THE SOLAR MODEL UP TO DATE: RECENT DEVELOPMENTS

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Outline

Solar abundances and models

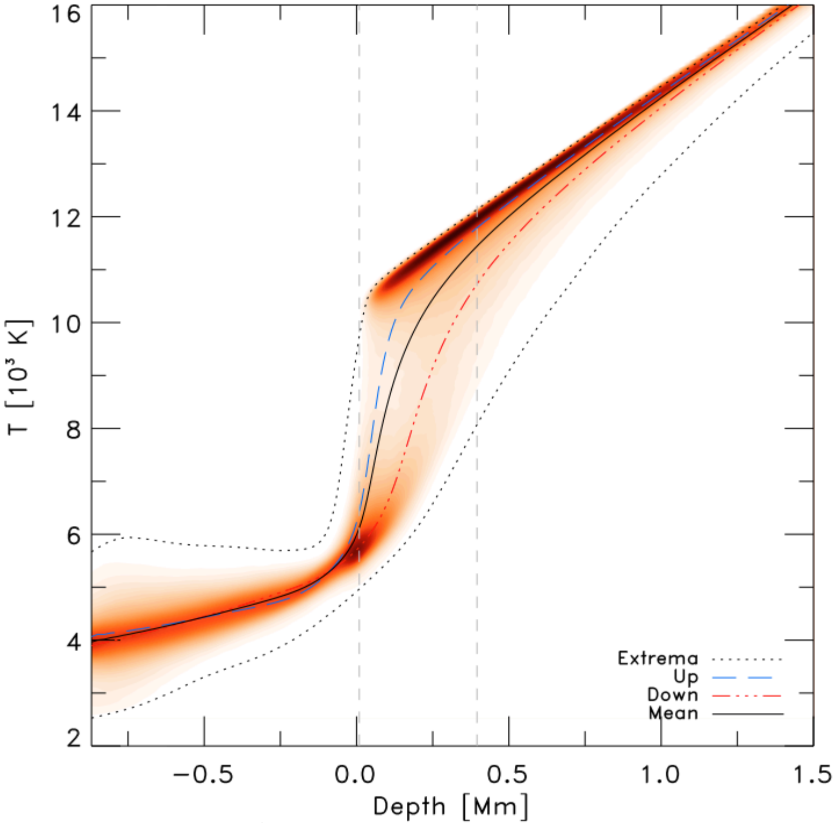
Recap on solar abundance problem

Updates in physical inputs to SSMs: opacities, nuclear rates

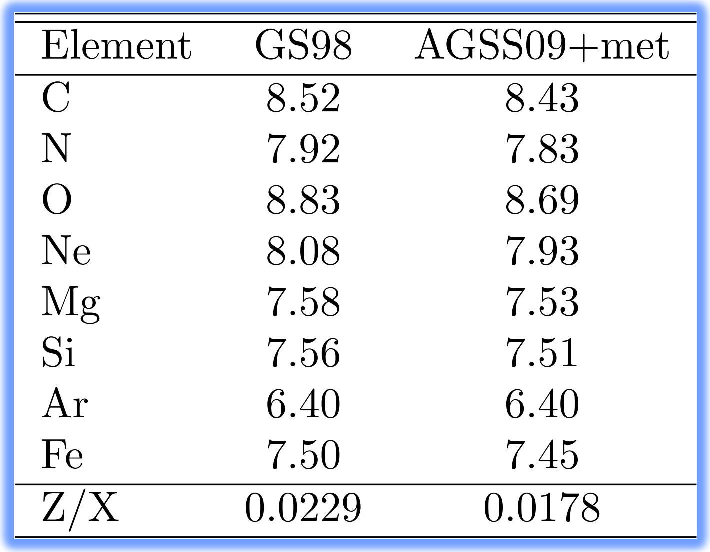
A new generation of SSMs: Barcelona 16 (B16)
    results for helioseismology and updated solar neutrino fluxes

Solar abundances based on 3D atmospheres (+NLTE + atomic data)

Solar surface (photospheric) abundances determined from spectroscopy



Magic et al. 2014



Element	GS98	AGSS09+met
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

$\log(n_x/n_H)+12$

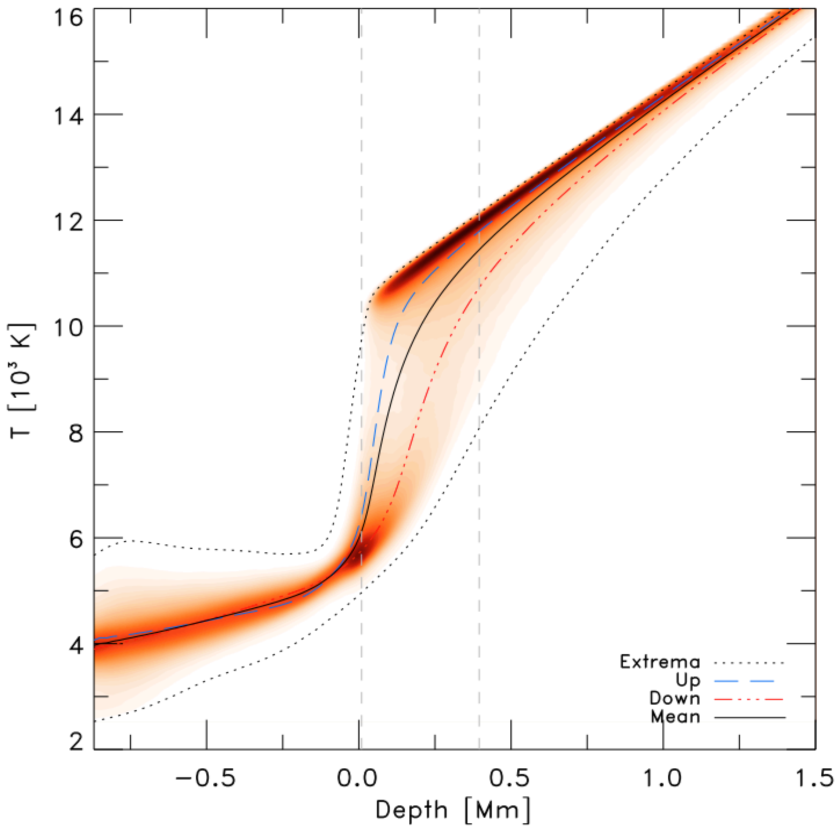
"Sub-solar" solar metallicity

Asplund et al. 2009, Scott et al. 2015

CNO(Ne)~30-40%

refractories~10%

Solar abundances based on 3D atmospheres (+NLTE + atomic data)



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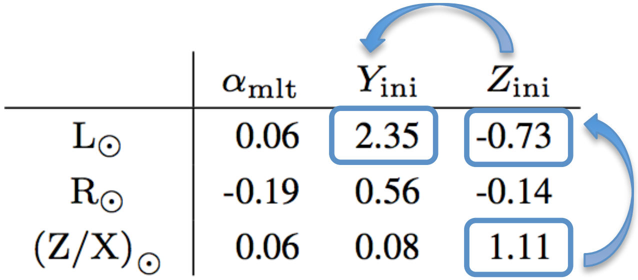


	$\alpha_{\rm mlt}$	$Y_{\rm ini}$	$Z_{\rm ini}$
$L_\odot$	0.06	2.35	-0.73
$R_\odot$	-0.19	0.56	-0.14
$(Z/X)_\odot$	0.06	0.08	1.11

