Dark Matter Scattering Constraints From Stars Surrounding Sgr A*

arXiv:2311.16228 & arXiv:2405.12267

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Together with
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and
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Dark Tools
Turin

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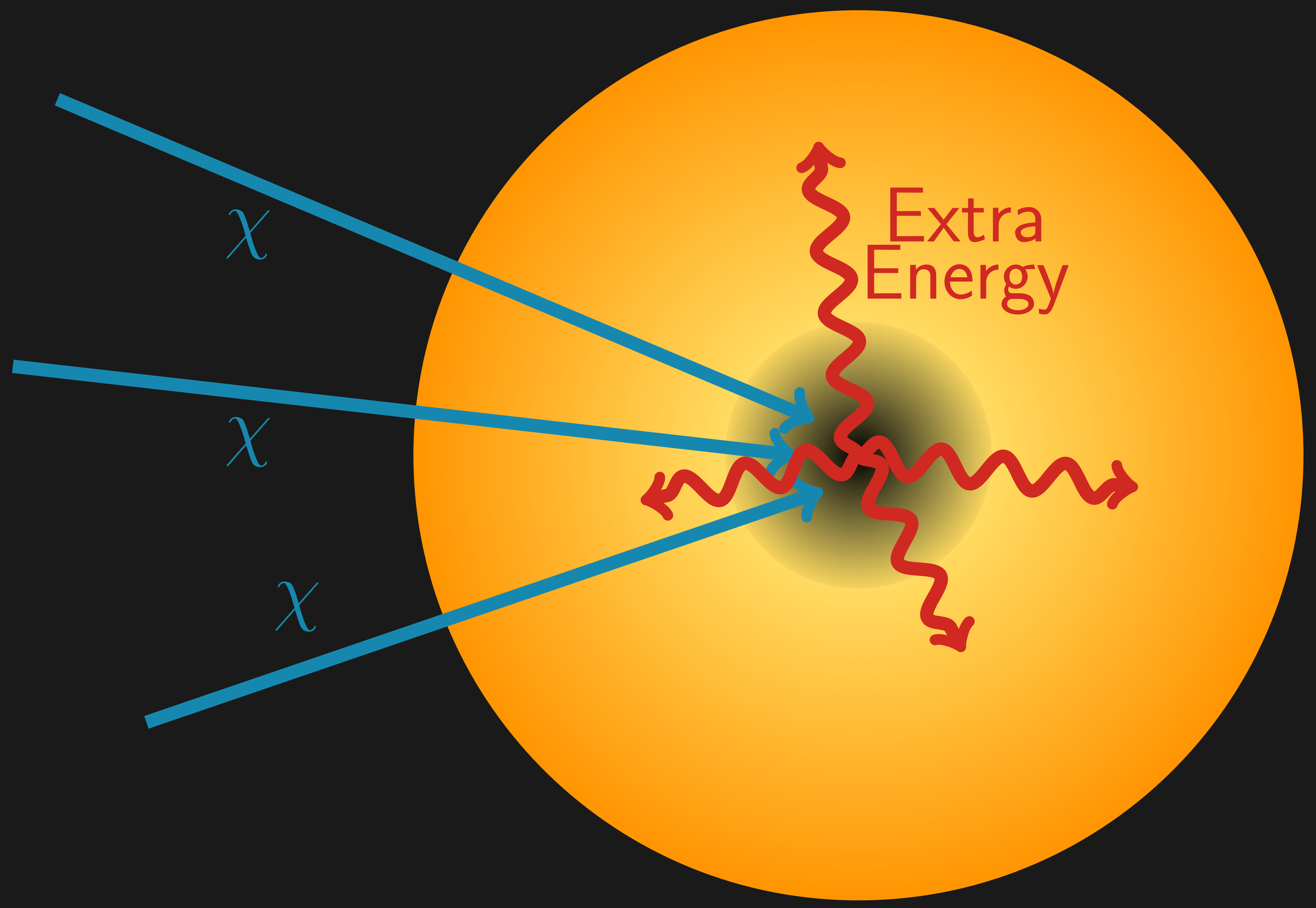
Dark Matter Capture in Celestial Bodies

Dark matter is captured and accumulates in the core, where it annihilates, acting as an additional energy source.

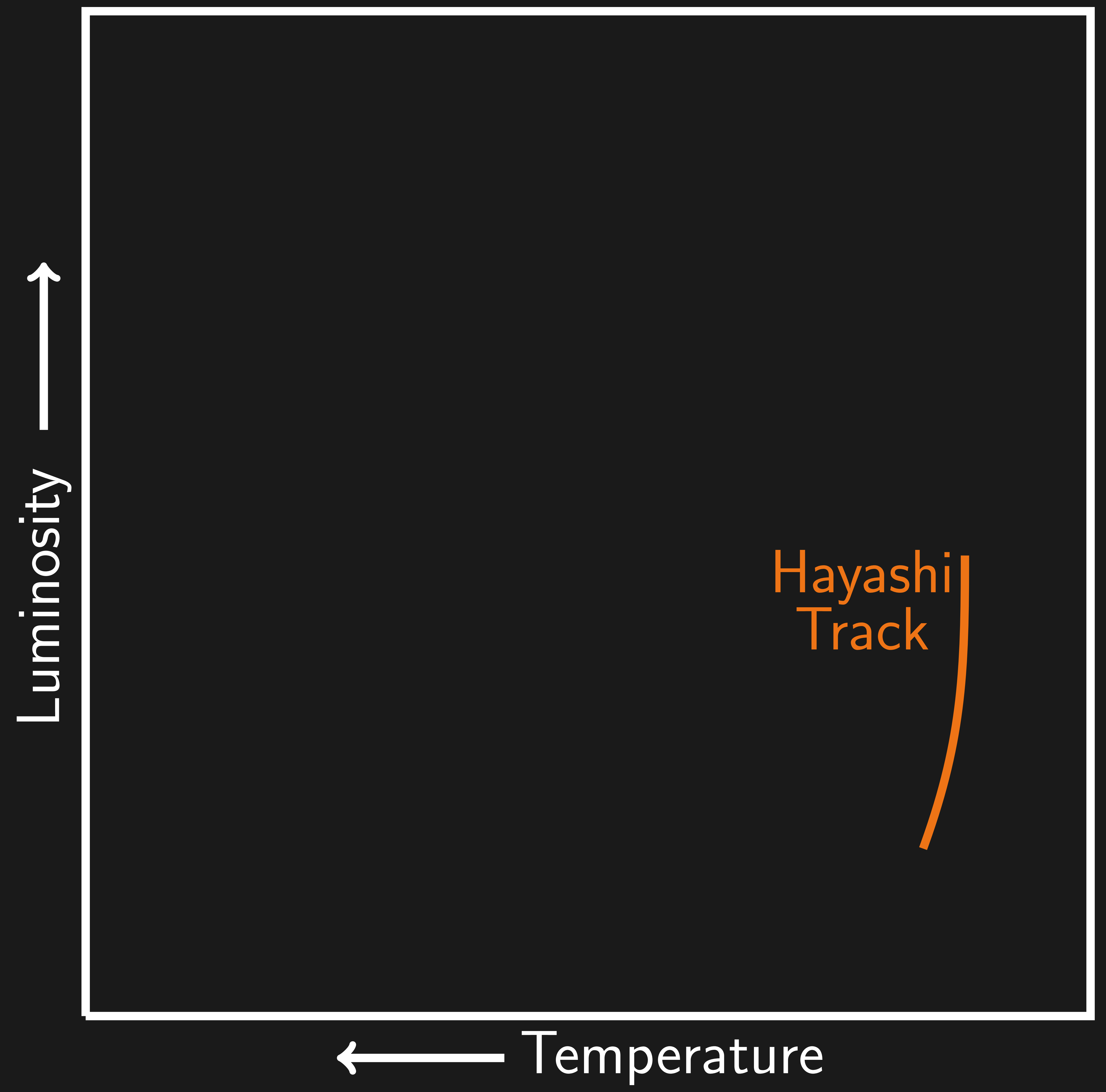


Dark matter assumptions:

- WIMP-like dark matter
- High dark matter density at Galactic Center — Stars around Sgr A*

Stellar Evolution Stages on HR Diagram

Hertzsprung–Russell (HR) Diagram



Hayashi track: newly forming star contracts

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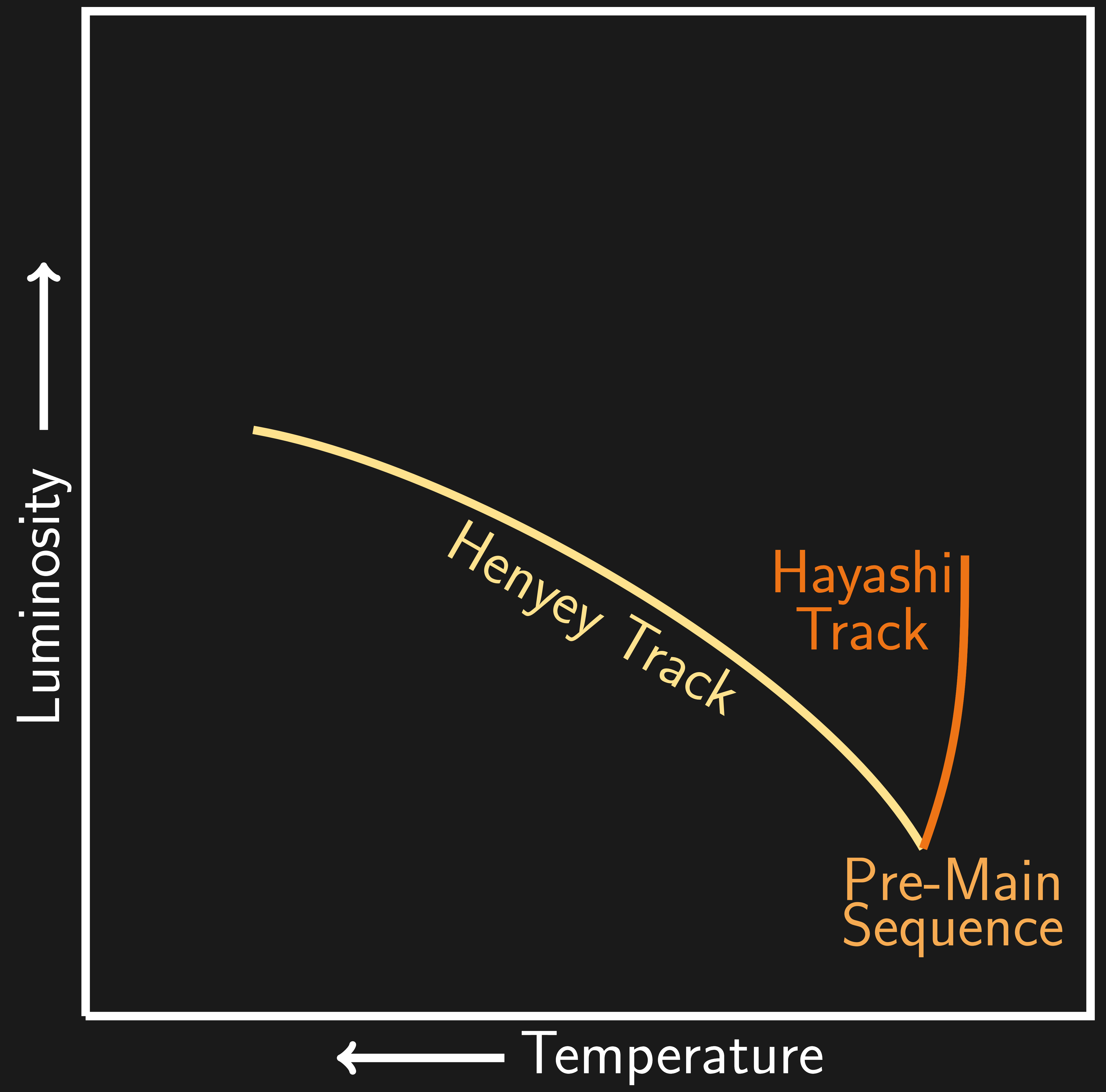

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Henyey track: hydrogen fusion starts

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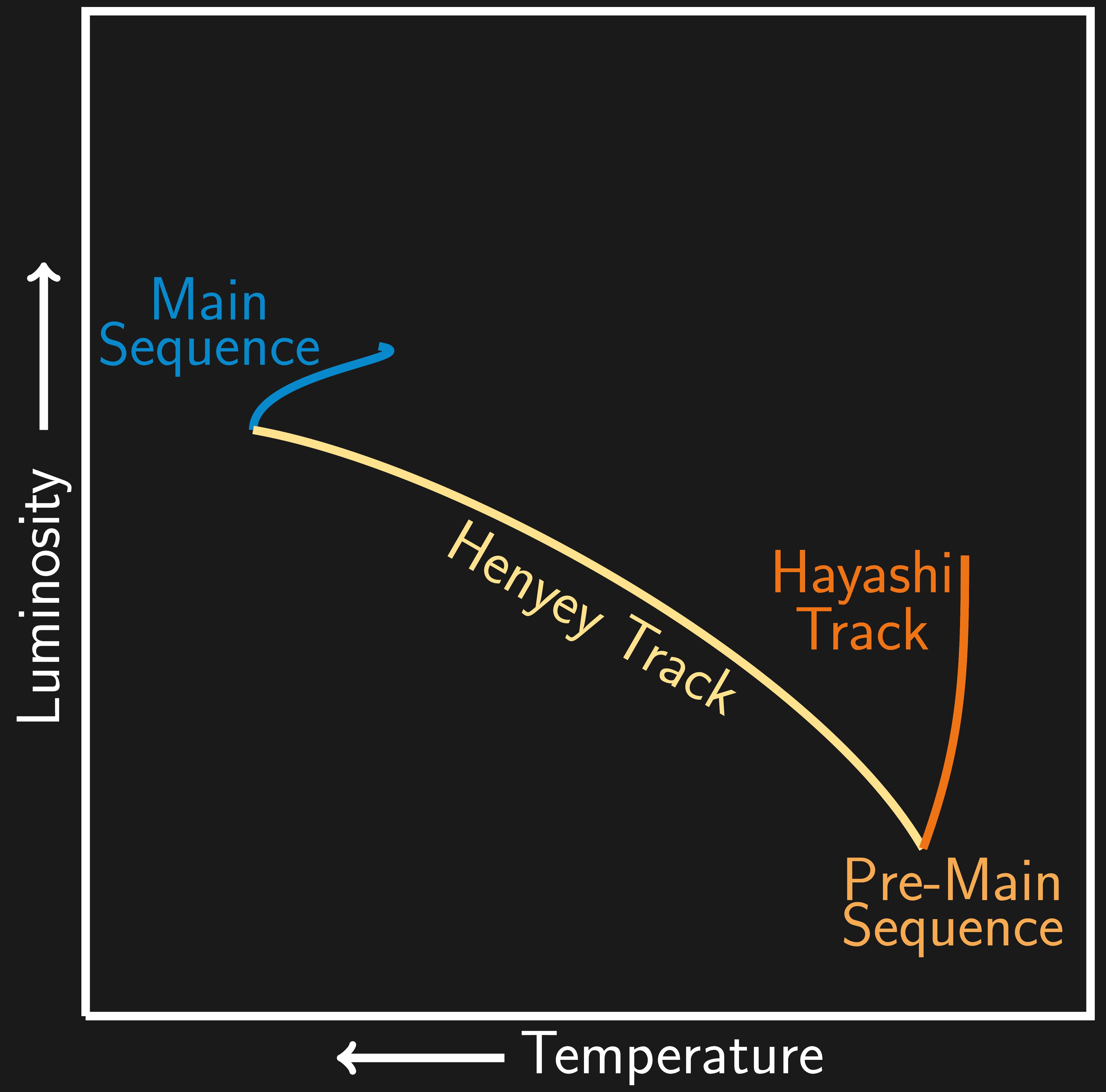

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Main sequence: star in stable equilibrium between hydrogen fusion and gravitational forces

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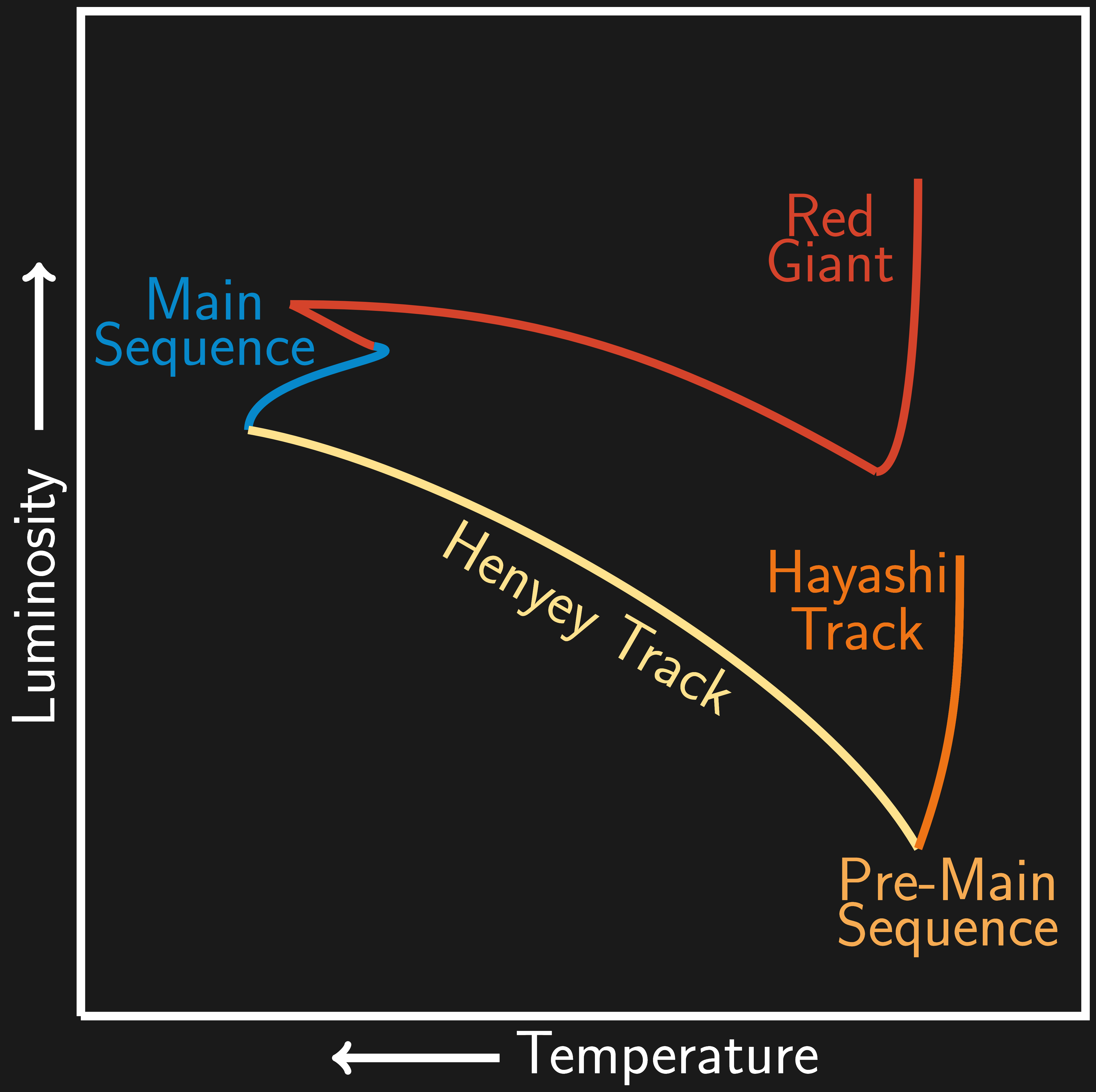


Hayashi track: newly forming star contracts

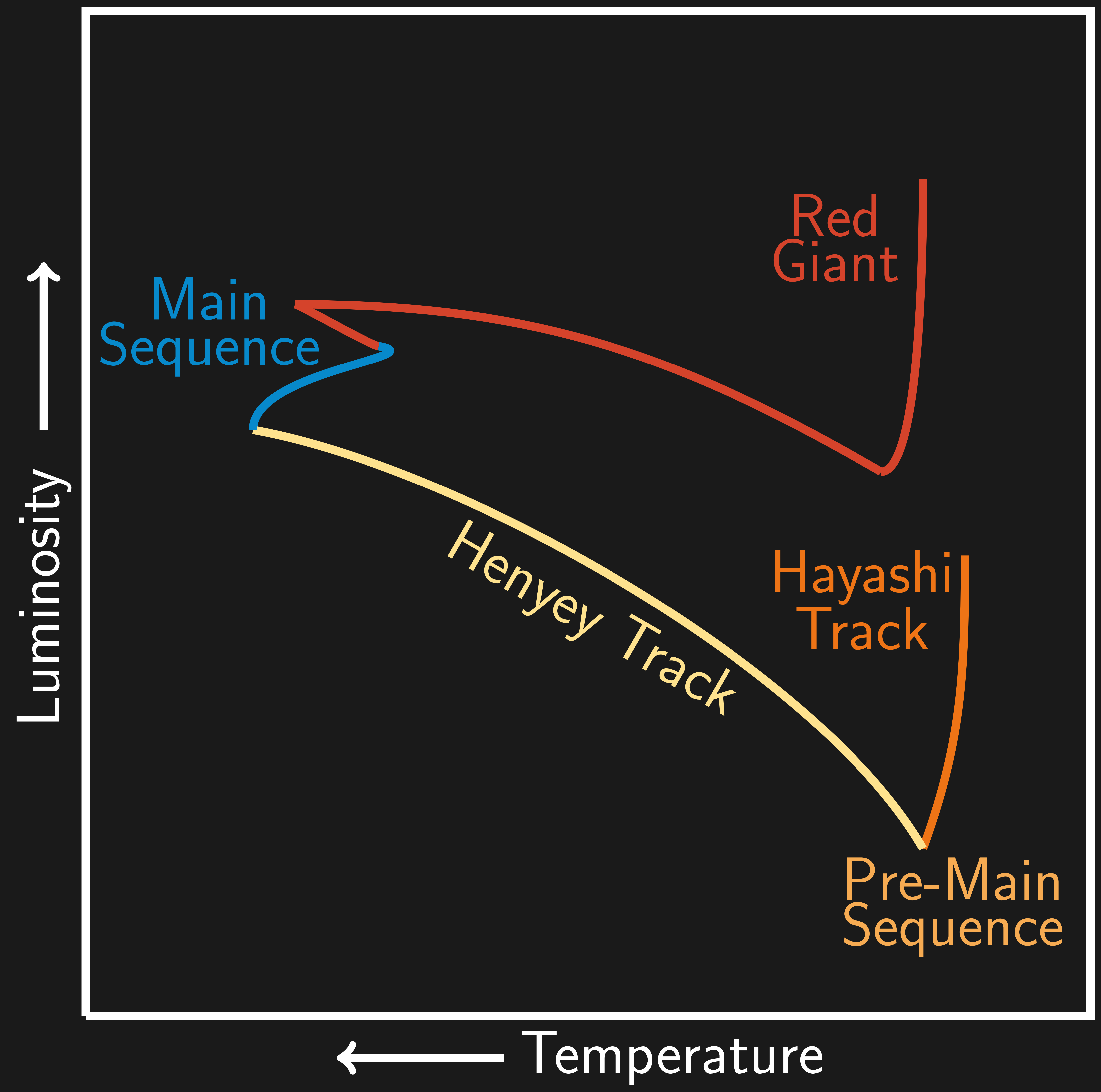
Henyey track: hydrogen fusion starts

Main sequence: star in stable equilibrium between hydrogen fusion and gravitational forces

