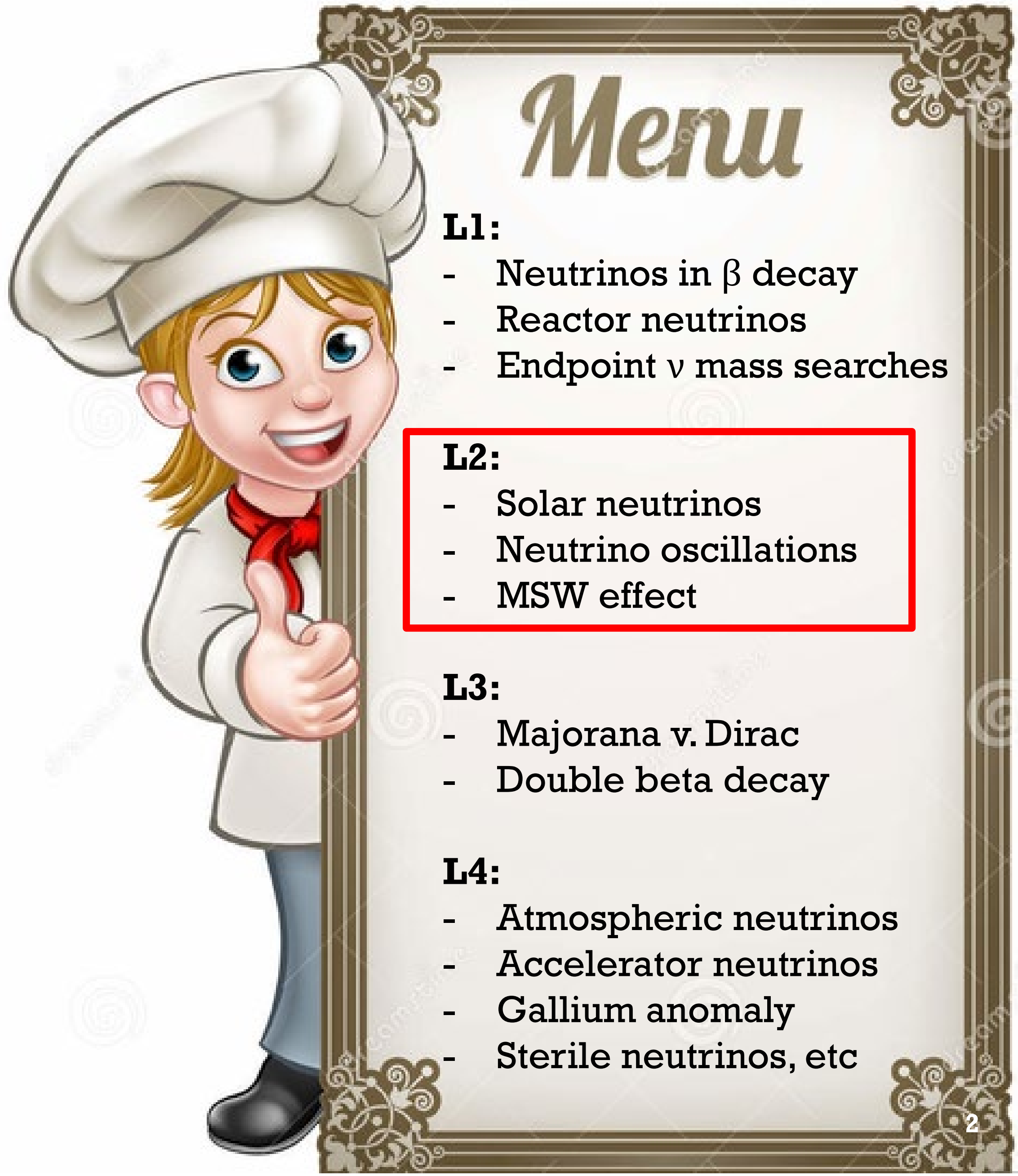
NEUTRINOS IN NUCLEAR PHYSICS

Ben Jones, University of Texas at Arlington

2

ON THE MENU



Menu
L1:
- Neutrinos in β decay
- Reactor neutrinos
- Endpoint ν mass searches
L2:
- Solar neutrinos
- Neutrino oscillations
- MSW effect
L3:
- Majorana v. Dirac
- Double beta decay
L4:
- Atmospheric neutrinos
- Accelerator neutrinos
- Gallium anomaly
- Sterile neutrinos, etc

More black-and-white photos of old dudes!

Pop quiz:

Who dis? →

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York

(Received September 7, 1938)

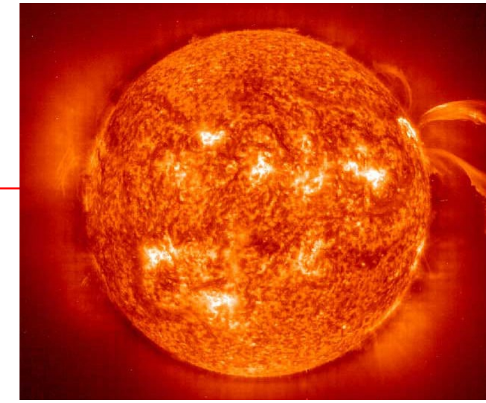


TABLE V. *Probability of nuclear reactions at $2\cdot10^7$ degrees.***

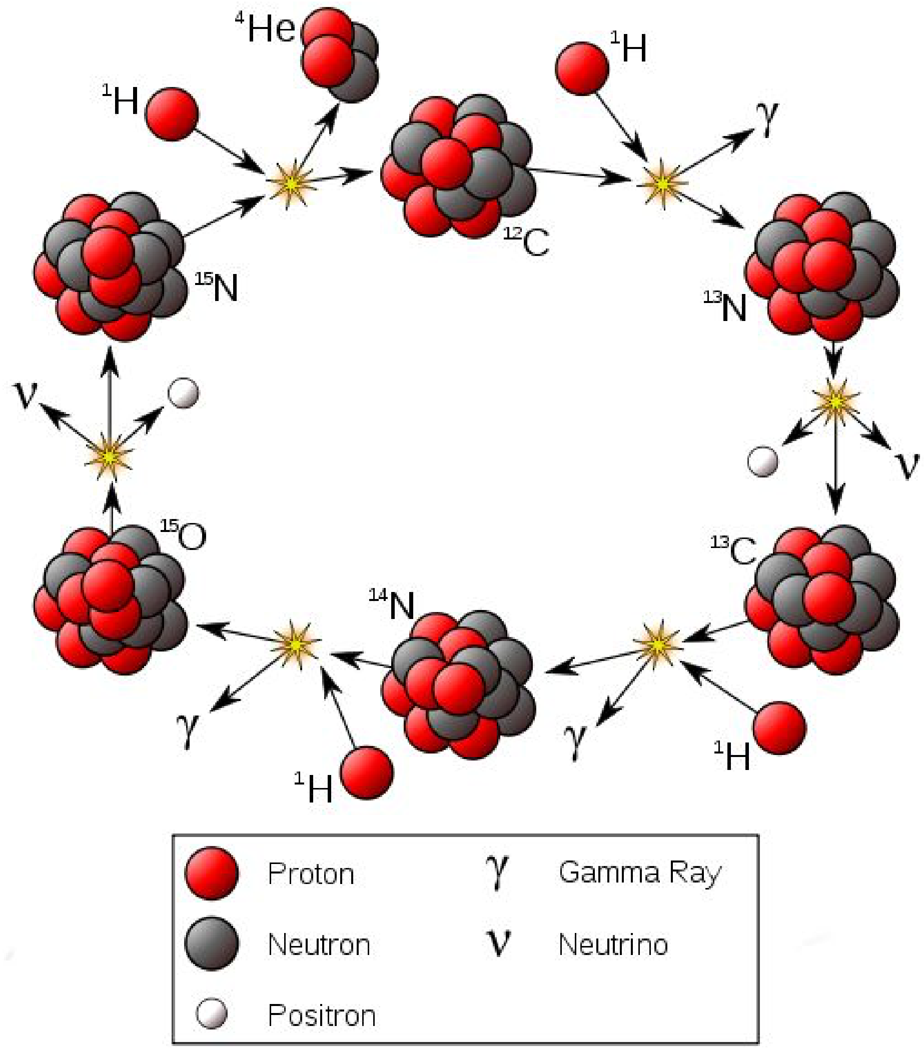
REACTION	Q (MMU)	Γ (EV)		P (SEC.$^{-1}$)	LIFE, FOR $\rho x_1=30$
$H+H=H^2+\epsilon^+$	1.53	Ref. 16	12.5	$8.5\cdot10^{-21}$	$1.2\cdot10^{11}$ yr.
$H^2+H=He^3$	5.9	1 E	13.8	$1.3\cdot10^{-2}$	2 sec.
$H^3+H=He^4$	21.3	10 E	14.3	$1.7\cdot10^{-1}$	0.2 sec.
$He^3+H=Li^{4*}$	(0.5)	0.02 D	22.7	$3\cdot10^{-7}$	1 day
$He^4+H=Li^{5*}$	(0.2)	0.005 D	23.2	$6\cdot10^{-8}$	6 days
$Li^6+H=He^4+He^3$	4.1	$5\cdot10^5$ X	31.1	$7\cdot10^{-3}$	5 sec.
$Li^7+H=2\,He^4$	18.6	$4\cdot10^4X$	31.3	$6\cdot10^{-4}$	1 min.
$Be^7+H=B^8?$	(0.5)	0.02 D	38.1	$6\cdot10^{-13}$	2000 yr.
$Be^9+H=Li^6+He^4$	2.4	10^6 X	38.1	$4\cdot10^{-5}$	15 min.
$B^9+H=C^{10*}$	3.5	2 D	44.6	$2\cdot10^{-13}$	5000 yr.
$B^{10}+H=C^{11}$	9.2	10 D	44.6	10^{-12}	1000 yr.
$B^{11}+H=3\,He^4$	9.4	10^6 E	44.6	$1.2\cdot10^{-7}$	3 days
$C^{11}+H=N^{12}$	(0.4)	0.02 D	50.6	10^{-17}	10^8 yr.
$C^{12}+H=N^{13}$	2.0	0.6 X	50.6	$4\cdot10^{-16}$	$2.5\cdot10^6$ yr.
$C^{13}+H=N^{14}$	8.2	30 X	50.6	$2\cdot10^{-14}$	$5\cdot10^4$ yr.
$N^{14}+H=O^{15}$	7.8	5 D	56.3	$2\cdot10^{-17}$	$5\cdot10^7$ yr.
$N^{15}+H=C^{12}+He^4$	5.2	10^5 E	56.3	$5\cdot10^{-13}$	2000 yr.
$O^{16}+H=F^{17}$	0.5	0.02 D	61.6	$8\cdot10^{-22}$	10^{12} yr.
$F^{19}+H=O^{16}+He^4$	8.8	10^5 E	66.9	$4\cdot10^{-17}$	$3\cdot10^7$ yr.
$Ne^{22}+H=Na^{23}$	10.7	10 D	71.7	$5\cdot10^{-23}$	$2\cdot10^{13}$ yr.
$Mg^{26}+H=Al^{27}$	8.0	10 D	81.3	10^{-26}	10^{17} yr.
$Si^{30}+H=P^{31}$	7.0	10 D	90.4	$4\cdot10^{-30}$	$3\cdot10^{20}$ yr.
$Cl^{37}+H=A^{38}$	12.0	10 D	103.1	$5\cdot10^{-35}$	$2\cdot10^{25}$ yr.
$H^2+H^2=He^3+n$	3.5	$3\cdot10^5$ X	15.7	10^3	
$Be^7+H^2=B^{9*}$	18.5	10 D'	45.9	$2\cdot10^{-13}$	
$Be^7+H^3=B^9+n^*$	11.9	10^6 E	50.7	$2\cdot10^{-10}$	
$Be^7+He^3=C^{10}$	16.2	1 D'	80.5	$3\cdot10^{-28}$	
$H^2+He^4=Li^6$	1.7	$4\cdot10^{-3}$ Q	27.5	$3\cdot10^{-10}$	
$He^3+He^4=Be^7$	1.6	0.02 D'	47.3	$3\cdot10^{-17}$	$3\cdot10^7$ yr.
$He^4+He^4=Be^{8*}$	(0.05)	$5\cdot10^{-9}$ Q	50.0	10^{-24}	
$Li^7+He^4=B^{11}$	9.1	1 D'	71.0	$2.5\cdot10^{-24}$	
$Be^7+He^4=C^{11}$	8.0	1 D'	86	$3\cdot10^{-30}$	$3\cdot10^{20}$ yr.
$C^{12}+He^4=O^{16}$	7.8	1 Q'	119	$7\cdot10^{-43}$	

Hans Bethe
Nobel prize 1967

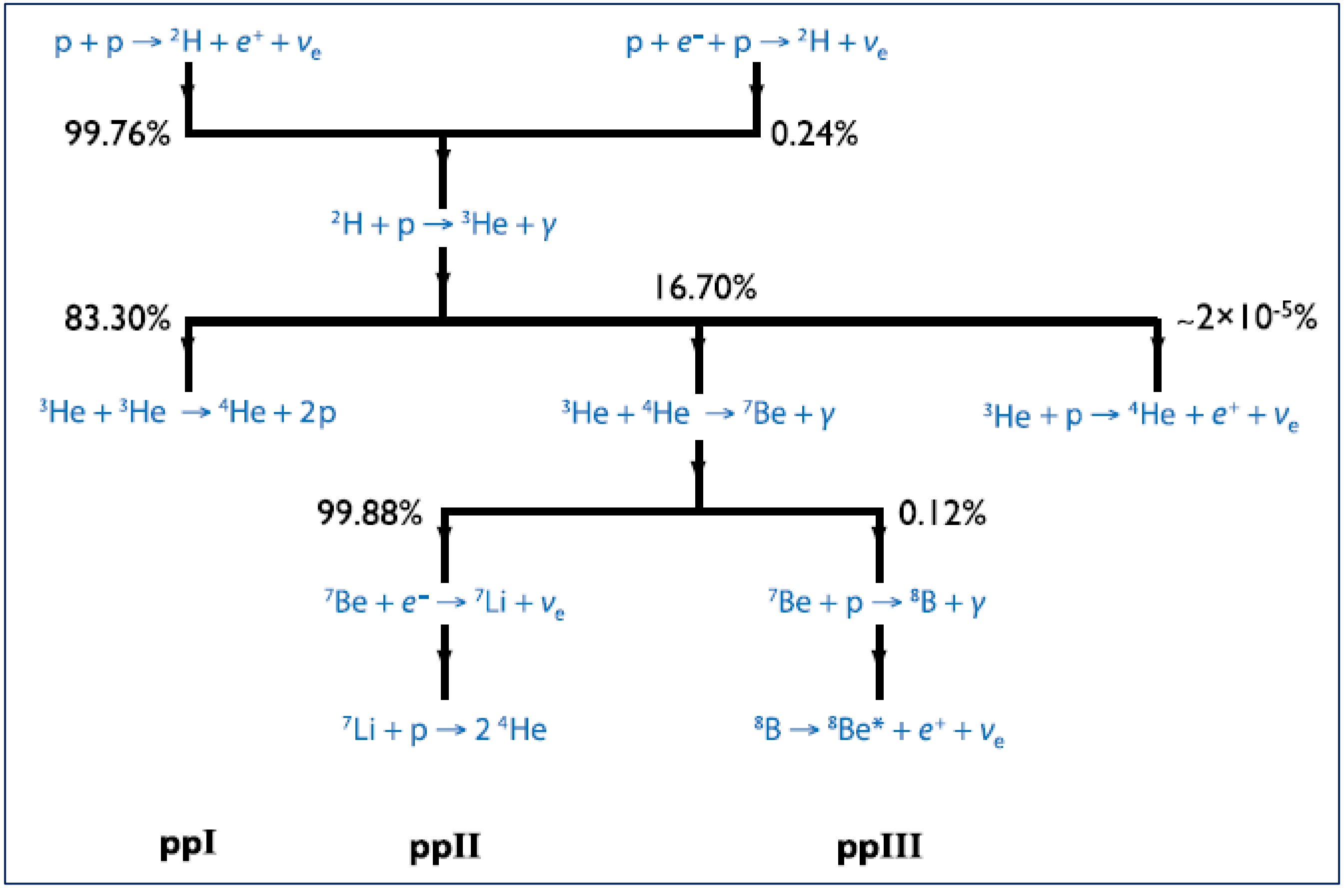
CNO CYCLE

- Most of the mass of the sun is H, and a little He.
- It seemed it was producing heat through H→ He fusion, but how?
- Bethe exhaustively surveyed all known nuclear reactions and proposed a cycle whereby hydrogen is burned to helium via C,N,O isotopes as catalysts.
- It clearly emits several neutrinos on the way around too

→ the Sun should be a source of neutrinos

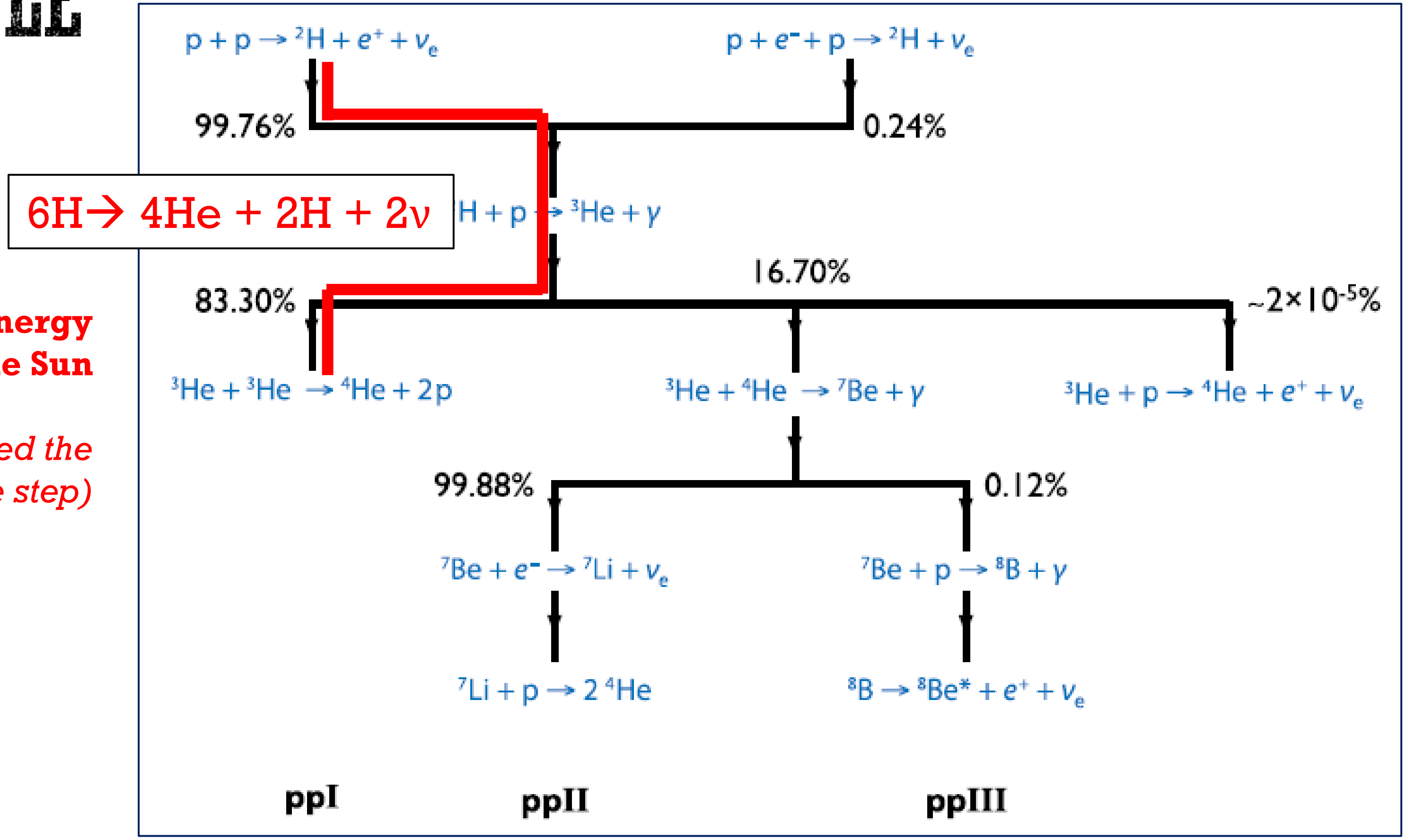


PP CYCLE



- Stars heavier than the Sun to burn through the CNO cycle.
- But the sun actually generates most of its energy through another process, the pp-cycle.
- This one also spits out multiple neutrinos on the way down.

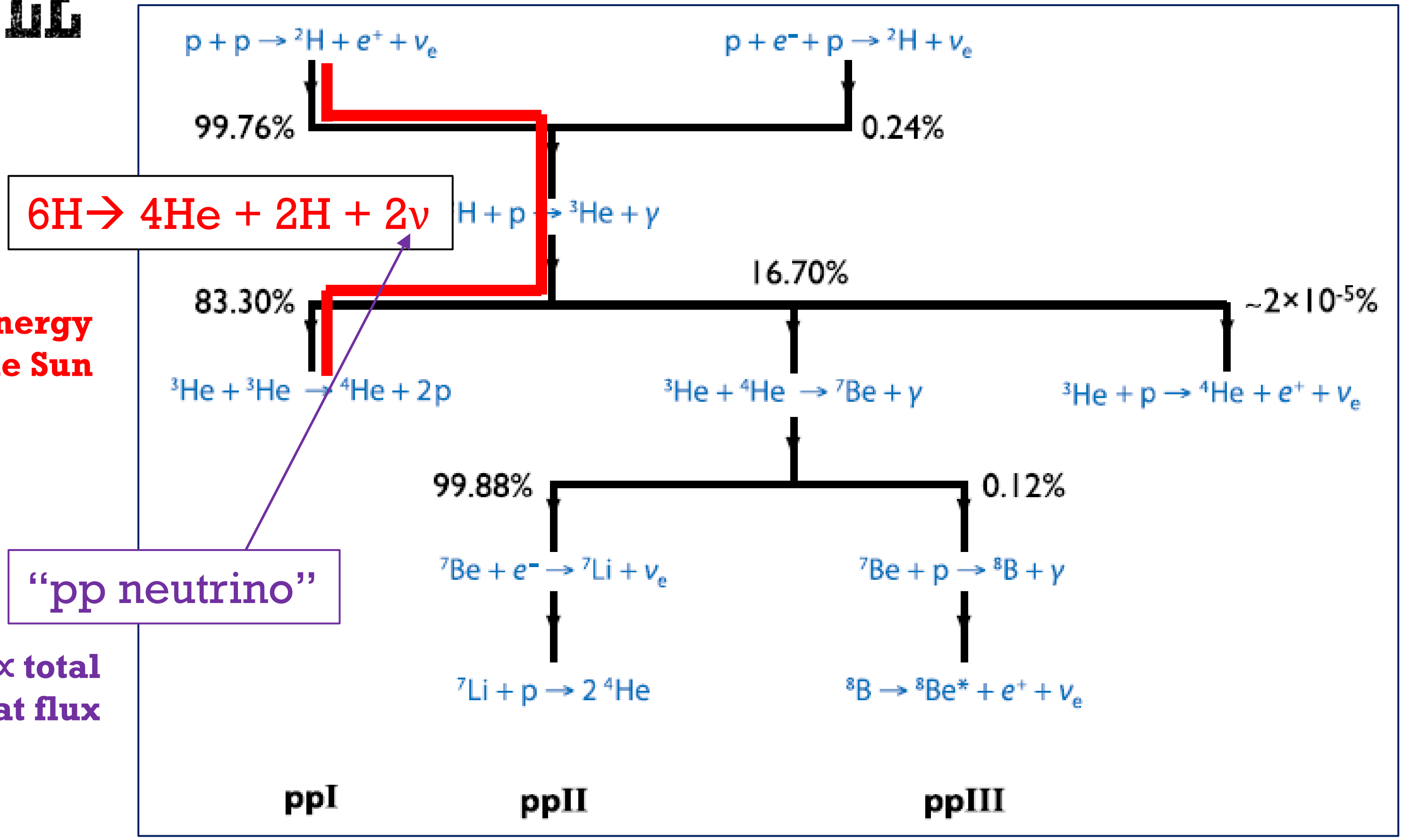
PP CYCLE



= most of the energy production in the Sun

(Bethe missed the $^3He + {}^3He$ step)

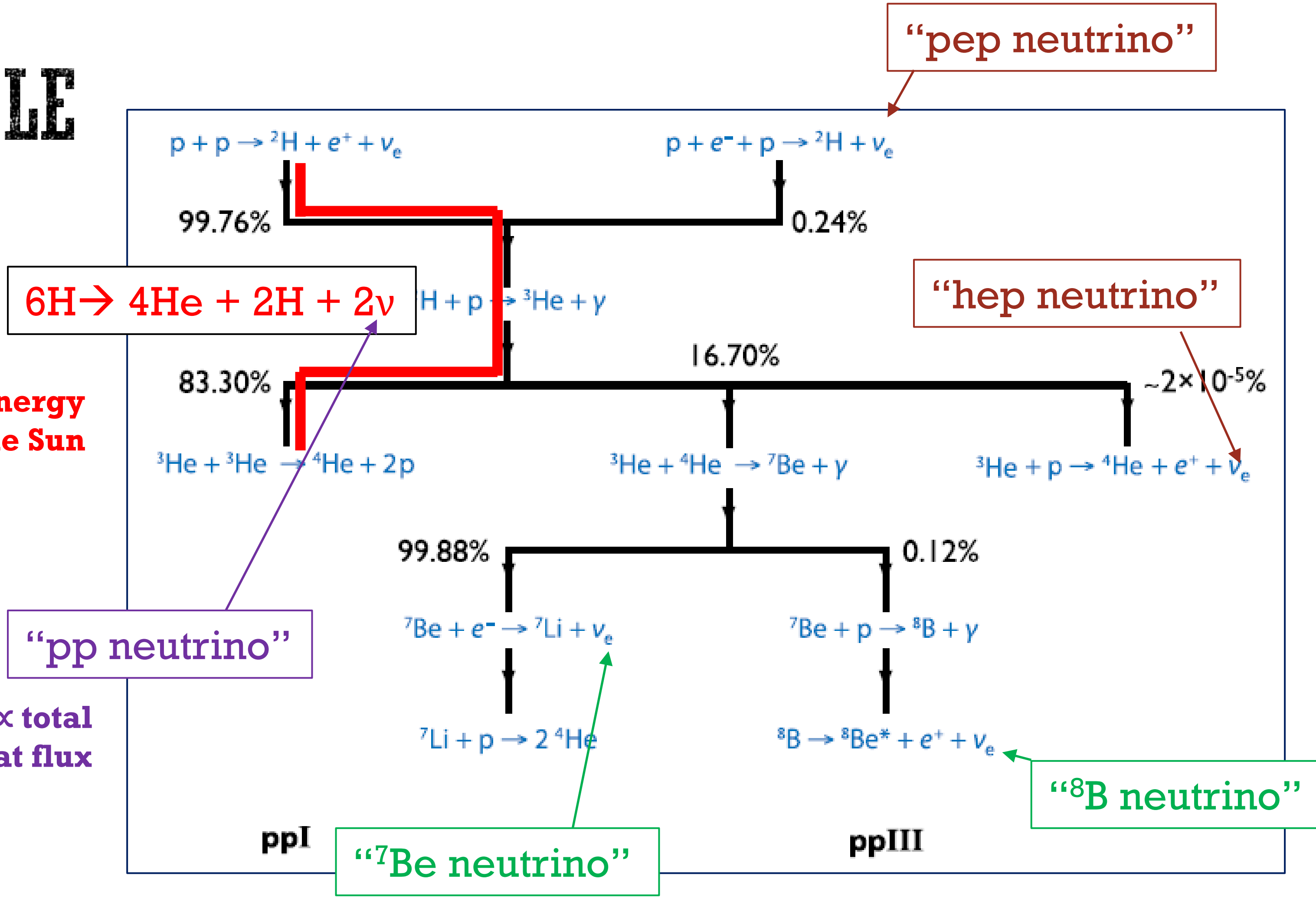
PP CYCLE



= most of the energy production in the Sun

flux basically ∝ total solar heat flux

PP CYCLE



= most of the energy production in the Sun

flux basically ∝ total solar heat flux

Depend on rates of several serial fusions, which each depend on solar temperature.

