
SOLAR MODELS AND NEUTRINOS: LATEST DEVELOPMENTS

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NEUTRINOS: RECENT DEVELOPMENTS AND FUTURE CHALLENGES

NOVEMBER 3, 2014, SANTA BARBARA

OBSERVATIONAL CONSTRAINTS TO BUILD MODELS

At solar age (4.57Gyr)

SSM

Solar (photon) luminosity (initial helium)

Solar radius (convection parameter – mixing length)

Relative metal to hydrogen surface abundance (initial metal abundances)

non-SSM

surface rotation rate (initial angular momentum)

THEORY VS DATA

SSM

Depth of convective envelope

Sound speed & density profiles

Neutrino fluxes

Frequency ratios (information about solar core)

Surface helium abundance

Surface metal abundance(s)

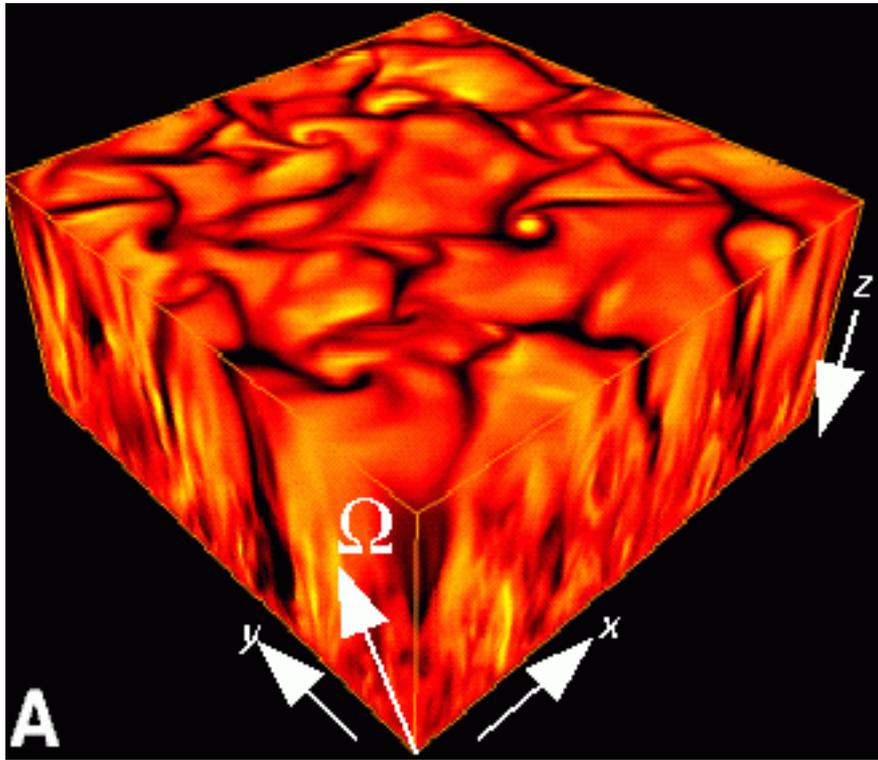
non-SSM

Surface lithium abundance

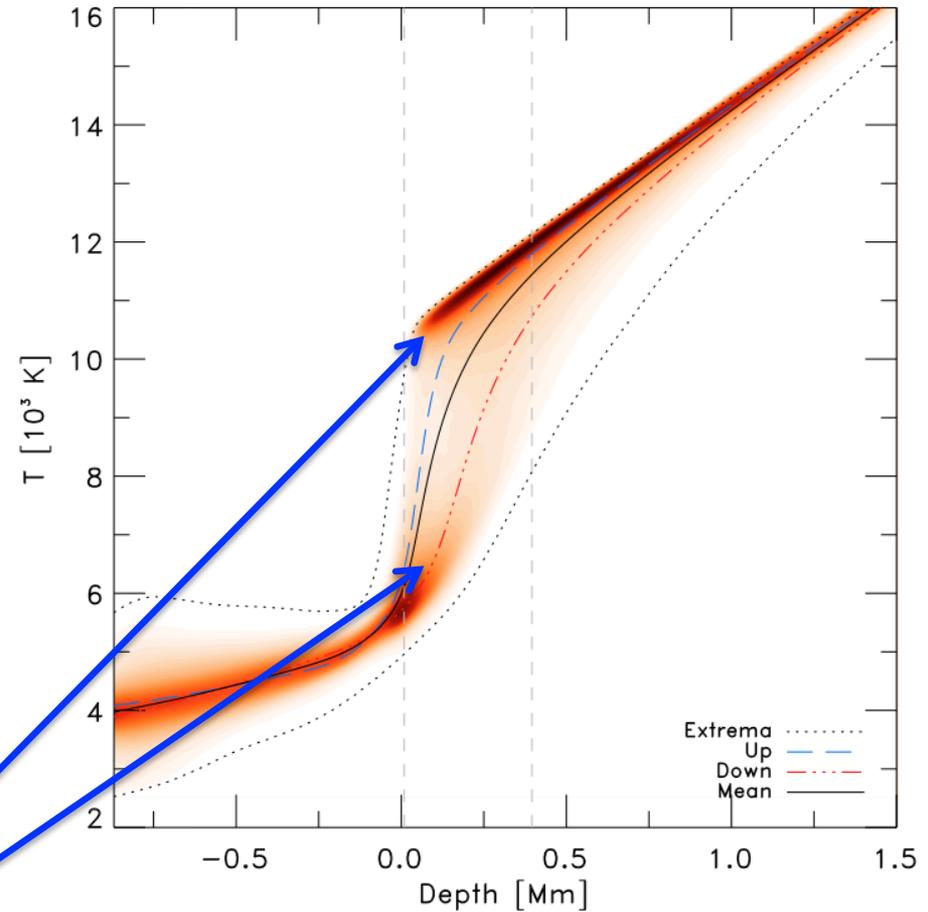
Internal rotation profile

SOLAR ABUNDANCES

Dealing with convection



Credit: N. Brummell



Hard to mimic with 1D
models

Magic et al. 2014

SOLAR ABUNDANCES

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

Differences of

CNO(Ne)~30-40%

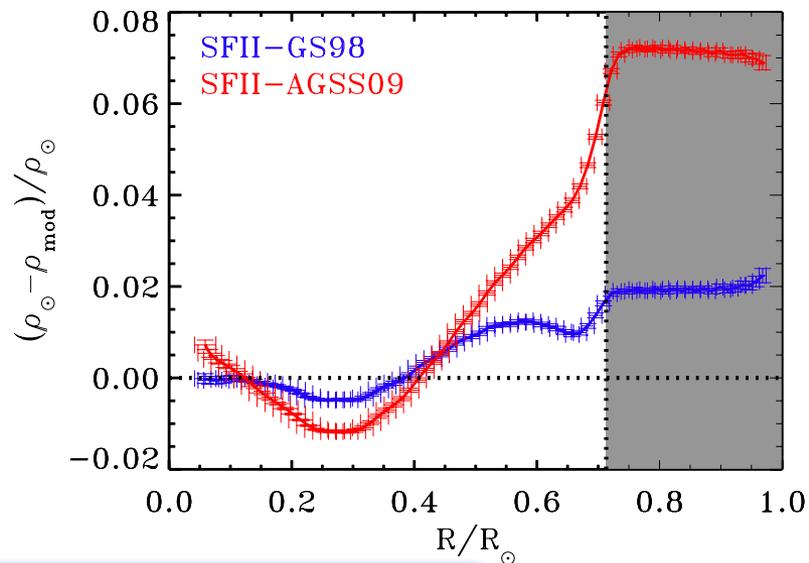
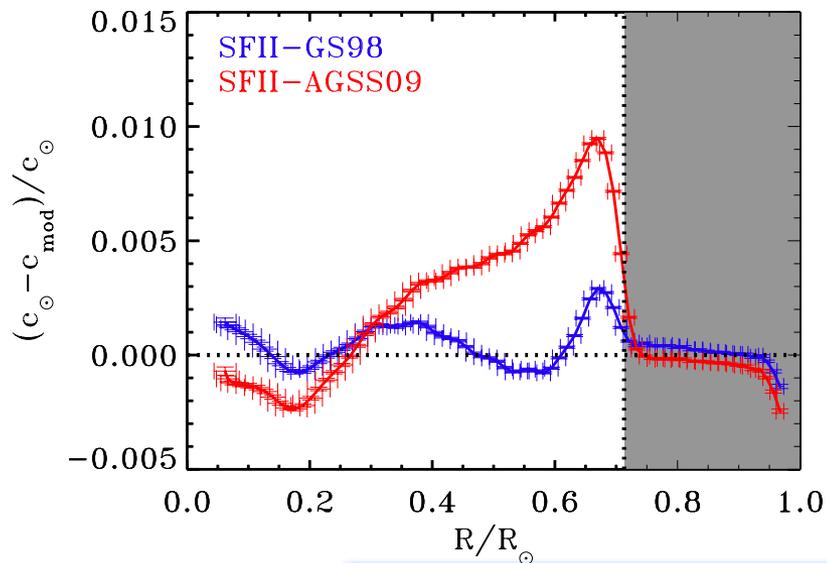
refractories~10%

Full revision underway: Scott et al. (2014), Grevesse et al. (2014)

Silicon same as before → refractories (meteoritic) not modified

CNO not yet available – but small changes expected

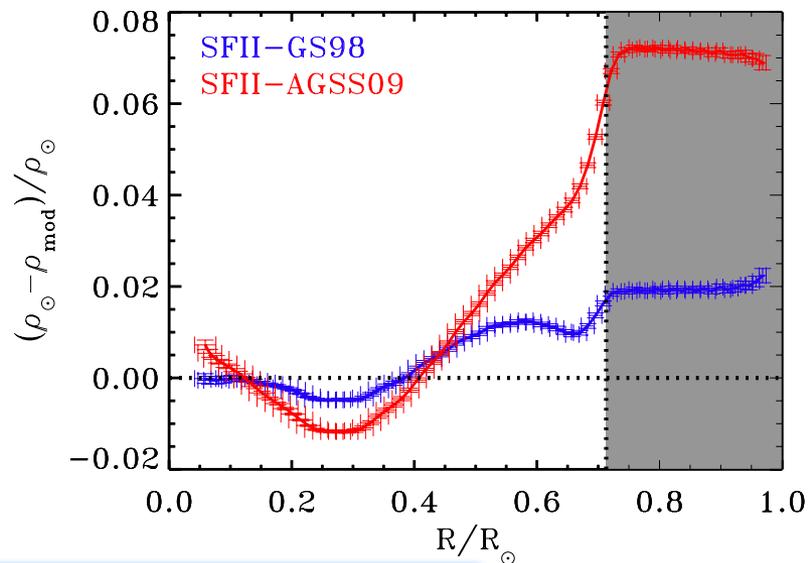
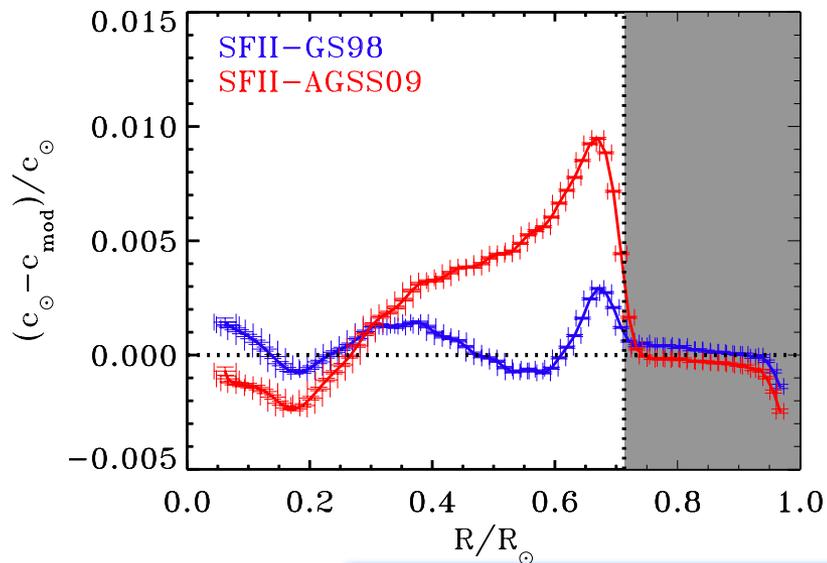
STANDARD SOLAR MODELS: HELIOSEISMOLOGY



