Crossroads: Solar Models and Particle Physics

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Outline

Part I

* Standard solar models and the abundance problem

  what is helioseismology and solar neutrinos really tell us

Part II

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

  revisiting solar limits for axion-photon coupling and hidden photons

Part III

* Asymmetric dark matter in the Sun with 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

- initially homogeneous – well mixed by convection
- constant mass evolution – 1 $M_\odot$
- evolve up to solar system age 4.57 Gyr

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

Solar radius -- > convection parameter
Solar (photon) luminosity -- > initial He abundance
Metal to hydrogen surface abundance (Z/X) -- > initial metallicity
(metals = all elements heavier than He)

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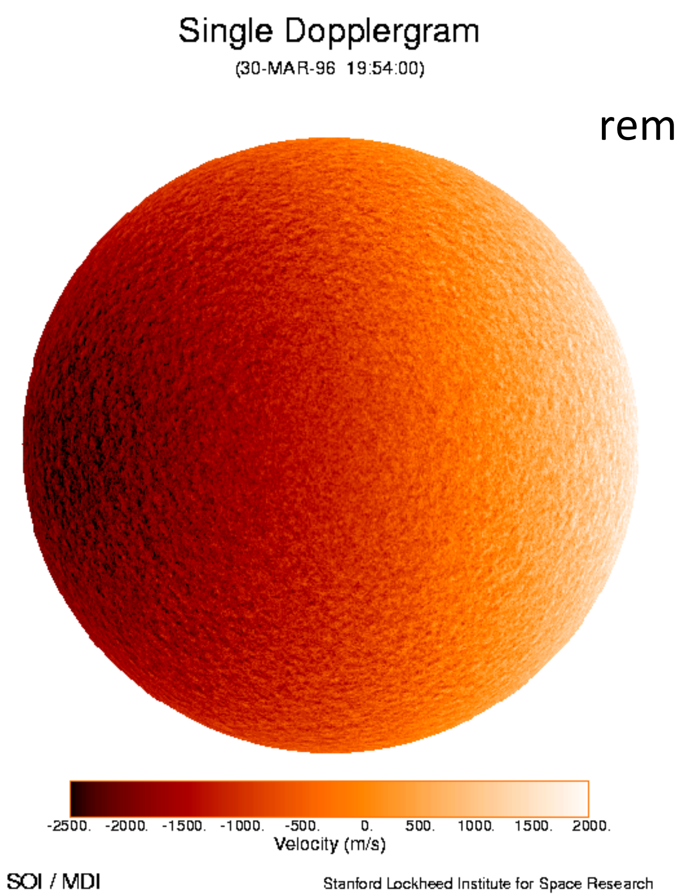
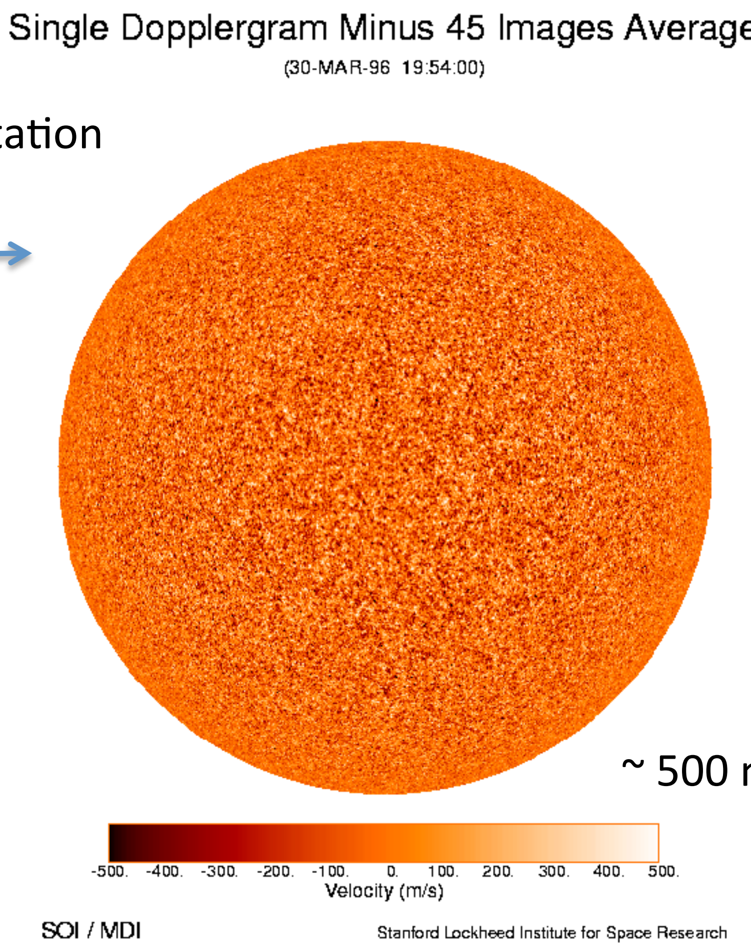
What observables to test models?

Helioseismology: sound speed, surface helium, depth convective zone, etc.
Solar neutrinos

Helioseismology

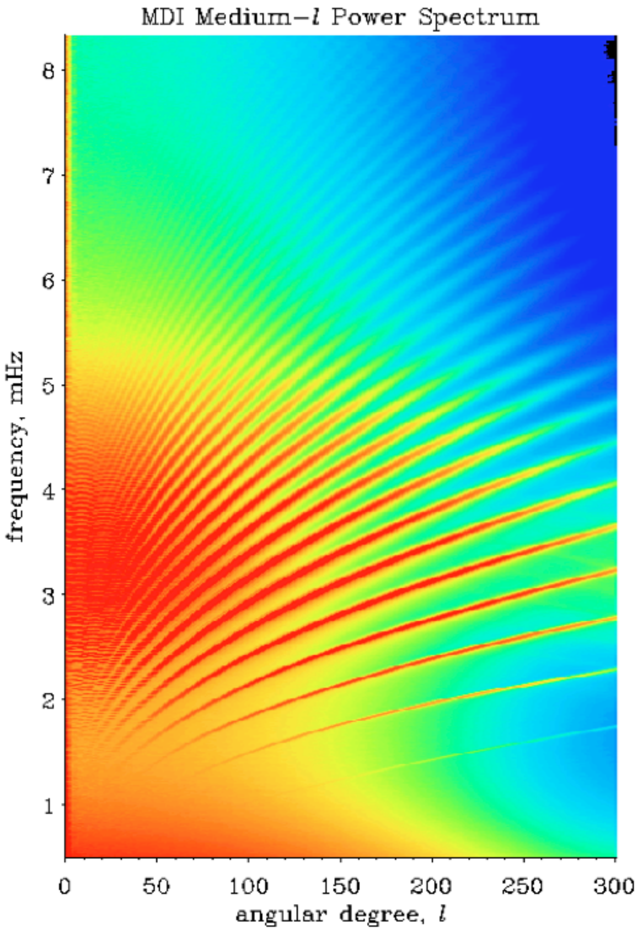


remove solar rotation



~ 500 m/s

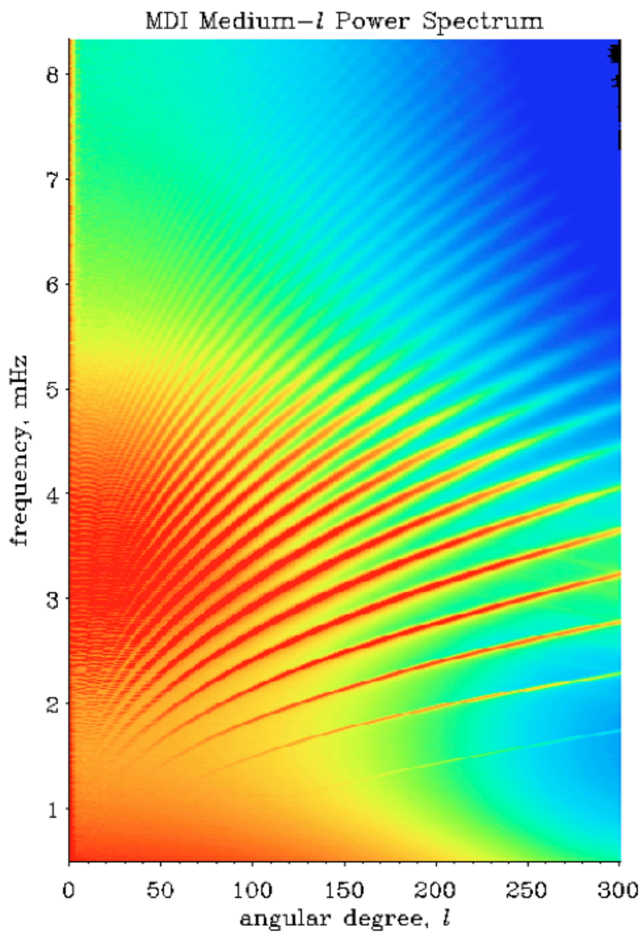
Helioseismology

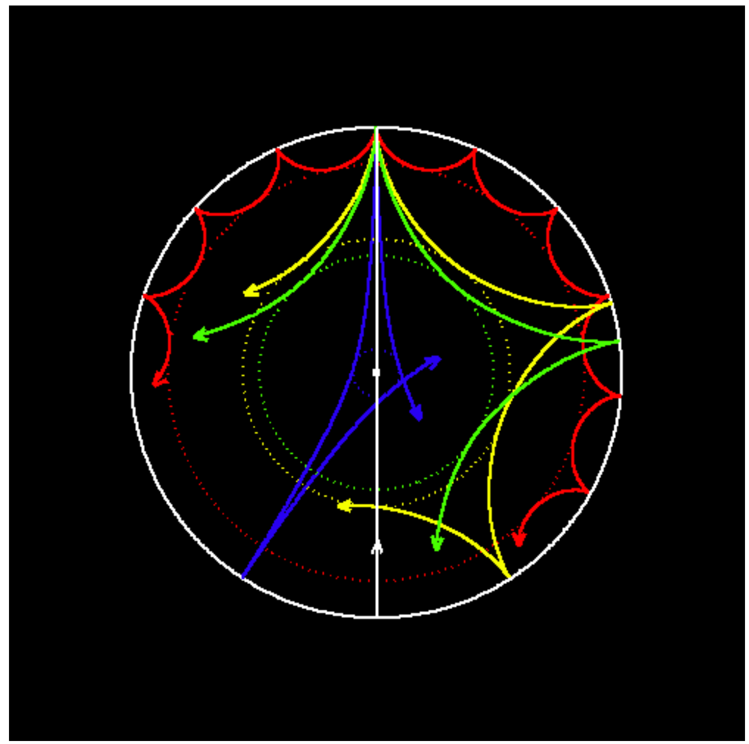


$$c^2 = \frac{\Gamma_1 p}{\rho}$$

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

Helioseismology





$\ell = 0$

$\ell = 2$

$\ell = 20$

$\ell = 25$

$\ell = 75$

probe different regions of the Sun

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

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

Helioseismology

Inversions used to derive sound speed and density profiles

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

Helioseismology

Inversions used to derive sound speed and density profiles

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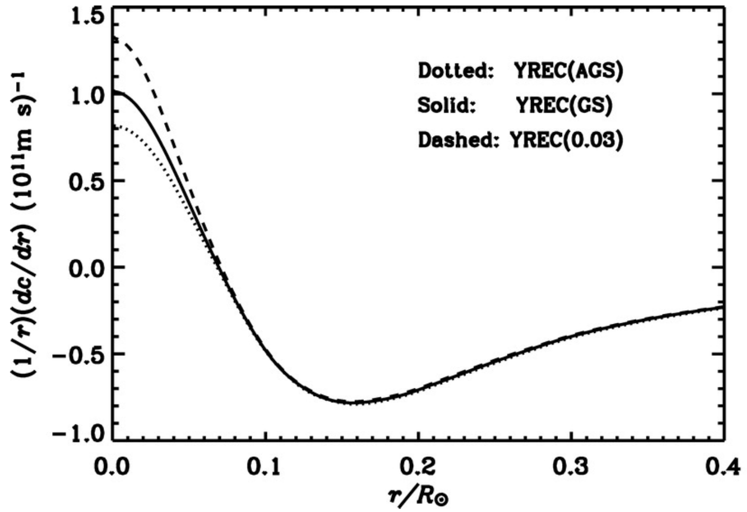
Low degree modes; l=0, 1, 2, 3 – frequency separation ratios (solar core)

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



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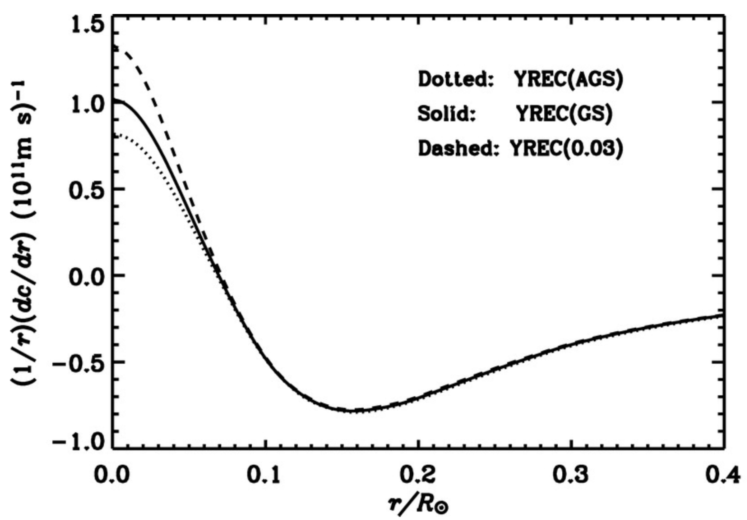
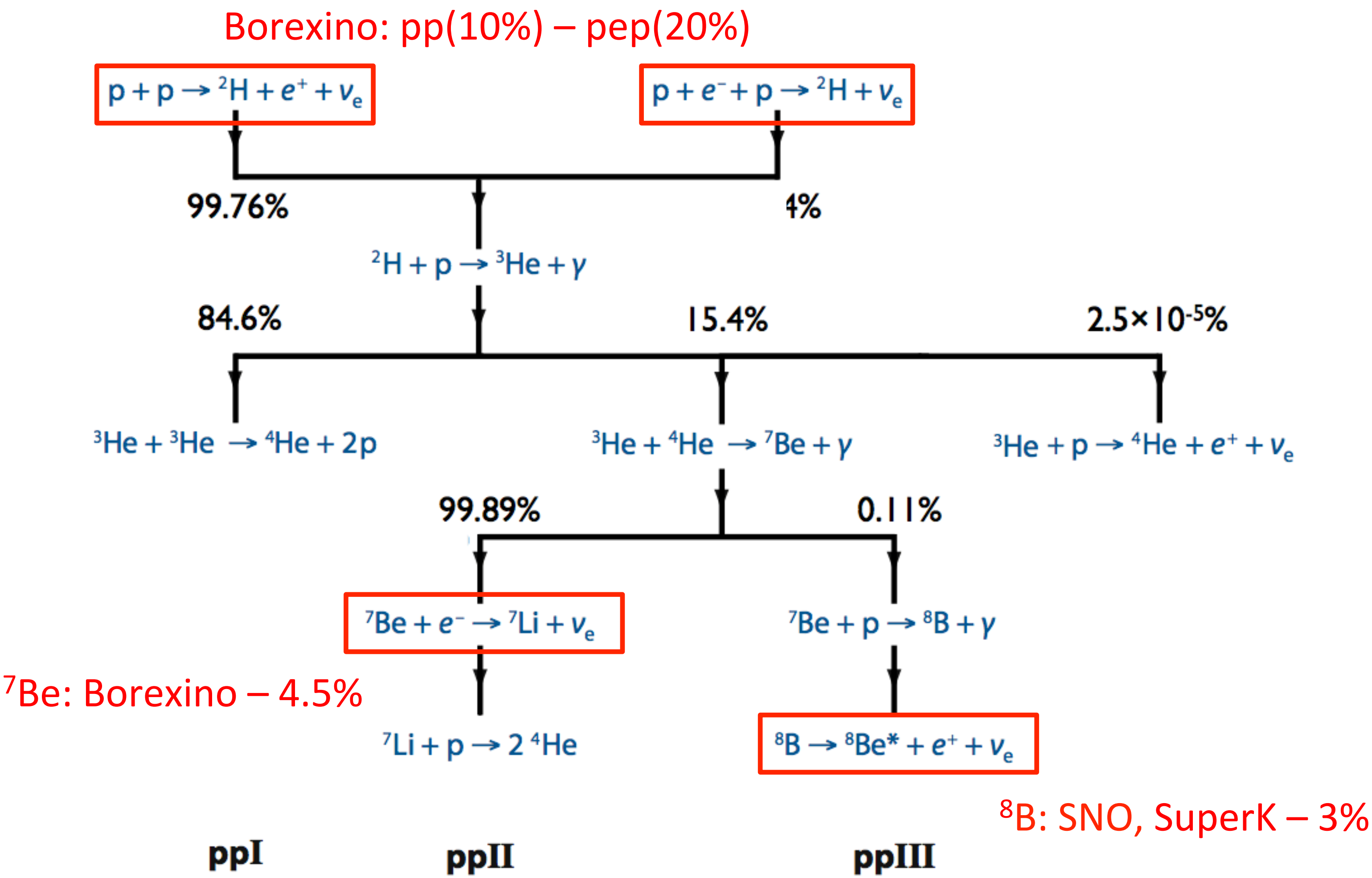


