Illuminating dark matter with the tip of the red giant branch

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Arthur B. McDonald

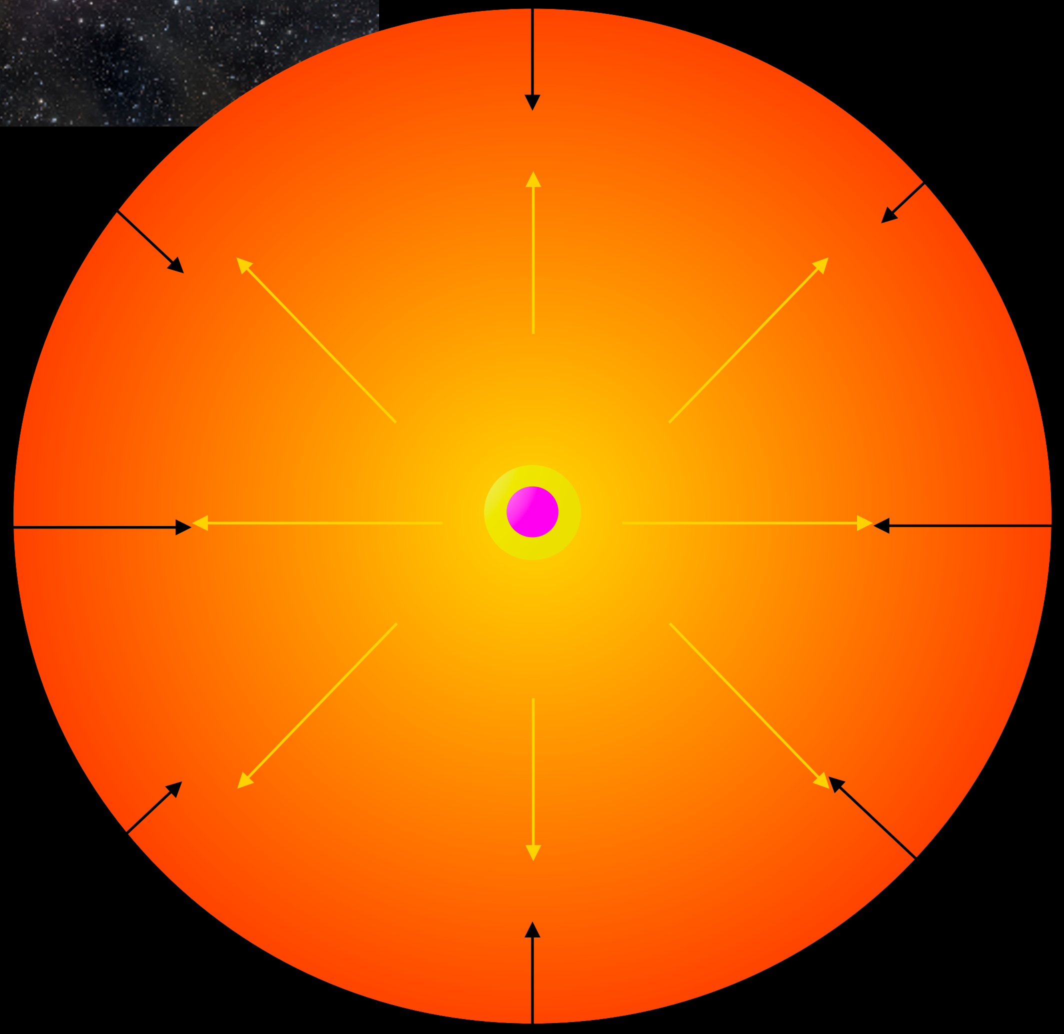
Canadian Astroparticle Physics Research Institute

