Asymmetric Main Sequence

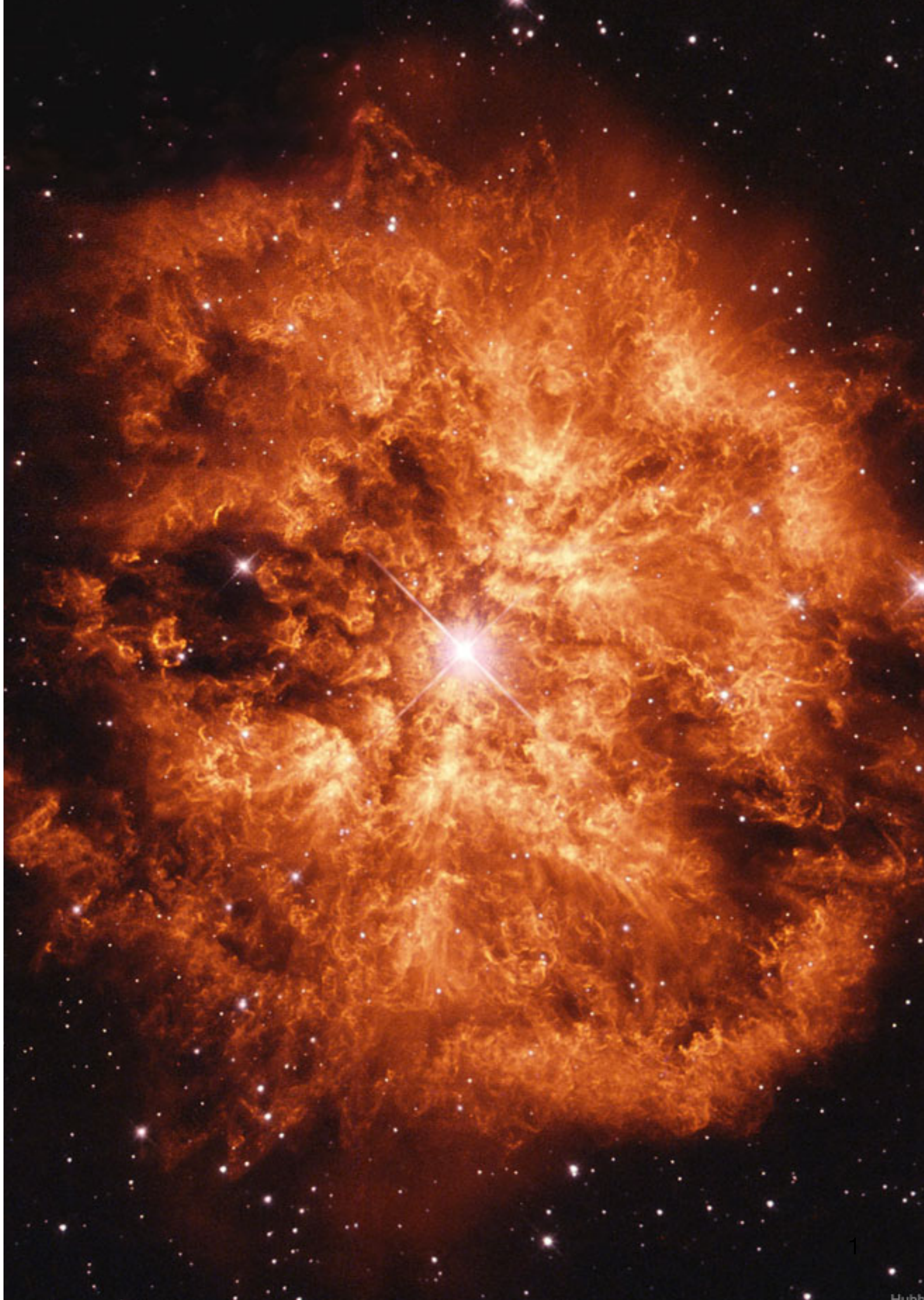
Dark matter in stars

Aaron Vincent

CAP 2021 — Cosmology Symposium — June 8 2021

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

Queen's University



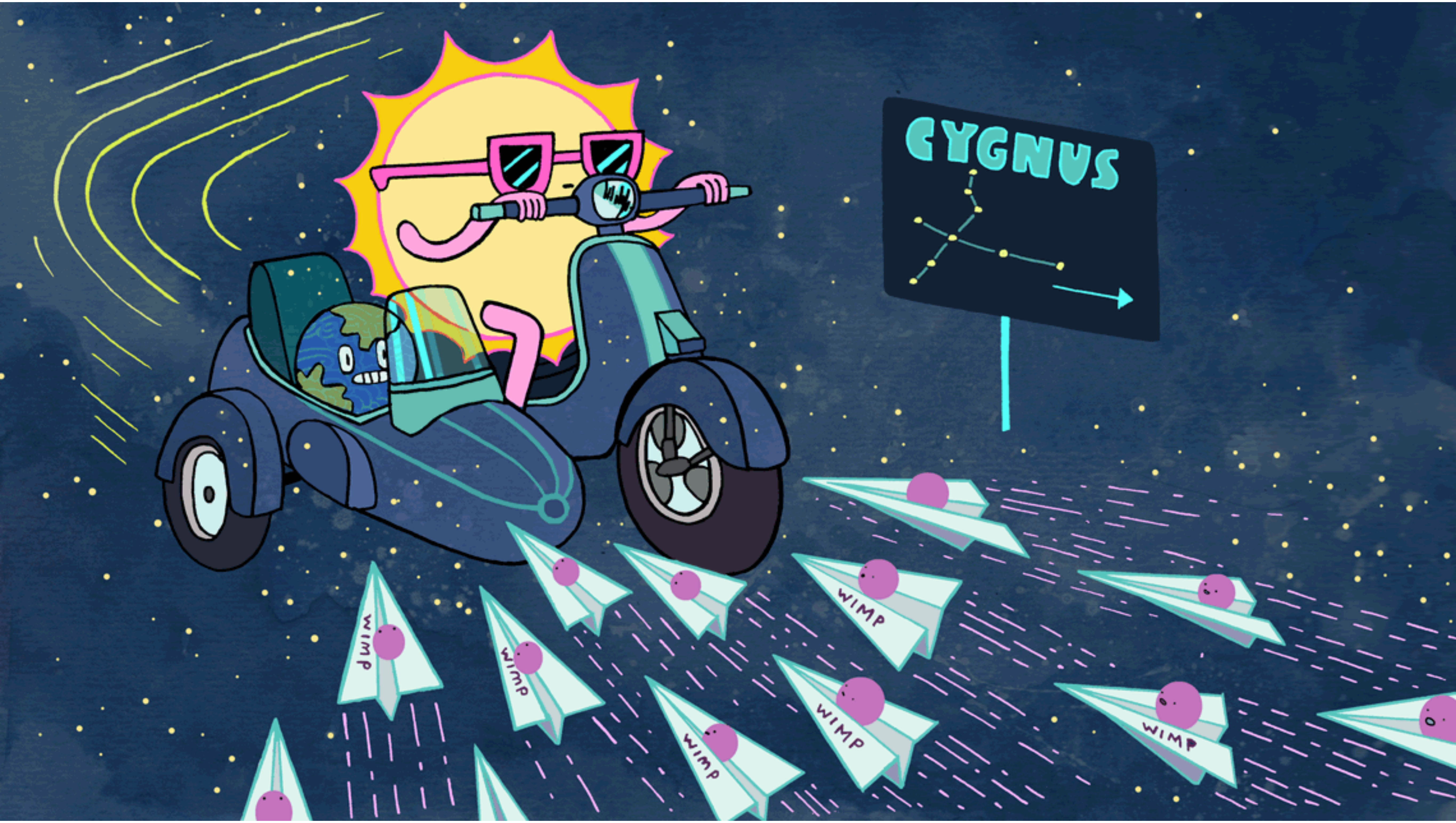
Overview

1. Dark matter in the Stars: results

2. Everything is wrong

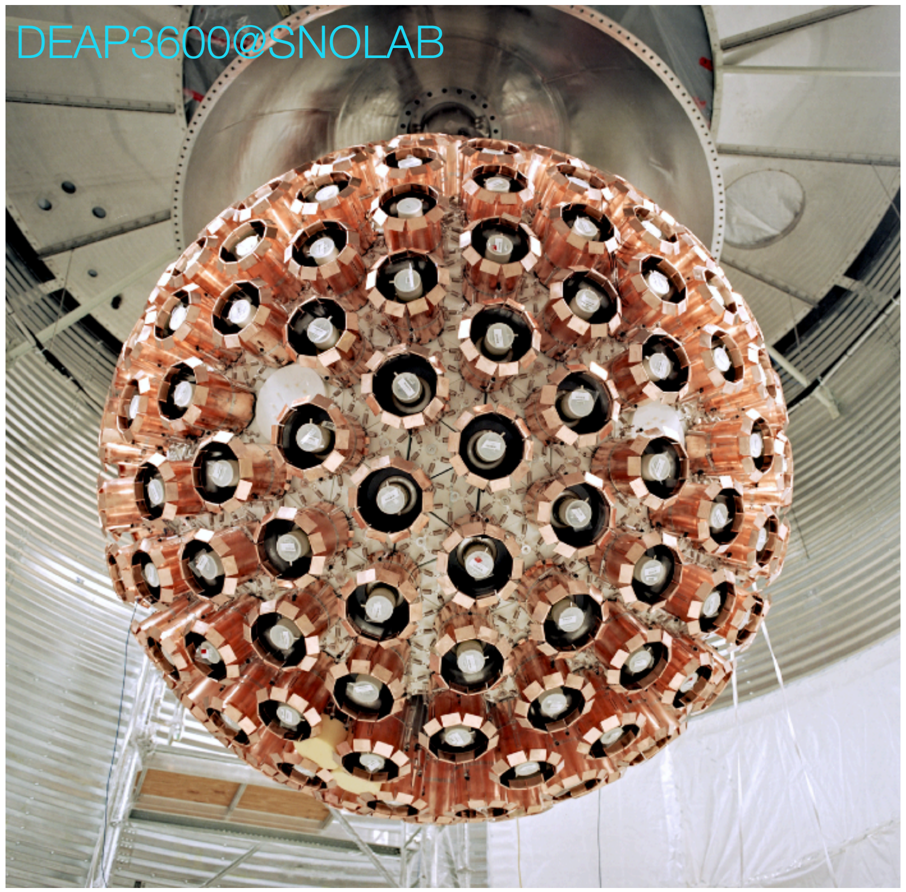
3. The way forward?