Beyond main sequence: As star runs out of core hydrogen, other fusion processes begin and further evolutionary stages follow

Dark Matter Changes Stellar Evolution

Hertzsprung–Russell (HR) Diagram



- Dark matter annihilation provides power similar to nuclear fusion

See also:

Salati & Silk 1989

Fairbairn, Scott & Edsjö arXiv:0710.3396

Scott, Fairbairn & Edjsö arXiv:0809.1871

See also Dark Stars in the early Universe:

Iocco, arXiv:0802.0941

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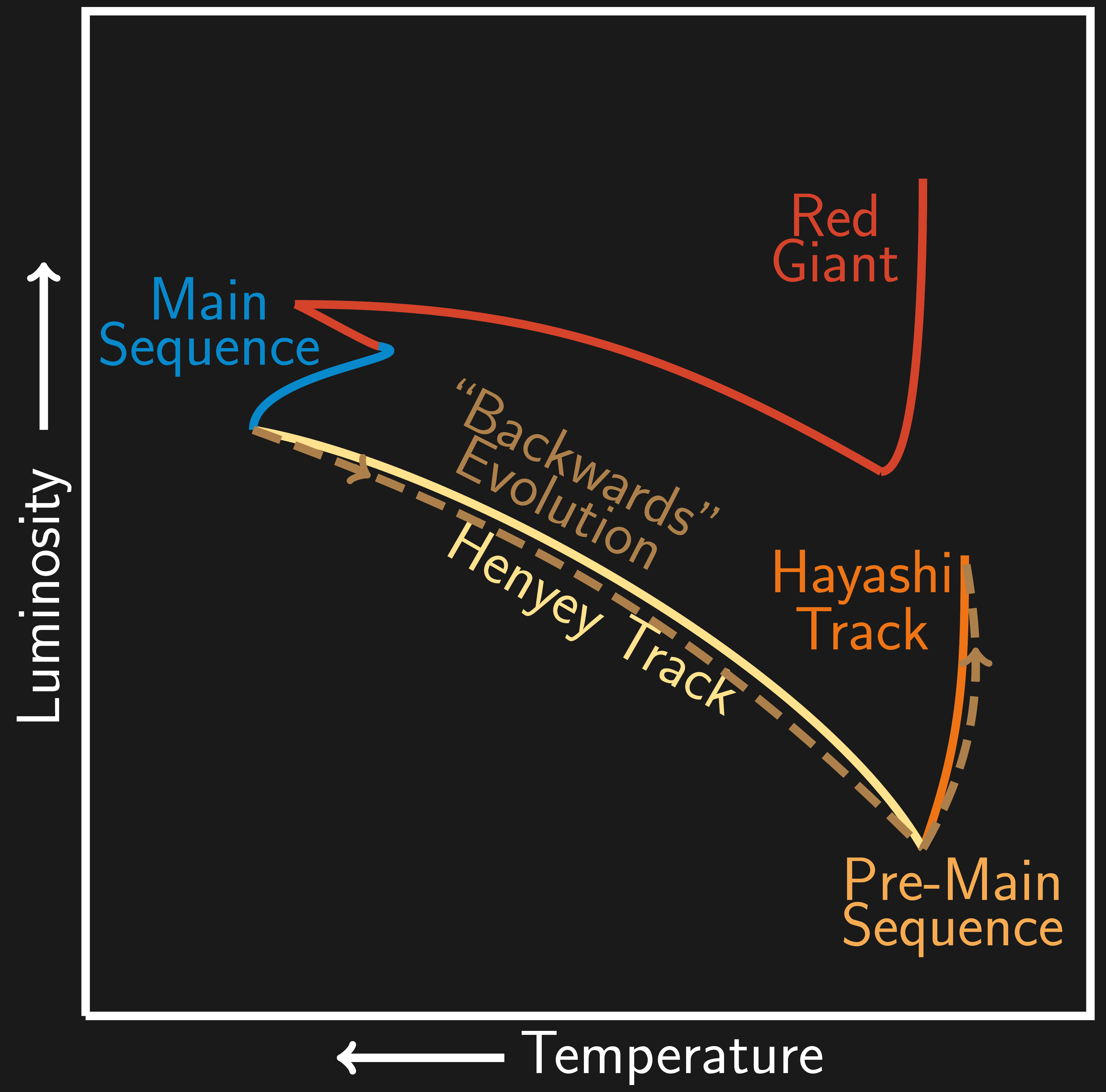

- Dark matter annihilation provides power similar to nuclear fusion
- Stars move "backwards" to different locations

See also:

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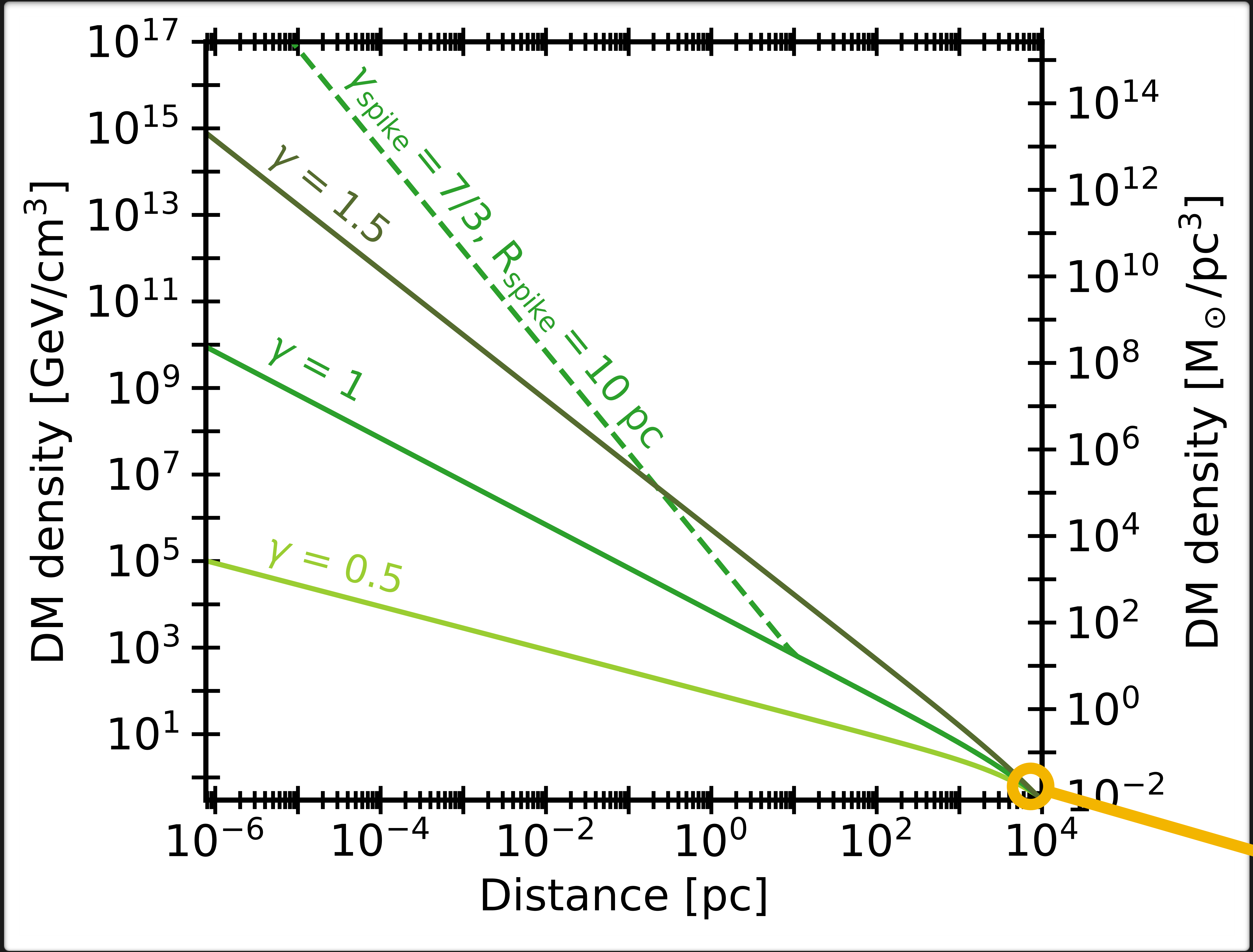
Galactic Dark Matter Density and Profile

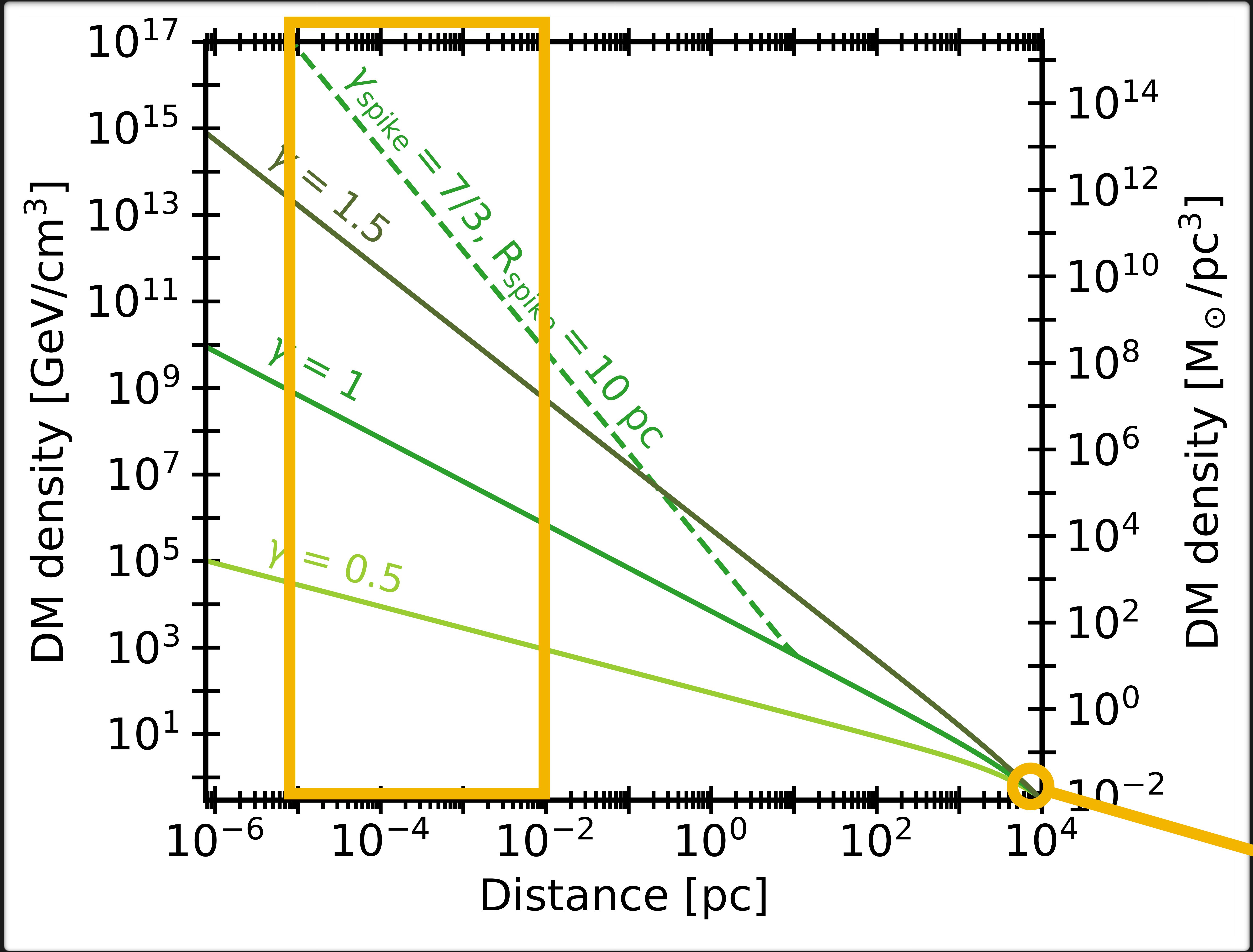


Dark matter density at Galactic Center is

- **Very high**: significant dark matter capture in stars
- **Very uncertain**: test dark matter profile models

Local dark matter density:
0.4 GeV/cm^3

Galactic Dark Matter Density and Profile



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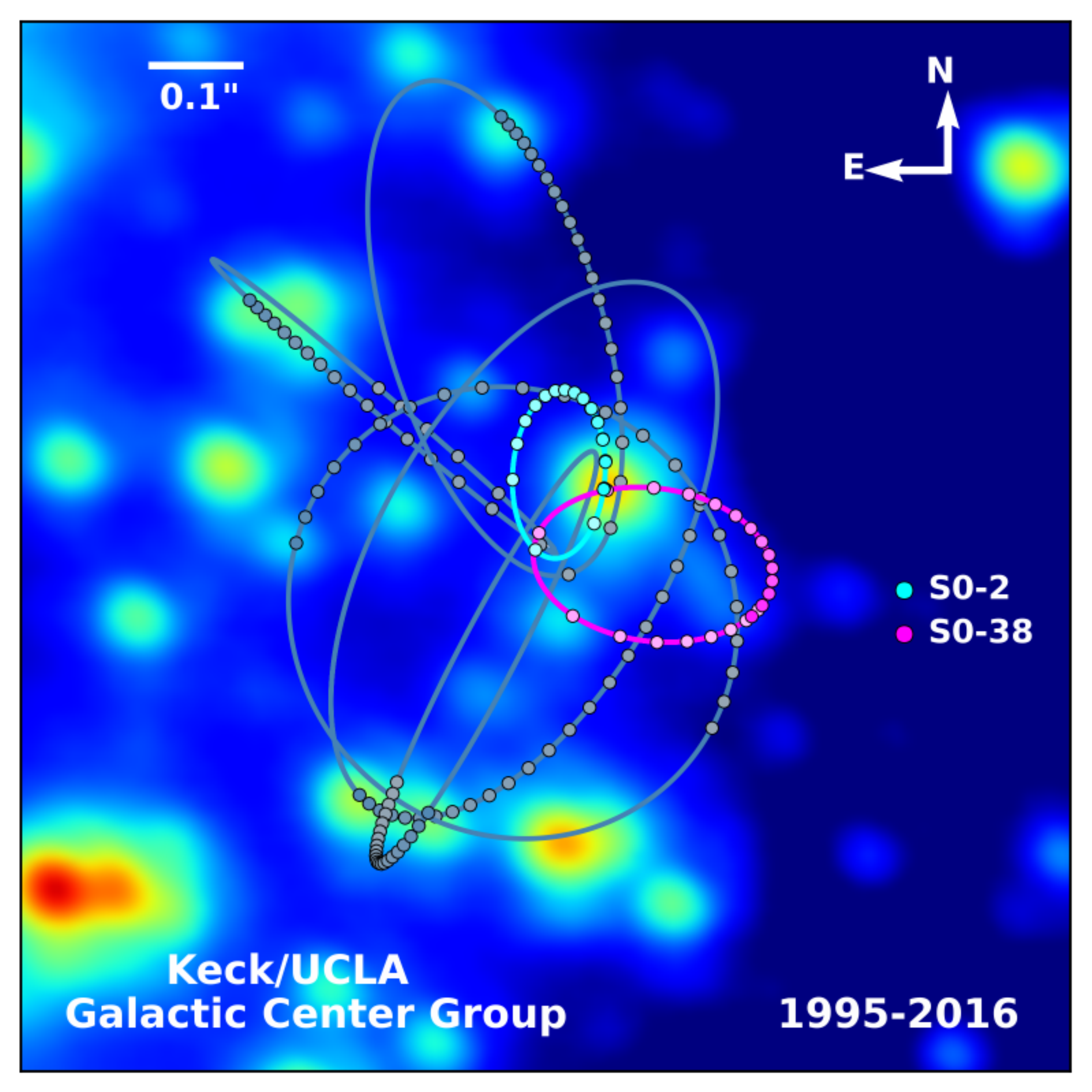
Local dark matter density: 0.4 GeV/cm^3

Stars at the Galactic Center

S–Cluster Stars:

- Closely orbit Sgr A* (< 0.04 pc)
- Very eccentric orbits and high velocities
- Few to ~20 solar masses
- Mainly main sequence stars



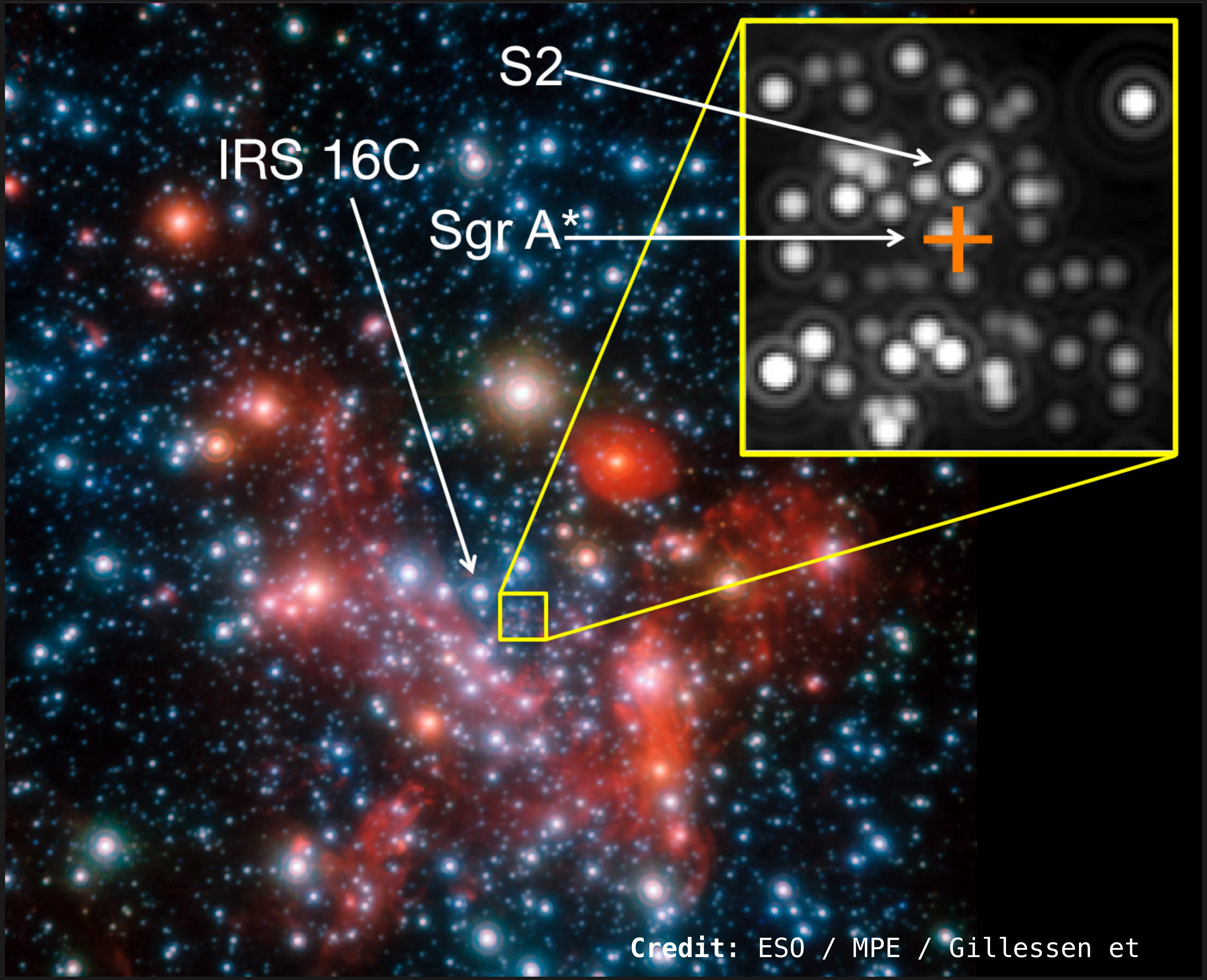
Unusual Properties of S-Cluster Stars

Origin not well understood: in situ formation or migration?

