The tale of solar neutrinos

Shirley Li

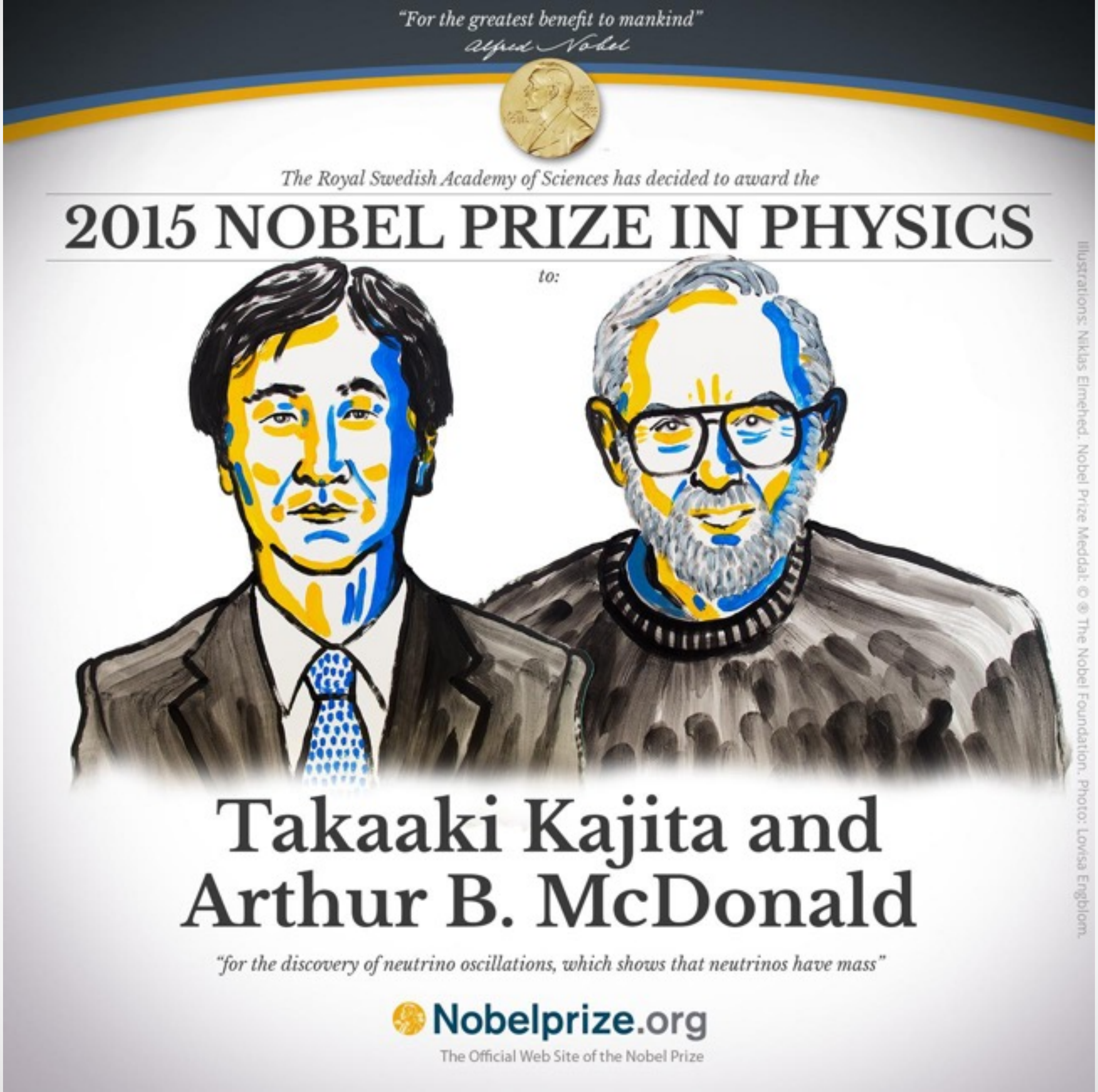
NNPSS 2022, Boston

About me

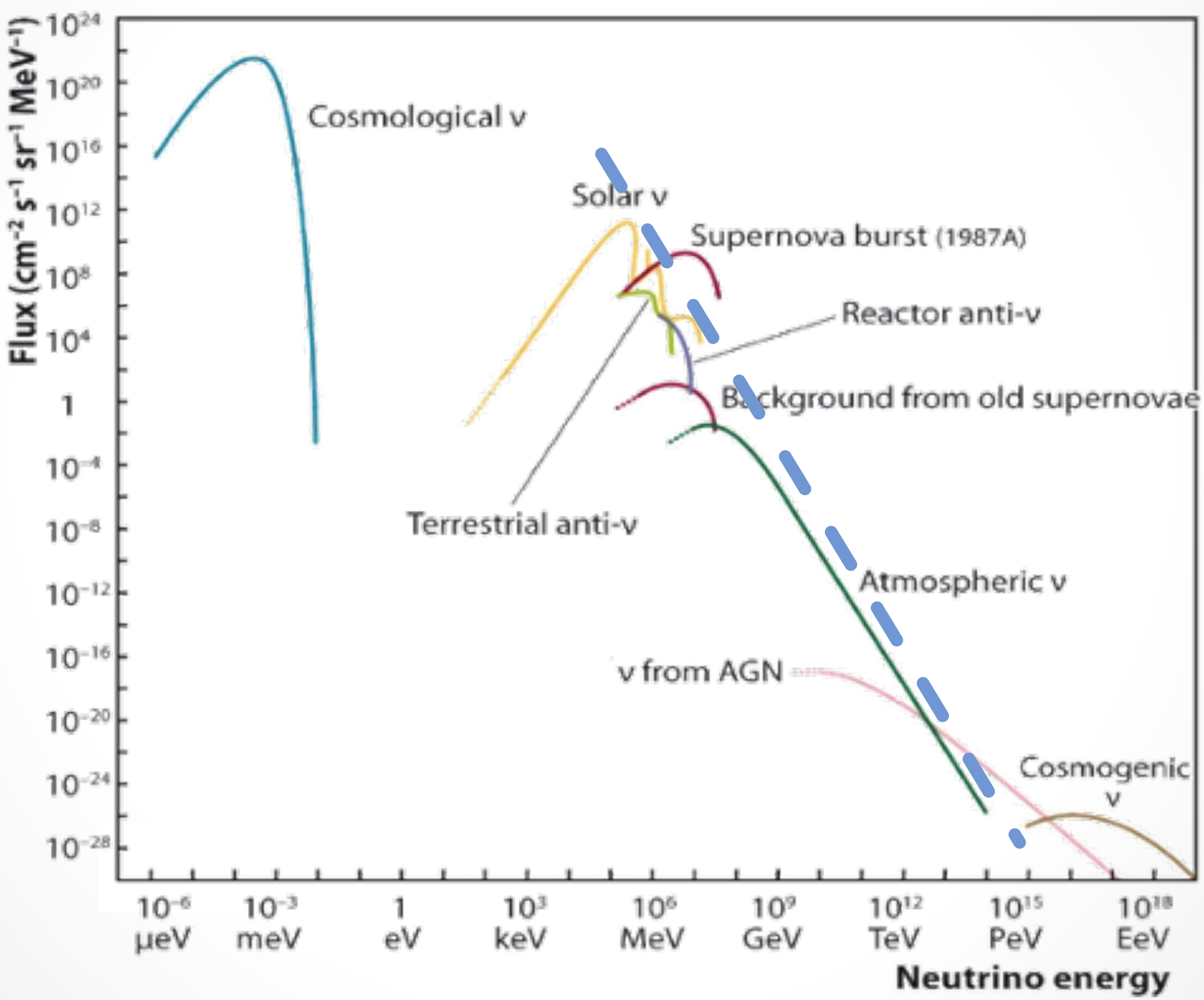
• • •

The plan

- Lecture 1: the tale of solar neutrinos
- Lecture 2: how do neutrinos oscillate?
- Lecture 3: neutrino-nucleus cross sections


"For the greatest benefit to mankind"
Alfred Nobel
The Royal Swedish Academy of Sciences has decided to award the
2015 NOBEL PRIZE IN PHYSICS
to:
Takaaki Kajita and
Arthur B. McDonald
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"
Nobelprize.org
The Official Web Site of the Nobel Prize
Illustrations: Niklas Elmehed. Nobel Prize Medal: © ® The Nobel Foundation. Photo: Lovisa Engblom.

Neutrinos in the Universe



Katz and Spiering, 2012

Solar neutrino

• • •

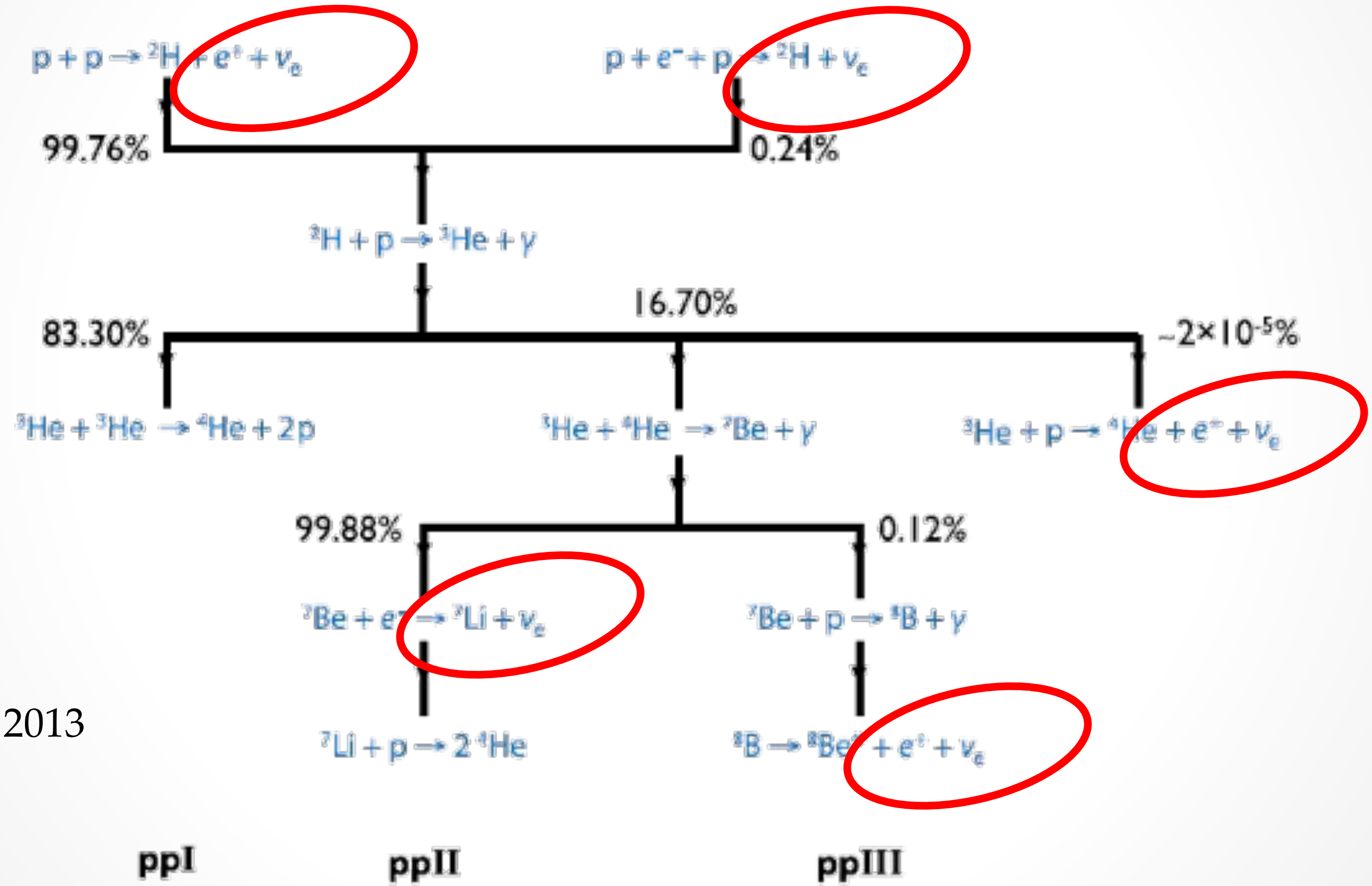
fighting against the odds

… *and winning*

Quote stole from Bustamante

Where everything begins

The Sun is powered by the p-p chain



Haxton *et al.*, 2013

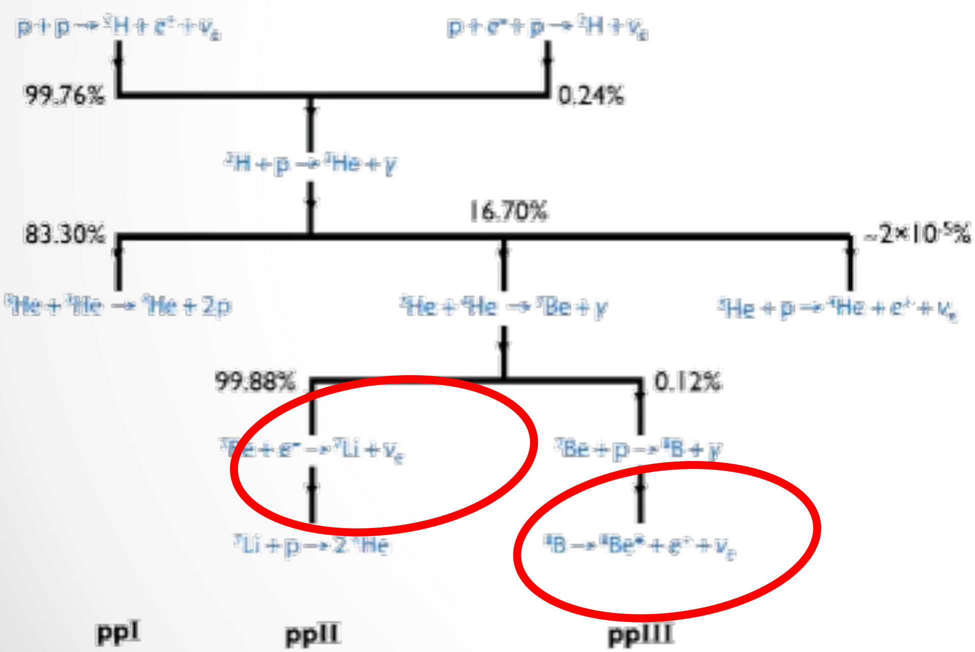
Detect these neutrinos?