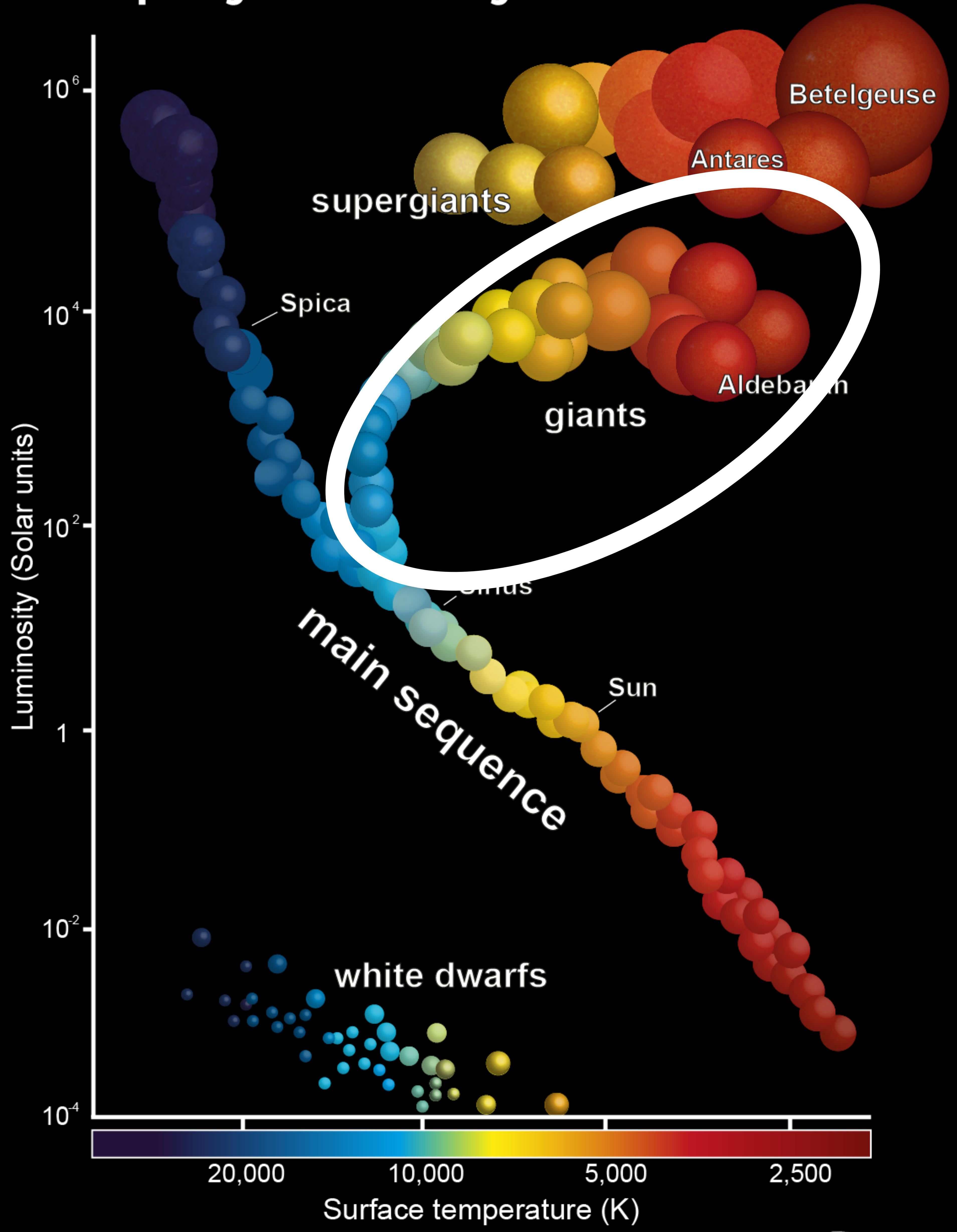
Based on Hong + ACV arXiv:2407.08773

Red giant branch

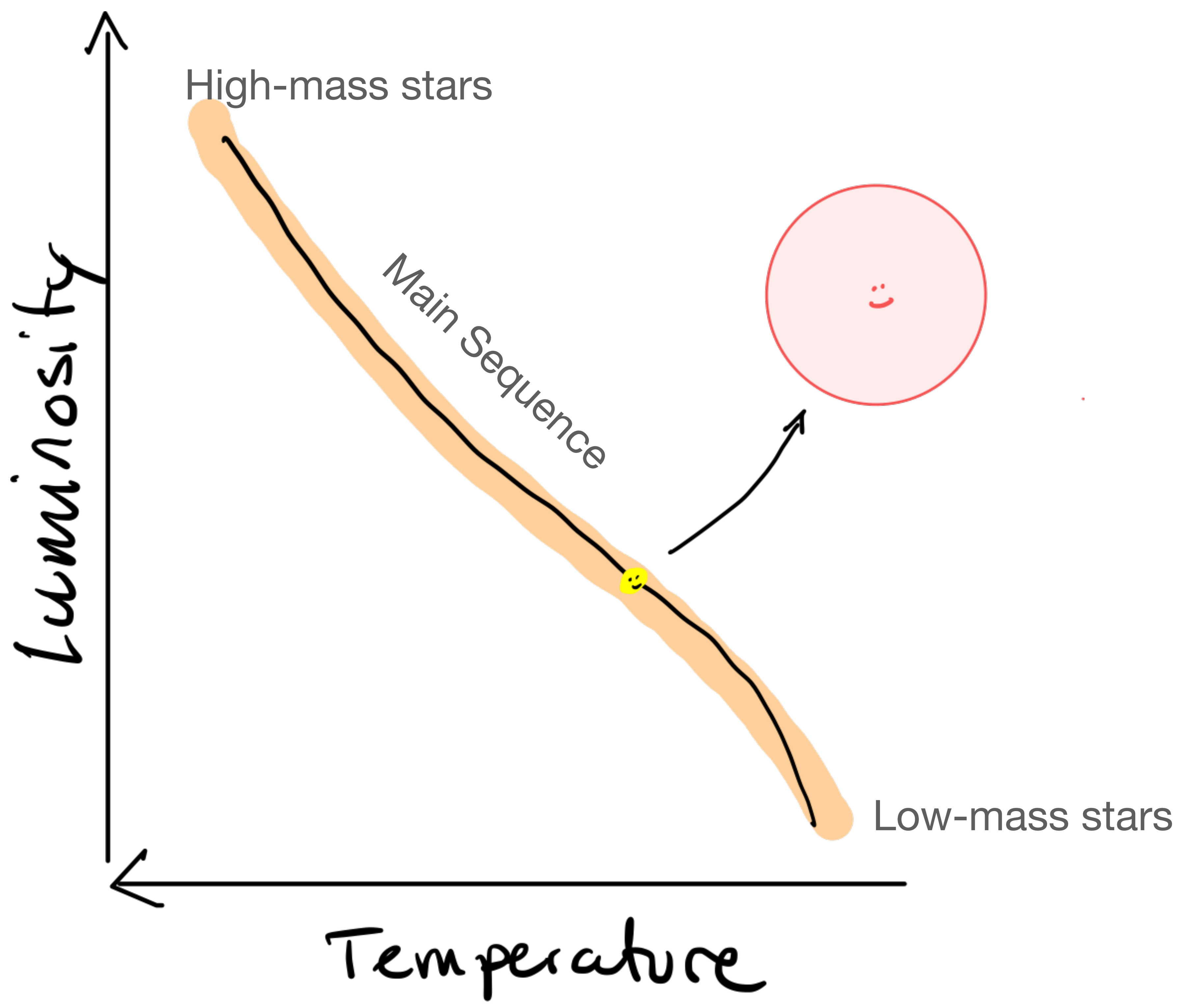
Helium core

Hydrogen shell burning





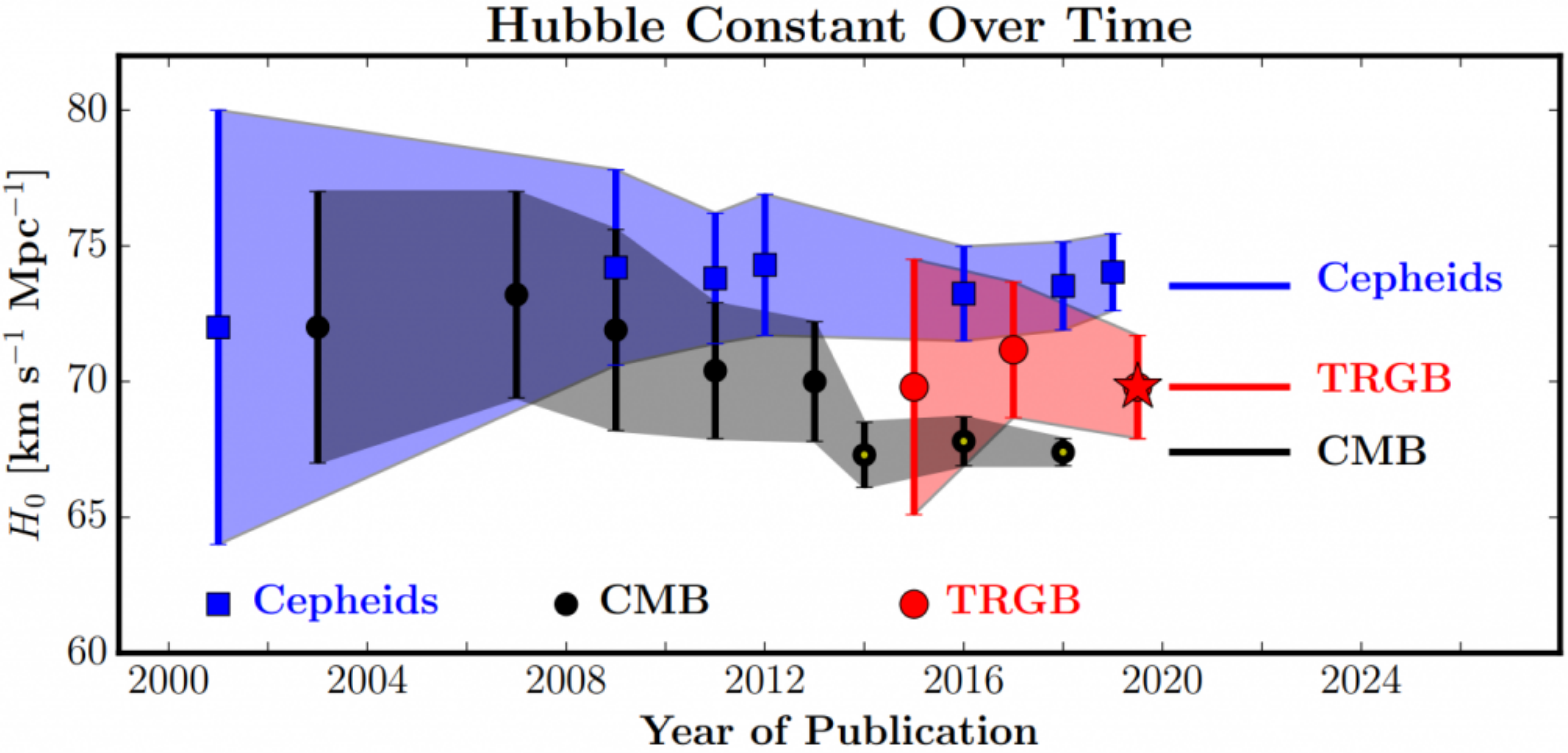
Tip of the red giant branch



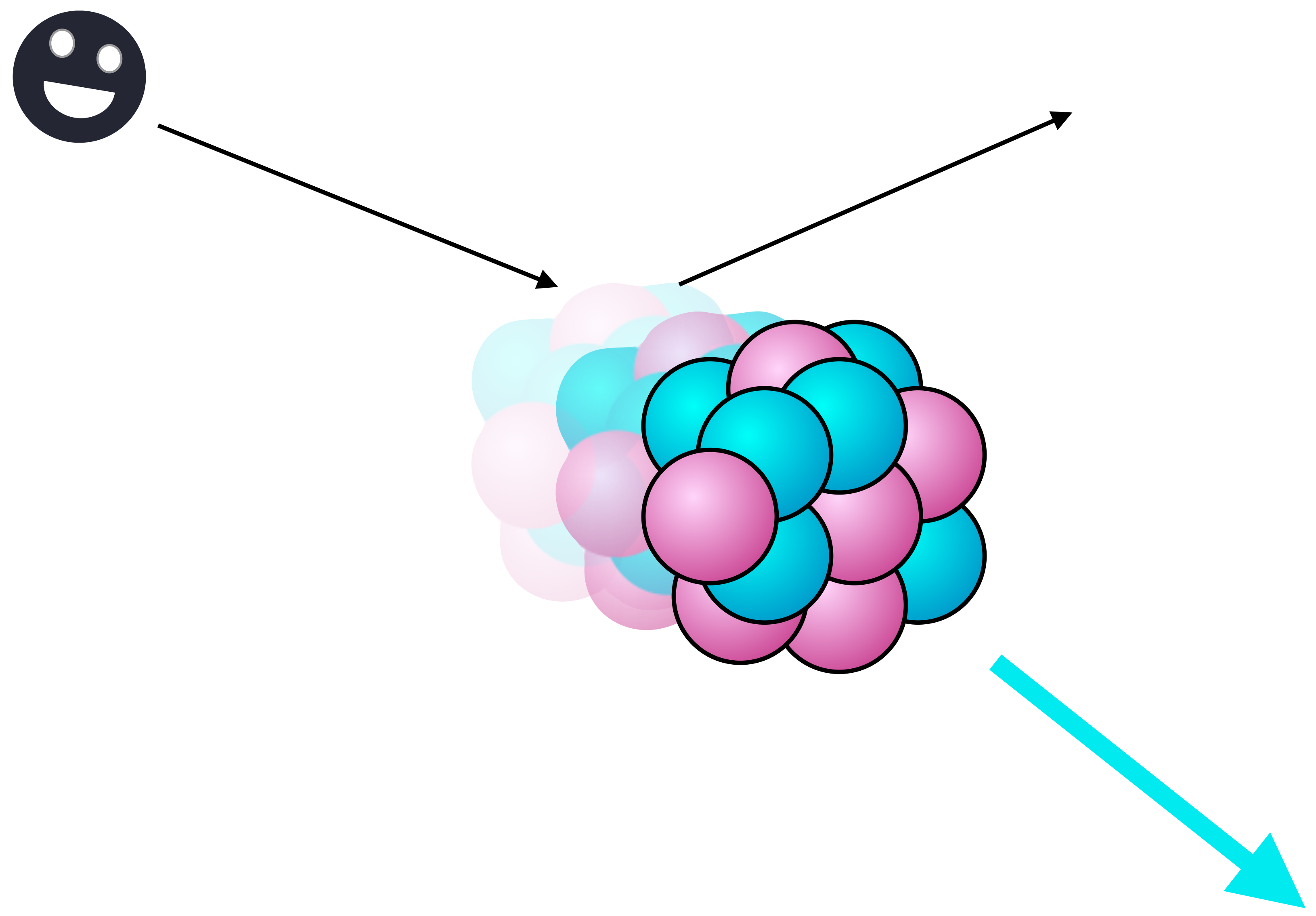
Stars on the **Main Sequence** are powered by hydrogen fusion into He

When H in the core is exhausted, they leave the main sequence and turn into **red giants**

The **tip of the red giant branch** is where the inert helium core ignites from heating to ~ 10^8K. It has an approximately constant luminosity across different stars— it is a **standard candle**


Hubble Constant Over Time
H_0 [km s^{-1} Mpc^{-1}]
80
75
70
65
60
2000
2004
2008
2012
2016
2020
2024
Year of Publication
Cepheids
TRGB
CMB
Cepheids
CMB
TRGB

Dark matter-nucleus elastic scattering

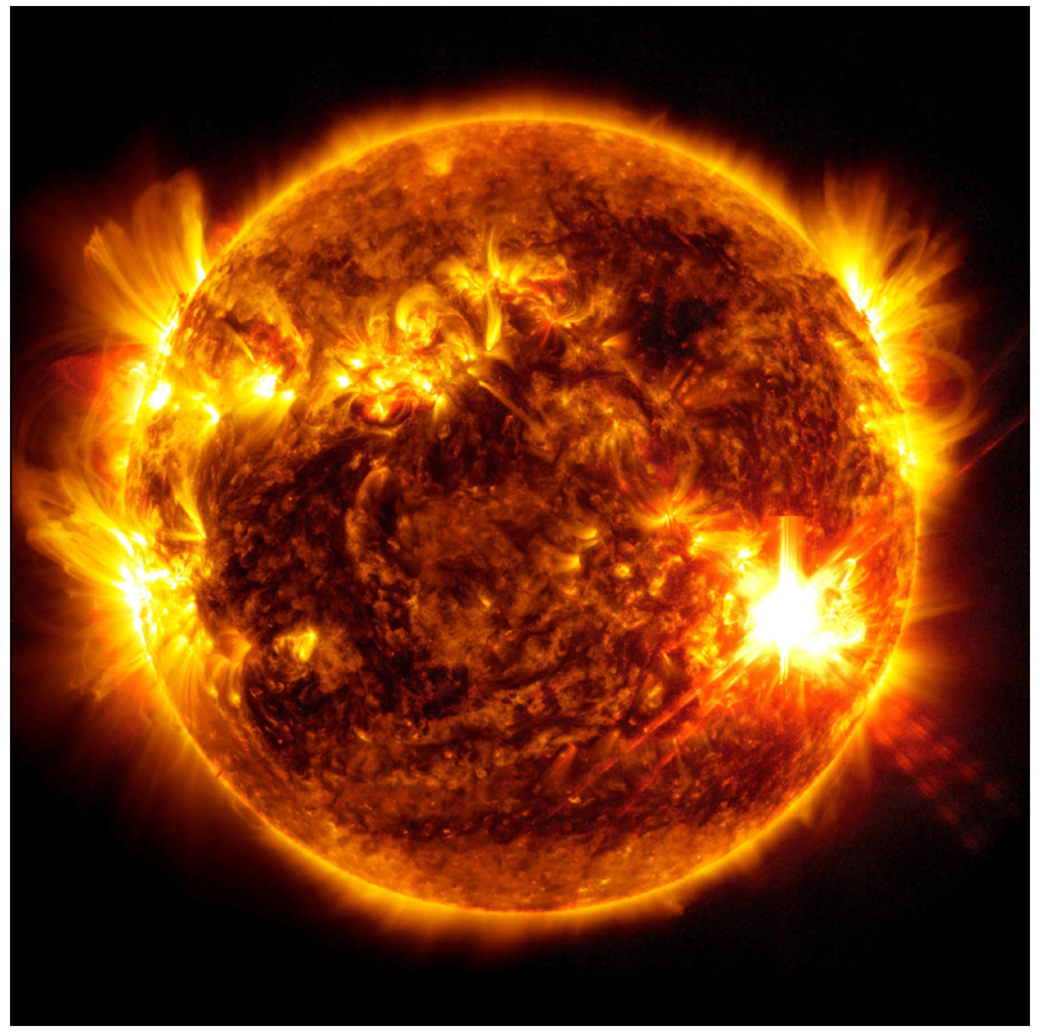


If this happens here

(a direct detection experiment)

It also happens here

(a star)



Igniting the TRGB early with WIMP dark matter

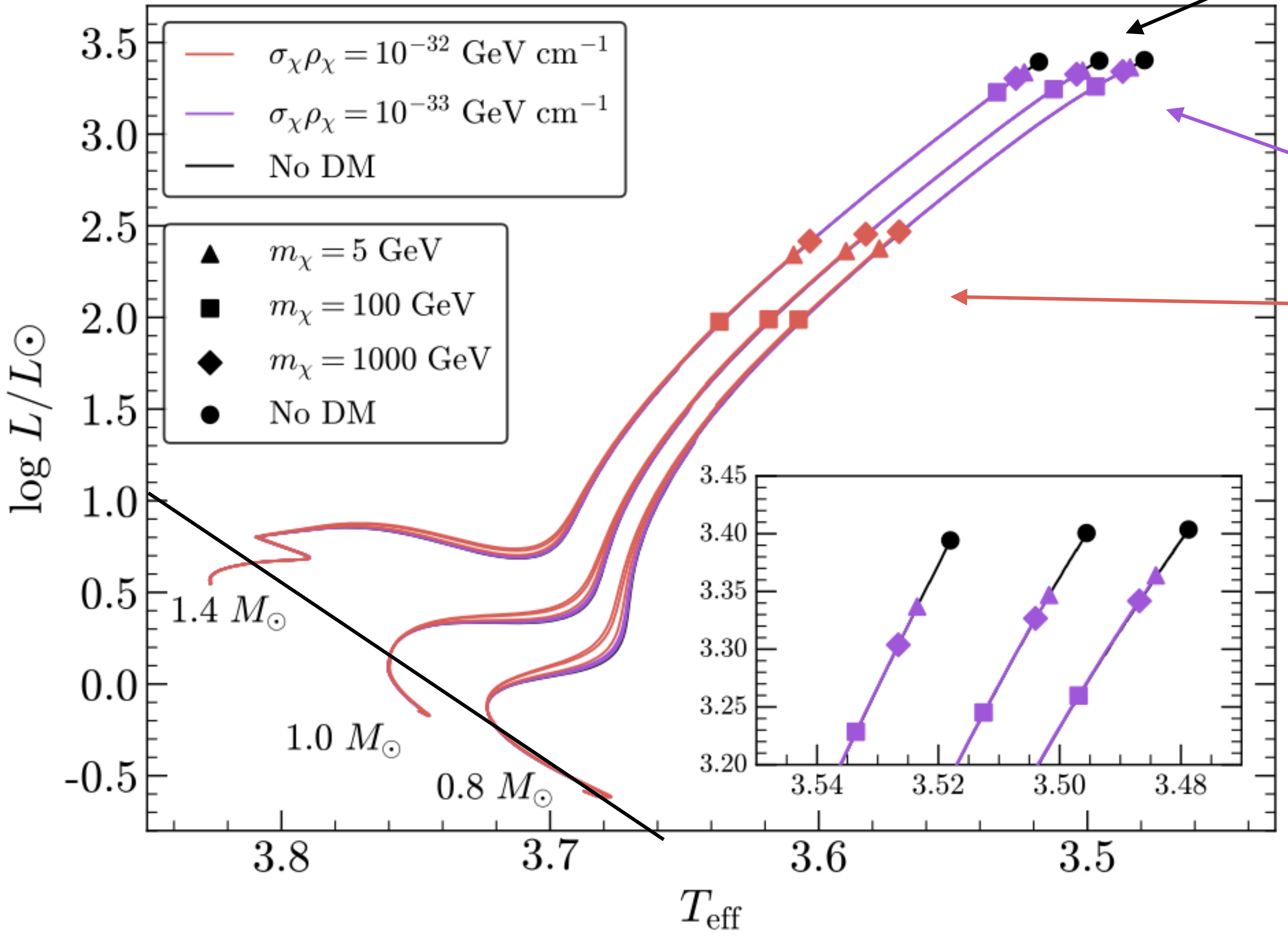
- When dark matter scatters in a star, it can fall below the local escape velocity
- Trapped particles can meet each other and annihilate
- Lopes & Lopes 2107.13885: dark matter capture and annihilation provides an extra source of heating (from everything except the neutrinos).
- This can lead to **premature ignition** of the helium core in a red giant star.

