Probing Dark Matter with Red Giants

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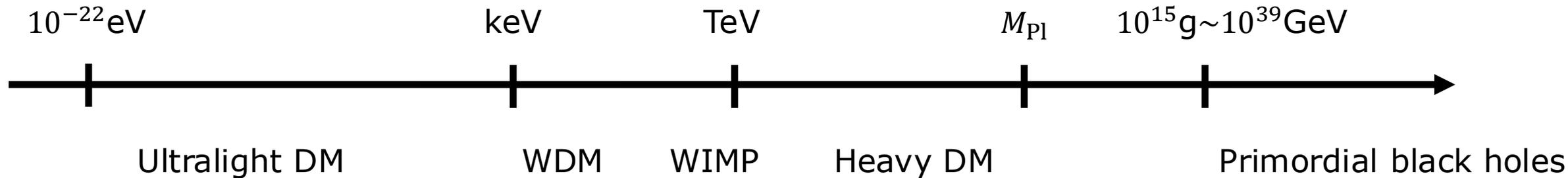
Collaborators: Sougata Ganguly, Chang Sub Shin, Seokhoon Yun

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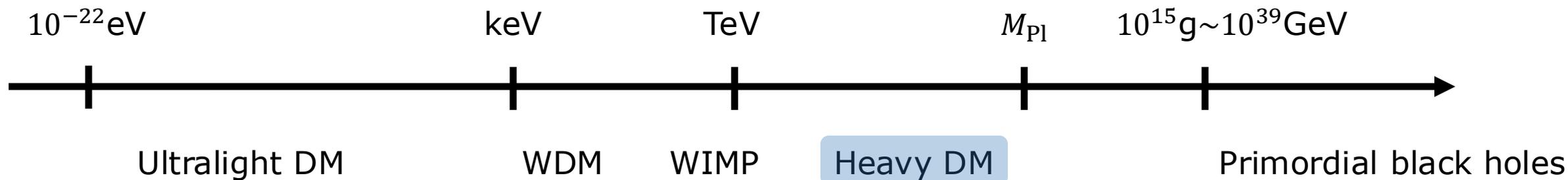
- Constraints on heavy asymmetric dark matter

- Summary

Introduction

- Dark matter (DM)
  - Existence of DM
  - Interact gravitationally
  - Stable within cosmological time scale

10^{-22}eV   keV   TeV $M_{\rm Pl}$ 10^{15}g$\sim 10^{39}$GeV

Ultralight DM   WDM   WIMP   Heavy DM   Primordial black holes

Introduction

- Dark matter (DM)
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10^{-22}eV keV TeV M_{Pl} 10^{15}g~10^{39}GeV