Z/X determines solar model composition

Solar Abundance Problem

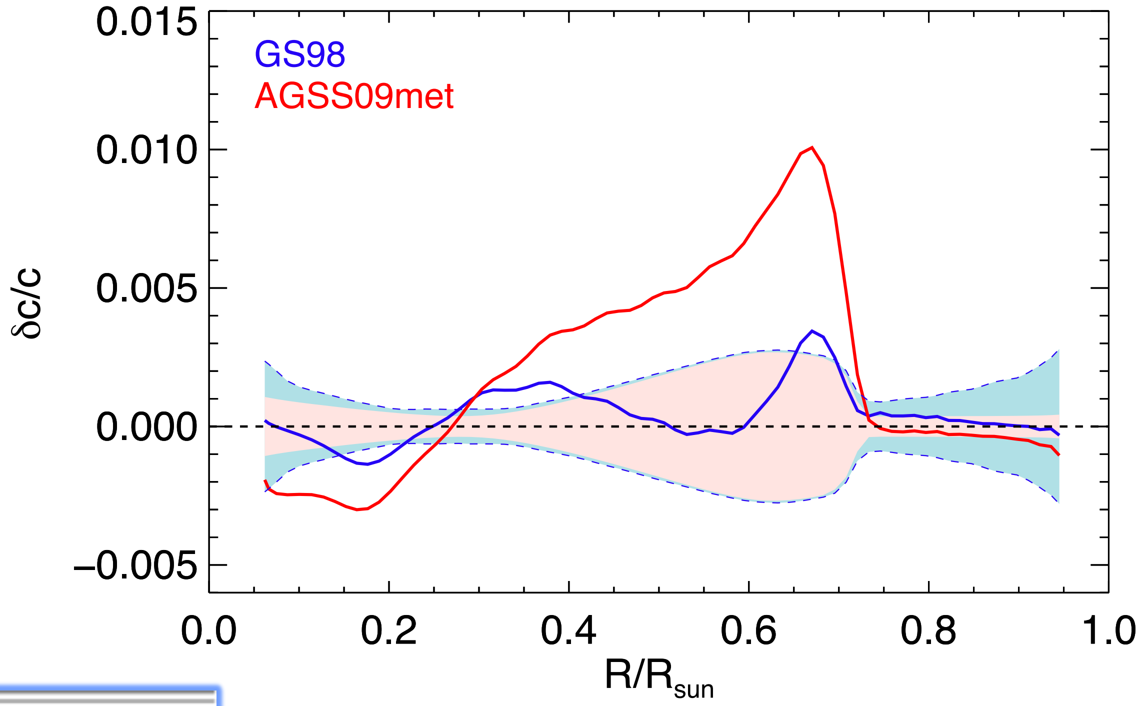
Discrepancies with low-Z solar composition in all helioseismic probes of solar properties:

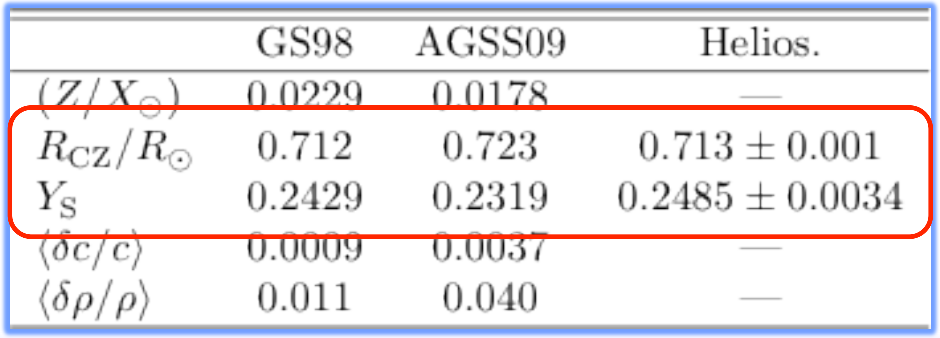
sound speed profile

density profile

depth of convective envelope

surface helium abundance





	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	—

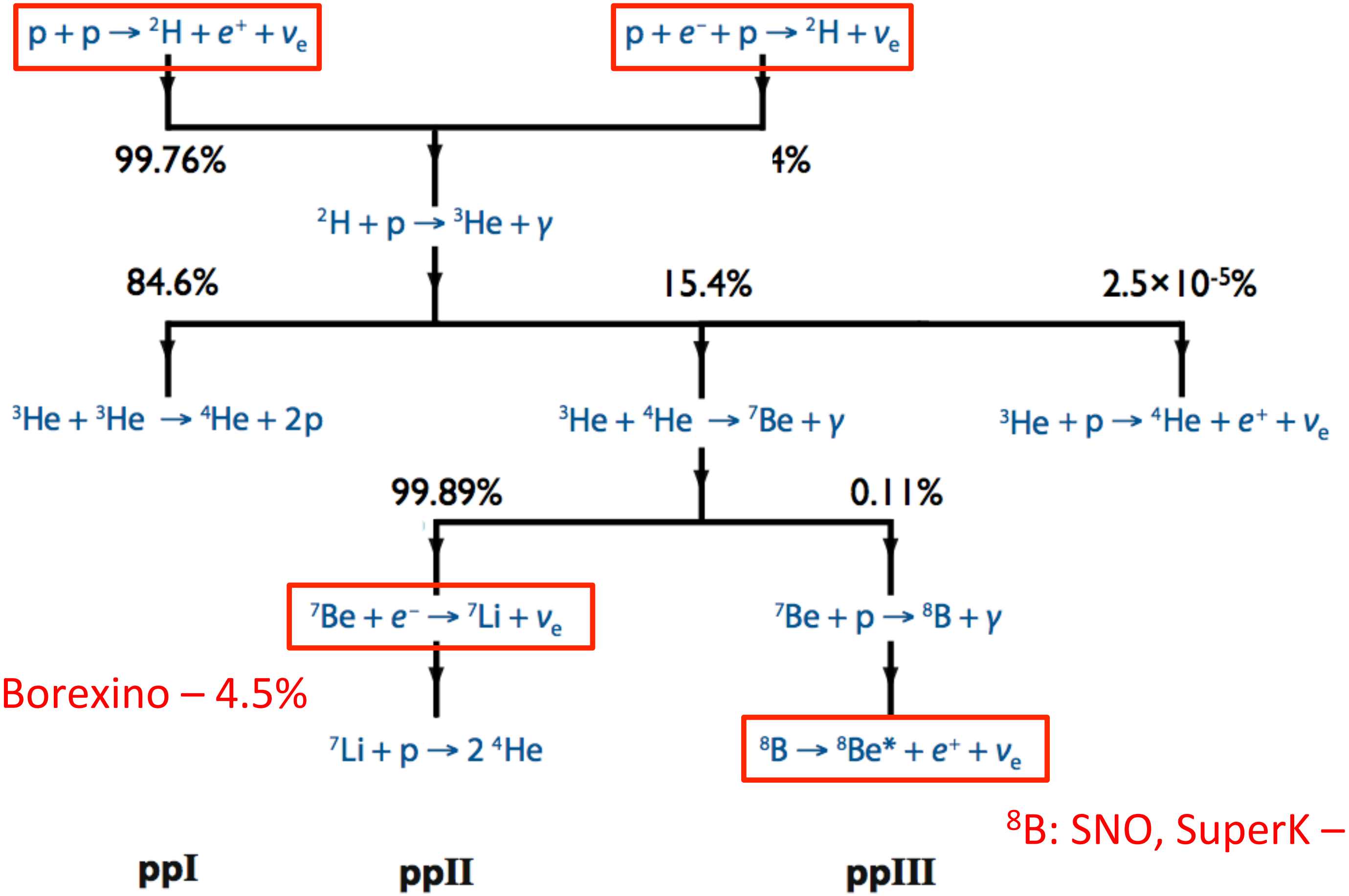
*** High-Z models are preferred**

*** But modern spectroscopy points towards low-Z**

Solar neutrinos

Borexino: pp(10% - 2014)

pep(20% - 2012)



