Solar Constraints for Particle Physics

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IFAE – 22/05/2015

Plan

Part I

- Standard solar models and the abundance problem

  what is helioseismology and solar νs really tell us

- 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

- A non-standard look at the solar abundance problem

  evidence for ADM in the Sun

Standard Solar Models

SSM assumes

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

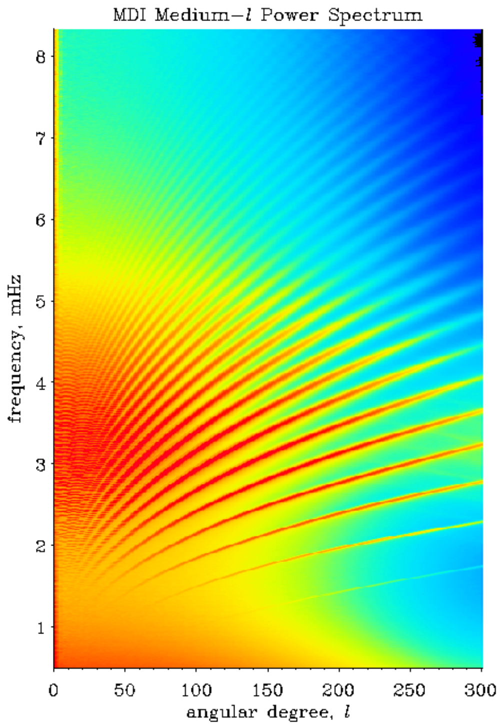
3 present-day constraints <--> 3 adjustable quantities

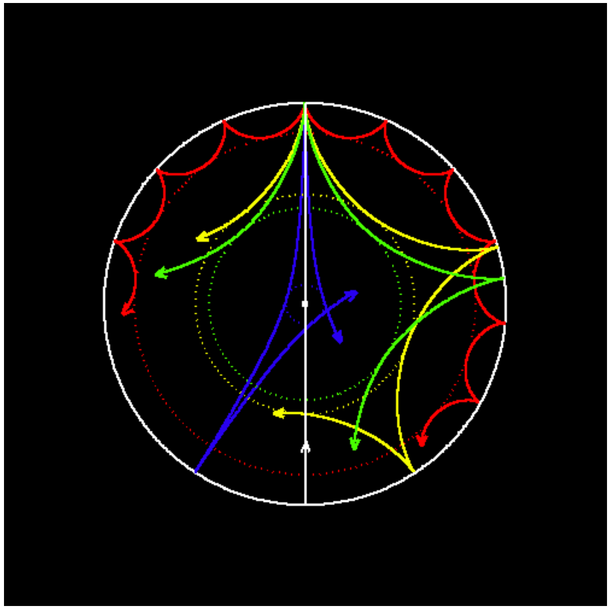
Solar radius -- > convection parameter – mixing length

Solar (photon) luminosity -- > initial helium

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

Helioseismology





$\ell = 0$ $\ell = 2$ $\ell = 20$ $\ell = 25$ $\ell = 75$

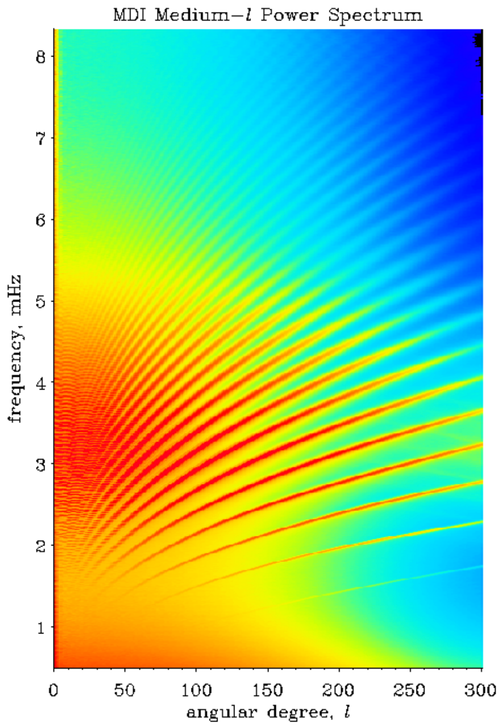
Acoustic p-modes – standing sound waves

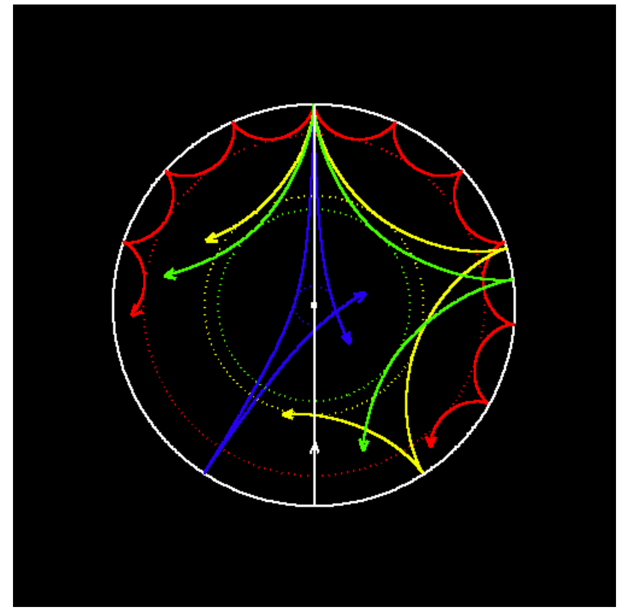
$$c^2 = \frac{\Gamma_1 p}{\rho}$$

Low degree modes – probe the solar core

Mid/high degree – outer regions

Helioseismology





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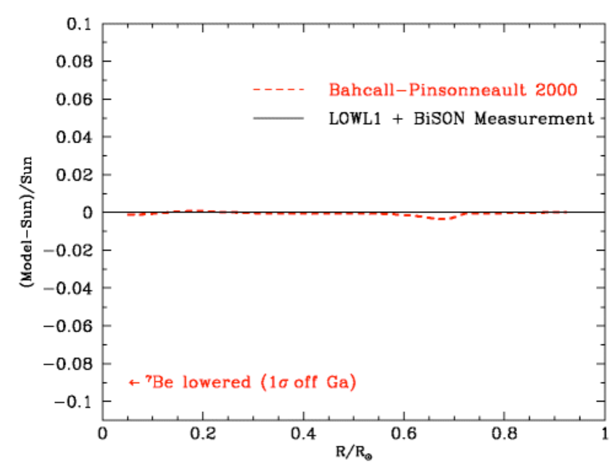
Low degree modes – probe the solar core
Mid/high degree – outer regions

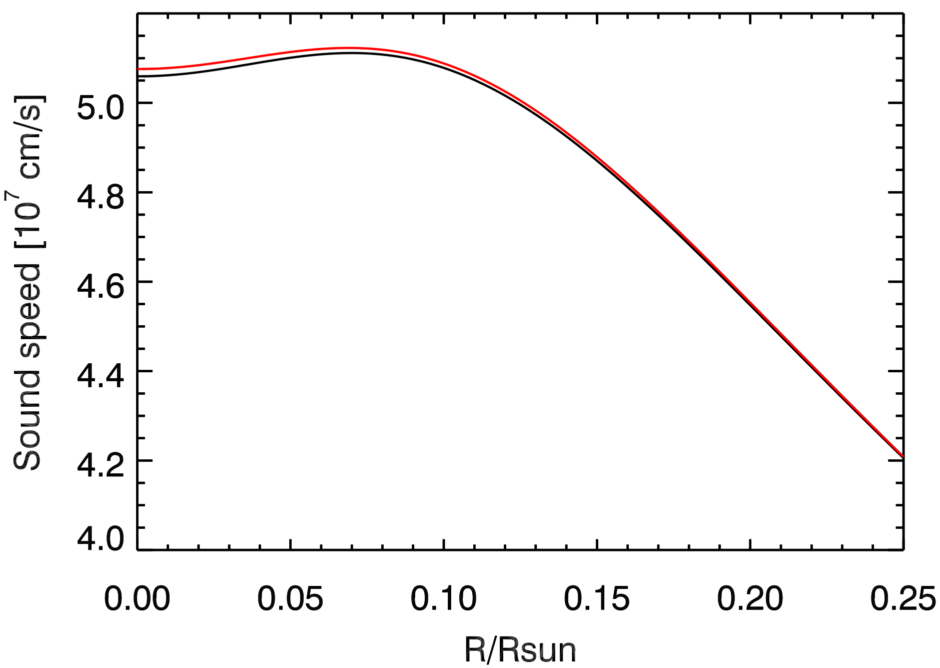
Sound speed profile from inversions -- >

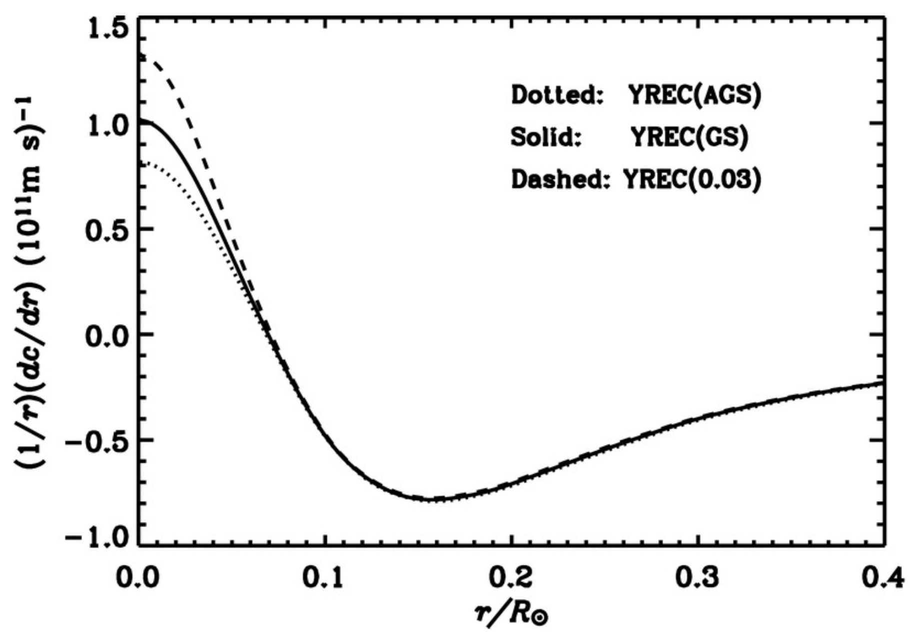


Helioseismology

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

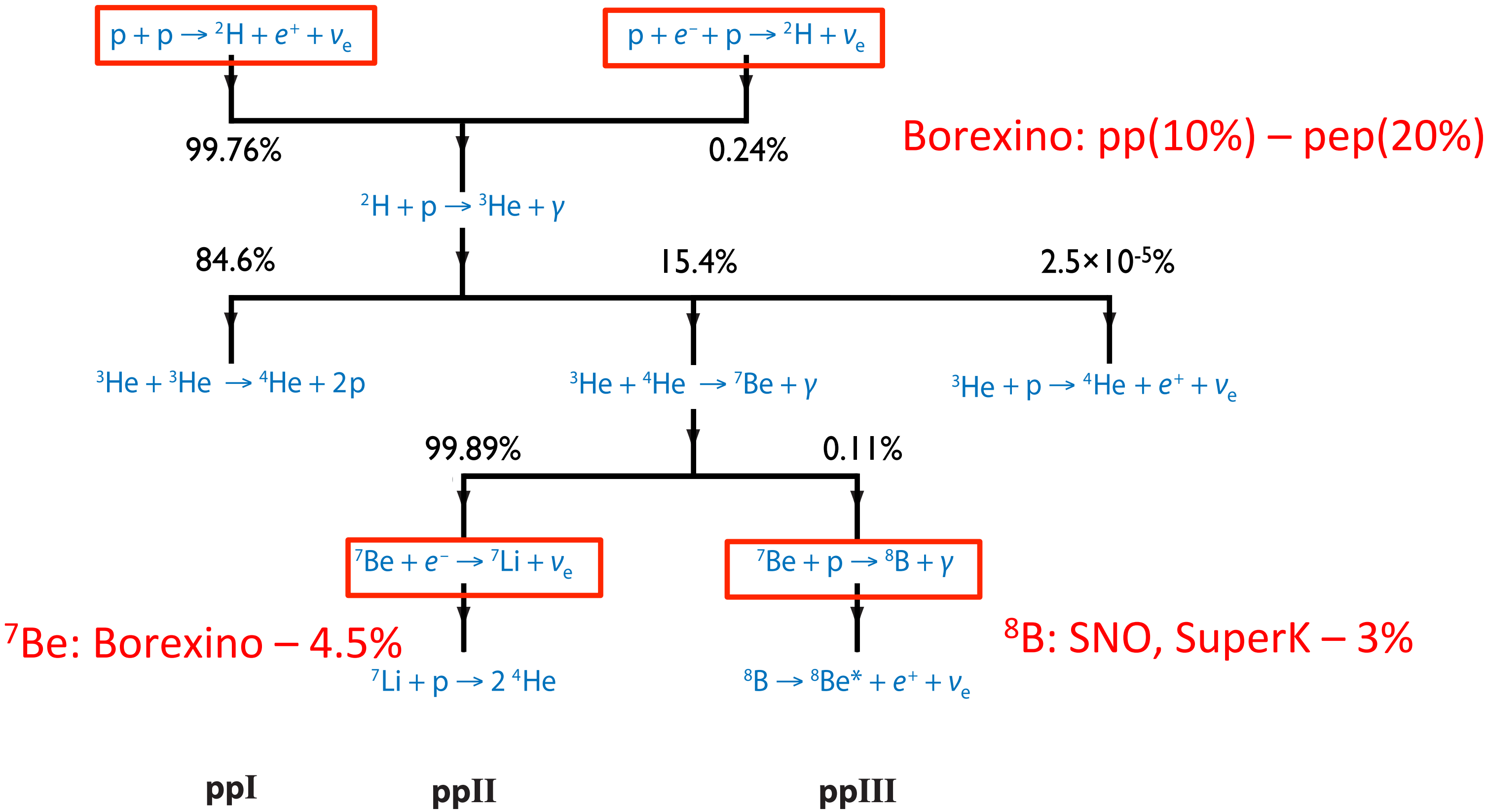
$$\left.\begin{array}{l} r_{02} = \frac{\nu_{n,0} - \nu_{n-1,2}}{\nu_{n,1} - \nu_{n-1,1}} \\ \\ r_{13} = \frac{\nu_{n,1} - \nu_{n-1,3}}{\nu_{n+1,0} - \nu_{n,0}} \end{array}\right\} \propto \int_0^R \frac{dc}{dr}\frac{dr}{r}$$





