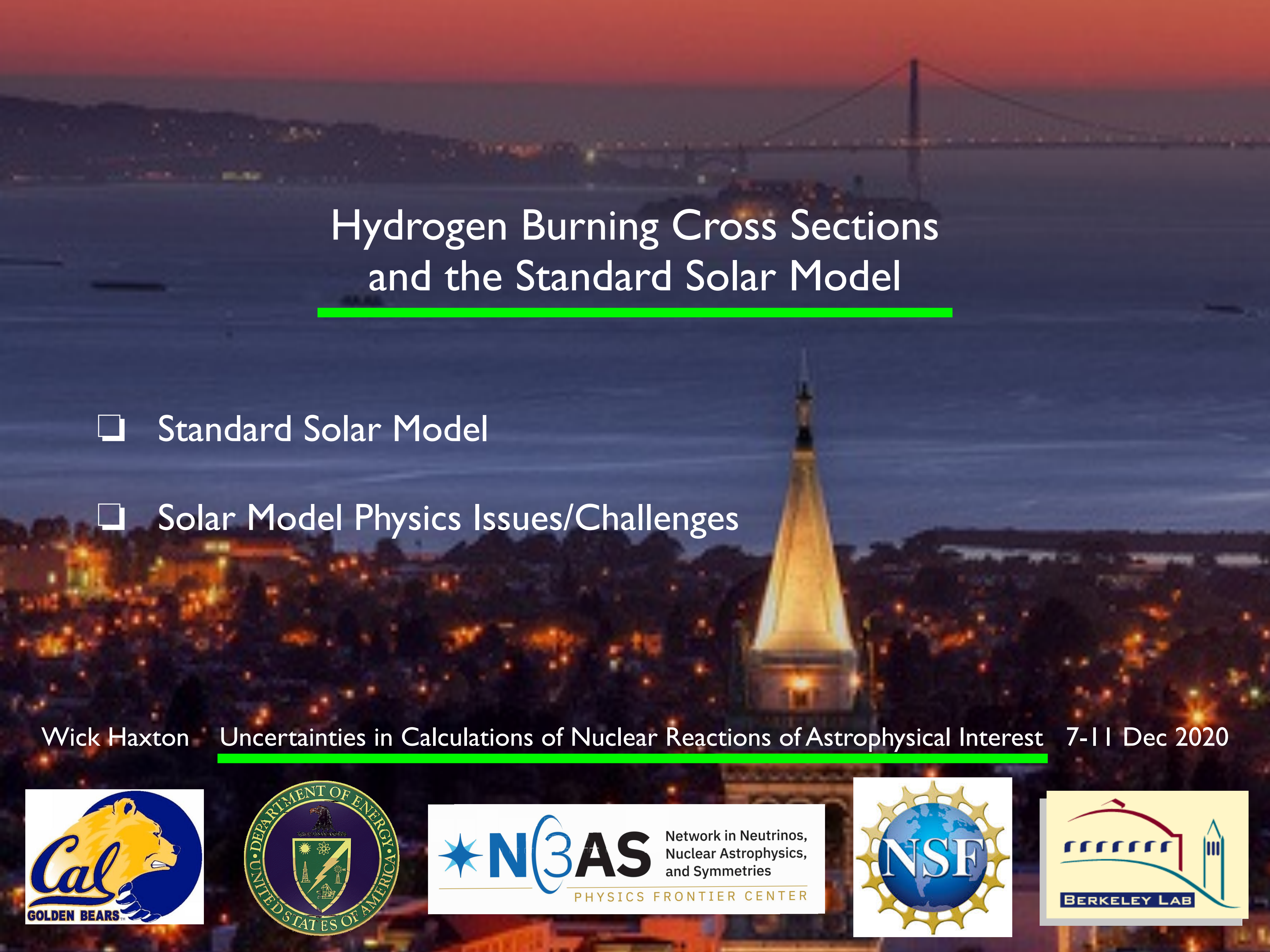


Hydrogen Burning Cross Sections and the Standard Solar Model

- Standard Solar Model
- Solar Model Physics Issues/Challenges

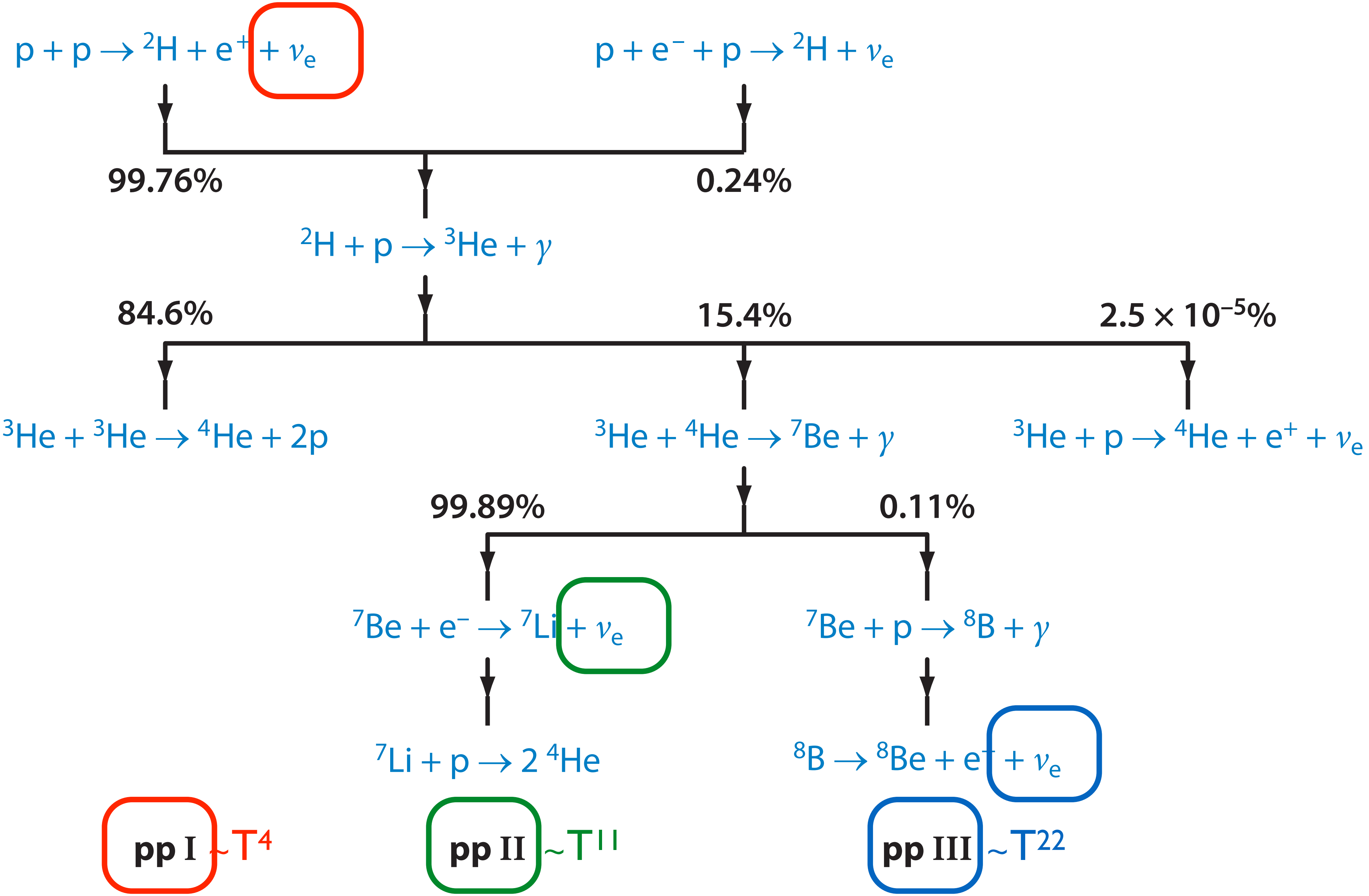
Wick Haxton Uncertainties in Calculations of Nuclear Reactions of Astrophysical Interest 7-11 Dec 2020

The Standard Solar Model

- Origin of solar neutrino physics: desire to test a model of low-mass, main-sequence stellar evolution
  - local hydrostatic equilibrium: gas pressure gradient counteracting gravitational force
  - hydrogen burning: pp chain, CN cycle
  - energy transport by radiation (interior) and convection (envelope)
  - boundary conditions: today's mass, radius, luminosity

- The implementation of this physics requires
  - electron gas EOS
  - low-energy nuclear cross sections
  - radiative opacity
  - some means of fixing the composition at ZAMS, including the ratios X:Y:Z

$$2e^- + 4\mathrm{p} \rightarrow {}^4\mathrm{He} + 2\nu_e + 26.73\ \mathrm{MeV}$$



$\mathrm{p} + \mathrm{p} \rightarrow {}^2\mathrm{H} + \mathrm{e}^+ + \boxed{\nu_\mathrm{e}}$

$\mathrm{p} + \mathrm{e}^- + \mathrm{p} \rightarrow {}^2\mathrm{H} + \nu_\mathrm{e}$

99.76%

0.24%

${}^2\mathrm{H} + \mathrm{p} \rightarrow {}^3\mathrm{He} + \gamma$

84.6%

15.4%

2.5×10^{-5}%

${}^3\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^4\mathrm{He} + 2\mathrm{p}$

${}^3\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$

${}^3\mathrm{He} + \mathrm{p} \rightarrow {}^4\mathrm{He} + \mathrm{e}^+ + \nu_\mathrm{e}$

99.89%

0.11%

${}^7\mathrm{Be} + \mathrm{e}^- \rightarrow {}^7\mathrm{Li} + \boxed{\nu_\mathrm{e}}$

${}^7\mathrm{Be} + \mathrm{p} \rightarrow {}^8\mathrm{B} + \gamma$

${}^7\mathrm{Li} + \mathrm{p} \rightarrow 2\ {}^4\mathrm{He}$

${}^8\mathrm{B} \rightarrow {}^8\mathrm{Be} + \mathrm{e}^+ + \boxed{\nu_\mathrm{e}}$

pp I $\sim T^4$

pp II $\sim T^{11}$

pp III $\sim T^{22}$

Composition/metallicity in the SSM:

- Standard picture of pre-solar contraction, evolution
  - Sun forms from a contracting primordial gas cloud
  - passes through the Hayashi phase: cool, highly opaque, large temperature gradients, slowly contracting ↔ convective (mixed)
  - radiative transport becomes more efficient at star's center: radiative core grows from the center outward
  - when dense and hot enough, nuclear burning starts...