Ultralight DM   WDM   WIMP   Heavy DM   Primordial black holes
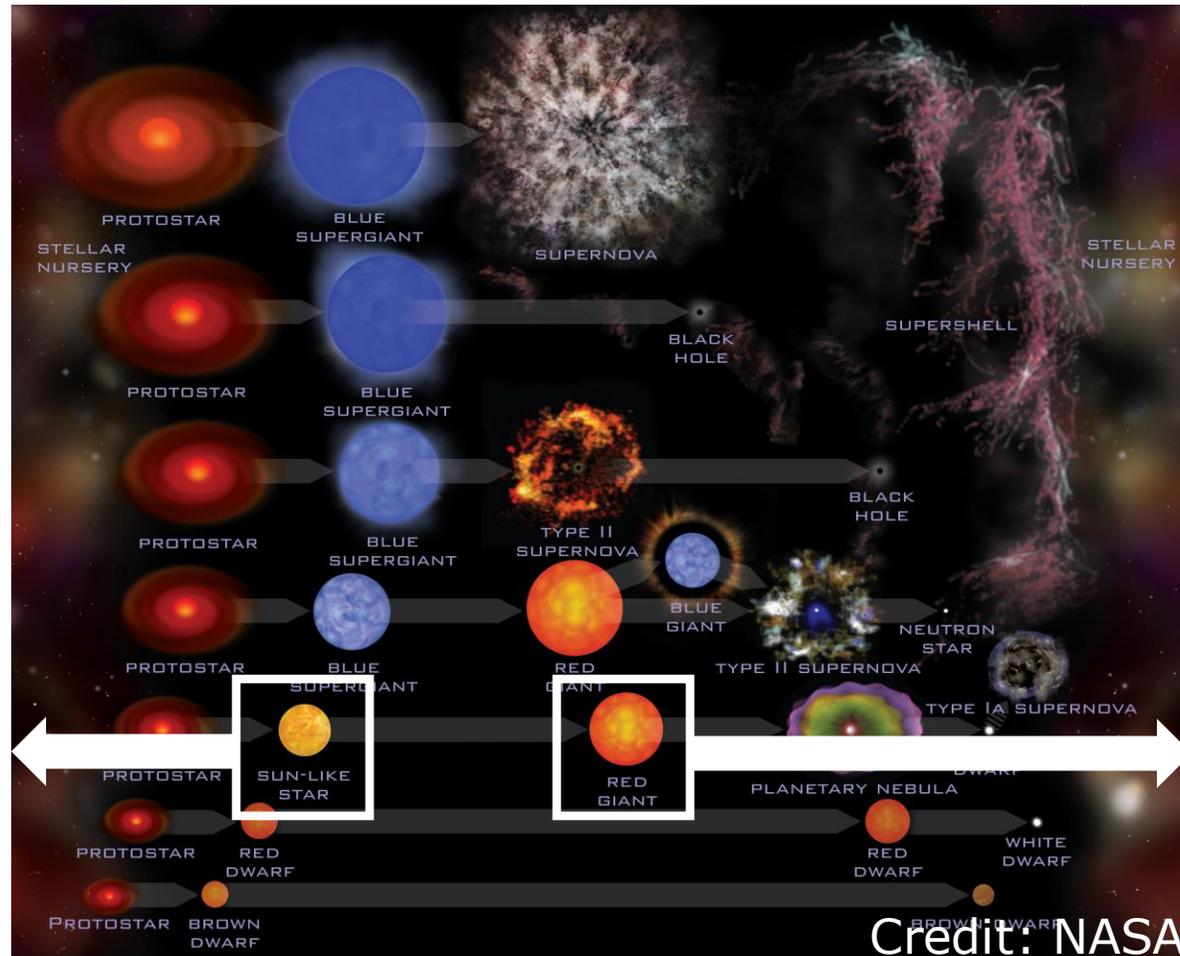
- Less explored
- Too heavy to be produced in current colliders...

(See Chang Sub's talk for more detail)

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Introduction

- Red giant (RG)