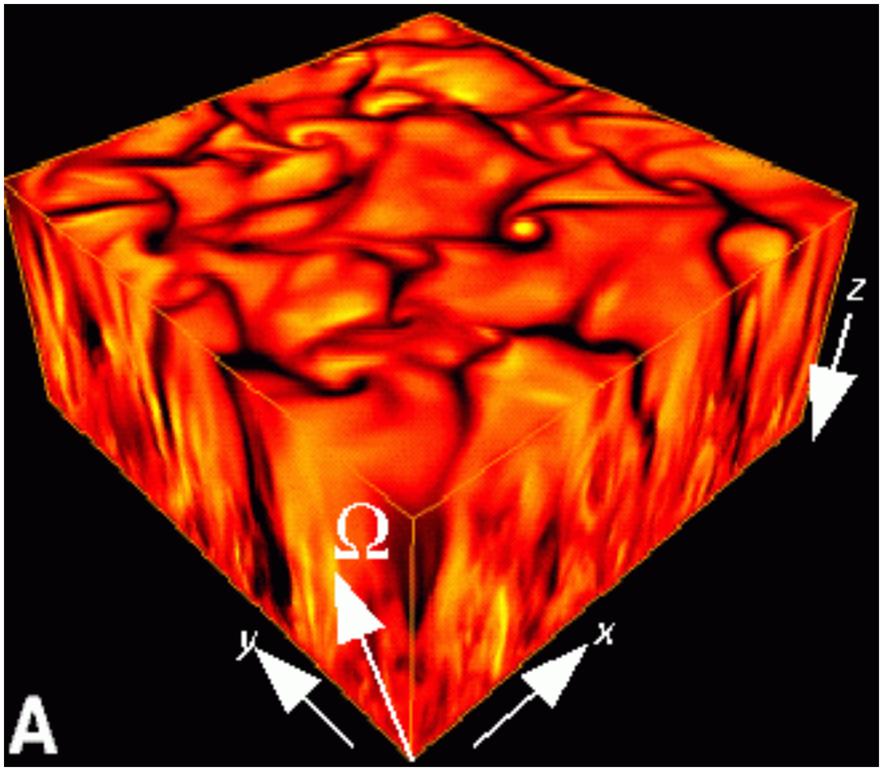
Frequency ratios: probing solar core

Solar Neutrinos: pp-chains

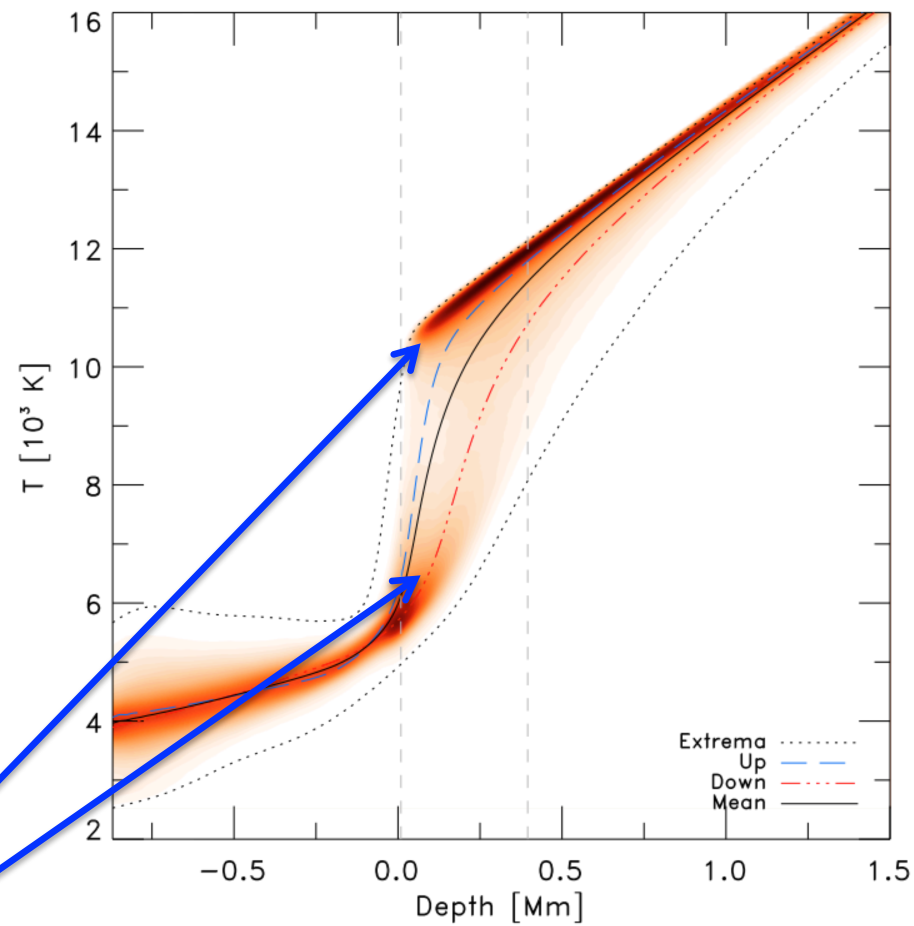


Solar Atmospheres & Abundances

Dealing with convection



Credit: N. Brummell



Hard to mimic with 1D models

Magic et al. 2014

Solar Abundances: End Product

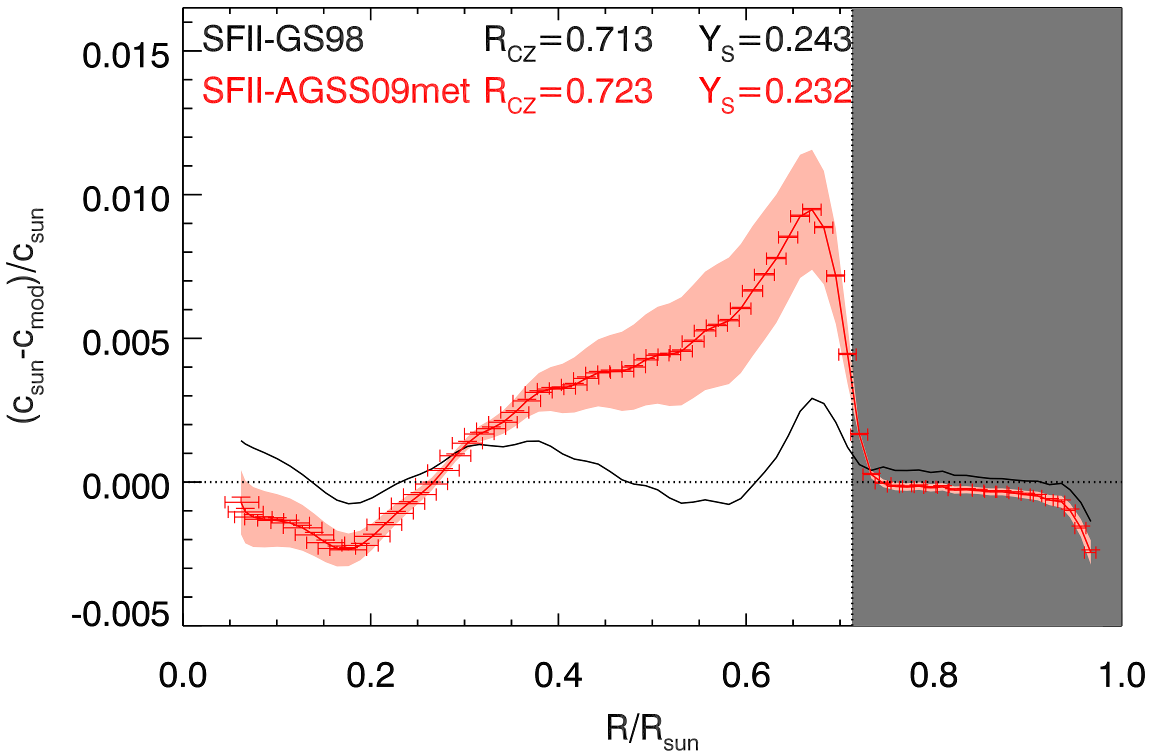
Element	GS98	AGSS09+met
C	8.52	8.43
N	7.92	7.83
O	8.83	8.69
Ne	8.08	7.93
Mg	7.58	7.53
Si	7.56	7.51
Ar	6.40	6.40
Fe	7.50	7.45
Z/X	0.0229	0.0178

Differences of

CNO(Ne)~30-40%

refractories~10%

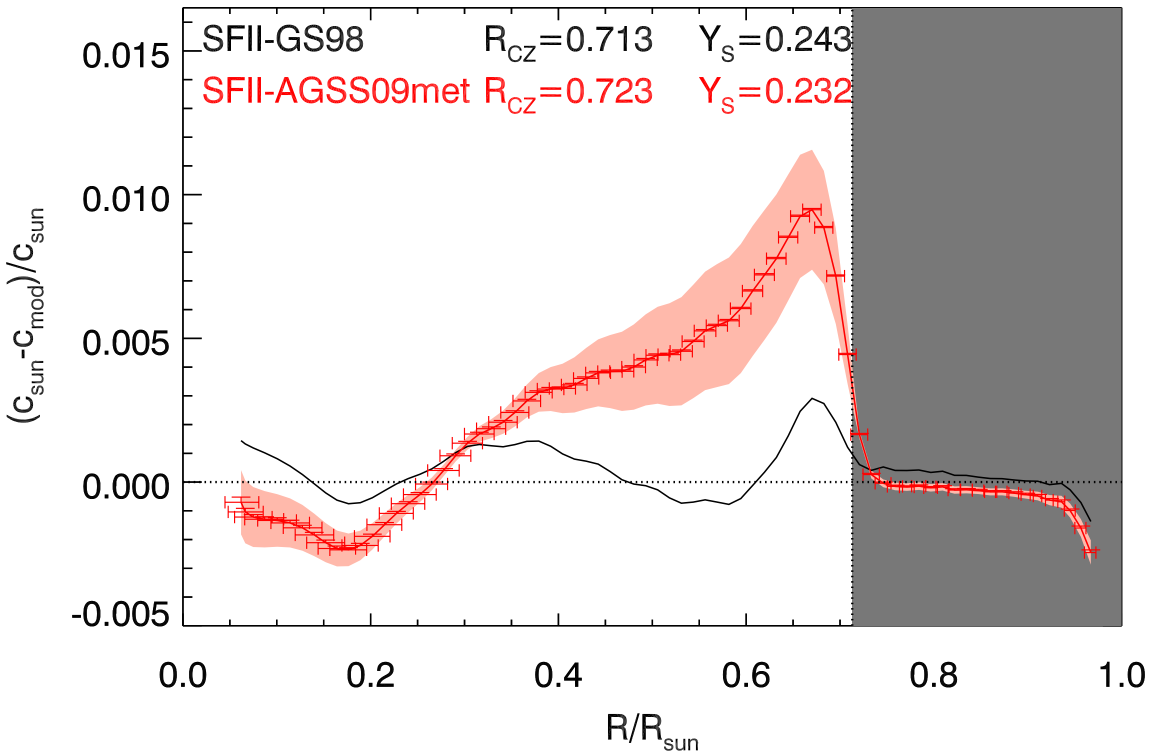
Standard Solar Models: Helioseismology



	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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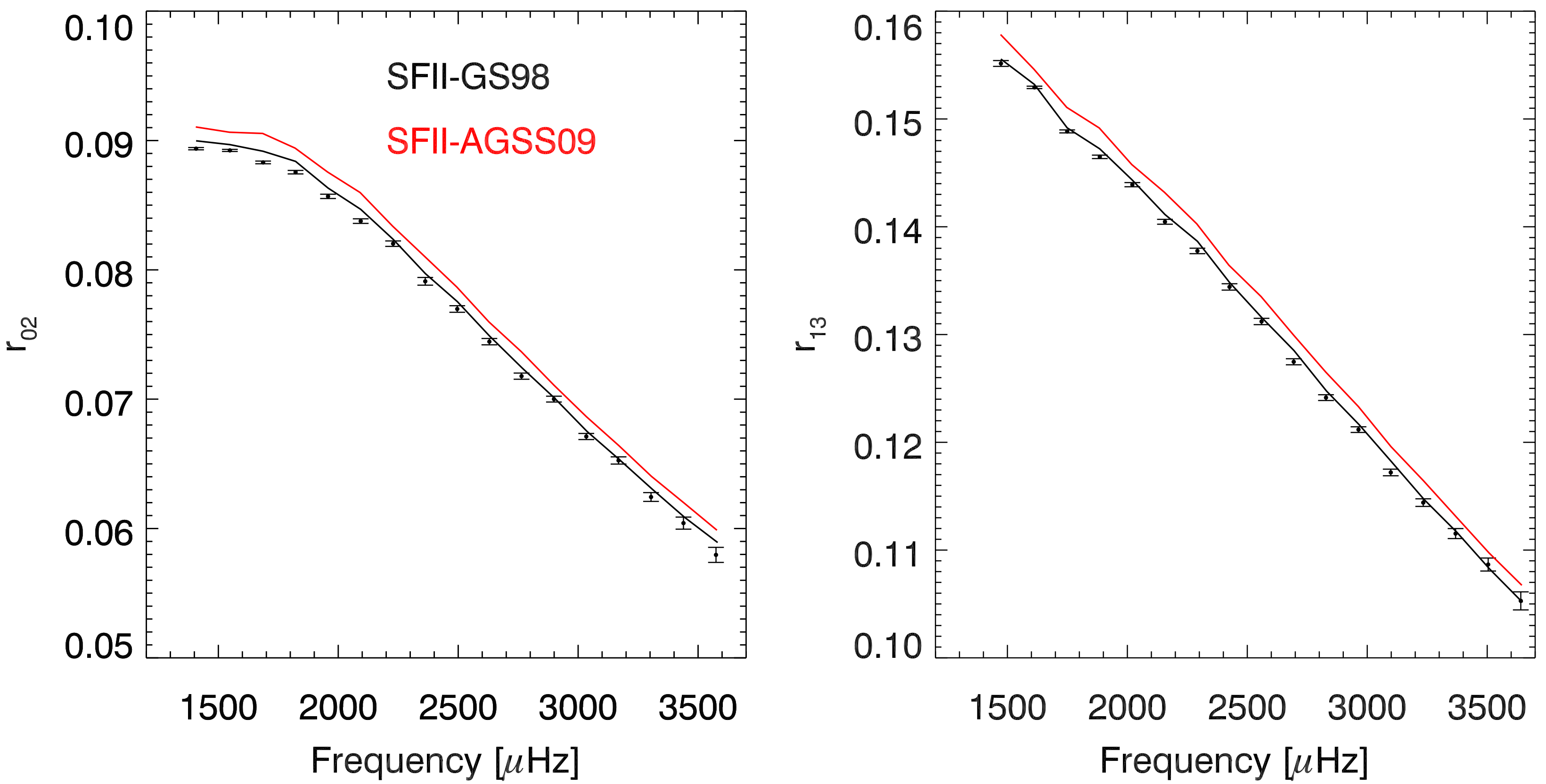
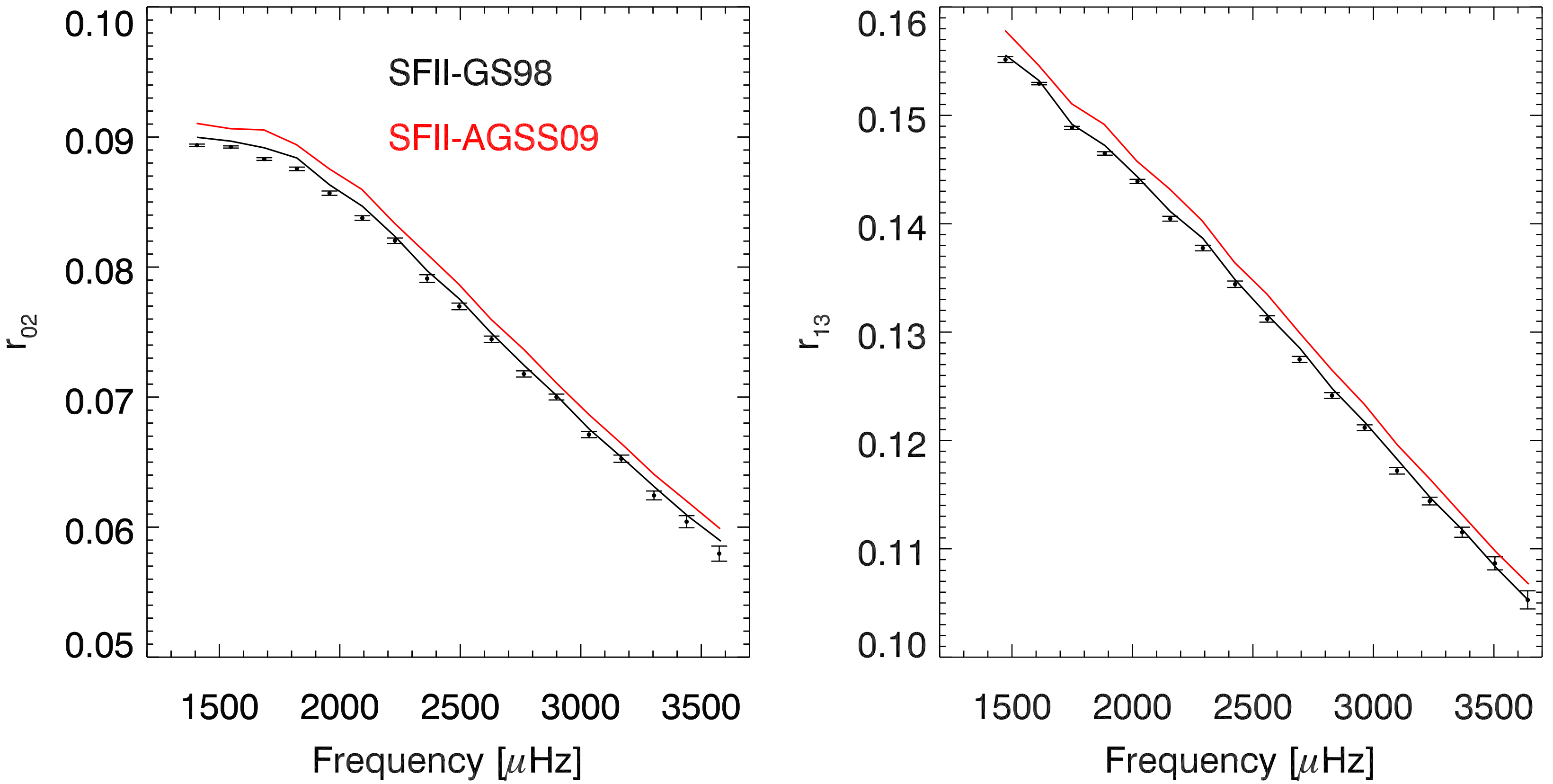


Standard Solar Models: Helioseismology



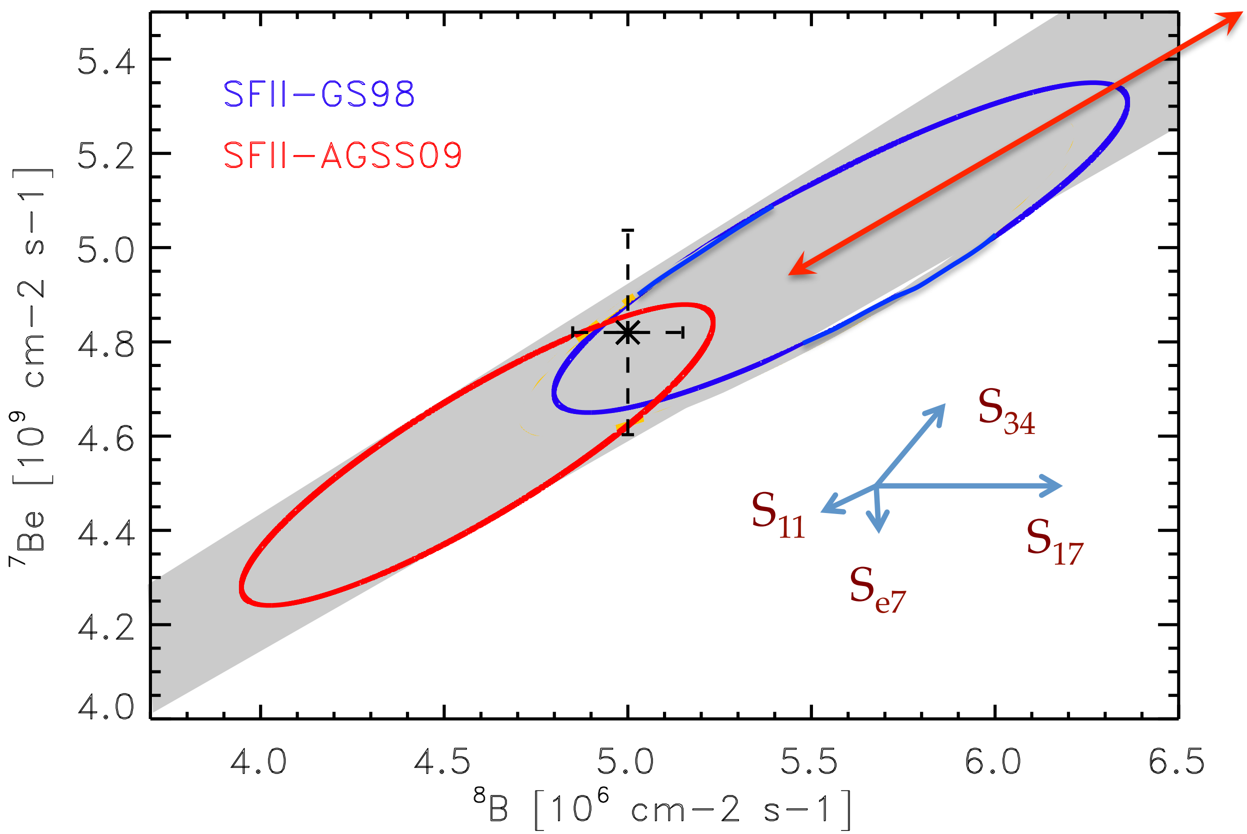
Helioseismic predictions of SSM --> high-Z
Solar atmospheres & spectroscopy -- > low-Z

Solar Abundance Problem

Standard Solar Models: Neutrinos

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

Dependence on core temperature



Robust Inferences from SSMs?

