

Probing Heavy Dark Matter in Red Giants

Seokhoon Yun

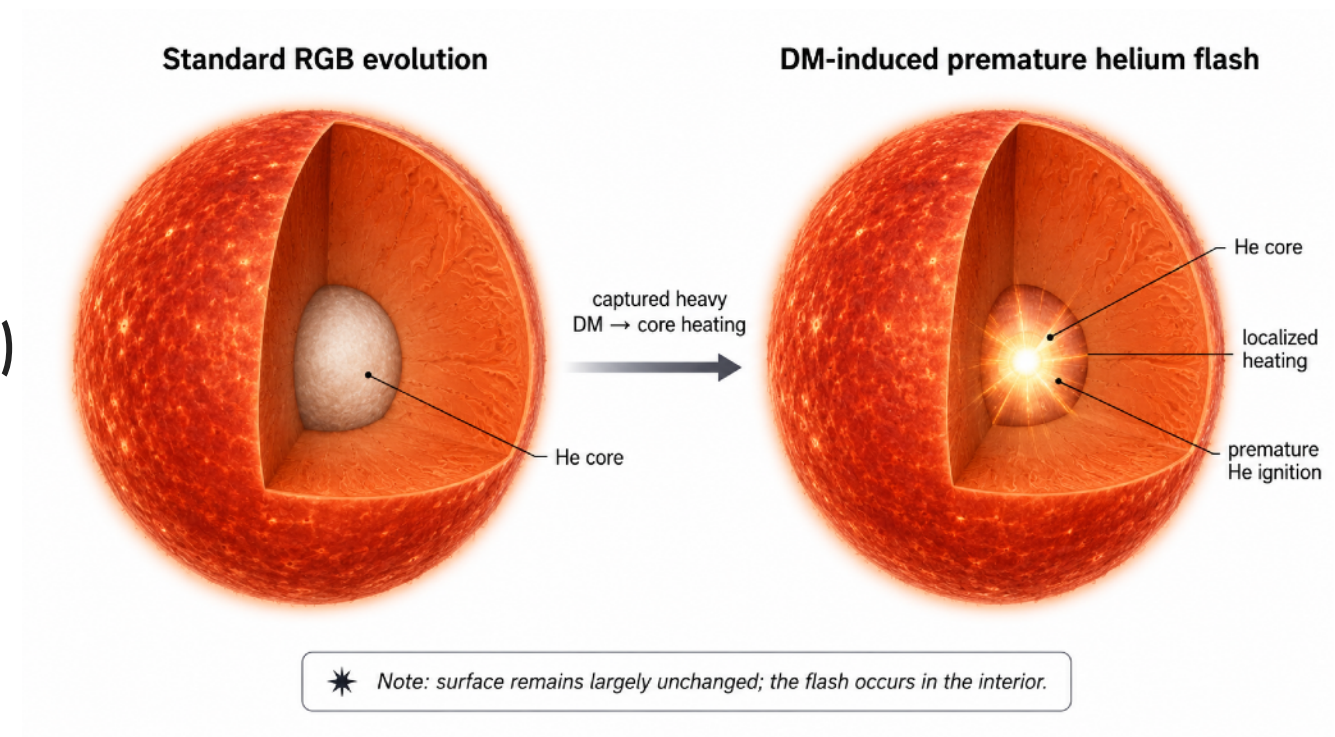


KNU

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), Minxi He (NAOJ),
Audrey Feng (APCTP) **[2611.XXXXX]**

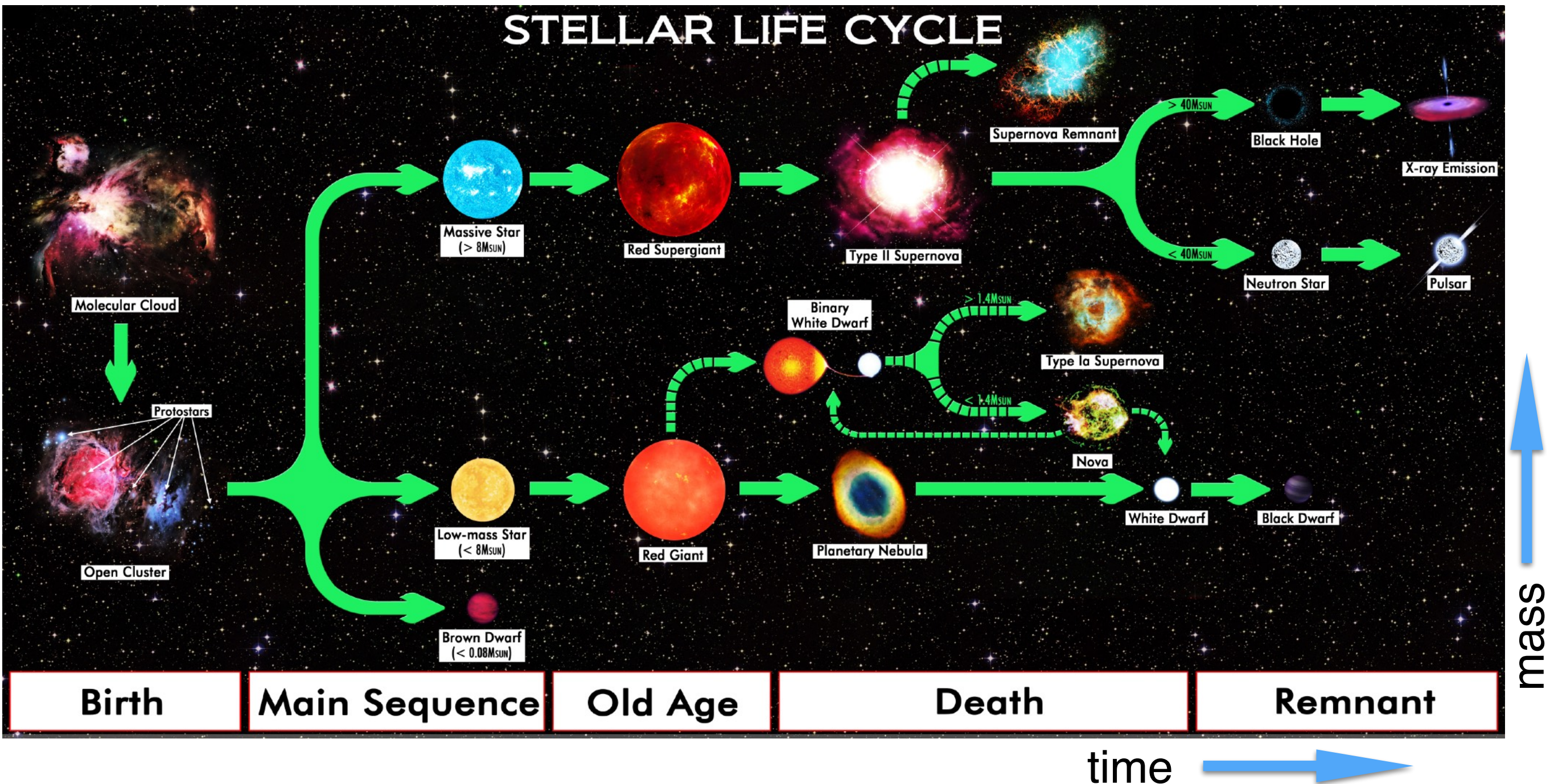
Outline

- 01 Introduction** ▪ Stellar evolution to probe BSM ✓ Cooling argument w/o DM
✓ Heating w/ DM capture
- 02 Heavy DM capture & heating** ✓ scatterings & annihilations
✓ black hole evaporation & luminosity
- 03 Helium ignition**
▪ Triple-alpha process
▪ Trigger mass (burning VS diffusion)
- 04 Conclusion**



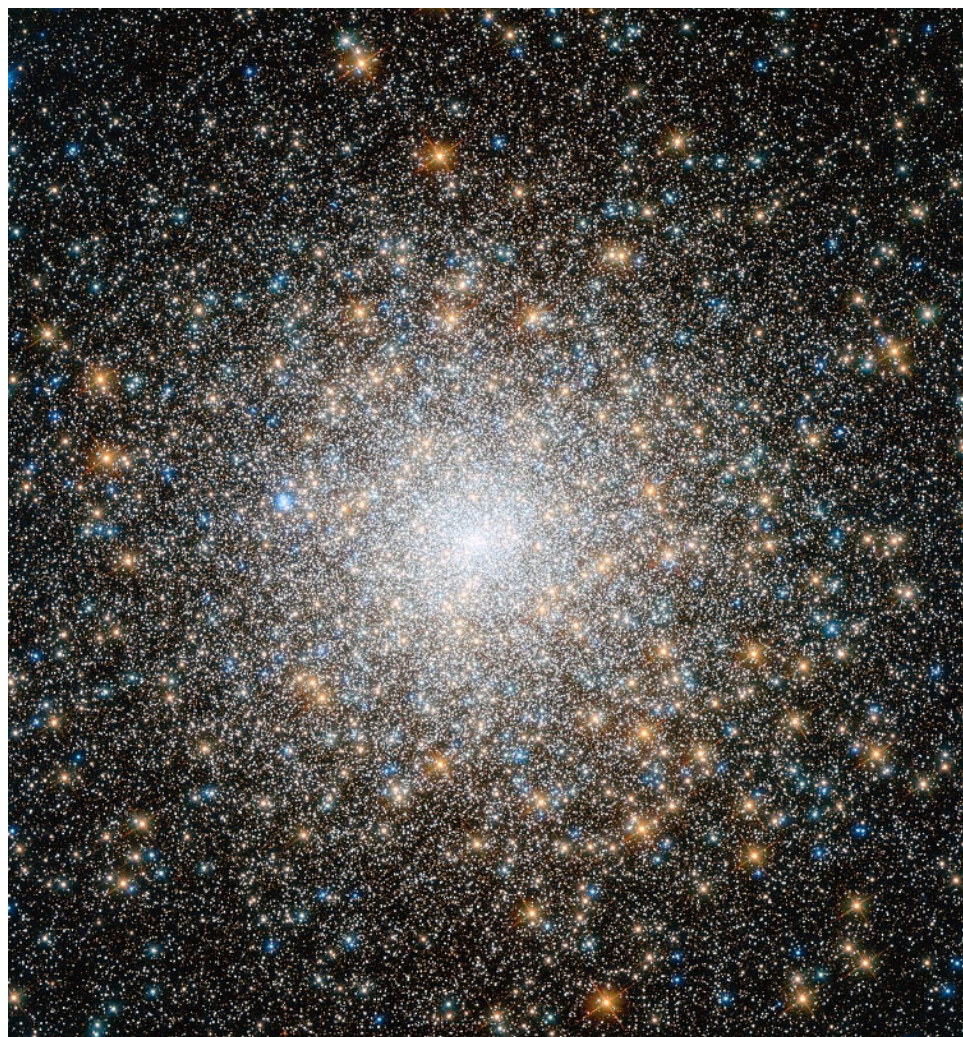
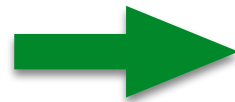
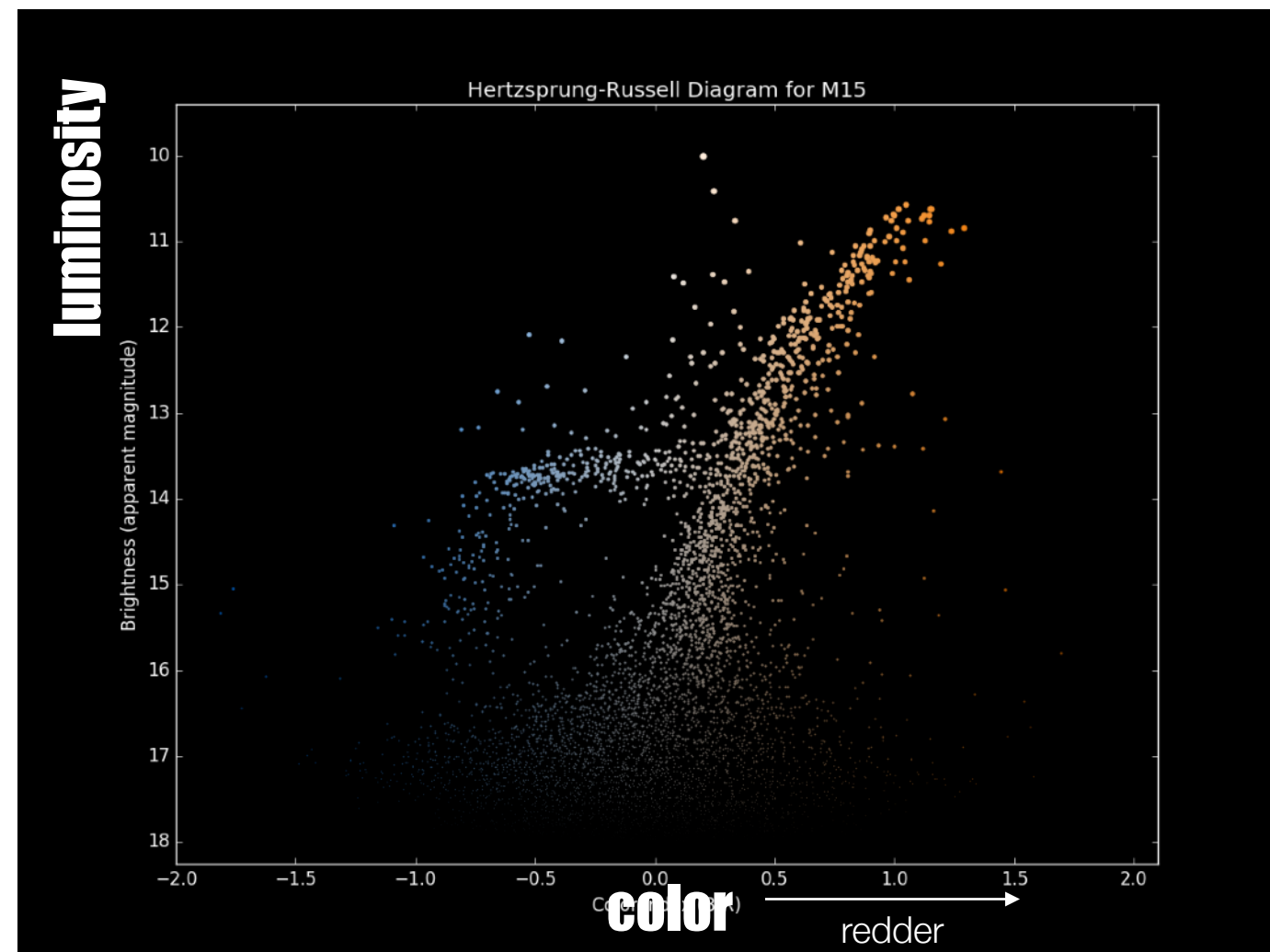
Stellar Evolution