First calculation

SOLAR NEUTRINOS. I. THEORETICAL*

John N. Bahcall
California Institute of Technology, Pasadena, California
(Received 6 January 1964)

Haxton *et al.*, 2013



- ^{8}B, ^{7}Be neutrino flux
  - the Standard Solar Model
- $\nu_e + {}^{37}\mathrm{Cl} \rightarrow e + {}^{37}\mathrm{Ar}$
- 7.5 ± 3.3 SNU (1968)

First experiment

SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

bnl.gov

- Homestake Experiment
- 0.61 kton C_2Cl_4
- $\nu_e + {}^{37}\mathrm{Cl} \rightarrow e + {}^{37}\mathrm{Ar}$
- Measured 3 SNU

Theory is wrong?

Refining the Solar Model

> Most likely, the solar neutrino problem has nothing to do with particle physics. It is a great triumph that astrophysicists are able to predict the number of ^{8}B neutrinos to within a factor of 2 or 3… -- Georgi

- 10,000 Standard Solar Models: A Monte Carlo Simulation

Author(s):John N. Bahcall and M. H. Pinsonneault
Journal: *Phys. Rev. Lett.*, **92**, Number 12, 121301 (2004), astro-ph/0402114.

Abstract: Solar model predictions of ^{8}B and p-p neutrinos agree with the experimentally-determined fluxes (including oscillatio
improved input data for nuclear fusion reactions, the equation of state, and the chemical composition of the Sun. The solar comp
calculated ^{7}Be neutrino flux.

Postscript file. Pdf file.

- **How Do Uncertainties in the Surface Chemical Composition of the Sun Affect the Predicted Solar Neutrino Fluxes?**

Author(s): John N. Bahcall and Aldo Serenelli
Journal: *ApJ*, **626**, 530 (June 10, 2005), astro-ph/0412096

Abstract: We show that uncertainties in the values of the surface heavy element abundances of the Sun are the largest source of
neutrino flux with respect to the surface abundance of each element. We then calculate the uncertainties in each neutrino flux usi
8B neutrino flux is 11.6% (5.0%) when sensitivities to individual element abundances are used. The traditional method that lump
sulphur, and iron abundances all make significant contributions to the uncertainties in calculating solar neutrino fluxes; the uncer
of the important 7Be and 8B solar neutrinos. Carbon is the largest contributor to the uncertainty in the calculation of the p-p, 13N

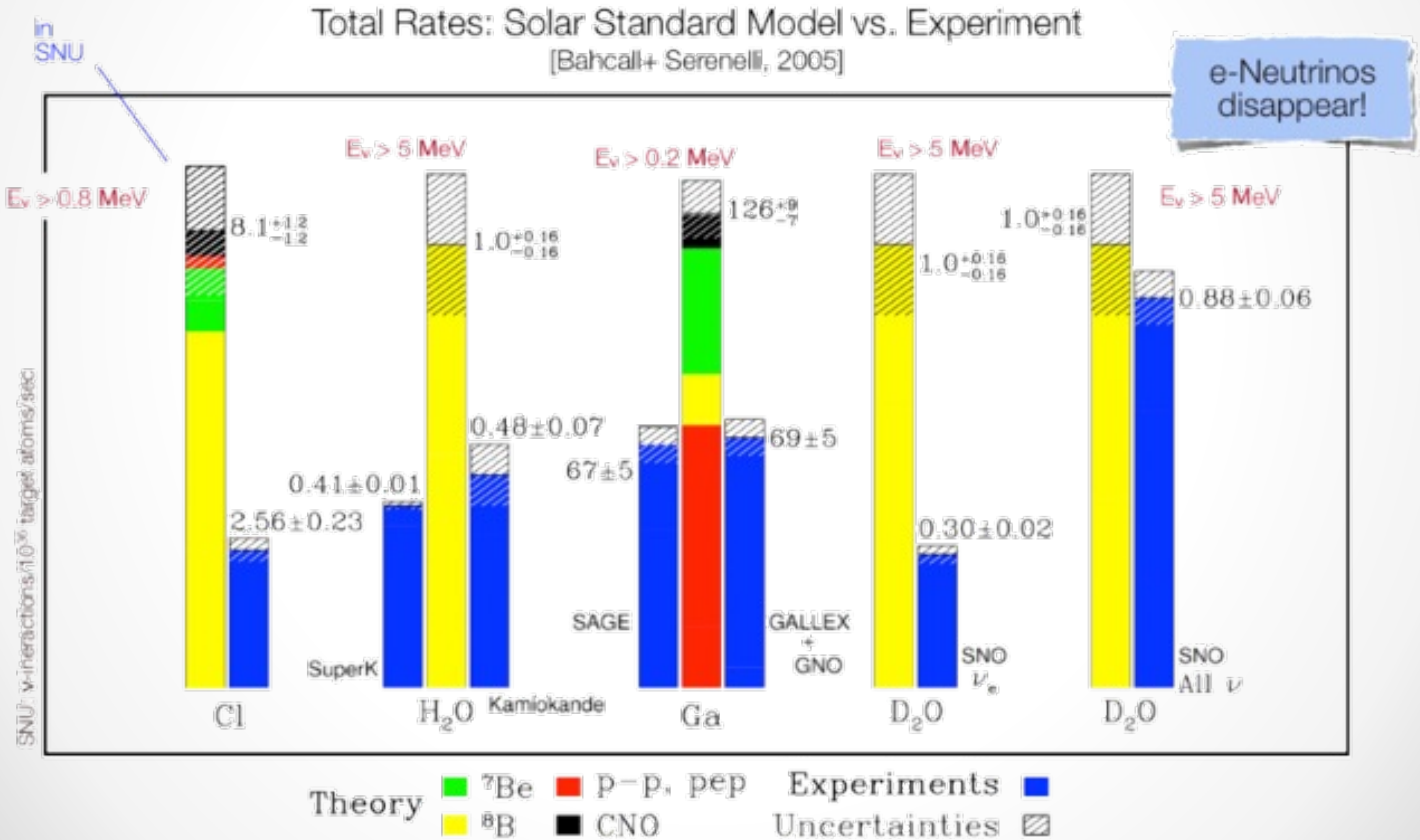
Postscript file. Pdf file.

- **How Accurately Can We Calculate the Depth of the Solar Convective Zone?**

Author(s): John N. Bahcall, Aldo M. Serenelli, and Marc Pinsonneault

Experiment is wrong?

Continuing effort



New physics??

Physics Letters B

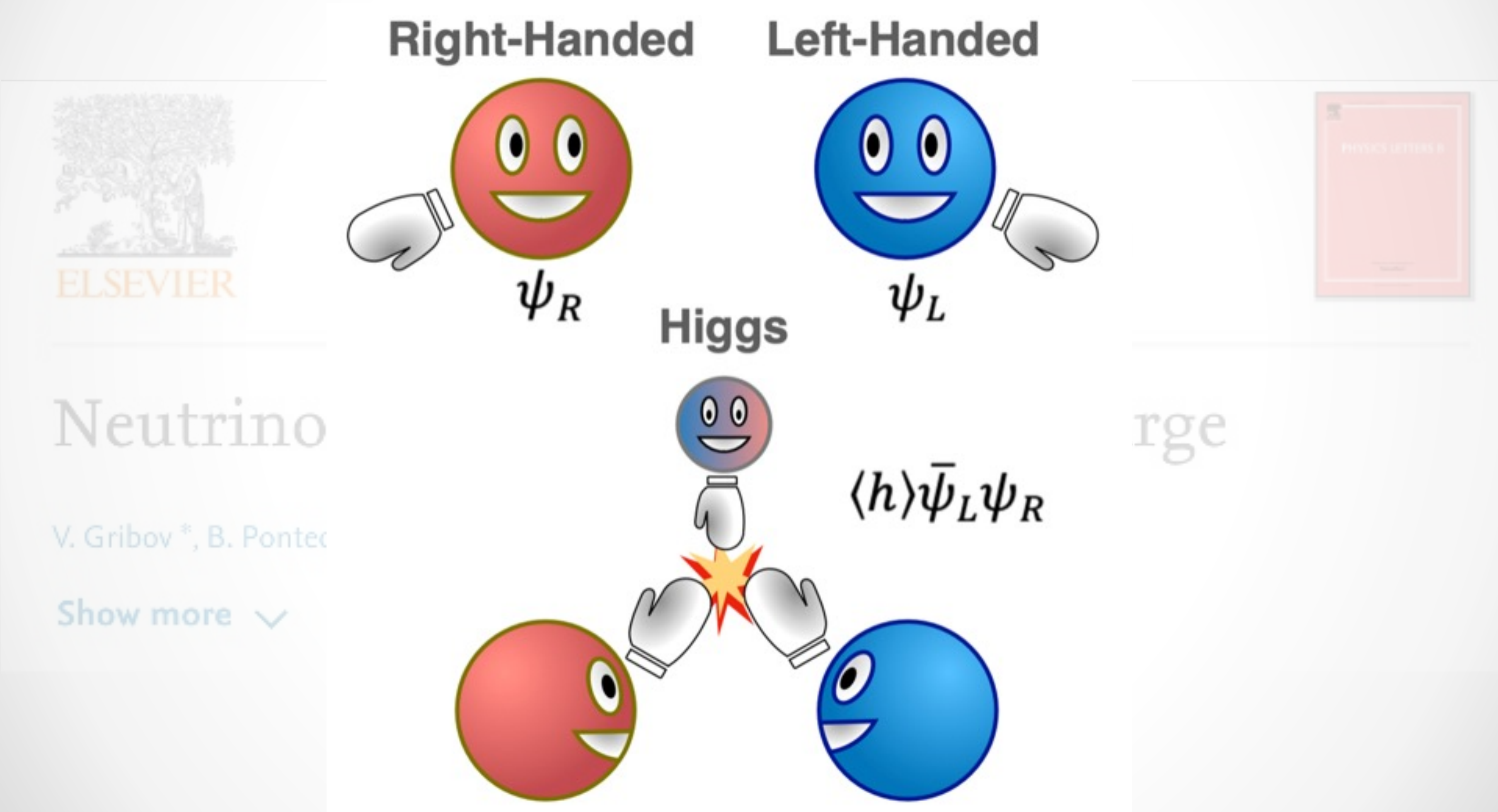
Volume 28, Issue 7, 20 January 1969, Pages 493-496

Neutrino astronomy and lepton charge

V. Gribov *, B. Pontecorvo

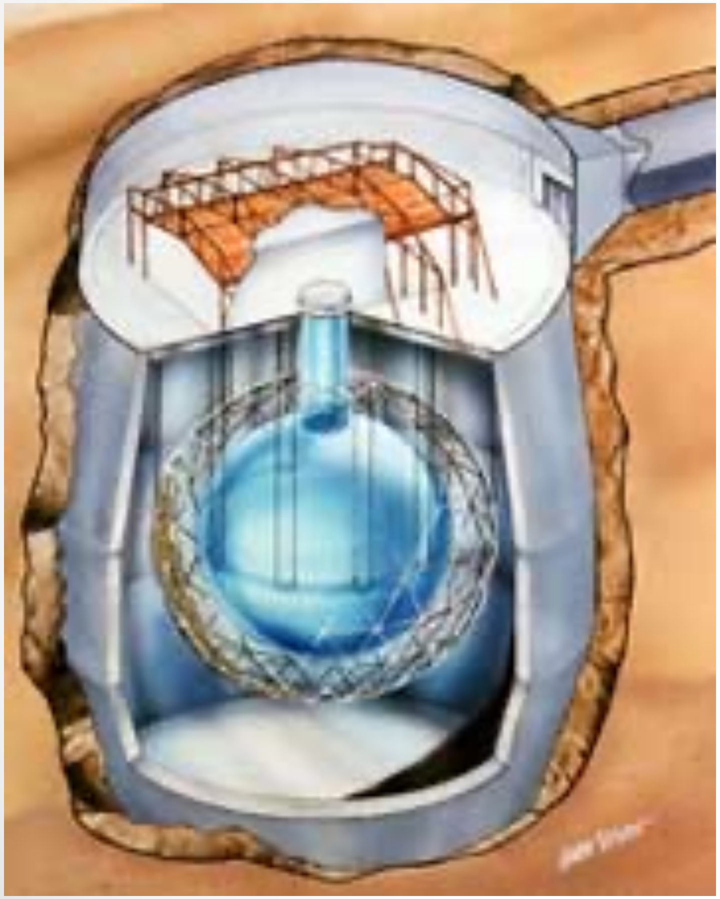
Show more

New physics??