$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$

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

99.76%

4%

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

84.6%

15.4%

$2.5 \times 10^{-5}\%$

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

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

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

99.89%

0.11%

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$

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

^{7}Be: Borexino – 4.5%

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

${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu_e$

^{8}B: SNO, SuperK – 3%

ppI

ppII

ppIII

Solar neutrinos

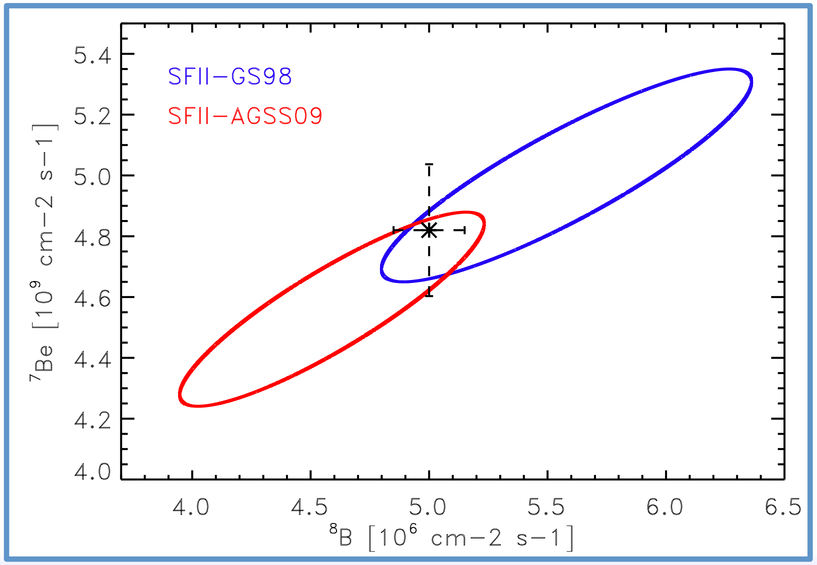
Model fluxes based on Solar Fusion II (SFII; Adelberger et al. 2011)

Flux	SFII-GS98	SFII-AGSS09	Solar
pp	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.006)$	$6.05(1^{+0.003}_{-0.011})$
pep	$1.44(1 \pm 0.011)$	$1.47(1 \pm 0.012)$	$1.46(1^{+0.010}_{-0.014})$
hep	$8.04(1 \pm 0.30)$	$8.31(1 \pm 0.30)$	$18(1^{+0.4}_{-0.5})$
^{7}Be	$5.00(1 \pm 0.07)$	$4.56(1 \pm 0.07)$	$4.82(1^{+0.05}_{-0.04})$
^{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%	

Luminosity constraint: $L_{\odot} = L_{\mathrm{nuc}}$

Experimental uncertainty

No discrimination between models

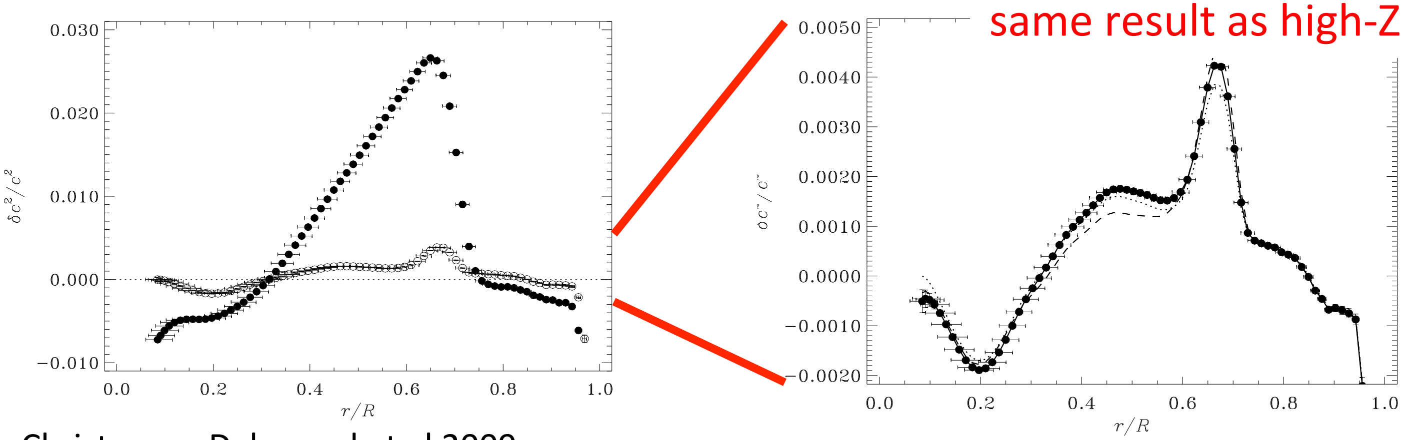


The role of radiative opacities: dT/dr scales with κ

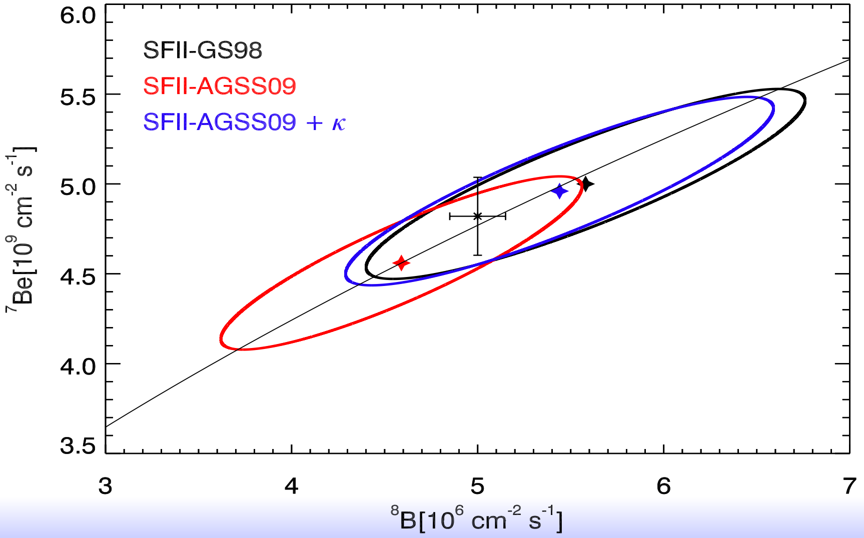
Low metallicity + increased opacity -- > good solar models

