Exploring new physics with the tip of the red giant branch

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arXiv:2309.06465

Katelin Schutz
Saniya Heeba
Varun Muralidharan

Howard Hong

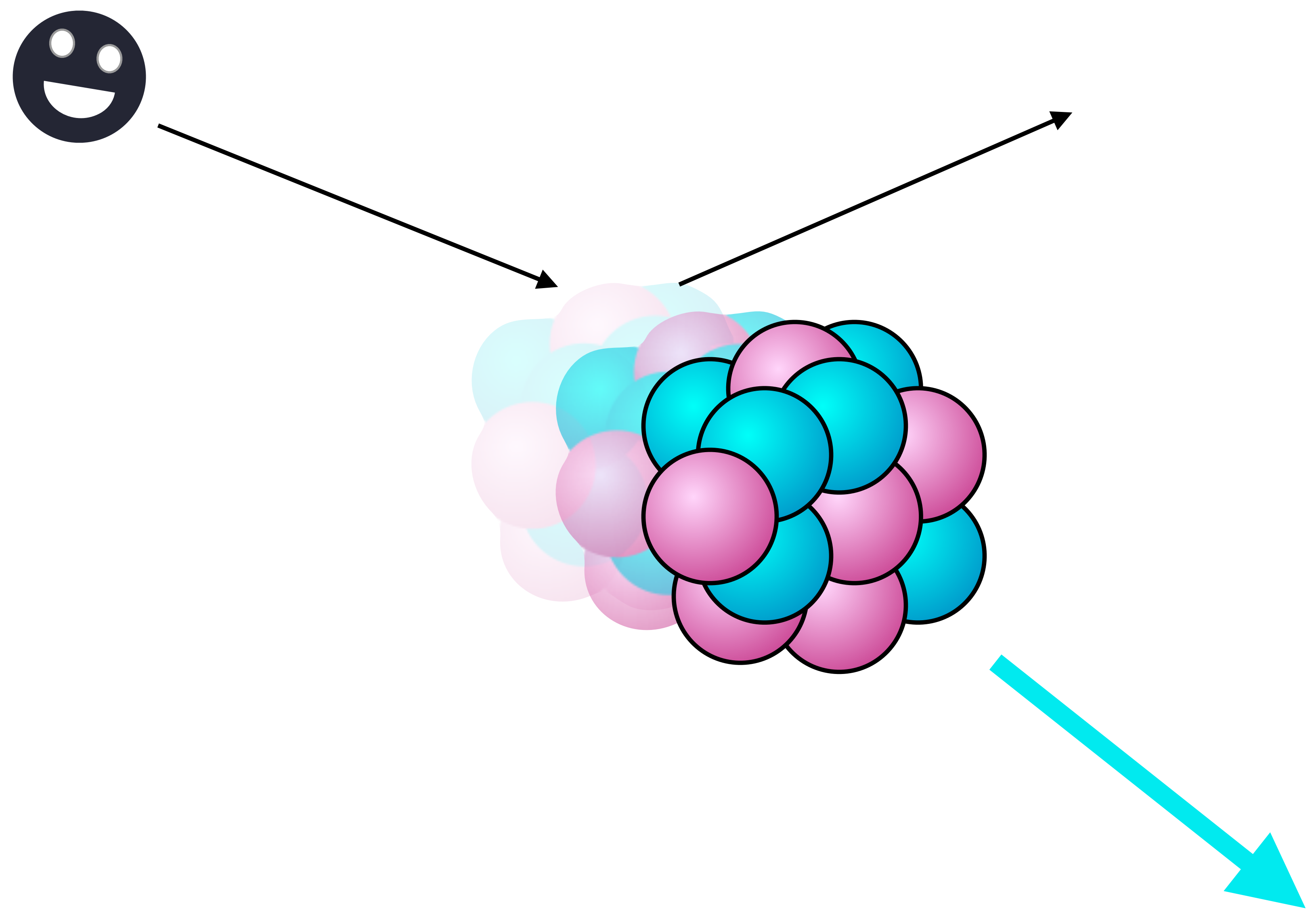
arXiv:2407.08773

Plan

1. Dark matter igniting the TRGB
2. Energy loss to millicharged particles delaying the TRGB

I. Dark matter and the red giants

Dark matter-nucleus elastic scattering

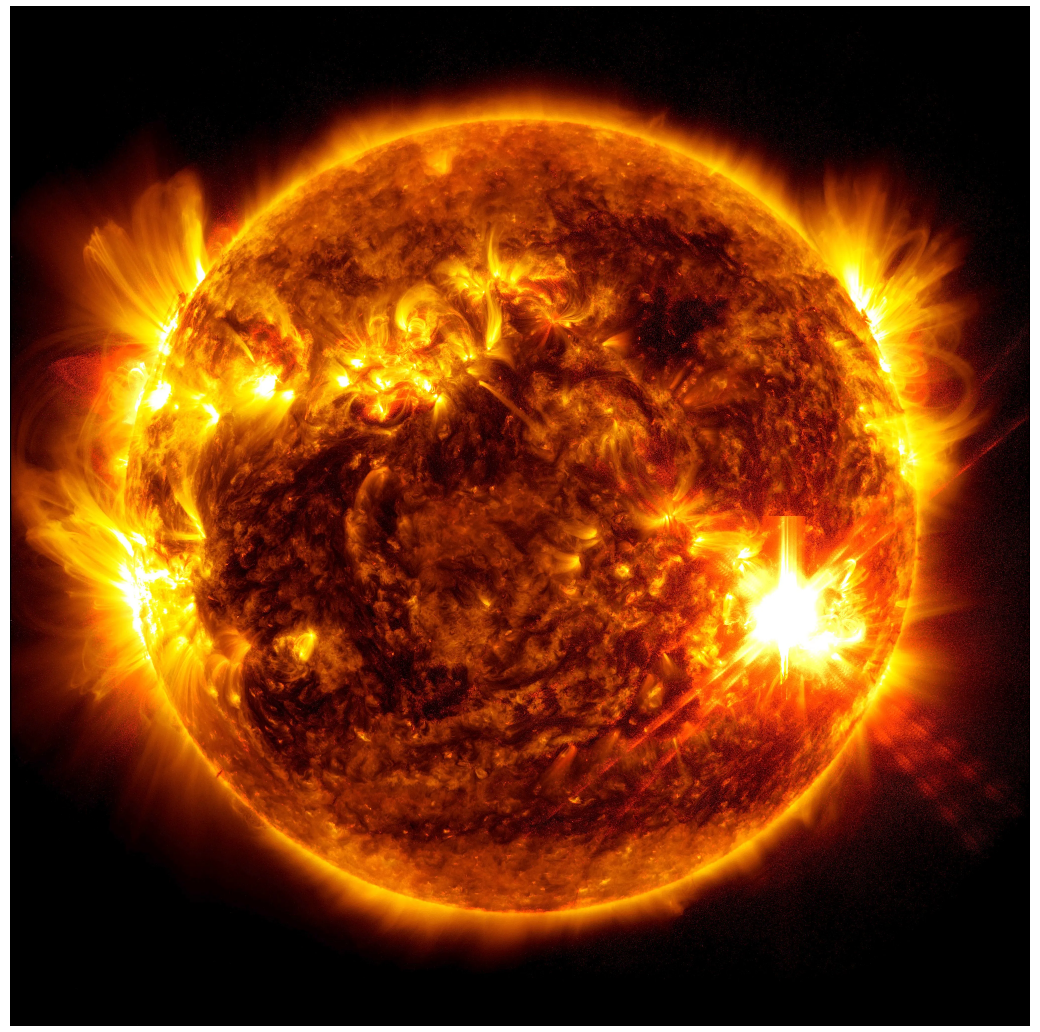


If this happens here

(a direct detection experiment)

It also happens here

(a star)



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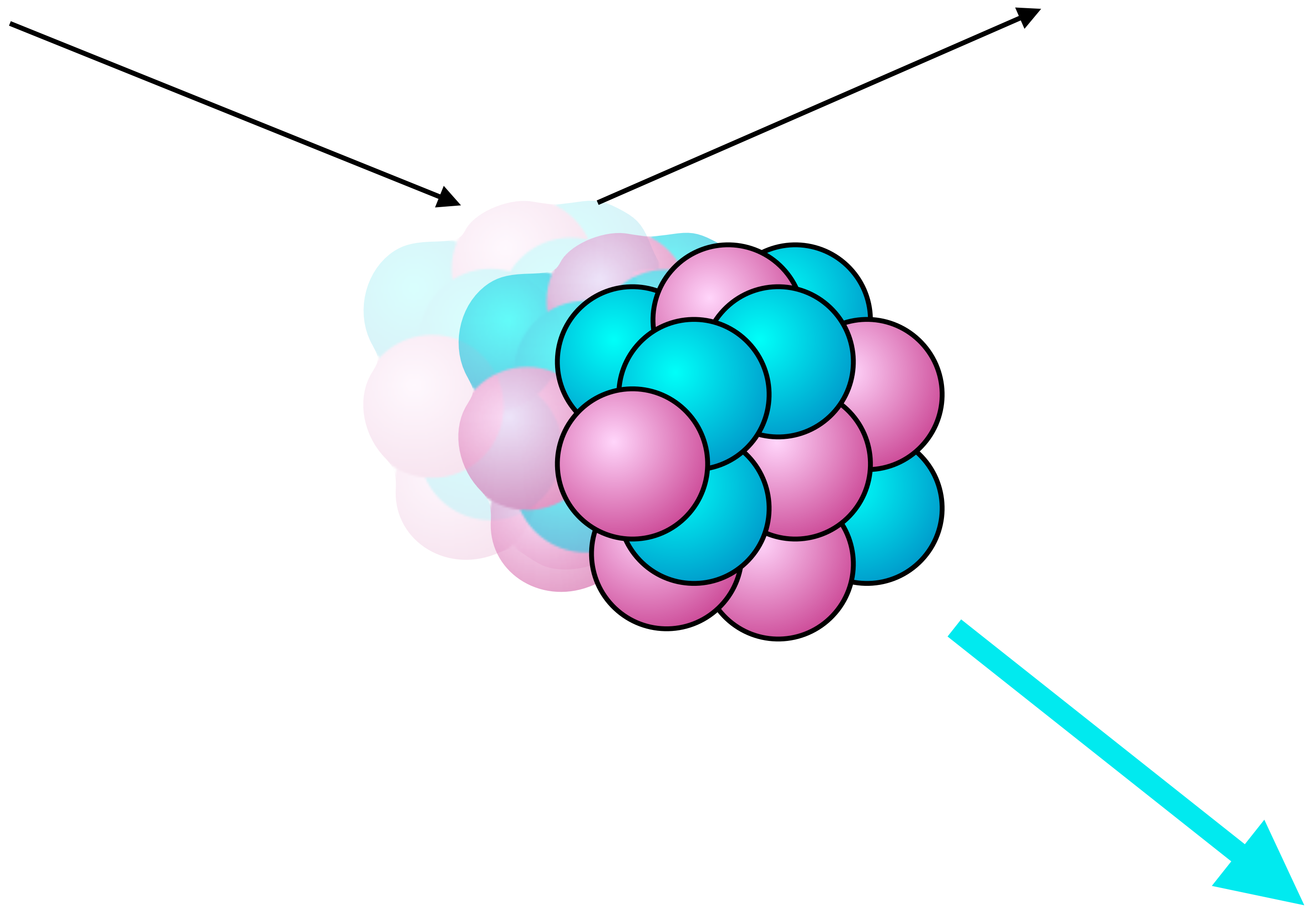

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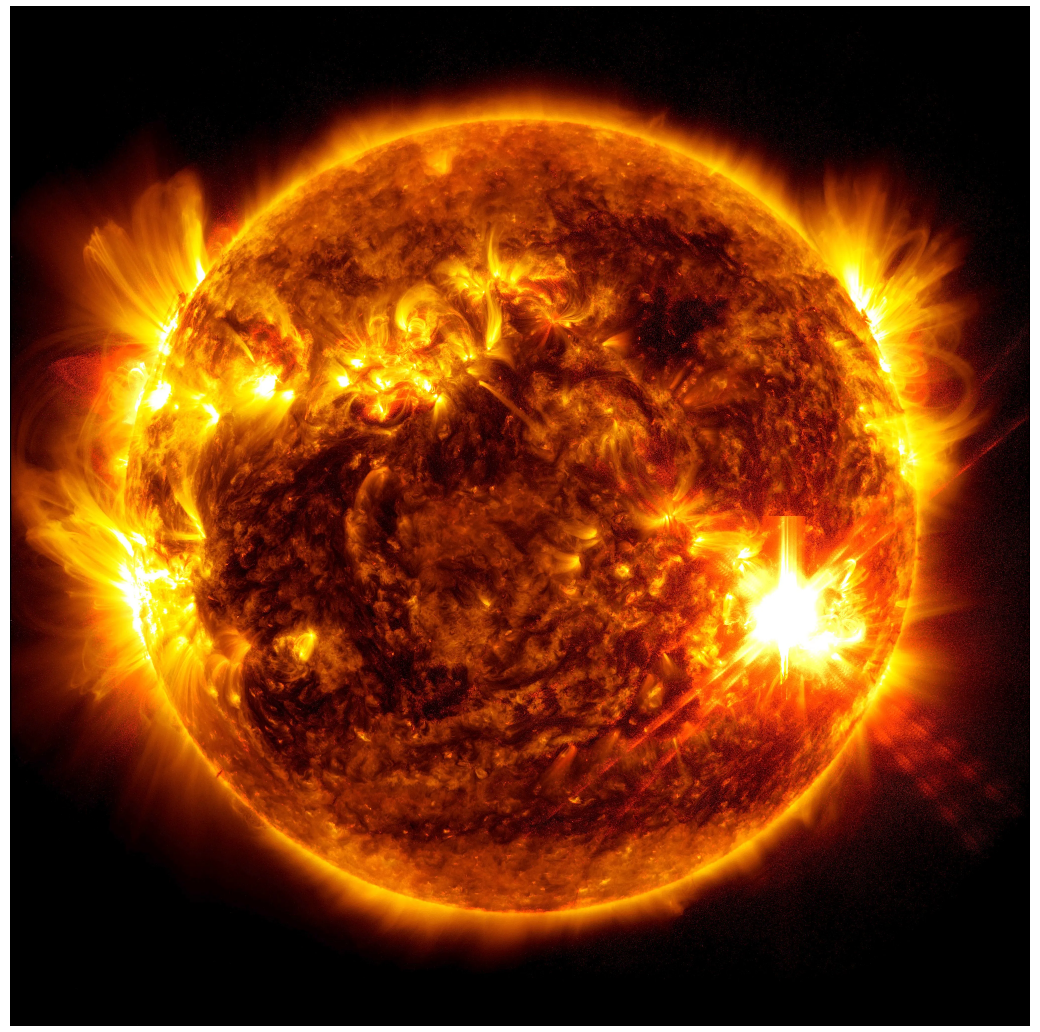
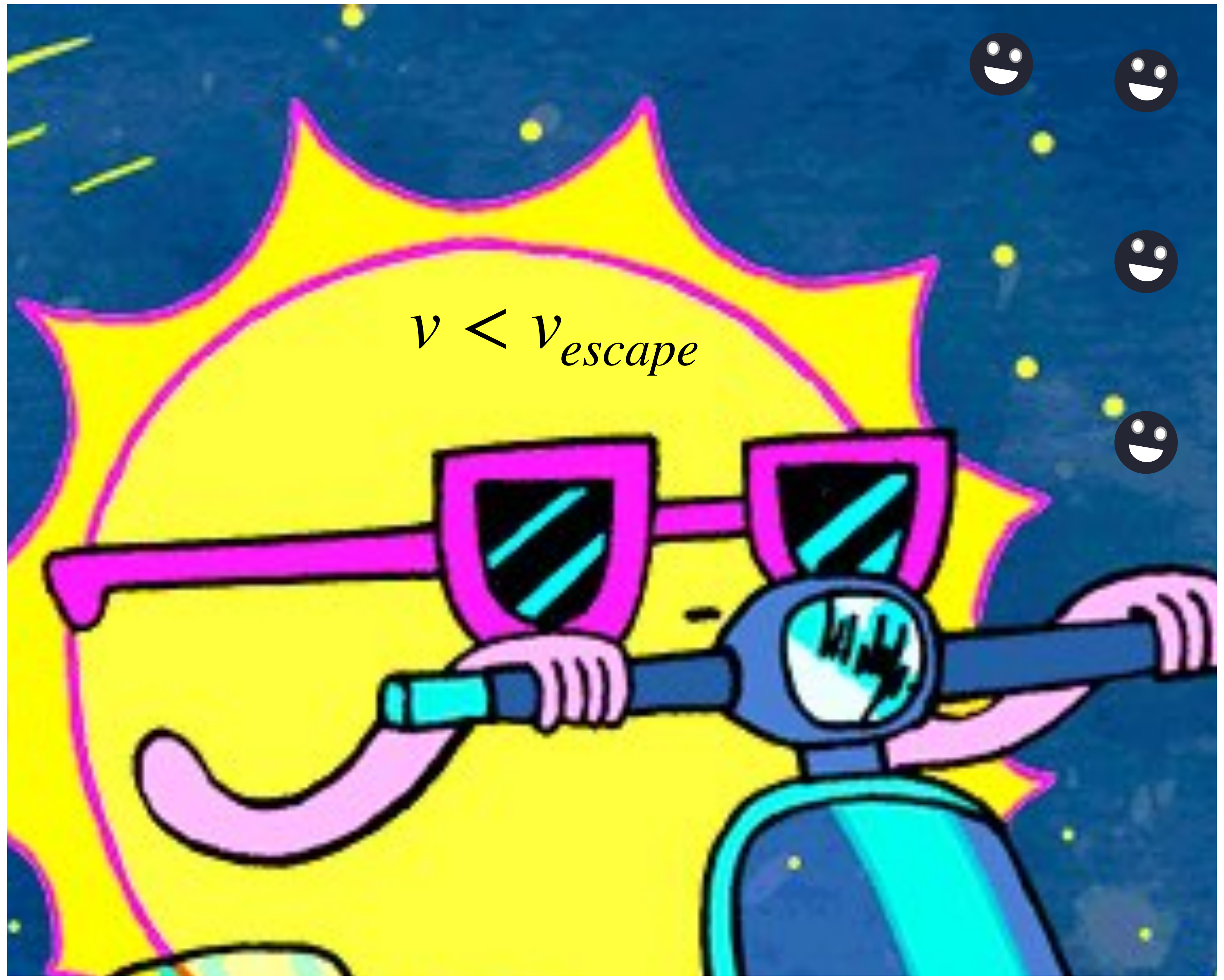


Dark matter in stars



Dark matter falls in
Scatters with nucleus

$v < v_{esc}$?

Capture,
Equilibrates with star

relativistic?

Dark kinetic heating

asymmetric?

transport heat,
affect neutrinos,
asteroseismology
2111.06895

symmetric/
WIMP?

Self-annihilate

to neutrinos

high-energy neutrinos
at IceCube, SuperK, etc.
2310.15392

to charged particles

heat the core,
lower the TRGB

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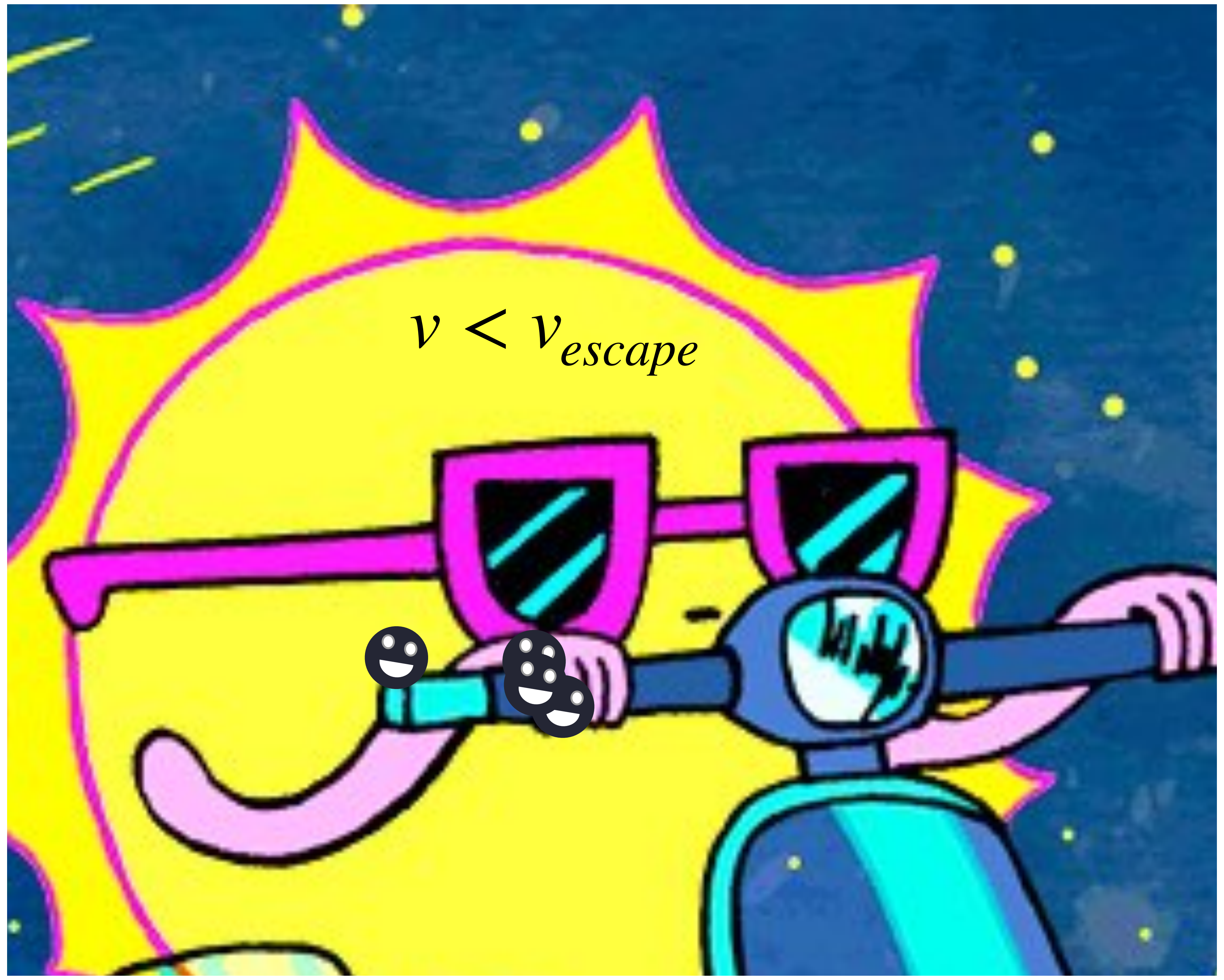

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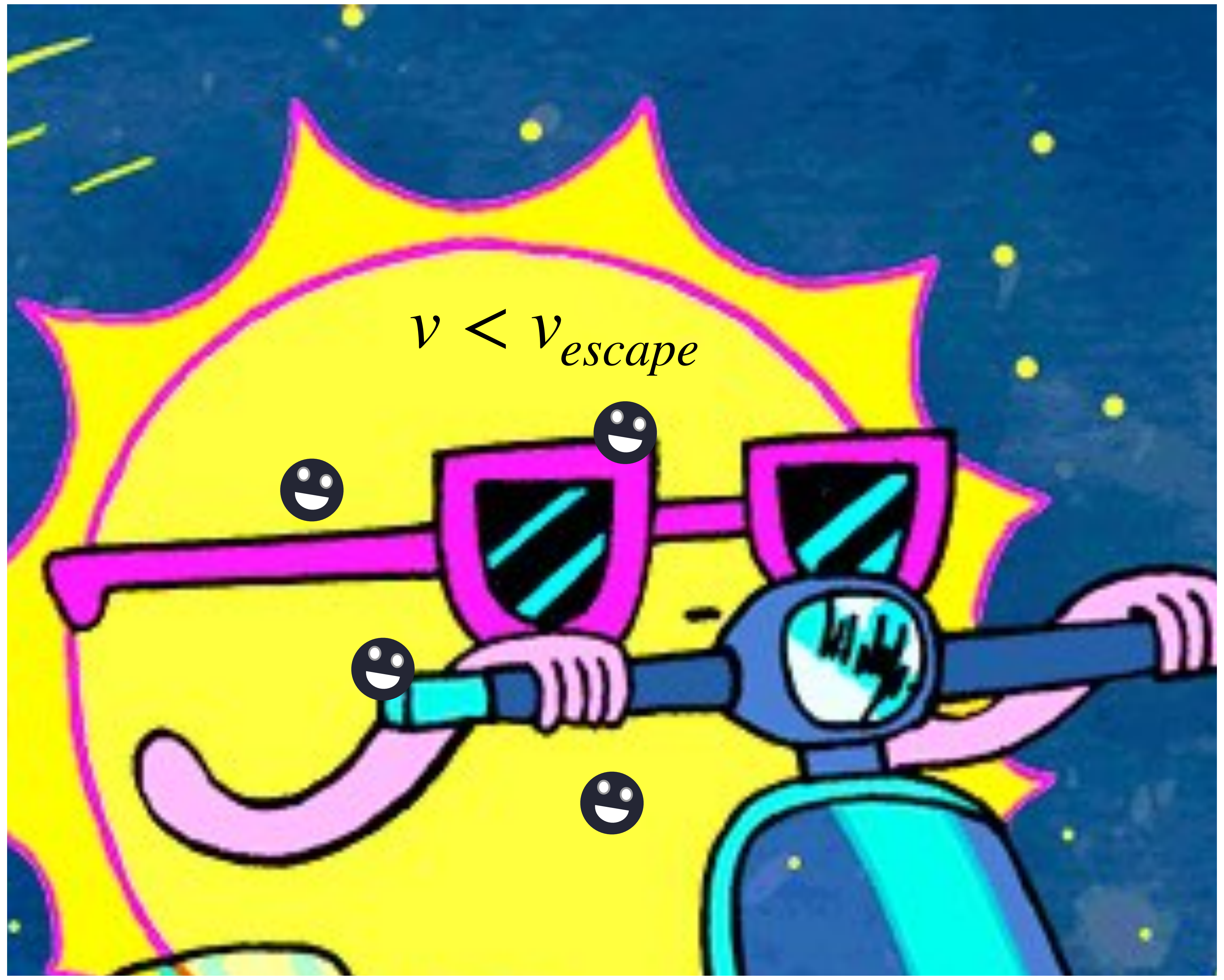
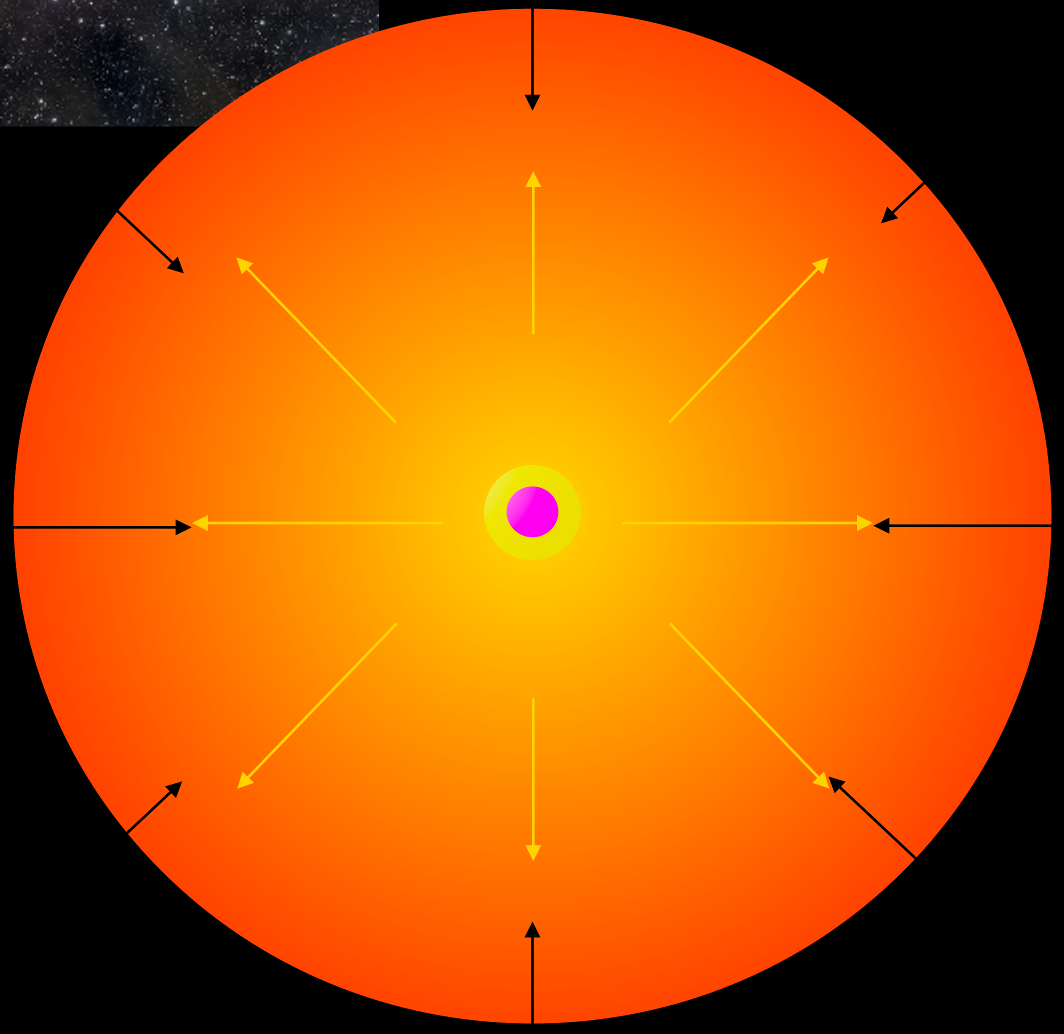


