Dark matter in stars

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EDSU2020 - Pointe-à-Pitre - March 11 2020

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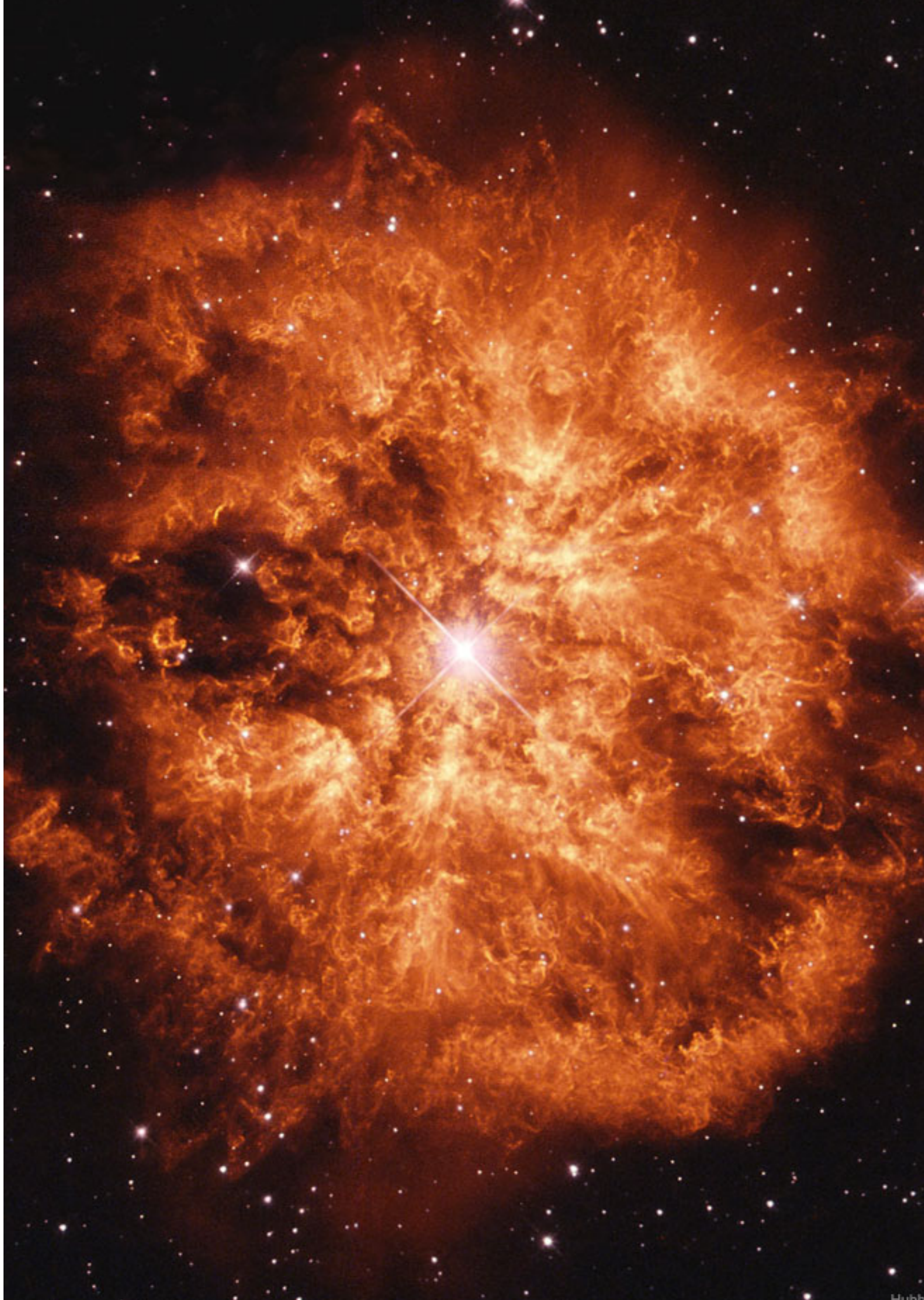


Dark Matter in the Sun

arXiv:1311.2074 / JCAP/04019 (ACV, P. Scott)
Thermal conduction by dark matter with velocity and momentum-dependent cross-sections

arXiv:1411.6626/ PRL 114.081302 (ACV, P. Scott, A. Serenelli)
Possible Indication of Momentum-Dependent Asymmetric Dark Matter in the Sun

arXiv:1504.04378/ JCAP 1508 (2015) 08, 040 (ACV, Scott, Serenelli)
Generalised form factor dark matter in the Sun

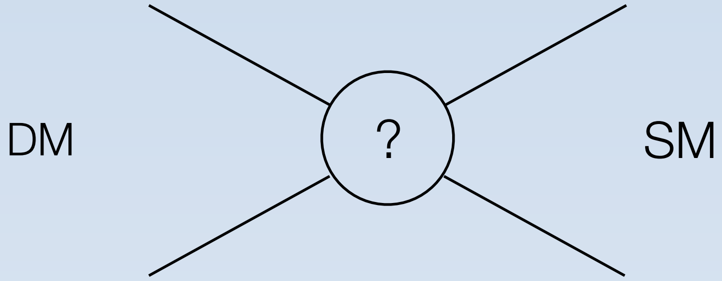
arXiv:1605.06502 /JCAP1611 (2016) 007 (ACV, Scott, Serenelli)
Updated constraints on velocity and momentum- dependent asymmetric dark matter

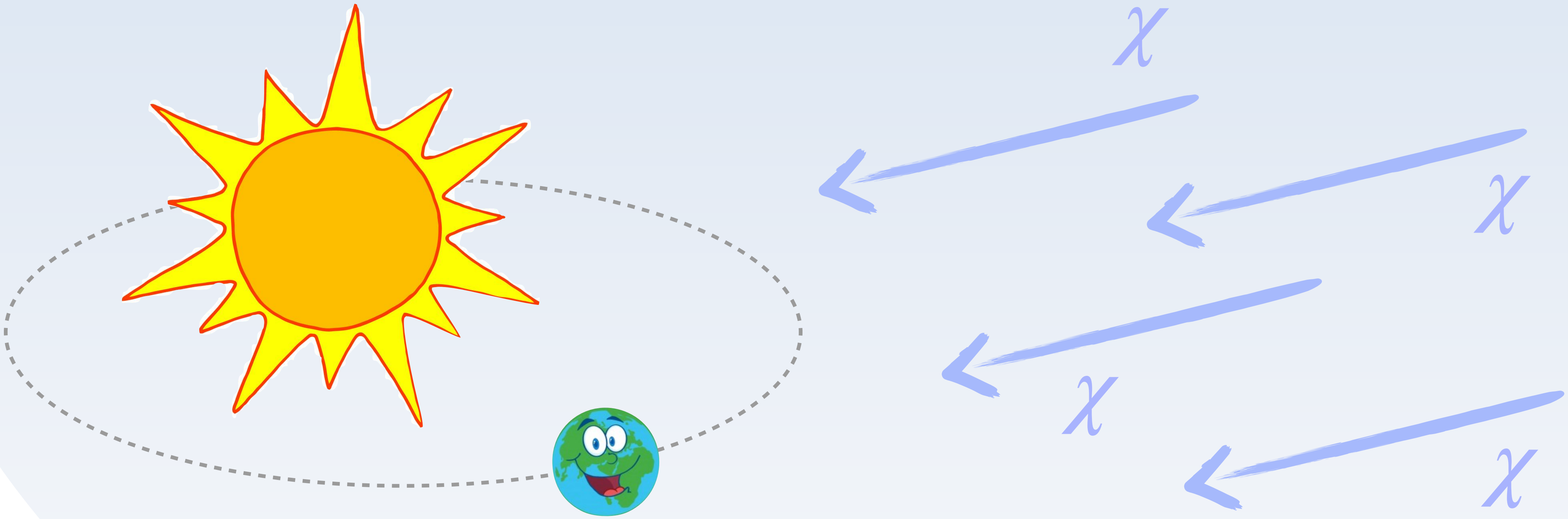
arXiv:1610.06737/JCAP03(2017)029 (B. Geytenbeek, S. Roa, P. Scott, A. Serenelli, ACV, M. White, A. Williams)
Effect of electromagnetic dipole dark matter on energy transport in the solar interior

arXiv:1703.07784/JCAP 1710 (2017)10 037: G.Busoni, A. de Simone, P. Scott, ACV
Generalised solar capture and evaporation of DM

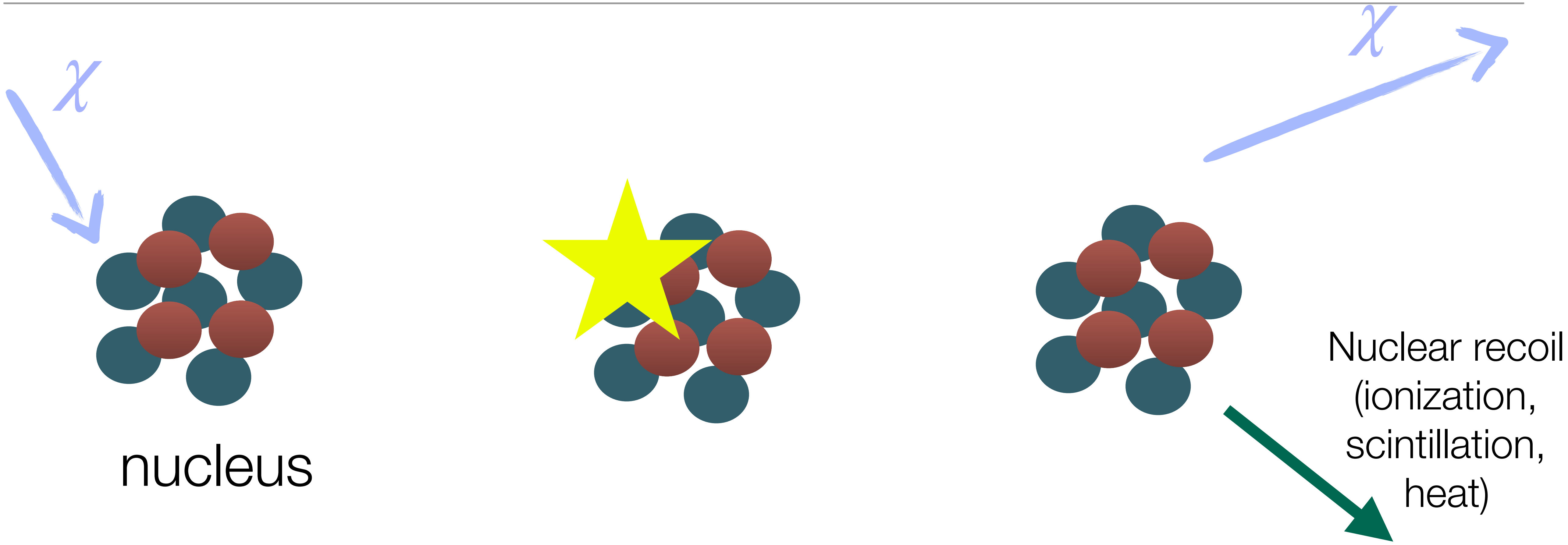
++ work in progress w/ Hannah Banks, Siyam Ansari (Imperial), Neal Kozar (Queen’s)