Degeneracy exists between composition and κ

Low-Z model + κ increase (15 to 20%)
same result as high-Z model



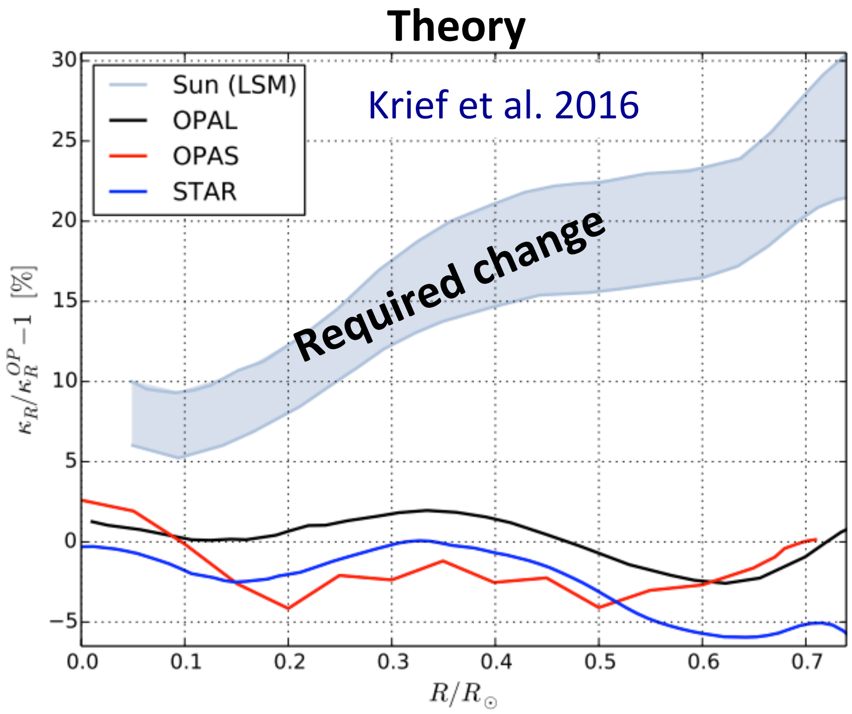
Christensen Dalsgaard et al 2009



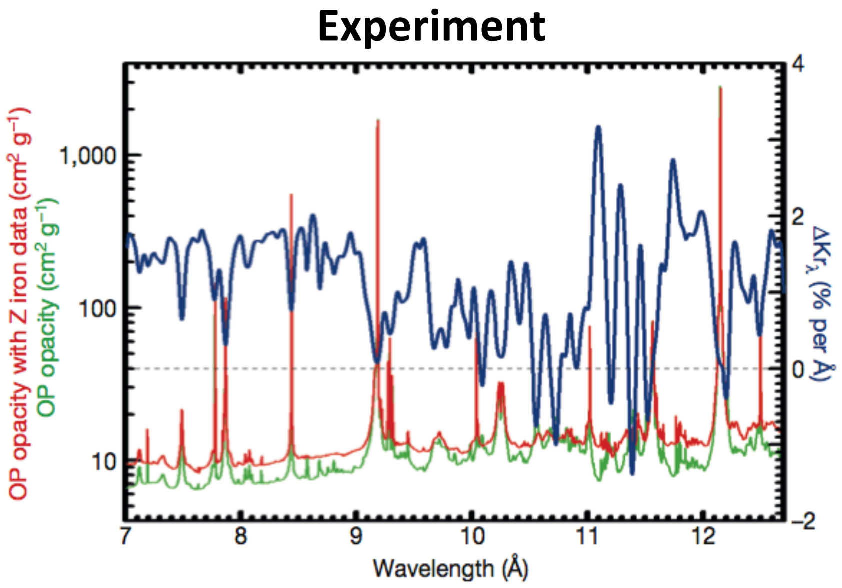
Sound speed and pp-chain neutrinos
-- > recover GS98 "like" values

All probes sensitive to effective opacity; not composition

Opacities: theoretical calculations



Theory



Experiment

@Sandia lab – Z-facility - Iron opacity exper.

OP – OPAL – STAR – OPAS – Los Alamos

First ever measurement at conditions close to bottom of solar CE (x4 too low in density)

Typical differences ~ few %

Required level of change much larger than seen in theoretical calculations

When included in Rosseland mean -- > 7% increase (15-20% needed)

Recent developments in SSM inputs

Nuclear reaction rates

p+p: new calculation includes now S and P waves – full determination of S(E)

increase ~ 1.5% (Marcucci et al. 2013)

p+^{7}Be: more general assessment of models for extrapolating to S(0)

increase ~ 2% (Zhang et al. 2015)

p+14N: new determination of $S_{GS}(0)$ by LUNA

decrease ~ 4% (Marta et al. 2011)

Radiative opacities

more generous estimate of uncertainty (7% at convective envelope – before 2.5%)

implementation of flexible scheme based on opacity kernels

Other changes & revisions

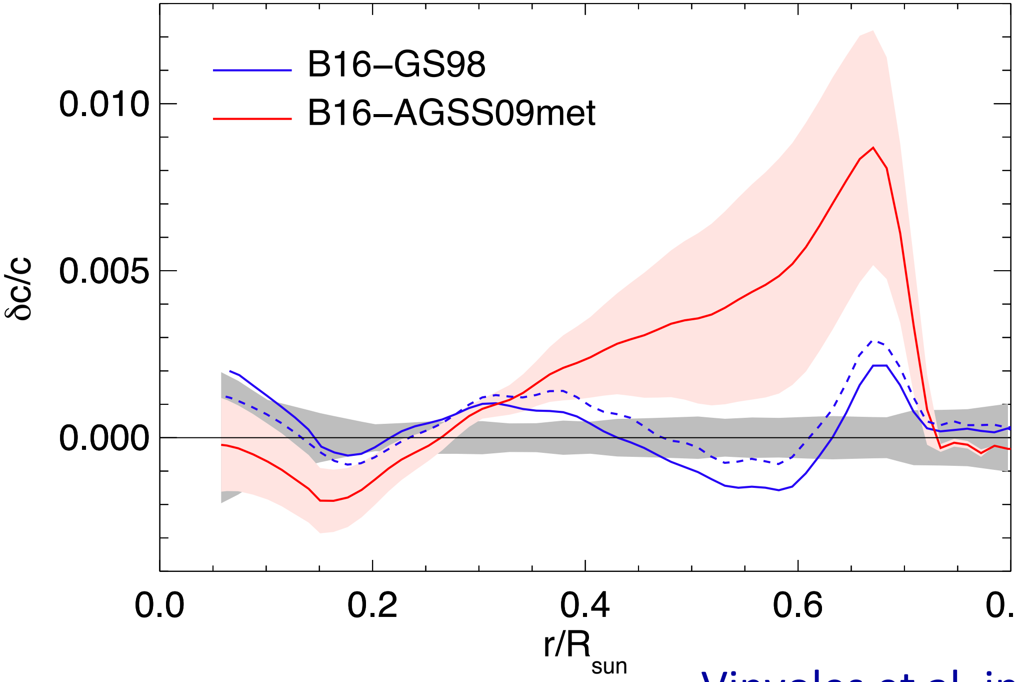
consistent implementation of EoS

new revision of solar composition – does not include CNO elements

New SSMs – Barcelona 16 (B16)

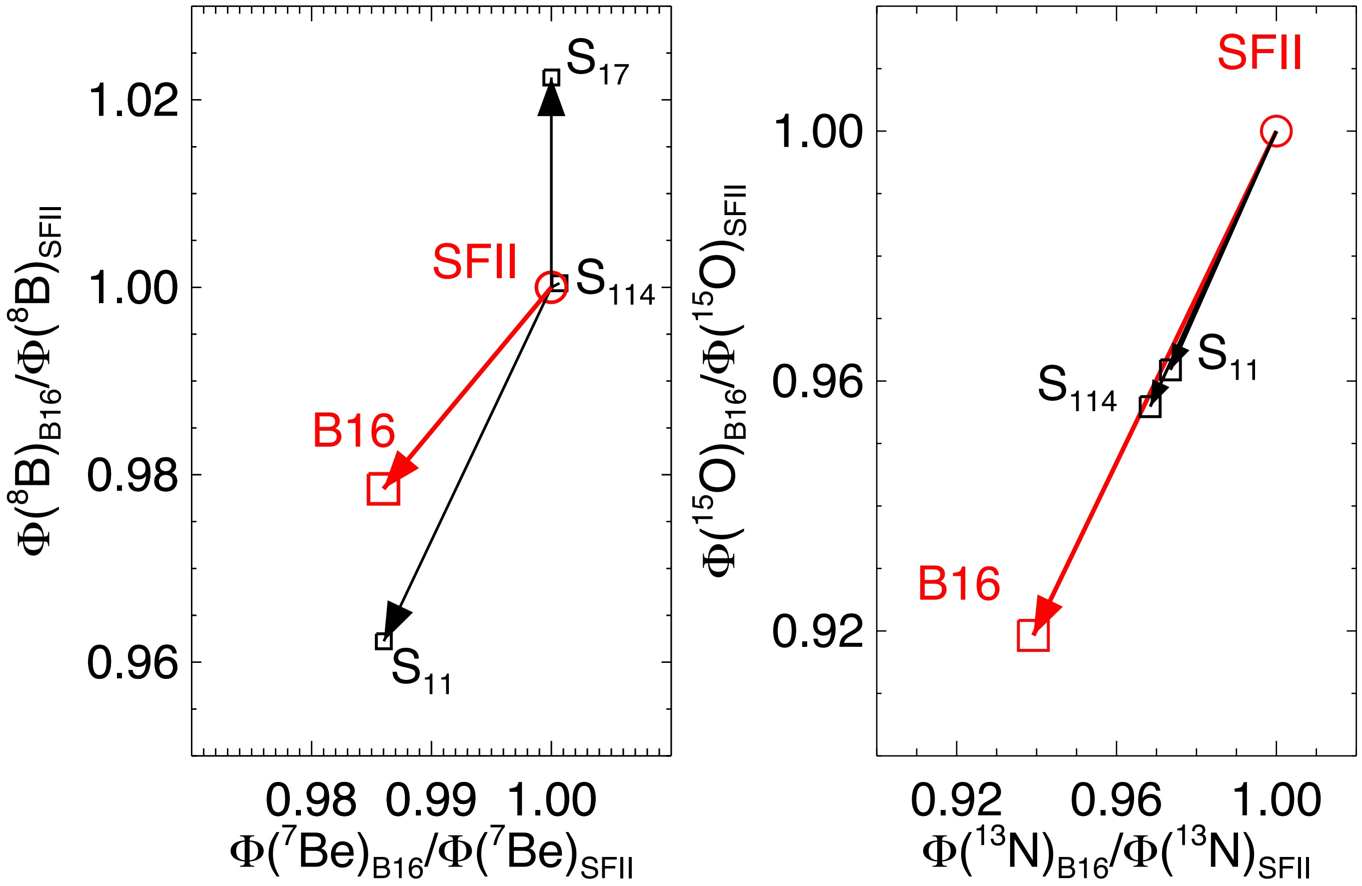
Minor changes in helioseismic quantities with more generous model uncertainties

