Standard Solar Model
(and the solar abundance problem)

@Ecole Chalonge 16th
Paris – 26.07.12

Aldo Serenelli – ICE (CSIC-IEEC)

OUTLINE

- Basics of Standard Solar Model

- Solar abundances and impact on solar modeling: solar abundance problem

- Solar neutrino fluxes

- Overview on the Sun as CDM detector

SSM: Defining Characteristics

Basic assumptions

- 1 $M_\odot$ star – negligible mass loss through stellar winds
- chemically homogeneous – pre-MS fully convective phase
- evolutionary model, solar system age 4.57 Gyr (radioactive dating from primitive meteorites - e.g. Bahcall, Pinsonneault, Wasserburg 1995)
- spherical symmetry
- no rotation & no magnetic fields – might affect mixing and angular momentum transport

SSM: Defining Characteristics

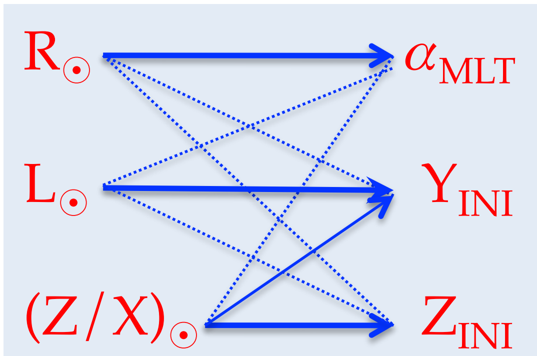
3 Present-day constraints

- solar radius ($R_\odot$) = 6.9598•10^{10} cm
- solar luminosity ($L_\odot$) = 3.8418•10^{33} erg s^{-1}
- surface metals-to-hydrogen ratio $(Z/X)_\odot$ = 0.0245 – 0.0178

  fractional abundances of individual metals also fixed

3 Free parameters

- Convection parameter α_{MLT}
- Initial helium Y_{INI}
- Initial metallicity Z_{INI}



Solar Abundances

"Direct" determinations

- solar spectrum (photospheric - volatiles)

  requires atmosphere and detailed radiative transfer models to reproduced observed spectrum

- meteorites (refractories)

  requires anchor element(s) to solar photosphere scale. Assumes ratios of metal abundances have not changed in solar surface during solar evolution

- others – solar wind, chromosphere (eg. Ne, Ar)

Meteoritic are most reliable but...
abundant CNO elements only from spectrum

Solar Abundances

1D models do not capture
basic structure of atmosphere

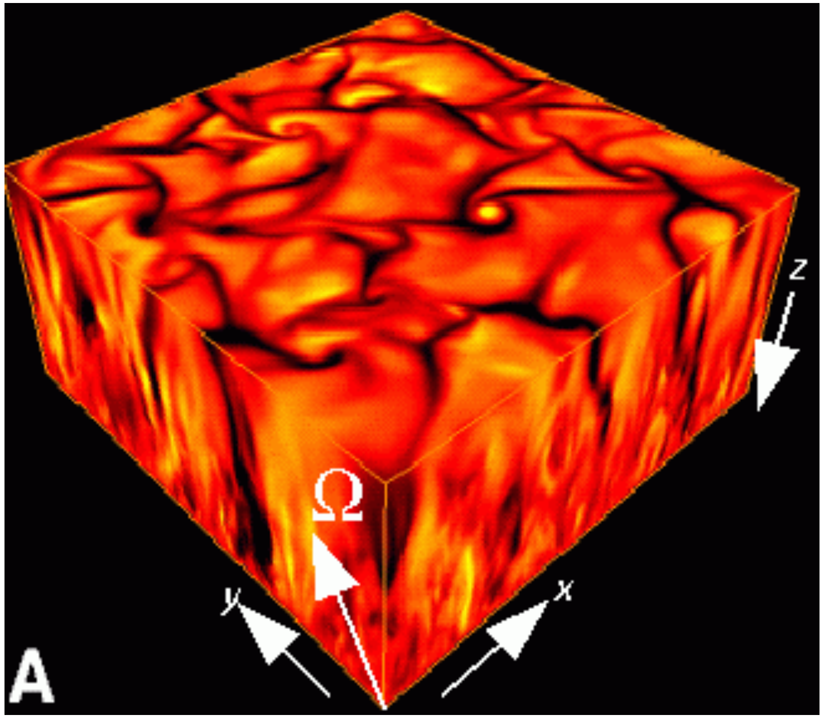
Energy transported by convection,
radiated away at the top

Flow is turbulent

Up- and downward flows asymmetric

Not unique relation T vs. depth

Magnetic fields



Credit: N. Brummell

Solar Abundances

"Box in a star": simultaneous solution of radiative transfer (RT) and hydrodynamic equations

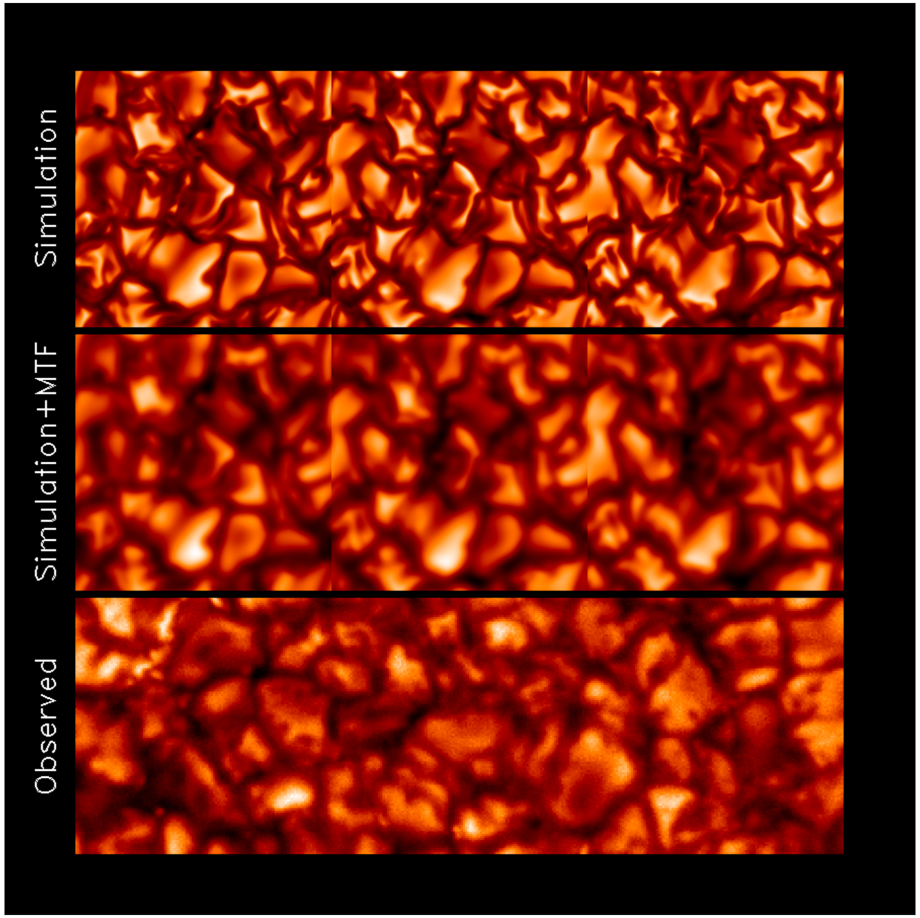
RT is "rudimentary":

frequency dependent opacities combined in a few (4 to 12) bins (10^5 in 1D)

LTE → not good opacities
(e.g Mg I, Ca I, Si I, Fe I)

1D models used as benchmark effects on 3D may be different

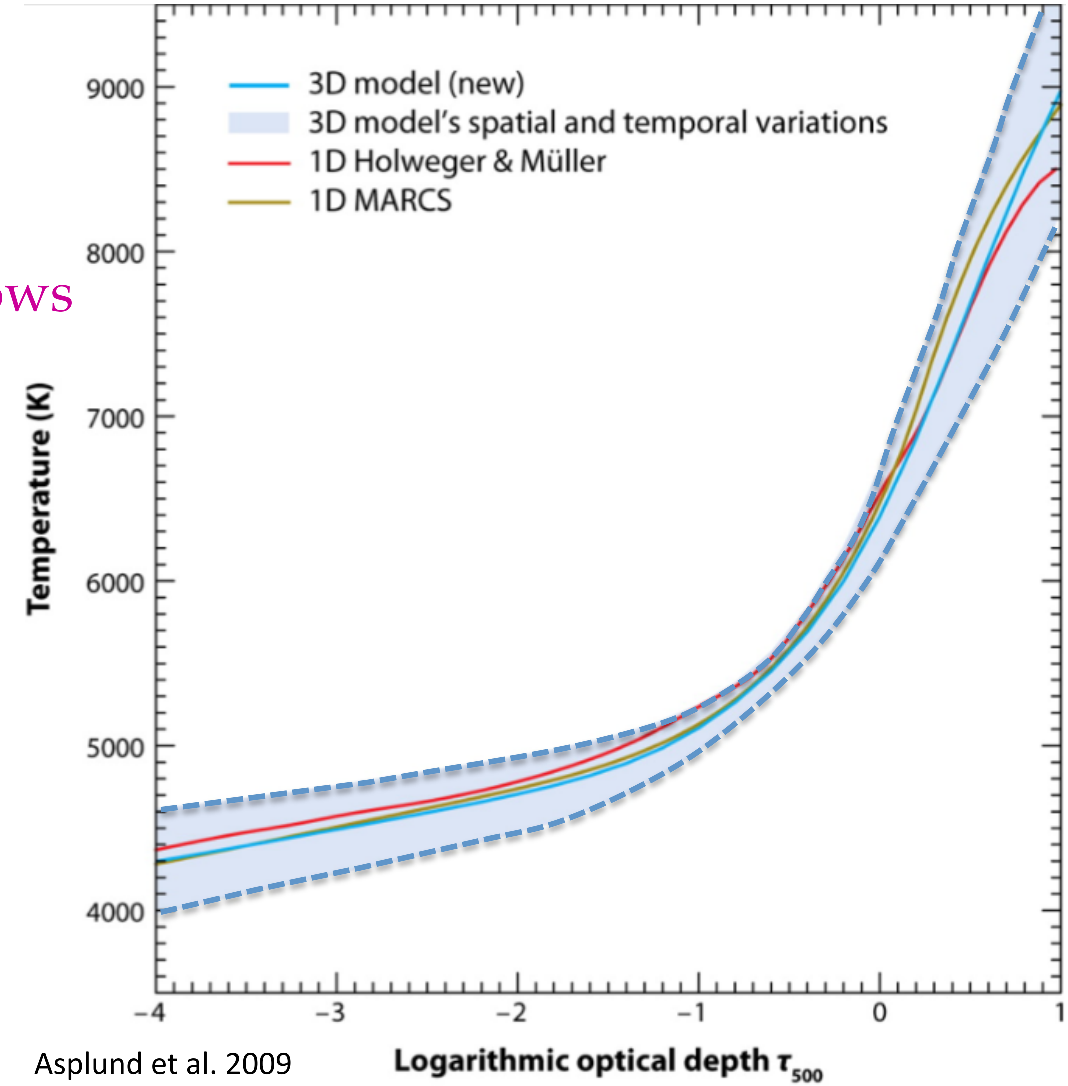
However… it looks good



Credit: Bob Stein

Solar Abundances

Temperature stratification shows fluctuations – changes in very temperature sensitive lines e.g. molecular lines



Asplund et al. 2009

SOLAR ABUNDANCES

Solar "direct" abundances

Two paradigmatic sets

Element	GS98	AGSS09
C	8.52	8.43
N	7.92	7.83
O	8.83	8.69
Ne	8.08	7.93
Mg	7.58	7.53
Si	7.56	7.51
Ar	6.40	6.40
Fe	7.50	7.45
Z/X	0.0229	0.0178

$\log \varepsilon_X = \log (N_X/N_H) + 12$

GS98: Grevesse & Sauval (1998)

AGSS09: Asplund et al. (2009)