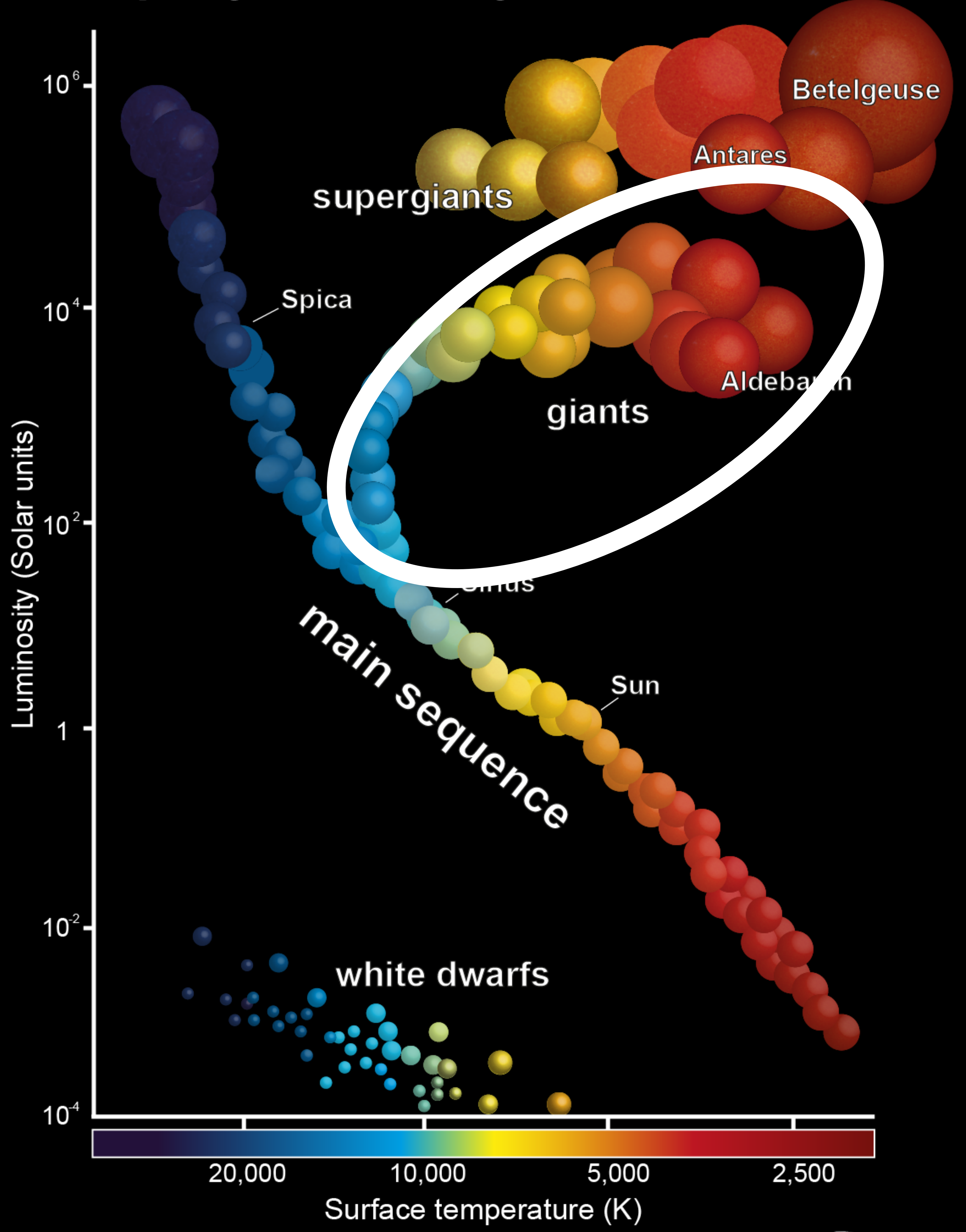
Red giant branch

Helium core

Hydrogen shell burning



Hertzsprung–Russell Diagram



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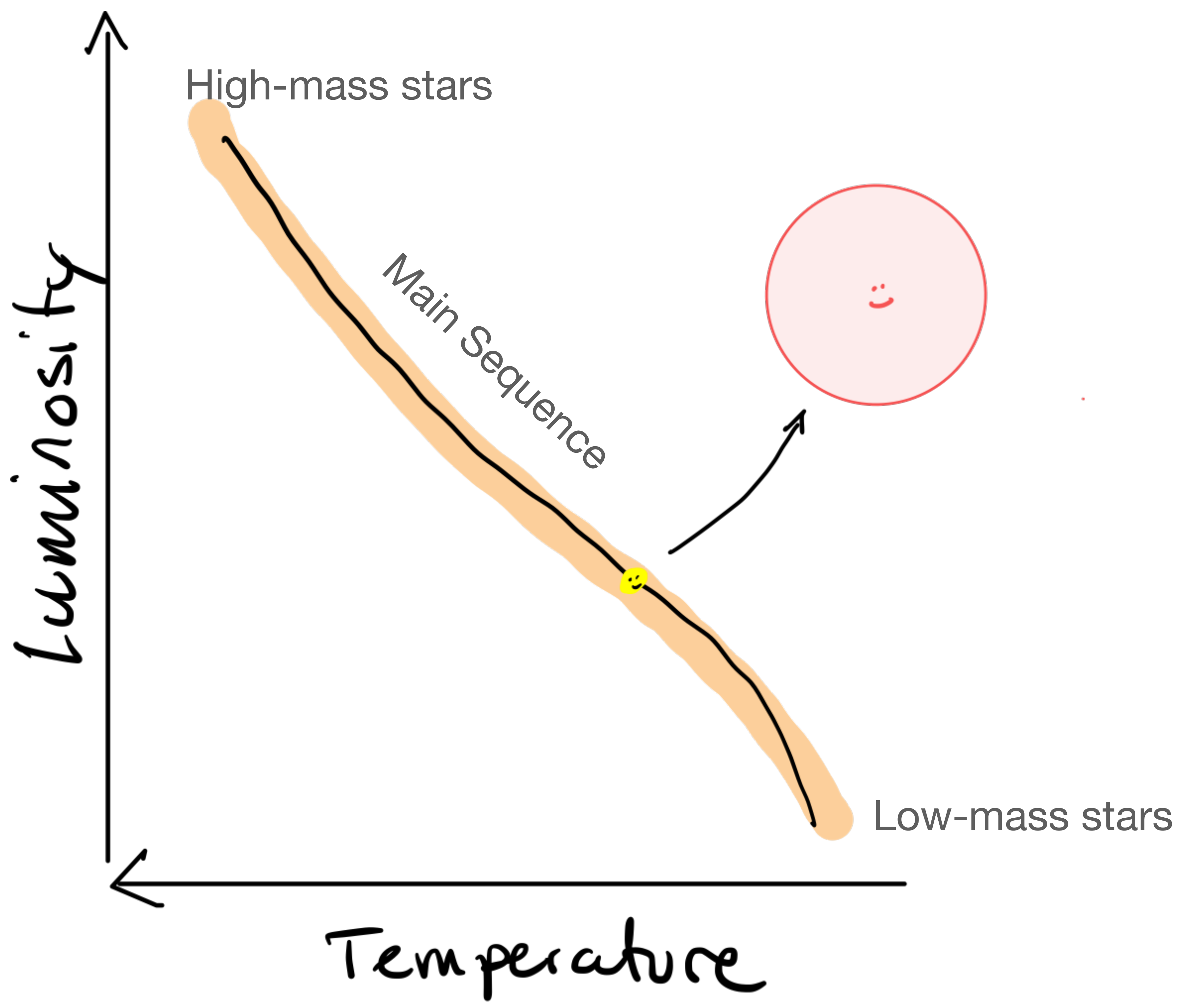
NSO

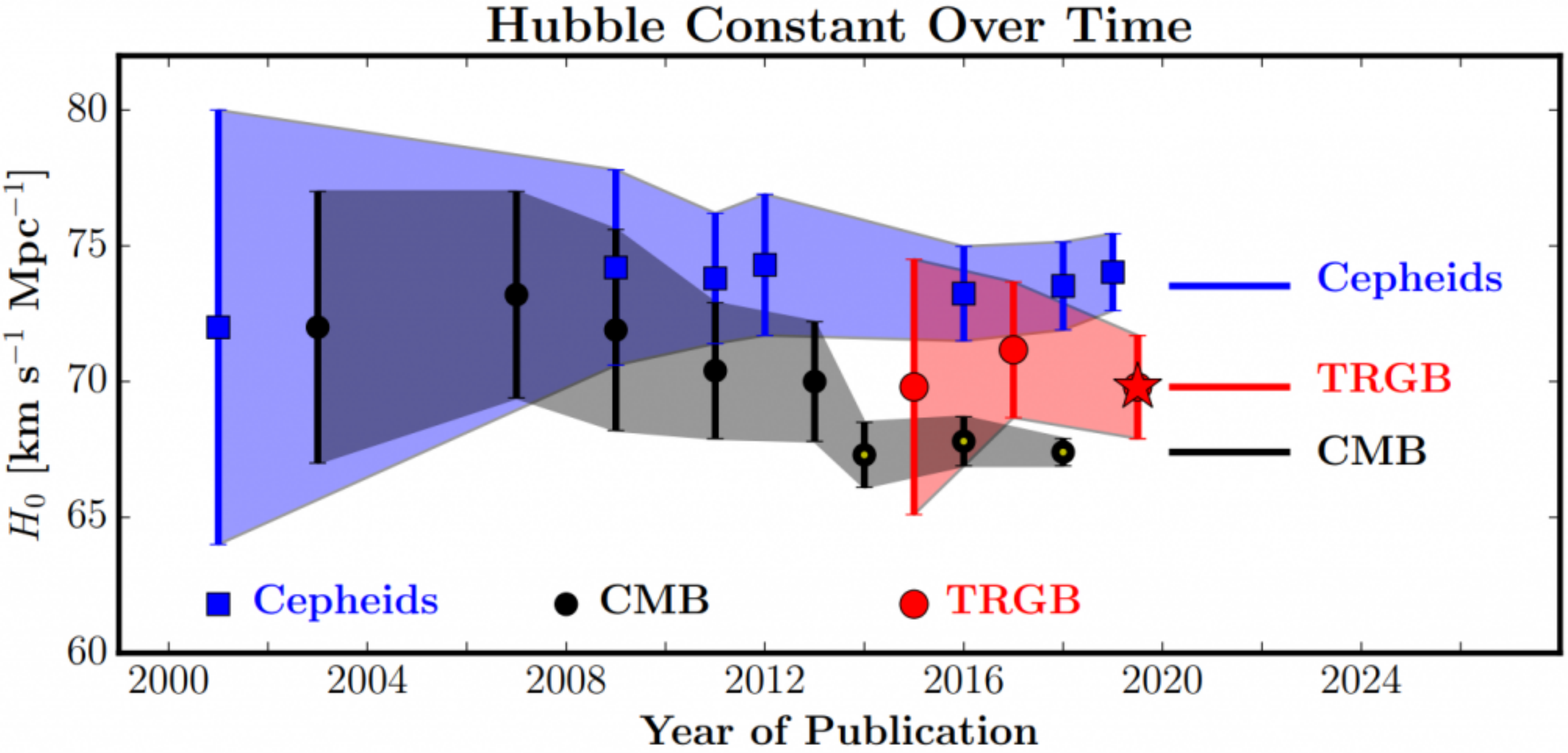
Tip of the red giant branch



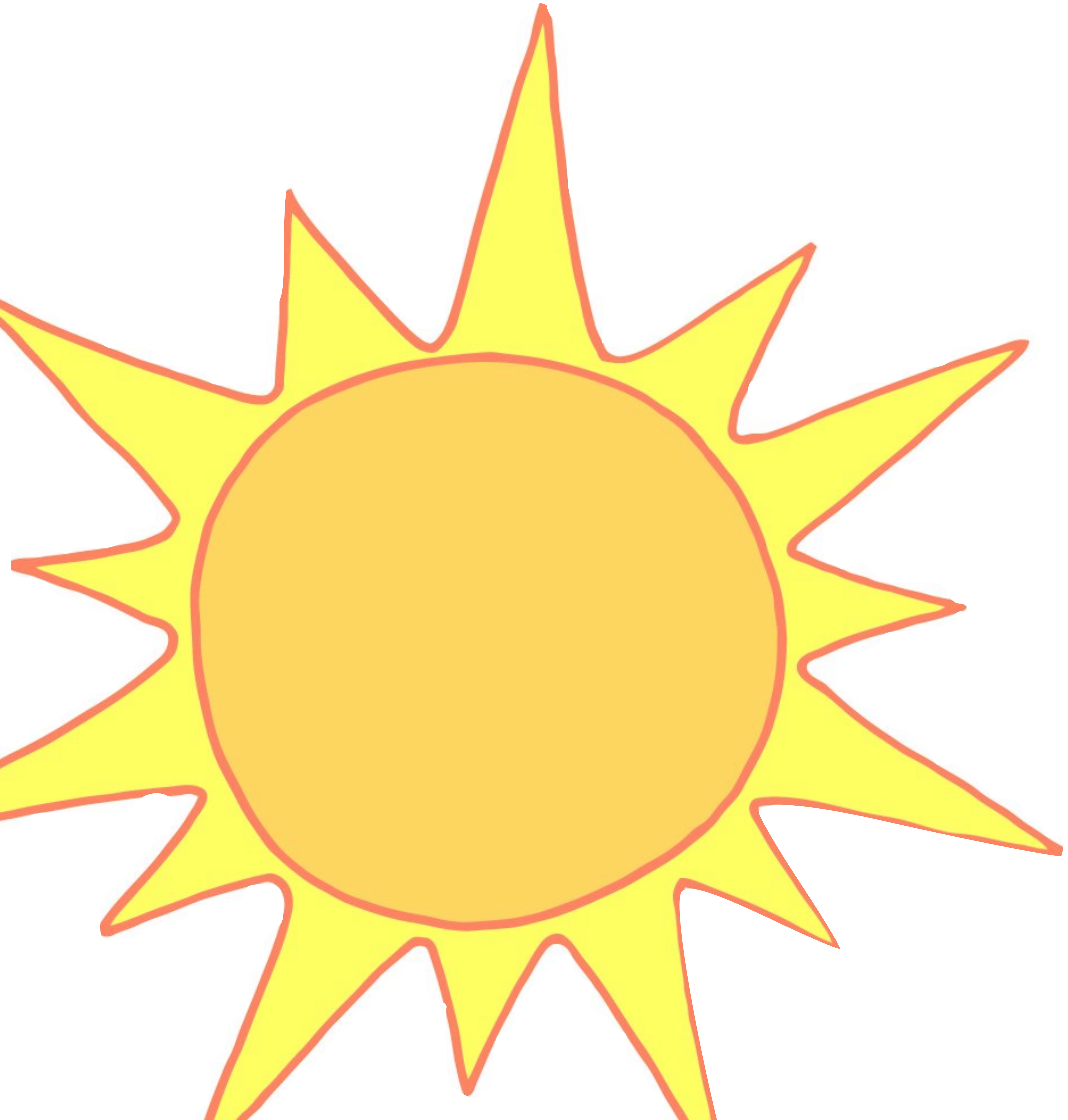
Stars on the **Main Sequence** are powered by hydrogen fusion into He

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

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.

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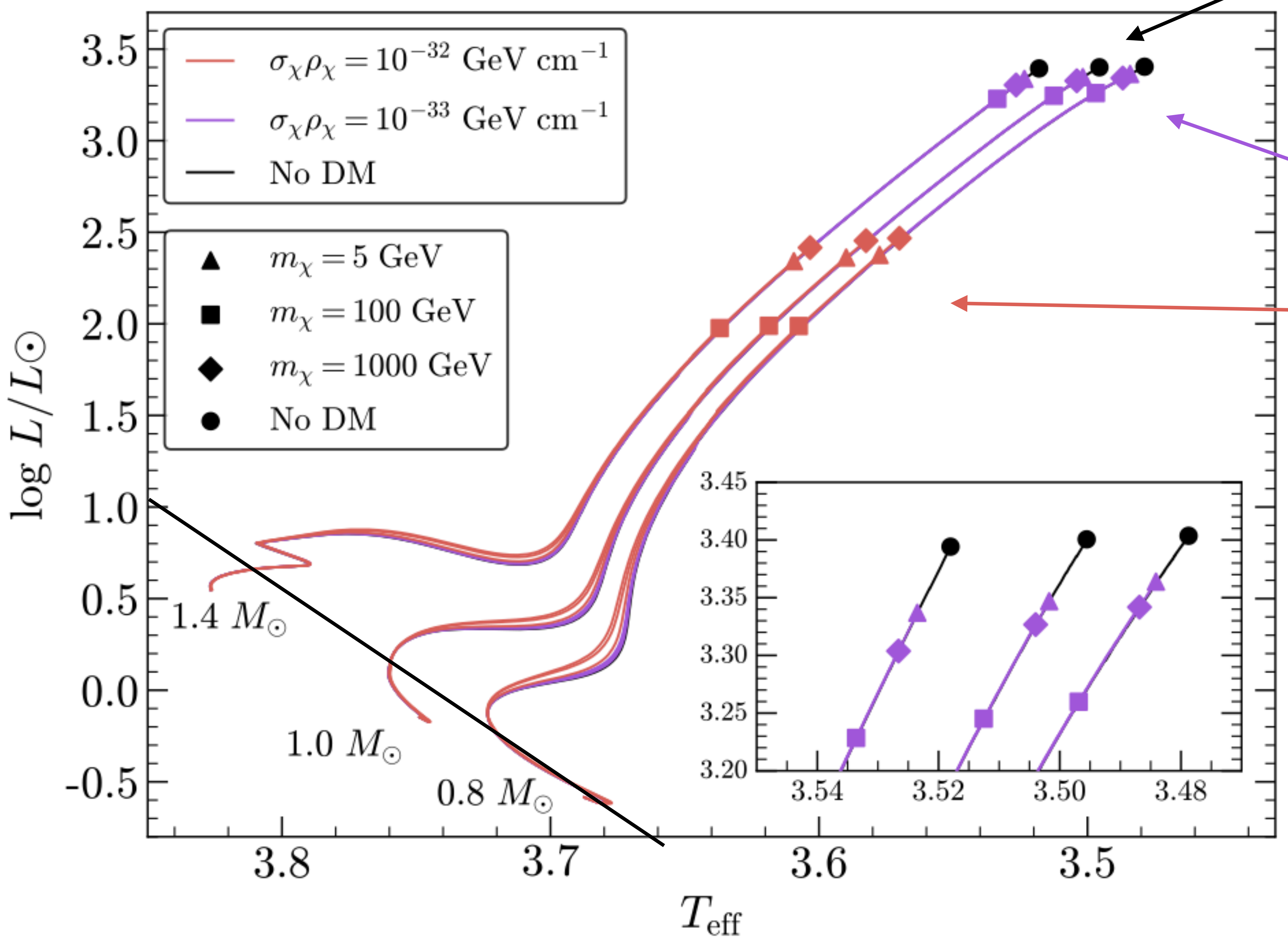


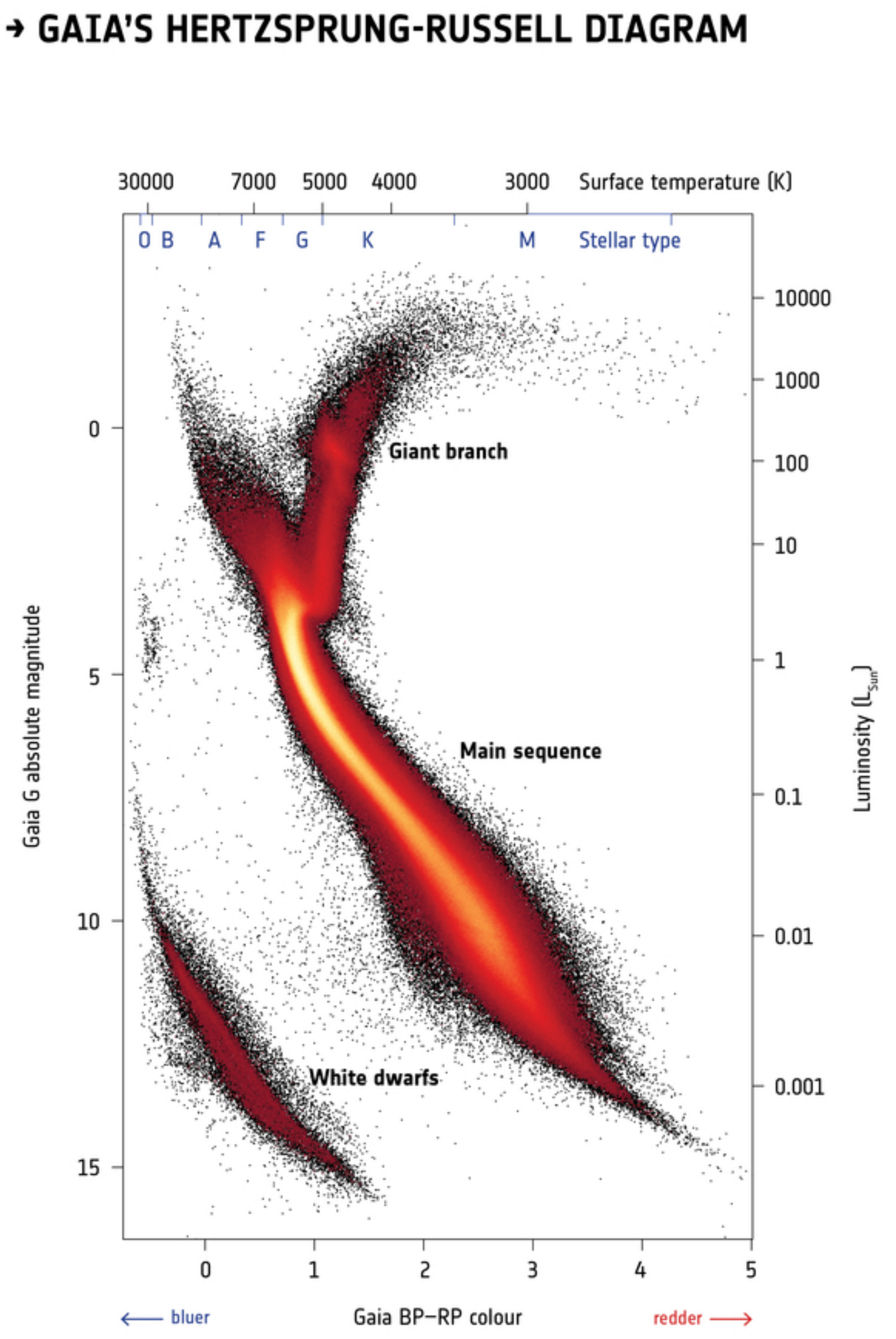
Stellar evolution simulations with no dark matter

A lot of dark matter

an obscene amount of dark matter

Lopes & Lopes 2107.13885

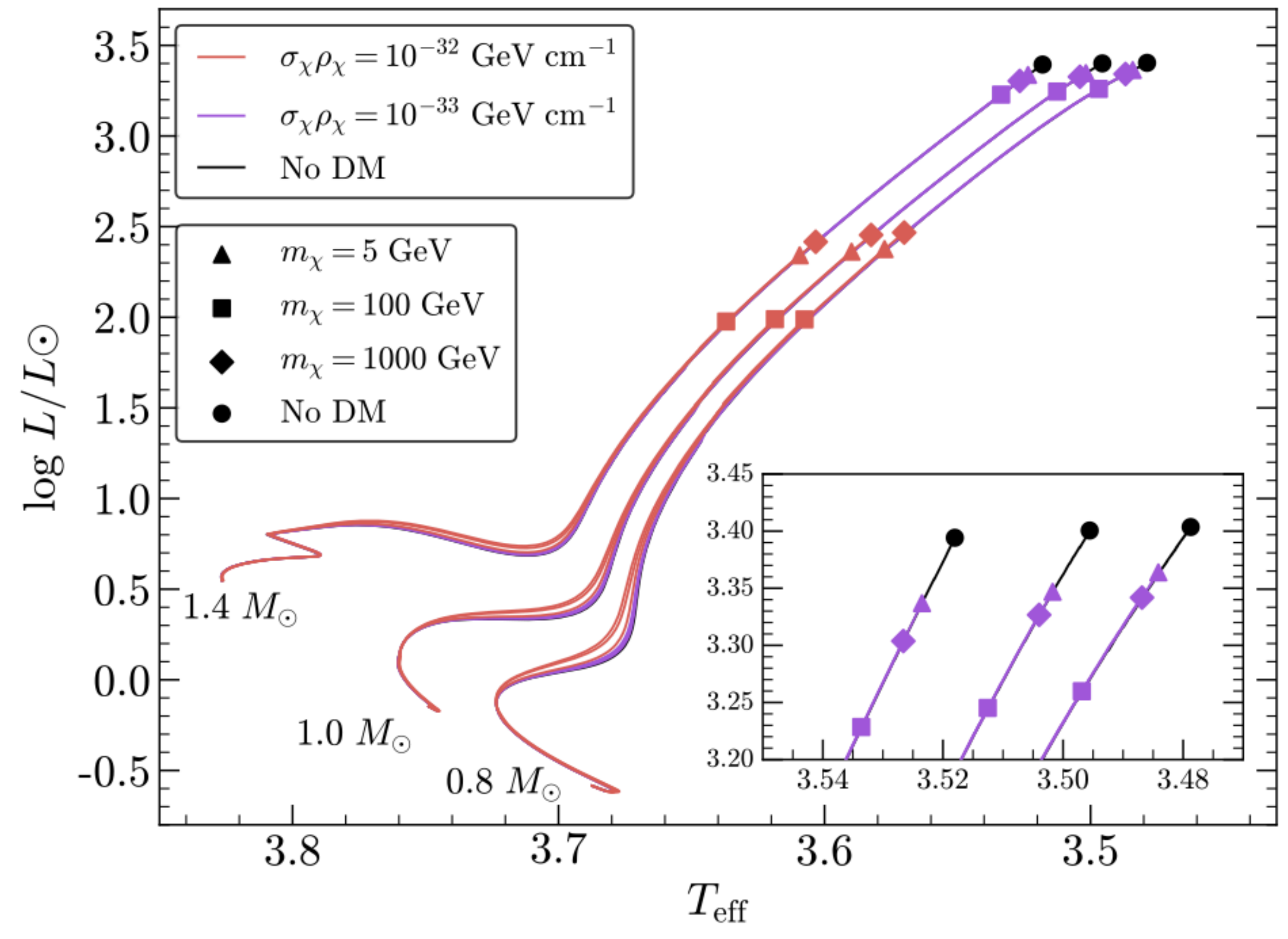
How do we test this?