- Because the Hayashi phase fully mixes the proto-Sun, a chemically homogeneous composition is traditionally assumed at ZAMS
  - $X_{ini} + Y_{ini} + Z_{ini} = 1$
  - relative metal abundances taken from a combination of photospheric (volatile) and meteoritic (refractory) abundances
  - Z_{ini} fixed by model's present-day Z_S, corrected for diffusion
  - Y_{ini} and α_{MLT} adjusted to produce present-day $L_\odot$ and $R_\odot$

Model tests:

- Solar neutrinos: direct measure of core temperature to ~ 0.5%
  - once the flavor physics has been sorted out

- Helioseismology: inversions map out the local sound speed, properties of the convective zone

Neutrino flux predictions depend critically on the nuclear cross sections: customary in the field to evaluate impact of cross section uncertainties on SSM predictions via log derivatives

$$\frac{\partial \ln\phi}{\partial \ln\sigma}\Big|_{SM} \quad \Rightarrow \quad \frac{\delta\phi}{\phi} = \frac{\partial \ln\phi}{\partial \ln\sigma}\Big|_{SM} \frac{\delta\sigma}{\sigma}$$

Or in general for all contributing σ_j in a chain leading to a flux ϕ

$$\Rightarrow \frac{\delta\phi}{\phi} = \left[\sum_j \left(\frac{\partial \ln\phi}{\partial \ln\sigma_j}\Big|_{SM} \frac{\delta\sigma_j}{\sigma_j}\right)^2\right]^{1/2}$$

Impetus for the Solar Fusion series - to determine cross section best values and their uncertainties - came from an INT workshop in 1997

Solar Fusion I, Reviews of Modern Physics 70, 1265 (1998)
Solar Fusion II, Reviews of Modern Physics 83, 195 (2011)
Solar Fusion III workshop, Feb 28 - March 3, 2022

TABLE I The Solar Fusion II recommended values for S(0), its derivatives, and related quantities, and for the resulting uncertainties on S(E) in the region of the solar Gamow peak – the most probable reaction energy – defined for a temperature of 1.55×10^7K characteristic of the Sun's center. See the text for detailed discussions of the range of validity for each S(E). Also see Sec. VIII for recommended values of CNO electron capture rates, Sec. XI.B for other CNO S-factors, and Sec. X for the ^{8}B neutrino spectral shape. Quoted uncertainties are 1σ.

Reaction	Section	S(0) (keV-b)	S′(0) (b)	S″(0) (b/keV)	Gamow peak uncertainty (%)
$p(p,e^+\nu_e)d$	III	$(4.01 \pm 0.04)\times10^{-22}$	$(4.49 \pm 0.05)\times10^{-24}$	–	± 0.7
$d(p,\gamma)^3He$	IV	$(2.14^{+0.17}_{-0.16})\times10^{-4}$	$(5.56^{+0.18}_{-0.20})\times10^{-6}$	$(9.3^{+3.9}_{-3.4})\times10^{-9}$	± 7.1 [a]
$^3He(^3He,2p)^4He$	V	$(5.21 \pm 0.27) \times 10^3$	-4.9 ± 3.2	$(2.2 \pm 1.7) \times 10^{-2}$	± 4.3 [a]
$^3He(^4He,\gamma)^7Be$	VI	0.56 ± 0.03	$(-3.6 \pm 0.2)\times10^{-4}$ [b]	$(0.151 \pm 0.008)\times10^{-6}$ [c]	± 5.1
$^3He(p,e^+\nu_e)^4He$	VII	$(8.6 \pm 2.6)\times10^{-20}$	–	–	± 30
$^7Be(e^-,\nu_e)^7Li$	VIII	See Eq. (40)	–	–	± 2.0
$p(pe^-,\nu_e)d$	VIII	See Eq. (46)	–	–	± 1.0 [d]
$^7Be(p,\gamma)^8B$	IX	$(2.08 \pm 0.16)\times10^{-2}$ [e]	$(-3.1 \pm 0.3)\times10^{-5}$	$(2.3 \pm 0.8)\times10^{-7}$	± 7.5
$^{14}N(p,\gamma)^{15}O$	XI.A	1.66 ± 0.12	$(-3.3 \pm 0.2)\times10^{-3}$ [b]	$(4.4 \pm 0.3)\times10^{-5}$ [c]	± 7.2

[a] Error from phenomenological quadratic fit. See text.

[b] S′(0)/S(0) taken from theory; error is that due to S(0). See text.

[c] S″(0)/S(0) taken from theory; error is that due to S(0). See text.

[d] Estimated error in the pep/pp rate ratio. See Eq. (46)

[e] Error dominated by theory.

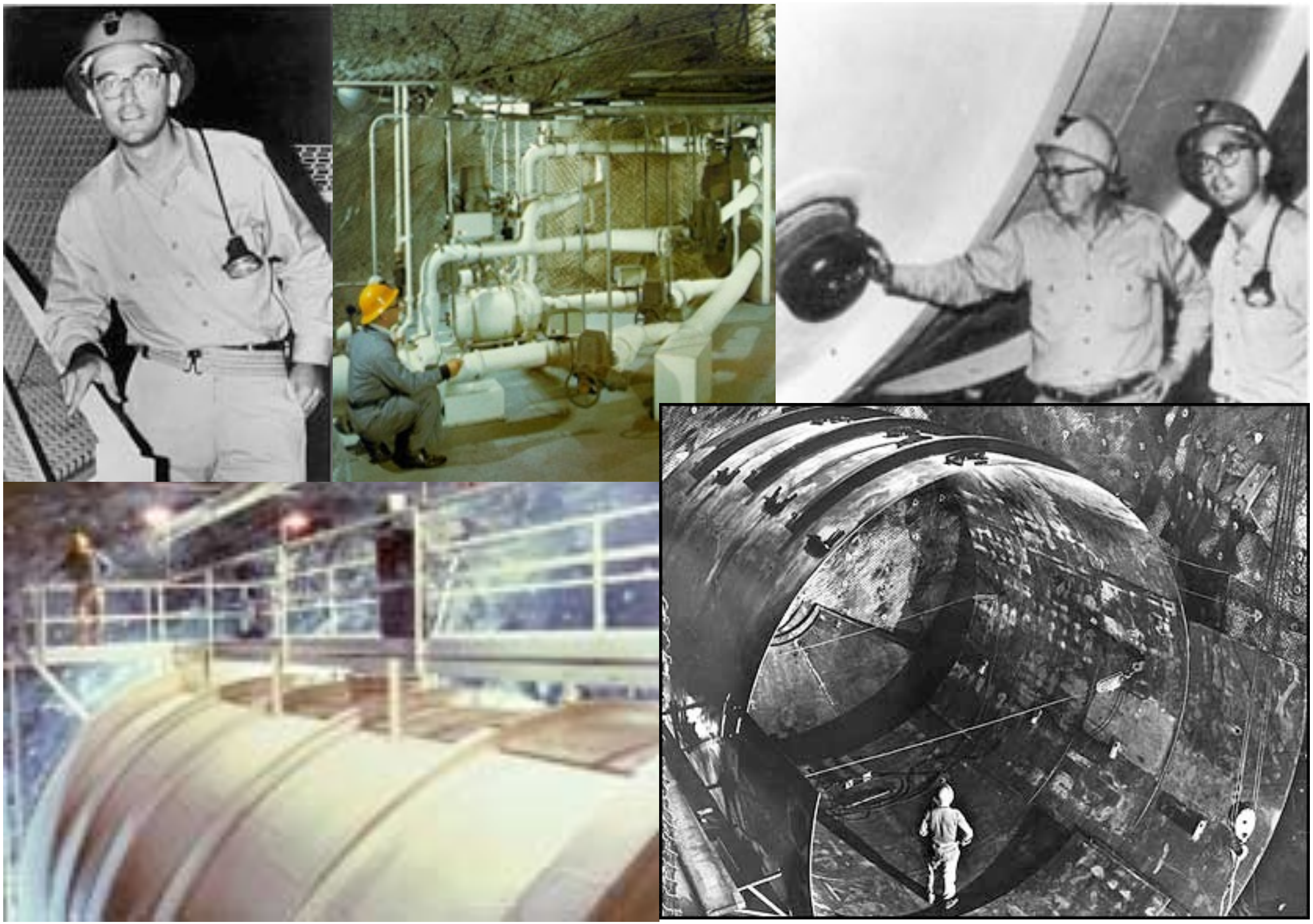
The SSM contains about 19 free parameters that must be fixed to observation.

The precision of this input is the most important factor in SSM predictions.

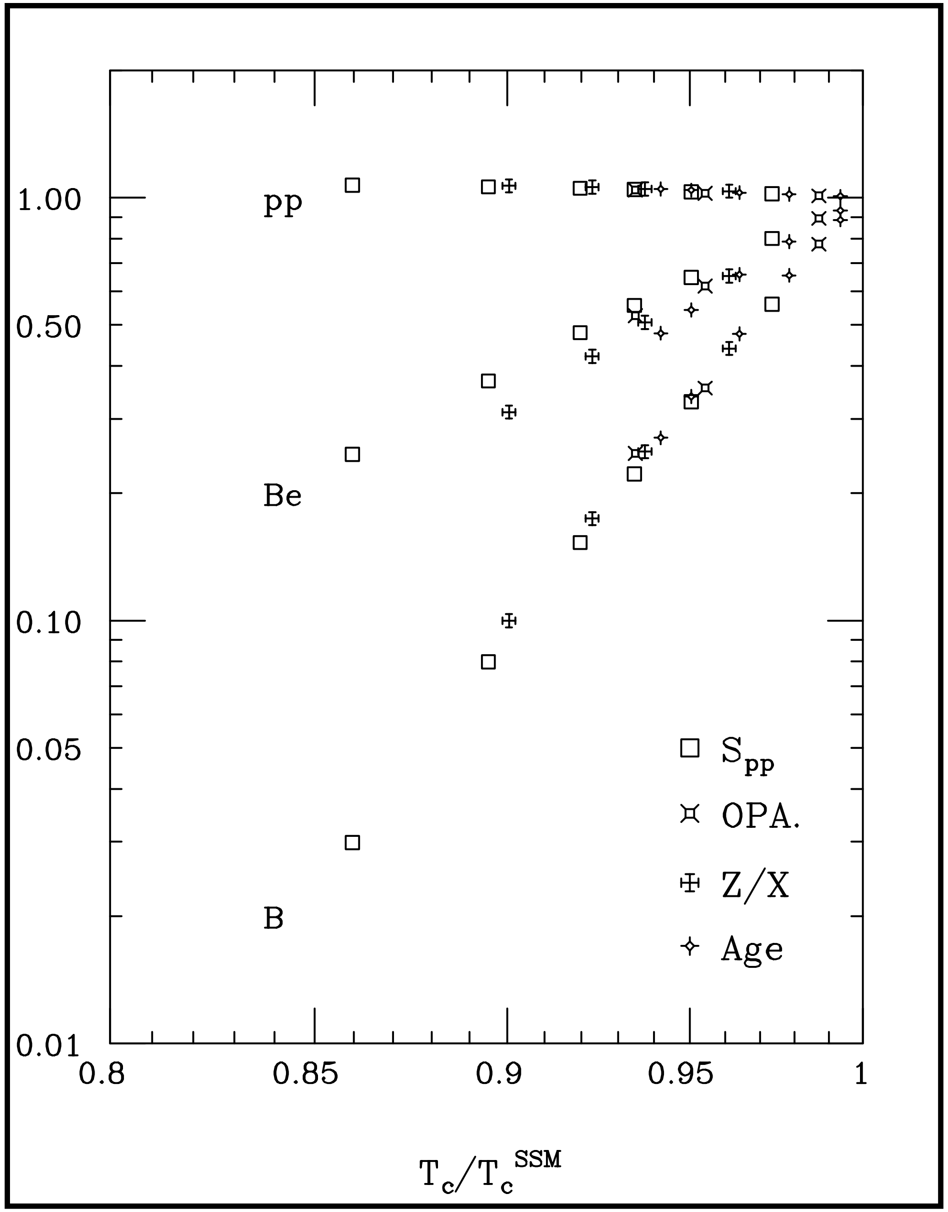
Why is a precise SSM important?

