Probing Heavy Dark Matter in Red Giants

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Collaborated with Chang Sub Shin (CNU), Sougata Ganguly (IBS-CTPU-PTC), Minxi He (IBS-CTPU-PTC), Oscar Straniero (INAF), ***Phys.Rev.D 113 (2026) 7, 075038***
Collaborated with Boris Betancourt Kamenetskaia(IBS-CTPU-CGA), Mini He(NAOJ), Audrey Feng(APCTP) **[Work in progress]**

Outline

01 Introduction

- Stellar evolution to probe BSM

✓ Cooling argument w/o DM

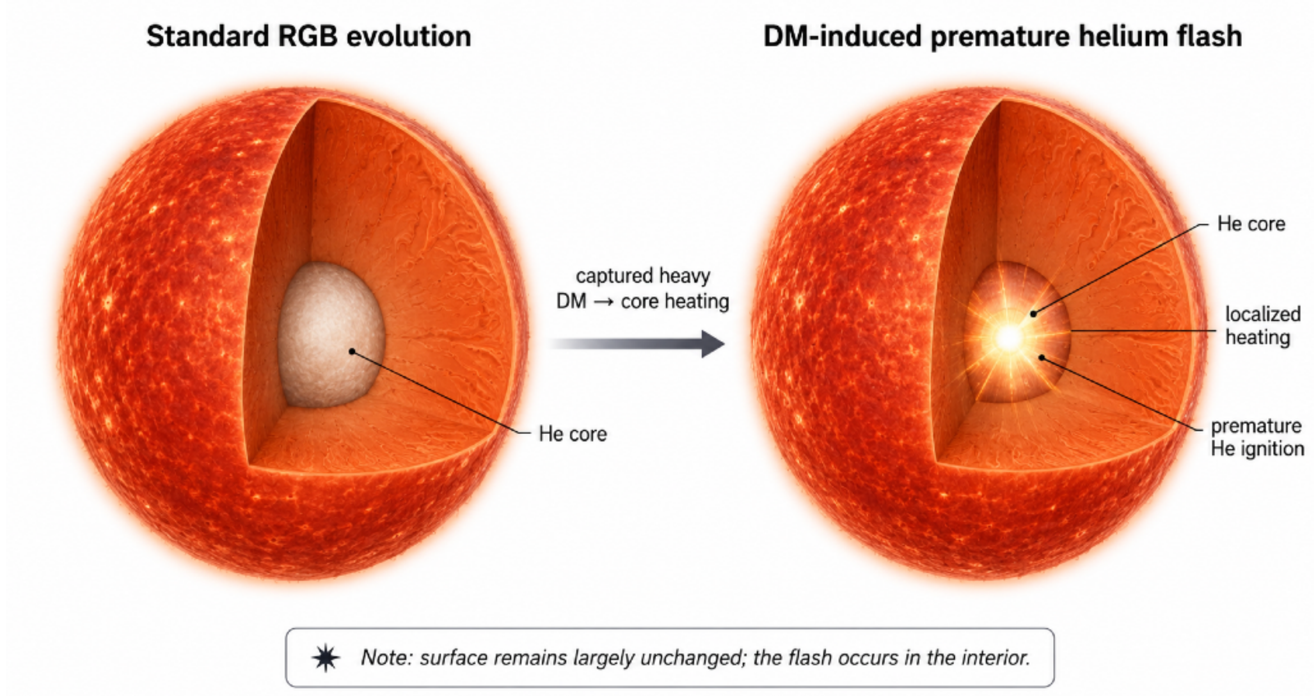
✓ <u>Heating w/ DM capture</u>

02 Heavy DM capture & Its impact on TRGB

03 Helium ignition

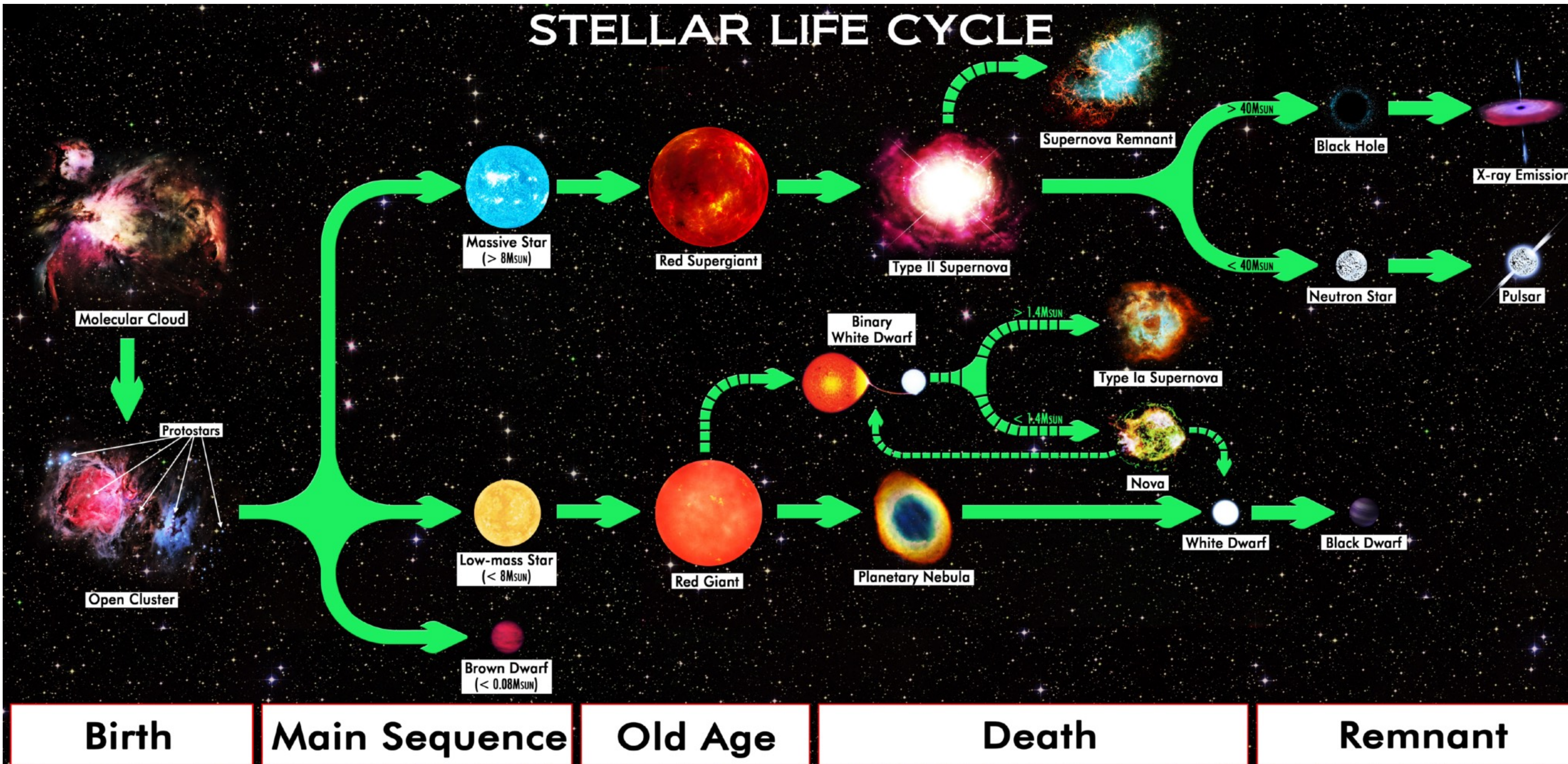
- Triple-alpha process
- Trigger mass (burning VS diffusion)

04 Conclusion



Stellar Evolution

[image from Wikipedia]

