Neutrinos, Metals, and the Protoplanetary Disk

- ❑ Solar formation and evolution: the Standard Solar Model
- ❑ The photospheric absorption line - helioseismology conflict
- ❑ Metal segregation: the protoplanetary disk and solar convective zone
- ❑ New data from solar twins
- ❑ SNO+ and its nuclear physics and mixing angle uncertainties

Wick Haxton: Neutrino Mass Workshop 10 February 2010

Composition/metalicity 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 $\leftrightarrow$ convective (mixed)
  - radiative transport becomes more efficient at star's center: radiative core grows from the center outward
  - ZAMS: thermonuclear energy generation compensates emissions

- ❑ The SSM assumes that, because the Hayashi phase fully mixed the sun, the radiative and convective zones will be chemically identical
  - as H+He+Z=1, two conditions needed to fix ZAMS composition
  - Z fixed to contemporary abundances: volatile elements from photospheric absorption lines; others from meteoritic abundances, assumed representative the primordial gas
  - H/He fixed by condition that luminosity reproduced at 4.6 b.y.

Model tests:

- Solar neutrinos: direct measure of core temperature to ~ 0.5%
  - but Davis's quest to make this measurement was de-railed for ~ 30 years by massive neutrinos

- Helioseismology: inversions map out the local sound speed
  - prior to 2000, the SSM - helioseismology concordance was considered a significant confirmation on the model
  - acoustic modes sensitive to the depth of the convective zone and surface He abundance

Recent Re-evaluations of Photospheric Abundances

- SSM requires as input an estimate of core metalicity at t=0

- Taken from meteoritic abundances or from photospheric absorption lines: the latter are the only practical way to determine the abundances of volatile heavy elements, such as C, N, O, Ne, Ar
  - SSM then assumes a homogeneous zero-age sun characterized by these abundances, for reasons previously described

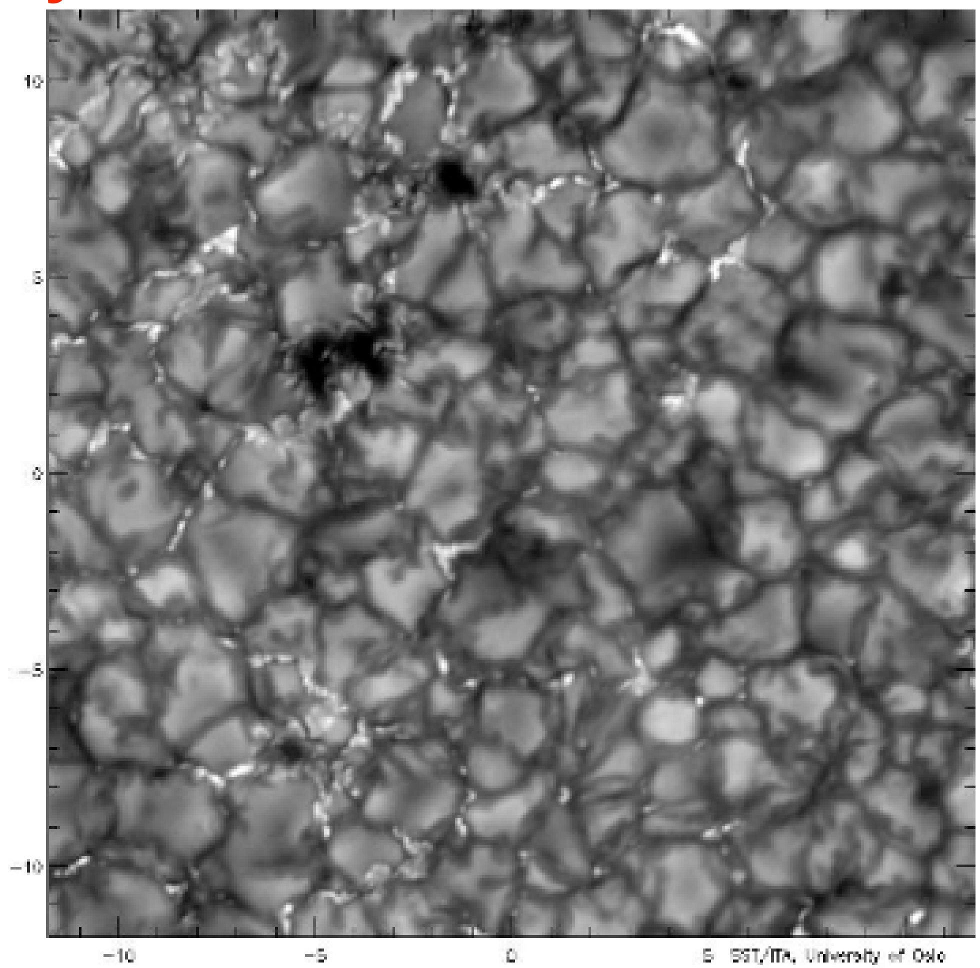
- These metals influence solar dynamics: free-bound transitions important to opacity, influencing local sound speed: different metals dominate in different solar regions

- The once excellent agreement between SSM and helioseismology due in part to this input (Grevesse & Sauval 1998)

- The classic analyses modeled the photosphere in 1D, despite stratification, velocities, inhomogenieties

- But new 3D, parameter-free methods have been introduced, significantly improving consistency of line analyses