Depth of convective envelope

Envelope helium abundance

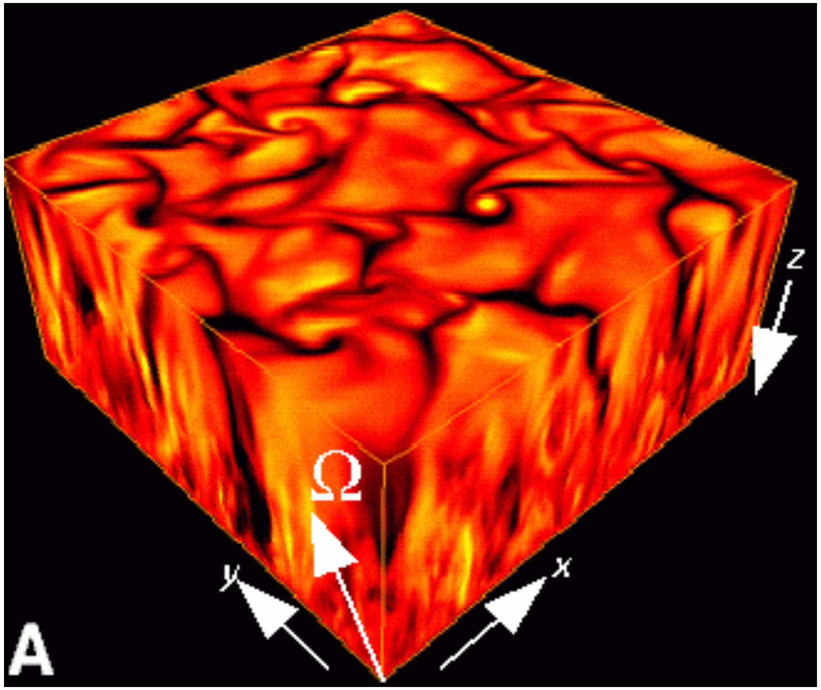
Solar Neutrinos



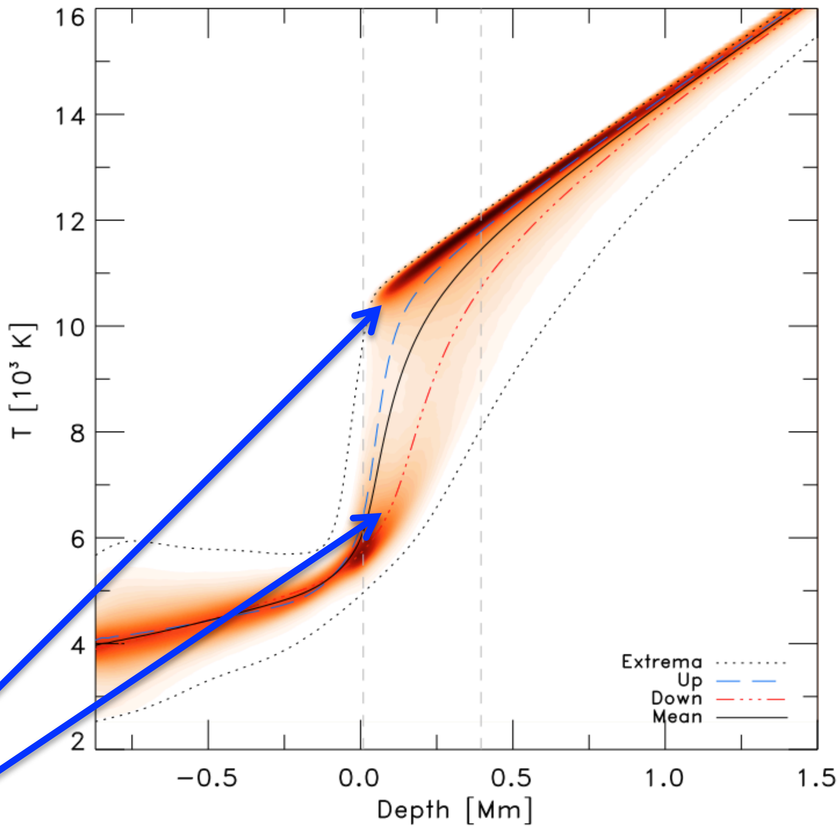
Solar Atmospheres & Abundances

Present day metal to hydrogen surface abundance (Z/X)

Spectroscopic analysis relies upon solar atmosphere models – 3D models of convection



Credit: N. Brummell



Hard to mimic with 1D models

Magic et al. 2014

Solar Atmospheres & Abundances

Fundamental differences between (old) 1D based and (new) 3D based 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

$A(i) = \log(n_i/n_H) + 12$

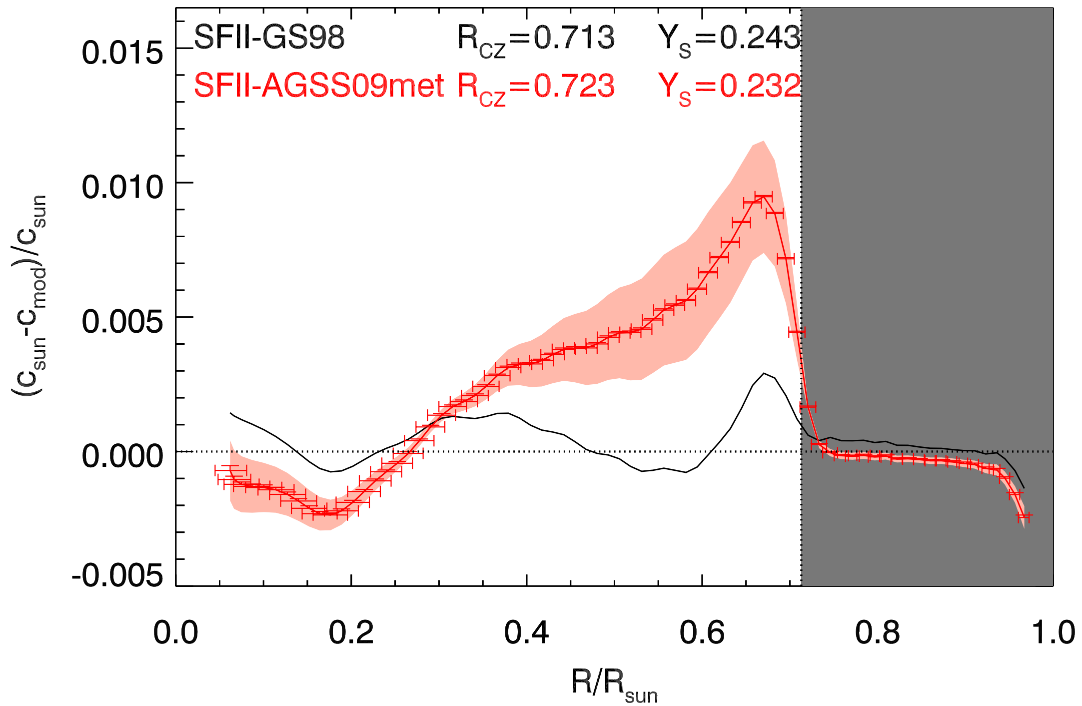
Differences of

CNO(Ne)~30-40%

refractories~10%

Sun has a sub-solar metallicity according to newest spectroscopic analysis

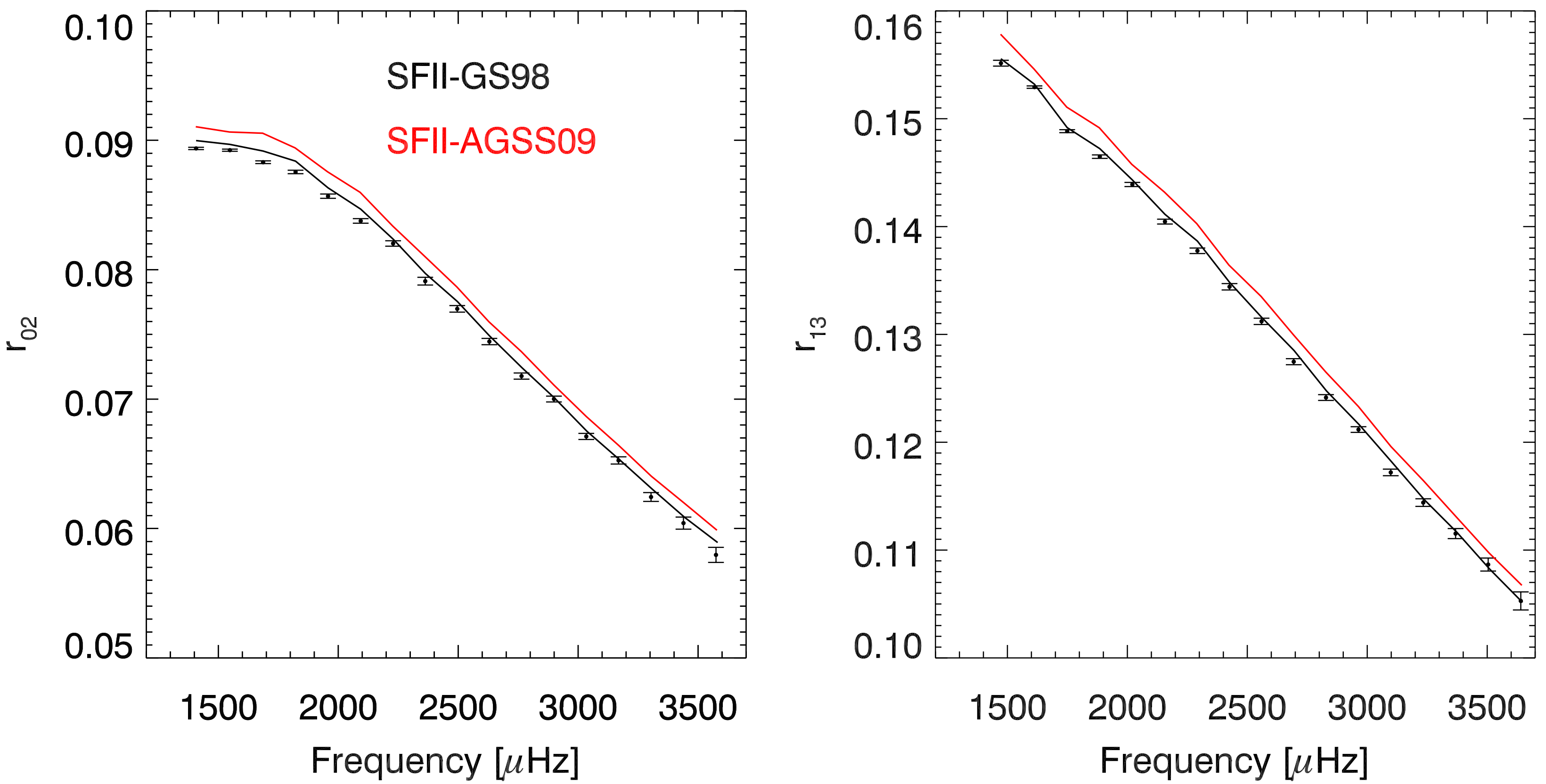
SSM: helioseismology



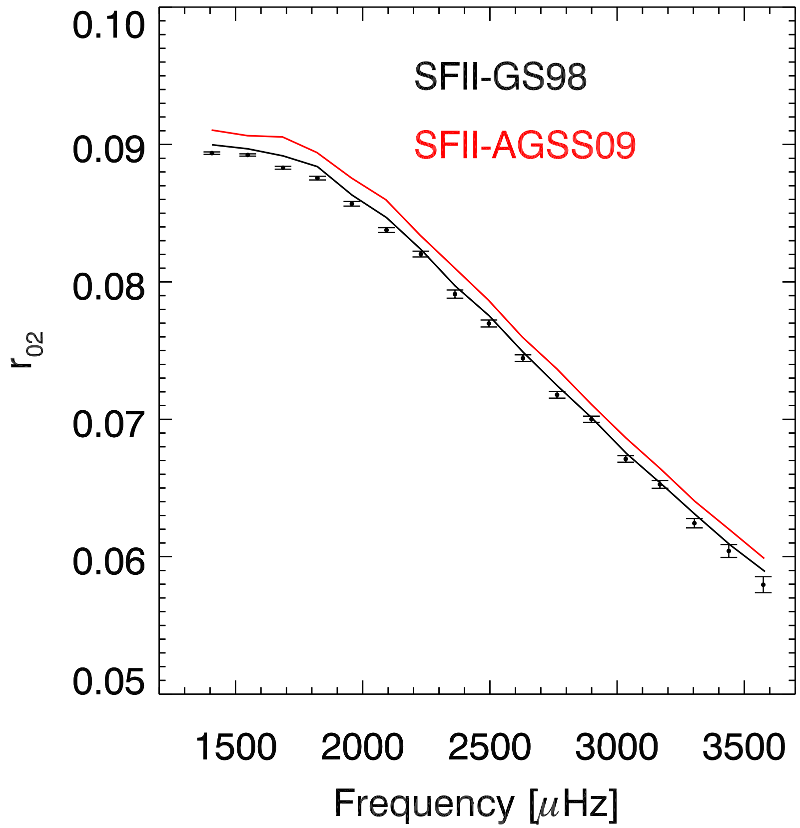
	GS98	AGSS09	Helios.
$(Z/X_\odot)$	0.0229	0.0178	—
$R_{CZ}/R_\odot$	0.712	0.723	0.713 ± 0.001
Y_S	0.2429	0.2319	0.2485 ± 0.0034
$\langle \delta c/c \rangle$	0.0009	0.0037	—
$\langle \delta \rho/\rho \rangle$	0.011	0.040	—

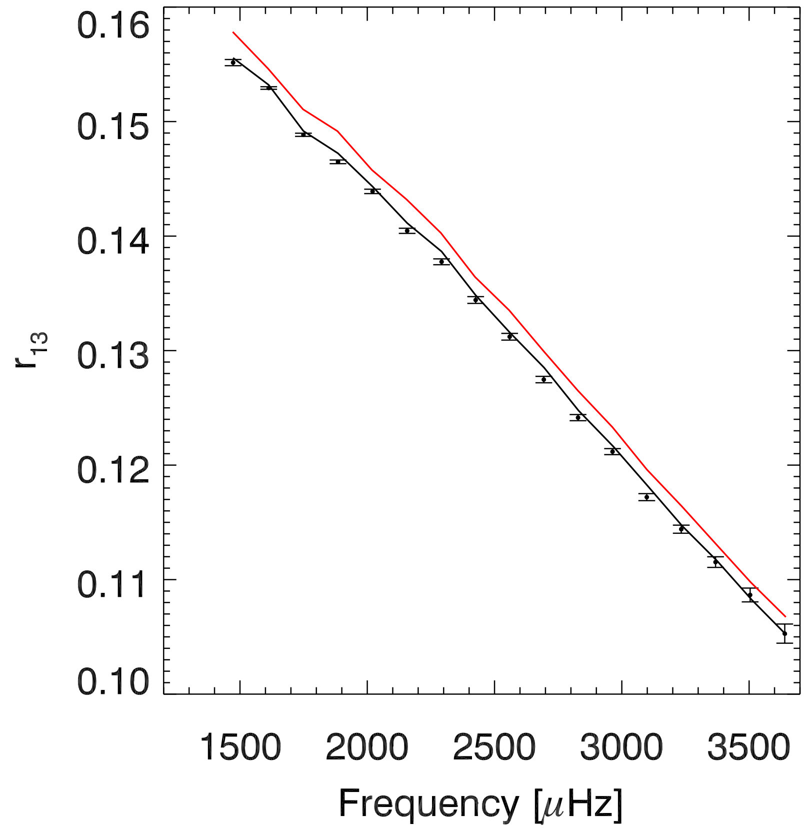
Helioseismology --> high-Z

SSM: helioseismology



SSM: helioseismology





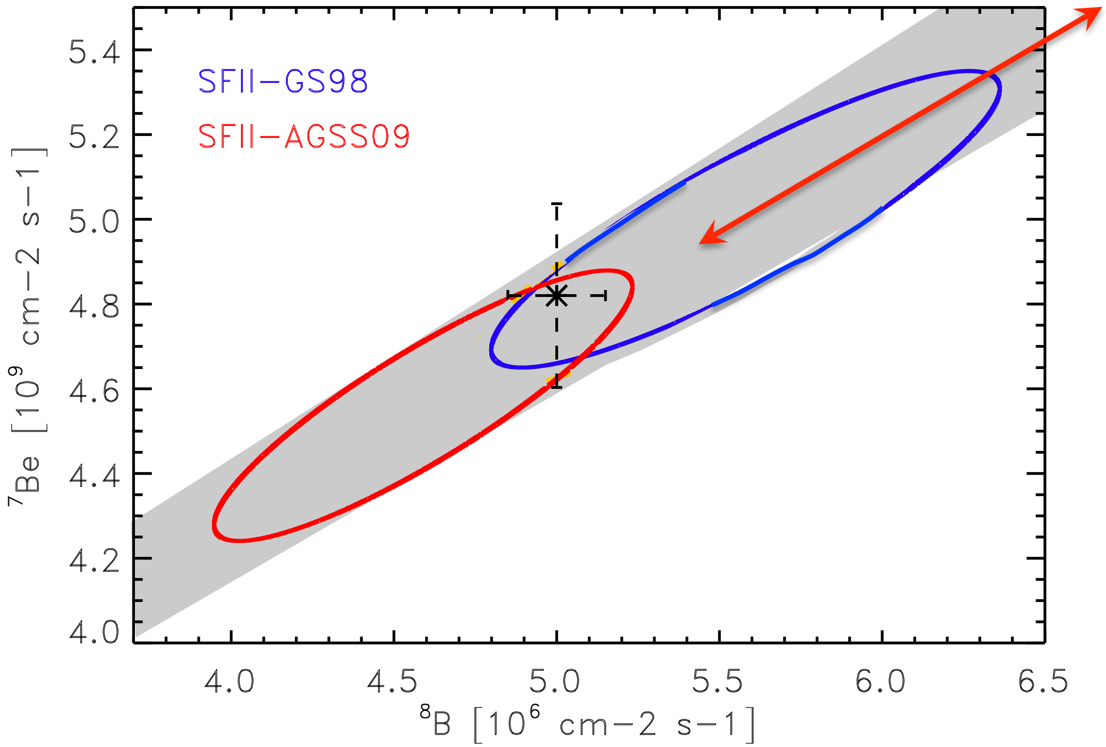
Helioseismic predictions of SSM --> high-Z
Solar atmospheres & spectroscopy -- > low-Z