1. <u>Importance of solar νs in pointing us to new ν physics</u>

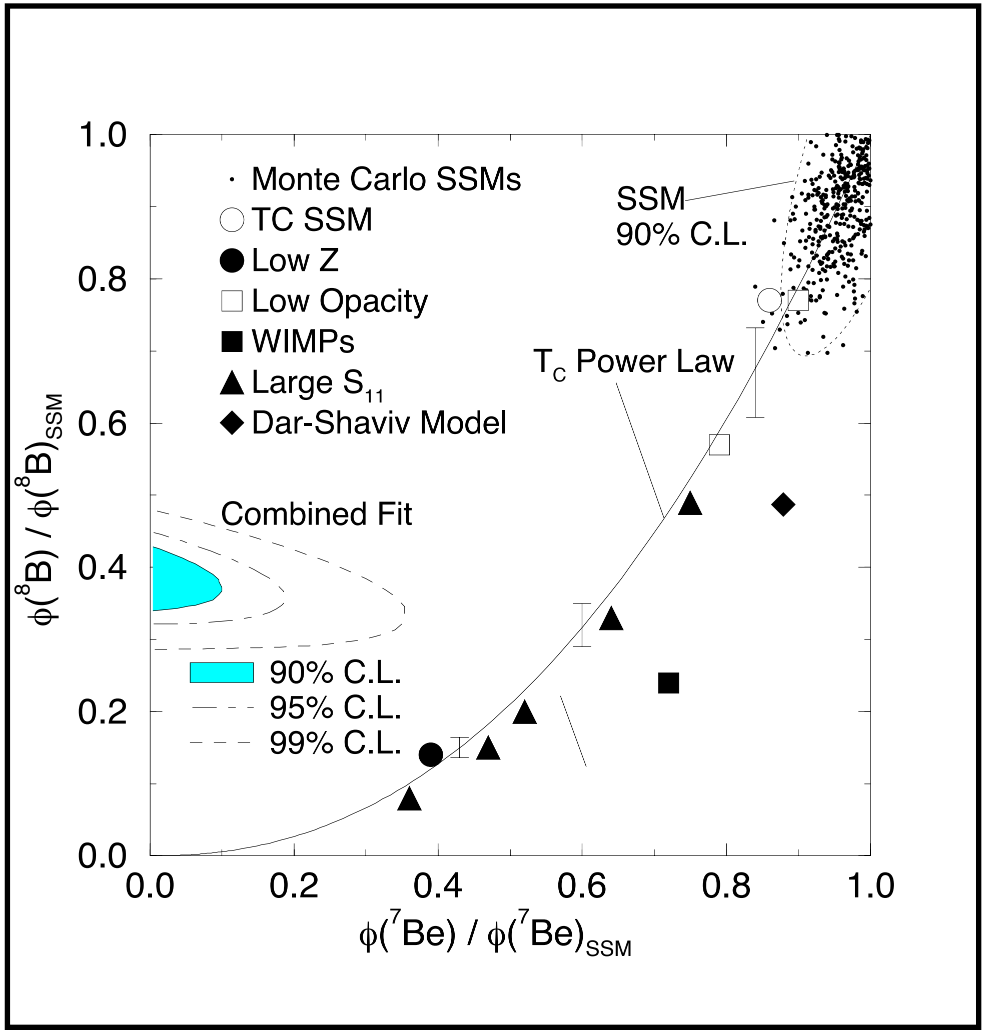
Cl, Ga, and Kamioka Experiments



By mid-1990s model-independent arguments developed showing that no adjustment in the SSM could reproduce observed ν fluxes (Cl, Ga, water exps.)

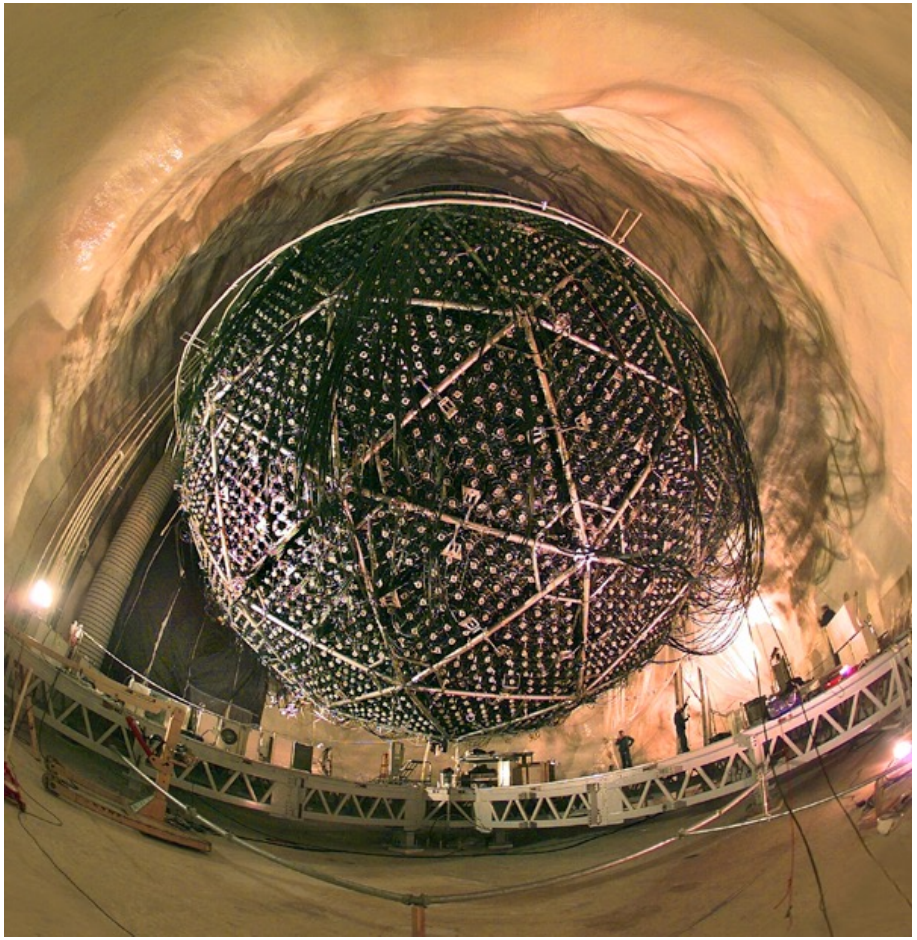


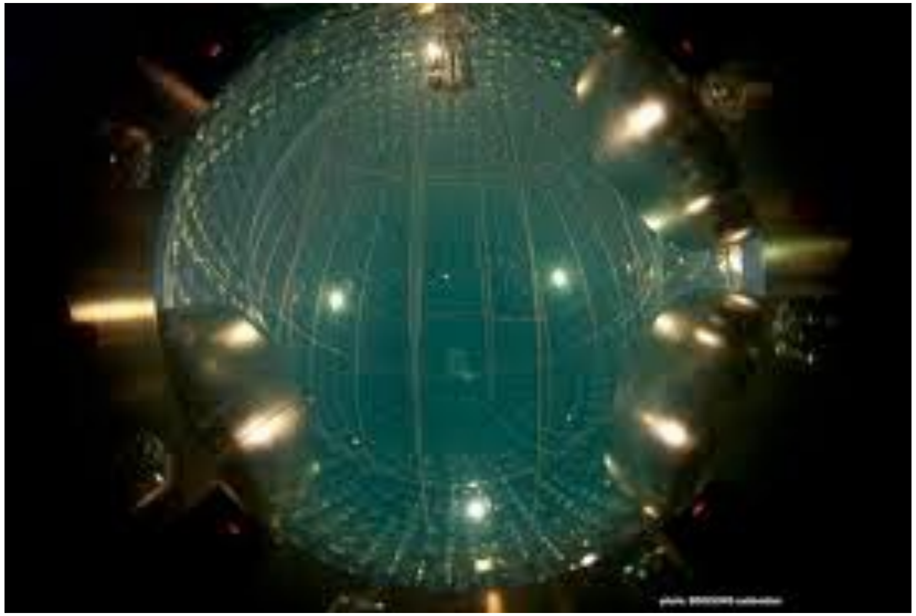
Castellani et al.

