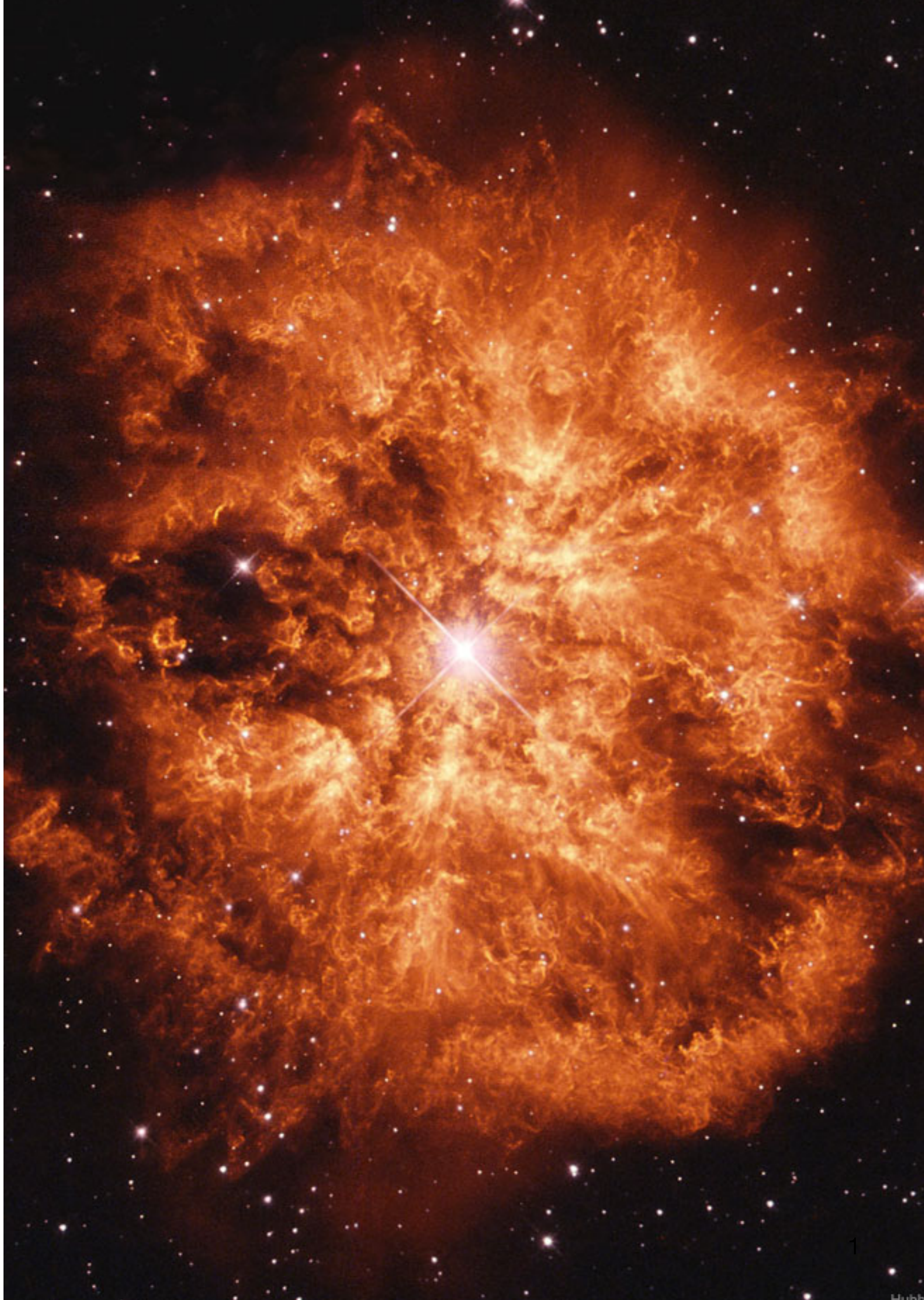
Dark matter in stars

Aaron Vincent

MPI Heidelberg - Online - December 6 2020



Institut Canadien de Recherche en Physique des Astroparticules
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Queen's University

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

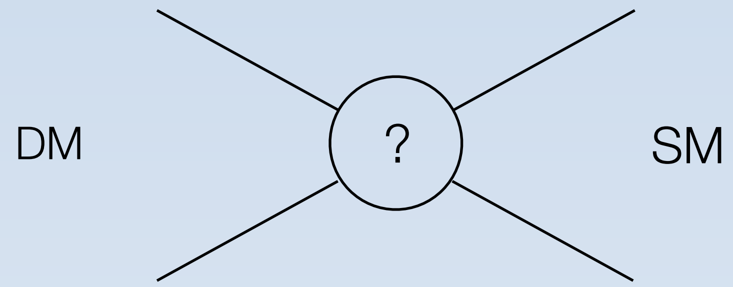
arXiv:1703.07784/JCAP 1710 (2017)10 037: G.Busoni, A. de Simone, P. Scott, ACV
Generalised solar capture and evaporation of DM

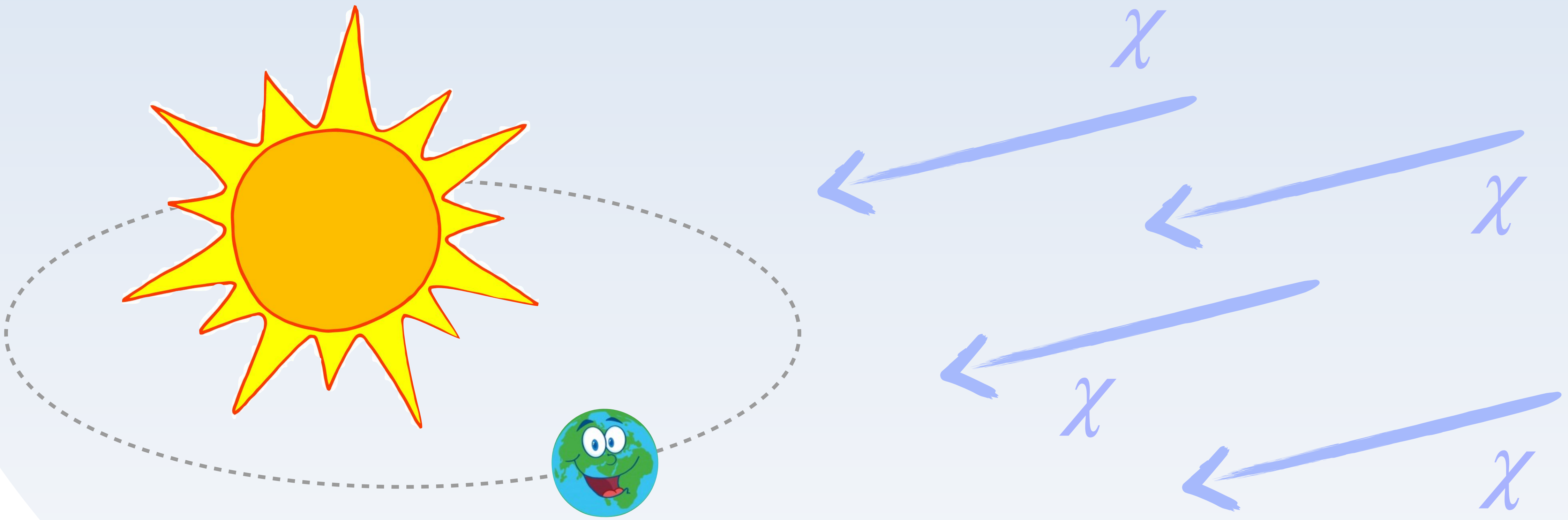
++ work in progress w/ Hannah Banks, Siyam Ansari (Imperial), Neal Kozar (Queen’s)

Overview

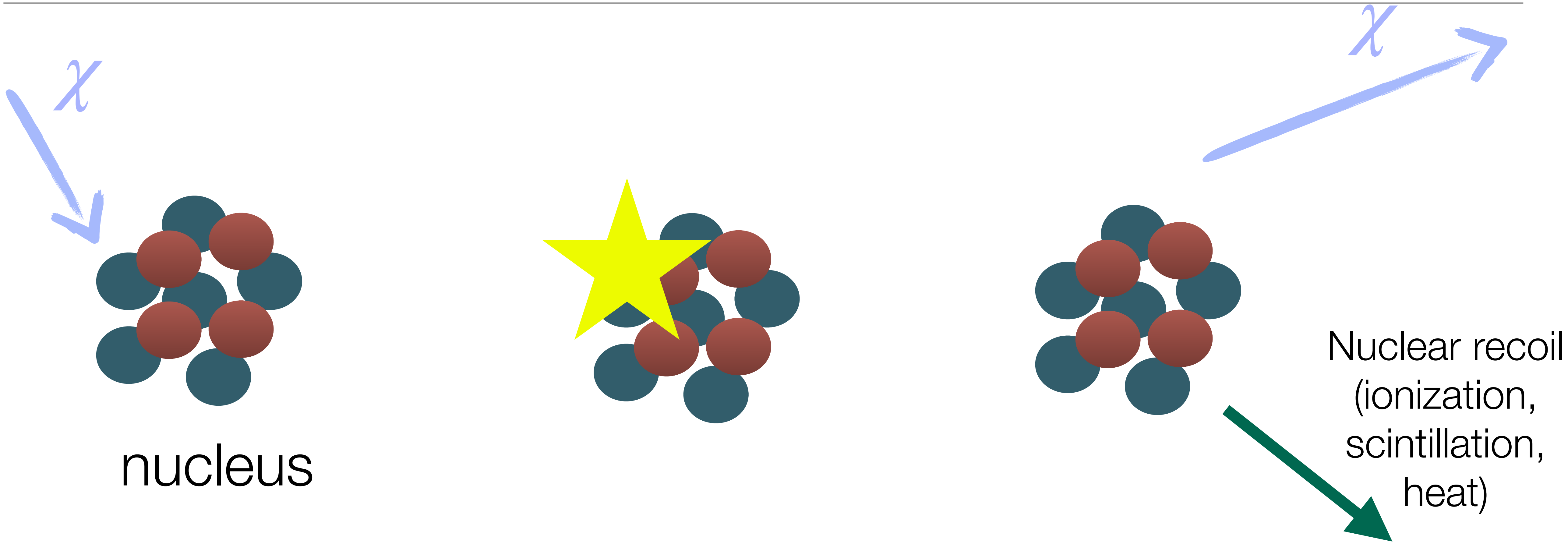
1. **Dark matter capture in the Sun**
2. Asymmetric dark matter
3. Beyond the Sun — the Danger zone

Direct detection





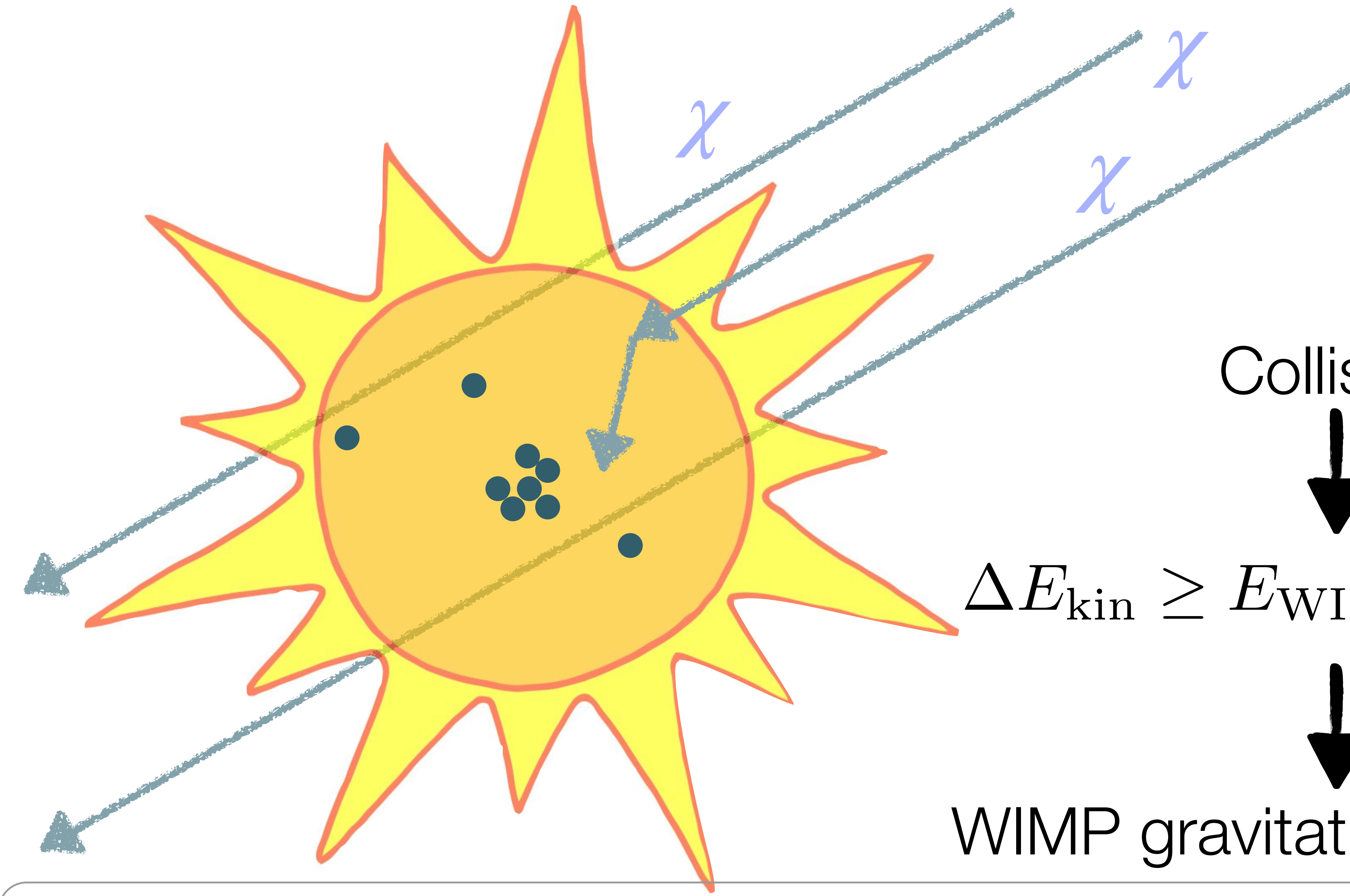
Direct detection



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



Collision

↓

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

↓

WIMP gravitationally bound

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

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

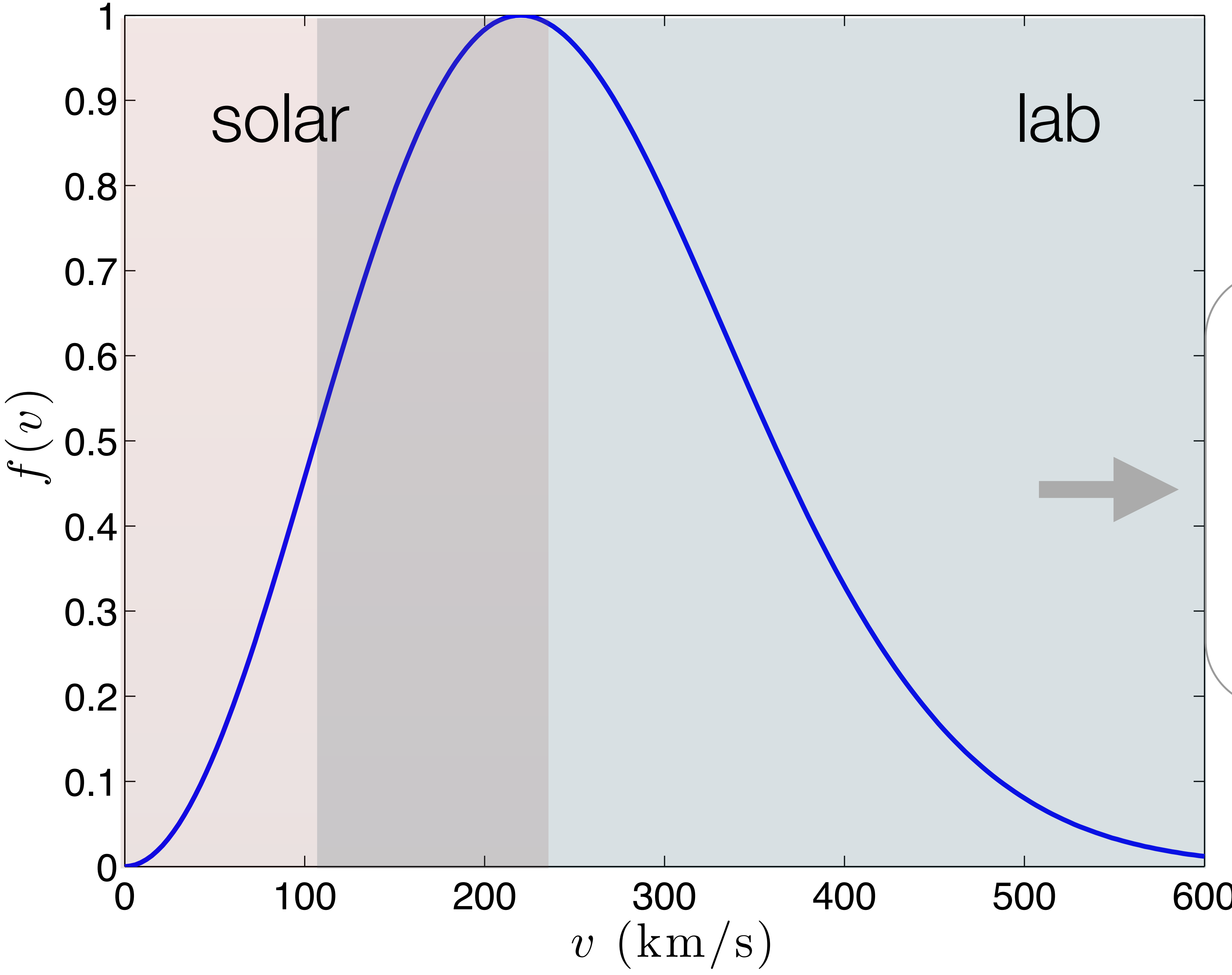
$C(t)$ Capture rate $\propto \frac{\rho_\odot}{m_\chi} \int dV_\odot \int dv \frac{f(v)}{v} \sigma$

$A(t)$ Annihilation rate $\propto N_\chi^2$

$E(t)$ Evaporation rate (m <~ 4 GeV) $\propto N_\chi$

(see Busoni, de Simone, Scott, AV 1703.07784)