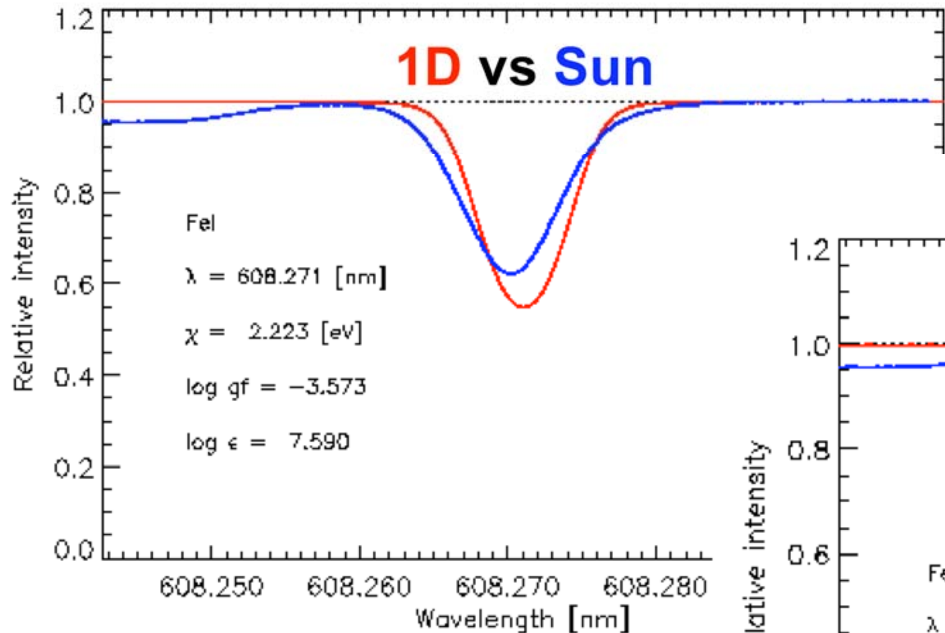
Dynamic and 3D due to convection

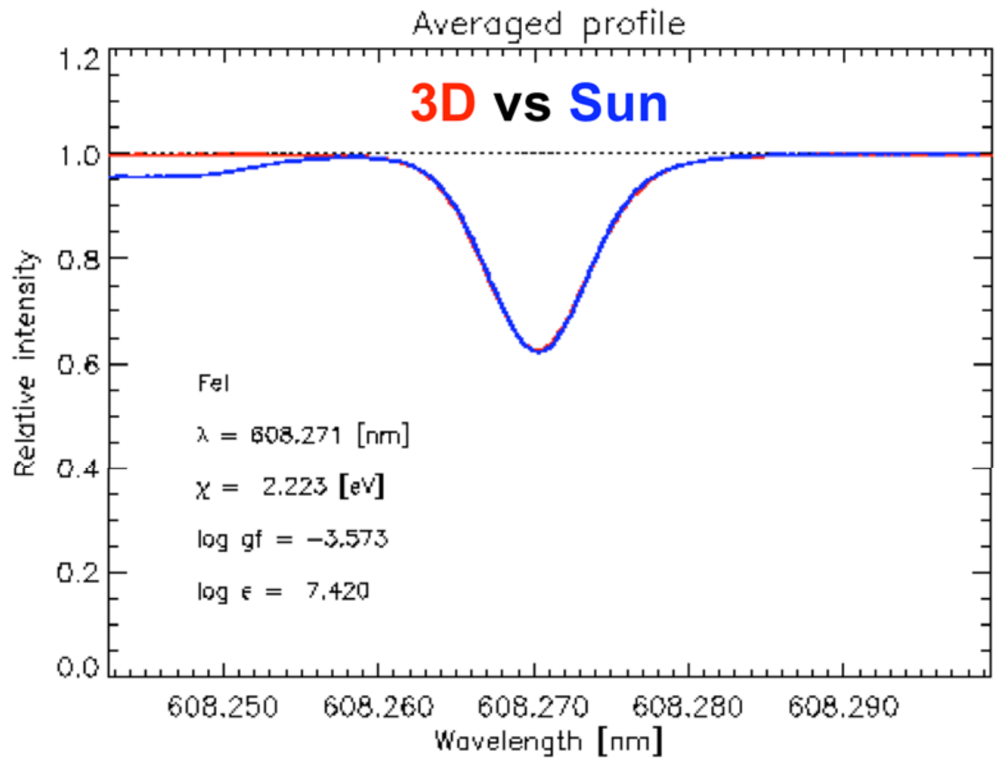


Mats Carlsson (Oslo)

Sun

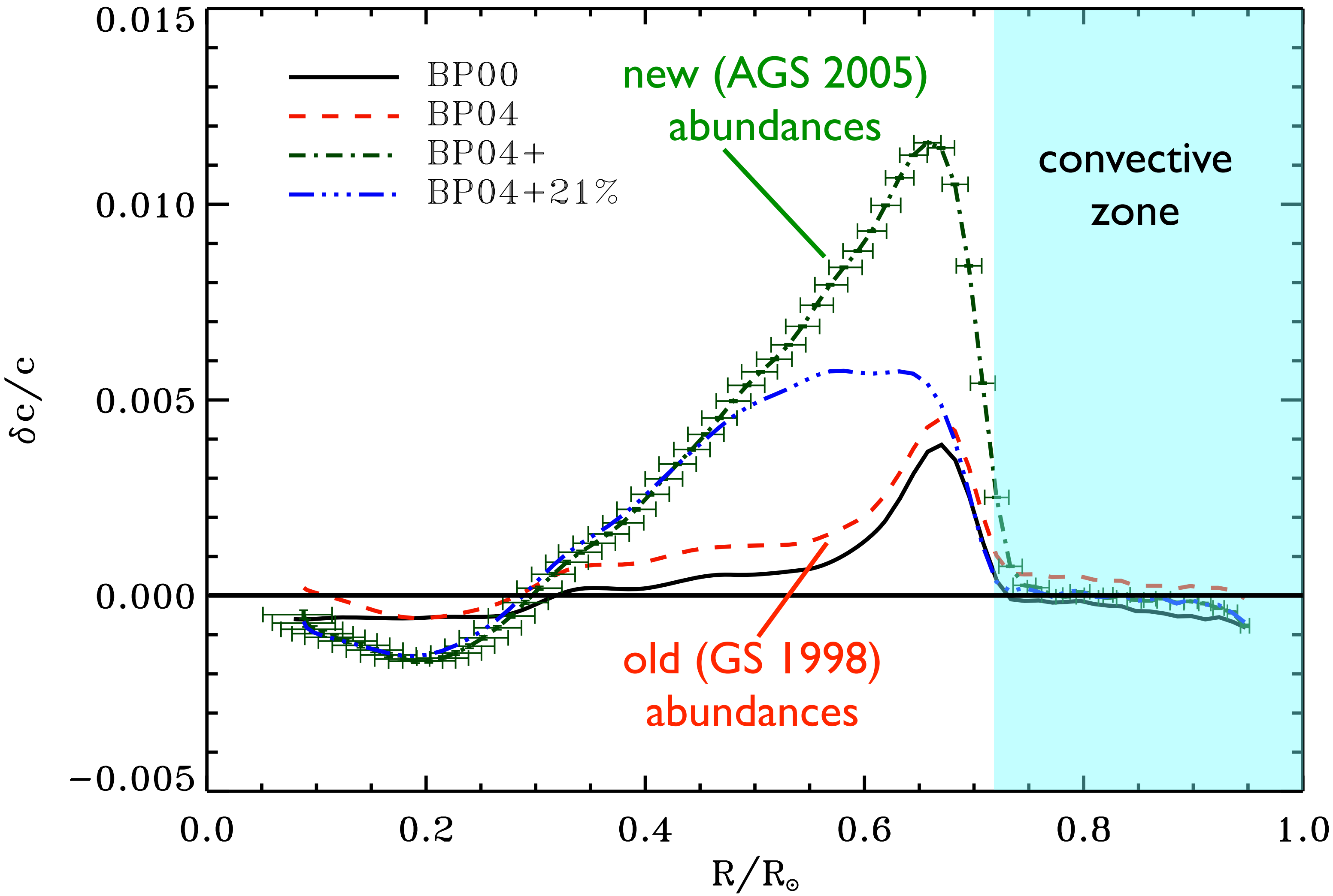
Averaged line profiles
(from Asplund 2007)





- 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



Bahcall, Basu, Pinsonneault, Serenelli 2004

- Discrepancy largest for T ~ 2-5 $\times 10^6$ K: C, N, O, Ne, and Ar are partially ionized, with O and Ne particularly important to the opacity

- Troubling because the previous concordance between the SSM and helioseismology helped establish the credibility of the SSM, and thus the plausibility of a neutrino mixing solution to the solar ν problem

