models	-4.5	0.5	-1.0	0.2	-6.8	2.8	^{210}Bi, E-scale, response
Inclusion of ^{85}Kr constraint	-2.2	2.2	0	0.4	-3.2	0	**R(^{85}Kr)<7.5 @ 95%**
Live Time	-0.05	0.05	-0.05	0.05	-0.05	0.05	**LS mass** (Live Time, Scintillator density, Fiducial volume)
Scintillator density	-0.05	0.05	-0.05	0.05	-0.05	0.05	
Fiducial volume	-1.1	0.6	-1.1	0.6	-1.1	0.6	
Total systematics (%)	-7.1	4.7	-1.5	0.8	-9.0	5.6	

B8

Three-fold Coincidence technique (TFC) for ^{11}C tagging



^{11}C production in muon interactions is accompanied by neutron:

$$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$$

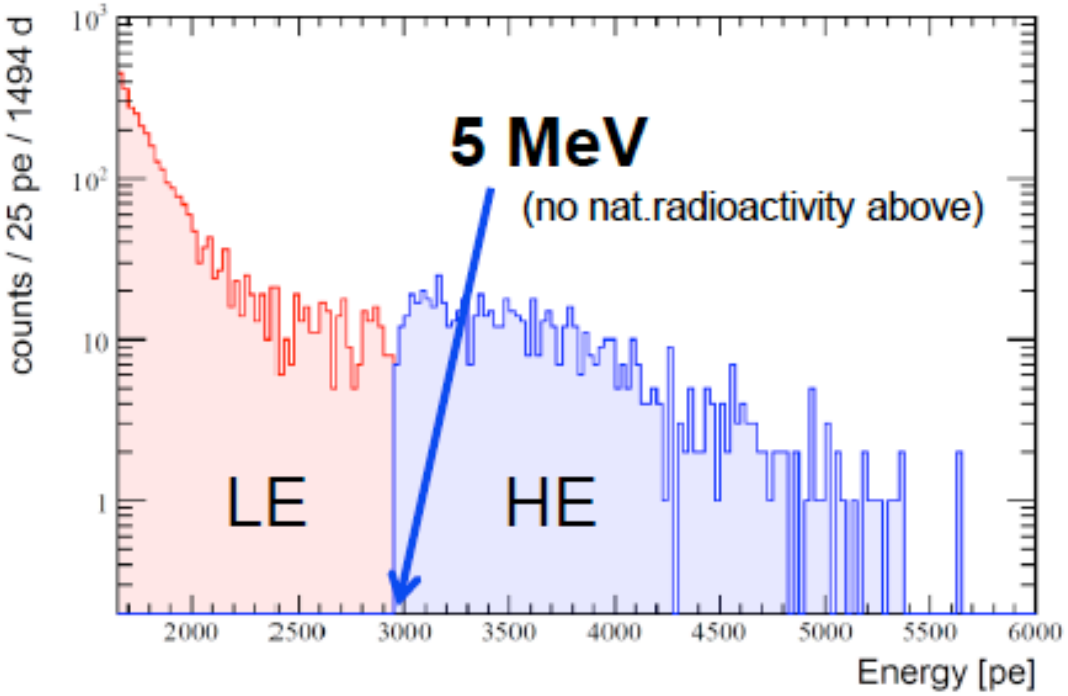
~30 min: $^{11}B + e^+ + \nu_e$

~250 us: $+p \rightarrow d + \gamma(2.2\ MeV)$

The likelihood for ^{11}C tagging is using:

- distance in space and time from the μ-track;
- distance from the neutron;
- neutron multiplicity;
- muon dE/dx and number of muon clusters in an event

The TFC algorithm has (92±4)% ^{11}C-tagging eciency, while preserving (64.28±0.01)% of the total exposure in the TFC-subtracted spectrum.



$$R_{LE} = 0.133^{+0.013}_{-0.013}\,(stat)\,^{+0.003}_{-0.003}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t},$$

$$R_{HE} = 0.087^{+0.08}_{-0.010}\,(stat)\,^{+0.005}_{-0.005}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t},$$

$$R_{LE+HE} = 0.220^{+0.015}_{-0.016}\,(stat)\,^{+0.006}_{-0.006}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t}.$$

