Immortal Stars at the Galactic Center

arXiv:2311.16228 & arXiv:2405.12267

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Together with
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and
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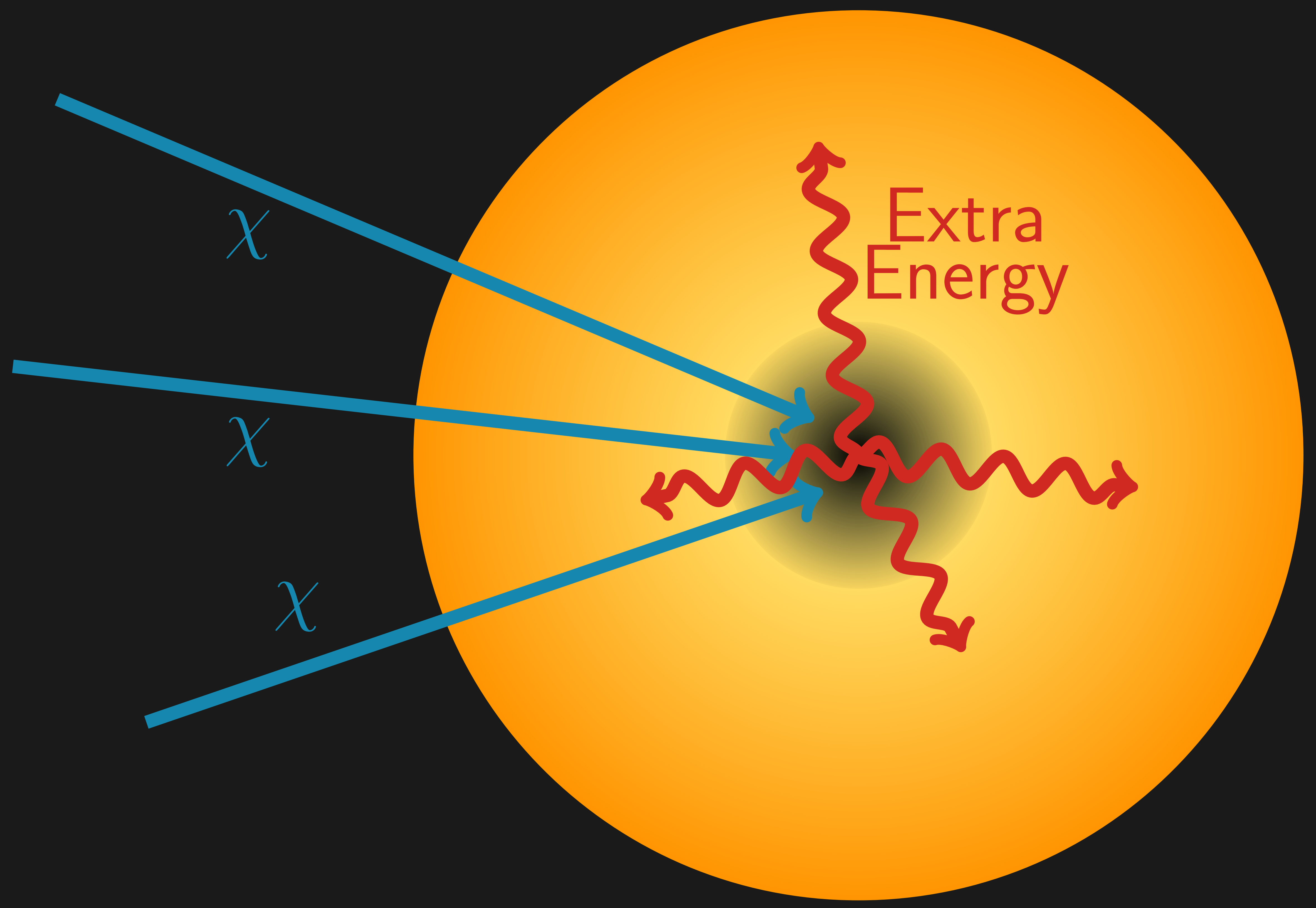
10 July 2024
Identification of Dark Matter
L'Aquila

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
- Dark matter-nucleon scattering
- Dark matter annihilation through short-lived mediator (decays inside star)

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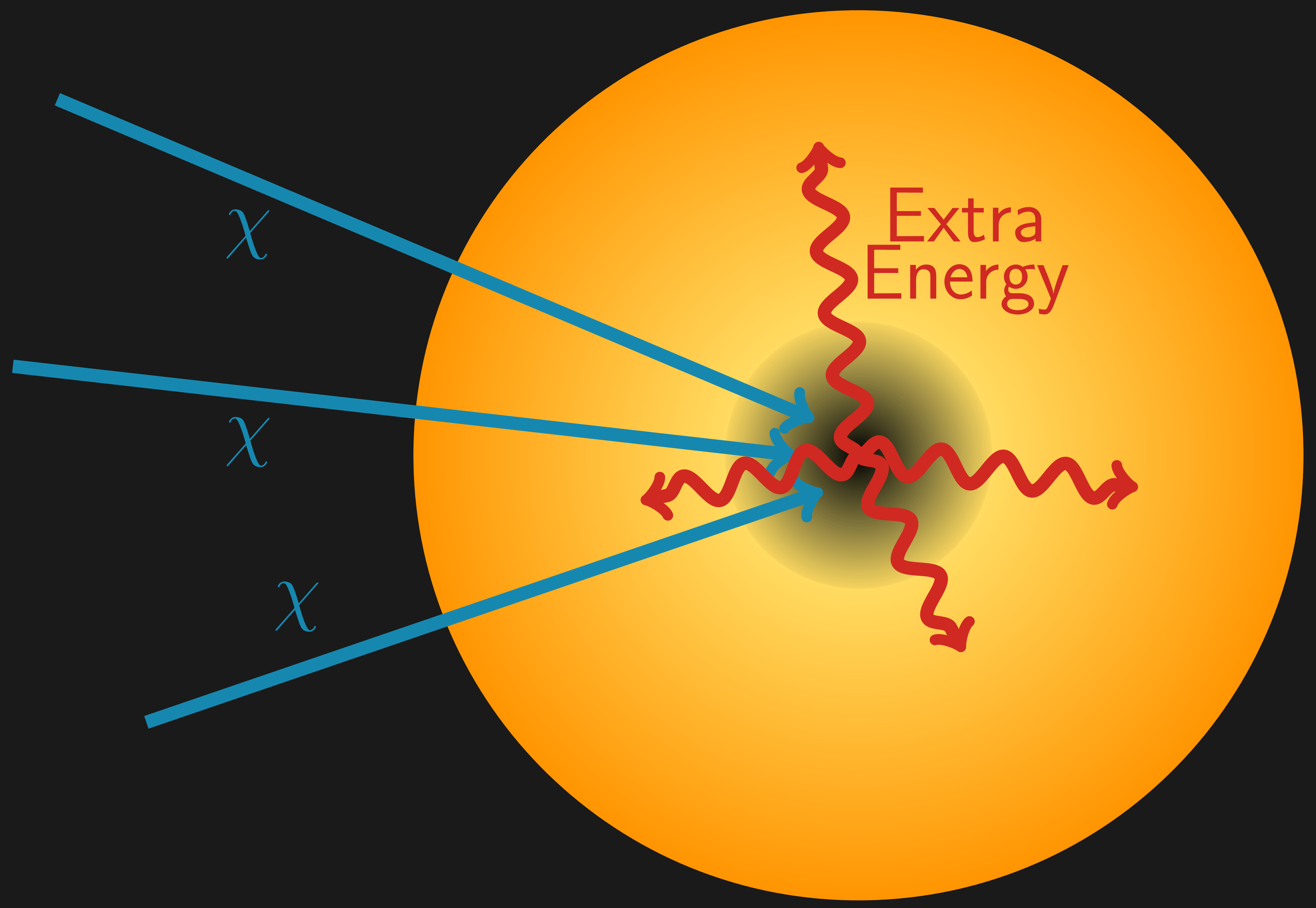
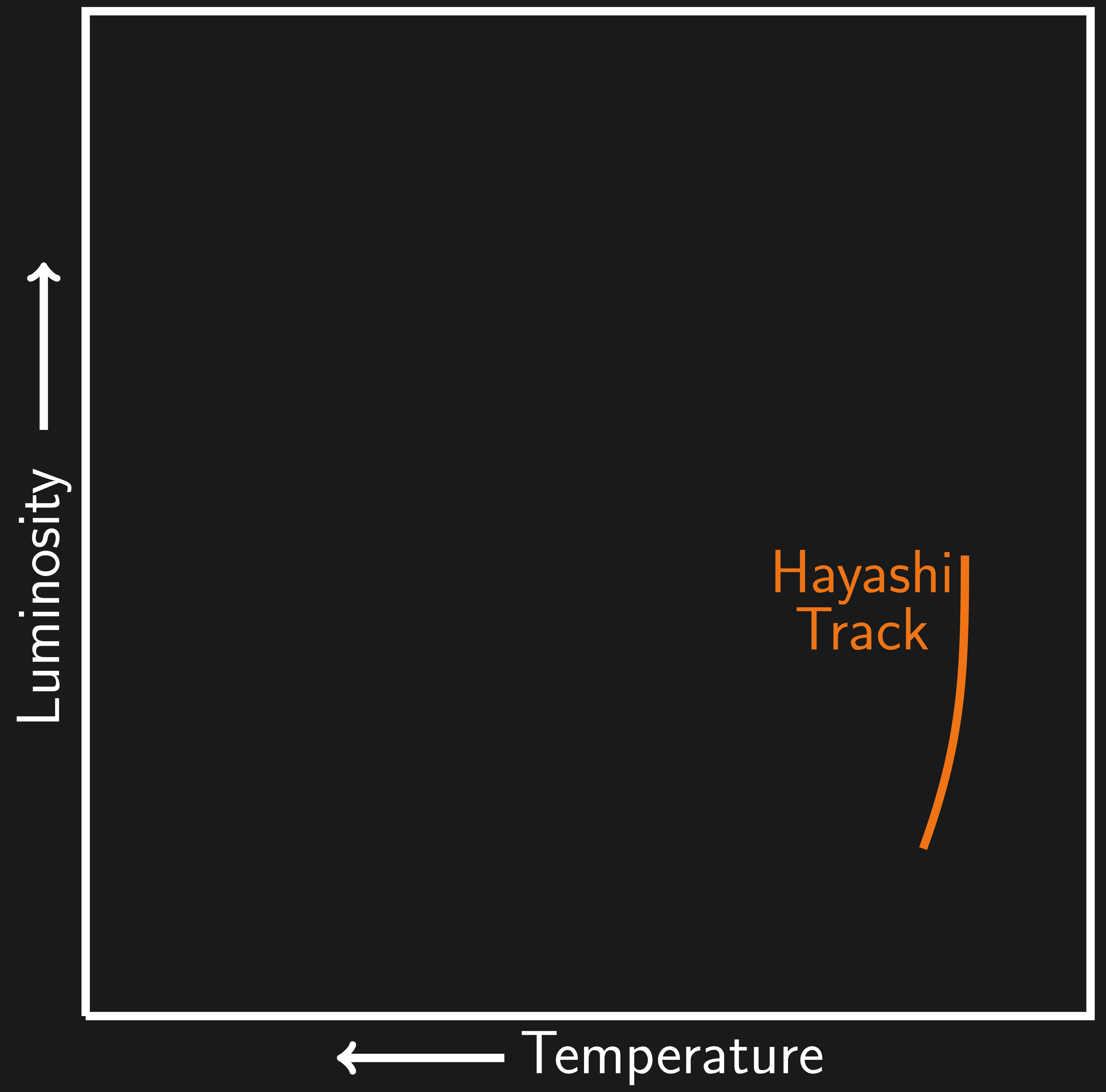


Optimal capture rate:

- High nucleon density: capture DM more efficiently
- Large radius: encounter more DM
- High dark matter density: Galactic Center

Stellar Evolution Stages on HR Diagram

Hertzsprung–Russell (HR) Diagram



Hayashi track: newly forming star contracts

Stellar Evolution Stages on HR Diagram

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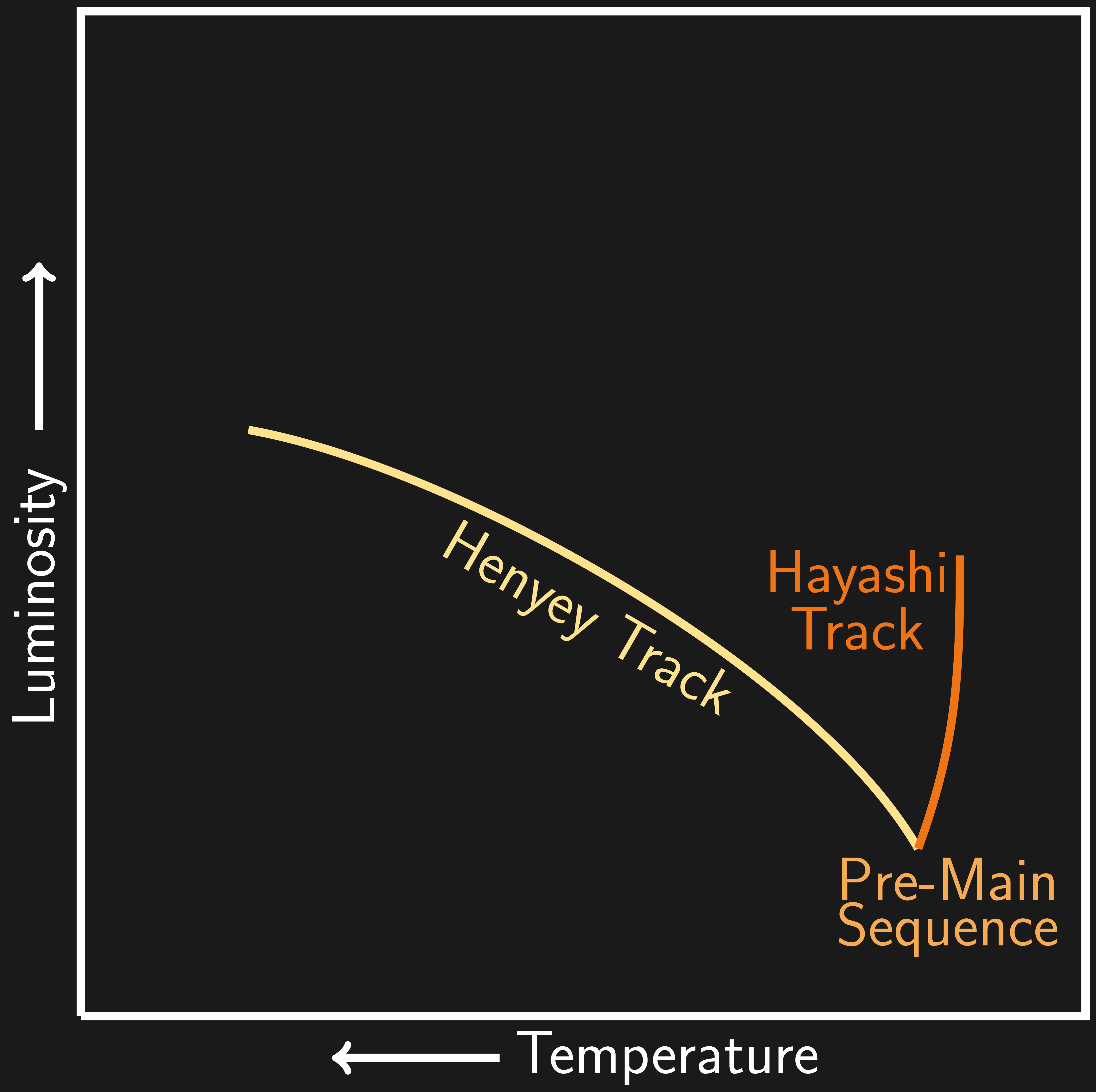
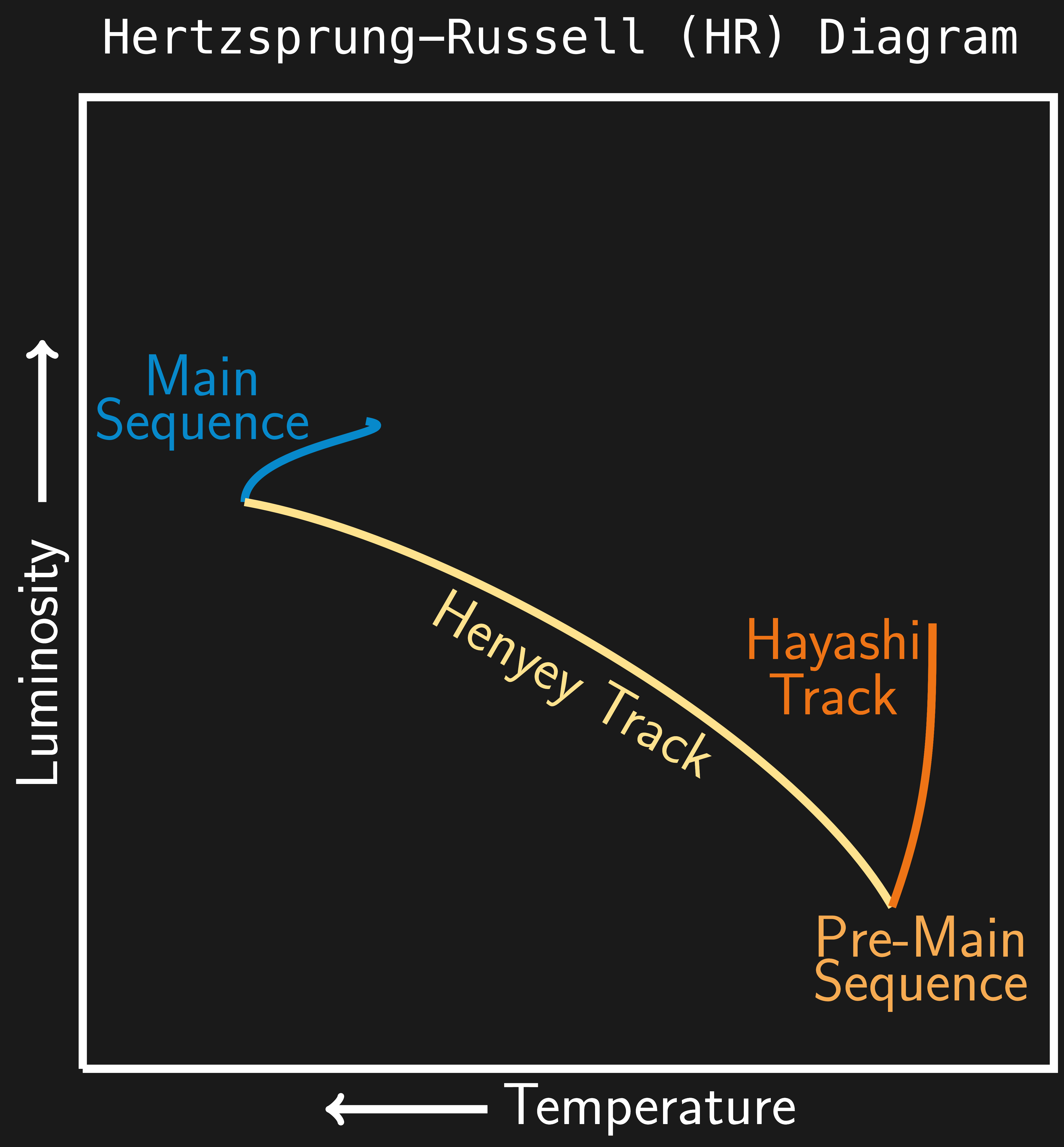


Hayashi track: newly forming star contracts

Henyey track: hydrogen fusion starts

Stellar Evolution Stages on HR Diagram



Hayashi track: newly forming star contracts

Henyey track: hydrogen fusion starts

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

Stellar Evolution Stages on HR Diagram

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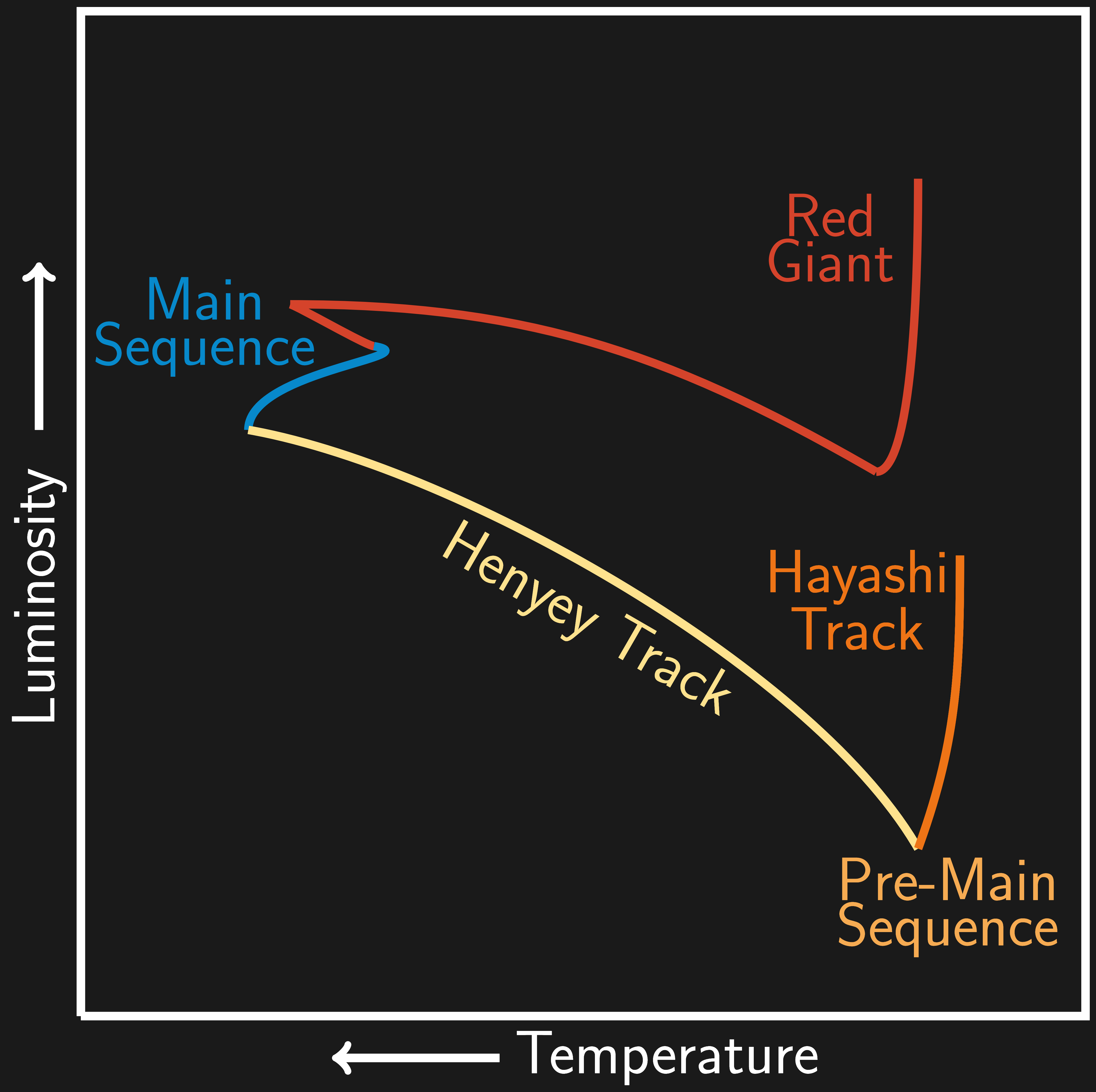