$\rho_{\text{core}} \sim 10^2 \text{g/cm}^3$
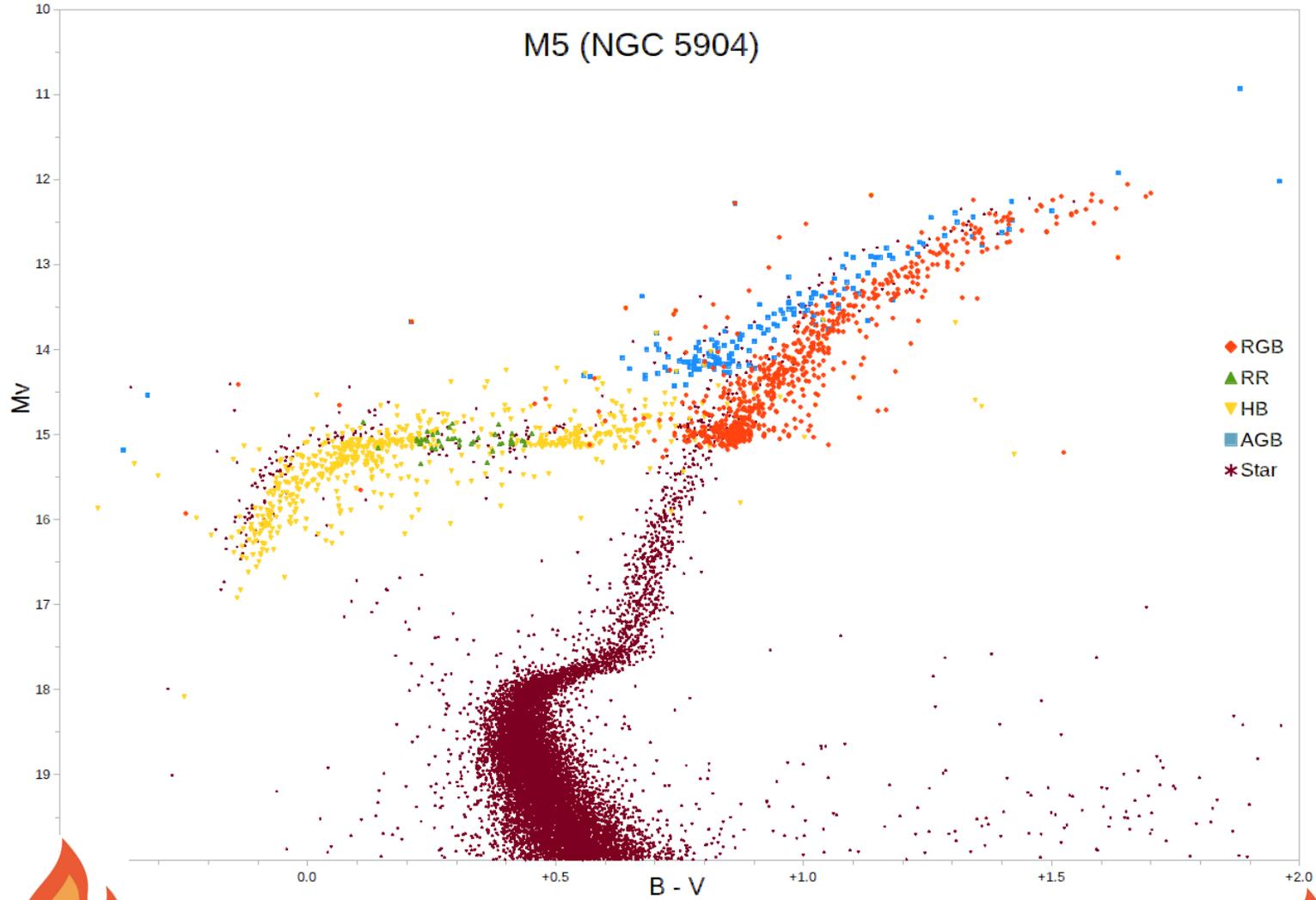$T \sim 10^6 \text{K}$
$\tau_\odot \sim 10 \text{Gyr}$

$\rho_{\text{core}} \sim 10^6 \text{g/cm}^3$
$T \sim 10^8 \text{K}$
$\tau_{\text{RG}} \sim 1 \text{Gyr}$

Credit: NASA

Introduction

Hertzsprung-Russell diagram

M5 (NGC 5904)

Absolute magnitude (or equivalently, luminosity)

Mv

B - V

Color (or equivalently, temperature)

Legend:
- ◆ RGB
- ▲ RR
- ▼ HB
- ■ AGB
- ＊ Star

Introduction

Hertzsprung-Russell diagram

Red giant
Core components: helium
Energy source: hydrogen shell

M5 (NGC 5904)

Tip of RG

Absolute magnitude (or equivalently, luminosity)

Color (or equivalently, temperature)

◆ RGB
▲ RR
▼ HB
■ AGB
✳ Star

Ignition of the helium core in a red giant

Main sequence

Red giant

Hydrogen burning → Helium "ash"

Hydrogen shell burning → Helium core

Ignition of the helium core in a red giant

3α process

Proton
Neutron
Gamma ray γ

Red giant

- $\rho_{\mathrm{RG}} \sim 10^6 \mathrm{g/cm^3}$
- $T \sim 10^8 \mathrm{K}$
- $R_{\mathrm{core}} \sim 10^4 \mathrm{km}$
- Degenerate electrons