Direct detection of dark matter

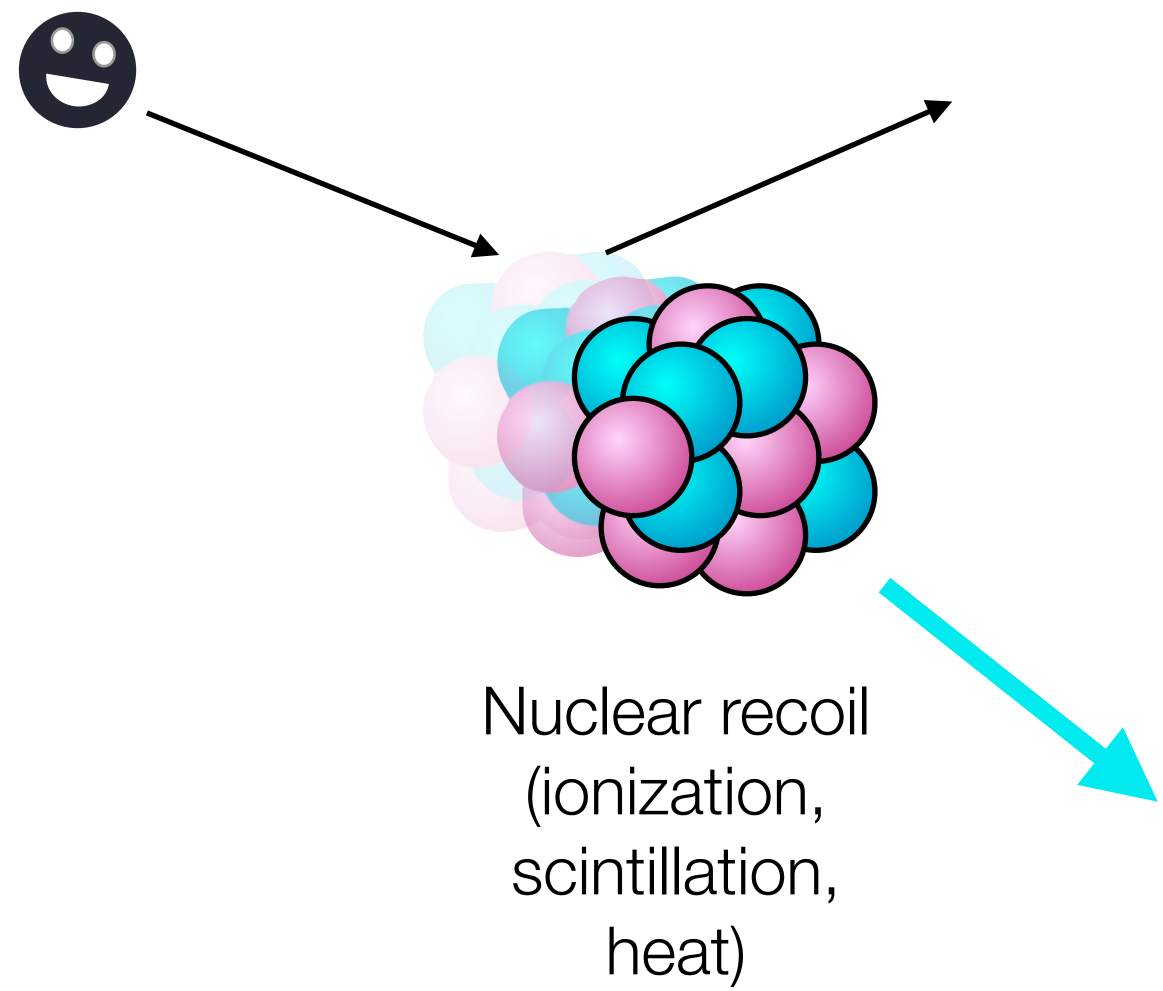


symmetrymagazine.org — Artwork by Sandbox Studio, Chicago/Corinne Mucha

Direct detection of dark matter



Detector full of target material
Shielded deep underground
Low backgrounds



Most sensitive to **heavy**, **fast** particles → larger recoil signal

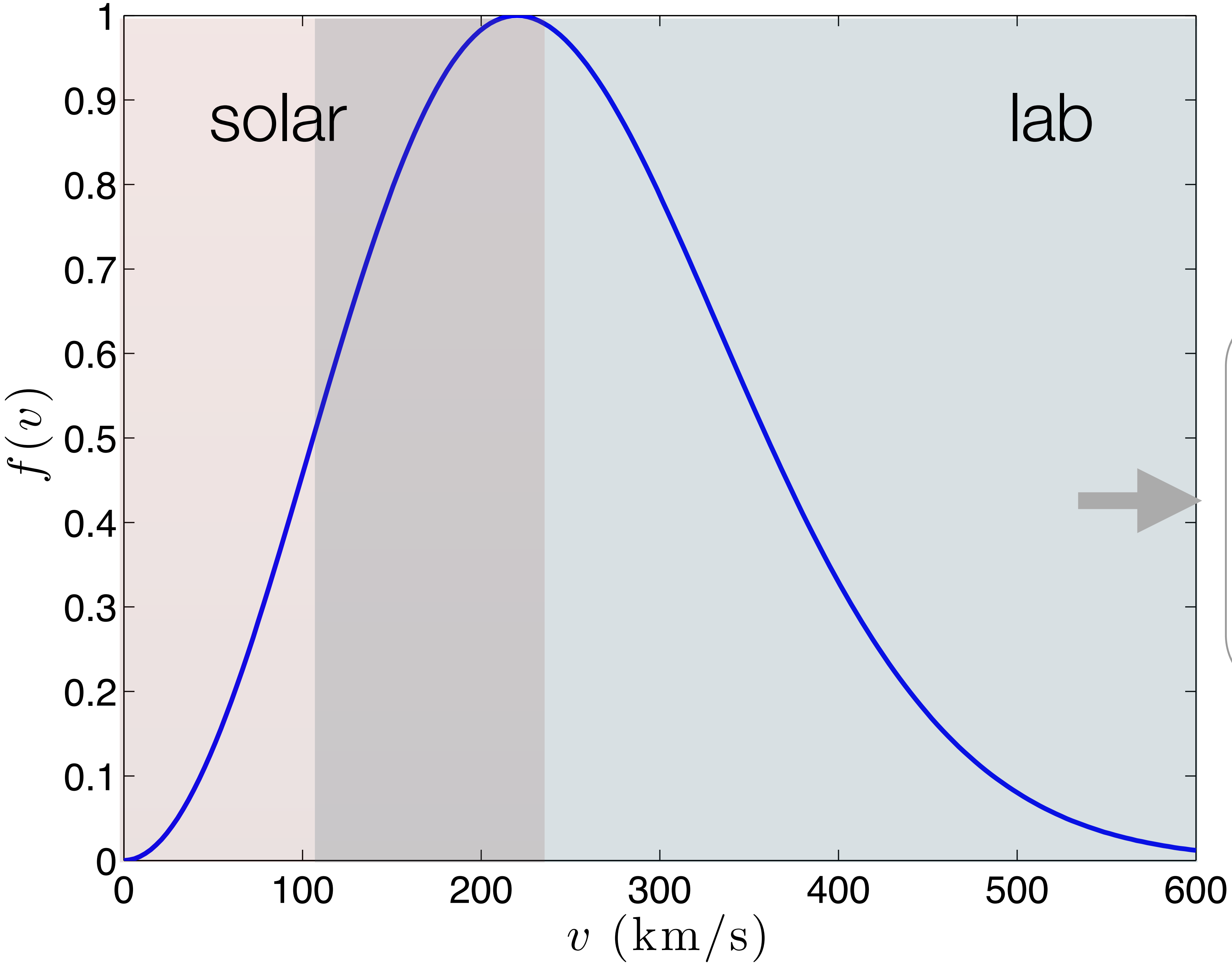
Signal ∝ detector mass (now ~ 1000 kg)

The sun is a direct detection experiment

DM scatters with nuclei, losing kinetic energy & becoming gravitationally bound

- $M = 2 \times 10^{30}$ kg
- 73% Hydrogen
- 25% Helium
- 2% Heavier elements (important since $\sigma_{SI} \propto A^2$)
- Not supercooled: need to be clever about “readout”