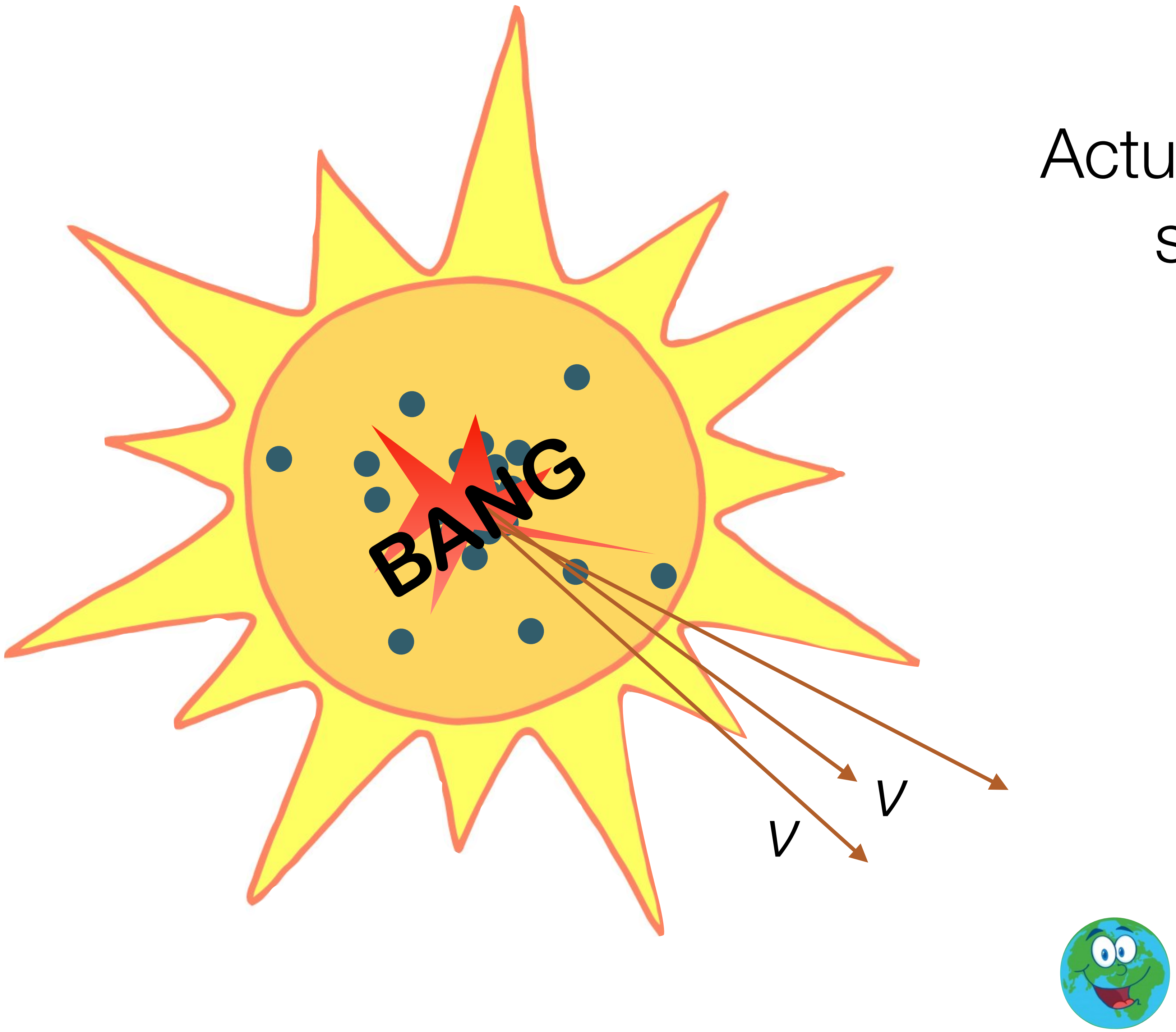
Differences with earth-based detection



More sensitive to lighter DM

Different particle couplings

If DM annihilates: look for neutrinos



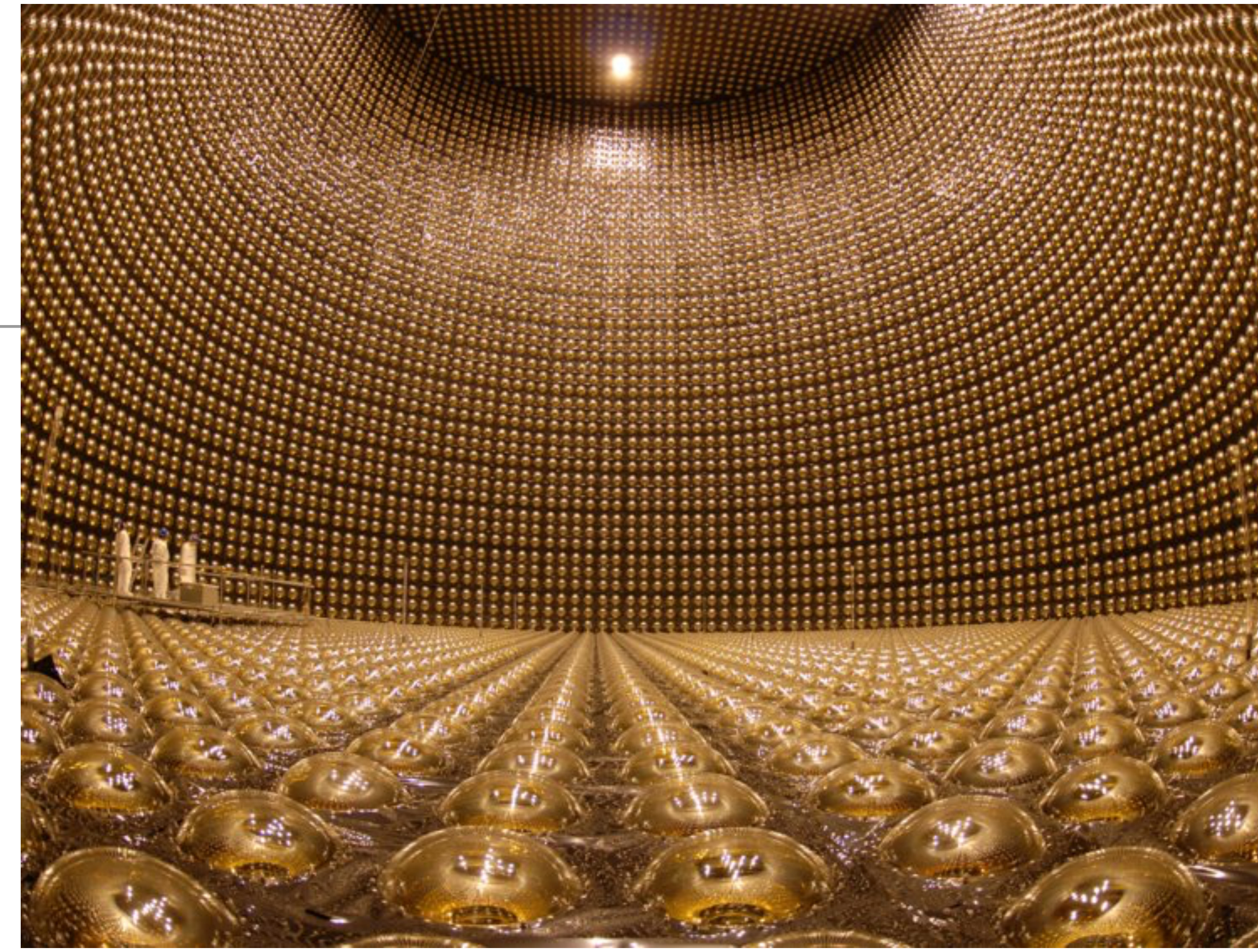
Actually, you reach a steady state:
$C(t) = A(t)$

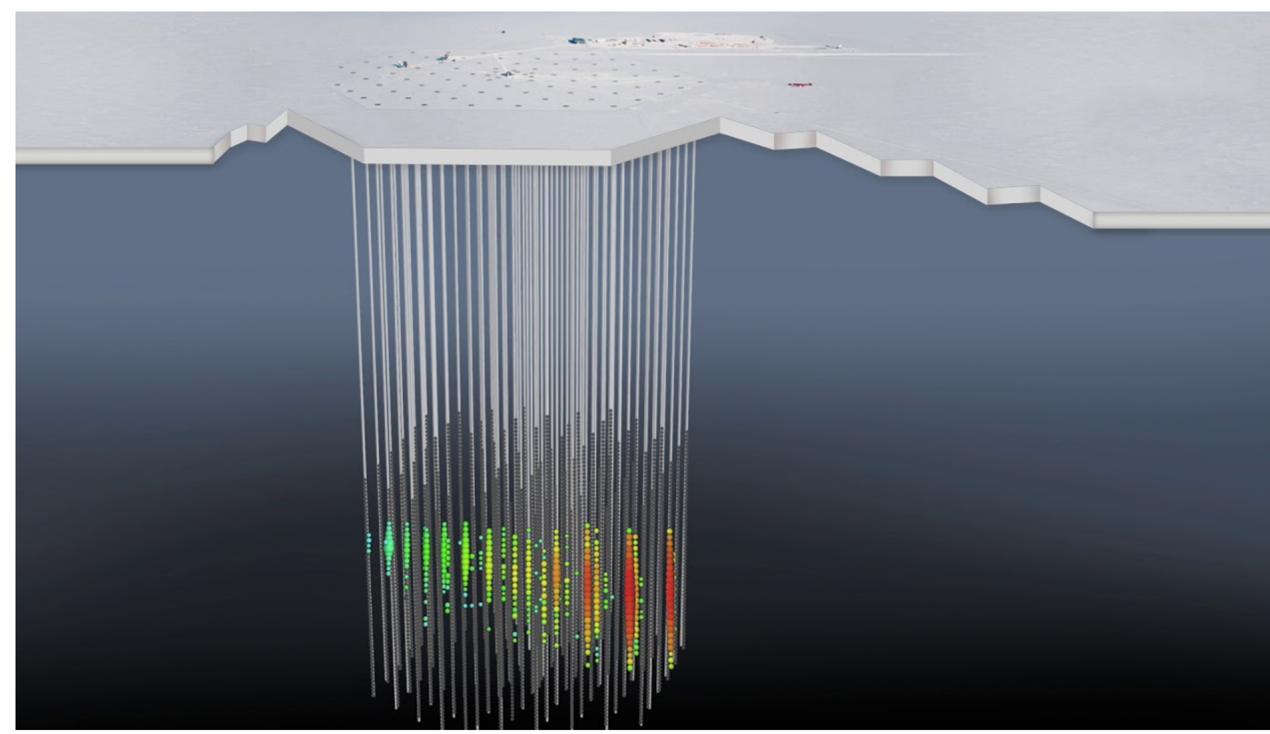
Neutrinos at Earth

$$E_\nu \simeq m_\chi / f$$

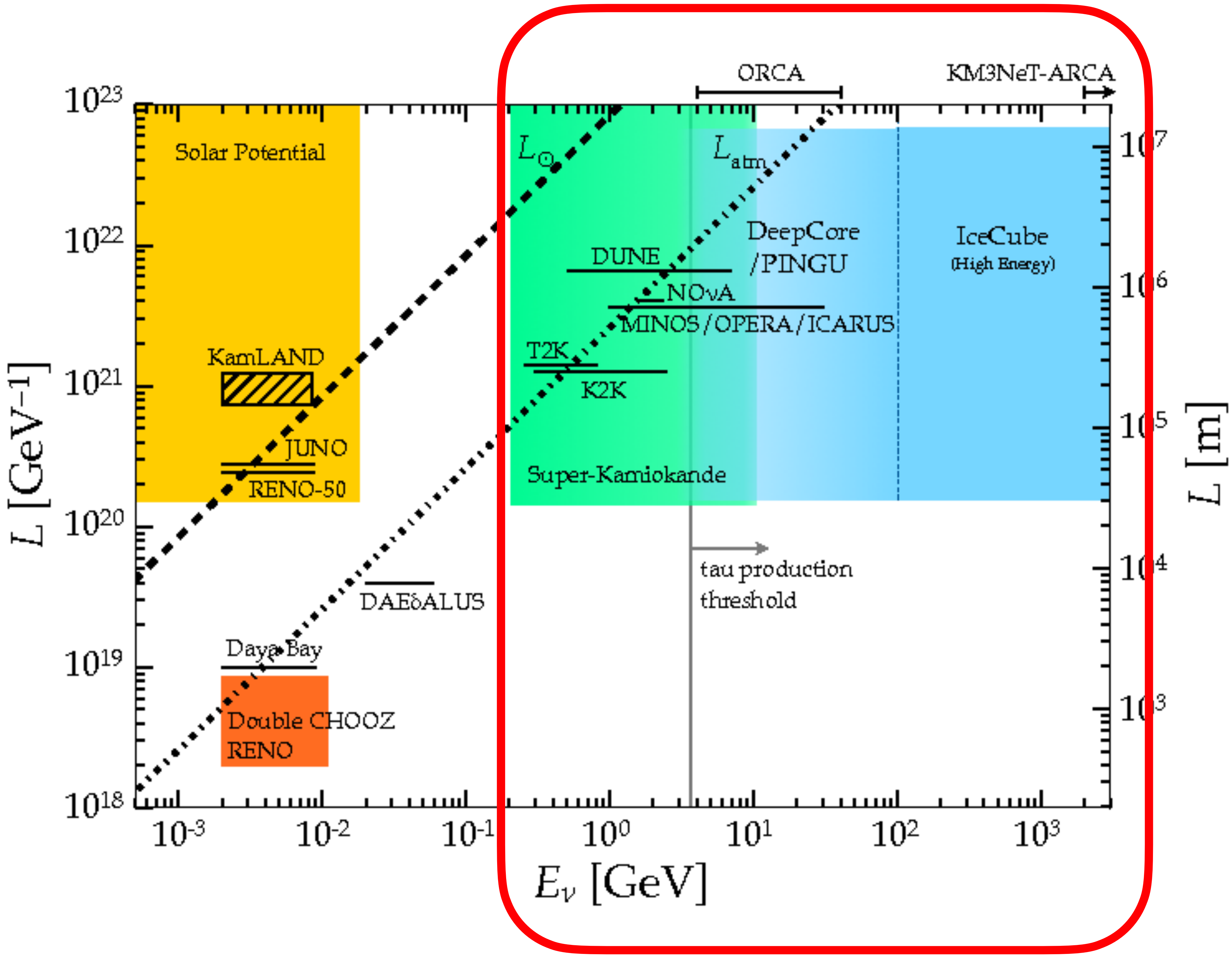
f is a number of O(1-10)

Solar neutrinos (the ones from nuclear fusion) produce < 10 MeV scale neutrinos. This means that **GeV or higher neutrino** signals from the solar core are a **smoking gun for new physics**.*

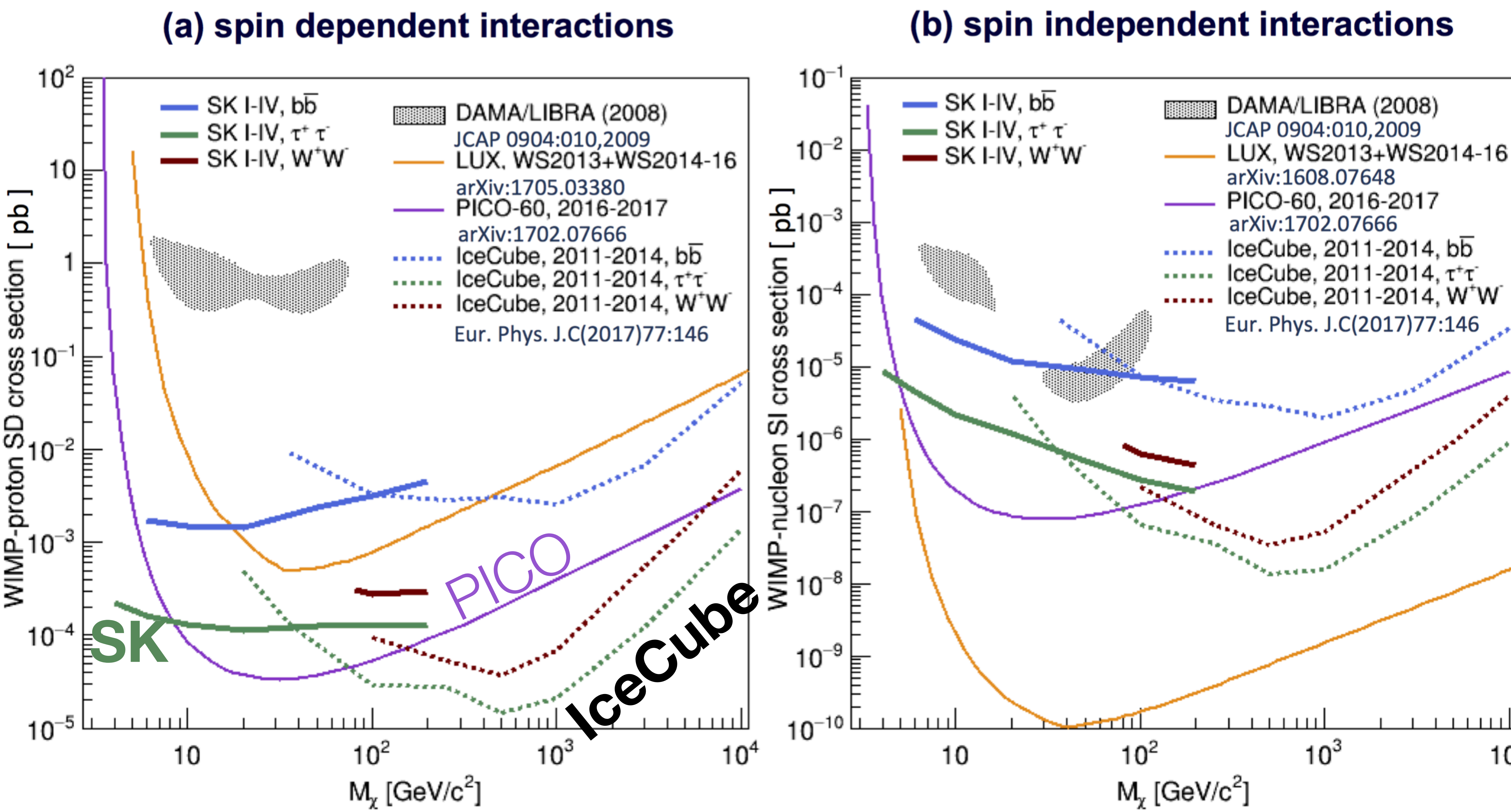




*except for solar atmospheric neutrinos shh



ORCA
KM3NeT-ARCA
Solar Potential
$L_\odot$
L_{atm}
DeepCore
/PINGU
IceCube
(High Energy)
DUNE
NOνA
MINOS/OPERA/ICARUS
T2K
K2K
KamLAND
JUNO
RENO-50
Super-Kamiokande
tau production
threshold
DAEδALUS
Daya Bay
Double CHOOZ
RENO
L [GeV^{-1}]
L [m]
E_ν [GeV]