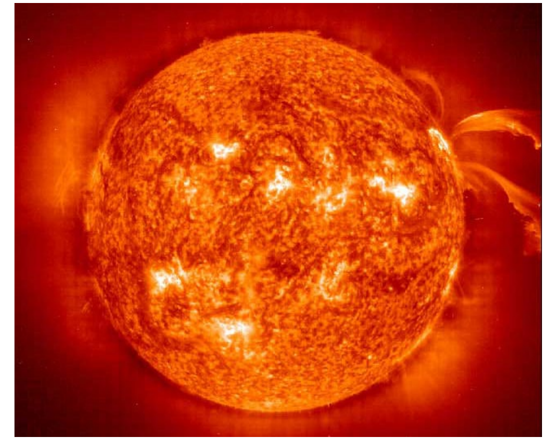
10,000 STANDARD SOLAR MODELS: A MONTE CARLO SIMULATION

John N. Bahcall[1]
Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540

Aldo M. Serenelli
Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540; and Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, 85748 Garching, Germany

and

Sarbani Basu
Department of Astronomy, Yale University, New Haven, CT 06520-8101
Received 2005 November 18; accepted 2006 March 7



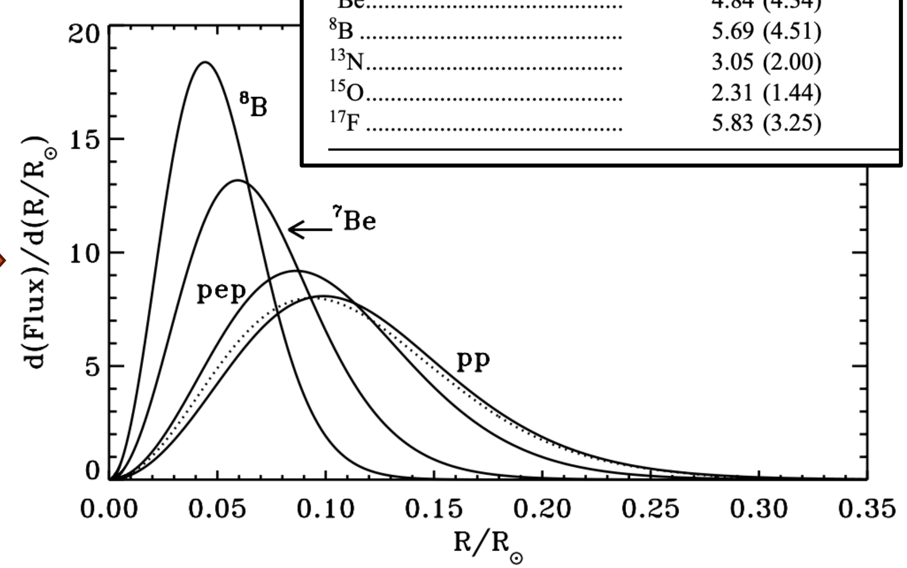
John Bahcall and collaborators published a series of important papers using the hydrodynamic, seismological and nuclear properties of the Sun to predict the solar neutrino flux.

Neutrino Source (1)	Neutrino Flux (2)
p-p	5.99 (6.06)
pep	1.42 (1.45)
hep	7.93 (8.25)
^{7}Be	4.84 (4.34)
^{8}B	5.69 (4.51)
^{13}N	3.05 (2.00)
^{15}O	2.31 (1.44)
^{17}F	5.83 (3.25)

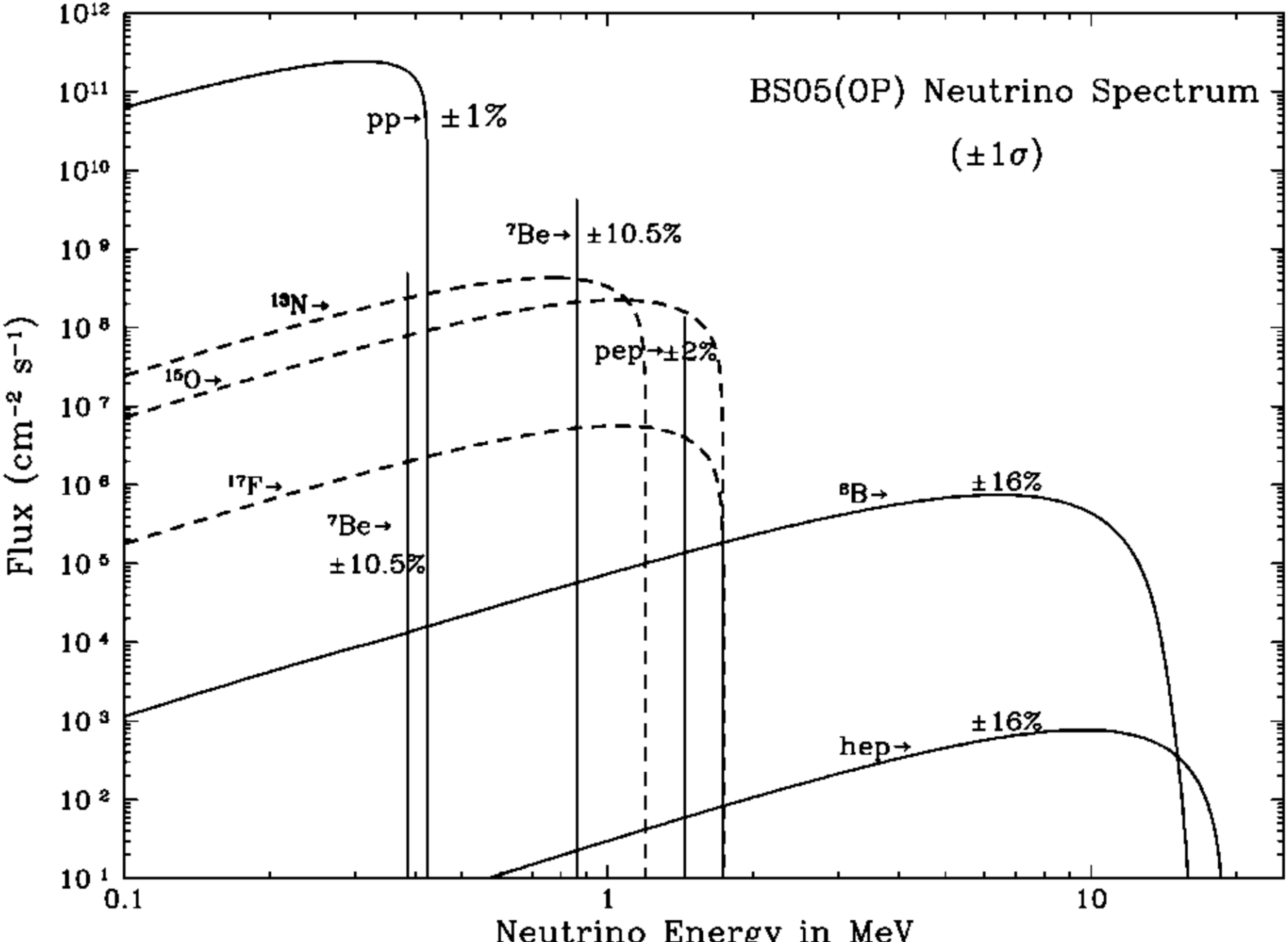
TABLE 1

Best Estimates and 1 σ Uncertainties for 10 Important Input Parameters for Solar Models

Quantity (1)	Best Estimate (2)	1 σ Uncertainty (%) (3)	Reference (4)
p-p	3.94×10^{-25} MeV b	0.4	1
^{3}He+^{3}He.............	5.4 MeV b	6.0	2, 3
^{3}He+^{4}He.............	0.53 keV b	9.4	3, 4
^{7}Be + e^-.............	Eq. (26), ref. 3	2	3, 5
^{7}Be+p.................	20.6 eV b	3.8	6
hep	8.6×10^{-20} keV b	15.1	1
^{14}N+p	1.69 keV b	8.4	7, 8
age	4.57×10^9 yr	0.44	9
diffusion	1.0	15.0	10
luminosity...........	3.8418×10^{33} ergs s^{-1}	0.4	11, 12



Predicted neutrino spectrum of the Sun:



They also have uncertainties! Cool!

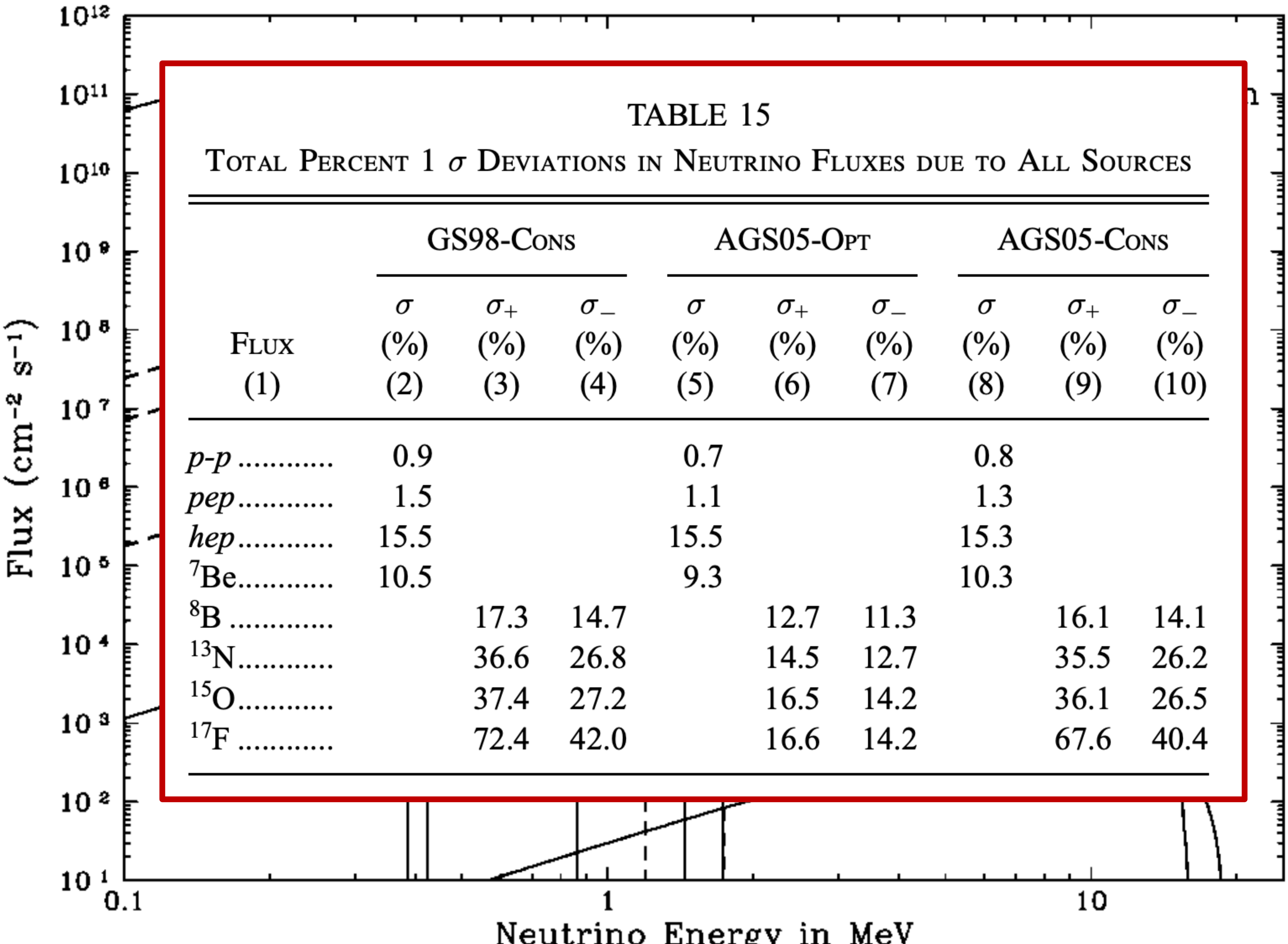


TABLE 15

TOTAL PERCENT 1 σ DEVIATIONS IN NEUTRINO FLUXES DUE TO ALL SOURCES

	GS98-CONS			AGS05-OPT			AGS05-CONS		
FLUX (1)	σ (%) (2)	σ_+ (%) (3)	σ_- (%) (4)	σ (%) (5)	σ_+ (%) (6)	σ_- (%) (7)	σ (%) (8)	σ_+ (%) (9)	σ_- (%) (10)
p-p	0.9			0.7			0.8		
pep	1.5			1.1			1.3		
hep	15.5			15.5			15.3		
^{7}Be............	10.5			9.3			10.3		
^{8}B		17.3	14.7		12.7	11.3		16.1	14.1
^{13}N............		36.6	26.8		14.5	12.7		35.5	26.2
^{15}O............		37.4	27.2		16.5	14.2		36.1	26.5
^{17}F		72.4	42.0		16.6	14.2		67.6	40.4

High up the pp chain the uncertainties are pretty small…

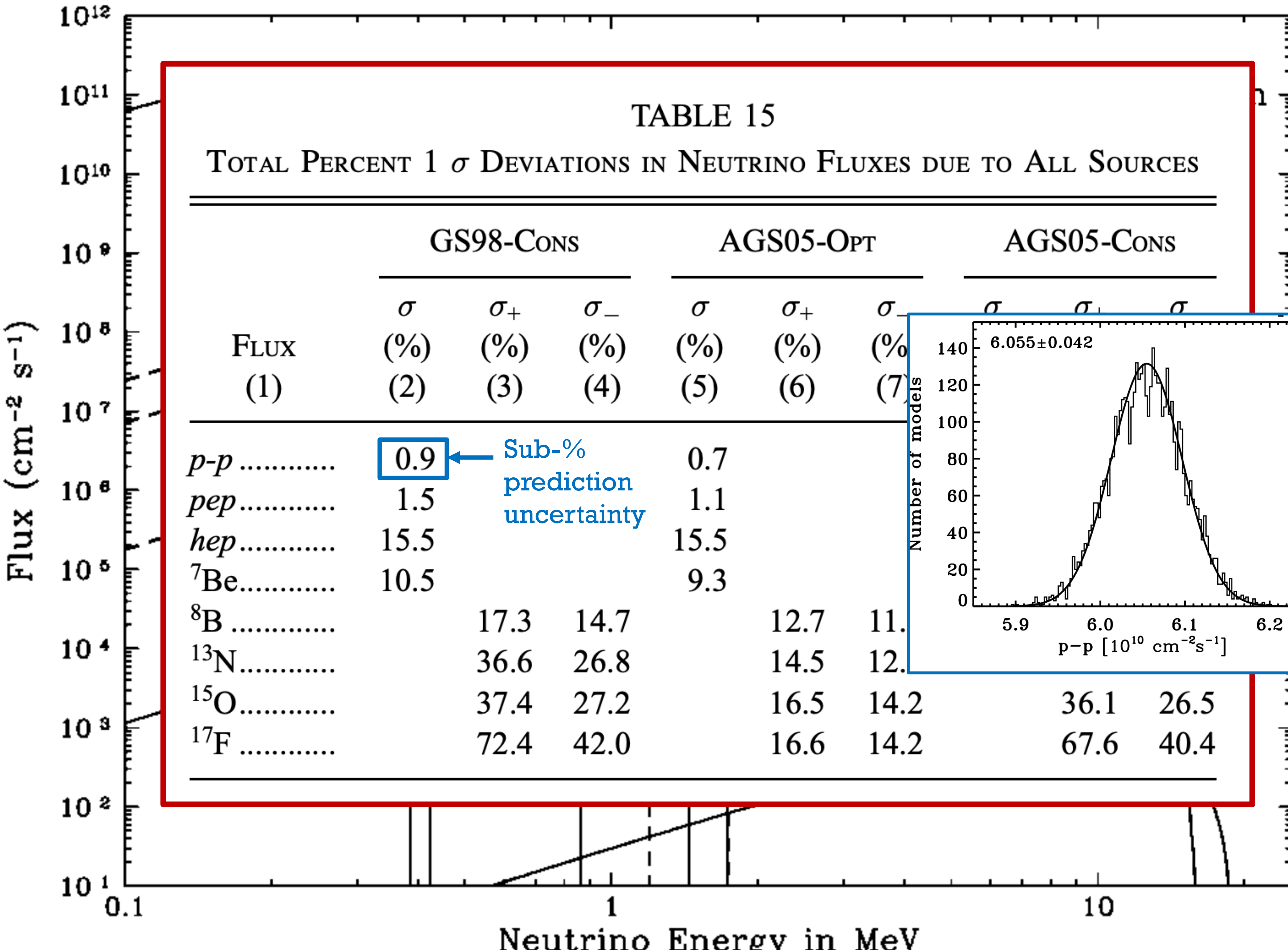


TABLE 15

TOTAL PERCENT 1 σ DEVIATIONS IN NEUTRINO FLUXES DUE TO ALL SOURCES

	GS98-CONS			AGS05-OPT			AGS05-CONS		
FLUX (1)	σ (%) (2)	σ_+ (%) (3)	σ_- (%) (4)	σ (%) (5)	σ_+ (%) (6)	σ_- (% (7)	σ	σ_+	σ
p-p …………	0.9			0.7					
pep …………	1.5			1.1					
hep …………	15.5			15.5					
^{7}Be…………	10.5			9.3					
^{8}B …………		17.3	14.7		12.7	11.			
^{13}N…………		36.6	26.8		14.5	12.			
^{15}O…………		37.4	27.2		16.5	14.2		36.1	26.5
^{17}F …………		72.4	42.0		16.6	14.2		67.6	40.4

Sub-% prediction uncertainty

Admittedly, it gets harder, further down the chain…

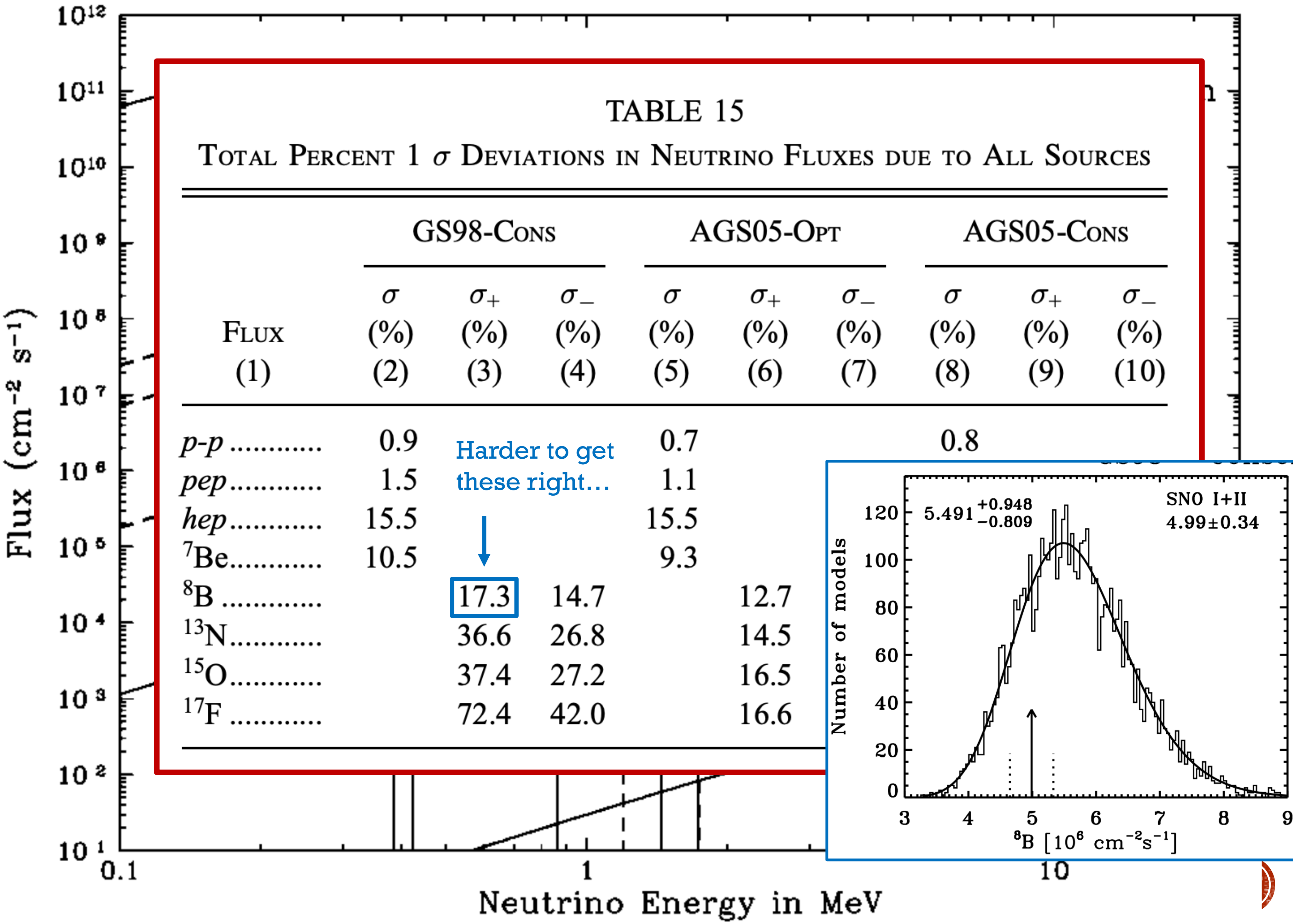


TABLE 15

Total Percent 1 σ Deviations in Neutrino Fluxes due to All Sources

Flux (1)	GS98-Cons σ (%) (2)	GS98-Cons σ_+ (%) (3)	GS98-Cons σ_- (%) (4)	AGS05-Opt σ (%) (5)	AGS05-Opt σ_+ (%) (6)	AGS05-Opt σ_- (%) (7)	AGS05-Cons σ (%) (8)	AGS05-Cons σ_+ (%) (9)	AGS05-Cons σ_- (%) (10)
p-p	0.9			0.7			0.8		
pep	1.5			1.1					
hep	15.5			15.5					
^{7}Be	10.5			9.3					
^{8}B		17.3	14.7		12.7				
^{13}N		36.6	26.8		14.5				
^{15}O		37.4	27.2		16.5				
^{17}F		72.4	42.0		16.6				

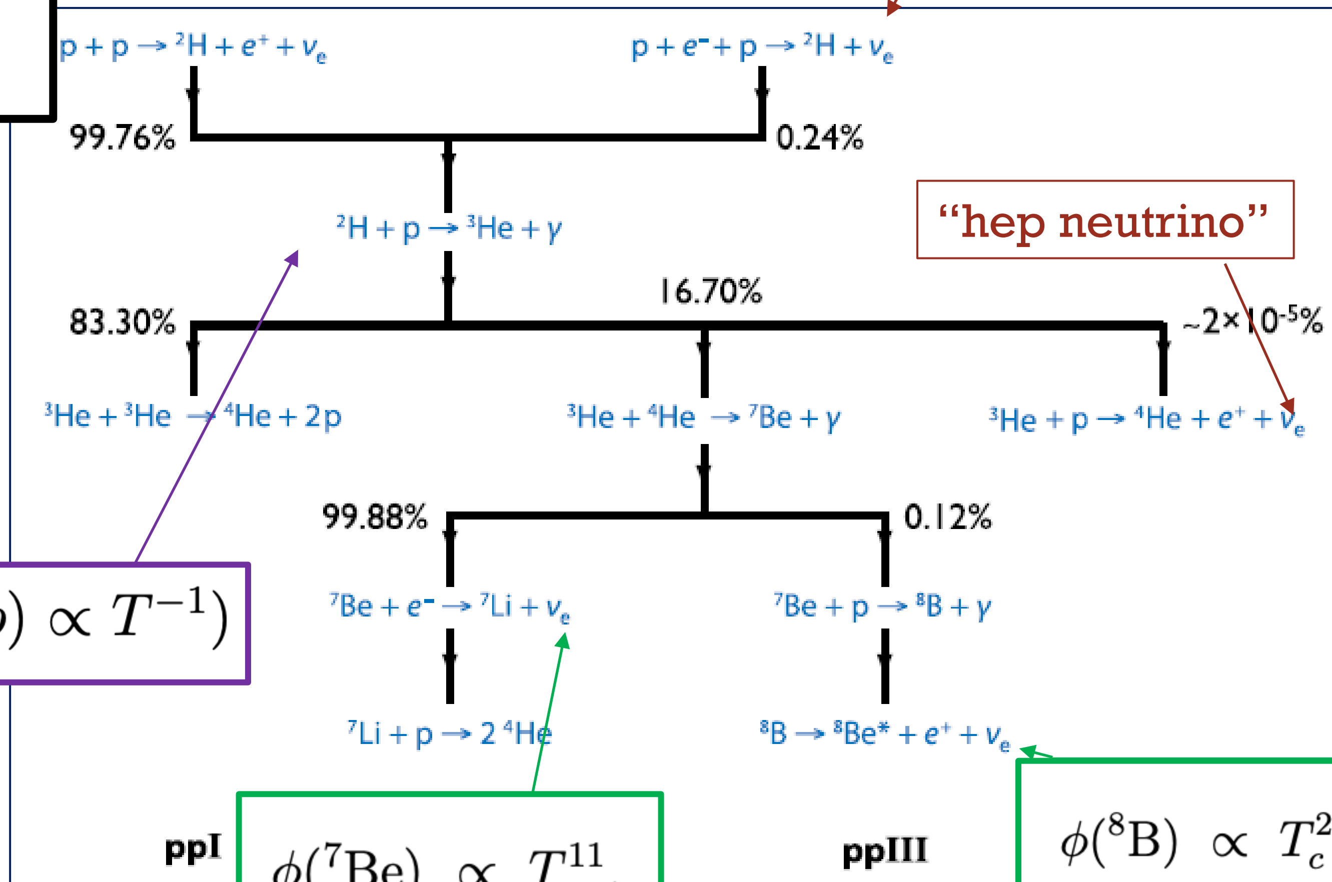
Harder to get these right…

The Temperature Dependence of Solar Neutrino Fluxes

John N. Bahcall
Institute for Advanced Study, Princeton, New Jersey 08540

Andrew Ulmer
Princeton University Observatory, Princeton, New Jersey 08544

$$\phi(pep) \ \propto \ T_c^{-1/2}(T_c^m) = T_c^{-1.4}.$$



"hep neutrino"

$$(\phi(pp) \ \propto T^{-1})$$

flux basically ∝ total solar heat flux

$$\phi(^7\mathrm{Be}) \ \propto \ T_c^{11},$$

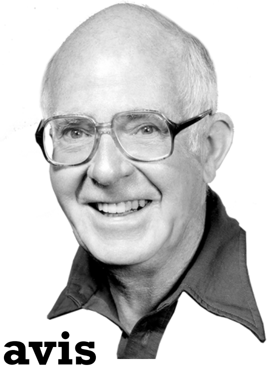
$$\phi(^8\mathrm{B}) \ \propto \ T_c^{25}.$$

Difficulty partly connected with steeper difficult scaling with solar core temperature.

