Immortal Stars at the Galactic Center

arXiv:2311.16228 & arXiv:2405.12267

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Together with
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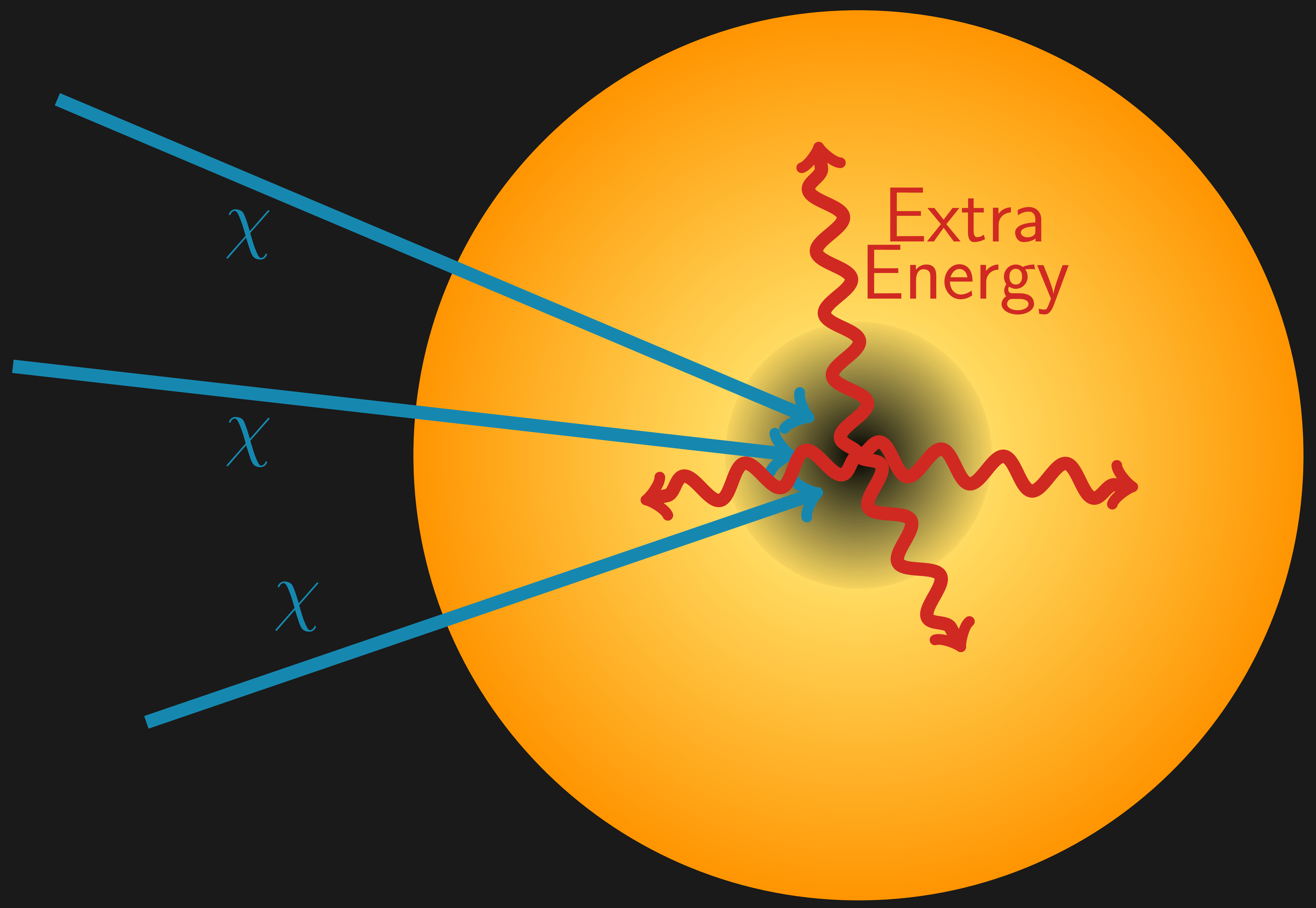
TeVPA
Chicago

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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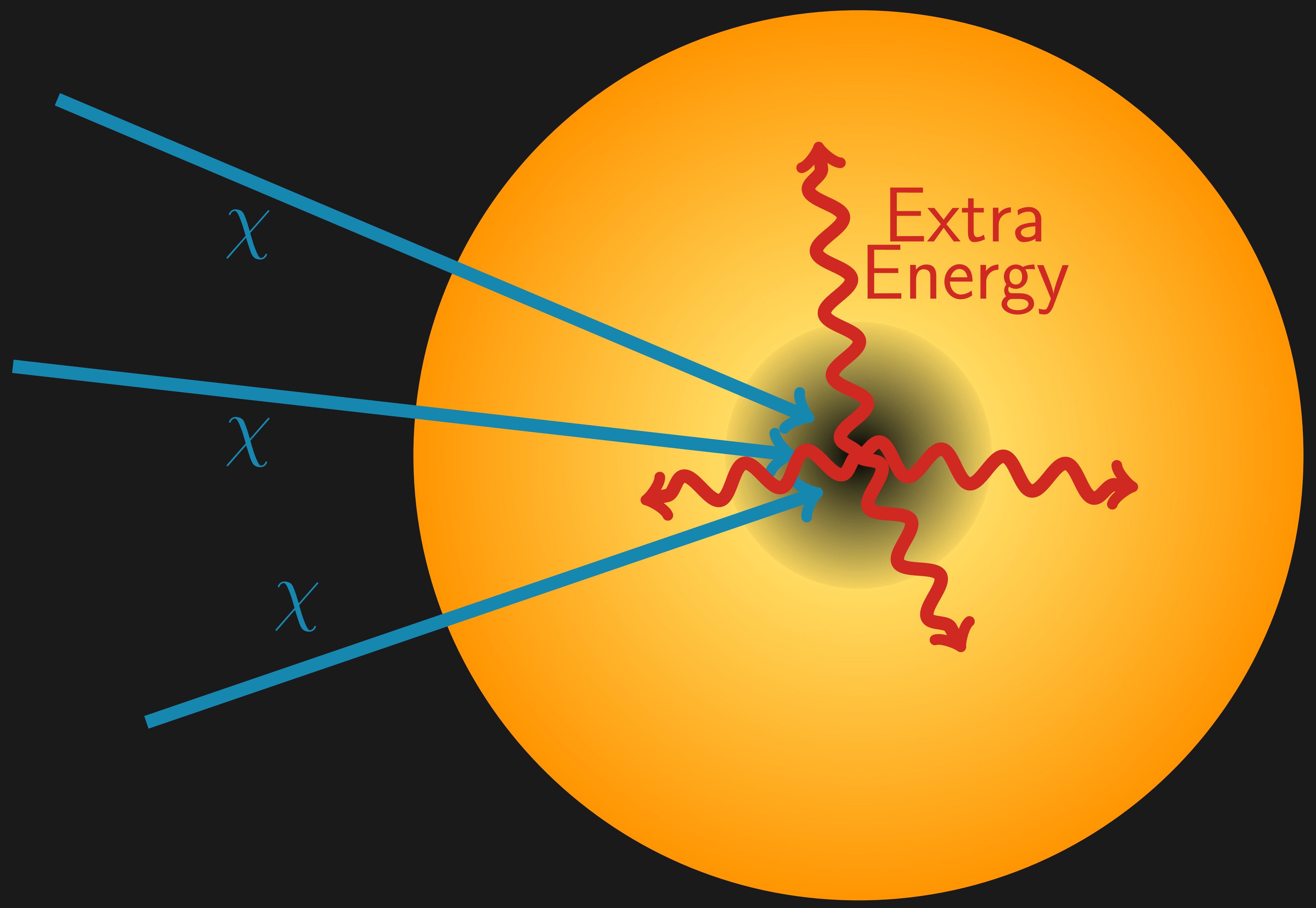
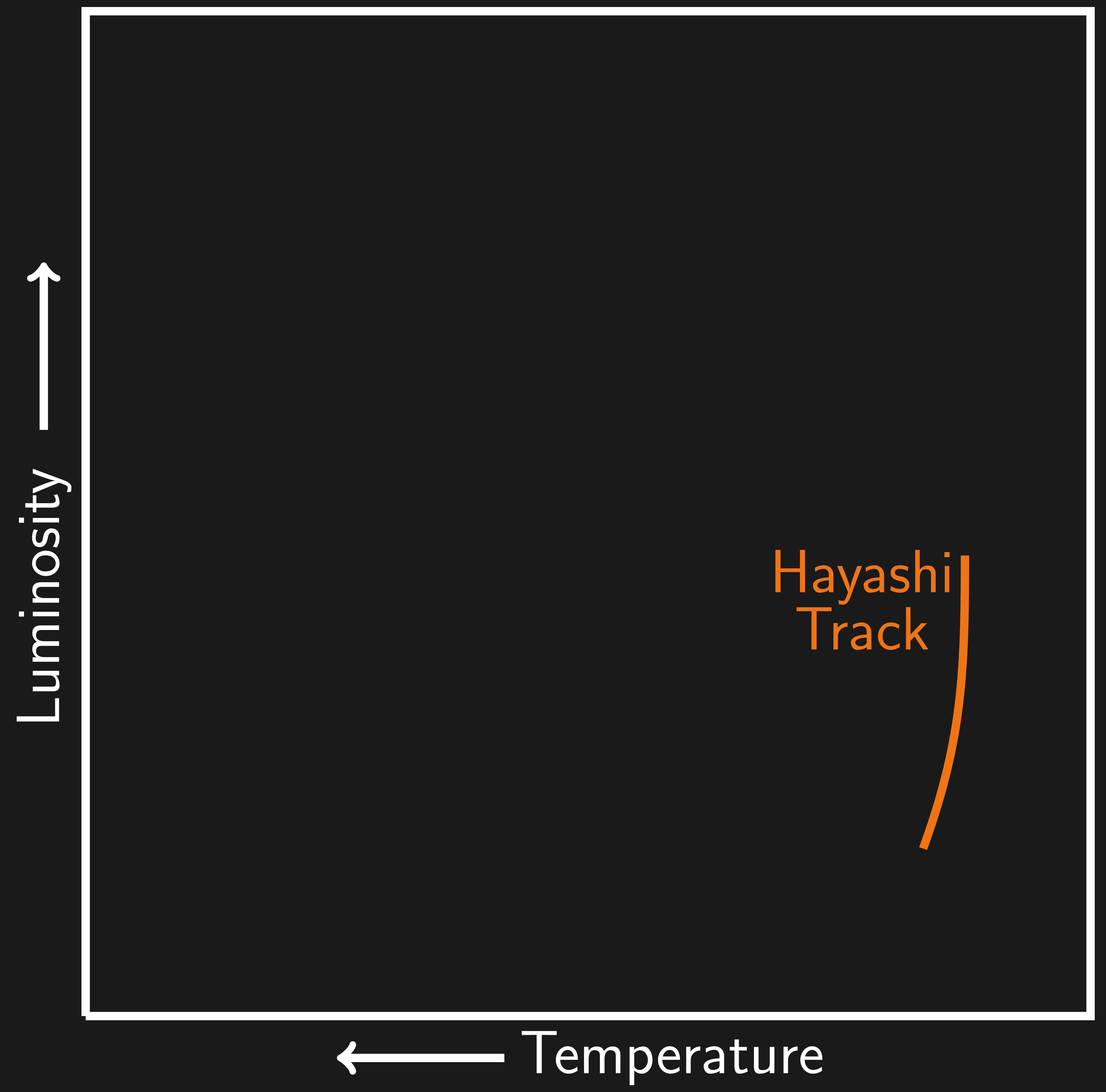


Optimal capture rate:

- 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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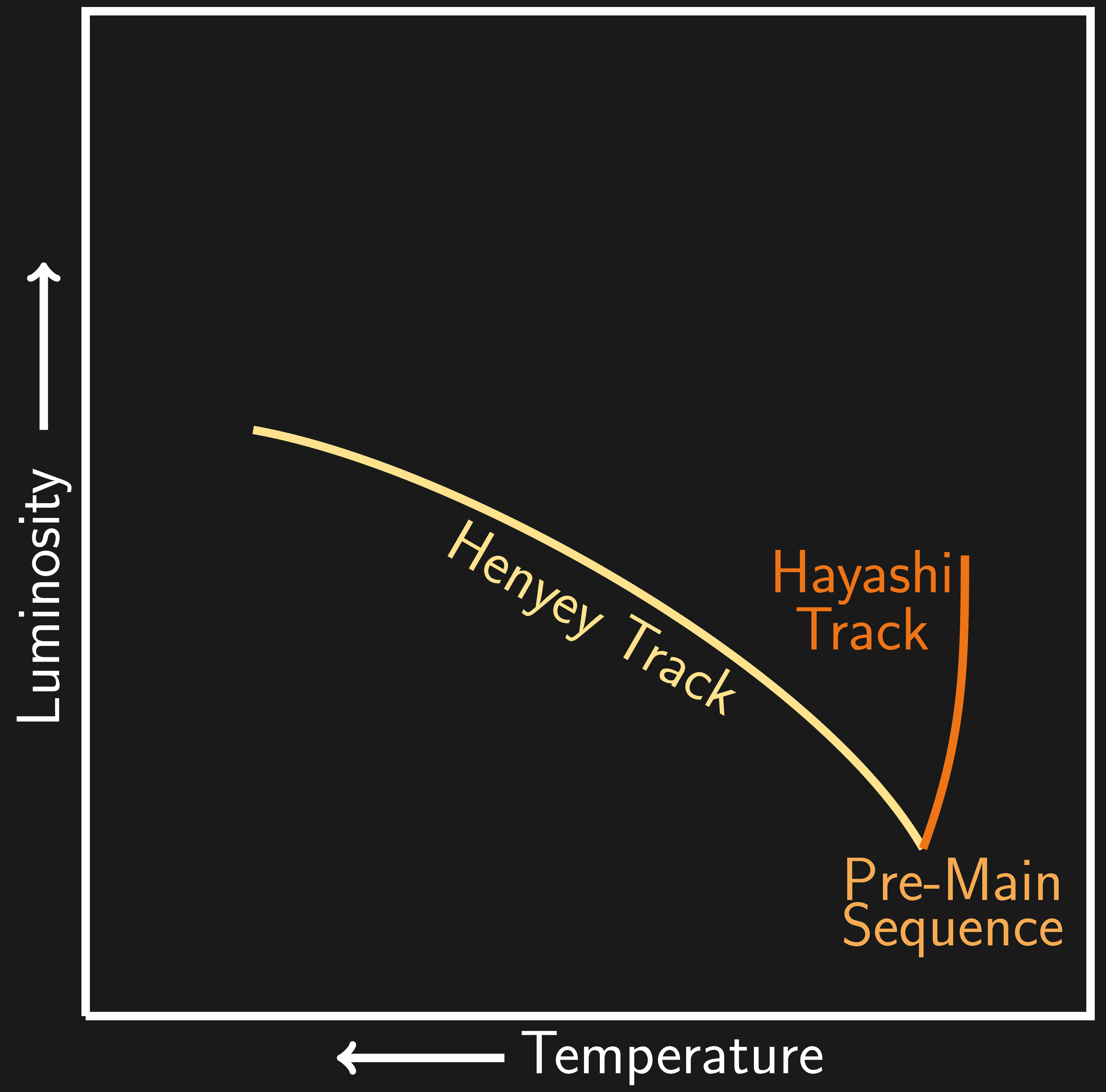

Hayashi track: newly forming star contracts

Henyey track: hydrogen fusion starts

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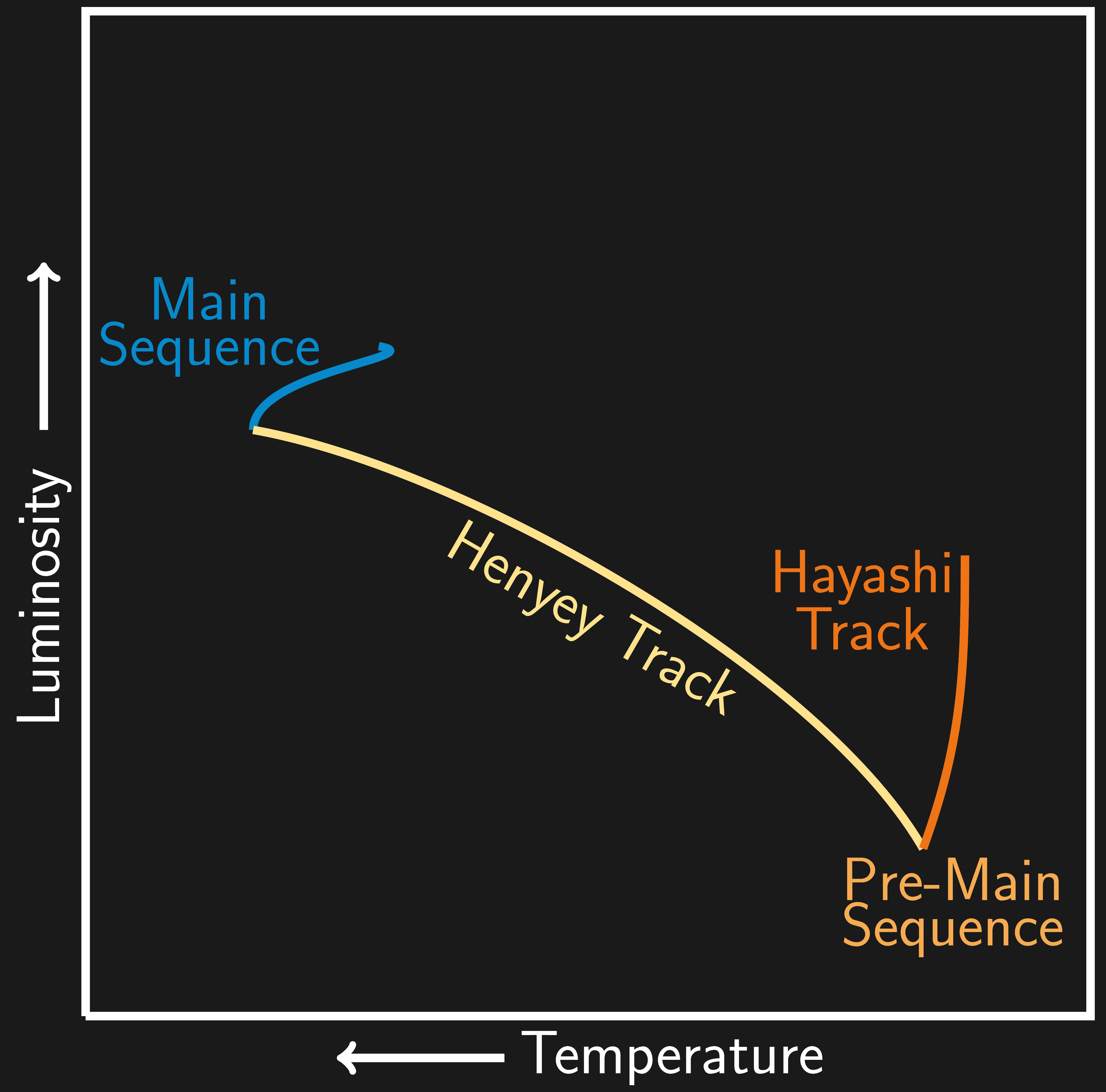

Hayashi track: newly forming star contracts

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

Stellar Evolution Stages on HR Diagram

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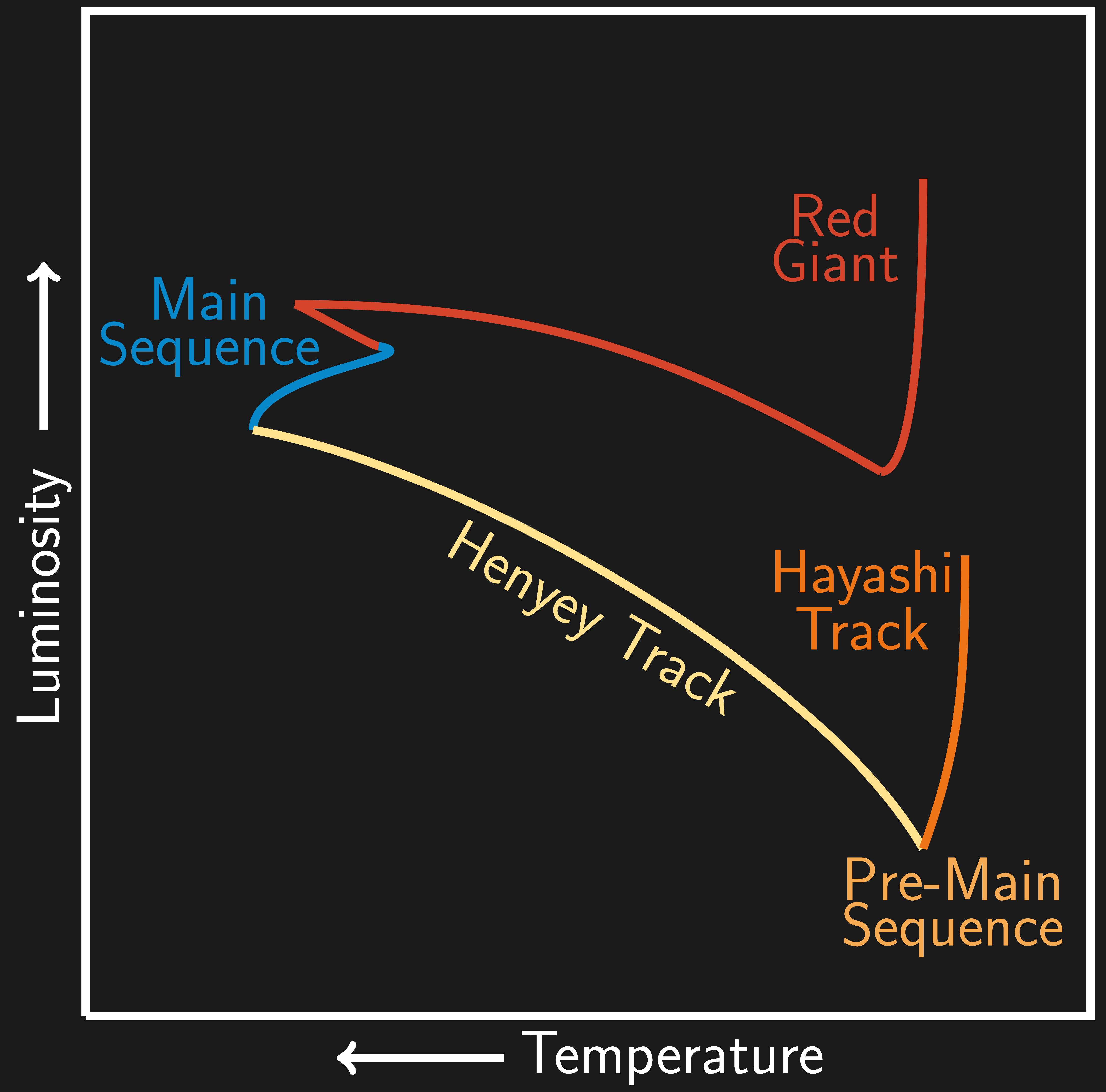