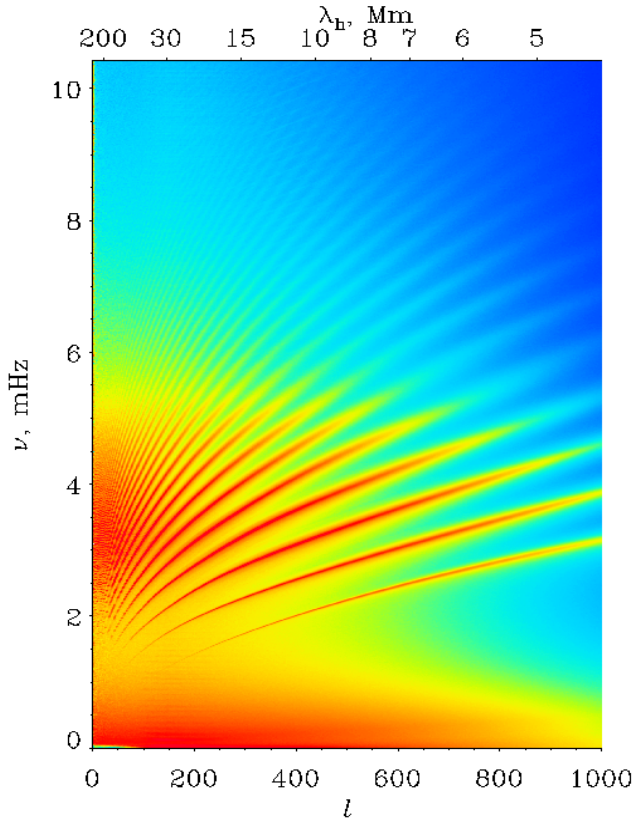
Differences

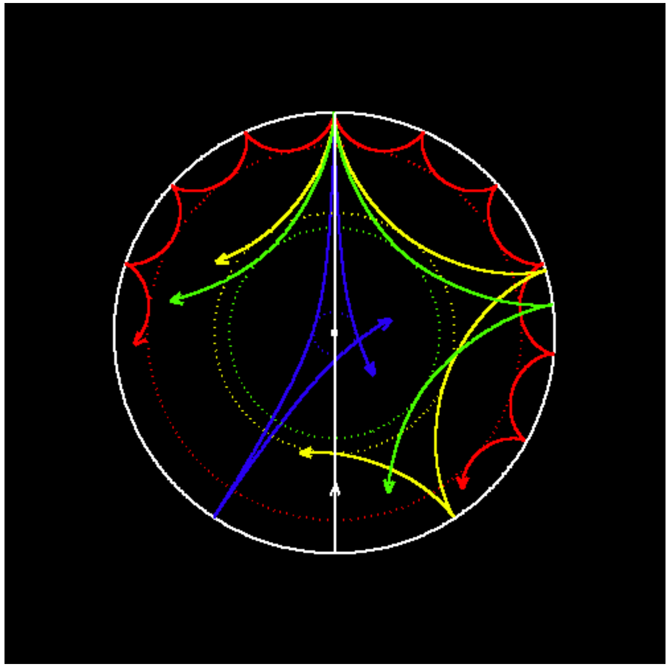
- New 3-D hydrodynamic models of solar atmosphere
- NLTE treatment of some elements
- Refined selection of lines (e.g. identification of blends)

Reduction of CNO(Ne) ~ 30-40%

Testing the SSM: Helioseismology

Solar oscillations: acoustic standing waves (p-modes)
Period ~ 5 min



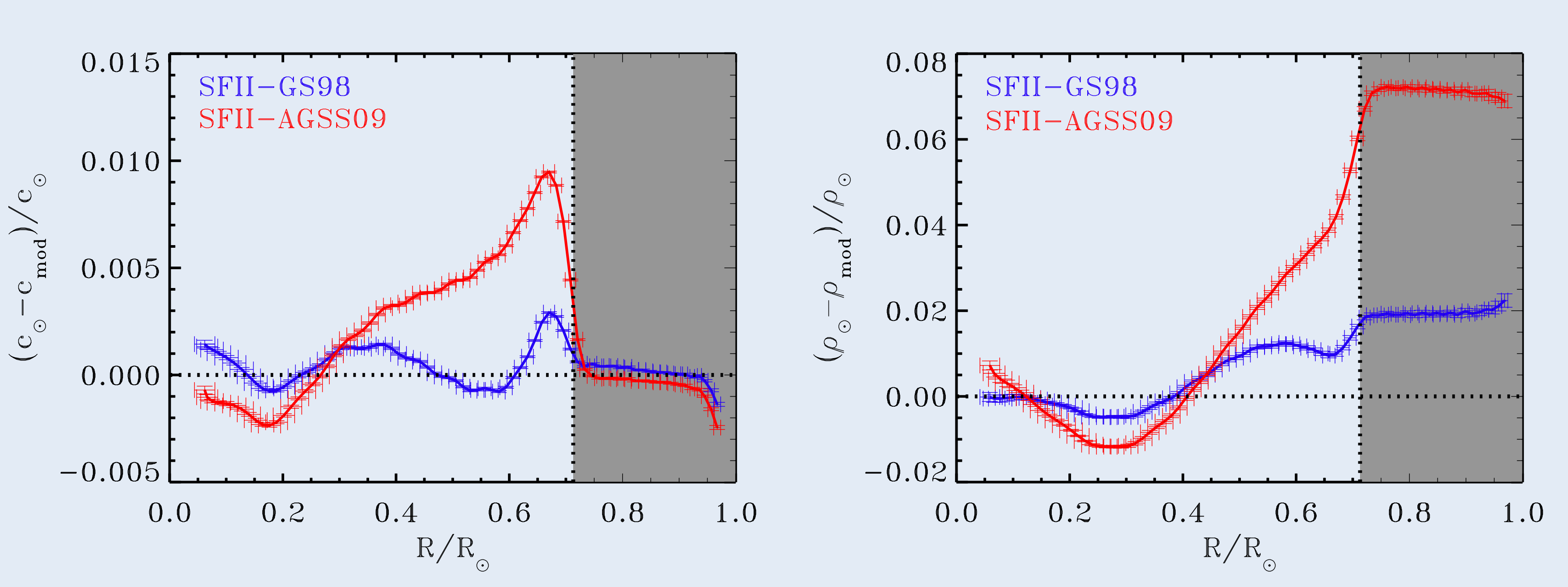


Inner turning point is function of the degree (l) of the mode
Only low-l modes reach the core

Allows determination of solar structure - sound speed, density, internal rotation, some information on composition

Solar Abundance Problem

Clear examples: sound speed and density profiles



Solar abundance problem

	GS98	AGSS09	Helios.
$(Z/X_\odot)$	0.0229	0.0178	—
$R_{CZ}/R_\odot$	0.712	0.723	0.713 ± 0.001
Y_S	0.2429	0.2319	0.2485 ± 0.0034
$\langle \delta c/c \rangle$	0.0009	0.0037	—
$\langle \delta \rho/\rho \rangle$	0.011	0.040	—

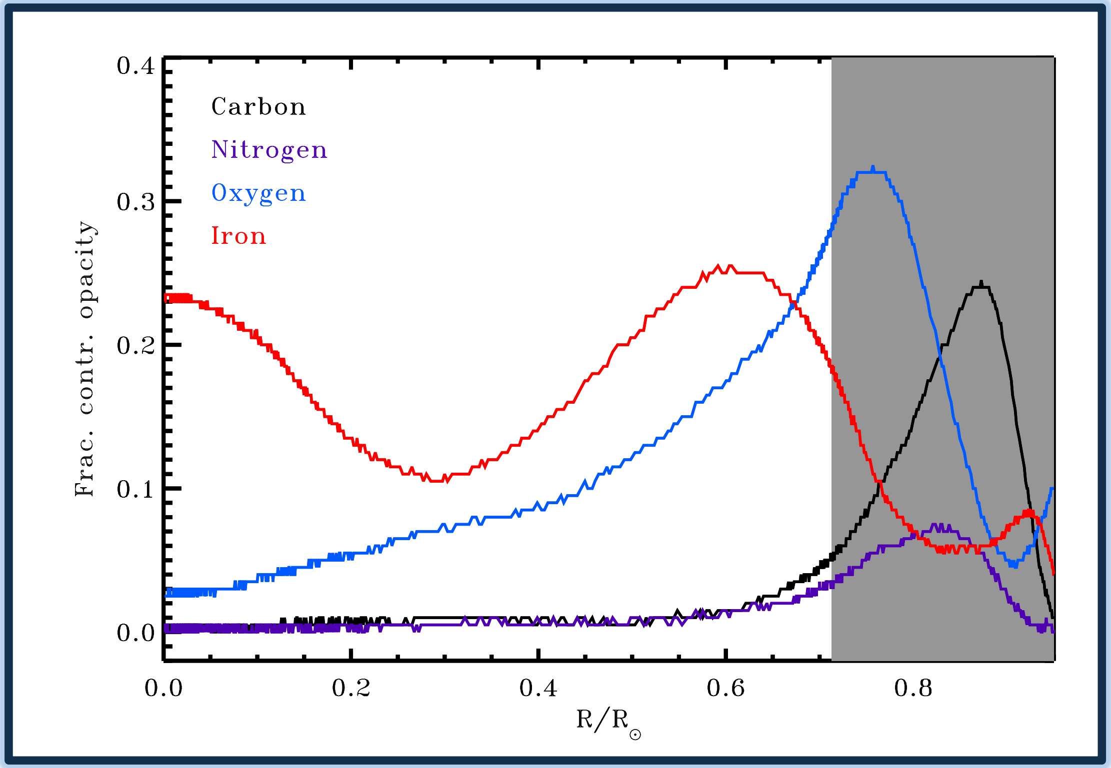
WHY METALS MATTER?

Effect of individual elements on radiative opacity

Heavy (eg. Fe, Si) : solar core → helium

Intermediate (Ne, O): radiat. envelope → R_{CZ}

Light (C, N): convective envelope



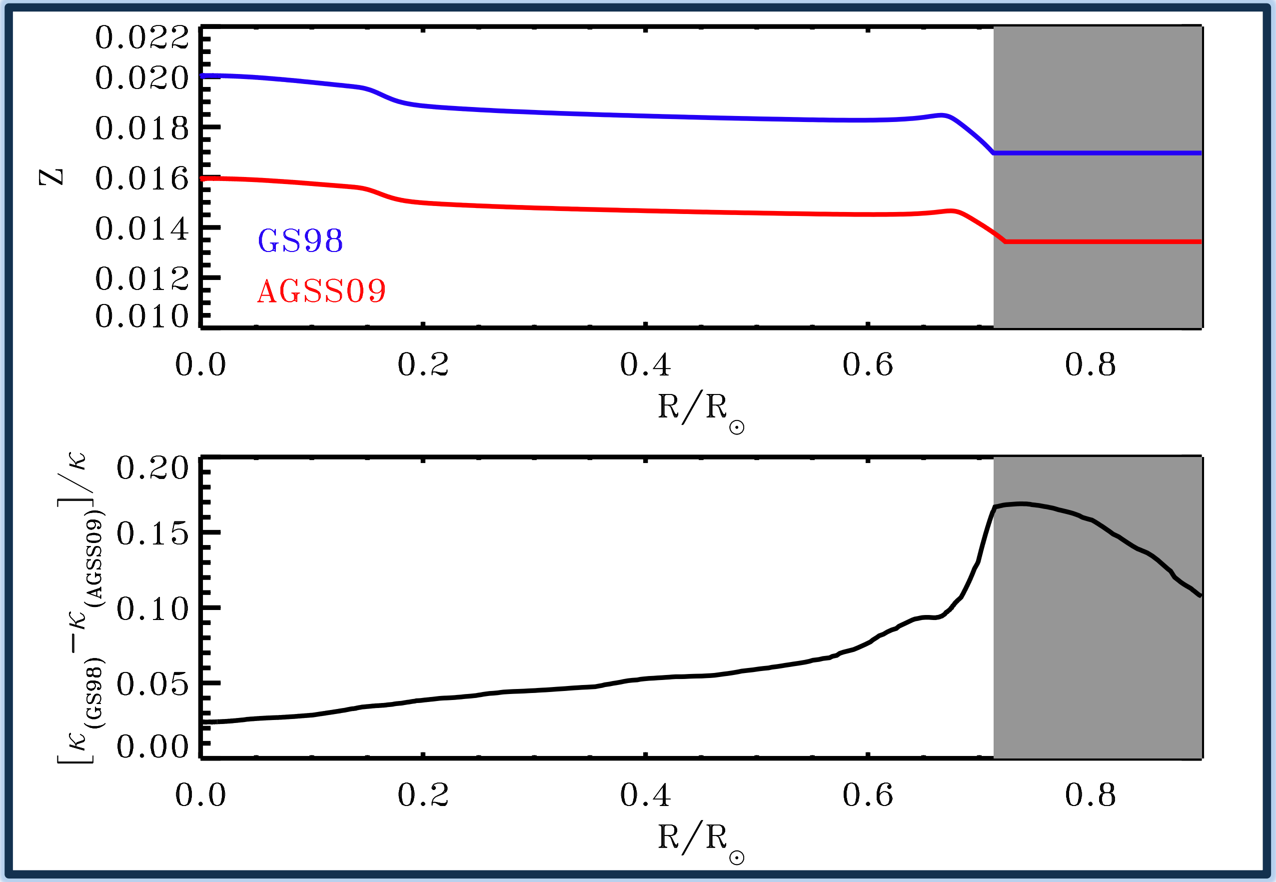
Why Metals Matter?