	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	—

Helioseismology --> high-Z

STANDARD SOLAR MODELS: HELIOSEISMOLOGY



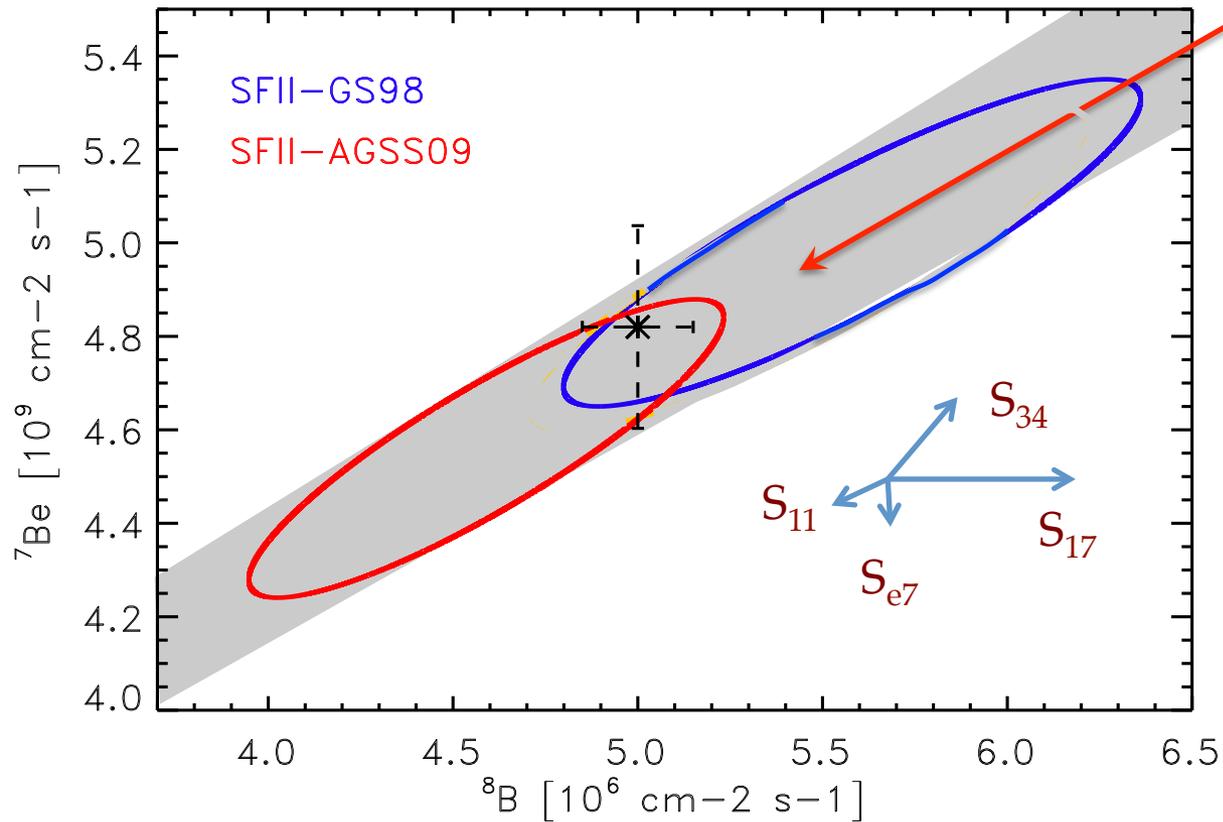
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STANDARD SOLAR MODELS: NEUTRINOS

Borexino (${}^7\text{Be}$) – SNO & SuperK (${}^8\text{B}$)

Core temperature dependence



STANDARD SOLAR MODELS: NEUTRINOS

Flux	SFII-GS98	SFII-AGSS09	Solar	
pp	5.98(1 ± 0.006)	6.03(1 ± 0.006)	6.05(1 ^{+0.003} _{-0.011})	
pep	1.44(1 ± 0.011)	1.47(1 ± 0.012)	1.46(1 ^{+0.010} _{-0.014})	
hep	8.04(1 ± 0.30)	8.31(1 ± 0.30)	18(1 ^{+0.4} _{-0.5})	
⁷ Be	5.00(1 ± 0.07)	4.56(1 ± 0.07)	4.82(1 ^{+0.05} _{-0.04})	~10%
⁸ B	5.58(1 ± 0.14)	4.59(1 ± 0.14)	5.00(1 ± 0.03)	~20%
¹³ N	2.96(1 ± 0.14)	2.17(1 ± 0.14)	≤ 6.7	~30%
¹⁵ O	2.23(1 ± 0.15)	1.56(1 ± 0.15)	≤ 3.2	~30%
¹⁷ F	5.52(1 ± 0.17)	3.40(1 ± 0.16)	≤ 59	
χ^2/P^{agr}	3.5 / 90%	3.4 / 90%	—	

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

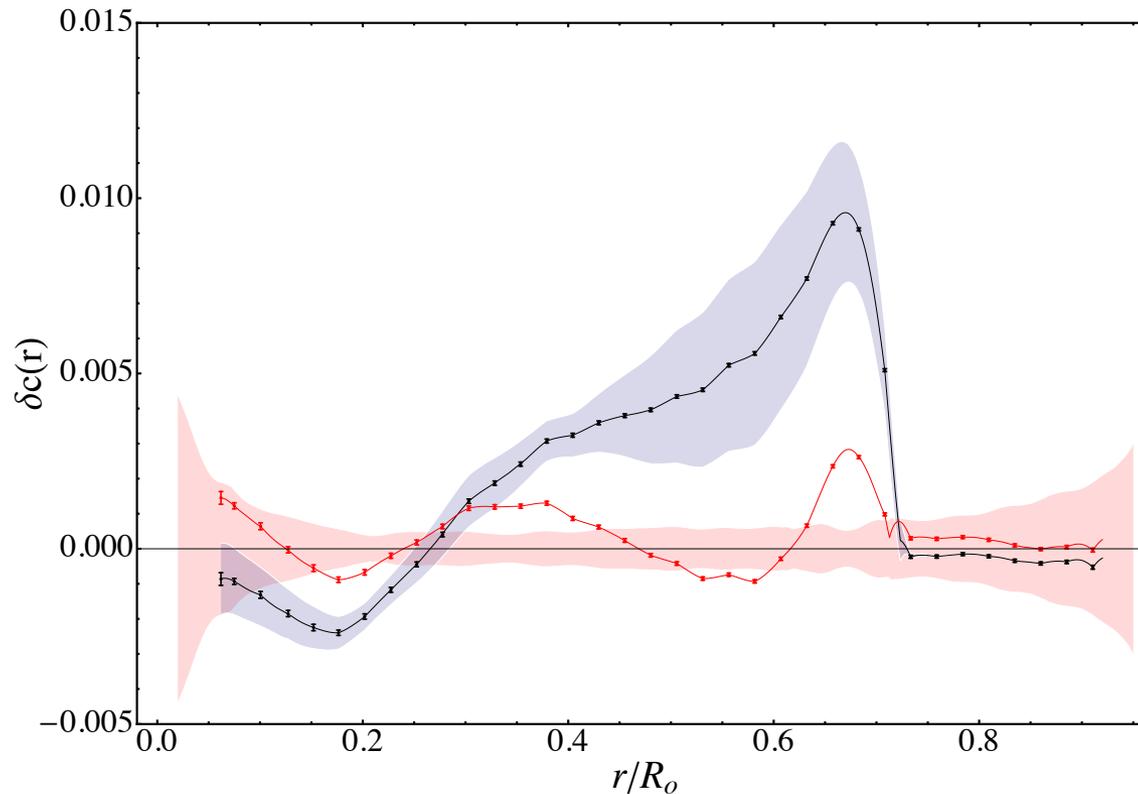
pp and pep are strongly bound by the “luminosity constraint”
otherwise solar luminosity matched @ 15% (Maltoni et al. 2010)

Direct measurement of pp now to 11% Borexino

SOLAR COMPOSITION: WHAT DATA REALLY TELL US

Use sound speed radial profile, not just rms

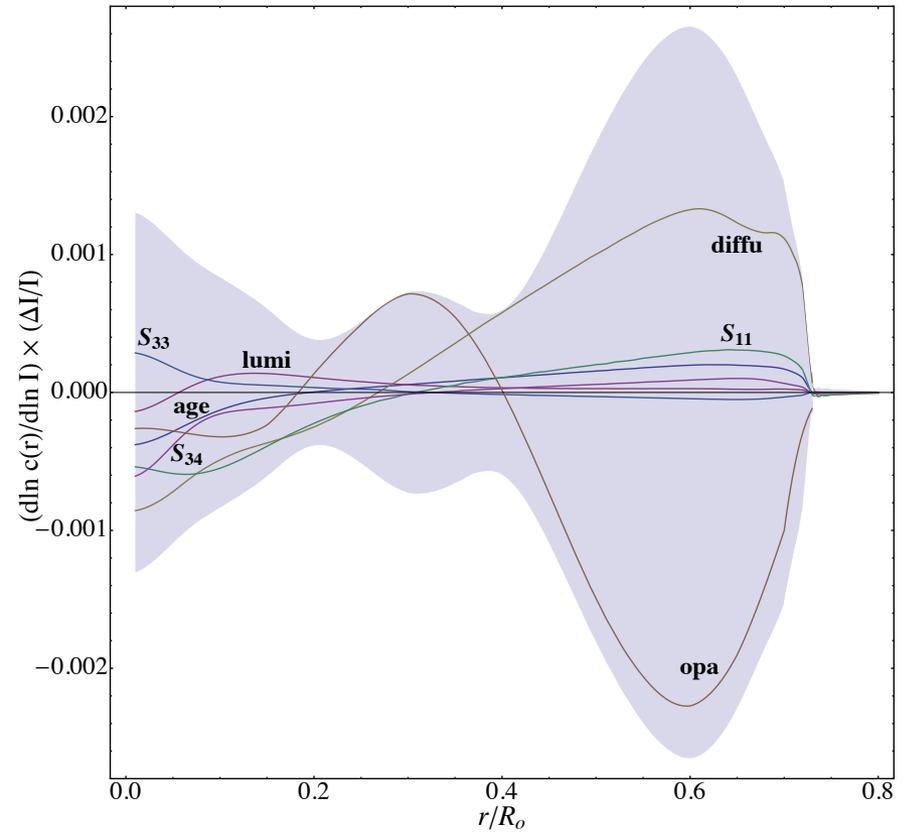
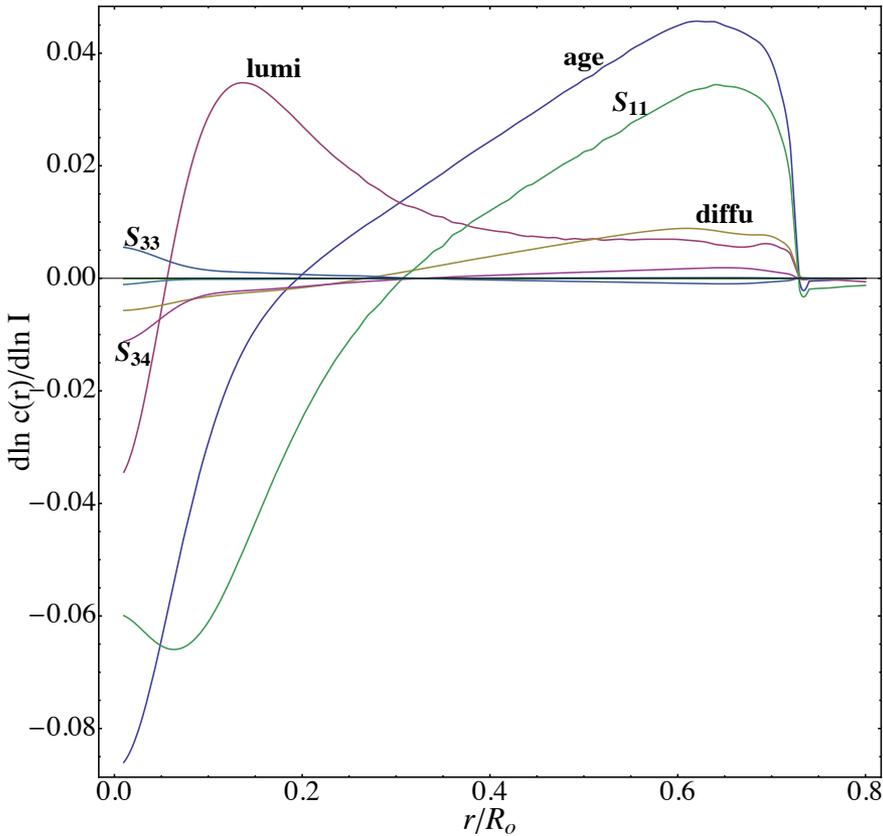
Include (as much as possible) systematic sources of errors
correlations in solar models



