Indications of momentum-dependent dark matter-nucleon interactions in the Sun

Pat Scott

Imperial College London

With: Aaron Vincent (IPPP Durham)
Aldo Serenelli (UAB Barcelona)

Based on: Vincent, PS & Serenelli, *Phys. Rev. Lett* **114**:081302 (2015)
arXiv:1411.6626
Vincent & PS, *JCAP* **04**:019 (2014), arXiv:1311.2074

Slides available from `tinyurl.com/patscott`

Imperial College London

Outline

Outline

Nuclear scattering cross-sections

In standard (read: SUSY) WIMP-land, everything is nice and constant...

$$\chi\bar{\chi}Q\bar{Q} \quad \rightarrow \sigma_{\mathrm{SI}} \qquad \mathrm{spin-independent} \tag{1}$$

$$\chi\gamma_\mu\gamma_5\bar{\chi}Q\gamma^\mu\gamma_5\bar{Q} \quad \rightarrow \sigma_{\mathrm{SD}} \qquad \mathrm{spin-dependent} \tag{2}$$

No dependence on

- v_{rel} – relative velocity
- q – momentum exchange between DM (χ) and quarks (Q)

Nuclear scattering cross-sections

In standard (read: SUSY) WIMP-land, everything is nice and constant...

$$\chi\bar{\chi}Q\bar{Q} \quad \rightarrow \sigma_{\rm SI} \qquad \text{spin} - \text{independent} \tag{1}$$

$$\chi\gamma_\mu\gamma_5\bar{\chi}Q\gamma^\mu\gamma_5\bar{Q} \quad \rightarrow \sigma_{\rm SD} \qquad \text{spin} - \text{dependent} \tag{2}$$

No dependence on

- $v_{\rm rel}$ – relative velocity
- q – momentum exchange between DM (χ) and quarks (Q)

...but in e.g. pseudoscalar exchange

$$\chi\gamma_5\bar{\chi}Q\gamma_5\bar{Q} \quad \rightarrow \sigma_{\rm SD'} \qquad \text{spin} - \text{dependent}, \ \sigma \propto q^4 \tag{3}$$

Nuclear scattering cross-sections

In standard (read: SUSY) WIMP-land, everything is nice and constant...

$$\chi\bar{\chi}Q\bar{Q} \quad \rightarrow \sigma_{\rm SI} \qquad \text{spin} - \text{independent} \tag{1}$$

$$\chi\gamma_\mu\gamma_5\bar{\chi}Q\gamma^\mu\gamma_5\bar{Q} \quad \rightarrow \sigma_{\rm SD} \qquad \text{spin} - \text{dependent} \tag{2}$$

No dependence on

- $v_{\rm rel}$ – relative velocity
- q – momentum exchange between DM (χ) and quarks (Q)

...but in e.g. pseudoscalar exchange

$$\chi\gamma_5\bar{\chi}Q\gamma_5\bar{Q} \quad \rightarrow \sigma_{\rm SD'} \qquad \text{spin} - \text{dependent}, \ \sigma \propto q^4 \tag{3}$$

In general $\sigma(q, v_{\rm rel})$ – but **consider one at a time for now**:

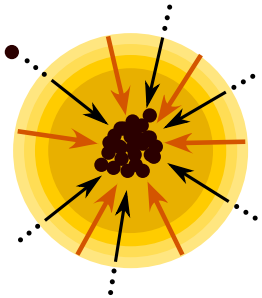
$$\sigma_q = \sigma_0 \left(\frac{q}{q_0}\right)^{2n}, \qquad \sigma_{v_{\rm rel}} = \sigma_0 \left(\frac{v_{\rm rel}}{v_0}\right)^{2n}. \tag{4}$$

Doing “indirect direct detection” with the Sun

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

Doing “indirect direct detection” with the Sun

DM-nucleon scattering allows DM collisions with nuclei in the Sun
$\longrightarrow$ gravitational capture and settling the to solar core

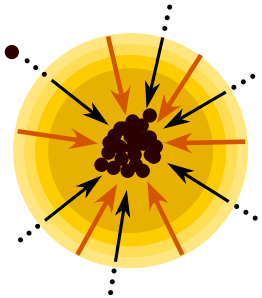


Doing “indirect direct detection” with the Sun

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

$\longrightarrow$ gravitational capture and settling the to solar core

$\longrightarrow$ 1. observable: high-E neutrinos from annihilation

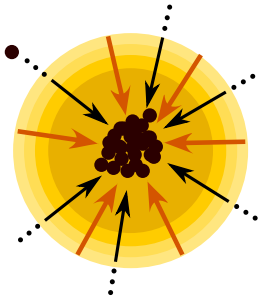


Doing “indirect direct detection” with the Sun

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

$\longrightarrow$ gravitational capture and settling the to solar core

- $\longrightarrow$ 1. observable: high-E neutrinos from annihilation
- $\longrightarrow$ 2. nuclear scattering inside the Sun

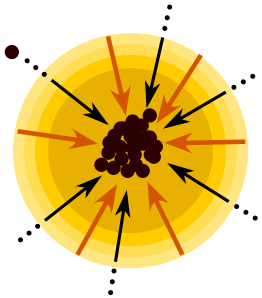


Doing “indirect direct detection” with the Sun

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

$\longrightarrow$ gravitational capture and settling the to solar core

- $\longrightarrow$ 1. observable: high-E neutrinos from annihilation
- $\longrightarrow$ 2. nuclear scattering inside the Sun
  - $\longrightarrow$ additional energy transport

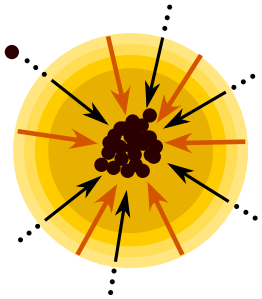


Doing “indirect direct detection” with the Sun

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

$\longrightarrow$ gravitational capture and settling the to solar core

- $\longrightarrow$ 1. observable: high-E neutrinos from annihilation
- $\longrightarrow$ 2. nuclear scattering inside the Sun
  - $\longrightarrow$ additional energy transport
    - $\longrightarrow$ modified solar structure



Doing "indirect direct detection" with the Sun

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

$\longrightarrow$ gravitational capture and settling the to solar core

$\longrightarrow$ 1. observable: high-E neutrinos from annihilation

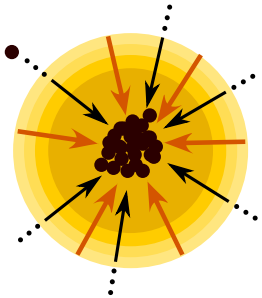
$\longrightarrow$ 2. nuclear scattering inside the Sun

$\longrightarrow$ additional energy transport

$\longrightarrow$ modified solar structure

$\longrightarrow$ 1. observables: (helioseismology)

- sound speed
- oscillation frequencies
- convective zone depth
- surface helium frac.



Doing "indirect direct detection" with the Sun

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

→ gravitational capture and settling the to solar core

→ 1. observable: high-E neutrinos from annihilation

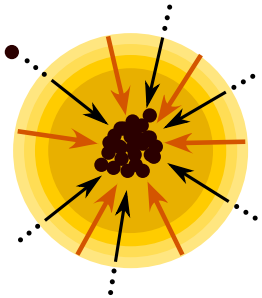
→ 2. nuclear scattering inside the Sun

→ additional energy transport

→ modified solar structure

→ 1. observables: (helioseismology)
- sound speed
- oscillation frequencies
- convective zone depth
- surface helium frac.

→ 2. different core temperature



Doing "indirect direct detection" with the Sun

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

→ gravitational capture and settling the to solar core

→ 1. observable: high-E neutrinos from annihilation

→ 2. nuclear scattering inside the Sun

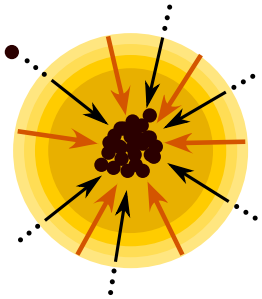
→ additional energy transport

→ modified solar structure

→ 1. observables: (helioseismology)
- sound speed
- oscillation frequencies
- convective zone depth
- surface helium frac.

→ 2. different core temperature

→ observable: solar neutrino rates



Doing "indirect direct detection" with the Sun

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

$\longrightarrow$ gravitational capture and settling the to solar core

- $\longrightarrow$ 1. observable: high-E neutrinos from annihilation
- $\longrightarrow$ 2. nuclear scattering inside the Sun
  - $\longrightarrow$ additional energy transport
    - $\longrightarrow$ modified solar structure
      - $\longrightarrow$ 1. observables: (helioseismology)
        - – sound speed
        - – oscillation frequencies
        - – convective zone depth
        - – surface helium frac.
      - $\longrightarrow$ 2. different core temperature
        - $\longrightarrow$ observable: solar neutrino rates

WIMPS

$\langle \sigma v \rangle \neq 0$

$\sigma_{\rm nuc} \neq 0$

Doing "indirect direct detection" with the Sun

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

$\longrightarrow$ gravitational capture and settling the to solar core

- $\longrightarrow$ 1. ~~observable: high-E neutrinos from annihilation~~
- $\longrightarrow$ 2. nuclear scattering inside the Sun
  - $\longrightarrow$ additional energy transport
    - $\longrightarrow$ modified solar structure
      - $\longrightarrow$ 1. observables: (helioseismology)
        - – sound speed
        - – oscillation frequencies
        - – convective zone depth
        - – surface helium frac.
      - $\longrightarrow$ 2. different core temperature
        - $\longrightarrow$ observable: solar neutrino rates

