The Sun as an Axion Source

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Outline

Solar Models 101

Current Standard Solar Models

solar composition

finding a best fit SSM – reference model for particle physics

Revisiting solar limits on axions and axion spetrum

Calibration of SSM

3 free parameters

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

3 observational constraints

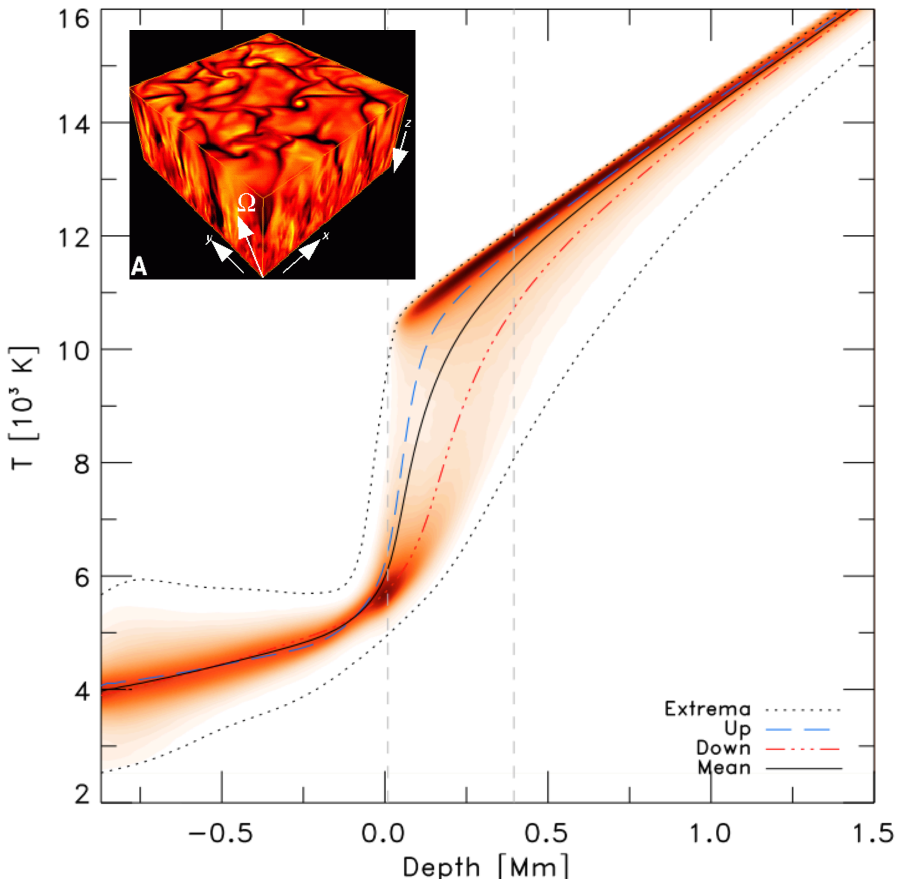
solar radius – $R_\odot$
solar luminosity – $L_\odot$
surface metal to hydrogen abundances ratio – $(Z/X)_\odot$

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

	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 (+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%

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 Abundance Problem

Discrepancies with low-Z solar composition show up in:

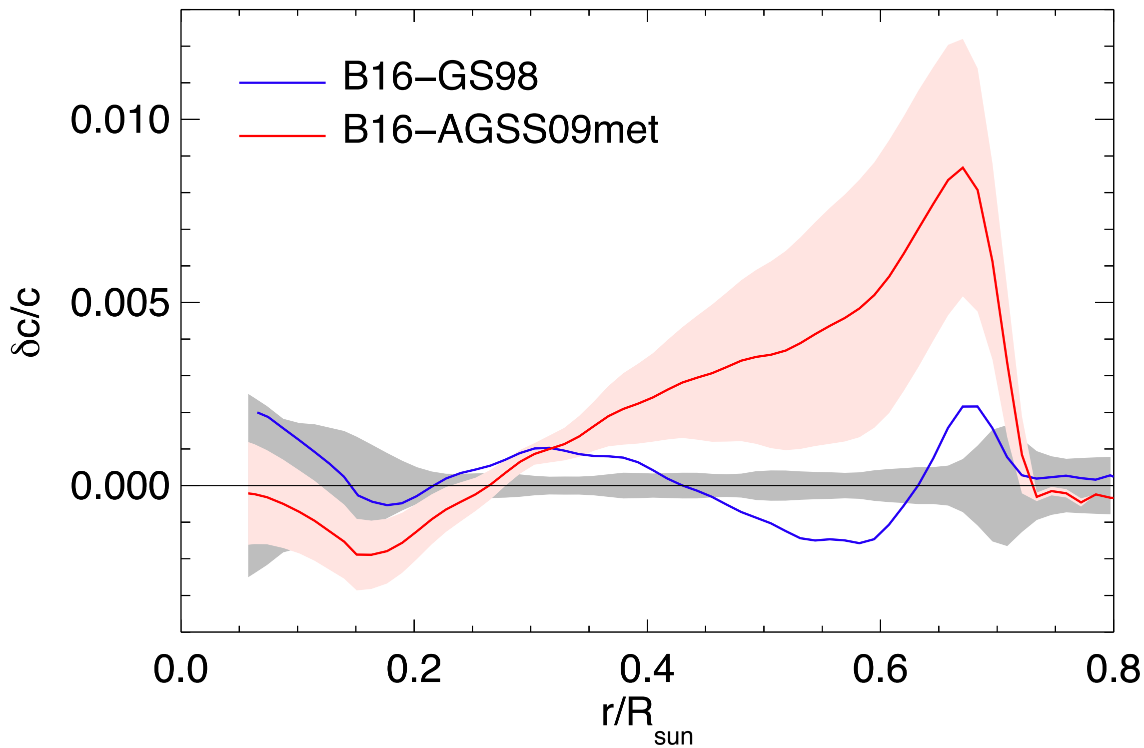
sound speed profile

density profile

depth of convective envelope

surface helium abundance

Vinyoles et al. 2016



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	-

High-Z models are preferred

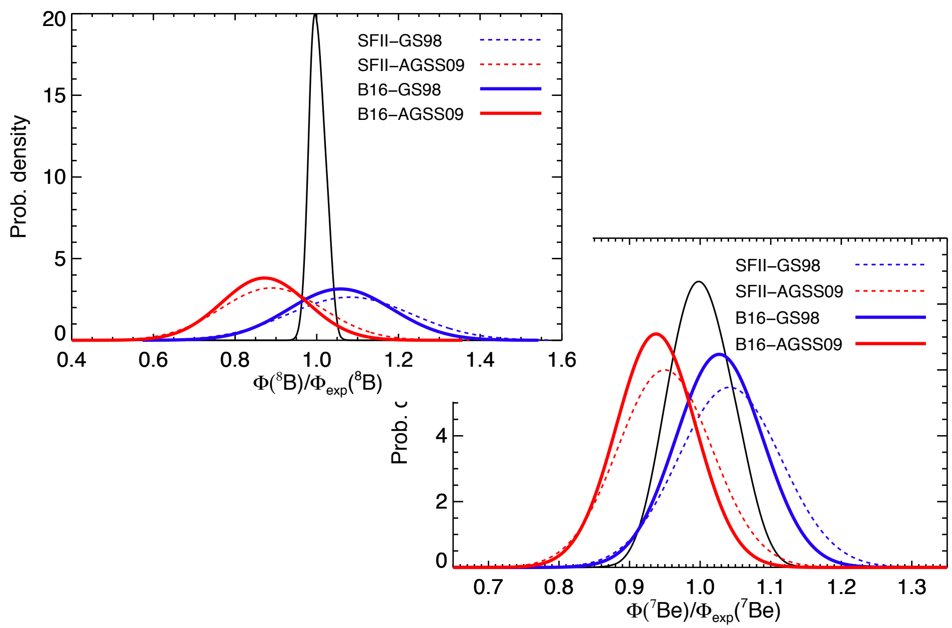
Solar neutrinos

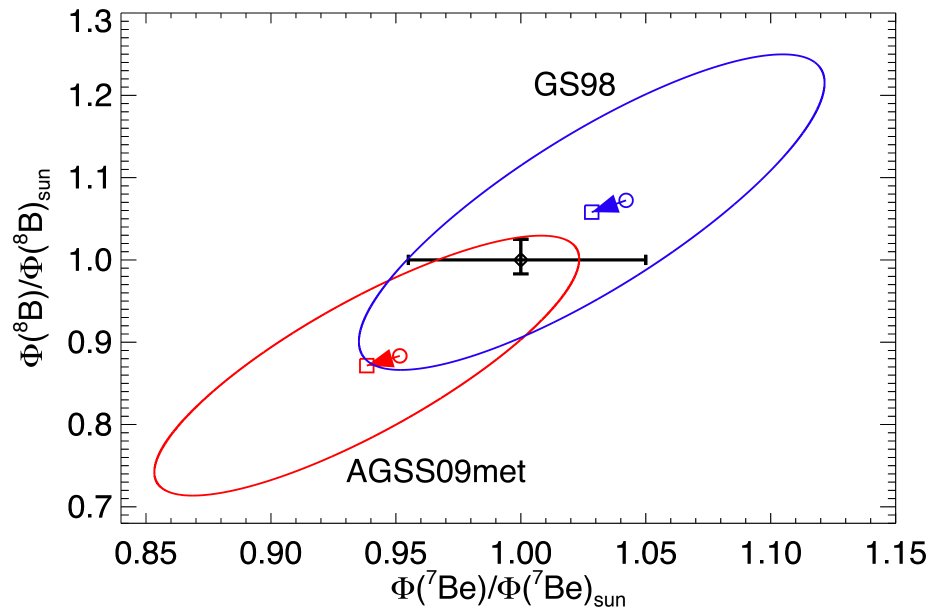
Flux	B16-GS98	B16-AGSS09met	Solar
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.971^{(1+0.006)}_{(1-0.005)}$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.448(1 \pm 0.009)$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$\leq 19^{(1+0.63)}_{(1-0.47)}$
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$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

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

Experimental uncertainty

Vinyoles et al. 2016





Robust inferences from SSMs?

Helioseismology and pp-chain neutrinos sensitive to temperature profile

--> T-profile well constrained by data

Construct a SSM that best fits available data

--> physical dependence included through linear expansions around reference SSM

--> allow SSM input parameters vary: 2 parameters for composition & 10 parameters for nuclear rates, etc.

$$\chi^2 = \min_{\{\xi_I\}} \left[\sum_Q \left(\frac{\delta Q_{\rm obs} - \sum_I \xi_I C_{Q,I}}{U_Q} \right)^2 + \sum_I \xi_I^2 \right]$$

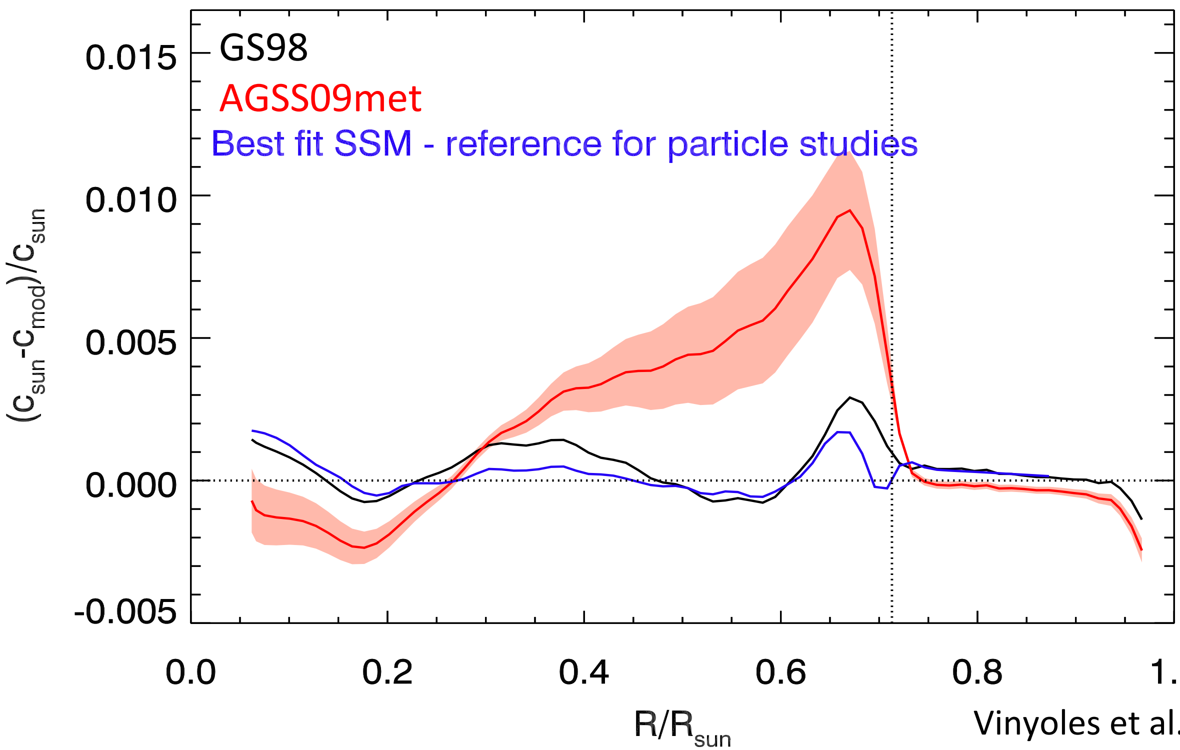
seismic + neutrino observables

model correlations & pulls ξ_I of input parameters

Best-fit SSM

Even better than the real thing !!