Opacity changes

Affects energy transport

$$\left[\frac{dT^4}{dr}\right]_{\rm rad} \propto \kappa$$

Modifies model structure - sensitivity of helioseismic observables (and neutrinos)



However, opacities from different groups (OPAL, OP, OPAS) differ by not more than 3%

Solar Abundance Problem

...in the context of solar modeling

- Model atmospheres that lead to lower CNO abundances represent very well the dynamics of the solar atmosphere: granulation, shape of spectral line profiles, limb darkening.
- Agreement between different groups

- Determination of abundances not so robust.
- No agreement between different groups have different results (e.g. Asplund et al. 2009, Caffau et al. 2010)

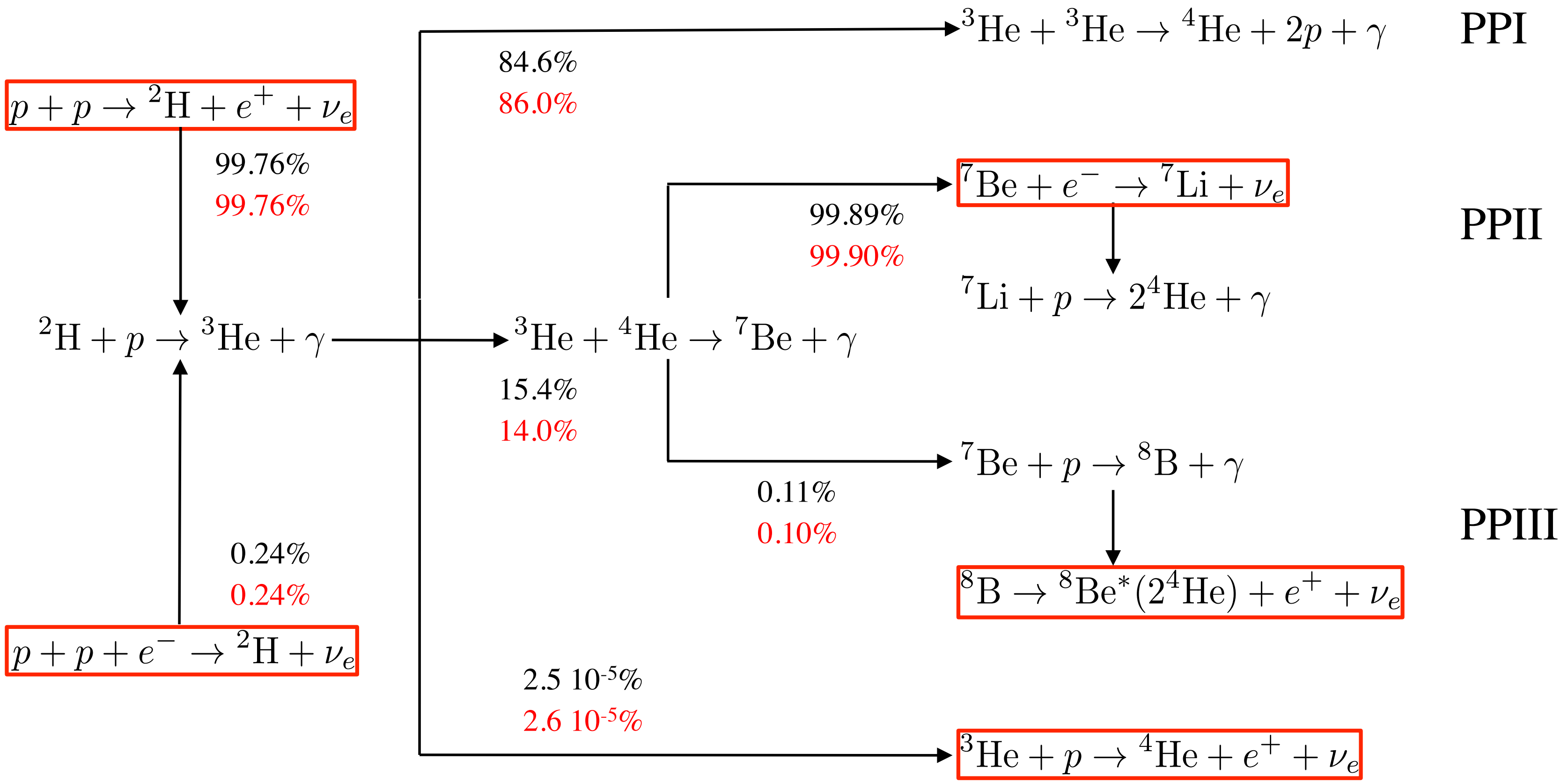
- In solar structure there is a degeneracy between metal abundances and radiative opacity. Is there missing opacity in the SSM?

- Is there a more fundamental defficiency in SSM?

Non-SSM (including rotation, additional mixing processes, magnetic fields) not succesful in solving the problem

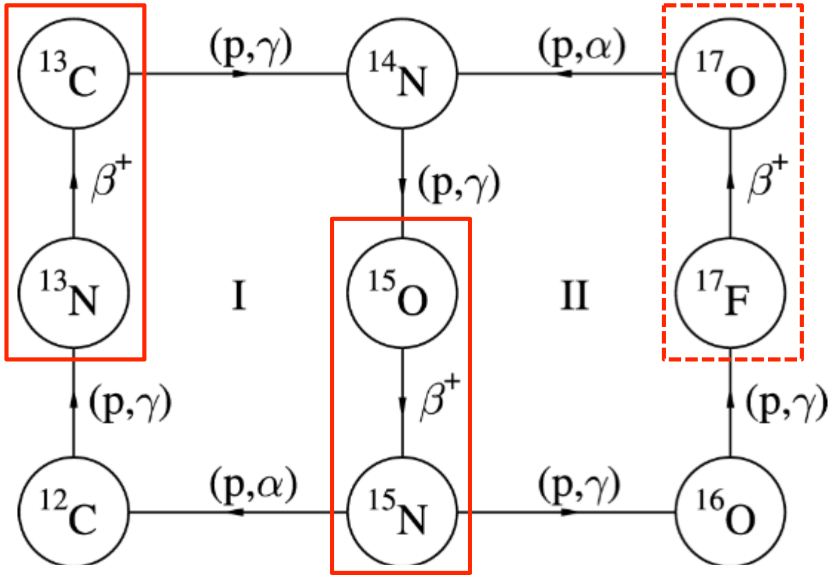
SOLAR νs

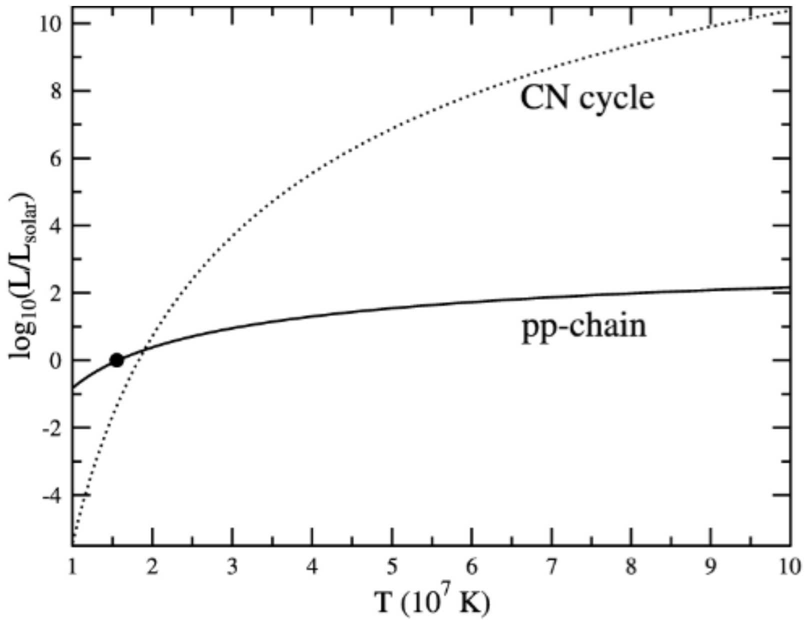
Neutrino sources: pp chains ~99.5% nuclear energy



SOLAR νs

Neutrino sources: CNO-bicycle ~ 0.5% nuclear energy



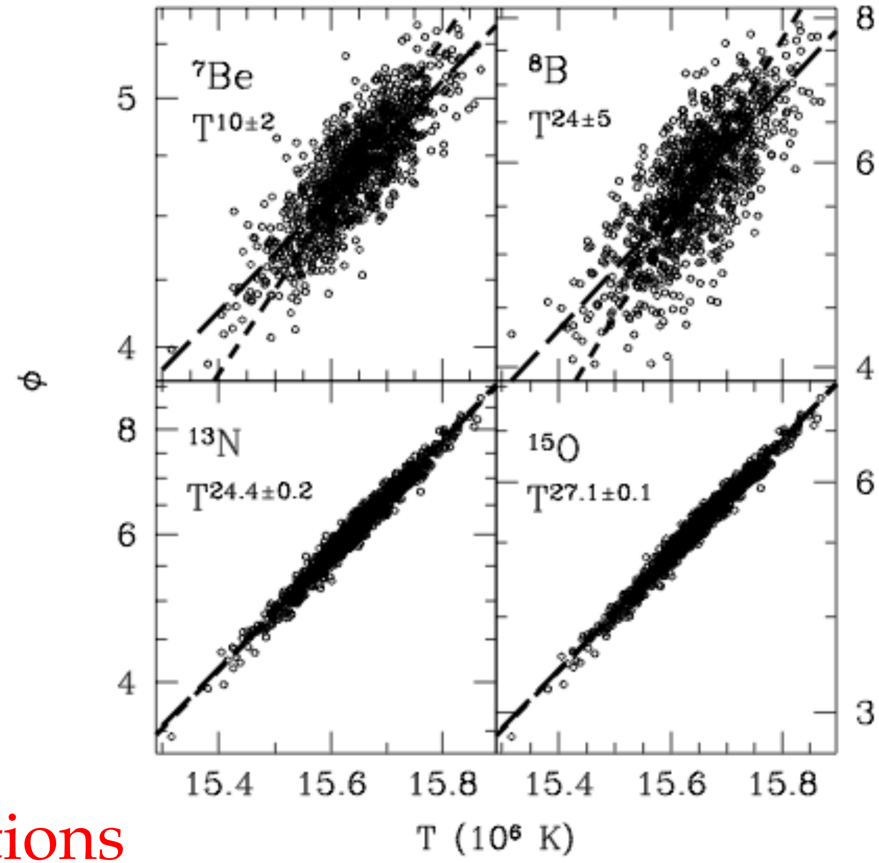


CN-cycle regulated by core C+N abundance, C&N are catalyzers
→ important information on solar composition

SOLAR νs - TEMPERATURE SENSITIVITY

$$\phi \propto T^m$$

Neutrino Flux	Monte Carlo Exponent	Estimated Uncertainty
$\phi(pp), m$	-1.1	0.1
$\phi(pep)$	-2.4	0.9
$\phi(^7\mathrm{Be})$	10	2
$\phi(^8\mathrm{B})$	24	5
$\phi(^{13}\mathrm{N})$	24.4	0.2
$\phi(^{15}\mathrm{O})$	27.1	0.1
$\phi(^{17}\mathrm{F})$	27.8	0.1

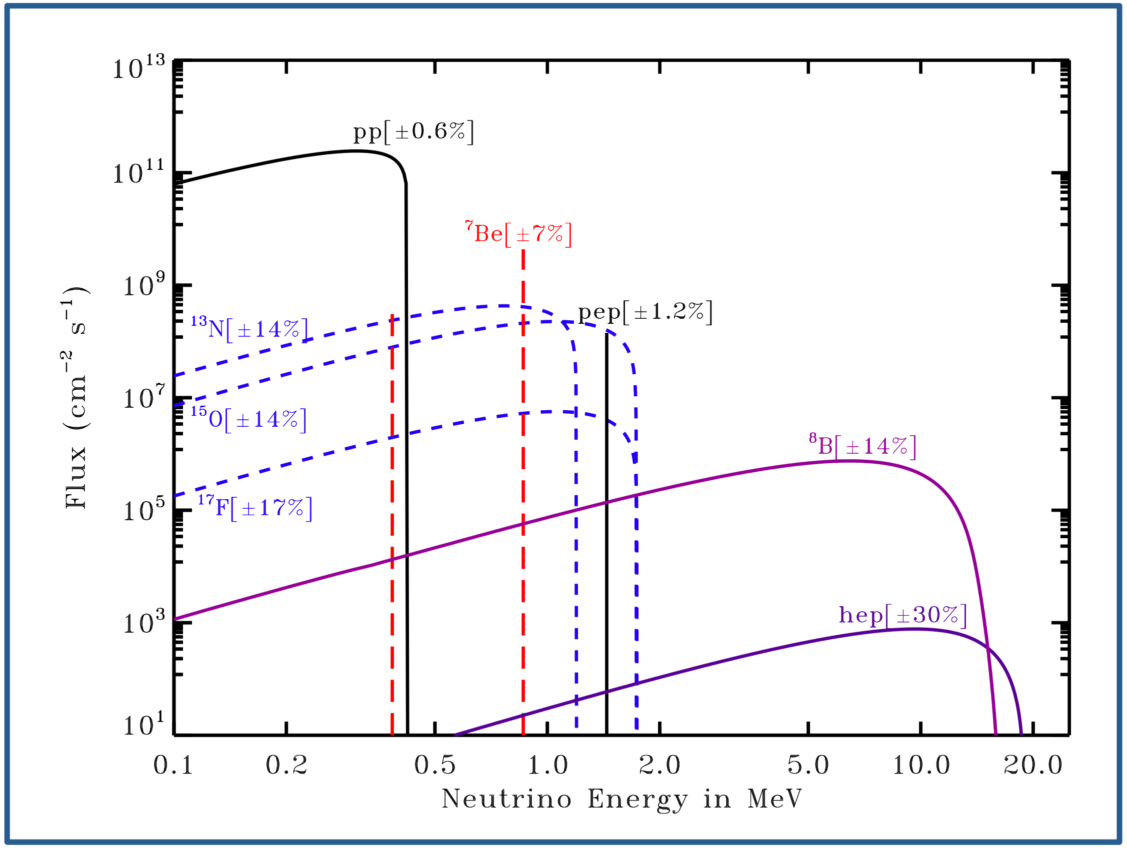


Bahcall & Ulmer (1996)