Igniting the TRGB early with WIMP dark matter

Stellar evolution simulations with no dark matter

A lot of dark matter

an obscene amount of dark matter



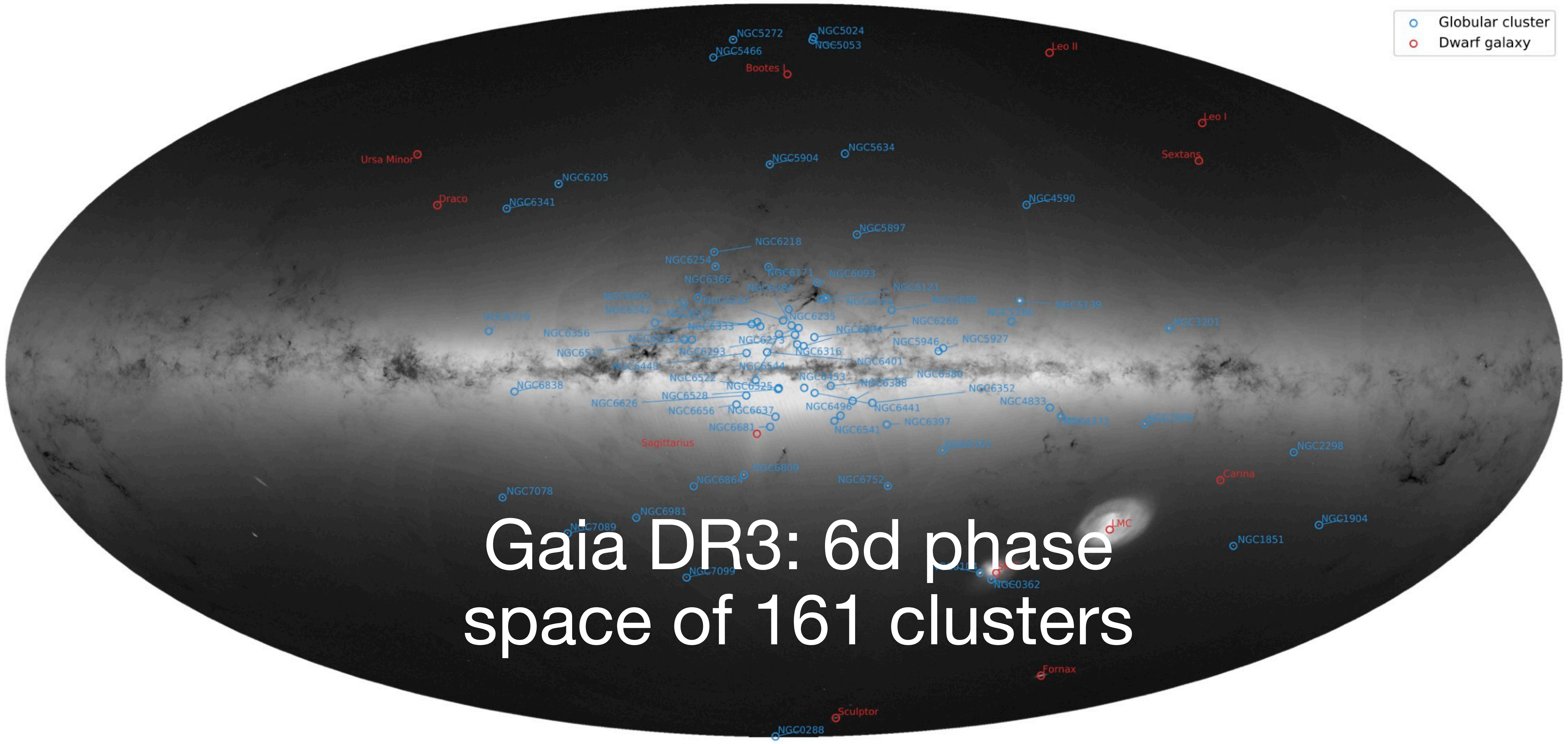
Lopes & Lopes 2107.13885

How do we test this?

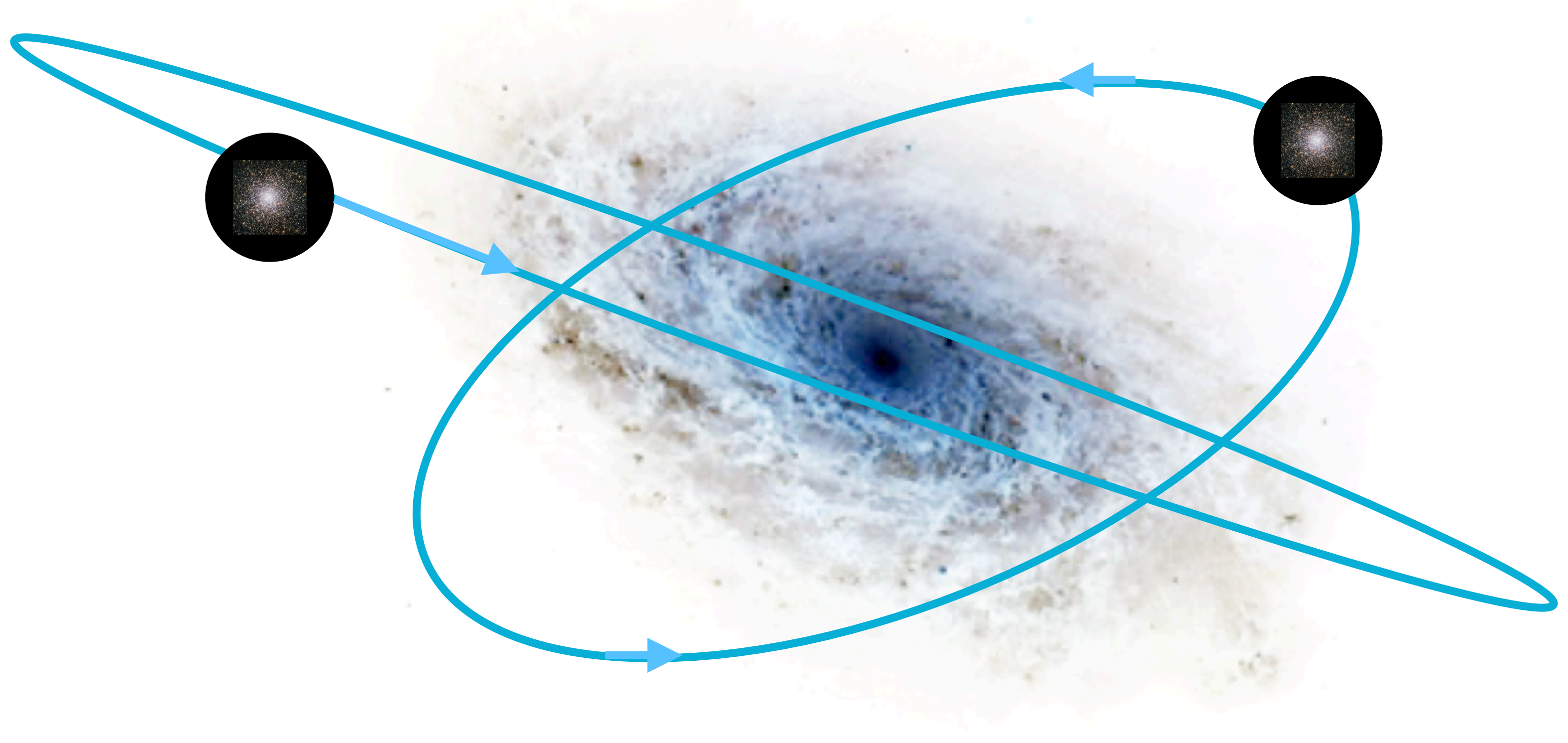
Globular clusters

Look at globular clusters: populations of $\gtrsim 10^6$ stars bound in the same orbit of the Milky Way Galaxy.

They are fairly homogeneous, each containing stars with similar ages and metallicities



Gaia DR3: 6d phase space of 161 clusters

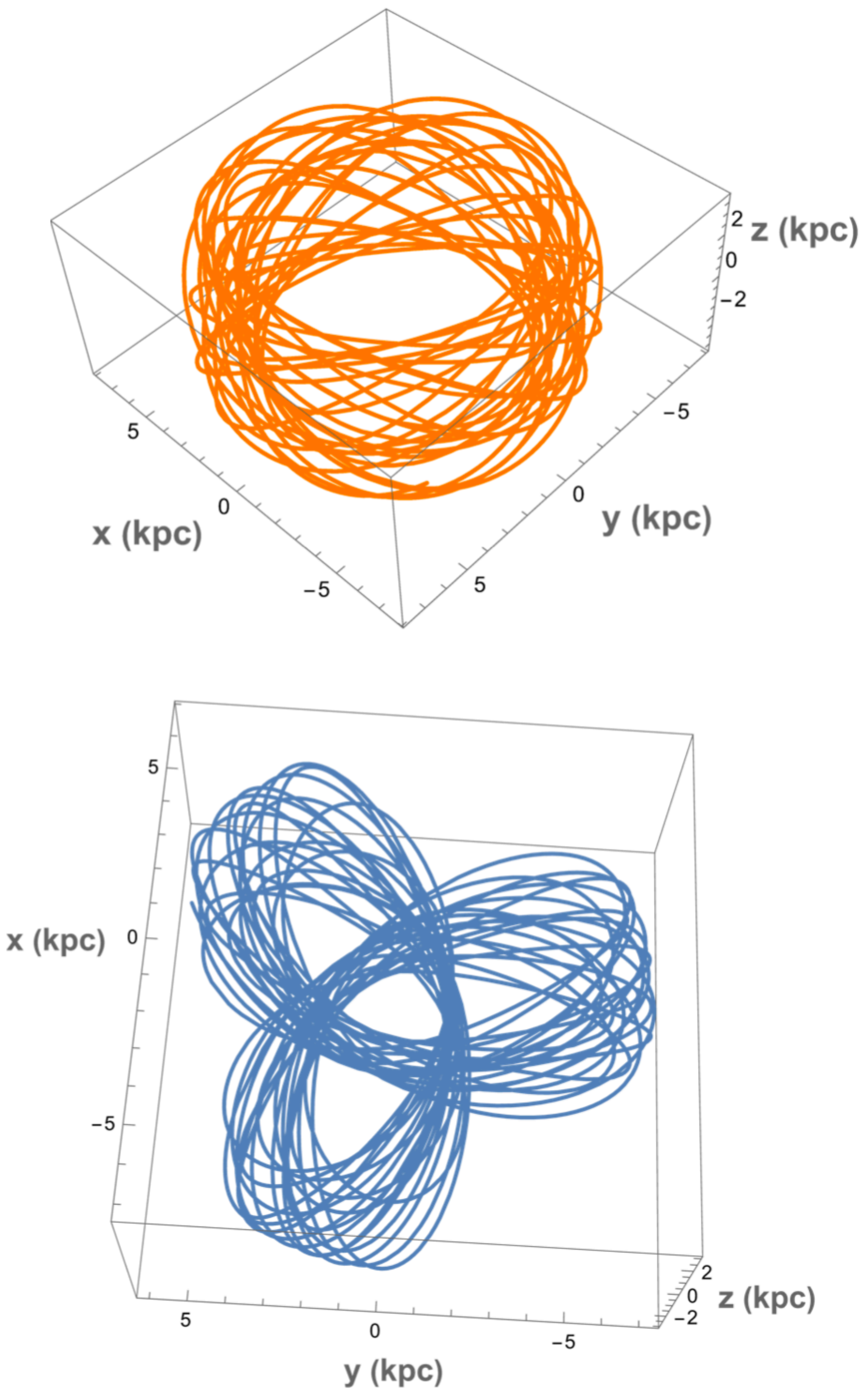


Some clusters have wide circular orbits others have more radial orbits that bring them closer to the galactic centre

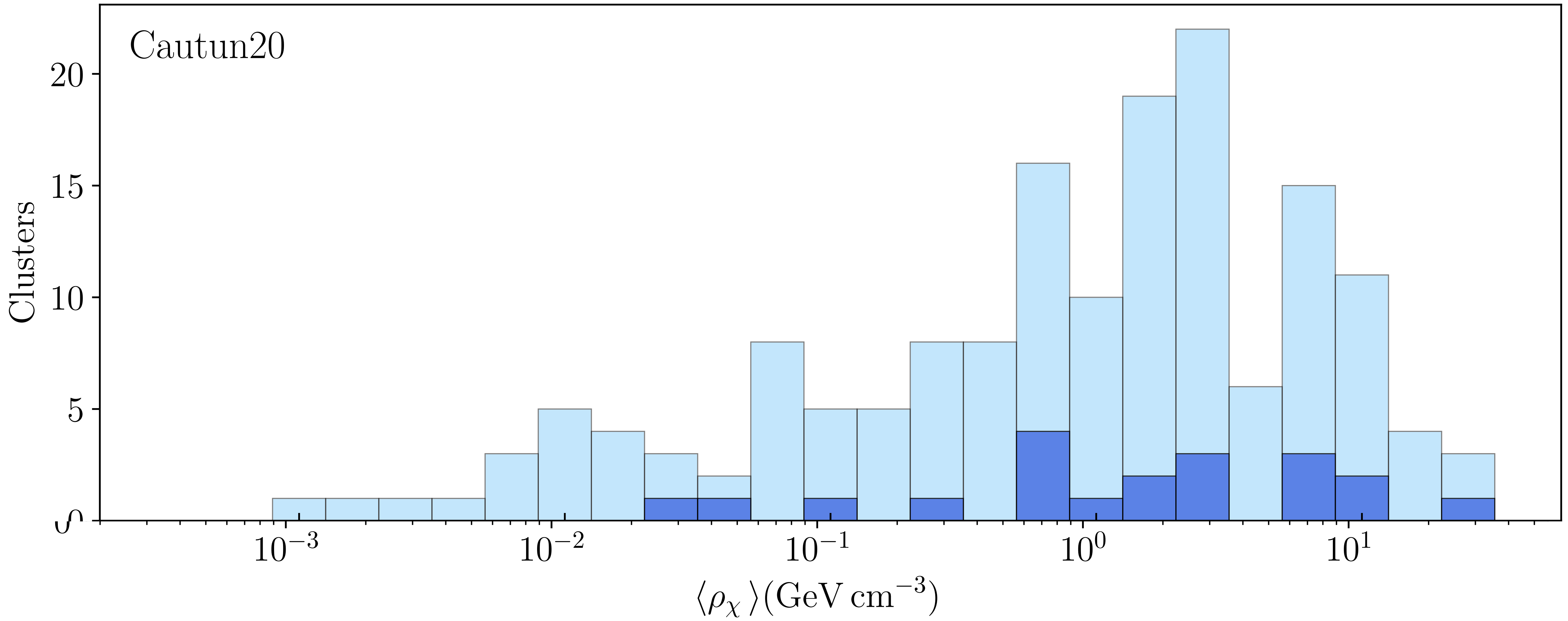
How much dark matter does a globular cluster "see"?