Pulls from systematics of order 1 (1-σ) + free variation of composition



Vinyoles et al. 2015

Good reference for particle studies **IF** emissivity depends predominantly on Temperature and Density

Limits on axion-γ coupling

$$\mathcal{L}_{a\gamma} = g_{a\gamma} B \cdot E a$$
$$g_{a\gamma} = g_{10}\, 10^{-10}\, \mathrm{GeV}^{-1}$$

Schlattl et al. 1999 – $g_{10} < 10$

Sound speed at $R = 0.1\, R_\odot$ – equivalent to $L_a < 20\%\, L_\odot$

Gondolo & Raffelt 2009 – $g_{10} < 7$

^8B flux < 1.5 $^8B_{SSM}$ (3-σ) – equivalent to $L_a < 10\%\, L_\odot$

Maeda & Shibahashi 2013 – $g_{10} < 2.5$

^8B flux constrained by sound speed (1-σ)

seismic (not evolutionary models – neglect basic physics)

Vinyoles et al. 2015 – $g_{10} < 4$ (3-σ)

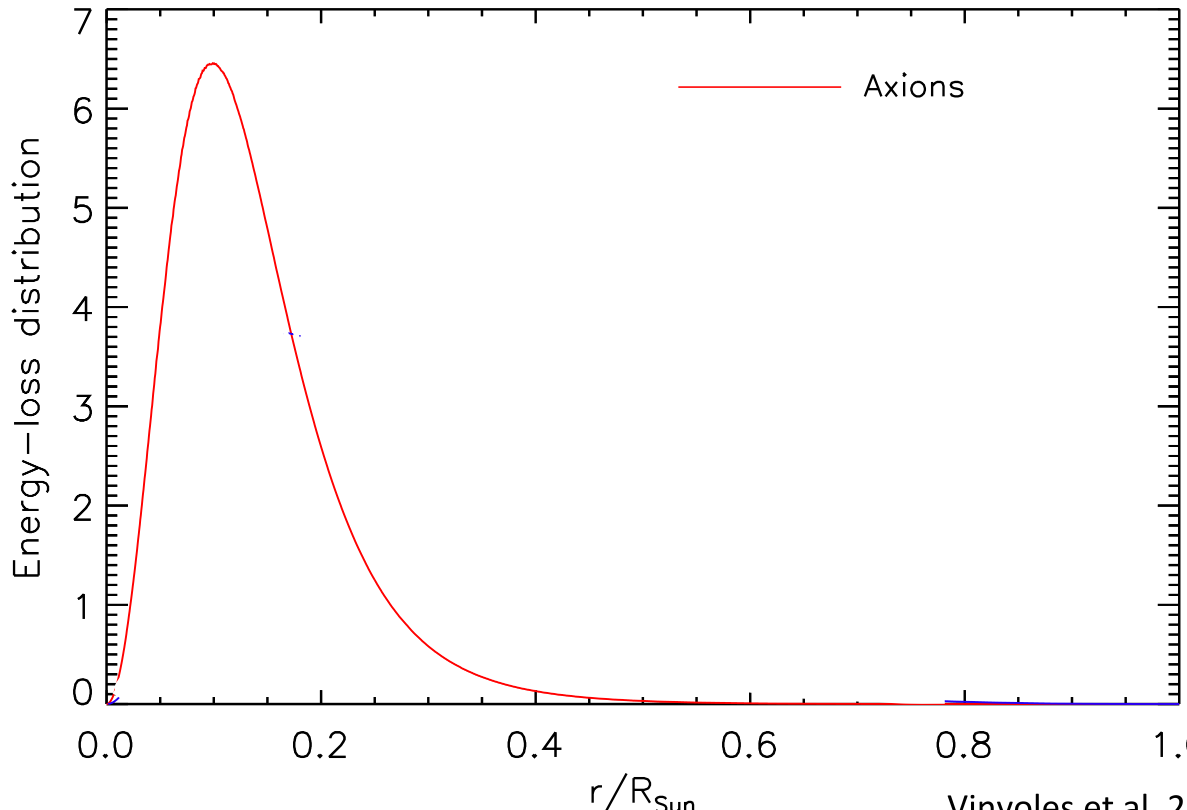
helioseismic + neutrino data

extend the method used to construct best-fit SSM

Limits on axion-γ coupling

$$\epsilon_{a\gamma} \propto g_{a\gamma}^2 T^7 F(\kappa^2) \sim g_{a\gamma}^2 T^6$$

