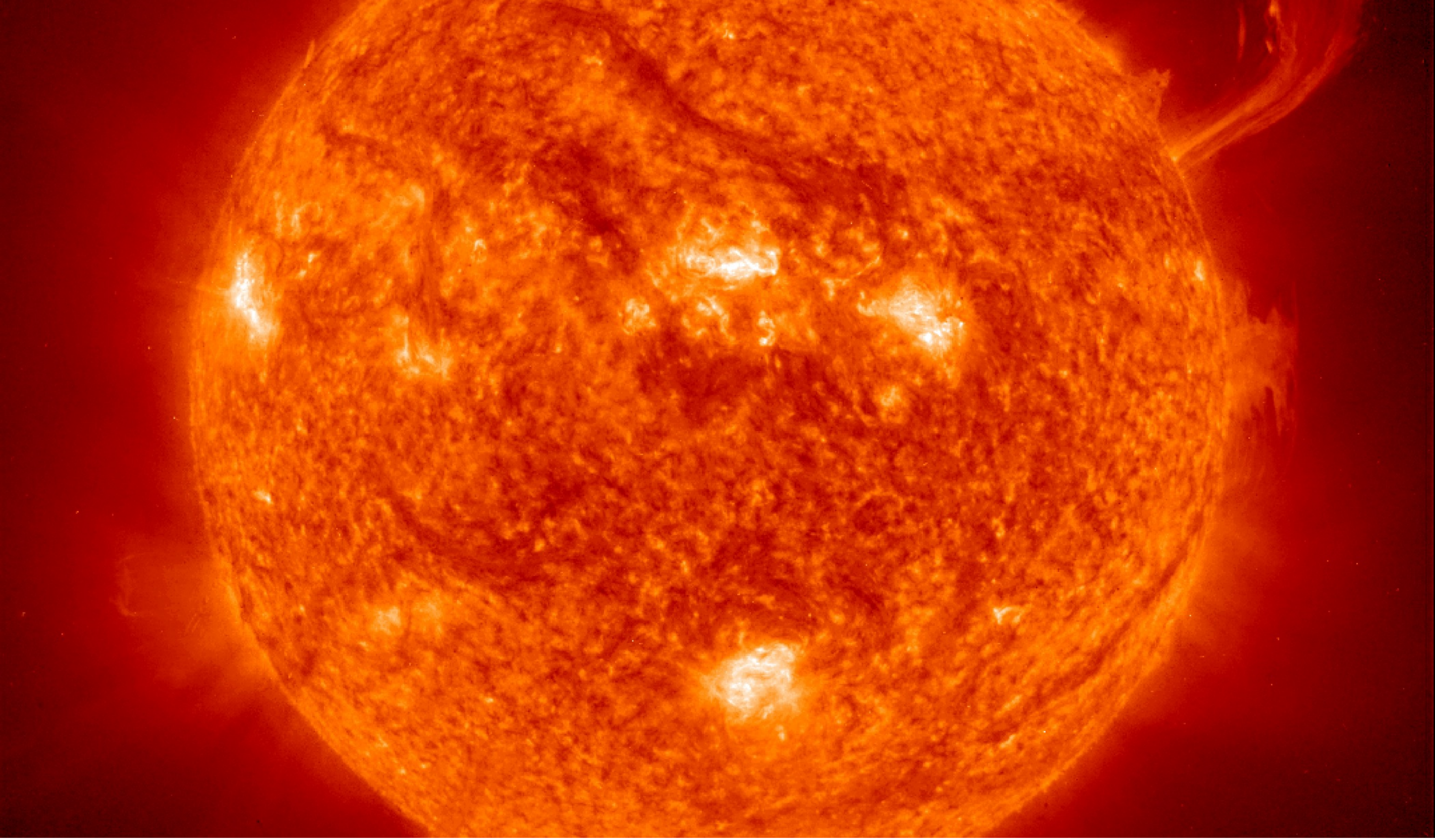


Evidence of Dark Matter in the Sun?

Aaron Vincent
IPPP / U. Durham

Dark Matter in the Sun

Based on work with **Pat Scott** (Imperial College London)
Aldo Serenelli (U. Autonoma Barcelona)

arXiv:1311.2074 / JCAP/04019
Thermal conduction by dark matter with velocity and momentum-dependent cross-sections

arXiv:1411.6626/ PRL 114.081302
Possible Indication of Momentum-Dependent Asymmetric Dark Matter in the Sun

arXiv:1504.04378
Generalised form factor dark matter in the Sun

Motivation

Motivation

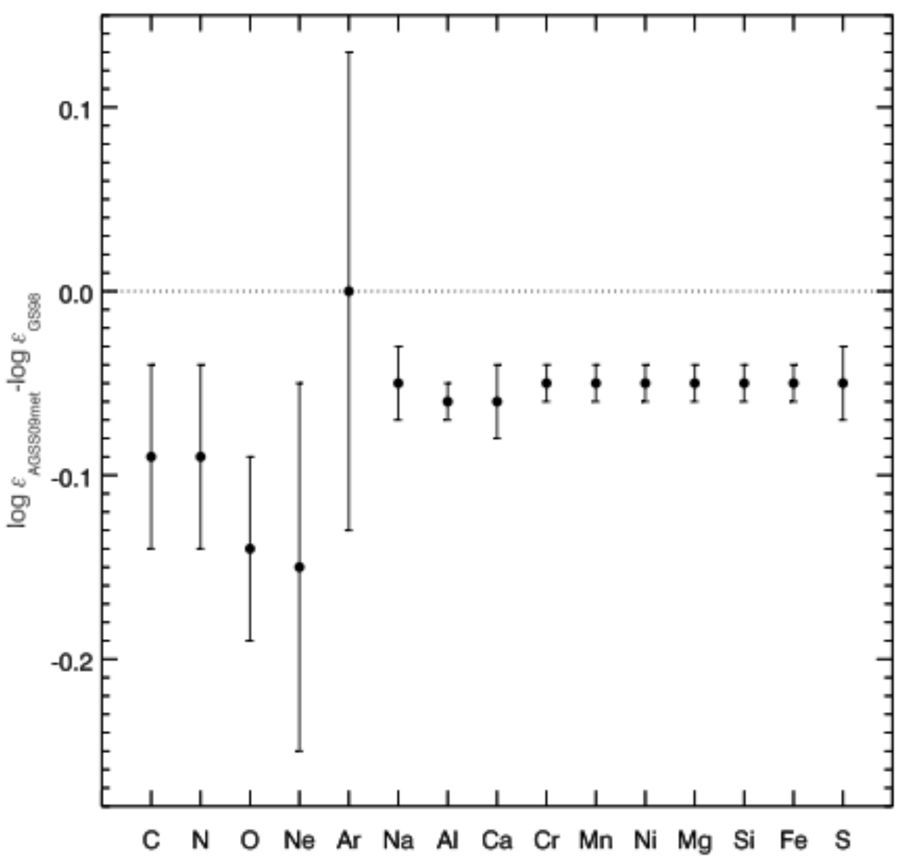
- Discovering the interactions of dark matter

Motivation

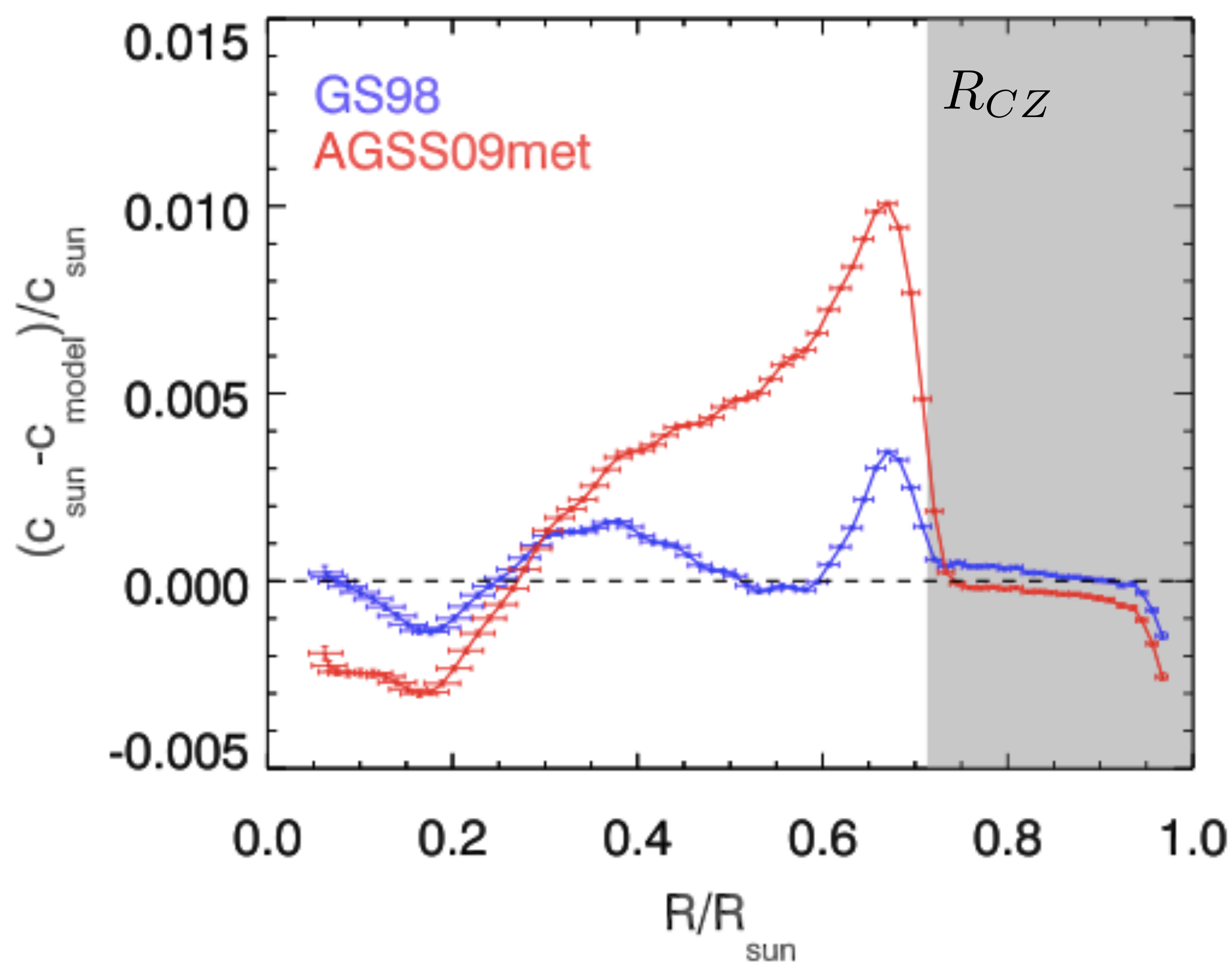
- Discovering the interactions of dark matter
- but also: the Solar Composition Problem

Solar composition problem

After more accurate measurements of the abundances of metals in the early 2000s, it was found that the sound speed from the *Standard Solar Model* are **not in agreement with measurements** inferred from **helioseismology**.



revised - old composition



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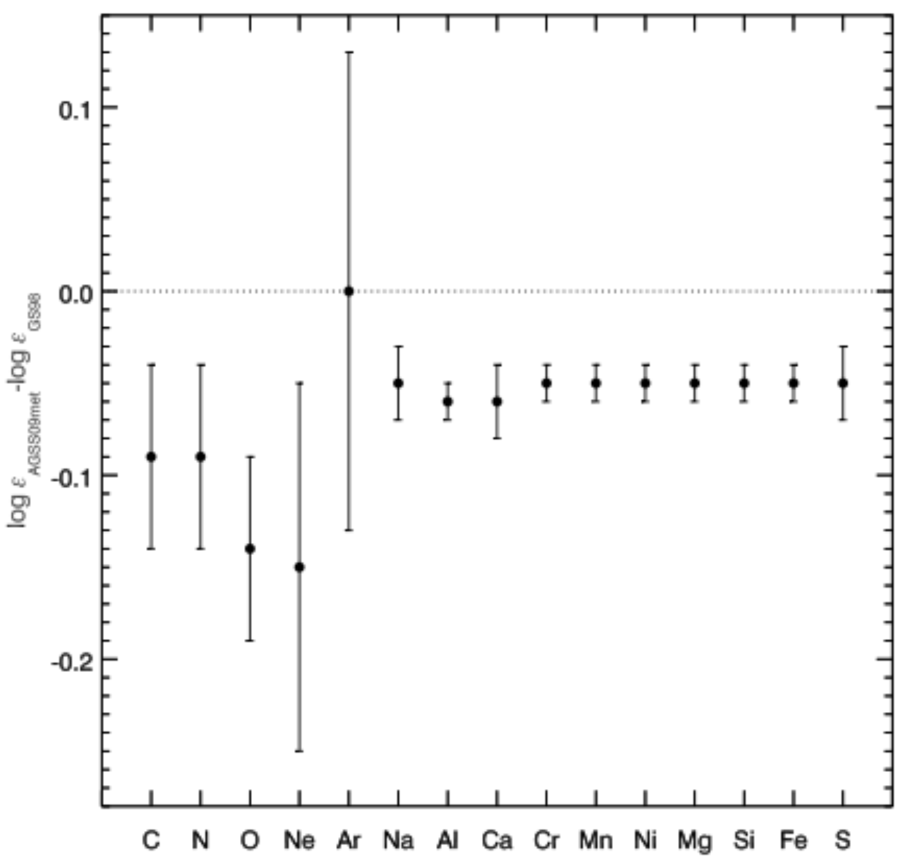

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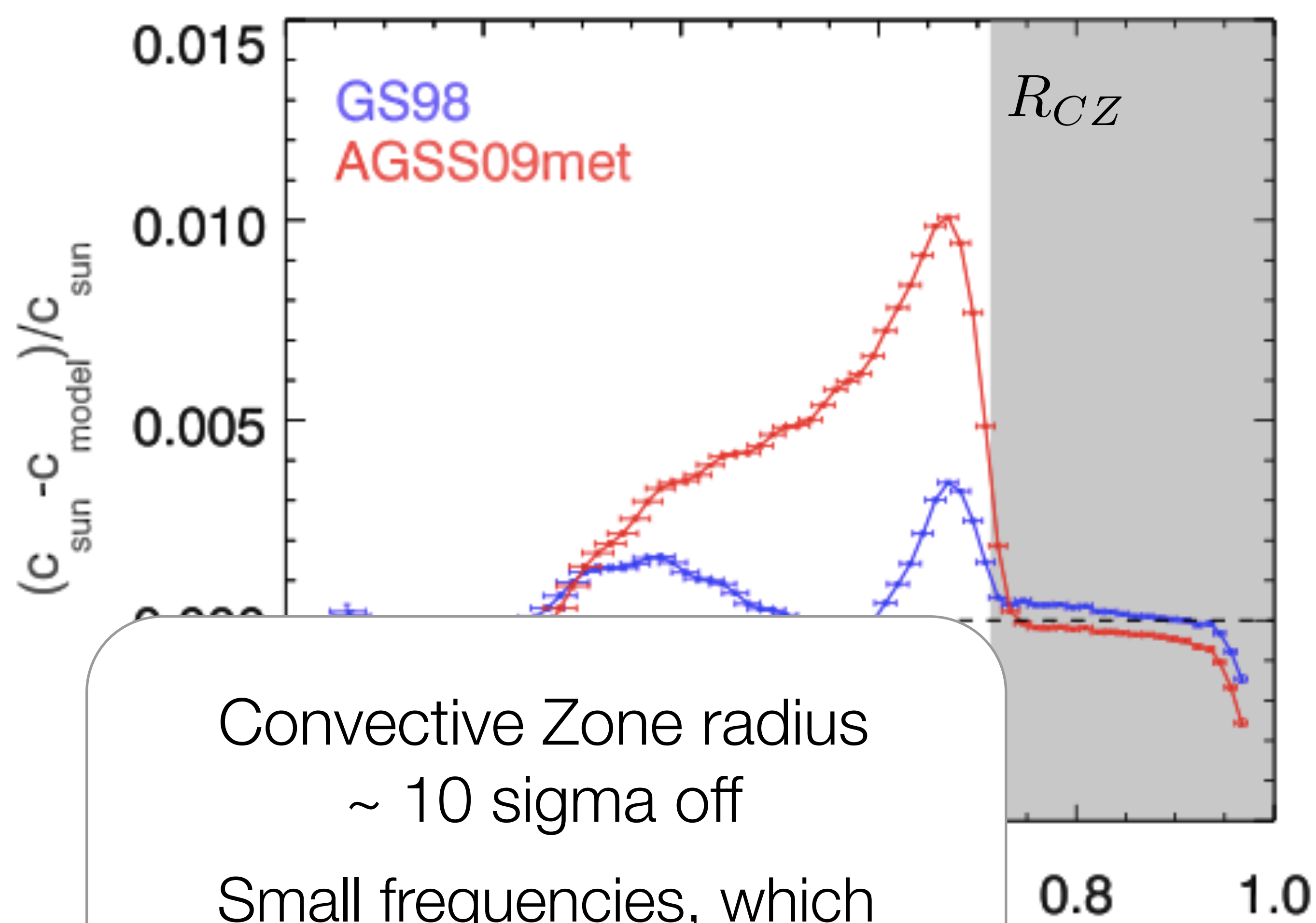
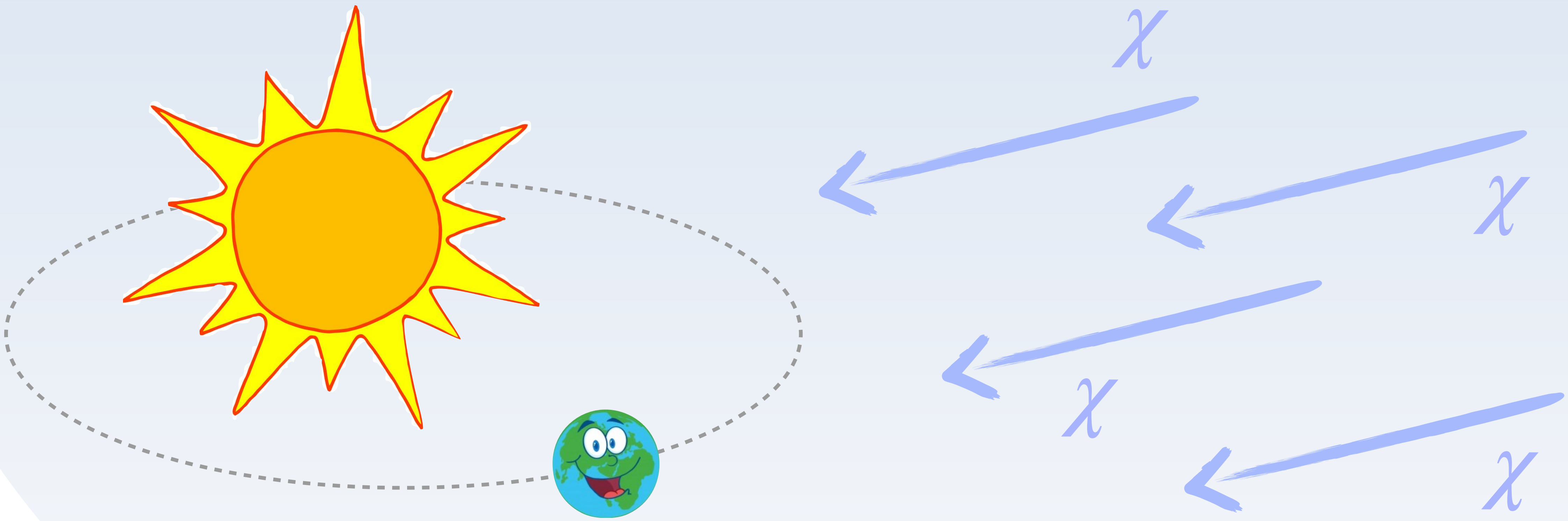


