SOLAR MODELS AND NEUTRINOS: WHAT'S NEW UNDER THE SUN?

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Outline

Solar abundances and solar models

Recap on solar abundance problem

Updates in physical inputs to SSMs: opacities, nuclear rates, etc.

A new generation of SSMs: Barcelona 16 (B16)

results for helioseismology and updated solar neutrino fluxes

Calibration of SSM

3 free parameters

convection parameter - α_{MLT}
initial helium – Y_{ini}
initial metallicity – Z_{ini}

3 observational constraints

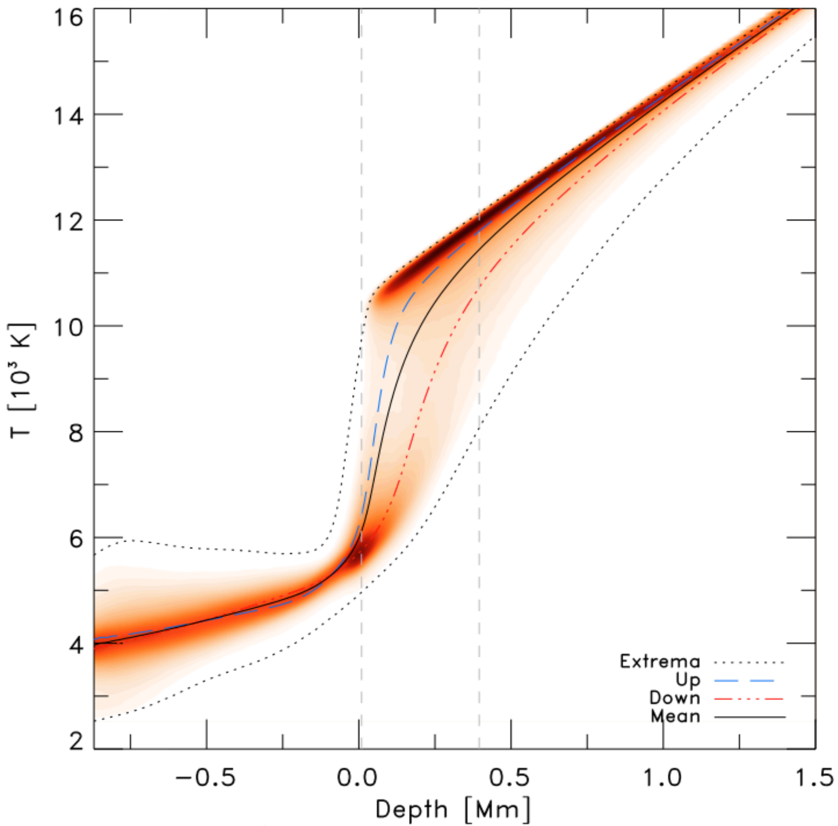
solar radius – $R_{\odot}$
solar luminosity – $L_{\odot}$
surface metal to hydrogen abundances ratio – $(Z/X)_{\odot}$

$$m_{ij} = \frac{\partial \log c_i}{\partial \log p_j}$$

	α_{mlt}	Y_{ini}	Z_{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

$R_{\odot}$ and $L_{\odot}$ well known – $(Z/X)_{\odot}$ has changed dramatically (> 30%) in last 15 years

Solar abundances based on 3D atmospheres

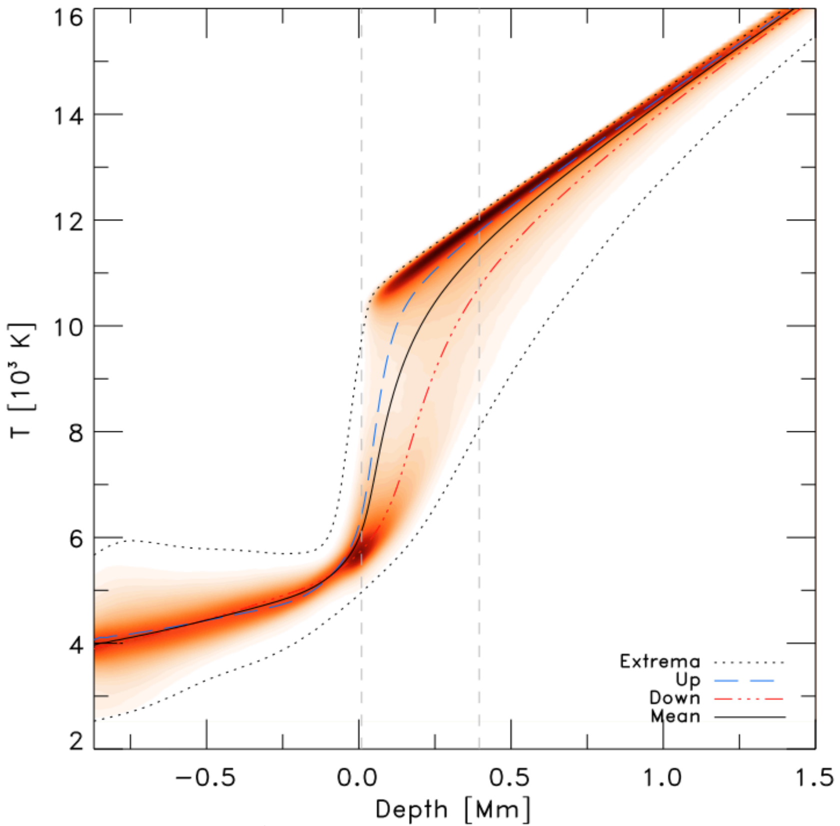


Magic et al. 2014

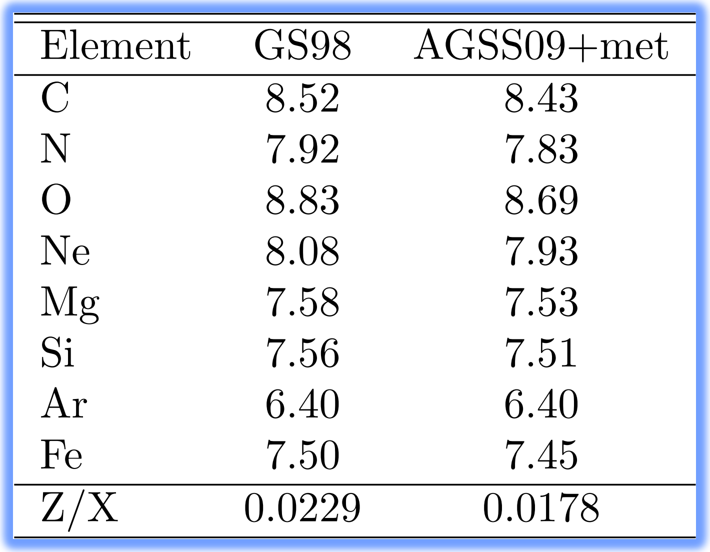
Fluctuations around mean + nonlinearity of Planck function (T) and line formation (T & ρ)