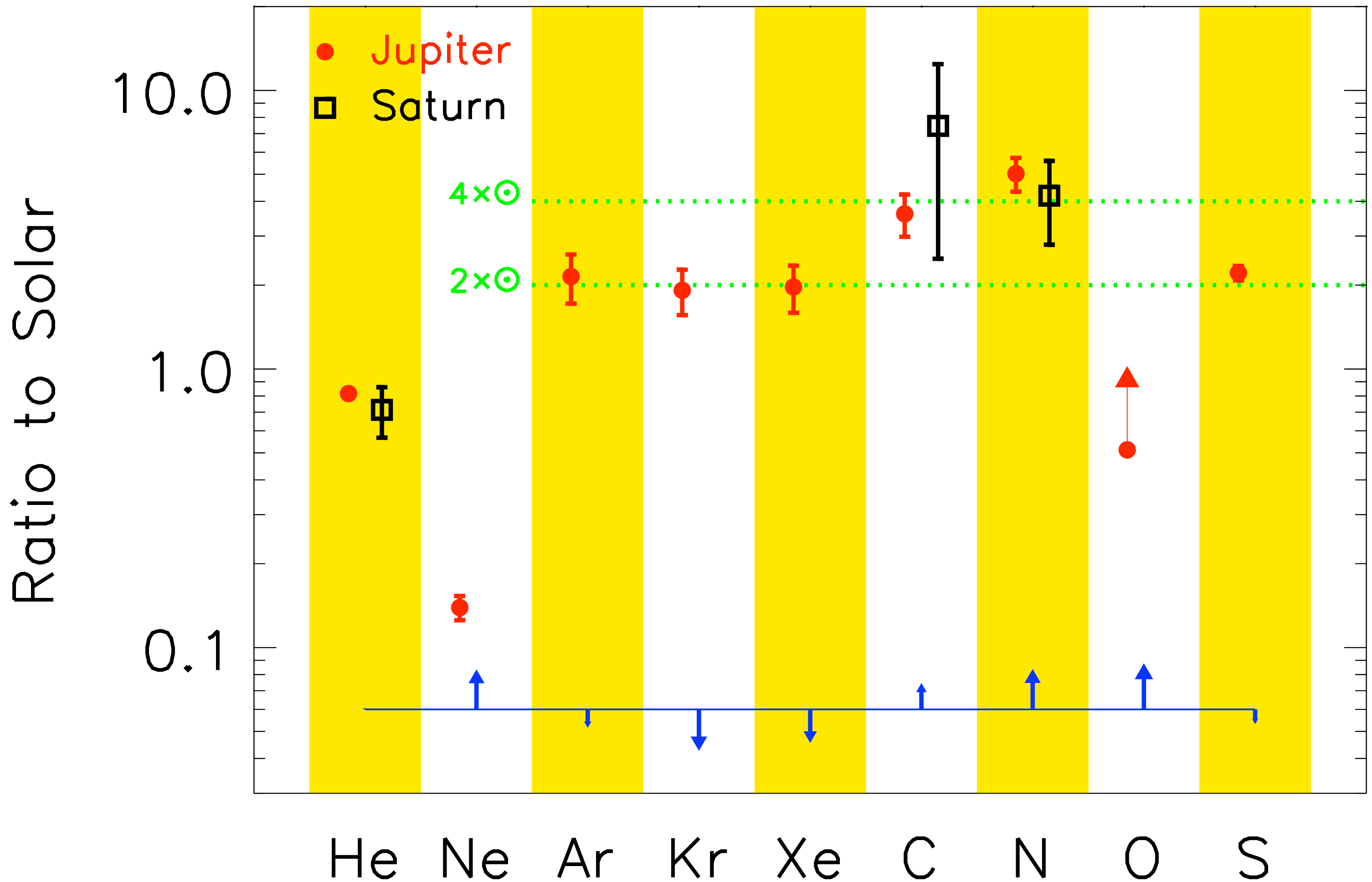
idea for a resolution:
"CN cycle and solar metalicity,"
W. Haxton and A. Serenelli   Ap J 687 (2008) 678

Metals and the Proto-planetary Disk

- Accept the photospheric and helioseismic results at face value: the convective zone (2.6% of the Sun's mass) has a lower metal content than the radiative zone: deficit in the convective zone is 50 $M_\oplus$

- Galileo, Cassini, and subsequent planetary modeling show that significant metal differentiation occurred late in the evolution of the solar system, associated with formation of the gaseous giants
  - planets form late, involving the last ~ 5% of the gas
  - angular momentum transfer: that gas is in a thin disk
  - metal-rich grains and ice collect at the disk midplane
  - formation of the 10 $M_\oplus$ rock cores of the giant planet, which scour out this enriched material
  - rapid (1-few My) formation of gaseous envelopes, after the bulk of the nebular gas has already dissipated (Bodenheimer and Lin 2002)
  - timing: the sun already has developed its radiative core

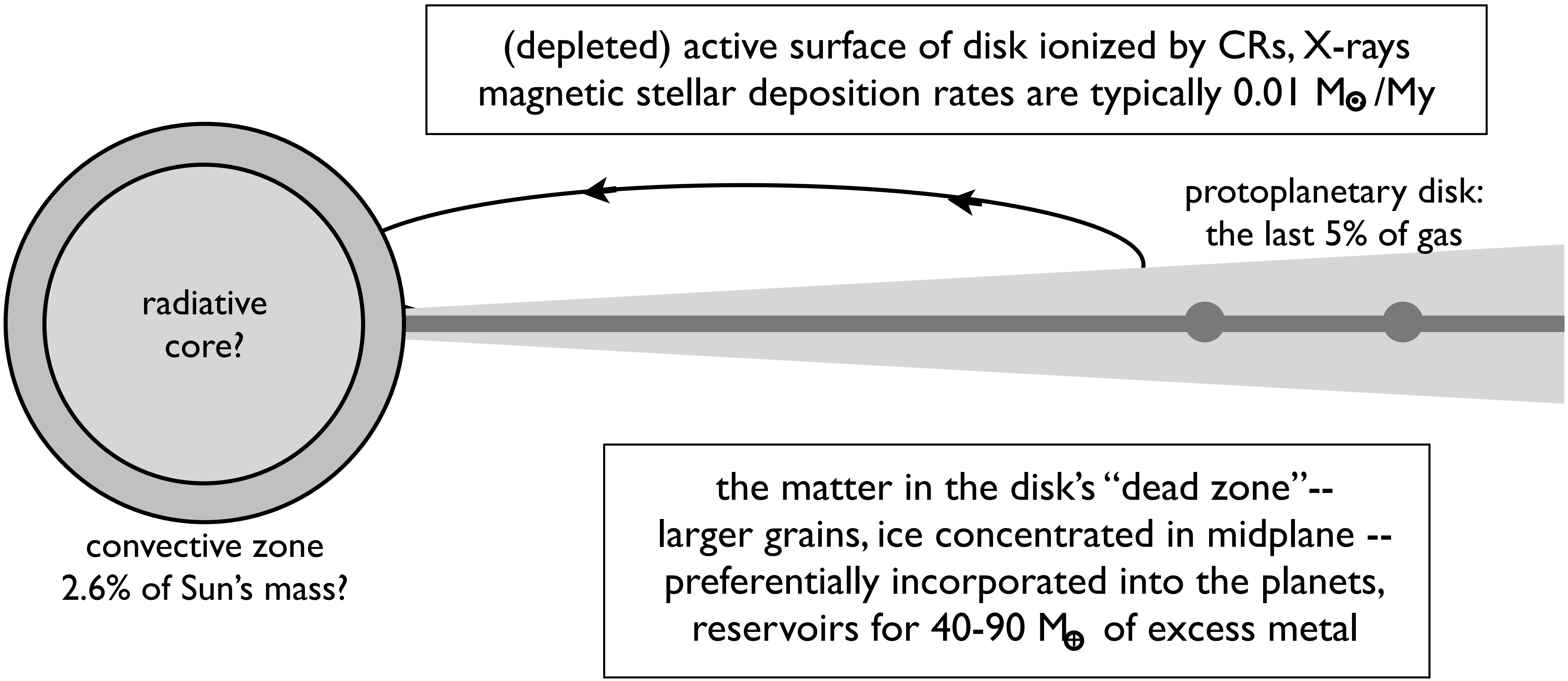
- The observed atmospheric enrichments indicate a total metal excess of (40-90) $M_\oplus$, depending on planetary modeling uncertainties (Guillot 2005)