Fluxes with large sensitivity:
good probes of solar core conditions

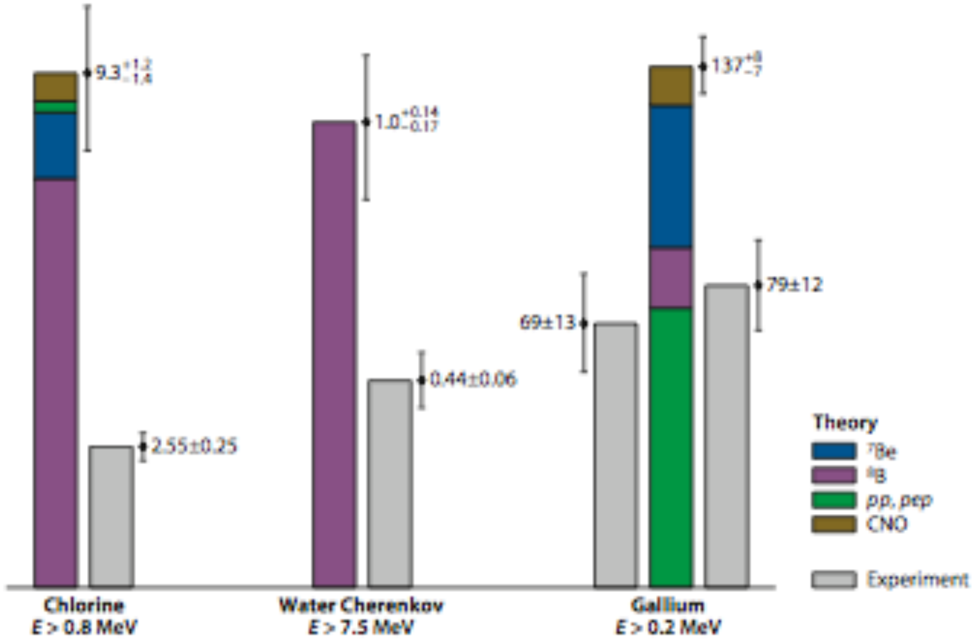
SOLAR νs – SOLAR ν PROBLEM

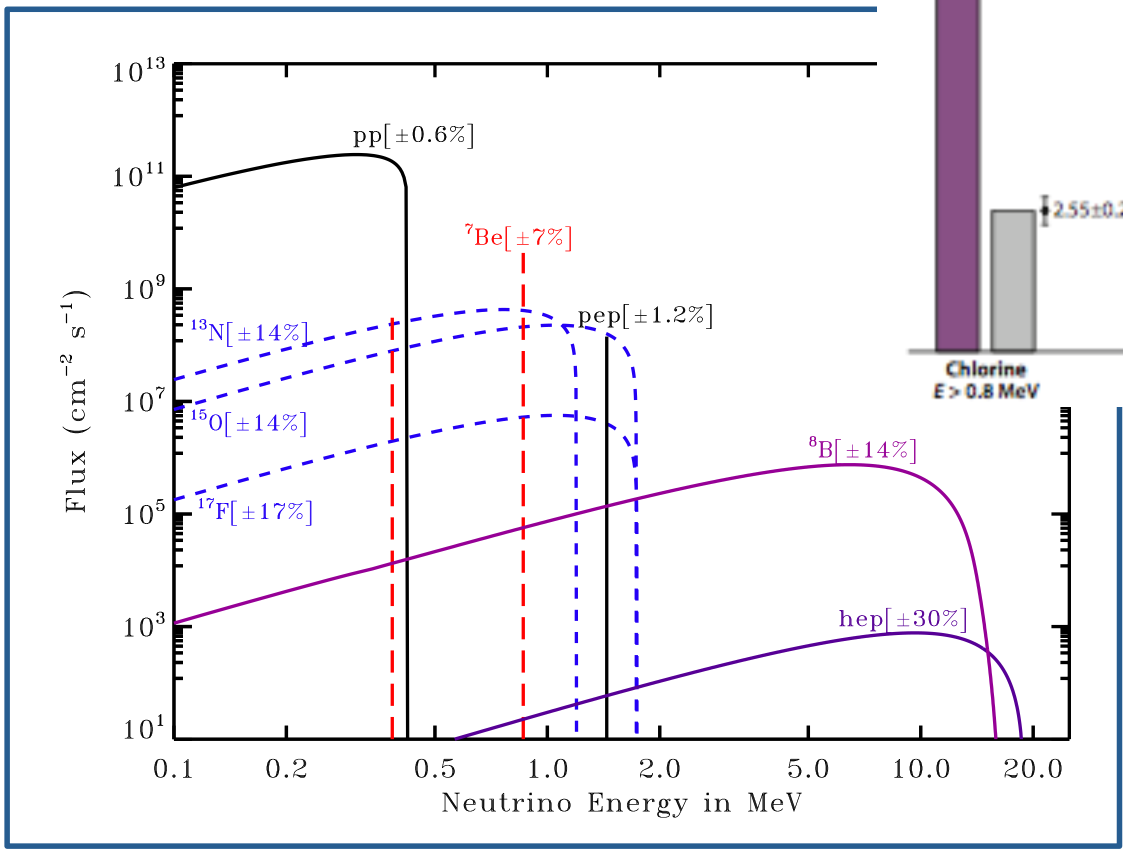
νs with higher end-point energy easier to detect:
larger cross section and lower backgrounds



Solar νs – Solar ν Problem

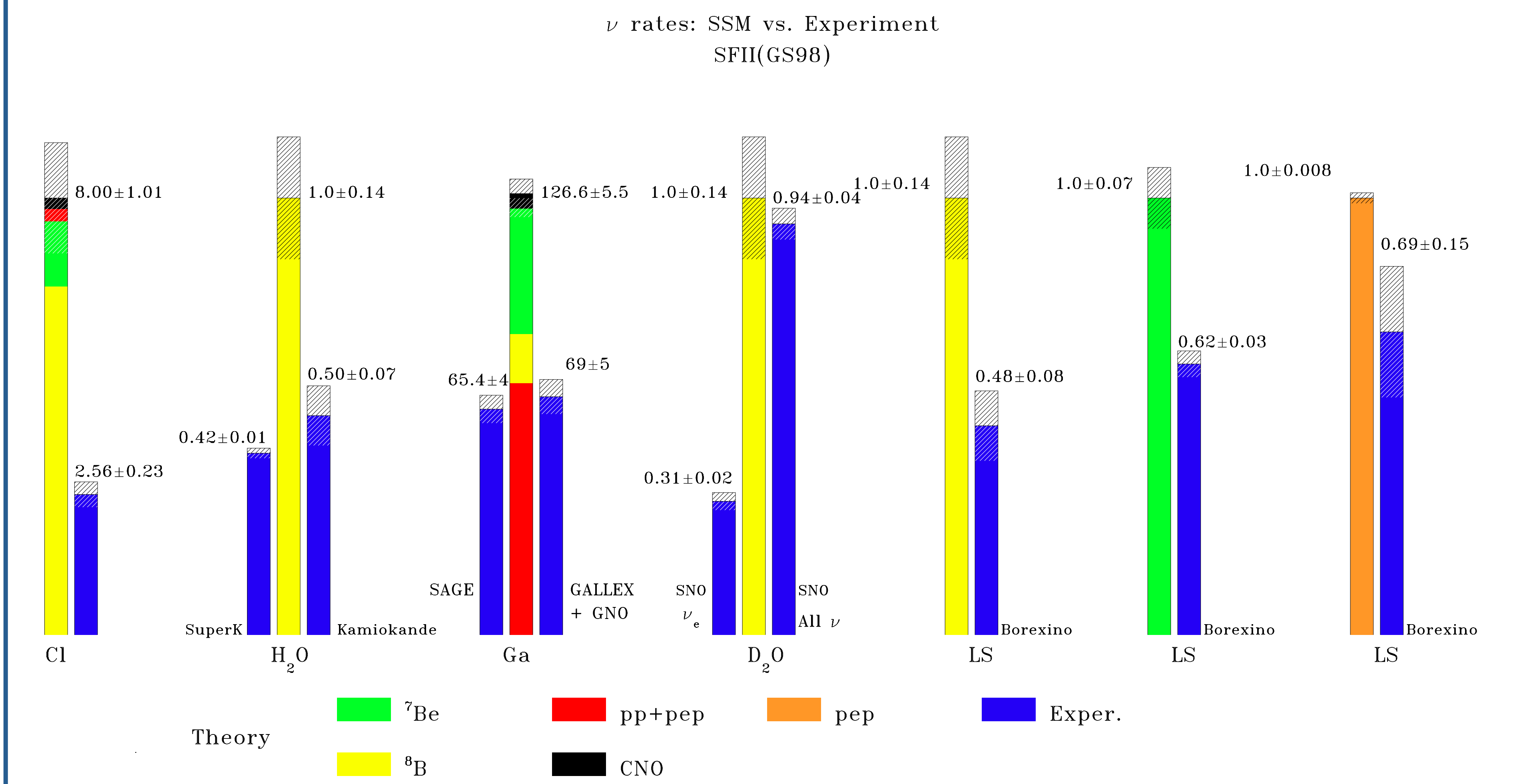
νs with higher end-point energy ea
larger cross section and lower back





Initially: only ^{8}B detected + high T-dependence → "solar solution to neutrino problem"

