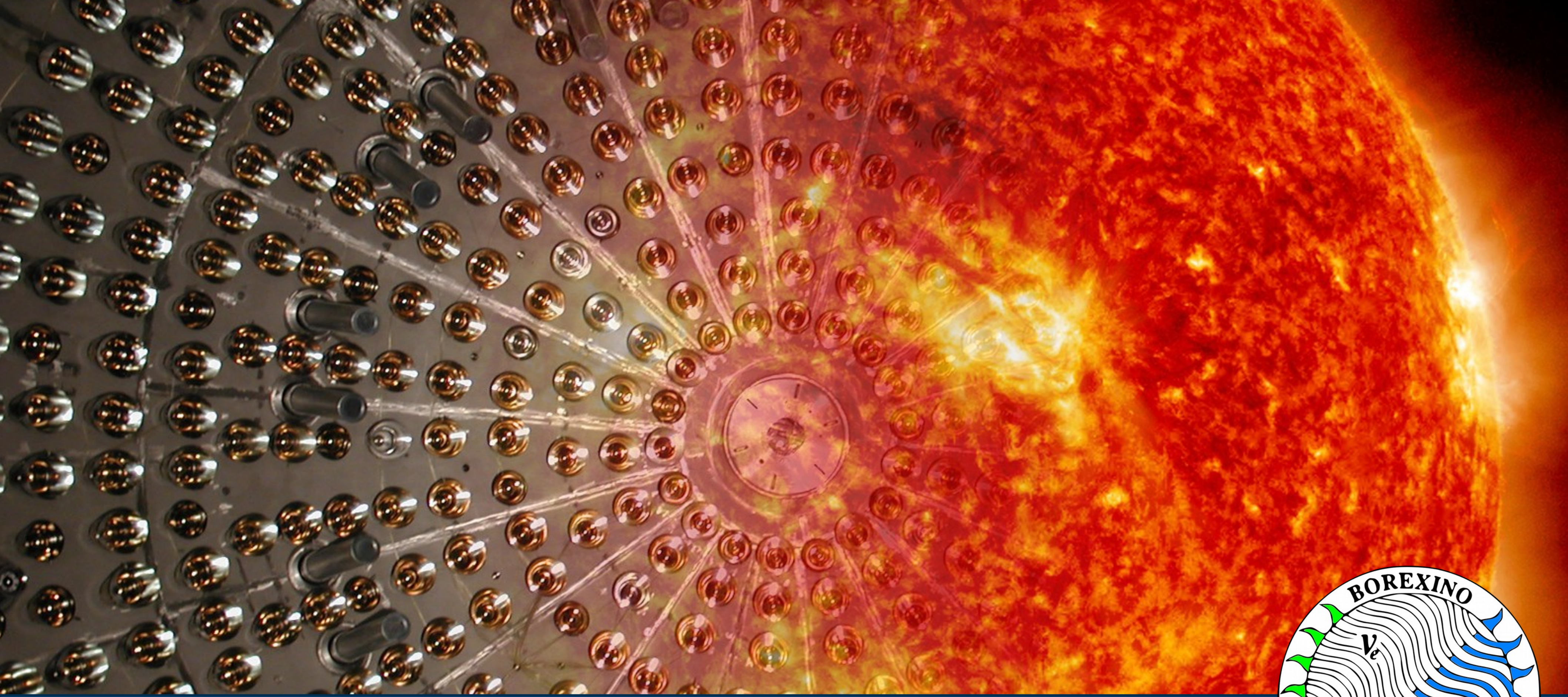


Comprehensive measurement of pp-chain solar neutrinos with Borexino

Mariia Redchuk on behalf of the **Borexino collaboration**

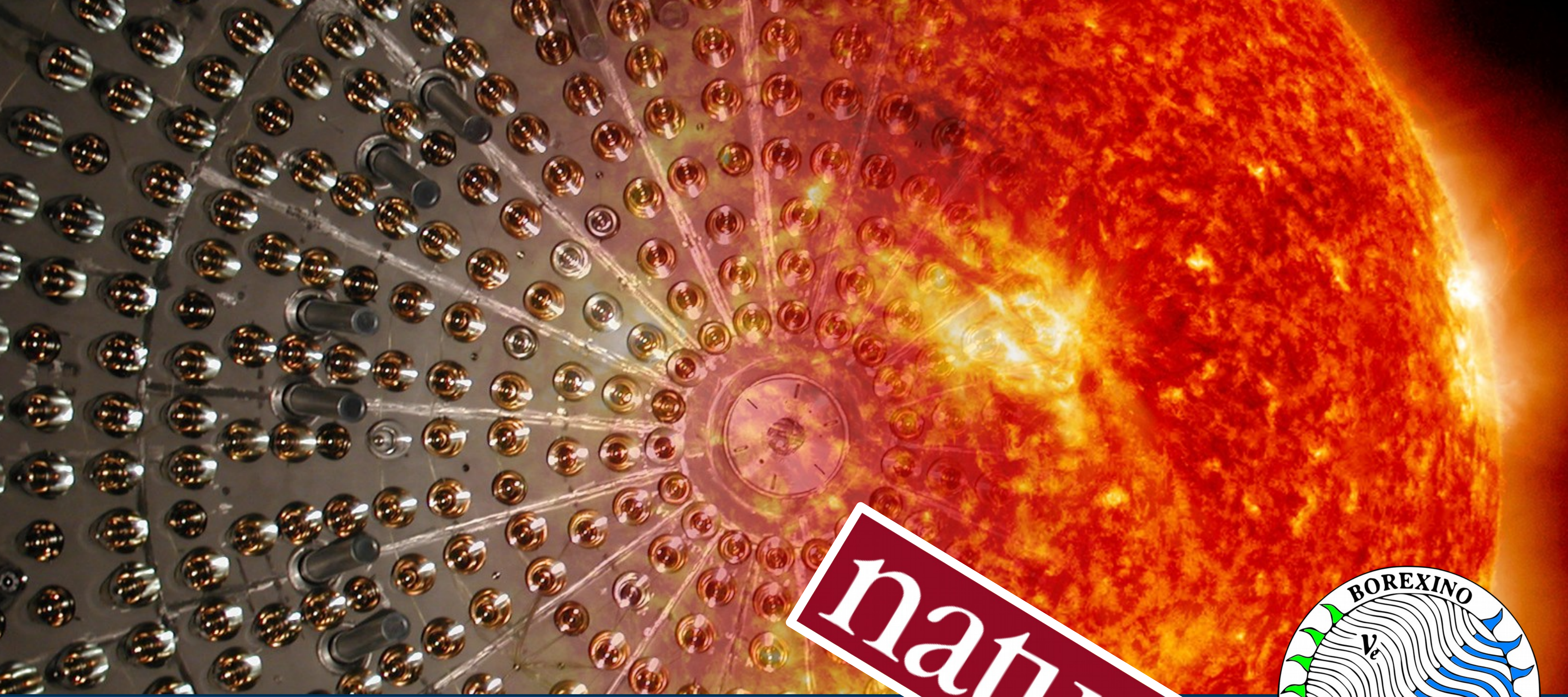
[1] Institut für Kernphysik, Forschungszentrum Jülich, Germany
[2] III. Physikalisches Institut B, RWTH Aachen, Germany

11.07.2019
EPS-HEP2019
Ghent, Belgium

Mitglied der Helmholtz-Gemeinschaft

RWTH AACHEN UNIVERSITY

JÜLICH Forschungszentrum



Comprehensive measurement of pp
solar neutrinos with Borexino

nature

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BOREXINO GRAN SASSO

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OUTLINE

Comprehensive measurement of pp-chain solar neutrinos with Borexino

1. What are **solar neutrinos**?
2. What is **Borexino**?
3. What did we **measure** and **how**?
4. What are the **implications**?
5. What’s **next**?
6. **Summary**

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WHAT ARE SOLAR NEUTRINOS?

- **Fusion** reactions that convert **p** → ^{4}**He** produce ***ν***

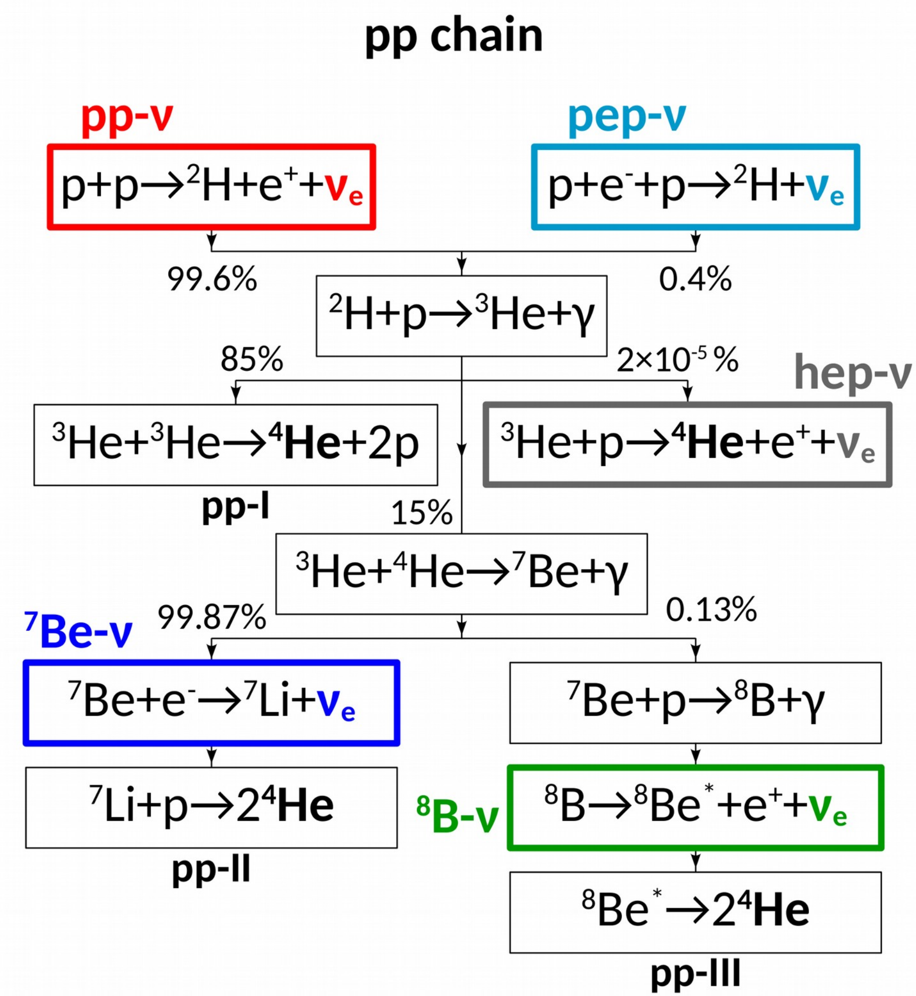
Intense natural *ν* beam

- Study ***ν*** using the **sun**
  → **oscillation** parameters
  → **MSW-LMA** (matter effect)

Direct probe of the sun's core

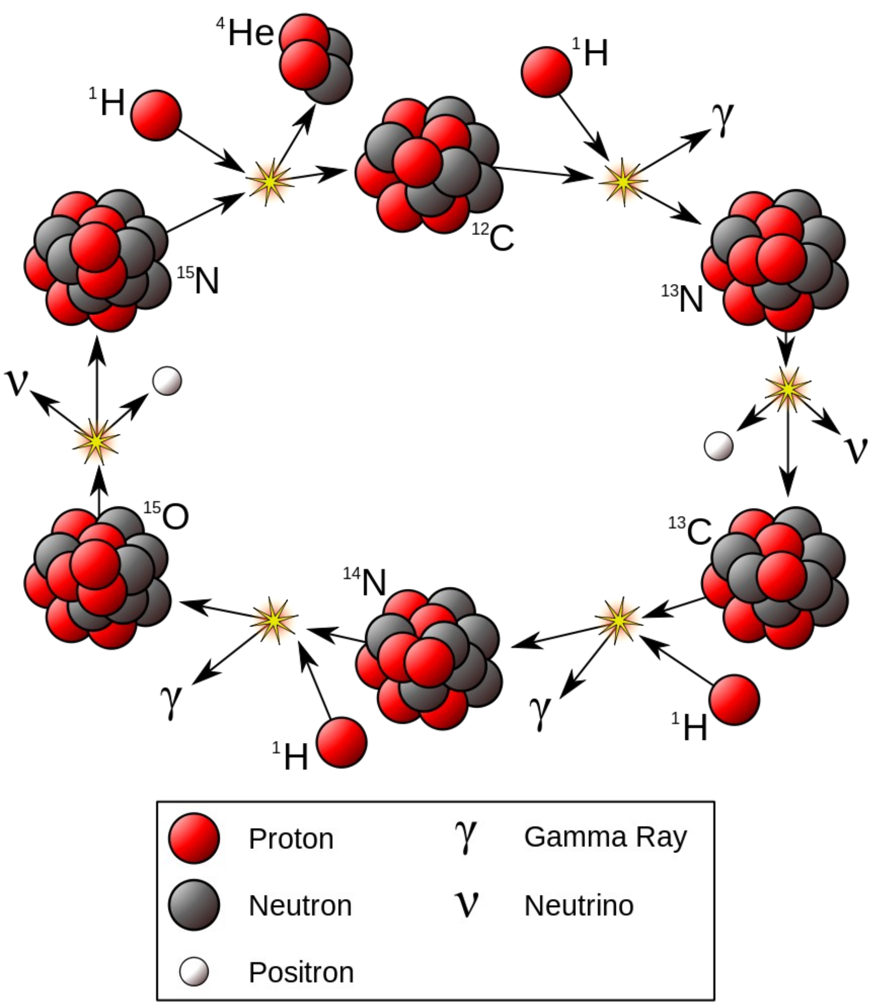
- Study the **sun** using ***ν***
  → fusion **rates**
  → **metallicity**

99% of the solar energy



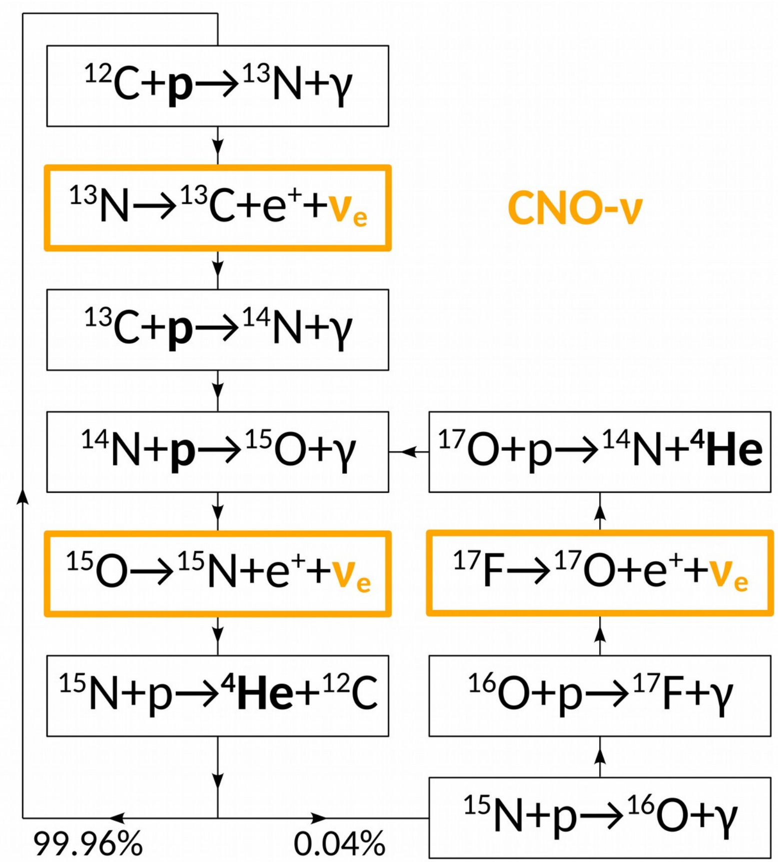
WHAT ARE SOLAR NEUTRINOS?