* all robust helioseismic probes
* pp-chain neutrinos depend

→ depend on T stratification, i.e. energy transport not directly on composition

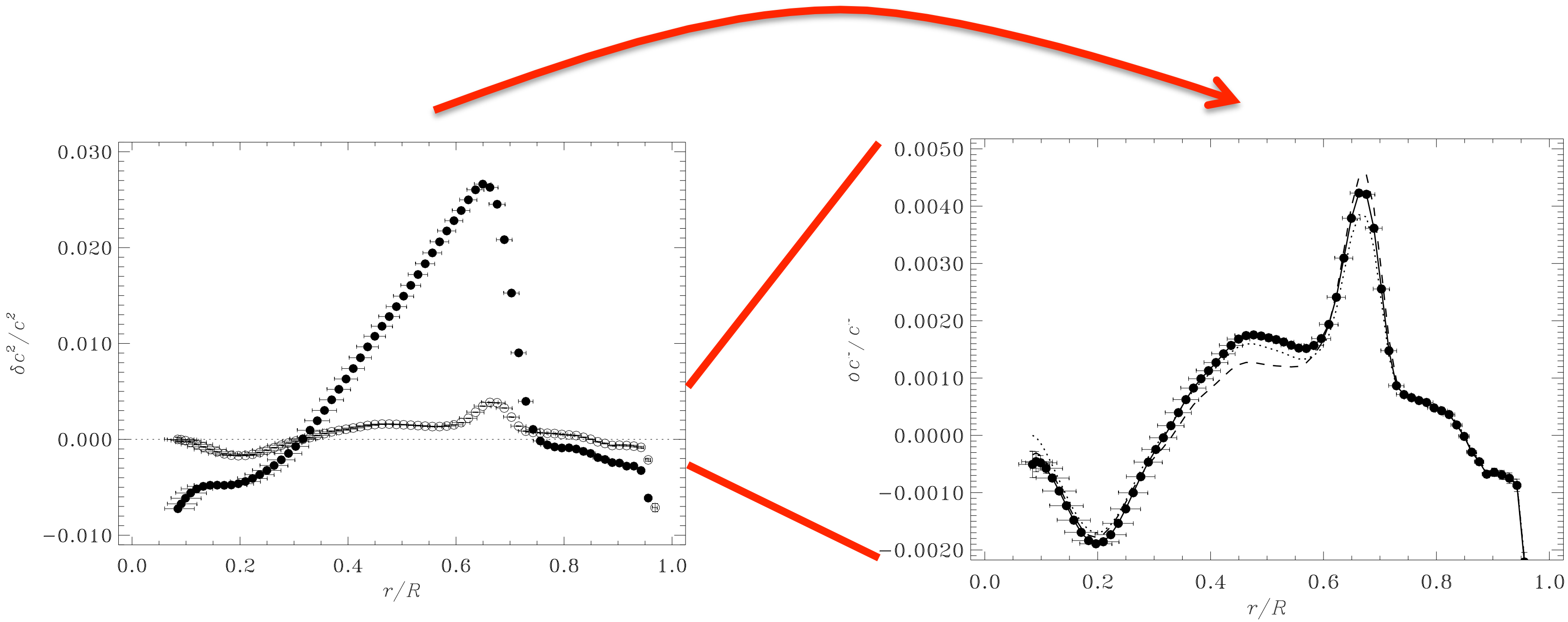
in solar interior T grad. scales with radiative opacity κ

degeneracy between κ and composition

Seismic data and pp-chain neutrinos constraint radiative gradient / opacity profile

Robust Inferences from SSMs?

1st solution: modify opacity profile to recover good agreement with helioseismology



Christensen Dalsgaard et al 2009

Robust Inferences from SSMs?

2nd solution: * solar composition (2 parameters) free
* SSM input (~10) parameters move around central values
(nucl. x-sect., solar parameters, etc.)

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

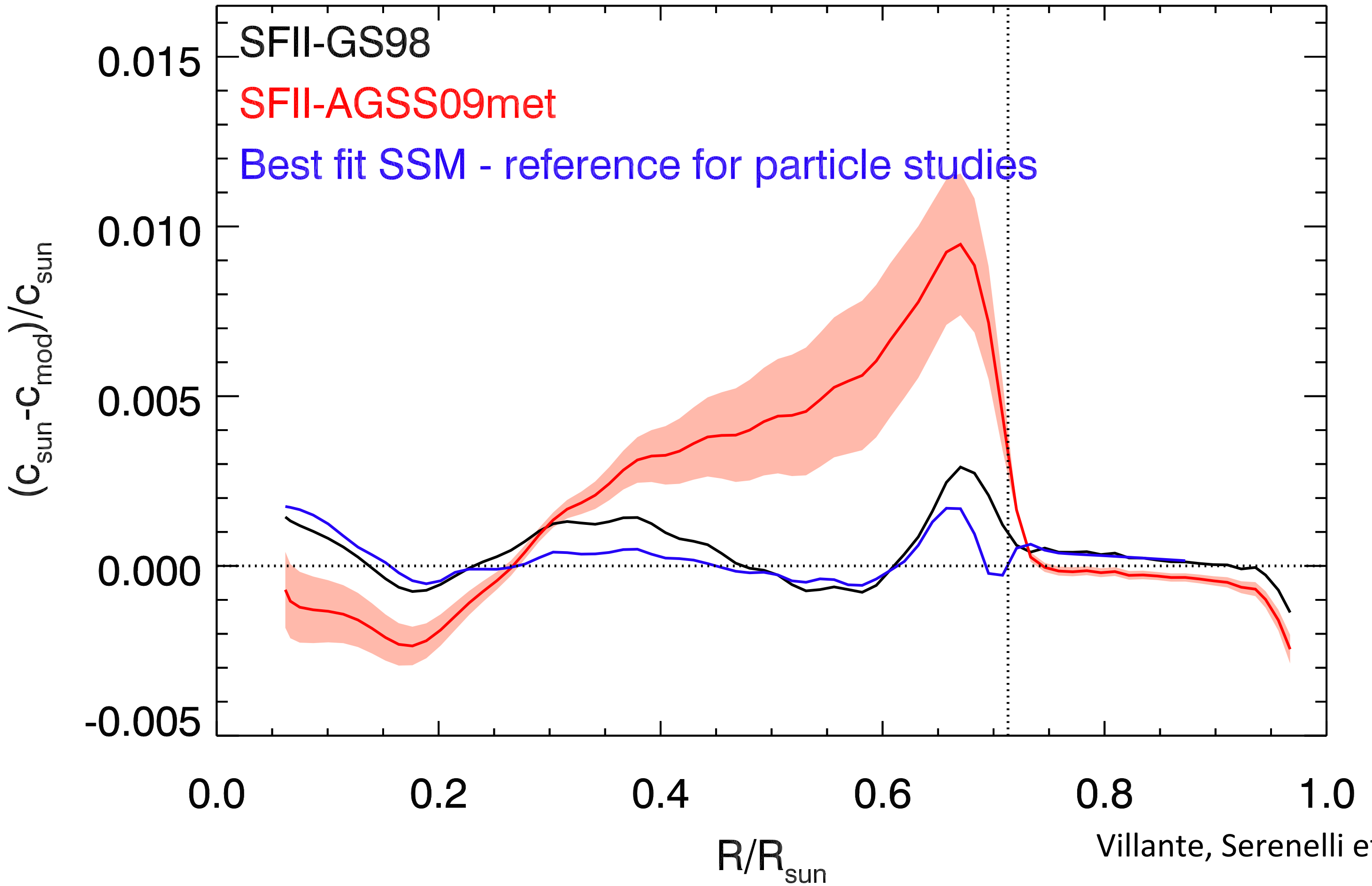
seismic + neutrino observables

model correlations & pulls ξ_I of input parameters

Robust Inferences from SSMs?

Even better than the real thing !!

Pulls from systematics of order 1 (1-σ)



Villante, Serenelli et al. 2014

Testing the Method: Axions-Photon Coupling

Solar limits on axion-photon 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 $L_a < 0.2\ L_\odot$

Gondolo & Raffelt 2009 – $g_{10} < 7$

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

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

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

seismic (not evolutionary models – neglect basic physics)

Vinyoles et al. 2015 – g10 < 4 (3-σ)

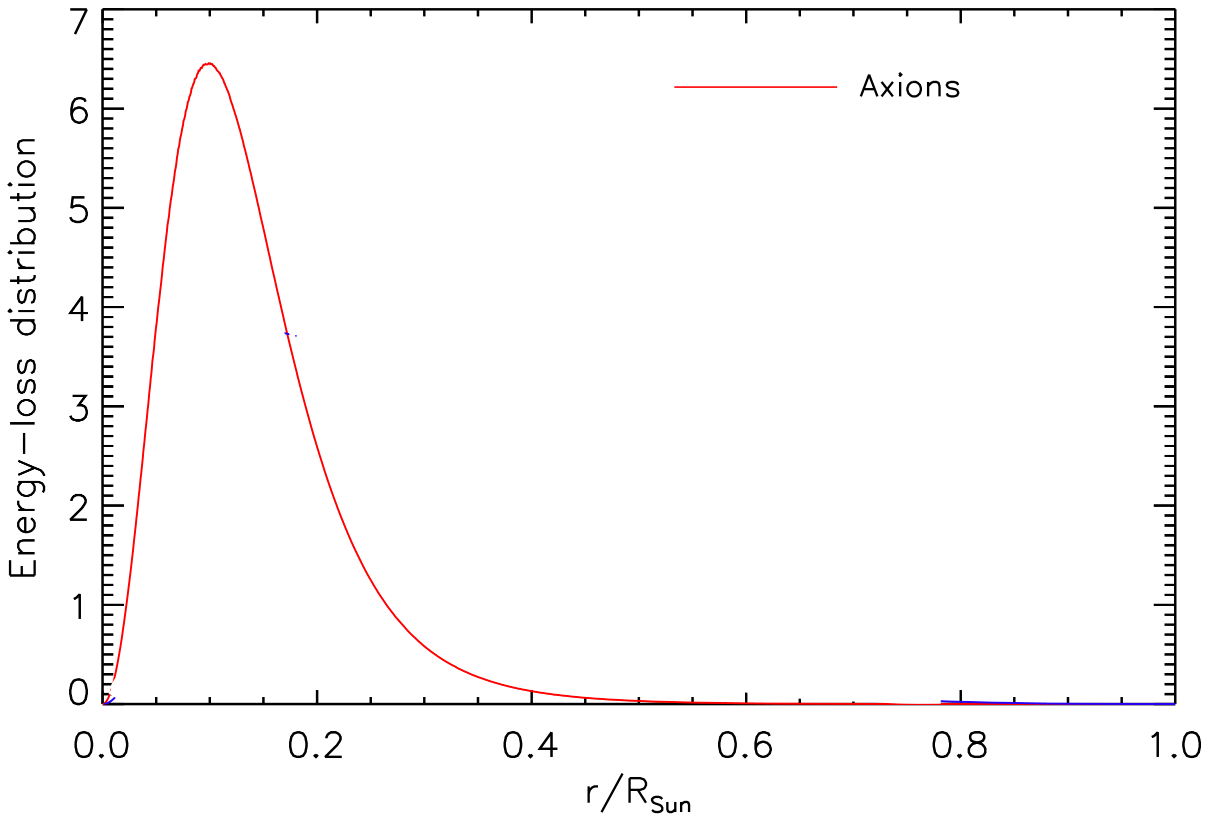
seismic + neutrino data

extend the method used to construct best-fit SSM

Testing the Method: Axions-Photon Coupling

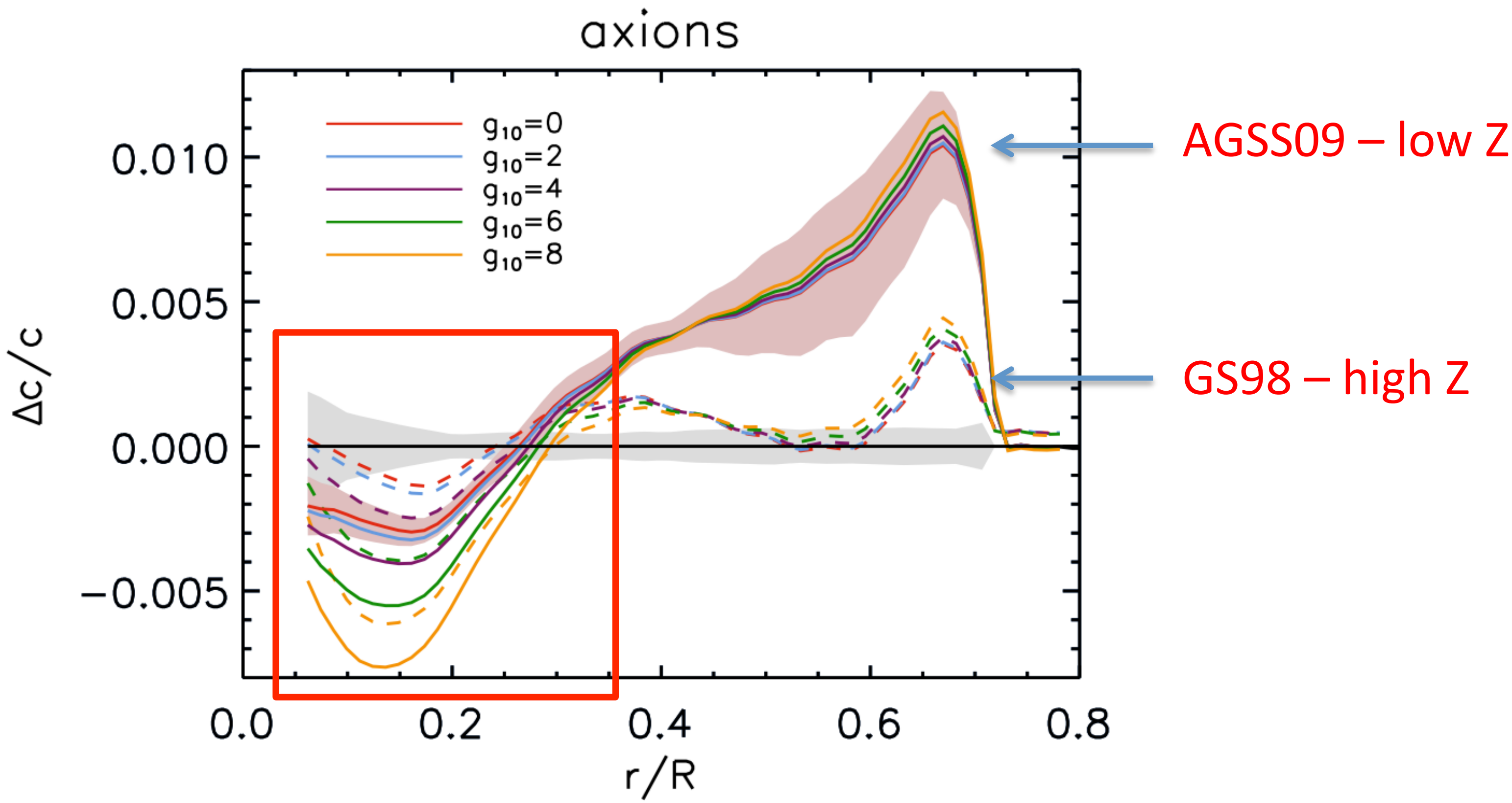
$$\epsilon_{a\gamma} \propto g_{a\gamma}^2 T^7 F(\kappa^2) \sim g_{a\gamma}^2 T^6$$

No explicit composition dependence



Testing the Method: Axions-Photon Coupling

Variations in sound speed without variations in composition and pulls



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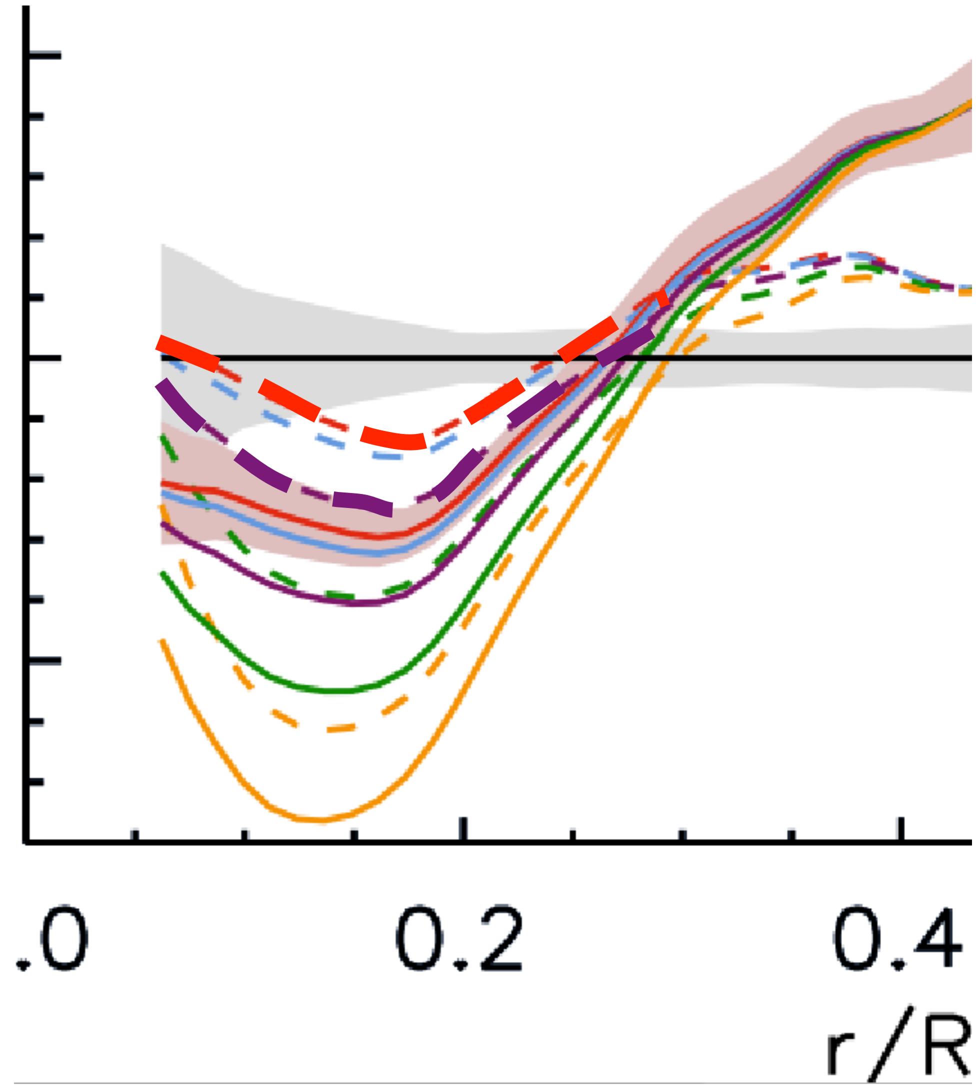
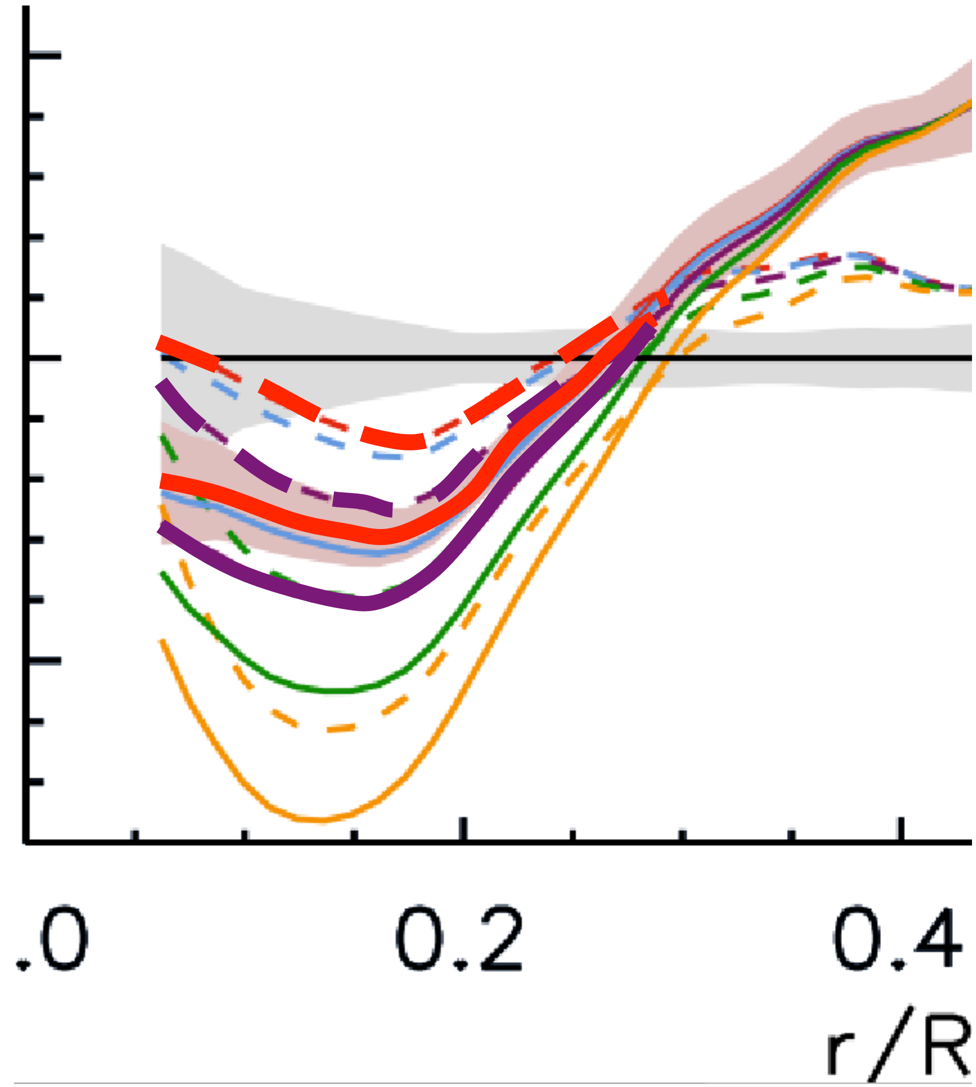


