The Solar Neutrino Results from Borexino and Gallex:

Astrophysical Implications for our Understanding of the Sun and Other Stars

- ❑ The historical development of the solar neutrino problem
- ❑ The roles of Gallex and Borexino
- ❑ Remaining opportunities

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Solar Neutrino Astrophysics at LNGS

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N3AS Network in Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

The early days

In 1946 Bruno Pontecorvo suggested reactor neutrinos might be detectable using a radiochemical method based on ^{37}Cl

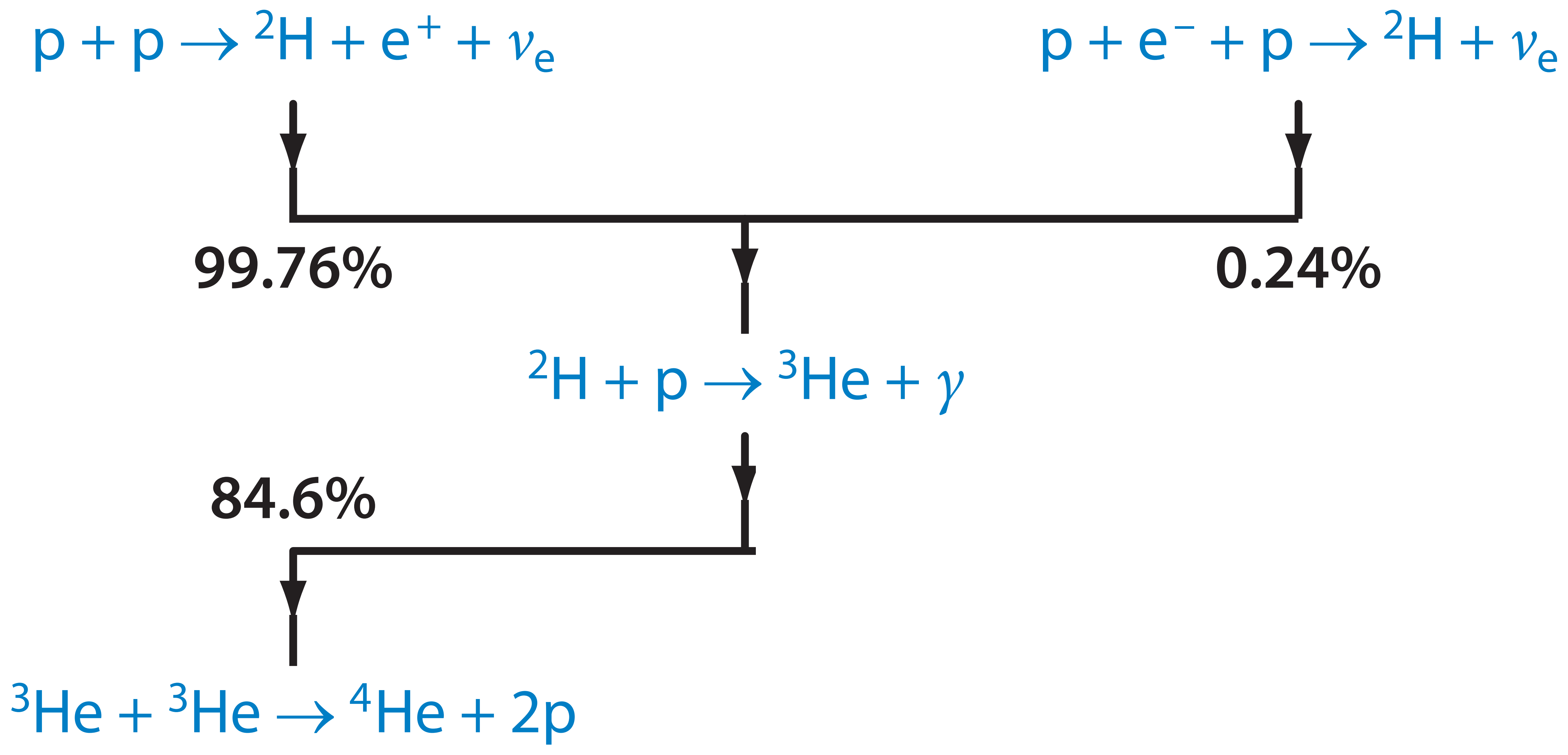
The idea was developed by Louie Alvarez, who estimated backgrounds and cross sections, proposed chemical methods for extracting ^{37}Ar, etc.

These studies were done before parity violation was discovered, and at a time when there were suggestions (later retracted) that the neutrino might be a Majorana particle

Davis mounted a 3.8 ton C_2Cl_4 detector at Brookhaven, buried 18 ft underground, to assess backgrounds

- placed a limit on the solar neutrino flux 40,000 SNU, assuming the Sun generated its energy from the CNO cycle

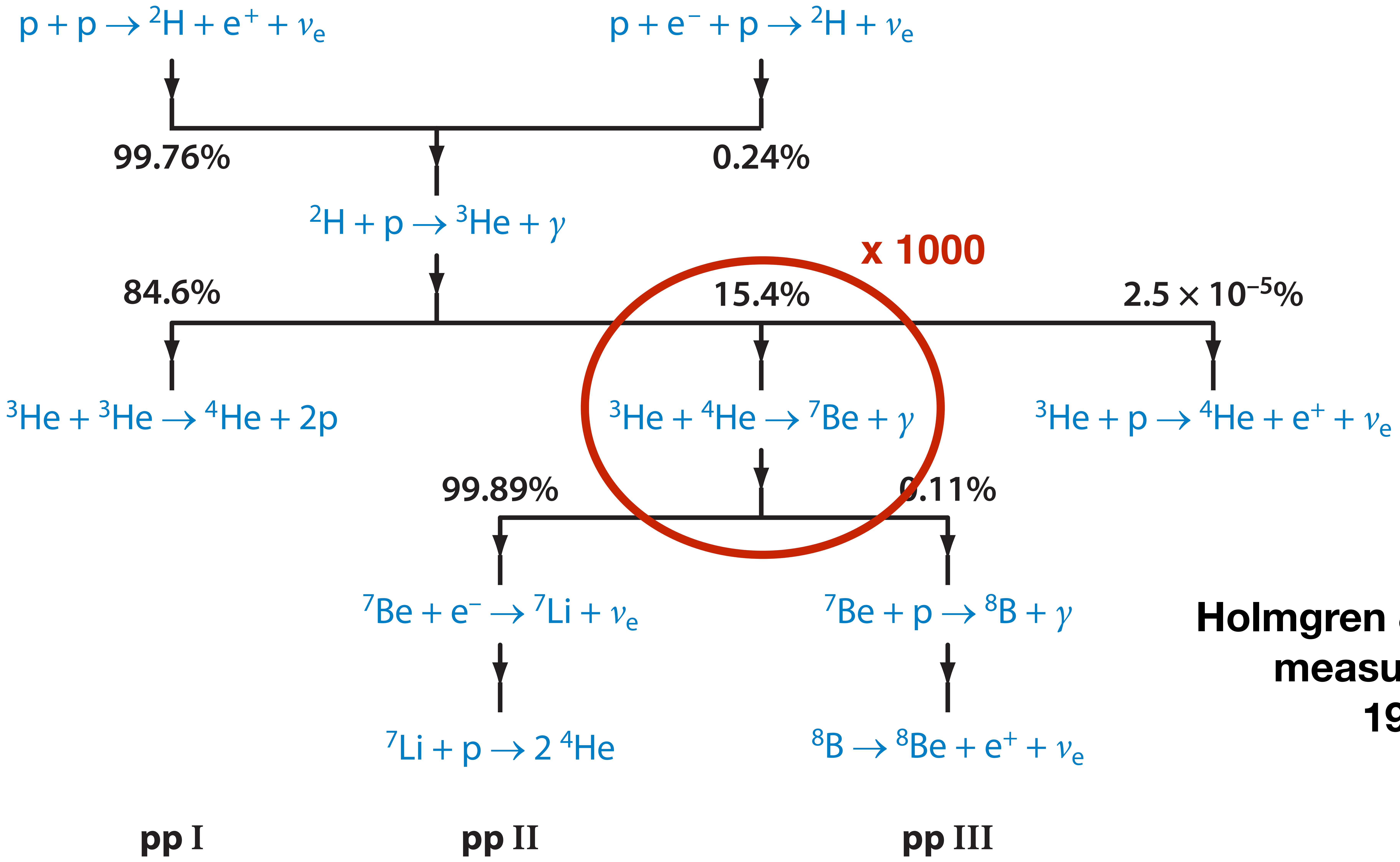
$$4\mathrm{p} \rightarrow {}^{4}\mathrm{He} + 2e^{+} + 2\nu_e + 26.7\ \mathrm{MeV}$$



pp I

Although Alvarez considered solar neutrinos, the expectation that the Sun operated on the ppI chain many that solar neutrinos were below the detection threshold for ^{37}Cl

$$4\mathrm{p} \rightarrow {}^{4}\mathrm{He} + 2e^{+} + 2\nu_e + 26.7\ \mathrm{MeV}$$



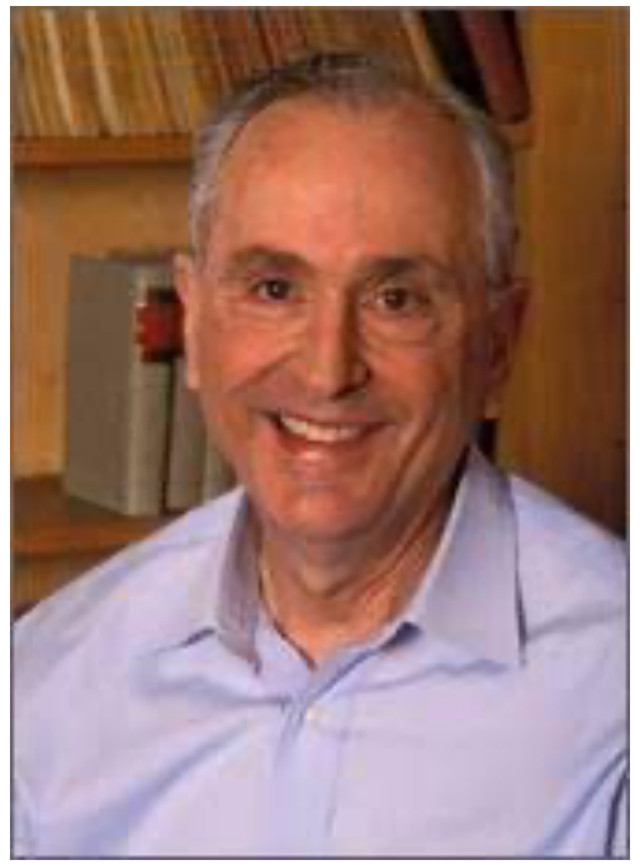
Holmgren & Johnston measurement 1959

Willie Fowler recognized the implications (Fowler 58) for the Cl detector

John Bahcall had spent his first postdoctoral year at Indiana, with Konopinski, working on electron capture in stellar plasmas

In 1962 Willie recruited John to join the Caltech stellar modeling group off Icko Ben and Dick Sears, with the goal of creating the first quantitative numerical model of the Sun, one able to predict the core temperature profile

John computed the neutrino fluxes "off line," from that profile: 1 capture/day/100,000 g of C_2Cl_4

The experiment appeared to be very challenging, given the capture rate

The capture rate estimate had been based on the known strength off the transition to the ^{37}Ar ground state: $^{37}\mathrm{Cl}(g.s)(\nu + e^-)^{37}\mathrm{Ar}(g.s)$

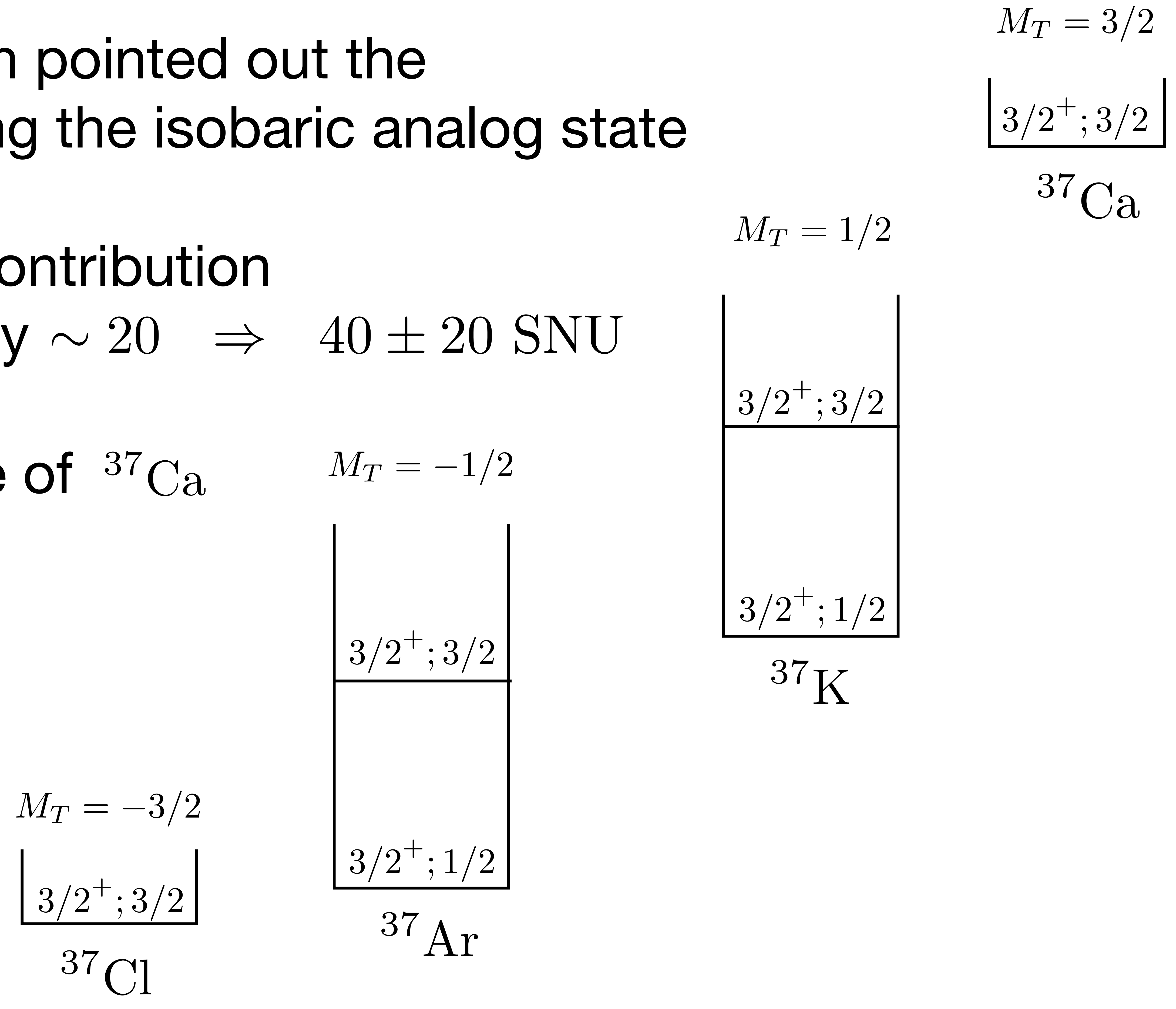
During a seminar by Bahcall in 1963, Mottelson pointed out the potential importance of excited states, including the isobaric analog state

Bahcall built a nuclear model to estimate the contribution of the excited states: capture rate increased by $\sim 20 \quad \Rightarrow \quad 40 \pm 20$ SNU