Alternative way to convert **p → ^{4}He**, closed-loop **catalyzed CNO chain**
Has never been experimentally **observed**
Expected to be the **main source** of energy in **heavier stars**



Credit: Wikimedia Commons

< 1% solar energy



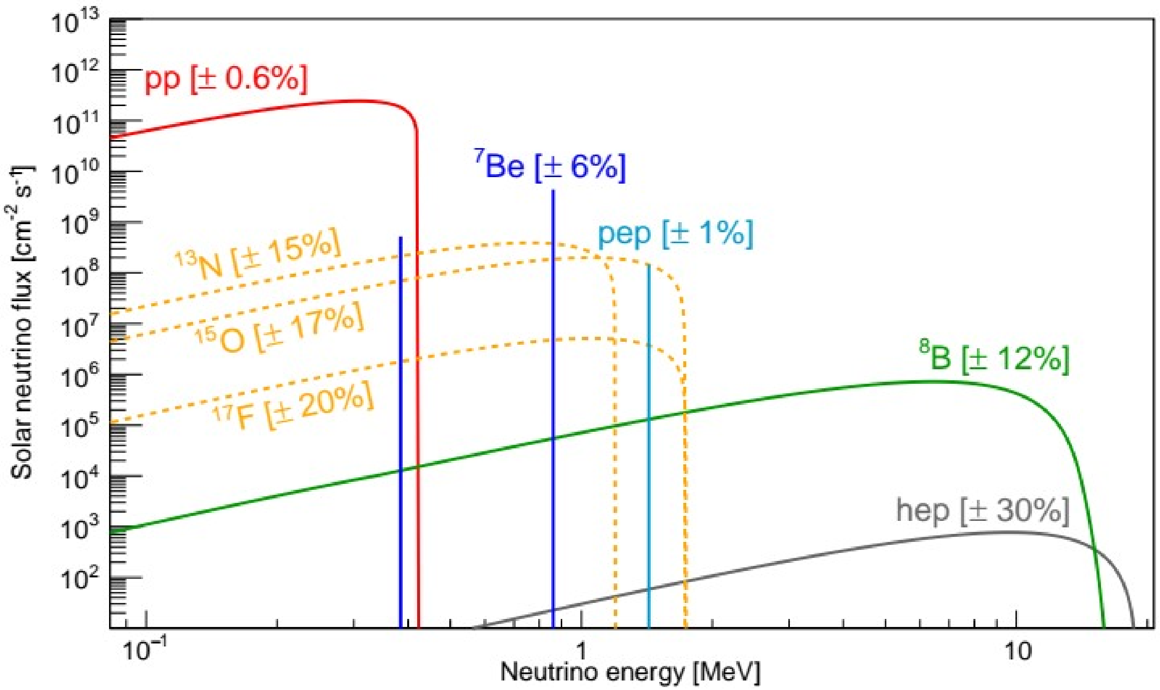
WHAT ARE SOLAR NEUTRINOS?

Solar metallicity

abundance of elements **heavier** than **He**

Solar ν	High M	Low M	Difference
pp	$5.98\ (1 \pm 0.006) \times 10^{10}$	$6.03\ (1 \pm 0.005) \times 10^{10}$	0.83%
^7Be	$4.93\ (1 \pm 0.06) \times 10^{9}$	$4.50\ (1 \pm 0.06) \times 10^{9}$	8.72%
pep	$1.44\ (1 \pm 0.009) \times 10^{8}$	$1.46\ (1 \pm 0.009) \times 10^{8}$	1.39%
CNO	$4.88\ (1 \pm 0.11) \times 10^{8}$	$3.51\ (1 \pm 0.010) \times 10^{8}$	28.07%
^8B	$5.46\ (1 \pm 0.12) \times 10^{6}$	$4.50\ (1 \pm 0.12) \times 10^{6}$	17.58%

Metallicity → **opacity** of the solar plasma → **central T°C** → ***V*** fluxes



Different **fluxes** are predicted by different **Standard Solar Models**

Metallicity is **fundamental** but still **poorly understood!**

N. Vinyoles et al., “A new Generation of Standard Solar Models,” Astrophys. J., vol. 835, no. 2, p. 202 (2017)

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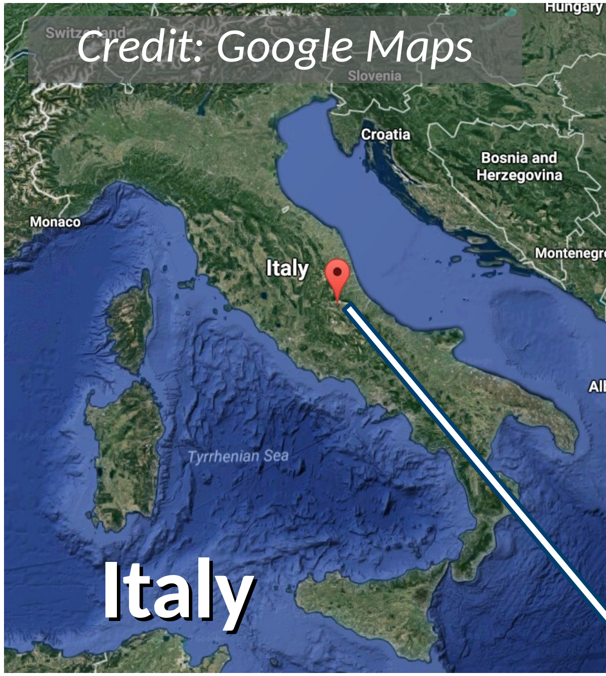
WHAT IS BOREXINO?

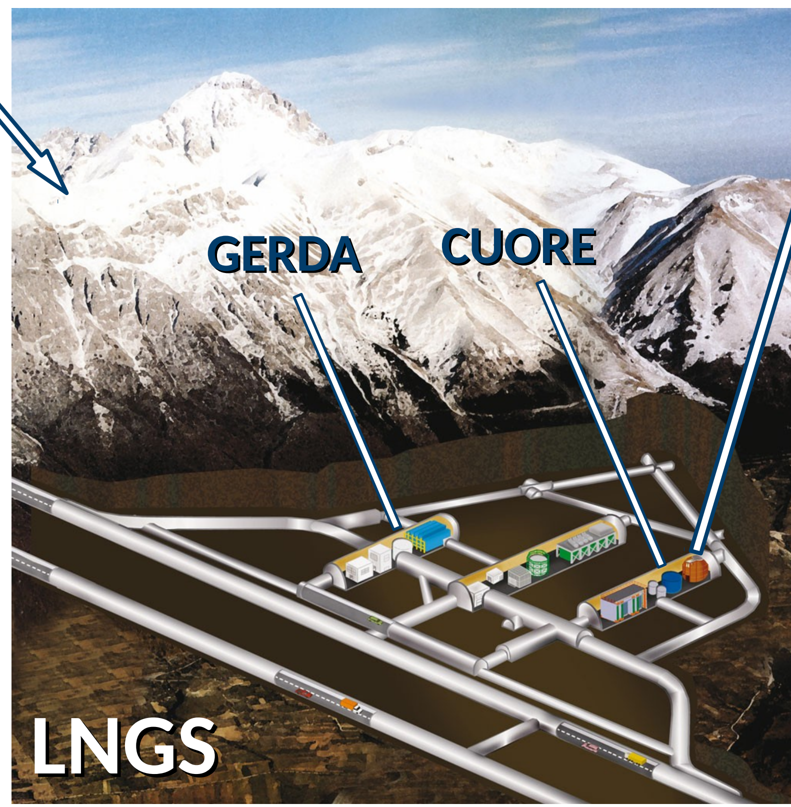


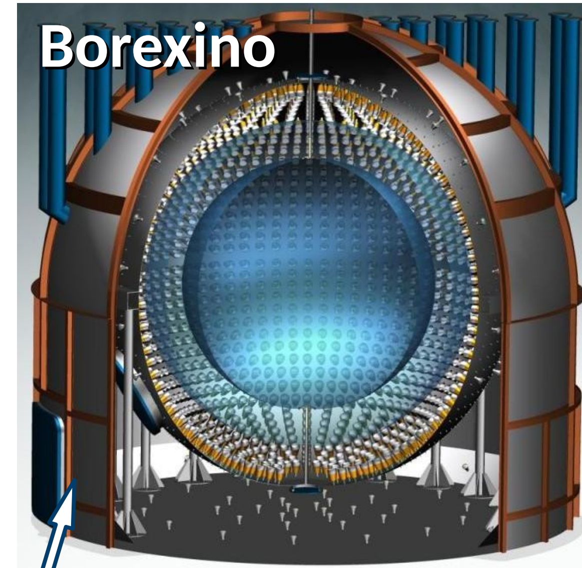
the world's

most radio-pure

liquid scintillator detector

the **largest underground research center** in the world

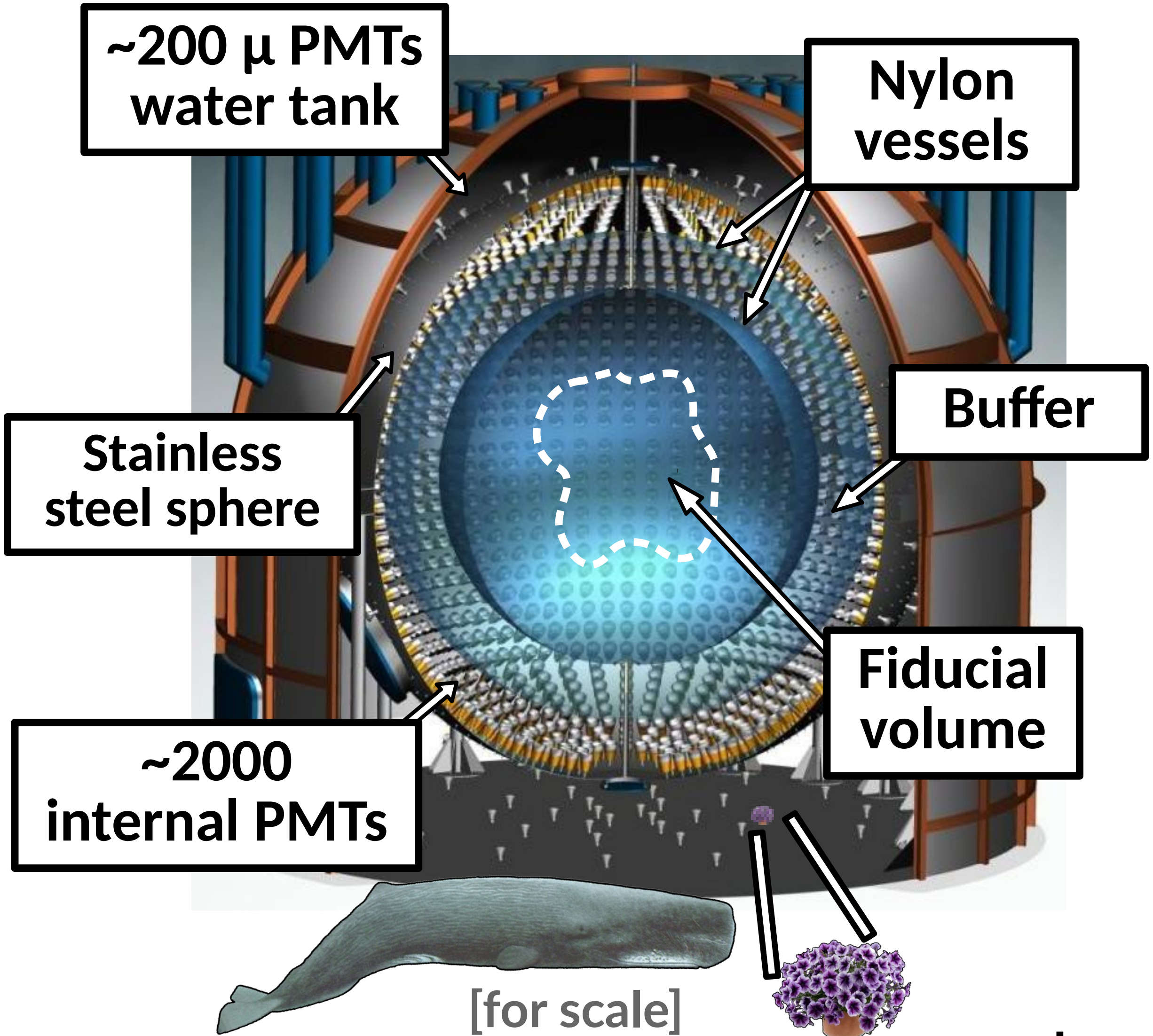




- **3800m** water equivalent
- **μ** suppressed by factor ~10^6

Credit: Laboratori Nazionali del Gran Sasso

WHAT IS BOREXINO?



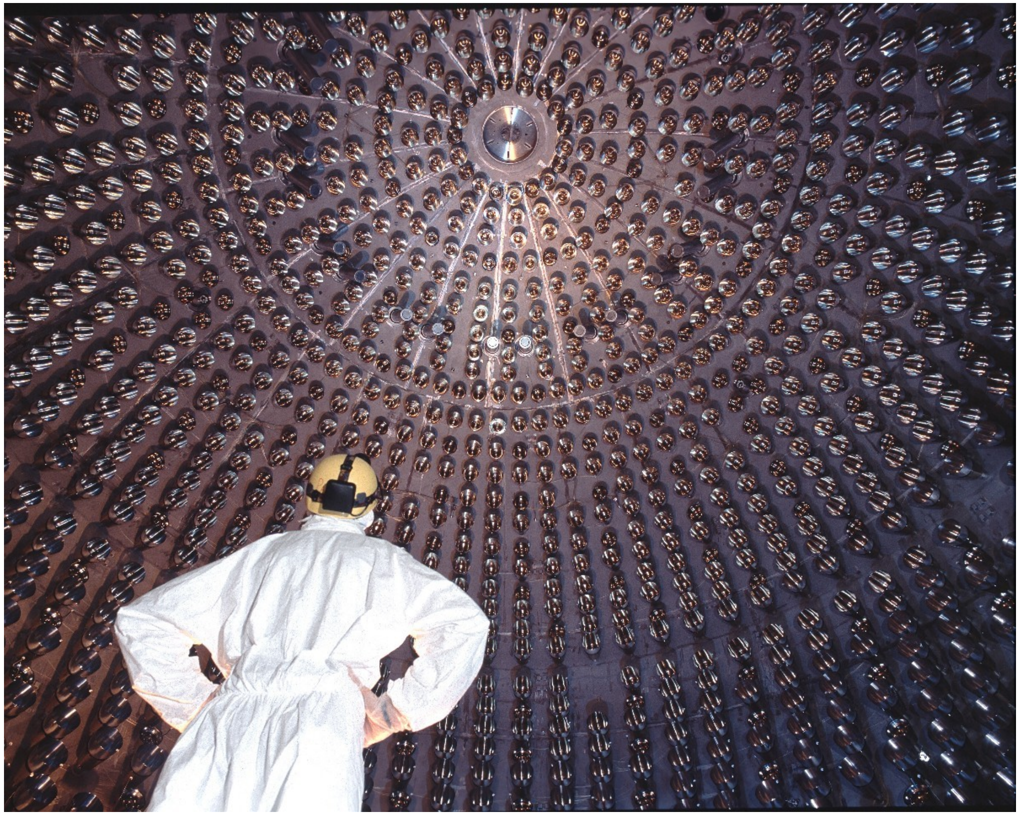
$$\nu + e^- \rightarrow \nu + e^-$$

- **50 keV** @ 1 MeV
  12 cm @ 1 MeV
  ~500 p.e./MeV
- **Lowest** energy threshold
- **Unprecedented radiopurity**
  - high purity materials
  - Using **Fiducial Volume**
  - **Purification** campaign

⇩

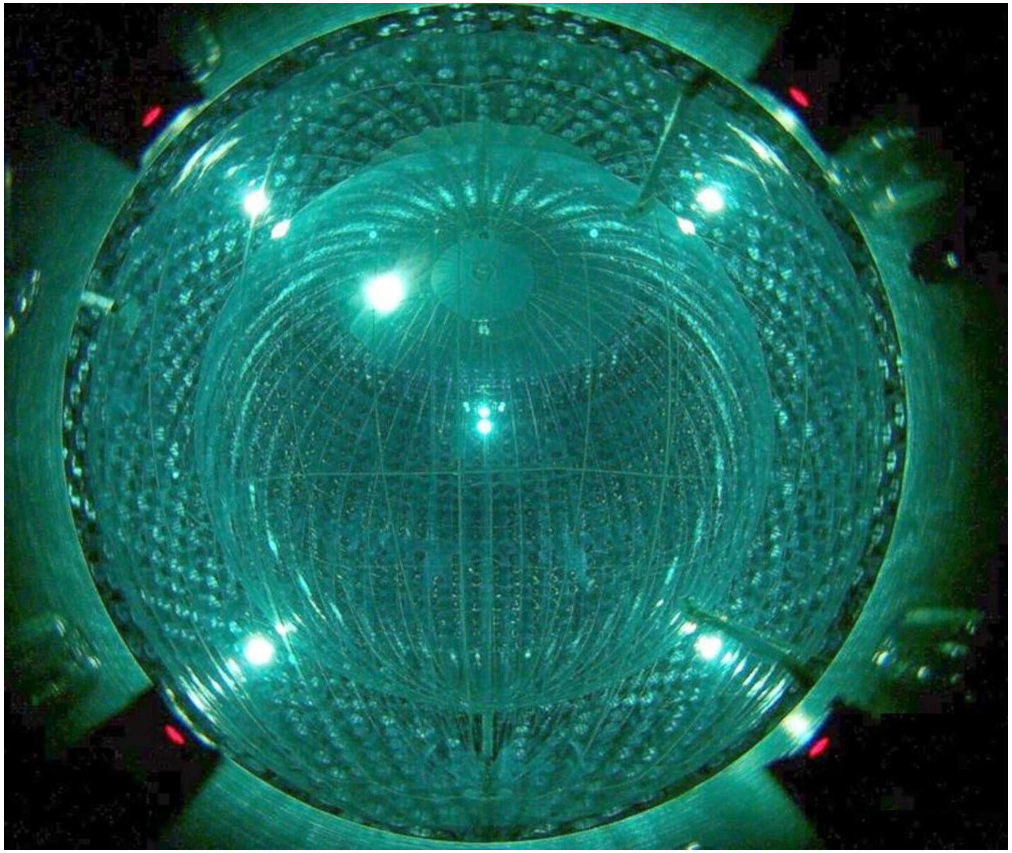
the best for **solar neutrinos**

WHAT IS BOREXINO?



Inner detector PMTs

Nylon vessels



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WHAT DID WE MEASURE?