Galileo data, from Guillot AREPS 2005

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

A speculation (AS+WH): a single mechanism perturbs and segregates the last few percent of nebular gas, resulting in the enrichment of planetary atmospheres and dilution of the convective zone



The sun's deep interior would reflect the composition of the primordial gas cloud; the planets and solar surface would be processed

Issues

- *Solar pp-chain neutrinos -- not yet sufficiently sensitive to core metalicity*:
  SNO 391-day NCD-phase results: $(5.54 \pm 0.51) \times 10^6/\text{cm}^2\text{s}$
  SSM, 1998 GS abundances (Z=0.0169): $5.95 \times 10^6/\text{cm}^2\text{s}$
  SSM, 2005 AGS abundances (Z=0.0122): $4.72 \times 10^6/\text{cm}^2\text{s}$
  but a higher metalicity core not disfavored

- *Convective zone*: requires a mature convective at the time the protoplanetary disk formed: this is consistent with modern numerical simulations that generate SSM initial conditions from collapse of a gas cloud (e.g., Wuchterl and Klessen 2001)

- *Observations*: one can study solar twins -- if the formation of planets alters a host star's metalicity, then one might have a new tool for planet hunting

- *Measurement*: find a way to determine the metal content of the solar core -- an additional motivation for SNO+

Follow-up work has been interesting

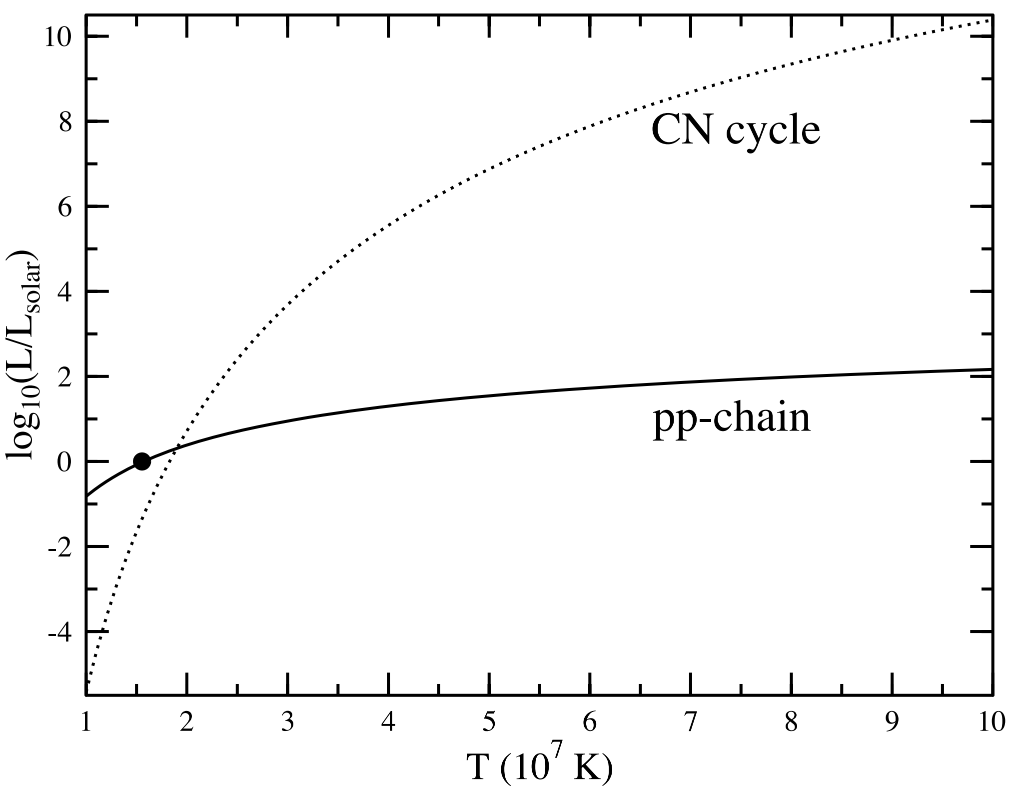
- *Melendez, Asplund, Gustafsson, Young Ap J L 704 (2009) L66*
  Ramirez, Melendez, Asplund A&A 508 (2009) L17
  systematic differences in heavy-element abundances between Sun and nearby solar twins, tightly correlated with the condensation temperature of the elements - so it is chemistry

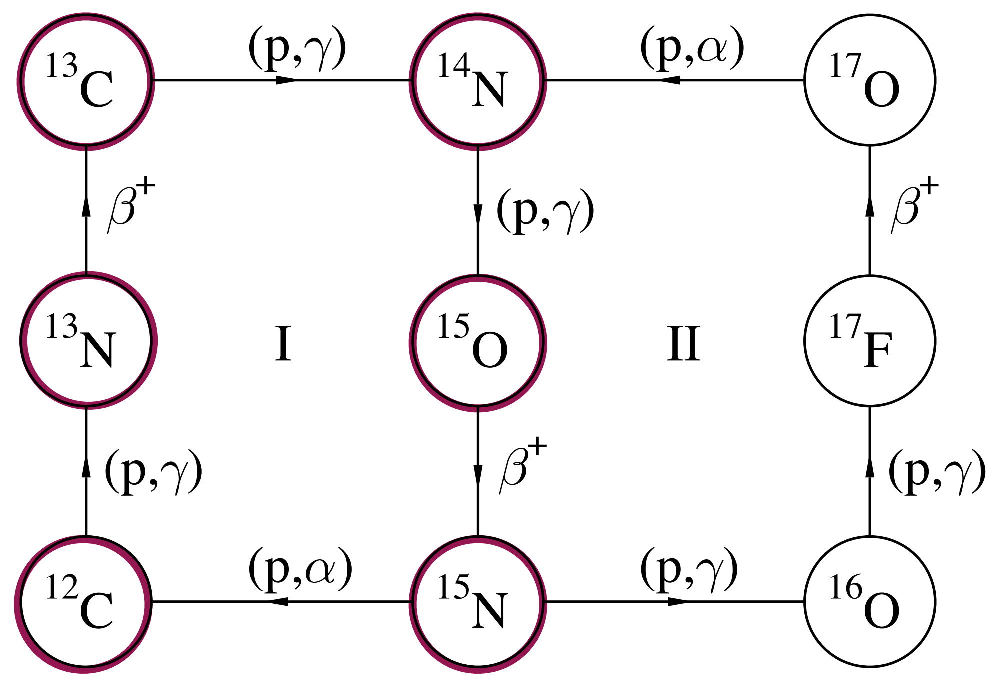
- *Nordlund, Ap J L (in press, 2009)*
  argued that the nearly hydrostatic initial state for pre-stellar core collapse (adopted by Wuchterl and Klessen) is not only reasonable, but possibly necessary to produce the observed power-law of the initial mass function

- *Israelian et al., Nature 462 (2009) 189*
  established a direct correlation between solar twin abundance of Li and the presence of planets: otherwise identical systems with planets have roughly 1/10 the Li of those without planets
  - hypothesized a rather exotic "mechanical" explanation

We argued that a key test of this hypothesis could come as a byproduct of the ββ decay/solar neutrino program of SNO+