Helium core

- Sensitive to temperature (typically $T \gtrsim 10^8 \mathrm{K}$)
- Gravity provides positive feedback for fusion → runaway reaction → helium flash

$$\dot{S} = \frac{Q_{3\alpha} r_{3\alpha}}{\rho_{\mathrm{core}}}$$

$$\simeq 3.2 \times 10^{26} \mathrm{~GeV/(s \cdot g)} \left(\frac{\rho_{\mathrm{core}}}{10^6 \mathrm{g\,cm^{-3}}} \right)^2 \left(\frac{T}{10^8 \mathrm{K}} \right)^{-3} \exp\left[-\frac{4.4027 \times 10^9 \mathrm{~K}}{T} \right]$$

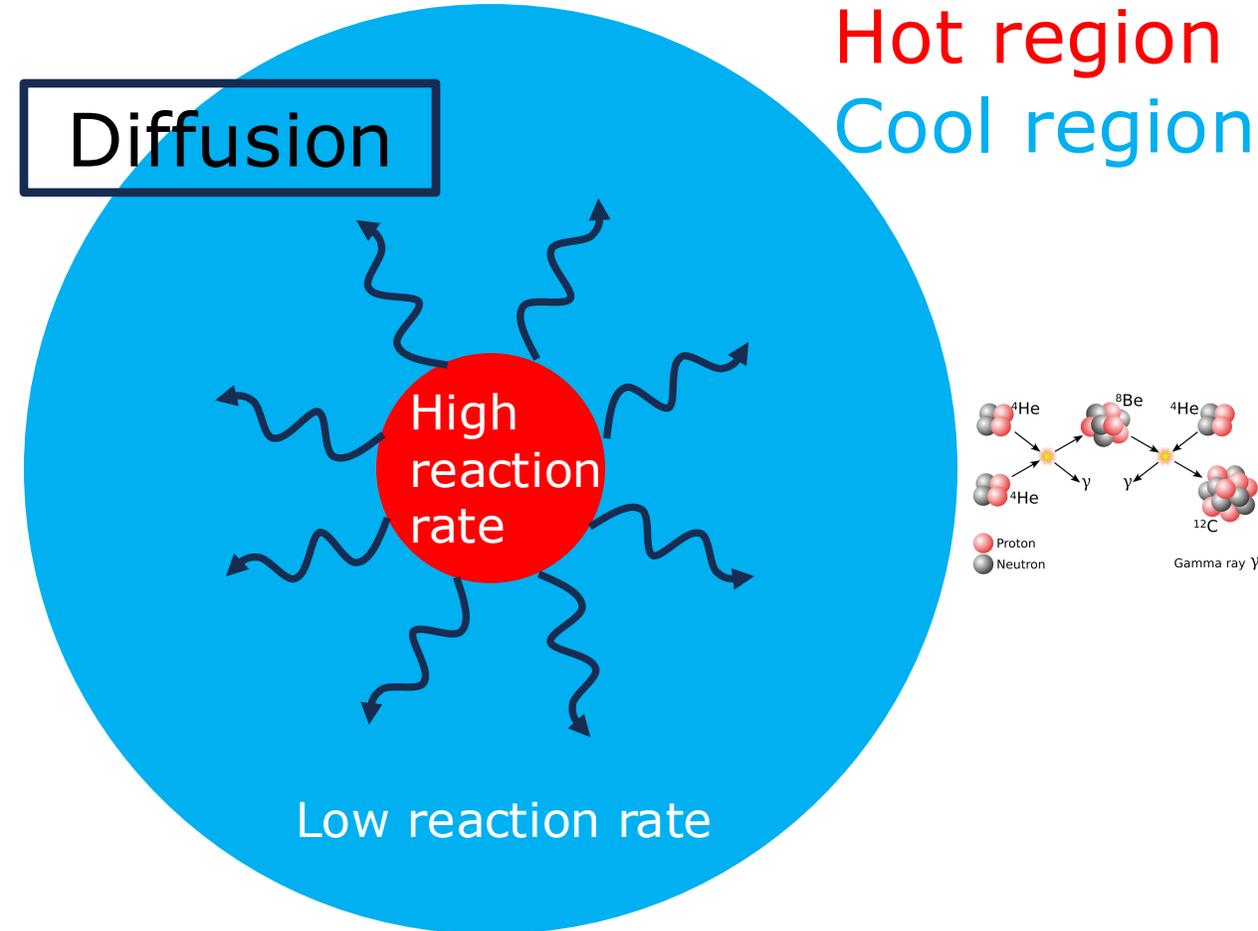# Ignition of the helium core in a red giant

