Revealing Dark Matter through Red Giants

Chang Sub Shin

Chungnam National University

based on work in progress
with Sougata Ganguly, Minxi He, Seokhoon Yun (IBS), Oscar Straniero (INAF)
and 1912.04238 for a heavy DM model

2024 Korea-France STAR & the 12th KIAS Workshop
on Particle Physics and Cosmology
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Outline

Introduction of Dark Matter

- Unitarity Bound and Heavy Thermal Dark Matter

Stellar Evolution for Probing DM

- Red Giant, Triple Alpha Fusion, and Helium Flash

Effects of Dark Matter on the evolution of RG and Constraints

- Capture, Thermalization and Self Gravitational Collapse
- Ignition of Helium fusion earlier than the Standard Prediction
- Constraints

Summary

Introduction of Dark Matter
(thermal heavy dark matter)

Two triumphs in 20th century: General Relativity & The Standard Model

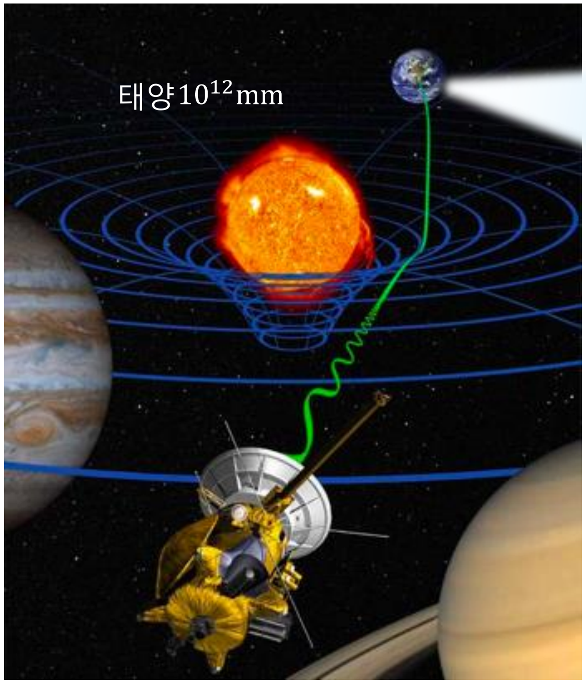
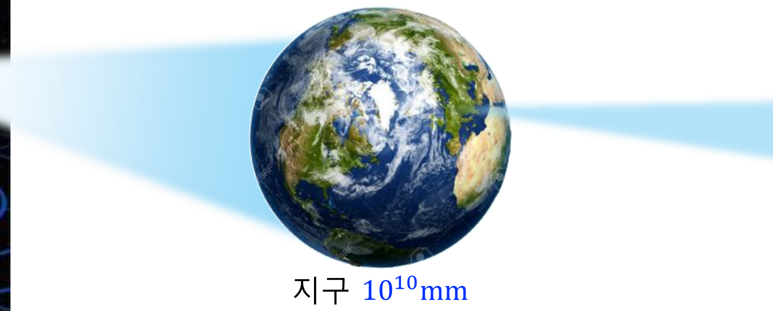


Image from NASA, Cassini spacecraft



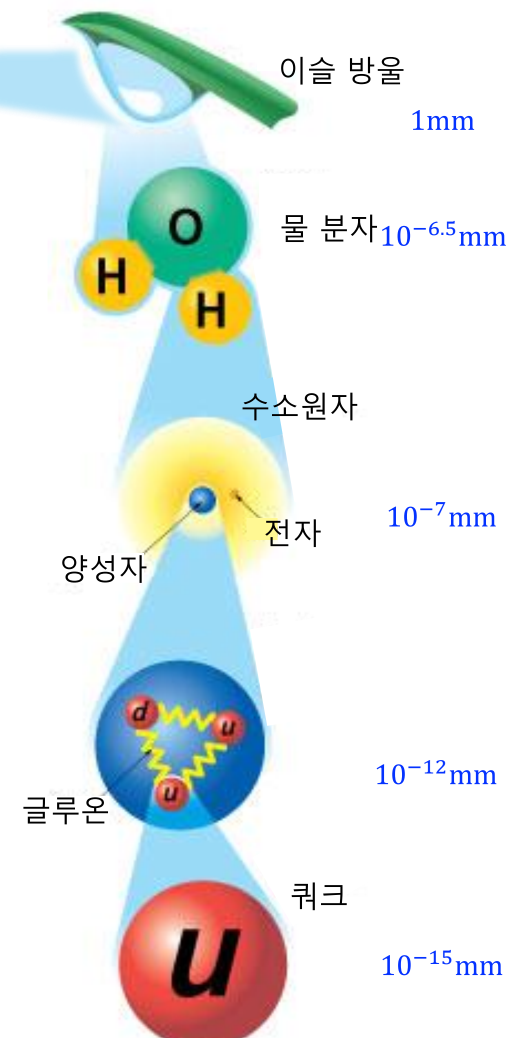
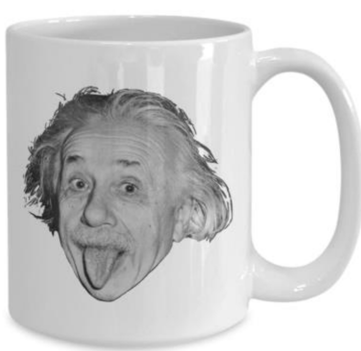


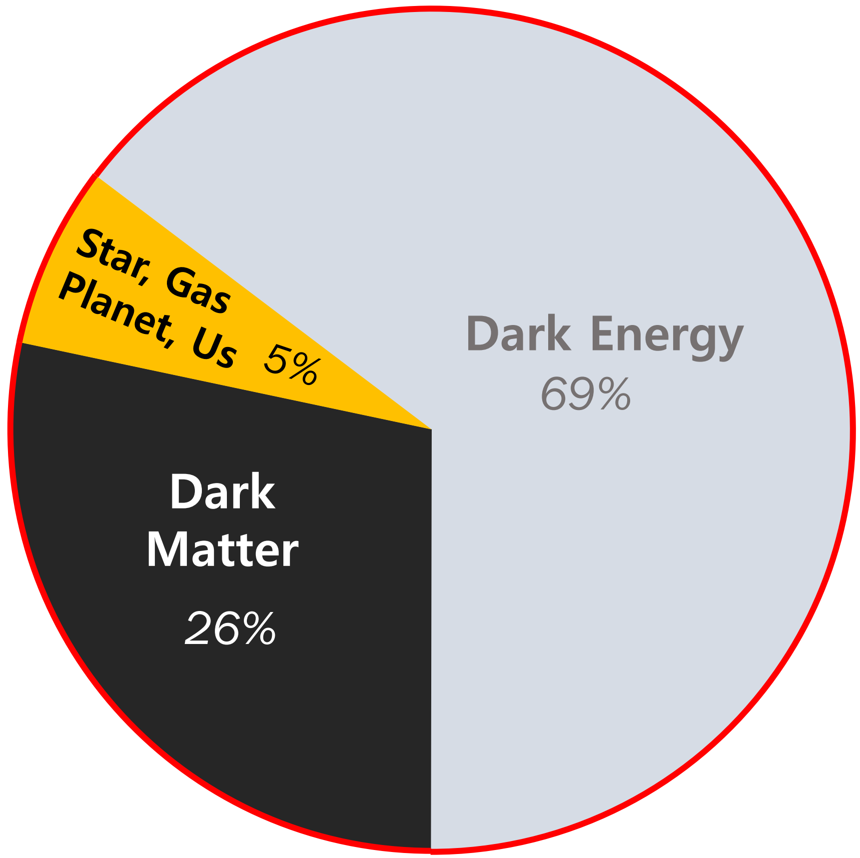
Image from CERN



gravity = curved spacetime

elementary particles = quark, lepton, gauge bosons, Higgs

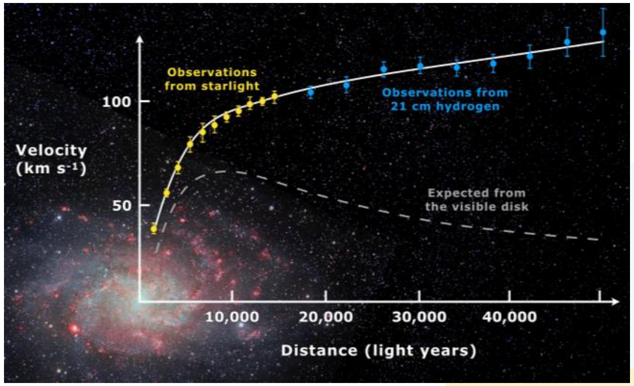
Content of the Universe



It is very difficult to properly understand the origin of the each content from GR and the list of particles of the SM

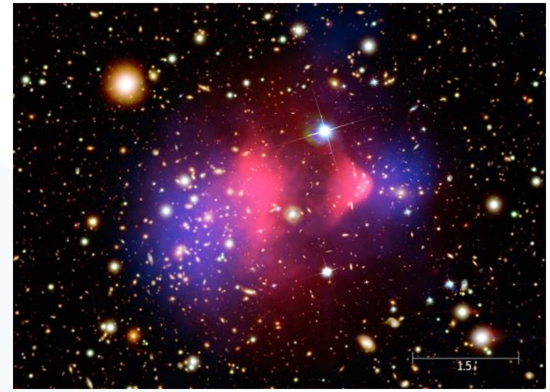
Content of the Universe - DM

Image of Galaxy Messier 33

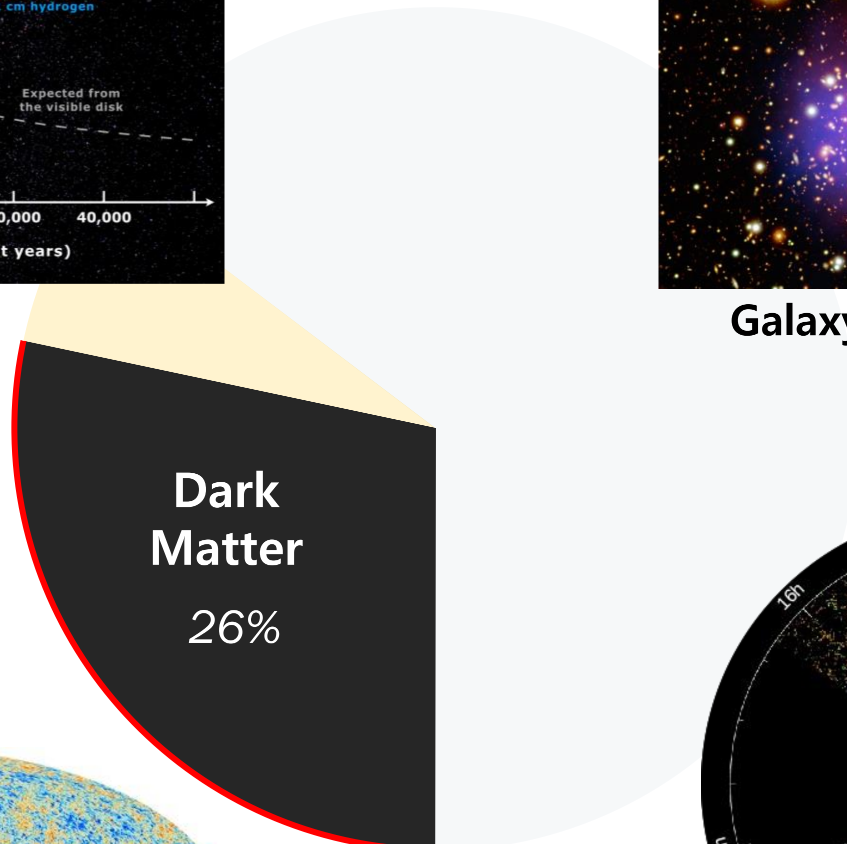


Galaxy Scale

Image of Bullet Cluster 1E 0657-558



Galaxy Cluster Scale



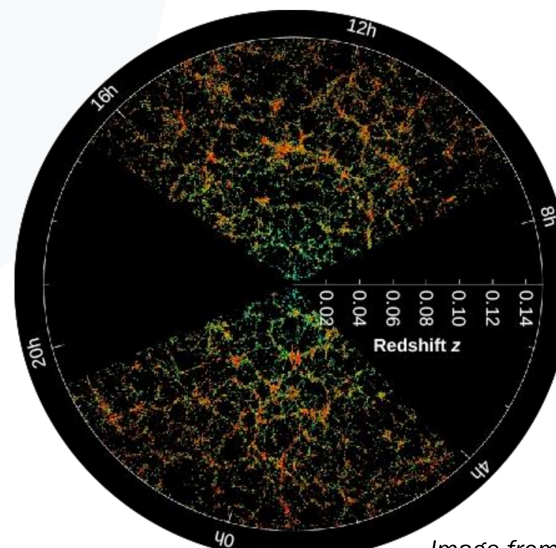


Image from SDSS

Large Scale Structure of the Universe

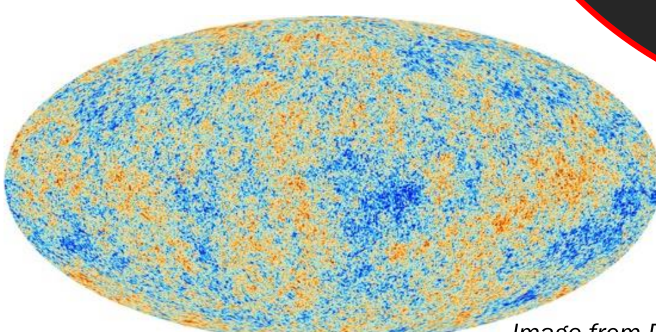


Image from PLACK

Cosmic Microwave Background

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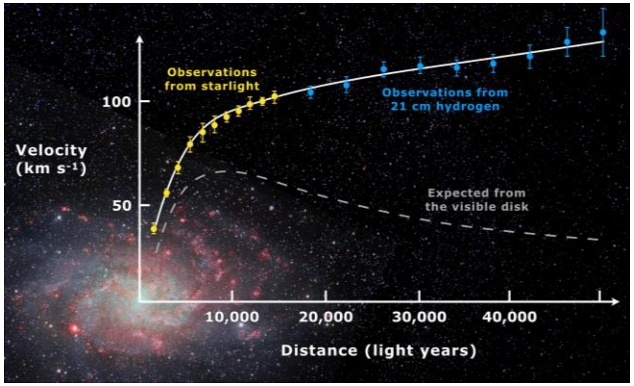