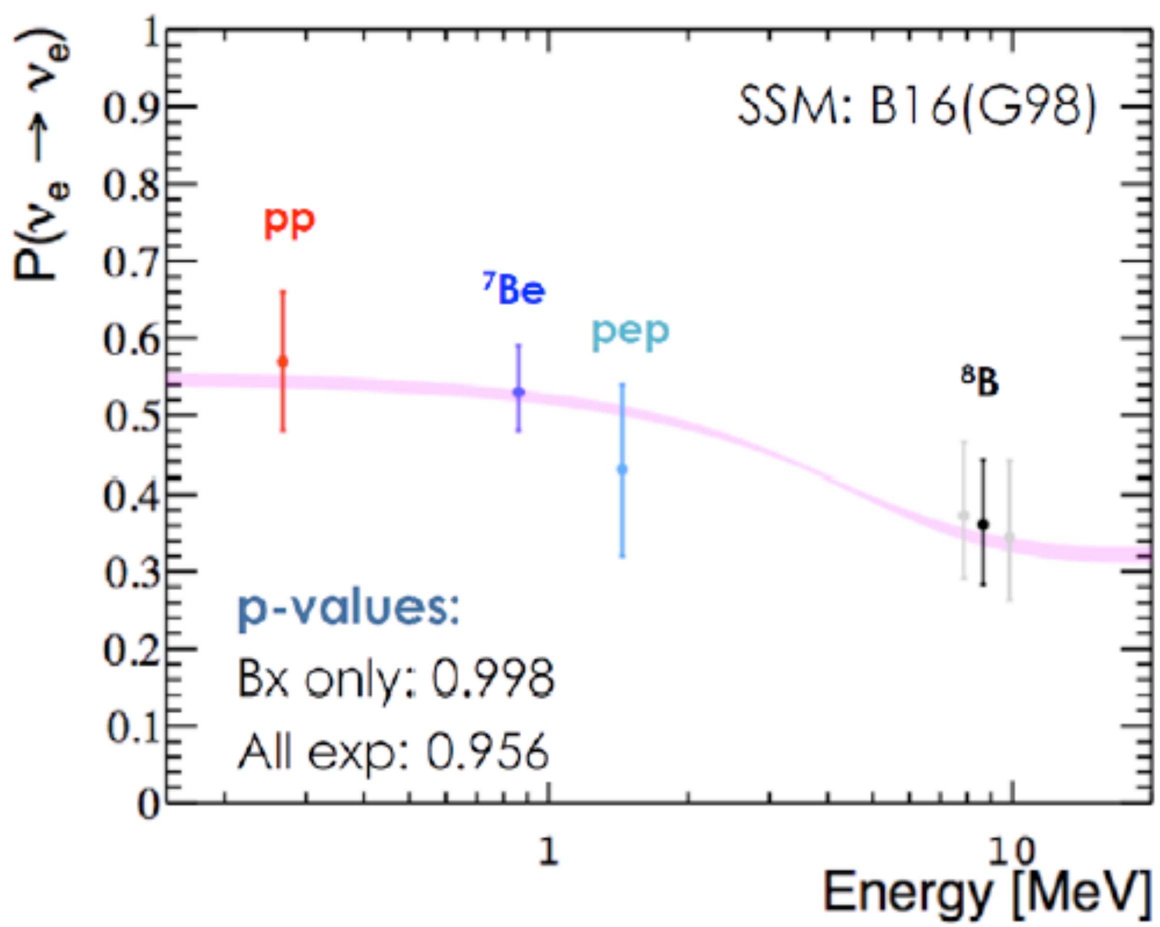
Expected rate in the LE+HE range:

0.211± 0.025 cpd/100 t

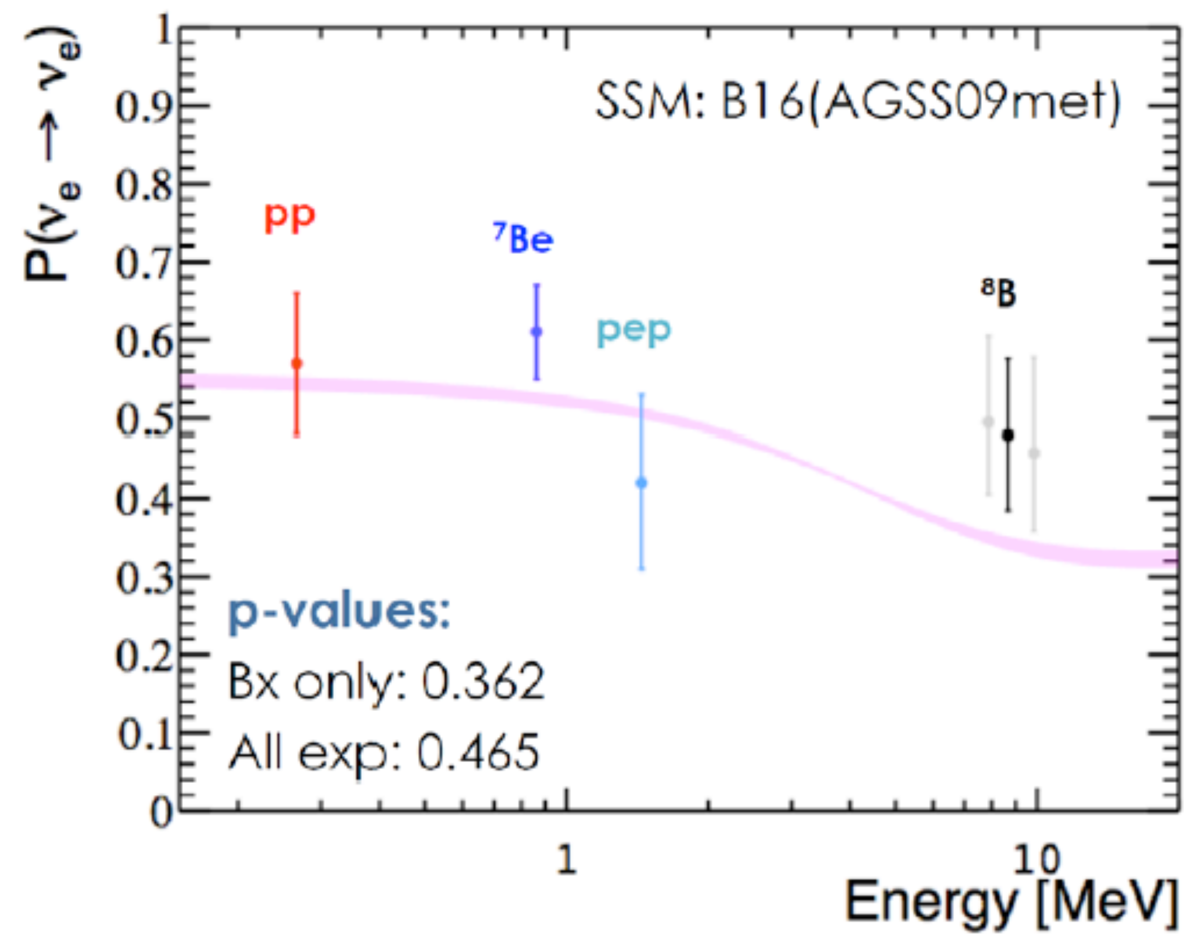
Assuming B16(G98) SSM and MSW+LMA

φ(hep)<2.2 × 10^5 cm^{-2} s^{-1} (90% C.L.)
vs 7.98/8.25 × 10^3 in HZ/LZ SSM.