-- > spectral analysis in 3D cannot be represented by 1D (Uitenbroek & Criscuoli 2011)

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



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

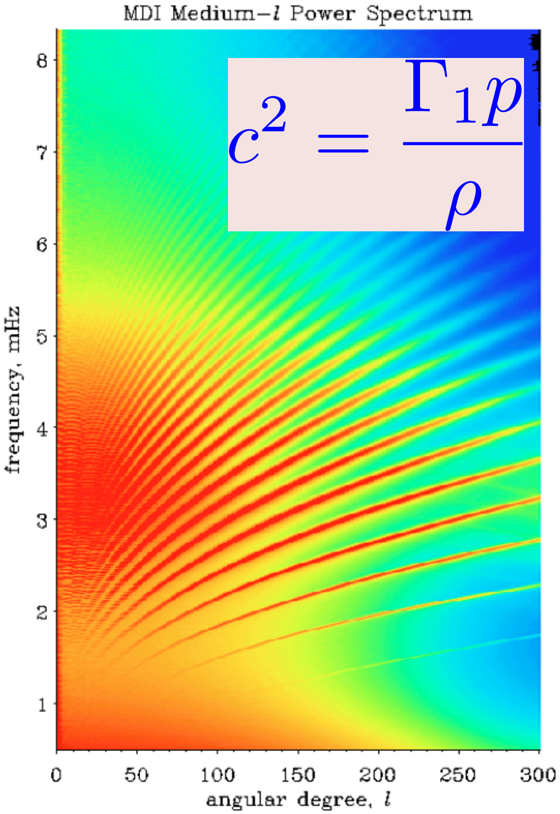
$\log(n_x/n_H)+12$

“Sub-solar” solar metallicity

CNO(Ne)~30-40%

refractories~10%

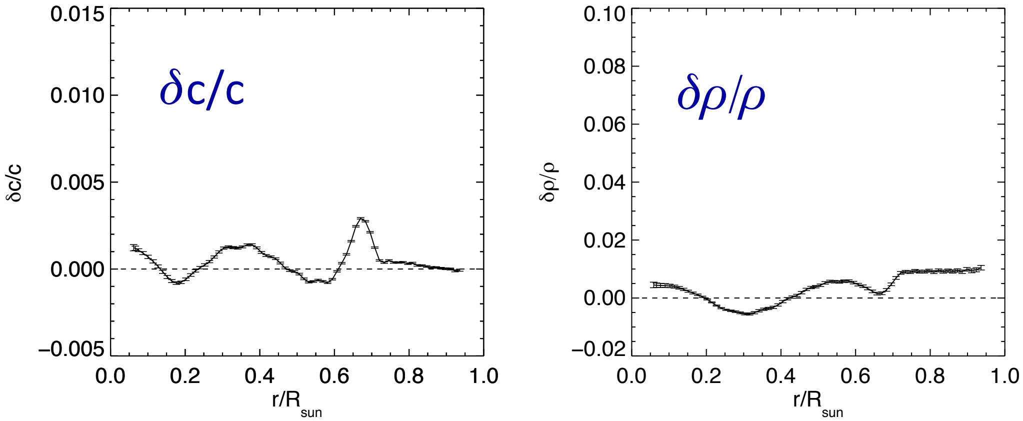
Helioseismology



$$c^2 = \frac{\Gamma_1 p}{\rho}$$

Inversion of profiles of solar properties: c^2, r, Γ_1, Y

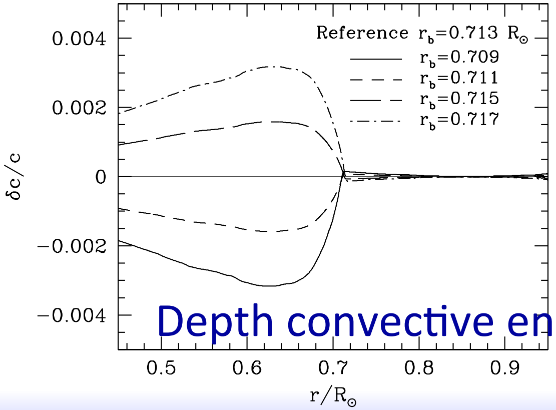
$$\frac{\delta\omega_i}{\omega_i} = \int K^i_{c^2,\rho}(r)\boxed{\frac{\delta c^2}{c^2}}(r)\,dr + \int K^i_{\rho,c^2}(r)\boxed{\frac{\delta\rho}{\rho}}(r)\,dr + F_{surf}(\omega_i)$$



δc/c

$\delta\rho/\rho$

acoustic standing waves (p-modes)
typical period 5 minutes (~ 3 mHz)
amplitudes ~ few cm/s in radial velocity
~ parts per million in brightness



Depth convective envelope

Solar Abudance Problem

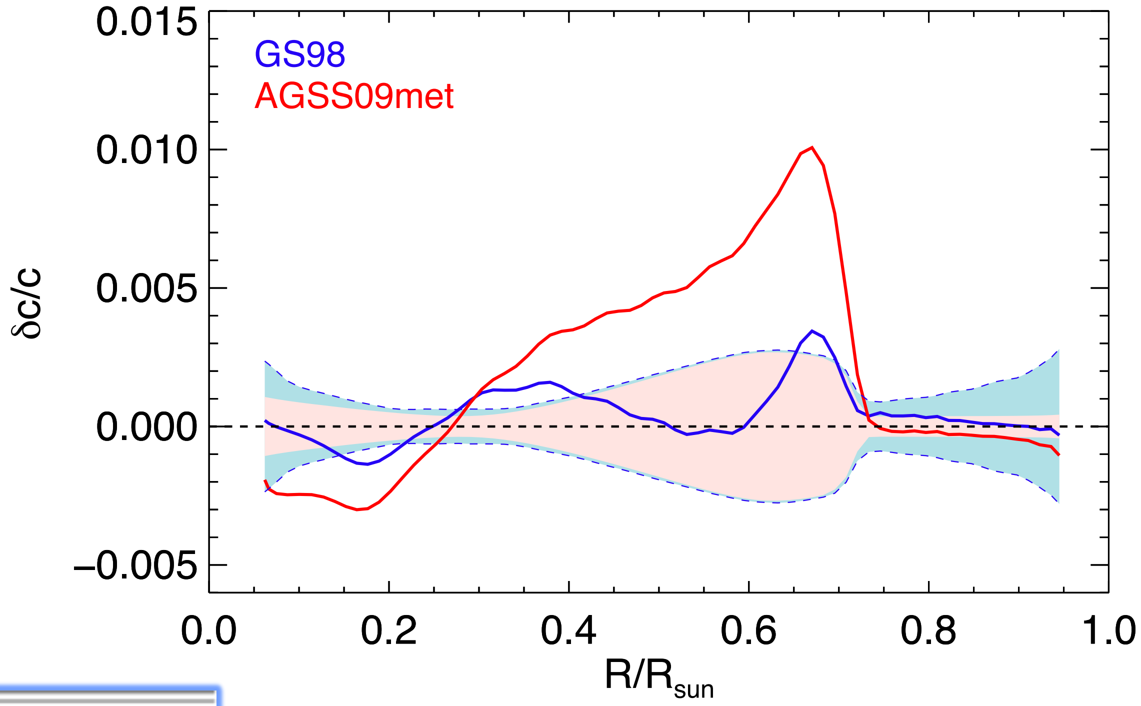
Discrepancies with low-Z solar composition show up in:

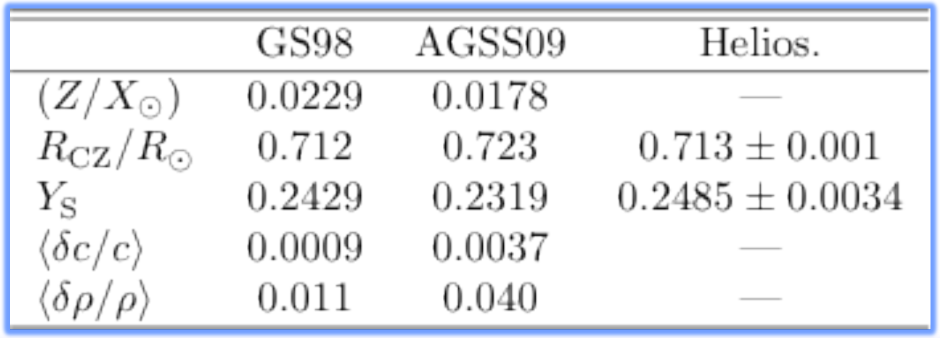
sound speed profile

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

Solar neutrinos

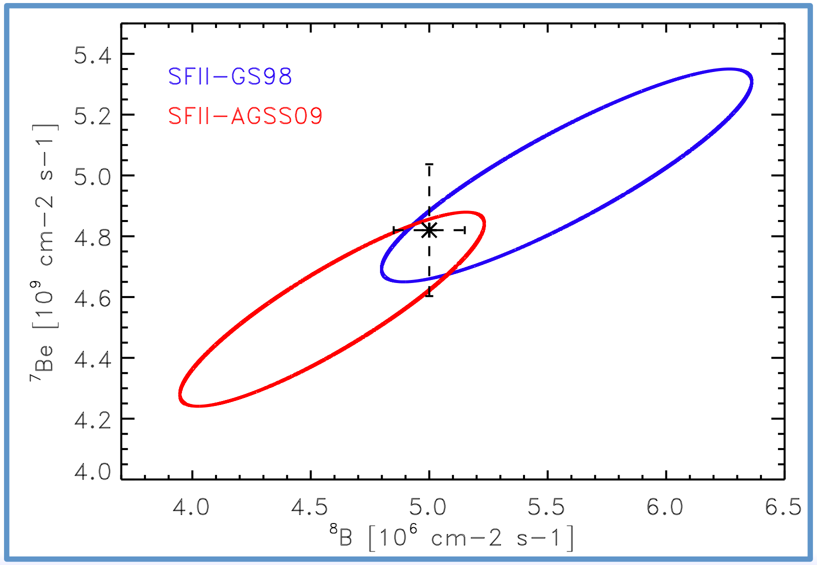
Model fluxes based on Solar Fusion II (Adelberger et al. 2011)

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
$\chi^2/P^{\rm agr}$	3.5 / 90%	3.4 / 90%	

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

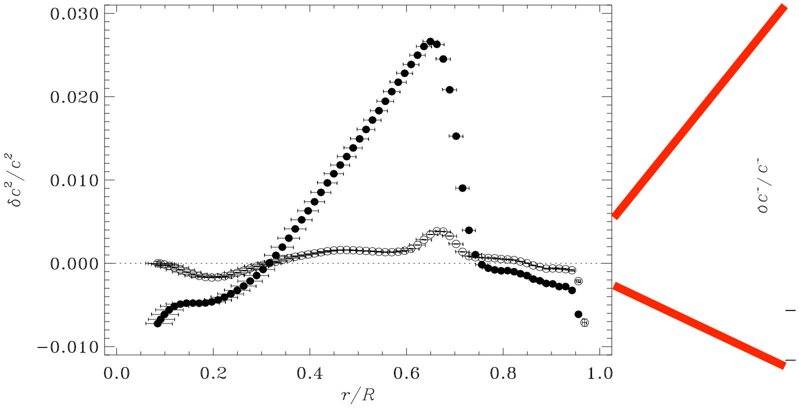
Experimental uncertainty

No discrimination between models

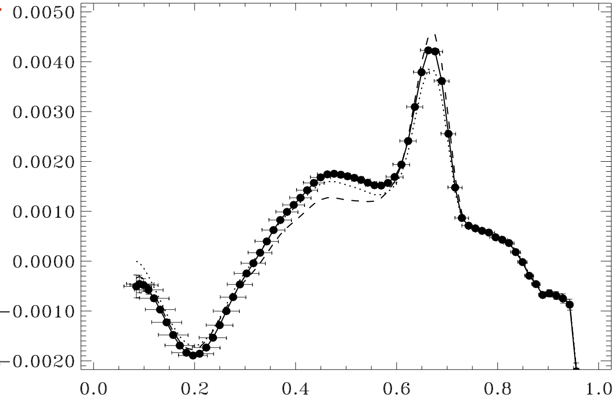


The role of radiative opacities

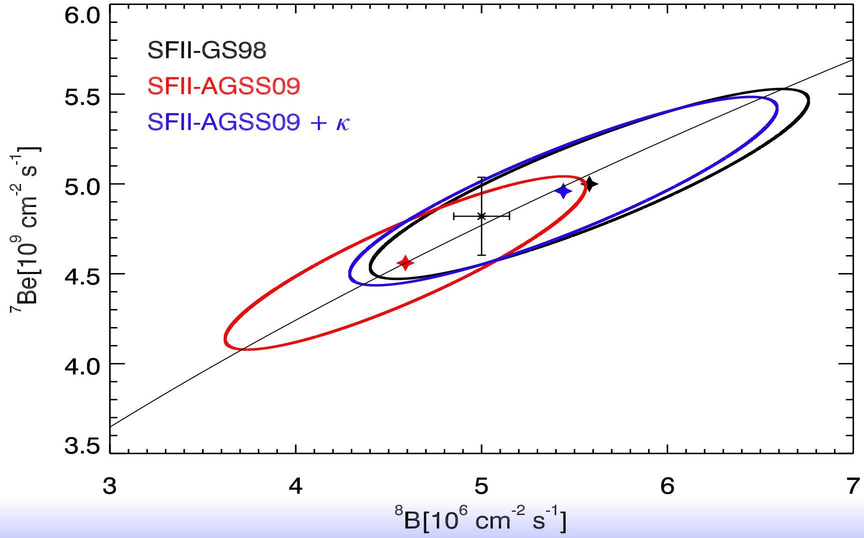
Helioseimic probes and νs from pp-chains not directly sensitive to Z, but to radiative opacity -- > degeneracy exists between composition and κ