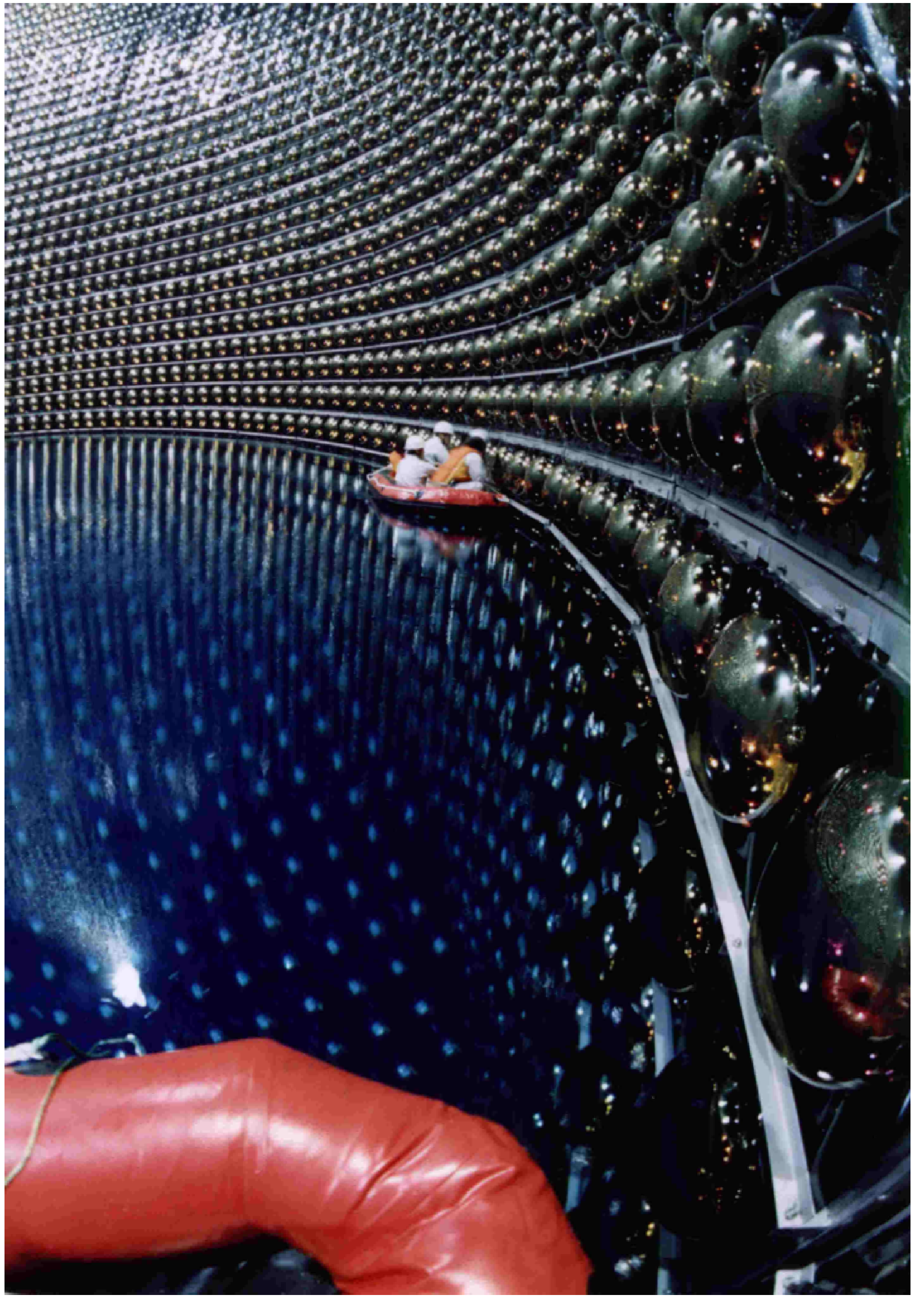


Hata et al.

(and Heeger and Robertson)

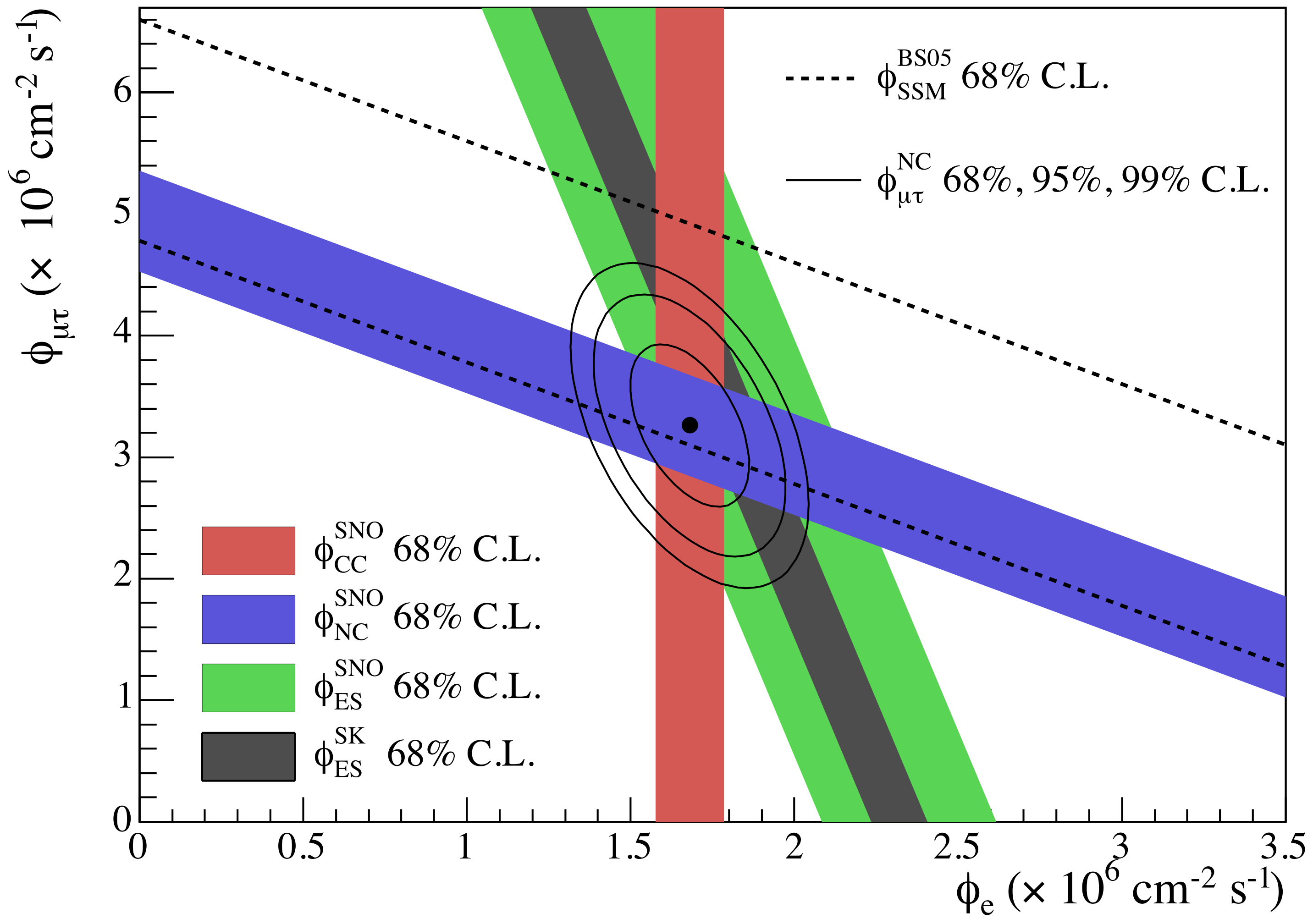






SNO, Super-Kamiokande, Borexino

the "solar ν problem" was definitively traced to new physics by SNO
flavor conversion $\nu_e \rightarrow \nu_{heavy}$



requires an extension of the SM -- Majorana masses or ν_R

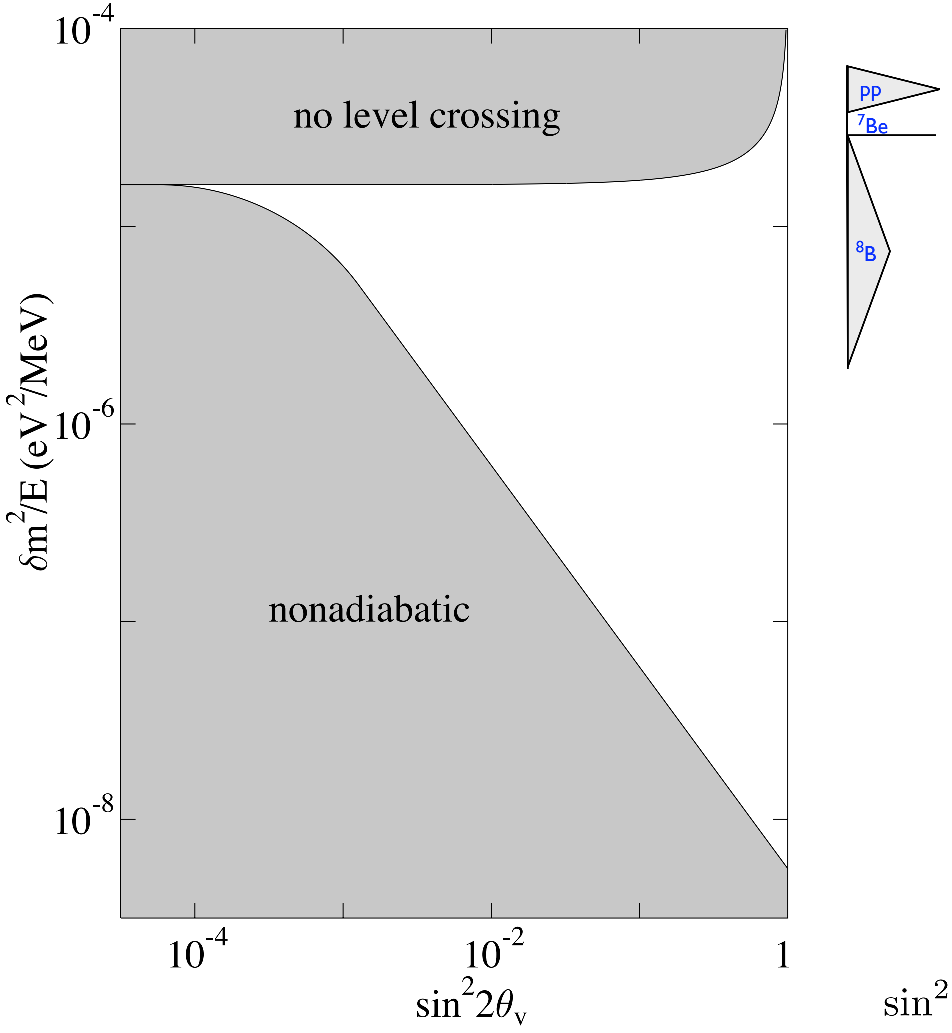
2. The unique role solar νs in constraining neutrino parameters

Our most important constraint on θ_{12} and on $\dfrac{m_{12}}{|m_{12}|}$

$$|\nu_e\rangle \sim (0.823 \pm .022)|\nu_1\rangle + (0.547 \pm .033)|\nu_2\rangle + (0.148 \pm .011)|\nu_3\rangle$$

$\mathrm{Cos}\ \theta_{12}\ \mathrm{Cos}\ \theta_{13}$

MSW Mechanism



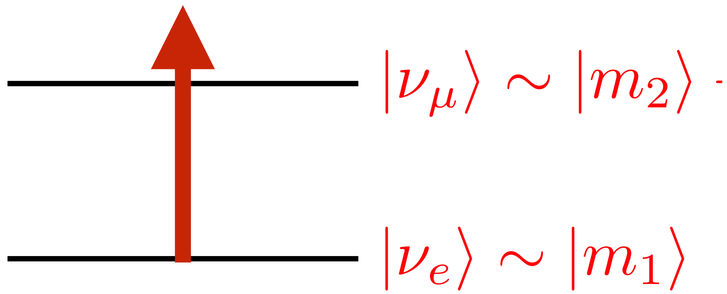
$\sin^2 2\theta_{12} \sim 0.85$

2. The unique role solar ν in constraining neutrino parameters

Our most important constraint on θ_{12} and on $\frac{m_{12}}{|m_{12}|}$

$$|\nu_e\rangle \sim (0.823 \pm .022)|\nu_1\rangle + (0.547 \pm .033)|\nu_2\rangle + (0.148 \pm .011)|\nu_3\rangle$$