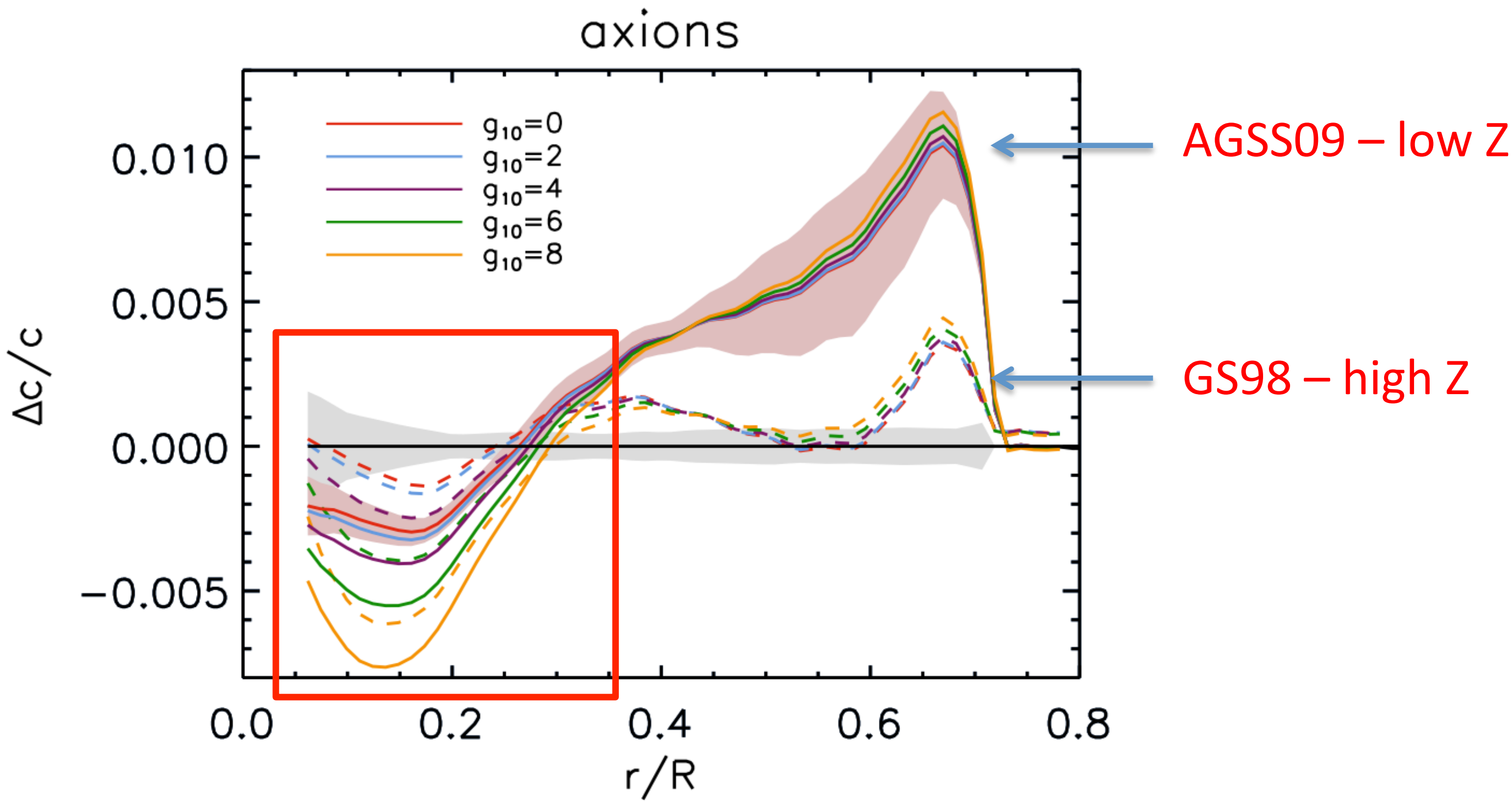
No explicit composition dependence



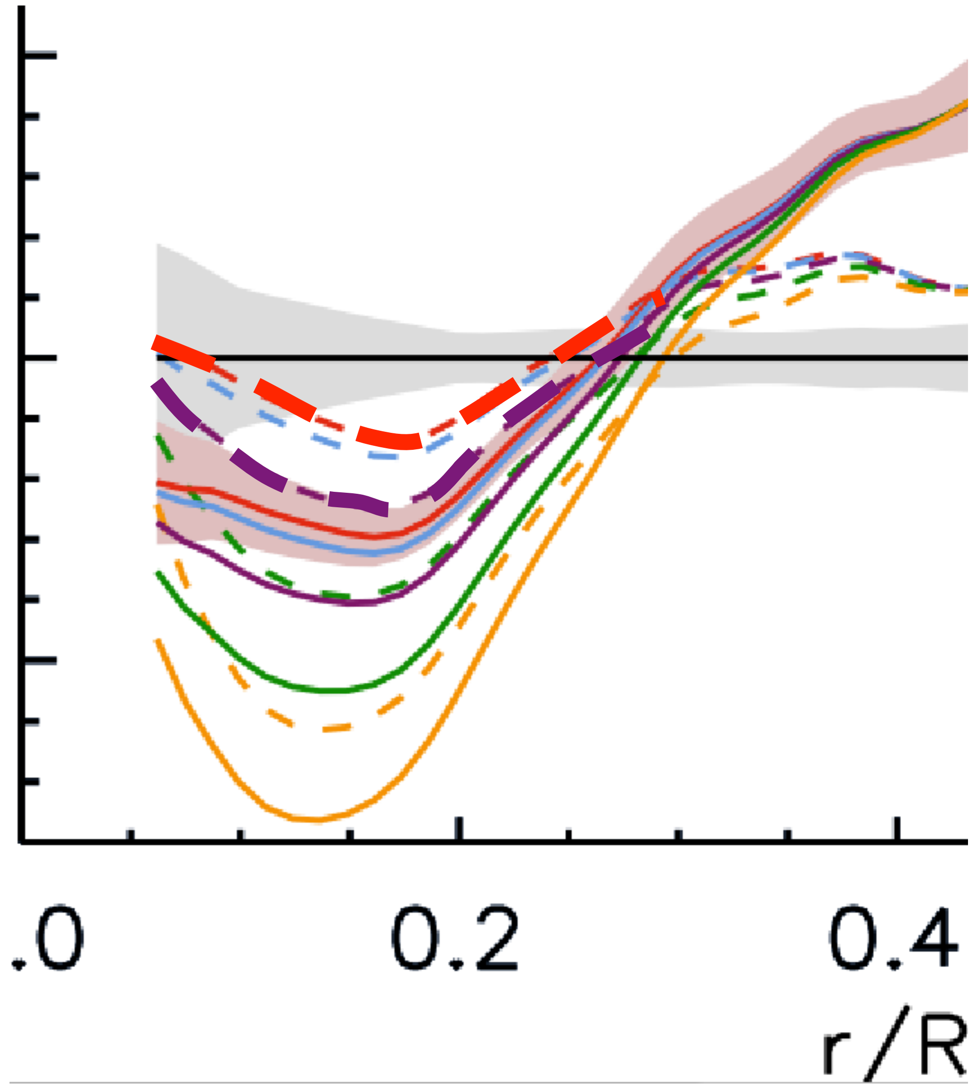
Vinyoles et al. 2015

Limits on axion-γ coupling

Variations in sound speed without variations in composition and pulls