Solar Abundance Problem

SSM: neutrinos

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

Dependence on core temperature



^{7}Be & ^{8}B consistent with any model

pp and pep uncertainties too large and models too similar

SSM: neutrinos

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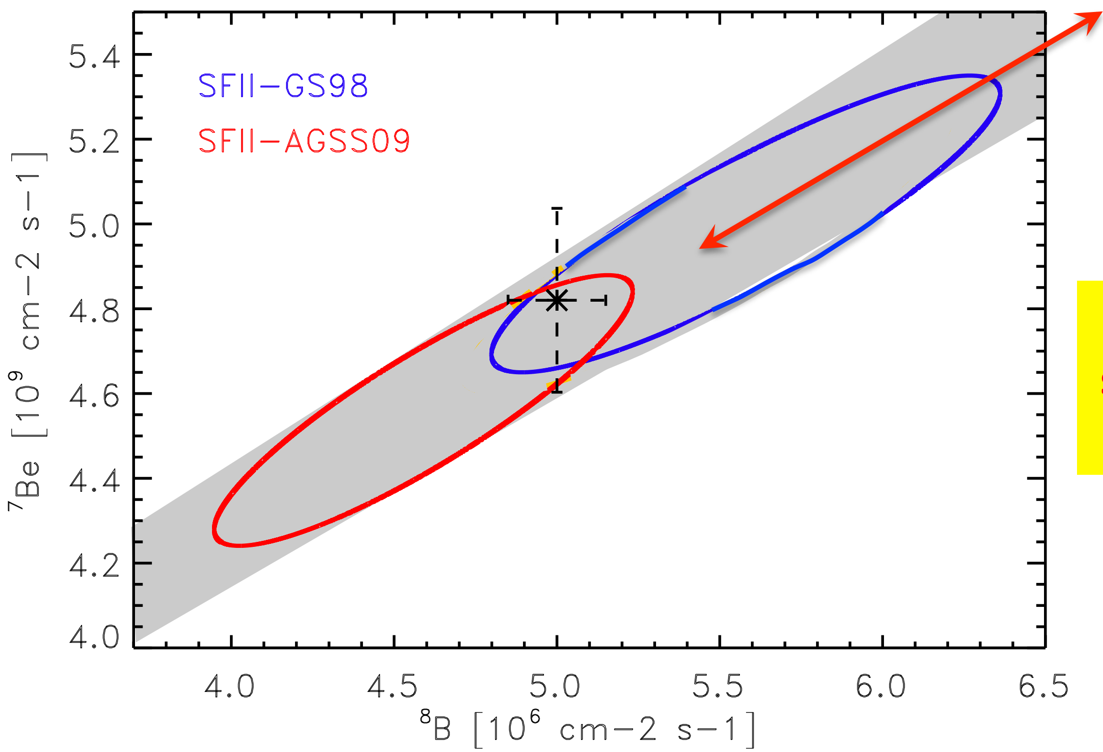


all fluxes from pp-chains sensitive to temperature not really composition

AND....

^{7}Be & ^{8}B consistent with any model

pp and pep uncertainties too large and models too similar

Composition/radiative opacity degeneracy

* 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

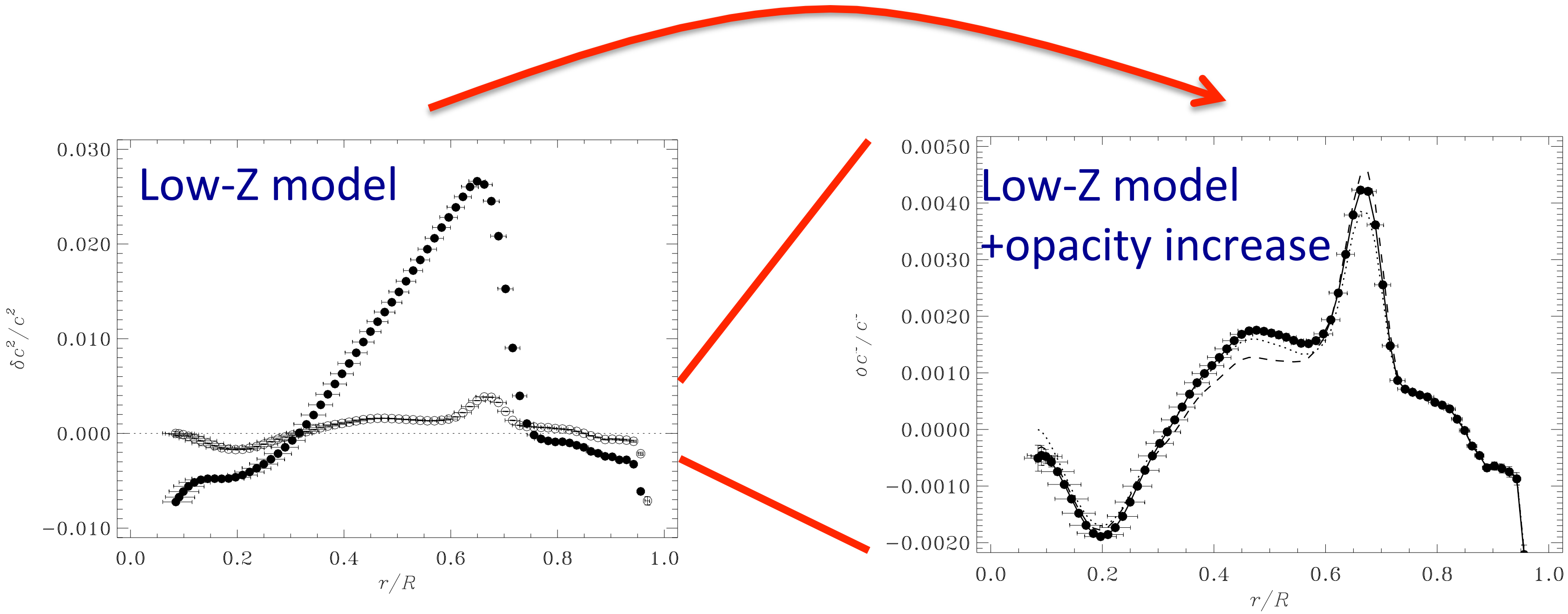
atomic opacity calculations were and still are Achilles' heel in solar physics

Seismic data and neutrinos from pp-chains constrain radiative gradient / opacity profile

CNO neutrino fluxes constrain directly composition (they are unique)

Composition/radiative opacity degeneracy

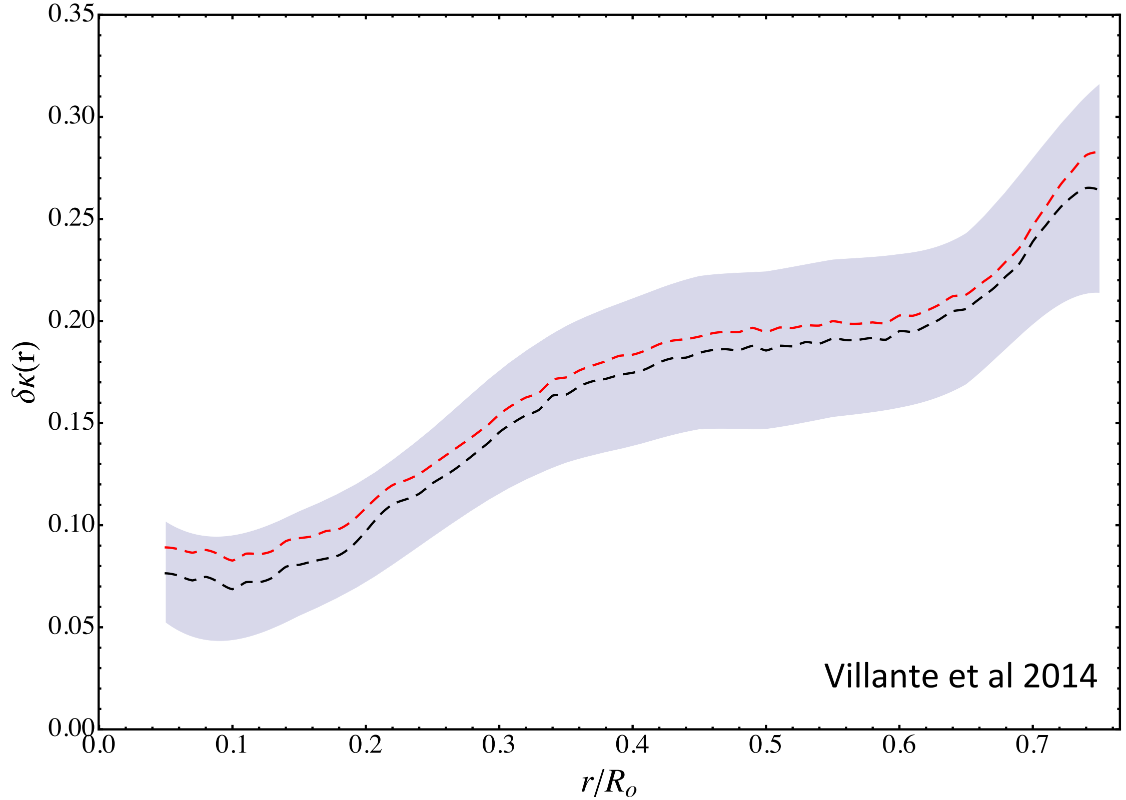
Modify opacity profile -- > agreement with helioseismology



Christensen Dalsgaard et al 2009

Composition/radiative opacity degeneracy

Using helioseismic data and solar neutrinos – obtain solar opacity profile



Fractional opacity difference wrt AGSS09 solar model

few % center to 20% at convective boundary

Composition/radiative opacity degeneracy

* let solar composition free – 2 parameters (volatiles / refractories)
* SSM input (~10) parameters move around central values
(nucler cross sections, solar parameters, efficiency of chemical mixing, 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

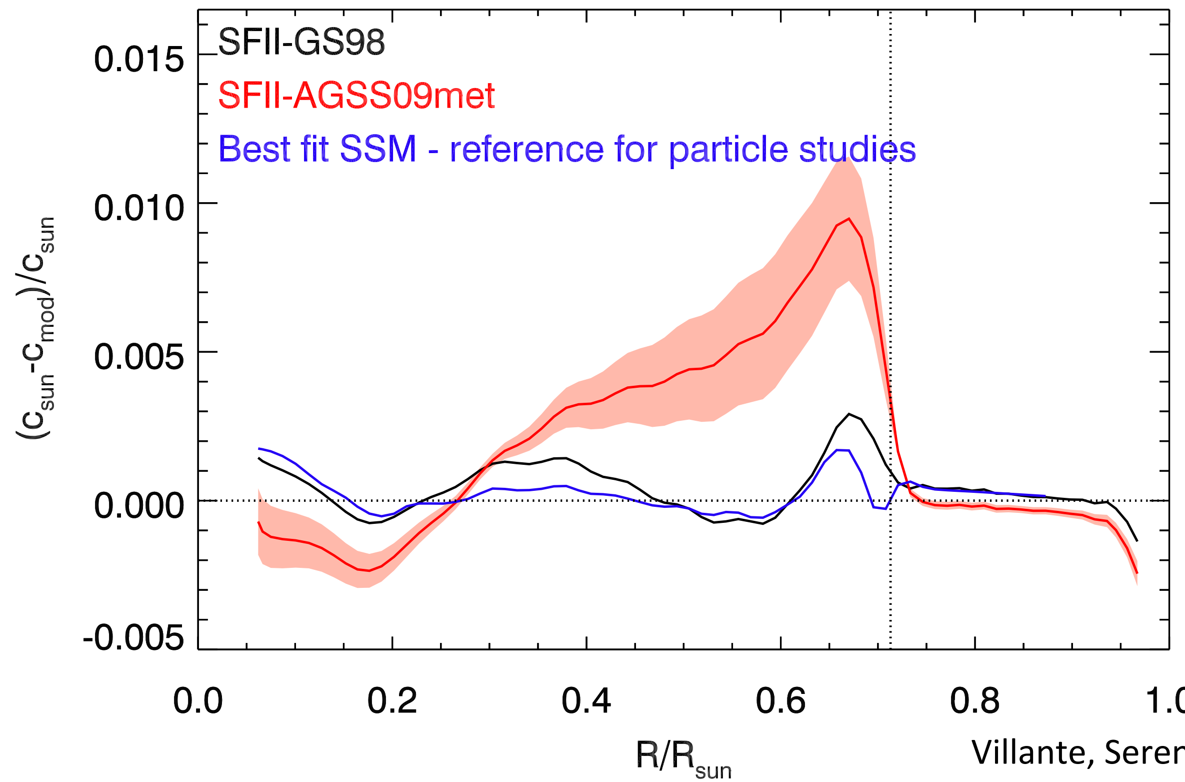
-- > find the best possible Standard Solar Model

Composition -- > high (old) metallicity (not surprising)

Best-fit Standard Solar Model

Pulls from systematics of order 1 (1-σ)

Even better than the real thing !!