Direct detection





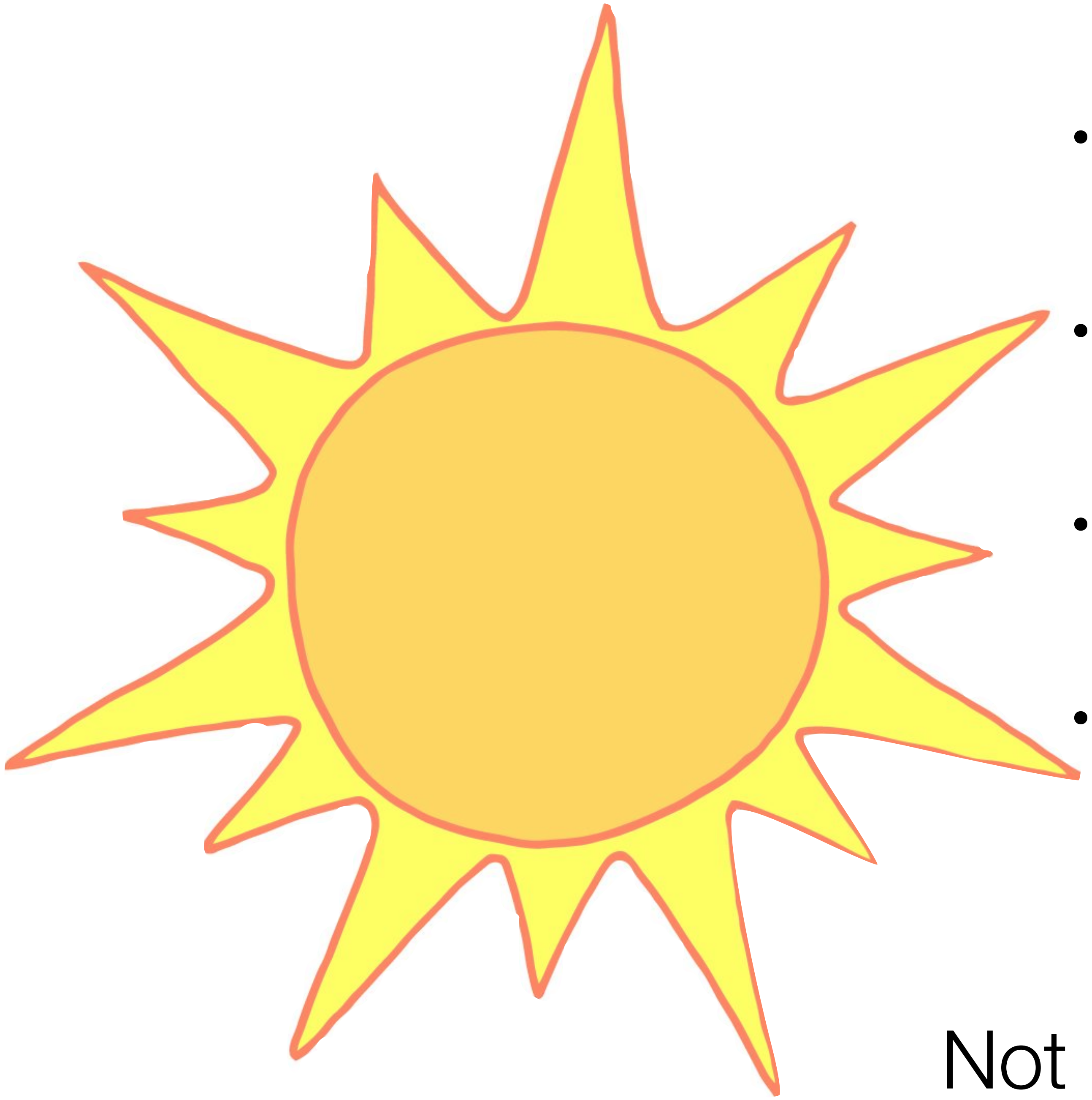
Direct detection



Most sensitive to **heavy**, **fast** particles —> larger recoil signal

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

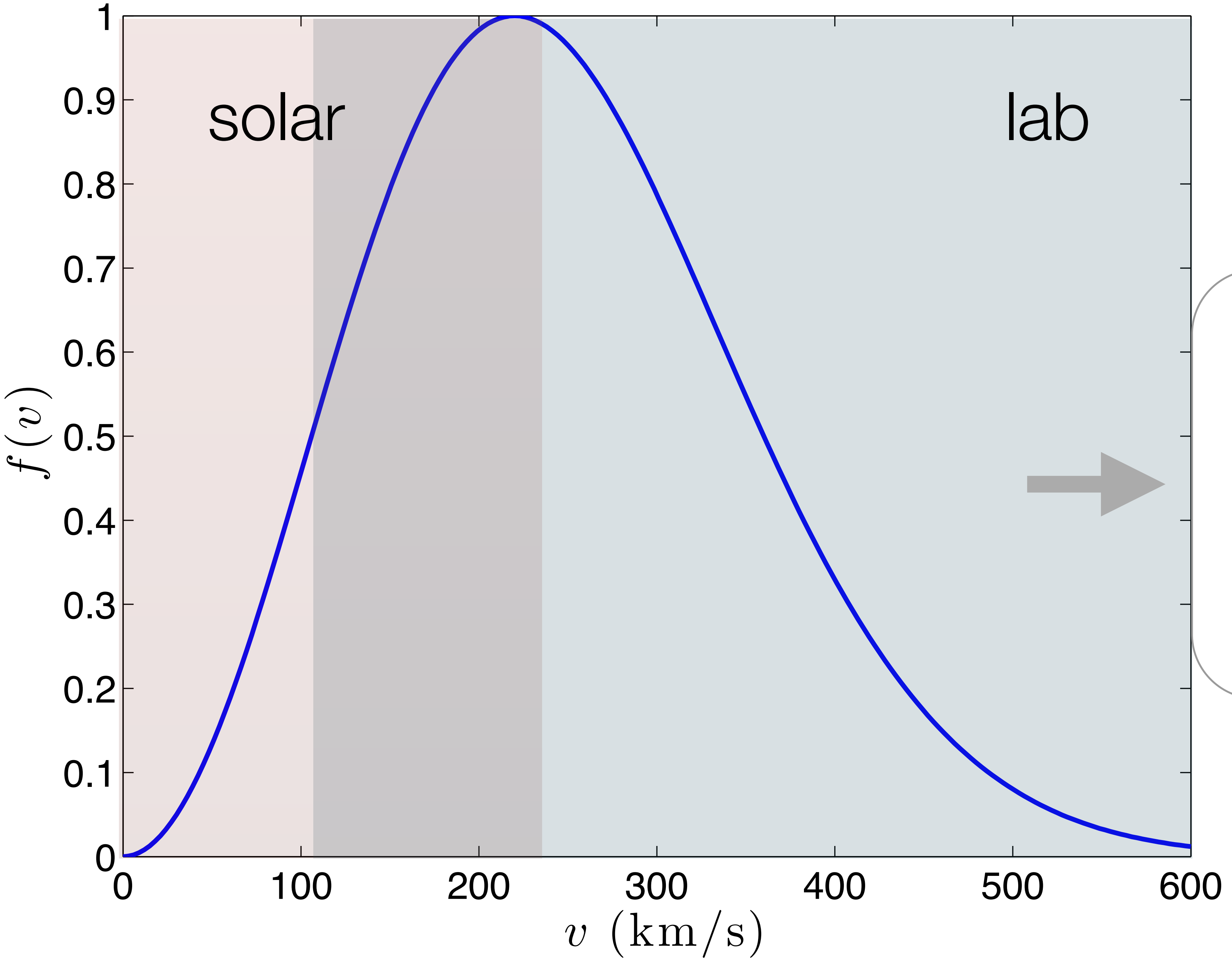
The sun is a direct detection experiment



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

Not supercooled: need to be clever about “readout”

Differences with earth-based detection

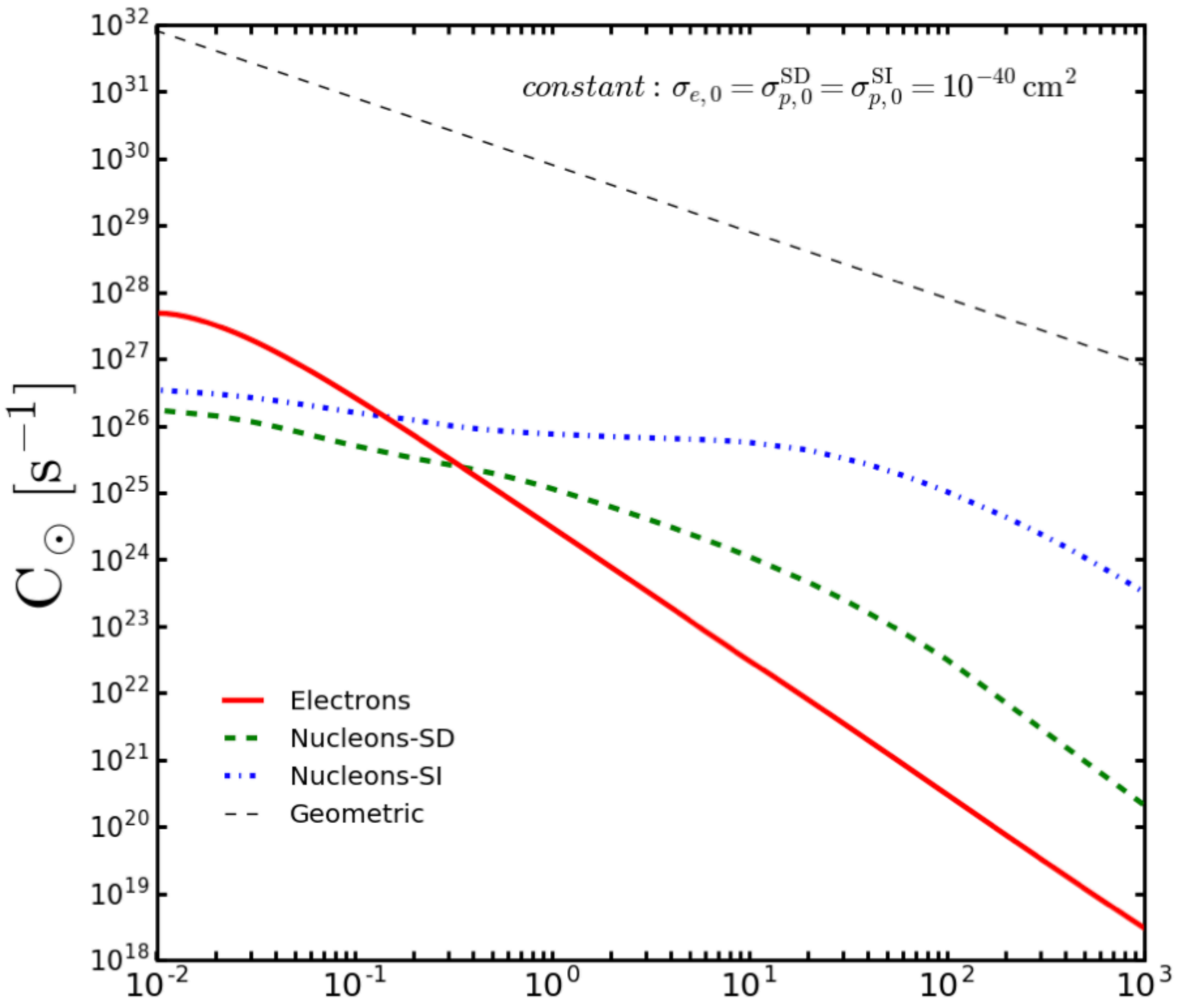


More sensitive to lighter DM

Different particle couplings

Capture on electrons

For certain DM masses, DM-electron scattering can efficiently capture DM



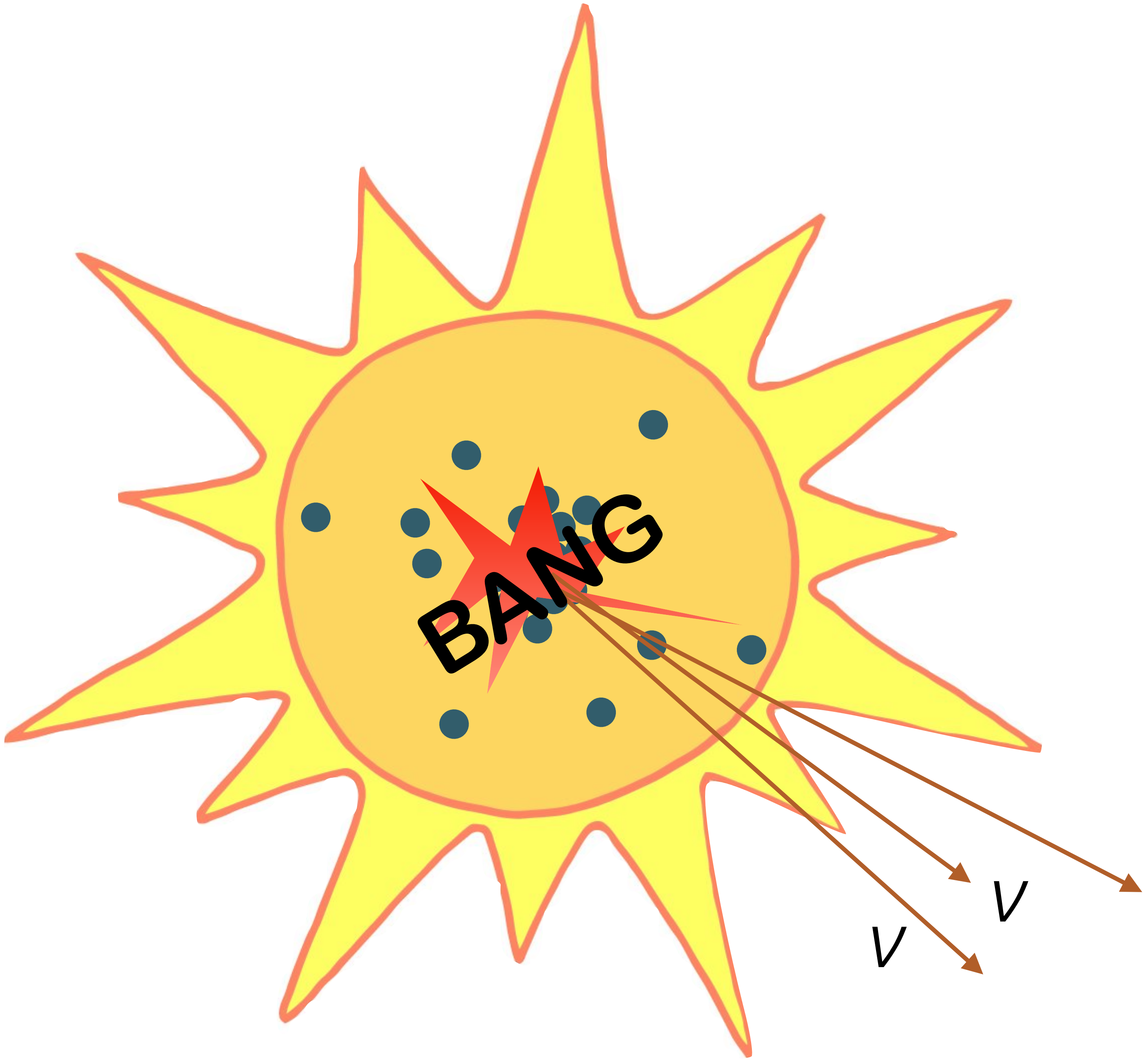
great paper

Ask Sergio

Raghuveer Garani[1] and Sergio Palomares-Ruiz[2]

https://arxiv.org/pdf/1702.02768.pdf

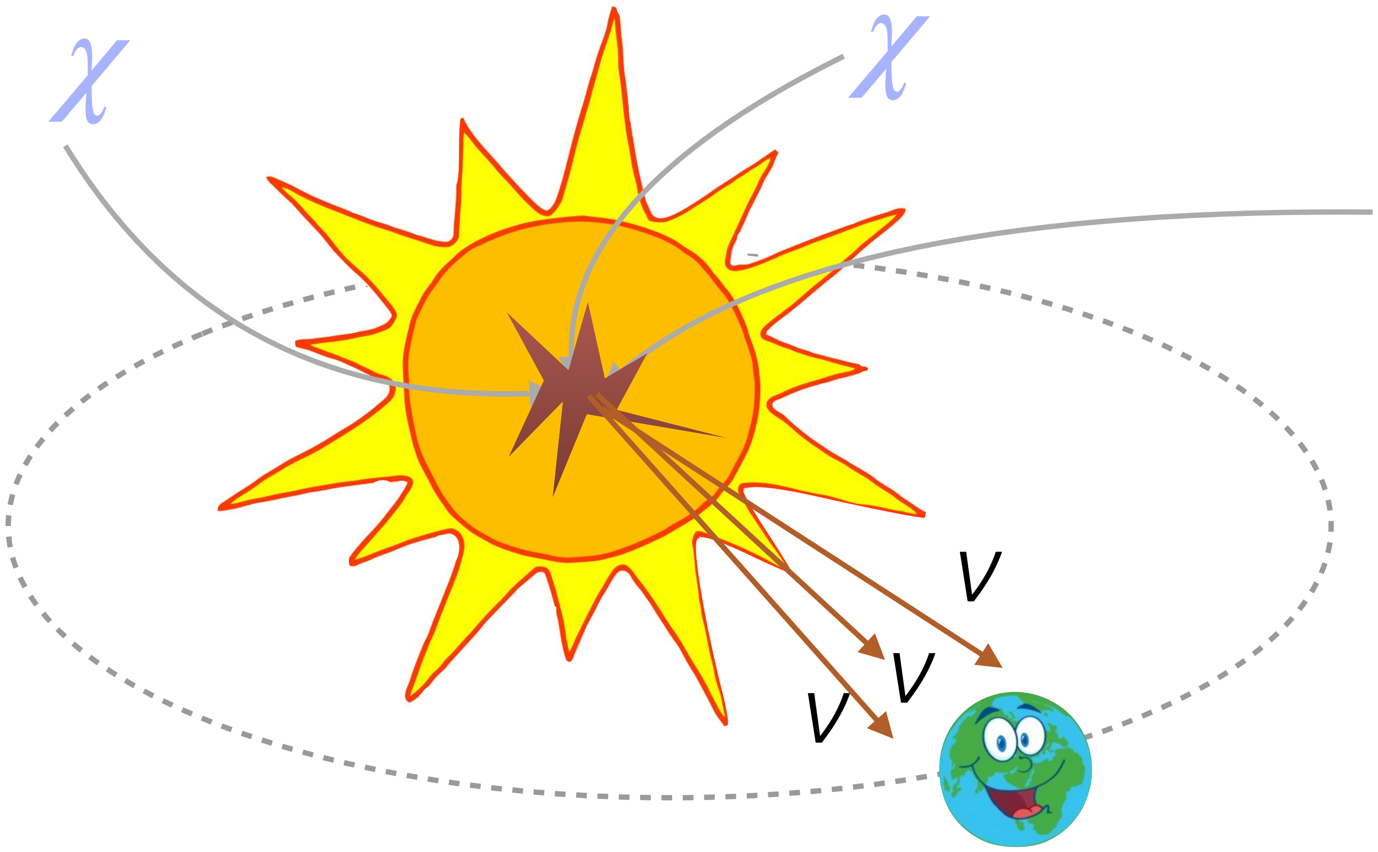
If DM annihilates: look for neutrinos



Actually, you reach a steady state:

$C(t) = A(t)$

Signals of DM in a star: annihilation

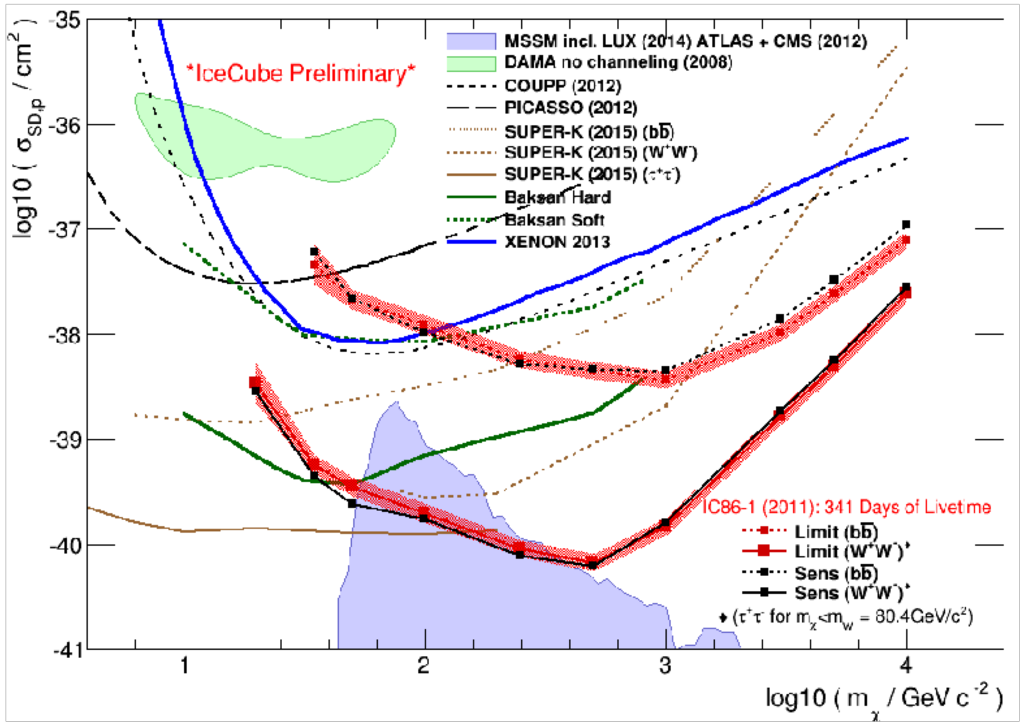


Extra energy source?