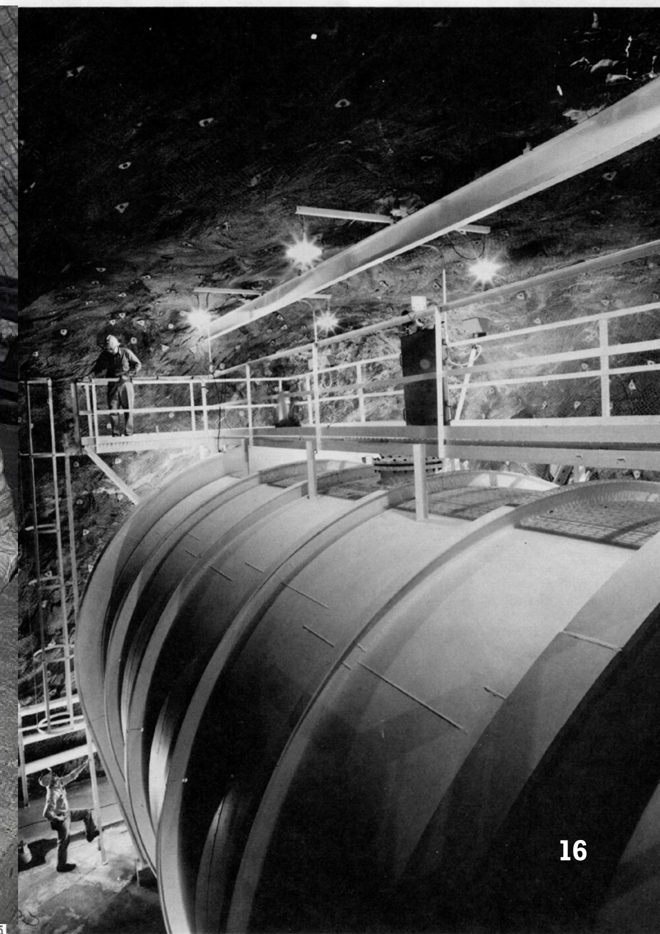
Ray Davis has re-entered the chat

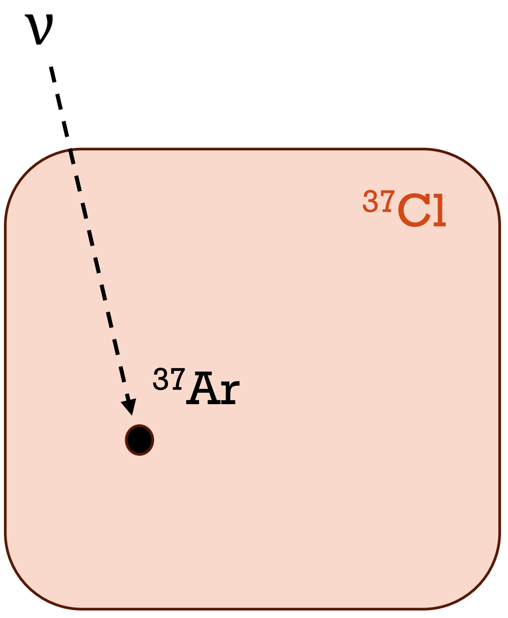
Unlike reactors, the Sun actually **does** make neutrinos!

The Homestake Chlorine Detector should be able to see them at a rate of 1-2 per day.

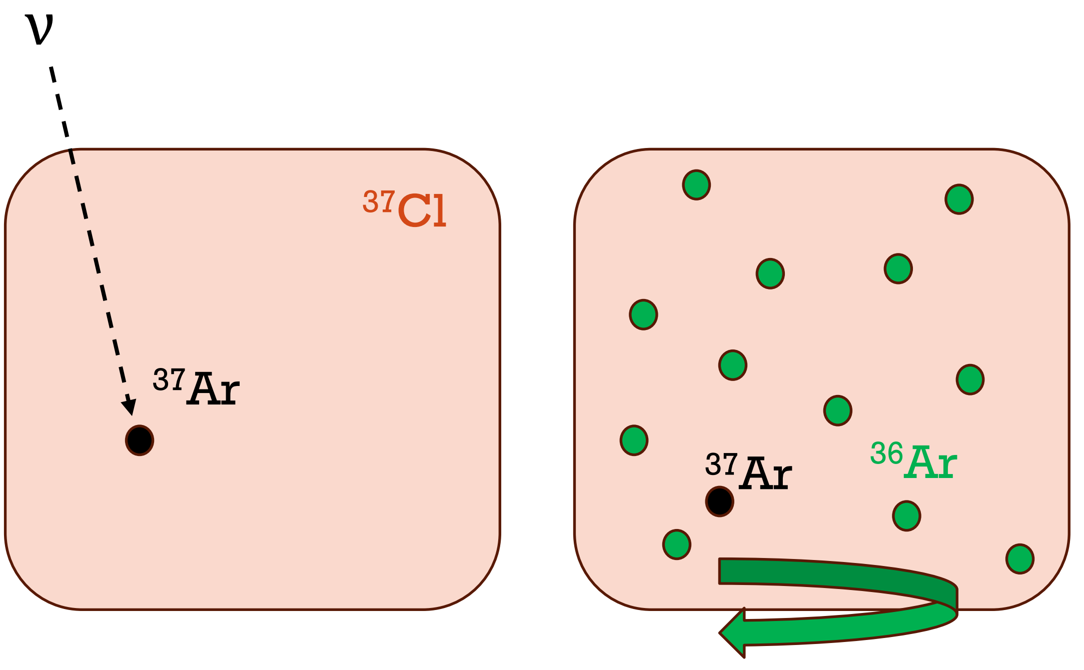


Ray Davis

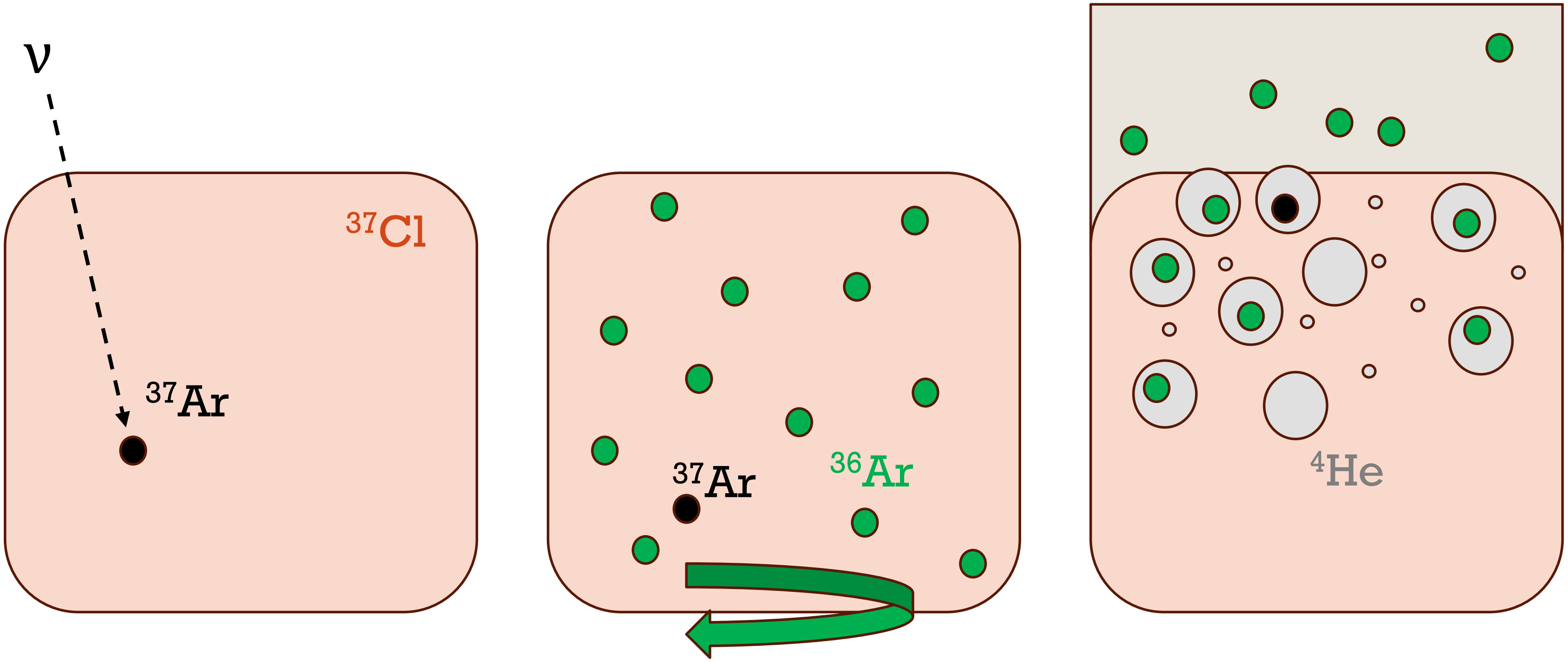




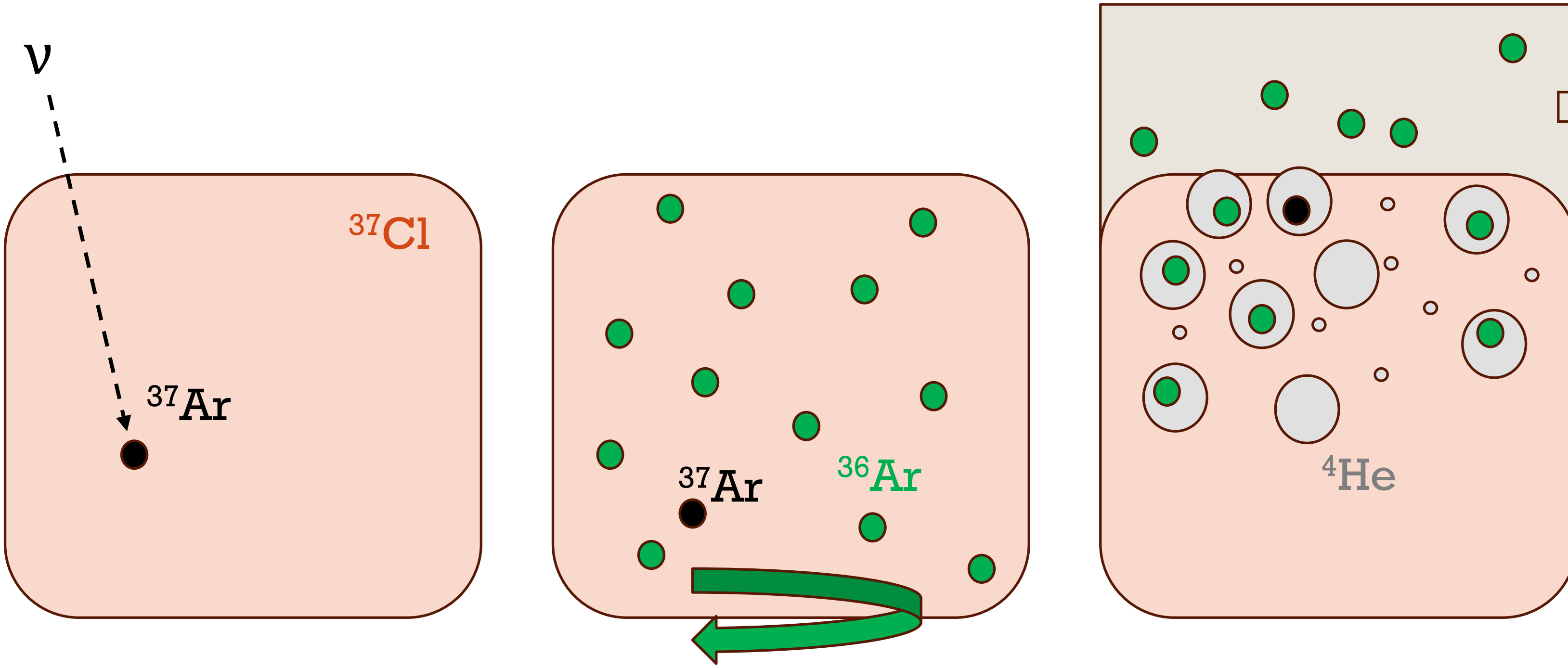
1. Neutrino captures on ^{37}Cl to make ^{37}Ar



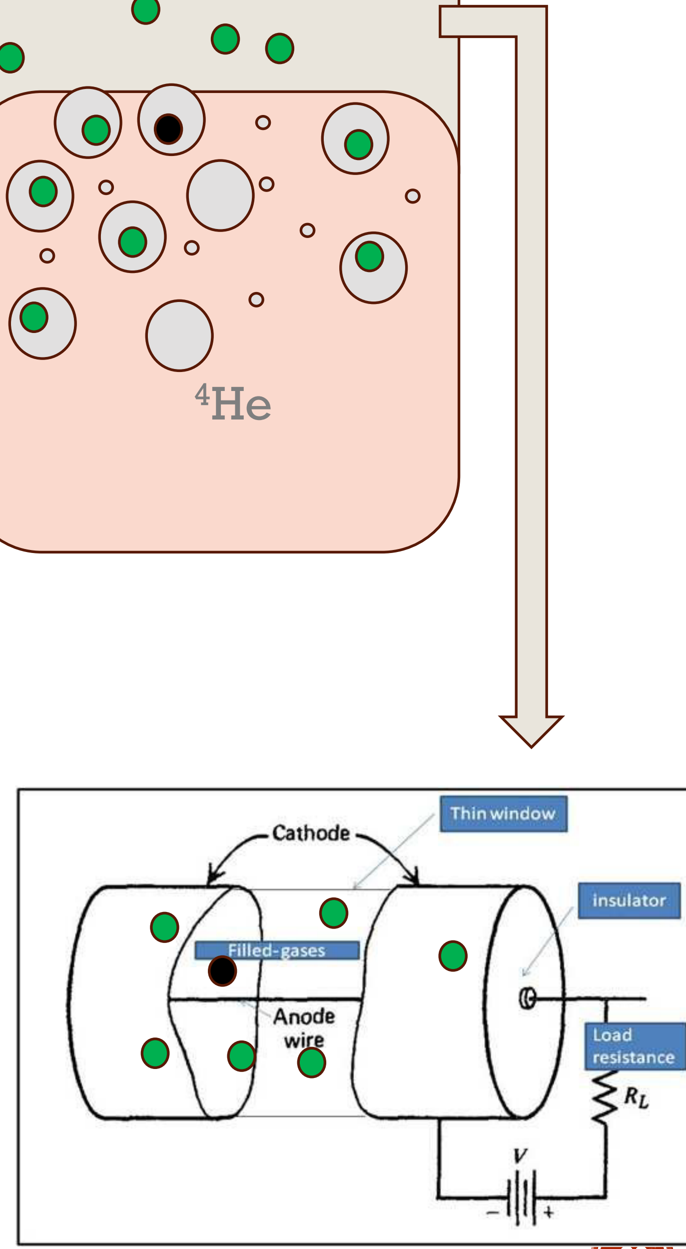
2. Stir in well known quantity of stable ^{36}Ar to act as carrier

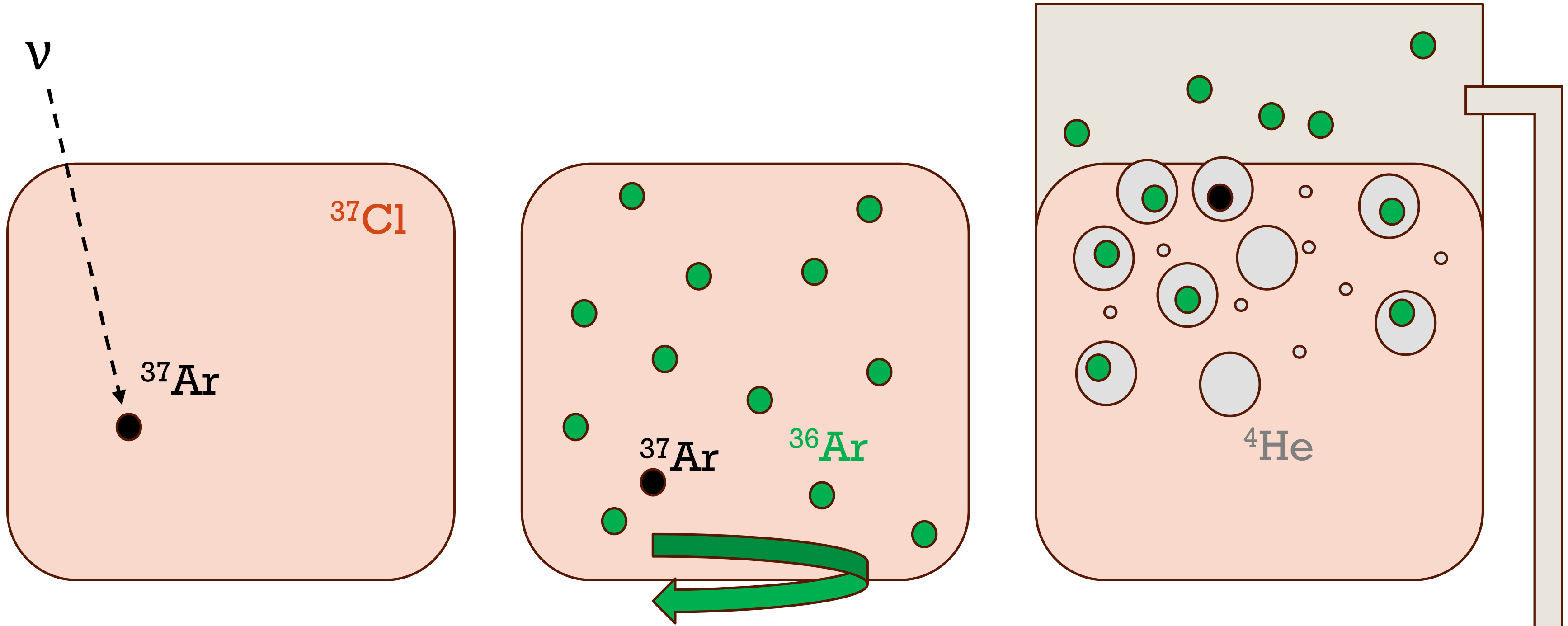


3. Bubble He gas through to extract all the argon
(37Ar and 36Ar are chemically identical)

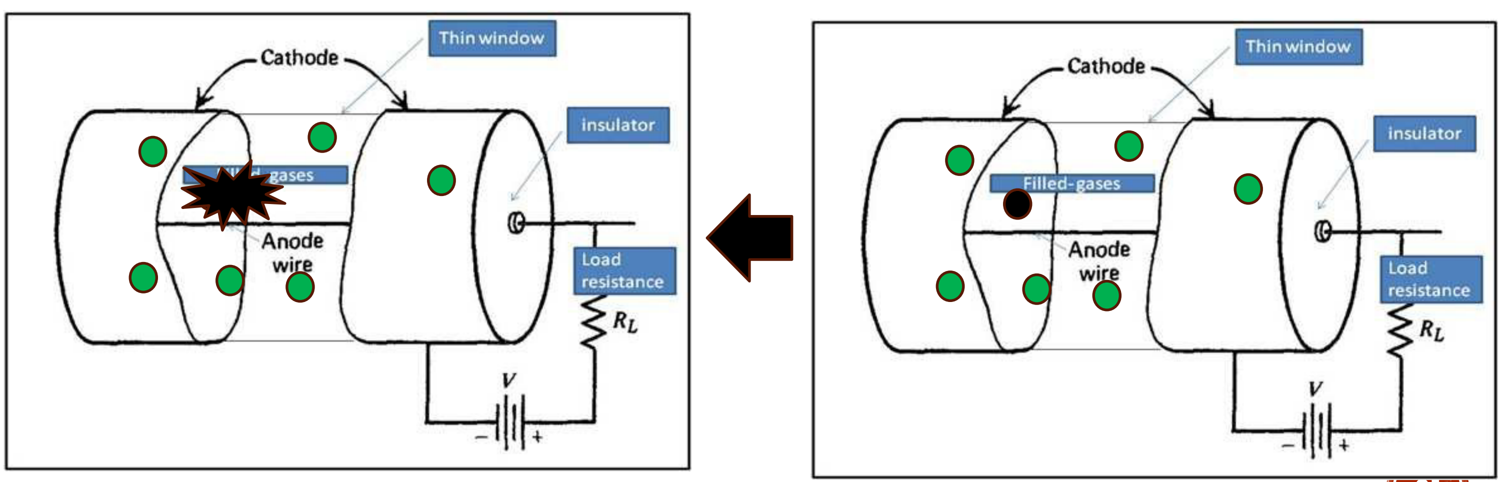


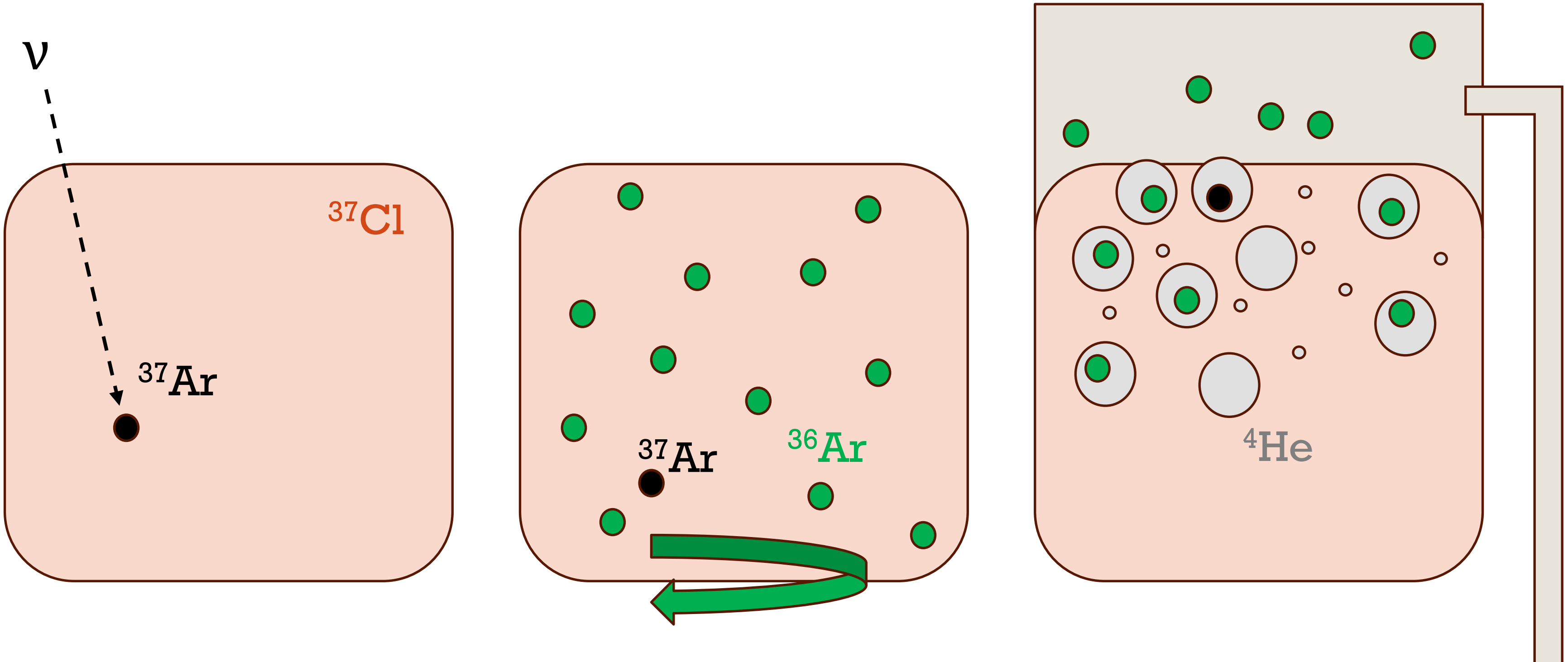
4. Add the gas to a proportional counter