Heating rate > Cooling rate

Timmes, Woosley, 1992

High reaction rate is maintained
Heat up surroundings
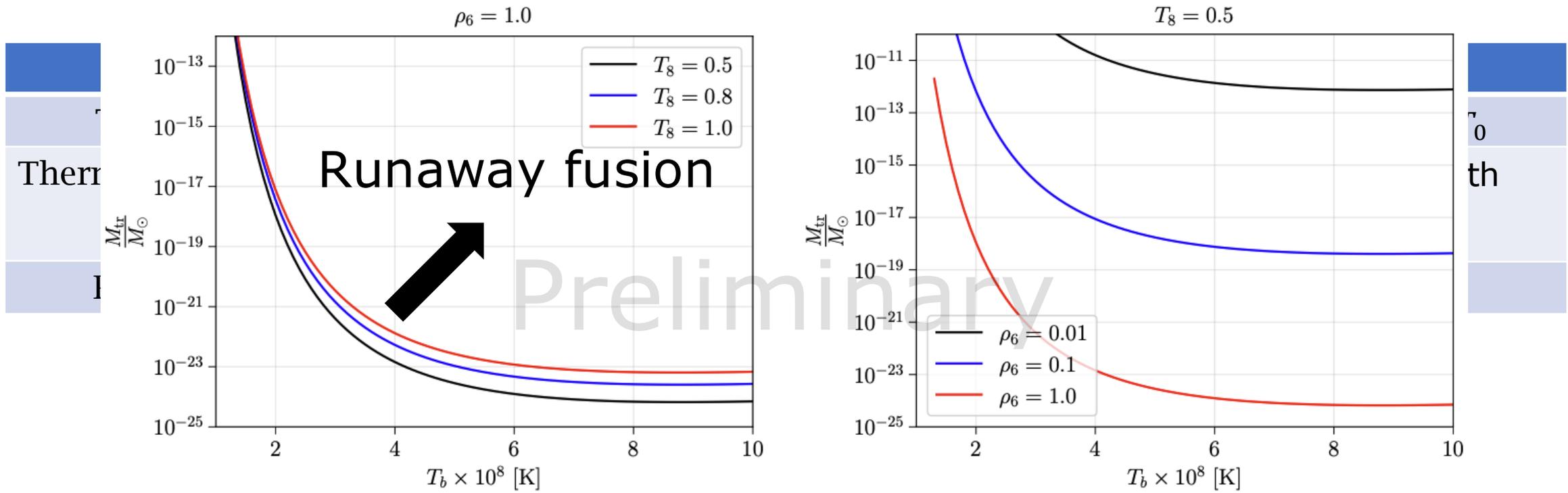
Ignition of the core

Diffusion

Hot region
Cool region

High reaction rate

Low reaction rate

Ignition of the helium core in a red giant

	Heating
Temperature	High temp. T_b
Thermal energy excess	$\int c_m(\rho, T)\, dT$
Reaction rate	$\dot{S}$

	Cooling
Temperature	Low temp. T_0
Size	δ
Conduction	Mean free path $\lambda_{\mathrm{eff}}(\rho, T)$