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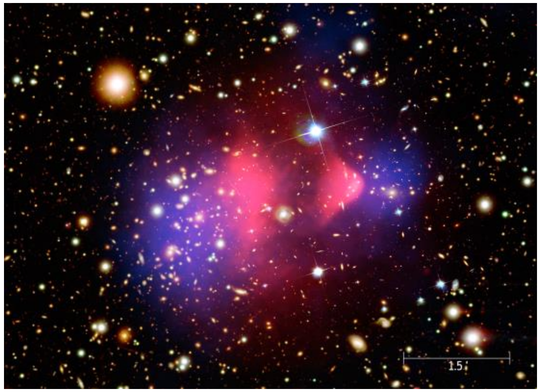
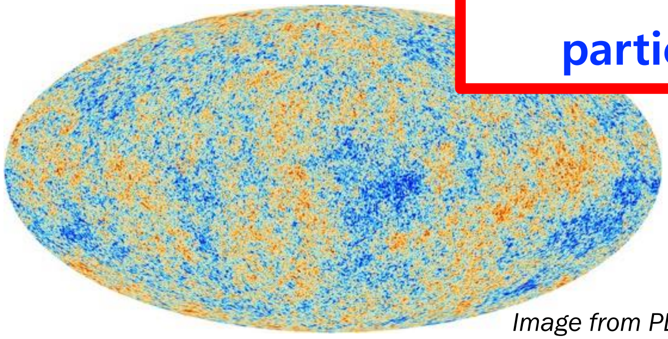


Galaxy Cluster Scale

<Dark Matter>

Feels Gravity,
Cosmologically Stable,
No Light Emission, No EM Charge

CANNOT be explained by the particle contents of the SM



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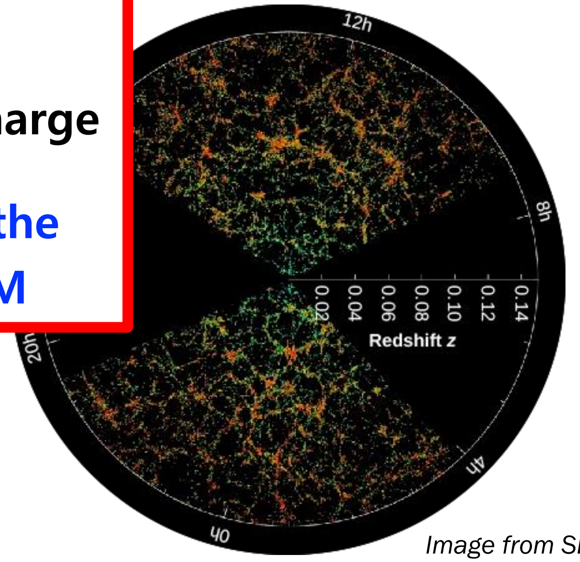
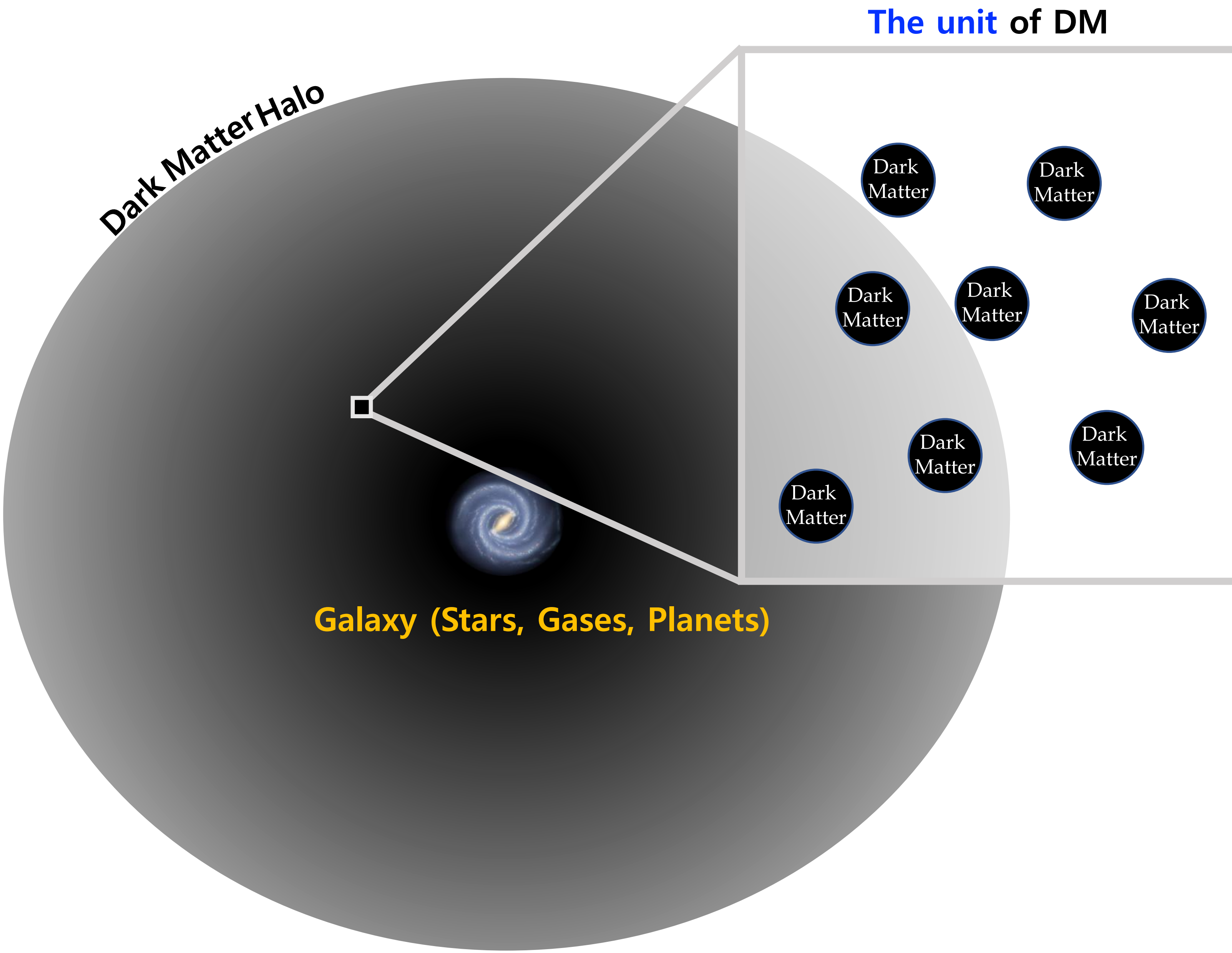


Image from SDSS

Large Scale Structure of the Universe

What is the nature of dark matter?



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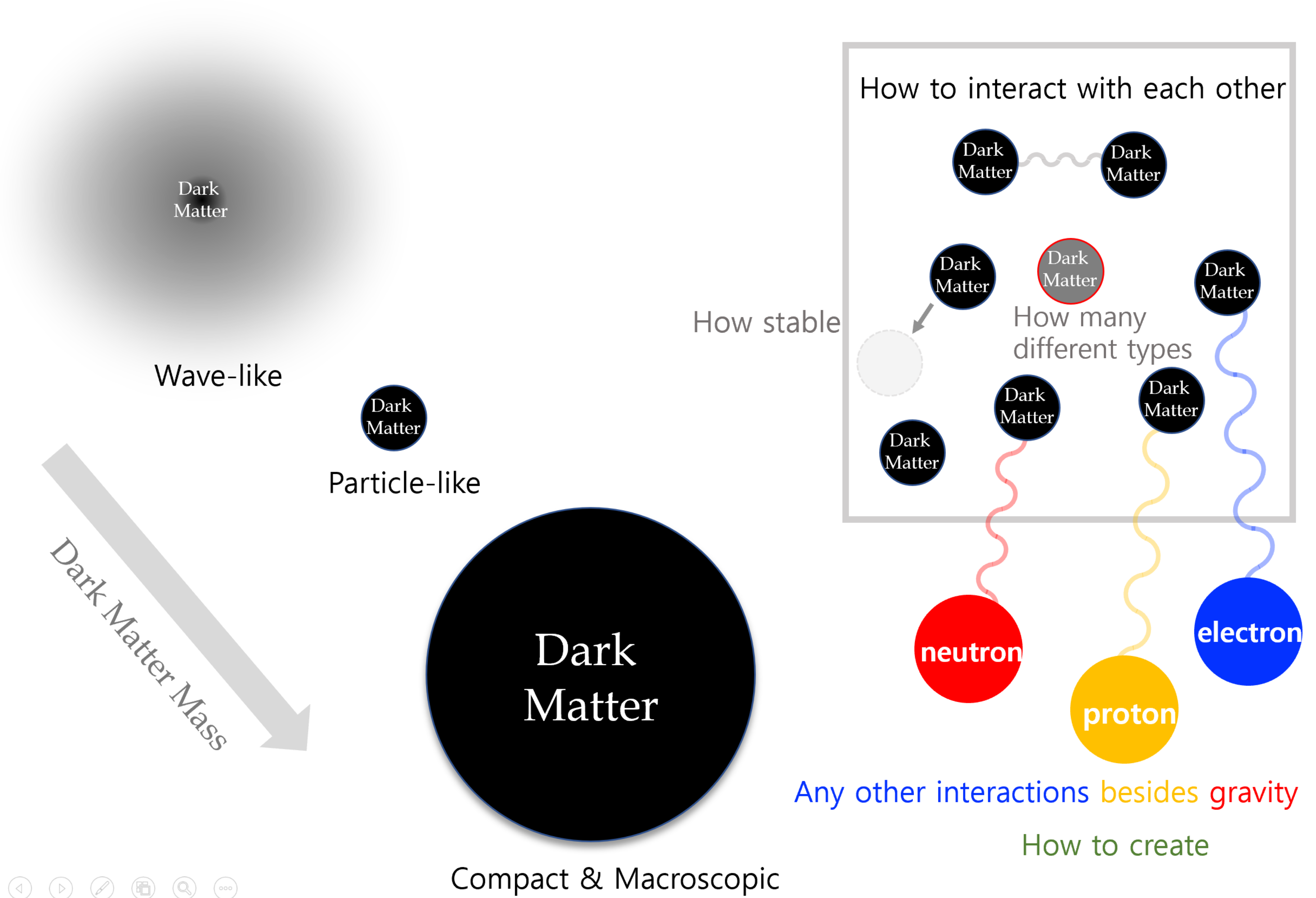
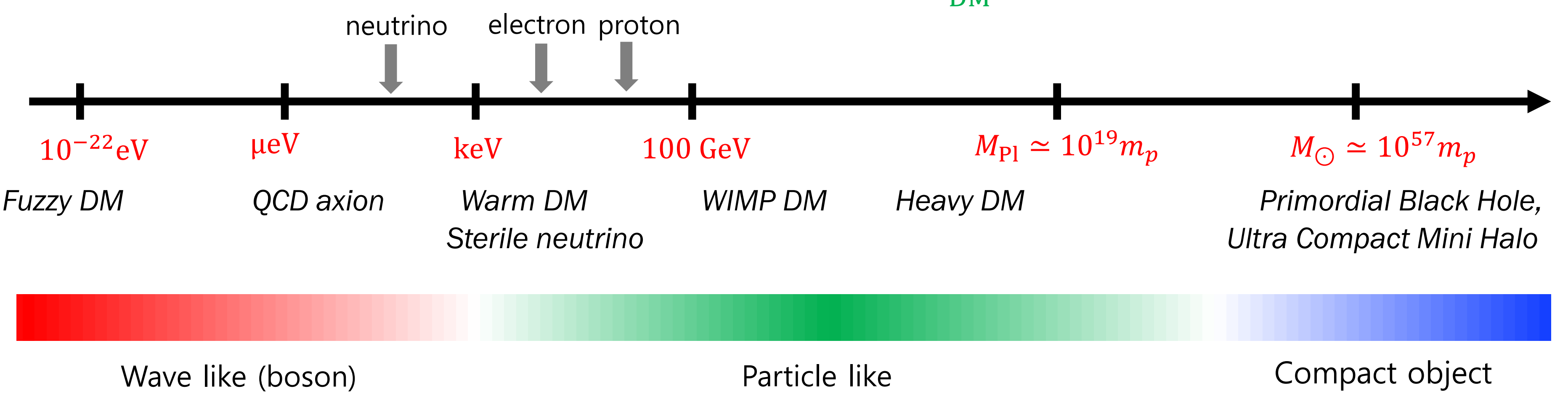


Candidates of DM for its mass

$$\bar{\rho}_{\mathrm{DM}} = M_{\mathrm{DM}}\, \bar{n}_{\mathrm{DM}} = (0.25 - 0.27)\bar{\rho}_{\mathrm{tot}} \simeq 1.2 \times 10^{-6}\mathrm{GeV/cm^3}$$

$$G = \frac{1}{M_{\mathrm{Pl}}^2} \quad \left(M_{\mathrm{Pl}} = \sqrt{\frac{\hbar c}{G}} \simeq 1.22 \times 10^{19}\mathrm{GeV} \right)$$

$\bar{n}_{\mathrm{DM}}\lambda_{\mathrm{Compton}}^3 \gg 1$ $\quad$ $R_{\mathrm{BH}} = 2GM_{\mathrm{DM}} \ll \lambda_{\mathrm{Compton}} = \frac{1}{m_{\mathrm{DM}}} \ll \bar{n}_{\mathrm{DM}}^{-1/3}$ $\quad$ $R_{\mathrm{BH}} \gg \lambda_{\mathrm{Compton}}$