- ❑ pp chain (primary) vs CN cycle (secondary): catalysts for CN cycle are pre-existing metals (except ij the interesting case of the first stars)





- the CN-cycle contributes modestly to solar energy generation ~ 1%
- but produces measurable 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, but also have an additional linear dependence on the total C+N in the Sun's core

$$\phi_\nu^{\mathrm{CN}} = F[S_{14}{}_{N+p}; \quad T; \quad \theta_{12}; \quad CN]$$

what we want to determine

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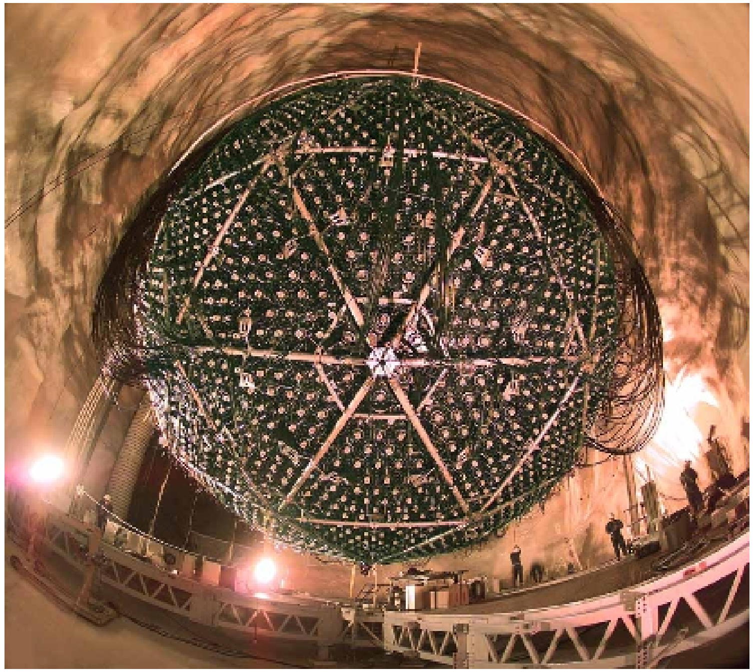
well enough measured by SNO and KamLAND



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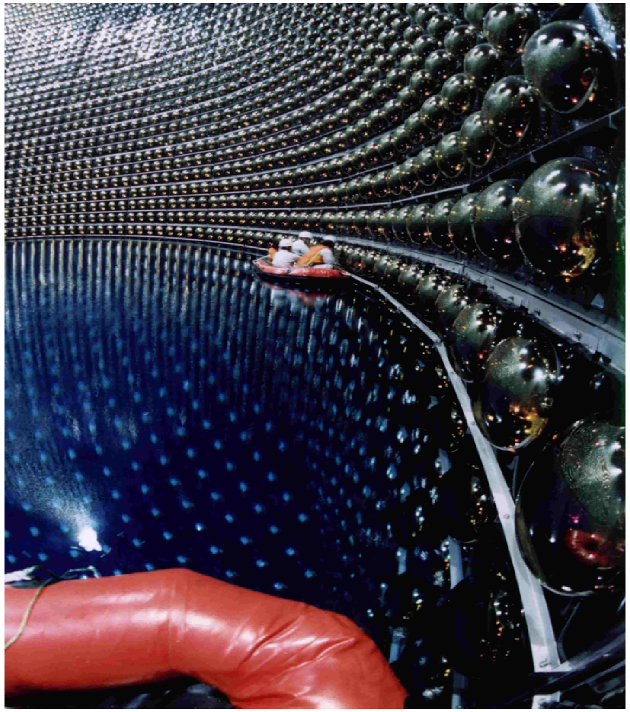
calibrated to 0.5% by Super-Kamiokande



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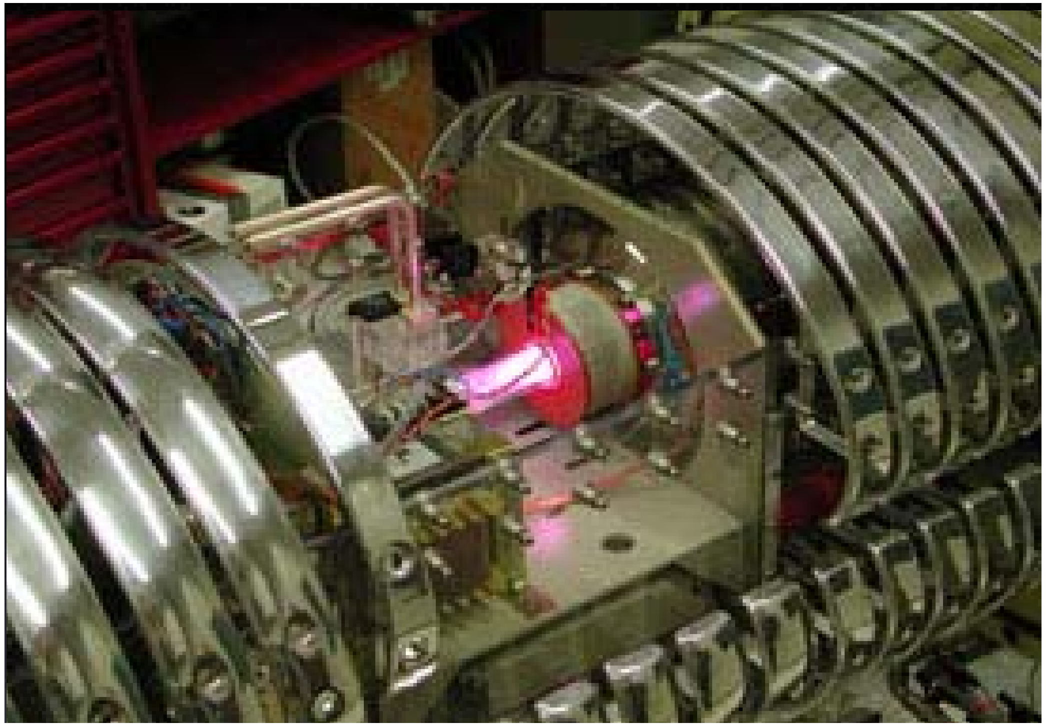
a significant problem until recently