- Model trajectory over the past few Gyr using
- Gravitational potential (Newton…) from
  - Dark matter
  - Gas
  - Stars
- Initial conditions from *Gaia* 6d phase space measurements

Use *Gaia* data + gravitational potential of Milky Way, simulate trajectories of 161 Globular Clusters



Determine average **exposure to dark matter** (proxy for capture rate) over past ~ Gyr and model **red giant evolution** in these environments



Look for correlation between **TRGB magnitude** and **dark matter** exposure

Preliminary work by Howie Hong (Queen's)

Milky Way mass distribution

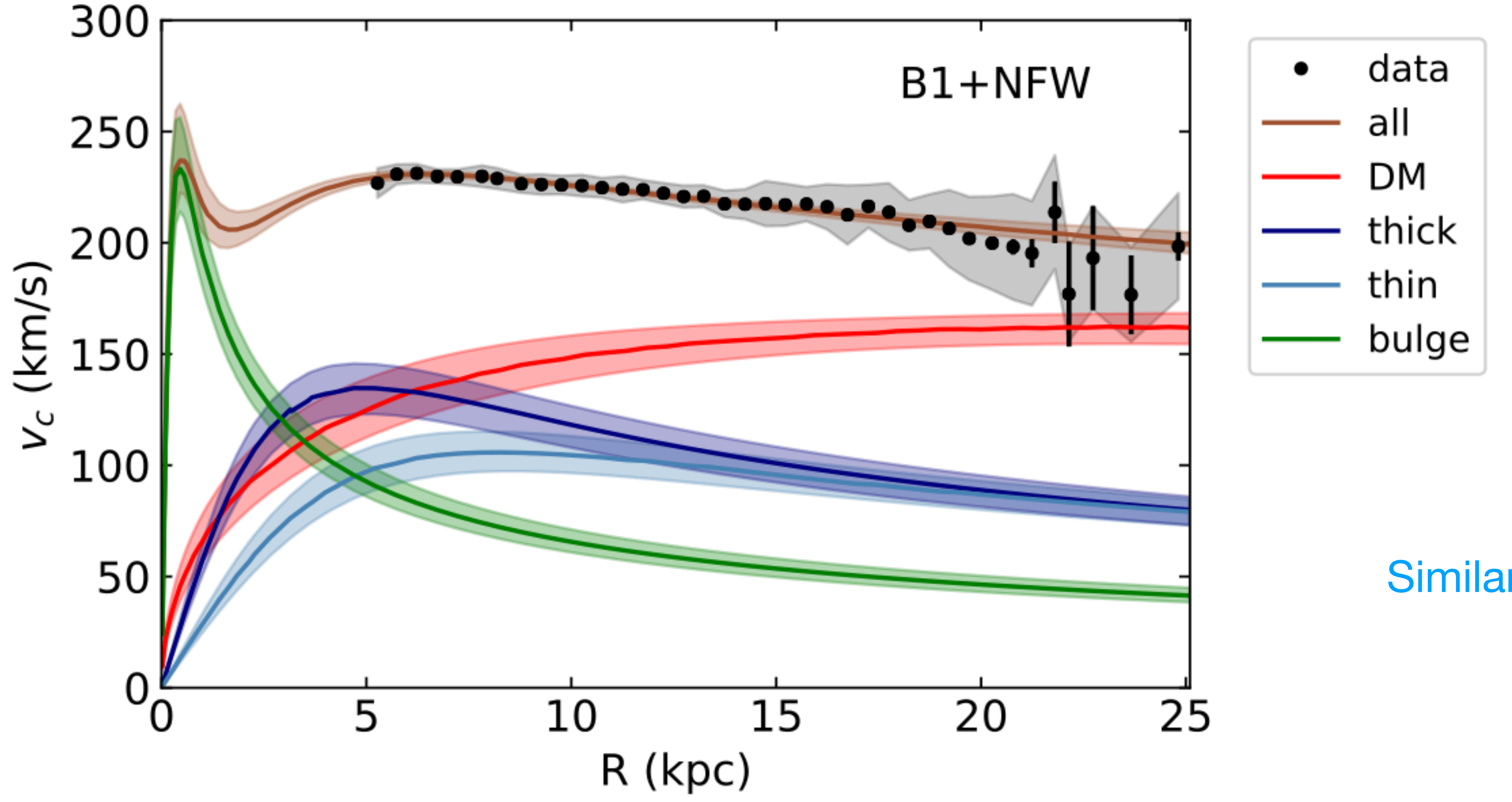
Test two representative distributions

both use data from Gaia DR2

“Pure” NFW

motivated by DM only sims

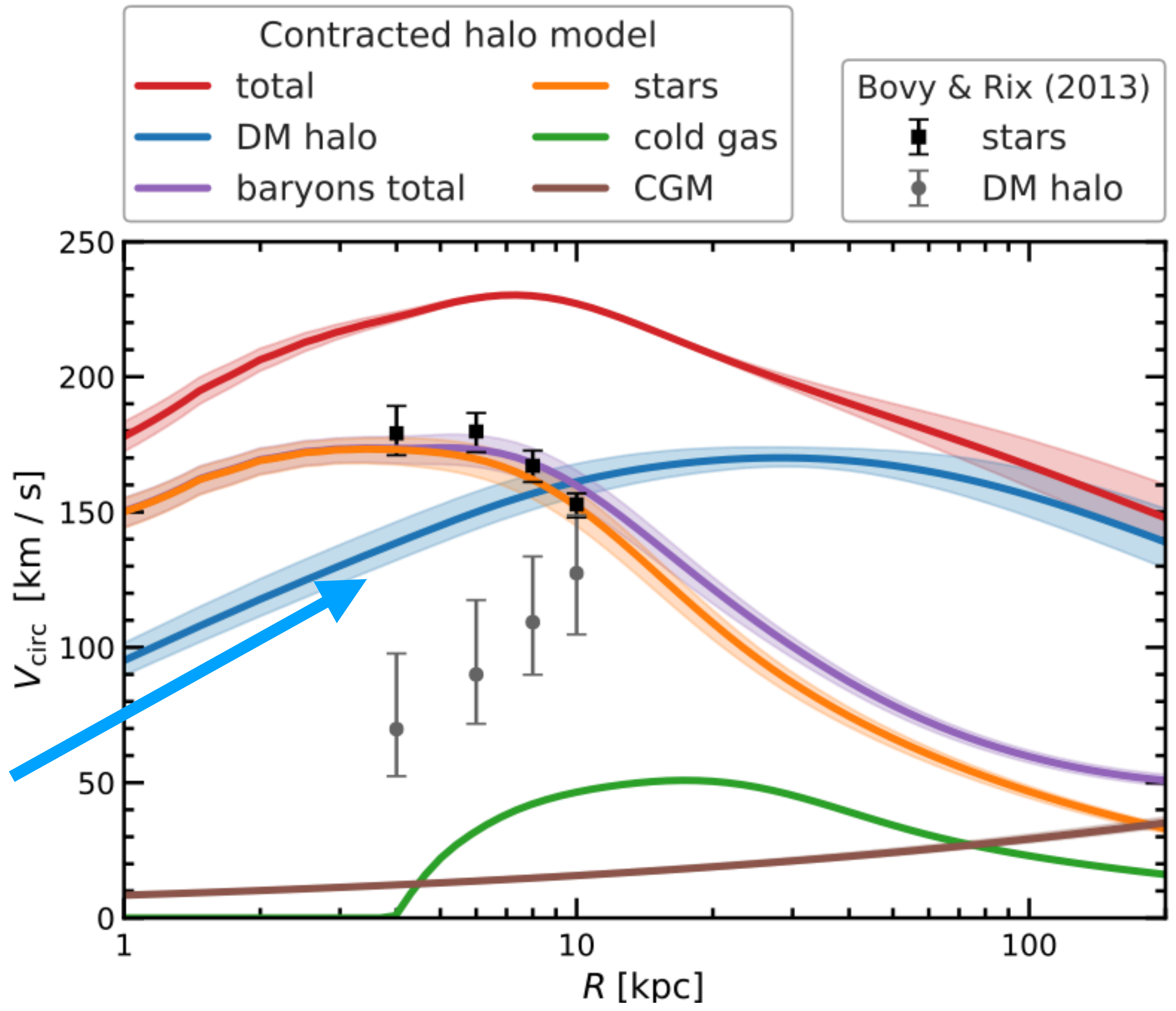
de Salas et al 1906.06133



Contracted halo

motivated by hydro sims

Cautun et al 1911.04557



Similar potentials, but higher DM contribution at low *r*

Cautun et al. point out their “pure NFW” fit to the *Gaia* data is just as good

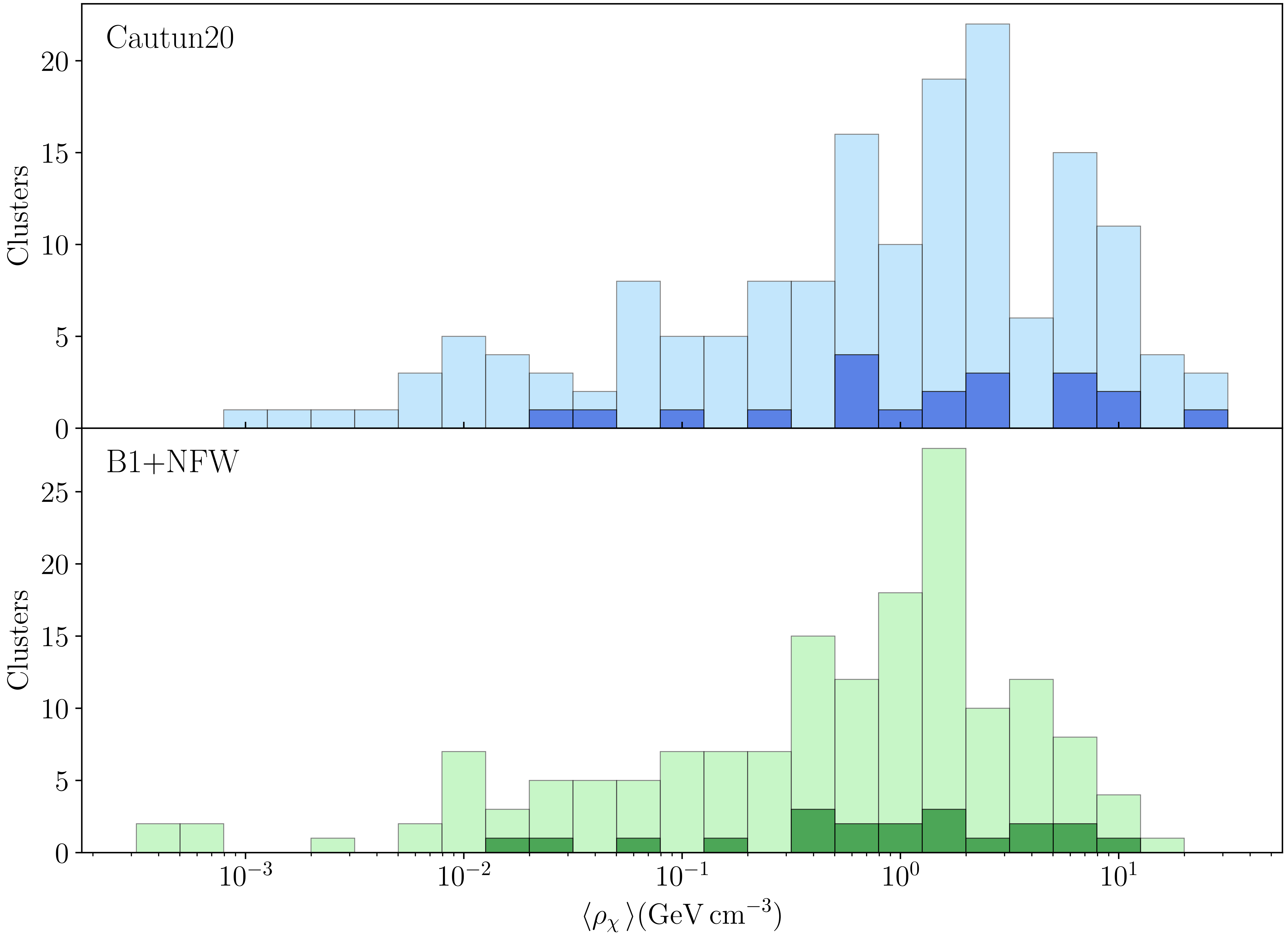
Dark matter seen by each Globular cluster

Light: the 161 GCs we have 6d kinematic data from (Vasiliev & Baumgardt 2021)

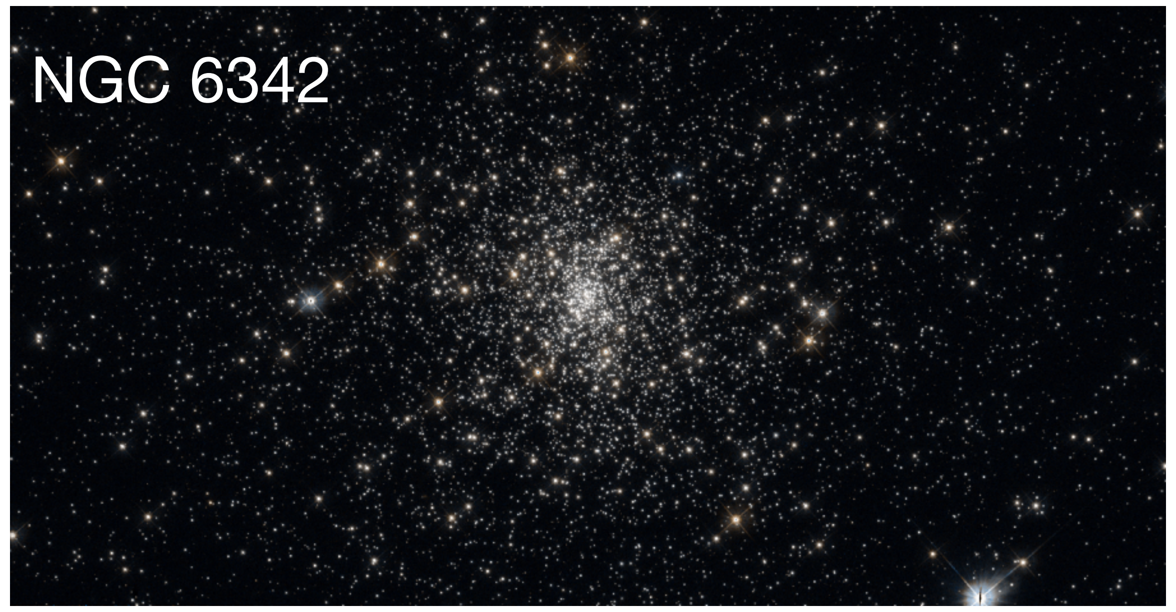
Dark: the 22 GCs we additionally have TRGB measurements for (HST + ground-based measurements, see Straniero et al. 2010.03833)

