

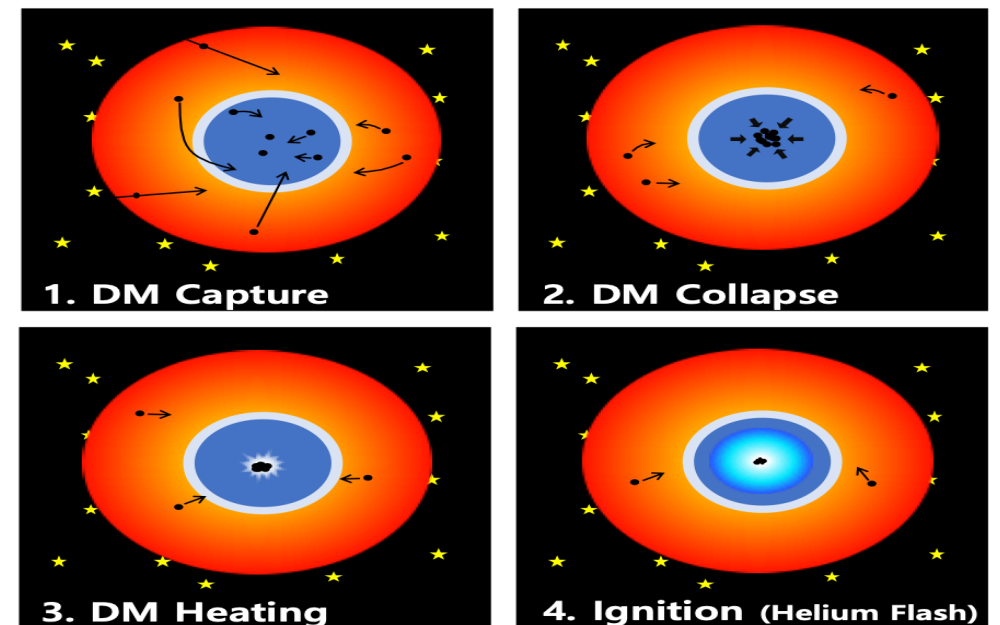
Probing Heavy Dark Matter in Red Giants

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Outline

- 01 Introduction
 - Stellar evolution to probe BSM
 - ✓ Cooling argument w/o DM
 - ✓ Heating w/ DM capture
- 02 Helium ignition
 - Triple-alpha process
 - Trigger mass (burning VS diffusion)
- 03 Heavy DM capture & Its impact on TRGB
 - Capturing, Ingress, Thermalization - scattering
 - Collapse to heat up VS diffusion - annihilation
- 04 Conclusion



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

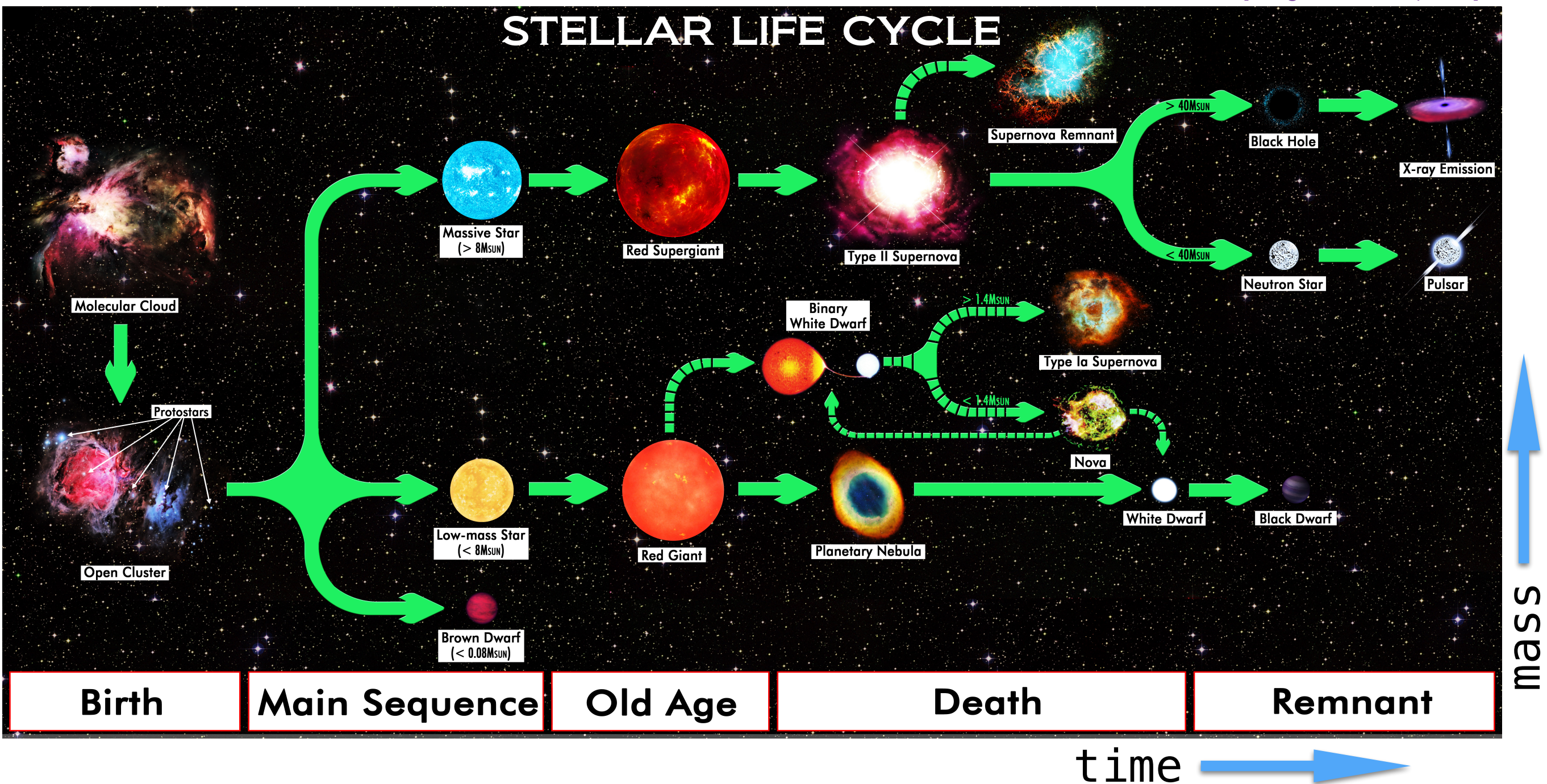
e.g. γ -ray spectral modulation which can be explained by axion-photon oscillations