Hayashi track: newly forming star contracts

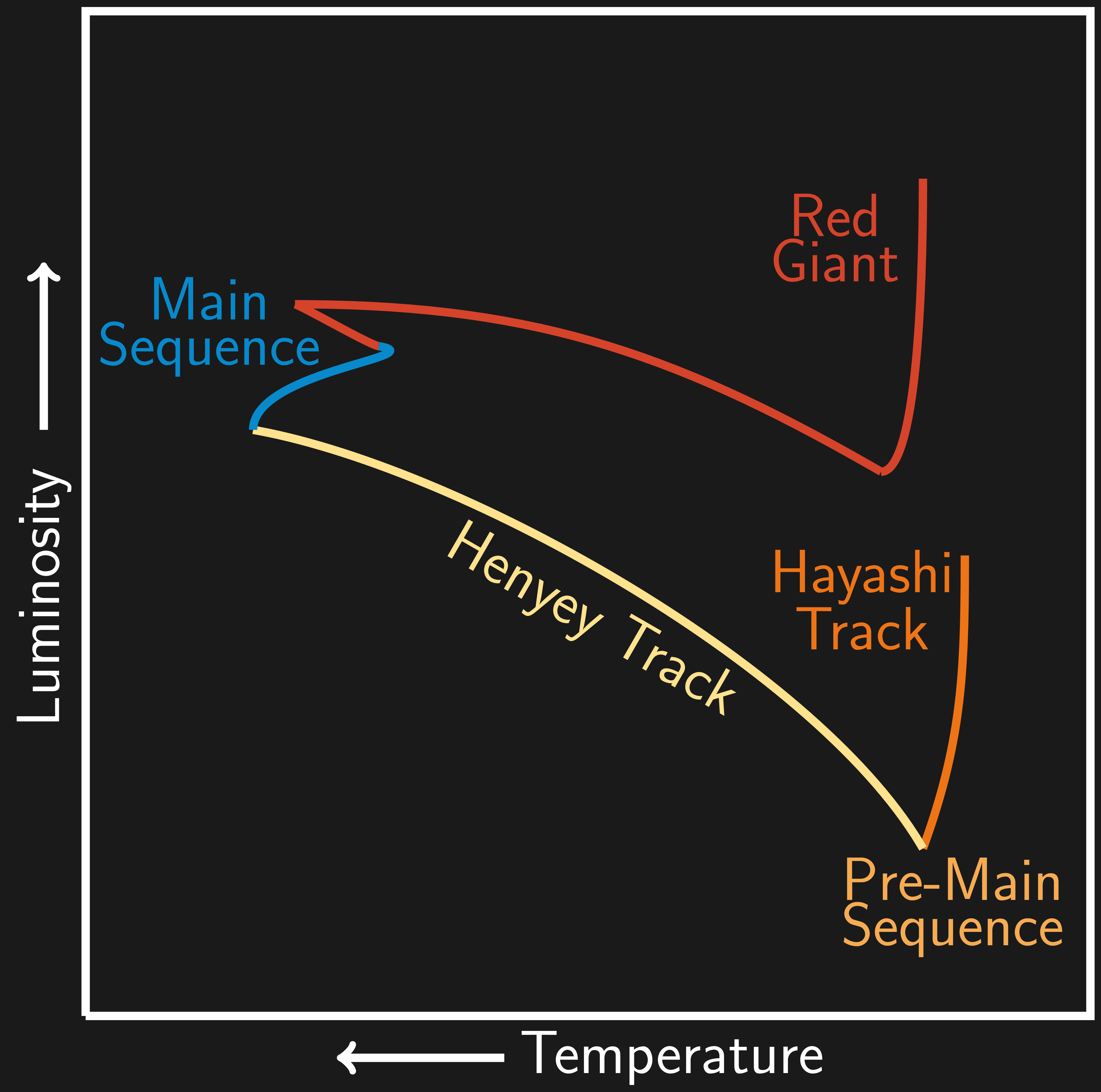
Henyey track: hydrogen fusion starts

Main sequence: star has reached 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

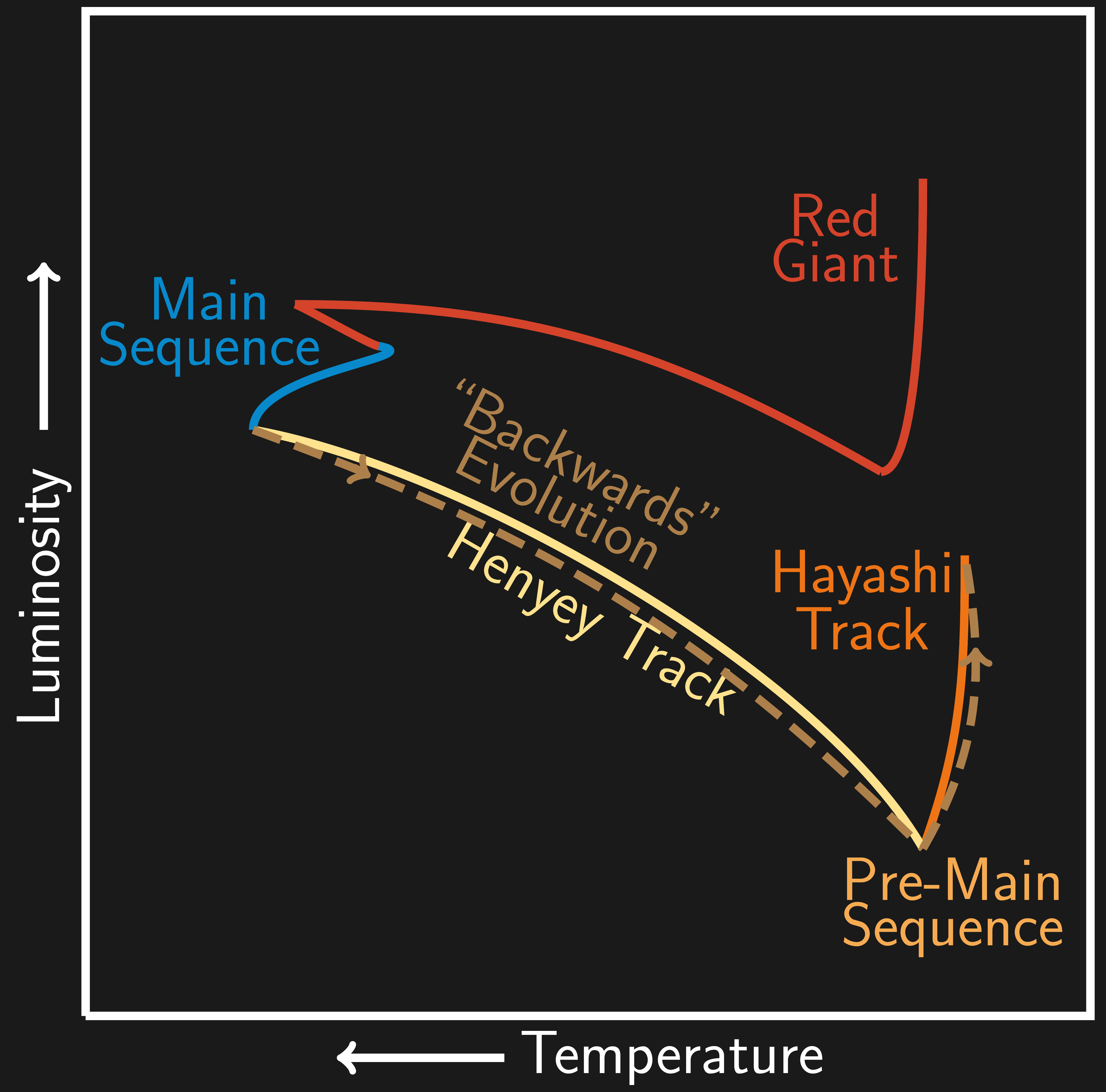
Hertzsprung–Russell (HR) Diagram



- Dark matter burning can provide similar pressure to balance gravitational force and create stable hydrostatic equilibrium

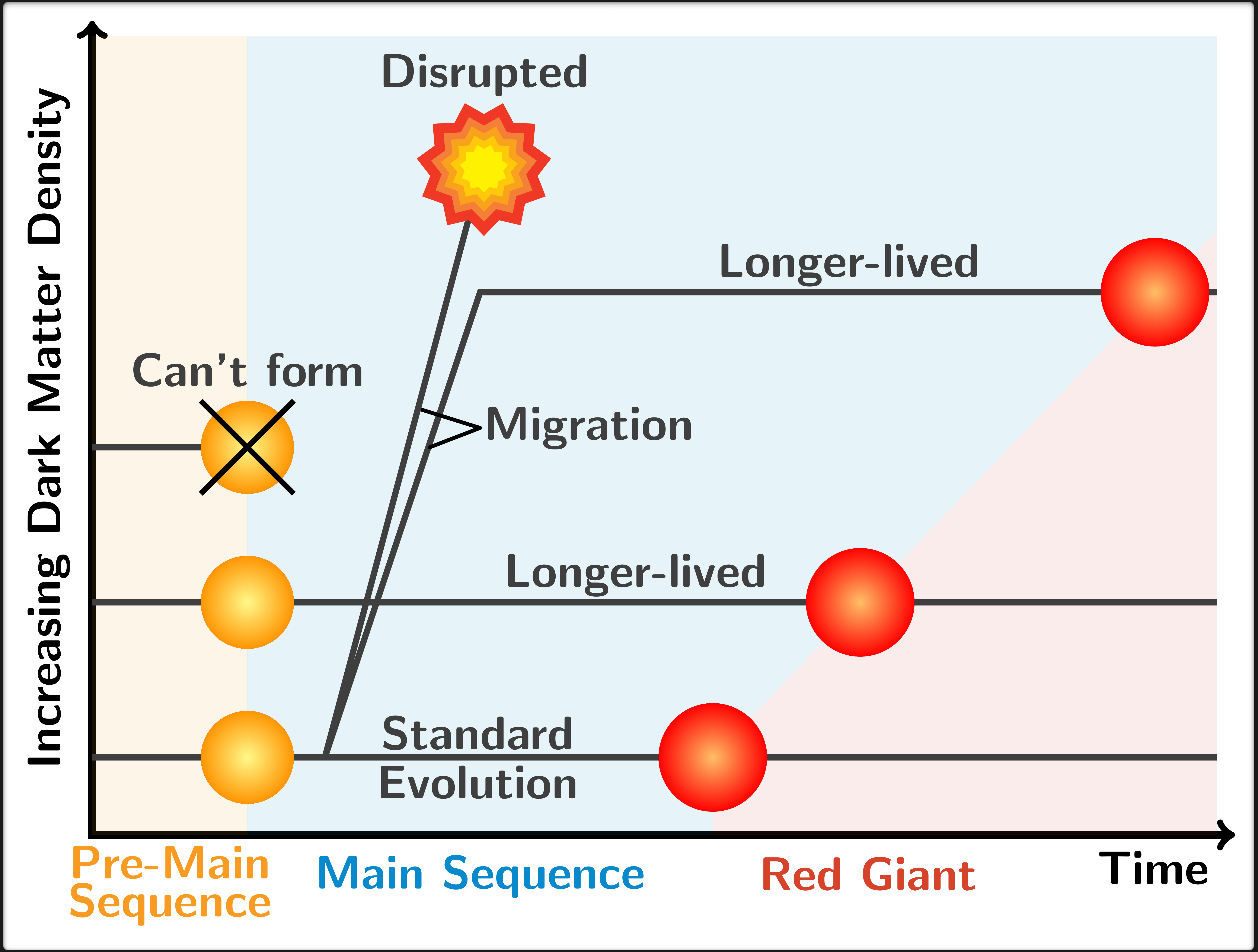
Dark Matter Changes Stellar Evolution

Hertzsprung–Russell (HR) Diagram



- Dark matter burning can provide similar pressure to balance gravitational force and create stable hydrostatic equilibrium
- Stars can evolve "backwards"

Dark Matter Changes Stellar Evolution



See also:

Salati & Silk 1989

Fairbairn, Scott & Edsjö arXiv:0710.3396

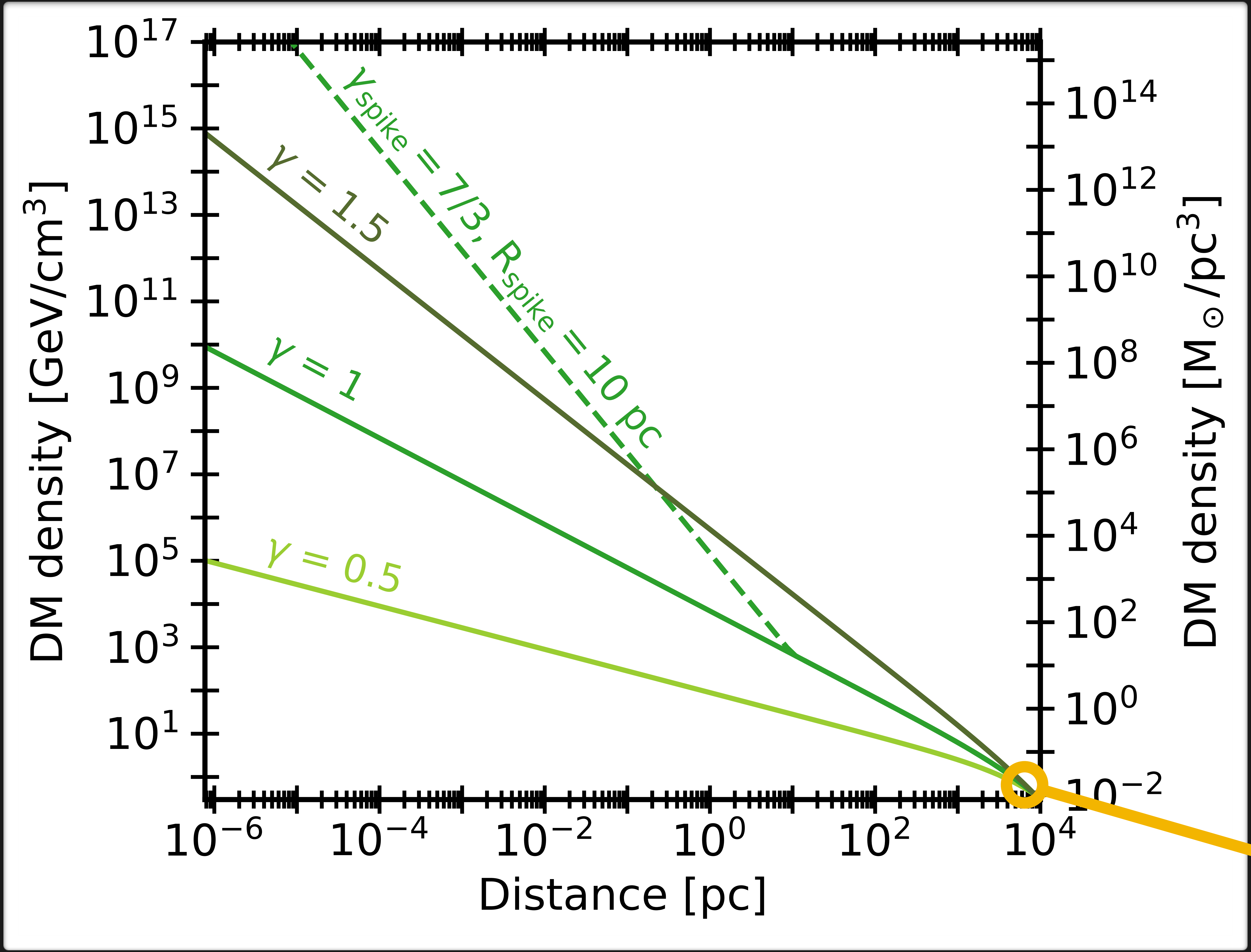
Scott, Fairbairn & Edjsö arXiv:0809.1871

See also Dark Stars in the early Universe:

Iocco, arXiv:0802.0941

Freese et al, arXiv:0805.3540

Galactic Dark Matter Density and Profile



Dark matter density at Galactic Center is

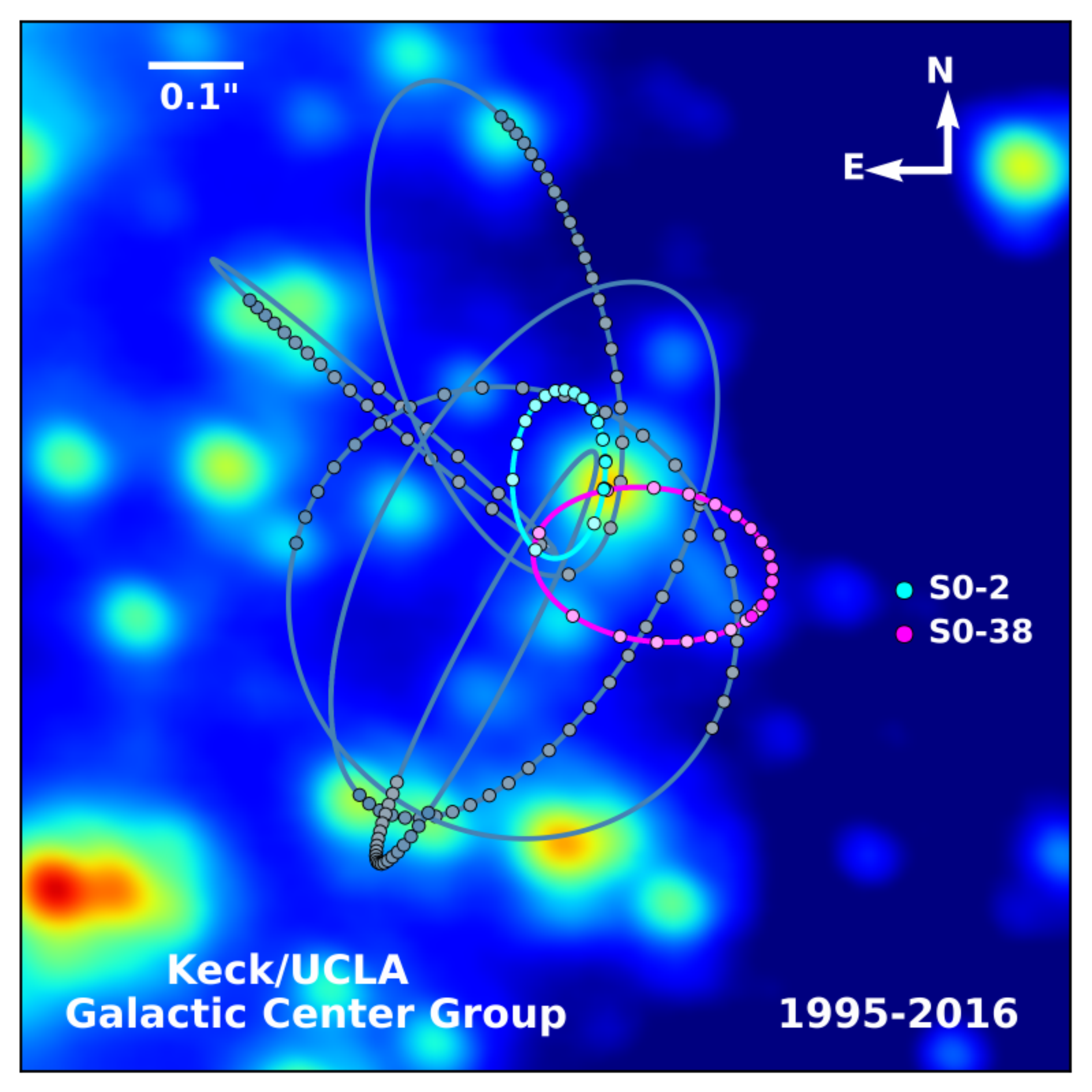
- Very high: significant dark matter capture in stars
- Very uncertain: test dark matter profile models

Local dark matter density: 0.4 GeV/cm^3

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



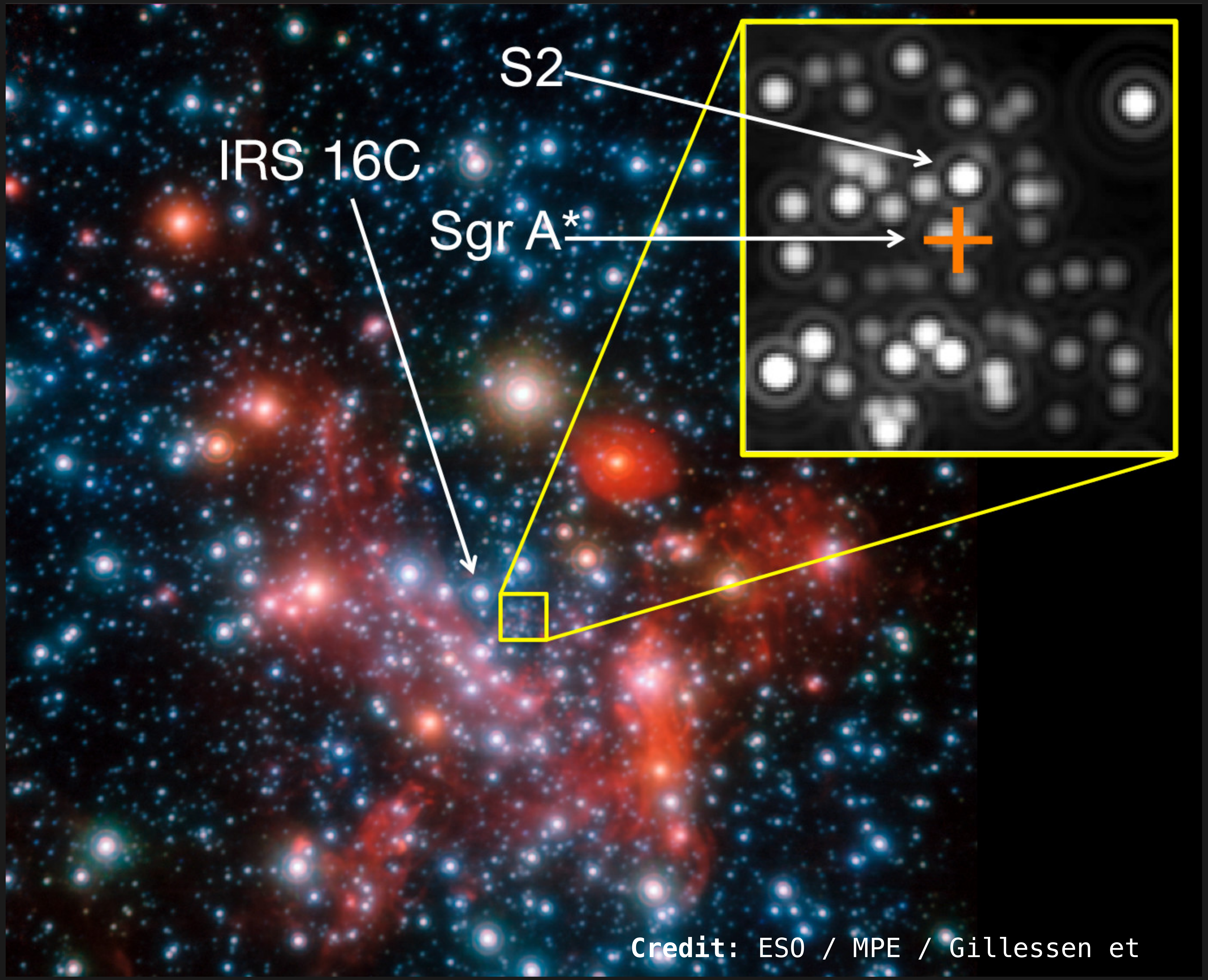
Unusual Properties of S–Cluster Stars

Origin not well understood: in situ formation or migration?