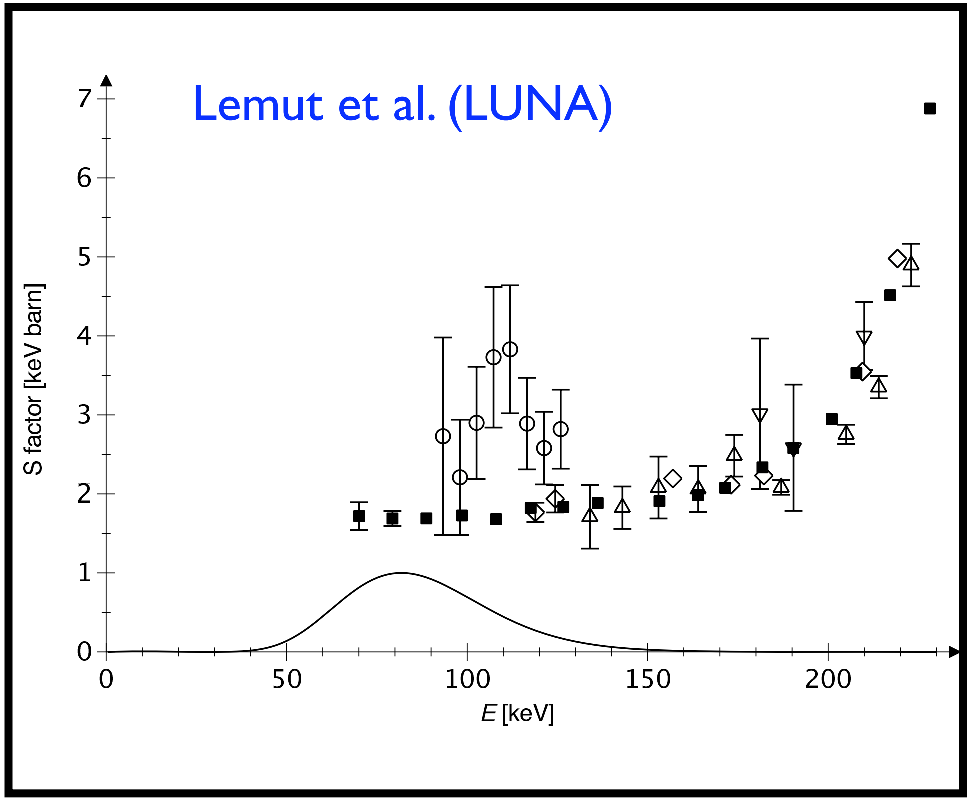
The nuclear physics is finally under control

LUNA and LENA measurements of $^{14}N(p,\gamma)$

Formicola (LUNA) et al. (2004); Imbriani et al. (2005);
Bemmerer et al (2006); Lemut et al. (2006);
Trautvetter et al. (2008); Runkle (TUNL) et al. (2005)

S-factor mapped down to 70 keV





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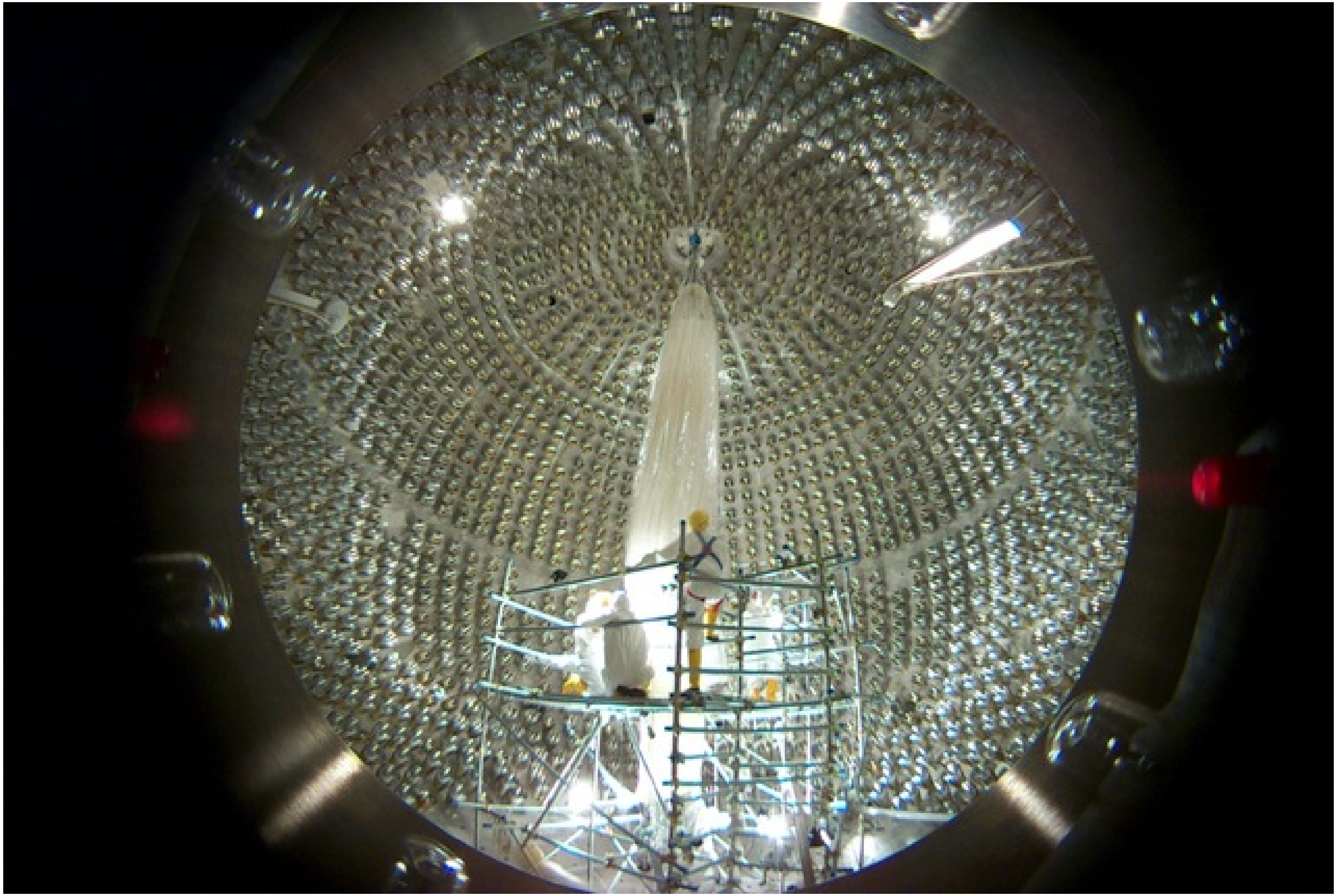
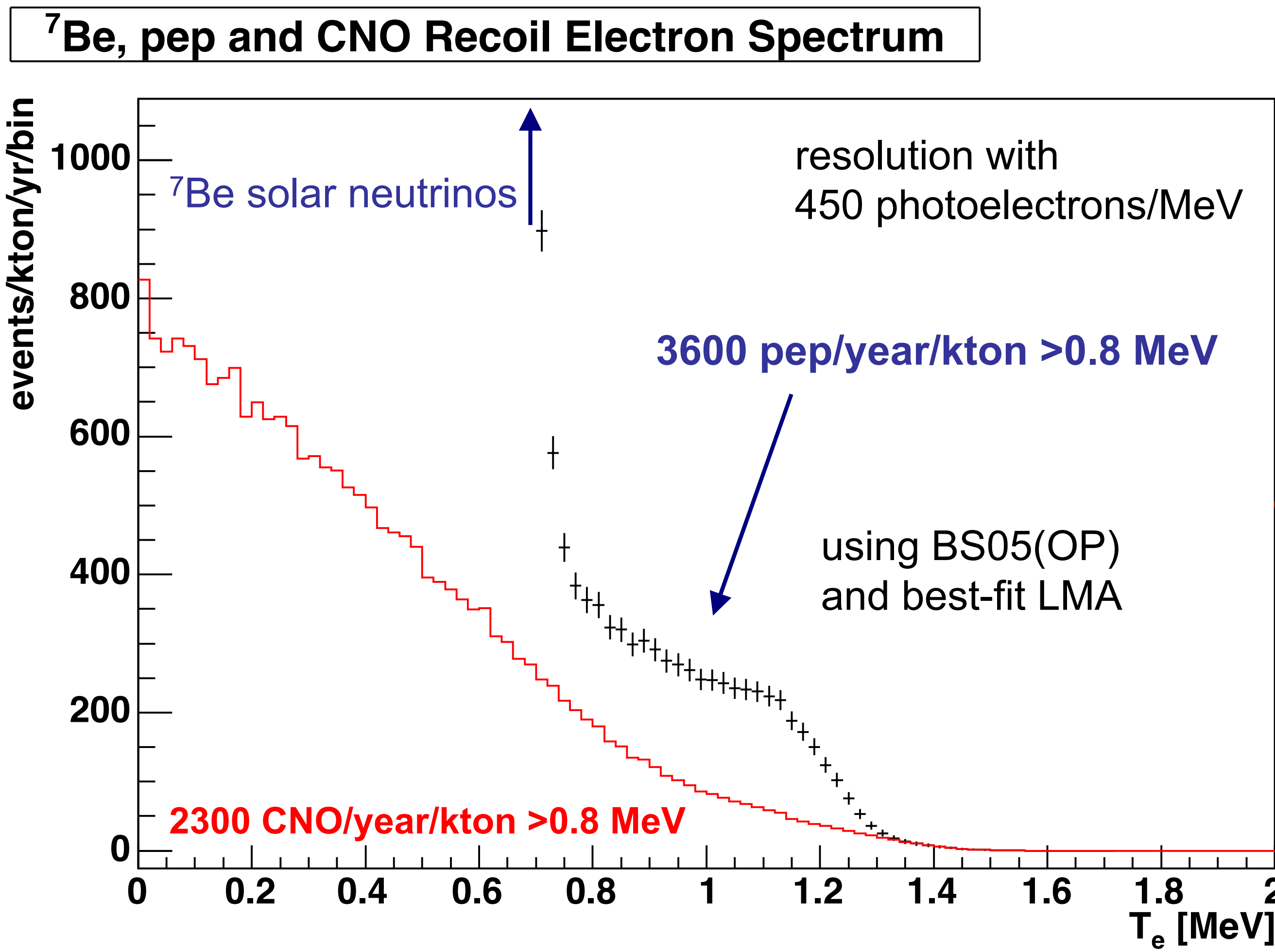
$\downarrow$