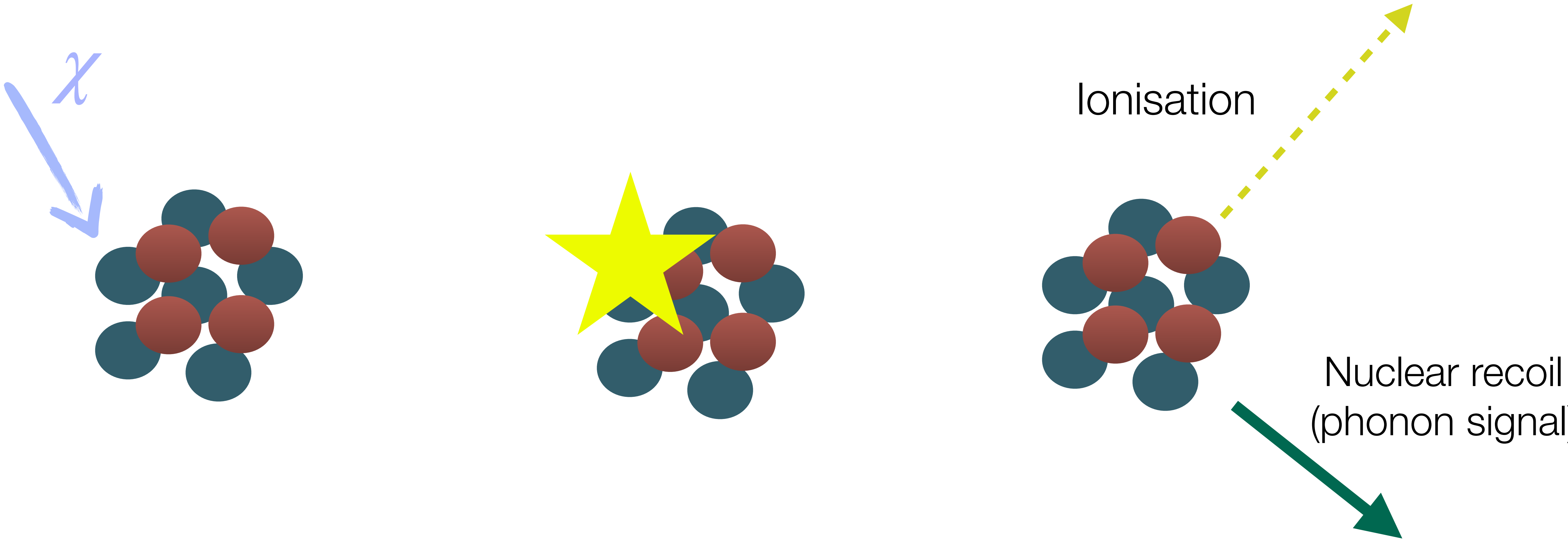
Convective Zone radius
~ 10 sigma off

Small frequencies, which probe the core, as much as 5 sigma

Direct detection



Direct detection



Seek to measure the interaction of “ambient” DM with quarks:

$$R = \int_{E_T}^{\infty} dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^{\infty} v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

Dark matter: Beyond $\boldsymbol{\sigma}_{\mathrm{SI}}$ and $\boldsymbol{\sigma}_{\mathrm{SD}}$

Until recently, people have focused on two constant cases:

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

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

However, in general

$$\sigma = \sigma(s, t, u)$$

Non-relativistic observables:

$$\left.\begin{array}{l} v_{\mathrm{rel}} \\ q = \sqrt{2m_{\mathrm{target}}E_R} \simeq m_{\mathrm{target}}\Delta v_{\mathrm{target}} \end{array}\right\} \text{small!}$$

Dark matter: Beyond σ_{SI} and σ_{SD}

Dipole coupling

Anapole coupling

Multiple massive mediators

p-wave

d-wave

Massive mediator

other effective operators

…

Dark matter: Beyond $\boldsymbol{\sigma}_{\mathrm{SI}}$ and $\boldsymbol{\sigma}_{\mathrm{SD}}$

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…

$\sigma(q, v_{\mathrm{rel}})$

Dark matter: Beyond $\boldsymbol{\sigma}_{\mathrm{SI}}$ and $\boldsymbol{\sigma}_{\mathrm{SD}}$

Dipole coupling

Anapole coupling

Multiple massive mediators

p-wave

d-wave

Massive mediator

other effective operators

...

$\sigma(q, v_{\mathrm{rel}})$

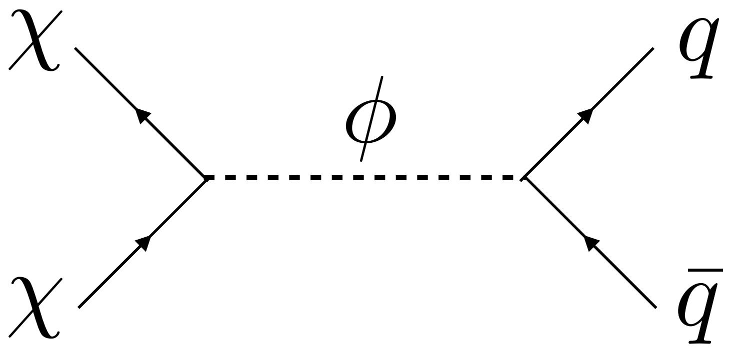
For concreteness, let's look at two forms:

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

where $n = \{-2, 2, 4\}$

Side-note: 3 popular approaches

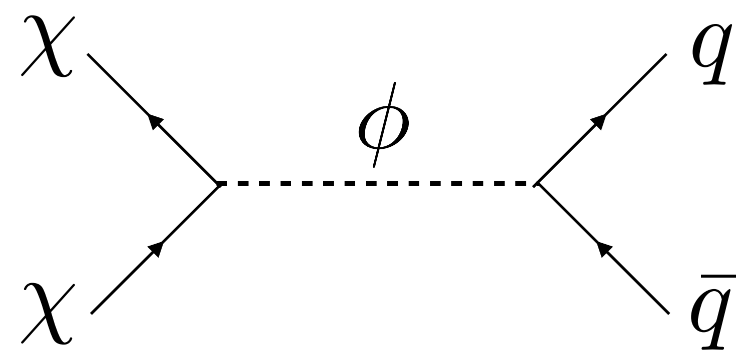
Simplified models



$, \cdots$

Side-note: 3 popular approaches

Simplified models



, ...

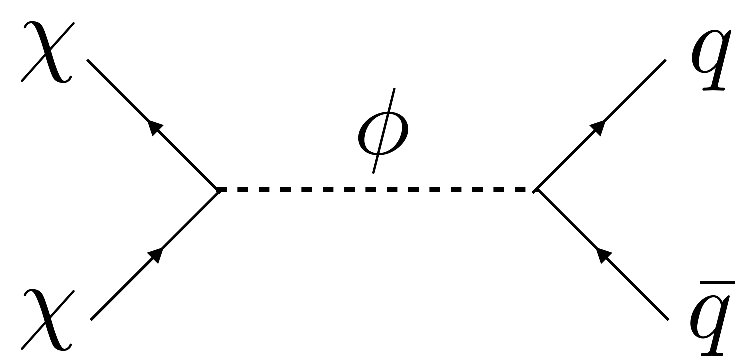
Effective operators (EFTs)

$$\chi\gamma^5\chi\bar{q}\gamma^5 q$$

, ...

Side-note: 3 popular approaches

Simplified models



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Effective operators (EFTs)

$$\chi\gamma^5\chi\bar{q}\gamma^5 q$$

, ...

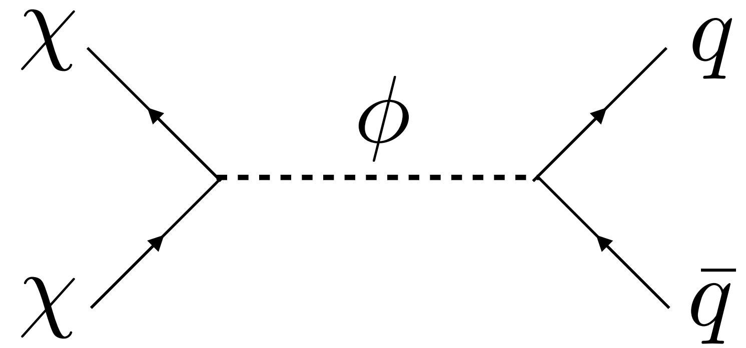
Effective cross sections

$$\sigma_{SD} = \sigma_0 \left(\frac{q}{q_0}\right)^4$$

, ...

Side-note: 3 popular approaches

Simplified models



, …

Effective operators (EFTs)

$$\chi\gamma^5\chi\bar{q}\gamma^5 q$$

, …

Effective cross sections

$$\sigma_{SD} = \sigma_0 \left(\frac{q}{q_0}\right)^4$$

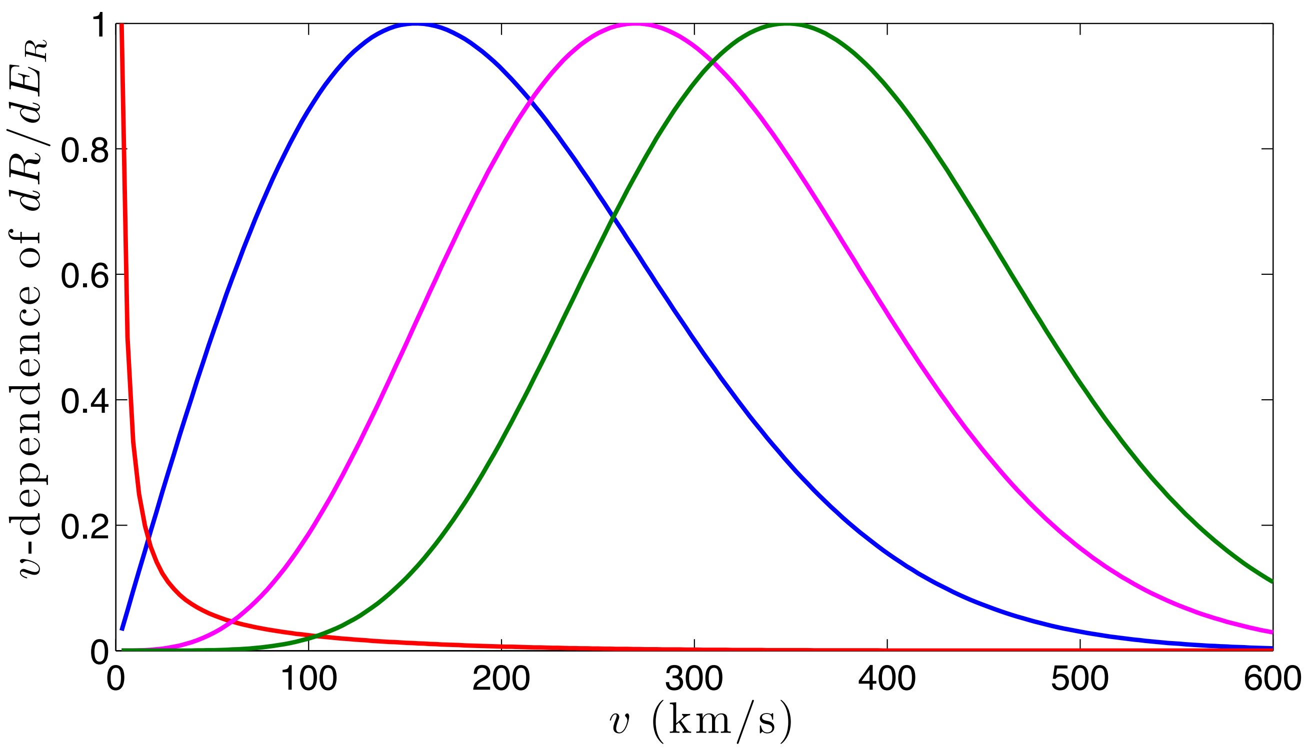
, …

Velocity and momentum-dependent DM

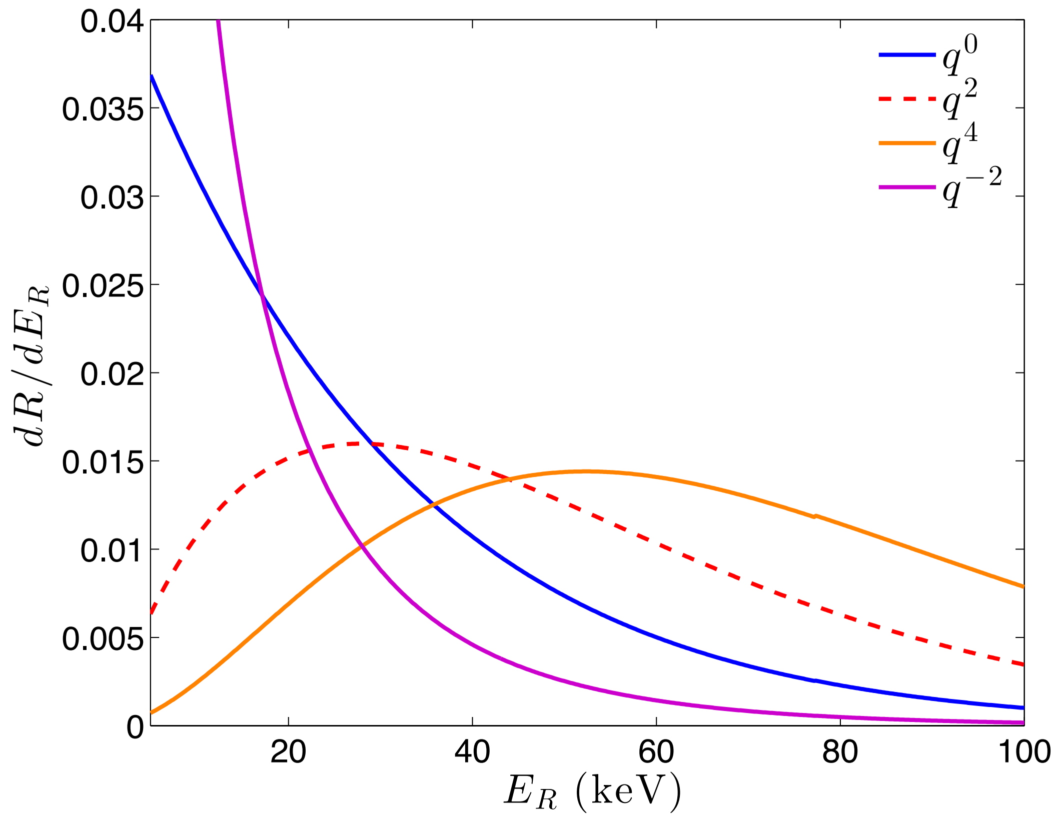
Probing different parts of the DM velocity distribution with a given experiment:

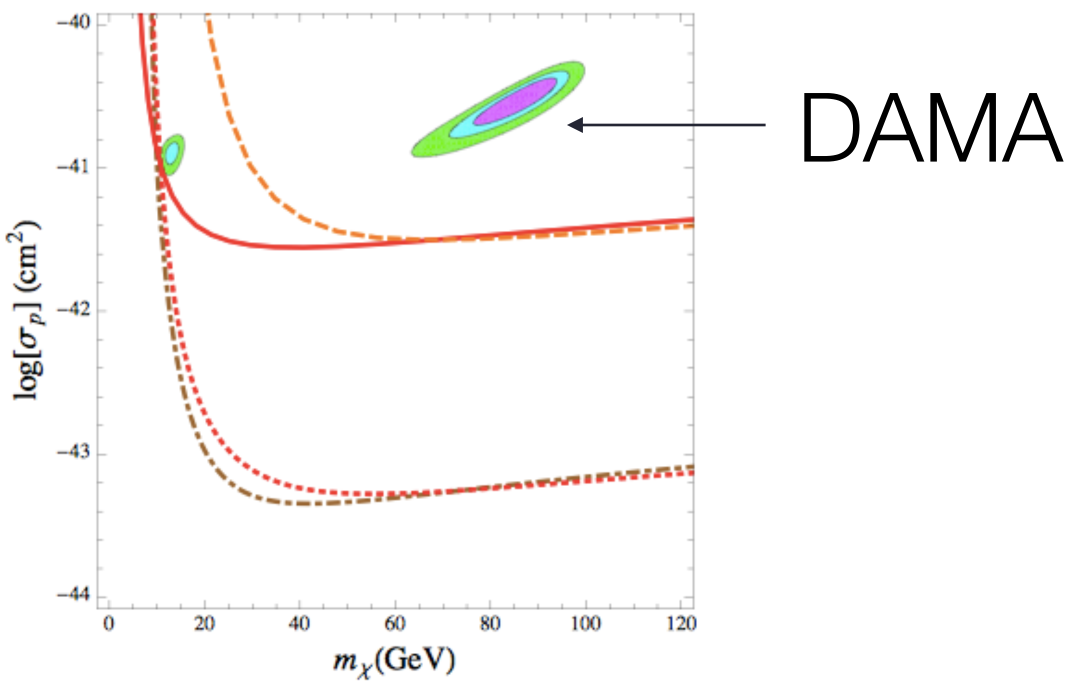
$\sigma \propto$

v_{rel}^{-2} $const.$ v_{rel}^{2} v_{rel}^{4}

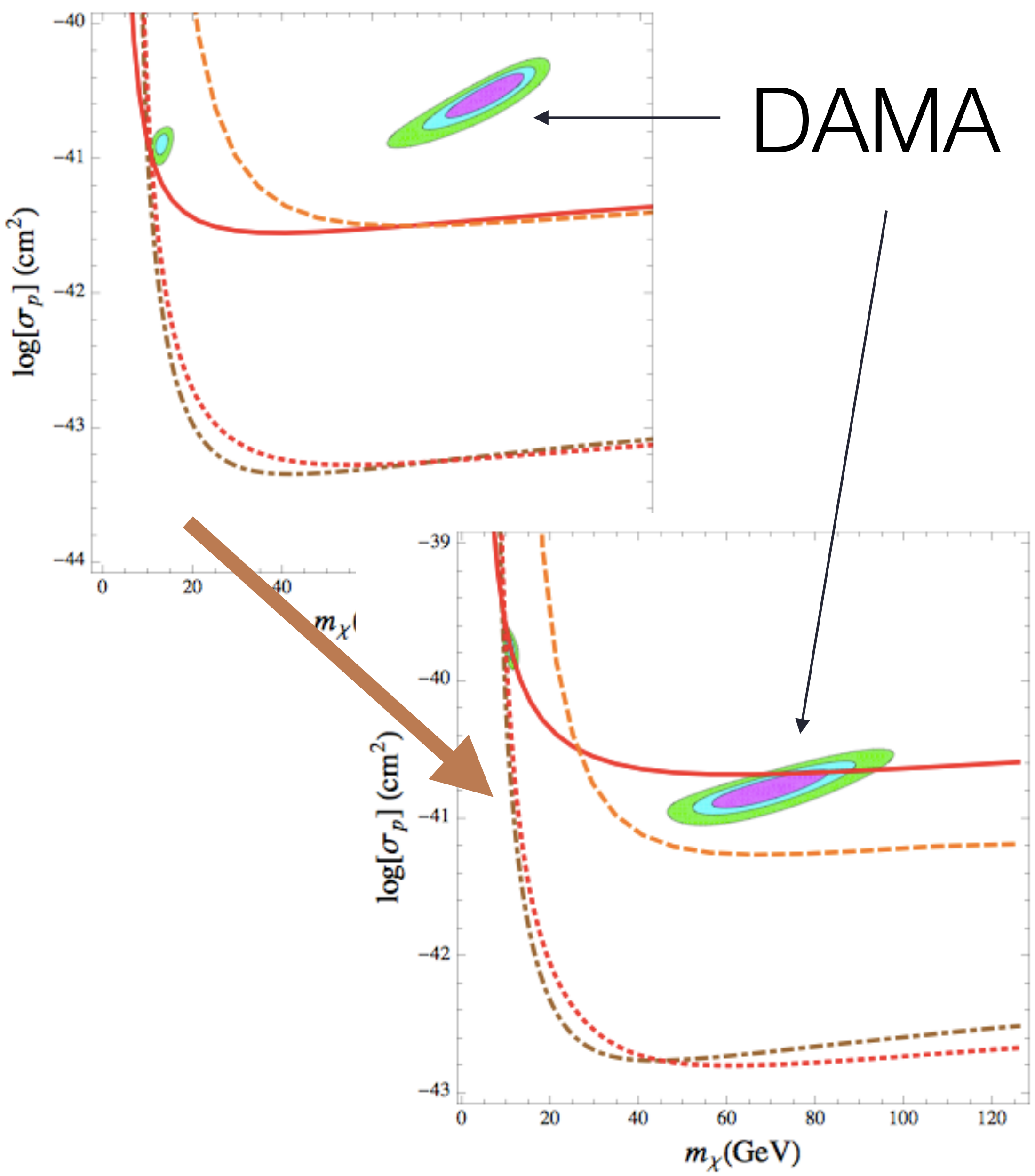


Different recoil spectra, mass dependence





(Chang, Pierce, Weiner 2009)