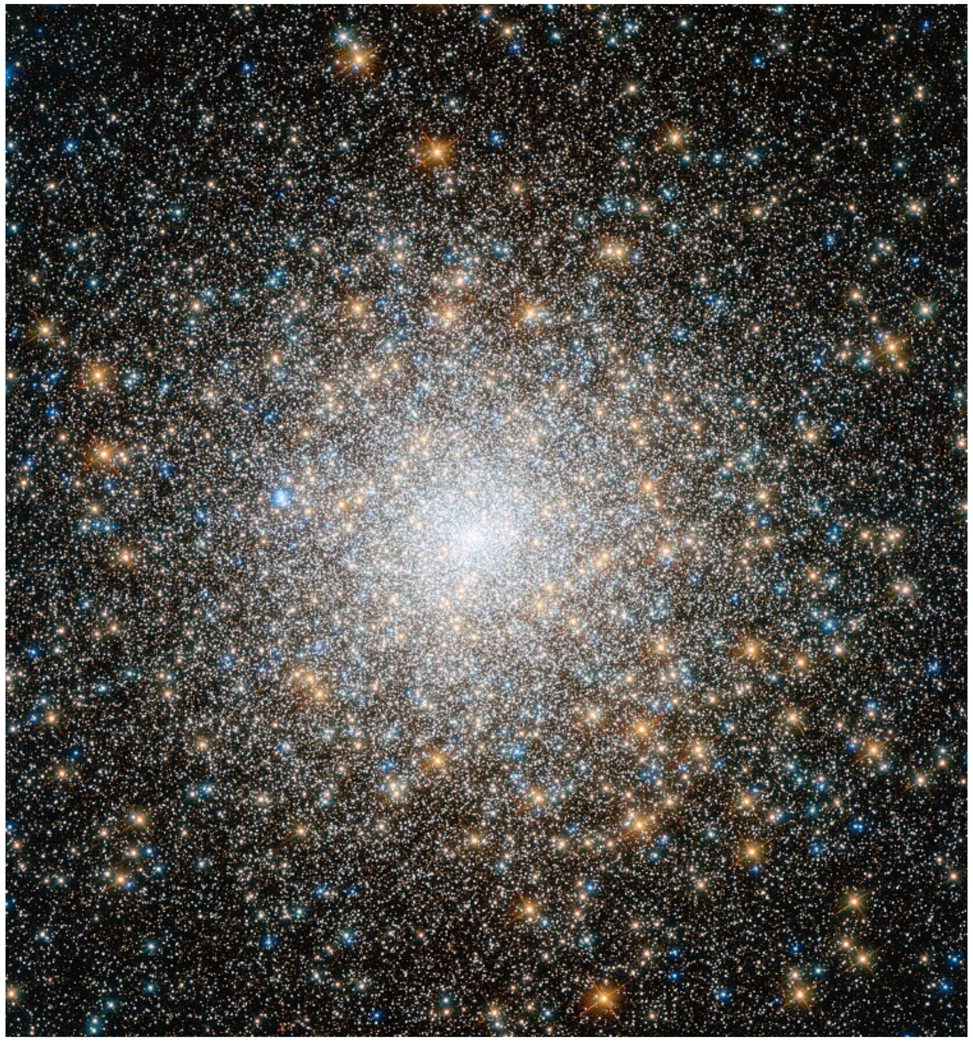


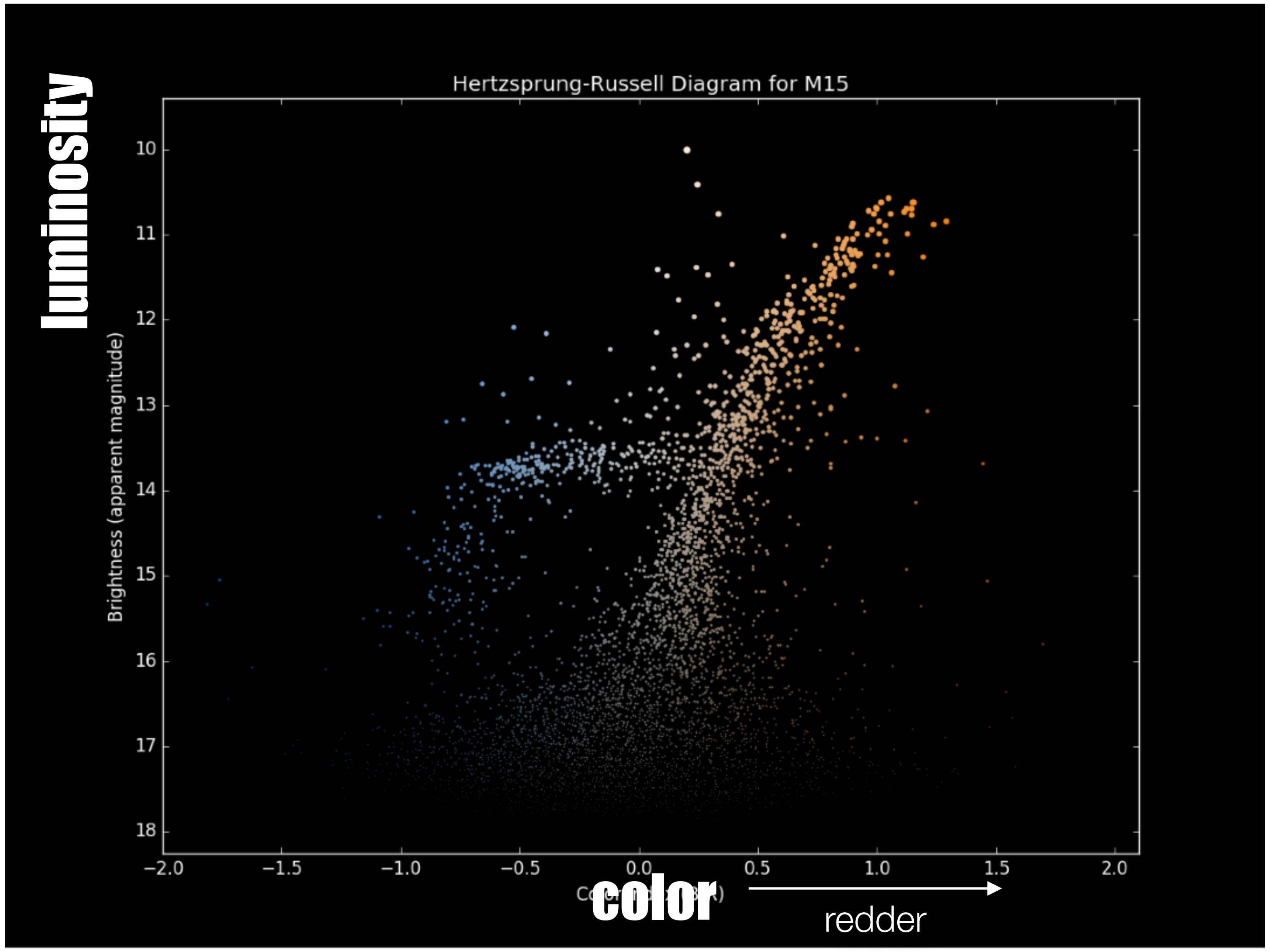
mass

time

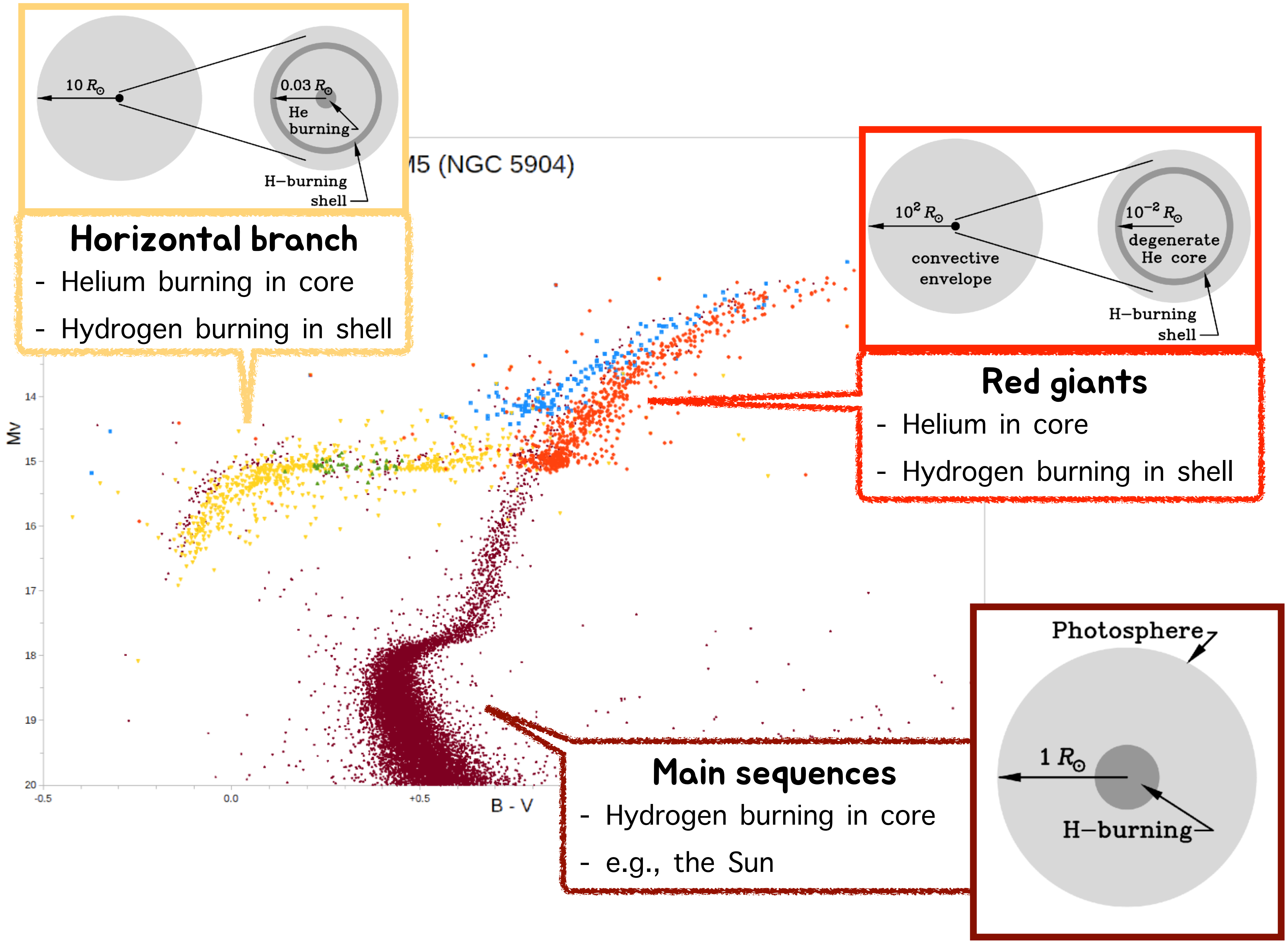
Globular Cluster

- Very clean laboratories for studies of stellar evolution
- Coeval and almost equal chemical compositions
- Only different initial mass

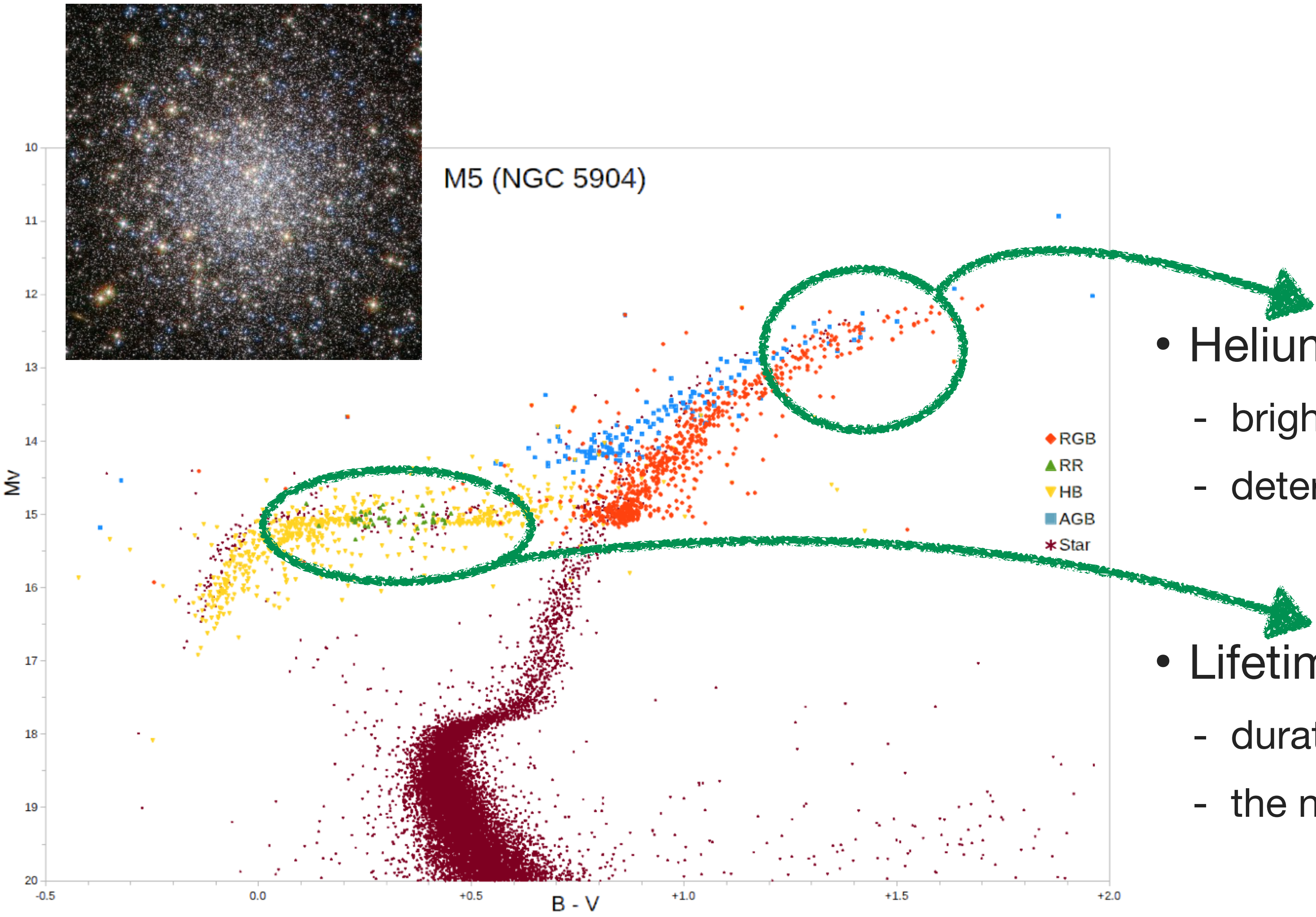




Stellar Evolutionary Phases

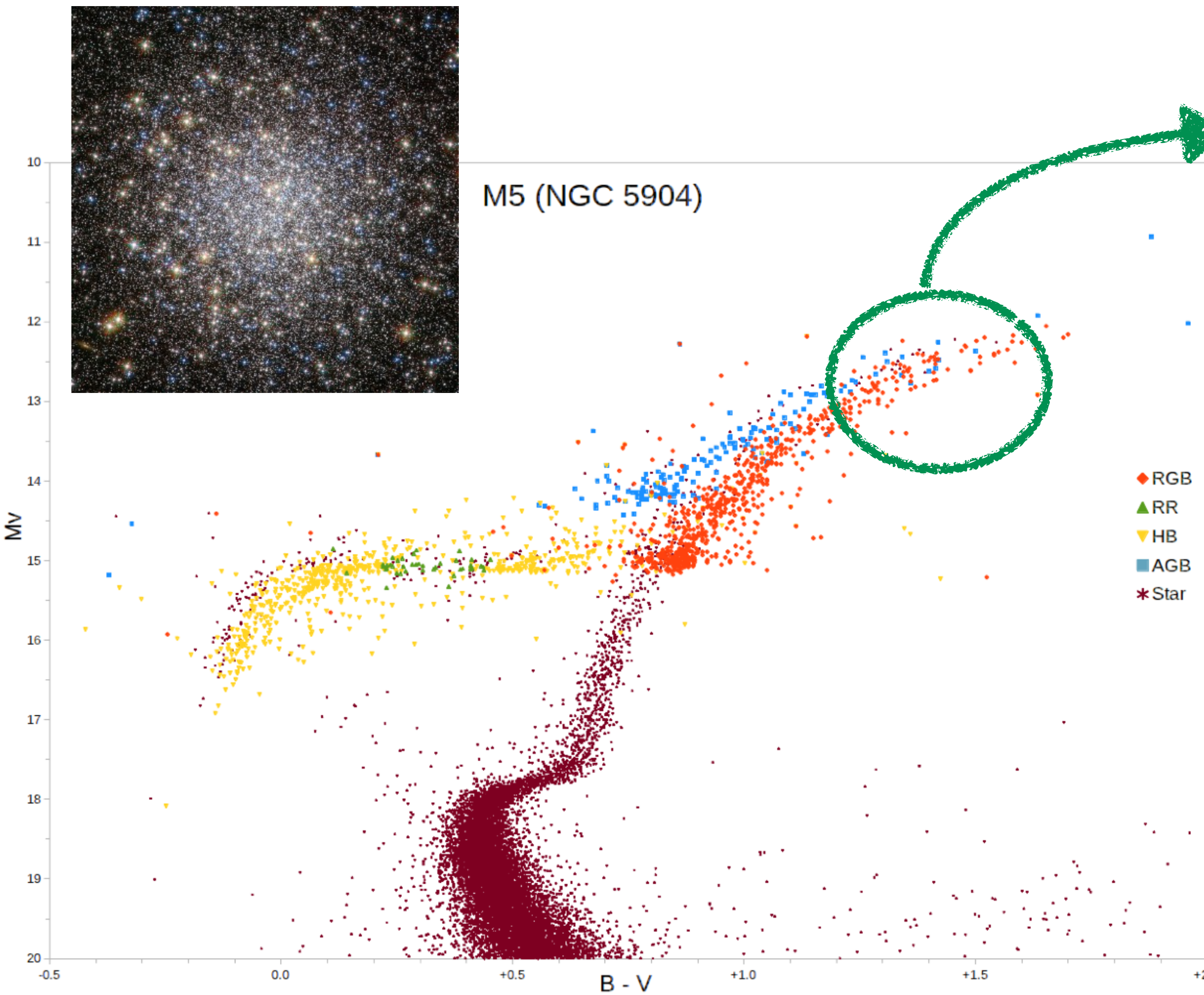


Observables to Probe BSM?