ELSEVIER
Neutrino
rge
V. Gribov *, B. Pontec
Show more
Right-Handed
Left-Handed
ψ_R
ψ_L
Higgs
$\langle h \rangle \bar{\psi}_L \psi_R$

SNO: the definitive test

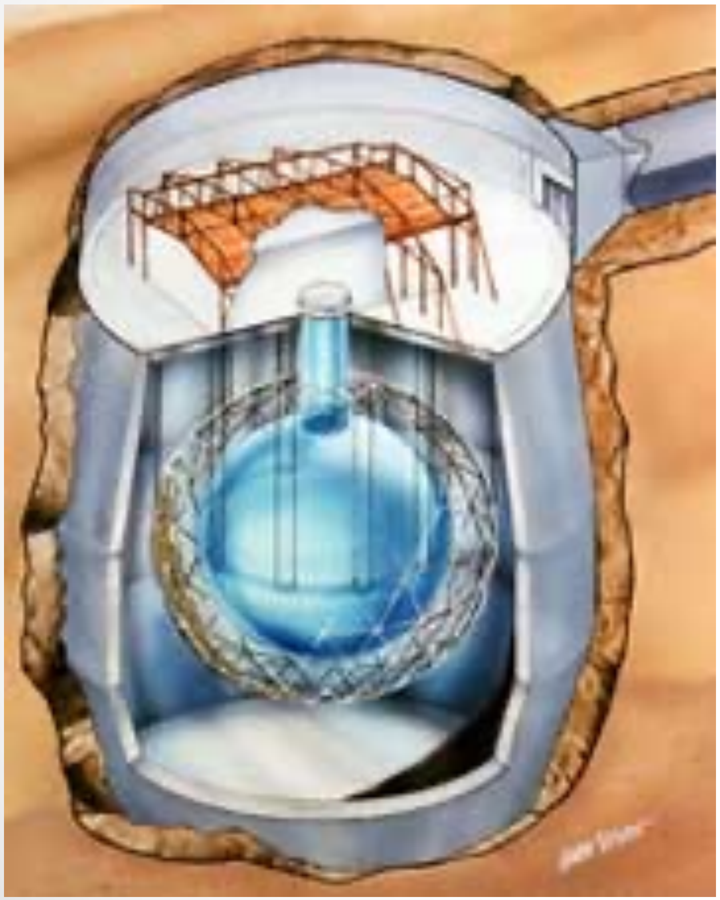
Neutrino oscillation



sno.phy.queensu.ca

SNO: the definitive test

Neutrino oscillation

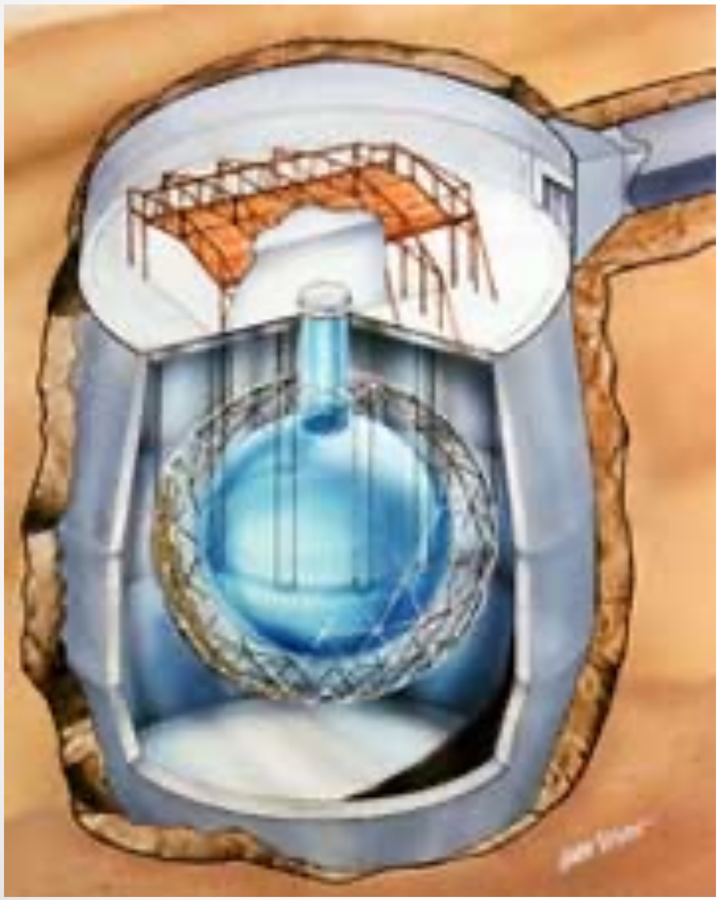


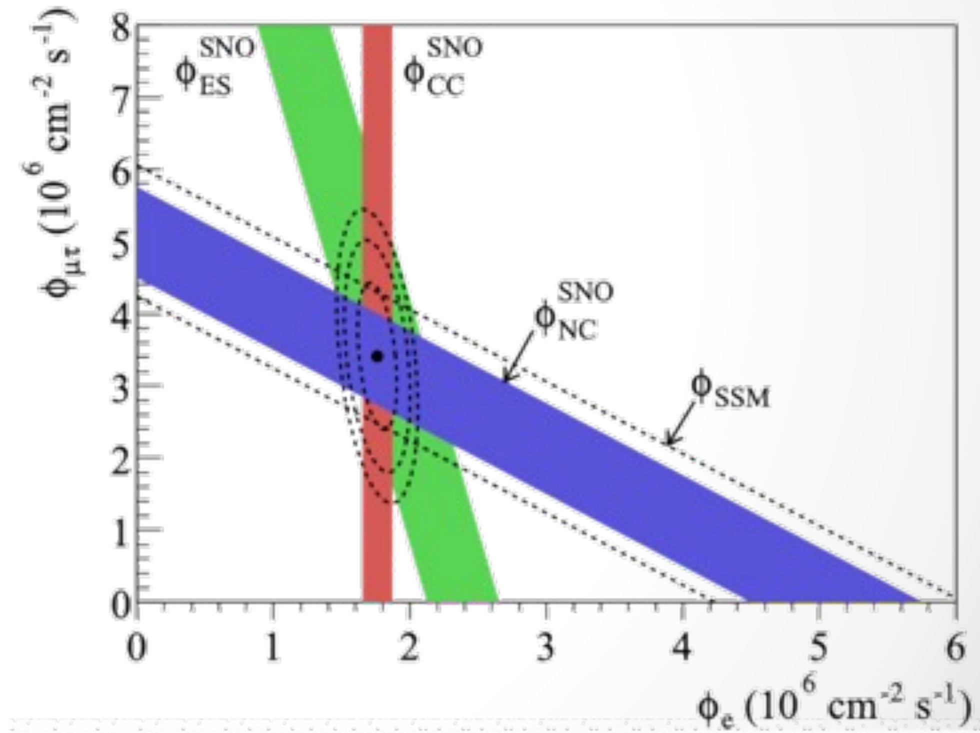
- $\nu_x + d \rightarrow \nu_x + p + n$
- $\nu_e + d \rightarrow e + p + p$
- $\nu_x + e \rightarrow \nu_x + e$