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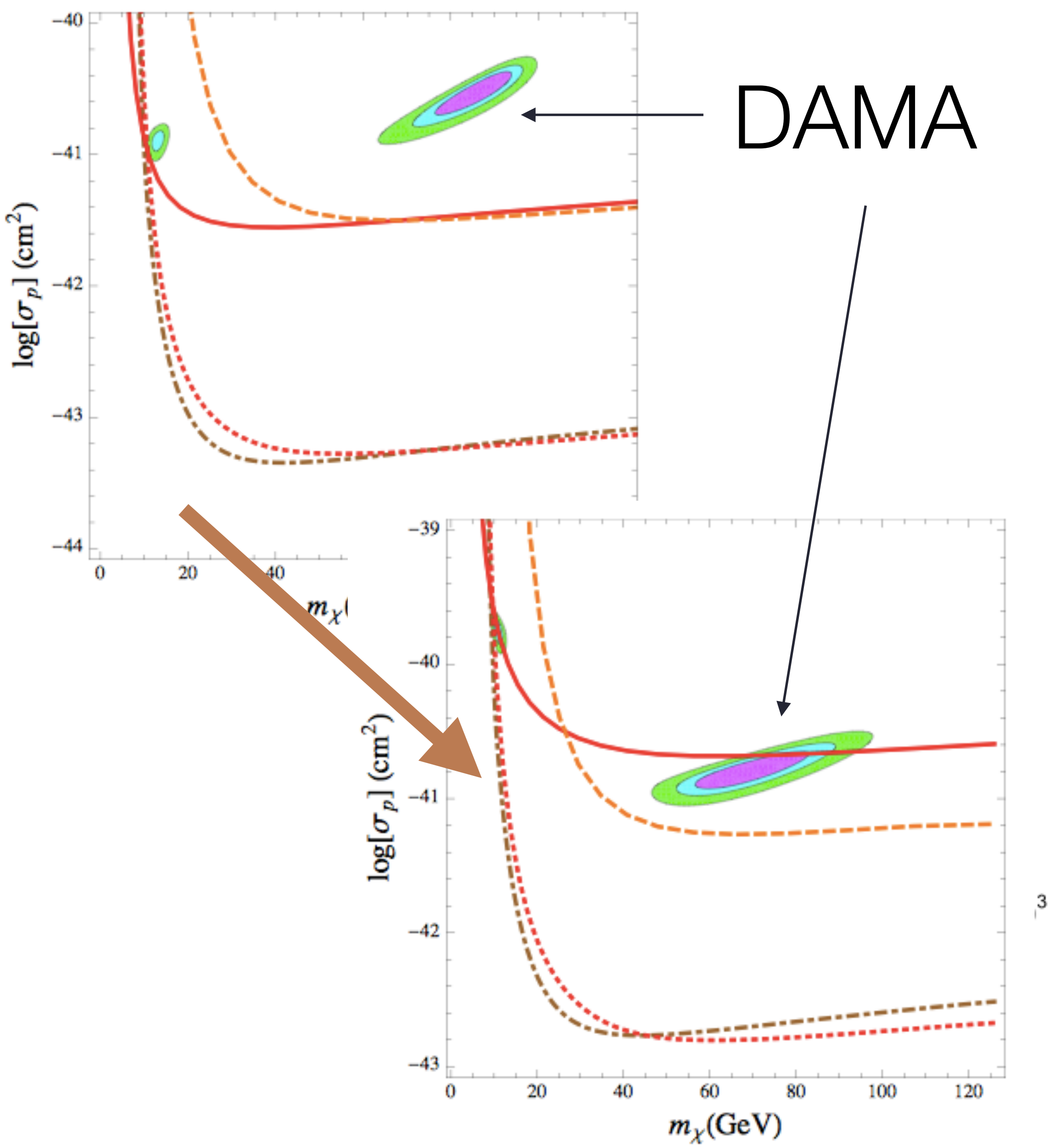

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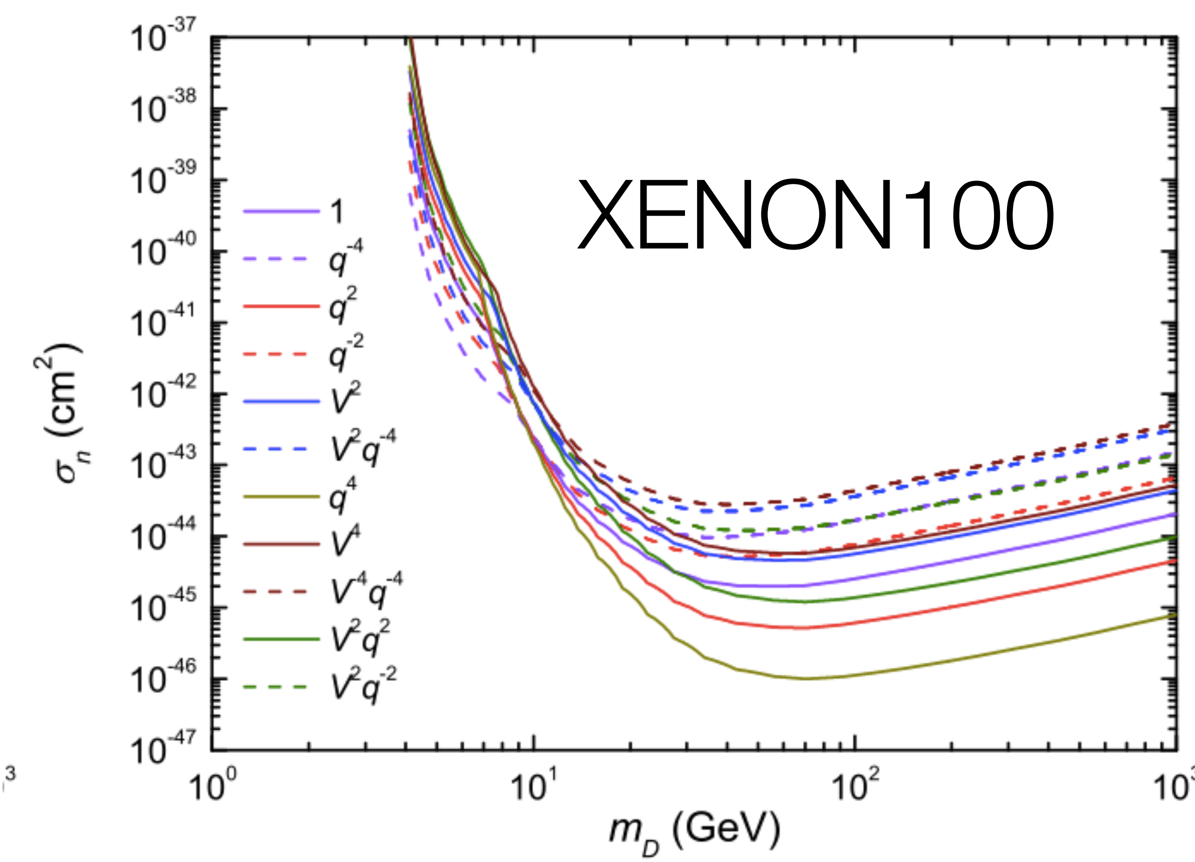
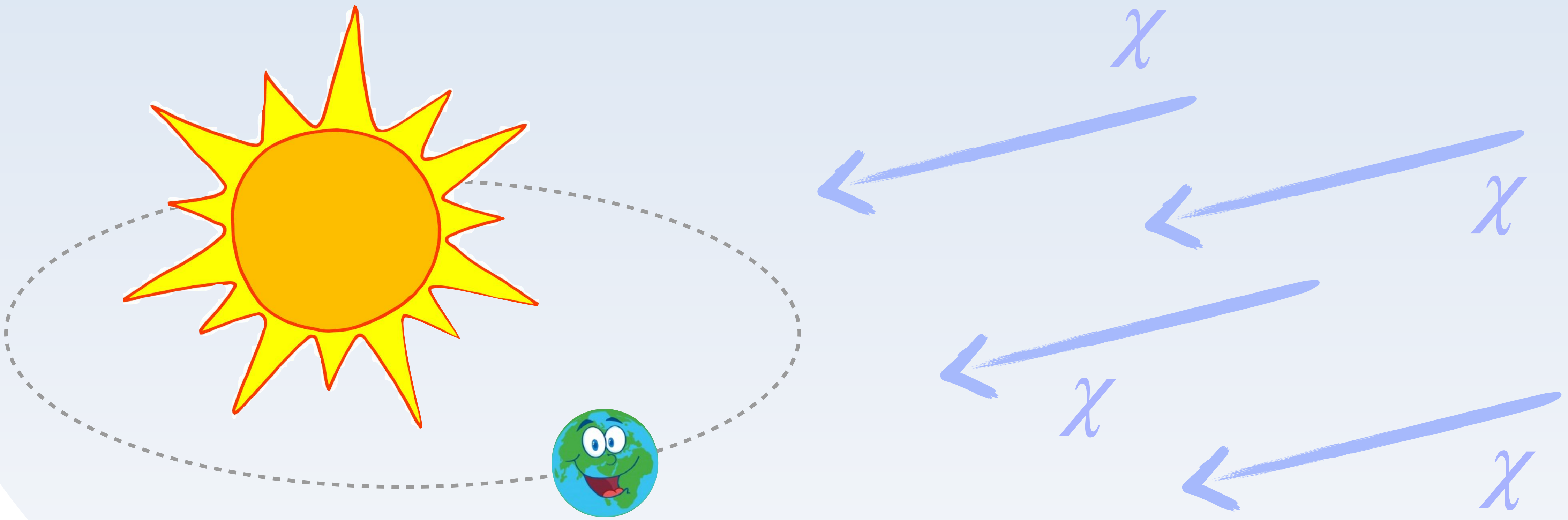


(Guo, Liang, Wu 2014)

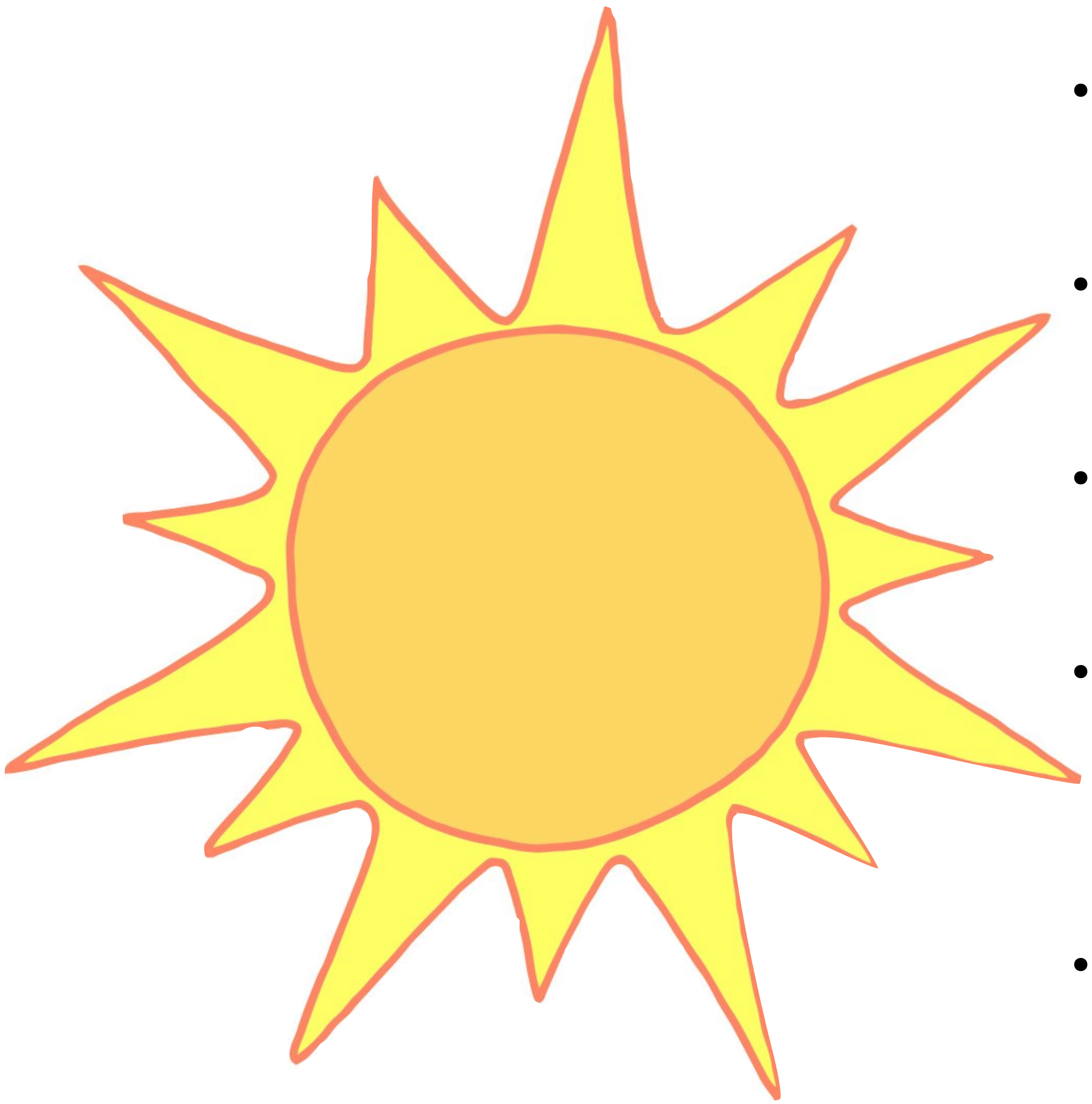
Dark Matter in the Sun

Direct detection



Probing the scattering cross-section between DM and quarks

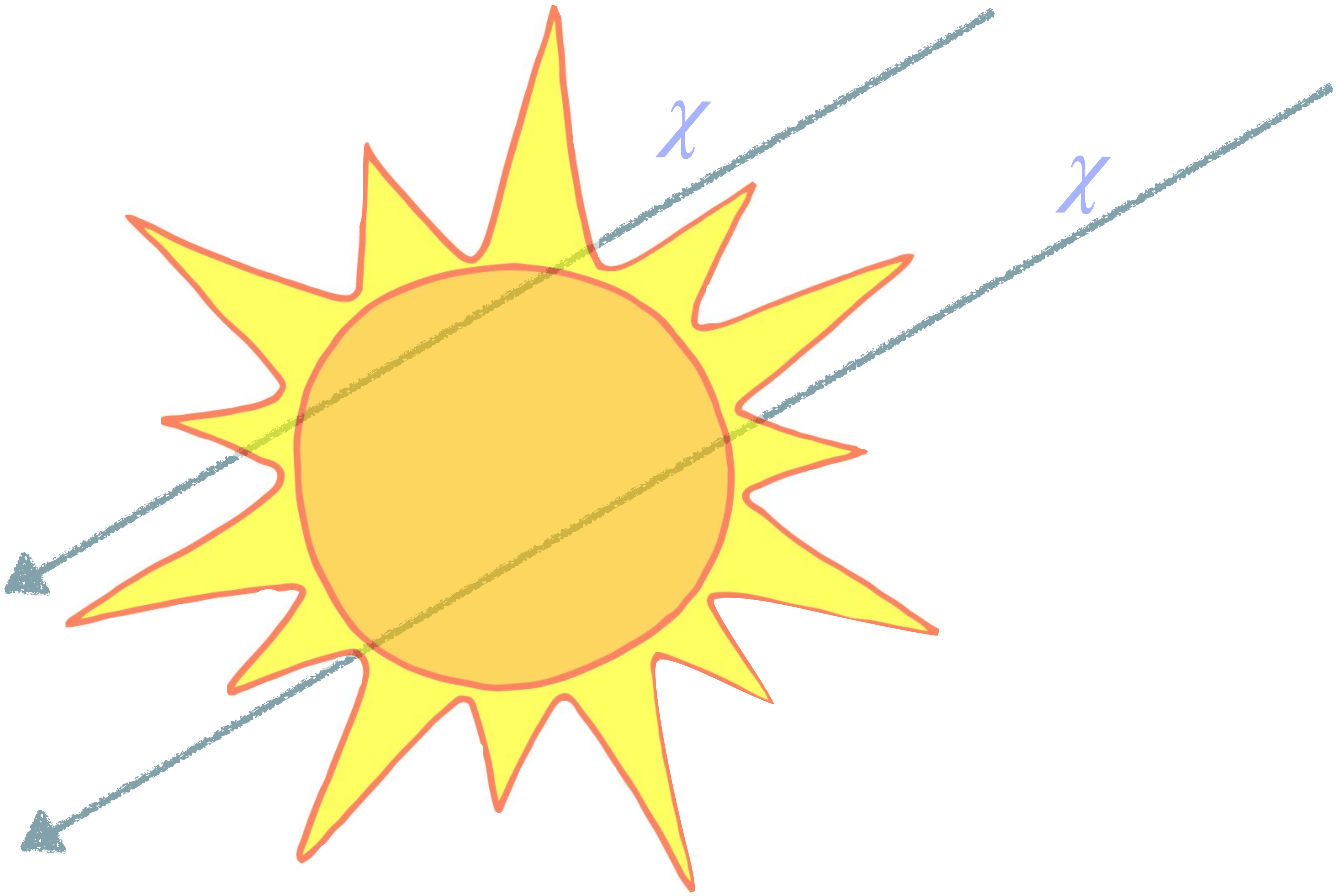
The sun is a direct detection experiment



- M = 2 x 10^{30} kg
- 73% Hydrogen
- 25% Helium
- 2% Heavier elements
  (important since $\sigma_{\chi N} \propto A^2$)
- T = 4.57 Gyr

10^{37} ton-year exposure (c.f. LZ: 5 ton-year)