- Stellar evolution

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

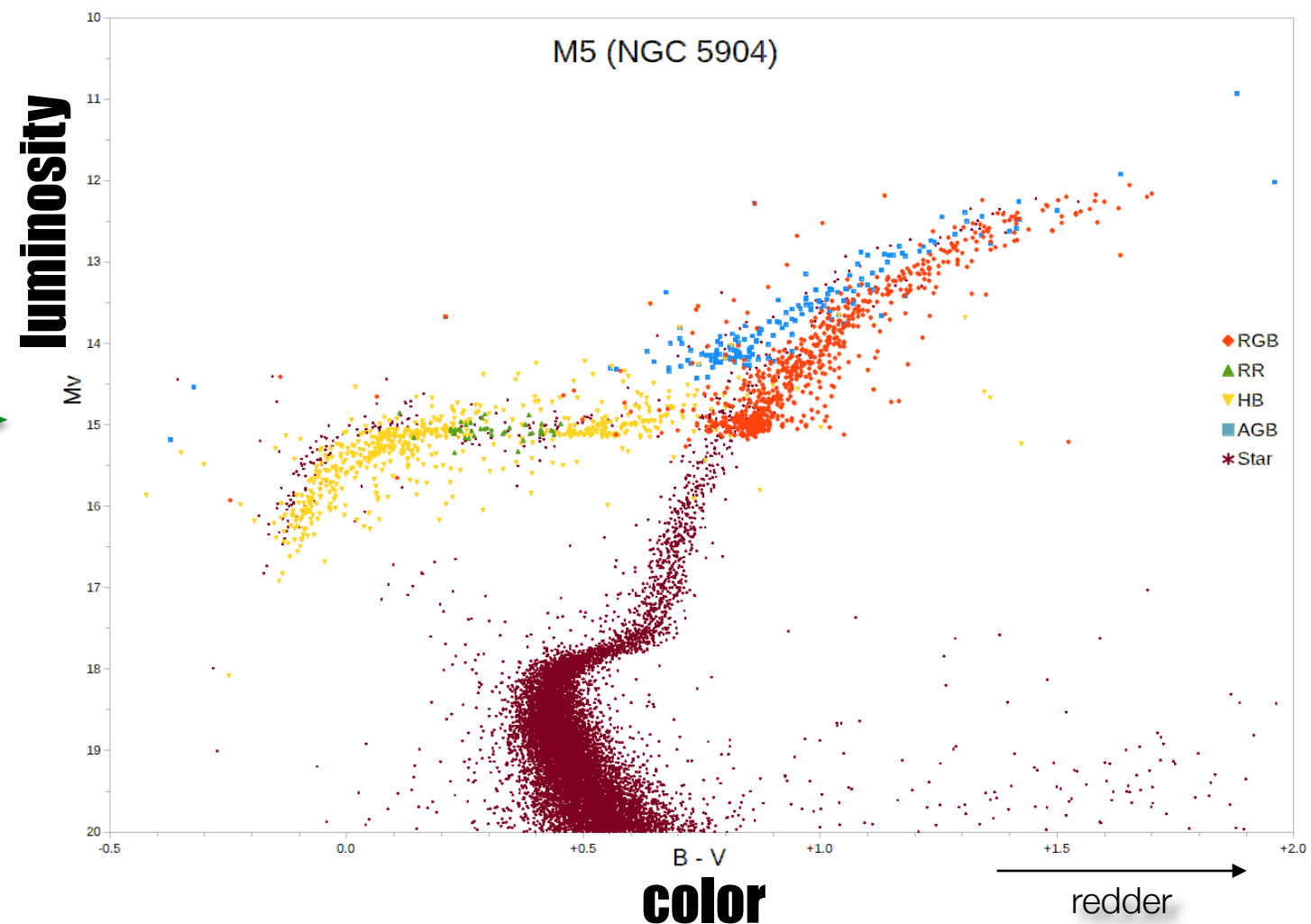
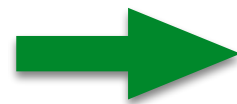
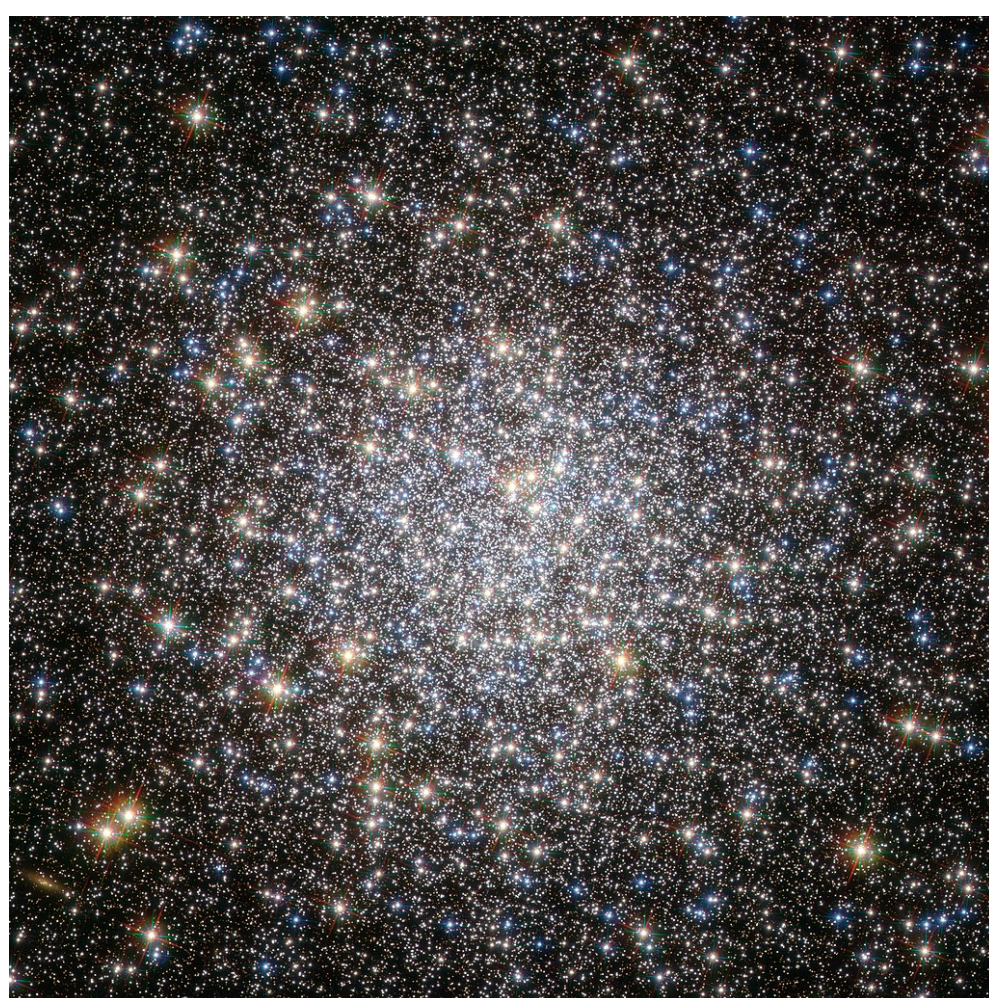
Stellar Evolution

[image from Wikipedia]