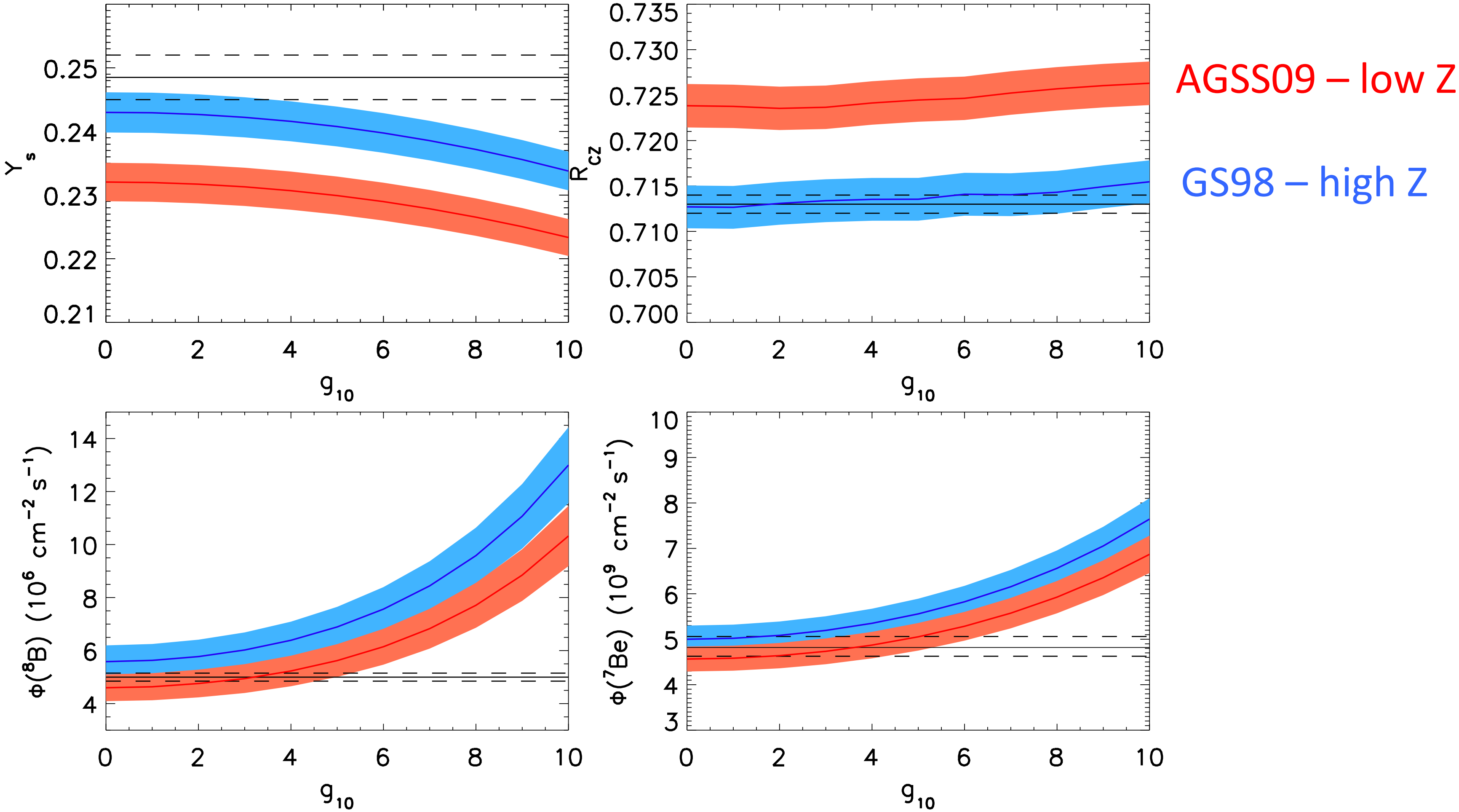
Testing the Method: Axions-Photon Coupling

Relative changes are similar



Testing the Method: Axions-Photon Coupling

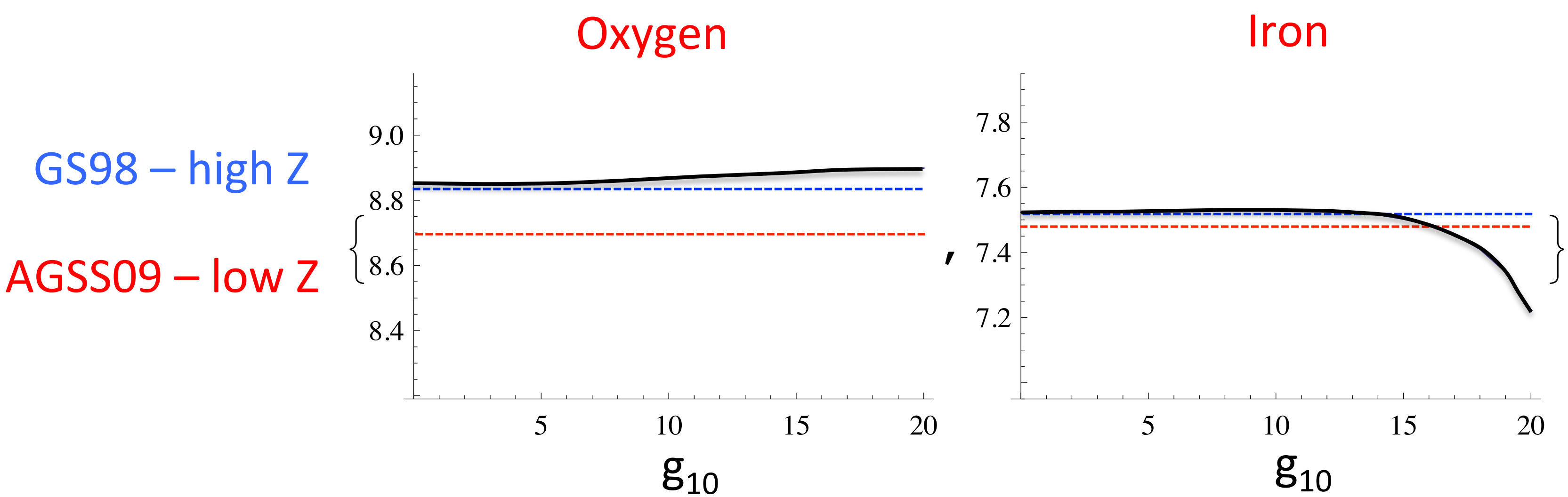
Variations in other quantities without variations in composition and pulls



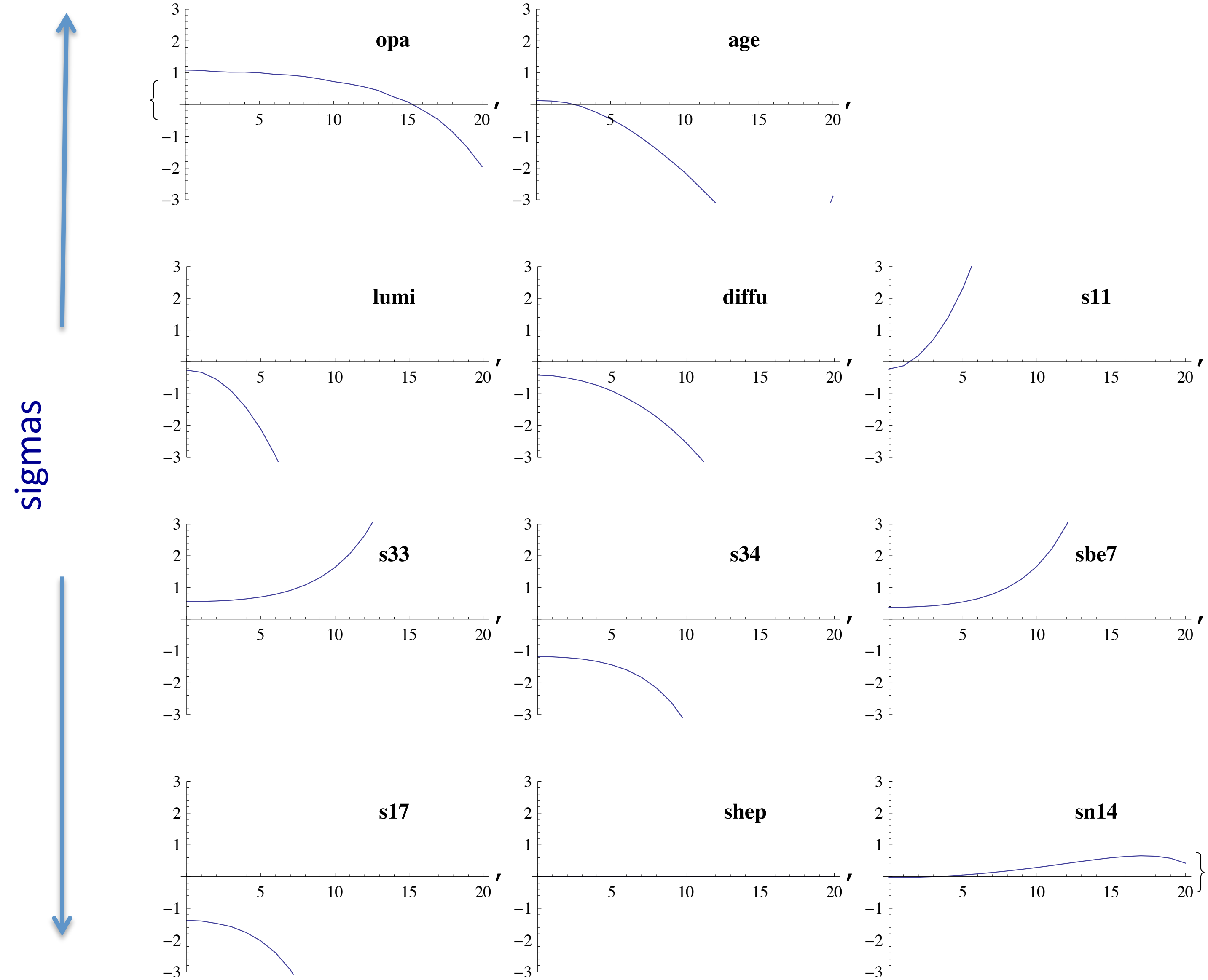
Changes due to axions and "zero point" of SSM to be accounted for by composition and systematics (pulls)

Testing the Method: Axions-Photon Coupling

Full solution: composition is free and pulls computed to minimize χ^2 for fixed g_{10}



Testing the Method: Axions-Photon Coupling



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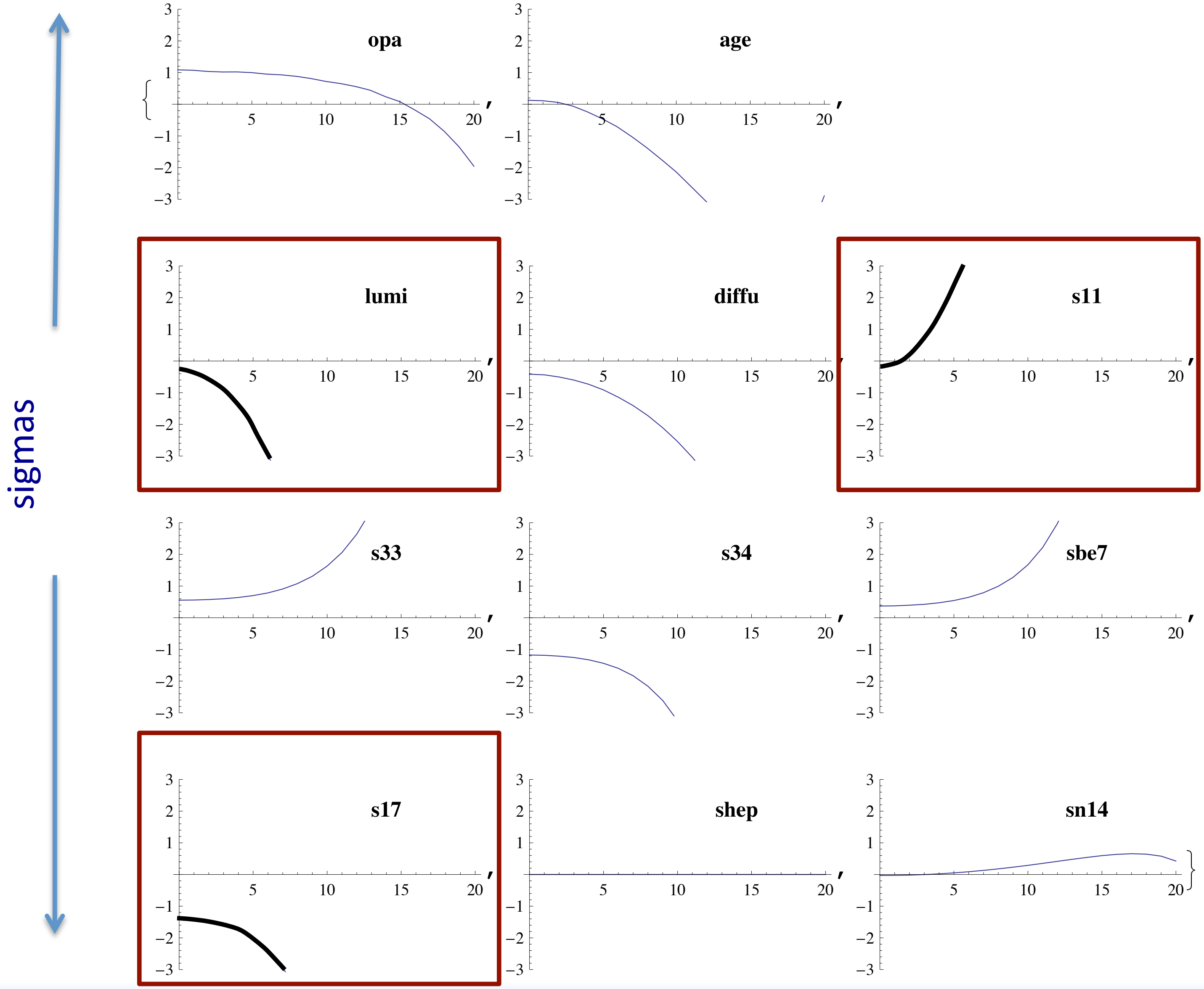
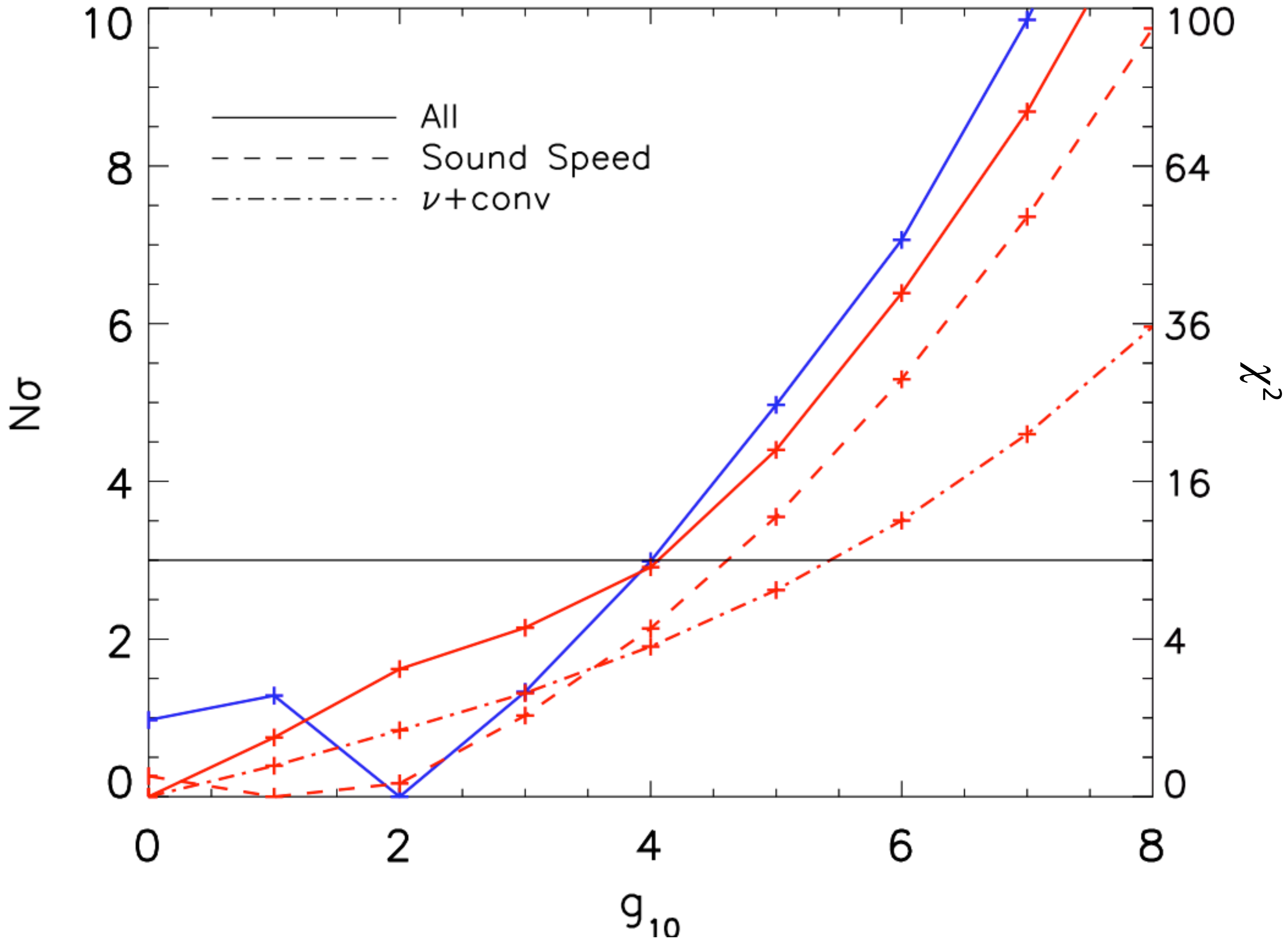


