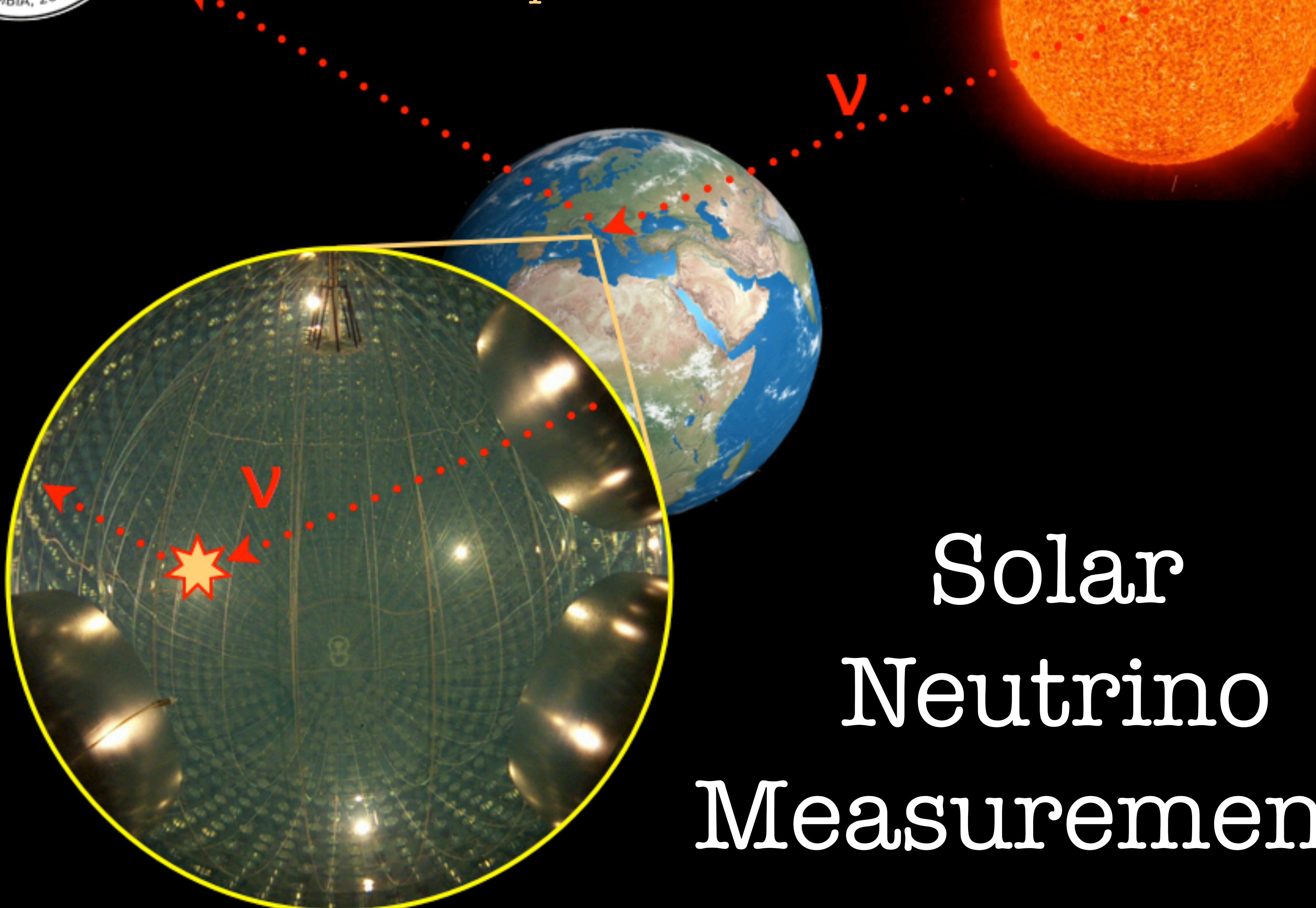
PIC 2018 — XXXVII International Symposium on Physics in Collision
Bogotá, Colombia
11-15 September 2018

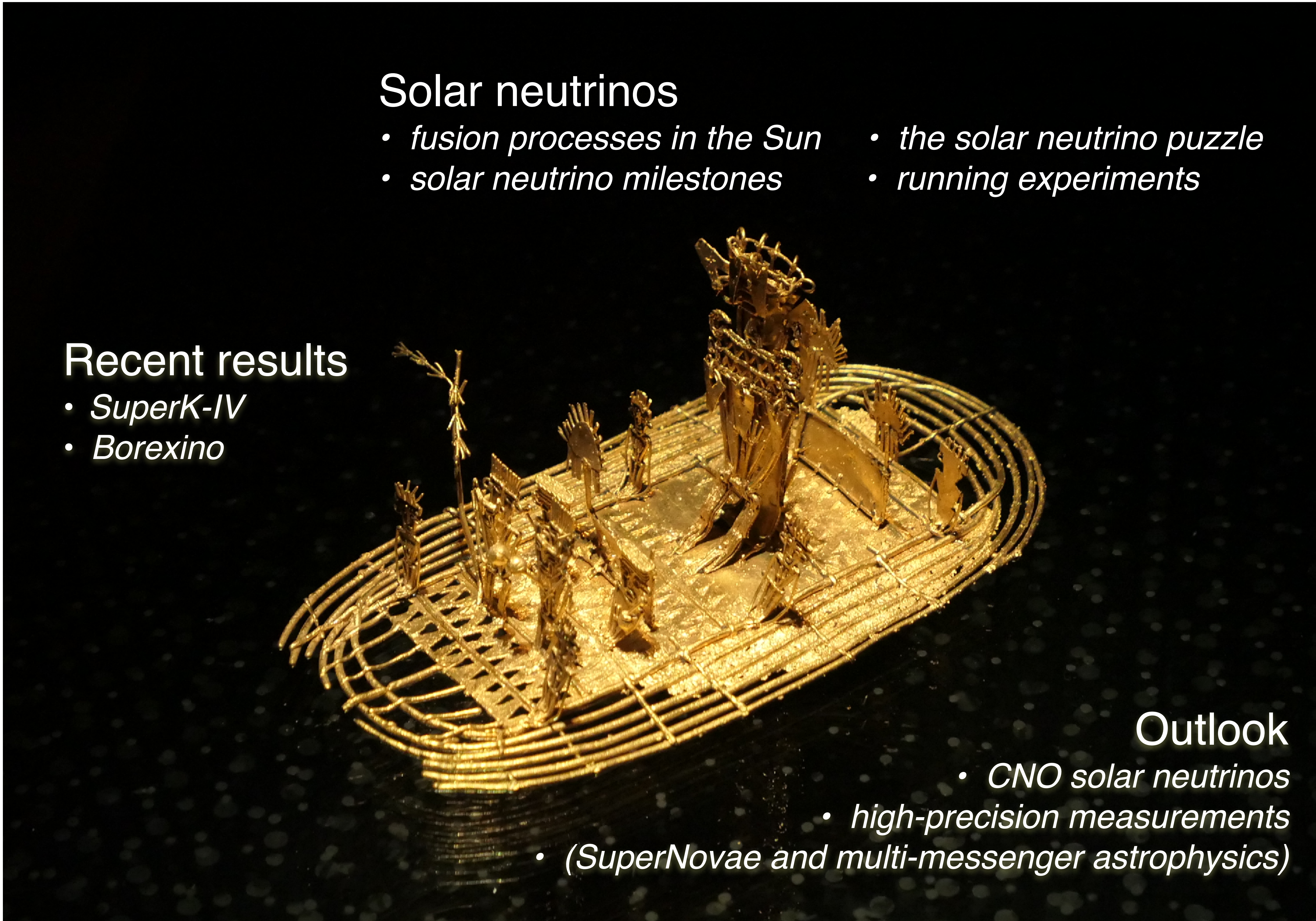


Solar Neutrino Measurements

Andrea Pocar
University of Massachusetts, Amherst

Amherst Center for Fundamental Interactions
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

Outline



Solar neutrinos

- *fusion processes in the Sun*
- *solar neutrino milestones*
- *the solar neutrino puzzle*
- *running experiments*

Recent results

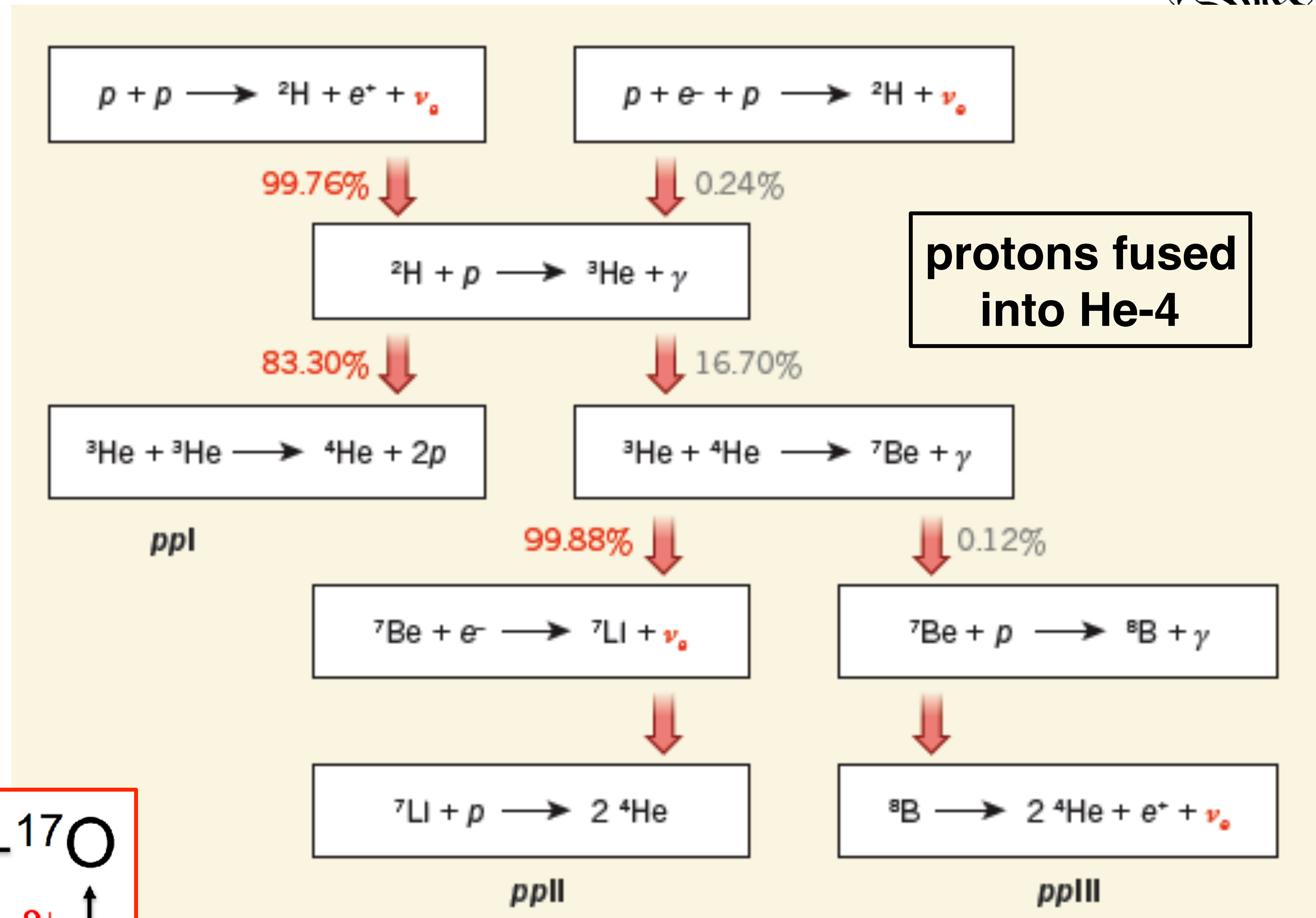
- *SuperK-IV*
- *Borexino*

Outlook

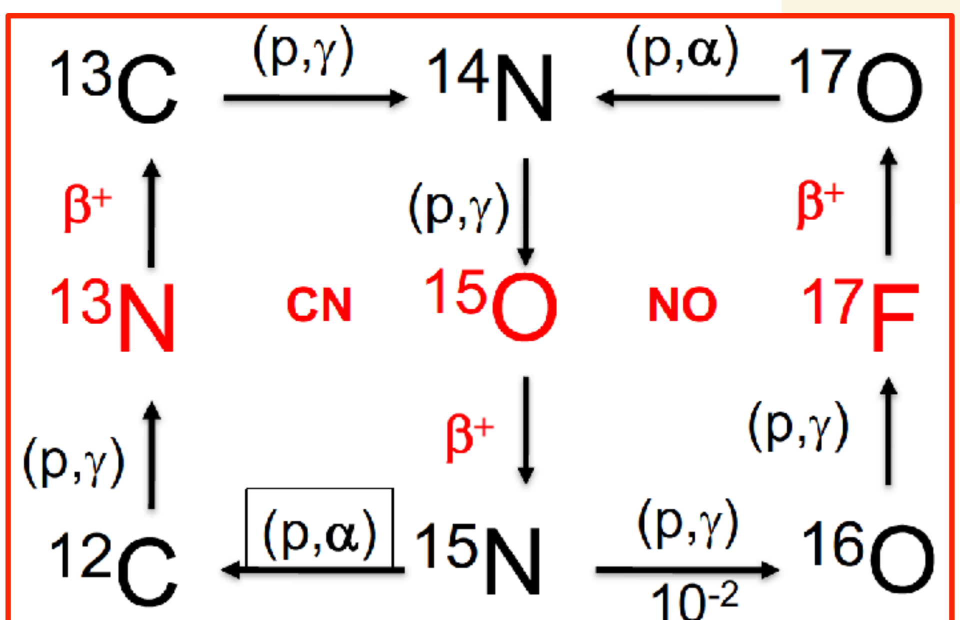
- *CNO solar neutrinos*
- *high-precision measurements*
- *(SuperNovae and multi-messenger astrophysics)*

Solar fusion and neutrino emission

H. Bethe (1906-2005)



protons fused into He-4



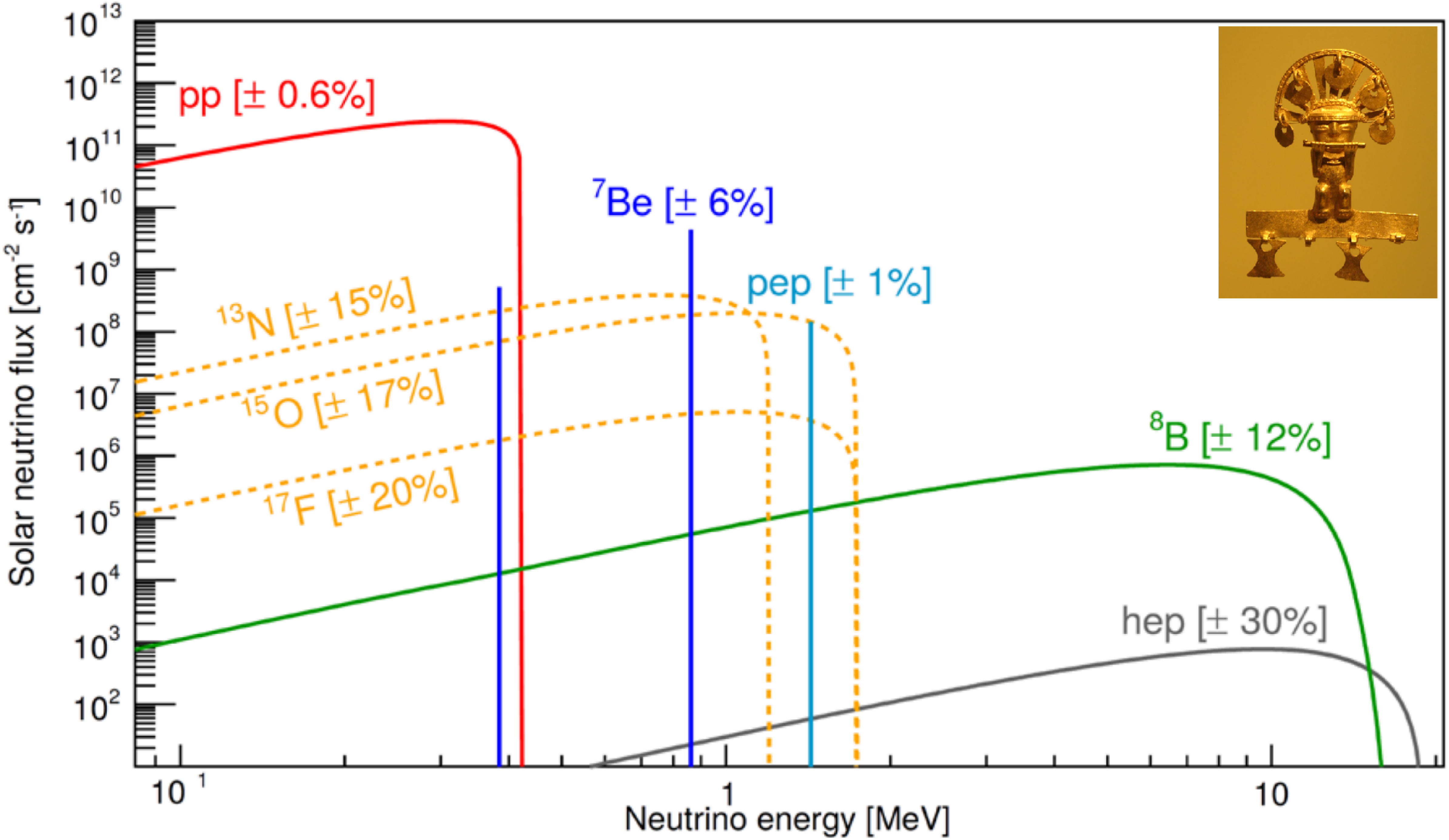
$$4p \rightarrow {}^4\text{He} + 2e^+ + (24.69 + 2m_e c^2)\,\text{MeV}$$

$$\langle E_\nu \rangle \sim 0.53\,\text{MeV}$$

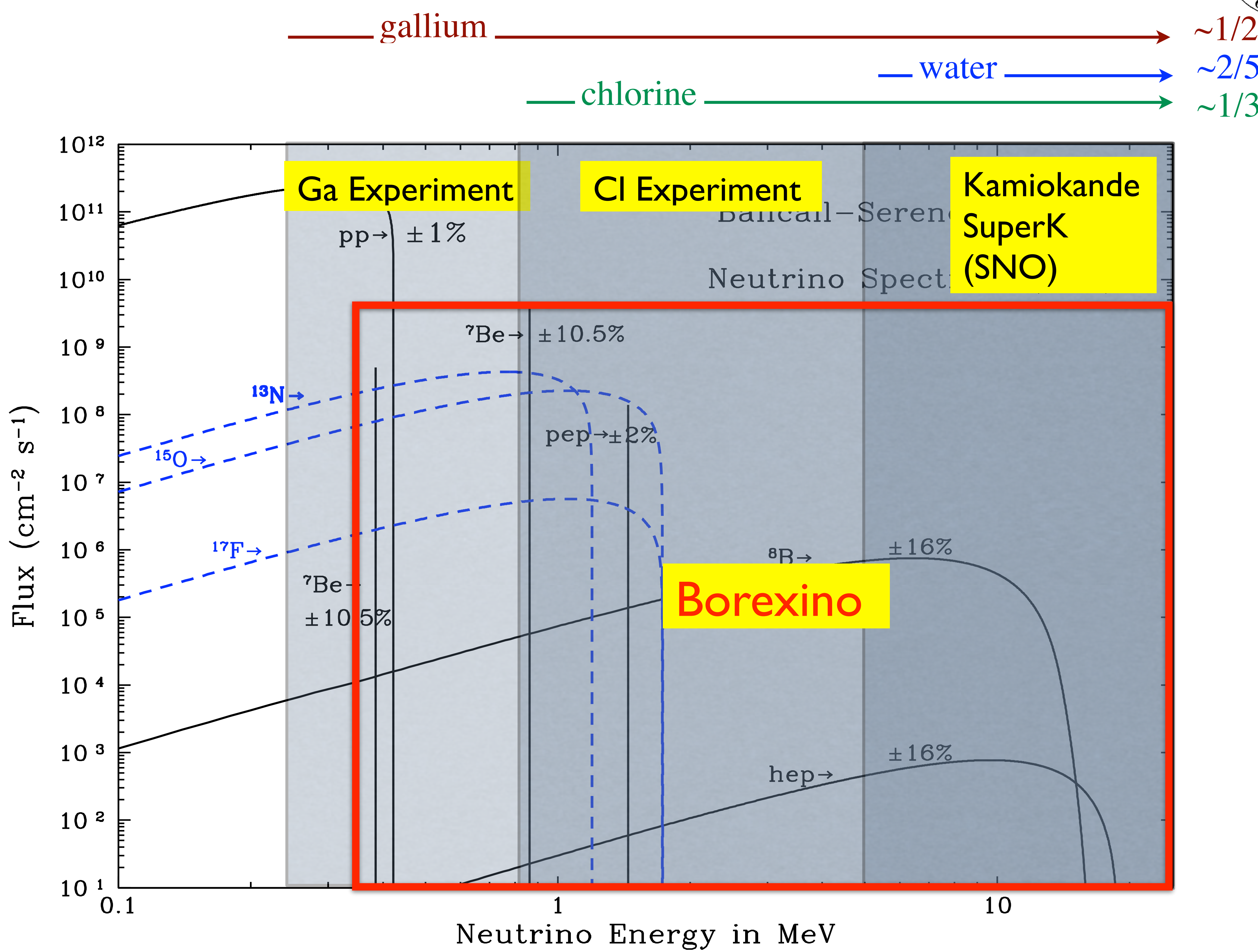
(~2% of the total energy)