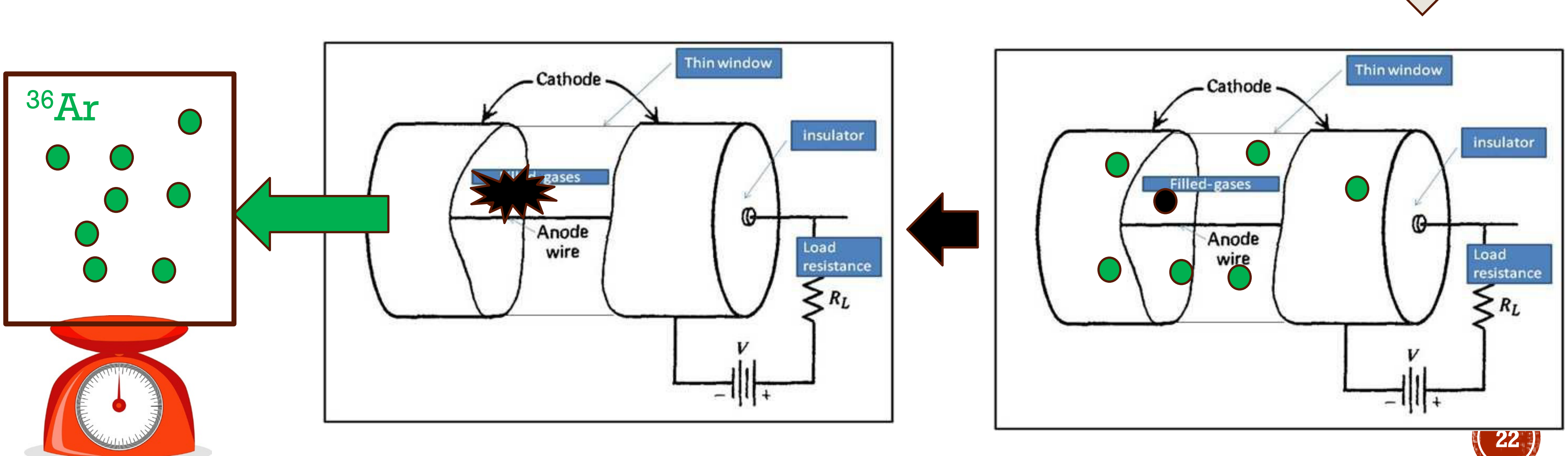


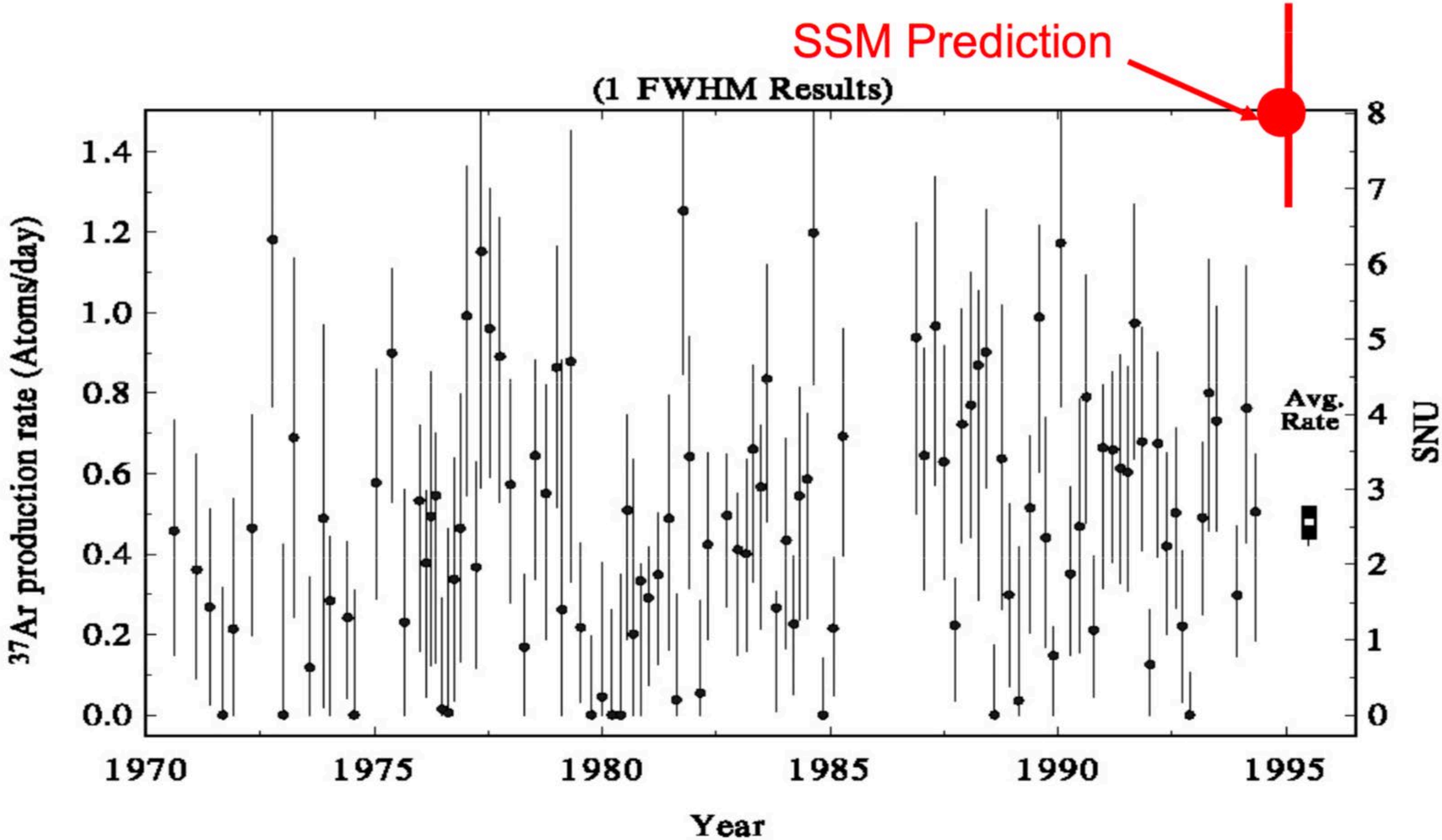
5. Wait and count 37Ar electron capture decays (35d half-life)





5. Check amount of ^{36}Ar matches amount put in to check efficiency



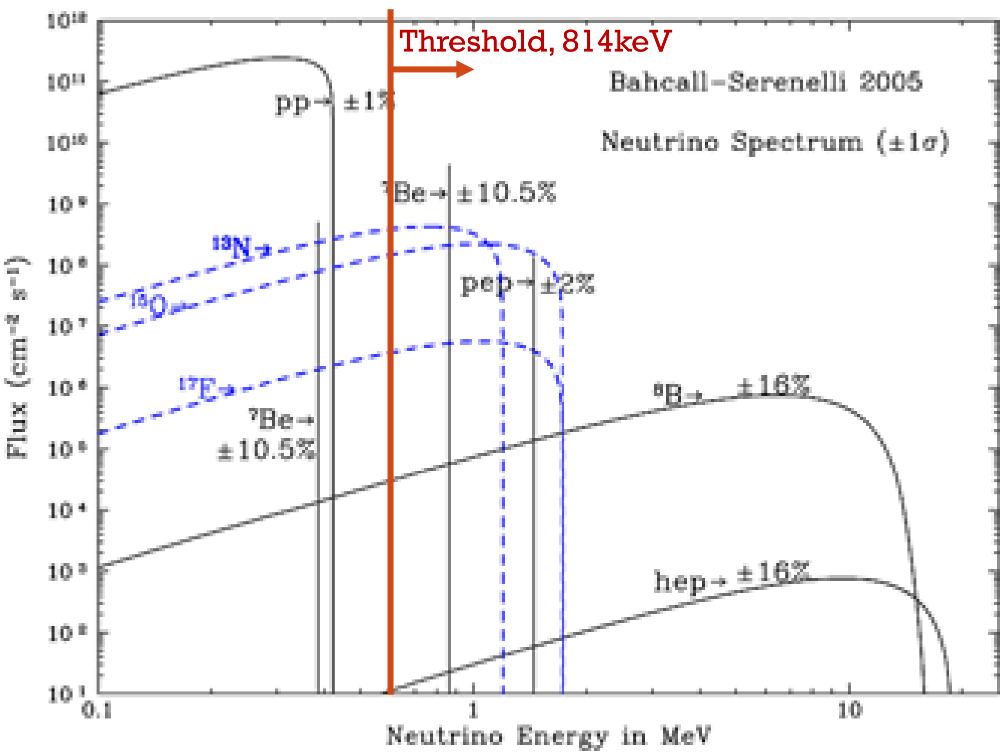


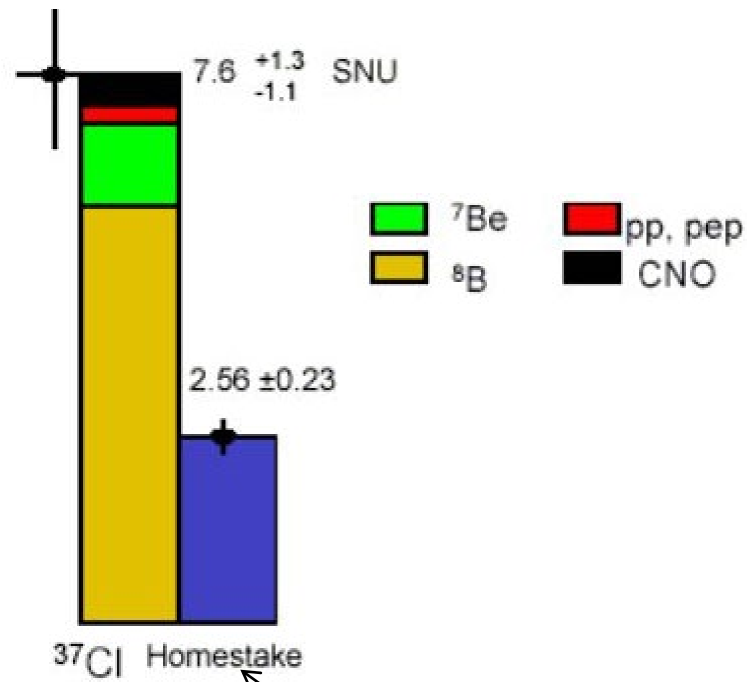
Davis detects solar neutrinos, but only 1/3 as many as standard solar model predicts

Davis experiment ran for 20+ years.

- A huge experiment / theory discrepancy observed.

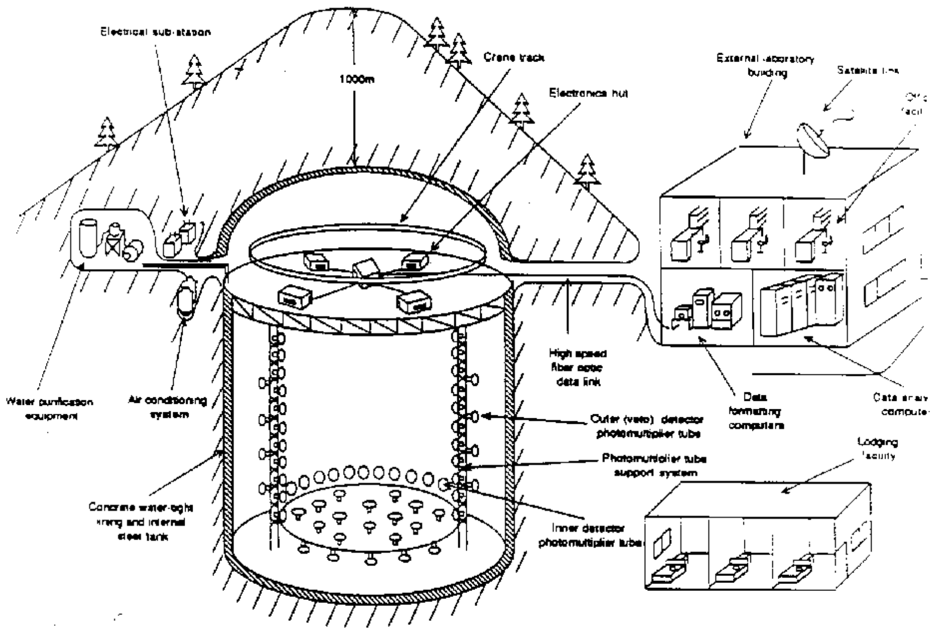
1SNU = 1e-36 captures per target atom per second

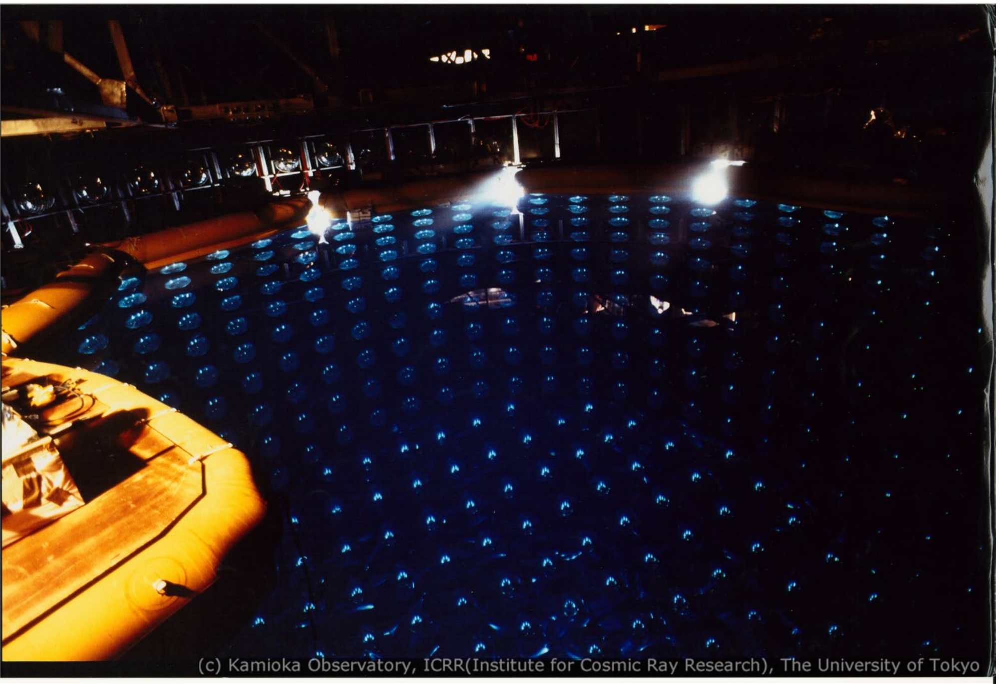


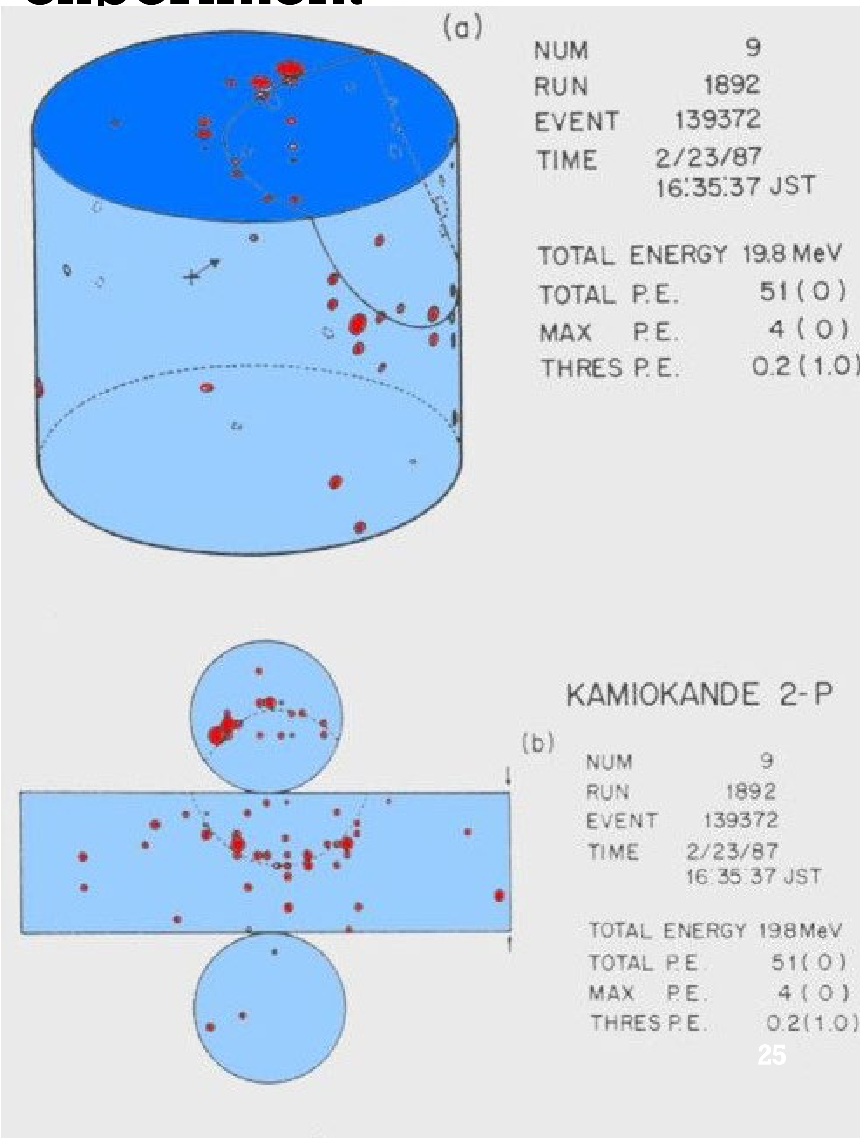


Kamiokande-II experiment –

2140 ton water Cerenkov experiment



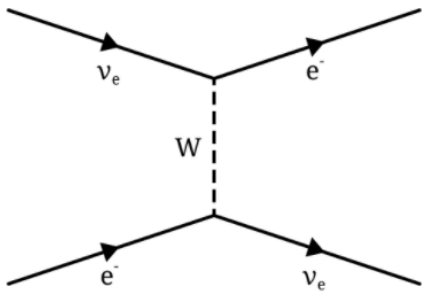




NEUTRINO ELECTRON SCATTERING

A key advantage of the Kamiokande signature:

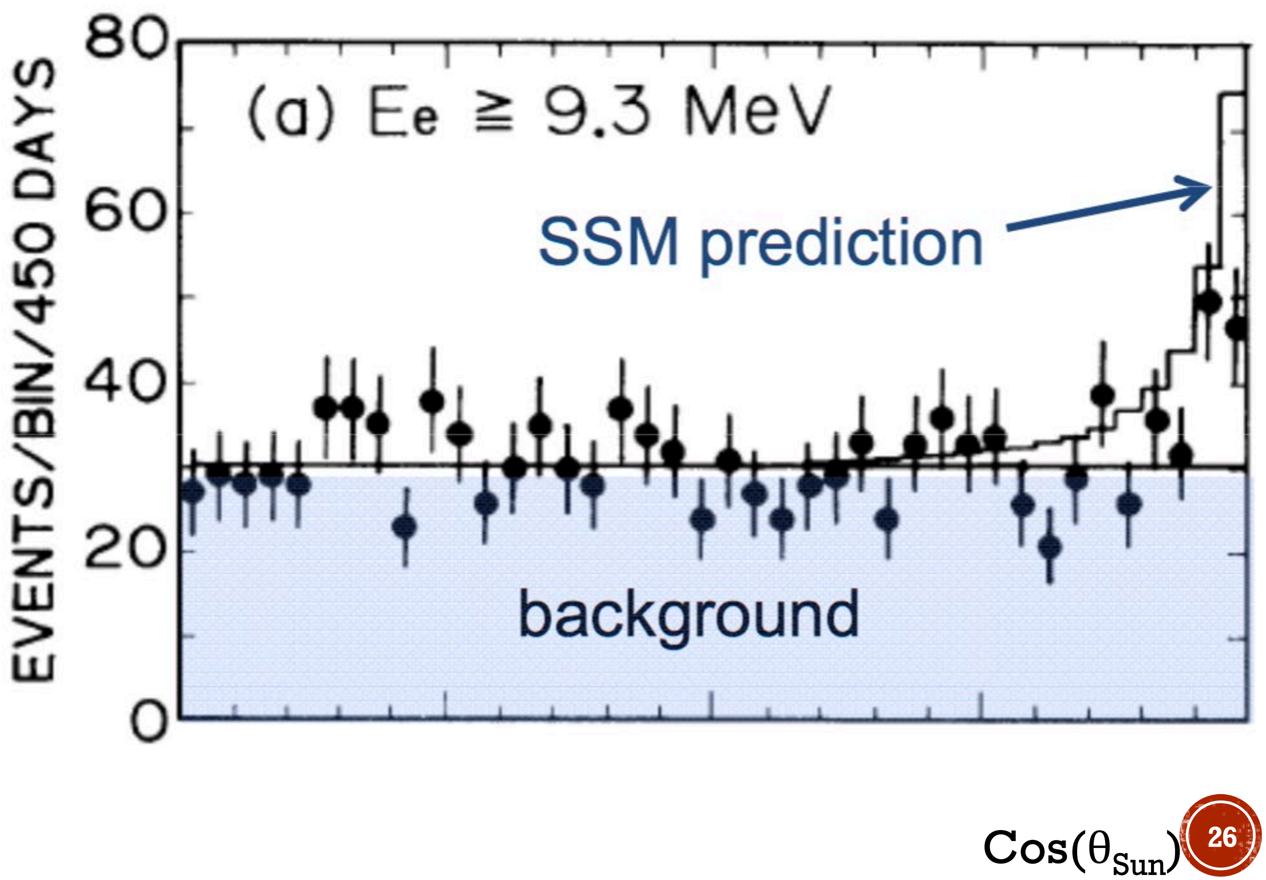
Electron neutrino elastic scattering is very forward: $\nu_e \, e \rightarrow \nu_e \, e$