sno.phy.queensu.ca

SNO: the definitive test

Neutrino oscillation





SNO 2016

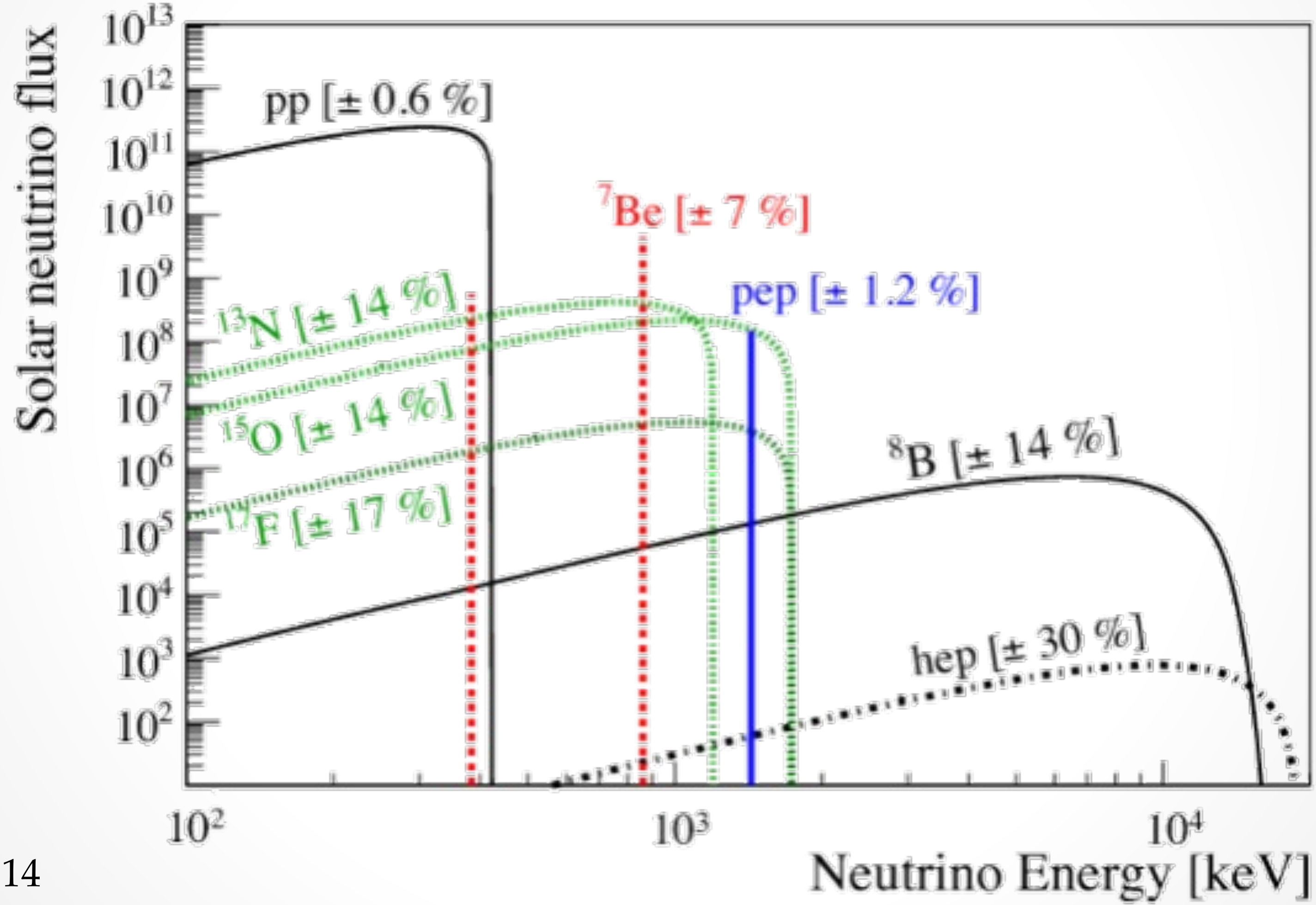
sno.phy.queensu.ca

Solar neutrino

• • •

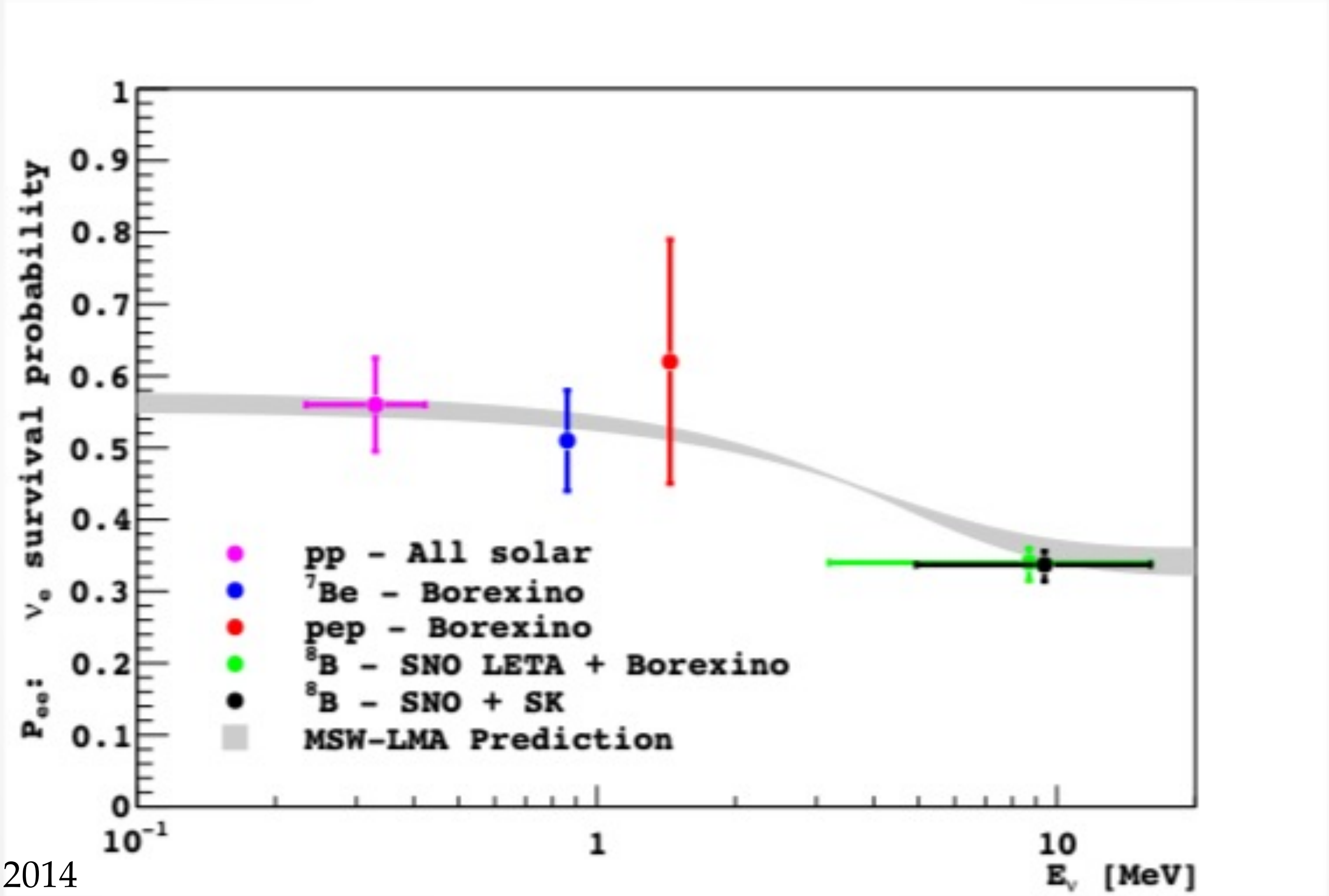
What do we know now

Solar neutrino spectra



Borexino 2014

Solar neutrino oscillation

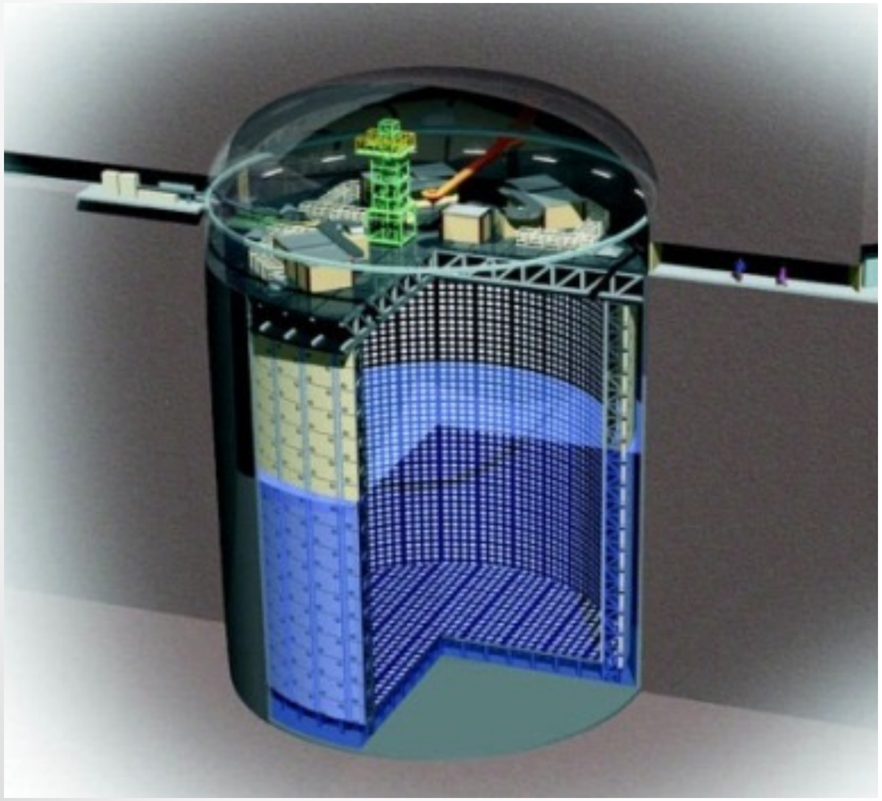


Borexino 2014

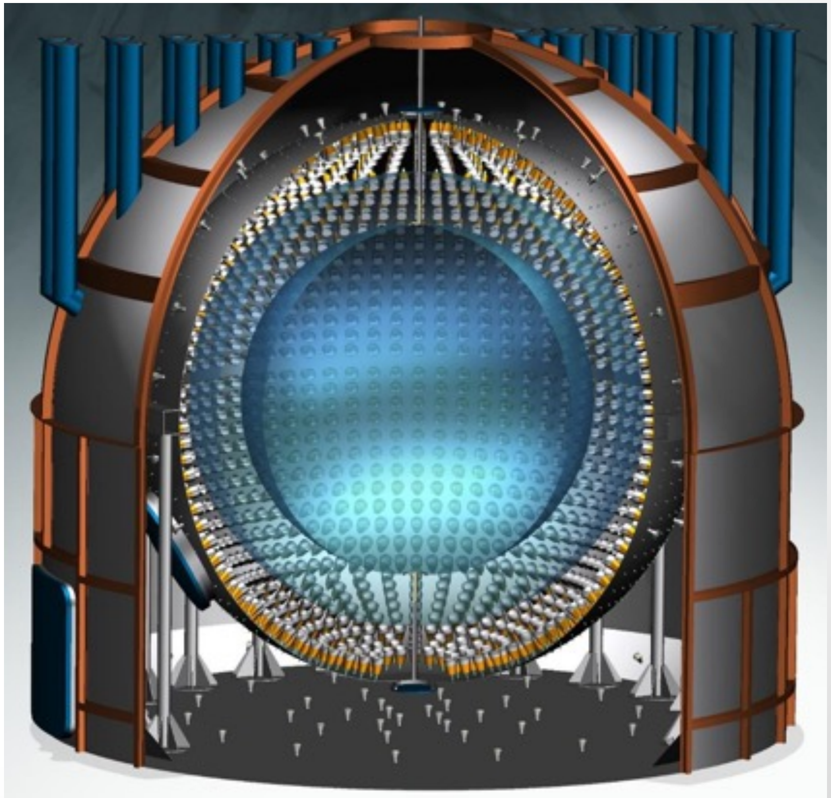
Solar neutrino detection

$$\nu + e \rightarrow \nu + e$$

Super-Kamiokande
Water-Cherenkov



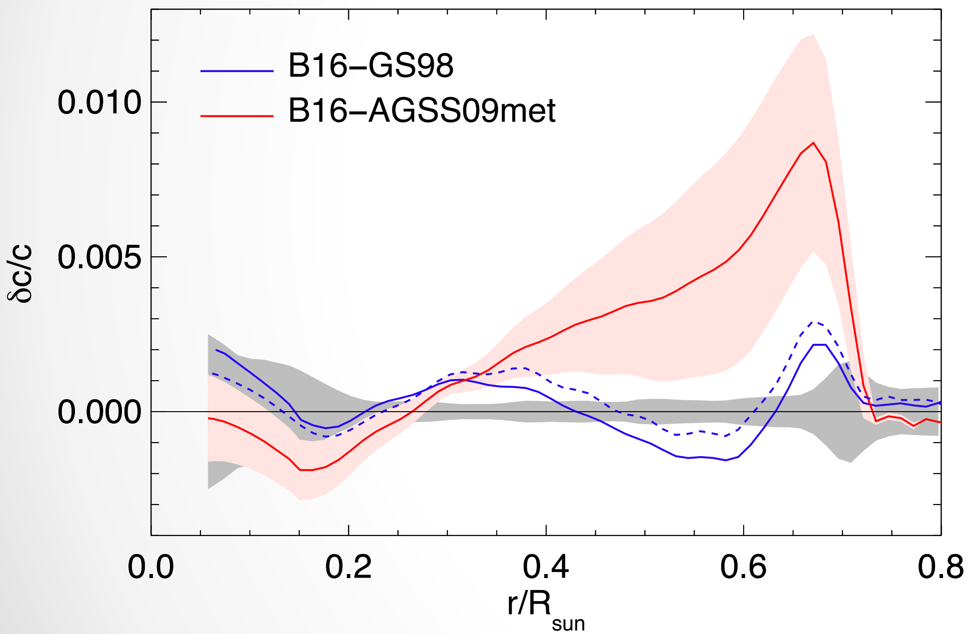
Borexino
Scintillator



But the story doesn't end here …

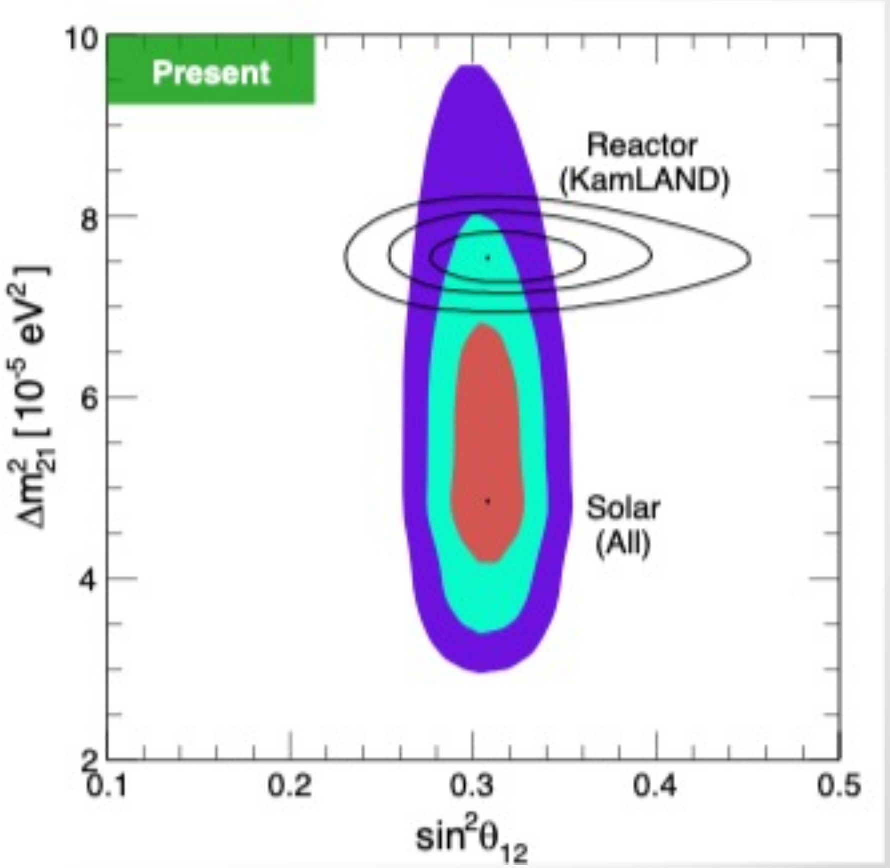
Open questions

Solar metallicity problem



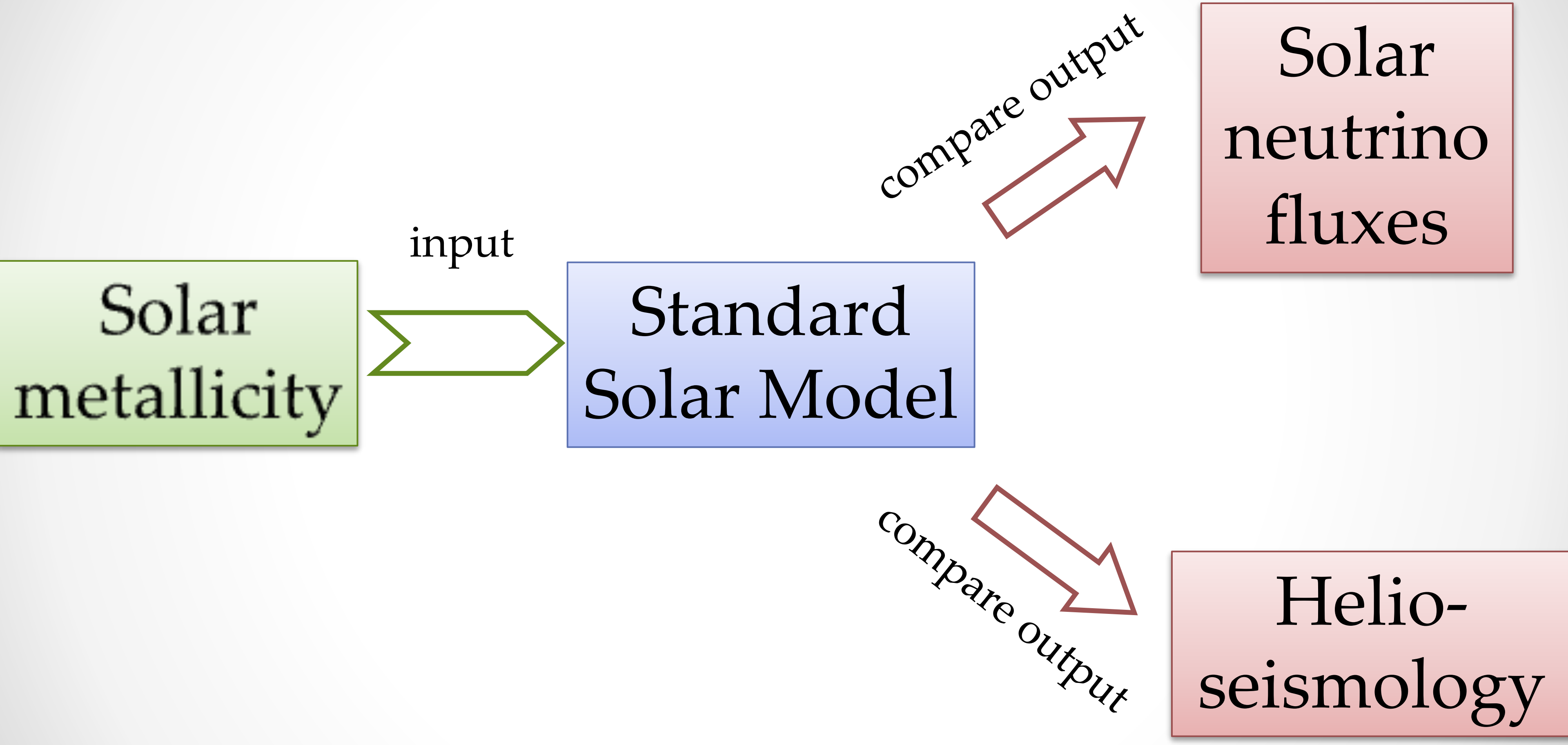
Vinyoles *et. al.*, 2017

Solar & reactor tension



Data from SK 2016

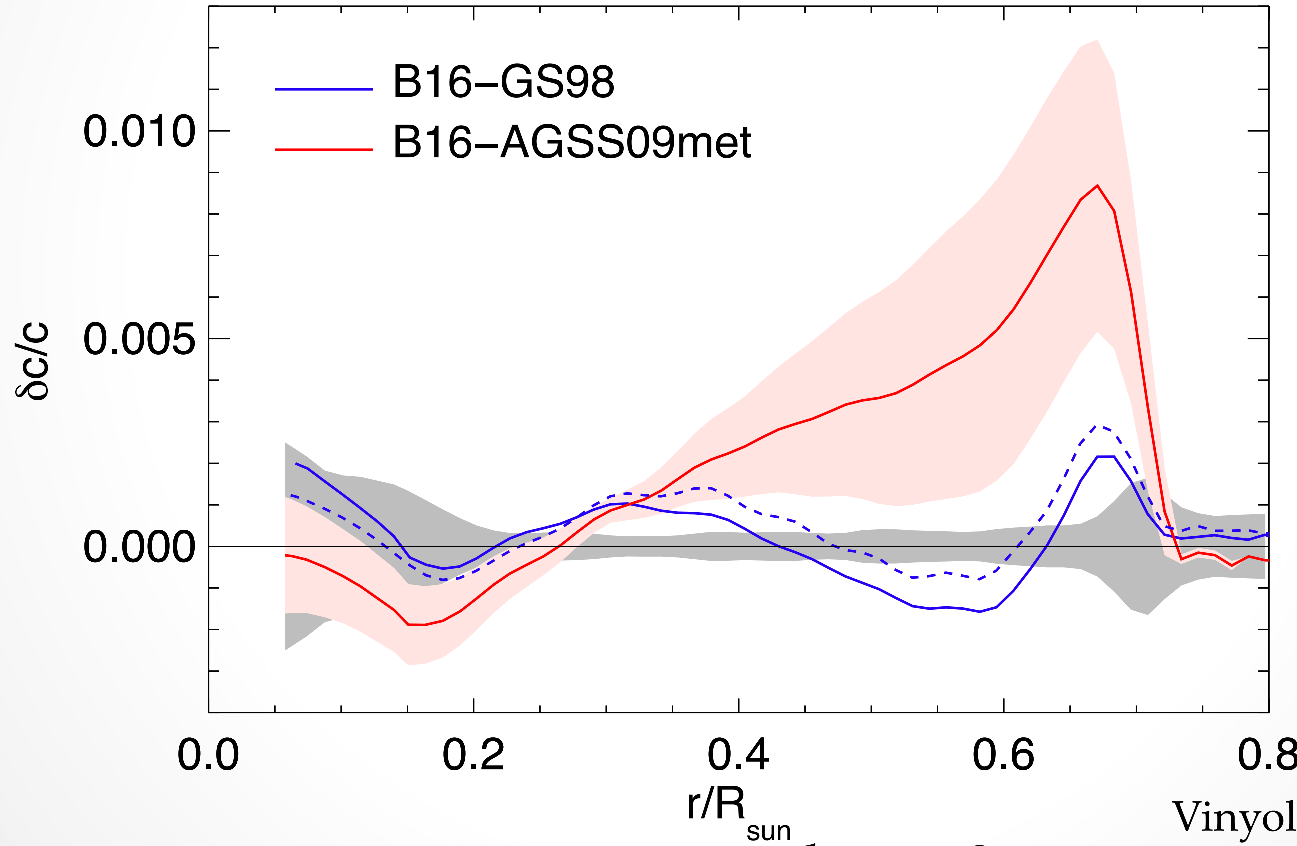
Solar metallicity



Solar metallicity problem

Two *inconsistent* sets of metallicities

Compare to helioseismology