Solar neutrino spectrum

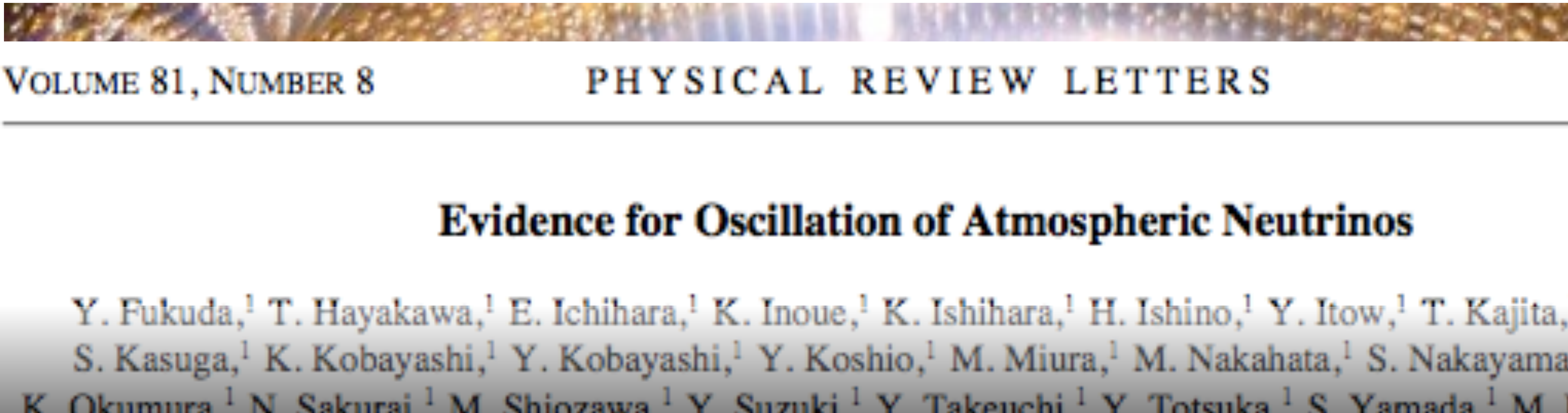
Aldo Serenelli et al, Astrophys. J. 835 (2017) no.2, 202



The Solar Neutrino "Puzzle"



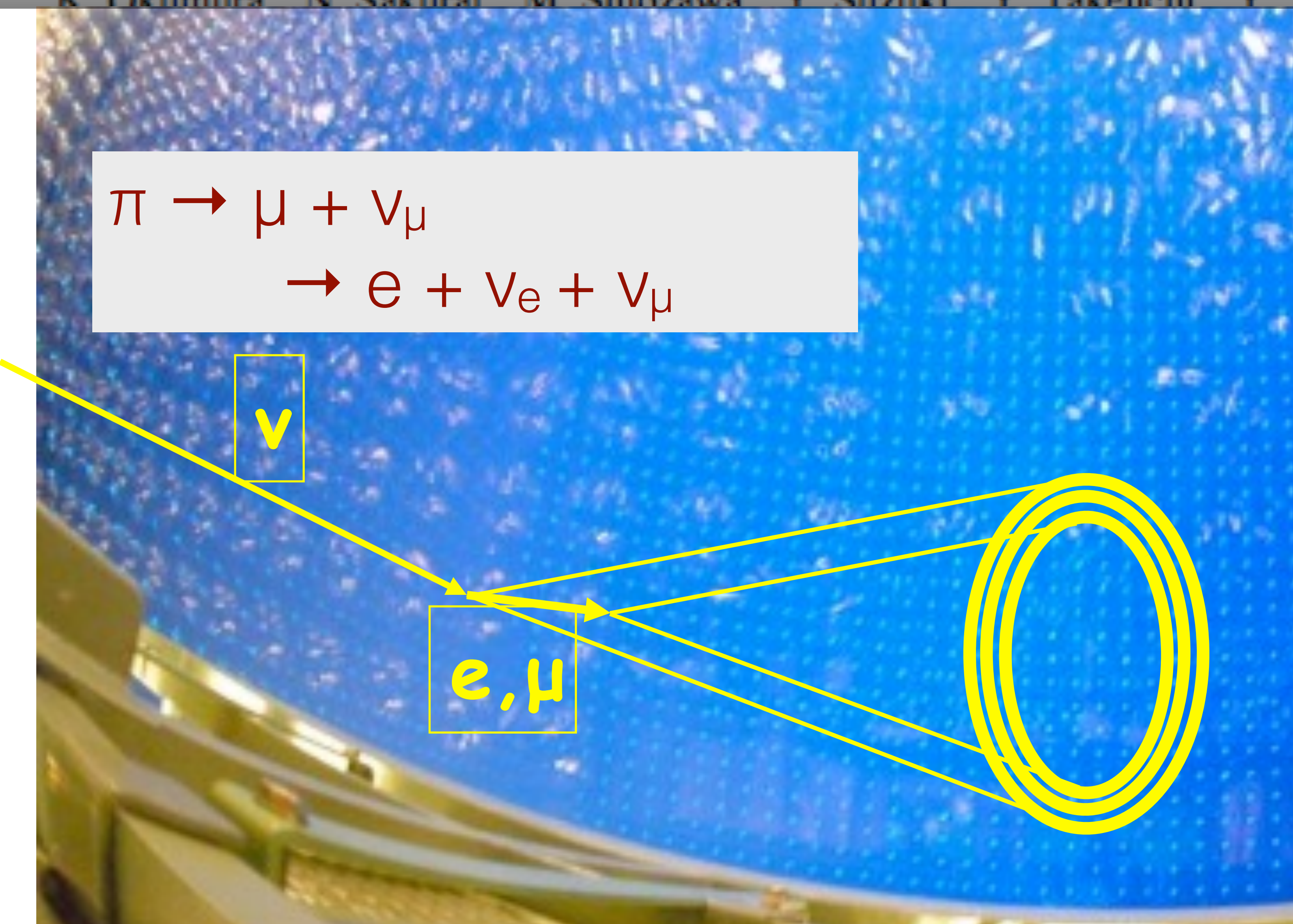
Atmospheric neutrino oscillations

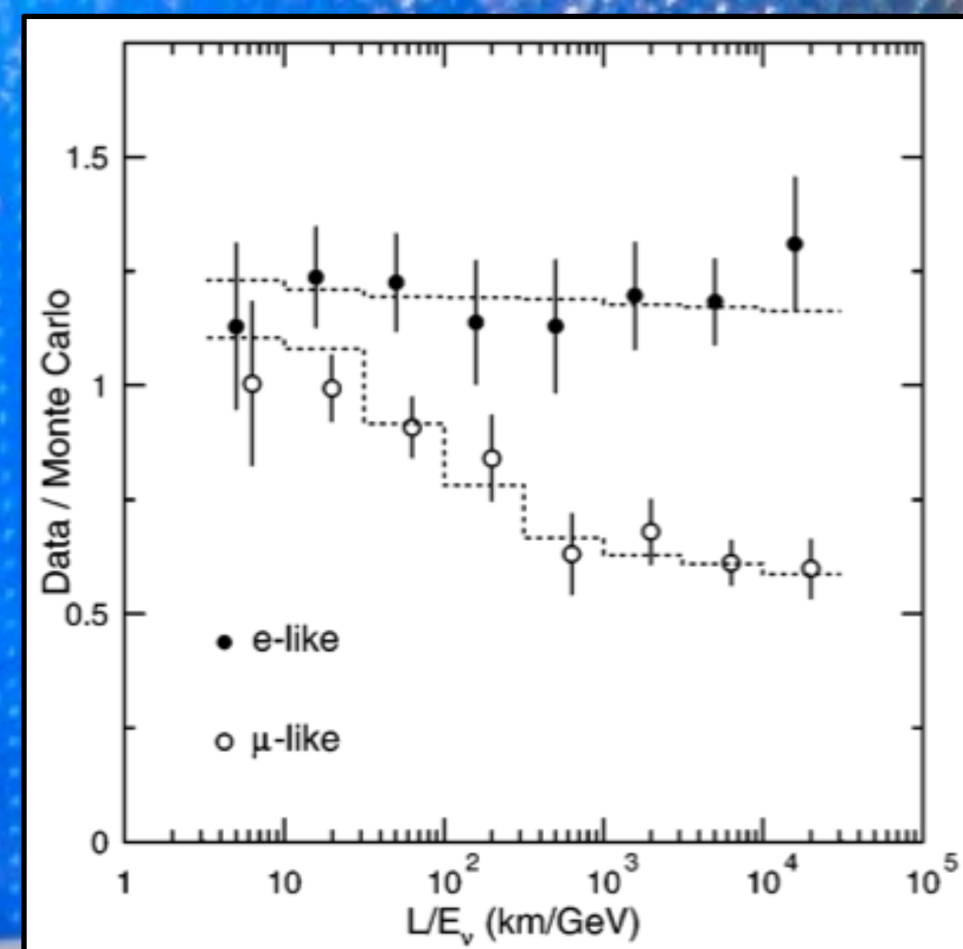


VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

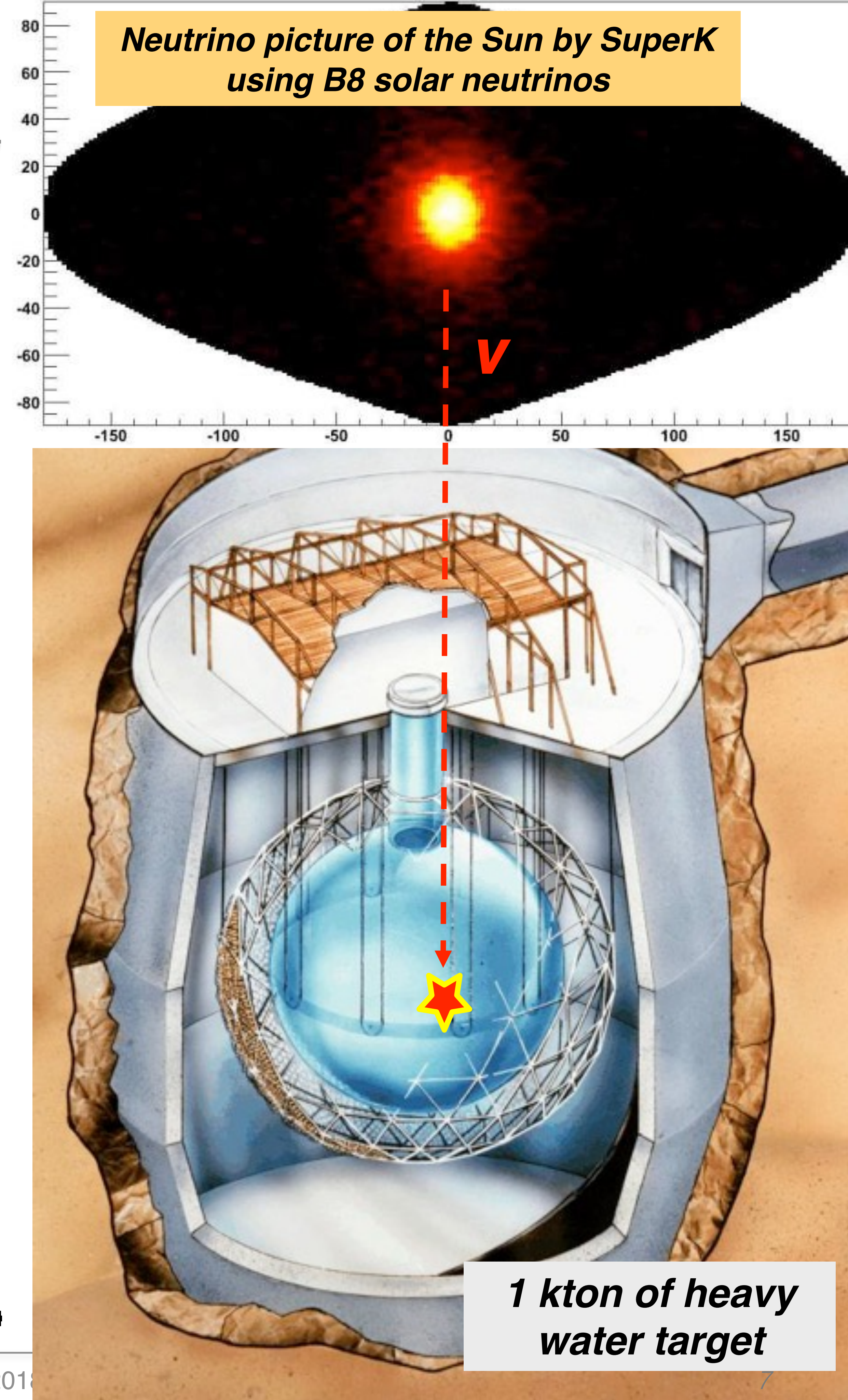
Y. Fukuda,[1] T. Hayakawa,[1] E. Ichihara,[1] K. Inoue,[1] K. Ishihara,[1] H. Ishino,[1] Y. Itow,[1] T. Kajita,[1]
S. Kasuga,[1] K. Kobayashi,[1] Y. Kobayashi,[1] Y. Koshio,[1] M. Miura,[1] M. Nakahata,[1] S. Nakayama,
K. Okumura,[1] N. Sakurai,[1] M. Shiozawa,[1] Y. Suzuki,[1] Y. Takeuchi,[1] Y. Totsuka,[1] S. Yamada,[1] M. F



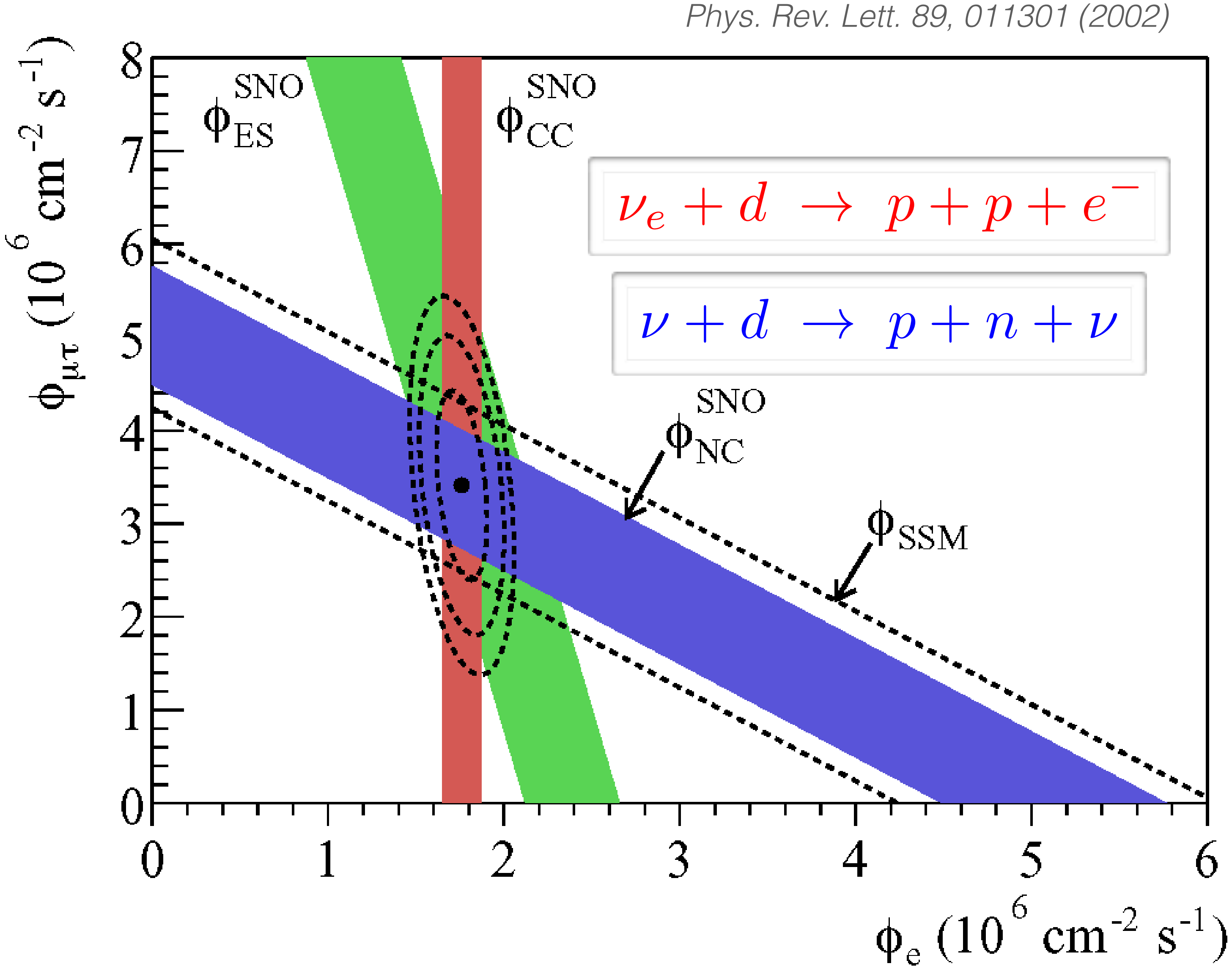


Solar ν oscillations

2002:
by exploiting 2 different reactions on deuterium, the SNO experiment proved that ν_e produced in fusion reactions in the sun have turned (oscillated) into $\nu_{\mu,\tau}$ when they are detected on earth



Phys. Rev. Lett. 89, 011301 (2002)



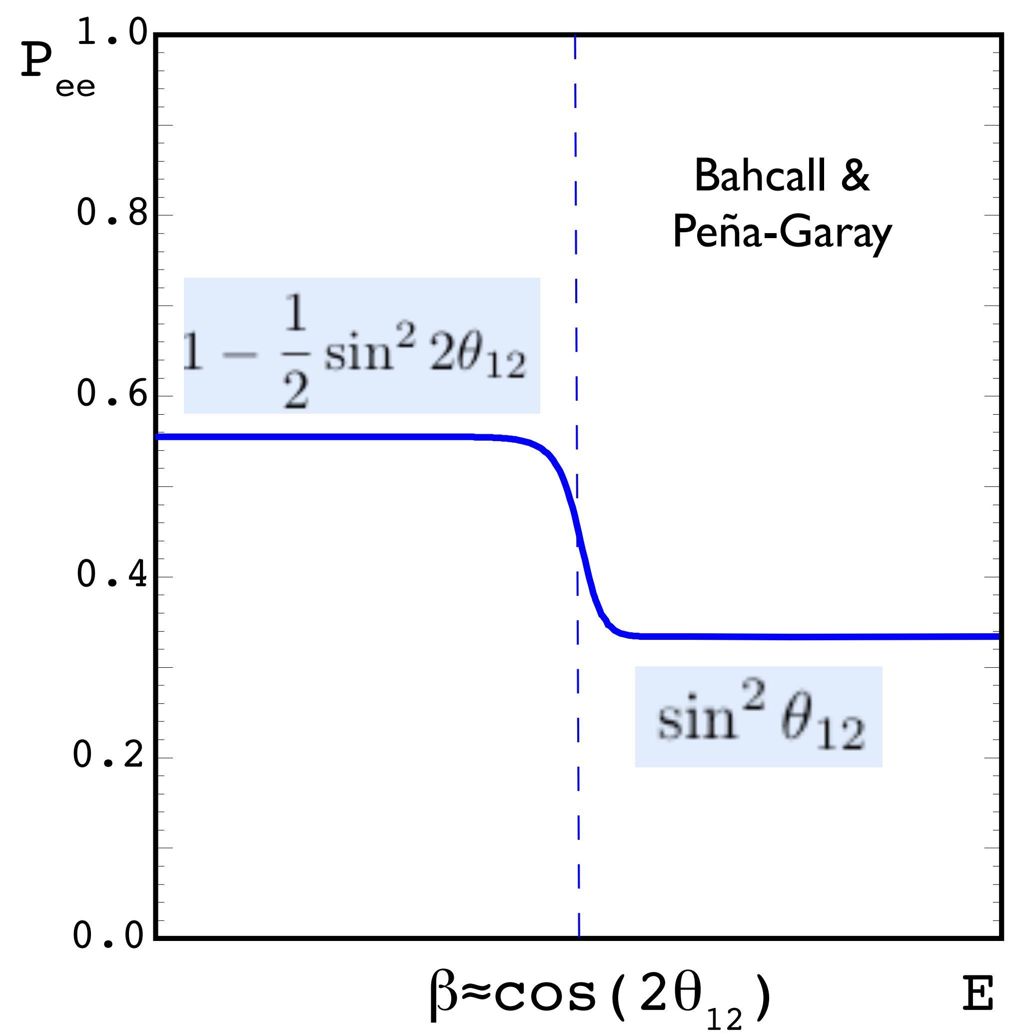
two almost block diagonal 2-flavor ν mixings

solar, atmospheric, reactor, beam neutrinos build a picture of the oscillation of three active flavours

$$\delta m^2_{12} \sim 7.5 \times 10^{-5} \mathrm{eV}^2$$
$$\sin^2\theta_{12} \sim 0.3$$
$$\delta m^2_{23} \sim 2.4 \times 10^{-3} \mathrm{eV}^2$$
$$\sin^2\theta_{23} \sim 0.4$$
$$\sin^2\theta_{13} \sim 0.02$$

neutrino oscillations firmly established

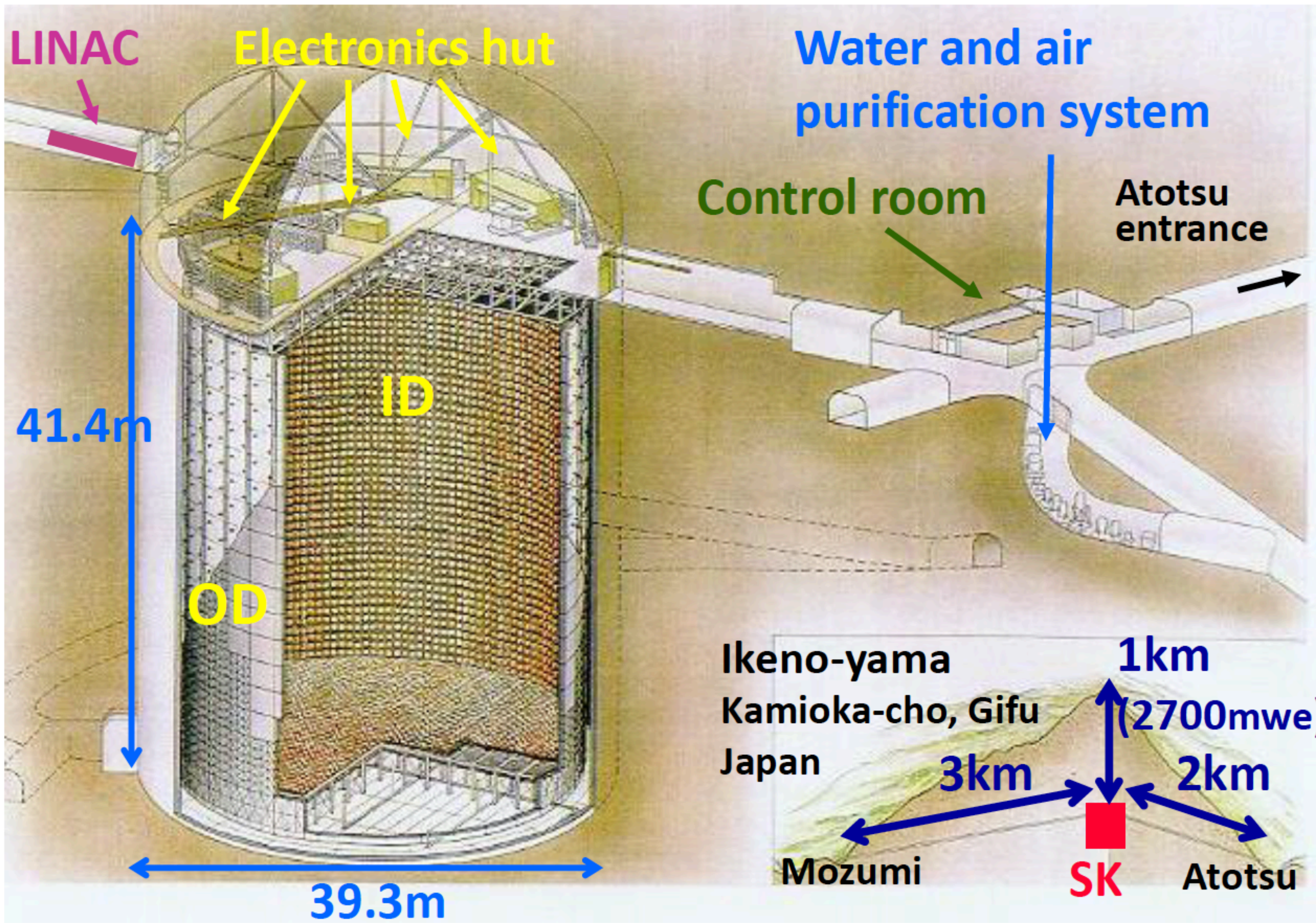
the MSW-LMA solution for solar neutrinos predicts an energy-dependent survival probability for electron neutrinos