Contracted halo

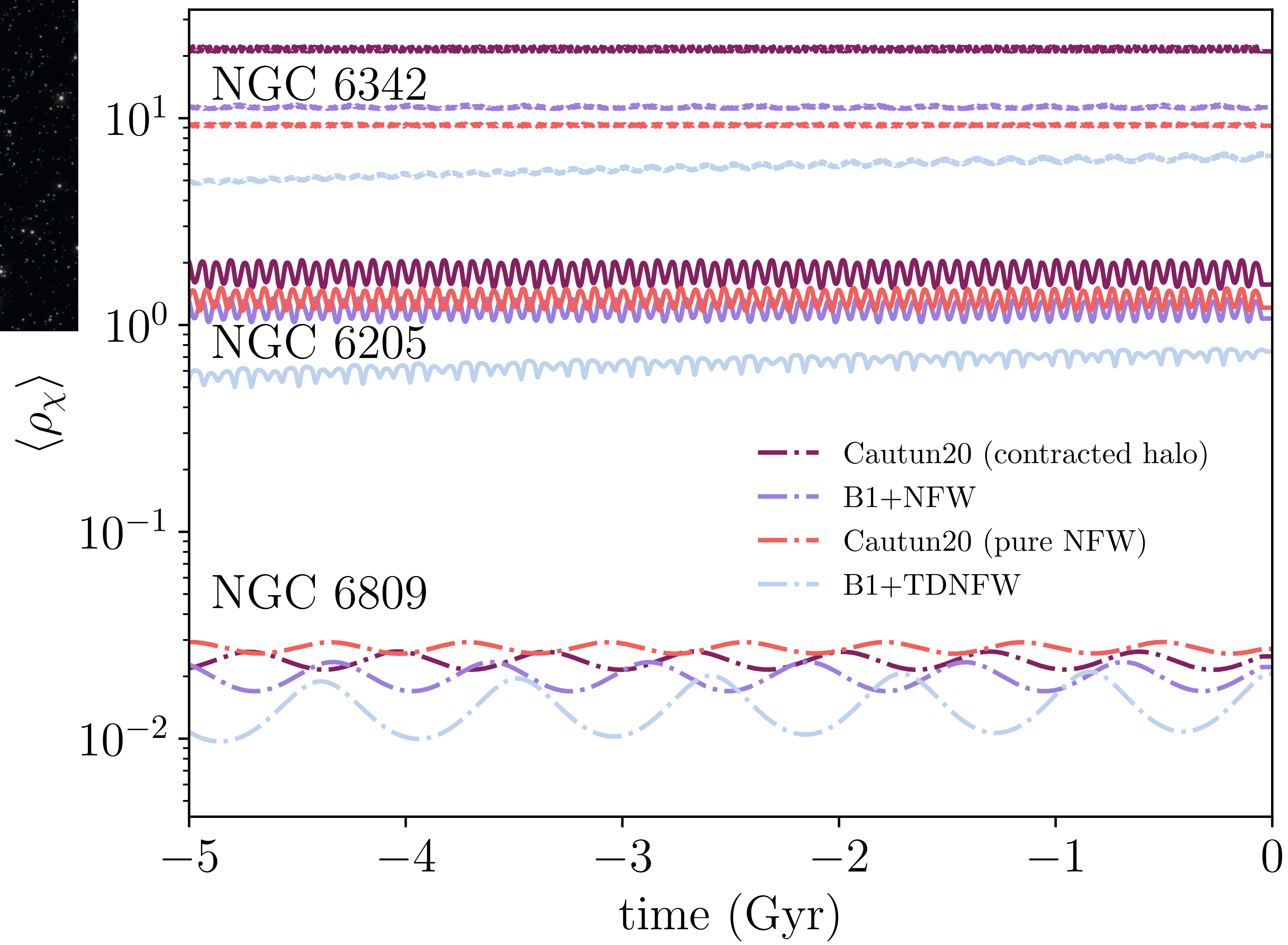
“Pure” NFW

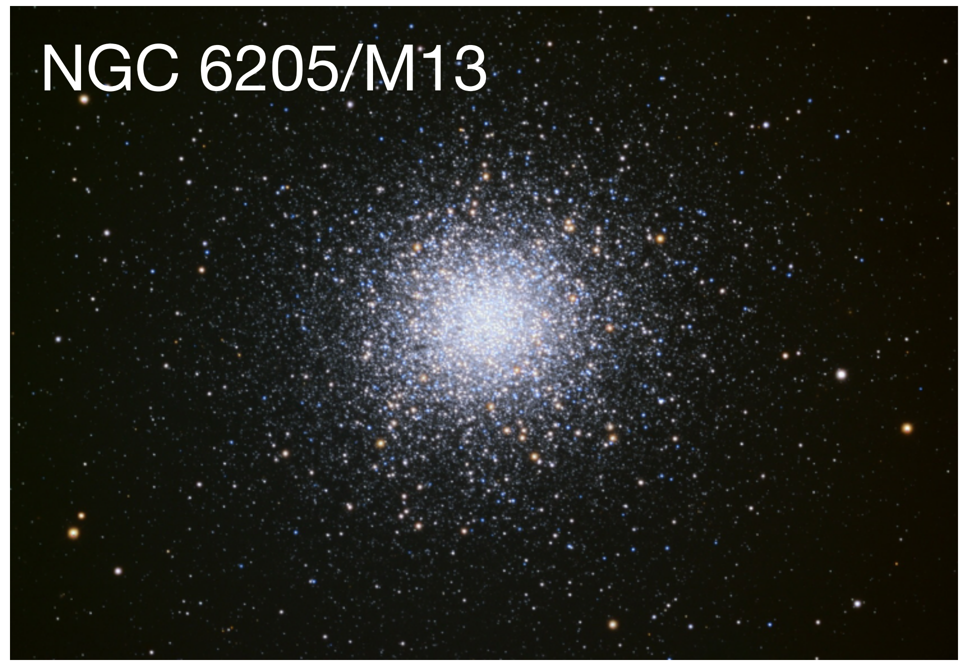


Time dependence?



Hubble





Sid Leach/Adam Block/Mount Lemmon SkyCenter

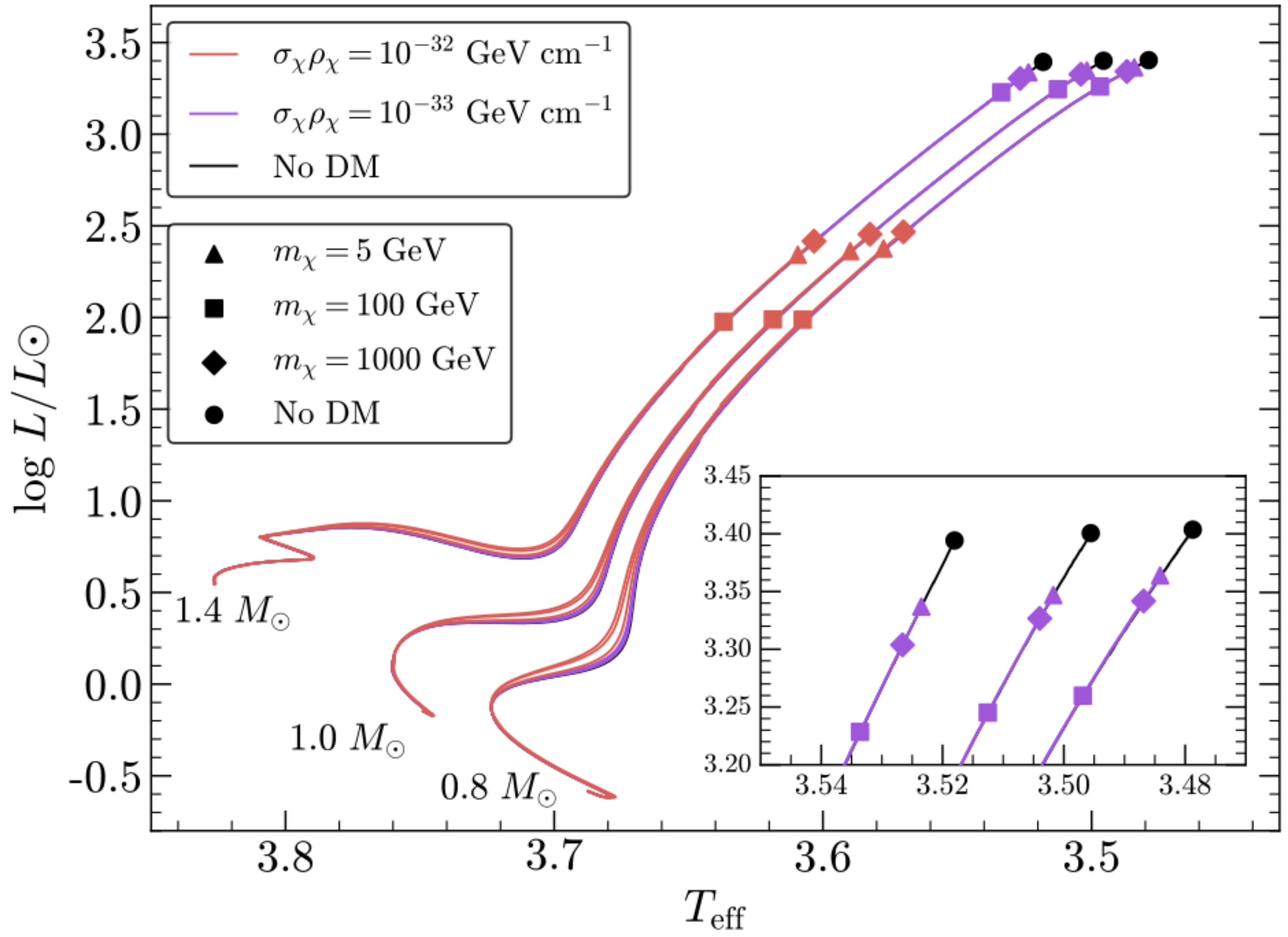
ESO/J. Emerson/VISTA

Time dependence of the potential follows concentration paramter c(t) from Dutton & Macciò (1402.7073), but not calibrated to MW rotation curve (simulation results)

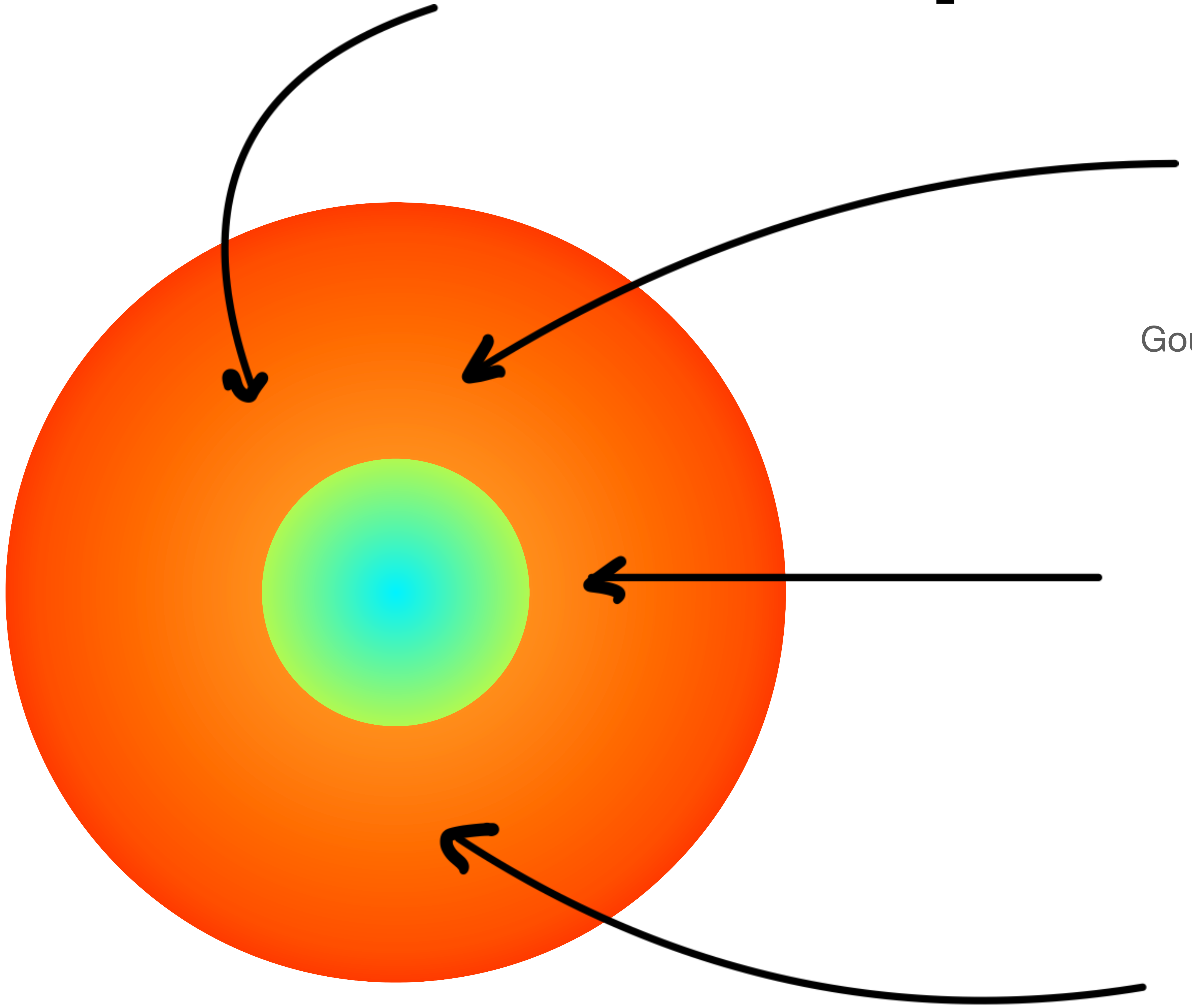
Upshot: differentiation between clusters is robust

Dark matter capture & stellar modelling

- Modify MESA module from Lopes & Lopes
- Includes dark matter capture based on the local DM density
- Deposit heat in the red giant core
- Evolve a set of 0.8 $M_\odot$ stars to the tip of the red giant branch (TRGB).