The TRGB luminosity is constant over a ranger of stellar masses, **but** depends on metallicity

The Milky Way's disk (i.e. us) is a mess of stellar populations

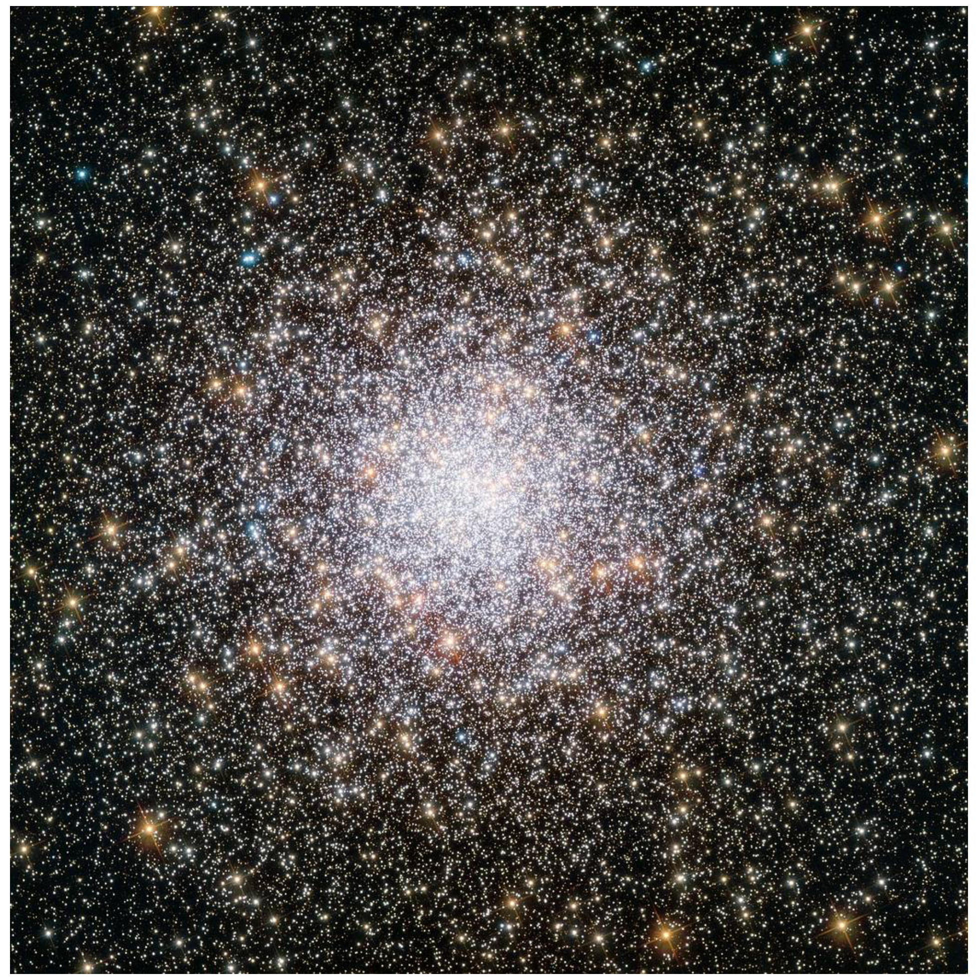
Ideally, we would like to compare the TRGB at different locations, where stars sample different amounts of dark matter

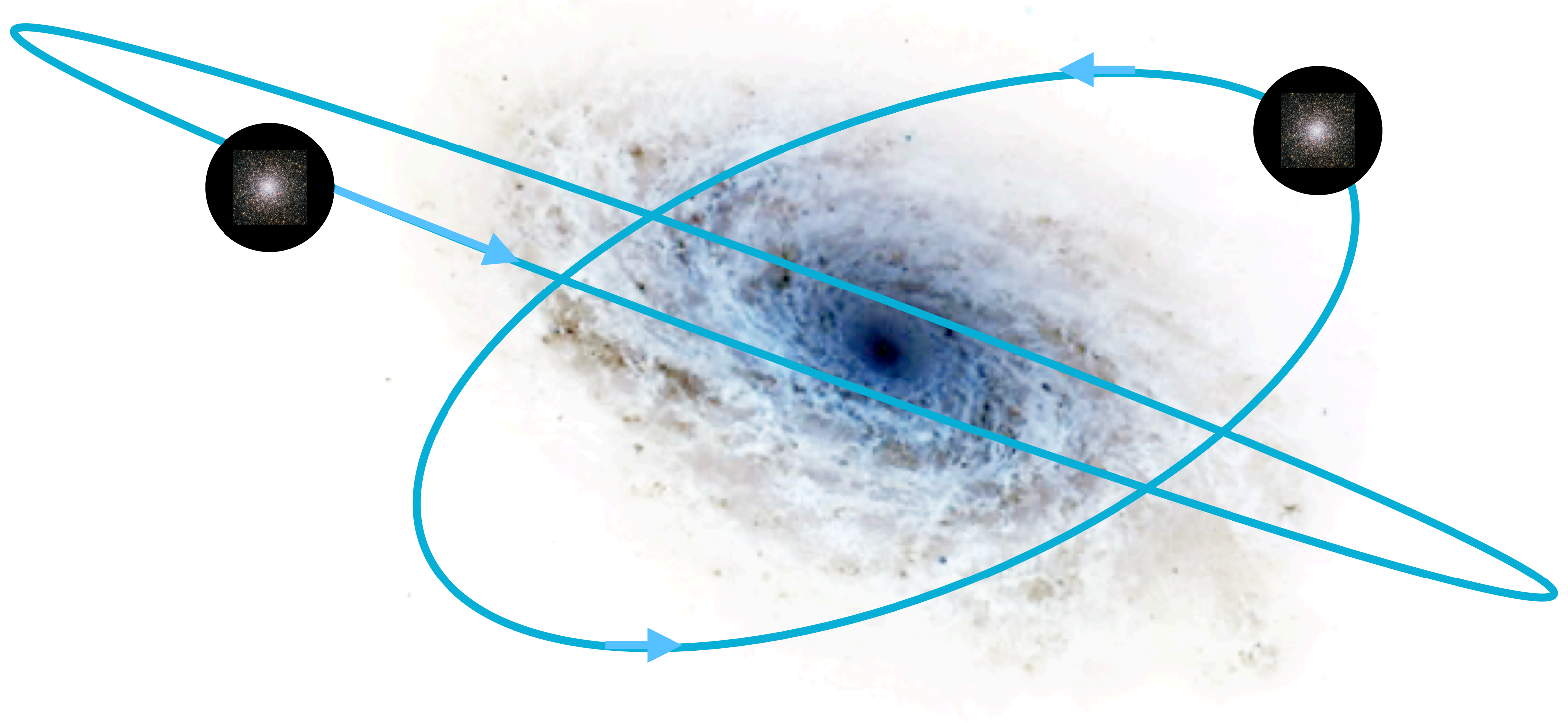


Globular clusters

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





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

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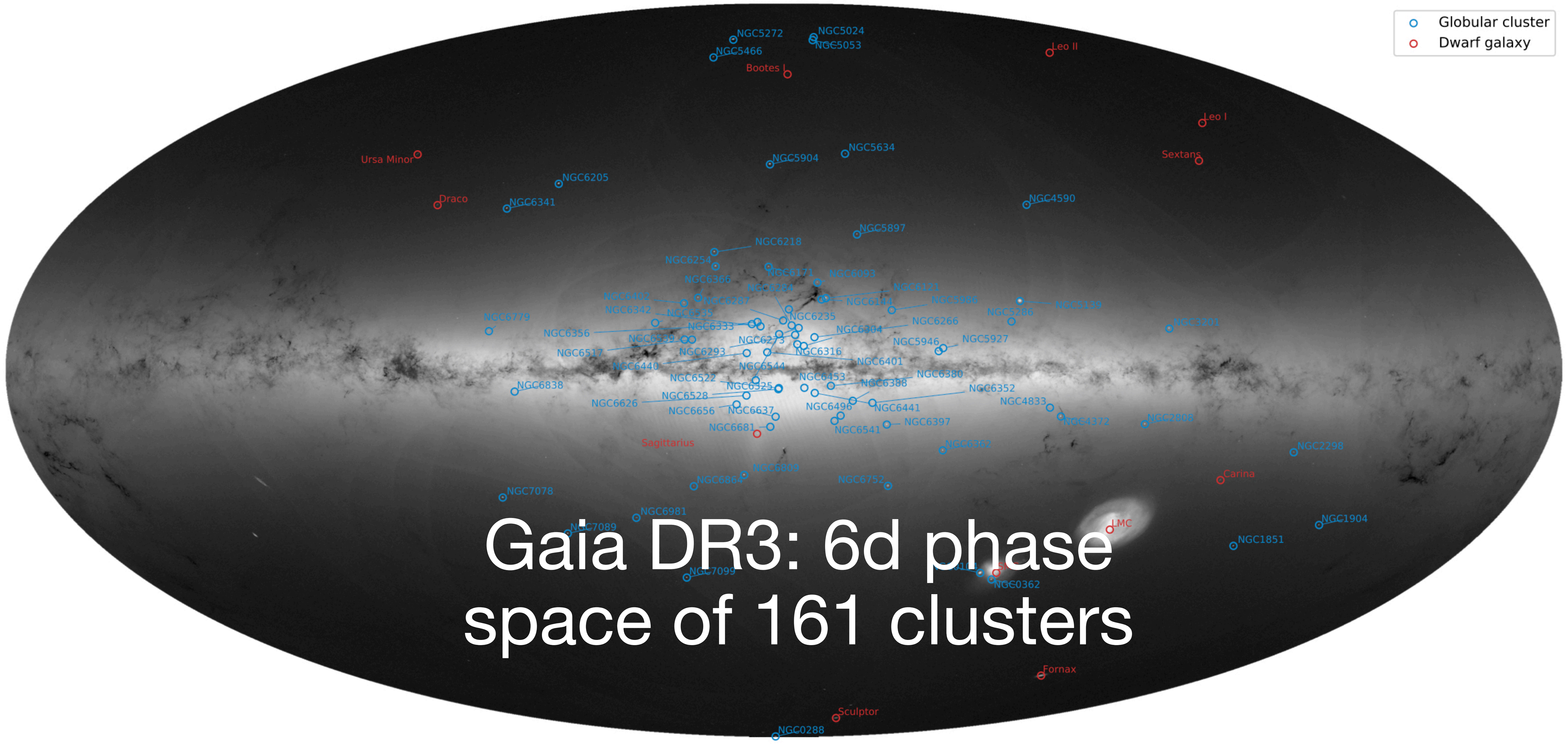

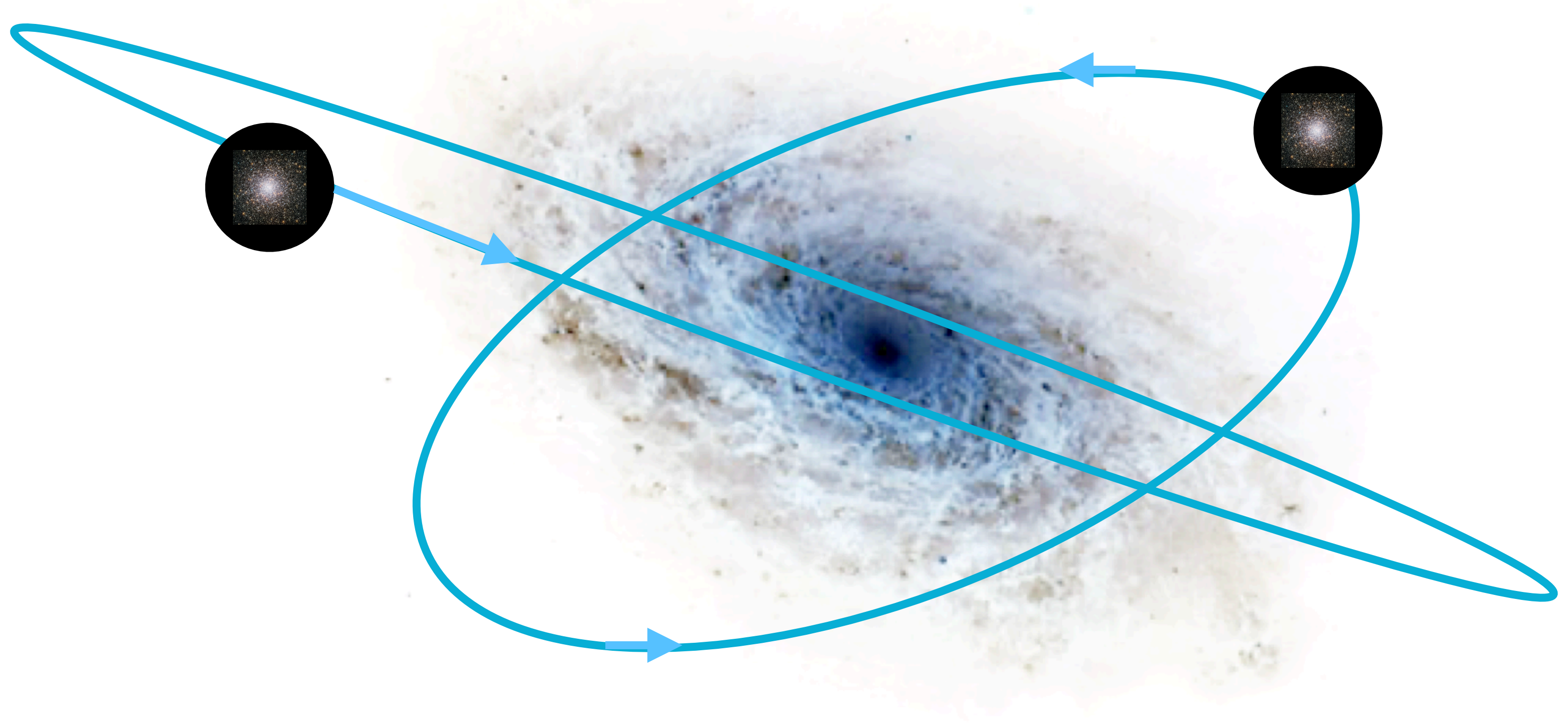

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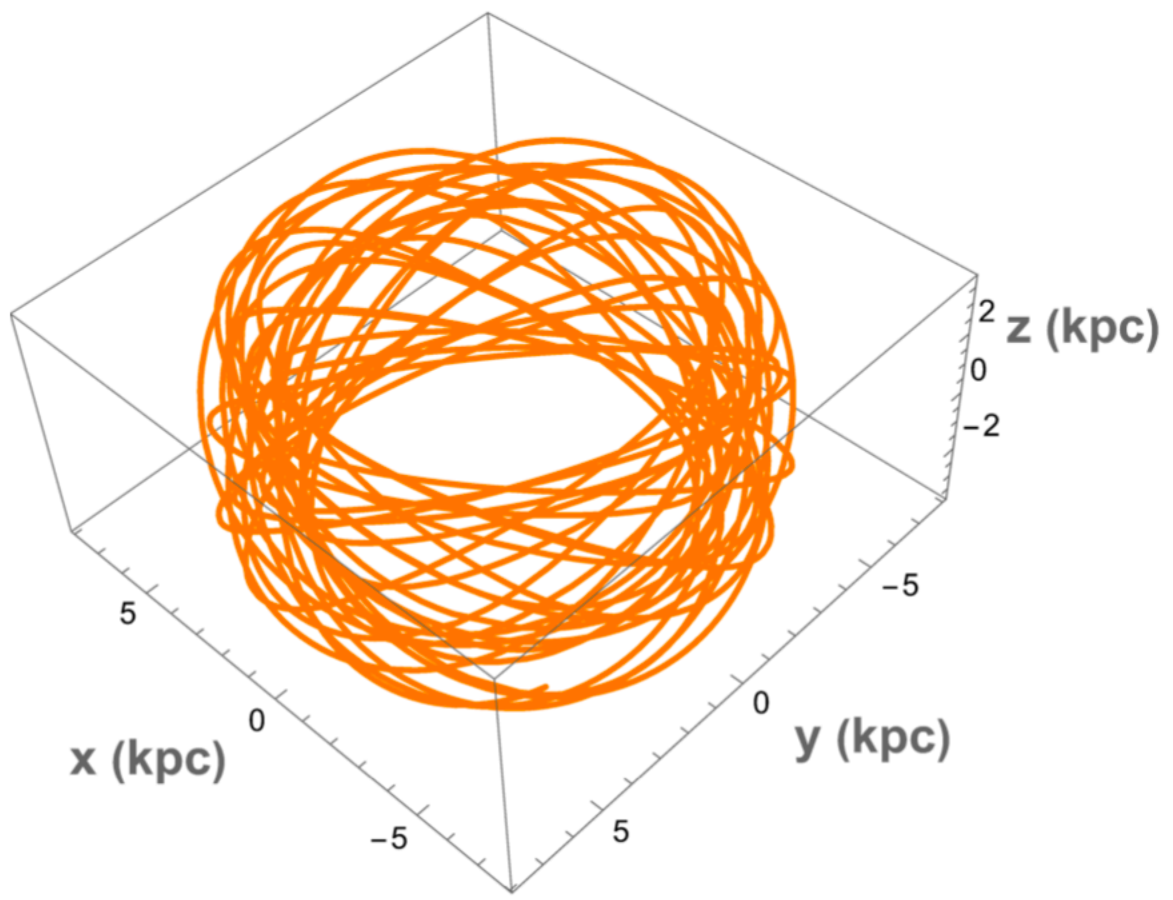
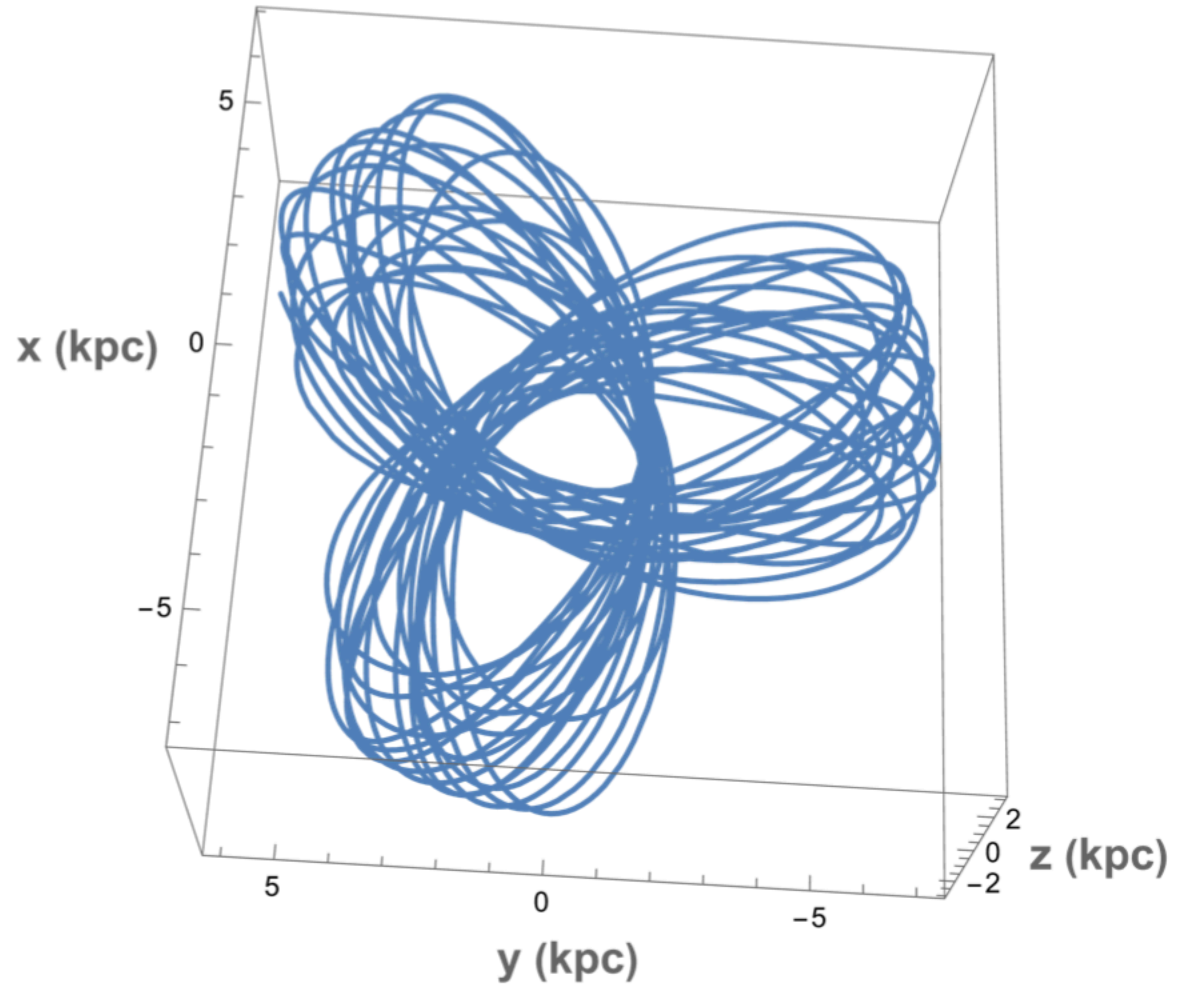
How much dark matter does a globular cluster “see”?

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

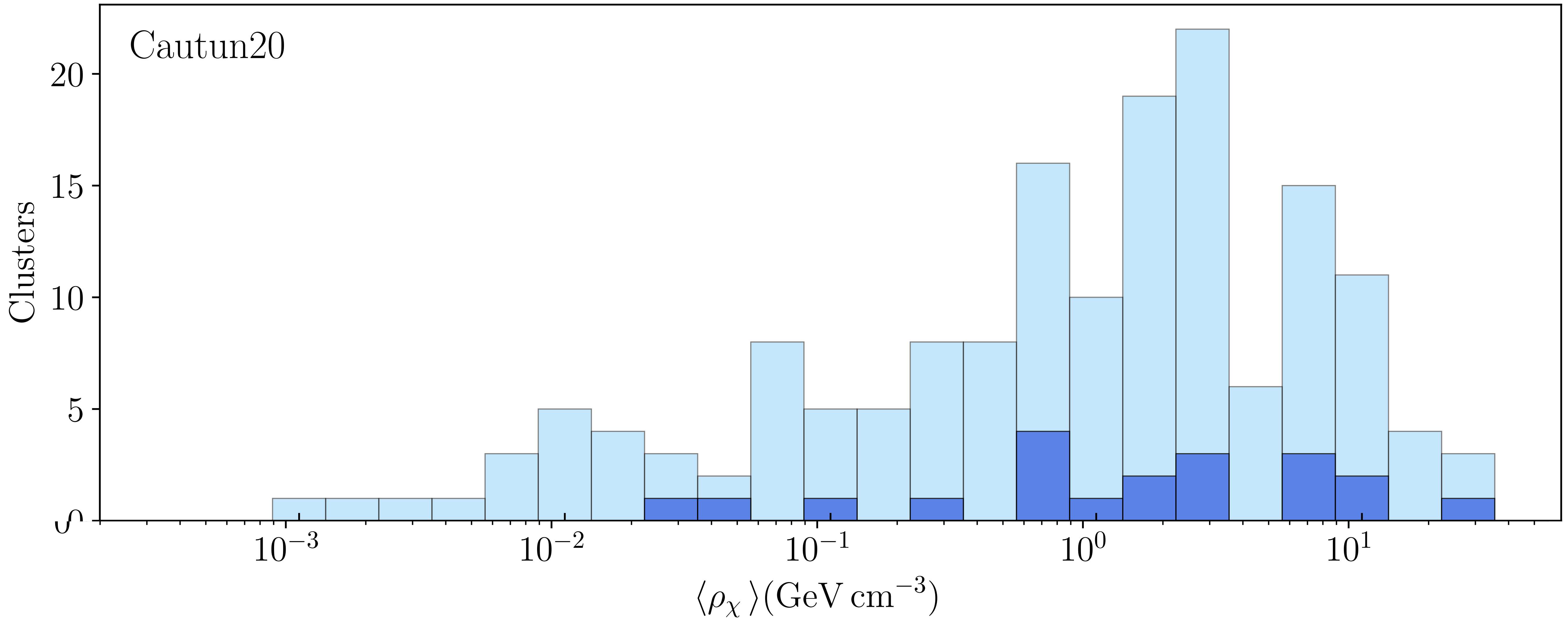
Use *Gaia* data + gravitational potential of Milky Way, simulate trajectories of 161 Globular Clusters