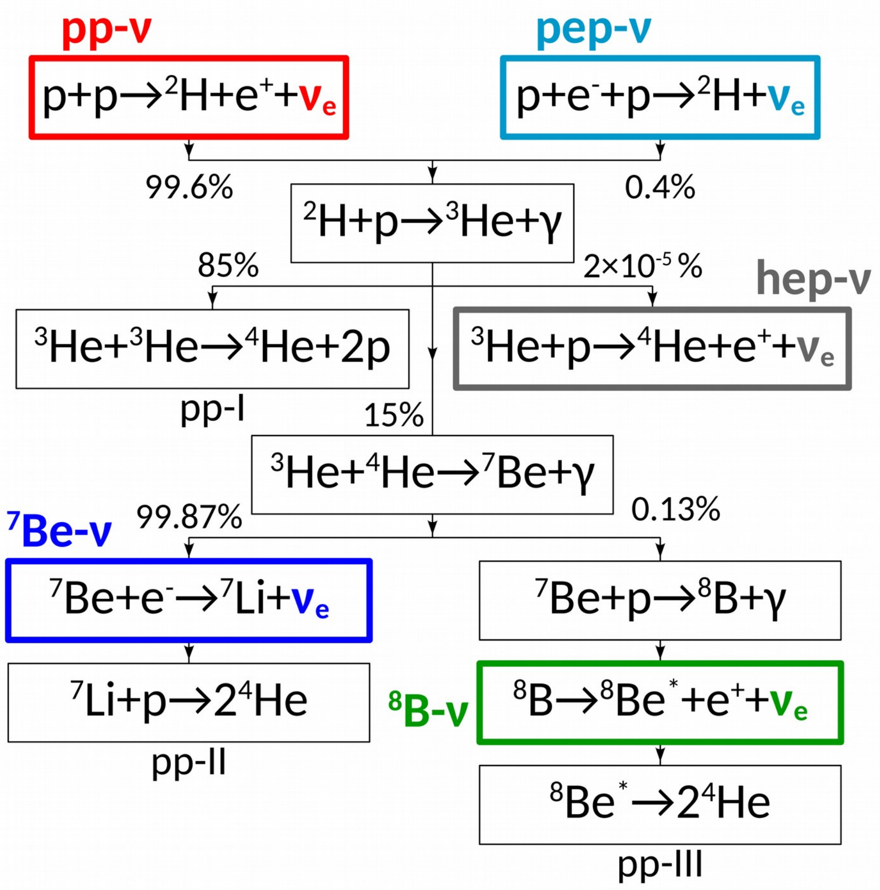
Comprehensive measurement of **pp-chain solar neutrinos** with Borexino

M. Agostini et al., (Borexino Collaboration), Nature, 562, 505 (2018)

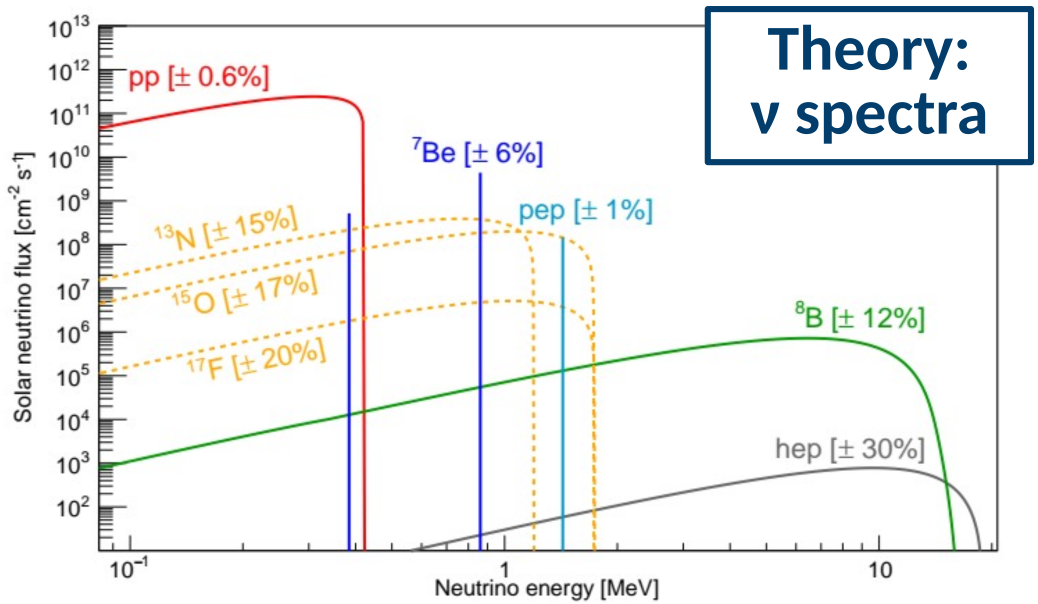
All measurements have improved precision

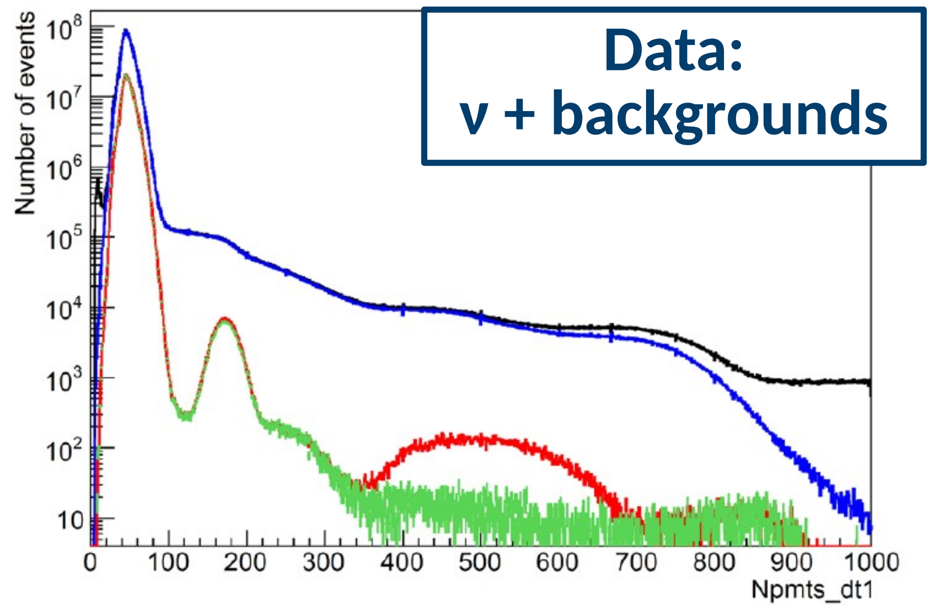
- **pp → 9.5%**
- **^{7}Be → 2.7%**
  × 2 more precise than theory
- **^{8}B → 8%**
- **pep → 16%**
  > 5σ discovery
- **hep** → 90% CL upper limit
  NEW!
- **CNO** → 95% CL upper limit
  most stringent so far

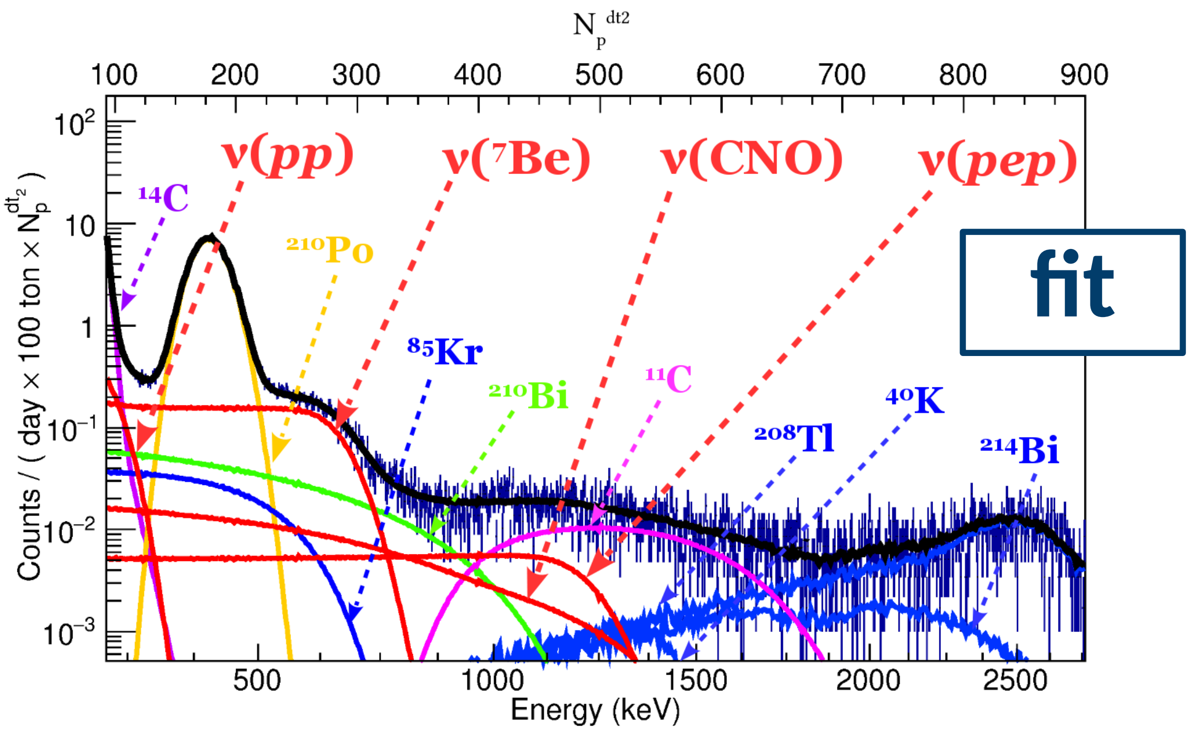
pp chain



HOW DID WE DO IT?



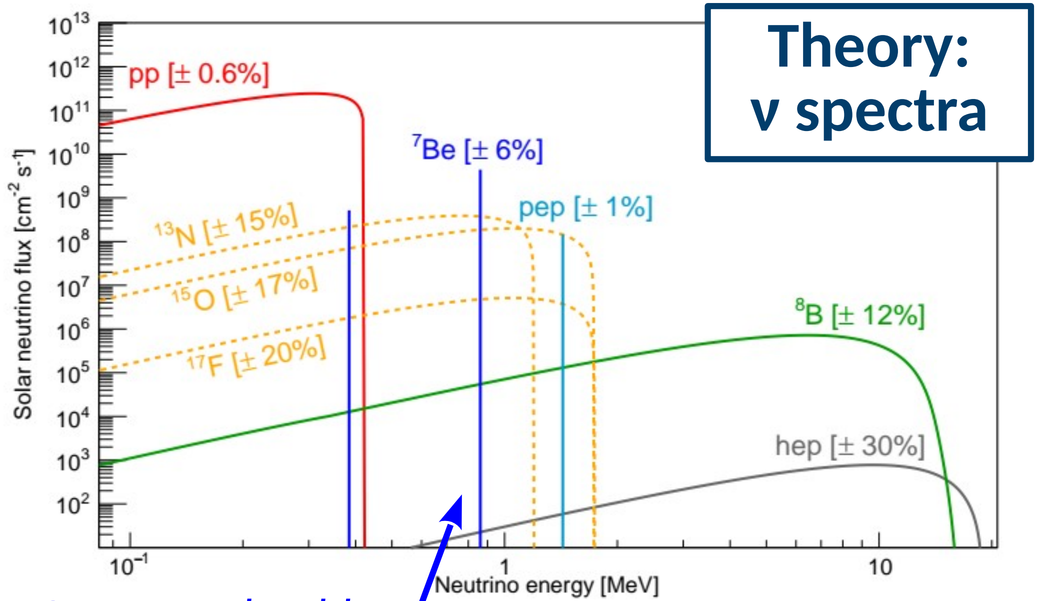




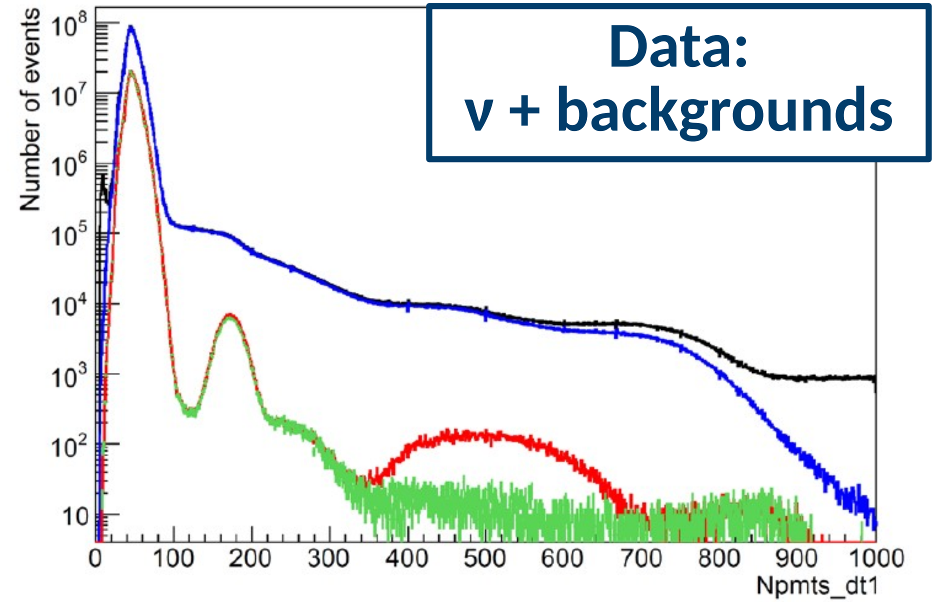
neutrino
&
background
rates

HOW DID WE DO IT?

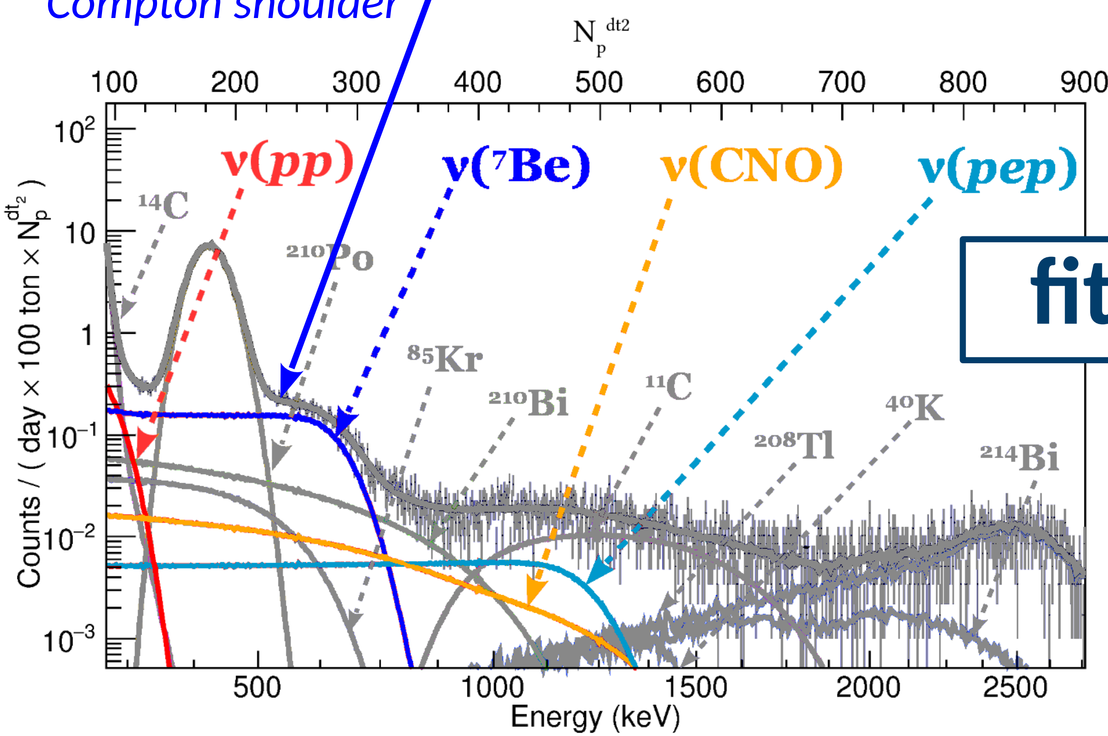
Theory: ν spectra



Data: ν + backgrounds



Compton shoulder

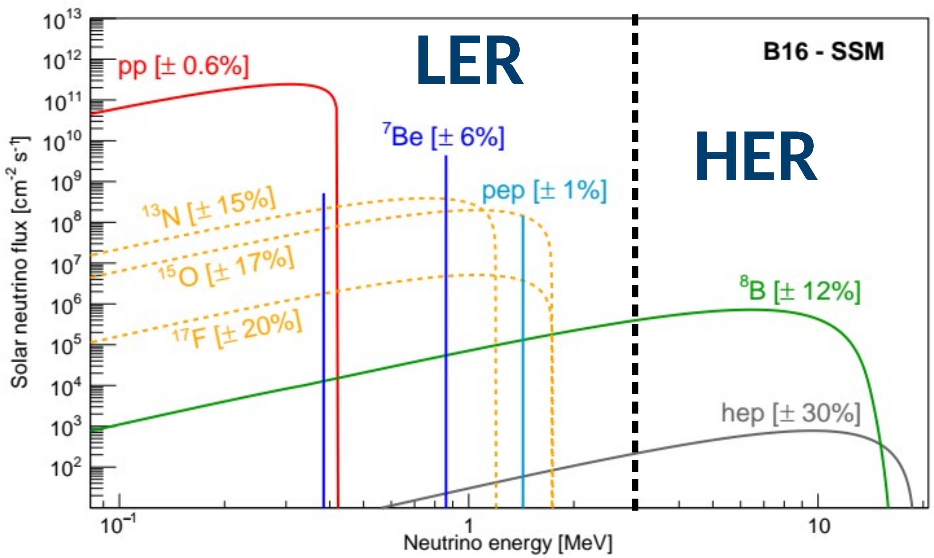


fit

⇨

neutrino & background rates

HOW DID WE DO IT?