Villante, Serenelli et al. 2014

composition – opacity degeneracy cannot be removed but…

phenomenological description of solar structure (T, r stratification) is excellent

Revisiting solar axion-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 – $g_{10} < 7$
^8B flux < 1.5 $^8B_{SSM}$ (3-σ) – equivalent to $L_a < 0.1\, L_\odot$

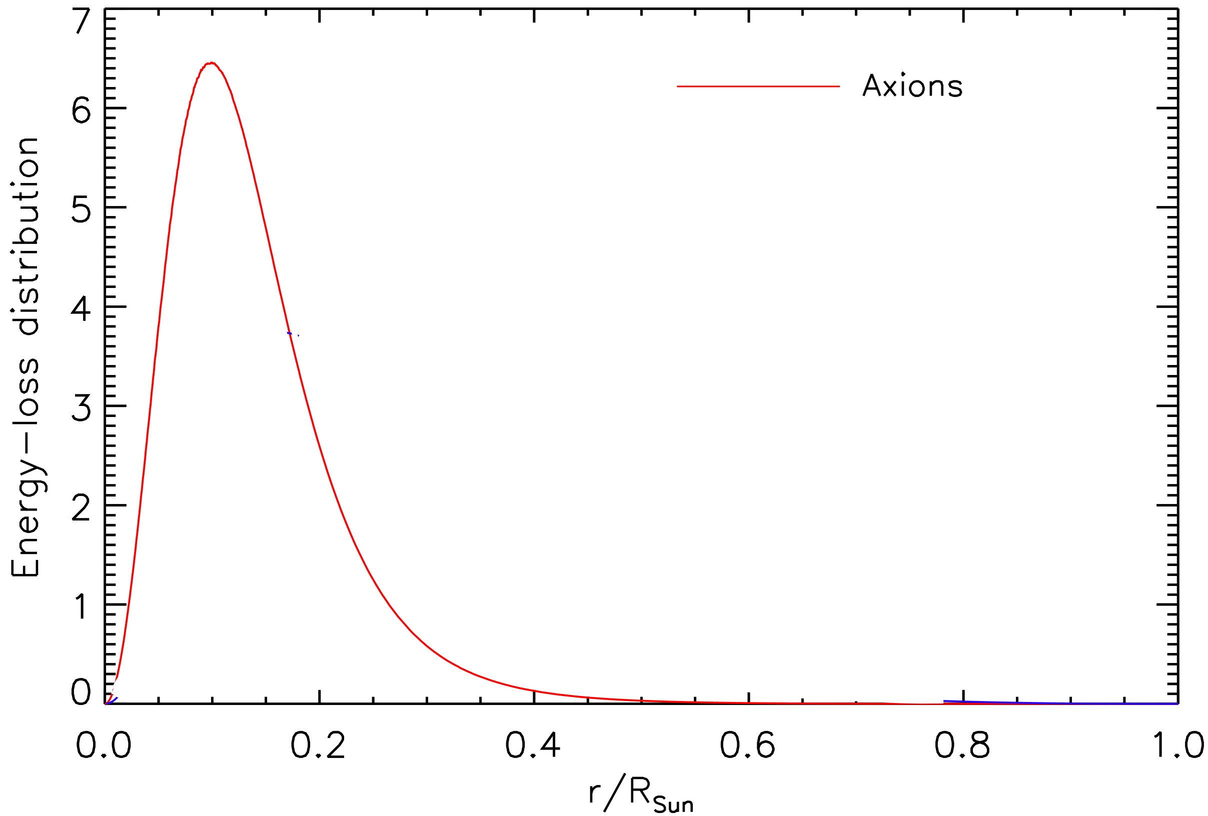
Maeda & Shibahashi 2013 – $g_{10} < 2.5$
^8B flux constrained by sound speed (1-σ)
seismic (not evolutionary models – neglect basic physics)

Vinyoles et al. 2015 – g10 < 4 (3-σ)
seismic + neutrino data
extend the method used to construct best-fit SSM

Revisiting solar axion-photon coupling

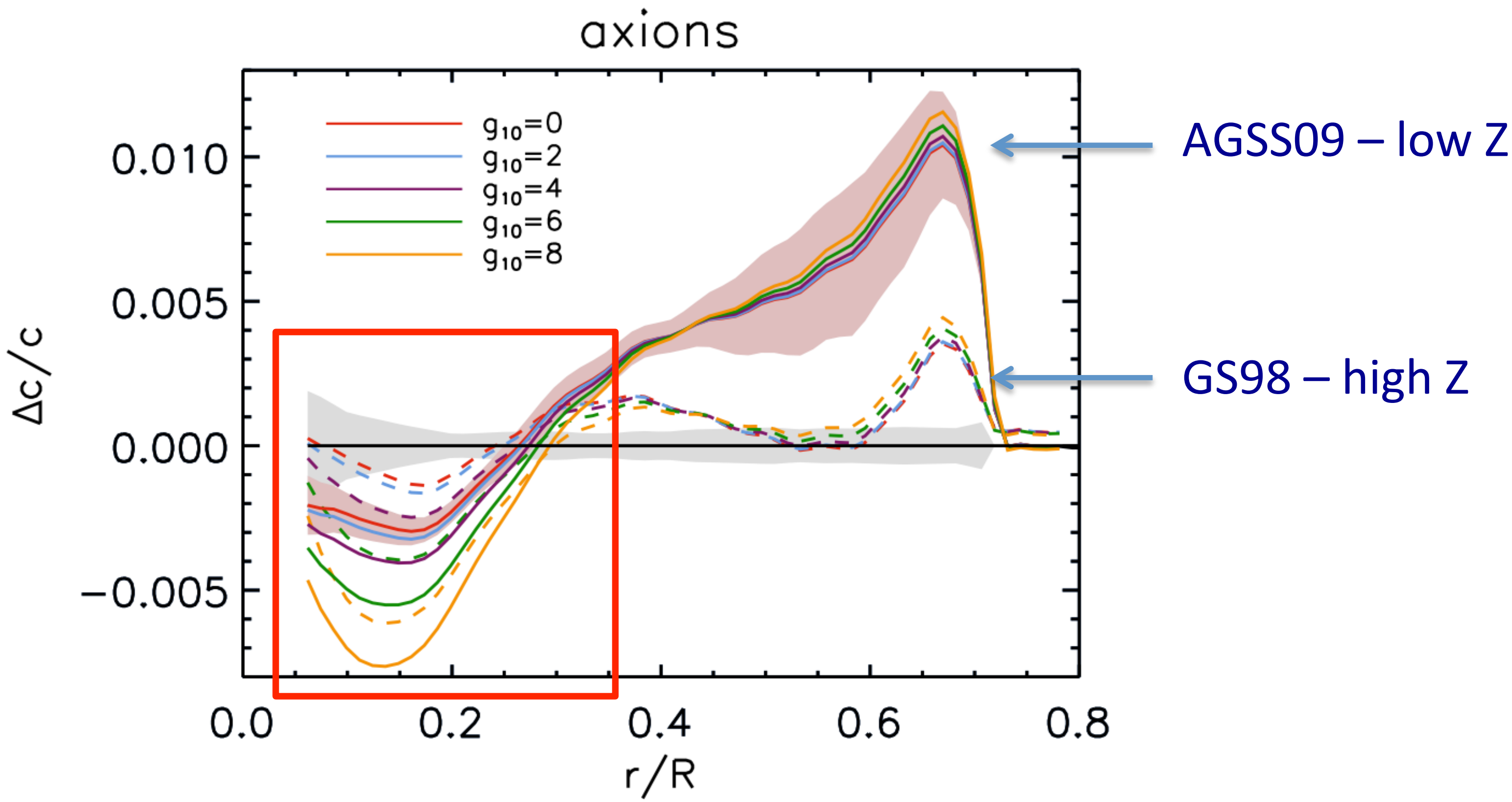
$$\epsilon_{a\gamma} \propto g_{a\gamma}^2 T^7 F(\kappa^2) \sim g_{a\gamma}^2 T^6$$

No explicit composition dependence



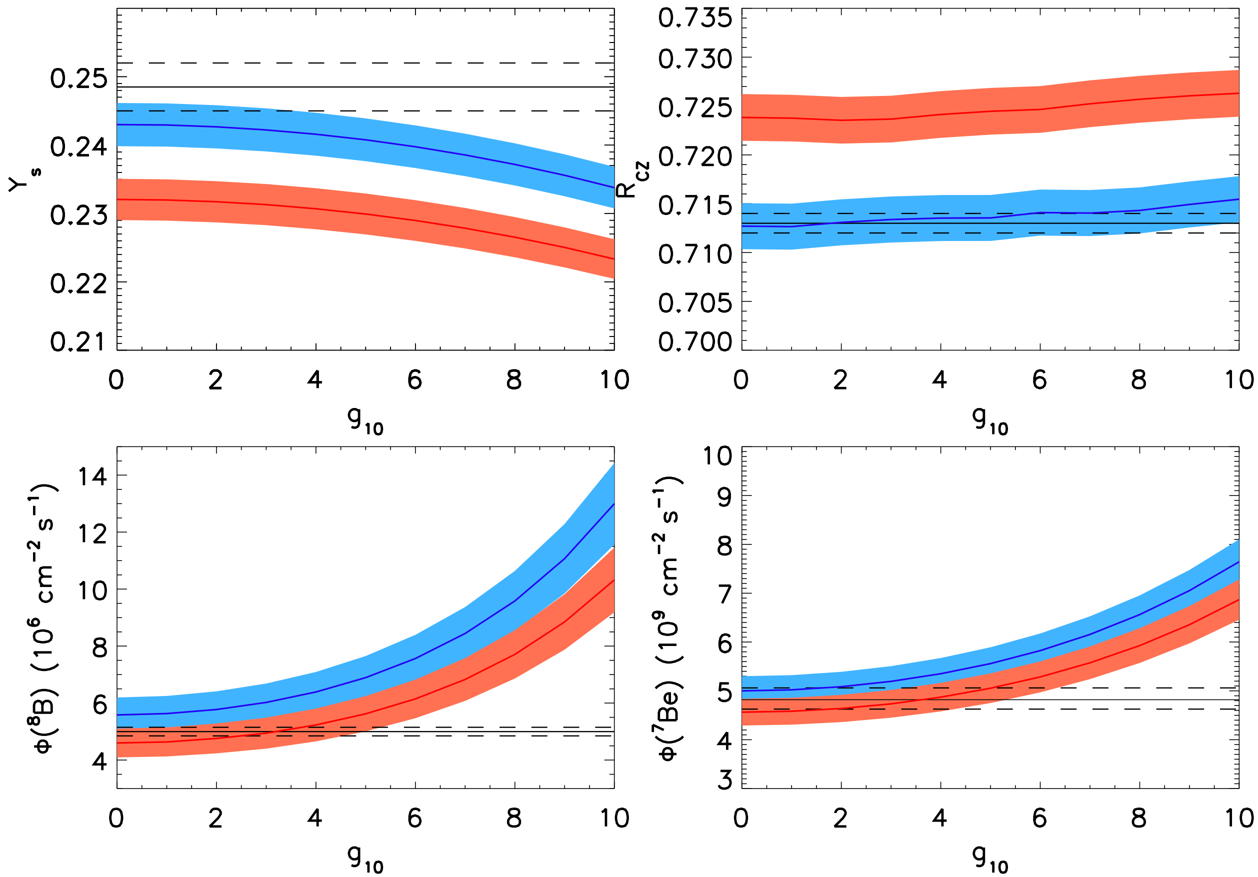
Revisiting solar axion-photon coupling

Variations in sound speed without variations in composition and pulls



Revisiting solar axion-photon coupling

Variations in other quantities without variations in composition and pulls



AGSS09 – low Z

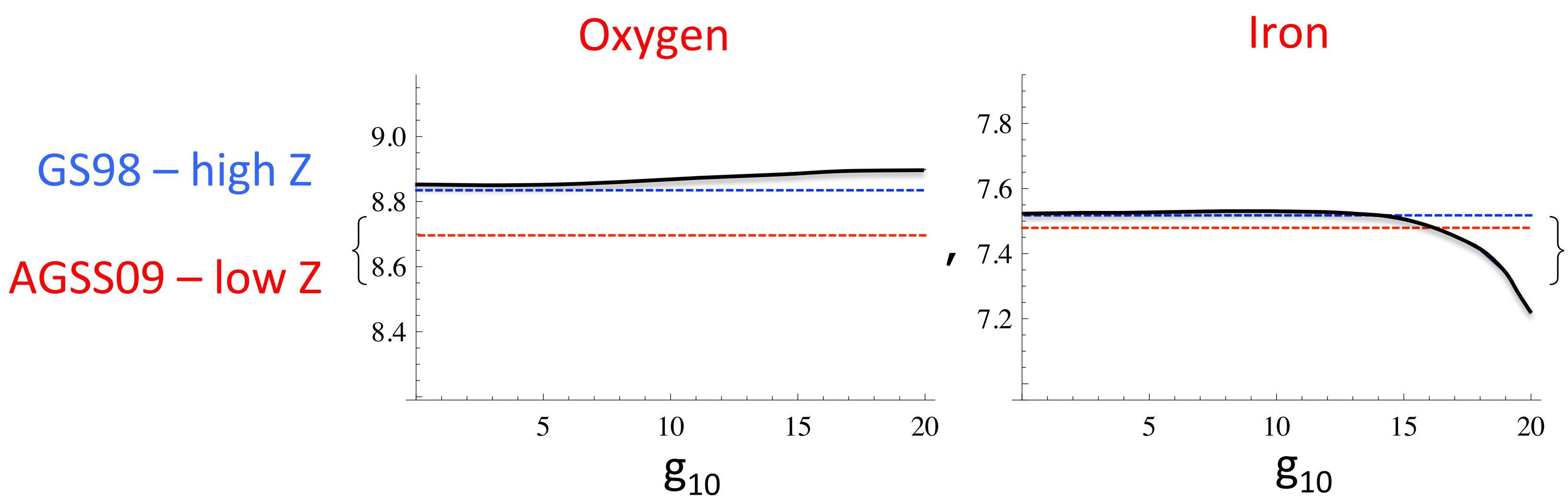
GS98 – high Z

Vinyoles et al. 2015

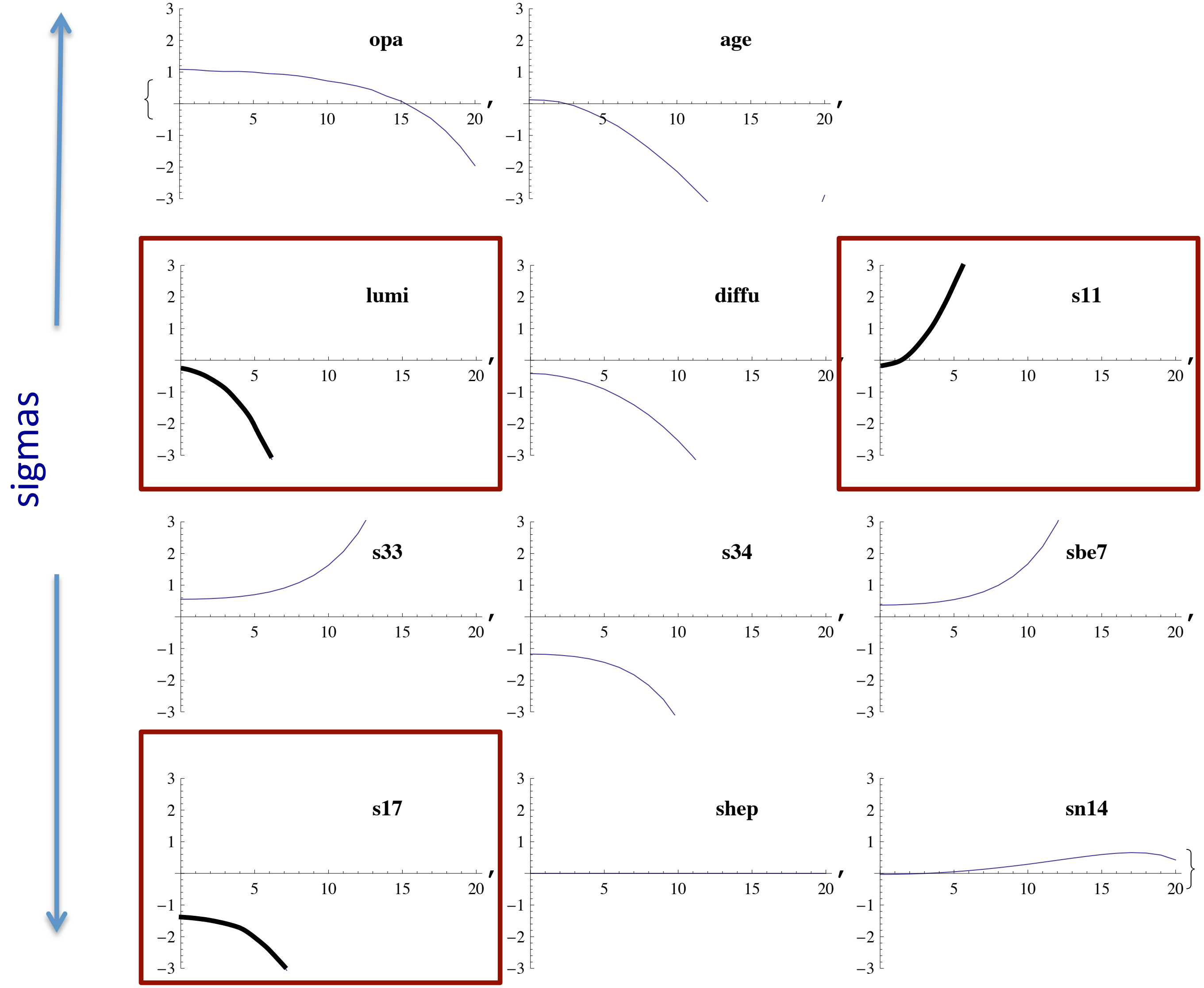
Changes due to axions and "zero point" of SSM to be accounted for by composition and systematics (pulls)