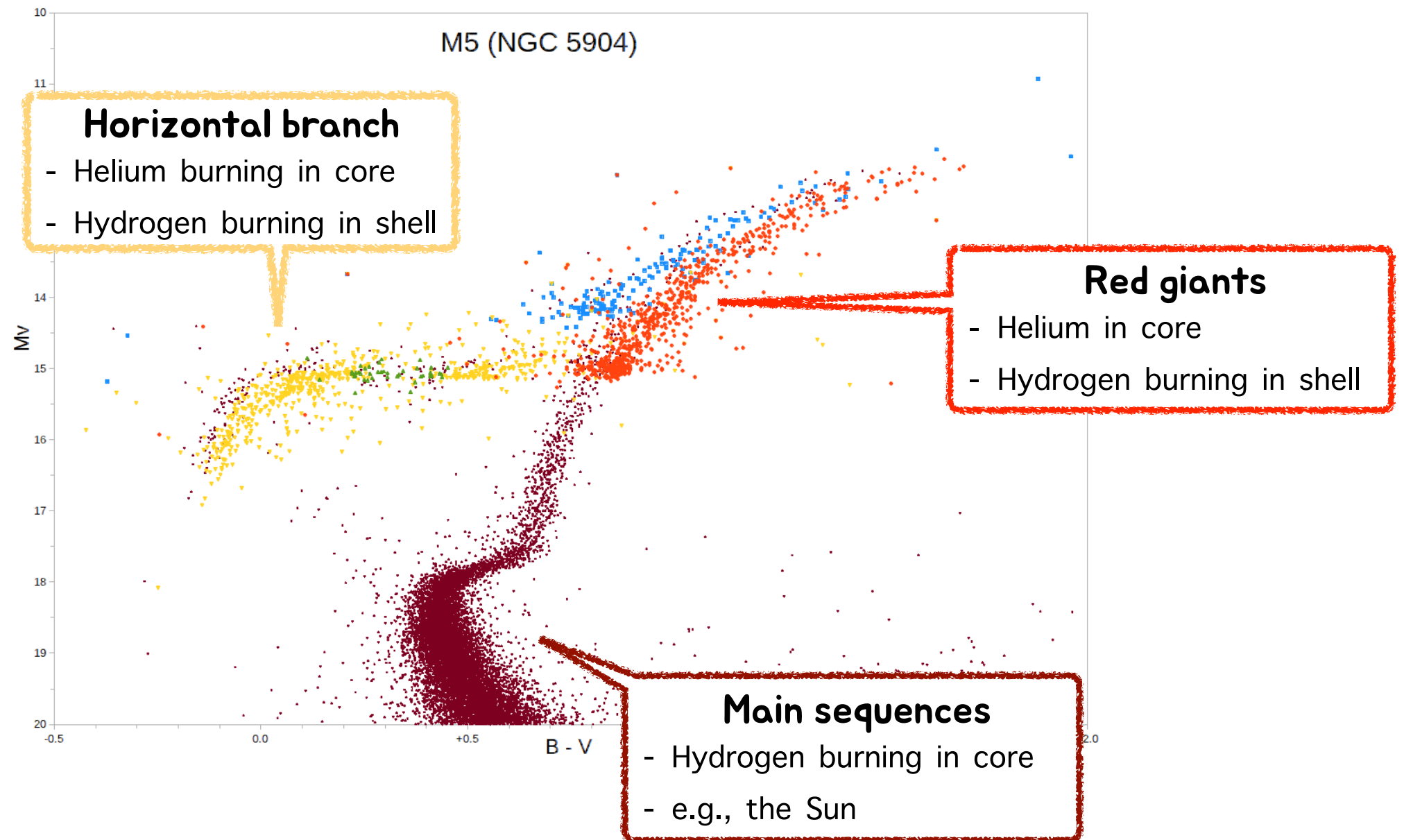


Globular Cluster

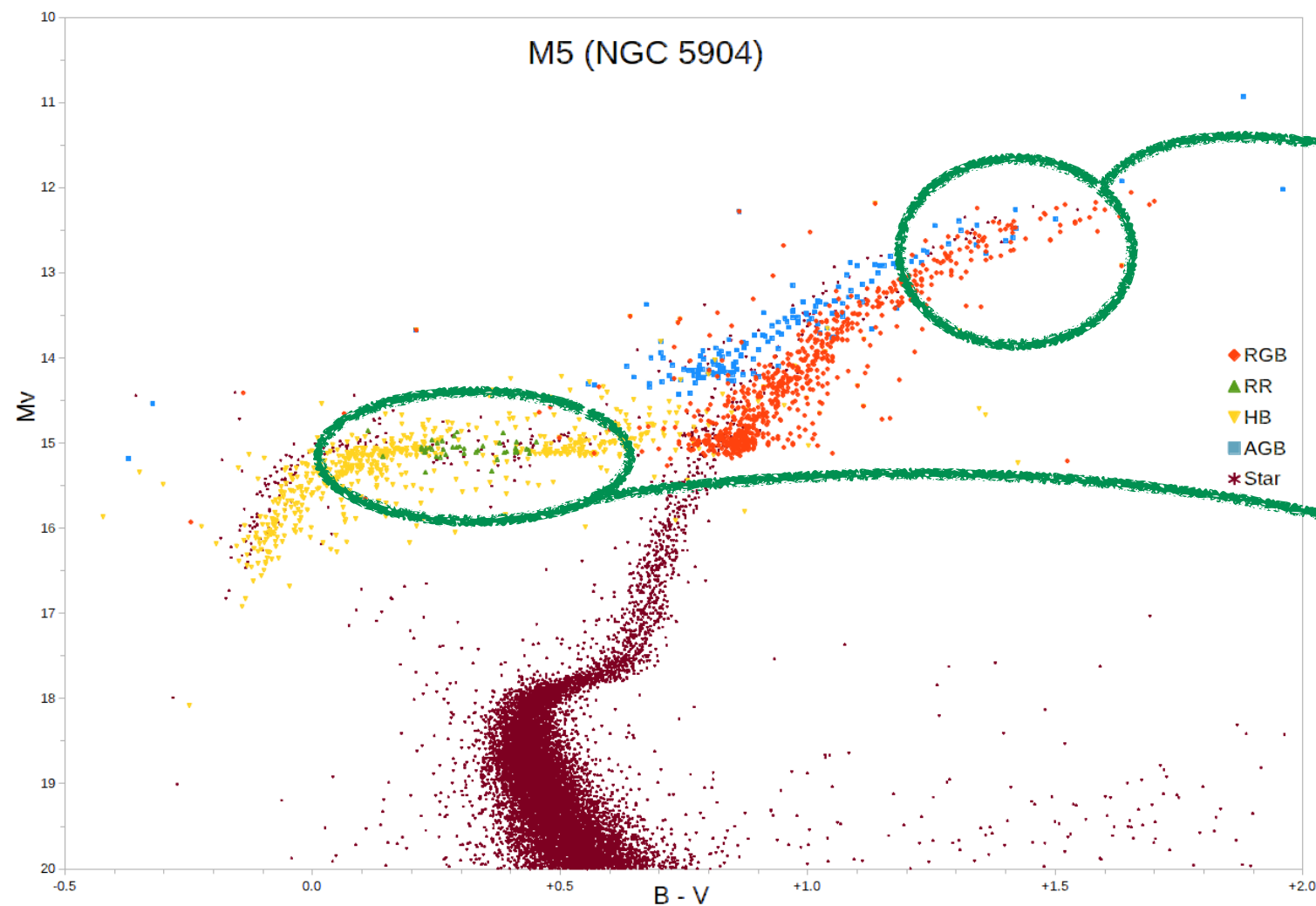
- Very clean laboratories for studies of stellar evolution
- Coeval and almost equal chemical compositions
- Only different initial mass



Stellar Evolutionary Phases

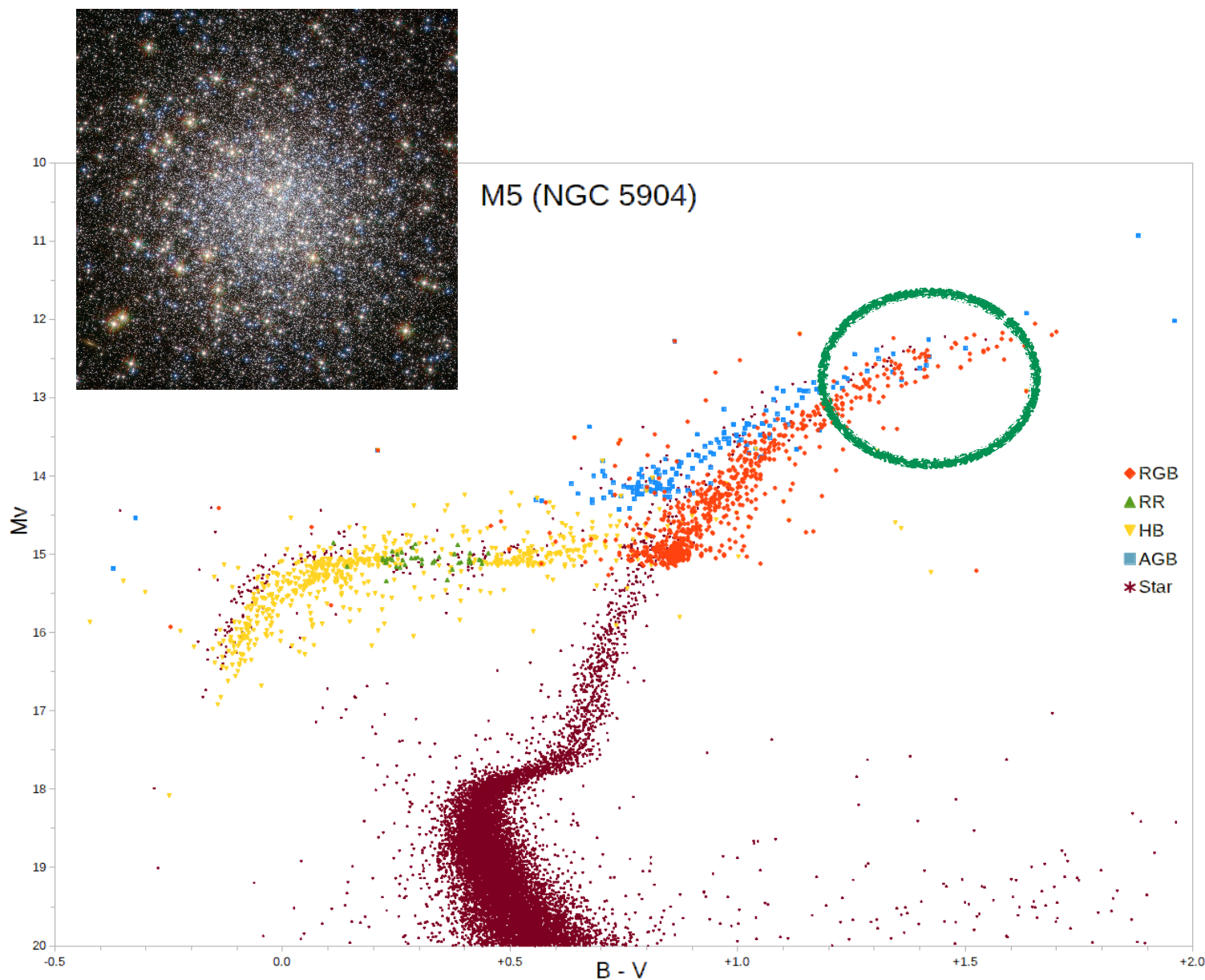


Observables to Probe BSM?



- 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

✓ Cooling

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

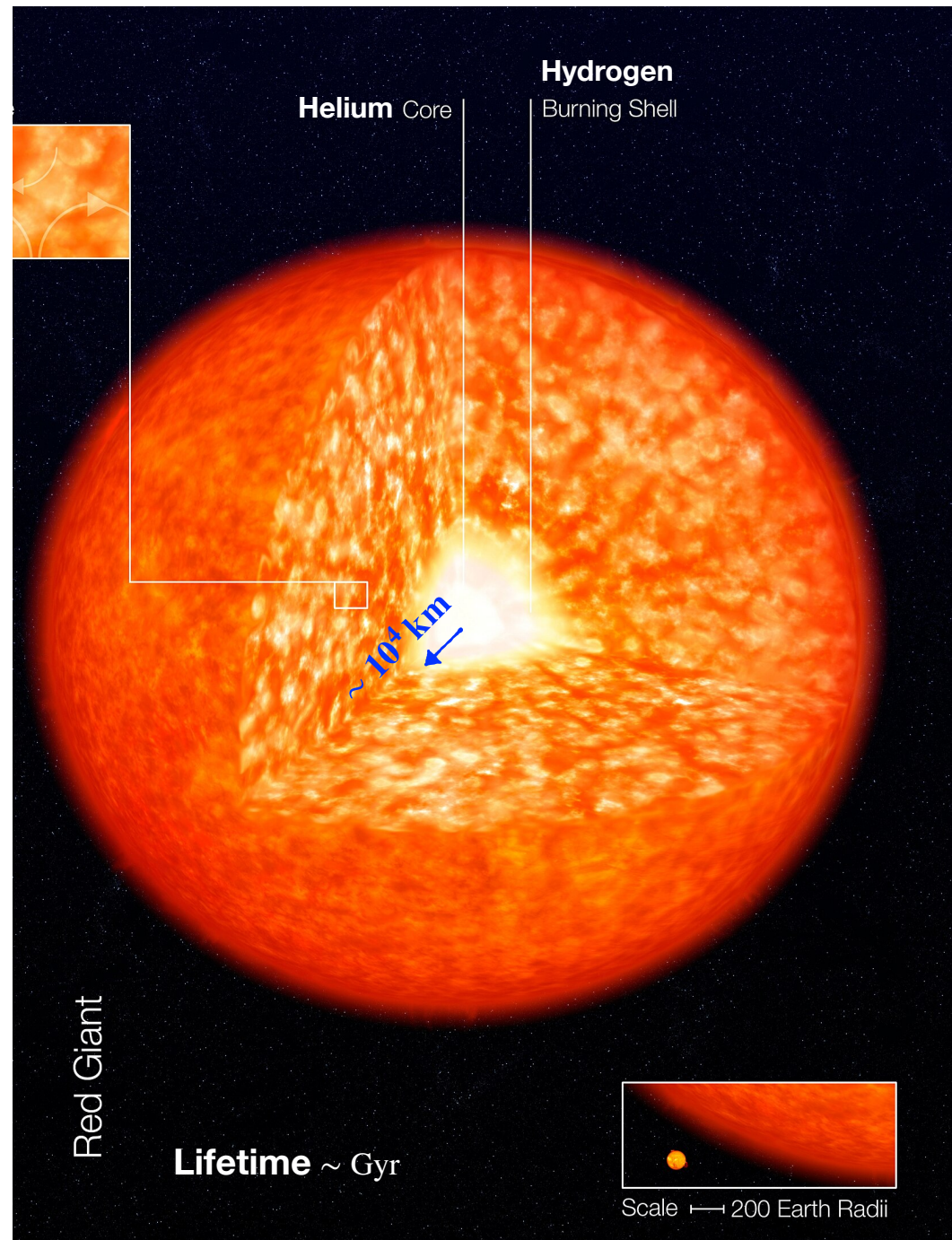
“Raffelt criterion”