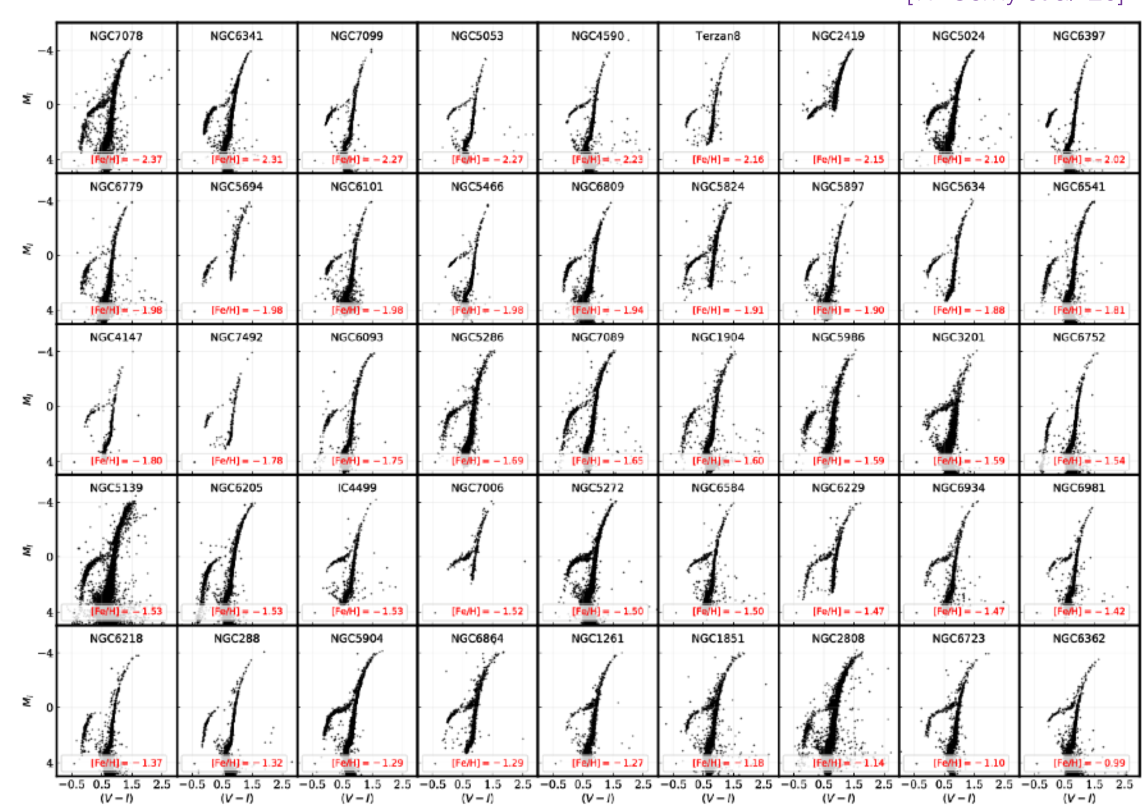
- Helium ignition in red-giant phase
  - brightness at the tip of a red-giant branch
  - determined by core mass at helium flash
- Lifetime of horizontal-branch stars
  - duration of helium burning
  - the number ratio of HB vs. RGB

Tip of the Red Giant Branch



- Helium ignition in red-giant phase
  - brightness at the tip of a red-giant branch
  - determined by core mass at helium flash

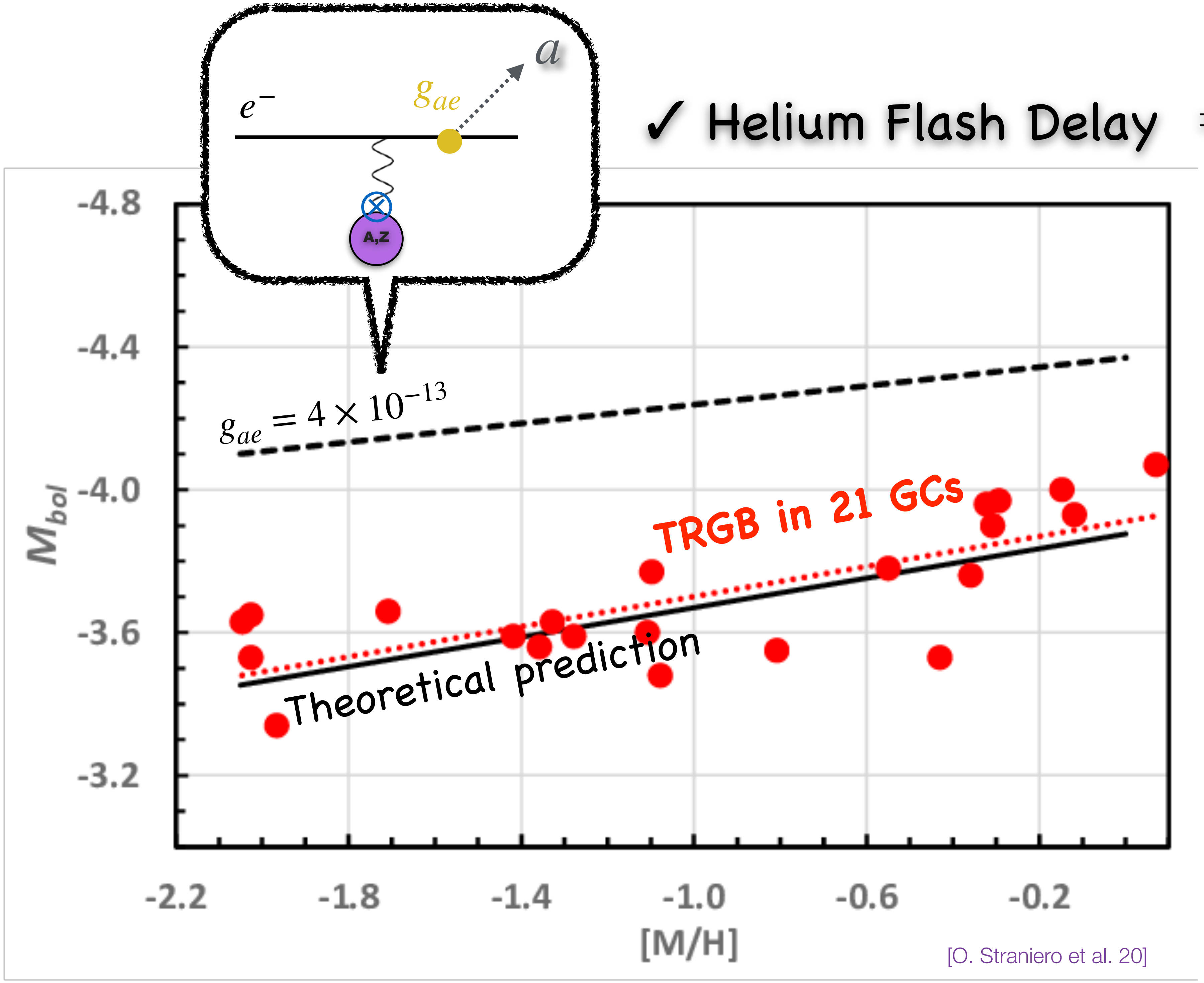
[W. Cerny et al. 20]



✓ Consistent w/ the standard prediction

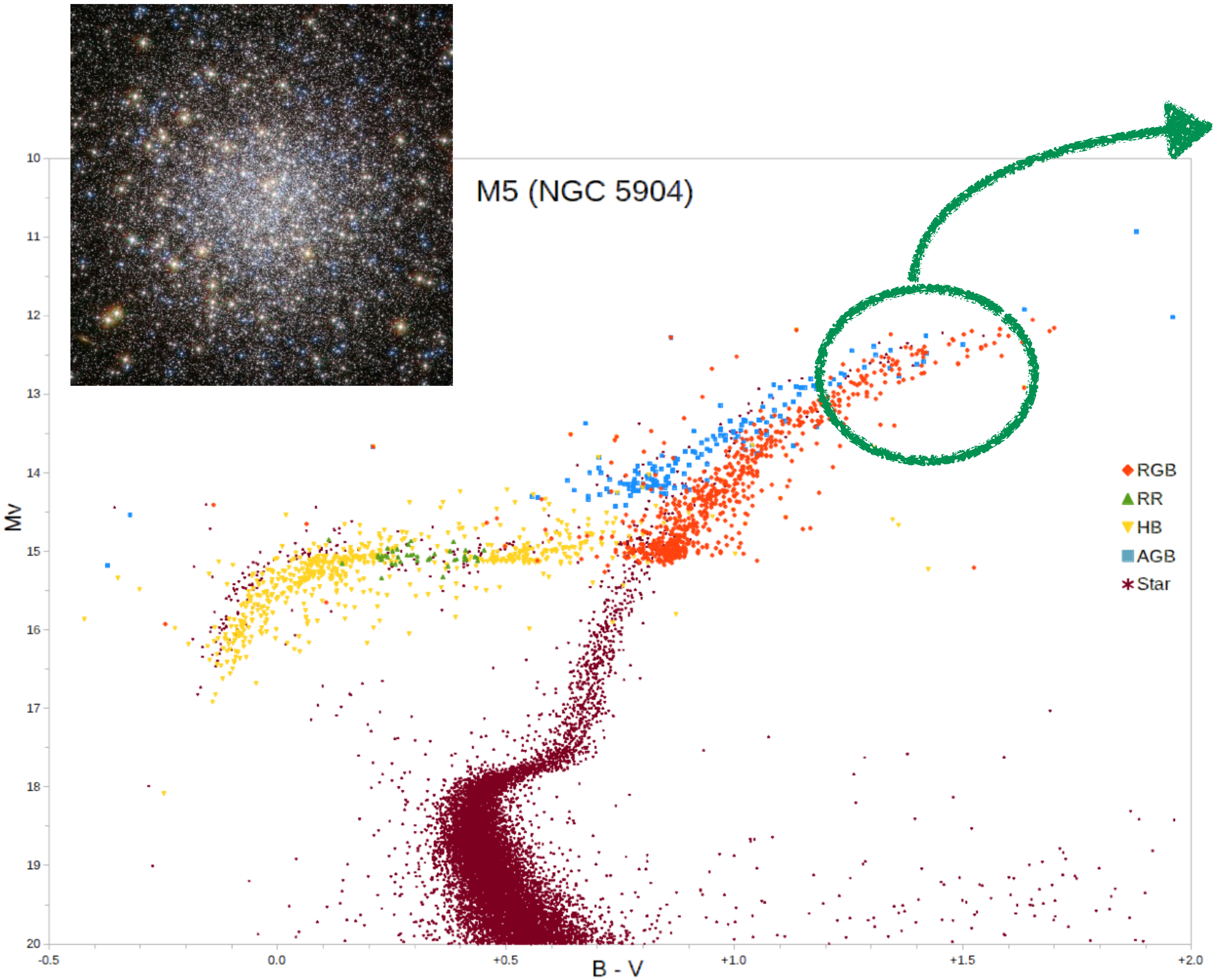
Core Mass Increase by Cooling

✓ Helium Flash Delay $\Rightarrow$ L_{TRGB} ⬆



[O. Straniero et al. 20]

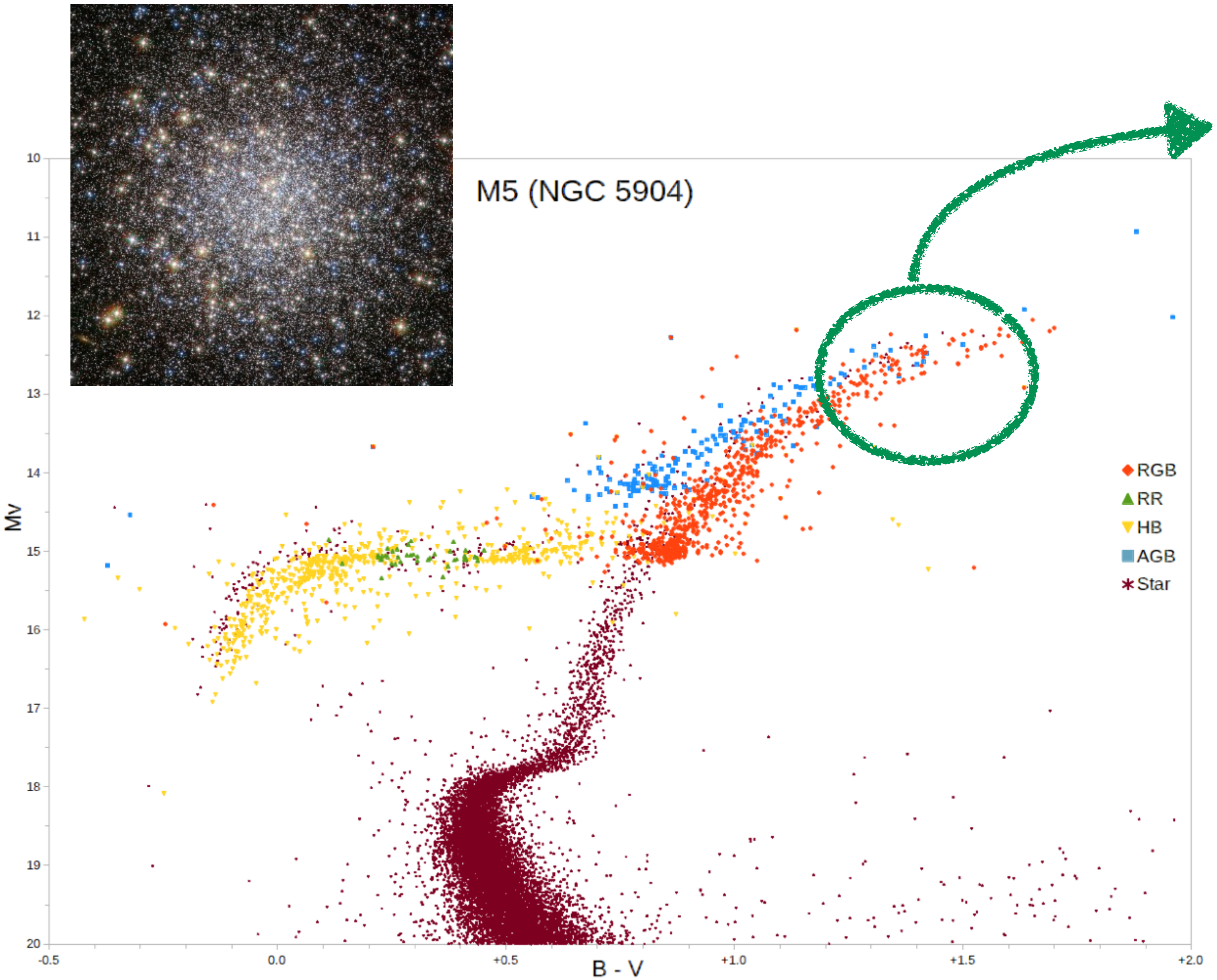
BSM probe of TRGB



- Helium ignition in red-giant phase
  - brightness at the tip of a red-giant branch
  - determined by core mass at helium flash