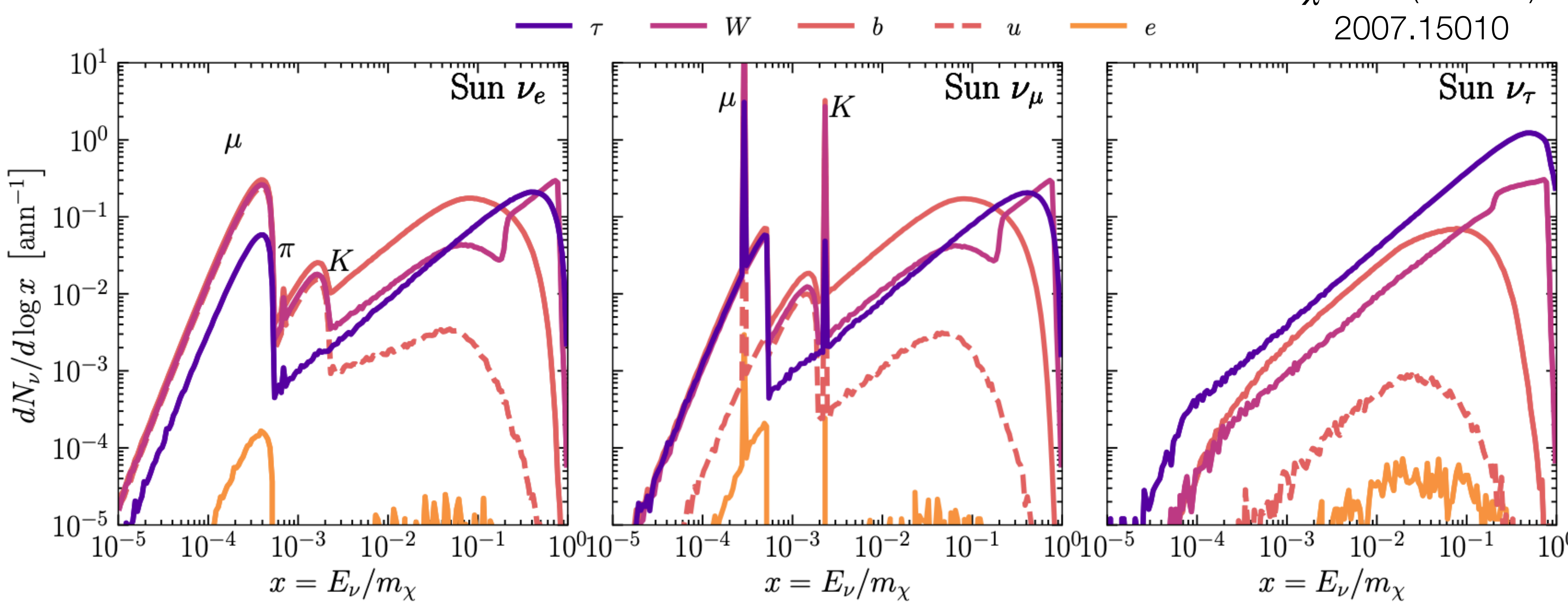


Mijakowski/SuperK 2020

Stopped mesons

Monoenergetic neutrinos from stopped meson (pi, K) decay can provide complementary constraints at low mass

$\chi aro\nu$ (Liu et al) 2007.15010



https://github.com/IceCubeOpenSource/charon

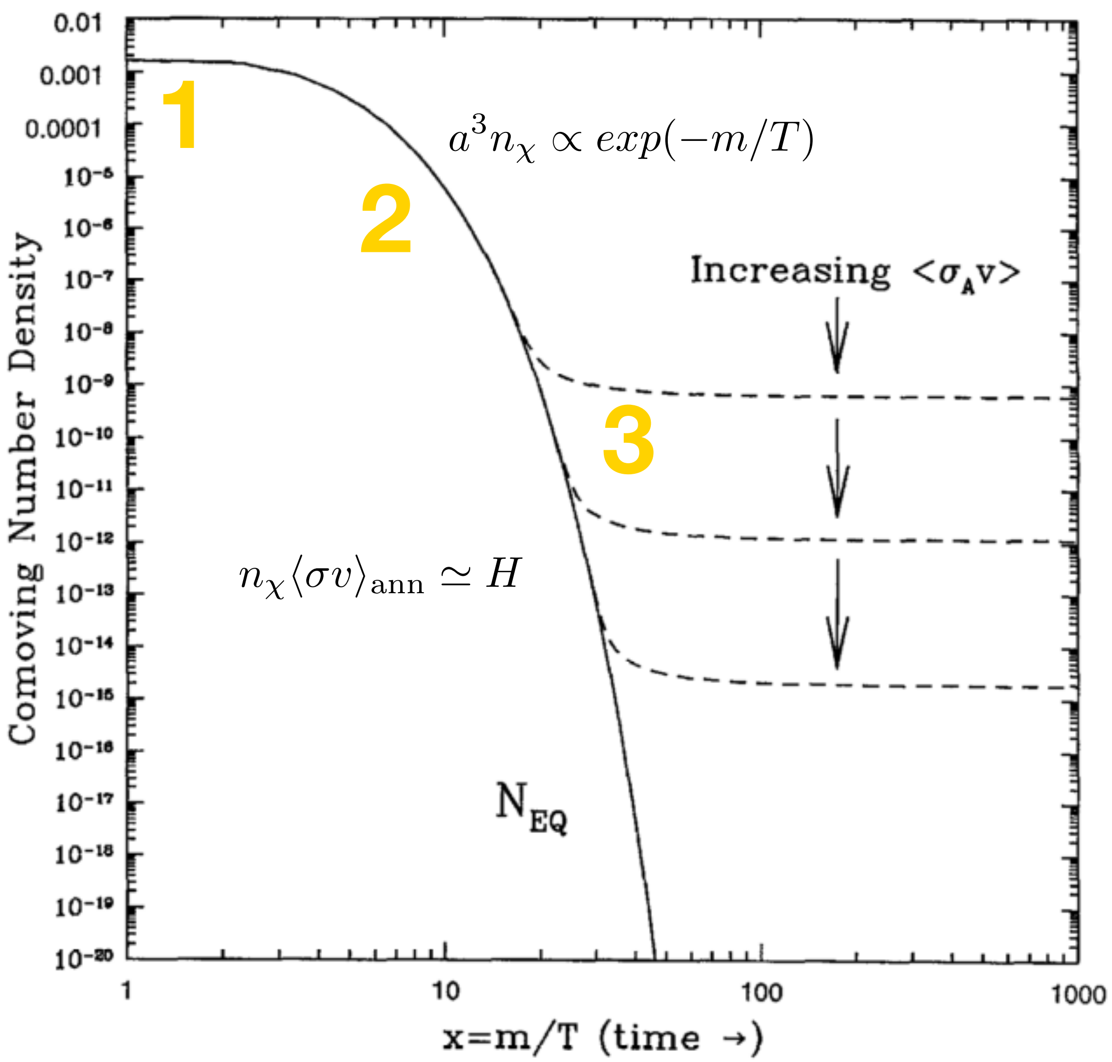
See also Rott et al 1609.04876

1. Dark matter capture in the Sun

2. **Asymmetric dark matter**

3. Beyond the Sun — the Danger zone

"WIMP miracle"



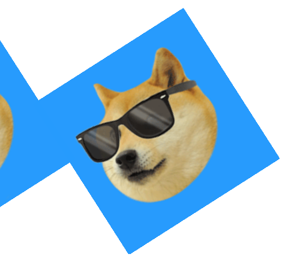
"Weak scale" cross section

$m_{DM} \gtrsim 100$ GeV $\qquad \Omega_{DM} h^2 \sim 0.1$

If we try with SM

Similar approach with **Neutrinos** (keeping in mind m << T)

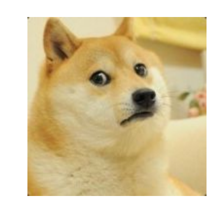
$$\Omega_{\nu,FO} = \Omega_{\nu,obs}$$
$$(N_{\nu,eff} = 3.046)$$

Baryons?

Annihilation of a symmetric baryon component:

$$\Omega_{B,FO} \sim 10^{-10}$$



"baryon disaster" (Sarkar)

Require an **initial asymmetry**

Starting over:

Require $\eta_b = \frac{n_B - \bar{n}_B}{n_\gamma} \sim 10^{-9}$

Note $\Omega_{DM} \sim 5\Omega_b$

So if we start with an initial (shared) asymmetry such that

$$n_b \sim n_{DM}$$

$$\Rightarrow m_{DM} \sim 5m_b$$

Observed abundance-> prediction of a mass scale

If asymmetry is generated before thermal freeze-out

$$\Downarrow$$

Exponential Boltzmann suppression means

$$\langle \sigma v \rangle_{ann} \gtrsim \text{few} \times \langle \sigma v \rangle_{\rm WIMP}$$

Mass-asymmetry relation:

$$\frac{m_{DM}}{m_p}\frac{\eta_D/q}{\eta_B} = \frac{1 - r_\infty}{1 + r_\infty}\frac{\Omega_{DM}}{\Omega_b}$$

Reviews

Petraki & Volkas 1305.4939

Zurek 1308.0338

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

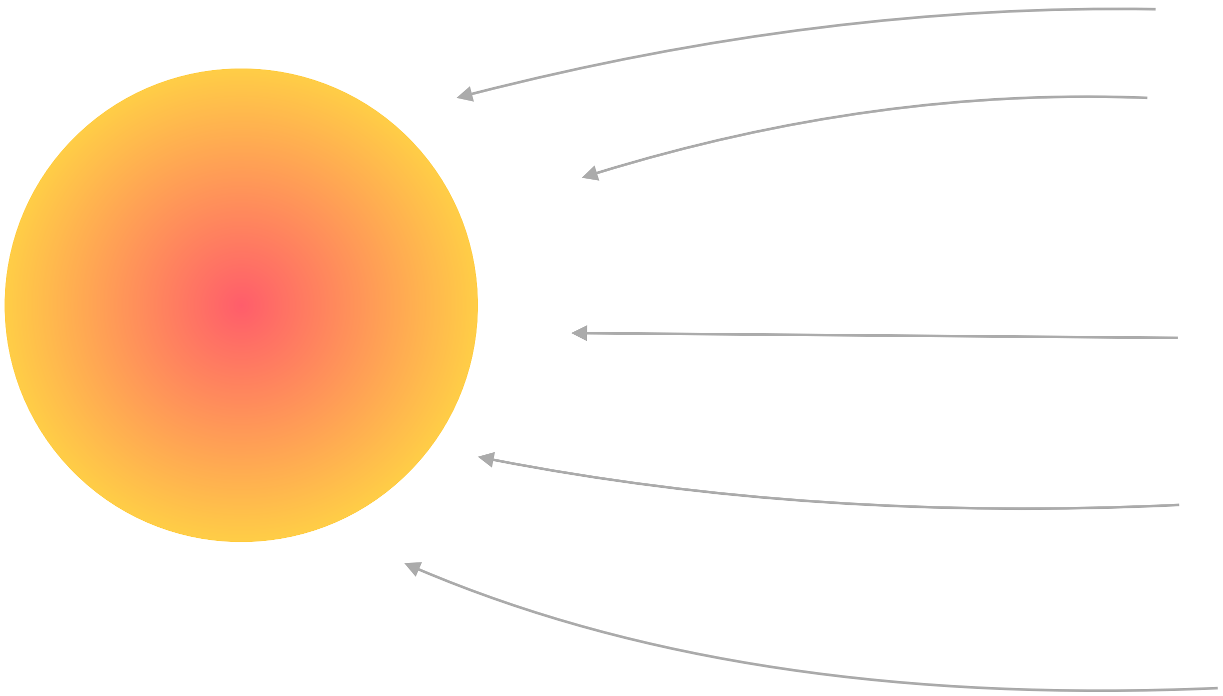
Suppressing annihilation (Asymmetric DM)

No annihilation: DM just accumulates…

Can accumulate a lot of DM

$$N_\chi \lesssim 2\pi R_\odot^2 (\rho_\chi / m_\chi) v_\odot T_\odot$$

$$\simeq 10^{-10} n_p \sim 10^{46}$$

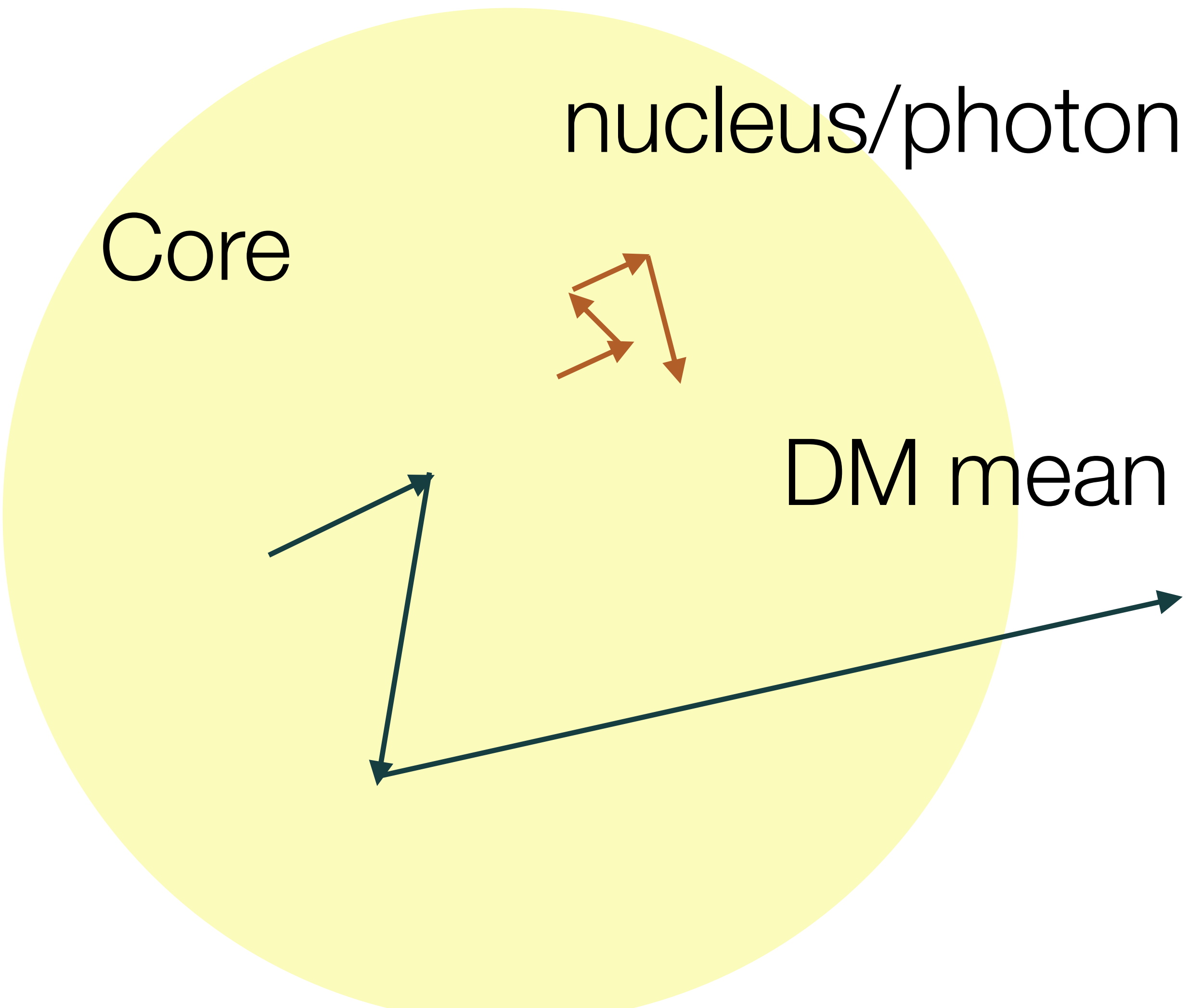


(impact parameter a little bigger than $R_\odot$ thanks to gravity)

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 $\phi_{\nu, ^8\mathrm{B}} \propto T_c^{25}$

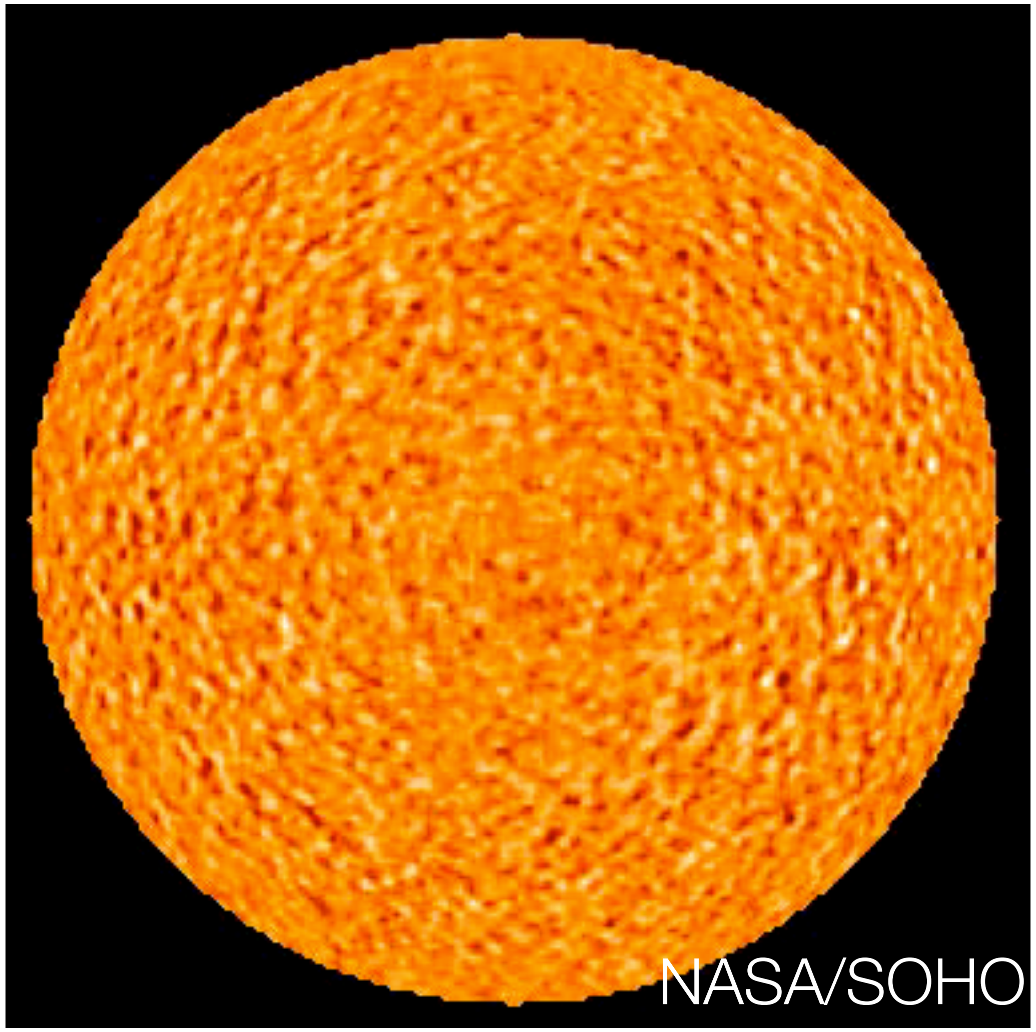
*actually this mechanism was first studied as part of the solar neutrino problem: lower than expected solar core T —> fewer neutrinos

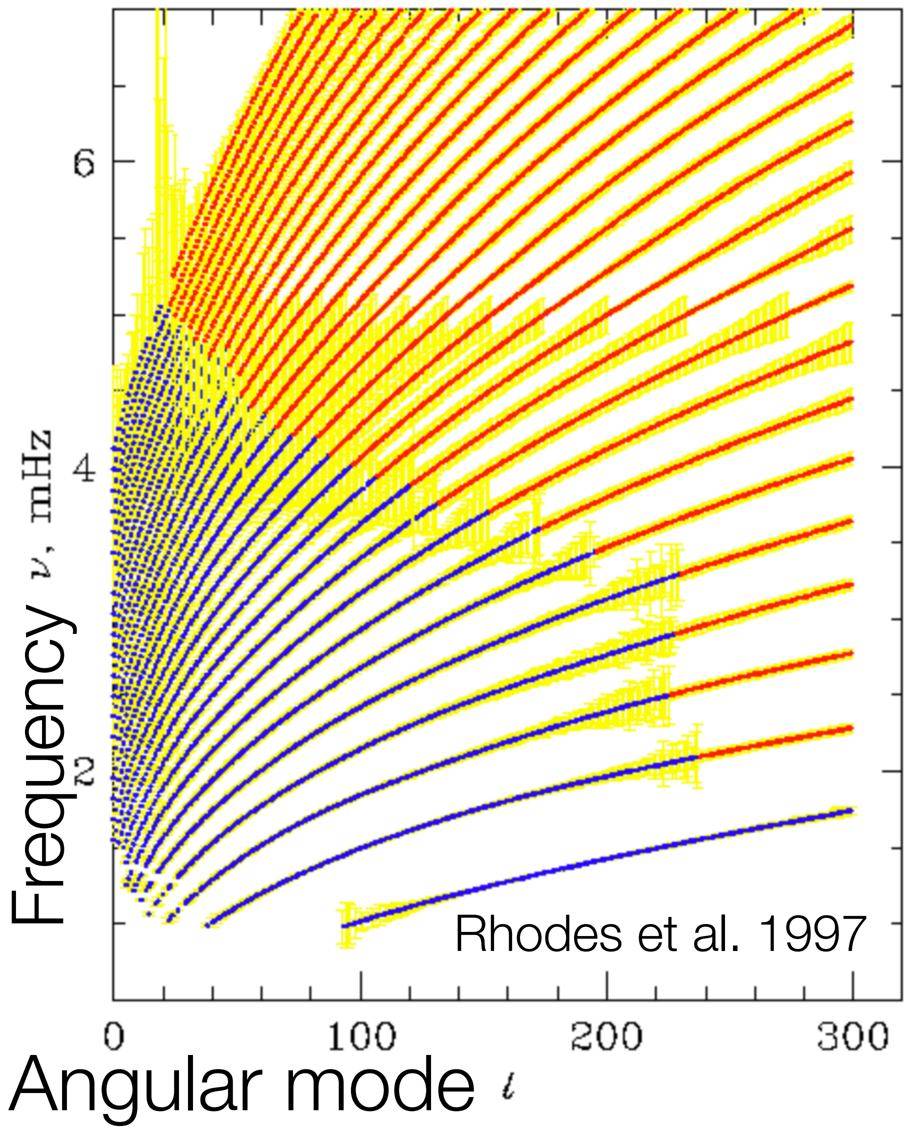
Helioseismology?