—> need a **lot** of DM

but “Dark stars” could exist in very high-DM density environments

Neutrinos from annihilation can escape the sun and make their way here



Some of the strongest limits on spin-dependent wimps are from this process (SuperKamiokande, IceCube)

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

$C(t)$ Capture rate

~~$A(t)$ Annihilation rate~~

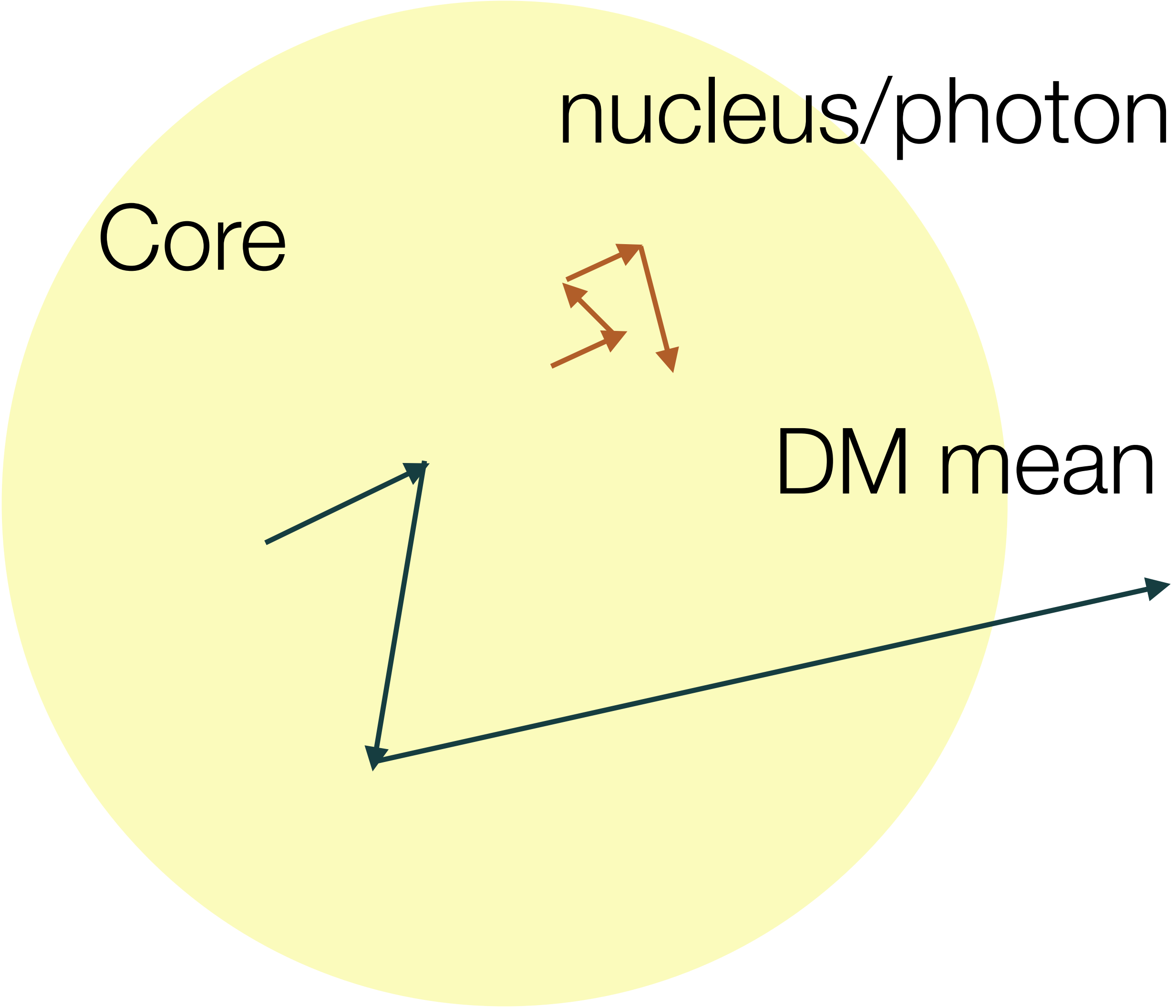
~~$E(t)$ Evaporation rate (low m)~~

No anti-DM leftover in the universe: asymmetric dark matter

Asymmetric DM in stars

$$\sigma \simeq \sigma_T$$

nucleus/photon mean free path $\lambda_{\rm nuc} \ll r_{\rm core}$



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

$$\sigma \ll \sigma_T$$

Heat can be transported, changing the stellar temperature, density and pressure profiles

Can this be observed?

Probes of Solar structure

Obvious

Mass, age, radius, luminosity are extremely well-measured and are the first thing any solar model must satisfy.

Neutrinos*

pp constrained by overall luminosity, but other byproducts of pp chain extremely sensitive to *T*. e.g $\phi_{\nu,{}^{8}\mathrm{B}} \propto T_c^{25}$

*actually this mechanism was first studied as part of the solar neutrino problem: lower than expected solar core T —> fewer neutrinos

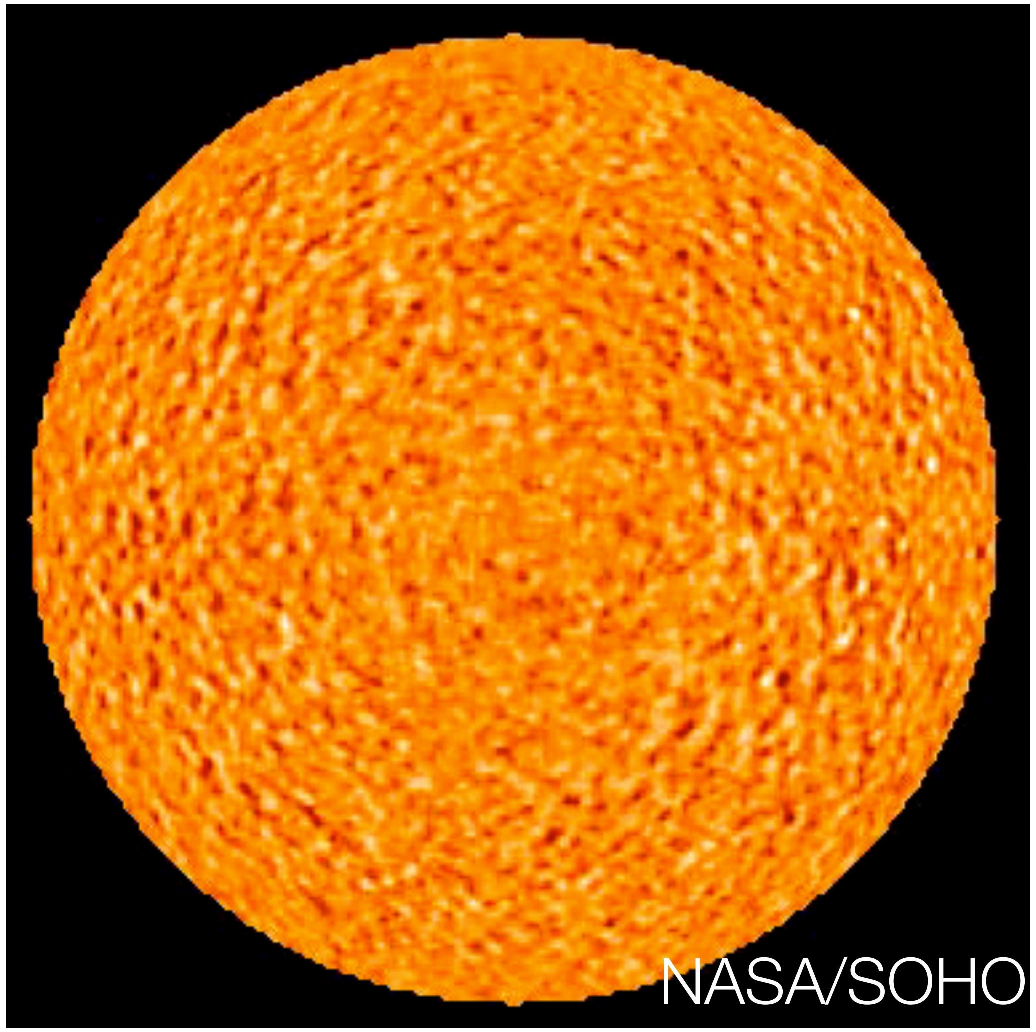
Helioseismology?

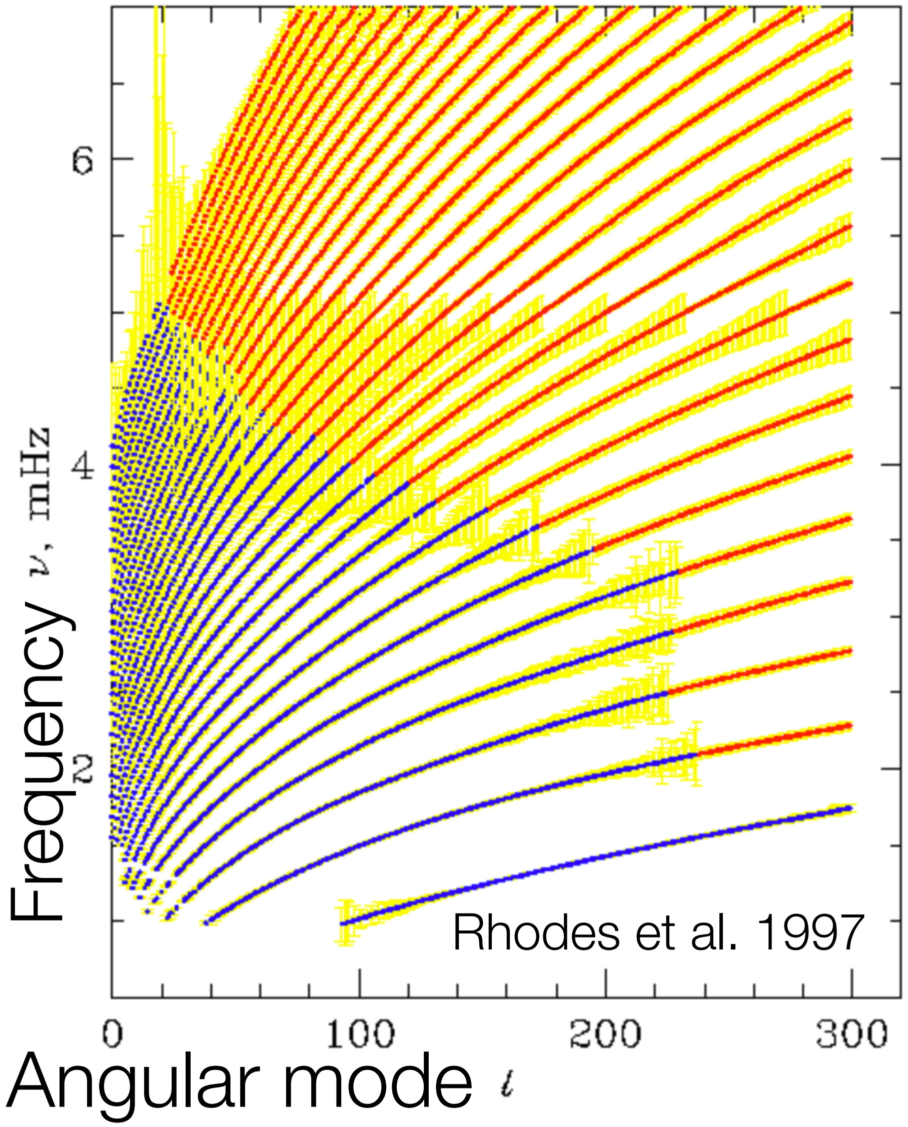
No, it's because neutrinos change flavour as they propagate to Earth

Art McDonald (Queen's)

Nobel Prize

Helioseismology


NASA/SOHO



Rhodes et al. 1997

The **frequencies** of these **eigenmodes** should be predictable from:

-**density**

-**sound speed**

-molecular weight (i.e. **elemental composition**)

-**convective zone radius**

Standard Solar Model (since 1970s)