Howard Hong

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

Milky Way mass distribution

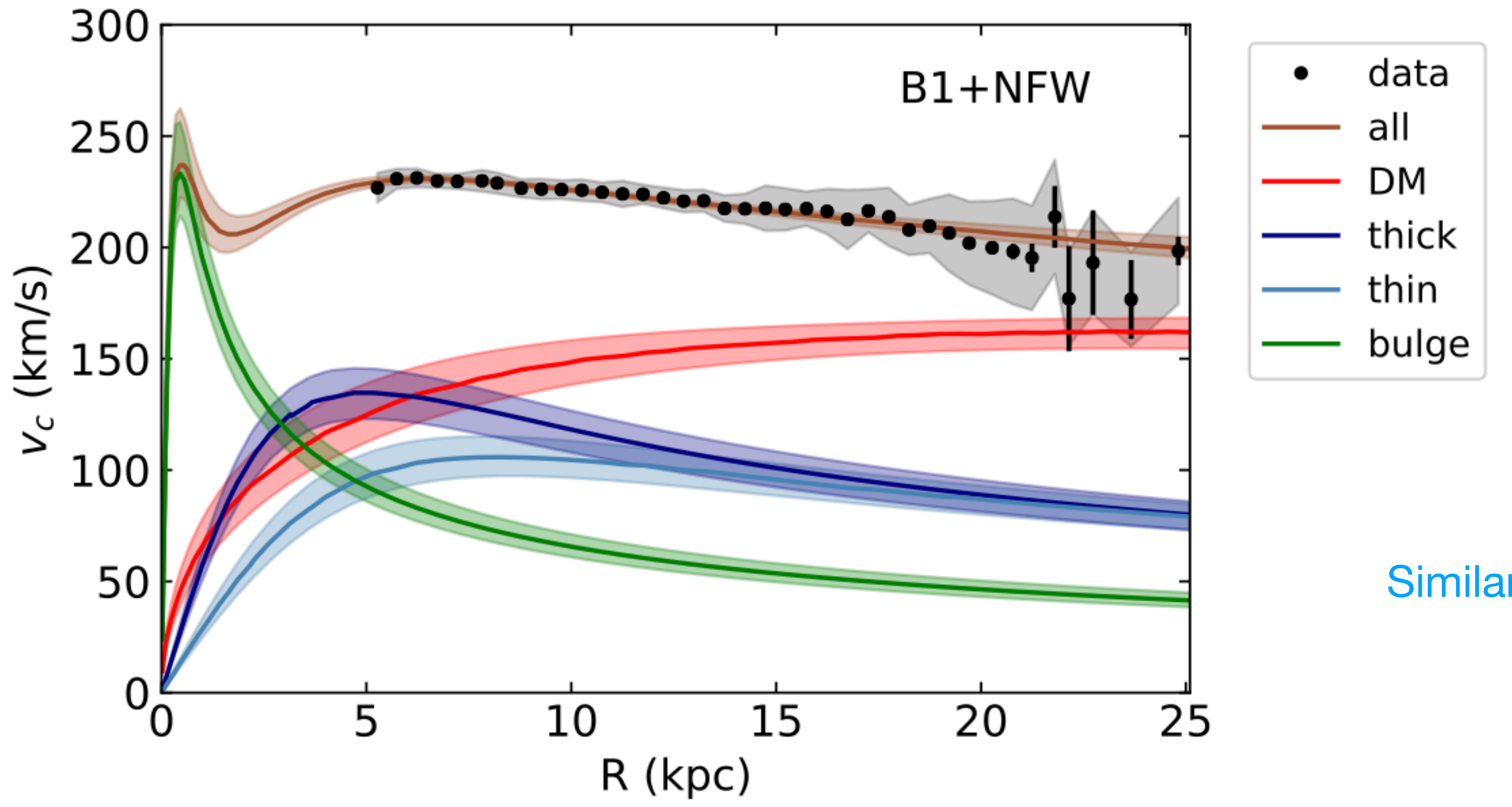
Test two representative distributions

both use data from Gaia DR2

“Pure” NFW

motivated by DM only sims

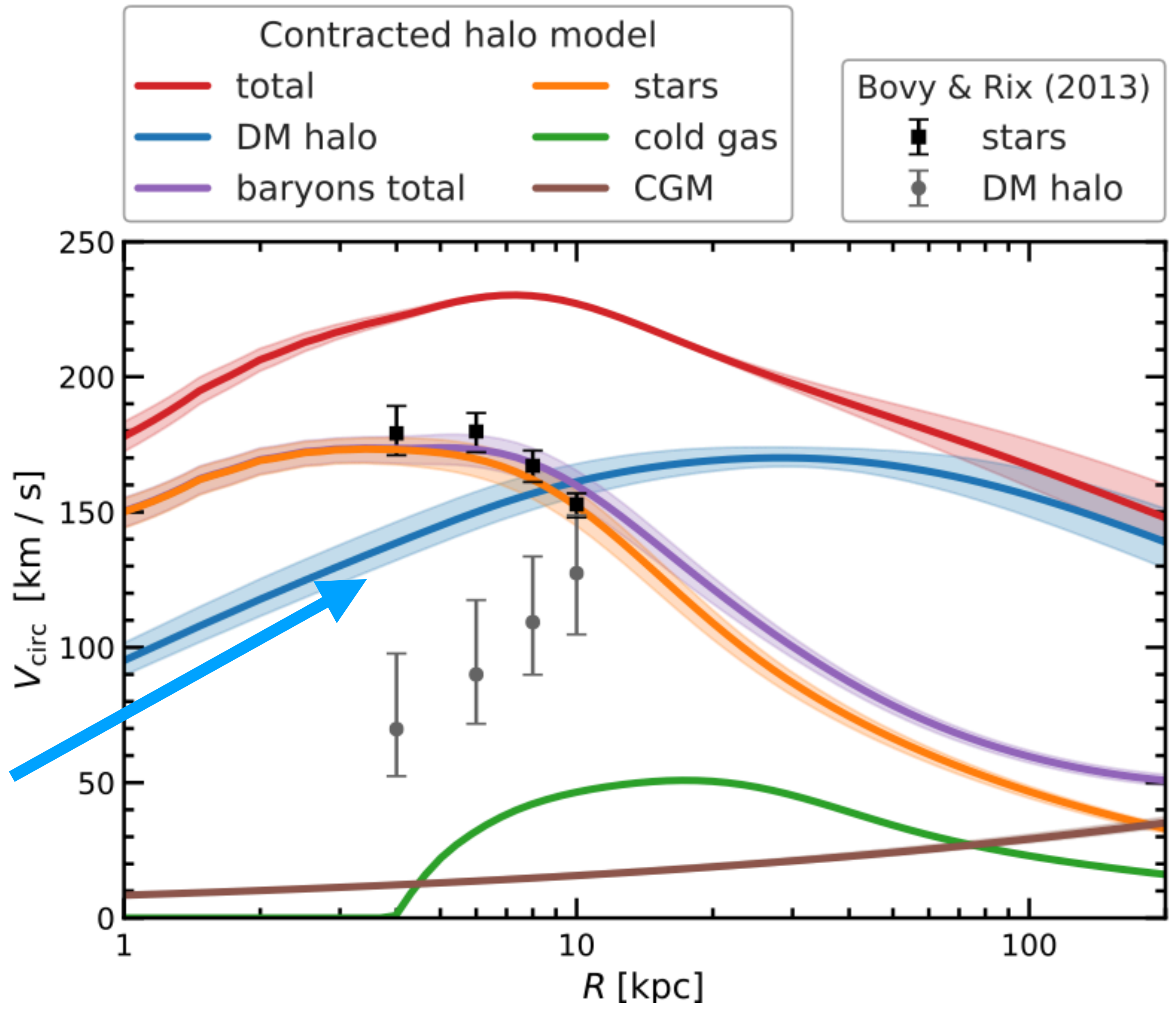
de Salas et al 1906.06133



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

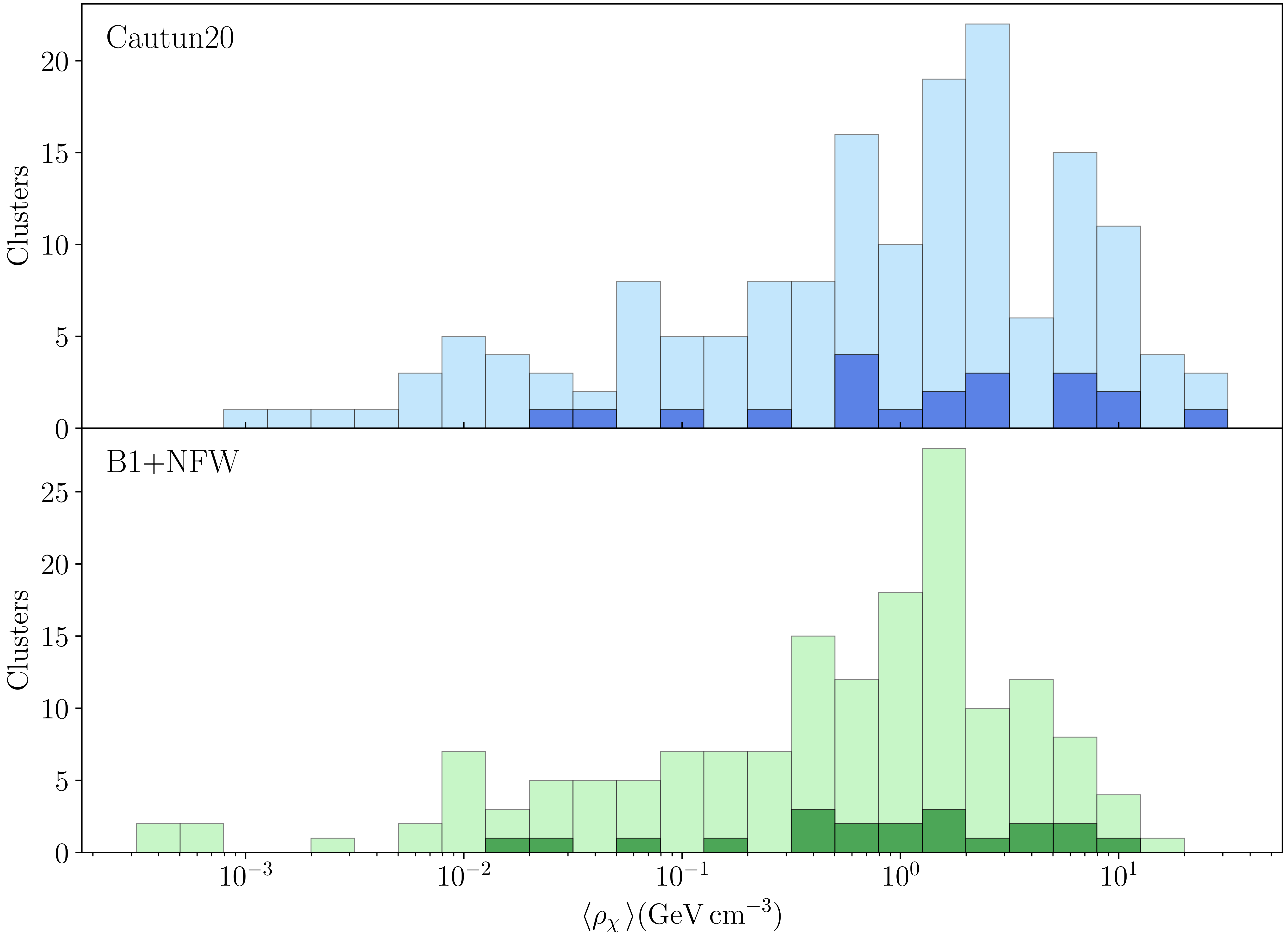
Dark matter seen by each Globular cluster

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

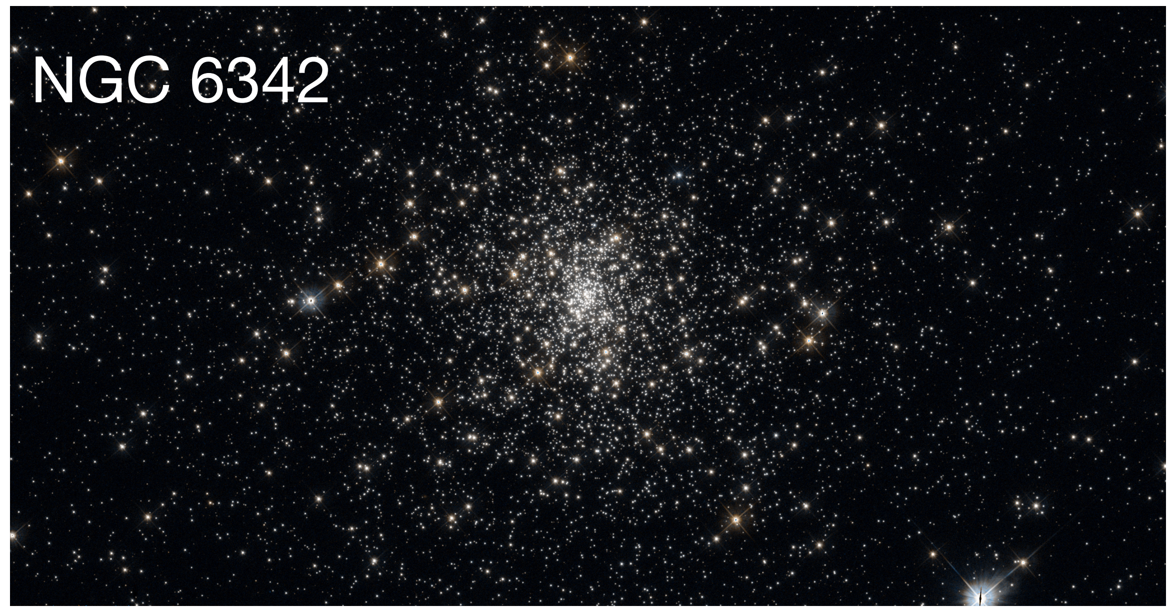
Dark: the 22 GCs we additionally have TRGB measurements for (HST + ground-based measurements, see Straniero et al. 2010.03833)

Contracted halo

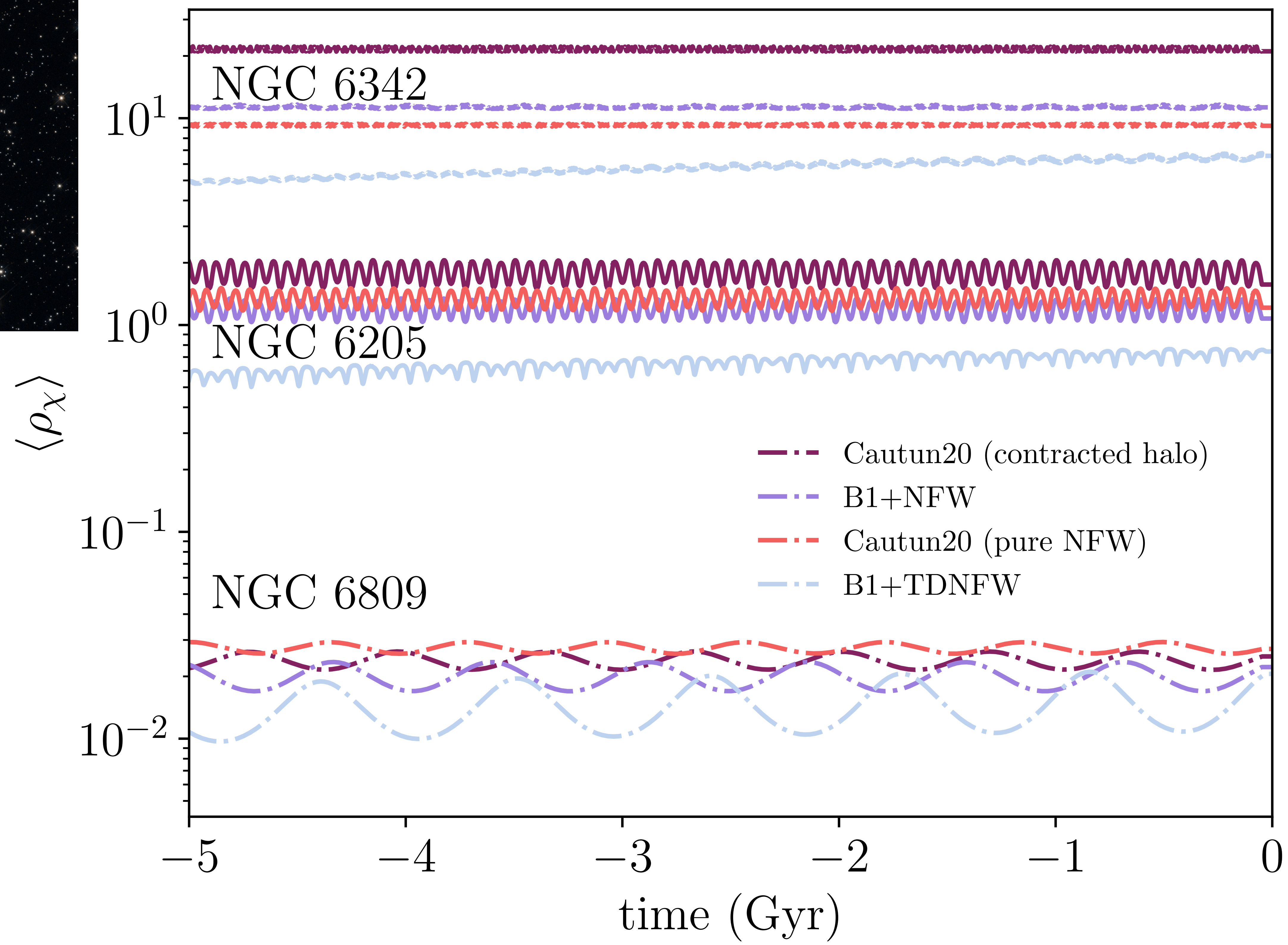
“Pure” NFW

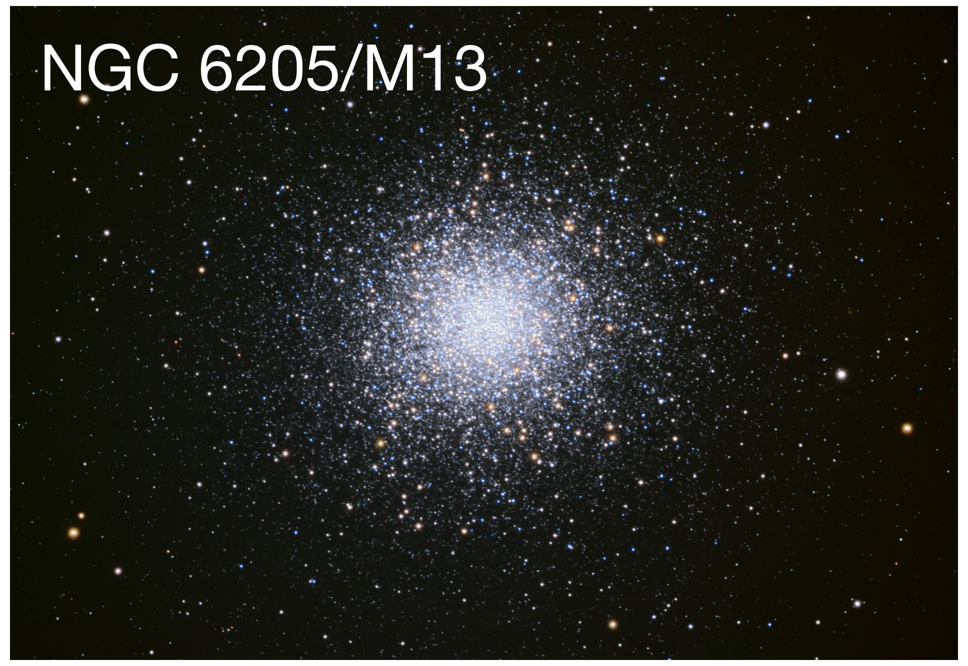


Time dependence?



Hubble





Sid Leach/Adam Block/Mount Lemmon SkyCenter

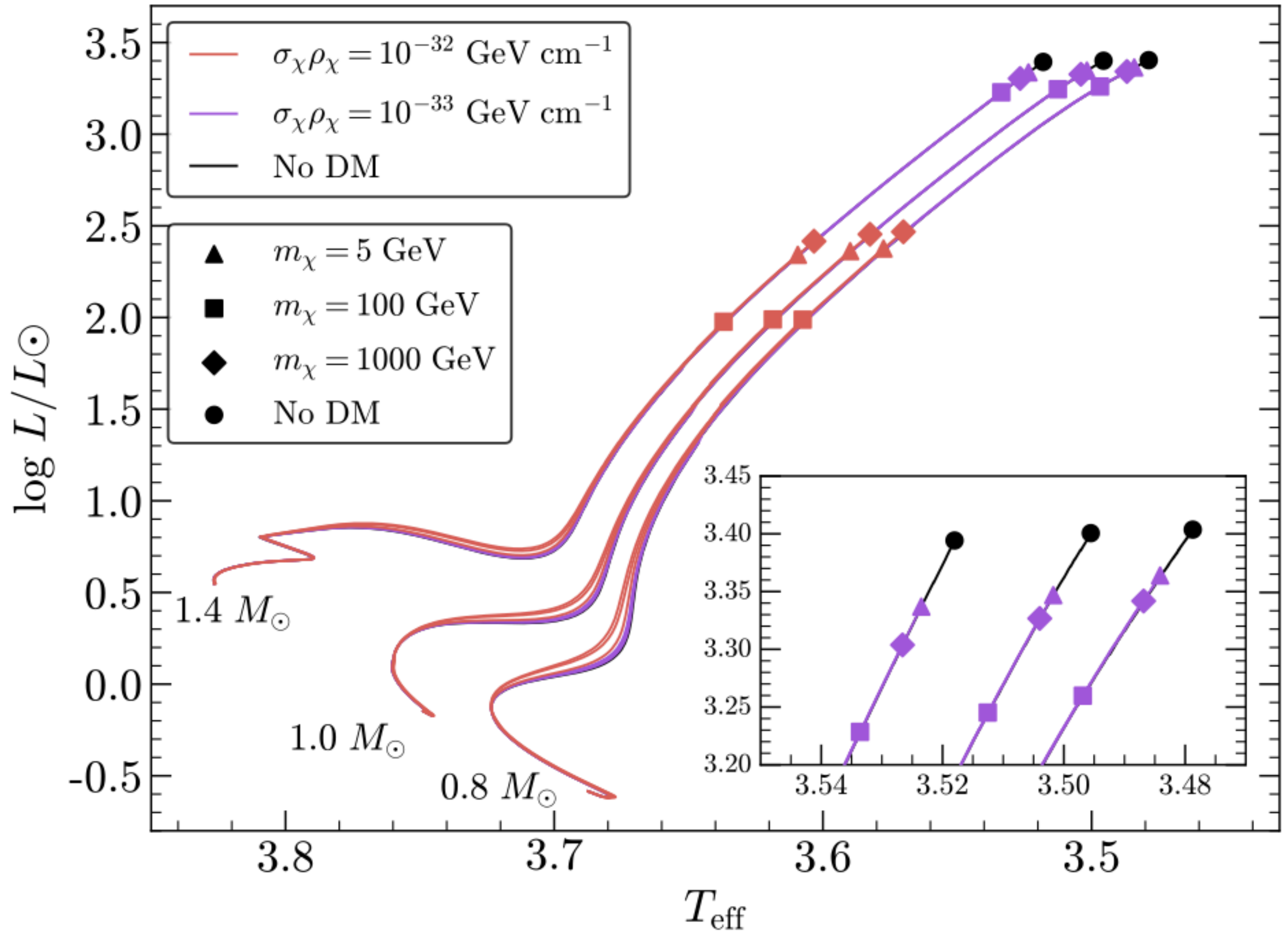
Time dependence of the potential follows concentration paramter c(t) from Dutton & Macciò (1402.7073), but not calibrated to MW rotation curve (simulation results)

ESO/J. Emerson/VISTA

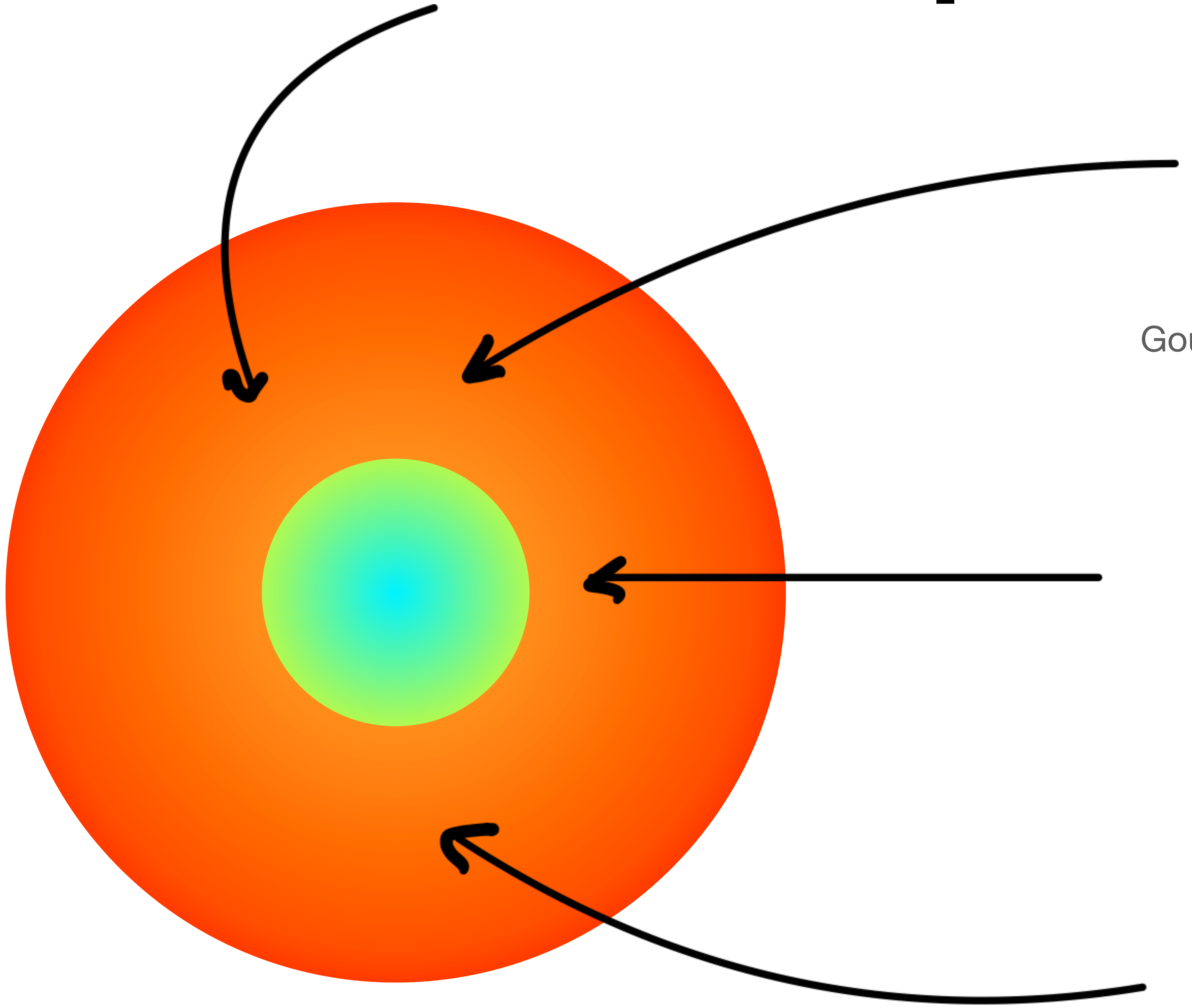
Upshot: differentiation between clusters is robust

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



Dark matter velocity distribution in the star's frame

Gould 1985: $$C_\star(t) = 4\pi \int_0^{R_\star} r^2 \int_0^\infty \frac{f_\star(u)}{u} w\Omega(w) du dr,$$

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

Integral over the star

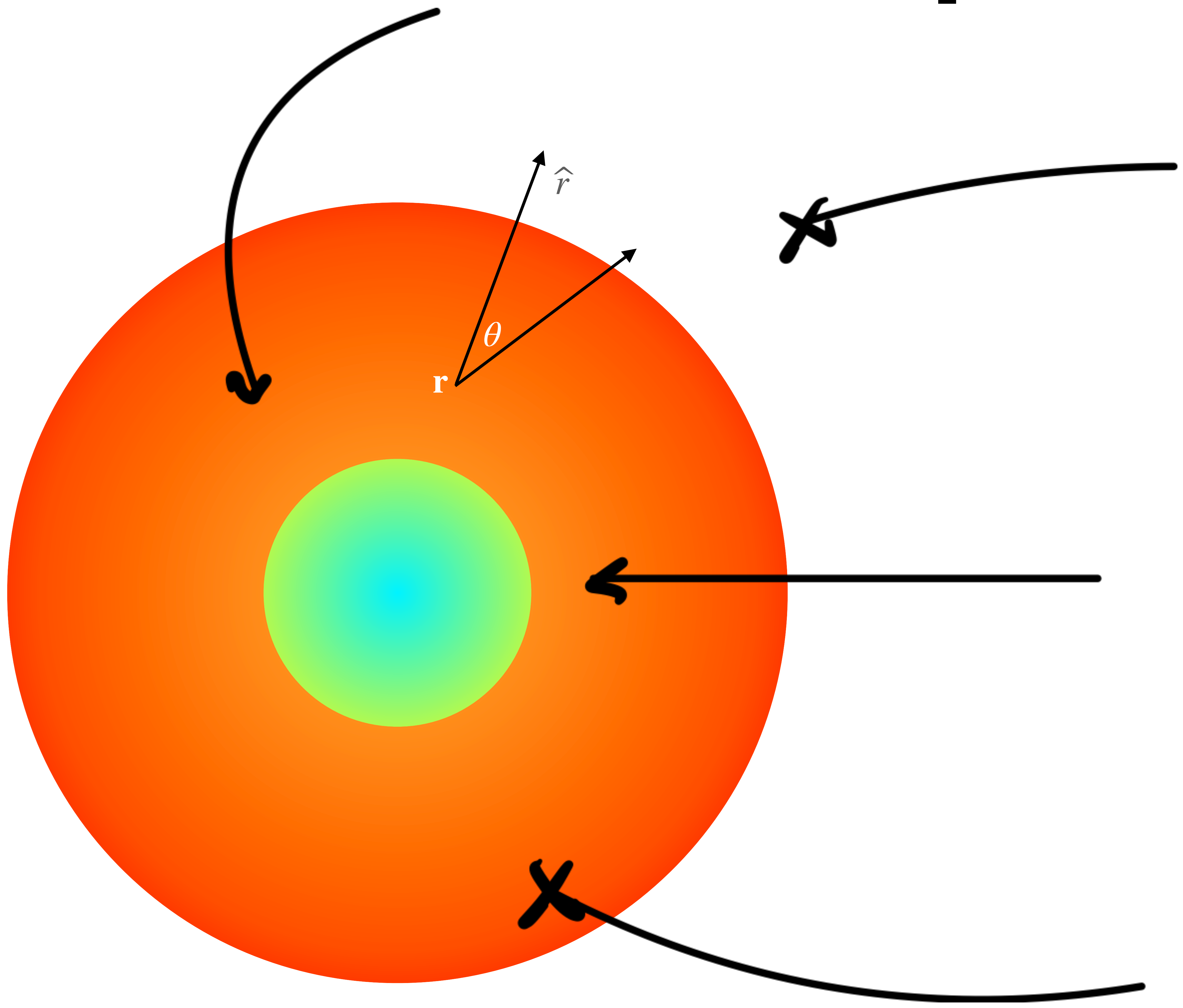
$$\Omega \propto \sigma_{SI}$$

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



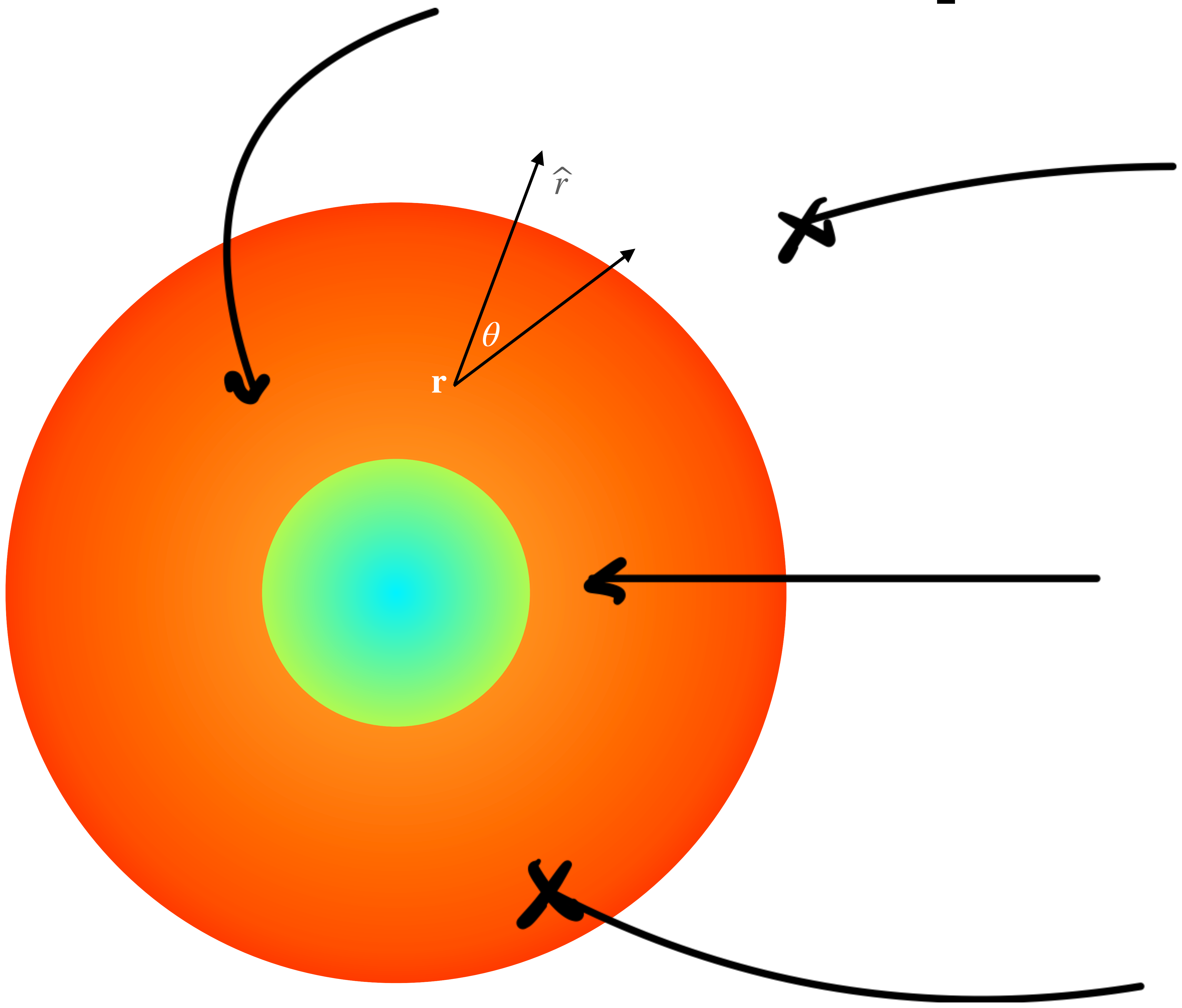
Gould's approach:

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

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

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

Dark matter capture & saturation



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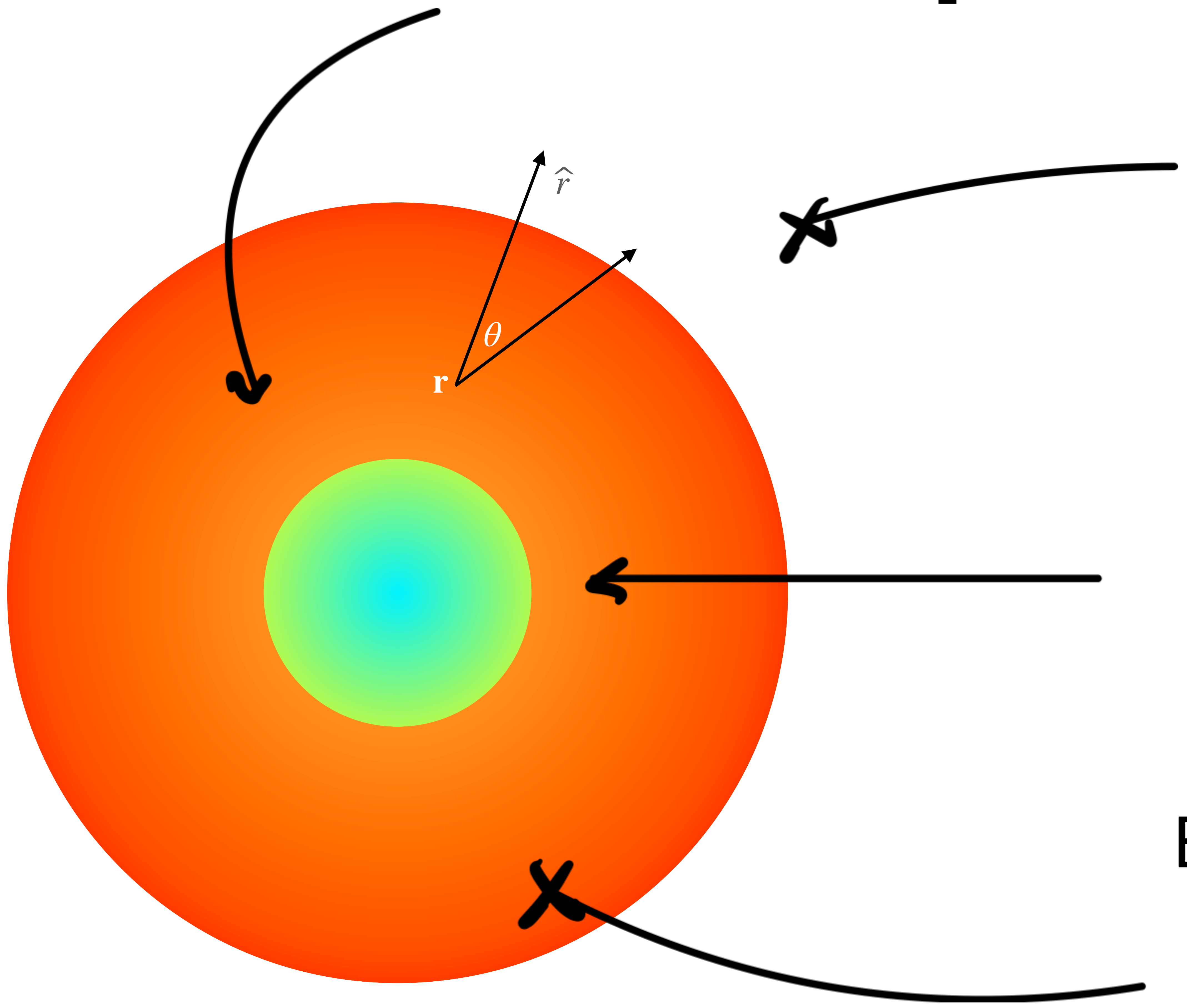
optical depth to the surface for every line of sight $z = cos\theta$

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

Dark matter capture & saturation



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

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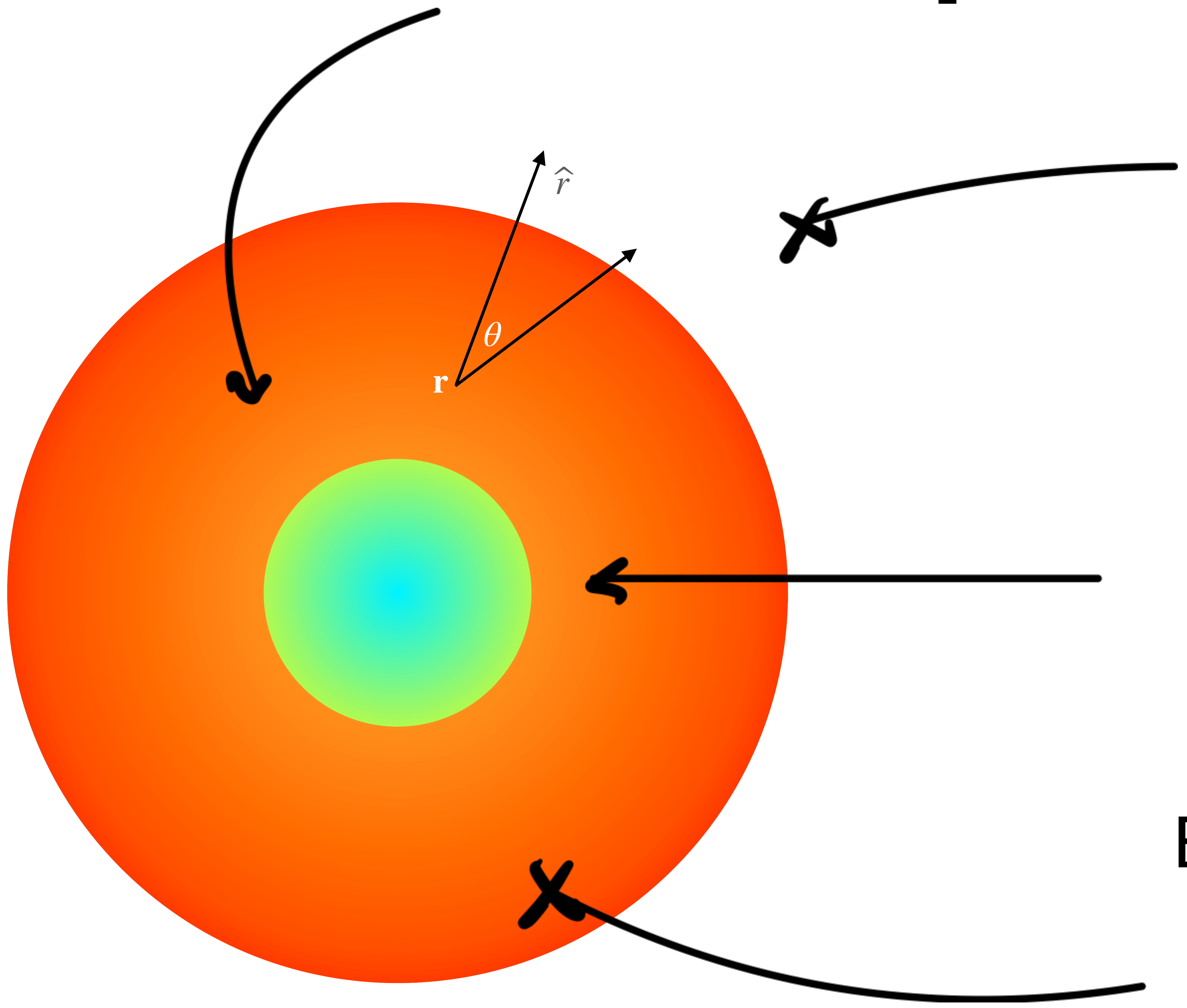

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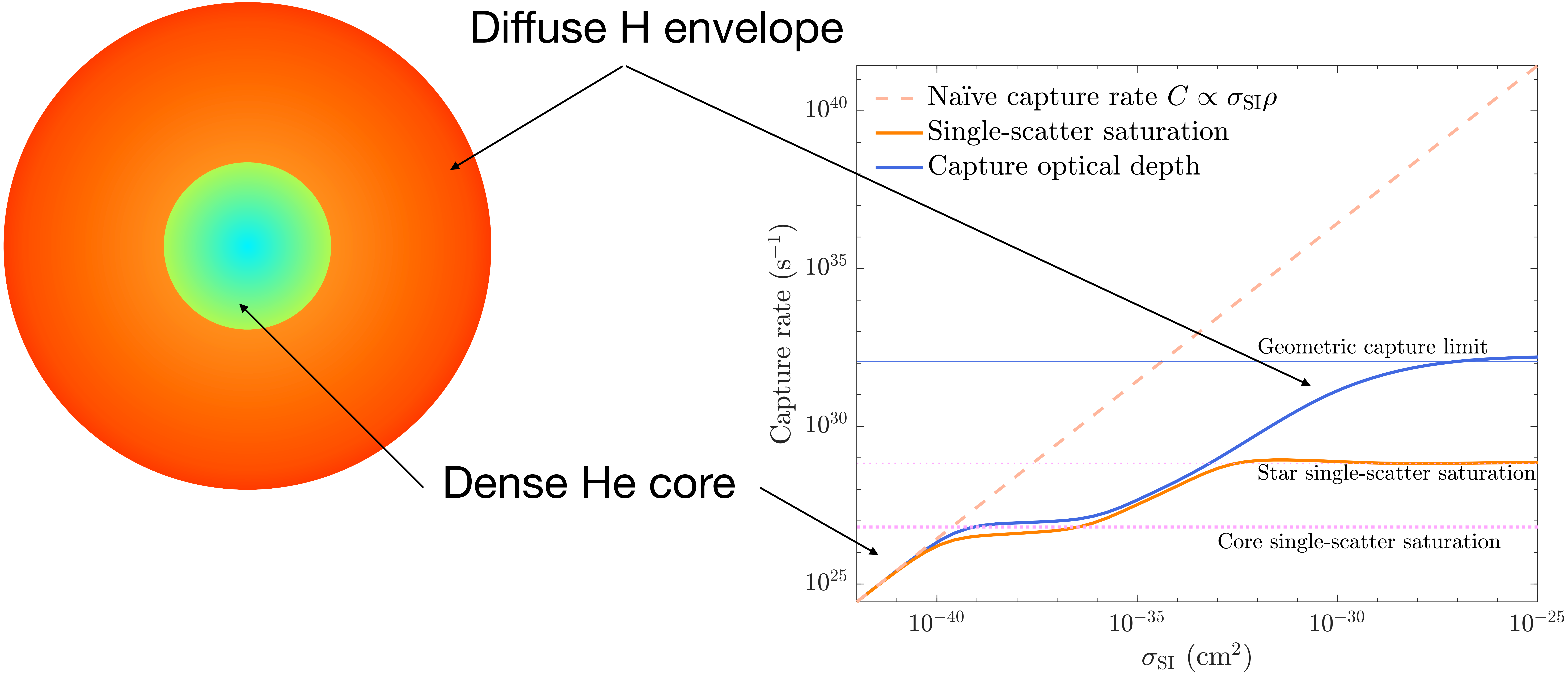
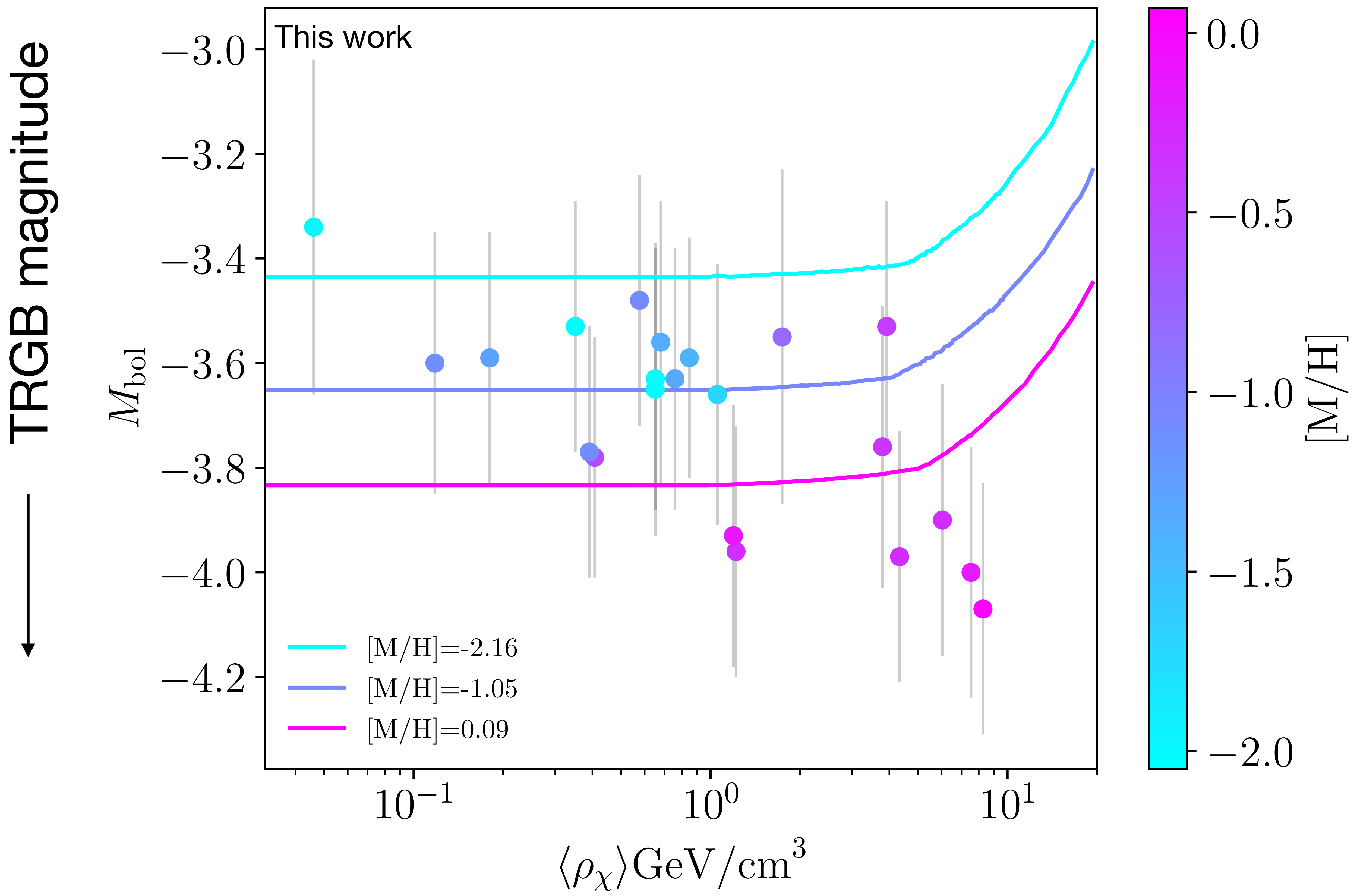
Use **optical depth** to *capture*

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

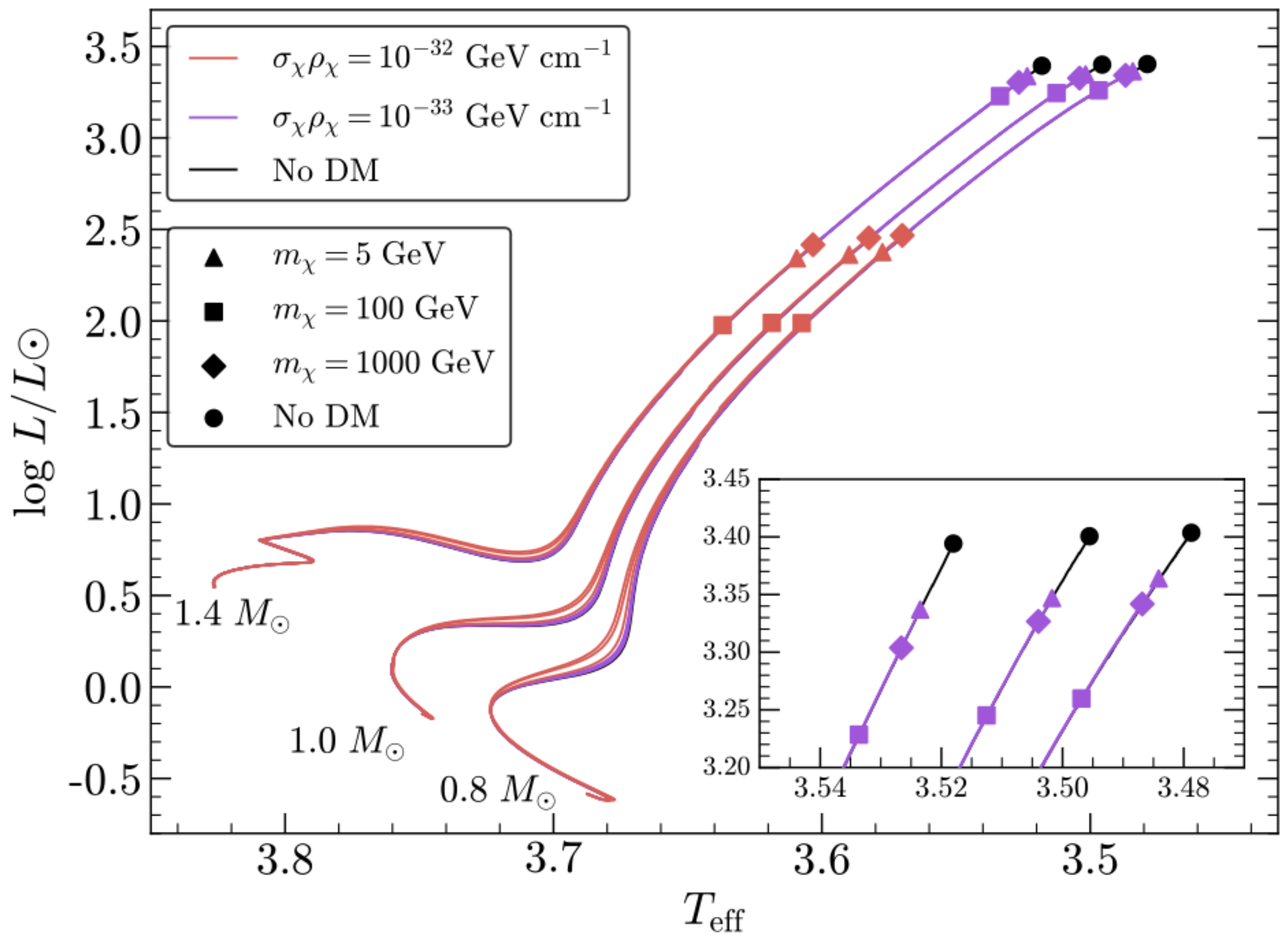
Dark matter capture & Saturation





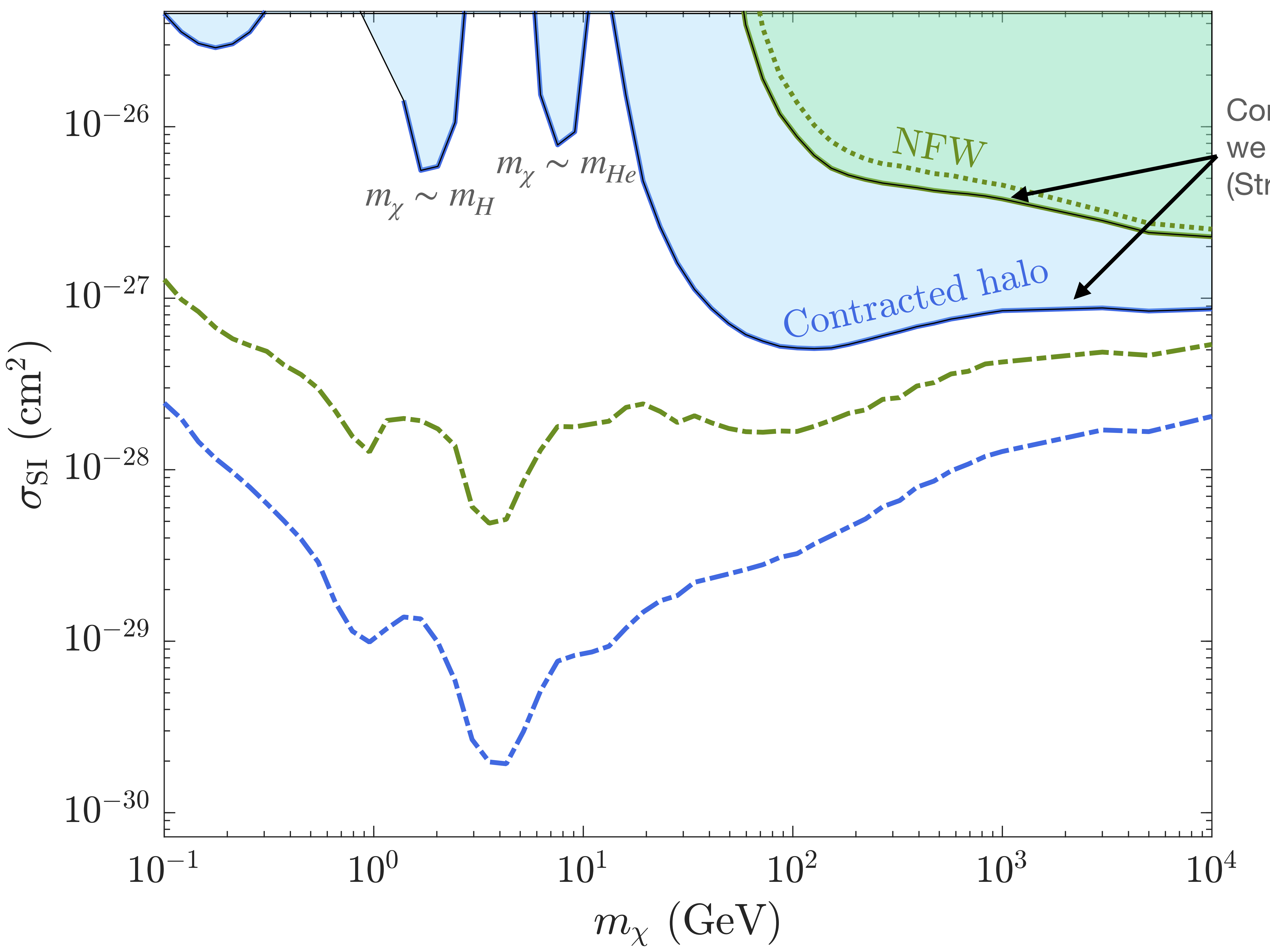
Cluster exposure to dark matter

Lopes & Lopes 2107.13885



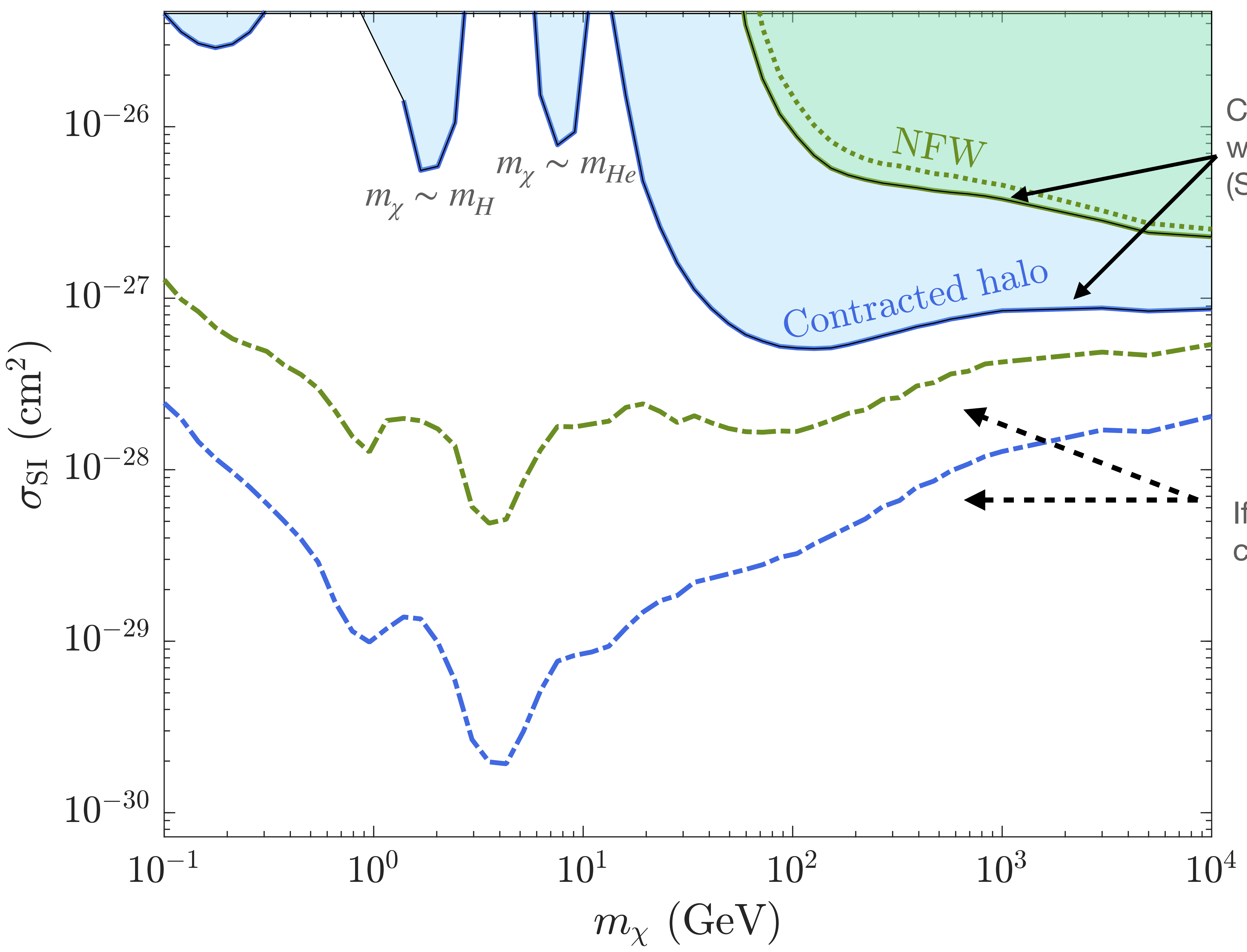
Now we can compare predicted luminosities as a function of DM mass and cross section to the measured ones and extract a limit