Dark matter capture & saturation



Gould 1985:

$$C_\star(t) = 4\pi \int_0^{R_\star} r^2 \int_0^\infty \frac{f_\star(u)}{u} w\Omega(w) du dr,$$

Dark matter velocity distribution in the star's frame

Probability to scatter $w \rightarrow \leq v_{escape}$

Integral over the star

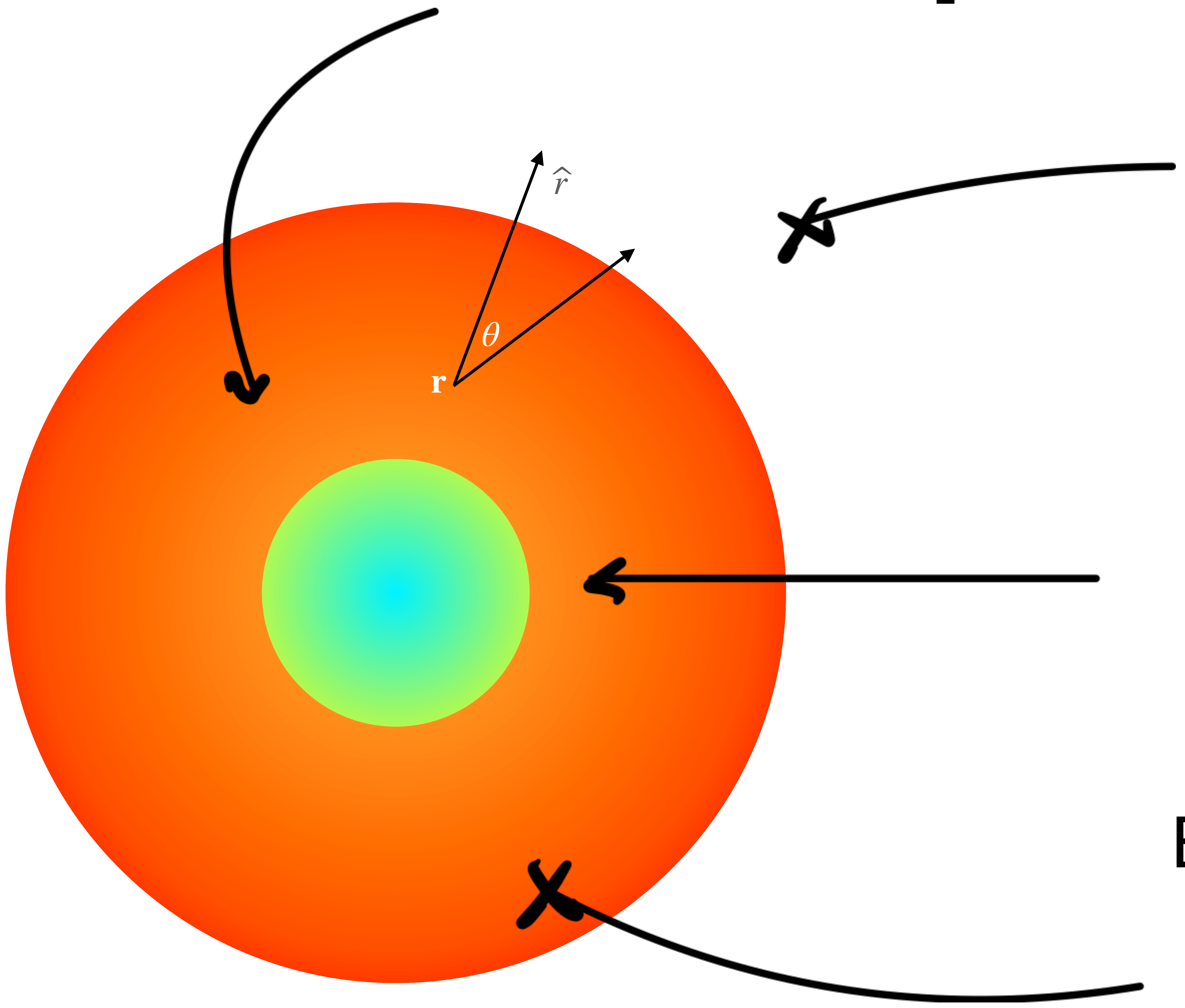
$\Omega \propto \sigma_{SI}$

This overestimates the capture rate: you can't just keep increasing σ_{SI}

At some point, **all** the dark matter intersecting the star is captured.

Especially problematic in a red giant: the dense core saturates well before the diffuse envelope

Dark matter capture & saturation



Gould's approach:

$$C_\star(t) = 4\pi \int_0^{R_\star} r^2 \int_0^\infty \eta(r) \frac{f_\star(u)}{u} w\Omega(w) du dr,$$

$$\eta(r) = = \frac{1}{2}\int_{-1}^{1} dz e^{-\tau(r,z)}$$

Remove flux of particles that may have already scattered on their way in

optical depth to the surface for every line of sight $z = cos\theta$

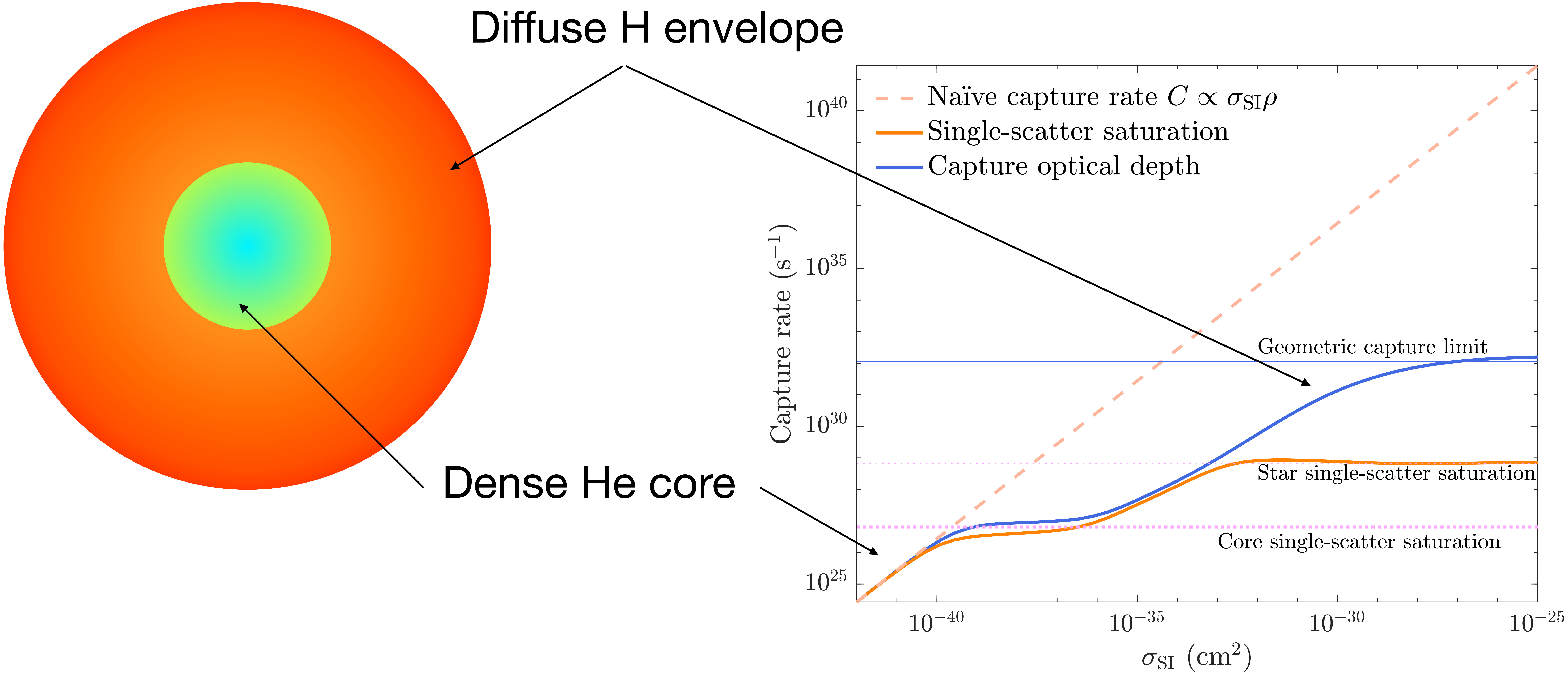
$$\tau(r,z) = \int_{rz}^{\sqrt{R^2 - r^2(1-z^2)}} dx \sum_i n_i(r') \langle \sigma_{i,Tot} \rangle$$

But this removes **all** particles that have scattered

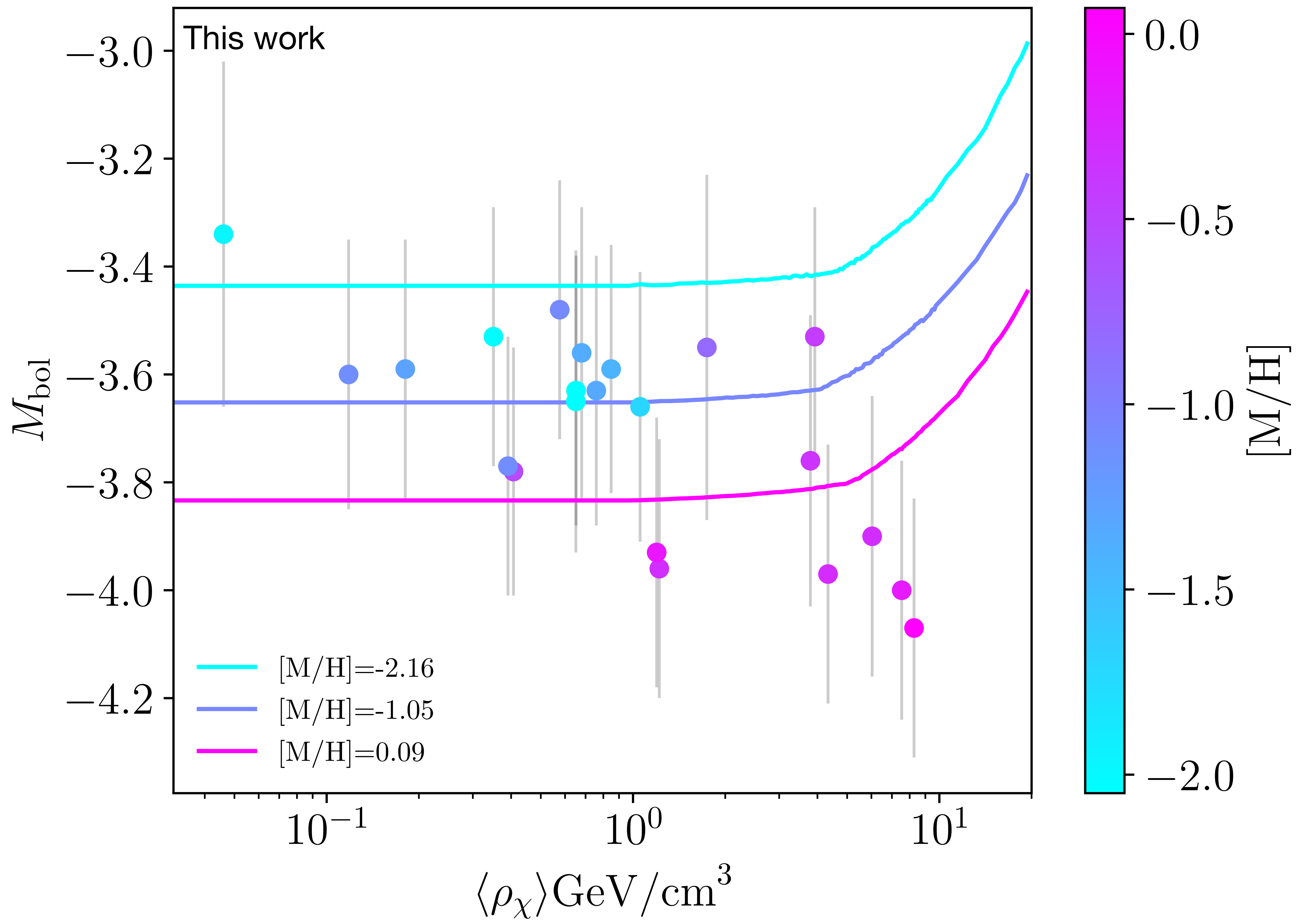
Use **optical depth** to *capture*

$$\tau(r,z) = \int_{rz}^{\sqrt{R^2 - r^2(1-z^2)}} dx \int du \Omega(w) \frac{w f_\star(u)}{u}$$