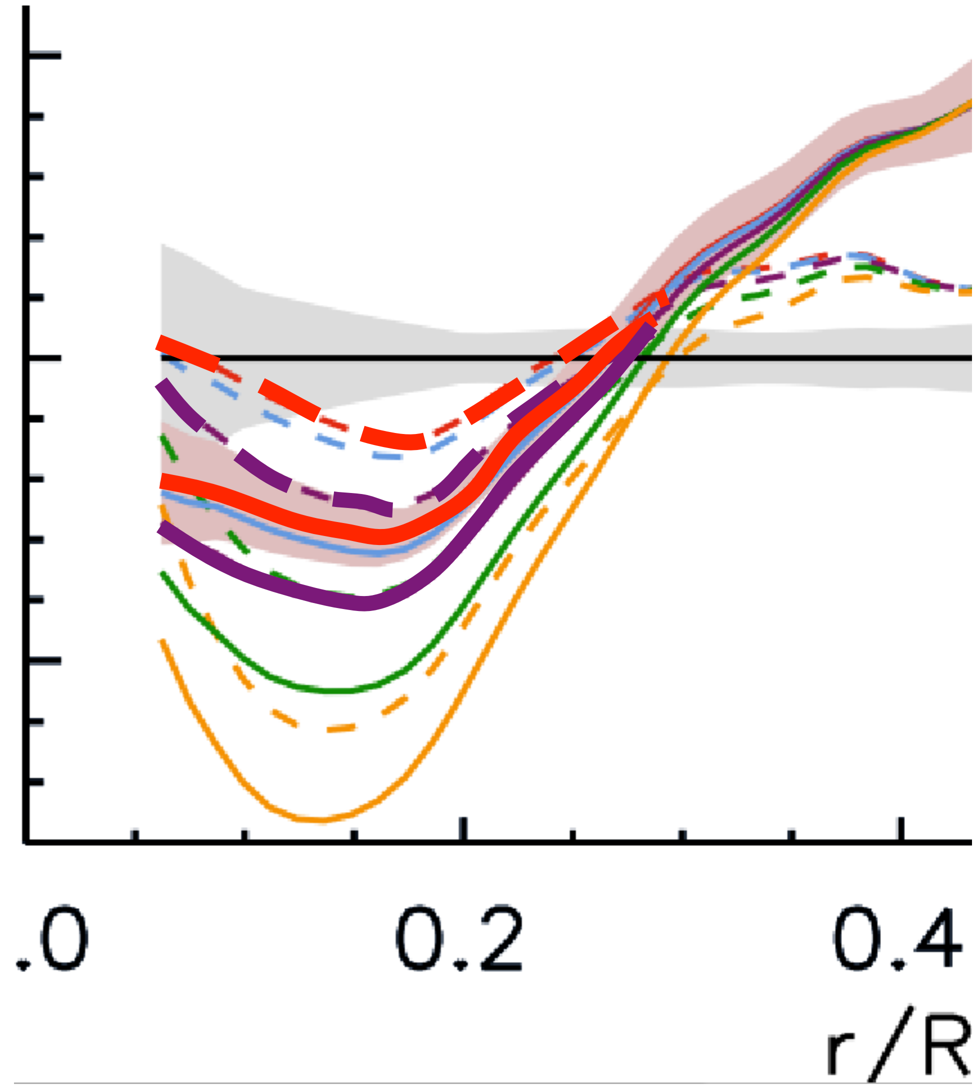


Limits on axion-γ coupling



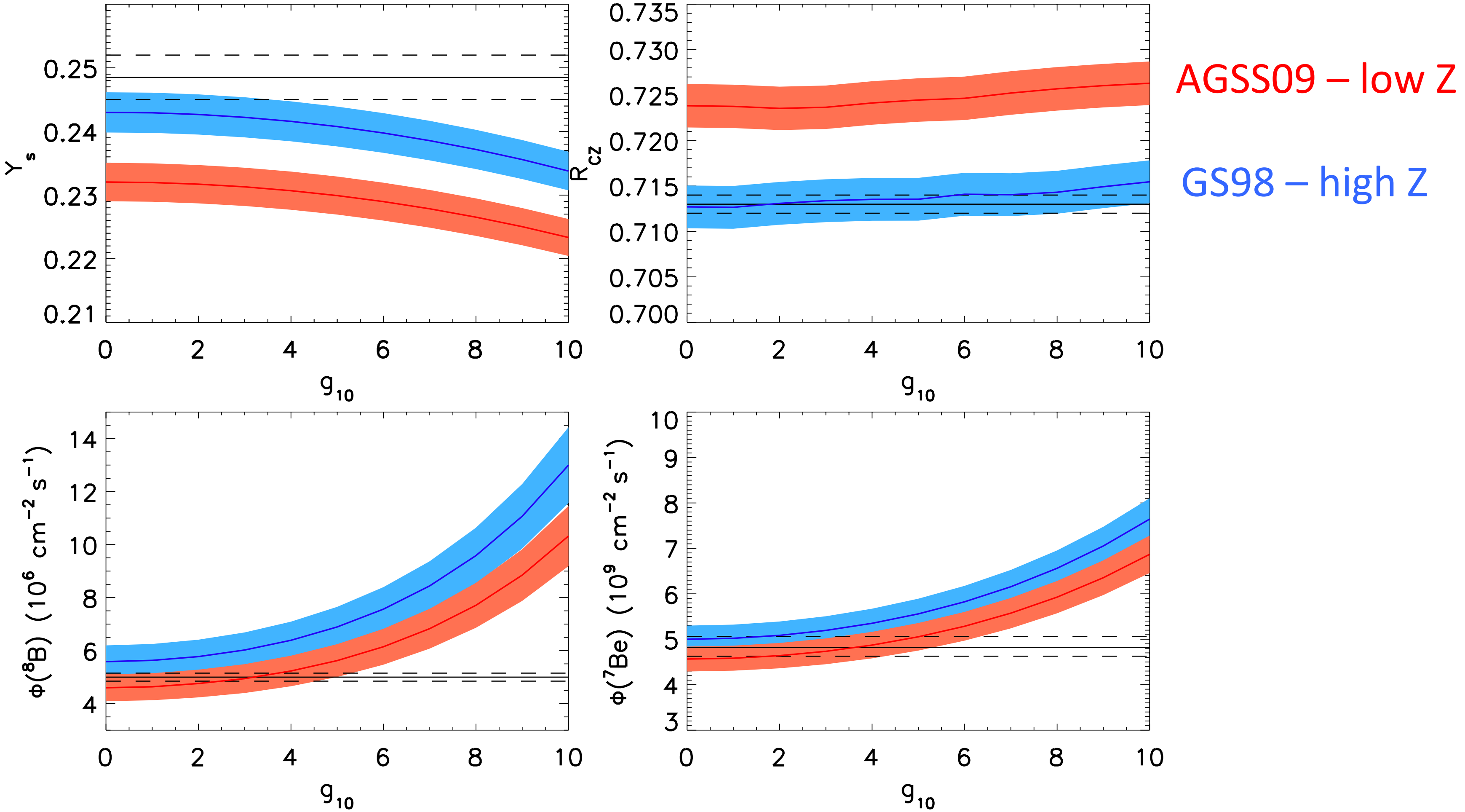
Limits on axion-γ coupling

Relative changes are similar for both compositions



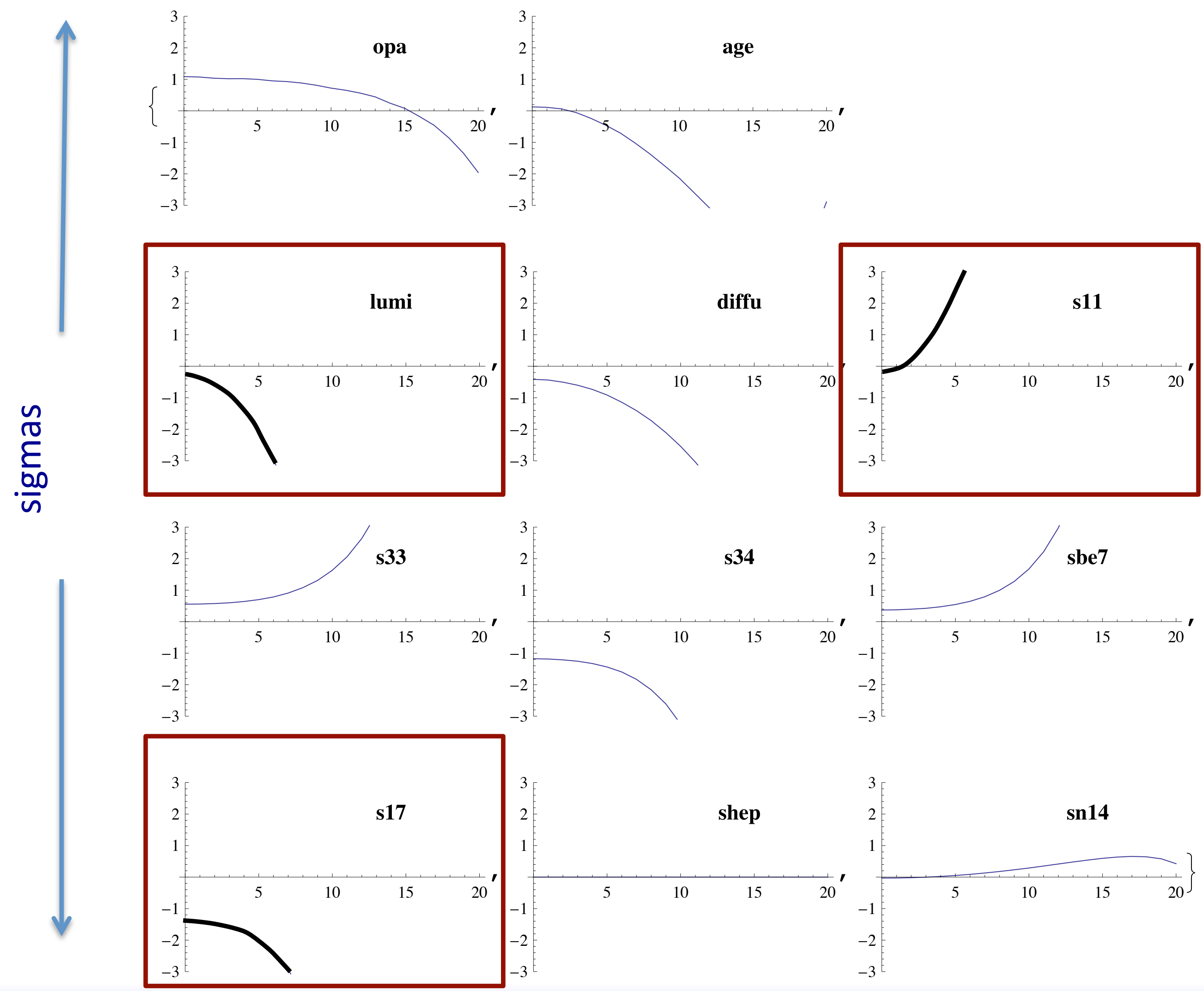
Limits on axion-γ coupling