Validation: predicted the then unknown lifetime of $^{37}\mathrm{Ca}$

Subsequently measured, agreed to 20%

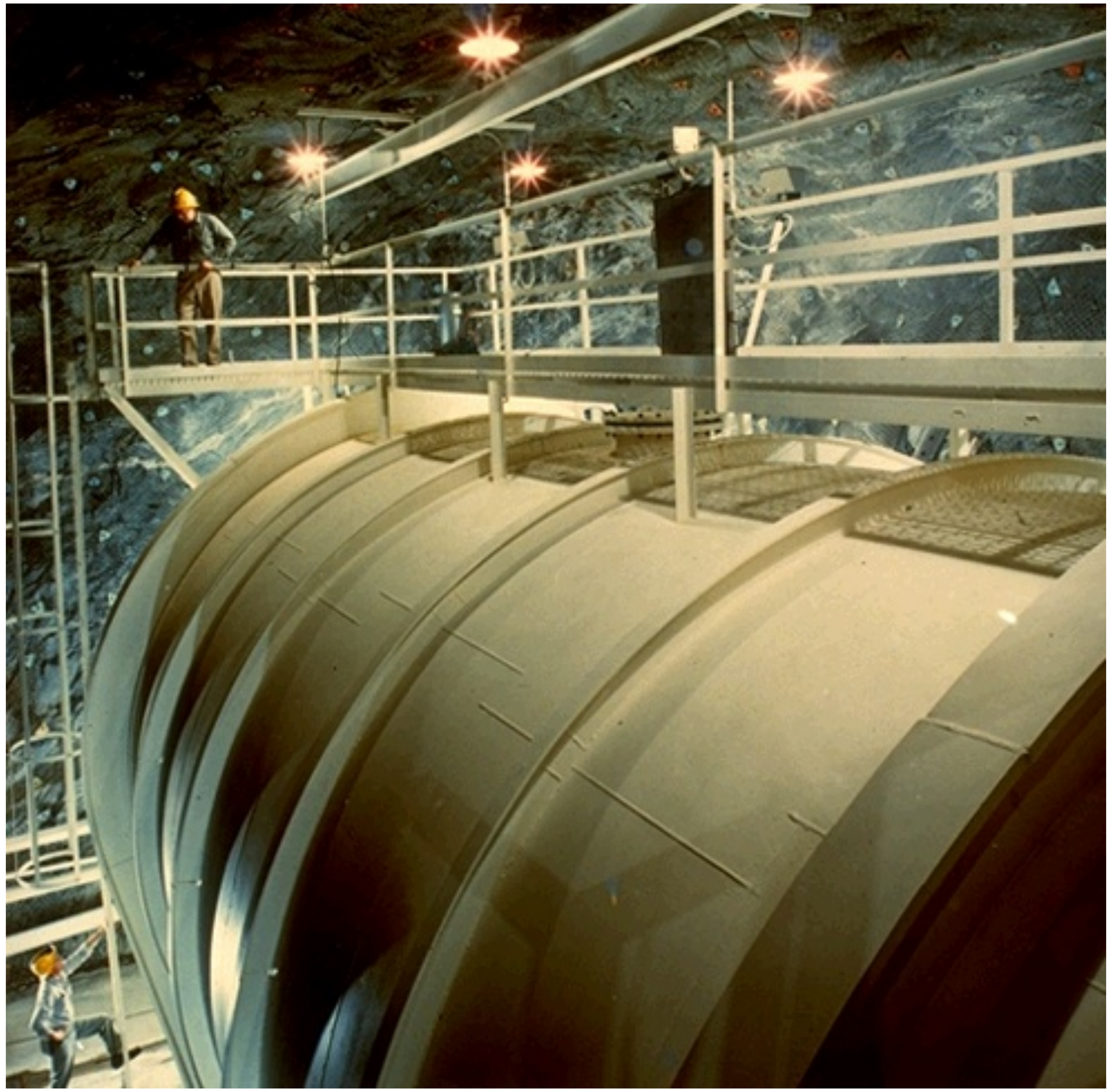
1964: Bahcall and Davis published back-to-back PRLs arguing that solar neutrinos could now be measured



The Homestake Experiment

In 1964 Homestake agreed to host the experiment: cavern complete in mid-1965 on th 4850 ft level of the mine

The steel containment vessel was fabricated in Chicago, shipped in pieces to Homestake, and finished in 1966.



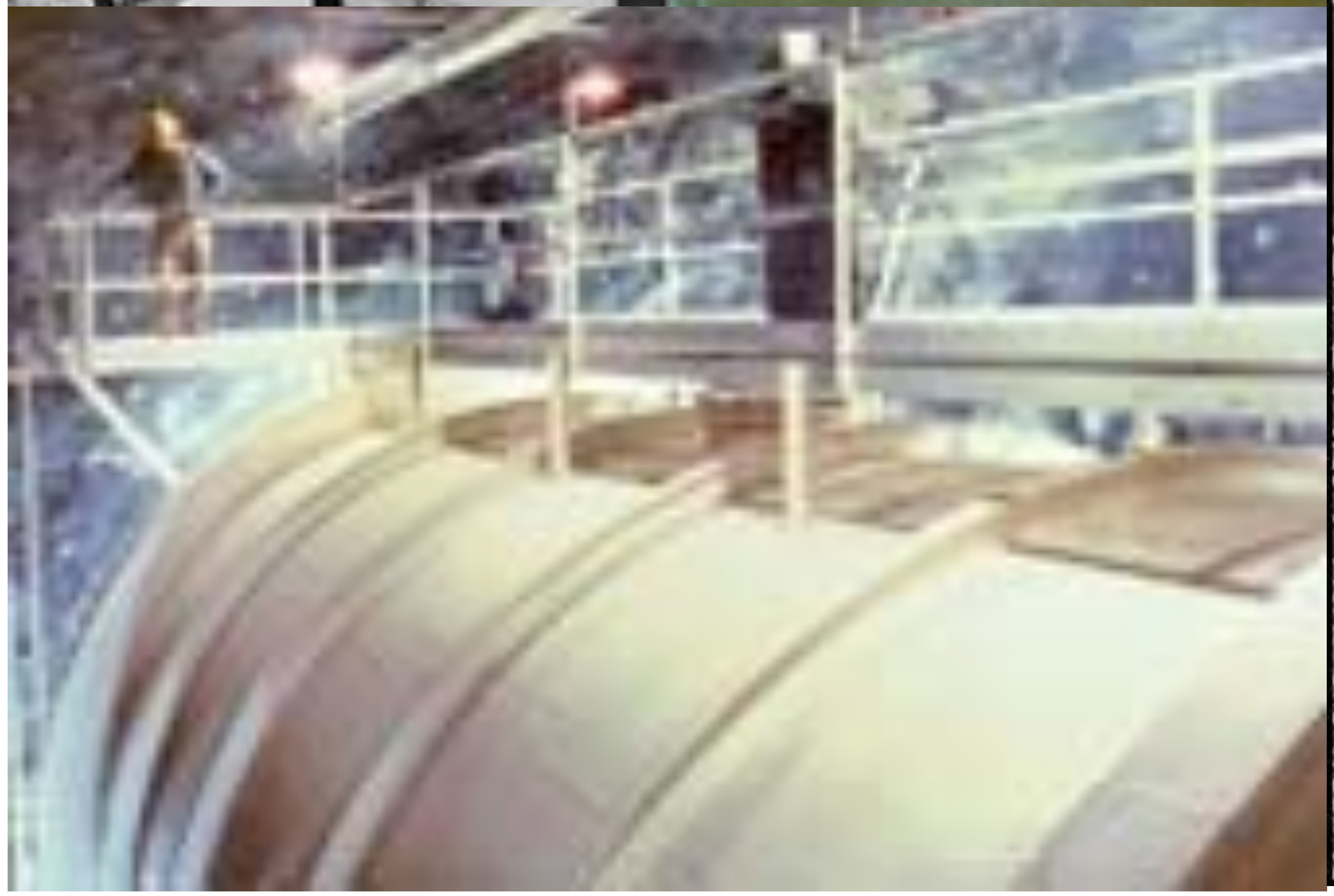
The C_2Cl_4 was brought to the mine in 10 railway tankers, then taken underground by hoist, in small batches

Th first results from the experiment were announce in 1968, an upper bound of 3 SNU

The theoretical prediction at the time was 7.5 ± 3 SNU (Bahcal, Bahcall, Shaviv)

This focused attention on the credibility of the SSM




The Standard Solar Model

- Origin of solar neutrino physics: desire to test our model of low-mass, main-sequence stellar evolution
  - local hydrostatic equilibrium: gas pressure gradient counteracting gravitational force
  - hydrogen burning: 4p → 4He + energy (+ neutrinos)
  - energy transport by radiation (interior) and convection (envelope)
  - boundary conditions: today's mass, radius, luminosity, …

- The implementation of this physics requires
  - an electron gas EoS
  - cross sections for the very low energy nuclear reactions
  - radiative opacity
  - some means of fixing the composition at ZAMS, including the ratios H:He:metals

This model describes 70% of the stars in the Milky Way, critical to the interpretation of modern surveys like those of the ESA's Plato Mission

- our picture of pre-solar contraction, evolution impacts the SSM
  - Sun forms from a contracting primordial gas cloud
  - passes through the Hayashi phase: cool, opaque, large temperature gradients, slowly contacting — convective, mixed
  - radiative transport becomes more efficient at the stars center: radiative core grows from the center outward, reaching its modern form in about 30M yr
  - nuclear burning becomes the dominant source of energy

- Because of the Hayashi phase mixing, the proto-Sun is assumed to be homogeneous
  - $X_{\rm ini} + Y_{\rm ini} + Z_{\rm ini} = 1$
  - relative metal abundances are taken from a combination of photospheric (volatile) and meteoritic (refractory) measurements
  - $Z_{\rm ini}$ find to surface abundance, after correction for diffusion
  - $Y_{\rm ini}$ and $\alpha_{\rm MLT}$ adjusted to produce present-day $L_\odot$ and $R_\odot$

Result is a dynamic Sun, evolving over 4.6 b.y.

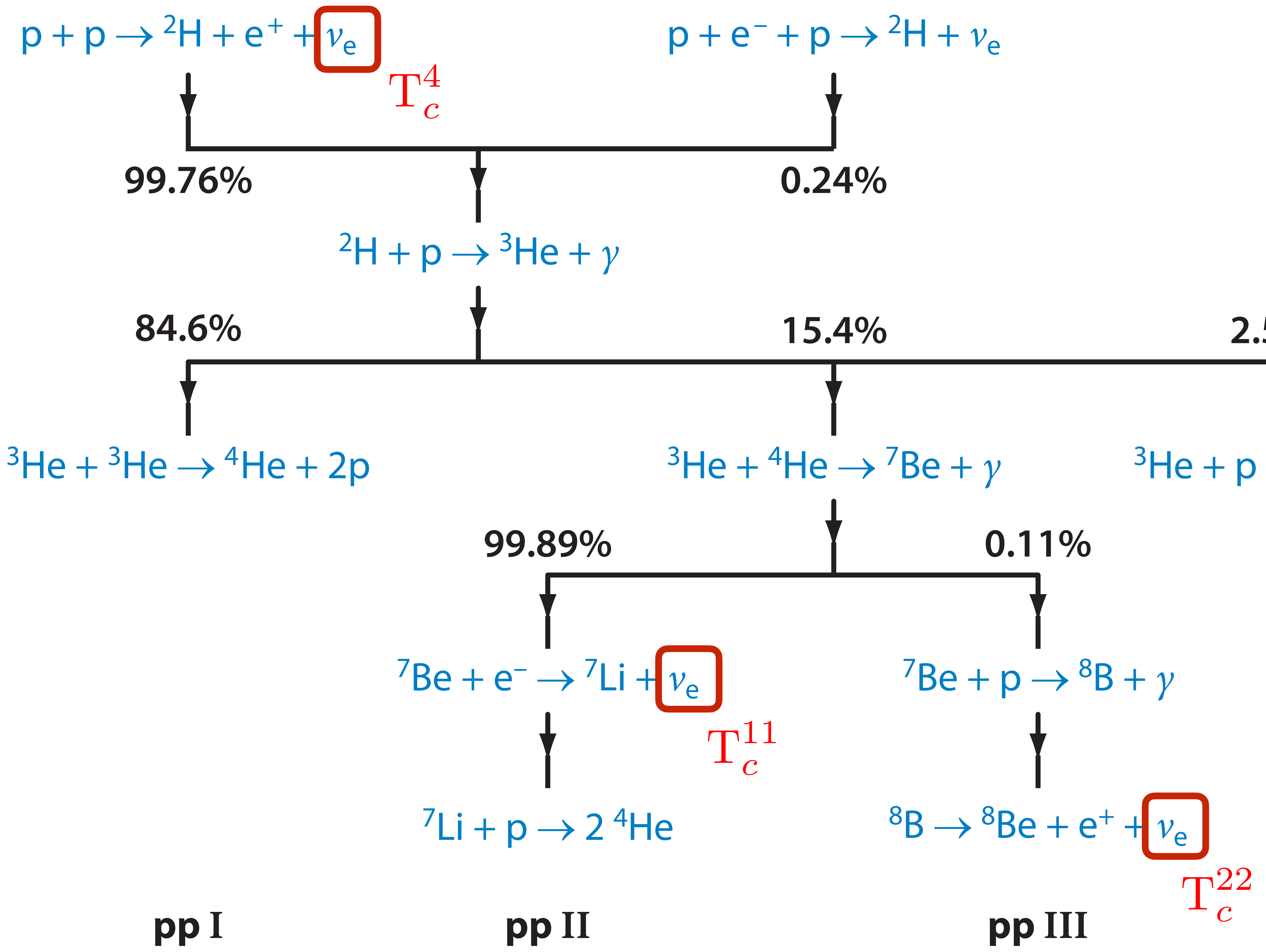
- 44% luminosity growth over solar lifetime
  - paleo-climate implications

- ^{8}B neutrino flux is relatively contemporary
  - $\phi(^8\mathrm{B}) \sim \phi_0\, e^{-\tau/\tau_0}.\ \ \tau_0 \sim 0.9\ \mathrm{b.y.}$

- significant compositional gradients established over time
  - over $\sim$ 10^8 years, all of the core's C and 6% of its O is burned to N, via the CNO cycle, prior to establishment of CNO equilibrium - drives early convection
  - central core's ^{4}He mass fraction Y_{ini} increases from 0.27 to 0.64 over 4.6 b.y.
  - a steep gradient in ^{3}He is formed in the core region, increasing with radius, extending over an increasing fraction of the core as the Sun evolves
  - slow diffusion of ^{4}He and metals, towards the core, reflecting their smaller Z/A: has an observable effect on helioseismology

The model predicts today's core temperature, T_c, which we can cross-check

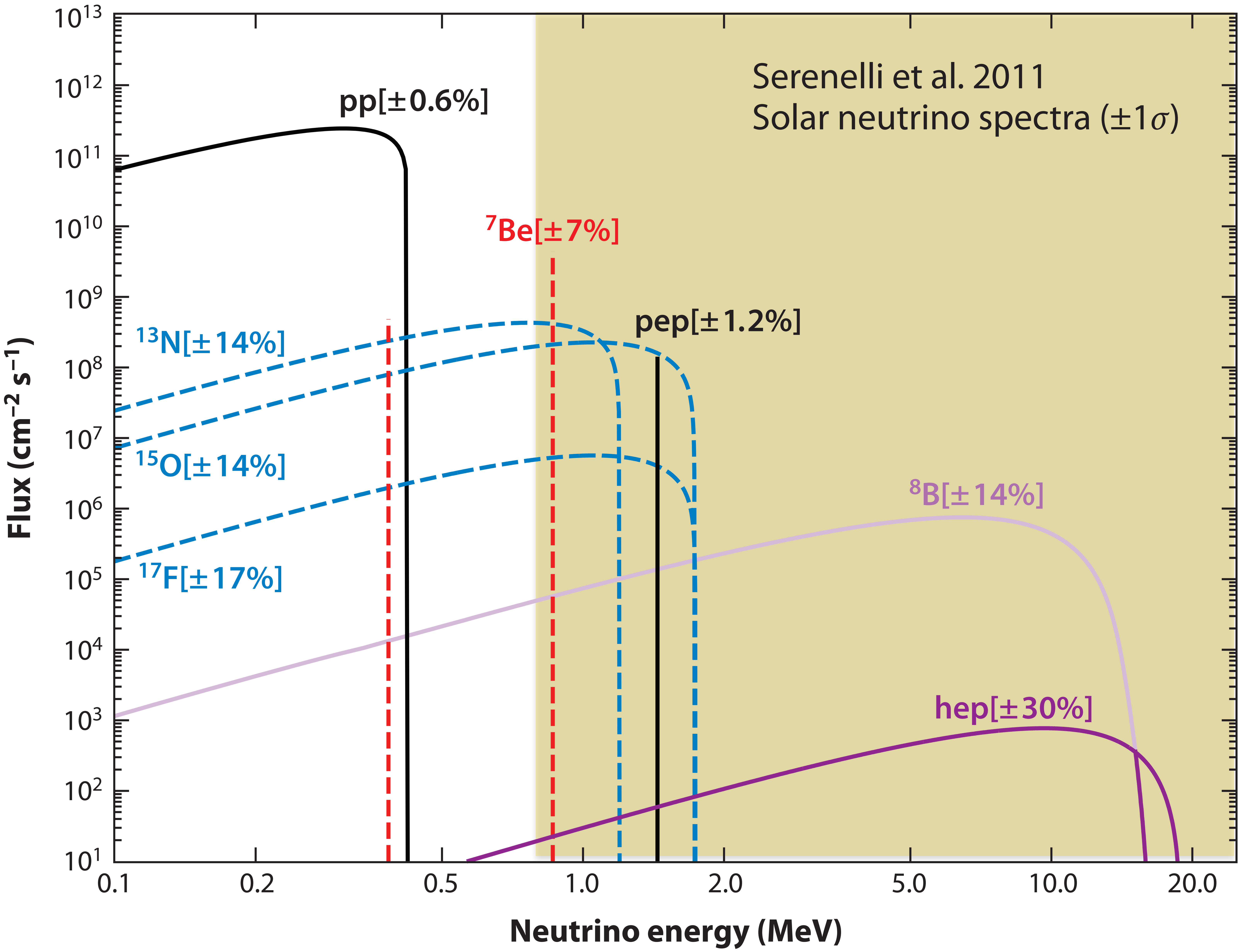
$$4\text{p} \rightarrow {}^4\text{He} + 2e^+ + 2\nu_e + 26.7\ \text{MeV}$$



dependence on the core temperature

Have a neutrino thermometer capable of measuring the solar core temperature to 1%