Input

-Chemical Composition
-Mass
-Age
-Physics

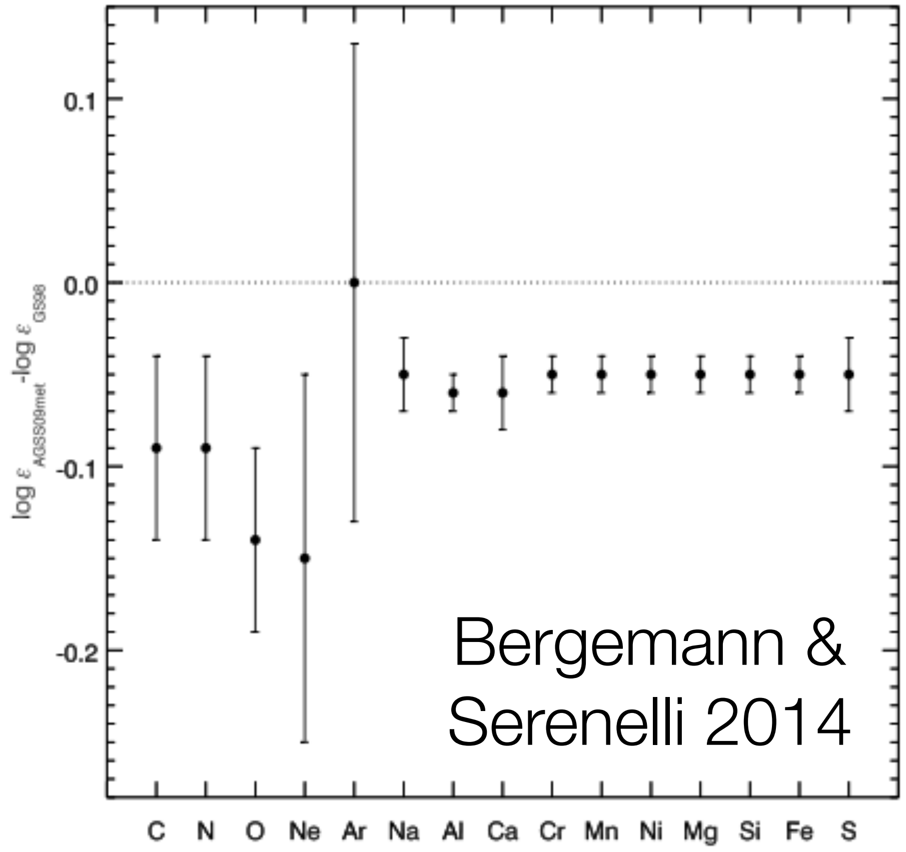
Solar/ stellar model

Output

-Luminosity (✓)
-Radius (✓)
-Neutrino fluxes ✓
-helioseismology ×

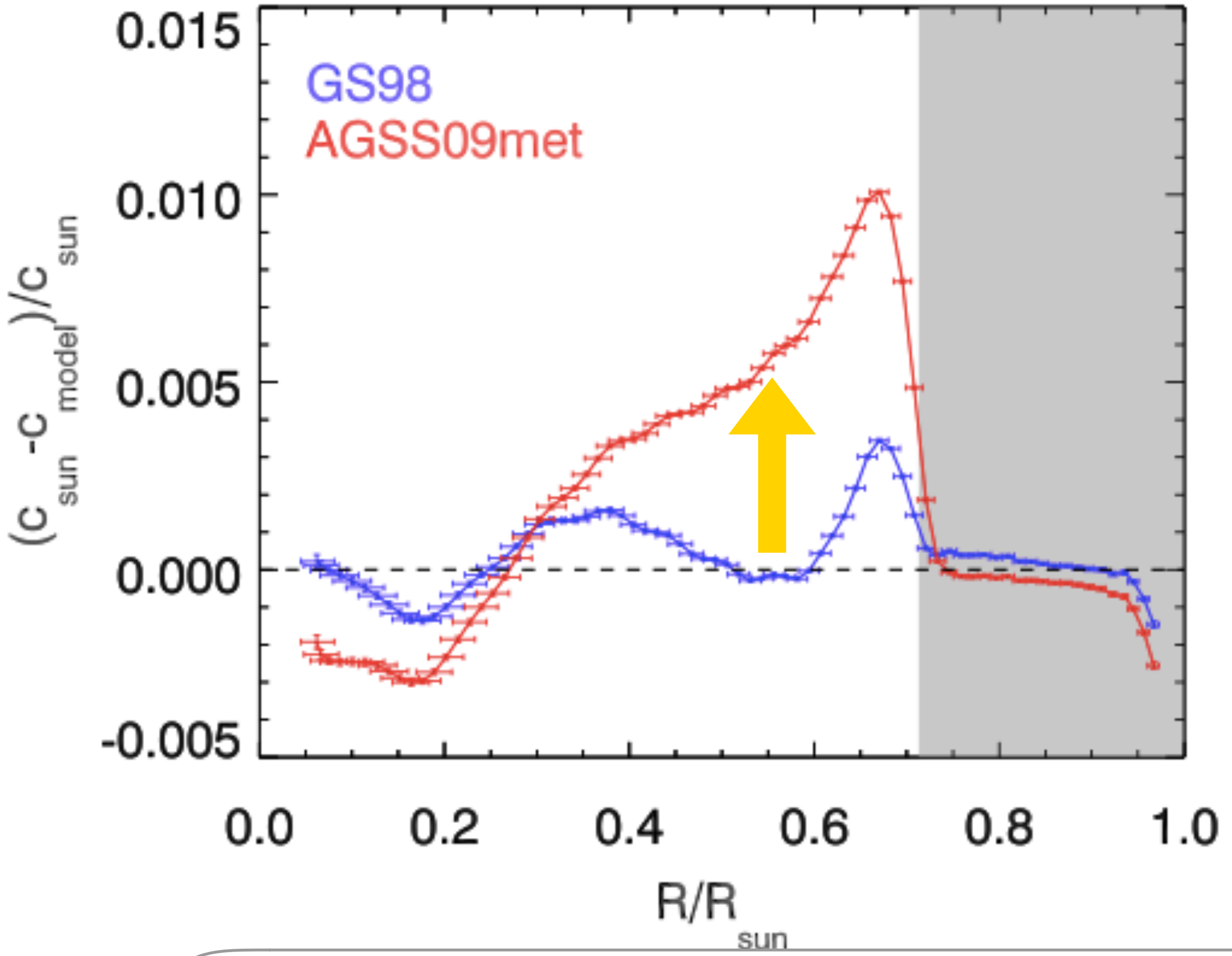
Known problem since 2004: still no solution!

Solar composition problem



Bergemann & Serenelli 2014

revised - old abundances

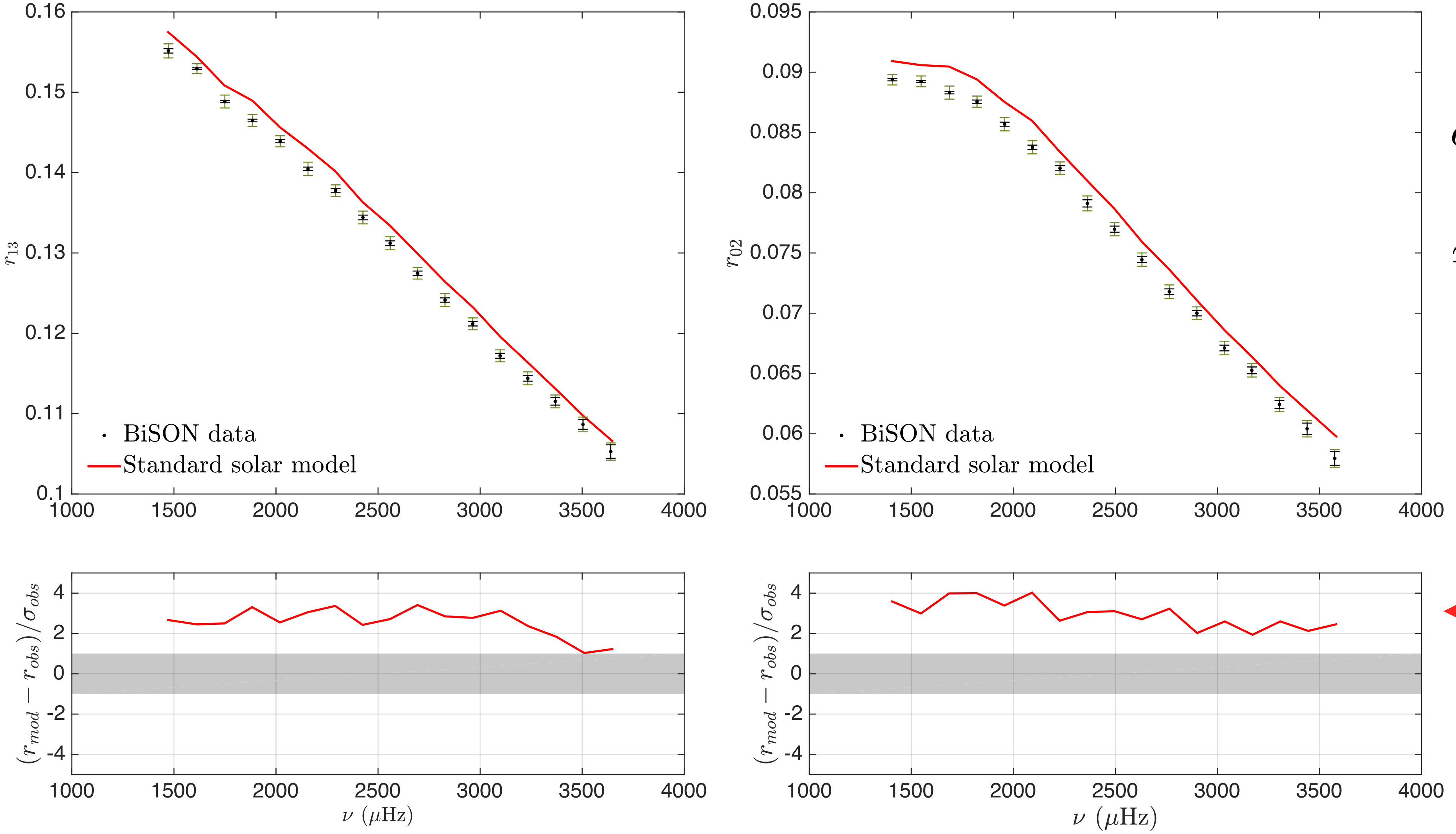


$$R_{\mathrm{CZ},\odot} = 0.713 \pm 0.001\, R_\odot$$
$$R_{\mathrm{CZ,SSM}} = 0.722 \pm 0.004\, R_\odot$$

Mainly: smaller mean molecular weight, which shifts temperature, pressure, density gradients

Solar composition problem

Small frequency separations: a probe of the core



$$\Delta_l(n) \equiv \nu_{n,l} - \nu_{n-1,l}$$

$$d_{l,l+2}(n) \equiv \nu_{n,l} - \nu_{n-1,l+2}$$

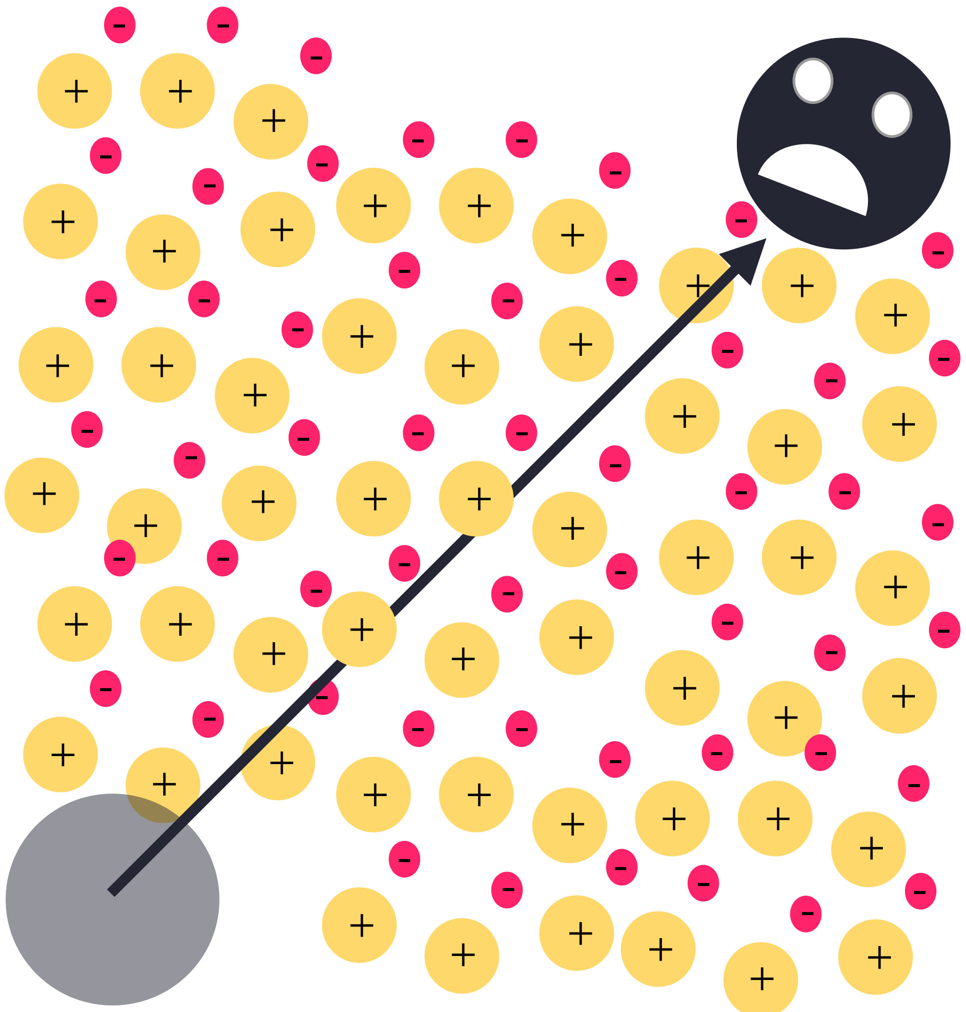
$$\simeq -(4l+6)\frac{\Delta_l(n)}{4\pi^2\nu_{n,l}}\int_0^{R_\odot}\frac{dc_s}{dr}\frac{dr}{r}$$