Revisiting solar axion-photon coupling

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



Revisiting solar axion-photon coupling



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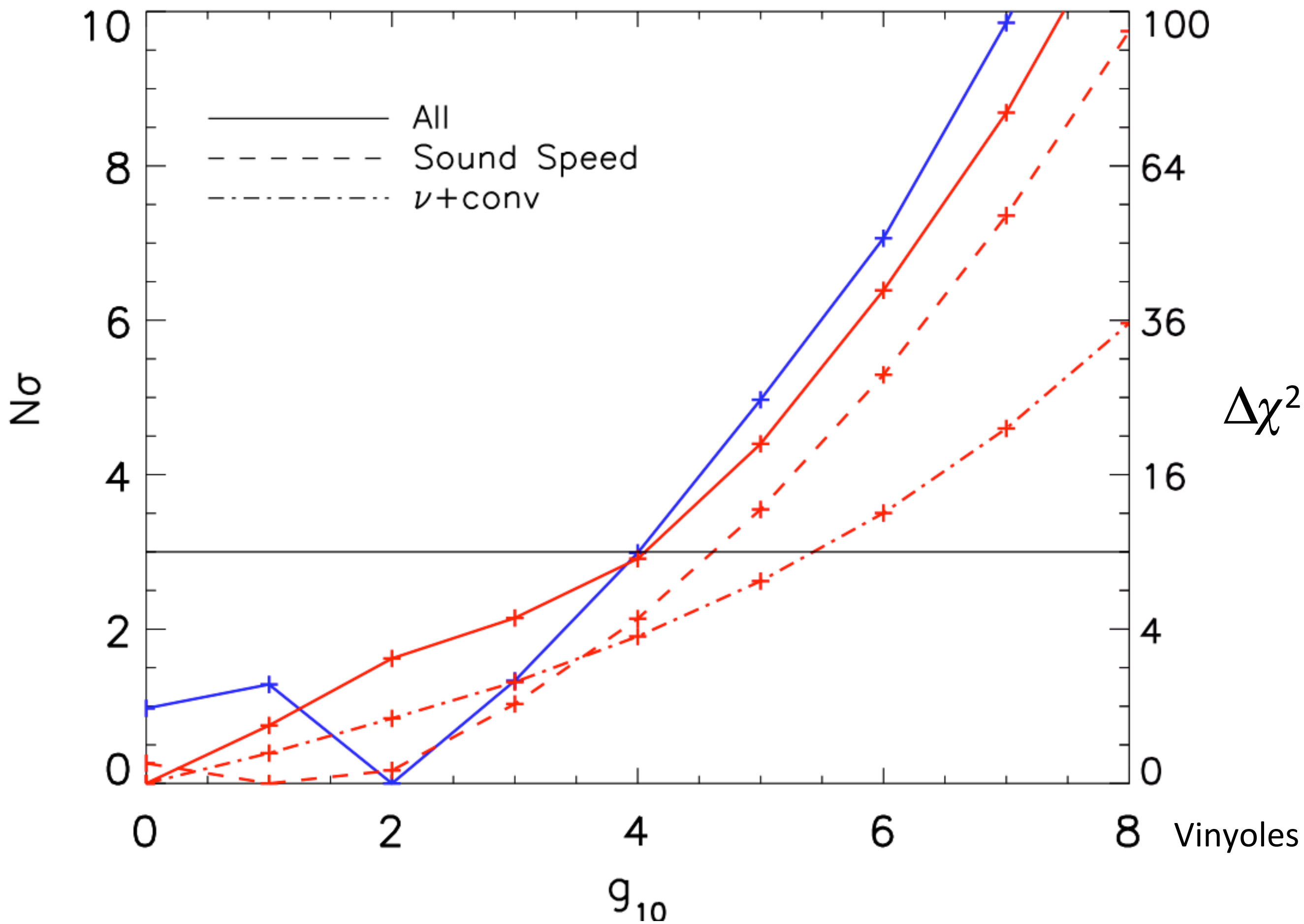


Vinyoles et al. 2015

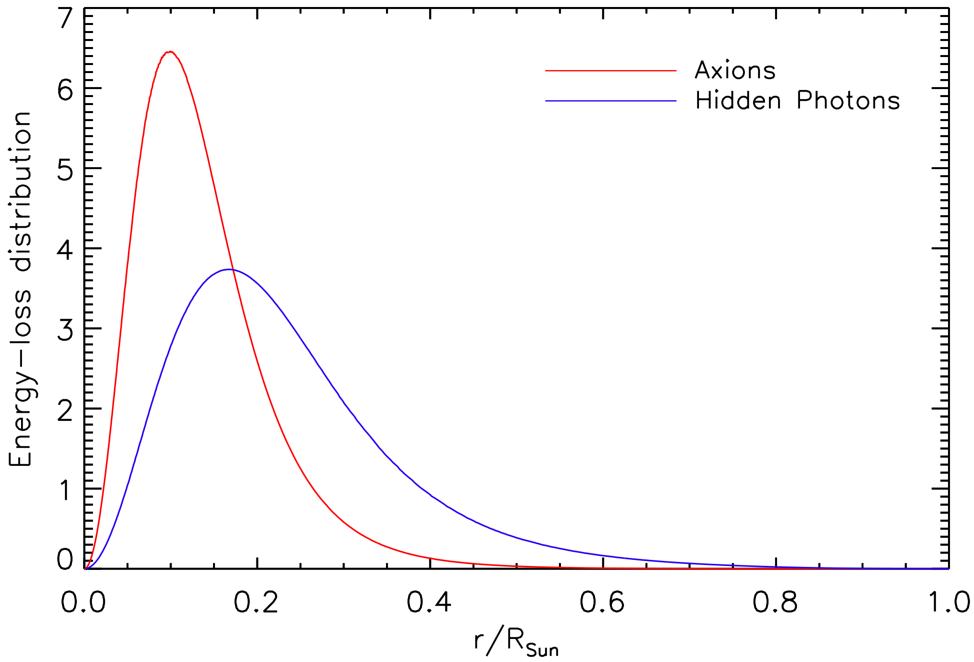
Final upper limit – g_{10} < 4 @ 3-σ C.L.
~ factor 2 better than previous solar limit

Hidden photons

Energy losses dominated by the L-channel

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

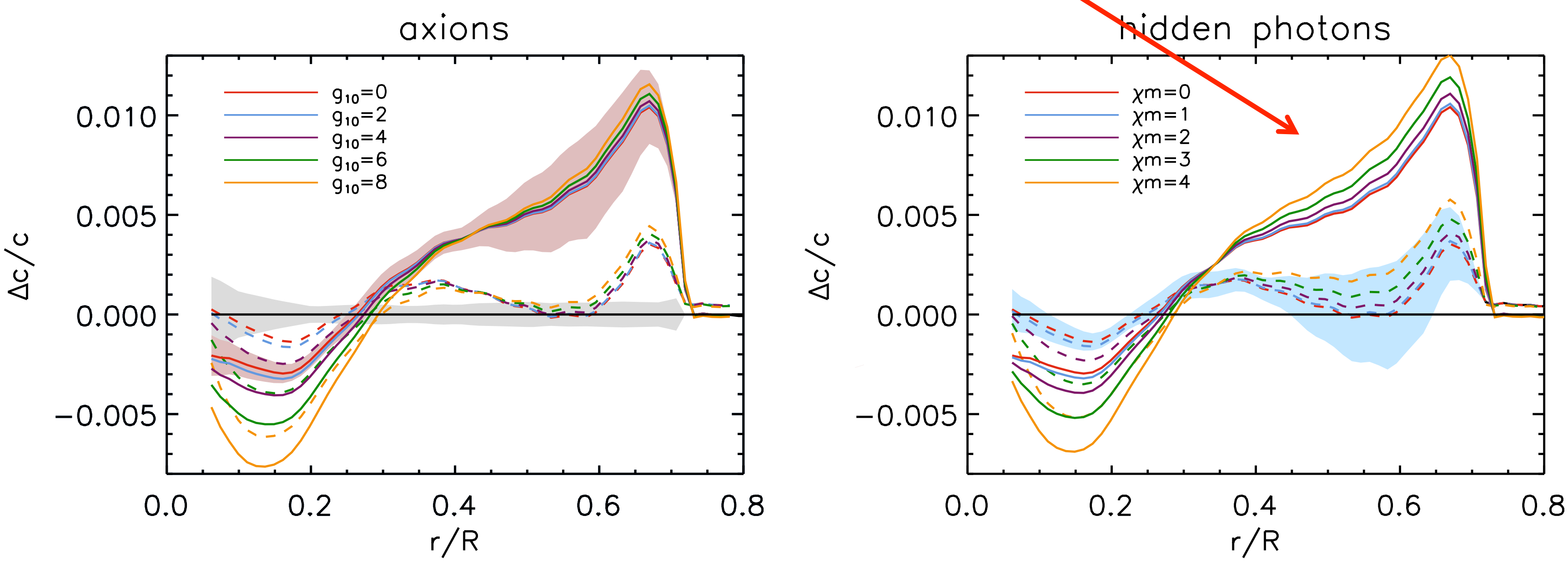
No explicit composition dependence



Weak T-dependence -- > broad production region
More relevant as T decreases (nucl. energy higher T-dependence)

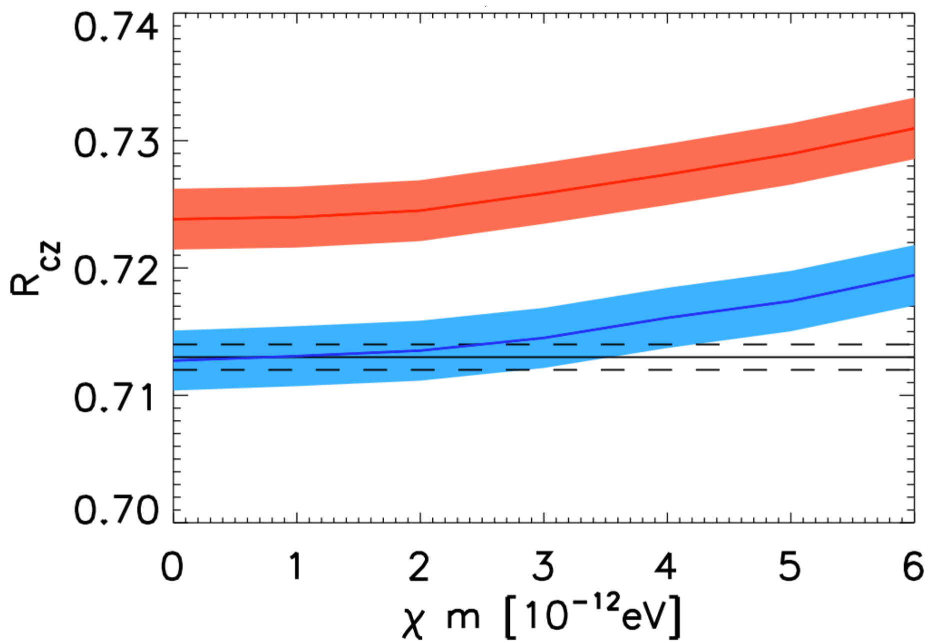
Hidden photons

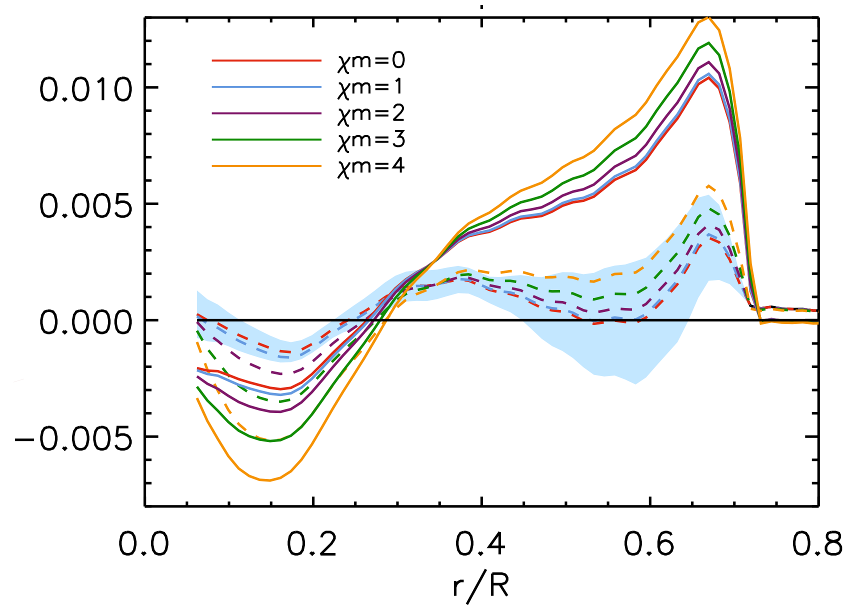
Variations in sound speed over whole radiative interior



Vinyoles et al. 2015

Hidden photons

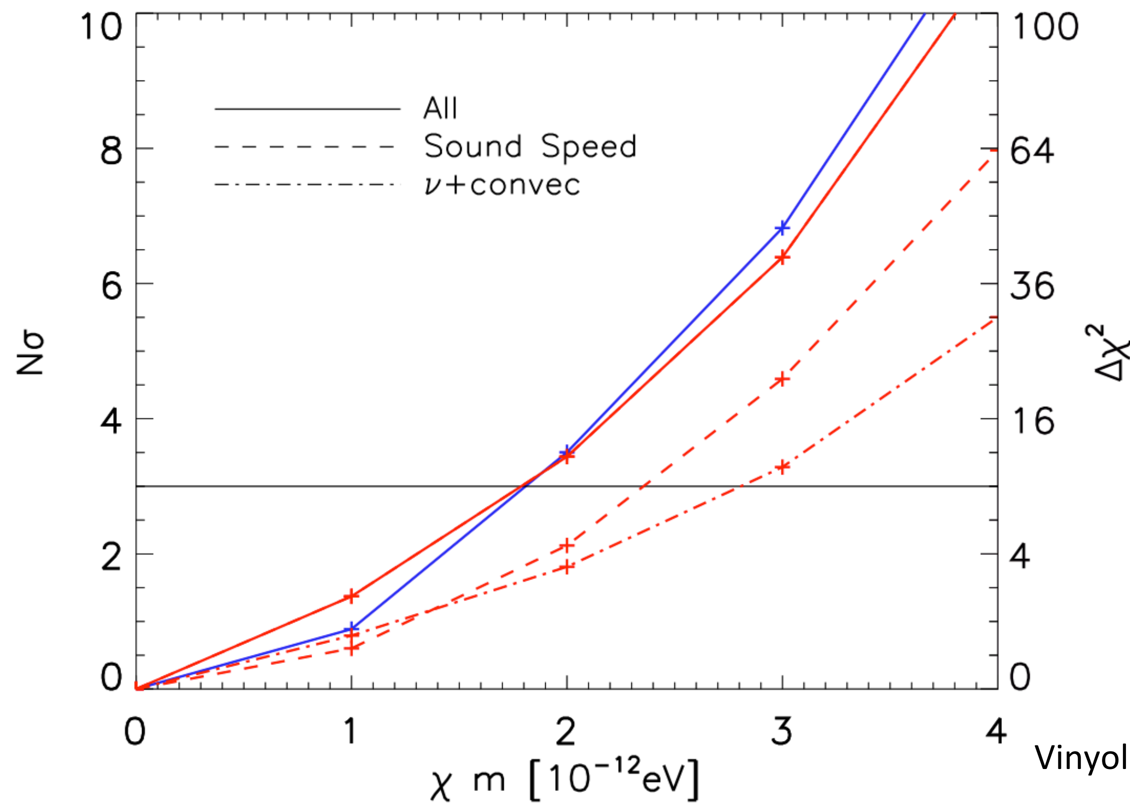




Our approach: solar model absorbs these variations without influencing boundaries derived for particle properties –
e.g. increase metal abundances: freely or constrained by spectroscopy