^{37}Cl (1968+)



This steep temperature dependence of the 8B flux led some to discount the solar neutrino problem

Several dozen solar-model “solutions” were suggested in the 1970s

Most strived to reduce the core temperature by 5%, thereby suppressing the ^{8}B neutrino flux dominating the ^{37}Cl rate

Some of the more interesting ideas focused on physics assumptions of the SSM

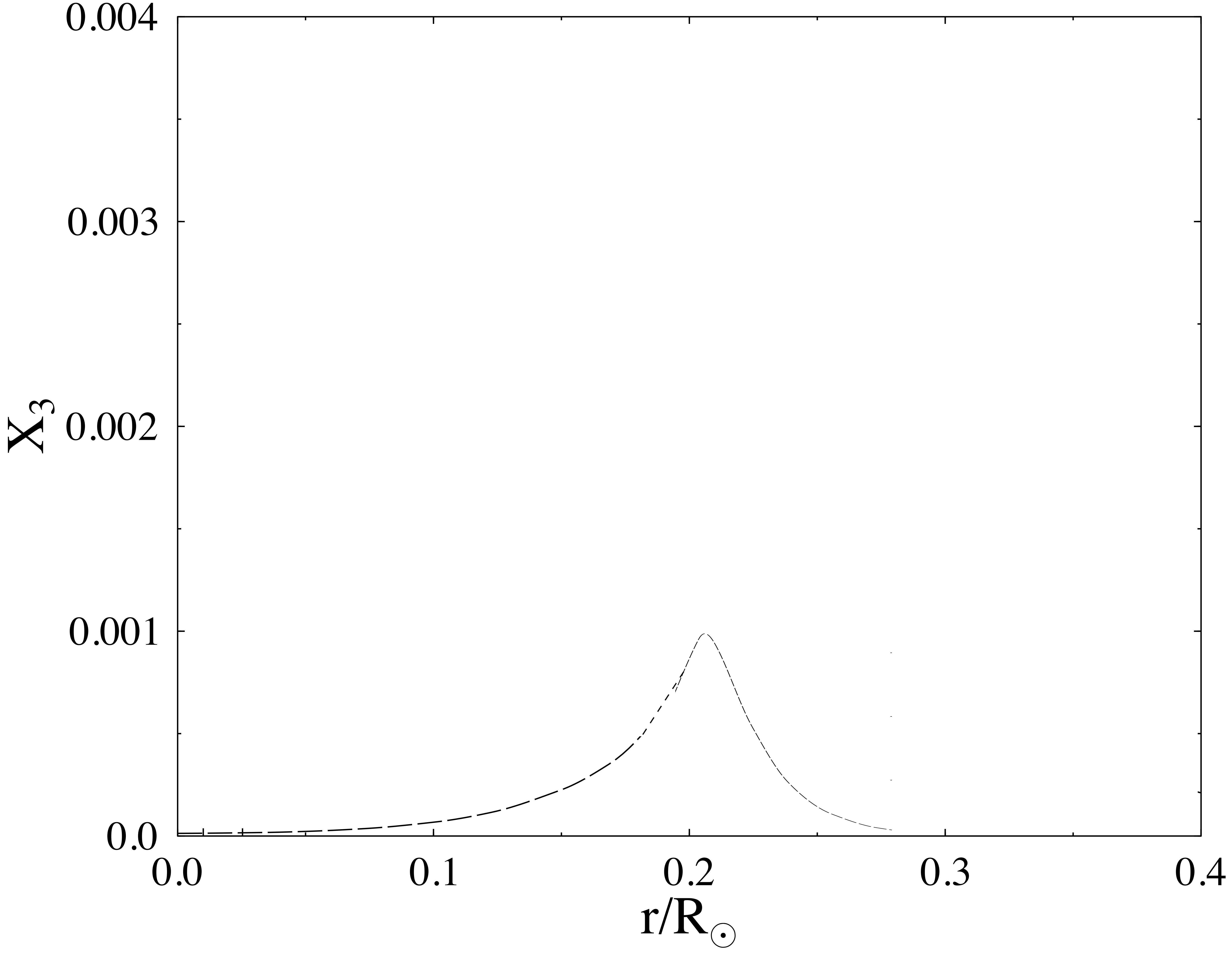
- the homogeneity of the Sun: passage through a dust cloud, infall of planets

- the Sun’s 1D character: perhaps the earliest ida was that of Ezer and Cameron, of core mixing that would replenish core hydrogen — thus both lowering the core temperature and reducing the long-term luminosity growth of the SSM

- relaxing the assumption of hydrostatic equilibrium

“Solar Spoon,” Dilke and and Gough, Nature 240 (1972) 262

The Solar Spoon: Dilke and Gough



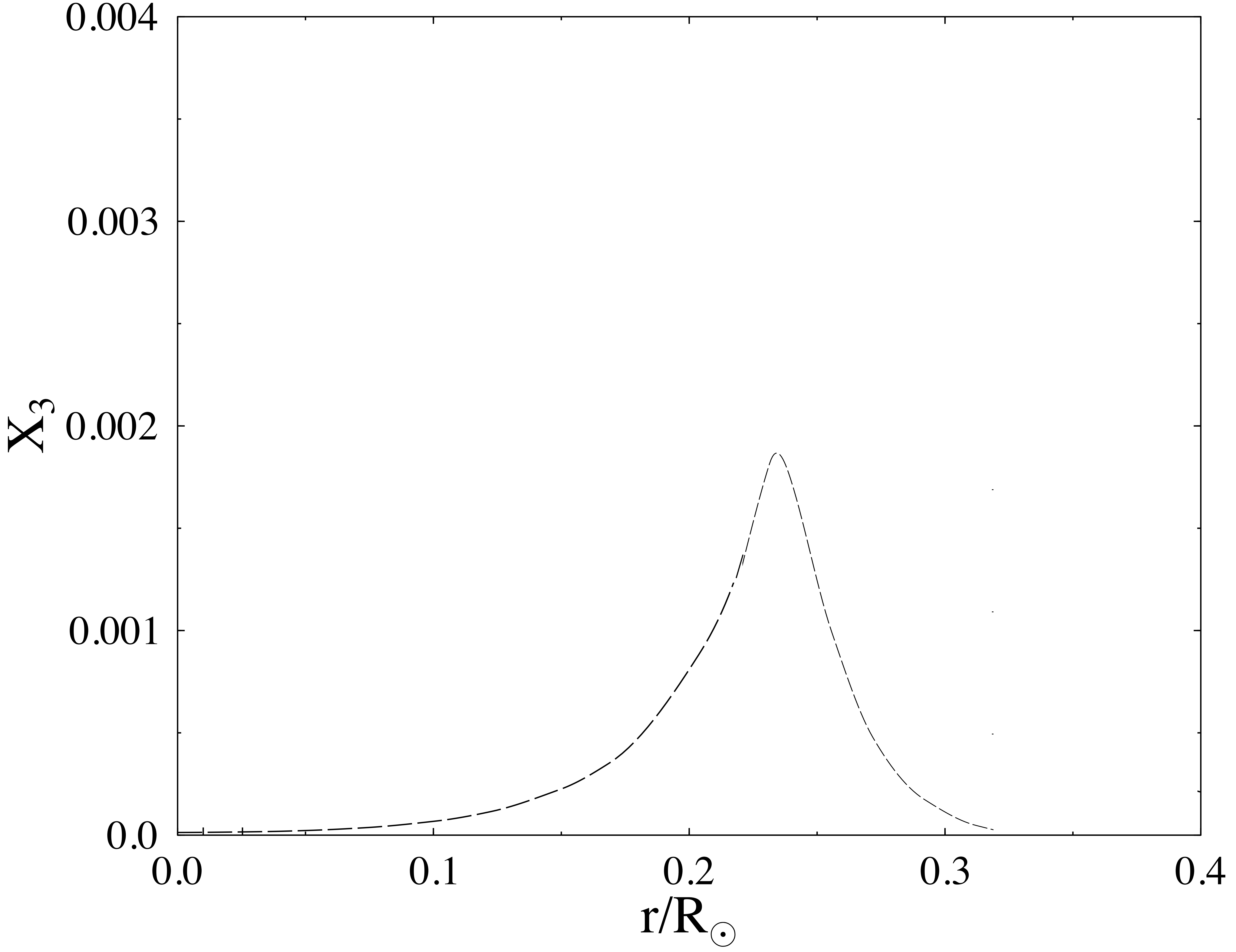
^{3}He is produced and consumed in the pp chain, acting as a catalyst

At a given radius/temperature, there is a time required to reach equilibrium

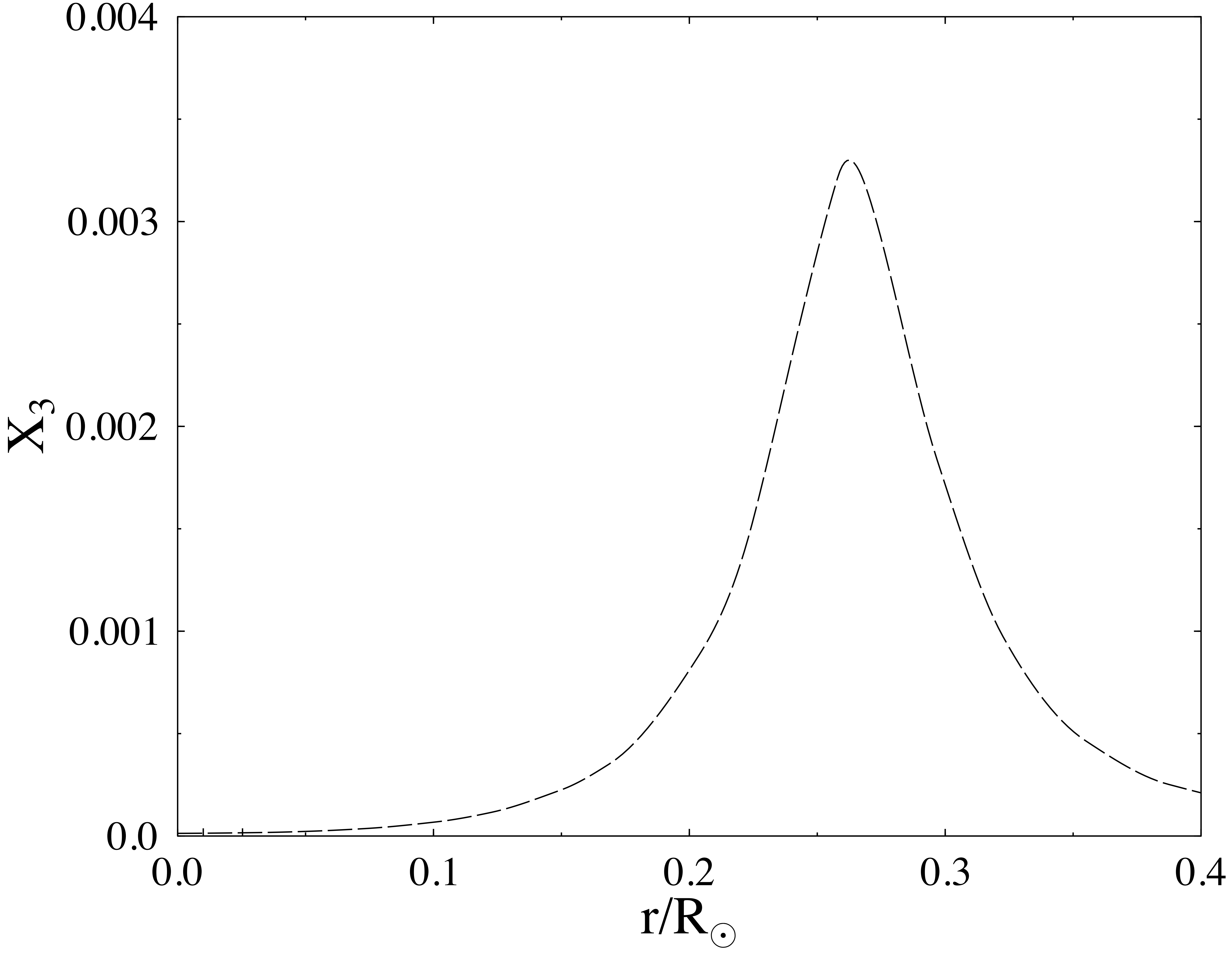
$$\tau_{\rm eq} \sim T_7^{-10}$$

and an equilibrium abundance

$$X_3^{\rm eq} \sim T_7^{-6}$$


0.004
0.003
0.002
0.001
0.0
X_3
0.0
0.1
0.2
0.3
0.4
$r/R_\odot$

The Solar Spoon: Dilke and Gough



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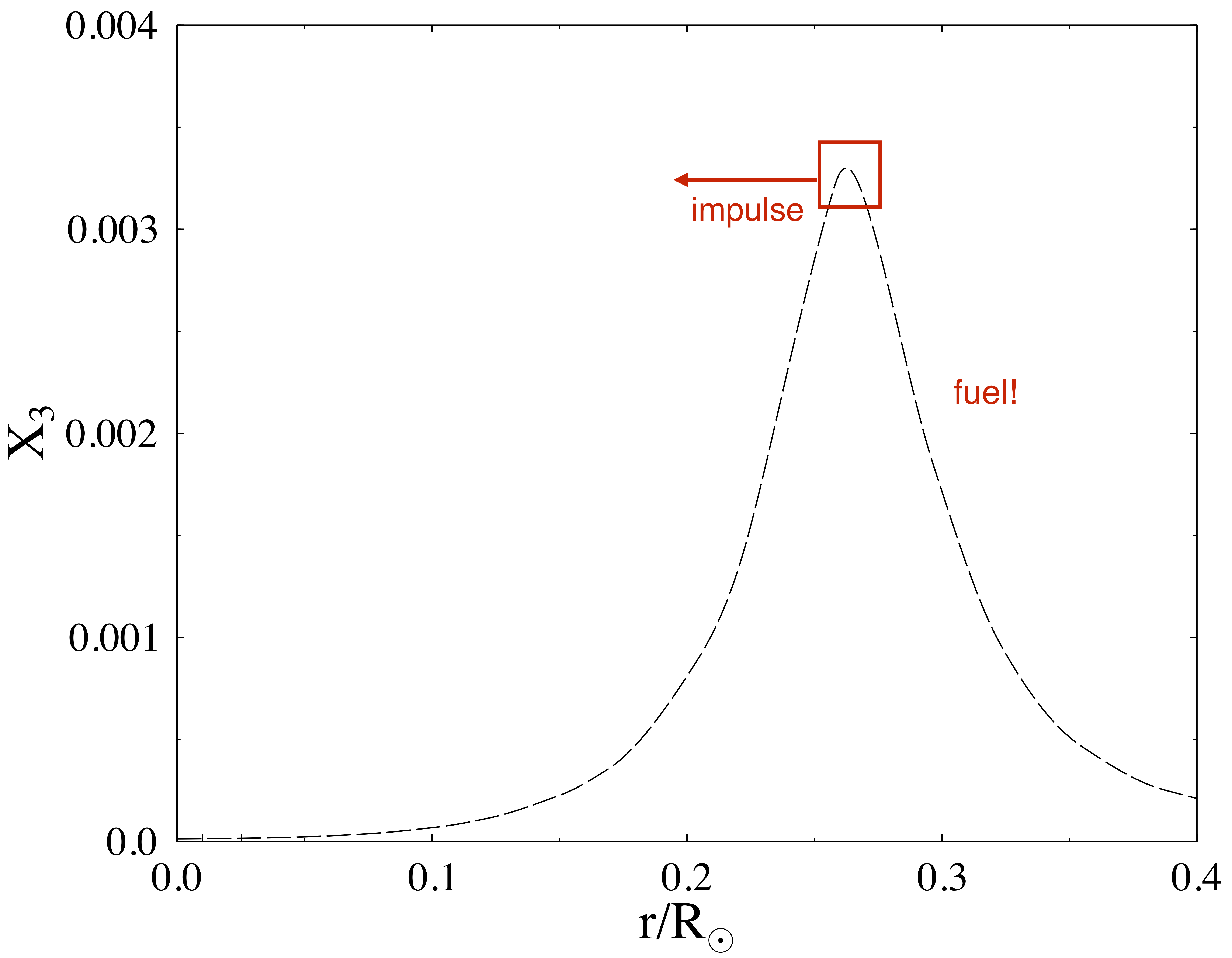