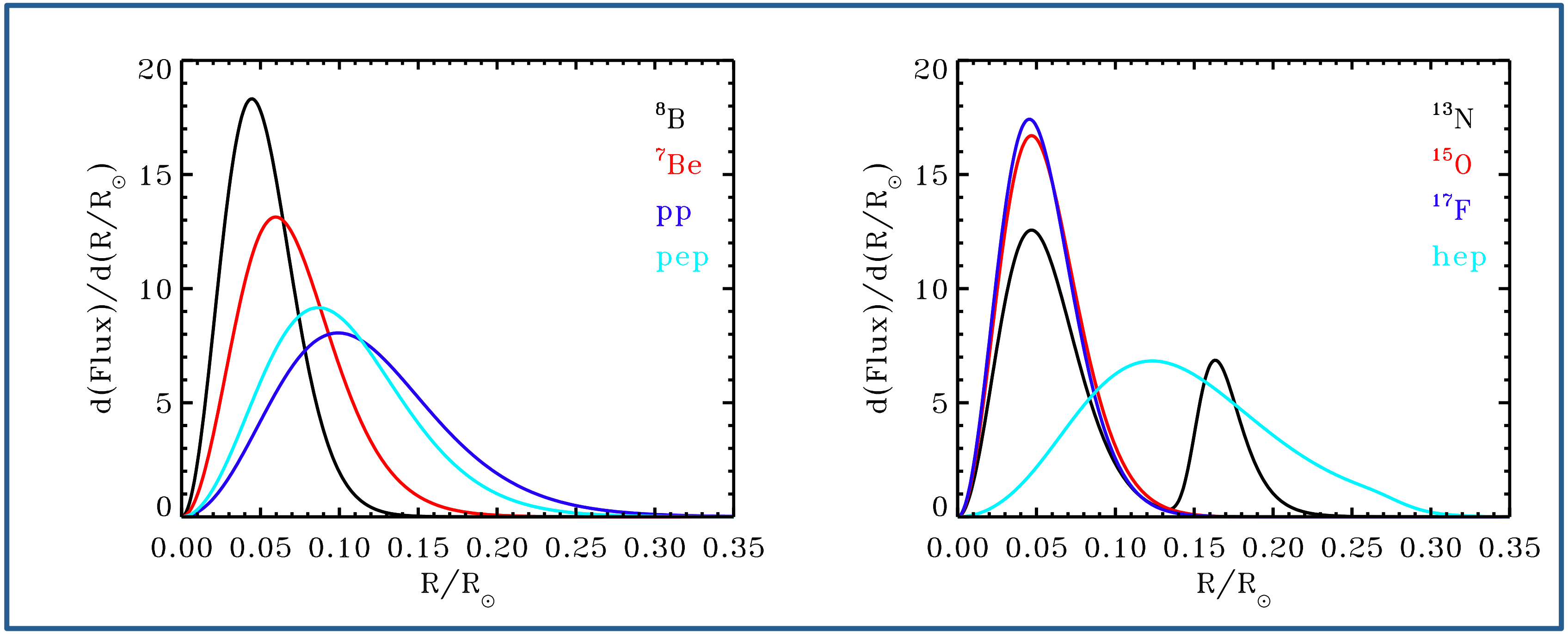
SOLAR νs – THEORY VS EXPERIMENT



SOLAR νs –PRODUCTION REGION

Production region determined by T-sensitivity of each flux

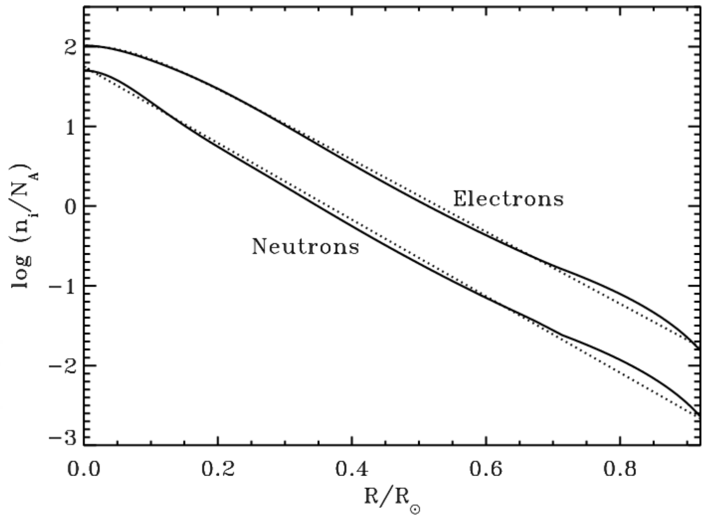
Important for matter effects in neutrino oscillations (MSW effect)

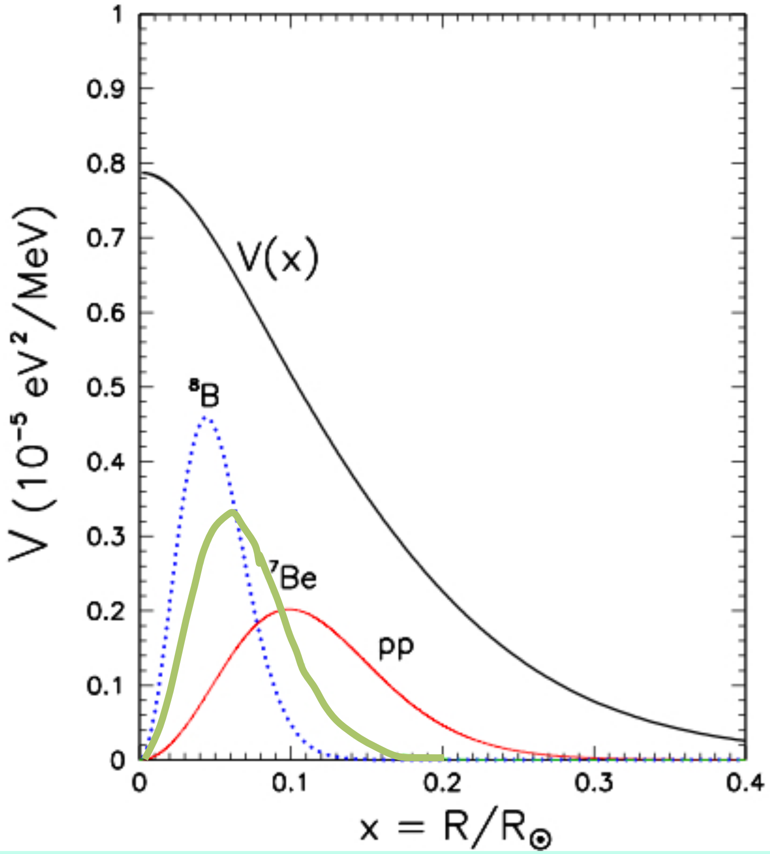


SOLAR νS – OSCILLATIONS

For active neutrinos, matter effects depend on electron density

$$V(r) = \sqrt{2} G_F n_e(r)$$





Fogli et al. (2006)

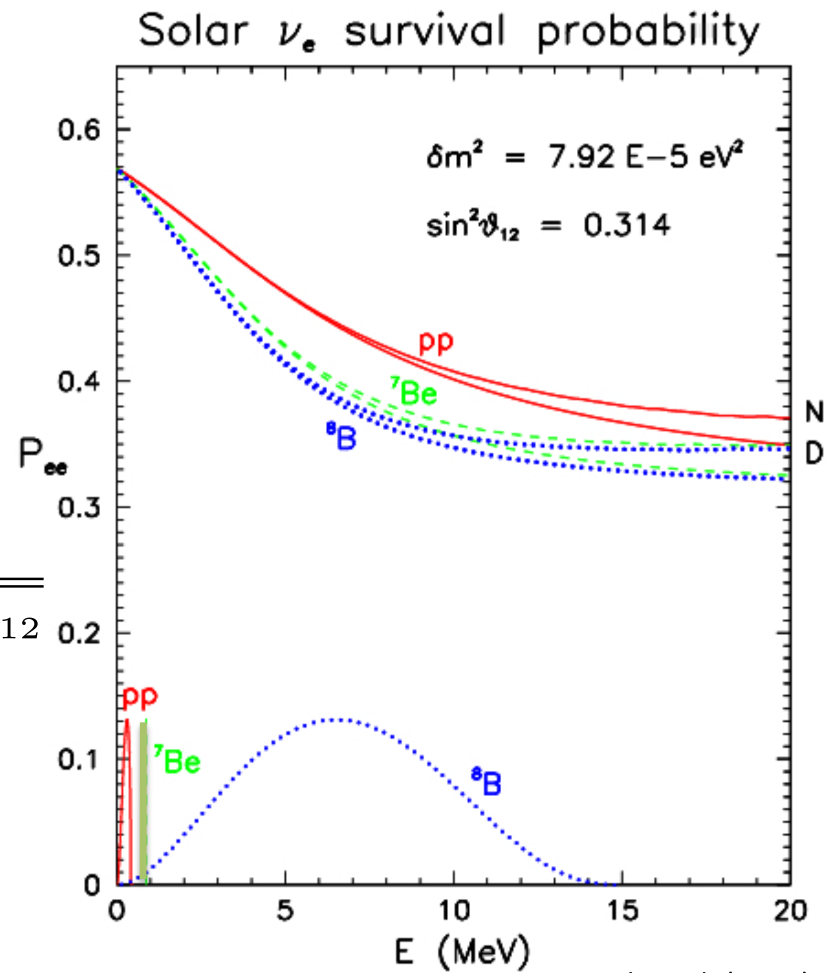
SOLAR νs – OSCILLATIONS

Assuming two-flavors oscillations

A(r)= $2E_\nu V(r)$
A(r) >> δm → matter effects
A(r) << δm → vacuum oscillations

$$P_{ee} = \frac{1}{2} + \frac{1}{2}\cos 2\hat{\theta}_{12}(r)\cos 2\theta_{12}$$

$$\cos 2\hat{\theta}_{12}(r) = \frac{\cos 2\theta_{12} - A(r)/\delta m^2}{\sqrt{(\cos 2\theta_{12} - A(r)/\delta m^2)^2 + \sin^2 2\theta_{12}}}$$



Fogli et al. (2006)

SOLAR νs – OSCILLATIONS

Assumin

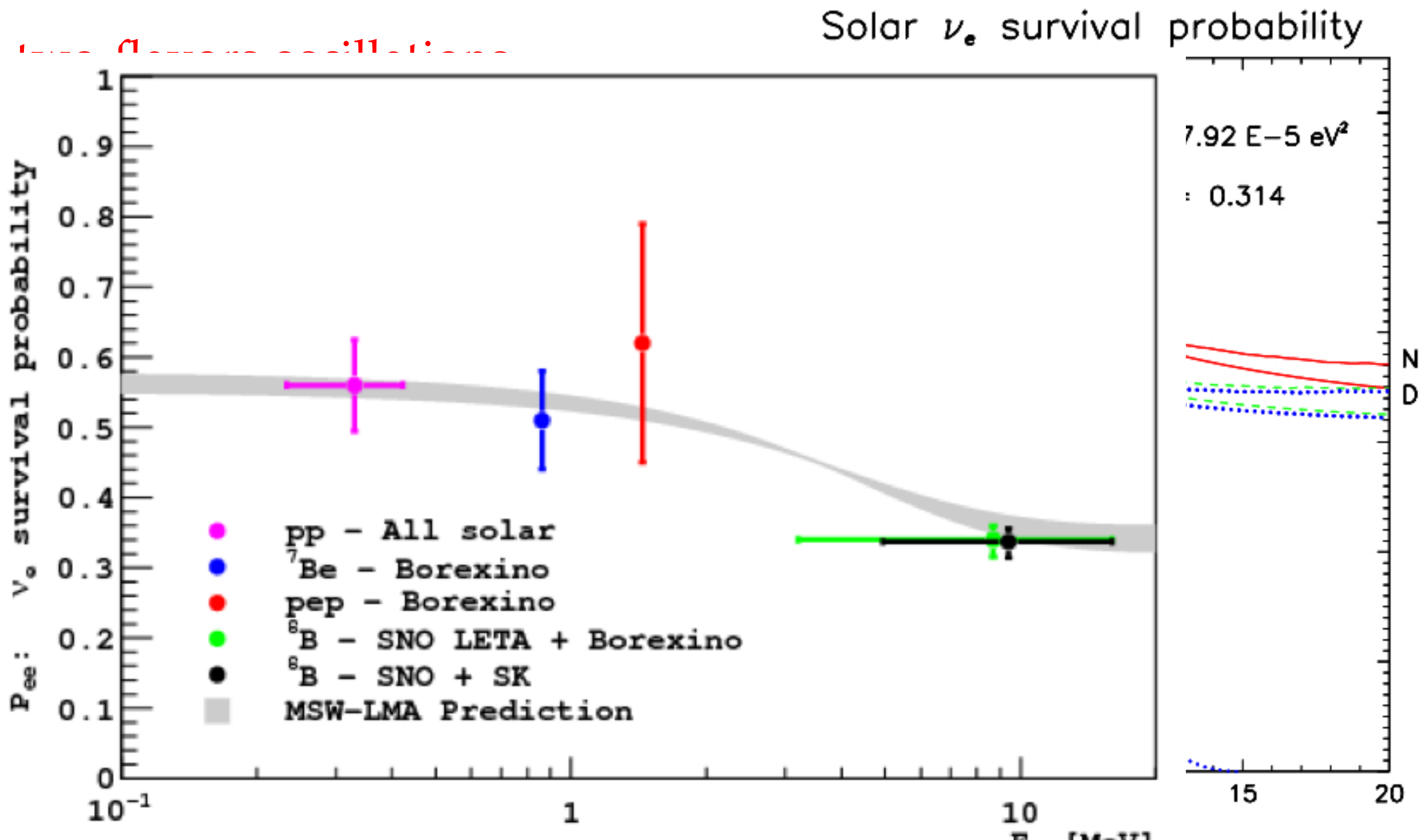
$A(r) = 2E_\nu$

$A(r) >> \delta$

$A(r) << \delta$

$P_{ee} = \frac{1}{2} +$

$\cos 2\hat{\theta}_{12}(r$



Fogli et al. (2006)

Solar Neutrinos

Solar neutrinos vs Solar abundances

	Flux	SFII-GS98	SFII-AGSS09	Solar
	pp	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$6.05(1 \pm 0.006)$
	pep	$1.44(1 \pm 0.011)$	$1.47(1 \pm 0.012)$	$1.46(1 \pm 0.012)$
	hep	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	$18(1 \pm 0.45)$
~10%	^{7}Be	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	$4.82(1 \pm 0.045)$
~20%	^{8}B	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	$5.00(1 \pm 0.03)$
~31%	^{13}N	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7
~35%	^{15}O	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.2
	^{17}F	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	≤ 59
	$\chi^2/P^{\rm agr}$	3.5 / 90%	3.4 / 90%	—

Differences between high-Z and low-Z models reflect changes in core temperature

CNO fluxes have extra linear dependence

Solar Neutrinos

Solar neutrinos vs Solar abundances

Flux	SFII-GS98	SFII-AGSS09	Solar
pp	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$6.05(1 \pm 0.006)$
pep	$1.44(1 \pm 0.011)$	$1.47(1 \pm 0.012)$	$1.46(1 \pm 0.012)$
hep	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	$18(1 \pm 0.45)$
^{7}Be	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	$4.82(1 \pm 0.045)$
^{8}B	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	$5.00(1 \pm 0.03)$
^{13}N	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7
^{15}O	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.2
^{17}F	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	≤ 59
χ^2/P^{agr}	3.5 / 90%	3.4 / 90%	—