✔ **Cooling**
- via (light) particle production
- delaying helium flash
- core mass ⬆ $L_{\rm tip}$ ⬆

BSM probe of TRGB



- Helium ignition in red-giant phase
  - brightness at the tip of a red-giant branch
  - determined by core mass at helium flash

✔ Cooling

- via (light) particle production
- delaying helium flash
- core mass ⬆ $L_{\rm tip}$ ⬆

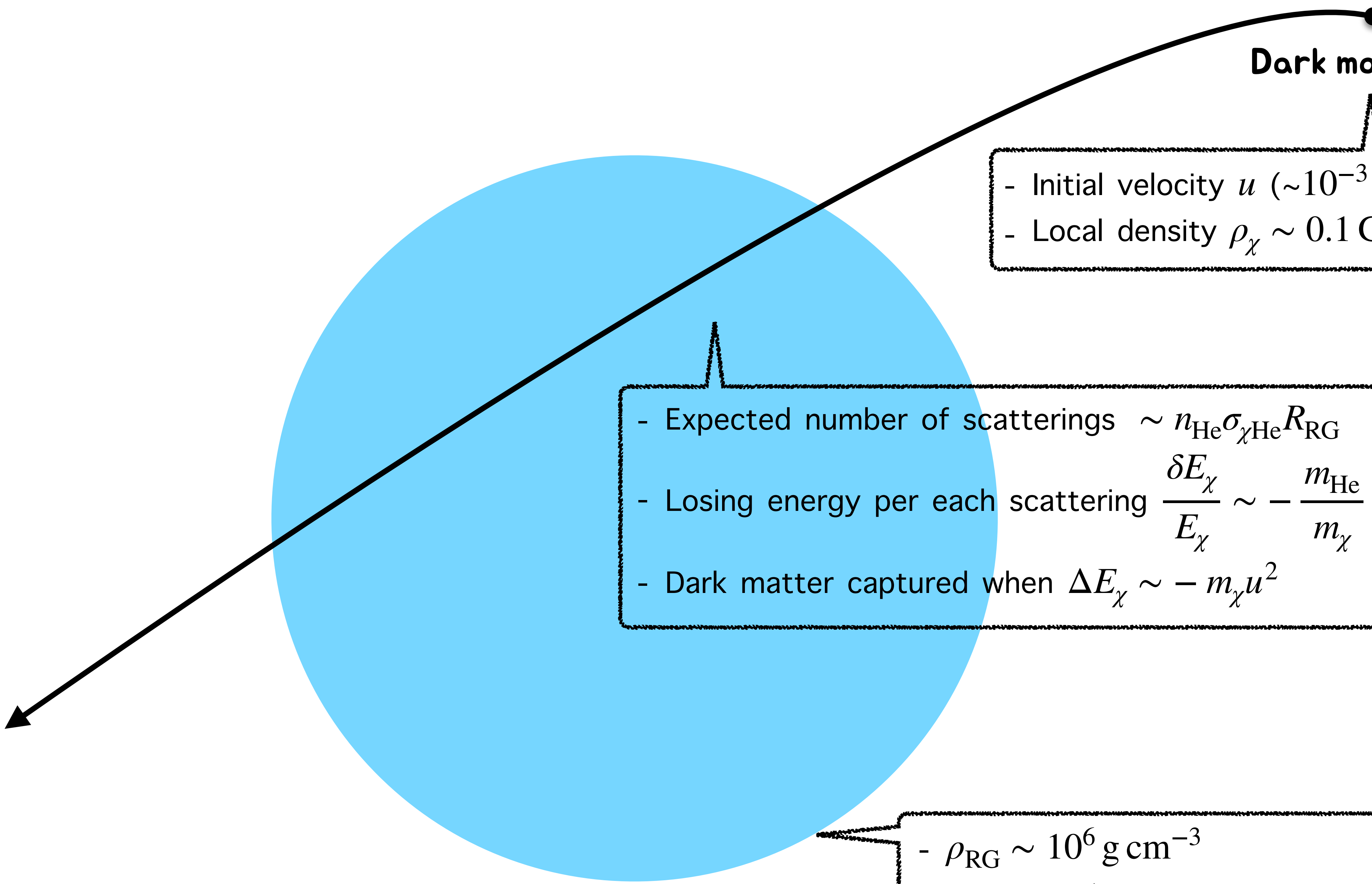
🤔 **Heating?**

- via **dark matter capture**
- premature helium flash
- core mass ⬇ $L_{\rm tip}$ ⬇

Dark Matter Capture

- Elastic Scattering w/ nuclei (DM kinetic energy loss)
  - ✓ 1) capturing, 2) ingress, 3) thermalization, 4) collapse
- DM self annihilation (DM mass energy transfer)
  - ✓ Later turned on for the heavy regime
  - ✓ Efficient heating in the central local region
- DM-induced Black Hole

Dark Matter Capture



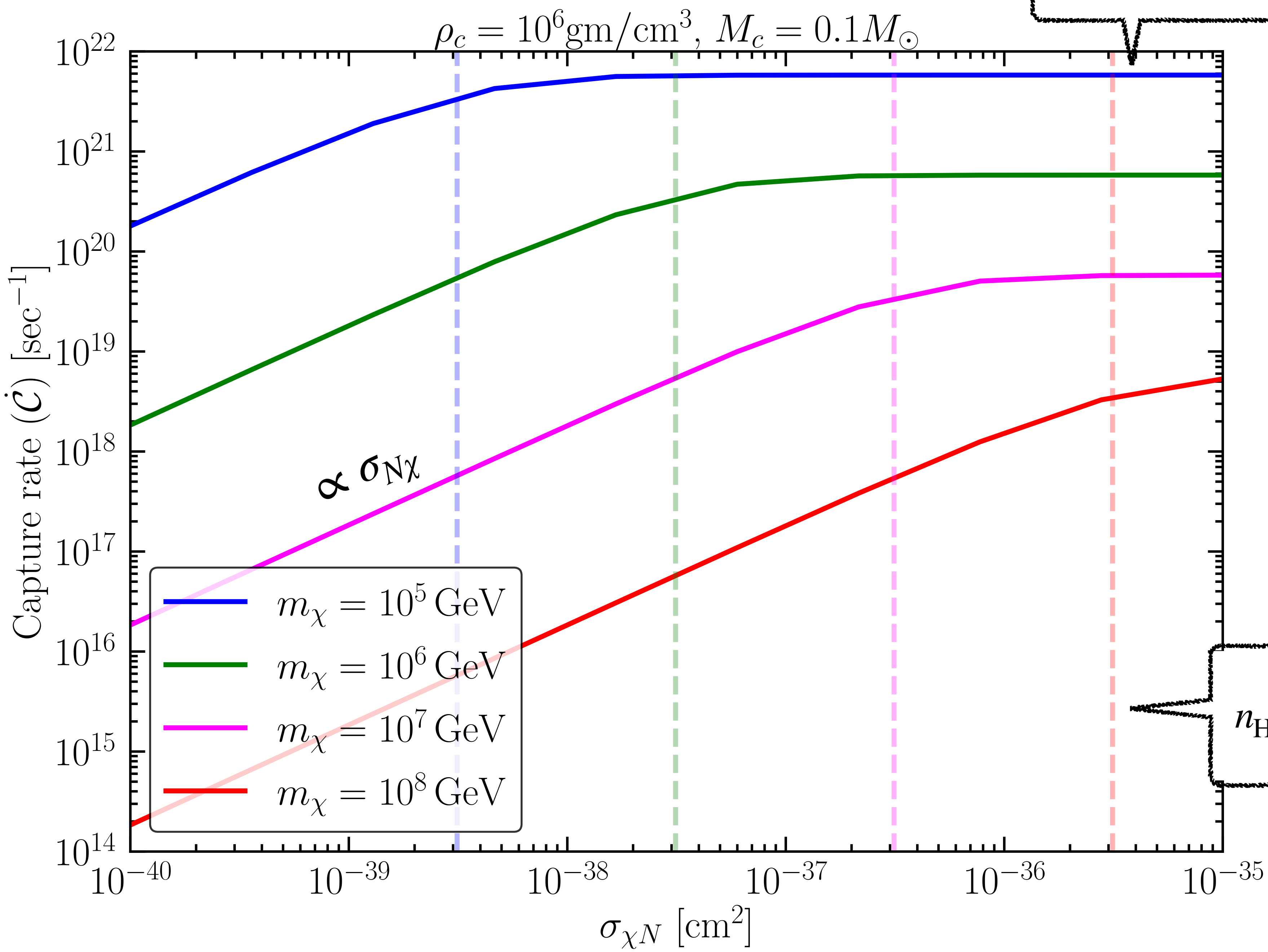
- Initial velocity u ($\sim 10^{-3}$ in average)
- Local density $\rho_\chi \sim 0.1\,\mathrm{GeV\,cm^{-3}}$

- Expected number of scatterings $\sim n_{\mathrm{He}}\sigma_{\chi\mathrm{He}}R_{\mathrm{RG}}$
- Losing energy per each scattering $\dfrac{\delta E_\chi}{E_\chi} \sim -\dfrac{m_{\mathrm{He}}}{m_\chi}$
- Dark matter captured when $\Delta E_\chi \sim -m_\chi u^2$

- $\rho_{\mathrm{RG}} \sim 10^6\,\mathrm{g\,cm^{-3}}$
- $R_{\mathrm{RG}} \sim 10^4\,\mathrm{km}$ ➡ $v_{\mathrm{esc}} \sim 0.01c$
- $T_{\mathrm{RG}} \sim 10^8\,\mathrm{K}$

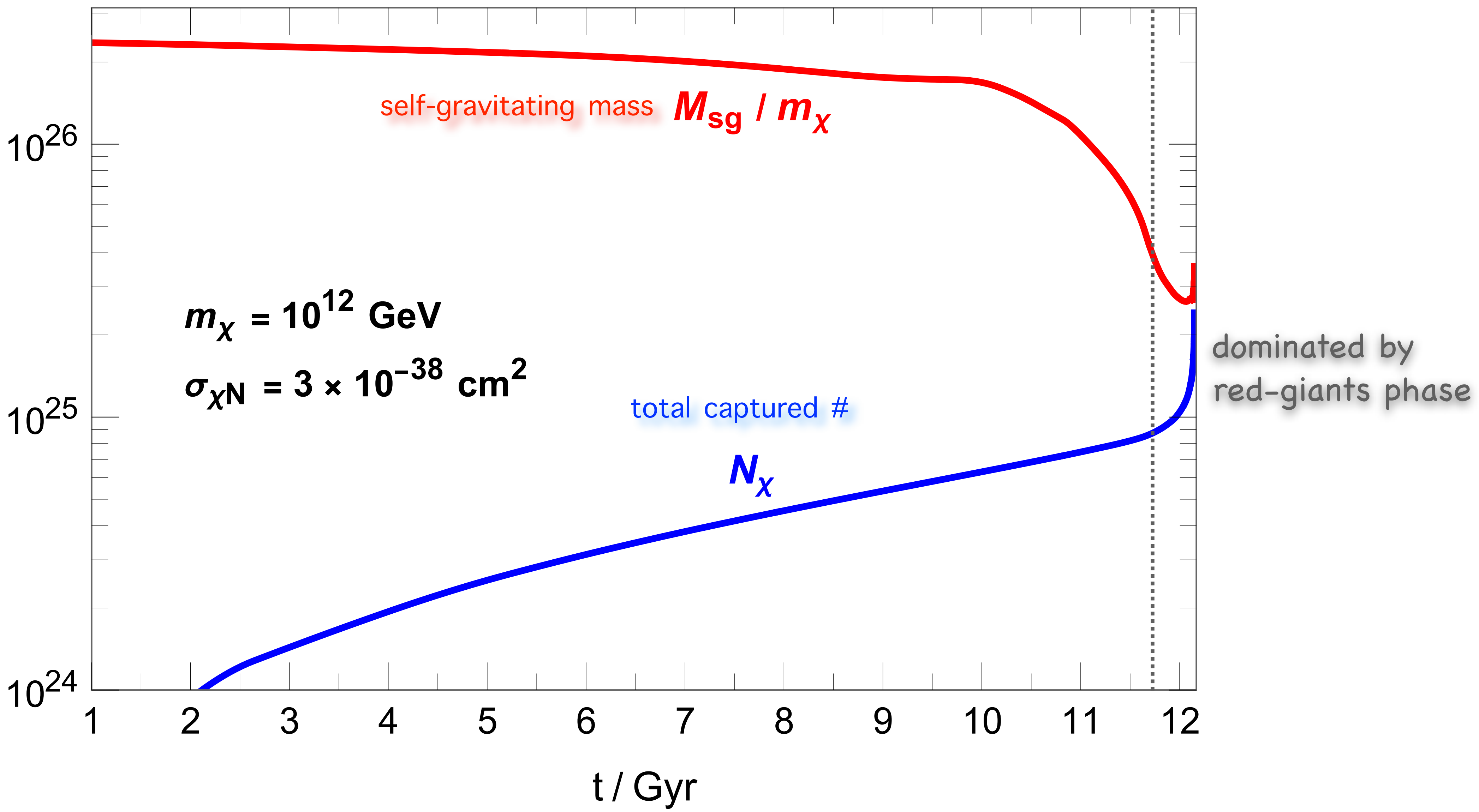
Capture Rate

- Almost all incident DM captured
- Geometric capturing rate $\sim 4\pi R_{\mathrm{RG}}^2 \mathscr{F}_\chi$