Vinyoles *et. al.*, 2017

How to solve it?

Metallicity & neutrinos

Measured branches

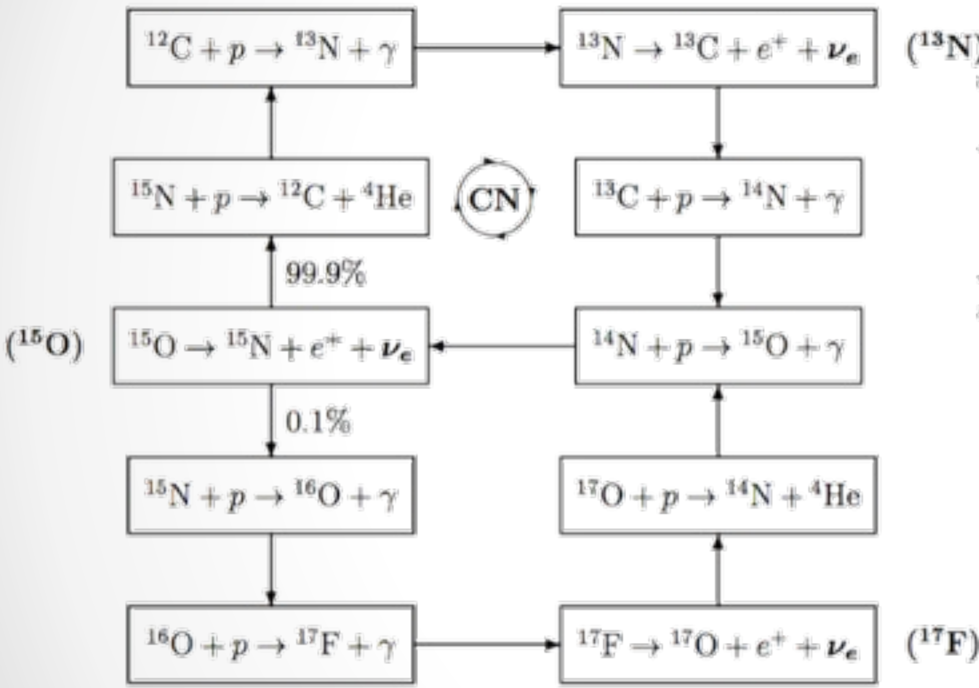
Quant.	Dominant theoretical error sources in %							
$\Phi(pp)$	$L_\odot$:	0.3	S_{34}:	0.3	κ:	0.2	Diff:	0.2
$\Phi(pep)$	κ:	0.5	$L_\odot$:	0.4	S_{34}:	0.4	S_{11}:	0.2
$\Phi(hep)$	S_{hep}:	30.2	S_{33}:	2.4	κ:	1.1	Diff:	0.5
$\Phi(^7Be)$	S_{34}:	4.1	κ:	3.8	S_{33}:	2.3	Diff:	1.9
$\Phi(^8B)$	κ:	7.3	S_{17}:	4.8	Diff:	4.0	S_{34}:	3.9
$\Phi(^{13}N)$	C:	10.0	S_{114}:	5.4	Diff:	4.8	κ:	3.9
$\Phi(^{15}O)$	C:	9.4	S_{114}:	7.9	Diff:	5.6	κ:	5.5
$\Phi(^{17}F)$	O:	12.6	S_{116}:	8.8	κ:	6.0	Diff:	6.0

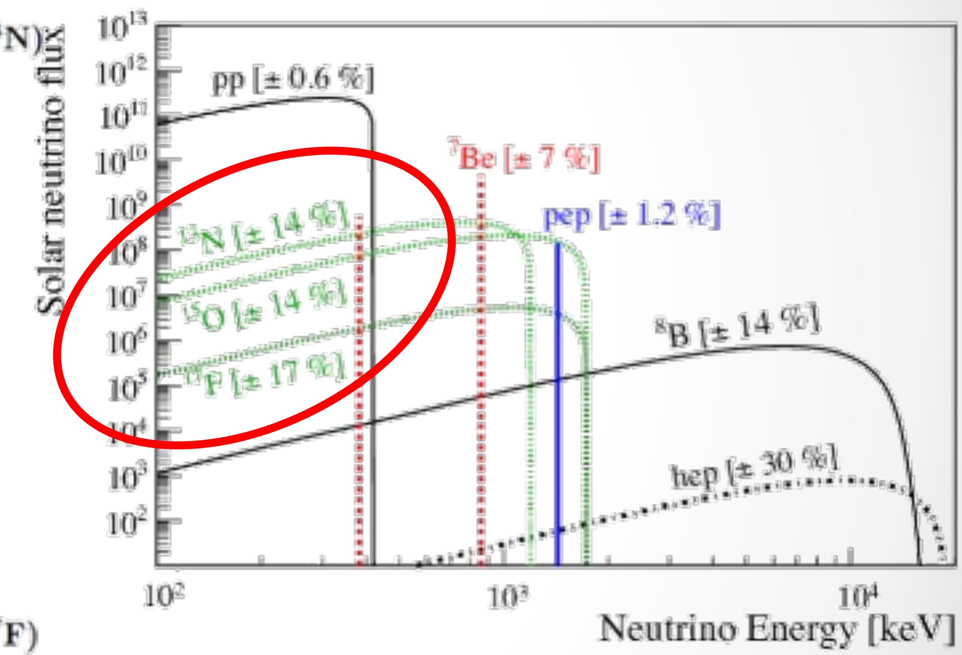
Vinyoles *et al.*, 2017

Better calculation needed

Metallicity & neutrinos

Not measured: CNO neutrinos





Giunti and Kim, 2007

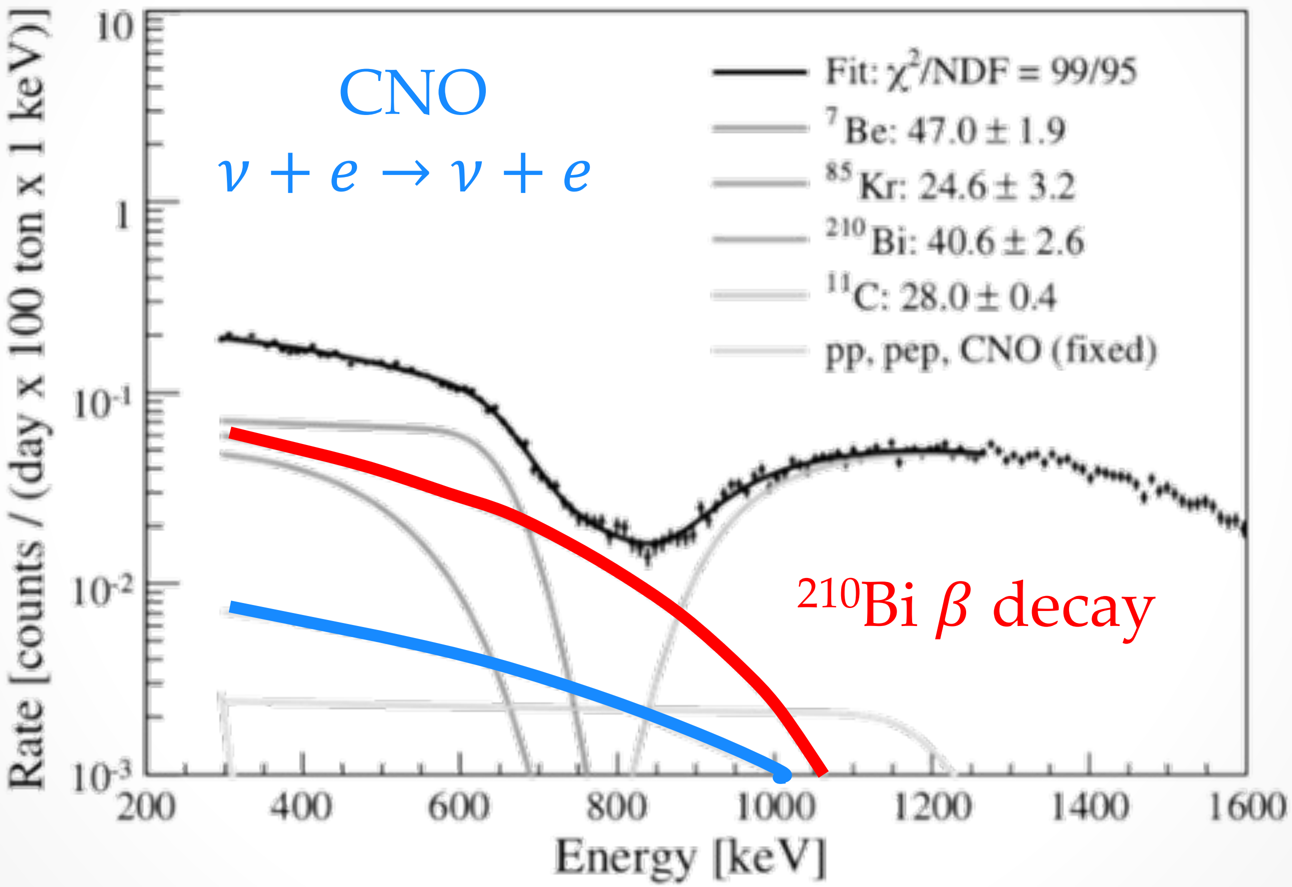
Vinyoles *et. al.*, 2017

Great potential at distinguishing metallicities

Why haven't we measured them?