Heating?

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

Red Giant Branch

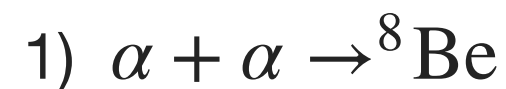
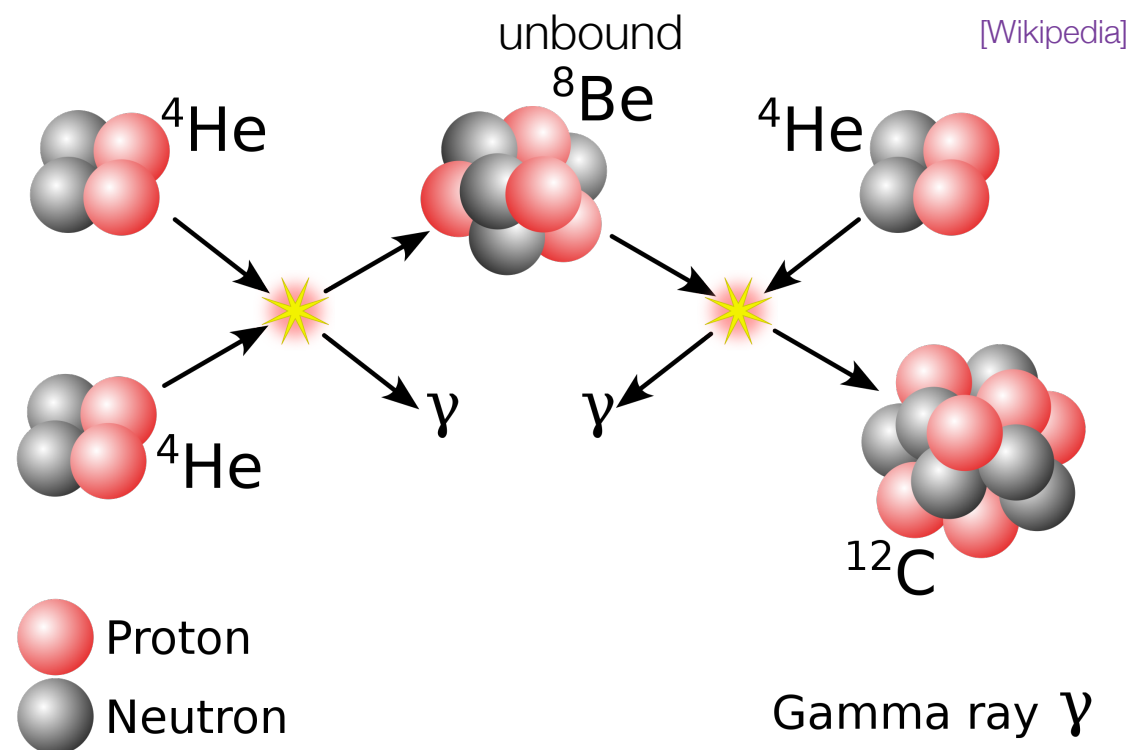


- Helium core governs properties of star
 - Sizable mass fraction $\mathcal{O}(1)M_{\odot}$
 - Very dense $\sim 10^6 \text{ g cm}^{-3}$
 - Degenerate electron pressure
 - Consistent burning condition ($r_{3\alpha} \propto T^{40}$ @ $T \sim 10^8 \text{ K}$)
- Hydrogen envelope
 - Dominant burning shell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

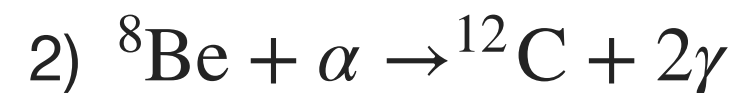
Trigger Mass for Helium Ignition

- 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



- ${}^8\text{Be}$ is very unstable
- But, an equilibrium abundance of ${}^8\text{Be}$