Villante et al. 2014

SOLAR COMPOSITION: WHAT DATA REALLY TELL US

Sound speed sensitivity and errors



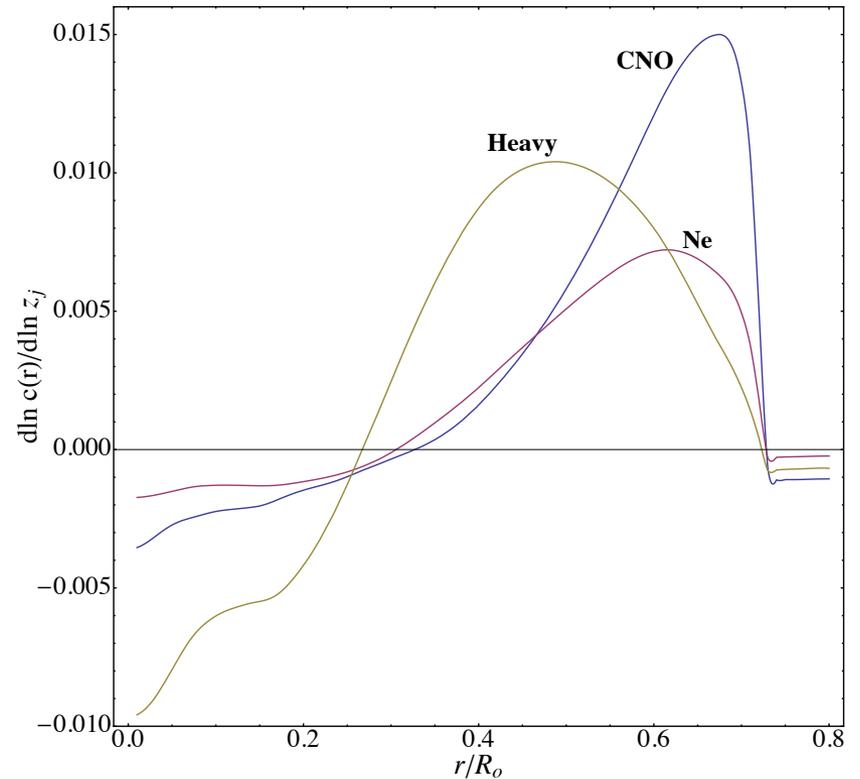
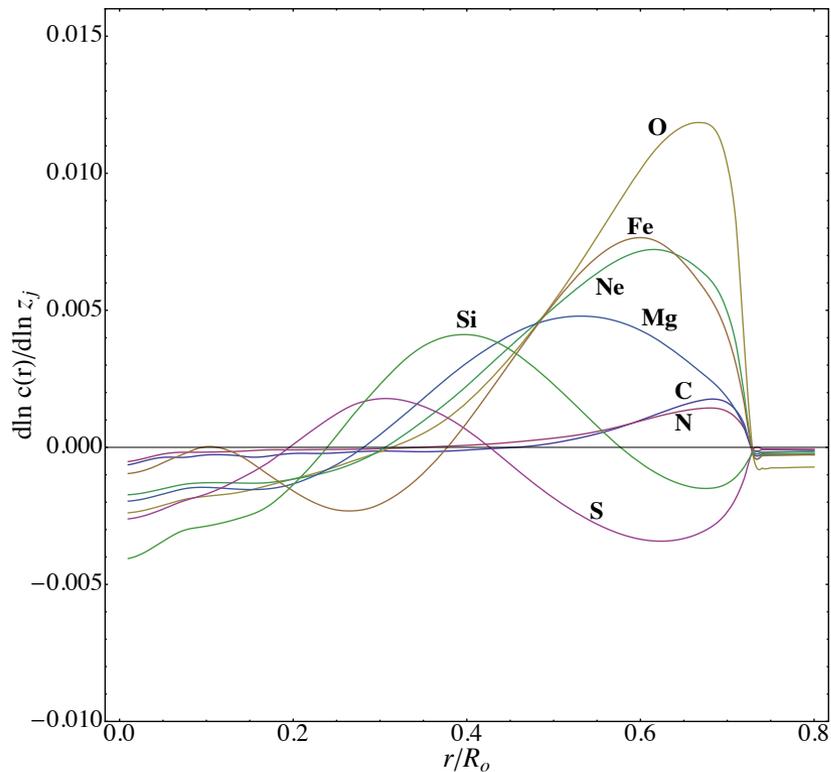
Villante et al. 2014

SOLAR COMPOSITION: WHAT DATA REALLY TELL US

Sound speed sensitivity to composition

Lowering expectations: 2 parameters (volatile – refractories)

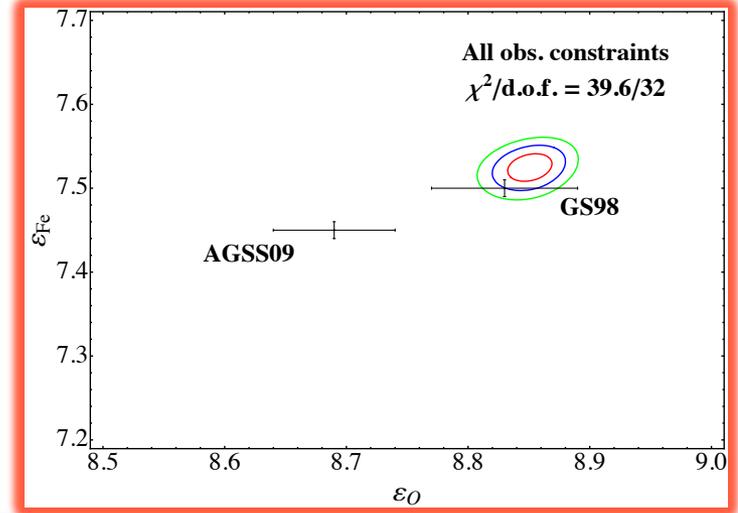
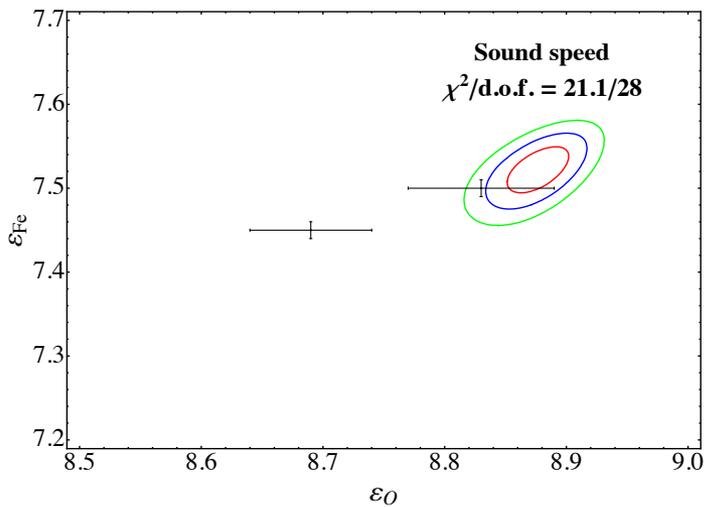
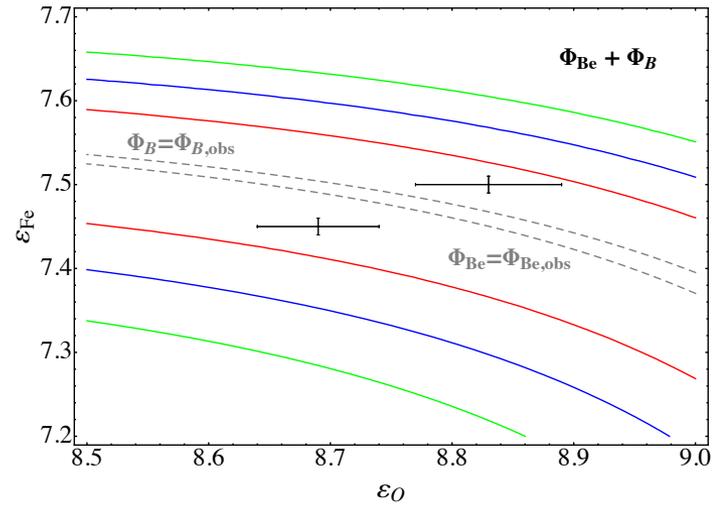
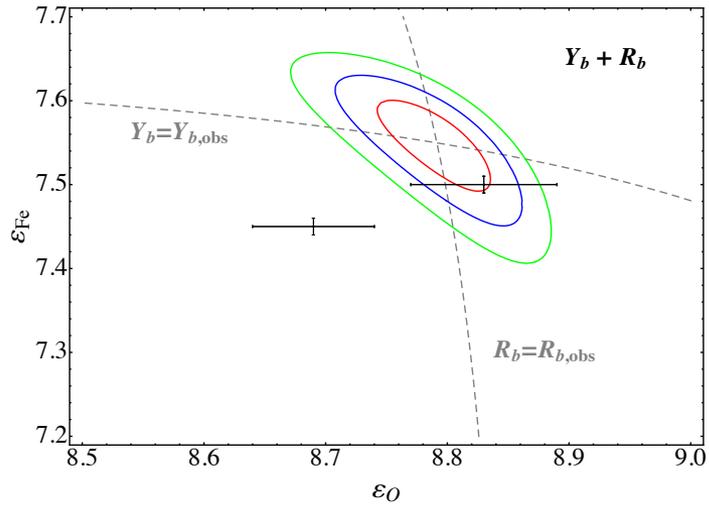
3 parameters (CNO – Ne – refractories)



