Solar Models and Neutrinos: The SSM and Beyond

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Plan

Part I

* Standard solar models and the abundance problem

  what helioseismology and solar νs really tell us (also talk by Villante)

* A generalized approach to solar models (with dark energy channels)

  revisiting solar limits for axion-photon coupling and hidden photons

Part II

* Asymmetric dark matter in the Sun

  q and v_{rel} dependent interactions and a non-standard look at the solar abundance problem

Standard Solar Models

SSM assumes

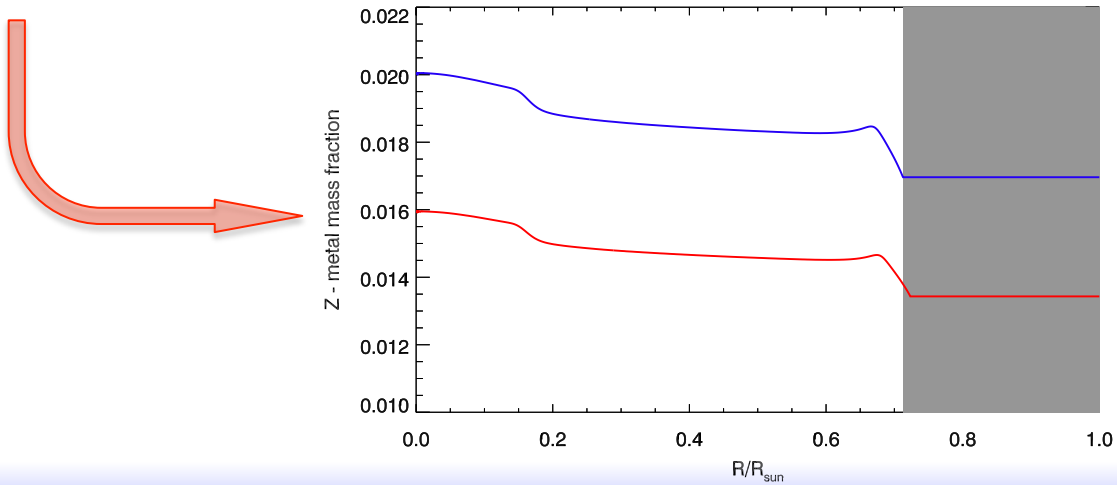
constant mass evolution – 1 $M_\odot$
initially homogeneous
solar system age 4.57 Gyr

3 present-day constraints <--> 3 adjustable quantities

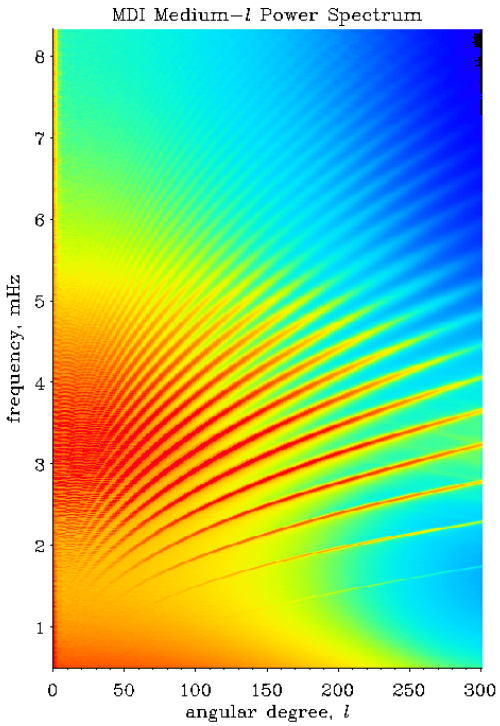
Solar radius -- > convection parameter – mixing length

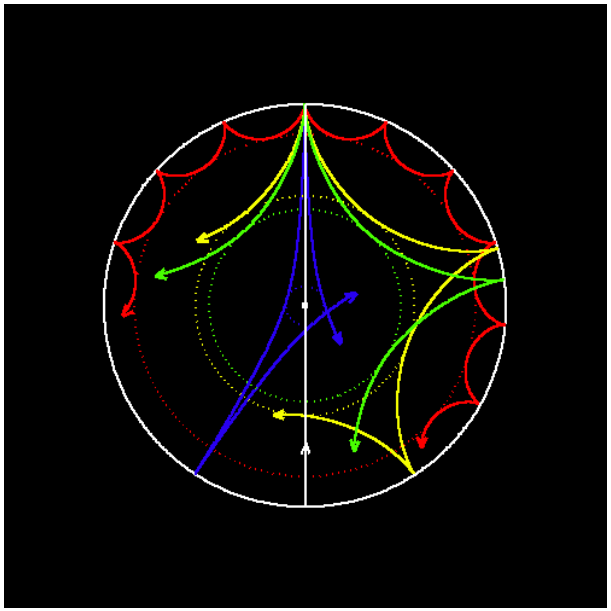
Solar (photon) luminosity -- > initial helium

Metal to hydrogen surface abundance (Z/X) -- > initial metallicity



Probing the Sun: Helioseismology





differential probing of solar structure

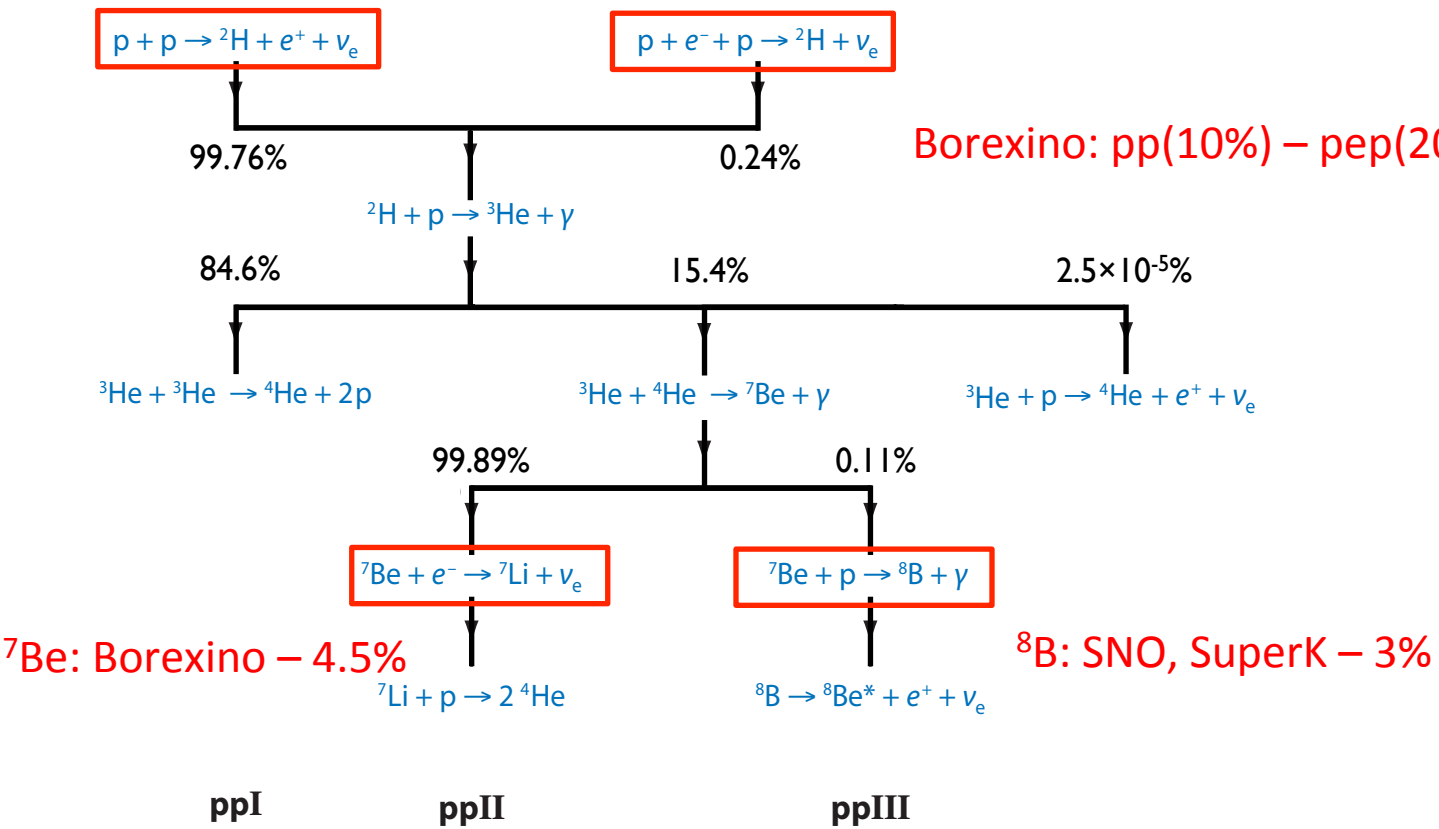
Sound speed (& density) profile

Solar core structure (low degree modes)

Depth of convection/radiation transition boundary

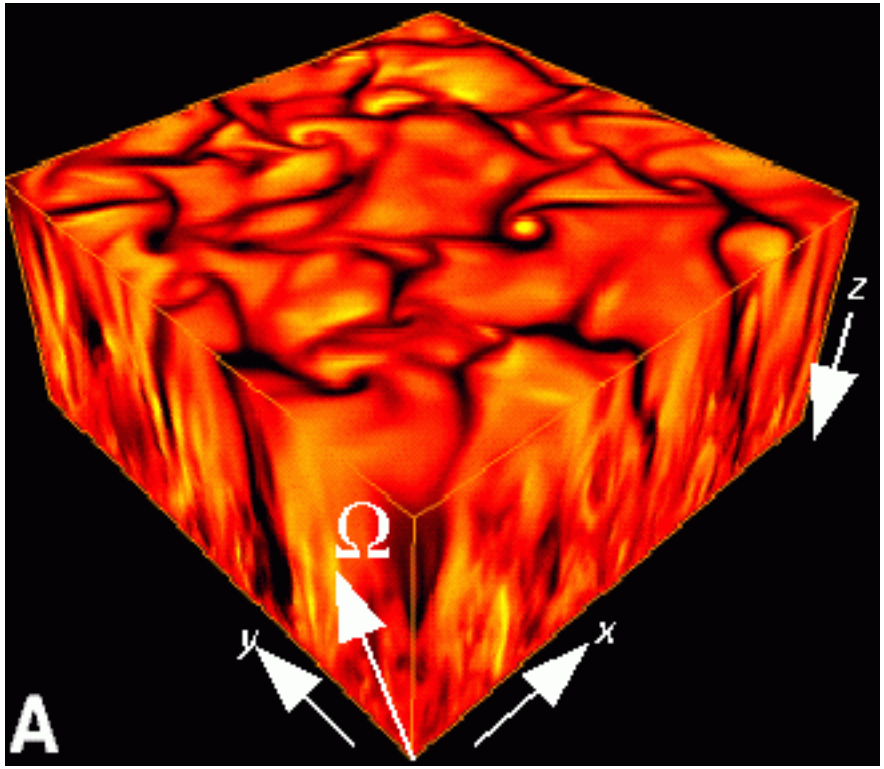
Envelope helium abundance

Probing the Sun: νs from pp-chains

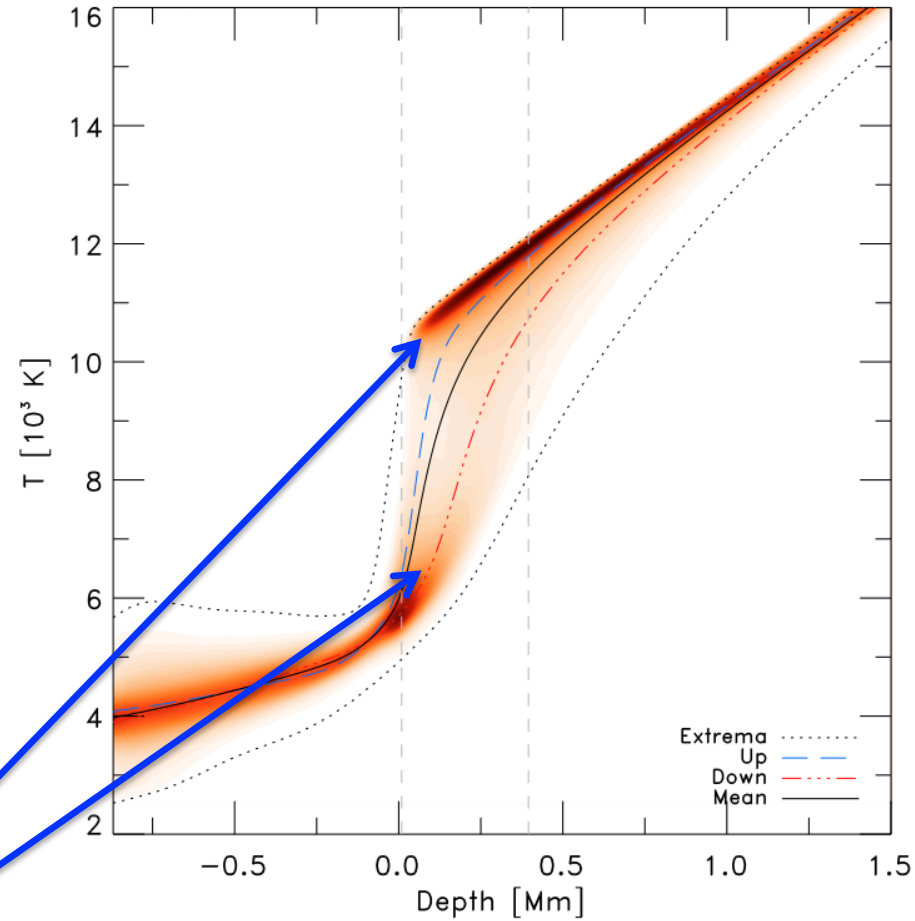


Solar Atmospheres & Abundances

Dealing with convection



Credit: N. Brummell



Hard to model with 1D models

Magic et al. 2014

Solar Abundances: End Product

* 3D-RHD simulations of solar convection

* improved atomic data (e.g. line blends)