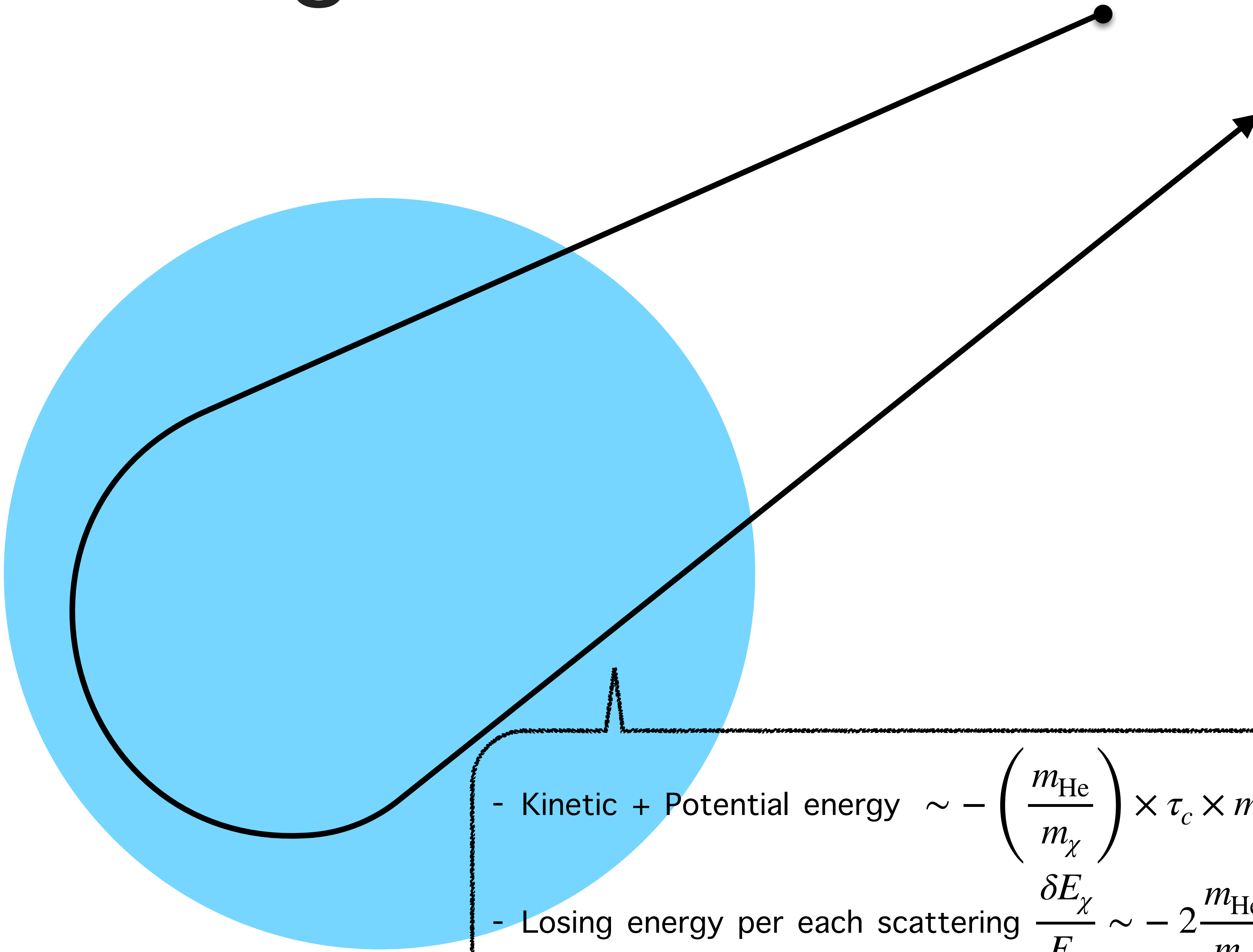


$$n_{\mathrm{He}} \sigma_{\chi \mathrm{He}} R_{\mathrm{RG}} \simeq \frac{m_\chi \bar{v}^2}{2 m_{\mathrm{He}} / m_\chi}$$

DM Capture in Time

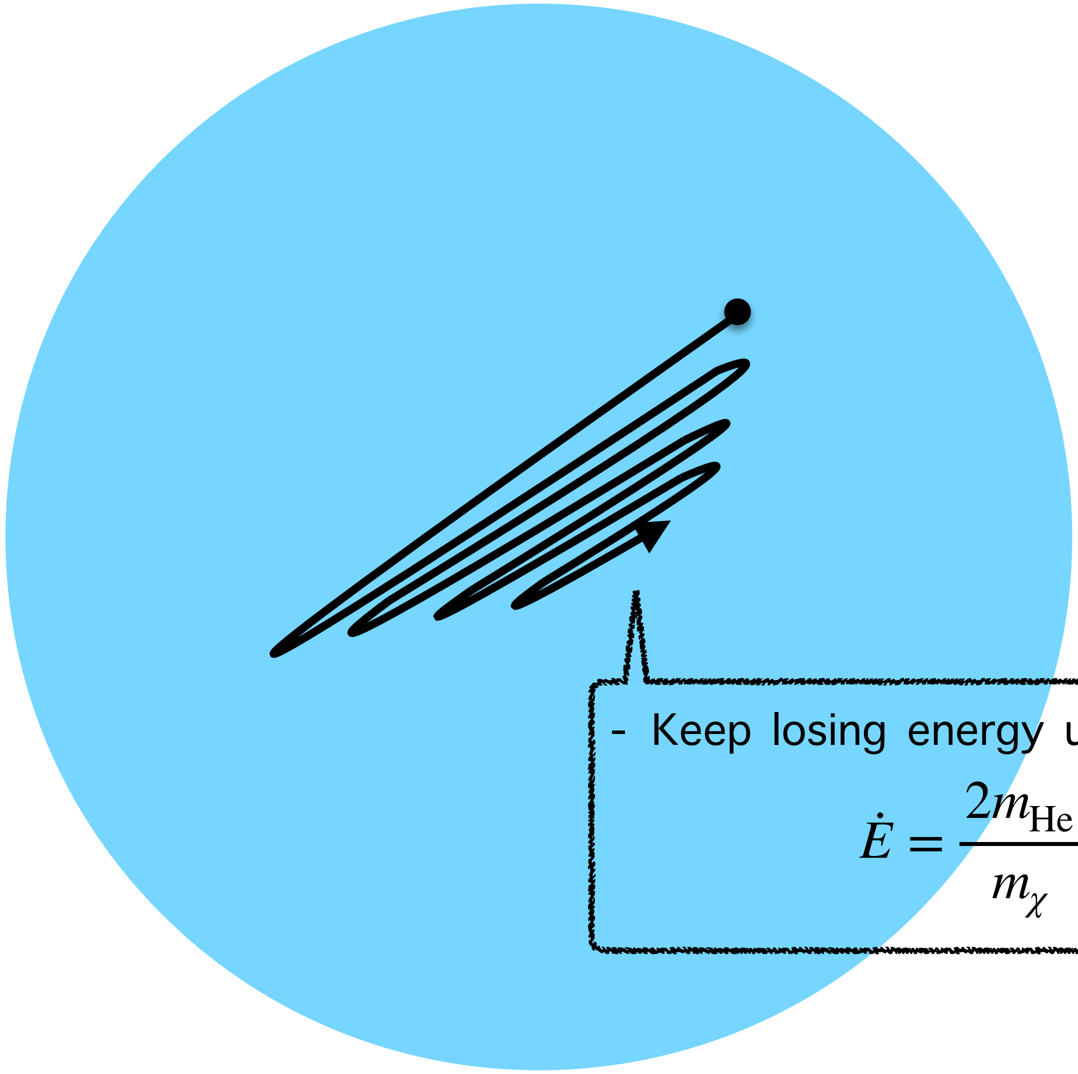


Ingress



- Kinetic + Potential energy $\sim -\left(\frac{m_{\rm He}}{m_\chi}\right) \times \tau_c \times m_\chi v_e^2$
- Losing energy per each scattering $\frac{\delta E_\chi}{E_\chi} \sim -2\frac{m_{\rm He}}{m_\chi}$
- Dark matter ingress when total energy $< -m_\chi v_{\rm esc}^2$

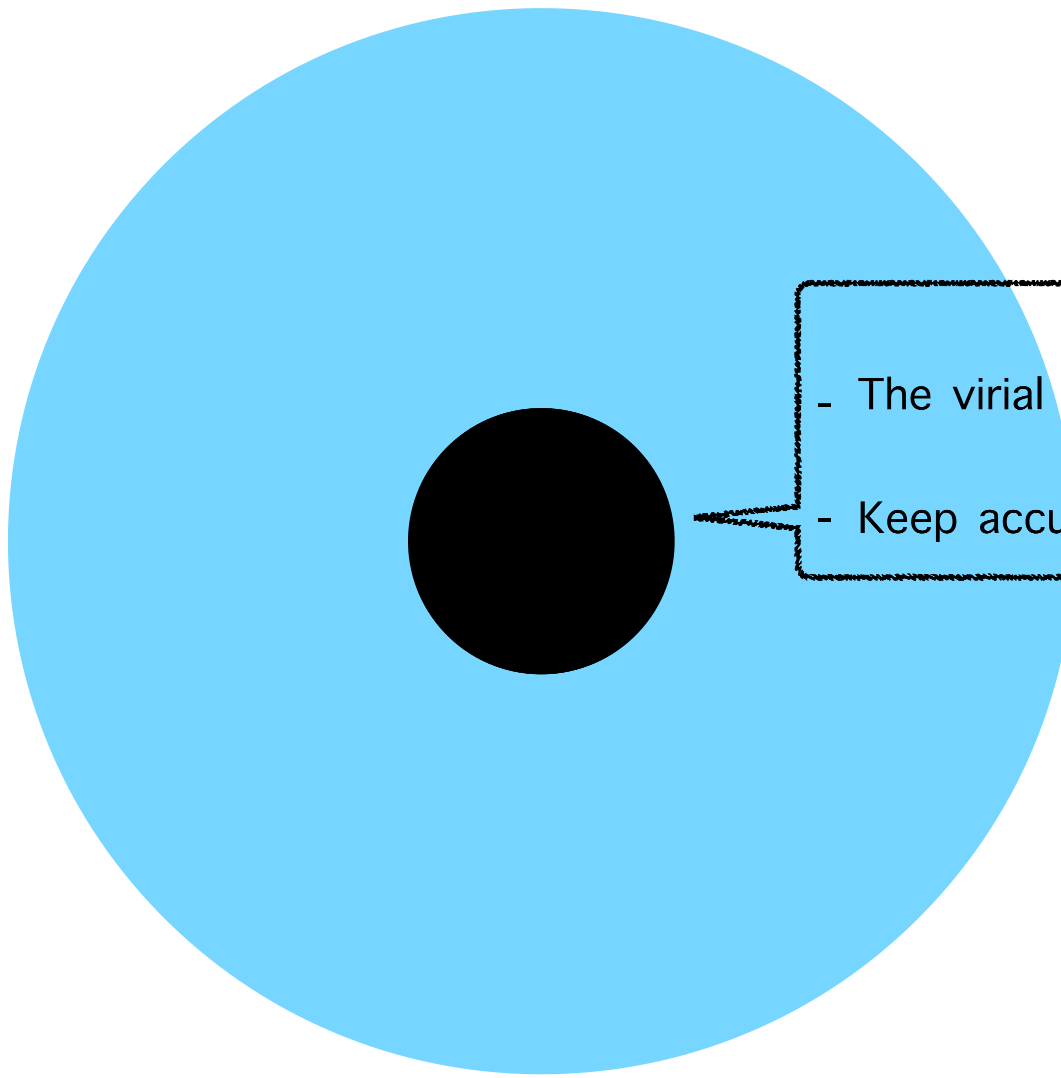
Thermalization



- Keep losing energy up to kinetic energy $\sim T$

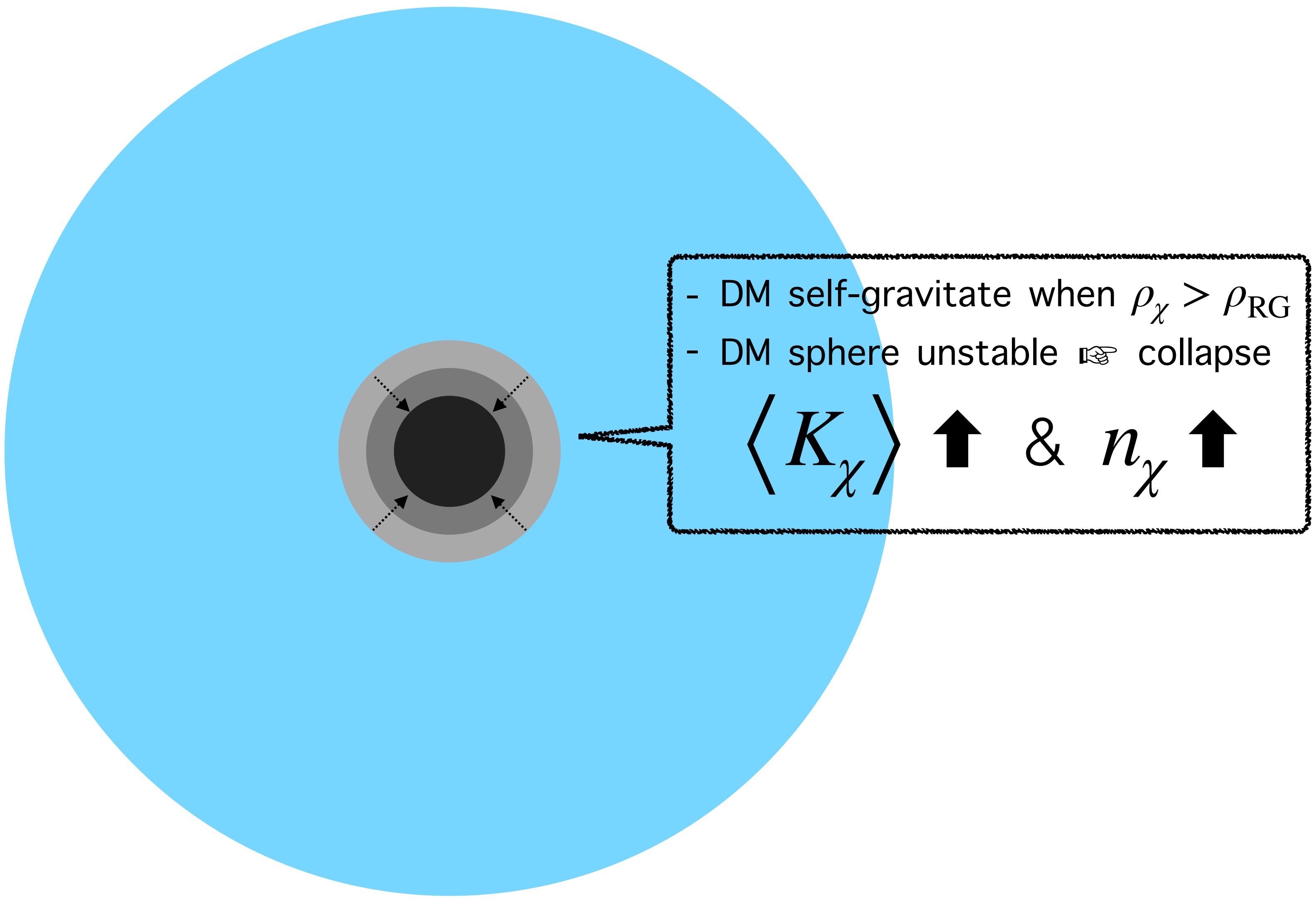
$$\dot{E} = \frac{2m_{\mathrm{He}}}{m_\chi}\left(\frac{3}{2}T - E\right)$$