Villante et al. 2014

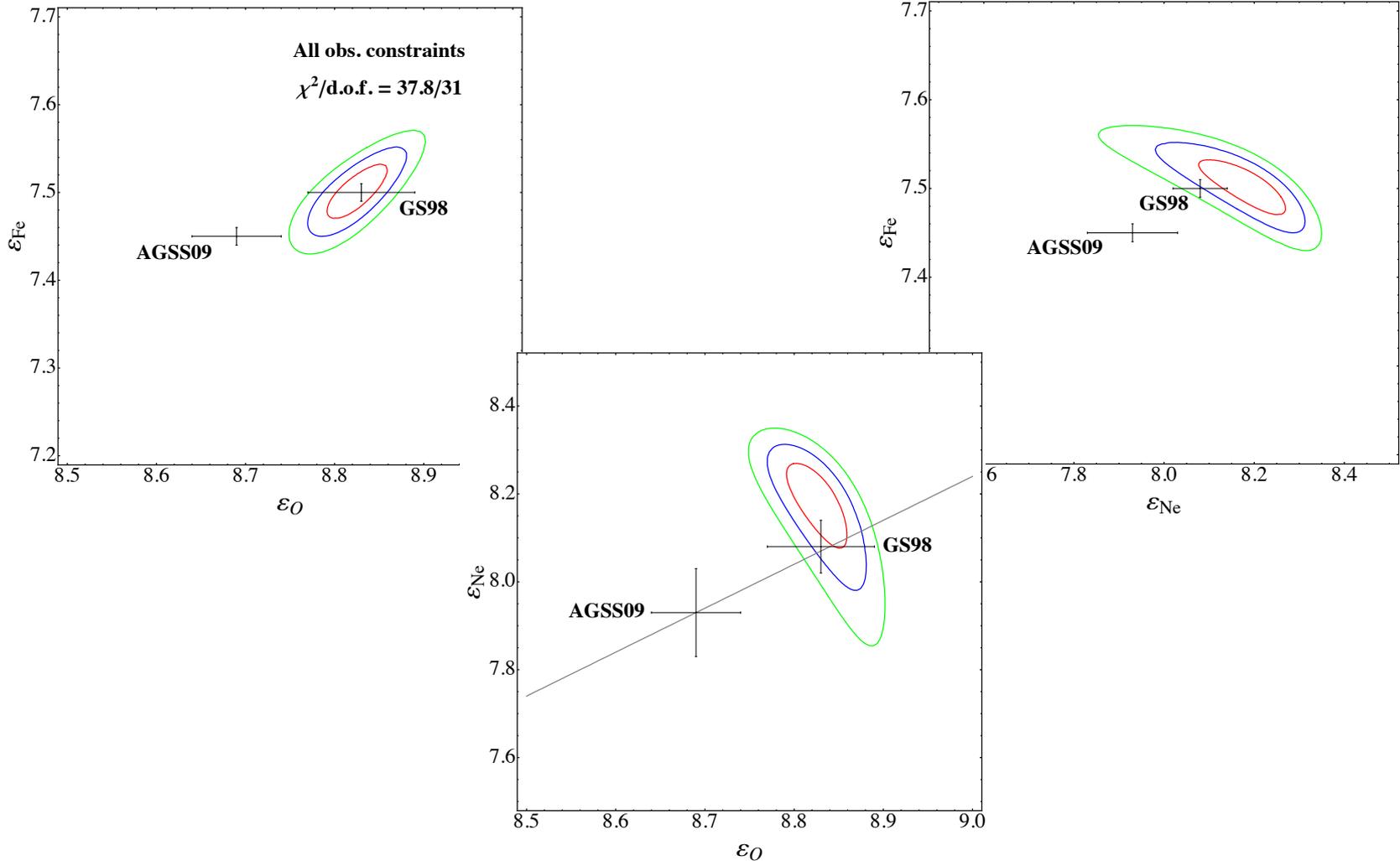
SOLAR COMPOSITION: 2-PARAMETER ANALYSIS

Volatiles (CNO) & Refractories



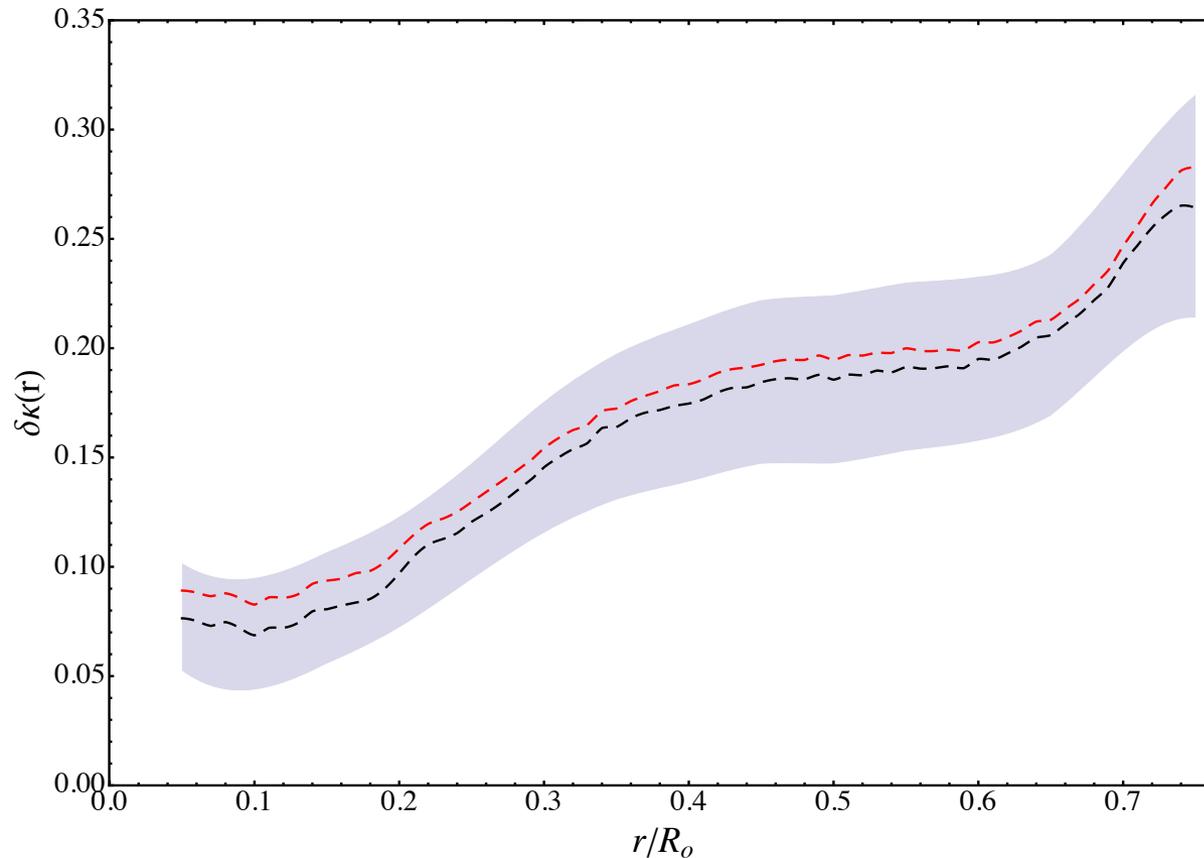
SOLAR COMPOSITION: 3-PARAMETER ANALYSIS

Volatiles (CNO), Ne & Refractories



LEARNING ON SOLAR OPACITY – NOT COMPOSITION

Current data, seismology + pp-chain fluxes, constrain radiative opacity profile – not composition!!

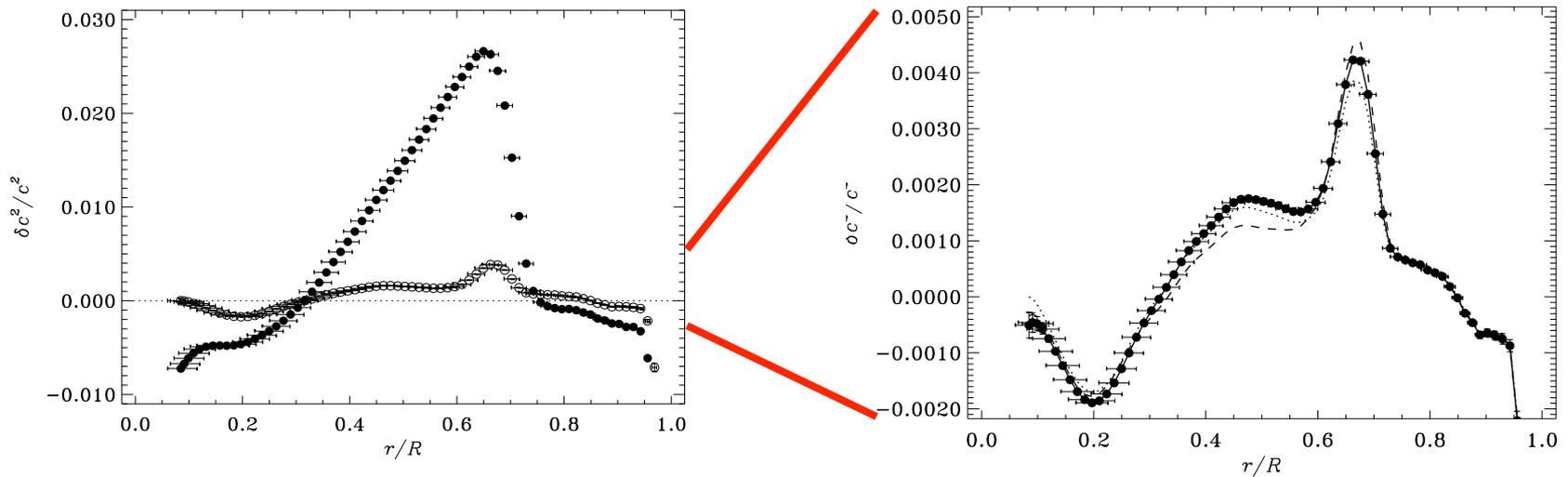


Fractional opacity difference wrt AGSS09 solar model

few % center to 20% at convective boundary

LEARNING ON SOLAR OPACITY – NOT COMPOSITION

AGSS09 model + increased κ



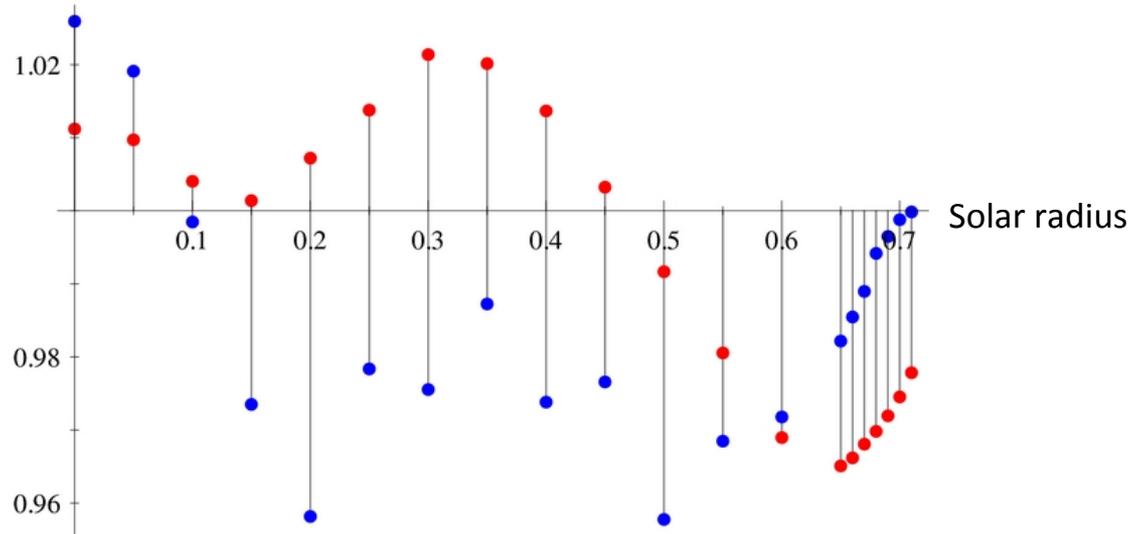
Christensen Dalsgaard et al 2009

Degeneracy between metals & opacity for helioseismic probes

UPDATE ON MICROPHYSICS: OPACITY

OPAS vs OPAL (red)

OPAS vs OP (blue)



Blancard et al. 2012

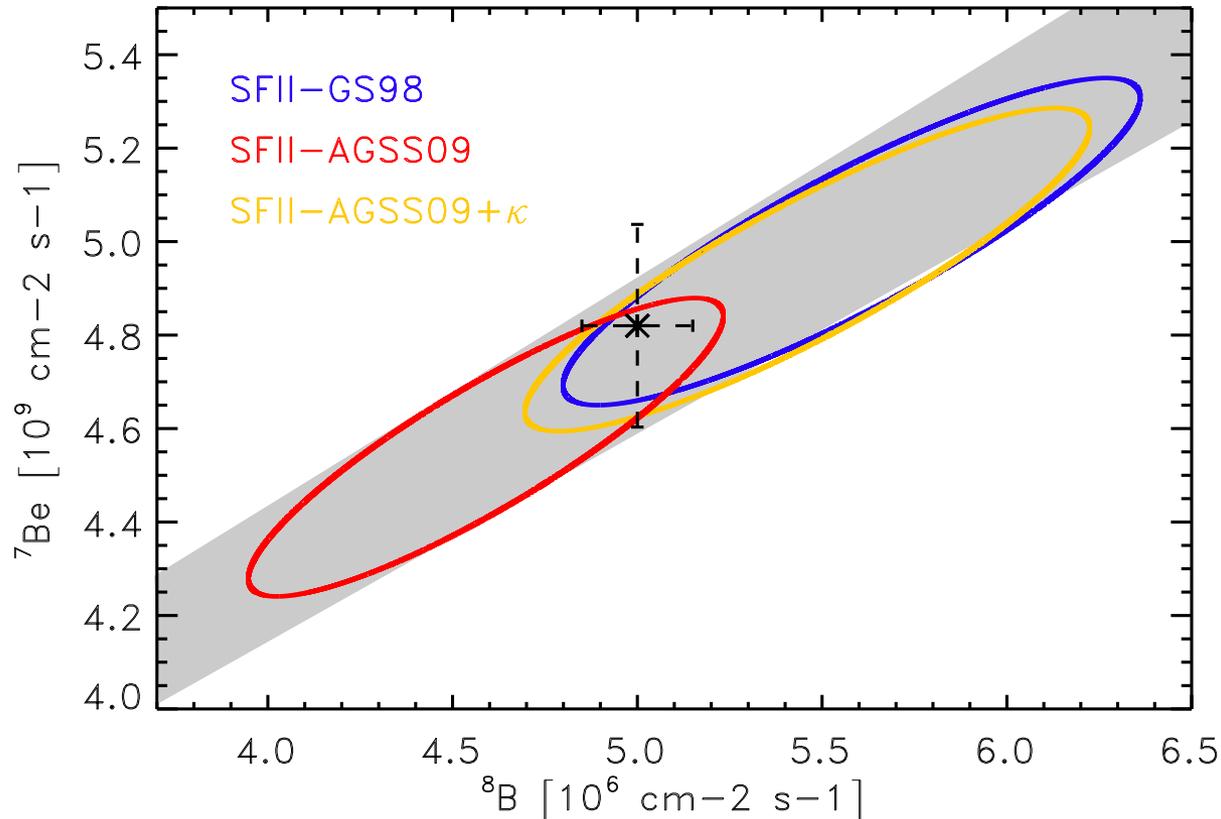
Just few percent in solar interiors but +20% needed

Multielectronic resonant recombination quite important (Beilmann et al. 2013) - effect not yet quantified for Rosseland mean

Rare elements contribution to opacity neglected (e.g. Ba – Pinsonneault priv.comm.)