Hayashi track: newly forming star contracts

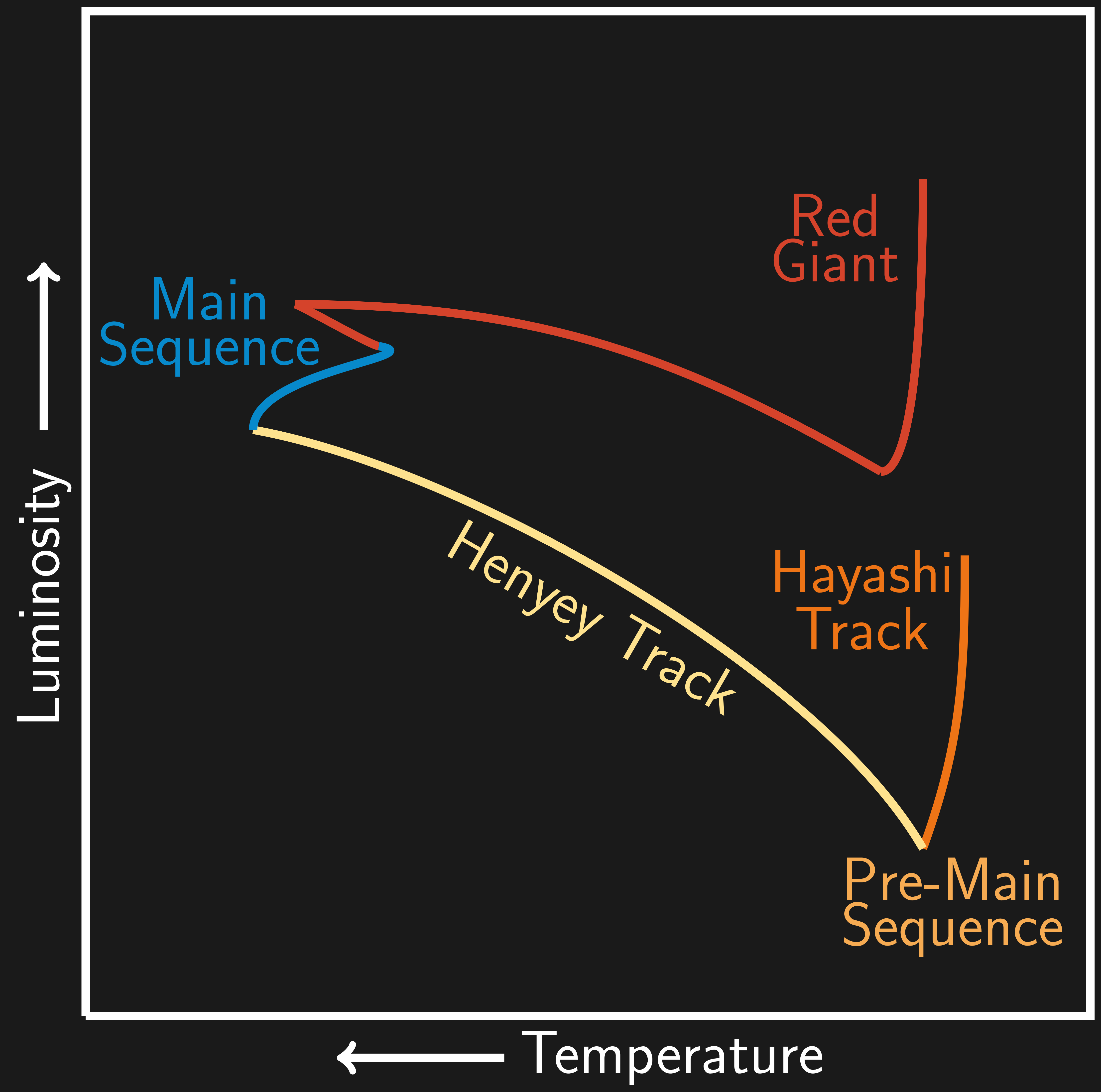
Henyey track: hydrogen fusion starts

Main sequence: star 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:

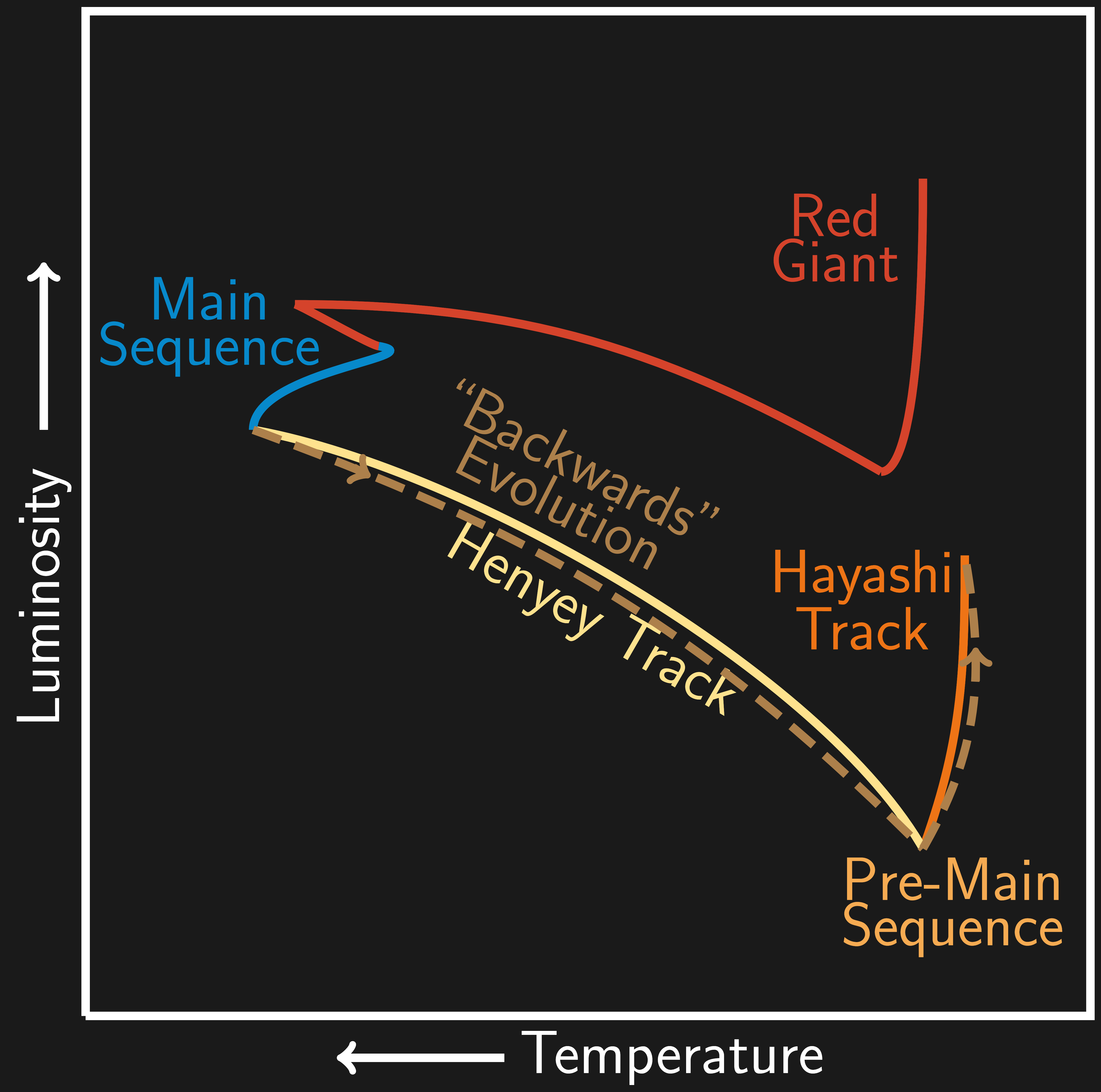
Salati & Silk 1989

Fairbairn, Scott & Edsjö arXiv:0710.3396

Scott, Fairbairn & Edjsö arXiv:0809.1871

Dark Matter Changes Stellar Evolution

Hertzsprung–Russell (HR) Diagram



- Dark matter annihilation provides power similar to nuclear fusion
- Stars can evolve "backwards"

See also:

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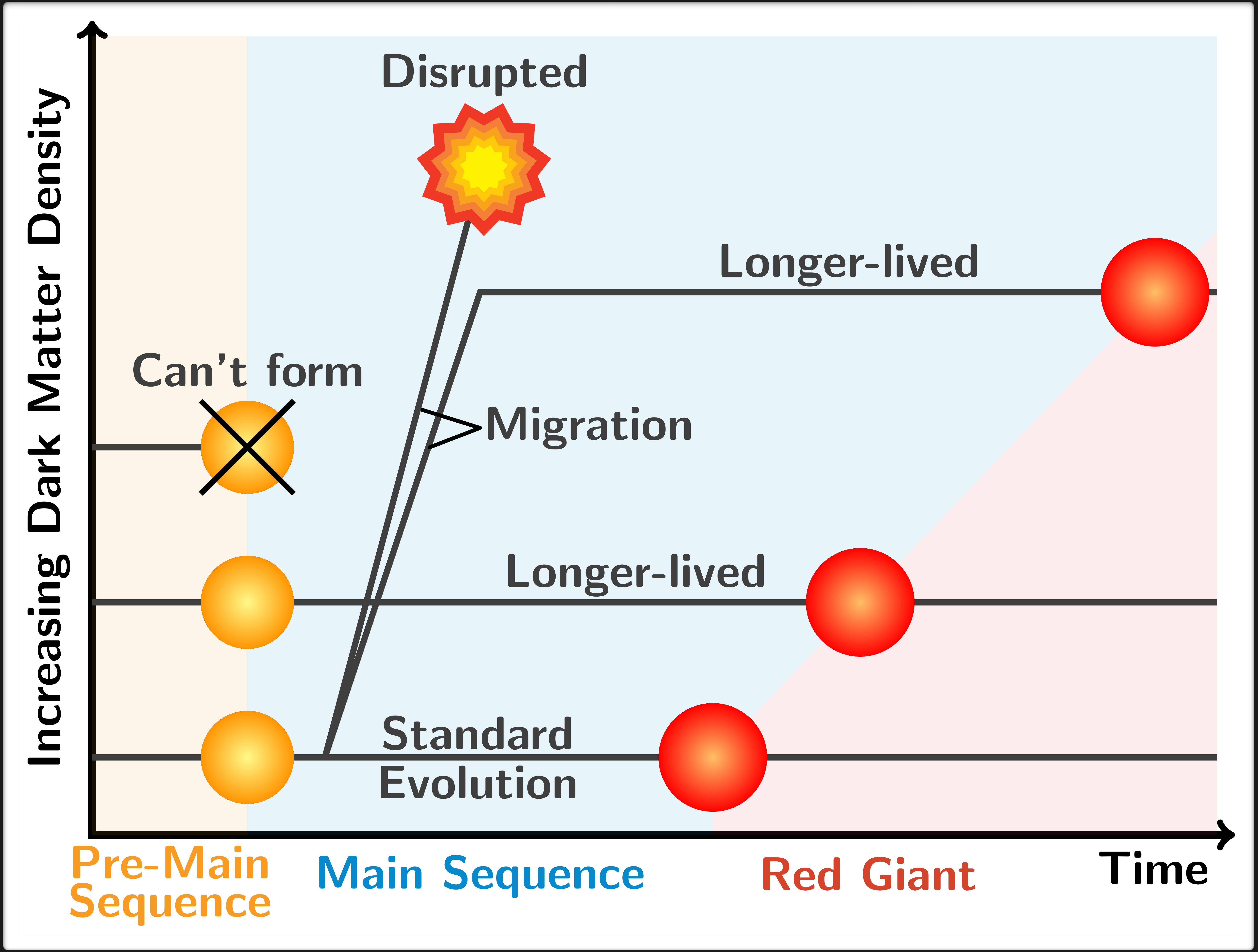
Dark Matter Changes Stellar Evolution



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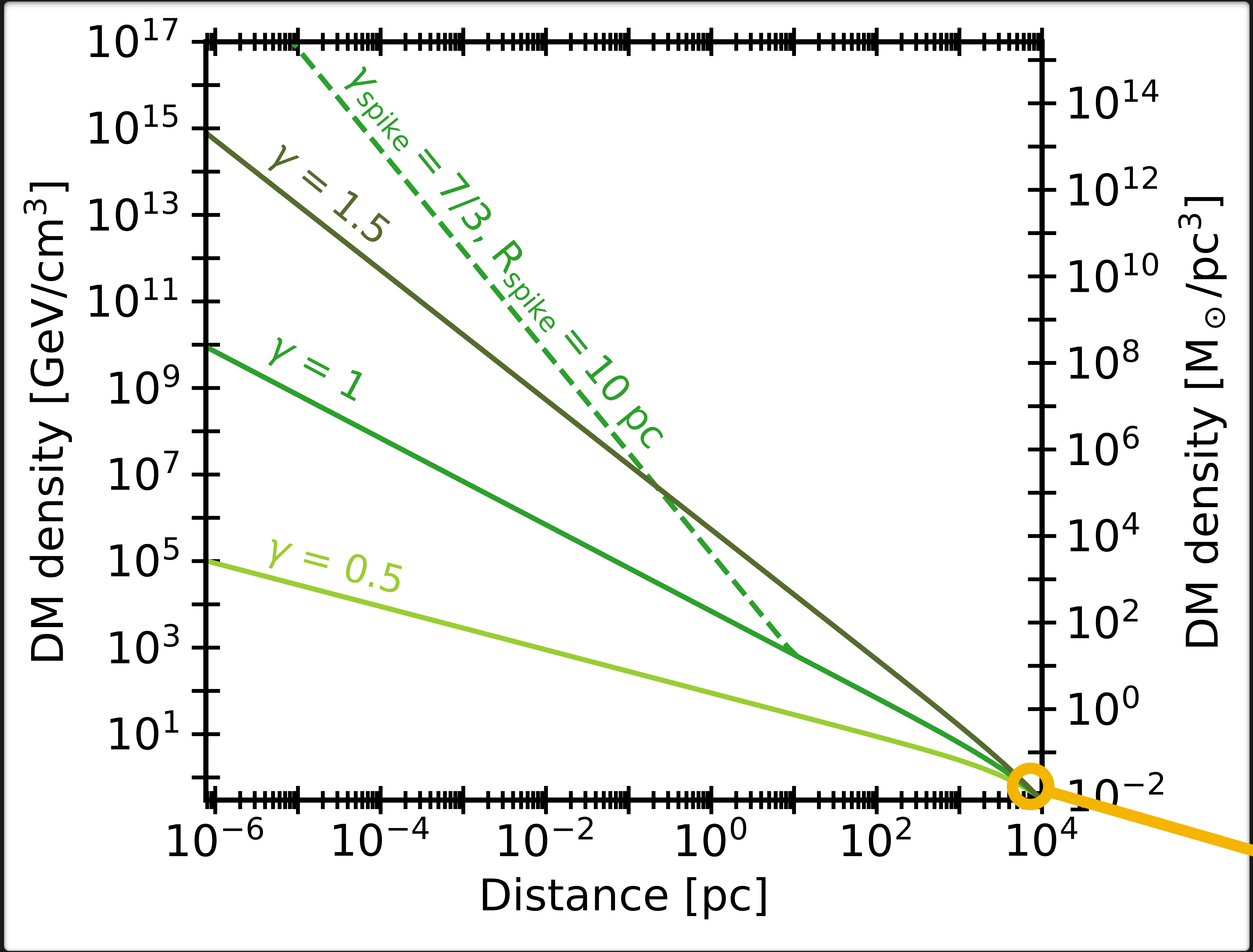
See also Dark Stars in the early Universe:

Iocco, arXiv:0802.0941

Freese et al, arXiv:0805.3540

Galactic Dark Matter Density and Profile



Dark matter density at Galactic Center is

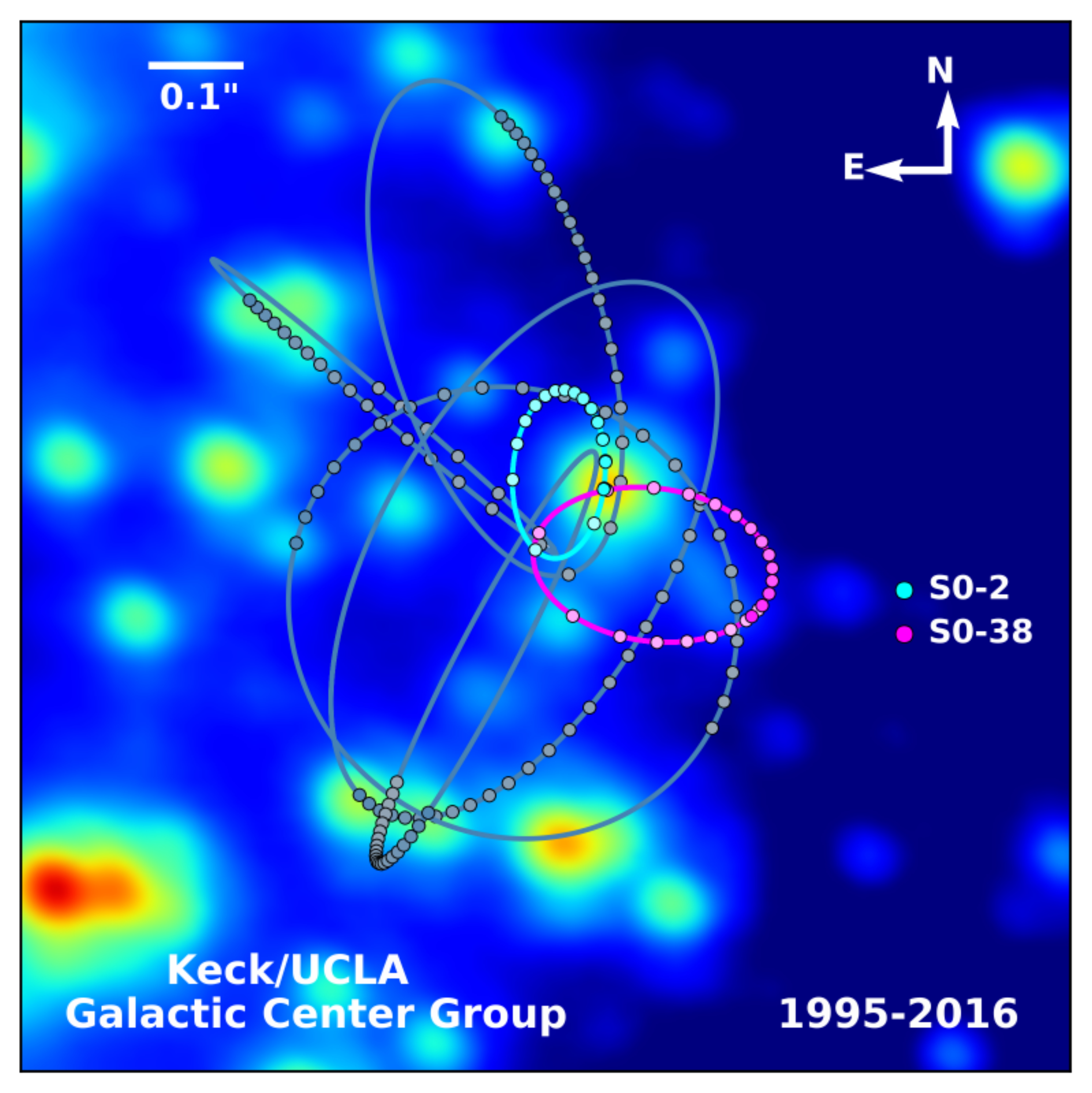
- Very high: significant dark matter capture in stars
- Very uncertain: test dark matter profile models