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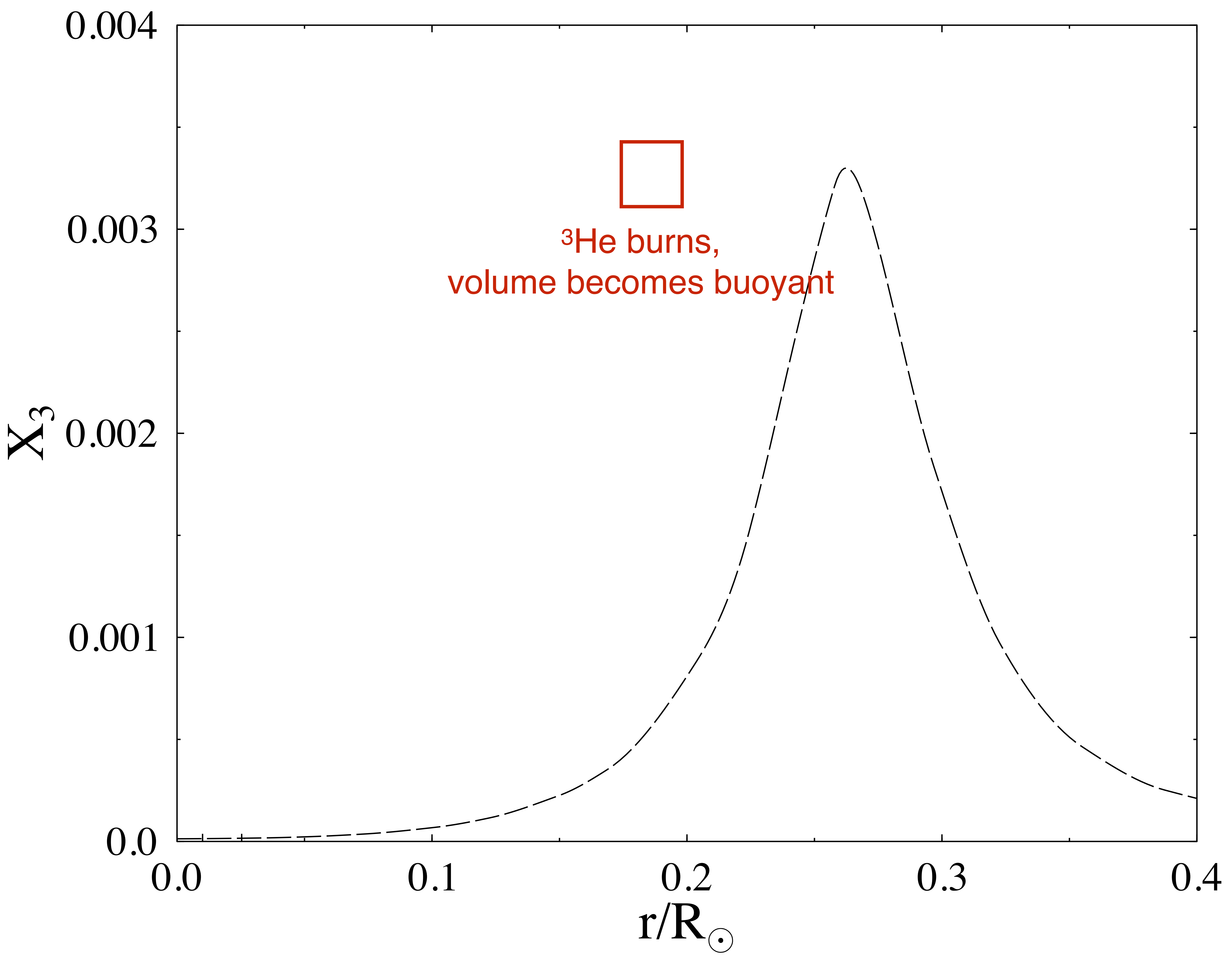
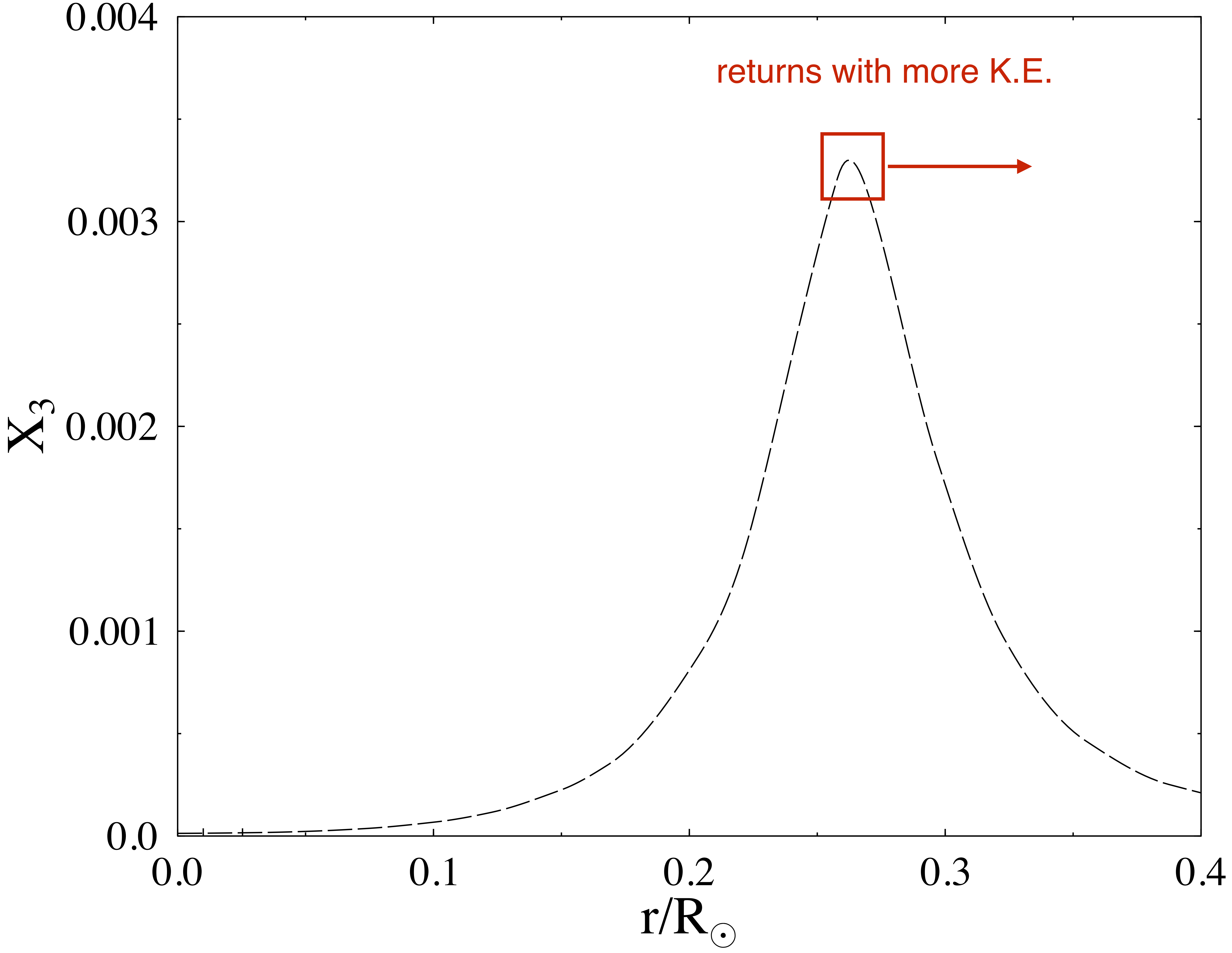


The Solar Spoon: Dilke and Gough



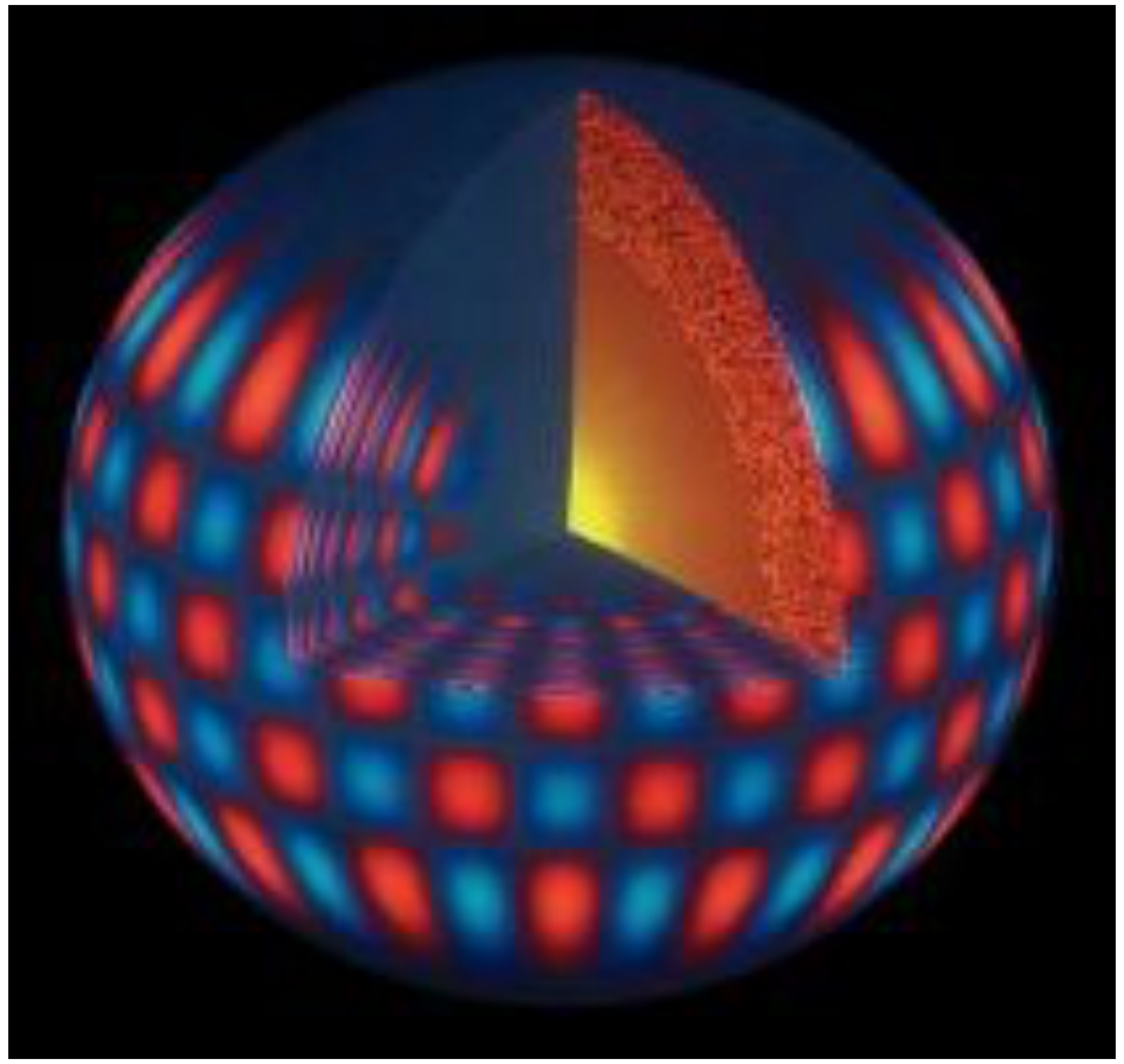
Dilke and Gough found that a sufficient gradient would arise after 3×10^8 yrs of normal solar burning

This over-stability was then conjectured to drive mixing of the core, forcing the Sun out of equilibrium for 2 My

Existence of the overstability was verified by several others, but whether it was capable of driving the mixing (rather than a finite amplitude oscillation) was debated

Two empirical tests became available to test such conjectures

From NSO/GONG



- helioseismology

Mixing models like the solar spoon, while triggered by ^{3}He, would necessarily change the ^{4}He profile as well, altering the sound speed in a characteristic way

Christensen-Dalsgaard and Gough in 1976 first used individual modes to constrain the solar model: data quality allowed for both mixed (low-Y) and standard (high-Y) solutions

By 1983 data and inversion methods had improved to the point that only the high-Y solution was viable (Duvall and Harvey, Nature 302 (1983) 24)

Observational improvements — BiSON, GONG, SoHO, SDO — ultimately yielding $\delta c \sim 0.5\%$

- new neutrino experiments: more especially, the Ga experiments

The Ga Experiments

- An international effort to realize a Ga experiment was organized in 1978, and included BNL, IAS, MPI Heidelberg, Univ. Pennsylvania, and the Weizman Institute

- Envisioned as a 50-ton experiment, cosponsored by the US DoE and MPI

- A 1.3-ton pilot experiment was done at BNL, demonstrating quantitative extraction of the produced ^{71}Ge from $GaCl_3$

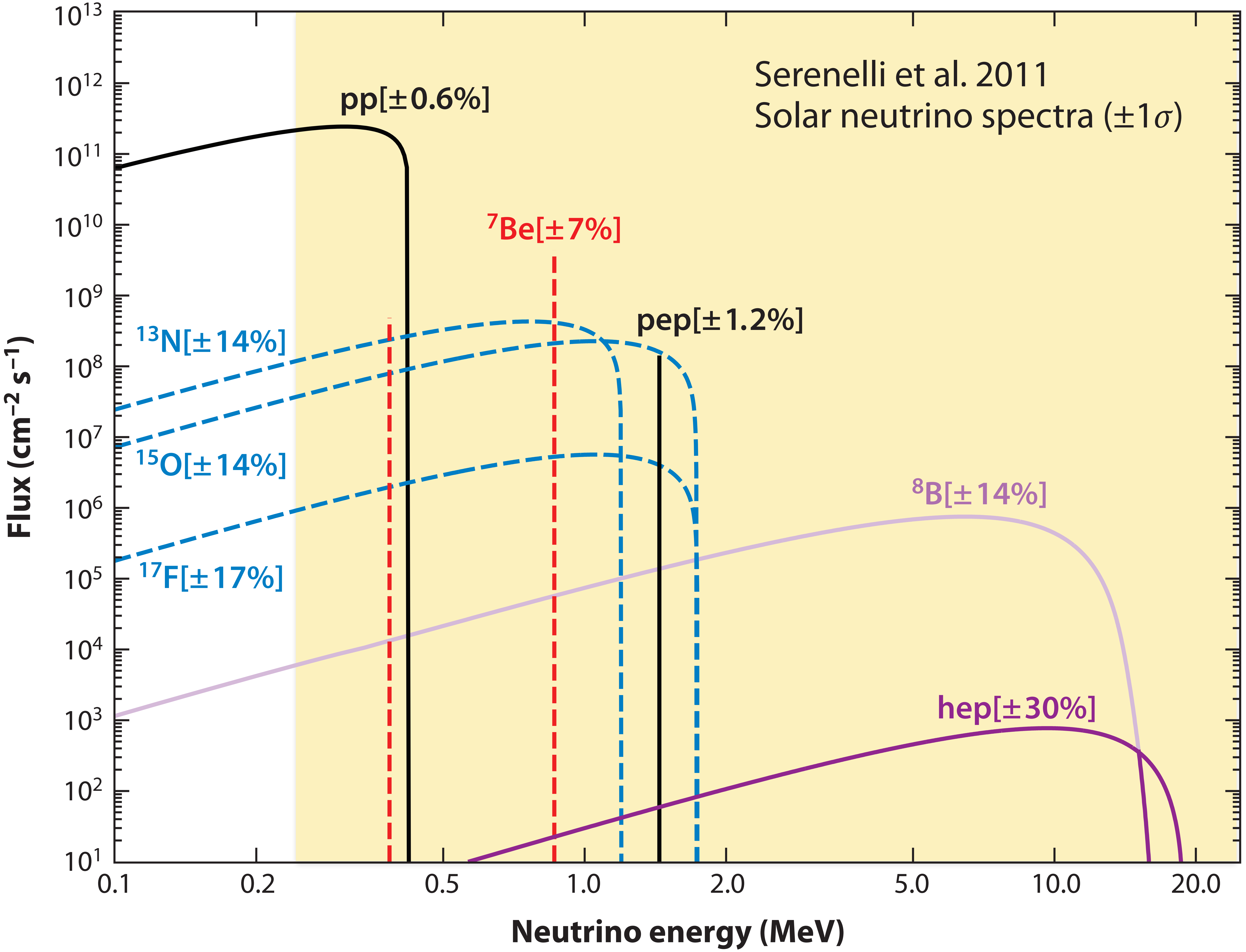
- The efficient counting of ^{71}Ge via its electron capture was demonstrated at MPI