Paradox of Youth: Spectroscopically old but bright as young stars

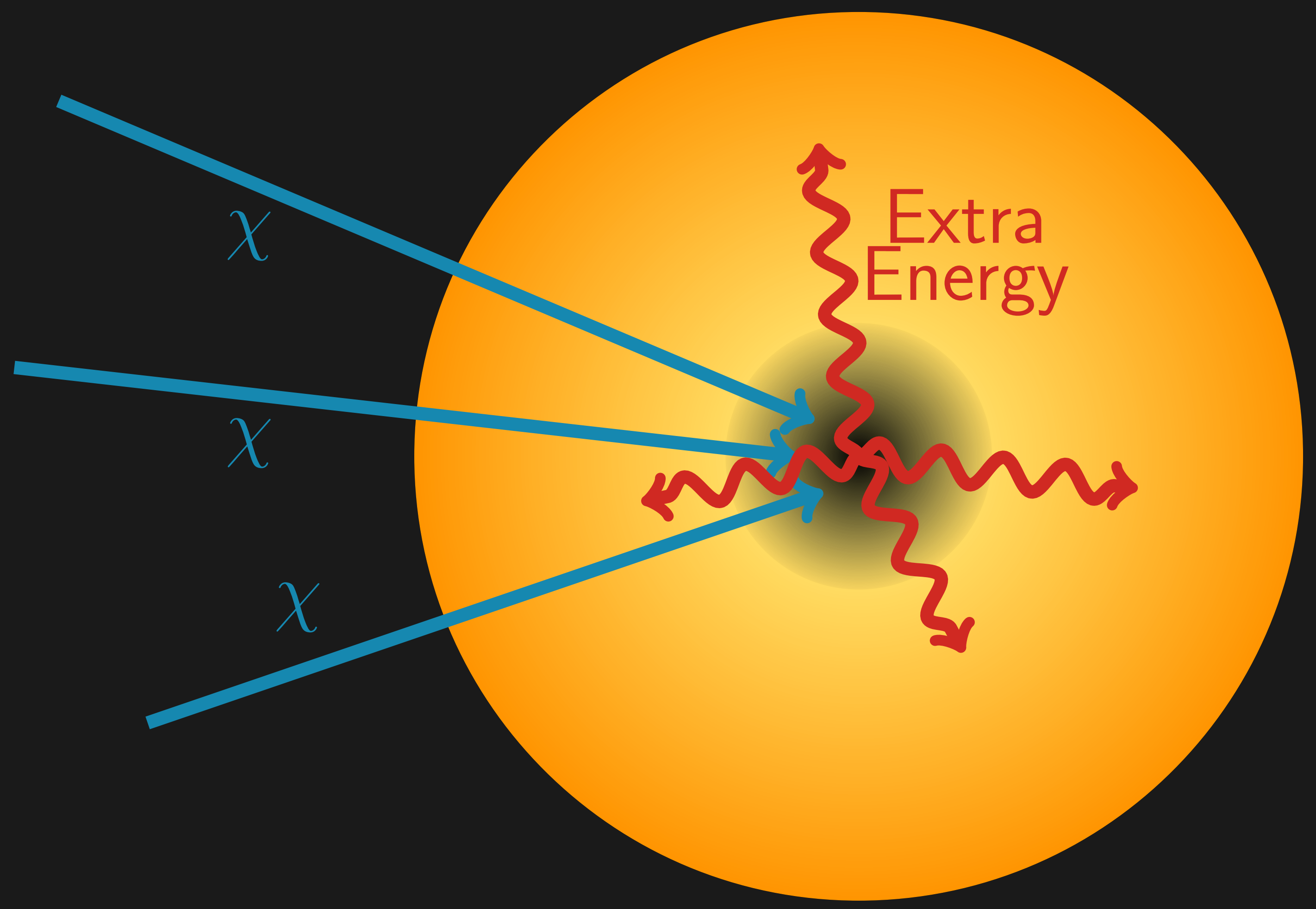
Conundrum of Old Age: Lack of old stars

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



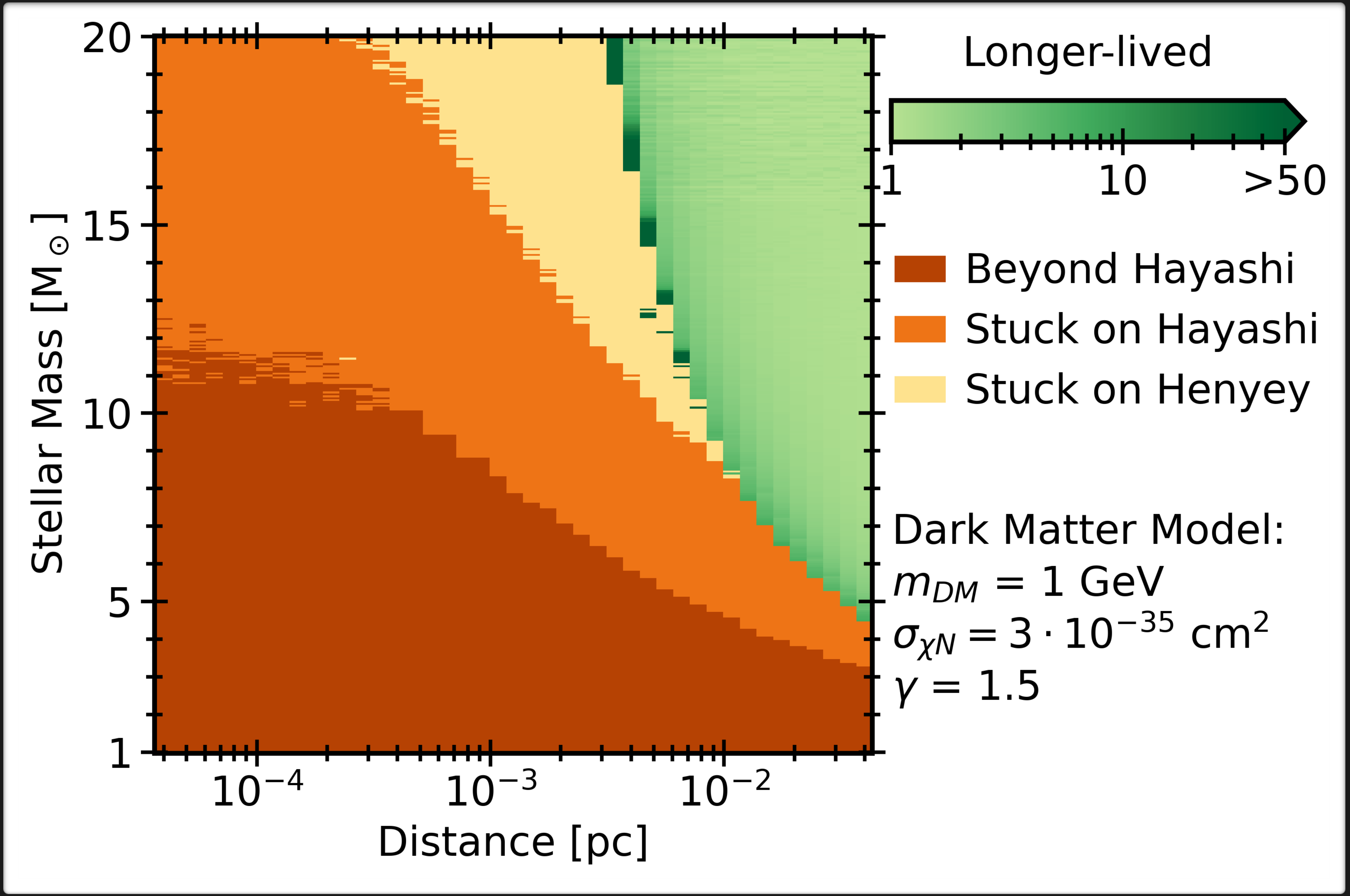
Modelling Stellar Evolution with Dark Matter

- 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]



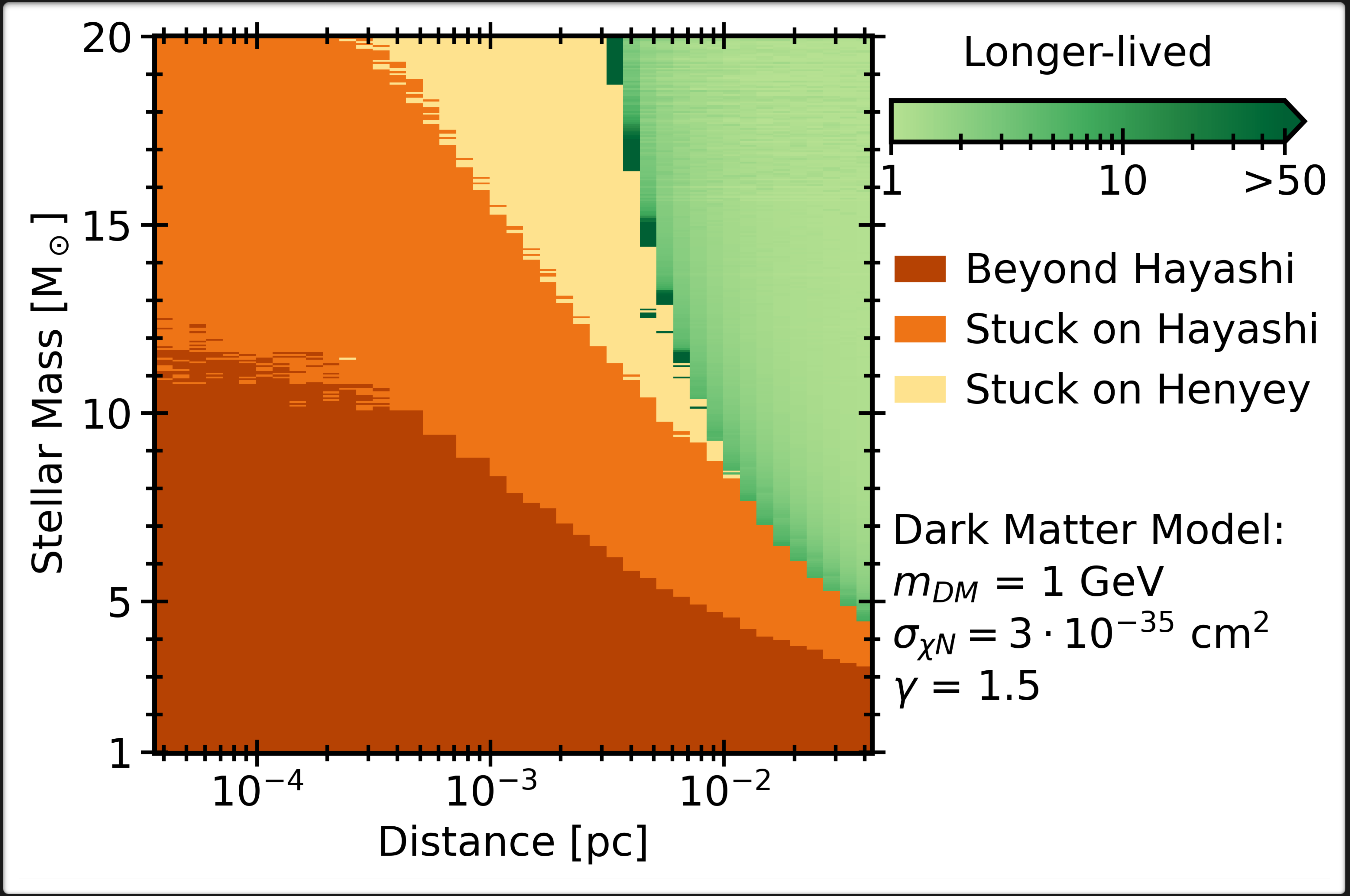
Evolutionary stage after main sequence or 10 billion years.

Effects depend on:

- Stellar mass
- Dark matter density

Dark Matter Slows Stellar Evolution

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



Longer–lived

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

Dark Matter Slows Stellar Evolution

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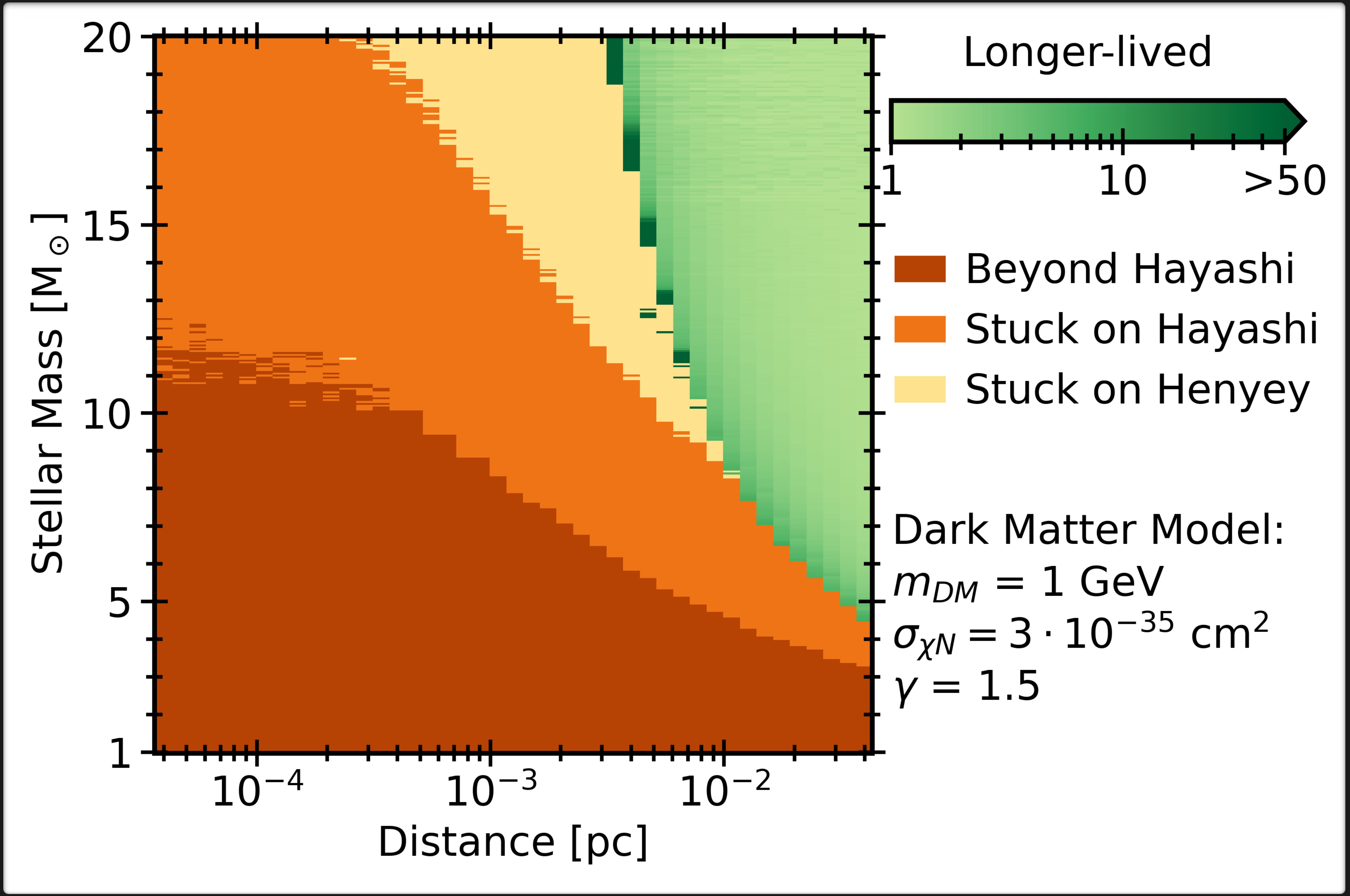
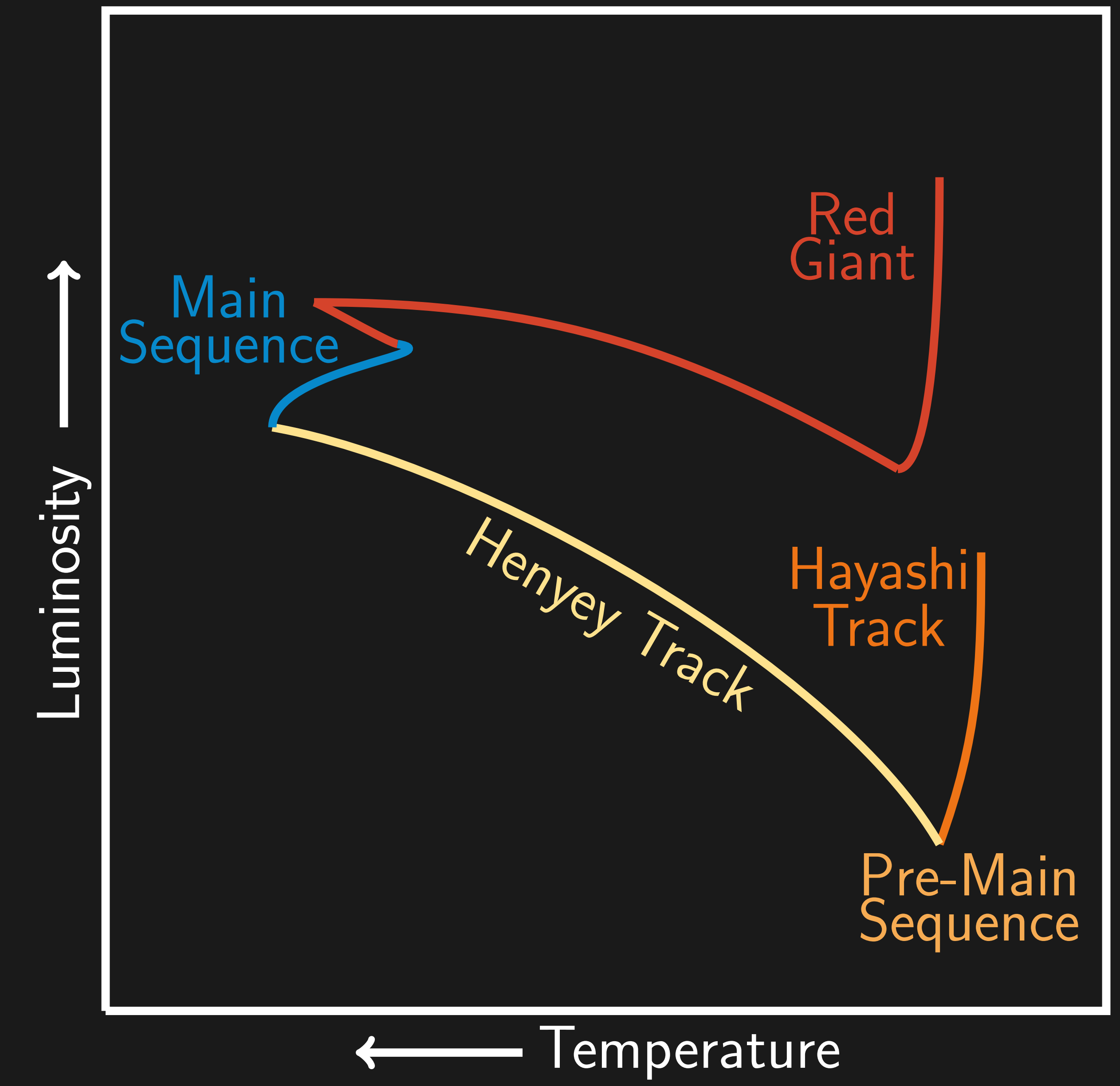