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



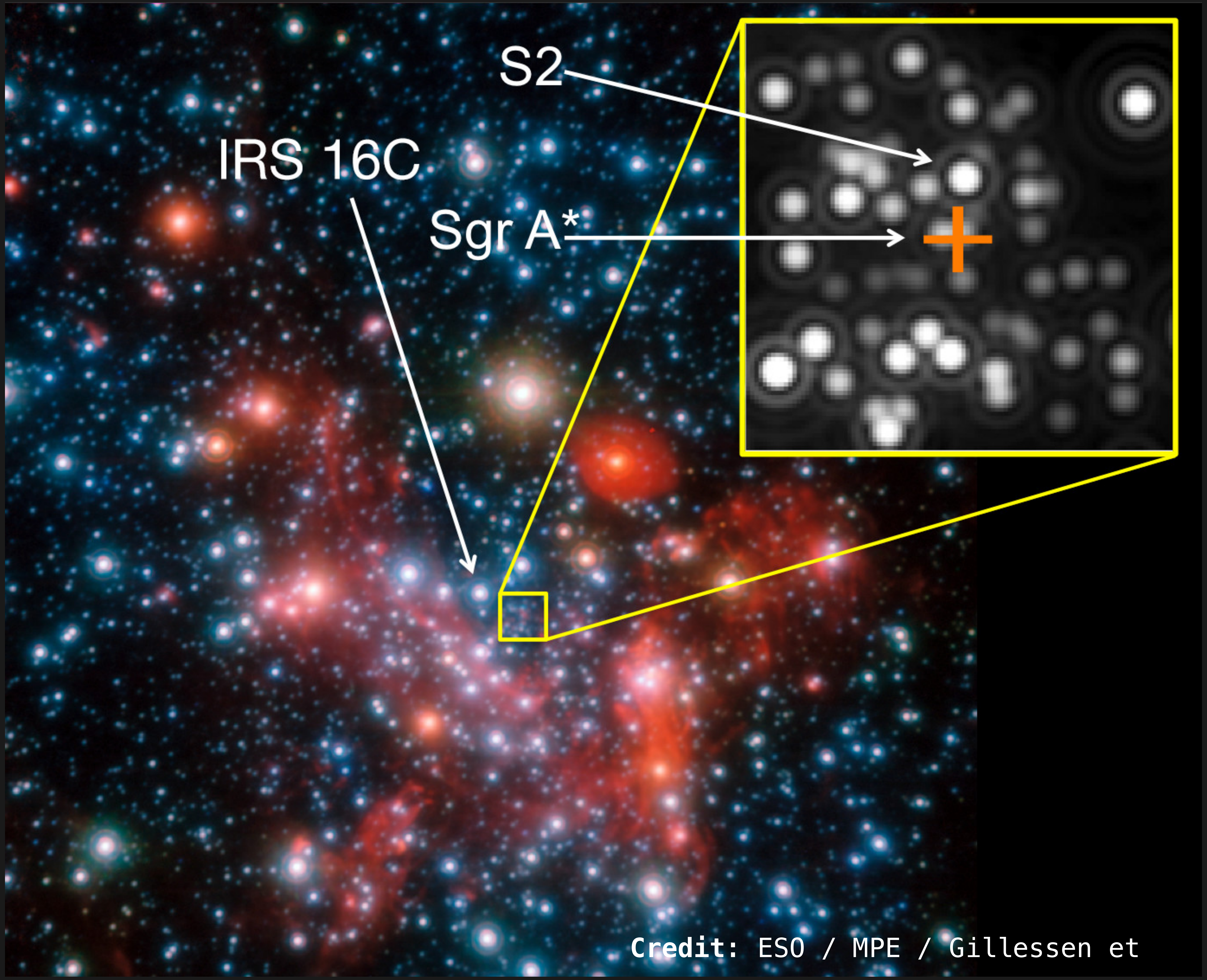
Unusual Properties of S–Cluster Stars

Origin not well understood: in situ formation or migration?

Paradox of Youth: Spectroscopically old but bright as young stars

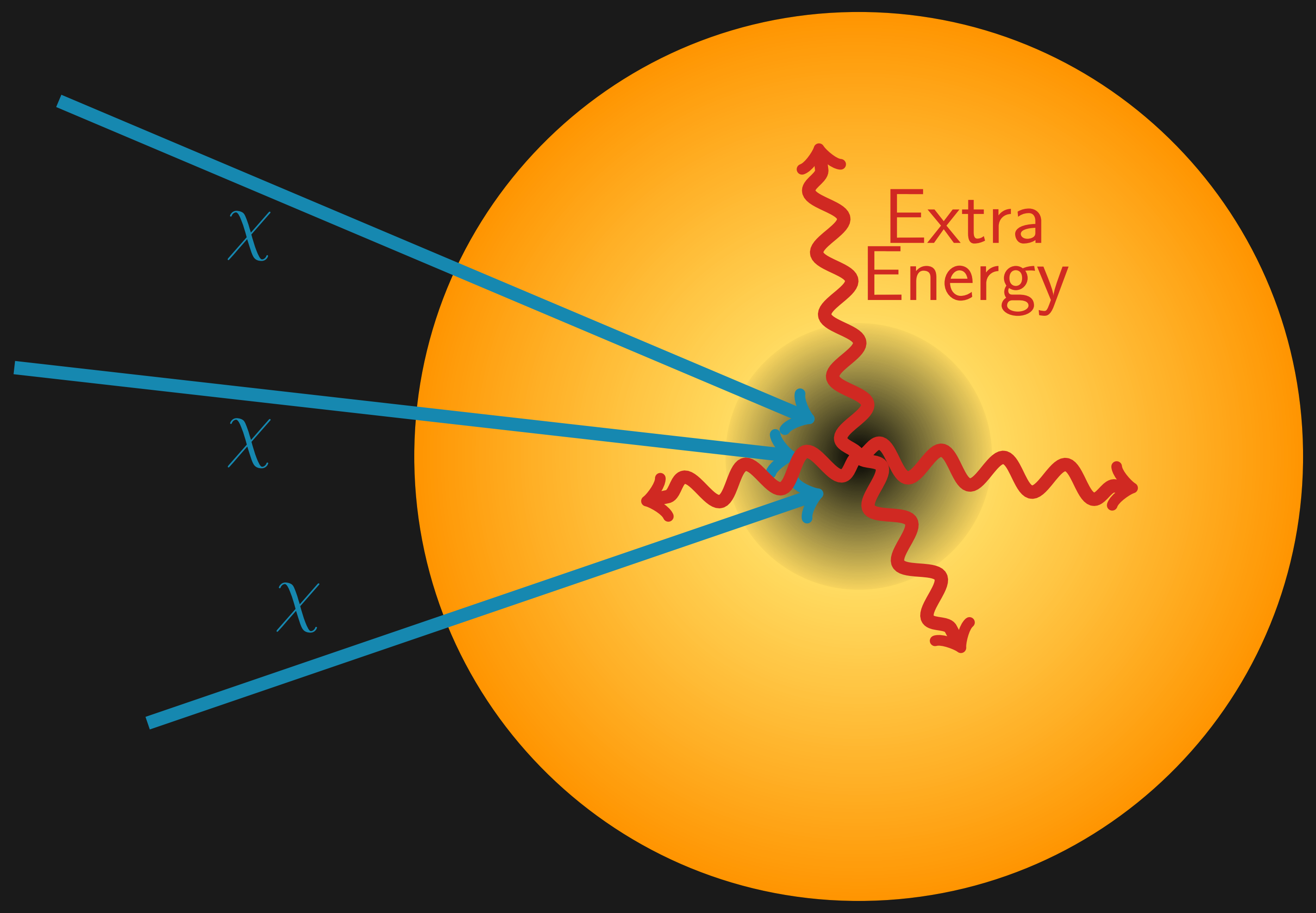
Conundrum of Old Age: Lack of old stars

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



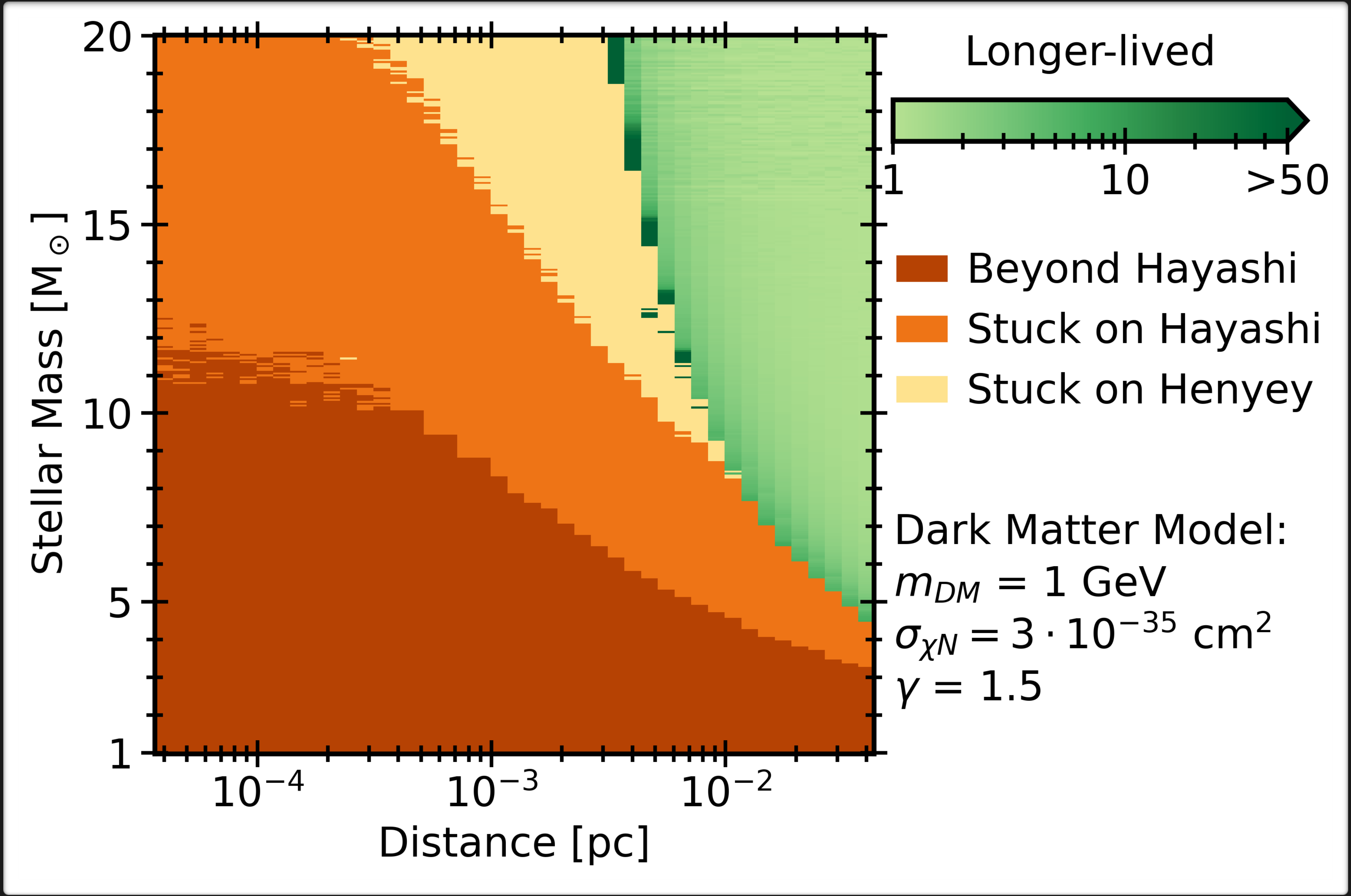
Modelling Stellar Evolution with Dark Matter

- 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]



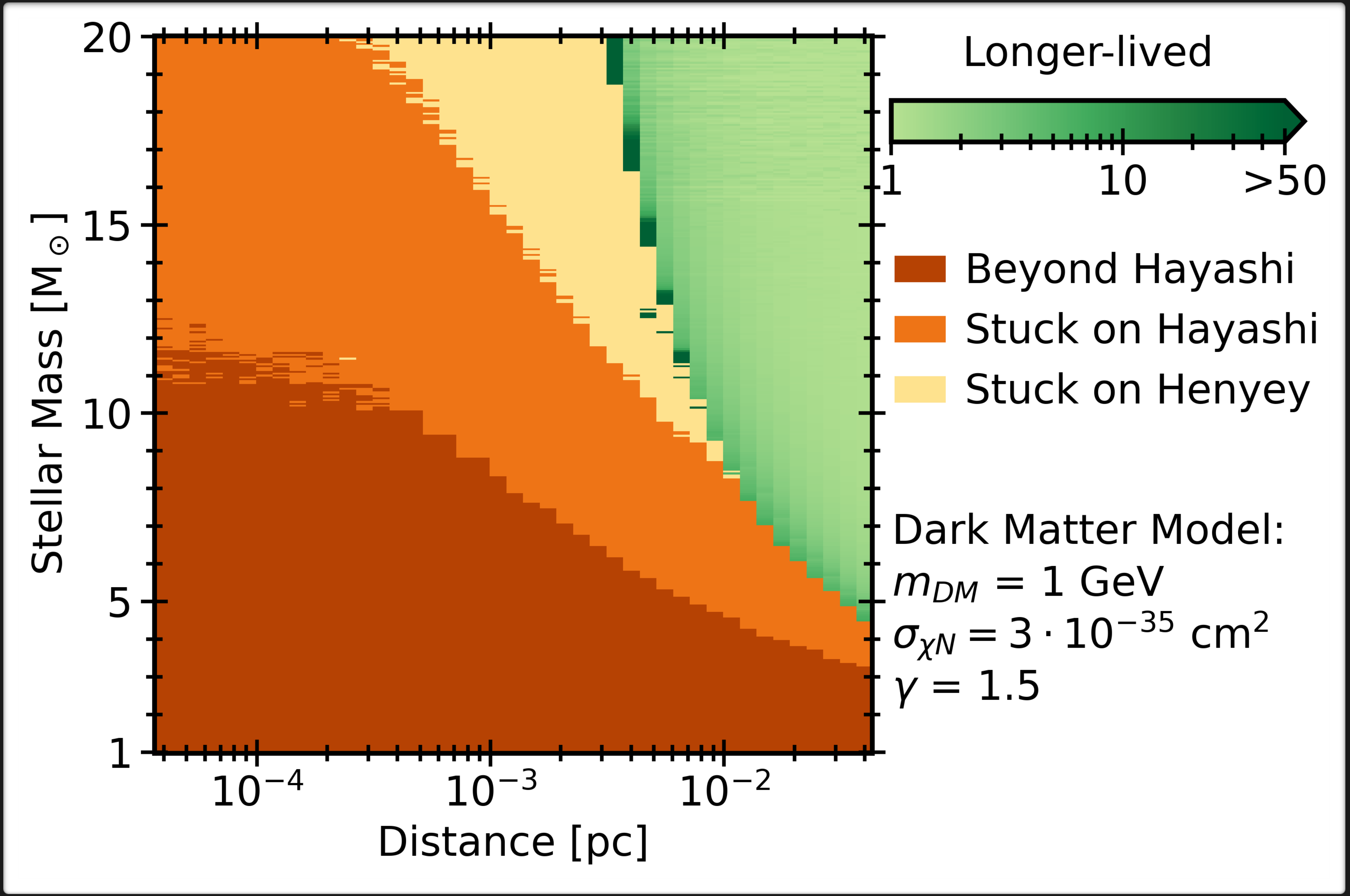
Evolutionary stage after main sequence or 10 billion years.

Effects depend on:

- Stellar mass
- Dark matter density

Dark Matter Slows Stellar Evolution

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

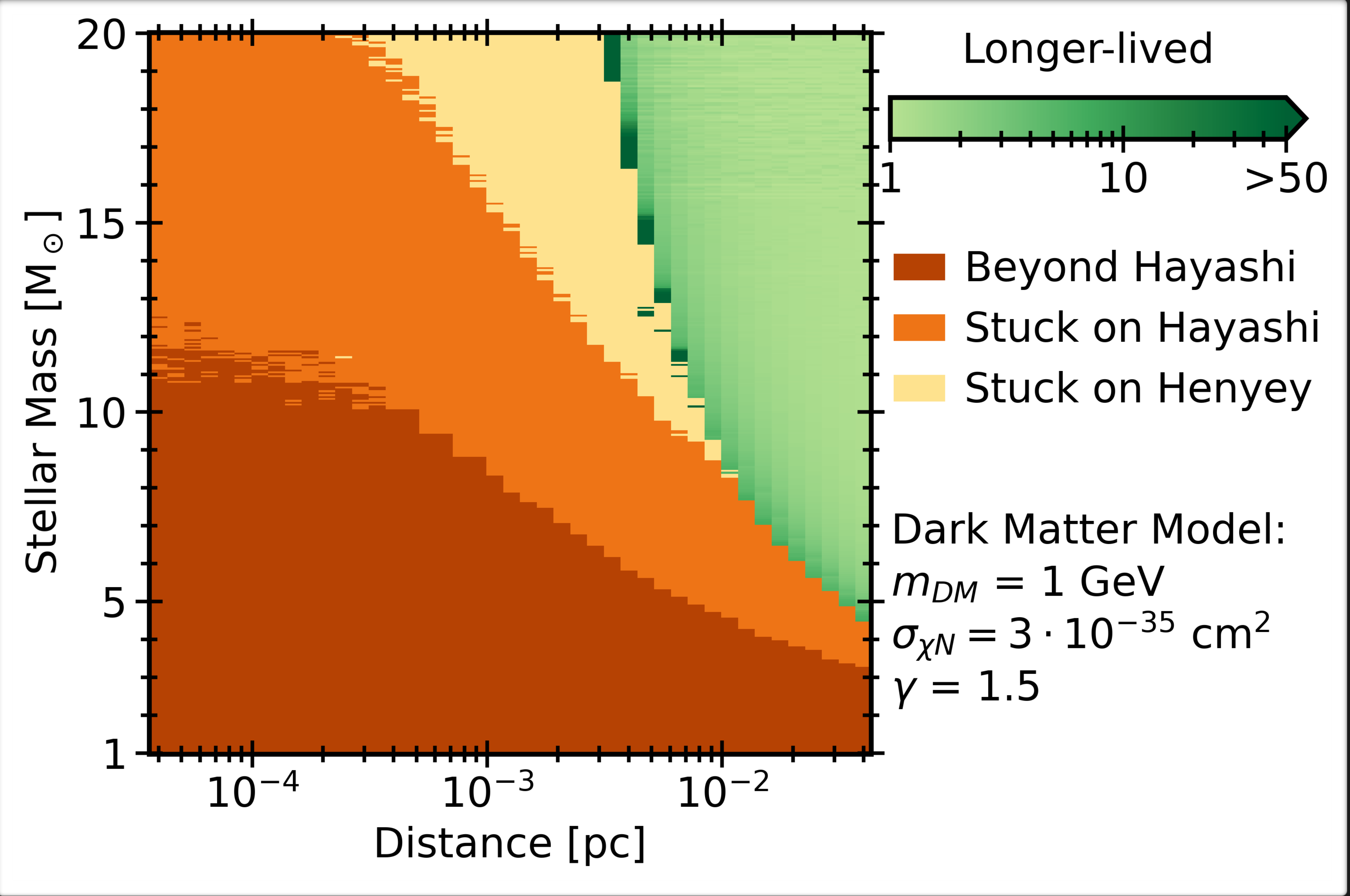


Longer−lived

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

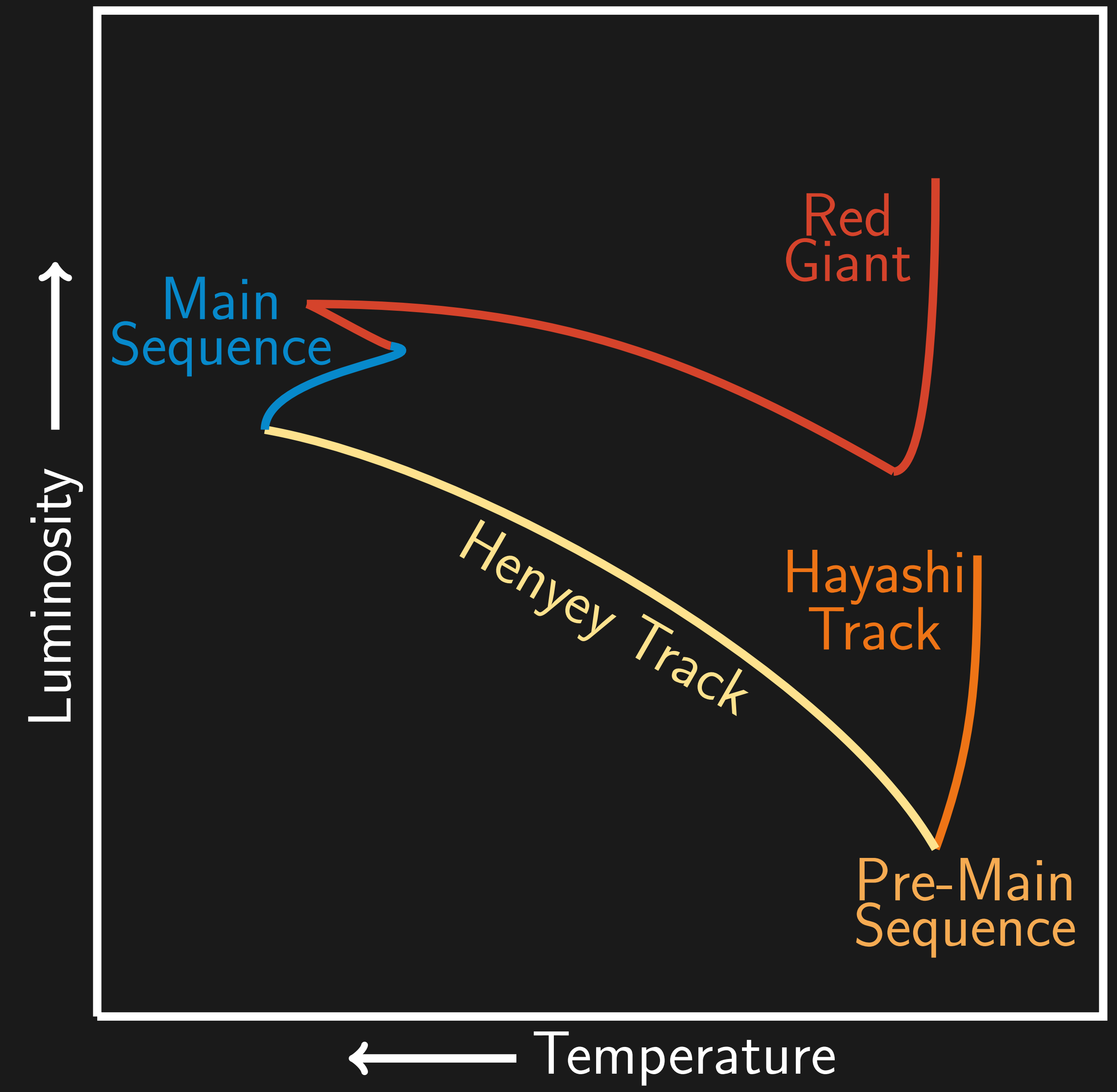
Dark Matter Slows Stellar Evolution

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



Stuck on Henyey

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



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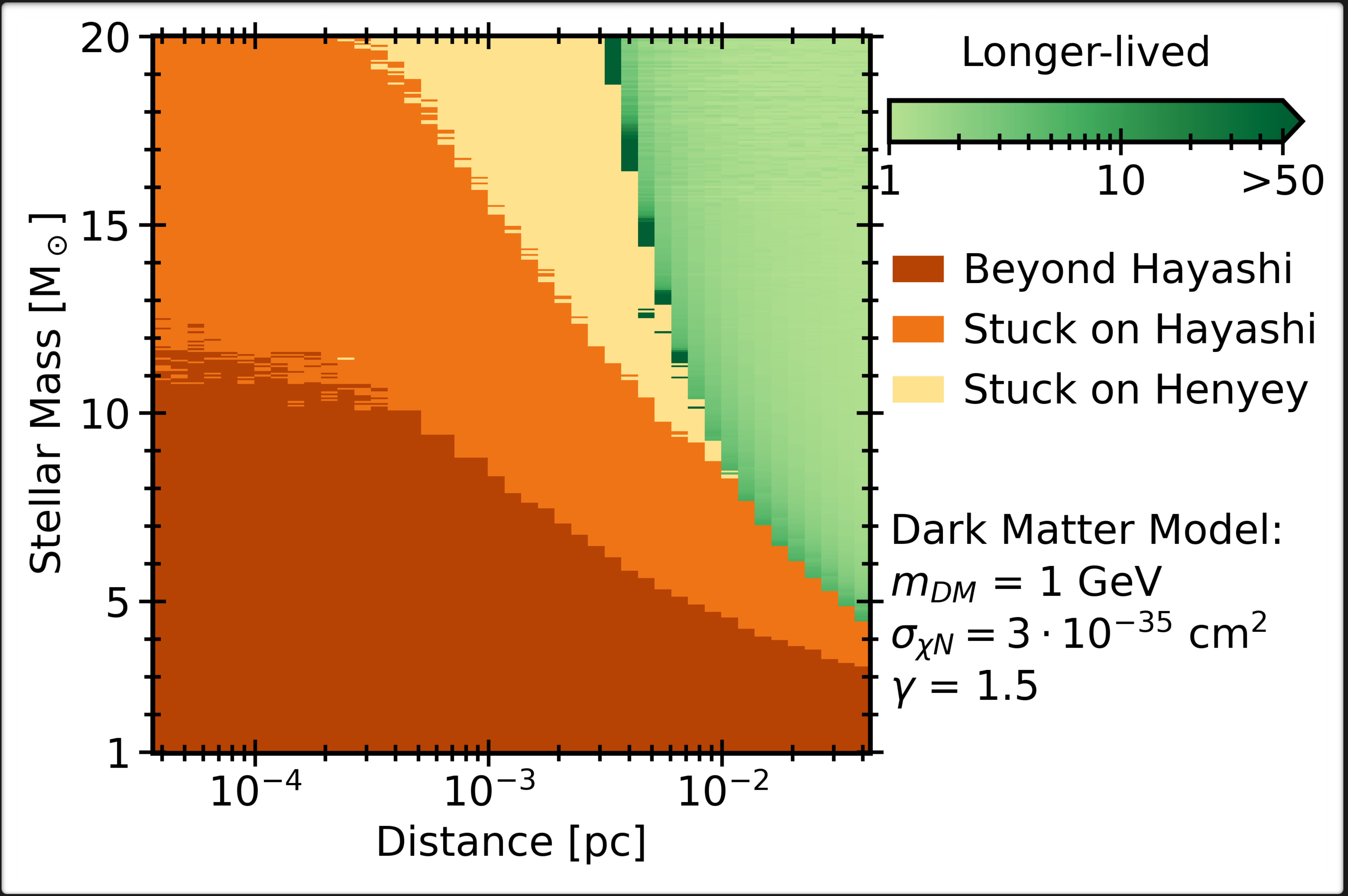
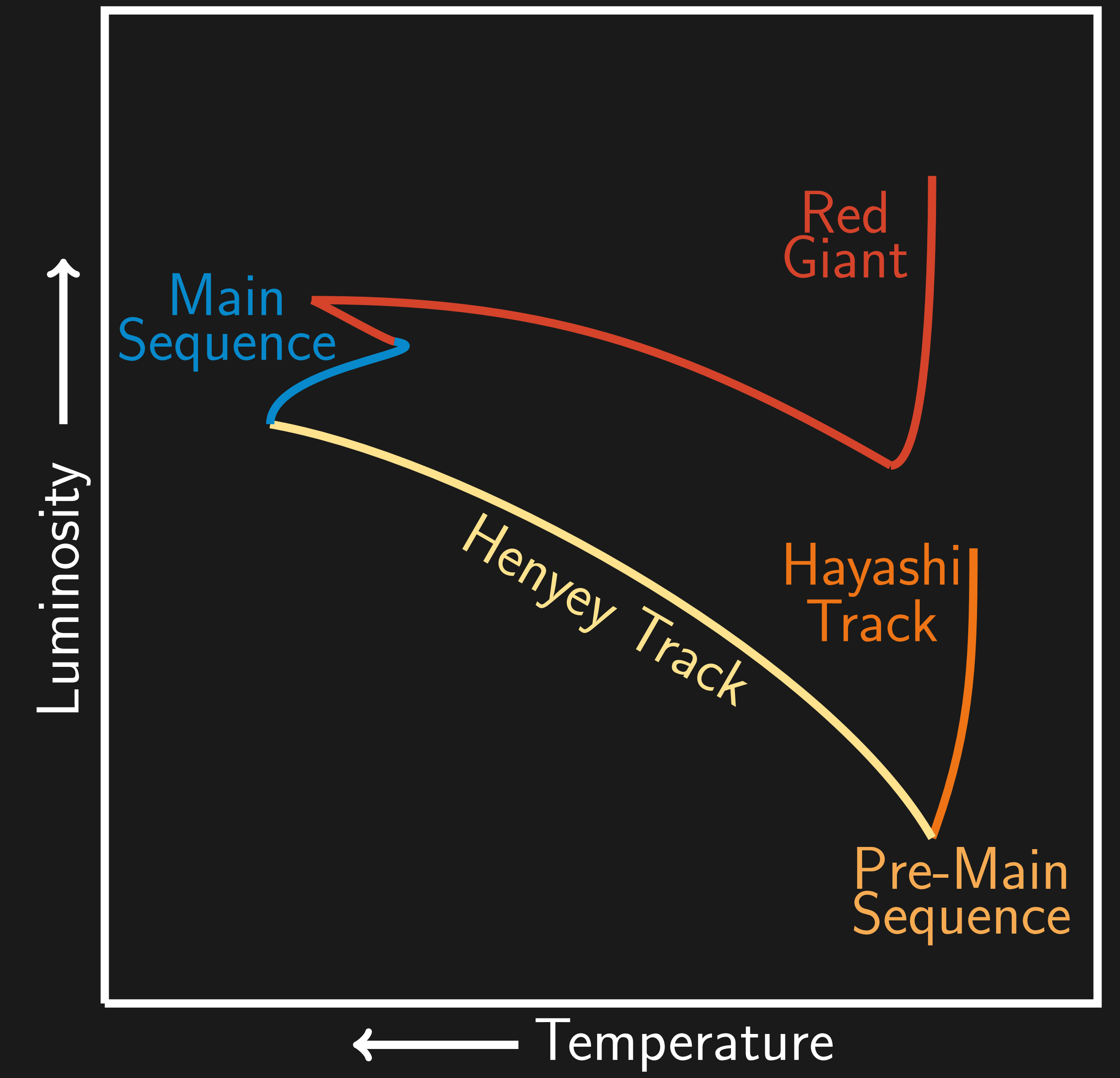


Beyond/Stuck on Hayashi

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



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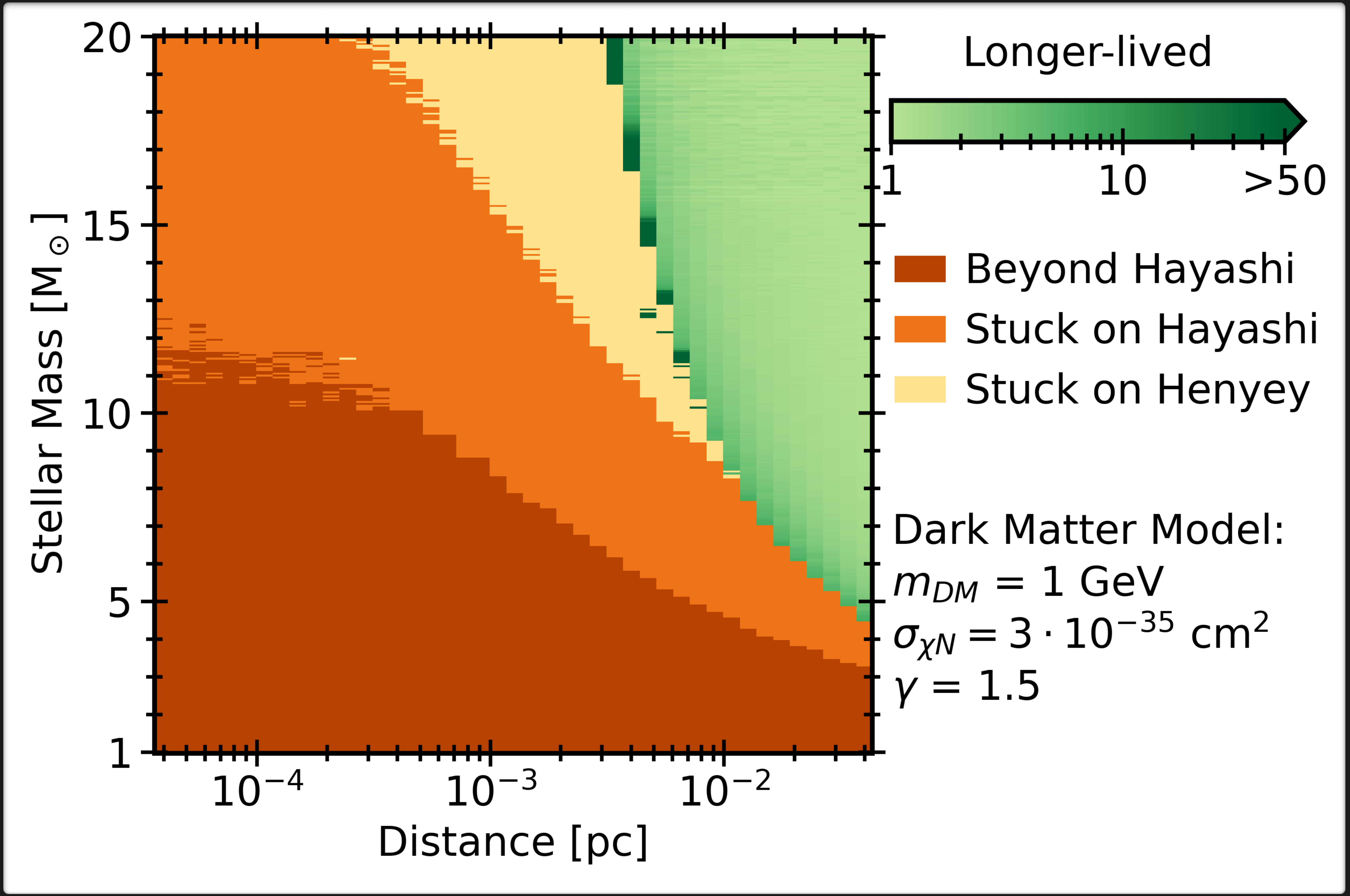

Beyond/Stuck on Hayashi

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

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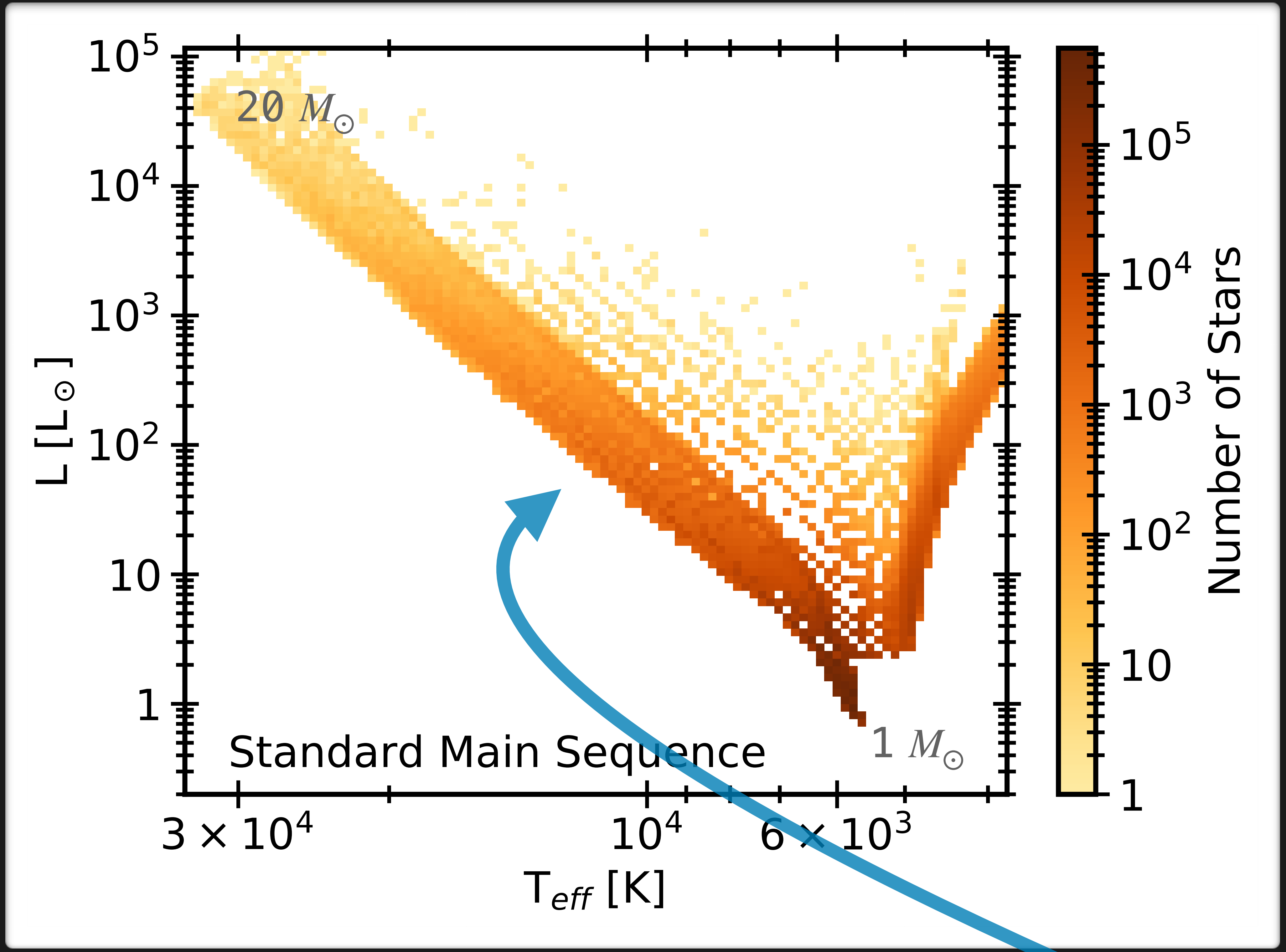
Dark matter can be captured continuously