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

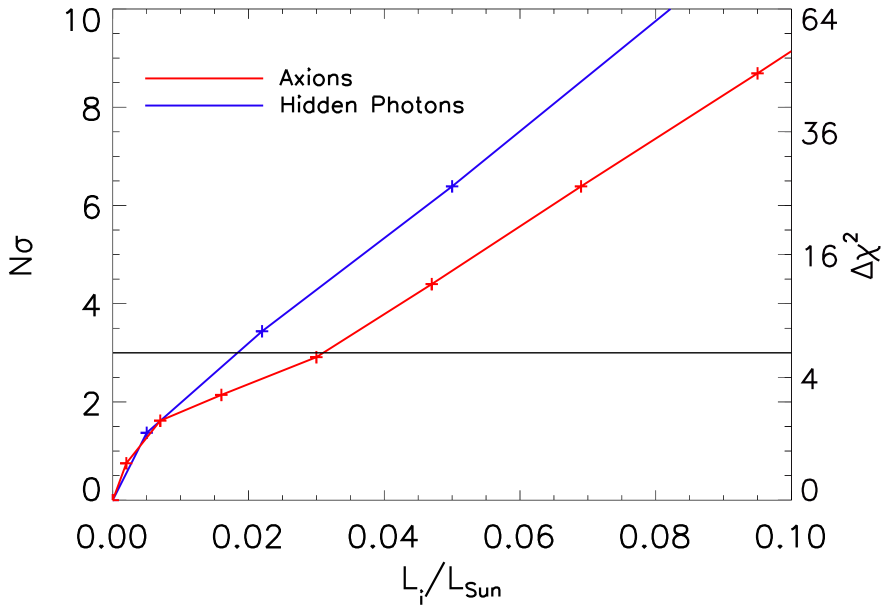
Hidden photons



Vinyoles et al. 2015

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

Comments on Solar Constraints

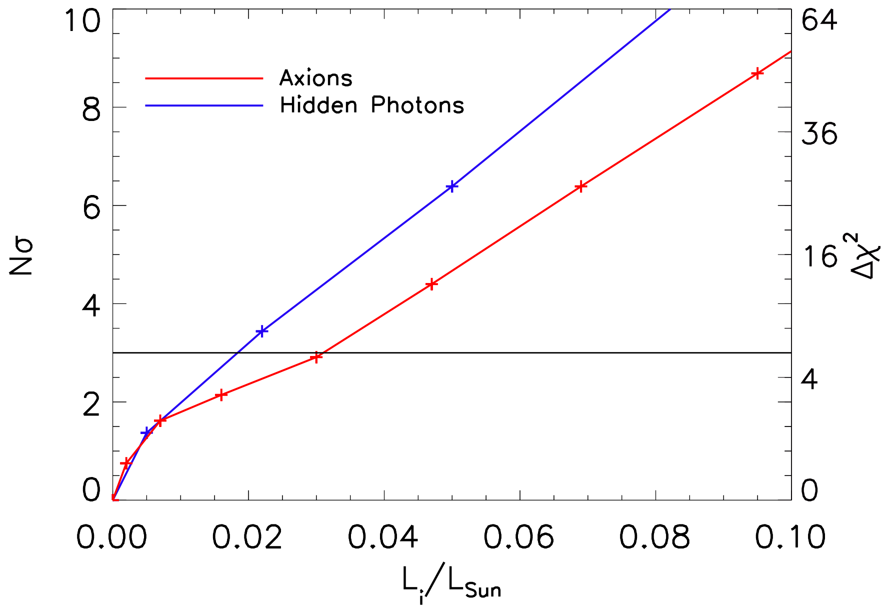


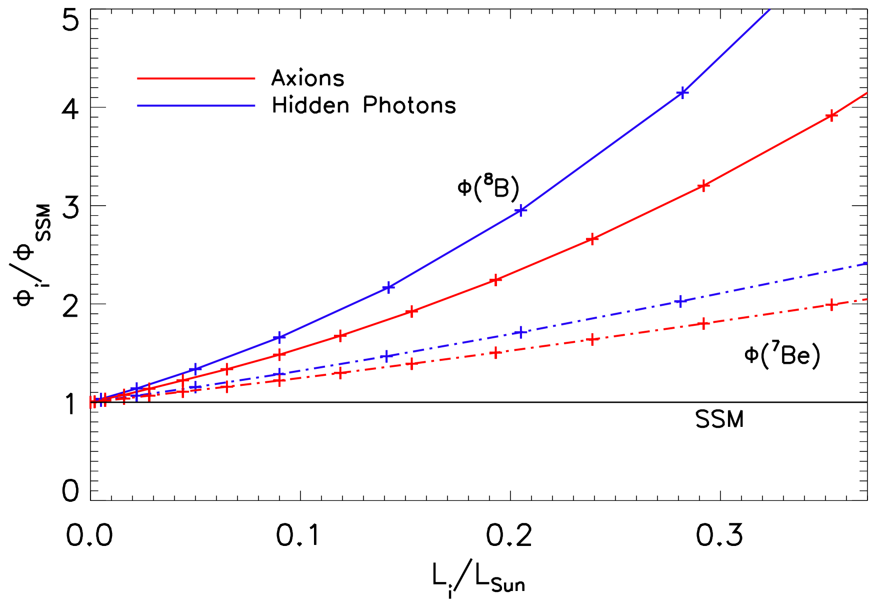
Effective limit in dark channels

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

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

Comments on Solar Constraints





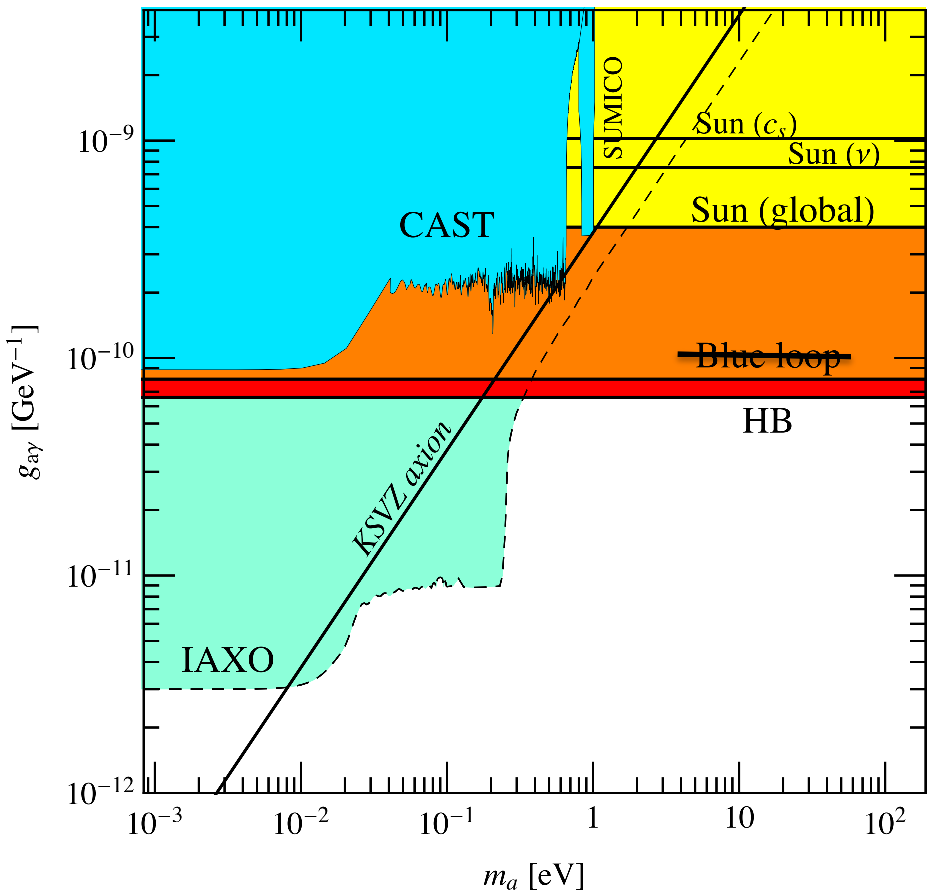
Effective limit in dark channels
$L_{hp} < 2\% \, L_\odot$ – $L_{a\gamma} < 3\% \, L_\odot$

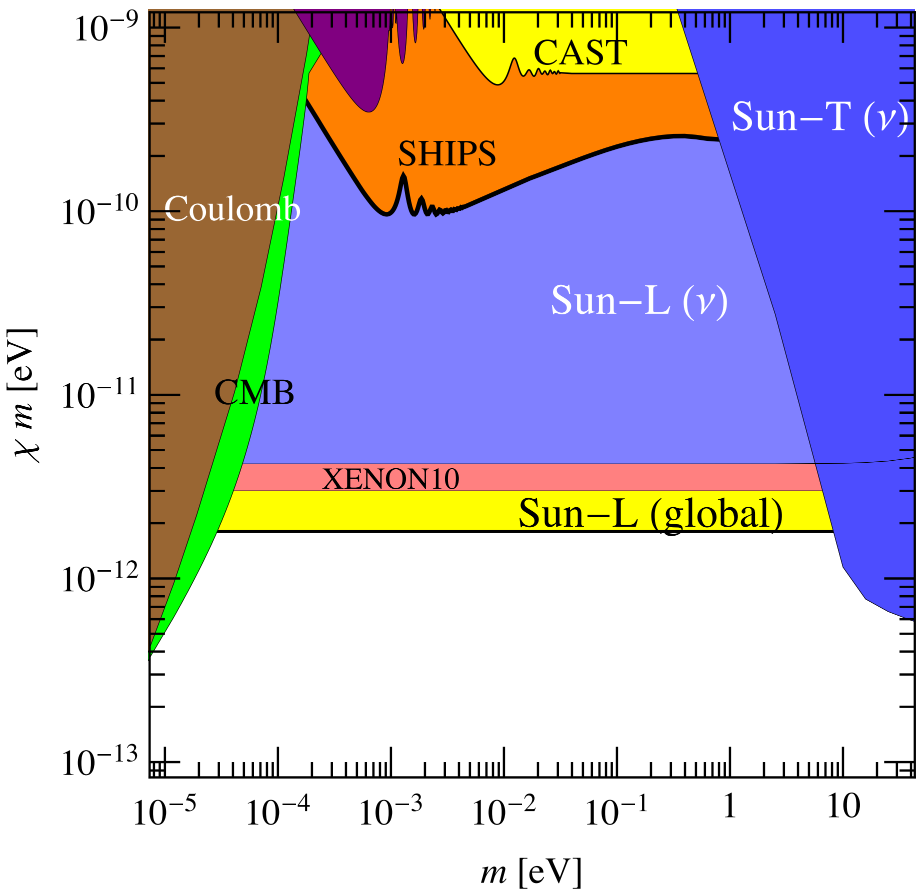
$$\frac{\Phi(^8\mathrm{B})}{\Phi_{\mathrm{SSM}}(^8\mathrm{B})} = \left(\frac{L_x + L_\odot}{L_\odot}\right)^\alpha$$

Relations are not universal
depend on the type of particle

α= 4.4 (ax)
α= 5.7 (hp)

Current Limits





Solar Models and Asymmetric Dark Matter

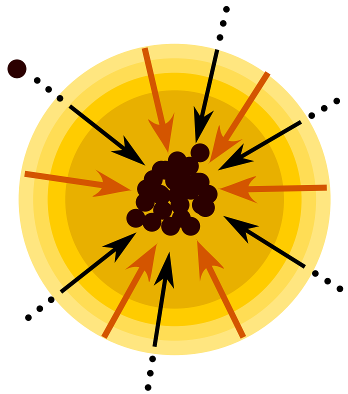
DM-nucleon scattering allows DM collisions with nuclei in the Sun

-- > gravitational capture and settling the to solar core

-- > nuclear scattering inside the Sun

-- > additional energy transport

-- > modified solar structure



Energy transport -- > lower central temperatures -- > lower ^{8}B flux
(solar neutrino problem, Press & Spergel, Faulkner & Gilliland Griest & Seckel, etc.)

Can DM help with solar abundance problem?

e.g. Taoso et al., Lopes et al. and other

Solar Models and Asymmetric Dark Matter

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-- > gravitational capture and settling the to solar core

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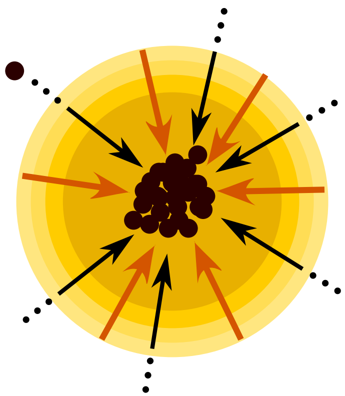


-- > 1. observables: different core temperature

– solar neutrino rates

-- > 2. observables: helioseismology

– sound speed

– oscillation frequencies

– convective zone depth

– surface helium fraction

Direct detection: high velocity tail of DM halo (higher recoil energy)

Solar capture: low velocity tail of DM halo (easier to capture gravitationally)

Solar Models and Asymmetric Dark Matter

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

SD – couples mostly to H

Energy Transport by ADM

Total number of DM particles

$$\frac{dN_\chi}{dt} = C_\odot(t) - A(t) - E(t) \longrightarrow$$

C(t) = capture rate

A(t) = annihilation rate = 0 (fully ADM)

E(t) = evaporation rate = 0 (ok for M_χ > 4Gev)

Energy Transport by ADM

Total number of DM particles

$$\frac{dN_\chi}{dt} = C_\odot(t) - A(t) - E(t)$$

C(t) = capture rate
A(t) = annihilation rate = 0 (fully ADM)
E(t) = evaporation rate = 0 (ok for M_χ > 4Gev)

DM number density distribution (LTE)

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

DM 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

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

$$\int_0^{R_\odot} L_\chi dr = 0$$

Energy Transport by ADM

Total number of DM particles

$$\frac{dN_\chi}{dt} = C_\odot(t) - A(t) - E(t)$$

DM number density distribution (LTE)

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

diffusivity

DM 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

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

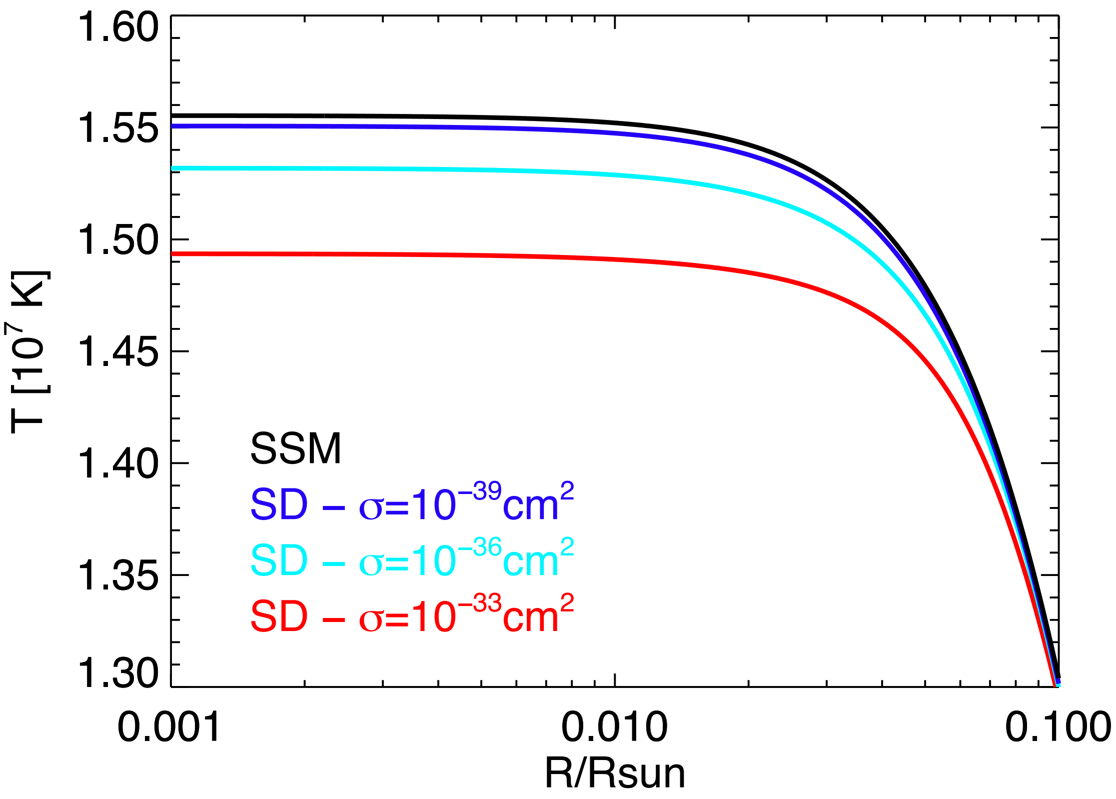
$v_0/v(r) - q_0/q(r)$

Two limiting behaviors: LTE & Isothermal

Intermediate: Knudsen regime $l_\chi \sim r_\chi$ --> Boltzmann eq. + corrections to LTE expressions