Obstacles for CNO ν

Borexino

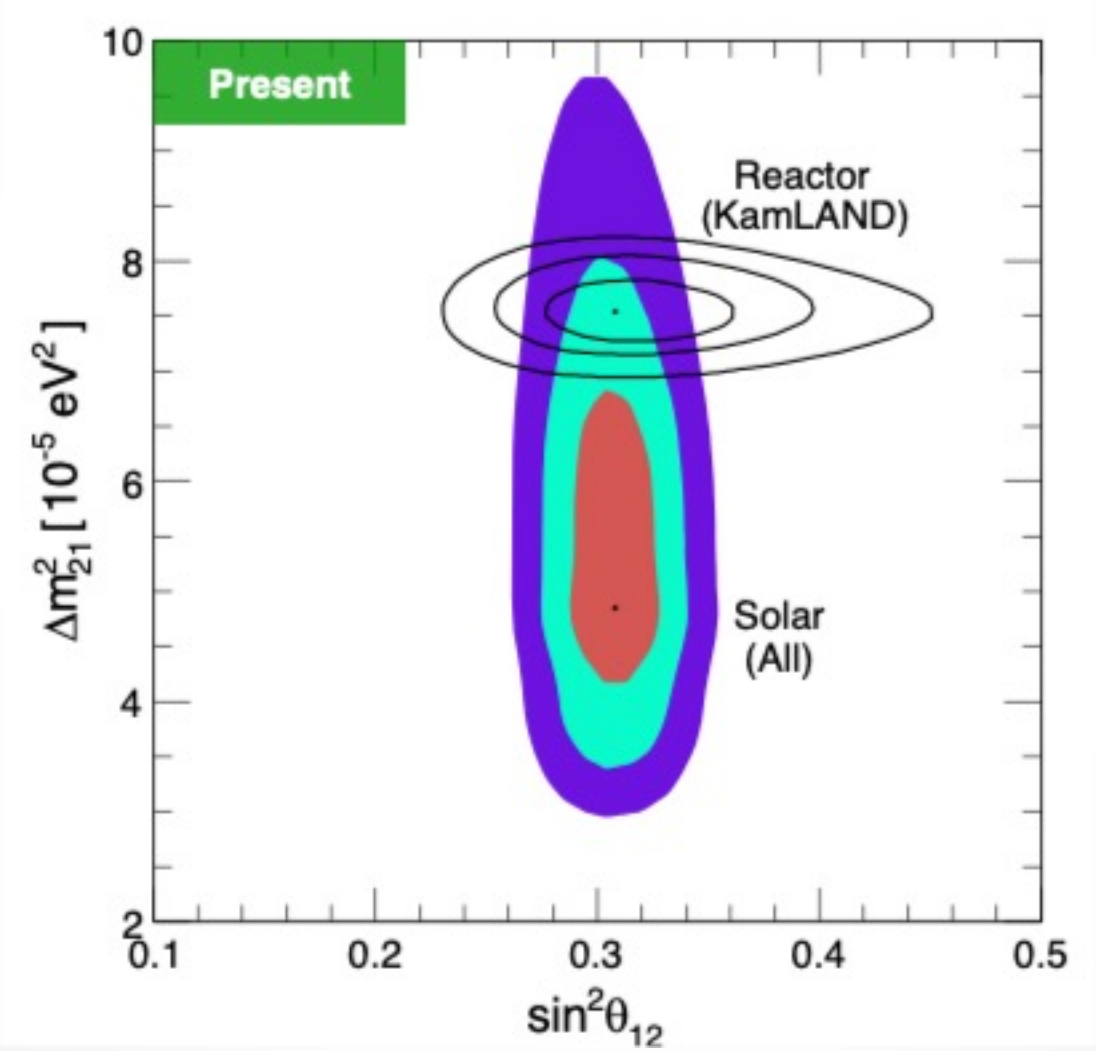


Borexino 2014

Hopeless?

Open questions

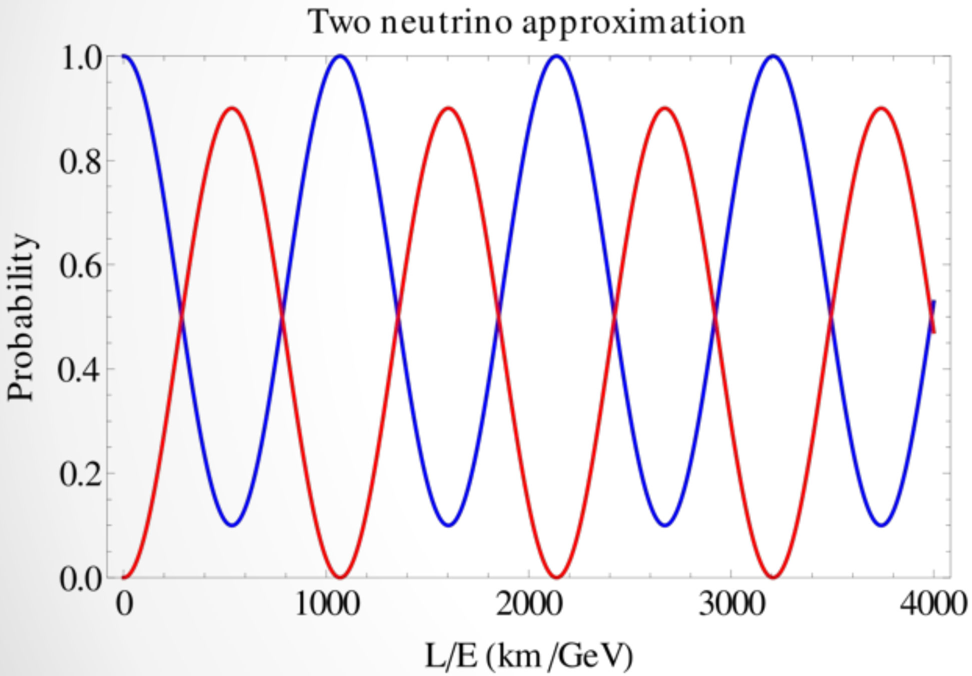
Solar & reactor tension



Data from SK 2016

Neutrino oscillation

Two-level system



- $P_{ee} = 1 - \sin^2 2\theta \sin^2(\frac{\delta m\hat{}2}{4}\frac{L}{E})$
- L_{osc} ~ 100 km

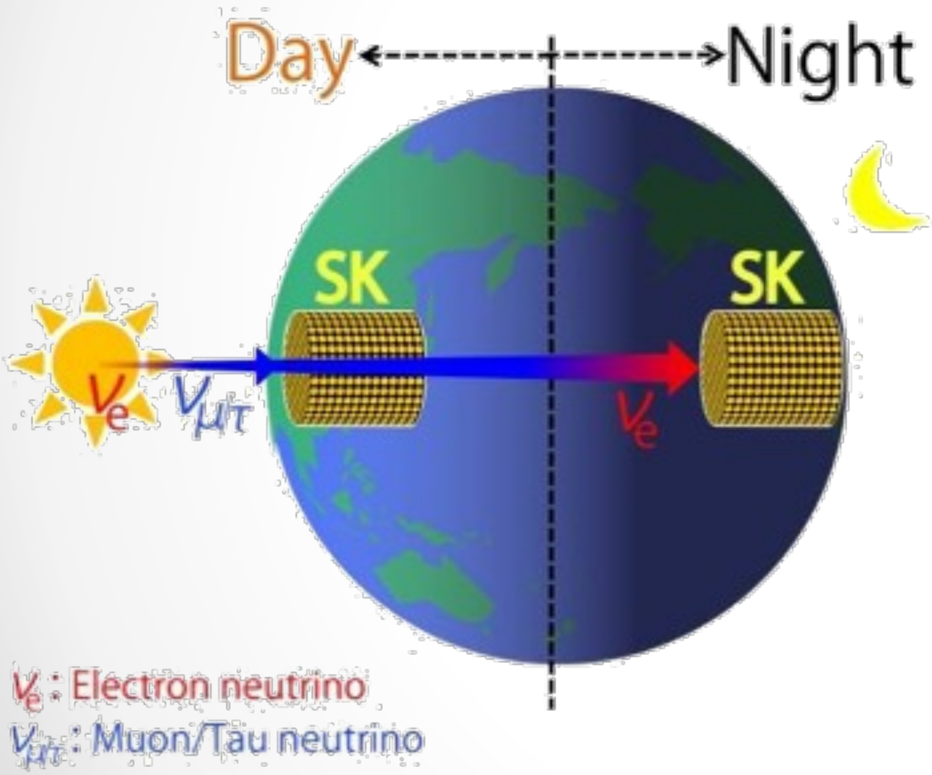
Average after L

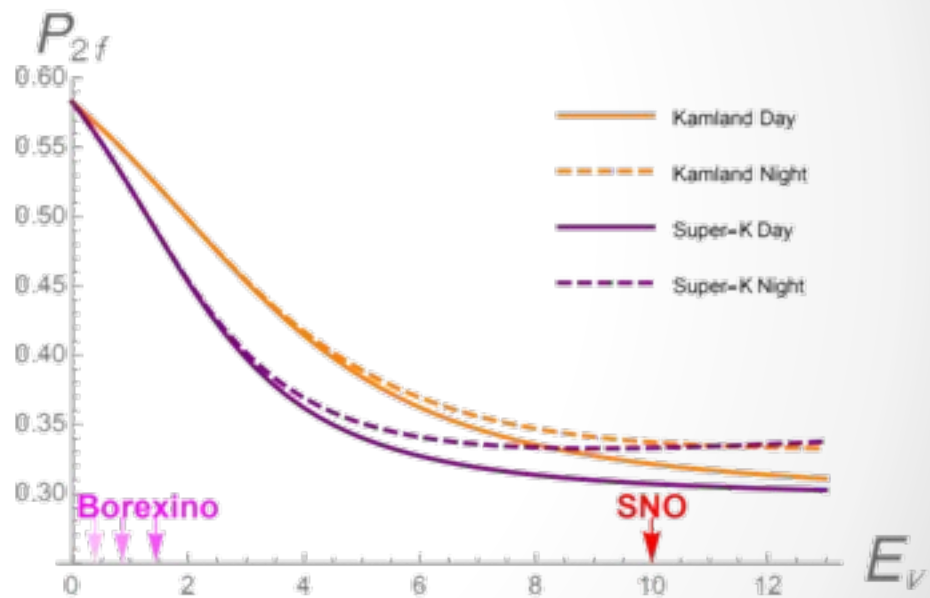
- $P_{ee} = 1 - \frac{1}{2}\sin^2 2\theta$