* NLTE line formation for certain elements

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

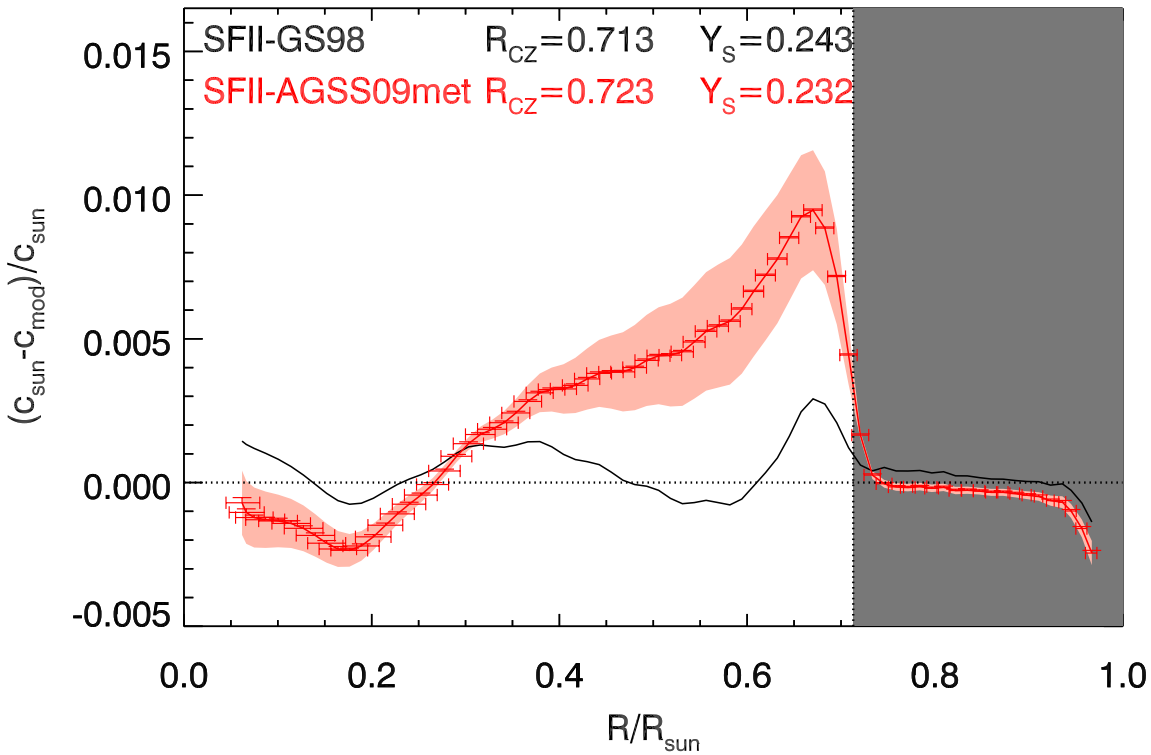
Differences of

CNO(Ne)~30-40%

refractories~10%

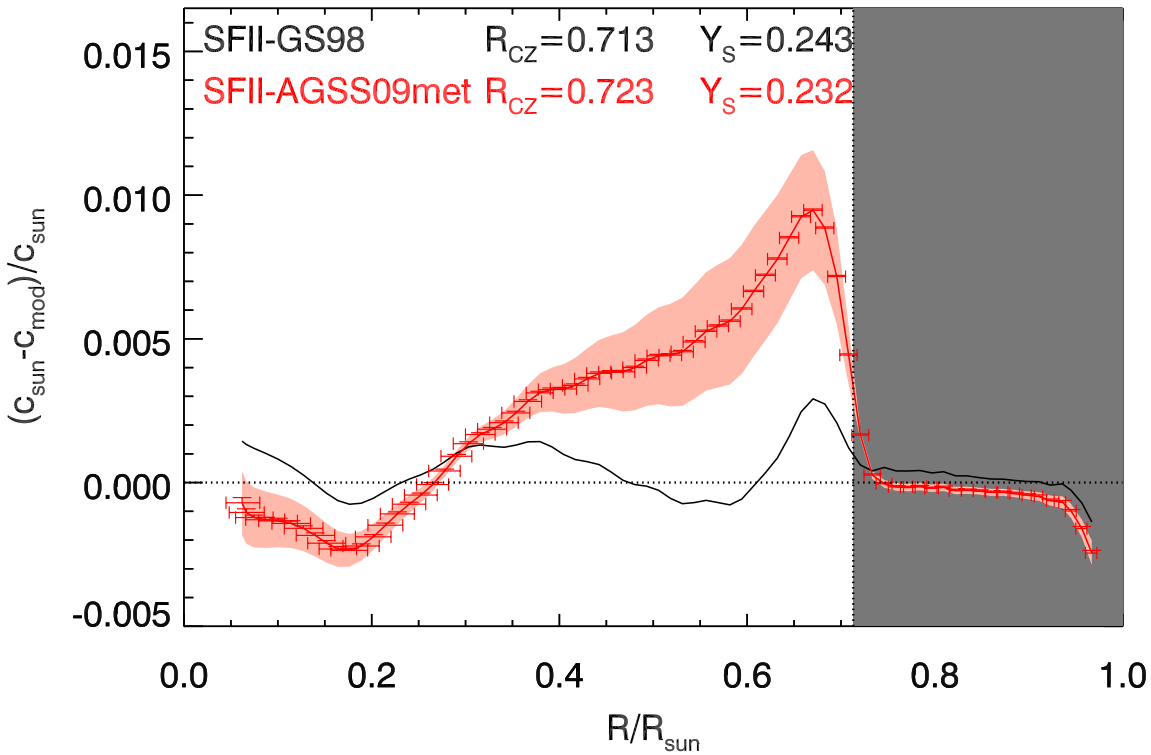
Standard Solar Models: Helioseismology

relative difference in sound speed



Standard Solar Models: Helioseismology

relative difference in sound speed

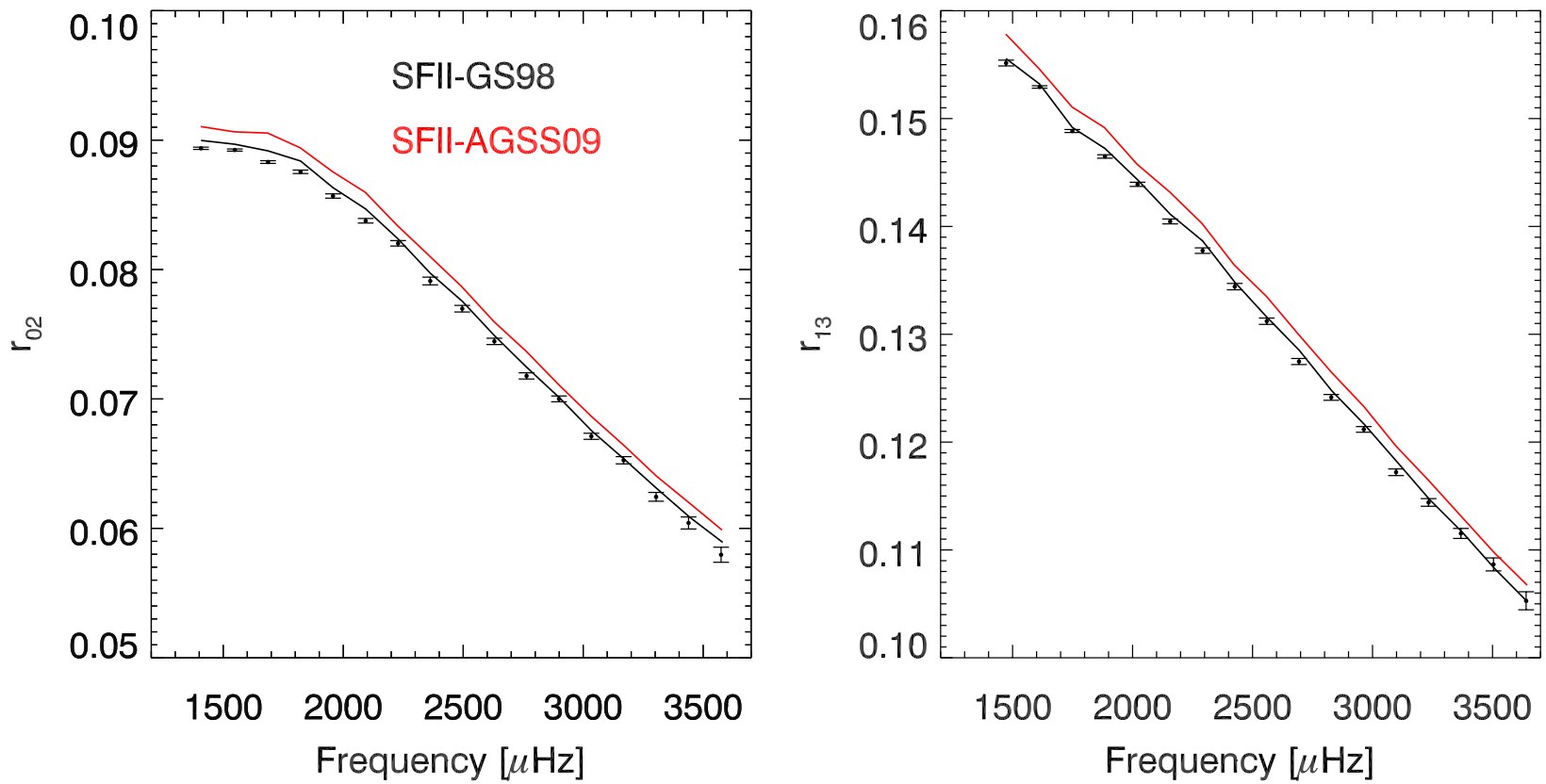


	GS98	AGSS09	Helios.
$(Z/X_\odot)$	0.0229	0.0178	—
$R_{CZ}/R_\odot$	0.712	0.723	0.713 ± 0.001
Y_S	0.2429	0.2319	0.2485 ± 0.0034
$\langle \delta c/c \rangle$	0.0009	0.0037	—
$\langle \delta \rho/\rho \rangle$	0.011	0.040	—

Standard Solar Models: Helioseismology

Frequency ratios sensitive to solar core

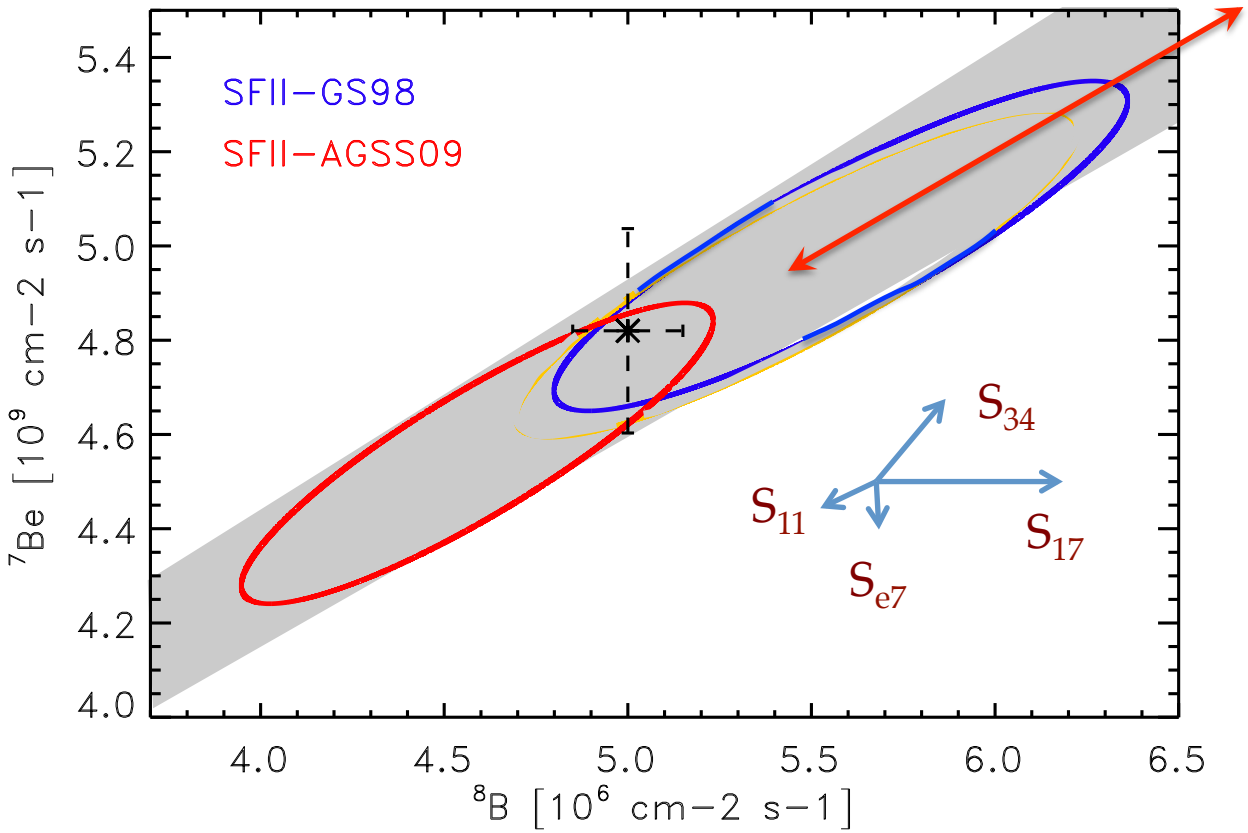
$$\int_0^R \frac{dc}{dr}\frac{dr}{r}$$



Standard Solar Models: Neutrinos

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

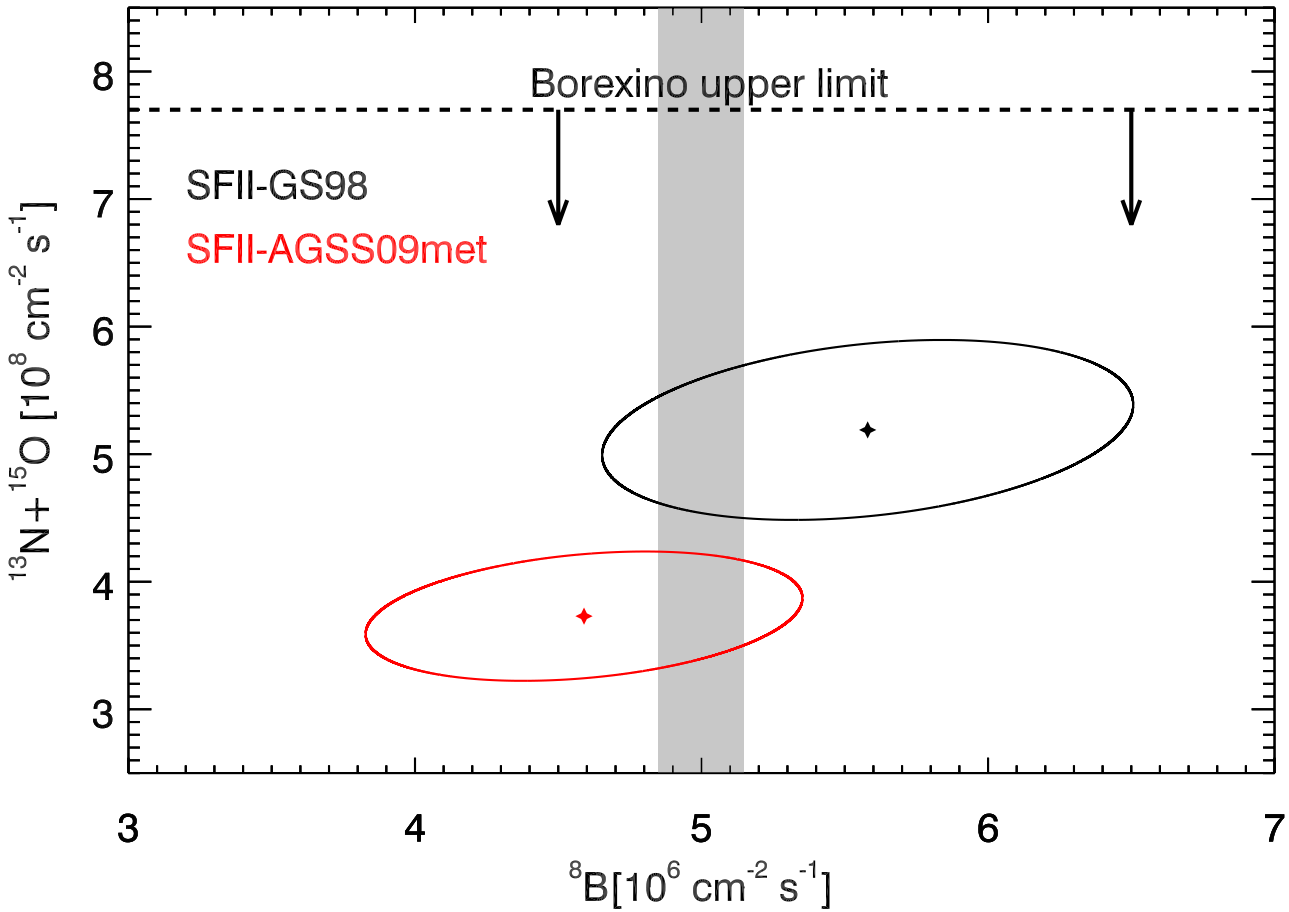
Dependence on core temperature



No current probe directly sensitive to composition (next talk by Villante)

Standard Solar Models: Neutrinos

CN(O) neutrinos store additional (linear) dependence



Next talk by F. Villante

Robust Inferences from SSMs?

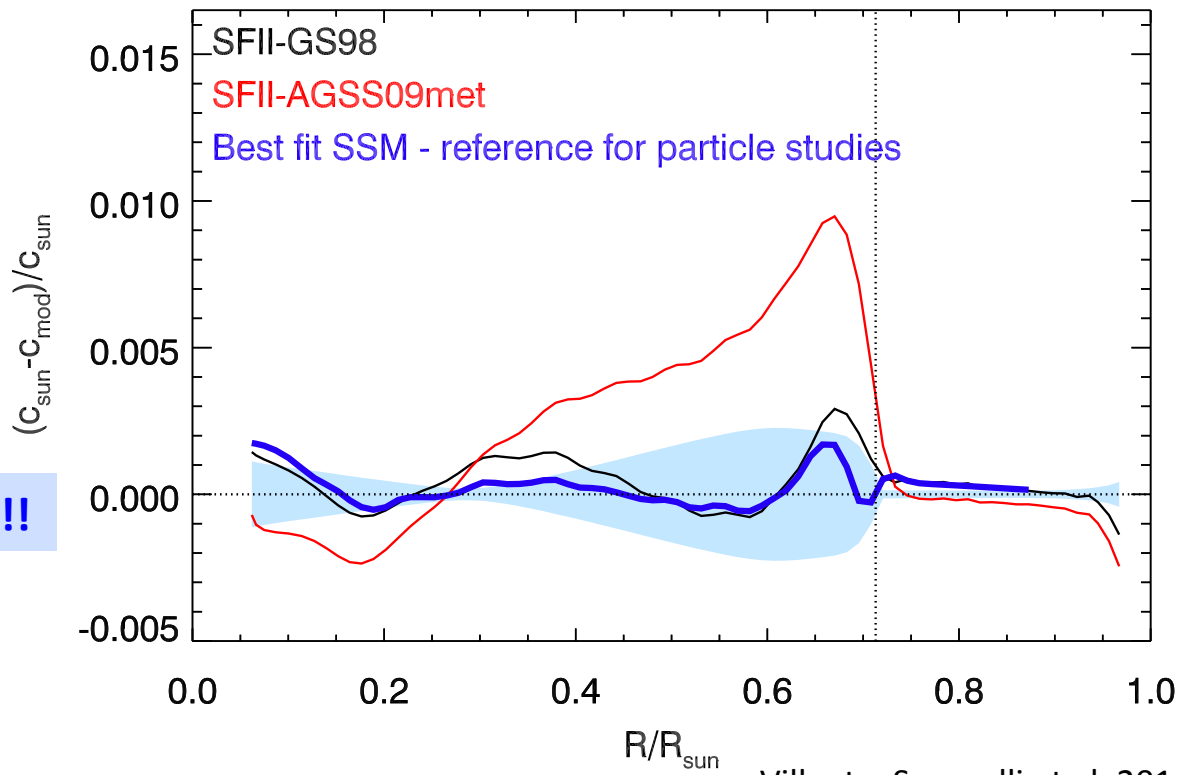
Phenomenological approach

-- > let input parameters vary and find SSM that best fits data

-- > changes in input parameters of order 1-σ & adjustment in composition

-- > excellent phenomenological description of solar structure

Even better than the real thing!!