$$t_{\mathrm{burn}} \sim t_{\mathrm{diff}}$$

Trigger mass $\qquad M_{\mathrm{tr}} \sim \dfrac{4\pi}{3}\delta^3 \rho_c$

Ignition of the helium core in a red giant

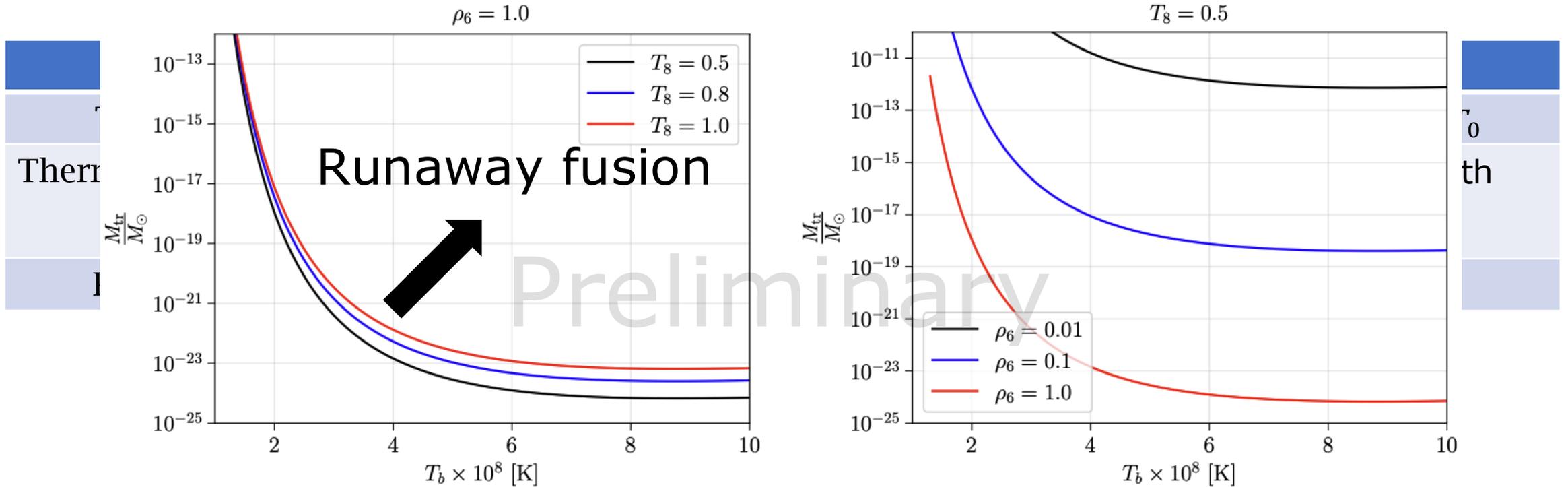

Runaway fusion

Preliminary

Trigger mass $M_{\mathrm{tr}} \sim \dfrac{4\pi}{3}\delta^3 \rho_c$

Ignition of the helium core in a red giant

Trigger mass $\qquad M_{\mathrm{tr}} \sim \dfrac{4\pi}{3}\delta^3 \rho_c$
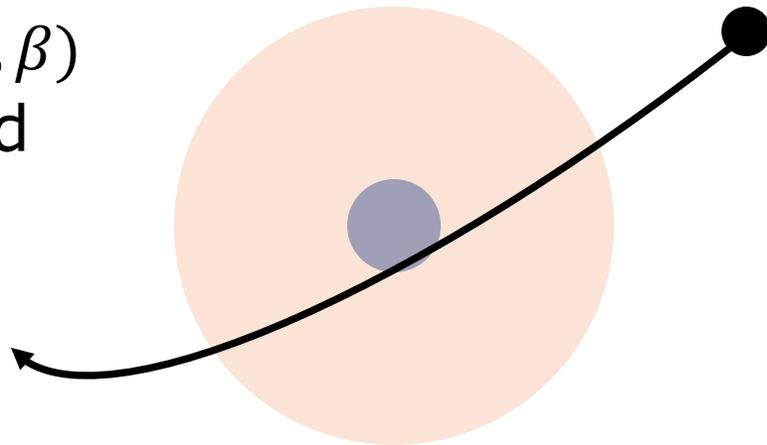
Question: can this probe DM?