Stuck on Henyey

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



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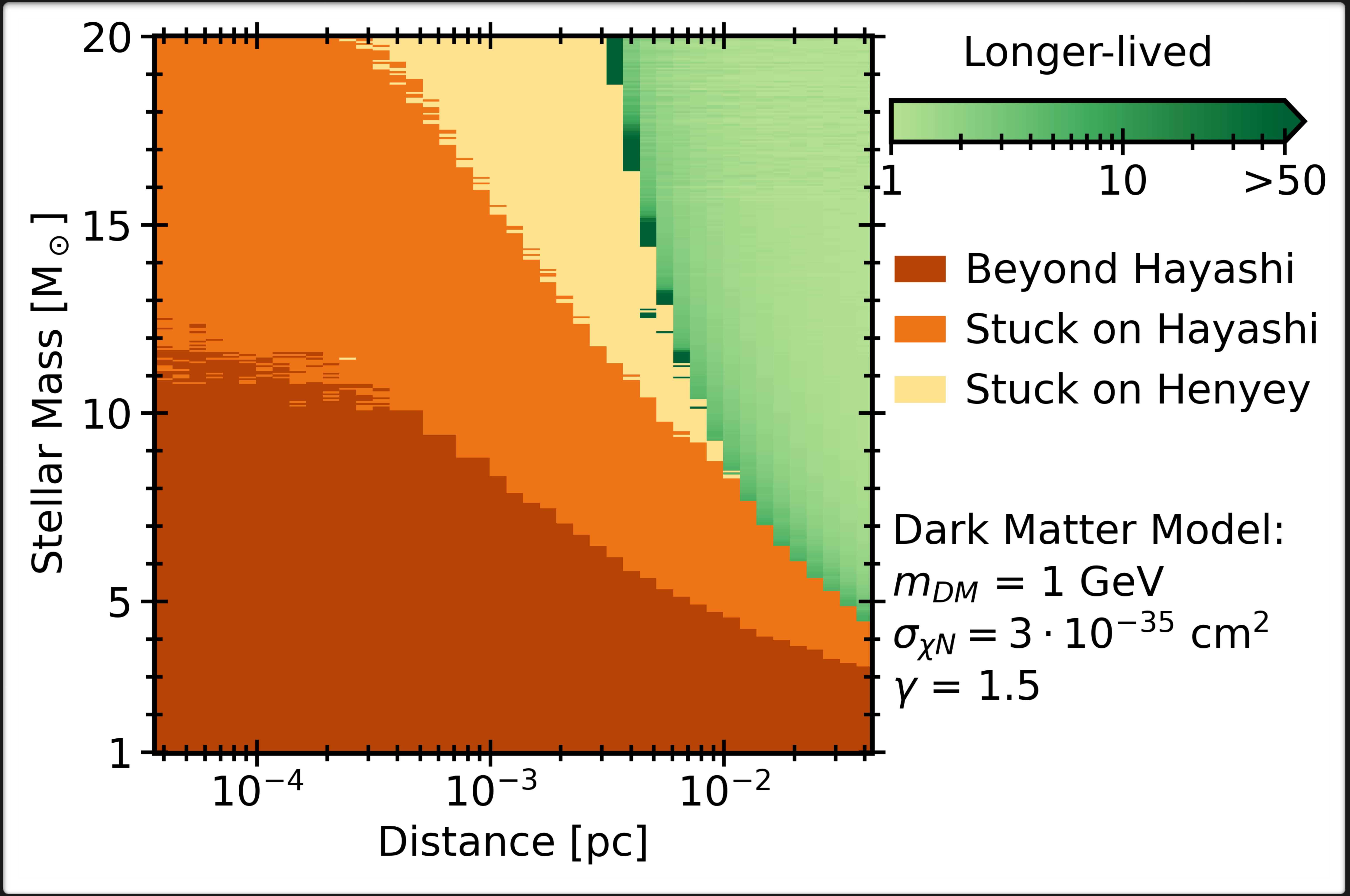
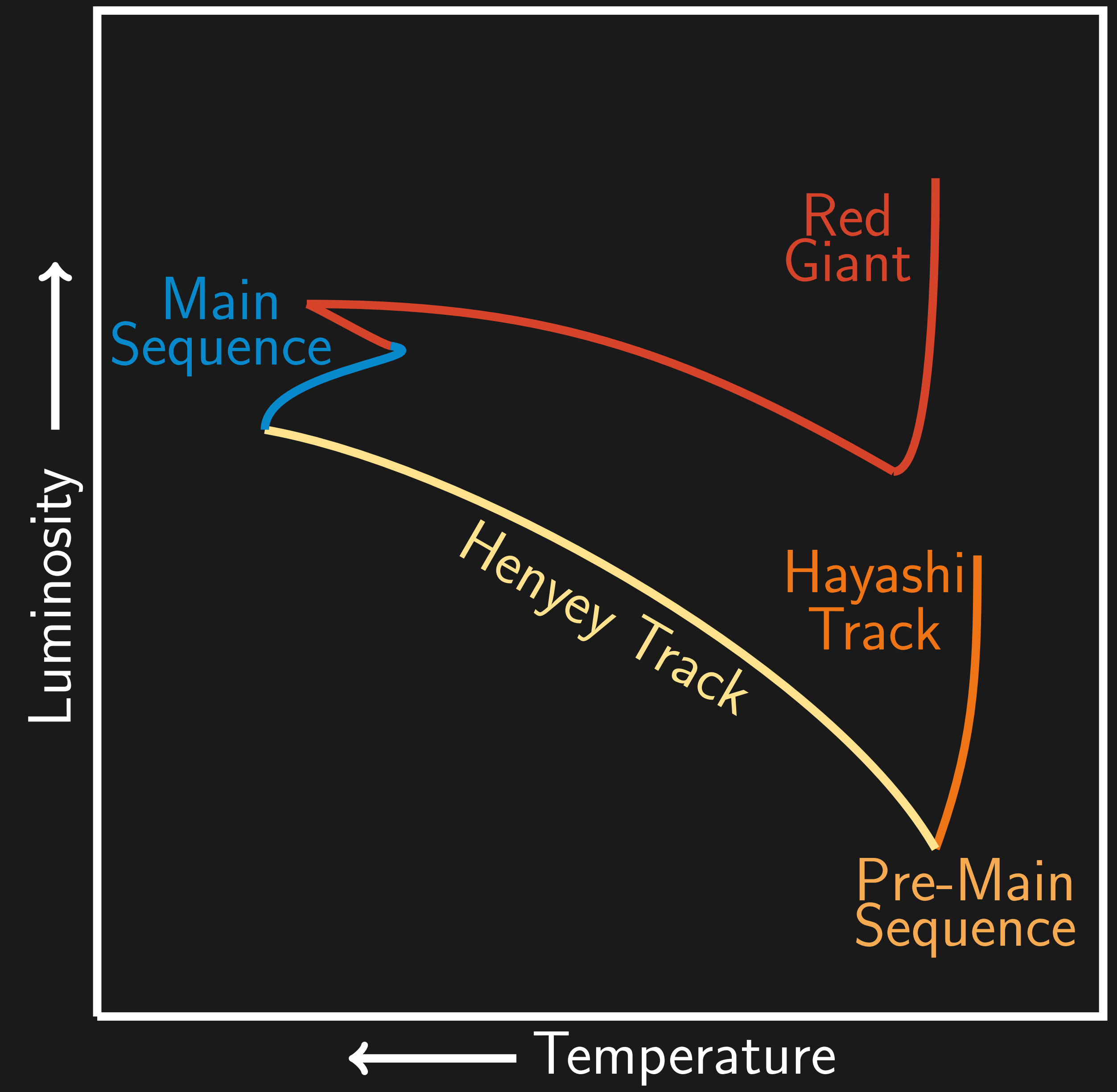


Beyond/Stuck on Hayashi

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



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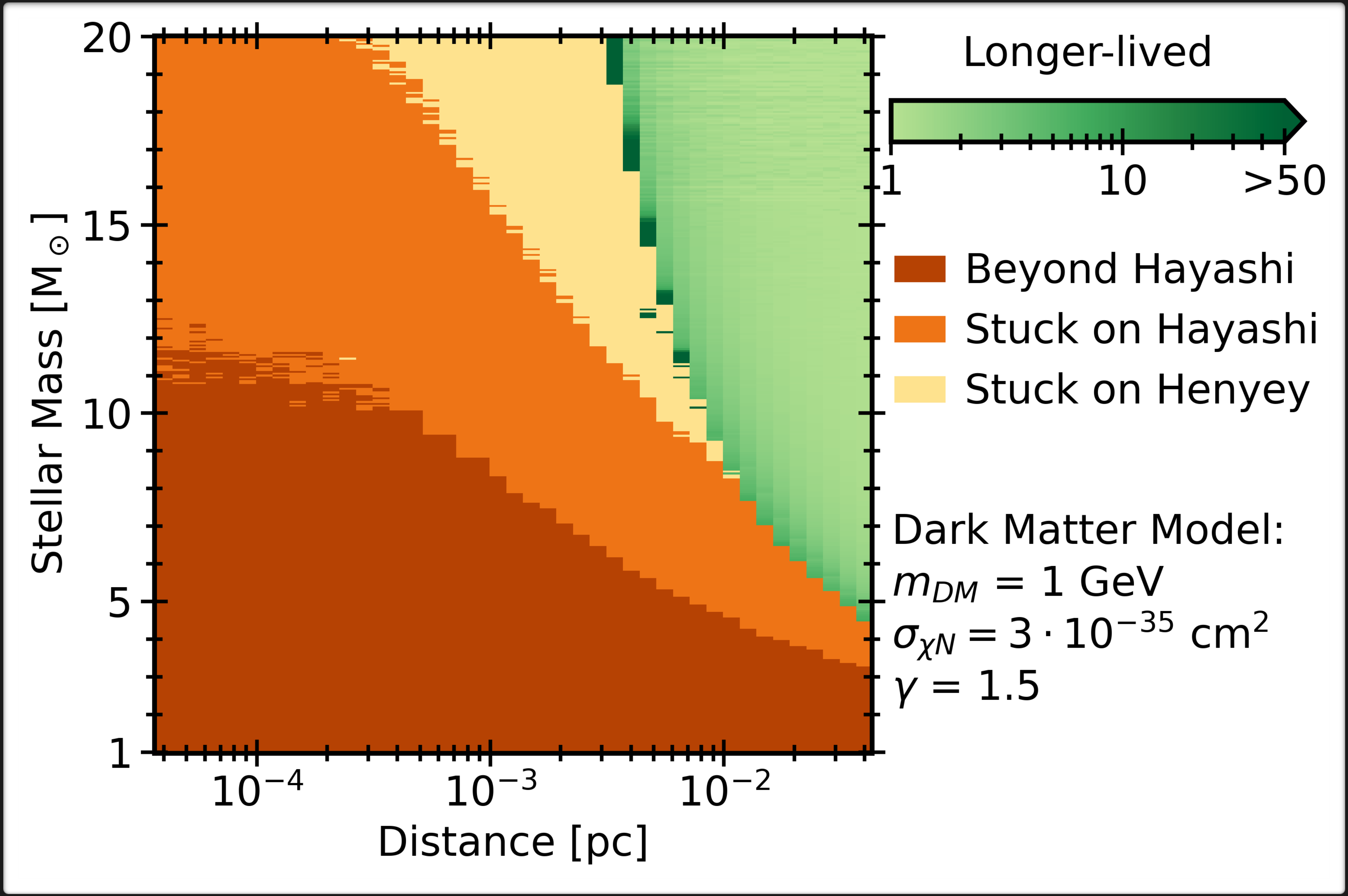

Beyond/Stuck on Hayashi

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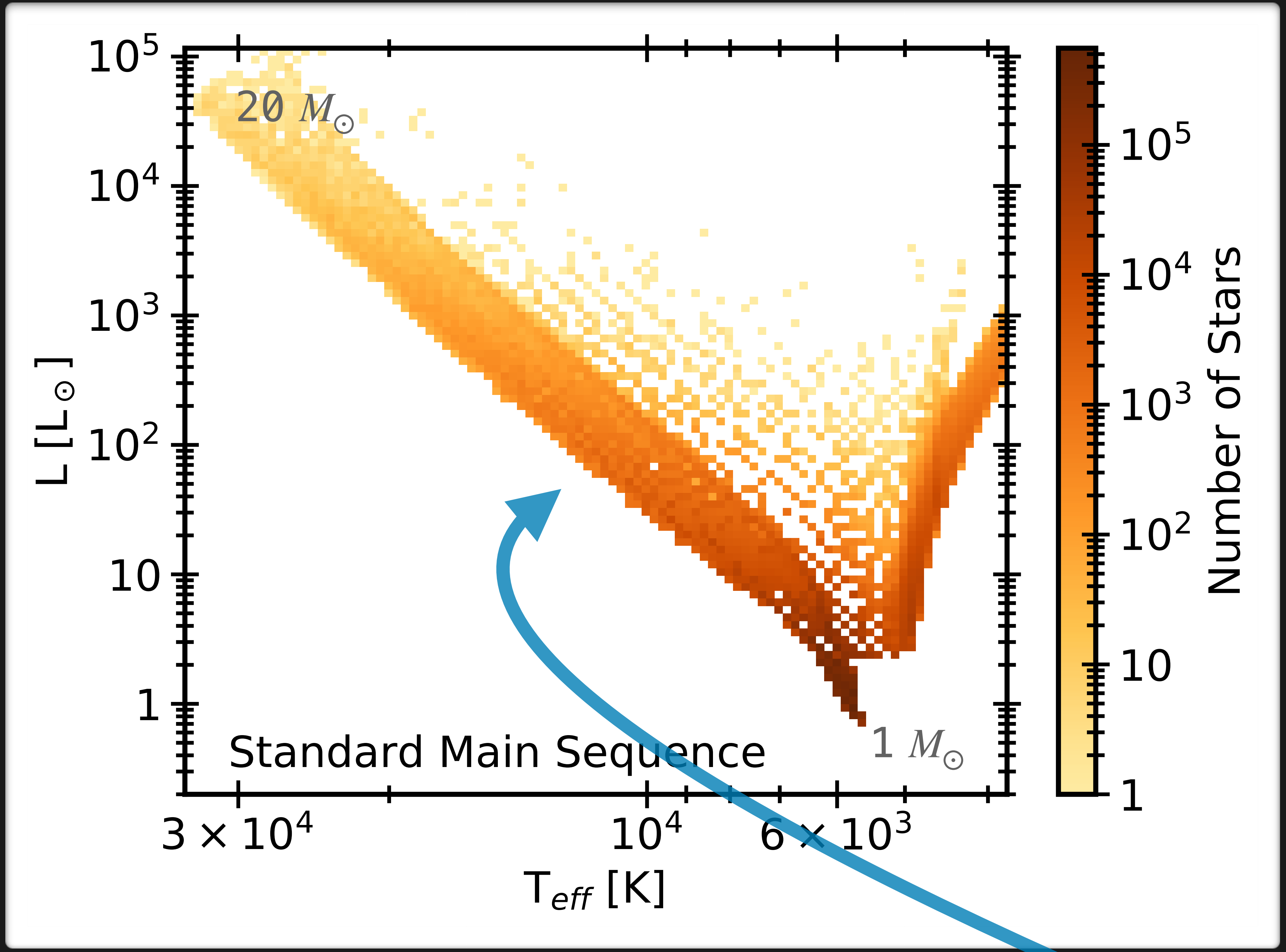
Dark matter can be captured continuously

Stars become effectively immortal

The Dark Main Sequence

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

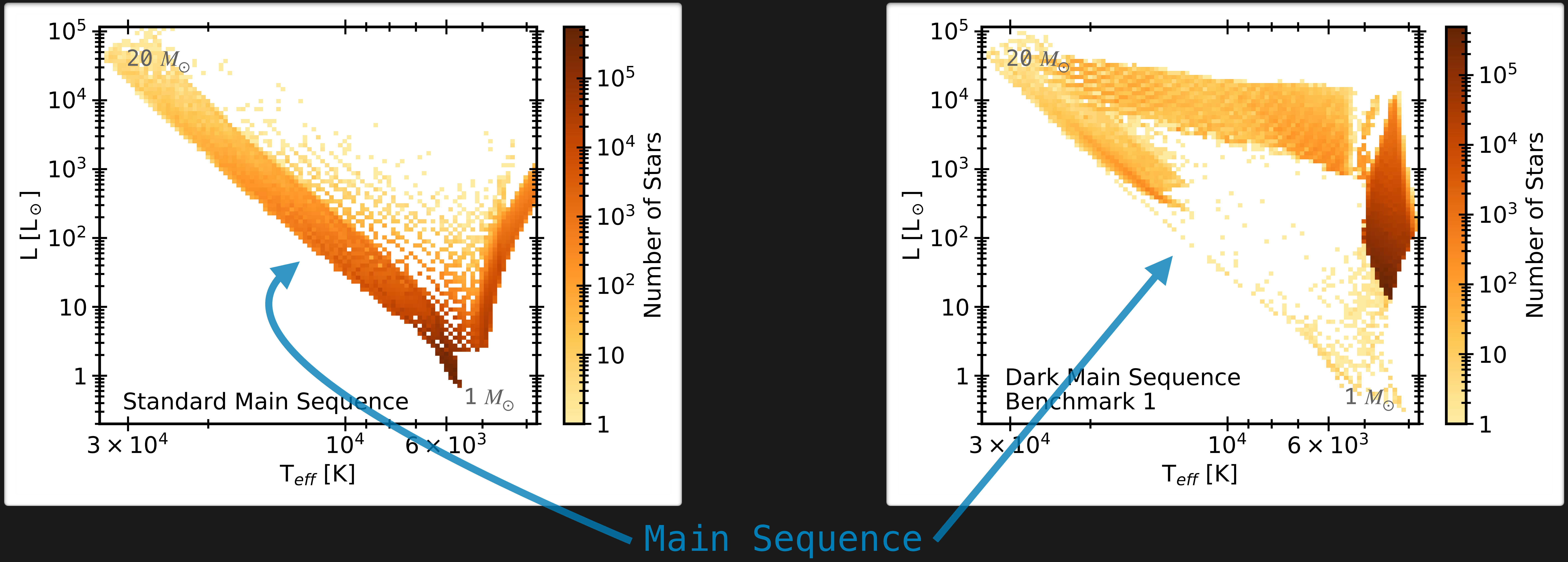


Main Sequence

The Dark Main Sequence

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

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



The Dark Main Sequence

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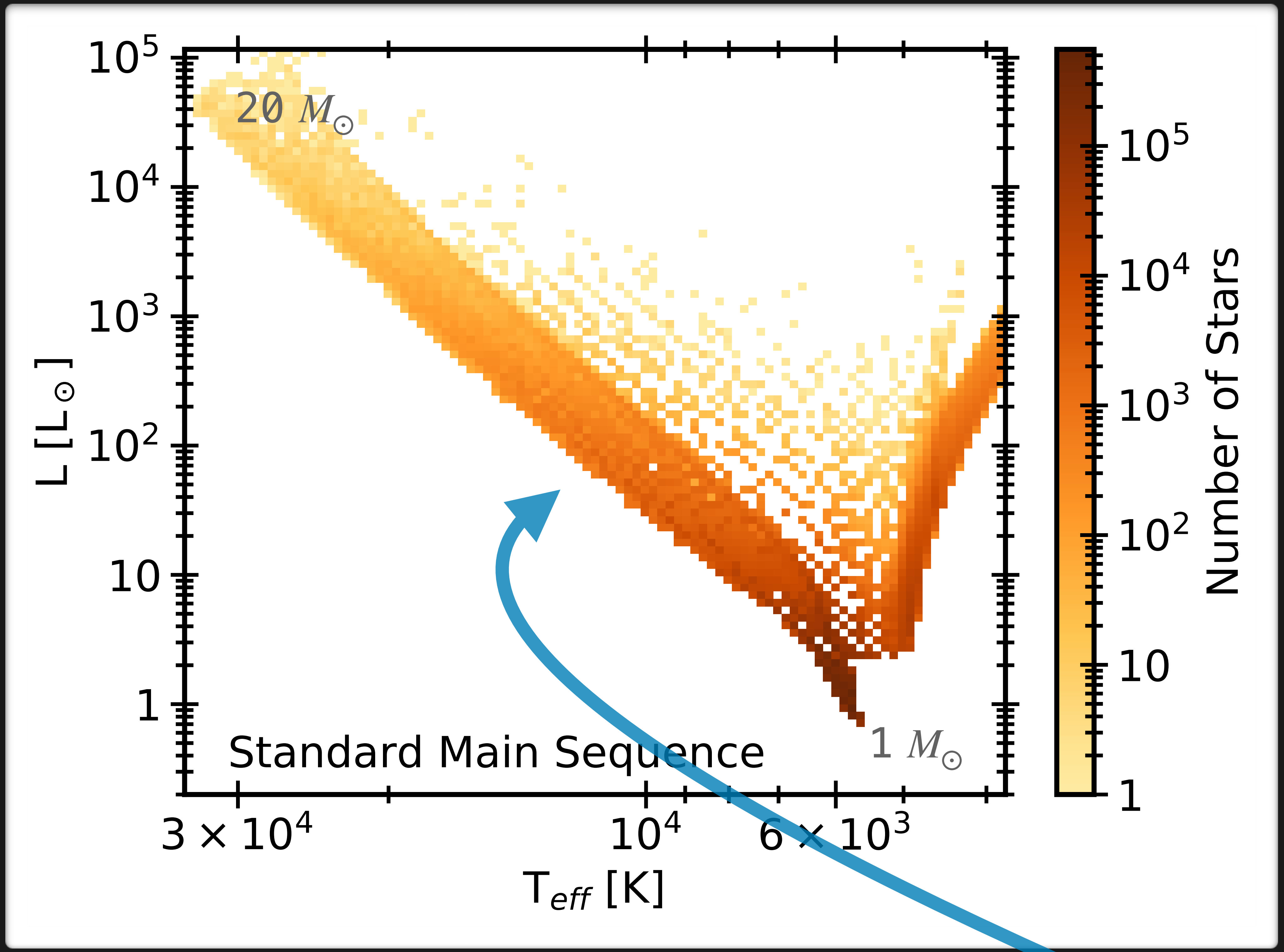
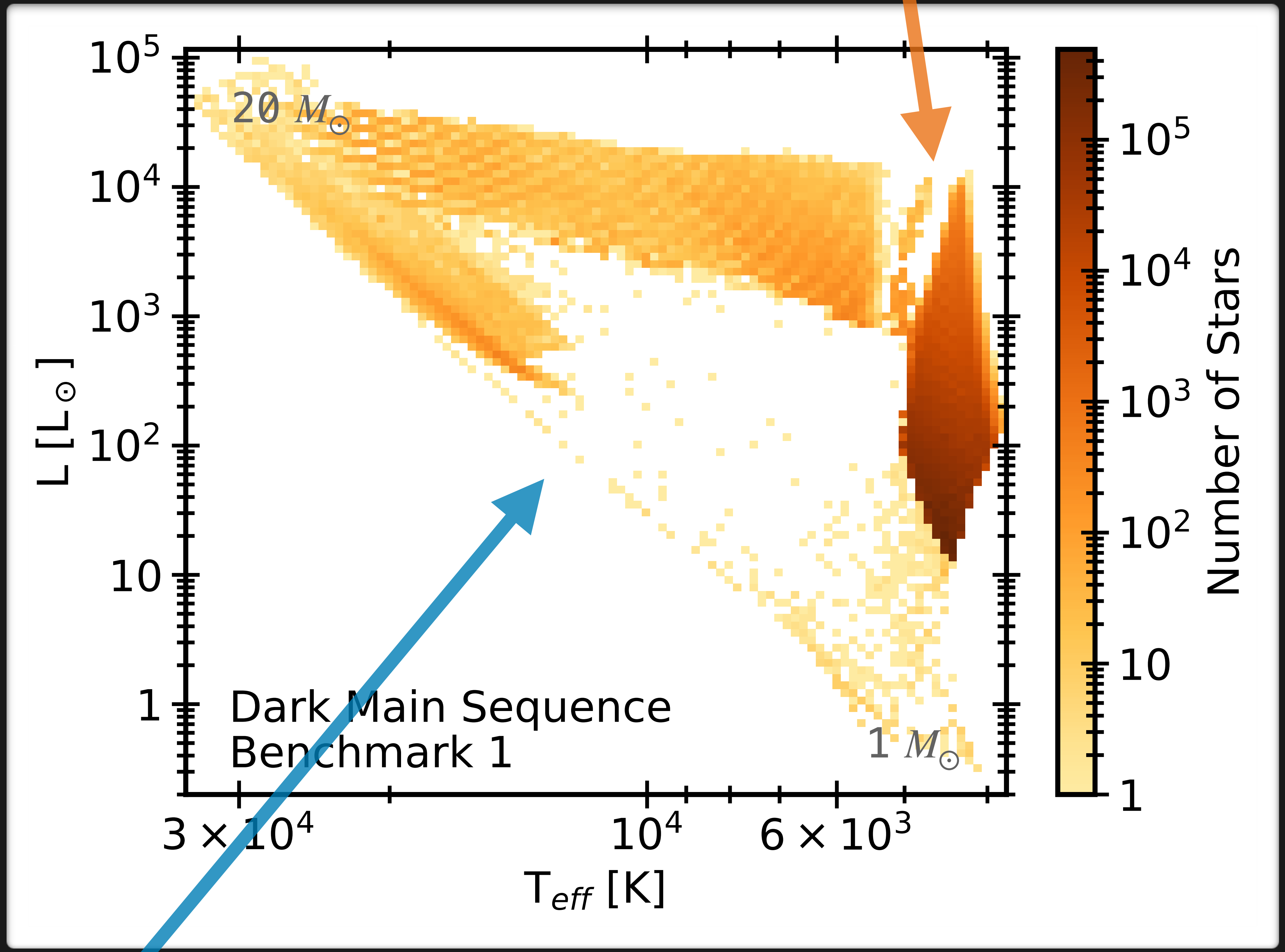
HR diagrams of stellar populations with dark matter burning show two new branches:

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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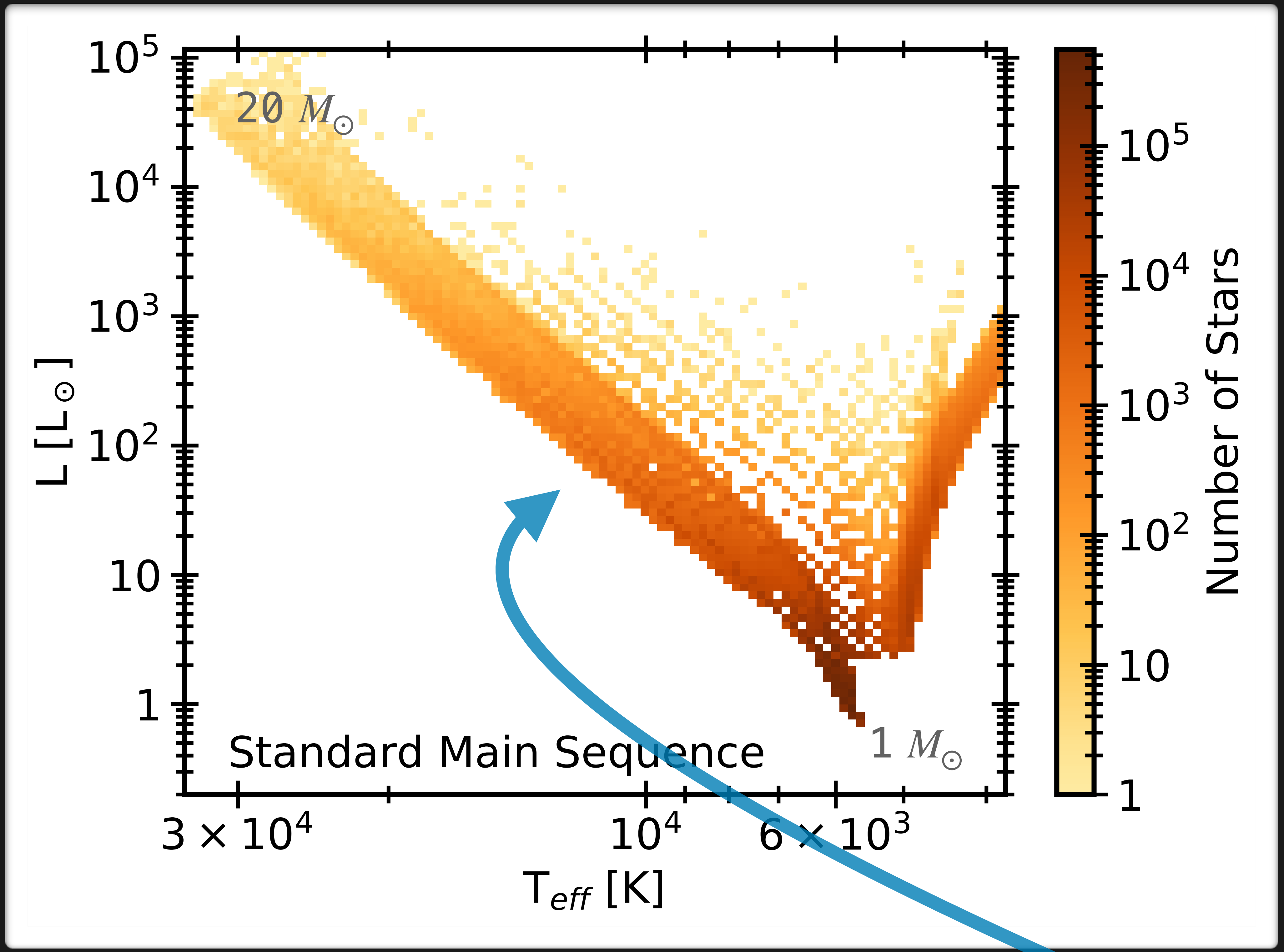
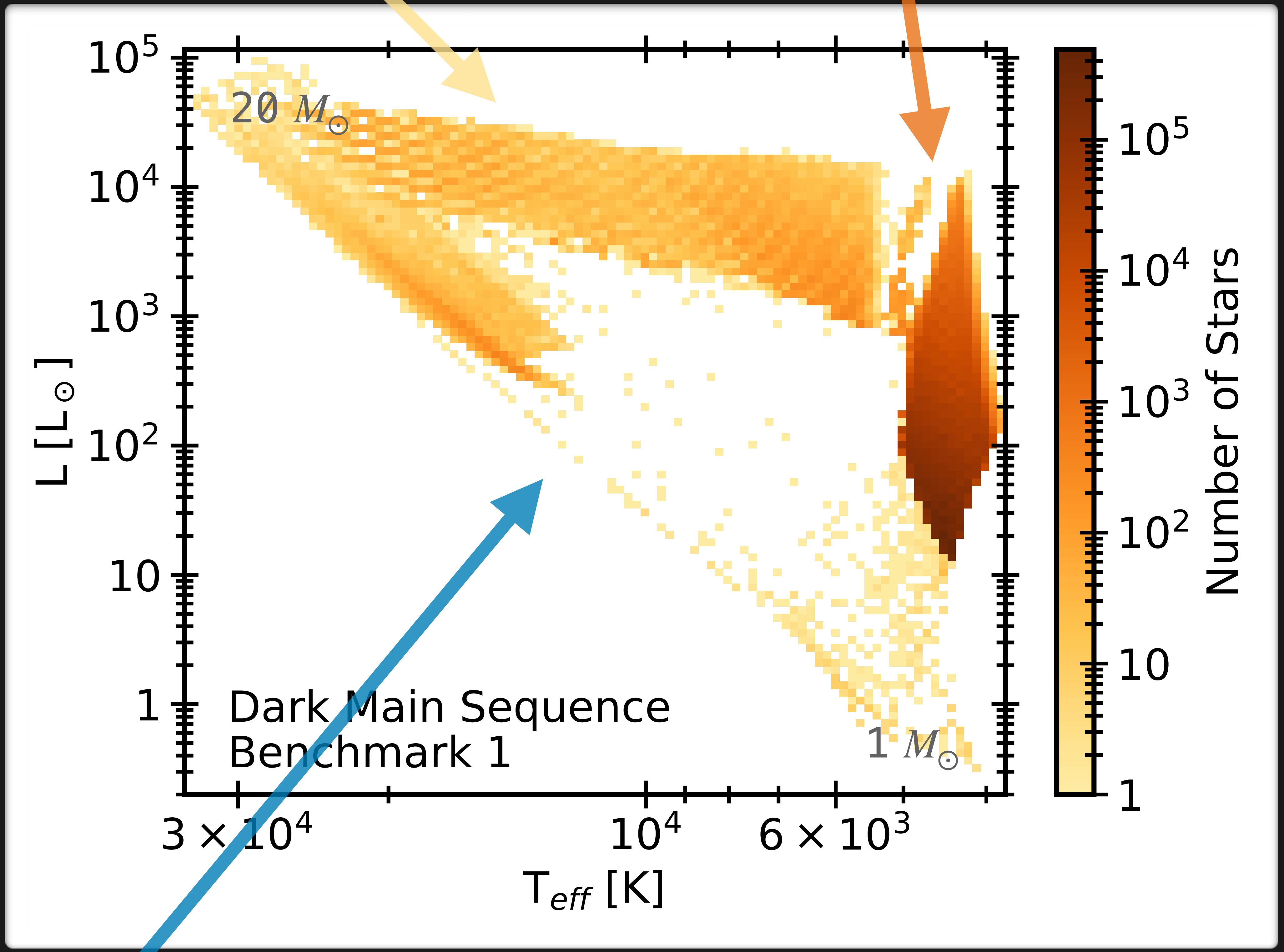




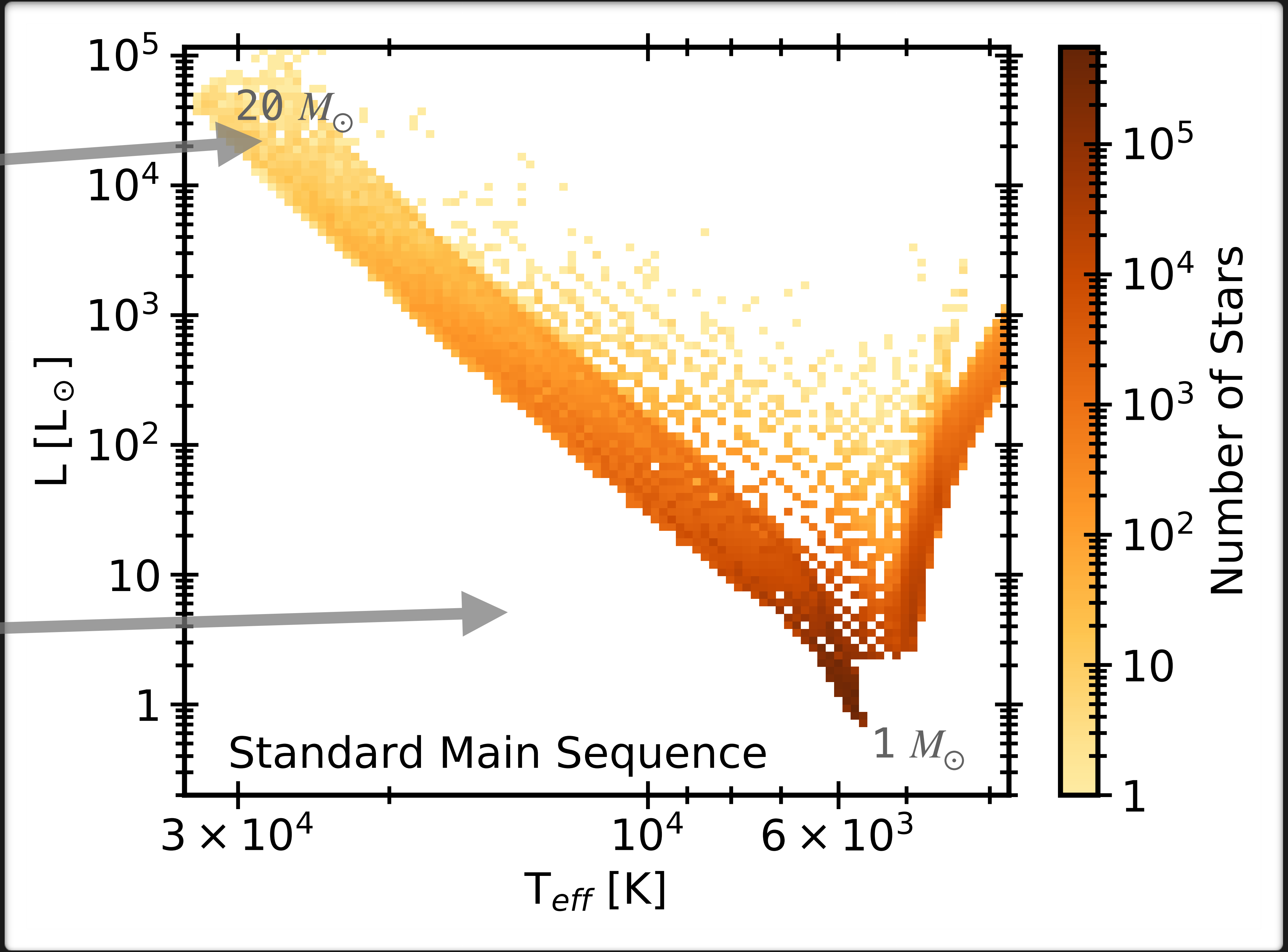
Main Sequence

Dark Matter Burning in S–Cluster Stars

Standard Evolution:

Massive stars evolve quickly

Light stars evolve slowly



Dark Matter Burning in S–Cluster Stars

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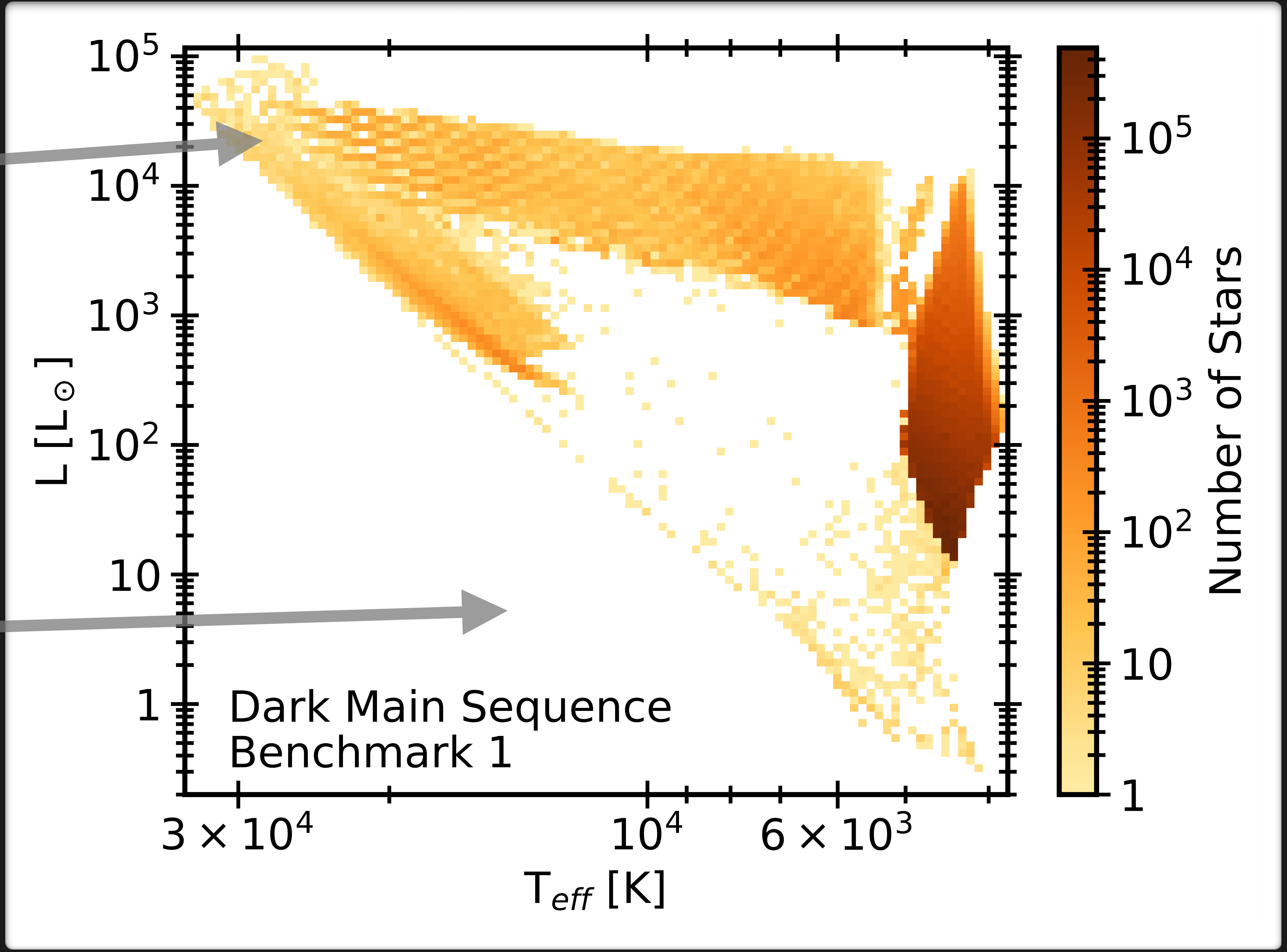

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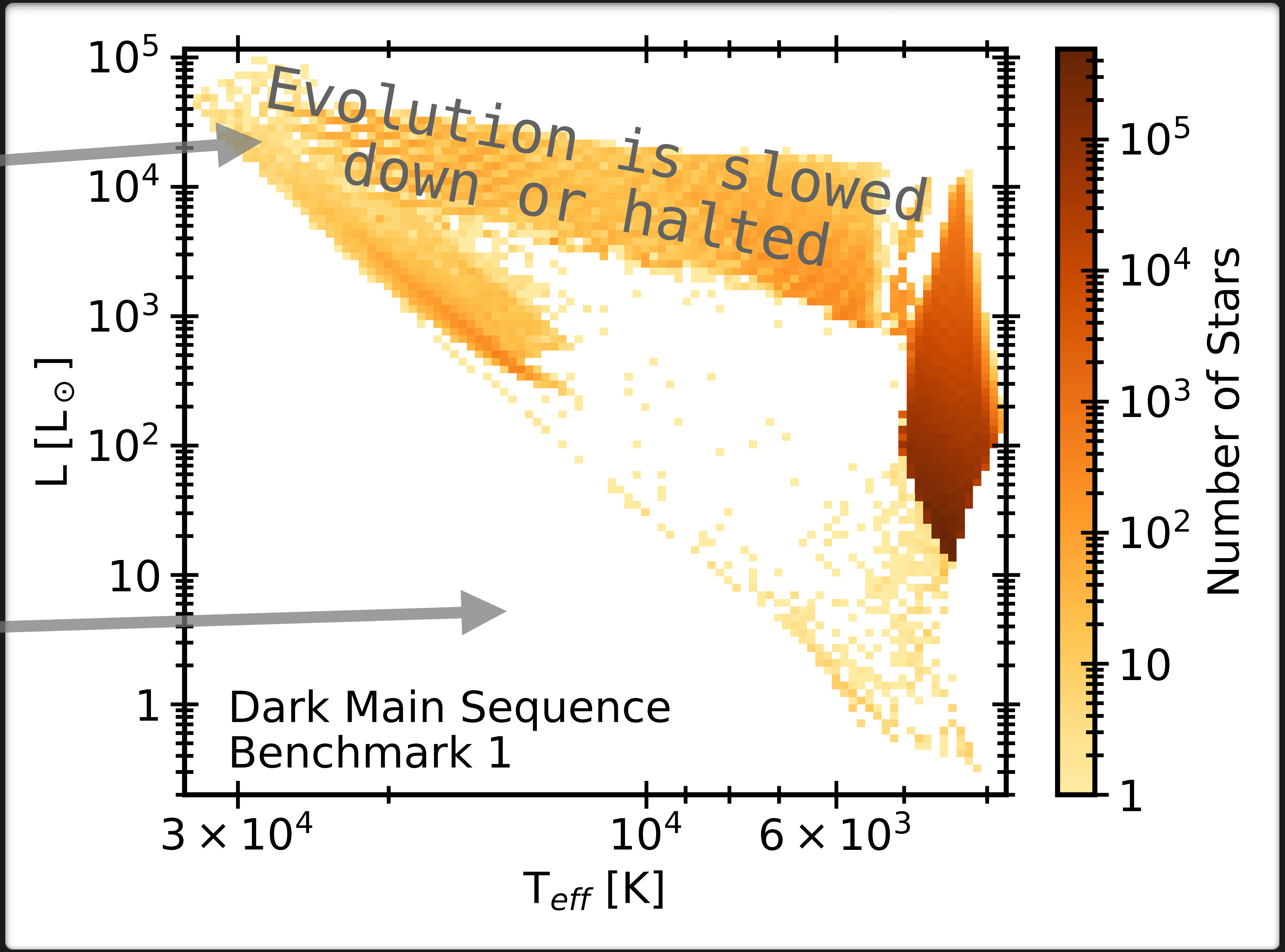