Christensen Dalsgaard et al 2009



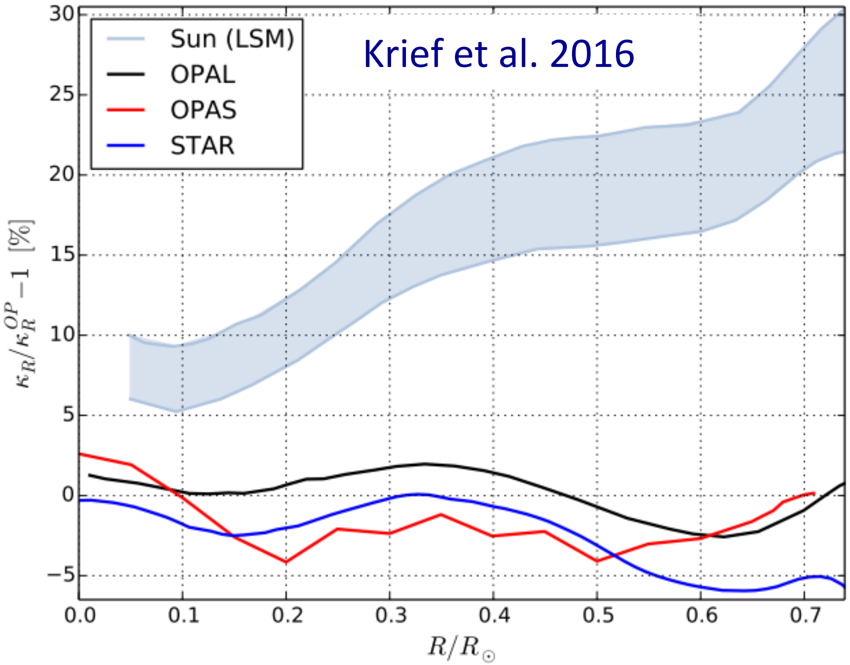
AGSS09 + opacity increase (15 to 20%)

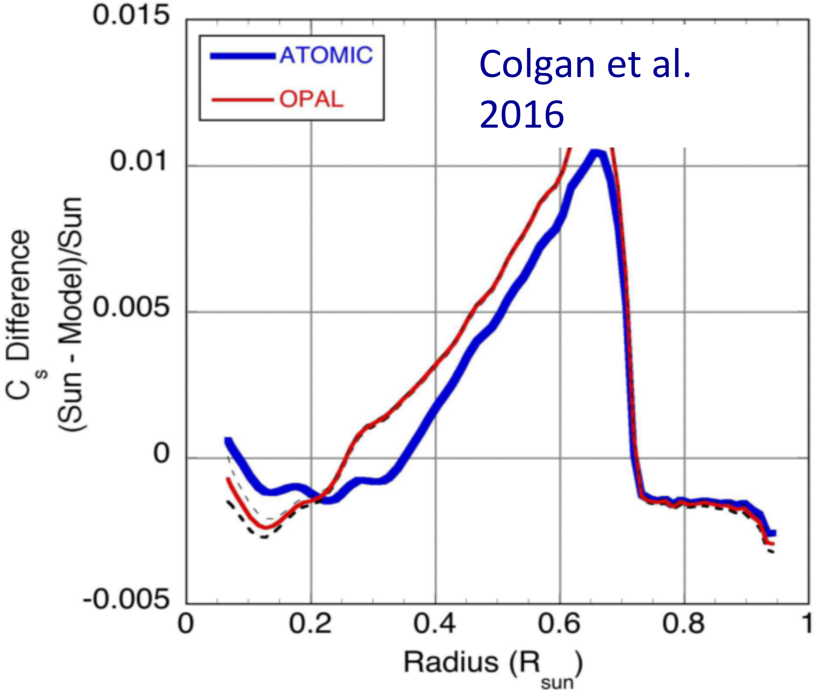


Sound speed and pp-chain neutrinos -- > recover GS98 “like” values

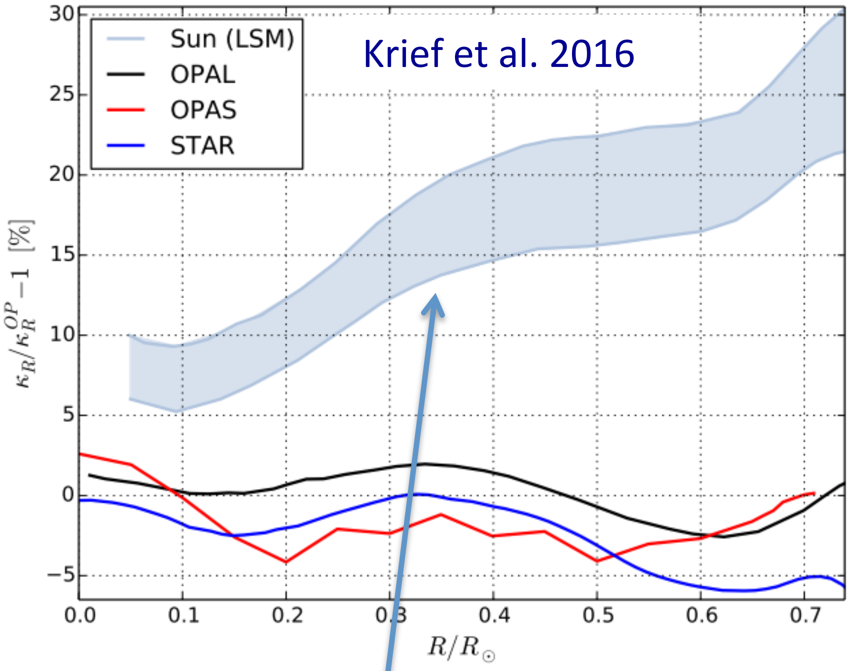
All probes sensitive to temperature profile not composition