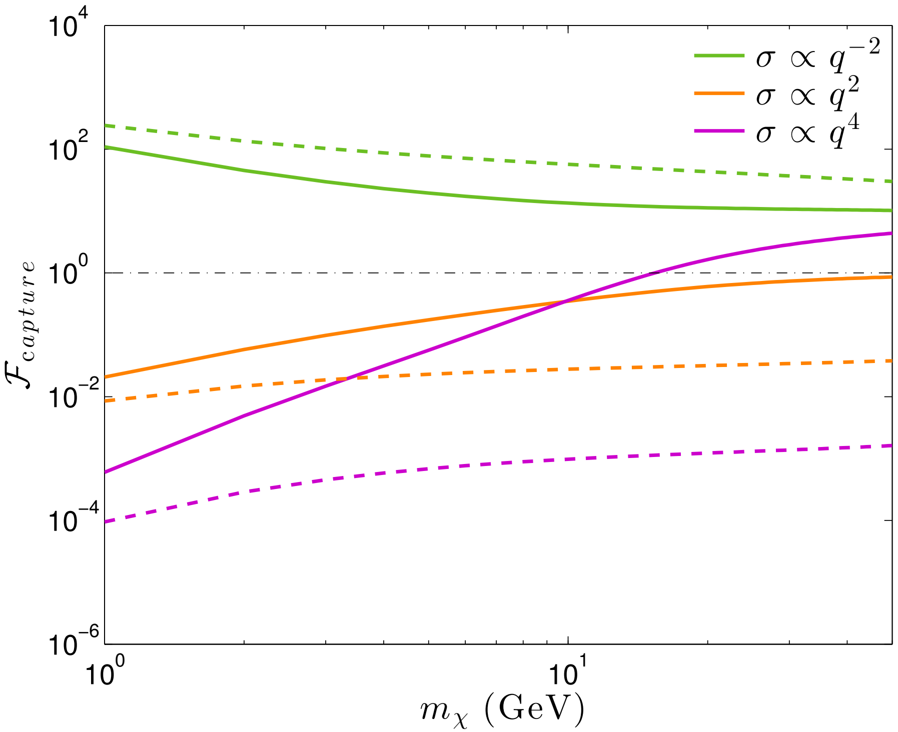
Energy Transport by ADM

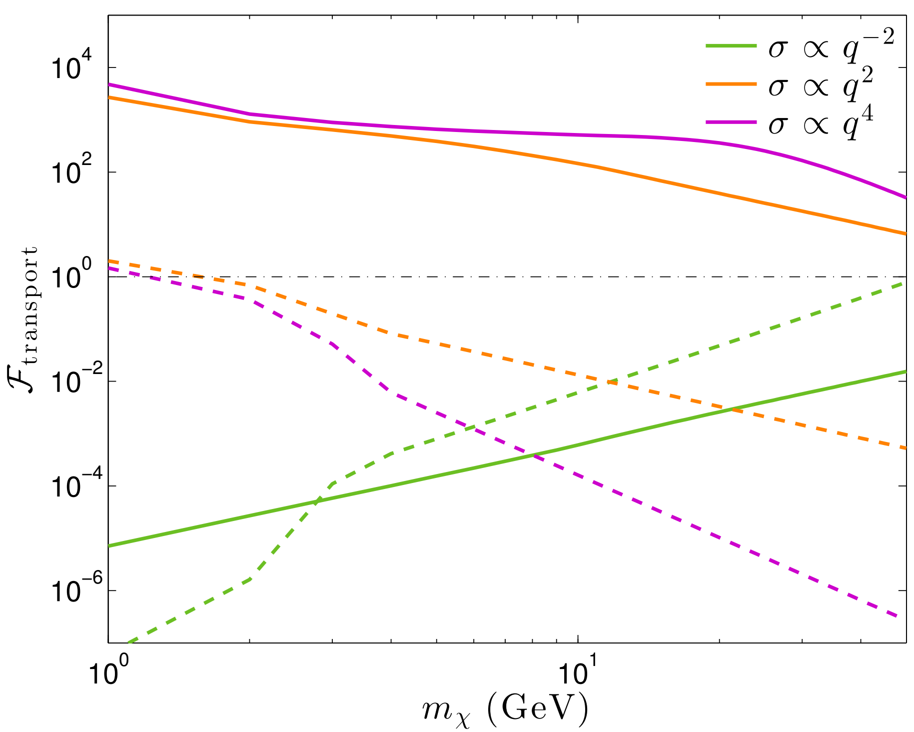
Extra energy transport
-- > lower core temperature



Capture & Transport

Enhancement/suppresion factors due to q / v dependences





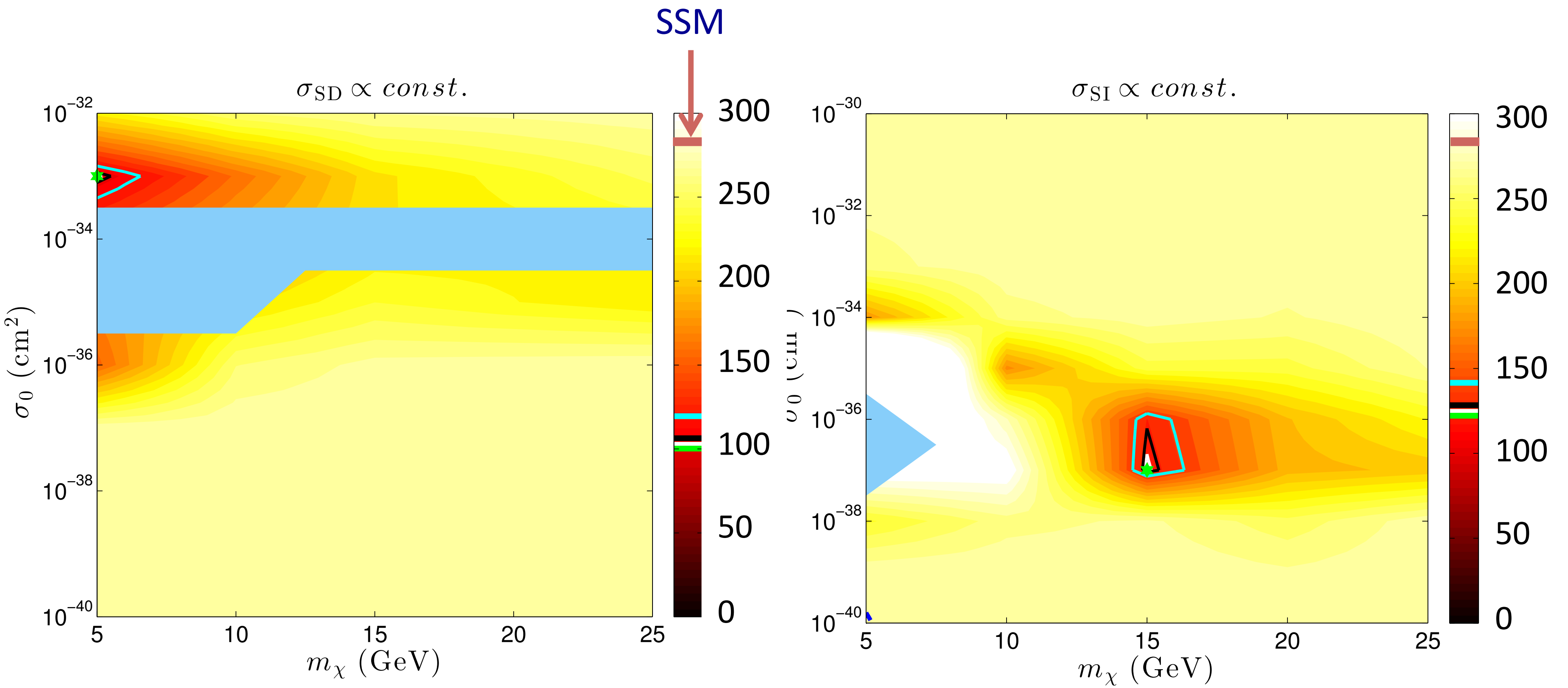
$\sigma_0 = 10^{-35}$ cm^2

Solid = SI, Dashed = SD

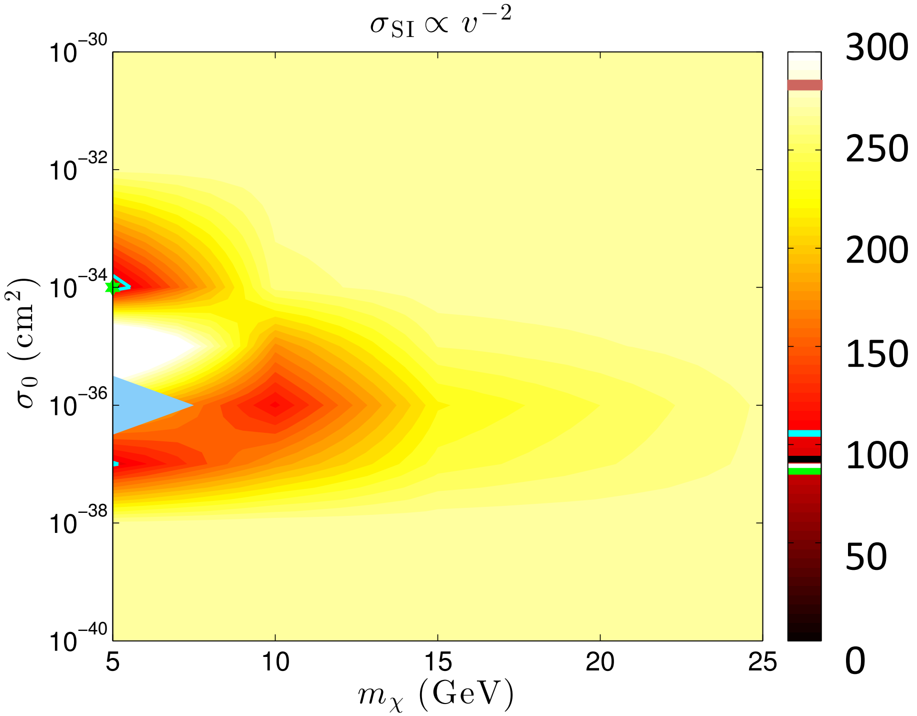
Global effect of DM from combining both figures

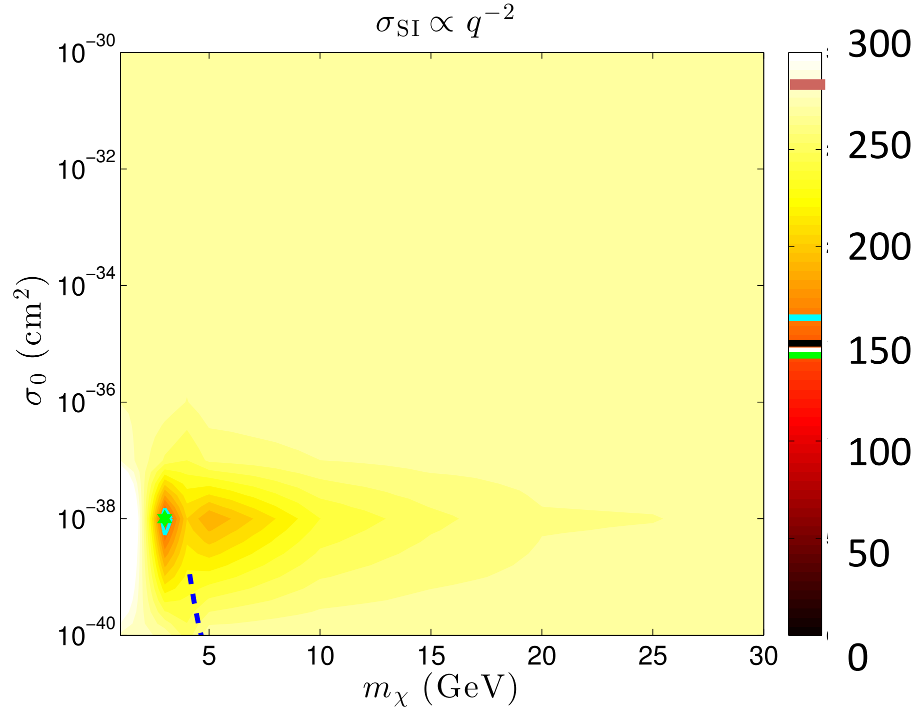
Impact on Observables: SI – SD – constant

Observables: ^{7}Be & ^{8}B neutrinos + convective radius + surface helium
frequency separation ratios r_{02}, r_{13} (solar core)