Development

- the 80's & the first solar crisis: Nauenberg, Press & Spergel, Gould & Raffelt
- The renaissance: Lopes/Bertone/Silk astro-ph/0205066++, Scott et al 0809.1871++
- The post-modern era (second solar crisis): Frandsen & Sarkar 1003.4505; Cumberbatch et al 1005.5102; Taoso et al 1005.5711; Lopes, Silk, Casanellas (+ many papers), ACV, Scott, Serenelli, Busoni (many papers)
- Other stars: Casanellas ++ 1212.2985 & a few more
- And a lot more…

Helioseismology





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

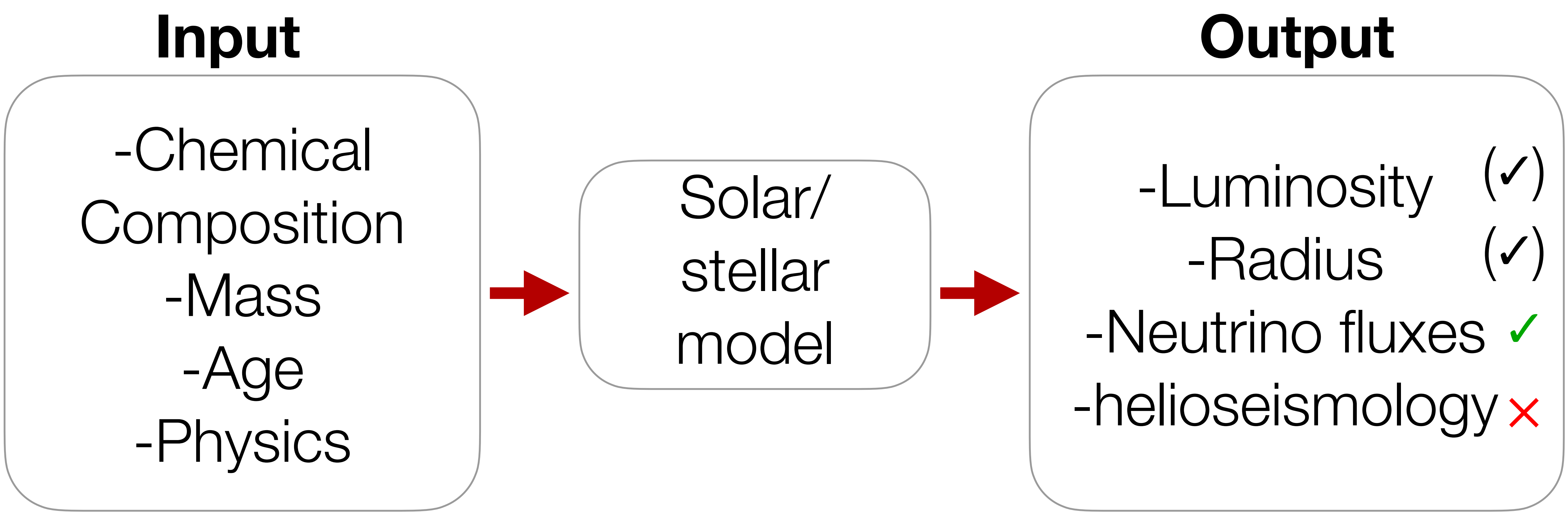
-**density**

-**sound speed**

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

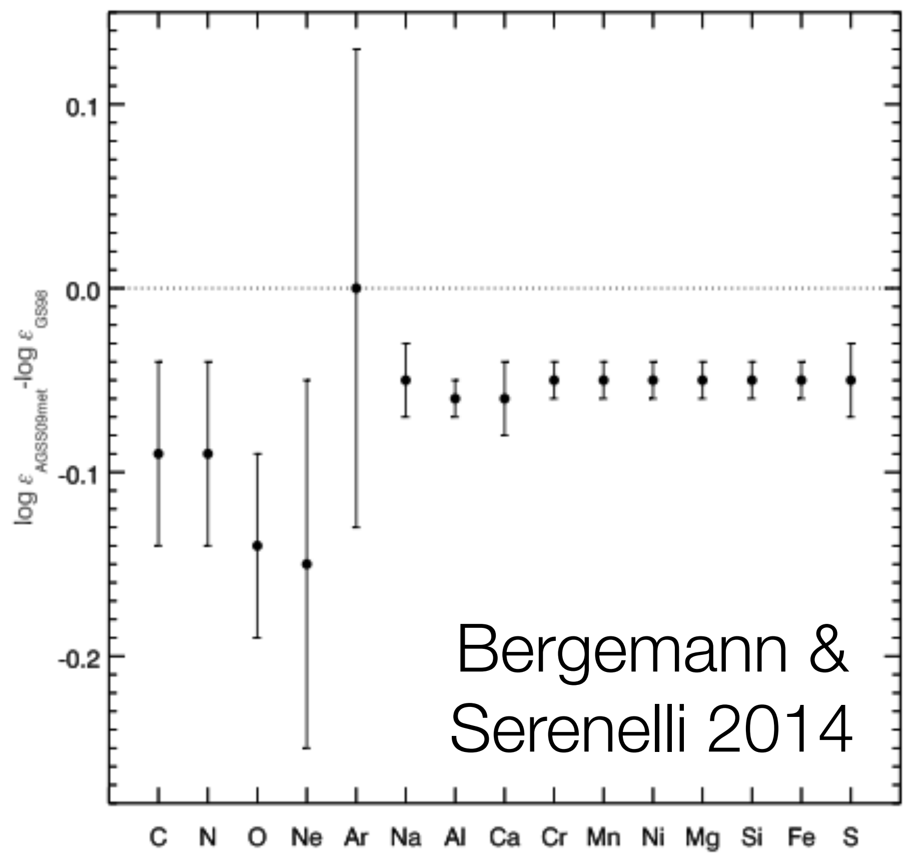
-**convective zone radius**

Standard Solar Model (since 1970s)

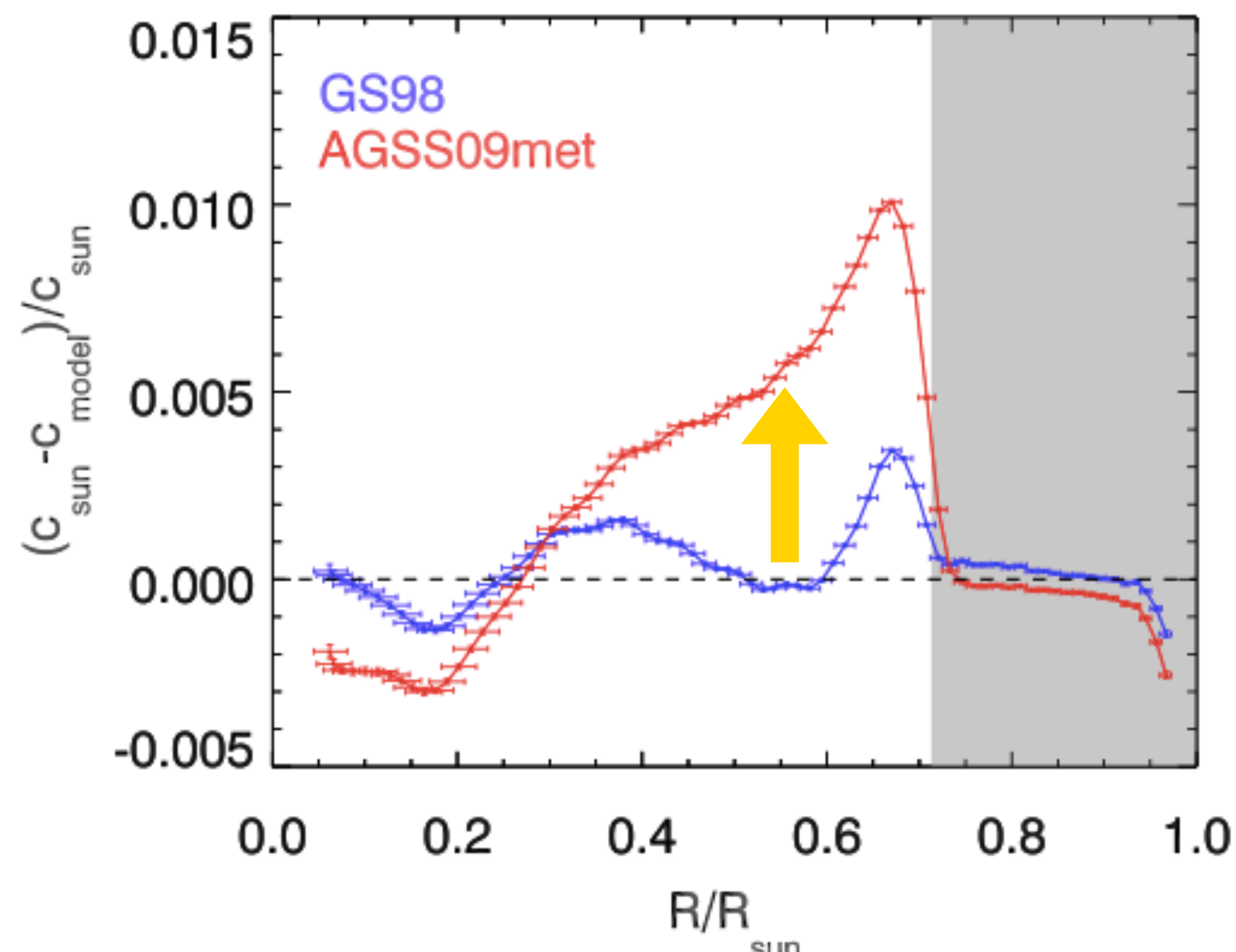


Known problem since 2004: still no solution!

Solar composition problem



revised - old abundances

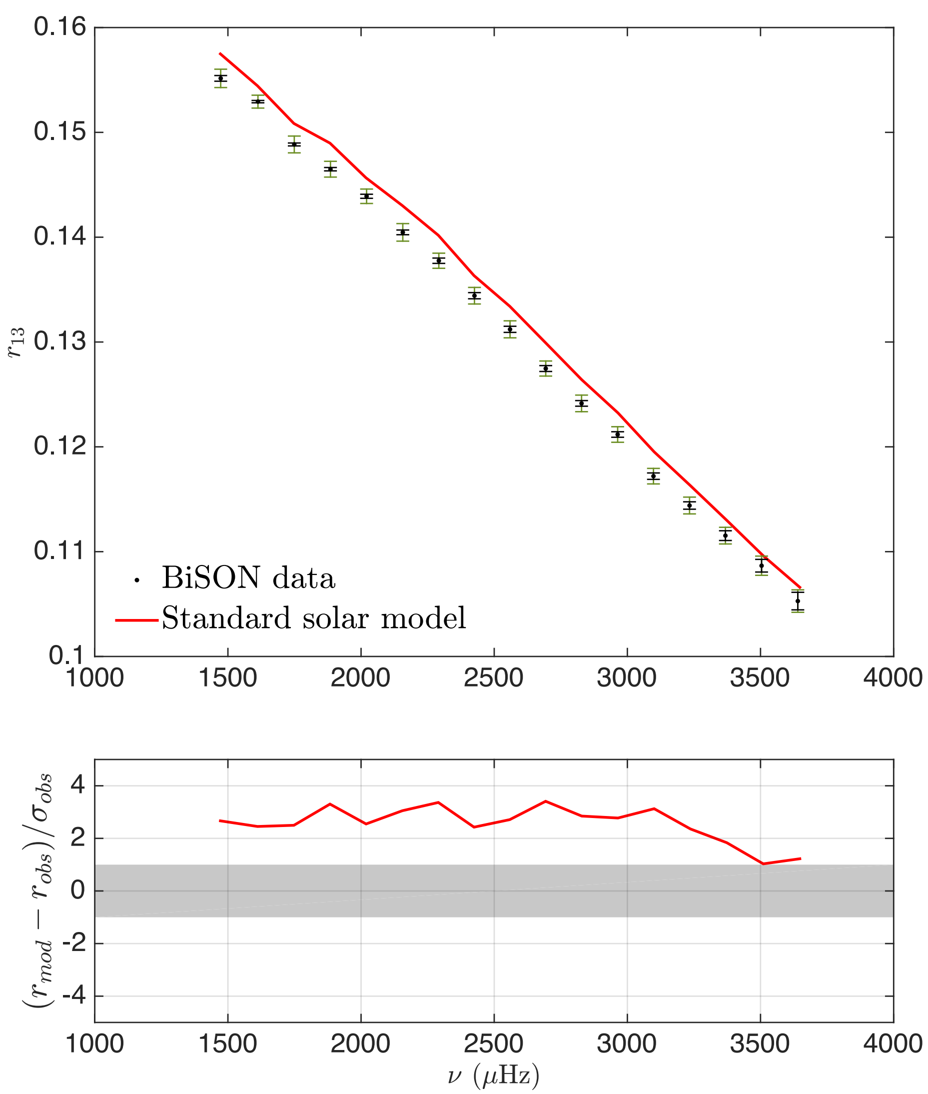


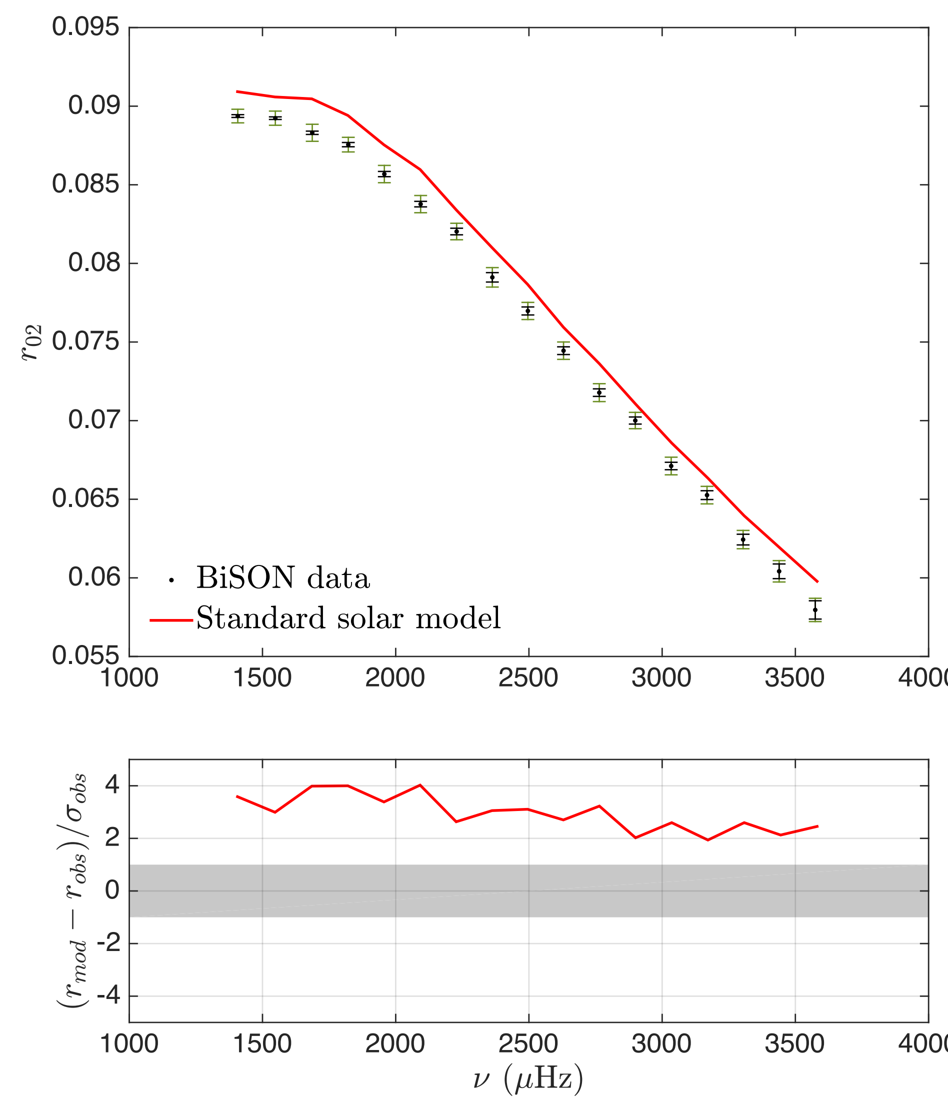
$$R_{\mathrm{CZ},\odot} = 0.713 \pm 0.001\, R_\odot$$
$$R_{\mathrm{CZ,SSM}} = 0.722 \pm 0.004\, R_\odot$$