Limits



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

Limits



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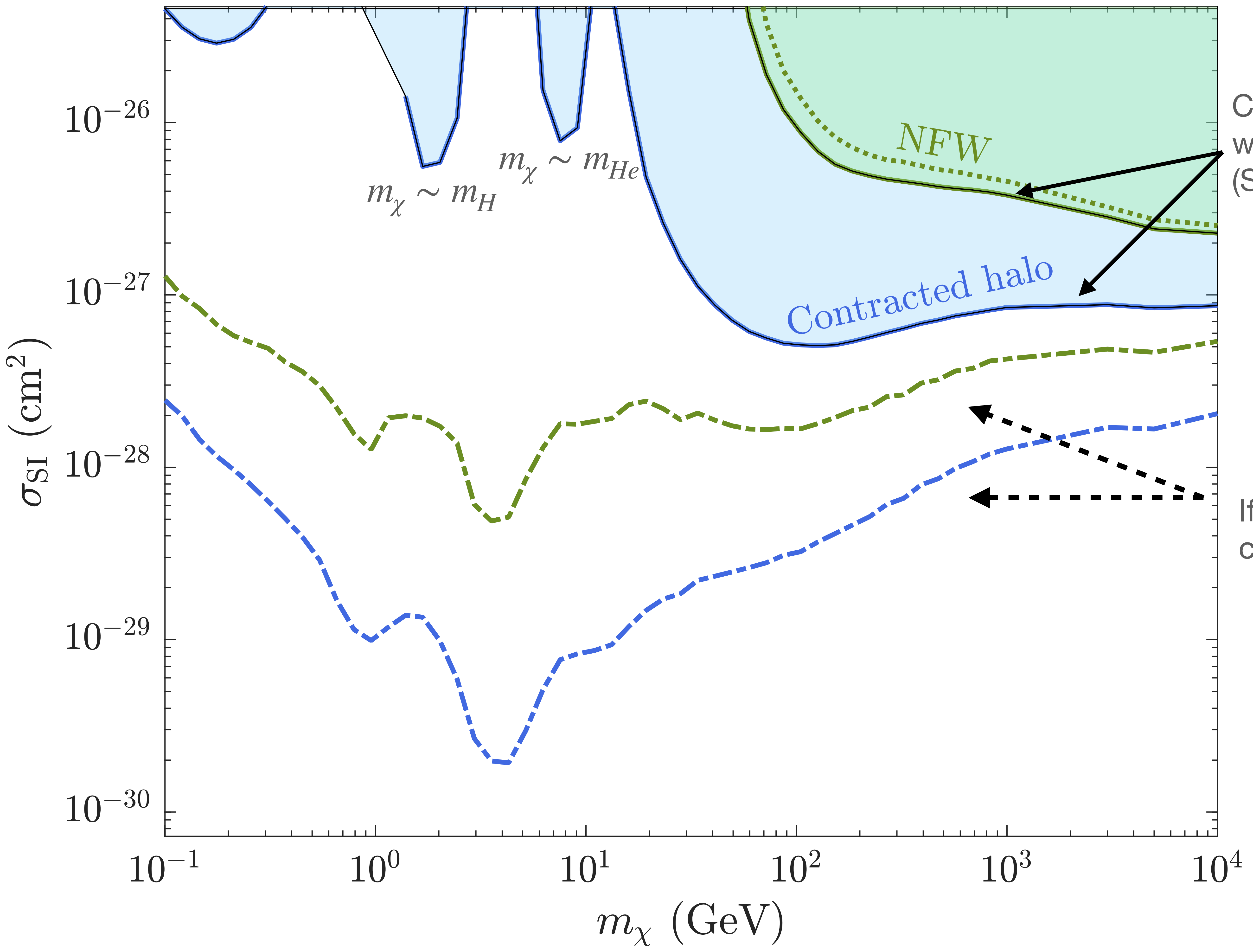
If we had TRGB magnitudes for all 161 clusters with 10x smaller errors

Limits

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



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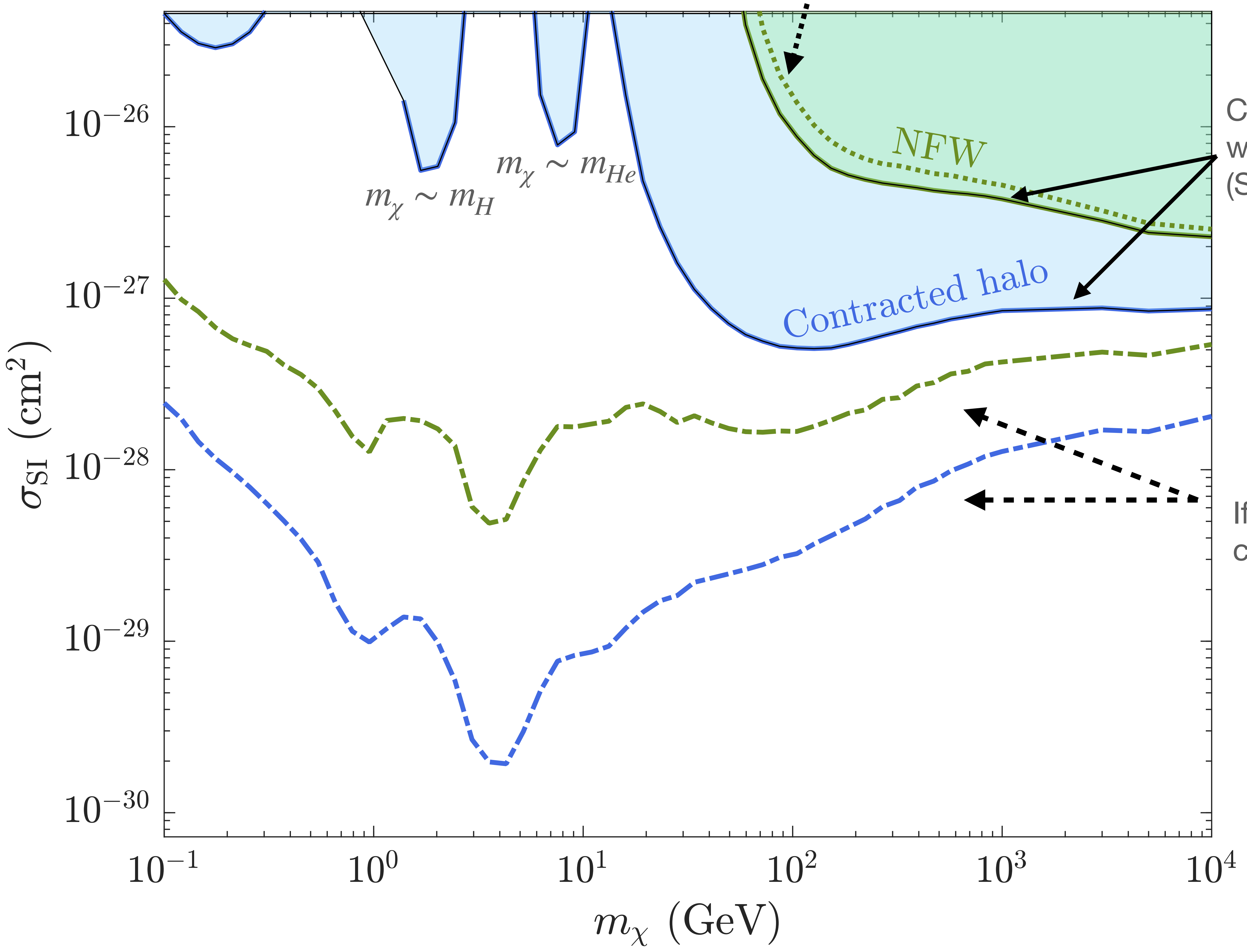

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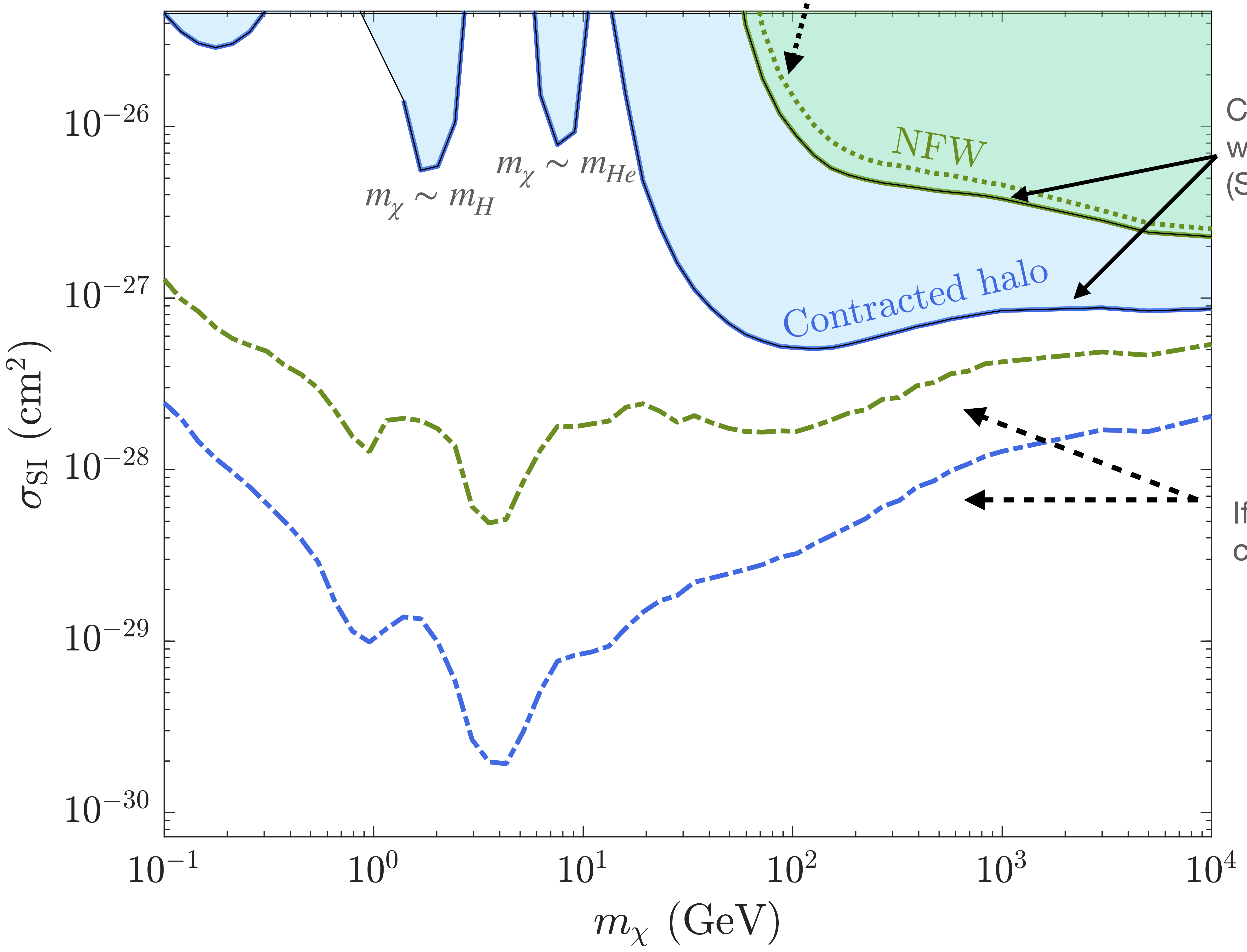

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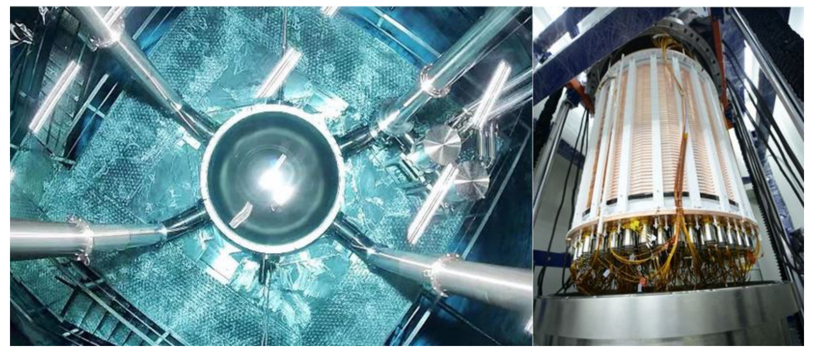


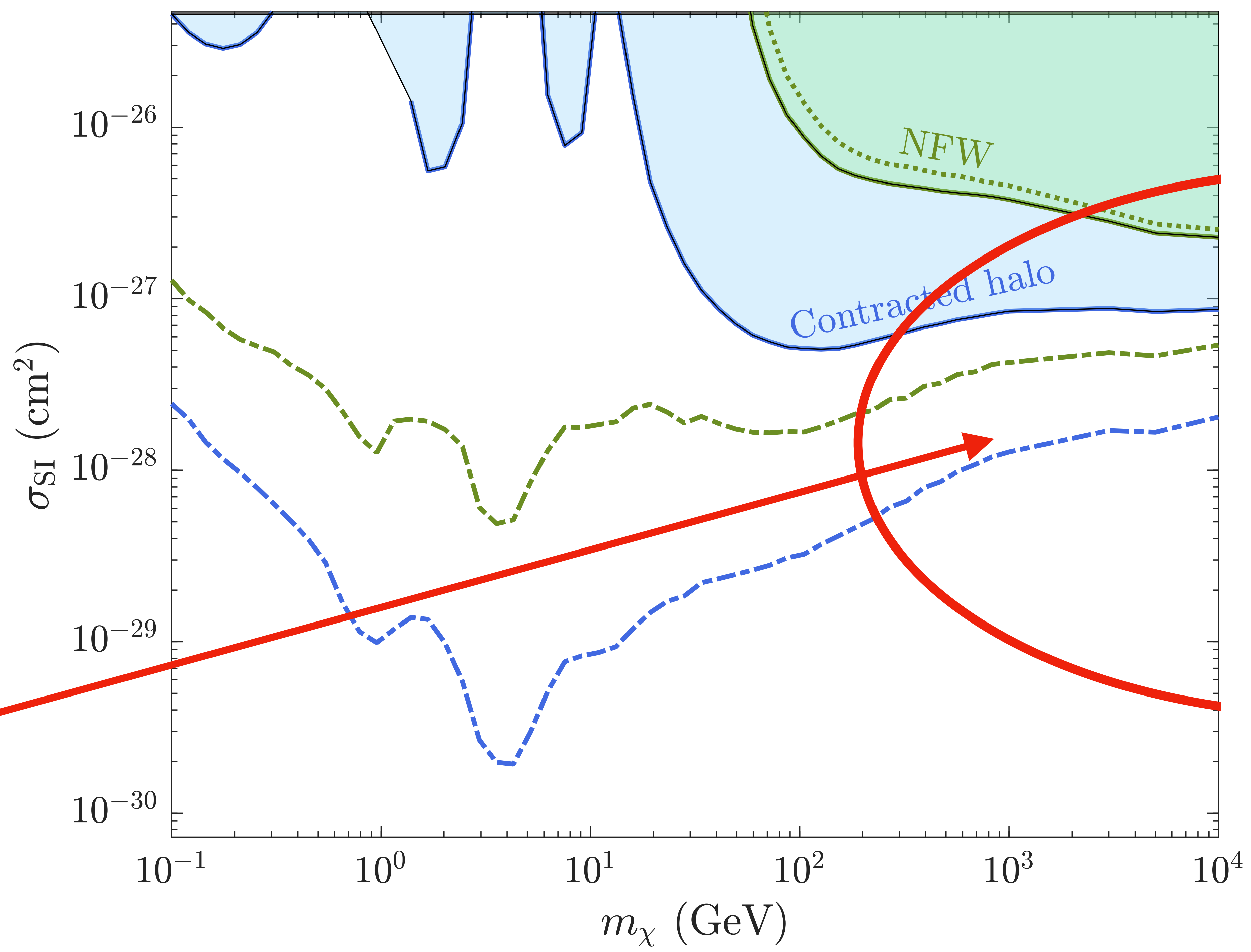
PandaX-4T →

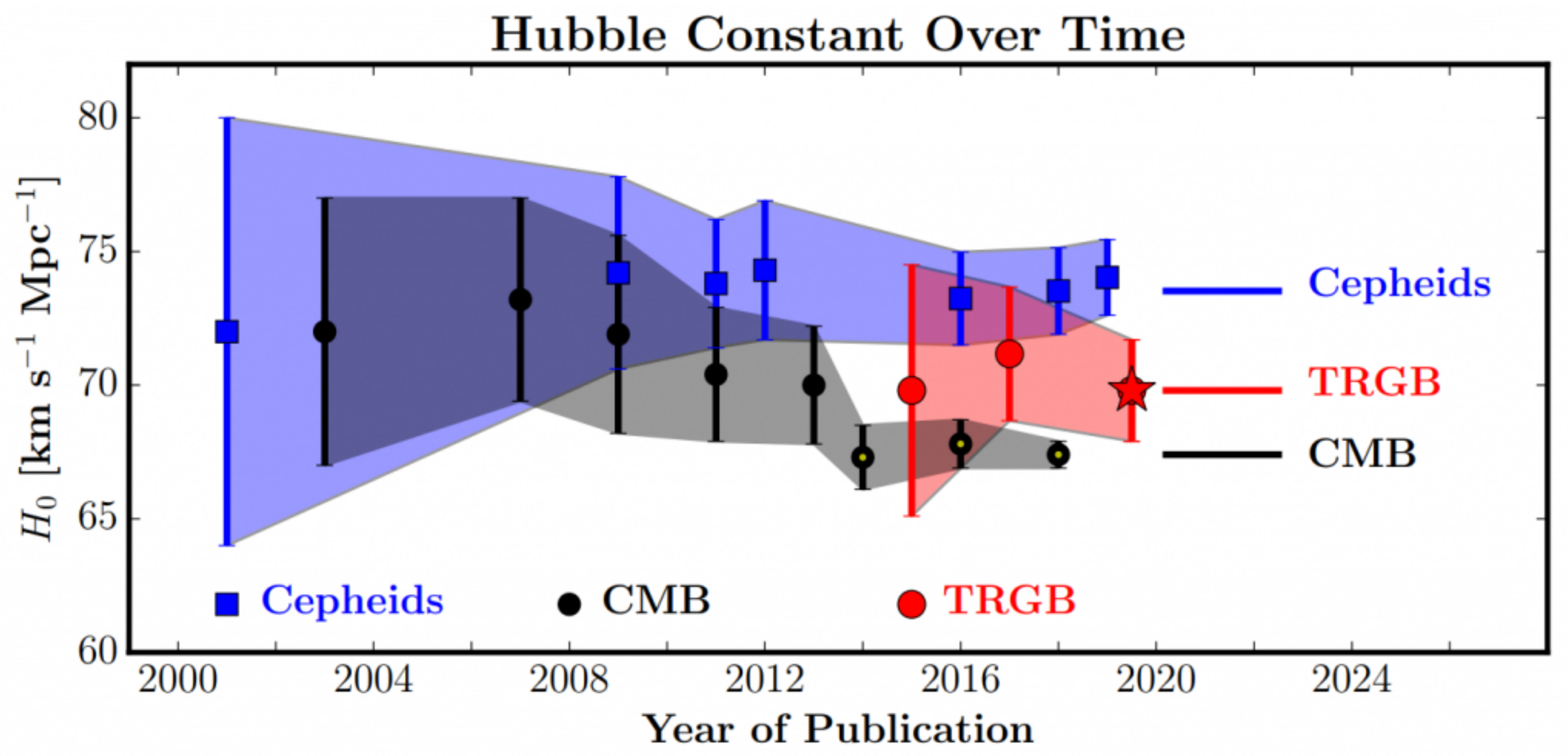

You are without doubt the worst
dark matter limit I've ever heard of.
But you have heard of me.

So what have we learned?

Dark matter effects on the TRGB

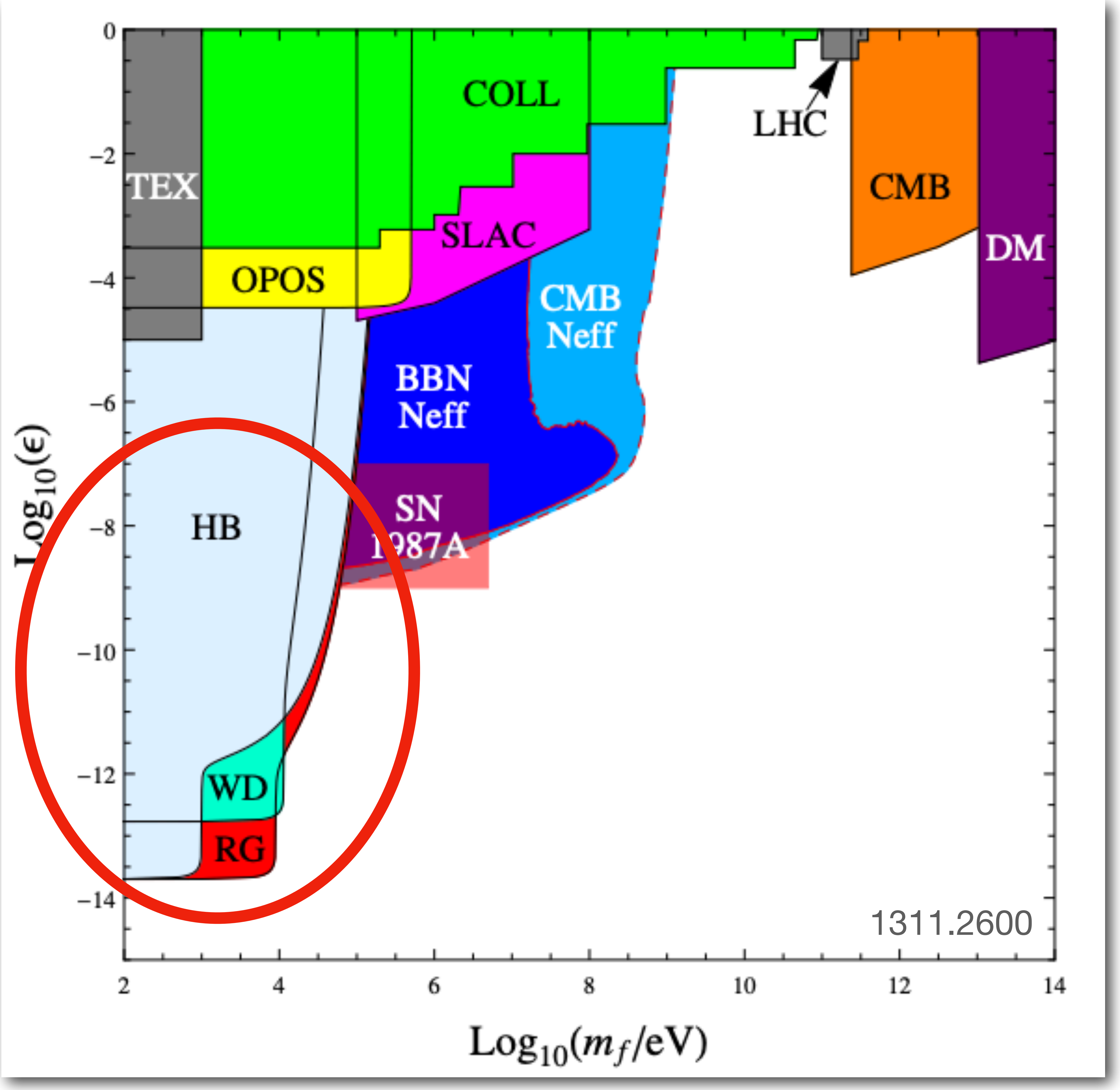
- You need a **lot** of dark matter to have a visible effect on the TRGB. More than the Milky Way seems to be telling us it contains
- Some space now closed if **local** DM is underabundant?
- Spin-independent dark matter-nucleon cross section limits that are **independent of any Earth/Sun-related systematics**
- 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.





II. Plasmon decay in the RGB

“millicharged” particles



fractional electric charge q (same as ϵ)

$$\mathcal{L} \supset qe\bar{\chi}\gamma_\mu\chi A^\mu + \bar{\chi}(i\gamma^\mu\partial_\mu - m)\chi$$

Plug: for bounds from atmospheric production see Wu, Hardy, Song 2406.01668

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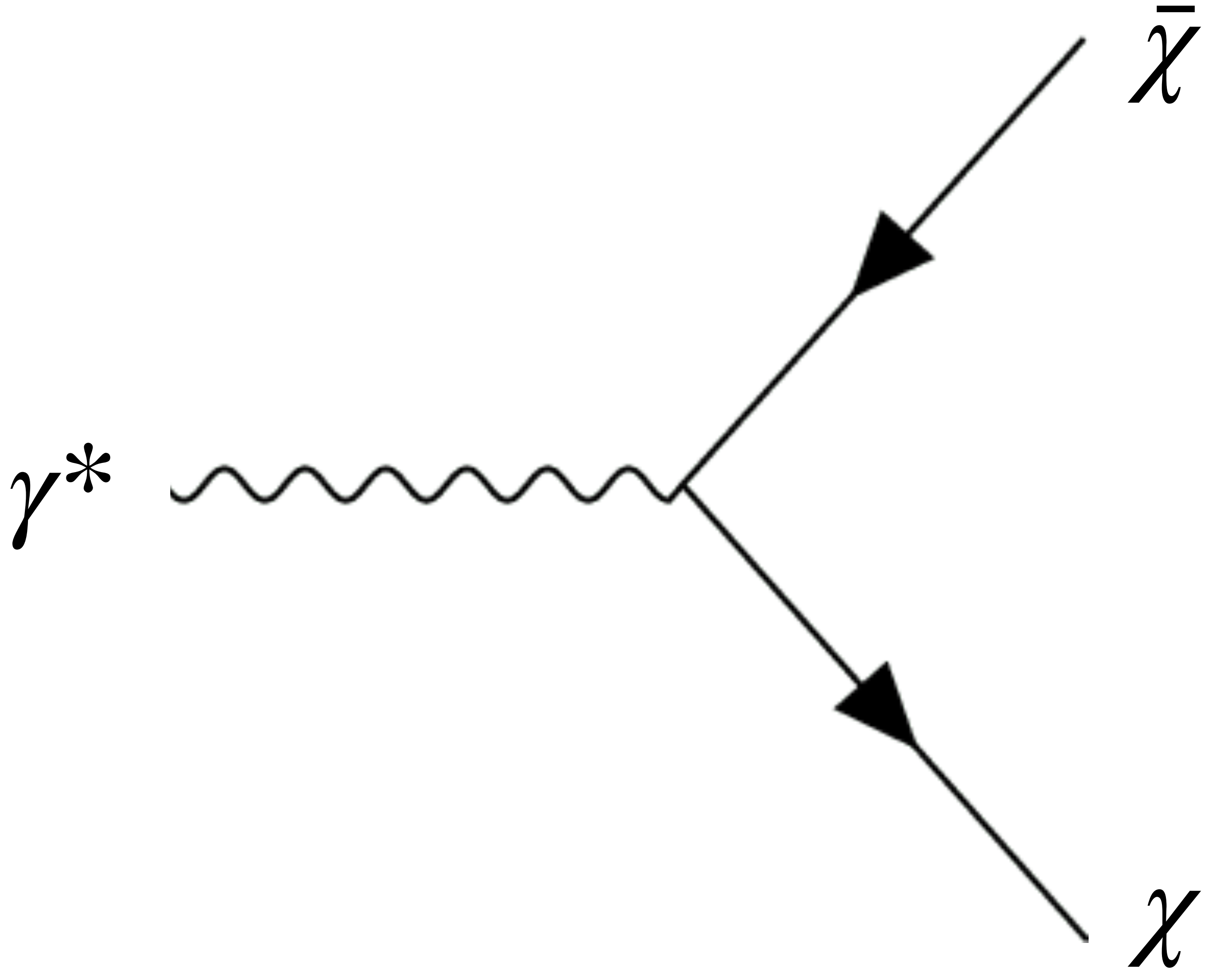
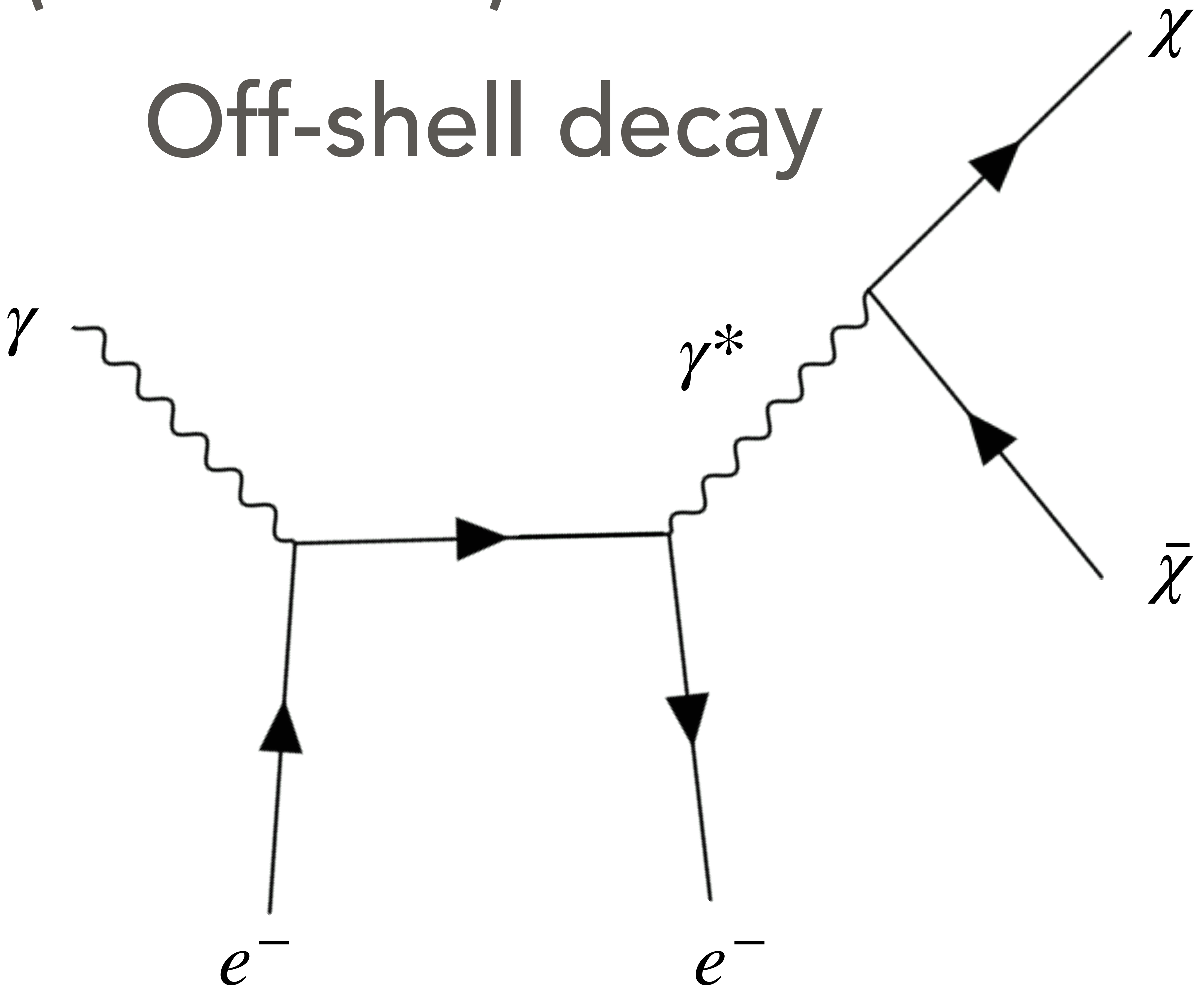
I. PLASMON DECAY → (FERMIONIC) MCP