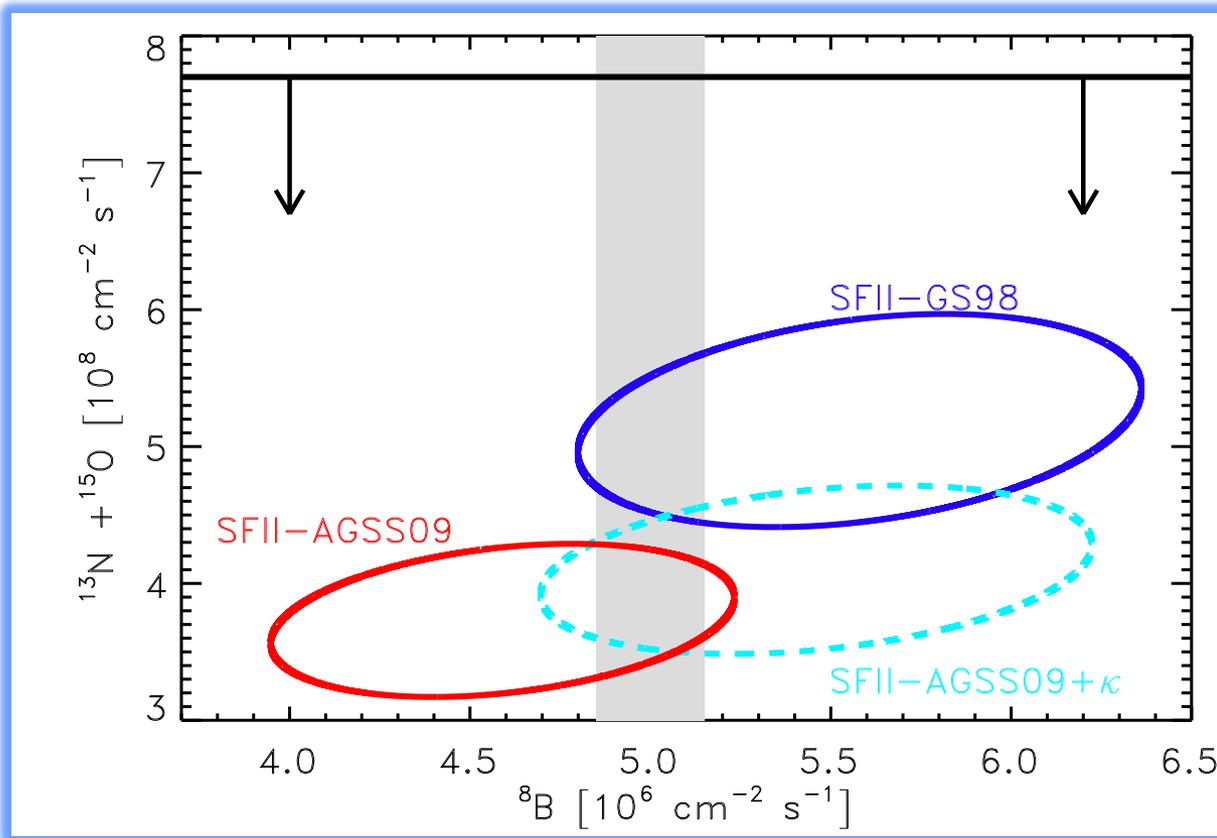
PP-CHAIN NEUTRINOS SENSITIVE TO OPACITY

Fluxes linked to pp-chains actually not sensitive to composition – indirect dependence through opacity



BREAKING THE DEGENERACY

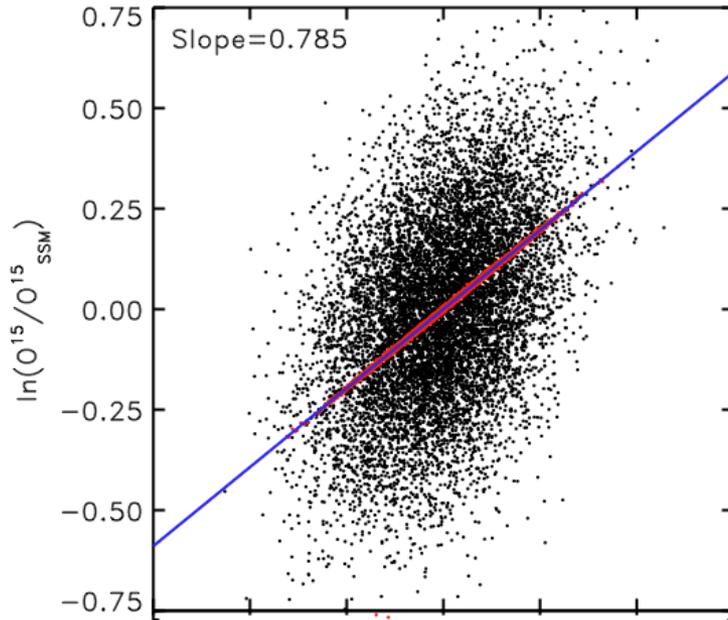
CN fluxes carry extra linear dependence on C+N abundance not associated with temperature



Upper limit by
Borexino

STANDARD SOLAR MODELS: NEUTRINOS

Relate CN and ^8B fluxes – similar temperature dependence



$$\frac{\phi(^{15}\text{O})}{\phi(^{15}\text{O})_{\text{SSM}}} / \left[\frac{\phi(^8\text{B})}{\phi_{\text{SSM}}(^8\text{B})} \right]^{0.785} = x_C^{0.794} x_N^{0.212} D^{0.172}$$

$$\times [L_{\odot}^{0.515} O^{-0.016} A^{0.308}]$$

$$\times [S_{11}^{-0.831} S_{33}^{0.342} S_{34}^{-0.685} S_{17}^{-0.785} S_{e7}^{0.785} S_{114}^{0.995}]$$

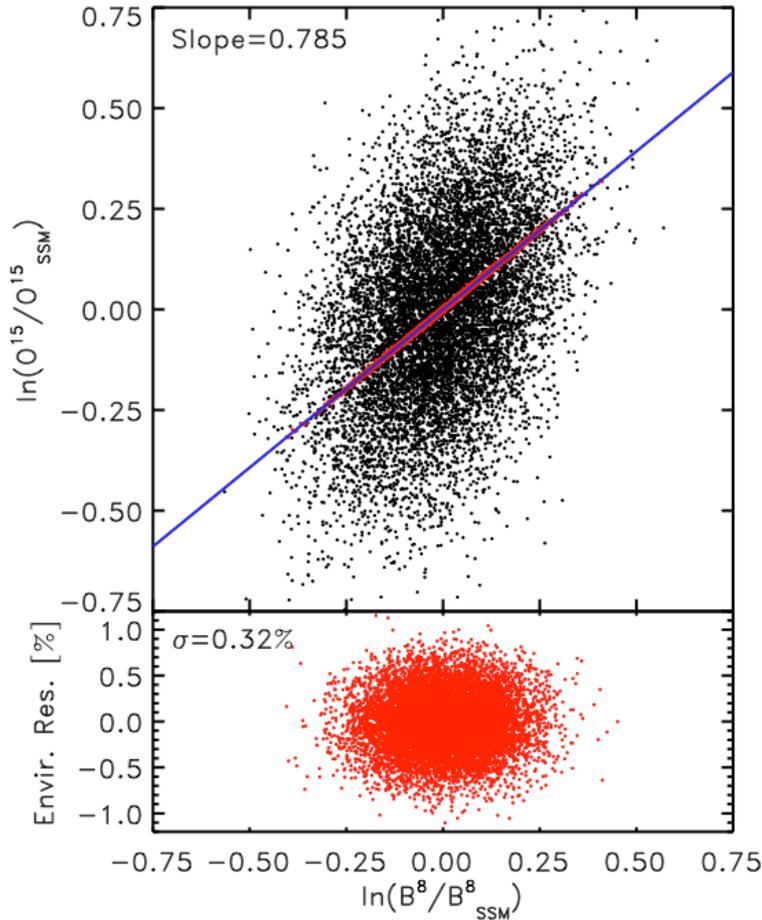
$$\times [x_O^{0.003} x_{\text{Ne}}^{-0.005} x_{\text{Mg}}^{-0.003} x_{\text{Si}}^{-0.001} x_{\text{S}}^{-0.001} x_{\text{Ar}}^{0.001} x_{\text{Fe}}^{0.003}]$$

→ Temp. dep.

→ Nuclear rates

→ Temp. dep.

STANDARD SOLAR MODELS: NEUTRINOS



$$\frac{\Phi(^{15}O)}{\Phi^{SSM}(^{15}O)} / \left[\frac{\Phi(^8B)}{\Phi^{SSM}(^8B)} \right]^{0.785} = \left[\frac{C + N}{C^{SSM} + N^{SSM}} \right]$$

$$[1 \pm 0.3\%(\text{env}) \pm 2.6\%(D) \pm 10\%(\text{nucl})]$$

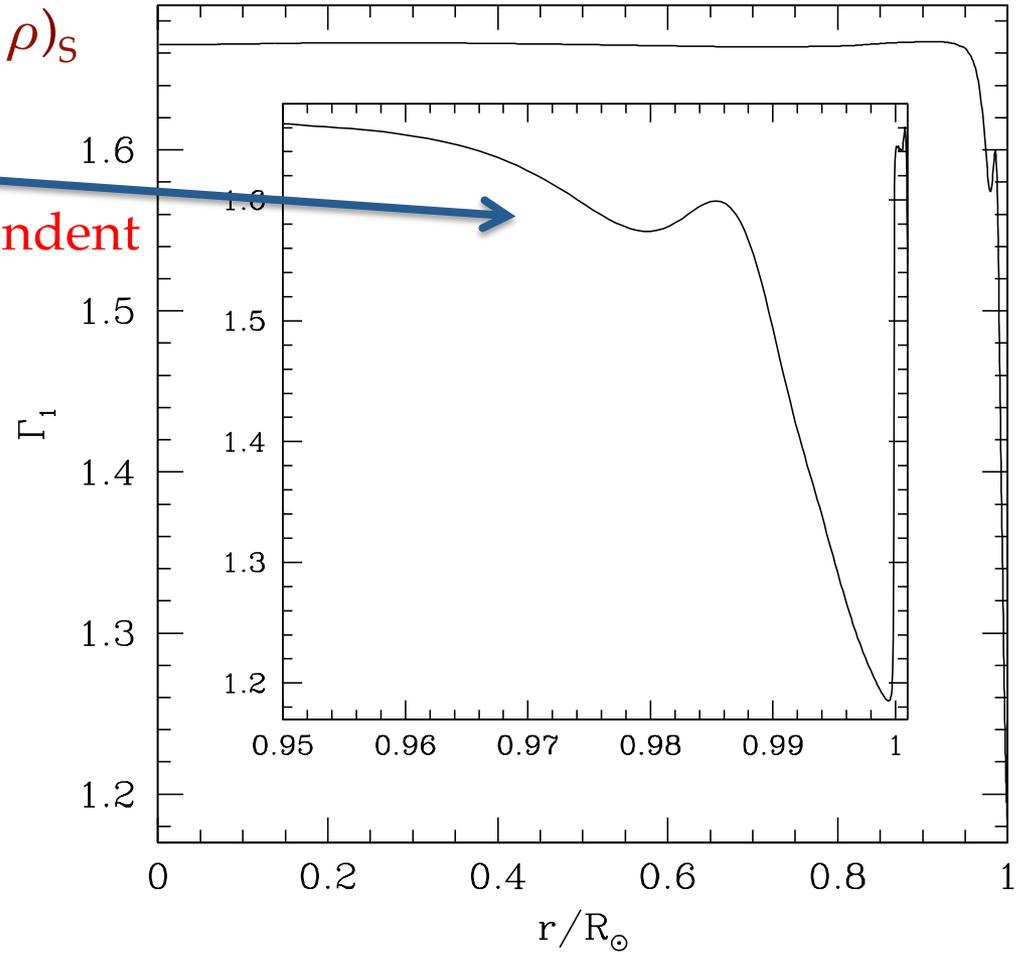
**“Direct” measurement of core CN
10% + exp. uncertainty**

Nuclear uncertainty: $S_{1,14}$ & S_{17} (~7% each)

UPDATE ON MICROPHYSICS: EOS

Partial ionization zones
leave imprints on $\Gamma_1 = (\text{dln } P / \text{dln } \rho)_S$