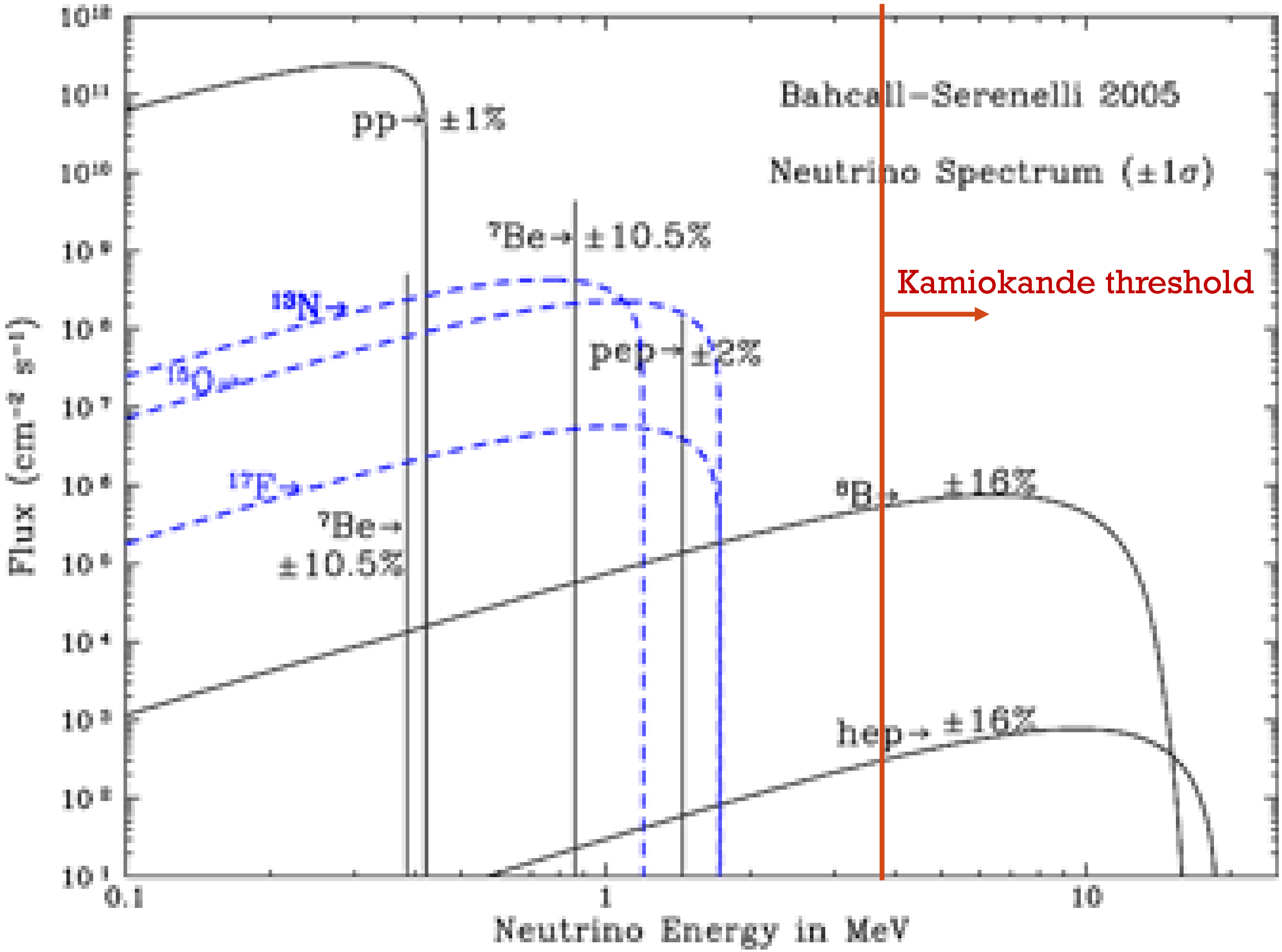


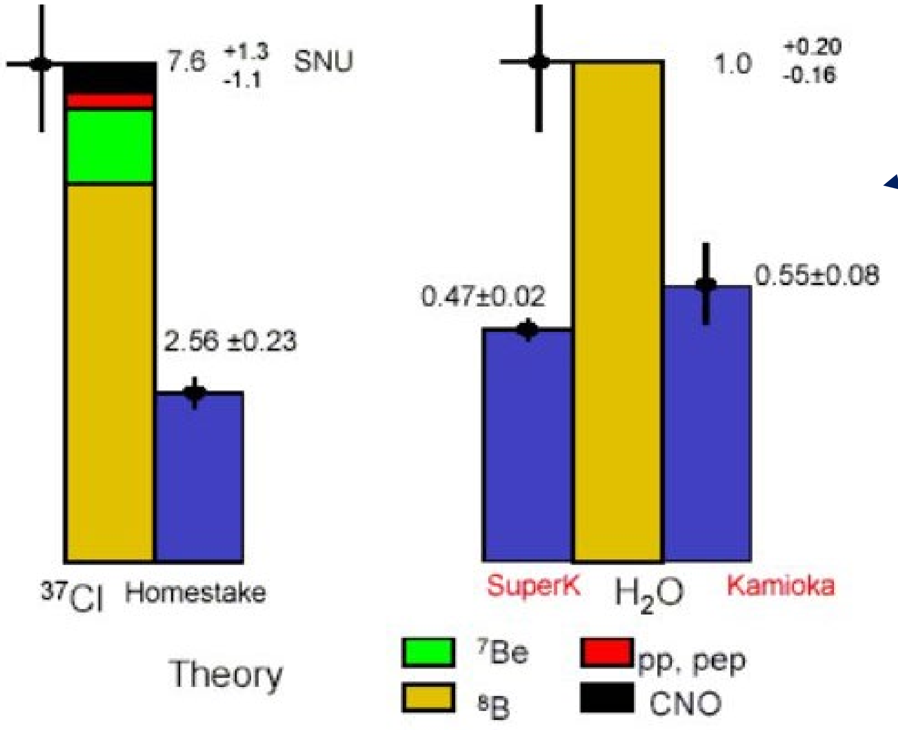
Reconstructed electrons point back to the Sun

And the cross section is very easy to calculate.

This a ***very clean*** signature.




Bahcall−Serenelli 2005
Neutrino Spectrum (±1σ)
Kamiokande threshold
pp→ ±1%
⁷Be→ ±10.5%
¹³N→
¹⁵O→
¹⁷F→
pep→ ±2%
⁸B→ ±16%
hep→ ±16%
⁷Be→
±10.5%
Flux (cm⁻² s⁻¹)
Neutrino Energy in MeV
0.1
1
10



Still see a low result, but not quite as low as the Chlorine experiment…

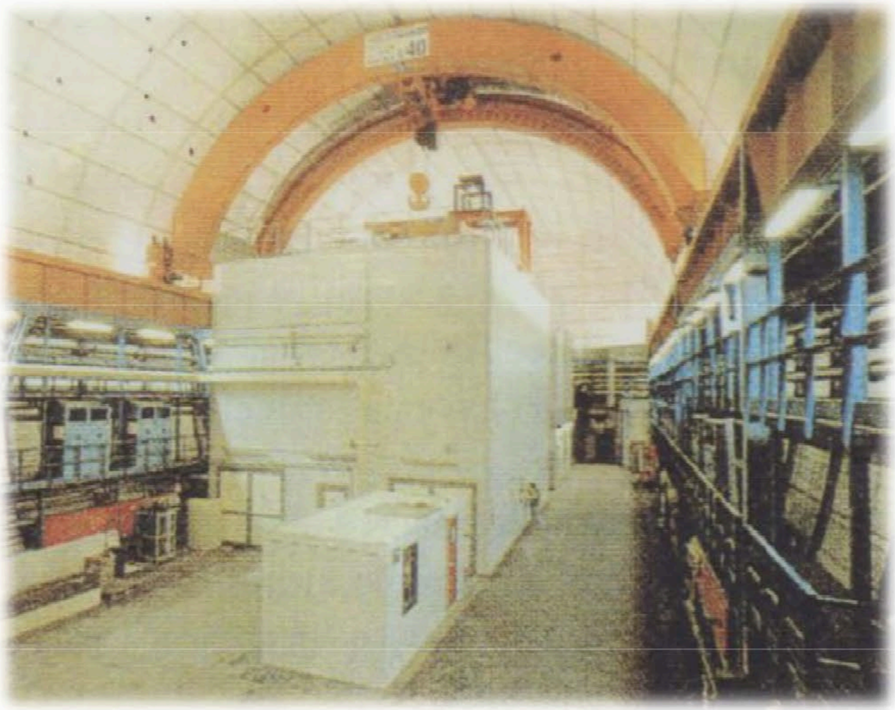
(but notice, K and SK see all ^{8}B neutrinos)

GALLIUM EXPERIMENTS

$^{71}Ga + \nu \rightarrow {}^{71}Ge + e$ has a threshold of only 233 keV. Can access pp neutrinos!

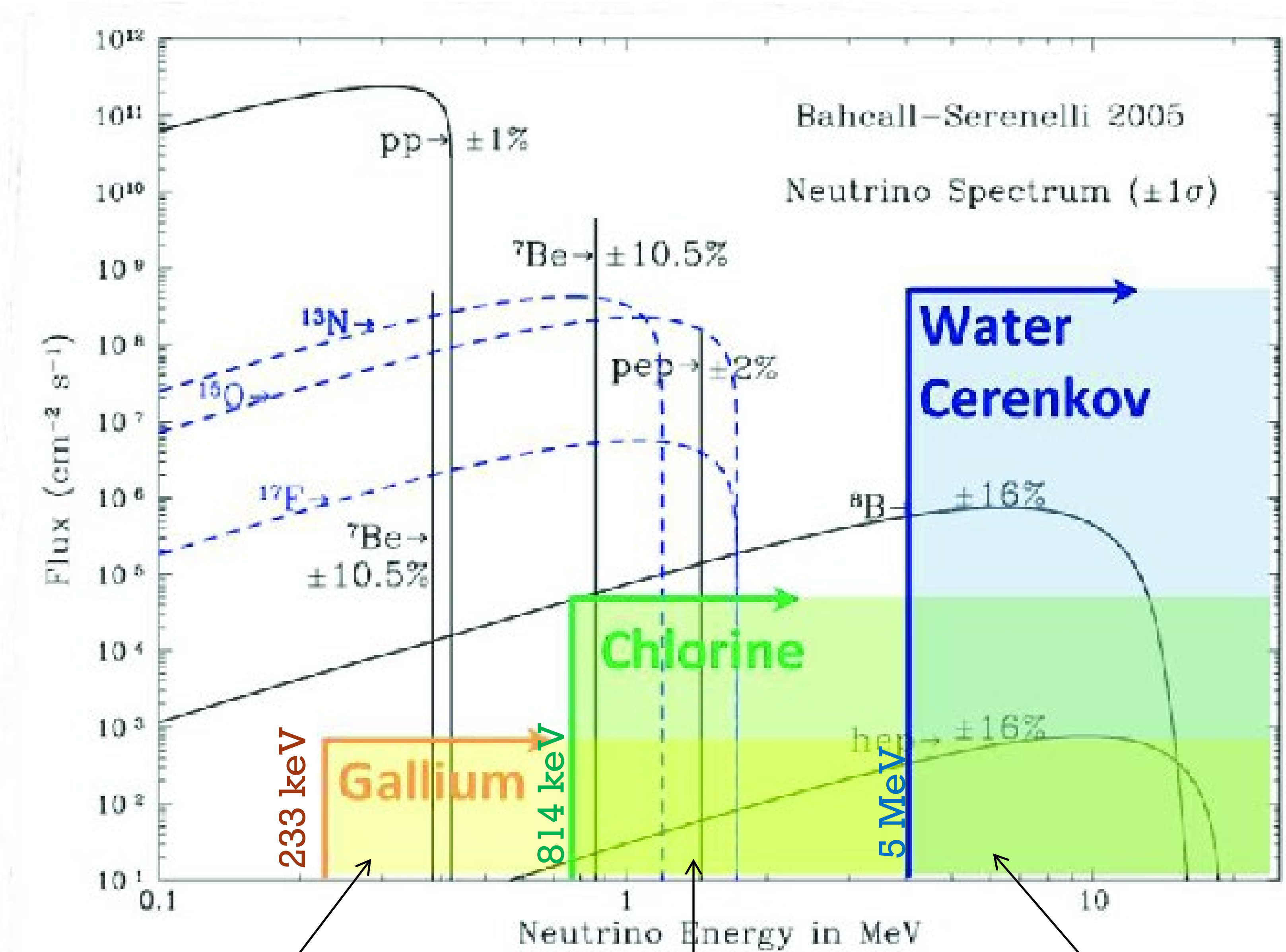
Gallium is a metal (though, low melting point). Can do a similar experiment to the chlorine detectors, though with more complex chemical engineering.

SAGE (Baksan, Russia)



Gallex/GNO (Gran Sasso, Italy)

Main benefit of Ga → pp neutrinos much less dependent on details of solar model

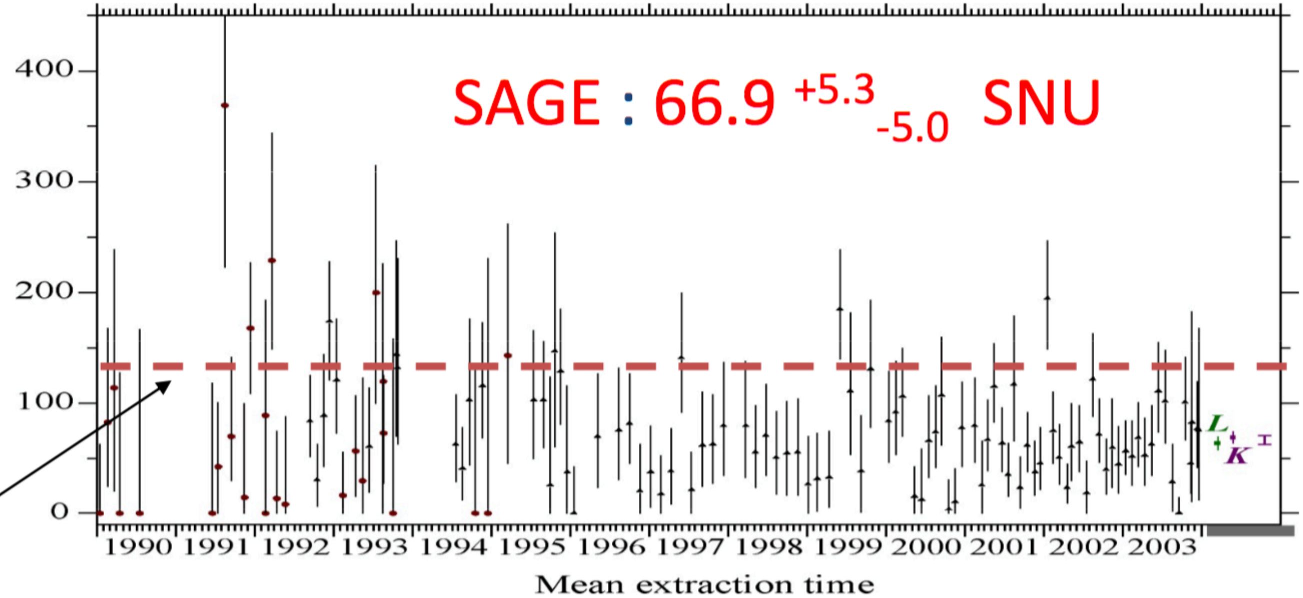


$^{71}Ga + \nu \rightarrow {}^{71}Ge + e$

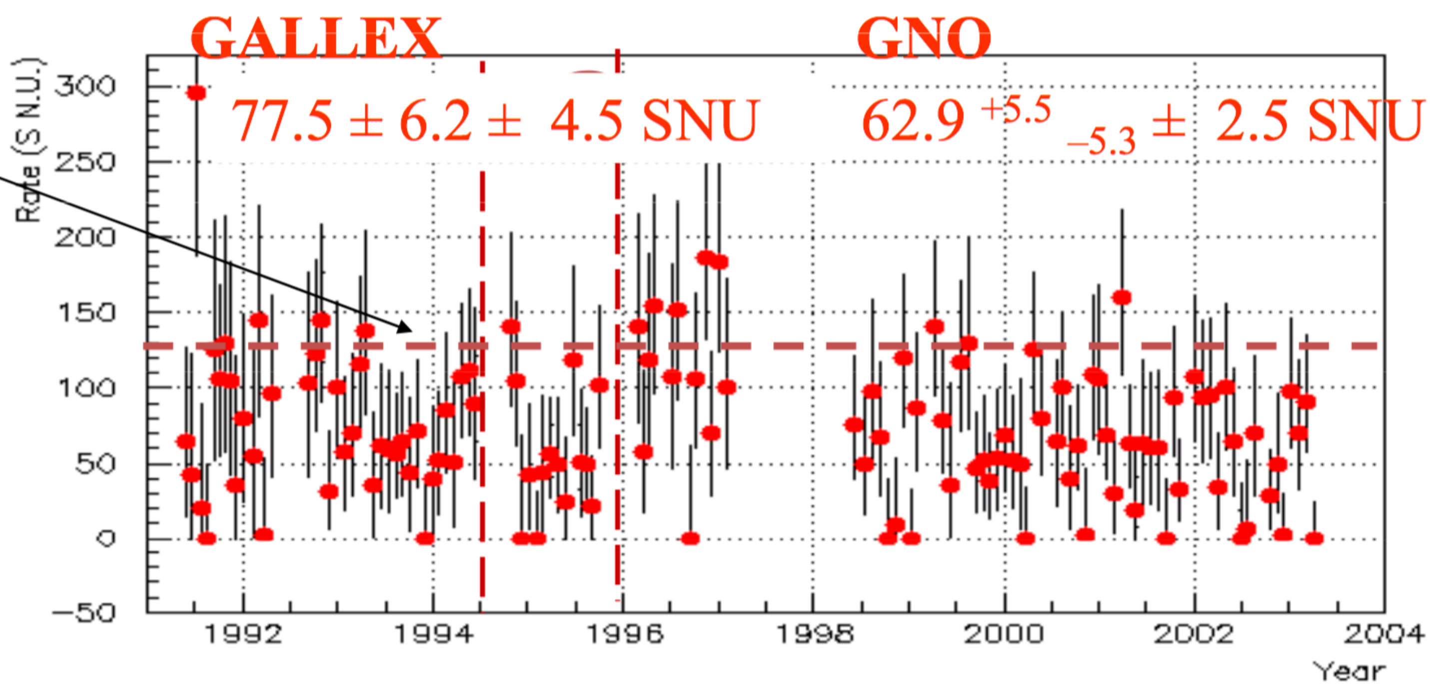
$^{37}Cl + \nu \rightarrow {}^{37}Ar + e$

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

GALLIUM SOLAR RESULTS



SSM prediction

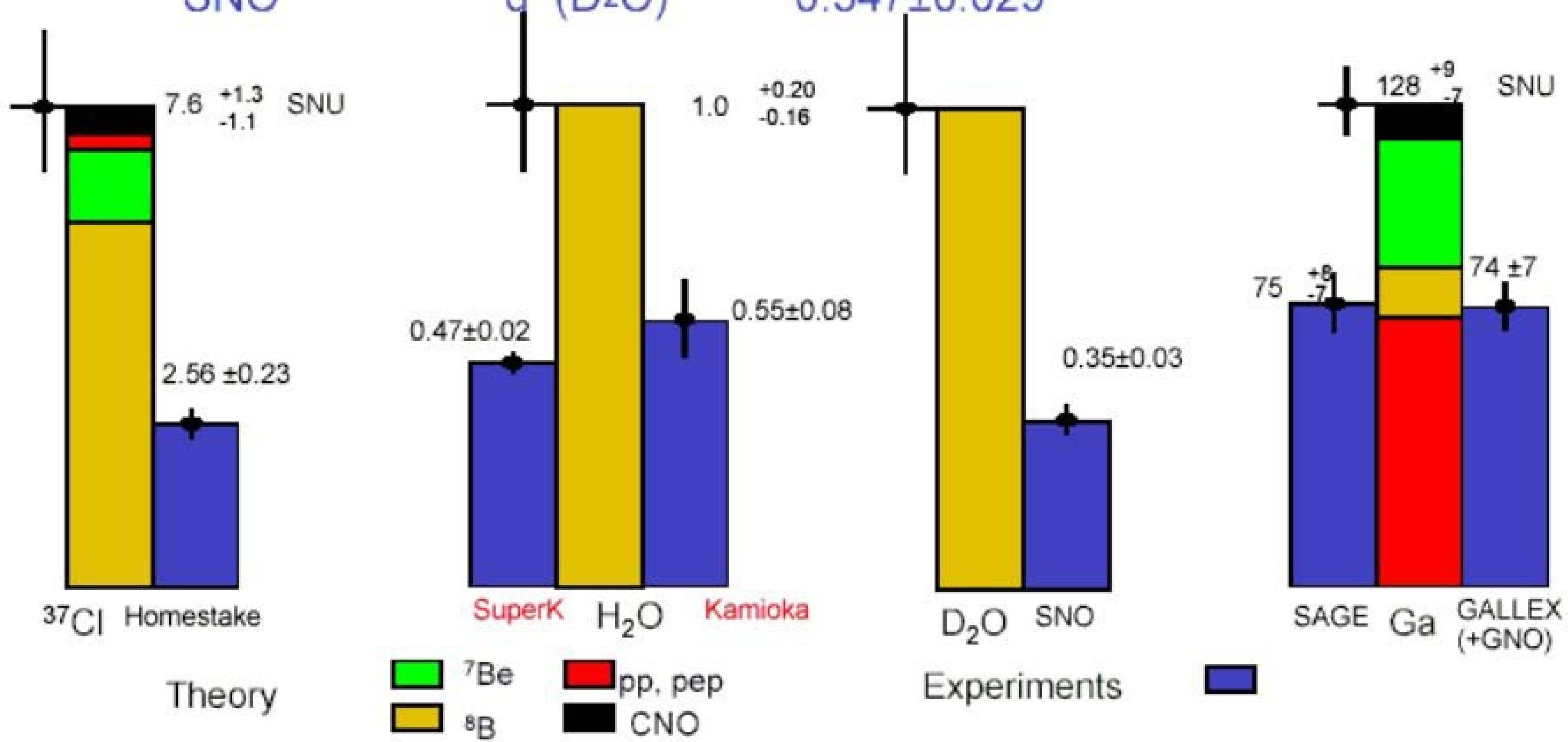


The Solar Neutrino Problem

Credit: some of these slides are borrowed from Wick Haxton, who borrowed them from Richard Kass. Thanks guys!

- Homestake ^{37}Cl 0.34±0.03
- SAGE ^{71}Ga 0.59±0.06
- GALLEX+GNO ^{71}Ga 0.58±0.05
- Super-K e^- (water) 0.465±0.016*
- SNO d (D_2O) 0.347±0.029

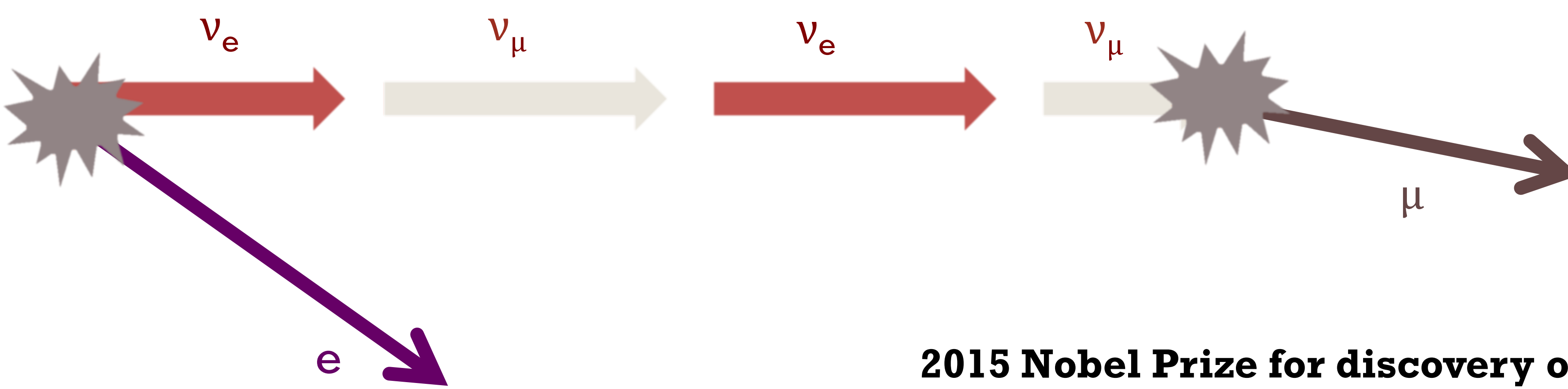
* 0.451 for BP2000_old



PERHAPS ITS NEUTRINO OSCILLATIONS?