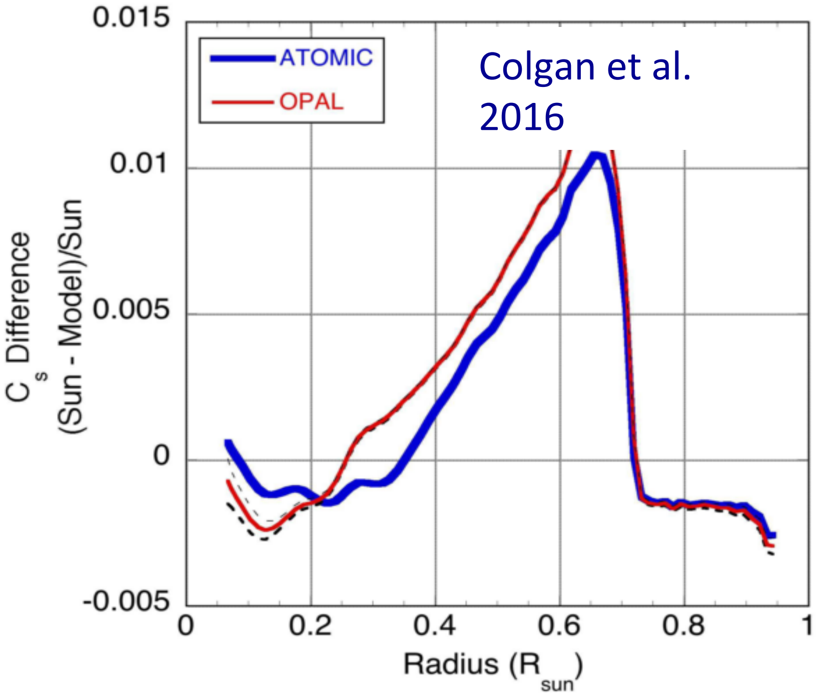
Opacities: theoretical calculations


Krief et al. 2016


Colgan et al. 2016

Opacities: theoretical calculations


Krief et al. 2016


Colgan et al. 2016

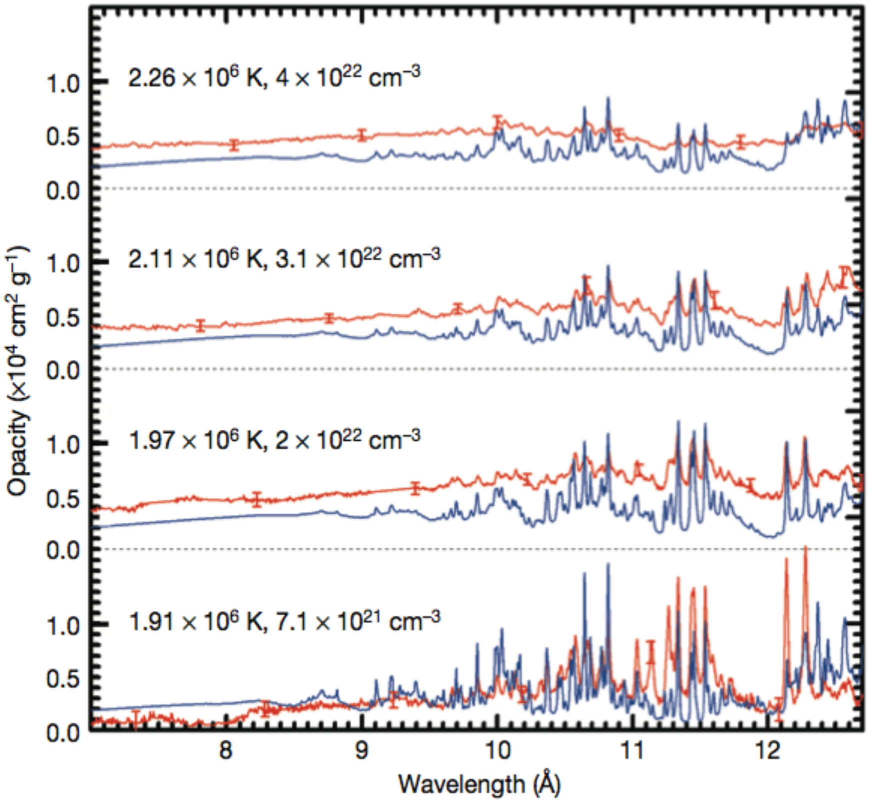
OP – OPAL – STAR – OPAS – Los Alamos (ATOMIC)

Typical differences in opacity calculations ~ few %

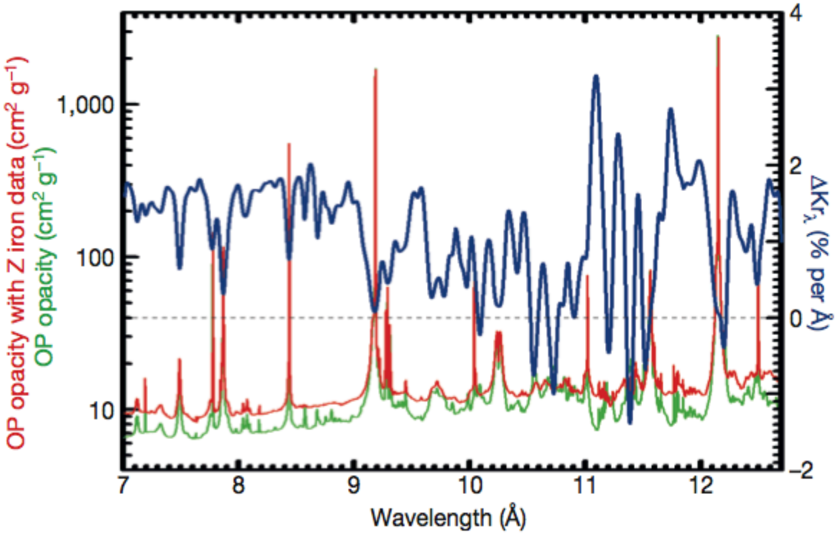
Required level of change much larger than seen in theoretical calculations

Opacities: experimental results

@Sandia lab – Z-facility – conditions close to solar (factor 4 too low in density)
Iron opacity measurements



Bailey et al. 2015



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

Are experimental results robust?

Recent developments in SSM inputs

Solar composition

Almost full revision of AGSS09 – Scott et al. 2015 A&A 573, 25&26

Photospheric abundance of refractories closer to meteoritic abundances

Meteoritic abundances (once again) robust -- > keep using them

CNO & Ne have not been revised (yet)

Equation of state

EoS always consistent with Z used in models but not with mixture

i.e. mixture always the same no matter if model had AGSS09 or GS98

Now EoS consistent – small, but measurable impact in some helioseismic qnts.