Candidates of DM for its mass and interactions

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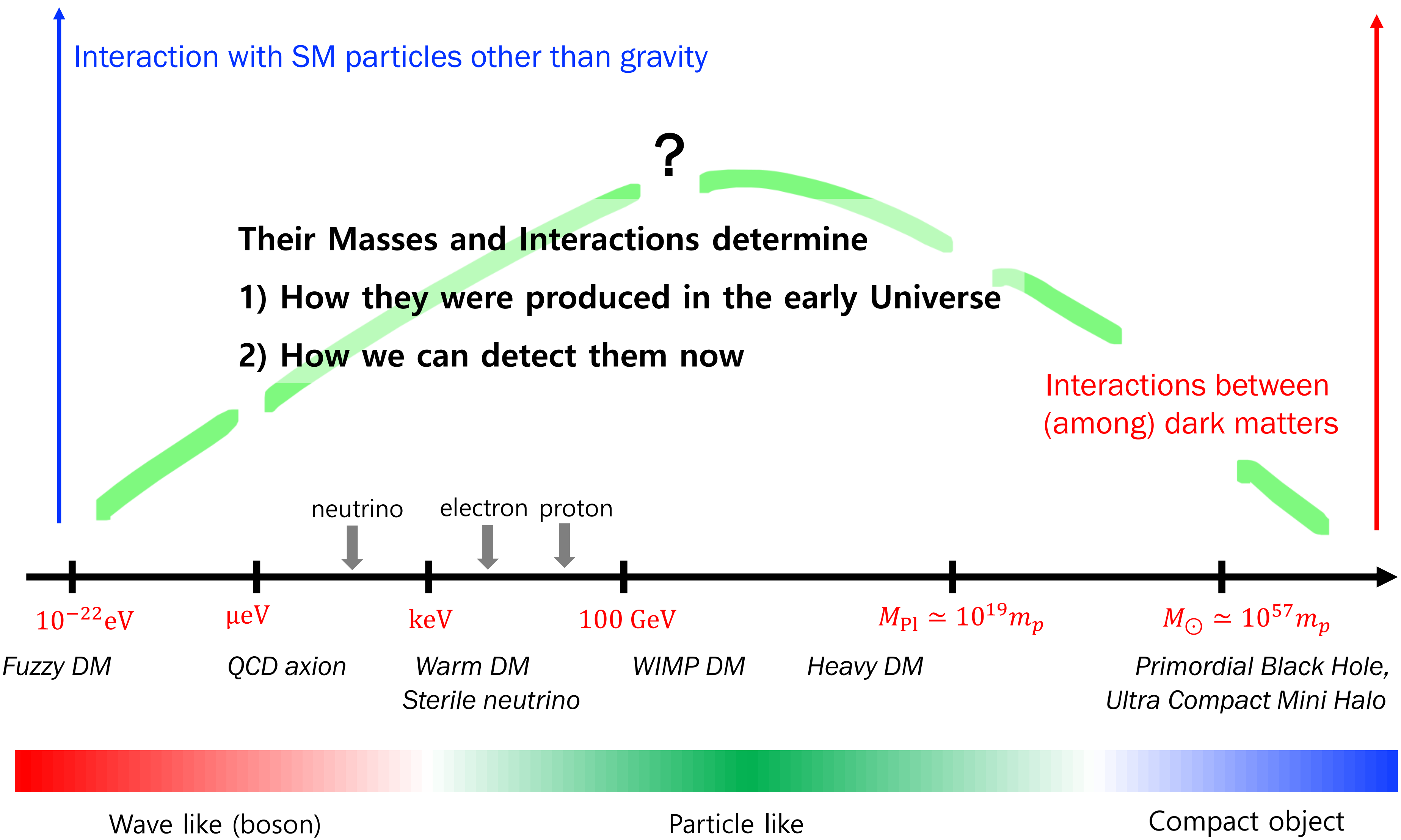
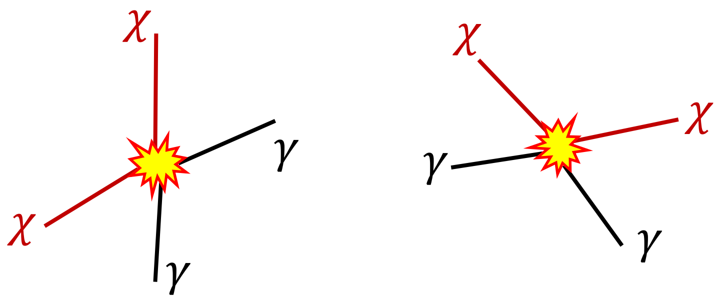


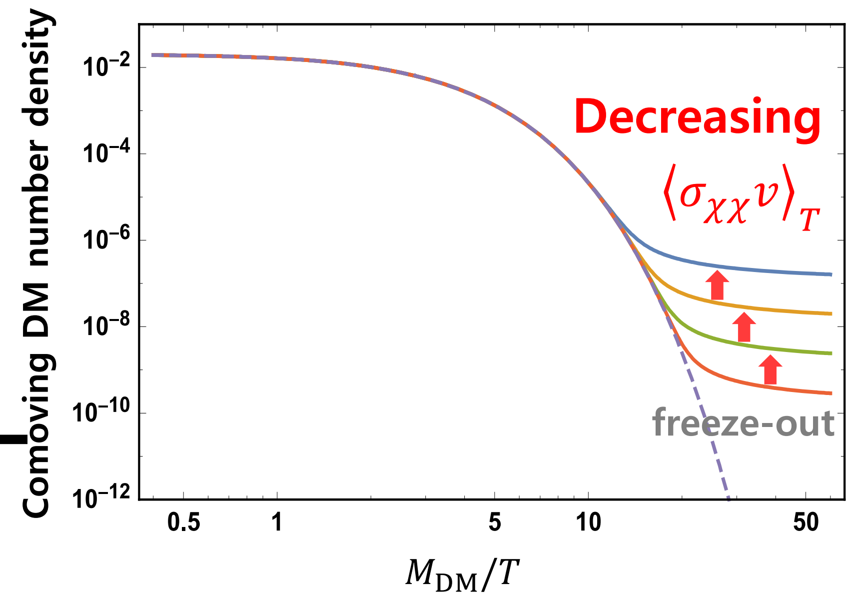
Thermal Dark Matter

Weakly Interacting Massive Particle (WIMP) : $(\mathbf{0.1} \sim \mathbf{1000})\ \mathrm{GeV}$

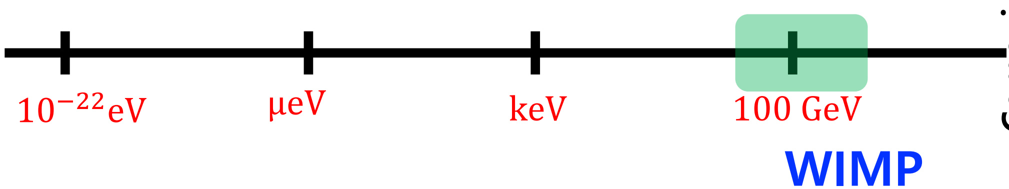
Dark matter density is determined by its annihilation cross-section



$$\Omega_{\mathrm{DM}} h^2 = 0.1 \left(\frac{3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\chi\chi} v \rangle_T} \right)$$



WIMP ($M_{\mathrm{DM}} \sim 100\ \mathrm{GeV}$, $\alpha_\chi \sim 0.01$)
is one of the best candidates for DM



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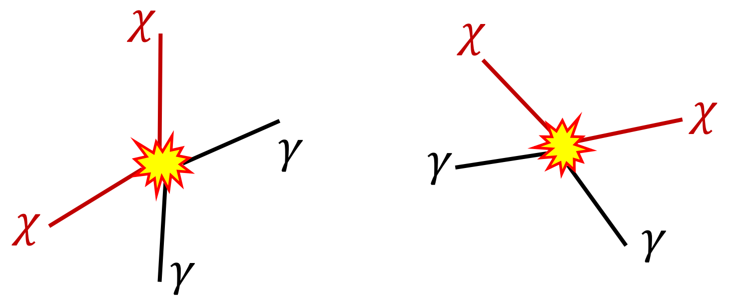

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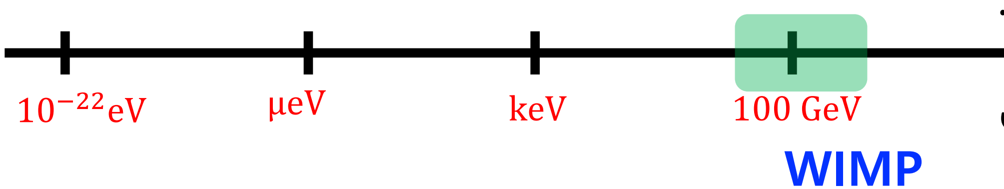

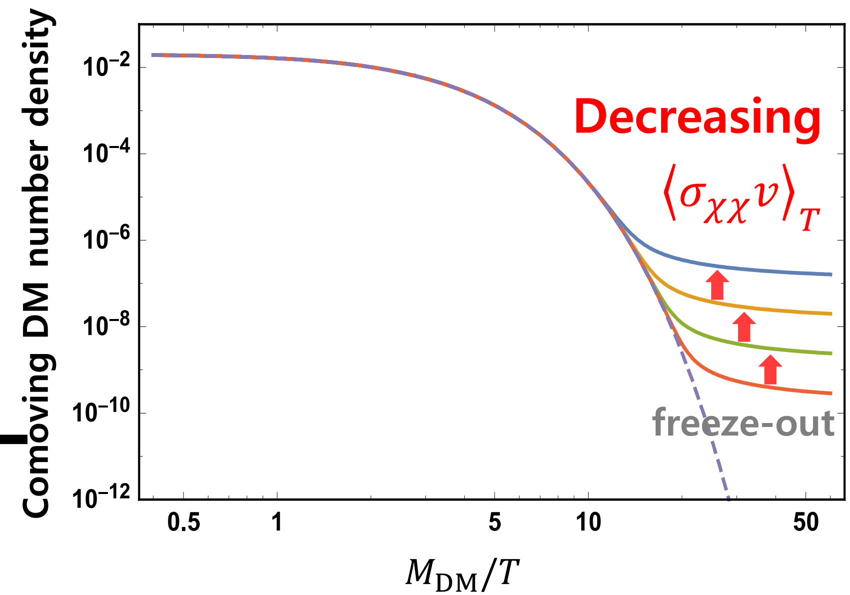

Dark matter cross-section is limited by its mass and the velocity

The perturbative Unitarity bound: $\langle \sigma_{\chi\chi} v \rangle_T \leq \dfrac{4\pi}{M_{\rm DM}^2 \langle v \rangle_T}$ $\quad \Omega_{\rm DM} h^2 \geq 0.1 \left(\dfrac{M_{\rm DM}}{130\ \mathrm{TeV}} \right)^2$

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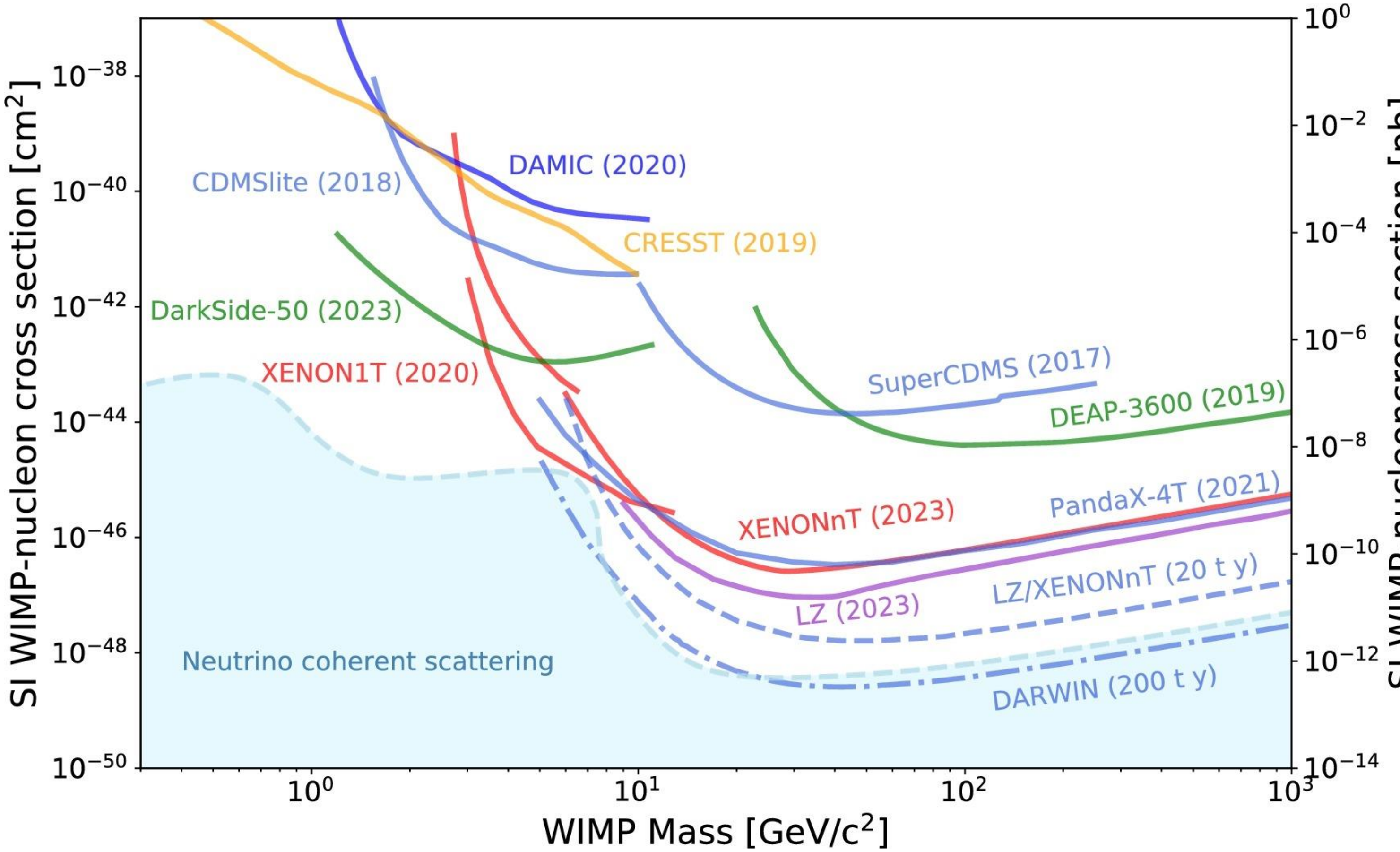

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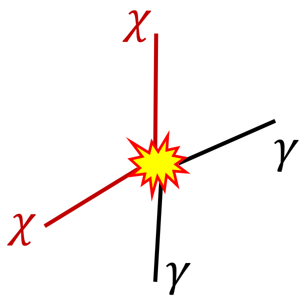