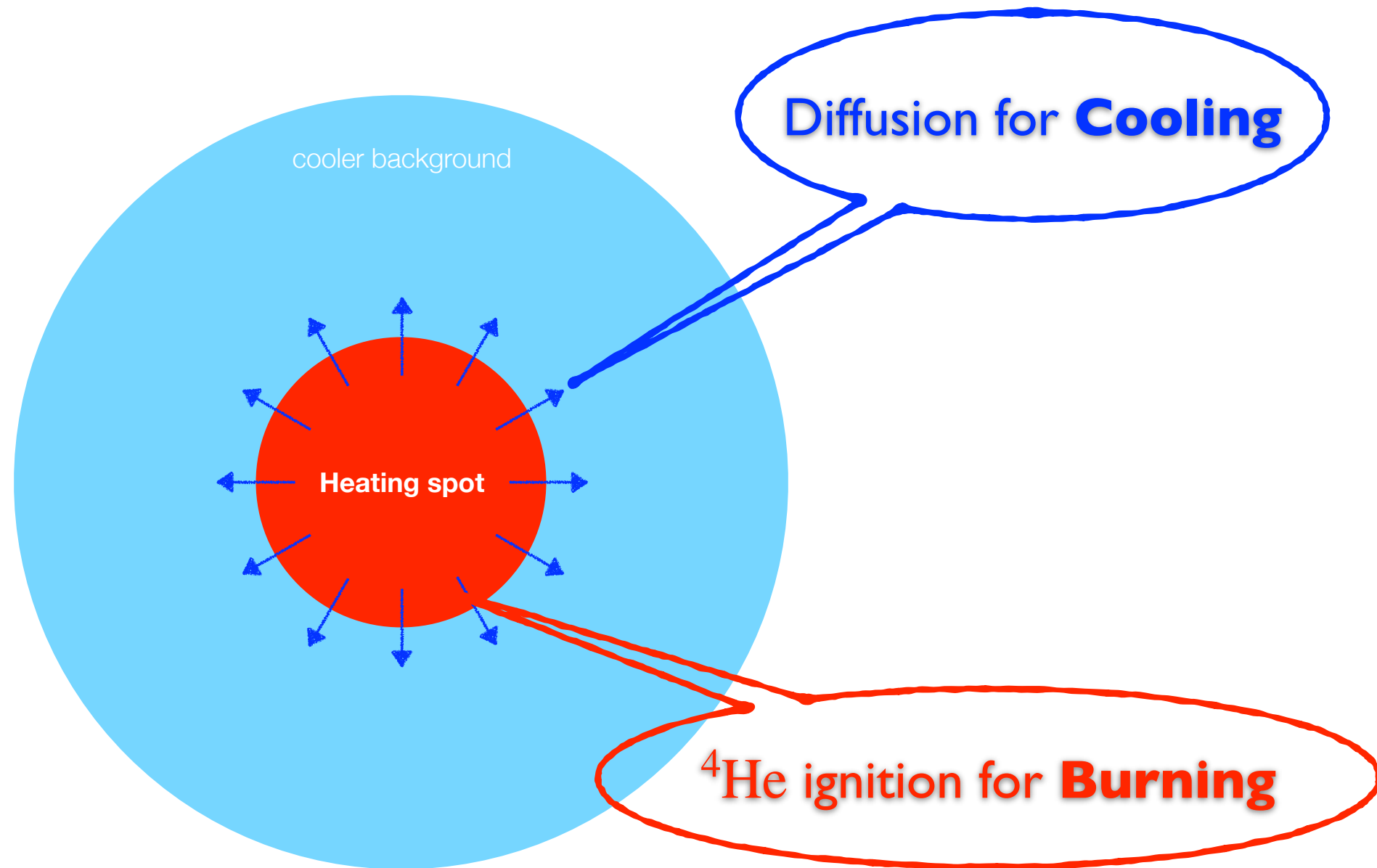
- Resonant reaction

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

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

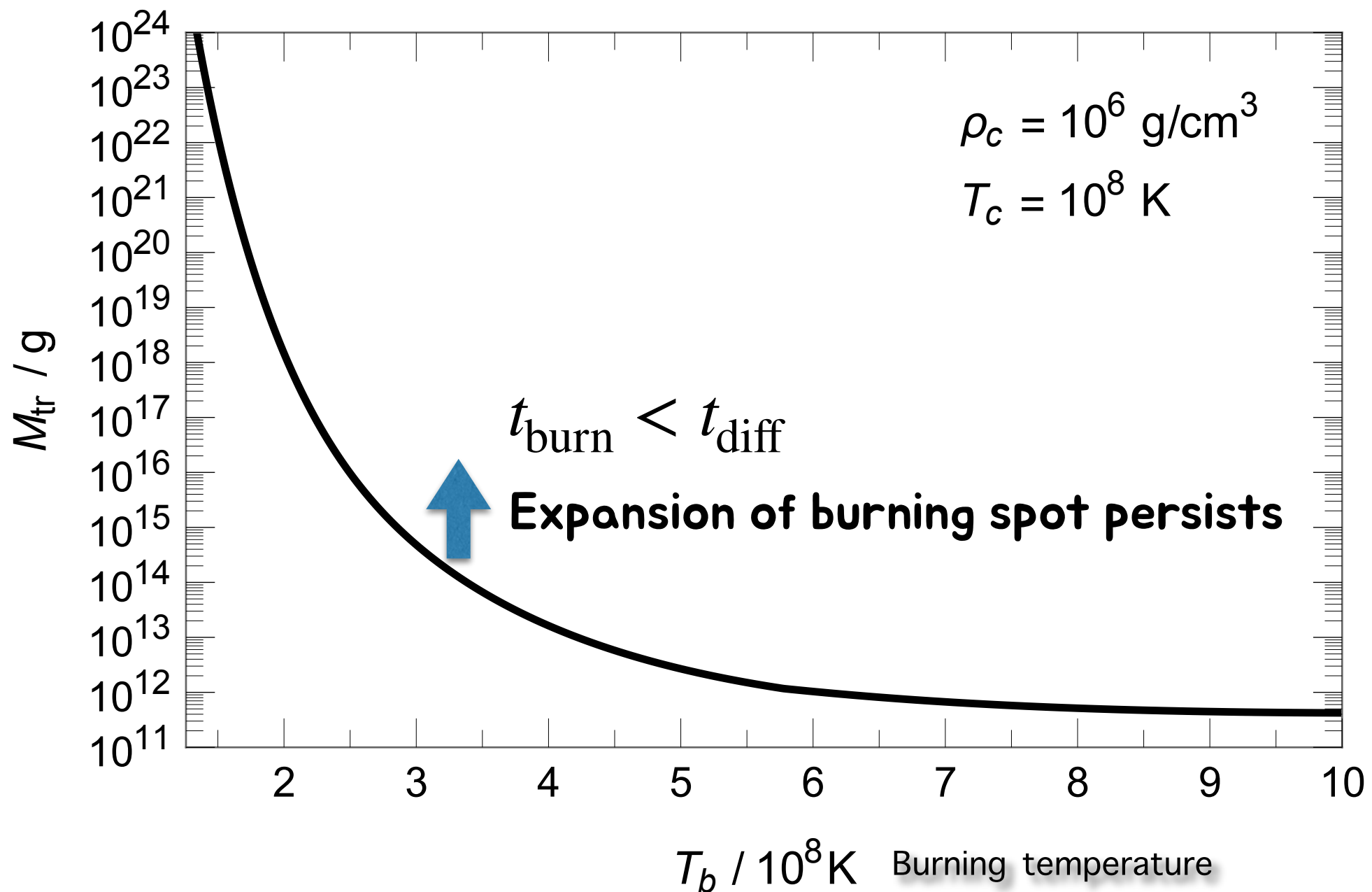
Width of heating spot

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

Thermal diffusivity
 $\sim \lambda \times v_c$