Dark matter capture & Saturation

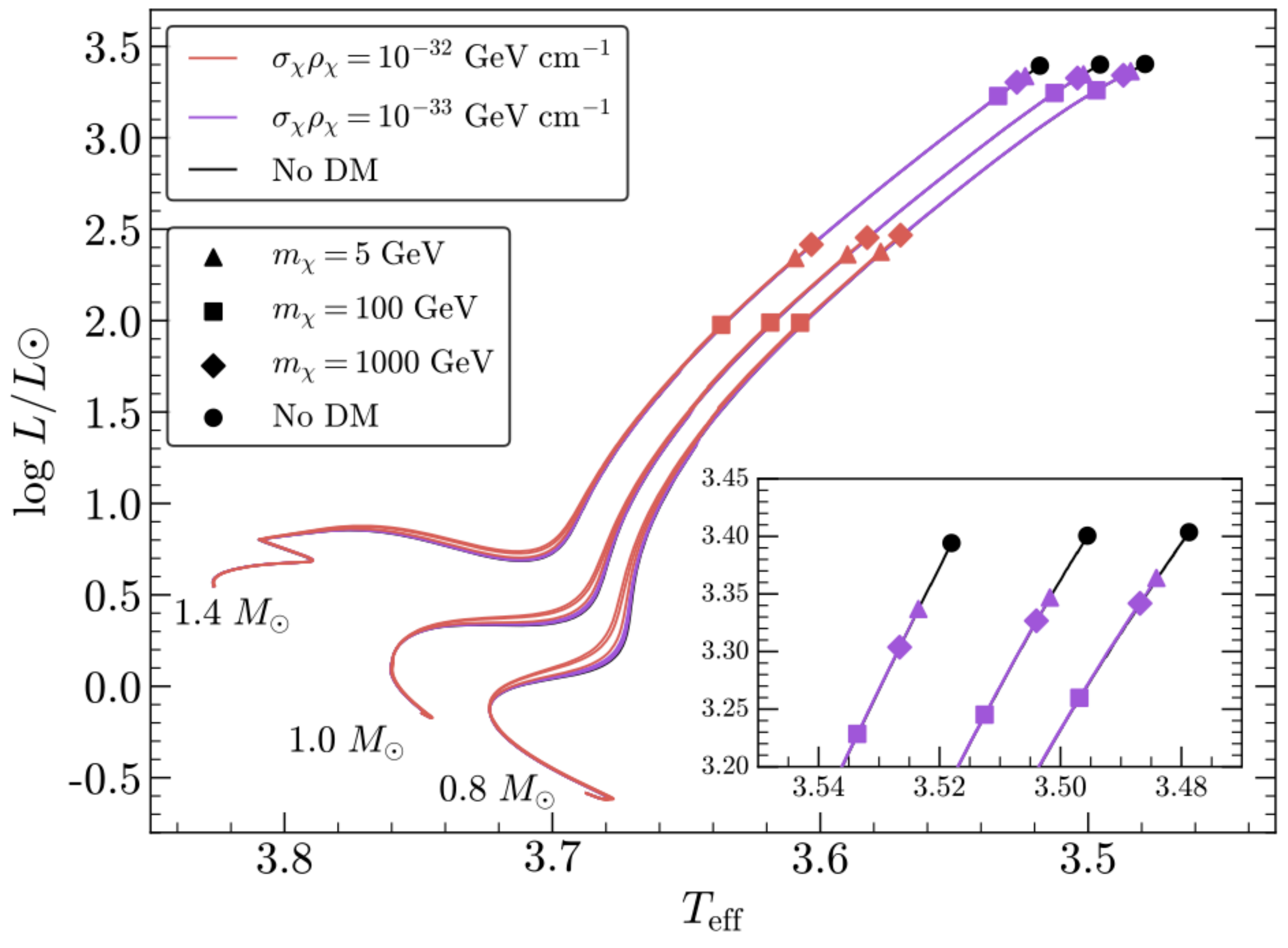


TRGB magnitude



Cluster exposure to dark matter

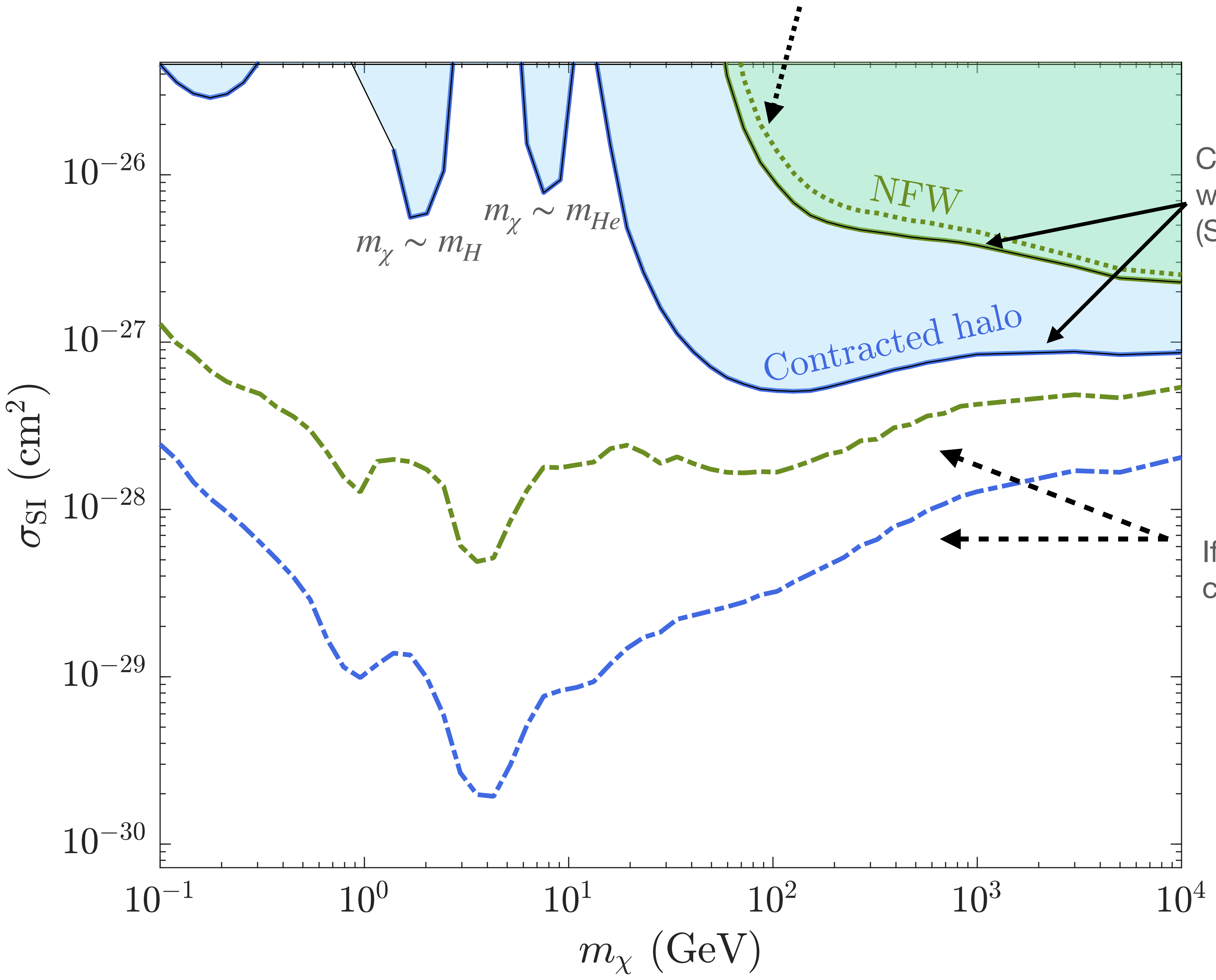
Lopes & Lopes 2107.13885



Now we can compare predicted luminosities as a function of DM mass and cross section to the measured ones and extract a limit

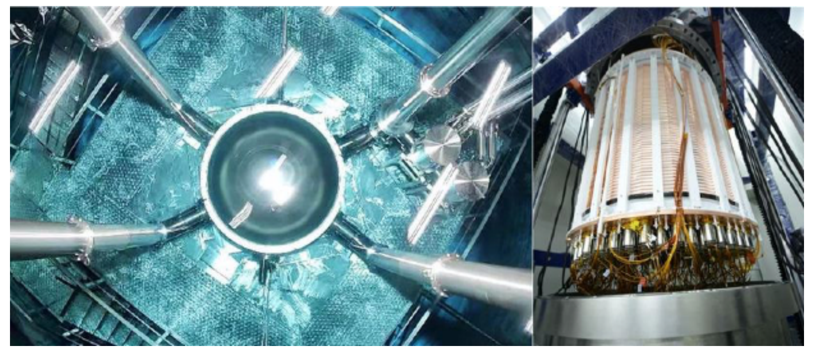
Limits

Include errors on NFW shape parameters
& propagating errors on the cluster positions and velocities



Constraints based on the 22 clusters we have TRGB measurements from (Straniero)

If we had TRGB magnitudes for all 161 clusters with 10x smaller errors



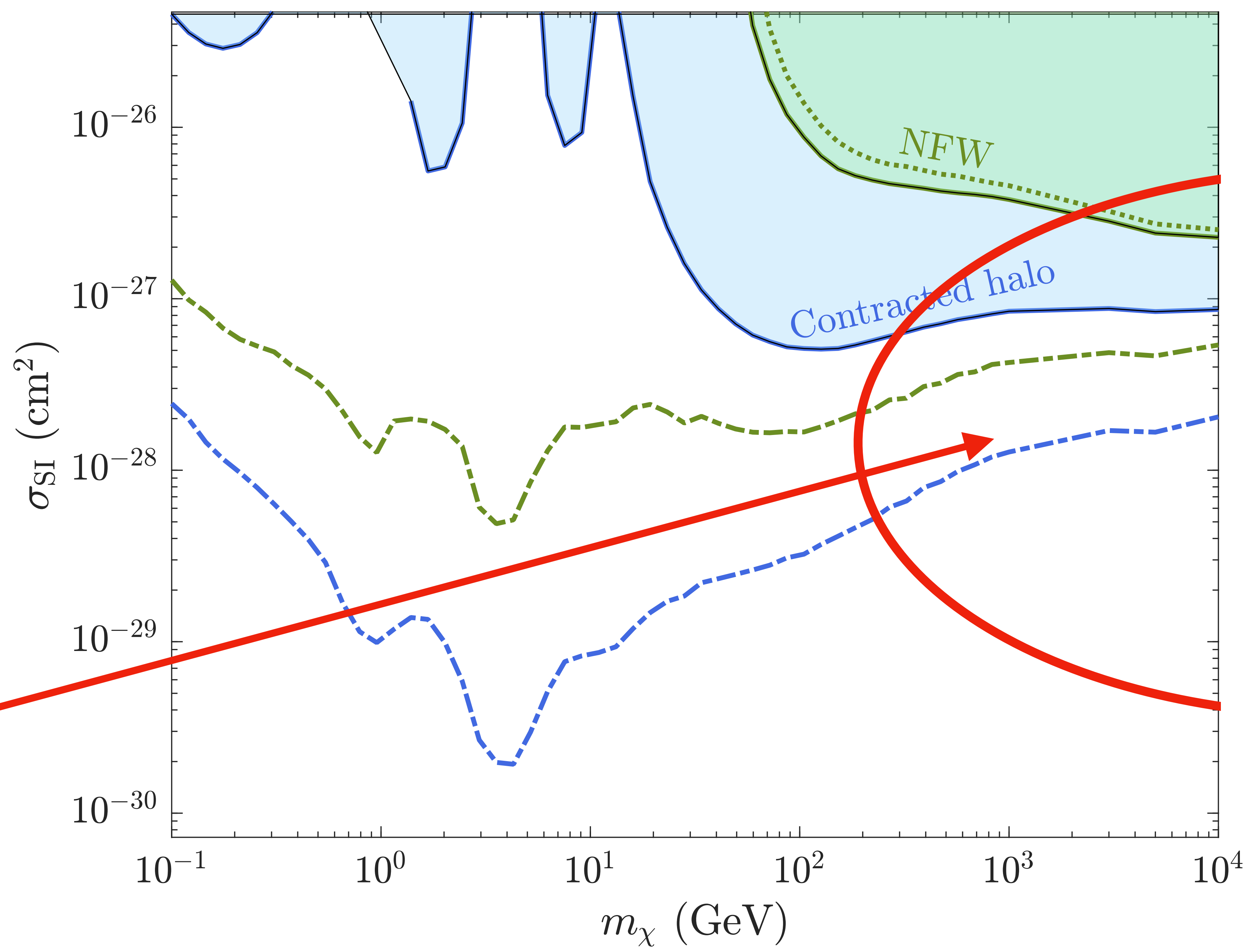
PandaX-4T →

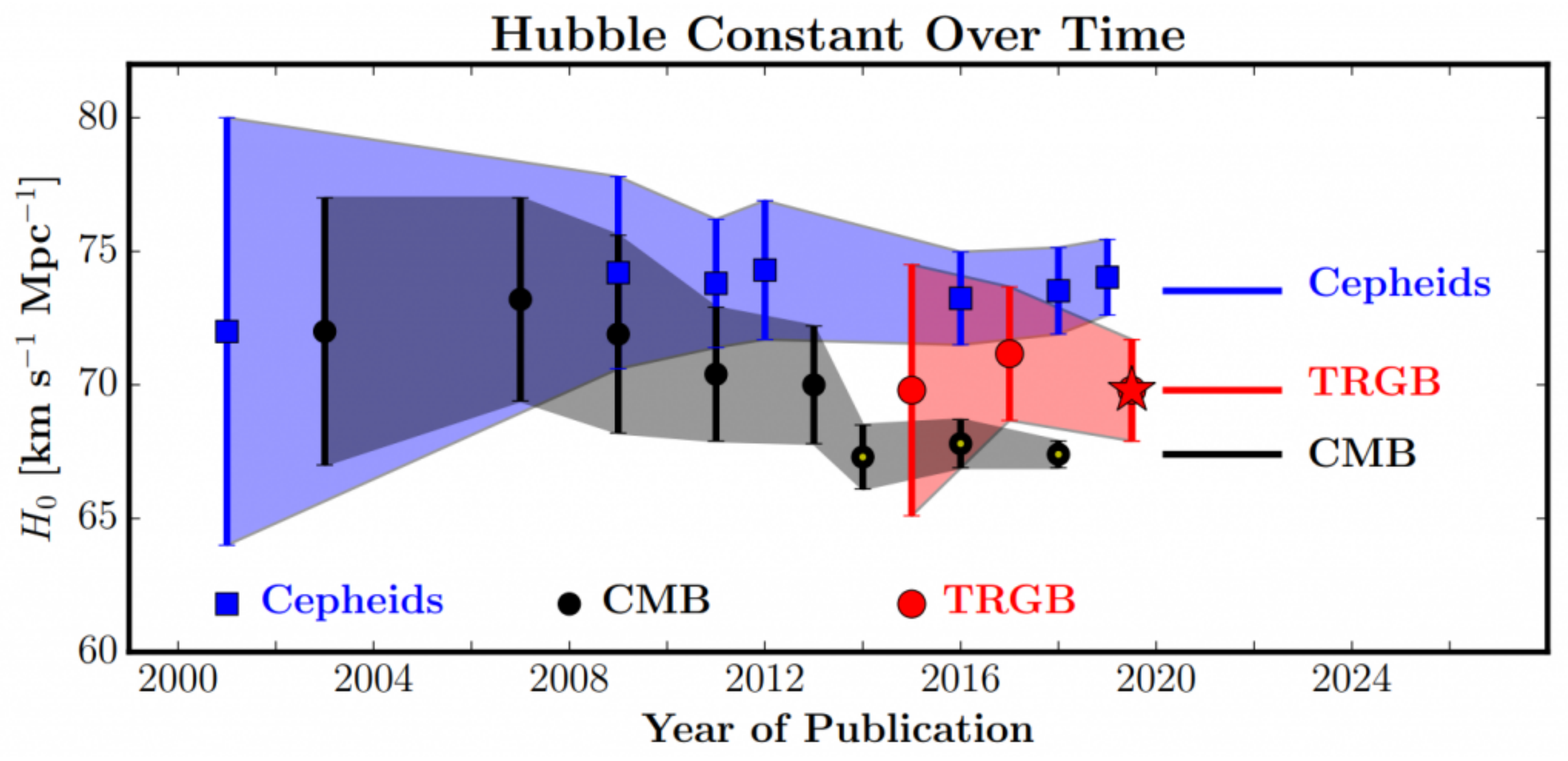

You are without doubt the worst
dark matter limit
I've ever heard of.
But you have heard of me.