Super-Kamiokande detector

http://www-sk.icrr.u-tokyo.ac.jp/sk/

from Y. Takeuchi @RICH18



- 50 kton water
- ~2m OD viewed by 8-inch PMTs
- 32kt ID viewed by 20-inch PMTs
- 22.5kt fid. vol. (2m from wall)
- SK-I: April 1996~
- Refurbishment work is ongoing

Physics targets:

- Nucleon decay search
- Neutrino oscillation study
- Astrophysical neutrino search

Inner Detector (ID) PMT: ~11100 (SK-I,III,IV), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

6

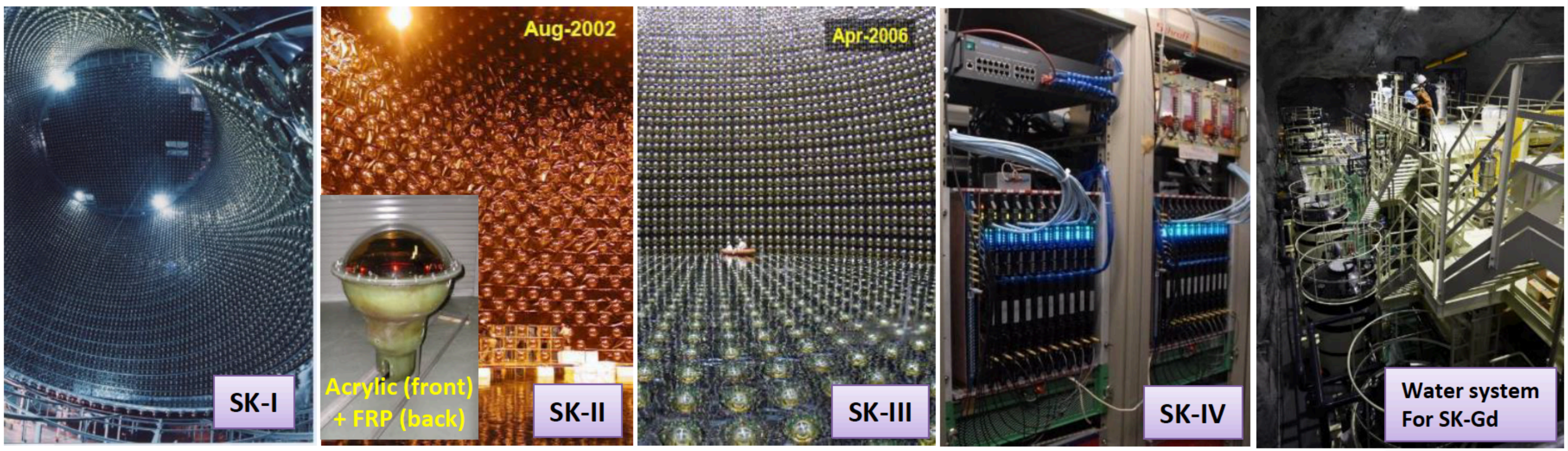
History & Plan of Super-Kamiokande

from Y. Takeuchi @RICH18

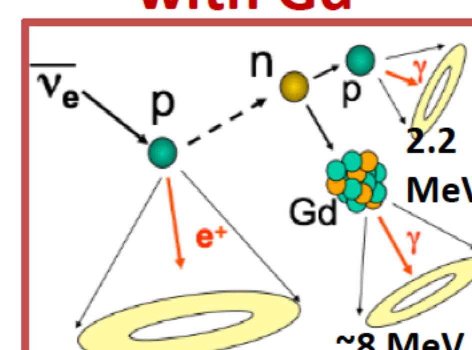
96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19

NOW

SK-I — SK-II — SK-III — SK-IV — Start upgrade for SK-Gd



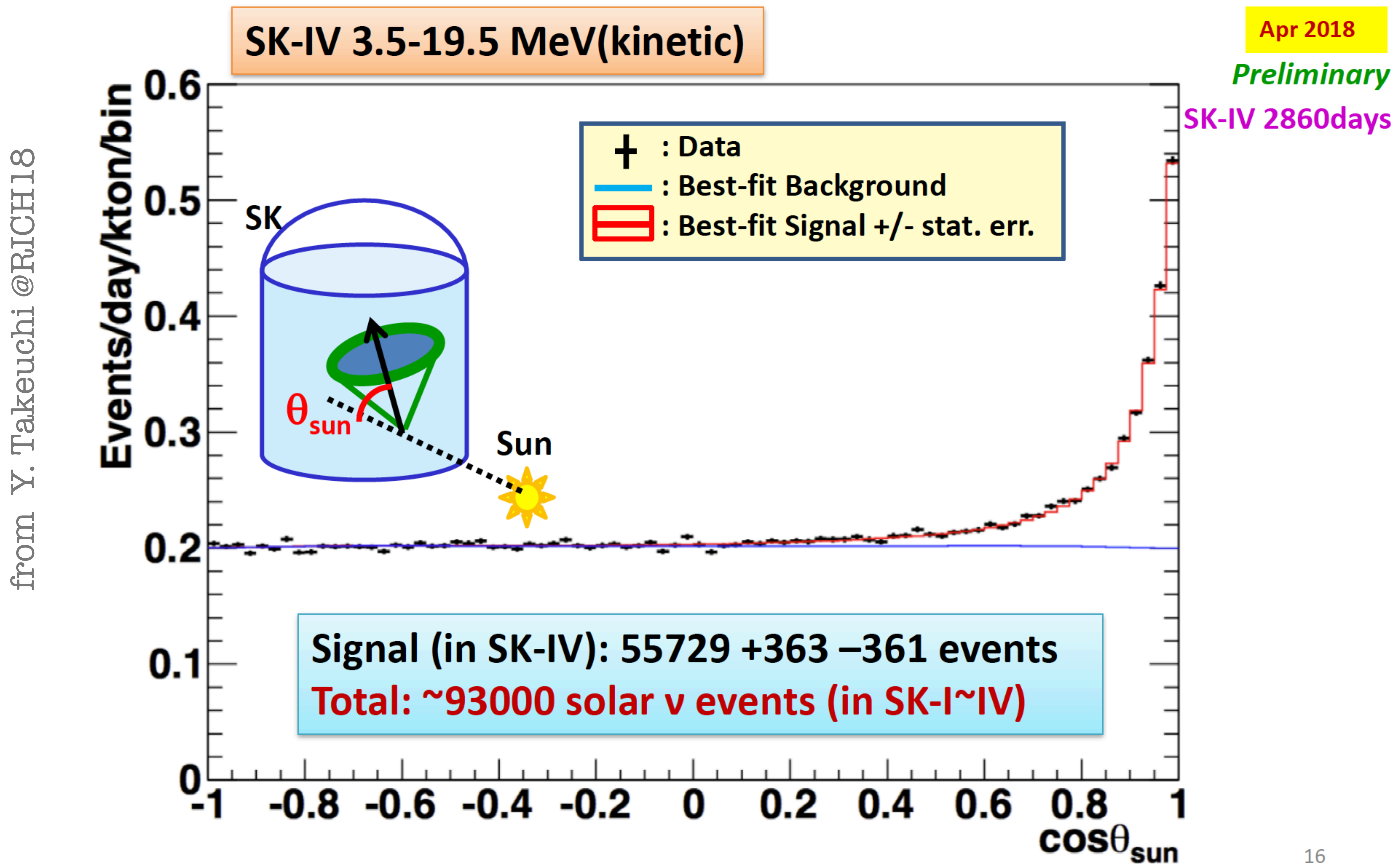
SK-I	SK-II	SK-III	SK-IV	SK-Gd
11146 ID PMTs (40% coverage)	5182 ID PMTs (19% coverage)	11129 ID PMTs (40% coverage)	Electronics Upgrade	Neutron tagging with Gd
4.5 MeV	6.5 MeV	4.5 MeV	3.5 MeV	
1496 days	791 days	548 days	2860 days	



- Analysis energy threshold (recoil electron kinetic energy)
- Live time for solar neutrino analysis

Current total: 5695 days

SK-IV solar neutrino signal

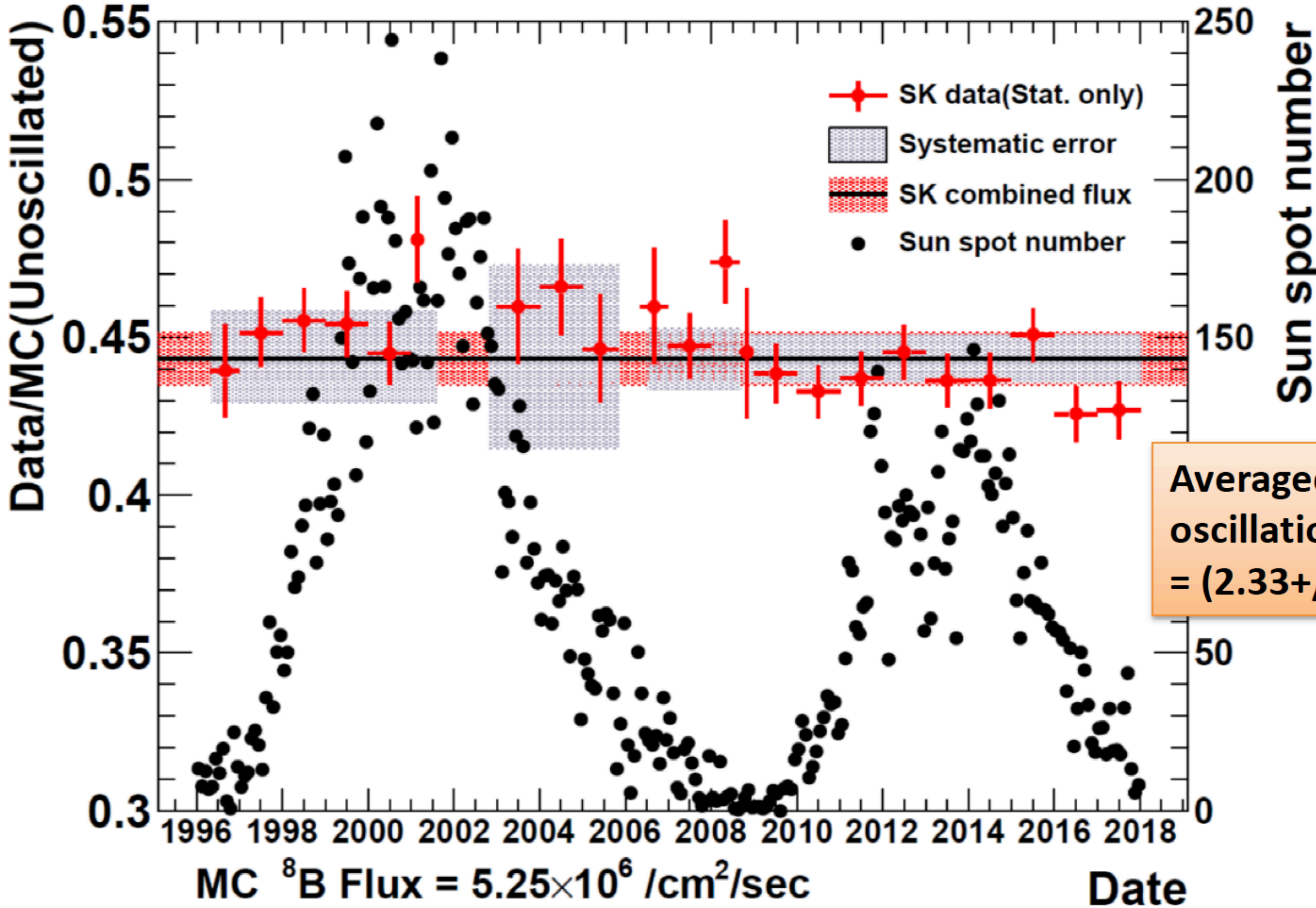


^{8}B solar neutrino flux: Yearly plot

Apr 2018

Preliminary

SK 5695 days



from Y. Takeuchi @RICH18

Averaged ^{8}B flux with no oscillation = (2.33+/-0.04) x10^6/cm^2/s

χ^2 = 21.57 / 21 d.o.f. → Confidence level = 41.4 %

Super-K solar rate measurements are fully consistent with a constant solar neutrino flux emitted by the Sun.

Sun spot number: WDC-SILSO, Royal Observatory of Belgium, Brussels

Solar ν oscillation results

Apr 2018

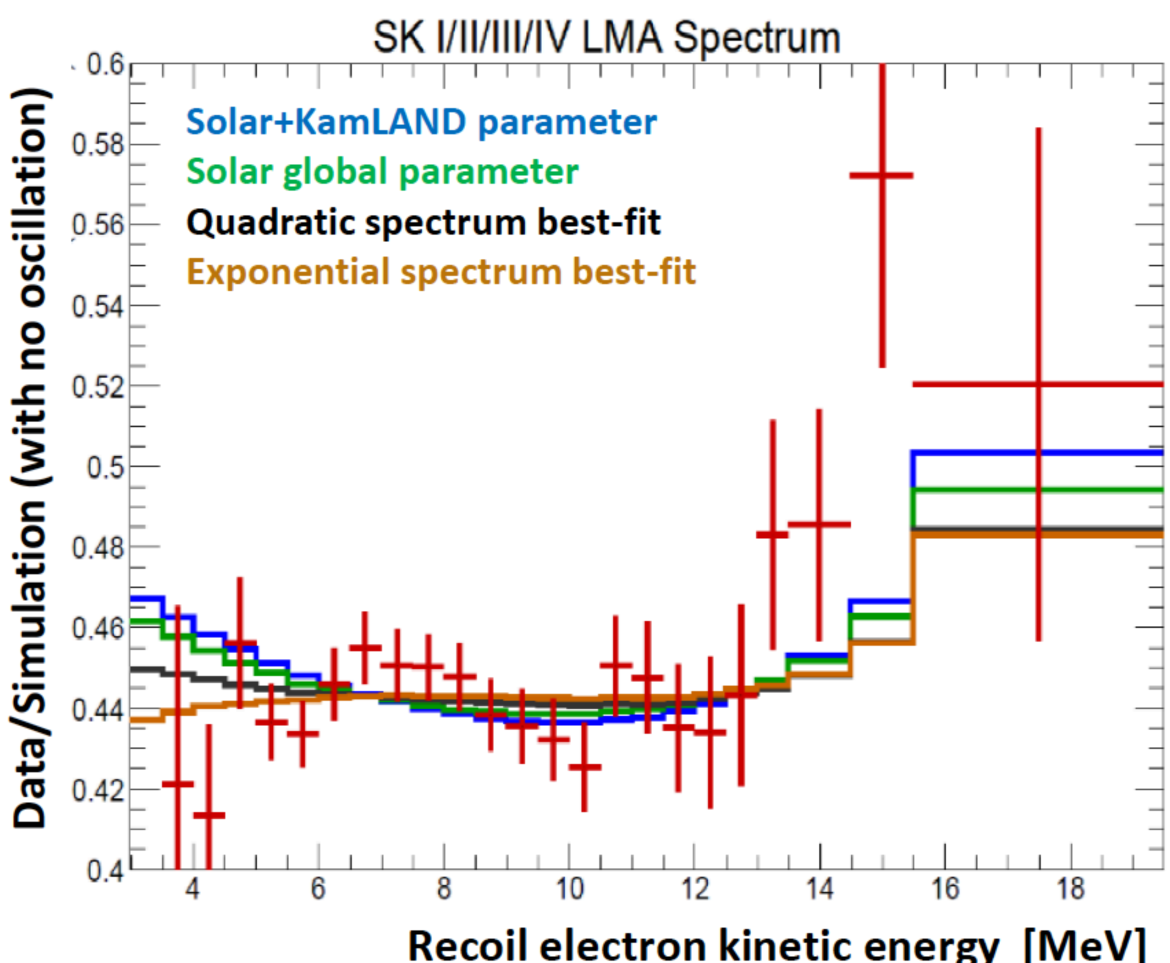
Preliminary

SK 5695 days

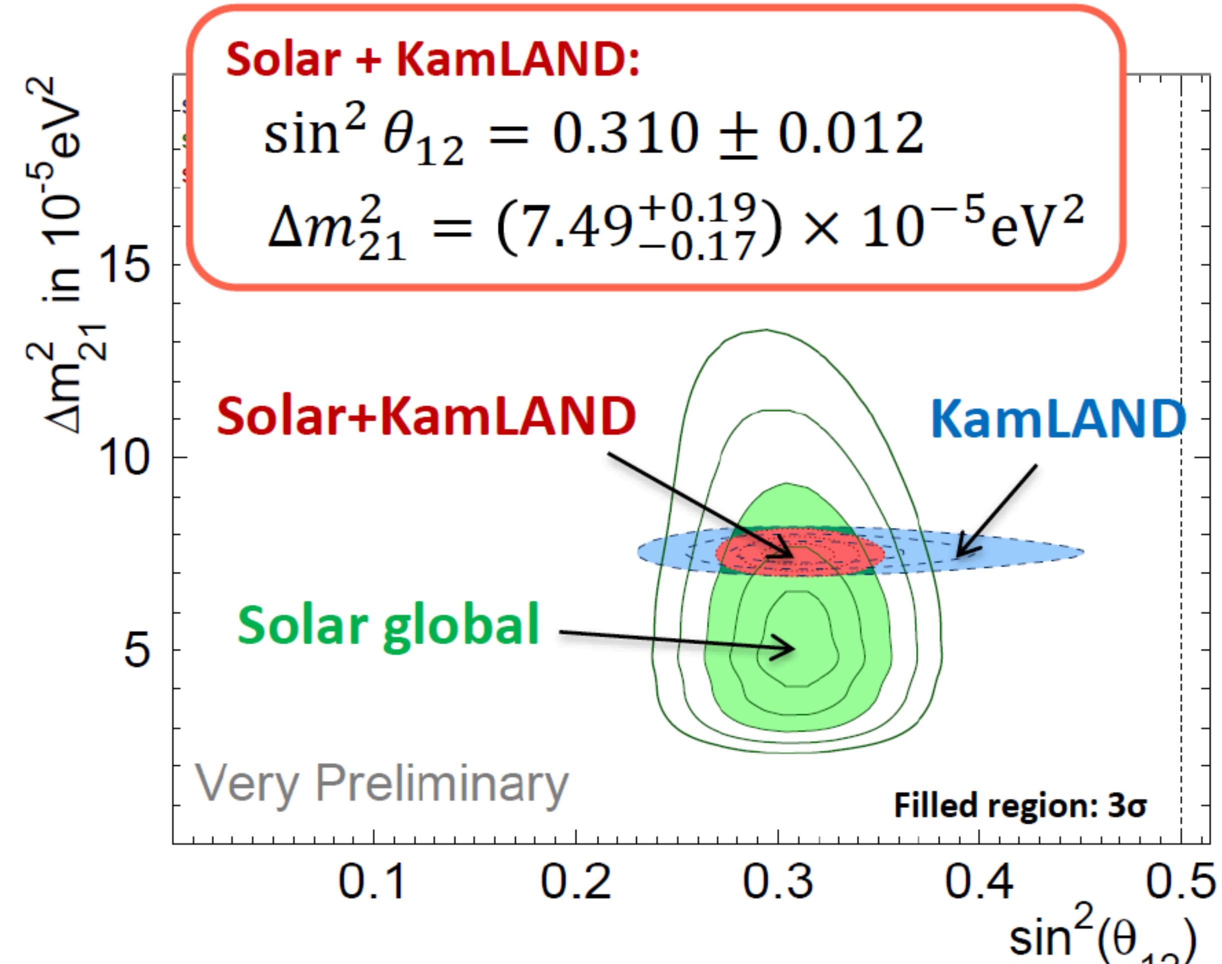
- Quadratic fit of SK spectrum is consistent with solar Δm^2_{21} within ~1.2 σ and disfavors KamLAND Δm^2_{21} by ~2.0 σ.
- ~2.0 σ level tension in Δm^2_{21} between solar global analysis and KamLAND is still remaining.