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

Solar composition problem

Small frequency separations: a probe of the core





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

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

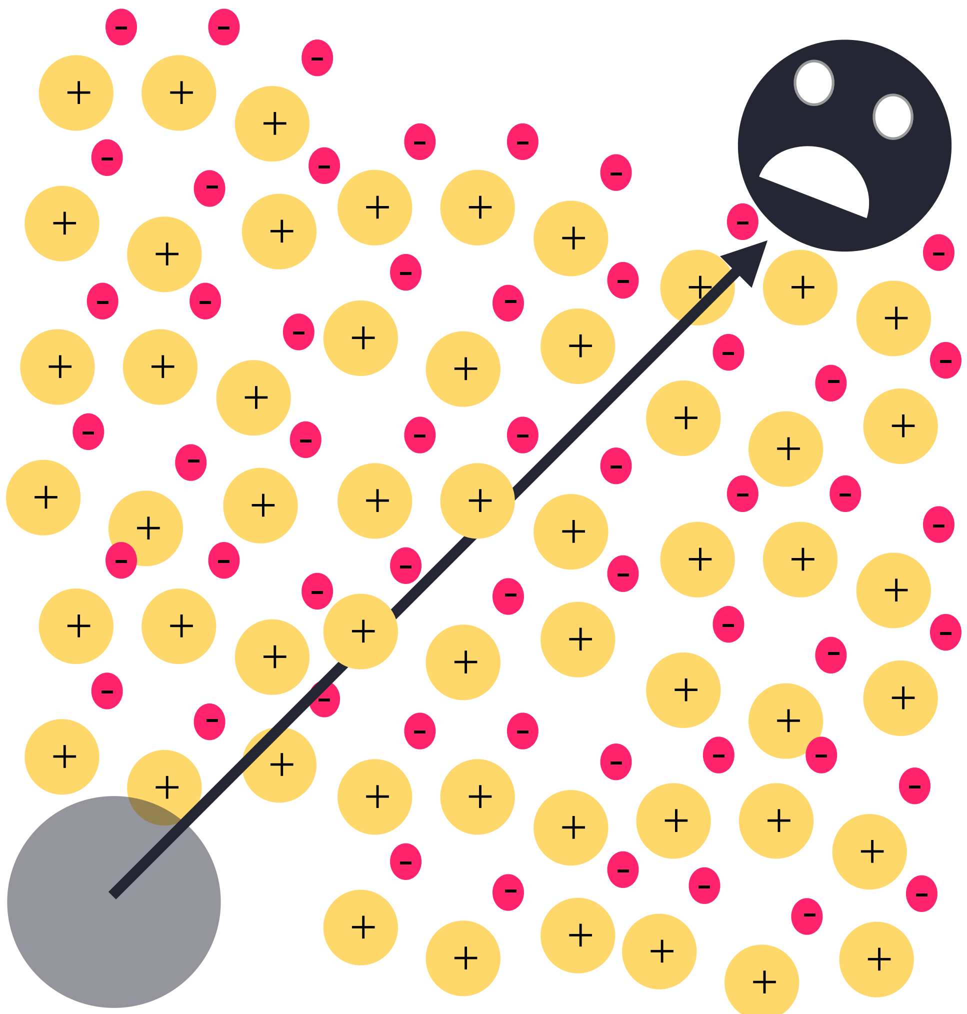
$$\simeq -(4l+6)\frac{\Delta_l(n)}{4\pi^2\nu_{n,l}}\int_0^{R_\odot}\frac{dc_s}{dr}\frac{dr}{r}$$

SSM describes the core **very badly**

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

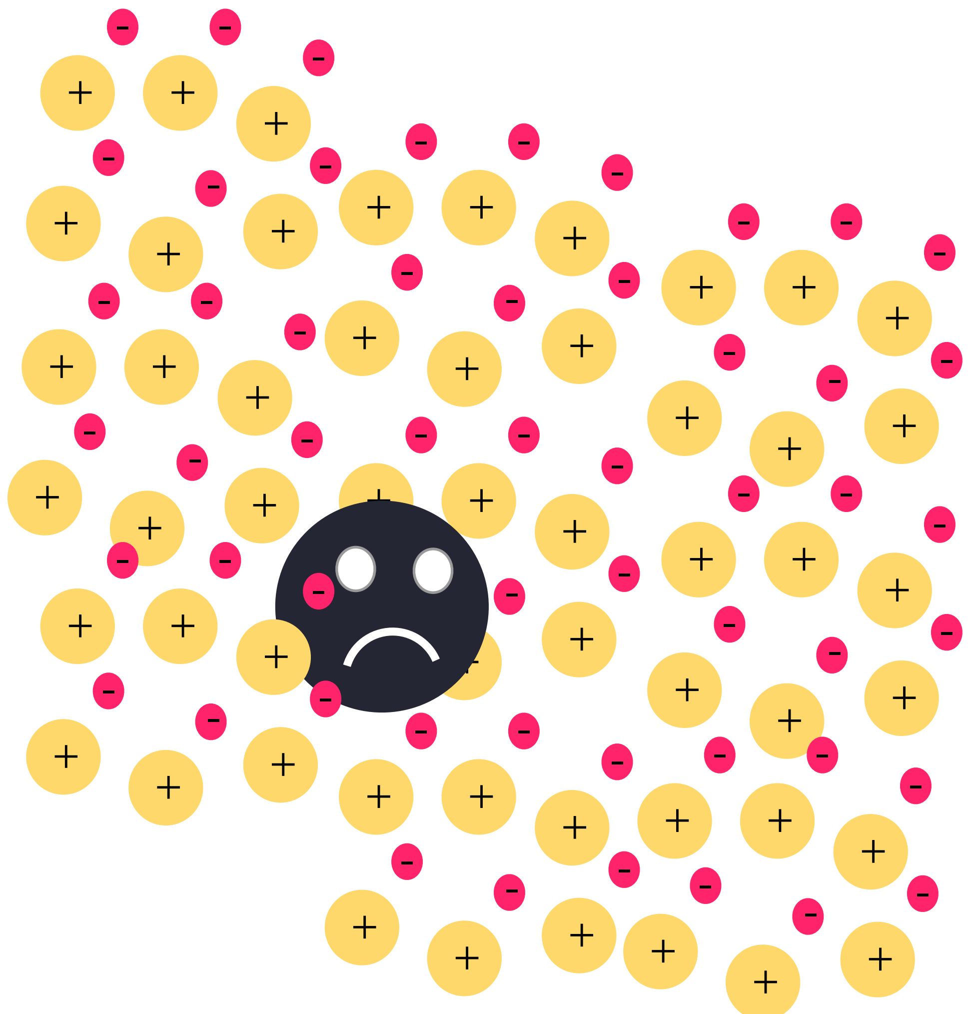
Heat transport: two regimes

Interactions too weak

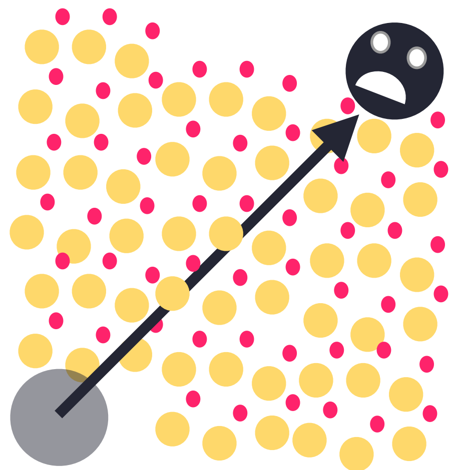


DM goes far but
cannot efficiently transfer momentum

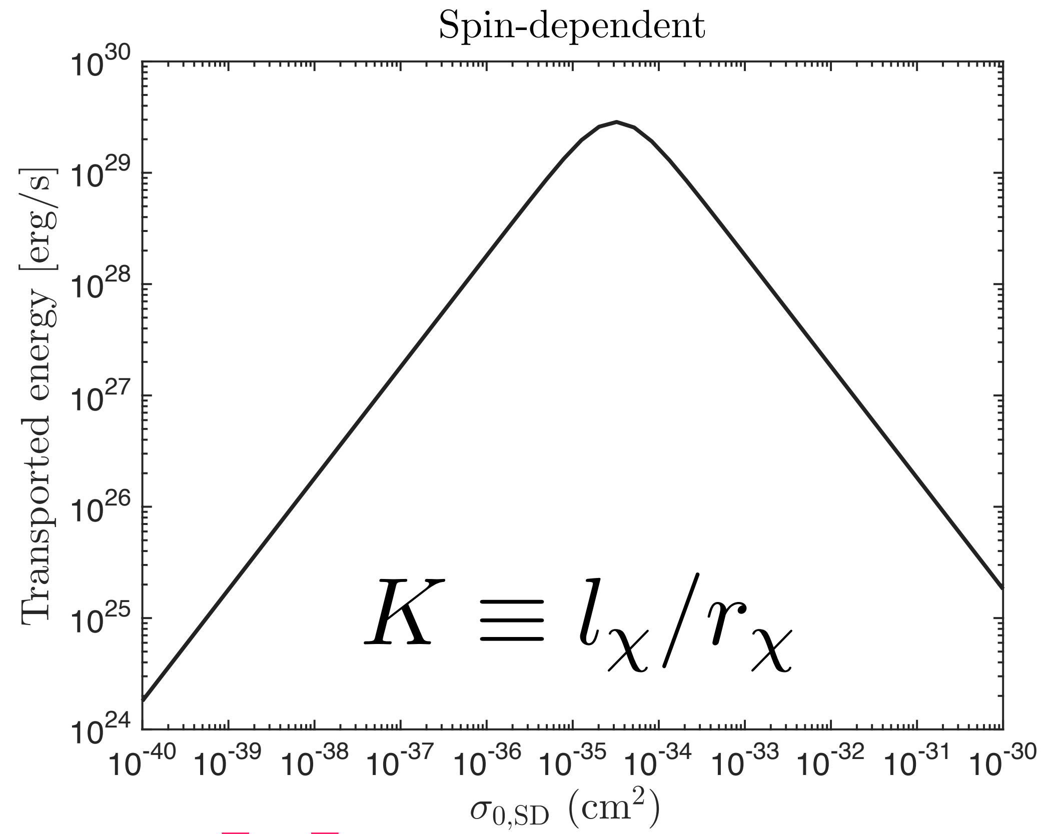
Interactions too strong

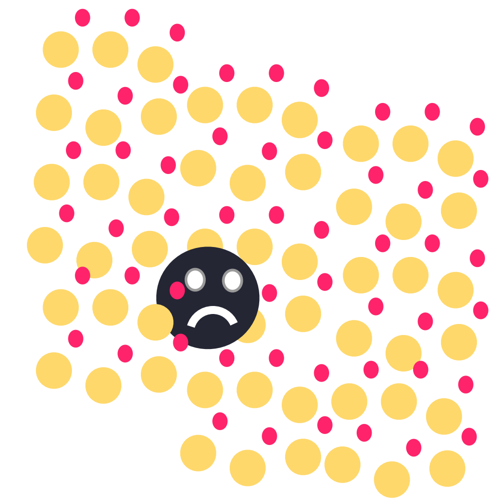


Efficient momentum transfer but
DM is “stuck"



Knudsen
(non-local)





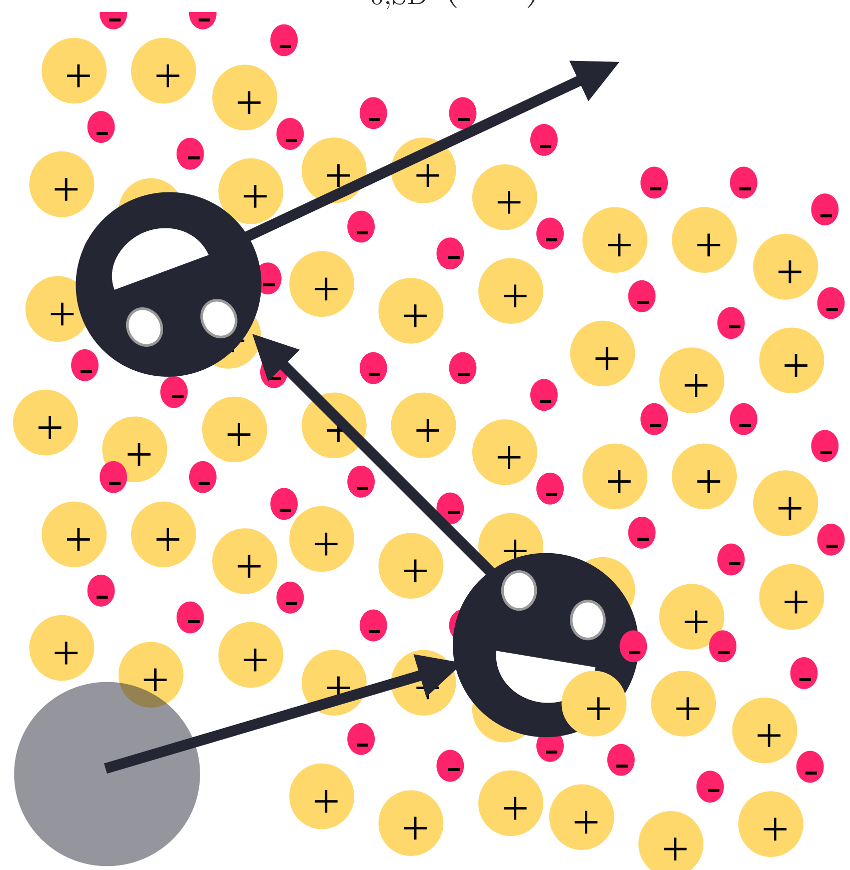
LTE

$K \gtrsim 1$

Calculable
(but wrong)

$K < 1$

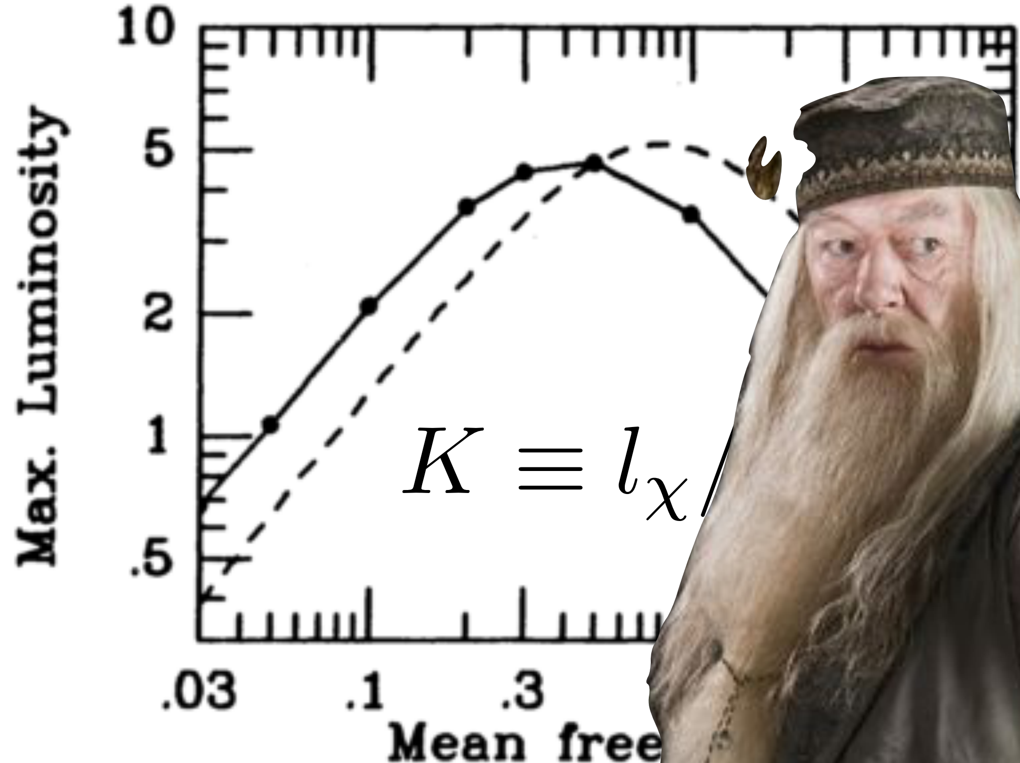
Somewhat
calculable
but unstable



optimal heat transport:
"Knudsen Peak"

not calculable

Stitching together: Monte Carlo (the "most correct" approach)



$K \equiv l_\chi /$

FIG. 11.—Maximum luminosity carried by
model described in Fig. 8. The maximum refers
the corresponding curves for other mean free
corresponds to a Monte Carlo run for that val
the formula used by Gilliland *et al.* (1986) in th
transport in the Sun.

Gould & R

Local nonlocal

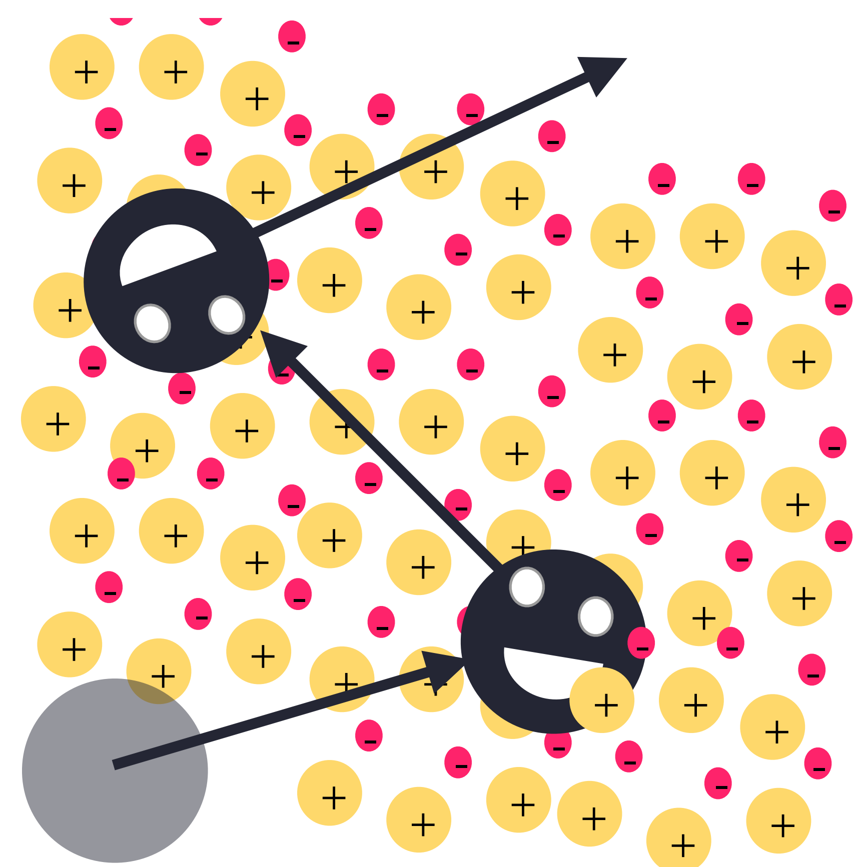
$$n_\chi(r) = \mathfrak{f}(K) n_{\chi,\mathrm{LTE}} + [1 - \mathfrak{f}(K)]\, n_{\chi,\mathrm{iso}},$$

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

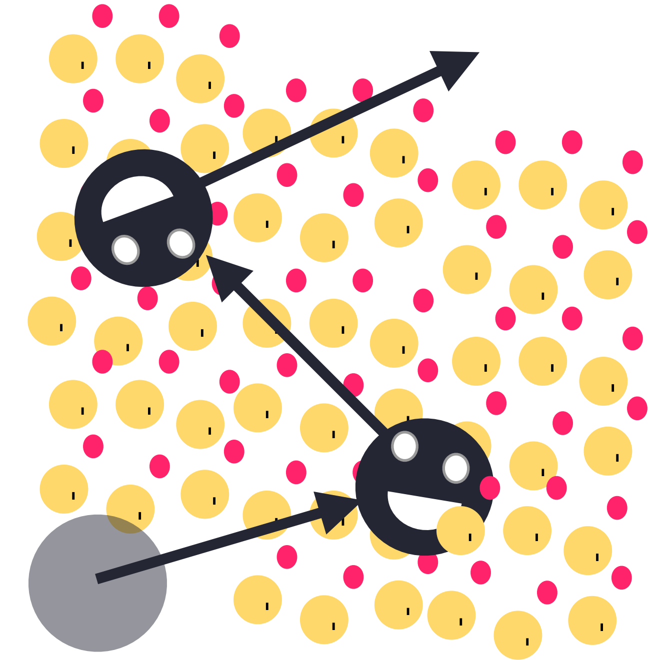
$$\mathfrak{h}(r) = \left(\frac{r - r_\chi}{r_\chi}\right)^3 + 1,$$

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

interpolating fcs



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



E.g. `` billiard ball”

1/r force

ACV & Pat Scott 2014

Systematic parametrization: NR EFT/ NREO

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

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

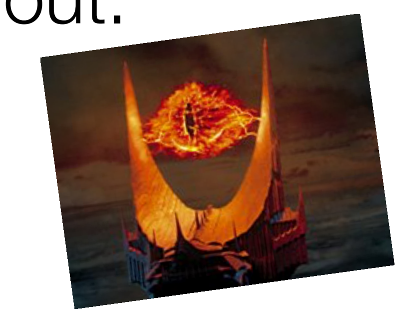
In the non-relativistic limit

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.