SSM describes the core **very badly**

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

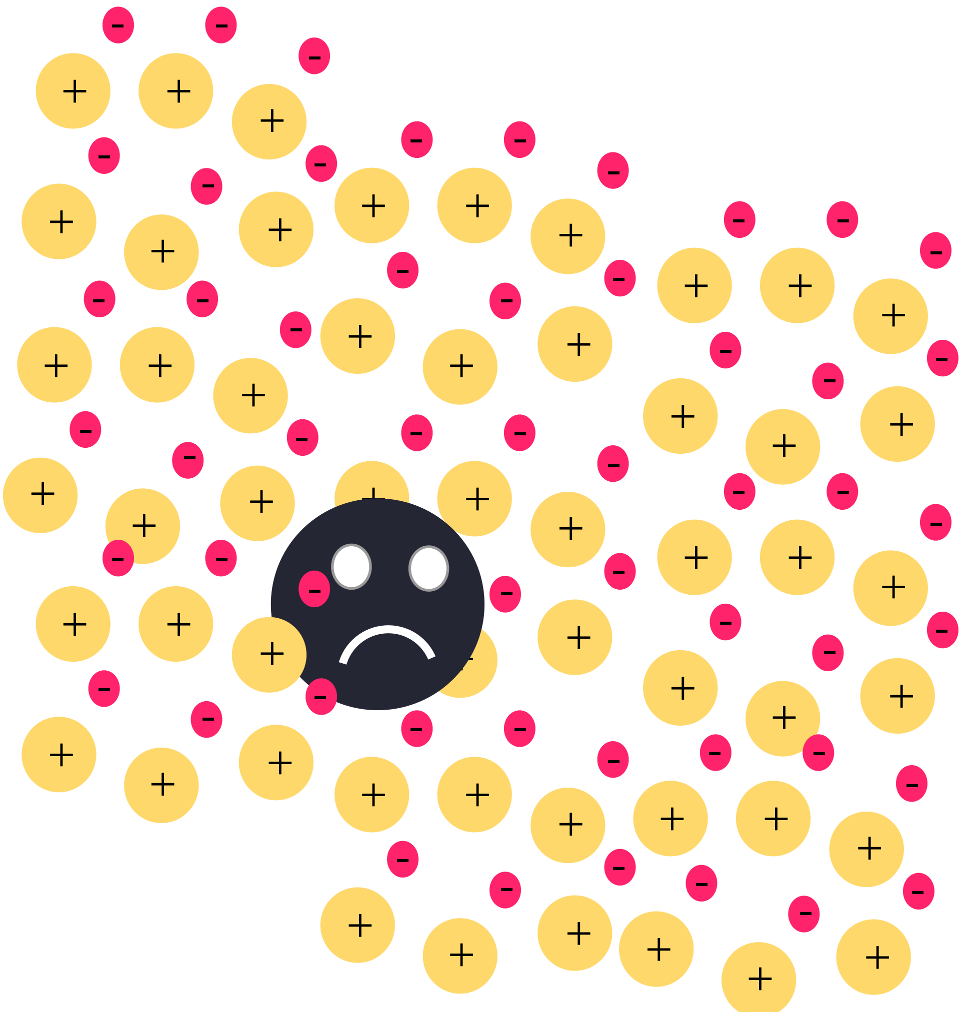
Heat transport: two regimes

Interactions too weak

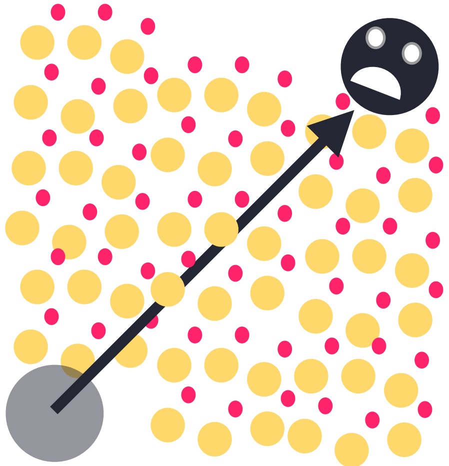


DM goes far but
cannot efficiently transfer momentum

Interactions too strong



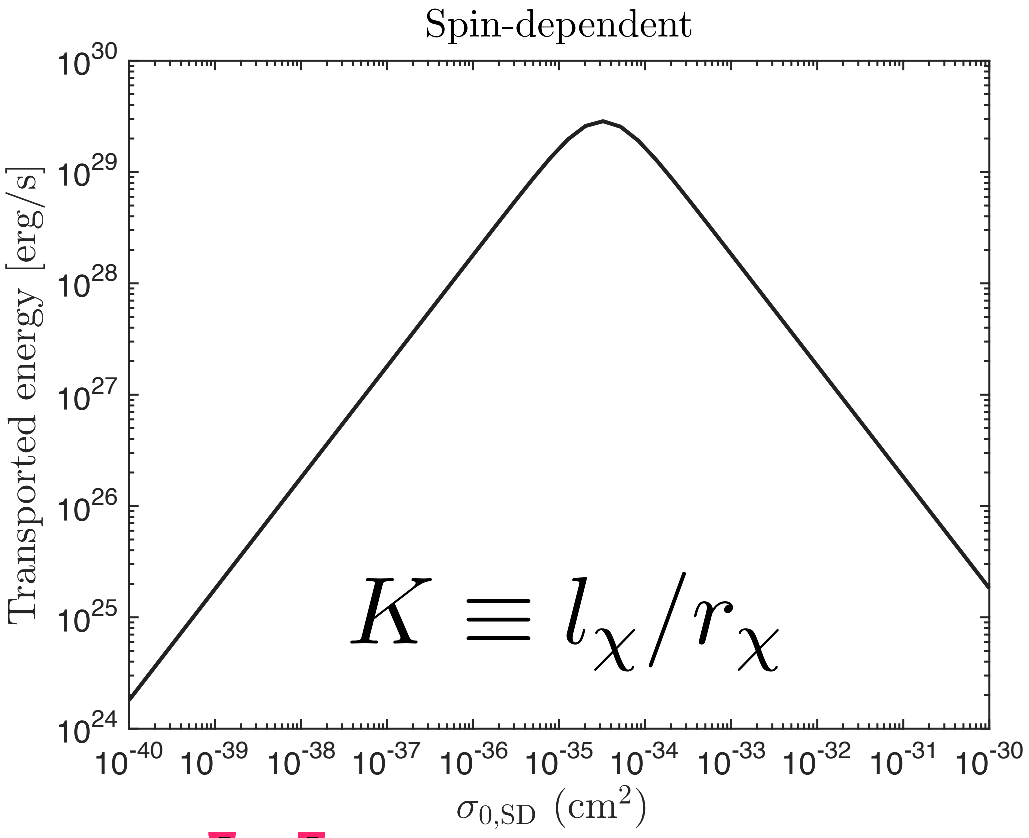
Efficient momentum transfer but
DM is “stuck"



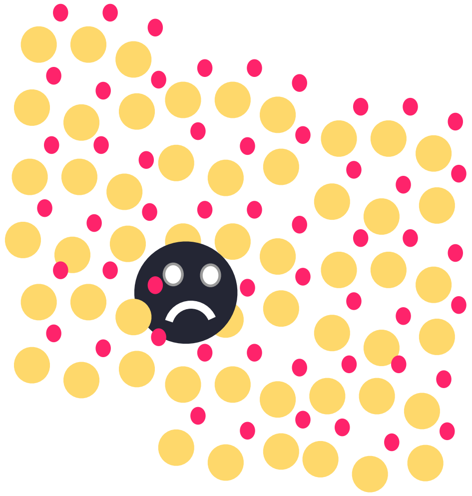
Knudsen
(non-local)

$K \gtrsim 1$

Calculable
(but wrong)



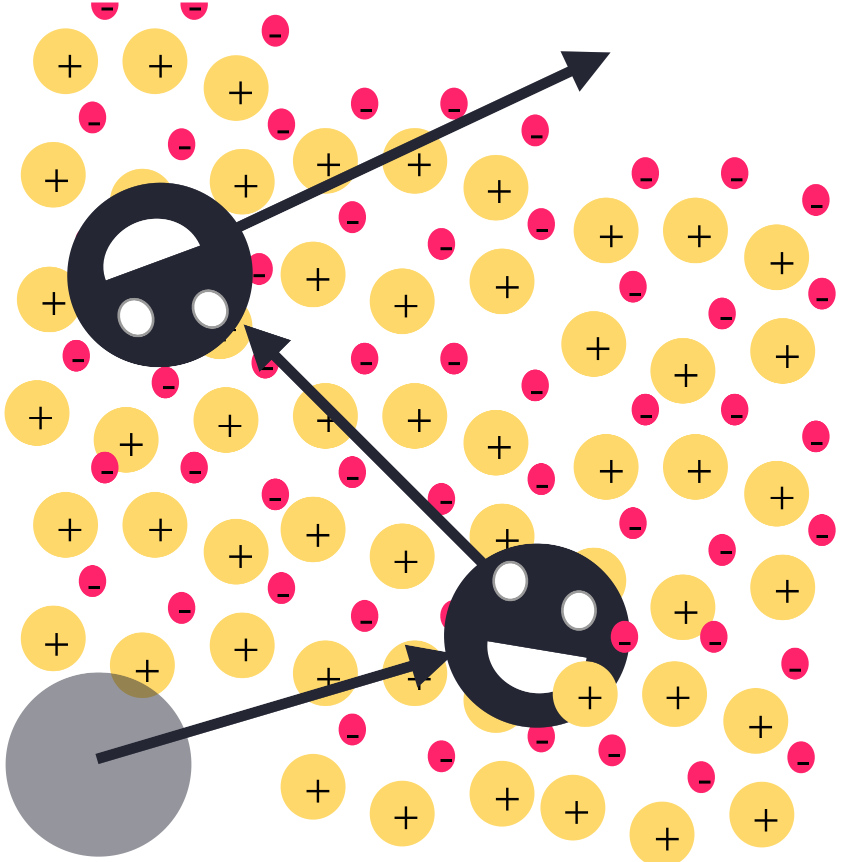
$$K \equiv l_\chi / r_\chi$$



LTE

$K < 1$

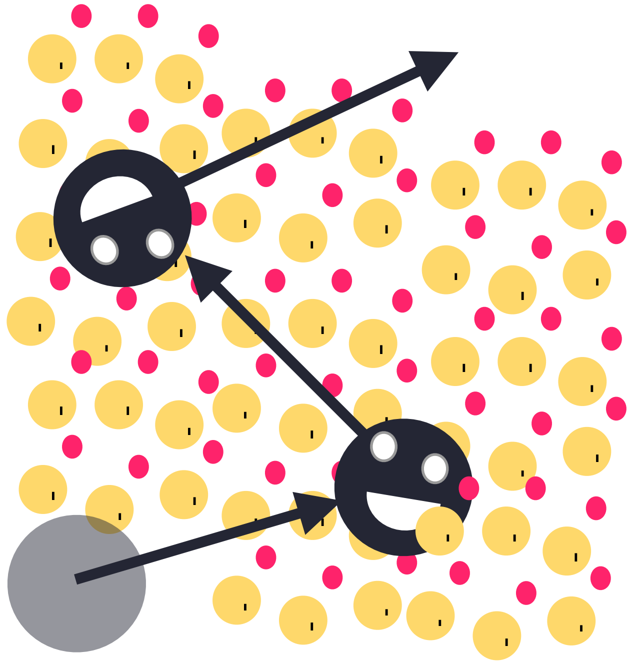
Somewhat
calculable
but unstable



optimal heat transport:
“Knudsen Peak”

not calculable

Knudsen peak depends sensitively on the microphysical interaction (i.e. the structure of the cross section)



E.g. `` billiard ball”

1/r force

$\mathbb{1}$ is the loneliest operator

$\mathcal{O}_1$	$1_\chi 1_N$
$\mathcal{O}_2$	$(\vec{v}^\perp)^2$
$\mathcal{O}_3$	$i\vec{S}_N \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
$\mathcal{O}_4$	$\vec{S}_\chi \cdot \vec{S}_N$
$\mathcal{O}_5$	$i\vec{S}_\chi \cdot (\frac{\vec{q}}{m_N} \times \vec{v}^\perp)$
$\mathcal{O}_6$	$(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\mathcal{O}_7$	$\vec{S}_N \cdot \vec{v}^\perp$
$\mathcal{O}_8$	$\vec{S}_\chi \cdot \vec{v}^\perp$
$\mathcal{O}_9$	$i\vec{S}_\chi \cdot (\vec{S}_N \times \frac{\vec{q}}{m_N})$
$\mathcal{O}_{10}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_N$
$\mathcal{O}_{11}$	$i\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi$
$\mathcal{O}_{12}$	$\vec{S}_\chi \cdot (\vec{S}_N \times \vec{v}^\perp)$
$\mathcal{O}_{13}$	$i(\vec{S}_\chi \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_N)$
$\mathcal{O}_{14}$	$i(\vec{S}_N \cdot \vec{v}^\perp)(\frac{\vec{q}}{m_N} \cdot \vec{S}_\chi)$
$\mathcal{O}_{15}$	$-(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N})\left((\vec{S}_N \times \vec{v}^\perp) \cdot \frac{\vec{q}}{m_N}\right)$

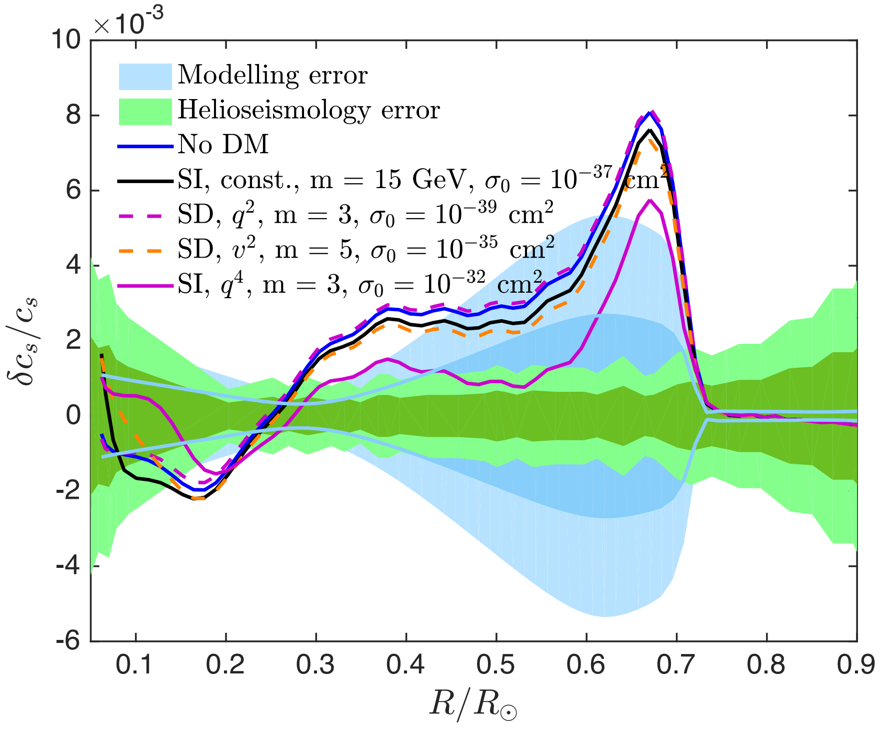
Theories of particle interactions can give scattering cross sections that depend on the kinematical quantities.

In the non-relativistic limit

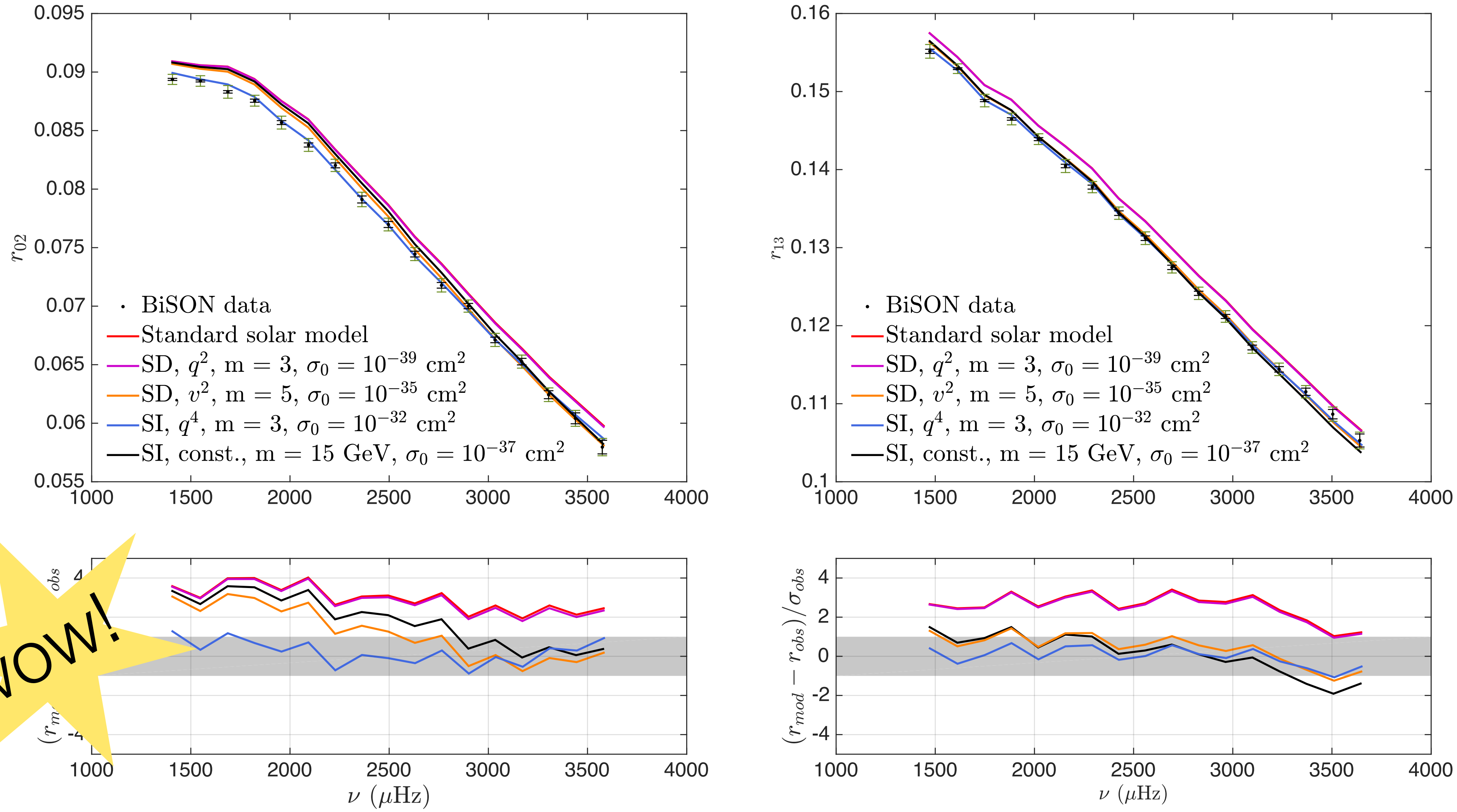
v_{rel}	Relative velocity
q	Exchanged momentum (scattering angle)
S_χ	Dark matter spin
S_N	Nuclear spin

In the Sun: expect very different sensitivity vs direct detection experiments.