[image from Wikipedia]

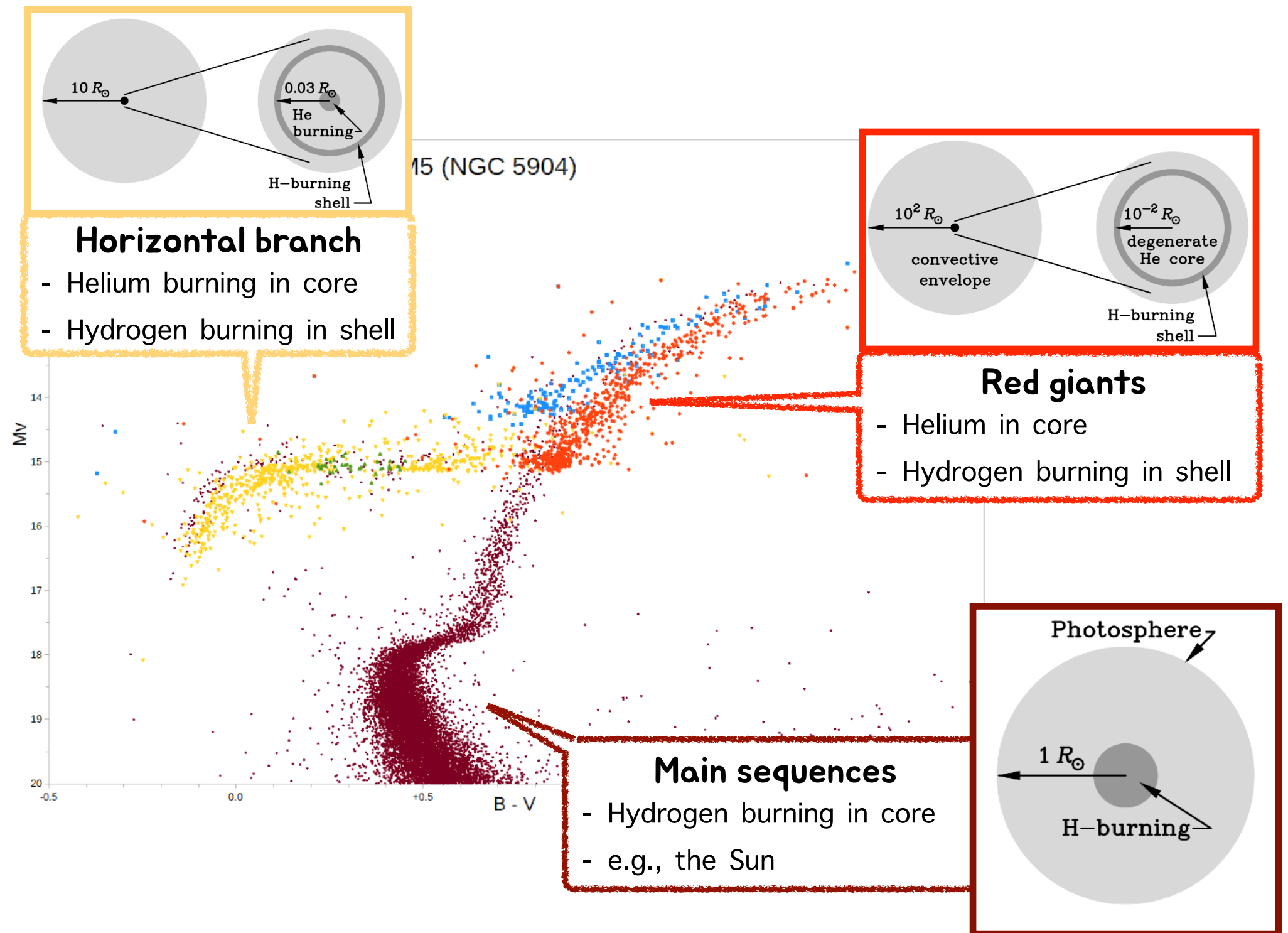


Globular Cluster

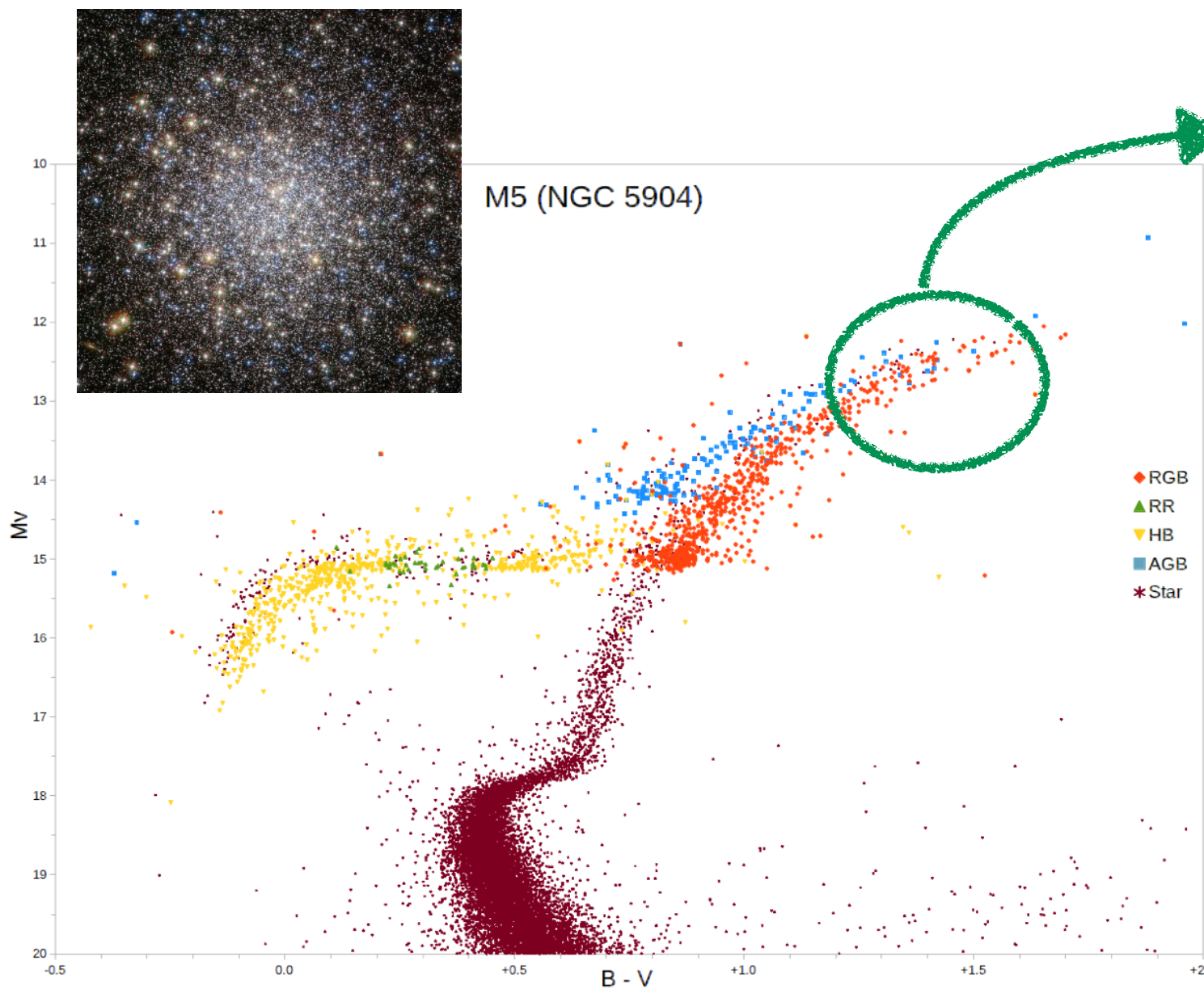
- Very clean laboratories for studies of stellar evolution
- Coeval and almost equal chemical compositions
- Only different initial mass