- Neutrinos have a tiny, but non-zero mass, and this makes them oscillate

Production **Detection**



2015 Nobel Prize for discovery of neutrino oscillations and neutrino mass!

MIXING

- A neutrino oscillation requires two things:
  - 1) Neutrinos states at multiple masses
  - 2) Interaction state is not a mass state

- Quantum mechanically, in a 2-flavor system:

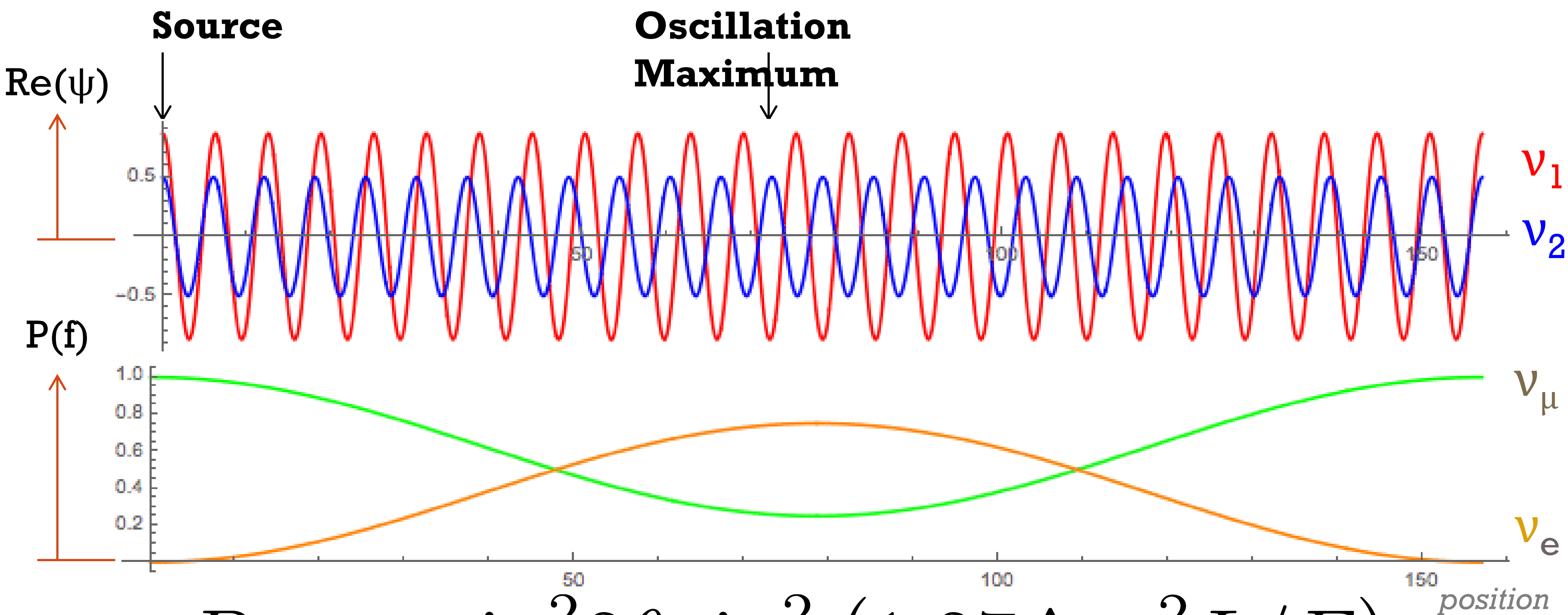
$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Basis states with definite flavor

"mixing matrix"

Basis states with definite mass

A NEUTRINO OSCILLATION:

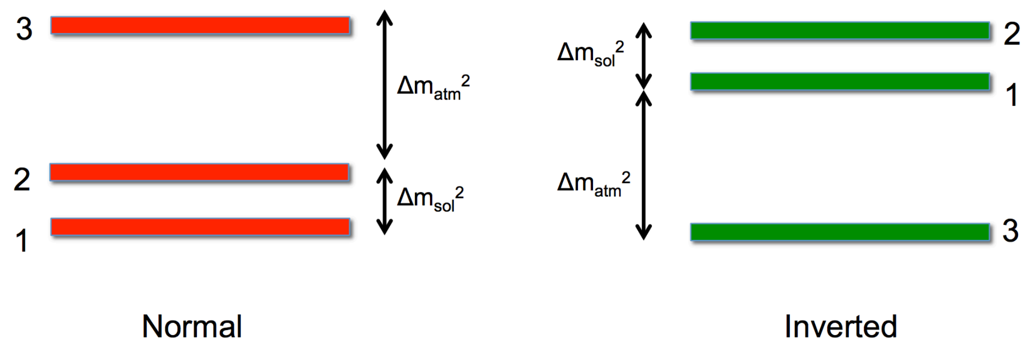


$$P_{osc} = \underbrace{\sin^2 2\theta}_{amplitude} \, \sin^2 \underbrace{\left(1.27 \Delta m^2 L / E\right)}_{wavelength}$$

amplitude *wavelength*

MASS AND MIXING : 3 NEUTRINO MODEL

- Two characteristic oscillation wavelengths.
- Experimentally, $\Delta m_{31}^2 >> \Delta m_{21}^2$
- Mass ordering unknown (hints exist, but inconclusive)



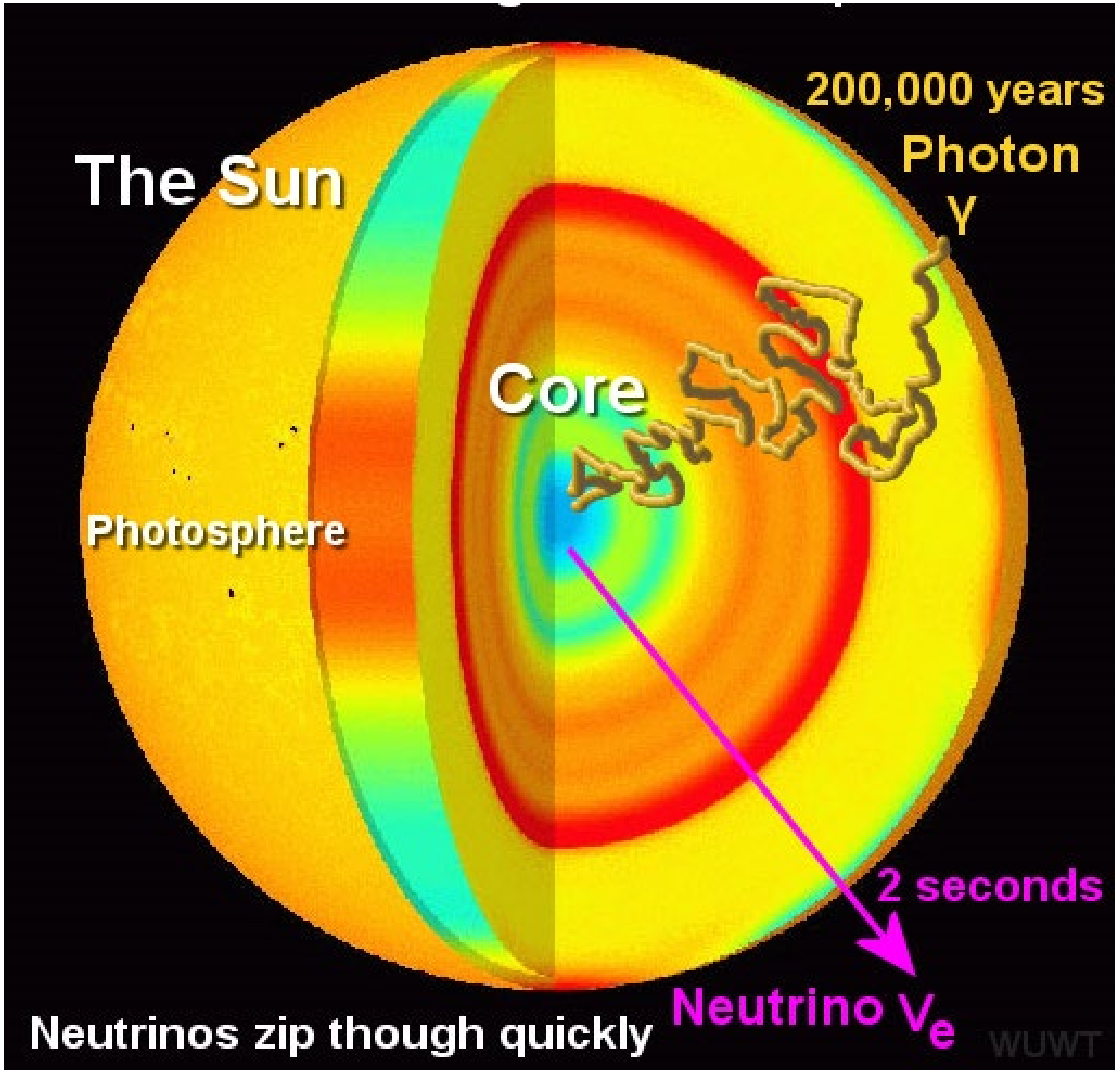
From PDG :

Parameter	best-fit ($\pm1\sigma$)	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	$7.54^{+0.26}_{-0.22}$	$6.99 - 8.18$
$\|\Delta m^2\|$ [10^{-3} eV ^{2}]	2.43 ± 0.06 (2.38 ± 0.06)	$2.23 - 2.61$ ($2.19 - 2.56$)

* Mixing between 3 states dictated by 3 mixing angles and (1 or 3) CP phases.

CAN IT EXPLAIN THE SOLAR NEUTRINO PROBLEM?

- **Not quite… one ingredient missing.**



REMINDER ABOUT REFRACTIVE INDEX

- A particle travelling in a vacuum evolves as:

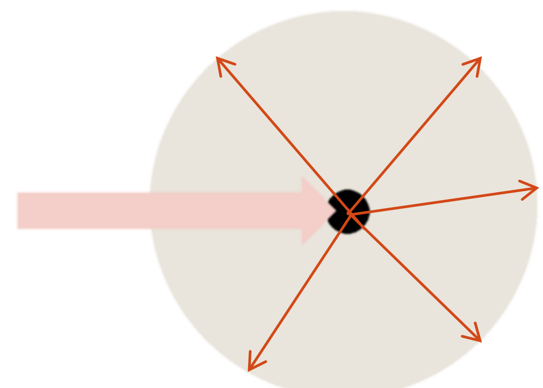
$$\psi_{plane}(\vec{x},t) = e^{i\vec{p}\vec{x}-i\omega t}$$

REMINDER ABOUT REFRACTIVE INDEX

- A particle travelling in a vacuum evolves as:

$$\psi_{plane}(\vec{x}, t) = e^{i\vec{p}\vec{x} - i\omega t}$$

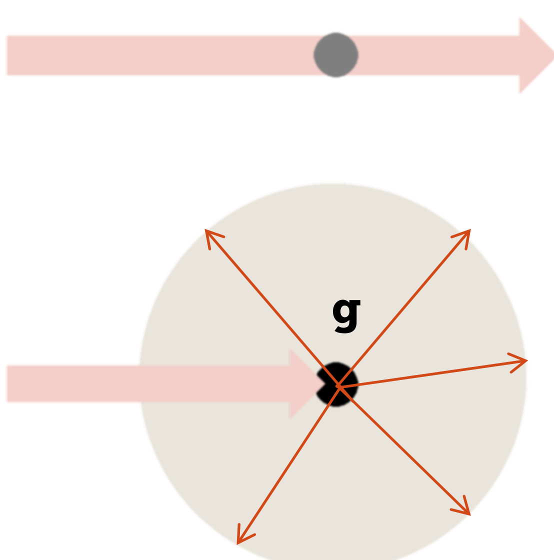
* A particle scattered (S-wave) from a small point object evolves as:



$$\psi_{scat}(\vec{x}, t) = e^{i|p|r - i\omega t}$$

REMINDER ABOUT REFRACTIVE INDEX

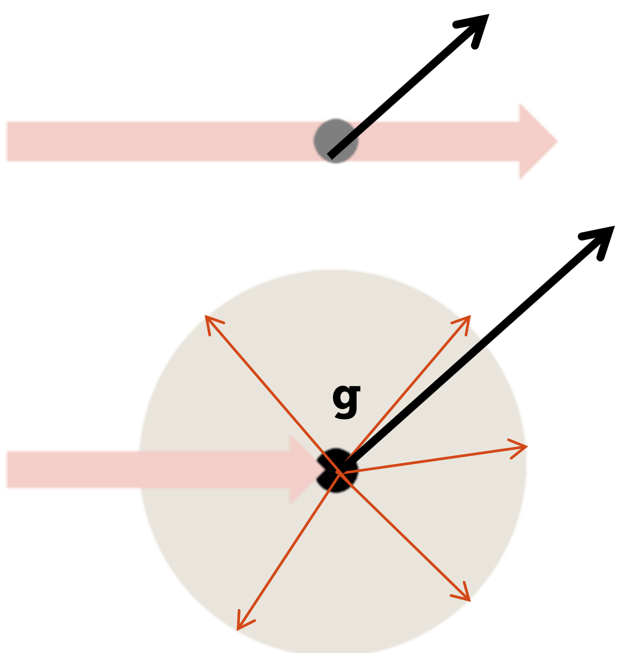
- A particle in material with some scattering strength g evolves as a superposition of scattered and unscattered waves



$$\psi_{total} = \psi_{plane} + g\psi_{scat}$$

REMINDER ABOUT REFRACTIVE INDEX

- In the NON-FORWARD direction, only scattered wave contributes. Finite probability for detection in any direction leads to **scattering cross section.**



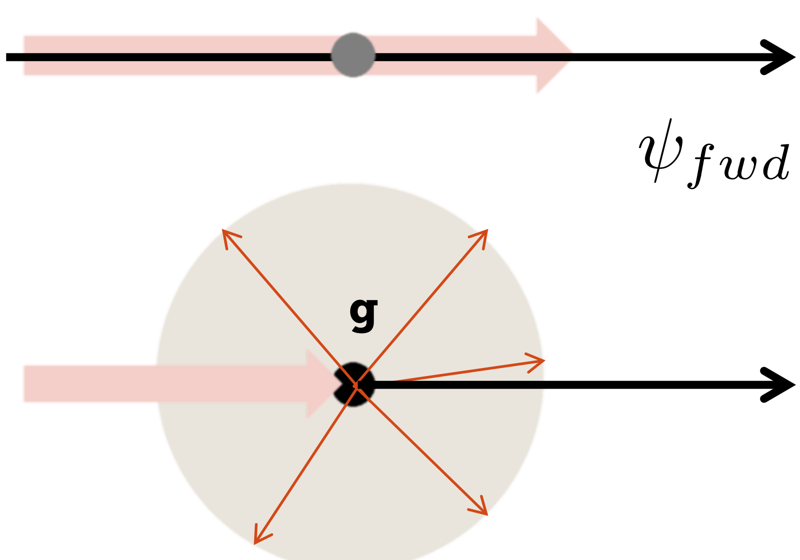
$$\psi_{non-fwd} = [g\psi_{scat}]_{(x!\|p)}$$

Cross section: $\sigma \propto g^2$

"Incoherent scattering"

REMINDER ABOUT REFRACTIVE INDEX

- In the FORWARD direction, scattered and scattered waves interfere. Components not independently detectable. Phase evolves faster than fwd alone, leading to **refractive index.**



$$\psi_{fwd} = \left[\psi_{plane} + g\psi_{scat}\right]_{(\vec{x}||\vec{p})} = e^{in\vec{p}\vec{x}}$$

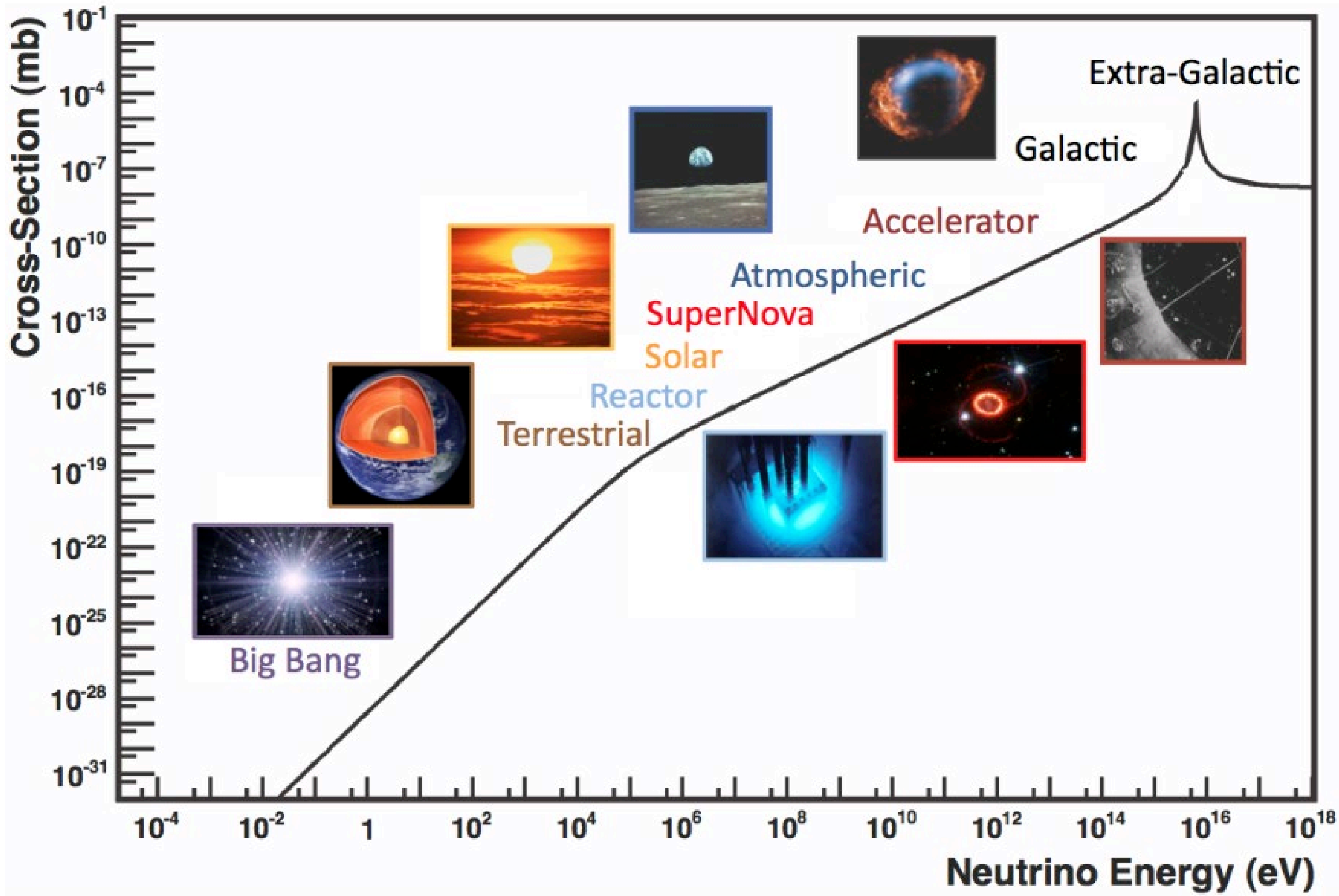
Refractive index: $(n-1) \propto g$

"Coherent forward scattering"

NEUTRINO CROSS SECTIONS

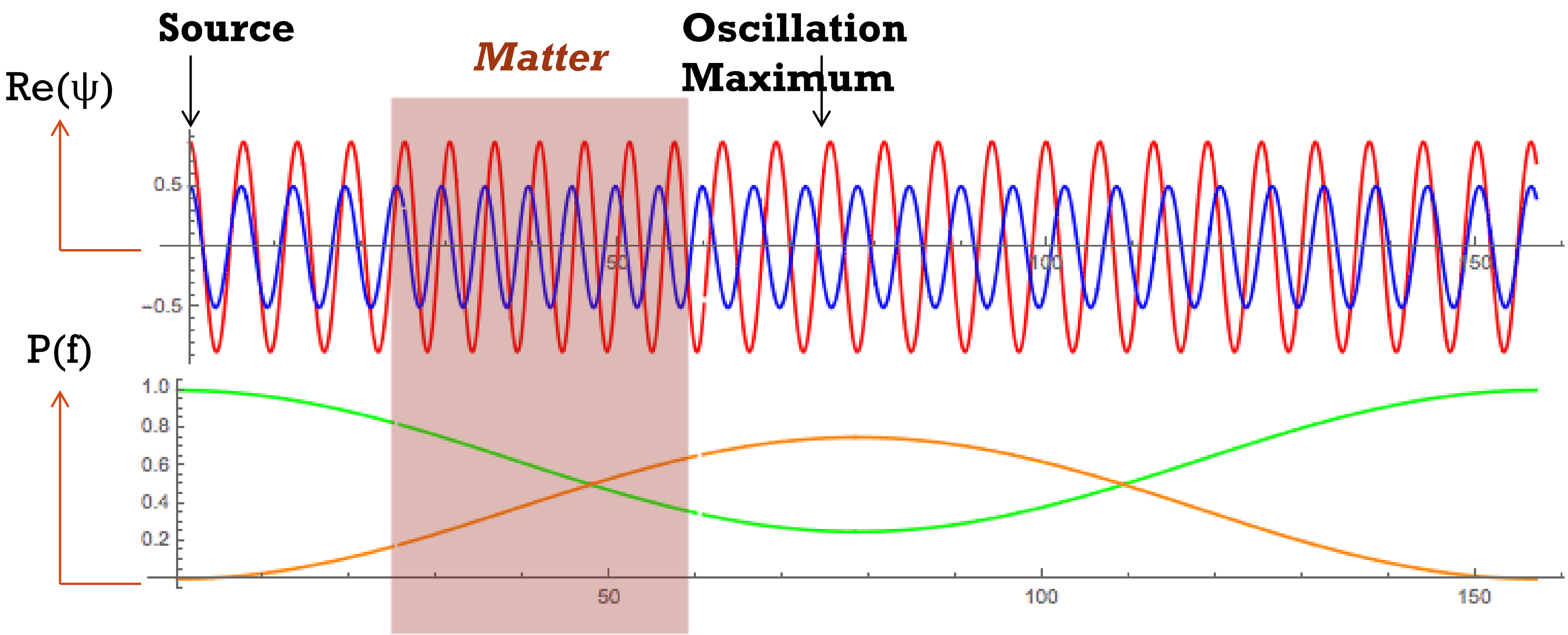
- Neutrinos interact very weakly, so g is very small
- Our experiments are typically more sensitive to refractive index than effects of incoherent scattering

$$(n-1) \propto g$$
$$\sigma \propto g^2$$



NEUTRINOS IN MATTER WITH REFRACTION

$$P_{Osc} = A_{mixing} \sin^2\left(1.27\Delta m^2 L / E\right)$$

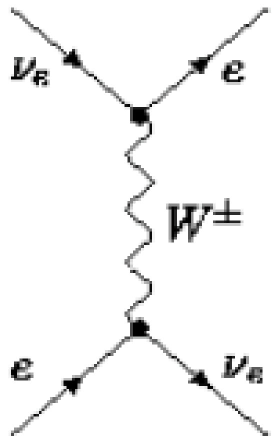


In this example, phases roll faster in matter → mass states are effectively **heavier**

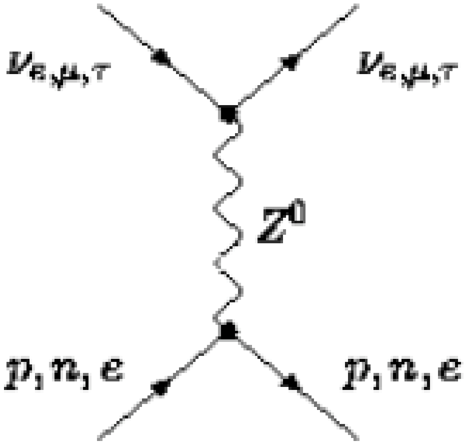
Both states have same interaction strength → **Δm^2 unchanged**

BUT THEY DON'T ALL HAVE THE SAME INTERACTIONS:

- Different neutrino flavors interact with matter differently:



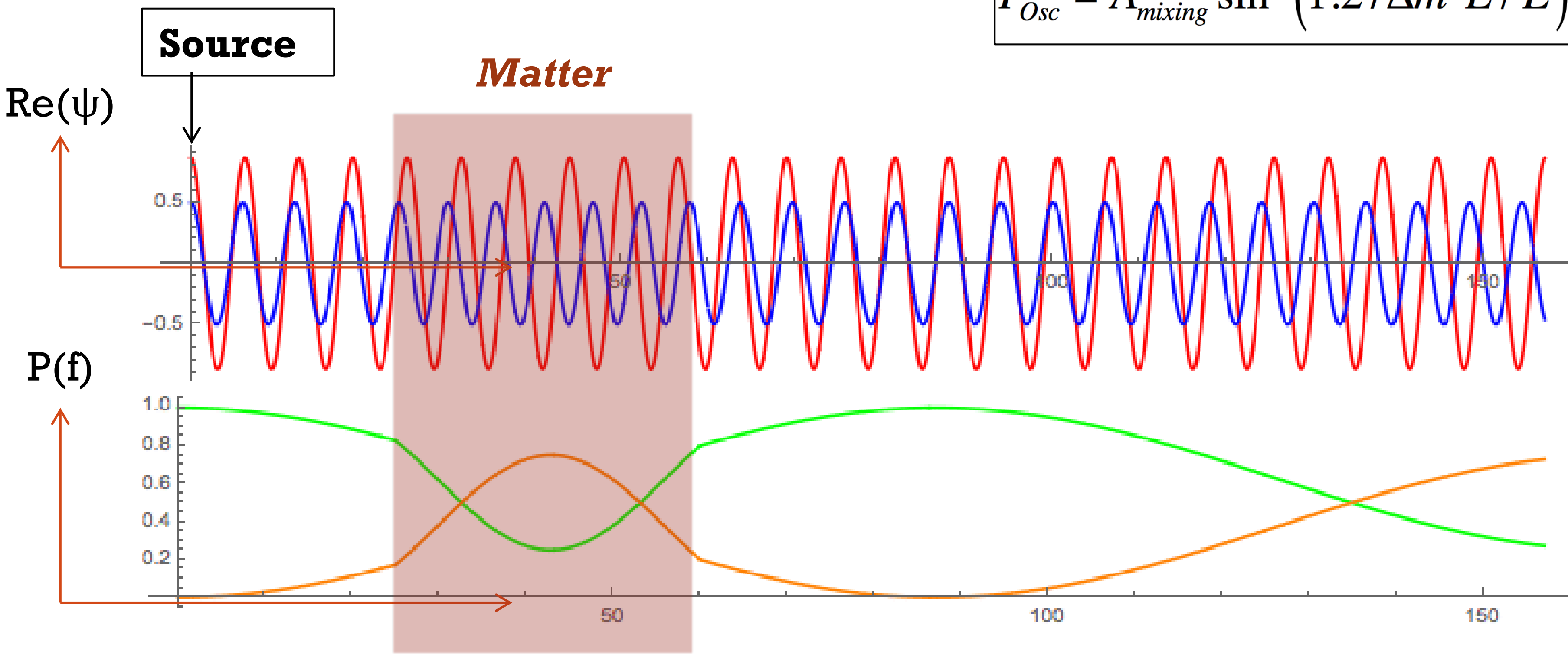
Electron flavor



e + mu / tau flavor

FROM NOW ON, MATTER MATTERS!