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Unusual Properties of S–Stars:

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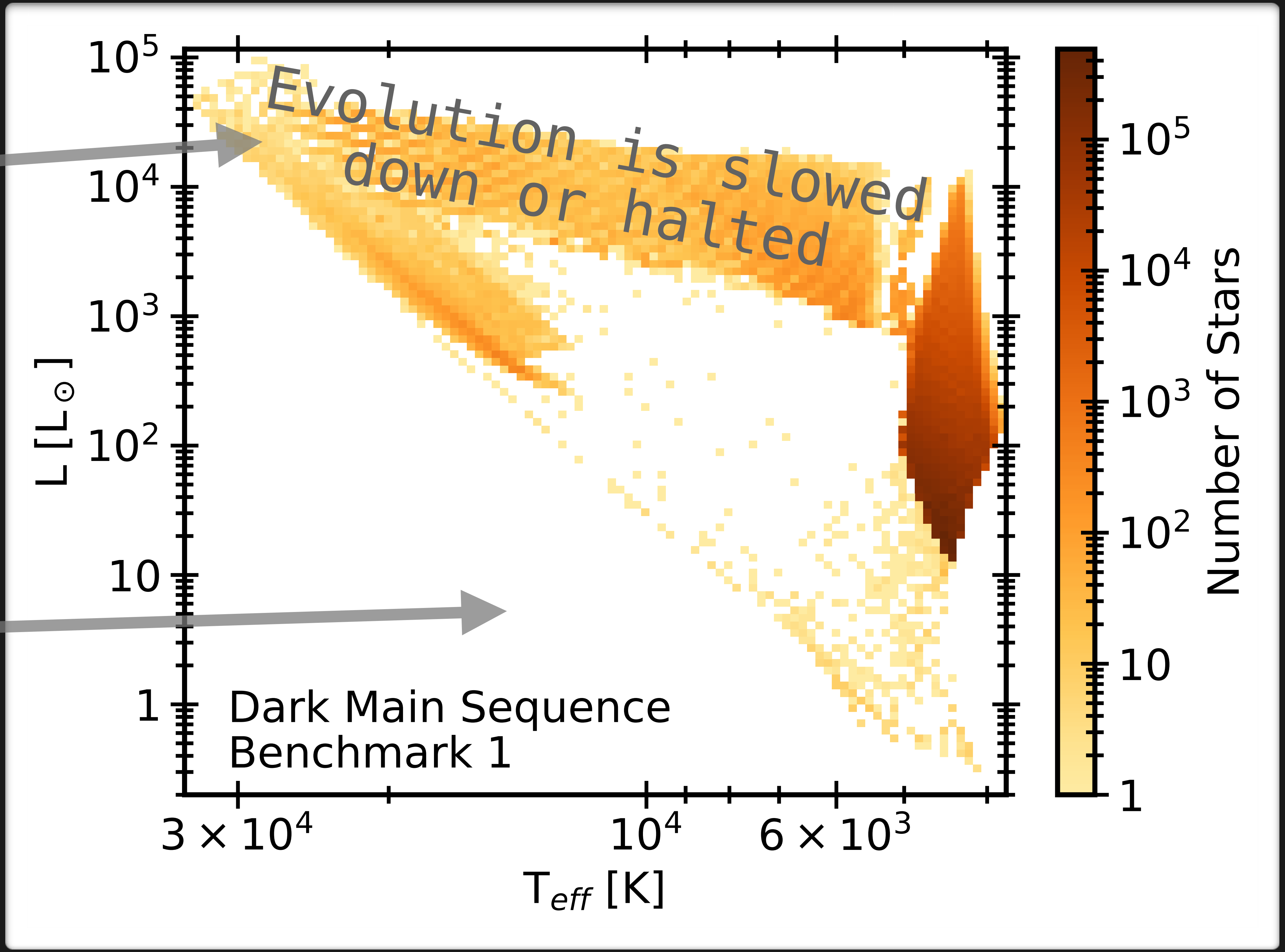

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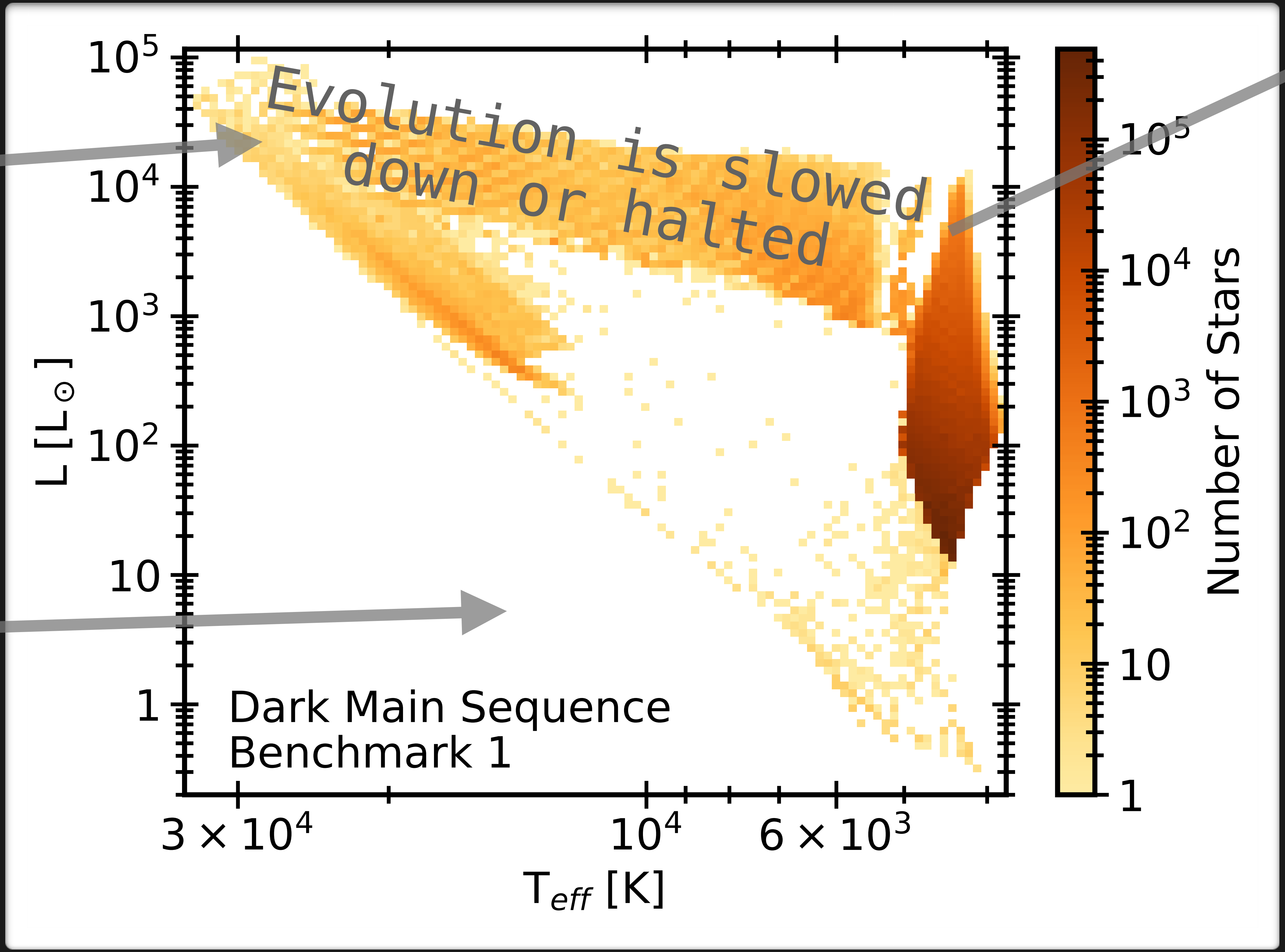

Unusual Properties of S-Stars:

Paradox of Youth – Stars look young

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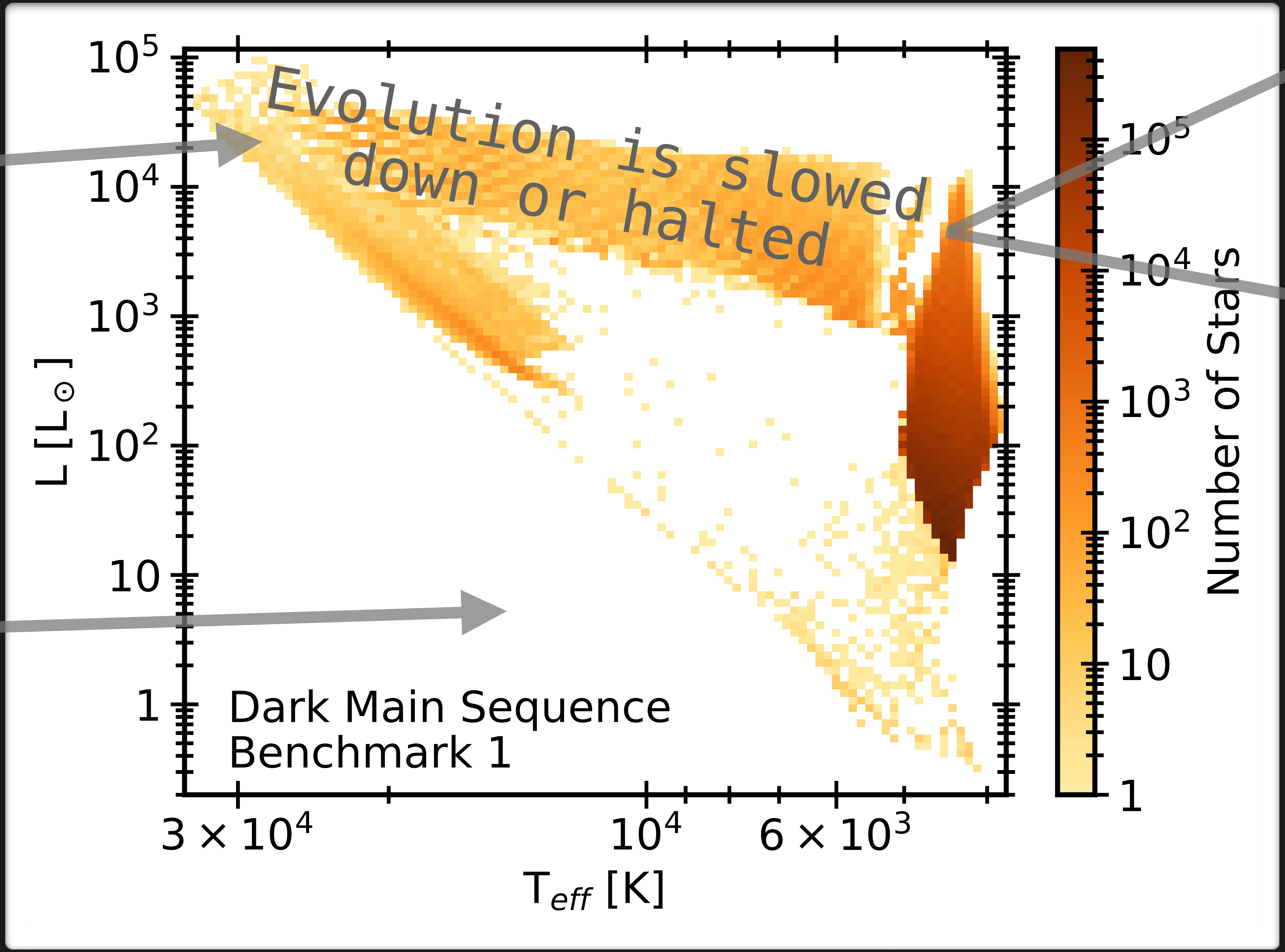

Paradox of Youth – Stars look young

Conundrum of Old Age – Lack of older stars

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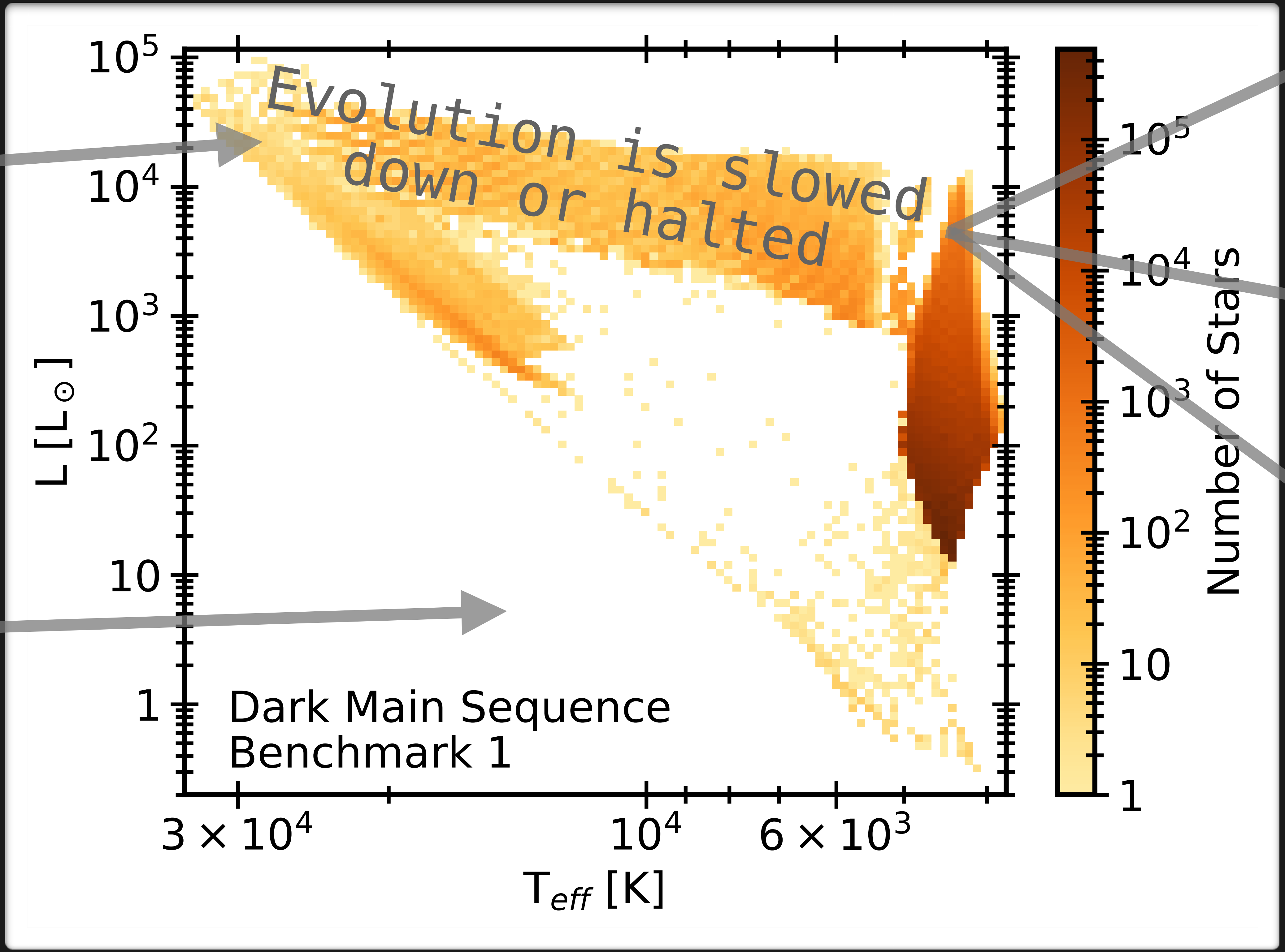

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Top–heavy initial mass distribution

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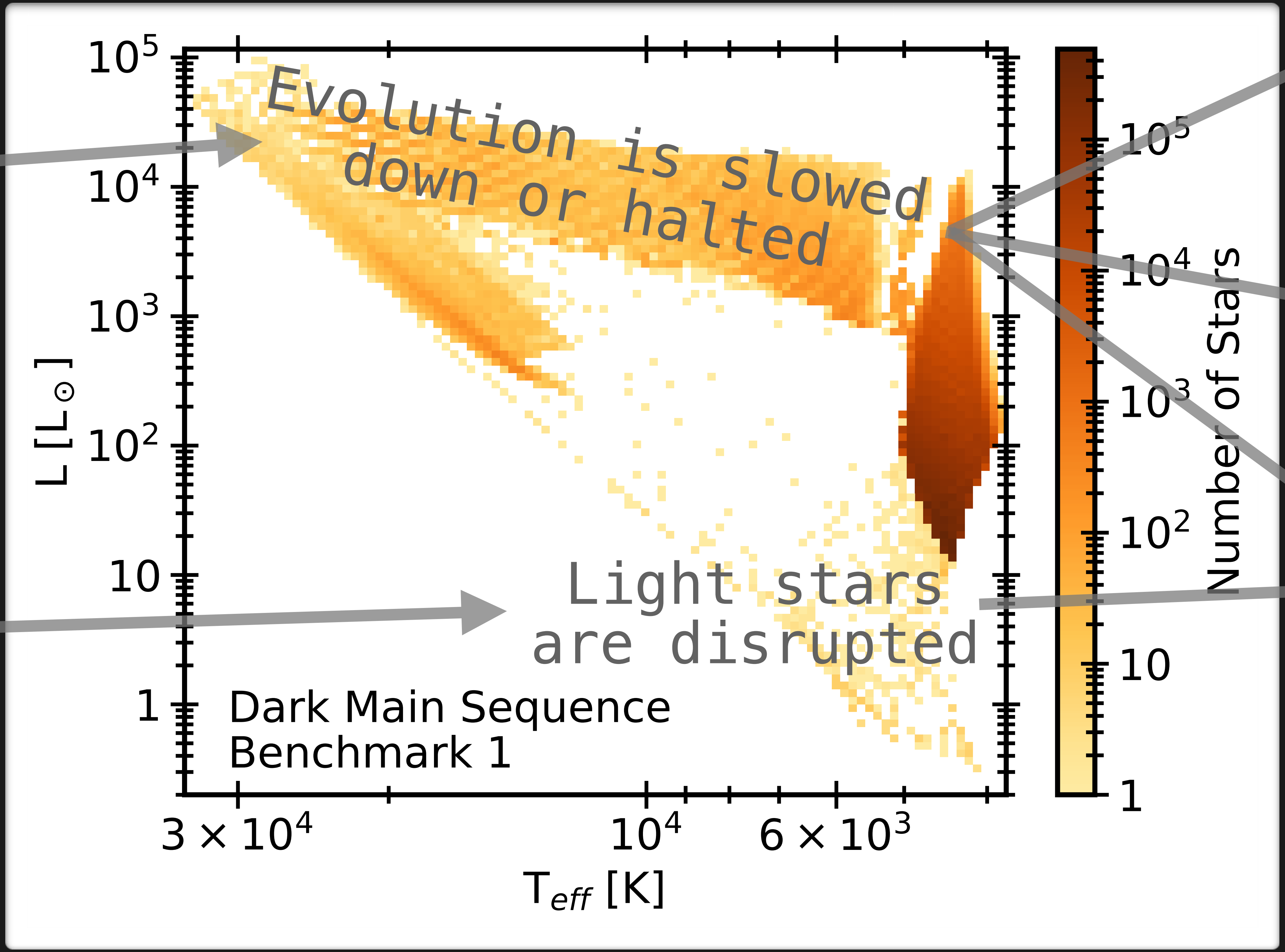

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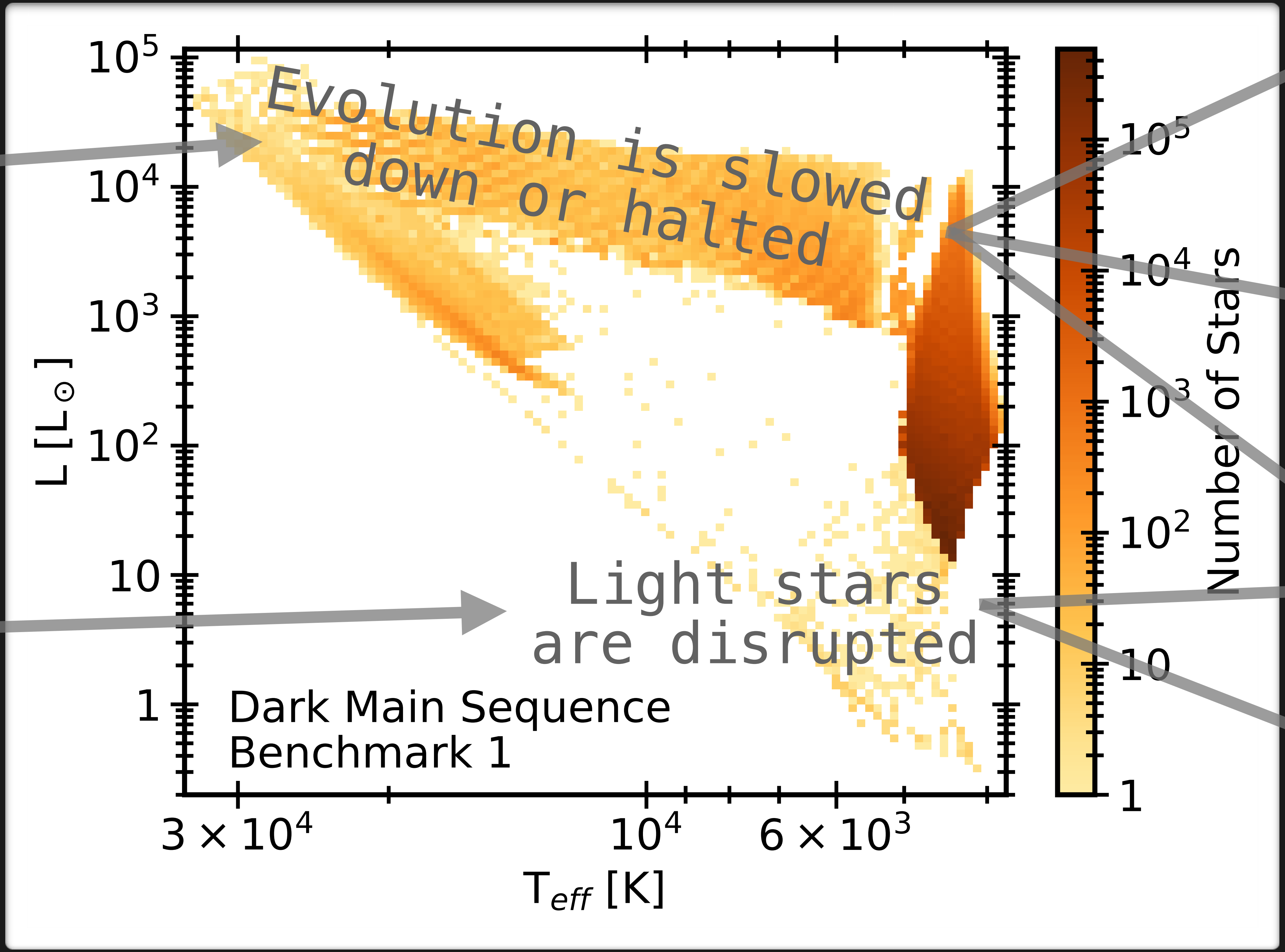