Stellar Evolutionary Phases

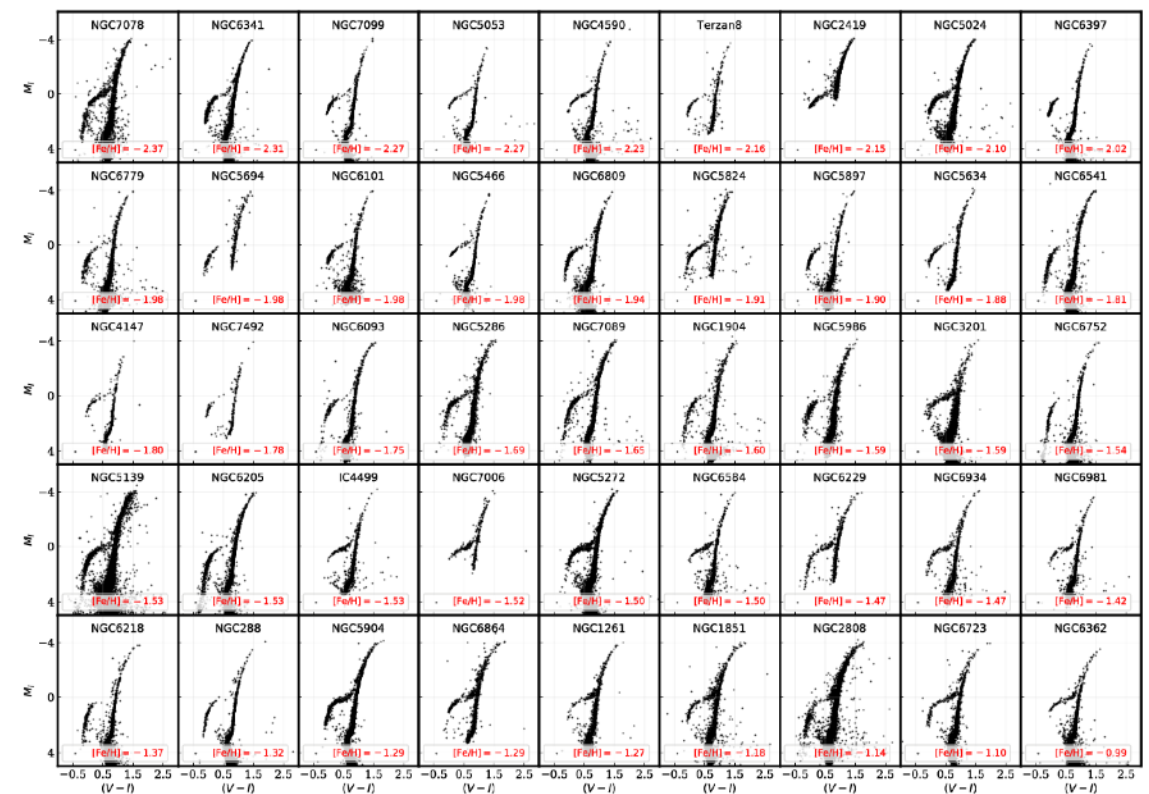


Tip of the Red Giant Branch



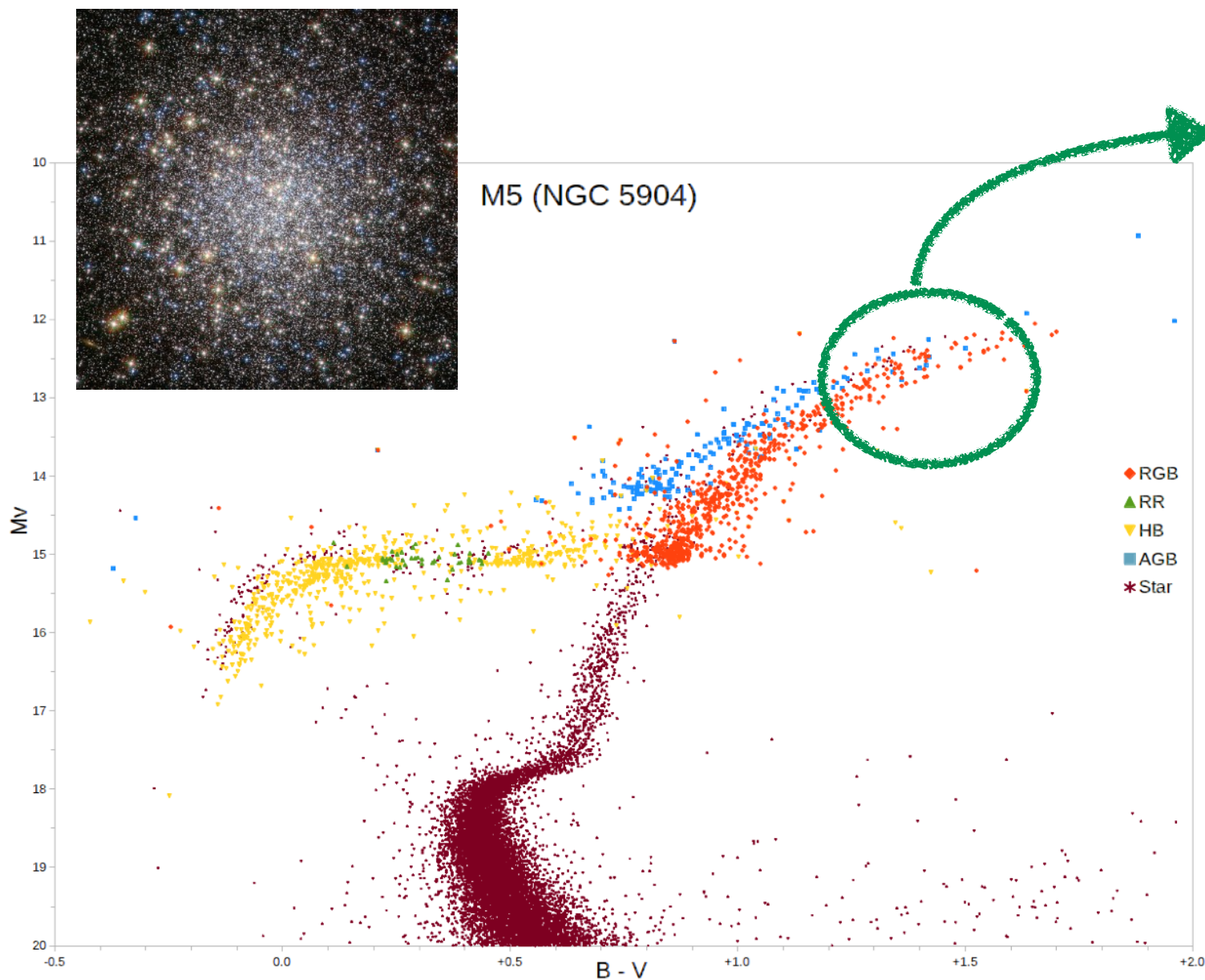
- Helium ignition in red-giant phase
 - brightness at the tip of a red-giant branch
 - determined by core mass at helium flash

[W. Cerny et al. 20]



✓ Consistent w/ the standard prediction

BSM probe of TRGB



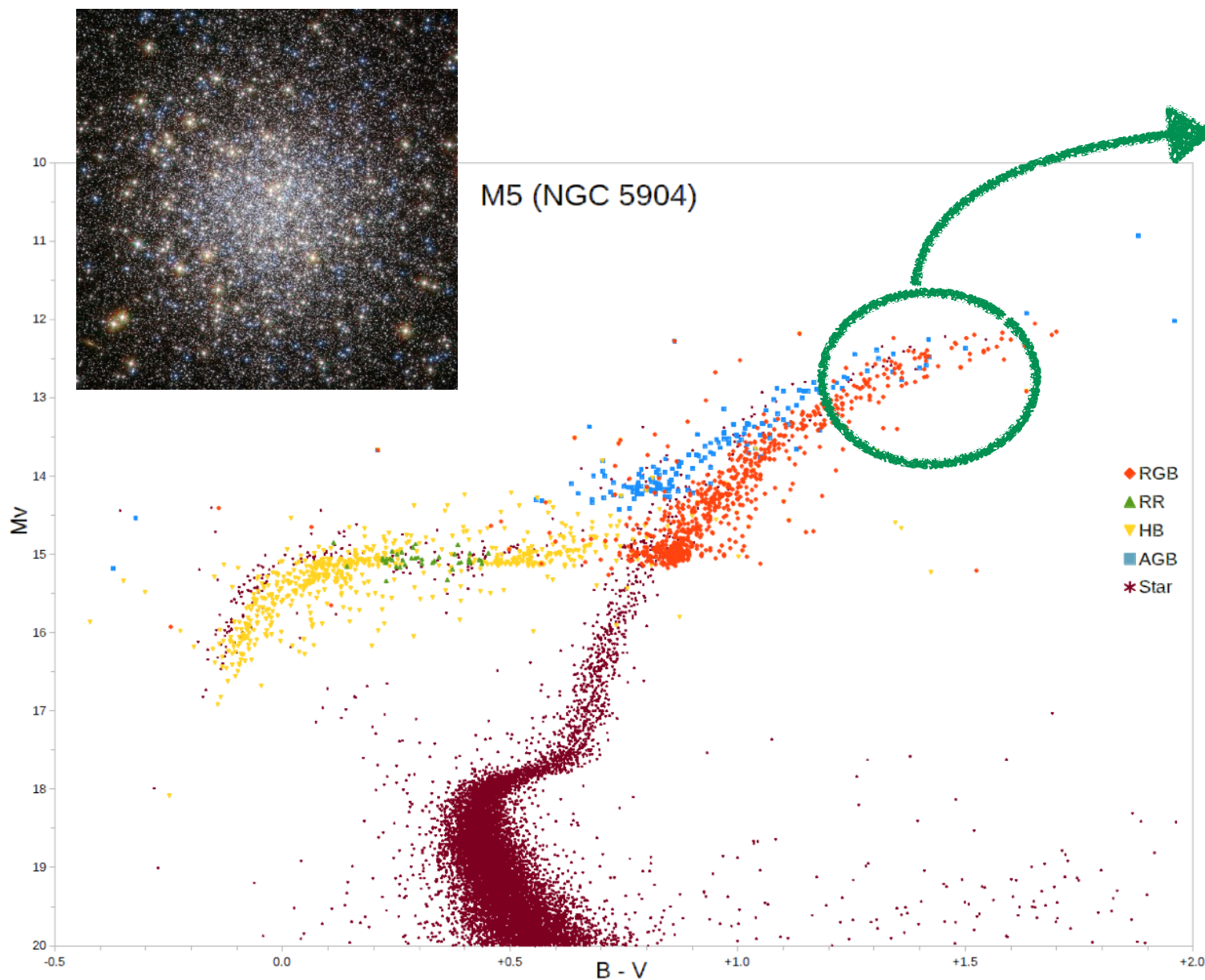
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✓ Cooling

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

“Raffelt criterion”

BSM probe of TRGB



- Helium ignition in red-giant phase
 - brightness at the tip of a red-giant branch
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“Raffelt criterion”



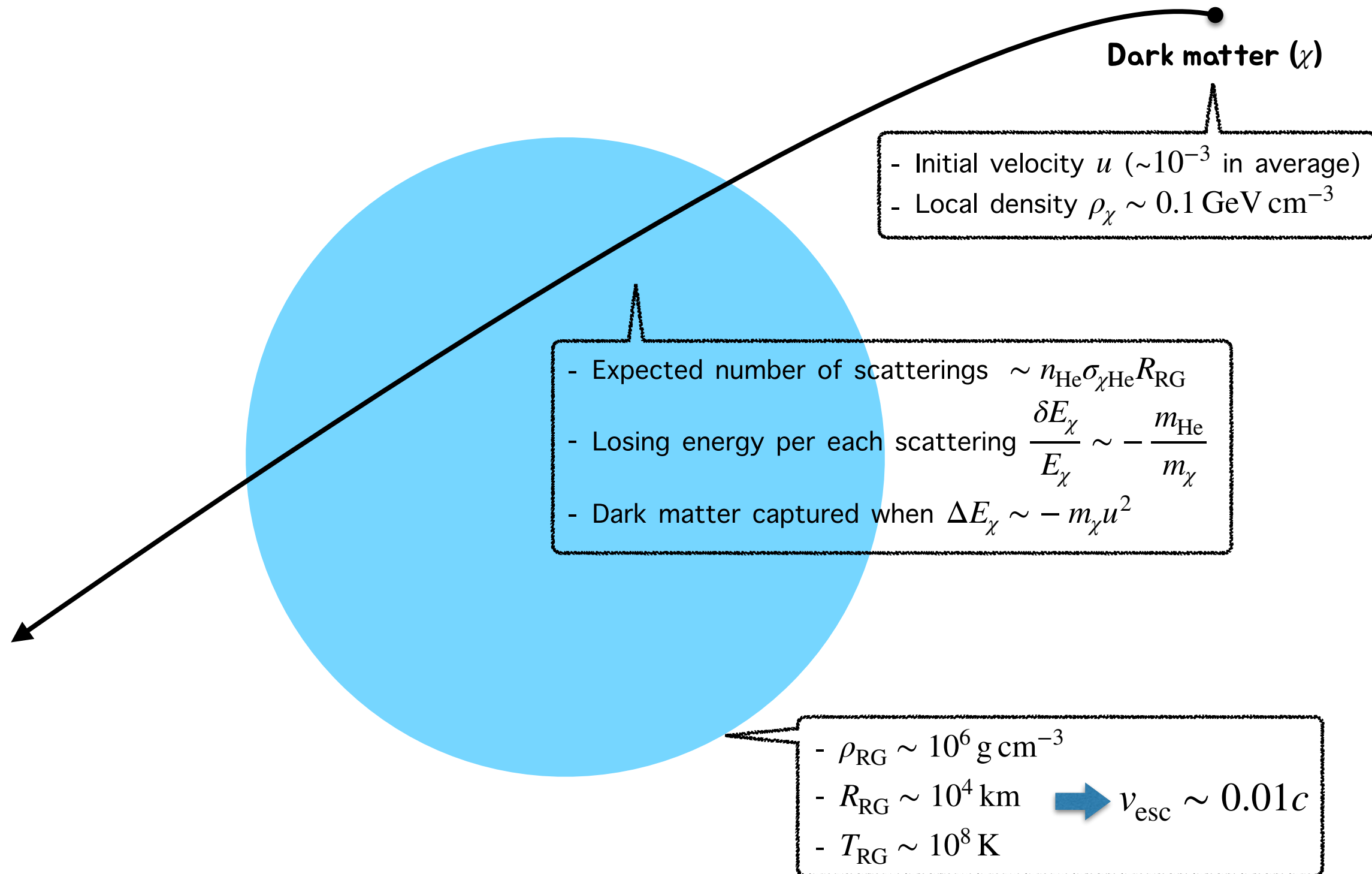
Heating?