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

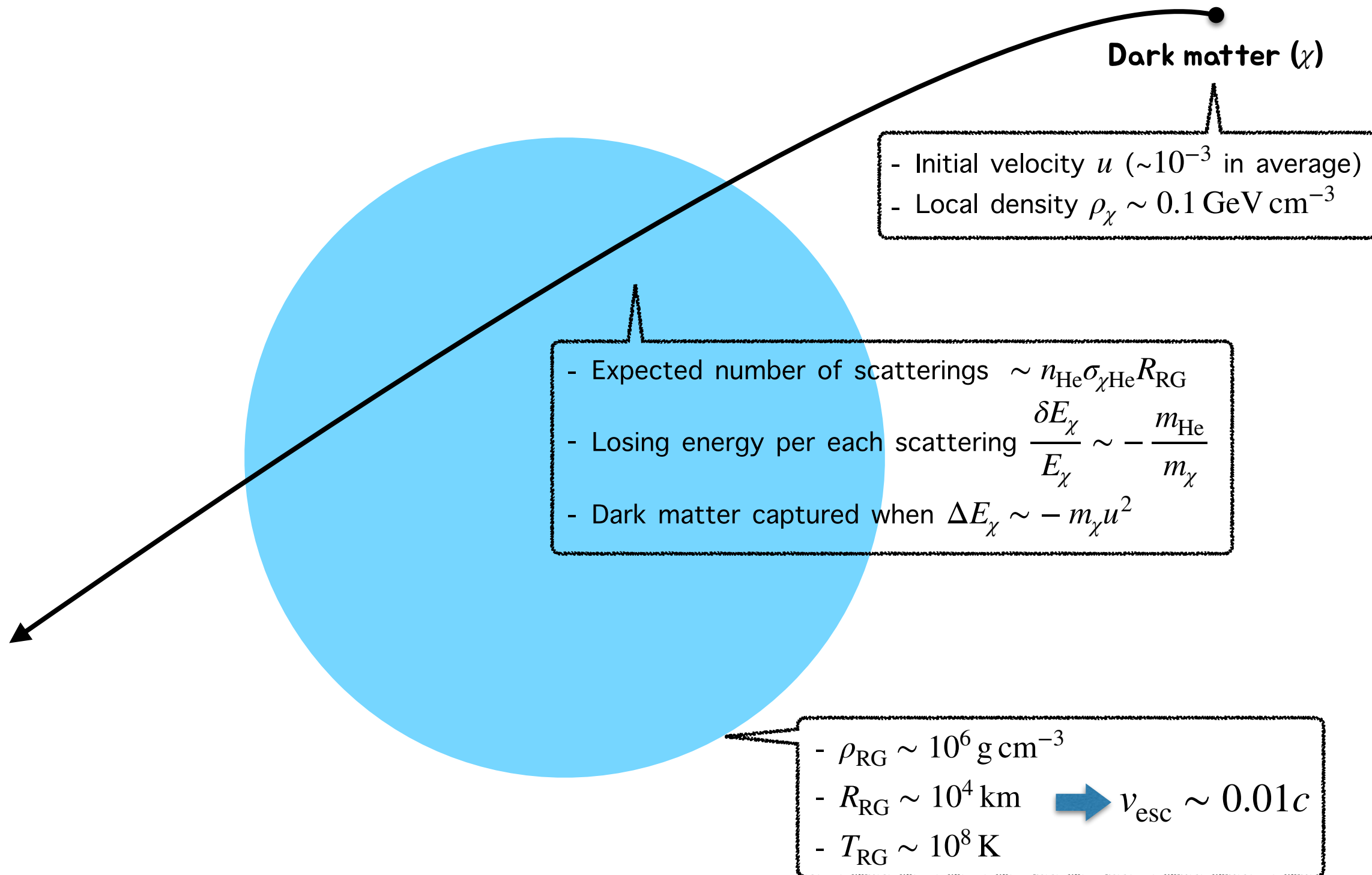
Trigger Mass for Helium Ignition



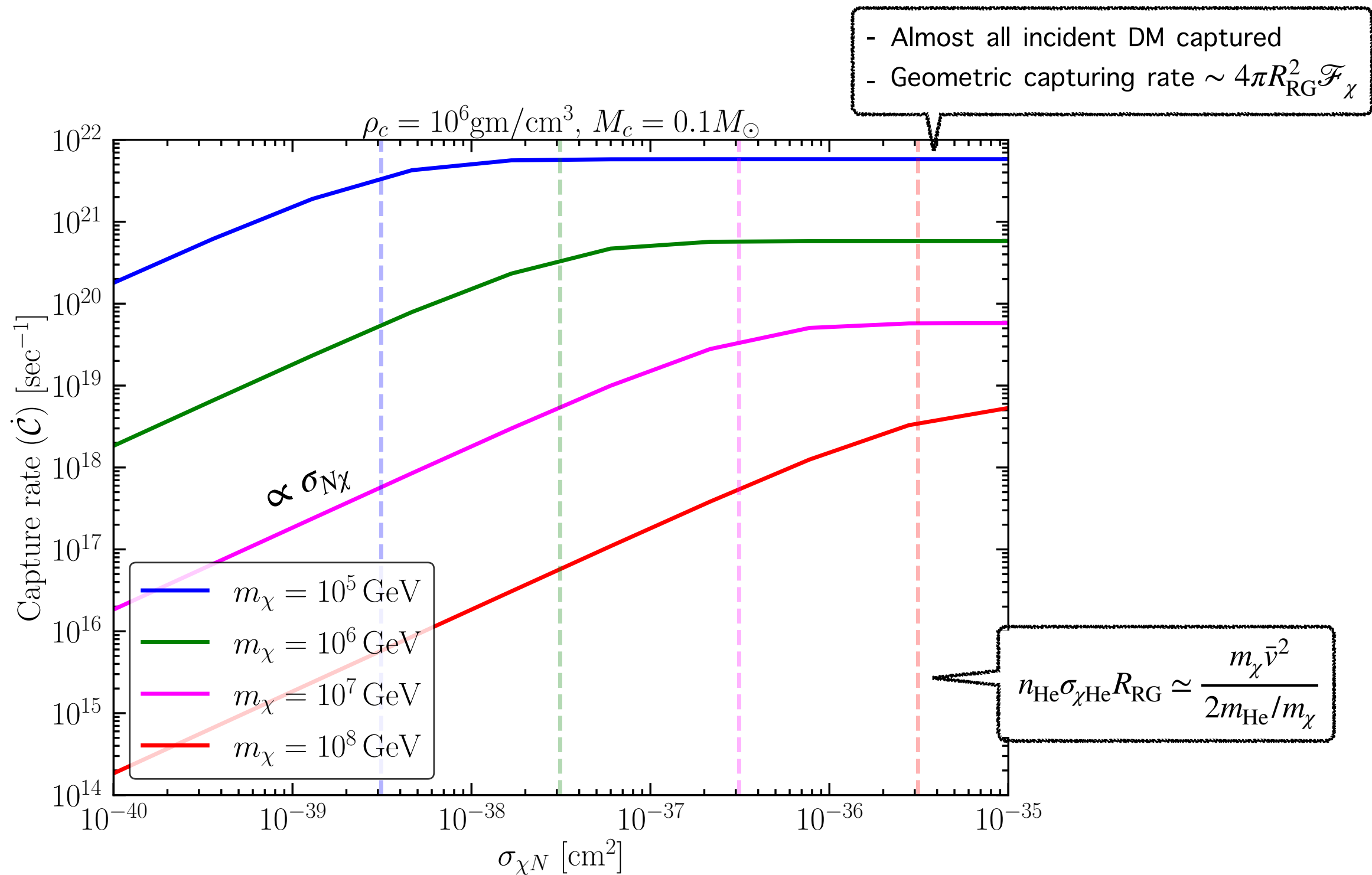
Dark Matter Capture

- 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

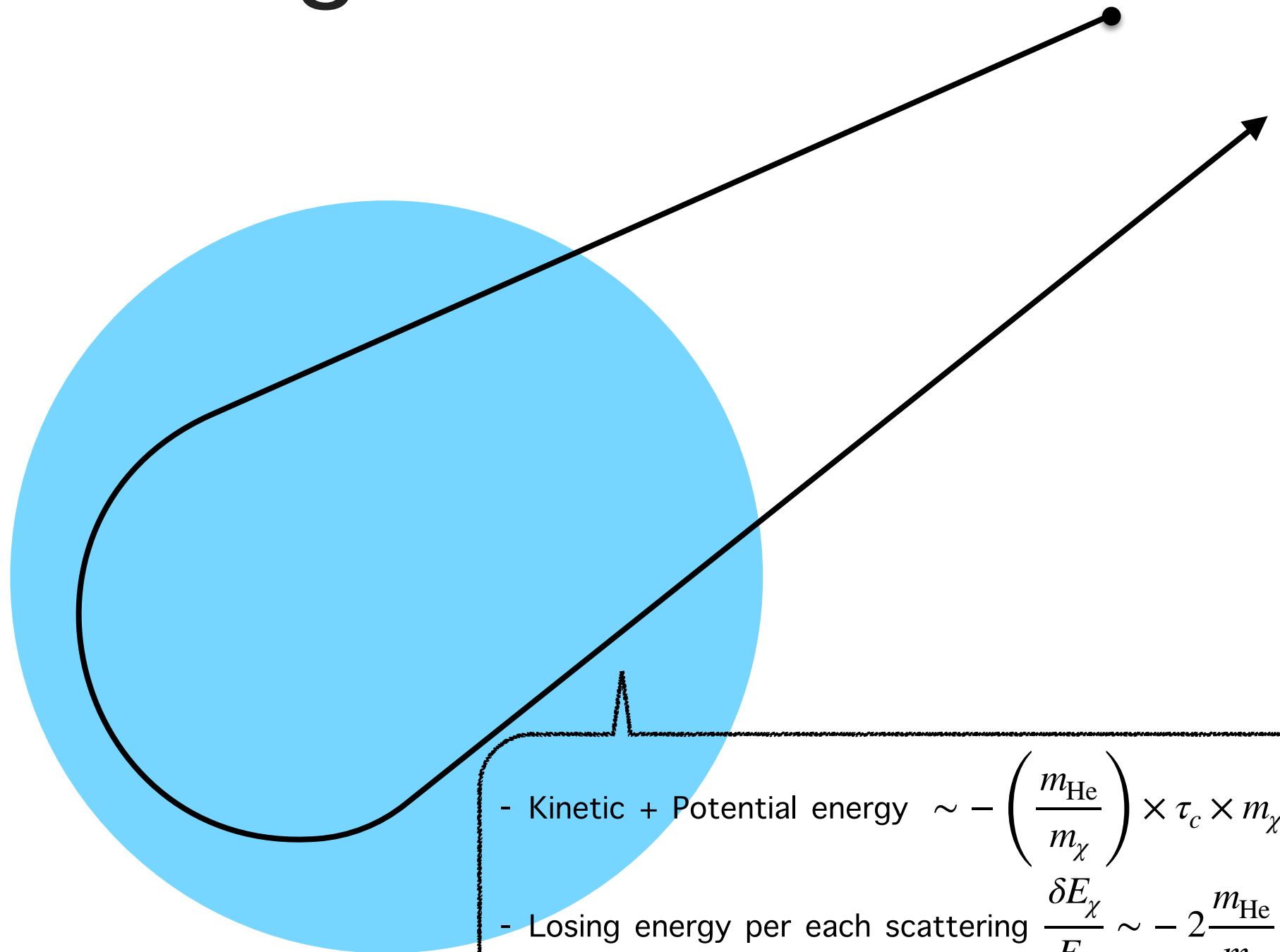
Dark Matter Capture



Capture Rate

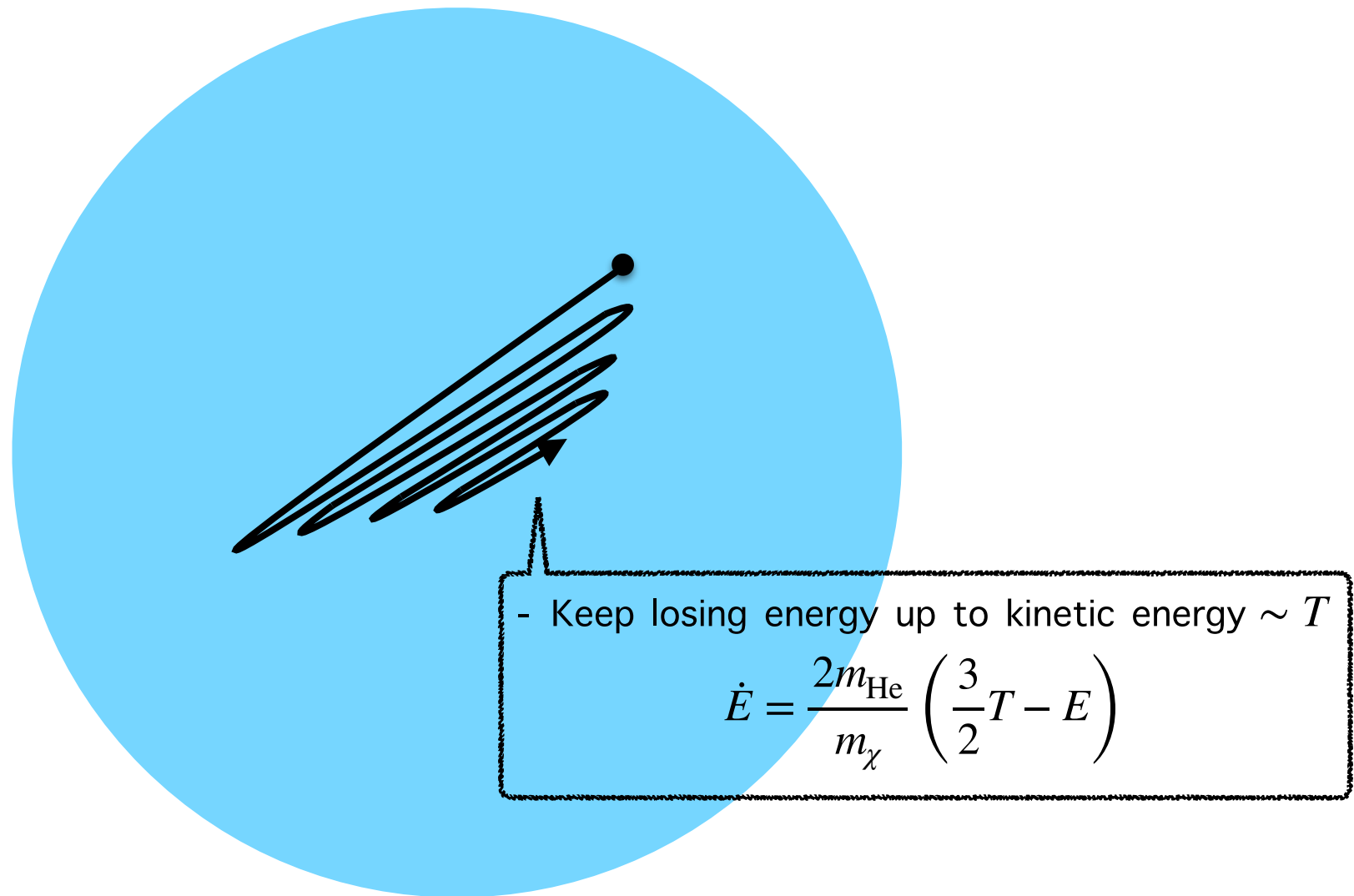