from Y. Takeuchi @RICH18

Solar ν energy spectrum



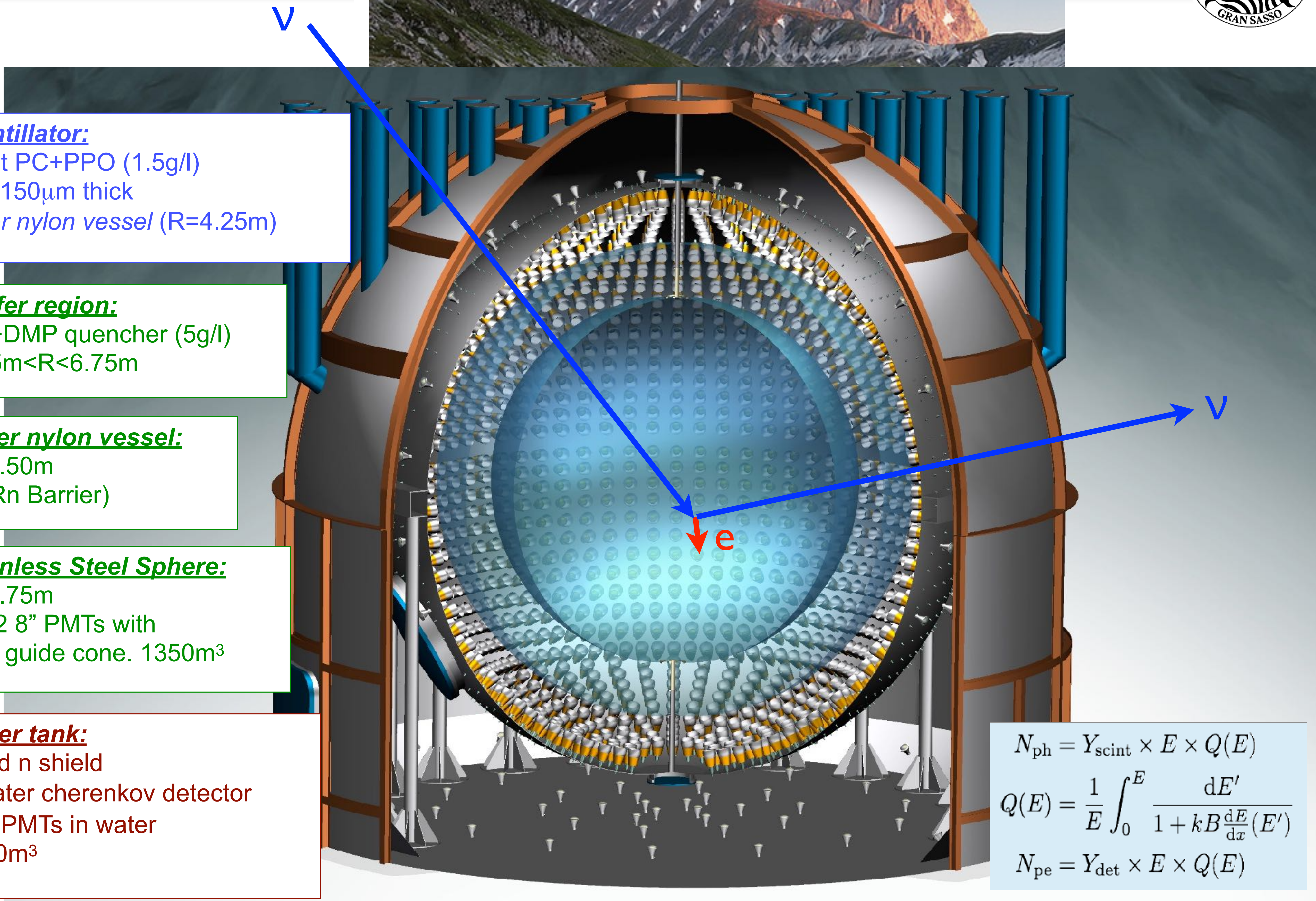
Solar ν oscillation parameters



The Borexino project

- Designed to solve the solar neutrino puzzle by finding Be-7 neutrinos
- After SuperK, SNO established neutrino oscillations:
  - precision neutrino oscillation studies
  - precision solar physics
- Has, in a way, become a standard against which to compare very large, low background experiments

Borexino



Scintillator:
270 t PC+PPO (1.5g/l)
in a 150μm thick
Inner nylon vessel (R=4.25m)

Buffer region:
PC+DMP quencher (5g/l)
4.25m<R<6.75m

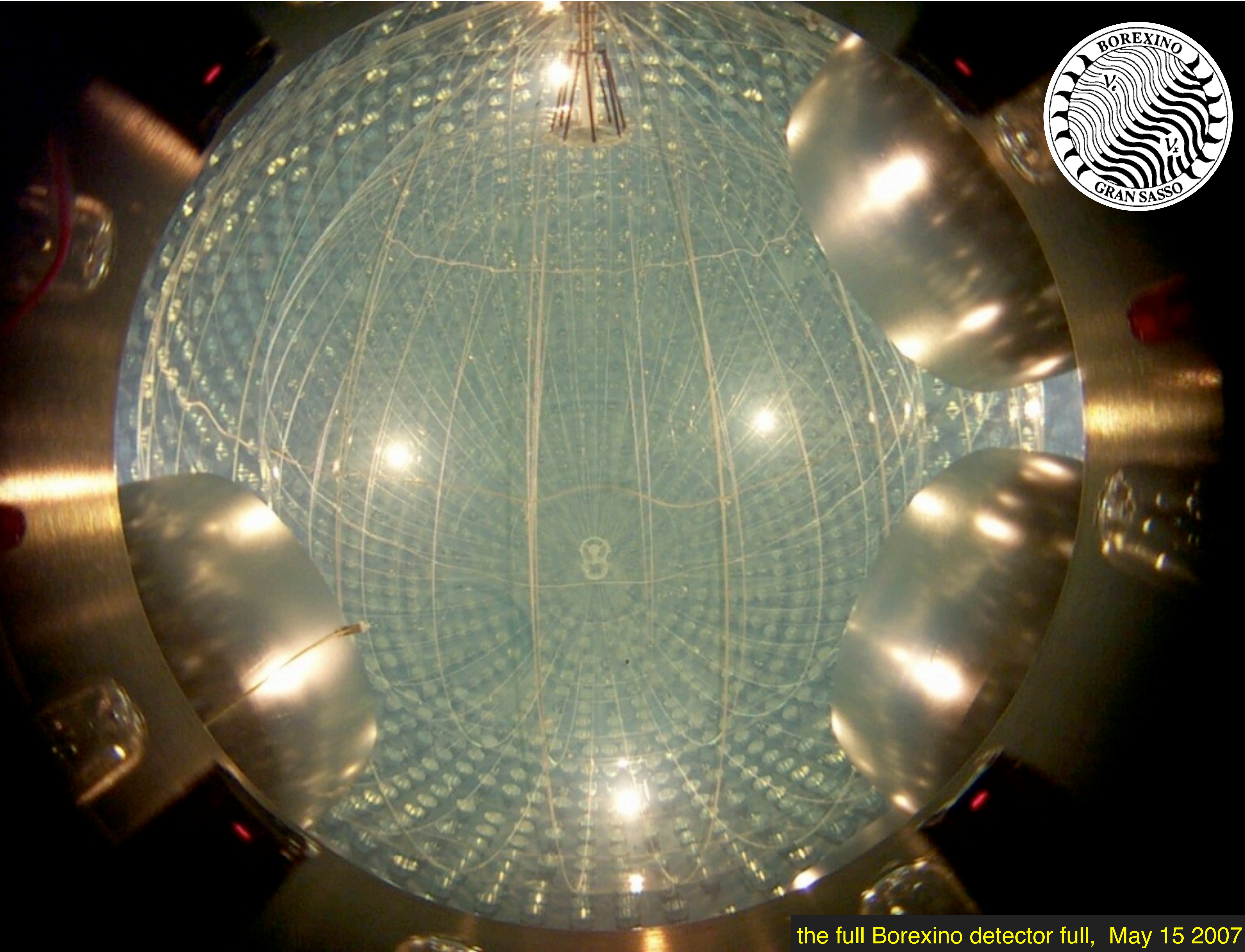
Outer nylon vessel:
R=5.50m
(^{222}Rn Barrier)

Stainless Steel Sphere:
R=6.75m
2212 8” PMTs with
light guide cone. 1350m^3

Water tank:
γ and n shield
μ water cherenkov detector
208 PMTs in water
2100m^3

$$N_{\rm ph} = Y_{\rm scint} \times E \times Q(E)$$
$$Q(E) = \frac{1}{E}\int_0^E \frac{{\rm d}E'}{1 + kB\frac{{\rm d}E}{{\rm d}x}(E')}$$
$$N_{\rm pe} = Y_{\rm det} \times E \times Q(E)$$

Borexino filled with scintillator

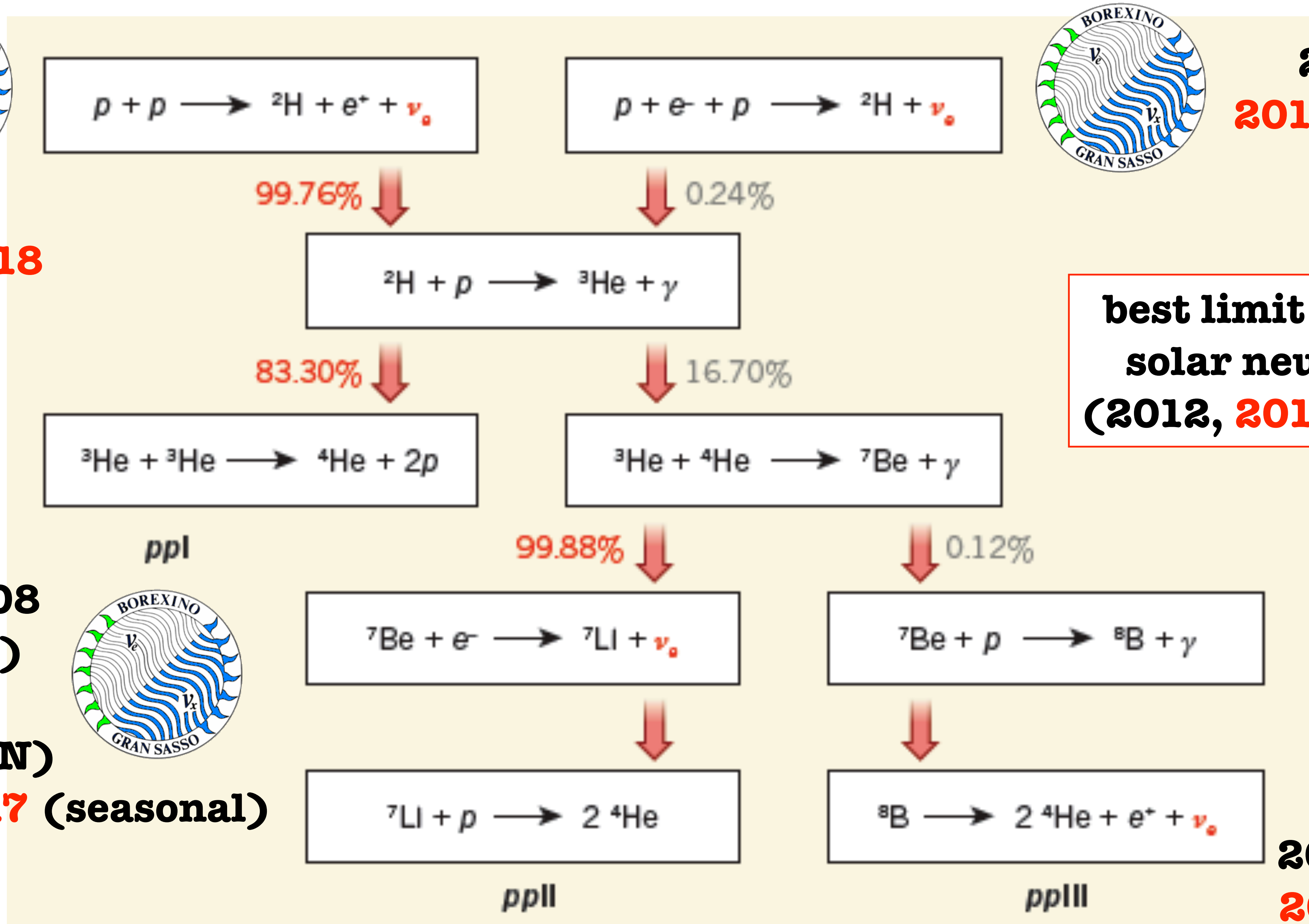


the full Borexino detector full, May 15 2007

Borexino milestone results

2014
2017/2018

2012
2017/2018



best limit on CNO solar neutrinos (2012, 2017/2018)

2007/2008
2011 (5%)
2017
2012 (D/N)
2014, 2017 (seasonal)

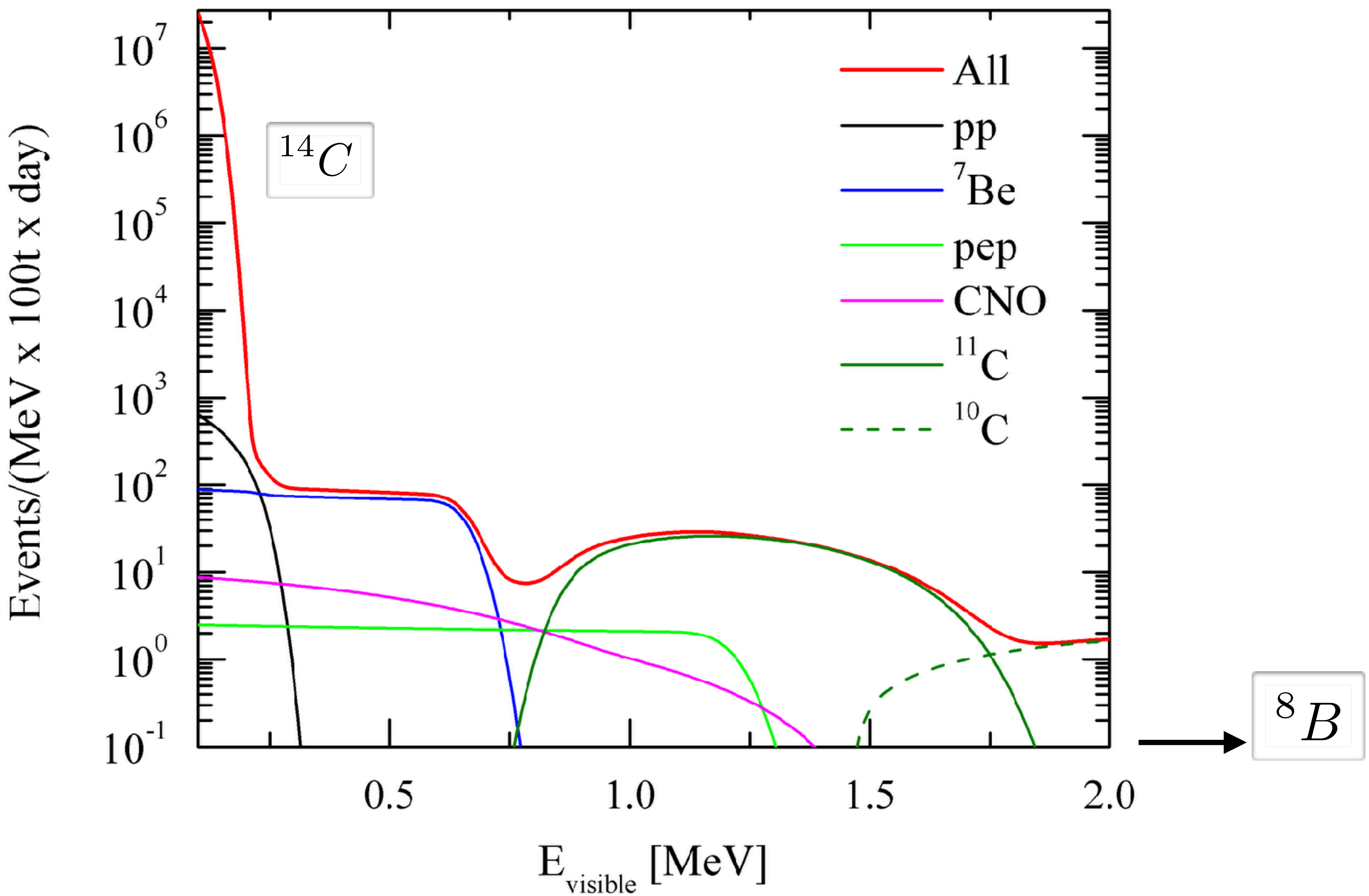
2010, 2013
2017/2018

— geoneutrinos (2010, 2013, 2015)
— search for solar axions (2008, 2012)
— search for solar, astro anti-ν (2011)

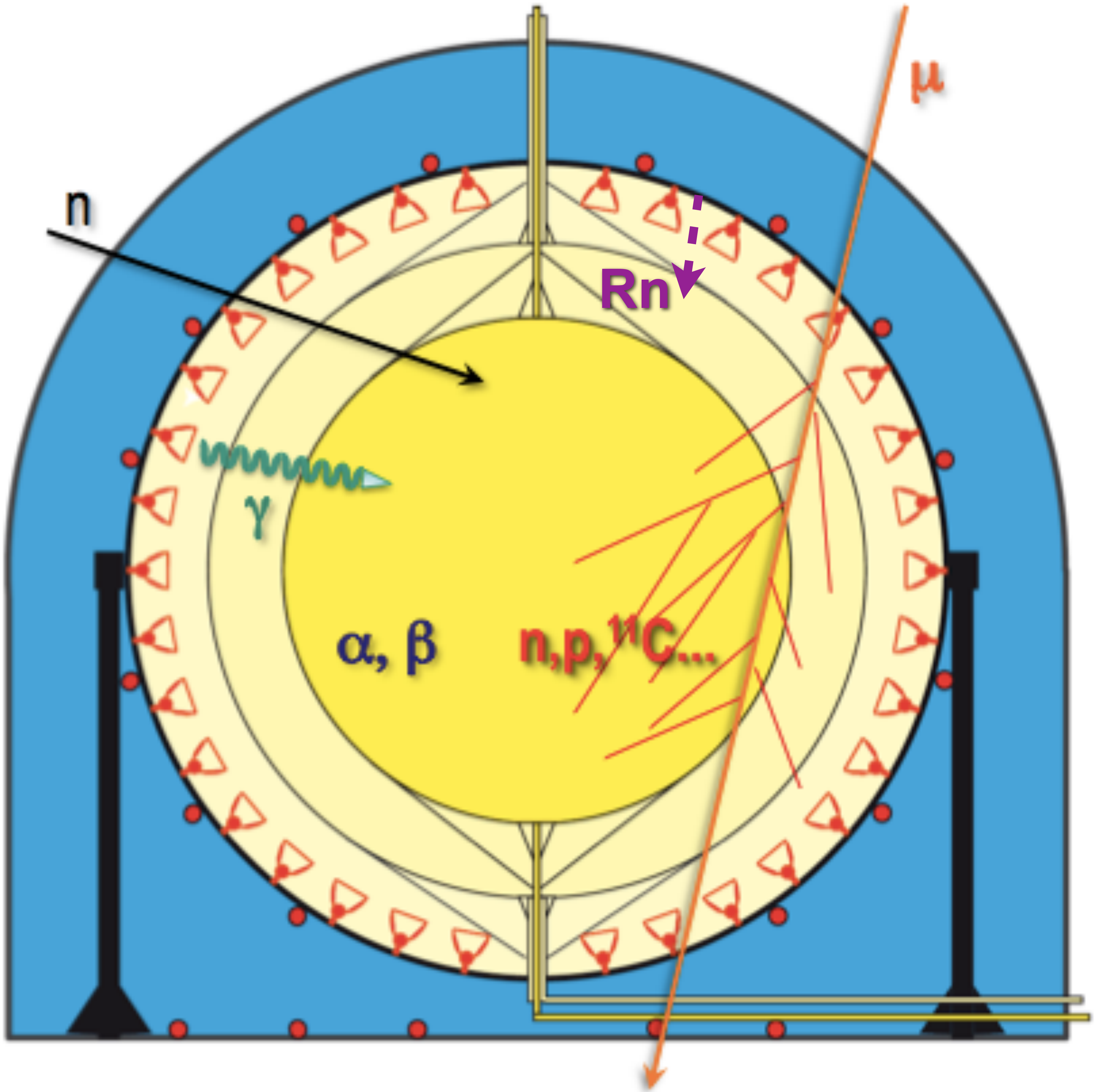
— test of electric charge conservation (2015)
— limits on ν magnetic moment (2017)
— coinc. with GRB's (2016), GW's (2017)

Borexino energy spectrum (expected)

with “irreducible” backgrounds



Extreme radio-purity



internal radioactivity
traces of radioisotopes in the scintillator (U,Th,^{40}K)

external γ rays
from fluid buffer, steel sphere, PMT glass and light concentrators (^{40}K,^{208}Tl,^{214}Bi)

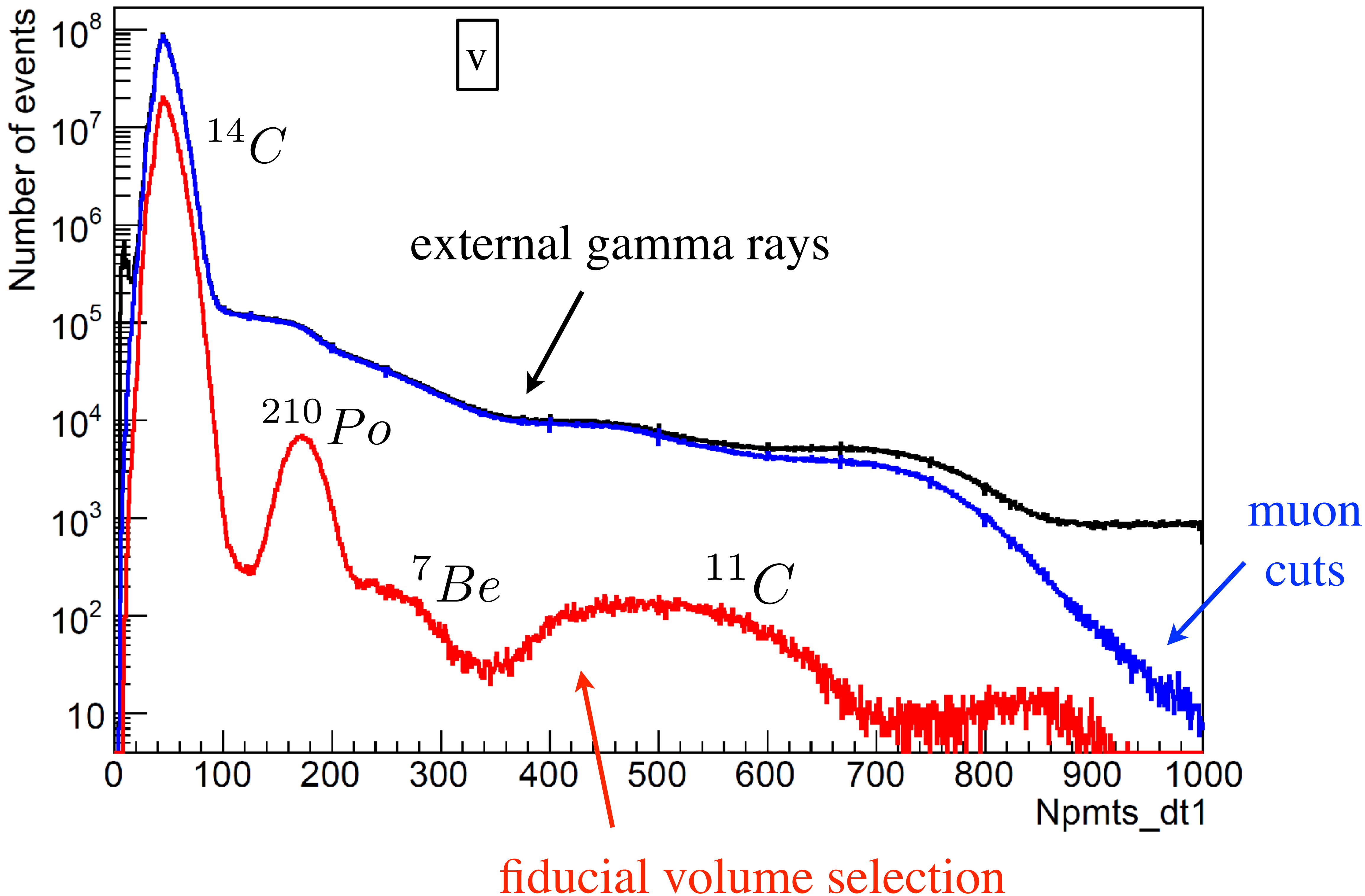
radon emanation
from the PMTs and steel sphere

cosmic muons
and their secondaries

cosmogenics
neutrons and radionuclides from μ spallation and hadronic showers

fast neutrons
from external muons

Borexino energy spectrum (data)