Only measure θ, not $\delta m\hat{}2$

Matter effect

Day-night asymmetry





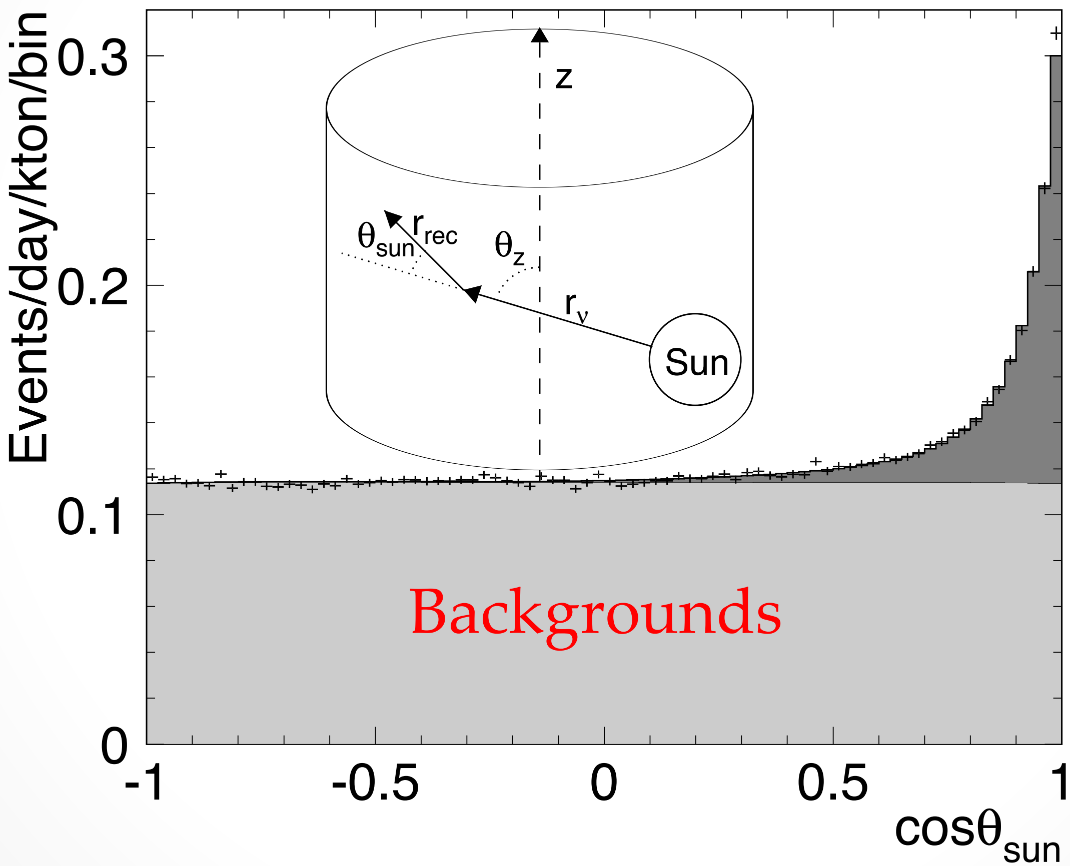
Vissani, 2017

sk.icrr.u-tokyo.ac.jp

Sensitive to δm^2

Obstacles for $^{8}B\ \nu$

Super-Kamiokande



Super-K 2016

$^{8}B\ \nu$

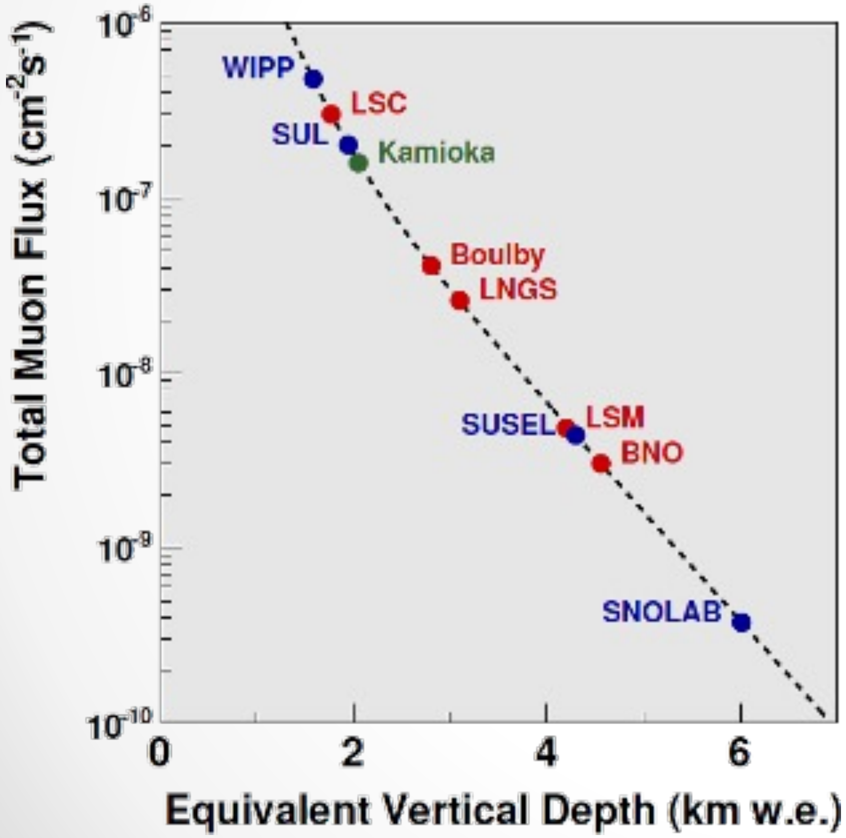
$\nu + e \rightarrow \nu + e$

What are the backgrounds?

Spallation backgrounds

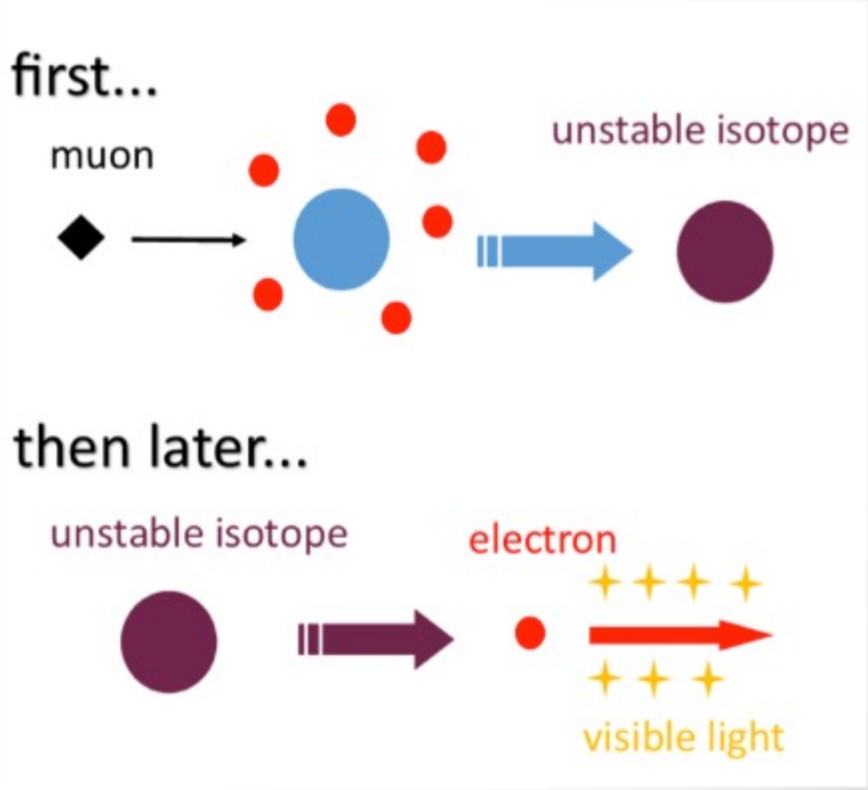
Dominant background between 6 – 20 MeV

Cosmic-ray muon fluxes



Gomez-Cadenas *et al.*, 2012

Spallation production



How to reject them?

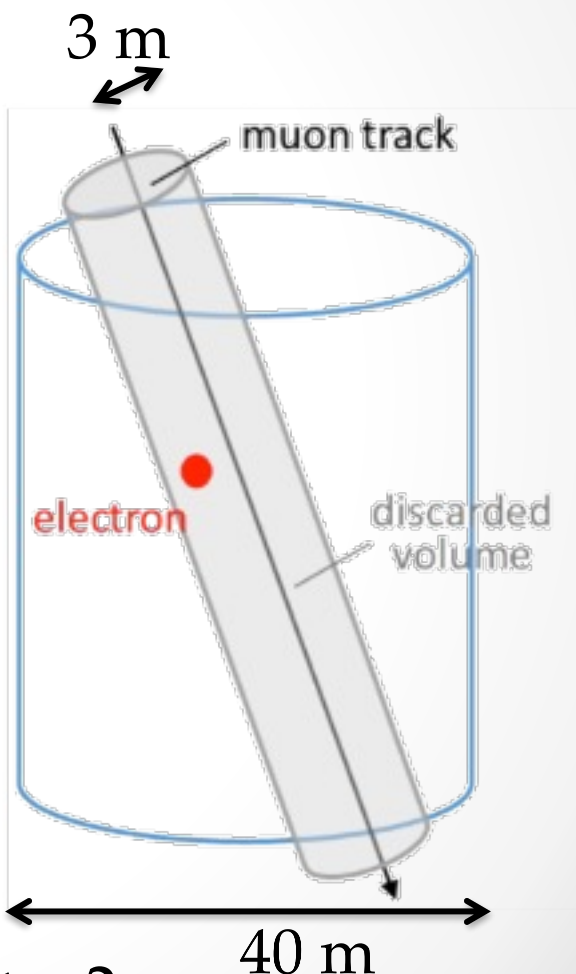
Correlation with muons

- Cylinder cut for a few s
  - muon rate 2 Hz

(signal ~ 15 / day)

  - isotope lifetime ~ 10 s

- Remove 90% backgrounds
- Lose 20% signals



Hopeless to do better?

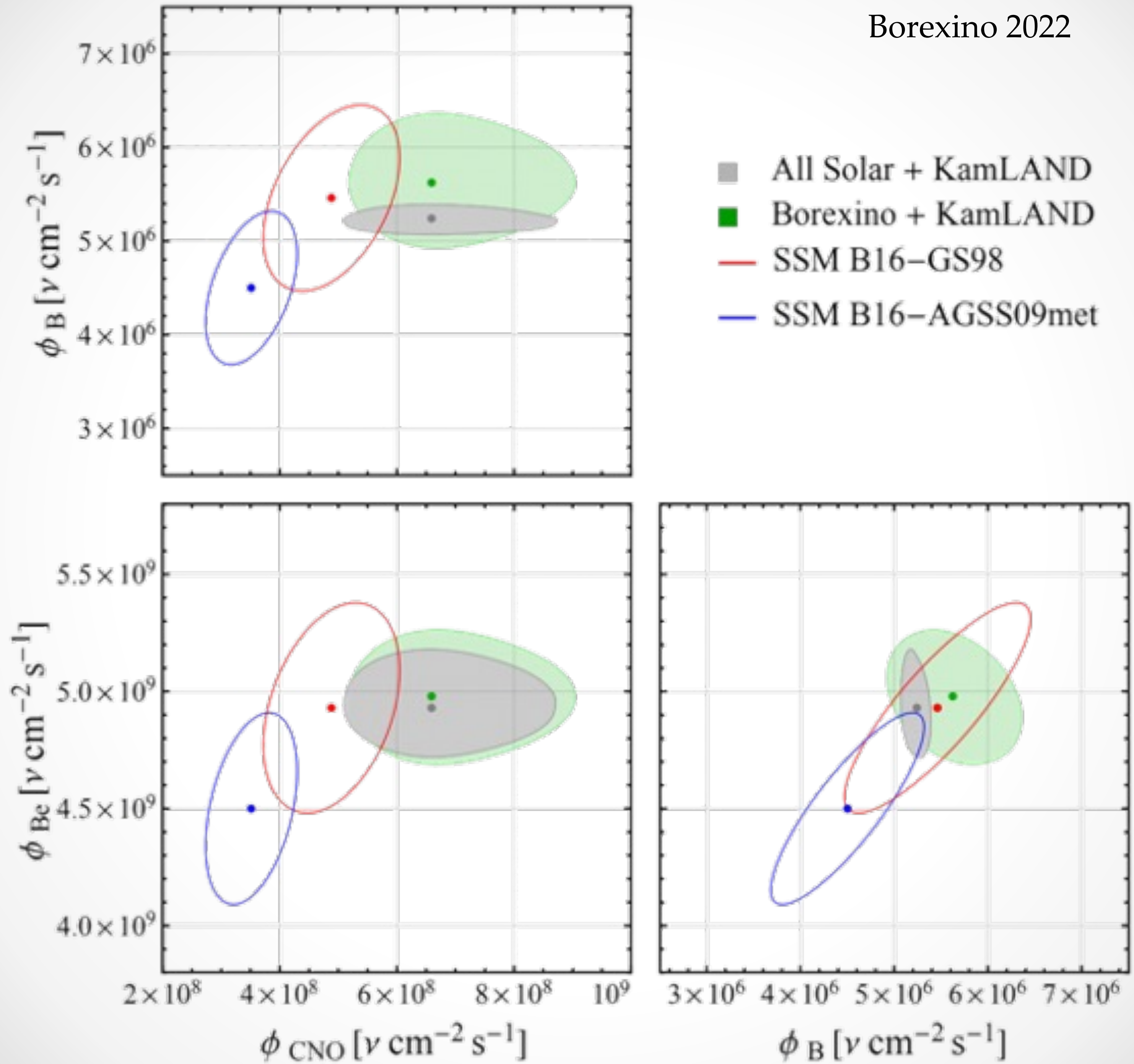
Solar neutrino
• • •
Going forward

Borexino: CNO ν

Calaprice talk at 10th

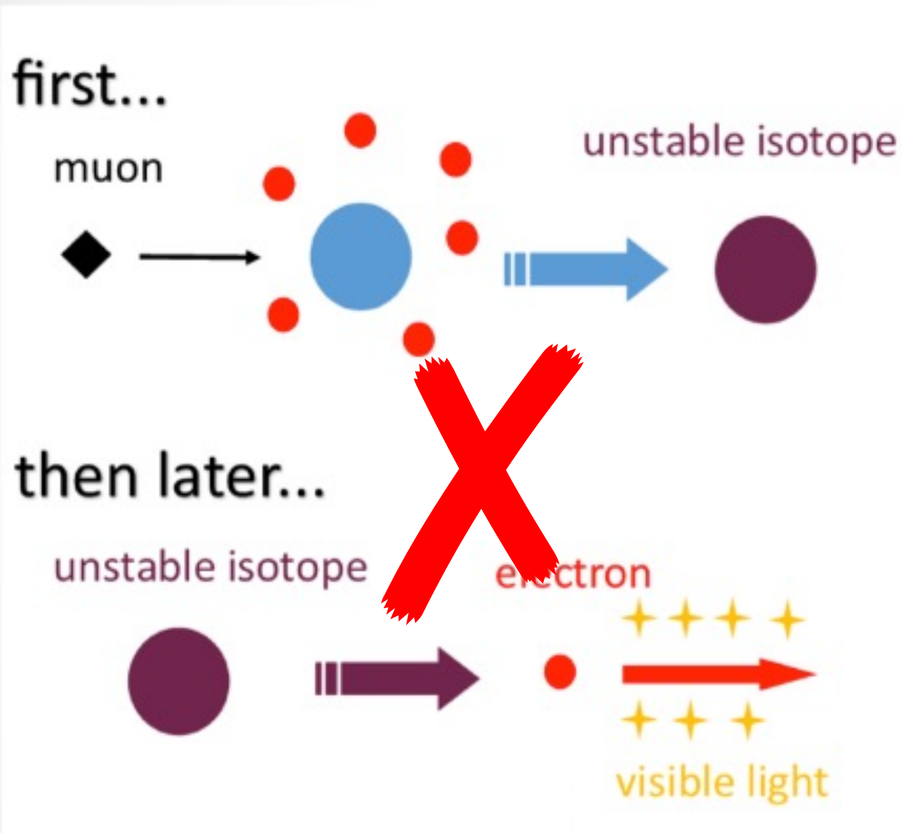
Summer 2017: stable T achieved!