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

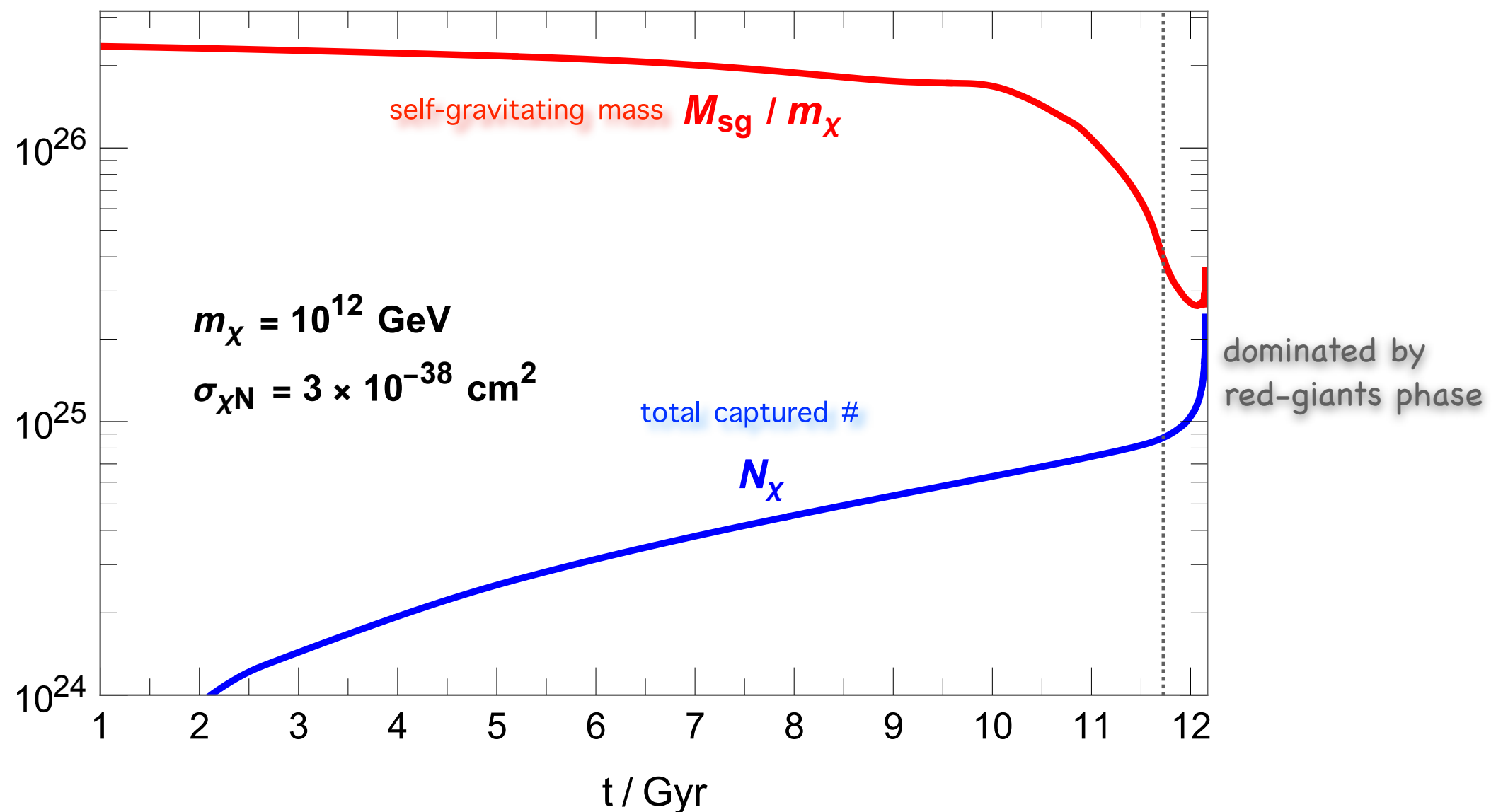
Dark Matter Capture

- Elastic Scattering w/ nuclei (DM kinetic energy loss)
 - ✓ 1) capturing, 2) ingress, 3) thermalization, 4) collapse