ADM

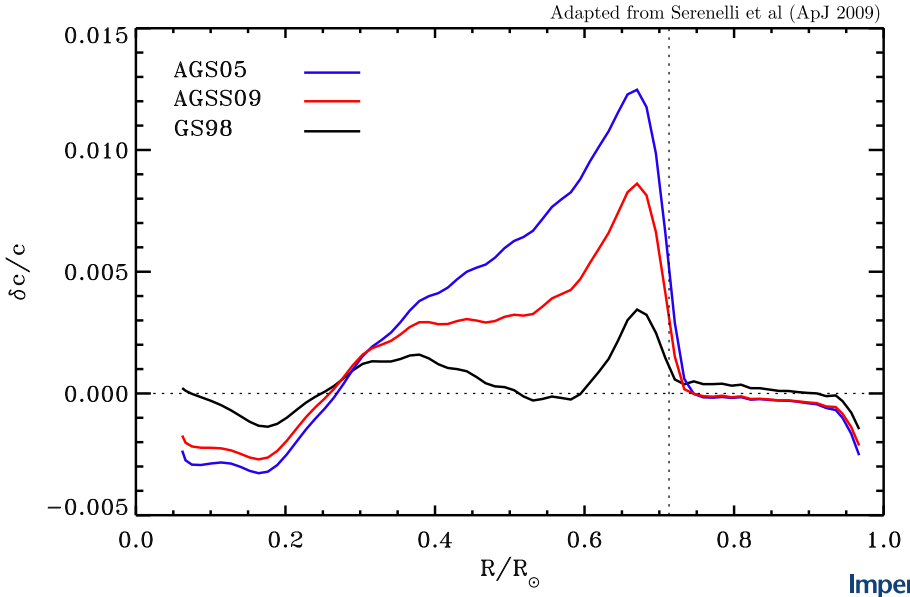
$\langle \sigma v \rangle \sim 0$

$\sigma_{\rm nuc} \neq 0$

The solar abundance problem

- Latest solar photospheric abundances (Asplund, Grevesse, Sauval & PS: AGS05, AGSS09) factor of $\sim$2 less than old ones (Grevesse & Sauval: GS98)
- Best atomic data, highly accurate observations, new 3D modelling, NLTE corrections, improved agreement with solar neighbourhood $\Longrightarrow$ highly reliable
- Messes up inferred sound speed profile, helium abundance and depth of convection zone from helioseismology
- Many solutions attempted in the last decade; none really successful.

$\Longrightarrow$ DM conduction?



Imperial College London

Outline

Conductive energy transport with dark matter

Dark matter number density:

$$n_\chi(r) = n_\chi(0)\left[\frac{T(r)}{T(0)}\right]^{3/2} \exp\left[-\int_0^r \mathrm{d}r' \, \frac{k_\mathrm{B}\alpha(r')\frac{\mathrm{d}T(r')}{\mathrm{d}r'} + m_\chi \frac{\mathrm{d}\phi(r')}{\mathrm{d}r'}}{k_\mathrm{B}T(r')}\right] \tag{5}$$

Dark matter conductive luminosity:

$$L_\chi(r) = 4\pi r^2 \zeta^{2n}(r)\kappa(r) n_\chi(r) l_\chi(r)\left[\frac{k_\mathrm{B}T(r)}{m_\chi}\right]^{1/2} k_\mathrm{B}\frac{\mathrm{d}T(r)}{\mathrm{d}r}, \tag{6}$$

Corresponding energy injection rate per unit mass of stellar material:

$$\epsilon_\chi(r) = \frac{1}{4\pi r^2 \rho(r)}\frac{\mathrm{d}L_\chi(r)}{\mathrm{d}r}. \tag{7}$$

$\phi(r)$: gravitational potential at height r in star
$T(r)$: temperature at height r
$\rho(r)$: stellar density at height r
$\zeta(r)$: $v_0/v_T(r)$ or $q_0/[m_\chi v_T(r)]$ depending on cross-section
$v_T(r)$: DM thermal velocity at height r

Imperial College London

Conductive energy transport with dark matter

Dark matter number density:

$$n_\chi(r) = n_\chi(0)\left[\frac{T(r)}{T(0)}\right]^{3/2} \exp\left[-\int_0^r \mathrm{d}r' \, \frac{k_\mathrm{B}\alpha(r')\frac{\mathrm{d}T(r')}{\mathrm{d}r'} + m_\chi \frac{\mathrm{d}\phi(r')}{\mathrm{d}r'}}{k_\mathrm{B}T(r')}\right] \tag{5}$$

Dark matter conductive luminosity:

$$L_\chi(r) = 4\pi r^2 \zeta^{2n}(r)\kappa(r) n_\chi(r) l_\chi(r)\left[\frac{k_\mathrm{B}T(r)}{m_\chi}\right]^{1/2} k_\mathrm{B}\frac{\mathrm{d}T(r)}{\mathrm{d}r}, \tag{6}$$

Corresponding energy injection rate per unit mass of stellar material:

$$\epsilon_\chi(r) = \frac{1}{4\pi r^2 \rho(r)}\frac{\mathrm{d}L_\chi(r)}{\mathrm{d}r}. \tag{7}$$

$\phi(r)$: gravitational potential at height r in star
$T(r)$: temperature at height r
$\rho(r)$: stellar density at height r
$\zeta(r)$: $v_0/v_T(r)$ or $q_0/[m_\chi v_T(r)]$ depending on cross-section
$v_T(r)$: DM thermal velocity at height r

So how do you get α and κ then?

The name of the game is solving the Boltzmann collision equation:

$$DF = CF/l_\chi \tag{8}$$

D: differential operator (change in)
F: DM phase space density
C: collision operator
l_χ: typical DM scattering length

with (roughly)

$$C(\boldsymbol{u}, \boldsymbol{v}, r, t) = C_{\text{in}}(\boldsymbol{u}, \boldsymbol{v}, r, t) - C_{\text{out}}(\boldsymbol{v}, r, t) \tag{9}$$

So how do you get α and κ then?

The name of the game is solving the Boltzmann collision equation:

$$DF = CF/l_\chi \tag{8}$$

D: differential operator (change in)
F: DM phase space density
C: collision operator
l_χ: typical DM scattering length

with (roughly)

$$C(\boldsymbol{u}, \boldsymbol{v}, r, t) = C_{\rm in}(\boldsymbol{u}, \boldsymbol{v}, r, t) - C_{\rm out}(\boldsymbol{v}, r, t) \tag{9}$$

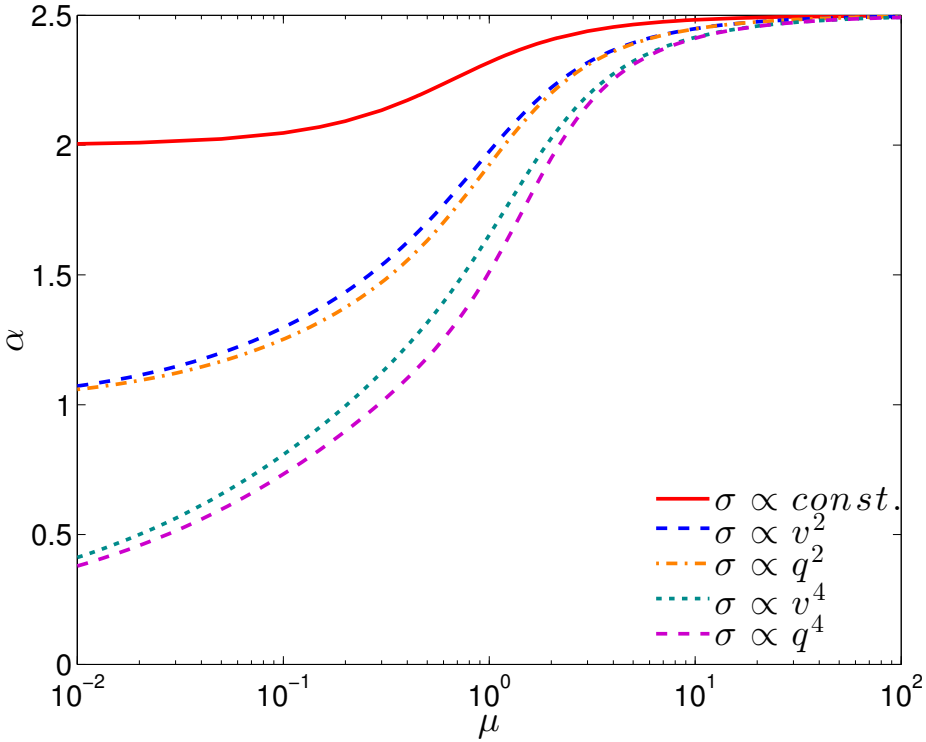
and then...

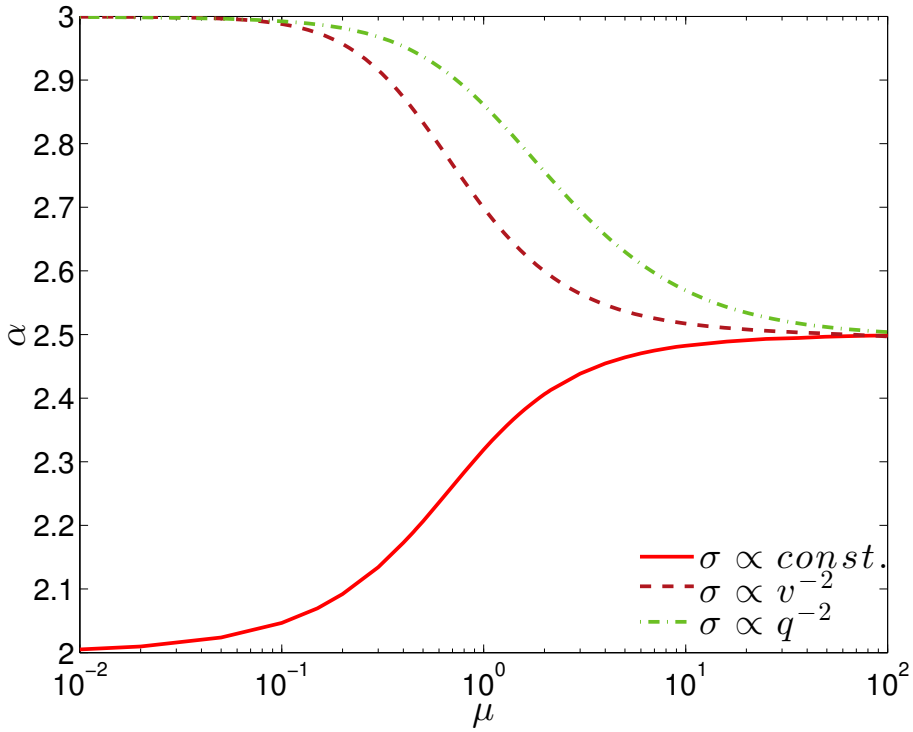
$$\alpha,\ \kappa = \mathfrak{horrible}(C^{-1}, n) \tag{10}$$