Central values almost unaffected



Vinyoles et al. in prep.

B16 SSMs – ν fluxes



Change in ν fluxes

~ 2 % reduction for ^8B and ^7Be

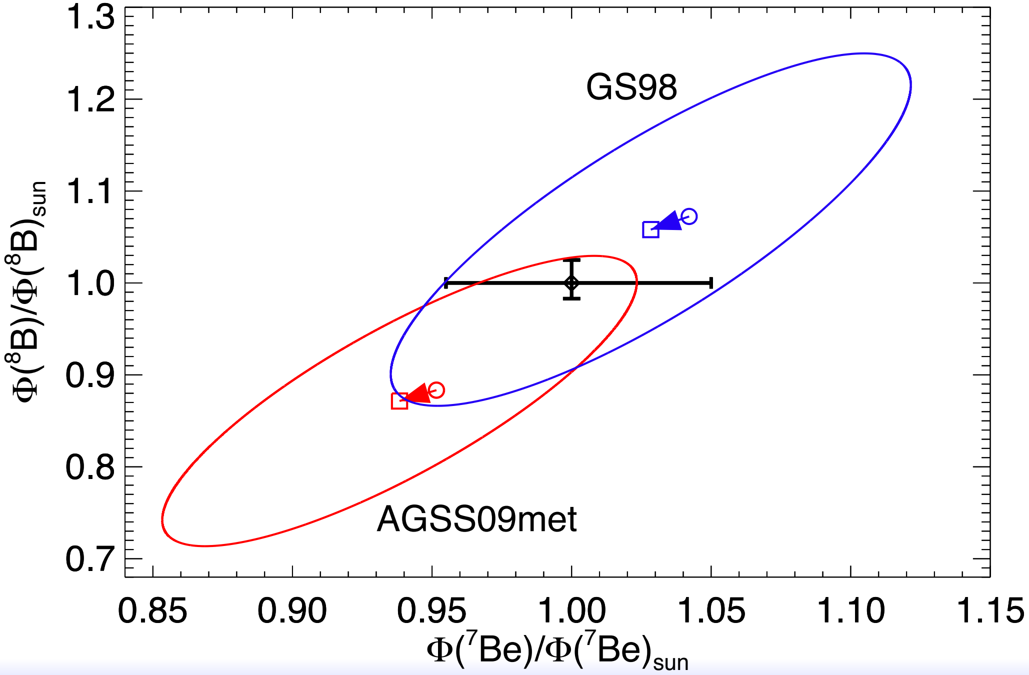
6 - 8% reduction for ^{13}N and ^{15}O

B16 SSMs and solar νs

Flux	B16-GS98	B16-AGSS09met	Solar
$\Phi(\mathrm{pp})$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.971^{(1+0.006)}_{(1-0.005)}$
$\Phi(\mathrm{pep})$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.448(1 \pm 0.009)$
$\Phi(\mathrm{hep})$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$\leq 19^{(1+0.63)}_{(1-0.47)}$
$\Phi(^{7}\mathrm{Be})$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046}$
$\Phi(^{8}\mathrm{B})$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$
$\Phi(^{13}\mathrm{N})$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 12.7
$\Phi(^{15}\mathrm{O})$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8
$\Phi(^{17}\mathrm{F})$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	≤ 85

Vinyoles et al. in prep.

Solar fluxes from
Bergstrom et al. 2016



Slight preference for high-metallicity solution (higher temperature in fact)

0.5 σ (B16-GS98)
0.8 σ (B16-AGSS09met)

B16 SSMs and solar νs

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Vinyoles et al. in prep.

Solar fluxes from Bergstrom et al. 2016

How does the Sun shine? (Bergstrom et al. 2016)

$$\frac{L_{\text{pp-chain}}}{L_\odot} = 0.991^{+0.005}_{-0.004}\left[^{+0.008}_{-0.013}\right] \Longleftrightarrow \frac{L_{\text{CNO}}}{L_\odot} = 0.009^{+0.004}_{-0.005}\left[^{+0.013}_{-0.008}\right]$$

with luminosity constraint

$$\frac{L_{\text{pp-chain}}}{L_\odot} = 1.03^{+0.08}_{-0.07}\left[^{+0.21}_{-0.18}\right] \quad \text{and} \quad \frac{L_{\text{CNO}}}{L_\odot} = 0.008^{+0.005}_{-0.004}\left[^{+0.014}_{-0.007}\right]$$

without luminosity constraint

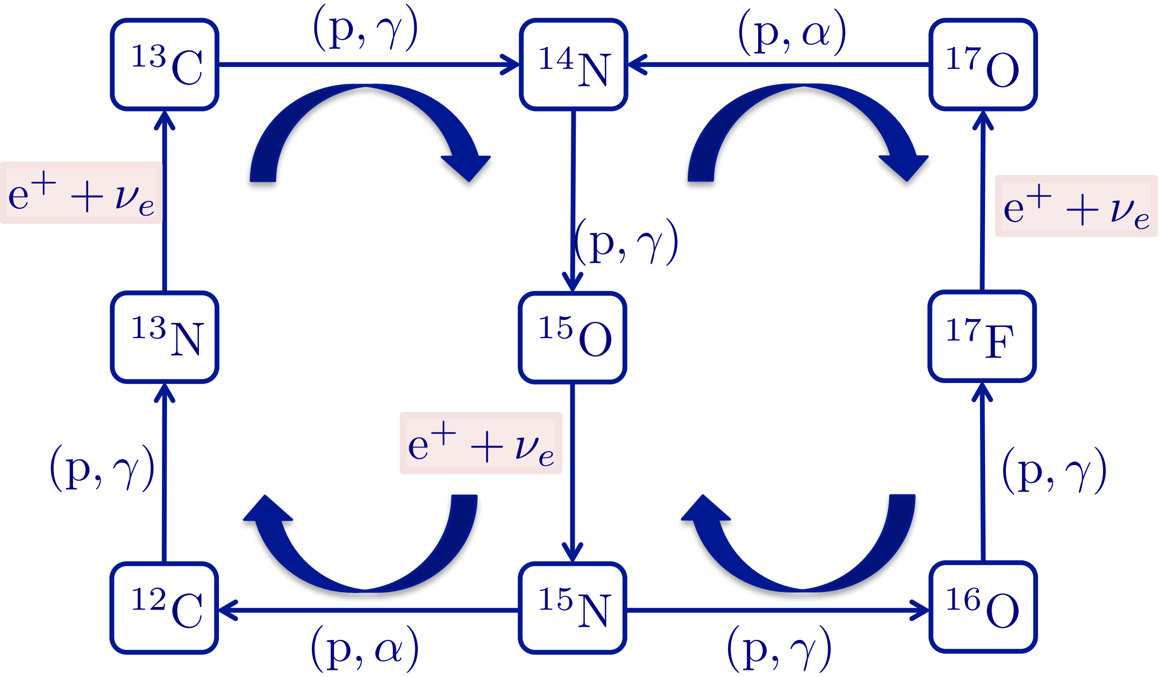
~ x2 improvement (Borexino)