Villante, Serenelli et al. 2014

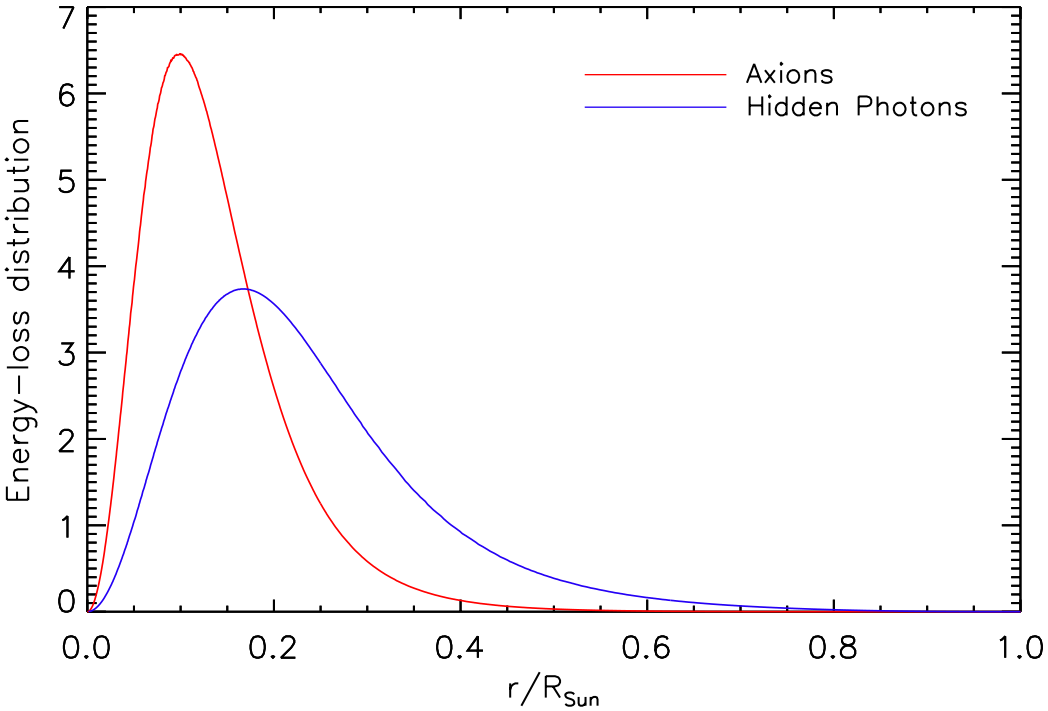
Extending the Method for Particle Studies

* Solar limits on axion-photon coupling (well-studied case – for comparison)

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

* Solar limits on hidden (dark) photons

$$\epsilon_{\rm hp} = \frac{\chi^2 m^2}{e^{\omega_P/T} - 1} \frac{\omega_P^3}{4\pi} \frac{1}{\rho} \sim \chi^2 m^2 T$$



No explicit composition dependence -- > relative changes are the same regardless composition

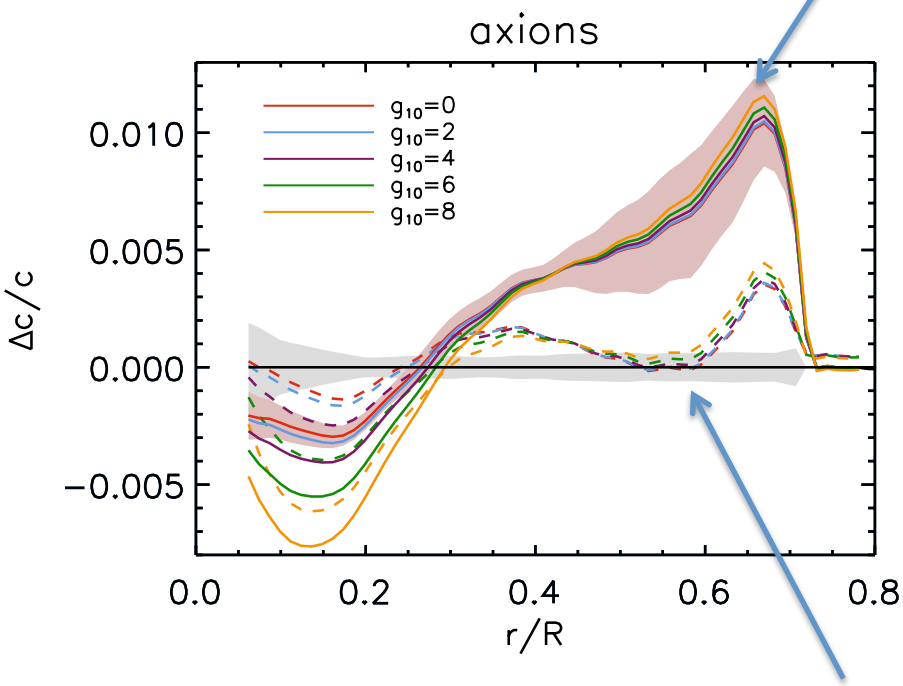
Robust limits as long as good T-ρ solar profiles

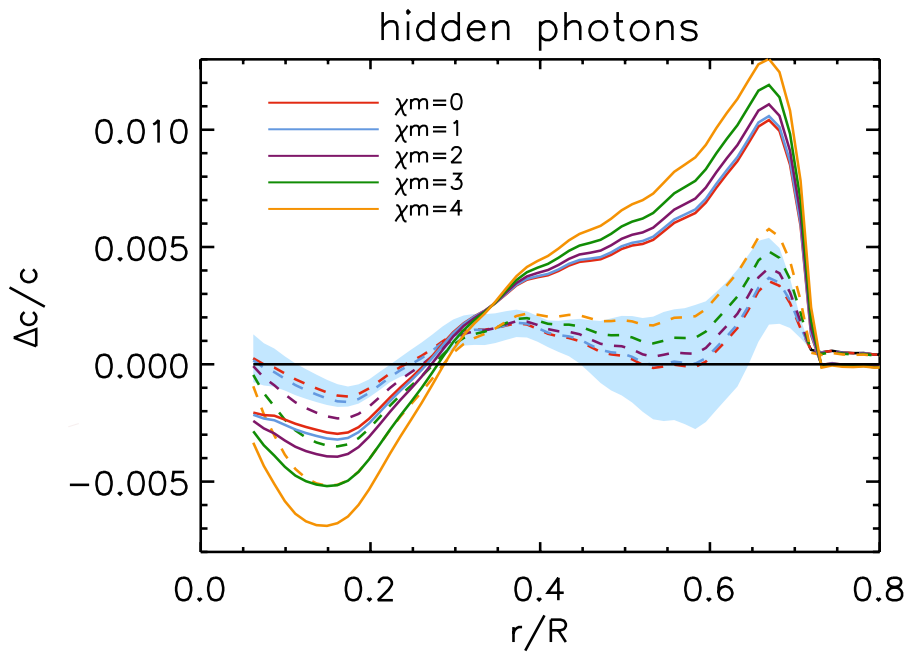
Vinyoles et al. arxiv:1501.01639

Extending the Method for Particle Studies

* Sound speed variations

AGSS09 – low Z

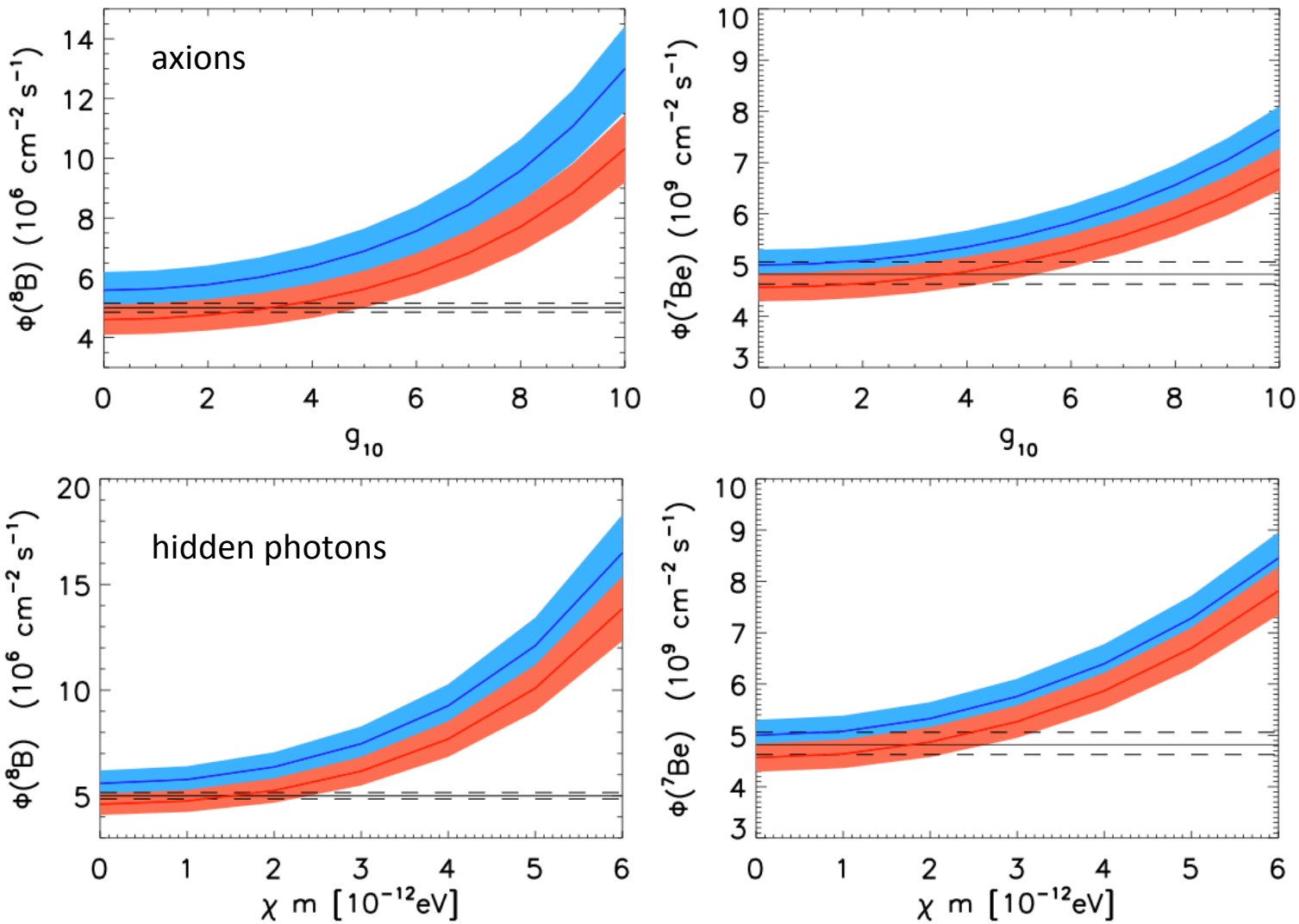




GS98 – high Z

Extending the Method for Particle Studies

* Variation of neutrino fluxes



Extending the Method for Particle Studies

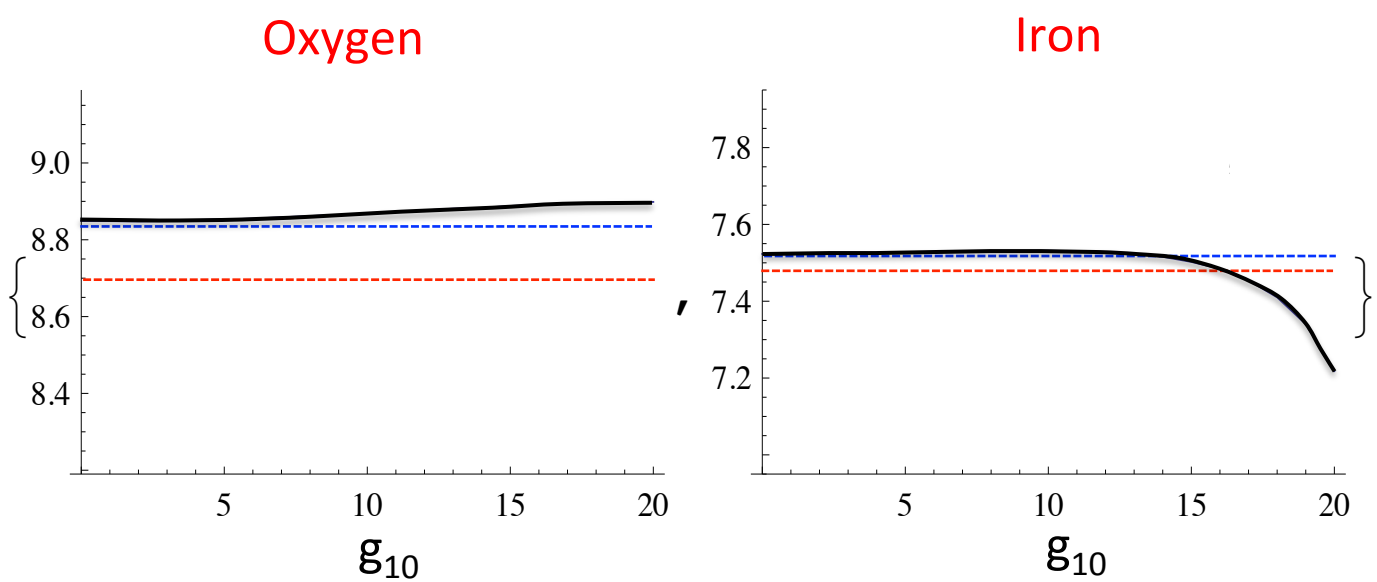
Our approach: input parameters absorb variations to get best possible fit –
e.g. increase metal abundances: freely or constrained by spectroscopy, S11, $L_{\odot}$, etc

Limits derived are based on forcing solar models (+ dark channel) to fit solar data as best as possible --- > limits then derived from irreducible residuals

Full solution: composition is free and pulls computed to minimize χ^2 for fixed g10

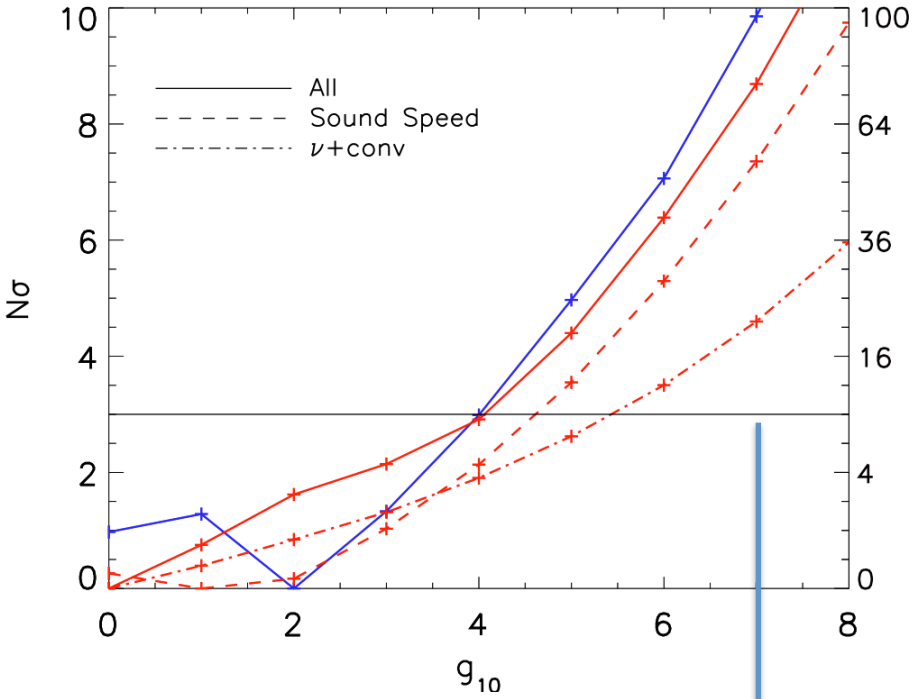
GS98 – high Z

AGSS09 – low Z



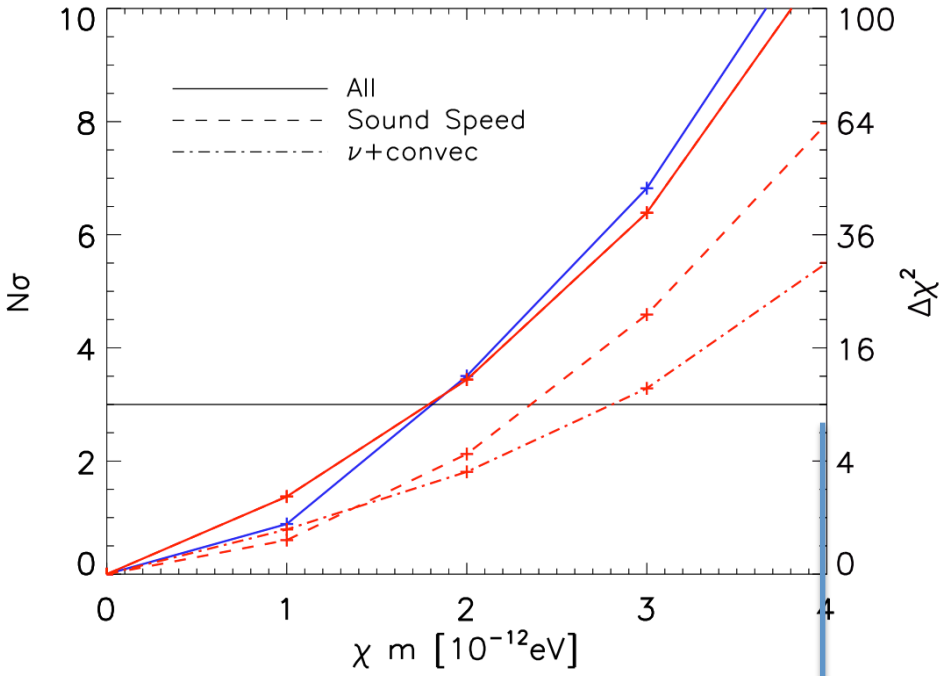
Extending the Method for Particle Studies

Final upper limit – $g_{10} < 4$ @ 3-σ C.L.
2 times better than previous solar limit