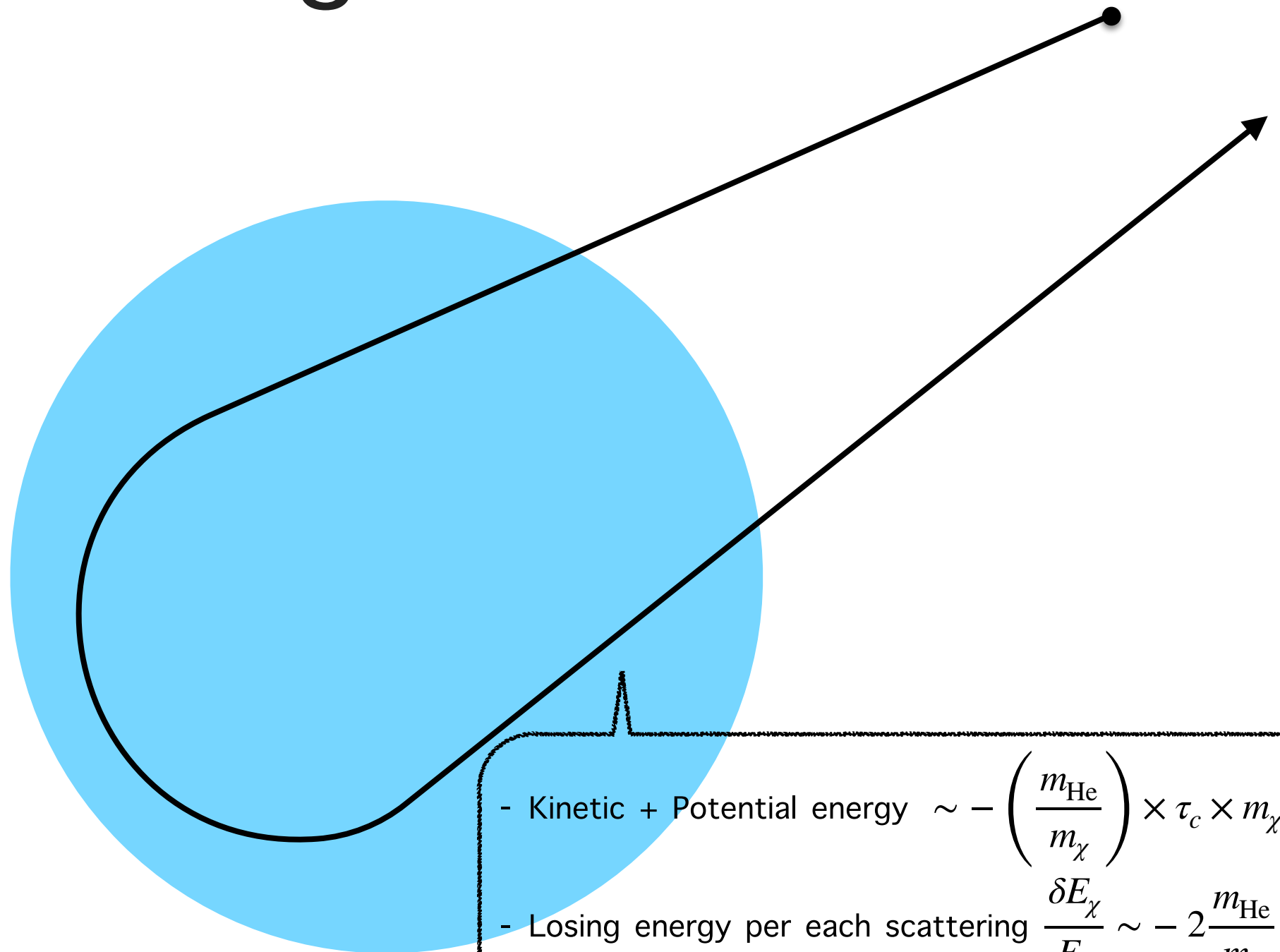
Dark Matter Capture



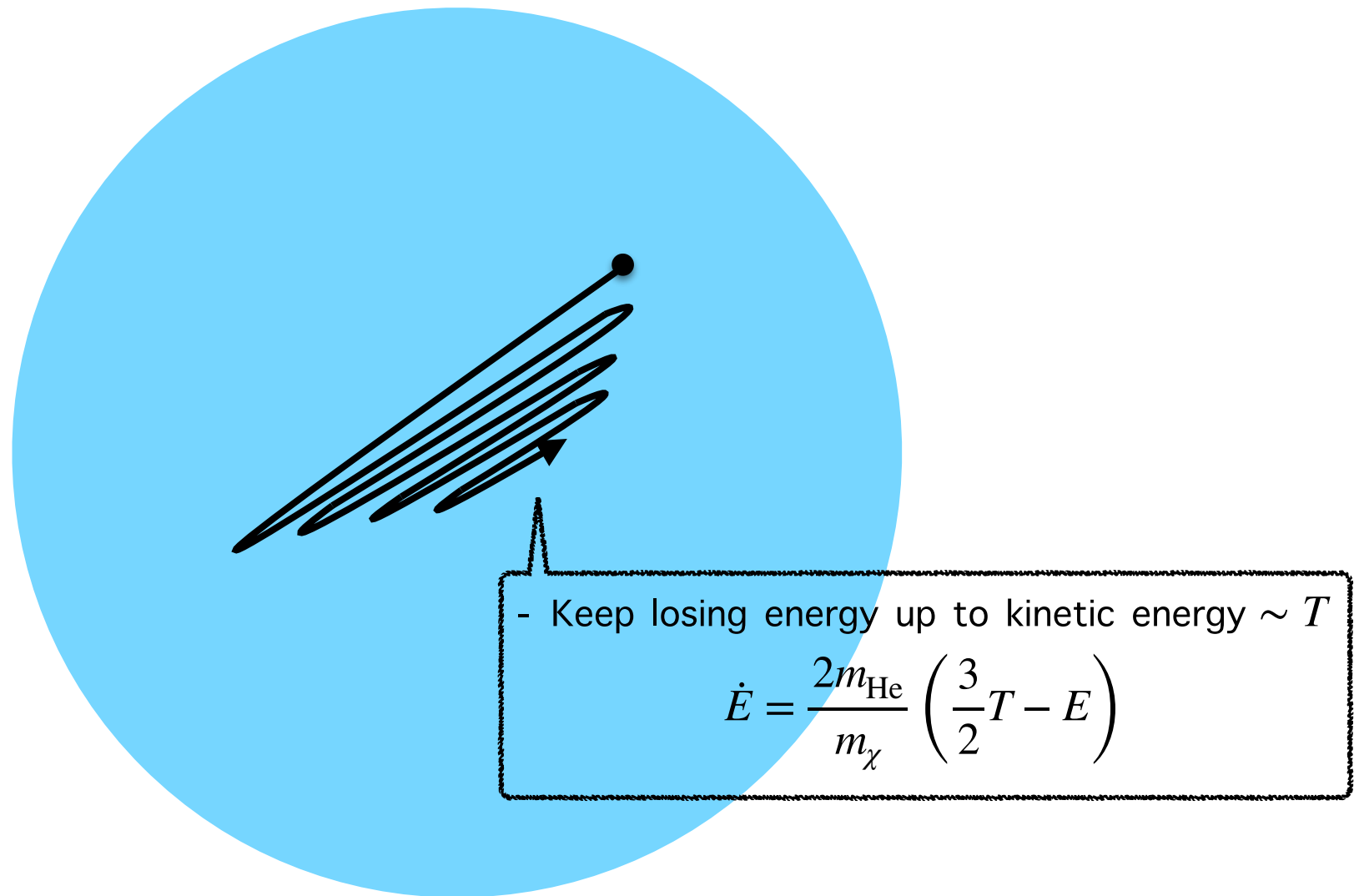
DM Capture in Time



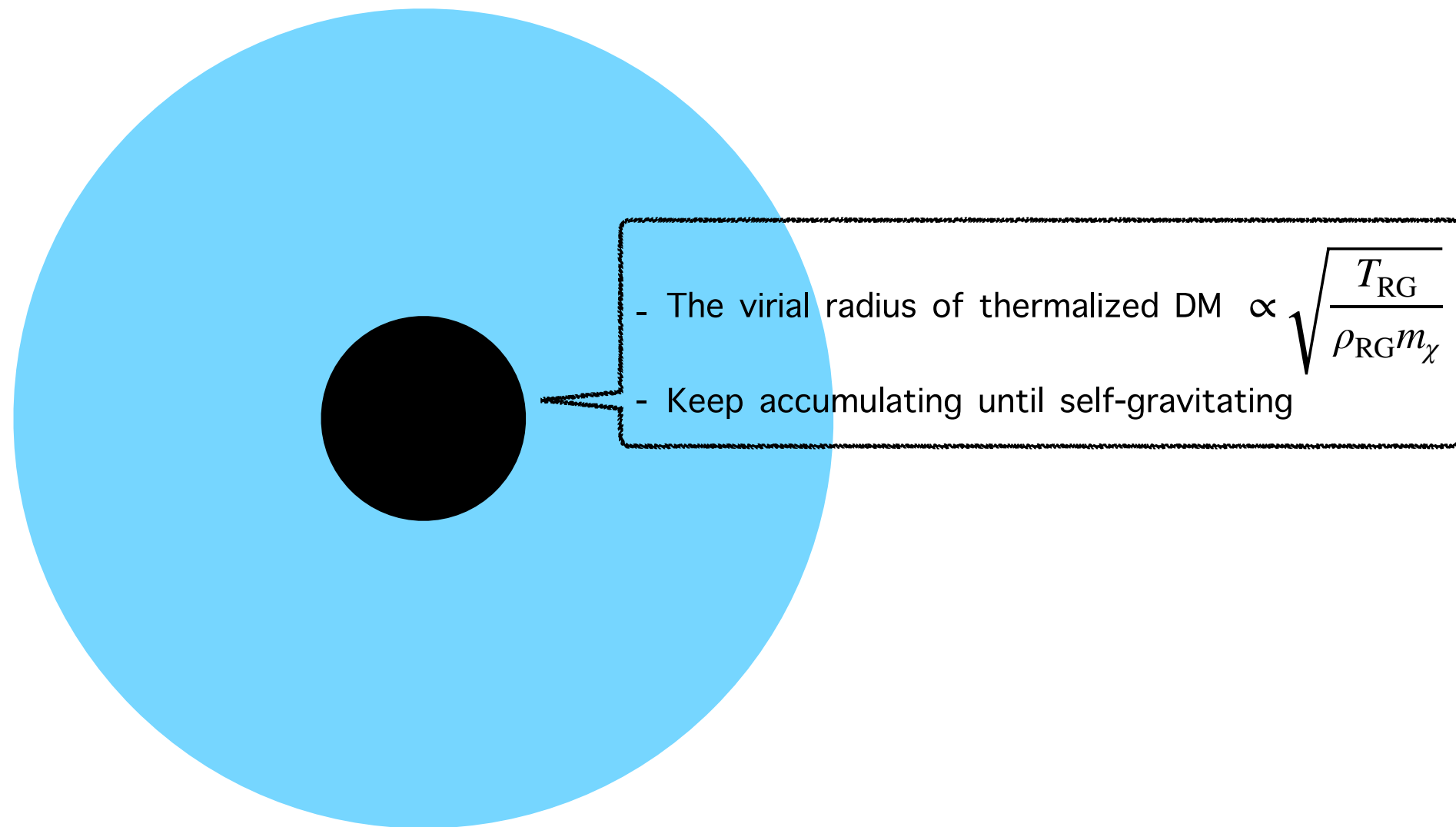
Ingress



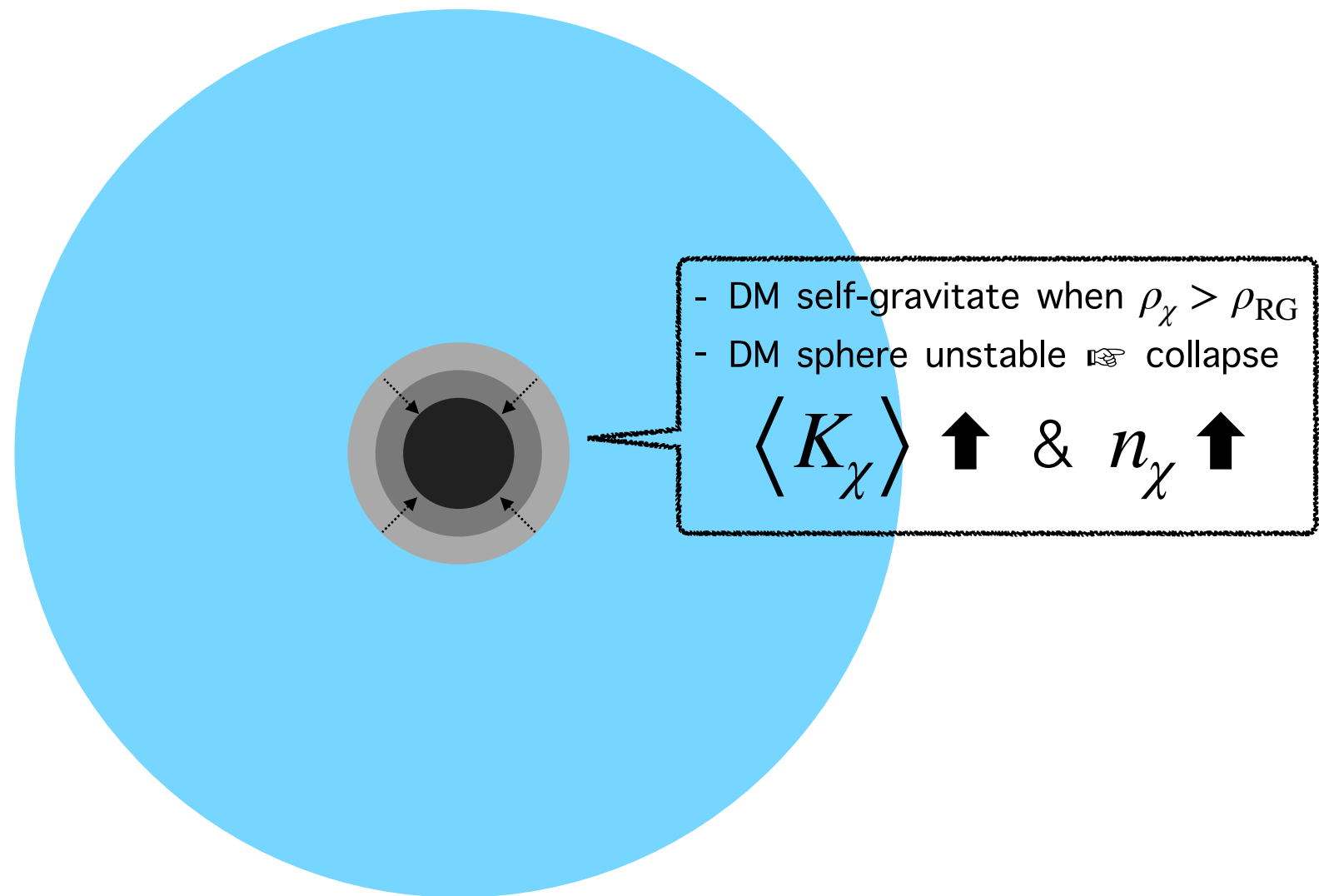
Thermalization



Thermalization



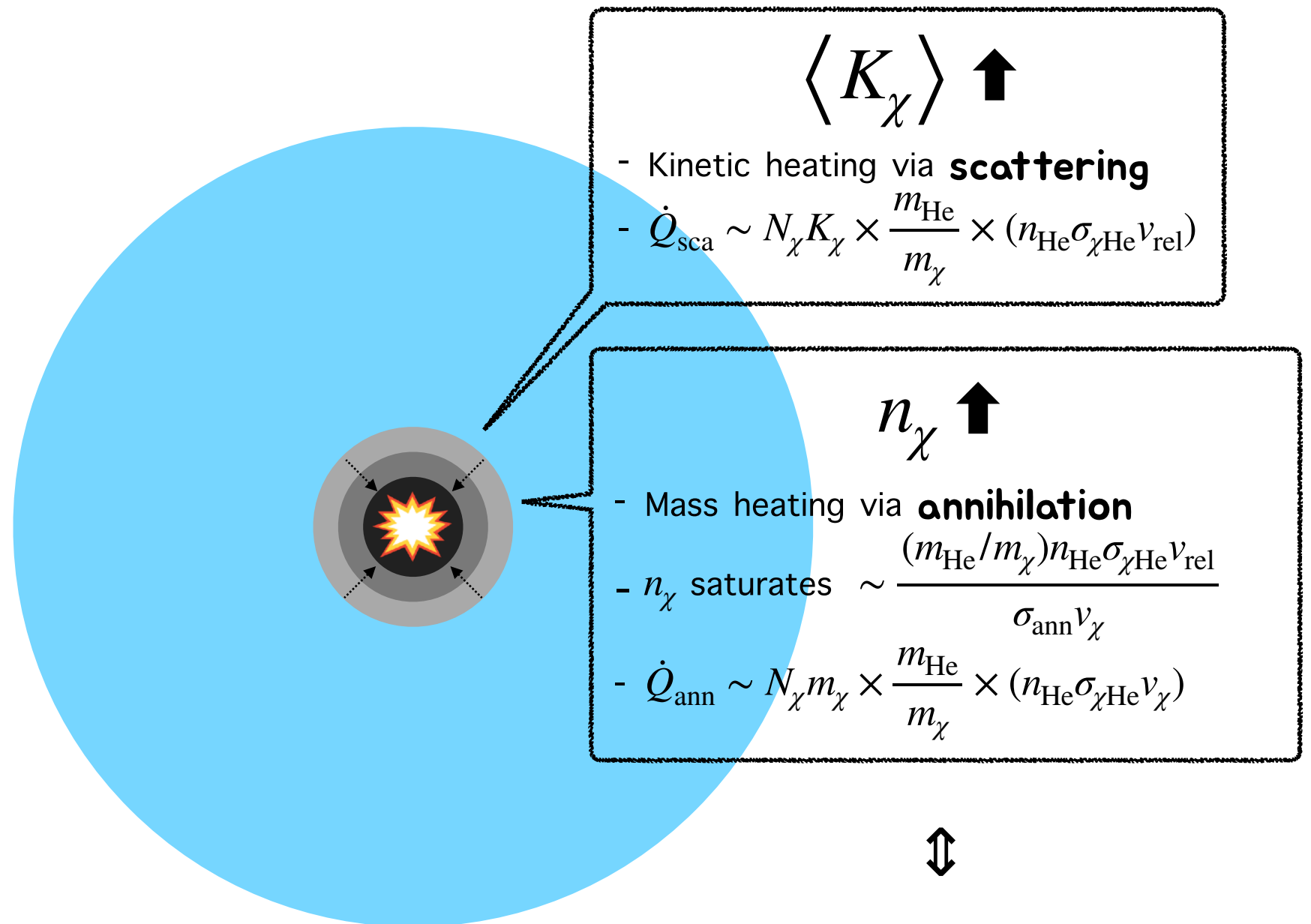
Gravitational Collapse



Dark Matter Heating

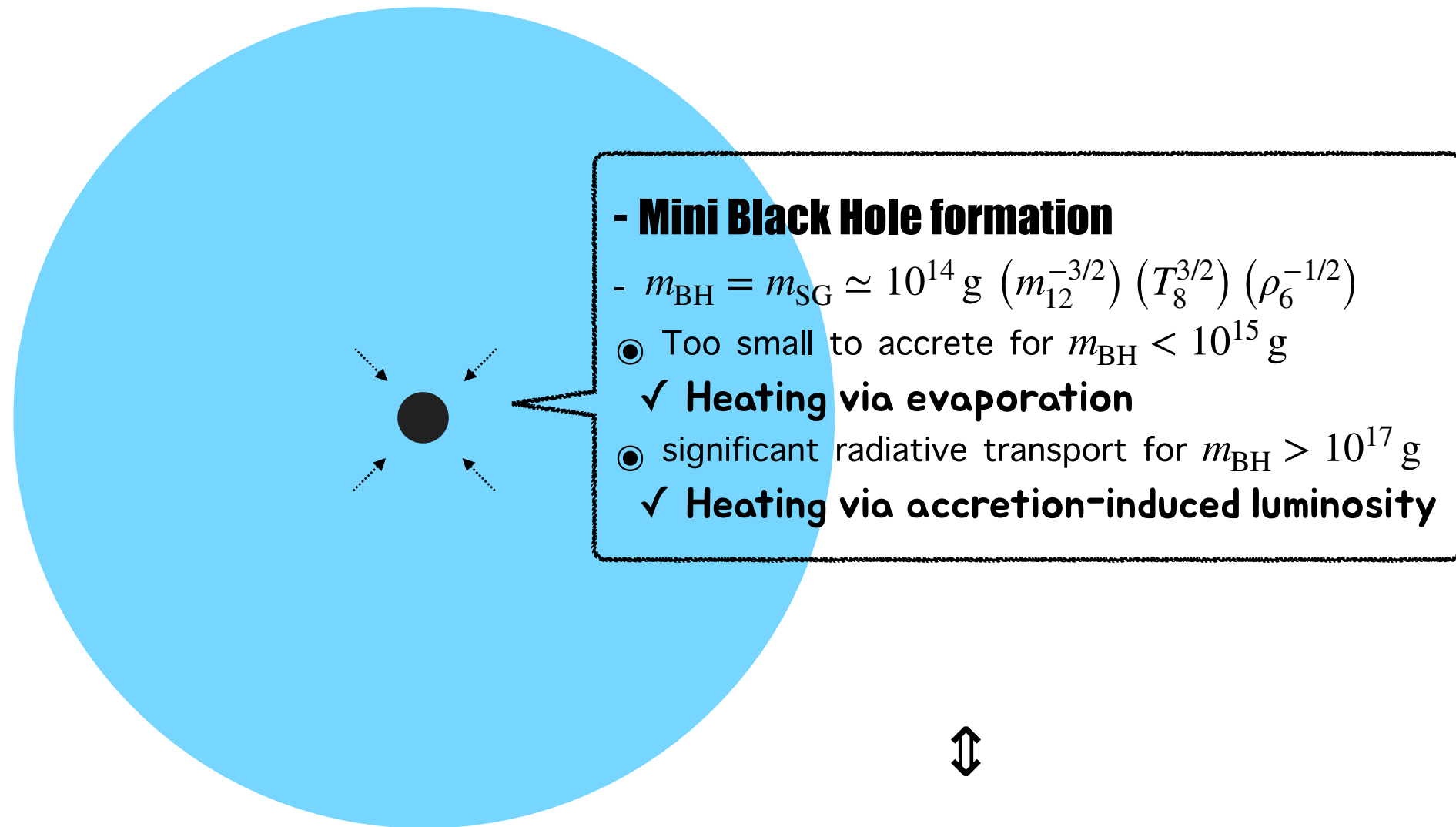
- Kinetic heating via elastic scatterings
- Mass heating via DM self annihilation
 - ✓ Later turned on for the heavy regime
- DM-induced Black Hole
 - ✓ Evaporation & radiative transportation from accretion