Gould & Raffelt (*ApJ* 1990) worked out + tabulated $\mathfrak{horrible}(C^{-1}, 0)$
We worked out + tabulated q-dep and $v_{\rm rel}$-dep $\mathfrak{horrible}(C^{-1}, n)$ for $n \neq 0$

Imperial College London

Diffusivity α





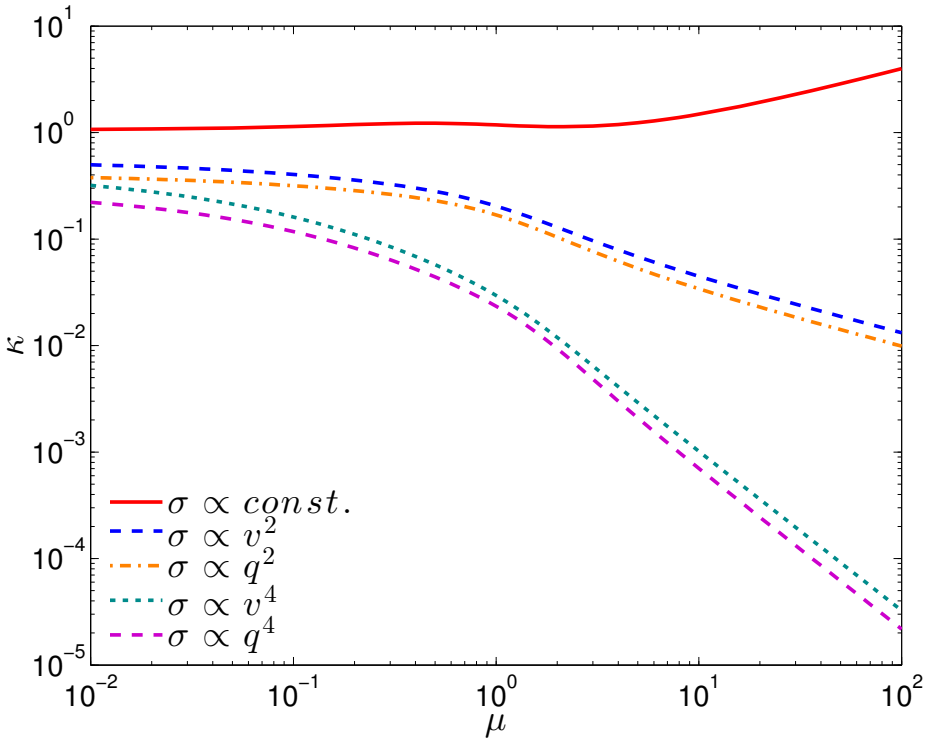
$$\mu \equiv m_\chi / m_{\rm nuc}$$

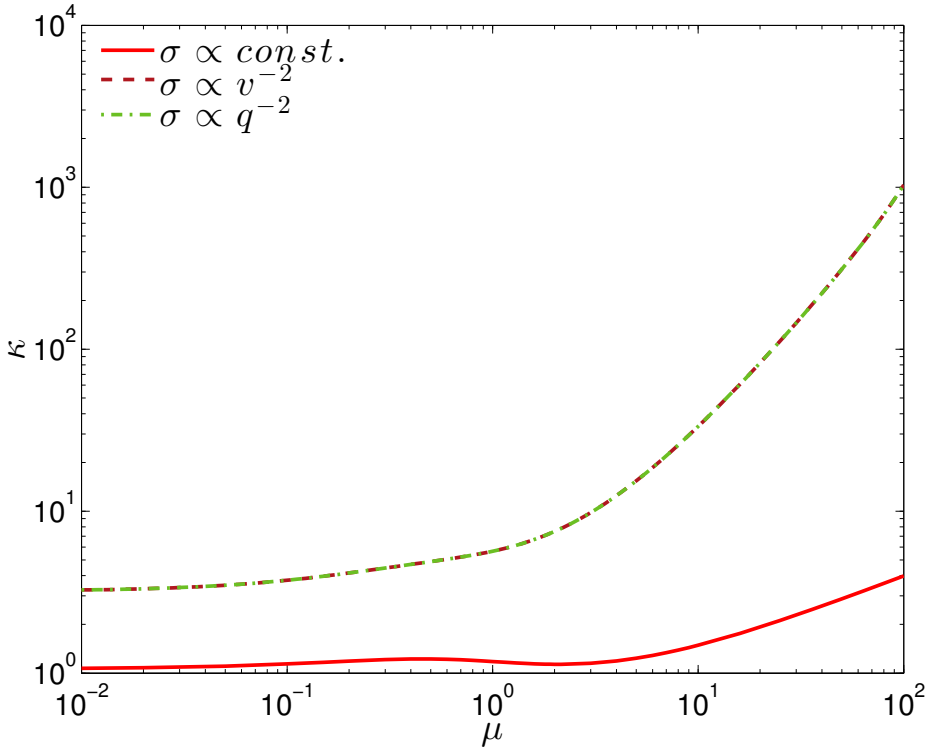
$n > 1 \implies \alpha$ smaller $\rightarrow$ 'tighter' dark matter core

$n < 1 \implies \alpha$ larger $\rightarrow$ 'fluffier' dark matter core

Imperial College London

Conductivity κ





$$\mu \equiv m_\chi / m_{\rm nuc}$$

$n > 1 \implies \kappa$ smaller $\rightarrow$ less effective conduction

$n < 1 \implies \kappa$ larger $\rightarrow$ more effective conduction

Partial summary…

- Derived necessary ingredients for including q and $v_{\rm rel}$-dependent cross-sections in solar models
- Calculated + tabulated corresponding α and κ for general consumption
- Big impacts on solar energy transport for $\sigma \propto v_{\rm rel}^{-2}$, $\sigma \propto q^{2n}$
- $\rightarrow$ next, put it all into a state-of-the-art solar evolution, helioseismology + neutrino code

Outline

DarkStec

PS et al (MNRAS 2009)
PS et al (Dark2009, 0904.2395)

DarkStars
Dark stellar evolution

DarkStec

PS et al (MNRAS 2009)
PS et al (Dark2009, 0904.2395)

Weiss & Schlattl (Ap&SS 2008)
Serenelli et al (ApJ 2011)

+

DarkStars
Dark stellar evolution

Garstec
Detailed solar structure, neutrinos and helioseismology

DarkStec ("The Monster")

PS et al (MNRAS 2009)
PS et al (Dark2009, 0904.2395)

Weiss & Schlattl (Ap&SS 2008)
Serenelli et al (ApJ 2011)