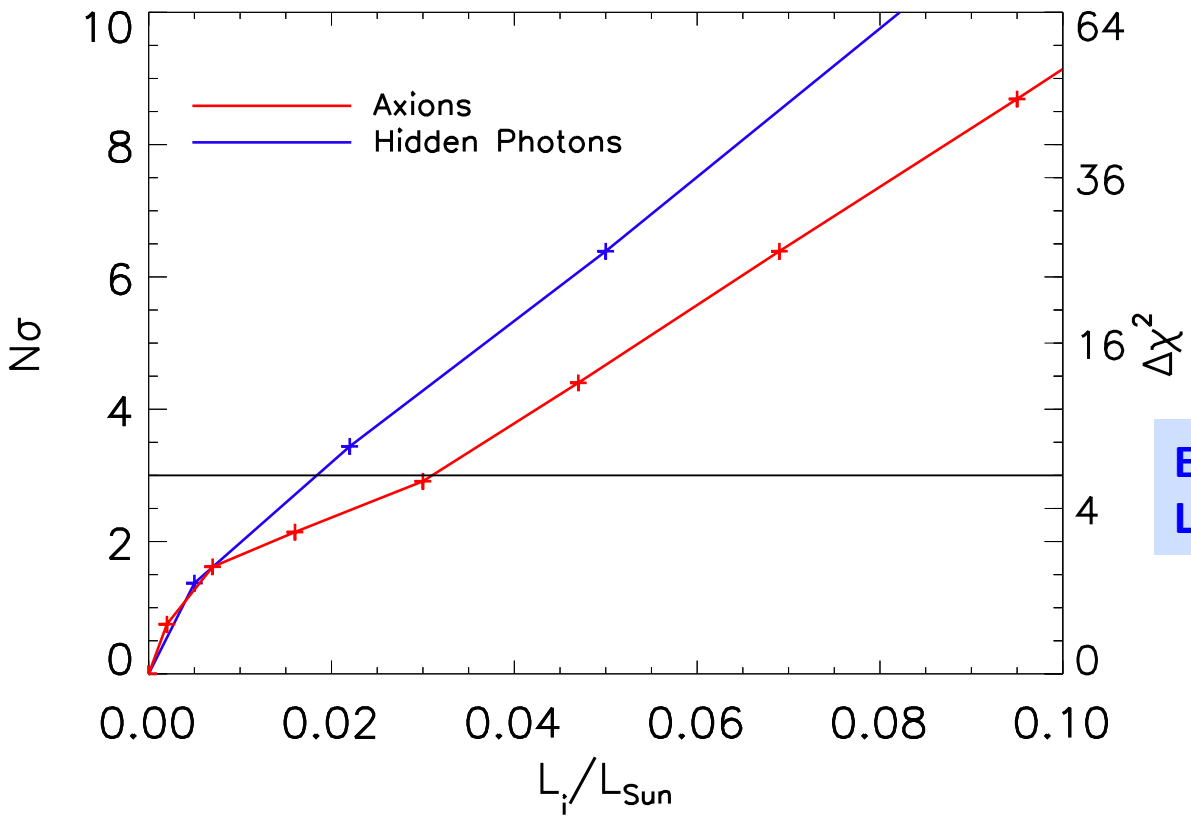
previous solar limit

χm < 2 @ 3-σ C.L.
improves previous limit by factor 2



previous solar limit

Comments on Solar Constraints

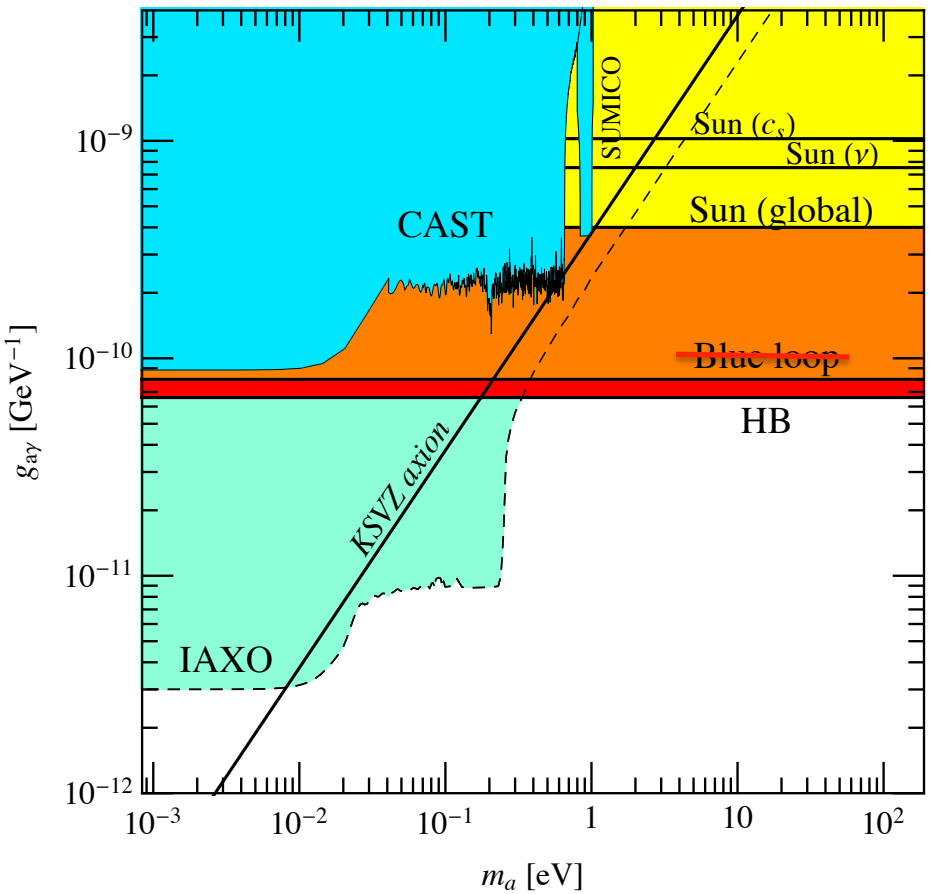


Effective limit in dark channels
$L_{hp} < 2\%\ L_\odot$ – $L_{a\gamma} < 3\%\ L_\odot$

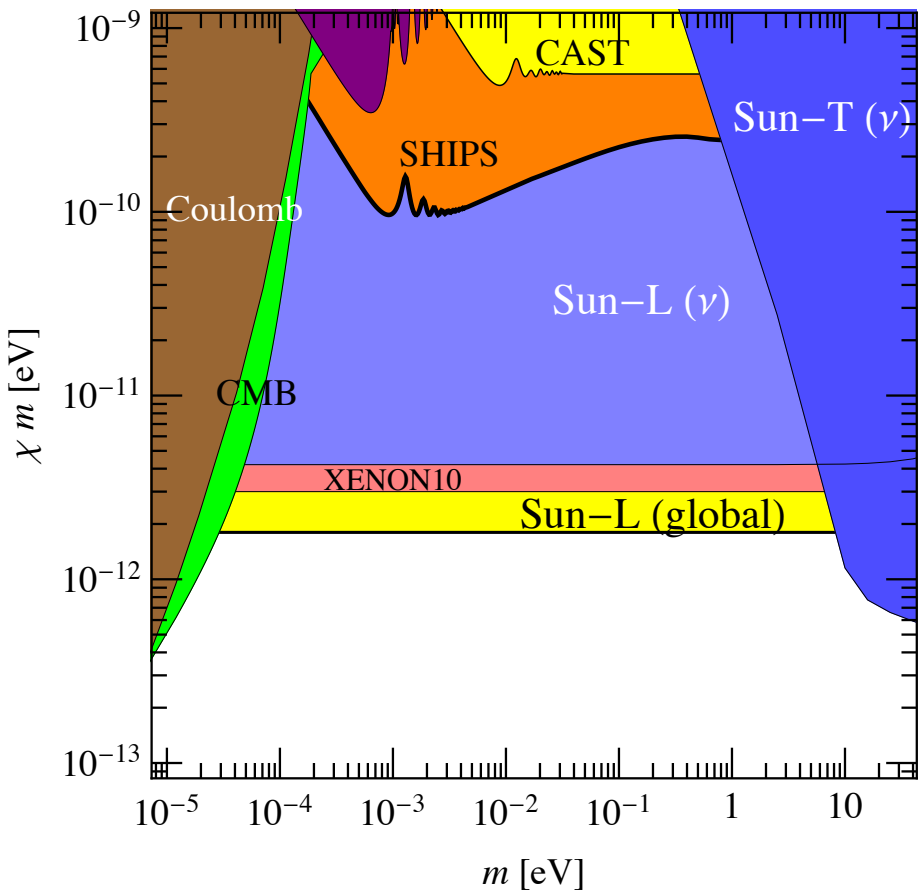
using pp ν flux offers a model independent test – but needs measurement ~ 1%

Current Limits

Hadronic axions



Hidden photons



Second Part --- ADM & Solar Abundance Problem

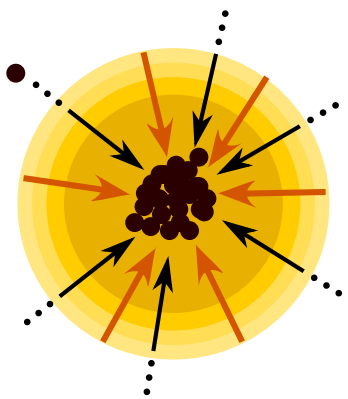
Vincent et al. – arxiv:1411.6626 / 1504.04378

DM-nucleon scattering allows DM collisions with nuclei in the Sun

→ gravitational capture and settling the to solar core

→ nuclear scattering inside the Sun

→ additional energy transport (abundance problem)



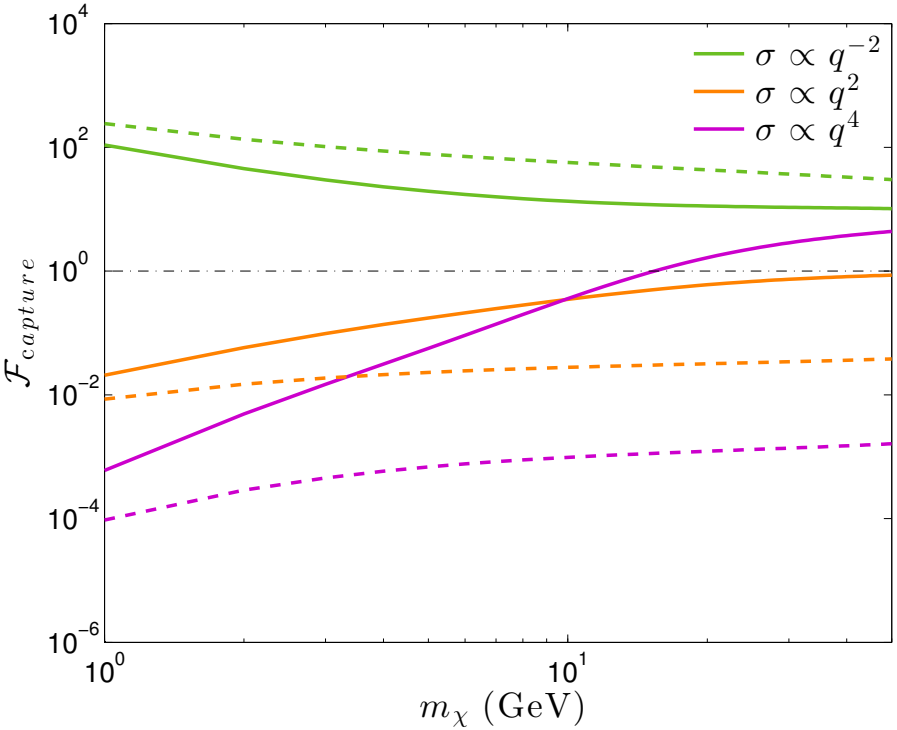
helioseismology

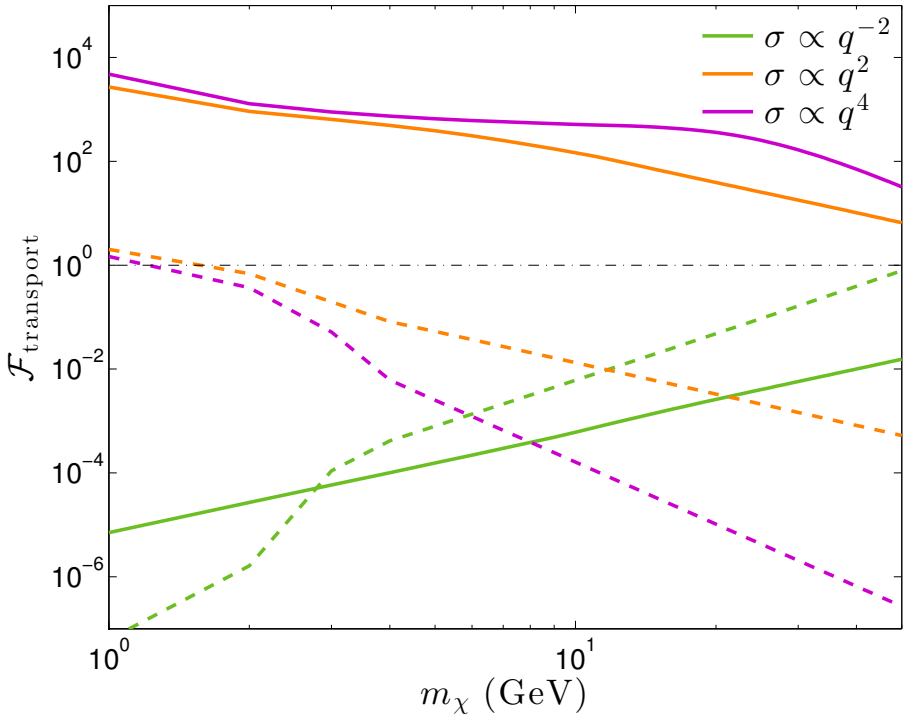
solar neutrinos

Capture & Transport

Enhancement/suppresion factors

$$\sigma = \sigma_0 \left(\frac{q}{q_0}\right)^{2n} \qquad \sigma = \sigma_0 \left(\frac{v_{\rm rel}}{v_0}\right)^{2n}$$

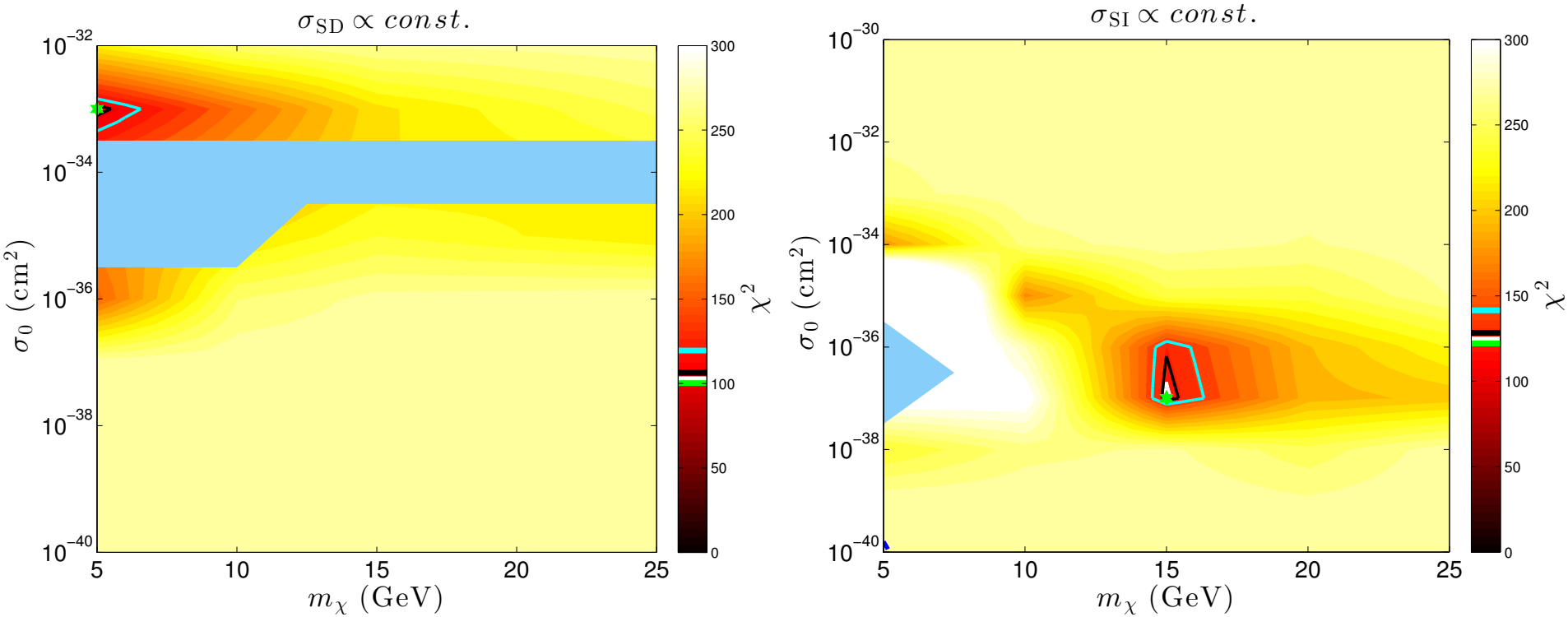




$\sigma_0 = 10^{-35}$ cm^2

Solid = SI, Dashed = SD

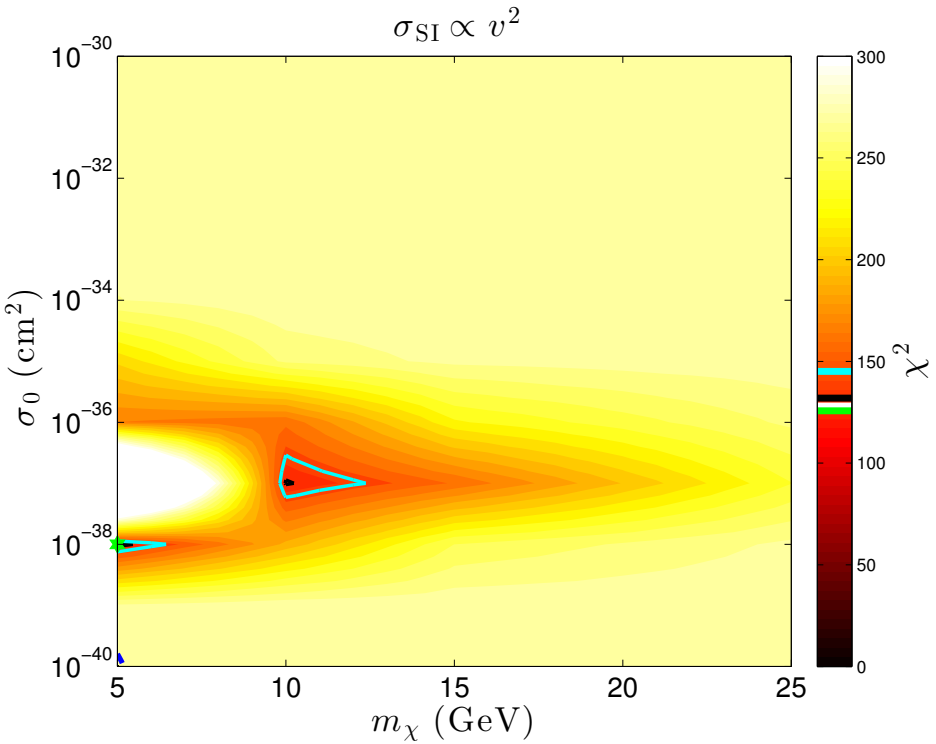
Impact on Observables: SD, SI - constant