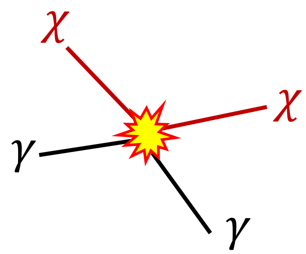

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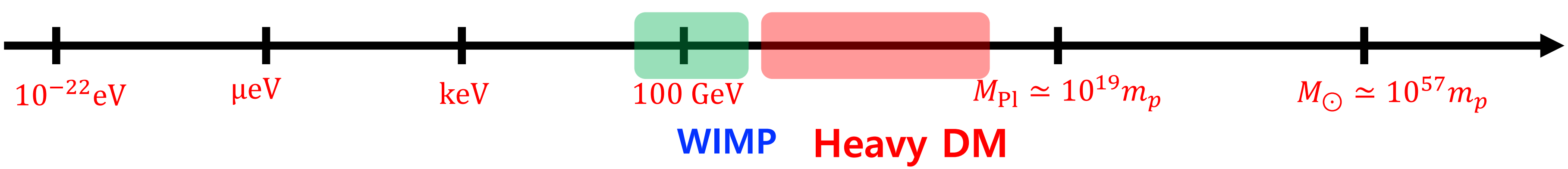


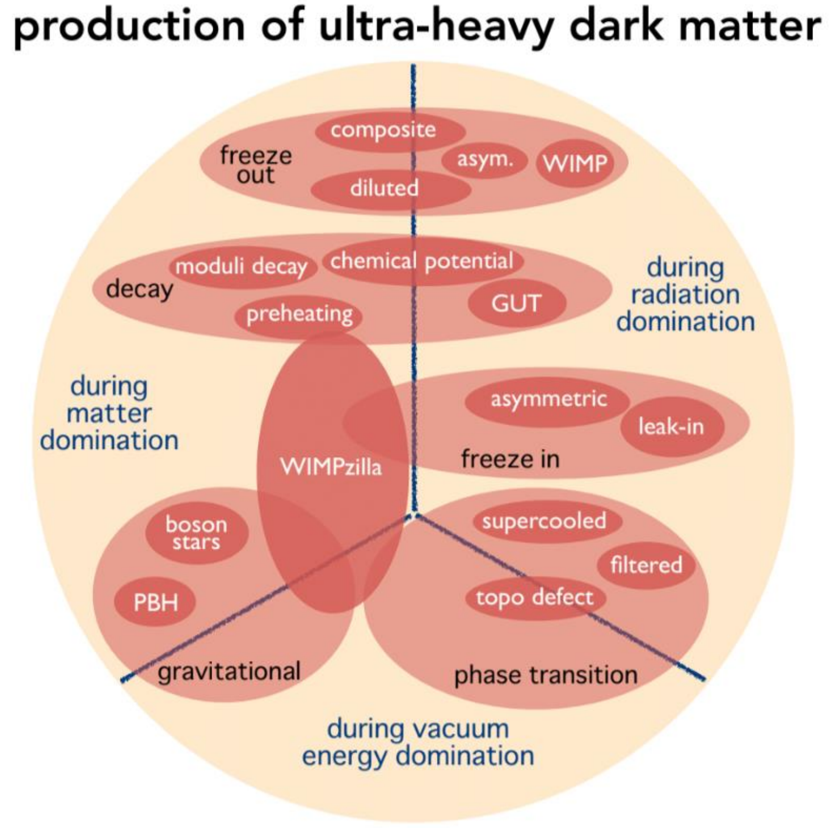
HOWEVER, No hints for WIMP DM so far:
Strong motivation of the beyond WIMP paradigm

Thermal DM Beyond the Unitarity Bound

How can the Unitarity bound be overcome to allow various DM masses?

$$\Omega_{\rm DM}h^2 \geq 0.1 \left(\frac{M_{\rm DM}}{130\ \rm TeV}\right)^2$$

What are the predictions for observables?



Snowmass2021 Ultra-heavy particle dark matter arXiv:2203.06508

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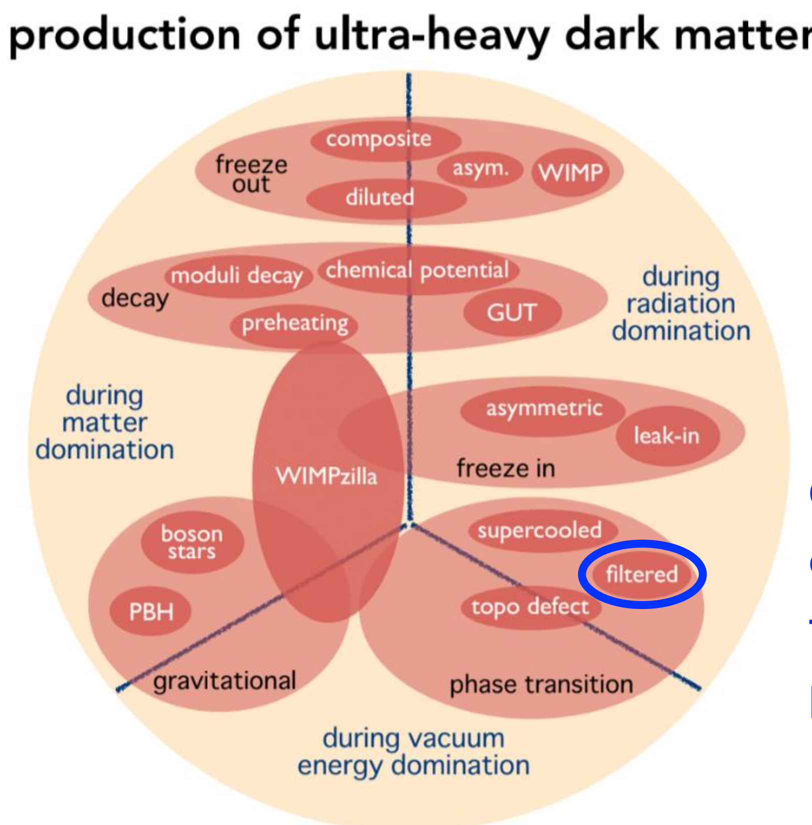

One can think the origin of dark matter mass tightly related with production mechanism

Snowmass2021 Ultra-heavy particle dark matter arXiv:2203.06508

Origin of Mass for particle DM: Expectation value of scalar field

Nonzero expectation value of the scalar field imposes DM mass

Temperature drops: **수증기 → 이슬**

Universe expands→ Temperature decreases → **Bubbles of scalar condensation form!**

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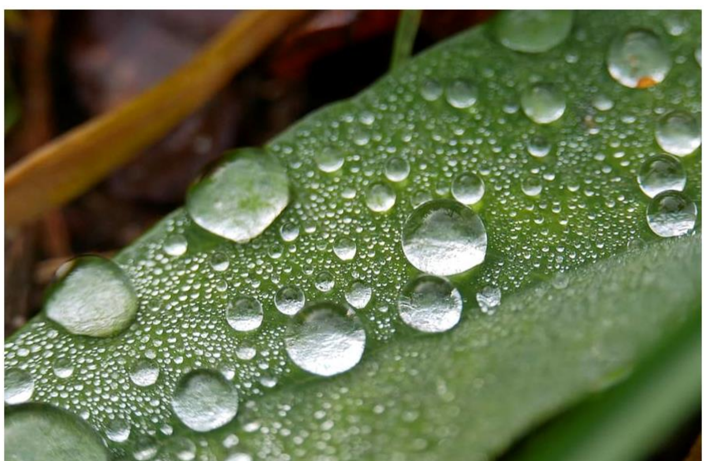
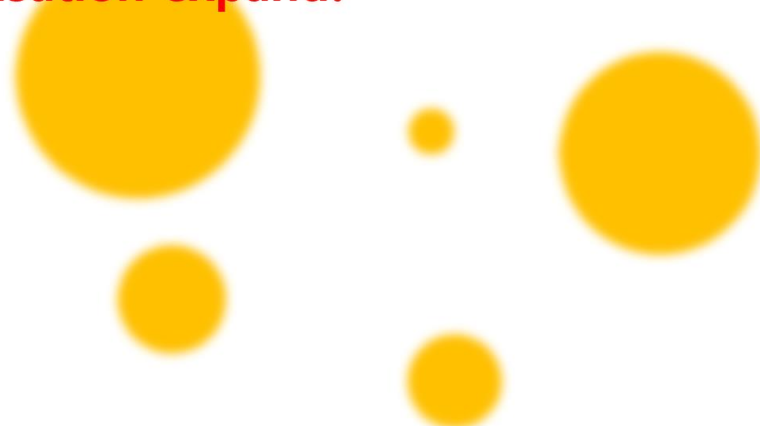


Universe expands→ Temperature decreases → **Bubbles of scalar condensation expand!**



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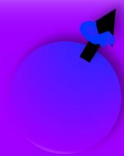


Higgs field (giving mass to the elementary particles)

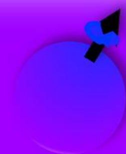
Nonzero expectation value of the scalar field imposes DM mass

Scalar Field (giving DM Mass)

Temperature drops: **수증기 → 이슬**

Universe expands→ Temperature decreases → **Bubbles of scalar condensation collide!**

Origin of Mass for particle DM: Expectation value of scalar field



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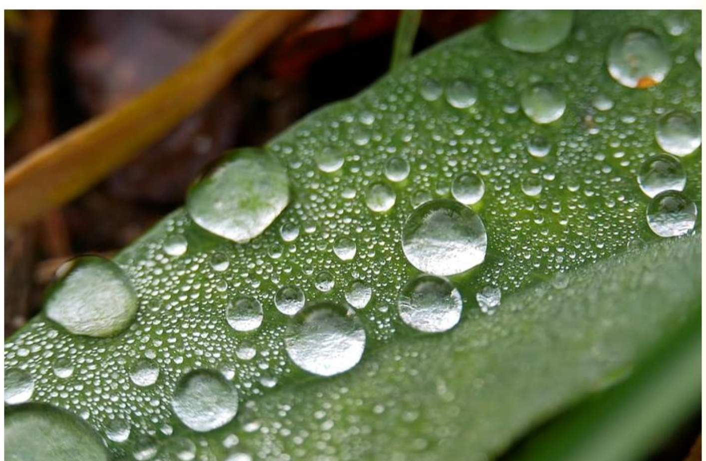


Universe expands→ Temperature decreases → **Bubbles of scalar condensation fill the Universe** → **Cosmic 1st order phase transition**

Origin of DM mass & its abundance

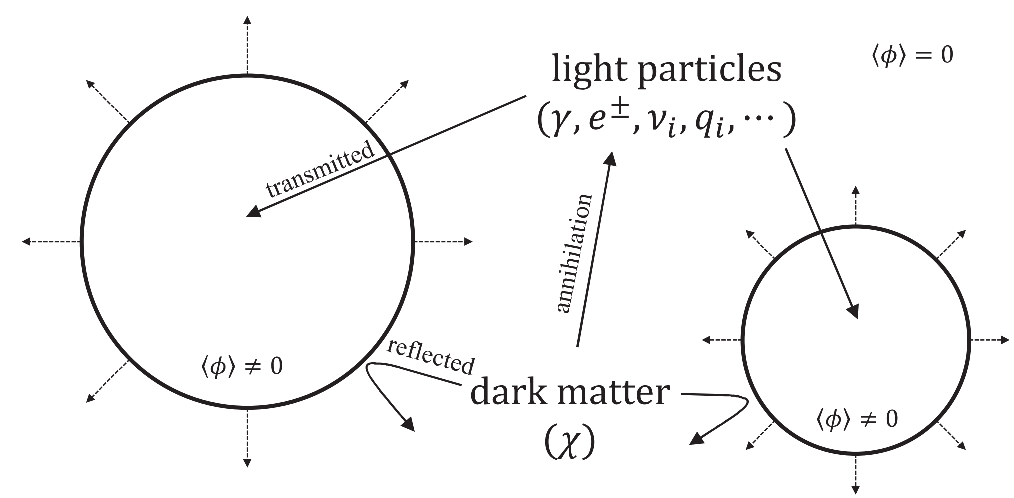
Proposing the mechanism working in a wide range of DM mass

D. Chway, T. H. Jung, ***CSS***
Phys. Rev. D 101, 095019 (2020)

Filtering-out Mechanism

Exponential suppression of heavy DM relic by Filtering Effects

$$\rho_{\text{DM}} \to (\rho_{\text{DM}})_{\text{before}} e^{-M/2\gamma_w T_c} = \text{present value}$$



Cosmic 1st order phase transition
→ Production of Gravitational Waves

Simulation from D. Cutting et al. 1802.05712

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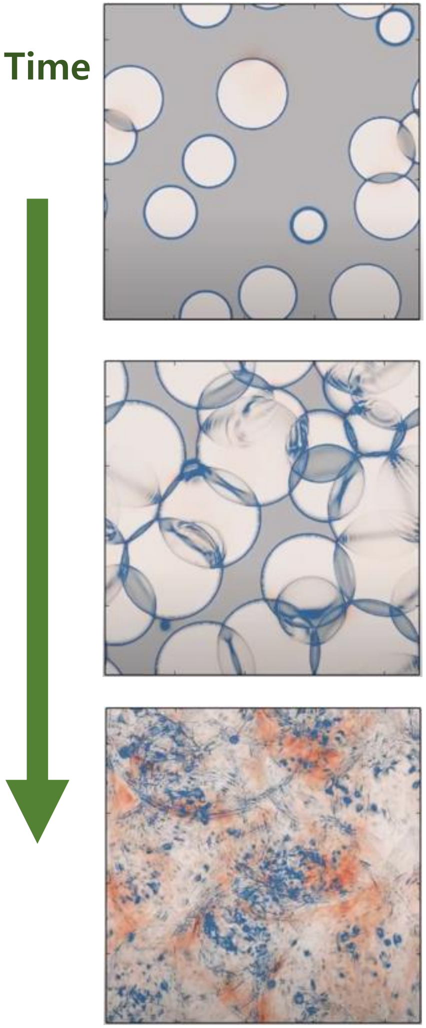