+

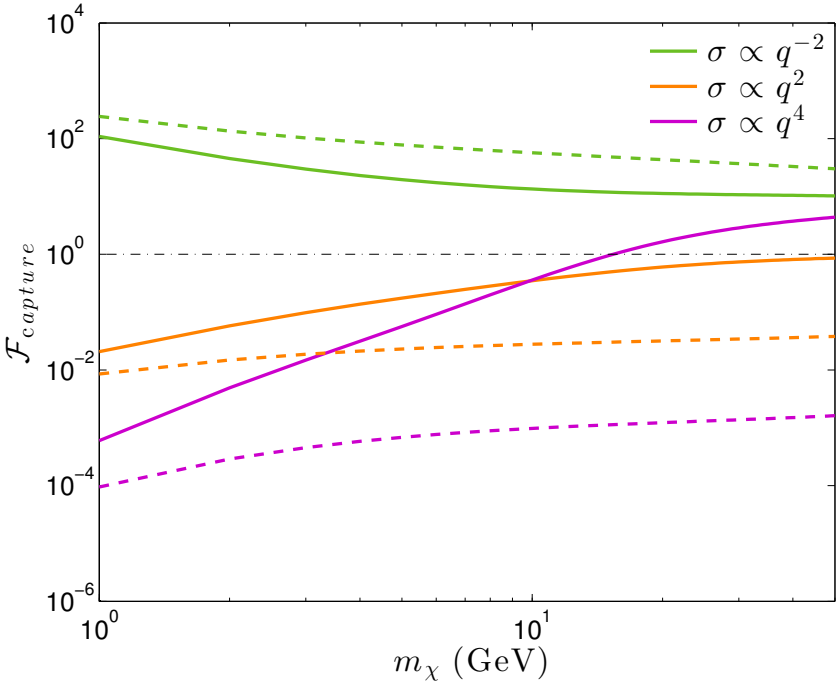
=

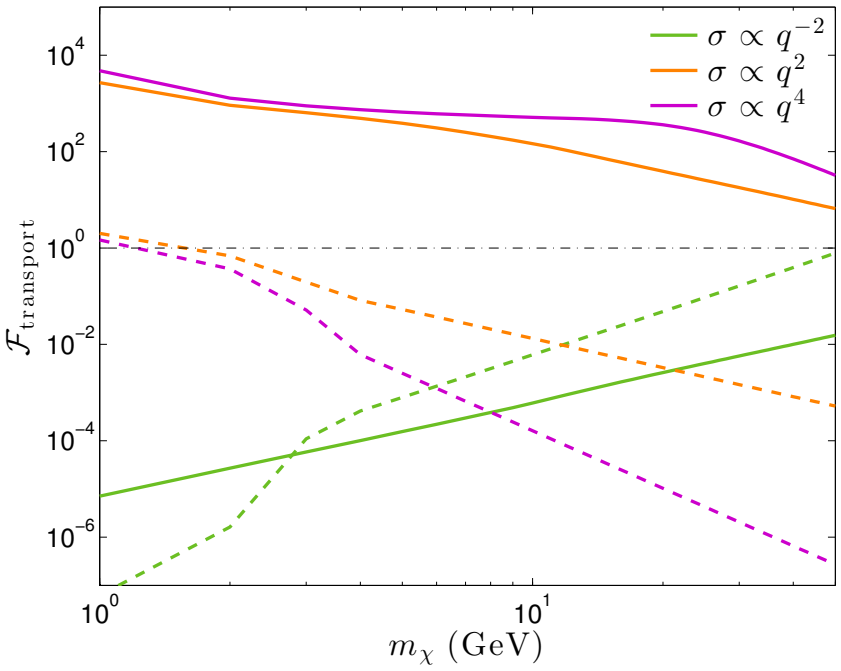
DarkStars
Dark stellar evolution

Garstec
Detailed solar structure, neutrinos and helioseismology

DarkStec
Precision dark solar physics code

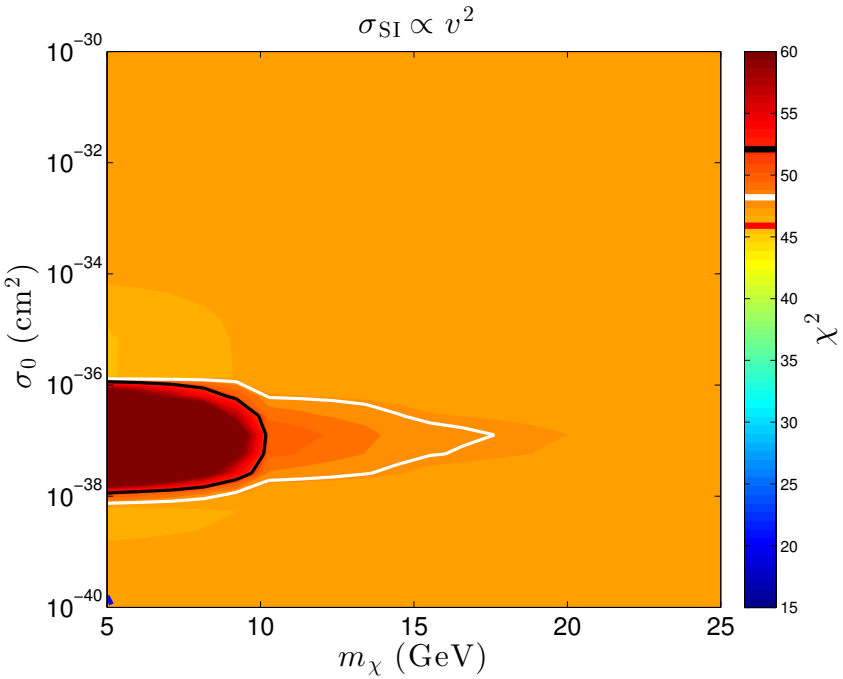
Impacts on capture and transport

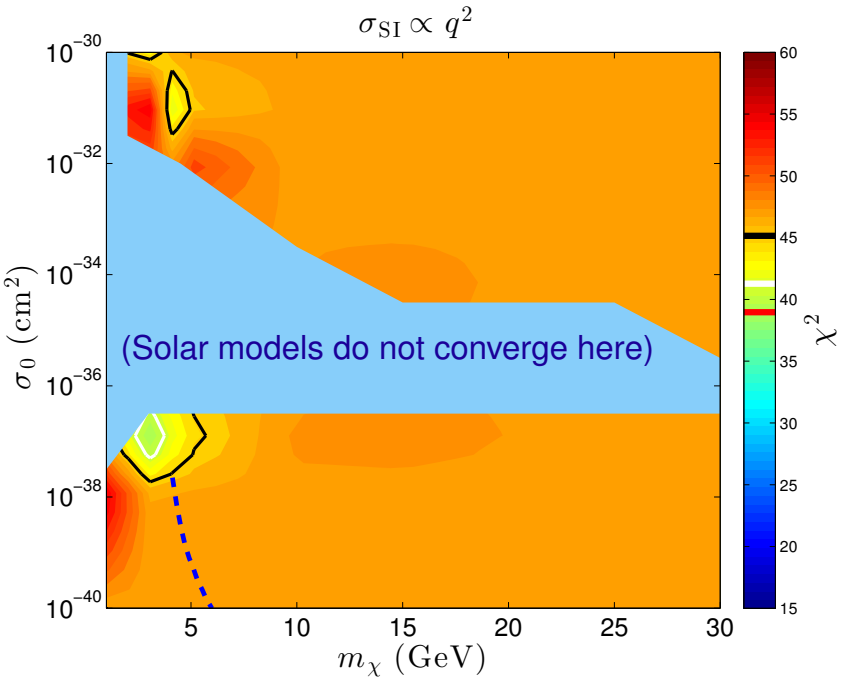




- Enhancement factors for capture and transport wrt constant cross-sections, for $q_0 = 10^{-35}\,\mathrm{cm}^2$
- Solid = SI, Dashed = SD
- transport similar for $v_{\rm rel}^{2n}$; capture enhanced as $\langle \sigma(v_{\rm rel}) \rangle$

Global impact on combined observables: SI $v_{\rm rel}^2$, q^2



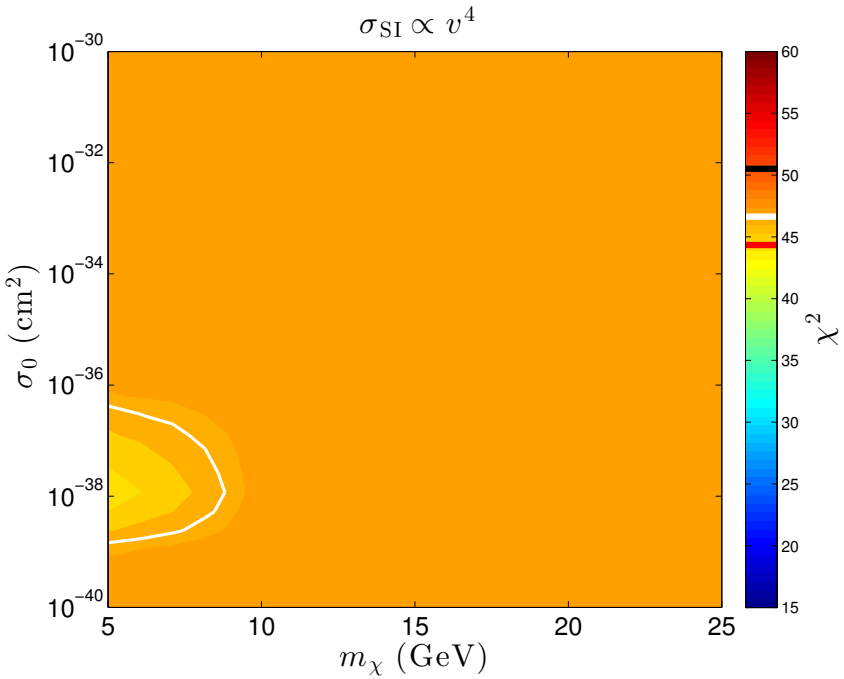


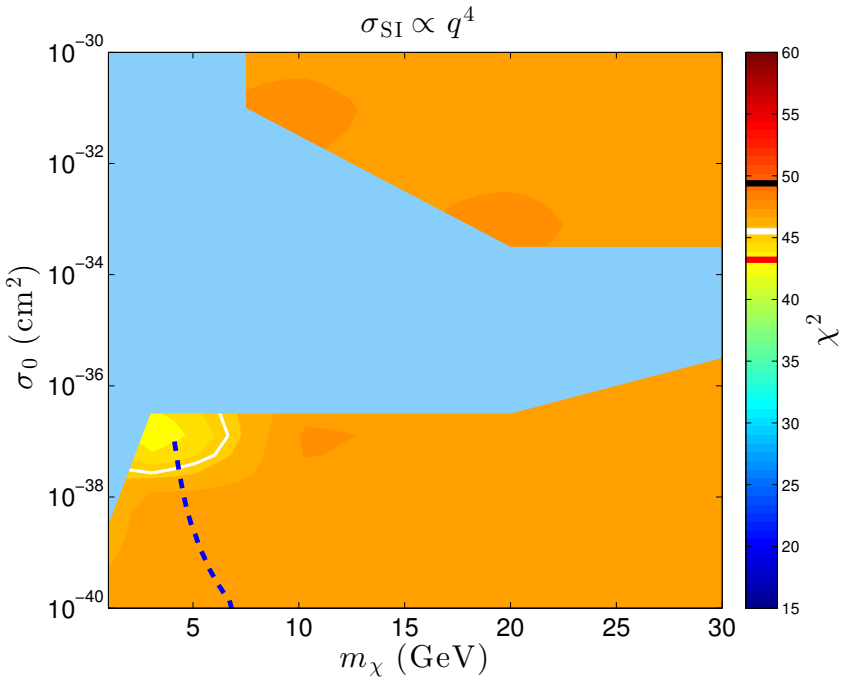
Global χ^2 includes:

- ^{8}B neutrino flux
- ^{7}Be neutrino flux
- depth of the convection zone $R_{\rm CZ}$
- surface helium abundance $Y_{\rm s}$
- sound speed profile (sparsely sampled to avoid correlations)

Imperial College London

Global impact on combined observables: SI $v_{\rm rel}^4$, q^4





Global χ^2 includes:

- ^{8}B neutrino flux
- ^{7}Be neutrino flux
- depth of the convection zone $R_{\rm CZ}$
- surface helium abundance $Y_{\rm s}$
- sound speed profile (sparsely sampled to avoid correlations)

Imperial College London

Preferred models

In general v_{rel}^{2n} models are basically no better than the Standard Solar Model (SSM) overall.

Preferred models

In general $v_{\rm rel}^{2n}$ models are basically no better than the Standard Solar Model (SSM) overall.

q^2 is great though.