Dark Matter Heating



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

DM-induced mini Black Hole



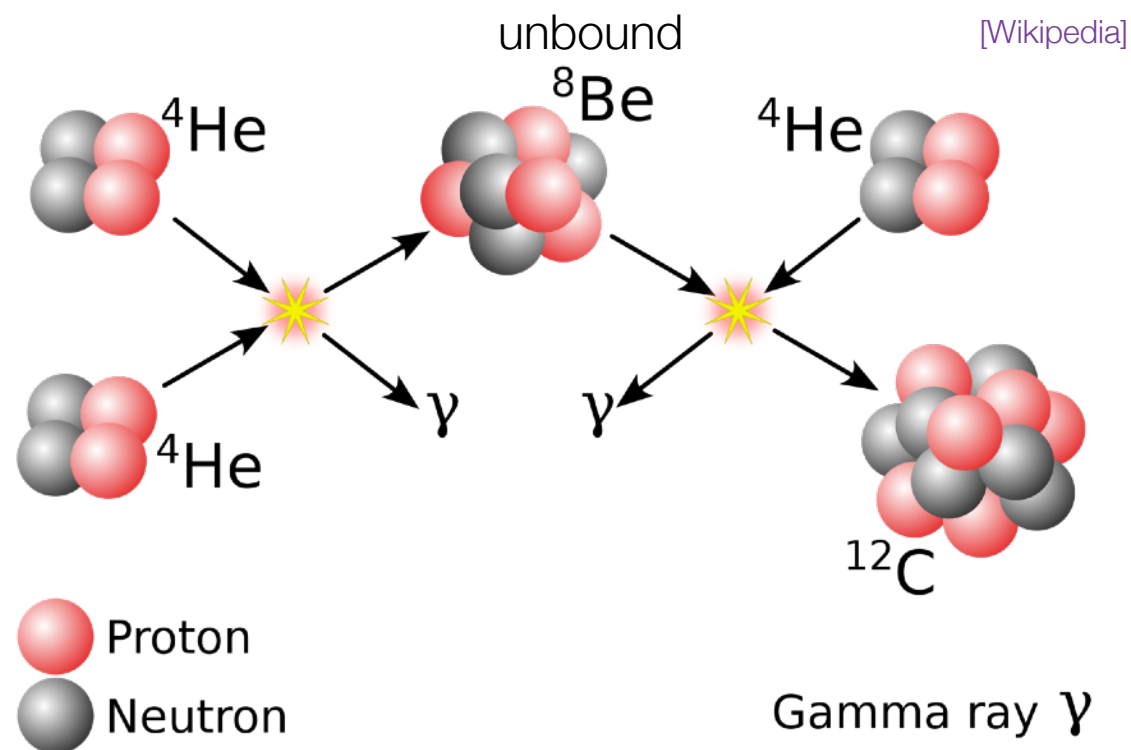
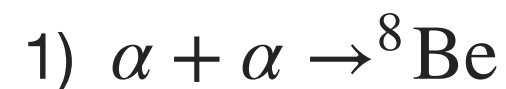
↕

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

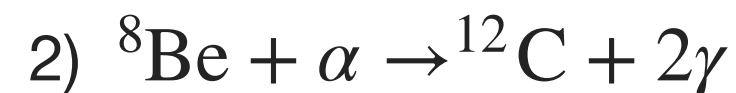
Trigger Mass for Helium Ignition

- Triple-alpha process: ${}^4\text{He} + {}^4\text{He} \rightarrow {}^8\text{Be} (+{}^4\text{He}) \rightarrow {}^{12}\text{C} + 2\gamma$
- Thermal diffusion (cooling) VS Nuclear reaction (burning)
 - ✓ Threshold burning width  Trigger mass

Triple- α process



- ^8Be is very unstable
- But, an equilibrium abundance of ^8Be



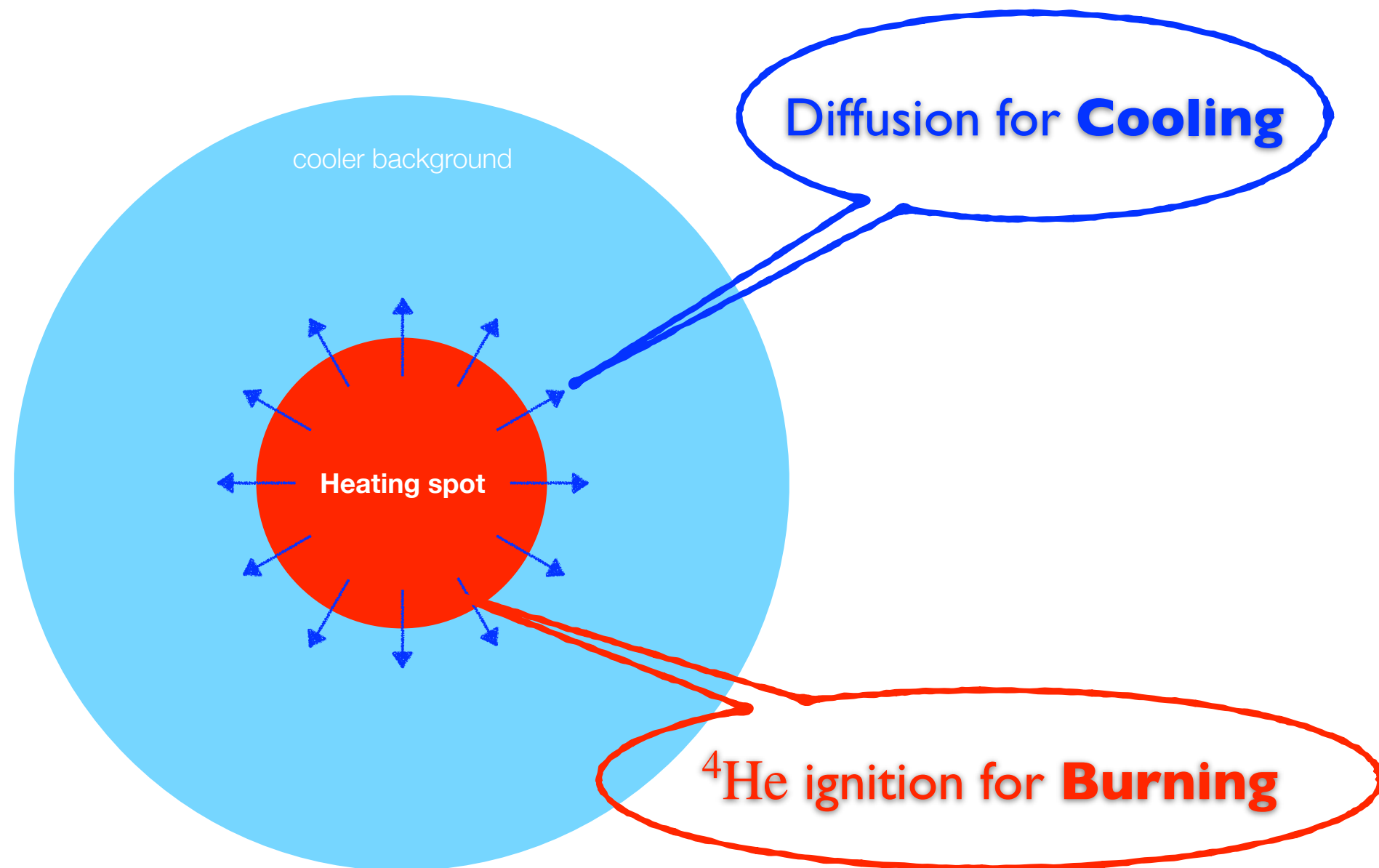
- Resonant reaction

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

3α reaction rate

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

Burning VS Diffusion



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

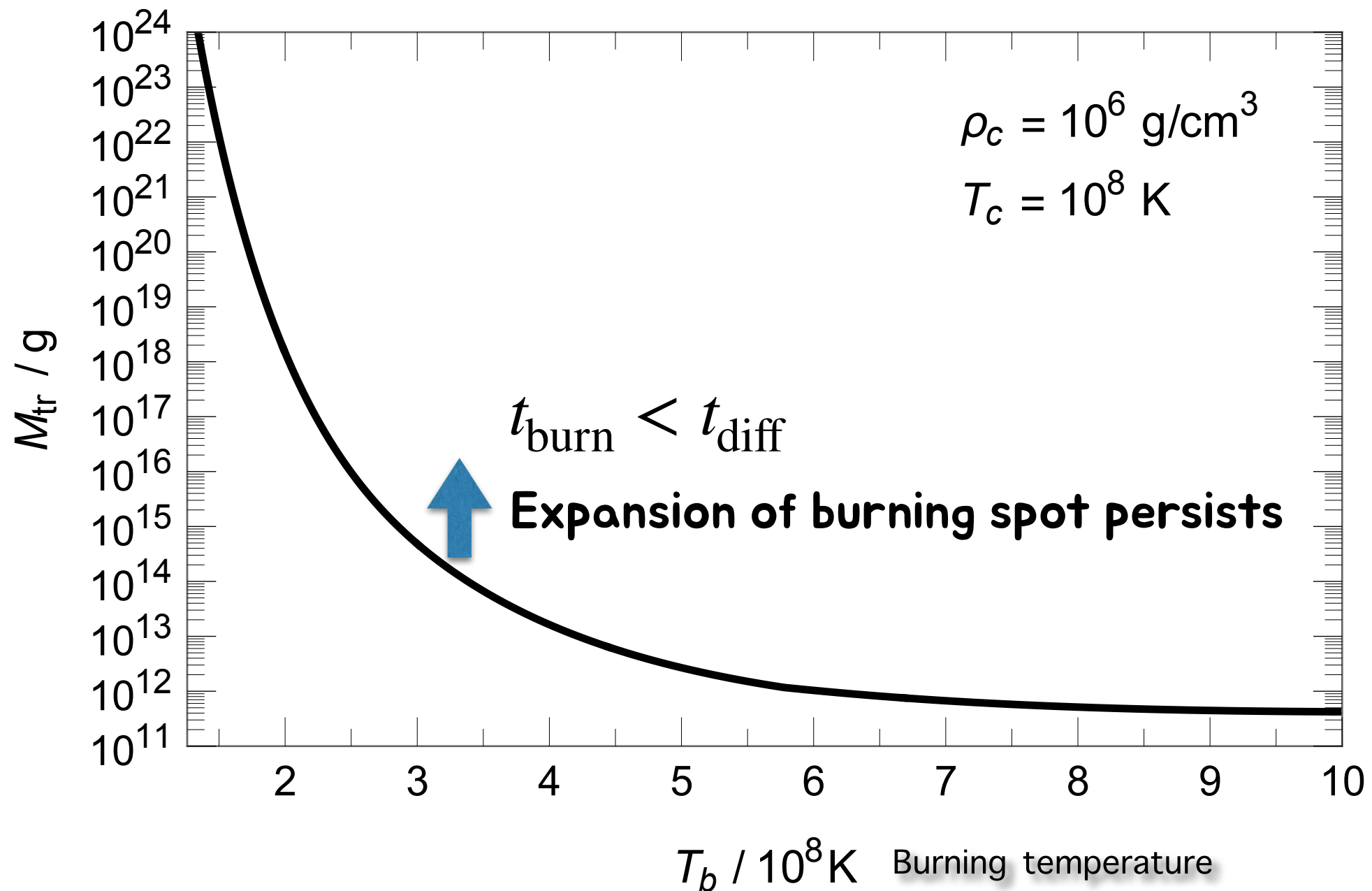
Width of heating spot

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

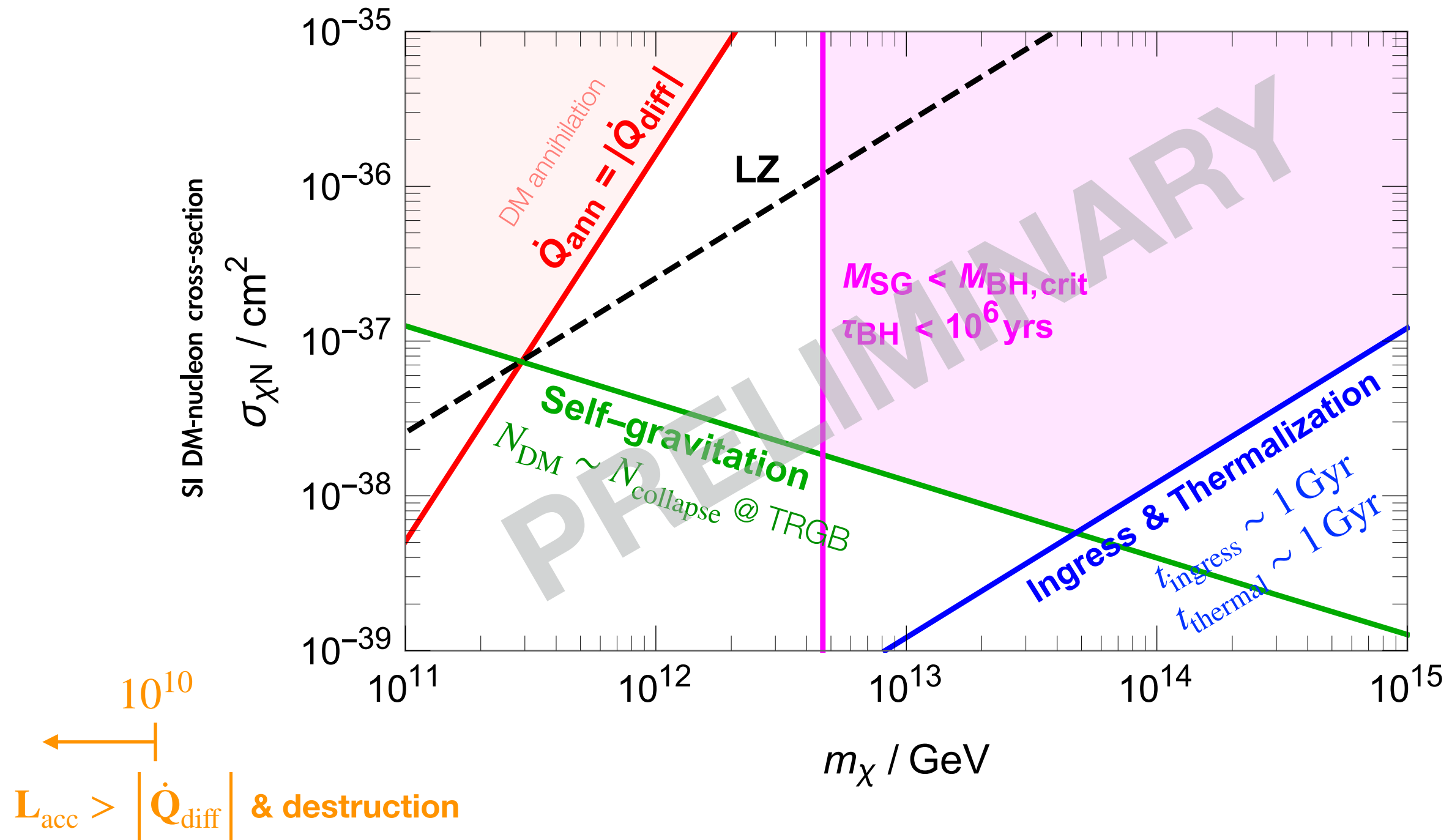
Thermal diffusivity
 $\sim \lambda \times v_c$