an experiment capable of measuring the fluxes



Borexino and KamLAND have developed the technology -- but one must be much deeper to avoid CR production of ^{11}C

SNO+: Borexino × 3 at SNOLab depts



(from Mark Chen)

A similar detector -- Borexino -- now operating at Gran Sasso, with exceptional low environmental radioativity rates

Assumes one kt scintillator at SNOLab depth: factor-of-70 reduction in long-lived cosmogenic ^{11}C, to 0.1 c/d/100 tons, relative to Borexino

7% CNO flux measurement predicted, based on BS05(OP) fluxes

Summary

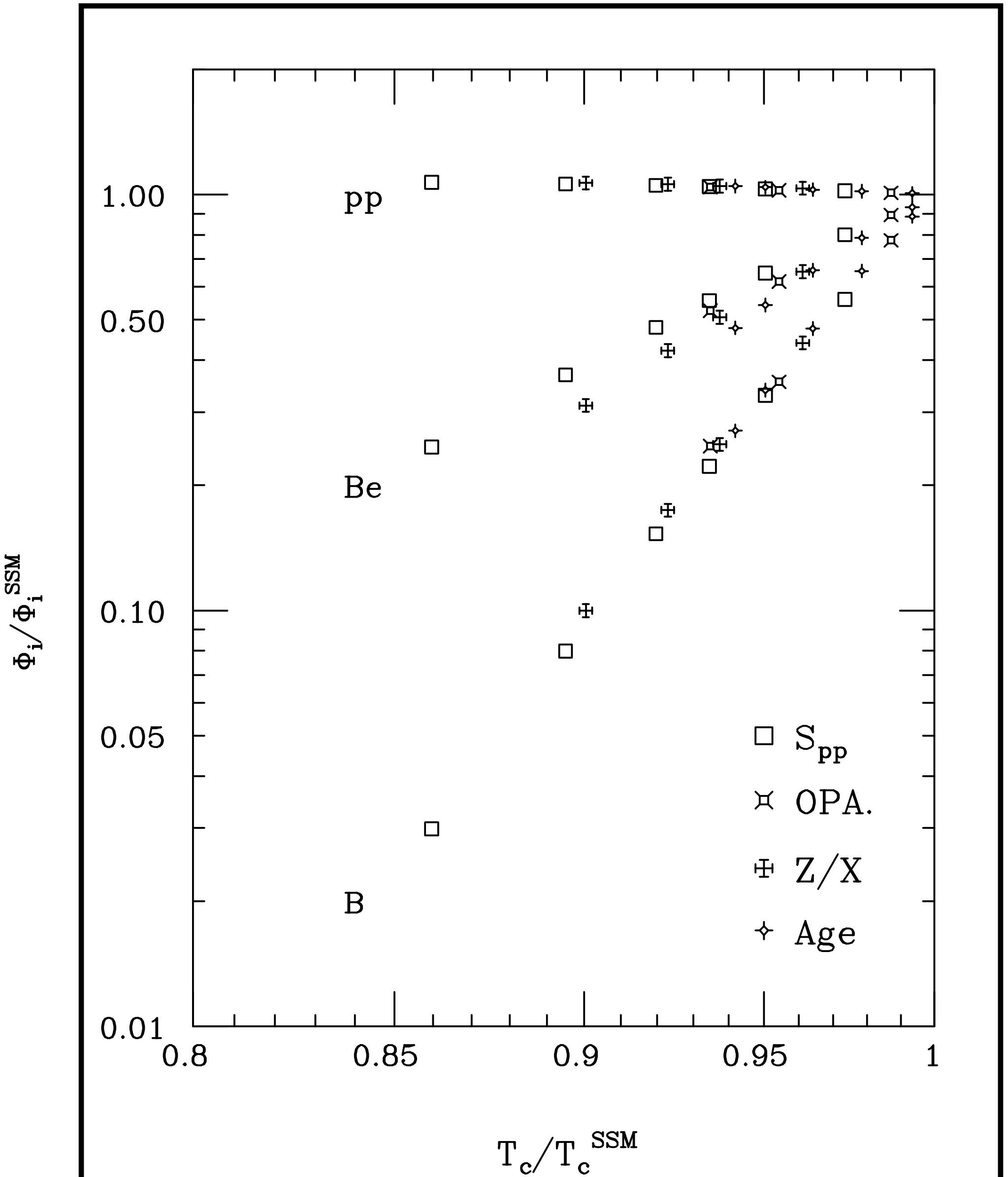
- we suggested planetary disk dynamics as a common origin to three puzzles
  - SSM conflict between helioseismology, photospheric abundances
  - the anomalous abundances of Jupiter, Saturn
  - the systematic chemical anomalies in solar twins

- now have the first clear proof that the existence of planets and host star abundances are strongly correlated: Li
  - solar Li depletion another long-standing problem

- our community could make a crucial contribution to demonstrating the mechanism if it can demonstrate that the Sun's core and surface C/N abundances differ

- with no further improvements, the CN core abundance could be determined to 12% by SNO+, compared to the 30% GS/AGS differences supplementary slides

ν fluxes track with core T -- regardless of the kind of SSM perturbation -- up to small corrections primarily due to the finite core size



Castellani et al.

Can one extract from such a measurement the core metalicity?