Borexino timeline

Purification I (filling)

Purification II

External tank insulation

Phase I (2007-2010)

Phase II (2012-2016)

2007 — **2010** — **2012** — **2017**

- ν (^{7}Be) flux, D/N
- ν (^{8}B) flux
- ν (pep) flux
- ν (CNO) limit
- geo-neutrinos

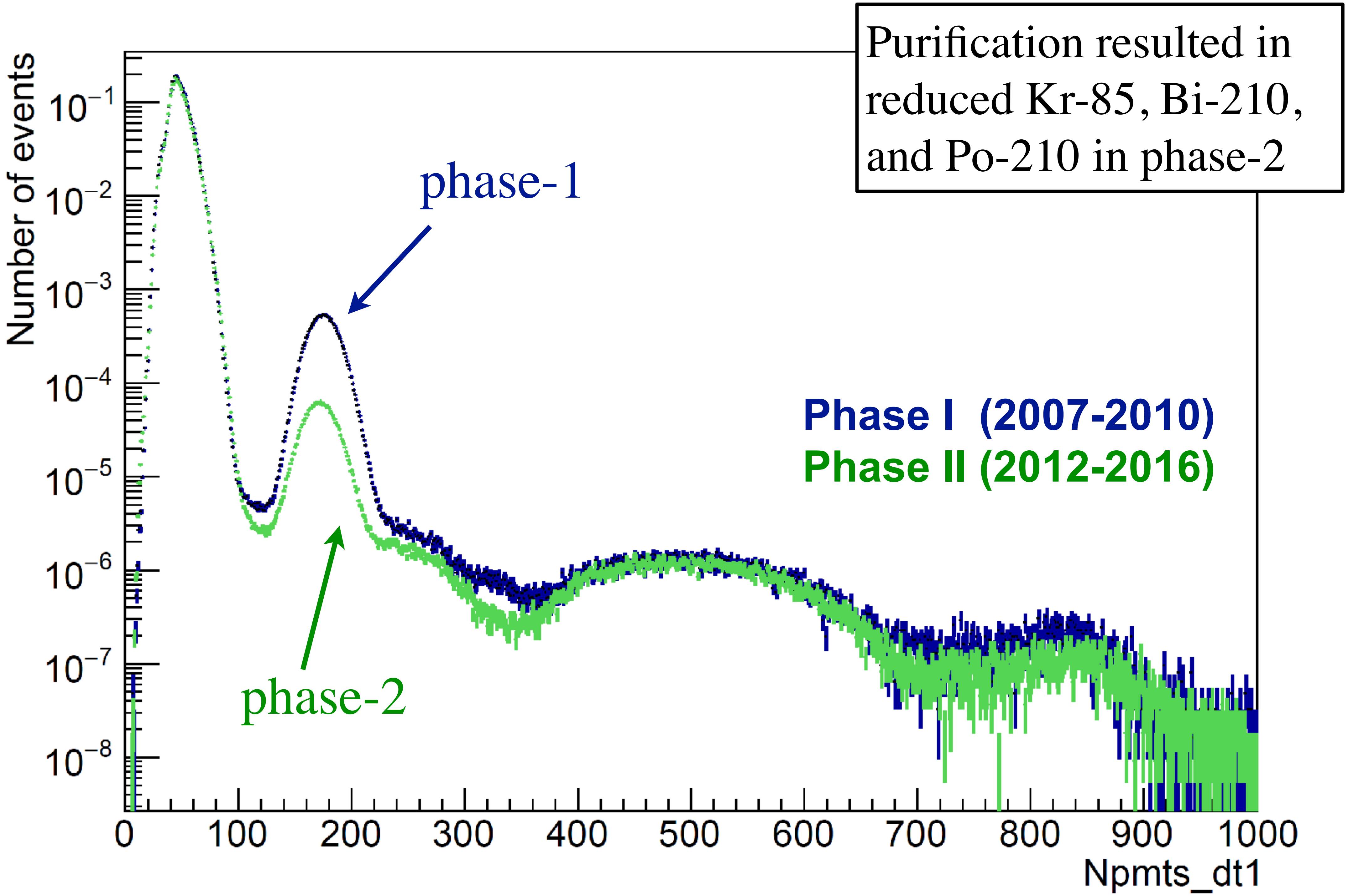
Improved radiopurity:
(6 cycles LS purification)

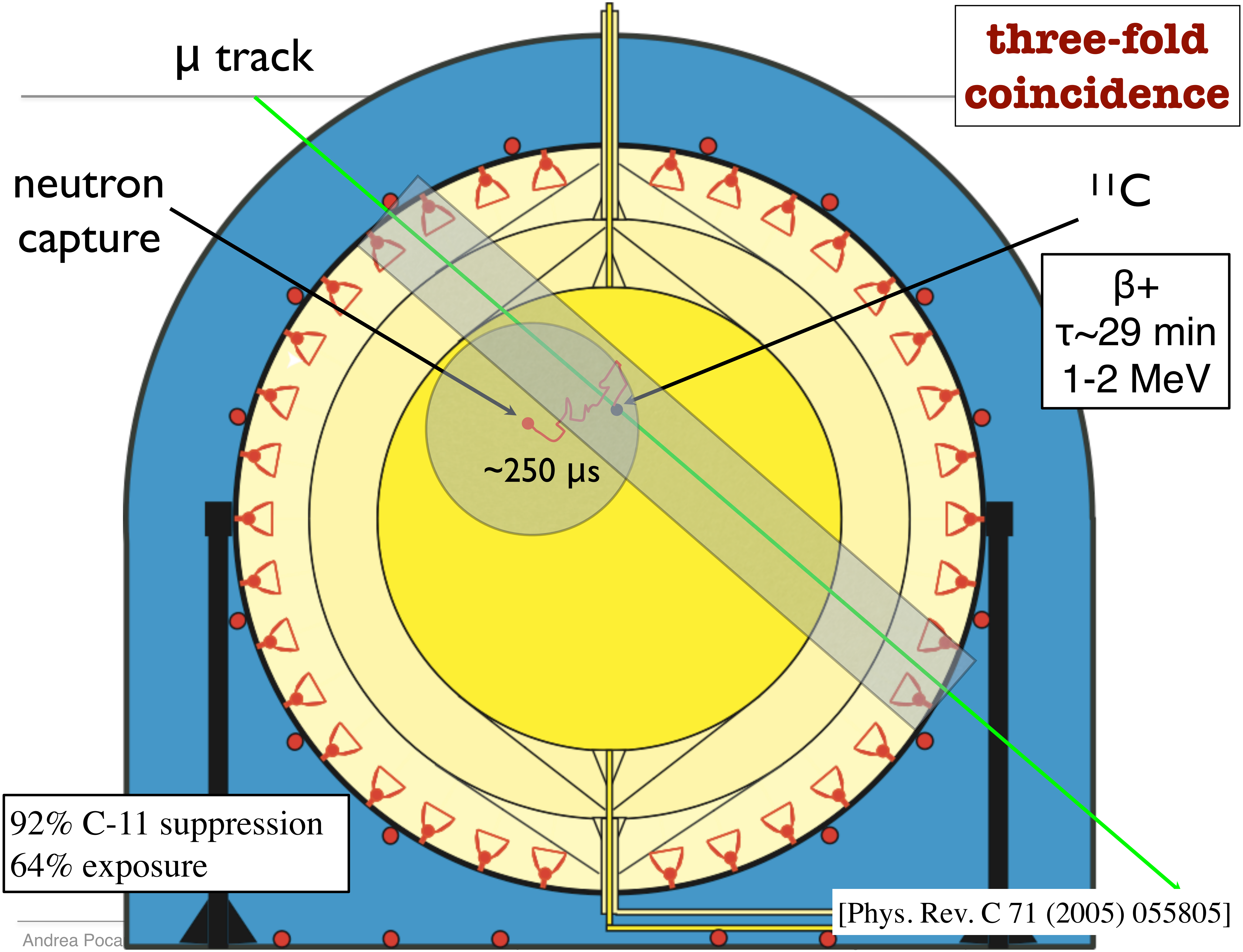
- ^{85}Kr: reduced by ~ 4.6
- ^{210}Bi: reduced by ~ 2.3
- Th and U negligible:
  - ^{238}U: < $9.4 * 10^{-20}$ g/g
  - ^{232}Th: < $5.7 * 10^{-19}$ g/g

- ν (pp) flux
- ν (^{7}Be) day-night
- geo-neutrinos
- ν magnetic moment
- Correlations with GWs and GRBs

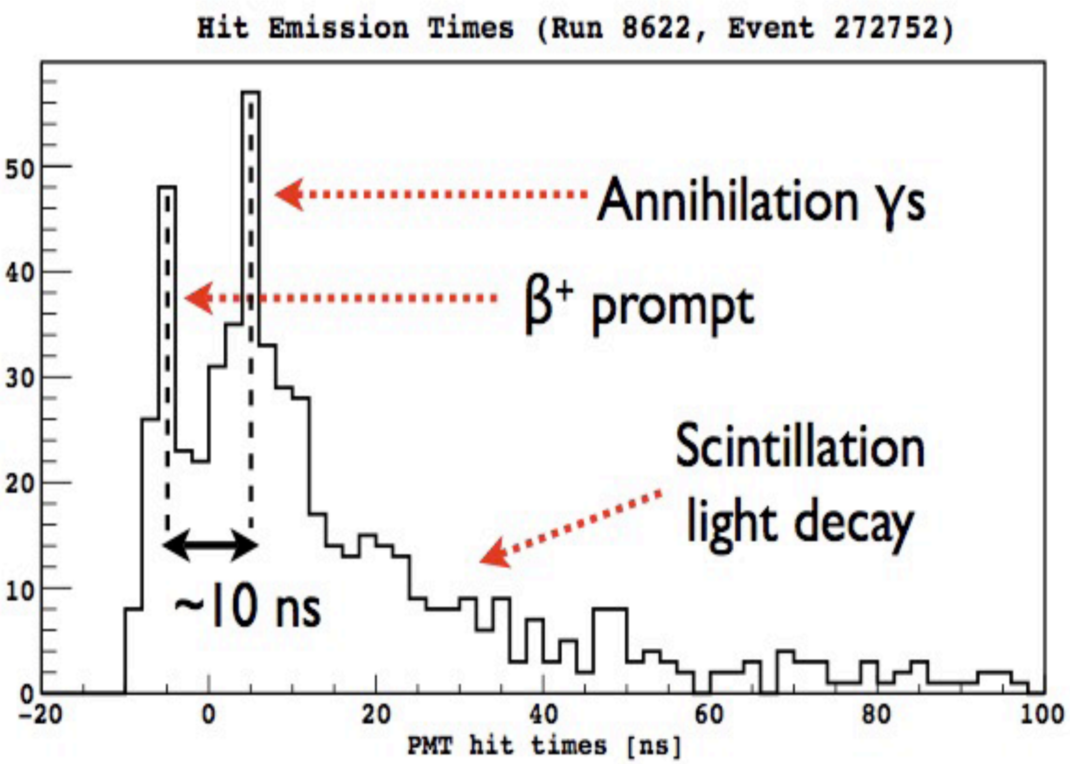
CNO campaign

Stability between phase 1 and phase-2



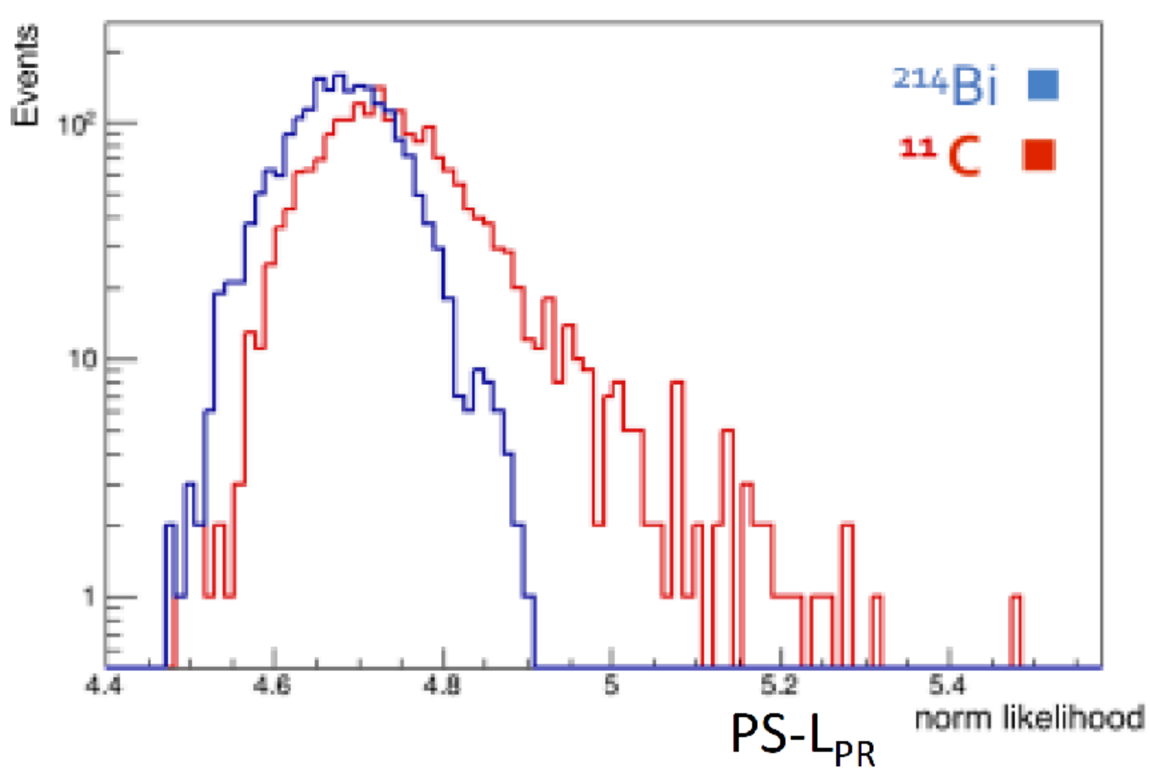

three-fold coincidence
μ track
neutron capture
^{11}C
β+
τ~29 min
1-2 MeV
~250 μs
92% C-11 suppression
64% exposure
[Phys. Rev. C 71 (2005) 055805]

Spectral fit: multivariate approach



50% of β^+ decays produce ortho-positronium ($t_{1/2}$ ~ 3 ns) —> pulse shape discriminator based on:

- time shift
- multi-site (gammas)
- ionization density profile

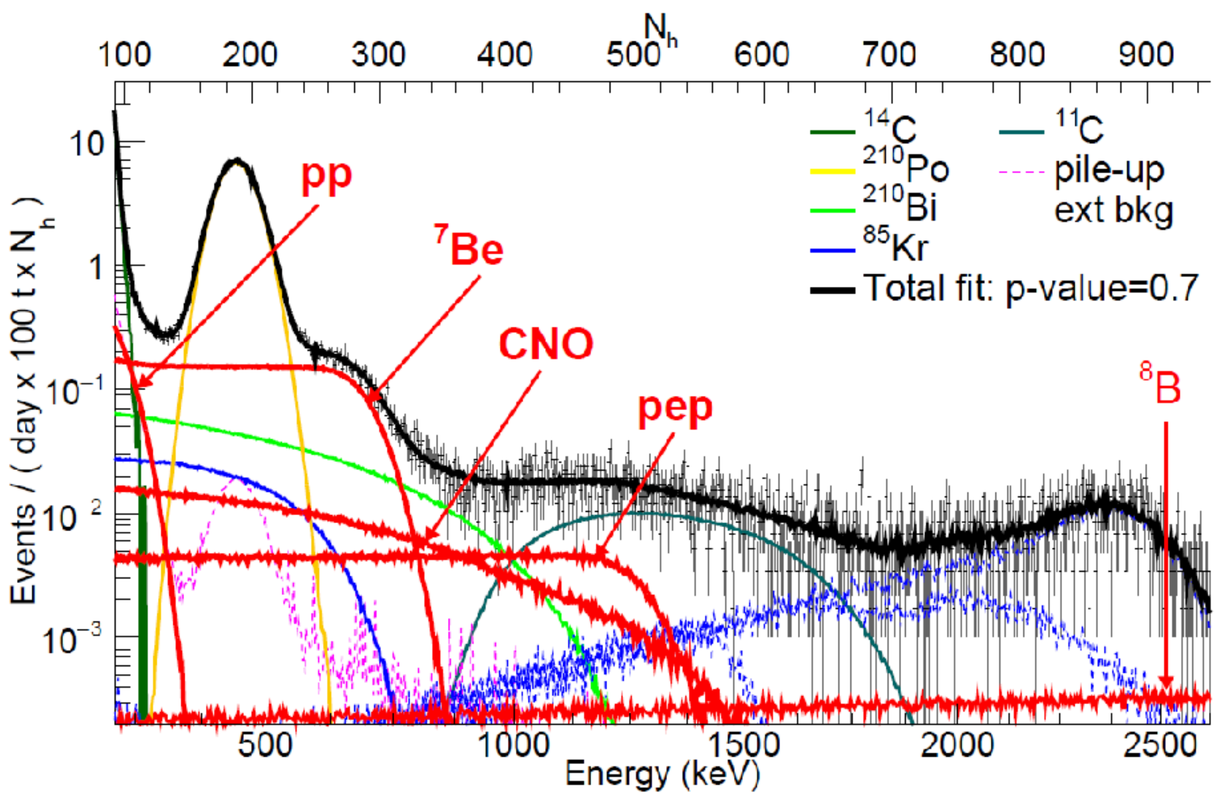


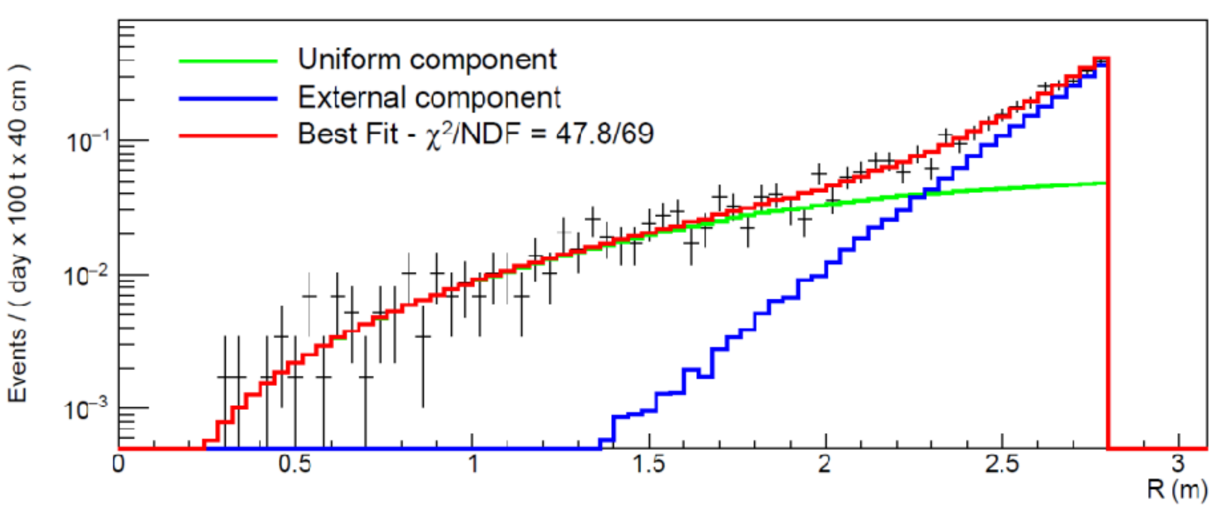
Likelihood built combining:

- simultaneous fit of TFC-tagged and TFC-subtracted energy spectra
- pulse-shape parameter
- radial distribution