CN ν fluxes

Very important because

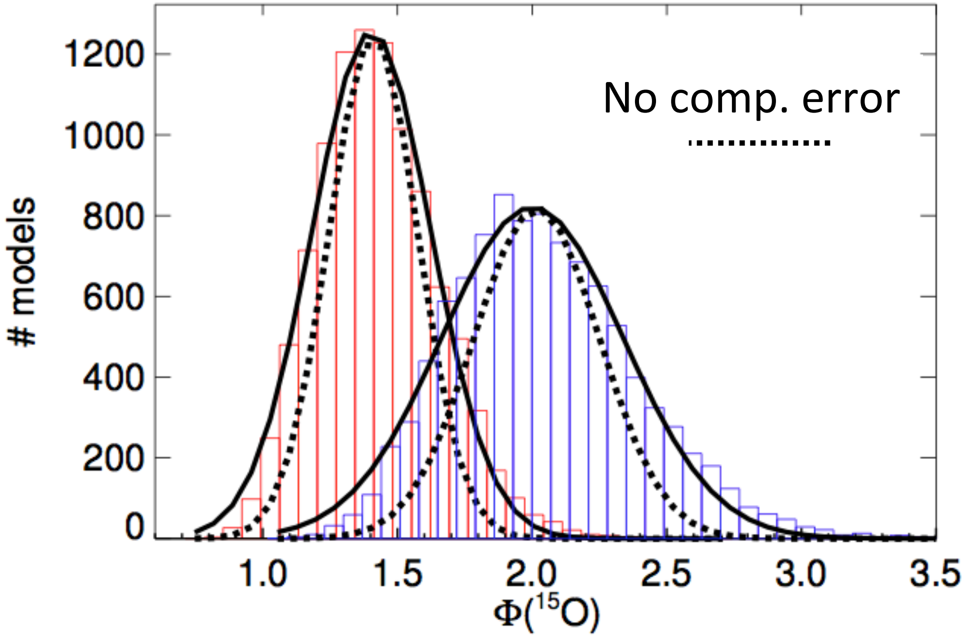
C+N catalyze CN-cycle -- > Extra linear dependence on C+N abundance

Not related to opacity

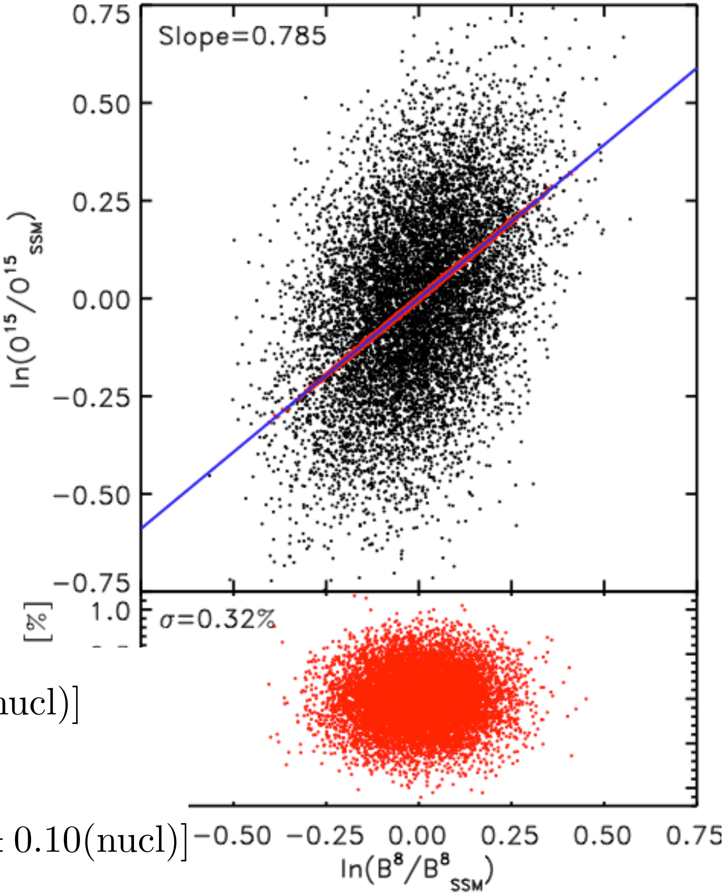


Borexino upper limit for $\Phi(^{13}N+^{15}O) = 7.7 \times 10^8$ cm^{-2} s^{-1}
B16-GS98 = 4.83 x 10^8 cm^{-2} s^{-1}
B16-AGSS09met = 3.48 x 10^8 cm^{-2} s^{-1}

CN ν fluxes



Temperature dependences can be cancelled out using ^{8}B (Serenelli et al. 2013)



ΔCNO ~ 35% (GS98 vs AGSS09)

$$\frac{\Phi(^{15}\mathrm{O})}{\Phi(^{15}\mathrm{O})^{\mathrm{SSM}}} = \left[\frac{\Phi(^{8}\mathrm{B})}{\Phi(^{8}\mathrm{B})^{\mathrm{SSM}}}\right]^{0.785} x_C^{0.749} x_N^{0.212}\,[1 \pm 0.003(\mathrm{env}) \pm 0.10(\mathrm{nucl})]$$

$$\approx \left[\frac{\Phi(^{8}B)}{\Phi(^{8}B)^{\mathrm{SSM}}}\right]^{0.785} \left[\frac{N_{\mathrm{C}} + N_{\mathrm{N}}}{N_{\mathrm{C}}^{\mathrm{SSM}} + N_{\mathrm{N}}^{\mathrm{SSM}}}\right] [1 \pm 0.003(\mathrm{env}) \pm 0.10(\mathrm{nucl})]$$