HeII dip used to determine
surface Υ (modulo EOS – independent
of opacities)



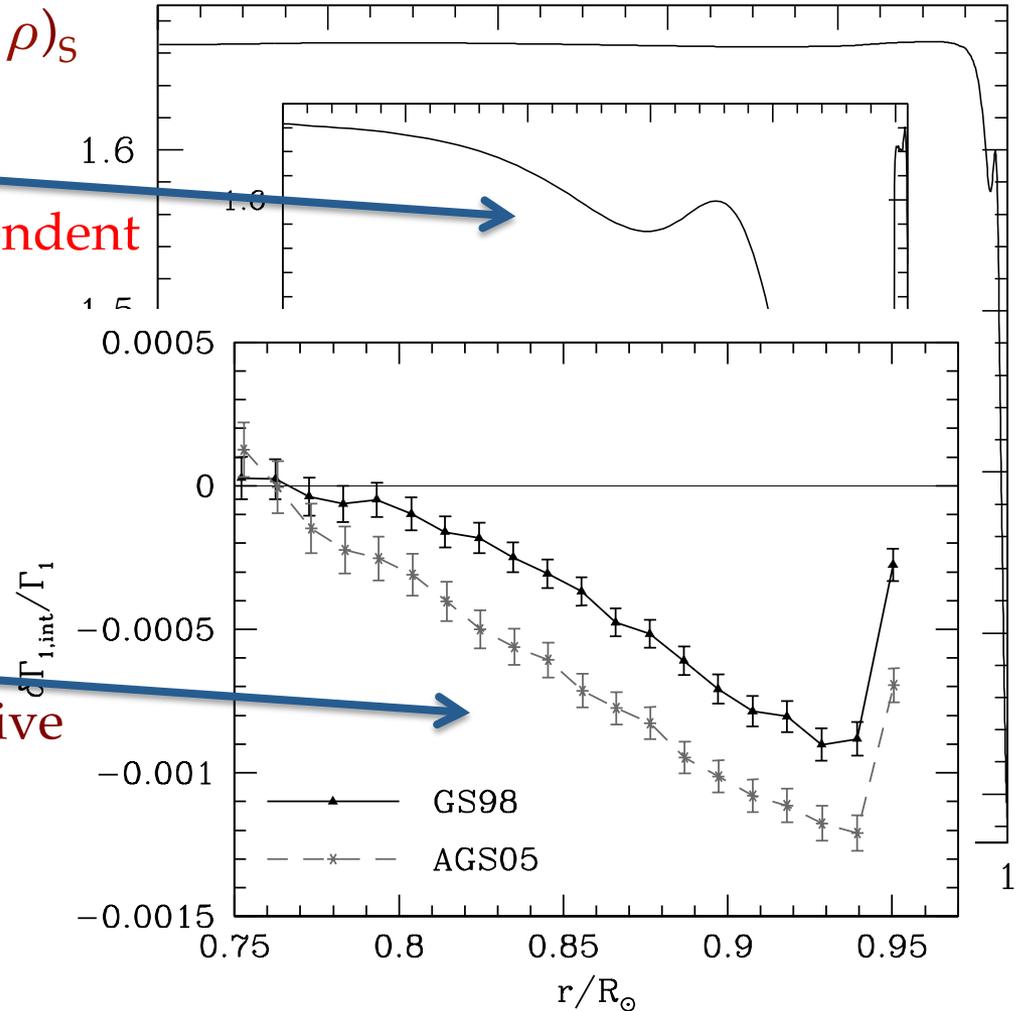
UPDATE ON MICROPHYSICS: EOS

Partial ionization zones
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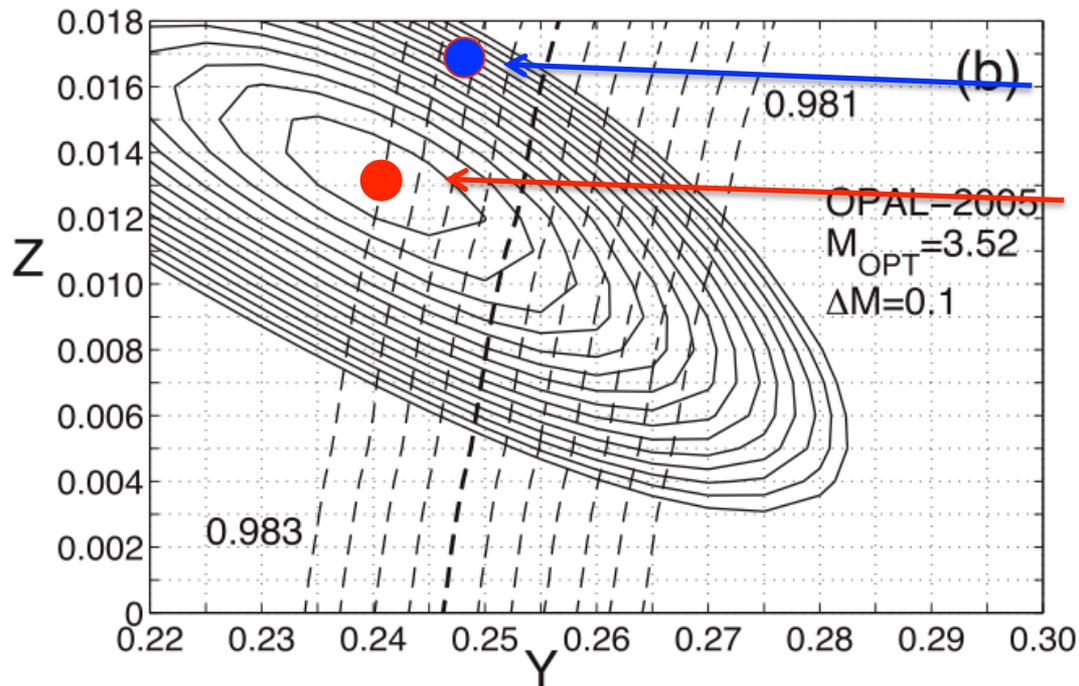
HeII dip used to determine
surface Y (modulo EOS – independent
of opacities)

By subtracting He-contribution
metals could be detected

... but EOS dependent & sensitive
to analysis details !!



UPDATE ON MICROPHYSICS: EOS



OPAL-EOS

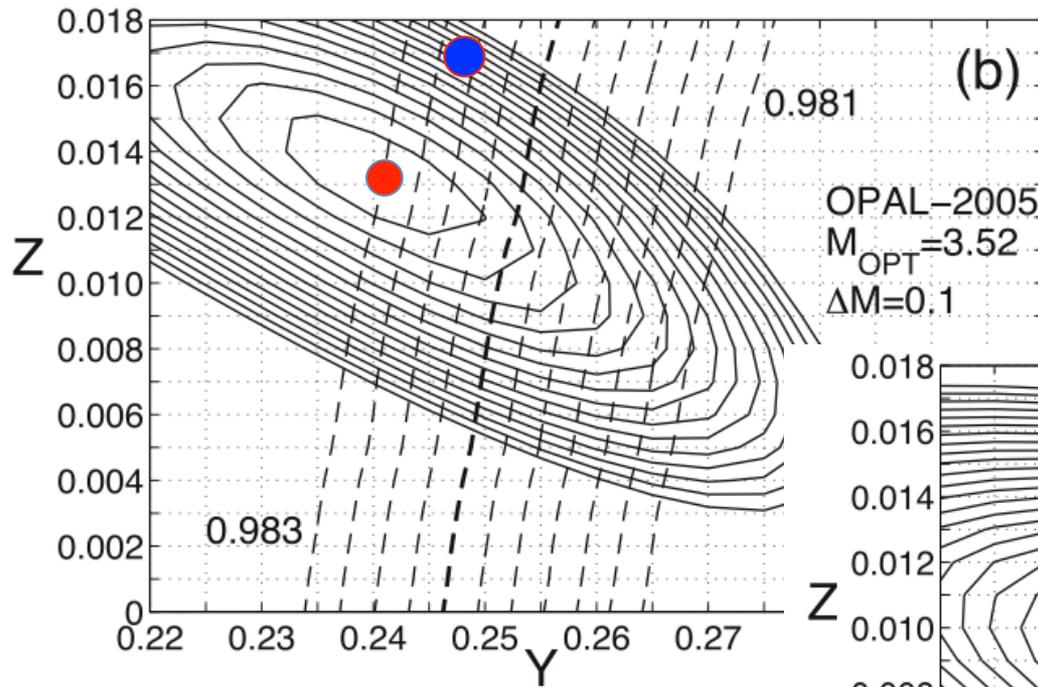
Lin et al. 2007

Vorontsov et al 2013

Y (and Z) sensitive to EoS

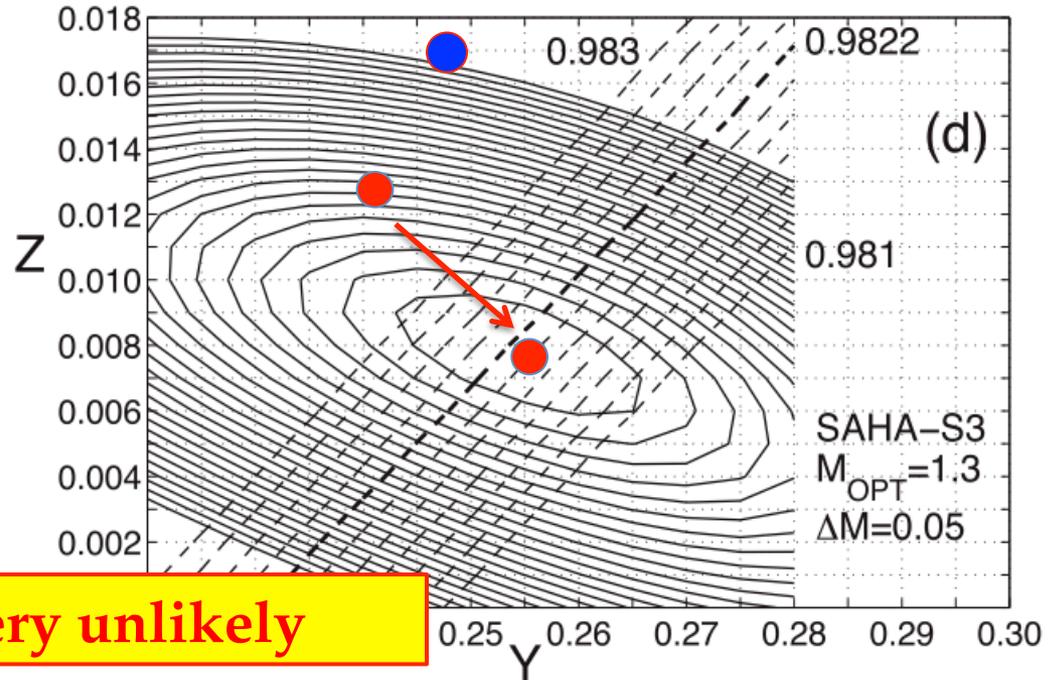
Similar technique, same EOS, lower Y and Z values

UPDATE ON MICROPHYSICS: EOS



OPAL-EOS

SAHA-S3



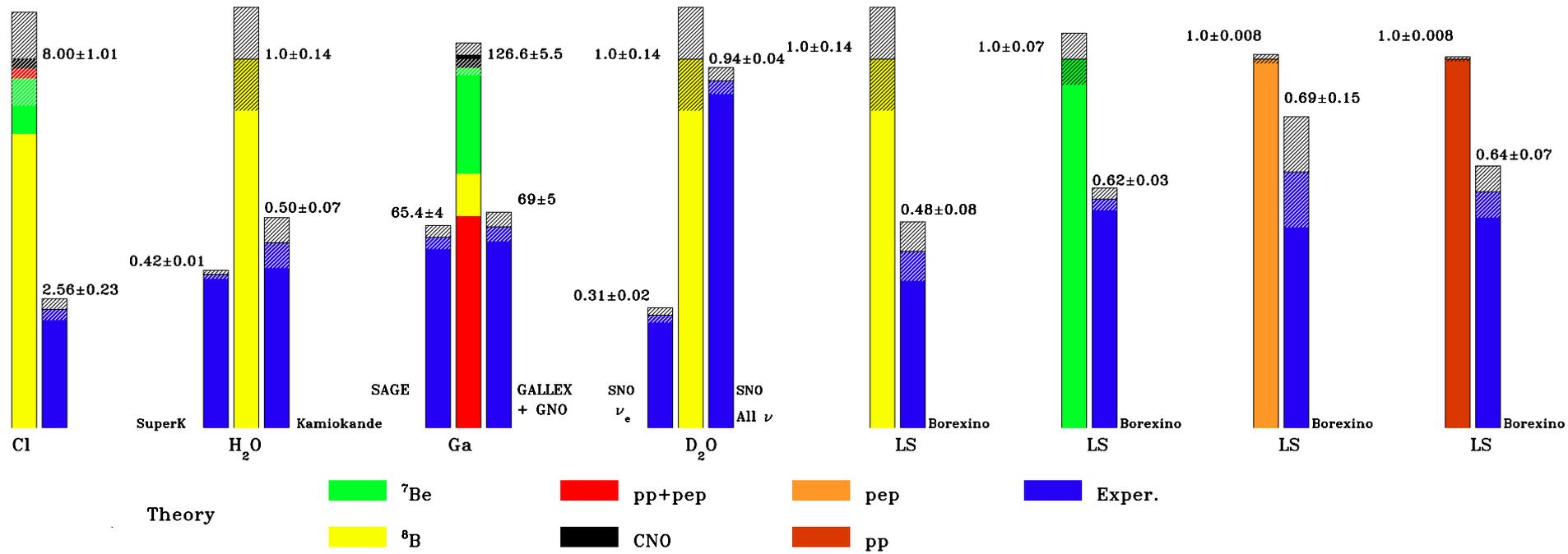
Y (and Z) sensitive to EoS

Z=0.008 with new EOS!!! – very unlikely

Reinforce the need for CN-neutrinos measurement

STATUS ON EXPERIMENTS

ν rates: SSM vs. Experiment
SFII(GS98)