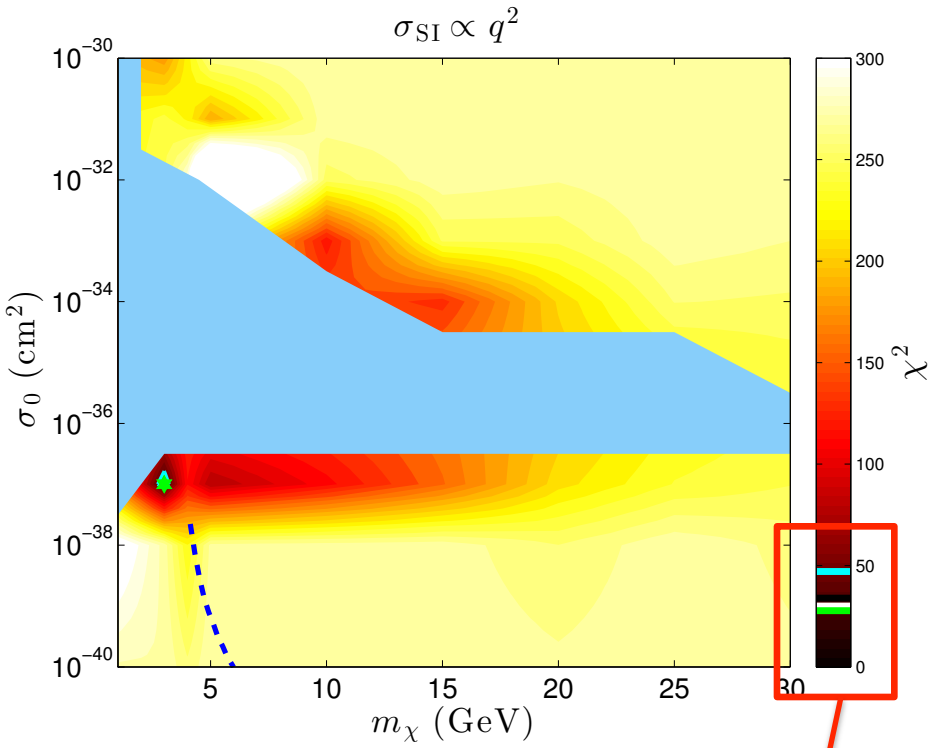


^{7}Be & ^{8}B neutrinos + convective radius + surface helium

Frequency separation ratios r_{02}, r_{13}

Impact on Observables: SI, v^2, q^2





^{7}Be & ^{8}B neutrinos + convective radius + surface helium

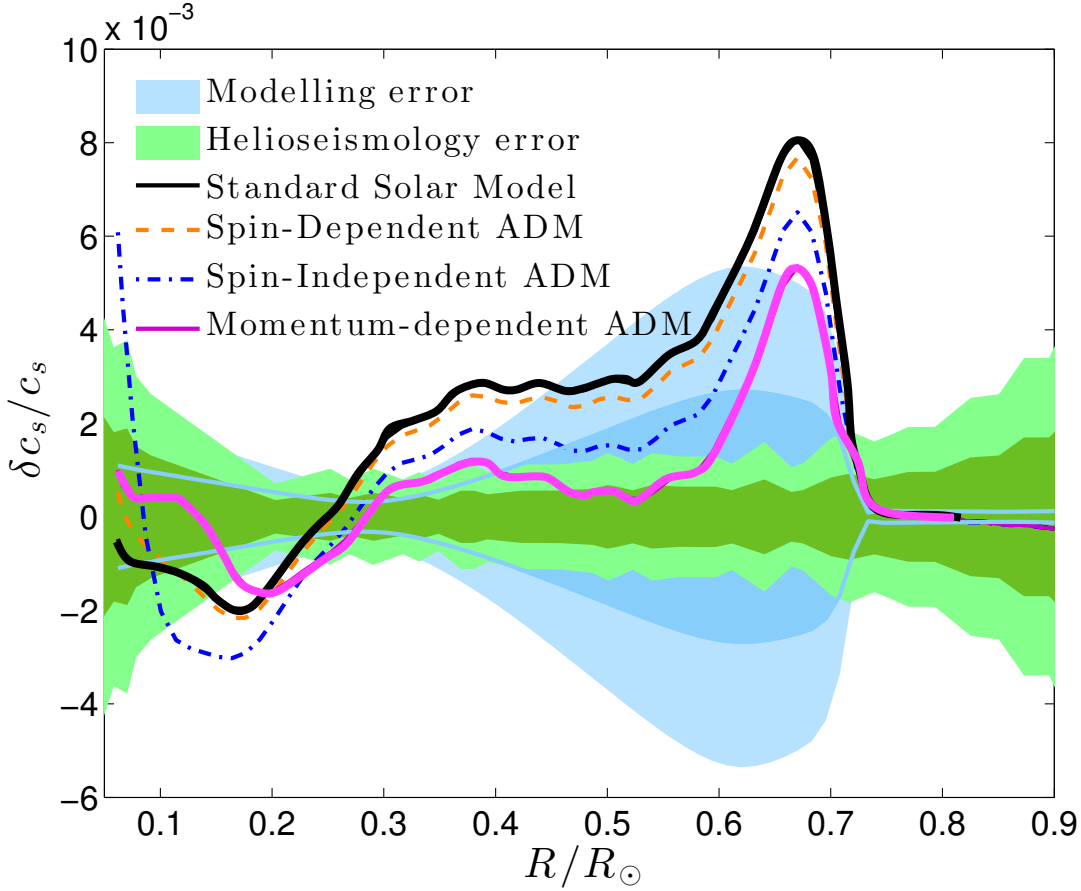
Frequency separation ratios r_{02}, r_{13}

Notice χ^2

Best Model – q^2

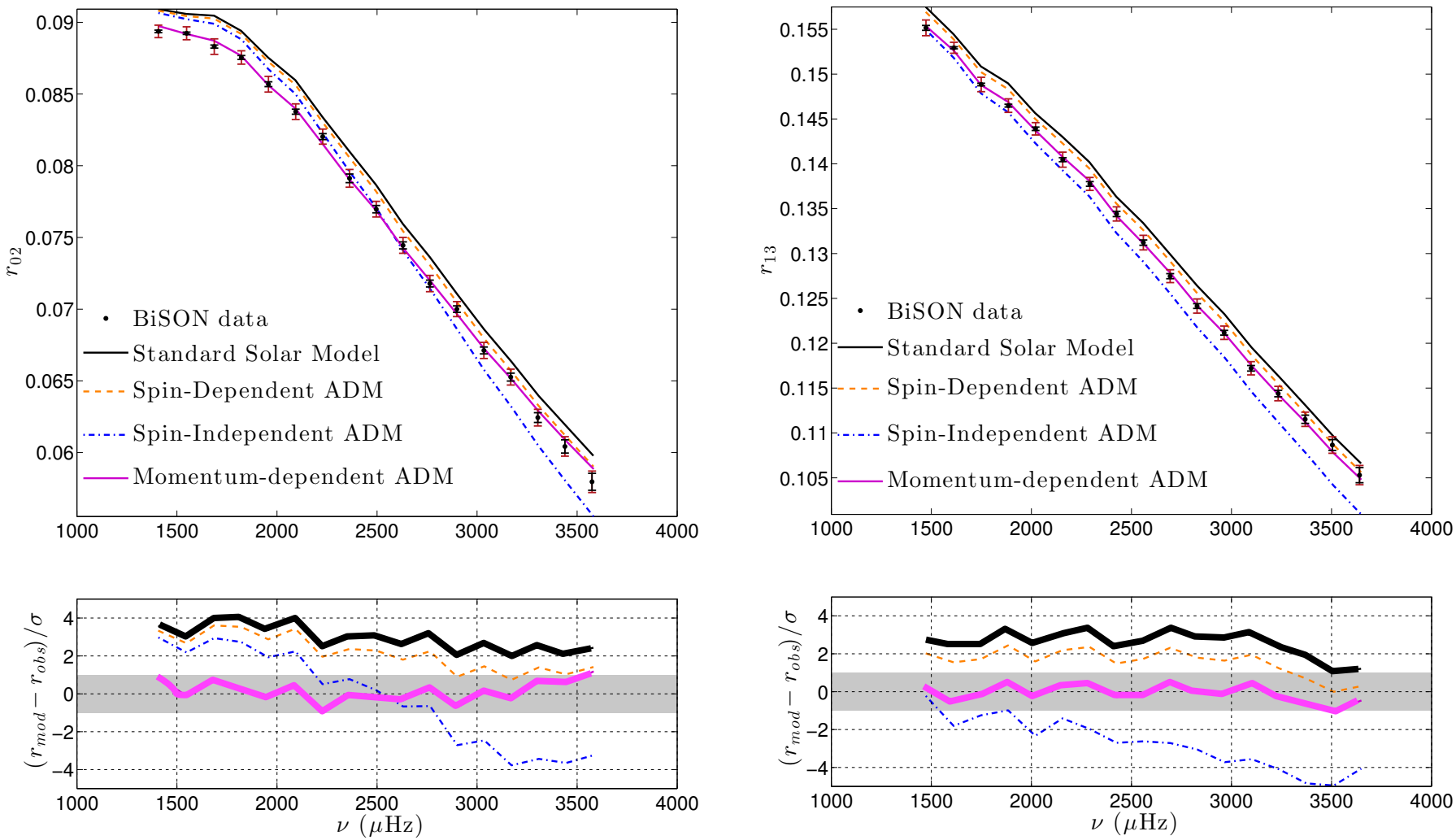
Sound speed for best q^2 SI and SD models

q^2 coupling
q_0= 40 MeV
m_χ = 3 GeV
σ_0 = 10^{-37} cm^2



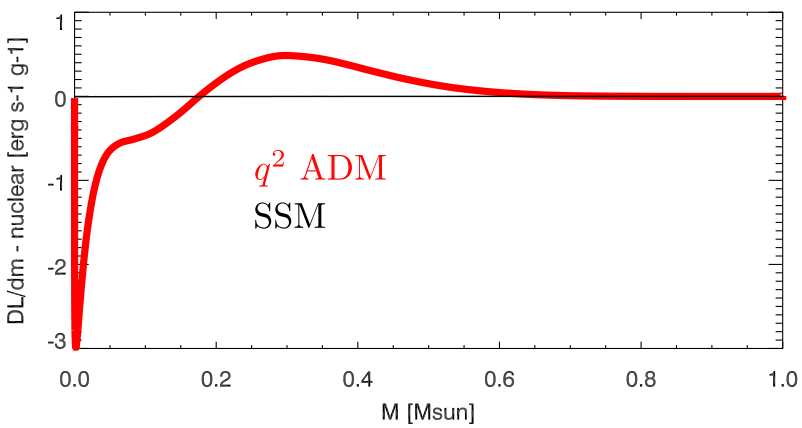
Best Model – q^2

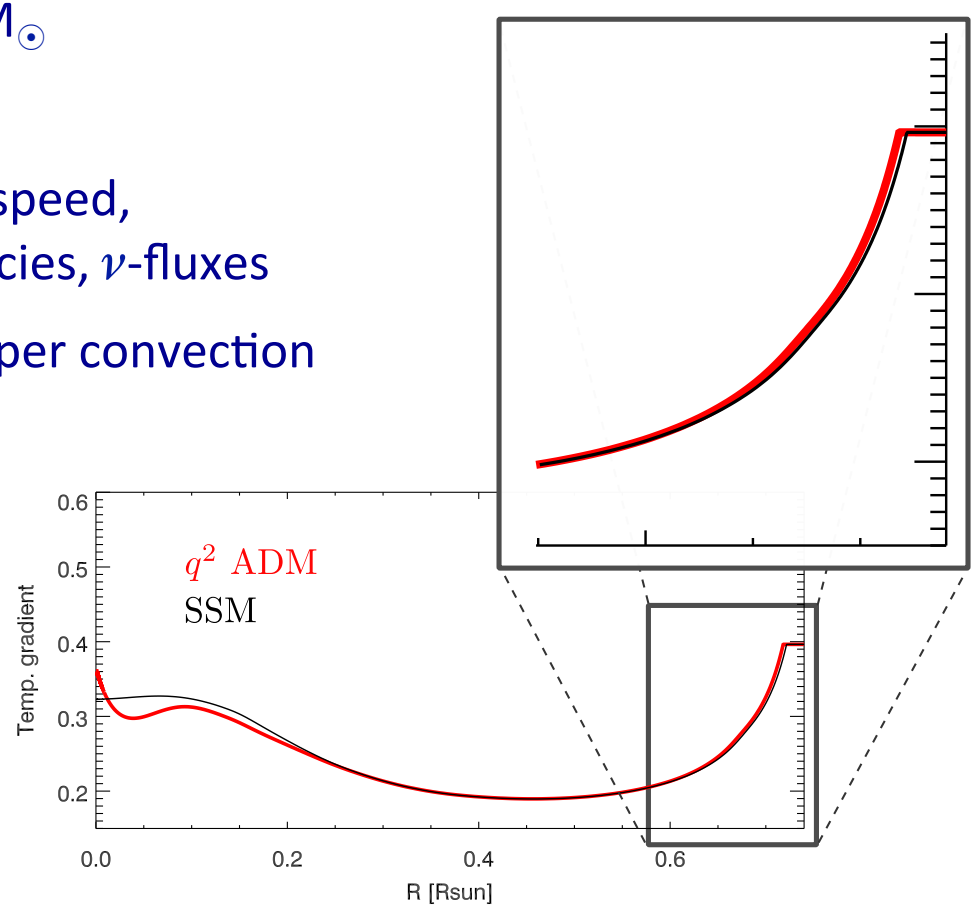
Frequency separation ratios – zooming into the solar core



Changes to Solar Structure

* Energy extracted from core M < 0.2 $M_\odot$
* Deposited at intermediate range
* Core change in T-gradient -- > sound speed, frequencies, ν-fluxes
* Smaller T-grad. change at R_{CZ} -- > deeper convection





Best Model – q^2

	SSM	SD	SI	q^2 SI	Obs.[a]	$\sigma_{\rm obs}$	$\sigma_{\rm model}$
$\phi_\nu^{^8\rm B}$ [b]	4.95	4.39	4.58	3.78	5.00	3%	14%
$\phi_\nu^{^7\rm Be}$ [c]	4.71	4.58	4.62	4.29	4.82	5%	7%
$R_{\rm CZ}/R_\odot$	0.722	0.721	0.721	0.718	0.713	0.001	0.004
$Y_{\rm s}$	0.2356	0.2351	0.2353	0.2327	0.2485	0.0034	0.0035
$\chi^2_{^8\rm B}$	0.0	0.9	0.9	4.9			
$\chi^2_{^7\rm Be}$	0.1	0.4	0.4	1.9			
$\chi^2_{R_{\rm CZ}}$	4.8	3.8	3.8	1.5			
$\chi^2_{Y_{\rm s}}$	7.0	7.5	7.3	10.5			
$\chi^2_{r_{02}}$	156.6	95.3	105.2	5.6			
$\chi^2_{r_{13}}$	119.3	50.7	67.2	3.1			
$\chi^2_{\rm total}$	287.8	158.5	185.2	27.5			
p	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	0.845			

Summary

First part

* Recap on standard solar models and solar abundance problem
* relevance of CNO
* SSM with correct T-ρ structure from data -- > phenomenological description of solar interior
* Extension to axion and hidden photons -- > new solar limits lower by x2

Second part

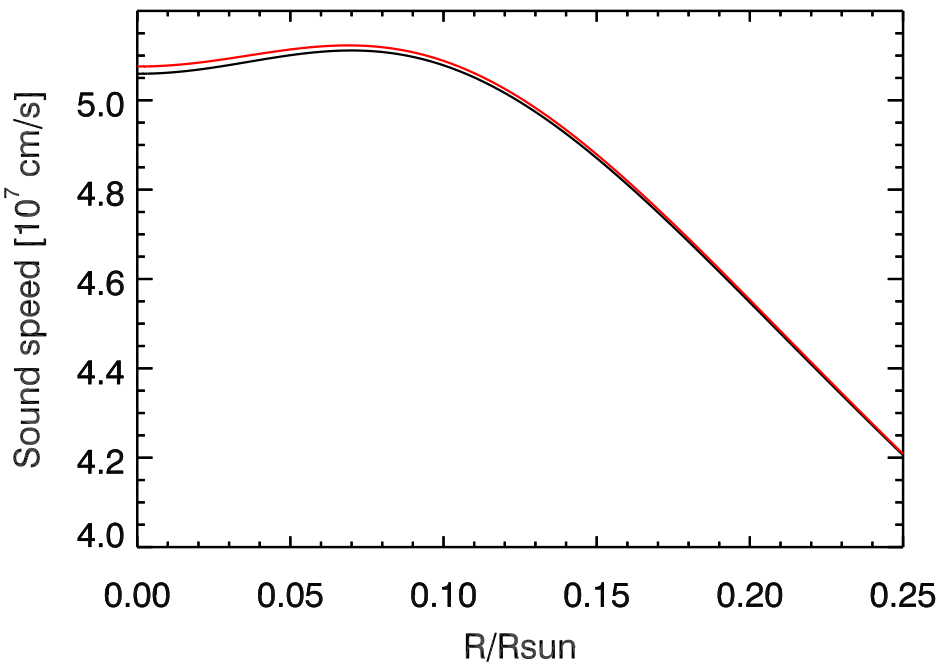
* Momentum exchange q^2 ADM models -- > agreement in solar data and models (σ_0=10^{-37} cm^2, m_χ = 3 GeV)
* Preferred mass and x-section range not excluded by direct experiment
* Caveat: evaporation not accounted for (will do)

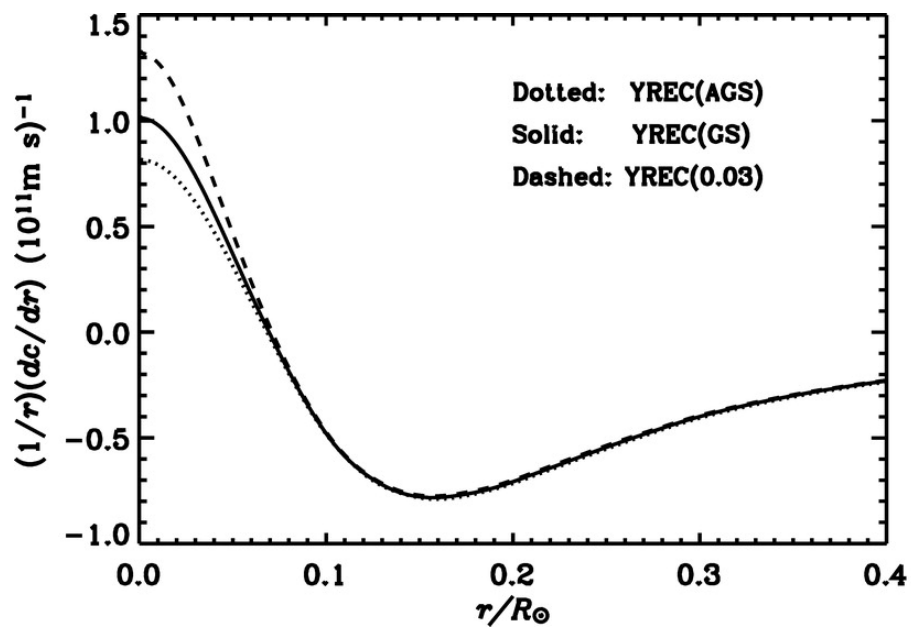
Extra Slides

Helioseismology

Low degree modes; l=0, 1, 2, 3 – frequency separation ratios

$$\left.\begin{aligned} r_{02} &= \frac{\nu_{n,0}-\nu_{n-1,2}}{\nu_{n,1}-\nu_{n-1,1}} \\ r_{13} &= \frac{\nu_{n,1}-\nu_{n-1,3}}{\nu_{n+1,0}-\nu_{n,0}} \end{aligned}\right\} \propto \int_0^R \frac{dc}{dr}\frac{dr}{r}$$