Multi-variate fits sampler

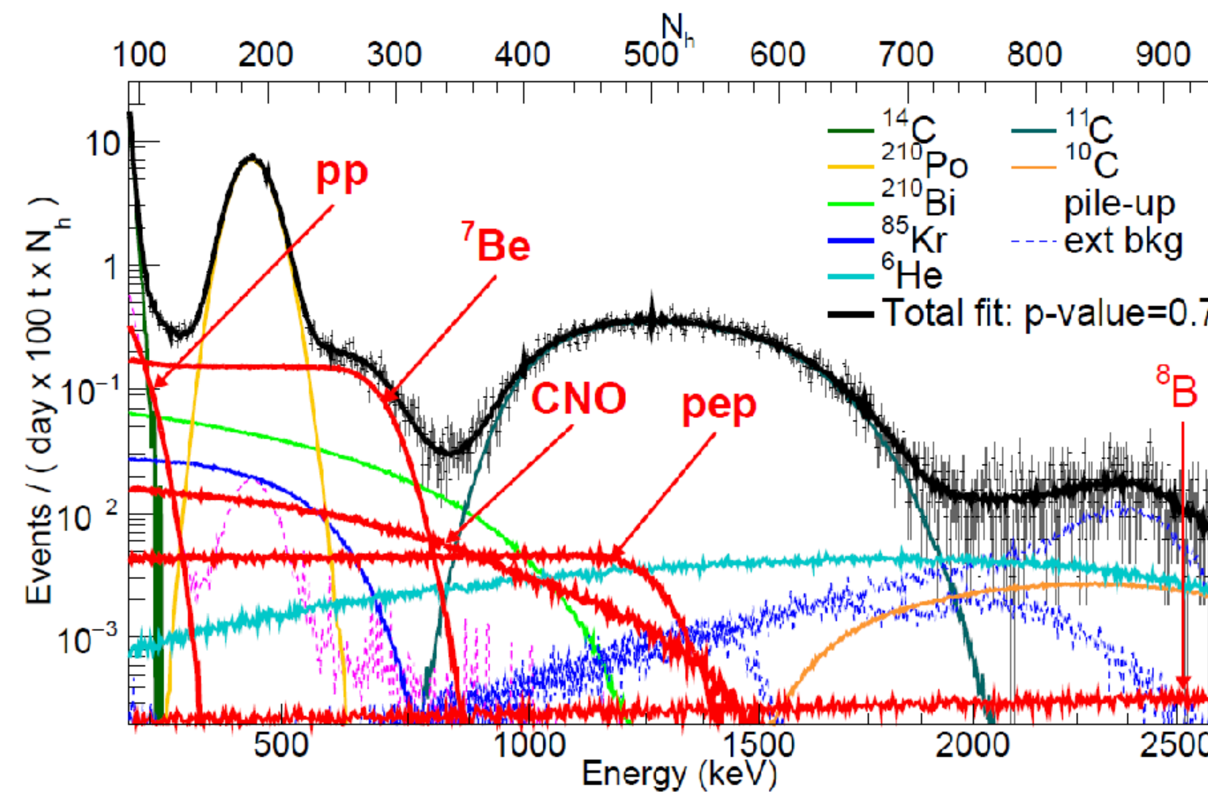
TFC subtracted energy spectrum

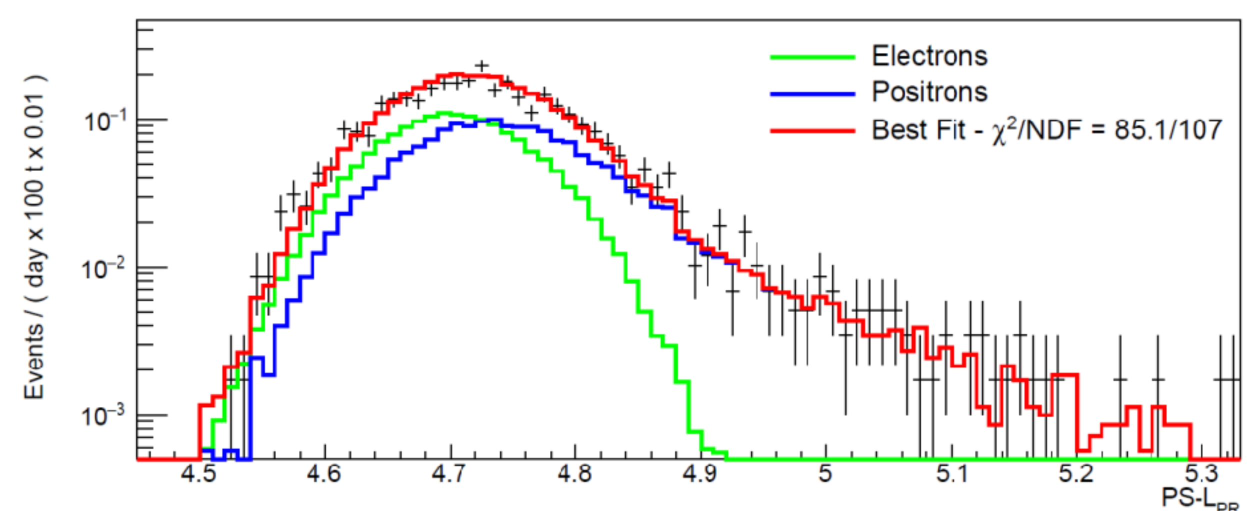




L_{rad}

TFC tagged (C-11 rich) energy spectrum



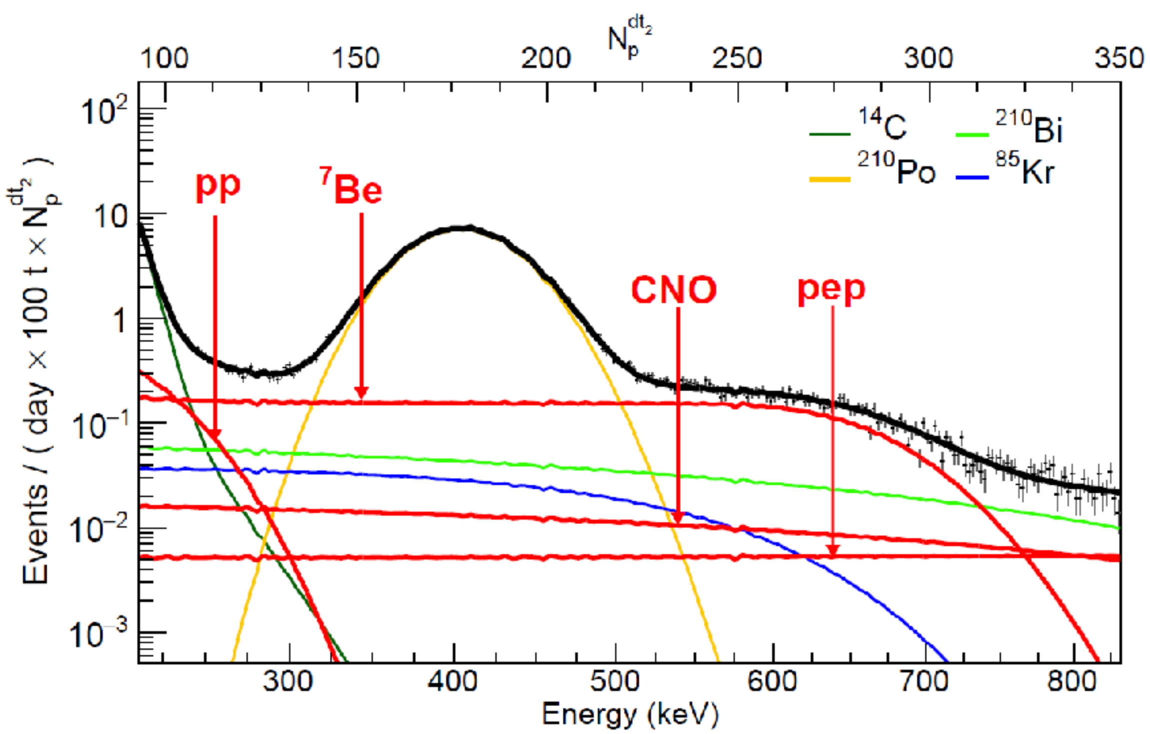


L_{PS}

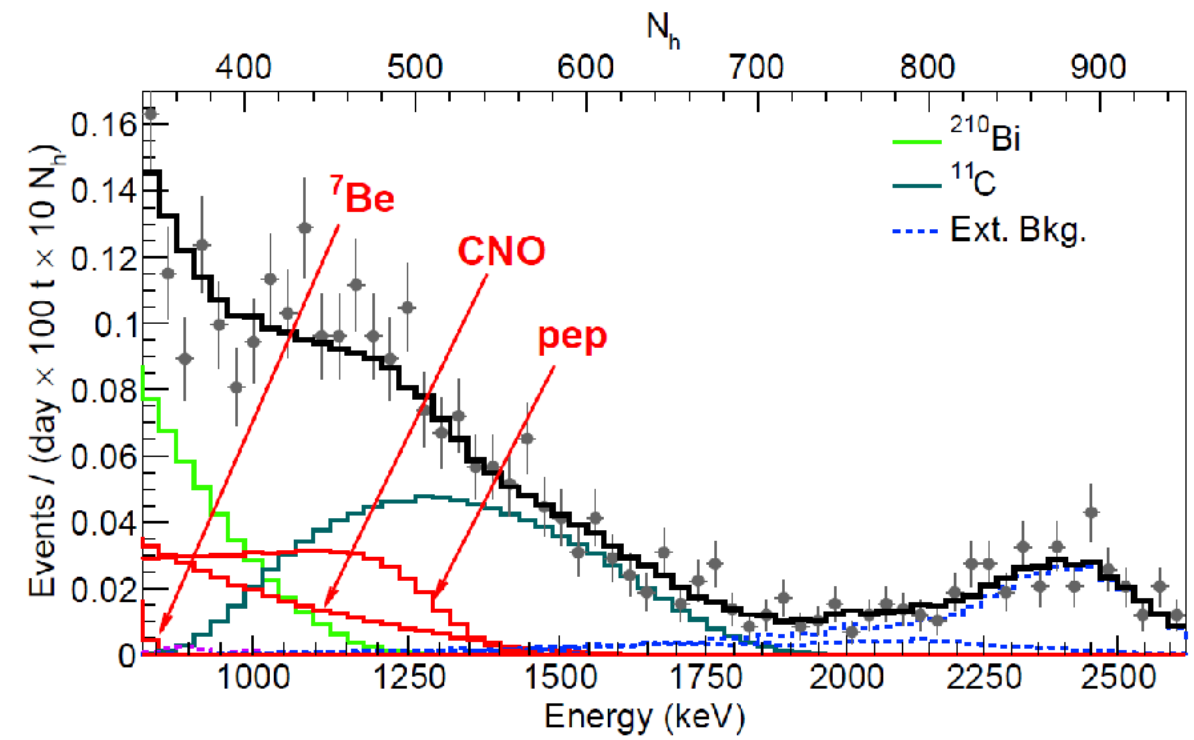
Simultaneous fit for all ν's

Astroparticle Physics 97 (2018) 136–15

Fits performed with analytical and Monte Carlo pdf's are consistent



lowest energy detail



R < 2.8 MeV and L_{PS} < 4.8
visible pep-shoulder

CNO ν's are included in the fit, but they are ~degenerate with Bi-210

CNO (MSW/LMA):
HZ: (4.92±0.55) cpd/100t
LZ: (3.52±0.37) cpd/100t

>5σ evidence of pep neutrinos
R(CNO)<8.1 cpd/100 t (95% CL)

Results — arXiv:1707.09279

Dec 14 2011 — May 21 2016
Fit range: (0.19-2.93) MeV

Exposure:
1291.51 days x 71.3 tons

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	$3.51\,(1 \pm 0.10) \times 10^8$

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

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 (see text)	-4.5	0.5	-1.0	0.2	-6.8	2.8	210Bi, E-scale, response
Inclusion of ^{85}Kr constraint	-2.2	2.2	0	0.4	-3.2	0	R(85Kr)<7.5 @ 95%
Live Time	-0.05	0.05	-0.05	0.05	-0.05	0.05	LS mass
Scintillator density	-0.05	0.05	-0.05	0.05	-0.05	0.05	LS mass
Fiducial volume	-1.1	0.6	-1.1	0.6	-1.1	0.6	LS mass
Total systematics (%)	-7.1	4.7	-1.5	0.8	-9.0	5.6	

Improved measurement of B-8 neutrinos

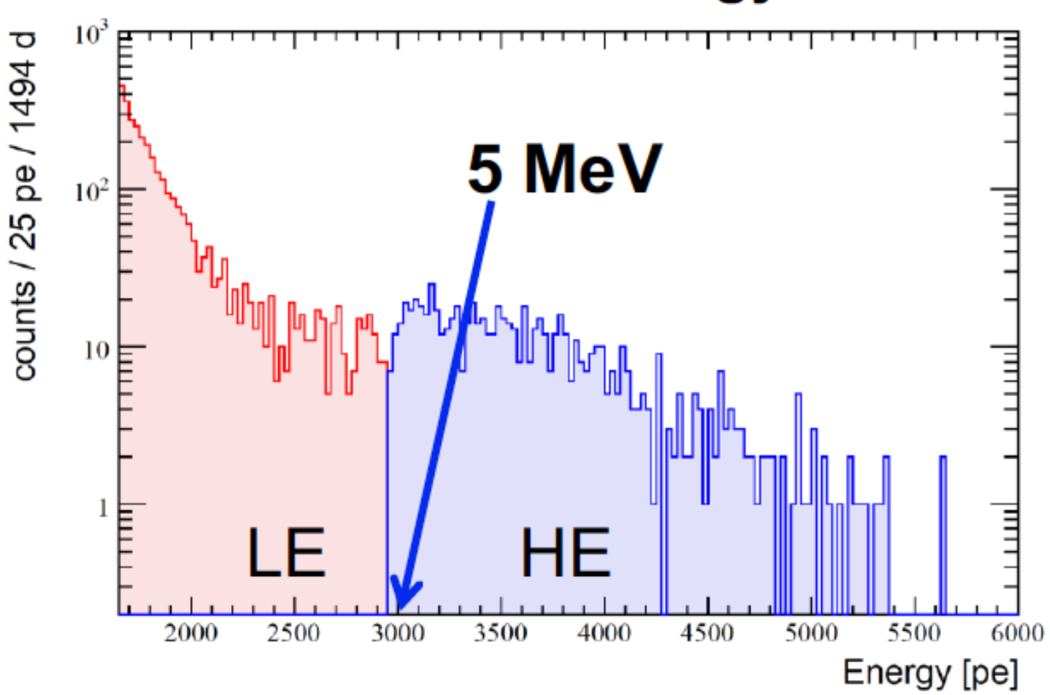
arXiv:1709.00756

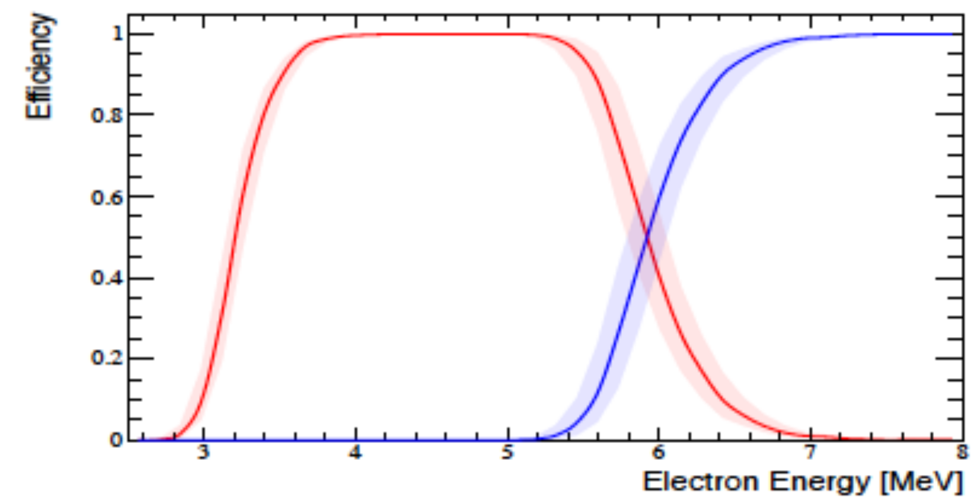
no FV cut, 3.2-17 MeV

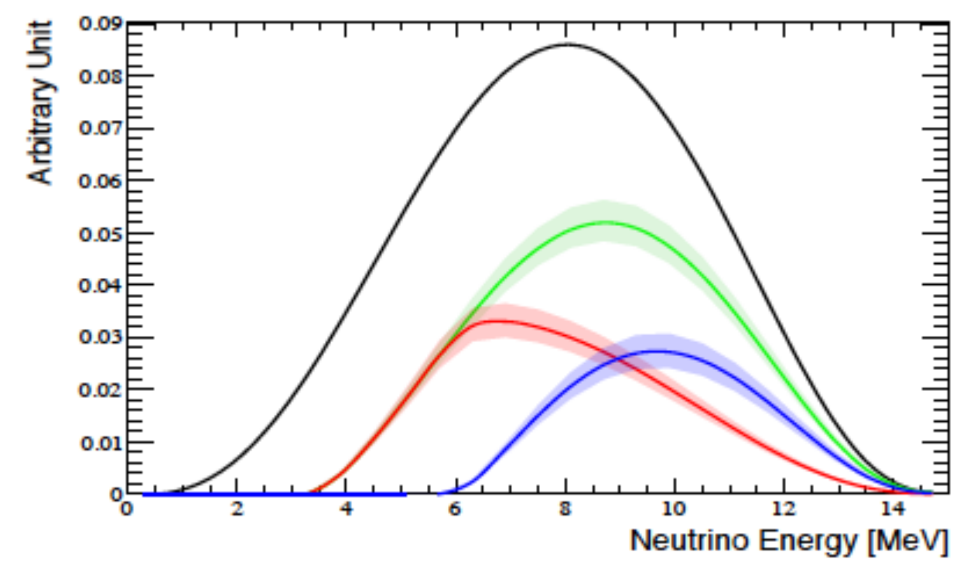
1.5 kton-yr exposure (x11 from phase-1)

better understanding of backgrounds
(cosmogenice Be-11, n-captures, surface)

> 3 MeV visible energy







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

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

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

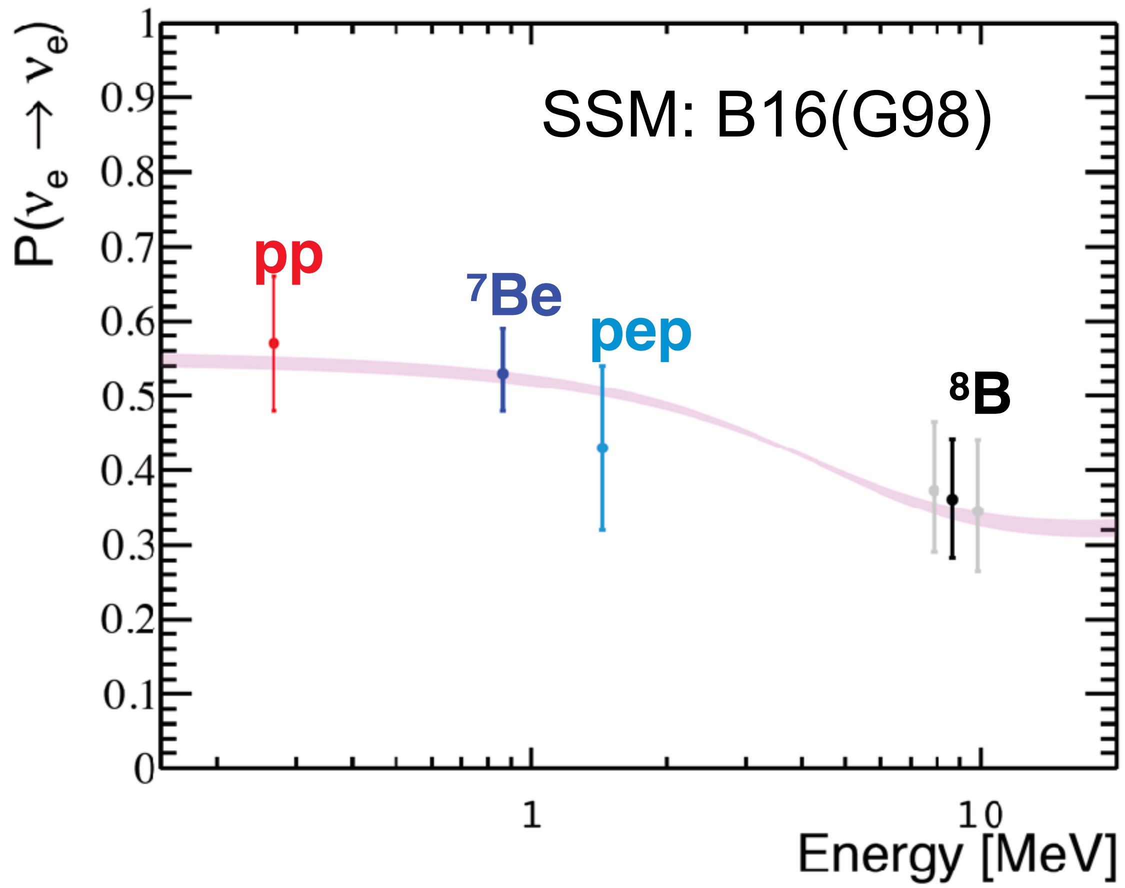
Borexino Phase 2 (2010-2016): Latest results

All rates are fully compatible with and improve the uncertainty of the previously published Borexino results

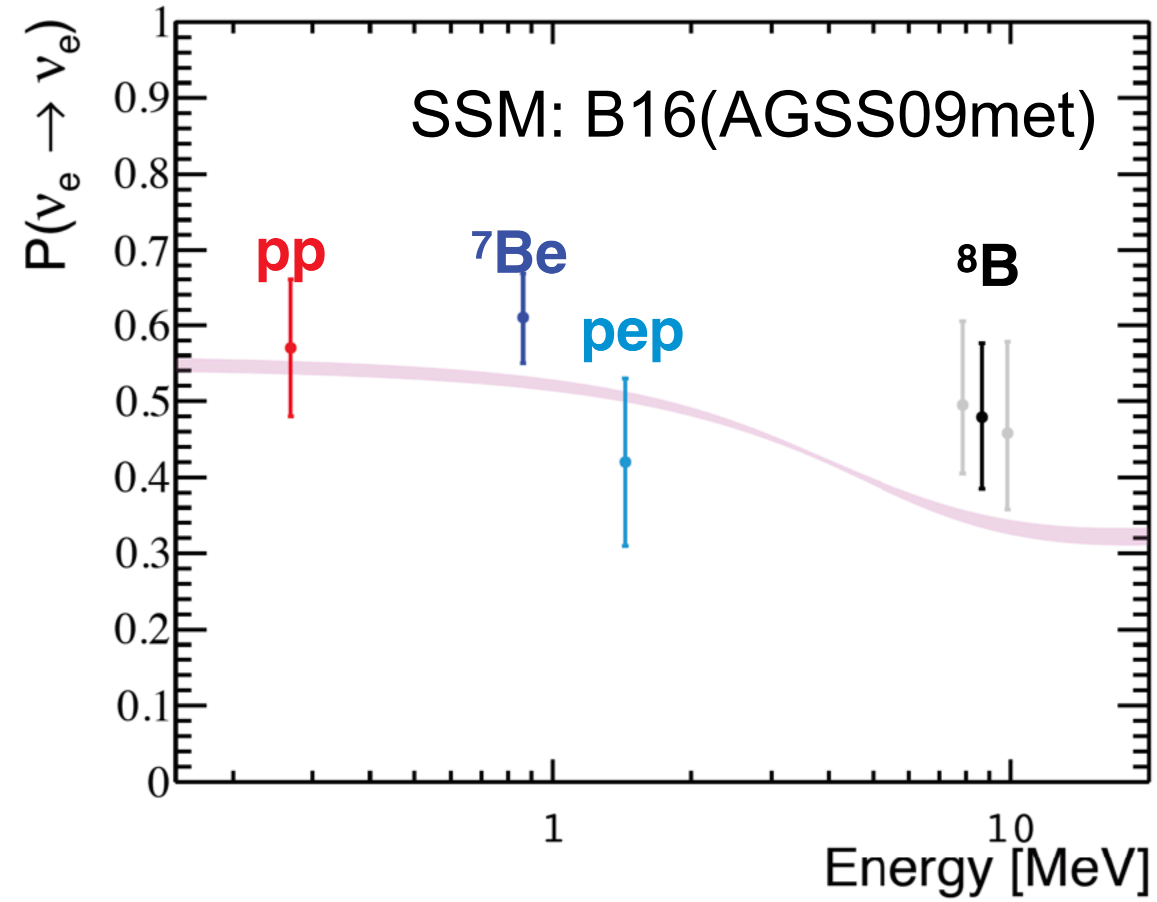
	Previous BX results (cpd/100t)	This work (cpd/100t)	Uncertainty reduction
pp	144 ± 13 ± 10	$134 \pm 10^{+6}_{-10}$	0.78
^{7}**Be**	48.3± 2.0 ± 0.9	$48.3 \pm 1.1^{+0.4}_{-0.7}$ **2.7% precision**	0.57
pep	3.1 ± 0.6 ± 0.3	(HZ) $2.43 \pm 0.36^{+0.15}_{-0.22}$ (LZ) $2.65 \pm 0.36^{+0.15}_{-0.24}$	0.61
^{8}**B**	0.217 ± 0.038 ± 0.008	$0.220^{+0.015}_{-0.016} \pm 0.006$	0.42