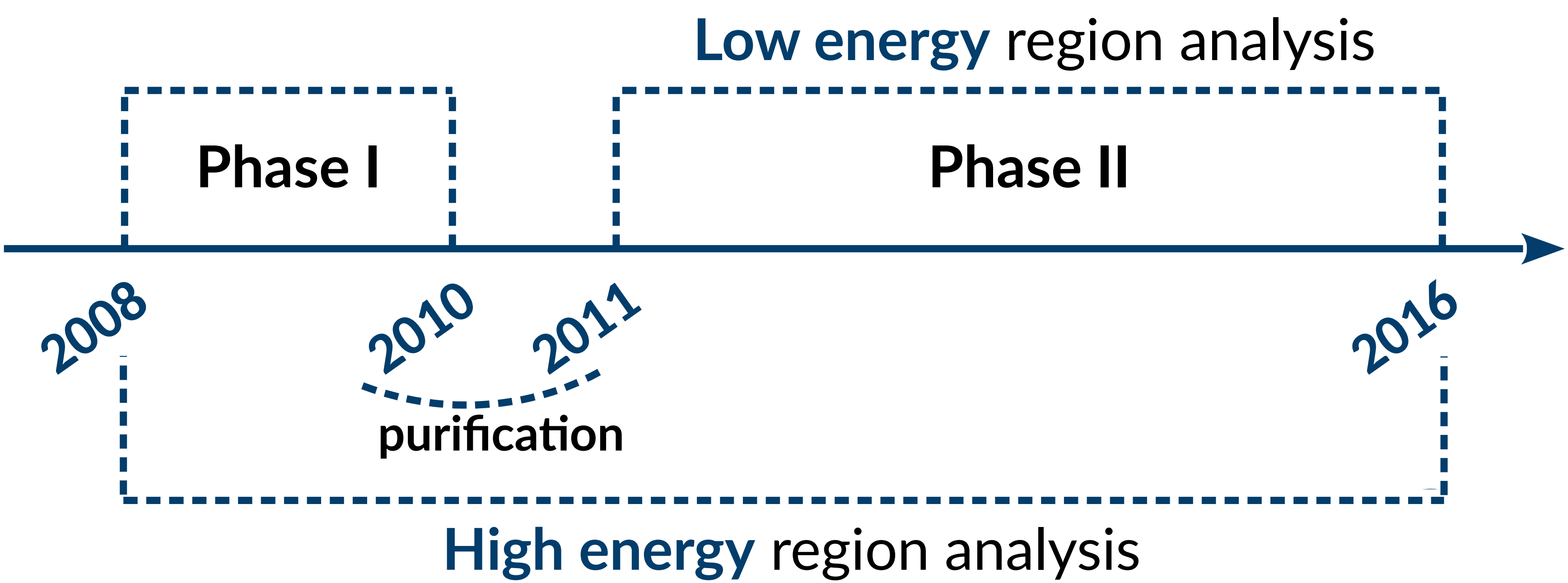


HER and **LER** have **different backgrounds**

LER → **pp**, **pep**, **^{7}Be**; **CNO** (0.19 - 2.93 MeV)
First **simultaneous extraction** of **pp**, **pep** and **^{7}Be** rates

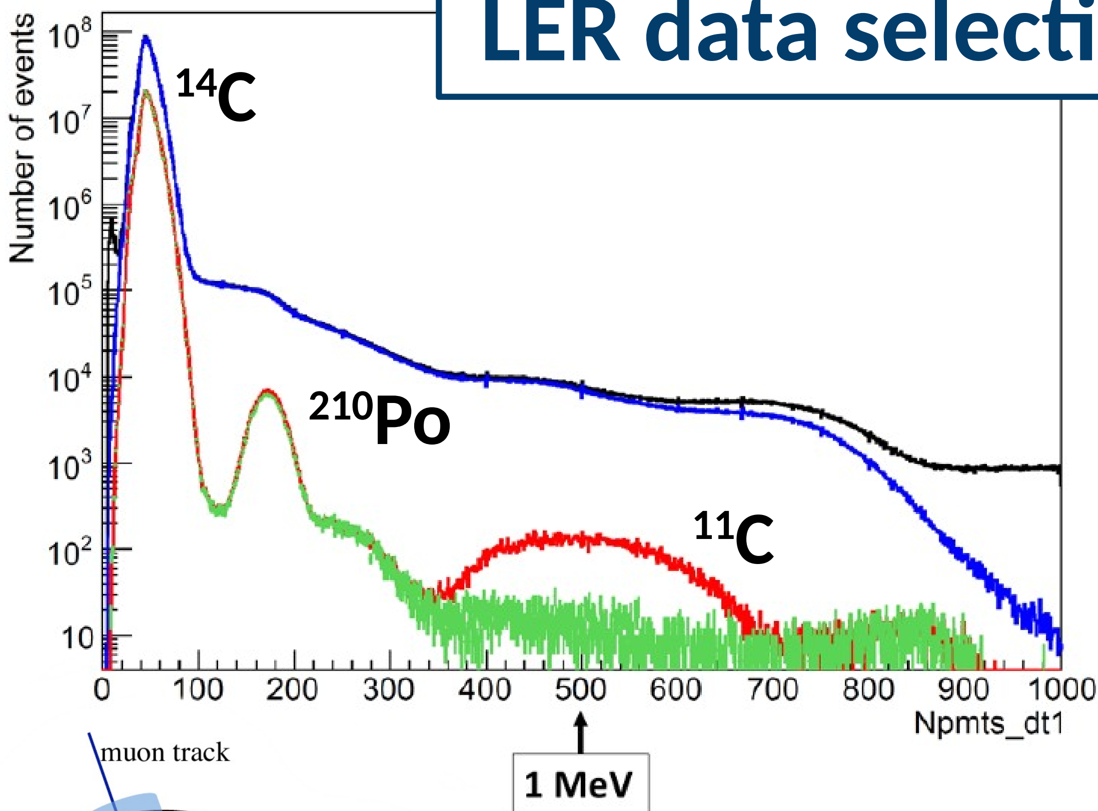
HER → **^{8}B**; **hep** (3.2 - 16 MeV)
Lowest energy threshold

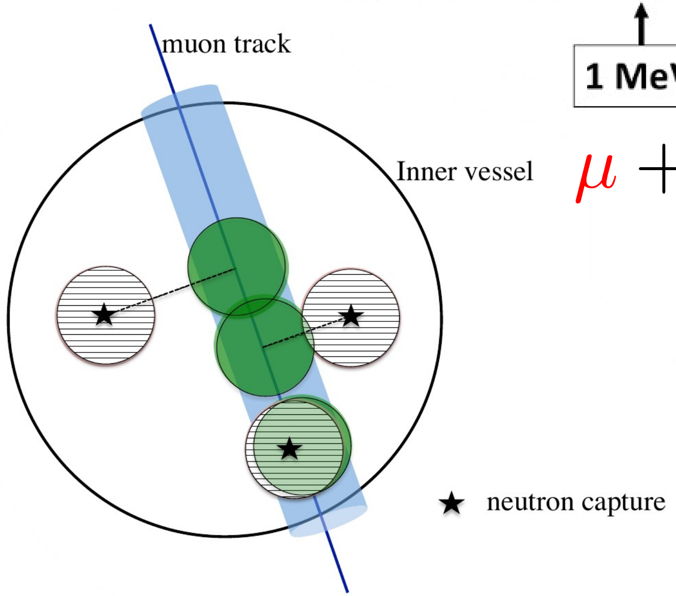
Some backgrounds can be **measured independently** and **constrained**



HOW DID WE DO IT?

LER data selection





no cuts

⇓ 99.992% efficiency

μ and μ daughter cut

⇓

Fiducial Volume cut

⇓

Three-fold coincidence cut

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

(29.4 min)

$${}^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + e^{+} + \nu_e$$

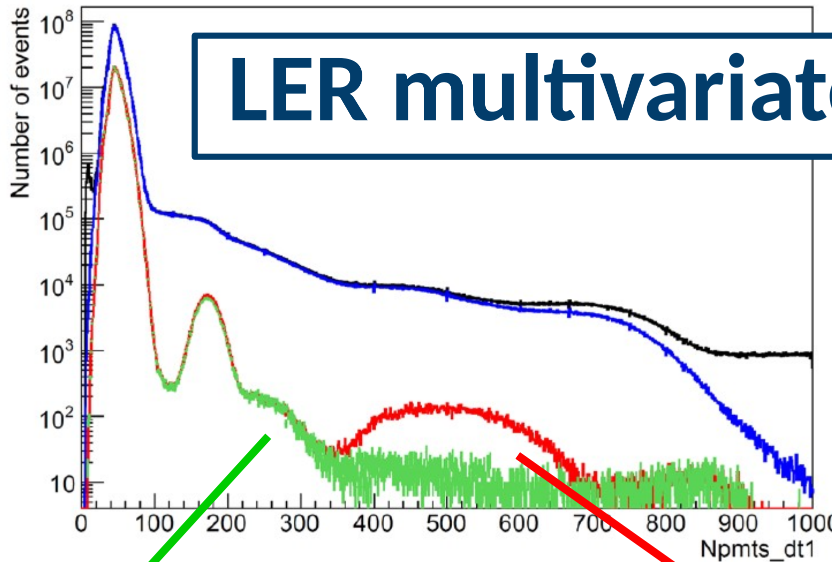
(250 μs) (2.2 MeV)

$$n + p \rightarrow D + \gamma$$

JÜLICH Forschungszentrum

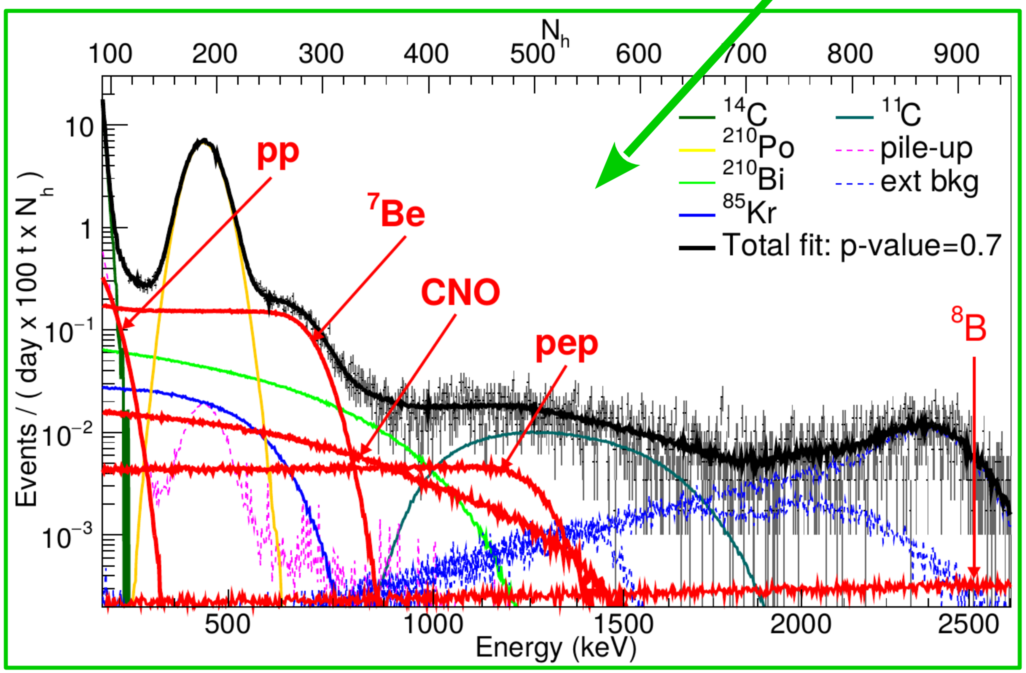
HOW DID WE DO IT?

LER multivariate fit



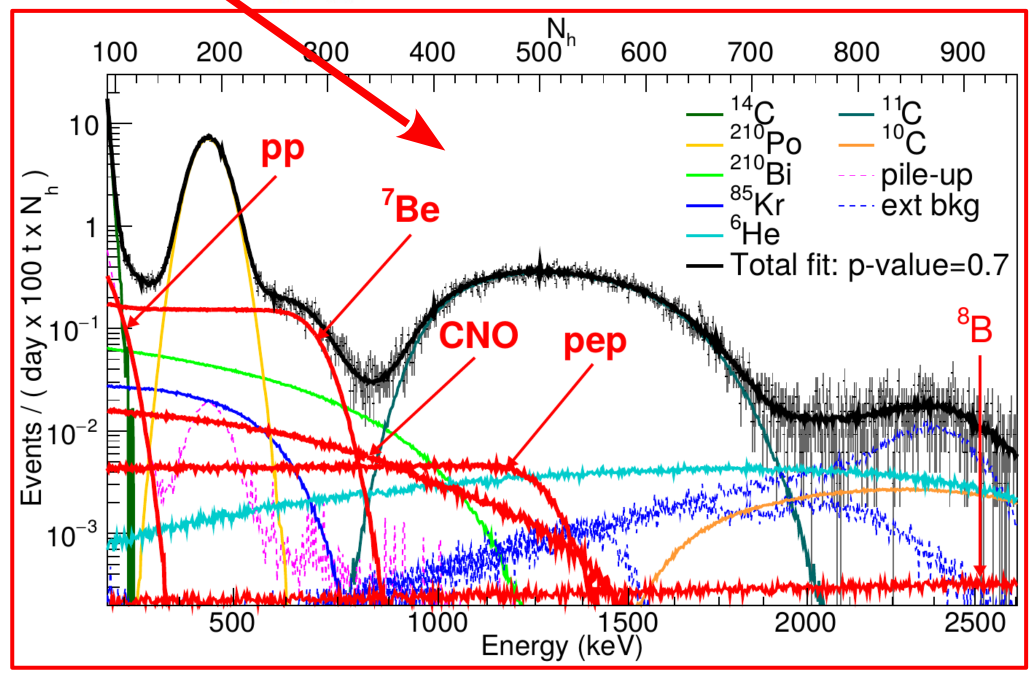
TFC subtracted

8% ^{11}C
~64% exposure



TFC tagged

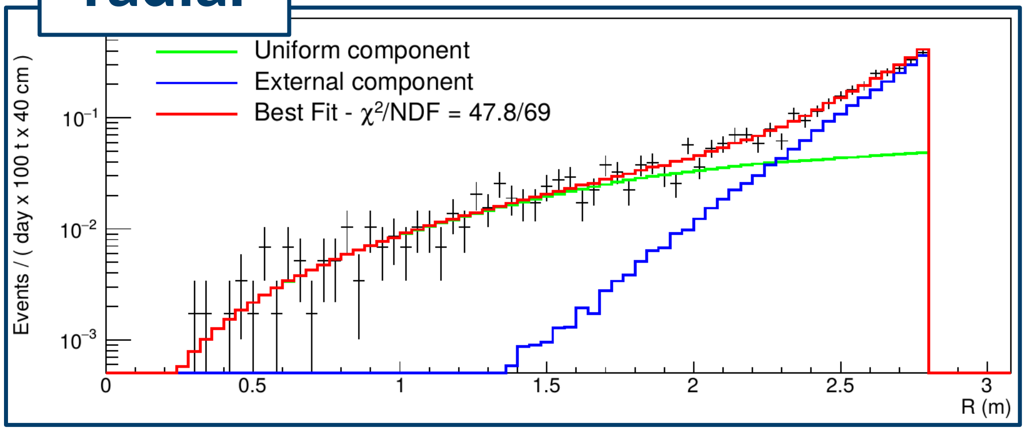
92% ^{11}C
~36% exposure



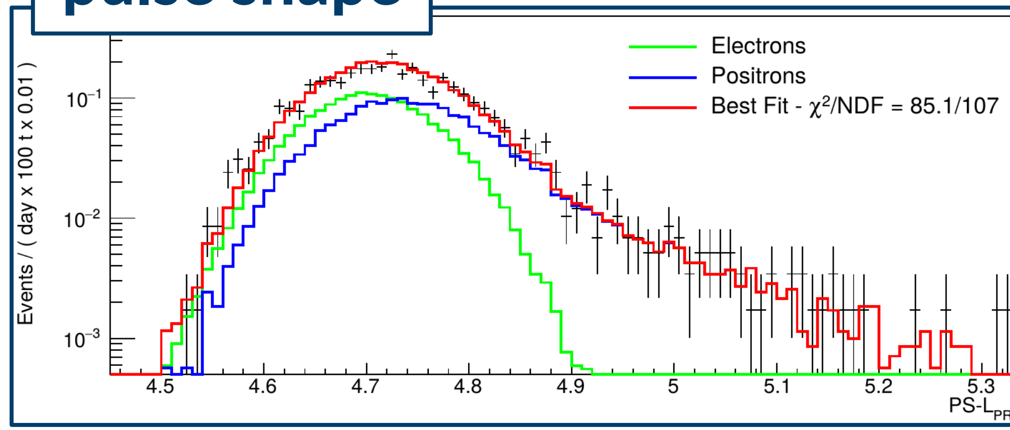
$$\mathcal{L}(\vec{\theta}) = \mathcal{L}_{\text{TFC-sub}}(\vec{\theta}) \cdot \mathcal{L}_{\text{TFC-tag}}(\vec{\theta})$$

HOW DID WE DO IT?