Sound speed



Core

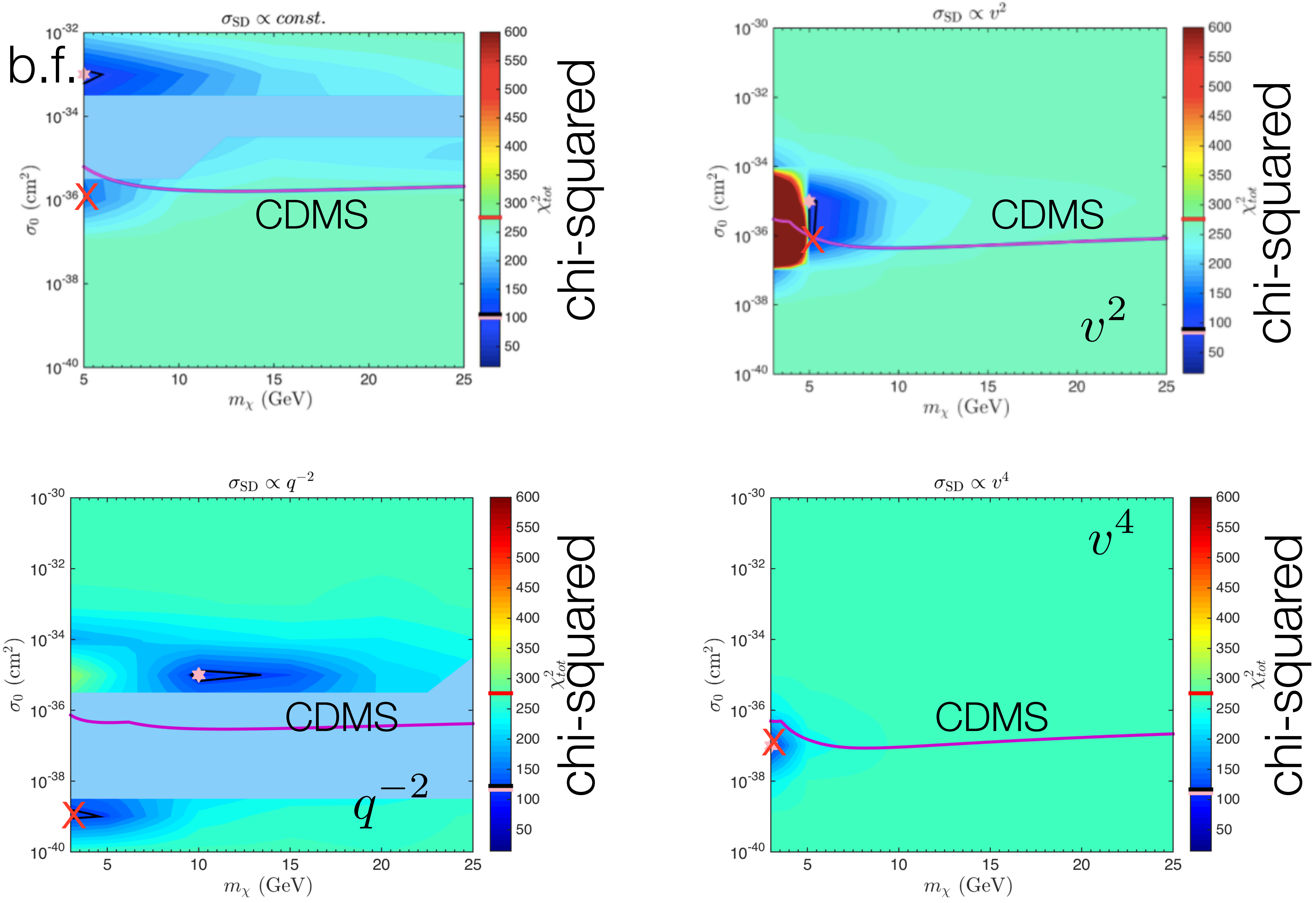


$\sigma_{n\chi} \propto q^4$

WOW!

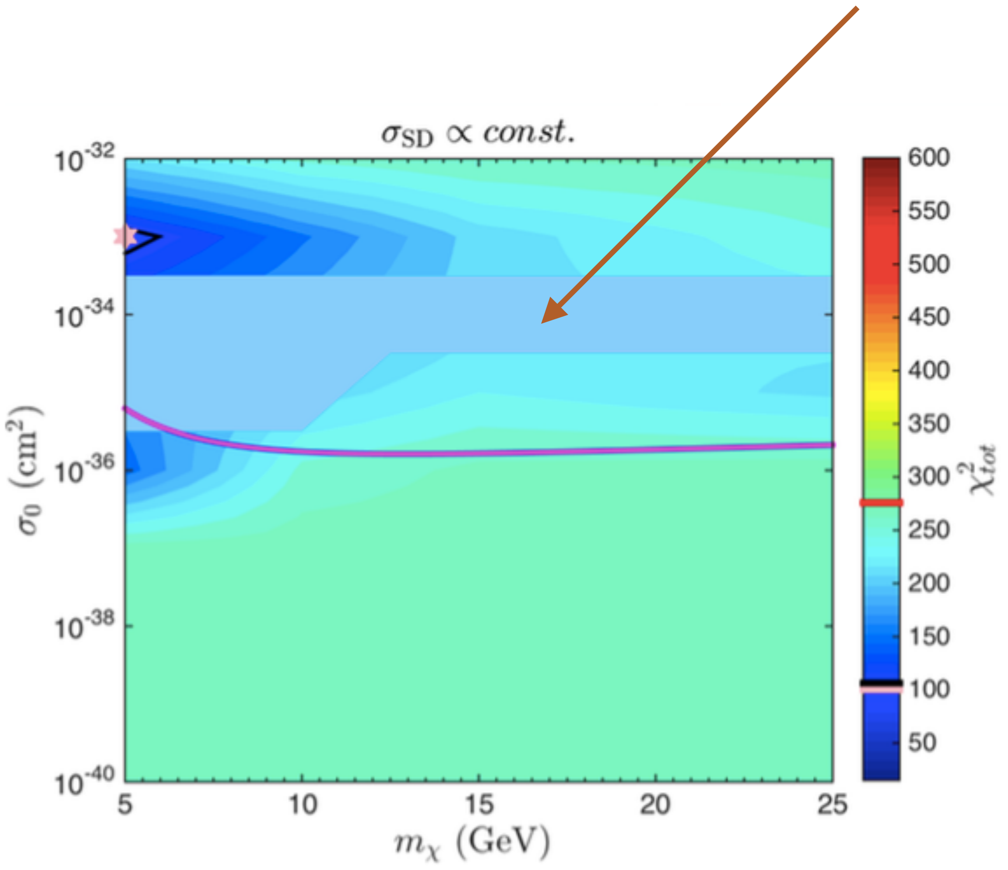
SI scattering ruled out by direct detection

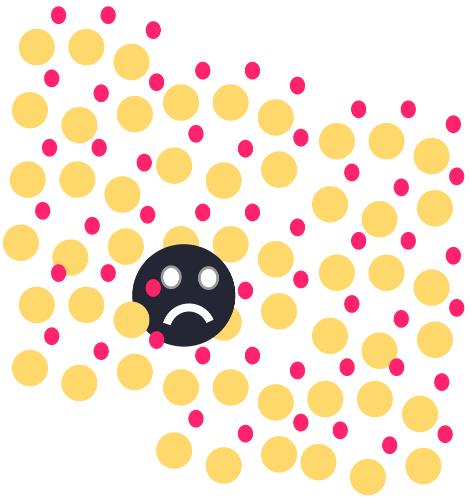
Spin-dependent scenarios



— SSM — Within 3 sigma of BF X Allowed

What's going on here?





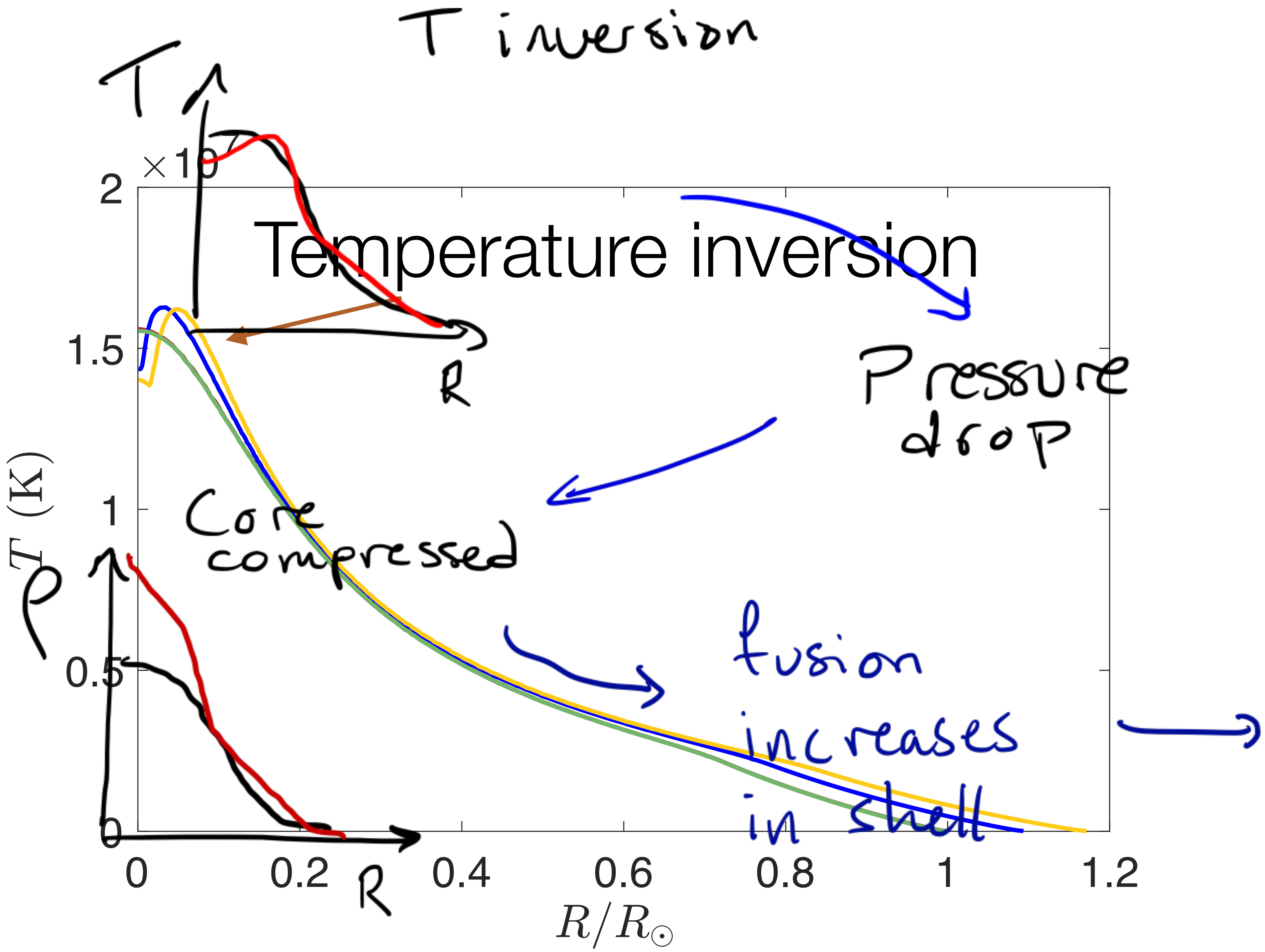
LTE

Somewhat calculable but unstable

- Very fast changes with respect to typical time scales
- Changes in structure are so strong that viable solar models (correct radius, temperature, luminosity) can't be obtained.
- **Similar effect occurs for smaller cross sections but to higher DM densities, e.g. in the galactic centre**

A bit more dark matter: shallower *T* gradient, pp fusion is “spread” a little more: star evolves a little slower with increasing DM concentrations.

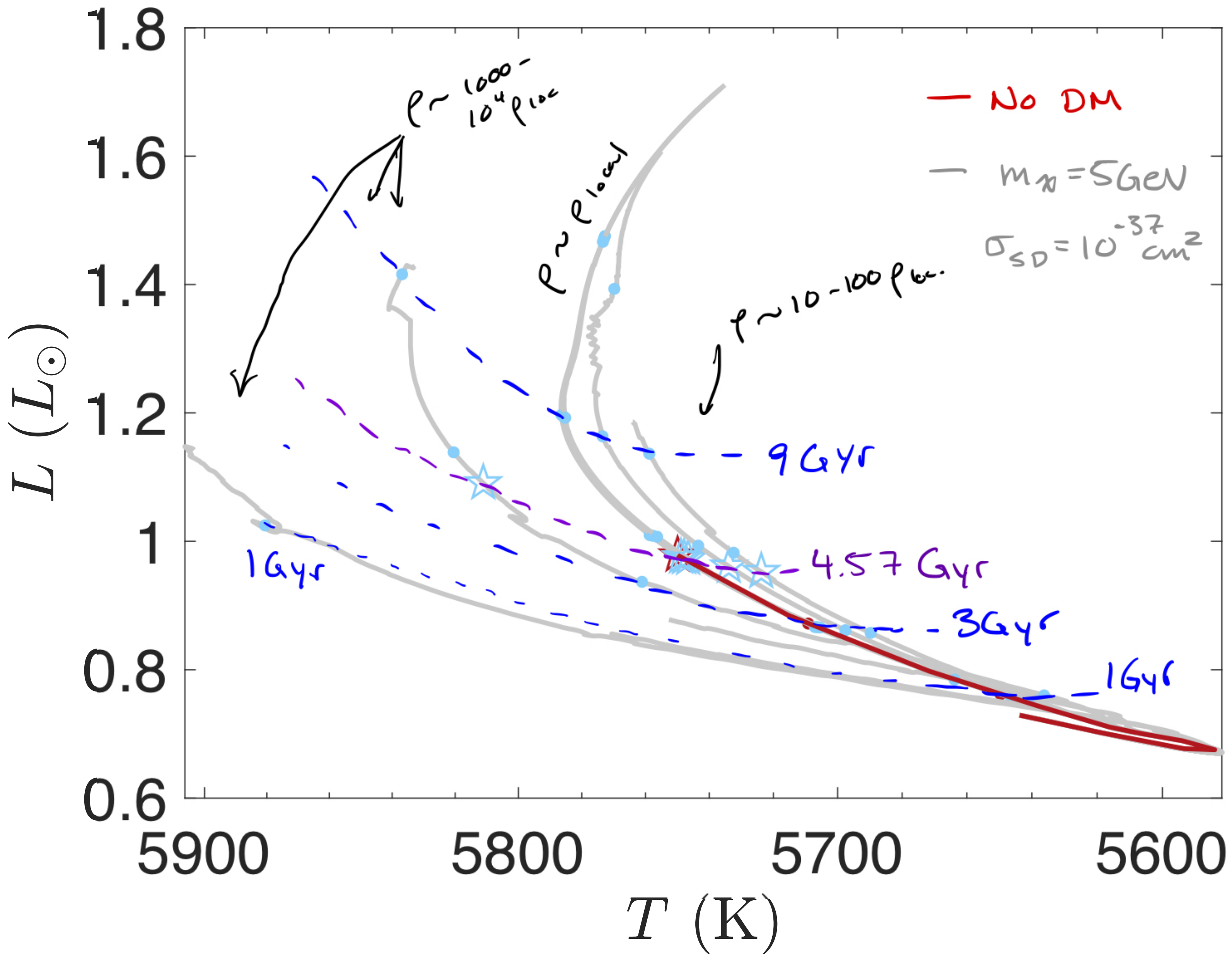
A lot more DM: crazy things start to happen