Thermalization

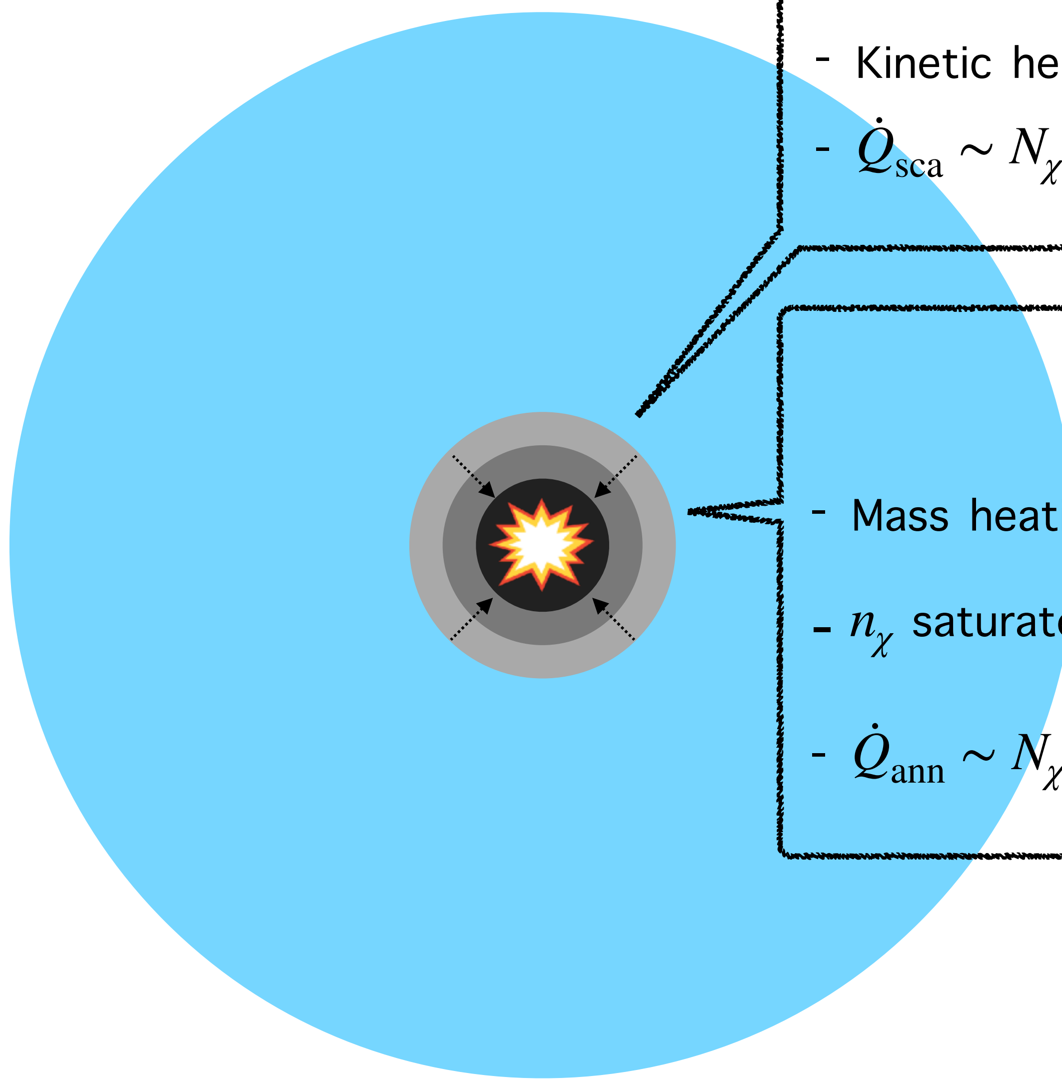


- The virial radius of thermalized DM $\propto \sqrt{\dfrac{T_{\rm RG}}{\rho_{\rm RG} m_\chi}}$
- Keep accumulating until self-gravitating

Gravitational Collapse



Dark Matter Heating



$\langle K_\chi \rangle \uparrow$

- Kinetic heating via **scattering**
- $\dot{Q}_{\rm sca} \sim N_\chi K_\chi \times \frac{m_{\rm He}}{m_\chi} \times (n_{\rm He} \sigma_{\chi {\rm He}} v_{\rm rel})$

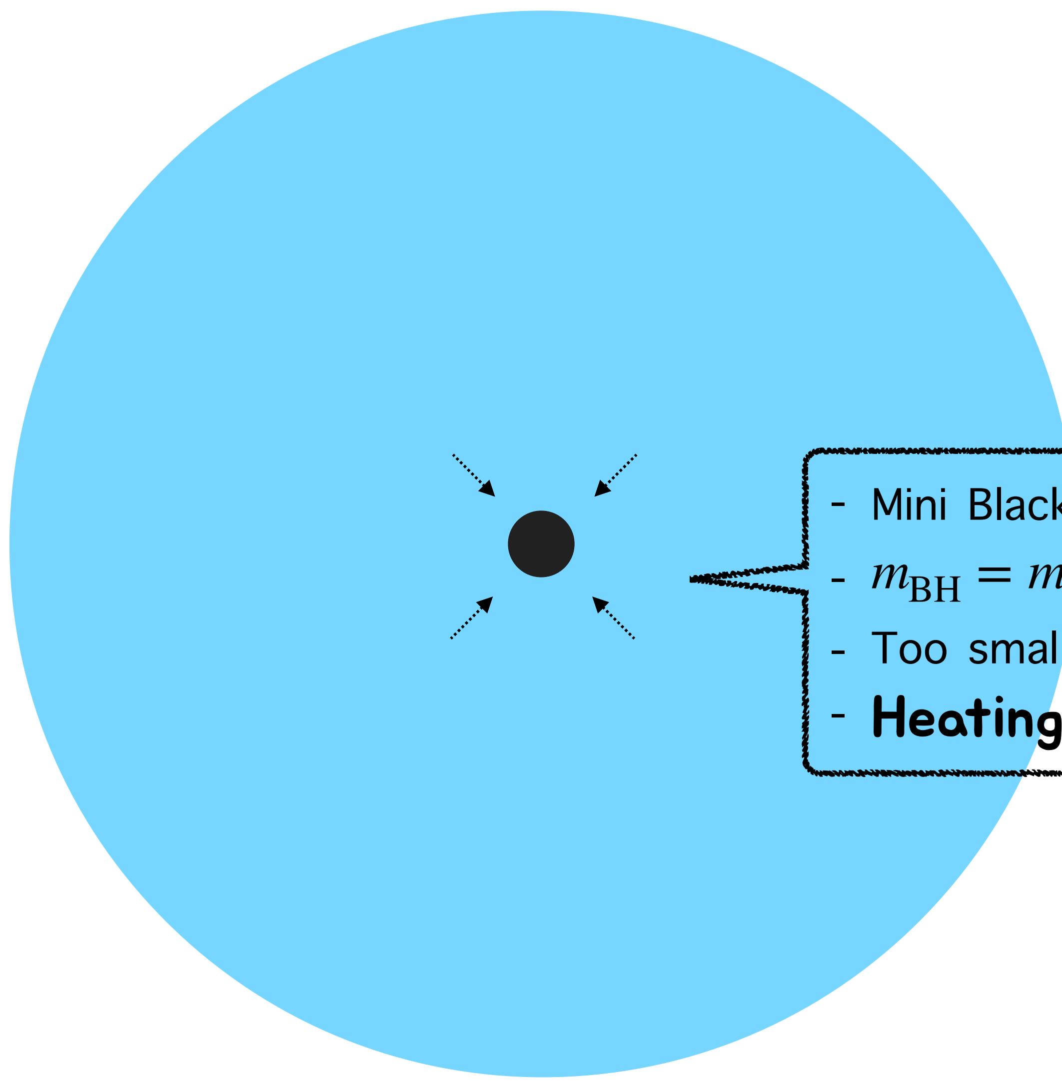
$n_\chi \uparrow$

- Mass heating via **annihilation**
- n_χ saturates $\sim \frac{(m_{\rm He}/m_\chi) n_{\rm He} \sigma_{\chi {\rm He}} v_{\rm rel}}{\sigma_{\rm ann} v_\chi}$
- $\dot{Q}_{\rm ann} \sim N_\chi m_\chi \times \frac{m_{\rm He}}{m_\chi} \times (n_{\rm He} \sigma_{\chi {\rm He}} v_\chi)$

$\Updownarrow$

✓ Conductive diffusion $|\dot{Q}_{\rm diff}| \sim \frac{\Delta E}{t_{\rm diff}}$ @ trigger mass size

DM-induced mini Black Hole



- Mini Black Hole formation
- $m_{\rm BH} = m_{\rm SG} \simeq 10^{14}\,{\rm g}\,\left(m_{12}^{-3/2}\right)\left(T_8^{3/2}\right)\left(\rho_6^{-1/2}\right)$
- Too small to accrete for $m_{\rm BH} < 10^{15}\,{\rm g}$
- **Heating via evaporation**

$\Updownarrow$

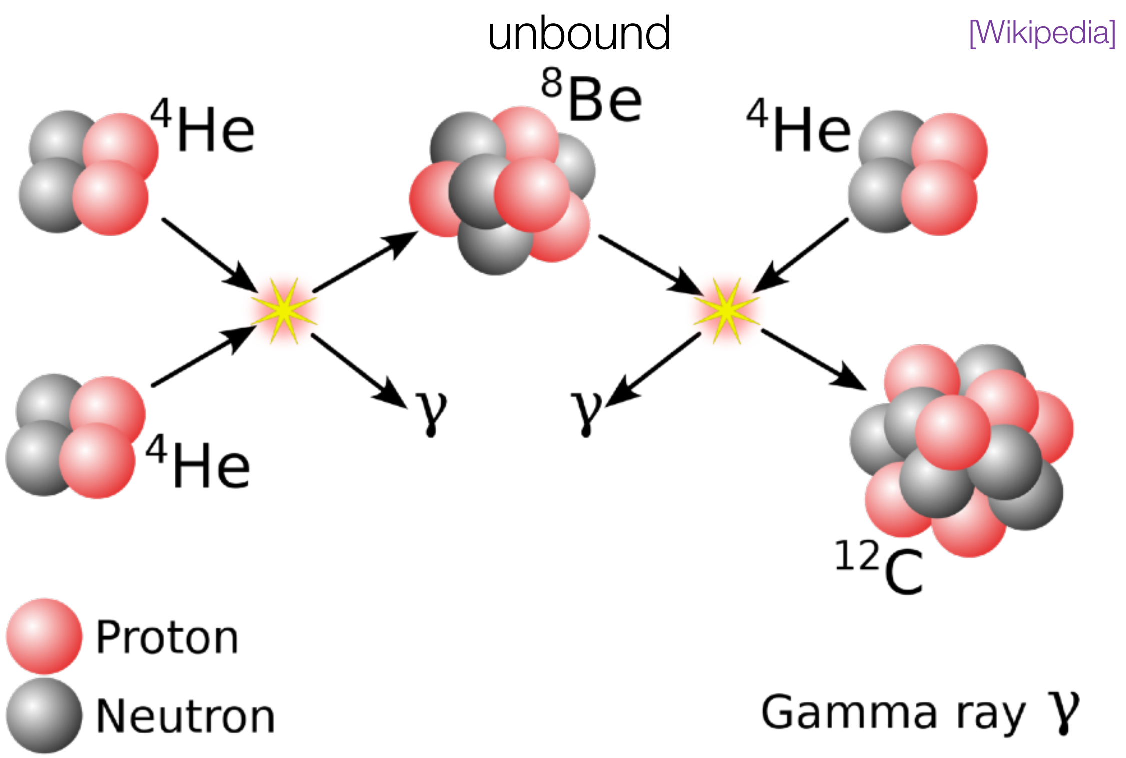
✓ Conductive diffusion $|\dot{Q}_{\rm diff}| \sim \dfrac{\Delta E}{t_{\rm diff}}$ @ trigger mass size