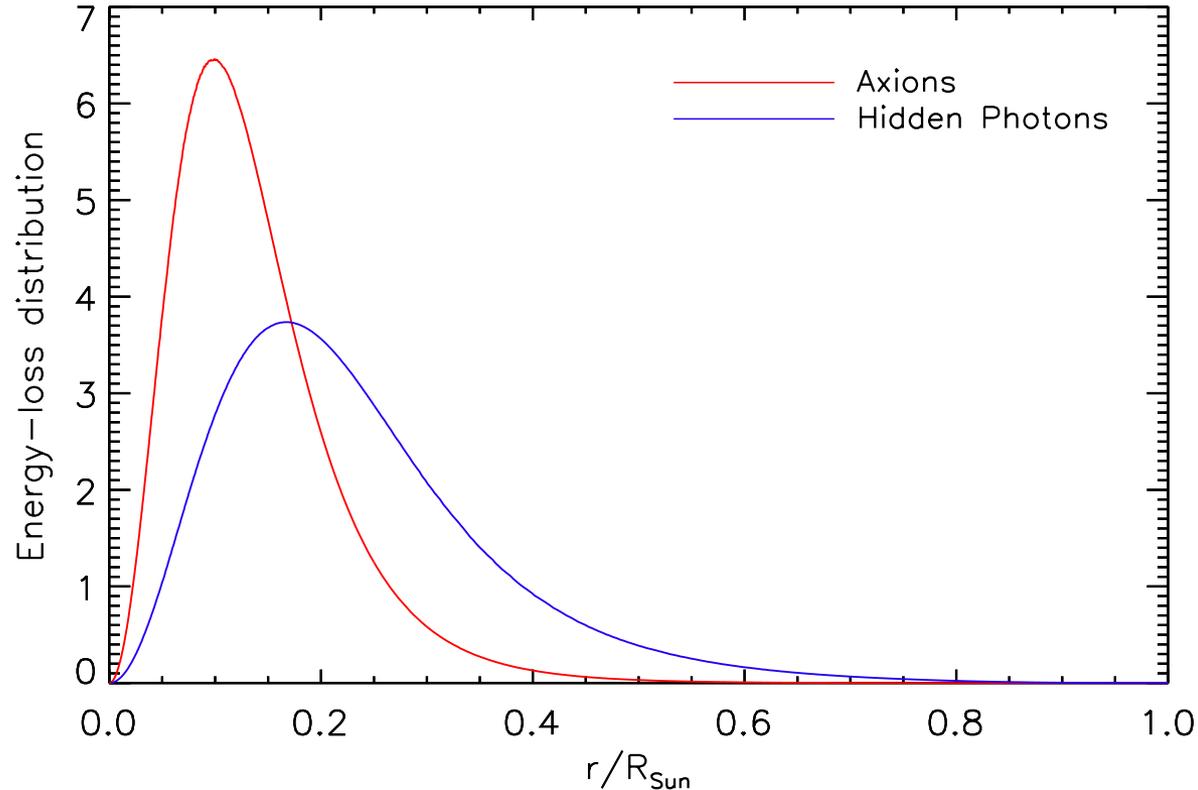
${}^8\text{B} \sim 3\%$
 ${}^7\text{Be} \sim 4\%$

pep $\sim 20\%$
pp $\sim 10\%$

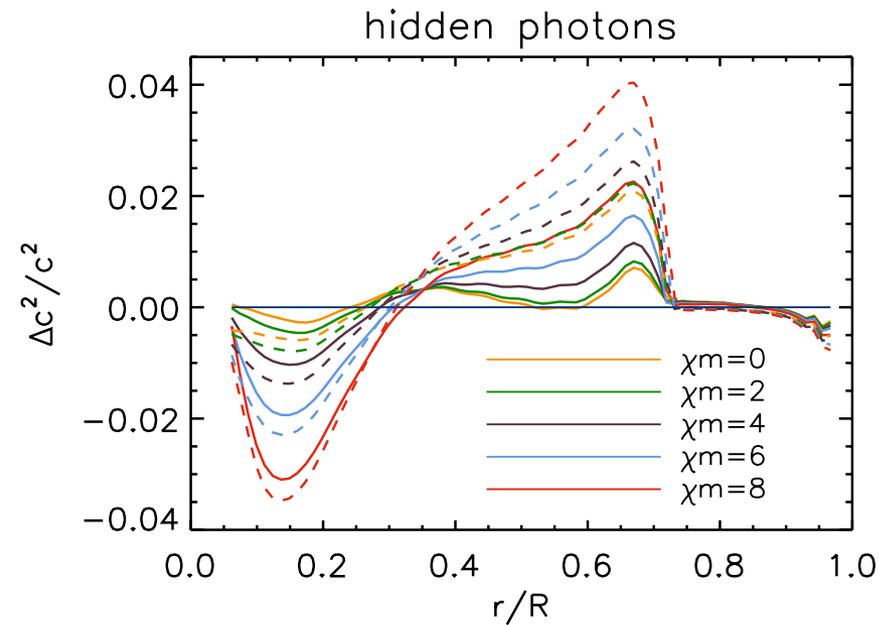
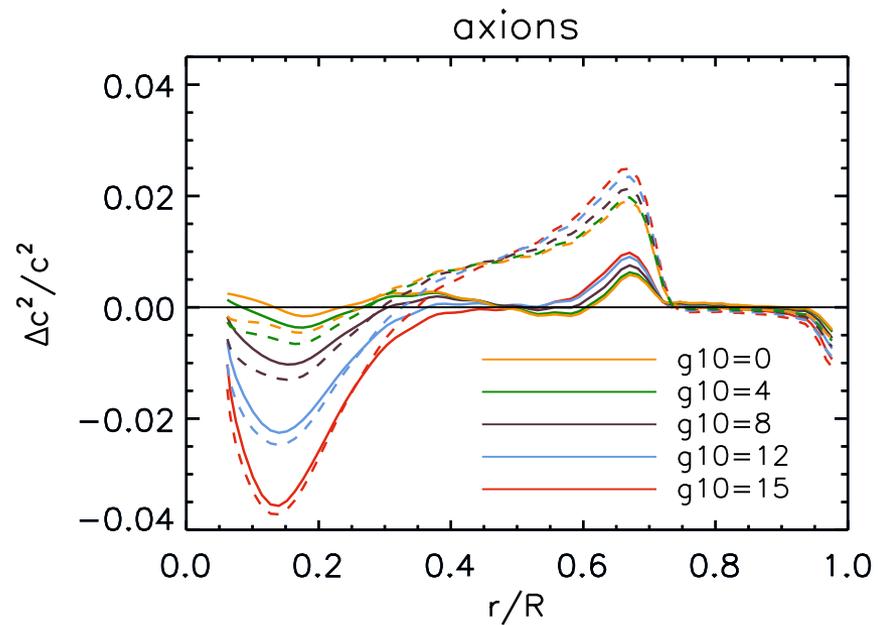
COMBINING SOLAR DATA: TEST CASES BEYOND SSM

Hadronic axions (Schlattl 1999, Gondolo & Raffelt 2009, Maeda & Shibahashi 2013, Redondo 2013)

Hidden photons (Redondo 2008, Redondo & Raffelt 2013, An et al. 2013)



COMBINING SOLAR DATA: TEST CASES

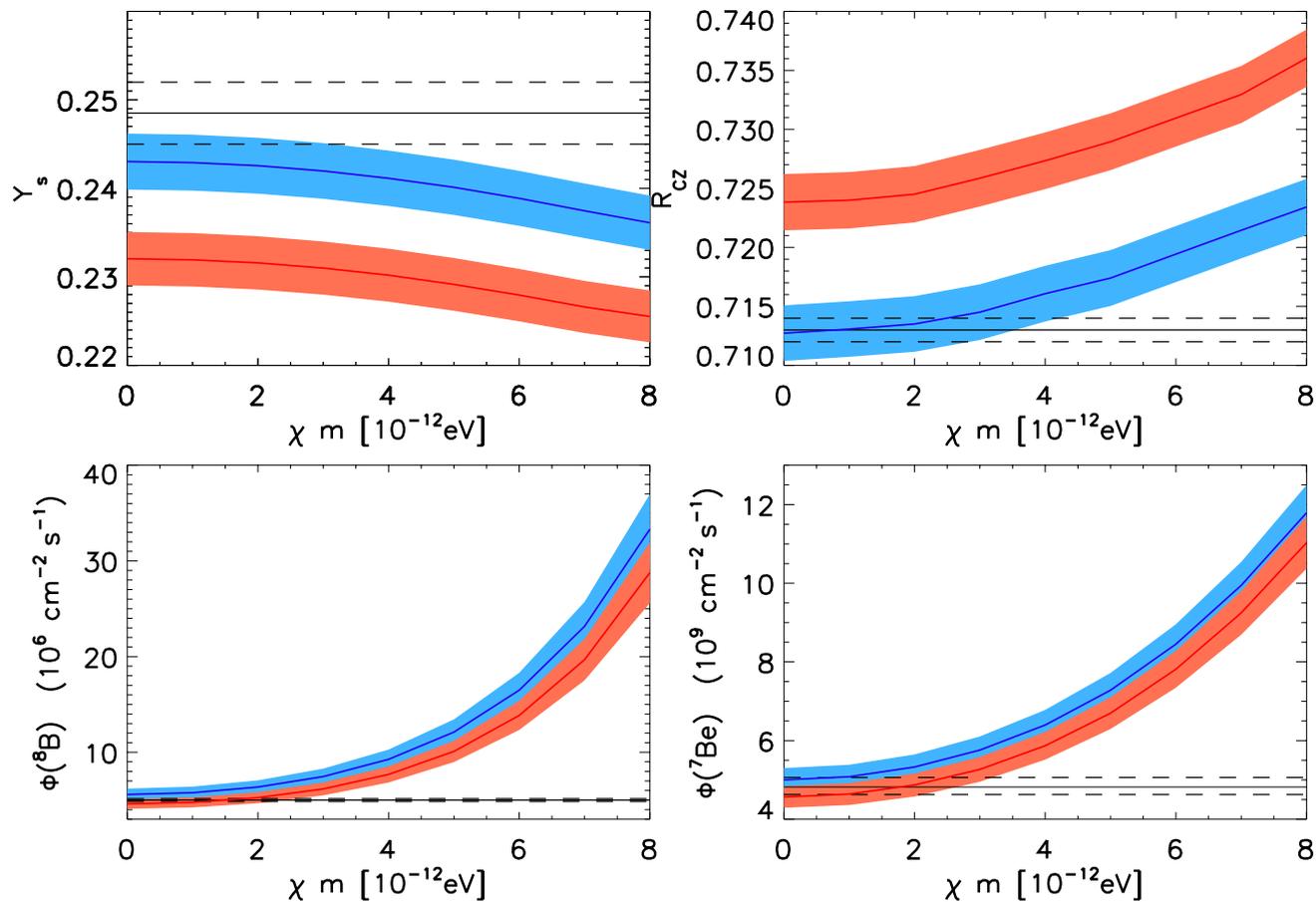


COMBINING SOLAR DATA: TEST CASES

GS98 (high-Z)