The sun is a direct detection experiment



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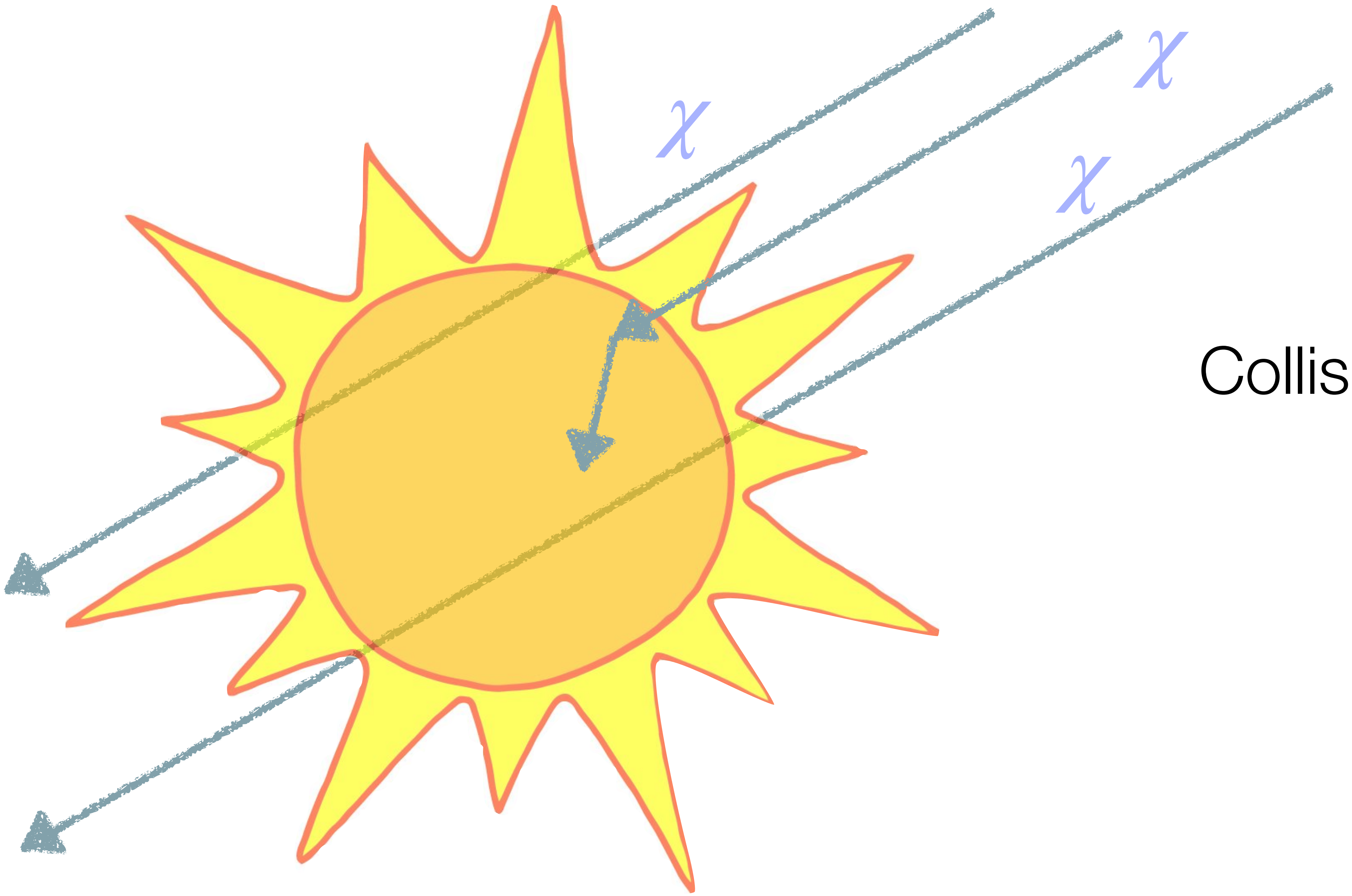
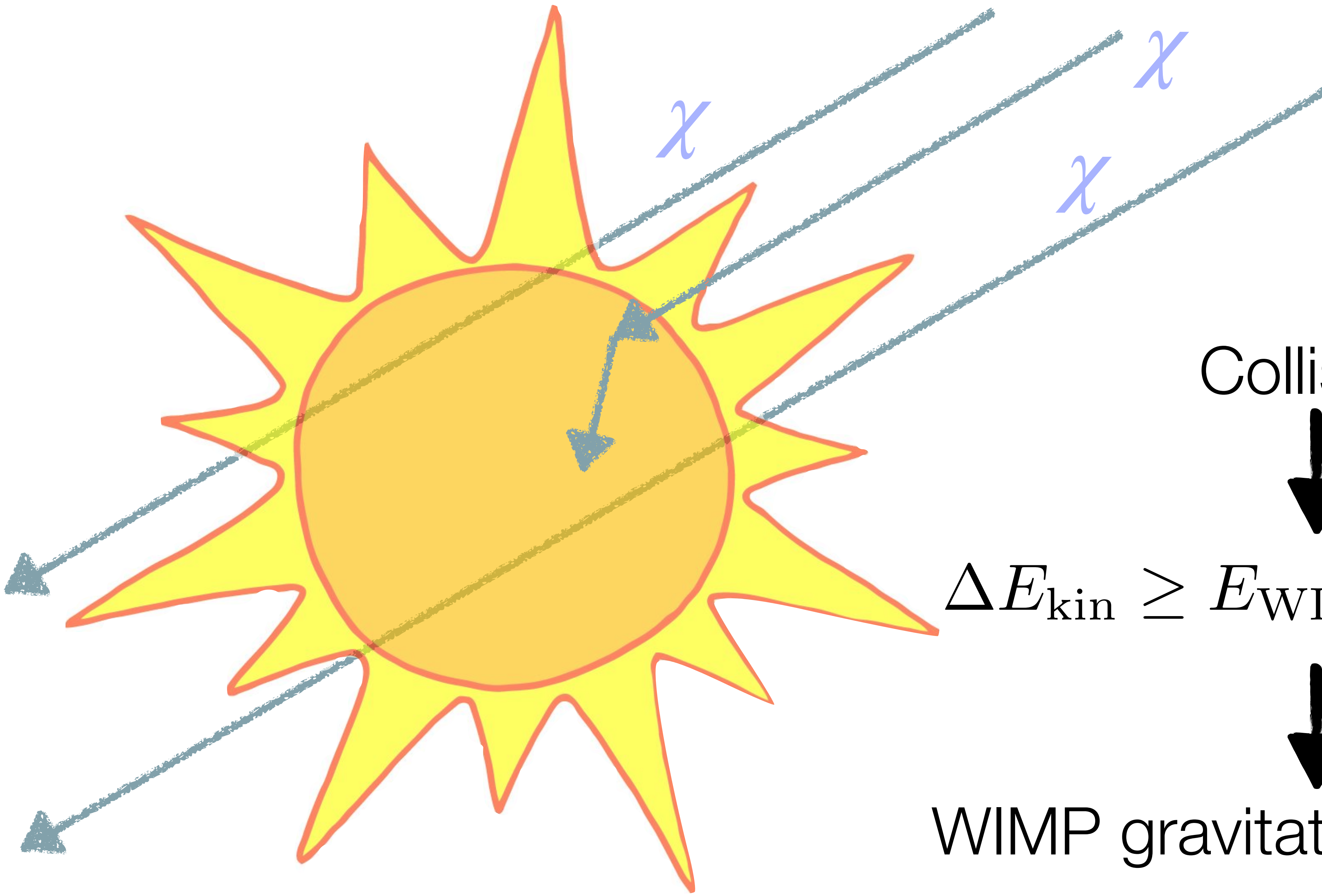


Collision

The sun is a direct detection experiment

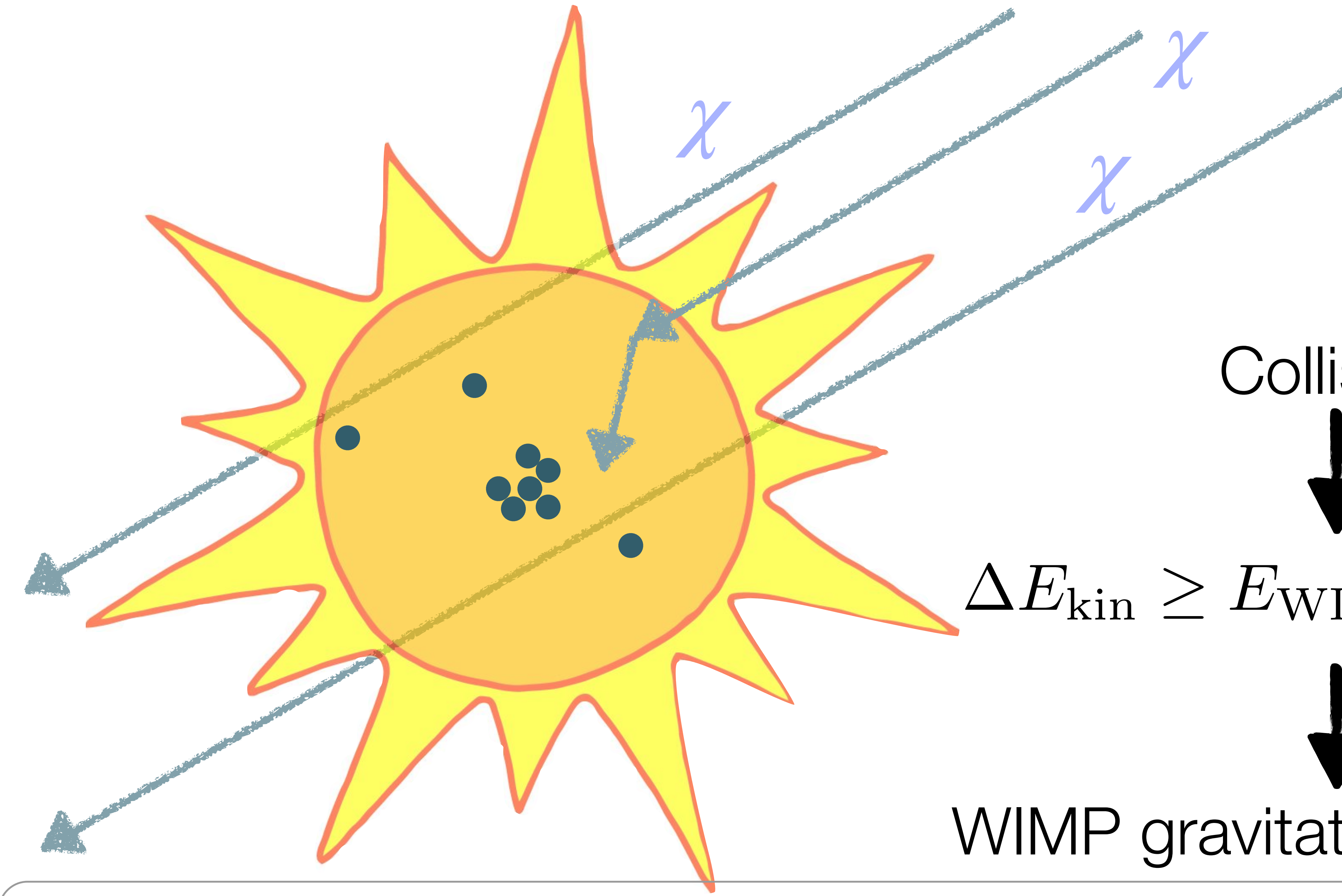


Collision

$$\Delta E_{\mathrm{kin}} \geq E_{\mathrm{WIMP}} - E_{\mathrm{escape}}$$

WIMP gravitationally bound

The sun is a direct detection experiment



Collision

↓

$$\Delta E_{\rm kin} \geq E_{\rm WIMP} - E_{\rm escape}$$

↓

WIMP gravitationally bound

Population: $$\frac{dN_\chi}{dt} = C(t) - 2A(t) - E(t)$$

Capture rate

$$C(t) = 4\pi \int_0^{R_\star} r^2 \int_0^\infty \frac{f(u)}{u} w\Omega_v^-(w)\,\mathrm{d}u\,\mathrm{d}r,$$

$f(u)$	Halo DM velocity distribution
$w(r) = \sqrt{u^2 + v_{esc}^2(r,t)}$	Velocity at *r*, due to gravity
$\Omega(w) \propto w \sum_i n_i \int \vert F_i(E_R)\vert^2 \frac{d\sigma_i}{dE_R} dE_R$	Rate at which a WIMP of velocity *w* can scatter below v_{esc}

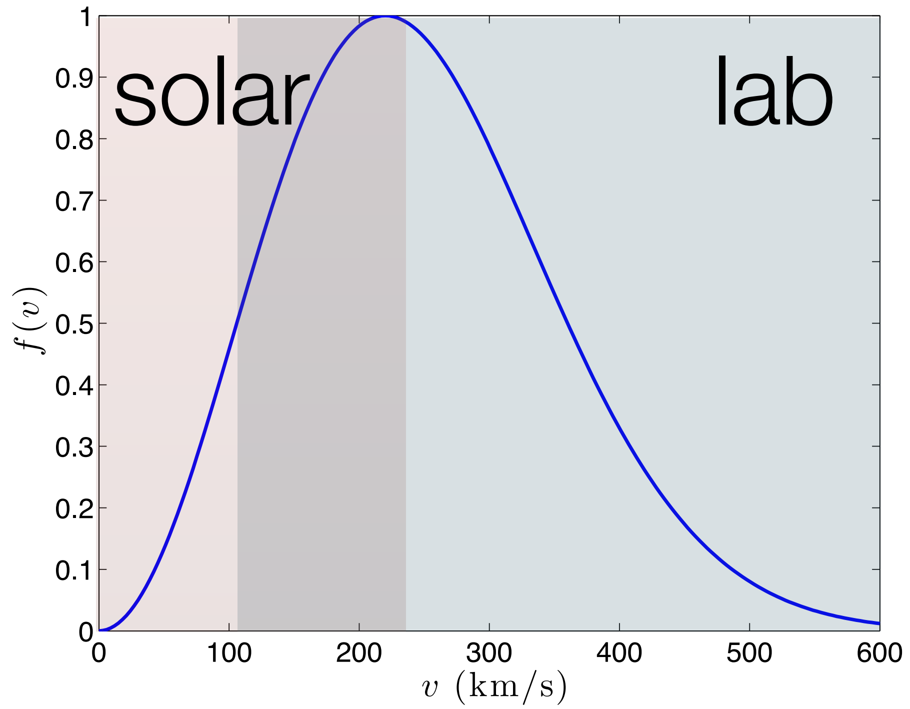
c.f. direct detection:

$$R = \int_{E_T}^\infty dE_R \frac{\rho_0}{m_N\, m_\chi} \int_{v_{min}}^\infty v f(v) \frac{d\sigma_{WN}}{dE_R}(v, E_R)\, dv$$

Differences with earth-based DD

Differences with earth-based DD

- Probing different parts of the halo velocity distribution
    - DD: above threshold
    - Solar: low part (v_{esc})



Differences with earth-based DD

- Probing different parts of the halo velocity distribution
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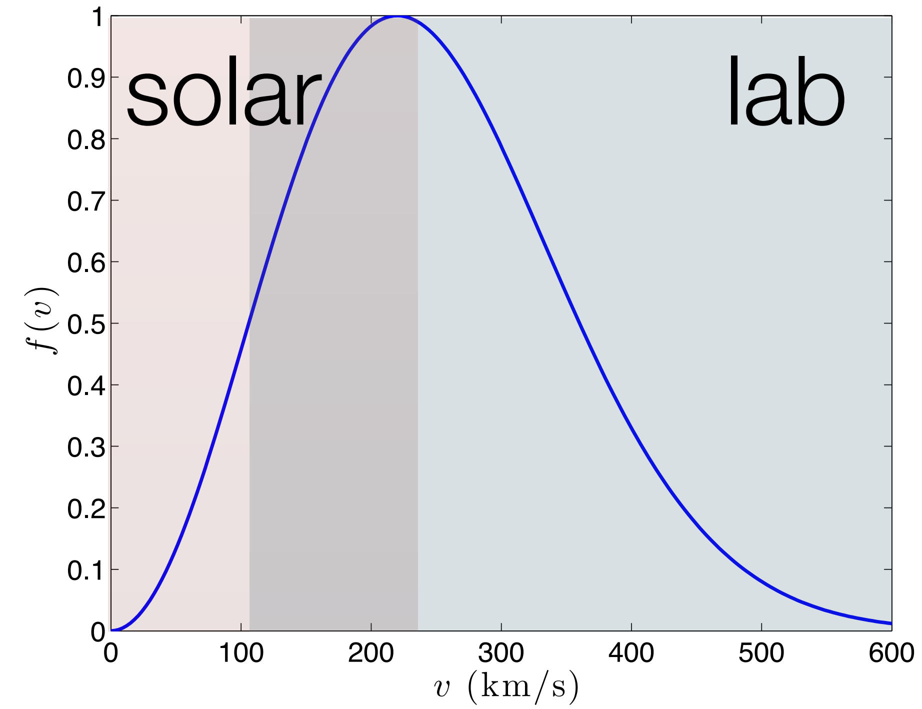
- Probing different kinematic range (scattering with lighter elements)



Differences with earth-based DD

- Probing different parts of the halo velocity distribution
    - DD: above threshold
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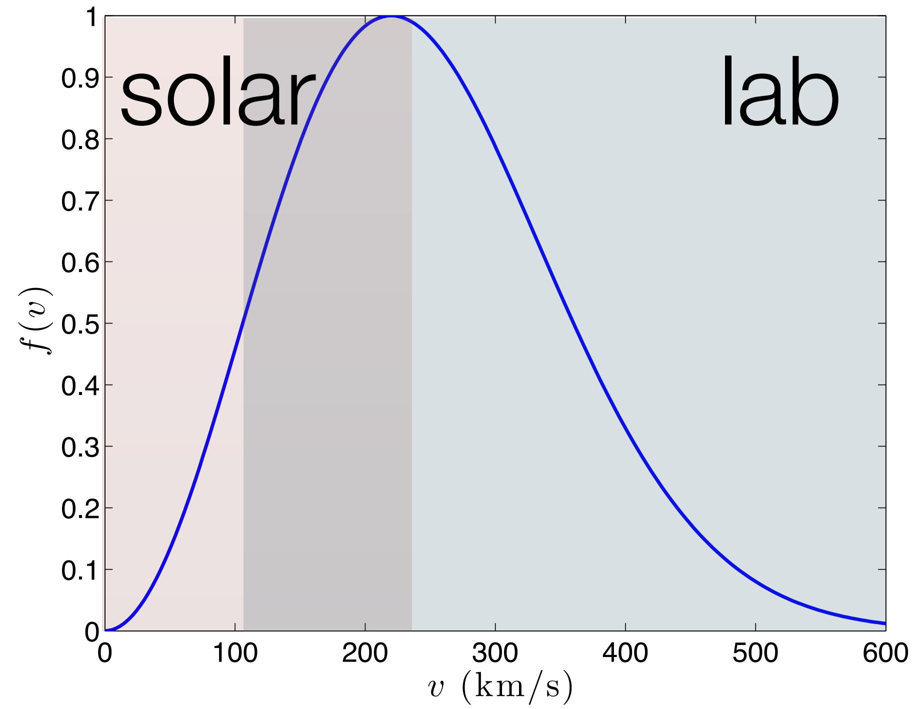
- Probing different kinematic range (scattering with lighter elements)
- Spin sensitivity

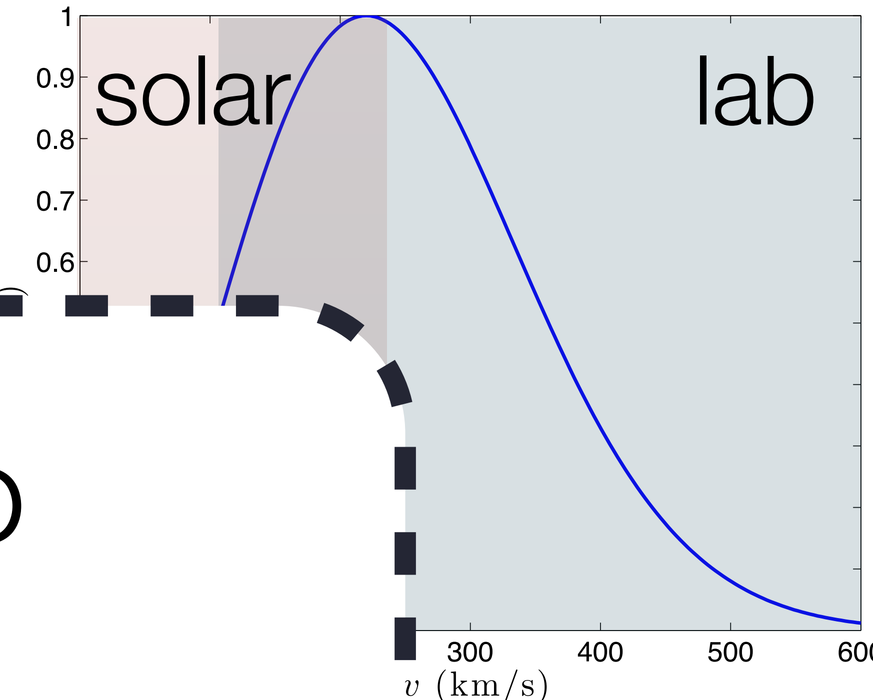


More sensitive to lighter DM

Different couplings?

Differences with earth-based DD

- Probing different parts of the halo velocity distribution
  - DD: ab
  - Solar: l
- Probing diff range (scatt elements)
- Spin sensitivity



Sensitive to

q $\quad v_{\mathrm{rel}}$

→ sitive to lighter DM

Different couplings?