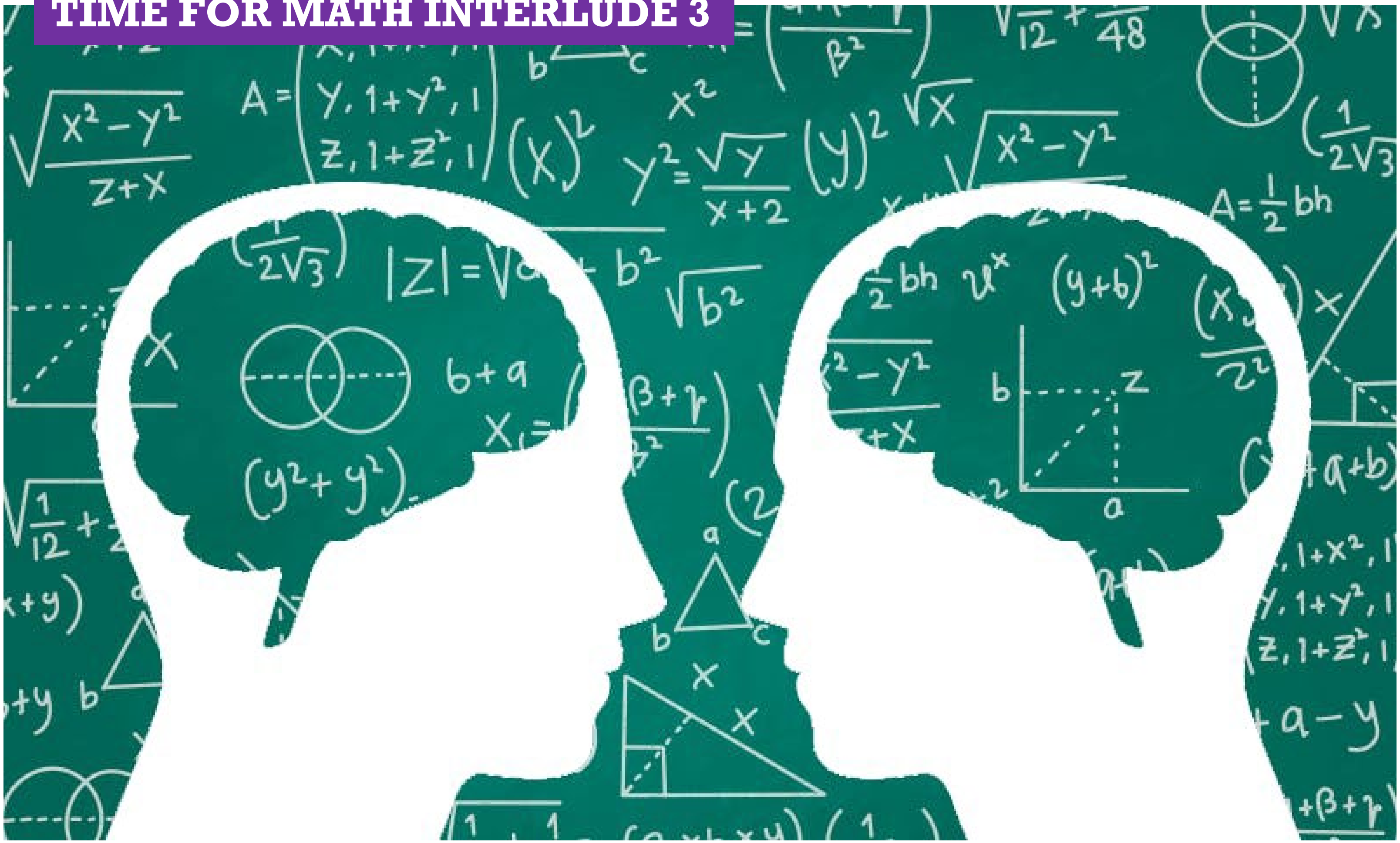
$$P_{Osc} = A_{mixing} \sin^2\left(1.27 \Delta m^2 L / E\right)$$



Couplings in matter change effective masses of the neutrinos. In the above cartoon (not physical!), one mass state has a matter coupling and the other does not.

Oscillation length changes → **Effective Δm^2 is modified**

TIME FOR MATH INTERLUDE 3



$$\sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} \quad ,$$

$$x \equiv \frac{V_W/2}{\Delta m^2/4E} = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2}$$

Neutrino energy

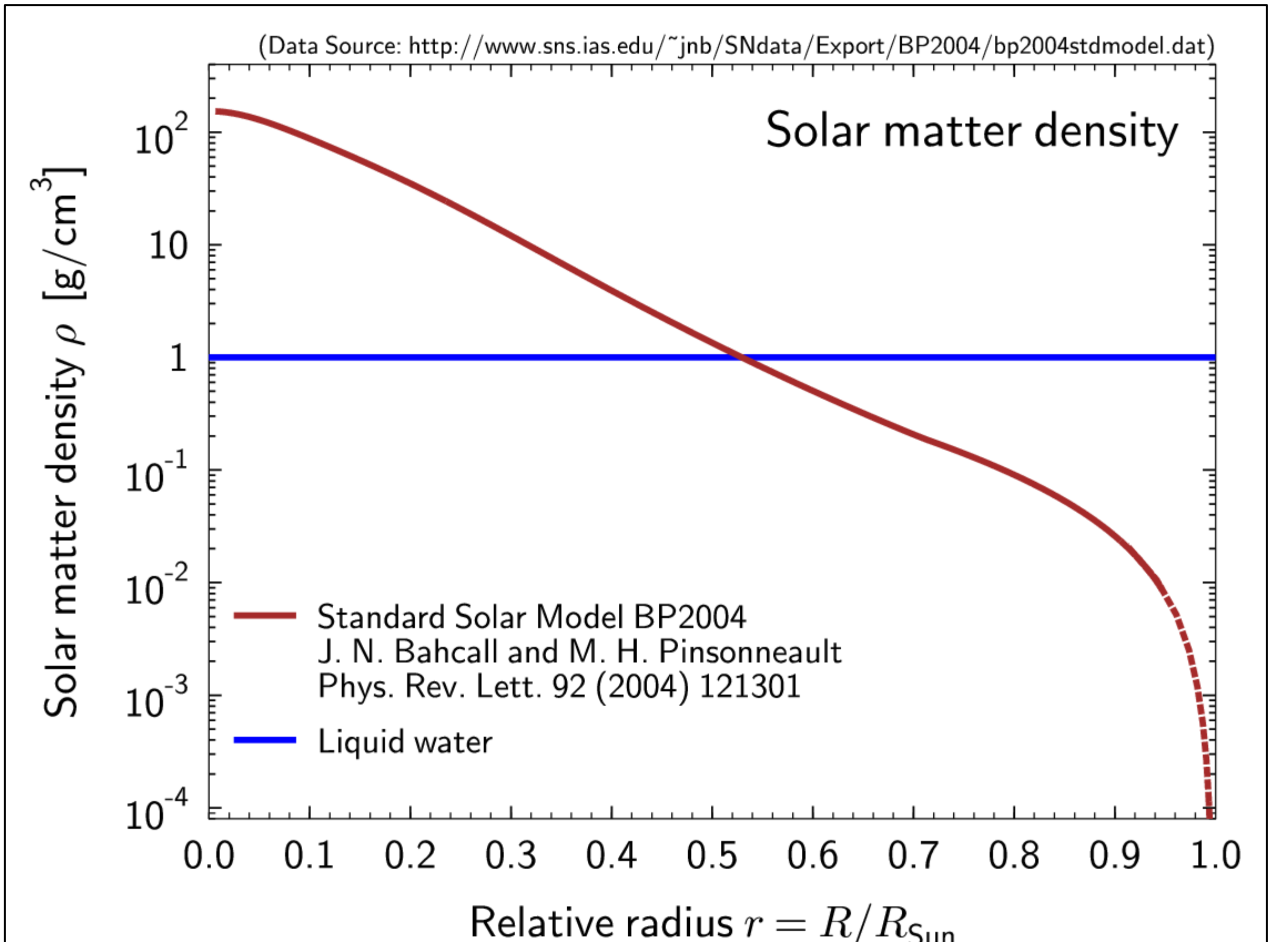
Electron density

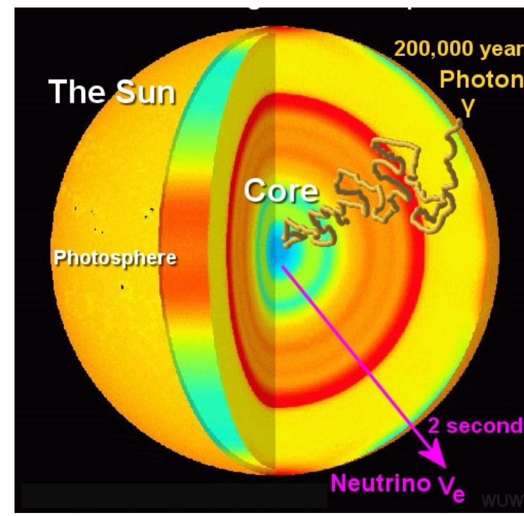
$$\sin^2 2\theta_M \equiv \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2} \ ,$$

$$x \equiv \frac{V_W/2}{\Delta m^2/4E} = \frac{2\sqrt{2} G_F N_e E}{\Delta m^2}$$

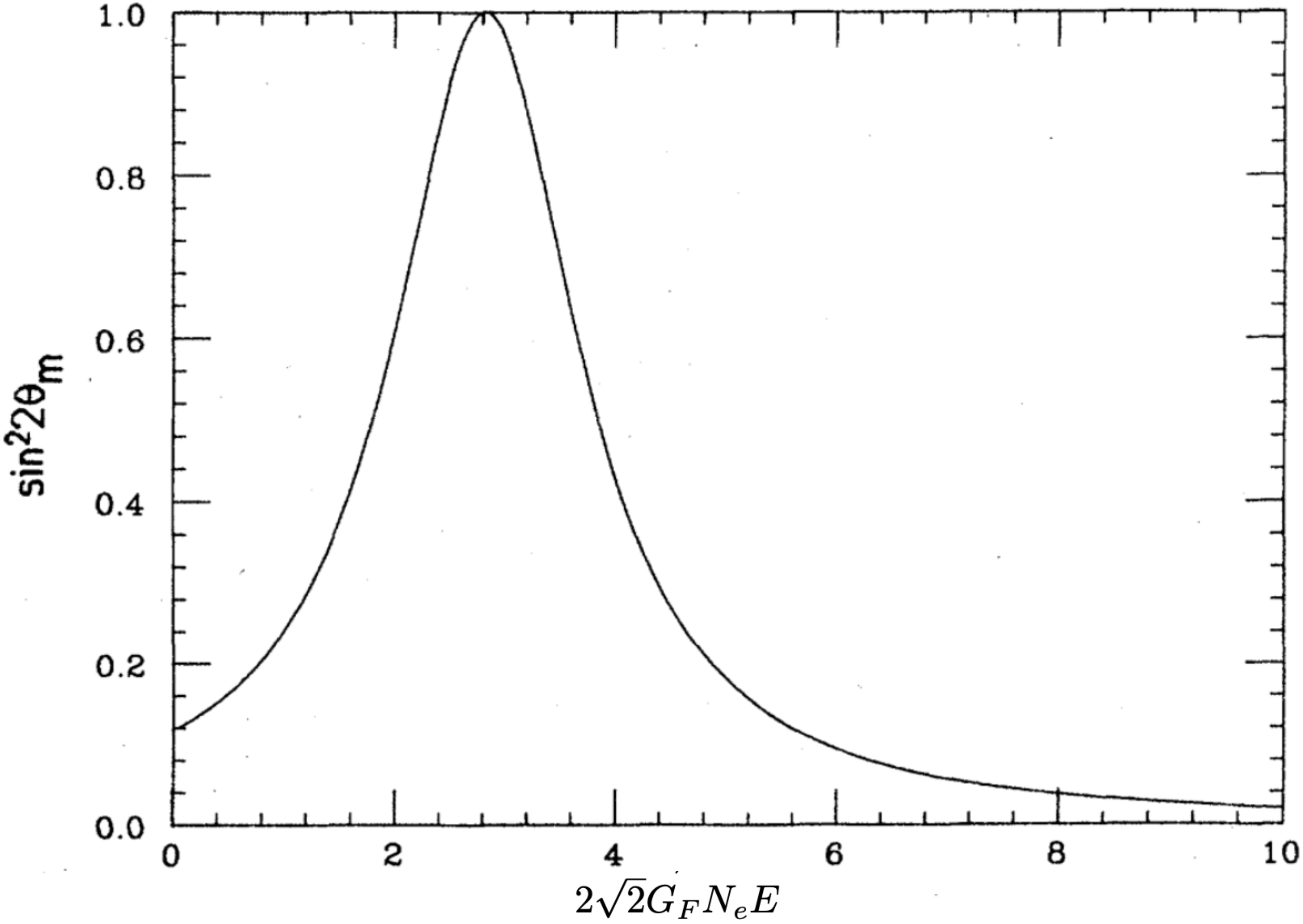
Neutrino energy

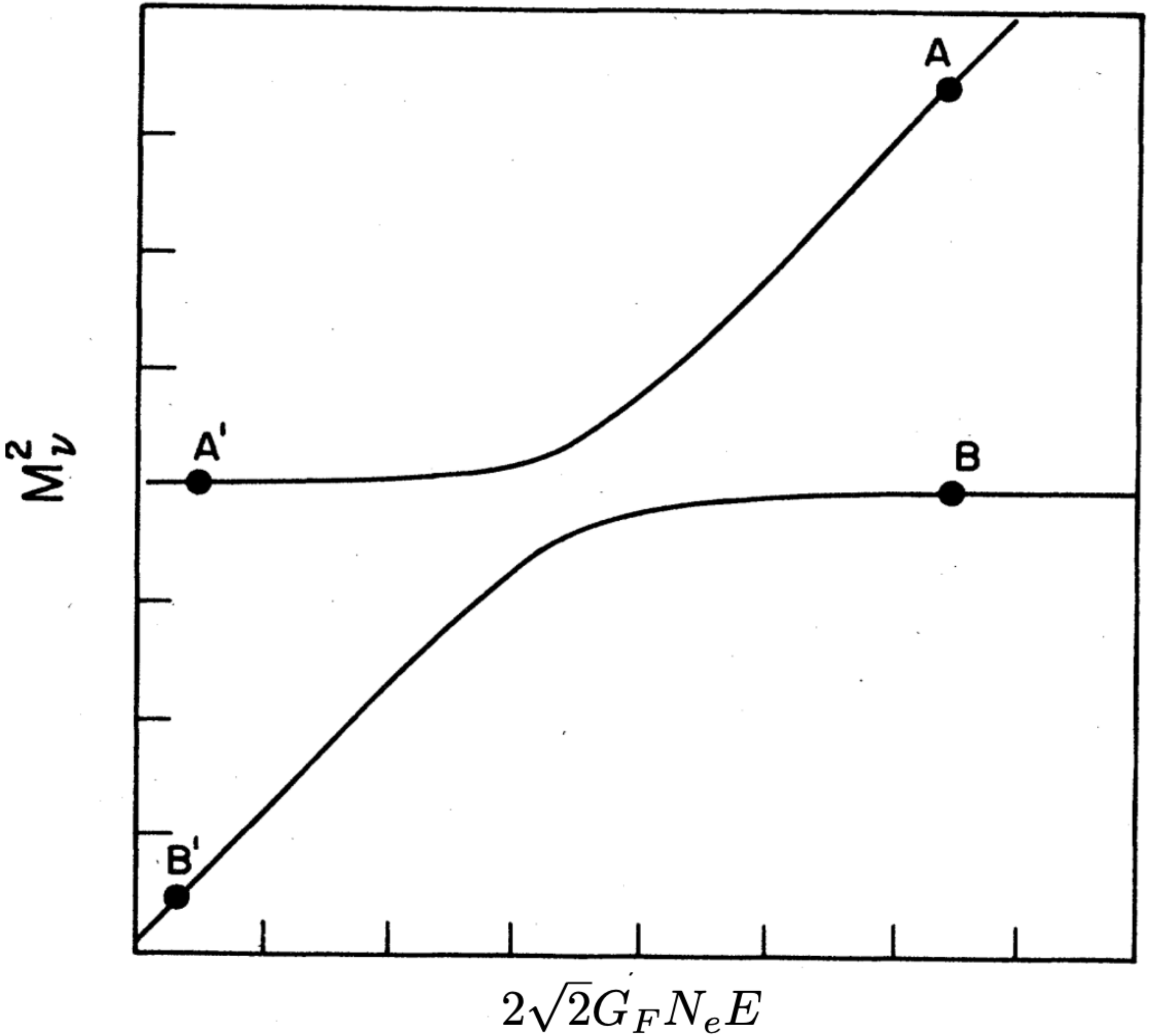
Electron density

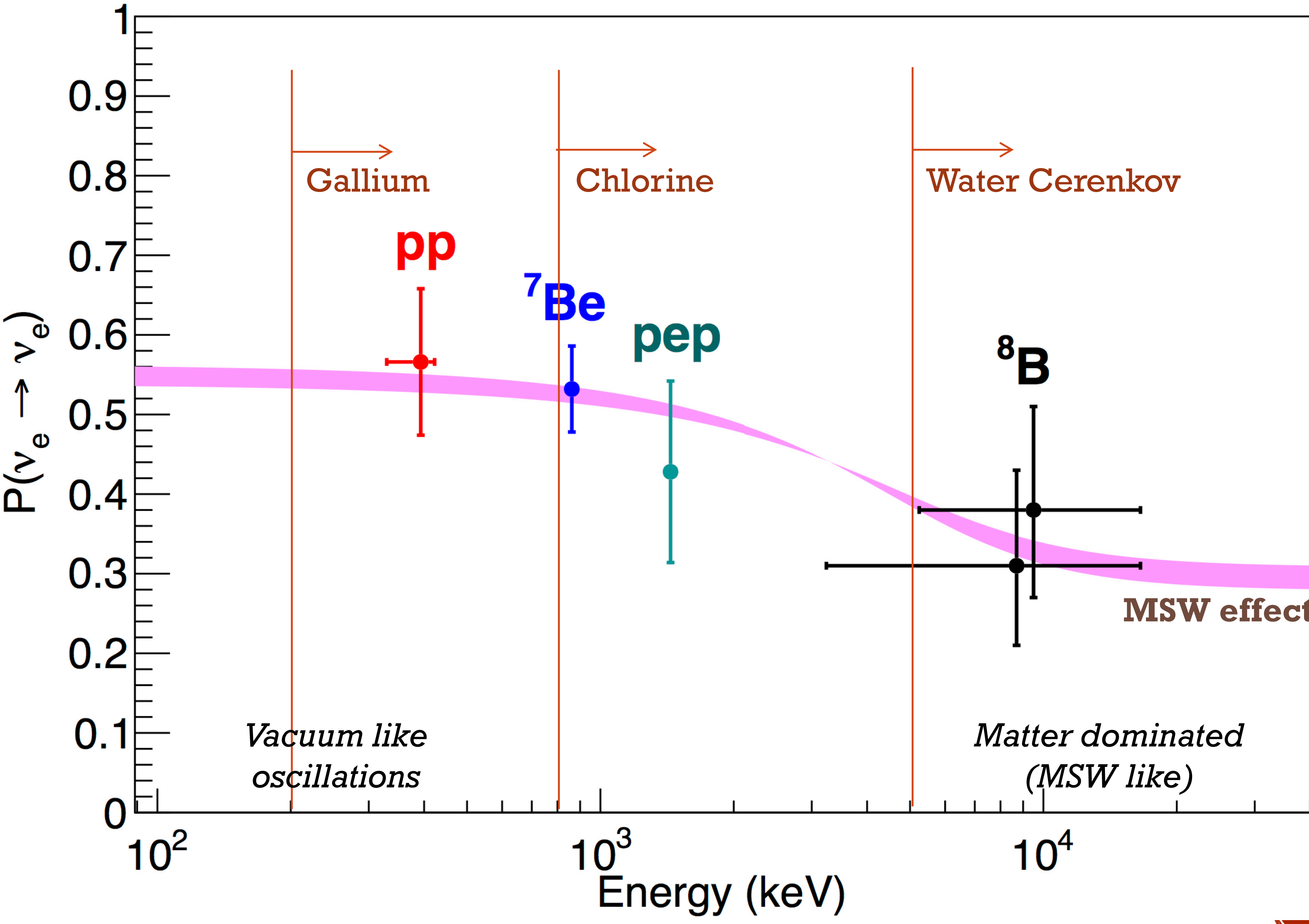




Neutrinos in the sun move from center to surface, exploring a range of x values


1.0
0.8
0.6
0.4
0.2
0.0
$\sin^2 2\theta_m$
0
2
4
6
8
10
$2\sqrt{2}G_F N_e E$


A
A'
B
B'
M_ν^2
$2\sqrt{2}G_F N_e E$

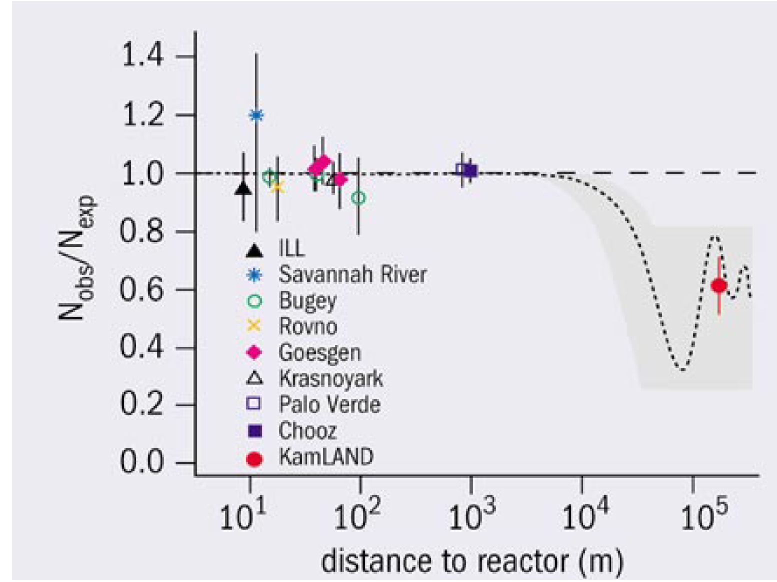


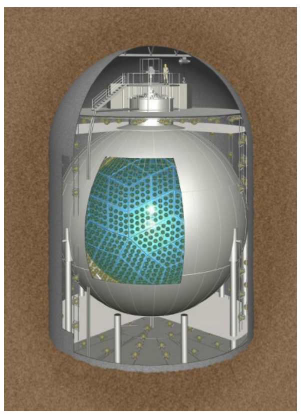
Gallium
Chlorine
Water Cerenkov
pp
7Be
pep
8B
MSW effect
Vacuum like
oscillations
Matter dominated
(MSW like)
P(νe → νe)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
10^2
10^3
10^4
Energy (keV)

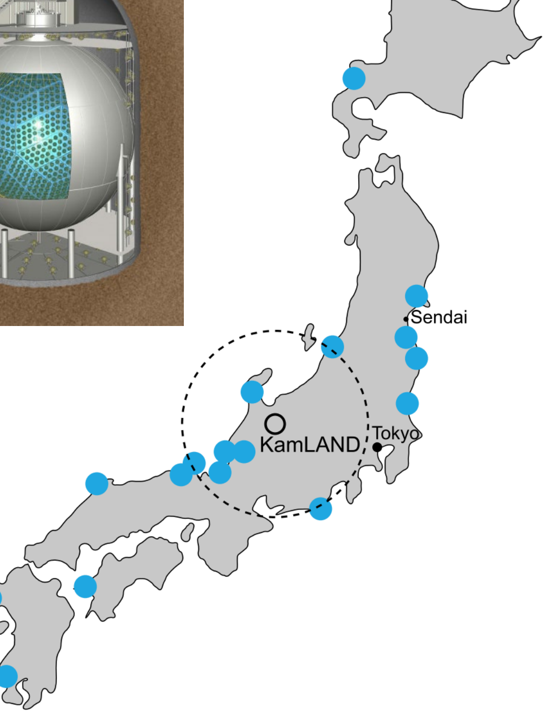
KAMLAND

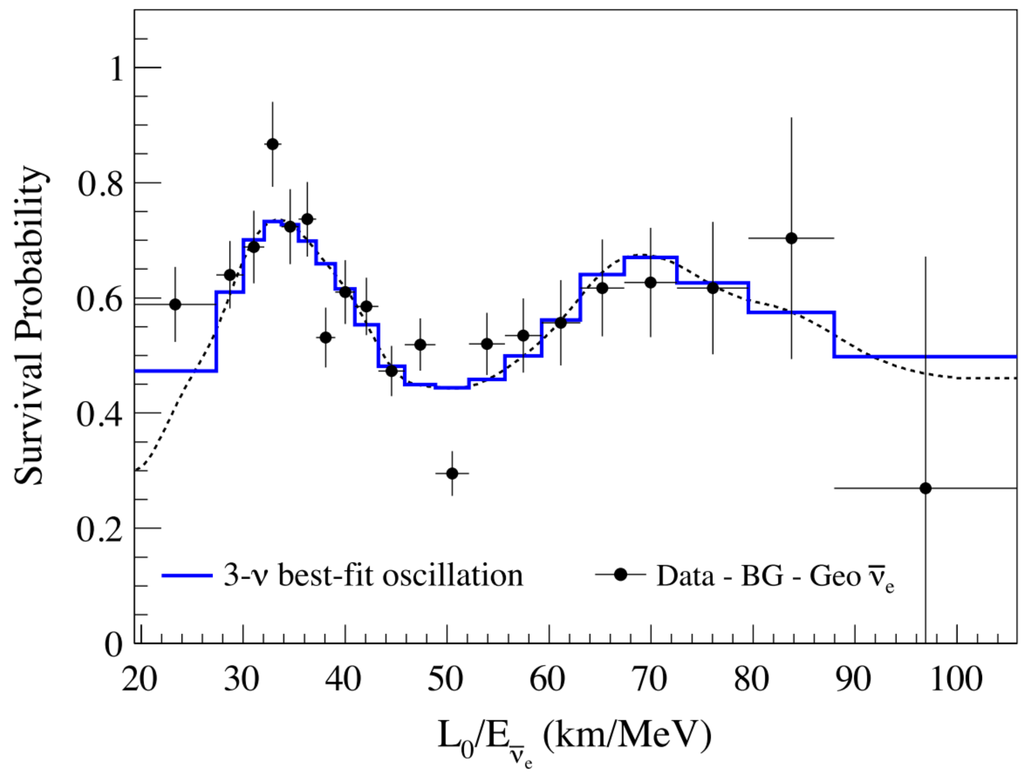
The flux-weighted average distance from Japan's power reactors to detector is 180km.

Kamland verified the oscillation pattern and directly "sees the wiggle".