So what have we learned?

Dark matter effects on the TRGB

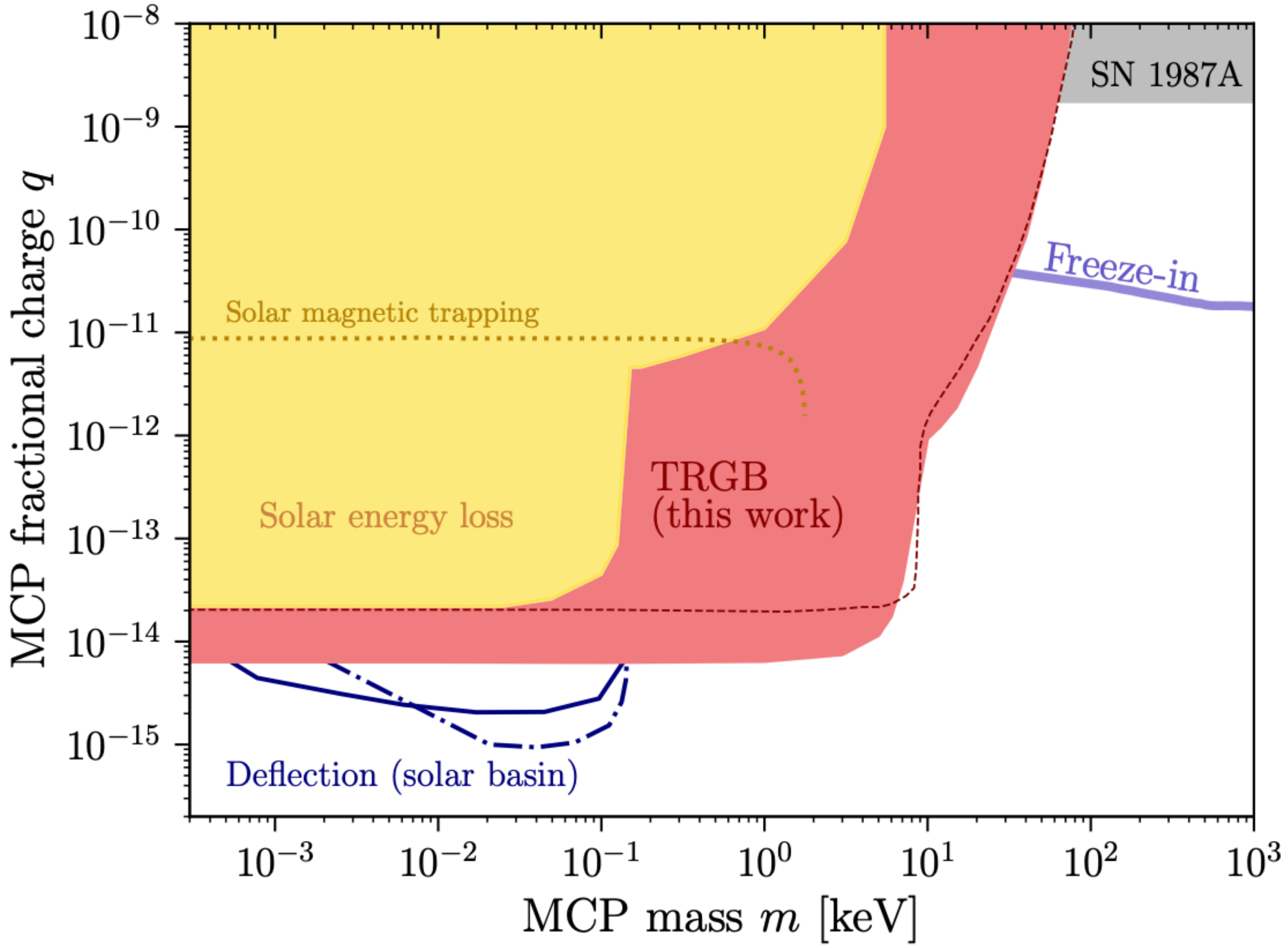
- You need a **lot** of dark matter to have a visible effect on the TRGB. More than the Milky Way seems to be telling us it contains
- Some space now closed if **local** DM is underabundant?
- Spin-independent dark matter-nucleon cross section limits that are **independent of any Earth/Sun-related systematics**
- TRGB as a **standard candle** seems pretty **robust**.
- **Unless** our higher-redshift TRGB measurements happen to be in very dark matter-rich environments
- Maybe you can constrain a dark matter spike.



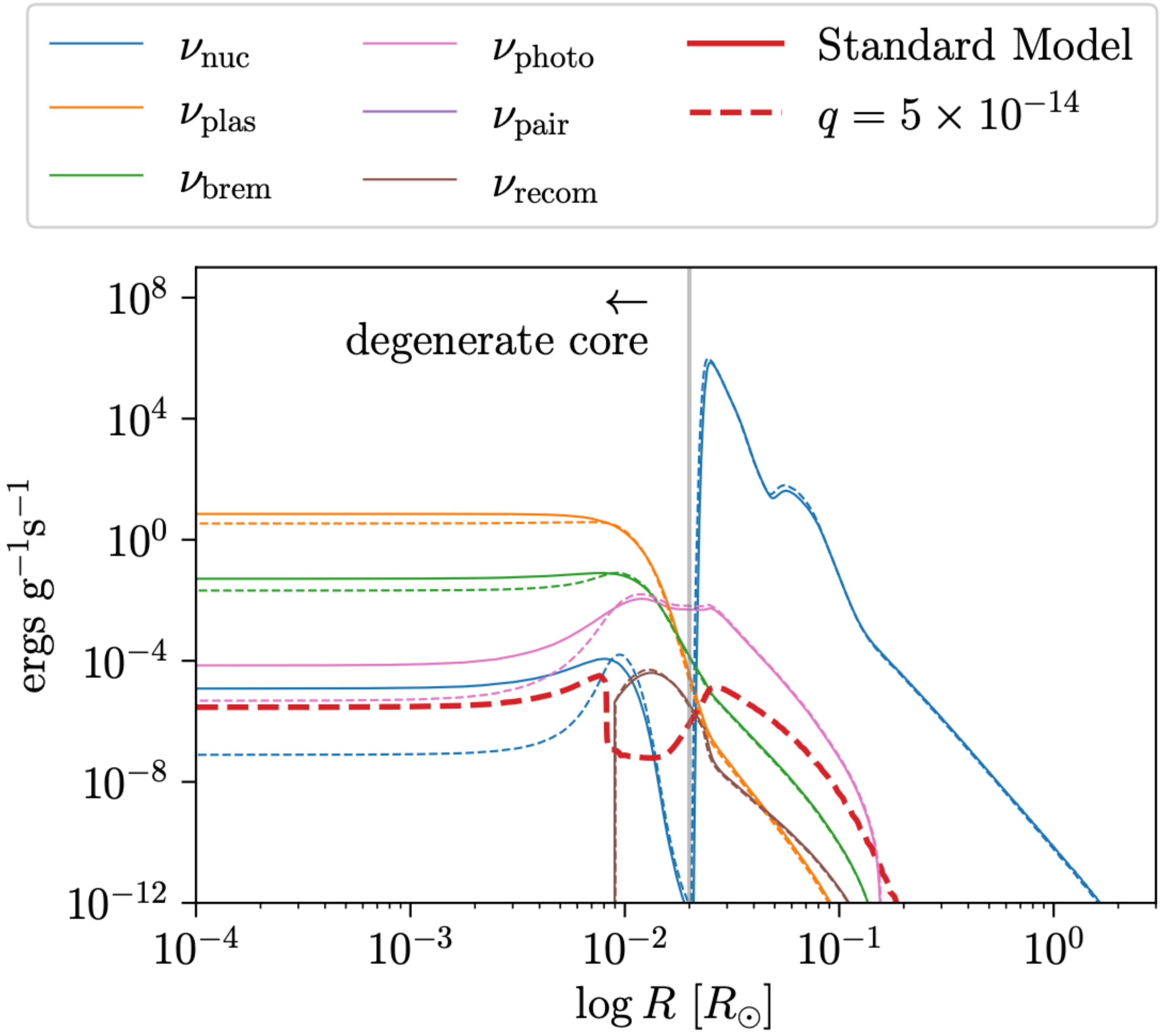


TRGB constraints on millicharged particles

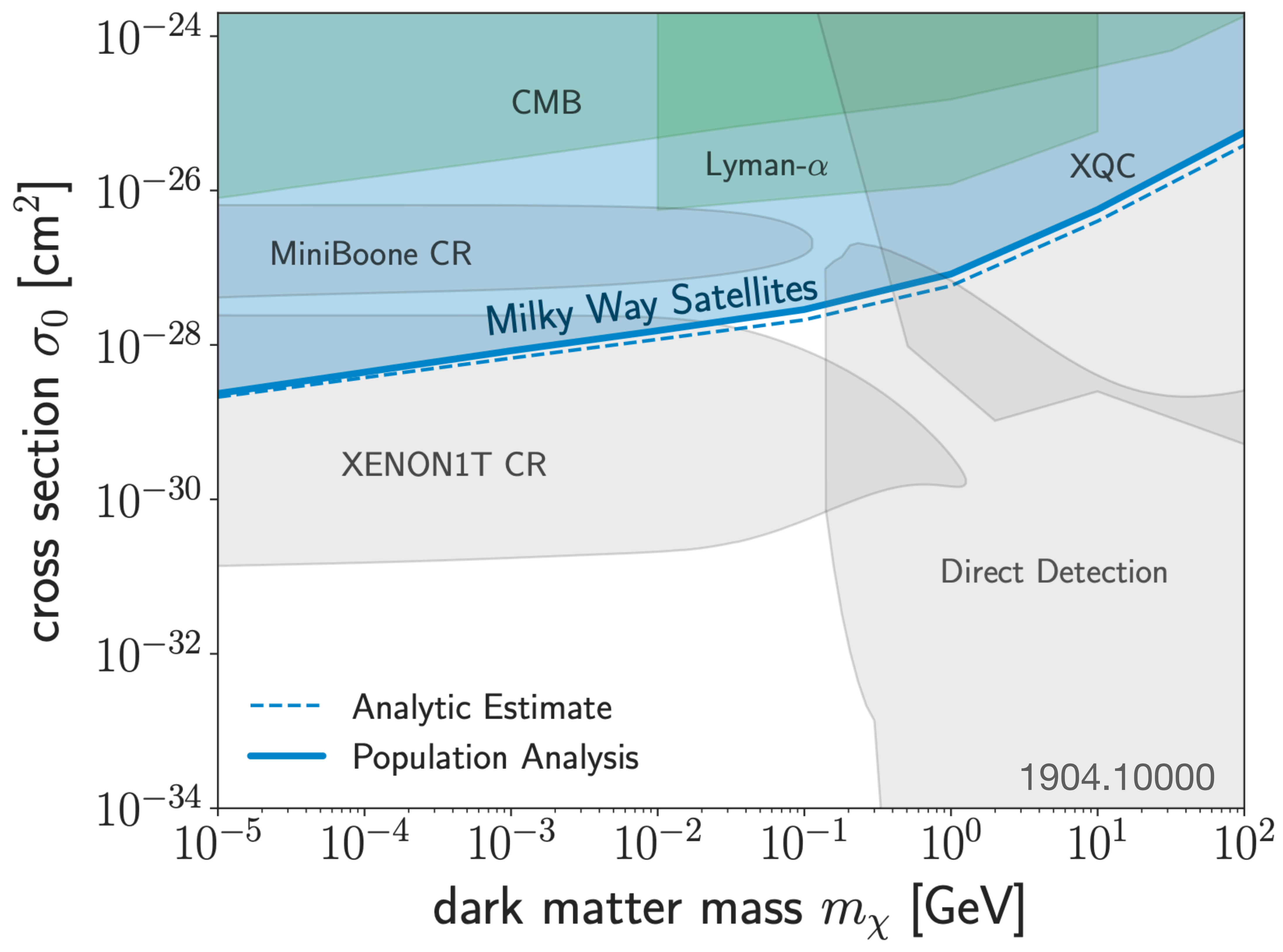
Plasmon decay to light particles



Energy loss from plasmon decay leats to a **brighter TRGB**



A. Fung, S. Heeba, Q. Liu, V. Muralidharan, K. Schutz, ACV 2309.06465/PRD


CMB
Lyman-α
XQC
MiniBoone CR
Milky Way Satellites
XENON1T CR
Direct Detection
Analytic Estimate
Population Analysis
1904.10000
cross section σ_0 [cm^2]
dark matter mass m_χ [GeV]
10^{-24}
10^{-26}
10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}