On-shell decay



Off-shell decay



longitudinal: $\omega_L = \omega_p$

Transverse: $\omega_T^2 = k^2 + \omega_p^2$

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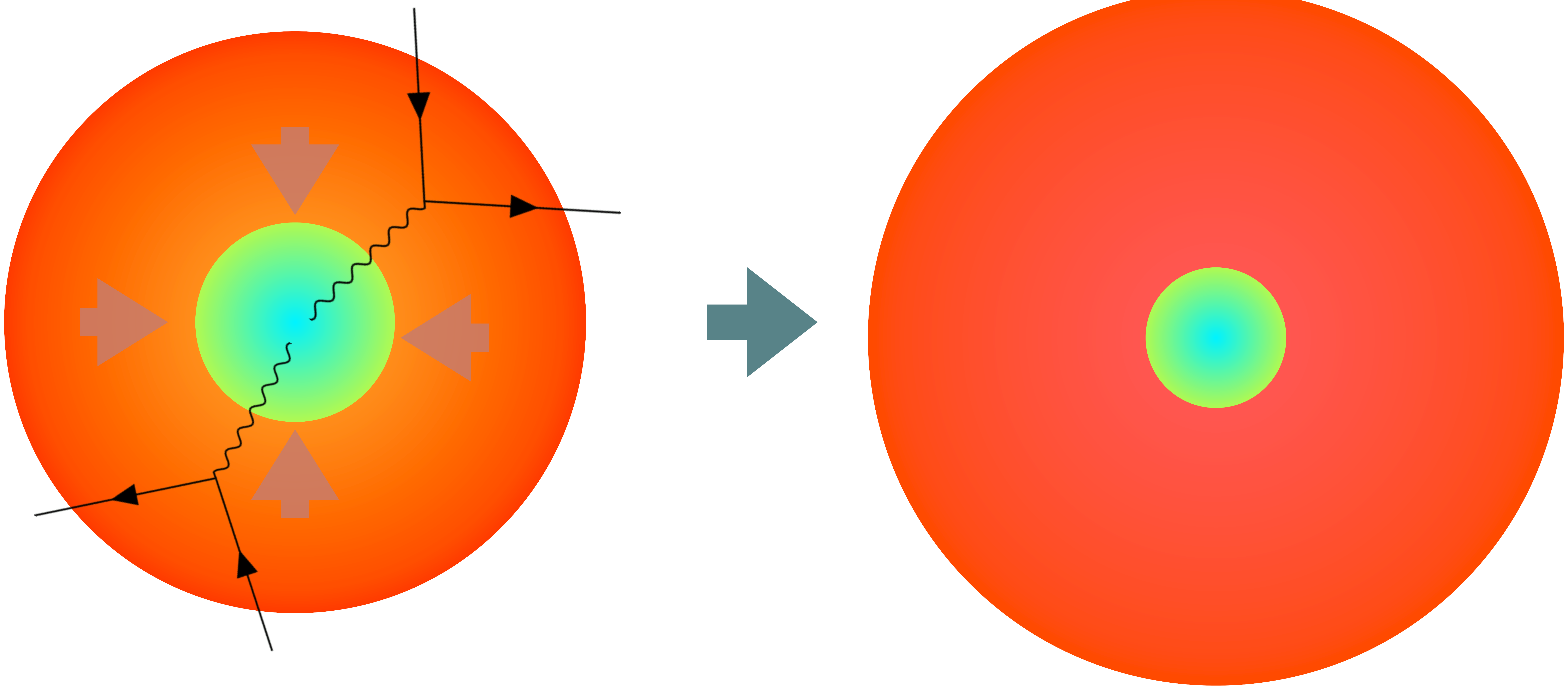

When the plasma frequency allows $A_\mu \to \chi\bar{\chi}$ weakly interacting particles can be produced and escape

This means the core must accumulate more He before it is hot enough to ignite

Note: plasmon decay to **neutrinos** is a SM process that already does this!

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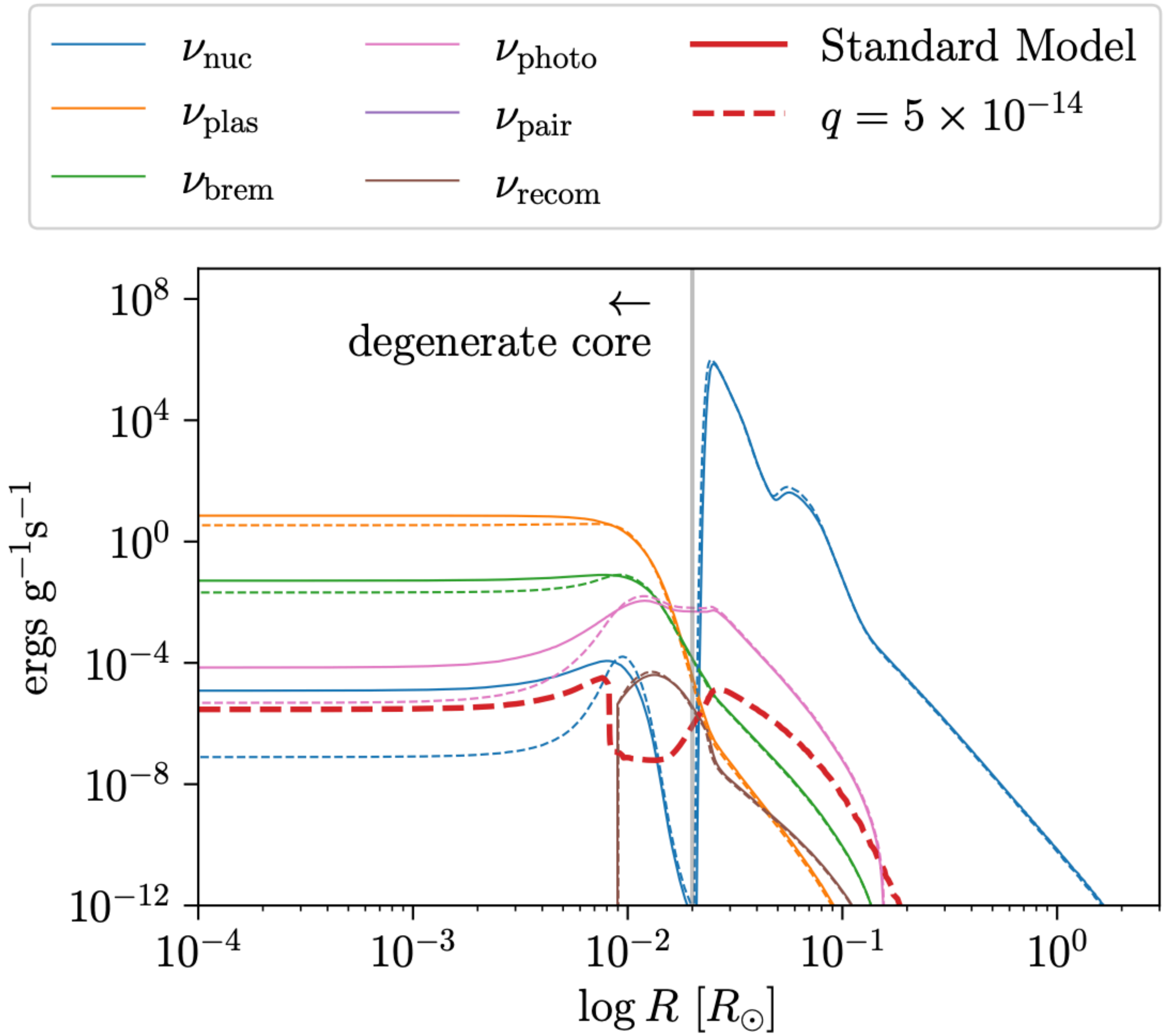
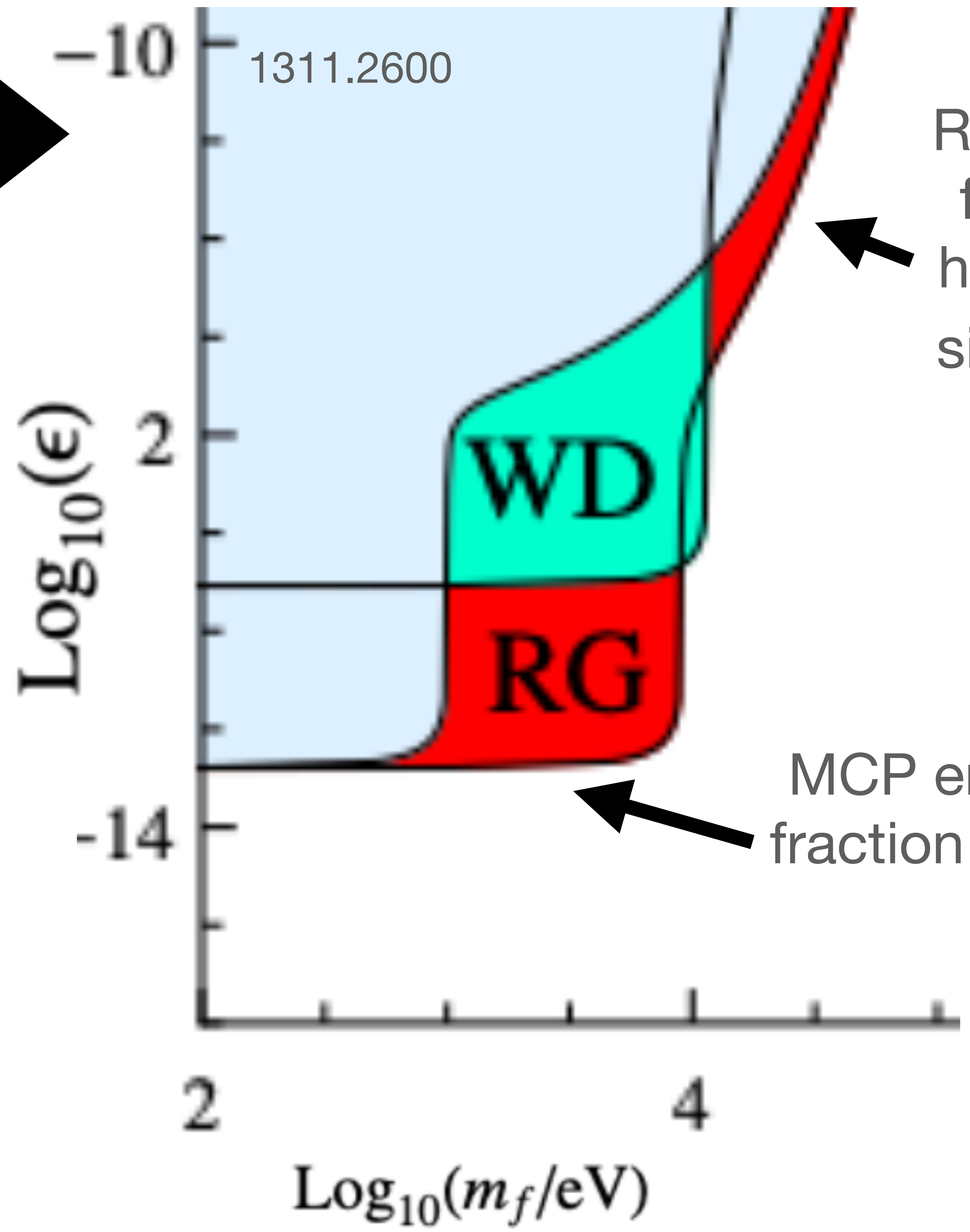
Previous work





Rescale this to account for virtual emission at higher mass (assuming single T, ω_{pl} in the star)

MCP energy loss shouldn't be an O(1) fraction of the predicted core luminosty (Raffelt, 1990's)

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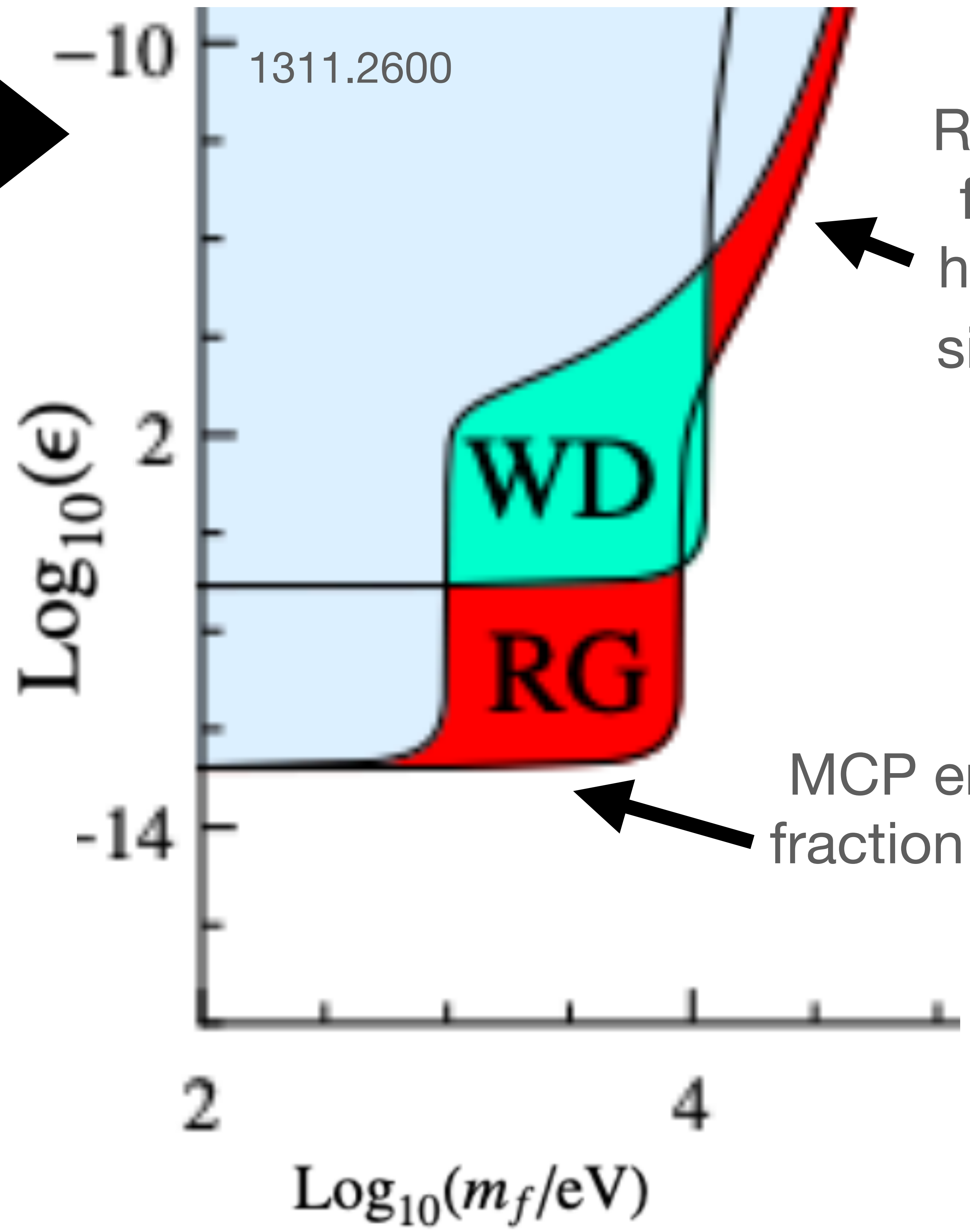
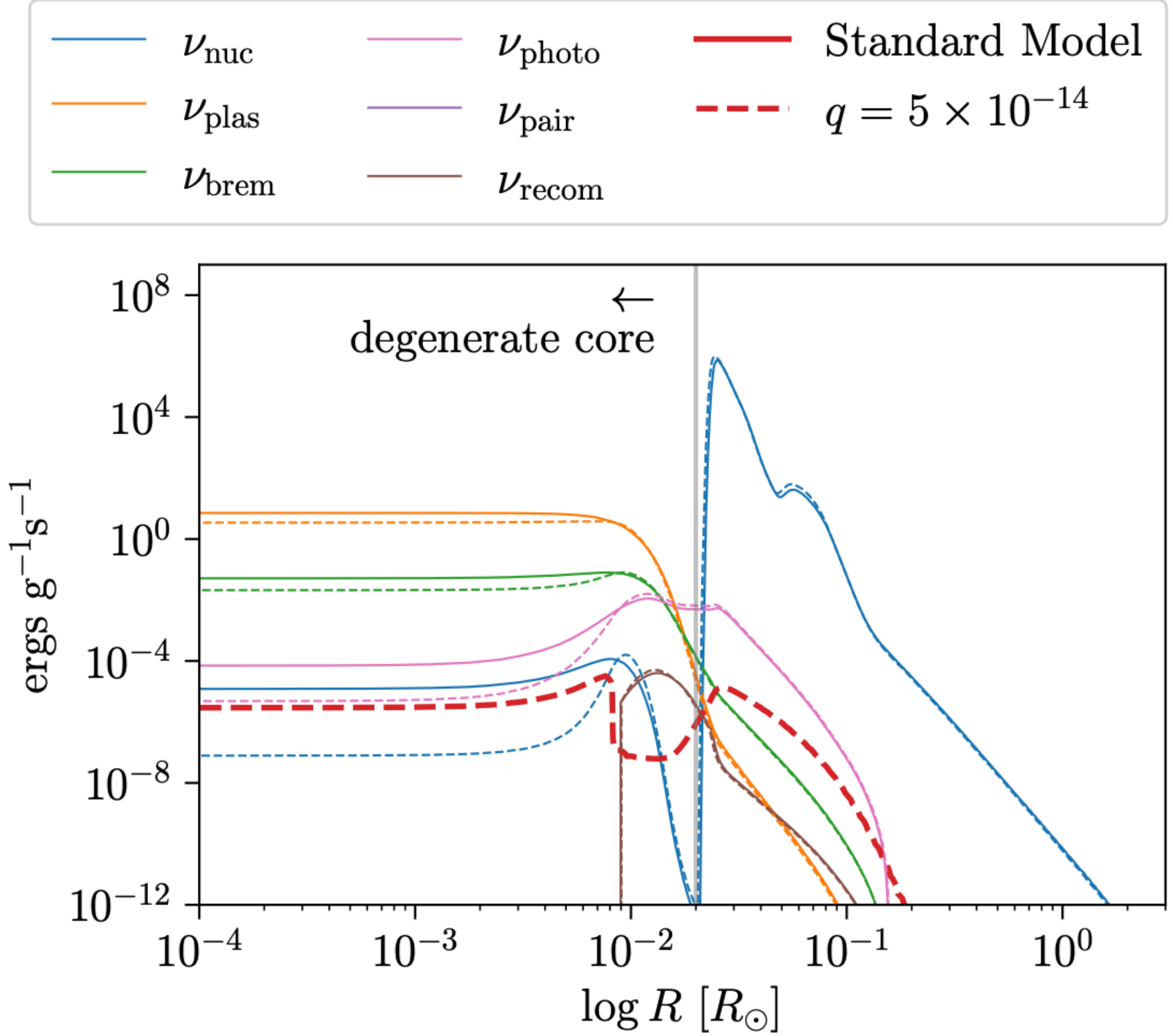
Previous work



Rescale this to account for virtual emission at higher mass (assuming single T, ω_{pl} in the star)

MCP energy loss shouldn't be an O(1) fraction of the predicted core luminosty (Raffelt, 1990's)



No modeling of the star's reaction!
No data!

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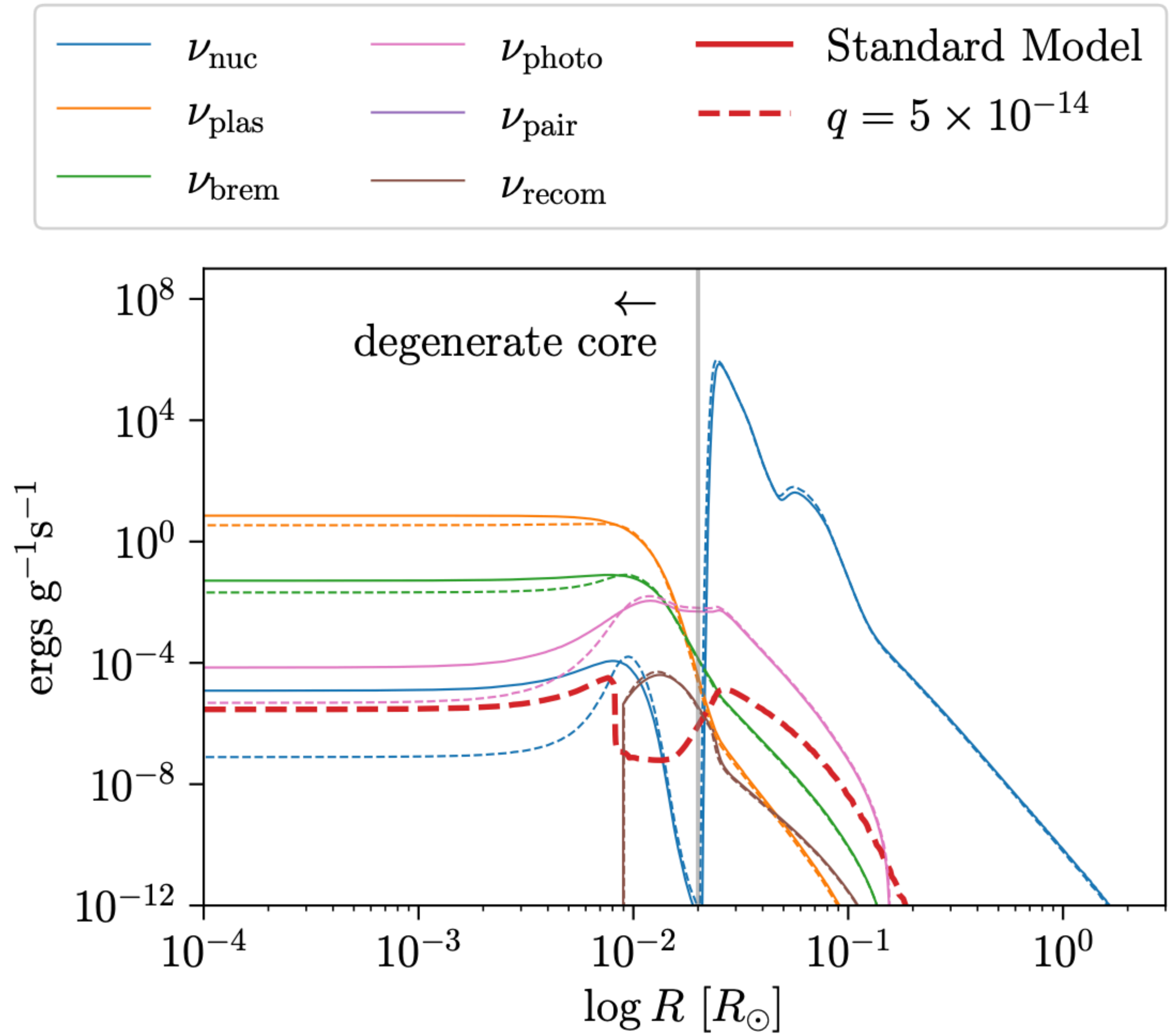
Previous work



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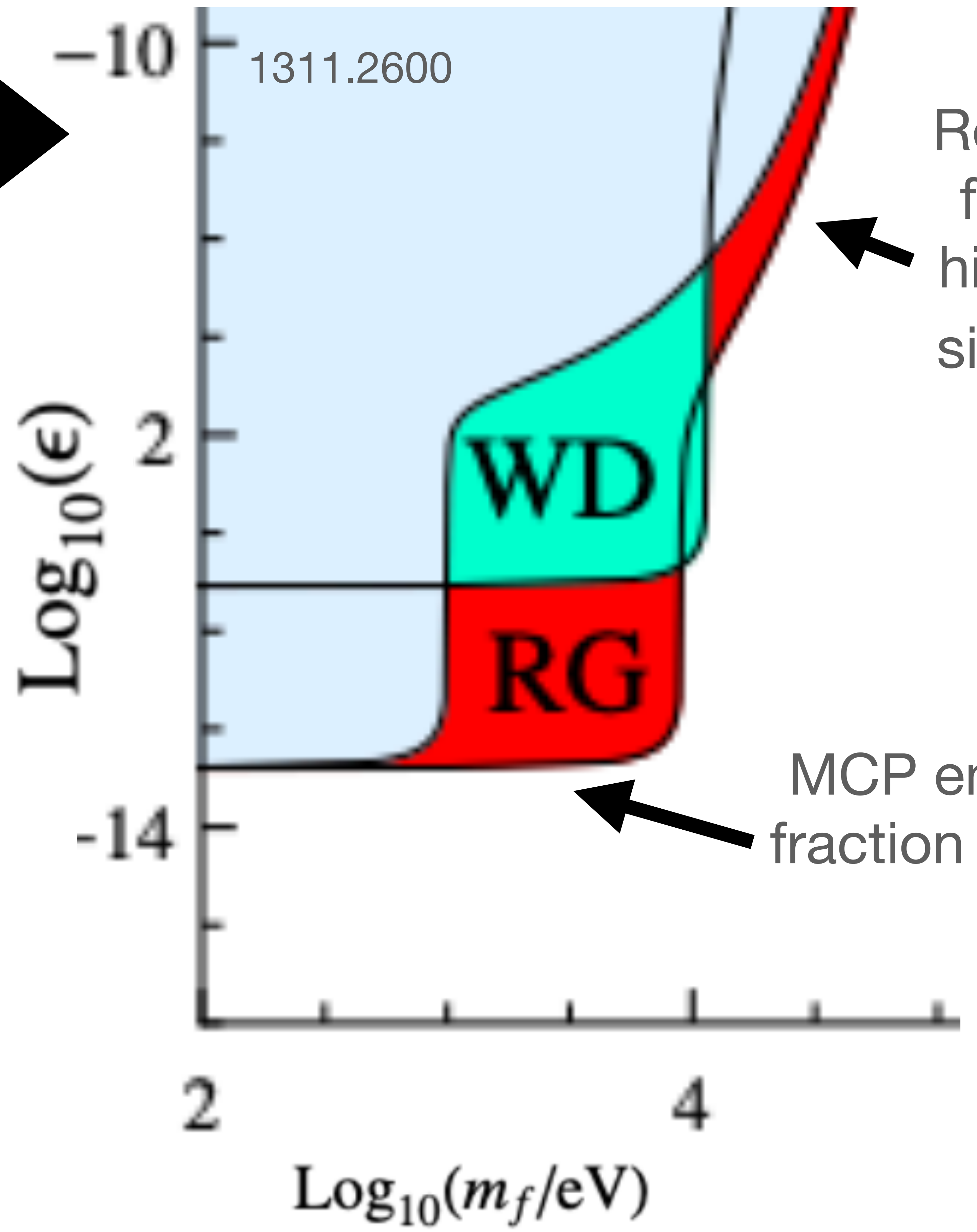


Rescale this to account for virtual emission at higher mass (assuming single T, ω_{pl} in the star)

MCP energy loss shouldn't be an O(1) fraction of the predicted core luminosty (Raffelt, 1990's)

No modeling of the star's reaction! No data!