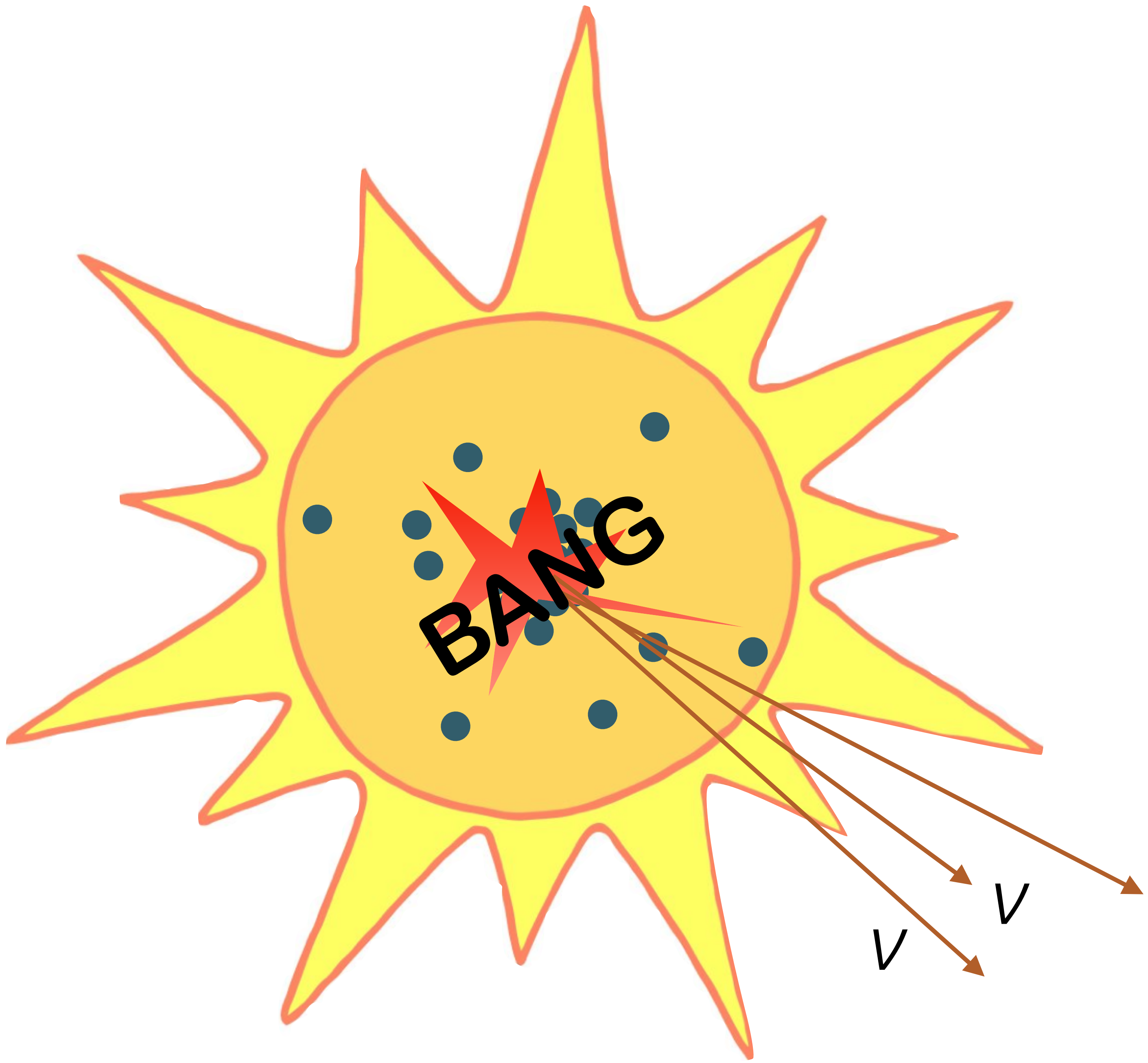
Differences with earth-based detection



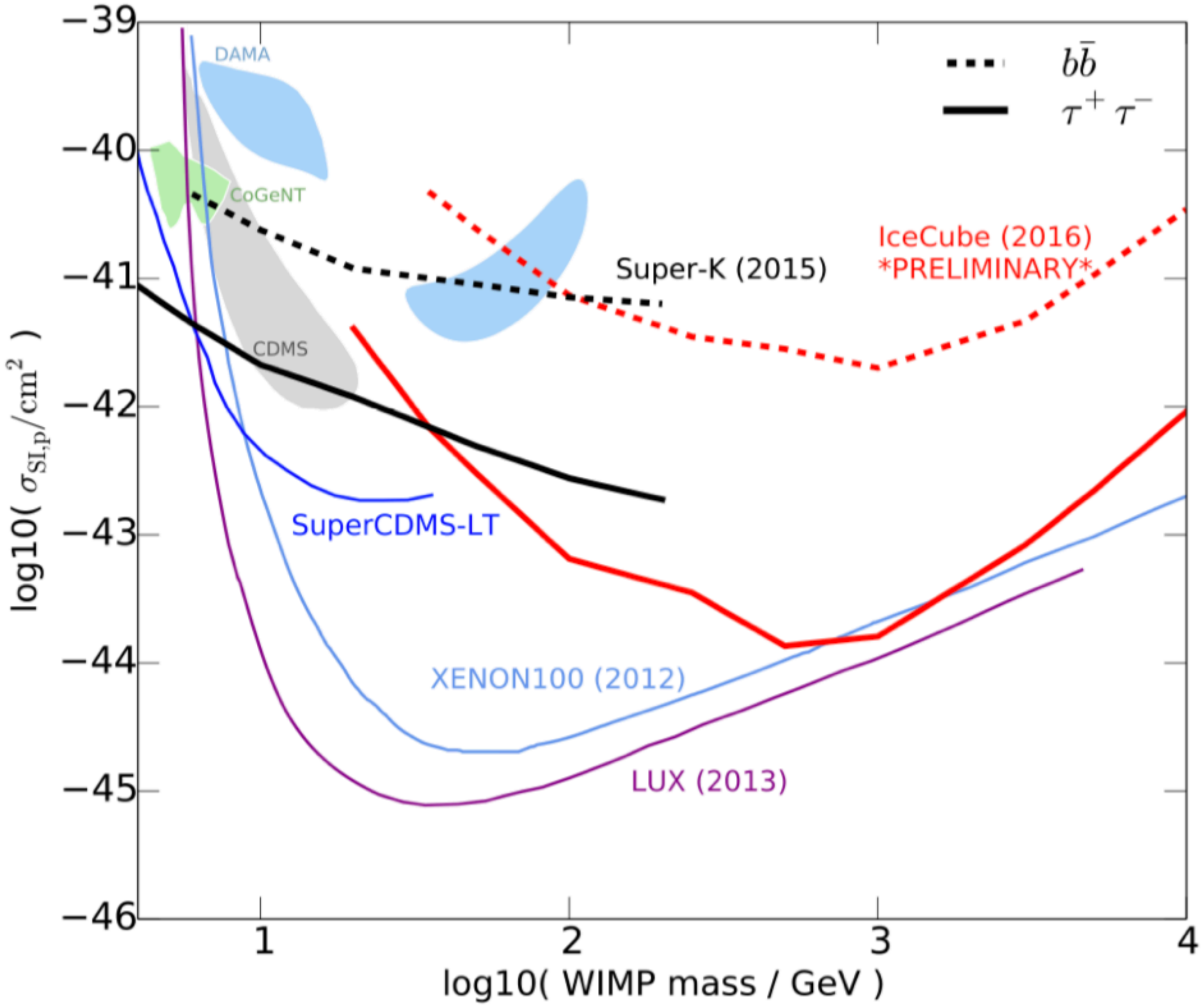
More sensitive to lighter DM

Different particle couplings

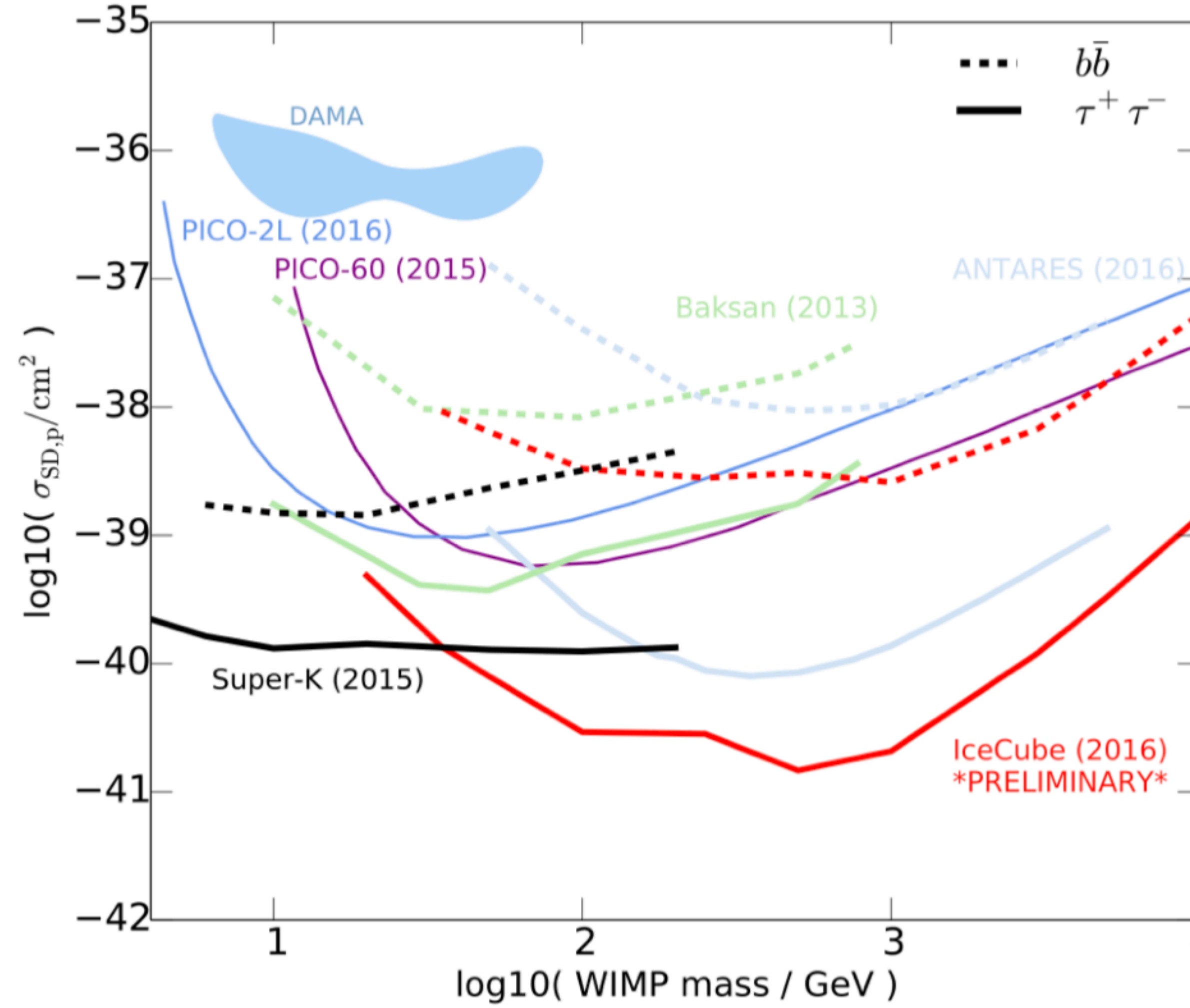
If DM annihilates: look for neutrinos



Spin-Independent



Spin-Dependent



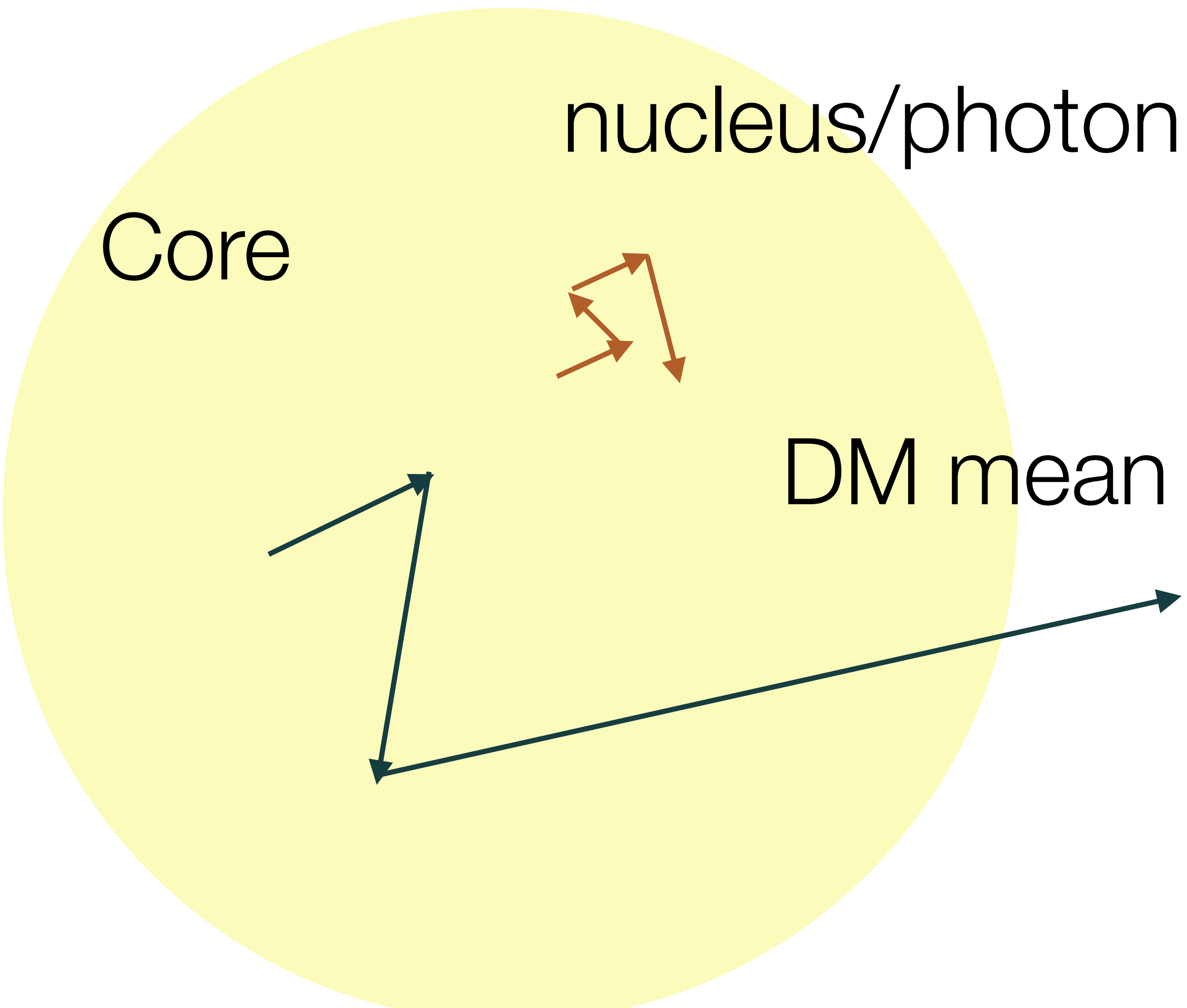
Figs from **Danninger** 2017

See also poster
by Neal Avis Kozar for
more interesting models

Asymmetric DM in stars: no annihilation; DM accumulates

$\sigma \simeq \sigma_T$

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



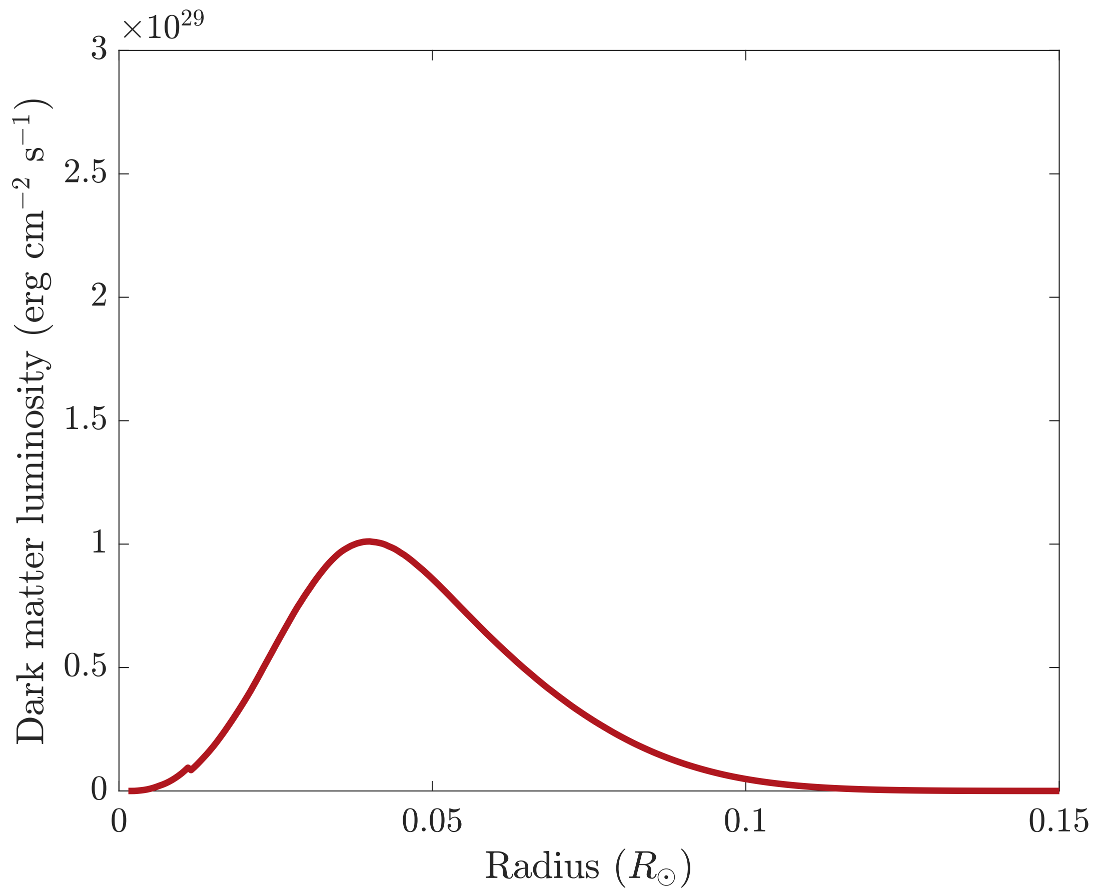
DM mean free path $\lambda_\chi \gg \lambda_{\rm nuc}$

$\sigma \ll \sigma_T$

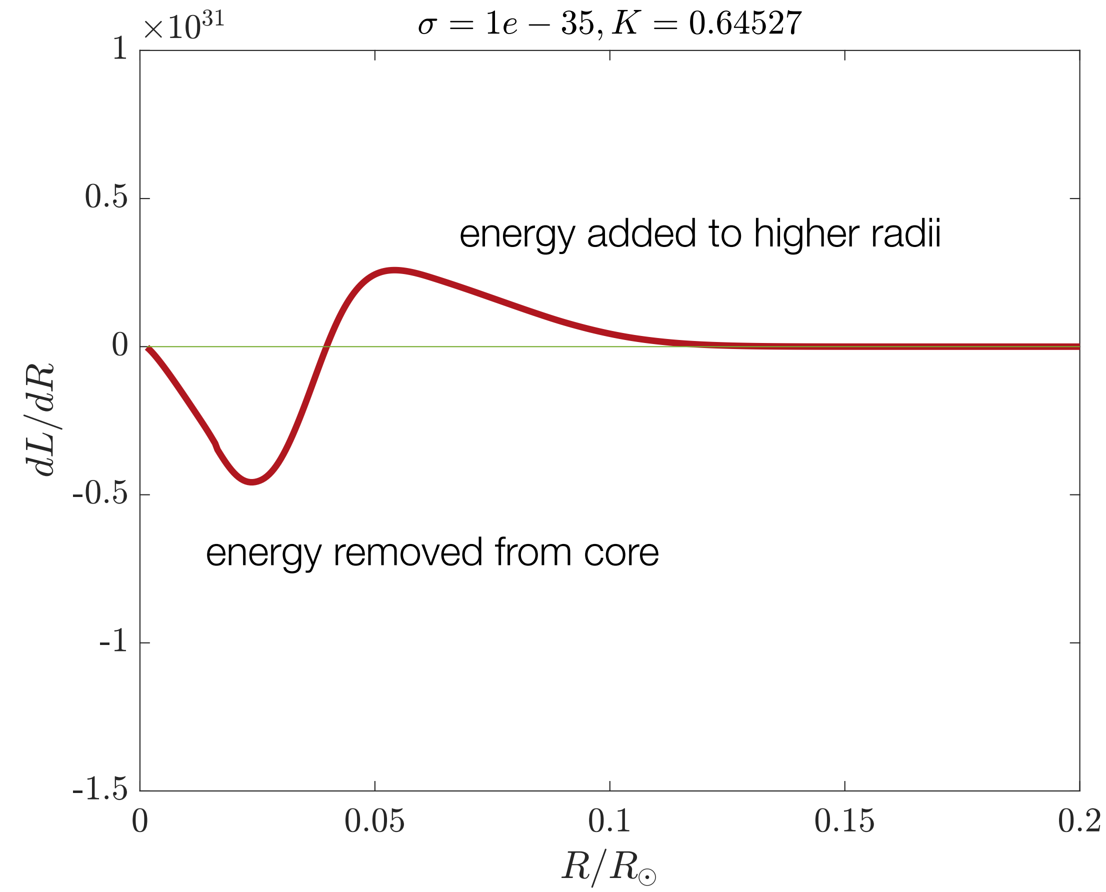
Heat can be transported, changing the stellar temperature, density and pressure profiles

Asymmetric DM in stars

Dark Matter luminosity*



transported energy



*for $n_{DM}/n_p = 10^{-15}$; recall $L_\odot \sim 10^{33}$ erg s^{-1}

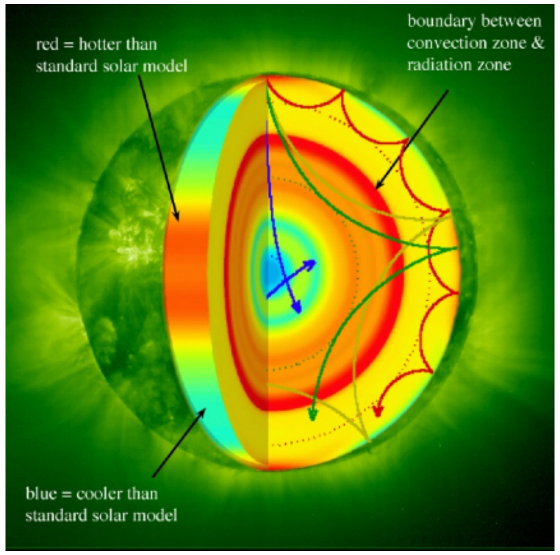
Observable?