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

Trigger Mass for Helium Ignition



Constraints on Heavy DM



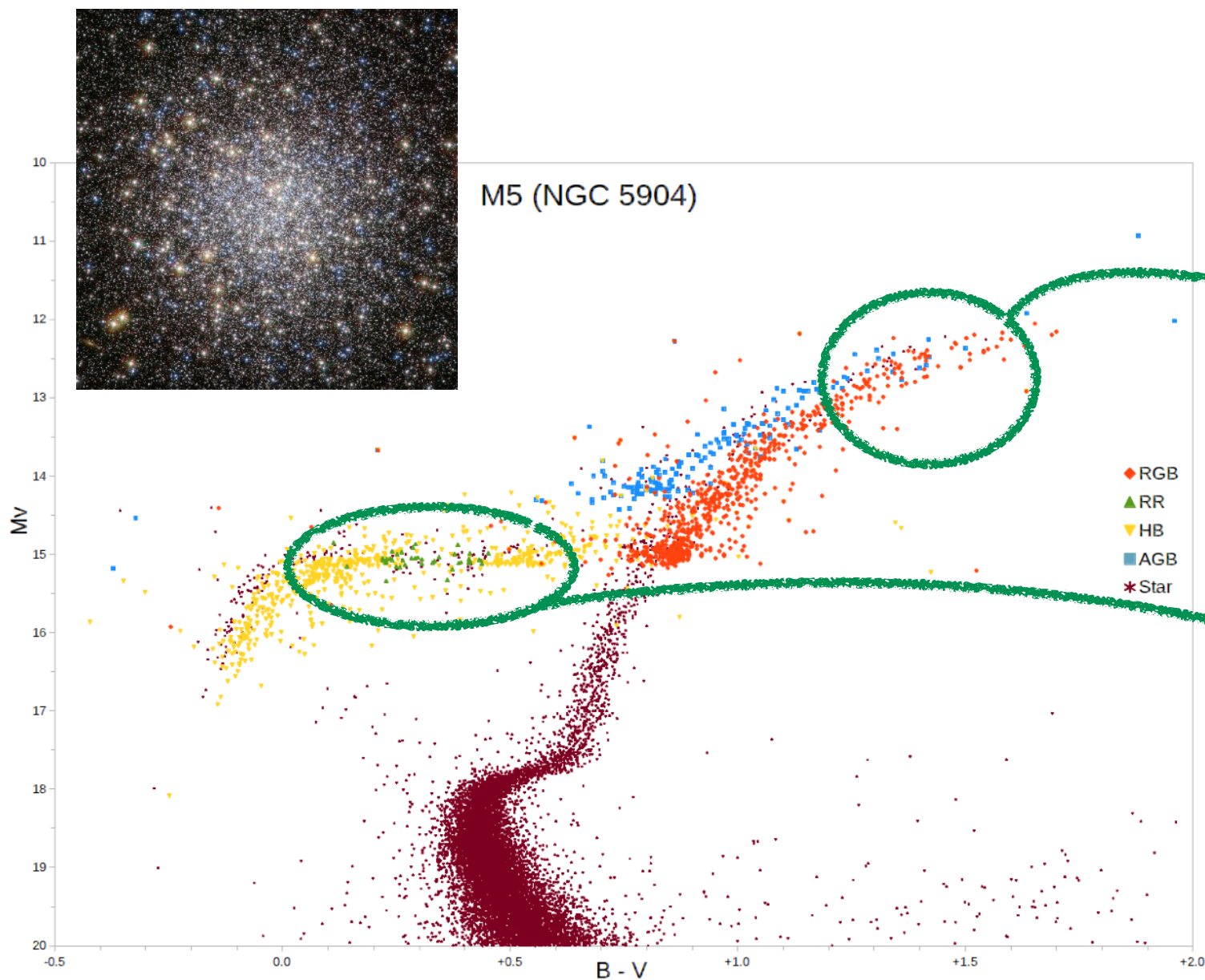
Conclusions & Discussion

- 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 & accretion-induction

Thank you!

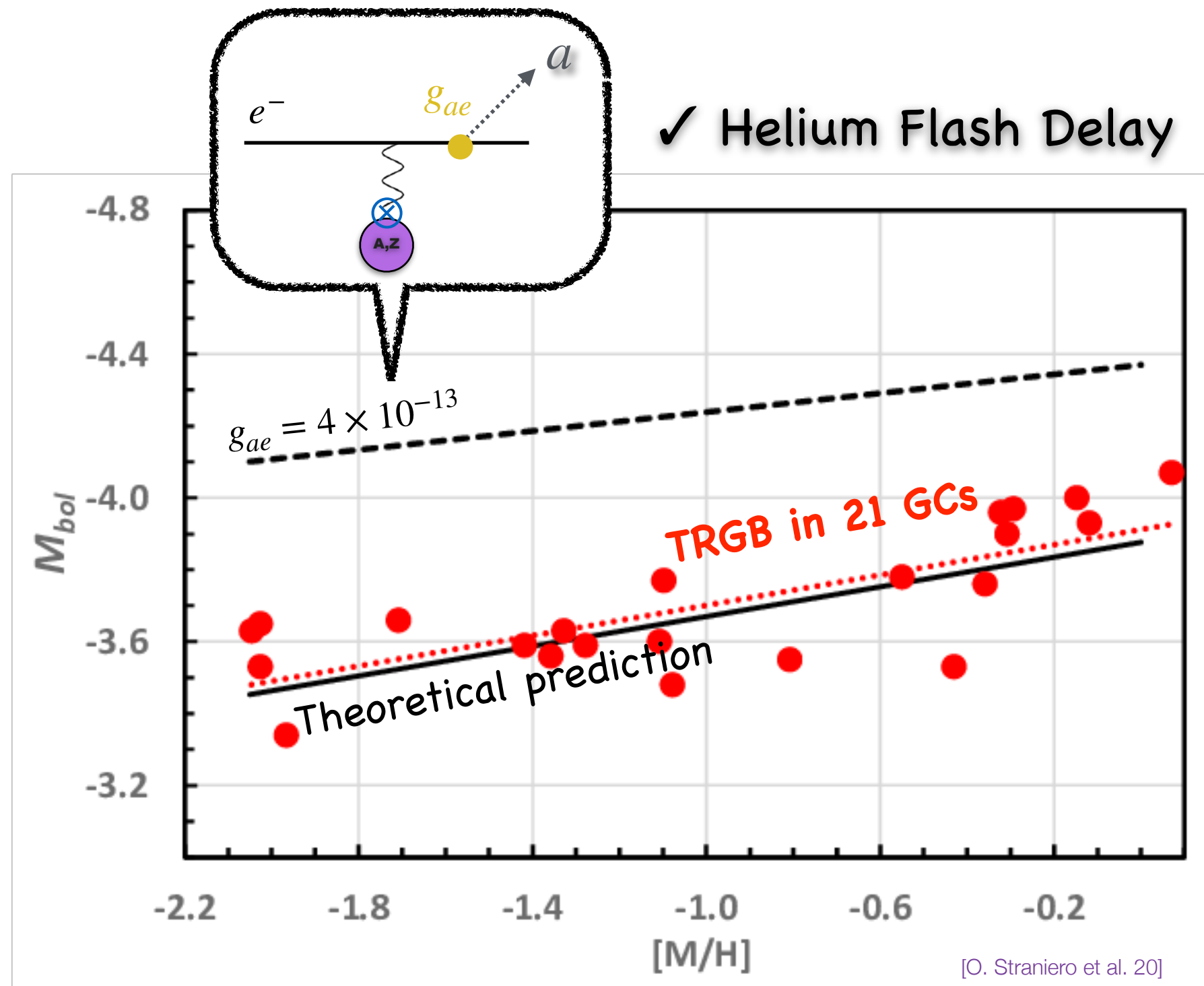
Back up

Observables to Probe BSM?



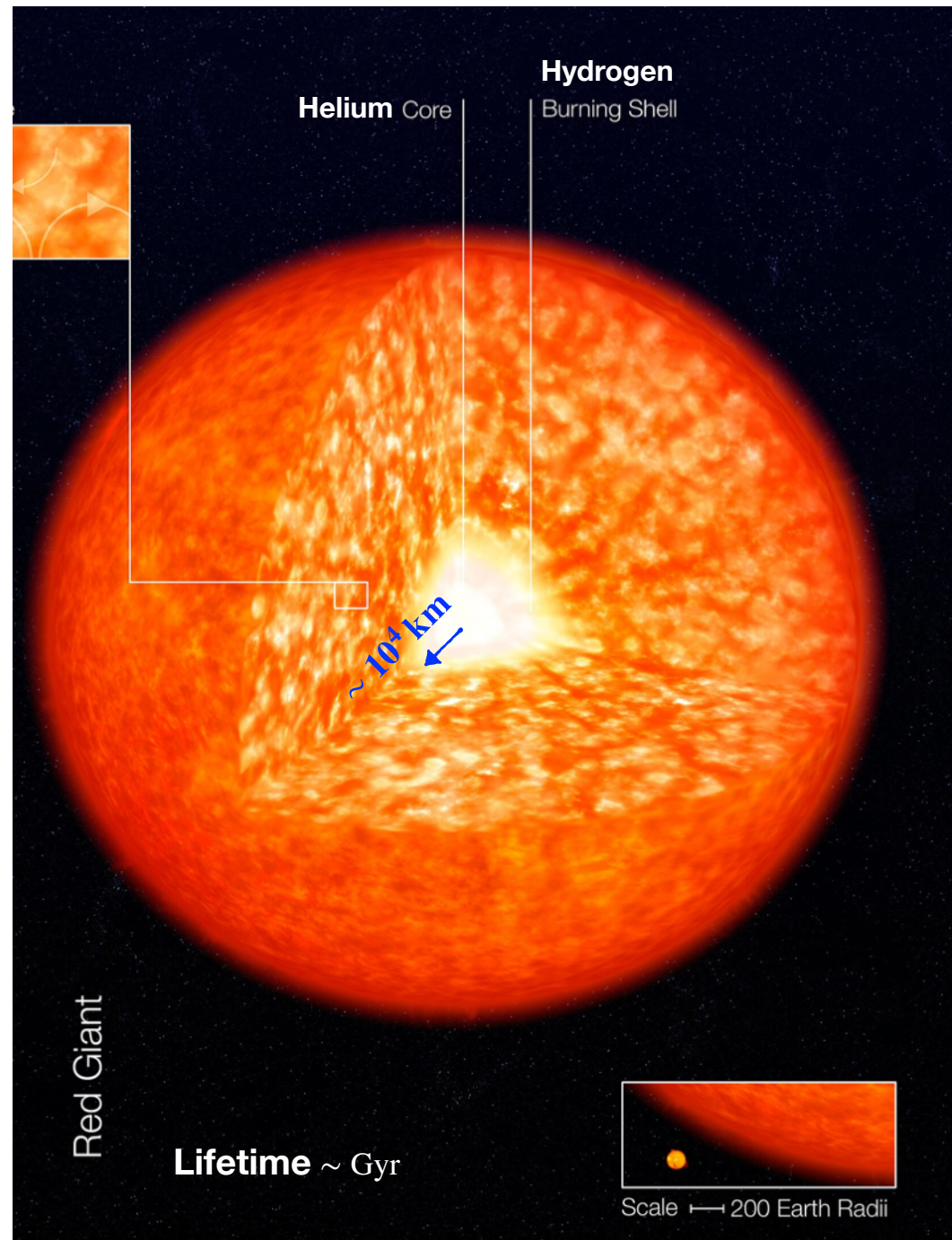
- Helium ignition in red-giant phase
 - brightness at the tip of a red-giant branch
 - determined by core mass at helium flash
- Lifetime of horizontal-branch stars
 - duration of helium burning
 - the number ratio of HB vs. RGB