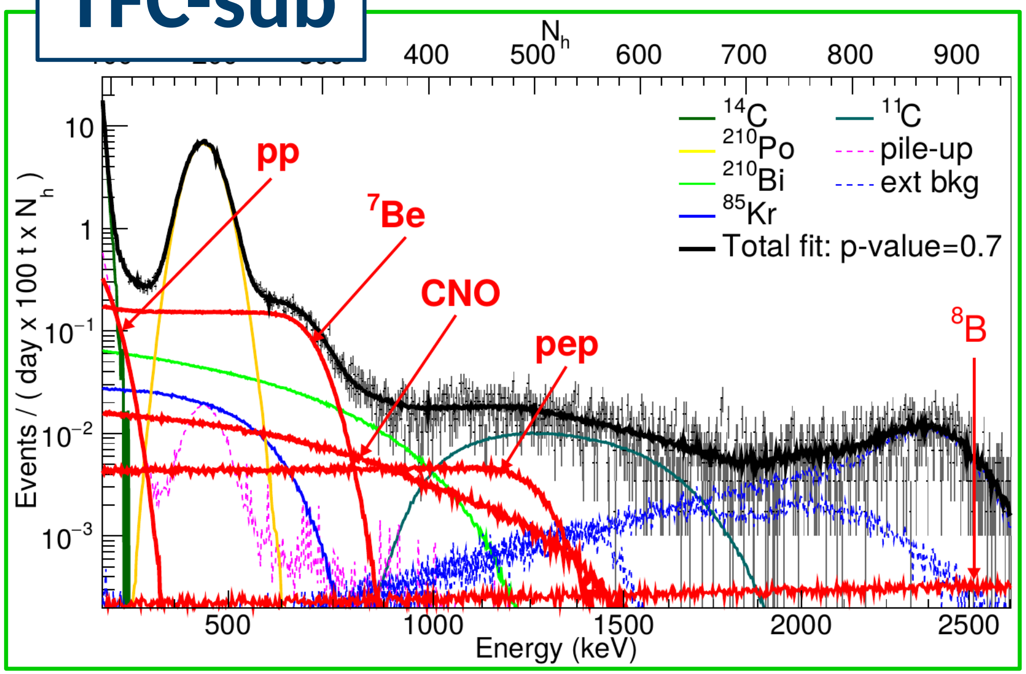
radial



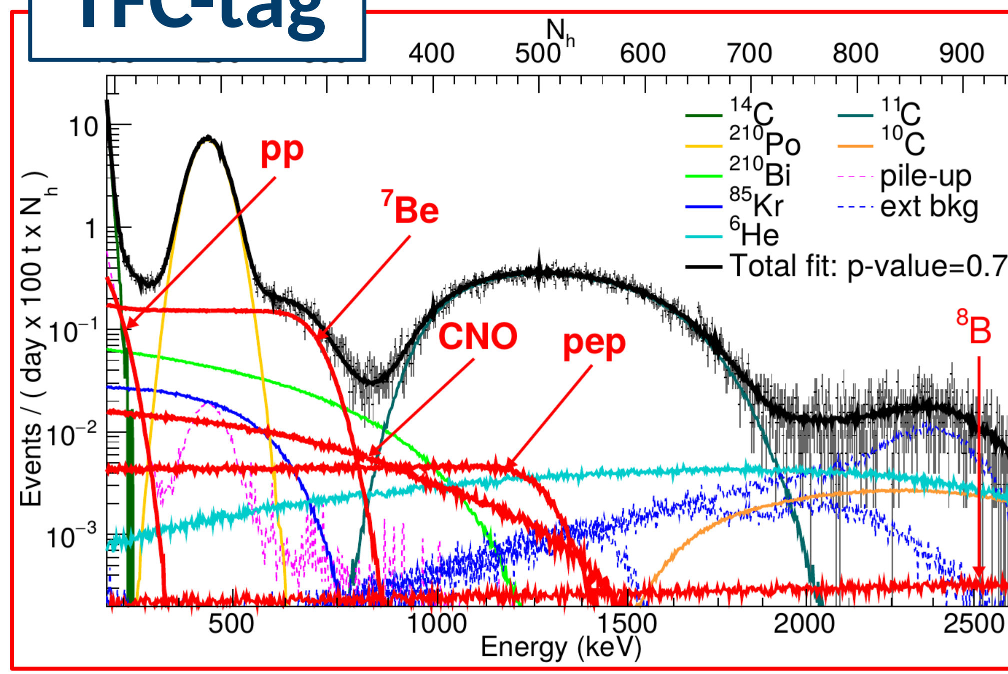
pulse shape



TFC-sub

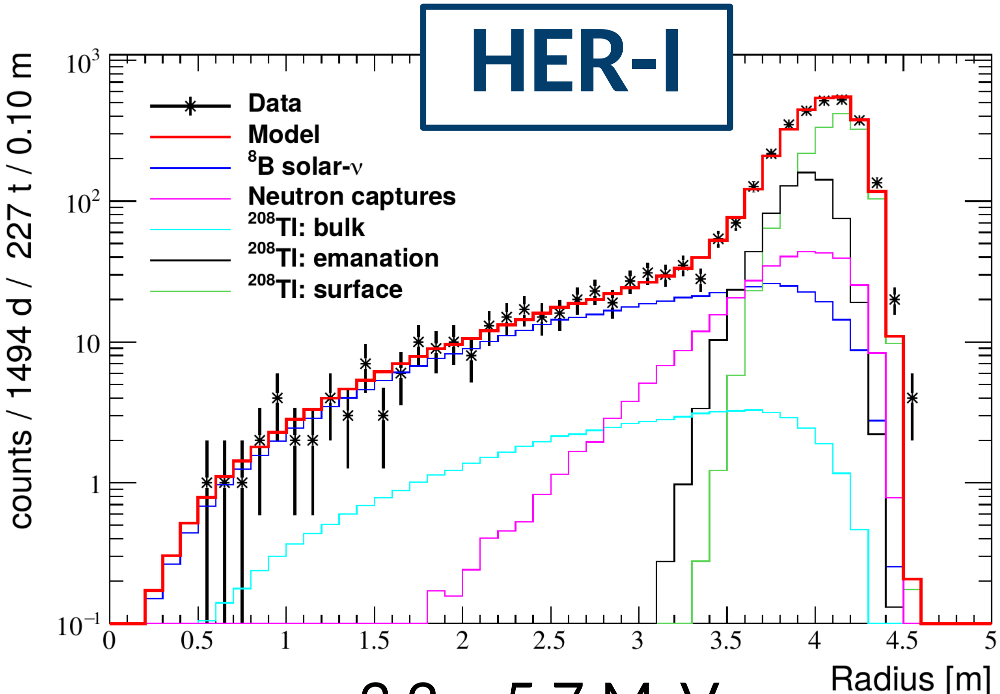


TFC-tag



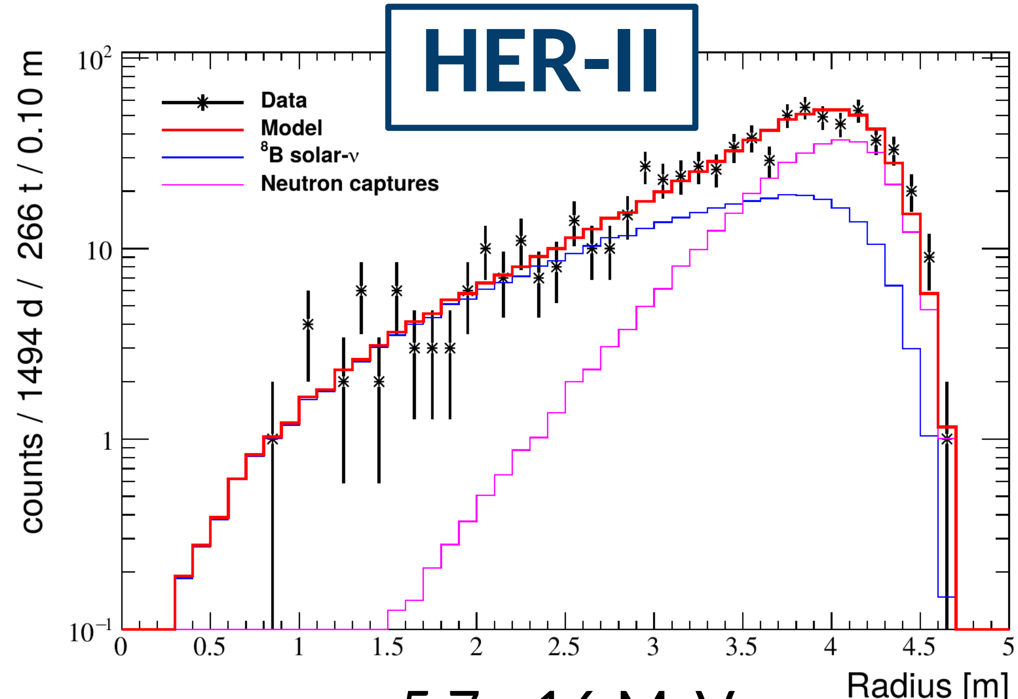
$$\mathcal{L}(\vec{\theta}) = \mathcal{L}_{\text{TFC-sub}}(\vec{\theta}) \cdot \mathcal{L}_{\text{TFC-tag}}(\vec{\theta}) \cdot \mathcal{L}_{\text{RD}}(\vec{\theta}) \cdot \mathcal{L}_{\text{PS}}(\vec{\theta})$$

HOW DID WE DO IT?



3.2 – 5.7 MeV

Background: natural **radioactivity**



5.7 - 16 MeV

Background: external **γ rays**

HER data selection:

- **neutron** cut
- **fast cosmogenics** cut
- ^{10}**C** cut
- ^{214}**Bi-Po** cut

- **Independent** radial fits
- **× 3** increase in **target mass**, **× 10** increase in **exposure**
- **No assumption** on **E_ν energy spectrum!**

→ no dependence on **$P_{ee}(E_\nu)$**

→ probe **deviations** from **MSW**

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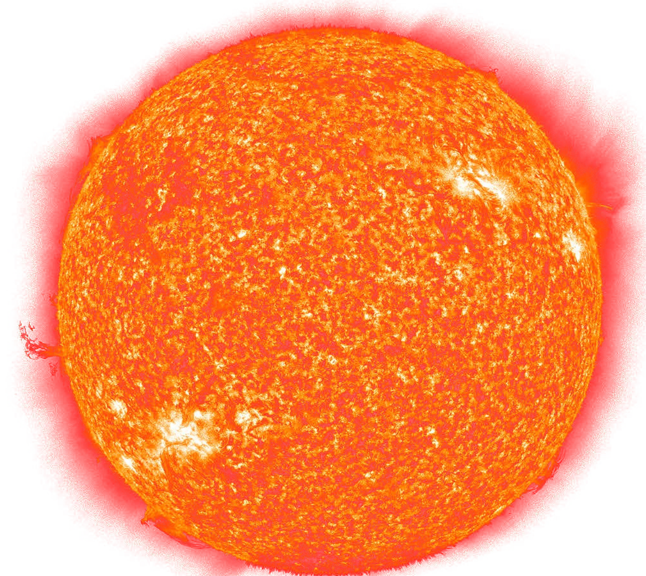
WHAT ARE THE IMPLICATIONS?

Real time picture of the **core of the sun**


Credit: NASA/SDO

→ **total power** from the nuclear reactions:

L = **3.89** ± 0.42 x 10^{33} erg s^{-1}

compatible with **photon output**

L = **3.846** ± 0.015 x 10^{33} erg s^{-1}

→ experimentally confirm **nuclear origin** of the solar power

best precision by a single solar-*ν* experiment

→ proves the sun has been in **thermodynamic equilibrium** over **10^5 years** time scale

WHAT ARE THE IMPLICATIONS?

Relative intensity of pp-I and pp-II

$$R_{I/II} = \frac{2\phi(^7Be)}{\phi(pp) - \phi(^7Be)}$$

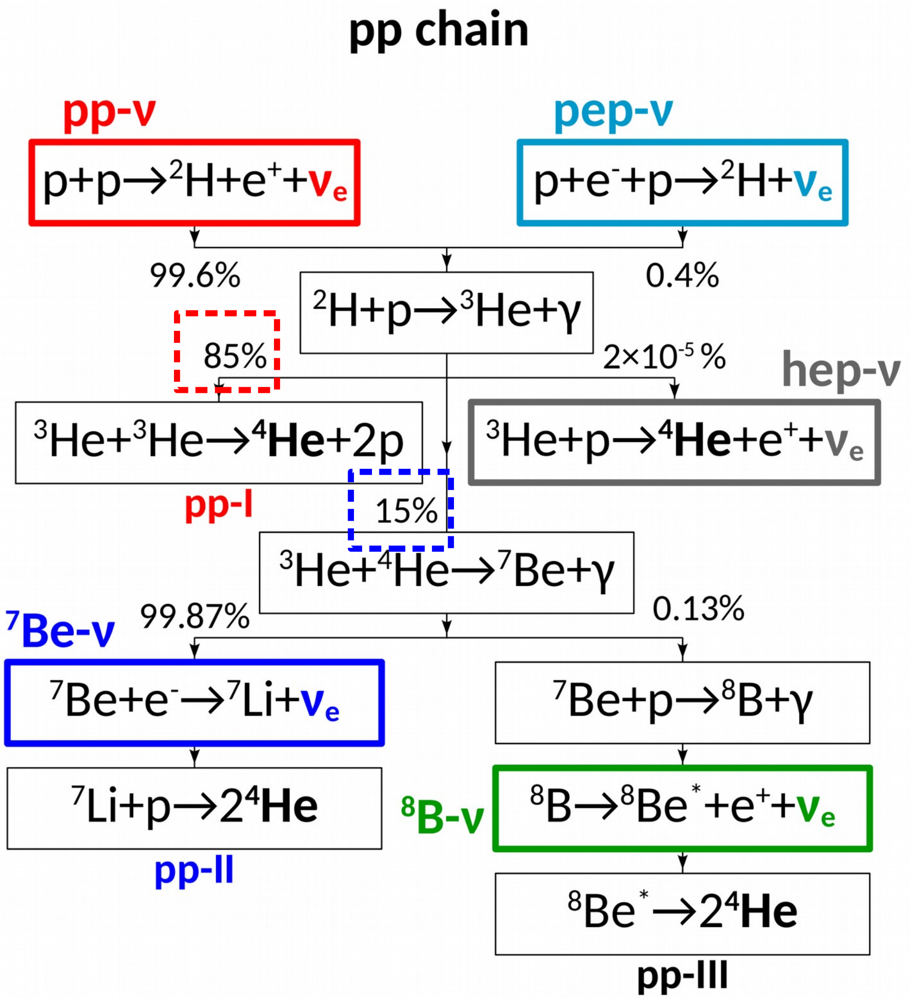
Theoretical prediction:

$R_{I/II}$(**HM**) = **0.180** ± 0.011

$R_{I/II}$(**LM**) = **0.161** ± 0.010

New experimental result:

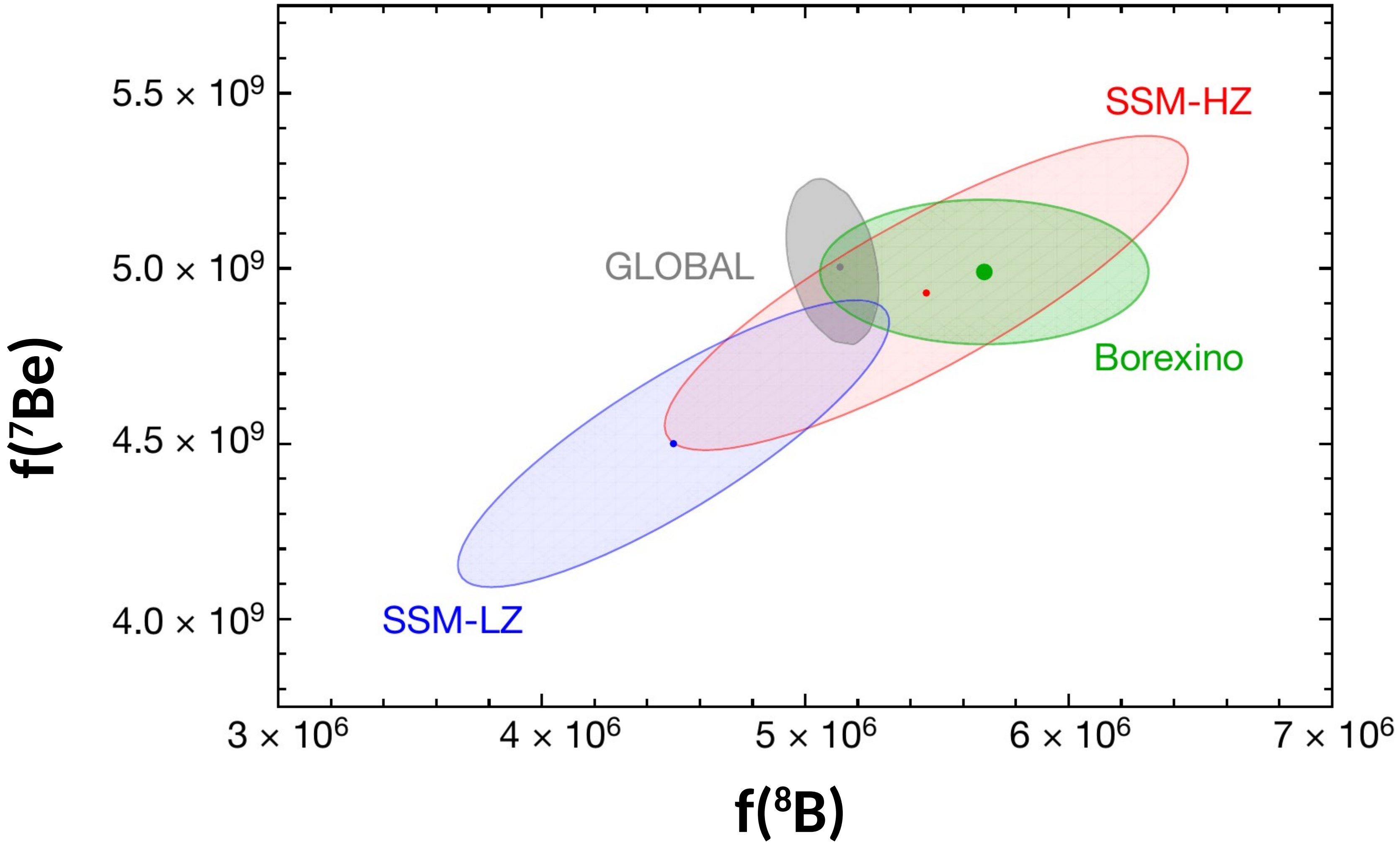
R = **0.178** ± 0.027



→ compatible with **expected values**

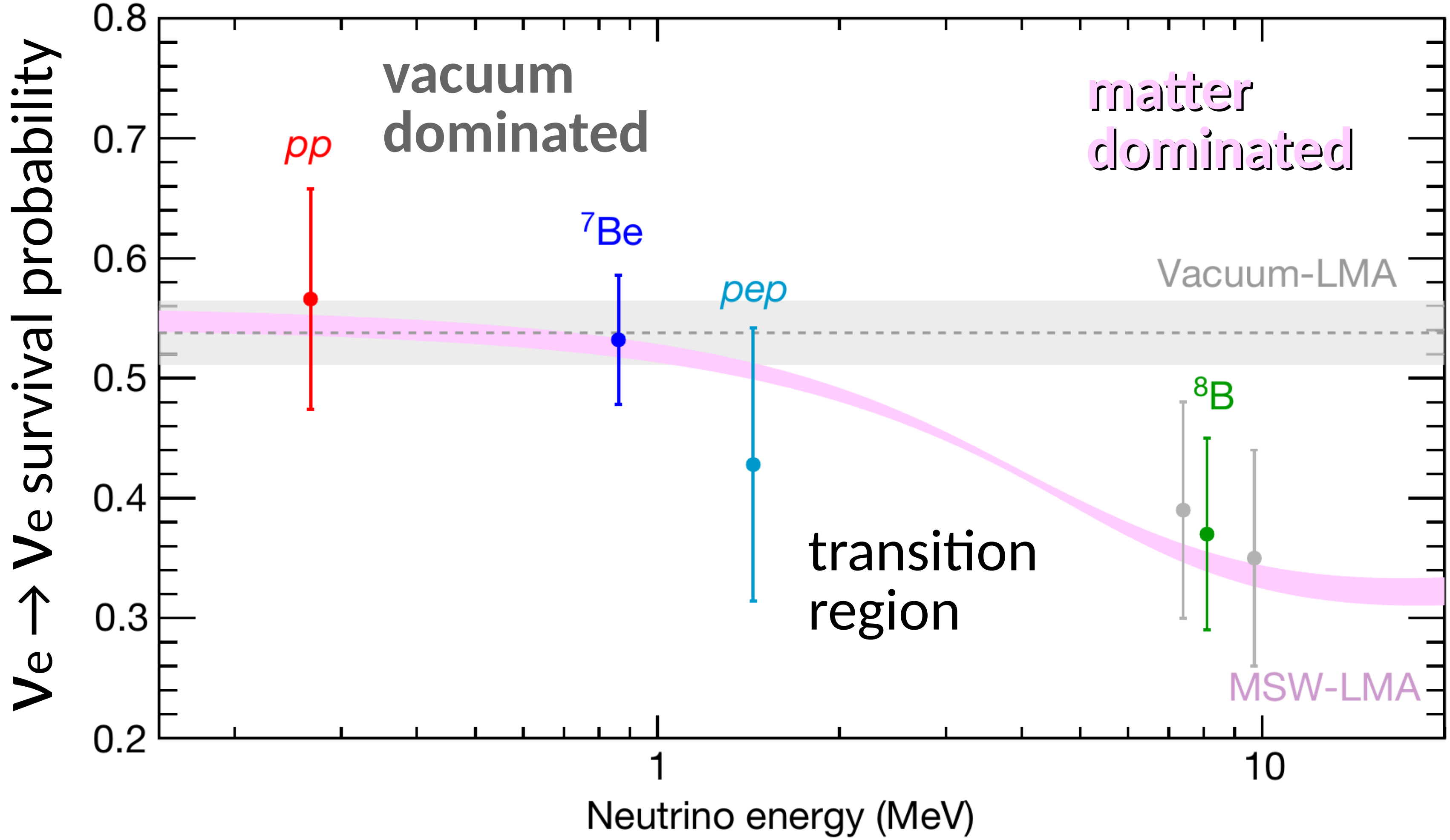
WHAT ARE THE IMPLICATIONS?

^{7}Be and **^{8}B** have the largest difference in HZ/LZ



→ weak hint towards **high metallicity**

WHAT ARE THE IMPLICATIONS?



Borexino is the **only experiment** that can probe the **ν_e survival probability** in **both** vacuum and matter dominated regions

Disfavour vacuum oscillations at **95% CL**

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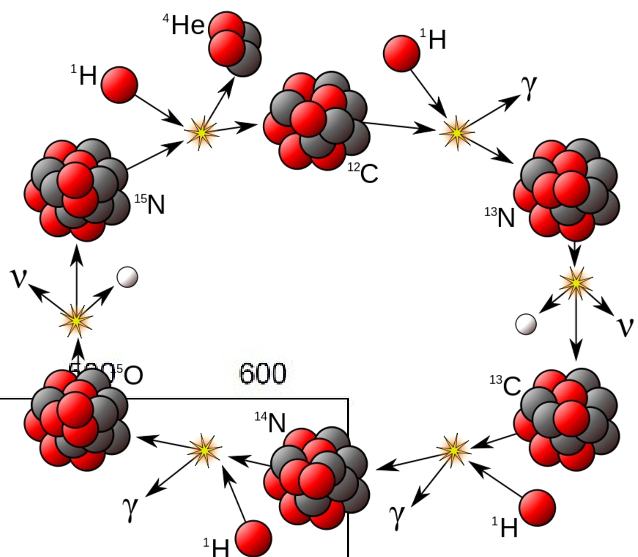
WHAT'S NEXT?

Phase I | Phase II | Phase III

2008 | 2010 | 2011 | 2016

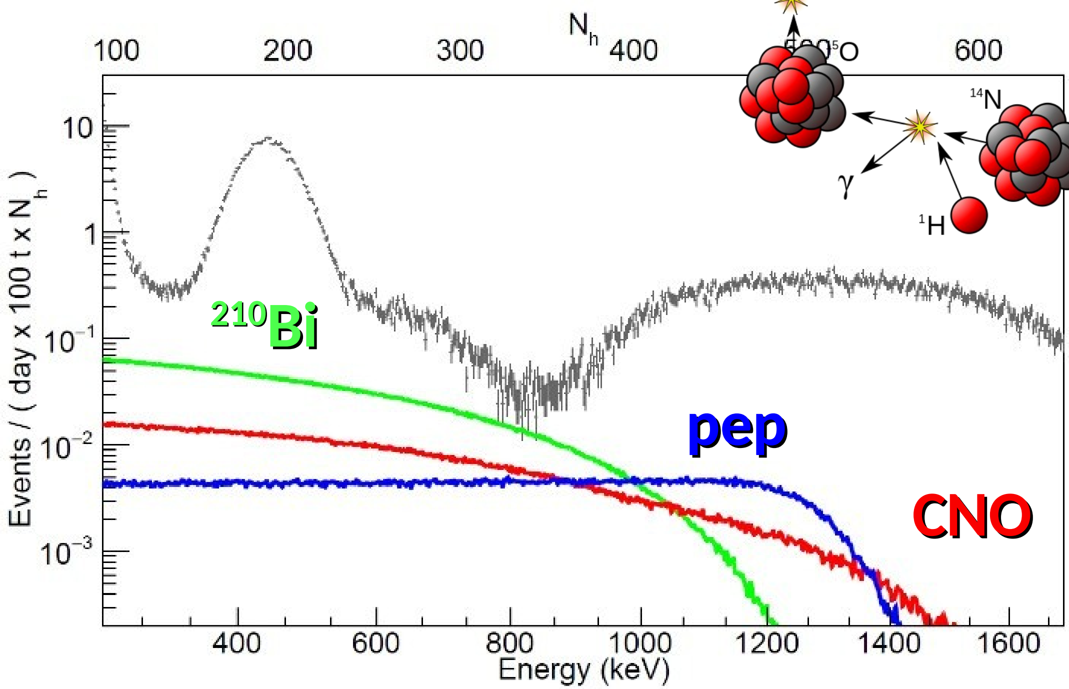
purification

new trigger system



CNO ν measurement

can solve the **metallicity puzzle**



Challenges:

- Extremely **low rate**
- Shape similar to ^{210}Bi and **pep**

WHAT'S NEXT? → TOWARDS CNO

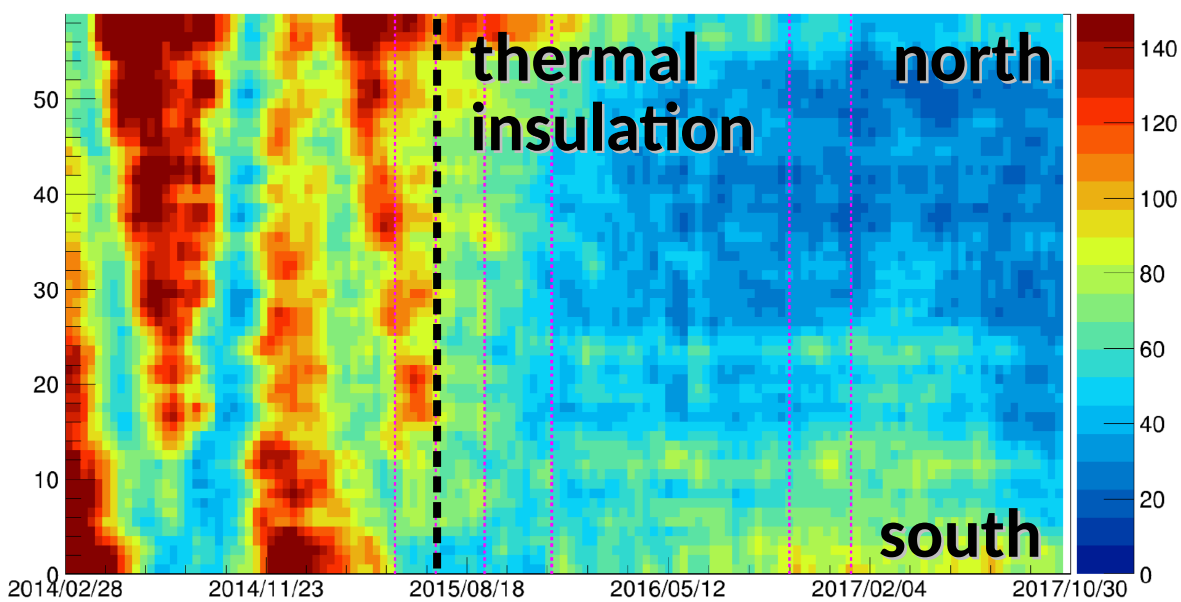
Constrain the rate of ^{210}Bi (β) by measuring ^{210}Po (α)

(the only α → event by event basis)

$$^{210}\text{Pb} \xrightarrow{32y} {}^{210}\text{Bi} \xrightarrow{7.23d} {}^{210}\text{Po} \xrightarrow{199.1d} {}^{206}\text{Pb}$$

- Disentangle vessel ^{210}Po contamination (not in equilibrium)

- **thermal stabilization**



Sensitivity studies with toy MC → possibility to get a **CNO measurement** between 2 and 4σ

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SUMMARY

- **Solar νs** are a useful tool to probe **solar models** and **neutrino physics**
- The **Borexino detector** is perfect for **solar neutrino analysis** due to its **radiopurity**
- New **Nature** publication by Borexino reports a **comprehensive study** of the **pp-chain νs** with improved precision:
  pp (9.5%), **^{7}Be** (2.7%), **^{8}B** (8%), **pep** (16%), **hep** (90% CL up. lim.)
- It was done using **extensive** Borexino dataset and a **multivariate fit** approach
- The results show a **weak hint** towards the **high metallicity** hypothesis, **exclude** vacuum oscillations with **95% CL**
- **Sensitivity studies** show promising perspective for the **CNO ν** measurement

Borexino Collaboration

Università degli Studi di Milano

INFN Istituto Nazionale di Fisica Nucleare

LNGS

Princeton University

Università degli Studi di Genova

National Research Center "Kurchatov Institute"

St. Petersburg Nuclear Physics Inst.

Technische Universität München

University of Houston

Jagiellonian University in Kraków

Jülich Forschungszentrum

Virginia Tech

Johannes Gutenberg Universität Mainz

Universität Hamburg

Skobeltsyn Institute of Nuclear Physics Lomonosov Moscow State University

University of Massachusetts Amherst 1863

Joint Institute for Nuclear Research

GSSI Gran Sasso Science Institute – Center for Advanced Studies, Istituto Nazionale di Fisica Nucleare

Università degli Studi di Ferrara

UCLA

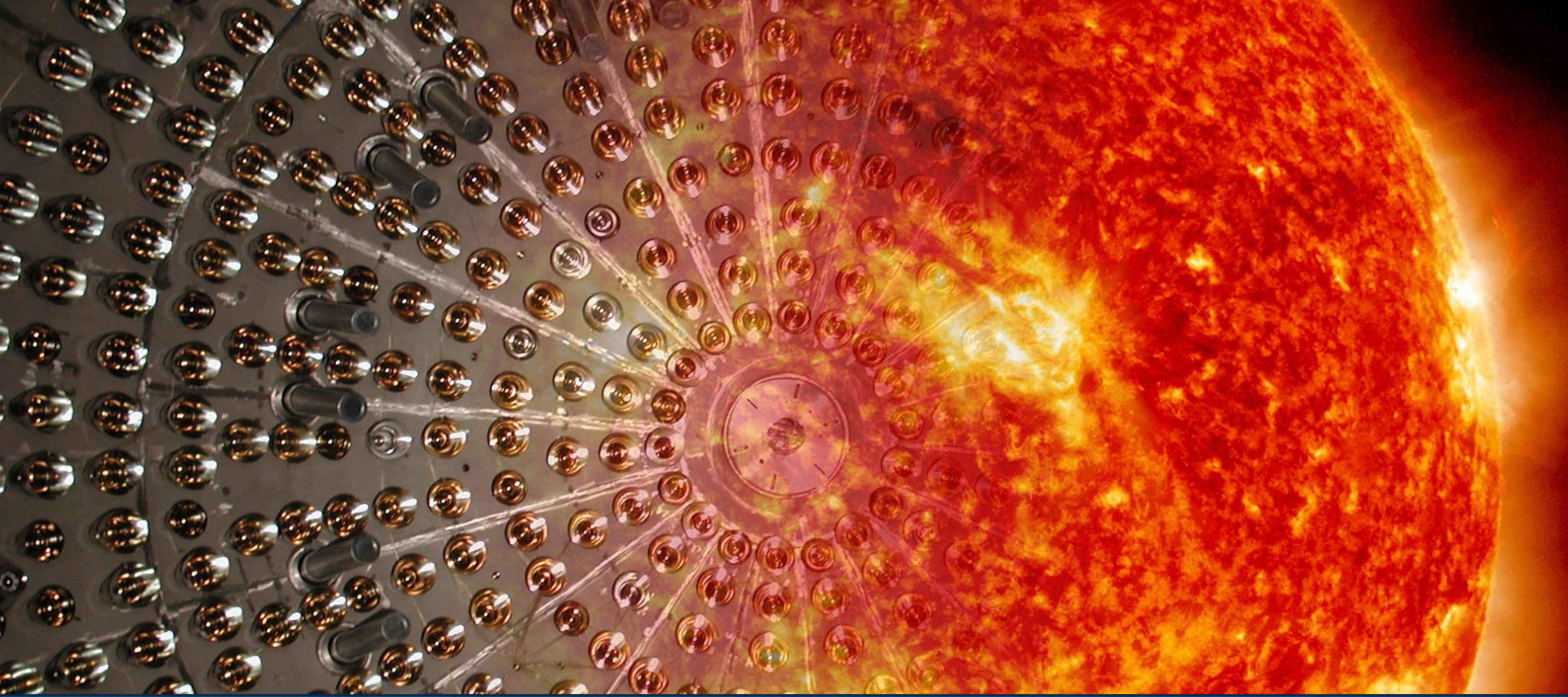
Technische Universität Dresden

APC

Università degli Studi di Perugia

Politecnico Milano 1863


Thanks for listening!