High metallicity SSM

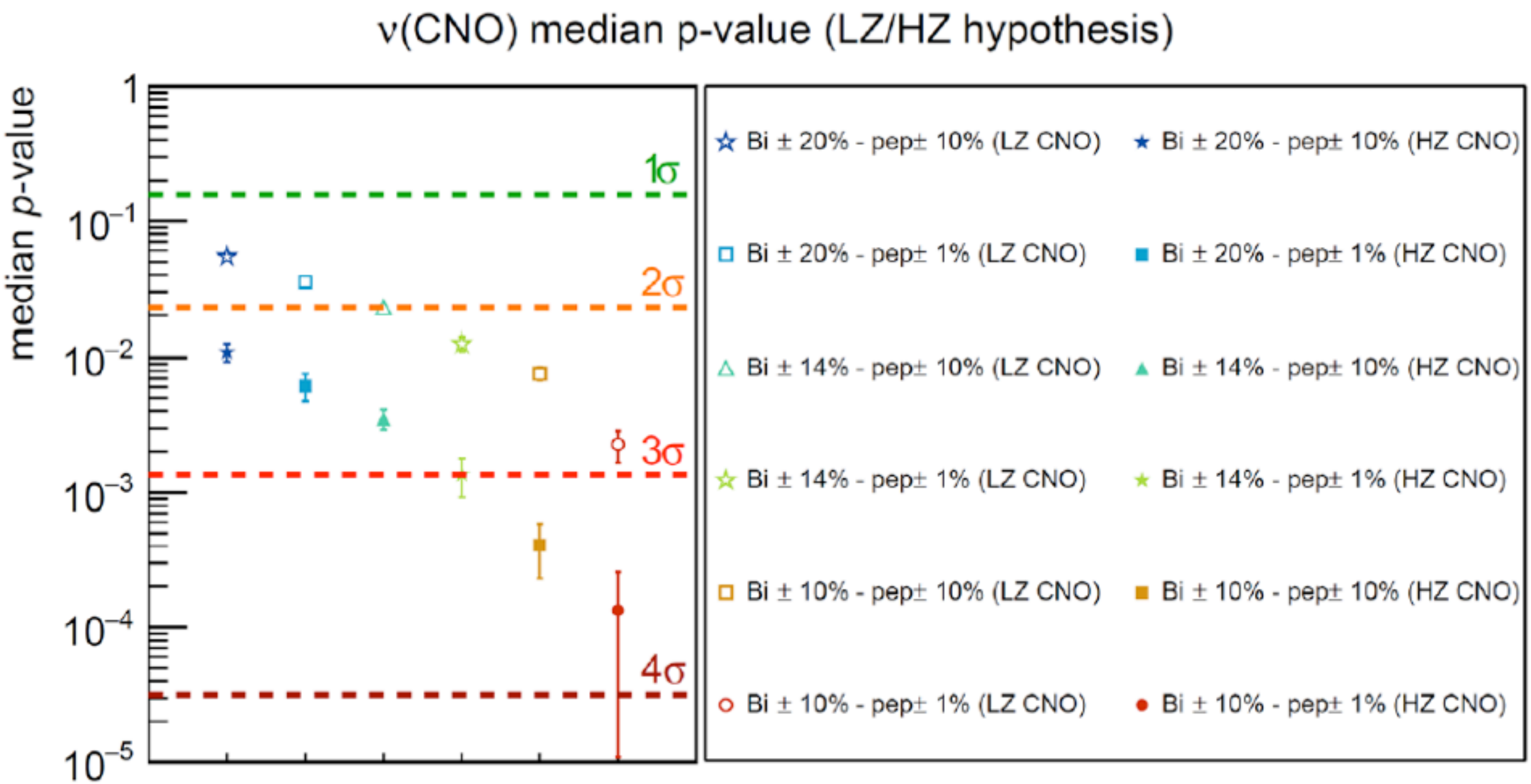


Low metallicity SSM



CNO sensitivity

Depends on both ^{210}Bi and pep-neutrino rates. We assume that ^{210}Bi will be measured (10-20%) and pep-rate can be constrained by constraining pp/pep ratio in the fit.