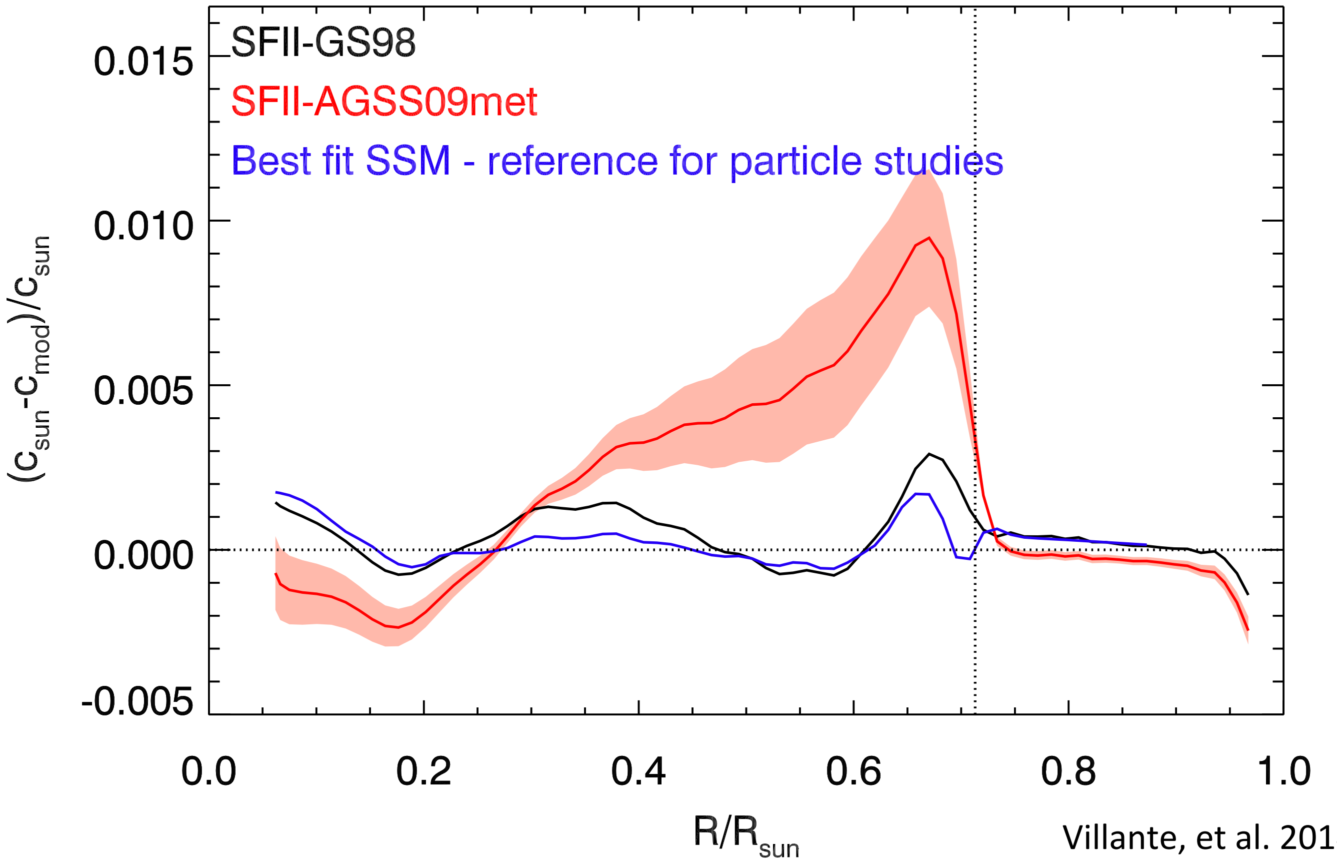
Discriminates compositions to ~ 3-σ before adding CN experimental error
Can be even improved reducing nuclear rate uncertainties

Can the SSM be used to make robust inferences (e.g. particle physics)

Allow input parameters vary within uncertainties (e.g. cross sections, gravitational settling)

Let composition (mainly volatiles) or opacities free

Resulting pulls from systematics of order 1 (1-σ) -- > χ^2 = 17 for 34 dof



Villante, et al. 2014 – Vinyoles et al. 2015

Robust reference for particle studies provided particle properties/interaction do not depend on detailed composition

Summary

Presentation of B16 SSMs

Updated nuclear reaction rates

Modified treatment of opacity uncertainties

Overall picture – solar abundance problem – remains

Wrong composition?

Missing opacity? 5 atomic calculations agree within 5%

experimental result on Fe opacity hints at 7% deficit in models

Small changes in νs from pp-chains – slightly better for high-Z models

GS98 – high-Z models : 0.5 σ

AGSS09 – low-Z models : 0.8 σ

CN fluxes very important – complemented with ^{8}B offer a unique probe of solar core composition: solar composition, mixing processes in stars

SSM is a robust and good (χ^2 = 17 for 34 dof) reference for placing constraints to exotic physics