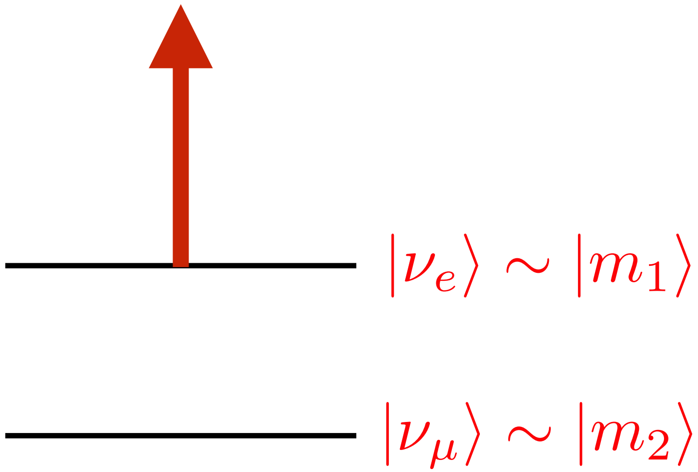
Crossing



$|\nu_\mu\rangle \sim |m_2\rangle$

$|\nu_e\rangle \sim |m_1\rangle$

No Crossing



$|\nu_e\rangle \sim |m_1\rangle$

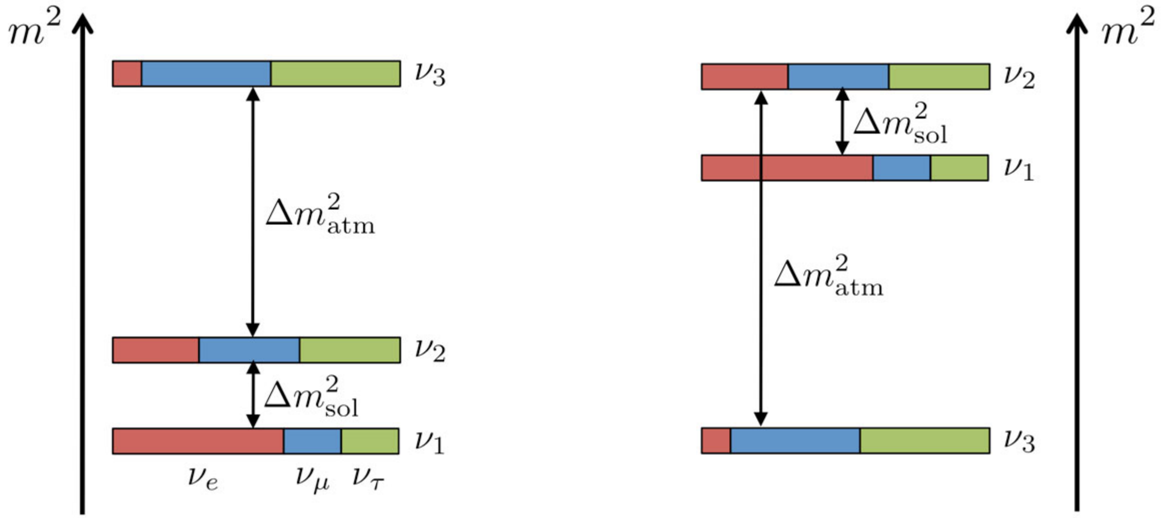
$|\nu_\mu\rangle \sim |m_2\rangle$

2. The unique role solar ν in constraining neutrino masses:

Our most important constraint on θ_{12} and on $\dfrac{m_{12}}{|m_{12}|}$

$$|\nu_e\rangle \sim (0.823 \pm .022)|\nu_1\rangle + (0.547 \pm .033)|\nu_2\rangle + (0.148 \pm .011)|\nu_3\rangle$$

The sign of m_{12} is a binary decision



But <u>cross sections errors</u> on the deduced solar θ_{12} are propagated through in global analyses of neutrino parameters

3. Solar luminosity test

The Sun’s energy production can be measured electromagnetically through its luminosity

Or it can be measured via weak interactions through its neutrino emission: The neutrinos “measure” the rates of the ppI, ppII, and ppIII cycles and the CNO chain, each of which produces a known energy calculable from nuclear masses

The equivalence of the solar E&M and weak luminosities tests

- the long-term stability of the sun: the weak luminosity measurement is nearly instantaneous, while the E&M emission reflects the Kelvin time delay
- new physics producing any unobserved weak emission at $\sim 1\%$

Two neutrinos produced per He nucleus synthesized

Energy carried off by neutrinos

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

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)

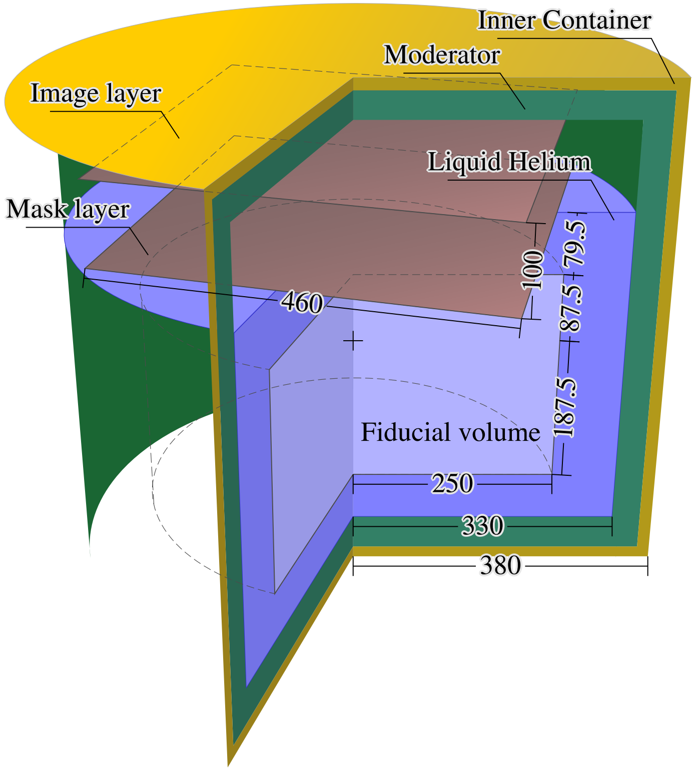
The fraction error of the RHS is $\delta L_\odot / L_\odot \sim 0.004$

The error of the LHS reflects both uncertainties on flux measurements and those on oscillation parameters necessary to extract the total flux from measurements: $\delta L_\nu / L_\nu \sim 0.1$

The oscillation parameter uncertainty in deducing the solar flux from the measured flux is currently 1% (1σ)

A meaningful test of the equivalence of the weak and electromagnetic luminosities reflects the absence of a high-quality pp measurement, which dominates the luminosity constraint and its error budget.

A technology that was well developed 10 years ago — capable of a sub-2% measurement of the pp neutrinos — is now being reconsidered because of interest in detecting low-mass WIMPs



Huang, Lanou, et al., Astropart. Phys. 30, 1 2008)

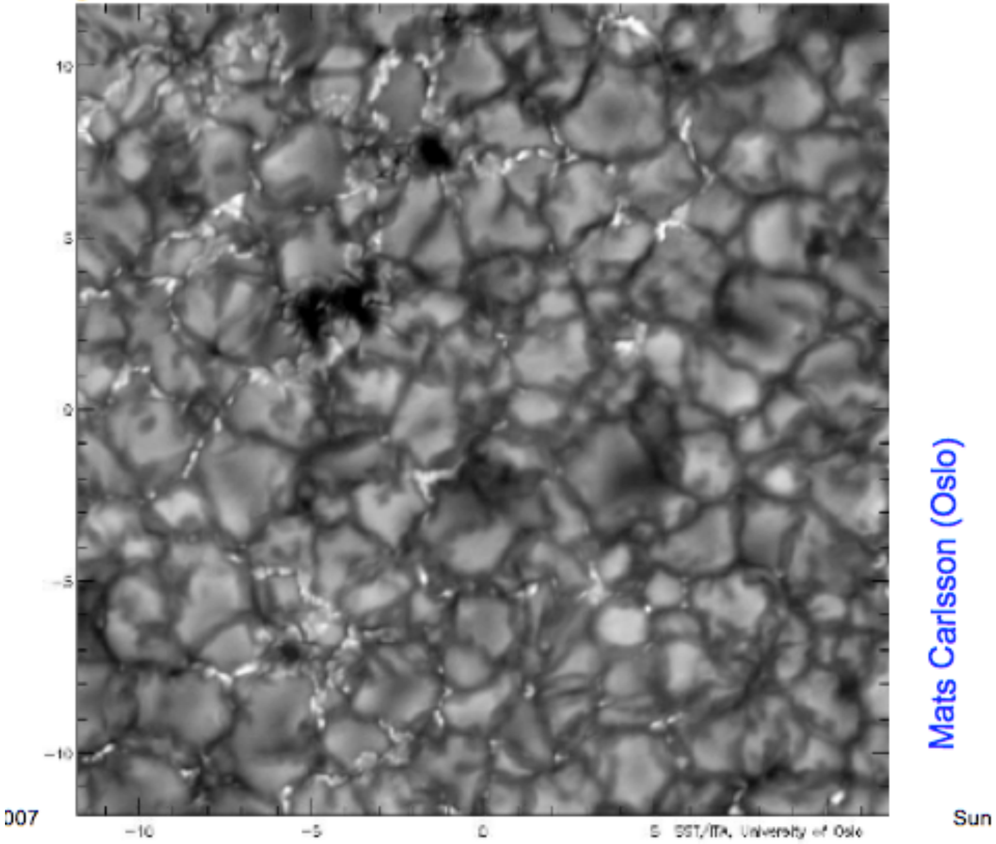
HERON superfluid helium detector

4. Solar abundance problem

- The classic analyses modeled the photosphere in 1D, without explicit treatments of stratification, velocities, inhomogenieties

- New 3D, parameter-free methods were then introduced, significantly improving consistency of line analyses: MPI-Munich