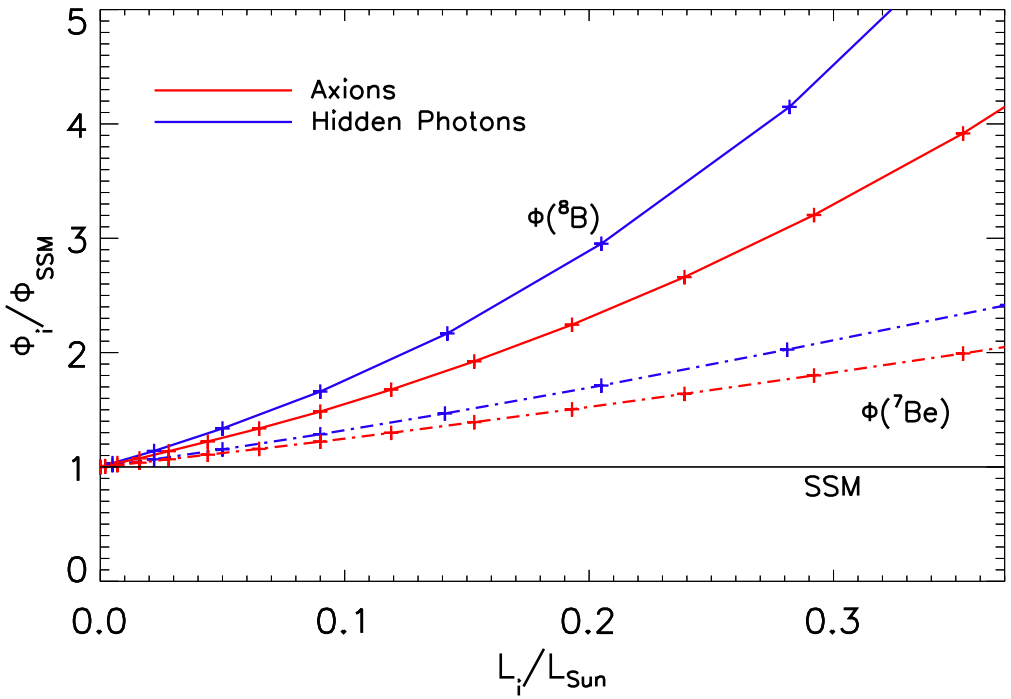




Frequency ratios: probing solar core

Extending the Method for Particle Studies

* Variation of neutrino fluxes



$$\frac{\Phi(^8\mathrm{B})}{\Phi_{\mathrm{SSM}}(^8\mathrm{B})} = \left(\frac{L_x + L_\odot}{L_\odot}\right)^\alpha$$

α= 4.4 (ax)

α= 5.7 (hp)

Testing the Method: Axions-Photon Coupling

Solar limits on axion-photon coupling

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

Schlattl et al. 1999 – $g_{10} < 10$

Sound speed at $R = 0.1\ R_\odot$ – equivalent to $L_a < 0.2\ L_\odot$

Gondolo & Raffelt 2009 – $g_{10} < 7$

^8B flux $< 1.5\ ^8B_{SSM}$ (3-σ) – equivalent to $L_a < 0.1\ L_\odot$

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

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

seismic (not evolutionary models – neglect basic physics)

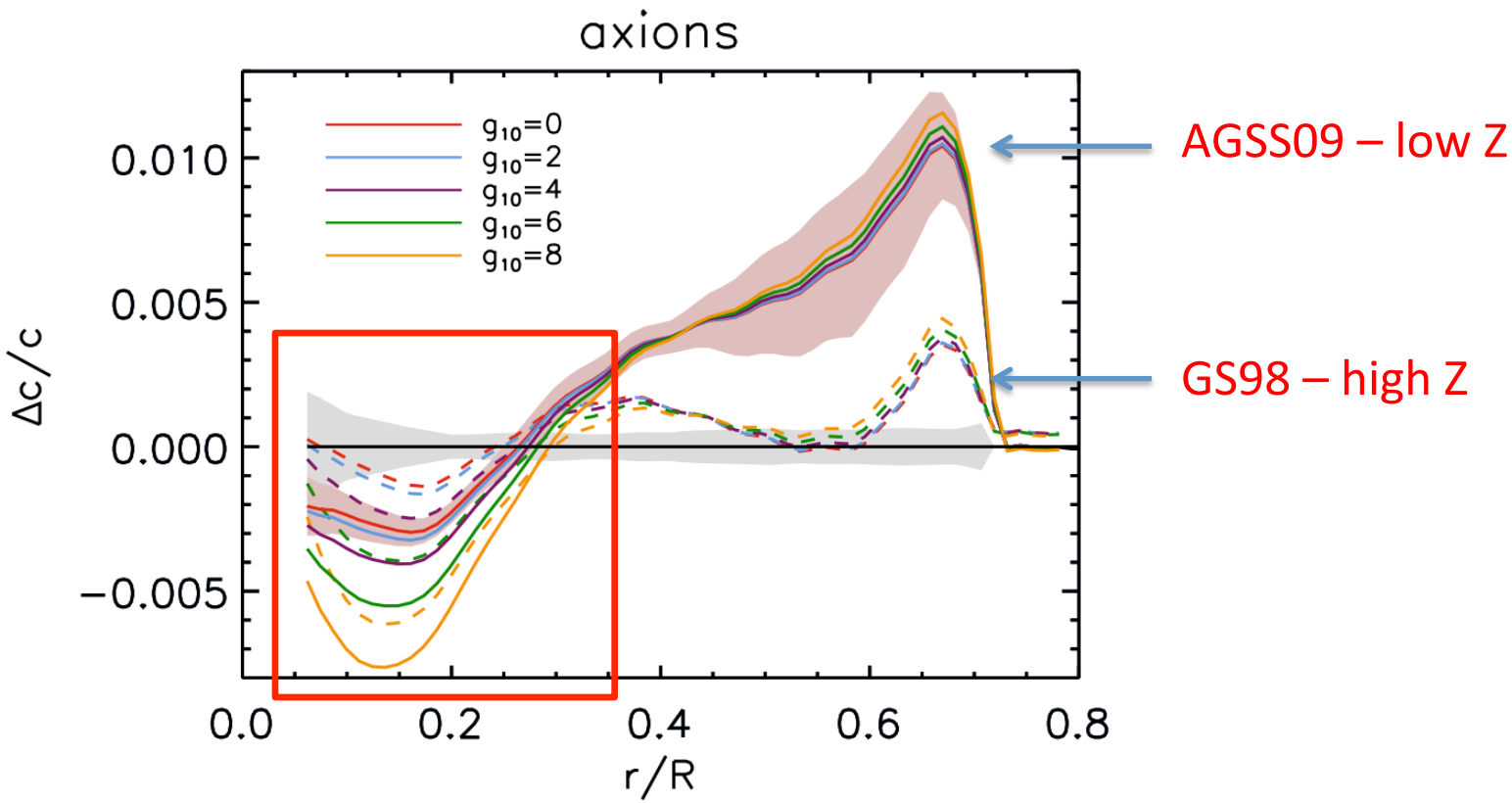
Vinyoles et al. 2015 – g10 < 4 (3-σ)

seismic + neutrino data

extend the method used to construct best-fit SSM

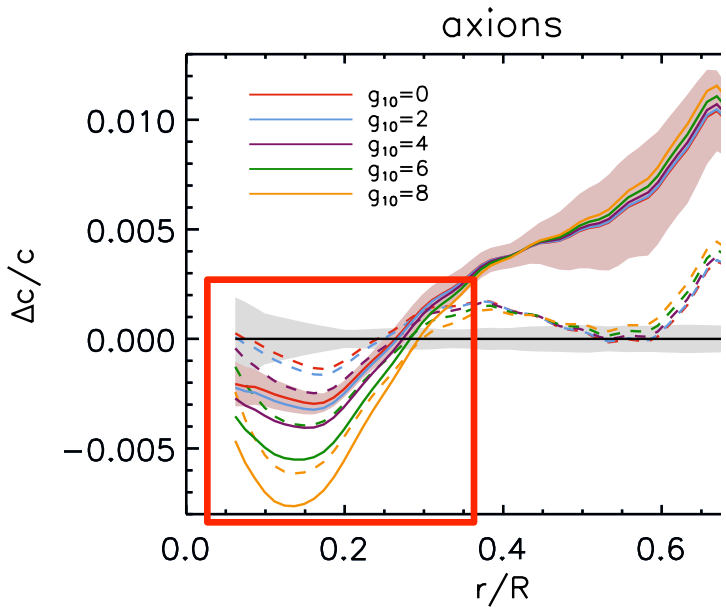
Testing the Method: Axions-Photon Coupling

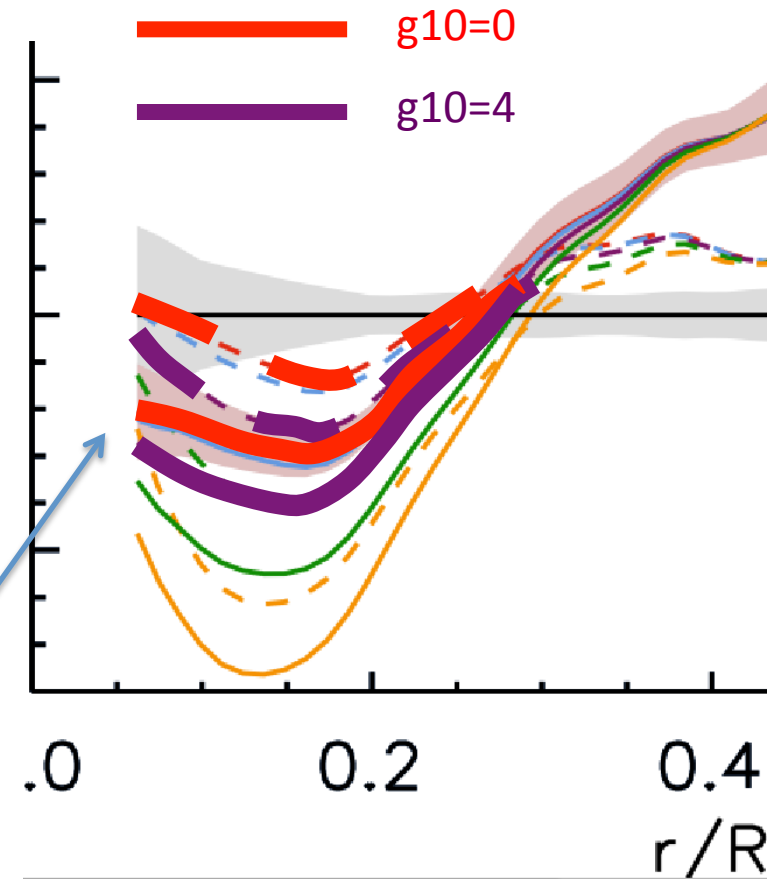
Variations in sound speed without variations in composition and pulls