Change in radial heat transport

Change in temperature profile

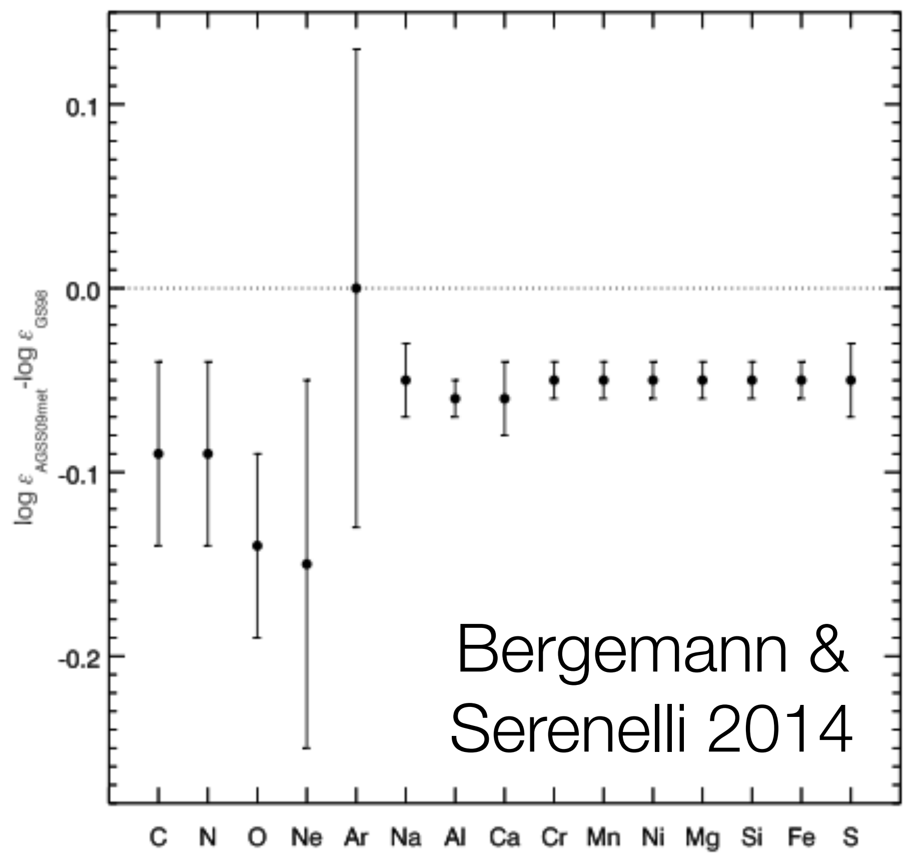
Small changes in pp fusion chain: reduction in ^{8}B and ^{7}Be **neutrino fluxes**

Change in **pressure and density:** sound speed, Convective zone boundary

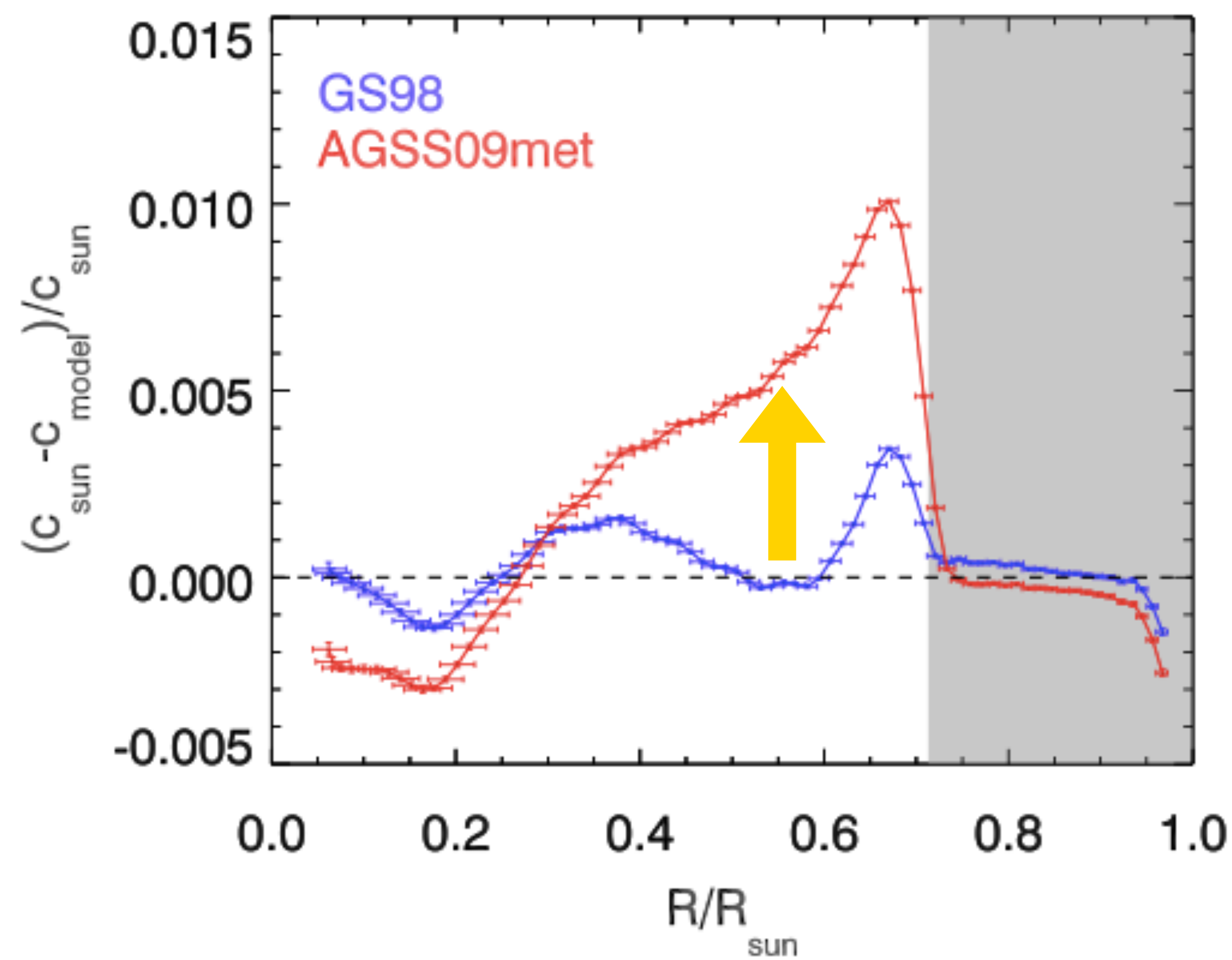


Helioseismology

Solar composition problem (since 2004)



revised - old abundances

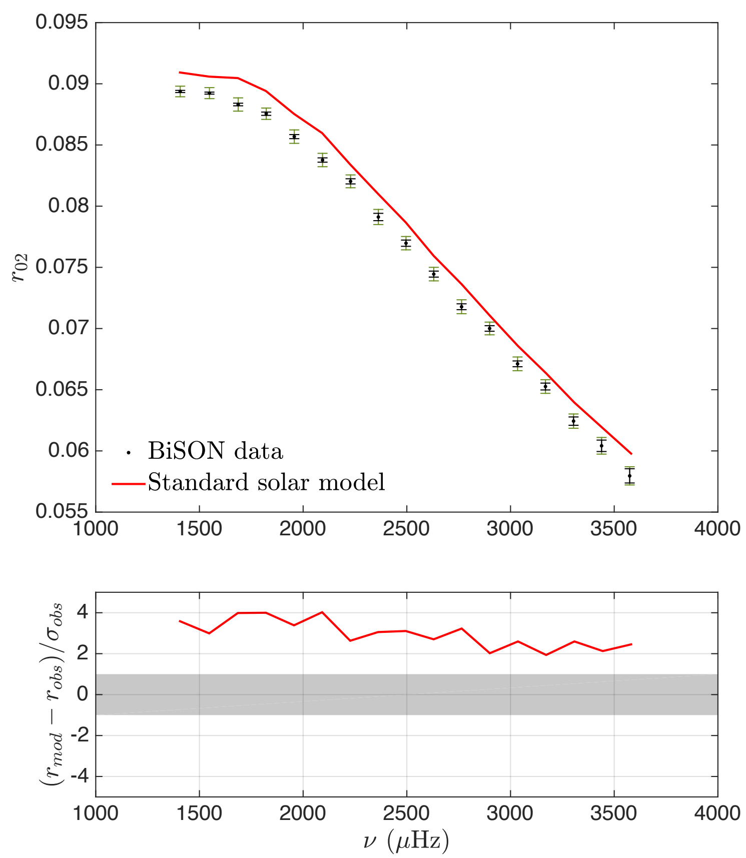


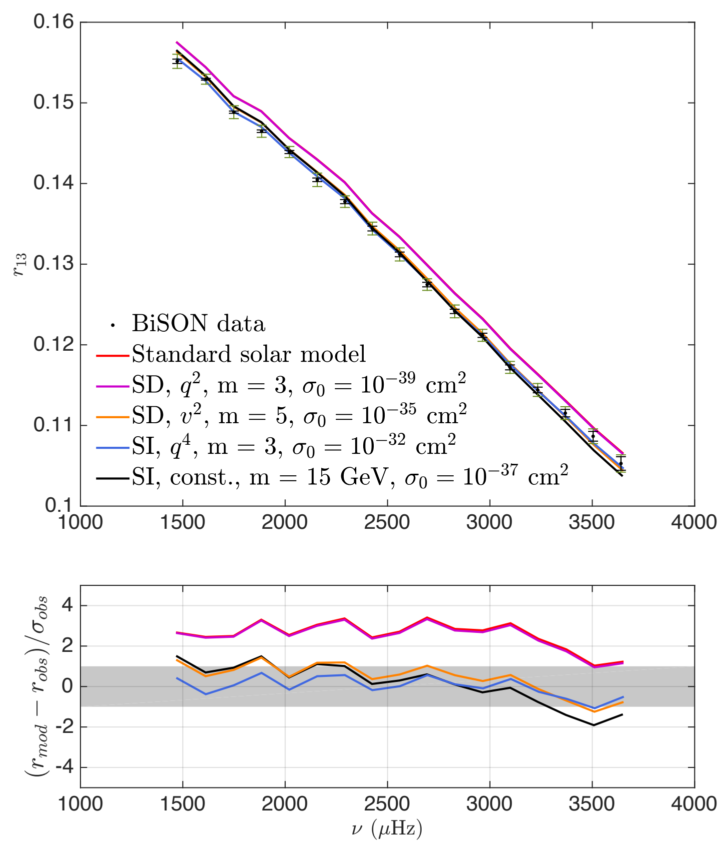
$$R_{\mathrm{CZ},\odot} = 0.713 \pm 0.001\, R_\odot$$
$$R_{\mathrm{CZ,SSM}} = 0.722 \pm 0.004\, R_\odot$$

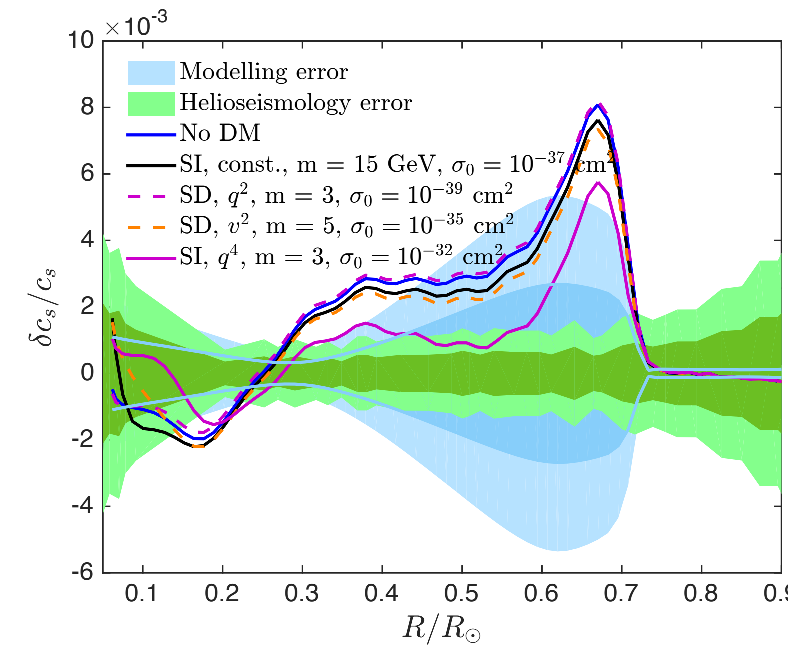
Sound speed off by $\sim 4-5\sigma$?