- Best fit:
  - q^2 coupling
  - $m_\chi = 3\,\text{GeV}$
  - $\sigma_0 = 10^{-37}\,\text{cm}^2$

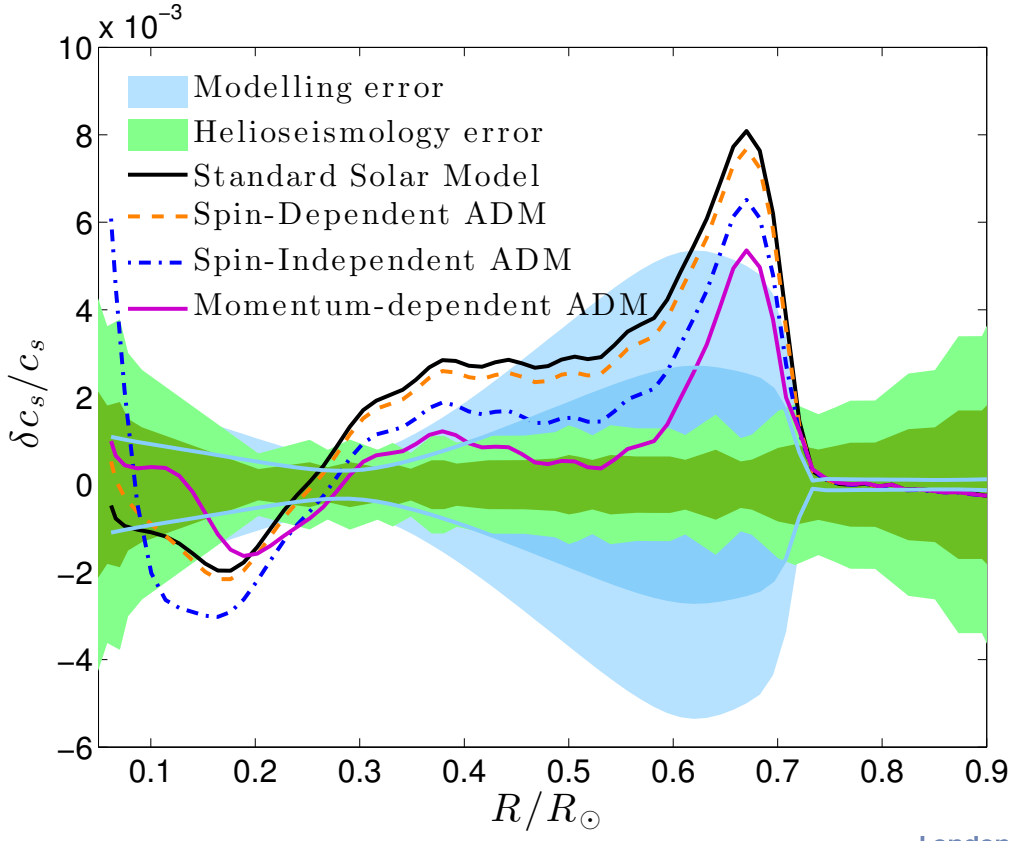
Preferred models

In general $v_{\rm rel}^{2n}$ models are basically no better than the Standard Solar Model (SSM) overall.

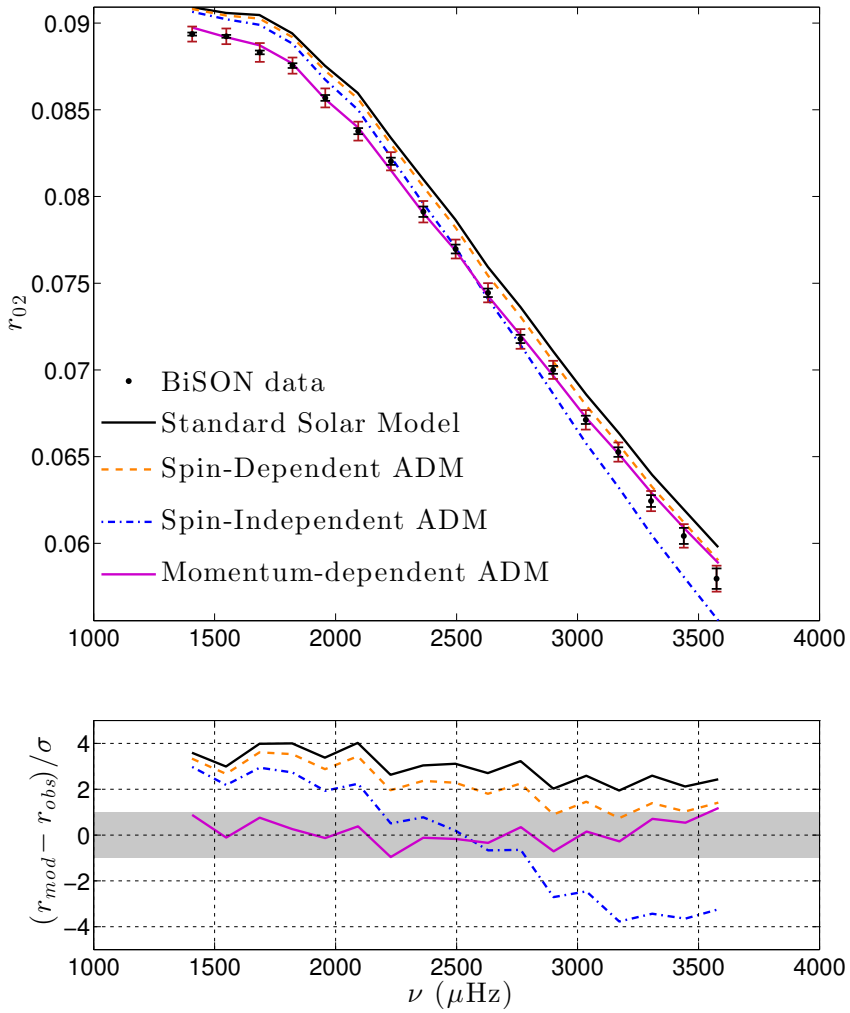
q^2 is great though.

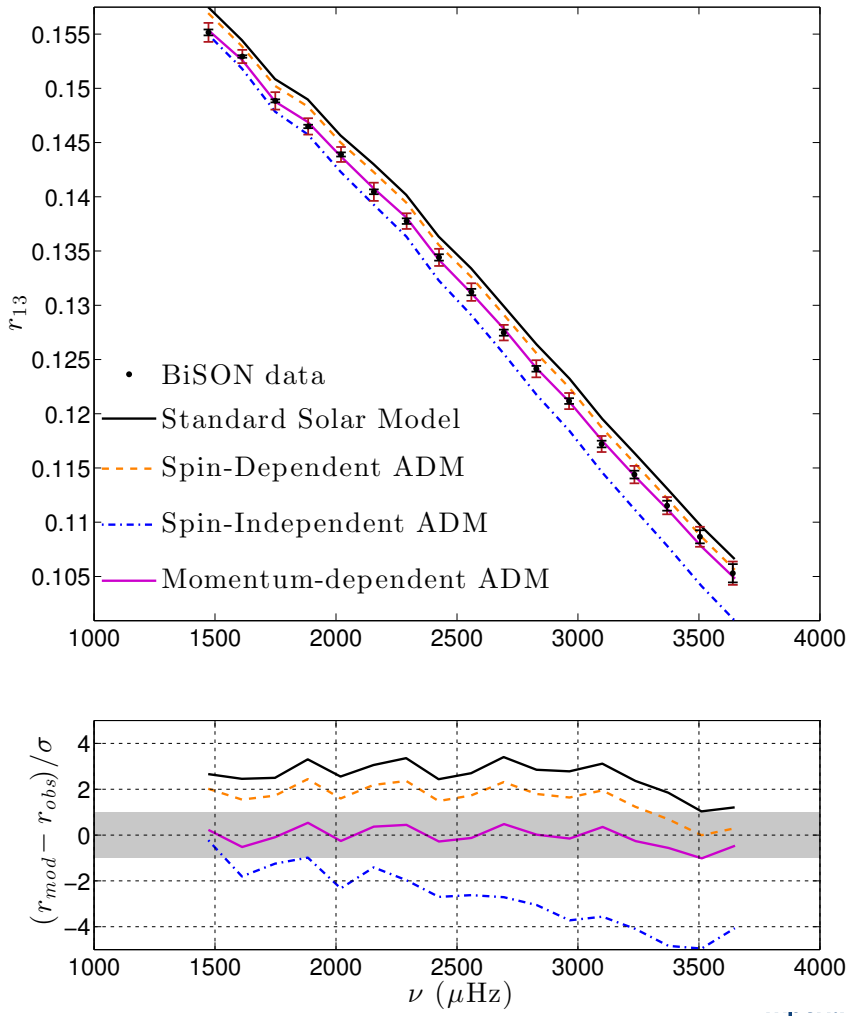
- Best fit:
  - q^2 coupling
  - $m_\chi = 3\,\text{GeV}$
  - $\sigma_0 = 10^{-37}\,\text{cm}^2$

Sound speed for best q^2, SI and SD models:



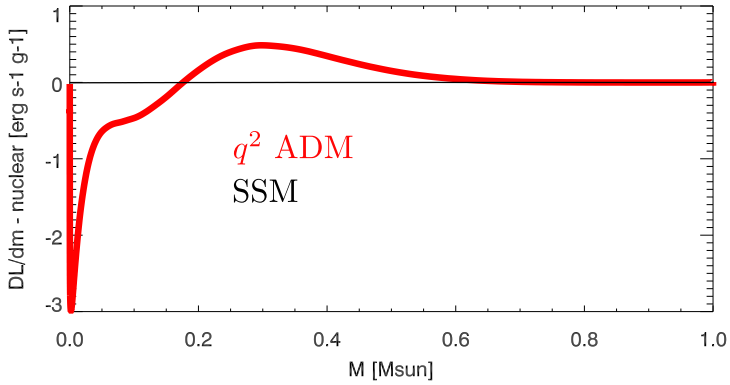
Best models – small frequency separations

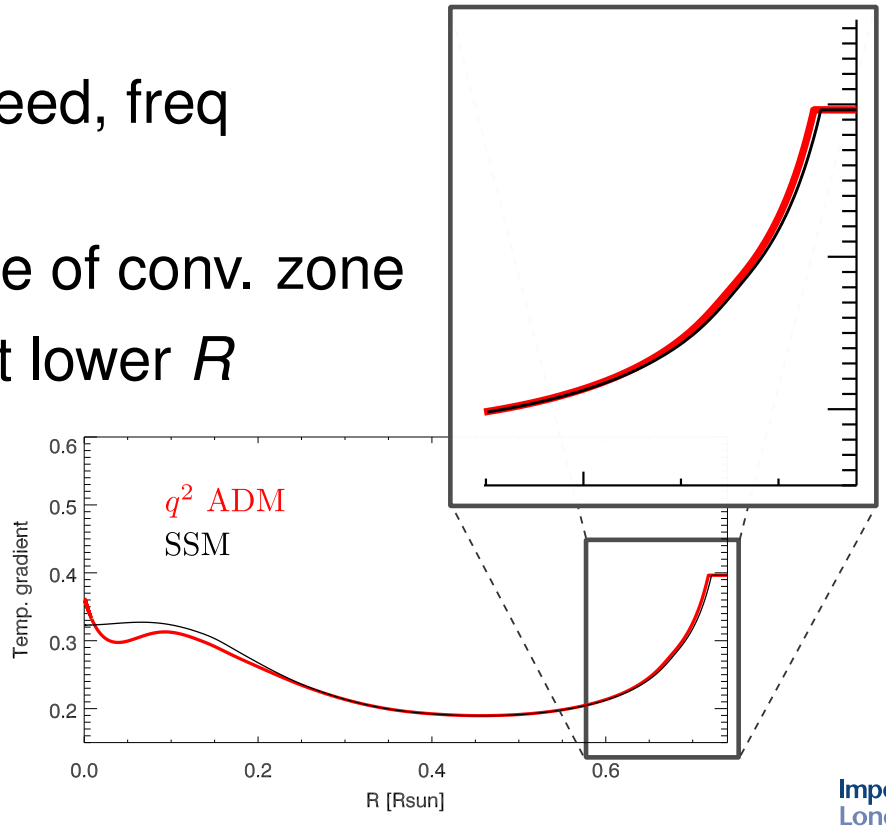




Best models – what is going on in the Sun?