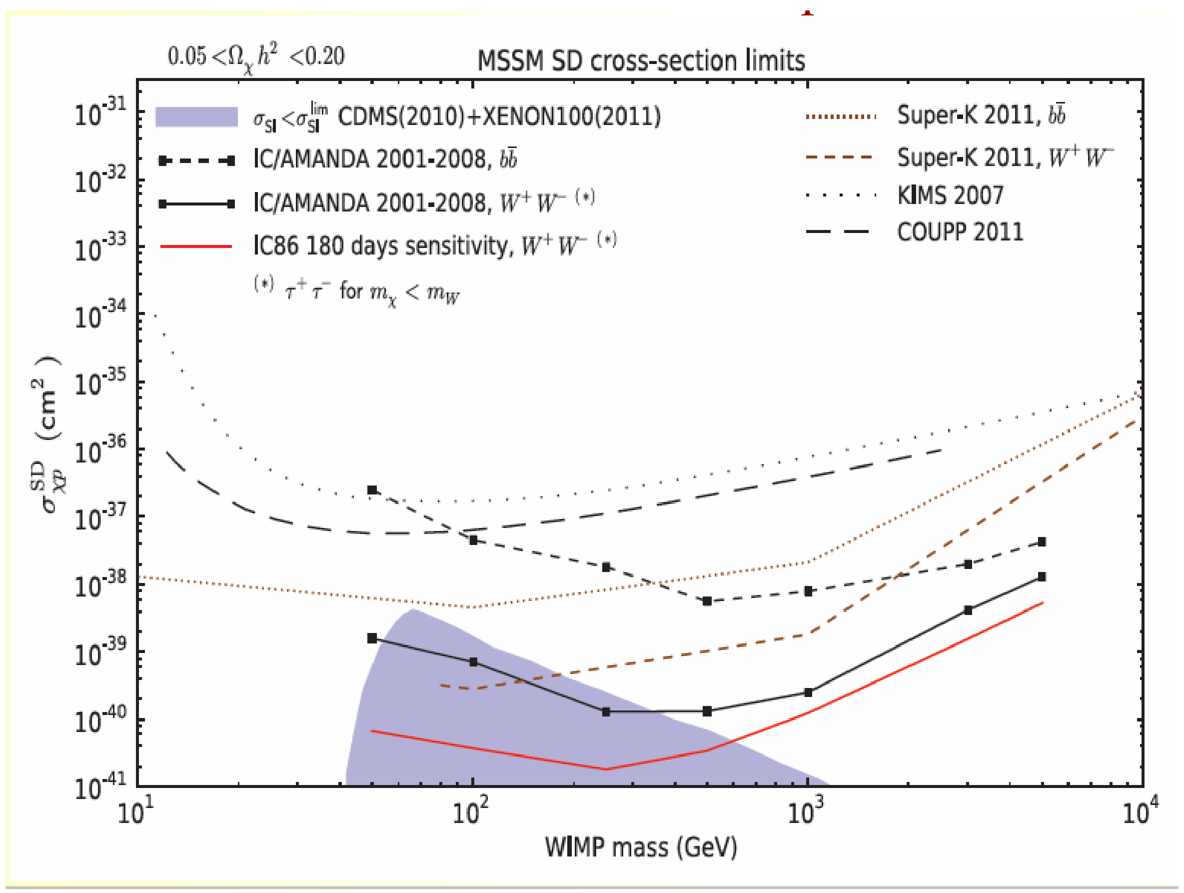
DM in the sun: observable effects

DM in the sun: observable effects

Annihilation

The most obvious observable effect is annihilation:

- DM-DM ⟶ neutrinos: direct observation



Very competitive

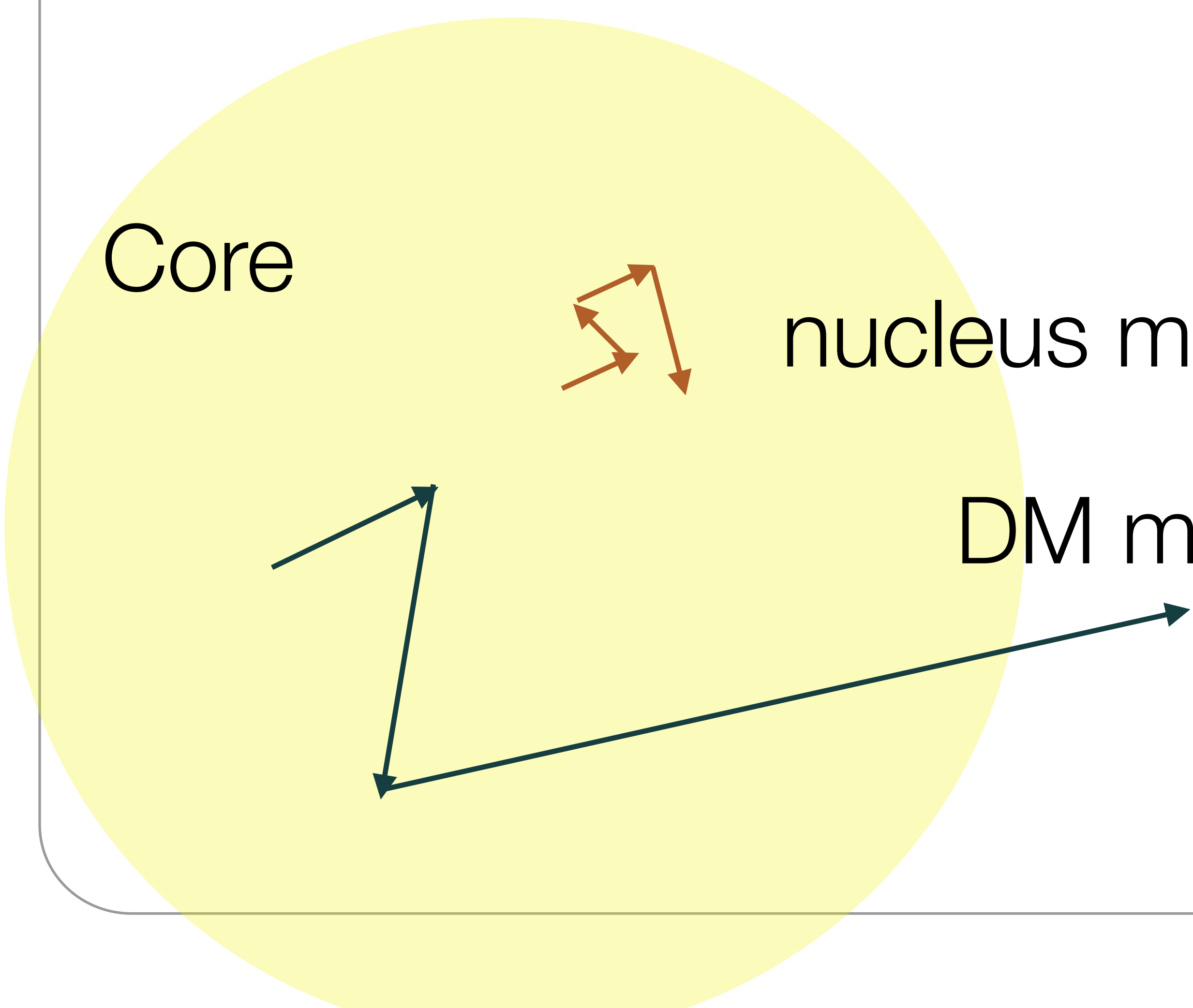
but

Model-dependent

DM in the sun: observable effects

Energy transport

If the self-annihilation is suppressed enough (e.g. in as in **asymmetric DM**), the “cloud” of DM accumulated in the solar core can transport kinetic energy outwards:



nucleus mean free path $\lambda_{\mathrm{nuc}} \ll r_{\mathrm{core}}$

DM mean free path $\lambda_\chi \gg \lambda_{\mathrm{nuc}}$

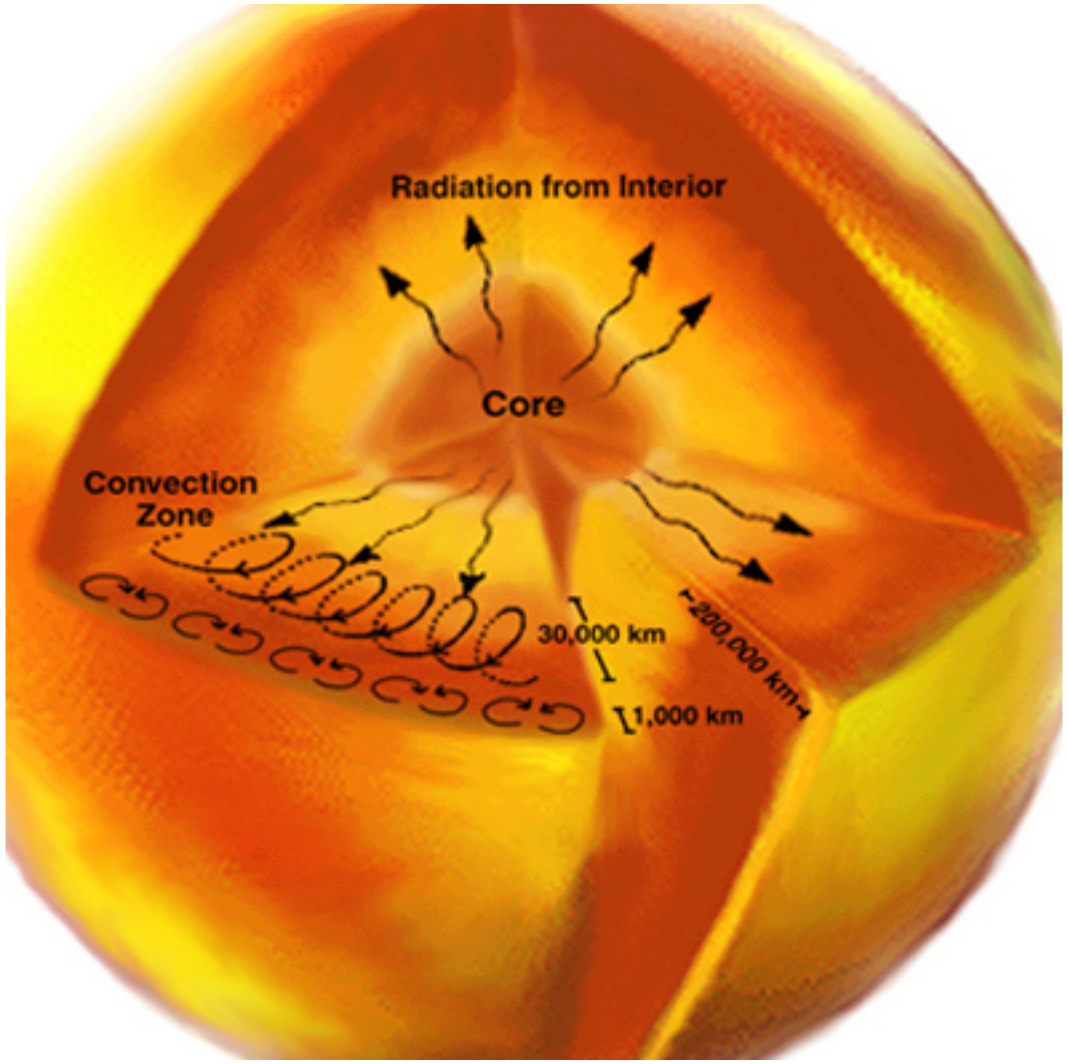
Wimps in the sun: observable effects

Energy transport

Heat transport away from the core — effects:

Change in temperature visible with ^{8}B **neutrinos**

$\phi_{\nu,{}^8\mathrm{B}} \propto T_c^{\beta}; \beta \sim 20 - 25\,!!$



Wimps in the sun: observable effects

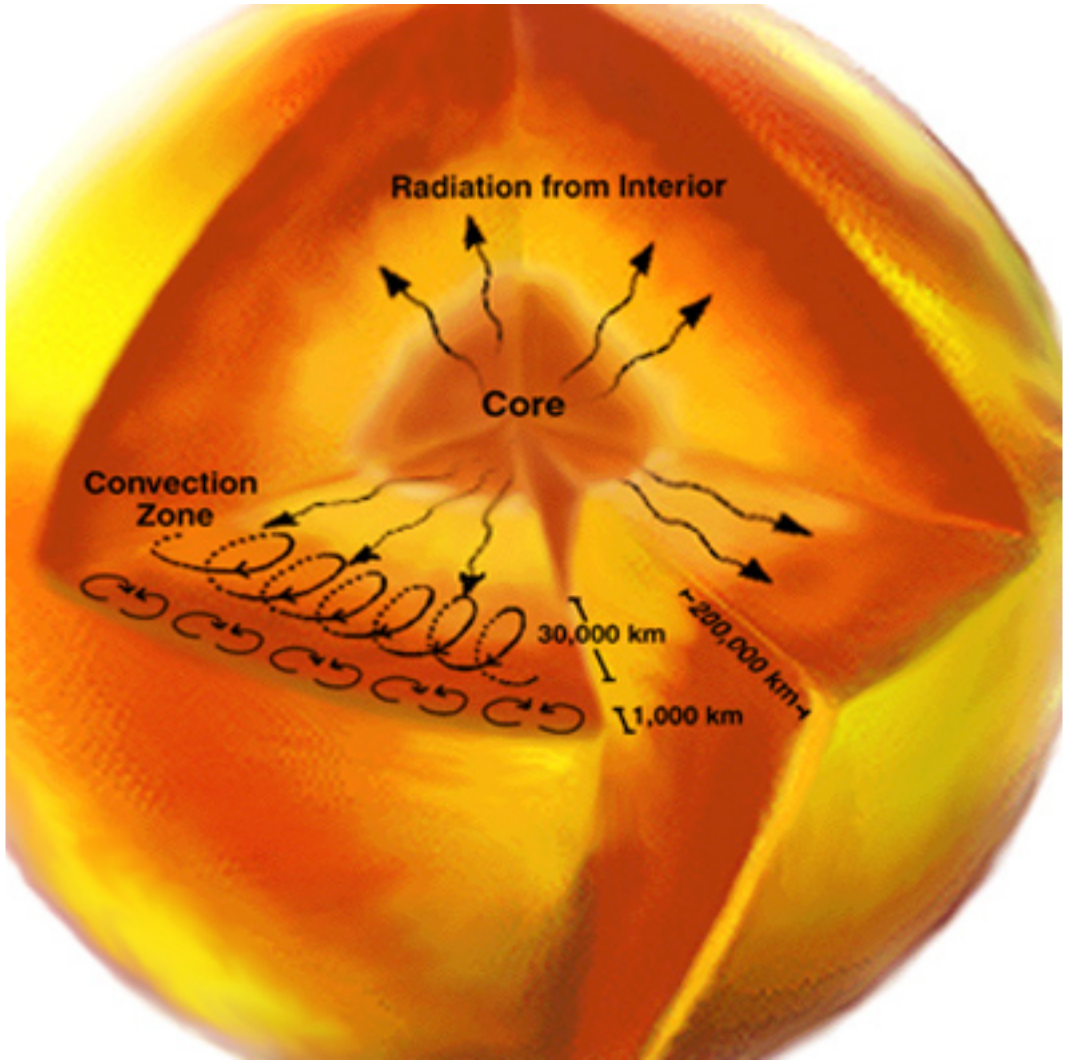
Energy transport

Heat transport away from the core — effects:

Change in temperature
visible with ^{8}B **neutrinos**

$$\phi_{\nu,^8\mathrm{B}} \propto T_c^{\beta};\beta \sim 20 - 25\,!!$$

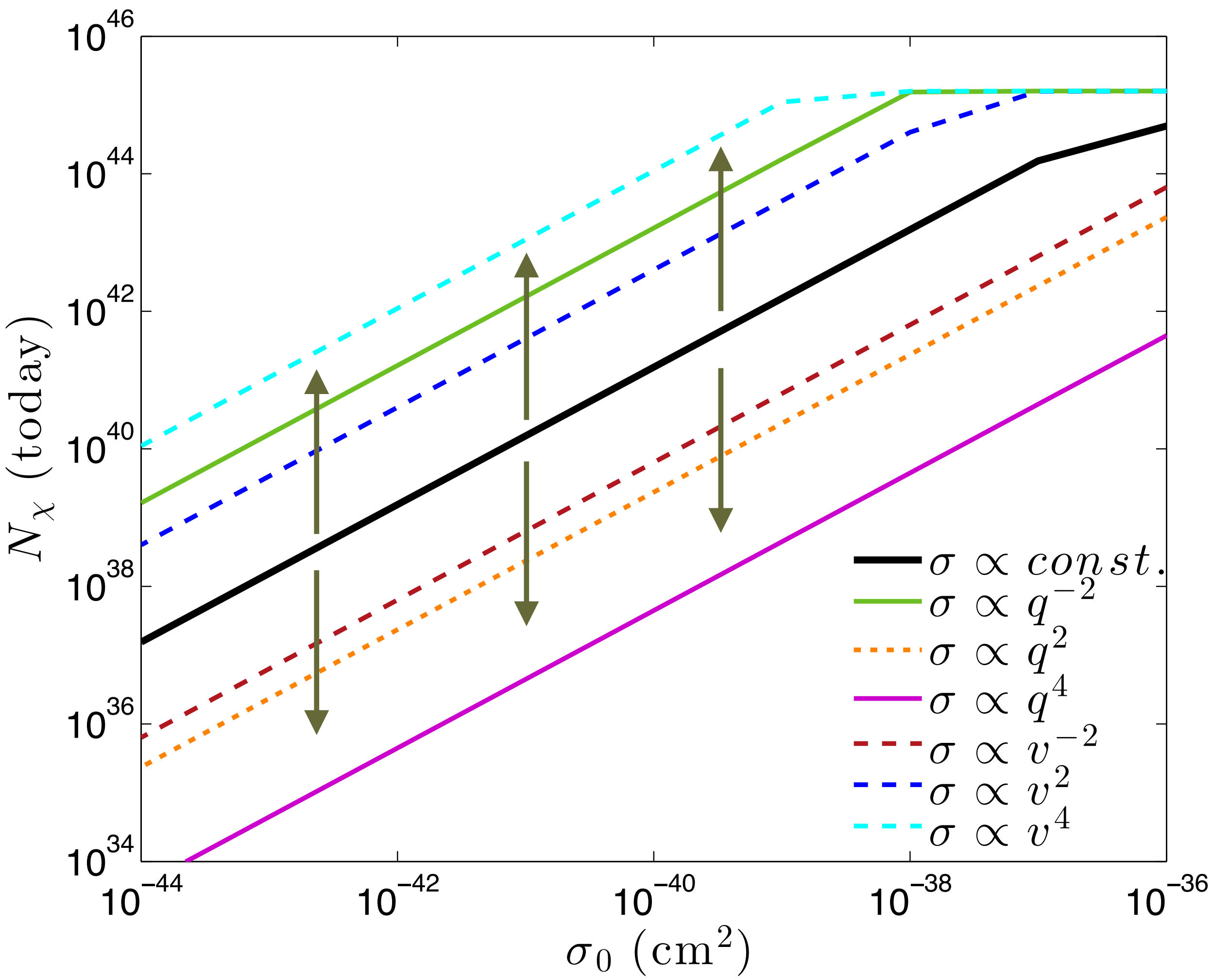
Change in structure
sound speed and height of the convective zone can be inferred from **helioseismology**