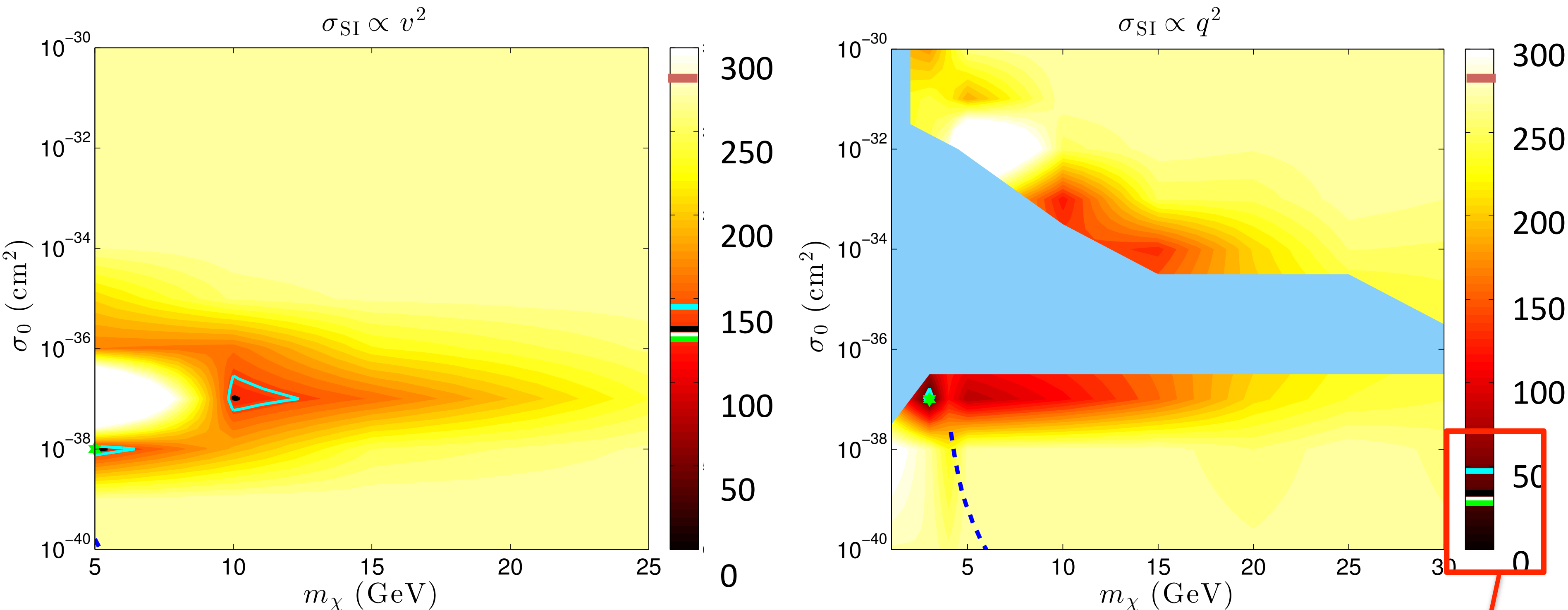


Impact on Observables: SI – SD – v^{-2}, q^{-2}



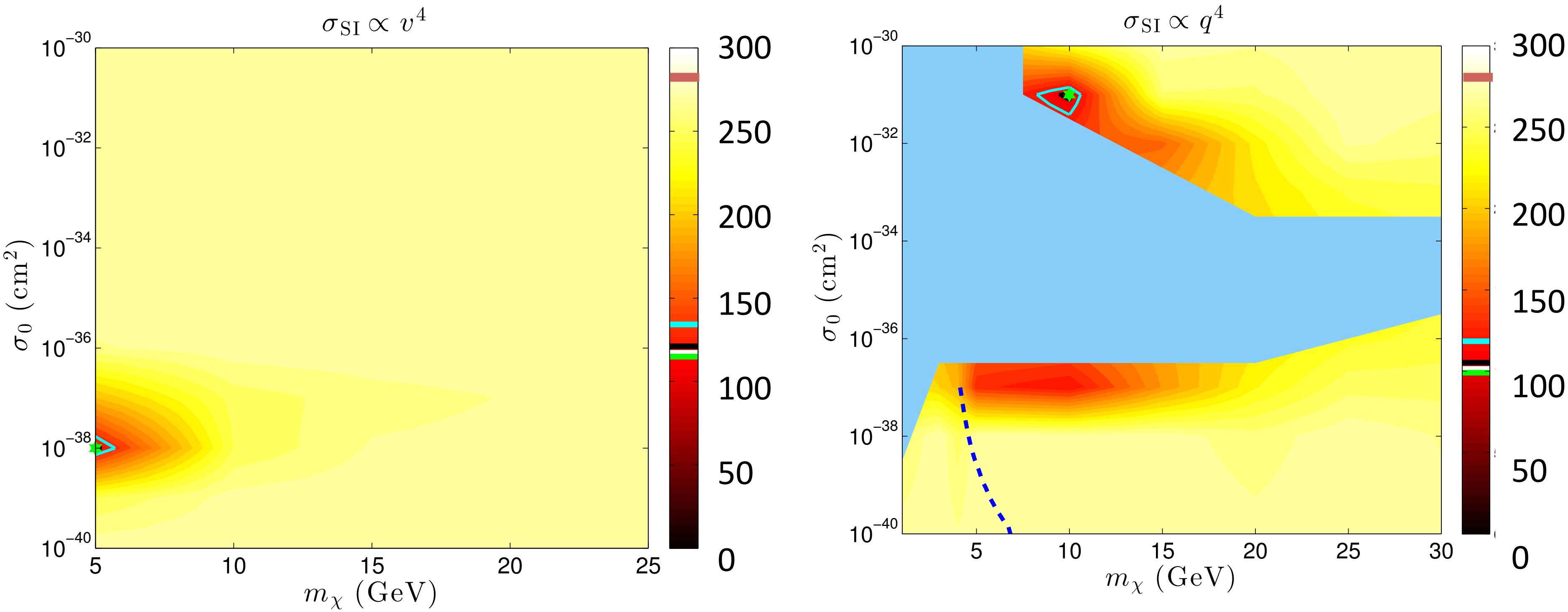


Impact on Observables: SI – SD – v^2, q^2



Notice low χ^2

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



Best Model – q^2

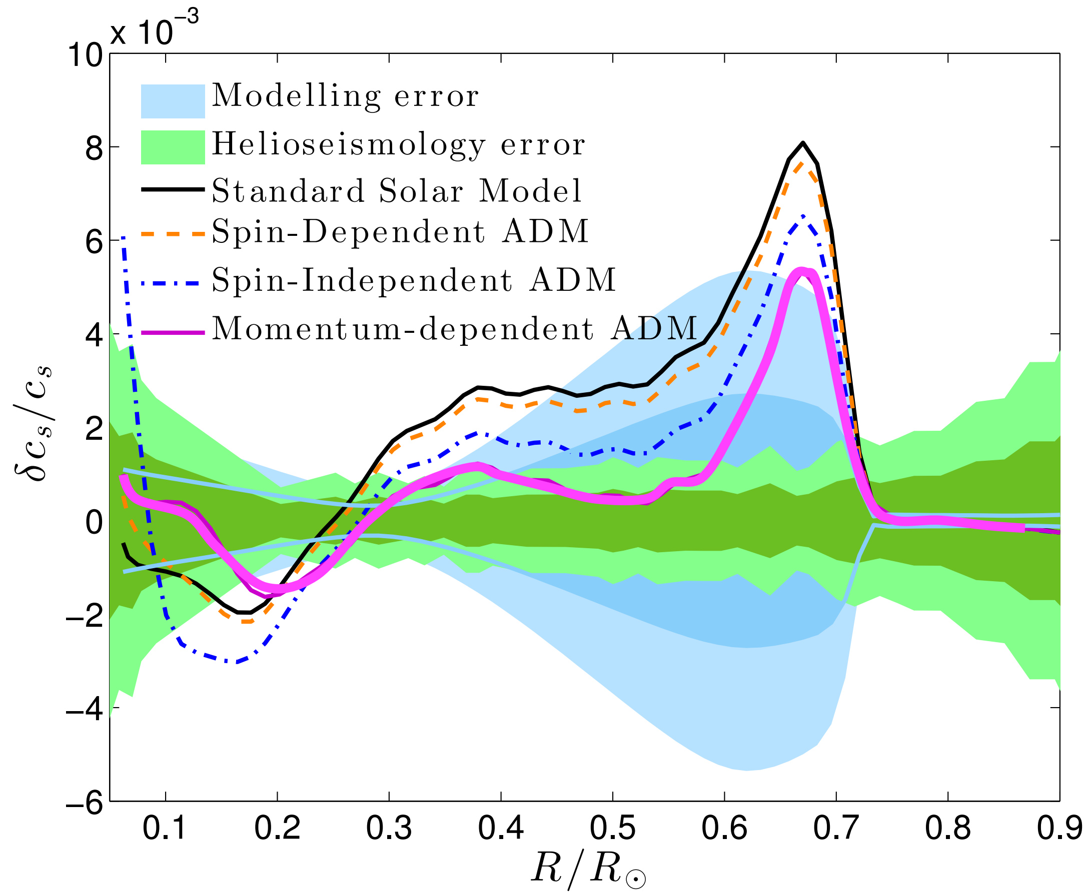
q^2 coupling

q_0= 40 MeV

m_χ = 3 GeV

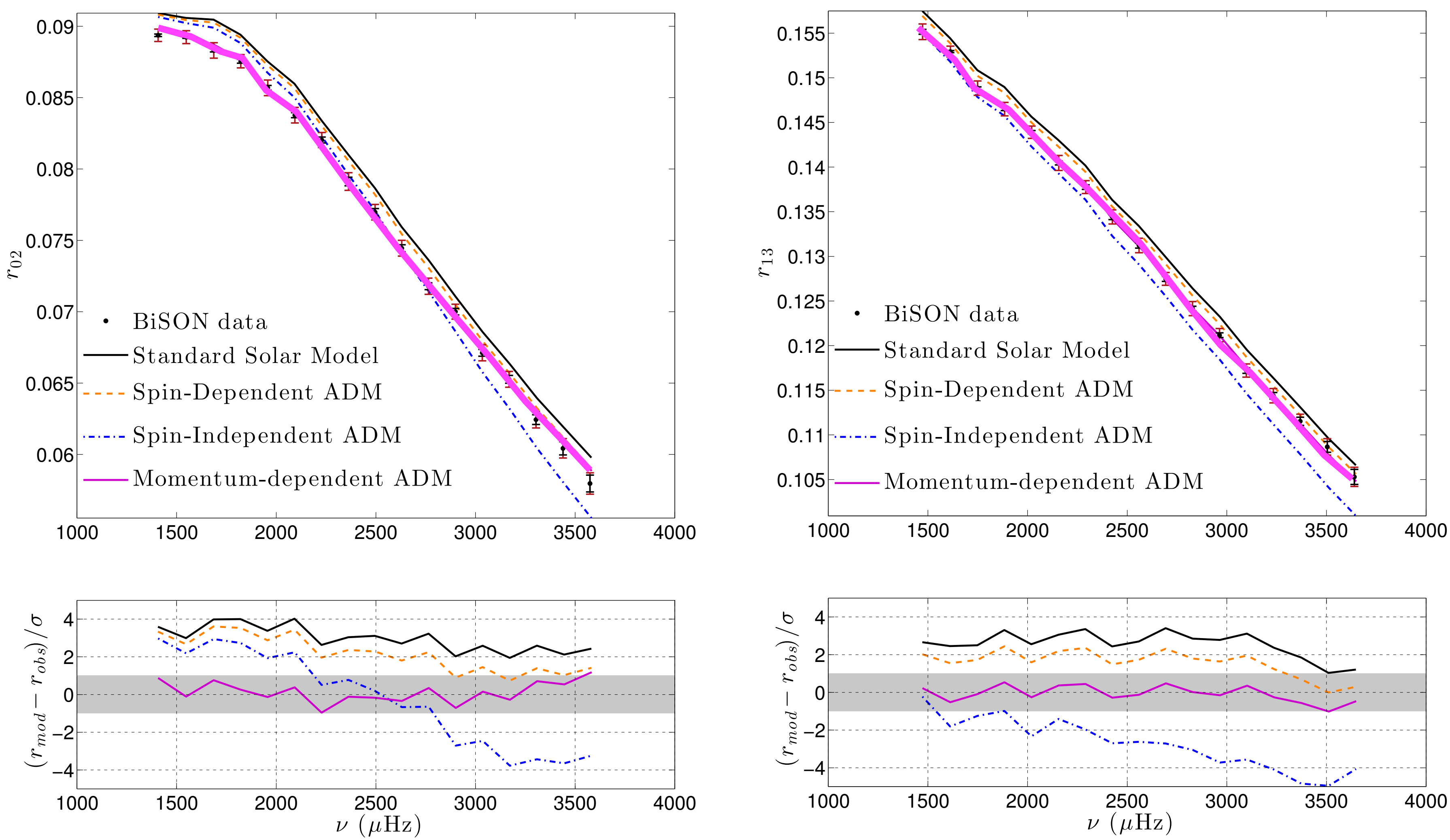
$\sigma_0 = 10^{-37}$ cm^2

Sound speed for best q^2
SI and SD models



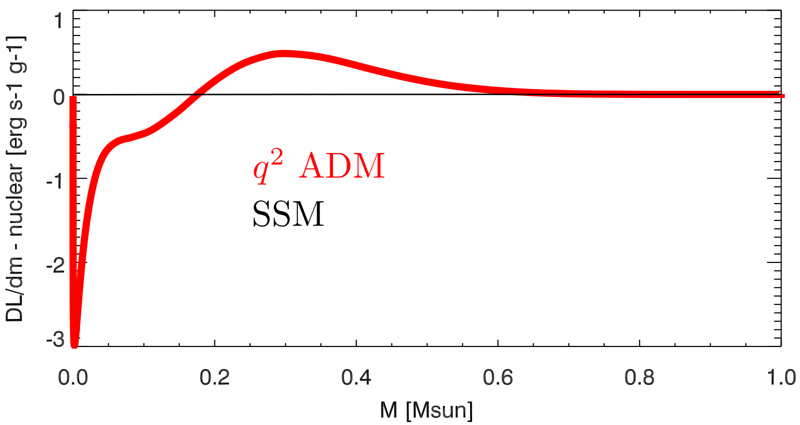
Best Model – q^2

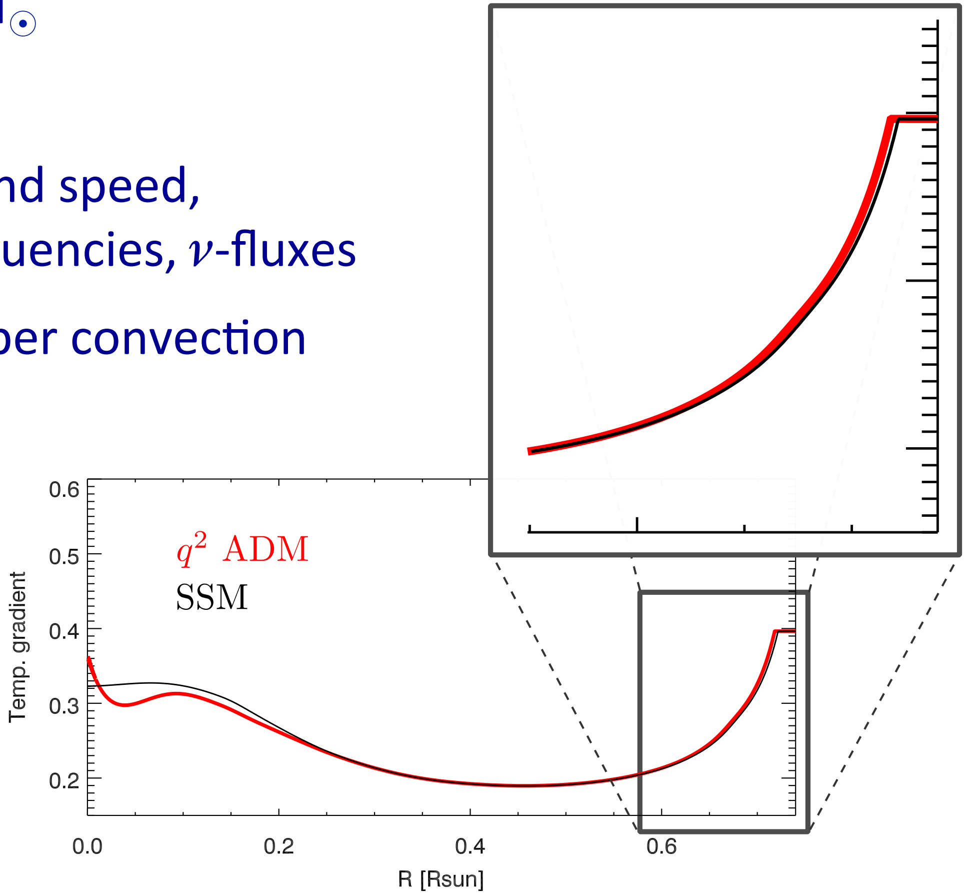
Frequency separation ratios – zooming into the solar core



Changes to Solar Structure

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



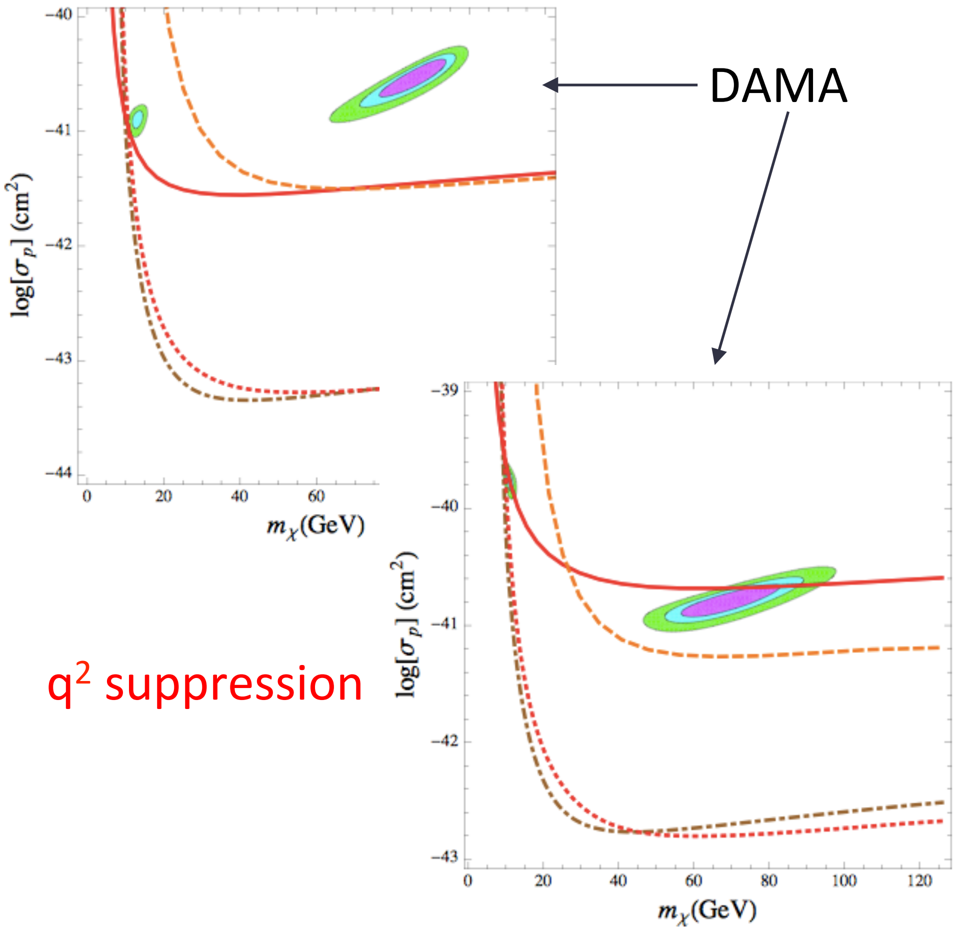


Best Model q^2

	SSM	SD	SI	q^2 SI	Obs.[a]	σ_{obs}	σ_{model}
ϕ_ν^{8B} [b]	4.95	4.39	4.58	3.78	5.00	3%	14%
ϕ_ν^{7Be} [c]	4.71	4.58	4.62	4.29	4.82	5%	7%
$R_{CZ}/R_\odot$	0.722	0.721	0.721	0.718	0.713	0.001	0.004
Y_s	0.2356	0.2351	0.2353	0.2327	0.2485	0.0034	0.0035
$\chi^2_{^8B}$	0.0	0.9	0.9	4.9			
$\chi^2_{^7Be}$	0.1	0.4	0.4	1.9			
$\chi^2_{R_{CZ}}$	4.8	3.8	3.8	1.5			
$\chi^2_{Y_s}$	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			
χ^2_{total}	287.8	158.5	185.2	27.5			
p	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	0.845			

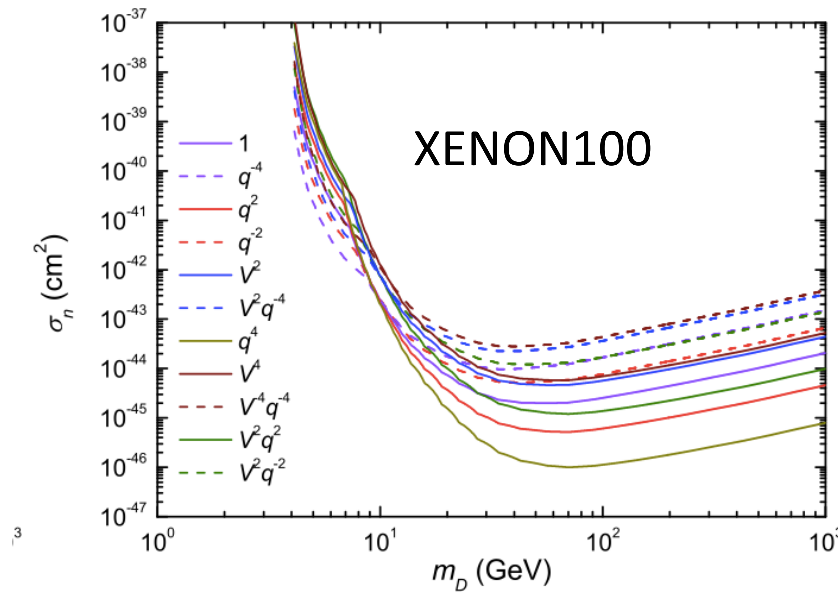
(very) non-standard solution
but goes a long way solving the solar abundance problem

Experimental limits



q^2 suppression

Chang et al. 2010



Guo et al. 2014

Summary

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

* 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 q^2 ADM models -- > agreement in solar data and models (σ_0=10^{-37} cm^2, m_χ = 3 GeV)

* Preferred mass and cross-section range not excluded by direct experiment

* Caveat: evaporation not accounted for (will do)!!!