- Despite the endorsements of two high-level review panels, US funding never came, delaying this important experiment for 6-7 years

- The effort was re-organized in Europe, with the necessary international agreements for Ga procurement quickly going forward, leading to Gallex @ Gran Sasso

- Parallel effort in the Soviet Union using Ga metal: SAGE @ Baksan

Gallex/SAGE (1990+)



- The experiment had the potential to distinguished between astrophysical and particle solutions to the solar neutrino problem: a minimum astronomical counting rate

$$\langle \sigma\phi \rangle \gtrsim 79 \text{ SNU} \qquad \text{if no new weak physics}$$

corresponding to the Sun producing all of its energy through the ppI cycle (pp and pep neutrino only), assuming only steady-state burning

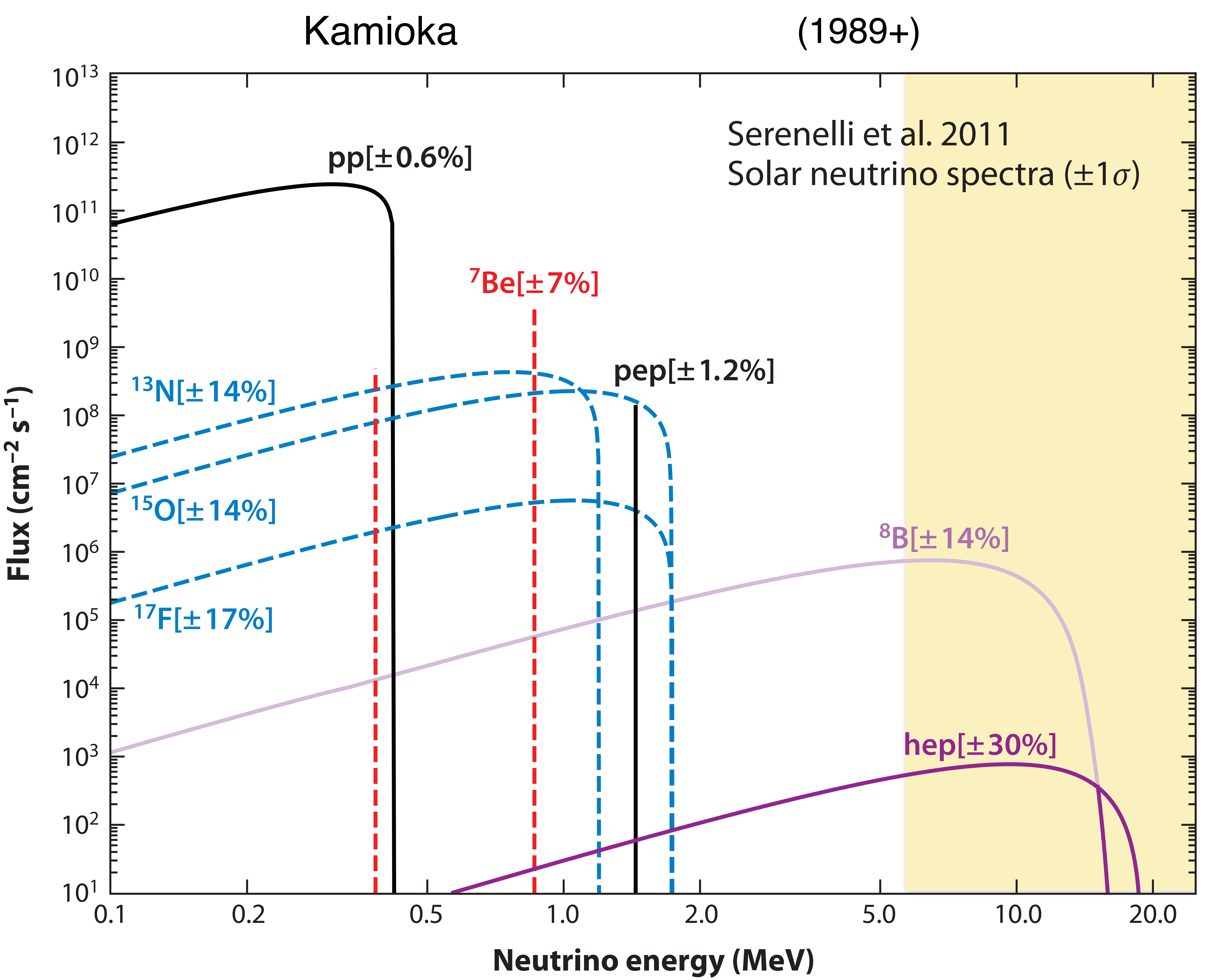
- It combination with results from ^{37}Cl and expected from Kamioka II, it was recognized that a Ga measurement would factor possible oscillation solutions into "islands" in $\Delta m^2 - \sin^2 2\theta$ plane, later to be named the LMA, SMA, and LOW solutions

- The results from the Gallex/GNO and SAGE experiments proved near the minimum astronomical value

$$69.3 \pm 5.5 \text{ SNU} \qquad \text{Gallex/GNO}$$

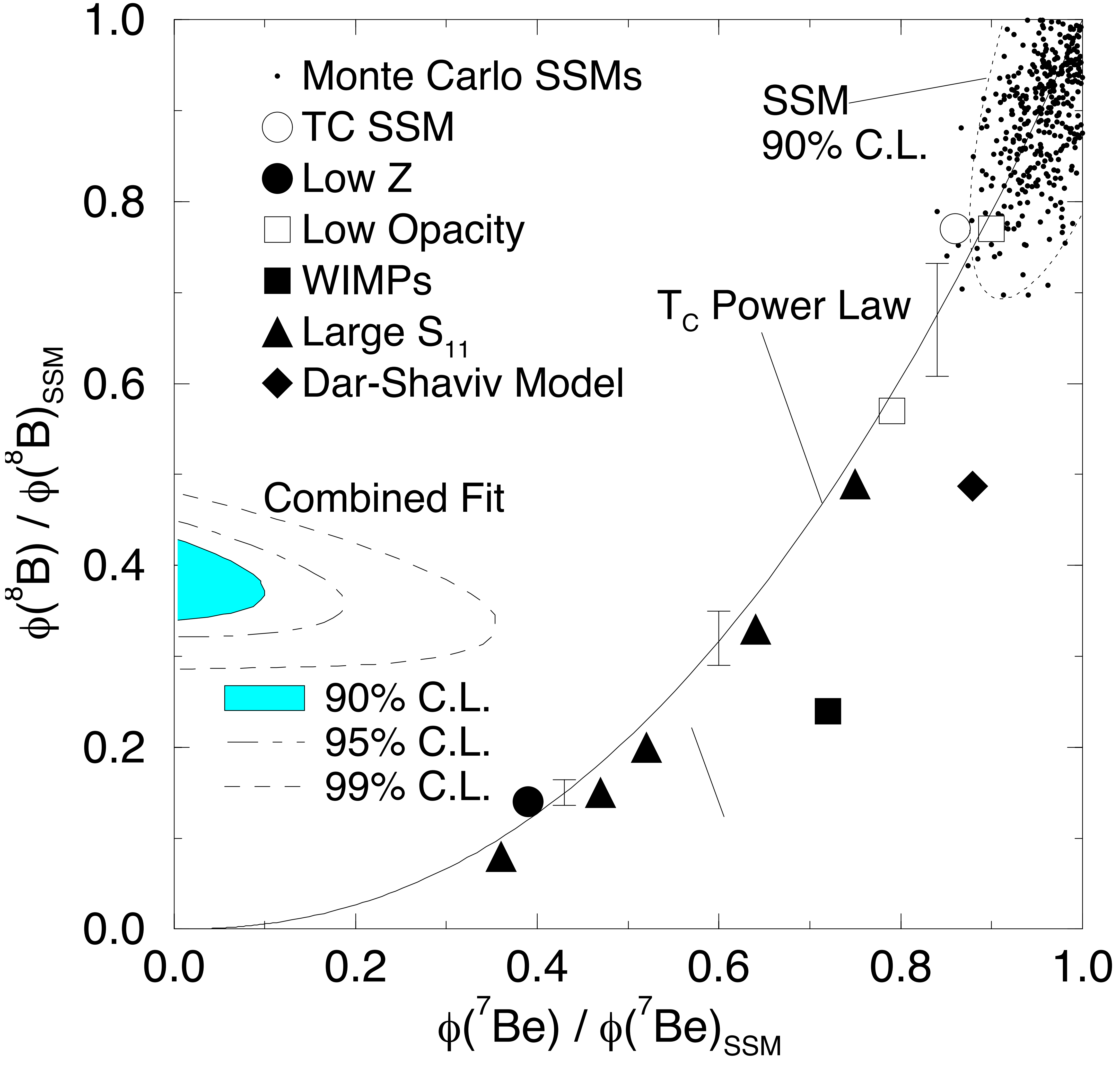
$$65.4^{+3.1}_{-3.0}(\text{stat})^{+2.6}_{-2.8}(\text{sys}) \text{ SNU} \qquad \text{SAGE}$$

- Further, when the Ga results were combined with those from ^{37}Cl and Kamioka II:


Kamioka
(1989+)
Serenelli et al. 2011
Solar neutrino spectra (±1σ)
pp[±0.6%]
7Be[±7%]
pep[±1.2%]
13N[±14%]
15O[±14%]
17F[±17%]
8B[±14%]
hep[±30%]
Flux (cm−2 s−1)
Neutrino energy (MeV)
10^13
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0

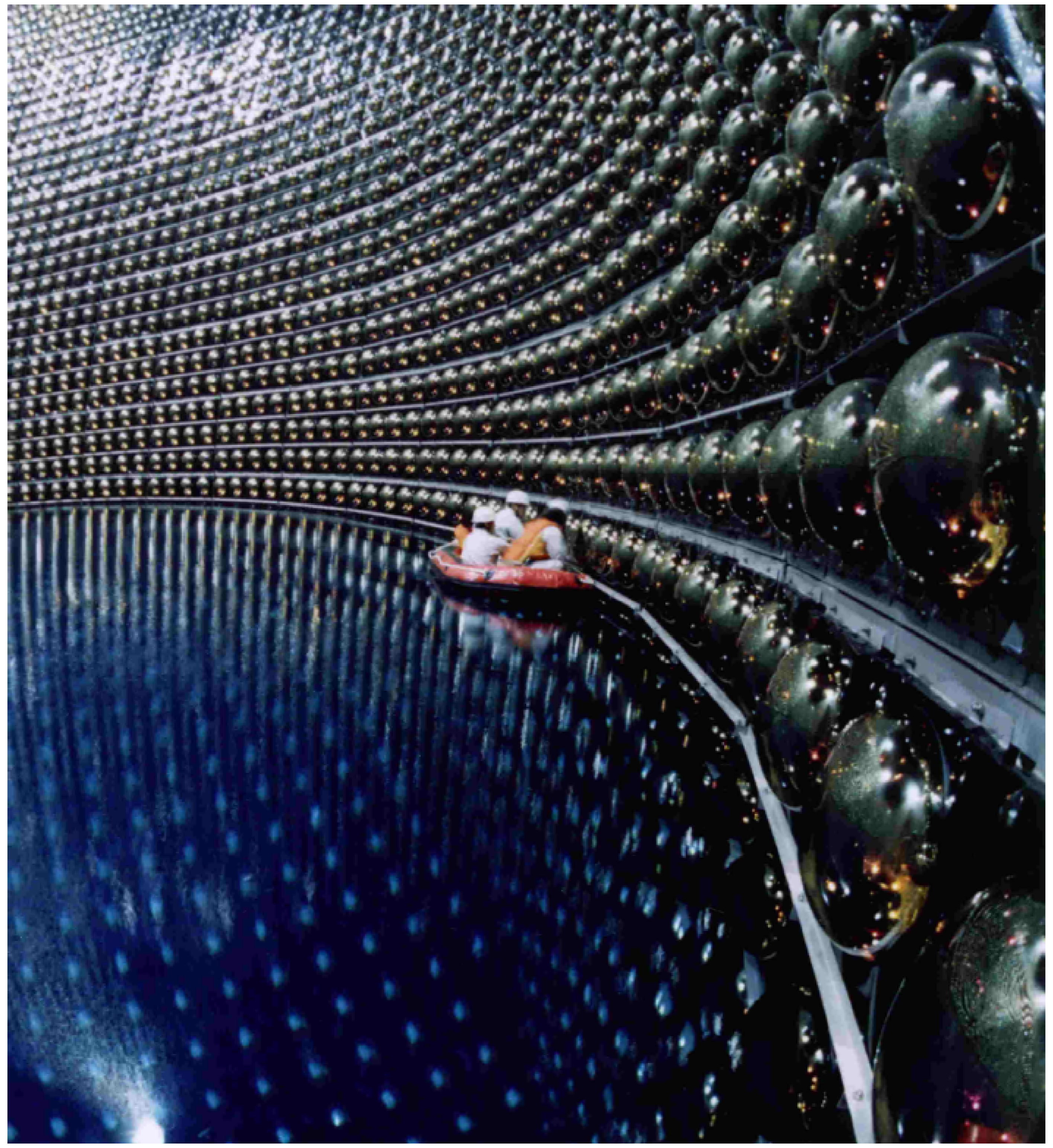
The results were not compatible with the SSM or any reasonable variation thereof - something novel was going on

So two "observables" — total flux, flux ratio — in great tension with any steady-state astrophysical solution