Extending the Method for Particle Studies

* Sound speed variations

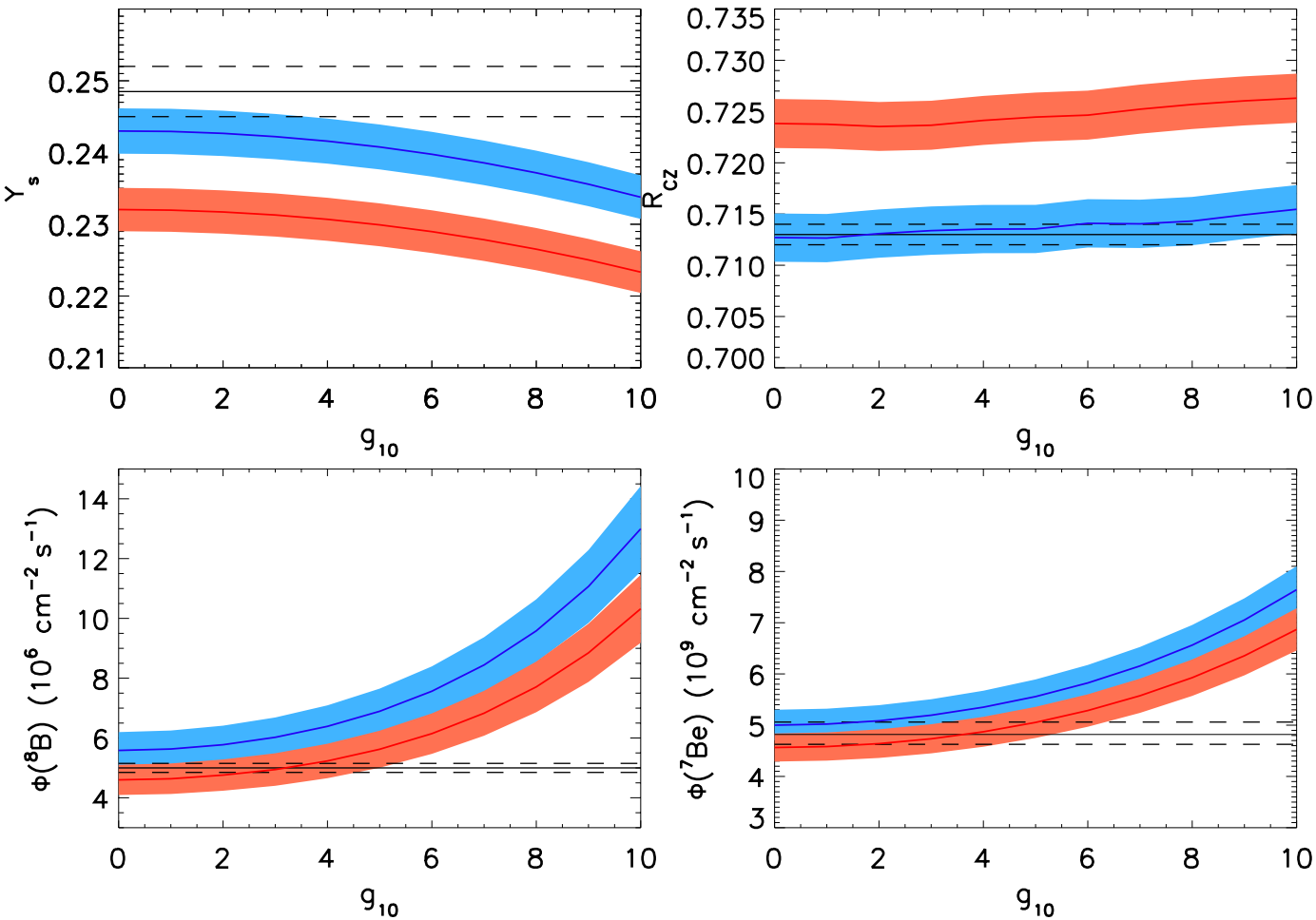




Relative changes are similar regardless of solar composition

Testing the Method: Axions-Photon Coupling

Variations in other quantities without variations in composition and pulls



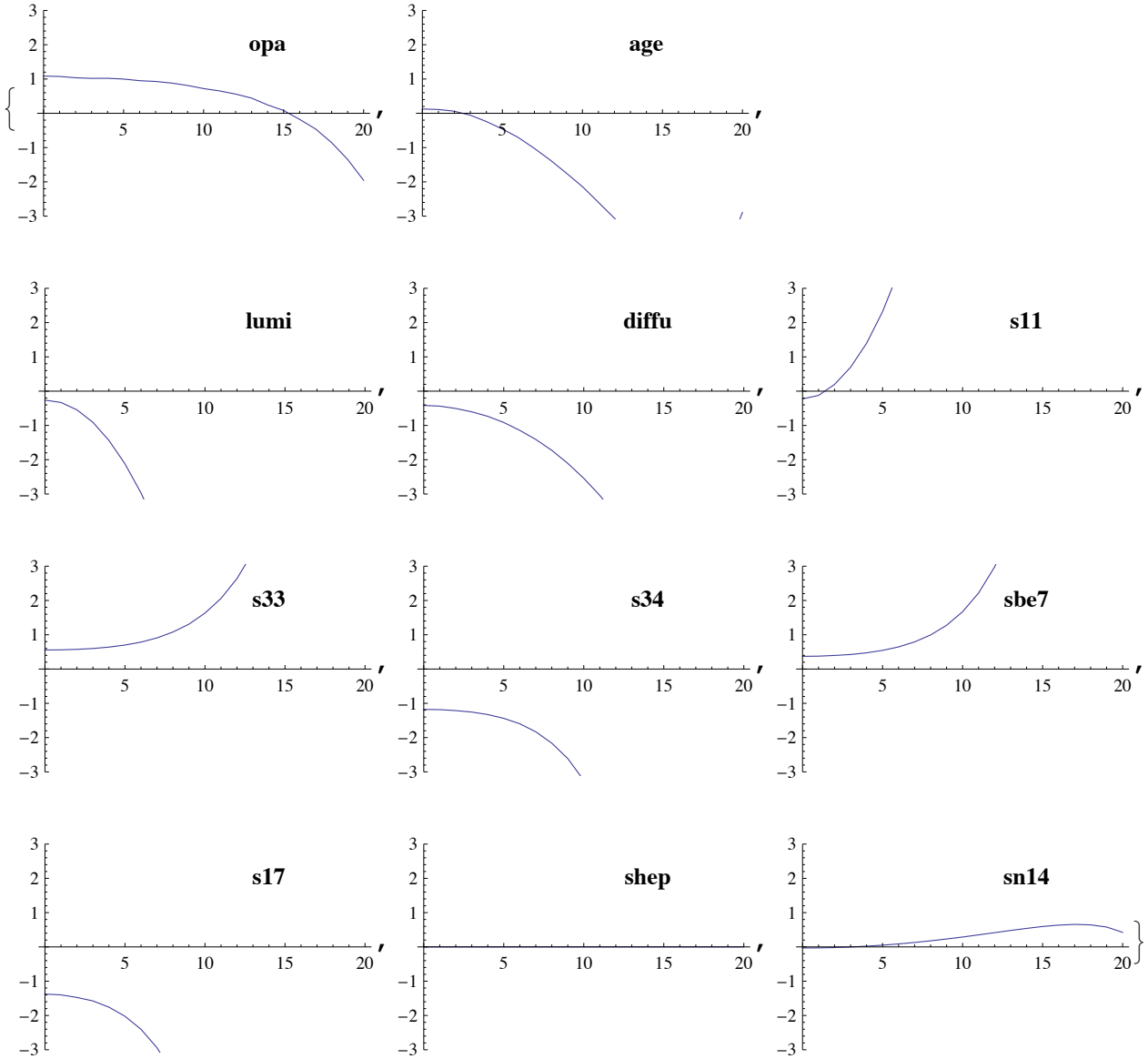
AGSS09 – low Z

GS98 – high Z

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

Testing the Method: Axions-Photon Coupling

sigmas



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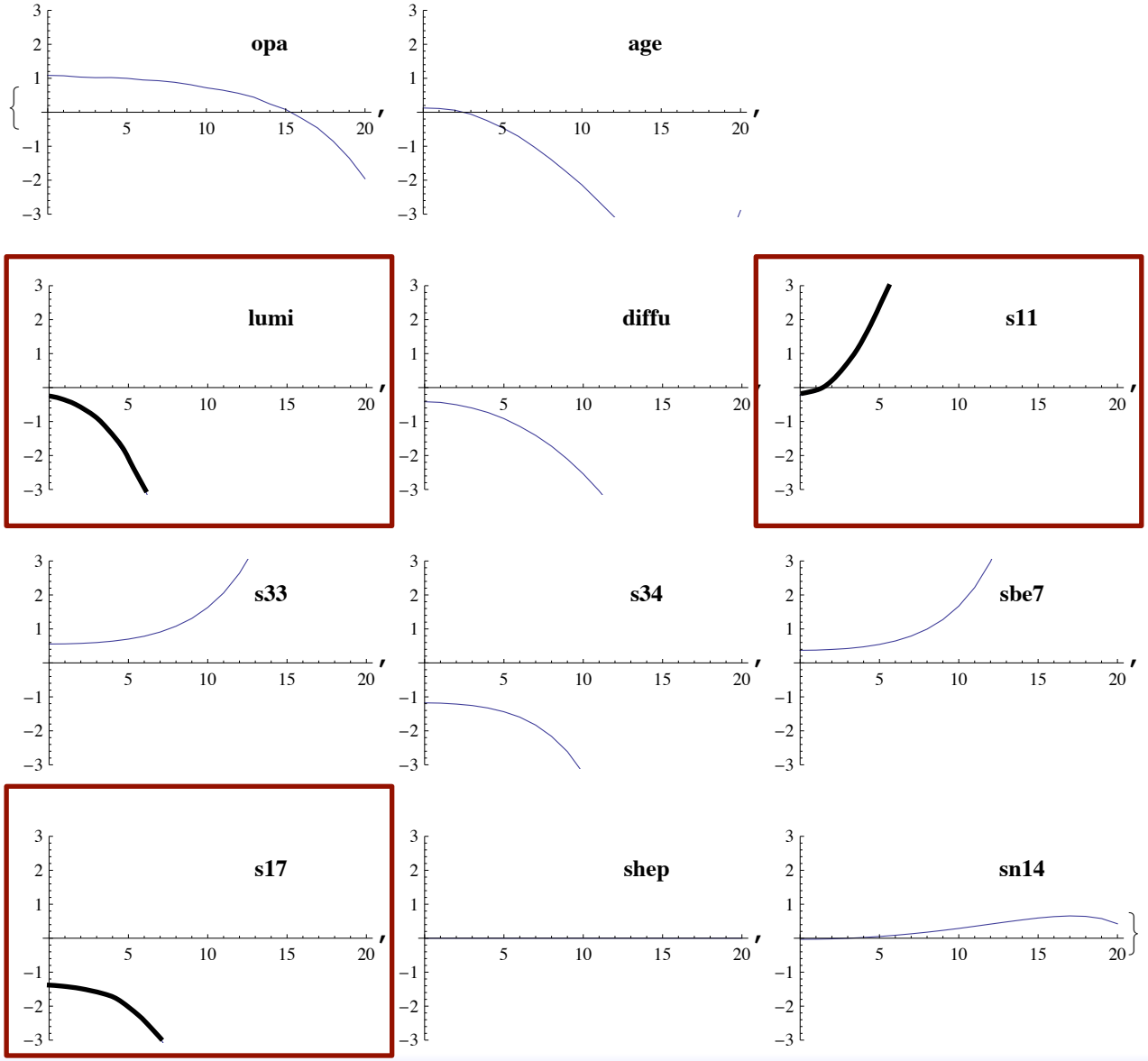


Recent Stellar Limits for $g_{a\gamma}$

Ayala et al. 2014 – $g_{10} < 0.66$

R parameter – HB/RGB stars – no syst. study of stellar uncertainties

He-core burning is a tricky business in stellar evolution

Friedland et al. 2013 – $g_{10} < 0.8$

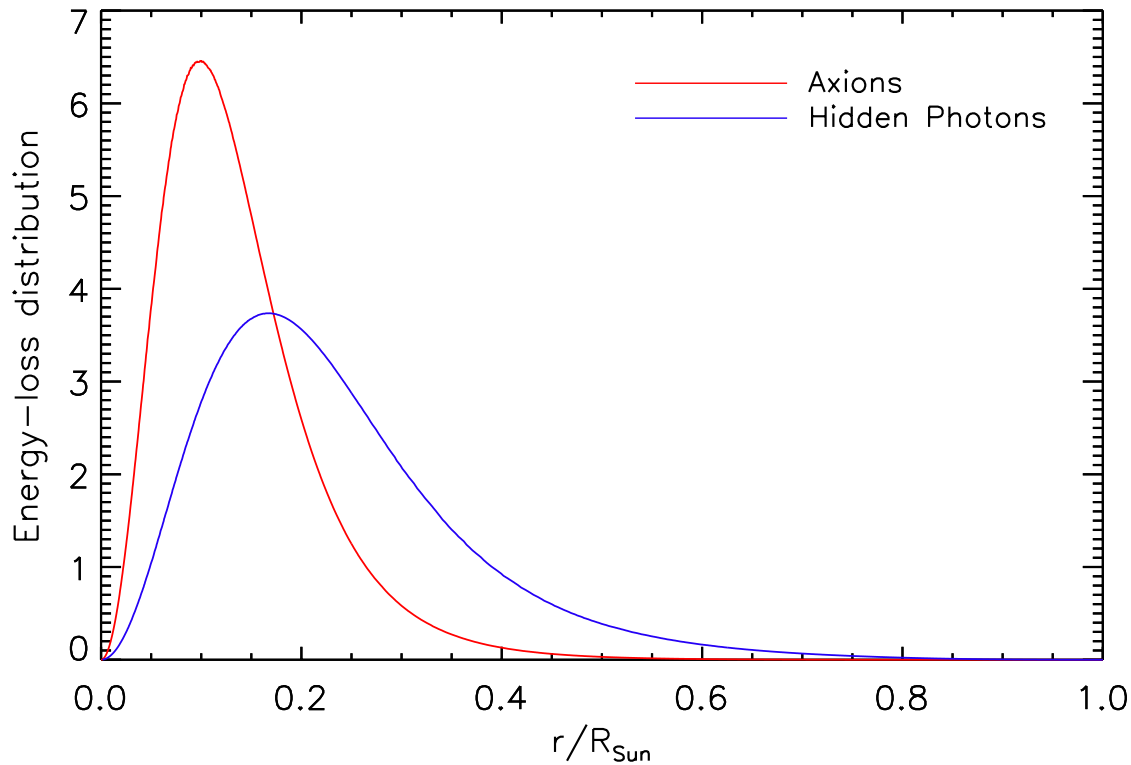
blue loop of Cepheids – stellar calculations are plainly wrong!!

Hidden Photons

Energy losses dominated by the L-channel

$$\epsilon_{\rm hp} = \frac{\chi^2 m^2}{e^{\omega_P/T}-1}\frac{\omega_P^3}{4\pi}\frac{1}{\rho} \sim \chi^2 m^2 T$$

No explicit composition dependence

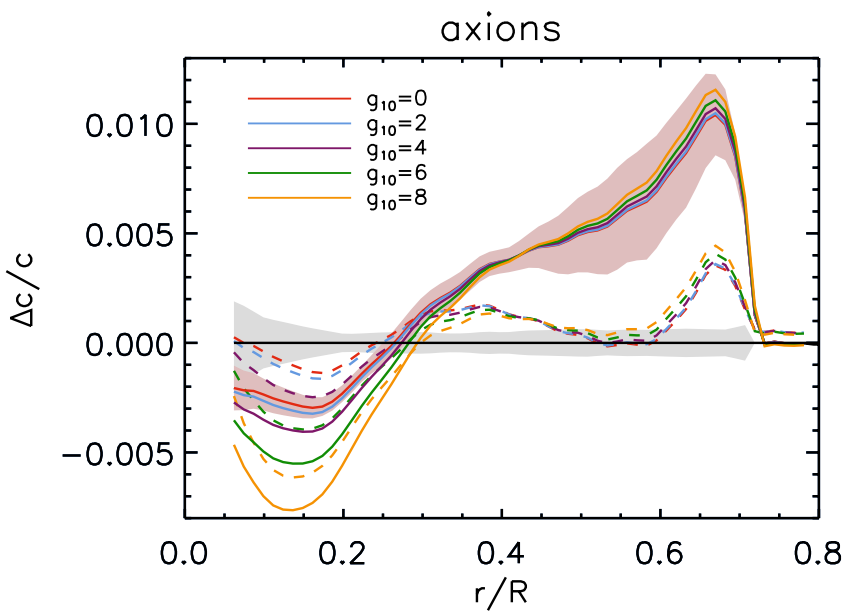


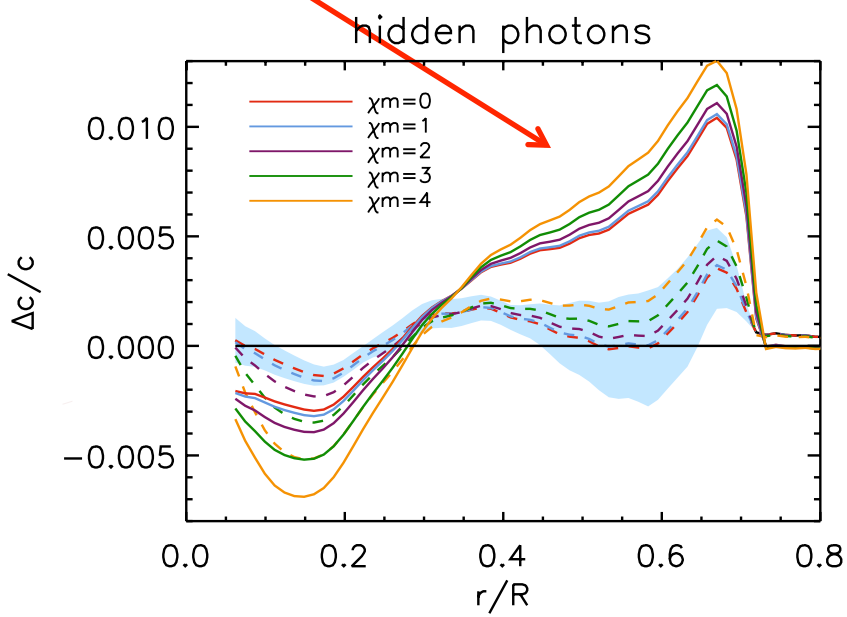
Weak T-dependence -- > broad production region

More relevant as T decreases (nucl. energy higher T-dependence)

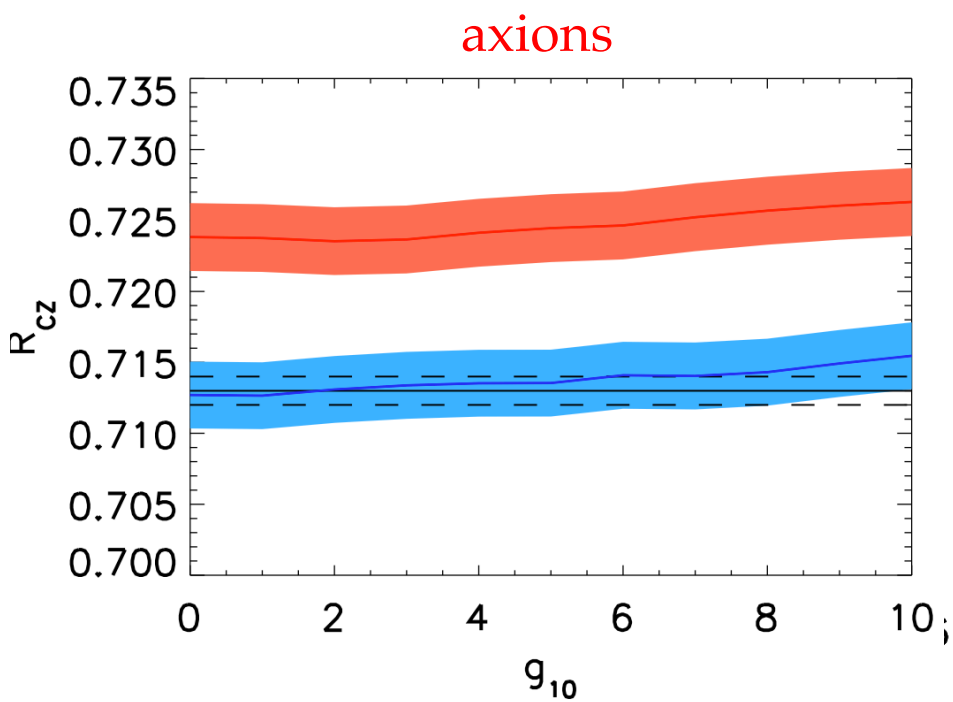
Hidden Photons

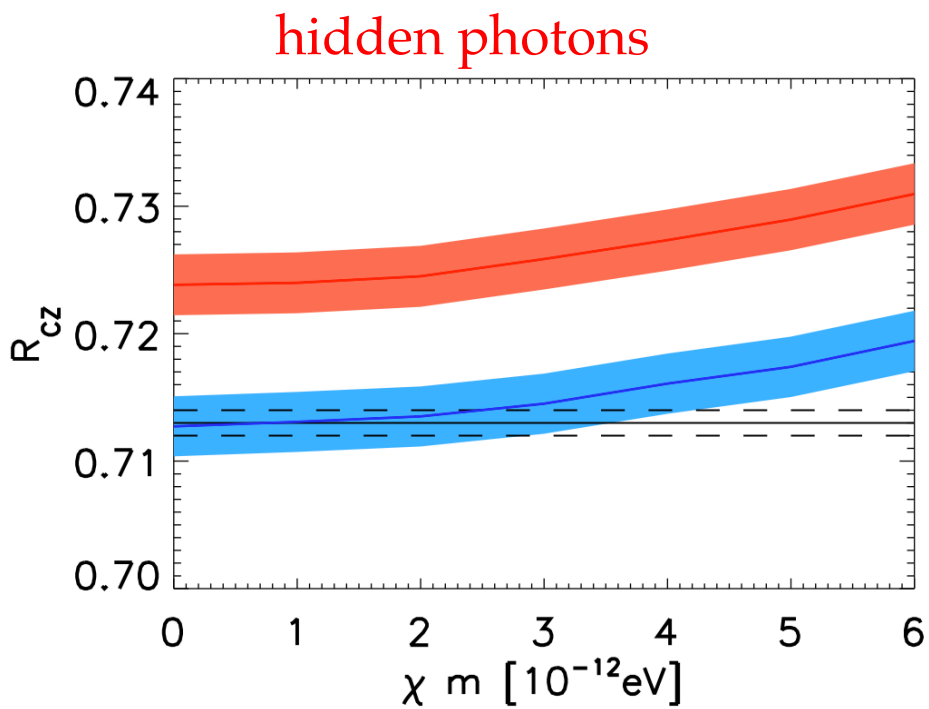
Variations in sound speed over whole radiative interior