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):

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

- 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

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

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

- Thus *d* can be formed also through:

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

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

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

30 years after the detection of SN1987A neutrinos

2017/2/23

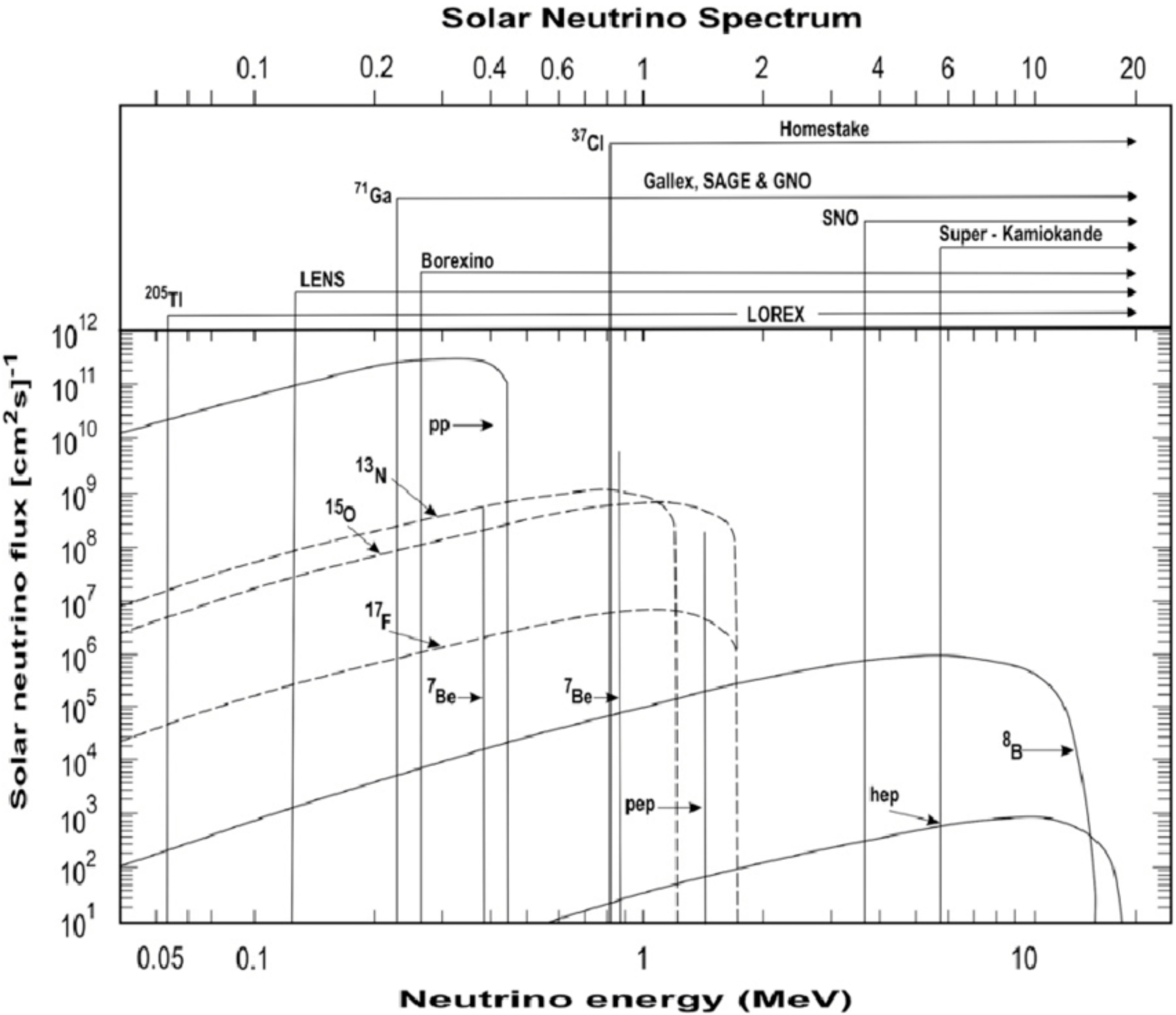
On February 23, 1987, just before 30 years from today, the neutrinos emitted from the supernova explosion SN1987A in the Large Magellanic Cloud, approximately 160,000 light-years away, reached the earth. Kamiokande, the predecessor detector of Super-Kamiokande, detected the 11 emitted neutrinos. Worldwide, 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