Solar composition problem

Small frequency separations: a probe of the core







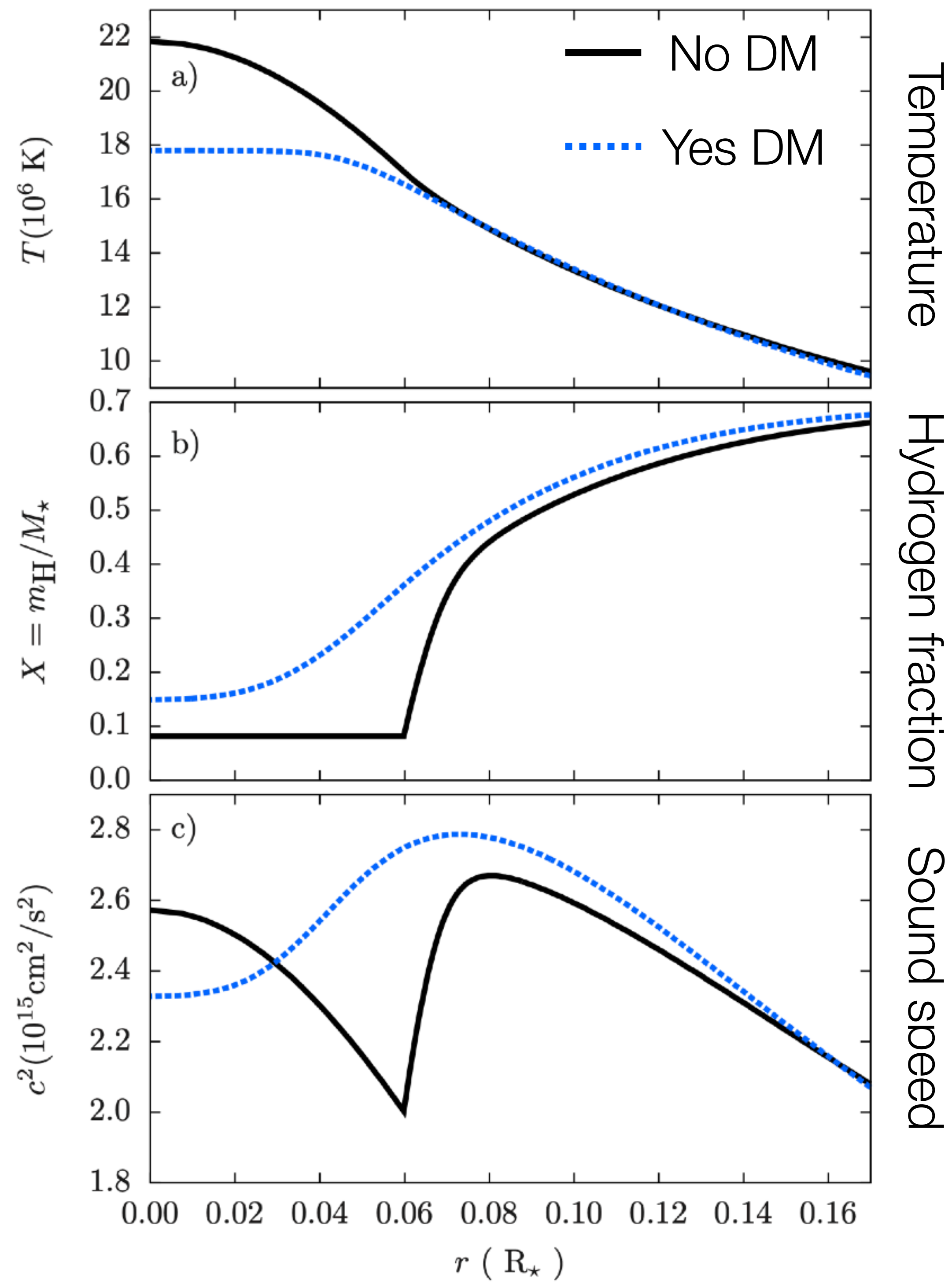
Sound speed

Asymmetric DM may be a solution to the solar composition problem

ACV, Pat Scott, Aldo Serenelli 1411.6626, 1504.04378,1605.06502

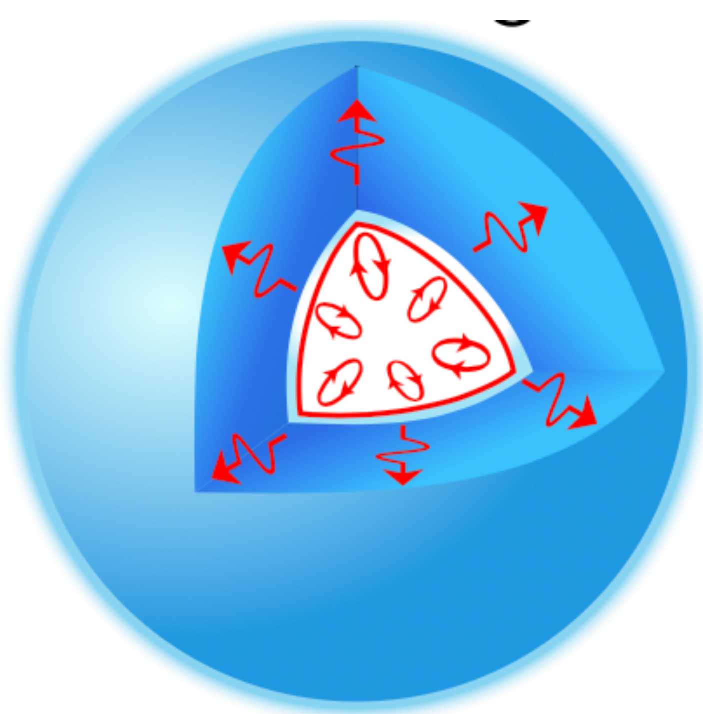
Dark matter in other stars

Casanellas et al 1505.01362



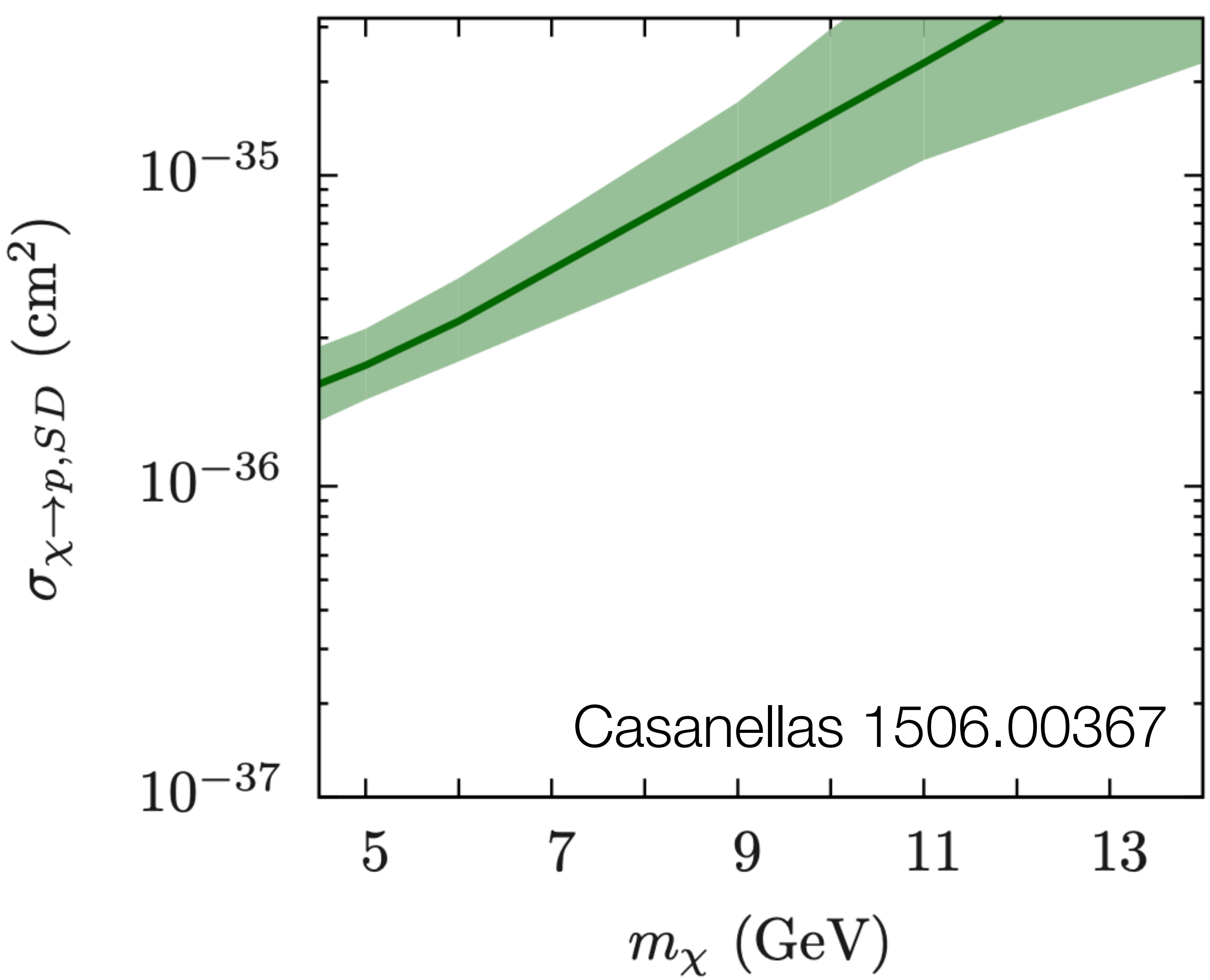
Nearby stars $\gtrsim$ 1.3 $M_\odot$:

Convective cores form in stars where the **temperature gradient** is too large to maintain hydrostatic equilibrium



DM can erase these cores, affecting **asteroseismology**

Convective core suppression

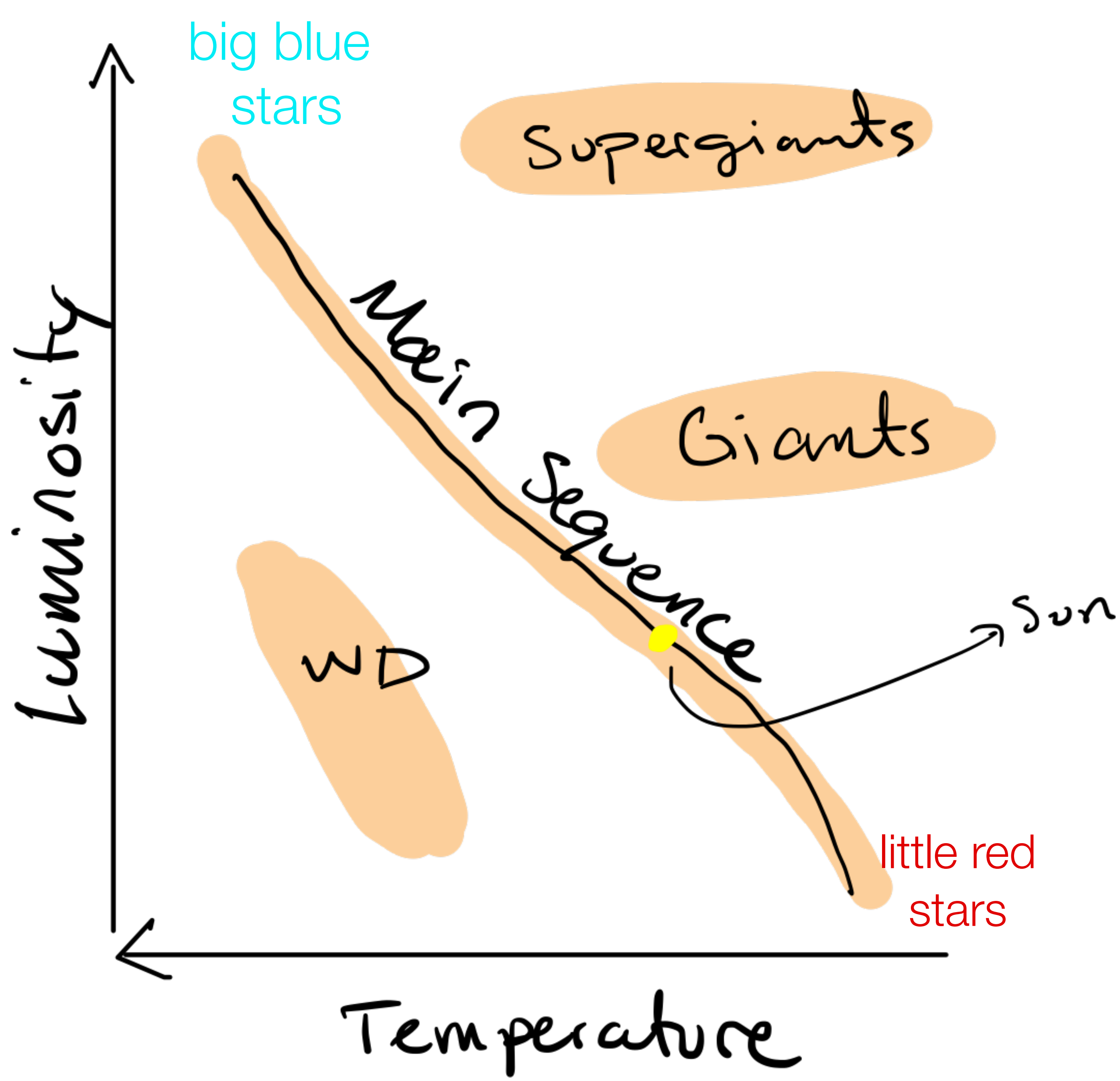


Constraint using α Cen B

Constraints are weak partly because the local DM density ~GeV cm^{-3} is small (and this is only one star)

Large amounts of dark matter?