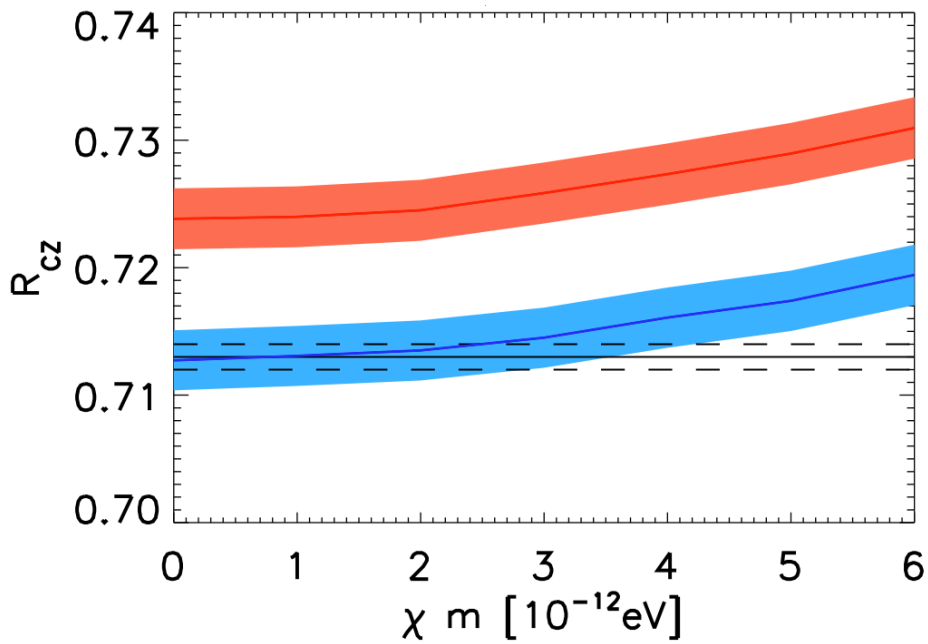
Hidden Photons

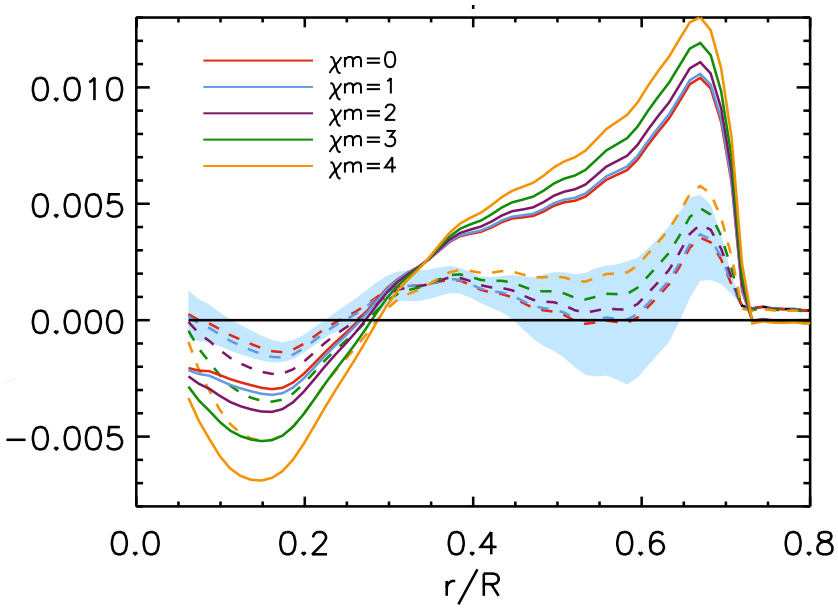




Depth of convective envelope more sensitive to hidden photons than axions

Hidden Photons

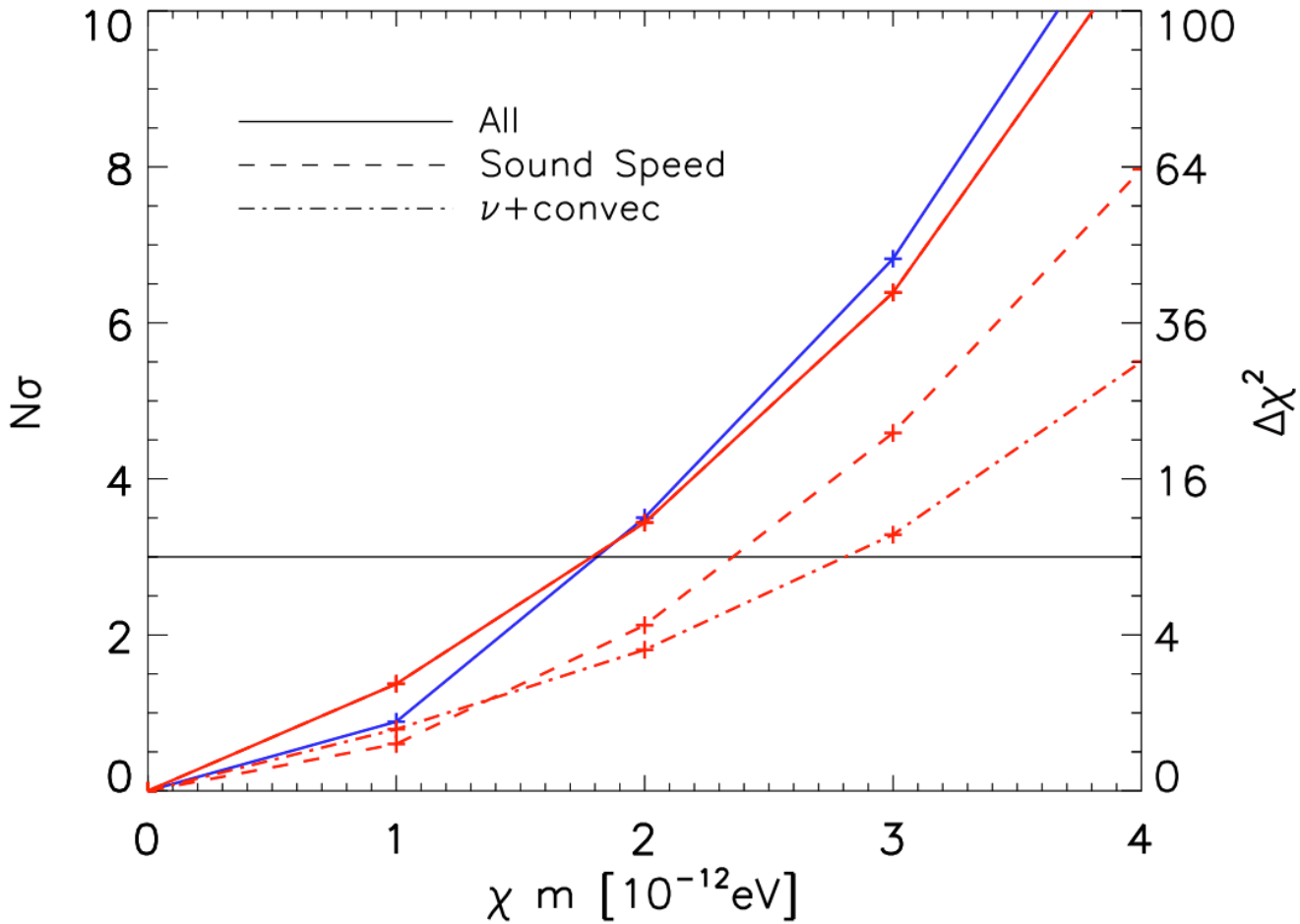




Our approach: solar model absorbs these variations without influencing boundaries derived for particle properties –
e.g. increase metal abundances: freely or constrained by spectroscopy

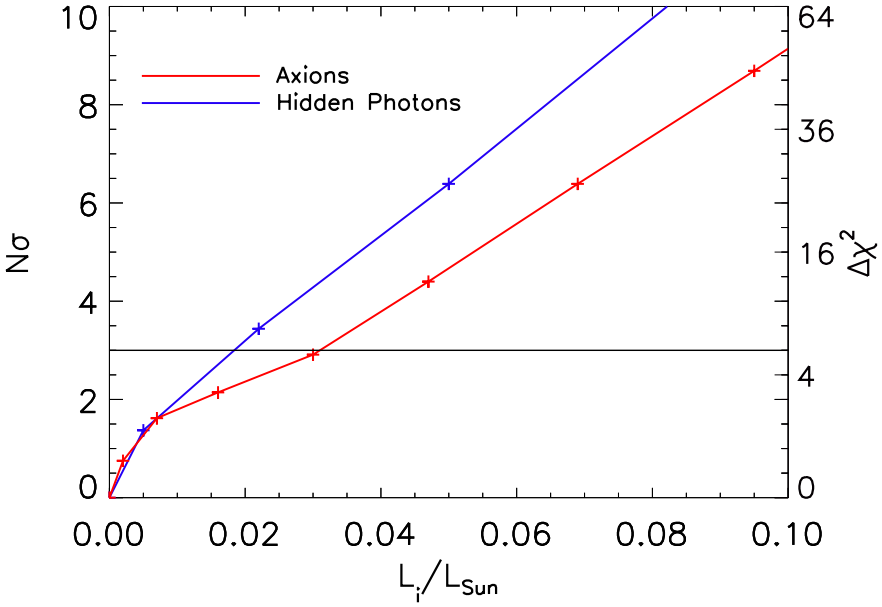
Limits derived are based on forcing solar models (+ dark channel) to fit solar data as best as possible --- > limits then derived from irreducible residuals

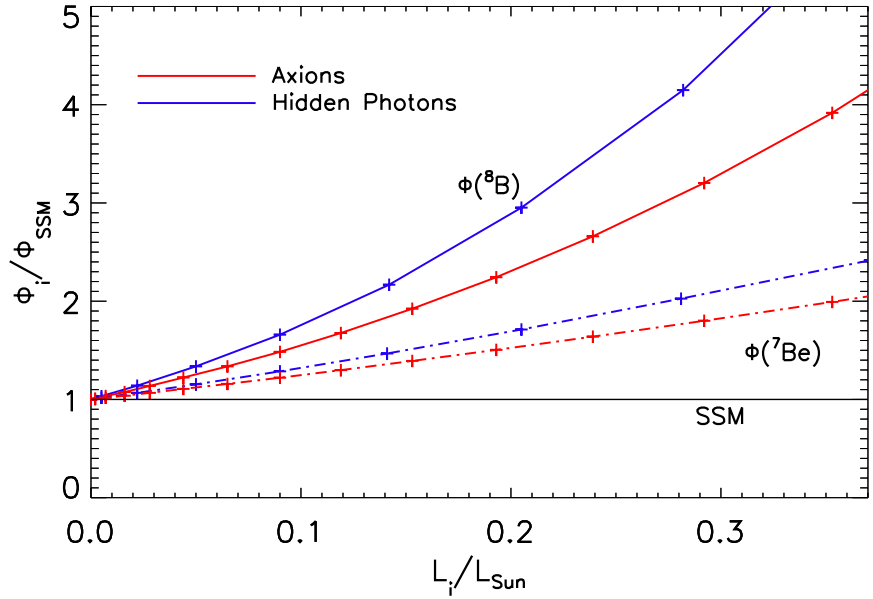
Hidden Photons



χm < 2 @ 3-σ C.L. -- improves previous limit by factor 2

Comments on Solar Constraints





Effective limit in dark channels

$L_{hp} < 2\% \, L_\odot$ – $L_{a\gamma} < 3\% \, L_\odot$

$$\frac{\Phi(^8\mathrm{B})}{\Phi_{\mathrm{SSM}}(^8\mathrm{B})} = \left(\frac{L_x + L_\odot}{L_\odot}\right)^\alpha$$

α= 4.4 (ax)

α= 5.7 (hp)

Relations are not universal
depend on the type of particle

Physical Motivation

Standard models – dominant term constant in DM-quarks interactions

$$\chi\bar{\chi}Q\bar{Q} \rightarrow \sigma_{SI}$$

$$\chi\gamma_\mu\gamma_5\bar{\chi}Q\gamma^\mu\gamma_5\bar{Q} \rightarrow \sigma_{SD}$$

Going beyond: non-zero particle radius, parity violation coupling, etc…

$$(\bar{\chi}\gamma_5\chi)(\bar{Q}Q)$$

$$(\bar{\chi}\chi)(\bar{Q}\gamma_5Q)$$

$$(\bar{\chi}\gamma_5\chi)(\bar{Q}\gamma_5Q)$$

$$(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{Q}\gamma^\mu Q)$$

can lead to dependence on the transferred momentum

$$\sigma_{\chi q} \propto q^n$$

ADM

DM-nucleon interaction with q or v_{rel} dependences

$$\sigma = \sigma_0 \left(\frac{q}{q_0}\right)^{2n} \qquad \sigma = \sigma_0 \left(\frac{v_{\rm rel}}{v_0}\right)^{2n}$$

$$\sigma_{N,i} = \frac{m_{\rm nuc}^2 (m_\chi + m_p)^2}{m_p^2 (m_\chi + m{\rm nuc})^2} \left[\sigma_{\rm SI} A_i^2\right] + \left[\sigma_{\rm SD} \frac{4(J_i+1)}{3J_i} |\langle S_{p,i}\rangle + \langle S_{n,i}\rangle|^2\right]$$

SI – A^2 dependence -- > enhanced by metals
sensitive to solar composition
can be dominant

SD– couples mostly to H

Energy Transport by ADM

Dark matter number density

$$n_{\chi,\mathrm{LTE}}(r) = n_{\chi,\mathrm{LTE}}(0)\left[\frac{T(r)}{T(0)}\right]^{3/2}\exp\left[-\int_0^r \mathrm{d}r'\,\frac{k_\mathrm{B}\alpha(r')\frac{\mathrm{d}T(r')}{\mathrm{d}r'}+m_\chi\frac{\mathrm{d}\phi(r')}{\mathrm{d}r'}}{k_\mathrm{B}T(r')}\right]$$

Dark matter conductive luminosity

$$L_{\chi,\mathrm{LTE}}(r) = 4\pi r^2\zeta^{2n}(r)\kappa(r)n_{\chi,\mathrm{LTE}}(r)l_\chi(r)\left[\frac{k_\mathrm{B}T(r)}{m_\chi}\right]^{1/2}k_\mathrm{B}\frac{\mathrm{d}T(r)}{\mathrm{d}r}.$$

Energy injection rate

$$\epsilon_{\chi,\mathrm{LTE}}(r) = \frac{1}{4\pi r^2\rho(r)}\frac{\mathrm{d}L_{\chi,\mathrm{LTE}}(r)}{\mathrm{d}r}$$

Two limiting behavior: LTE & Isothermal

Intermediate: Knudsen regime $l_\chi \sim r_\chi$ --> Boltzmann eq.

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diffusivity

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thermal conductivity

Energy injection rate

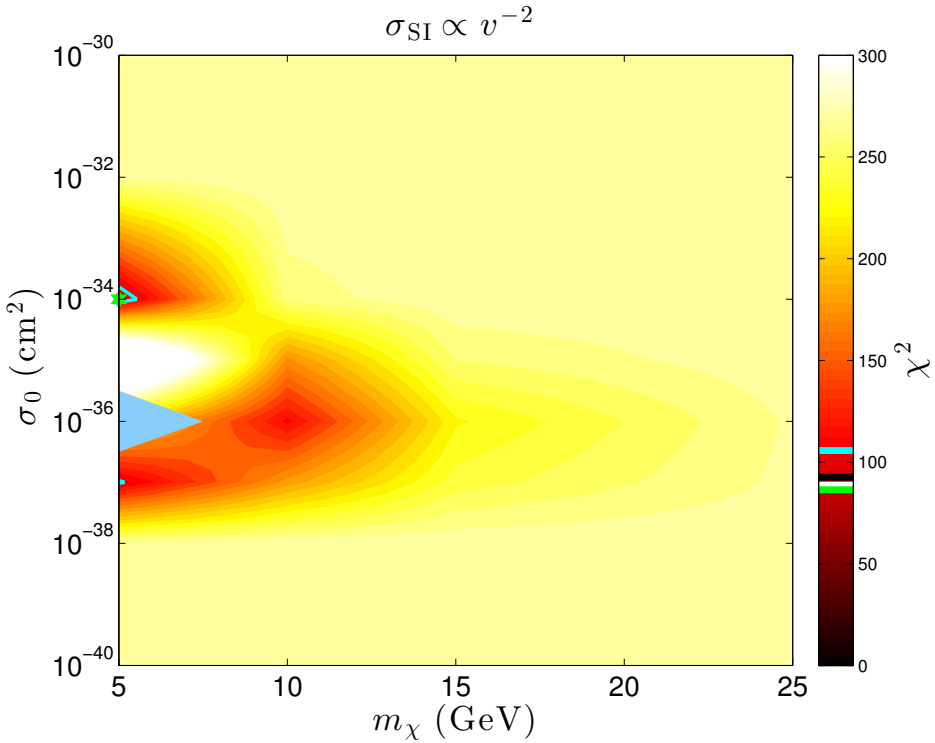
$$\epsilon_{\chi,\mathrm{LTE}}(r) = \frac{1}{4\pi r^2\rho(r)}\frac{\mathrm{d}L_{\chi,\mathrm{LTE}}(r)}{\mathrm{d}r}$$

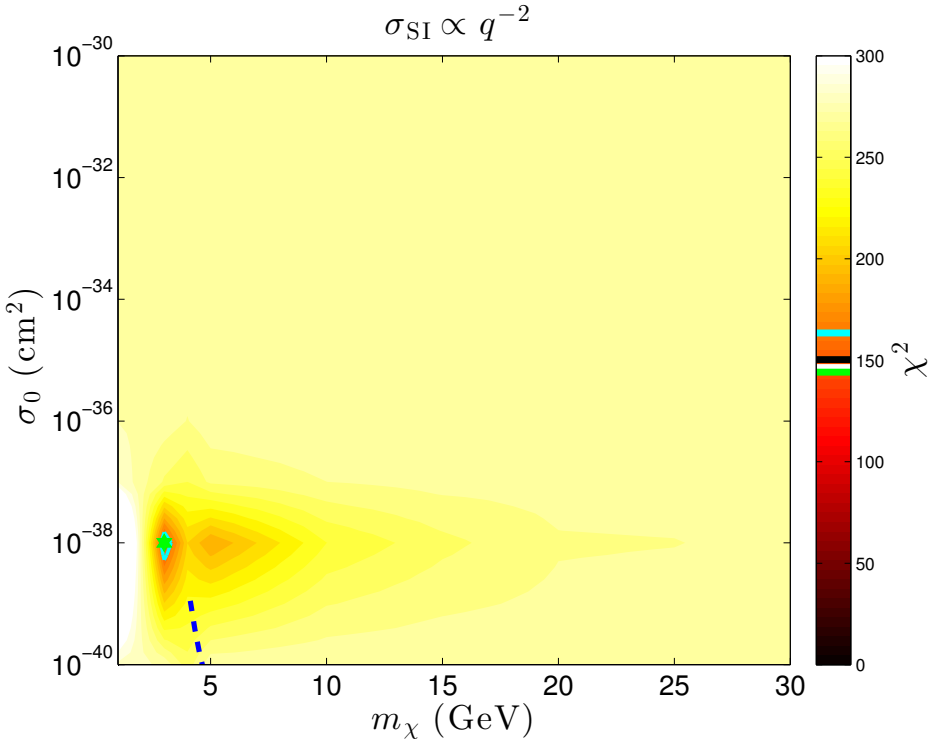
$v_0/v(r) - q_0/q(r)$

Two limiting behavior: LTE & Isothermal

Intermediate: Knudsen regime $l_\chi \sim r_\chi$ --> Boltzmann eq.

Impact on Observables: SI, v^{-2}, q^{-2}

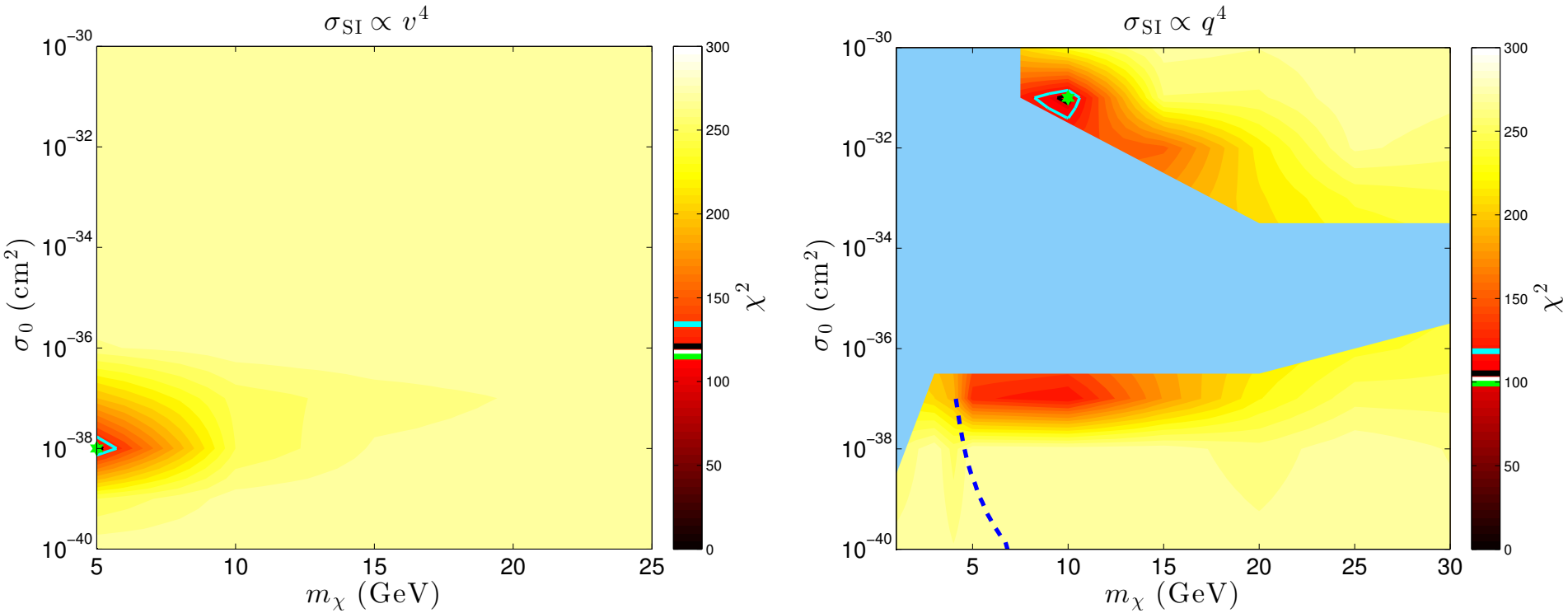




^{7}Be & ^{8}B neutrinos + convective radius + surface helium

Frequency separation ratios r_{02}, r_{13}

Impact on Observables: SI, v^4, q^4



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