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%)

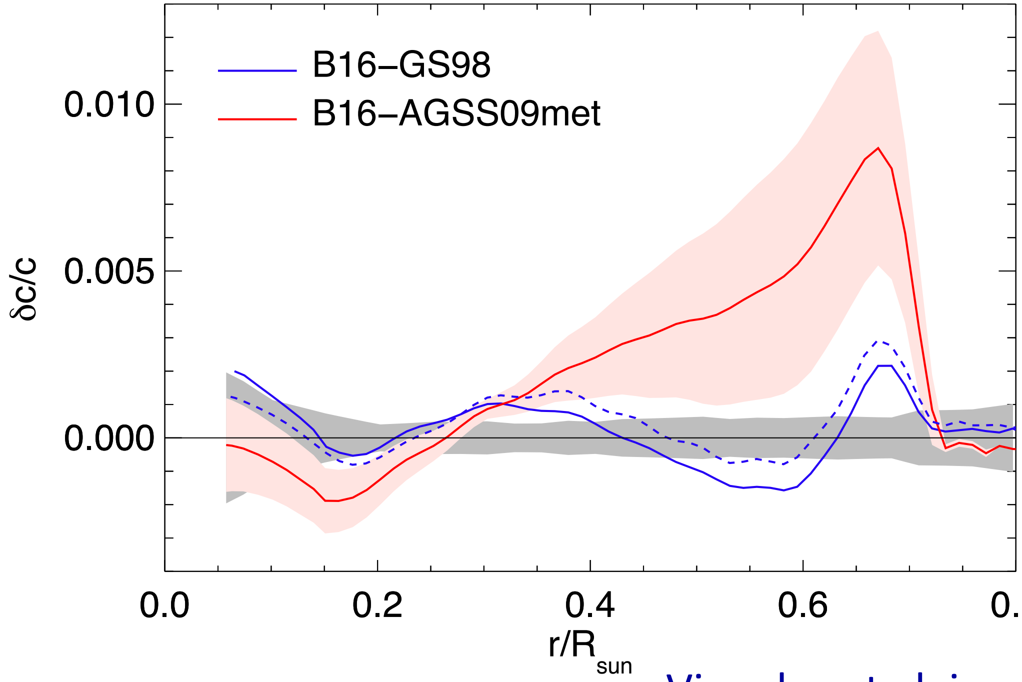
implementation of flexible scheme based on opacity kernels (Tripathy et al. 1998)

New SSMs – Barcelona 16 (B16)

Very modest changes in helioseismic quantities with more generous model uncertainties

Central values almost unaffected

Errors from new sets of Monte Carlo calculations of SSMs



Vinyoles et al. in prep.

Qnt.	B16-GS98	B16-AGSS09met	Obs.
Z_S	0.0170 ± 0.0012	0.0134 ± 0.0008	-
Y_S	0.2426 ± 0.0059	0.2317 ± 0.0059	0.2485 ± 0.0035
$R_{CZ}/R_\odot$	0.7116 ± 0.0048	0.7223 ± 0.0053	0.713 ± 0.001
$\langle \delta c/c \rangle$	$0.0005^{+0.0006}_{-0.0002}$	0.0021 ± 0.001	-

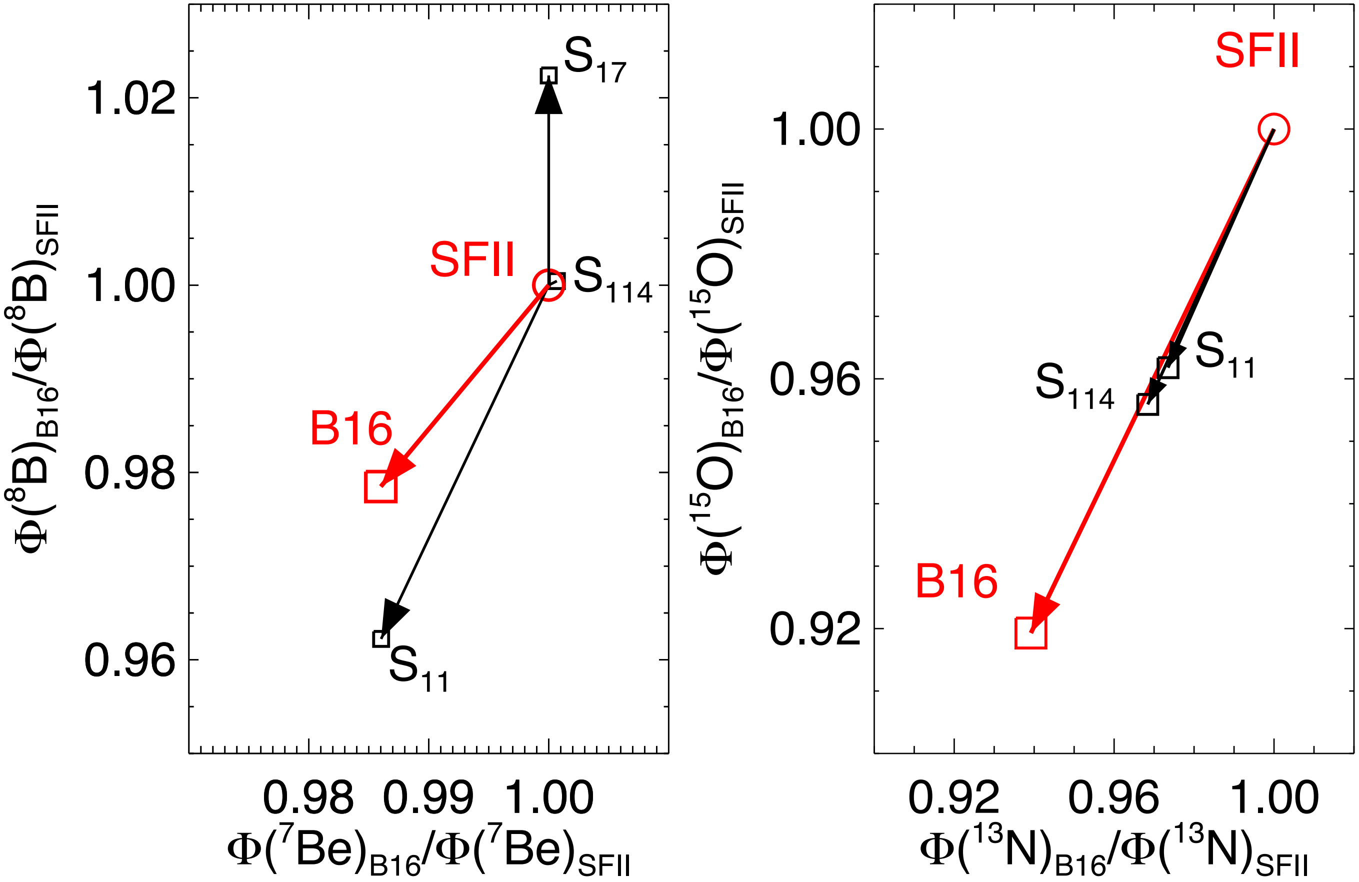
B16-AGSS09met : 2.5 σ for Y_S – 2 σ for R_{CZ} due to larger opacity errors (before 3.4 σ and 3 σ)