Star ages much faster, leaves MS at differen spot on HR diagram

Luminosity ↑
Surface T ↑
Radius ↑

Main Sequence evolution



A little more DM (10-100 times the local density): evolution slows down, star remains slightly cooler than Sun

A lot more DM (>500 times the local density): Temperature inversion causes very fast main sequence evolution: a little like the red giant phase

Weak interactions in DM-rich regions

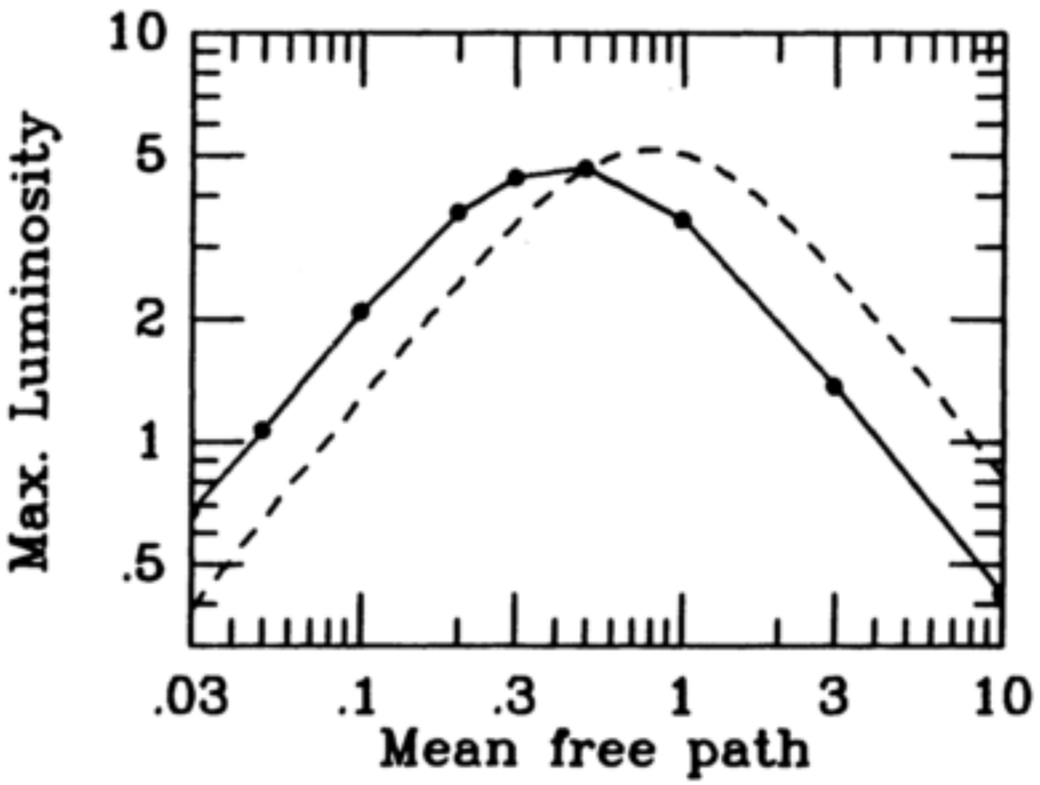
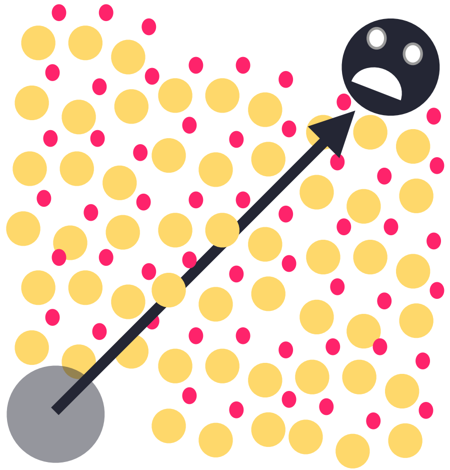
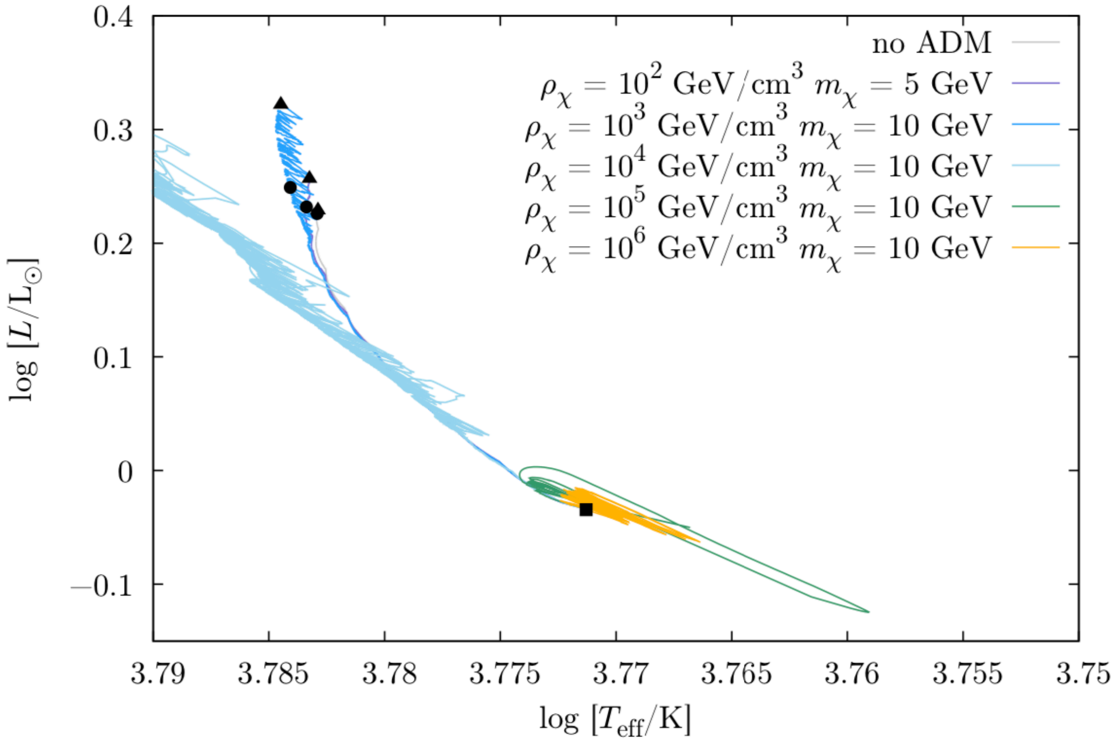


FIG. 11.—Maximum luminosity carried by WIMPs in our "generic" stellar model described in Fig. 8. The maximum refers to the luminosity curve 8c and the corresponding curves for other mean free paths. Each of the black dots corresponds to a Monte Carlo run for that value of the mfp. The dashed line is the formula used by Gilliland *et al.* (1986) in their investigation of WIMP heat transport in the Sun.

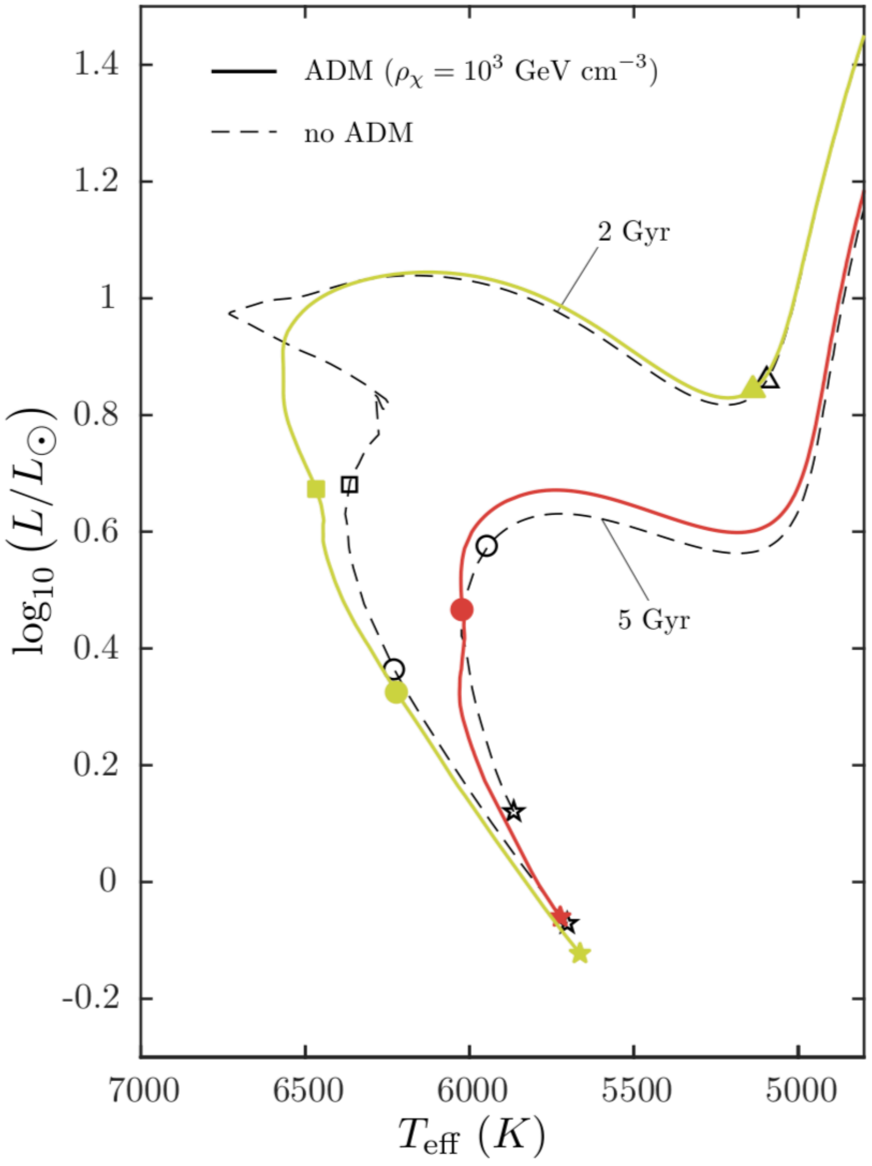


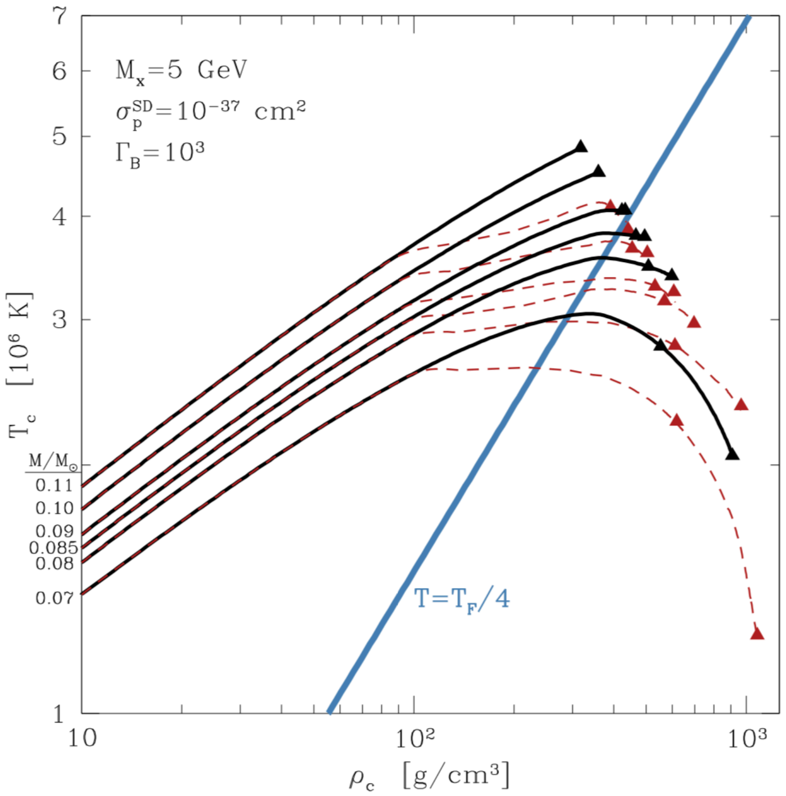
You can either use the nice, analytically tractable, wrong results from **Press and Spergel** (1987)
or the correct, semiempirical, unstable solution from **Gould and Raffelt** (1990)