Dark matter captured by red giants

Scattering

- Elastic scattering with hierarchical masses $\implies$ energy loss rate $\beta \propto m_T/m_\chi$
- Probability of N scatterings $p_N(\theta, \sigma)$
- Probability of capture after N scatterings $g_N(E_{\text{ini},\chi}, \beta)$
- $E_{\text{tot},\chi} < 0 \implies$ captured

DM χ

- $v_{\text{i}} \sim 10^{-3} c$
- $\rho_\chi \sim 0.1 \text{ GeV/cm}^3$
- Maxwell-Boltzmann

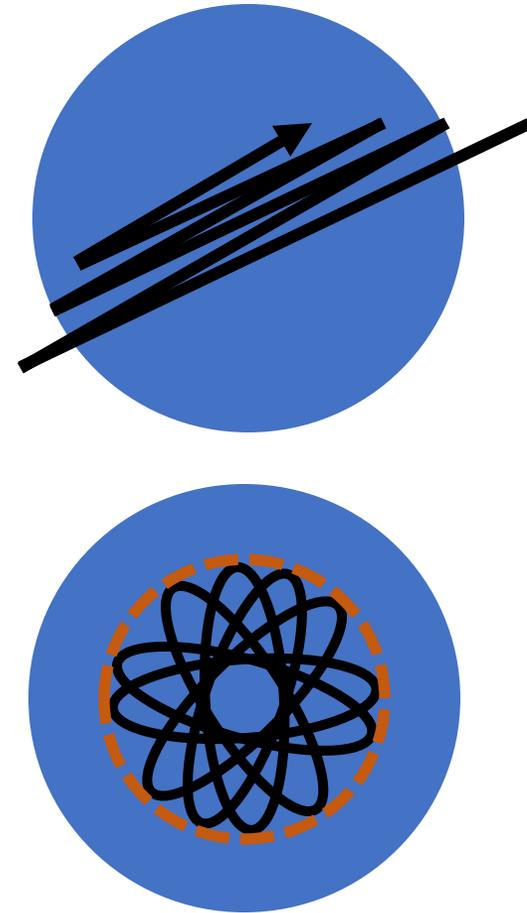Capturing process continues from main sequence phase to RG phase

Dark matter captured by red giants

Ingress after capture: orbits shrink until they are completely within the core

- Losing energy through scatterings $\Delta E = \beta E_{\text{kin}}$
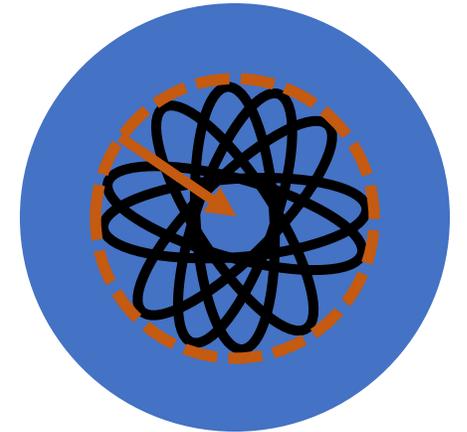- Time scale t_{ingress} (should be $< t_{\text{RG}}$)

Thermalization:

- Kinetic energy decreases down to $T \sim 10^8 \text{K}$

- Thermal radius $r_{\text{th}} \sim \sqrt{\dfrac{9T}{4\pi G \rho_{\text{RG}} m_\chi}}$

- Time scale t_{th} (should be $< t_{\text{RG}}$)