Backup

PREVIOUS AND NEW RESULTS

Neutrino	Previous	New (2018)
pp	144 ± 13 ± 10 → **11.5%** (2014)	$134 \pm 10^{+6}_{-10}$ → **9.5%**
^{7}Be	48.3 ± 2.0 ± 0.9 → **4.5%** (2014)	$48.3 \pm 1.1^{+0.4}_{-0.7}$ → **2.7%**
pep	3.1 ± 0.6 ± 0.3 → **21.5%** (2014)	$2.43 \pm 0.36^{+0.15}_{-0.22}$ → **16.5%** (HZ) $2.35 \pm 0.36^{+0.15}_{-0.24}$ → **15.5%** (LZ)
^{8}B	0.22 ± 0.04 ± 0.01 → **18.5%** (2010)	$0.223^{+0.015}_{-0.016}{}^{+0.006}_{-0.006}$ → **7.5%**
CNO	< **12** at 95% CL (2014)	< **8.1** at 95%CL
hep	–	< 0.002 at 90%CL → **NEW!**

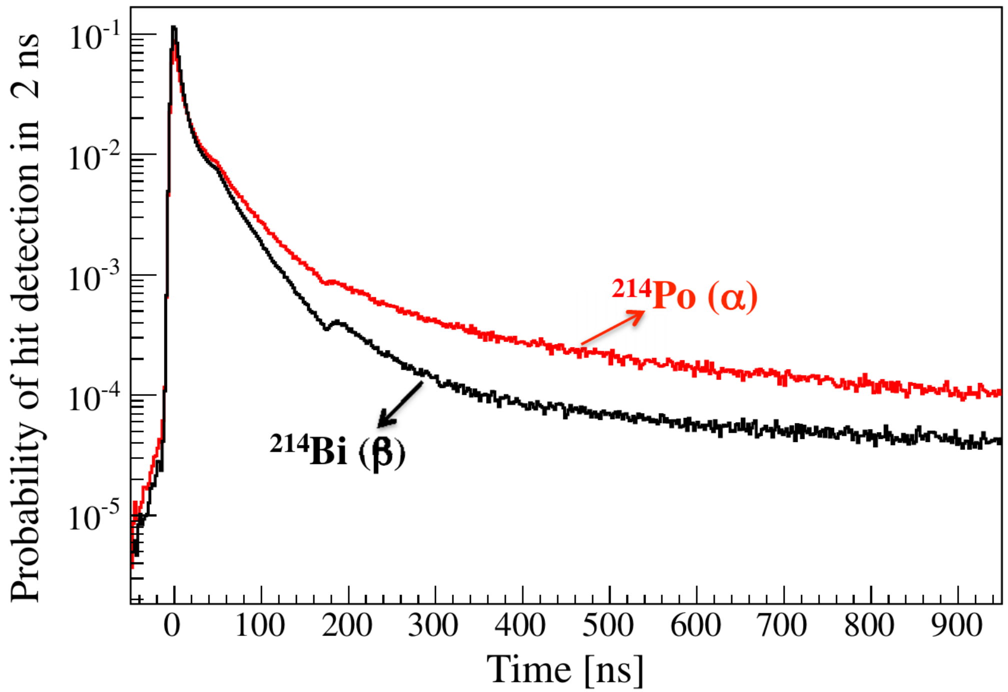
SOLAR NEUTRINO RESULTS

Solar neutrino	Rate (counts per day per 100 t)	Flux ($cm^{-2}\,s^{-1}$)	Flux–SSM predictions ($cm^{-2}\,s^{-1}$)
pp	$134 \pm 10^{+6}_{-10}$	$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}$	$5.98(1.0 \pm 0.006) \times 10^{10}$ (HZ) $6.03(1.0 \pm 0.005) \times 10^{10}$ (LZ)
^{7}Be	$48.3 \pm 1.1^{+0.4}_{-0.7}$	$(4.99 \pm 0.11^{+0.06}_{-0.08}) \times 10^{9}$	$4.93(1.0 \pm 0.06) \times 10^{9}$ (HZ) $4.50(1.0 \pm 0.06) \times 10^{9}$ (LZ)
pep (HZ)	$2.43 \pm 0.36^{+0.15}_{-0.22}$	$(1.27 \pm 0.19^{+0.08}_{-0.12}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
pep (LZ)	$2.65 \pm 0.36^{+0.15}_{-0.24}$	$(1.39 \pm 0.19^{+0.08}_{-0.13}) \times 10^{8}$	$1.44(1.0 \pm 0.01) \times 10^{8}$ (HZ) $1.46(1.0 \pm 0.009) \times 10^{8}$ (LZ)
$^{8}B_{HER\text{-}I}$	$0.136^{+0.013+0.003}_{-0.013-0.003}$	$(5.77^{+0.56+0.15}_{-0.56-0.15}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER\text{-}II}$	$0.087^{+0.080+0.005}_{-0.010-0.005}$	$(5.56^{+0.52+0.33}_{-0.64-0.33}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
$^{8}B_{HER}$	$0.223^{+0.015+0.006}_{-0.016-0.006}$	$(5.68^{+0.39+0.03}_{-0.41-0.03}) \times 10^{6}$	$5.46(1.0 \pm 0.12) \times 10^{6}$ (HZ) $4.50(1.0 \pm 0.12) \times 10^{6}$ (LZ)
CNO	<8.1 (95% C.L.)	$<7.9 \times 10^{8}$ (95% C.L.)	$4.88(1.0 \pm 0.11) \times 10^{8}$ (HZ) $3.51(1.0 \pm 0.10) \times 10^{8}$ (LZ)
hep	<0.002 (90% C.L.)	$<2.2 \times 10^{5}$ (90% C.L.)	$7.98(1.0 \pm 0.30) \times 10^{3}$ (HZ) $8.25(1.0 \pm 0.12) \times 10^{3}$ (LZ)

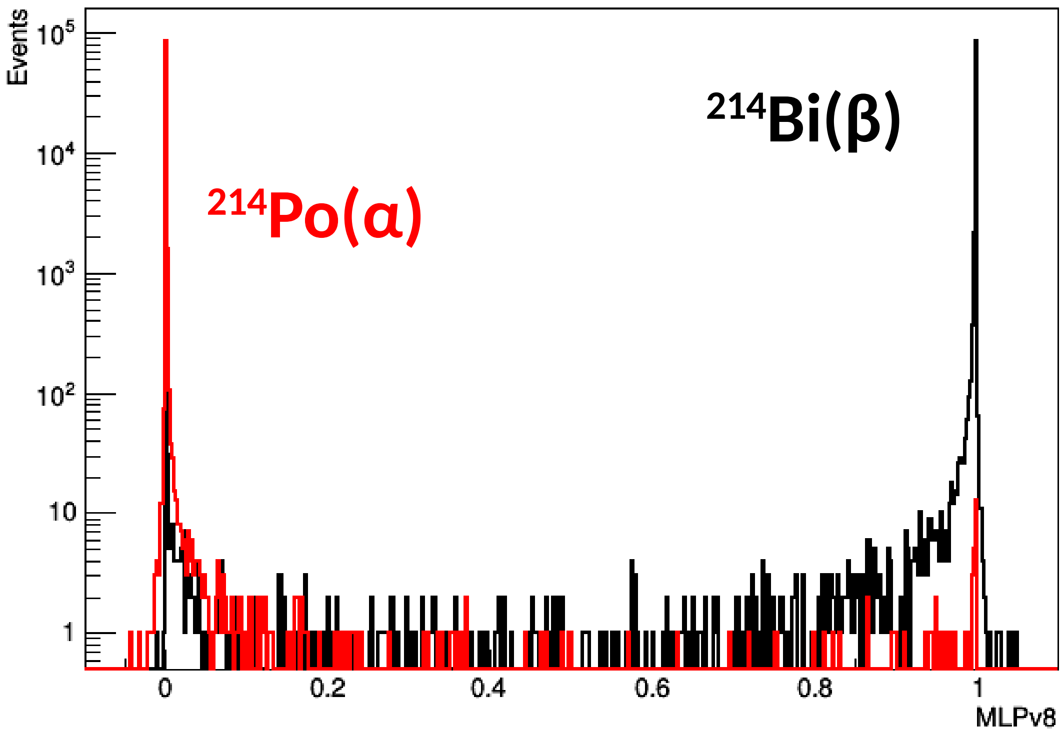
- **pep** are the only **ν** that show **difference** in HZ/LZ
- **CNO limit** is identical for HZ or LZ assumption on pp/pep constraint

TOWARDS CNO MEASUREMENT

α and β have different hit time distributions



Multi-Layer Perceptron variable to discriminate between α and β



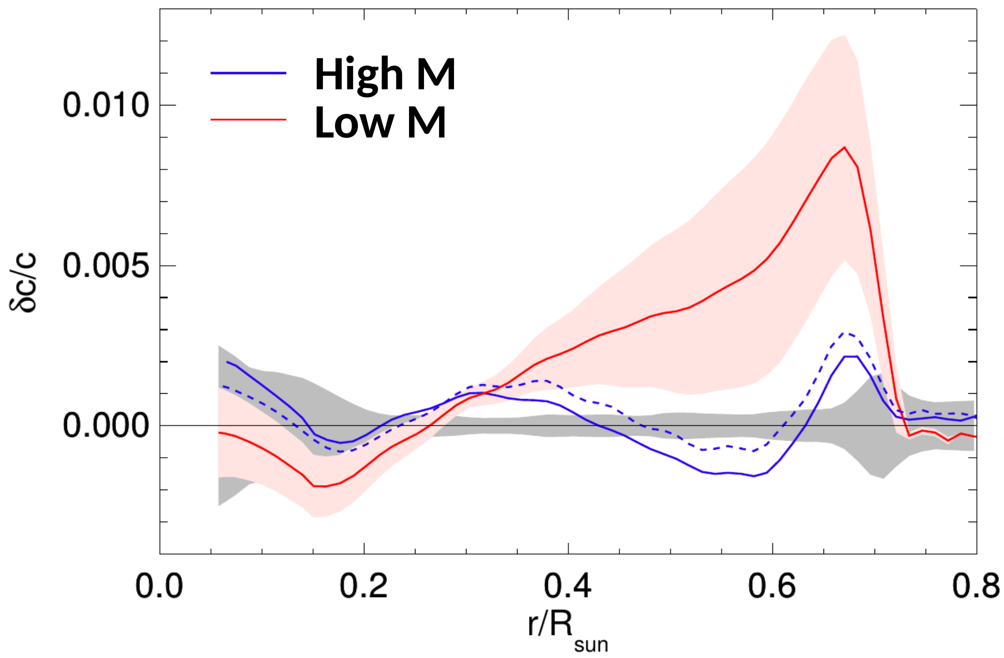
JÜLICH Forschungszentrum

THE SOLAR METALLICITY PUZZLE

metallicity

(metals)

Element	High M	Low M
C	8.52 ± 0.06	8.43 ± 0.05
N	7.92 ± 0.06	7.83 ± 0.05
O	8.83 ± 0.06	8.69 ± 0.05
Ne	8.08 ± 0.06	7.93 ± 0.10
Mg	7.58 ± 0.01	7.53 ± 0.01
Si	7.56 ± 0.01	7.51 ± 0.01
S	7.20 ± 0.06	7.15 ± 0.02
Ar	6.40 ± 0.06	6.40 ± 0.13
Fe	7.50 ± 0.01	7.45 ± 0.01
$(Z/X)_\odot$	0.02292	0.01780



Helioseismology (surface seismic waves) → **low M** agrees **less**

Solar **surface composition** → **lower** than assumed before

BOREXINO STRUCTURE

Outer detector
Water tank (**2100t**)
Shield + **μ veto**
~**200 PMTs**

Stainless Steel Sphere
R = **6.85m**

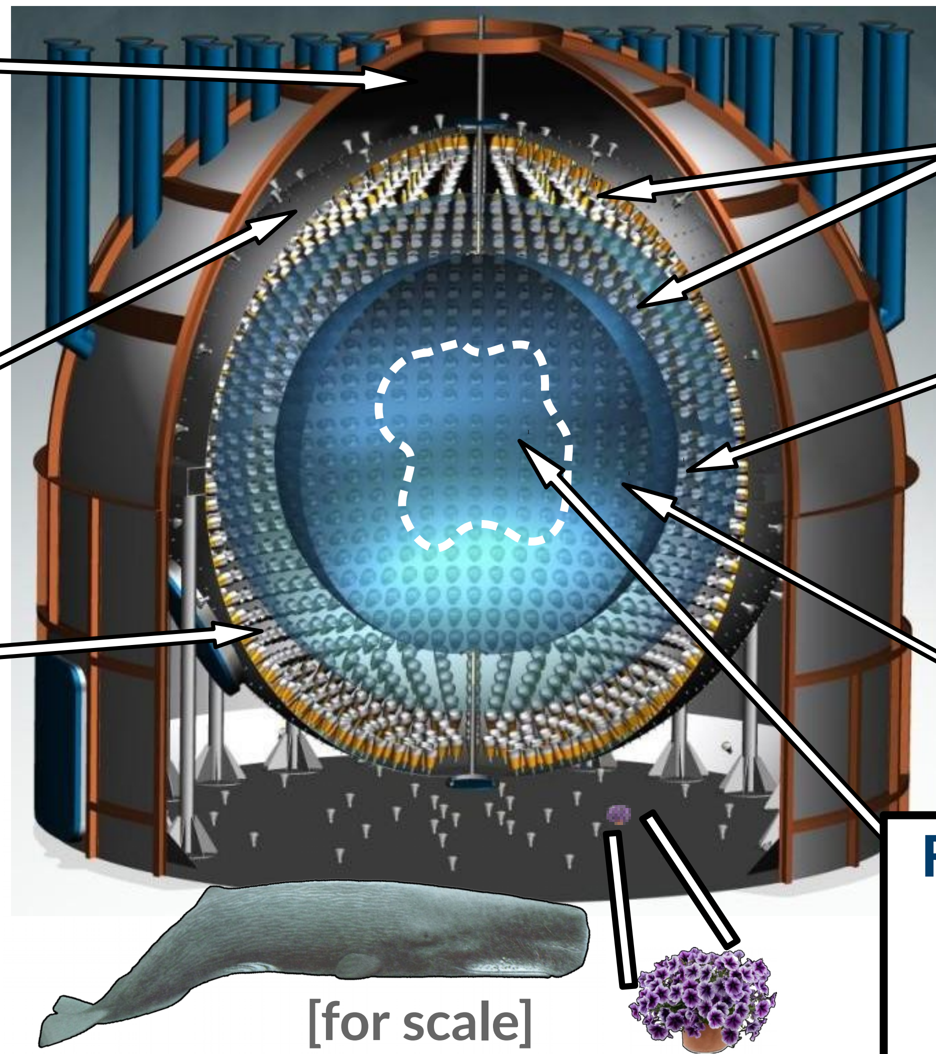
Inner detector
~**2000 PMTs**

Nylon vessels
Shield from PMTs and SSS
Barrier for **Rn**
Create **buffer**

Buffer
Diluted LS

Inner Vessel
R = **4.25m**
~280t LS

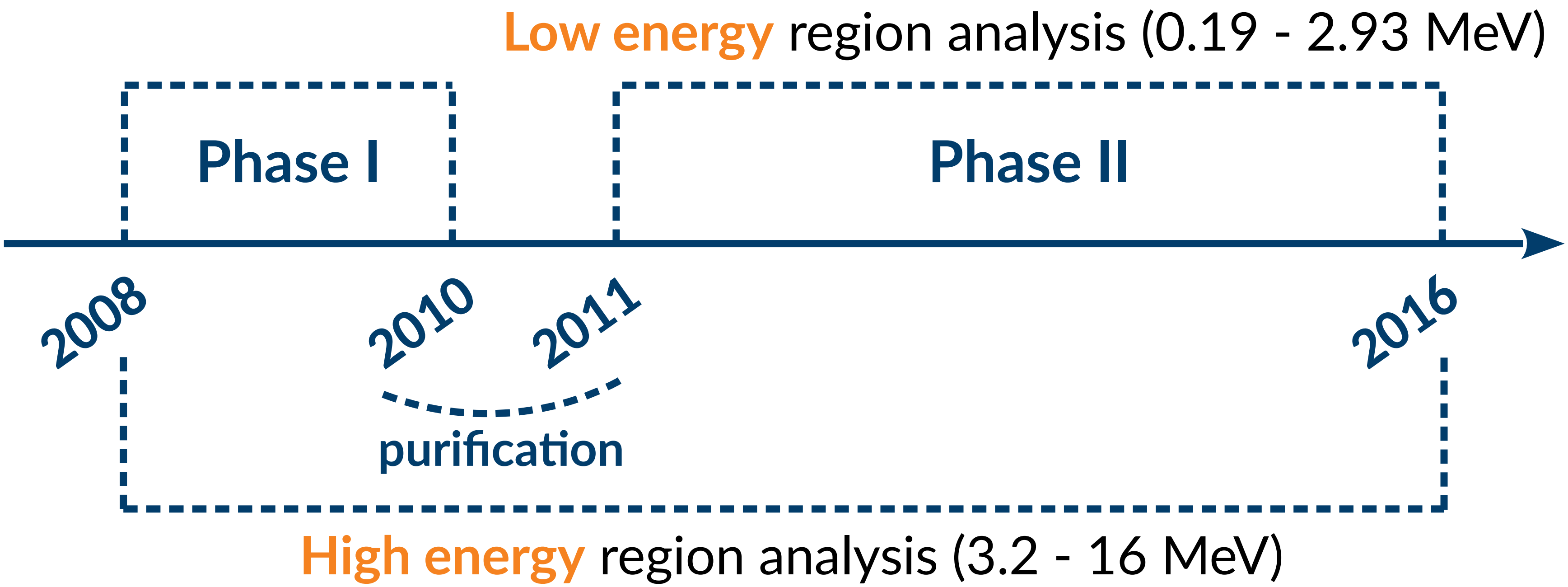
Fiducial volume
~70t
Software cut
Remove noise