Unusual Properties of S-Stars:

Paradox of Youth – Stars look young

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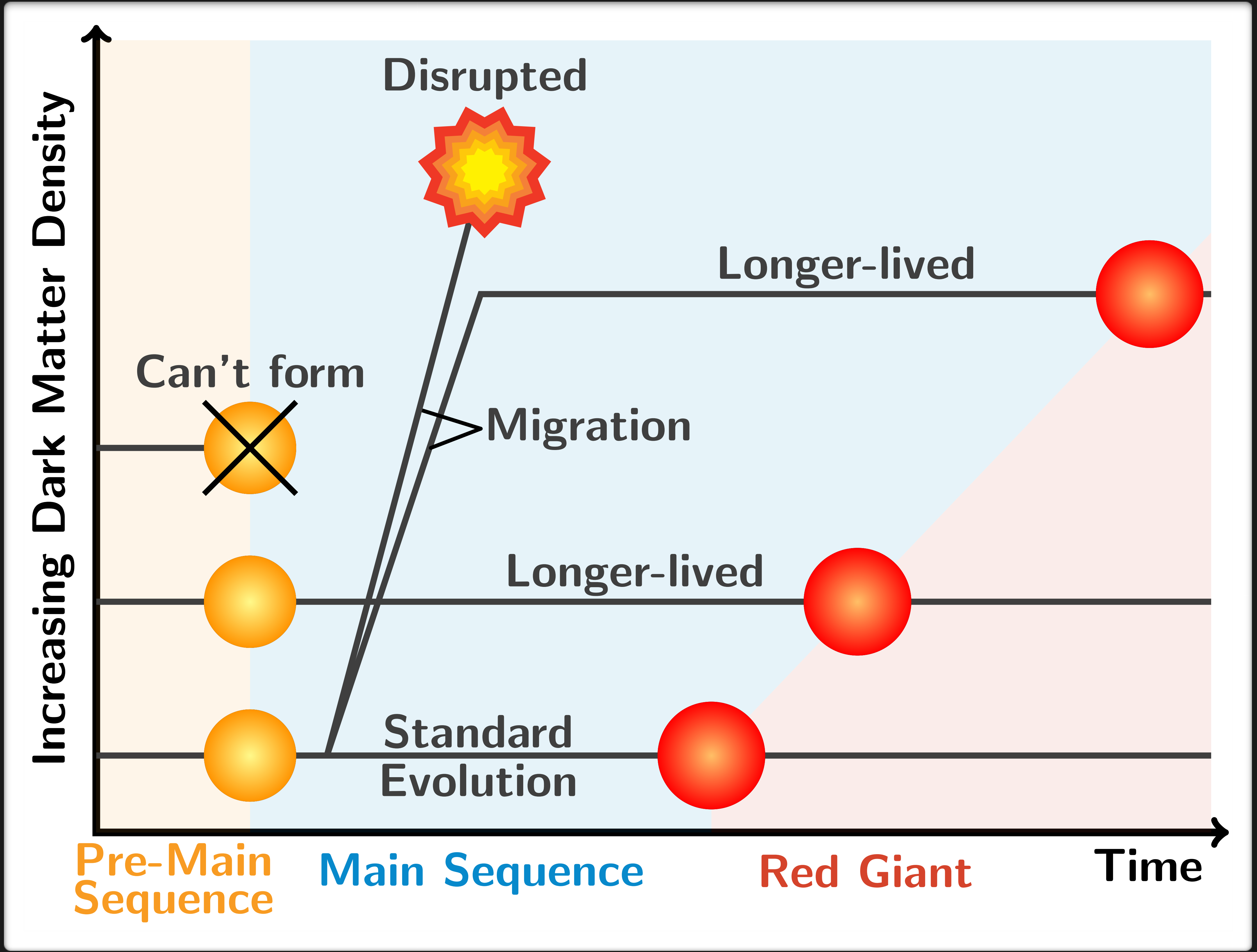
Top-heavy initial mass distribution

G objects ?

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

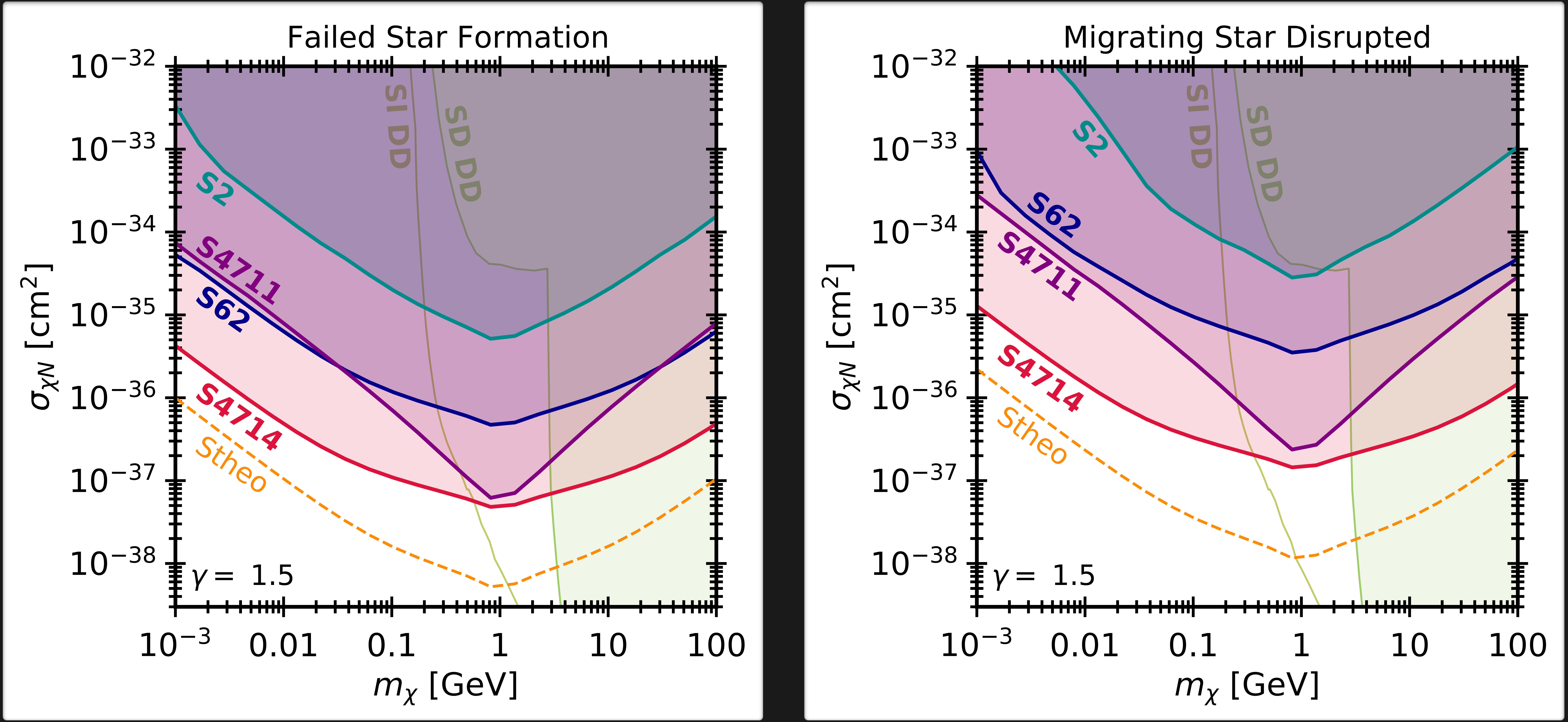
S62: 6.1 $M_\odot$
intermediate mass

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]

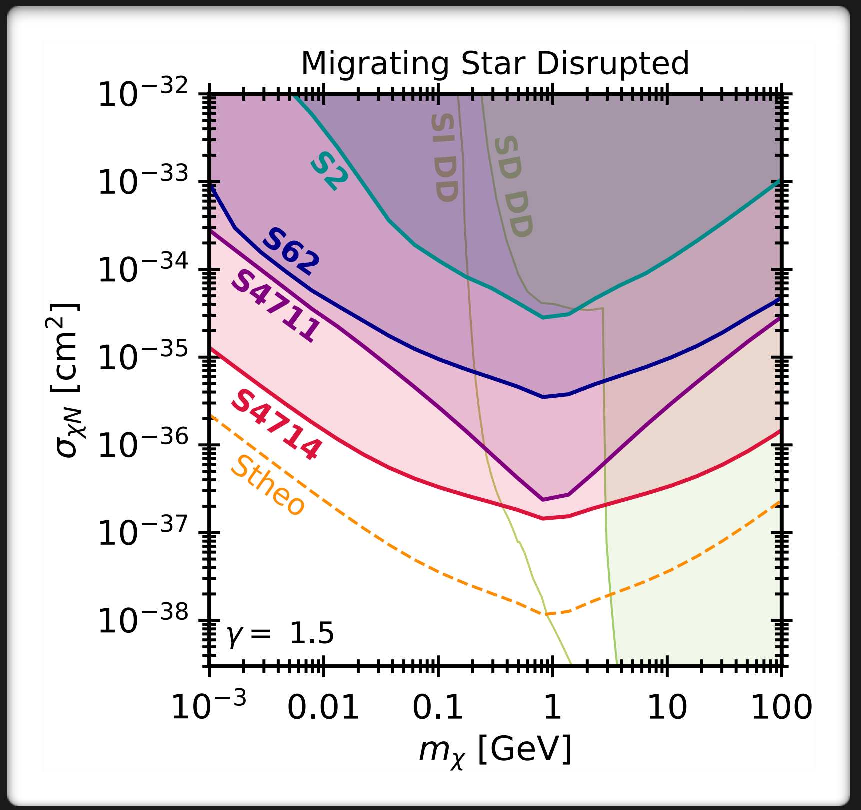


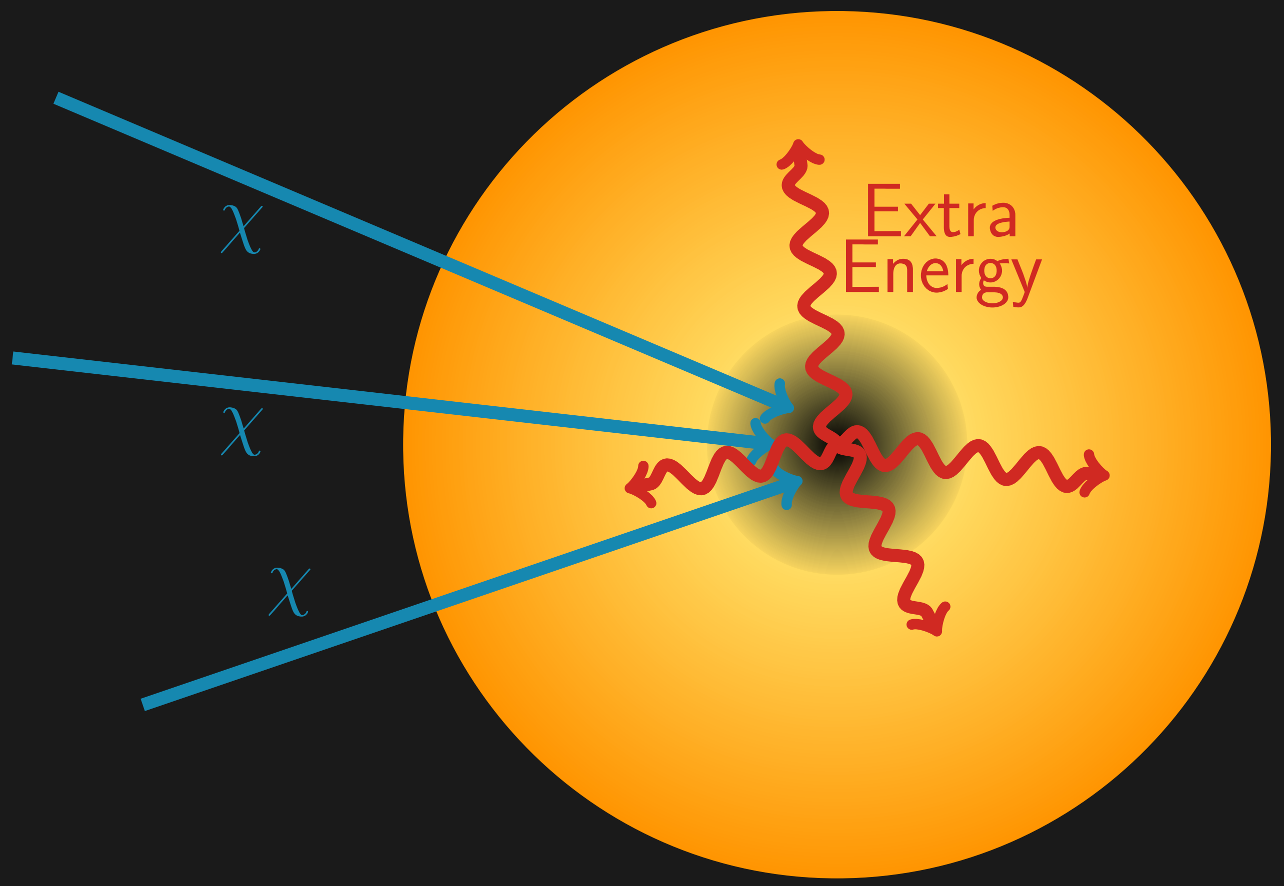
Summary and Conclusions

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

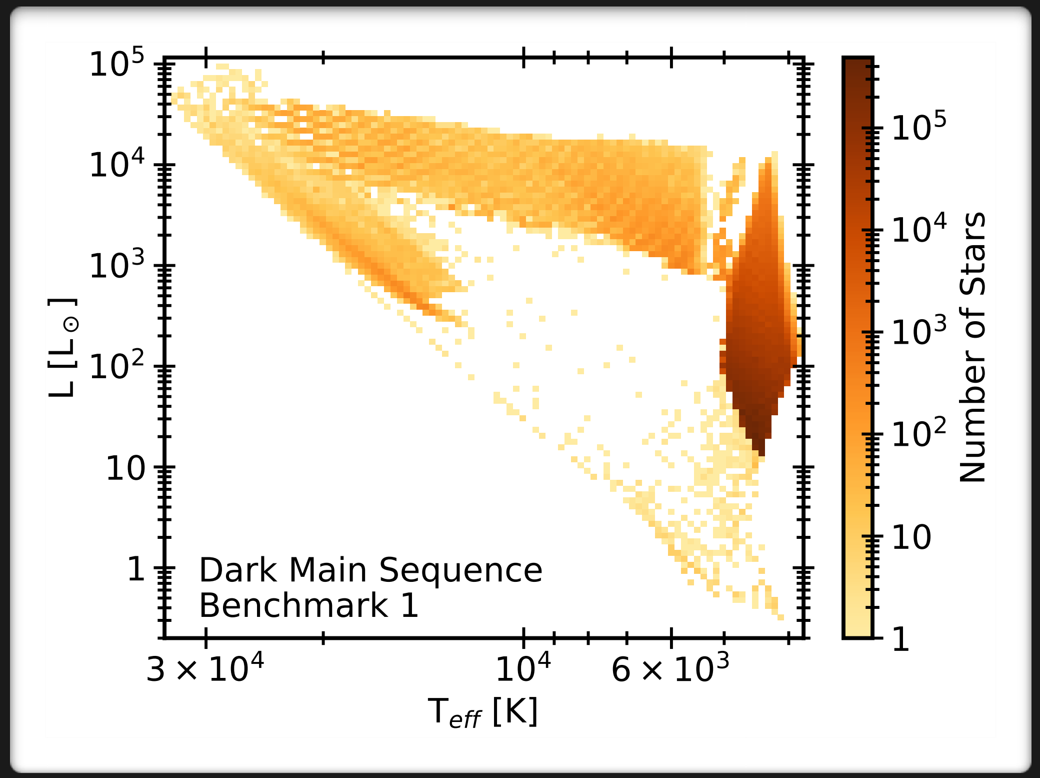
Dark matter capture and subsequent annihilation can (partially) replace nuclear fusion

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



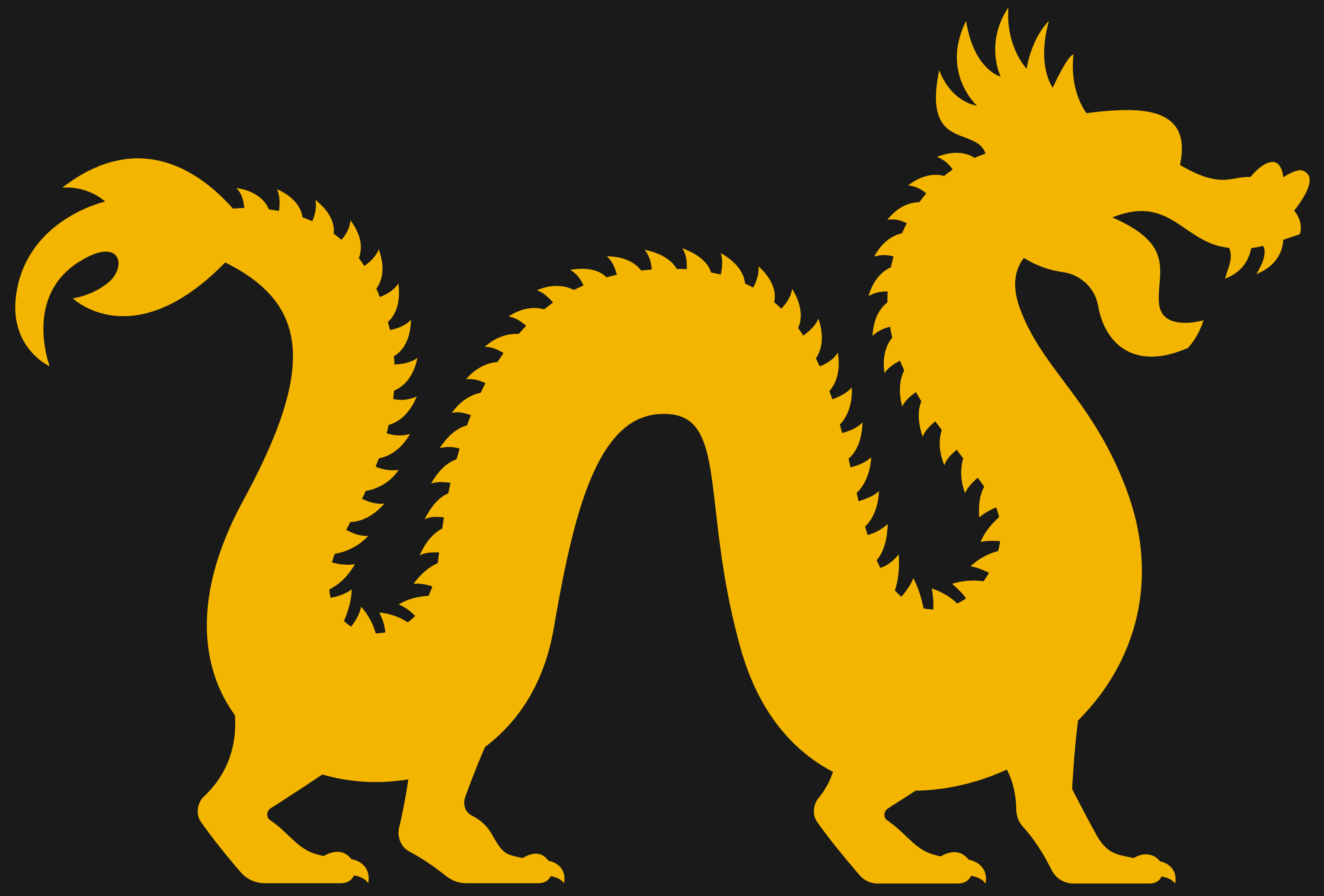


Stellar evolution is slowed down or halted: new distinct branches on HR diagram

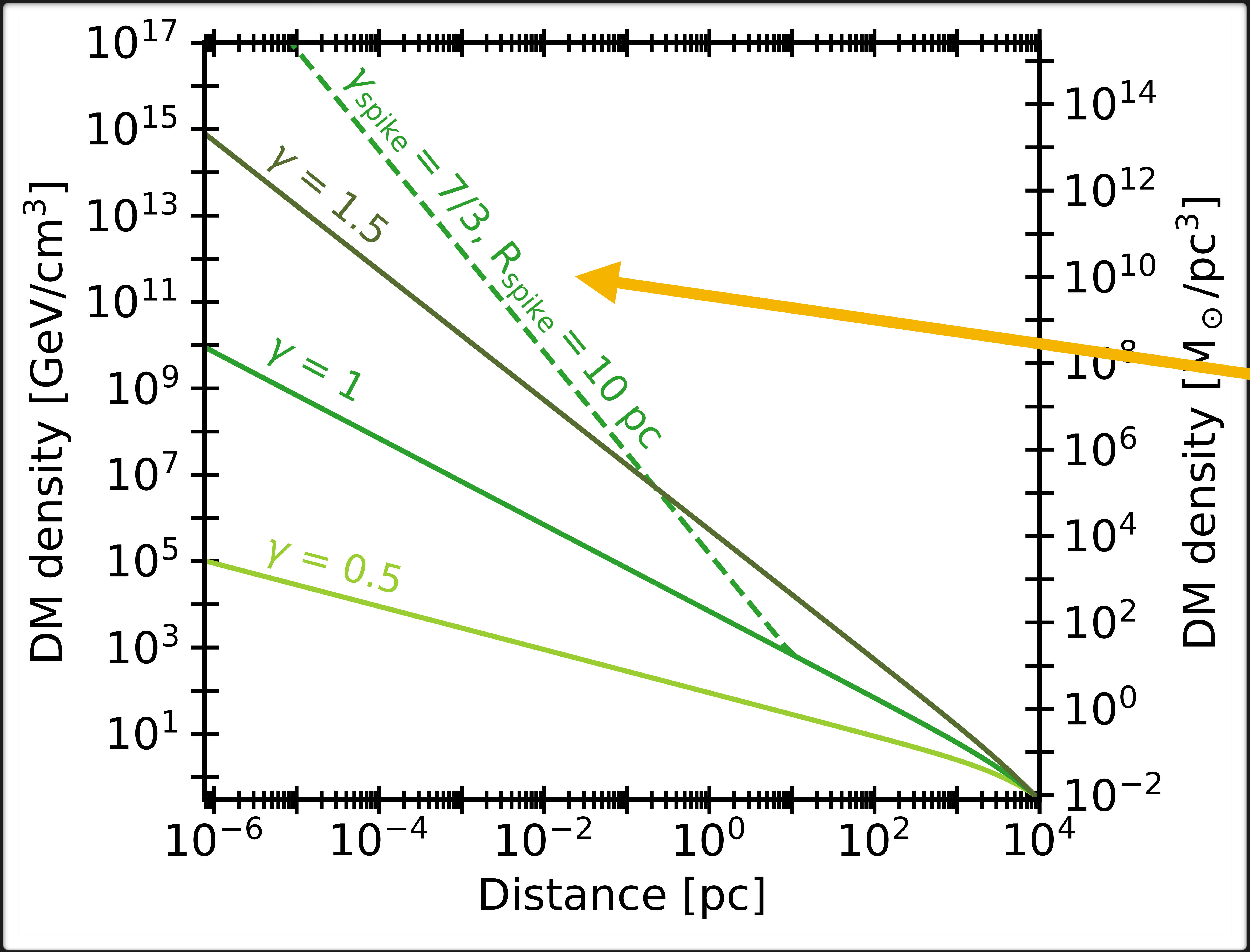


More precise observations of S-cluster stars needed to statistically test dark main sequence