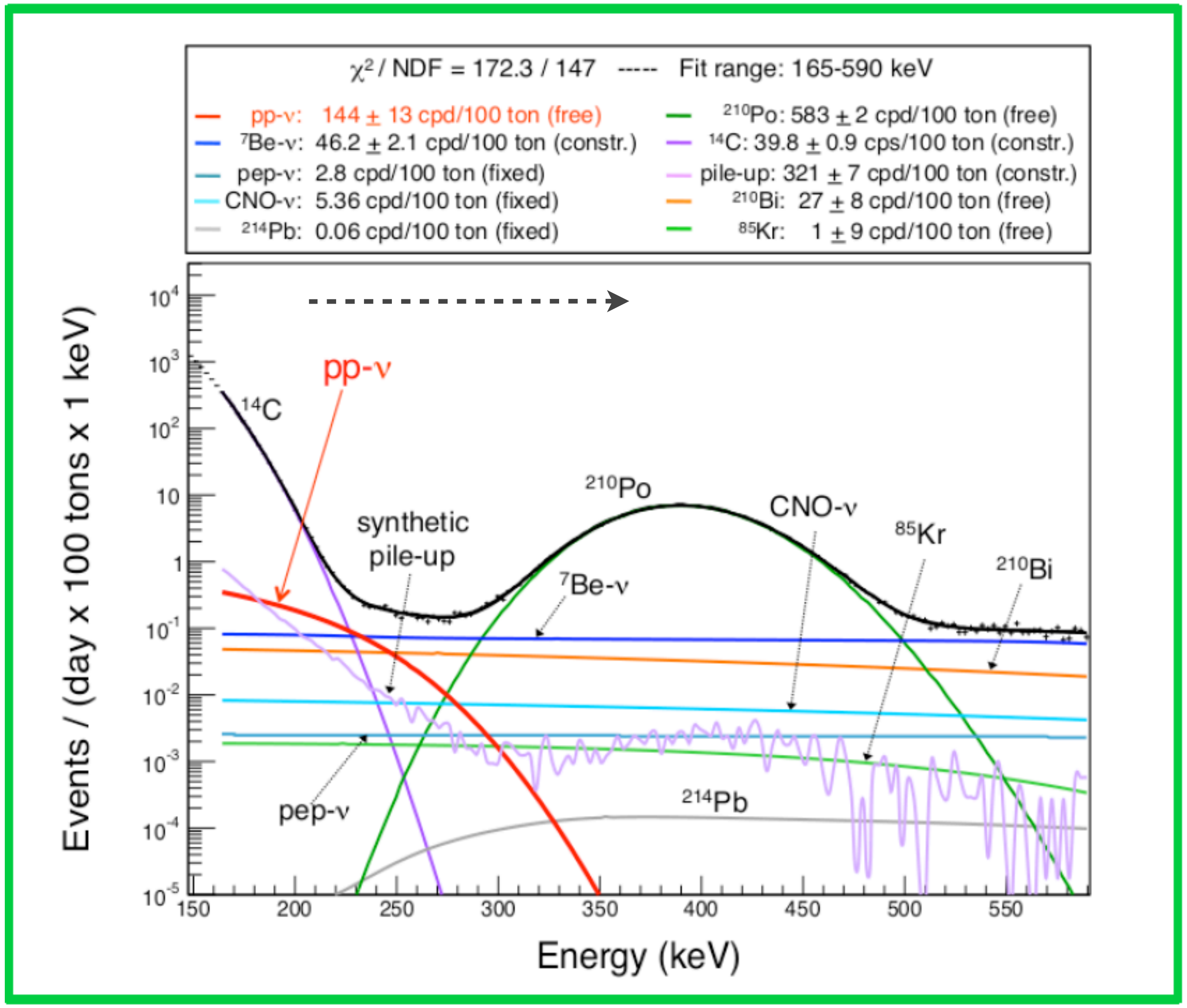
Errors in helioseismic inferences in determinations of solar structure

1. Observational errors
2. Departures from linearity in the relation between frequency and structure differences
3. Dependence on reference model
   – Systematic errors in reference model