Testing the Method: Axions-Photon Coupling

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



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 – $g_{10} < 0.8$

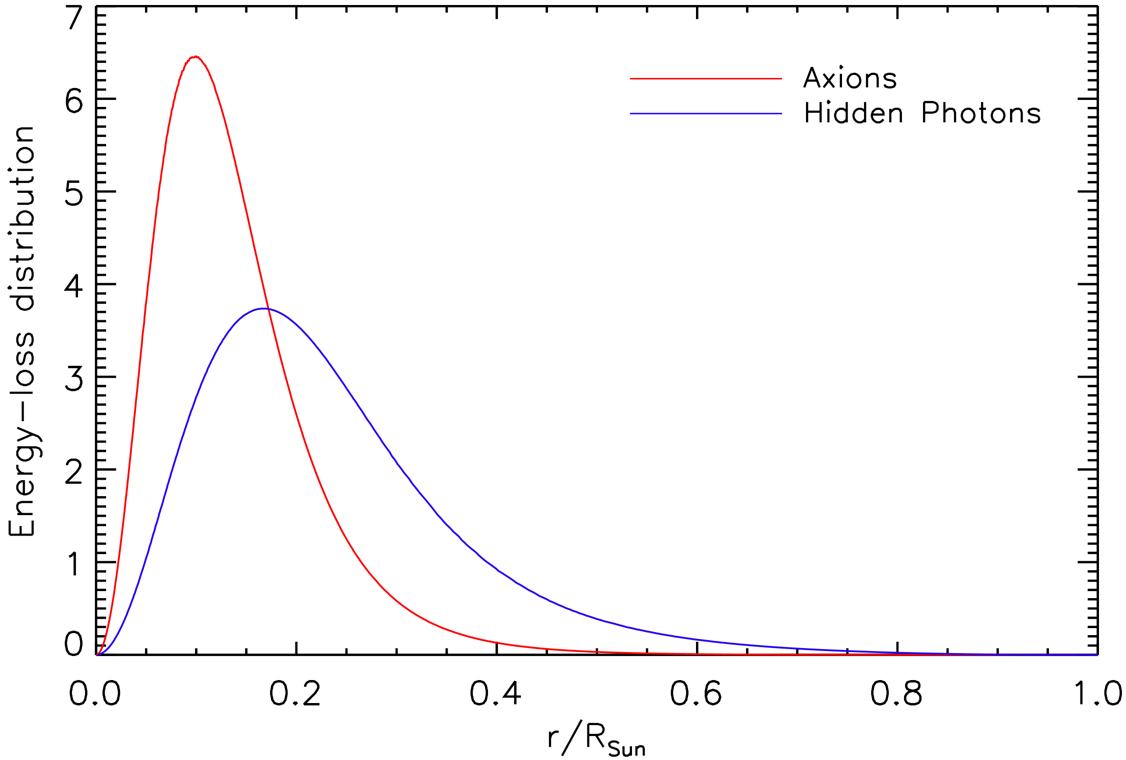
blue loop of Cepheids – stellar calculations are plainly wrong!!

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

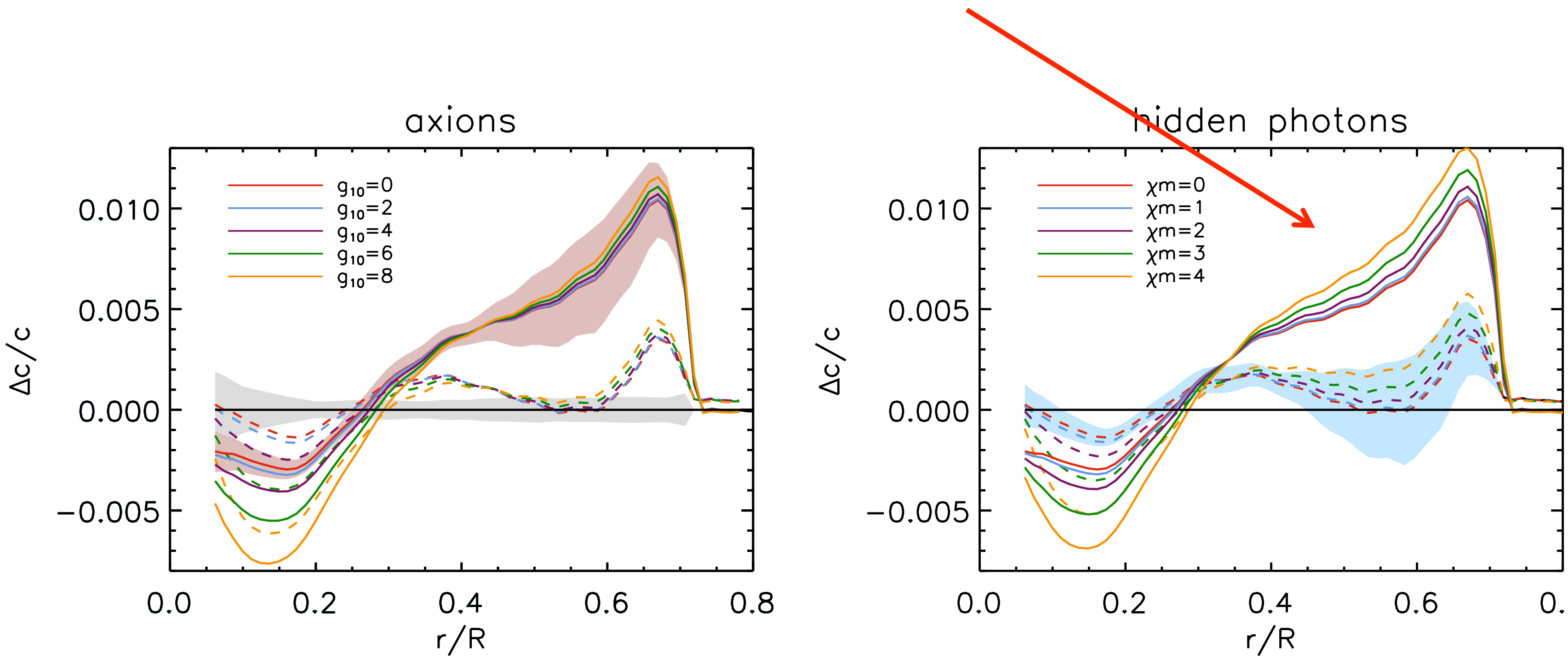


Weak T-dependence -- > broad production region

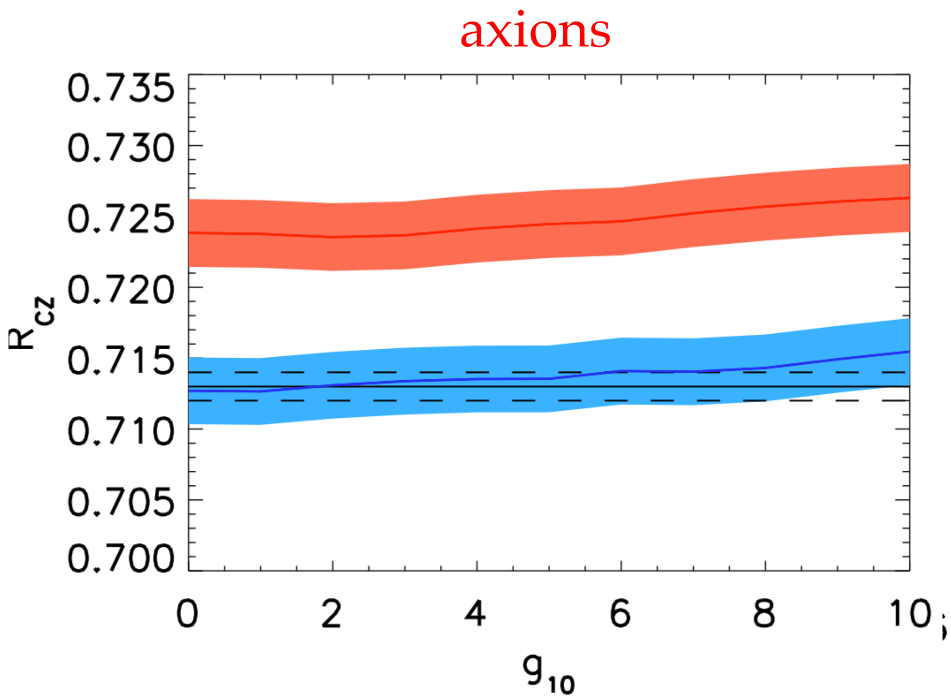
More relevant as T decreases (nucl. energy higher T-dependence)

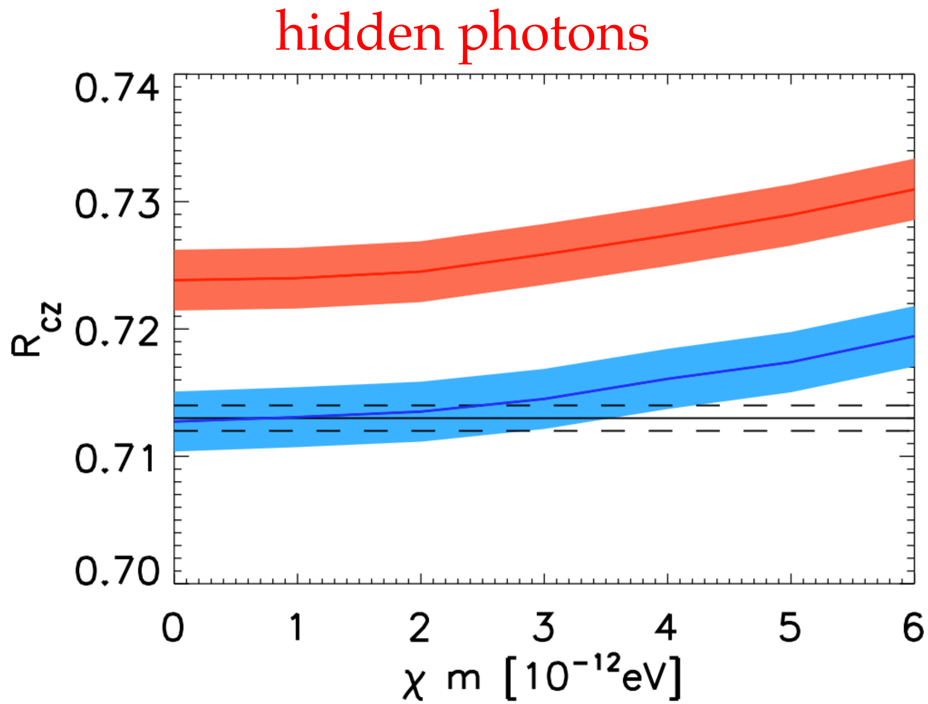
Hidden Photons

Variations in sound speed over whole radiative interior



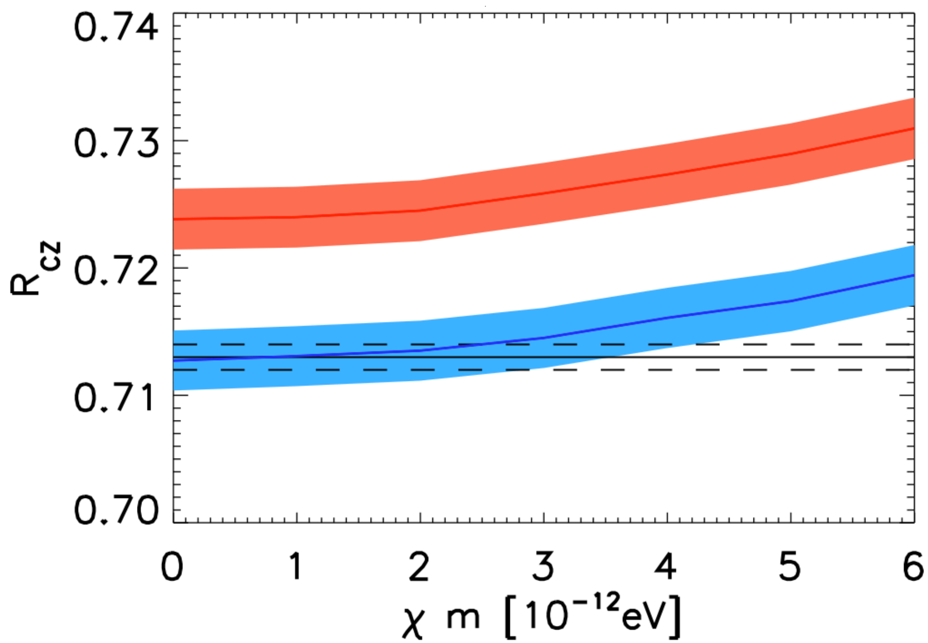
Hidden Photons

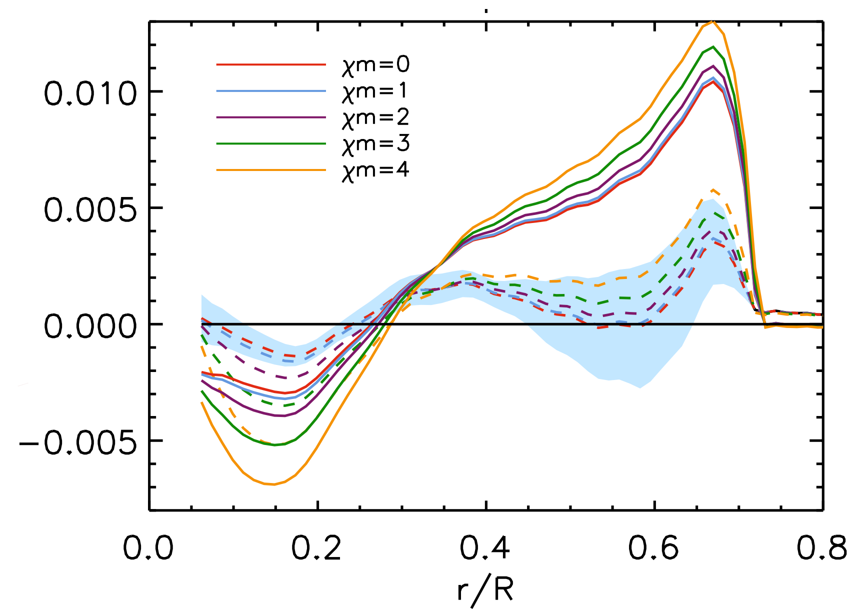




Depth of convective envelope more sensitive to hidden photons than axions

Hidden Photons

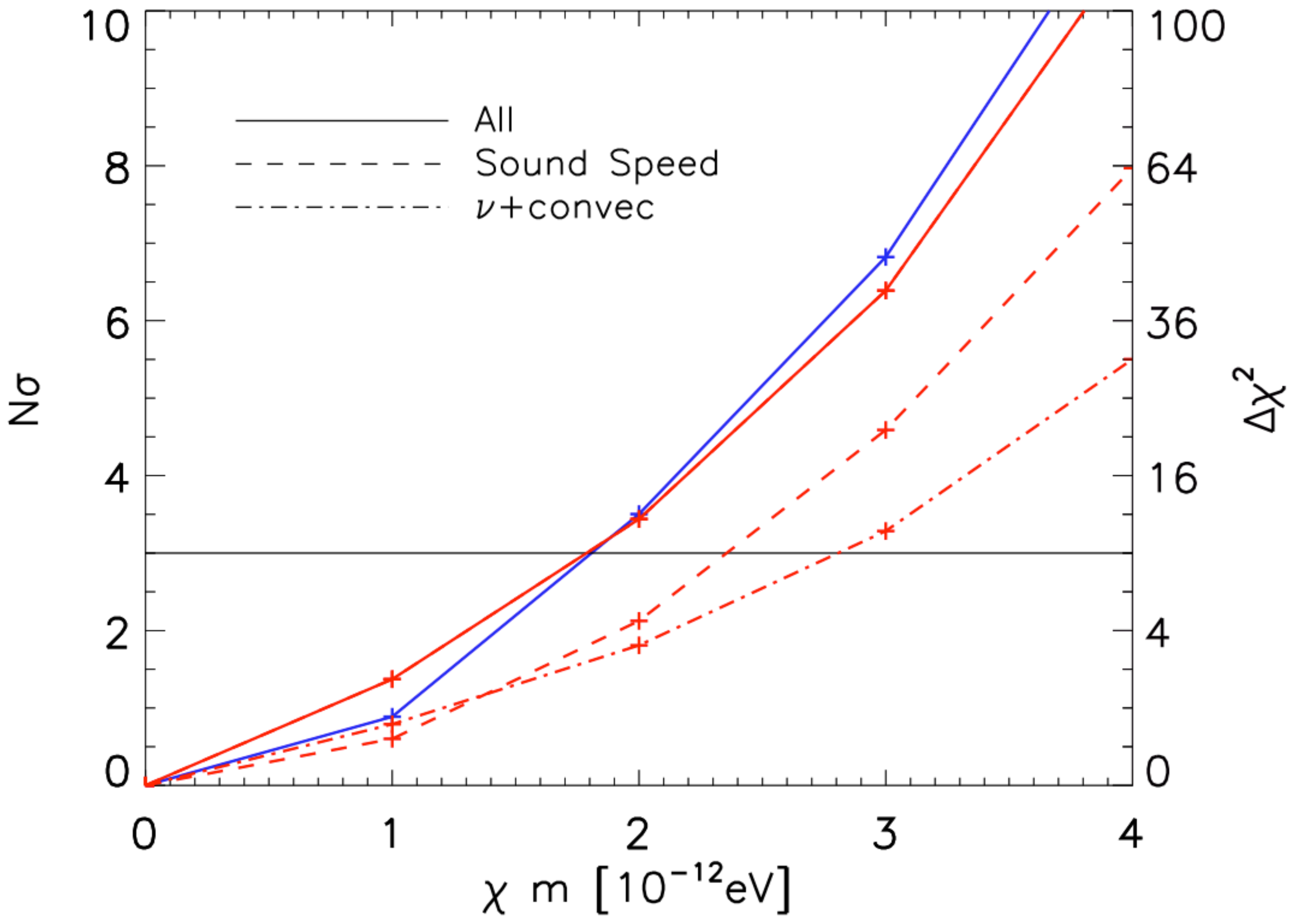




Our approach: solar model absorbs these variations without influencing boundaries derived for particle properties –
e.g. increase metal abundances: freely or constrained by spectroscopy