Survival probability, P_{ee}

High Metallicity



Low Metallicity



p-values:

Bx only: 0.998

All exp: 0.956

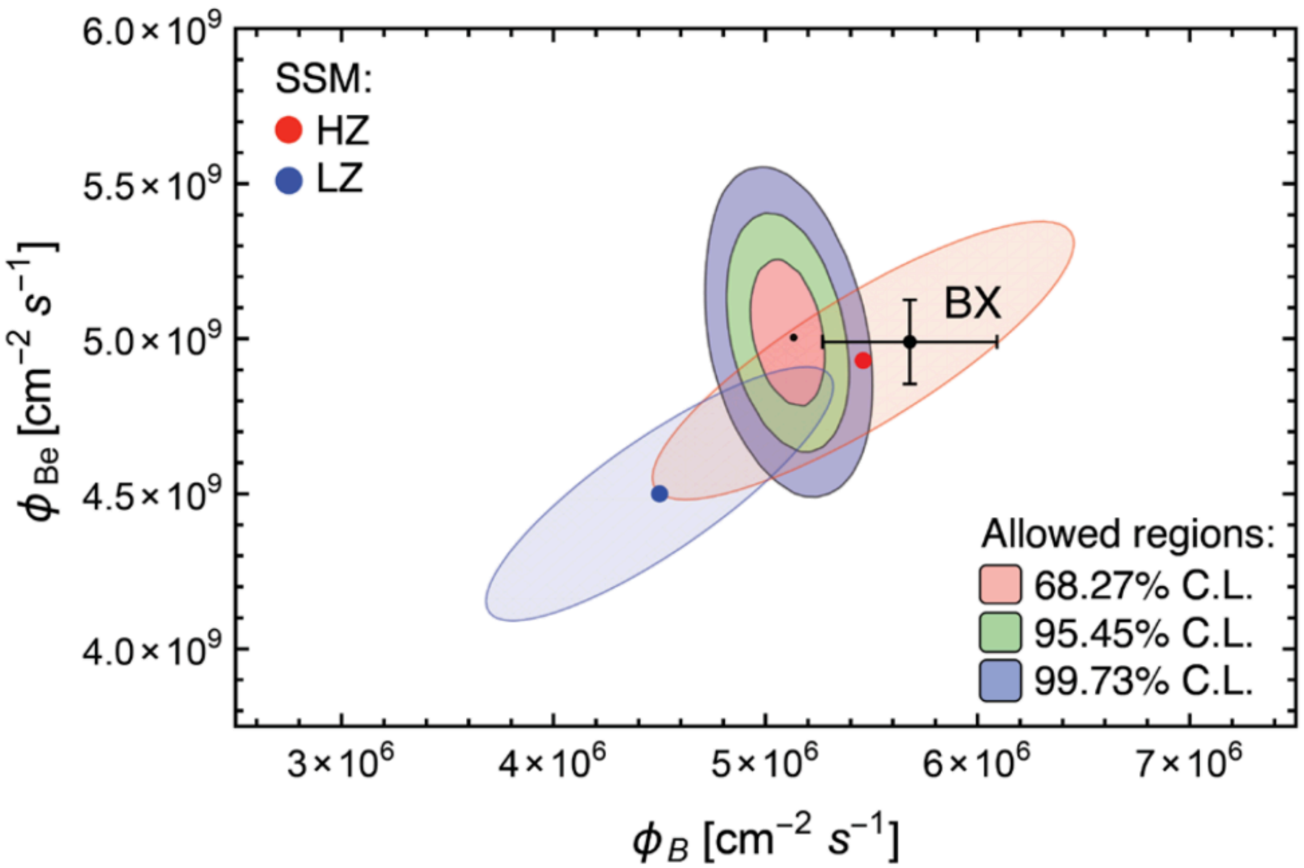
p-values:

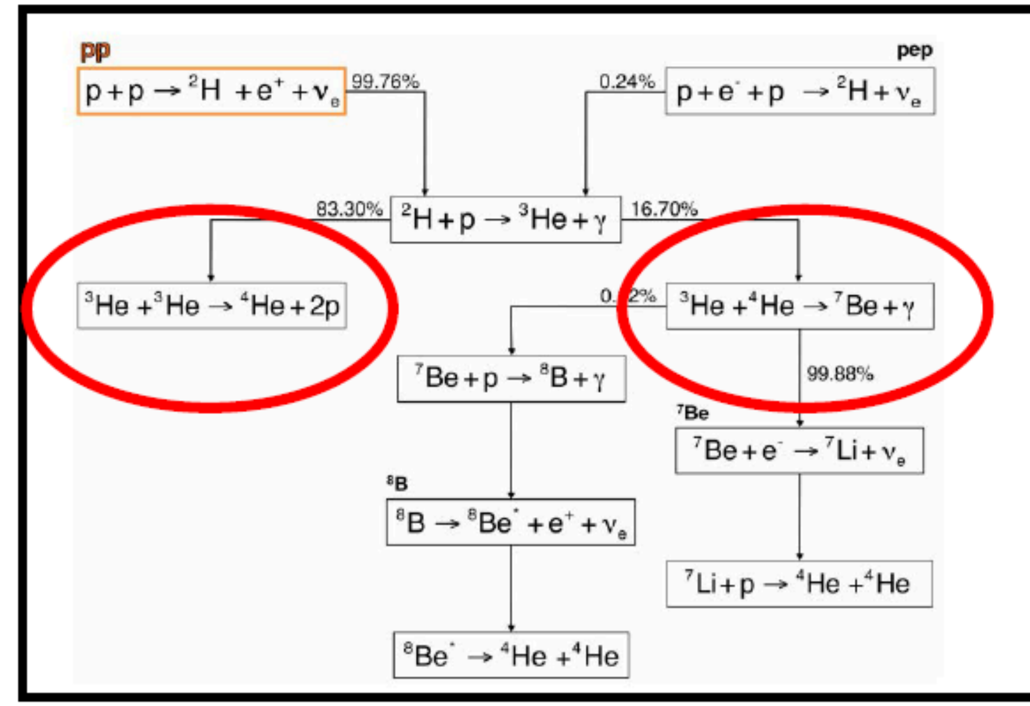
Bx only: 0.362

All exp: 0.465

30

Tests of the SSM





- **Global fit to all solar + Kamland data (including the new ^{7}Be result from BX)**

$$f_{Be} = \frac{\Phi(\mathrm{Be})}{\Phi(\mathrm{Be})_{HZ}} = 1.01 \pm 0.03$$

$$f_B = \frac{\Phi(\mathrm{B})}{\Phi(\mathrm{B})_{HZ}} = 0.93 \pm 0.02$$

- **a hint towards the HM :**
  LZ is excluded by BX data at 1.8σ level
- **theoretical errors are dominating**

$$R \equiv \frac{<^3\mathrm{He} + ^4\mathrm{He}>}{<^3\mathrm{He} + ^3\mathrm{He}>} = \frac{2\phi(^7\mathrm{Be})}{\phi(\mathrm{pp}) - \phi(^7\mathrm{Be})}$$

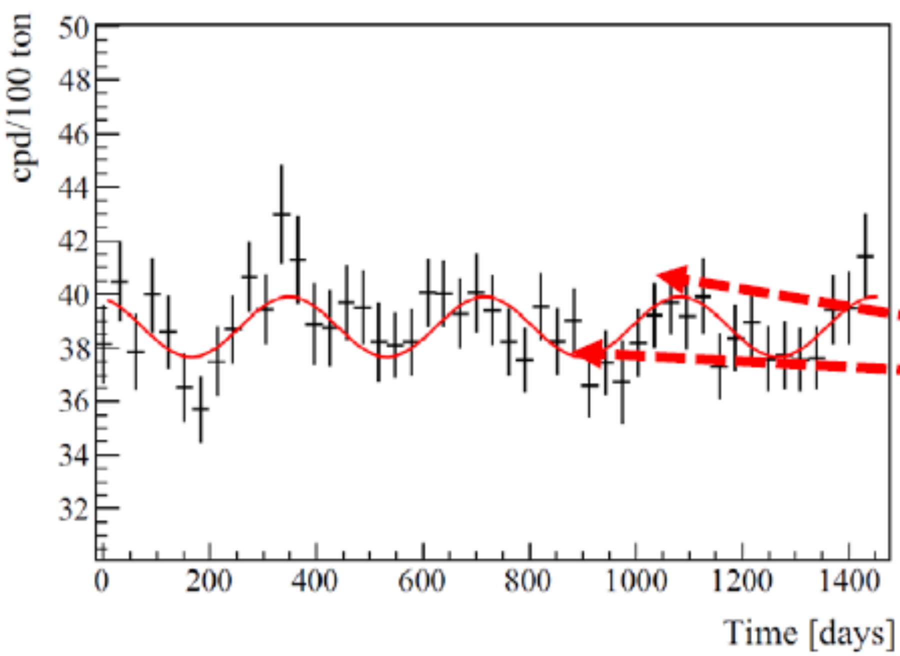
R(HZ) = 0.180 ± 0.011
R(LZ) = 0.161 ± 0.010

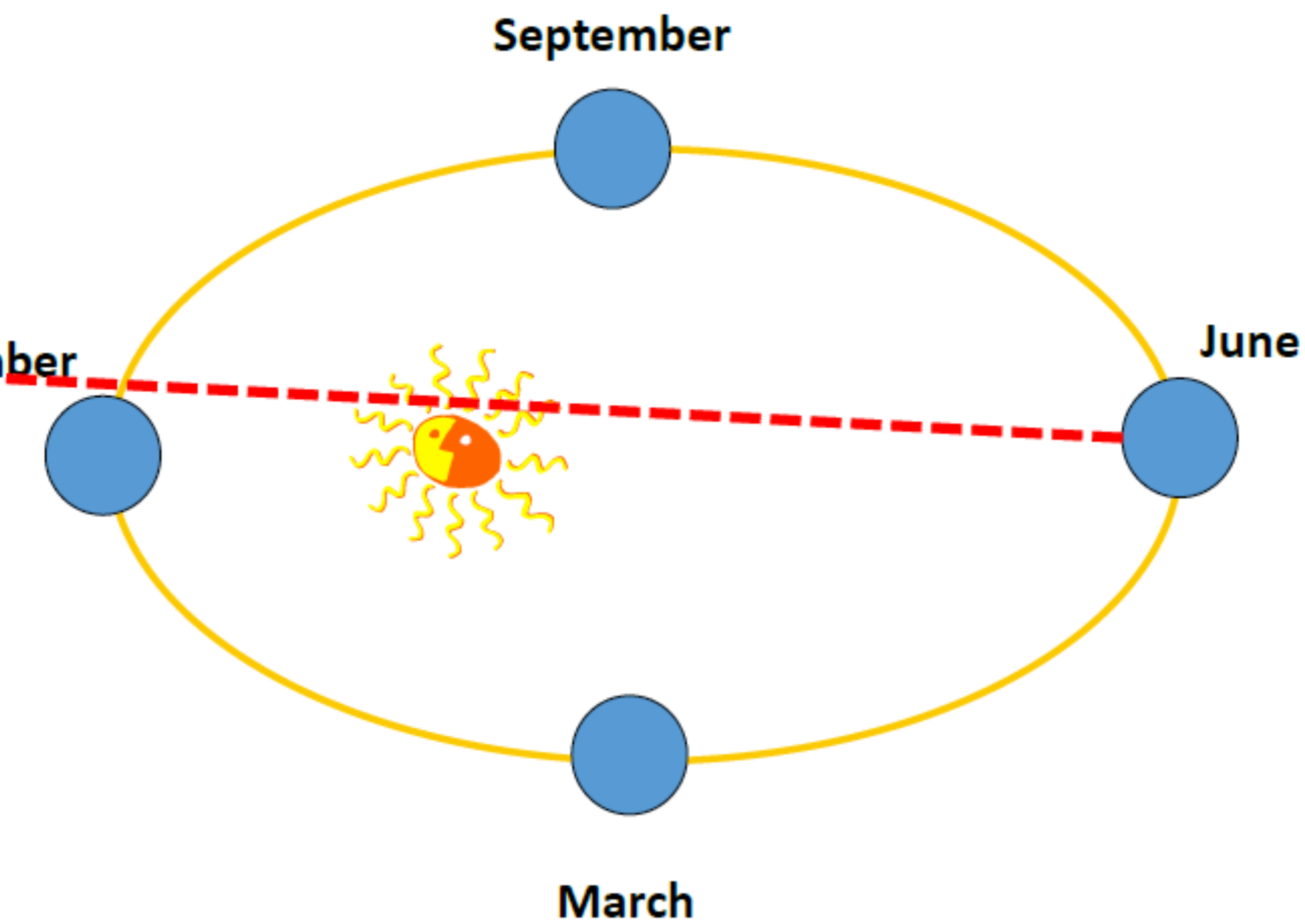
from pp and Be-7 measurements:

$R(BRX)=0.178^{+0.027}_{-0.023}$

Be-7 seasonal modulation

M. Agostini et al., Astropart.Physics 92 (2017) 21–29



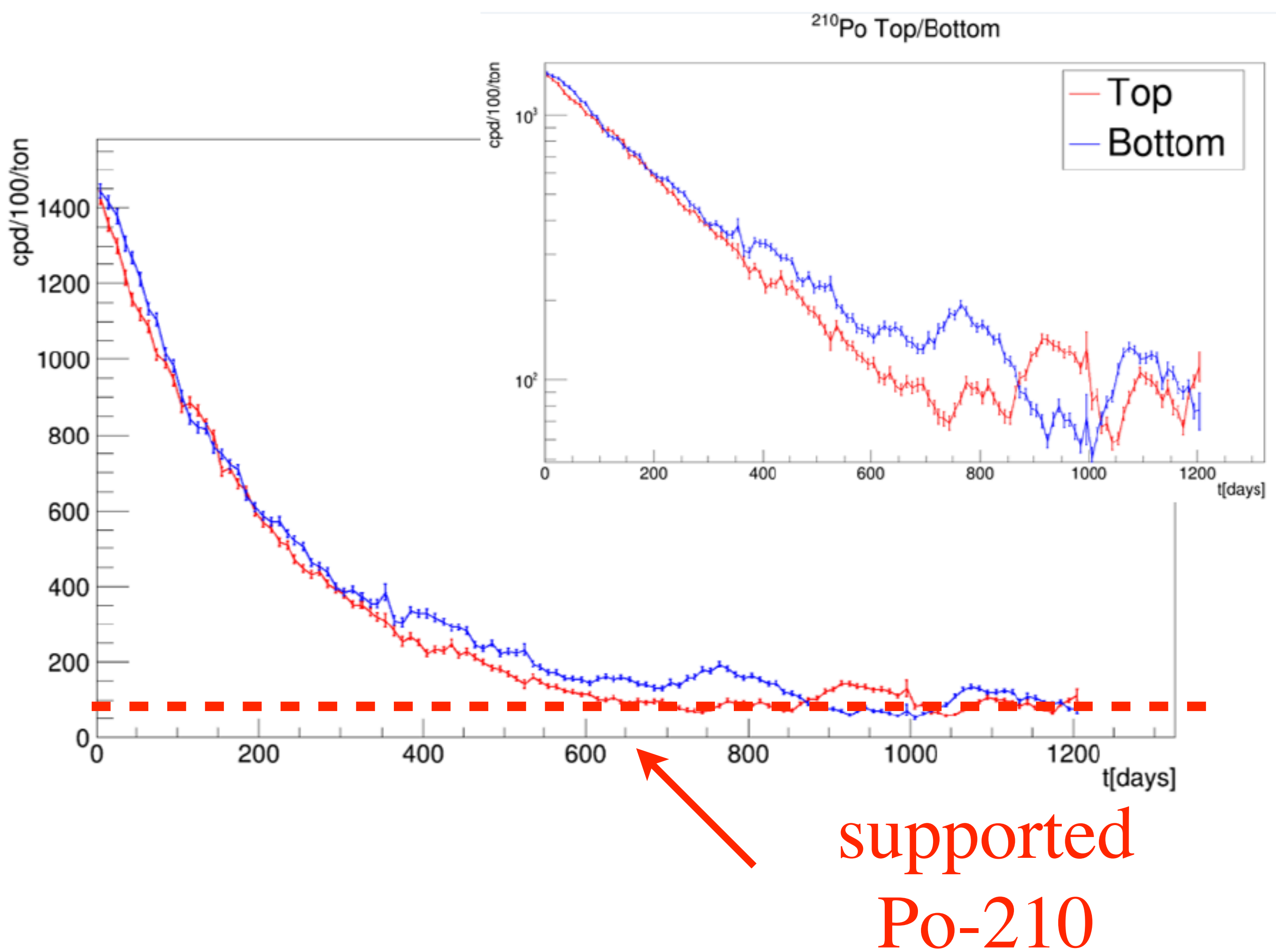


Fit to the evolution of the rate in time (bin of 30 days)

ε = (1.74 ± 0.45)%
T = (367 ± 10 days
Φ = (-18 ± 24) days

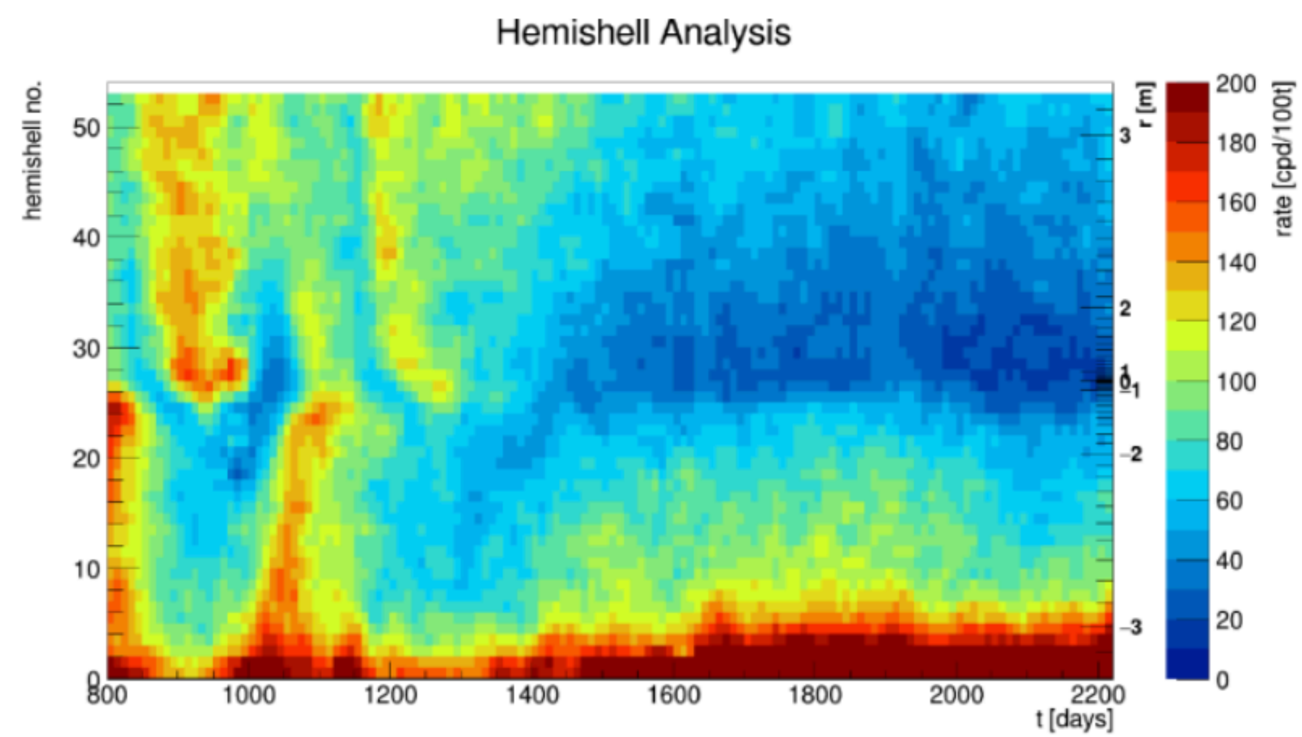
Towards a CNO solar neutrino measurement

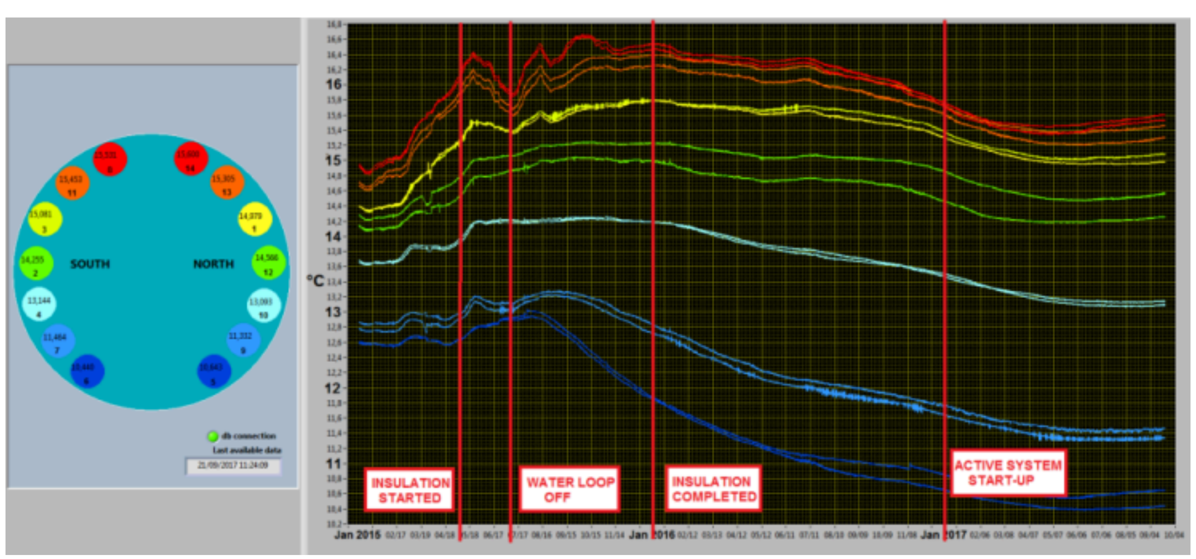
- CNO solar neutrinos: the direct measurement of their rate could help solve the solar metallicity controversy surrounding the Standard Solar Model (^{7}Be (12% difference) and CNO (50-60% difference))