Stars become effectively immortal

The Dark Main Sequence

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

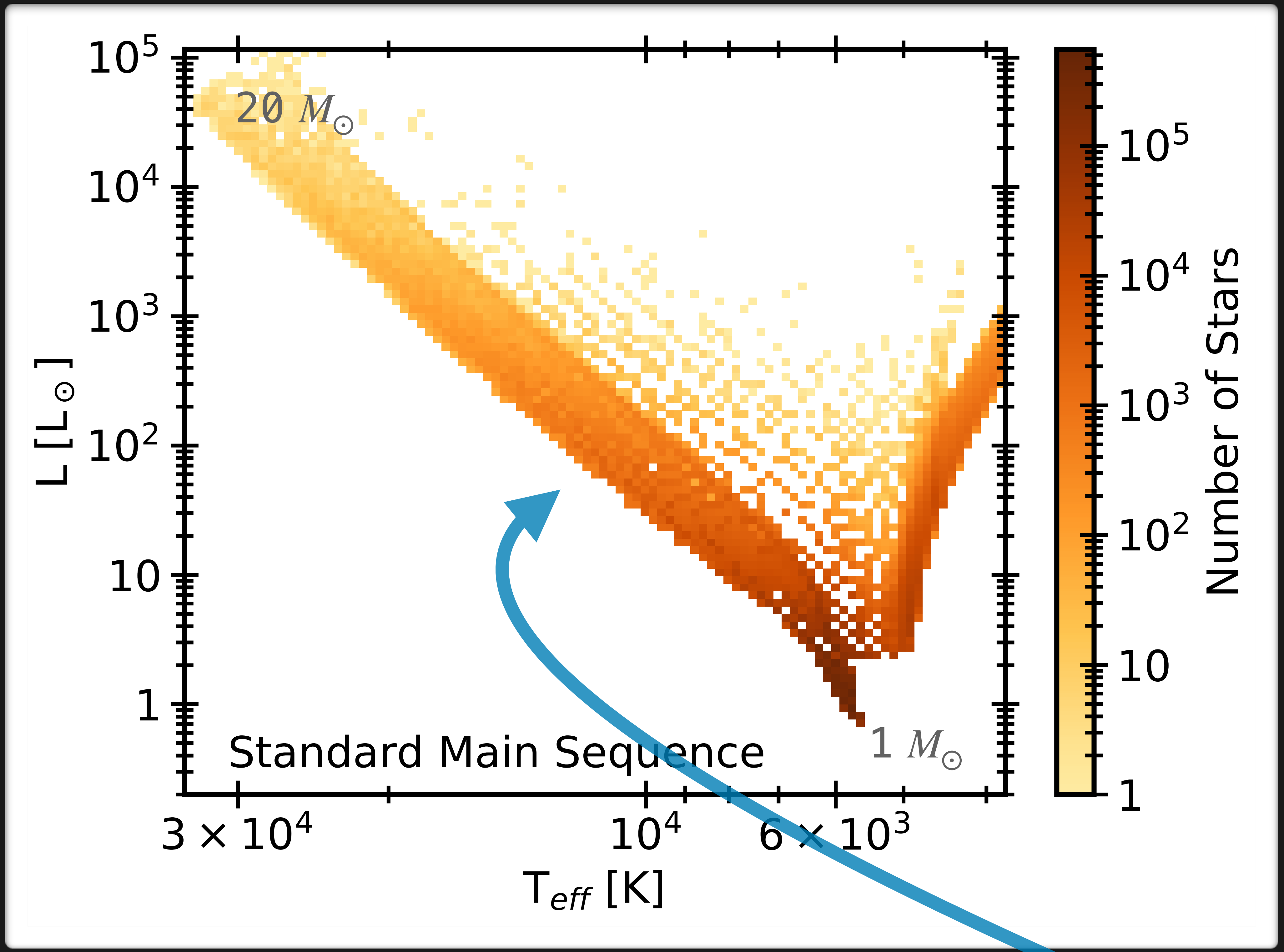


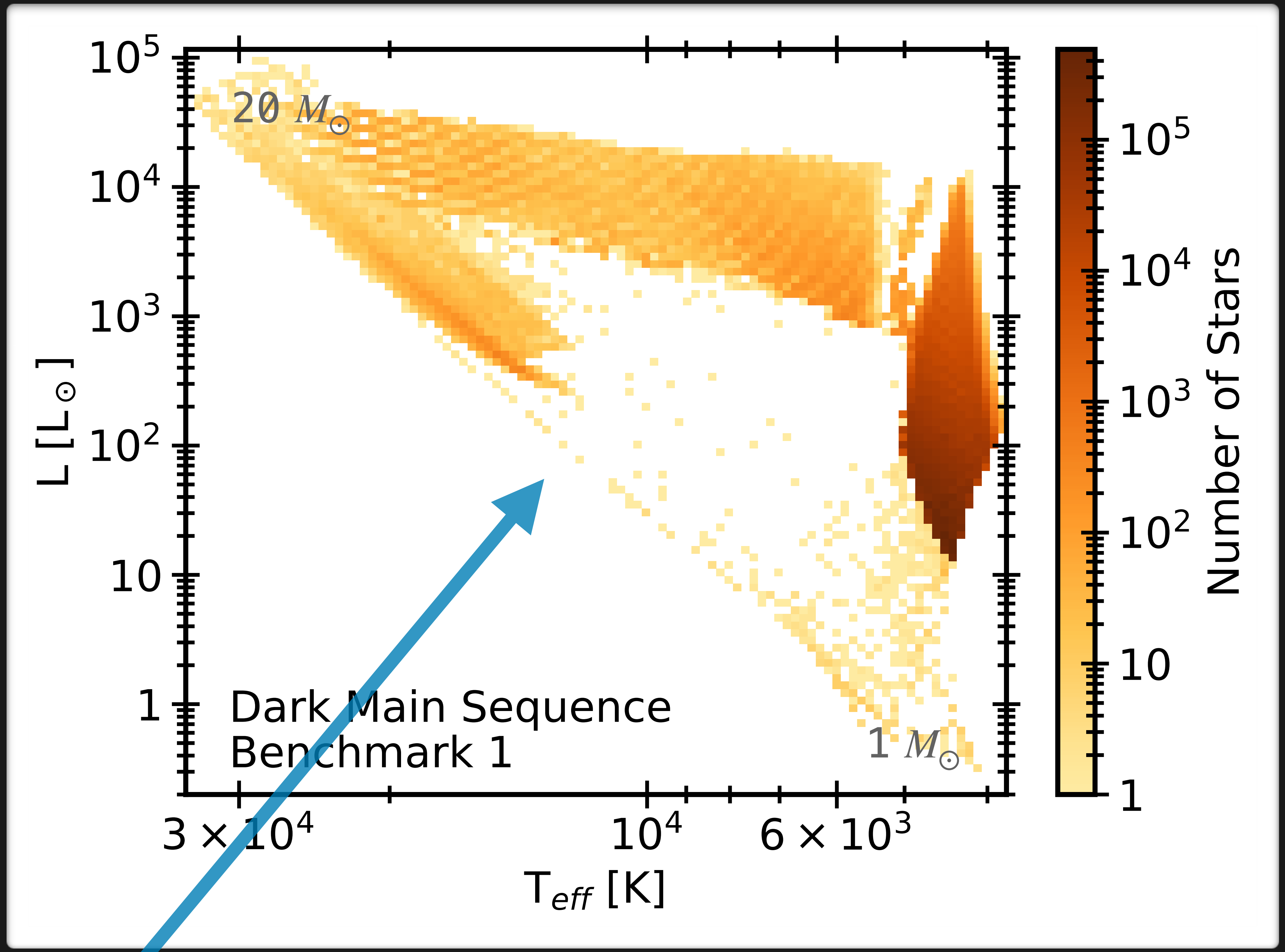
Main Sequence

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:





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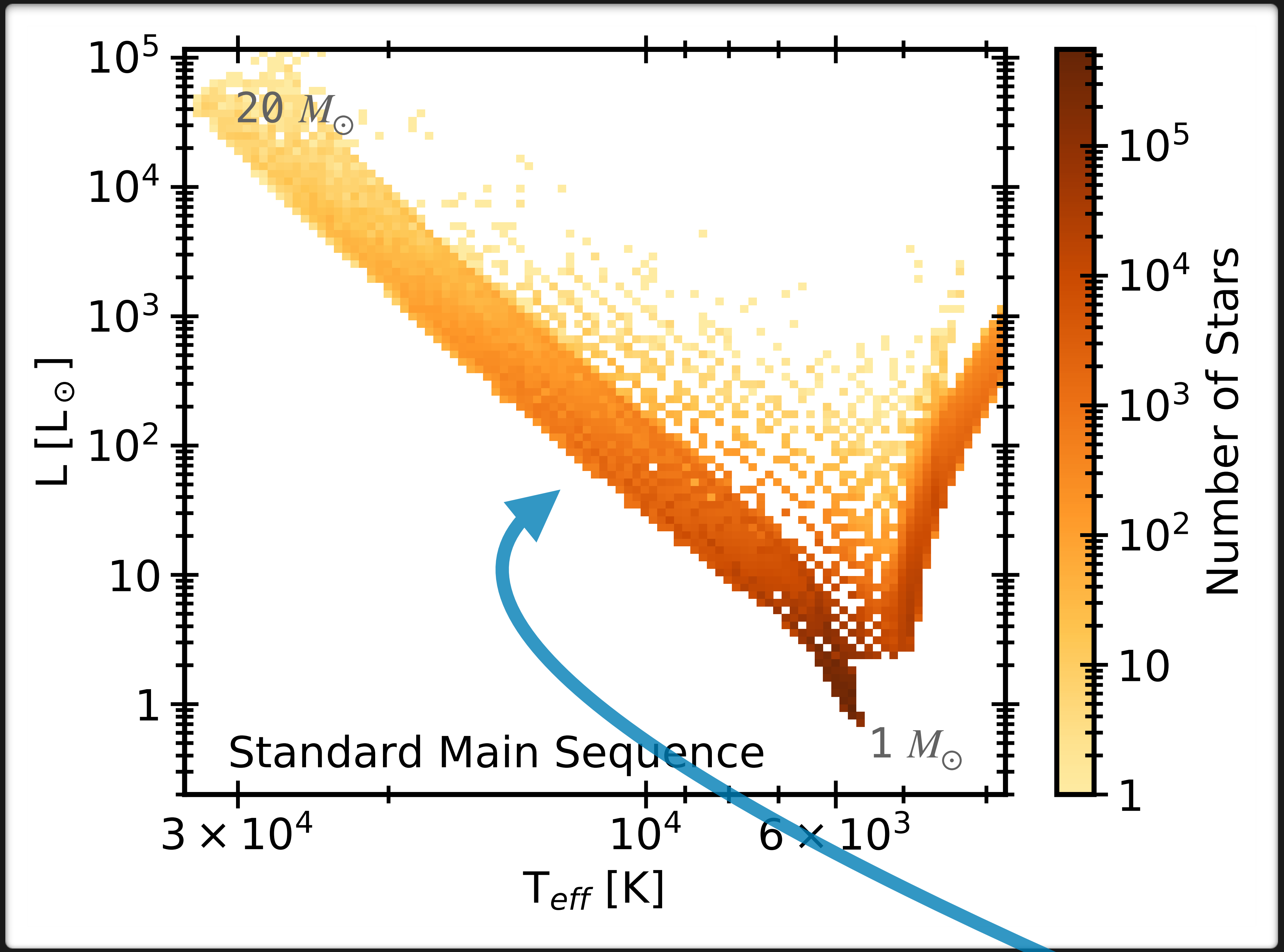
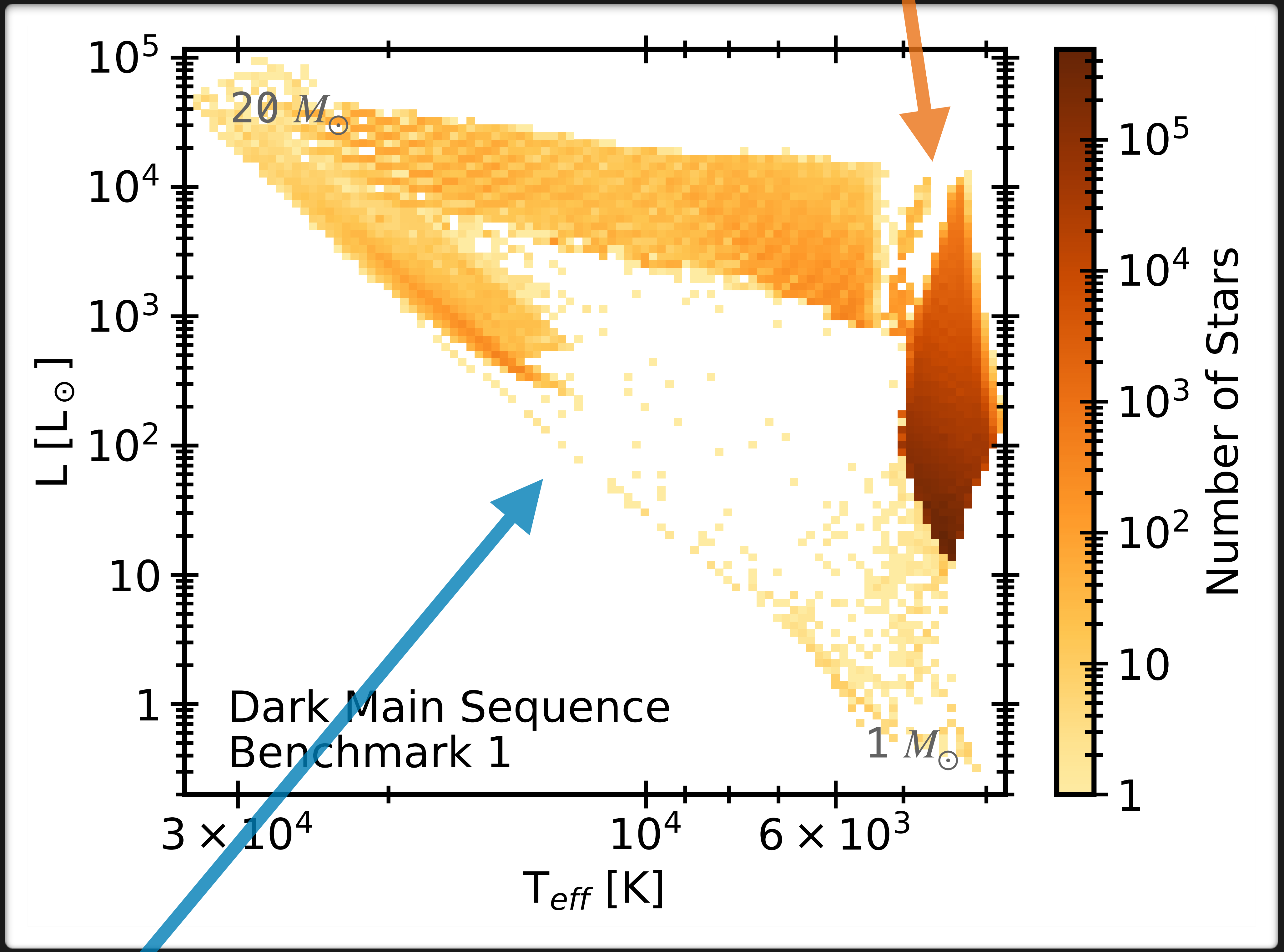




Overabundance of stars along Hayashi tracks

Main Sequence

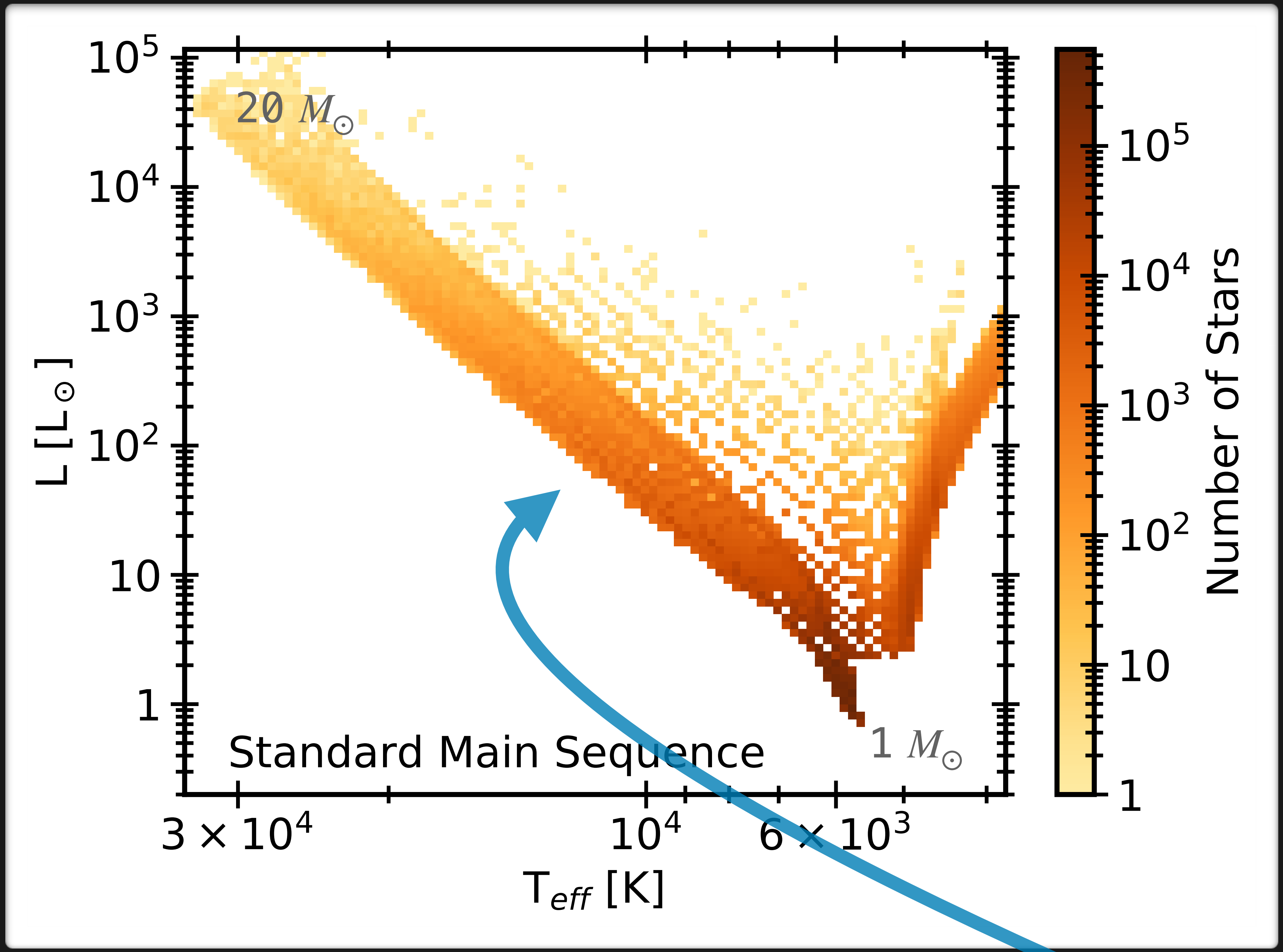
The Dark Main Sequence

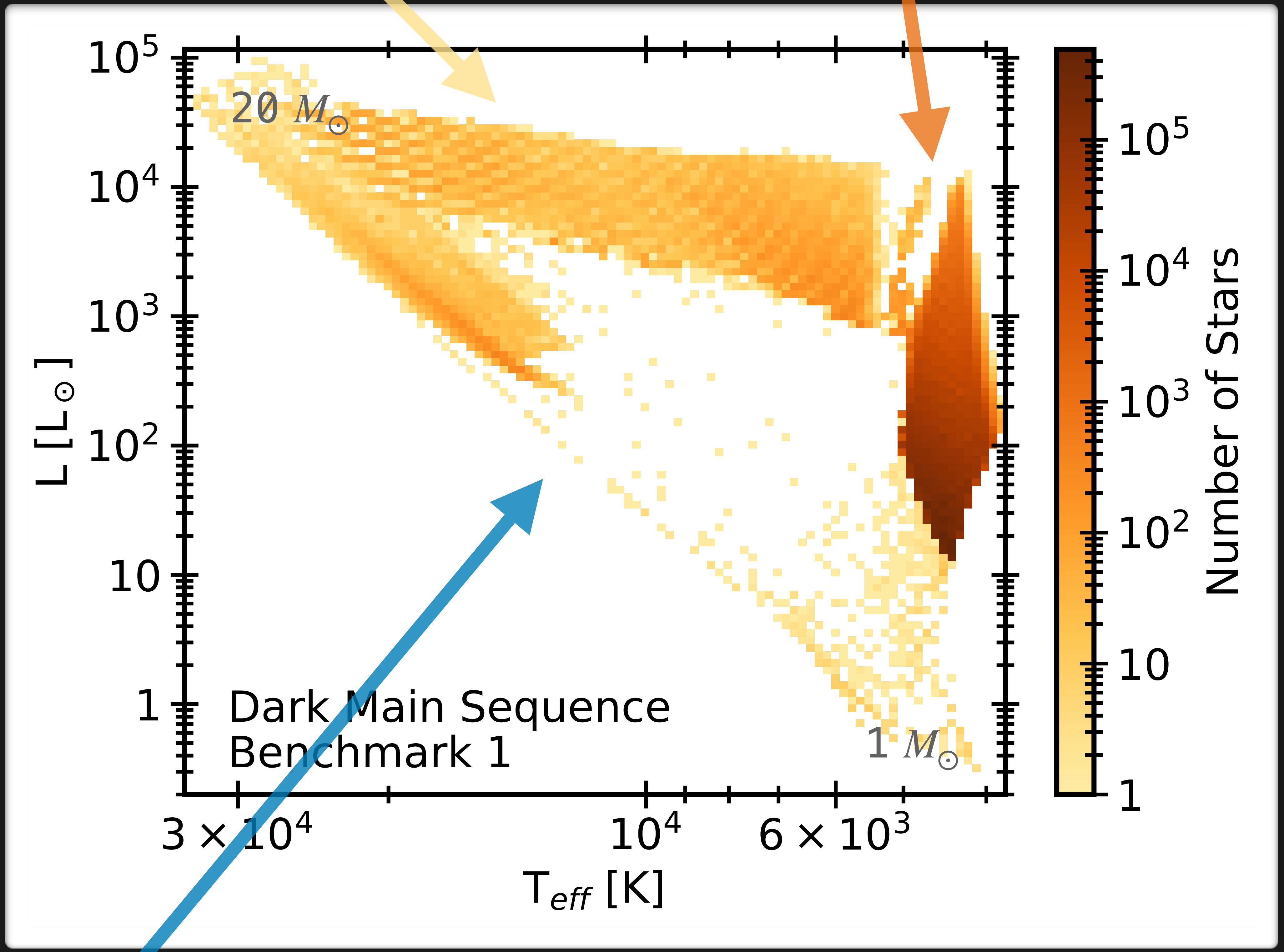
[I. John, R. Leane, T. Linden, arXiv:2405.12267]

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

Dark Main Sequence along Henyey tracks

Overabundance of stars along Hayashi tracks





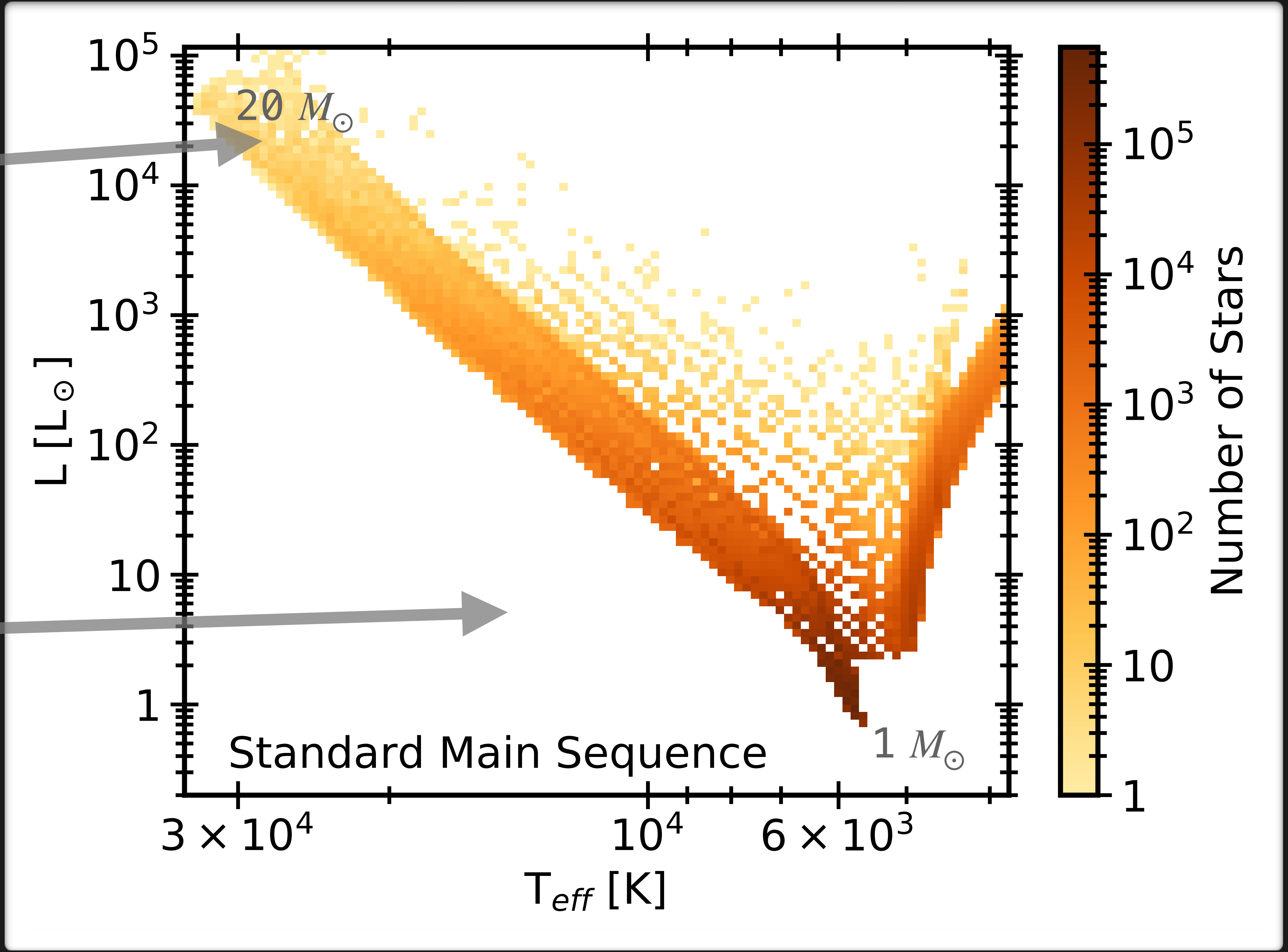
Main Sequence

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:

Evolution with Dark Matter:

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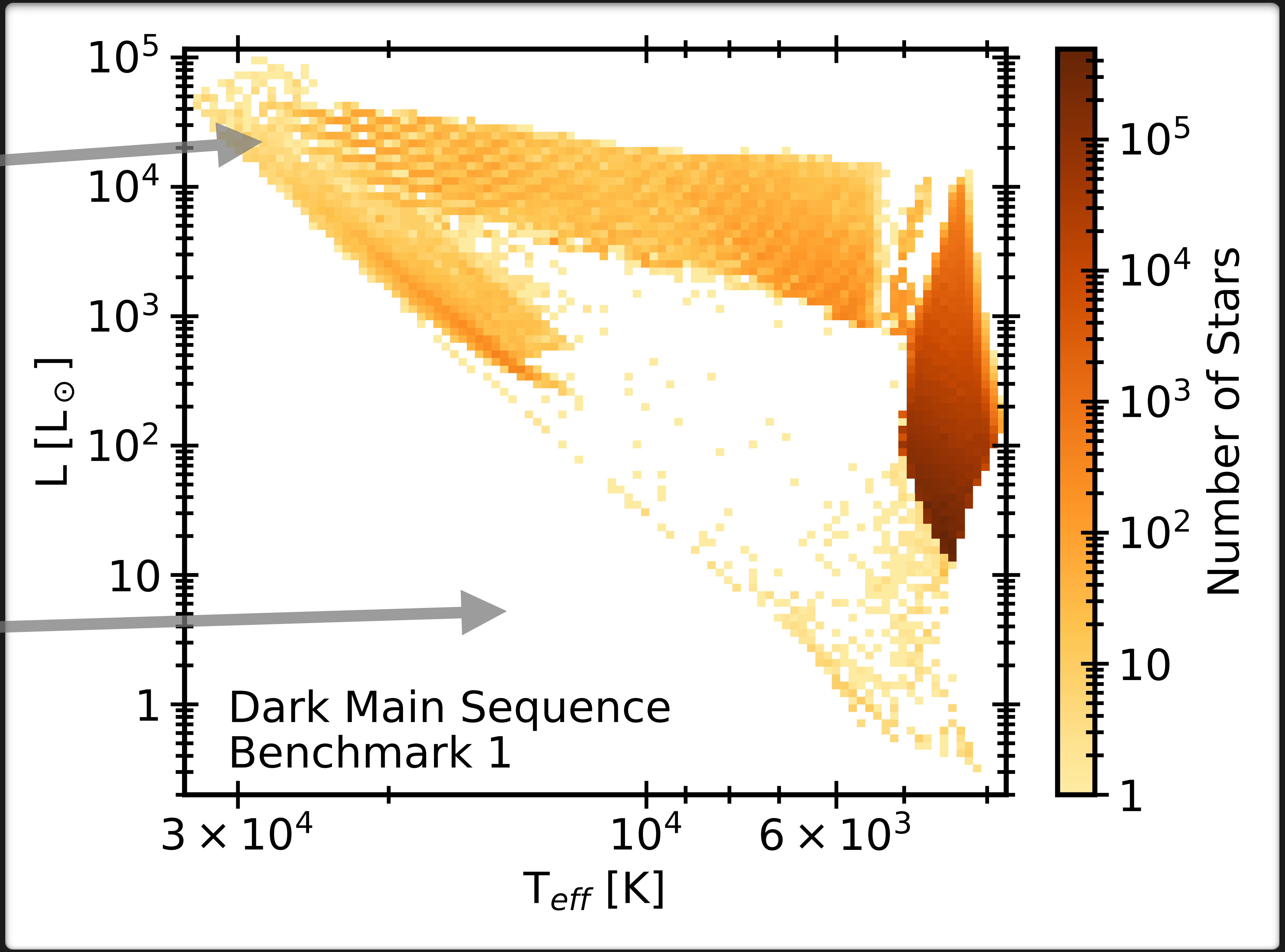

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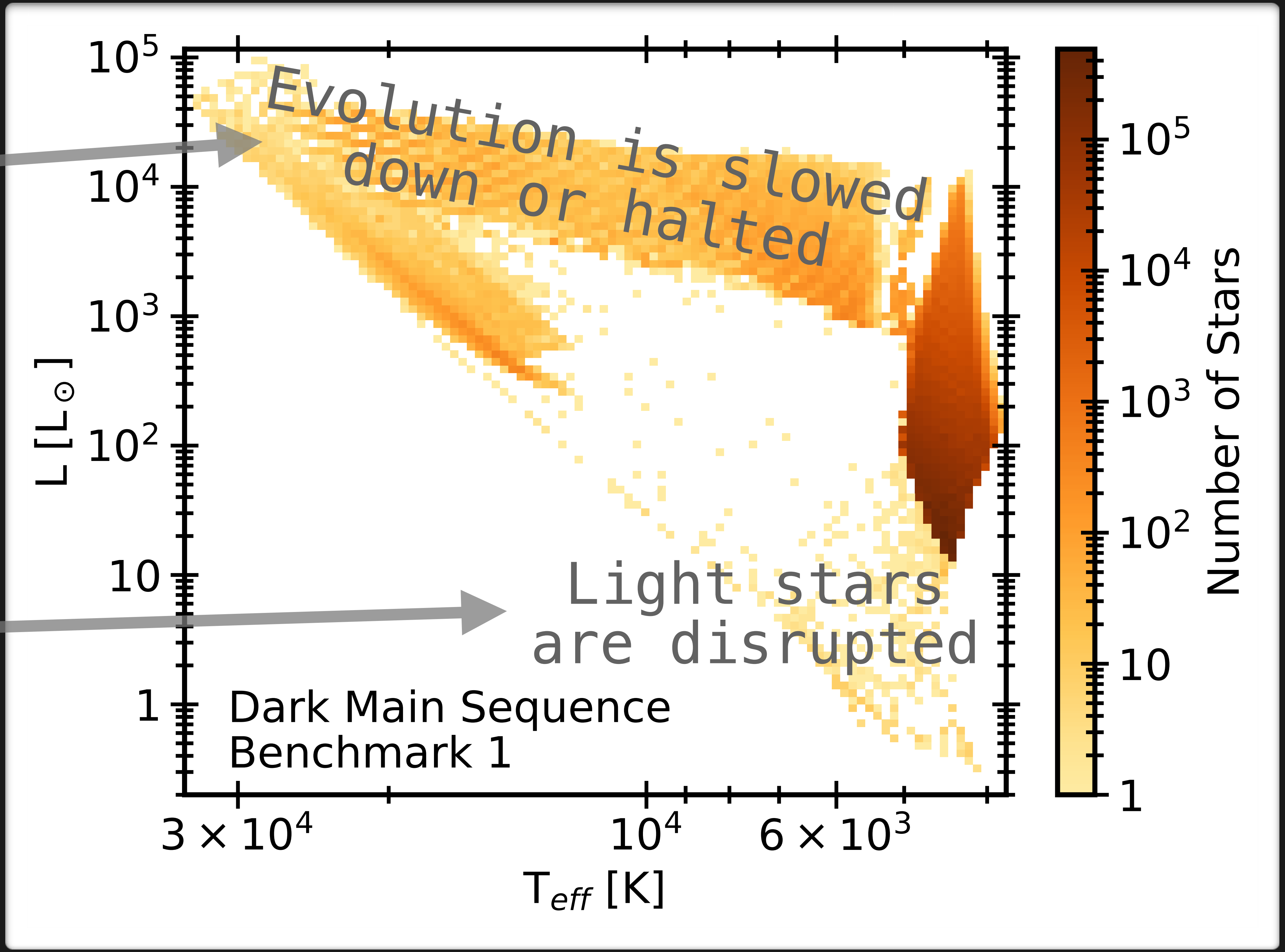

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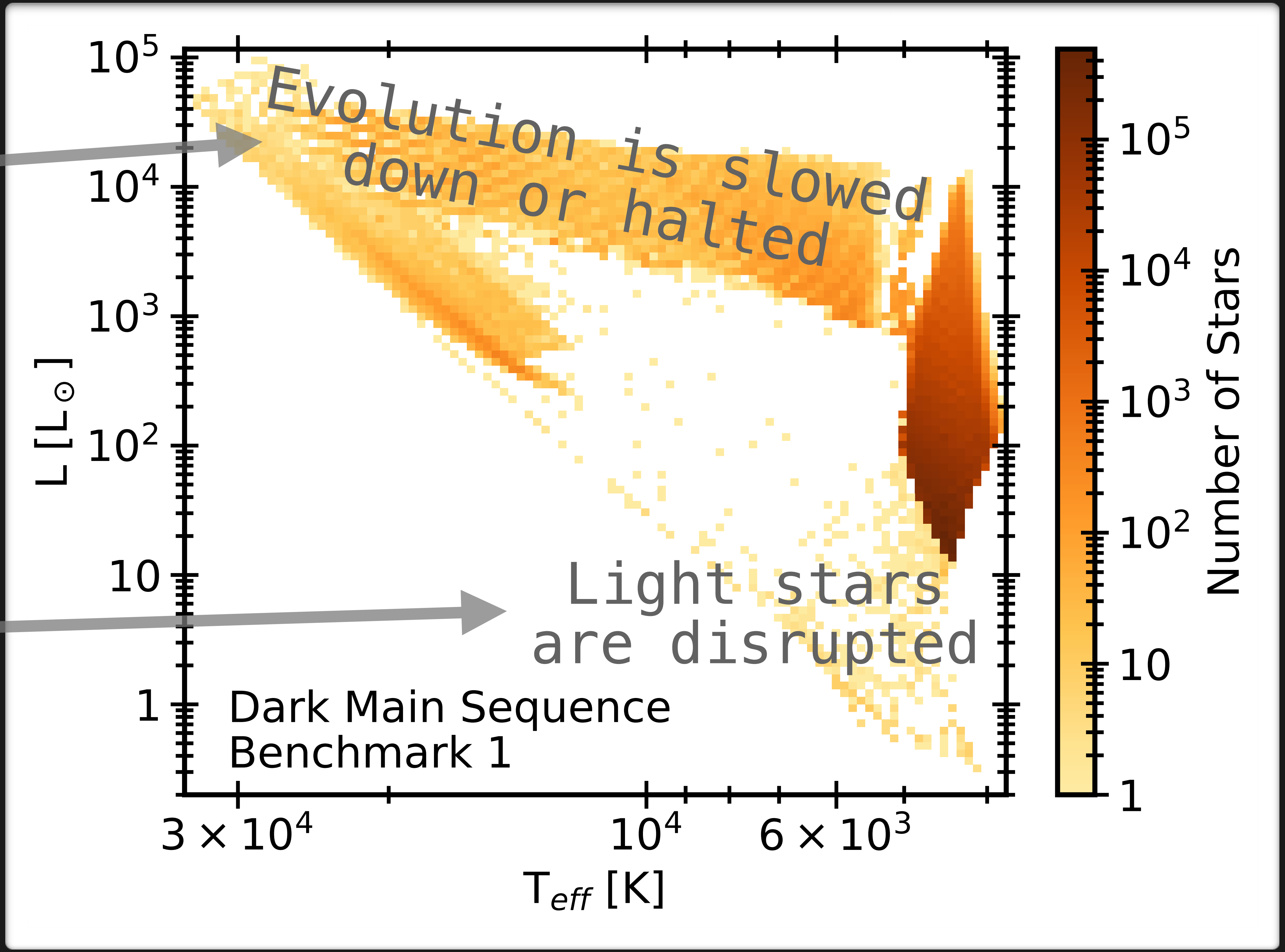


Unusual Properties of S-Stars:

Paradox of Youth – Stars look young

Conundrum of Old Age – Lack of older stars

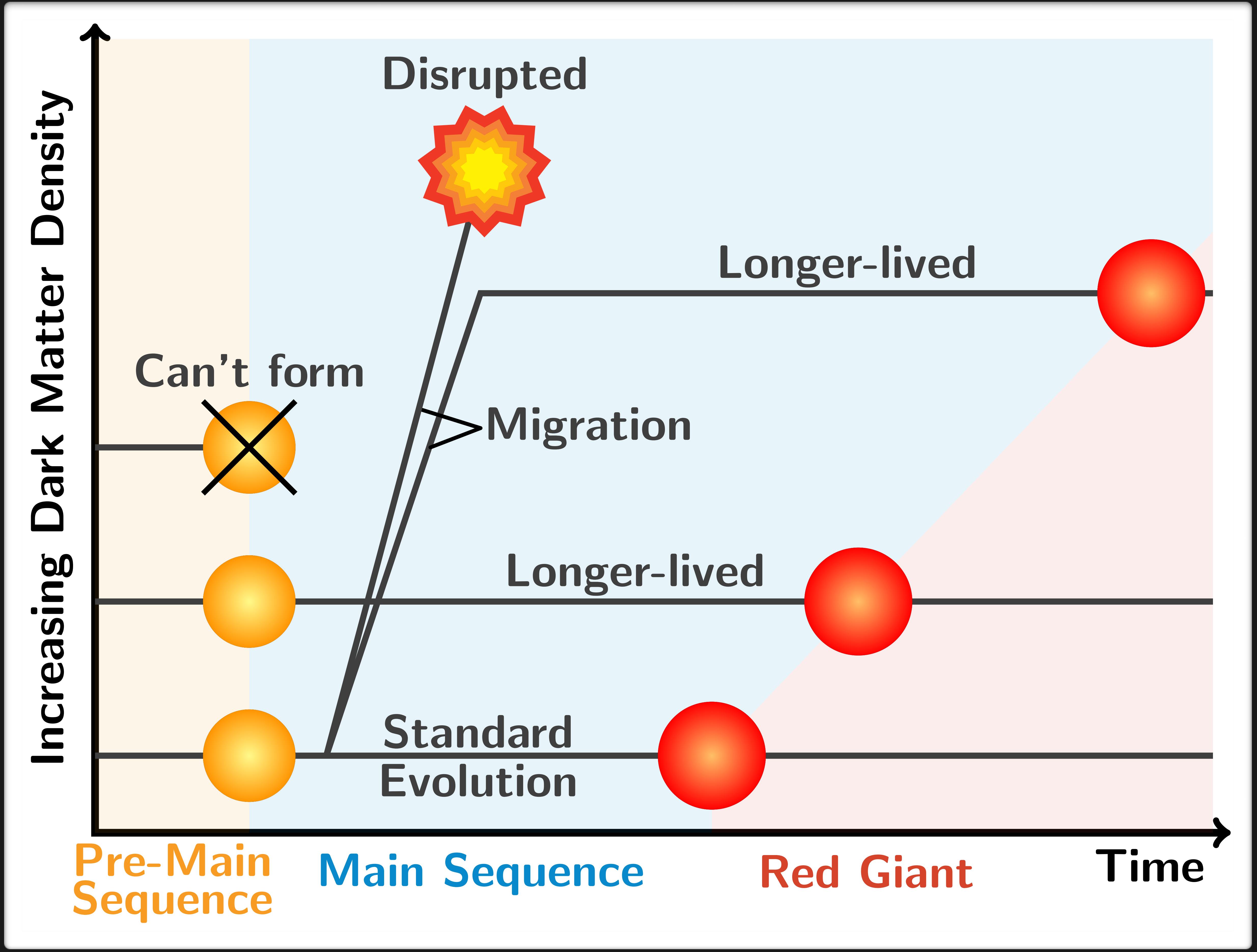
Top-heavy initial mass distribution

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

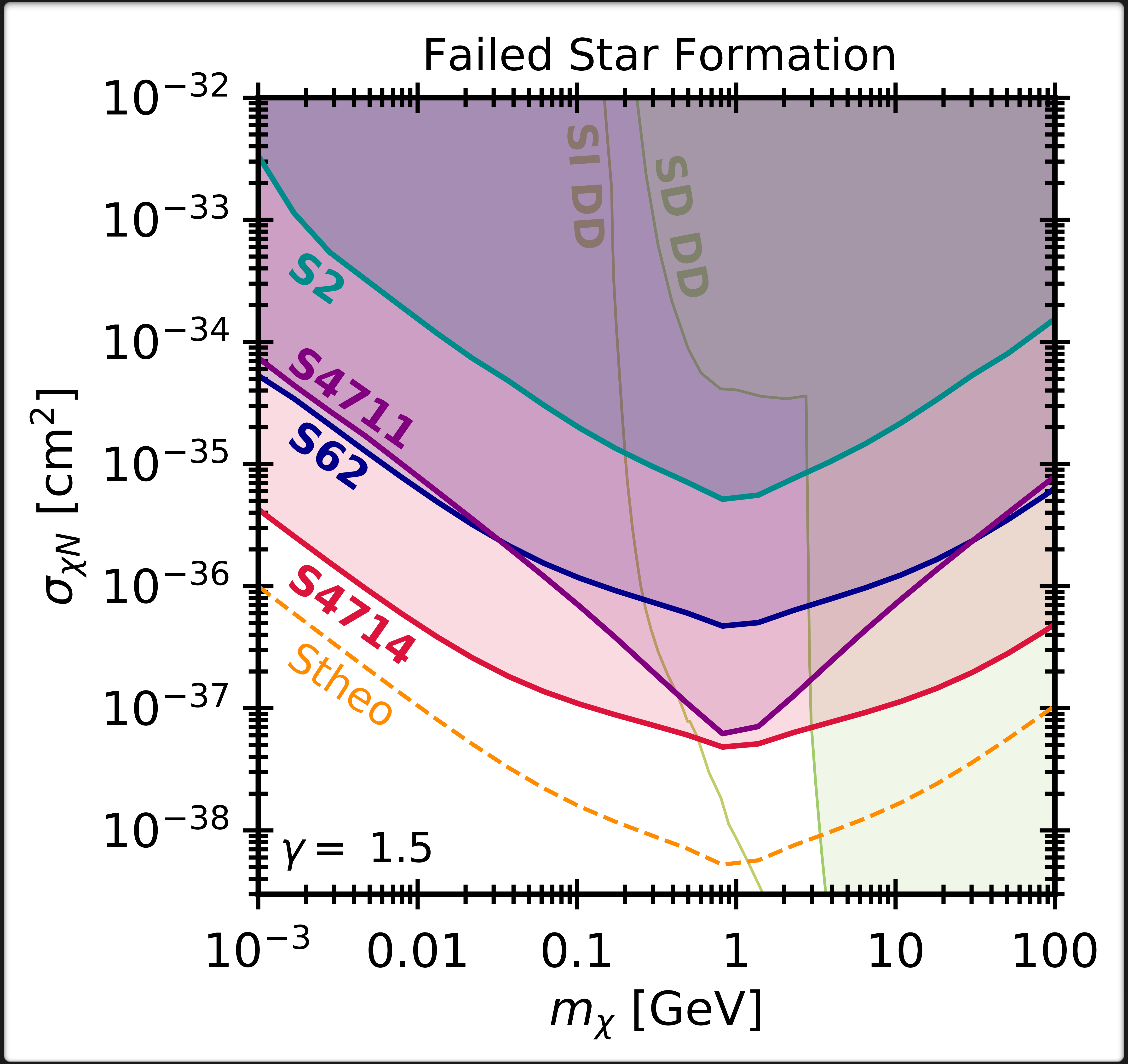
S62: 6.1 $M_\odot$
intermediate mass

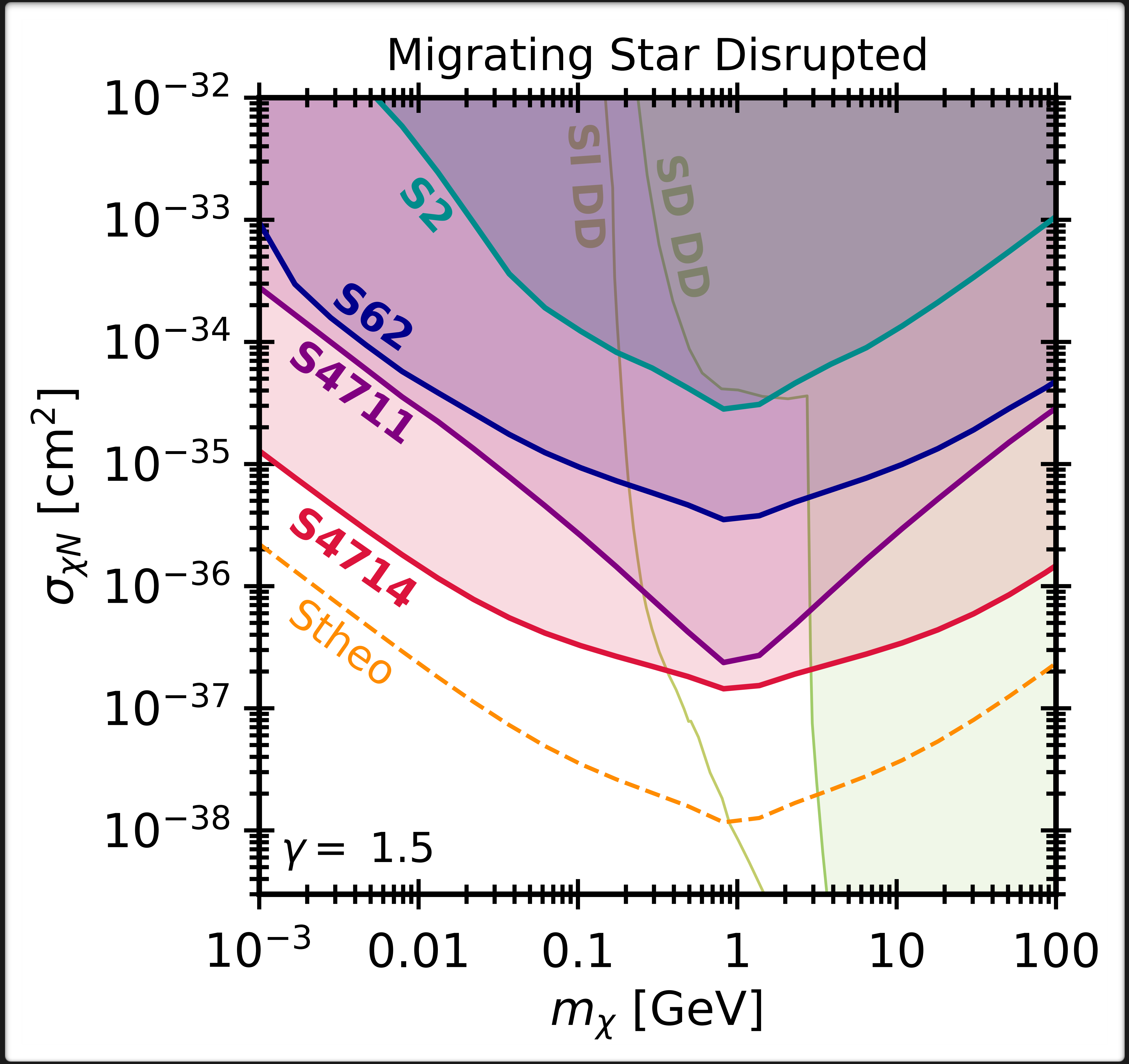
S4711: 2.2 $M_\odot$
light (fastest orbit)