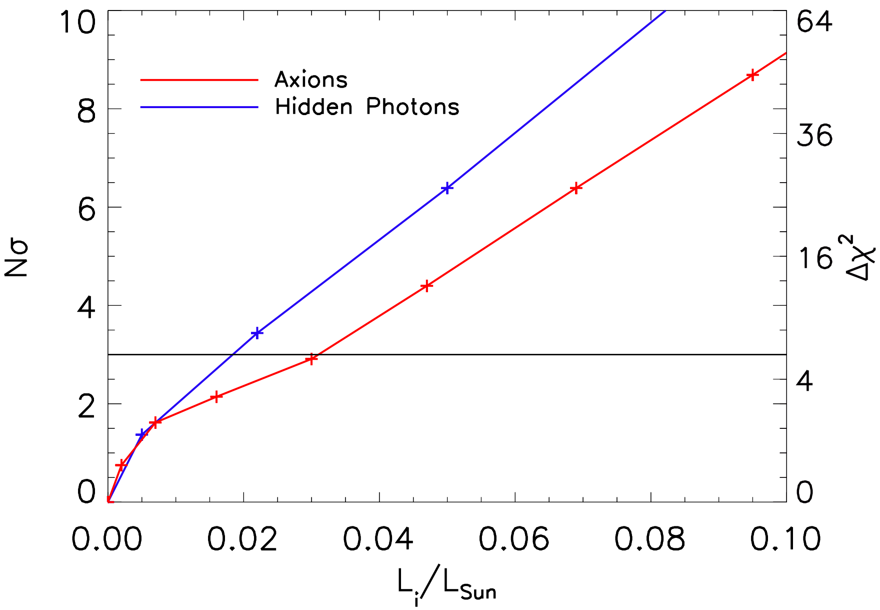
Limits derived are based on forcing solar models (+ dark channel) to fit solar data as best as possible --- > limits then derived from irreducible residuals

Hidden Photons



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

Comments on Solar Constraints

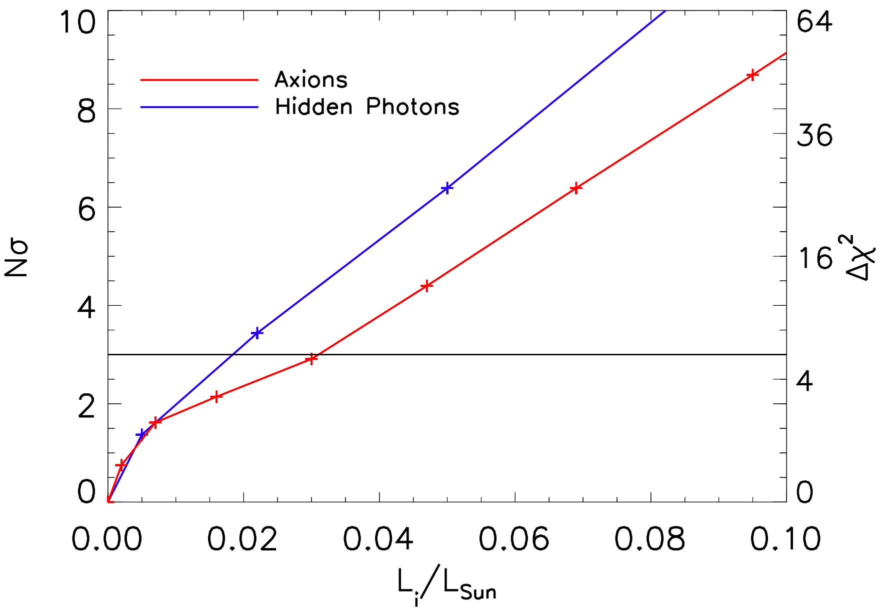


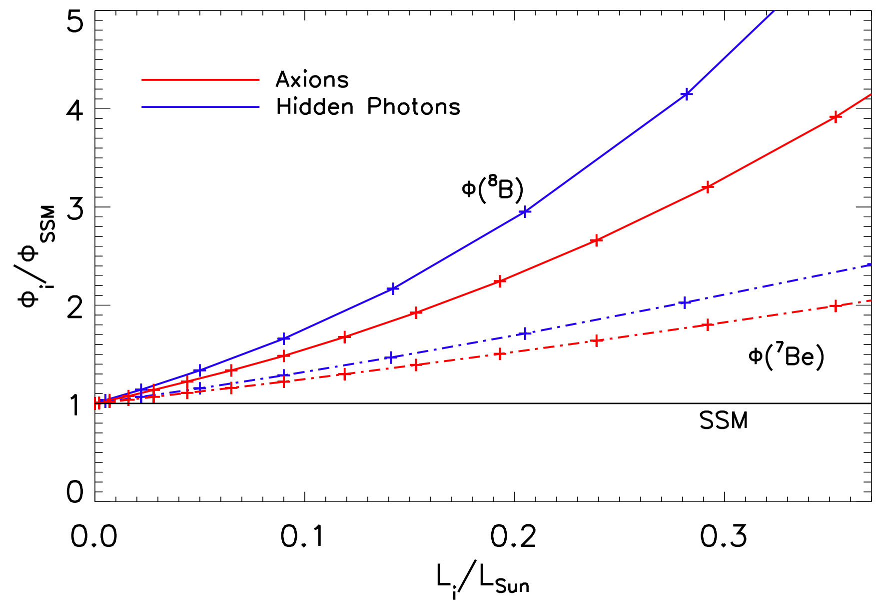
Effective limit in dark channels

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

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

Comments on Solar Constraints





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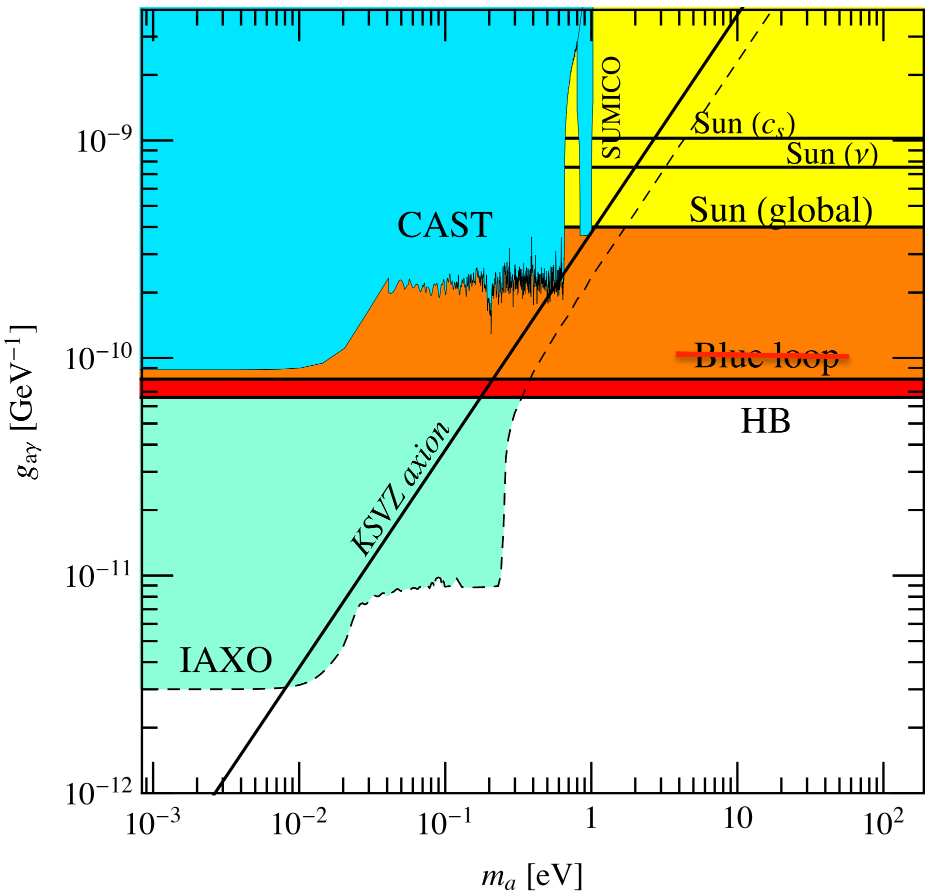
$$\frac{\Phi(^8\mathrm{B})}{\Phi_{\mathrm{SSM}}(^8\mathrm{B})} = \left(\frac{L_x + L_\odot}{L_\odot}\right)^\alpha$$

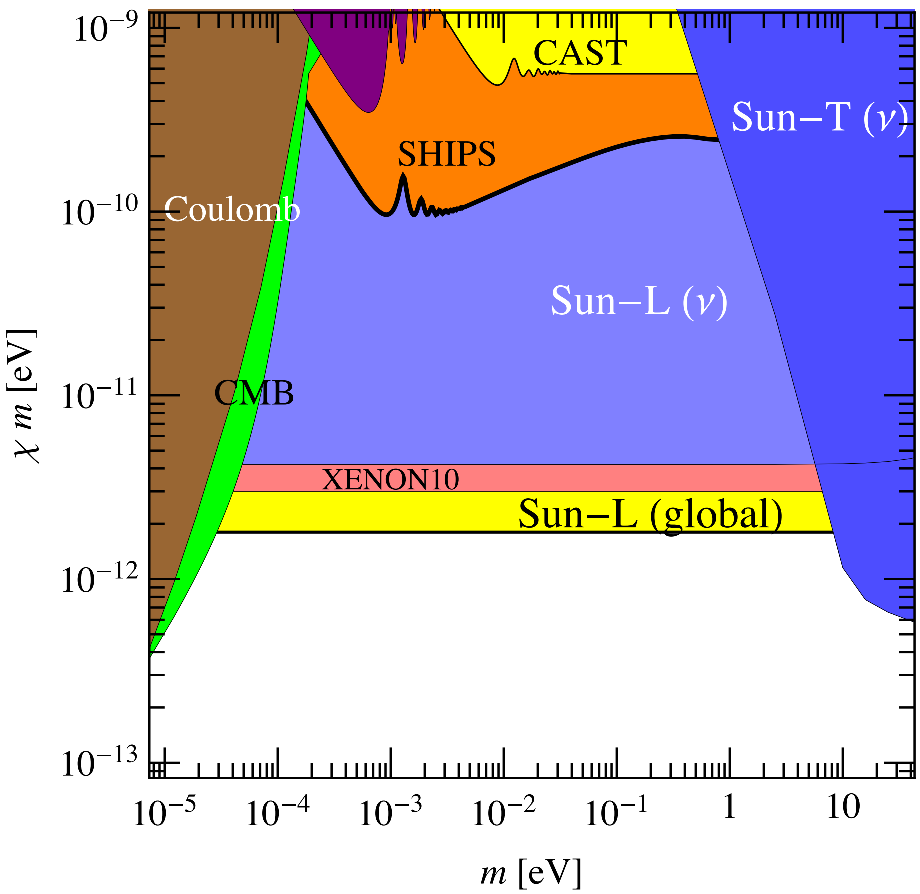
α= 4.4 (ax)

α= 5.7 (hp)

Relations are not universal depend on the type of particle

Current Limits



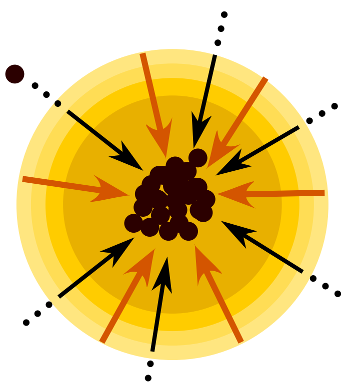


Second Part --- ADM & Solar Models

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



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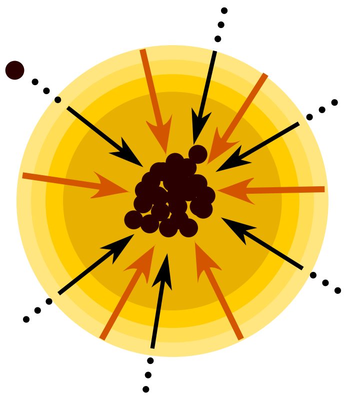

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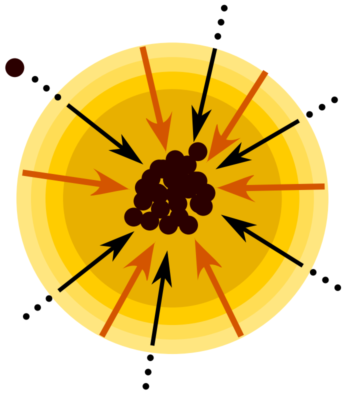
→ nuclear scattering inside the Sun

→ additional energy transport (abundance problem)



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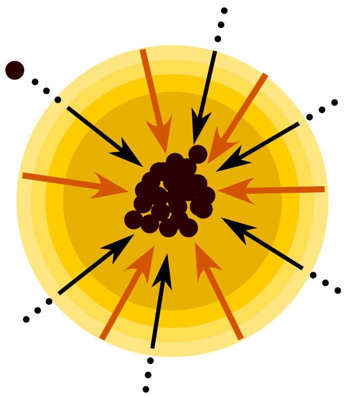
→ additional energy transport

→ modified solar structure



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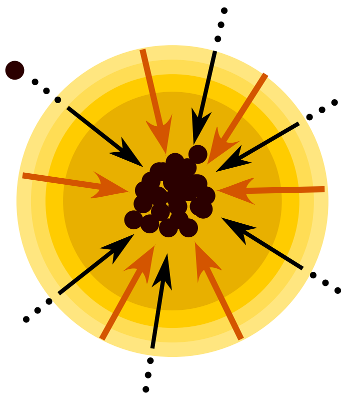
→ 1. observables: (helioseismology)

– sound speed

– oscillation frequencies

– convective zone depth

– surface helium frac.



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→ gravitational capture and settling the to solar core

→ nuclear scattering inside the Sun

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→ modified solar structure

→ 1. observables: (helioseismology)

– sound speed

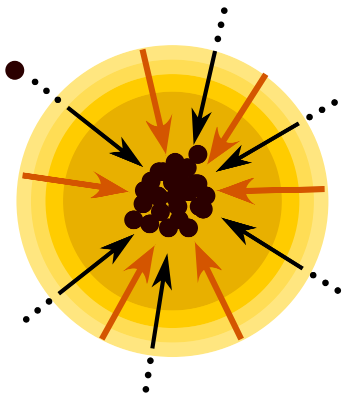
– oscillation frequencies

– convective zone depth

– surface helium frac.

→ 2. different core temperature

– solar neutrino rates



ADM

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

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

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

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_χ ~ r_χ --> Boltzmann eq.