Variations in other quantities without variations in composition and pulls

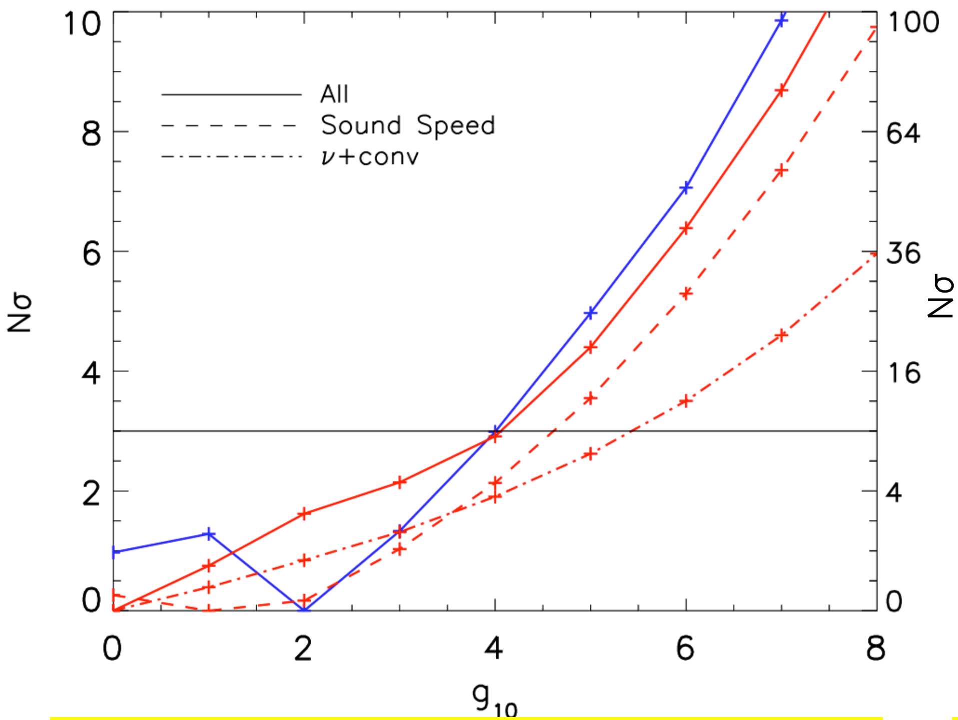


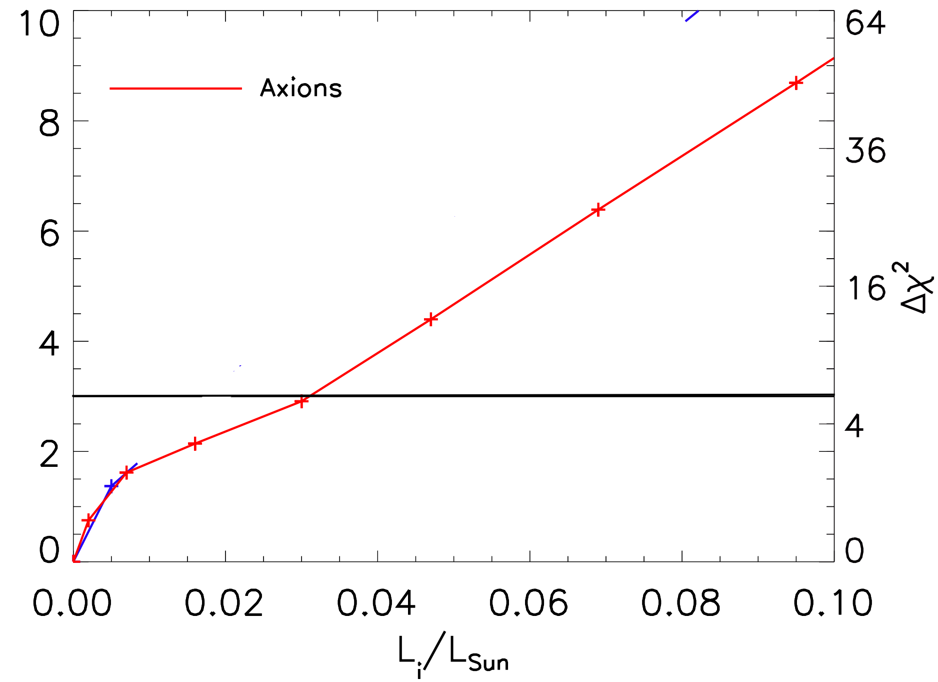
Changes due to axions and "zero point" of SSM to be accounted for by composition and systematics (pulls)