Paradox of Youth: Spectroscopically old but bright as young stars

Conundrum of Old Age: Lack of old stars

Top-heavy initial mass function: large abundance of massive stars



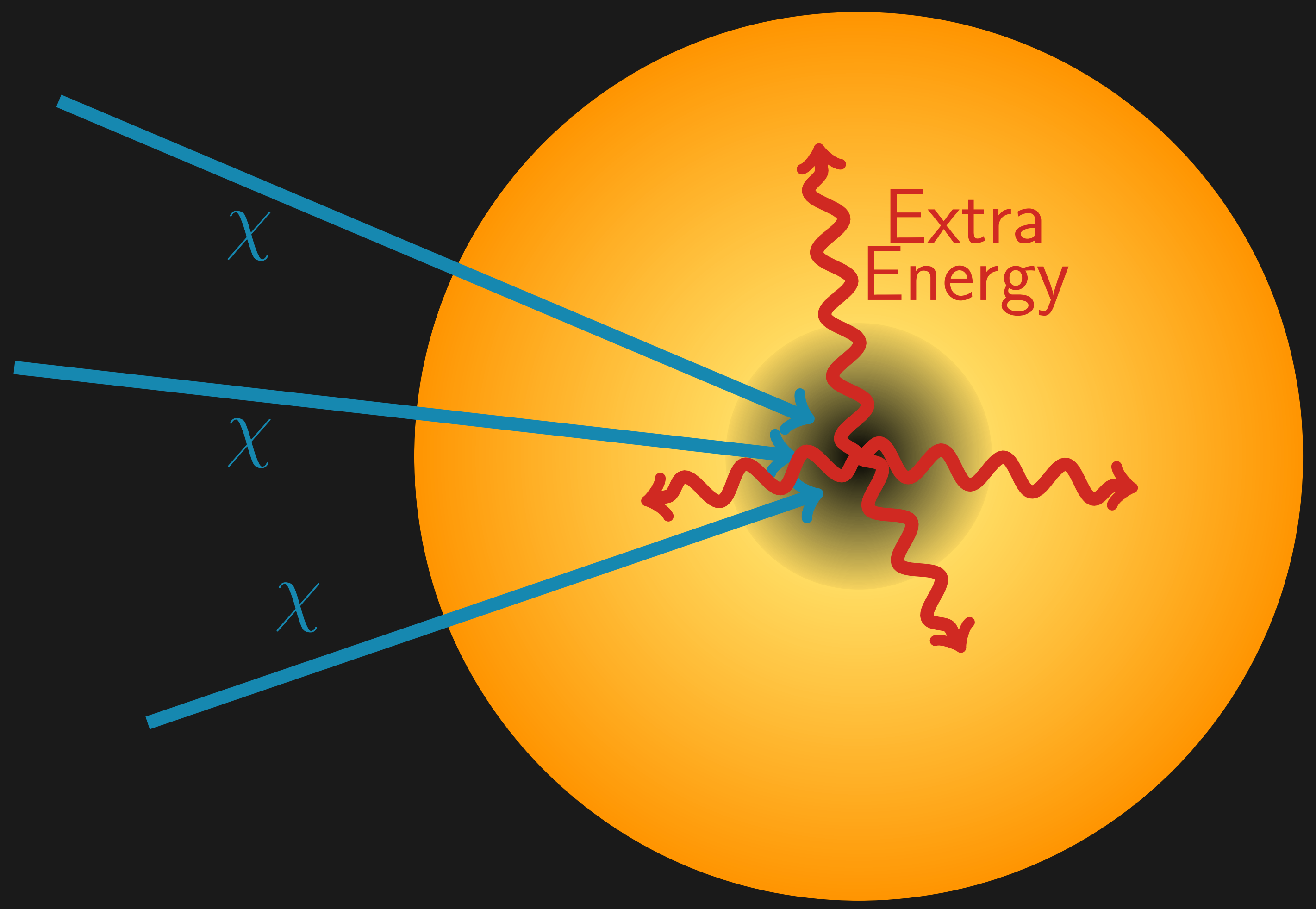
Modelling Stellar Evolution with Dark Matter

- Simulate stellar evolution using stellar evolution code MESA

- Calculate dark matter capture rate along stellar orbit

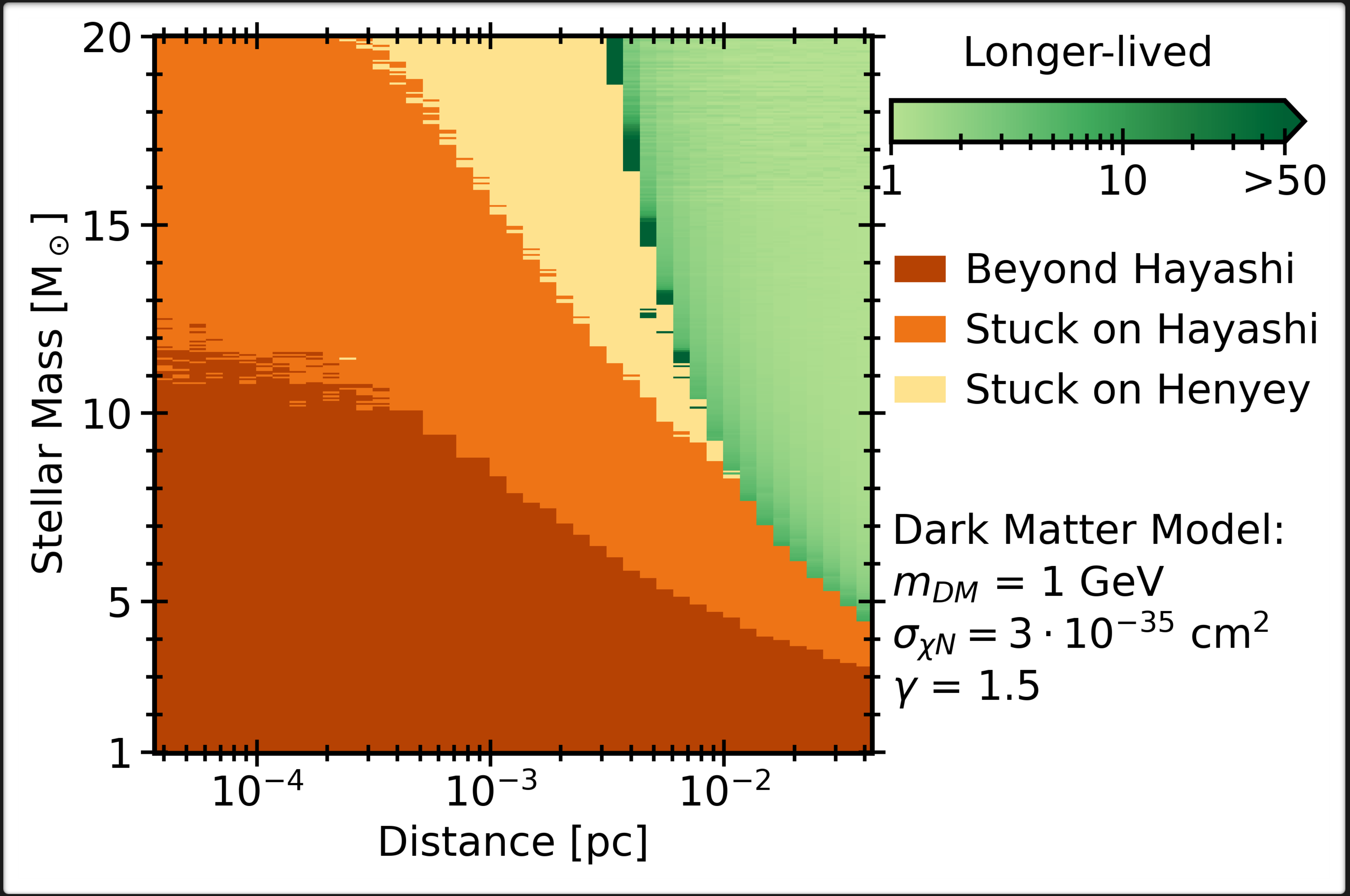
- Inject extra energy from dark matter burning in stellar core

- Simulate main sequence stars until red giant phase or 10 billion years have passed



Dark Matter Slows Stellar Evolution

[I. John, R. Leane, T. Linden, arXiv:2405.12267]



Evolutionary stage after main sequence or 10 billion years.

Effects depend on:

- Stellar mass
- Dark matter density

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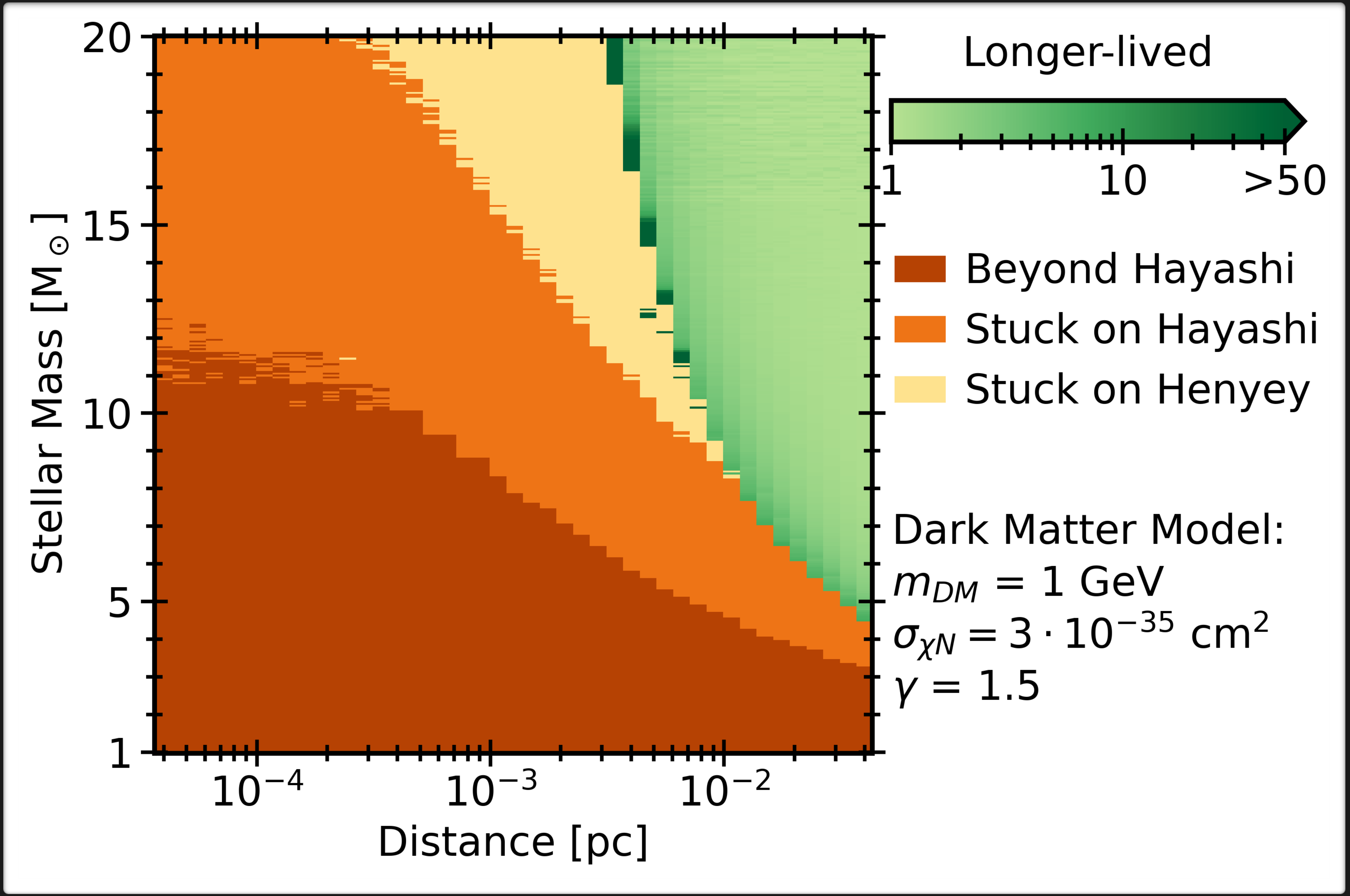

Longer–lived

Dark matter burning *partially replaces* nuclear fusion – typical evolution is slowed down

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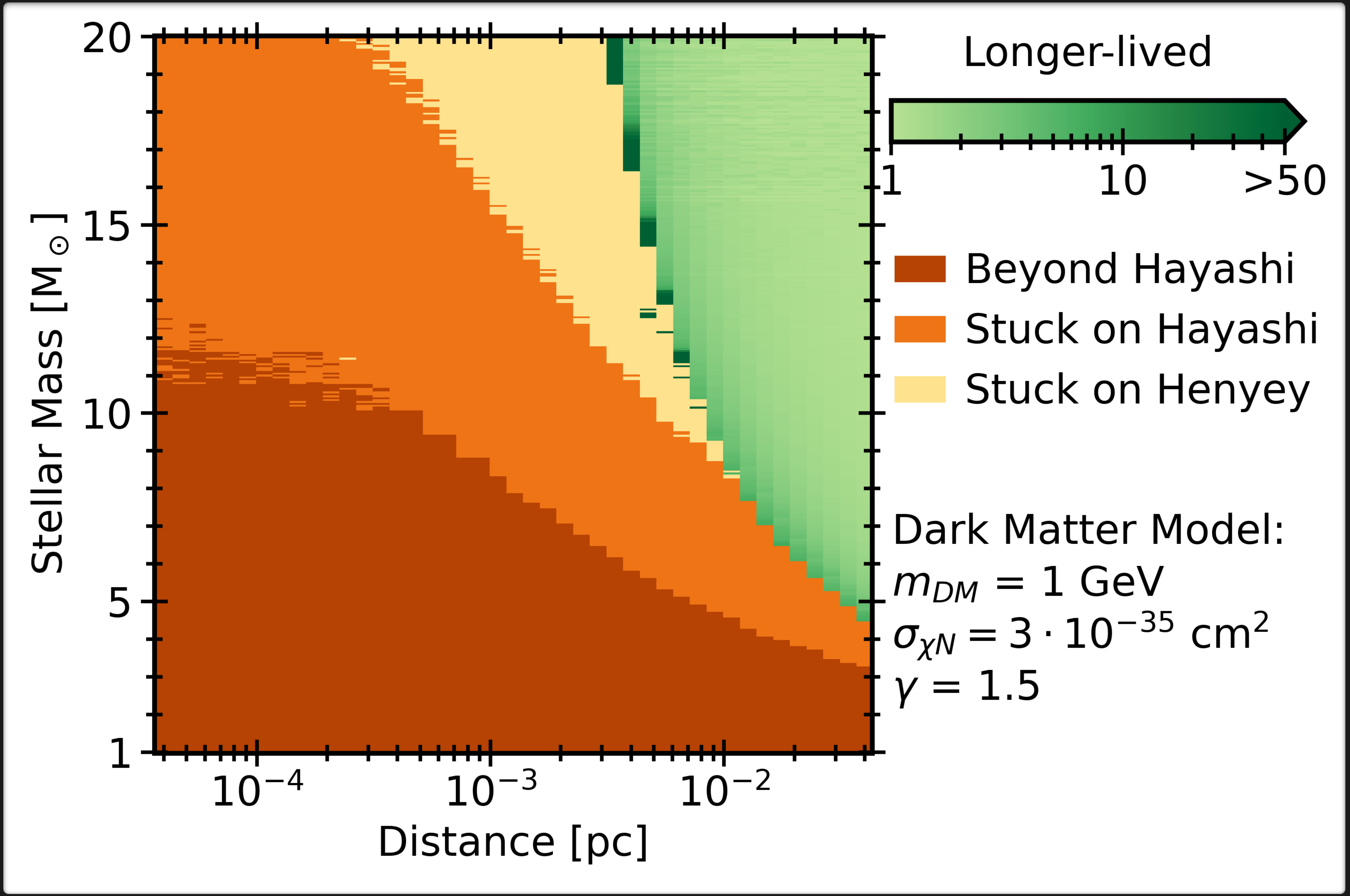
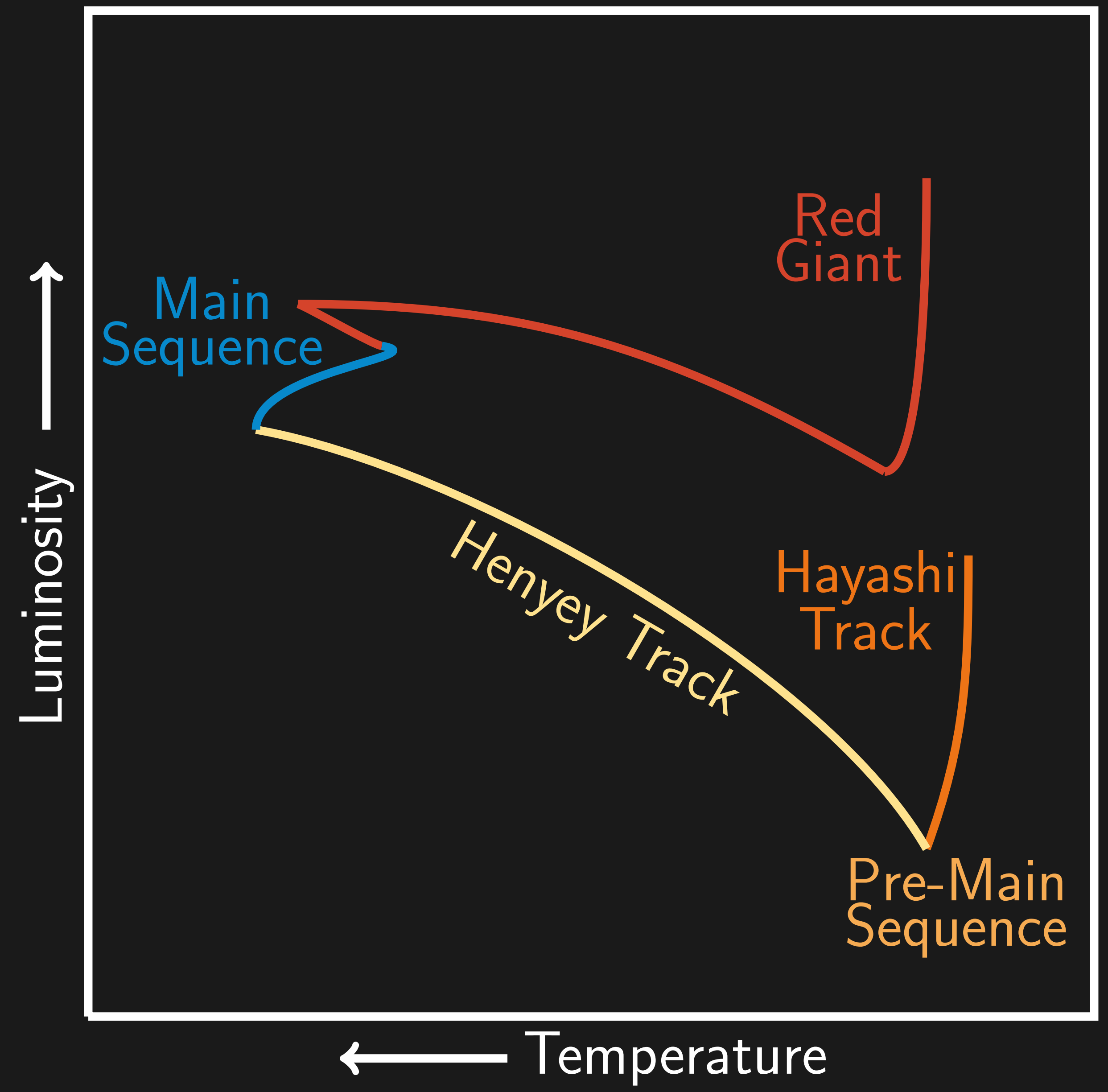


Stuck on Henyey

Dark matter burning *significantly replaces* nuclear fusion – stellar evolution halts on Henyey track



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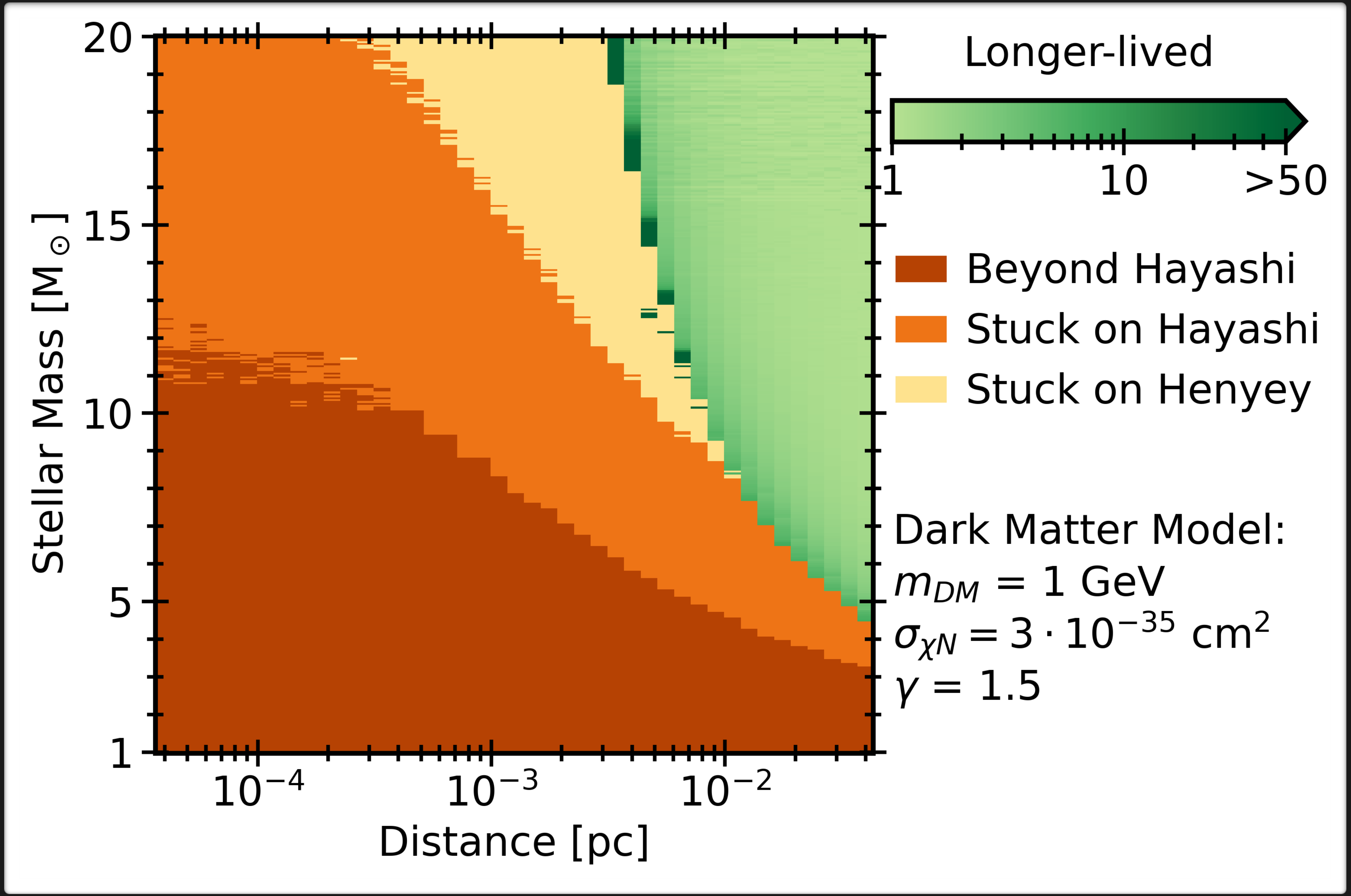
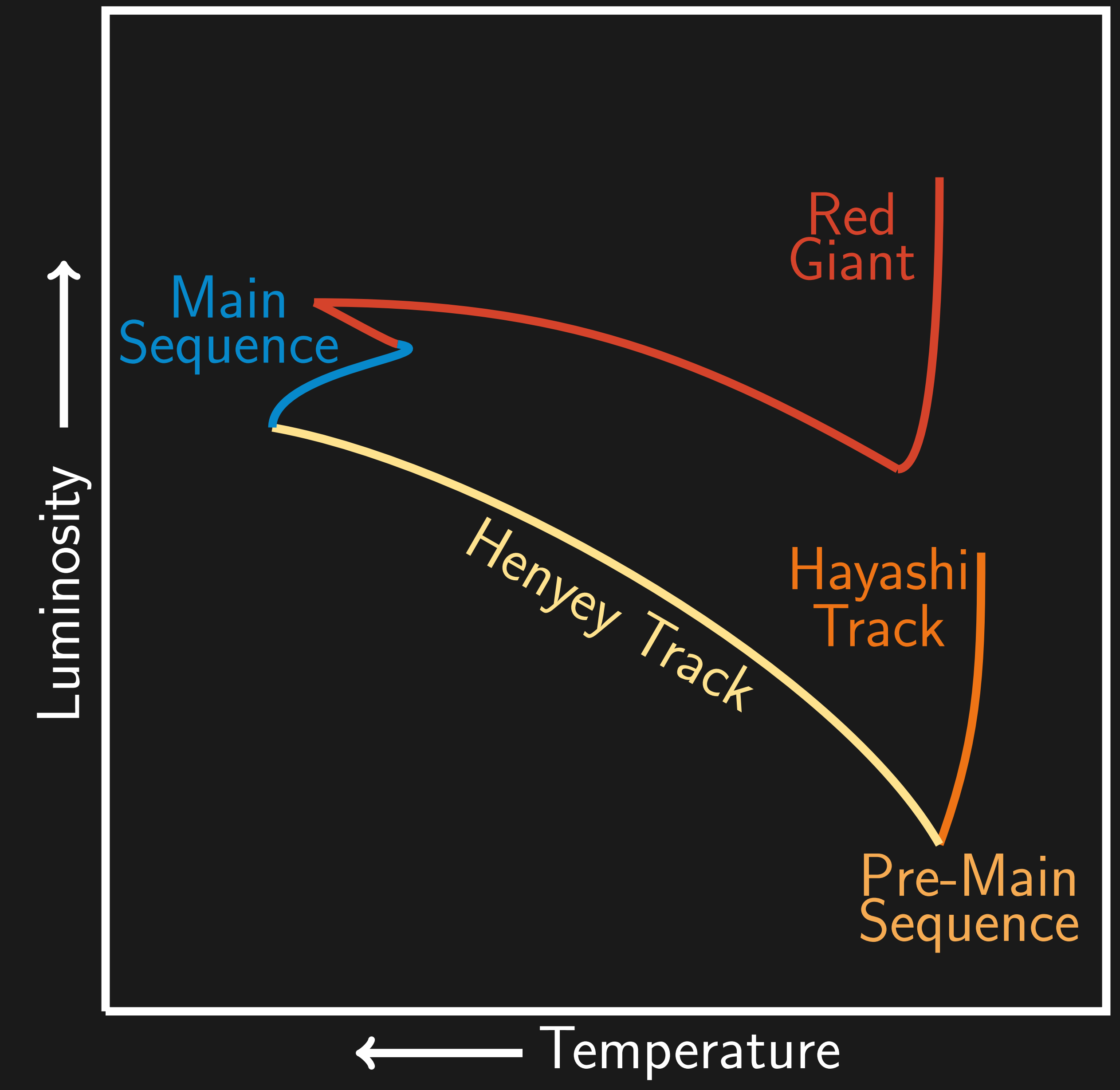