- **3800m** water equivalent
- **50 keV** @ 1 MeV
- **12 cm** @ 1 MeV
- **551** pe/MeV

$$\nu + e^- \rightarrow \nu + e^-$$

HER AND LER INFORMATION



HER → ^{8}B; hep

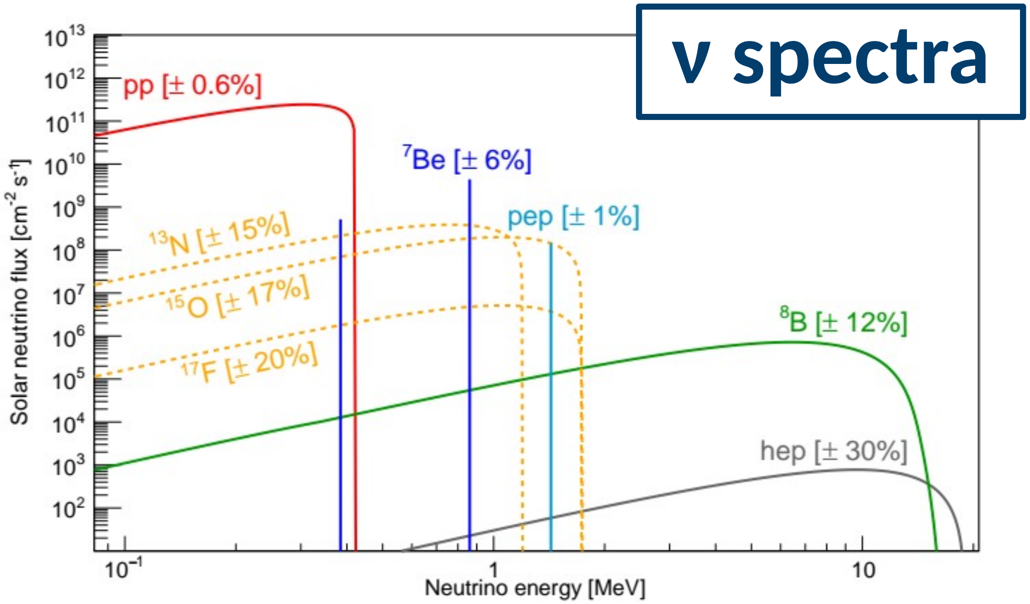
- not sensitive to low energy backgrounds
- **Whole IV** (280 t) is used (+ z-cut in HER-I), unlike LER which uses **Fiducial Volume (70t)**

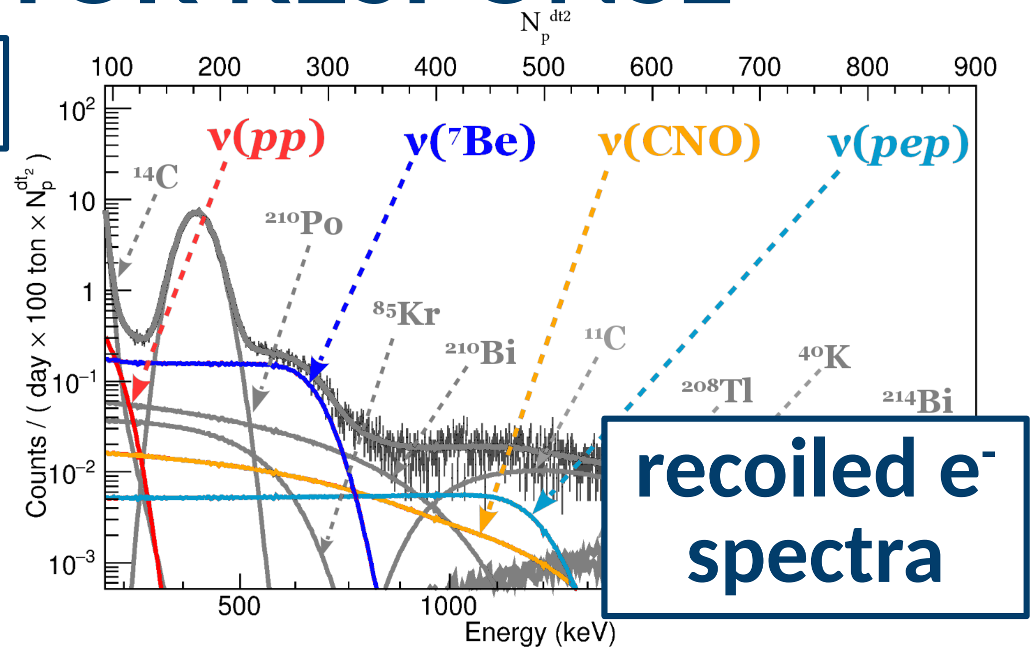
LER → pp, pep and ^{7}Be; CNO;

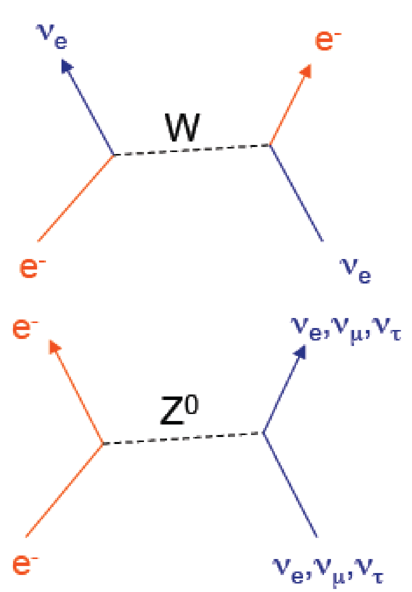
^{8}B is **constrained** to the value from HER

- pp, pep and ^{7}Be: CNO is **constrained** to HZ/LZ → 2 results for pep for HZ/LZ, the rest no difference
- CNO limit: pp/pep ratio is **constrained** (HZ/LZ)
- hep limit: **counting** analysis

COMPTON & DETECTOR RESPONSE







The electron takes a **fraction** of the ν energy
→ **Compton shoulder**

The **PDFs for the fit** are constructed in two ways (part of **systematics**)

- **MC simulation** of all the processes (tuned on calibration data)
- **Analytical description** of the **detector response**, some **nuisance parameters** are free in the fit

ENERGY ESTIMATORS

$$N_h \qquad N_{pe} \qquad N_p$$

of **hits** (**photons**)

of **triggered PMTs**

of **photoelectrons** (**charge**)

Monte Carlo method: simulate detector response

Analytical method:

$$N_{pe}(E) = LY \left(Q(E) \cdot E + f_{Cher} \cdot Ch(E) \right)$$

$$N_{\mathrm{p}}(E) = N_{\mathrm{live}} \left(1 - e^{-\frac{N_{\mathrm{pe}}}{N_{\mathrm{live}}}} \left[1 + p_t \frac{N_{\mathrm{pe}}}{N_{\mathrm{live}}} \right] \right) \left(1 - g_C \frac{N_{\mathrm{pe}}}{N_{\mathrm{live}}} \right)$$

DIFFERENT FIT METHODS

	Monte Carlo	Analytical
Detector response	Full simulation	Describe mathematically
Free parameters	Rates of signal and background	+ light yield + 6 response function parameters
Cons	Cannot account for unknown variations	More free parameters → more correlations
Pros	Tuning done on calibration data independent of analysis data	• More flexible • dark noise convolution • easier to deal with ^{14}C

SYSTEMATICS

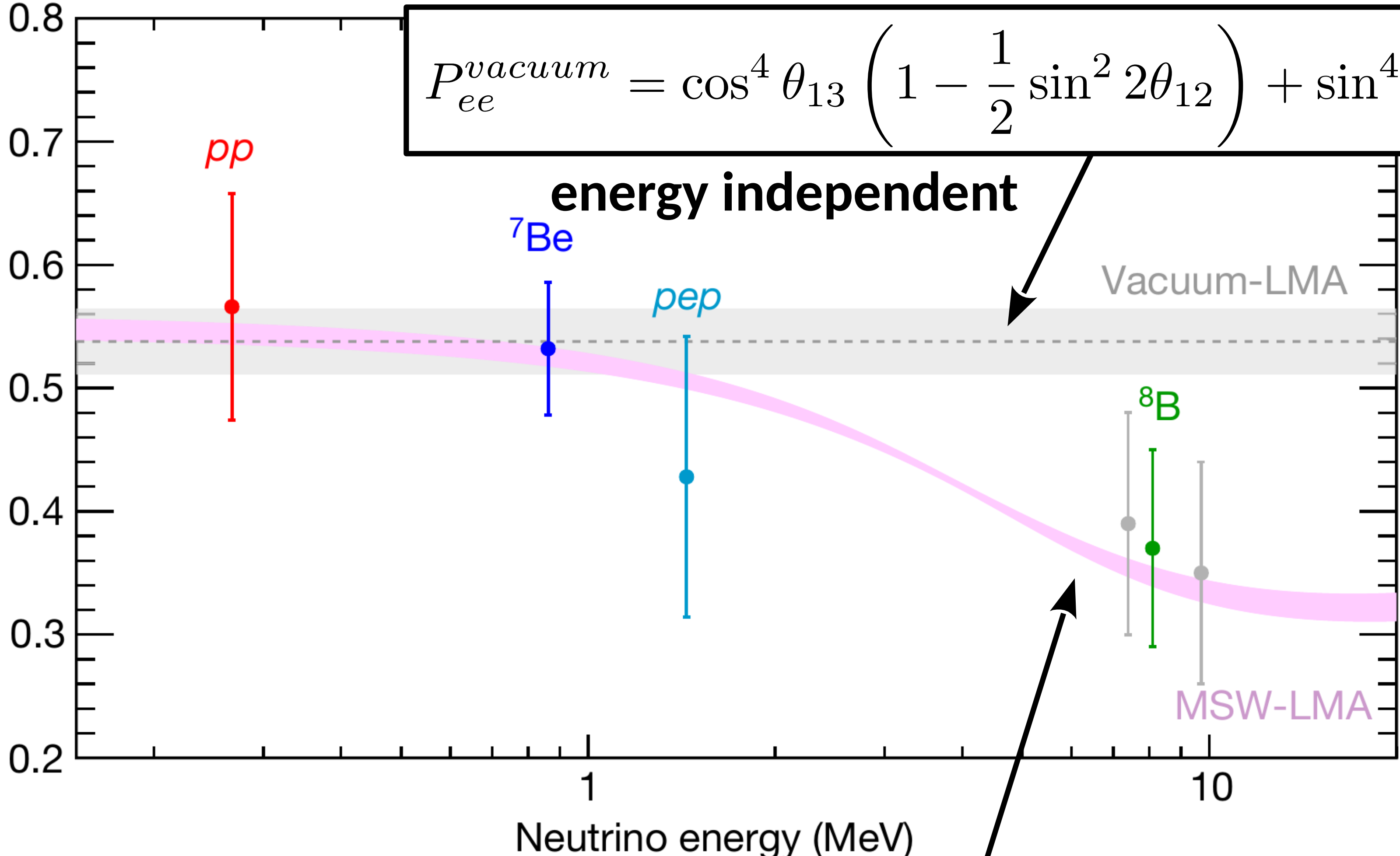
Source of uncertainty	*pp* neutrinos		^{7}Be neutrinos		*pep* neutrinos	
	-%	+%	-%	+%	-%	+%
Fit models (see text)	-4.5	+0.5	-1.0	+0.2	-6.8	+2.8
Fit method (analytical/Monte Carlo)	-1.2	+1.2	-0.2	+0.2	-4.0	+4.0
Choice of the energy estimator	-2.5	+2.5	-0.1	+0.1	-2.4	+2.4
Pile-up modeling	-2.5	+0.5	0	0	0	0
Fit range and binning	-3.0	+3.0	-0.1	+0.1	-1.0	+1.0
Inclusion of the ^{85}Kr constraint	-2.2	+2.2	0	+0.4	-3.2	0
Live time	-0.05	+0.05	-0.05	+0.05	-0.05	+0.05
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**

Relevant sources of systematic uncertainties and their contributions to the measured neutrino interaction rates for the LER analysis.

MSW-LMA (MATTER EFFECT)

$$P_{ee}^{vacuum} = \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2 2\theta_{12}\right) + \sin^4\theta_{13}$$

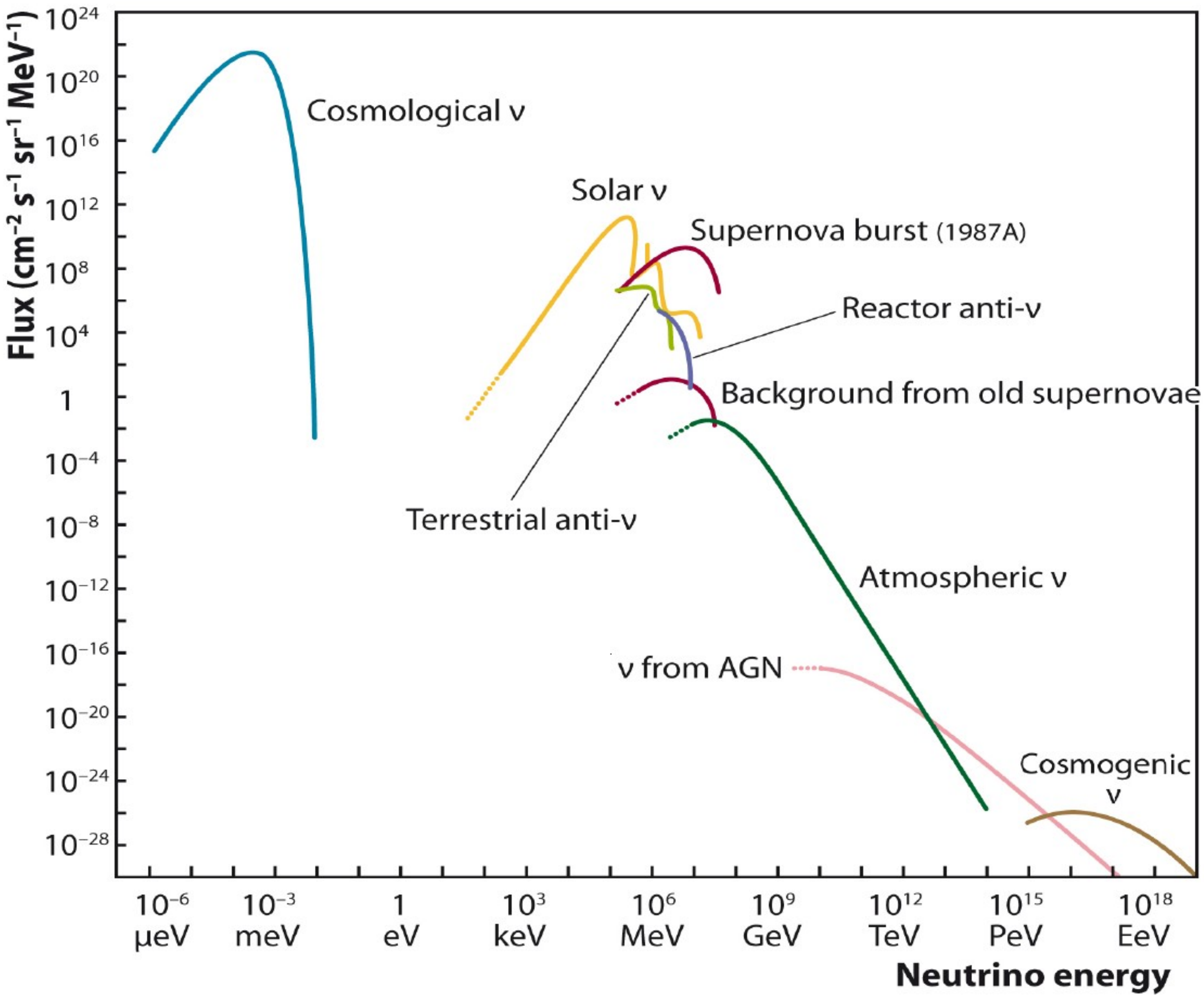
energy independent



$$P_{ee}^{\text{MSW-LMA}} = \frac{1}{2}\cos^4\theta_{13}(1 + \cos 2\theta_{12}^{\text{M}} \cos 2\theta_{12})$$

mixing angle in matter, depends on E_ν

NEUTRINO SPECTRA



U. F. Katz and C. Spiering, “High-Energy Neutrino Astrophysics: Status and Perspectives,” Prog. Part. Nucl. Phys., vol. 67, pp. 651–704, 2012
DOI: 10.1016/j.ppnp.2011.12.001