Trigger Mass for Helium Ignition

- Triple-alpha process: $^4\mathrm{He} + ^4\mathrm{He} \rightarrow ^8\mathrm{Be}\left(+^4\mathrm{He}\right) \rightarrow ^{12}\mathrm{C} + 2\gamma$
- Thermal diffusion (cooling) VS Nuclear reaction (burning)

✓ Threshold burning width ☞ Trigger mass

Triple-α process



1) $\alpha + \alpha \rightarrow {}^8\mathrm{Be}$
   - $^8\mathrm{Be}$ is very unstable
   - But, an equilibrium abundance of $^8\mathrm{Be}$

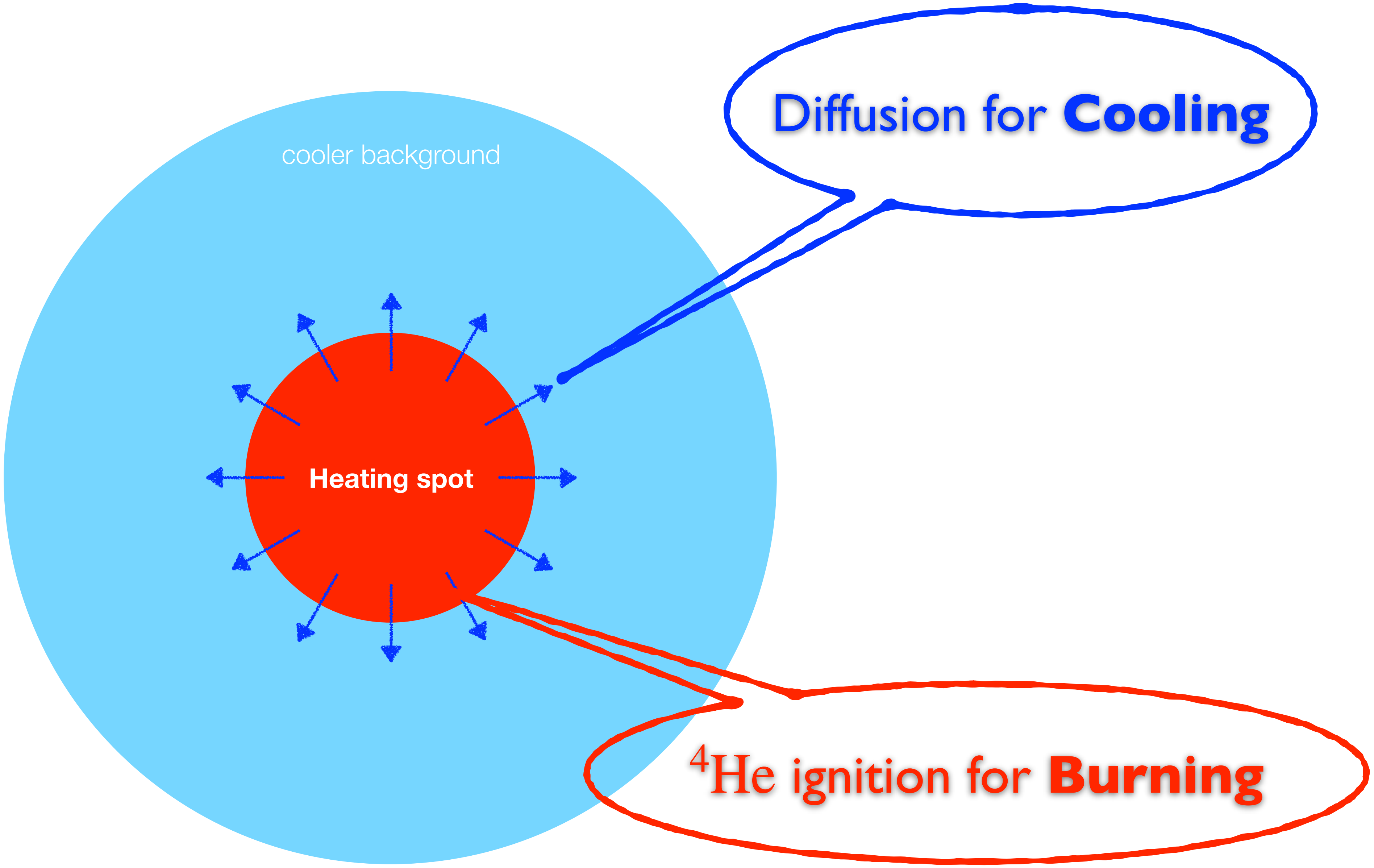
2) ${}^8\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C} + 2\gamma$
   - Resonant reaction

$$r_{3\alpha} \propto n_\alpha^3 \, e^{-43/T_8}$$

3α reaction rate

$$T_8 \equiv \frac{T}{10^8\,\mathrm{K}}$$

Burning VS Diffusion



[Schwarzschild & Harm, 1967]
[Timmes & Woosely, 1992]
[Timmes, 2000]

Burning VS Diffusion

- **Burning time scale**

Excessive free energy per unit mass

$\sim \text{Capacity} \times \Delta T$

$$t_{\text{burn}} \sim \frac{\Delta E_{\text{free}}}{\dot{S}_{3\alpha}}$$

Nuclear reaction rate for heating

$\sim Q_{3\alpha} \times r_{3\alpha} / \rho$

- **Diffusion time scale**

Width of heating spot

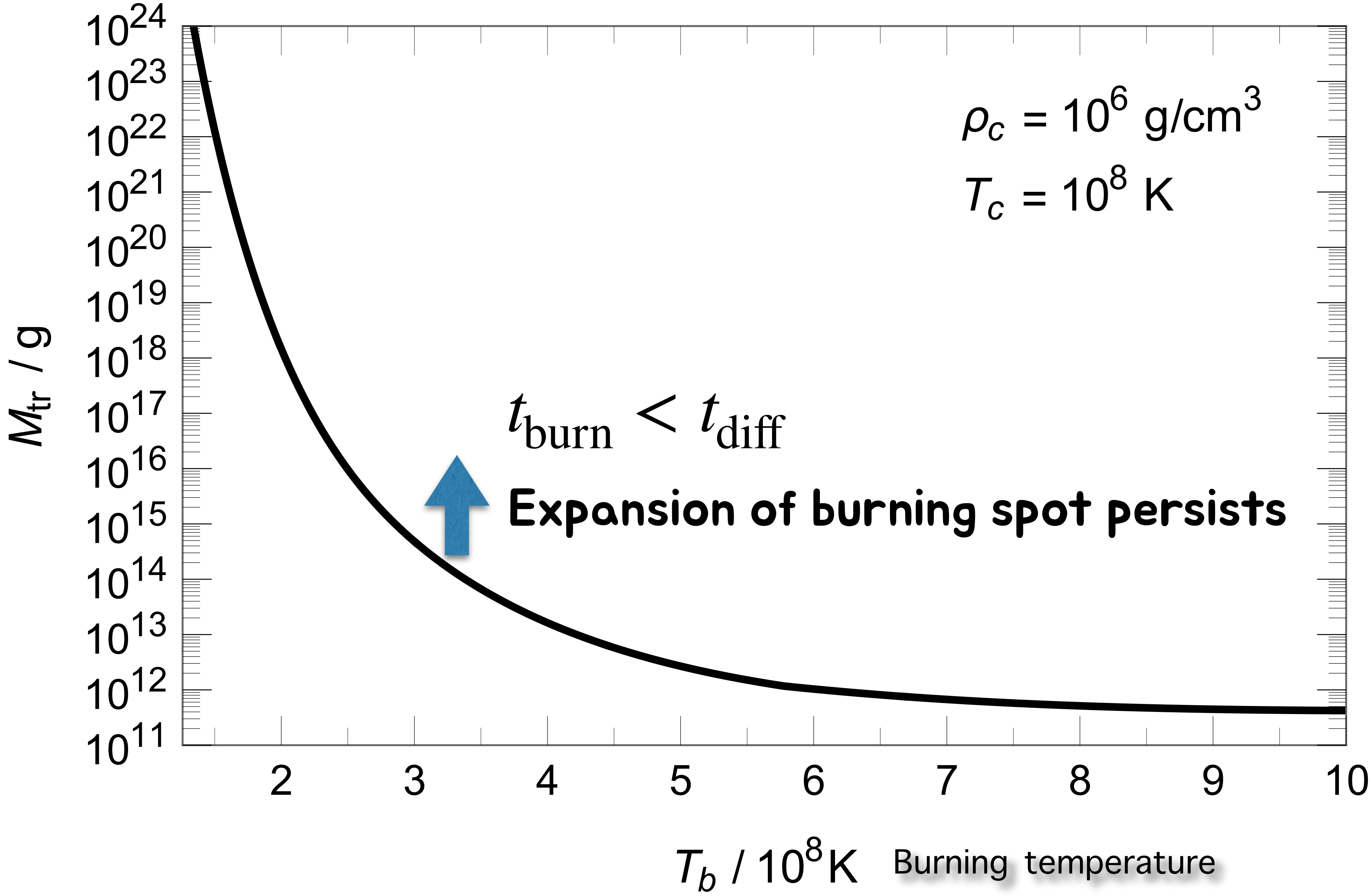
$$t_{\text{diff}} \sim \frac{\delta^2}{D}$$

Thermal diffusivity

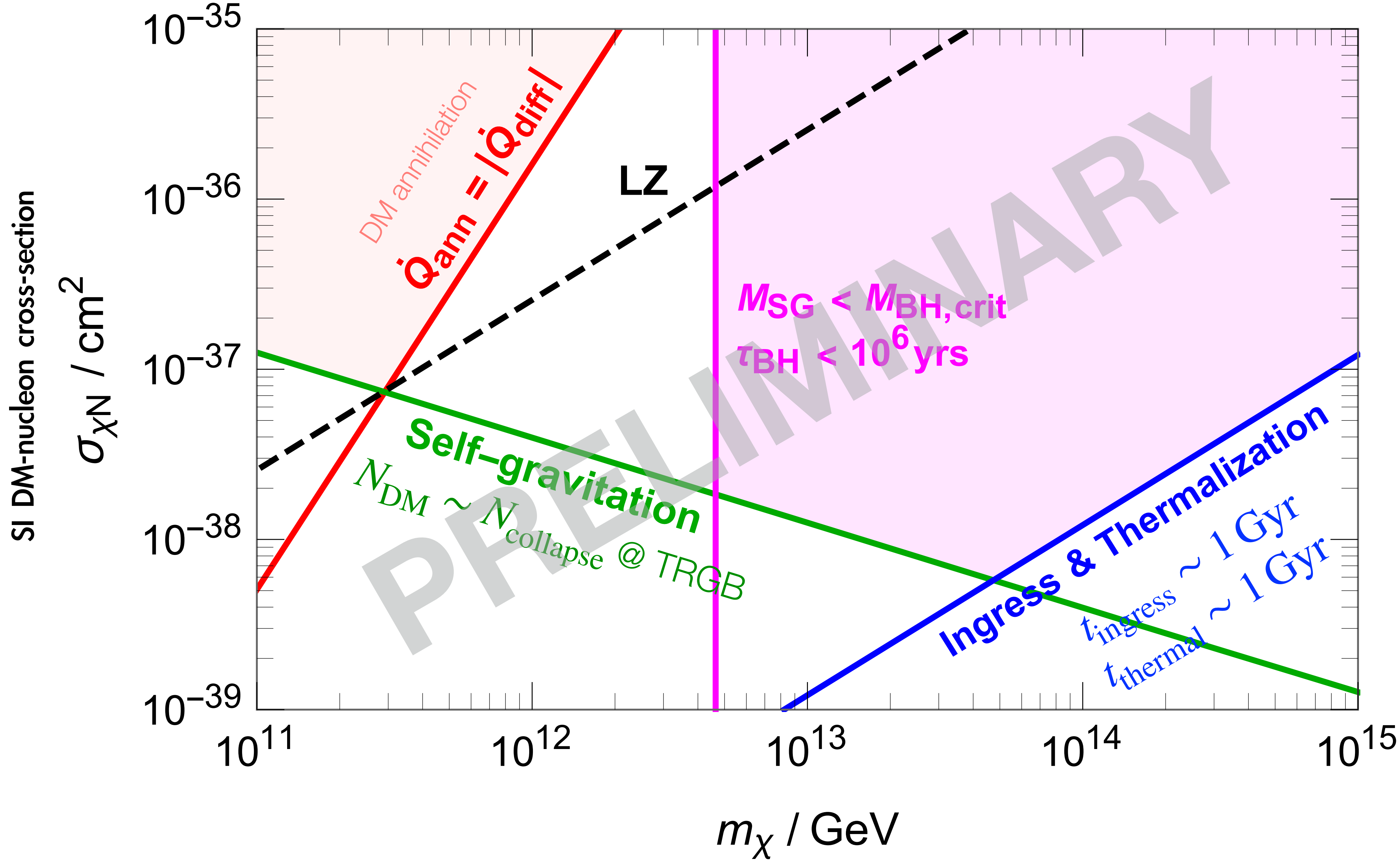
$\sim \lambda \times v_c$

- **Sparkled frame persists and expands when $t_{\text{burn}} < t_{\text{diff}}$**

Trigger Mass for Helium Ignition



Constraints on Heavy DM



Conclusions & Discussion

- Stellar evolution as a good way to probe BSM signals
  - Consistent with the SM prediction
  - ***Luminosity at the tip of RG***, lifetime of HB, etc
- Triple-alpha process in red-giant cores
  - Sensitive to temperature (due to resonant reaction)
  - Small spark can ignite a helium core in advance ☞ **Trigger mass**
- (Heavy) Dark matter capture in RG
  - Scatterings w/ nuclei ☞ capturing, ingress, and thermalization
  - Self-gravitating collapse for localized DM heating effect ☞ heavy mass DM
  - DM self-annihilation ☞ efficient heating for runaway helium ignition
  - Mini Black Hole ☞ heating via evaporation (maybe destruction?)