Additional Slides



Dark Matter Spike Models



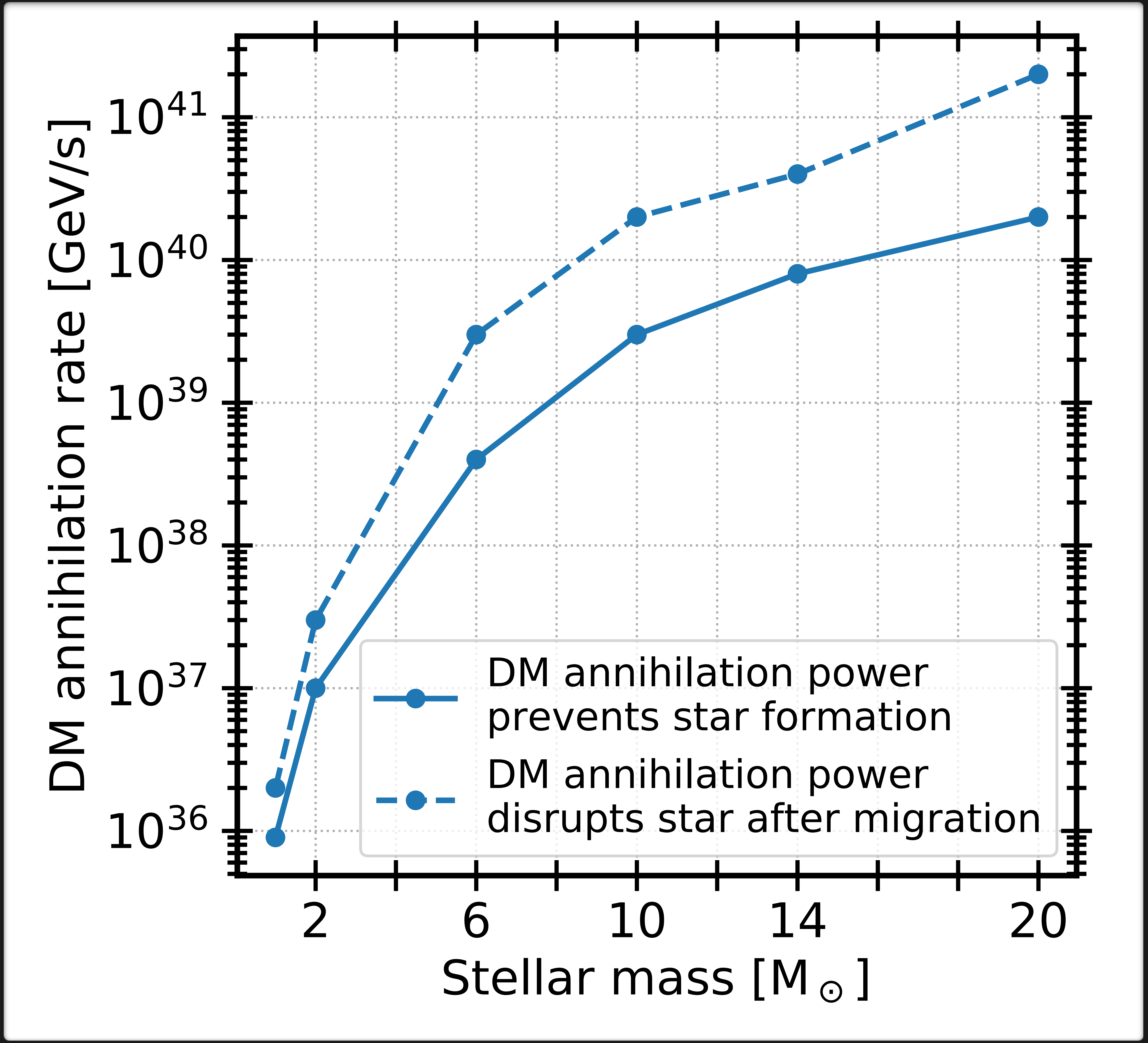
Adiabatic accretion of matter by central black hole can create a spike in dark matter density

Gondolo & Silk, arXiv:astro-ph/9906391

Lacroix, arXiv:1801.01308

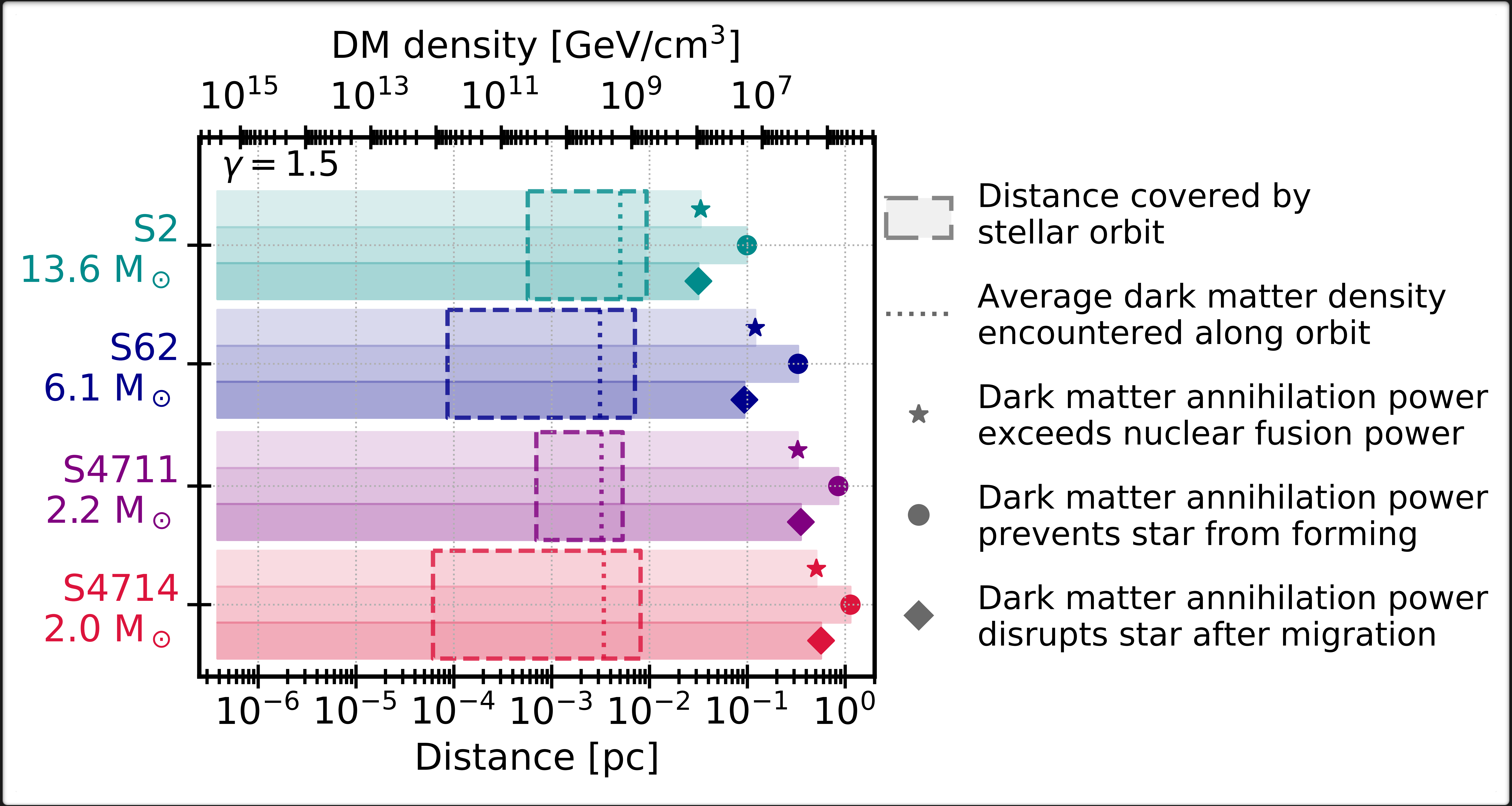
Dependence on Stellar Mass

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



Dark Matter in Individual Stars

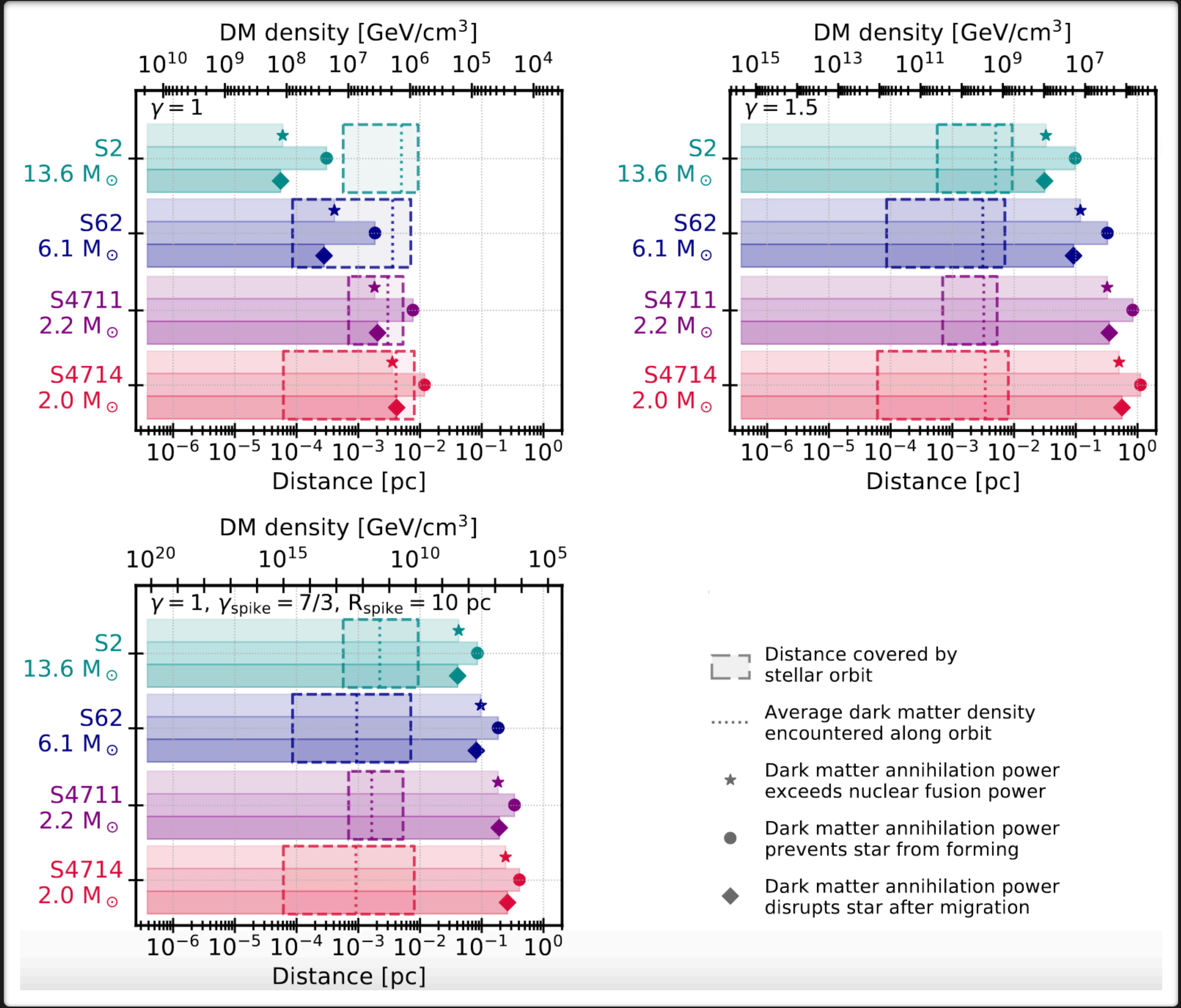
[I. John, R. Leane, T. Linden, arXiv:2311.16228]



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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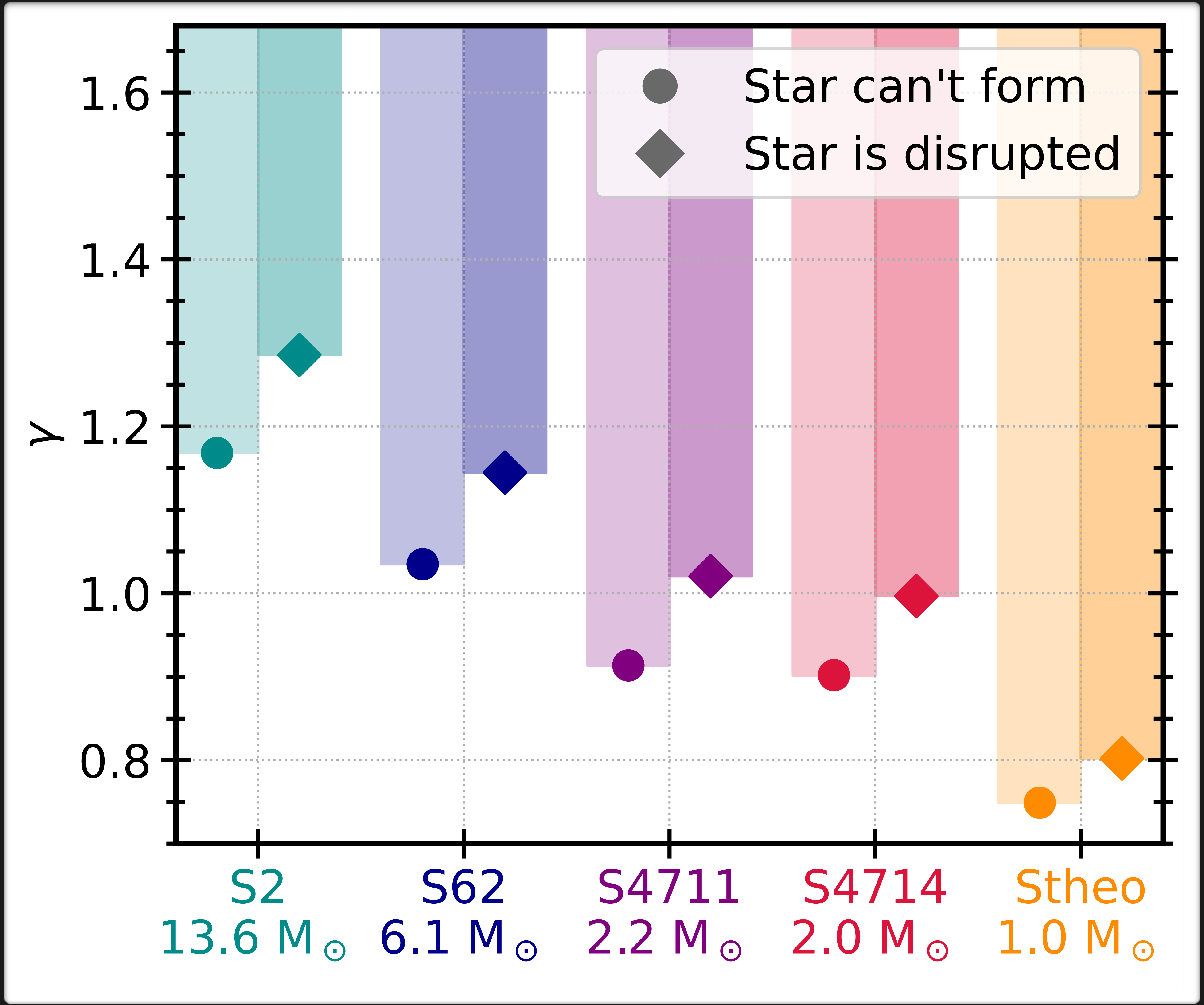
Constraints on Dark Matter Profile

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

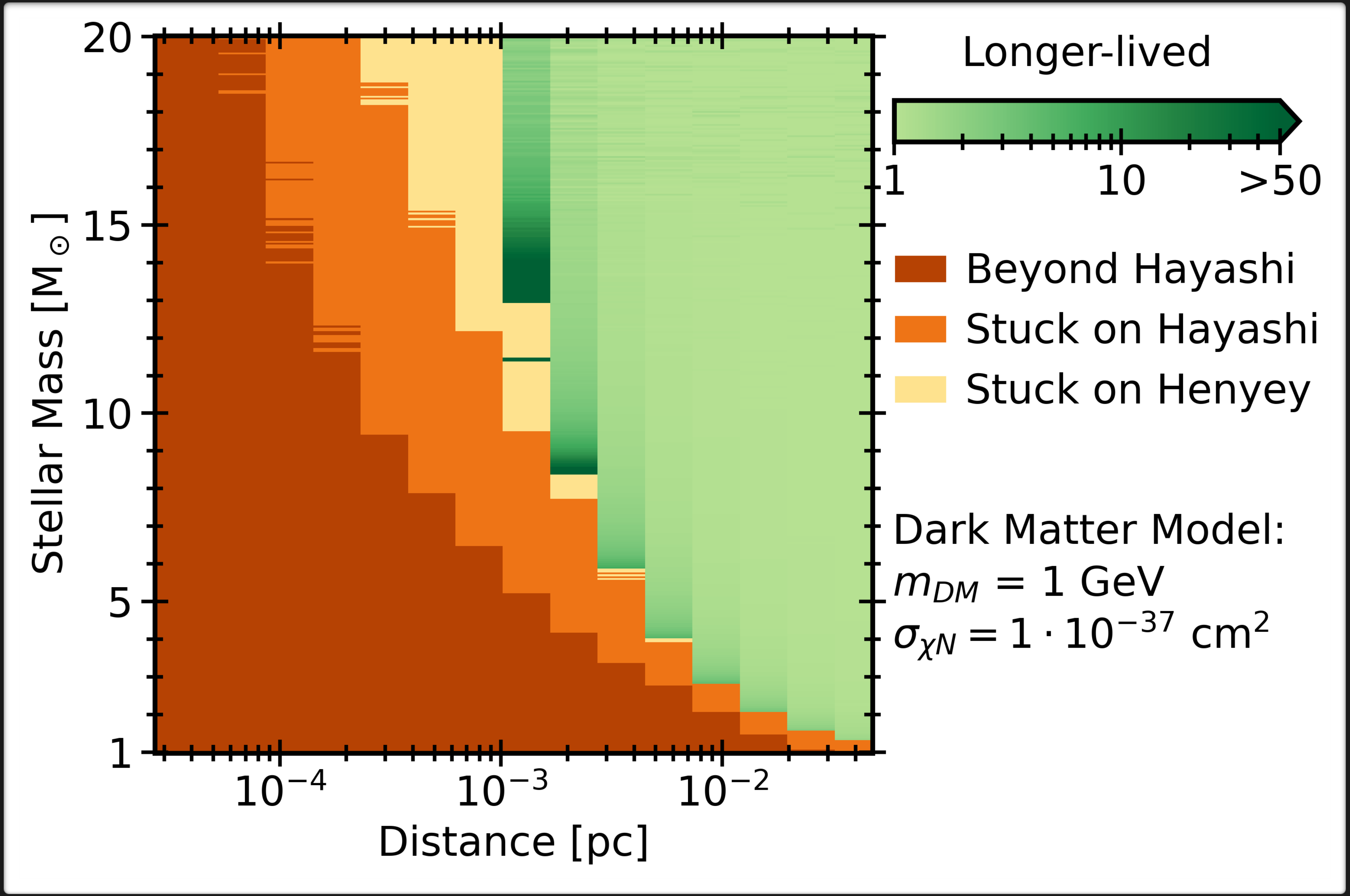


Index of generalised NFW profile

Assuming maximum dark matter capture rate.

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]