- energy extracted below $M(R) = 0.2\,M_\odot$, dumped in $0.2 < M(R)/M_\odot < 0.6$
- strong core ∇T change
- $\implies$ change in sound speed, freq separations, ν fluxes
- slight ∇T increase at base of conv. zone
- $\implies$ convection sets in at lower R





Best models – detailed likelihood figures

	SSM	SD	q^2 SI	Obs.[1]	$\sigma_{\rm obs}$	$\sigma_{\rm model}$
$\phi_\nu^{^8\rm B}$ (10^6 cm^{-2}s^{-1})	4.95	4.39	3.78	5.00	3%	14%
$\phi_\nu^{^7\rm Be}$ (10^9 cm^{-2}s^{-1})	4.71	4.58	4.29	4.82	5%	7%
$R_{\rm CZ}/R_\odot$	0.722	0.721	0.718	0.713	0.001	0.004
$Y_{\rm s}$	0.2356	0.2351	0.2327	0.2485	0.0034	0.0035
$\chi^2_{^8\rm B}$	0.0	0.9	4.9			
$\chi^2_{^7\rm Be}$	0.1	0.4	1.9			
$\chi^2_{R_{\rm CZ}}$	4.8	3.8	1.5			
$\chi^2_{Y_{\rm s}}$	7.0	7.5	10.5			
$\chi^2_{r_{02}}$	156.6	95.3	5.6			
$\chi^2_{r_{13}}$	119.3	50.7	3.1			
$\chi^2_{\rm total}$	287.8	158.5	27.5	(36 dof)		
p	$<10^{-10}$	$<10^{-10}$	0.845			

[1] Neutrino data and obs. errors inferred from Borexino data (Serenelli et al. ApJ 2011).

Best models – detailed likelihood figures

	SSM	SD	q^2 SI	Obs.[1]	$\sigma_{\rm obs}$	$\sigma_{\rm model}$
$\phi_\nu^{^8\rm B}$ (10^6 cm^{-2}s^{-1})	4.95	4.39	3.78	5.00	3%	14%
$\phi_\nu^{^7\rm Be}$ (10^9 cm^{-2}s^{-1})	4.71	4.58	4.29	4.82	5%	7%
$R_{\rm CZ}/R_\odot$	0.722	0.721	0.718	0.713	0.001	0.004
$Y_{\rm s}$	0.2356	0.2351	0.2327	0.2485	0.0034	0.0035
$\chi^2_{^8\rm B}$	0.0	0.9	4.9			
$\chi^2_{^7\rm Be}$	0.1	0.4	1.9			
$\chi^2_{R_{\rm CZ}}$	4.8	3.8	1.5			
$\chi^2_{Y_{\rm s}}$	7.0	7.5	10.5			
$\chi^2_{r_{02}}$	156.6	95.3	5.6			
$\chi^2_{r_{13}}$	119.3	50.7	3.1			
$\chi^2_{\rm total}$	287.8	158.5	27.5	(36 dof)		
p	$<10^{-10}$	$<10^{-10}$	0.845			

[1] Neutrino data and obs. errors inferred from Borexino data (Serenelli et al. ApJ 2011).

$\Longrightarrow$ q^2 model is a great fit, SSM + others ruled out at $> 6\sigma$!

Imperial College London

Other constraints?

Other constraints?

- Direct detection:
  - 3 GeV too low for DD limits (Guo et al Nuc Phys B 2014)
  - possibly interesting for CDMSlite and DAMIC though

Other constraints?

- Direct detection:
  - 3 GeV too low for DD limits (Guo et al Nuc Phys B 2014)
  - possibly interesting for CDMSlite and DAMIC though
- Collider limits:
  - model-dependent
  - $\bar{\chi}\gamma_5\chi\bar{q}q$ (**D2**) and $\bar{\chi}\sigma_{\mu\nu}\gamma_5\chi\bar{q}\sigma^{\mu\nu}q$ (**D10**) give q^2 SI ADM
  - D2 $\bar{\chi}\gamma_5\chi\bar{q}q$ still OK
  - D10 $\bar{\chi}\sigma_{\mu\nu}\gamma_5\chi\bar{q}\sigma^{\mu\nu}q$ a bit tight (Cheung et al JCAP 2012)

Other constraints?

- Direct detection:
  - 3 GeV too low for DD limits (Guo et al Nuc Phys B 2014)
  - possibly interesting for CDMSlite and DAMIC though
- Collider limits:
  - model-dependent
  - $\bar{\chi}\gamma_5\chi\bar{q}q$ (**D2**) and $\bar{\chi}\sigma_{\mu\nu}\gamma_5\chi\bar{q}\sigma^{\mu\nu}q$ (**D10**) give q^2 SI ADM
  - D2 $\bar{\chi}\gamma_5\chi\bar{q}q$ still OK
  - D10 $\bar{\chi}\sigma_{\mu\nu}\gamma_5\chi\bar{q}\sigma^{\mu\nu}q$ a bit tight (Cheung et al JCAP 2012)

→ Dedicated analyses of DD and LHC signatures would be very helpful

Conclusions

- Standard Solar Model and regular SI and SD ADM excluded at $> 6\sigma$

Conclusions

- Standard Solar Model and regular SI and SD ADM excluded at $> 6\sigma$
- q^2 ADM fits almost perfectly

Conclusions

- Standard Solar Model and regular SI and SD ADM excluded at $> 6\sigma$
- q^2 ADM fits almost perfectly
- Preferred mass and cross-section not excluded by direct detection or LHC

Conclusions

- Standard Solar Model and regular SI and SD ADM excluded at $> 6\sigma$
- q^2 ADM fits almost perfectly
- Preferred mass and cross-section not excluded by direct detection or LHC
- smaller masses might give even better fits

Conclusions

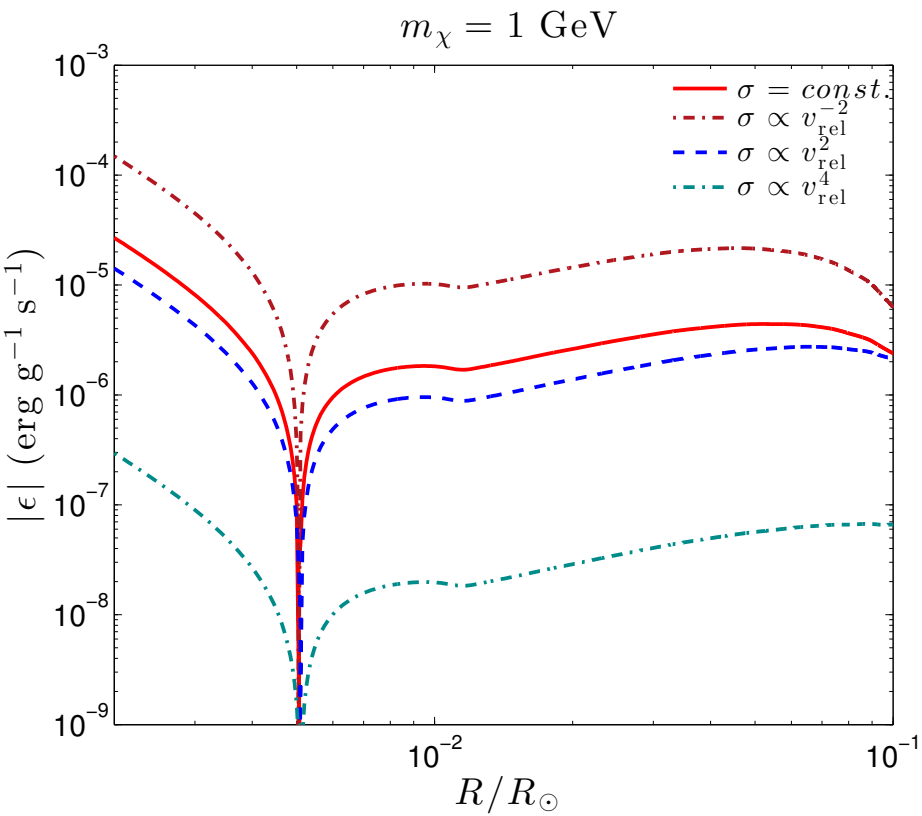
- Standard Solar Model and regular SI and SD ADM excluded at $> 6\sigma$
- q^2 ADM fits almost perfectly
- Preferred mass and cross-section not excluded by direct detection or LHC
- smaller masses might give even better fits
- $\rightarrow$ q^2 ADM looks like a viable solution to the solar abundance problem