Dark matter captured by red giants
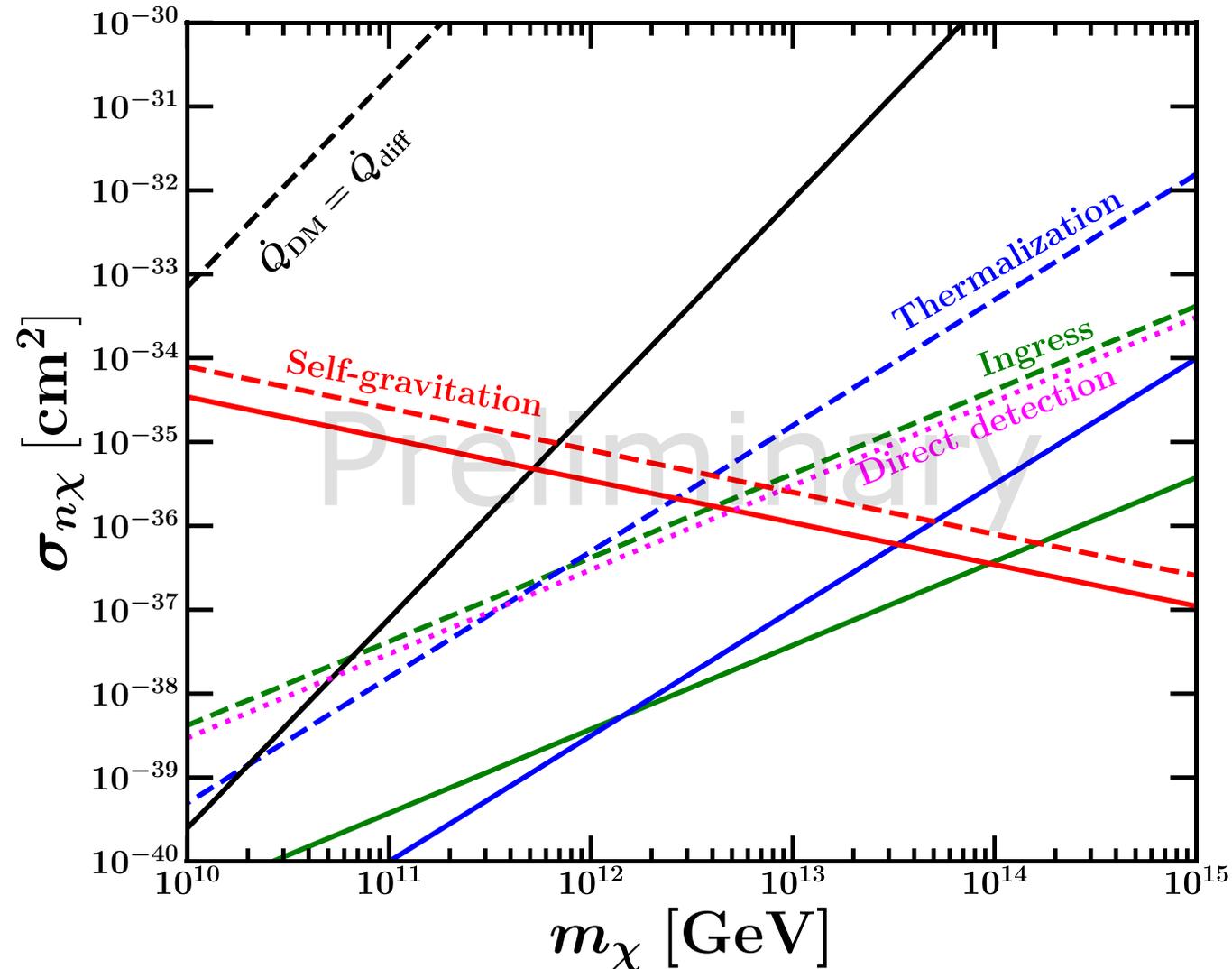
Self-gravitation:

- As more DM particles are captured, DM density overcome the core density
- Onset of self-gravitation: $\rho_\chi = \rho_{\text{core}}$
- Onset of collapse (or shrink): Jeans criterion
- Energy transfer from DM to core as shrinking $\dot{Q}_{\text{heat}}$

Ignition:

- $\dot{Q}_{\text{heat}} = \beta\, E_{\text{kin}}\, r_{\text{sca}}$
- $\dot{Q}_{\text{diff}} \propto r^2 T^3 \frac{dT}{dr}$
- Condition to maintain a high-temperature region: $\dot{Q}_{\text{heat}} = |\dot{Q}_{\text{diff}}|$

Constraints on heavy asymmetric dark matter

Summary

- Dark matter
  - Heavy dark matter ($\gg$ TeV)
- Red giant
  - Abundant, dense, hot
  - Trigger mass
- Capture of dark matter
  - Capture, ingress, thermalization
  - Self-gravity, heating, ignition
- Constraint

Thank you for listening!