^{8}B @ 3% (SNO & SK) and now ^{7}Be @ 4.5% (Borexino)

pp and pep are strongly bound by the "luminosity constraint"

Solar Neutrinos

Solar neutrinos vs Solar abundances

Flux	SFII-GS98	SFII-AGSS09	Solar
pp	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$6.05(1 \pm 0.006)$
pep	$1.44(1 \pm 0.011)$	$1.47(1 \pm 0.012)$	$1.46(1 \pm 0.012)$
hep	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	$18(1 \pm 0.45)$
^{7}Be	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	$4.82(1 \pm 0.045)$
^{8}B	$5.58(1 \pm 0.14)$	$4.59(1 \pm 0.14)$	$5.00(1 \pm 0.03)$
^{13}N	$2.96(1 \pm 0.14)$	$2.17(1 \pm 0.14)$	≤ 6.7
^{15}O	$2.23(1 \pm 0.15)$	$1.56(1 \pm 0.15)$	≤ 3.2
^{17}F	$5.52(1 \pm 0.17)$	$3.40(1 \pm 0.16)$	≤ 59
$\chi^2/P^{\rm agr}$	3.5 / 90%	3.4 / 90%	—

^{8}B @ 3% (SNO & SK) and now ^{7}Be @ 4.5% (Borexino)

pp and pep are strongly bound by the "luminosity constraint"

However... experimental results do not discriminate compositions (yet)

Composition from ν-fluxes

^{8}B precisely determined 3% - used as a thermometer

Combining expressions for ^{13}N and ^{15}O, including experimental sensitivity & neutrino oscillations (Haxton & Serenelli 2008)

$$\frac{\Phi^{\rm exp}(CN)}{\Phi^{\rm SSM}(CN)} = \left[\frac{\Phi^{\rm SK}(^8B)}{\Phi^{\rm SSM}(^8B)}\right]^{0.828} \left[\frac{X(C+N)}{X(C+N)_{\rm SSM}}\right]$$

$$\times \left[1 \pm 0.03({\rm SK}) \pm 0.028({\rm env}) \pm 0.03({\rm LMA}) \pm 0.105({\rm nucl})\right]$$

- **SSM only used as a reference point (and exponents)**
- **Exponents 'robust' to variations in solar model inputs**
- **Uncertainty dominated by experimental (S_{17} & $S_{1\,14}$) contributions**

"Perfect" CN measurement gives central C+N to about 12%

Using Borexino upper limit for $\Phi(^{13}N+^{15}O)$: $X(C+N)_{Borexino} < 0.072$

$X(C+N)_{GS98} = 0.048$ -- $X(C+N)_{AGSS09} = 0.039$

SSM as Lab for Particle Physics

Helioseismology favors high-Z models

but … degeneracy with radiative opacities

best SSM (and solar models in general) at odds with best solar atmosphere models – "solar abundance problem"

non-SSM (rotational mixing, magnetic fields, etc) do not improve agreement

Neutrino fluxes from both models agree with data – experimental uncertainty small and sensitive to solar core properties (more sensitive than helioseismology / barred g-modes – detection doubtful)
Useful probes even in the face of the solar abundance problem

CDM in the Sun

Some things change slowly... but they DO change

Early works (80s, early 90s), WIMPS as energy transport mechanism to lower predicted SSM ^{8}B flux and match experiments

Now, SSM ^{8}B flux and experiments agree, theoretical efforts aim at producing a mismatch that can constrain DM properties

DM can affect solar structure in two ways

Additional energy source for annhilating DM particles

Energy transport mechanism (effective lower radiative opacity)

CDM in the Sun

WIMPs accumulate in the core during Sun's life ($R \leq 0.05\, R_{\odot}$) and self-annihilating DM is effectively almost an energy point-source

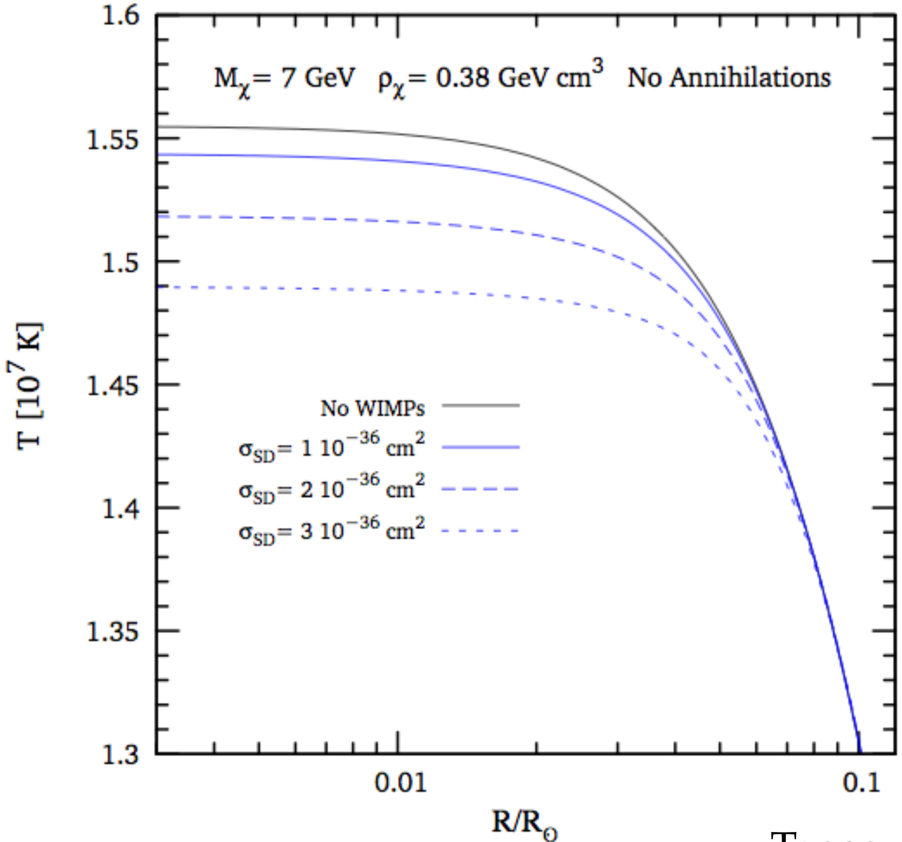
At fiducial DM density in solar neighborhood ~0.38 Gev cm^{-3} is a negligible energy source – no observable effects (Taoso et al. 2010)

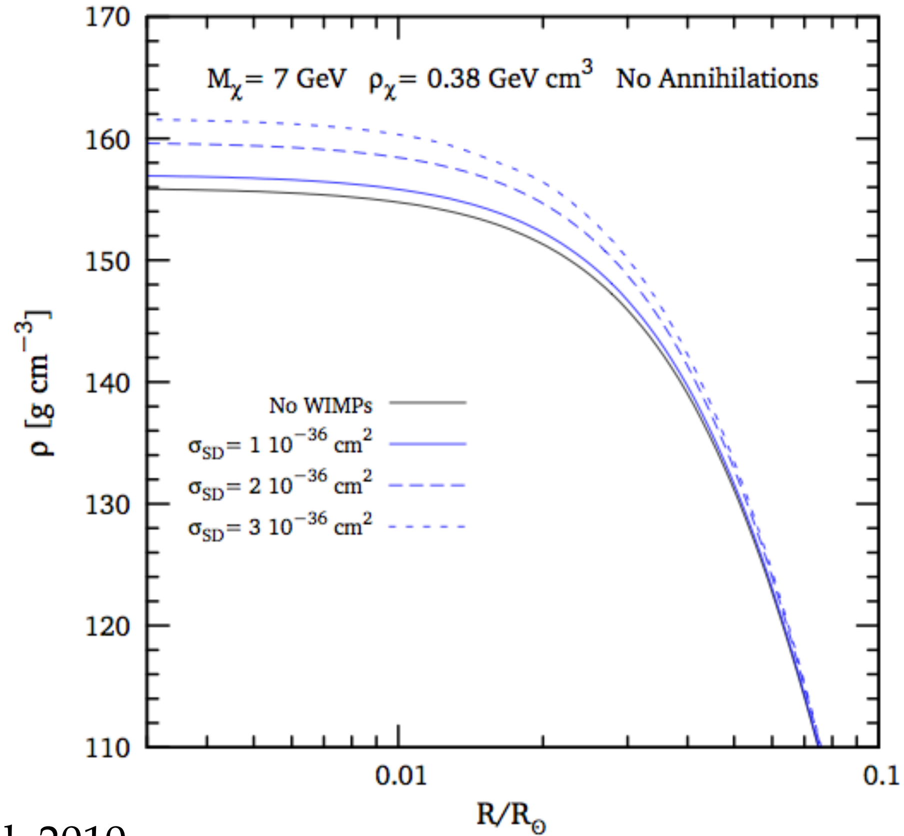
Densities of order ~100 Gev cm^{-3} necessary to affect evolution through energetics. Typical of galactic center (always assuming NFW-like DM profiles)

For the solar case, only non-(very weakly) annihilating CDM can be probed

CDM IN THE SUN

Asymmetric WIMPs can transport energy rather efficiently (function of cross section & mass)