Beyond/Stuck on Hayashi

Dark matter burning *completely replaces* nuclear fusion – stellar evolution halts on Hayashi track



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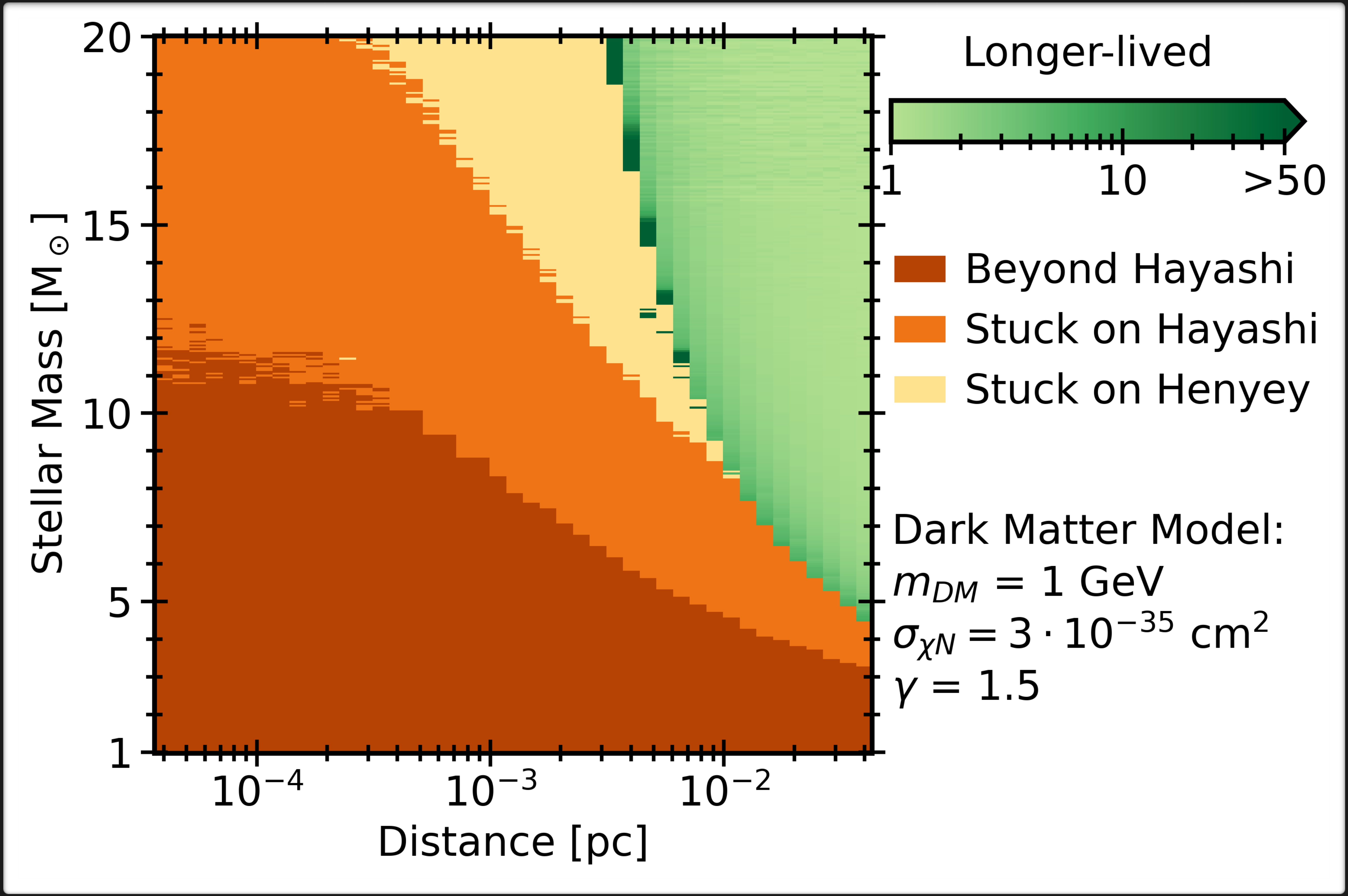

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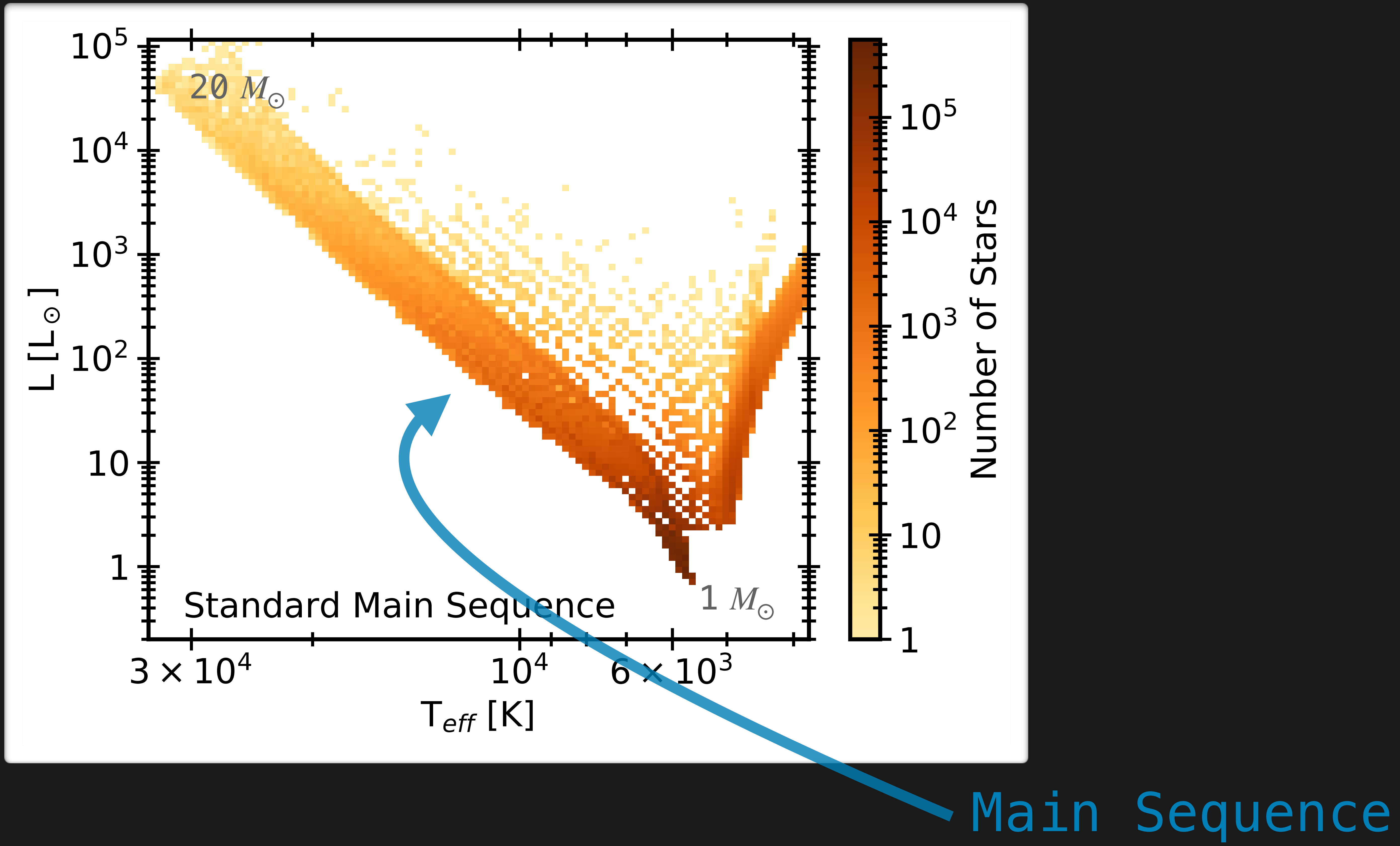
Dark matter can be captured continuously

Stars become effectively immortal

The Dark Main Sequence

[I. John, R. Leane, T. Linden, arXiv:2405.12267]



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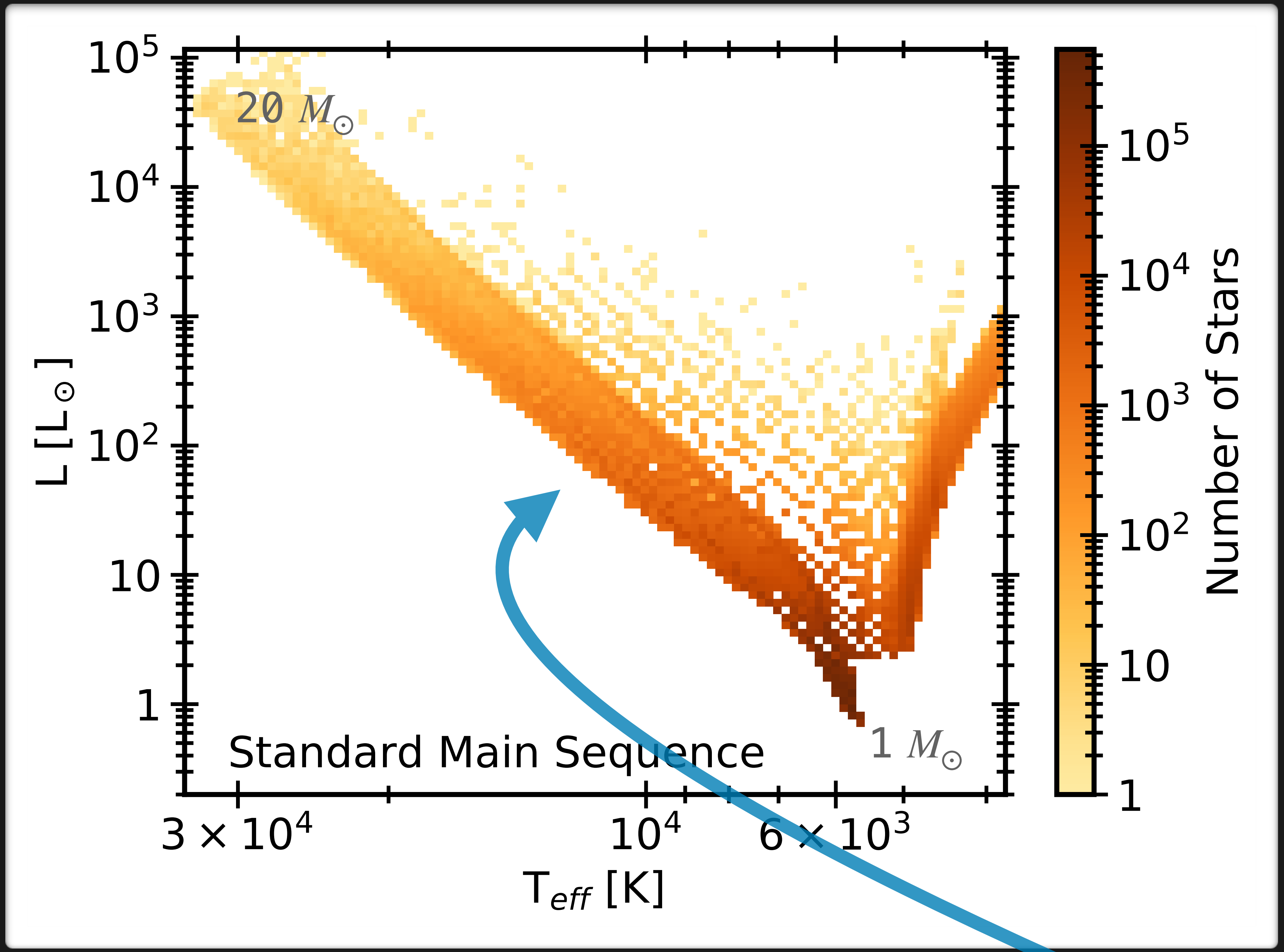
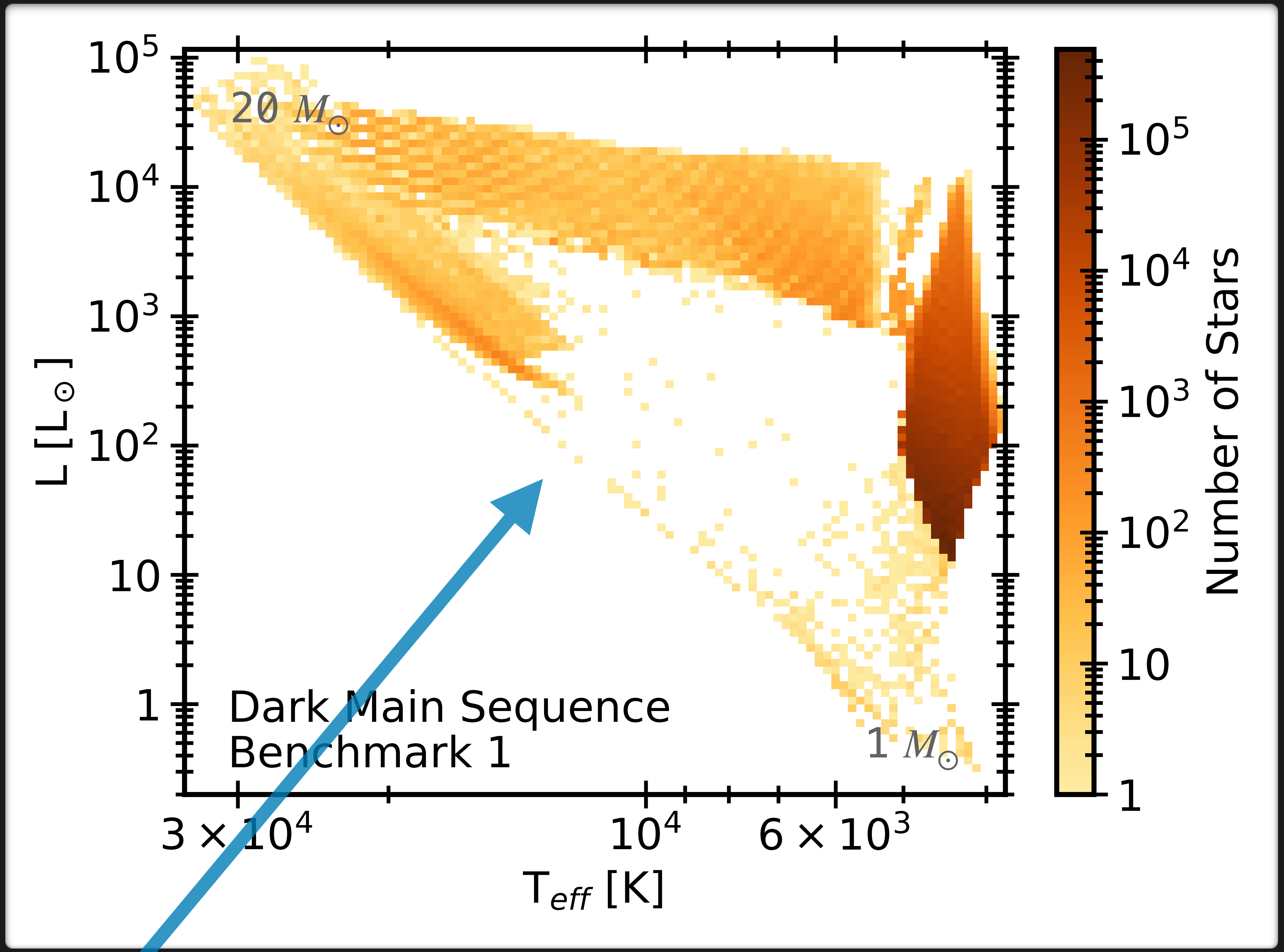
HR diagrams of stellar populations with dark matter burning show two new branches:





Main Sequence

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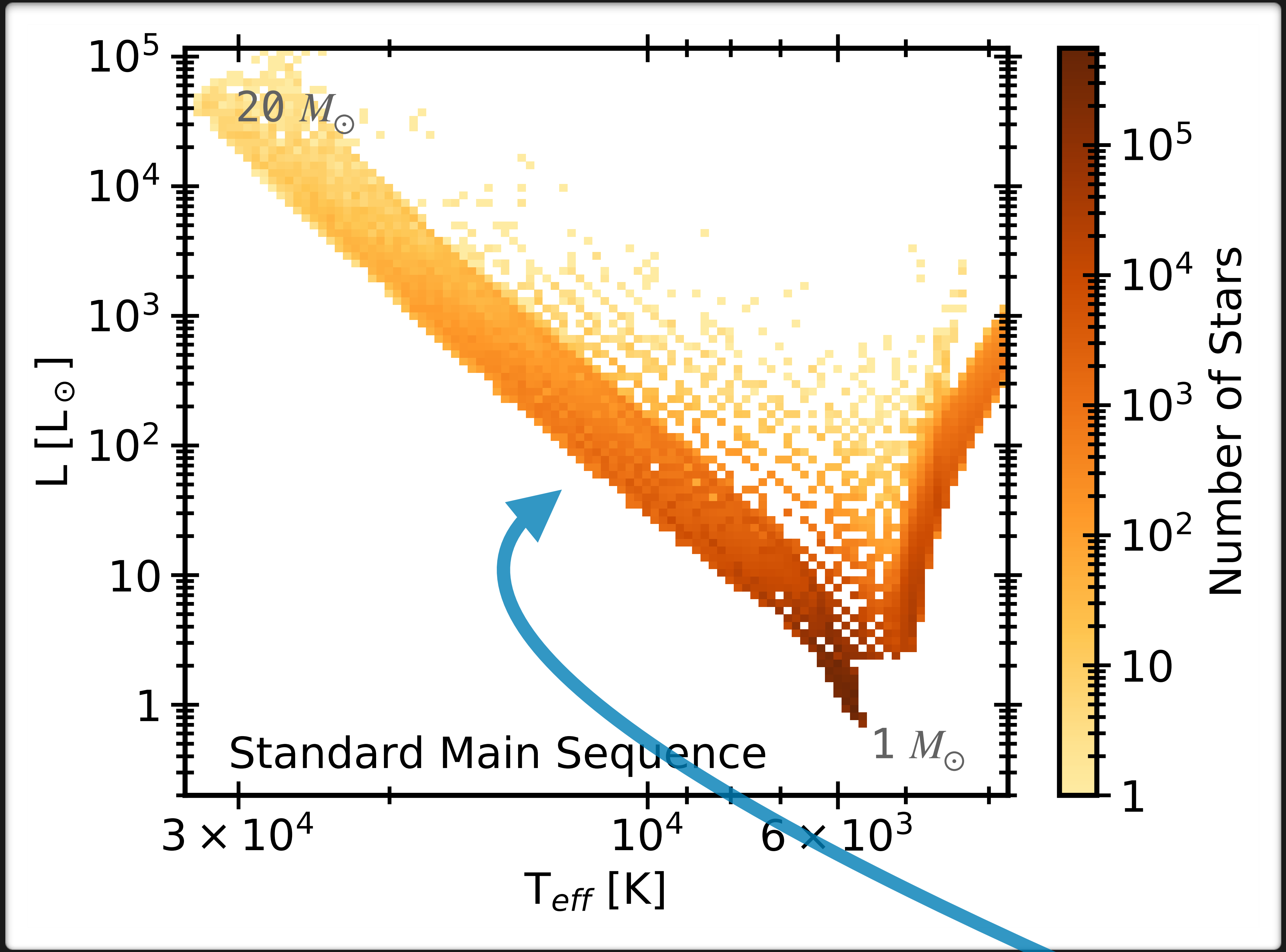
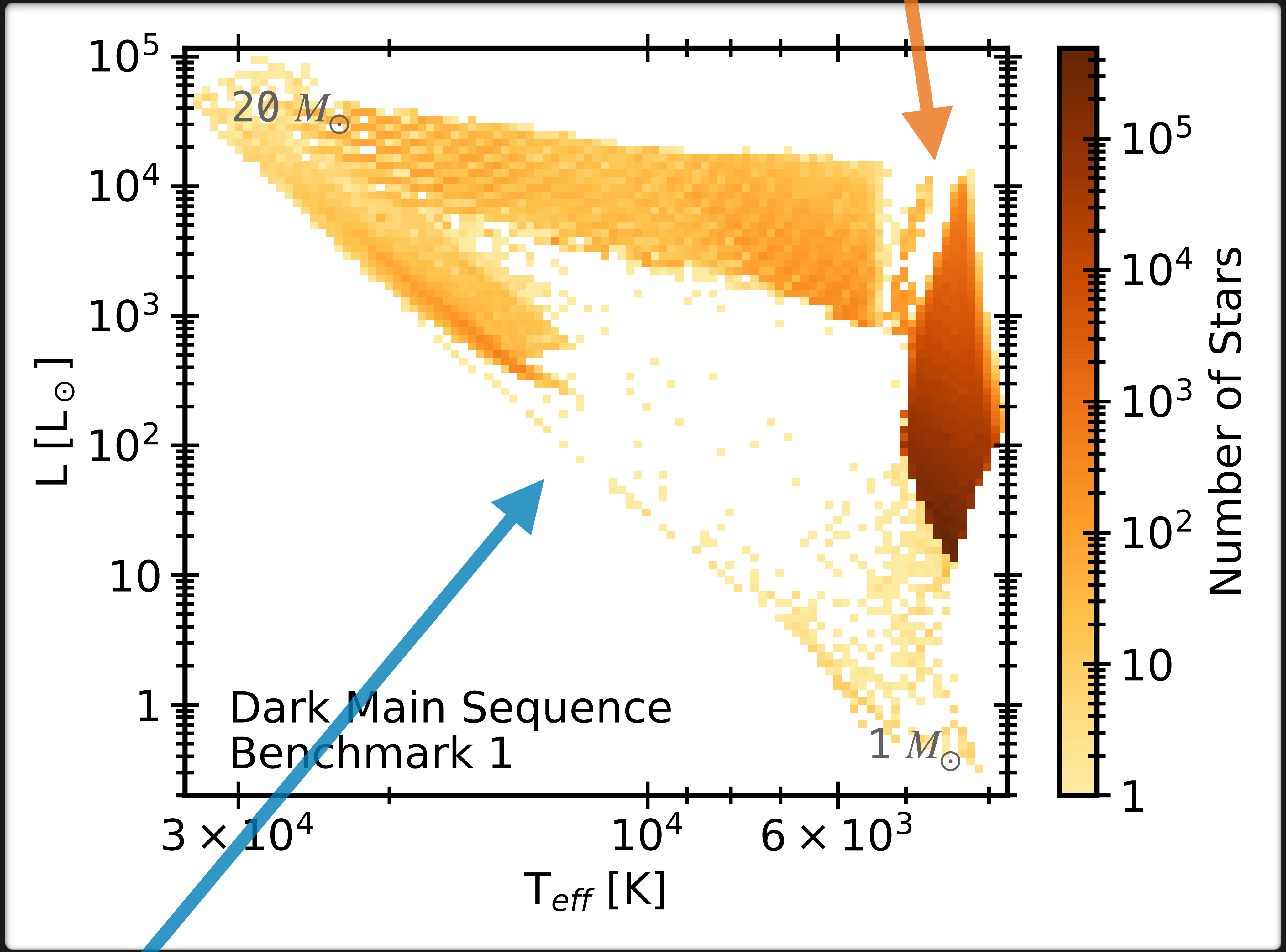
Overabundance of stars along Hayashi tracks