Intro astronomy reminder

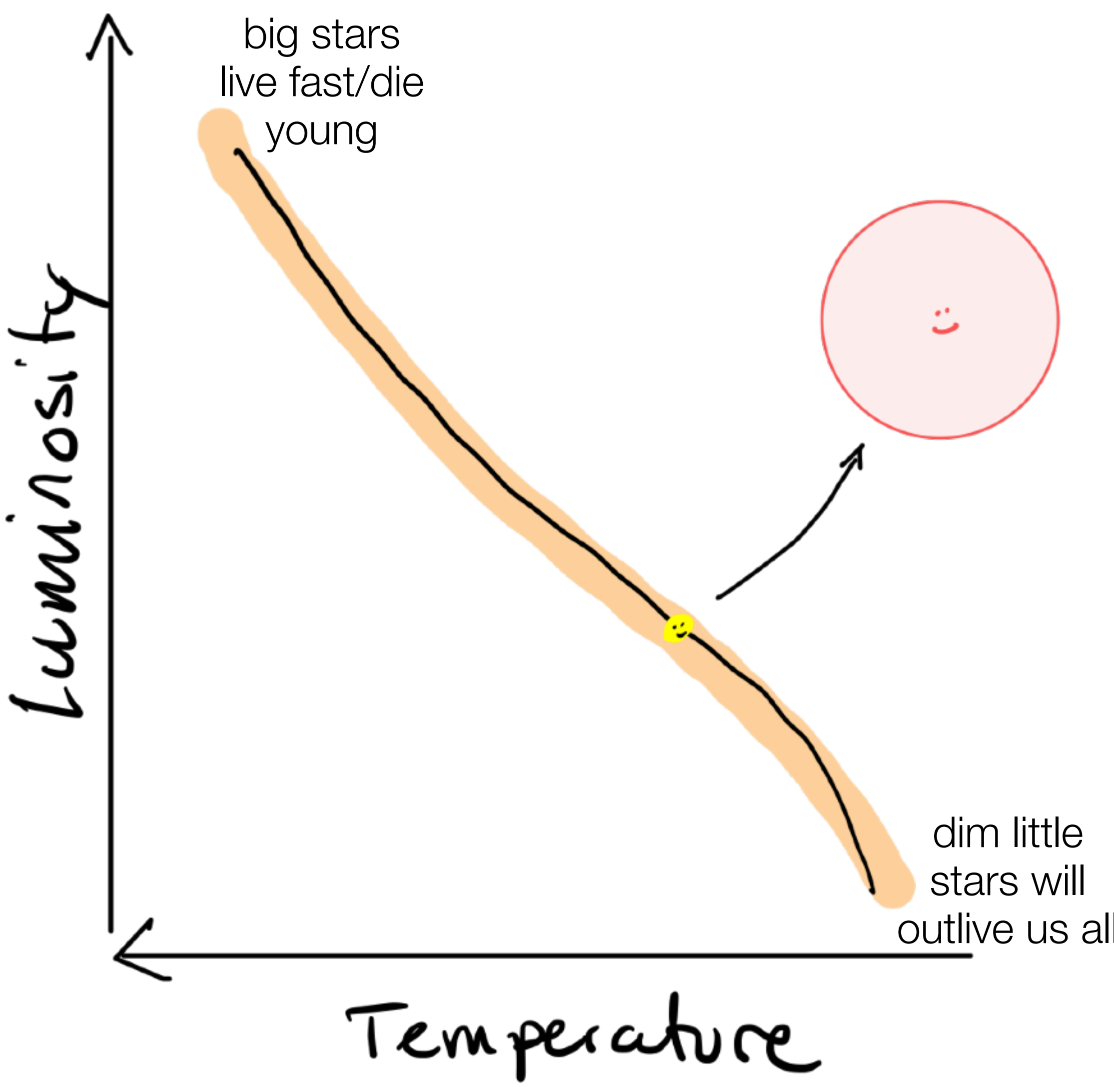


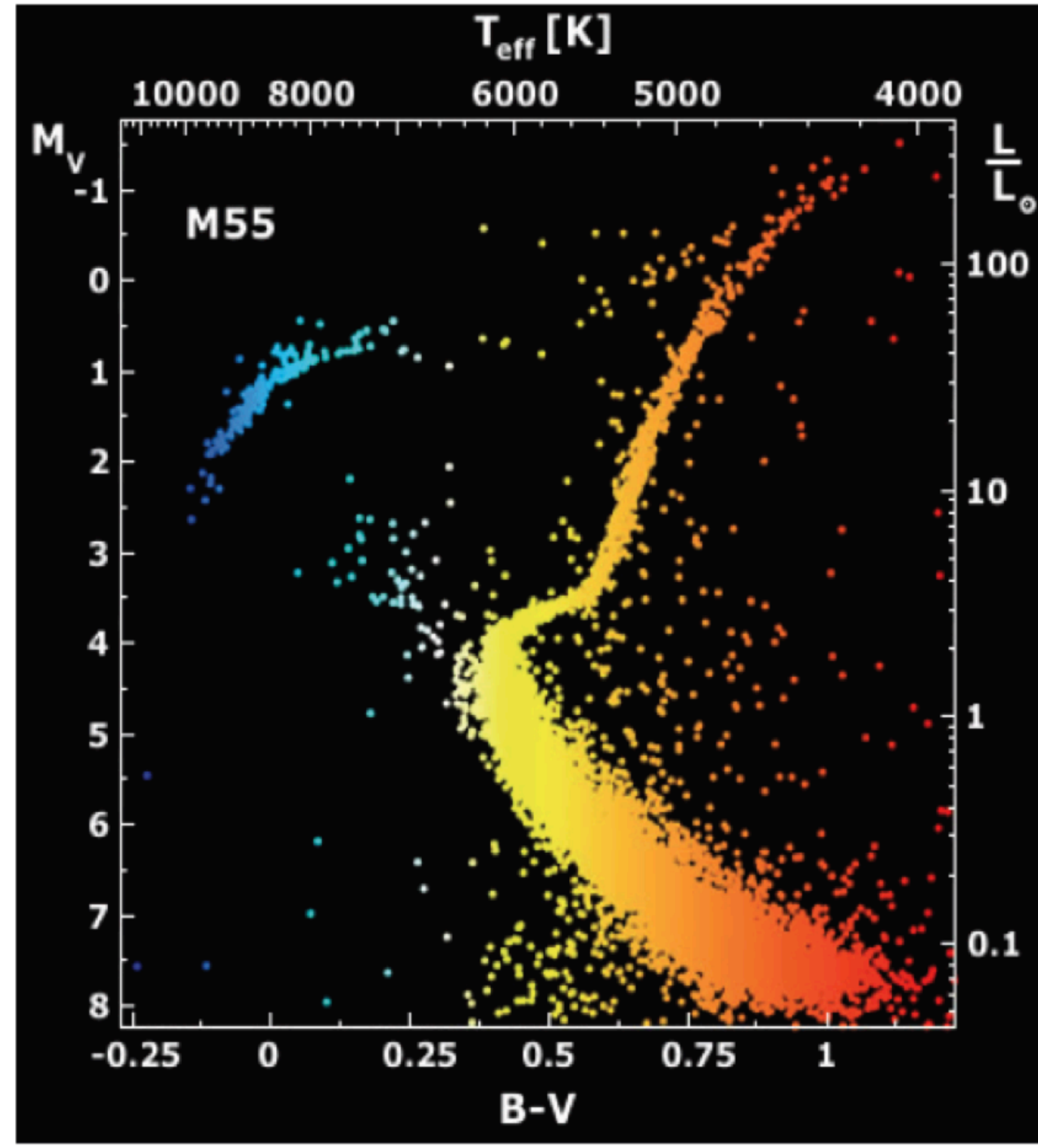
Main sequence stars are powered by **Hydrogen fusion**

Lifetime is limited by:

- How much fusion is needed to oppose gravitational pressure
- How much hydrogen ‘in the tank’ (in core above T required for fusion)

When a star exhausts its hydrogen it leaves the main sequence



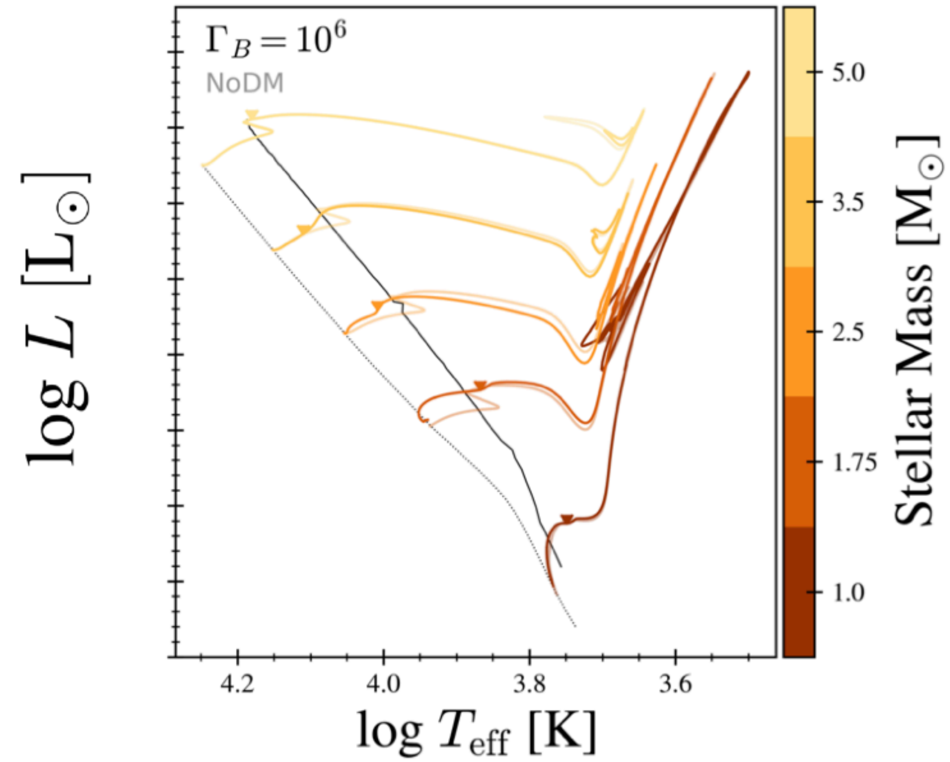


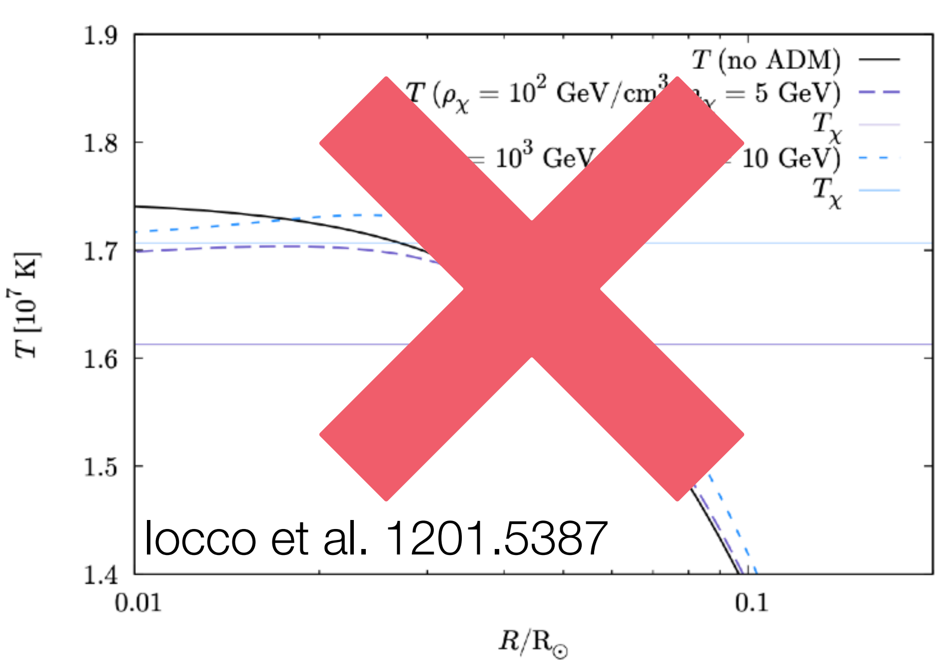
Not visible in our lifetime, but we can look at populations of stars to test stellar evolution (like looking at populations of humans to understand aging)

The Effects of Asymmetric Dark Matter on Stellar Evolution I: Spin-Dependent Scattering 2010.04184

Troy J. Raen,[1*], Héctor Martínez-Rodríguez[1], Travis J. Hurst[2], Andrew R. Zentner[1], and Carles Badenes[1], and Rachel Tao[3]

Large amounts of DM: change trajectory on HR diagram
erasure of convective 'hook' (because no convective cores)