B16 SSMs – ν fluxes

Fractional variations –

few % for ^{8}B and ^{7}Be

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

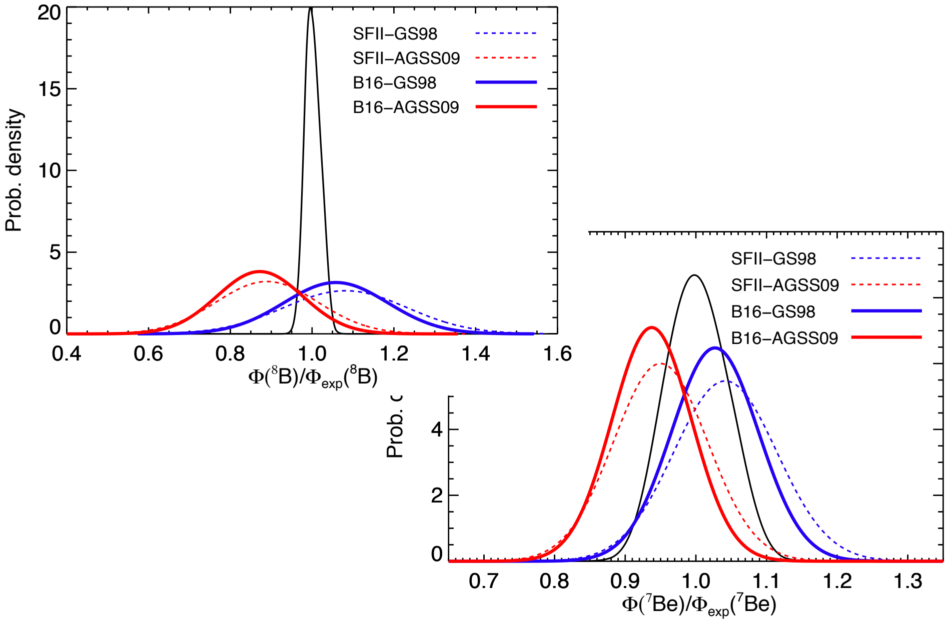


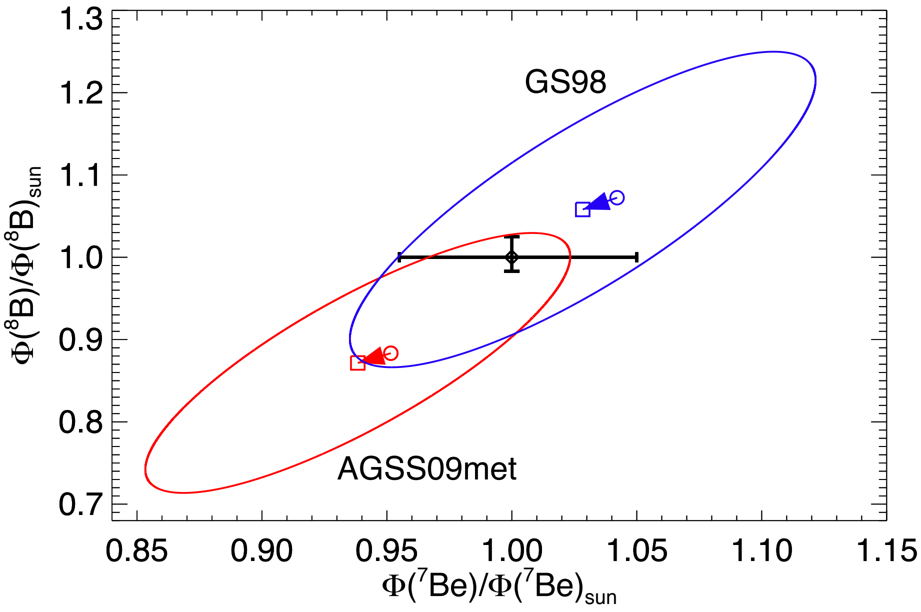
B16 SSMs – ν fluxes

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

Vinyoles et al. in prep.