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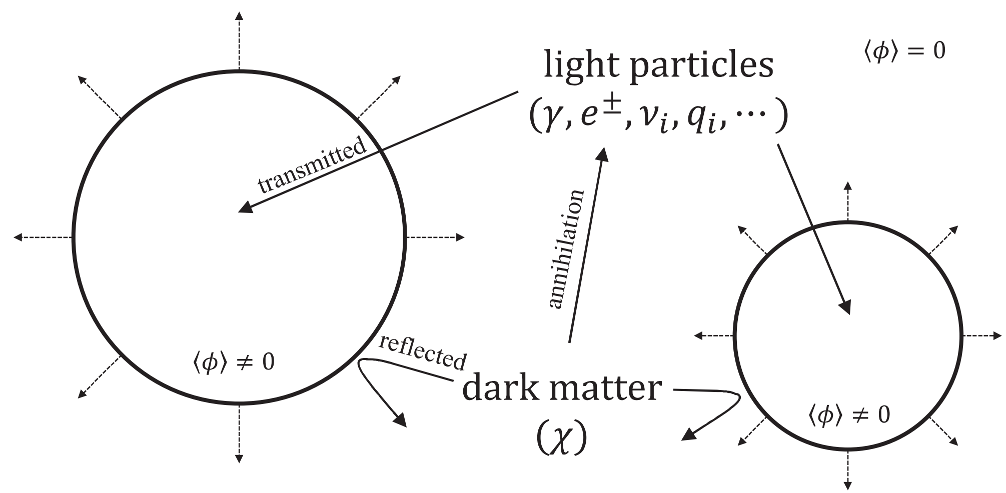
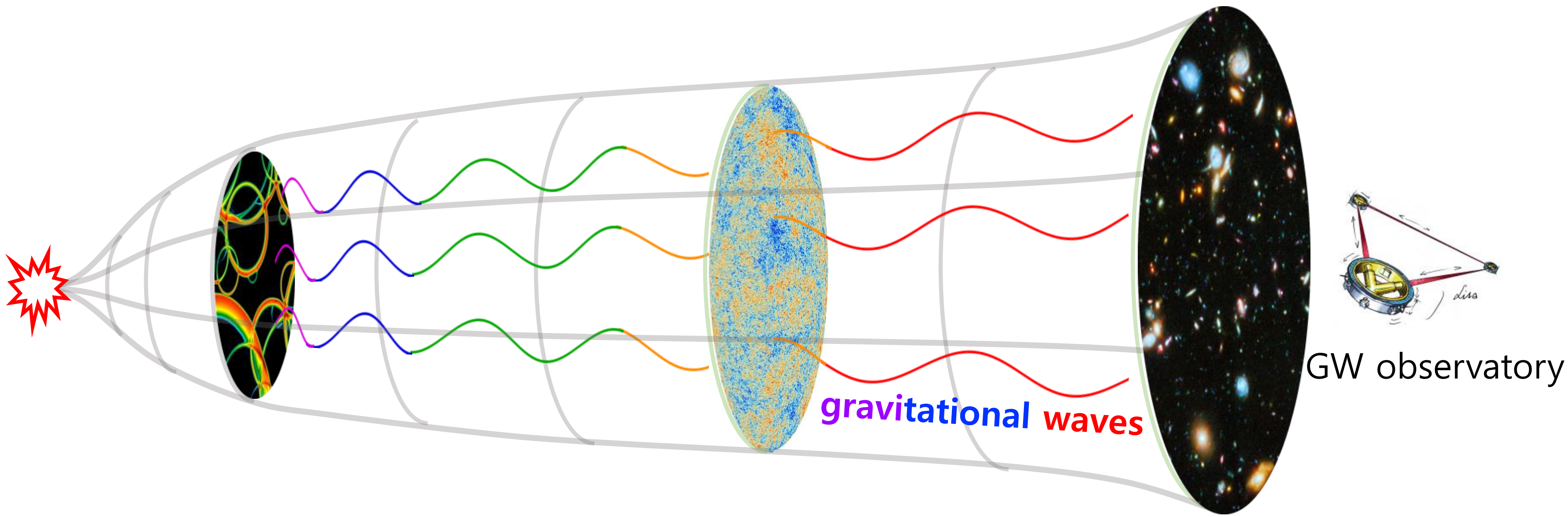


Cosmic 1st order phase transition
→ Production of Gravitational Waves

Understanding the origin of DM by GW observations

Stochastic Gravitational Waves

Proposing the mechanism working in a wide range of DM mass

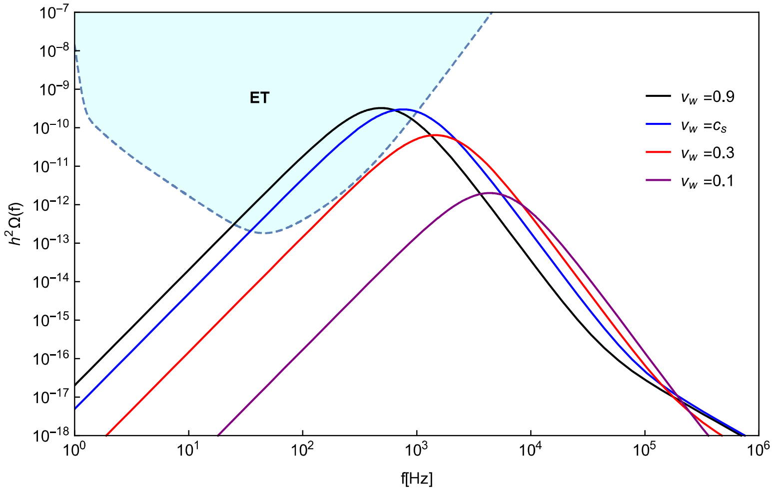


Understanding the origin of DM by GW observations

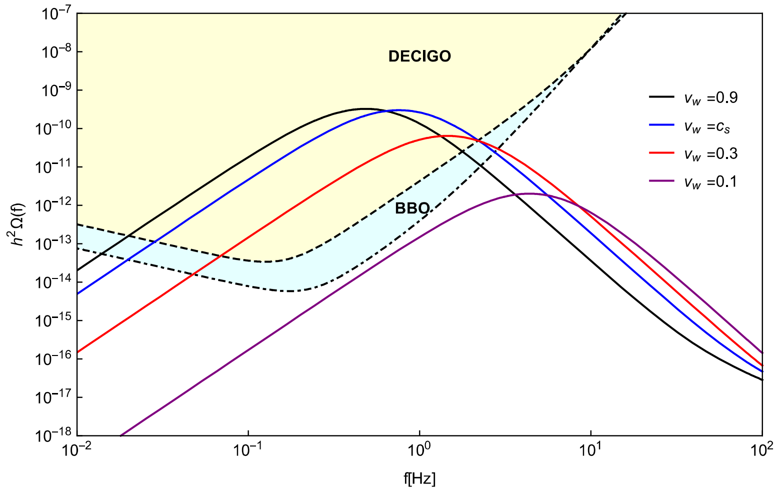
Origin of DM mass & GW observations

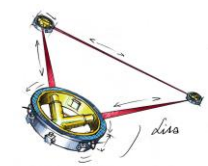
Proposing the mechanism working in a wide range of DM mass

Mass=100PeV



Mass=100TeV





GW observatory

M. Ahmadvand 2108.00958

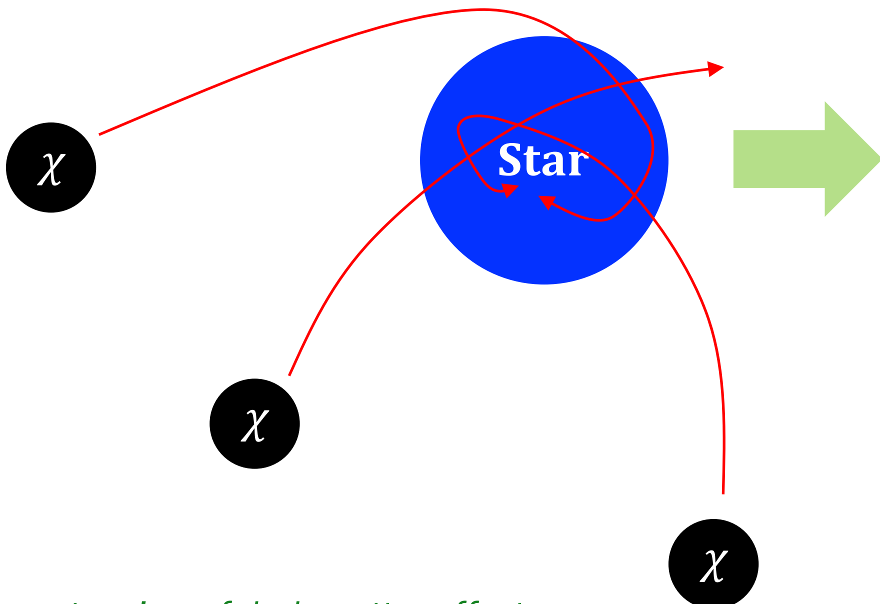
Understanding the origin of DM by GW observations

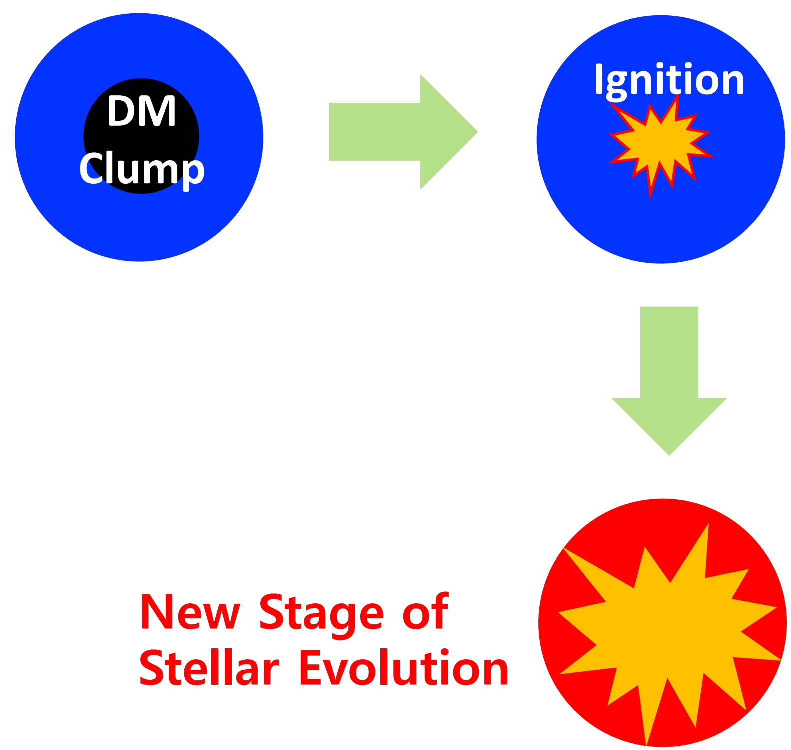
DM Probe via Stellar Evolution

The mechanism working in a wide range of DM mass : Interaction with the SM particles

Dark Matter around the Star can be captured and accumulated in the core of the star.

It can trigger the earlier nuclear reaction in a certain stage of stellar evolution by new heating sources.



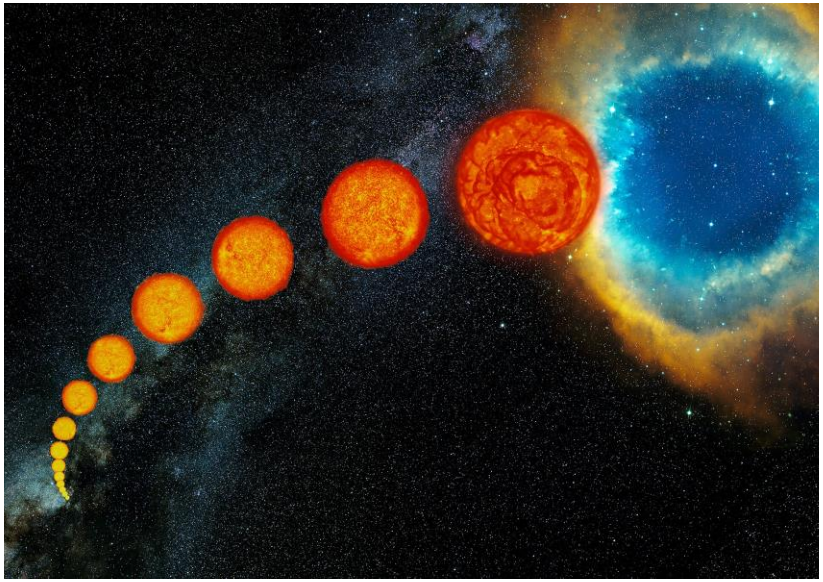


Recent review of dark matter effects on compact stars such as White Dwarf, Neutron Stars Phys.Rept. 1052 (2024) 1-48 arXiv:2307.14435

Heavy DM in WD: 1505.04444, 1505.07464, 1805.07381, 1905.00395, 2203.09054, 2404.16272, etc.