Ingress

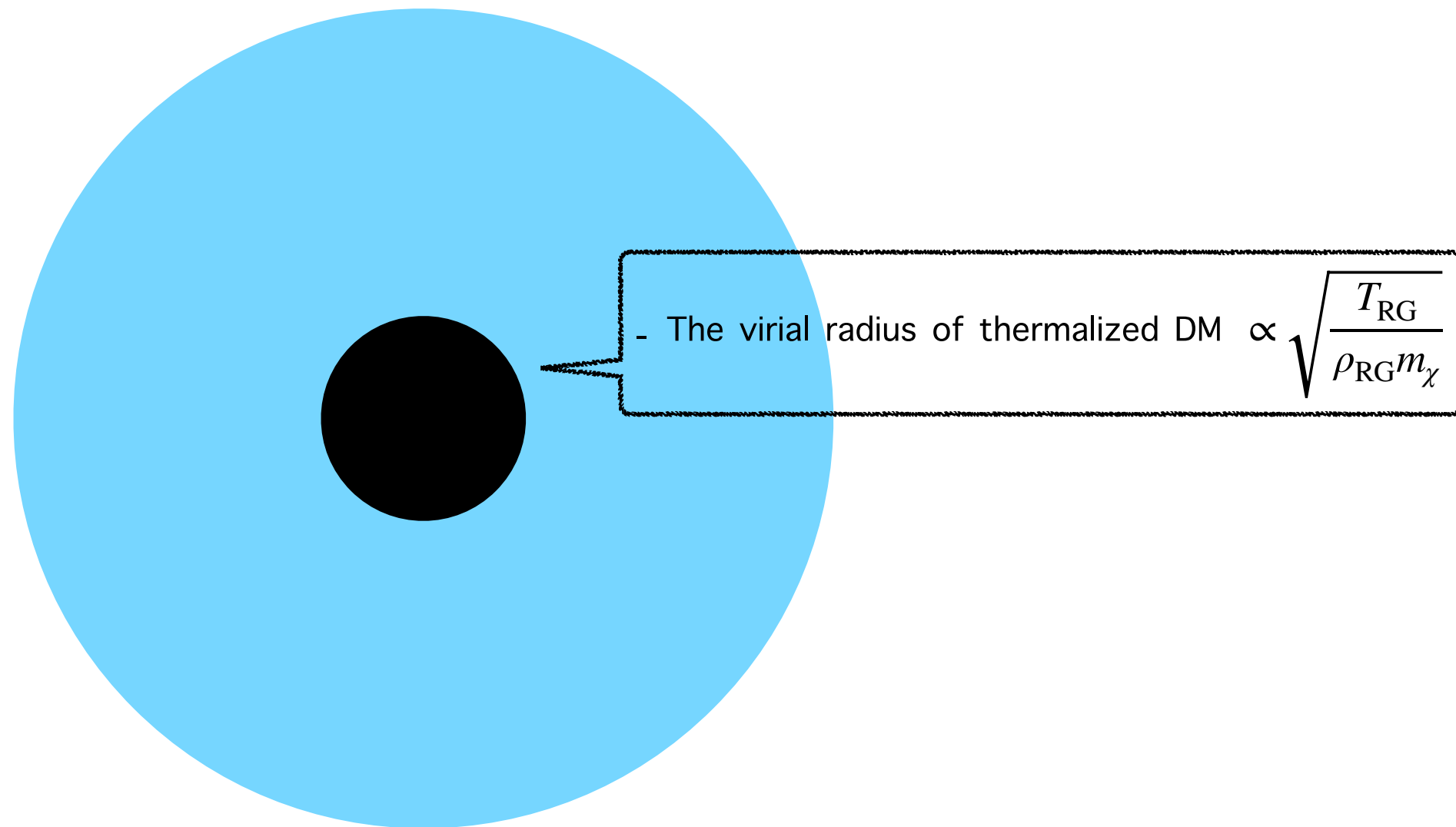


- Kinetic + Potential energy $\sim - \left(\frac{m_{\text{He}}}{m_{\chi}} \right) \times \tau_c \times m_{\chi} v_e^2$
- Losing energy per each scattering $\frac{\delta E_{\chi}}{E_{\chi}} \sim - 2 \frac{m_{\text{He}}}{m_{\chi}}$
- Dark matter ingress when total energy $< - m_{\chi} v_{\text{esc}}^2$