(but see Vinyoles & Vogel for solar constraints 1511.01122)

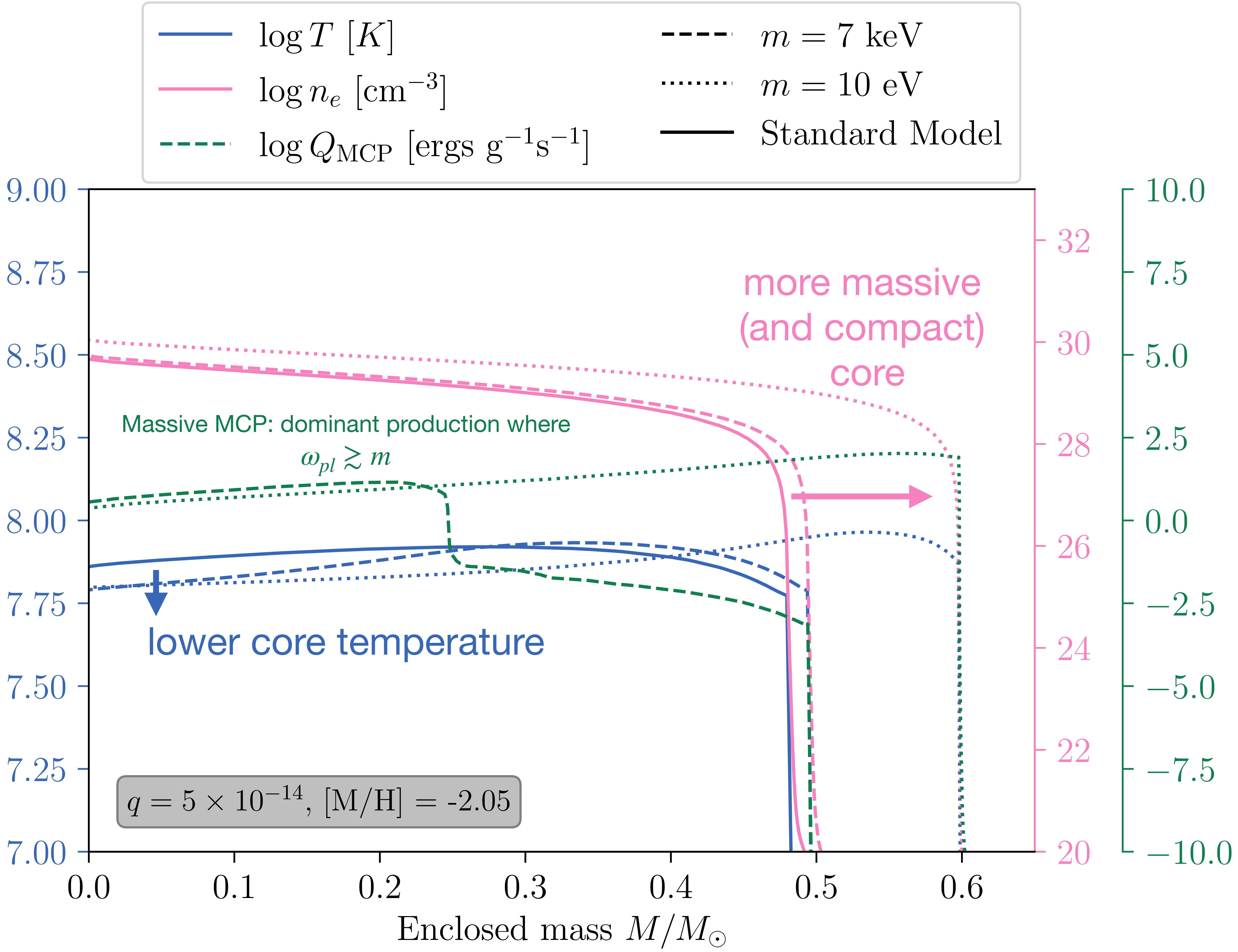
Mesa again:

- Model the energy loss from the presence of a new fractionally charged fermion
- Evolve stars up the red giant branch

Gaia again:

- Use the TRGB measurements compiled by Straniero et al. 2010.03833 (Gaia distances, HST/ground-based magnitudes)
- Note if MCPs are affecting the TRGB, it remains a standard candle

At the TRGB:

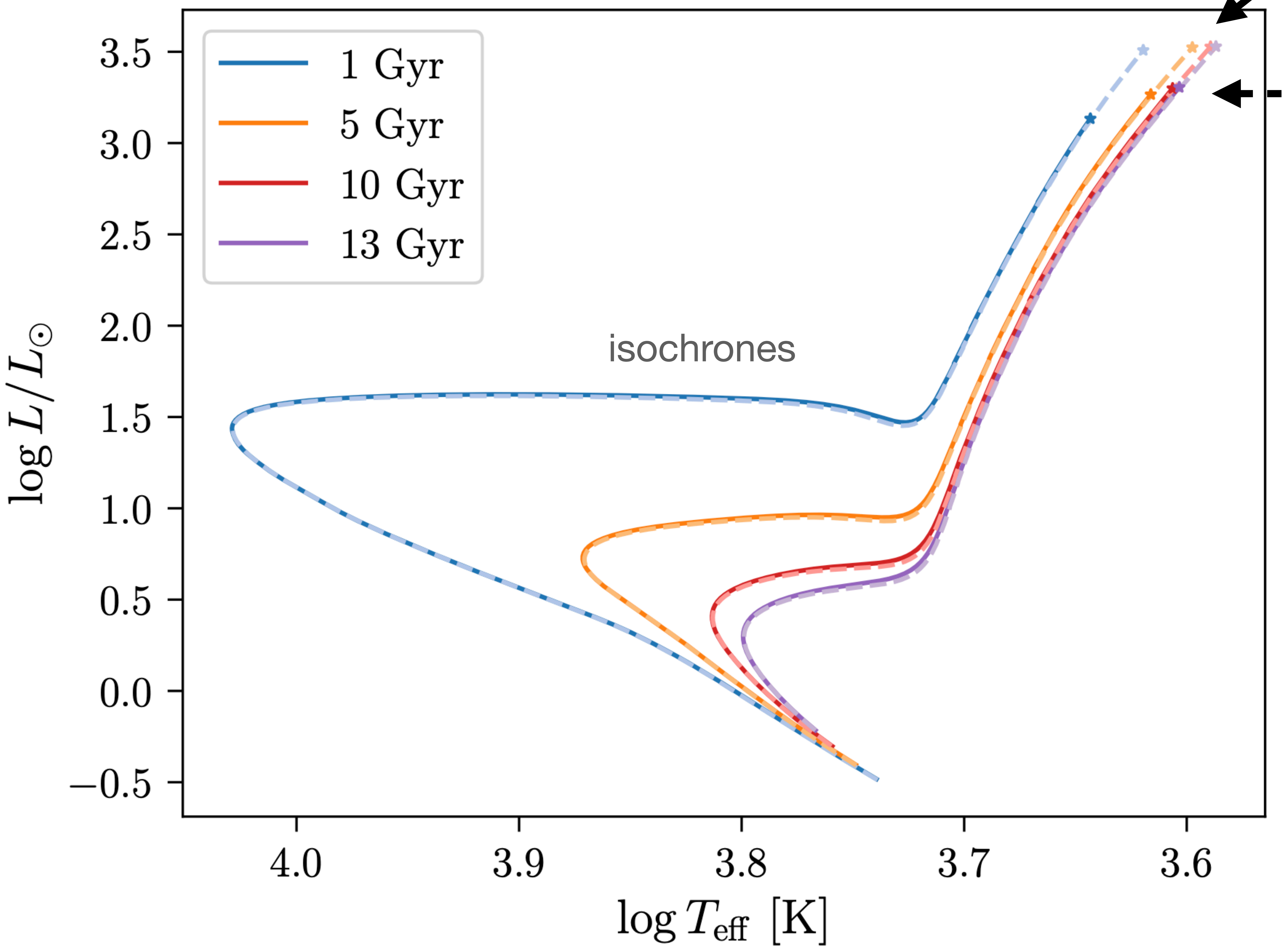


$\log T\ [K]$
$\log n_e\ [\mathrm{cm}^{-3}]$
$\log Q_{\mathrm{MCP}}\ [\mathrm{ergs\ g^{-1}s^{-1}}]$
$m = 7$ keV
$m = 10$ eV
Standard Model
9.00
8.75
8.50
8.25
8.00
7.75
7.50
7.25
7.00
32
30
28
26
24
22
20
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
more massive (and compact) core
Massive MCP: dominant production where $\omega_{pl} \gtrsim m$
lower core temperature
$q = 5 \times 10^{-14}$, [M/H] = -2.05
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Enclosed mass $M/M_\odot$

Globular clusters again

with MCP emission:
$m = 10$ eV
$q = 2 \times 10^{-14}$

standard evolution



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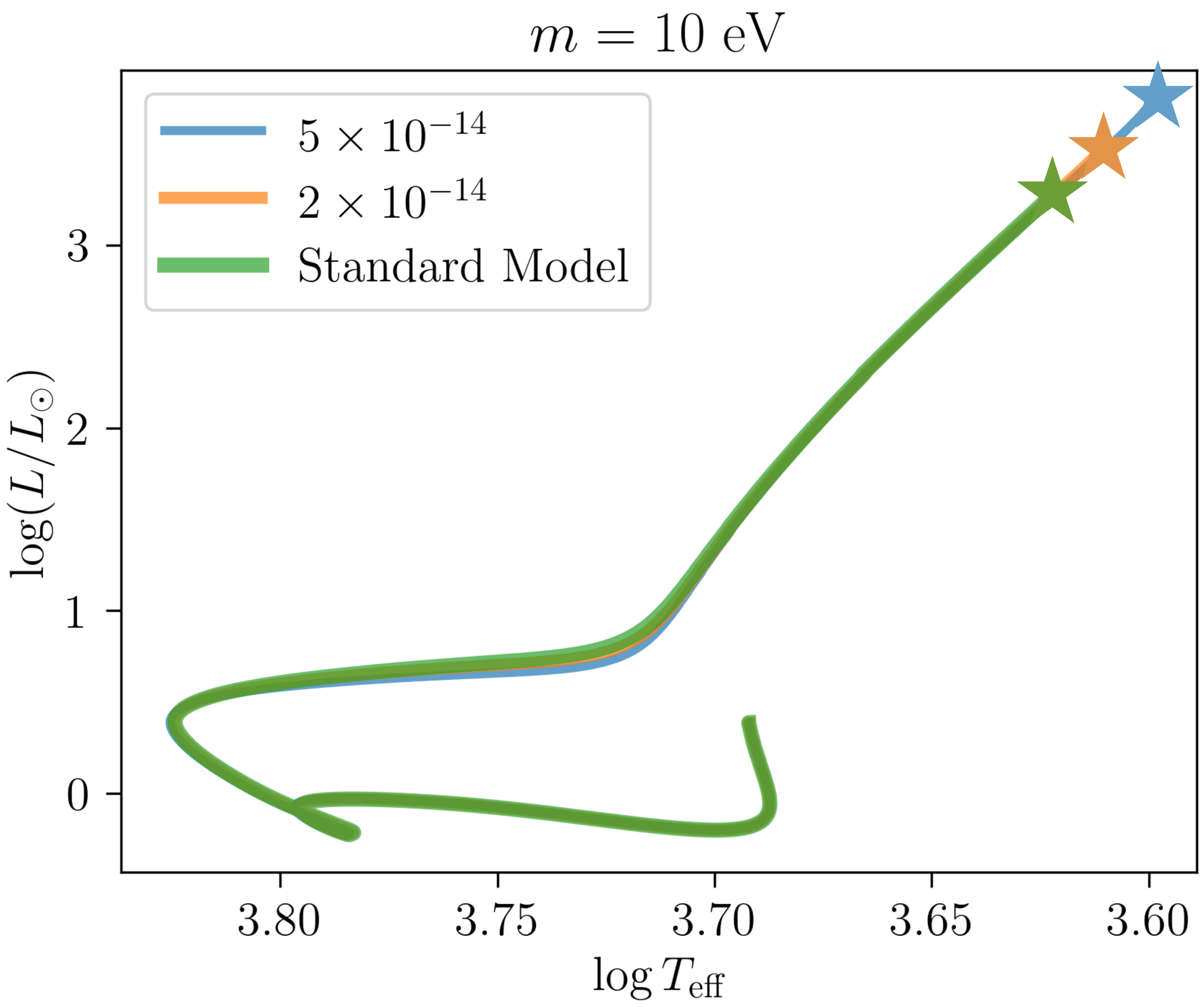

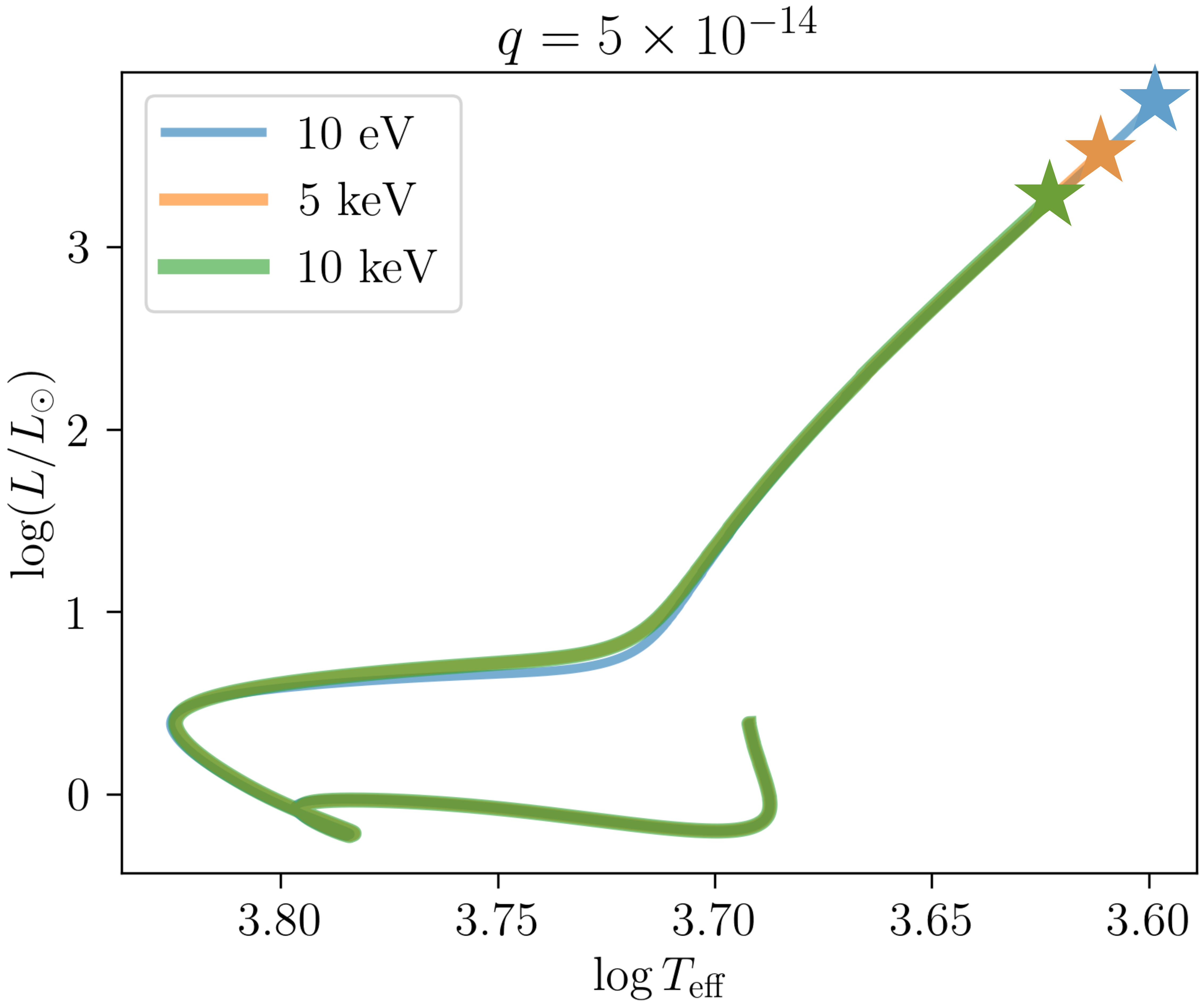

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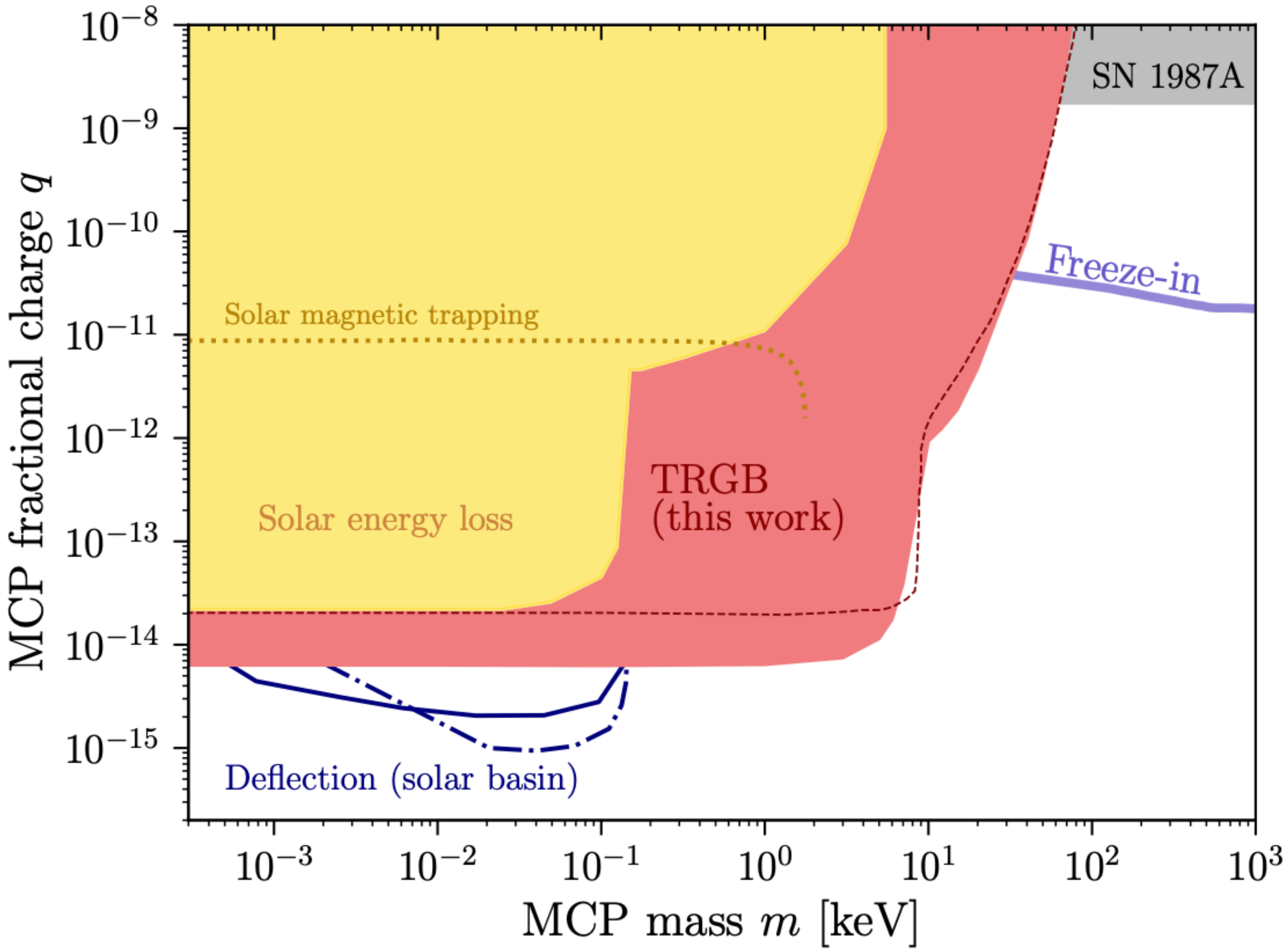
Combine MESA simulations & data:



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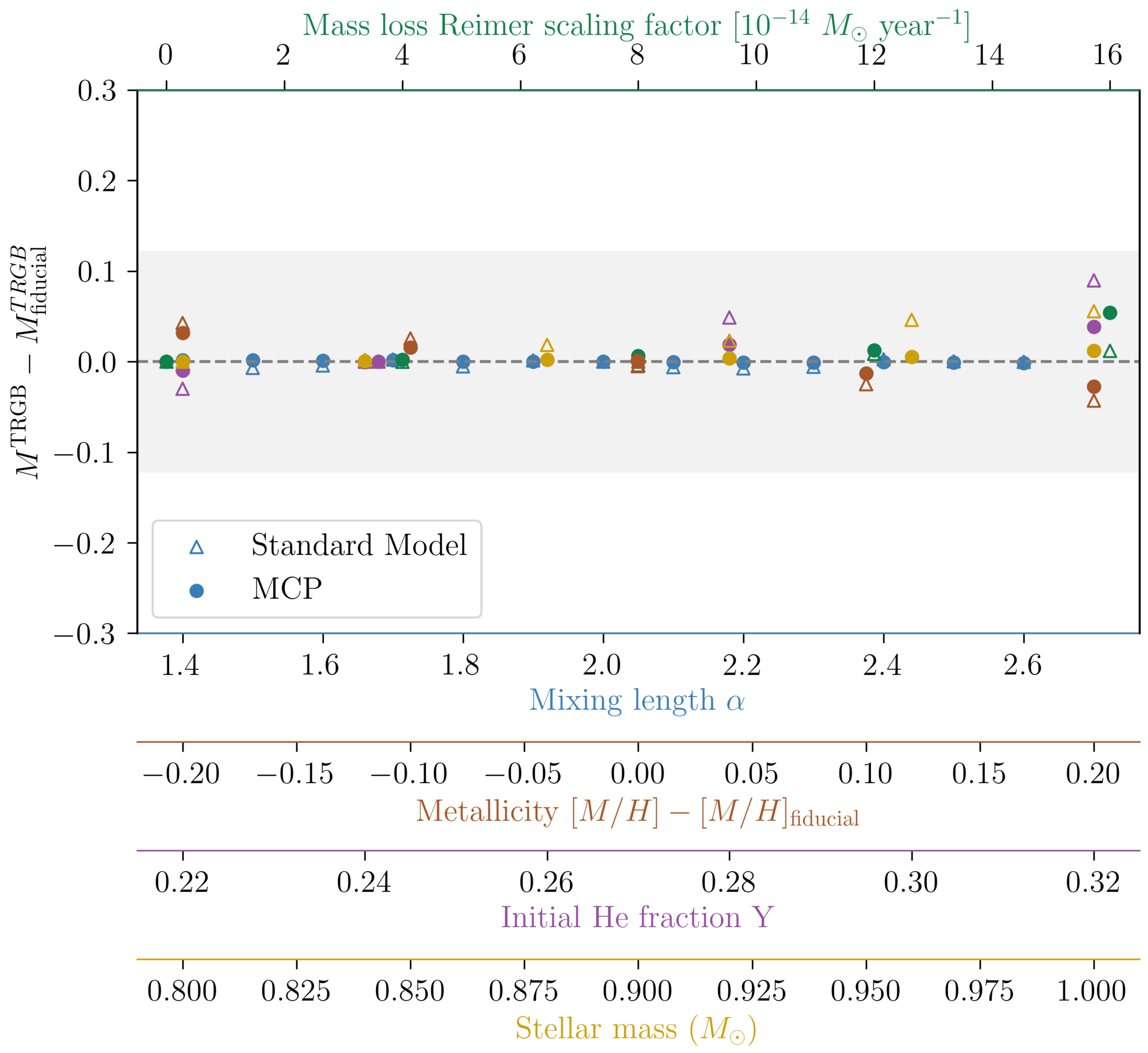
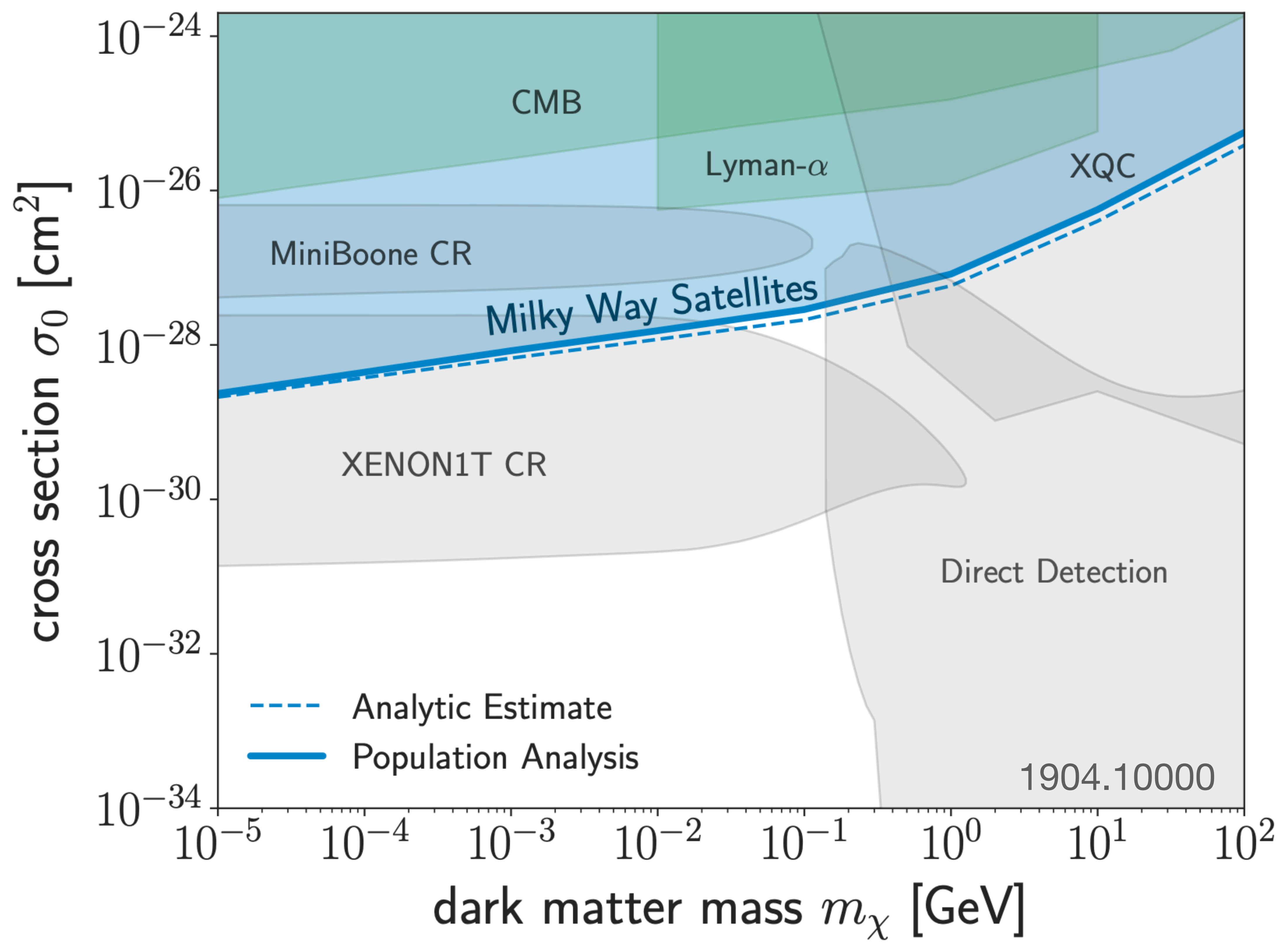
Concluding conclusions

- Tip of the red giant branch remains a competitive probe of new physics
- Sensitivity to dark matter limited by low densities
- Sensitivity to rare new physics processes thanks to hot, dense, core and insensitivity to most standard model nuisance parameters

Nuisance parameters




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}

$0.8M_\odot$ AT HE FLASH