Steller Evolution

(Red Giant and the Helium Flash)

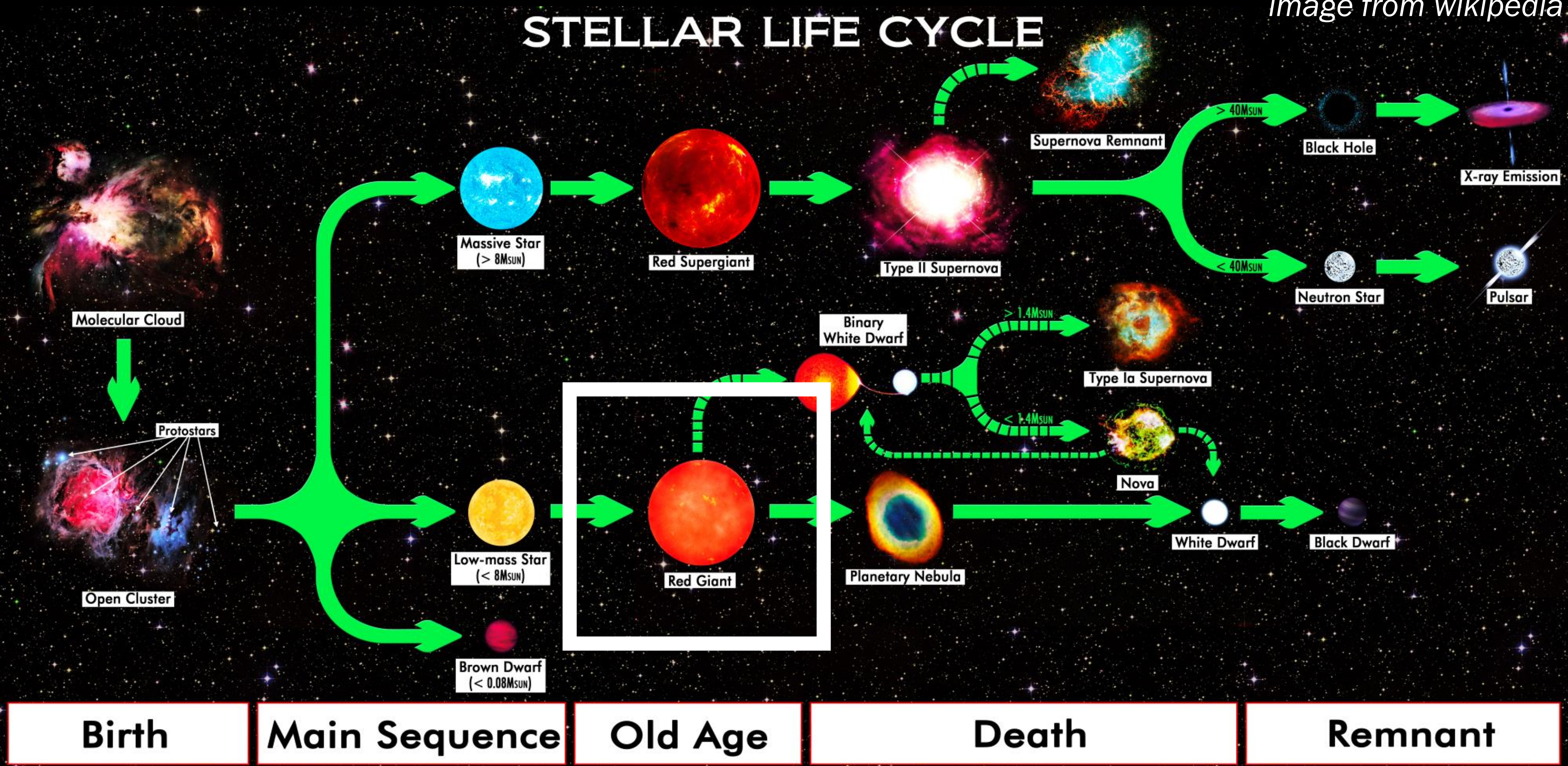


Stellar Evolution

Star: an astronomical object consisting of a luminous spheroid of plasma

held together by its own gravity

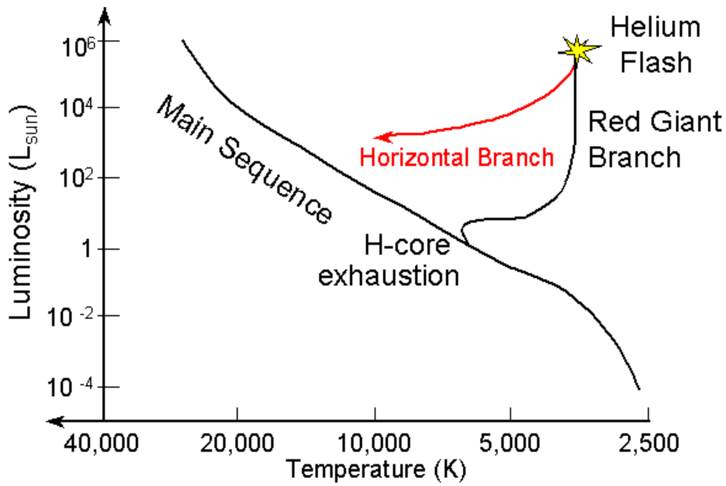
image from wikipedia



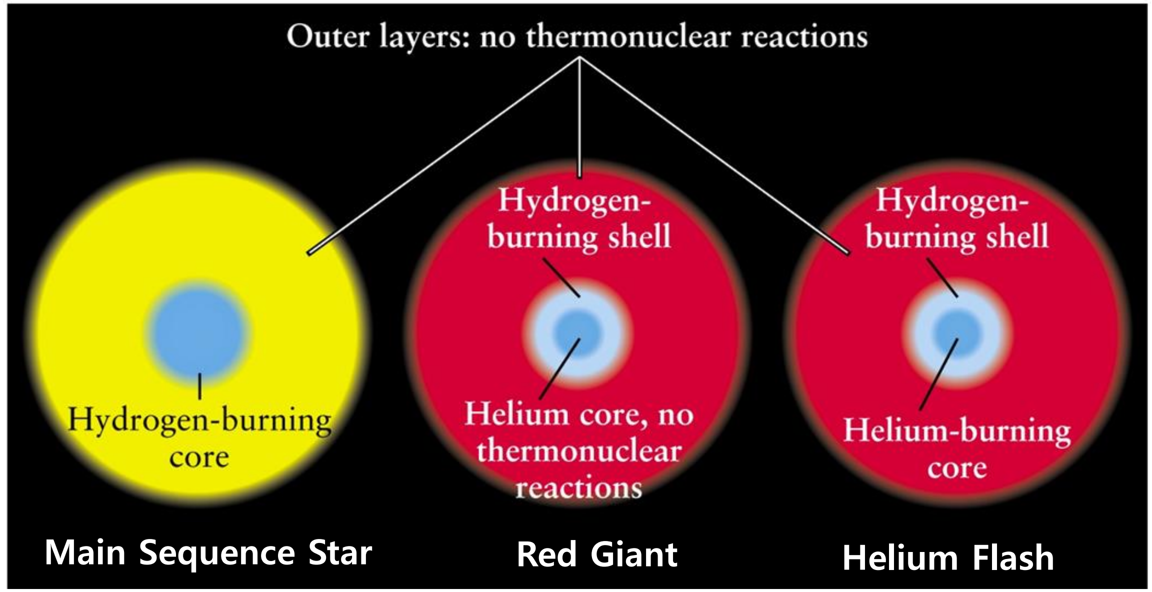
Stellar evolution could be changed if there is an extra energy heating/leakage source

Low Mass Stellar Evolution

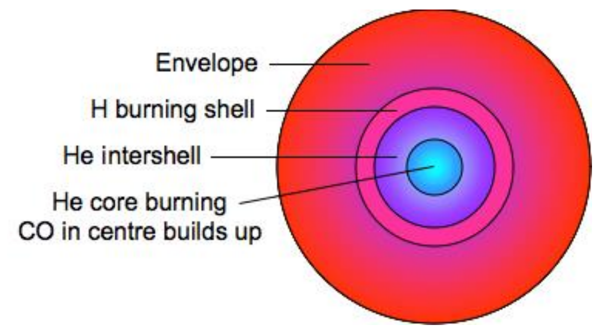
$(0.5M_\odot < M < 5M_\odot)$



Graphic by R. Pogge



Each phase experiences a different nuclear reaction



Horizontal Branch

Low Mass Stellar Evolution

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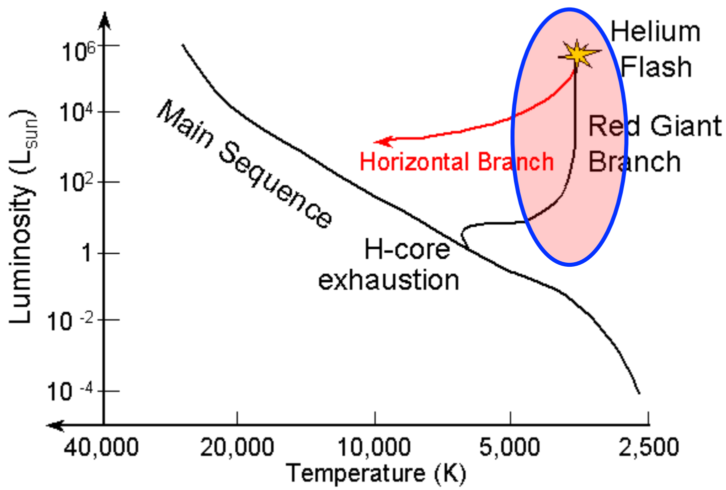

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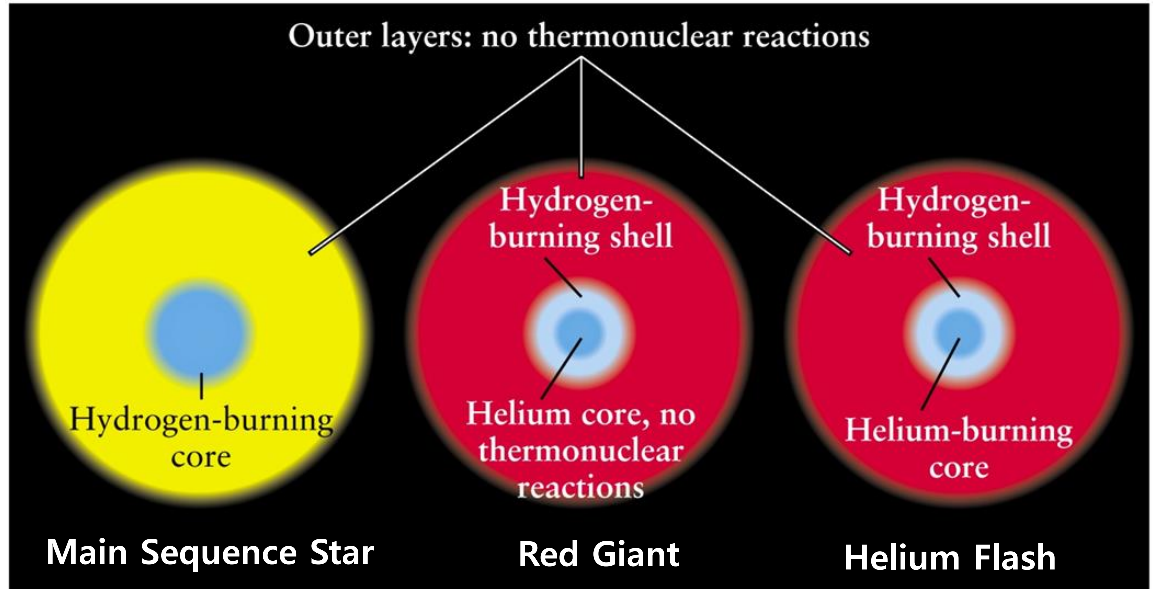
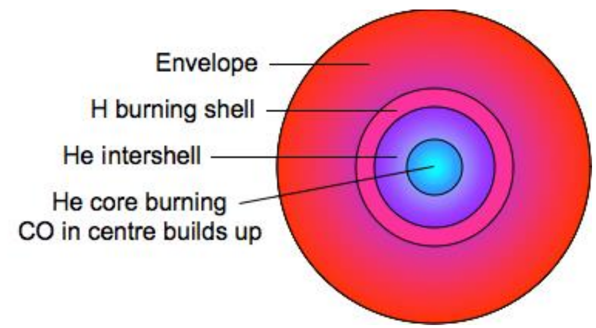




Horizontal Branch

Each phase experiences a different nuclear reaction

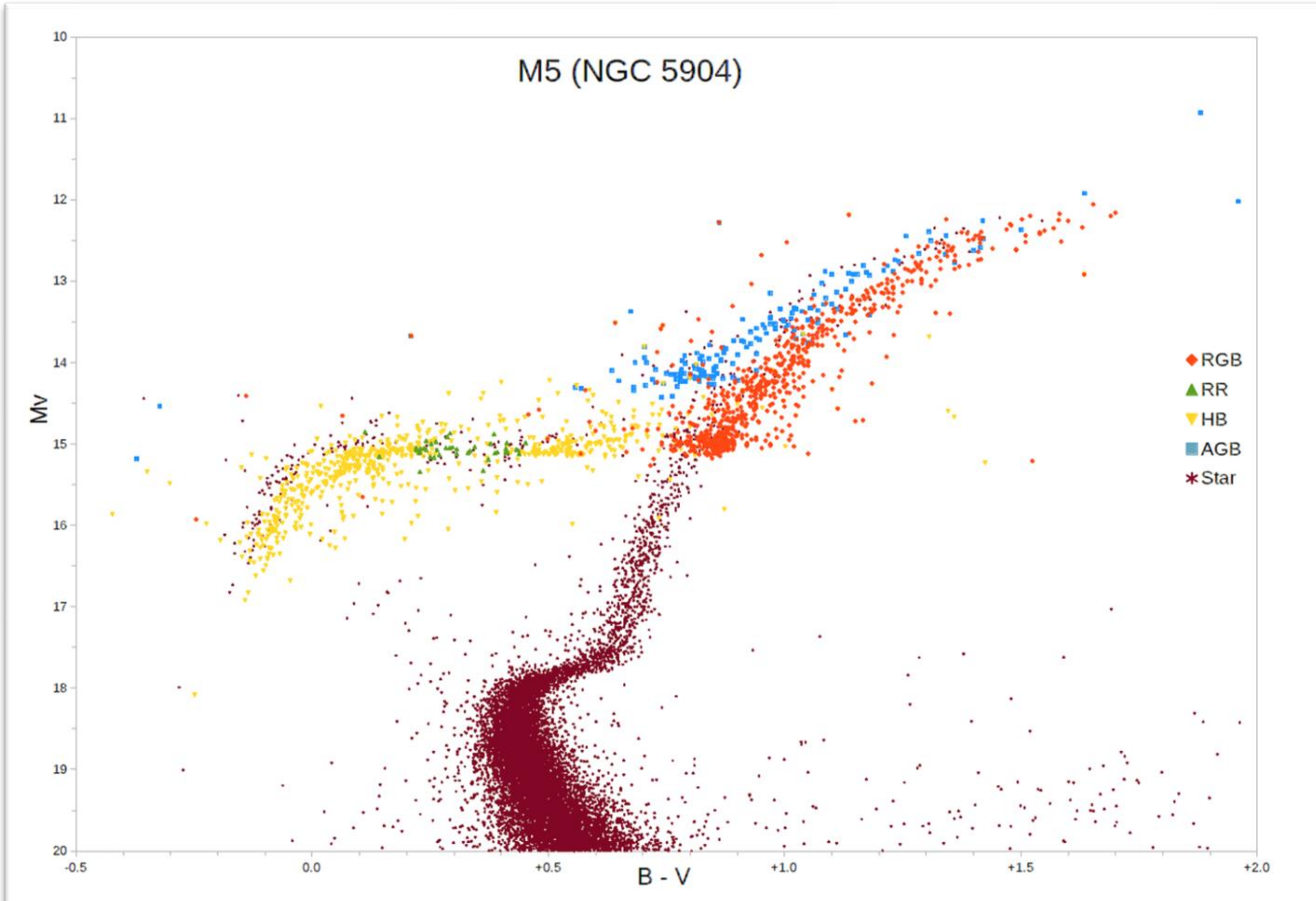
Main Sequence (core H fusion → He) O(10Gyr)