Backup slides

B16 SSMs – ν fluxes

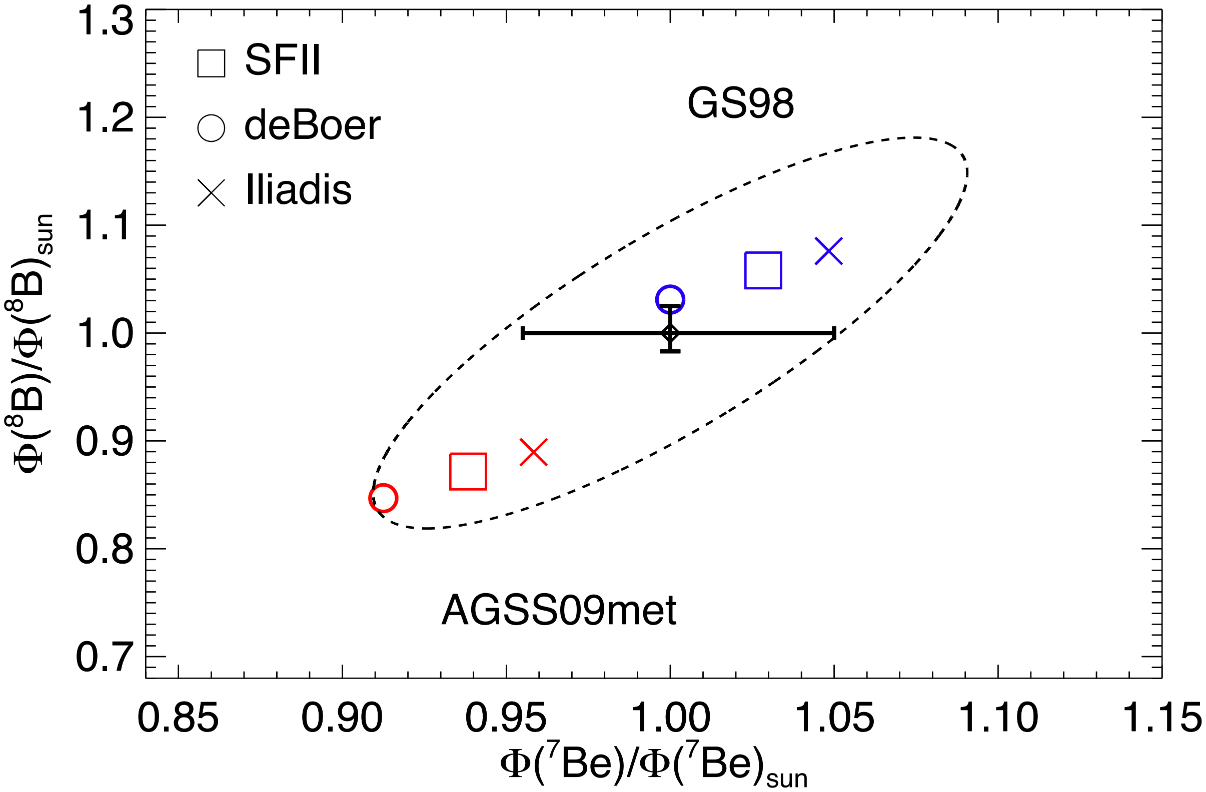
^{3}He + ^{4}He -- > ^{7}Be

Recent results on $S_{34}(0)$

Solar Fusion II (2011)
S34(0)= 5.6 x 10^{-5} (5%) MeVb

deBoer et al. (2014)
S34(0)= 5.42 x 10^{-5} (5%) MeVb

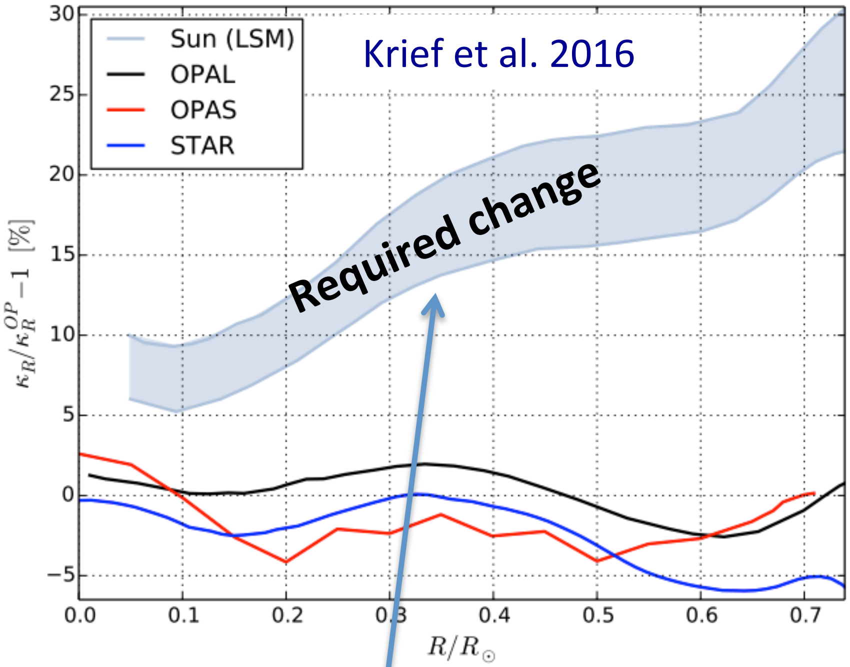
Iliadis et al. (2016)
S34(0)= 5.72 x 10^{-5} (3%) MeVb



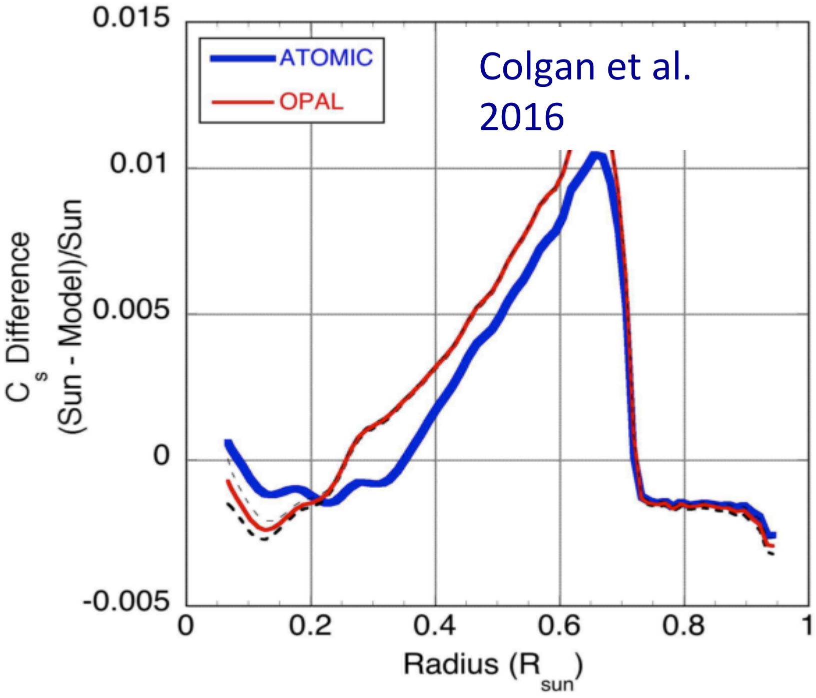
Better discrimination of SSMs by pp-chain fluxes important to check consistency with helioseismic view on the Sun

Nuclear uncertainties need be reduced (S_{34}, S_{17}) – systematics better understood but opacity uncertainty remain a difficult issue (dominant for ^{8}B ~8%)

Opacities: theoretical calculations


Krief et al. 2016

Required change


Colgan et al. 2016

OP – OPAL – STAR – OPAS – Los Alamos (ATOMIC)

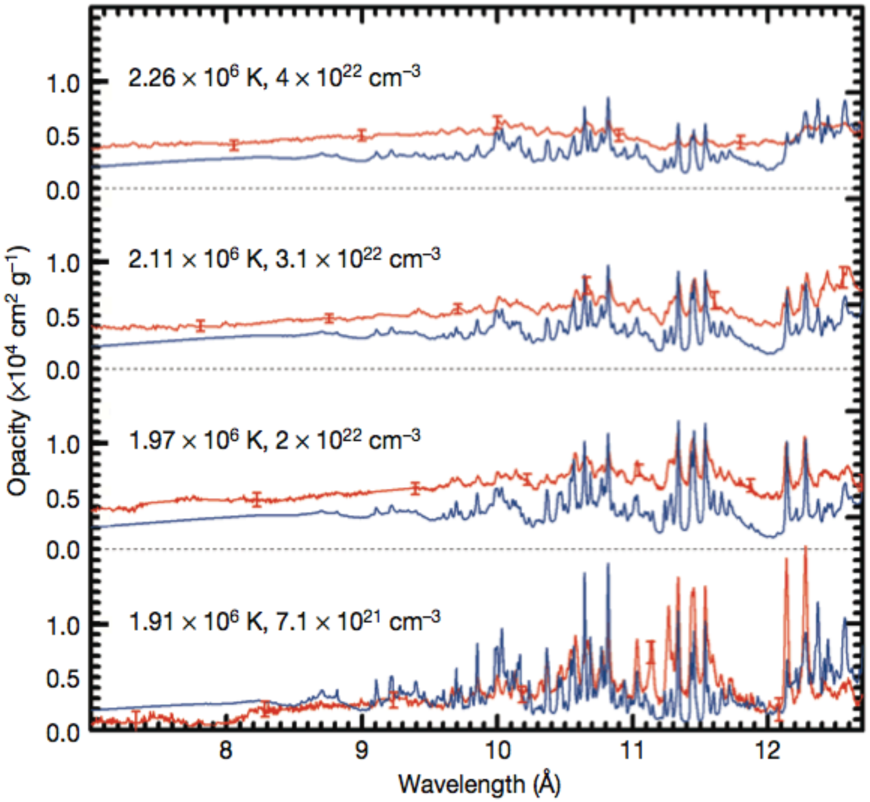
Typical differences in opacity calculations ~ few %

Required level of change much larger than seen in theoretical calculations

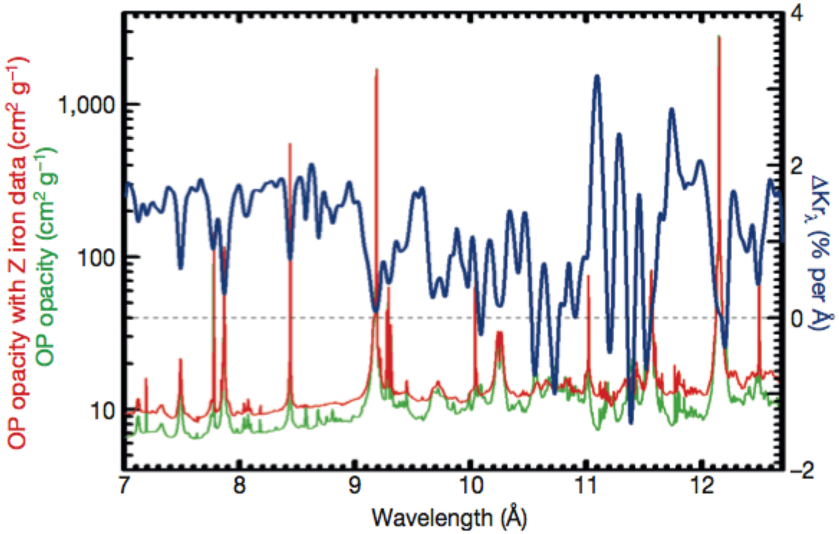
Opacities: experimental results

Iron opacity measurement @Sandia lab – Z-facility

First ever measurement at conditions close to bottom of solar convective envelope (factor 4 too low in density)



Bailey et al. 2015



When included in Rosseland mean -- > 7% increase (15-20% needed)