Energy Transport by ADM

Dark matter number density

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

diffusivity

Dark matter conductive luminosity

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

thermal conductivity

Energy injection rate

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

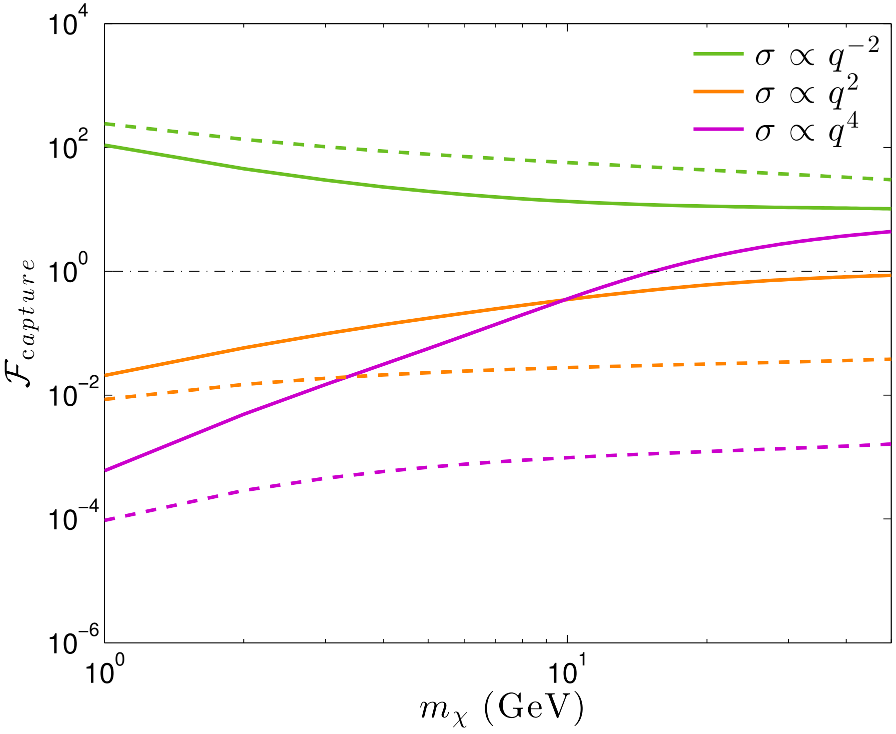
$v_0/v(r) - q_0/q(r)$

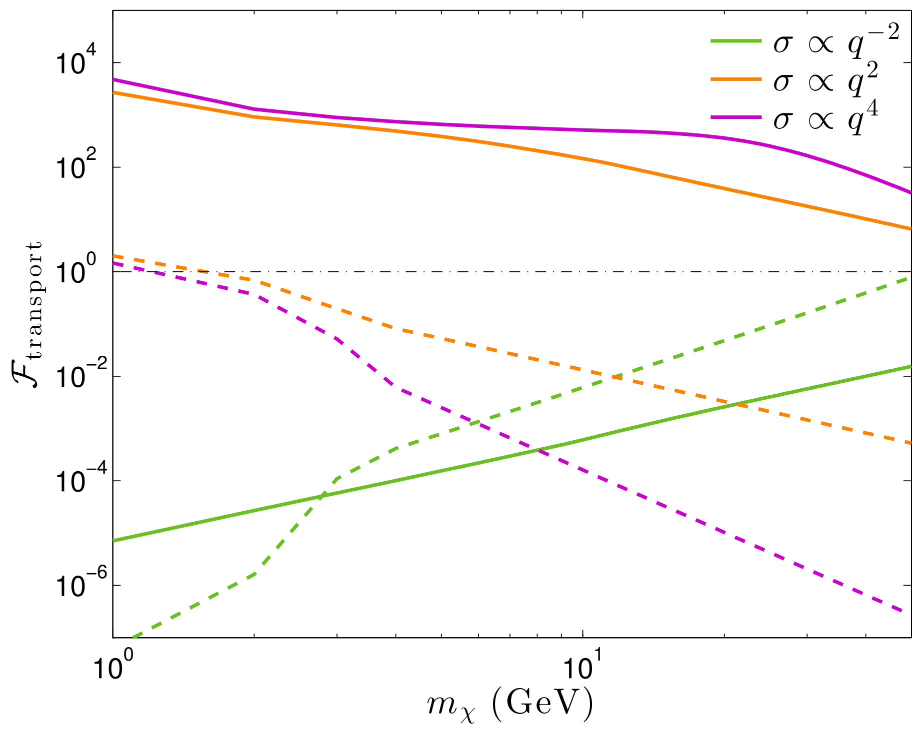
Two limiting behavior: LTE & Isothermal

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

Capture & Transport

Enhancement/suppresion factors

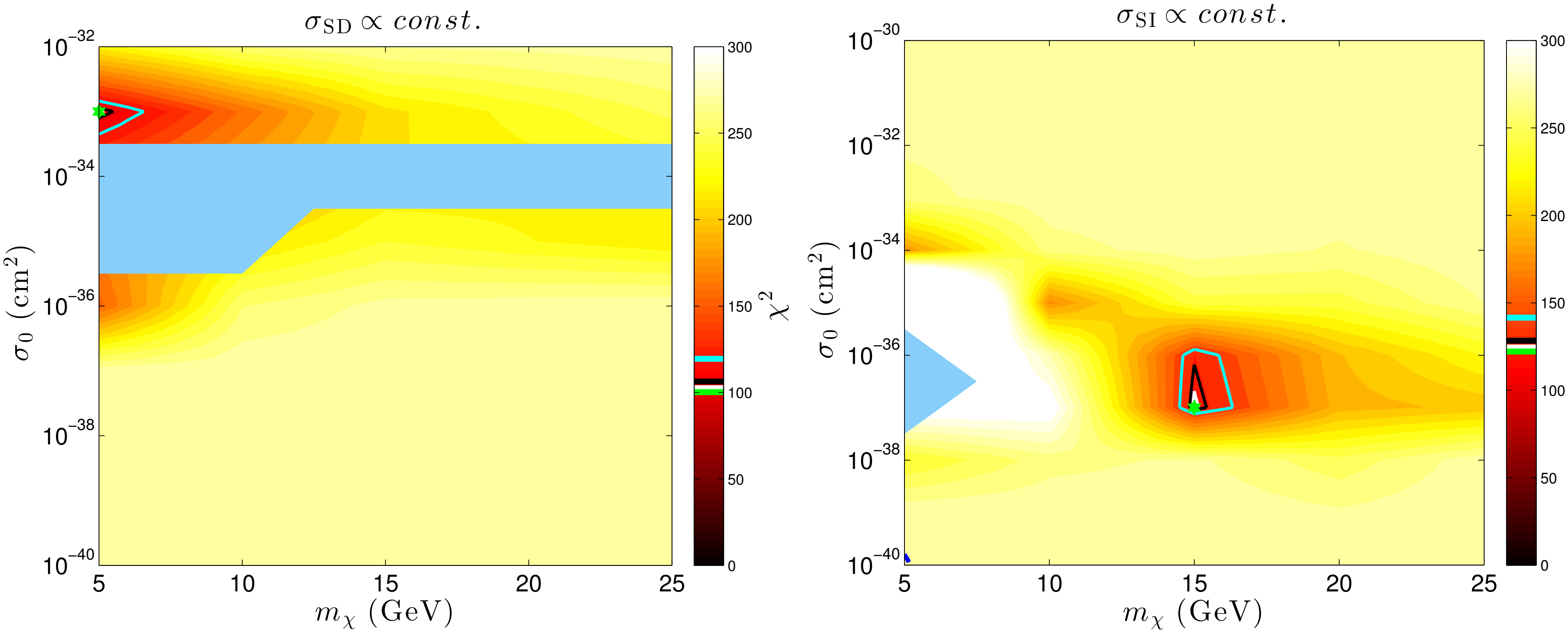




$\sigma_0 = 10^{-35}$ cm^2

Solid = SI, Dashed = SD

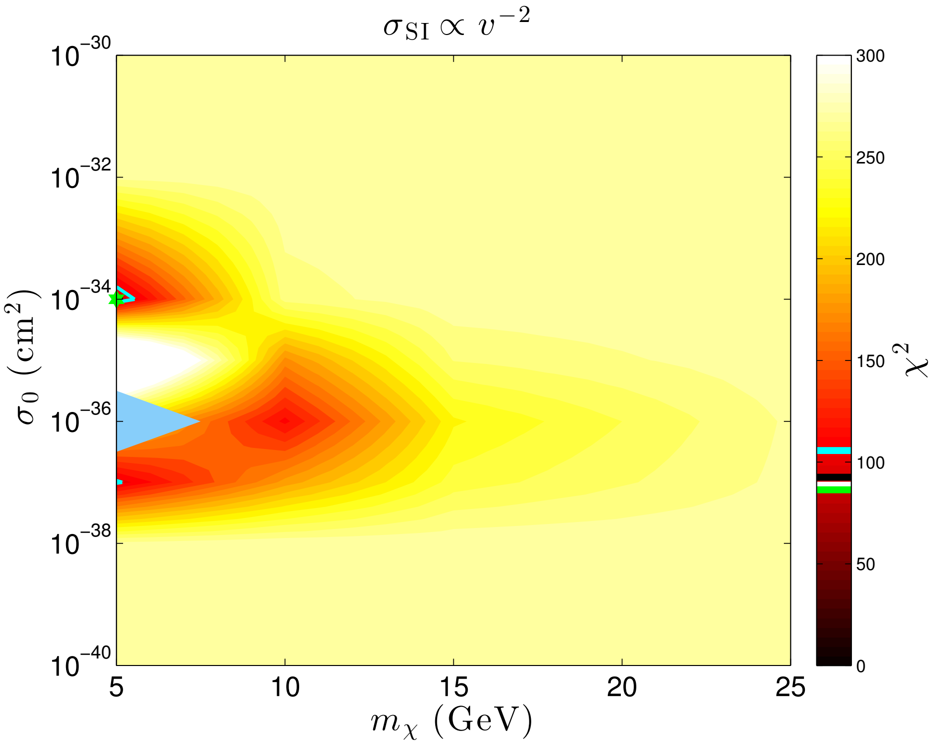
Impact on Observables: SI, SD - constant