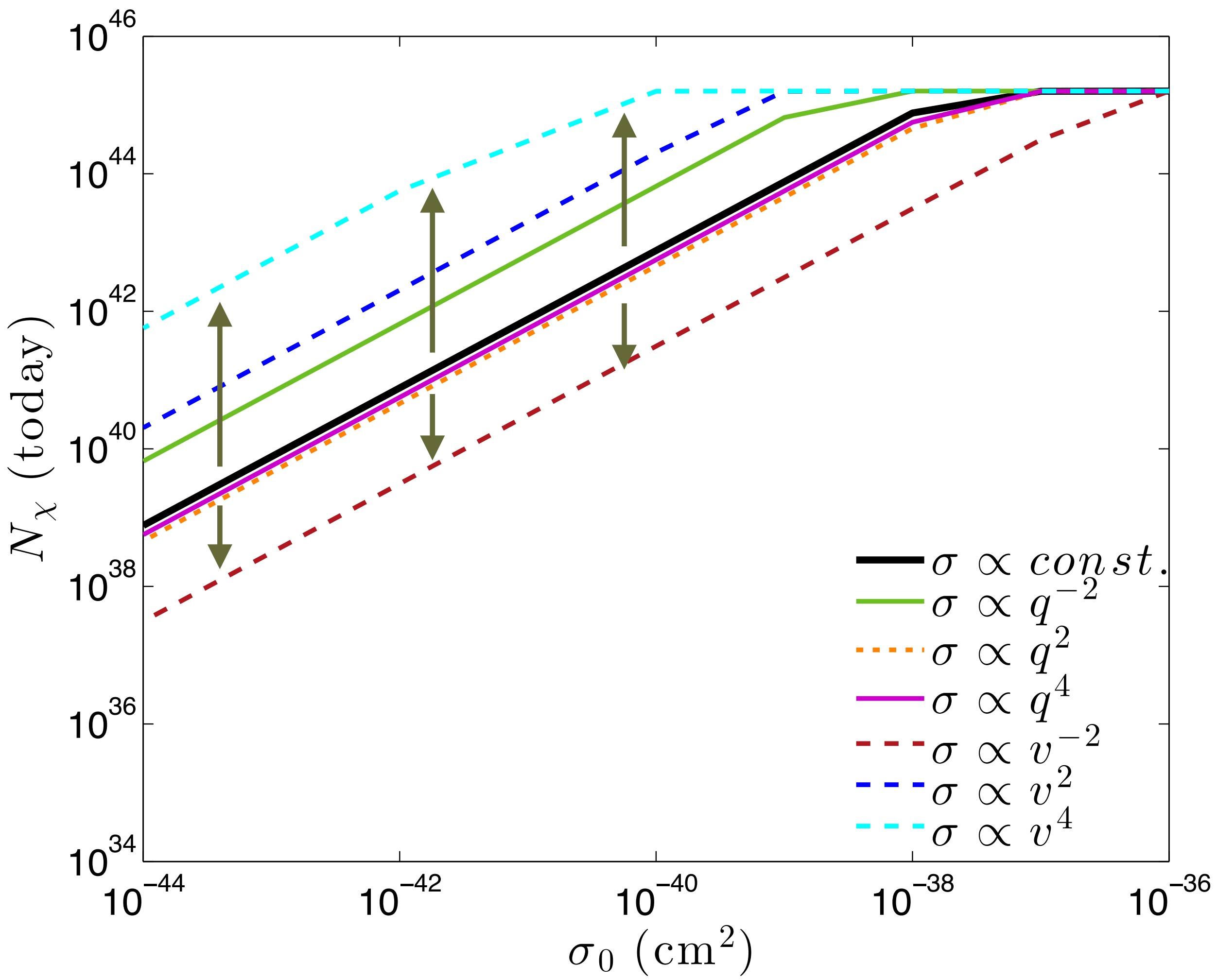
q and v-dependent DM in the Sun

Capture rates

Spin-dependent

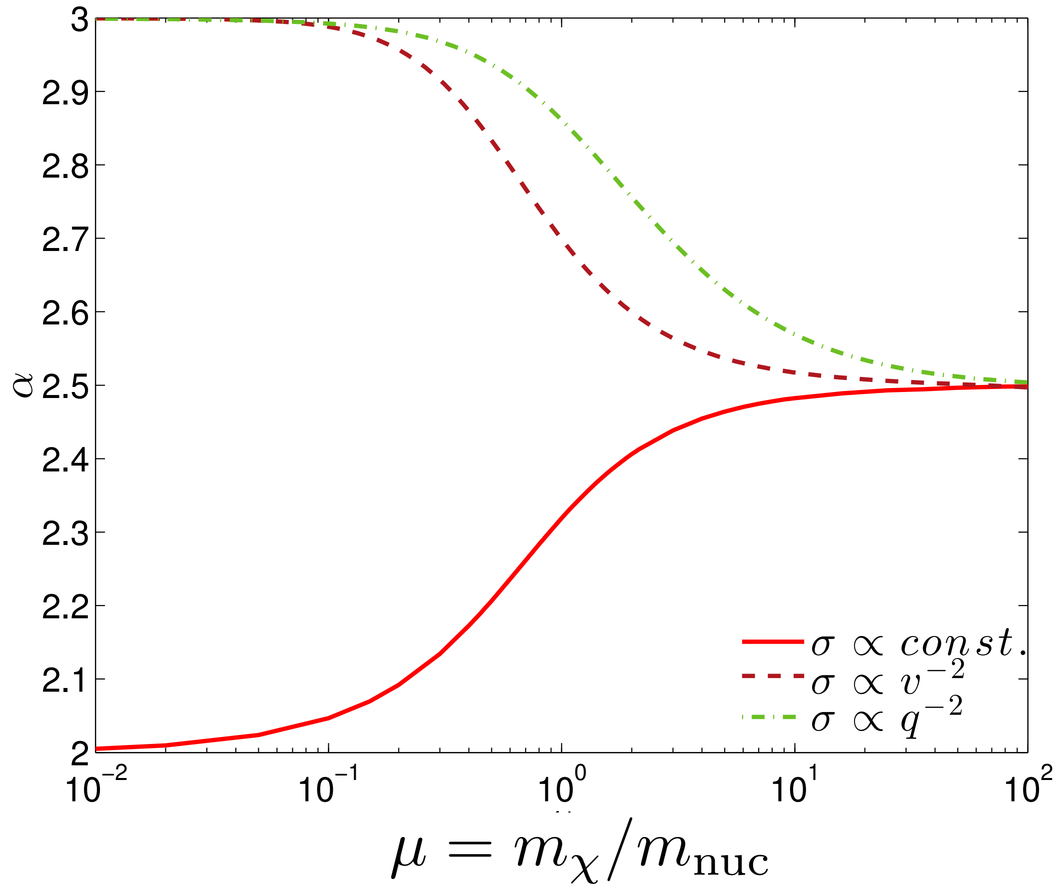


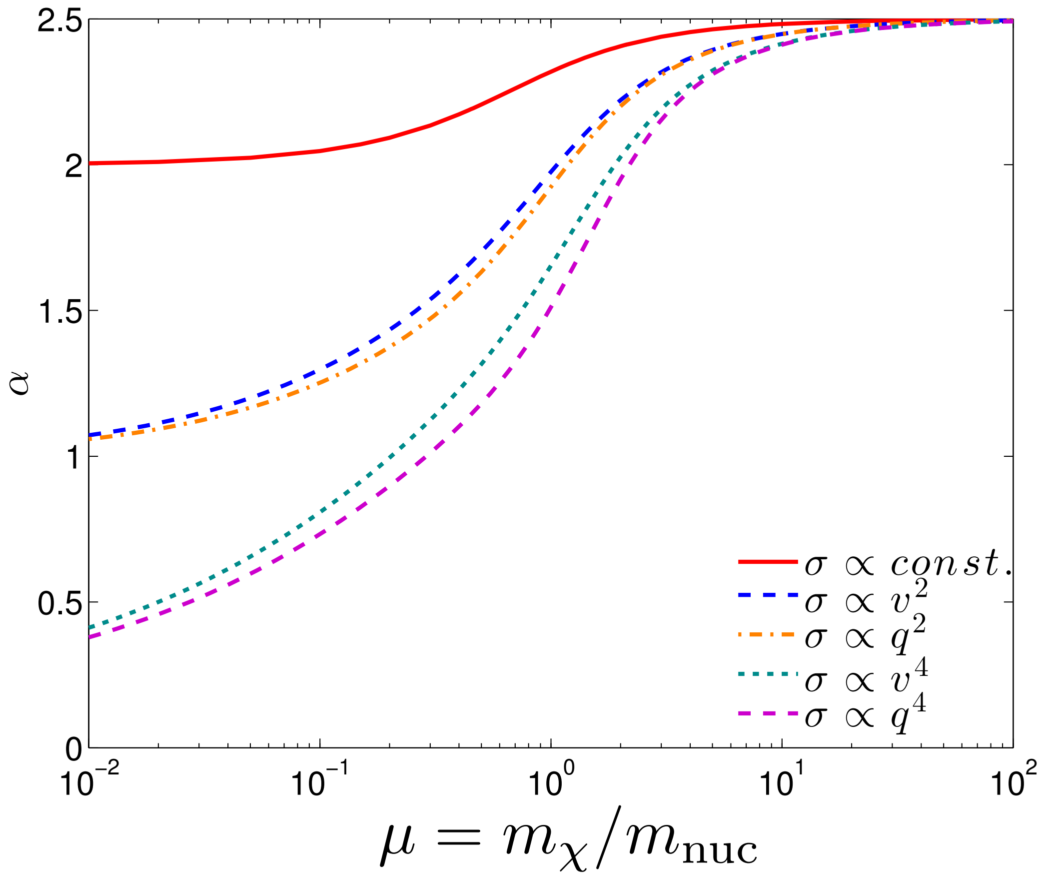
Spin-independent



Enhancement: v^{+n} or q^{-n}

Diffusion coefficient α

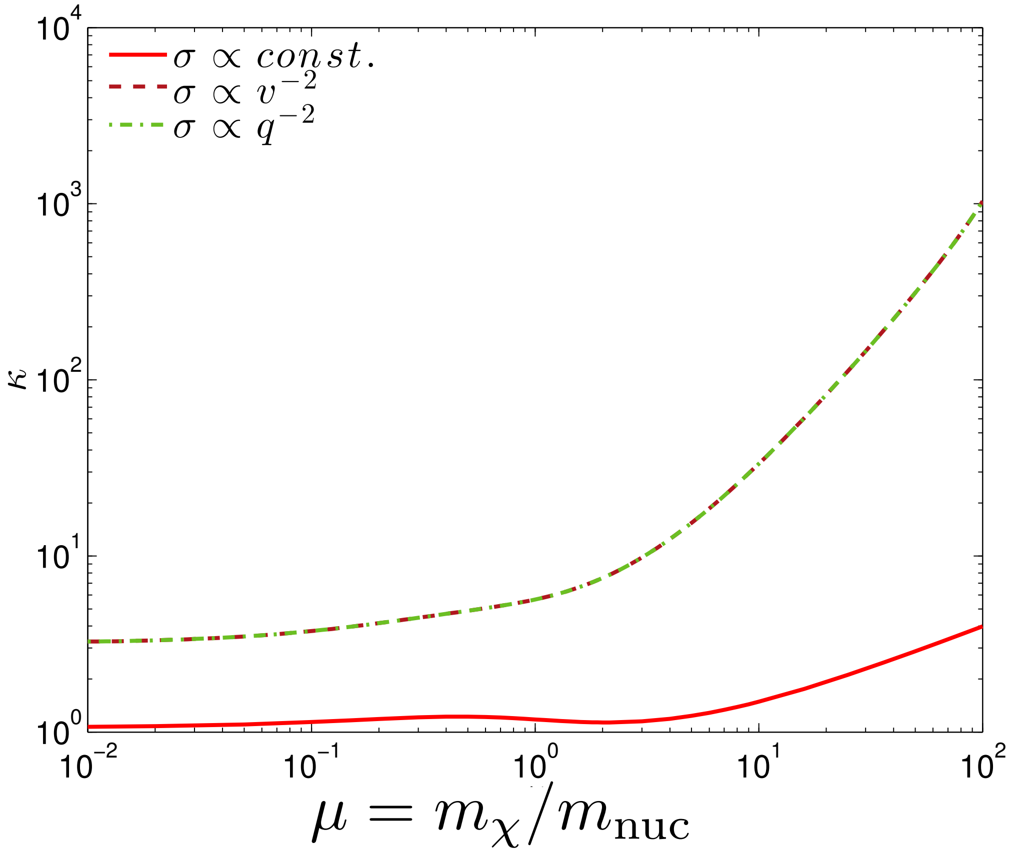


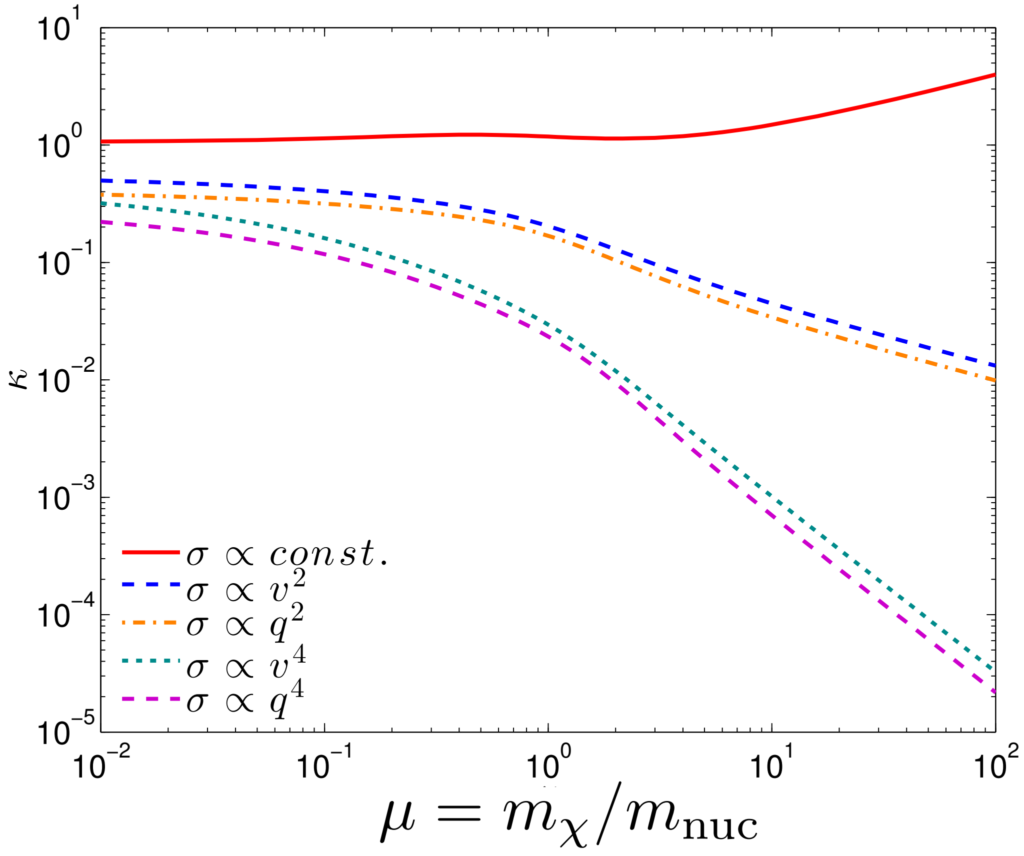


n < 1: "fluffier" dark matter core

n > 1: "tighter" dark matter core

Conduction coefficient κ





n < 1: more efficient energy transport

n > 1:less efficient energy transport

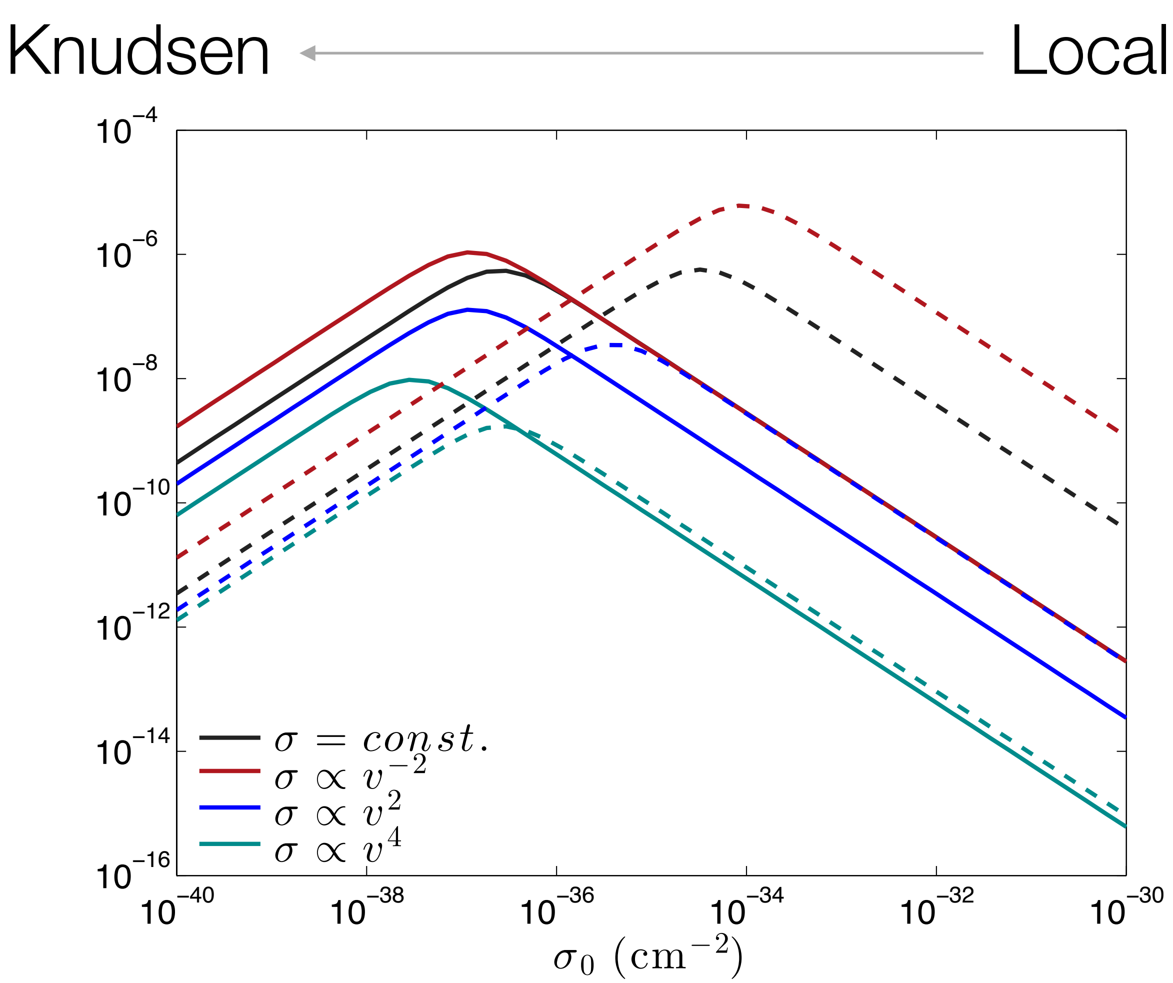
Heat transport

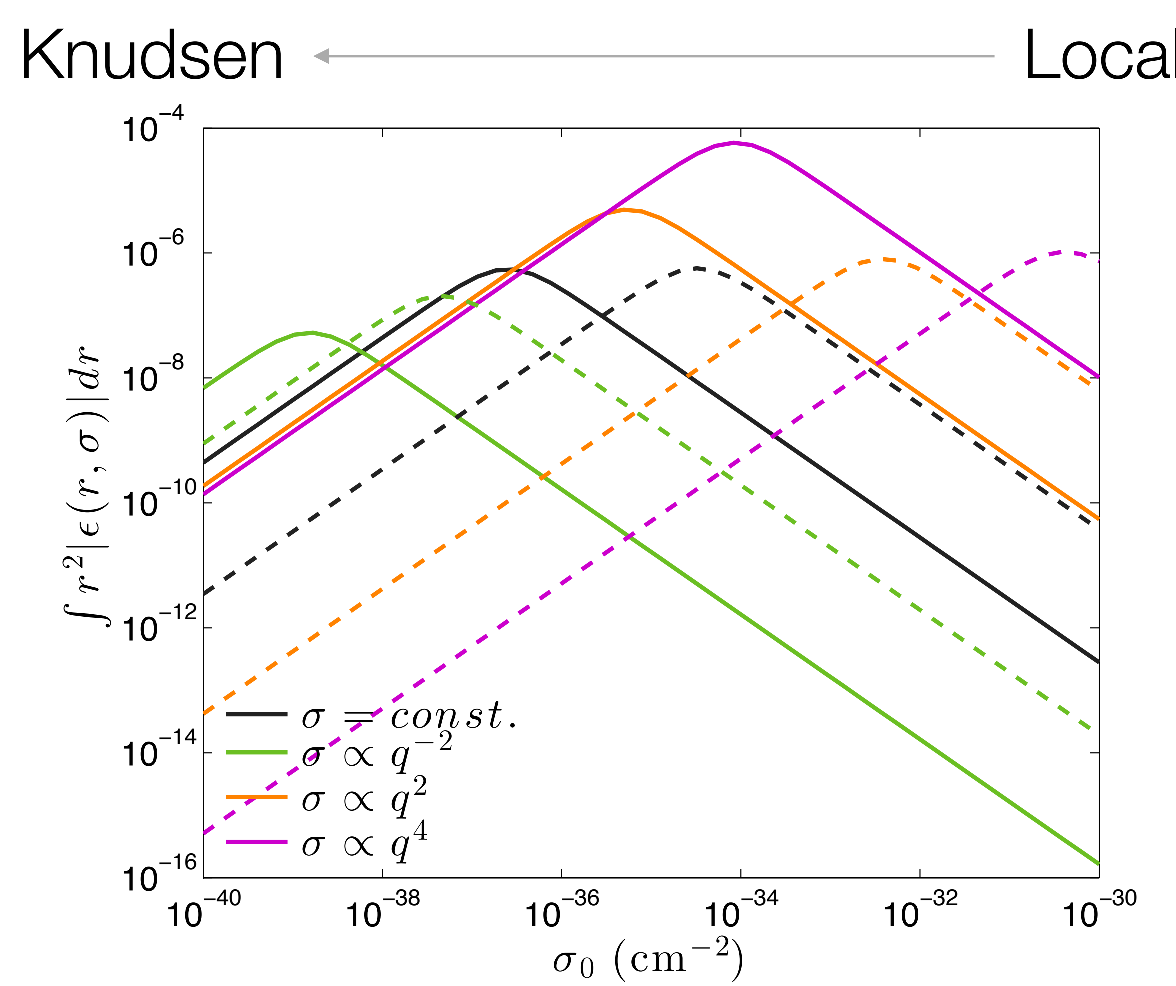
$$L_\chi(r) = 4\pi r^2 \zeta^{2n}(r)\kappa(r) n_\chi(r) l_\chi(r) \left[\frac{k_\mathrm{B} T(r)}{m_\chi}\right]^{1/2} k_\mathrm{B} \frac{dT(r)}{dr}$$

$$\propto \frac{1}{\langle\sigma\rangle}$$

Smaller cross-section: DM can deposit energy farther away

Local vs non-local





$$n_\chi(r) = \mathfrak{f}(K) n_{\chi,\mathrm{LTE}} + [1 - \mathfrak{f}(K)]\, n_{\chi,\mathrm{iso}},$$

$$L_{\chi,\mathrm{total}}(r,t) = \mathfrak{f}(K)\mathfrak{h}(r,t) L_{\chi,\mathrm{LTE}}(r,t).$$

$$\mathfrak{h}(r) = \left(\frac{r - r_\chi}{r_\chi}\right)^3 + 1,$$

$$\mathfrak{f}(K) = \frac{1}{1 + \left(\frac{K}{K_0}\right)^{1/\tau}},$$

DarkStars

(Scott, Edsjo, Fairbairn 2009)

STARS + DarkSUSY

WIMP capture, annihilation and heat transport

Generic stellar evolution

DarkStars

(Scott, Edsjo, Fairbairn 2009)

STARS + DarkSUSY

WIMP capture, annihilation and heat transport

Generic stellar evolution

+

GARSTEC

(Weiss & Schlattl 2008)

High-precision (10^{-5}) solar simulation code

Standard Solar Model: Full evolution from protostar to current age (4.57 Gyr)

Nuclear burning, heat transport, convection, accurate EOS, molecular diffusion.