Limits on axion-γ coupling



Limits on axion-γ coupling



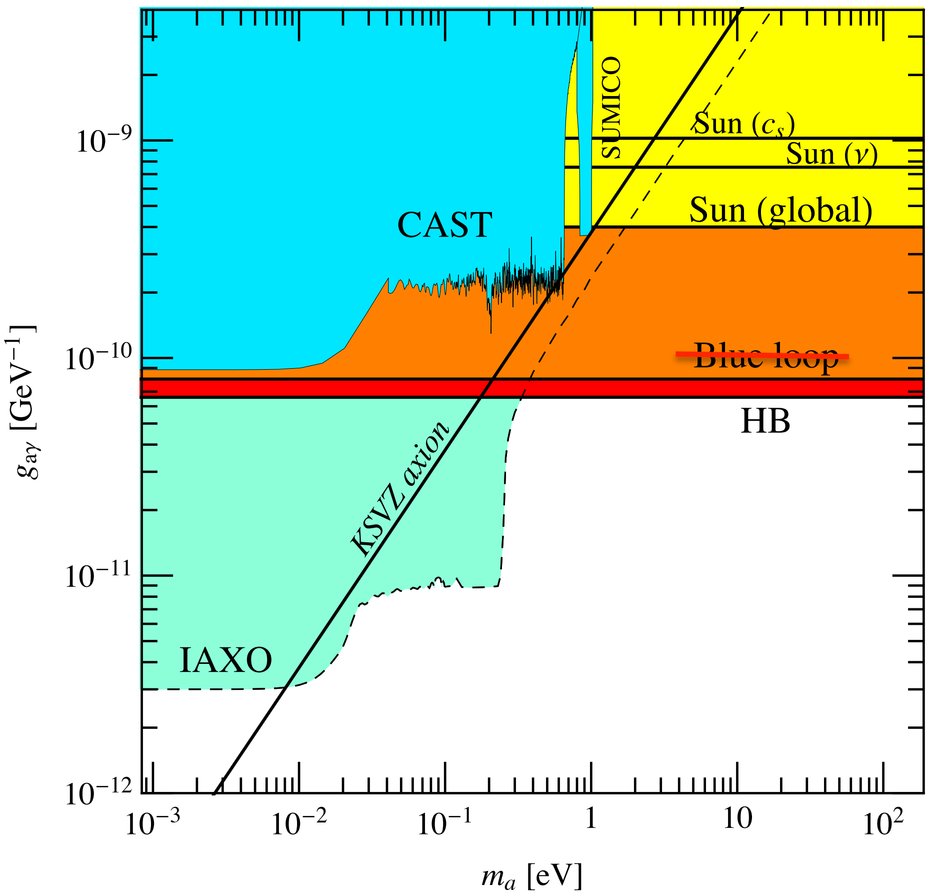


Final upper limit – g_{10} < 4 @ 3-σ C.L.

Effective limit in axion energy $L_{a\gamma}$<3% $L_{\odot}$

A model independent test is possible using pp ν flux – needs measurement to 1% currently at 10%

Limits on axion-γ coupling



Limits on axion-e^- coupling

Gondolo & Raffelt 2009 – $g_{ae} < 2.8 \times 10^{-11}$

^{8}B flux < 1.5 $^8B_{SSM}$ (3-σ) – equivalent to $L_a < 10\% \, L_\odot$

free-free transitions & Compton scattering

Redondo (2013) -- $g_{ae} < 2.3 \times 10^{-11}$

based on same constraint

incl. free-bound & bound-bound

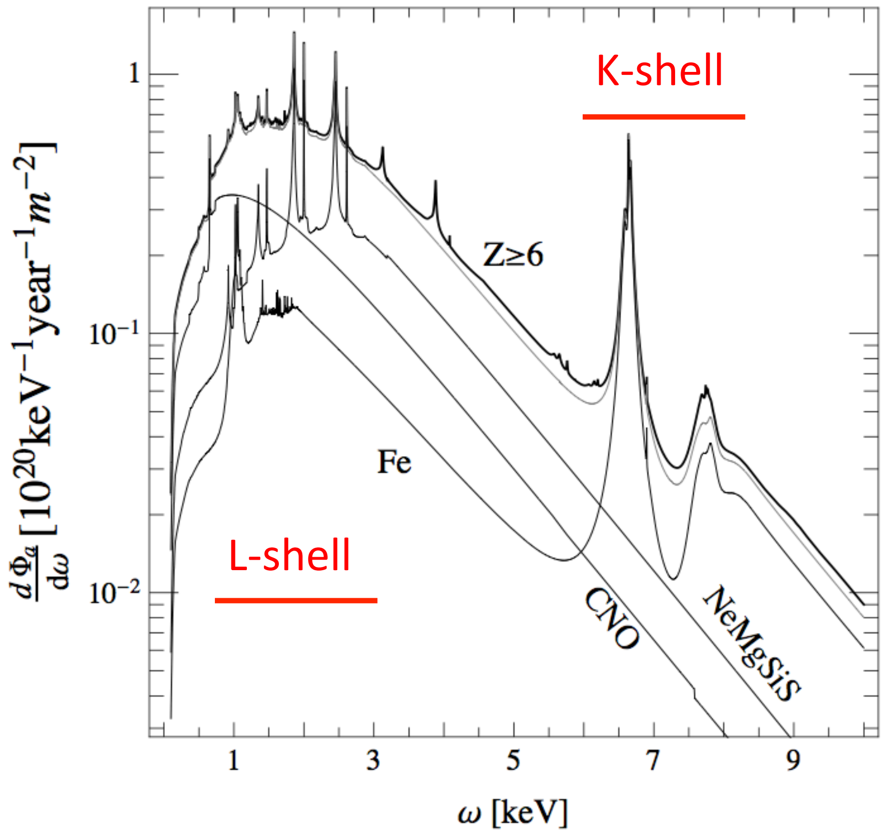
By adding other solar constraints such as helioseismology and the method described above, the limit can be pushed down by ~ x 2