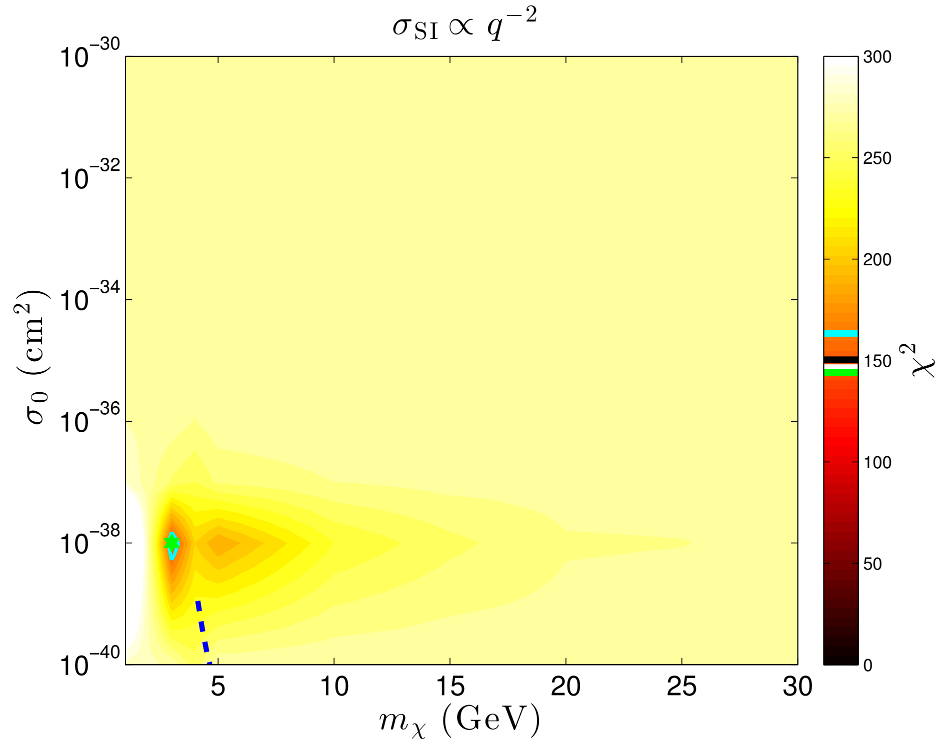


^{7}Be & ^{8}B neutrinos + convective radius + surface helium

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

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

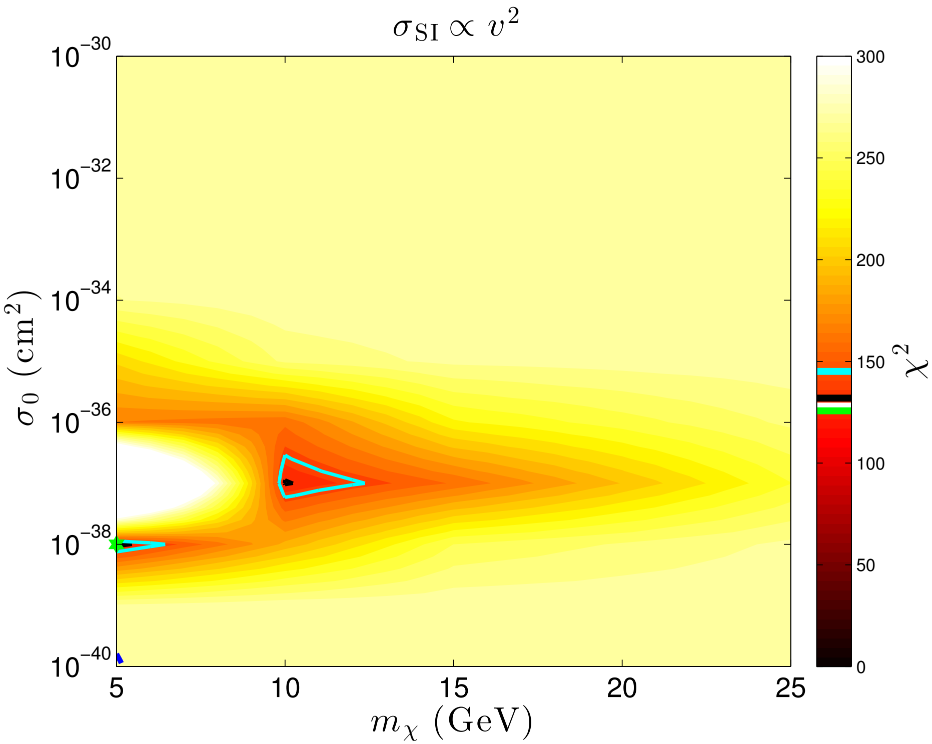


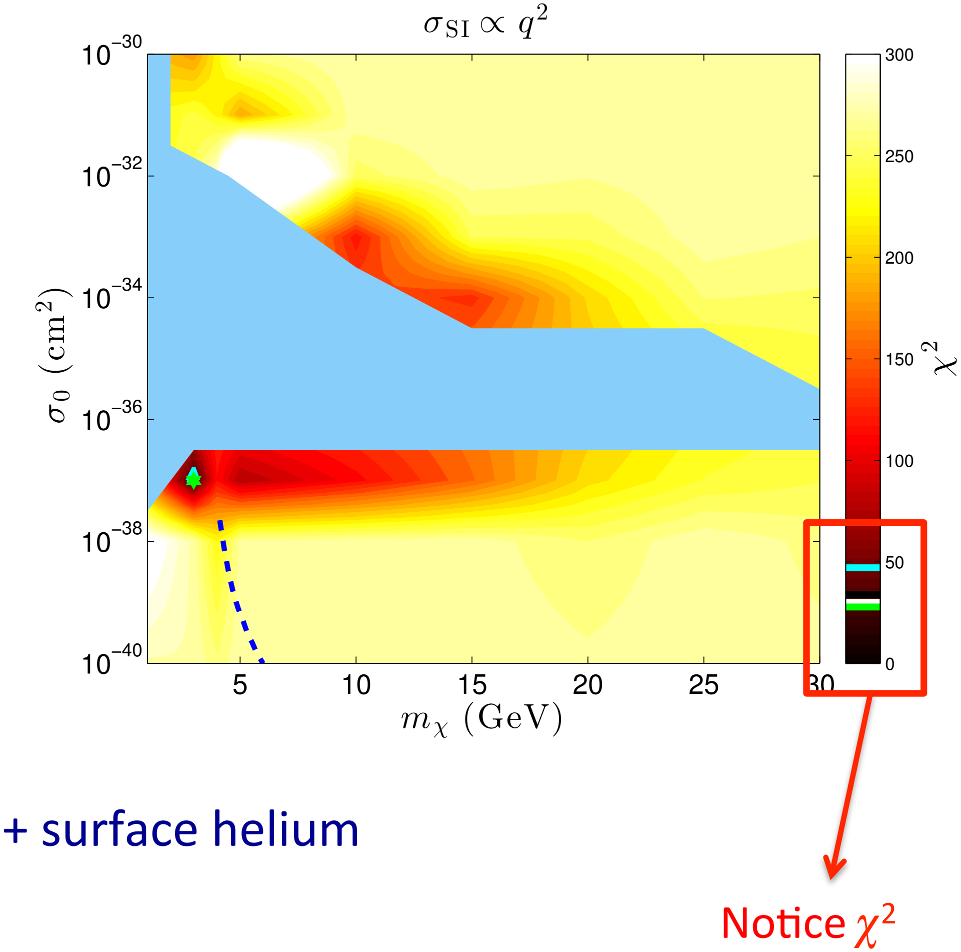


^{7}Be & ^{8}B neutrinos + convective radius + surface helium

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

IMPACT ON OBSERVABLES: SI, v^2, q^2

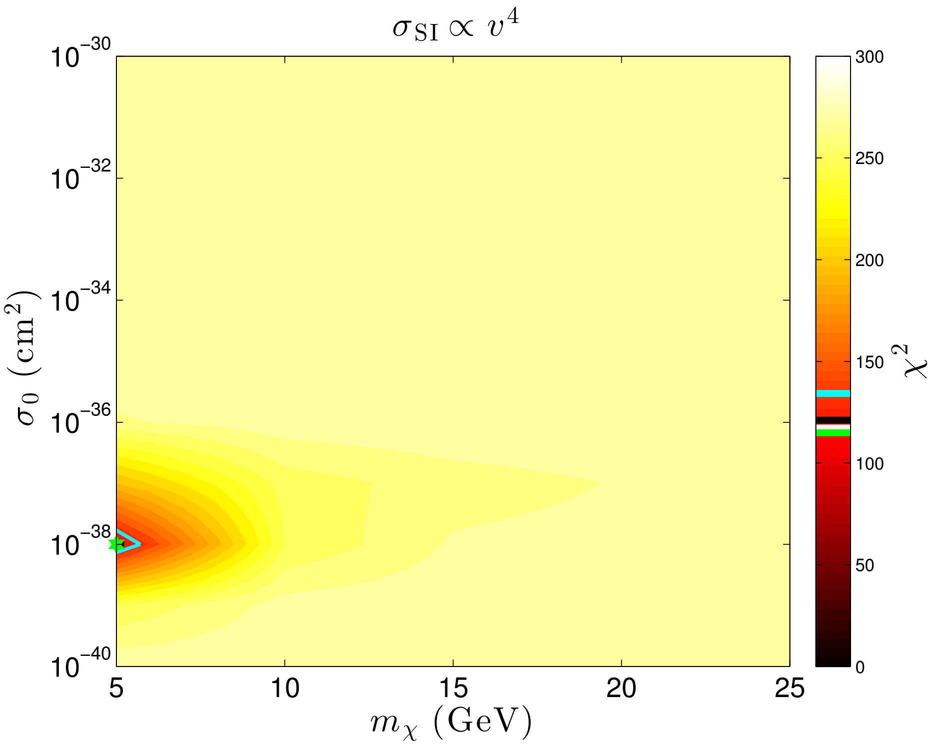


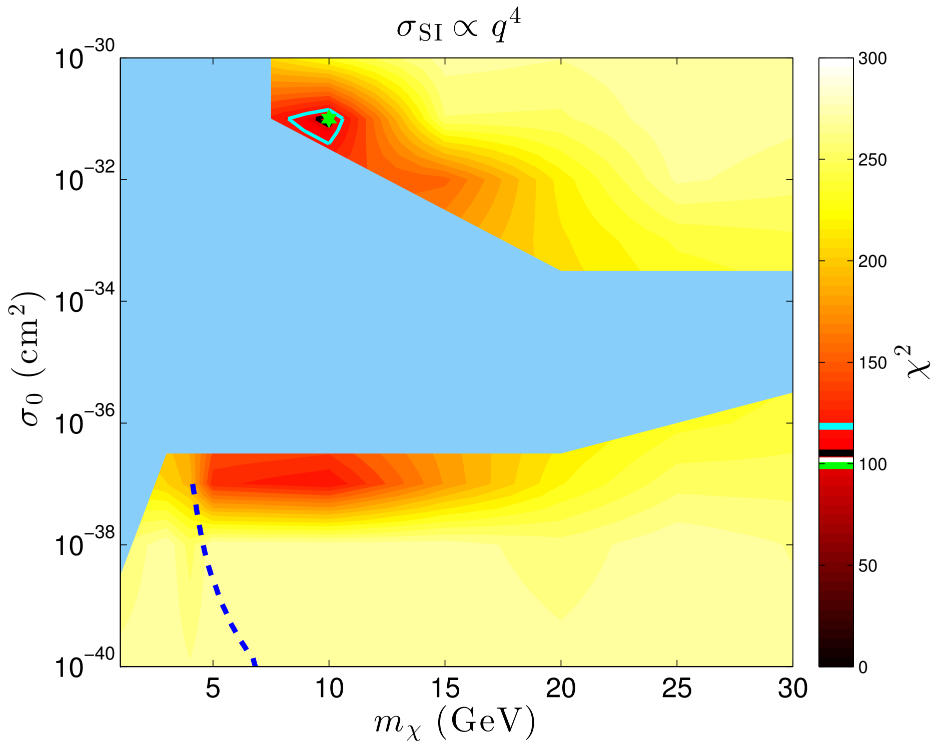


^{7}Be & ^{8}B neutrinos + convective radius + surface helium

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

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





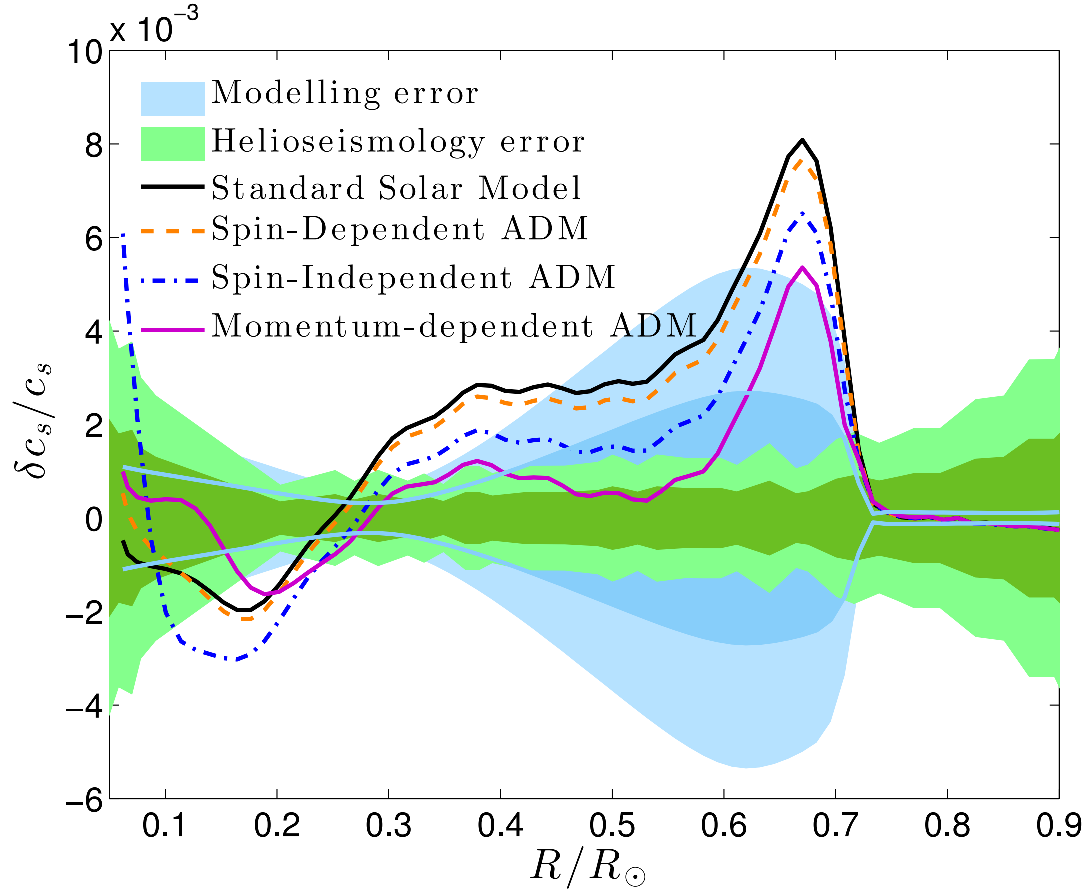
^{7}Be & ^{8}B neutrinos + convective radius + surface helium

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

Best Model – q^2

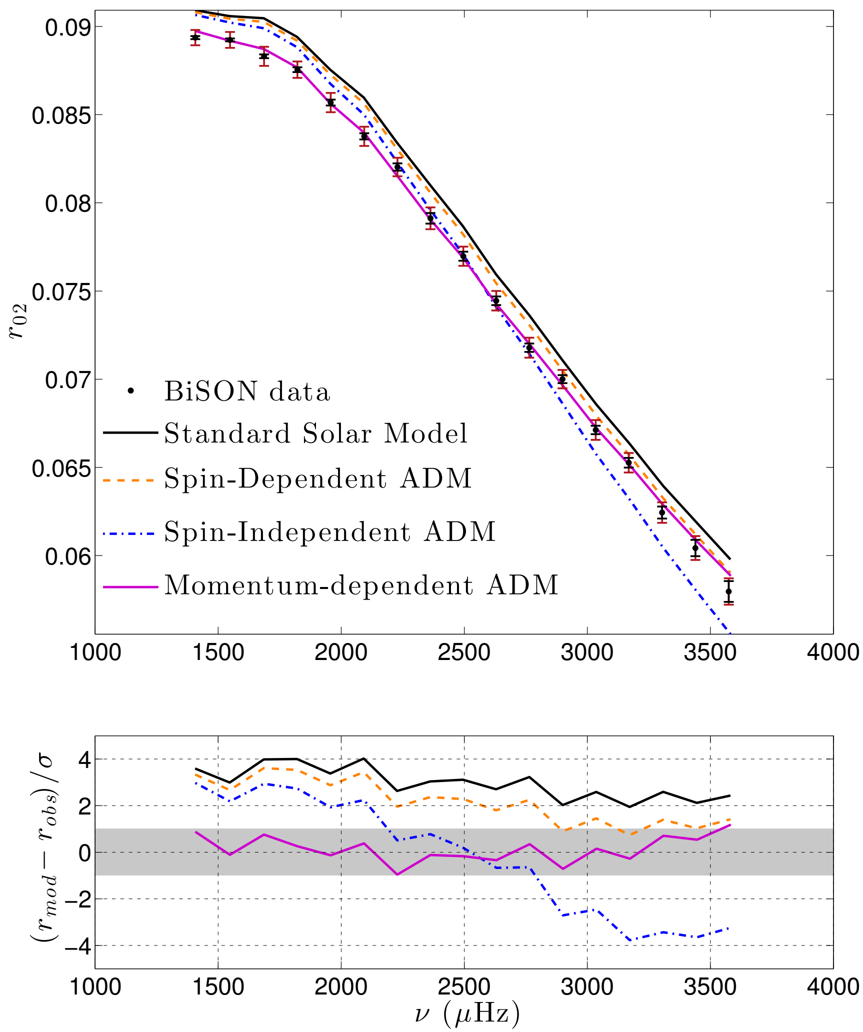
q^2 coupling
q_0= 40 MeV
m_χ = 3 GeV
σ_0 = 10^{-37} cm^2

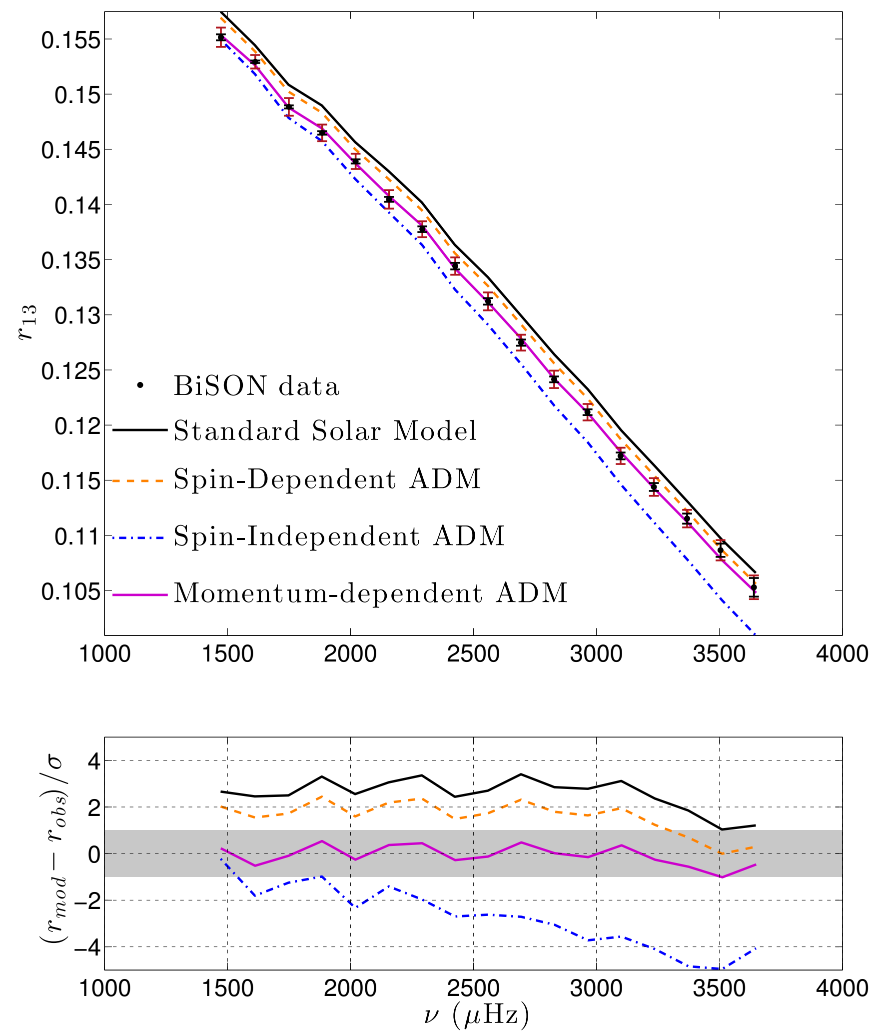
Sound speed for best q^2
SI and SD models



Best Model – q^2

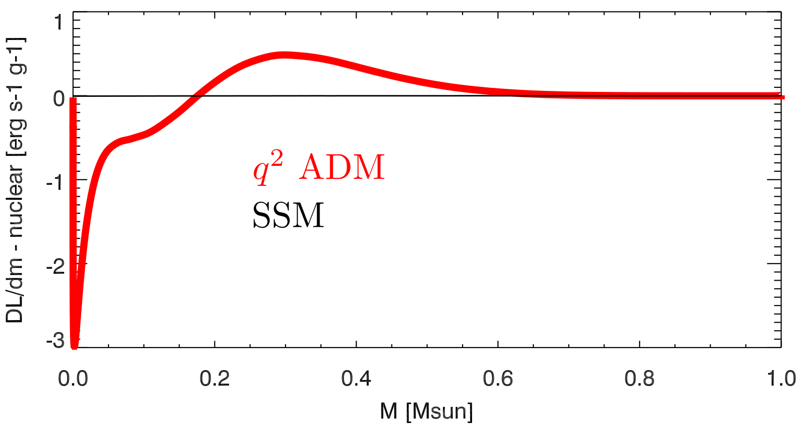
Frequency separation ratios – zooming into the solar core

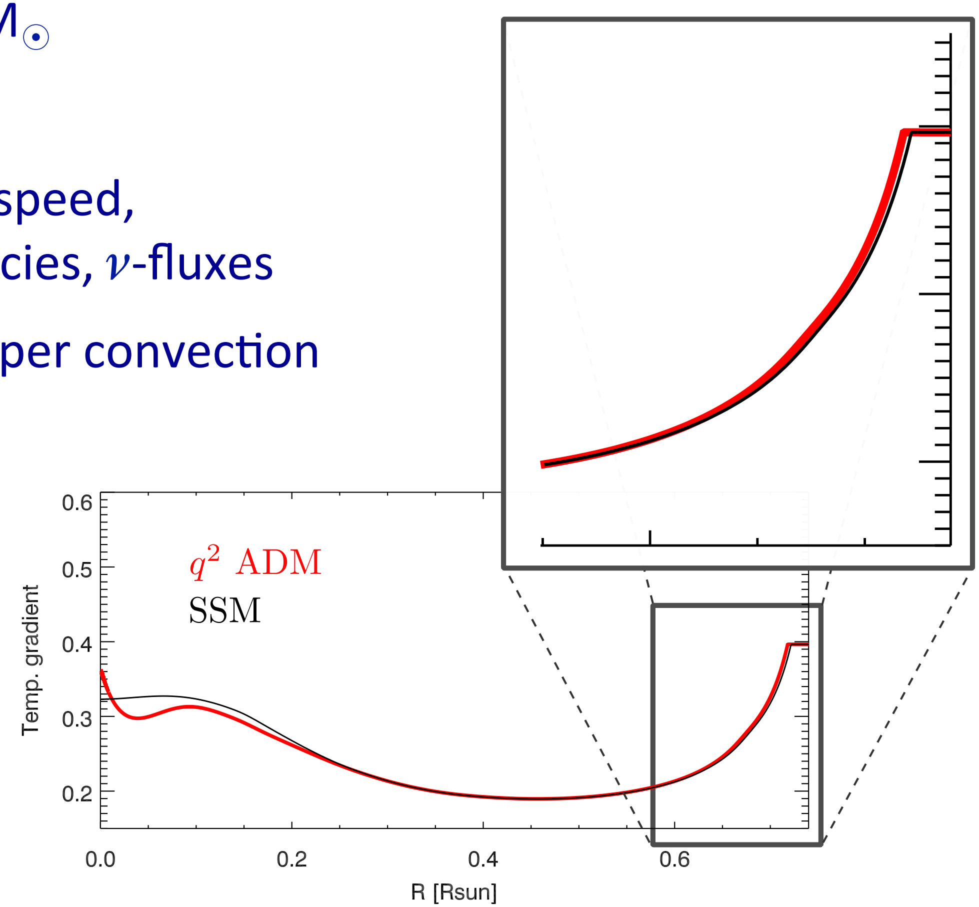




Changes to Solar Structure

* 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			

Physical Motivation

Standard models – dominant term constant in DM-quarks interactions

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

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

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

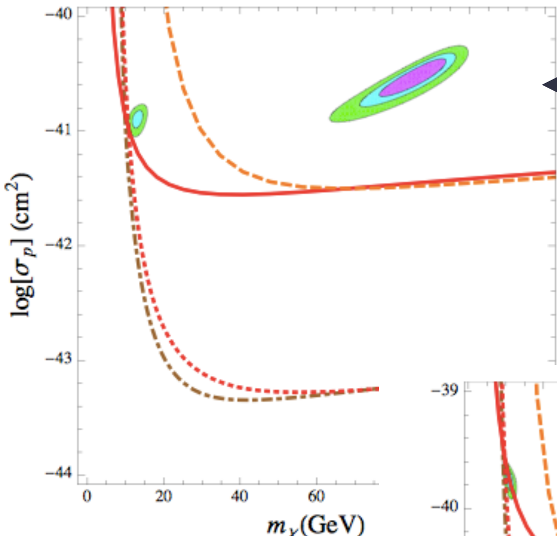
$$(\bar{\chi}\gamma_5\chi)(\bar{Q}Q)$$
$$(\bar{\chi}\chi)(\bar{Q}\gamma_5 Q)$$
$$(\bar{\chi}\gamma_5\chi)(\bar{Q}\gamma_5 Q)$$
$$(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{Q}\gamma^\mu Q)$$

can lead to dependence on the transferred momentum

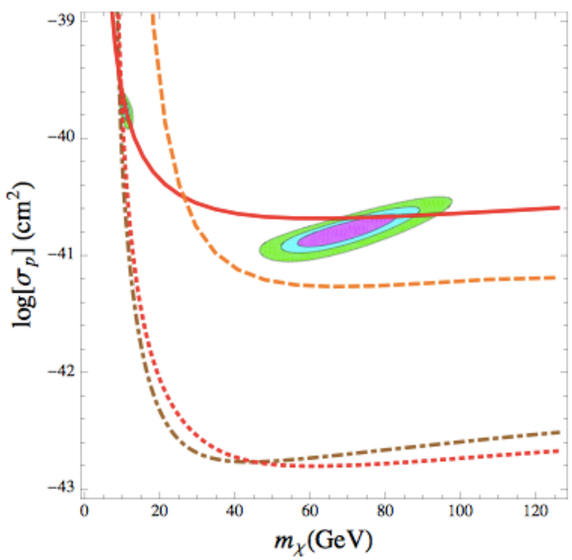
$$\sigma_{\chi q} \propto q^n$$

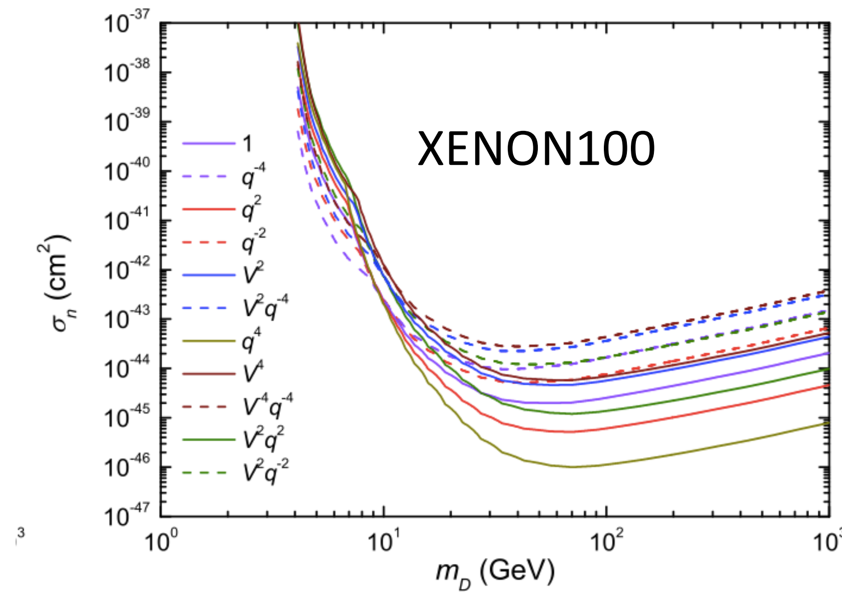
Physical Motivation

Standard models – dominant term constant in DM-quarks interactions



DAMA





q^2 suppression

Chang et al. 2010

Guo et al. 2014

SUMMARY

* Seismic and pp-chain νs not sensitive to detail compostion

* Solar abundance problem circumvented in particle studies by letting composition free and input parameters move in constrained way

* Combining helioseismic and solar νs data

* Solar limit on axion-photon coupling used as test of method

* Limit on hidden photon kinetic coupling revisited – x2 lower than previous

* Momentum exchange q2 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)