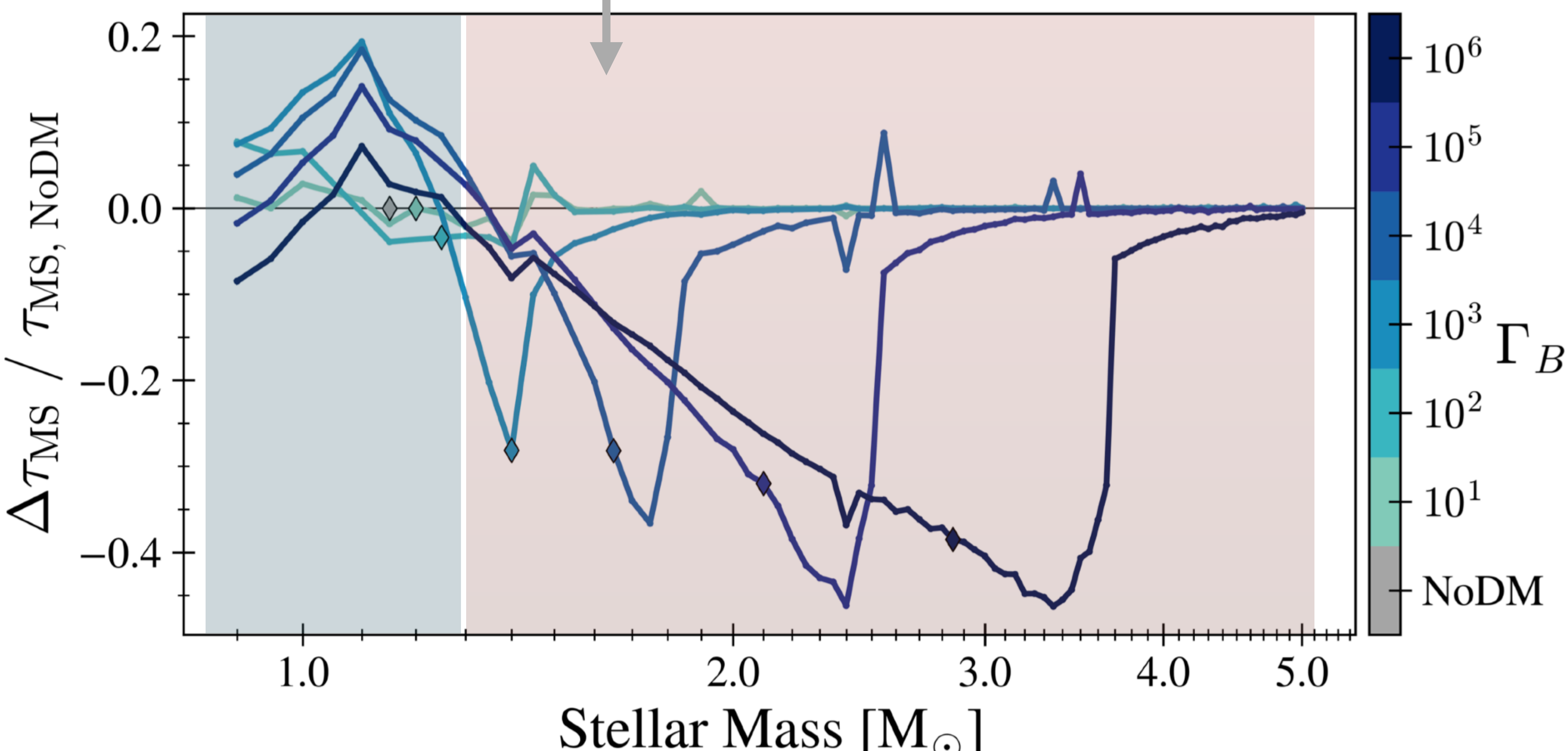


No temperature inversions as previous studies had found (this was a numerical artefact)

Raen et al 2010.04184: Main sequence lifetime

Low mass stars: larger core — more available H to fuse, longer lifetime

High mass stars: suppression of convective core — no mixing = less available fuel. Shorter lifetime



Heat conduction in stars

Boltzmann equation $$DF(\mathbf{v}, \mathbf{r}, t) = \frac{1}{\ell_\chi} CF(\mathbf{v}, \mathbf{r}, t)$$

D: Liouville operator (covariant derivatives)

$F(\mathbf{v}, \mathbf{r}, t)$: Dark matter phase space density

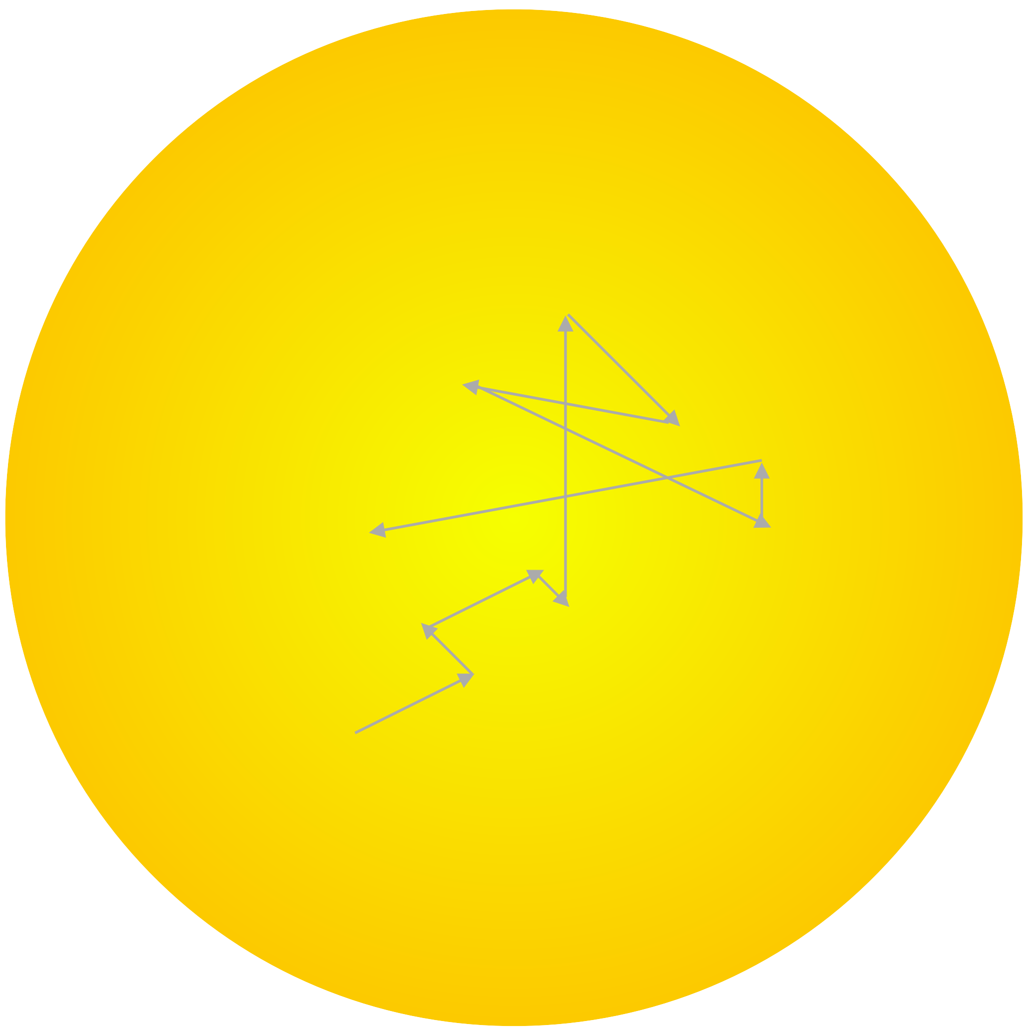
C: Collision operator (a bunch of integrals)

$\ell_\chi \propto \sigma_{\chi N}$: Mean free path

= 6-dimensional integro-differential equation

Must be solved consistently **at every time step** in stellar evolution

Only exact(ish) solution is Monte Carlo (random walk)



Let a particle bounce around for many iterations, histogram distribution, average heat transferred vs *r* using **ergodicity**

Cannot possibly do this for every simulated time step. Need some **approximations**

Solution method 1: isothermal (Spergel & Press)

$$DF(\mathbf{v}, \mathbf{r}, t) \simeq 0 \quad \rightarrow F \sim \exp\left(-\frac{\frac{1}{2}mv^2 + m\phi(r)}{kT_\chi}\right)$$

DM is at a single 'average' temperature T_χ

Conduction treated as contact between two weakly coupled heat baths

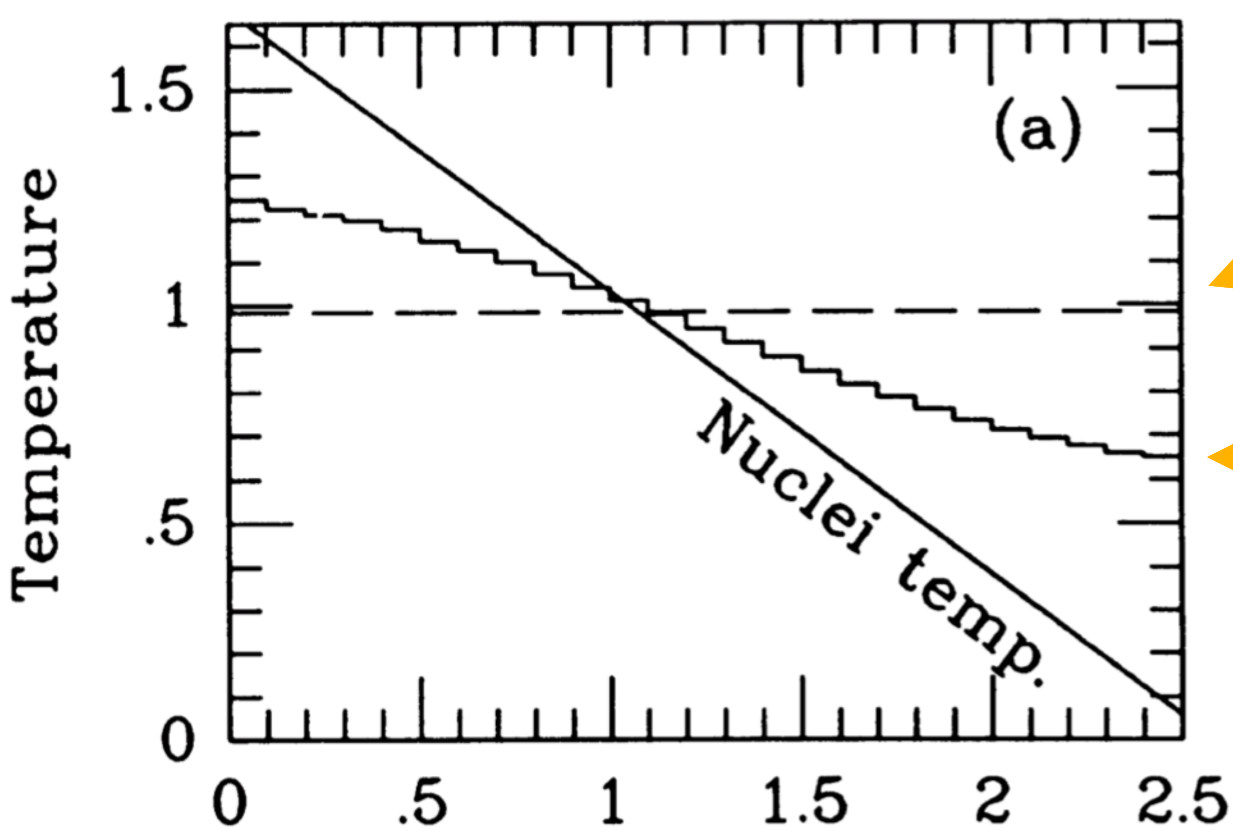
$$\epsilon \propto \sigma[T_\star(r) - T_\chi] \begin{cases} \text{Heat removed from star where } T_\star(r) > T_\chi \\ \text{Heat deposited in star where } T_\star(r) < T_\chi \end{cases}$$

Solution method 1: isothermal (Spergel & Press)

$$\epsilon \propto \sigma[T_\star(r) - T_\chi]$$

This has been known to be incorrect since 1990, but is still most widely used because it is numerically stable

Gould & Raffelt 1990 Monte Carlo simulation



Isothermal assumption T_χ

Actual DM temperature

ΔT overestimated $\rightarrow$heat transfer overestimated

Solution method 2: corrected LTE (Gould & Raffelt)

If $\ell \ll r_\chi$, conduction is **local** ($T_\chi(r) \simeq T_\star(r)$)

Expand $DF(\mathbf{v}, \mathbf{r}, t) = \dfrac{1}{\ell_\chi} CF(\mathbf{v}, \mathbf{r}, t)$ in a series in $\ell_\chi \,|\, \nabla \ln T_\star \,|$