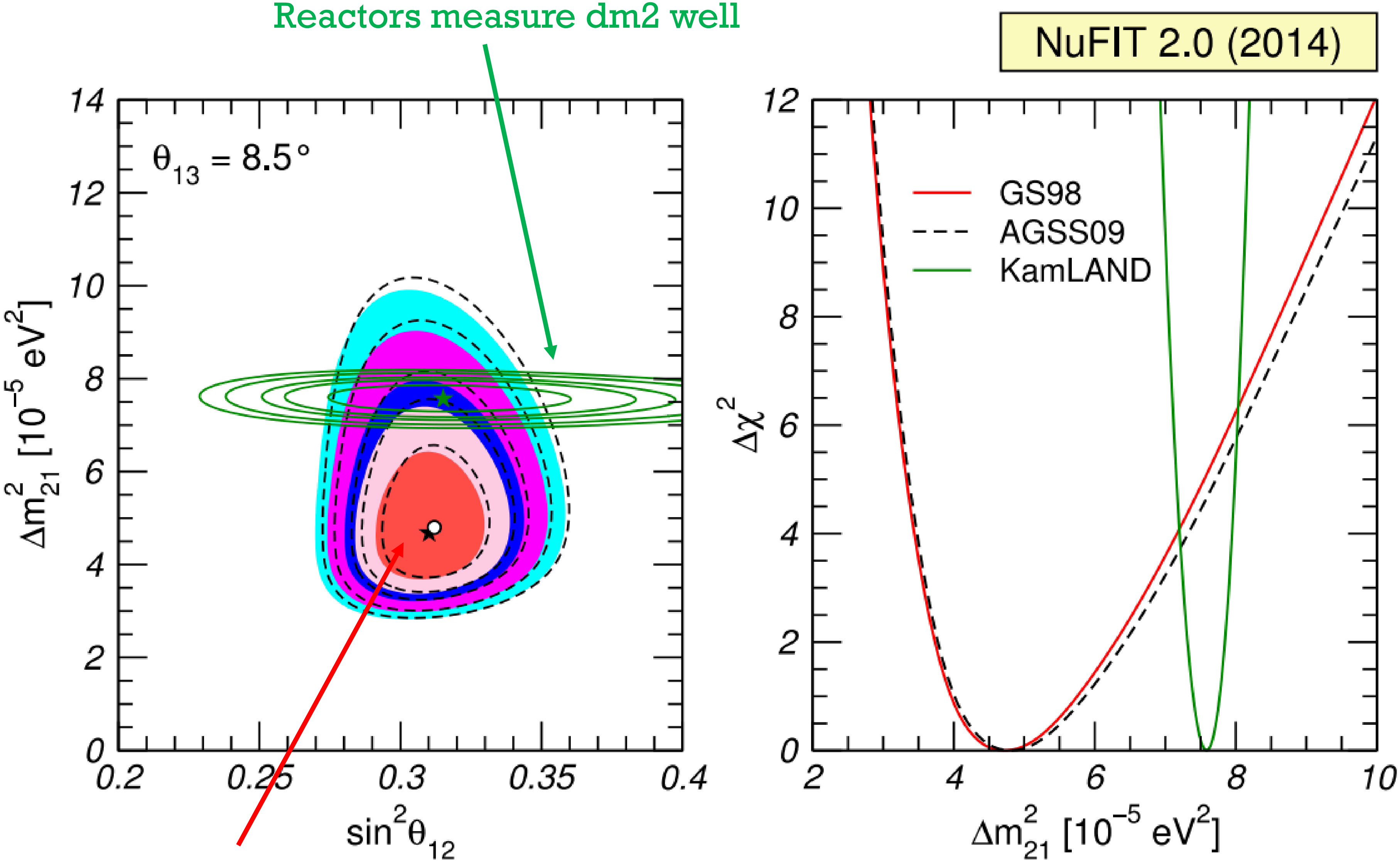






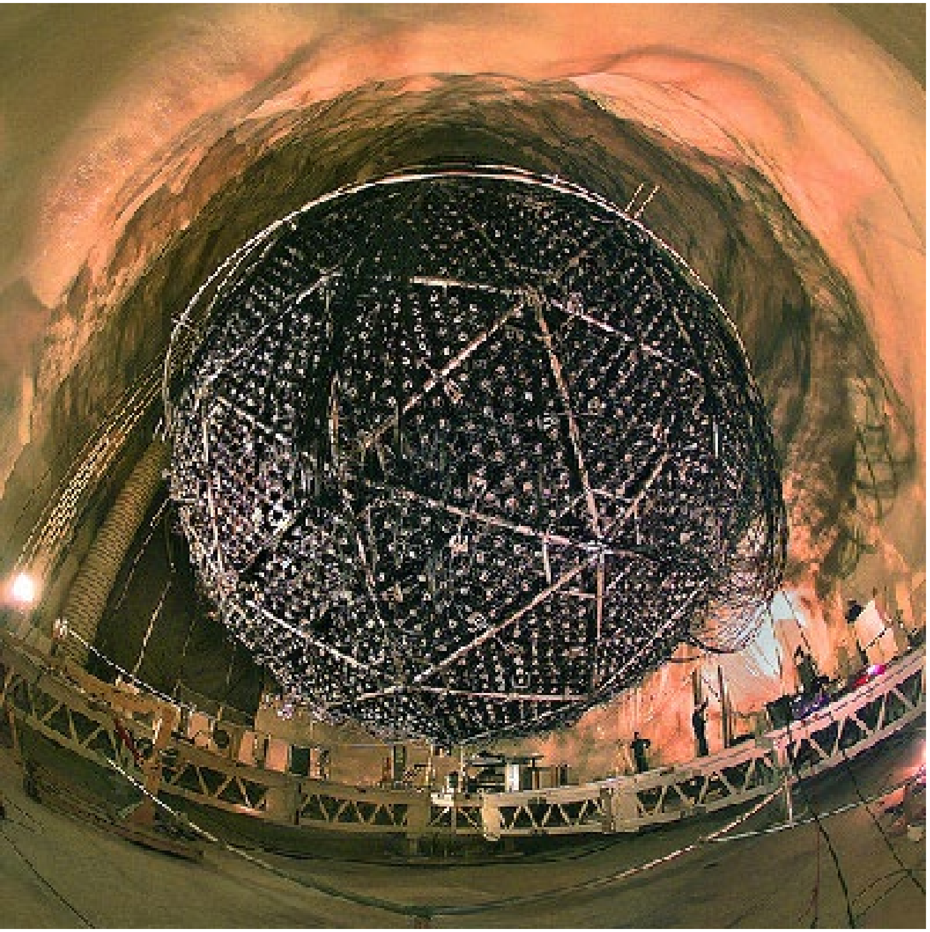


Reactors measure dm2 well



Solar measures mixing angle well

Some folks claim there is a tension here. It looks to me like a magnificent confirmation, given the different methods… but each to their own.



ARE THEY REALLY TRANSFORMING, OR JUST DISAPPEARING?

← SNO experiment, Sudbury, Canada.

Heavy water target for observing neutrinos through three channels:

$$\begin{aligned}
\nu_e + d &\rightarrow p + p + e^- && \text{(charged current, CC)}, \\
\nu_x + d &\rightarrow p + n + \nu_x && \text{(neutral current, NC)}, \\
\nu_x + e^- &\rightarrow \nu_x + e^- && \text{(elastic scattering, ES)}.
\end{aligned}$$

$$\nu_e + d \rightarrow p + p + e^- \quad \text{(charged current, CC),}$$

$$\nu_x + d \rightarrow p + n + \nu_x \quad \text{(neutral current, NC),}$$

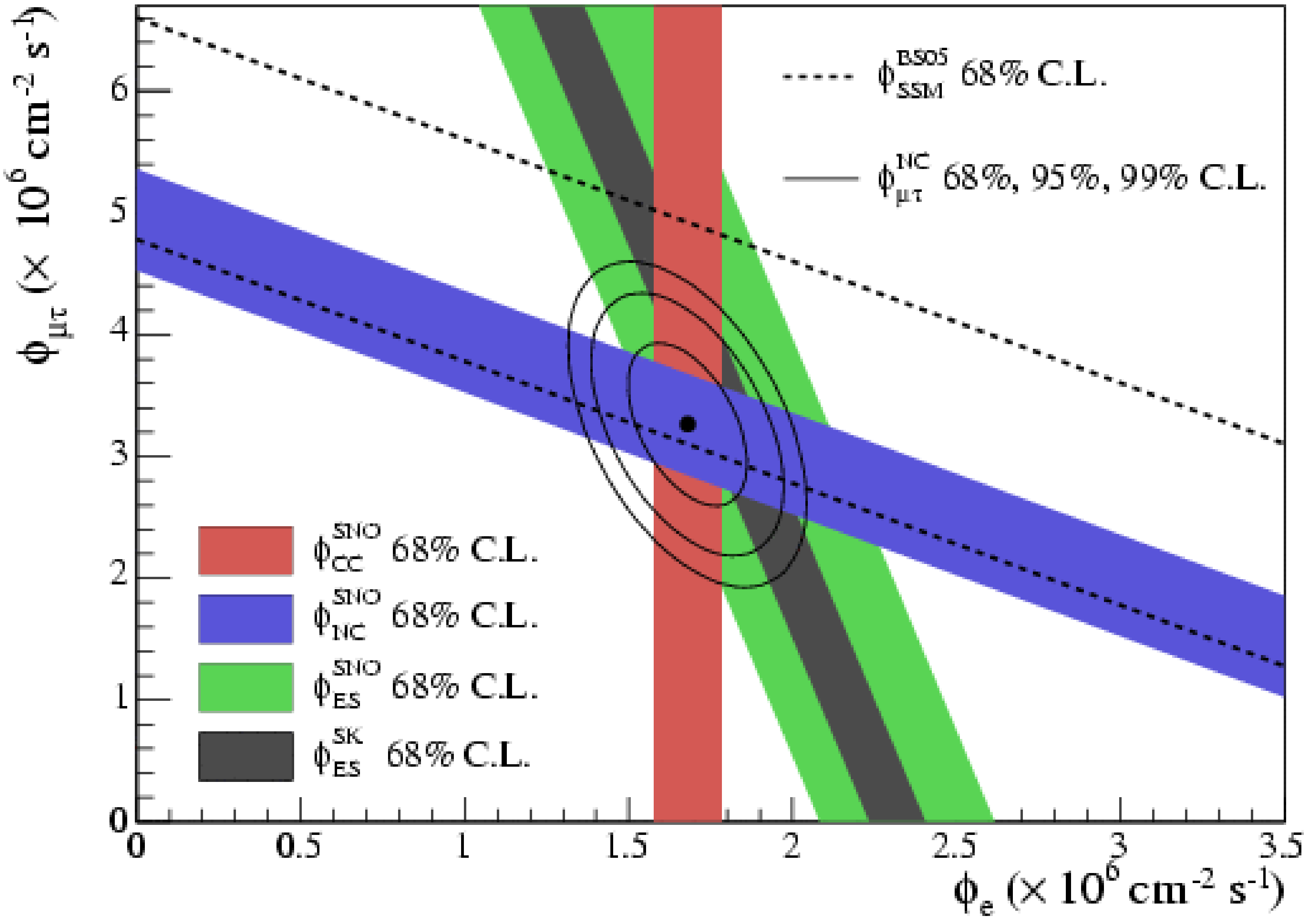
$$\nu_x + e^- \rightarrow \nu_x + e^- \quad \text{(elastic scattering, ES).}$$

ALL neutrinos experience this one but e do it more

ALL neutrinos do this equally

Only electron neutrinos do this

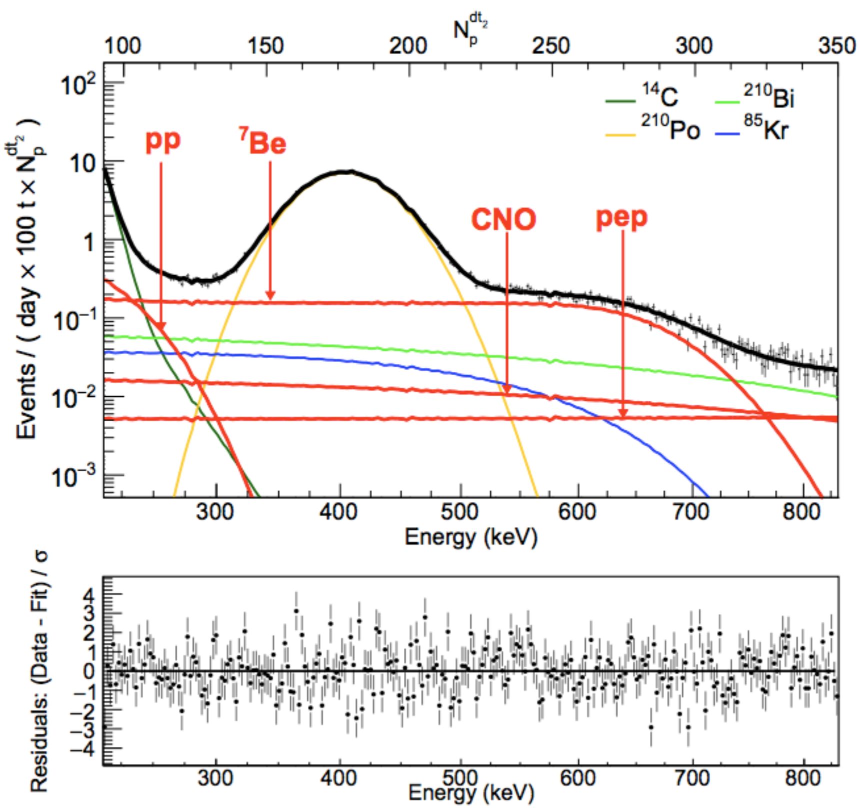
If neutrinos are oscillating rather than disappearing or underproducing, NC rate should match solar model but other rates should be low.

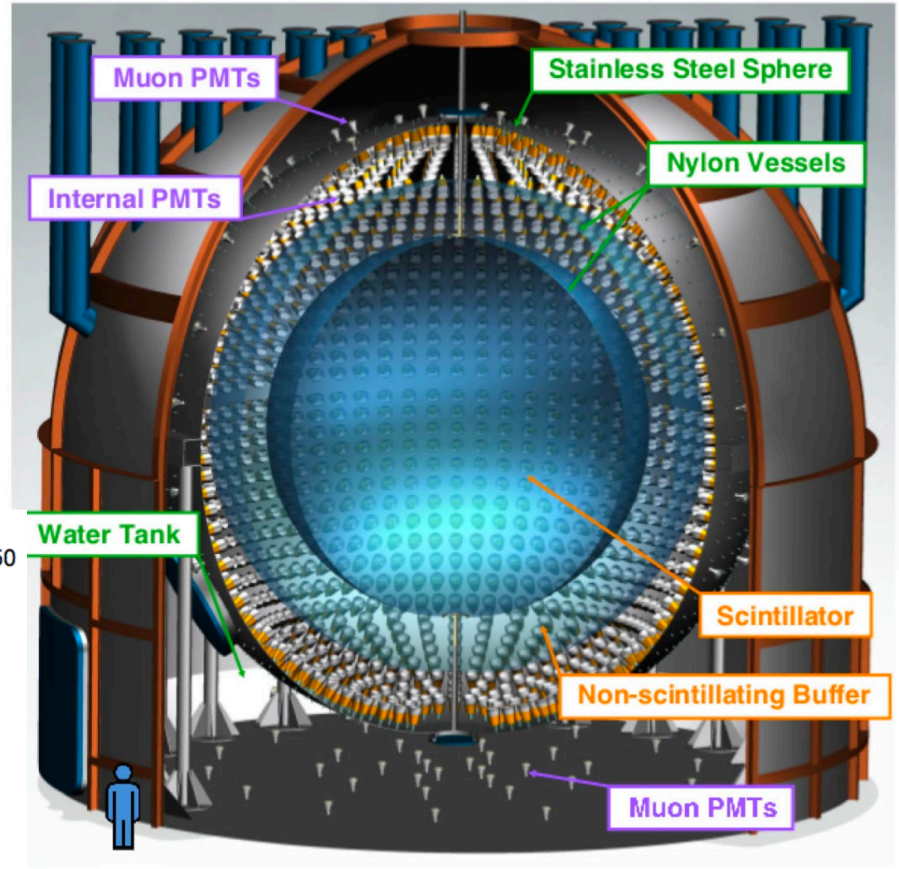


DEFINITIVE confirmation of oscillations between flavors. Nobel prize 2015.

BOREXINO

- The foremost precision solar neutrino observatory.
- Gran Sasso, 2007-2021
- Spectroscopically resolved ~all neutrinos in the pp chain



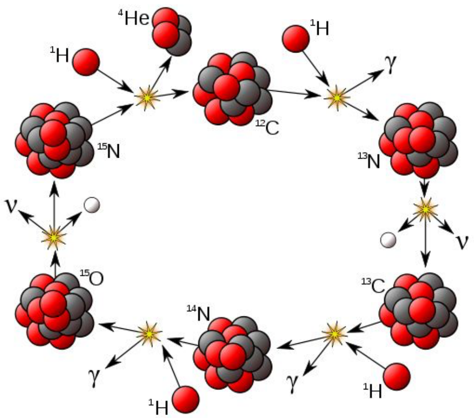


A masterpiece of detector instrumentation and radiopurity.

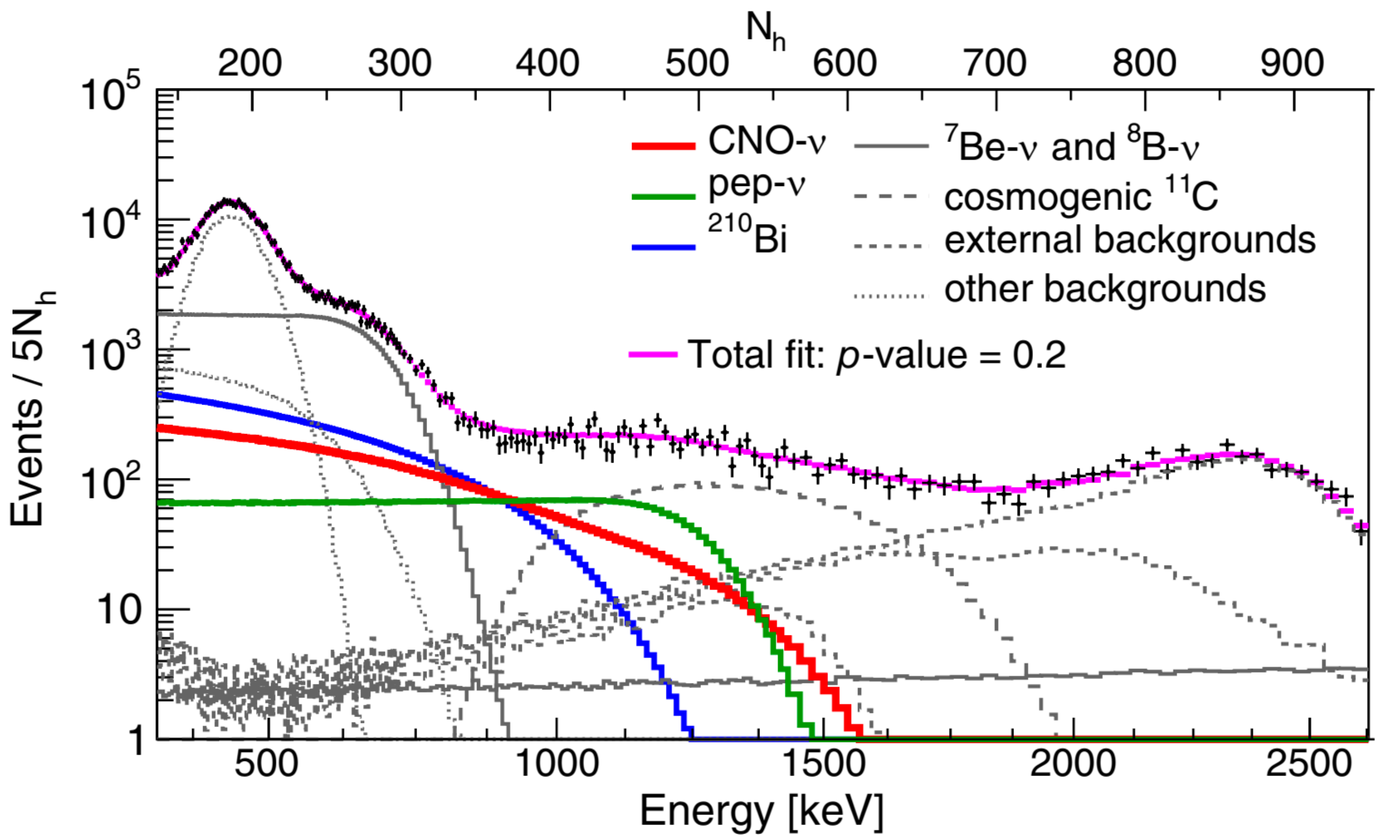
Borexino is the gold-standard for the field of low-background nuclear physics.

BOREXINO CNO

- The CNO cycle contributes only a tiny fraction of the Sun's neutrino flux, relative to pp cycle.
- It sits under numerous other flux contributions. Observing it is a tour-de-force in understanding detector responds and solar neutrino spectral shapes.



Borexino observes CNO flux at 7σ

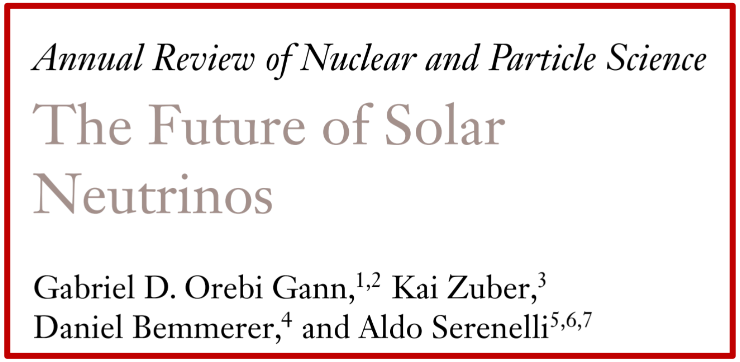


FUTURE OF SOLAR NEUTRINOS

As with reactors, predicting the absolute flux of solar neutrinos remains complicated.

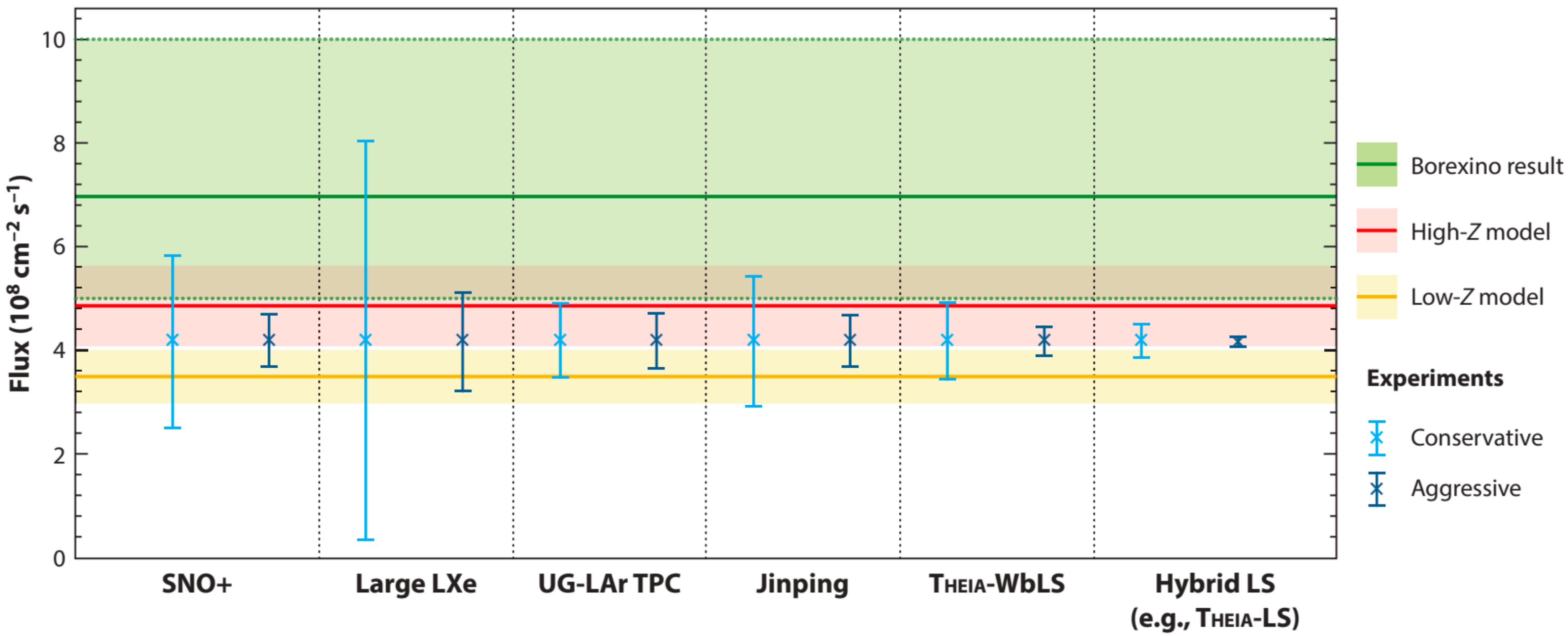
Solar metallicity from helioseismology still at odds with SSM tuned on neutrinos, at some level.

Various large, clean scintillator experiments have been discussed, to address this.


Annual Review of Nuclear and Particle Science

The Future of Solar Neutrinos

Gabriel D. Orebi Gann,[1,2] Kai Zuber,[3] Daniel Bemmerer,[4] and Aldo Serenelli[5,6,7]



SUMMARY

- Solar neutrinos were pivotal in establishing the mass and mixing of neutrinos.
- The transformation of solar neutrinos is energy dependent and reveals a rich phenomenology of neutrino oscillations and matter effects.
- All major species of solar neutrinos have now been detected.
- Their oscillations have been used to measure crucial parameters governing neutrino oscillations.
- Some complexities of the details of the solar model remain.