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Nuclear burning, heat transport, convection, accurate EOS, molecular diffusion.

DarkStec

High-precision solar DM code

including v and q-dependence

Net effect of asymmetric DM in the Sun

Large cross-section: more captured DM

Optimal transport at Knudsen-LTE boundary

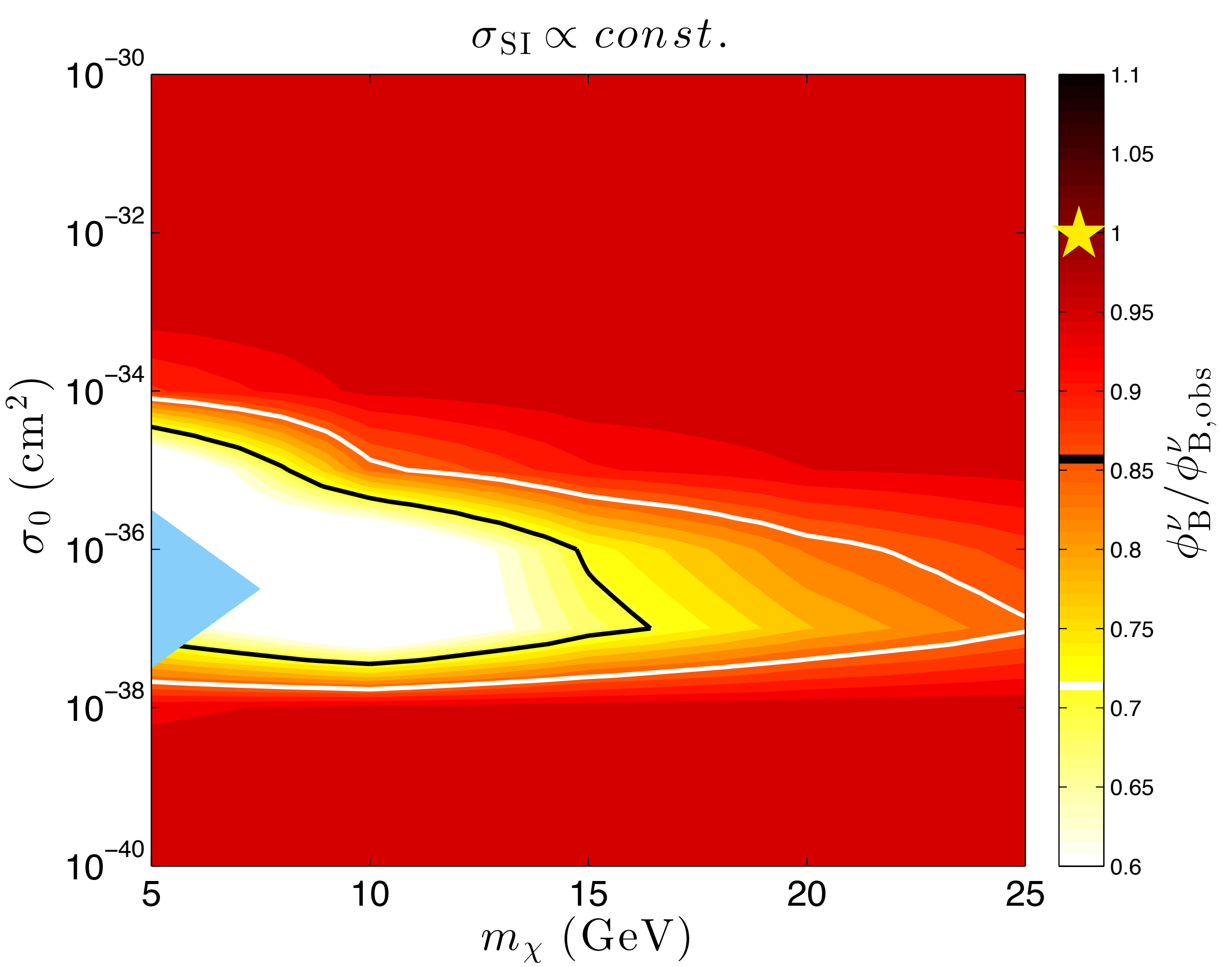
→

Maximum effect:

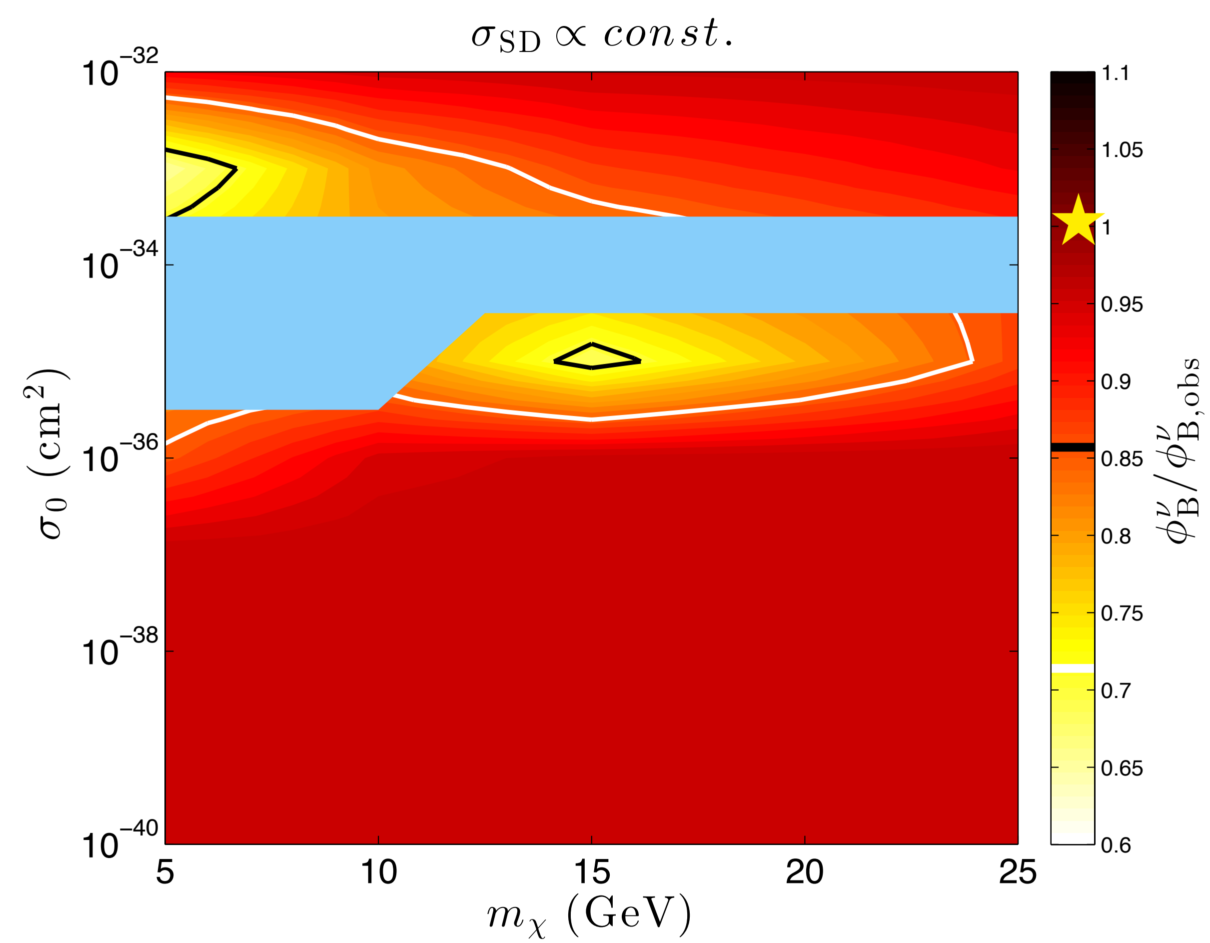
$\sigma_{SD} \sim 10^{-34}$ cm^2

$\sigma_{SI} \sim 10^{-37}$ cm^2

Neutrino fluxes: constant cross-section



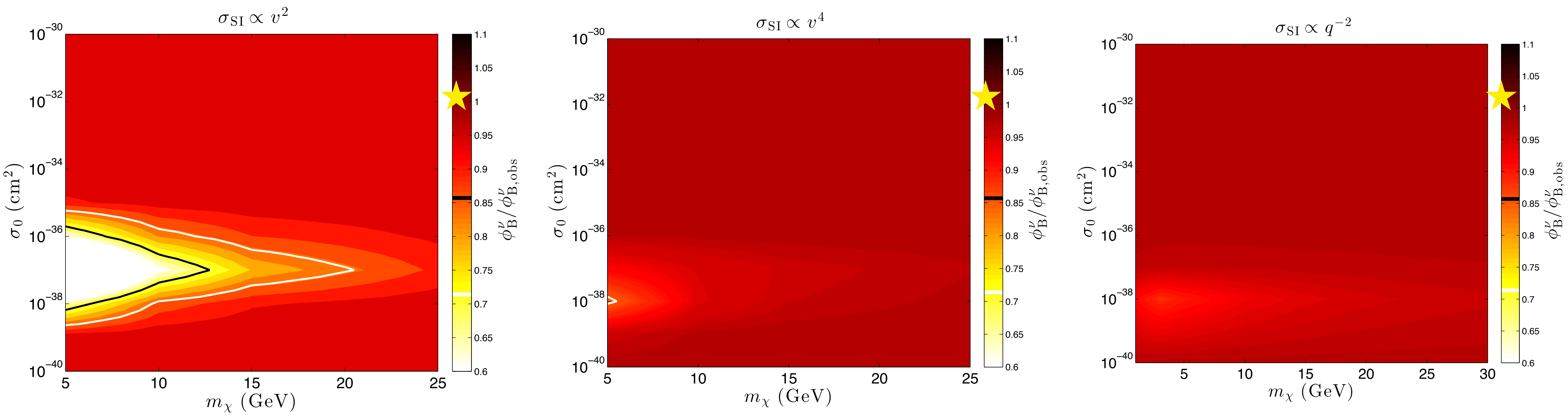
Spin dependent



Spin dependent

Unconverged models (changes too drastic)

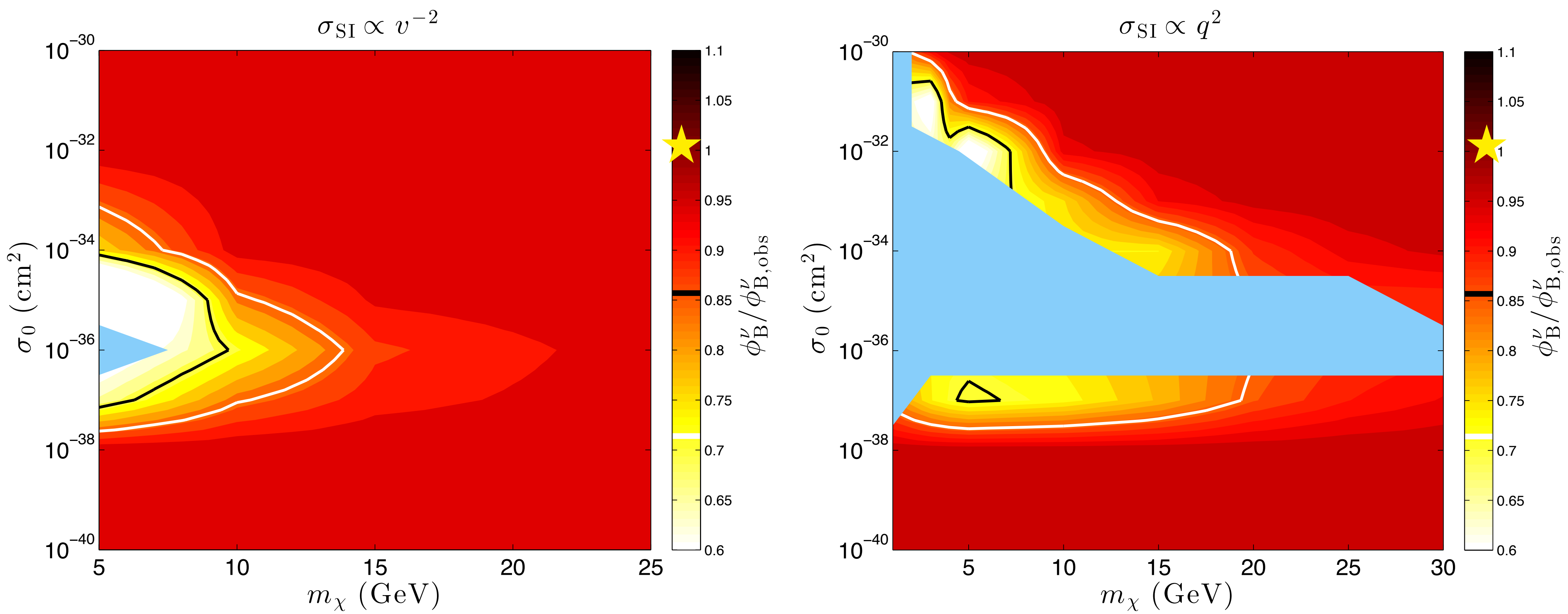
Neutrino fluxes: $\boldsymbol{\sigma} \sim v^2$, v^4, q^{-2}



Enhanced capture rate: maximum transport window at lower cross-section

Suppressed mean free path:
Less overall heat conduction

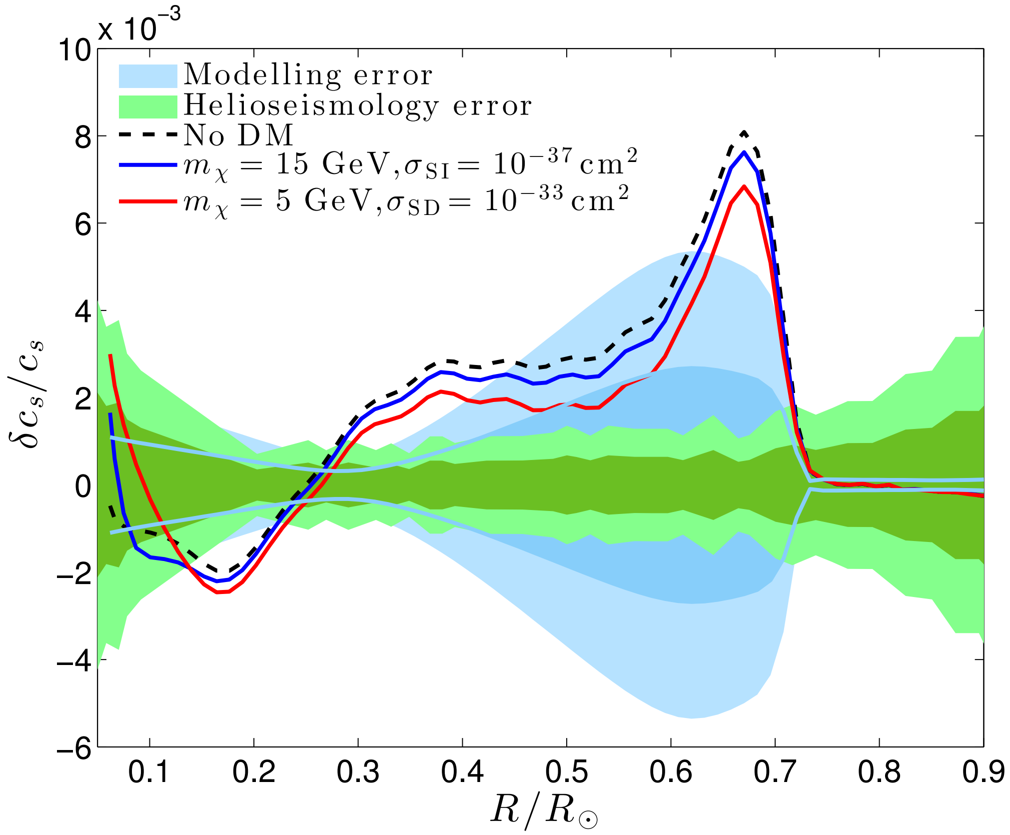
Neutrino fluxes: $\boldsymbol{\sigma} \sim v^{-2}, q^2$



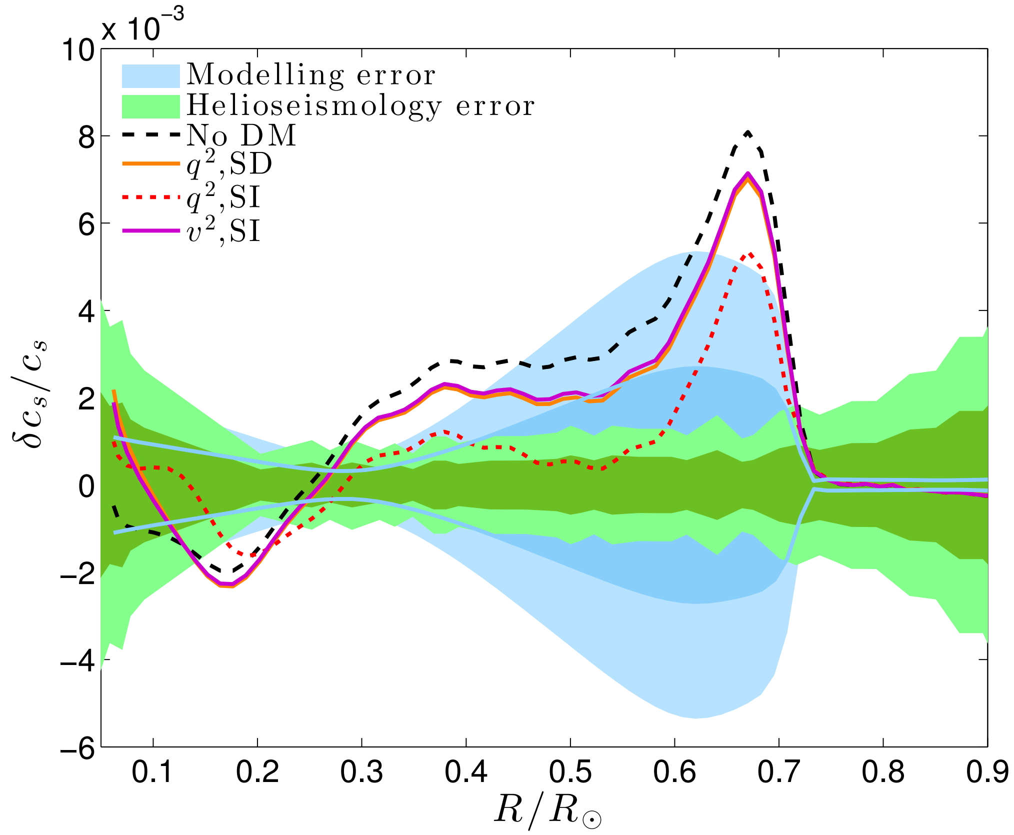
Suppressed cap. rate: maximum transport window at higher cross-section