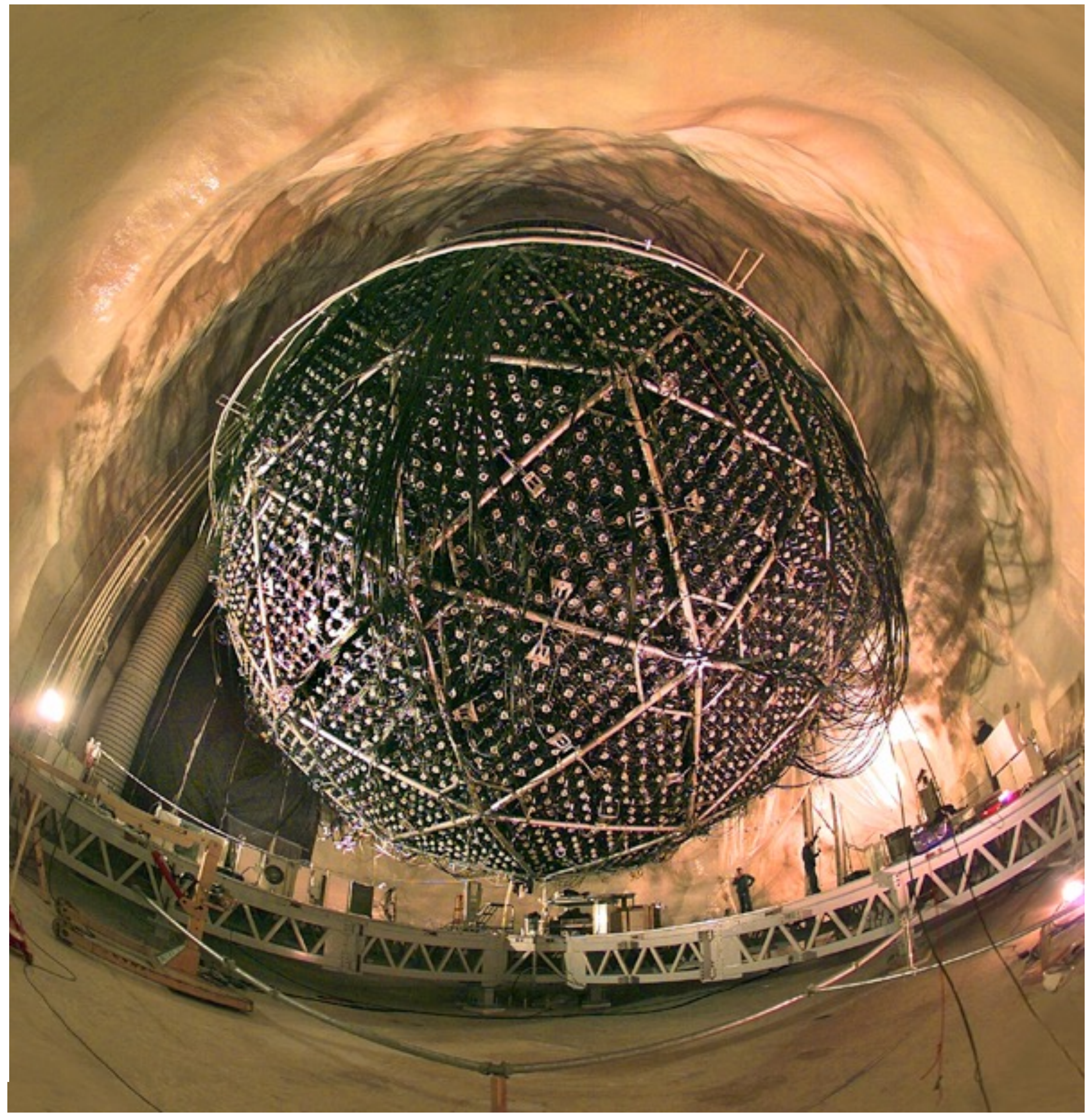
From Hata

This set the stage for a new generation of large, direct-counting experiments with sensitivities to aspects of oscillations



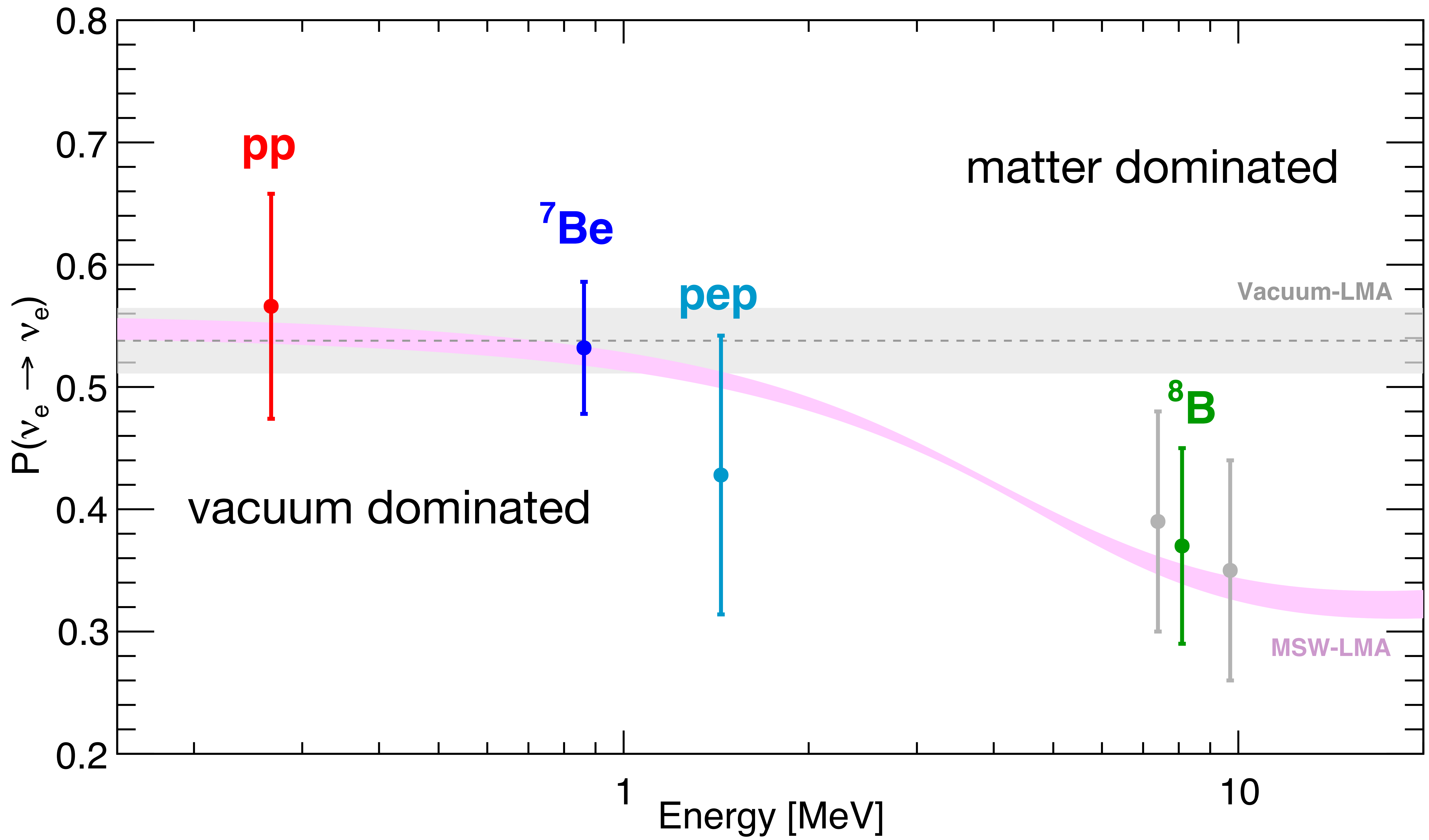
SuperKamiokande

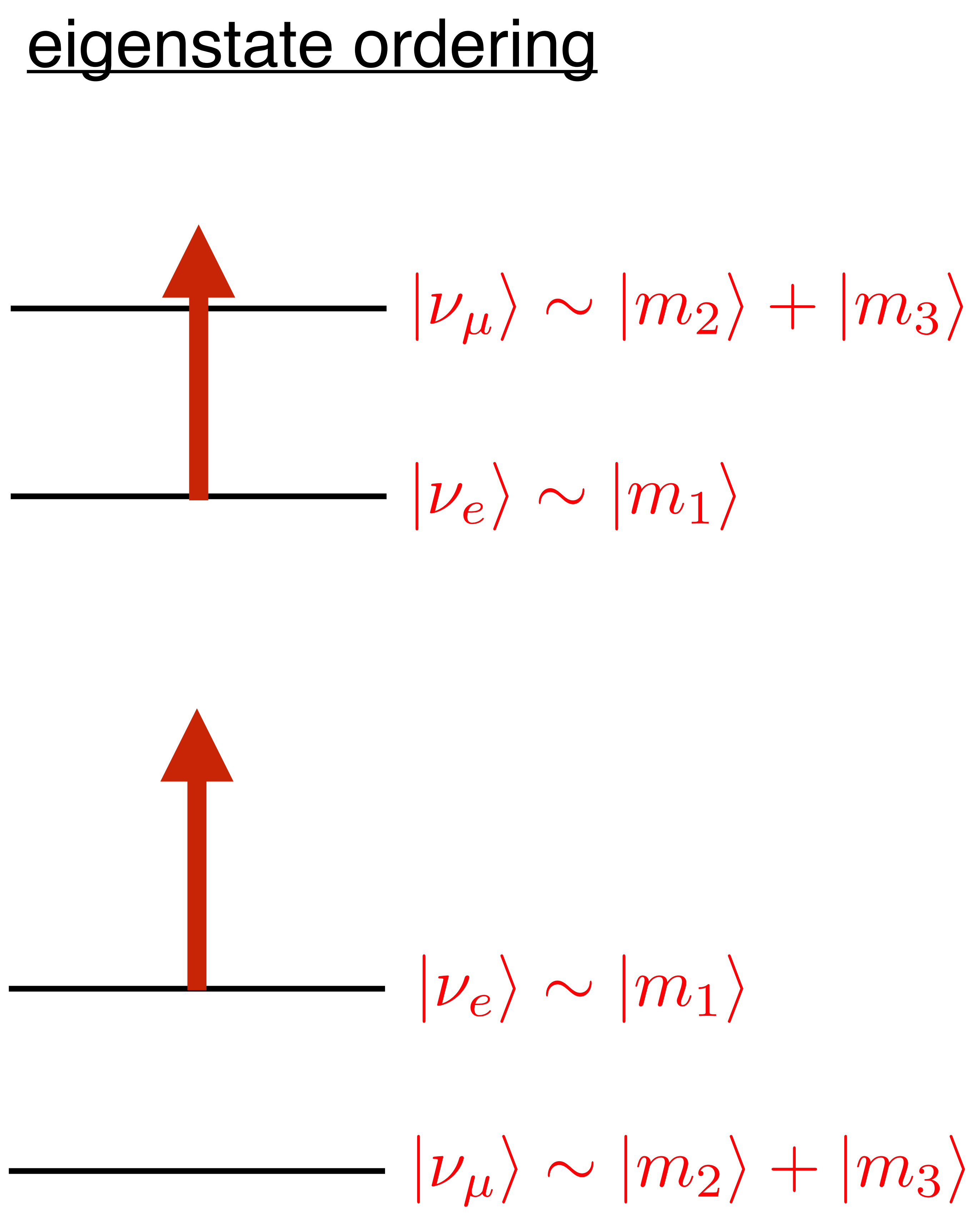
Borexino



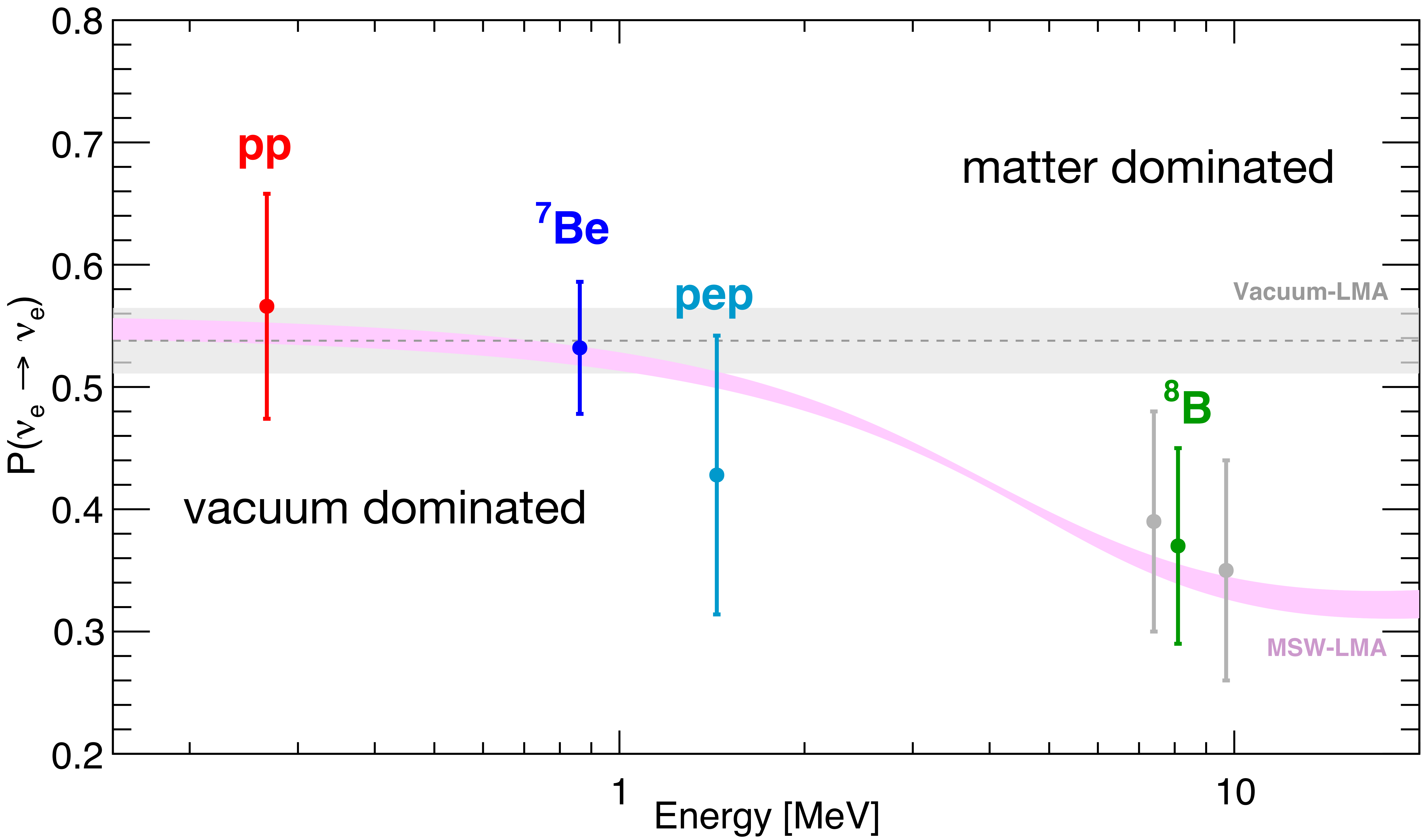
SNO

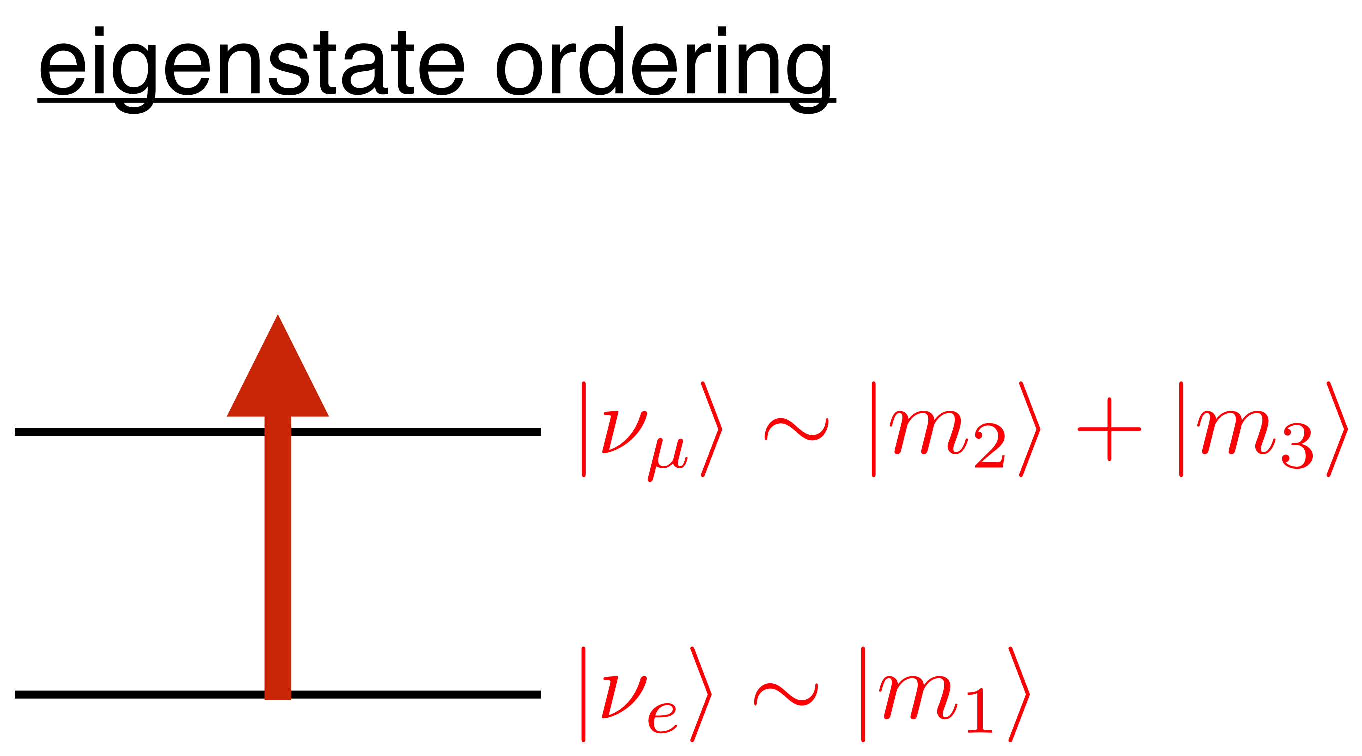
In addition to Borexino's impact on neutrino physics