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HR diagrams of stellar populations with dark matter burning show two new branches:

Dark Main Sequence along Henyey tracks

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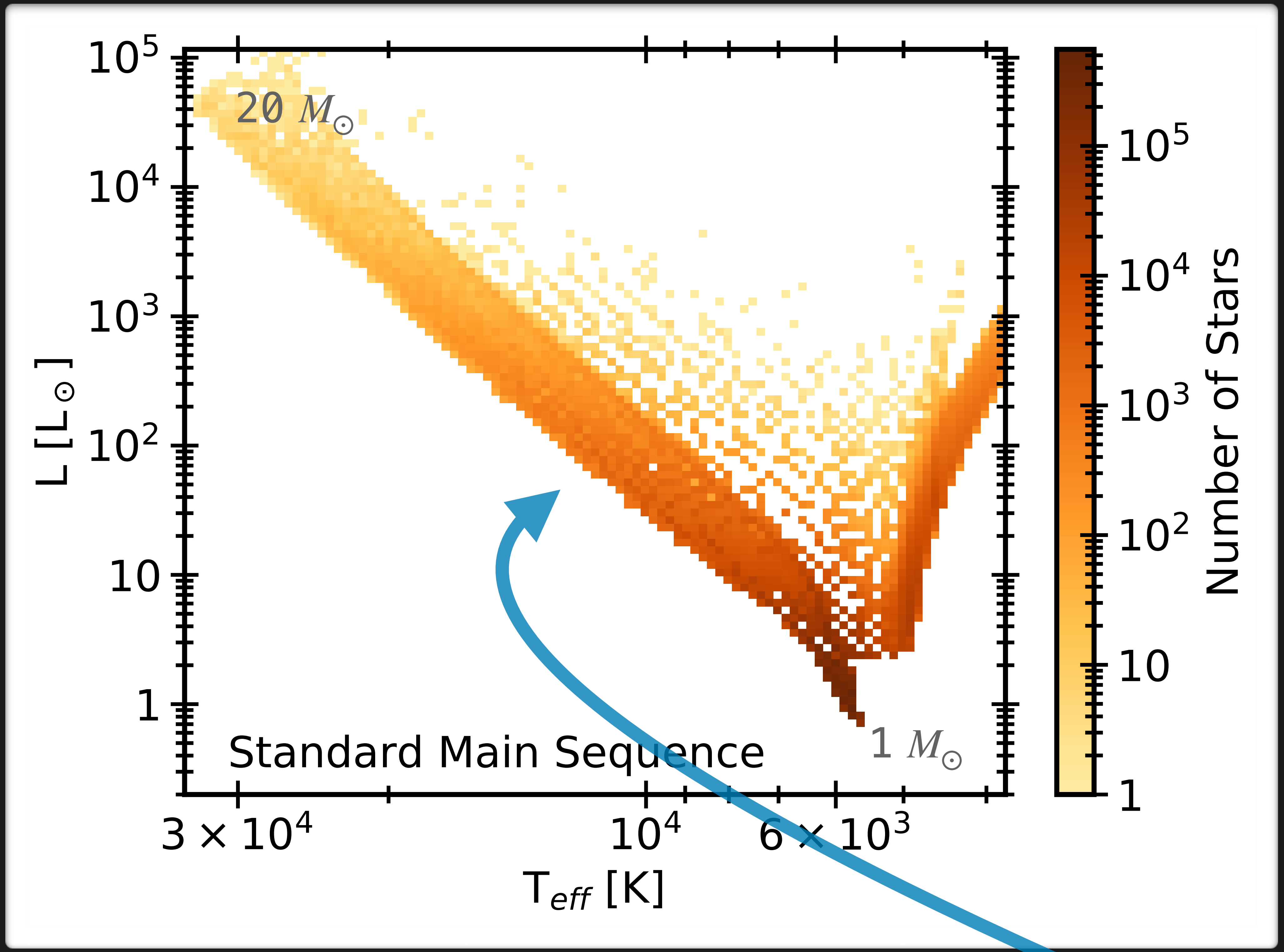
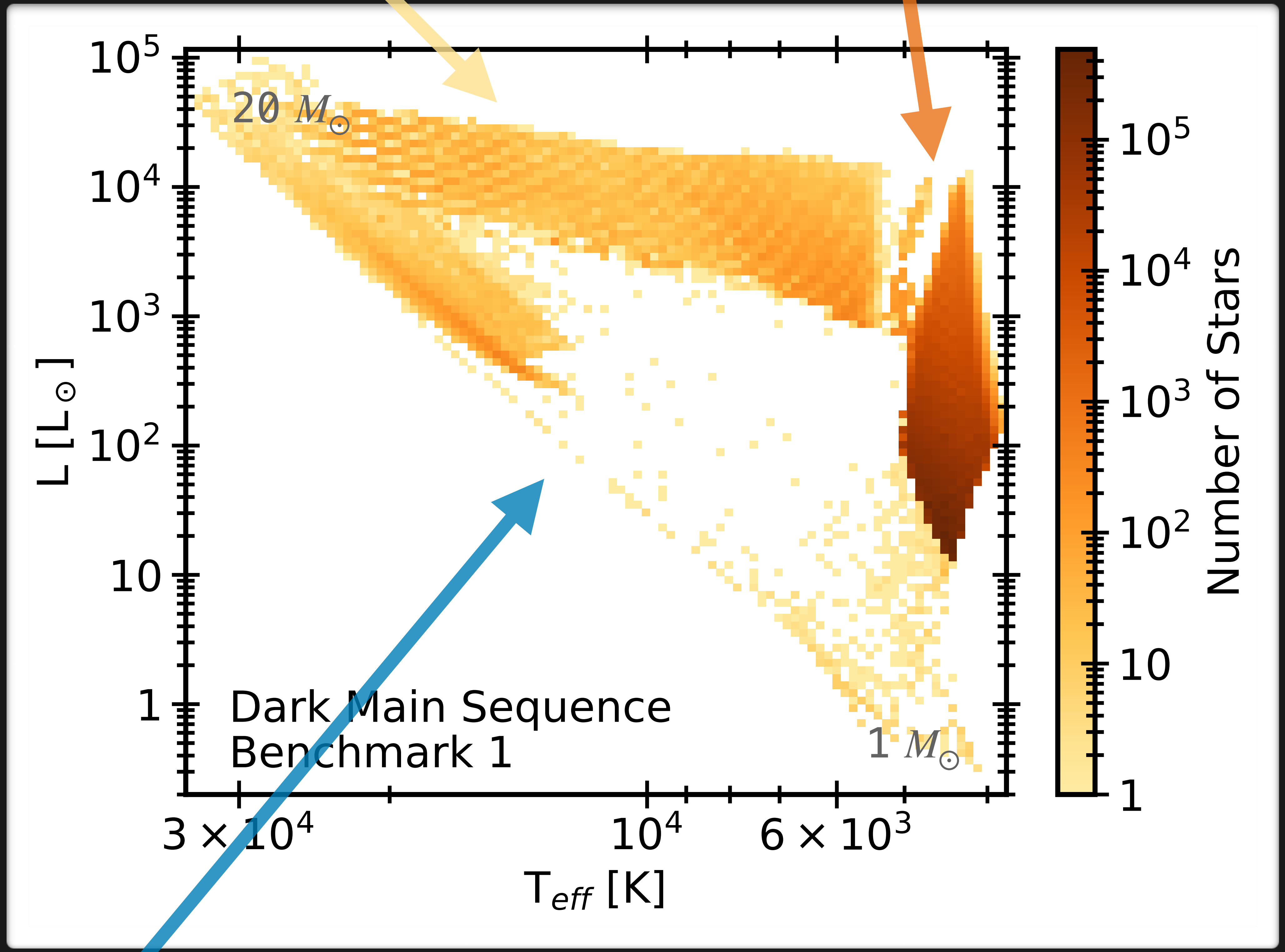




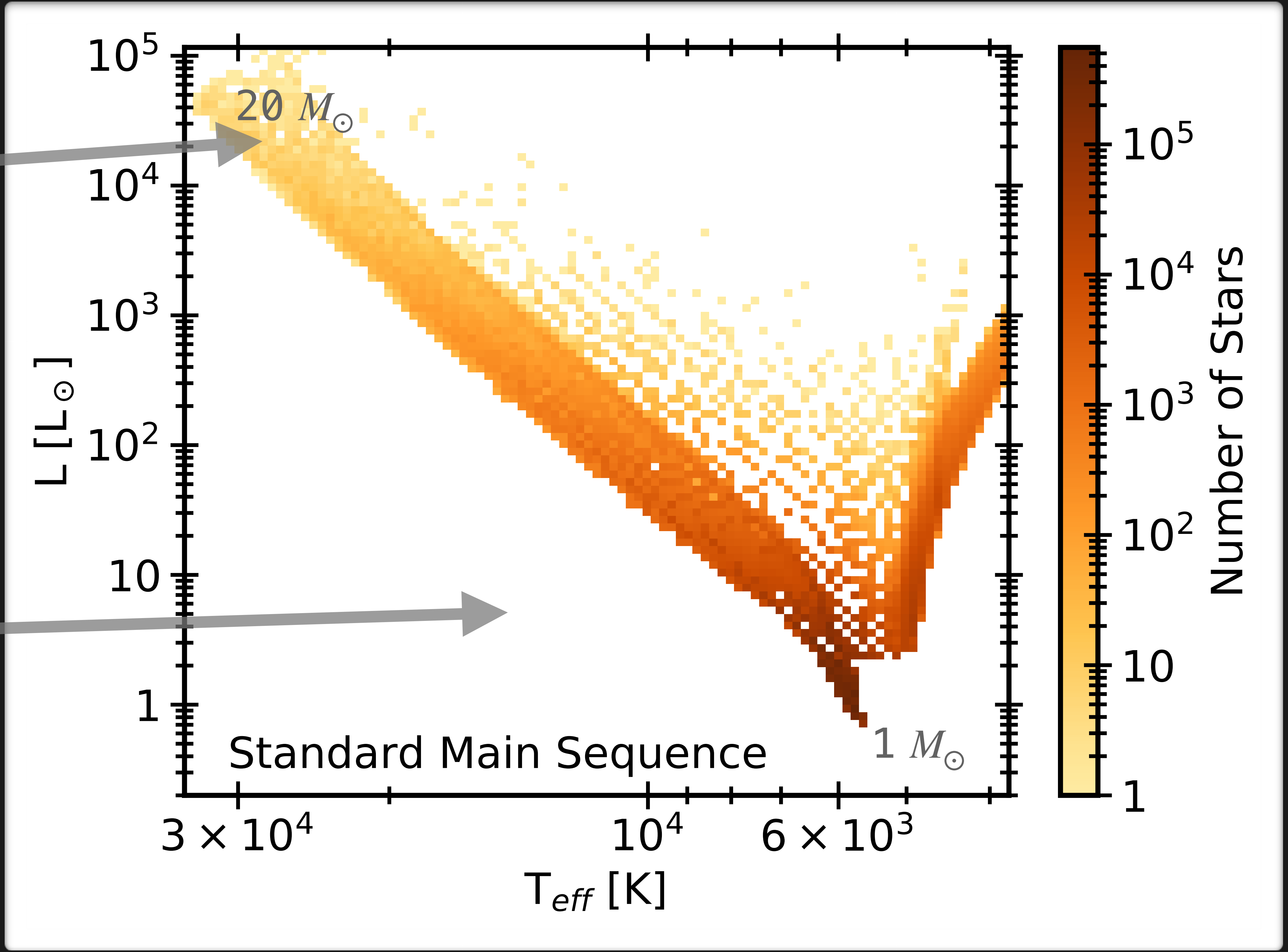
Main Sequence

Dark Matter Burning in S–Cluster Stars

Standard Evolution:

Massive stars evolve quickly

Light stars evolve slowly



Dark Matter Burning in S-Cluster Stars

Standard Evolution:

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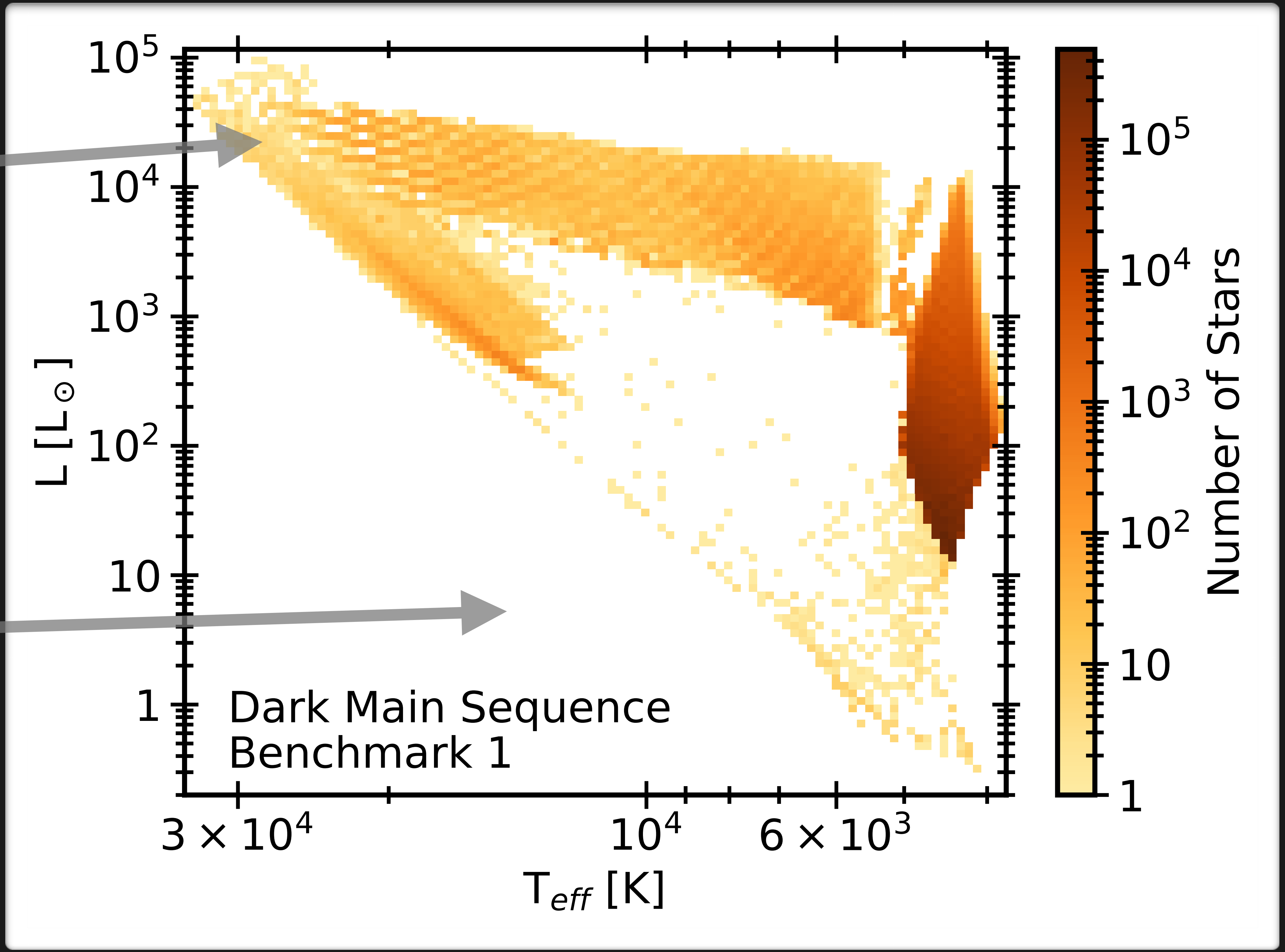

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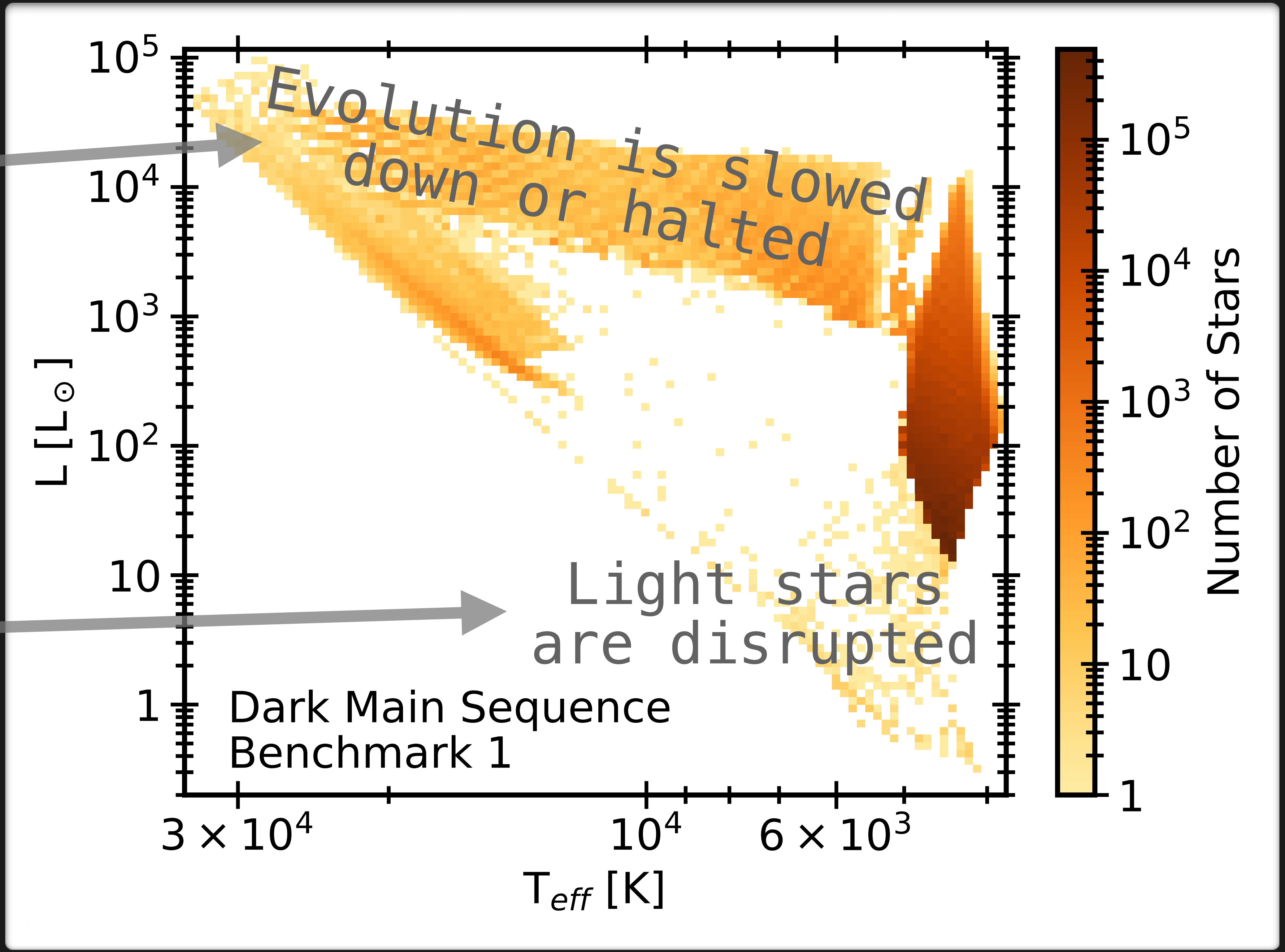

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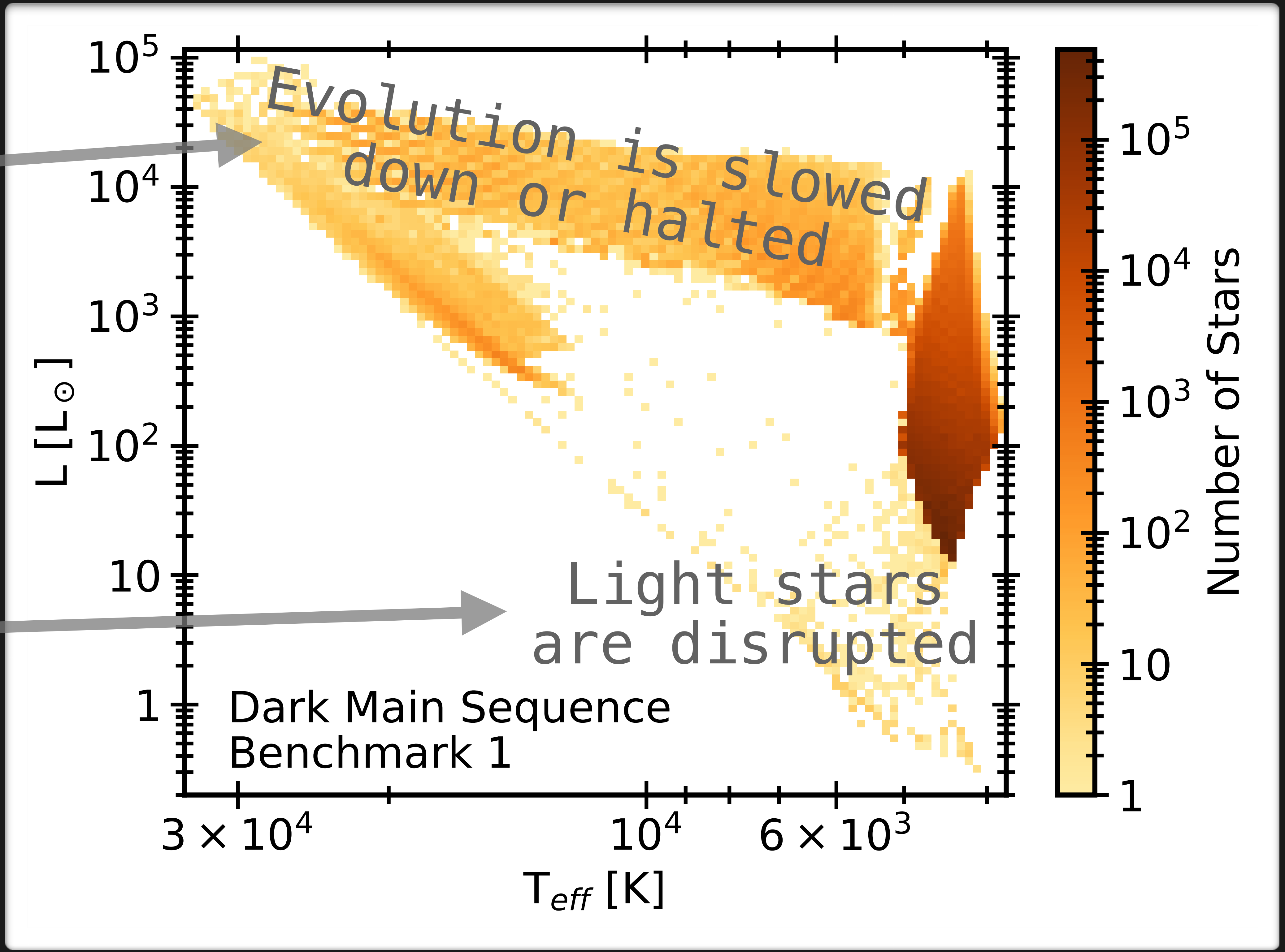