Thank you!

Back up

Stellar Object

> “ **Star**
>
> From Wikipedia, the free encyclopedia
>
> *This article is about the astronomical object. For other uses, see Star (disambiguation).*
>
> A **star** is an astronomical object consisting of a luminous spheroid of plasma held together by its own gravity. ”

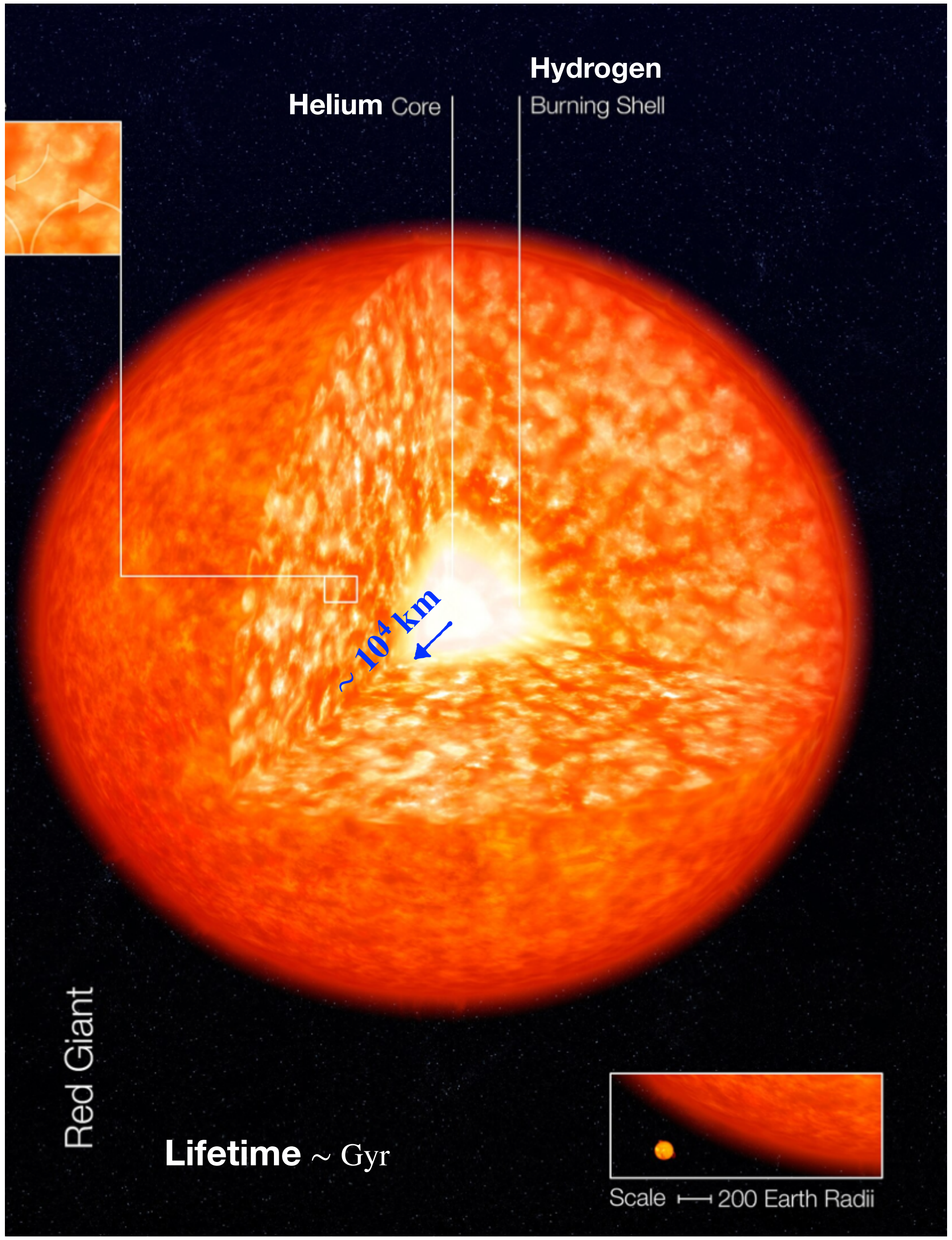
- can be used as laboratories to probe fundamental interactions.
  - observed photon or neutrino signal

    e.g. γ-ray spectral modulation which can be explained by axion-photon oscillations

  - Stellar evolution

    extra energy leakage/release could change
    the evolutionary path which fits well to the standard scenario

Red Giant Branch



- Helium core governs properties of star
  - Sizable mass fraction $\mathcal{O}(1) M_\odot$
  - Very dense $\sim 10^6\,\mathrm{g\,cm^{-3}}$
  - Degenerate electron pressure
  - Consistent burning condition ($r_{3\alpha} \propto T^{40}$ @ $T \sim 10^8\,\mathrm{K}$)
- Hydrogen envelope
  - Dominant burning shell near core (pp-chain & CNO)
  - More dense core, more luminosity
  - Expanding via thermal pressure (redder)

Late-onset Annihilation

- $\sigma_{\rm ann} v_\chi \equiv \dfrac{\alpha_\chi^2}{m_\chi^2}$ parametrized in context of *the unitarity limit*

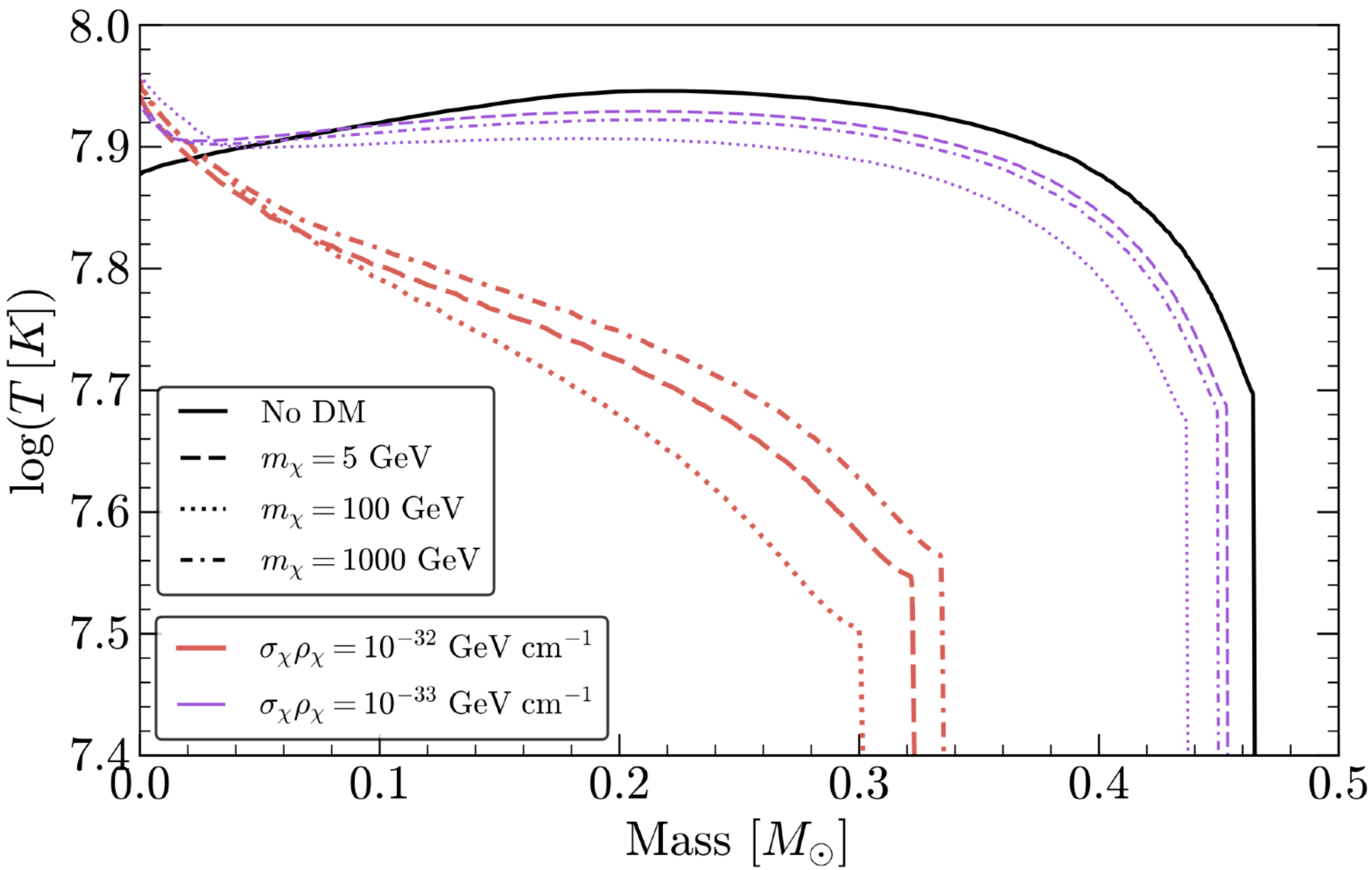
s-wave & α_χ: DM-SM coupling

- For a localized heating to trigger runaway helium burning

✓ **DM self-annihilation occurs after collapse (i.e., $\rho_\chi > \rho_{\rm RG}$)**

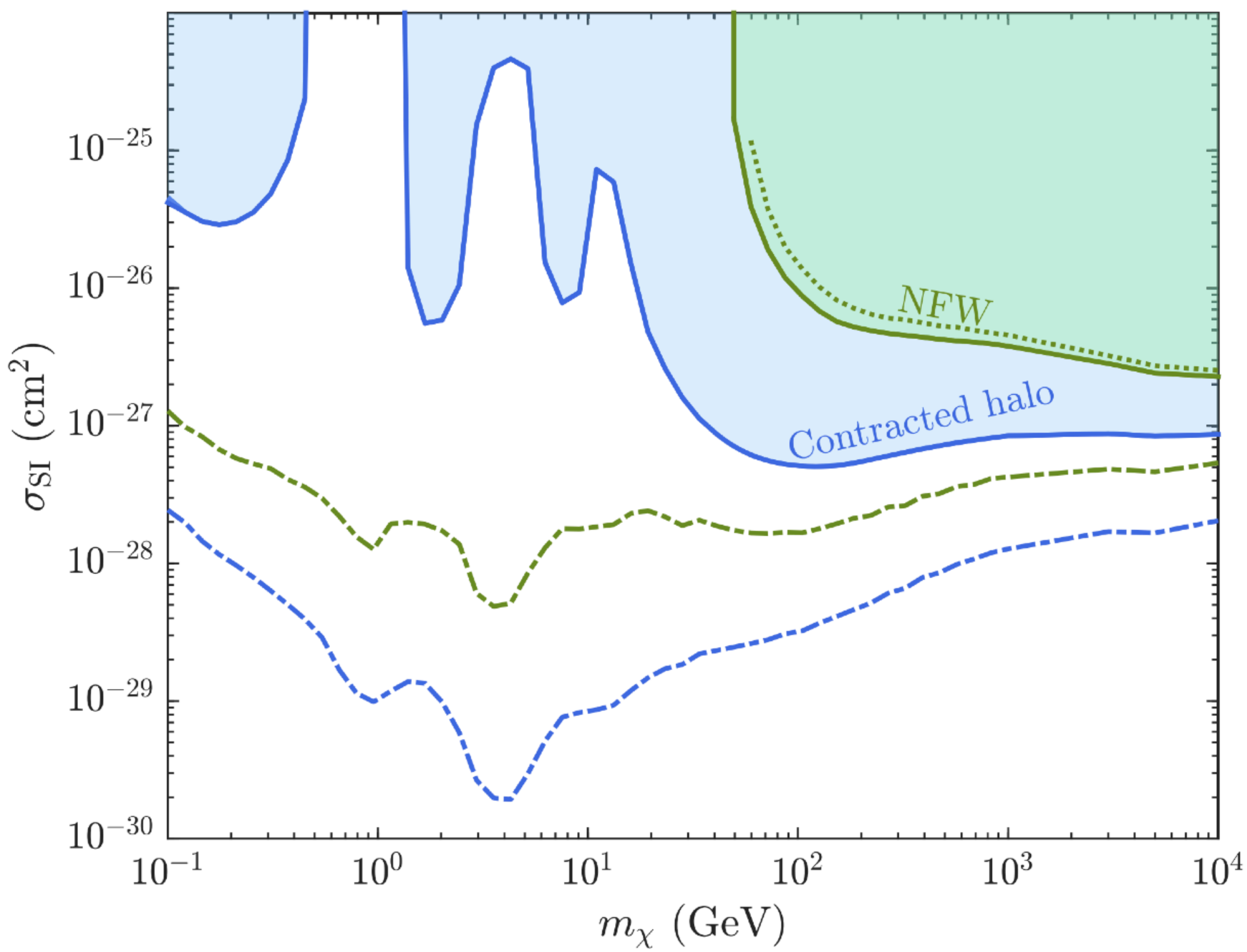
$$t_{\rm ann} \sim \frac{1}{(\rho_\chi / m_\chi)\sigma_{\rm ann} v_\chi} > 1\,{\rm Gyr} \;\Rightarrow\; m_\chi > 10^9\,{\rm GeV}\left(\frac{\rho}{10^6\,{\rm g/cm^3}}\right)^{1/3}\left(\frac{\alpha_\chi}{0.1}\right)^{2/3}$$

Other Mass Regime?



[J. Lopes, I. Lopes, 2021]

Other Mass Regime?



[H. Hong, A. Vincent, 2024]

Heavy Dark Matter Capture, Collapse, and Premature Helium Flash in a Red Giant