In addition to Borexino's impact on neutrino physics





Borexino provided pioneering tests of two of the most important questions we can ask about our rather simple SSM, the foundation for our understanding of main-sequence stars

- the equivalence of the sun's electromagnetic (photon) and weak (neutrino) luminosities:
  - — tests the assumption of steady-state nuclear burning
  - — important to arguments that use this equivalent to constrain additional cooling that might arise from BSM physics

- the assumption that the Sun was homogeneous when it formed
  - — tests our understanding of our early solar system and thus of evolving exoplanetary systems generally

The latter connected to the "solar abundance problem": measurements of the Sun's on the surface and in the core are not in good agreement

- — the photosphere (with recent rexamination of photo-absorption lines) → low
- — in the interior radiative zone (deduct through helioseismology) → high
- — the answers differ by 25%

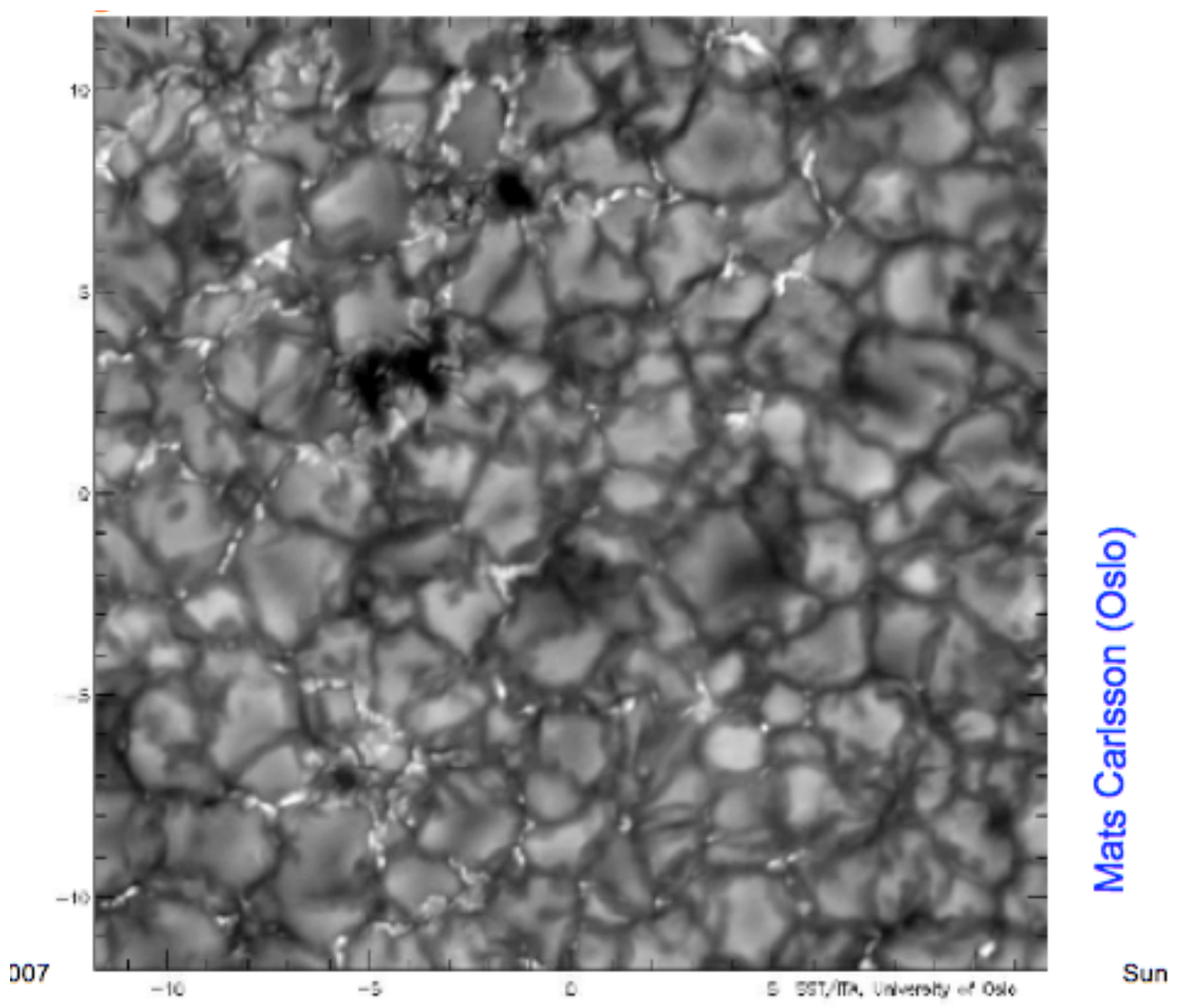
		high-Z SSM	low-Z SSM	luminosity constrained fit to data	
ν flux	E_ν^{max} (MeV)	GS98-SFII	AGSS09-SFII	Solar	units
$p+p \to {}^2H+e^++\nu$	0.42	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$6.05(1^{+0.003}_{-0.011})$	$10^{10}/cm^2s$
$p+e^-+p \to {}^2H+\nu$	1.44	$1.44(1 \pm 0.012)$	$1.47(1 \pm 0.012)$	$1.46(1^{+0.010}_{-0.014})$	$10^8/cm^2s$
${}^7Be+e^- \to {}^7Li+\nu$	0.86 (90%)	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	$4.82(1^{+0.05}_{-0.04})$	$10^9/cm^2s$
	0.38 (10%)				
${}^8B \to {}^8Be+e^++\nu$	~ 15	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	$5.00(1 \pm 0.03)$	$10^6/cm^2s$
${}^3He+p \to {}^4He+e^++\nu$	18.77	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	—	$10^3/cm^2s$
${}^{13}N \to {}^{13}C+e^++\nu$	1.20	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7	$10^8/cm^2s$
${}^{15}O \to {}^{15}N+e^++\nu$	1.73	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.2	$10^8/cm^2s$
${}^{17}F \to {}^{17}0+e^++\nu$	1.74	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	$\leq 59.$	$10^6/cm^2s$
χ^2/P^{agr}		3.5/90%	3.4/90%		

neutrino results sit roughly in between — not accurate enough to decide the issue

The changes came about because of more realistic modeling of the photosphere, not because the absorption line data changed

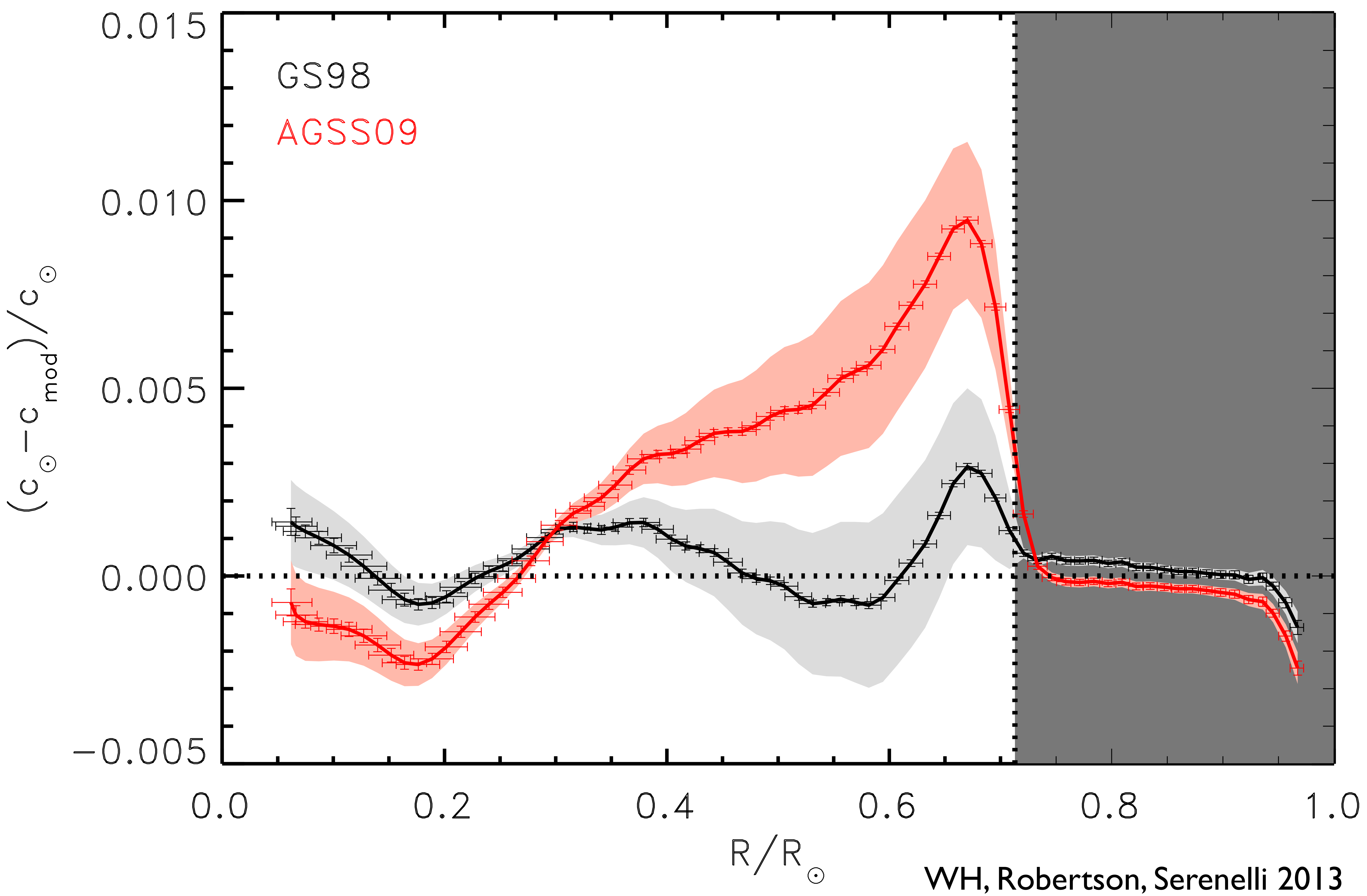
— 1D modeling, without statification, velocities, inhomogeneities

— vs. 3D modeling: MPI-Munich group argued that its approach was effectively parameter-free, yielding better agreement in line shapes and line consistency



Solar surface: 3D, convective

A low-metallicity core generates discrepancies in interior helioseismology



WH, Robertson, Serenelli 2013

Table 1 Standard solar model characteristics are compared to helioseismic values, as determined by Basu & Antia (1997, 2004)

Property[a]	GS98-SFII	AGSS09-SFII	Solar
$(Z/X)_S$	0.0229	0.0178	–
Z_S	0.0170	0.0134	–
Y_S	0.2429	0.2319	0.2485 ± 0.0035
$R_{CZ}/R_\odot$	0.7124	0.7231	0.713 ± 0.001
$\langle \delta c/c \rangle$	0.0009	0.0037	0.0
Z_C	0.0200	0.0159	–
Y_C	0.6333	0.6222	–
Z_{ini}	0.0187	0.0149	–
Y_{ini}	0.2724	0.2620	–

and in the convective zone:
helioseismology creates tension in a low-Z SSM

The abundance extraction as well as the tension with helioseismology, however, are coupled to other SSM uncertainties

— variations in abundances are degenerate with variations in atomic opacity profiles (Villante and Serenelli, arXiv:2004.06365, 5th Int. Solar Neutrino Conference)

— one needs additional observables to break this degeneracy

This has been underscored in a recent re-examination of the photospheric results (E. Magg et al., A&A 661, A140 (2022)) that combined

— new observational data

— non-equilibrium modeling of the photosphere

— new oscillator parameters affecting opacities

— new O, Ne abundances

leading to a revised photospheric abundance of Z/X=0.0225, much closer to older values

<u>My perspective</u>

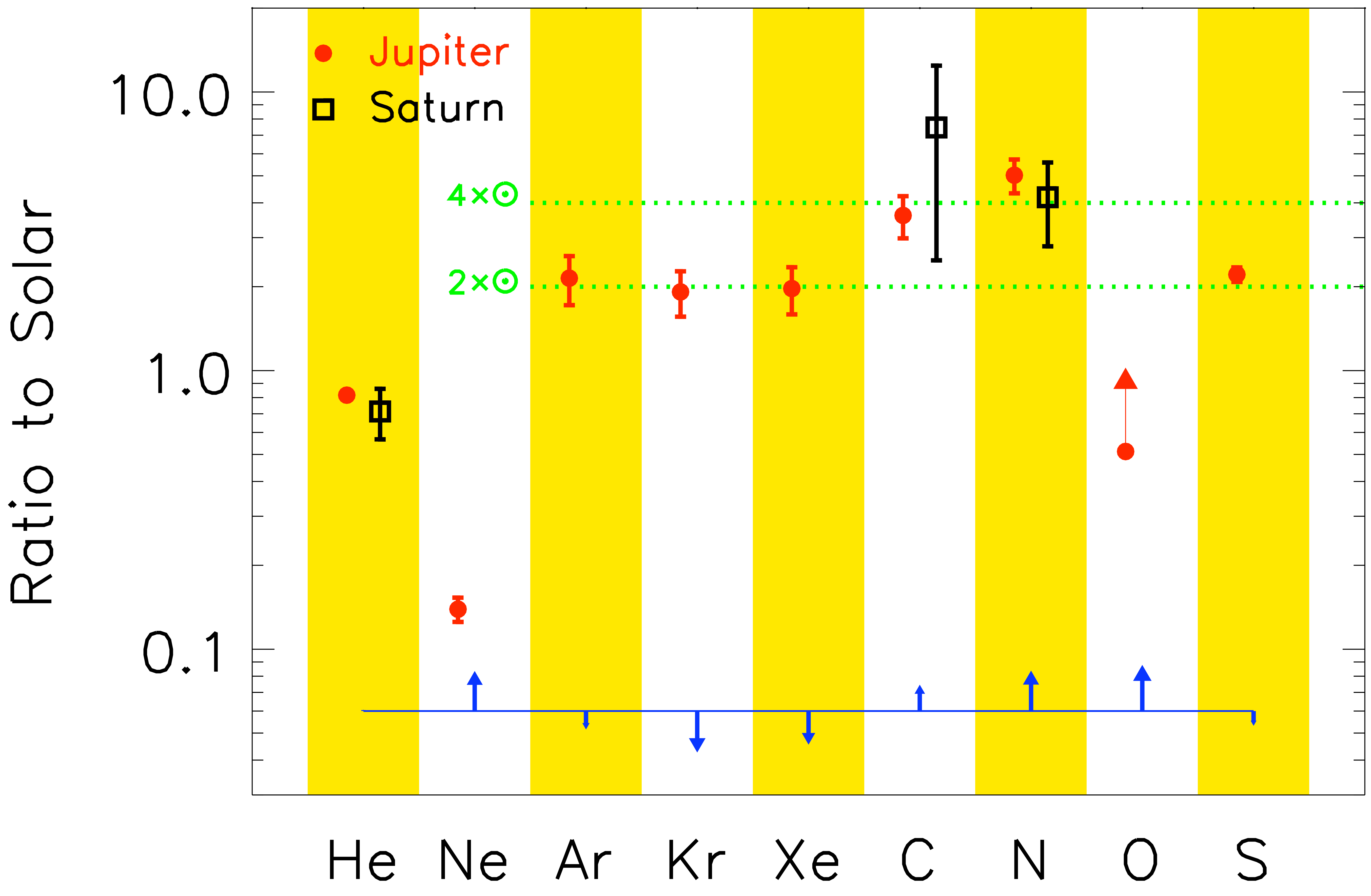
— this question is fundamental to the SSM, and needs to be addressed experimentally

— the real question is whether we can verify the SSM assumption of an initially homogeneous Sun

Do we have a convincing argument (e.g., Hayashi phase mixing) that the Sun formed from the collapse of a homogeneous gas cloud?