Solar fluxes from
Bergstrom et al. 2016





B16 SSMs – ν fluxes

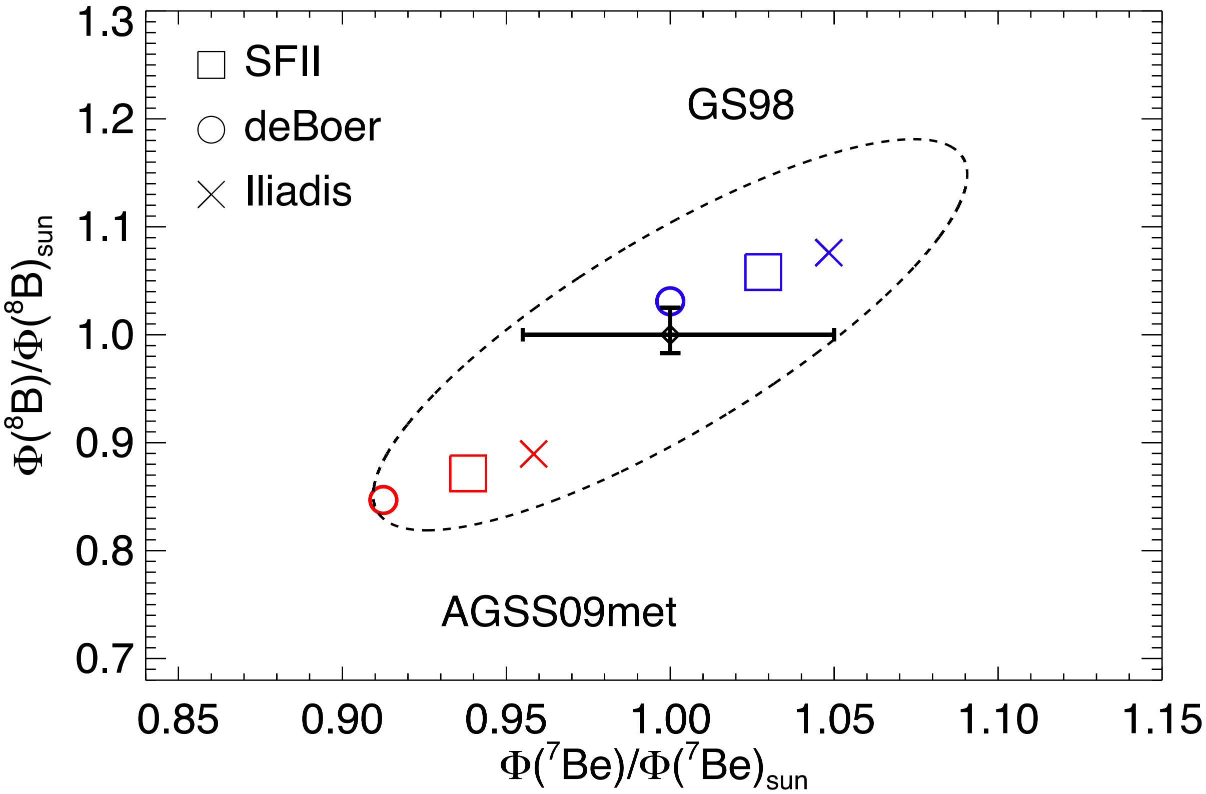
^{3}He + ^{4}He -- > ^{7}Be

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)= 5.6 x 10^{-5} (5%) MeVb

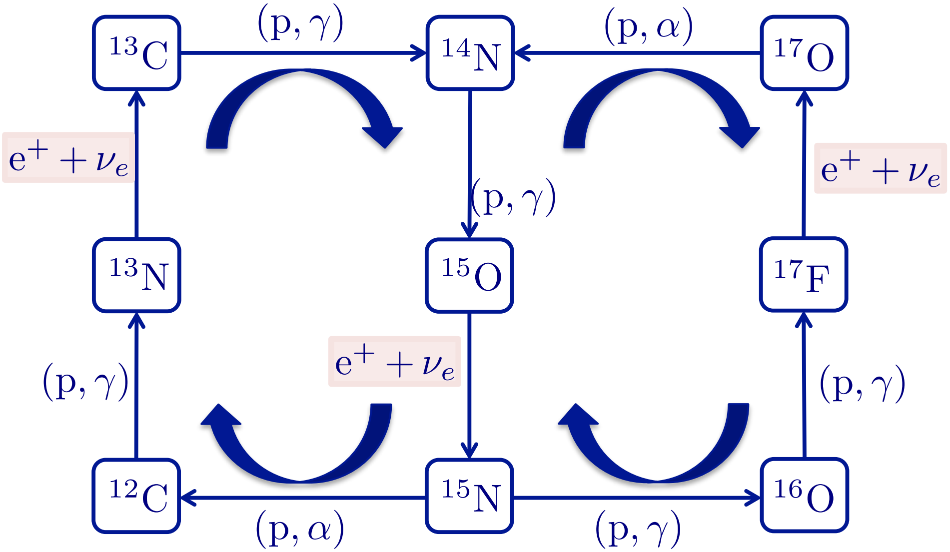
Iliadis et al. (2016)
S34(0)= 5.72 x 10^{-5} (3%) MeVb



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%)

CN ν fluxes



Very important because

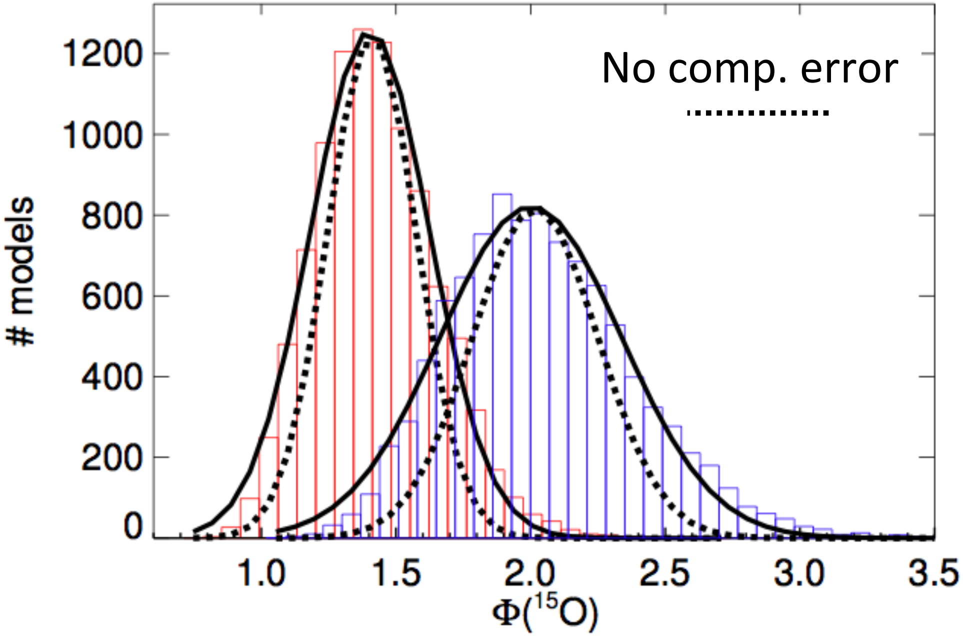
Extra linear dependence on C+N abundance due to their catalyzing role (not through opacity) and due to dominance of nuclear energy from pp-chains

Time evolution…

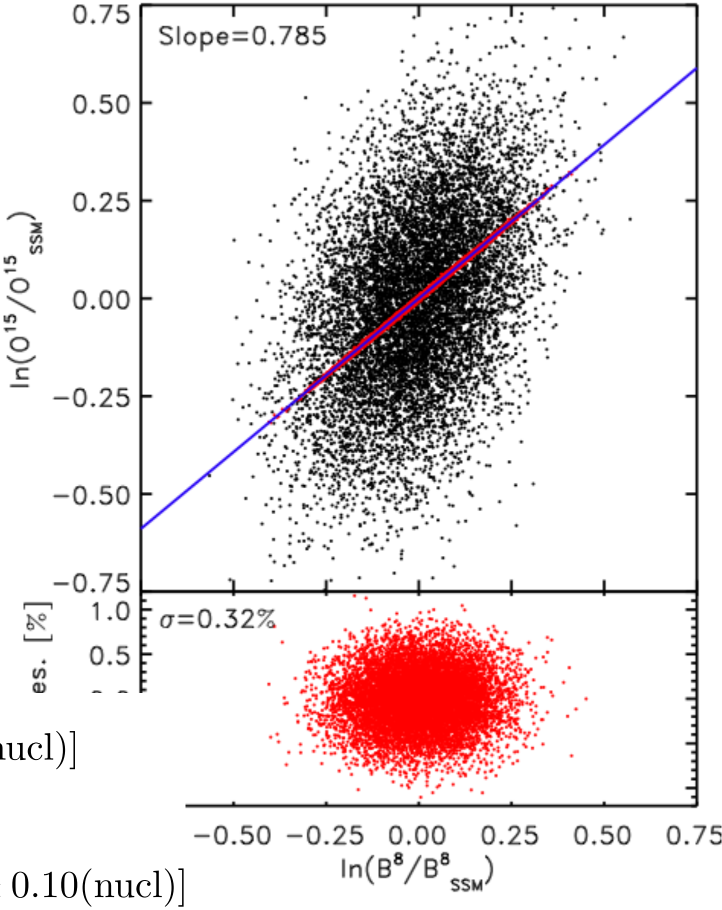
Model	^{13}N		^{15}O	
BP00	5.56		4.88	
BS05 (LUNA ^{14}N+p)	3.11		2.38	
	GS98	AGSS09	GS98	AGSS09
SFII	2.96	2.23	2.17	1.56
B16	2.78	2.05	2.05	1.44

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

CN ν fluxes



Temperature dependences can be cancelled out using ^{8}B



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

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

Discriminates compositions to ~ 3-σ before adding CN experimental error

Summary

Presentation of B16 SSMs
- Better treatment of EoS
- Updated nuclear reaction rates
- Modified treatment of opacity uncertainties

Small changes in helioseismic results

Small changes in νs from pp-chains – slightly better agreement for GS98 (high-Z) models

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
  - exp. results questioned by community

CN fluxes still very important – complemented with ^{8}B offer a unique probe of solar core composition