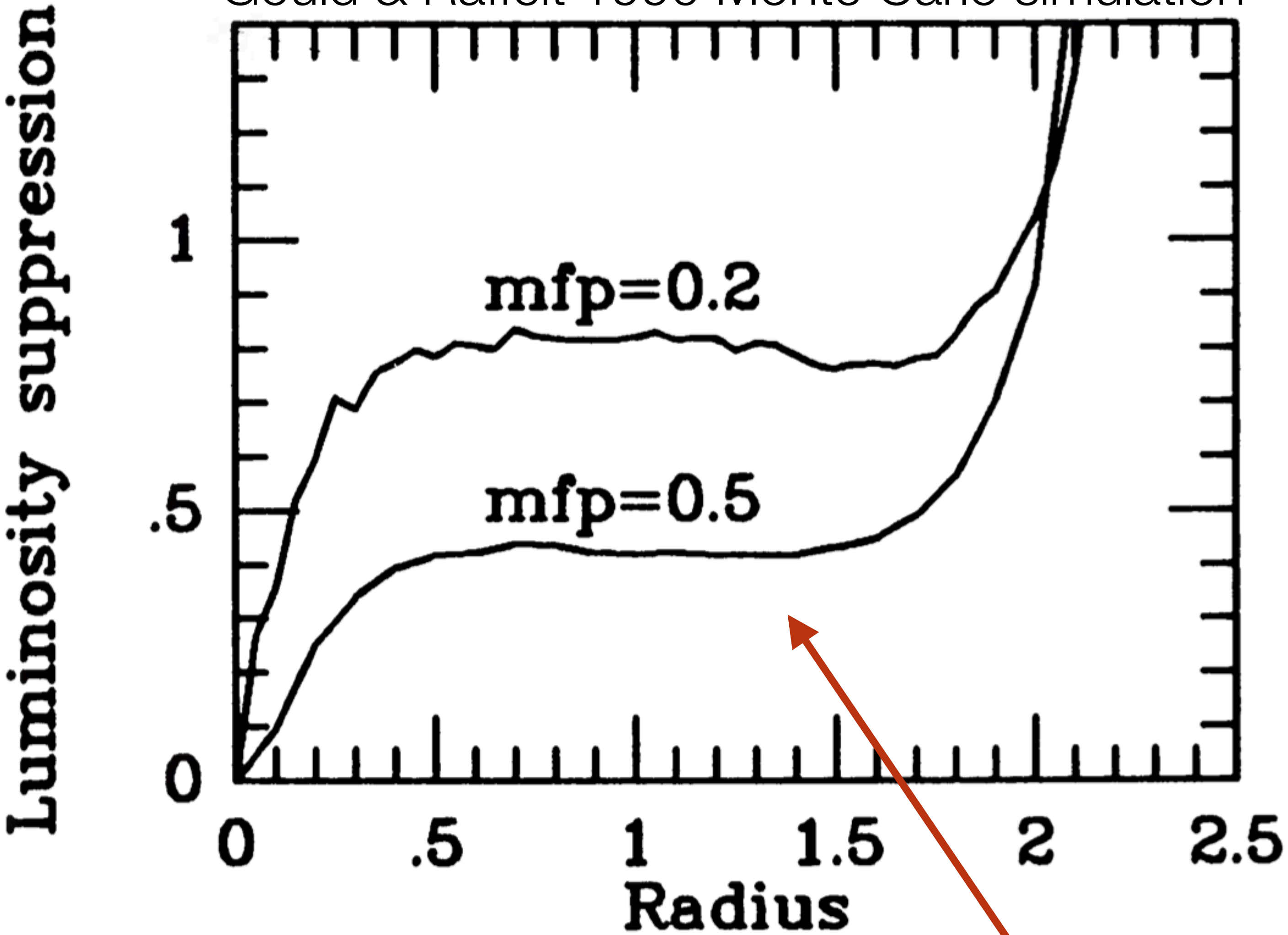
Solve first order dipole (only care about radial part)

$$\text{Luminosity} \propto \kappa(m_\chi) n_\chi(r) \ell_\chi \frac{dT_\star}{dr}$$

$\kappa(m_\chi)$: thermal conduction coefficient computed from C

Solution method 2: corrected LTE (Gould & Raffelt)

Gould & Raffelt 1990 Monte Carlo simulation



Two corrections still needed:

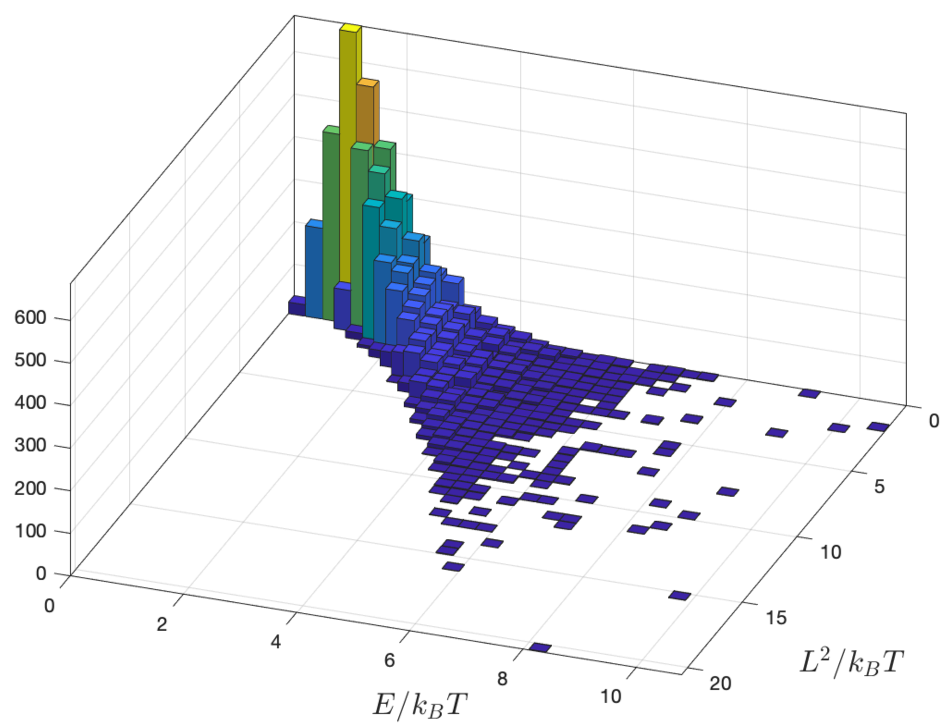
- **Knudsen suppression:** condition $\ell_\chi \ll |\nabla \ln T|^{-1}$ breaks down.
- **Radial suppression**: isotropy assumption breaks down at low radii

All “correct” results in the past 30 years use a fit to this graph to fix the LTE prediction

Additional technical issue: numerically unstable (reason method 1 still used)

Monte Carlo: A few thousand CPU hours

Hannah Banks (Cambridge)



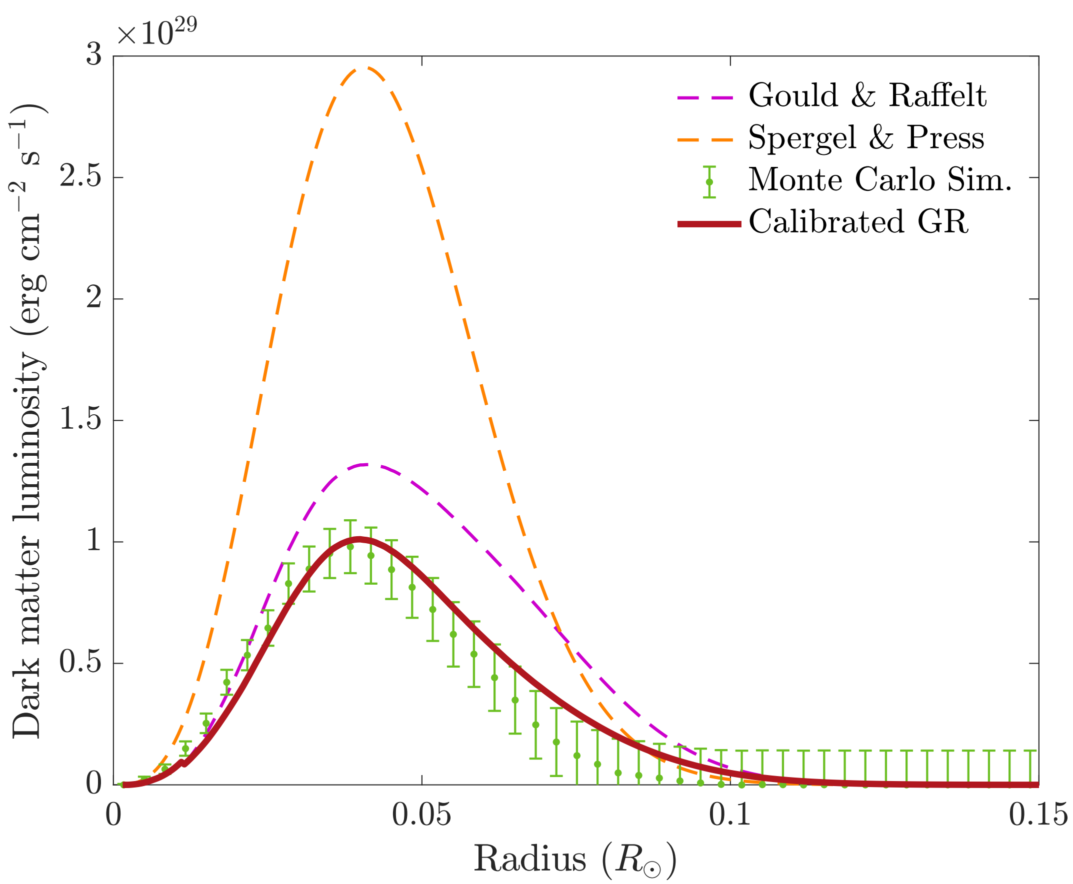
Angular momentum: distribution not fully specified by $E = \frac{1}{2}mv^2 + m\phi$

Anisotropy ↔ departure from Maxwell-Boltzmann

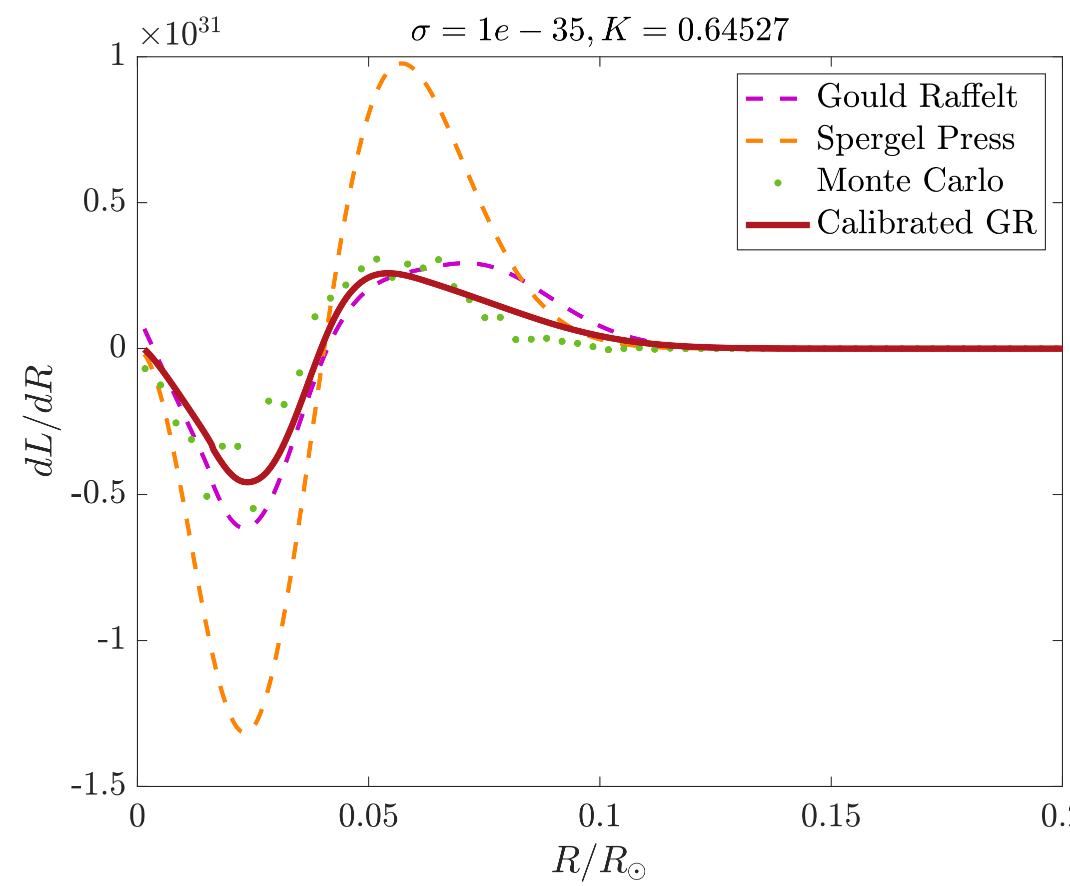
Interesting results from non-constant cross sections to come

Heat transport: theory vs Monte Carlo

Dark Matter luminosity



transported energy

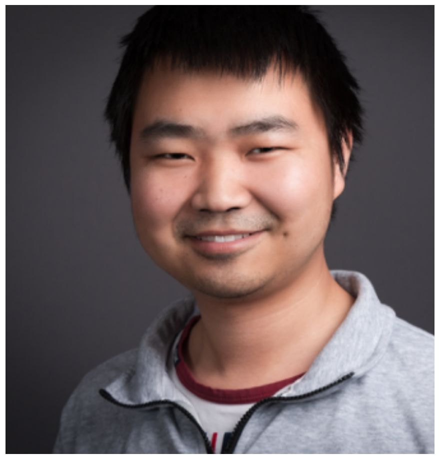


Currently working on a robust parametrization + next-gen simulations — stay tuned!

Summary

- Dark matter in the ‘traditional’ mass range ~ GeV-TeV can affect the Sun in observable ways
- Low-mass Asymmetric dark matter can do very interesting things to main sequence stars
- Current results are built on a theoretical framework that relies on some inconsistent assumptions
- The true effect of ADM in stars remains to be elucidated. Stay tuned!

Please check out



Ningqiang Song

Closing the window for WIMPy inelastic dark matter with heavy nuclei

Particle physics session 17:15 Jun 9

Avi Friedlander

Signatures of Primordial Black Holes in theories of Large Extra Dimensions (*← link to video*)

Neal Avis Kozar

Exploring dark matter detection using Solar capture and the Non-Relativistic Effective Operator formalism (*←link to poster*)

GatherTown Room 5, poster J83


Hubble Legacy Archive, NASA, ESA