→ Red Giant (inert He core, shell H fusion → He) O(1Gyr)

→ Helium Flash (with triple alpha (He) fusion → C in the core) O(minutes)

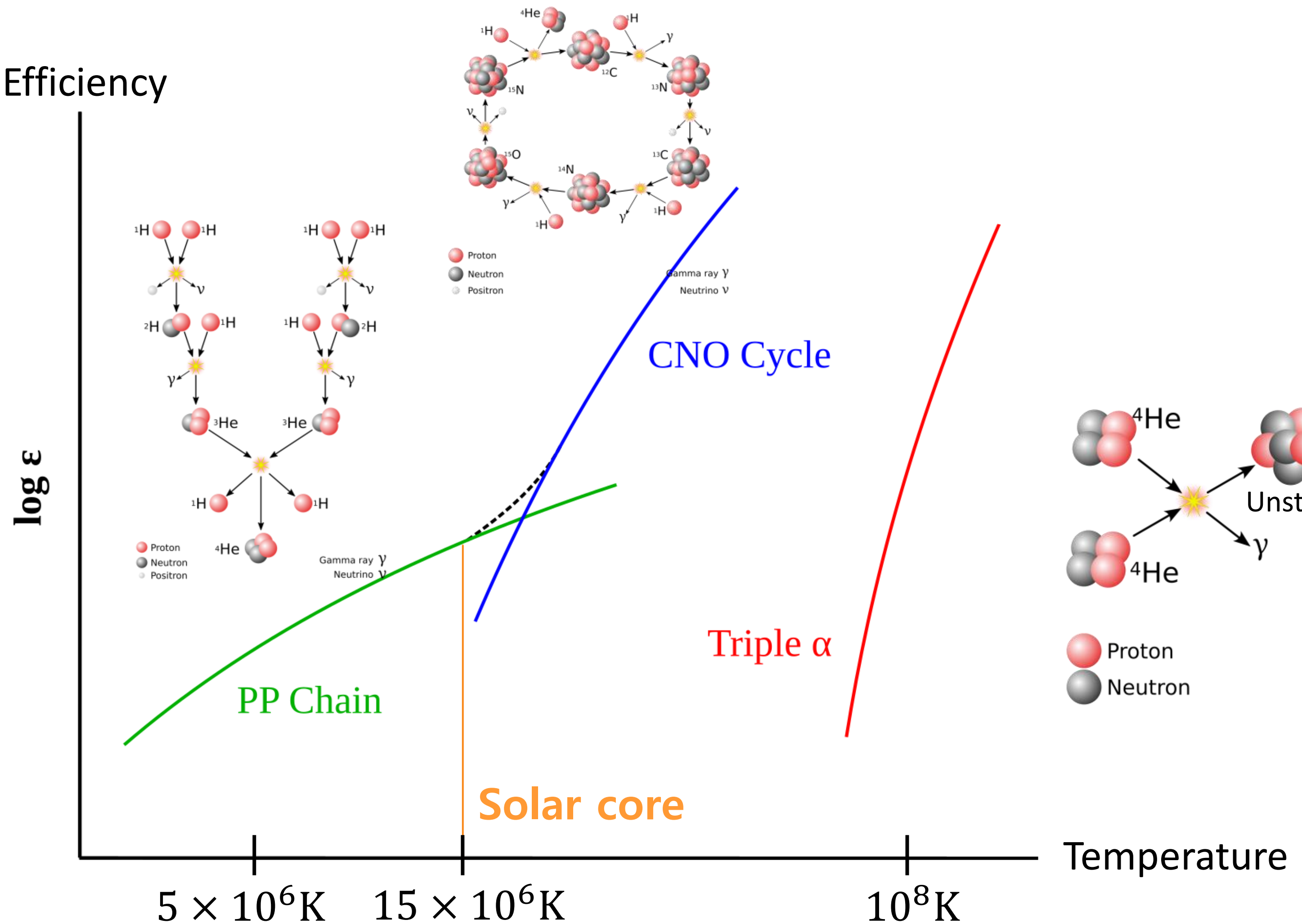
→ Horizontal Branch (core He fusion → C+O) O(0.1Gyr)

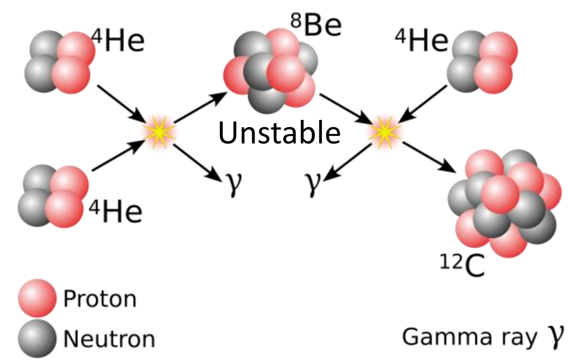
Low Mass Stellar Evolution



Red Giant and Helium Flash

The Nuclear Reactions (**especially triple alpha process**) highly depend on the temperature





Red Giant and Helium Flash

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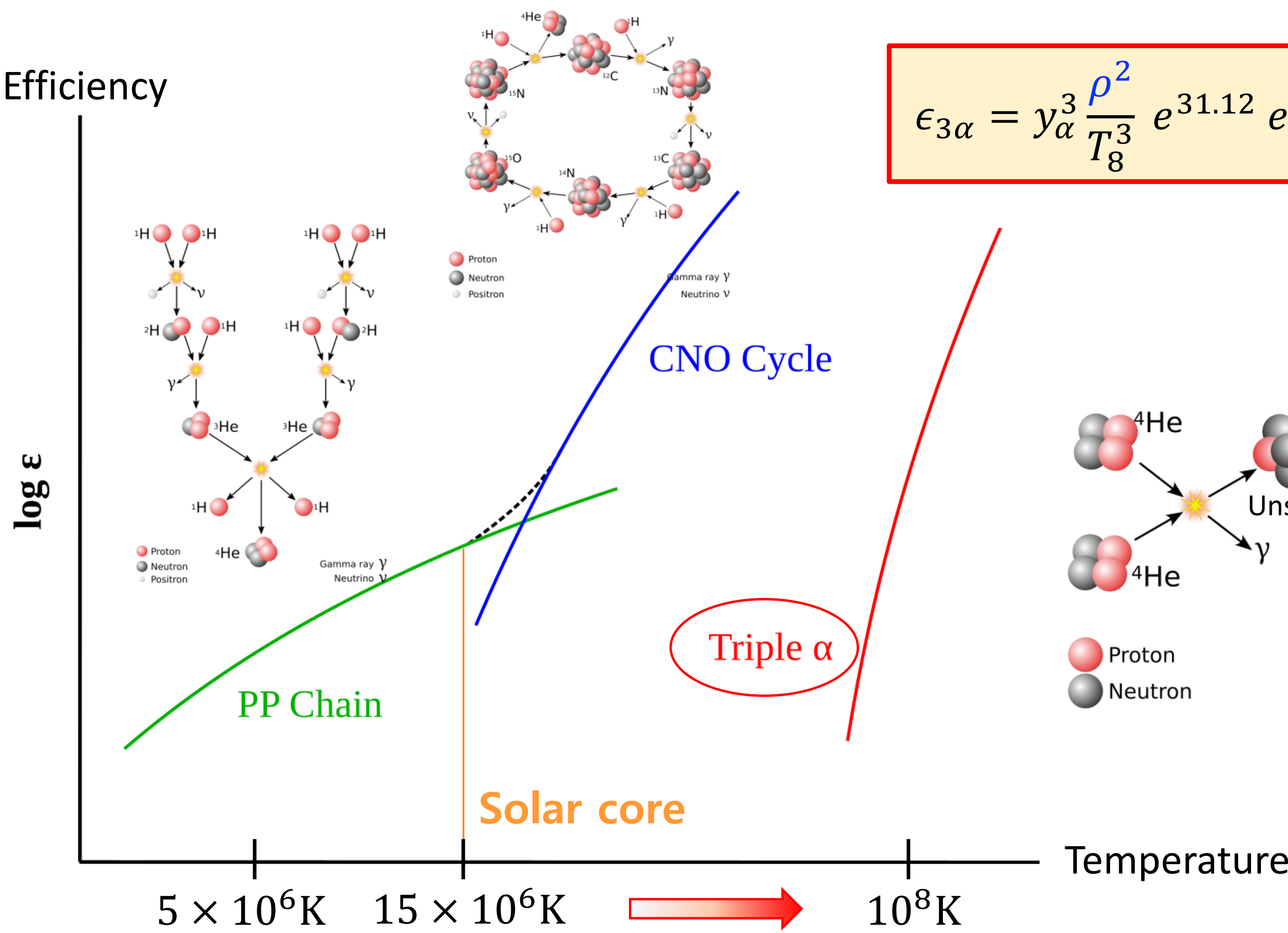
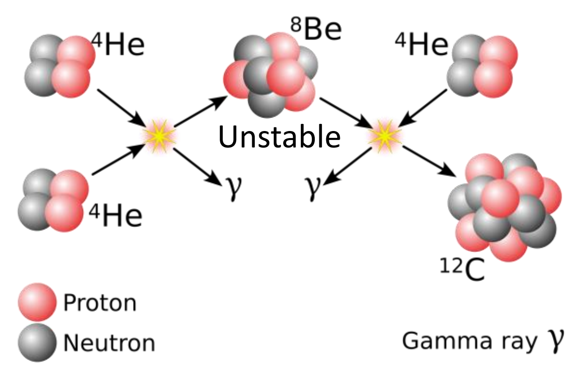
$$\epsilon_{3\alpha} = y_\alpha^3 \frac{\rho^2}{T_8^3} e^{31.12} e^{-\frac{44.0}{T_8}} \frac{\text{erg}}{\text{g sec}}$$

$$\left(T_8 = \frac{T}{10^8 \text{K}} \right)$$





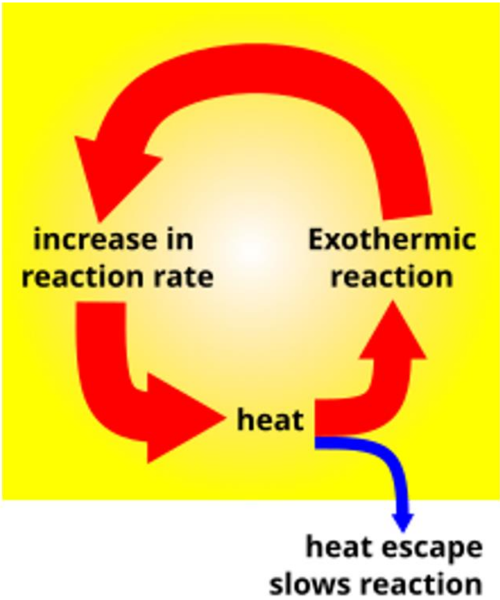
Red Giant and Helium Flash

The Nuclear Reactions (**especially triple alpha process**) highly depend on the temperature

The Helium Flash

Fusion Ignition in degenerate core of the RG: a bomb ready to explode

➔ **Runaway Helium Burning**: 100 billion times the solar output in a few seconds



Red Giant and Helium Flash

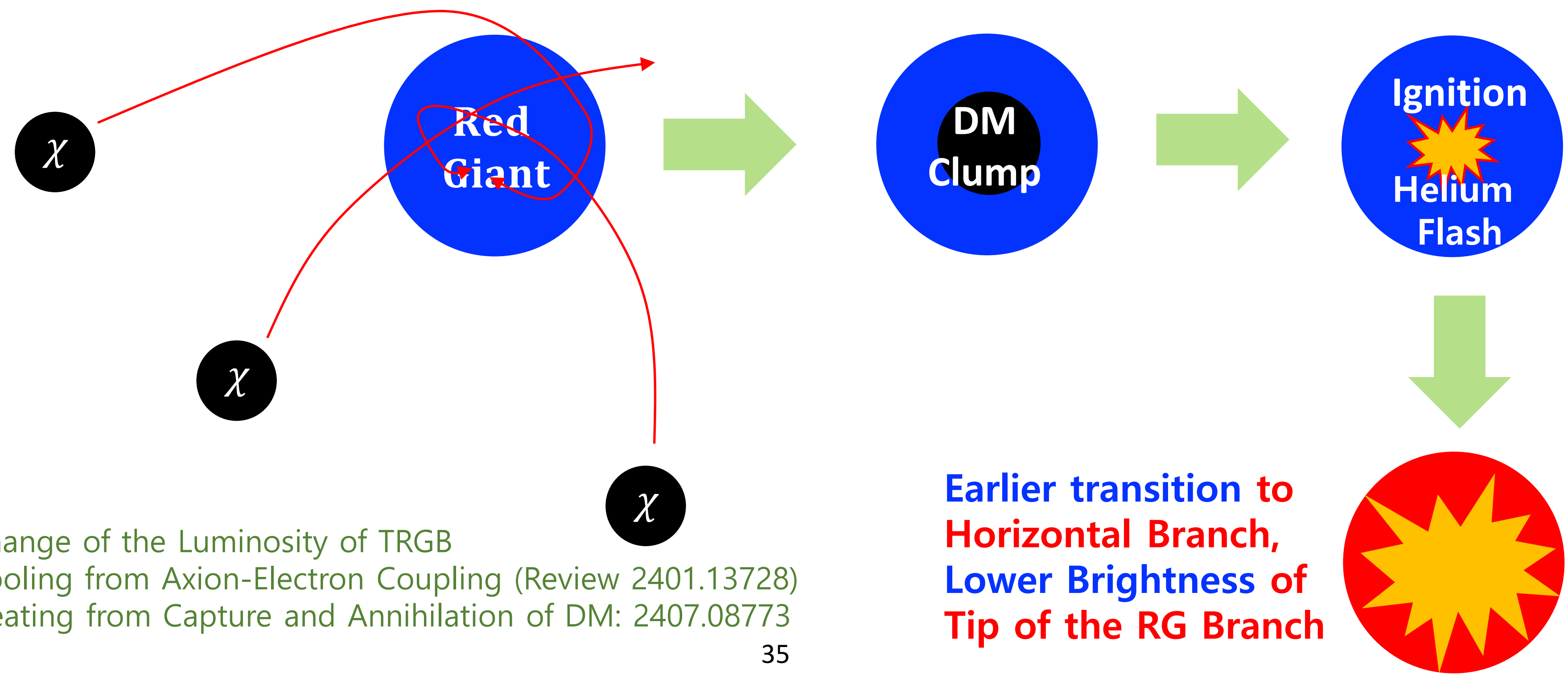
The Nuclear Reactions (**especially triple alpha process**) highly depend on the temperature

The Helium Flash

Fusion Ignition in degenerate core of the RG: a bomb ready to explode

➔ **Runaway Helium Burning**: 100 billion times the solar output in a few seconds

Dark Matter could **be a new ignition source for the triple-alpha process** due to its heating effects at the core of Red Giant.