Note: in differences inferred from inversion only 1. and 2. matter

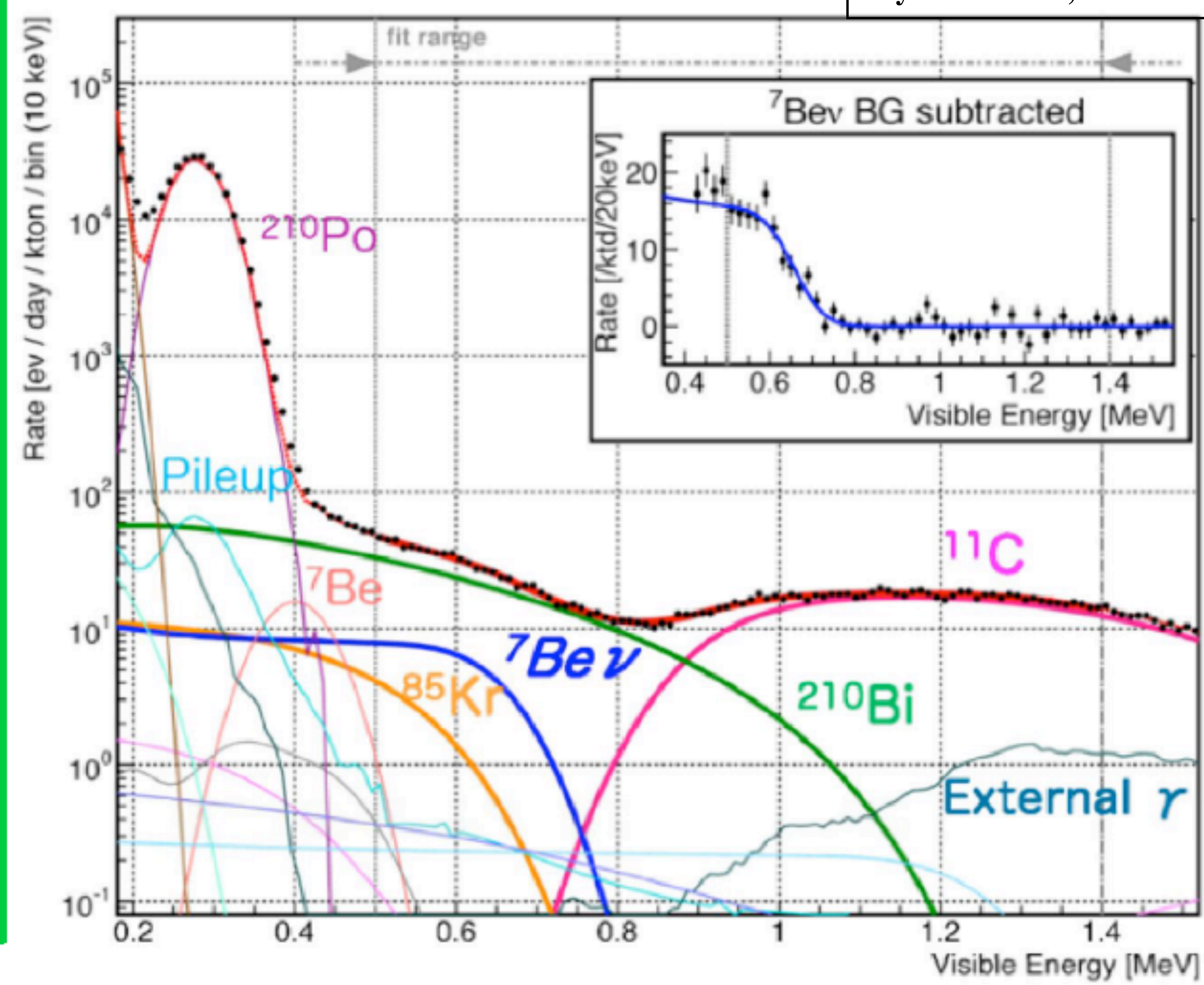

Solar Neutrino Spectrum
0.1
0.2
0.4
0.6
1
2
4
6
10
20
37Cl
Homestake
71Ga
Gallex, SAGE & GNO
SNO
Super - Kamiokande
Borexino
LENS
205Tl
LOREX
pp
13N
15O
17F
7Be
7Be
pep
hep
8B
Solar neutrino flux [cm2s]-1
0.05
0.1
1
10
Neutrino energy (MeV)

Comparison with Kamland



KamLAND signal[KL2015]