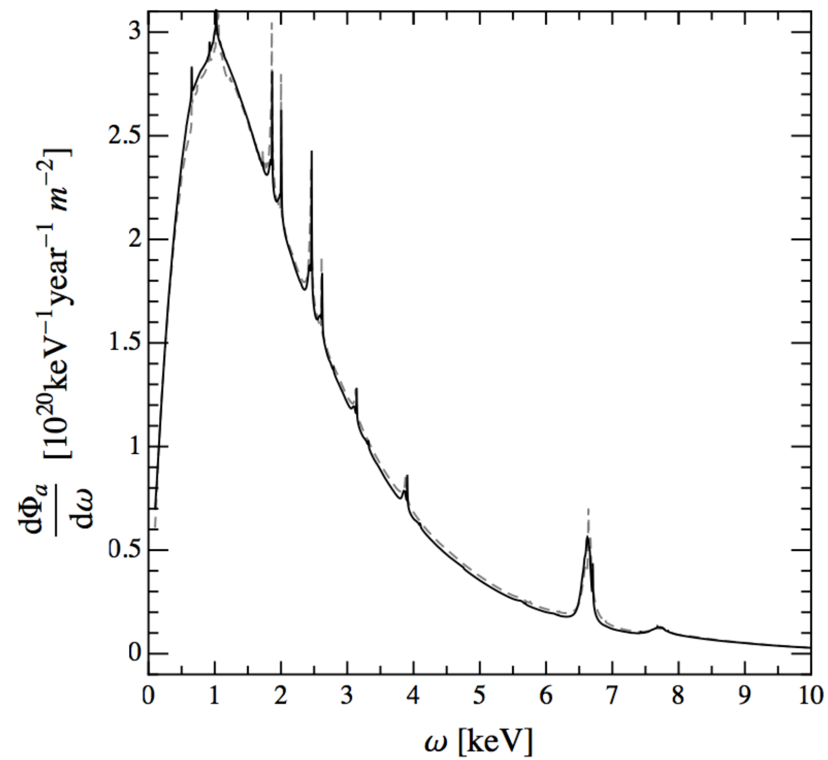
E.g. for photon coupling, $L_a < 3\% \, L_\odot$

Limits on axion-e^- coupling

Redondo (2013) – Atomic structure leads to prominent features in spectrum

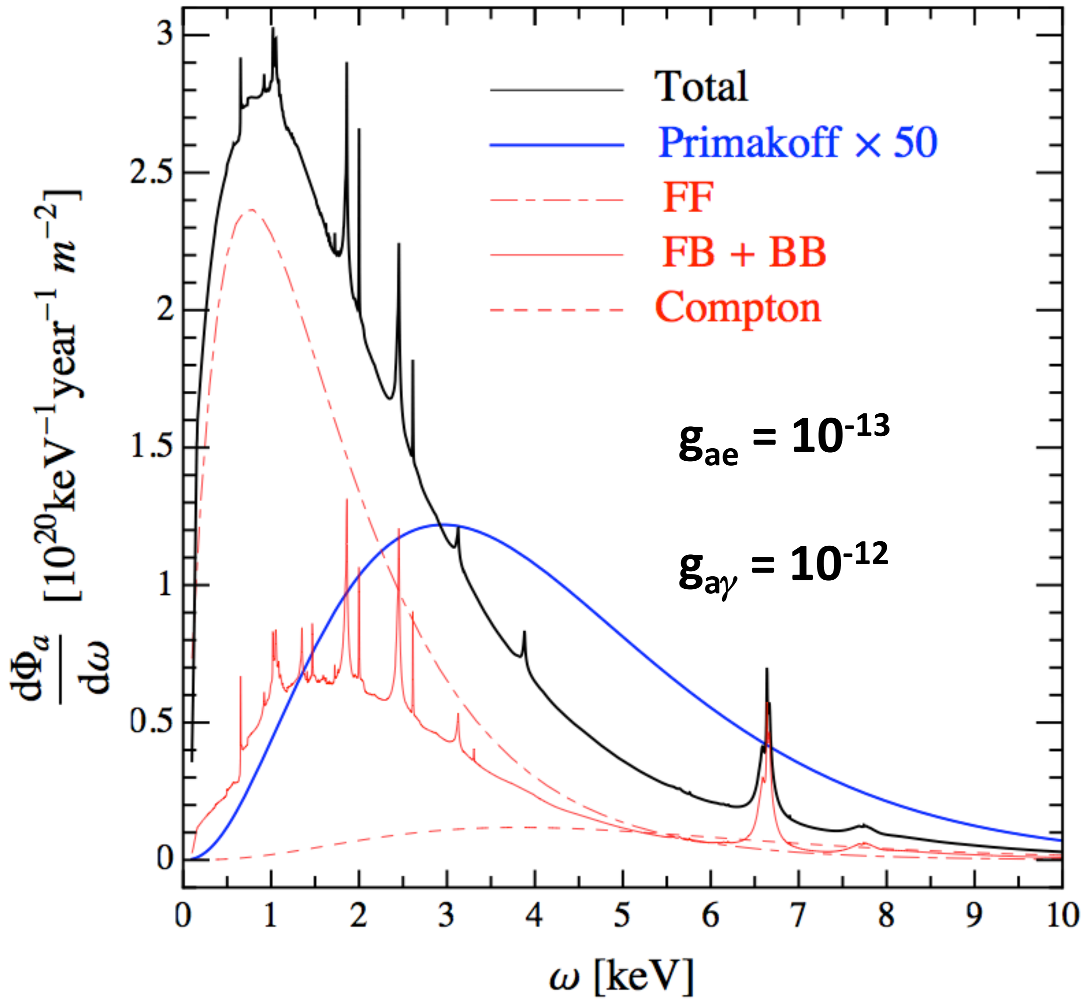
Based on atomic opacity calculations – scale factor with ω_{pl} dependence





Limits on axion-e⁻ coupling

Tests with different atomic opacity calculations



Summary

- Solar models offer a robust lab for particle physics – provided composition dependence not directly relevant
- Combination of solar neutrinos + helioseismic constraint more powerful than if considered individually -- > lower limits typically by factor of 2
- Extra cooling in the Sun ≈ < 0.03 $L_\odot$
- $g_{a\gamma} < 4 \times 10^{-10}$ (3-σ)
- $g_{ae} < 2.3 \times 10^{-13}$ (but only from 0.1 $L_\odot$) – so it can be lowered
- Current bounds for $g_{a\gamma}$ and g_{ae} from WDs, RG, HB much tighter -- >
- Solar axion production does not affect its internal structure, i.e. no indirect way possible to determine axion properties