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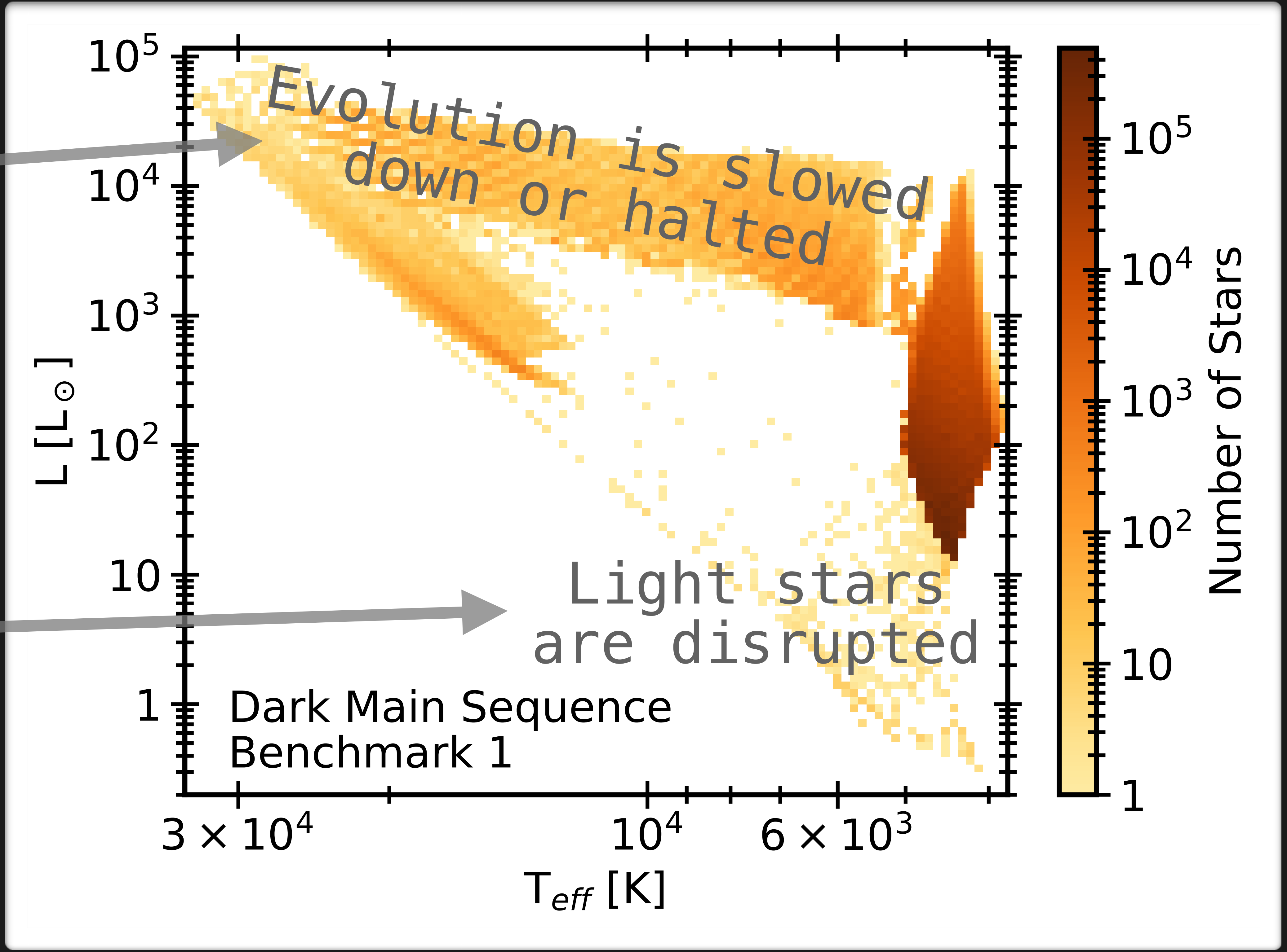

Unusual Properties of S-Stars:

Paradox of Youth – Stars look young

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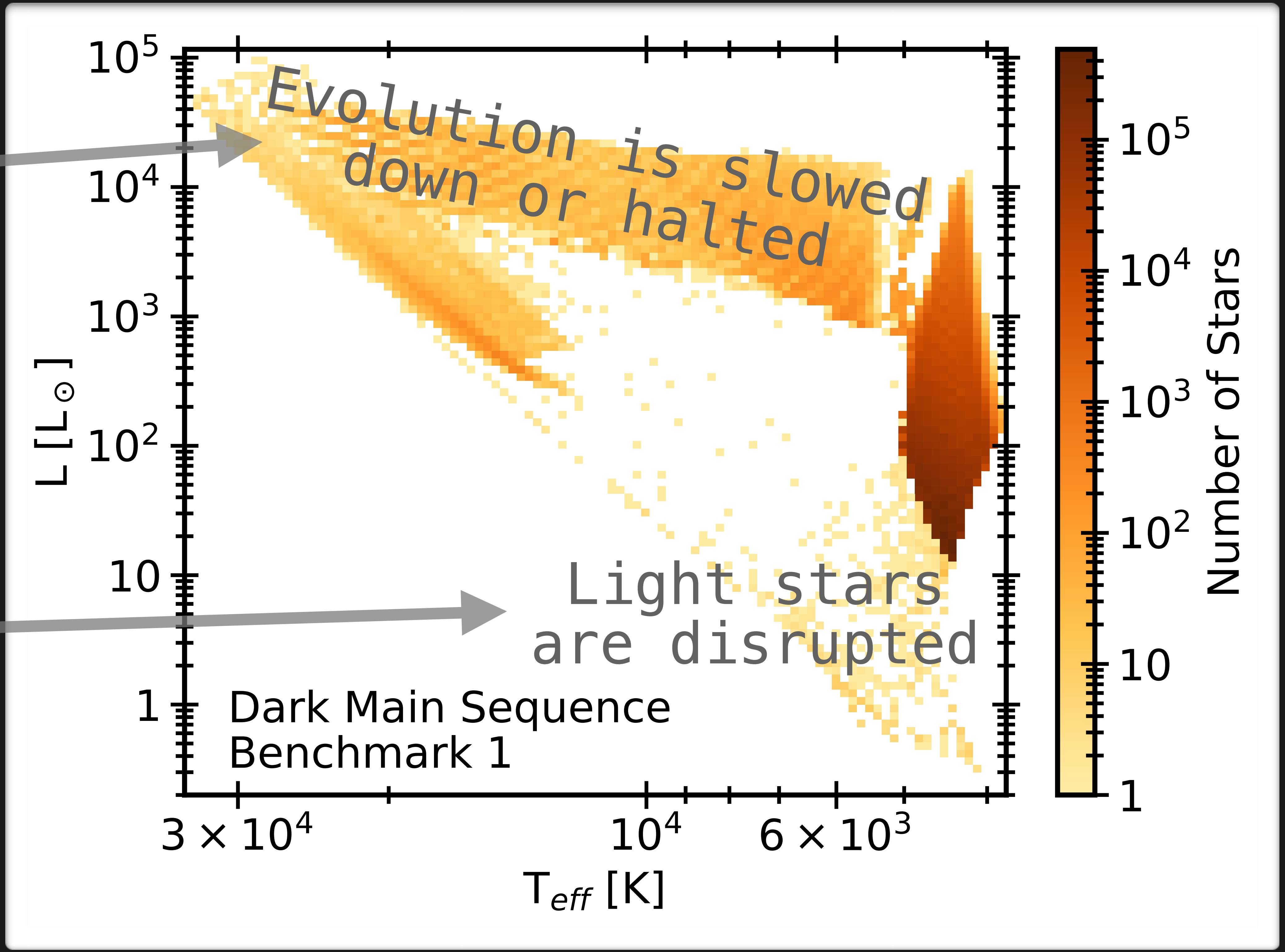

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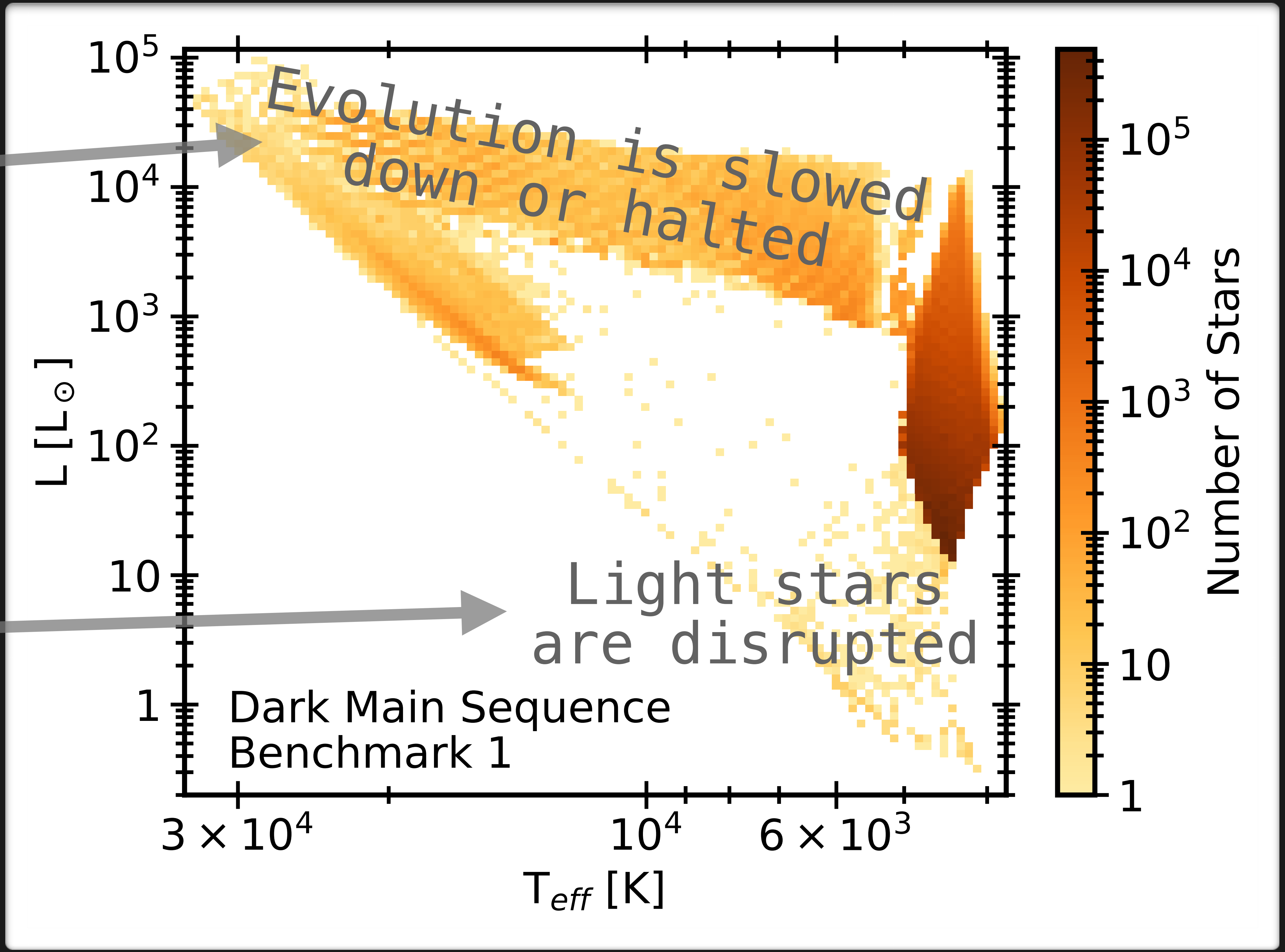

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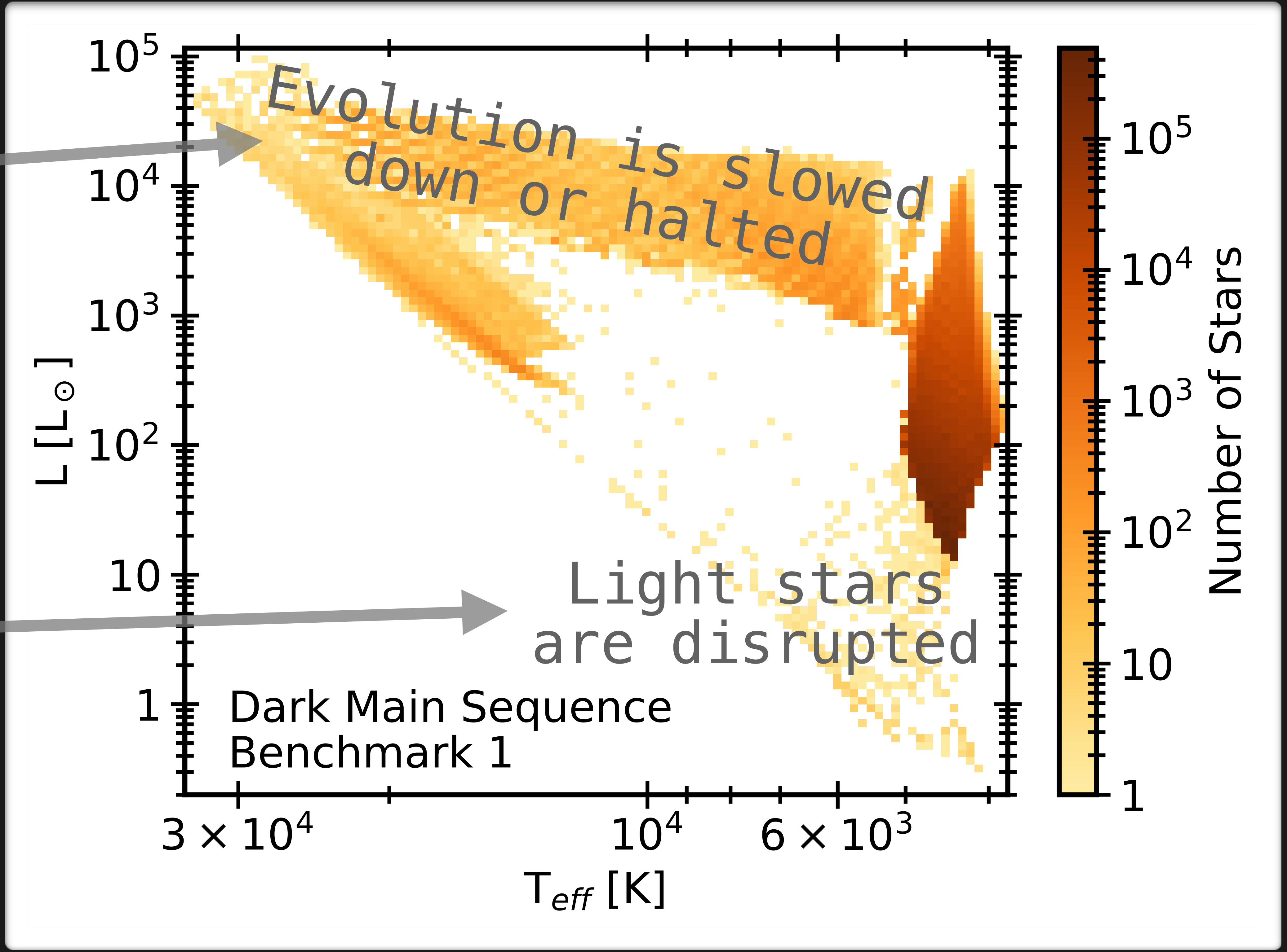

Unusual Properties of S-Stars:

Paradox of Youth – Stars look young

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Top-heavy initial mass distribution

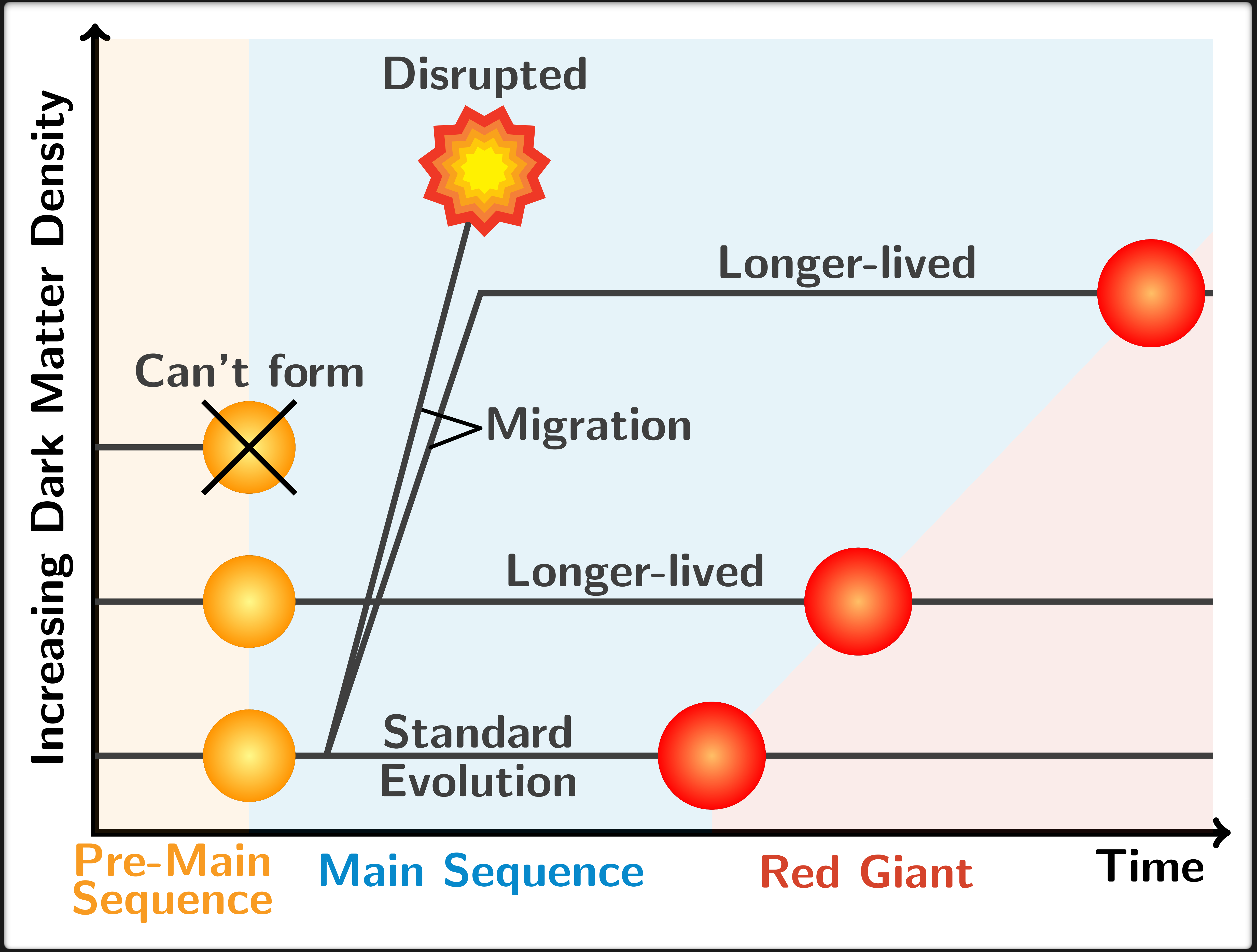
G objects ?

Dark main sequence is consistent with unusual S-cluster properties.

Constraining Dark Matter with Observed Stars

We can also use the observations of S-cluster stars to derive constraints on the dark matter properties.

Sufficiently high dark matter densities can prevent star formation and disrupt existing stars – derive constraints based on the fact that we can observe these stars.



Constraining Dark Matter with Observed Stars

Observations of S-stars provide precise orbital information and stellar properties for dark matter capture rate calculation.