Dynamic and 3D due to convection

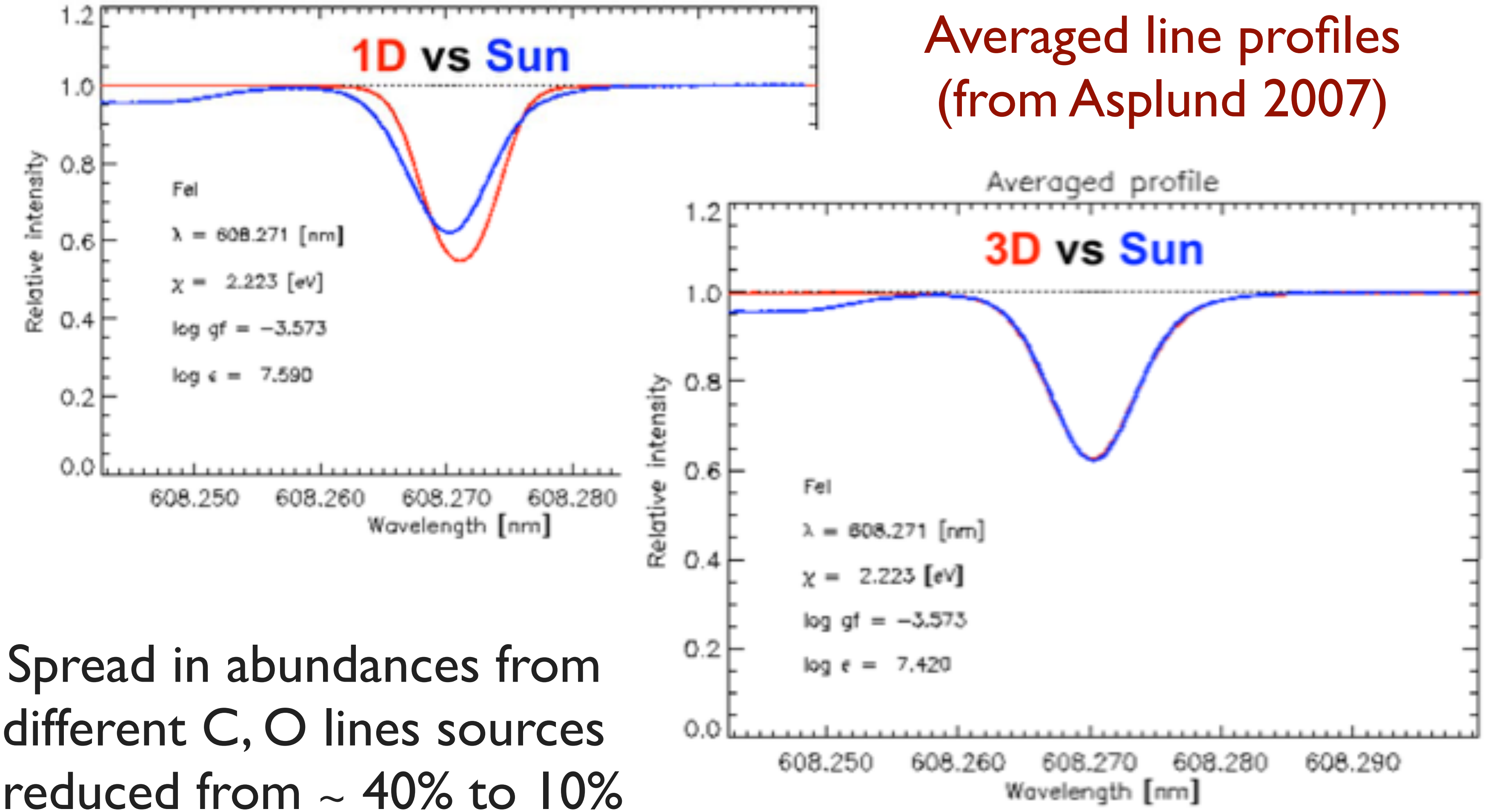


Mats Carlsson (Oslo)

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

With the new ν physics added, theory and experiment seem to coincide

Averaged line profiles
(from Asplund 2007)

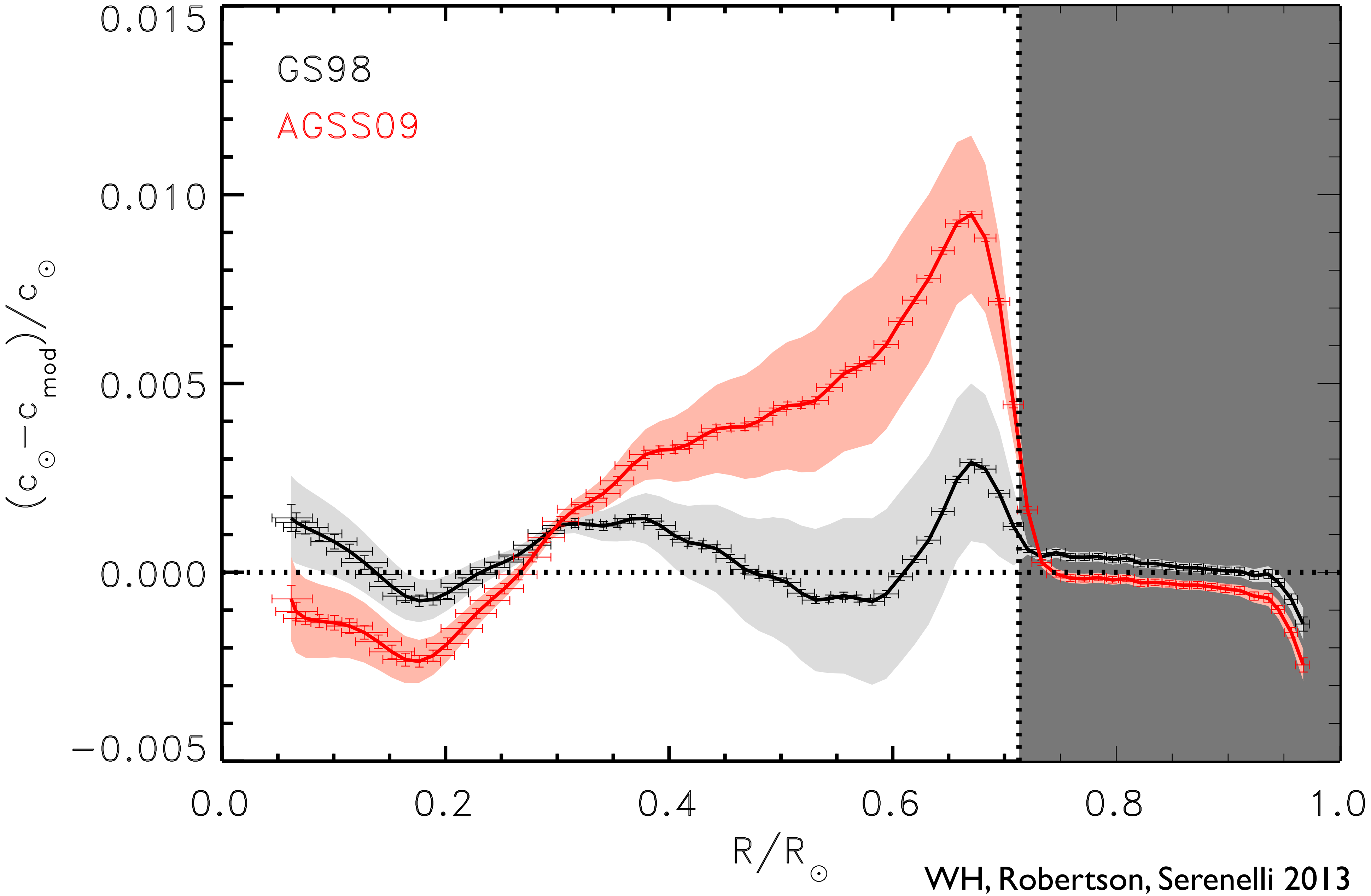


- Spread in abundances from different C, O lines sources reduced from ~ 40% to 10%

- But abundances significantly reduced Z: 0.0169 ⇒ 0.0122
- Makes sun more consistent with similar stars in local neighborhood

- Lowers SSM ^{8}B flux by 20%

But adverse consequences for 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
$(Z/X)_\mathrm{S}$	0.0229	0.0178	–
Z_S	0.0170	0.0134	–
Y_S	0.2429	0.2319	0.2485 ± 0.0035
$R_\mathrm{CZ}/\mathrm{R}_\odot$	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	–

Solar abundance problem: A disagreement between SSMs that are optimized to agree with interior properties deduced from our best analyses of helioseismology (high Z), and those optimized to agree with surface properties deduced from the most complete 3D analyses of photoabsorption lines (low Z).

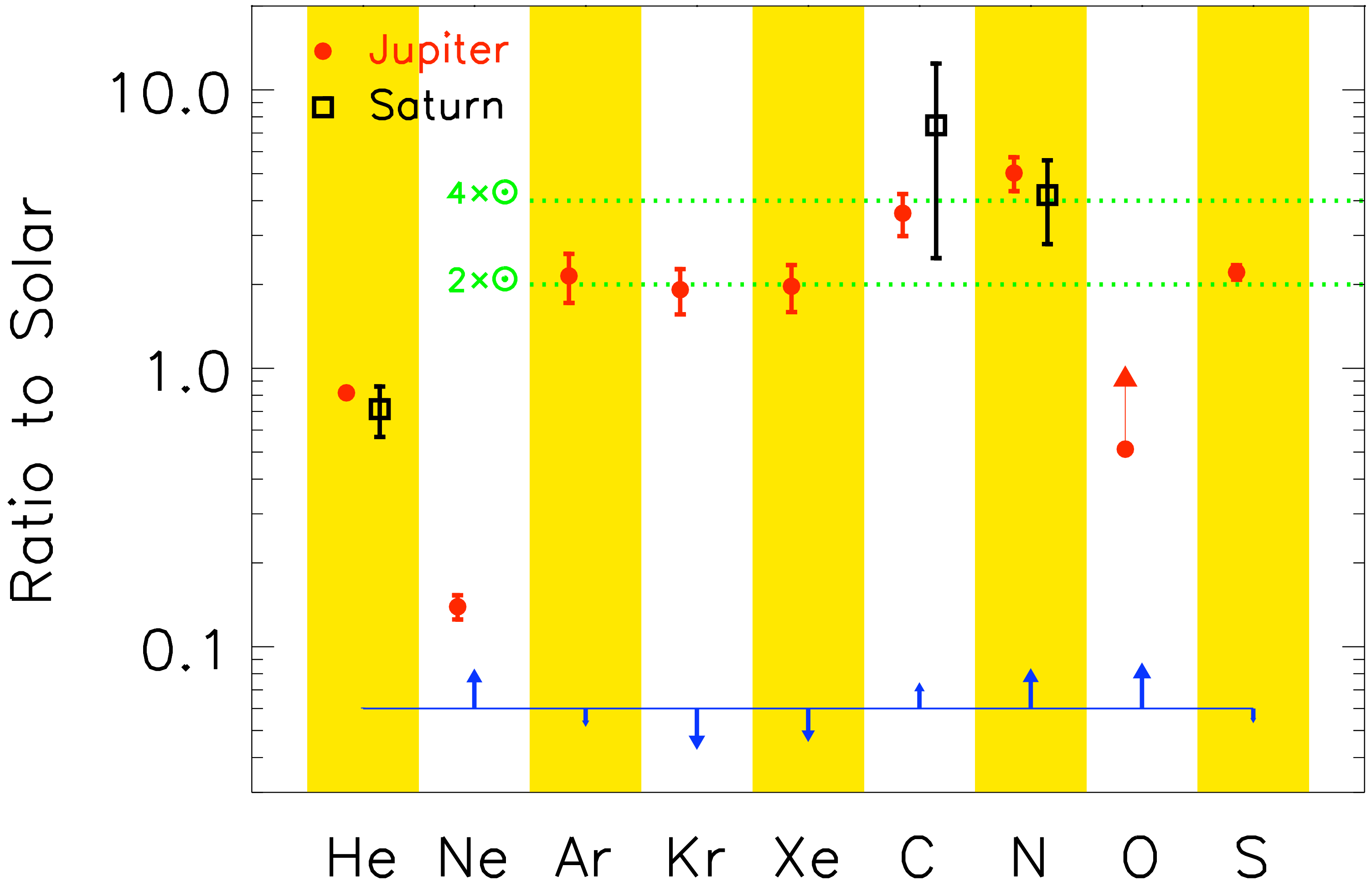
Difference is $\sim$ 40 $M_\oplus$ of metal, when integrated over the Sun’s convective zone (which contains about 2.6% of the Sun’s mass)