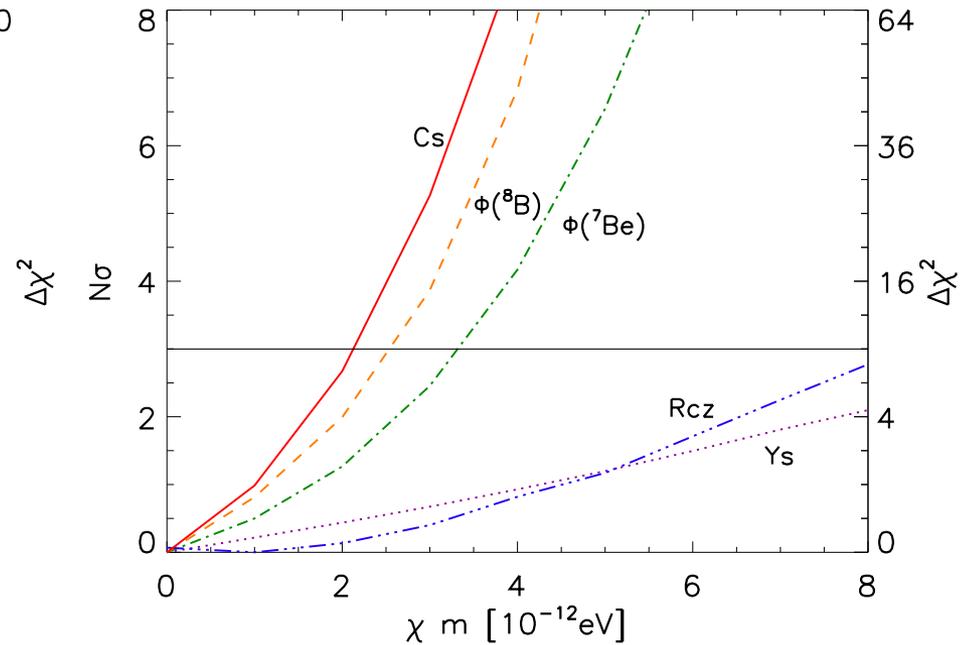
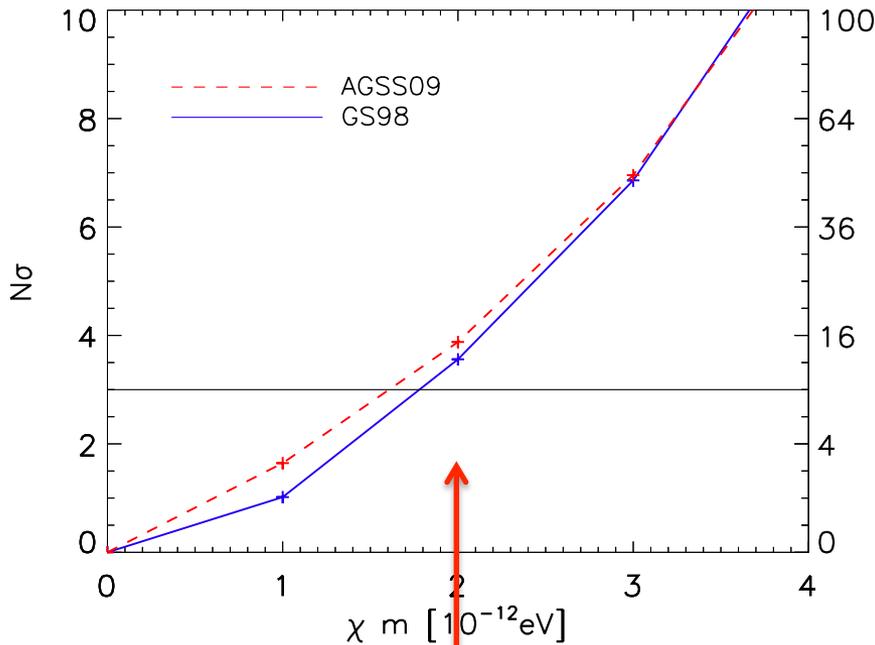
AGSS09 (low-Z)

hidden photons



COMBINING SOLAR DATA: TEST CASES

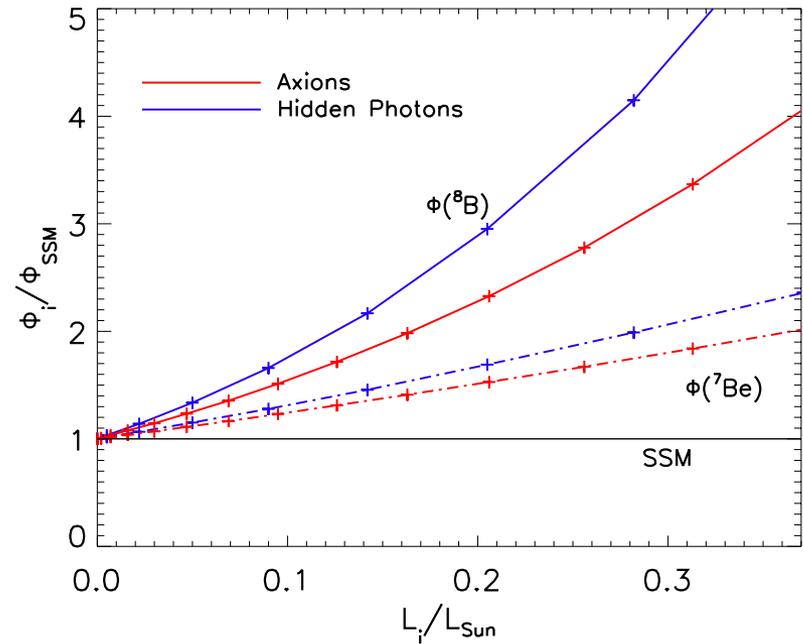
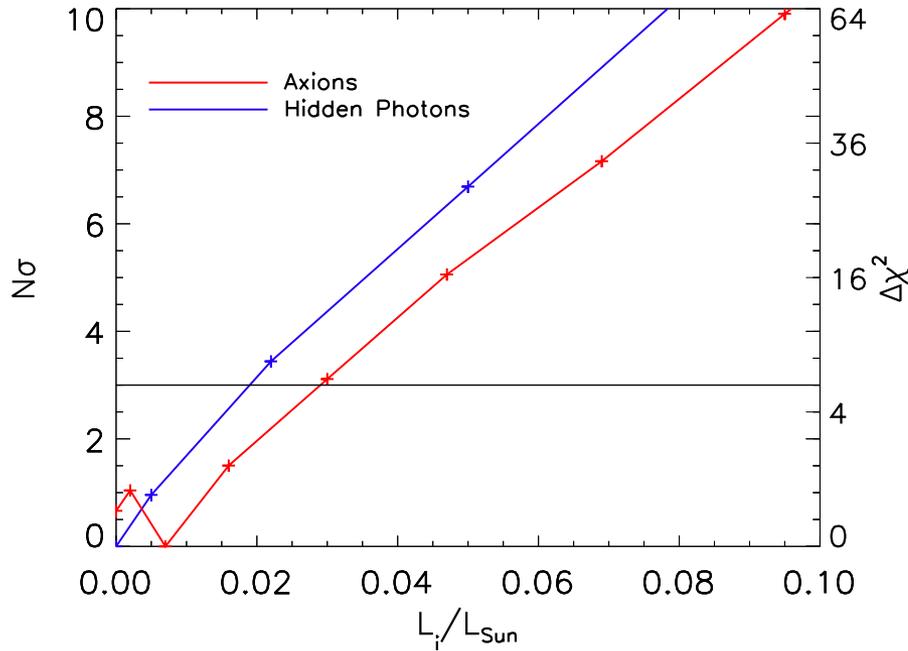
Global & individual limits



Combining available data improves previous limit by $\sim x2$

Similar (x1.5 lower) for axions

COMBINING SOLAR DATA: TEST CASES

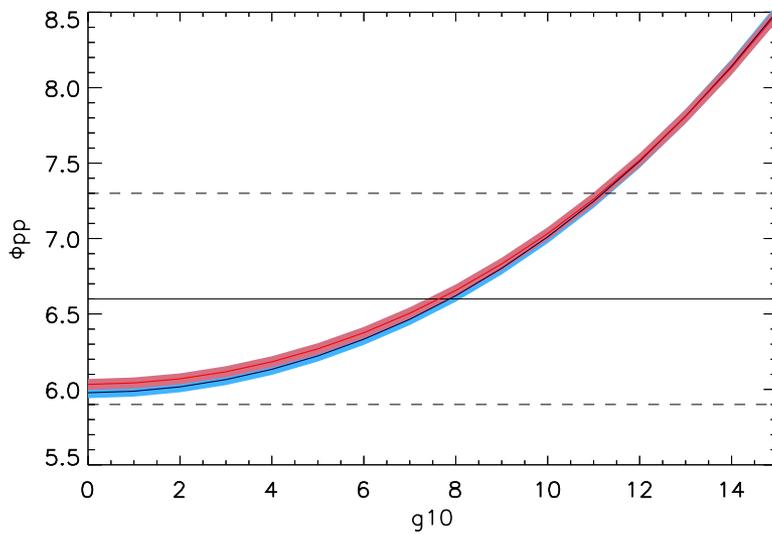


3σ limits obtained at 3% (axions) & 2% (HPs) of “exotic” luminosity L_x

L_x limit depends on type of particle – not just sound speed, ${}^8\text{B}$ as well
lower than the “canonical” 10% limit usually employed
5% seems a conservative enough limit to use

Uncertainties dominated by solar models – hard to make progress

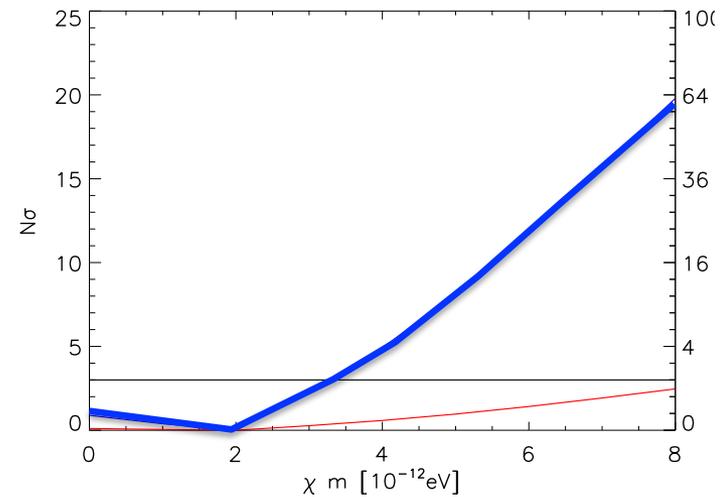
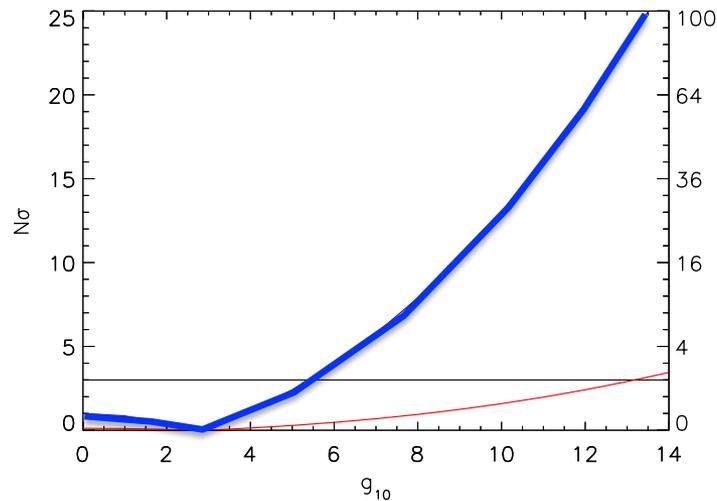
CAN $pp\text{-}\nu_s$ IMPROVE THIS?



Assume pp -measurement @ 1%

pp -only limit

Limit not so good but cleaner
errors almost purely experimental



SUMMARY

The solar composition controversy goes on...

Asplund 2009 abundances under revision (same group)

similar results for refractories (published 2014)

similar results expected for volatiles (not yet available)

Helioseismic & neutrino data constrain T-profile (opacities), not composition --> degeneracy

Global analysis of solar data -- > 20% change in opacity

only < 5% found in new opacity calculations

Helioseismic constrain on Z difficult (technique & new EOS, more problems)

CN neutrinos excellent alternative – good to 10% (nuclear) + experimental error

Extending global analysis to exotic particles improves current solar limits

renewed relevance (IAXO)

need to improve treatment of sound speed errors

error budget dominated by solar models

pp (1%) could give competitive limits free from solar models