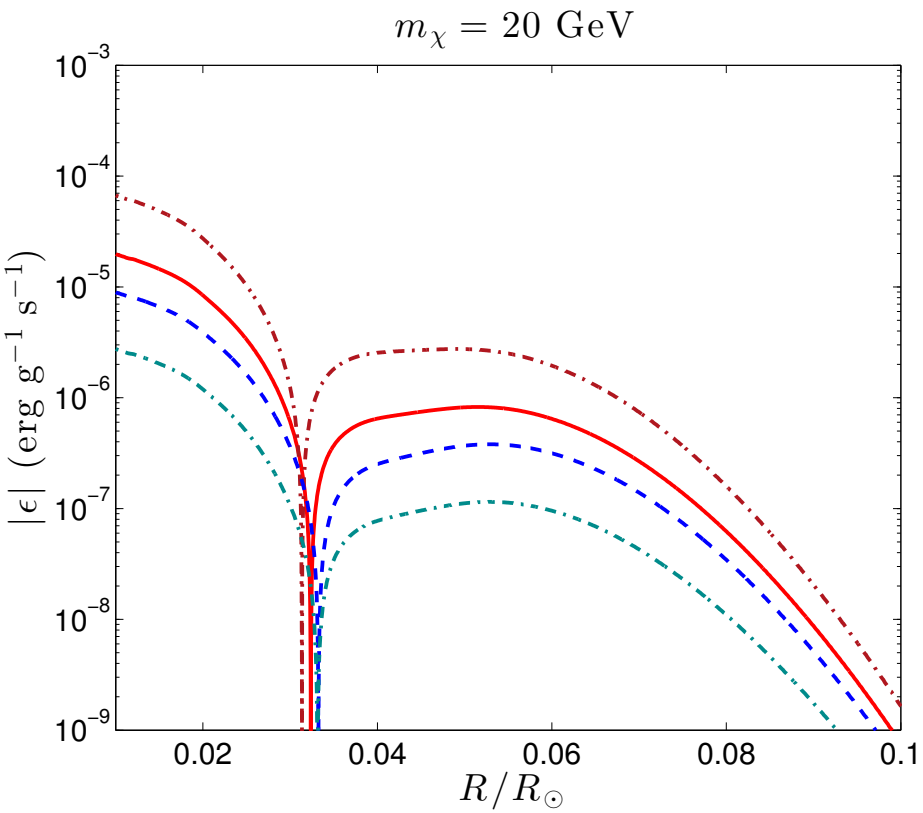
Conclusions

- Standard Solar Model and regular SI and SD ADM excluded at $> 6\sigma$
- q^2 ADM fits almost perfectly
- Preferred mass and cross-section not excluded by direct detection or LHC
- smaller masses might give even better fits
- $\rightarrow$ q^2 ADM looks like a viable solution to the solar abundance problem
- $\rightarrow$ On face value, over 6σ evidence for light, momentum-dependent ADM

Backup slides

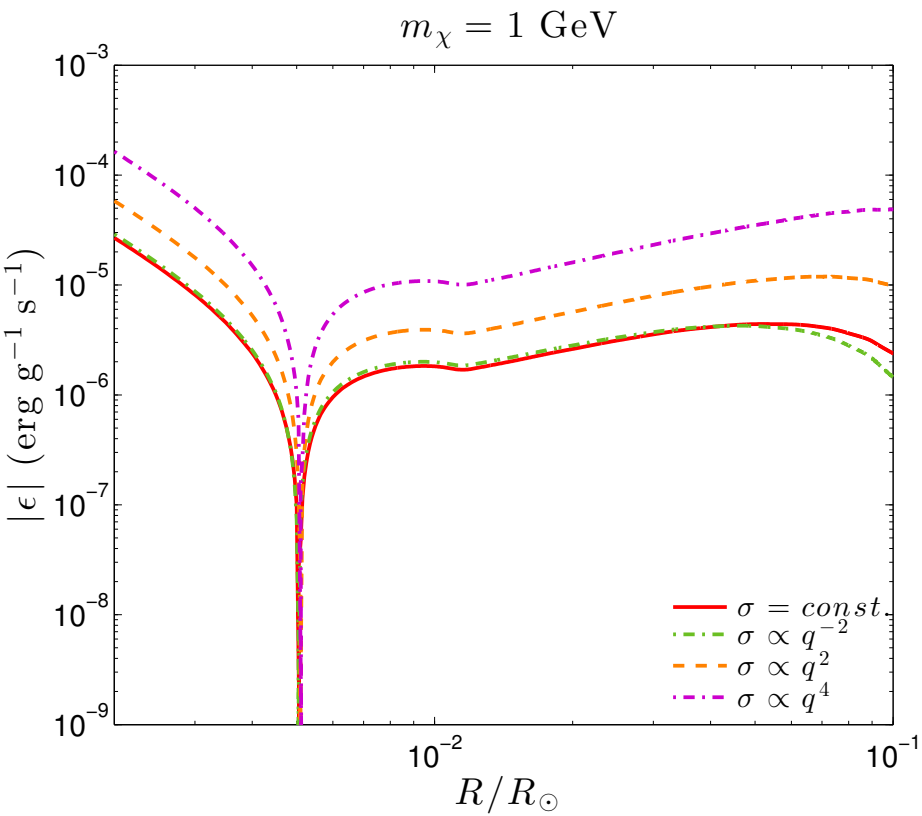
Implications of α and κ: energy injection for $\sigma \propto v_{\rm rel}^{2n}$

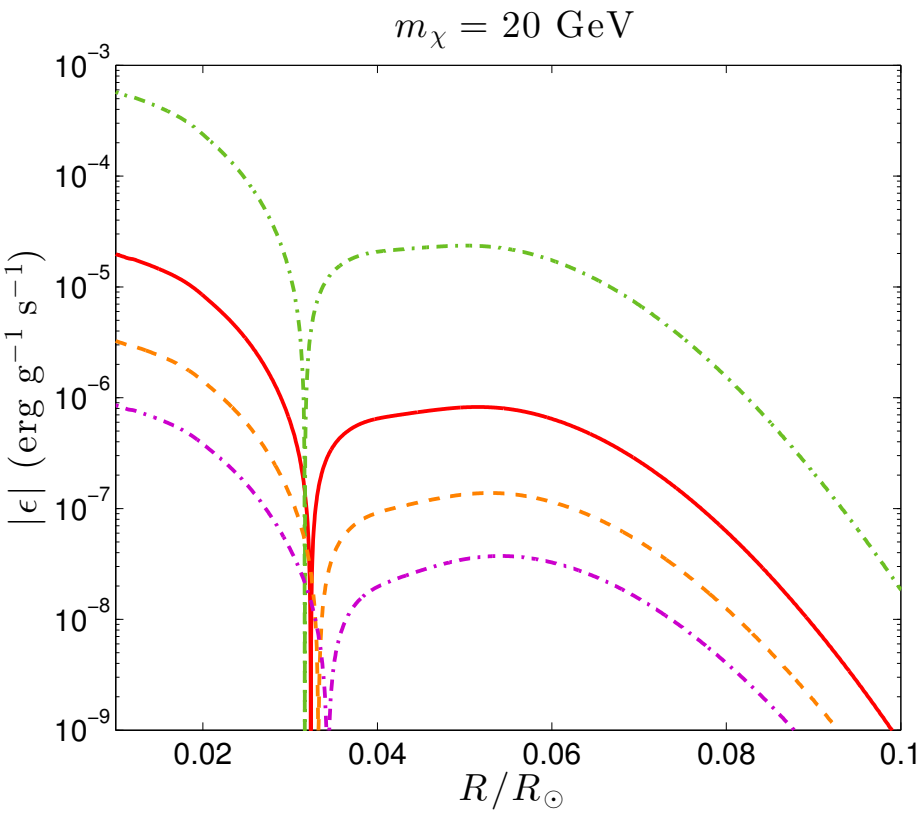




- $v_0 = 110$ km/s
- $\sigma_0 = 10^{-39}$ cm^2.
- $n_\chi/n_{\rm b} = 10^{-16}$ WIMPs per baryon
- Static AGSS09ph solar model (Serenelli et al. *ApJ* 2009)

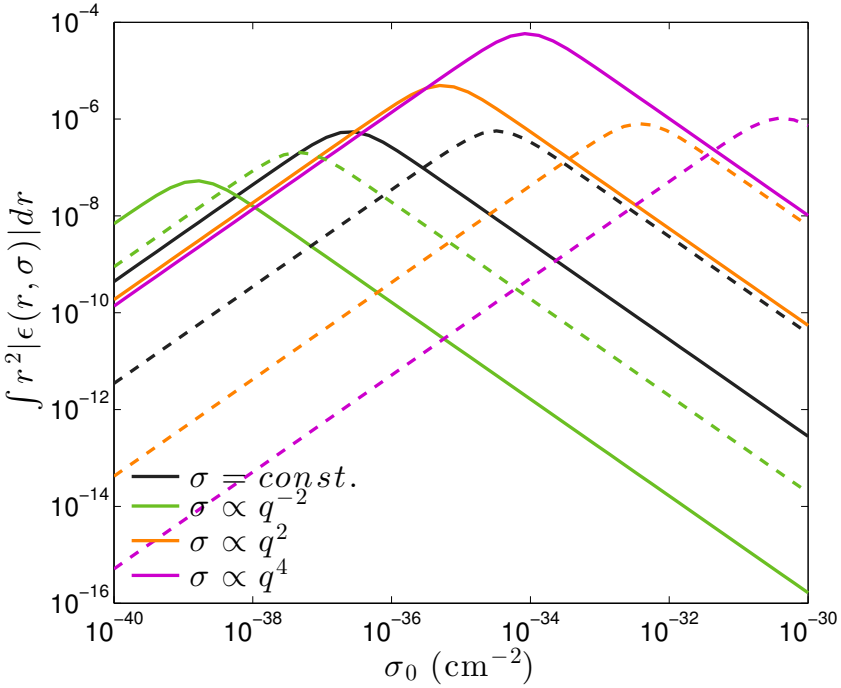
Implications of α and κ: energy injection for $\sigma \propto q^{2n}$