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]



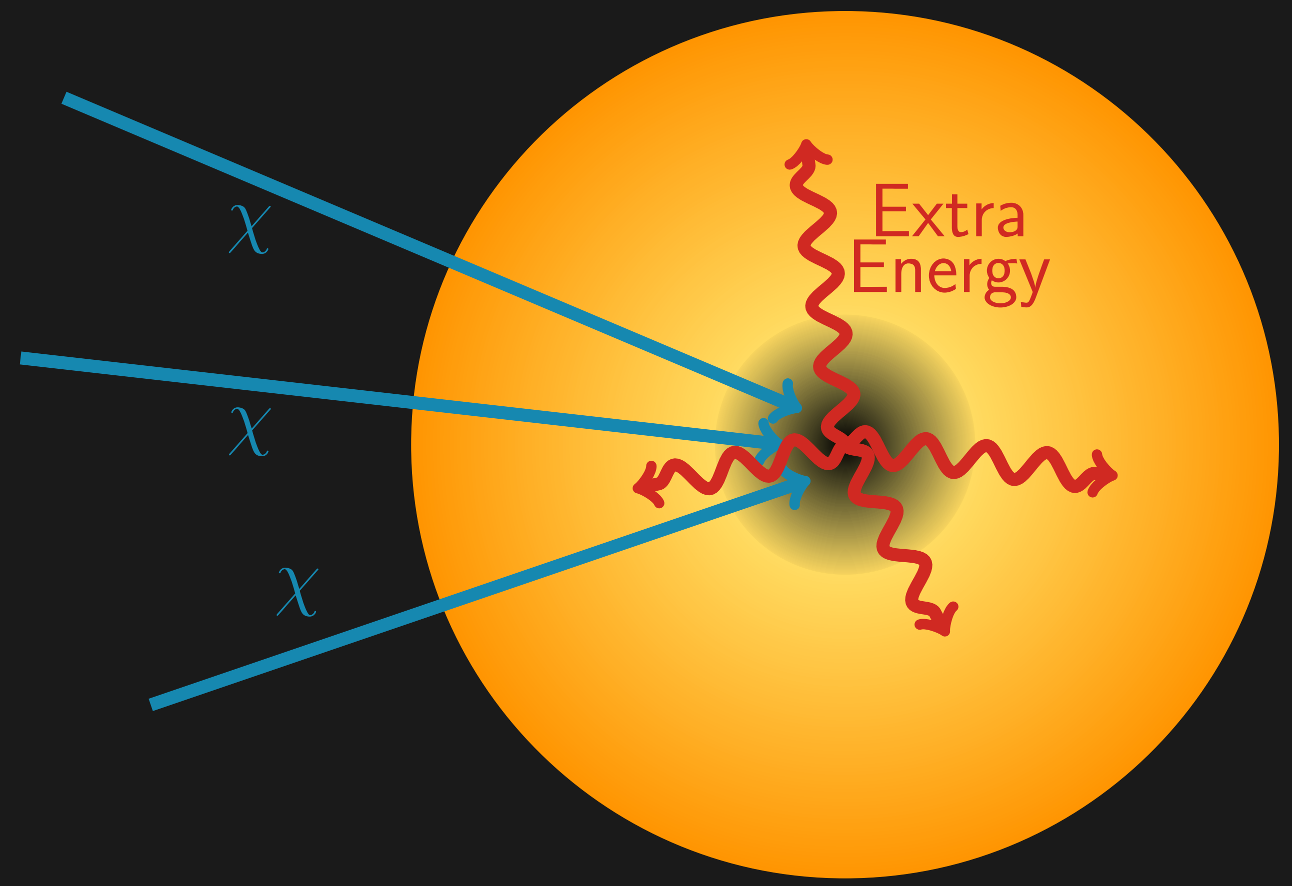


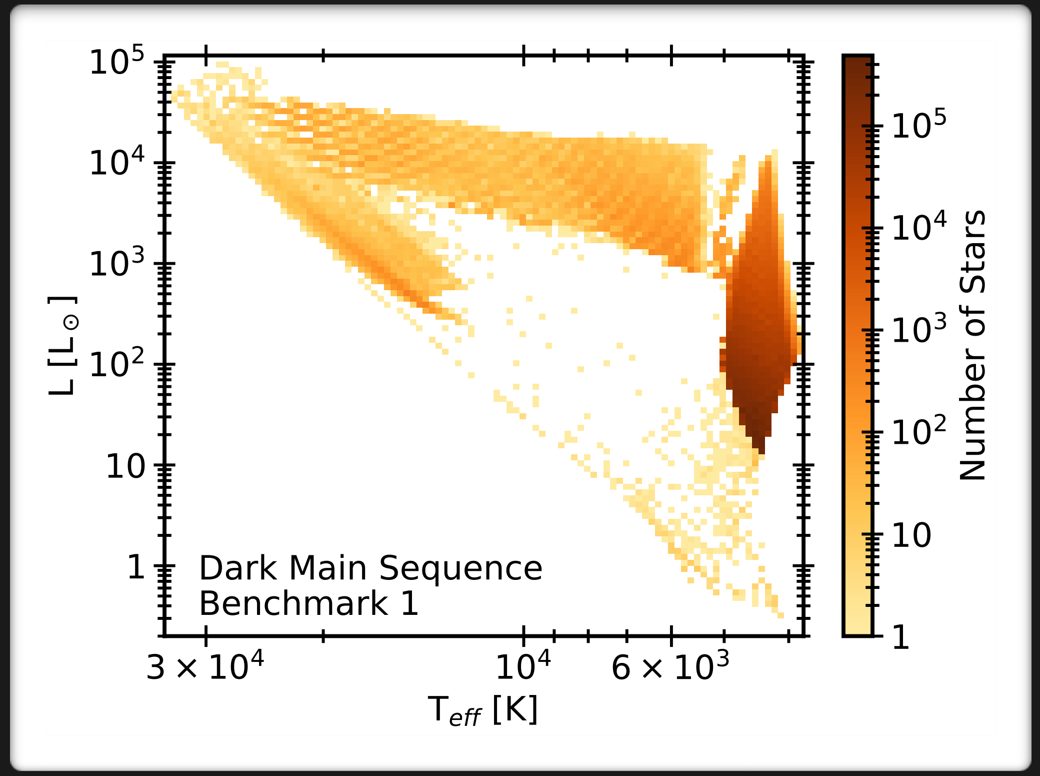
Summary and Conclusions

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

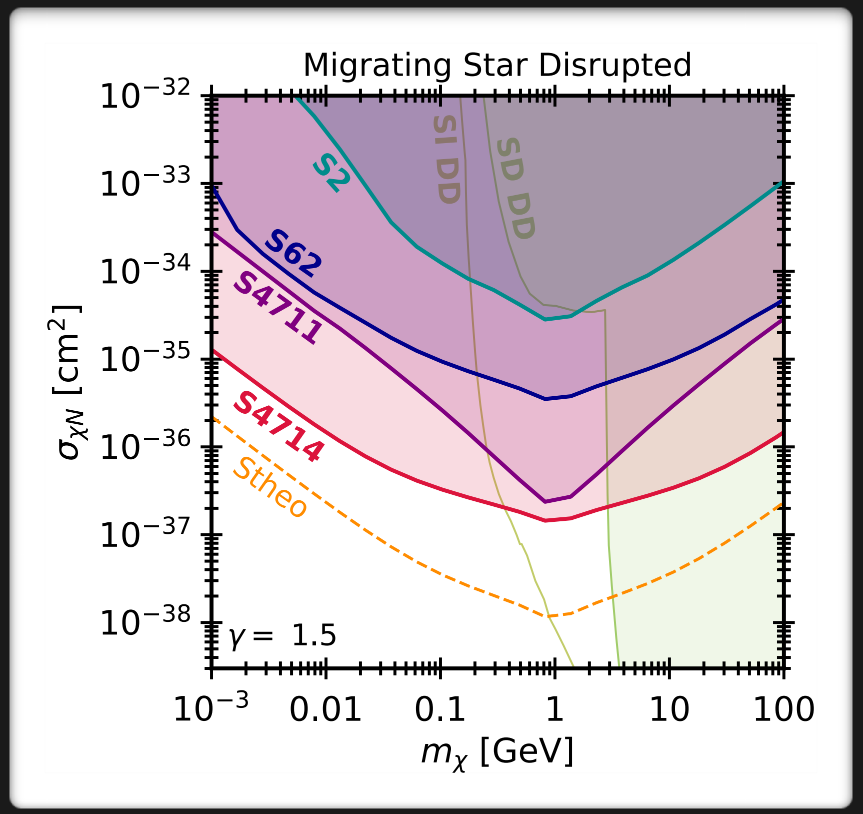
Dark matter capture and subsequent annihilation can (partially) replace nuclear fusion

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



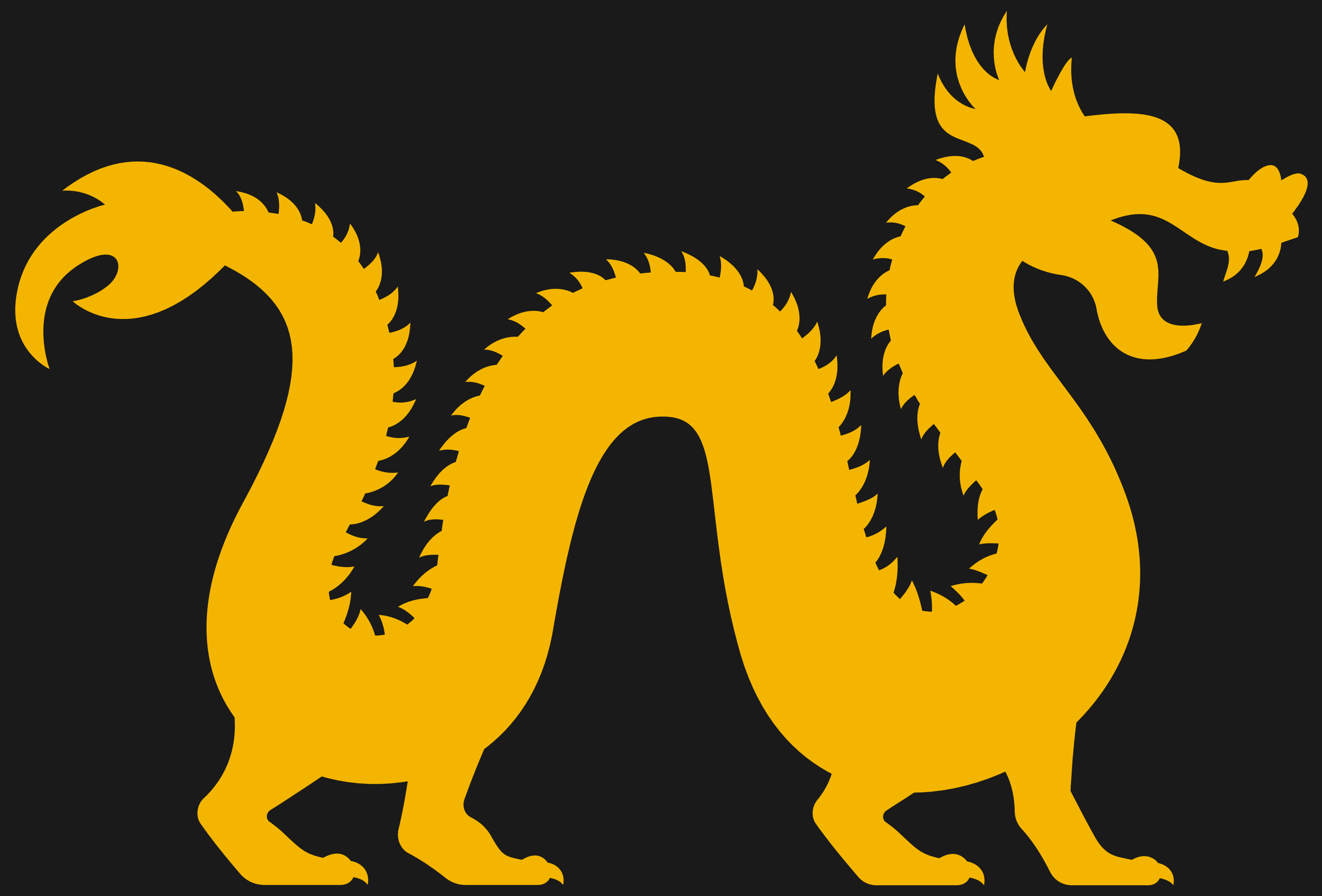


Constraints on dark matter profile and scattering cross section from observed S-stars



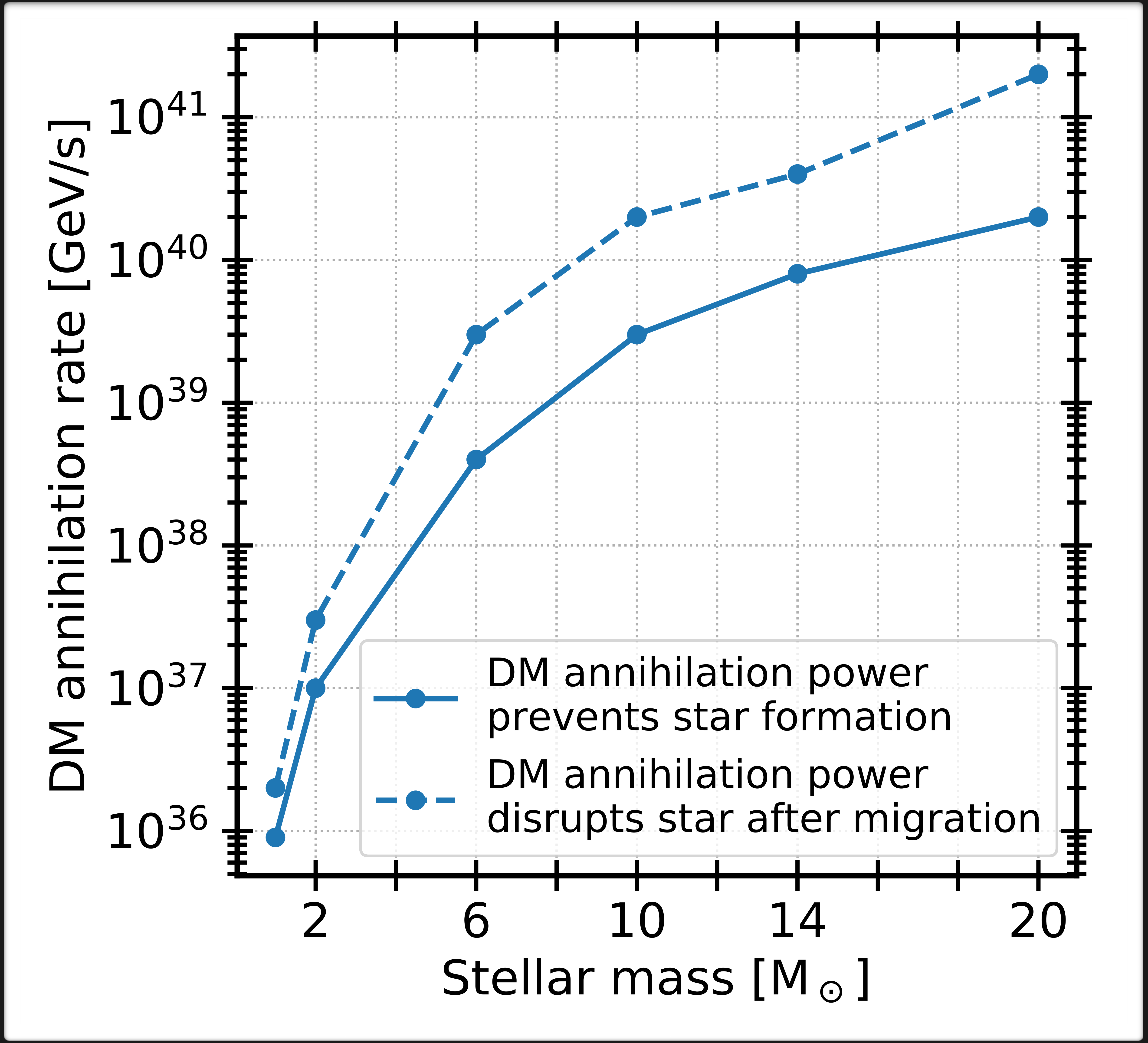
More precise observations of S-cluster stars needed to statistically test dark main sequence