Phys. Rev. C 92, 055808



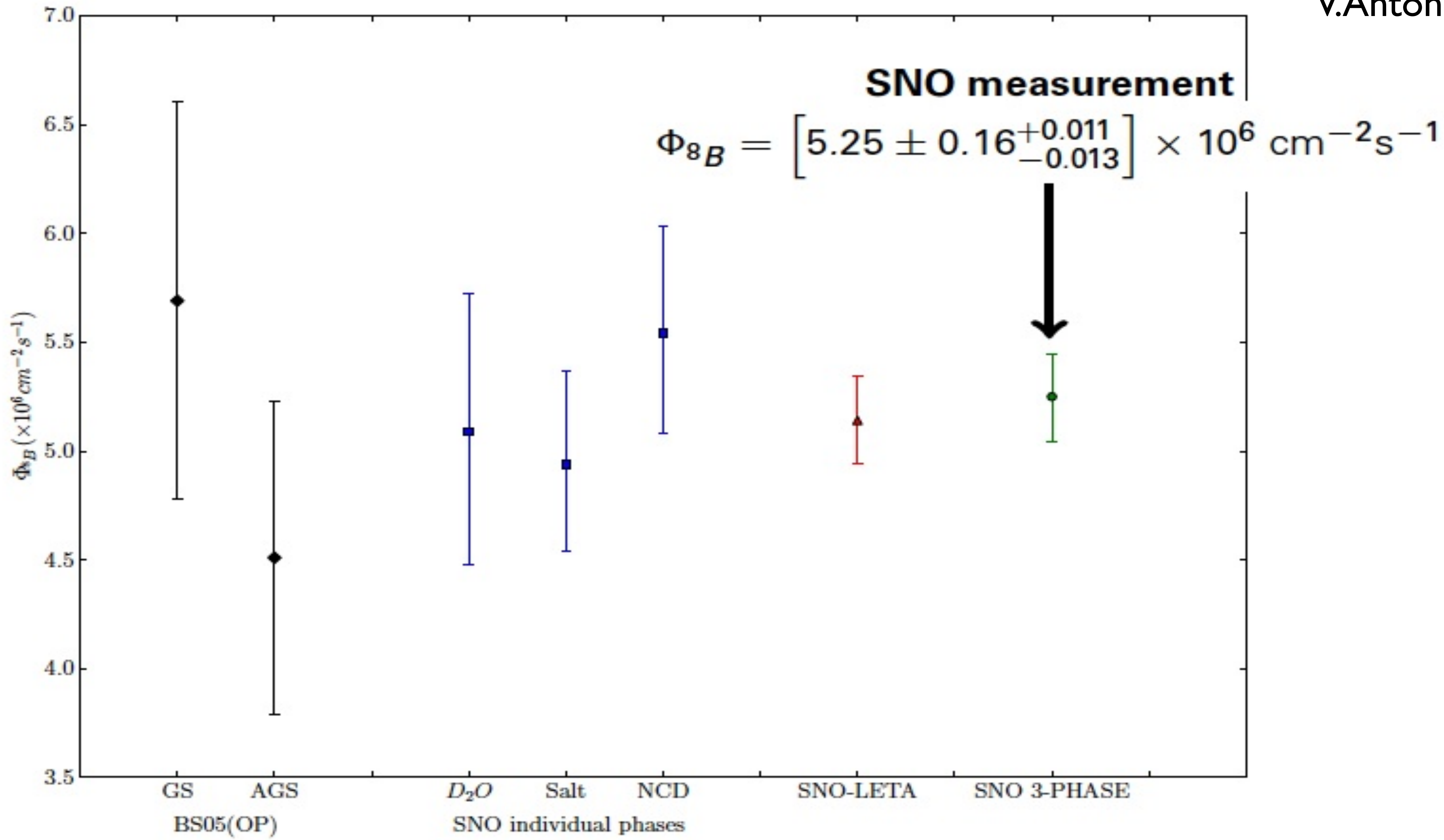
Low level of contamination from ^{14}C allow to gain ^{7}Be statistics in the fit

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

- was evaluated with special triggers

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

V.Antonelli



^8B 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}))