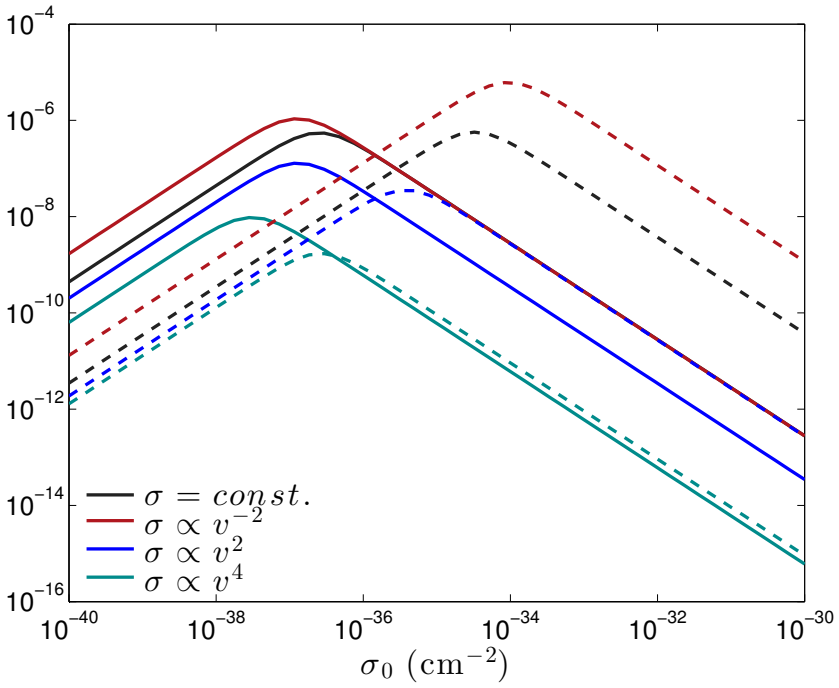




- $q_0 = 40$ MeV
- $\sigma_0 = 10^{-39}$ cm^2.
- $n_\chi/n_b = 10^{-16}$ WIMPs per baryon
- Static AGSS09ph solar model (Serenelli et al. *ApJ* 2009)

Transport regimes

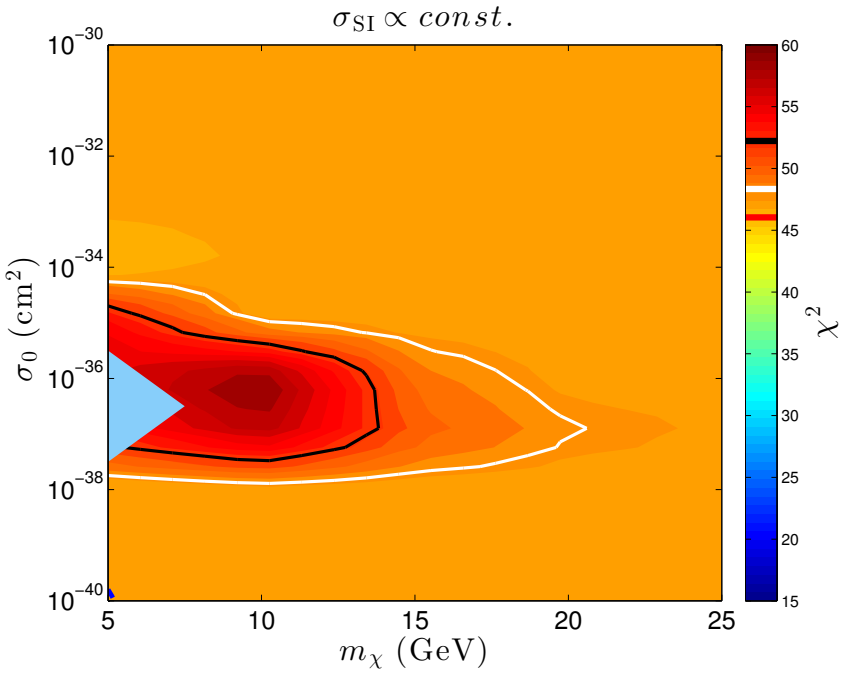


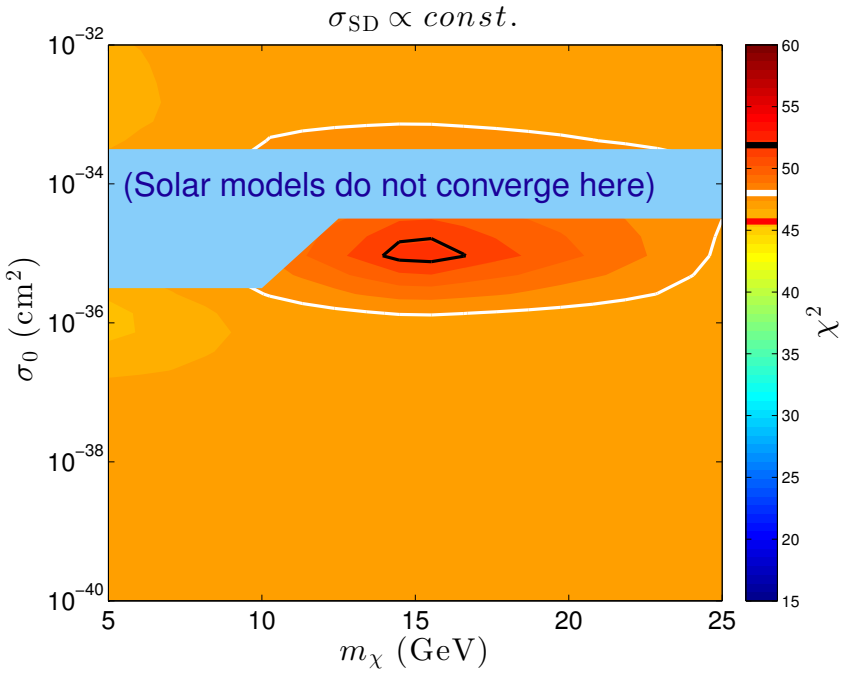


- Transport maximised at transition from non-local to local (LTE) regime
- $m_\chi = 10\,\text{GeV}$, $n_\chi / n_{\text{baryons}} = 10^{-15}$
- Left sides of curves = non-local, right sides = LTE

Imperial College London

Global impact on combined observables: regular SI and SD

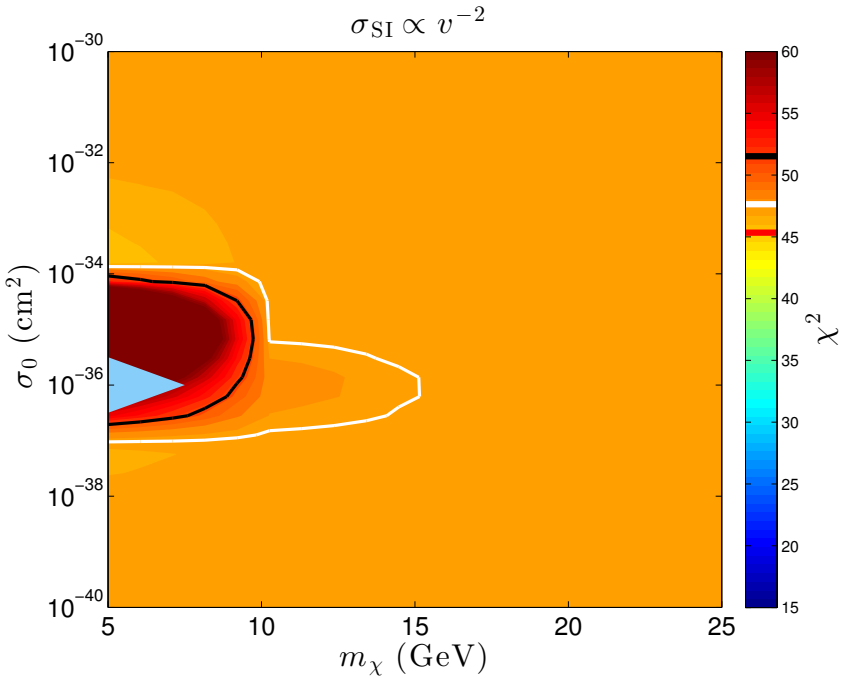


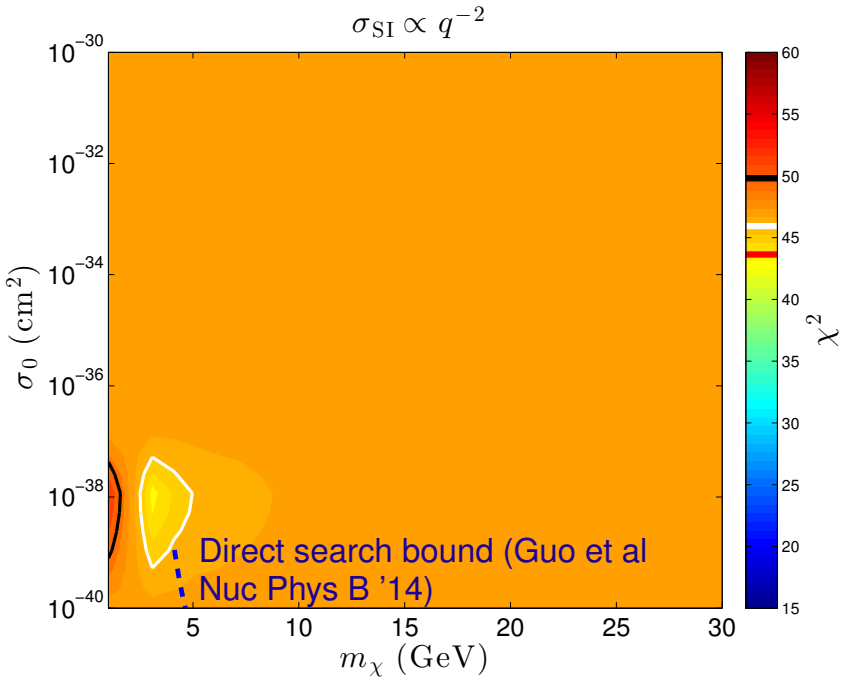


Global χ^2 includes:

- ^{8}B neutrino flux
- ^{7}Be neutrino flux
- depth of the convection zone R_{CZ}
- surface helium abundance Y_s
- sound speed profile (sparsely sampled to avoid correlations)

Global impact on combined observables: SI $v_{\rm rel}^{-2}$, q^{-2}





Global χ^2 includes:

- ^{8}B neutrino flux
- ^{7}Be neutrino flux
- depth of the convection zone $R_{\rm CZ}$
- surface helium abundance $Y_{\rm s}$
- sound speed profile (sparsely sampled to avoid correlations)