Perhaps not, as a lot happened after the Hayashi phase

metal enrichments of the gaseous giants

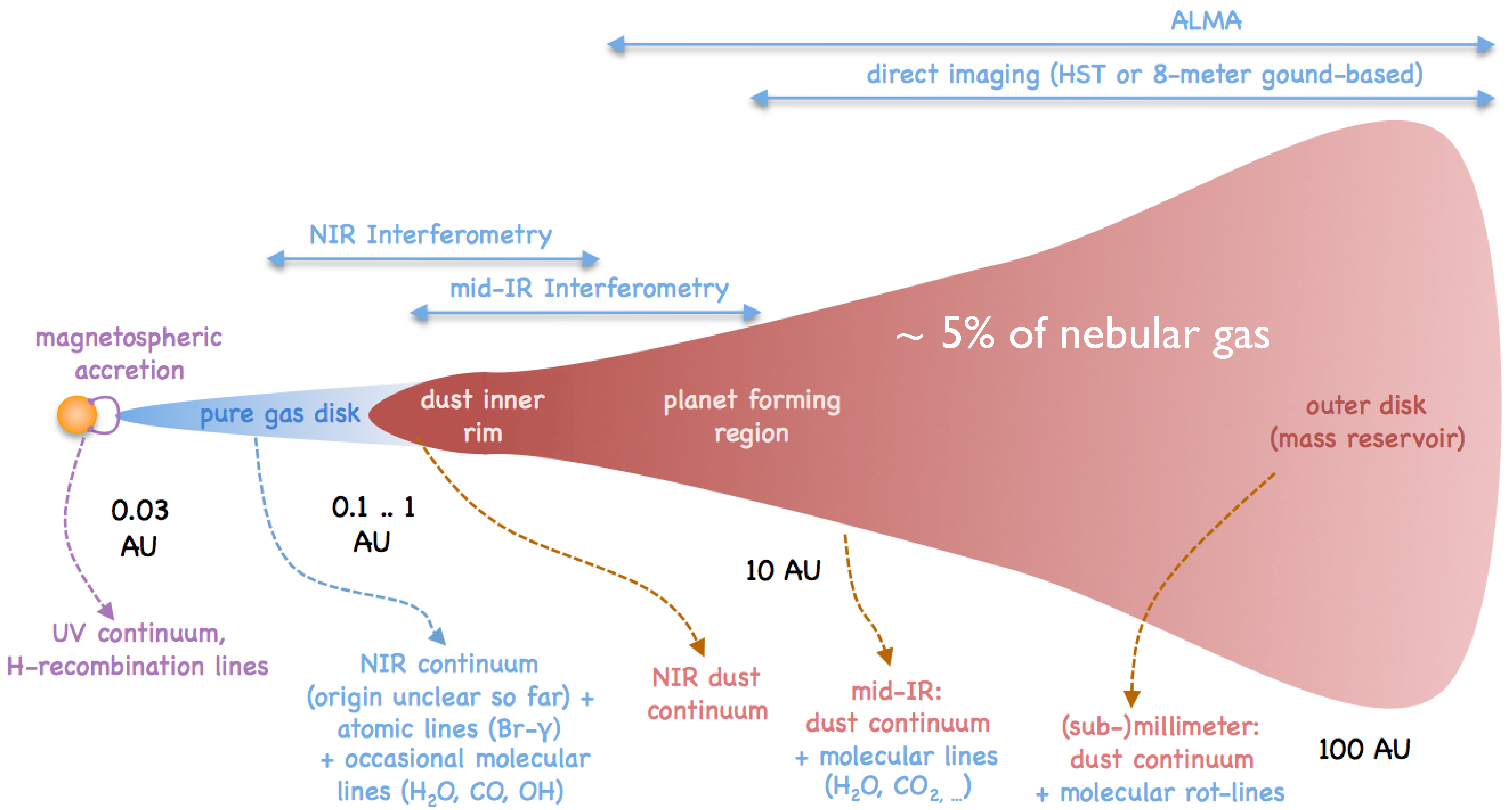


Galileo data, from Guillot AREPS 2005

Enrichments of 4-8 of C,N relative to solar in the gaseous giants

consequence of planetary formation in a chemically evolved disk over ~ 1 m.y. time scale

Cartoon picture of metal segregation, accretion



Dullemond and Monnier, ARA&A 2010

Jupiter's composition is consistent with a scenario where 2/3rds of the H/He that initially "belonged" to Jupiter was lost to the Sun (Guillot & Hueso (2006), Nordlund, arXiv:0908.3479)

<u>We see evidence of this today in young solar-like systems</u>

- Using Gaia observations, an analysis of the inner disks of 26 T Tauri stars found very large depletion of carbon in the accreting gas, with the carbon content of the gas phase reduced to below 2.5% of its initial value, in some cases

  (McClure, A&A 632, A32 (2019))

- Consistent with theory: in dynamical models of the disappearance of elements from the gas phase, molecular species such as CO and CH_4 always depleted

  (Booth and Ilie, MNRAS, 2019)

One can reasonably conclude that in the late stages of solar formation

— some 50-90 earth masses of metal was scrubbed from the gas cloud

— the depleted H/He gas remains in the solar system, accreting onto the Sun

A more difficult question to answer: did this appreciably affect solar structure?

— possibly yes if that gas were deposited when the Sun had a modern convective zone

— no if were accreted earlier, when the evolving convective zone contained much more than 2% of the solar mass

One of Borexino's last achievements was to demonstrate that the Sun's core metallicity could be measured directly, free of other SSM uncertainties like opacities

$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \;\; E_\nu \lesssim 1.199\ \mathrm{MeV} \;\; \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

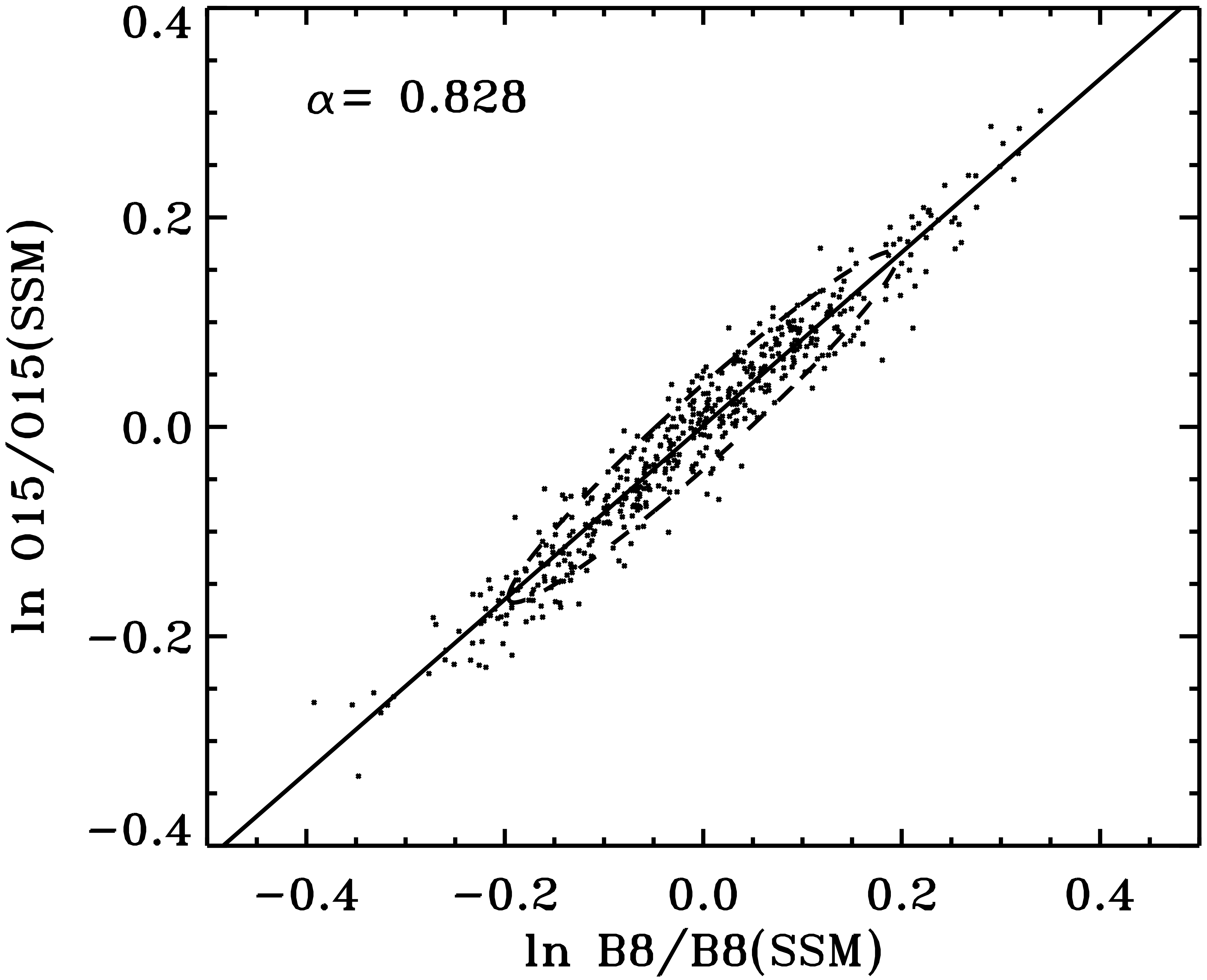
$$^{15}\mathrm{O}(\beta^+)^{15}\mathrm{N} \;\; E_\nu \lesssim 1.732\ \mathrm{MeV} \;\; \phi = (2.20^{+0.73}_{-0.63}) \times 10^8/\mathrm{cm}^2\mathrm{s}.$$

From the $^{15}\mathrm{O}$ and $^{8}\mathrm{B}$ neutrino fluxes, one c extract the core metallicity with virtually no dependence on solar model parameters

$$\frac{\phi(^{15}\mathrm{O})}{\phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\phi(^{8}\mathrm{B})}{\phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.729} x_{C+N}$$

$$\times\,[1 \pm 0.006(\mathrm{solar}) \pm 0.027(\mathrm{D}) \pm 0.099(\mathrm{nucl}) \pm 0.032(\theta_{12})]$$

This uses the $^{8}\mathrm{B}$ flux as a thermometer: by taking this ratio, we can remove the solar-model T_c dependence



WH and Serenelli

Borexino's final results were announced just this past summer, exploiting their Correlated Integrated Directionality method (D. Basilico et al., arXiv:2307.14636)

$$\phi_{\rm CNO} = 6.7^{+1.2}_{-0.8} \times 10^8/{\rm cm}^2\,{\rm s}$$

in good agreement with the high-Z SSM, and in 2σ tension with the low-Z SSM

<u>I would stress:</u> this is about much more than adjudicating a SSM dispute

- the most pristine sample of the primordial gas cloud is that isolated in the Sun's center: this gas was chemically sequestered from its environment earlier than any other

- Borexino's measurement directly determines the Z of that gas, in principle subject only to minor metal diffusion uncertainties

Gallex, Borexino, and the Solar Luminosity Constraint

A second fundamental assumption of the SSM is that the Sun burns in hydrostatic equilibrium, deriving its energy from H burning

This implies an equivalence between the Sun’ weak and electromagnetic luminosities

Energy carried off by neutrinos

Two neutrinos produced per He nucleus synthesized

$$\sum_i \Phi_i^\nu \left[1 - 2\frac{\langle E_i \rangle}{\mathcal{E}_{4\mathrm{p}\to{}^4\mathrm{He}}}\right] = \frac{2L_\odot}{4\pi R^2_{\mathrm{earth-Sun}}\mathcal{E}_{4\mathrm{p}\to{}^4\mathrm{He}}}$$

Neutrino fluxes: i = pp, pep, 7Be, 8B, hep, CNO

F. Vissani, World Scientific, Solar Neutrinos, pp 121-141 (2019)
D. Vescovi et al., J. Phys. G 48, 015201 (2021)

giving us an experimental test of this fundamental SSM assumption

The fractional error on the RHS of this relation is $\delta L_\odot / L_\odot \sim 0.004$
But on the right it is almost 0.1

While the error budget includes uncertainties in neutrino mixing, in ppII and ppIII fluxes, etc., 90% comes from uncertainties in the pp and pep fluxes

These are the fluxes that tell us the rate at which protons are being consumed

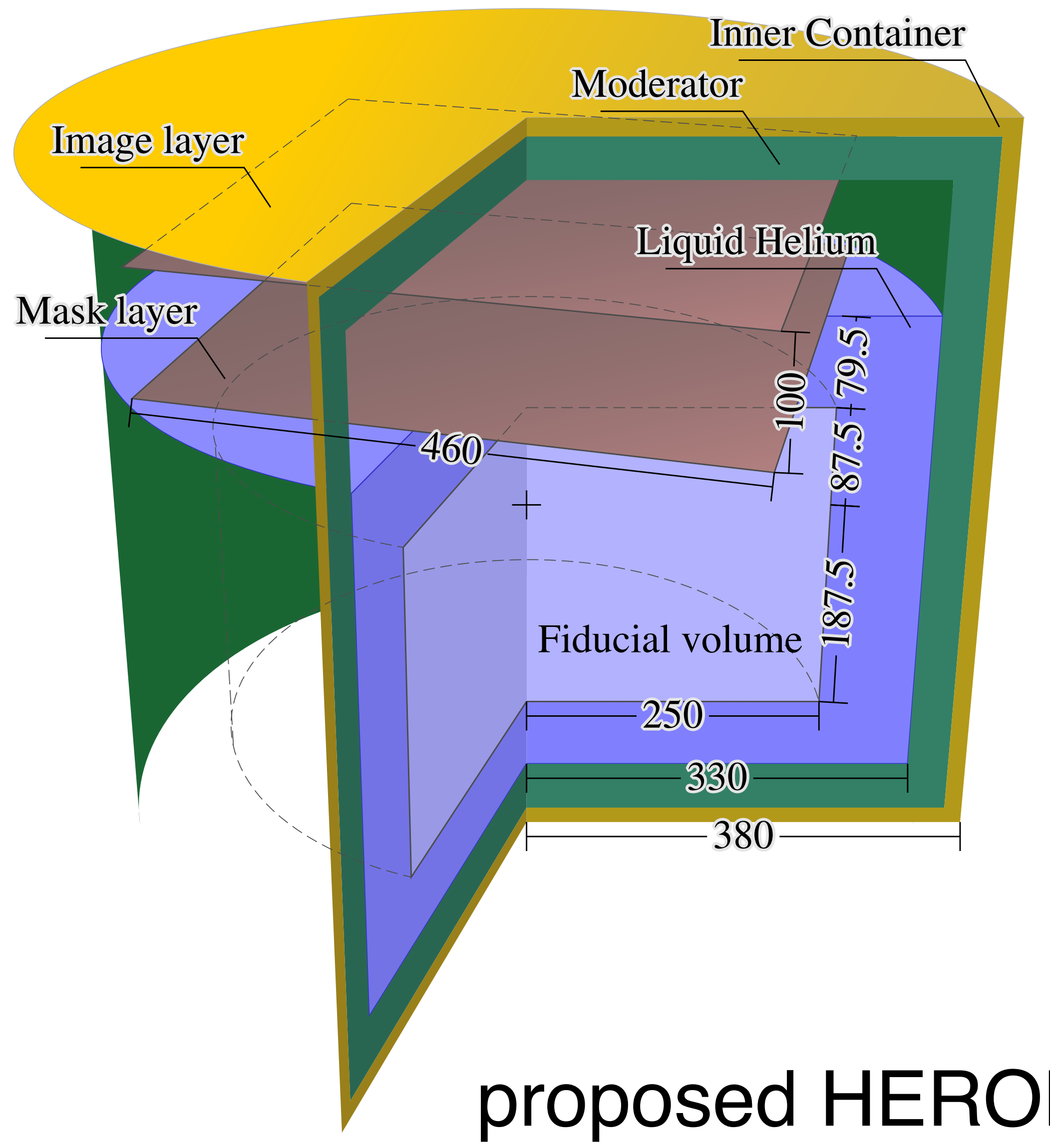
What we know about these fluxes comes entirely from the (combined) Ga and Borexino experiments

$$(6.1 \pm 0.5^{+0.3}_{-0.5}) \times 10^{10}/\mathrm{cm}^2\mathrm{s}$$ Agostini et al., Nature 562 (2018) 505

$$(6.0 \pm 0.8) \times 10^{10}/\mathrm{cm}^2\mathrm{s}$$ Abdurashitov et al., PRC 80 (2009) 015807

but the 12% uncertainty is limiting

More is needed: until our field measures this flux to 1% (the uncertainty defined by the precision of the p+p S-factor) we will not be done with solar neutrinos



proposed HERON superfluid helium detector

In Conclusion

- Sincere congratulations to the Gallex and Borexino collaborations for helping make solar neutrino physics into one of the great discovery stories of modern physics

- Thanks to Gran Sasso, for the consistent support it has provided to enable this success

- And thanks to my many friends in experiment and theory who have always made it such pleasure to work on solar neutrinos: their enthusiasm for the field and camaraderie have been and continue to be special