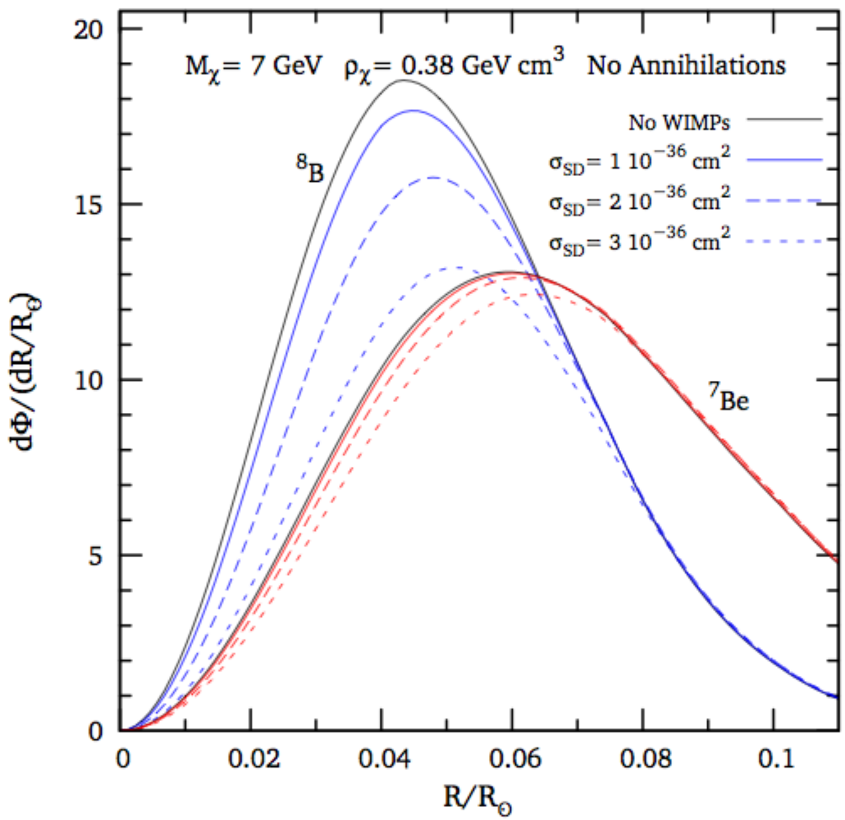




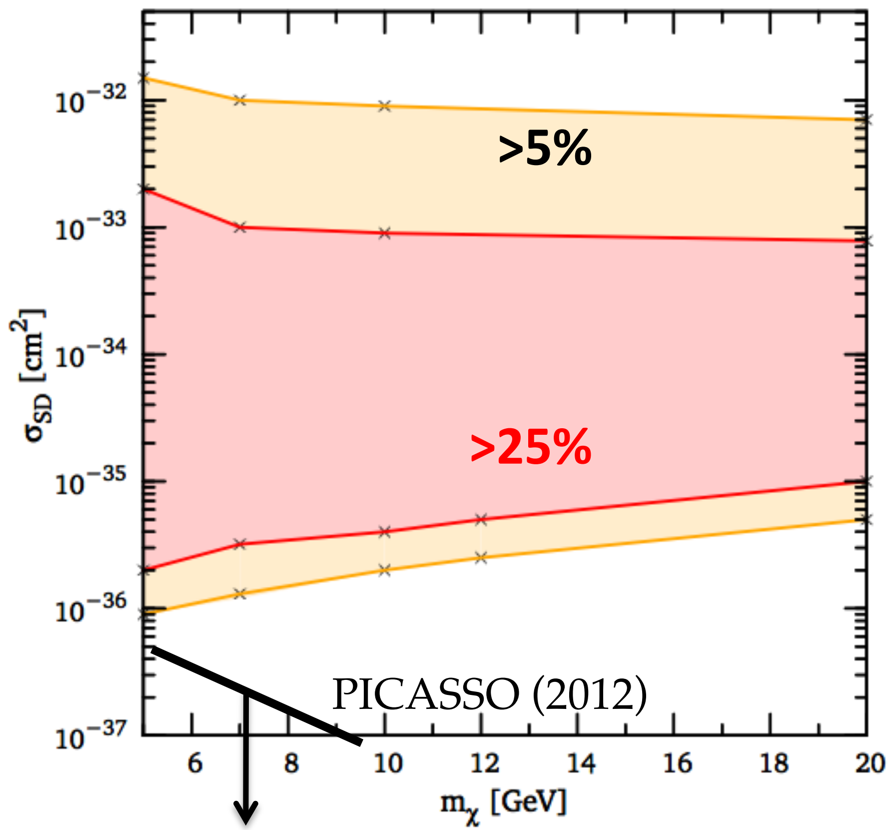
Taoso et al. 2010

CDM in the Sun

Spin dependent



Changes in ^{8}B flux

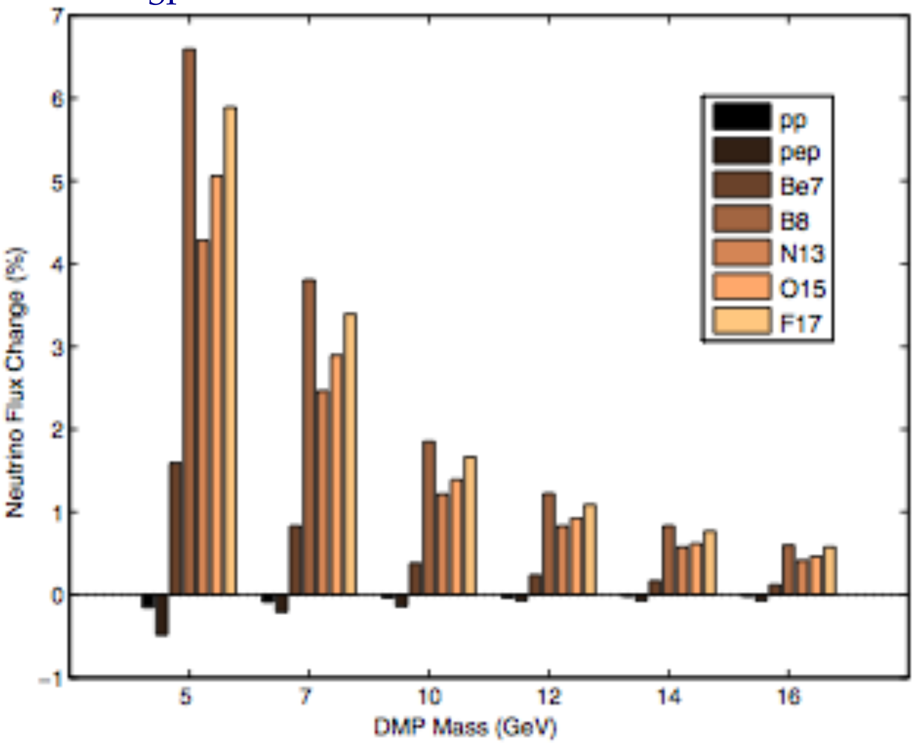


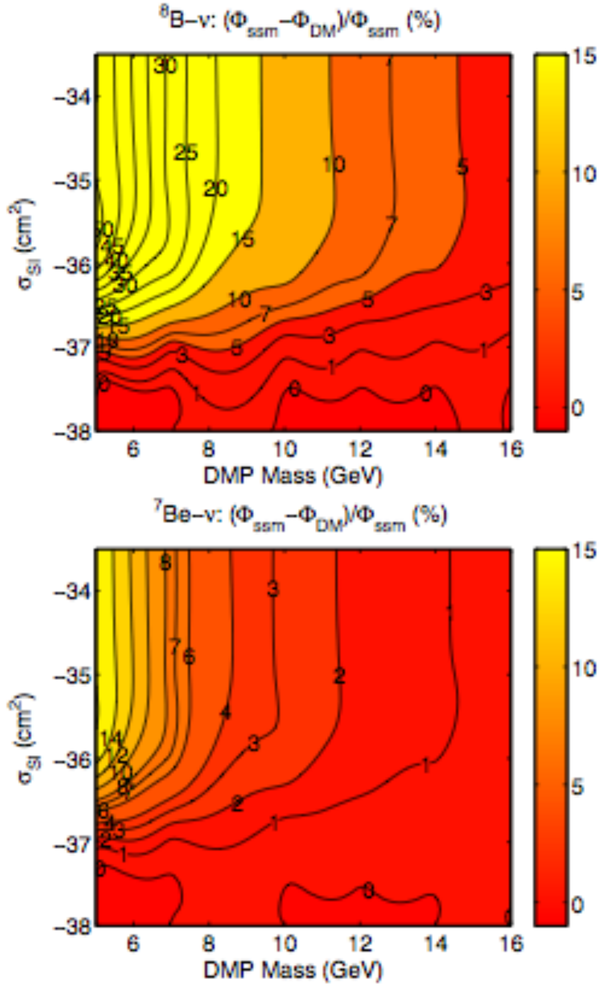
Taoso et al. 2010

CDM in the Sun

Fiducial DM density in solar neighborhood ~0.38 Gev cm^{-3}

$\sigma_{SI}= 10^{-37}$ cm^2

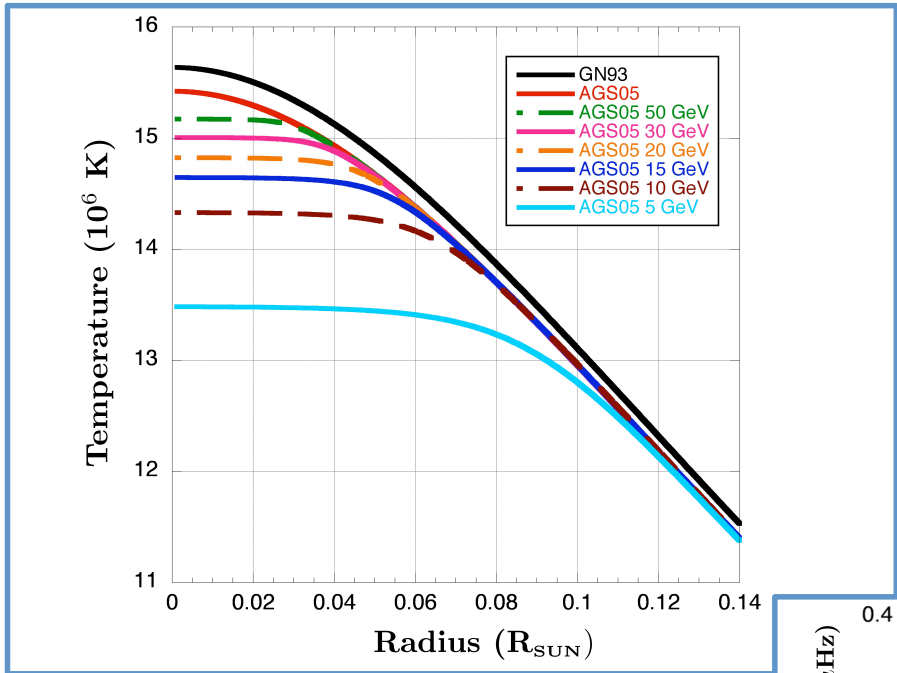


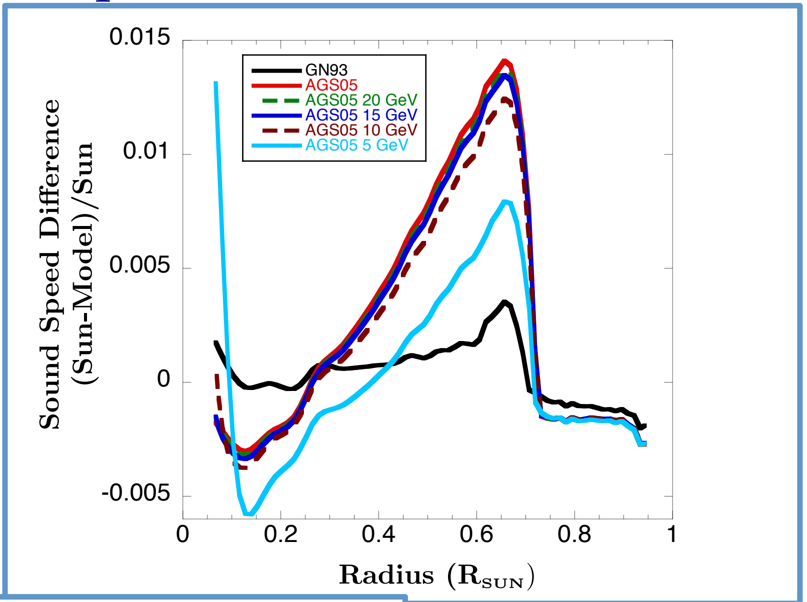


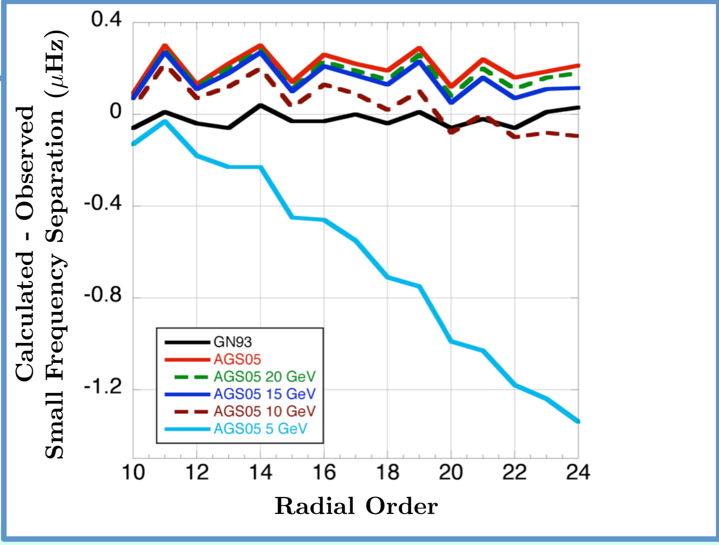
Lopes & Silk 2012

CDM in the Sun

Some helioseismic results & solar abundance problem







Cumberbatch et al. 2010

Effect on T large compared to Taoso et al.

Problems in the solar core – helium and T are too low

Summary

SSM in agreement with helioseismology IF high (older) metallicity used

Low-Z models conflict with helioseismology – Solar Abundance Problem

Problem for SSM? Maybe, but … non-SSM (rotation, ang. momentum transport, etc) perform even worse

Problem in input physics? Maybe: radiative opacities are the (usual) suspect

Solar models in excellent agreement with neutrino data

CNO neutrinos can break degeneracy between composition and opacity

Sun as CDM detector: ^{8}B very sensitive, however, effects noticeable for relatively large cross sections and low masses

Future: g-modes (if observed) could bring enhanced sensitivity in solar core

Updated Astro Factors - SFII

Reanalysis of available experimental and theoretical data for pp and CNO reactions (Adelberger et al. 2011)

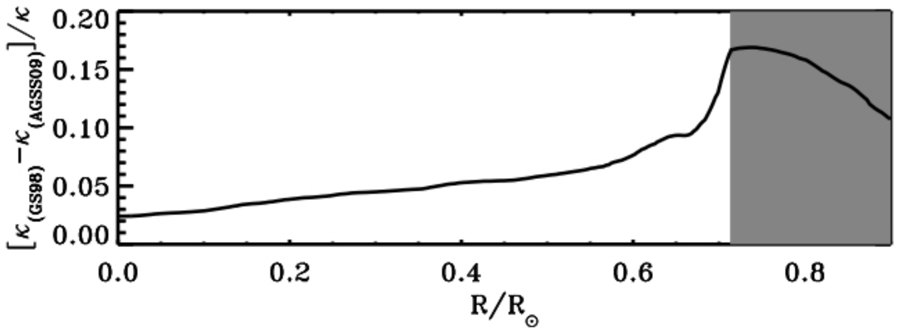
Few percent changes in S(0) and revised uncertainties (less optimistic – up to factor of 2) in key reactions

Reaction	SFII (keV-b)	Previous (keV-b)
S_{11}	$4.01 \times 10^{-22}(1 \pm 0.010)$	$3.94 \times 10^{-22}(1 \pm 0.004)$
S_{33}	$5.21 \times 10^{3}(1 \pm 0.052)$	$5.4 \times 10^{3}(1 \pm 0.06)$
S_{34}	$0.56(1 \pm 0.054)$	$0.567(1 \pm 0.03)$
S_{17}	$2.08 \times 10^{-2}(1 \pm 0.077)$	$2.14 \times 10^{-2}(1 \pm 0.038)$
$S_{1,14}$	$1.66(1 \pm 0.072)$	$1.57(1 \pm 0.08)$
R(pep)/R(pp)	$\uparrow 2.5\%$	—