What are we looking for?

Some models will **suppress neutrino** fluxes and/or mess up **helioseismology**: we can use this to constrain them rule them out.



Some models will affect helioseismology enough to reconcile the SSM with observations. These will lead to happy editors and articles about us in the Daily Mail

Daily Mail

FREE CERAMIC POPPY BROOCH

Beautiful. Unique. And we are giving away thousands to lucky readers

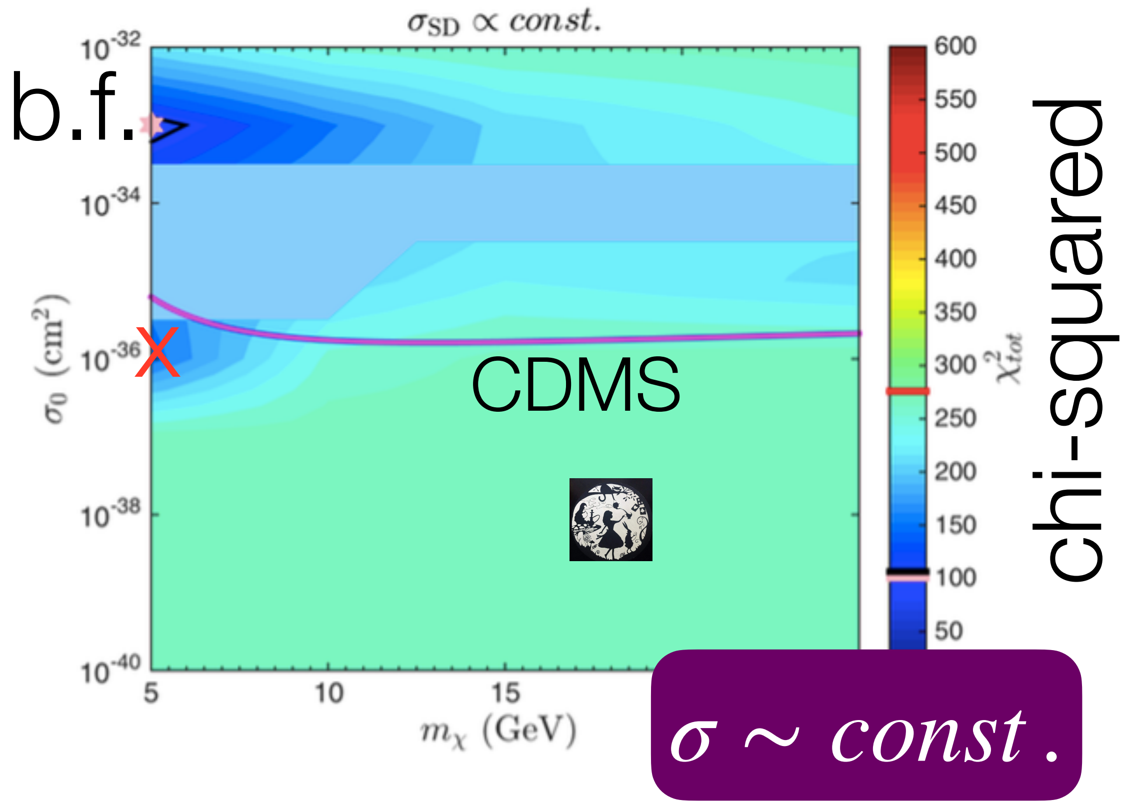
As company that supplies M&S and Tesco is forced to recruit 300 staff in Hungary...

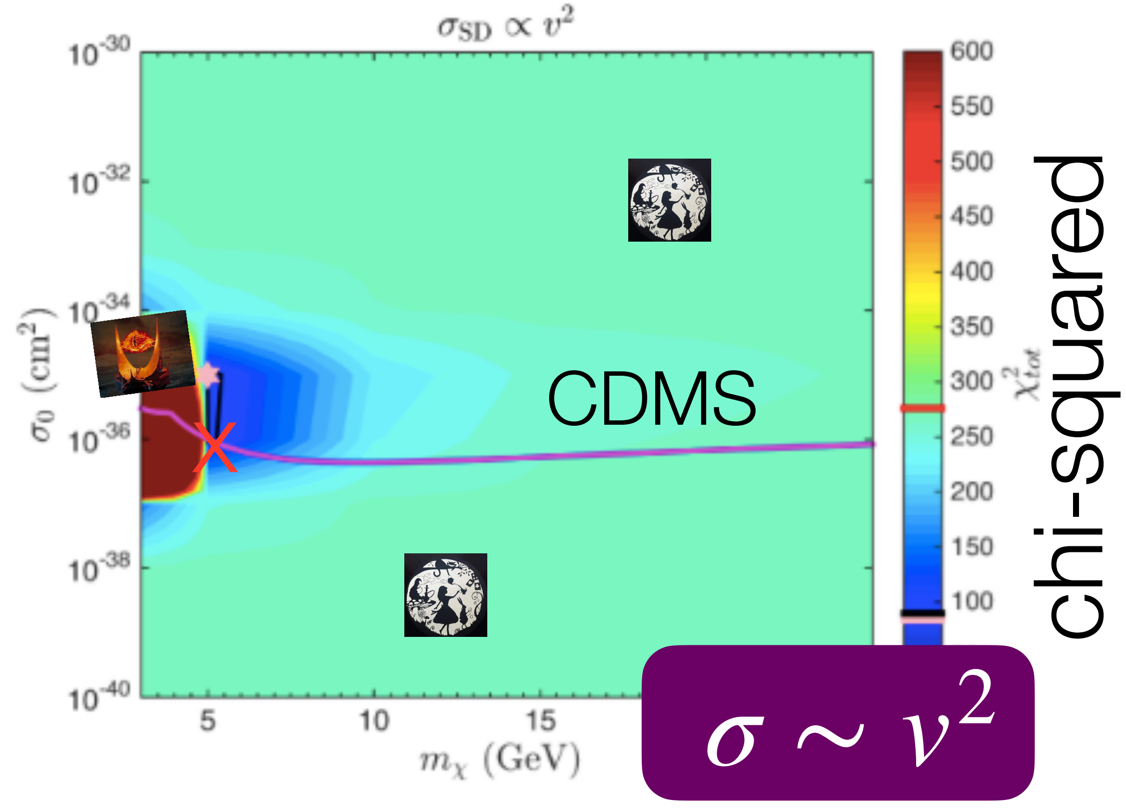
IS THERE NO ONE LEFT IN BRITAIN WHO CAN MAKE A SANDWICH?

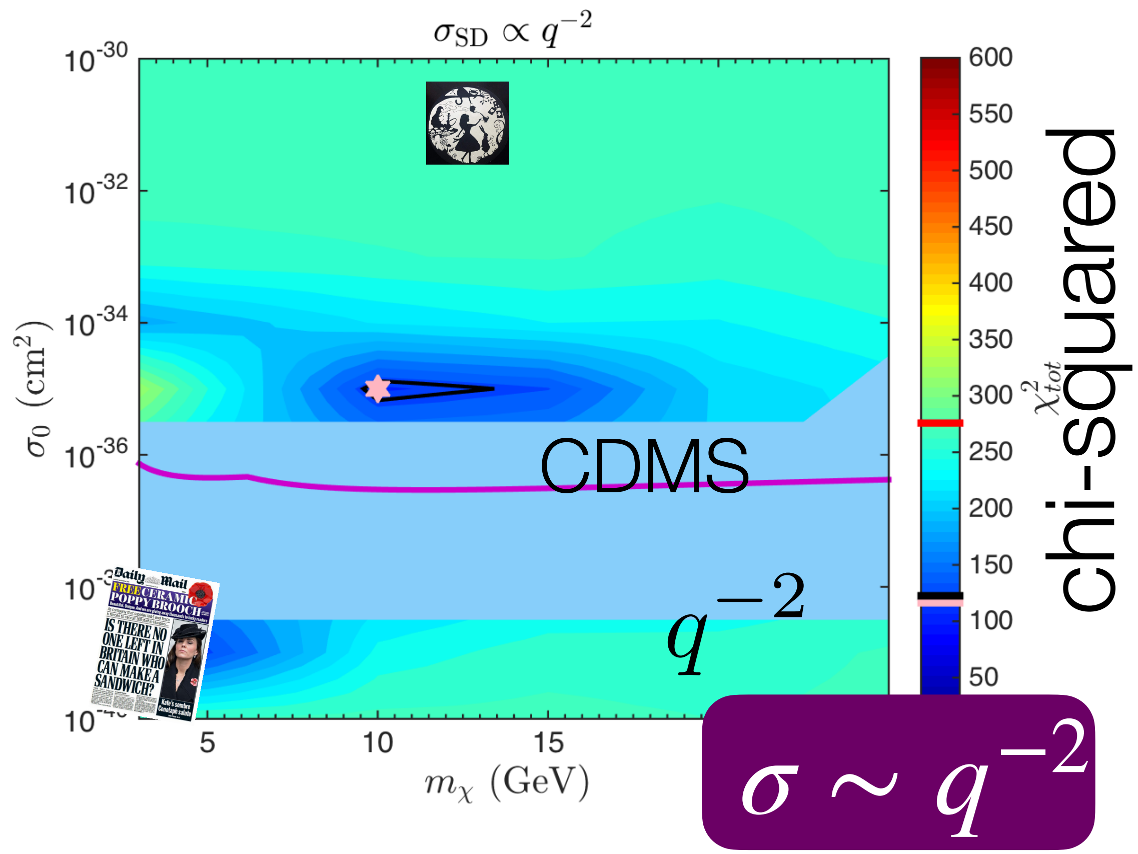
Kate's sombre

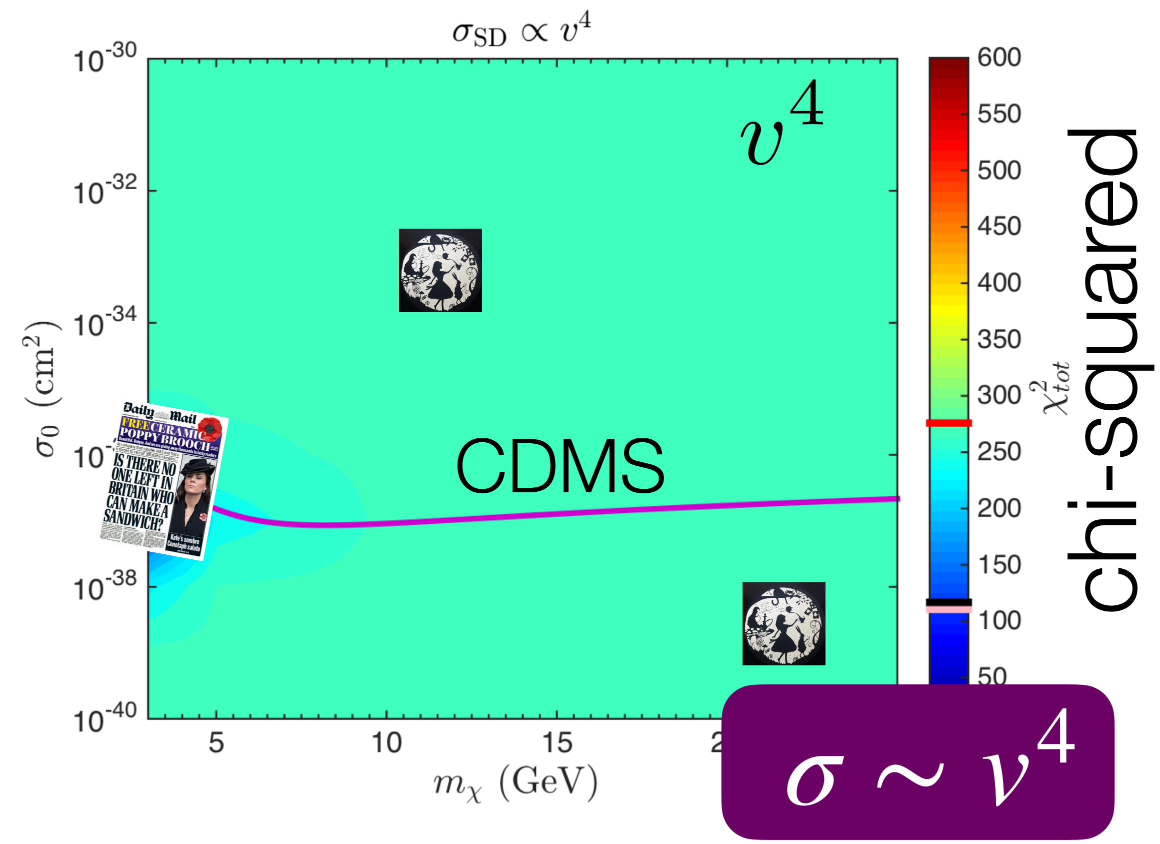
Some models will do nothing at all

Spin-dependent scenarios (ACV, Scott, Serenelli)









— SSM — Within 3 sigma of BF X Allowed

MailOnline Science & Tech

Home | News | U.S. | Sport | TV&Showbiz | Australia | Femail | Health | Science | Money | Video | Travel | Fashion Finder

Latest Headlines | Science | Pictures Login

Holocaust survivor reduces 'the

Ex-public schoolboy, 19, is

Send home asylum seekers rescued

Boob-job scrounger Josie Cunningham

Blueberries flush toxins, bananas

Pictured: Polish delicatessen worker

Young to dea

Is dark matter lurking inside the SUN? Mysterious particles may be reducing the star's core temperature

- Durham University scientists have proposed a new model for the sun
- They say that dark matter may be transferring heat around its interior
- This would help explain how pressure waves move around the sun
- Current models are insufficient to account for how they move
- The dark matter could be originating in the galactic halo of the Milky Way

By JONATHAN O'CALLAGHAN FOR MAILONLINE

PUBLISHED: 13:57, 2 March 2015 | **UPDATED:** 07:28, 3 March 2015

Share 182 shares 90 View comments

Scientists have discovered that there might be dark matter trapped inside the sun - and it could be the solar interior.

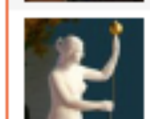
The bold new theory suggests that a form of the mysterious particle - which has yet to be directly observed - is absorbed by the sun from the centre of our galaxy.

Site Web Enter your search Search

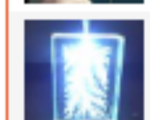
Like Daily Mail | Follow @dailymailtech | Follow Daily Mail | +1 Daily Mail

Today's headlines | Most Read

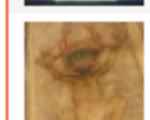
Welcome to your new home on MARS! Stunning drawings reveal what the red planet could look like if we...



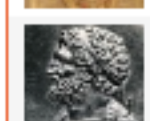
Was the Venus de Milo a PROSTITUTE? Reconstruction of iconic statue's missing arms suggests she was spinning...



Lightning trapped inside a 'BOX': Electron beam creates beautiful branches of electrical charge inside an...

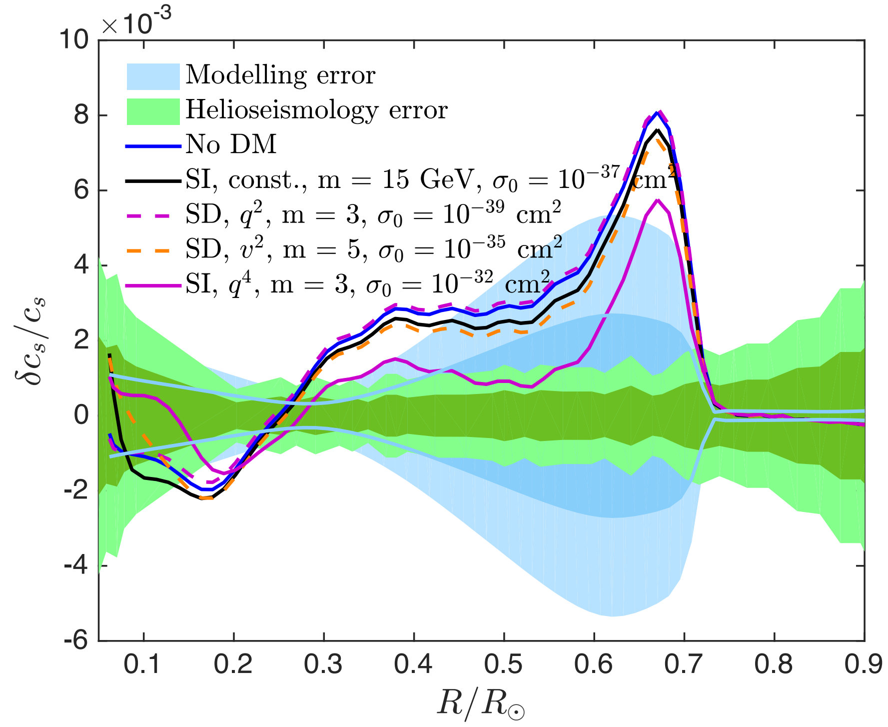


The mystery of the 'Devil's Bible': Sinister drawing inside 'cursed' medieval manuscript that legend says...