- There are 19 SSM parameters β_j with significant uncertainties

$$\alpha(i,j) \equiv \frac{\partial \ln\left[\phi_i/\phi_i(0)\right]}{\partial \ln\left[\beta_j/\beta_j(0)\right]} \Rightarrow \phi_i = \phi_i(0) \prod_{j=1}^{N} \left[\frac{\beta_j}{\beta_j(0)}\right]^{\alpha(i,j)}$$

(each β has some estimated SSM uncertainty)

- Divide this dependence into environmental, nuclear, CN terms

$$\phi_i = \phi_i^{SSM} \left(\prod_{j\in\{\mathrm{Solar}\}} \left[\frac{\beta_j}{\beta_j(0)}\right]^{\alpha(i,j)} \prod_{j\in\{\mathrm{Metals}\neq\mathrm{C,N}\}} \left[\frac{\beta_j}{\beta_j(0)}\right]^{\alpha(i,j)} \right) \prod_{j\in\{\mathrm{Nuclear}\}} \left[\frac{\beta_j}{\beta_j(0)}\right]^{\alpha(i,j)} \prod_{j\in\{\mathrm{C,N}\}} \left[\frac{\beta_j}{\beta_j(0)}\right]^{\alpha(i,j)}$$

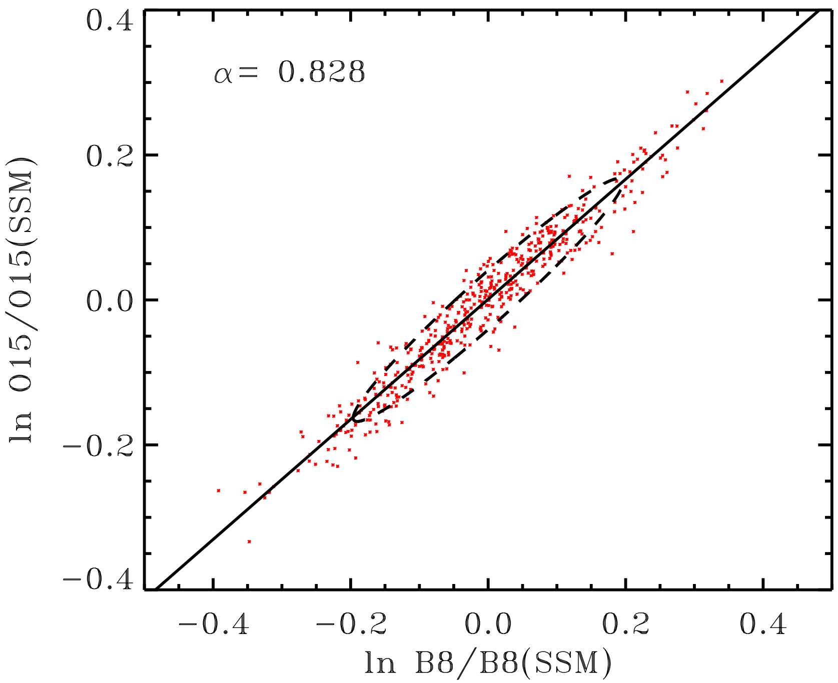
- bracketed "environmental" uncertainties: luminosity, radiative opacity, solar age, He and metal diffusion, fractional abundances of O, Ne, Mg, Si, S, Ar, and Fe -- not well controlled by lab constraints, but tend to affect all neutrino fluxes similarly

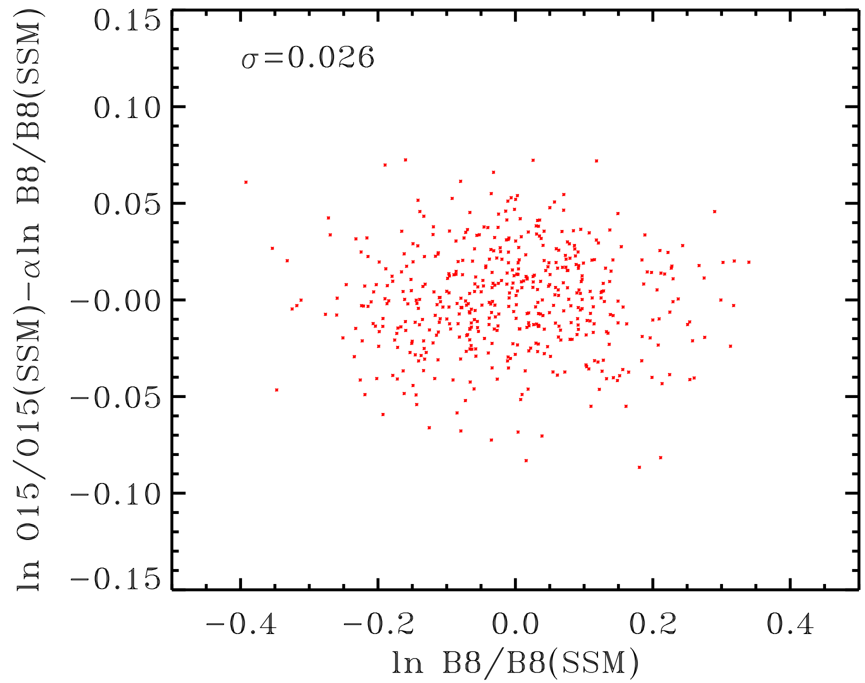
- what remains is a linear dependence on C, N -- our interest

	Environmental β_j				Nuclear β_j					
Source	$L_\odot$	Opacity	Age	Diffusion	S_{11}	S_{33}	S_{34}	S_{17}	S_{e7}	S_{114}
$\phi(^8\mathrm{B})$	7.16	2.70	1.38	0.28	-2.73	-0.43	0.85	1.0	-1.0	-0.020
$\phi(^{13}\mathrm{N})$	4.40	1.43	0.86	0.34	-2.09	0.025	-0.053	0.0	0.0	0.71
$\phi(^{13}\mathrm{N})/\phi(^8\mathrm{B})^{0.599}$	0.11	-0.19	0.03	0.17	-0.45	0.28	-0.56	-0.60	0.60	0.72
$\phi(^{15}\mathrm{O})$	6.00	2.06	1.34	0.39	-2.95	0.018	-0.041	0.0	0.0	1.00
$\phi(^{15}\mathrm{O})/\phi(^8\mathrm{B})^{0.828}$	0.07	-0.18	0.20	0.16	-0.69	0.37	-0.74	-0.83	0.83	1.02

The point: other neutrino measurements (SNO, Superk) have effectively calibrated the environmental uncertainties

Monte Carlo SSM studies of ^{8}B, ^{15}O ν correlations





The bottom line is a primordial abundances ↔ future experiment relation:

$$\frac{R^{B/S}_{exp}(\mathrm{CN})}{R^{B/S}_{cal}(^{15}\mathrm{O}, \delta m^2_{12}, \theta_{12}))} = \left(\frac{X(^{12}\mathrm{C})}{X(^{12}\mathrm{C})_{SSM}}\right)^{0.805} \left(\frac{X(^{14}\mathrm{N})}{X(^{14}\mathrm{N})_{SSM}}\right)^{0.199}$$

$$\times(1.120 \pm 0.003)[1 \pm 0.03(\mathrm{SK}) \boxed{\pm 0.026(\mathrm{resid\ env})} \boxed{\pm 0.049(\mathrm{LMA}) \pm 0.071(\mathrm{nucl})]}$$

diffusion: relating today's metals to primordial ones

errors that can be further improved in the laboratory:
nuclear physics
neutrino flavor physics

The net theory "error bar" in relating a SNO+ CN-ν measurement to primordial metallicity is thus about 9%

For details, see WH + Aldo Serenelli, ApJ 687 (2008) 678 (arXiv:0805.2013)