The SSM assumption of a homogeneous zero-age Sun is general argued to be a consequence of the Hayashi phase

Serenelli+WH argued that a possible solution to the solar abundance problem is a Sun with a high metallicity core, and a low metallicity convective zone.
(WH & Serenelli, Ap. J. 687 (2008) 678; Serenelli, WH, Pena-Garay, Ap. J. 743 (2011) 24)

The mechanism: When the sun is 95% formed,
planets form in the protoplanetary disks, sweeping out 50-90 $\mathrm{M}_\oplus$ of metal, leaving H/He gas that, when deposited on the sun, dilutes the convective zone

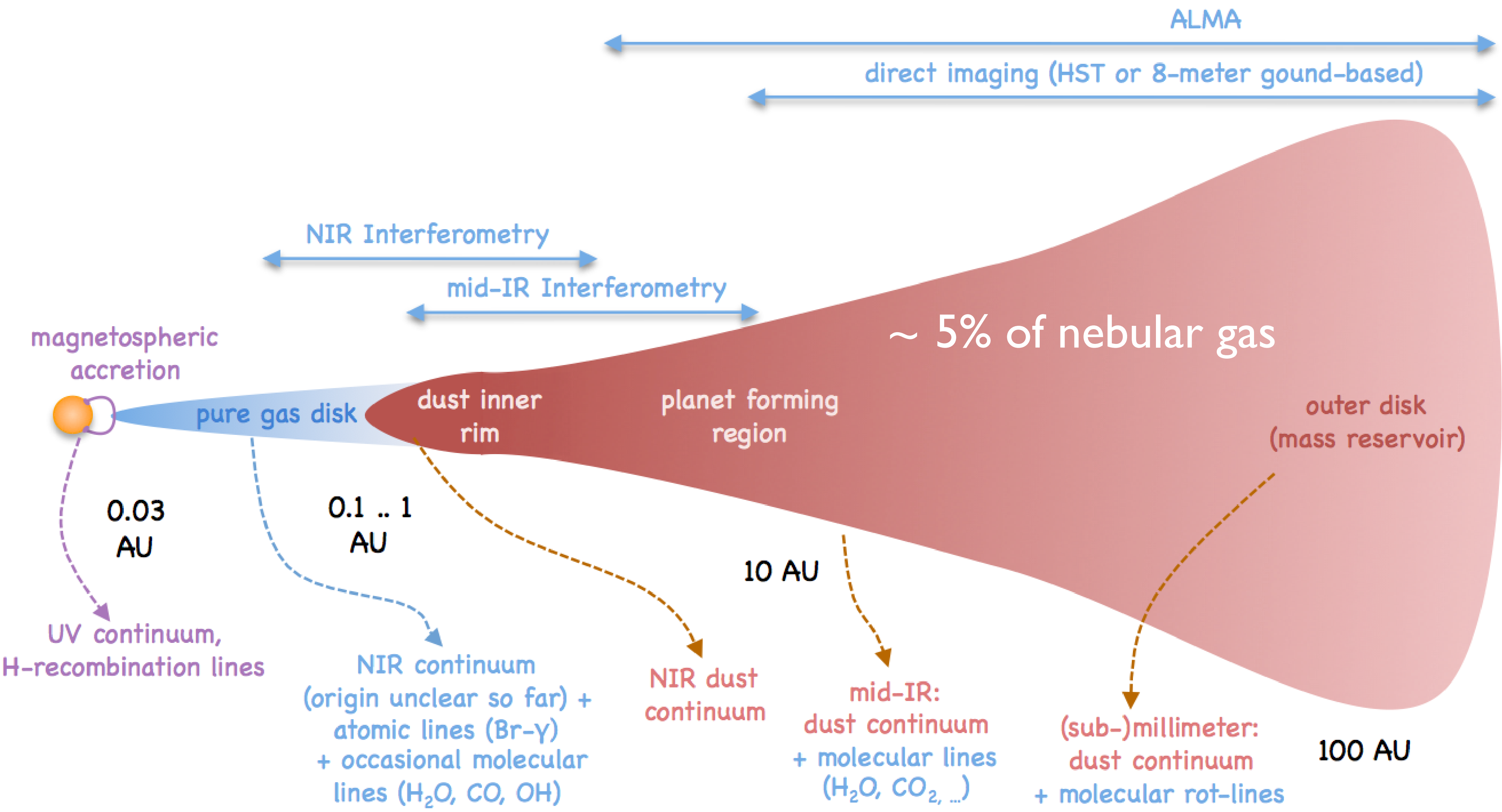
metal enrichments of the gaseous giants



Galileo data, from Guillot AREPS 2005

Standard interpretation: late-stage planetary formation in a chemically evolved disk over ~ 1 m.y. time scale

Cartoon picture of metal segregation, accretion



ALMA

direct imaging (HST or 8-meter gound-based)

NIR Interferometry

mid-IR Interferometry

~ 5% of nebular gas

magnetospheric accretion

pure gas disk

dust inner rim

planet forming region

outer disk (mass reservoir)

0.03 AU

0.1 .. 1 AU

10 AU

100 AU

UV continuum,
H-recombination lines

NIR continuum
(origin unclear so far) +
atomic lines (Br-γ)
+ occasional molecular
lines (H_2O, CO, OH)

NIR dust
continuum

mid-IR:
dust continuum
+ molecular lines
(H_2O, CO_2, ...)

(sub-)millimeter:
dust continuum
+ molecular rot-lines

Dullemond and Monnier, ARA&A 2010

At the time, there was significant justification for this proposal

- Jupiter’s composition is consistent with a scenario where 2/3rds of the hydrogen that initially “belonged” to Jupiter was lost to the Sun (Guillot & Hueso (2006))

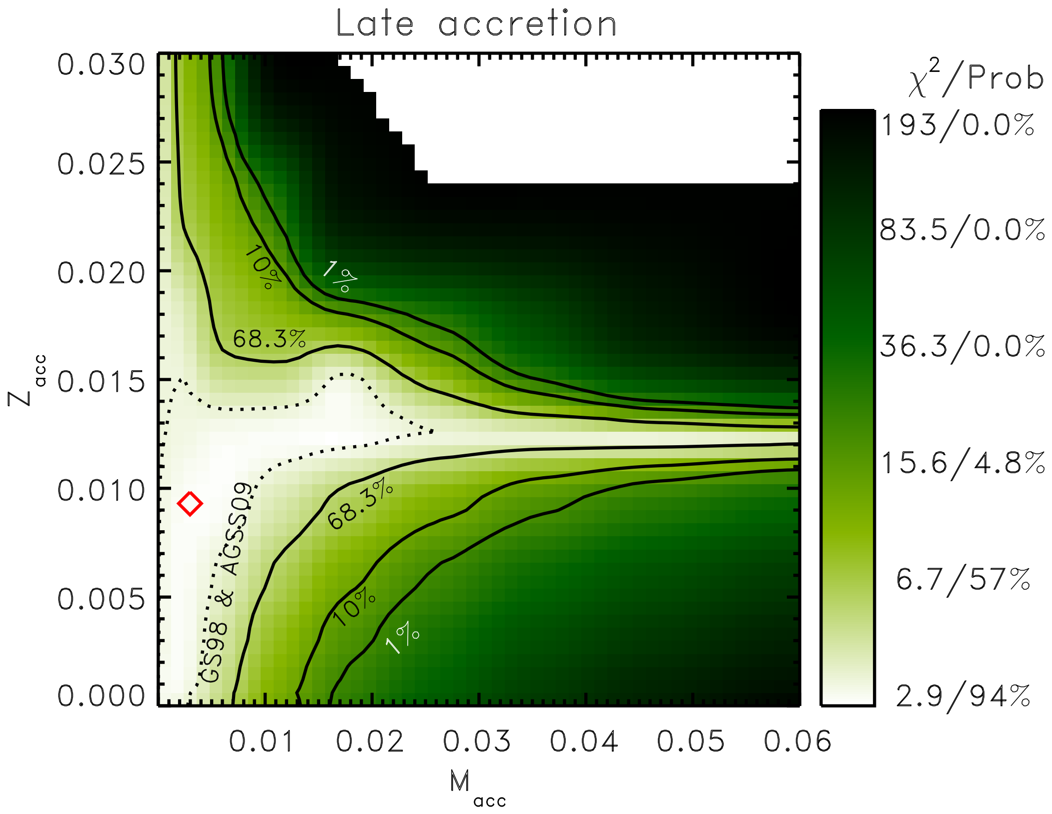
- The hydrogen remains in the solar system - below 30 AU this appears to case (Adams et al. (2006))

But very recently

- 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 by up to a factor of 42 (McClure, A&A 632, A32 (2019))

- The first realistic modeling of the disappearance of volatile species from the gas phase including accretion and radial drift, concluding that molecular species such as CO and CH4 always depleted (Booth and Ilie, MRAS, 2019)

We developed a self-consistent accreting SM and AS computed the effects of the accretion of depleted gas on an evolving young sun (helioseismologic and neutrino observables) with no real guidance on what metals might be depleted



Best fit to neutrino fluxes: modest accretion of metal-poor gas

We now are beginning to get the astrophysical data and supporting solar system modeling that we need to parameterize the accretion

Can we confirm the solar abundance abundance problem?