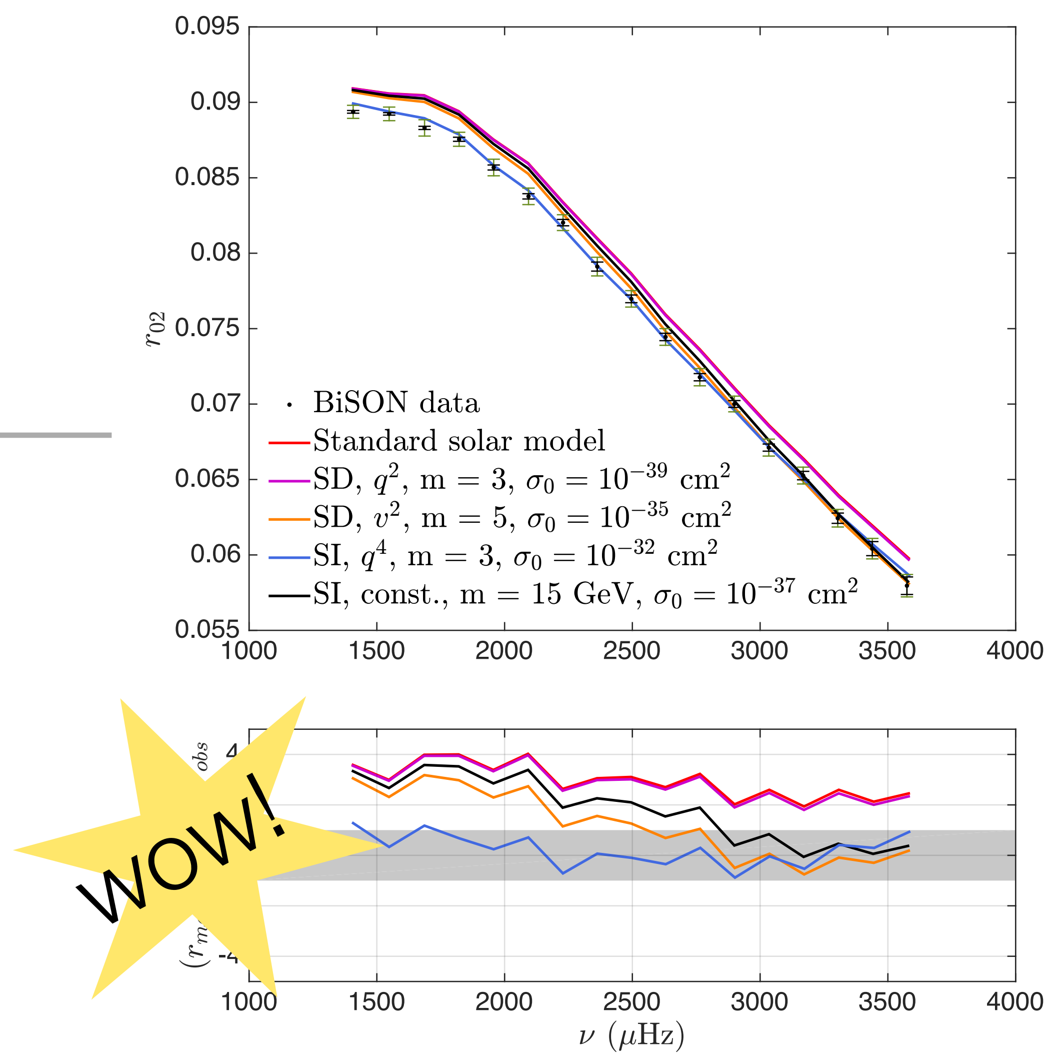
Alexander the Great's father WAS buried in Vergina: Bone analysis suggests remains with foreign princess do...

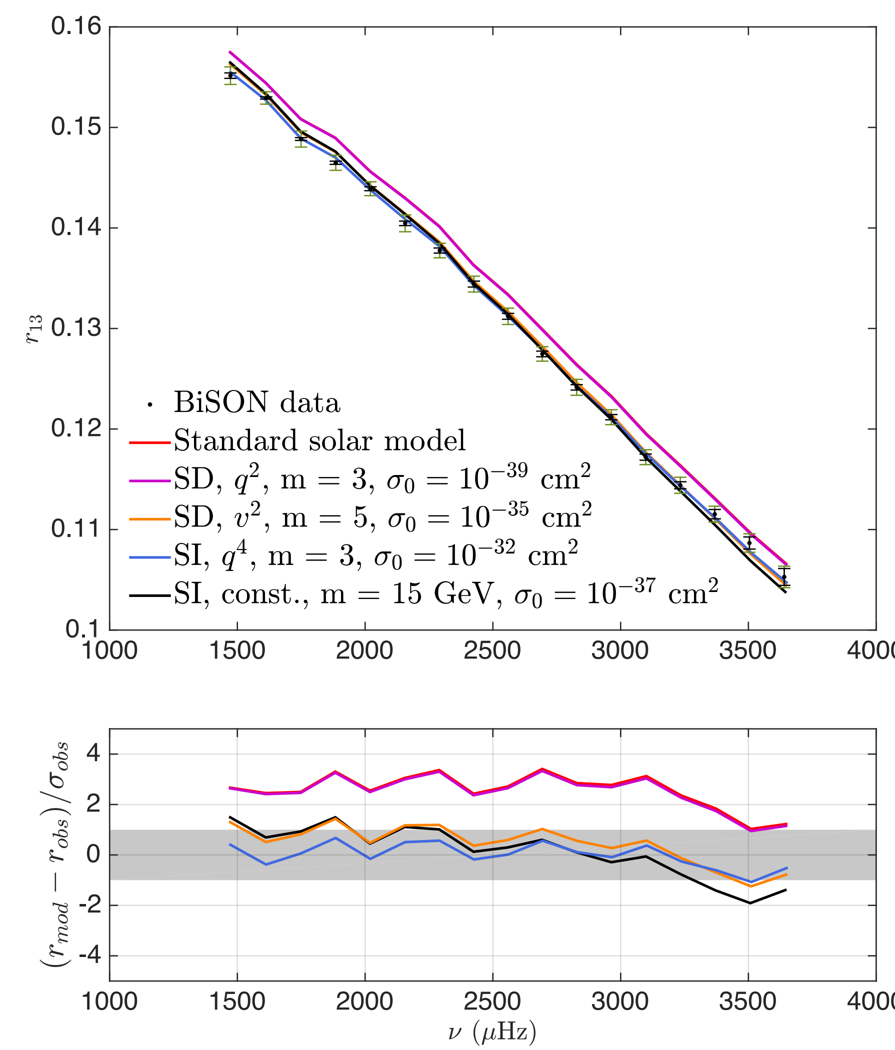
There is NO life on Mars, says author of The



Sound speed

Core



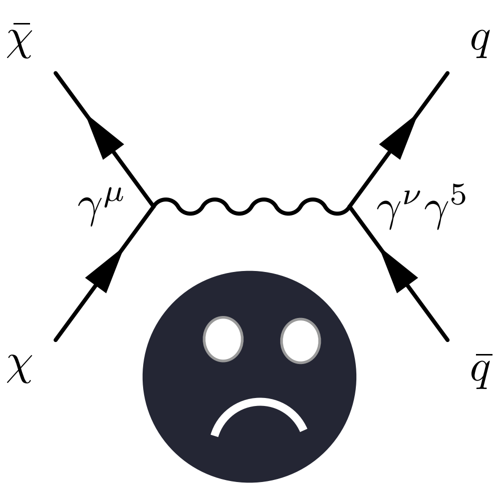


made with DarkSTEC

What could these successful models be?

All spin-dependent (to evade DD constraints)

$\sigma_{\chi-n} \propto v^2$



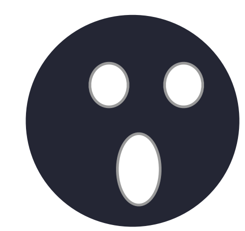
…but also leads to a larger q^2 coupling that is ruled out

$\sigma_{\chi-n} \propto q^{-2}$

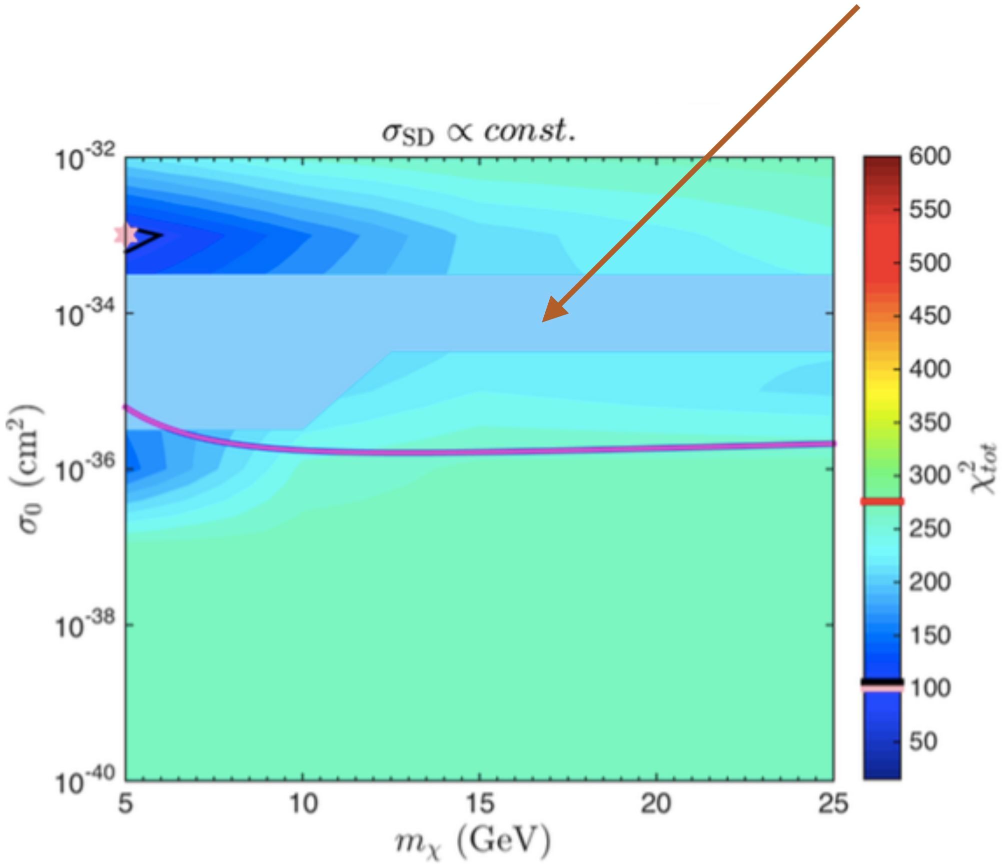
Simplified models don't produce this, but long-range forces? Light mediator?

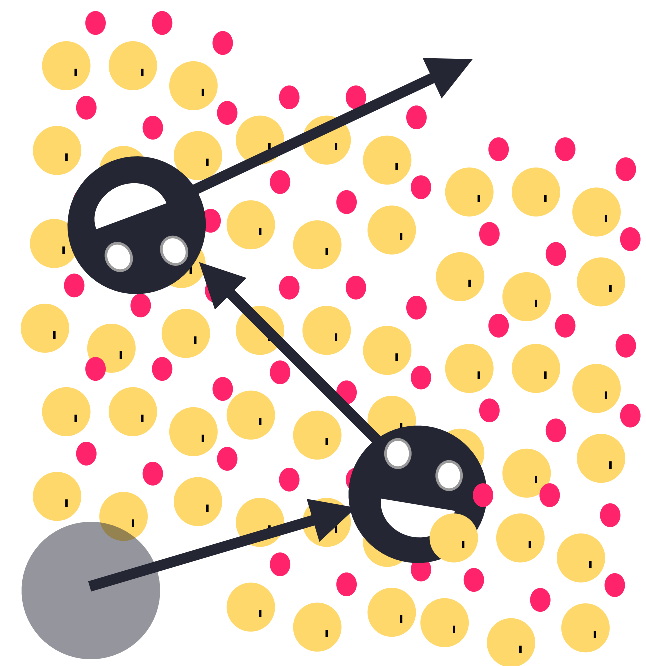
$\sigma_{\chi-n} \propto v^4$

???



What's going on here?

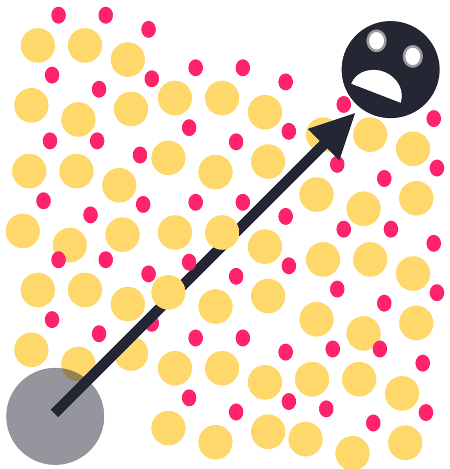




1. Dark matter capture in the Sun

2. Asymmetric dark matter

3. **Beyond the Sun — the Danger zone**



Knudsen

(non-local)

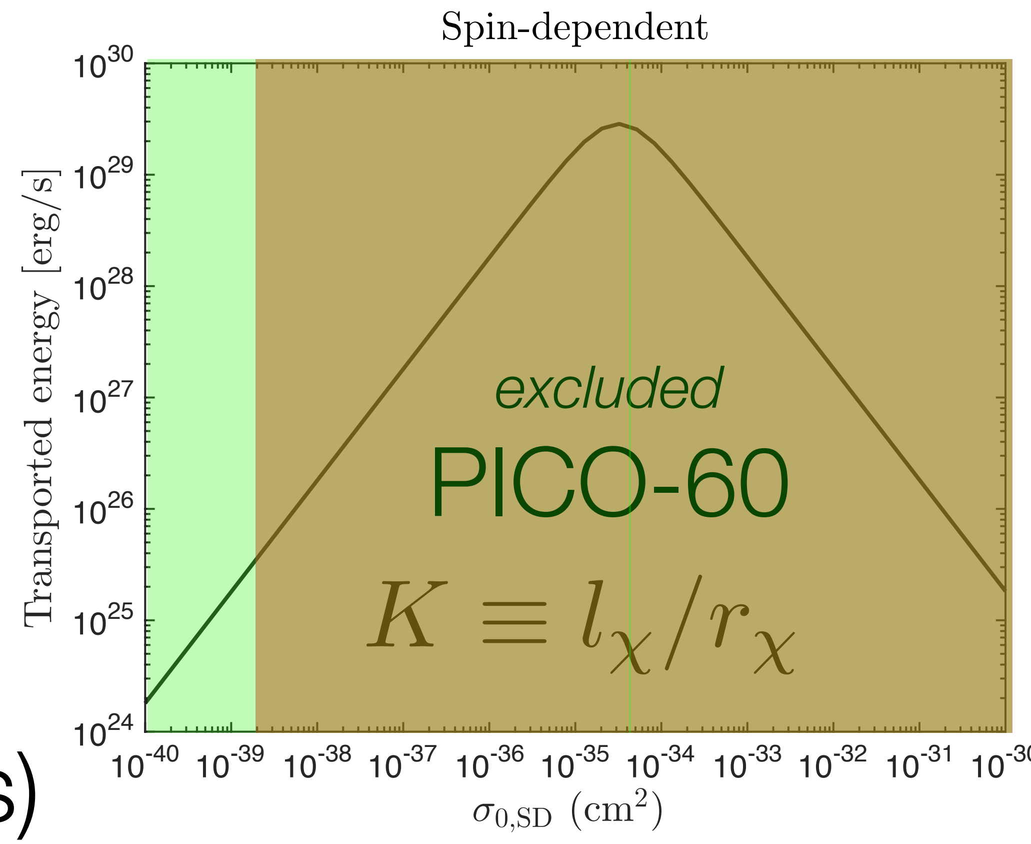
Small cross section

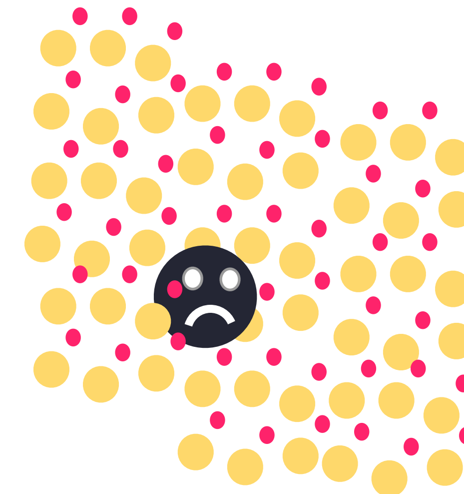
$$K \gtrsim 1$$

"easy" calculation

(Spergel and Press)

disagrees with Monte Carlo Simulation





LTE

large cross section

$$K < 1$$

Difficult calculation

Gould and Raffelt

"corrected" approach agrees with Monte Carlo everywhere

For small couplings we have:

-A corrected large-coupling solution

or

-An incorrect small-coupling solution

Why Spergel and Press is wrong

Boltzmann: $$DF = l_\chi^{-1} CF$$

Liouville operator: $$D(\vec{u}, \vec{r}, t) = \partial_t + \vec{u} \cdot \nabla_{\vec{r}} + \vec{g}(\vec{r}) \cdot \nabla_{\vec{u}}$$

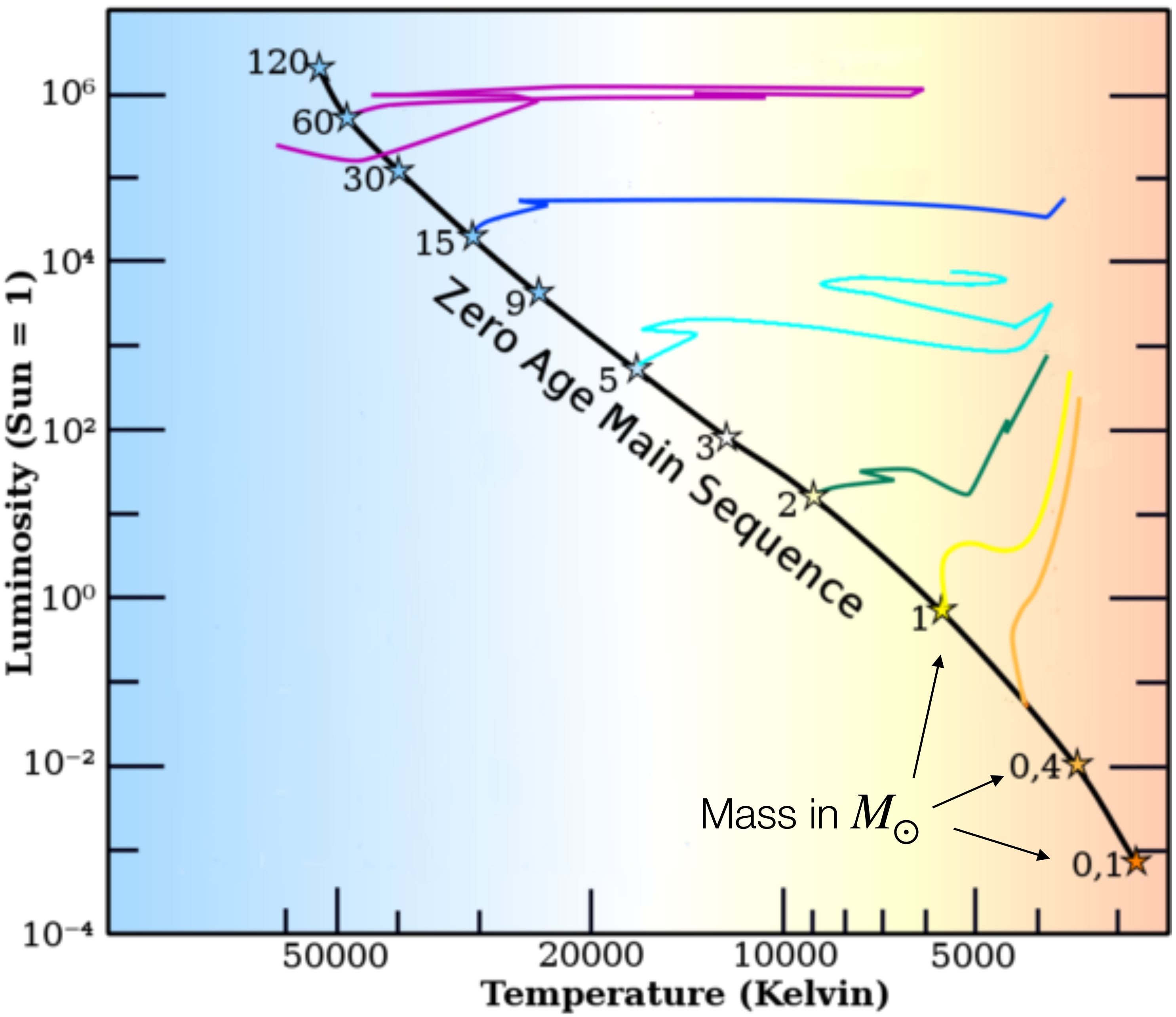
DM distribution: $$F(\vec{u}, \vec{r}, t)$$