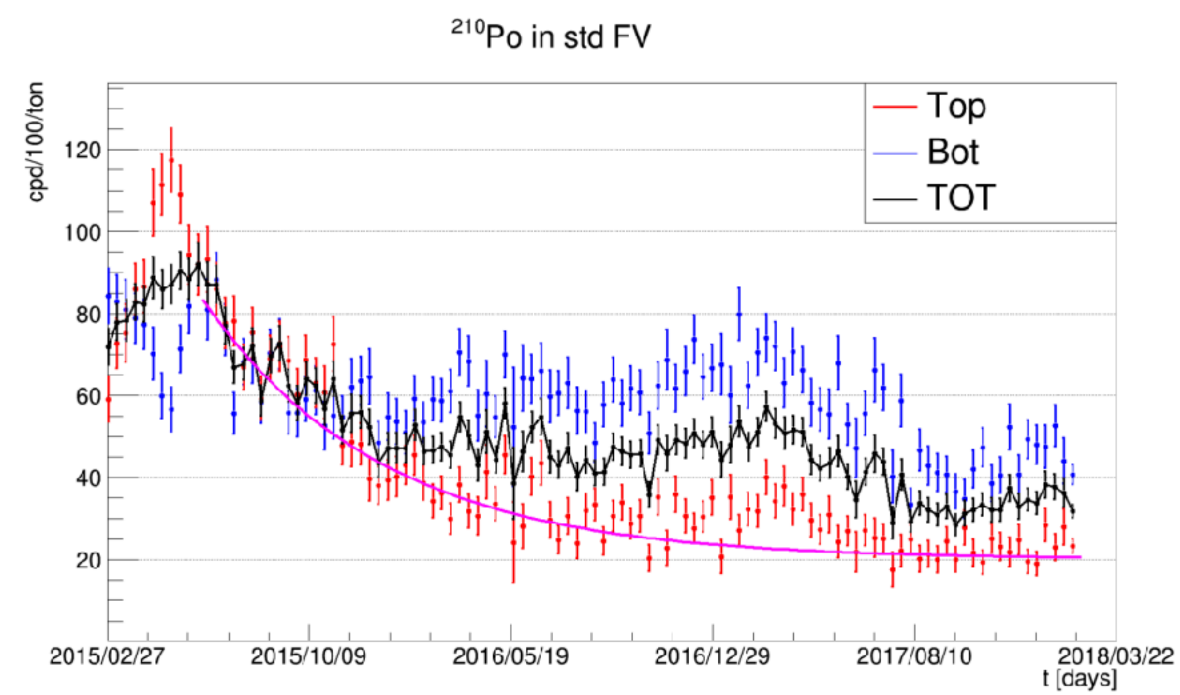


- supported Po-210 determines constrains residual Bi-210
- attempts plagued by fluid convection causing Po-210 mixing

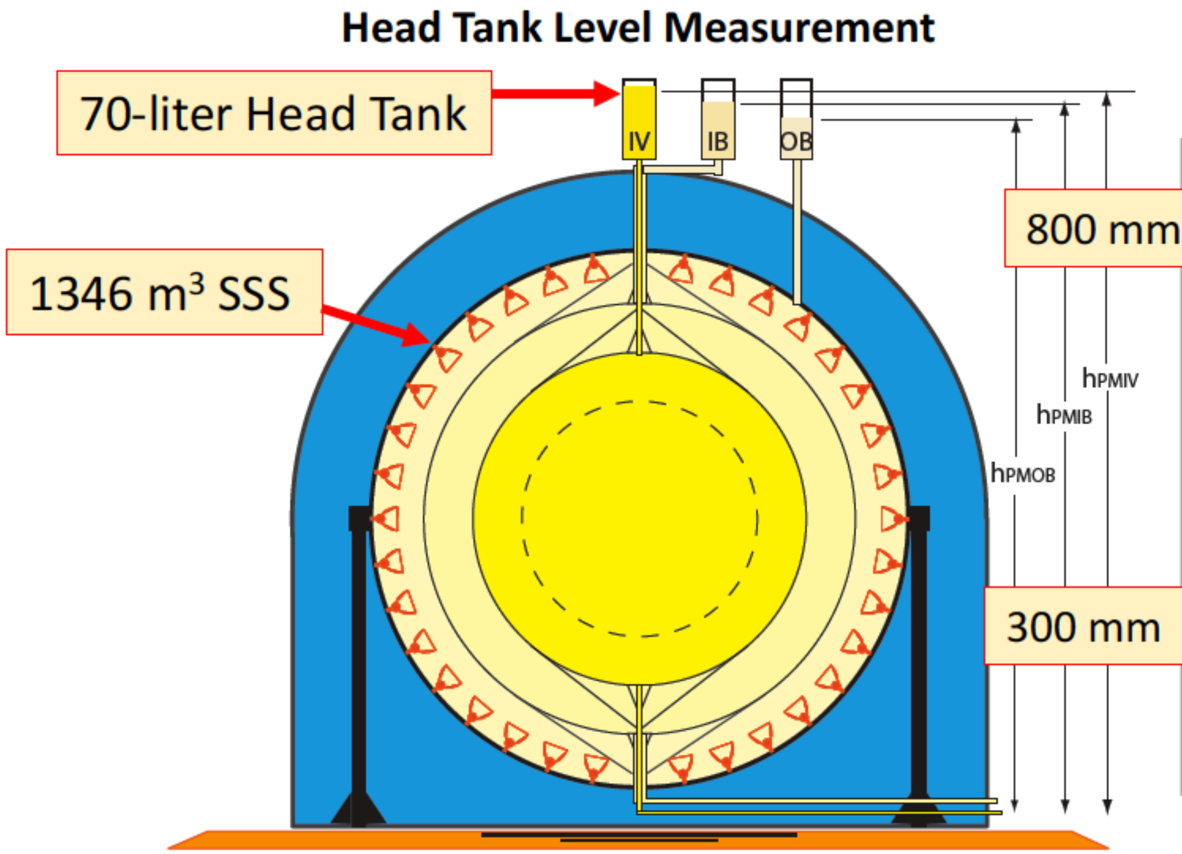
Detector thermal stabilization

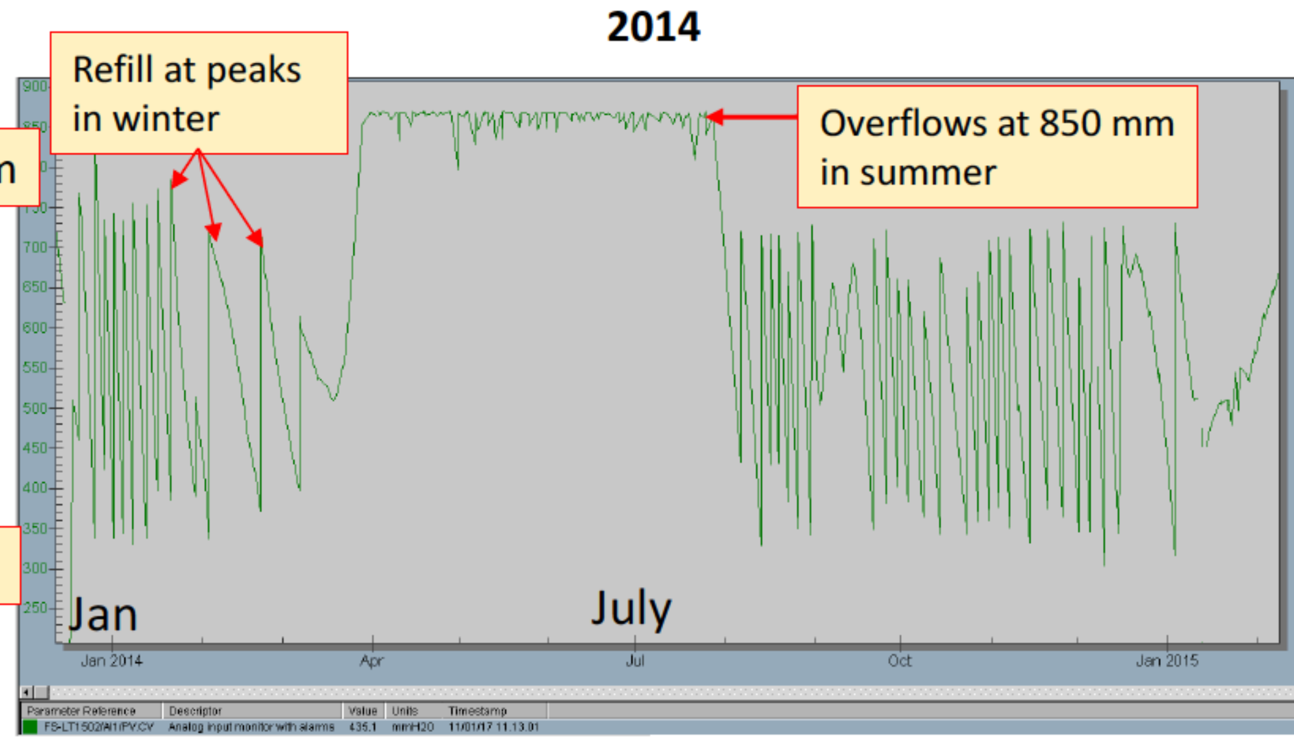


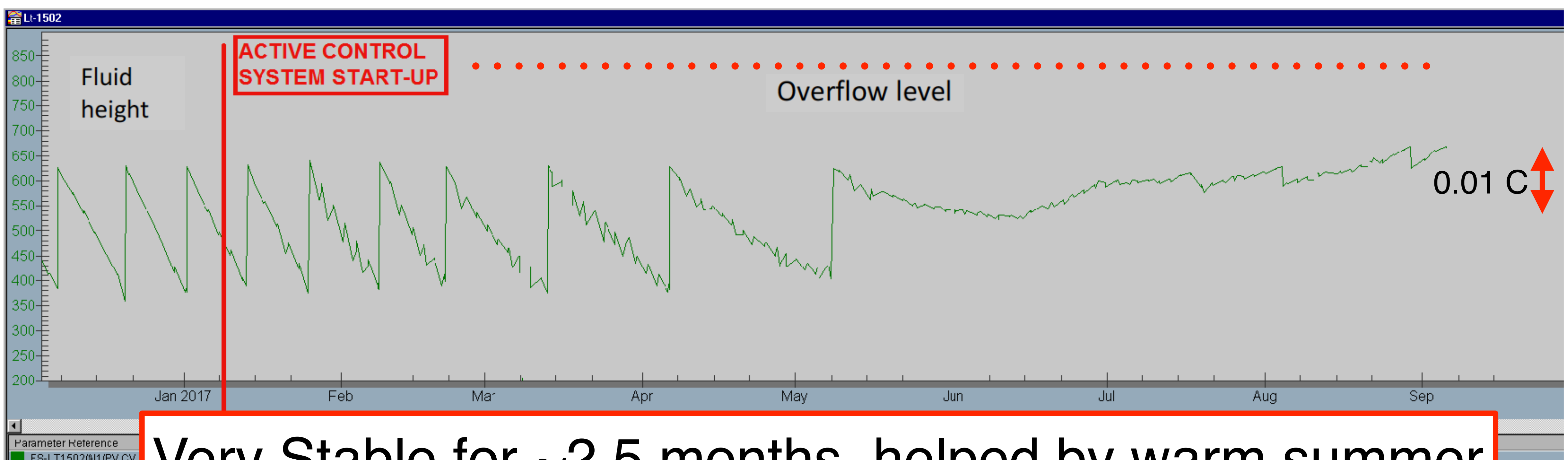




A very sensitive thermometer



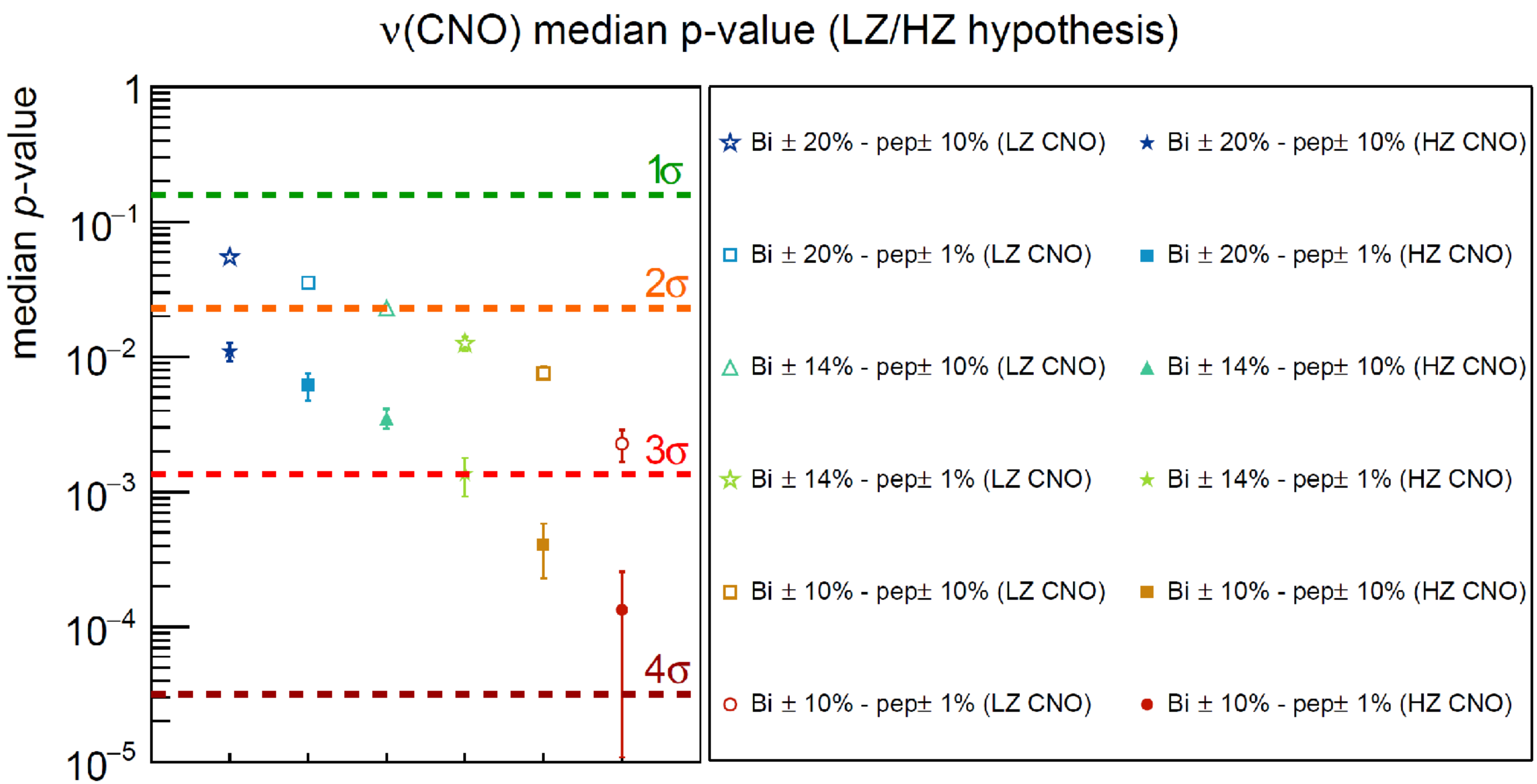




Very Stable for ~2.5 months, helped by warm summer

CNO sensitivity

- requires stable Bi-210, measured at 10-20%



Outlook

1) SNO+ could measure CNO neutrinos without C-11 background (alternative to $0\nu\beta\beta$ program)

2) JUNO (20 kton LS): 10-20 times the Borexino statistics (if LS is radio-pure enough)

arXiv:1809.03821

JCAP08(2016)017

3) A 300 ton LAr detector could:

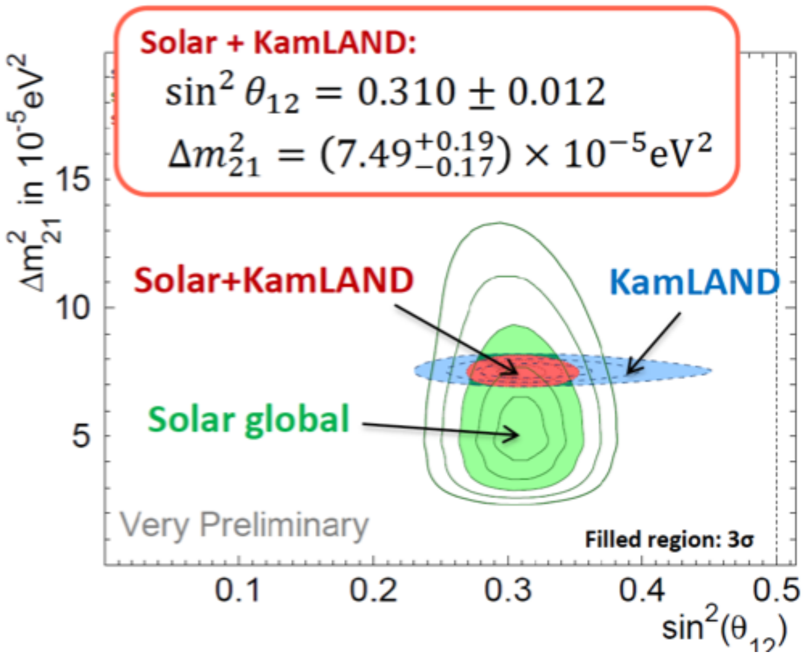
- *measure CNO solar neutrino flux with ~15% uncertainty*
- *measure Be-7 neutrinos at ~2%*
- *measure pep neutrinos at better than 10%*

4) DUNE could make precision measurements of B-8 neutrinos through different scattering channels (Ar-40 nuclei, electrons)

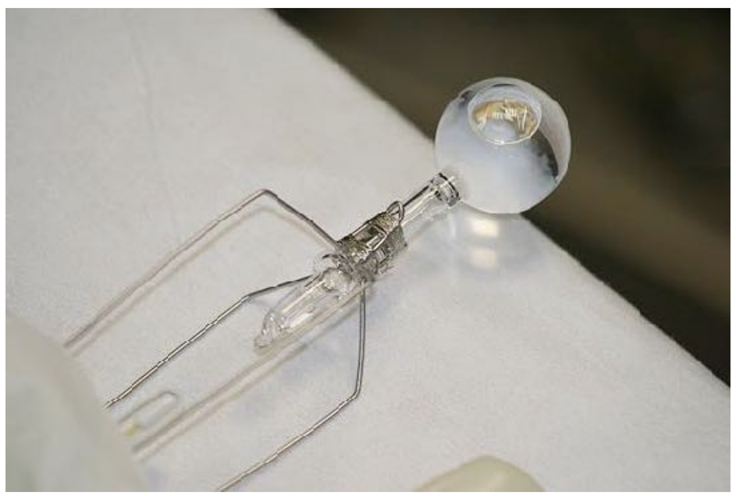
- *make precision measurements of B-8 neutrinos through different scattering channels (Ar-40 nuclei, electrons)*
- *precision day/night effect*
- *hep solar neutrinos*

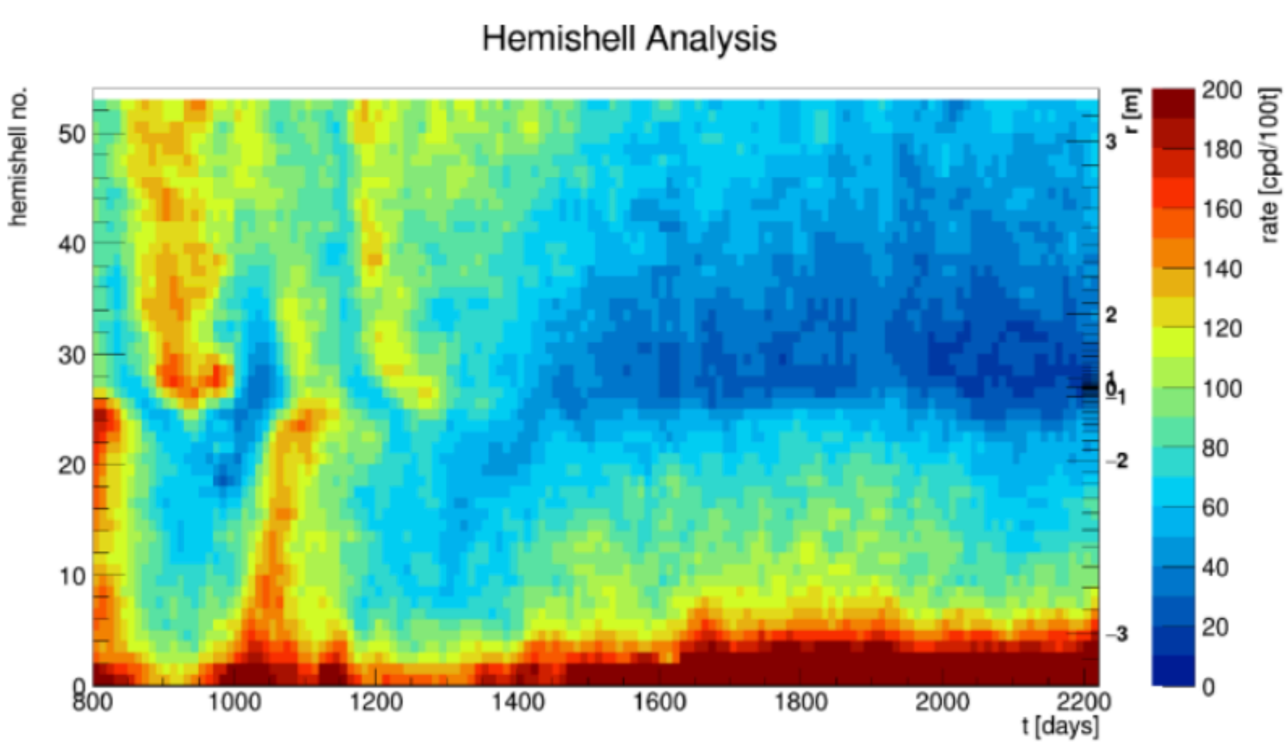
arXiv:1808.08232

Summary



- Solar neutrinos essential in discovering the physics of neutrino oscillations
- Two solar neutrino experiments are currently running (SuperK and Borexino)
- Borexino has mapped out the entire pp solar fusion chain with high precision
- A measurement of CNO neutrinos would give us key knowledge of the Sun's metallicity
- Low-background techniques developed by Borexino have defined the standard for rare-event physics
- Some upcoming experiments could continue this exciting branch of science





the Borexino collaboration

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