Recent Experimental Results

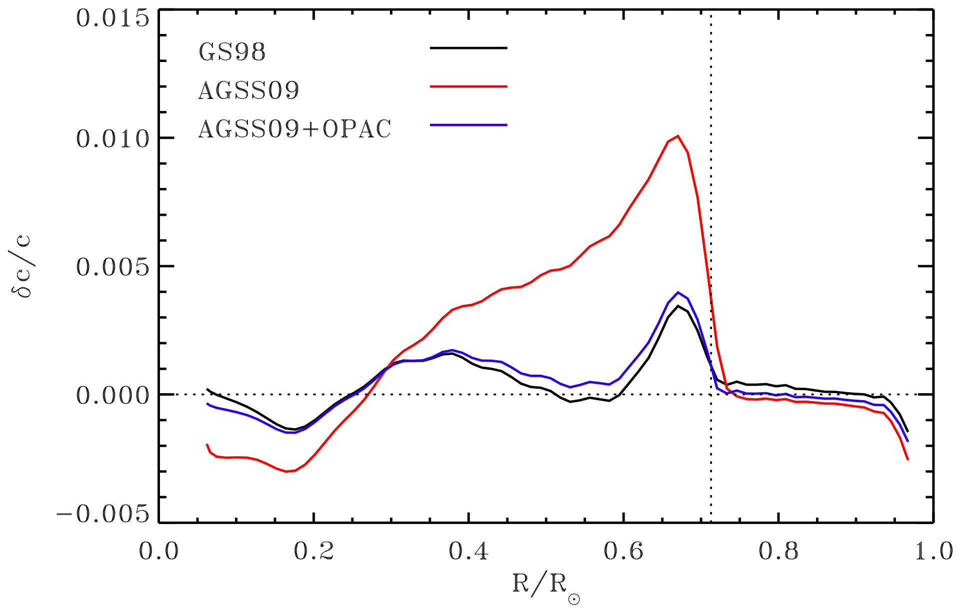
- Combined analysis of SAGE $<\sigma\Phi> = 65.4 \pm 4$ SNU (Abdurashitov et al. 2009)
- GALLEX I-IV $<\sigma\Phi> = 73.4 \pm 7.2$ SNU (Kaether et al. 2010)
- Super-Kamiokande I/II/III combined analysis (talk by Smy)
- Combined analysis of SNO I/II/III (talk by McDonald)
- $\Phi(^7Be)$, $\Phi(^8B)$, $\Phi(pep)$ and most stringest upper limit $\Phi(CNO)$ (talk by Pallavicini)

WHY Φ(CNO)?

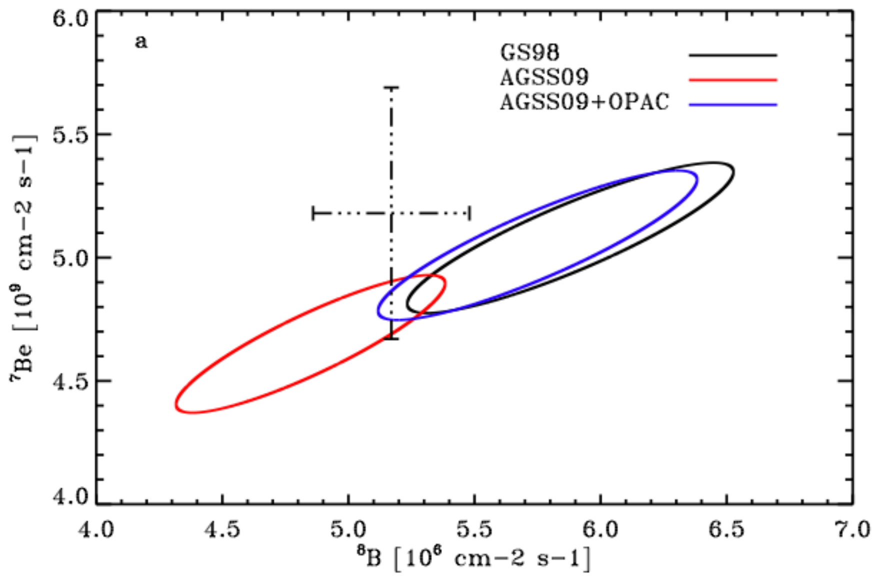


Opacity difference GS98 vs AGSS09

Degeneracy between composition & opacities: changing opacity fixes helioseismology

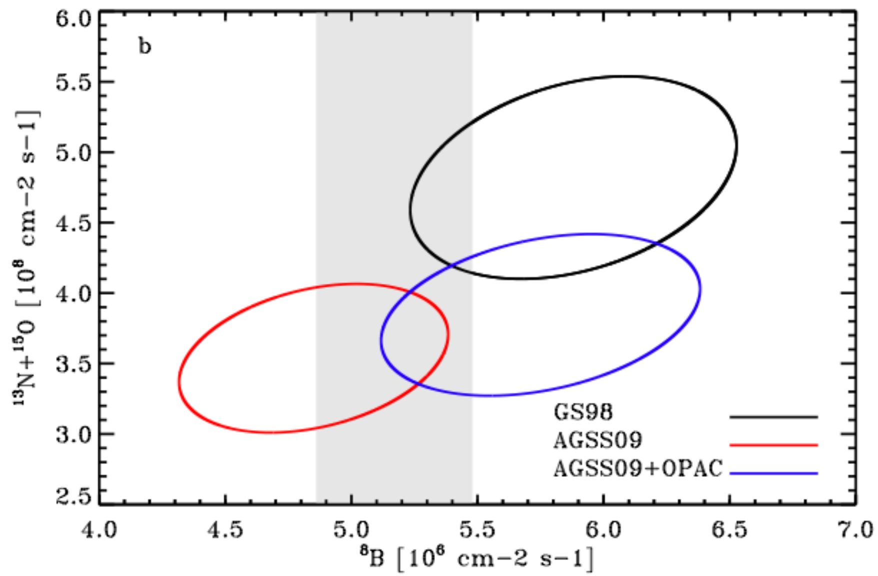


WHY Φ(CNO)?



Changing opacity recovers also $\Phi(^{8}B)$ & $\Phi(^{7}Be)$

CNO fluxes can break the degeneracy between abundances and radiative opacity



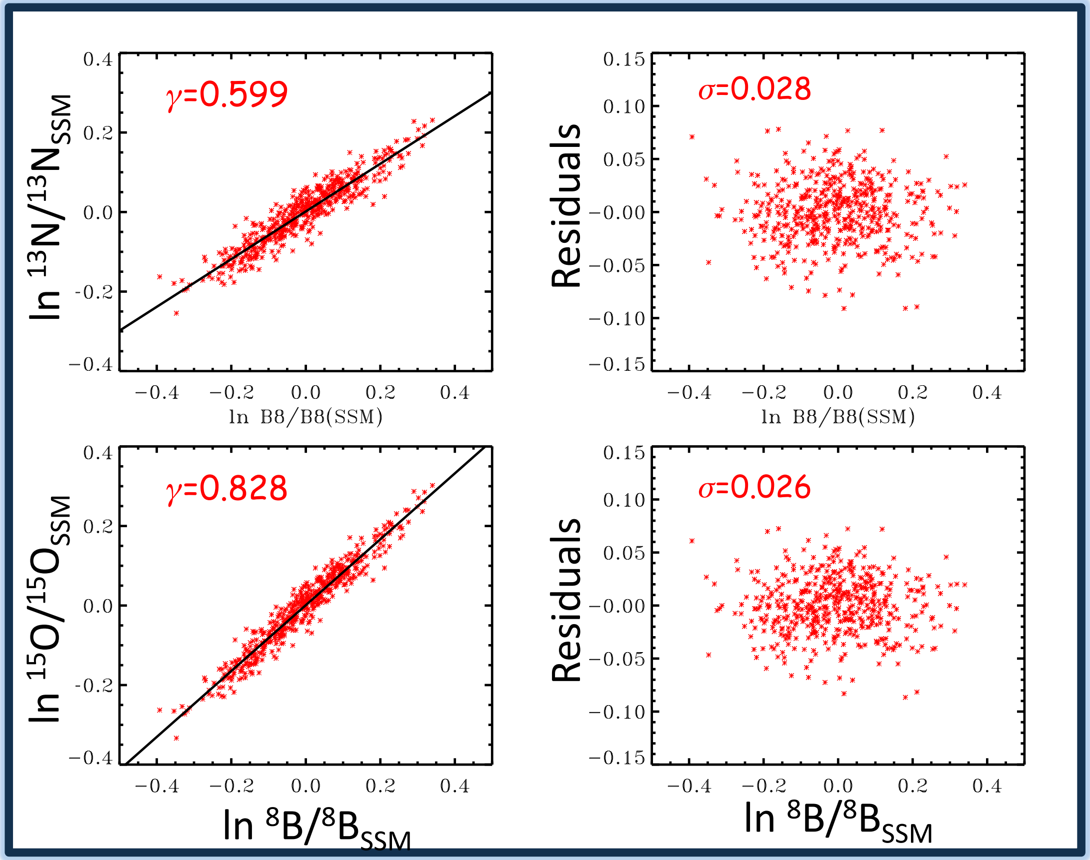
COMPOSITION FROM n-FLUXES

Correlations between ^{8}B and CN-cycle fluxes (only environmental)

Small dispersion <3%

Remaining contributions:

- **nuclear**
- **C&N abundances**



Haxton & Serenelli (2008)

$$\frac{\Phi(^{15}O)}{\Phi^{\rm SSM}(^{15}O)} = \left[\frac{\Phi(^{8}B)}{\Phi^{\rm SSM}(^{8}B)}\right]^{0.828} [1 \pm 2.8\%({\rm env}) \pm 10.5\%({\rm nucl})]$$

$$\times \left[\frac{X(C)}{X(C)_{\rm SSM}}\right]^{0.805} \left[\frac{X(N)}{X(N)_{\rm SSM}}\right]^{0.199}$$

COMPOSITION FROM ν-FLUXES

^{8}B precisely determined 3% - used as a thermometer

Combining expressions for ^{13}N and ^{15}O, including experimental sensitivity & neutrino oscillations

$$\frac{\Phi^{\rm exp}(CN)}{\Phi^{\rm SSM}(CN)} = \left[\frac{\Phi^{\rm SK}(^8B)}{\Phi^{\rm SSM}(^8B)}\right]^{0.828} \left[\frac{X(C+N)}{X(C+N)_{\rm SSM}}\right]$$

$$\times\,[1 \pm 0.03({\rm SK}) \pm 0.028({\rm env}) \pm 0.03({\rm LMA}) \pm 0.105({\rm nucl})]$$

- **SSM only used as a reference point (and exponents)**
- **Exponents 'robust' to variations in solar model inputs**
- **Uncertainty dominated by experimental (S_{17} & $S_{1\,14}$) contributions**

"Perfect" CN measurement gives central C+N to about 12%

Using Borexino upper limit for $\Phi(^{13}N+^{15}O)$: $X(C+N)_{\rm Borexino} < 0.072$

$X(C+N)_{\rm GS98} = 0.048$ -- $X(C+N)_{\rm AGSS09} = 0.039$

Why Φ(CNO)?

- Breaks degeneracy between composition & opacities: new light on solar abundance problem

- "Direct" determination of central C+N abundance: a potential test for mixing processes, e.g. gravitational settling of metals

- Impact of chemical differentiation in the protoplanetary disk suggested as a signature for the presence of terrestrial planets in stars → low content of CNO in the solar core

Summary

- Best SSM (high-Z) and best solar atmosphere models (low-Z) lead to contradicting results: solar abundance problem
- Solar abundance problem: missing metals, missing opacity, missing (relevant) physics?
- Current data on solar fluxes do not discriminate between abundances.
- Missing metals or missing opacity? CNO neutrinos can provide a "direct" measurement of C+N abundance and break the degeneracy
- Central abundance of C+N will help constrain solar (stellar) physical processes (gravitational settling, mixing)

Basic Equations

Set of ~ 20 coupled partial diff. eqs.

$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho} \qquad \text{Mass cons.}$$

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4} - \frac{1}{4\pi r^2}\frac{\partial^2 r}{\partial t^2} \qquad \text{Eq. motion}$$

$$\frac{\partial l}{\partial m} = \epsilon_{\rm nuc} - \epsilon_\nu + \epsilon_g \pm \epsilon_{\rm x} \qquad \text{Energy cons.}$$

$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P}\nabla \qquad \text{Energy transp.}$$

$$\frac{\partial n_i}{\partial t} = \sum_j r_{ij} - \sum_k r_{ik} + \frac{\partial}{\partial m}\left[4\pi r^2 \rho n_i \left(D_{\rm cm} + D_{\rm gs} + \ldots\right)\right] \qquad \text{Comp. changes, i=nuclear species}$$

$$\nabla \equiv \frac{d\log T}{d\log P} = \begin{cases} \nabla_{\rm rad} = \frac{3}{16\pi acG}\frac{\kappa l P}{mT^4} & \text{Rad. transp.} \\ \nabla_{\rm conv} & \text{Conv. transp.} \end{cases}$$