Collision rate with nuclei: $$l_\chi^{-1}(\vec{u}, \vec{r}, t) C(\vec{u}, \vec{r}, t)$$

Assume $DF = 0$ —> Isothermal solution

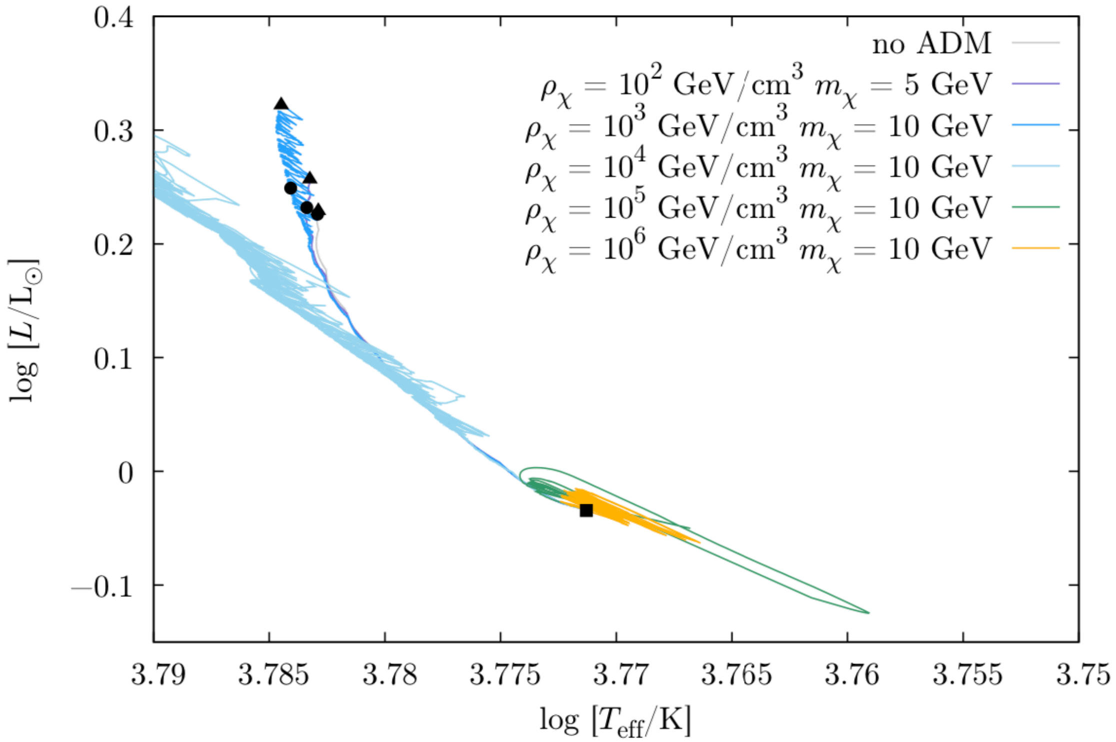
Then solve for heat exchanged with heat bath of the Sun: not self-consistent.

Main sequence stars near the galactic centre

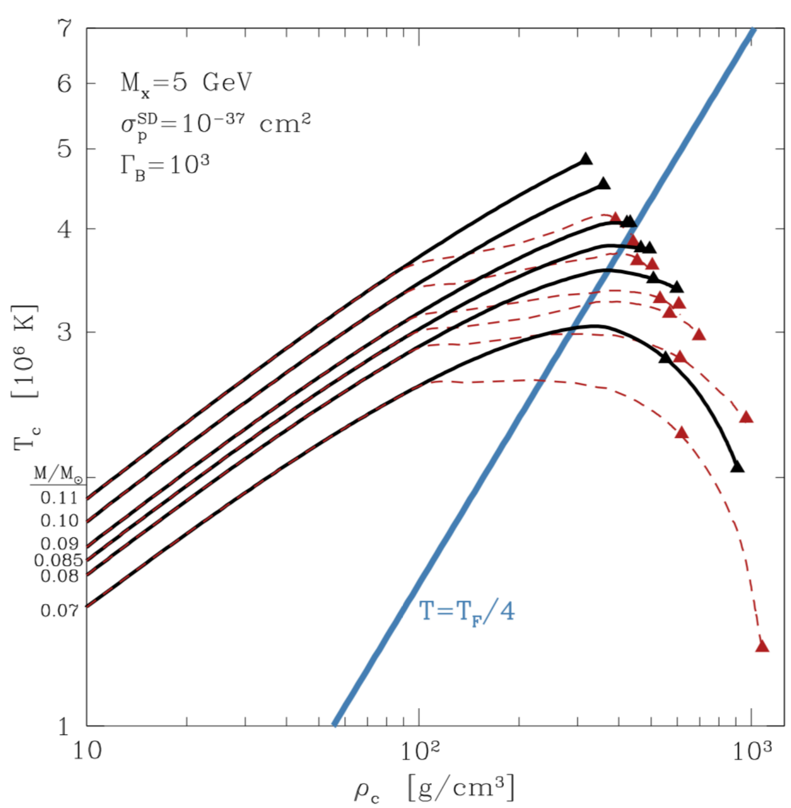


Time spent on the Main Sequence: how fast do you burn your nuclear fuel (hydrogen)?

Heat transport by DM: Core temperature can go up or down, changing stellar luminosity and fuel consumption rate?

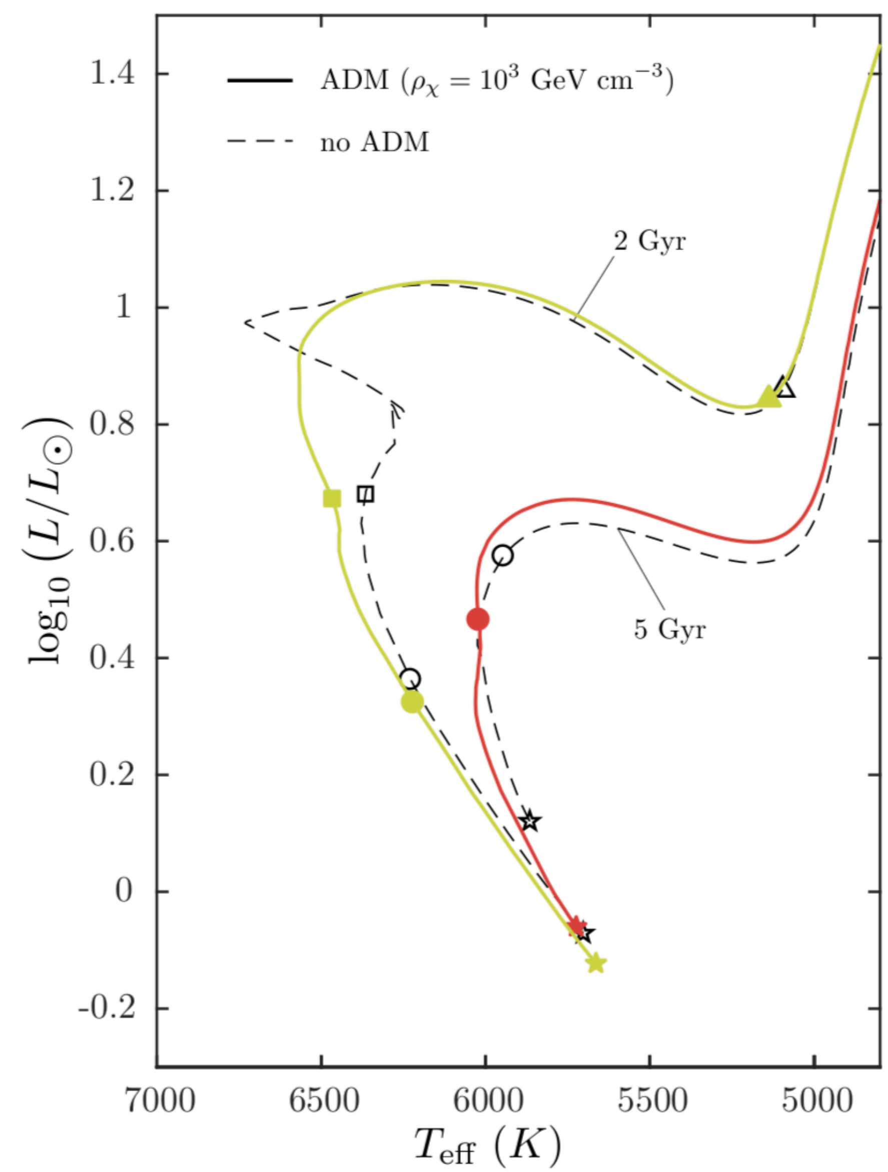


Iocco et al.1201.5387
Dangerous instabilities



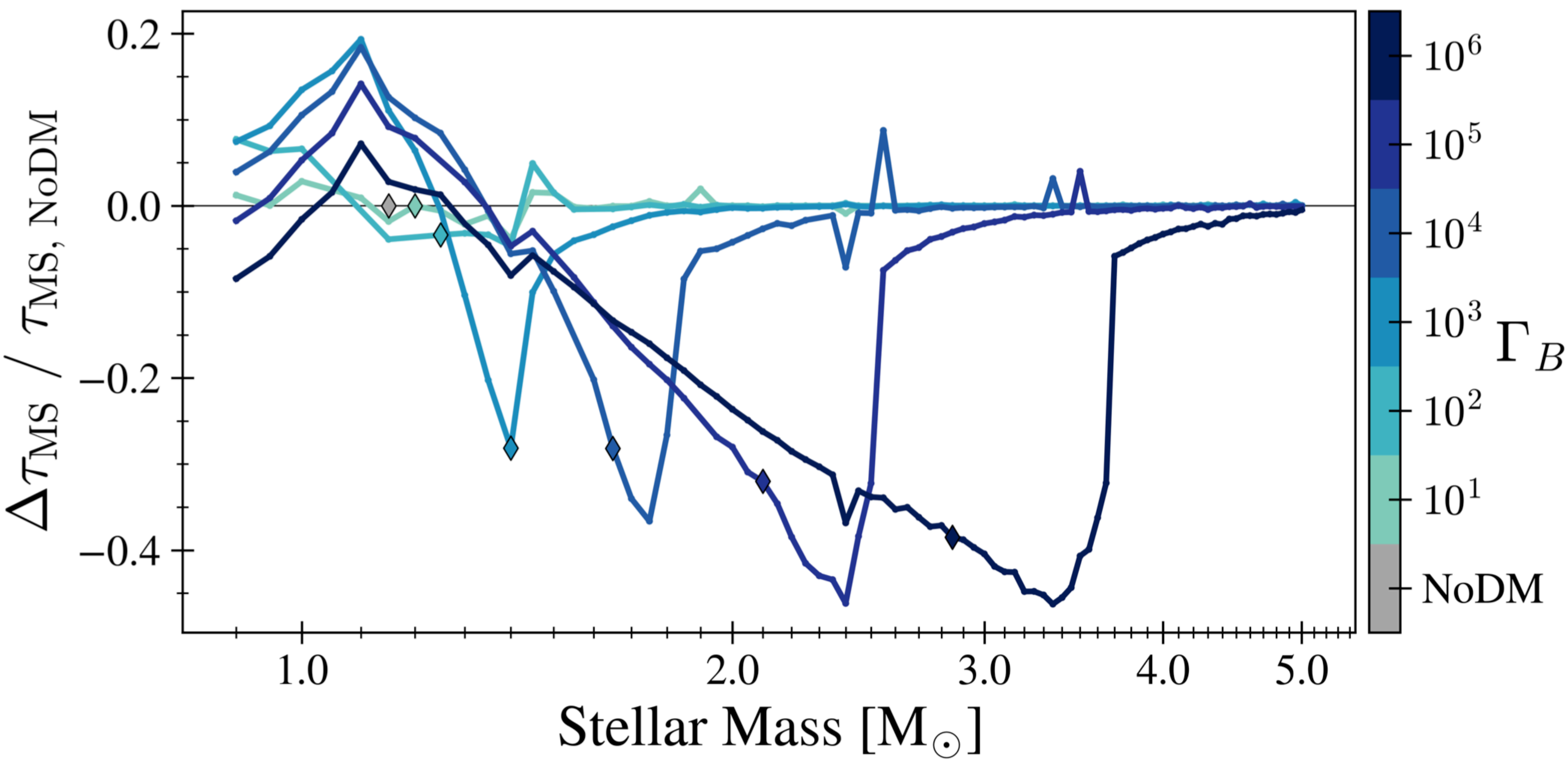
Hurst & Zentner 2011: Spergel & Press transport, some iffy approximations

Lopés and Lopés (2019)
use Spergel & Press transport



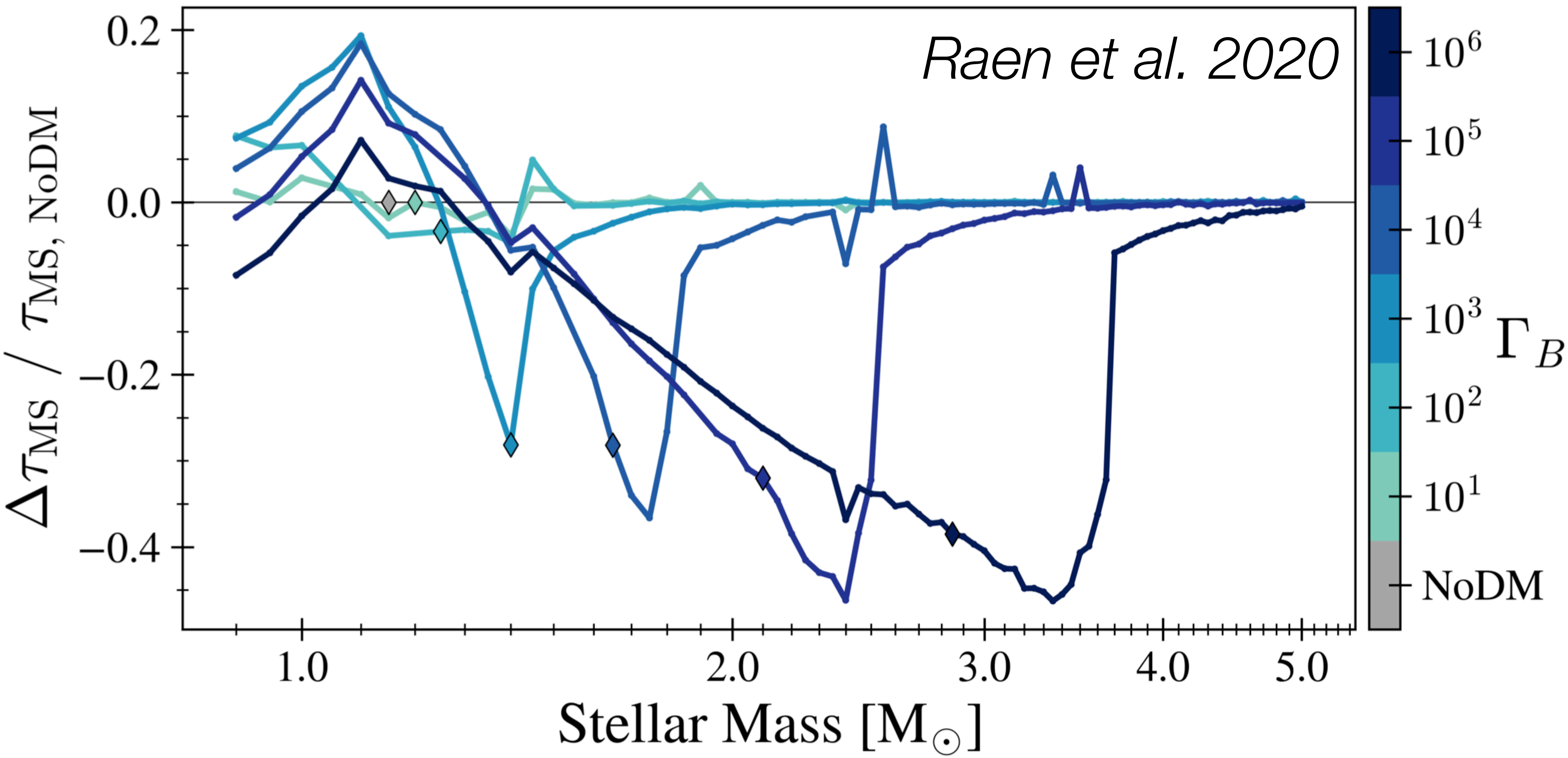
The Effects of Asymmetric Dark Matter on Stellar Evolution I: Spin-Dependent Scattering

Troy J. Raen,[1⋆], Héctor Martínez-Rodríguez[1], Travis J. Hurst[2], Andrew R. Zentner[1], and Carles Badenes[1],



Low mass stars:
ADM removes heat from center, leading to less fusion in the center, but heats up higher radii, allowing access to more fuel overall

Higher mass stars:
ADM suppresses the formation of a convective core*: H fuel is not replenished. Core is compressed, leading to higher burning rates and lower lifetime.



*see also work by Casanellas, Lopes

All of these use Spergel and Press (isothermal)

How do we properly compute heat transport
in the non-local regime?

Post Main-Sequence: even harder.

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!

We still don't understand DM heat transport in the correct regime. Clever work required.

Public code: **Captn' General.** Computes capture rates for DM with general q^n and v^n cross sections. NREFT operators available soon.
https://github.com/aaronvincent/captngen

Hubble Legacy Archive, NASA, ESA