Core Mass Increase by Cooling



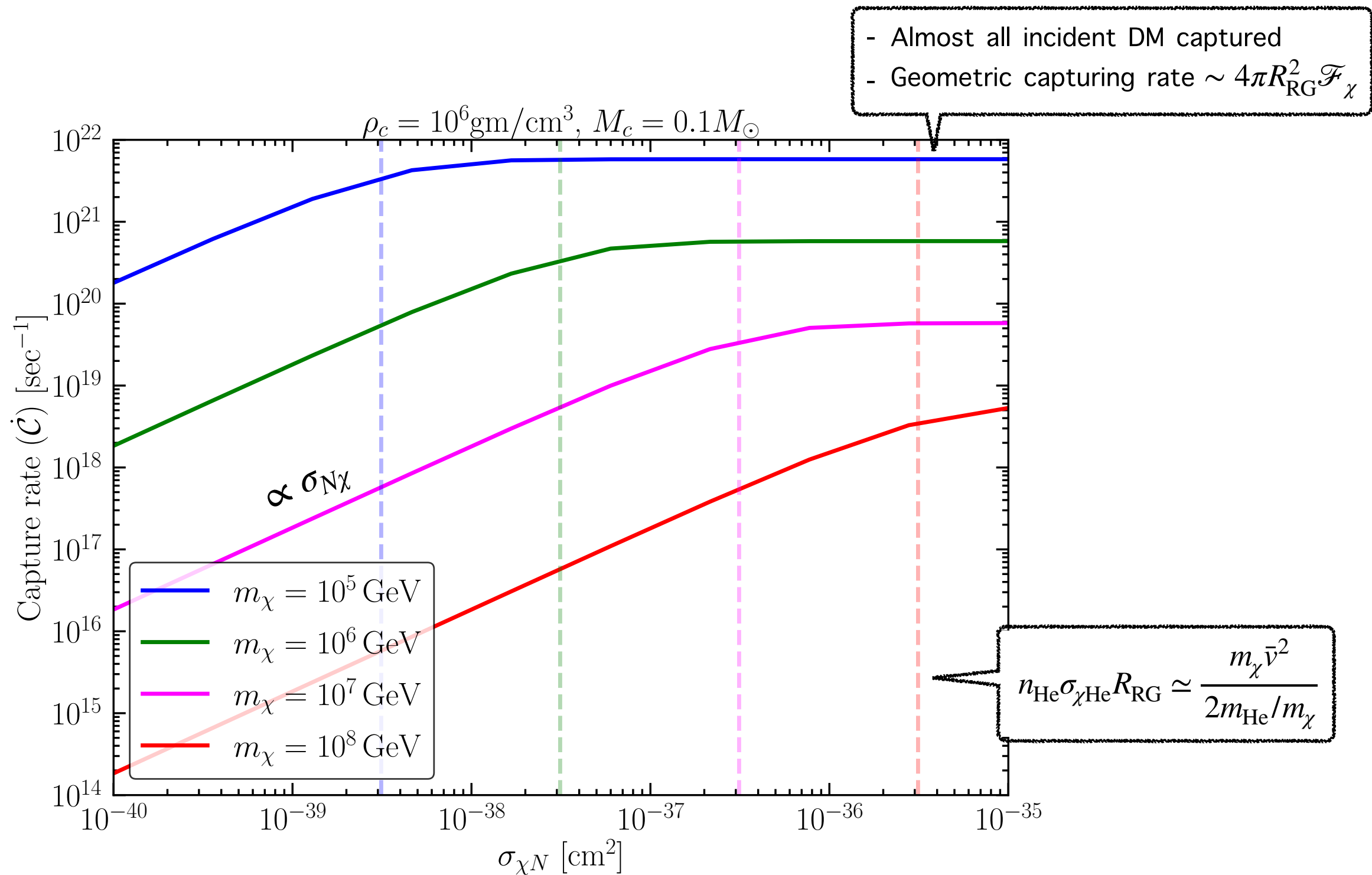
✓ Helium Flash Delay $\Rightarrow L_{TRGB} \uparrow$

Red Giant Branch



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

Capture Rate



Late-onset Annihilation

⊙ $\sigma_{\text{ann}} v_{\chi} \equiv \frac{\alpha_{\chi}^2}{m_{\chi}^2}$ parametrized in context of *the unitarity limit*

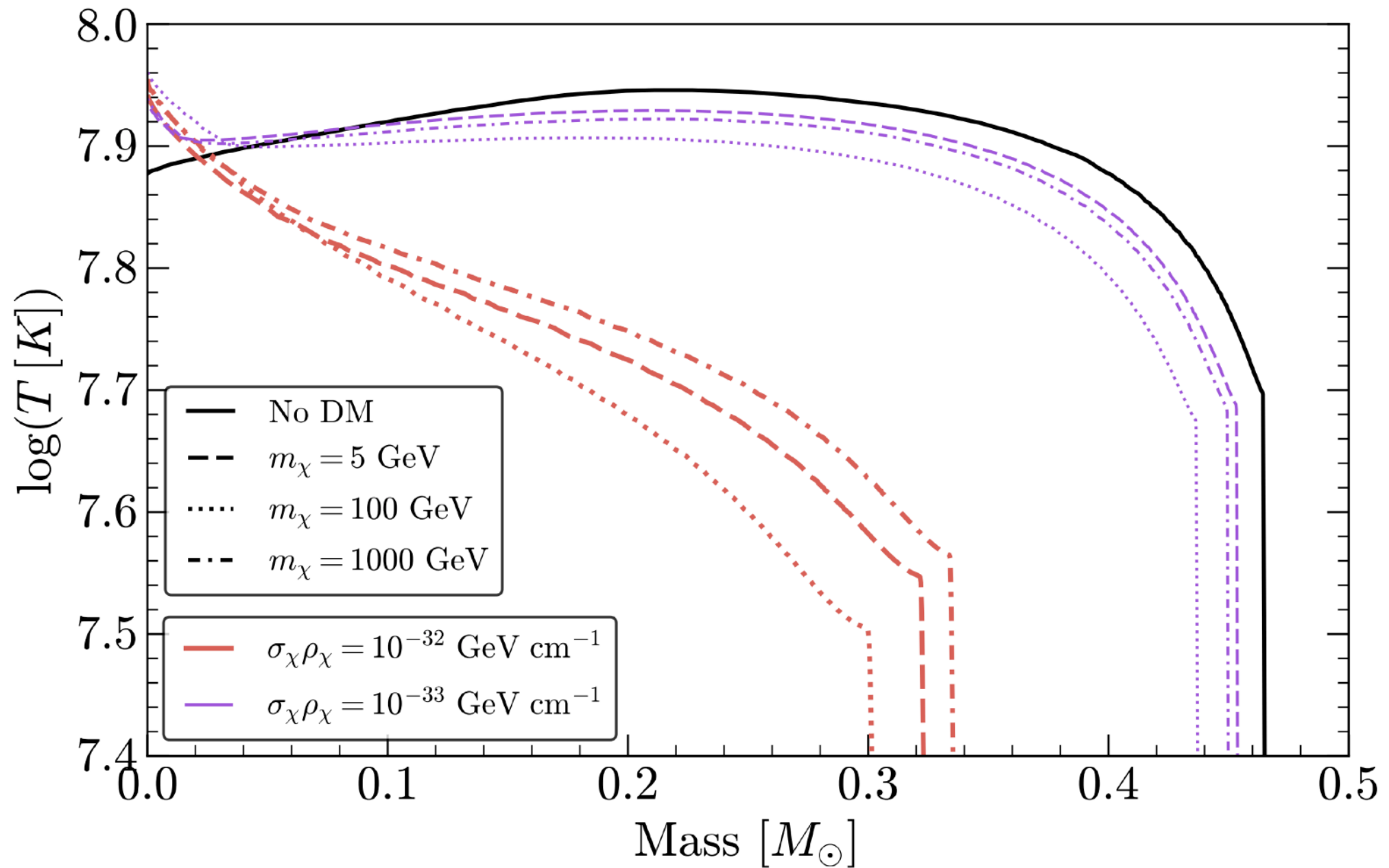
s-wave & α_{χ} : DM-SM coupling

⊙ For a localized heating to trigger runaway helium burning

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

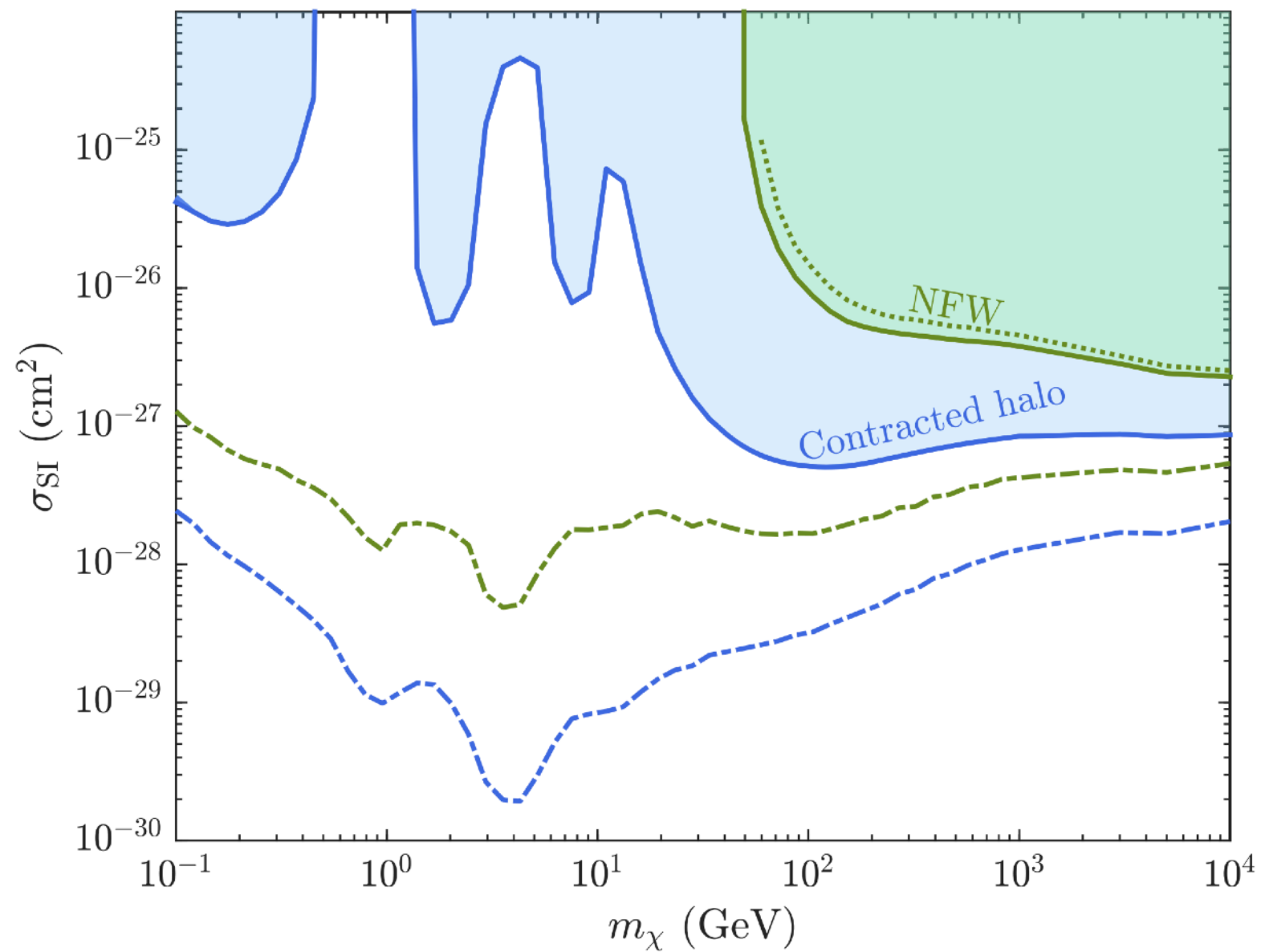
$$t_{\text{ann}} \sim \frac{1}{(\rho_{\chi}/m_{\chi})\sigma_{\text{ann}} v_{\chi}} > 1 \text{ Gyr} \rightarrow m_{\chi} > 10^9 \text{ GeV} \left(\frac{\rho}{10^6 \text{ g/cm}^3} \right)^{1/3} \left(\frac{\alpha_{\chi}}{0.1} \right)^{2/3}$$

Other Mass Regime?



[J. Lopes, I. Lopes, 2021]

Other Mass Regime?



[H. Hong, A. Vincent, 2024]