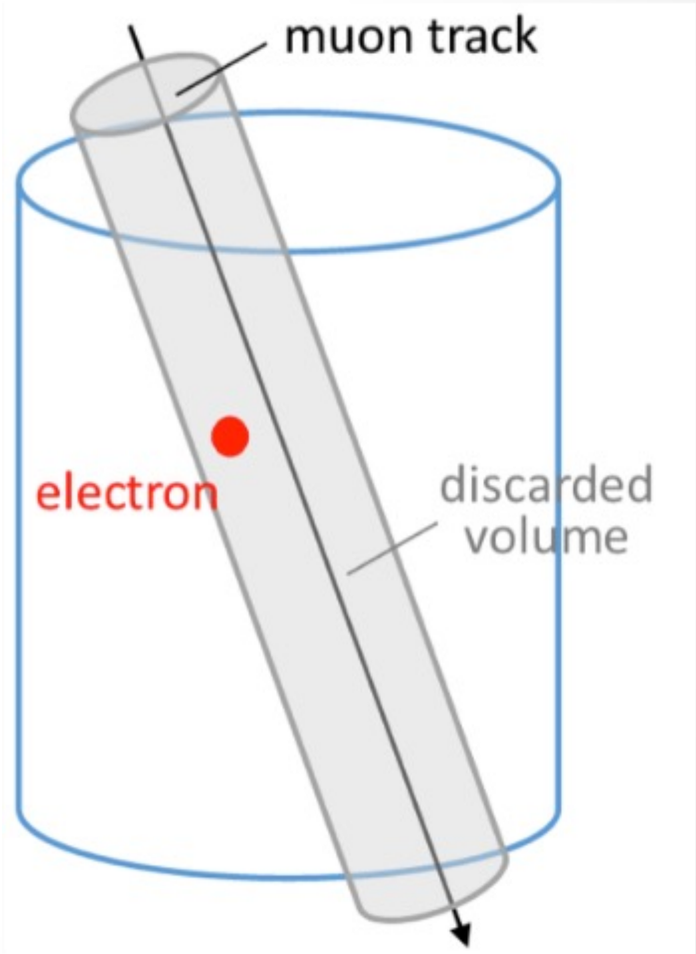
Borexino 2022



Super-K: 8B ν

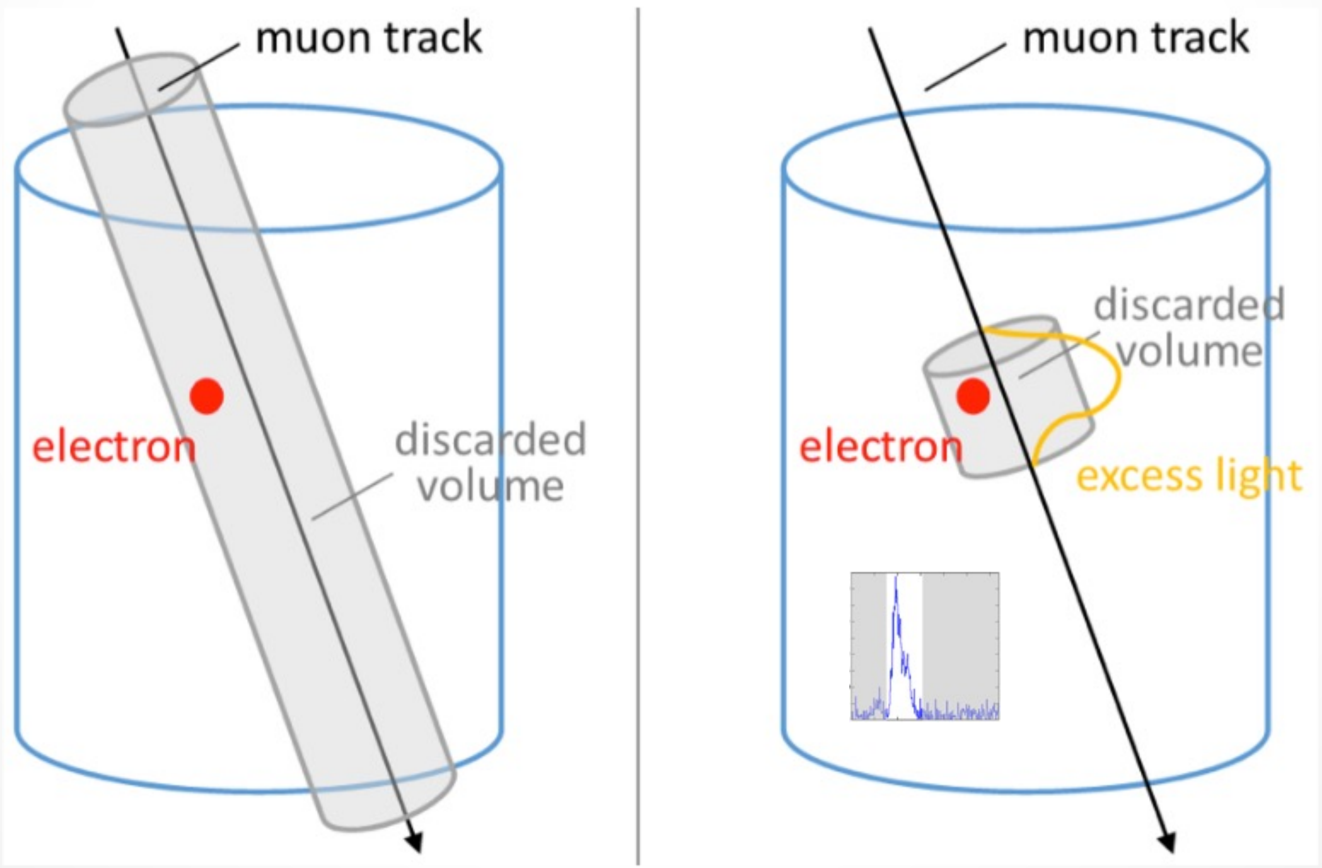
Reject spallation backgrounds

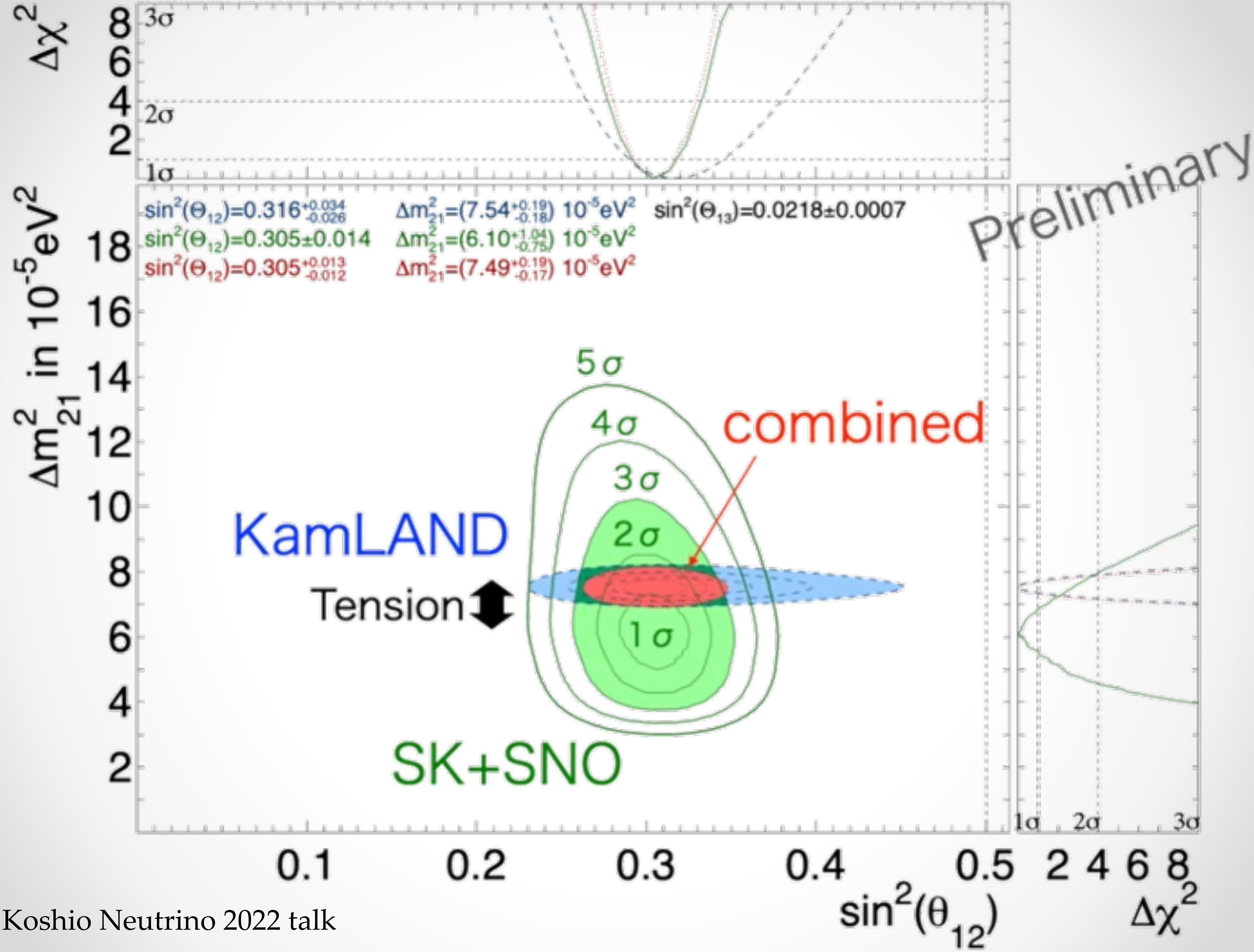




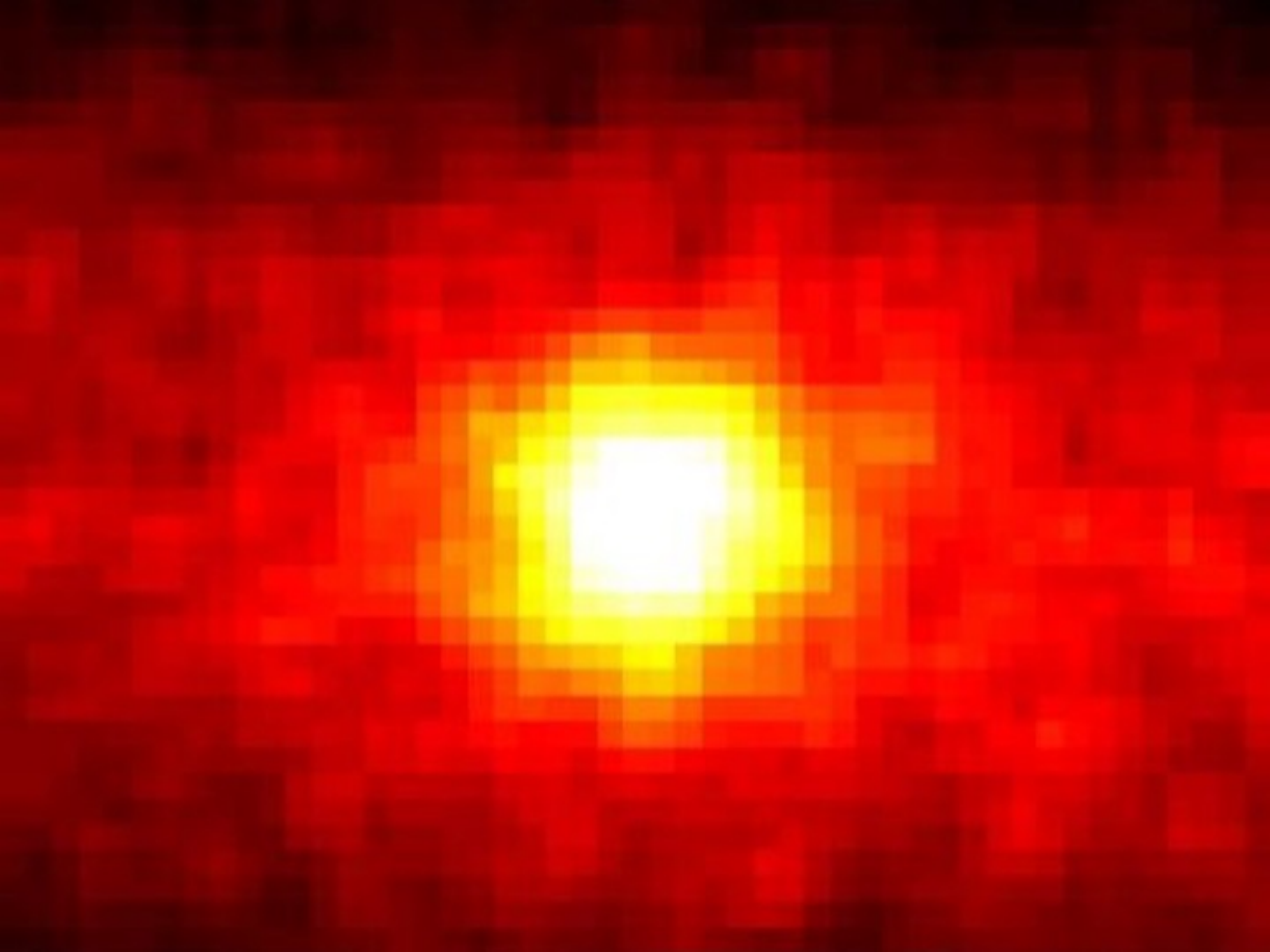
New background rejection

For each muon, small cut region → less signal loss
→ longer cut in time → fewer backgrounds





Koshio Neutrino 2022 talk



Questions?

Back up

Measured metallicities

Element	GS98	AGSS09met
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