Iocco et al.1201.5387
Dangerous instabilities

Lopés and Lopés (2019)
use Spergel & Press transport



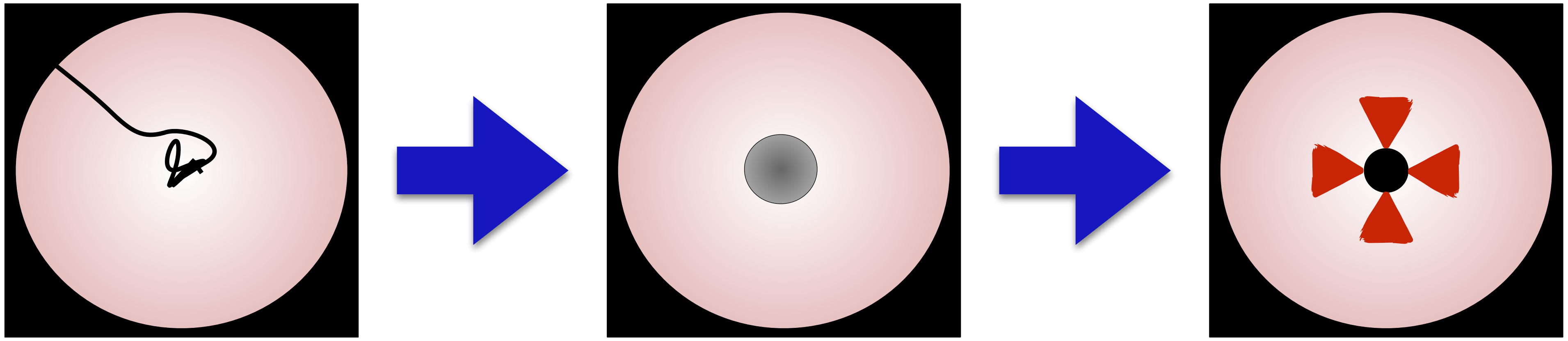


Hurst & Zentner 2011: Spergel & Press transport, some iffy approximations

Something is going on but nobody has managed to compute it correctly yet

Weird stars

Dark matter ignition of Type Ia SNe



Heavy asymmetric DM captured by White Dwarf

DM thermalizes at small radius

DM sphere collapses

DM sphere collapse
OR
BH evaporation

→ heats core to ~$\mathbf{10^{10}}$ **K** →

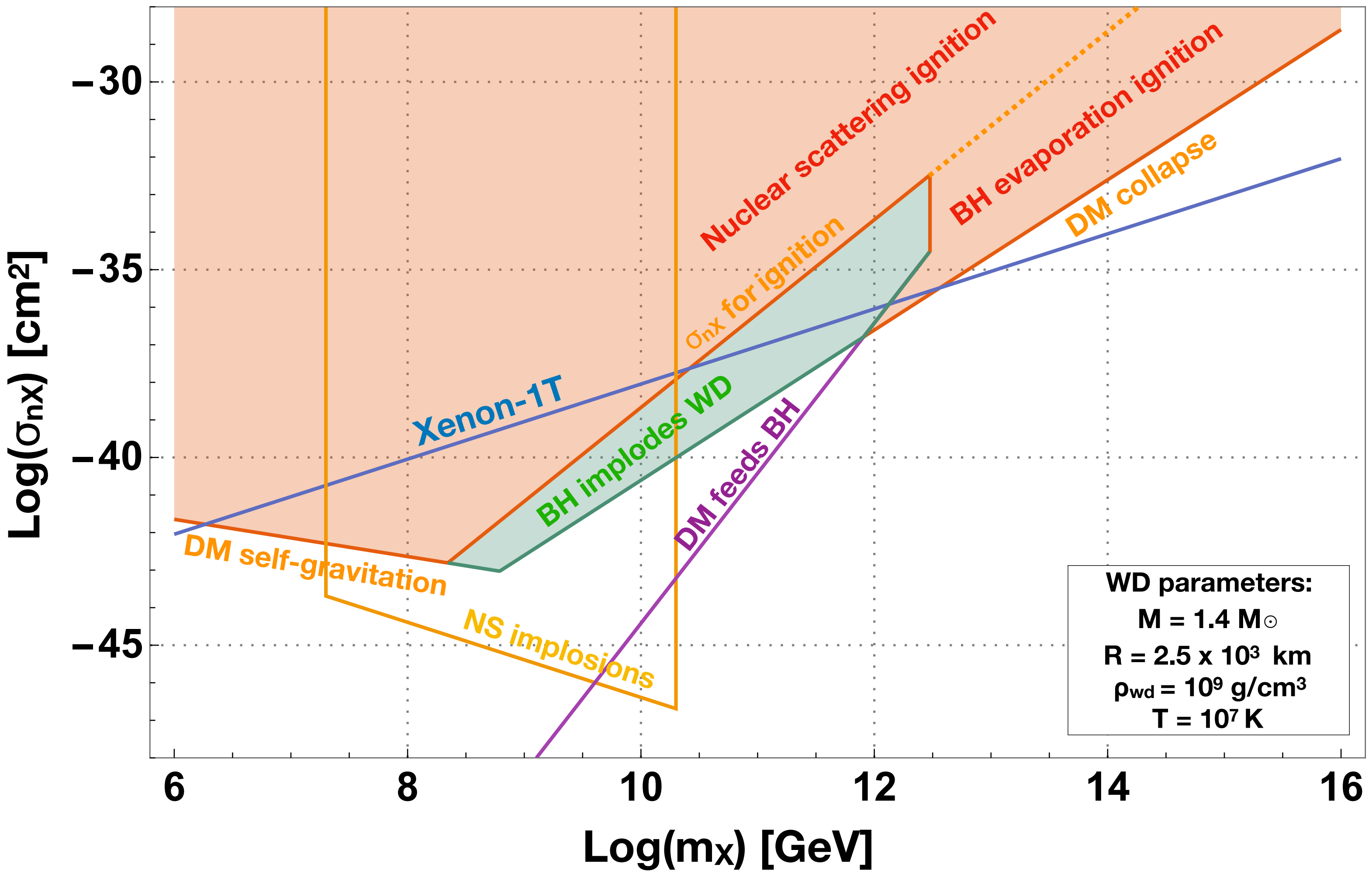
Type Ia SN is ignited in sub-Chandra mass WDs

Slide: Javier Fernandez-Acevedo Acevedo & Bramante, Phys. Rev. D **100** 043020, arXiv/1904.11993

Bounds from observation of a not-exploded WD

WD SDSS
J160420.40+05
5542.3

Age **~3.3 Gyrs**

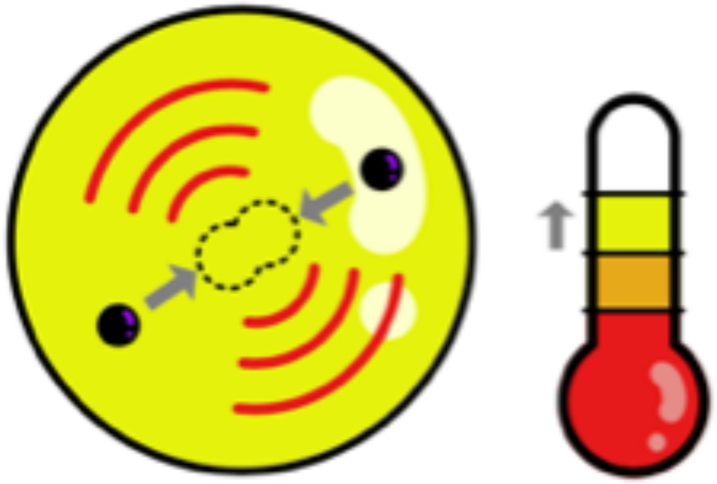


Slide: Javier Fernandez-Acevedo

Neutron stars (Nirmal Raj)

Minimum signature

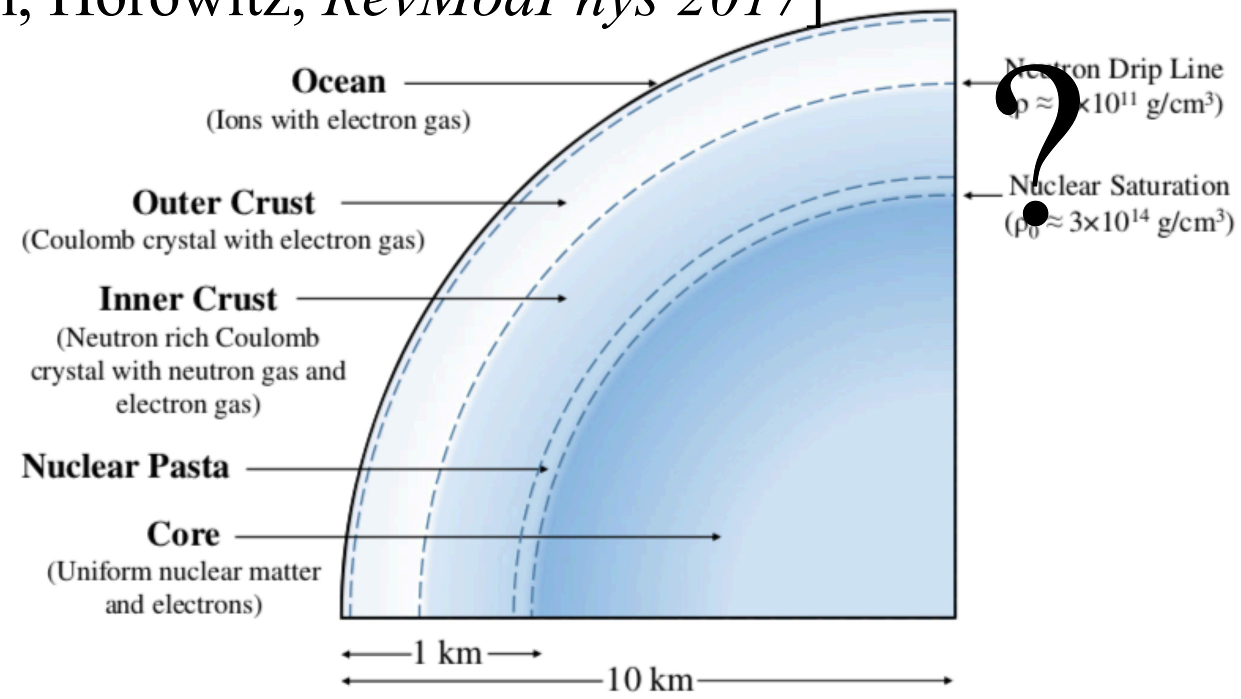
Possible bonus



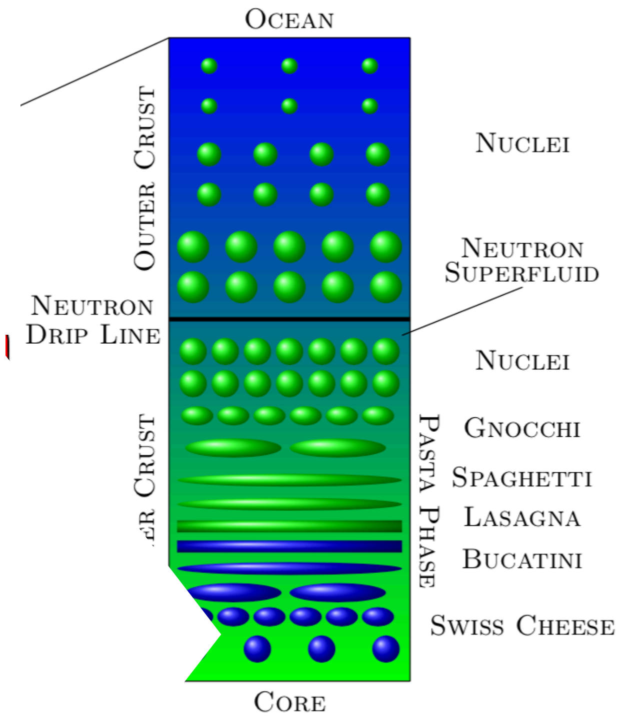
M Baryakhtar, J Bramante, S Li, T Linden, **N. Raj**
Phys.Rev.Lett. *119, 131801 (2017)*

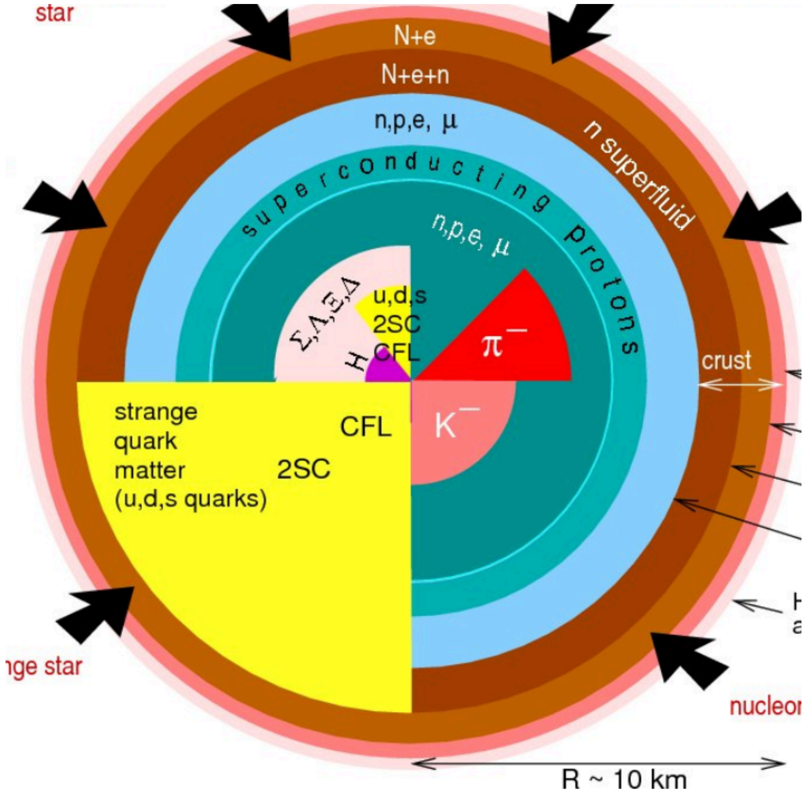
Heating nuclear pasta with DM (Nirmal Raj + friends)

[Caplan, Horowitz, *RevModPhys 2017*]

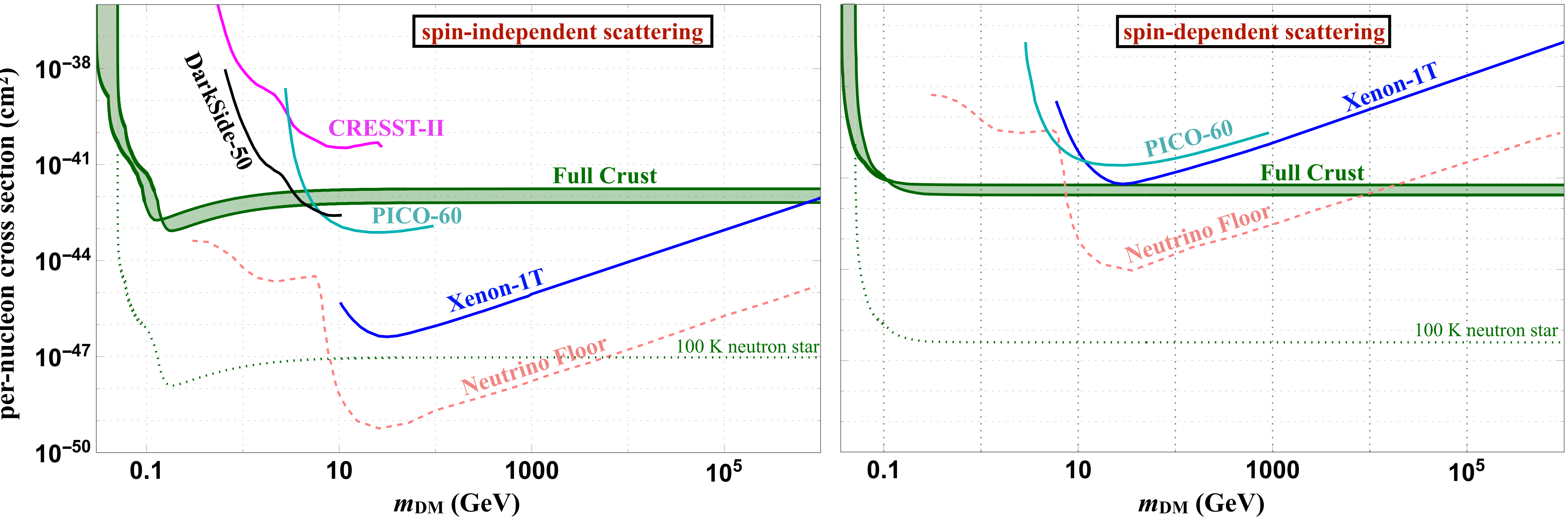


deeper =>
knowledge of structure
more uncertain





If you see a cool neutron star: limit on DM heating



Acevedo Bramante Leane Raj 1911.06334

Conclusions

There may be a connection between the solar composition and asymmetric dark matter

Can we see DM in distant stars? What happens when they stop burning hydrogen? More work needed!

Asymmetric dark matter: currently looking at **all** data with GAMBIT

DM can prevent cooling in WDs and neutron stars…
and can ignite WDs and act as a mechanism for type Ia supernova detonation

Hubble Legacy Archive, NASA, ESA