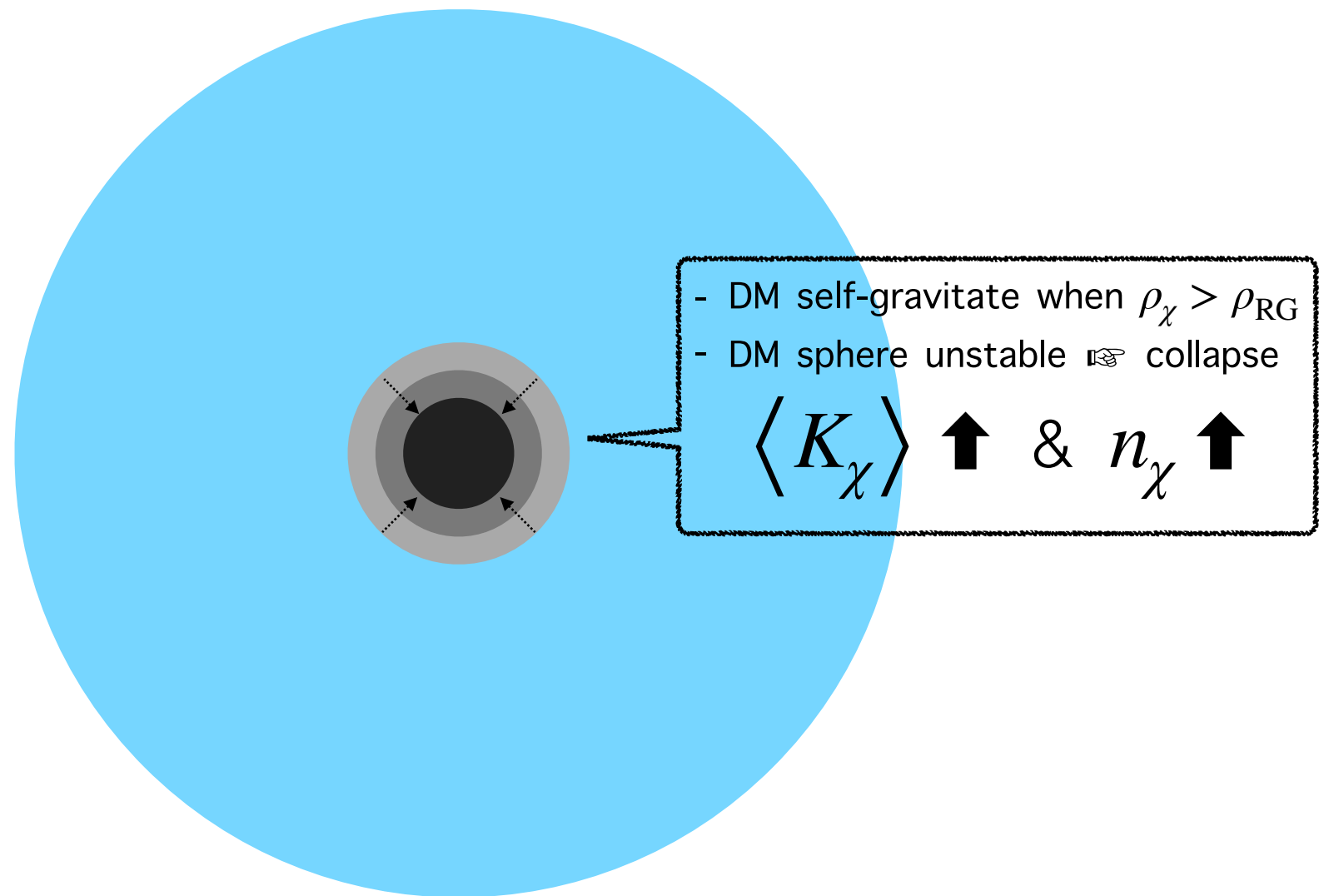
Thermalization



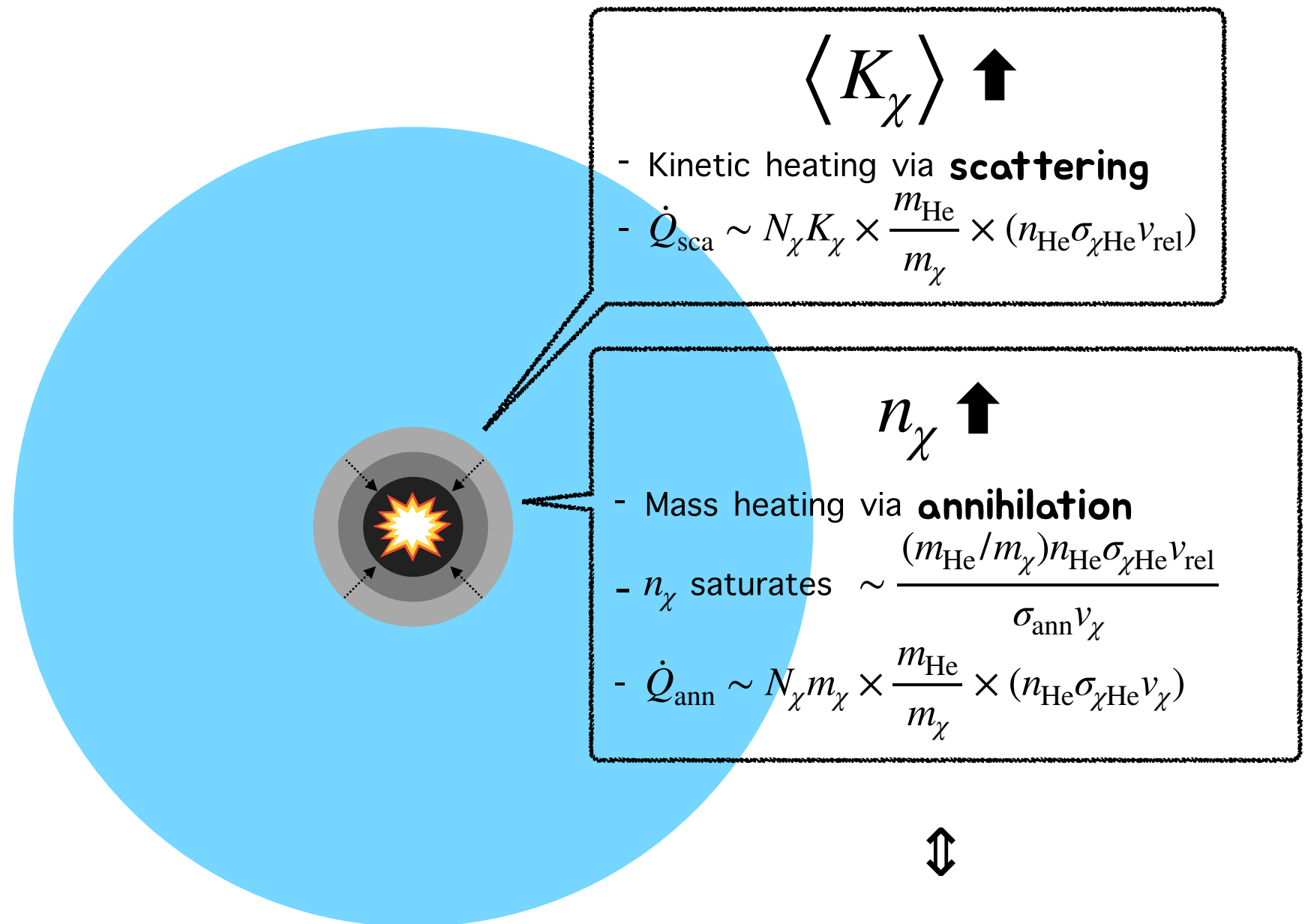
Thermalization



Gravitational Collapse



Dark Matter Heating



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

Late-onset Annihilation

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

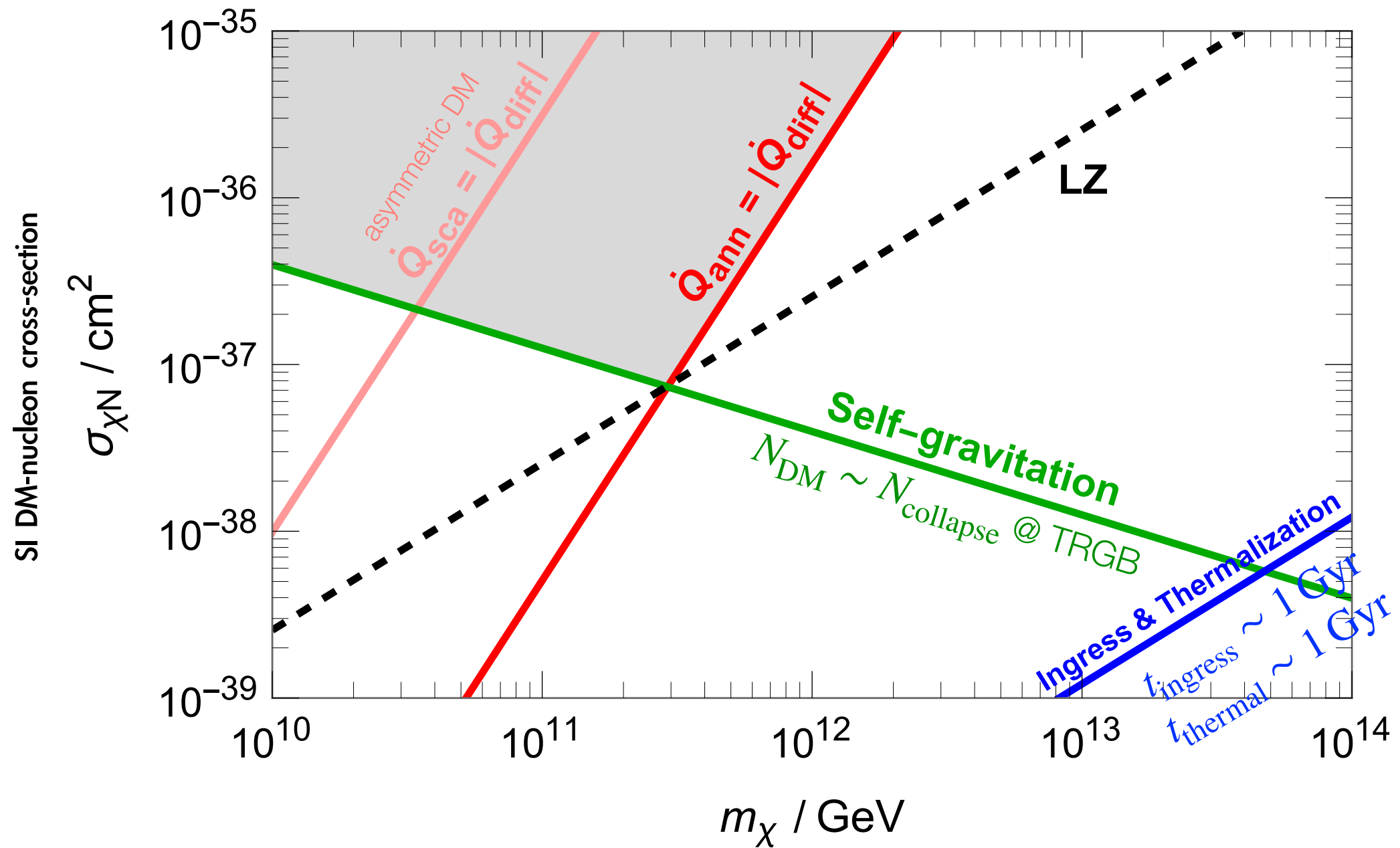
s-wave & α_{χ} : DM-SM coupling

⊙ For a localized heating to trigger runaway helium burning

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

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

Constraints



Conclusion

- Stellar evolution as a good way to probe BSM signals
 - Consistent with the SM prediction
 - For $M_i \sim 1 M_\odot$, i) Main sequence (like Sun), **ii) Red-giant (helium core)**, iii) Horizontal branch (helium burning), ...
 - ***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

Thank you!

Back up

Dark Matter Capture in time