Specific S-cluster stars we consider:

S2: 13.6 $M_\odot$
best-measured, large mass

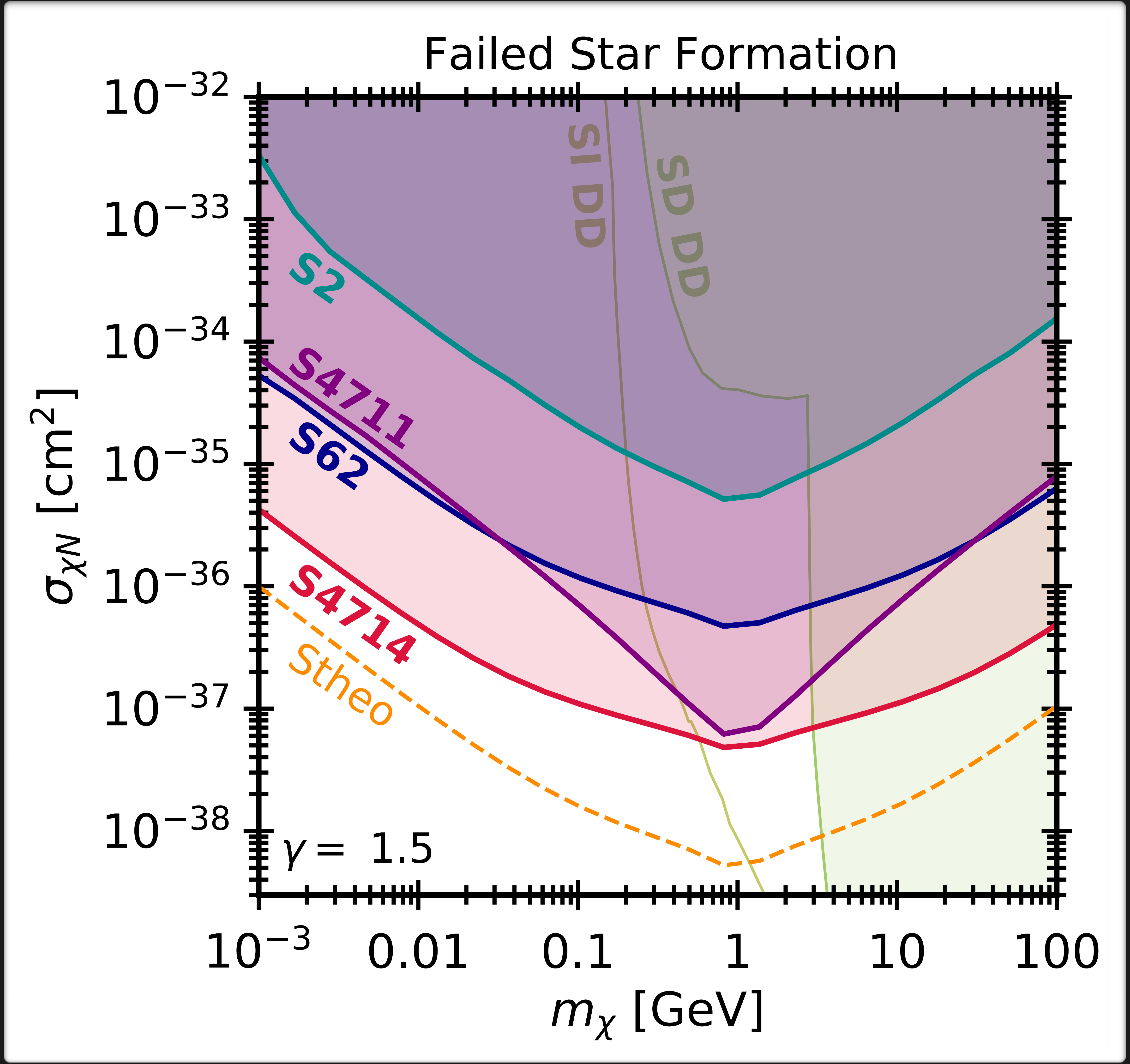
S62: 6.1 $M_\odot$
intermediate mass

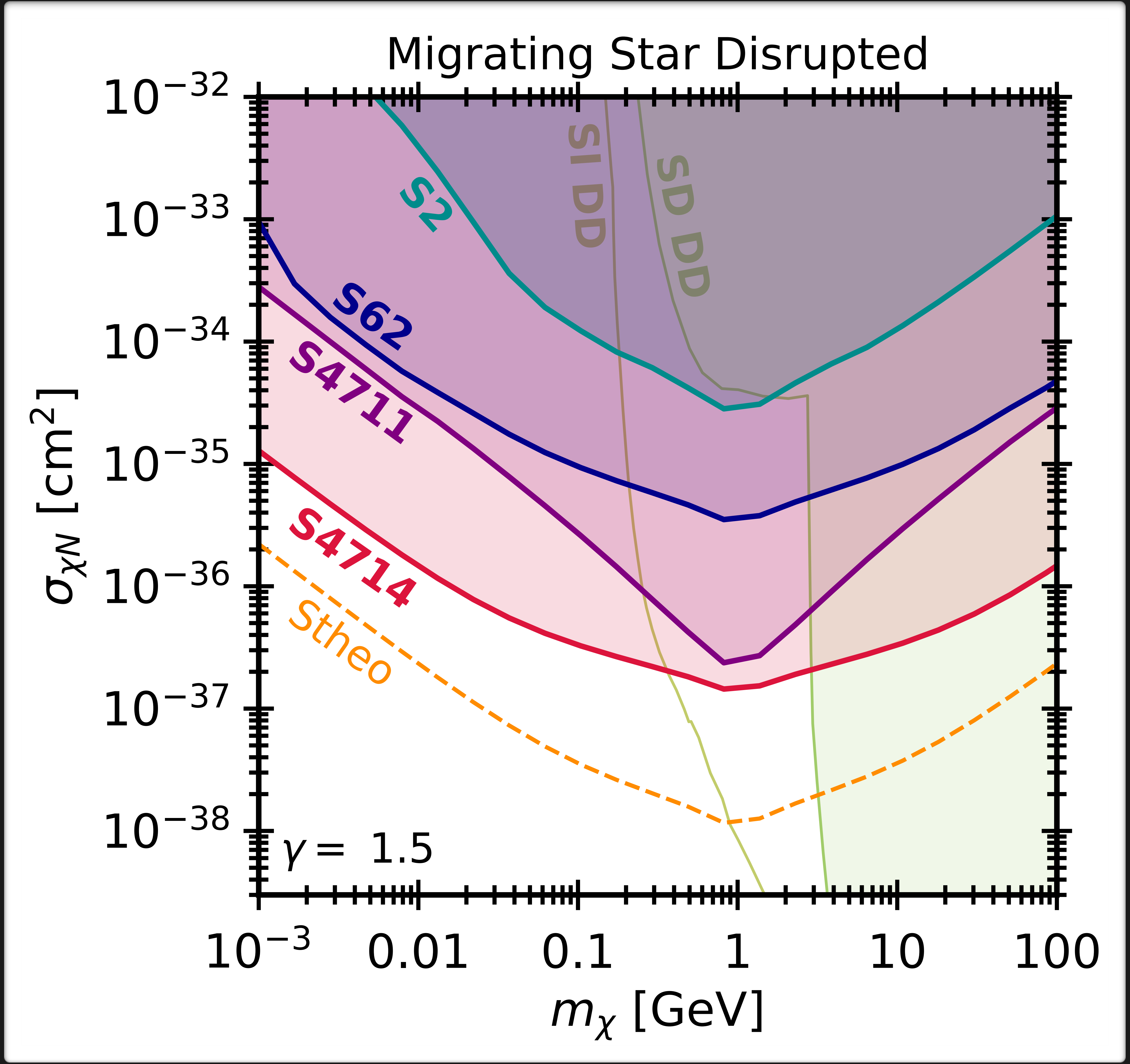
S4711: 2.2 $M_\odot$
light (fastest orbit)

S4714: 2.0 $M_\odot$
lightest (closest approach to Sgr A*)

Constraints on Scattering Cross Section

[I. John, R. Leane, T. Linden, arXiv:2311.16228]



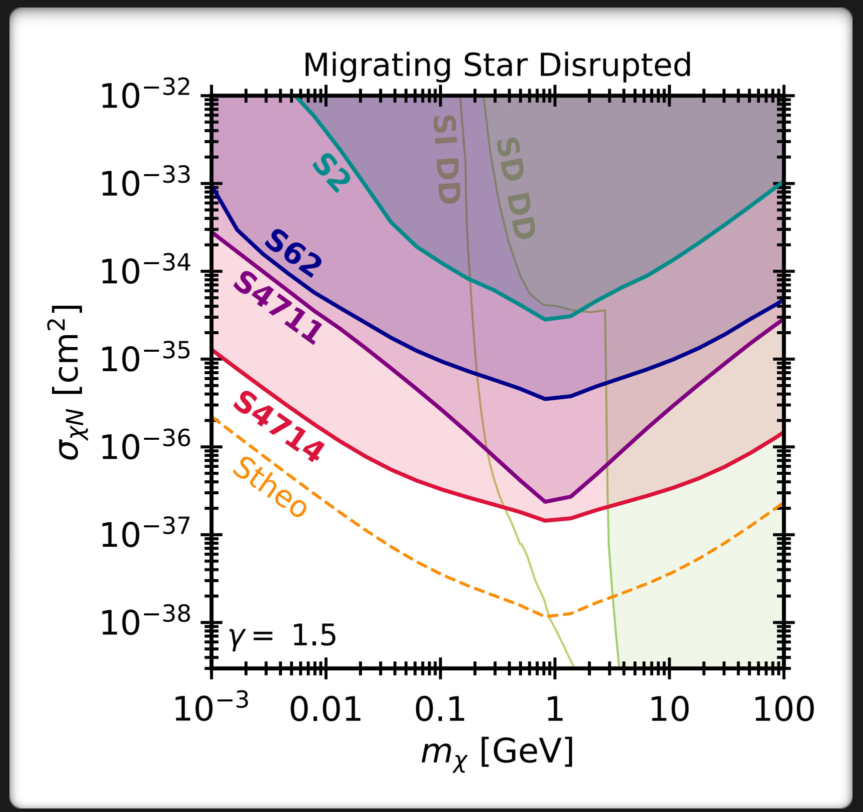


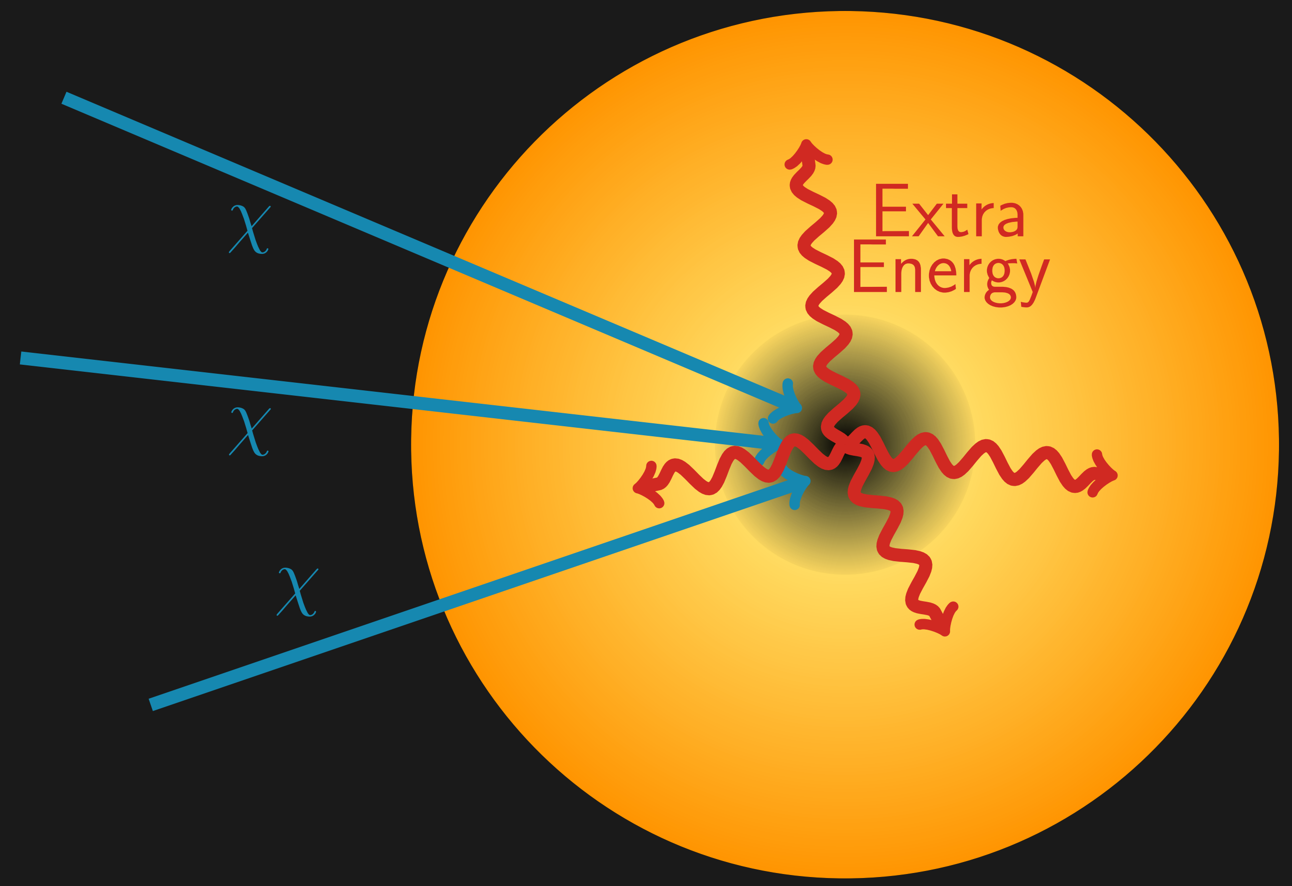
Summary and Conclusions

Stars at the Galactic Center offer a unique way to study dark matter:

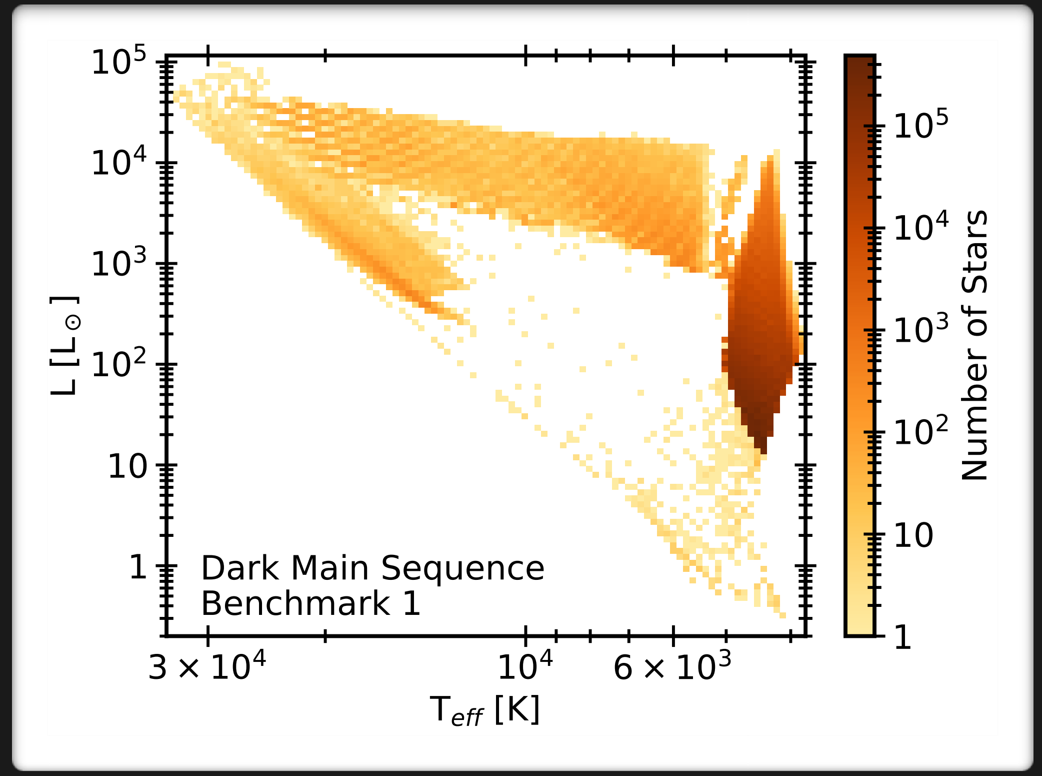
Dark matter capture and subsequent annihilation can (partially) replace nuclear fusion

Constraints on dark matter profile and scattering cross section from observed S-stars



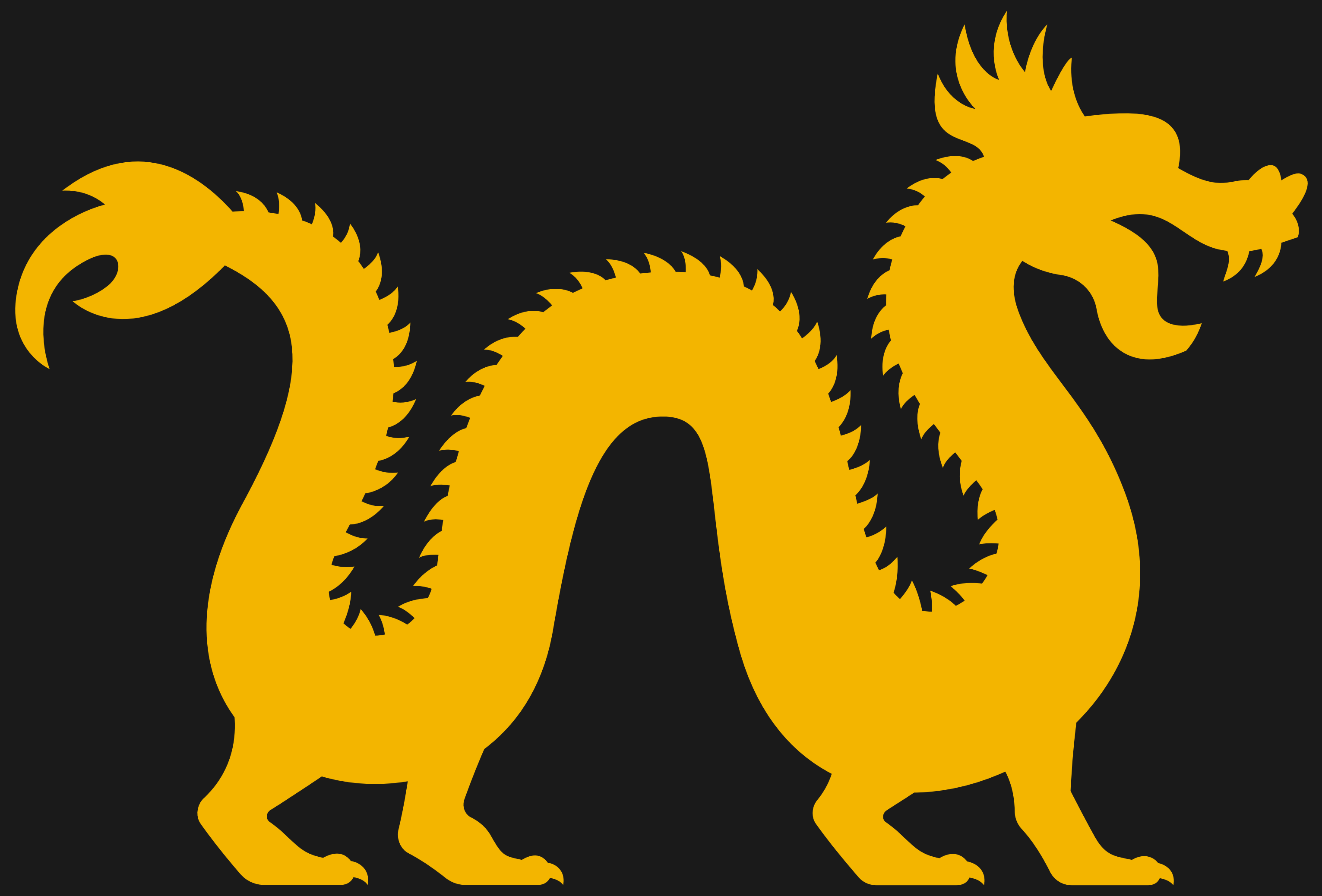


Stellar evolution is slowed down or halted: new distinct branches on HR diagram



More precise observations of S-cluster stars needed to statistically test dark main sequence

Additional Slides



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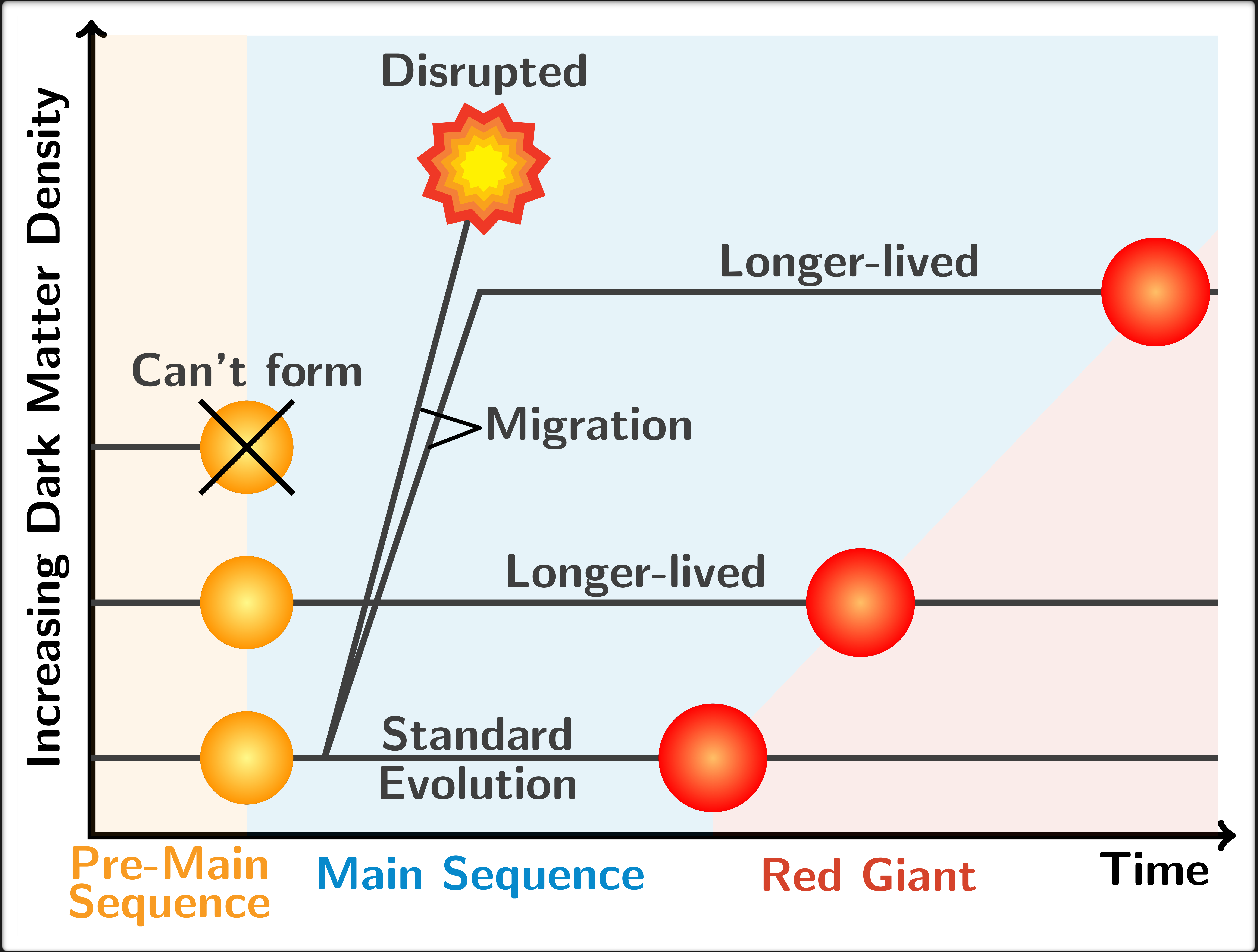

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See also Dark Stars in the early Universe:

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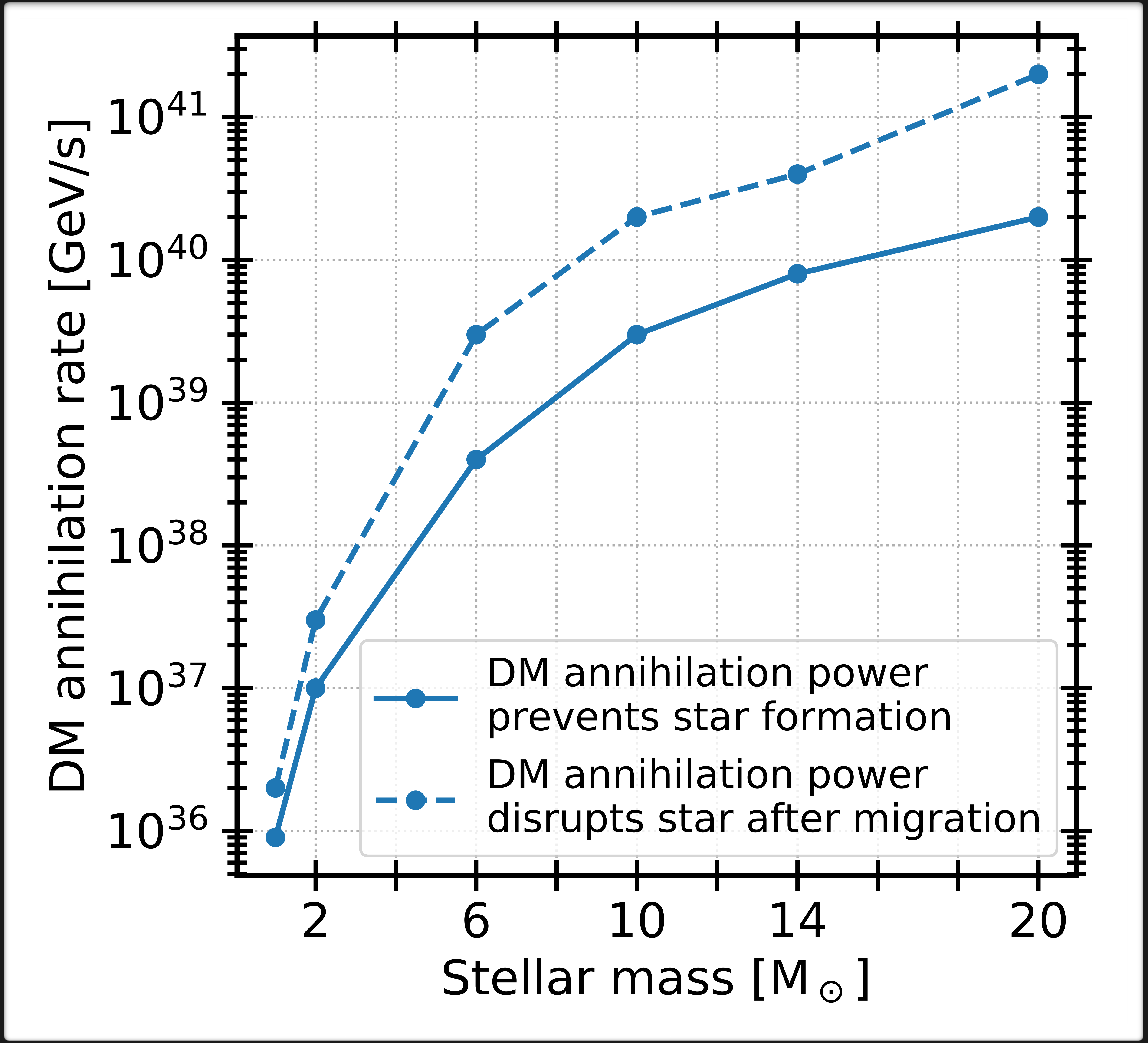
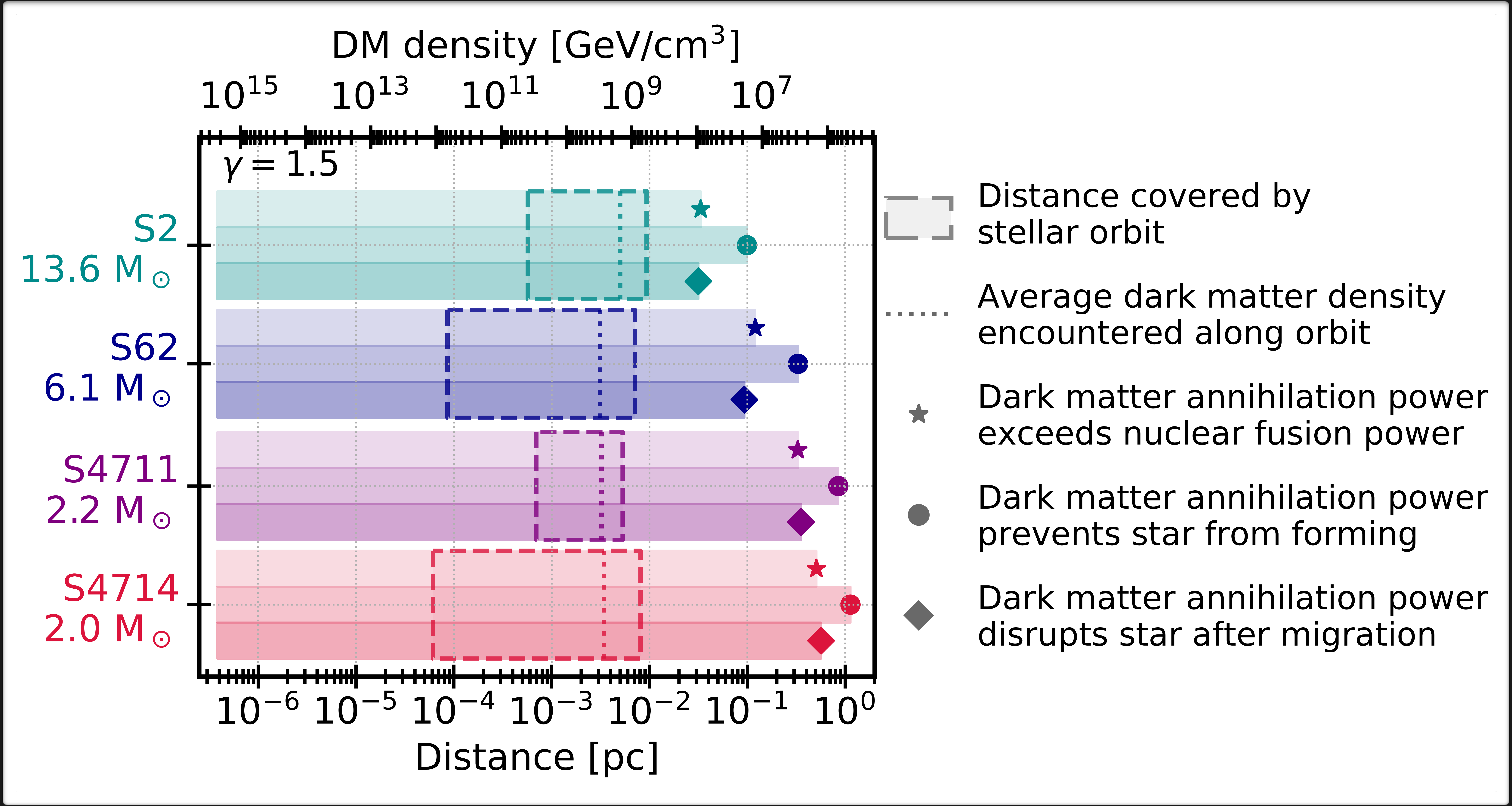
Dependence on Stellar Mass

[I. John, R. Leane, T. Linden, arXiv:2311.16228]



Dark Matter in Individual Stars

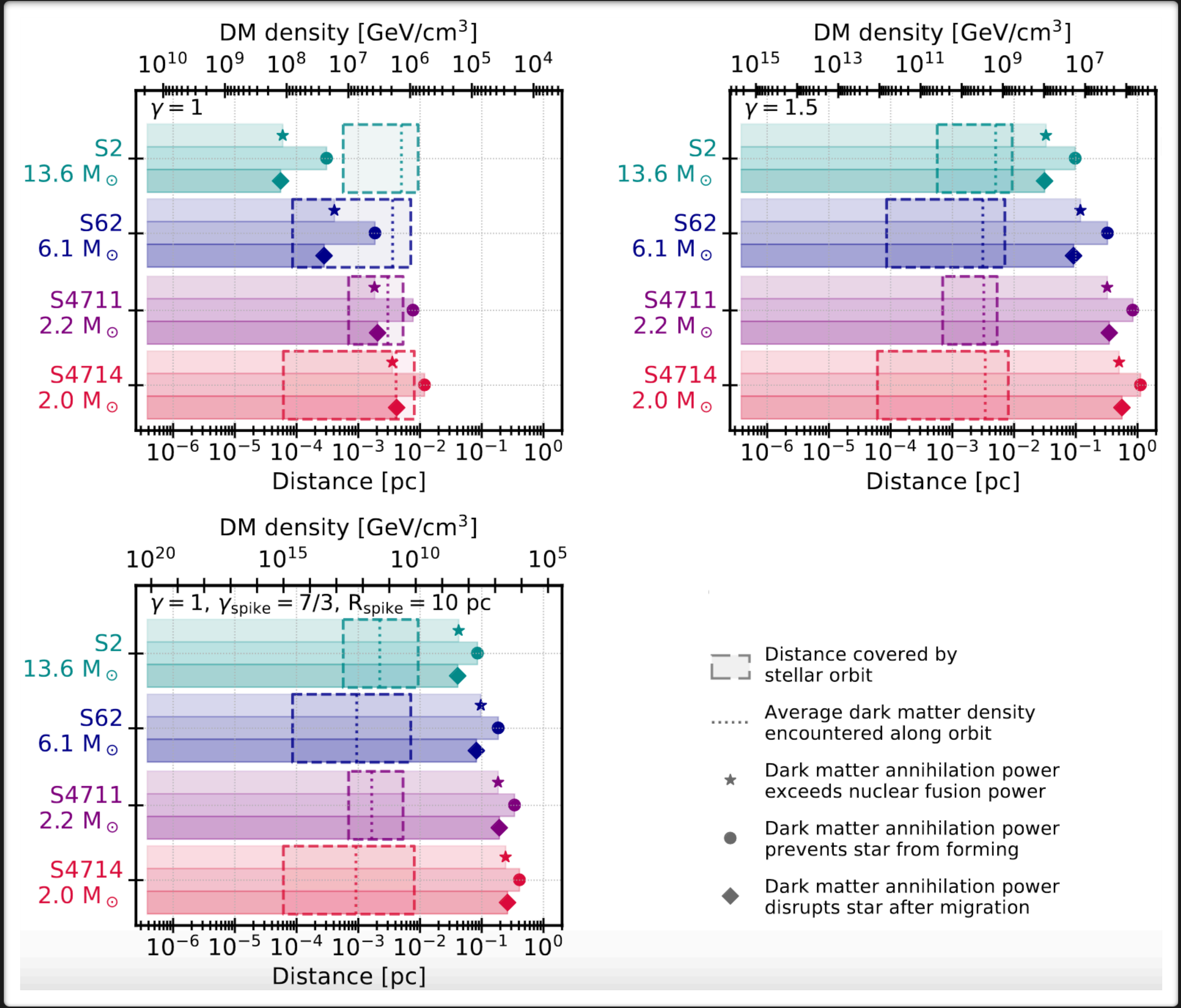
[I. John, R. Leane, T. Linden, arXiv:2311.16228]



Assuming maximum dark matter capture rate.

Effect on Stars for Different DM Profiles

[I. John, R. Leane, T. Linden, arXiv:2311.16228]



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Constraints on Dark Matter Profile

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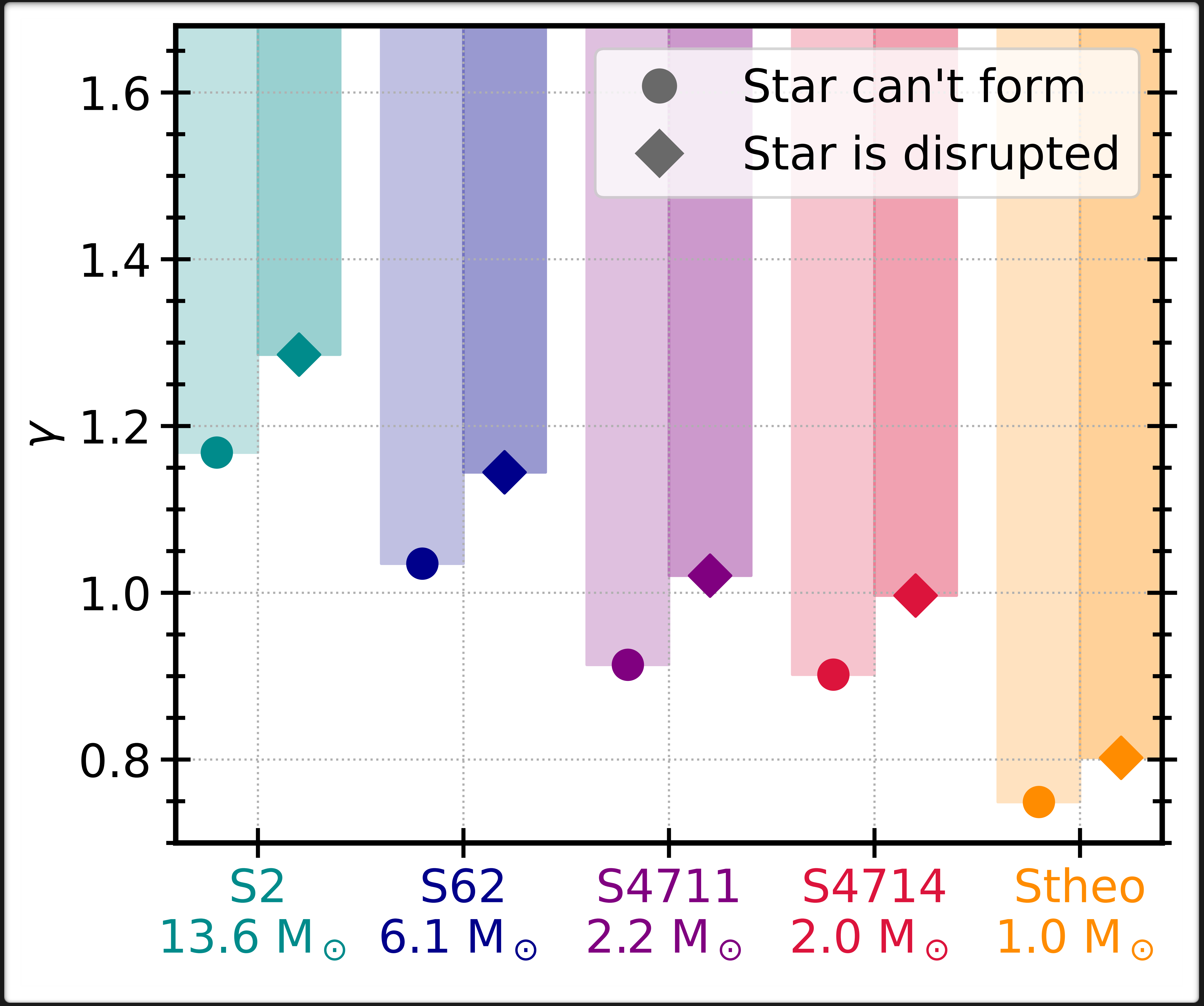
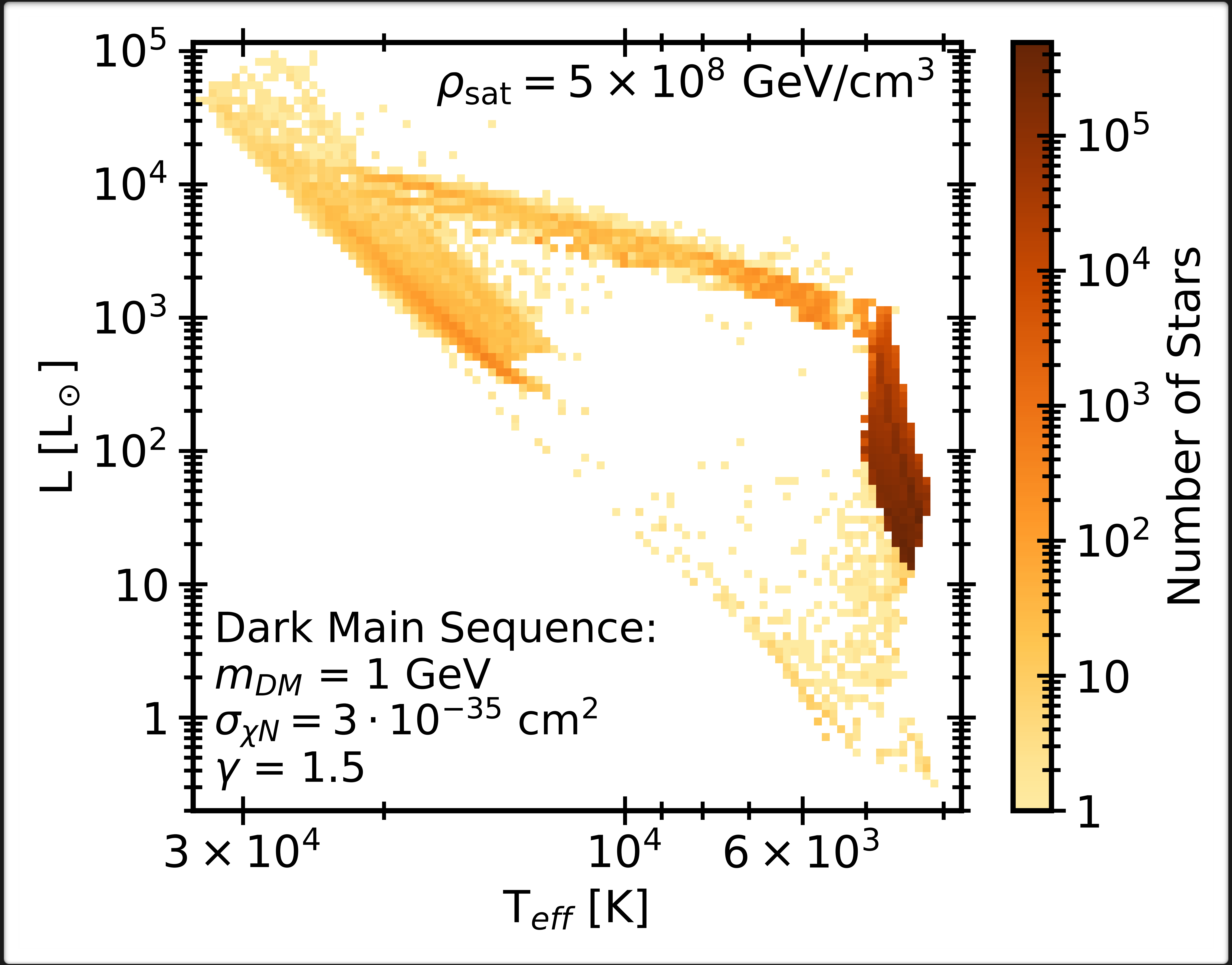


Index of generalised NFW profile

Assuming maximum dark matter capture rate.

HR Diagram with DM Density Saturation

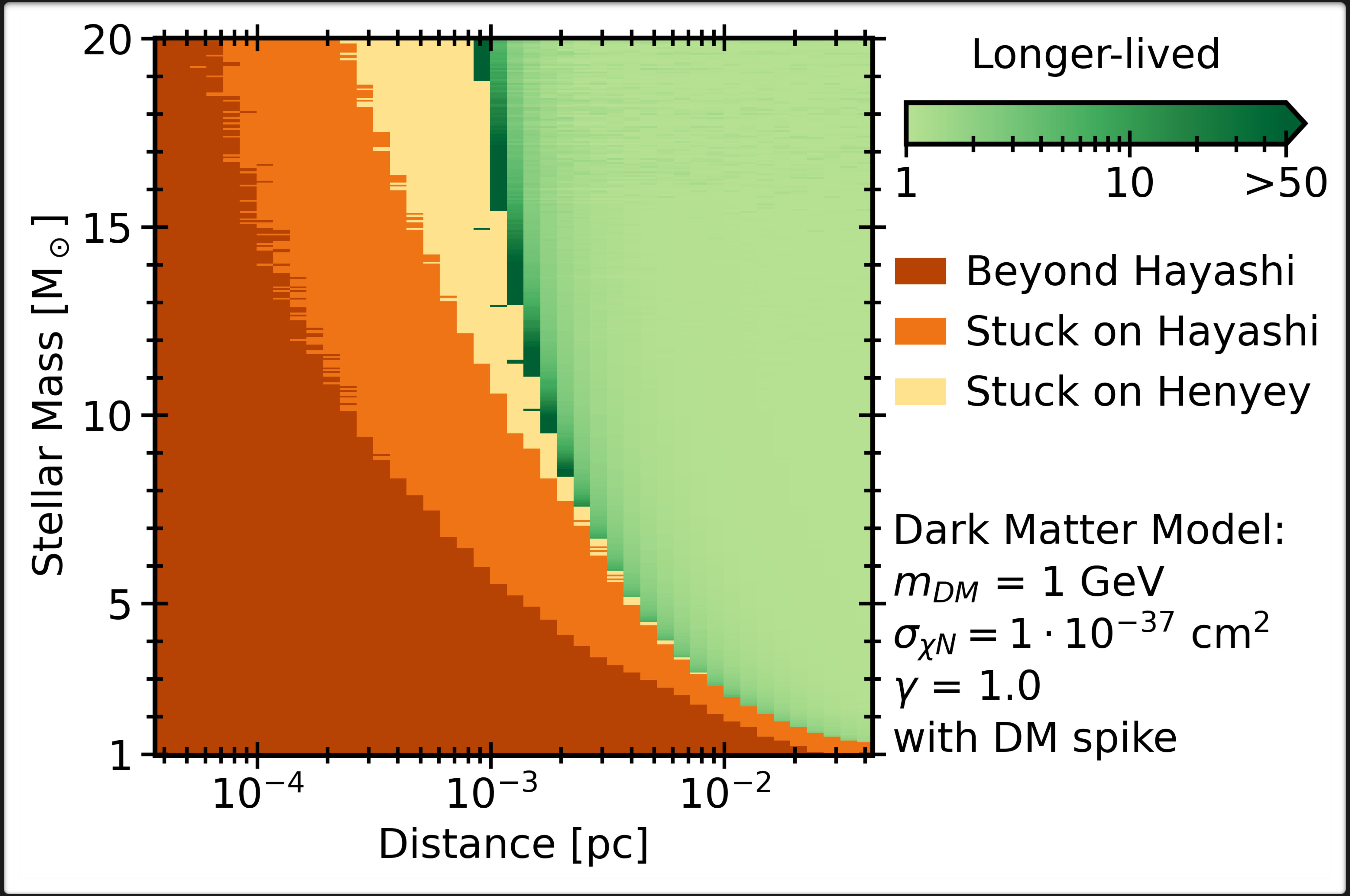
[I. John, R. Leane, T. Linden, arXiv:2405.12267]



- Dark matter density can saturate due to dark matter self-annihilation in the Galaxy
- Example for dark matter saturation limit (maximum dark matter density): 5×10^8 GeV/cm^3

Dark Matter Slows Stellar Evolution

[I. John, R. Leane, T. Linden, arXiv:2405.12267]



Benchmark Model 2:

- Dark matter density spike model from [Lacroix, arXiv:1801.01308]
- Scattering cross section: $10^{-37}\mathrm{cm}^2$

Dark Main Sequence for Benchmark 2 (DM Spike Model)

[I. John, R. Leane, T. Linden, arXiv:2405.12267]