Enhanced mean free path: Much more overall heat conduction

Sound speed: Constant cross-section



Excluded by direct detection experiments



Best improvement: q^2

$$\sigma_0 = 10^{-37}\,\mathrm{cm}^2$$
$$m_\chi = 3\,\mathrm{GeV}$$

Probing the core

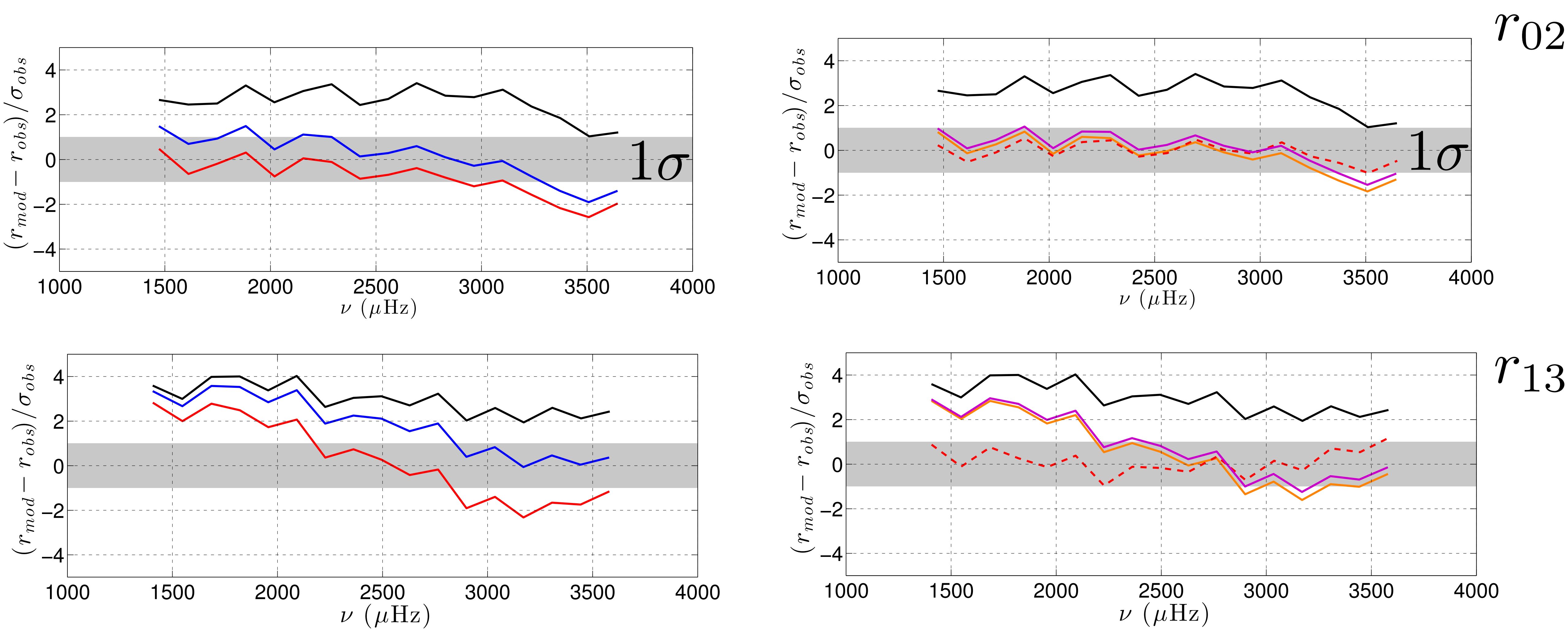
Measuring the frequency separation between the low-nu helioseismological modes allows us to probe the core while removing sources of error.

$$r_{02}(n) = \frac{d_{02}(n)}{\Delta_1(n)}, \quad r_{13}(n) = \frac{d_{13}(n)}{\Delta_0(n+1)},$$

$$d_{l,l+2}(n) \equiv \nu_{n,l} - \nu_{n-1,l+2} \simeq -(4l+6)\frac{\Delta_l(n)}{4\pi^2 \nu_{n,l}} \int_0^{R_\odot} \frac{dc_s}{dr}\frac{dr}{r}.$$

Solar core observable: model — observation

Constant cross section | q, v dependent



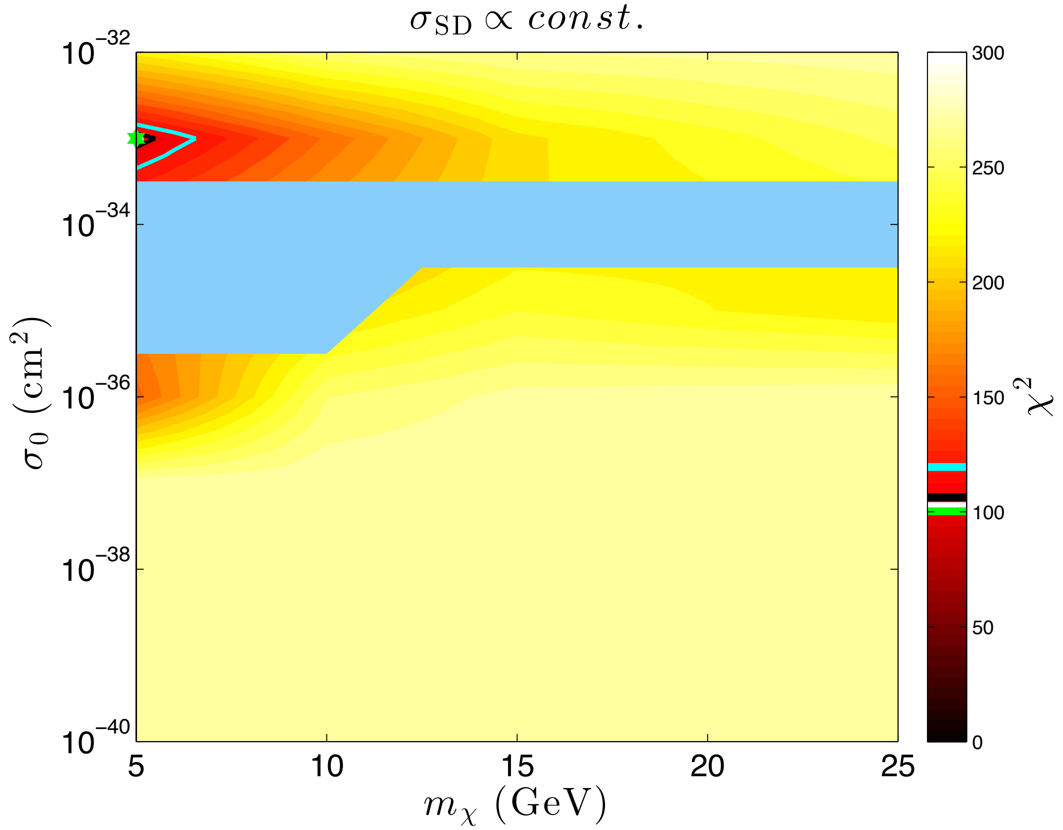
Standard solar model

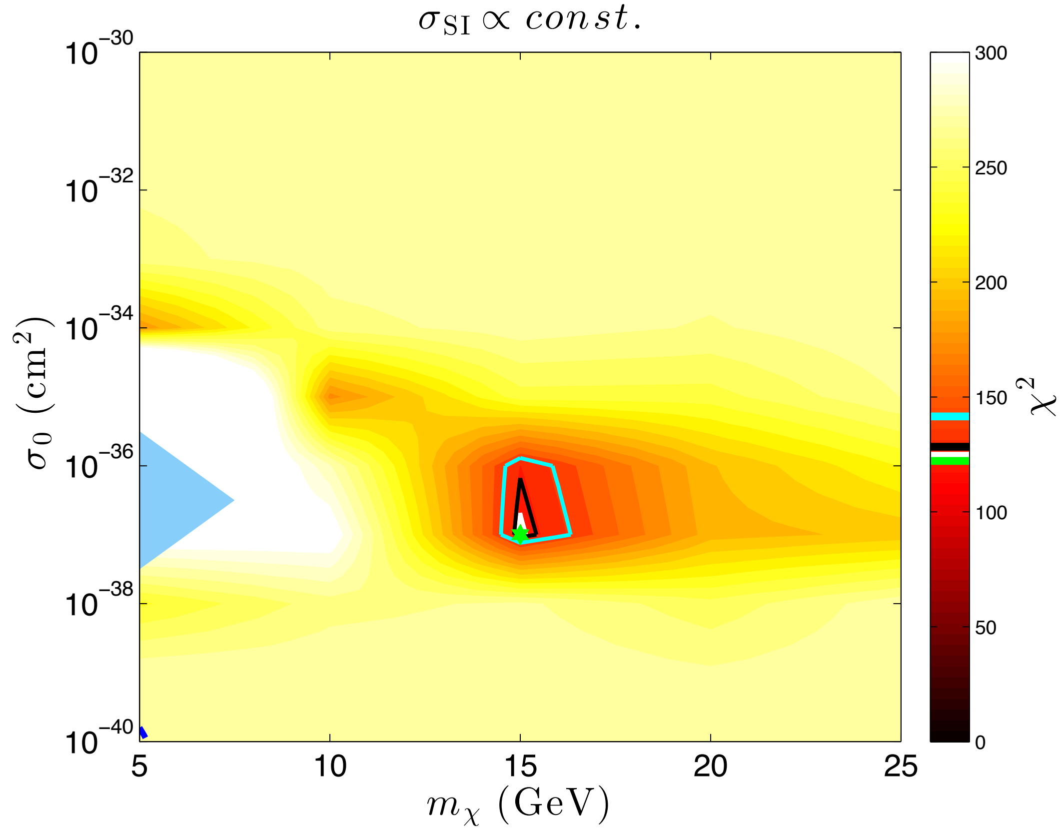
q2 dark matter

Combined limits

$$\chi^2 = \frac{(1-\phi^\nu_{\rm B,obs}/\phi^\nu_{\rm B})^2}{\sigma^2_{\rm B}} + \frac{(1-\phi^\nu_{\rm Be,obs}/\phi^\nu_{\rm Be})^2}{\sigma^2_{\rm Be}} + \frac{(r_{\rm CZ}-r_{\rm CZ,obs})^2}{\sigma^2_{\rm CZ}} + \frac{(Y_{\rm S}-Y_{\rm S,obs})^2}{\sigma^2_{Y_{\rm S}}} + \chi^2_{r_{02}} + \chi^2_{r_{13}}.$$

neutrinos — *CZ radius* — *surf. He* — *small freq.*





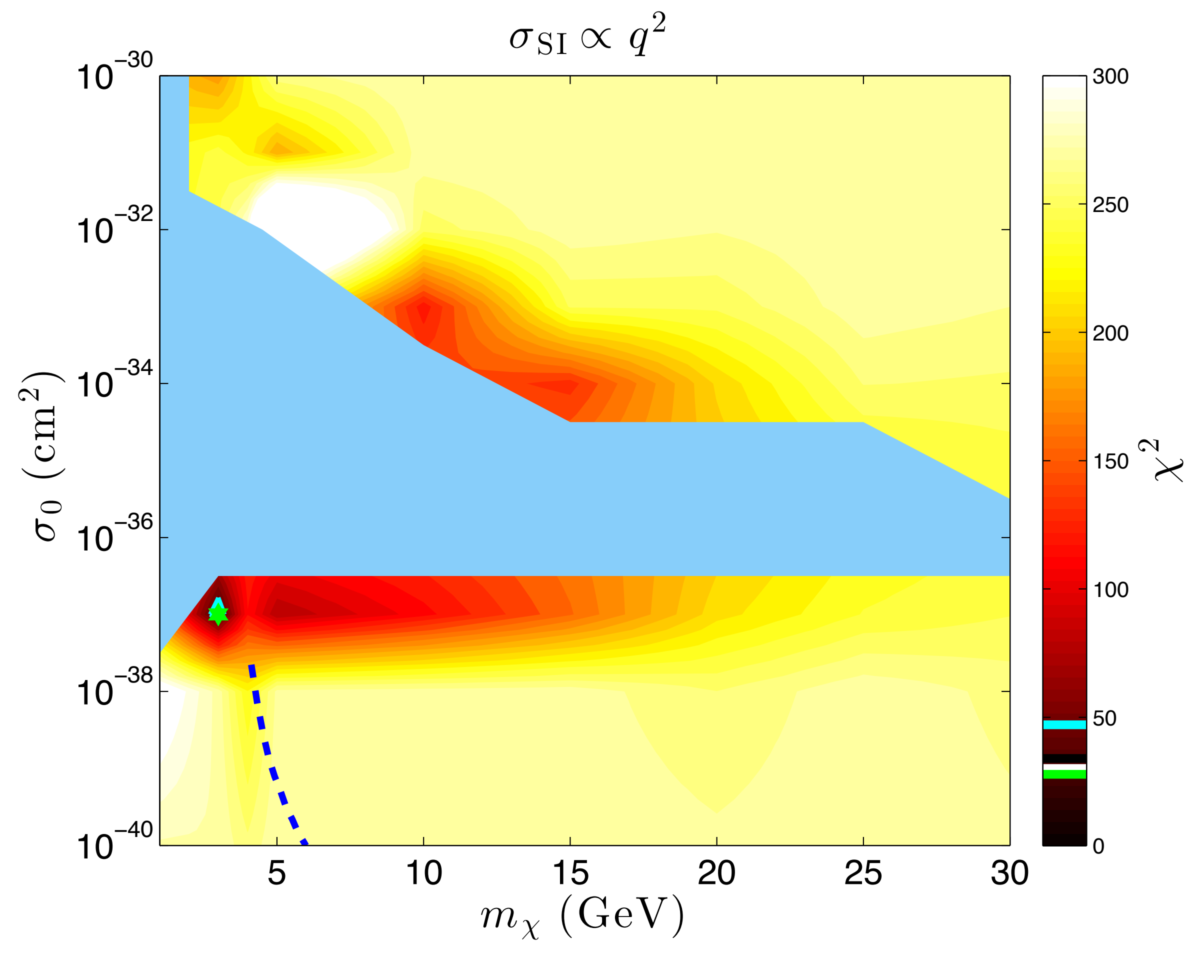
Combined limits: best models

$$\sigma_{SI} \propto q^2 \quad m_\chi = 3\,\mathrm{GeV}$$

TABLE I. Measured and predicted solar observables.

	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			

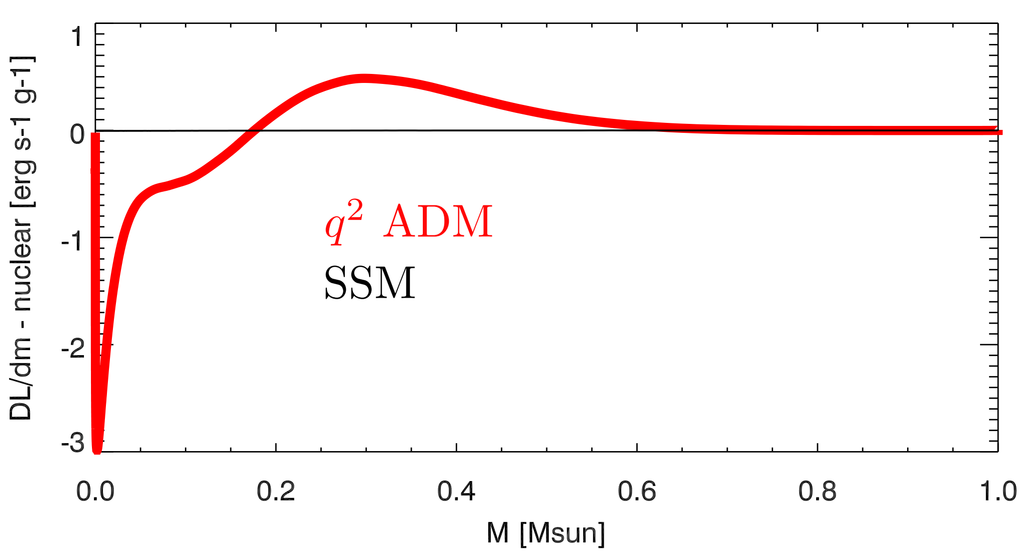
[a] Neutrino data and obs. errors inferred from Borexino data [4].
[b] In units of 10^6 cm^{-2}s^{-1}.
[c] In units of 10^9 cm^{-2}s^{-1}.

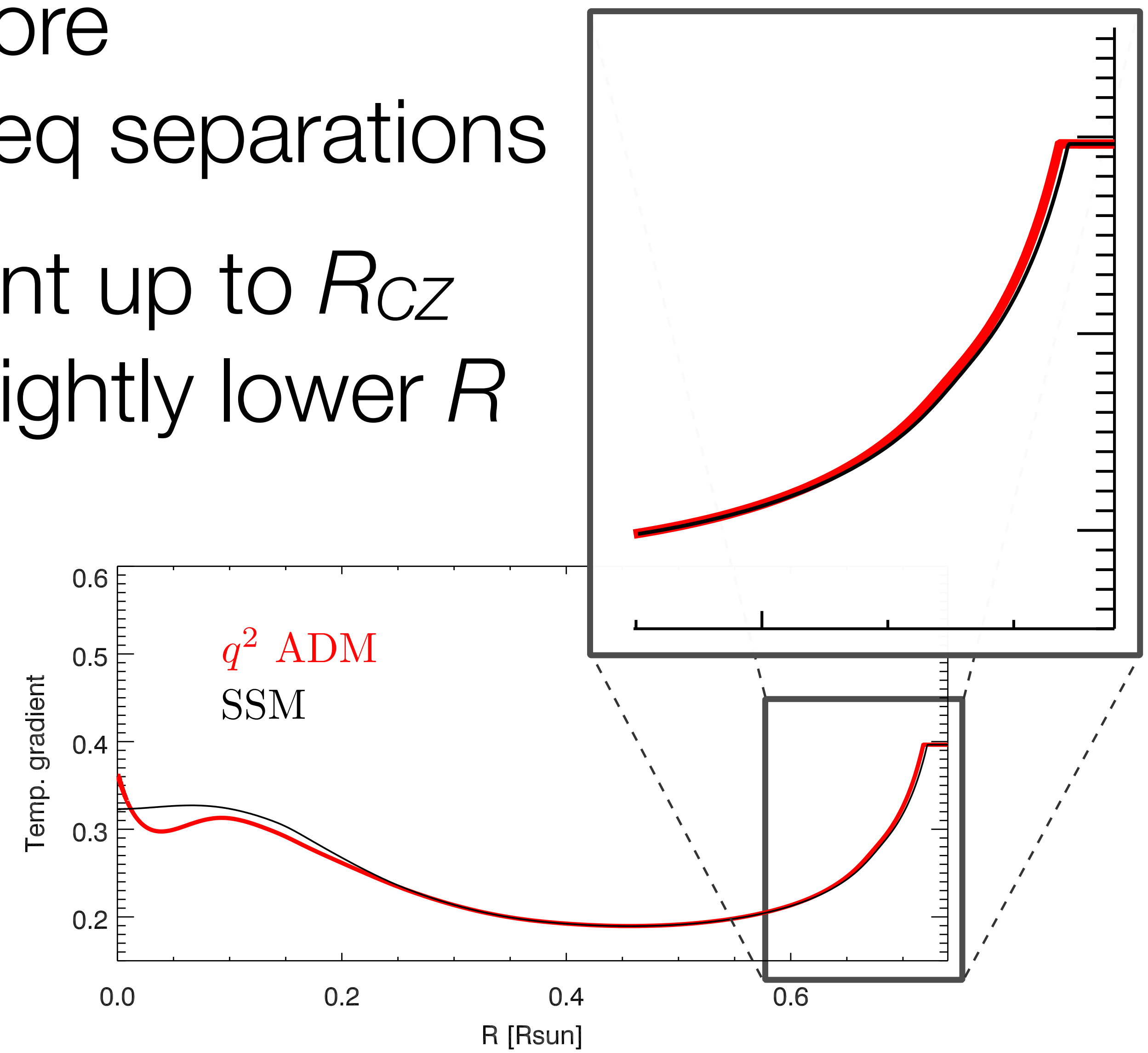


6 sigma improvement over SSM!

What is going on?

- Energy extracted from core to intermediate radii (0.2 < R < 0.6)
- Change in sound speed, core state variables —> small freq separations
- Temp. gradient readjustment up to R_{CZ}
  - ➡ Convection sets in at slightly lower *R*





Other constraints

- **Direct detection**
  - Mass (3 GeV) still too low to have been seen
  - CDMSlite, DAMIC, SuperCDMS should probe this range
- **Collider limits**
  - Effective operators ~ $\bar{\chi}\gamma^5\chi\bar{q}q$ still ok.

To summarise

- SI, SD constant cross-sections bring some observables closer to agreement but
  - Suppress neutrino fluxes too much
  - Do not do that well in the core (small-freq separations)
  - Do not yield significantly better fit than SSM
- All DM models we looked at give *some* improvement, but only q^2 gives a good fit, and a significant, **6 sigma improvement over the standard solar model.**
- Mass is low - evaporation?
- Could the solution to the solar abundance problem be the first hint of particle DM?

Thank you