Additional Slides



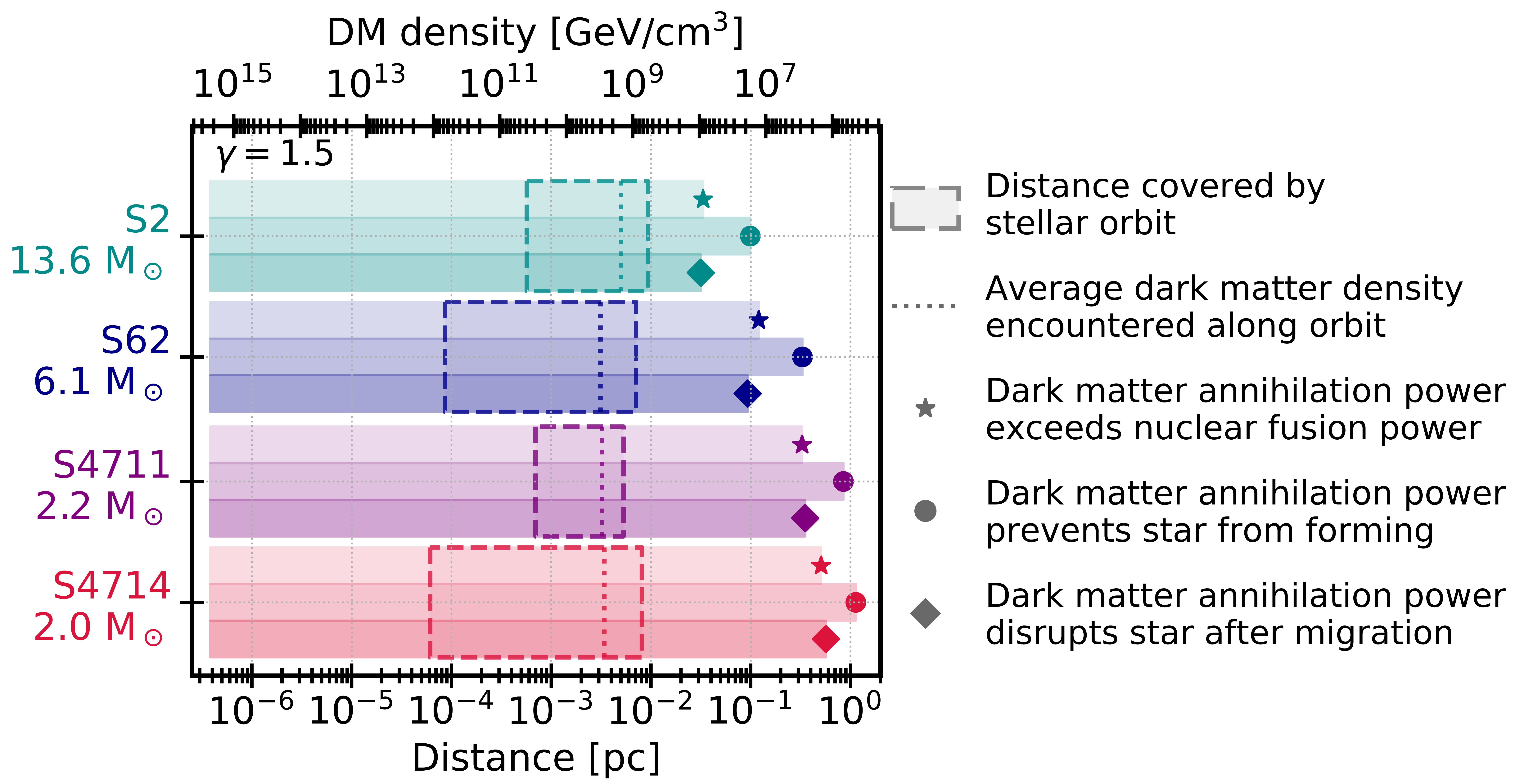
Dependence on Stellar Mass

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



Dark Matter in Individual Stars

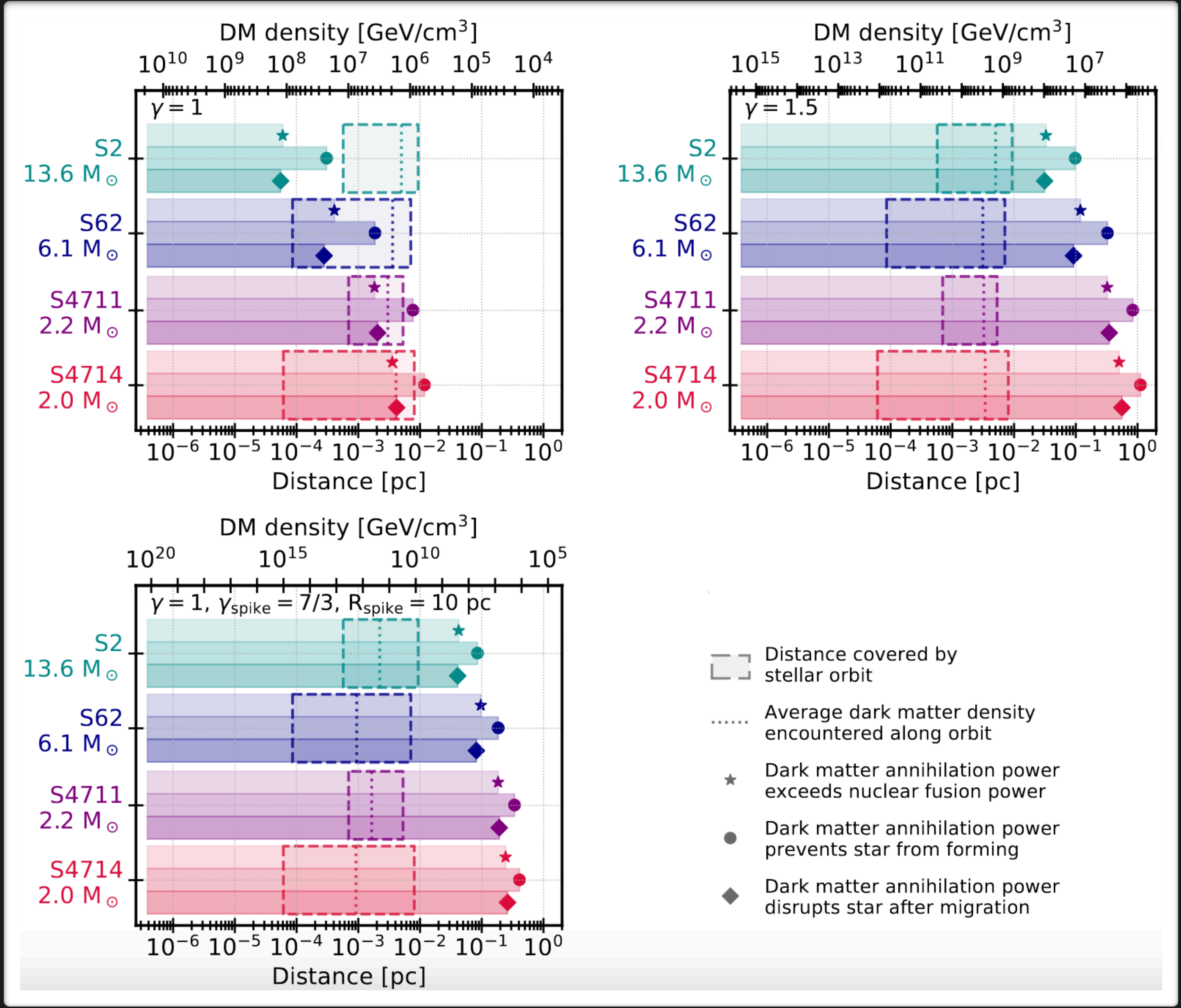
[I. John, R. Leane, T. Linden, arXiv:2311.16228]



Assuming maximum dark matter capture rate.

Effect on Stars for Different DM Profiles

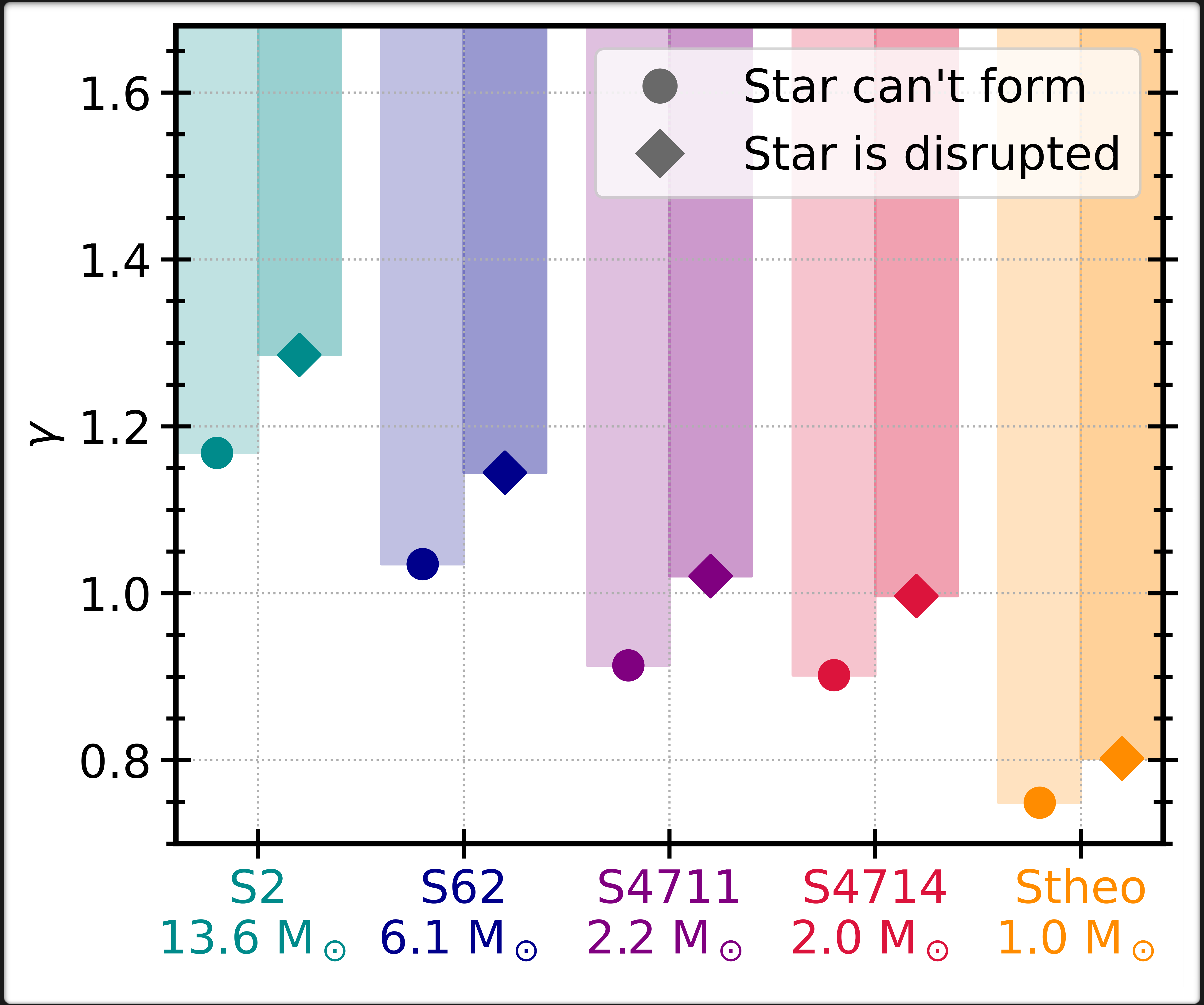
[I. John, R. Leane, T. Linden, arXiv:2311.16228]



Assuming maximum dark matter capture rate.

Constraints on Dark Matter Profile

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

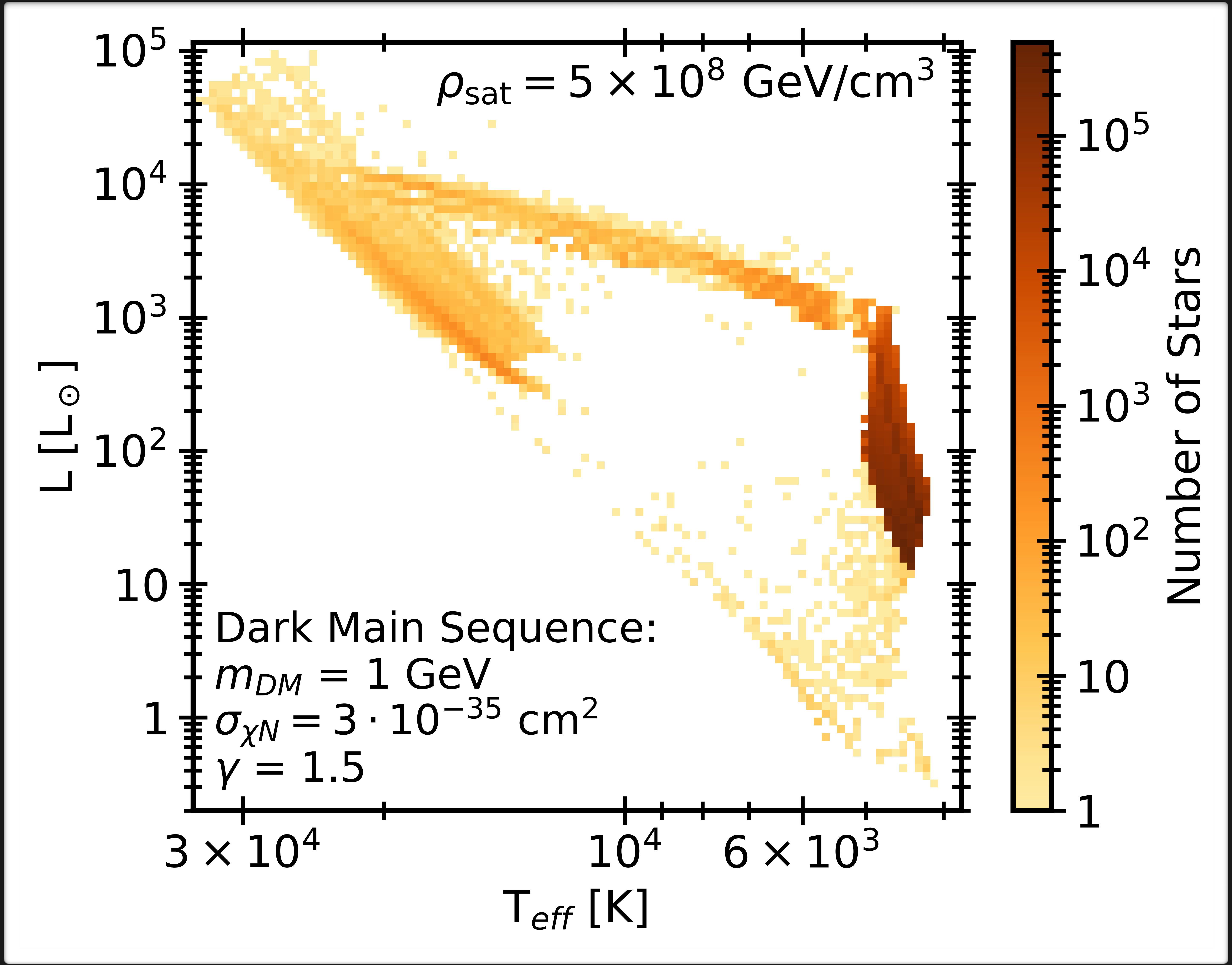


Index of generalised NFW profile

Assuming maximum dark matter capture rate.

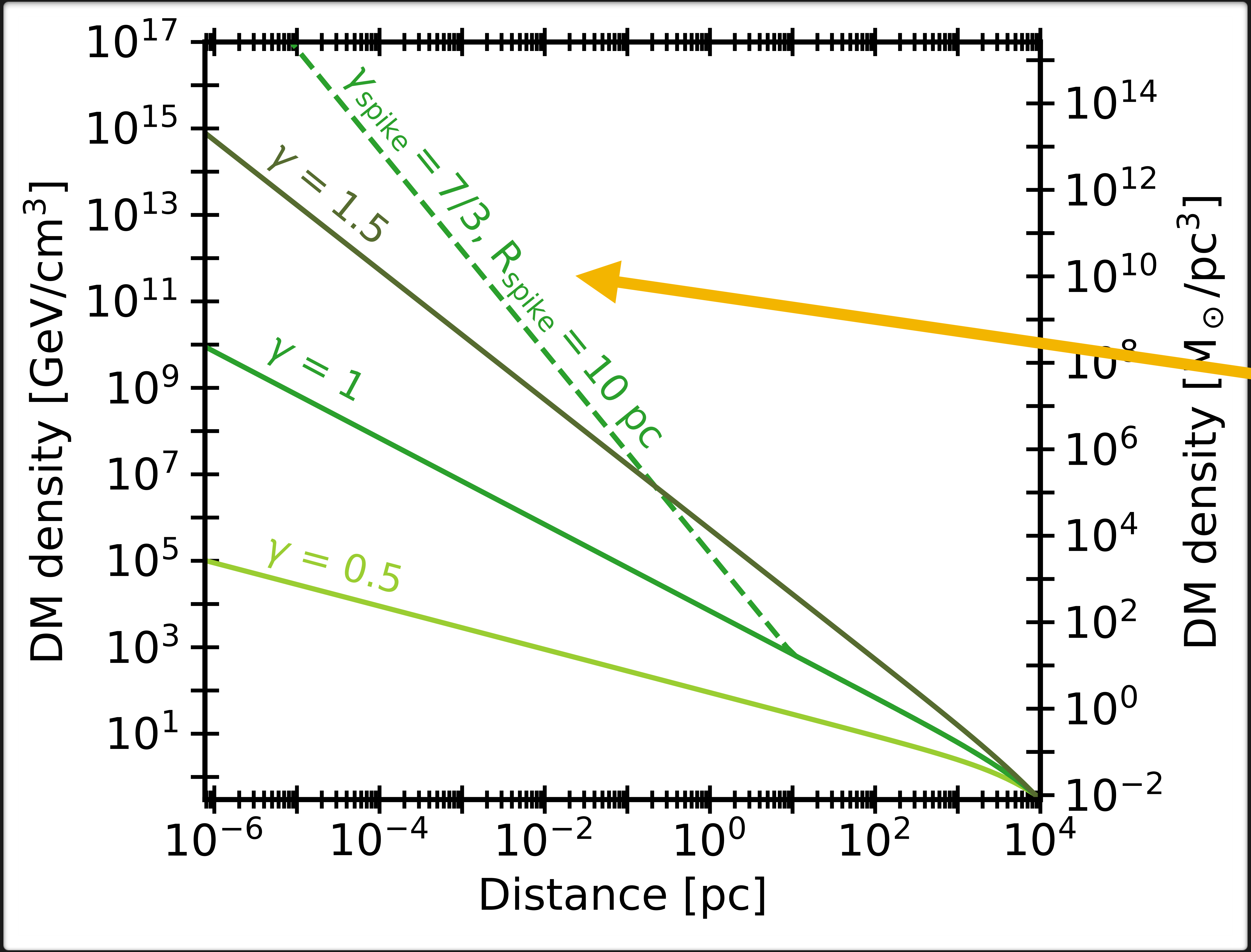
HR Diagram with DM Density Saturation

[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 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

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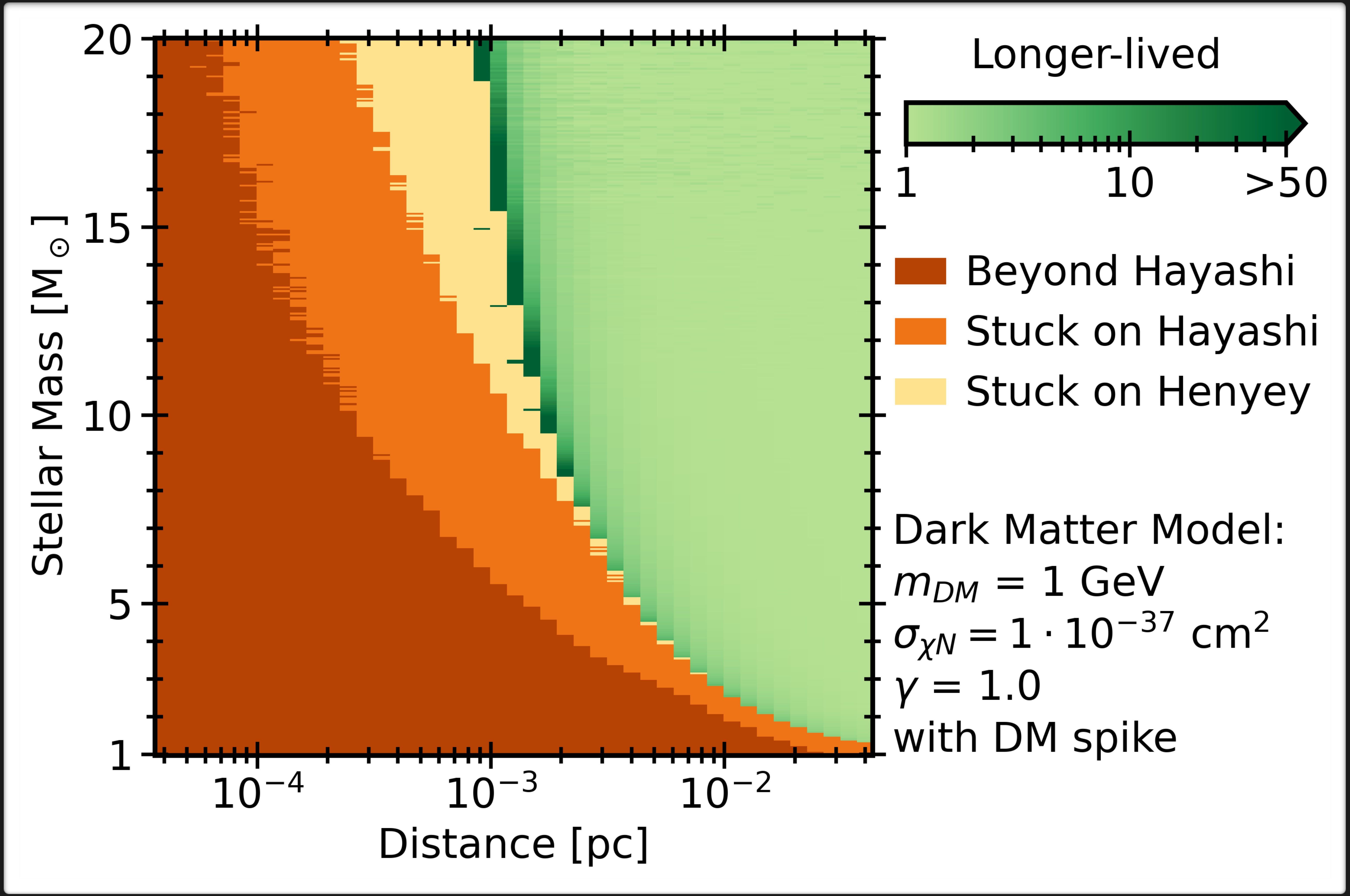
[I. John, R. Leane, T. Linden, arXiv:2405.12267]



Benchmark Model 2:

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

Dark Main Sequence for Benchmark 2 (DM Spike Model)

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