Idea: use CNO neutrino to directly determine the core metallicity

- measurable CNO neutrino fluxes

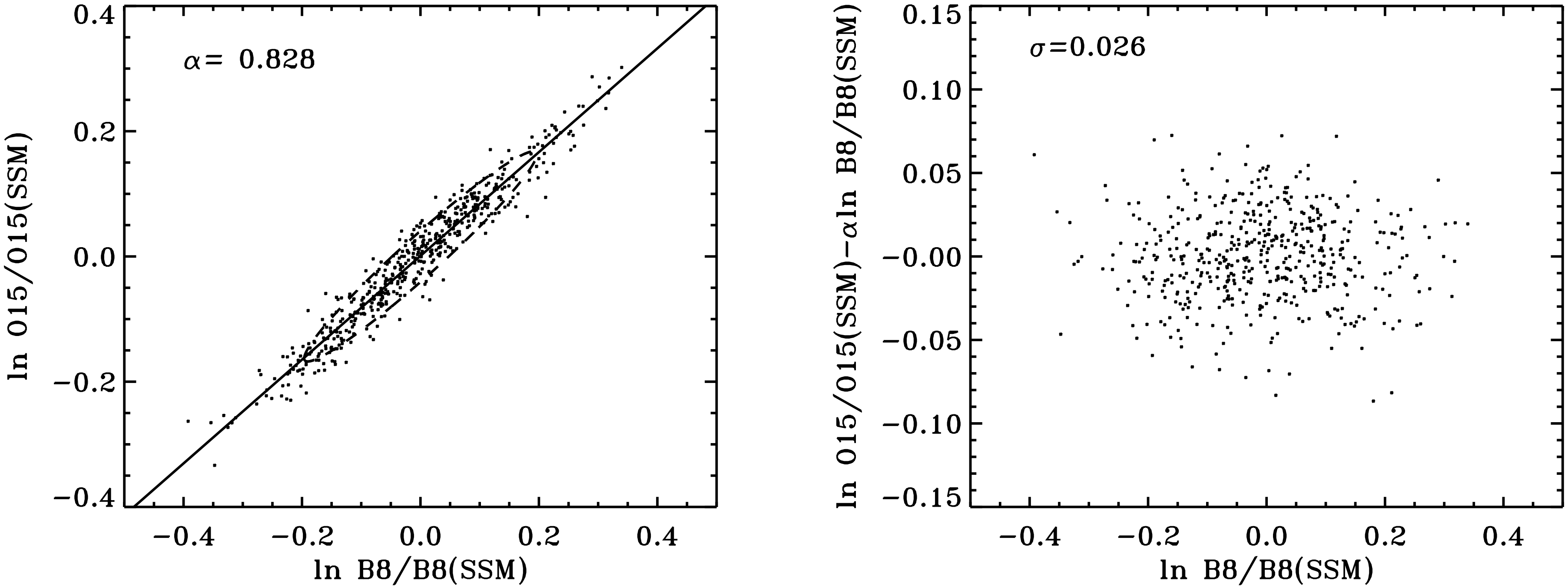
$$^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C} \quad E_\nu \lesssim 1.199 \text{ MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8/\mathrm{cm}^2\mathrm{s}$$

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

- these fluxes depend on the core temperature T (metal-dependent) but also have an additional linear dependence on the total core C+N

- absolute fluxes are uncertain, sensitive to small changes in many solar model uncertainties other than total metallicity

- but an appropriate ratio of the CN and ^{8}B ν flux is independent of these other uncertainties: the measured ^{8}B ν flux can be exploited as a solar thermometer

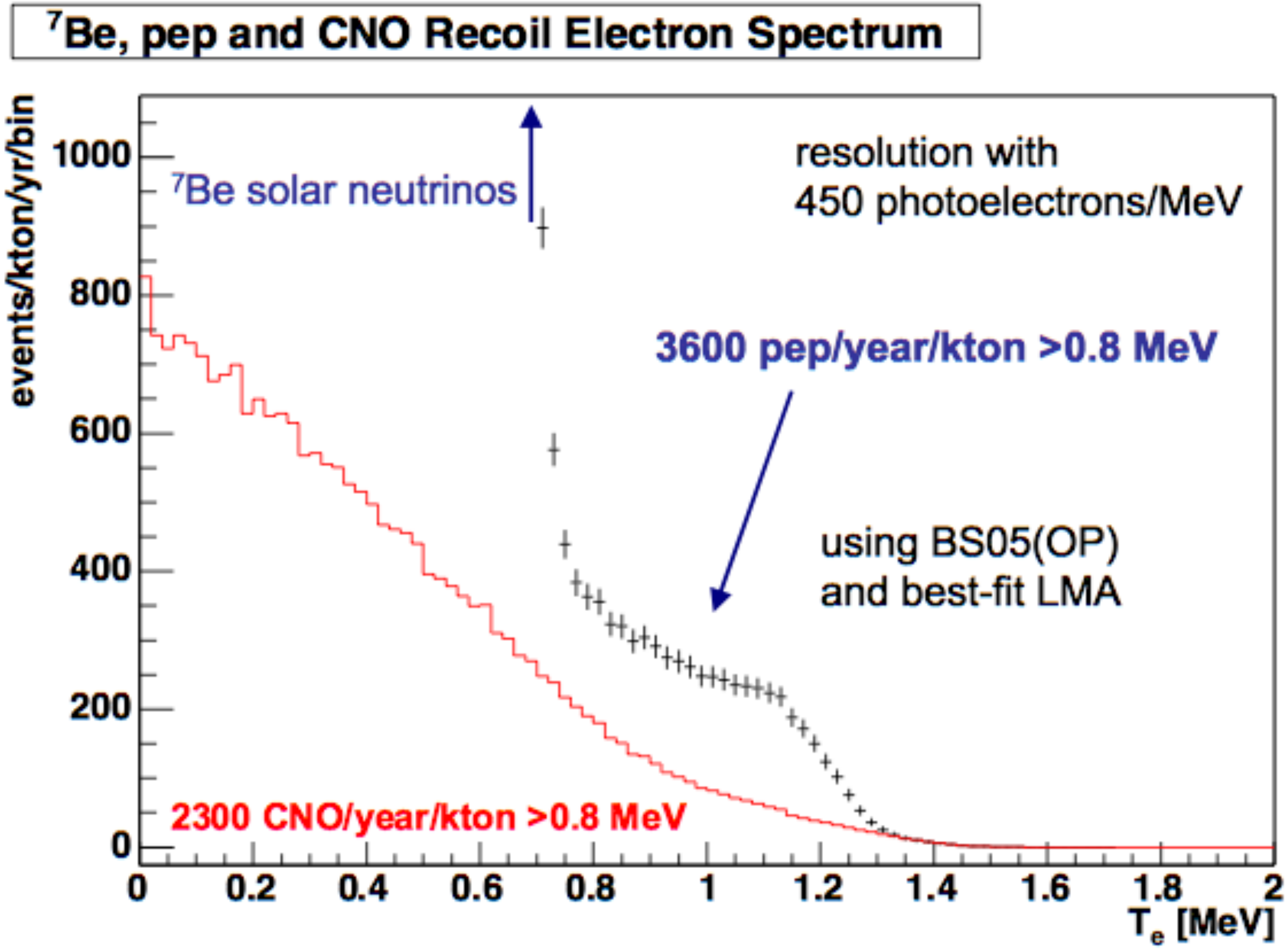


to be measured   known: SK   desired CN core abundance

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

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

based on Solar Fusion II uncertainties: nuclear physics dominates the error budget

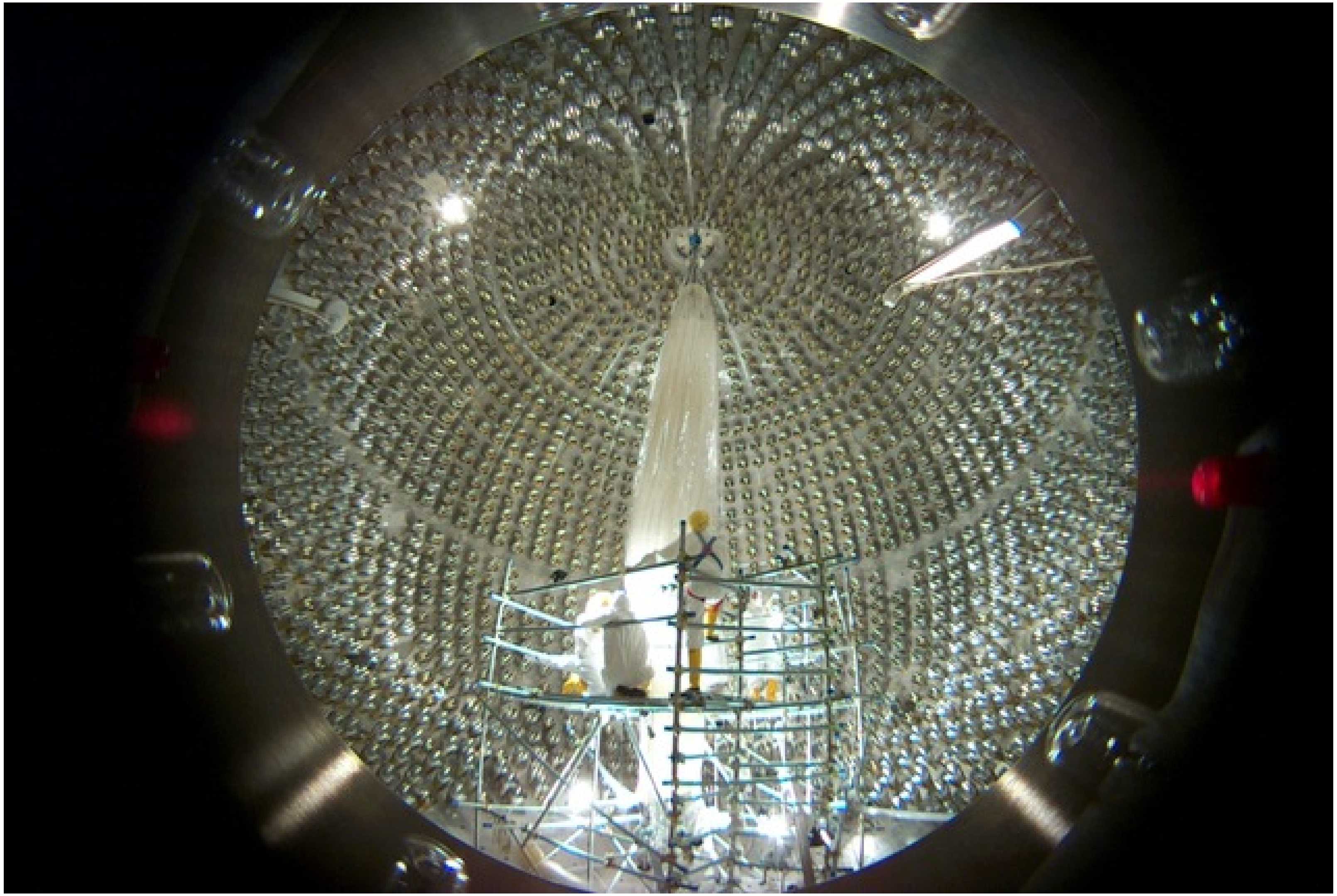


SNO+ simulation
(from Mark Chen)

one kton

Jinping: 2-3 ktons

<u>established the feasibility of a 10% measurement in a kiloton experiment</u>



Borexino has now shown the feasibility: no CNO νs reject at 5.1

needed: bigger and deeper (Jinping)

The inhibiting nuclear uncertainties in the $^{15}\mathrm{O}$ $\nu\mathrm{s}$ measurement

S(0) for $^{14}\mathrm{N}(p,\gamma)$ 7.2% SFII

S(0) for $^{7}\mathrm{Be}(p,\gamma)$ 5.9% SFII

There have been some improvements for both, and these errors will be re-examined in SFIII

The measurement would be fundamental

- Probes the purest sample of primordial solar system gas available to us today, the first gas to be sequestered
- The first opportunity in astrophysics to directly compare surface and deep interior (primordial) compositions
- A first step in creating "standard solar system models" that would link solar ν physics, solar system formation, planetary astrochemistry