Earlier transition to Horizontal Branch, Lower Brightness of Tip of the RG Branch

Change of the Luminosity of TRGB
Cooling from Axion-Electron Coupling (Review 2401.13728)
Heating from Capture and Annihilation of DM: 2407.08773

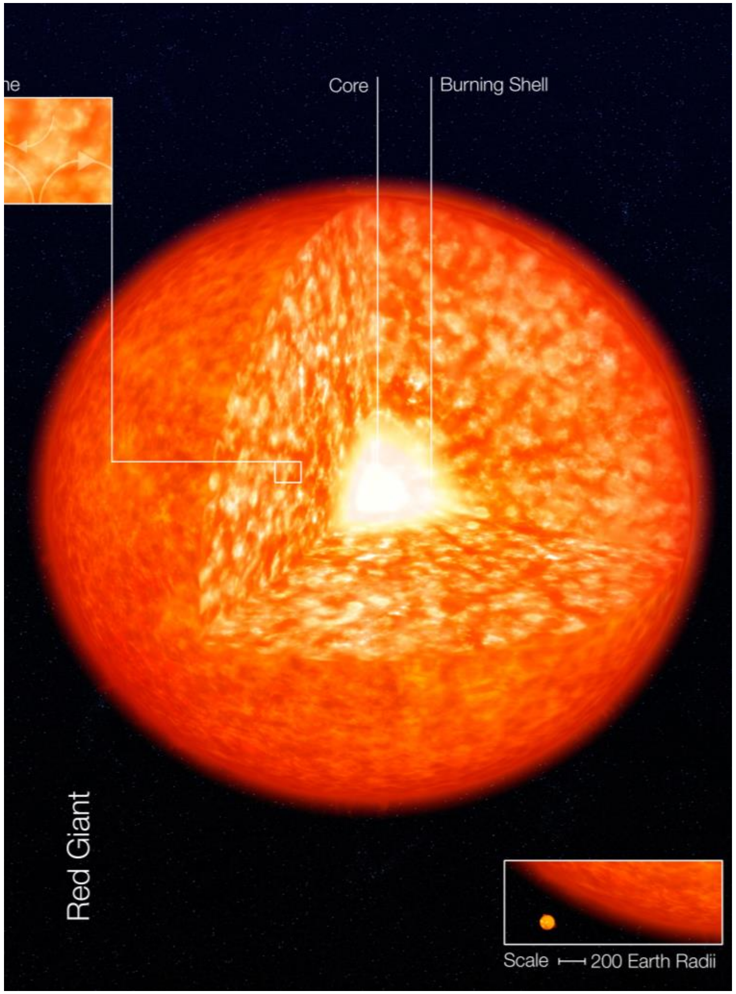
Dark Matter Probe via Red Giant

Sougata Ganguly, Minxi He, CSS, Oscar Straniero, Seokhoon Yun In progress

Red Giant – Dark Matter Interactions

Helium core governs properties of star

- Mass fractions of O(1)$M_\odot$
- Density up to $\rho_{\rm RG} \sim 10^6$ g/cm^3, Radius of $R_{\rm RG} \sim 10^4$km
- Maintained mainly by degenerate electron pressure not by thermal pressure
- The core temperature is gradually increasing to $\mathrm{O}(10^8)$K, which initiates triple alpha fusion process.



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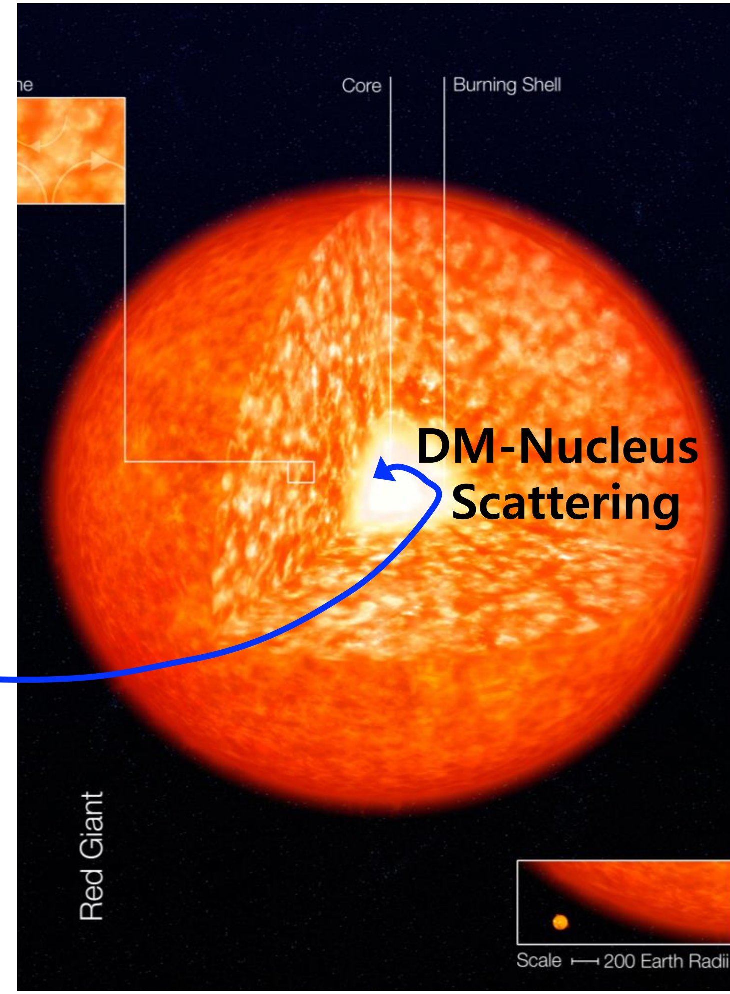
χ



Dark Matter can be captured by the nucleon-dark matter elastic scattering and gravitational attraction.

Considering the cross section $\sigma_{N\chi}$, and the DM mass m_χ, we can estimate the evolution of DM for

DM Capture → Ingress (trapped inside the core)

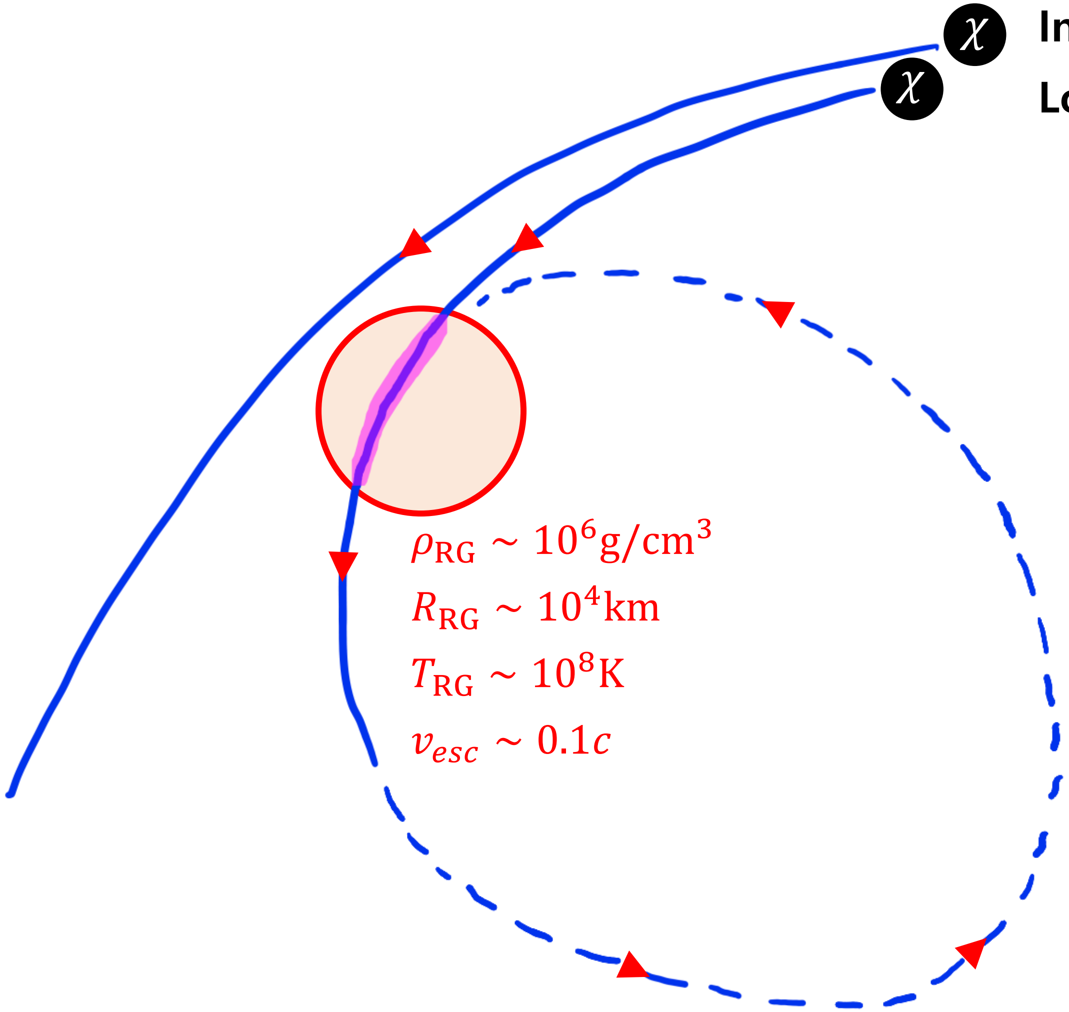
→ Thermalization (accumulation in the core) → DM Self Gravitational Collapse and Heating

Dark Matter Capture

We considering the heavy Dark Matter : $m_\chi \gg m_N$ and only the core of Red Giant

Initial DM speed: $v_i \sim 10^{-3}c$

Local DM density: $\rho_\chi \sim 0.1\ \mathrm{GeV/cm^3}$



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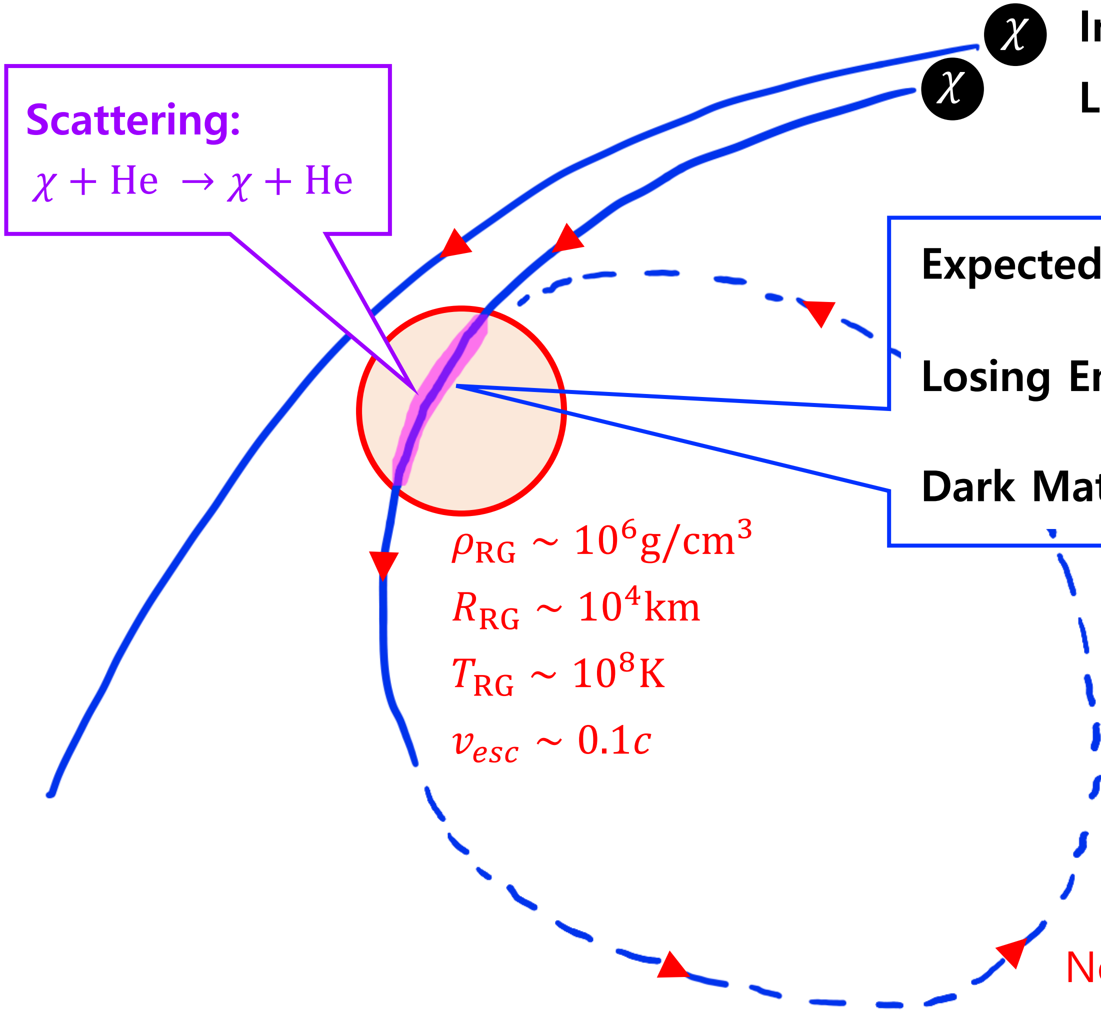


Initial DM speed: $v_i \sim 10^{-3} c$

Local DM density: $\rho_\chi \sim 0.1\ \mathrm{GeV/cm^3}$

Expected Number of Scattering: $n_{\mathrm{He}} \sigma_{\mathrm{He}\chi} R_{\mathrm{RG}}$

Losing Energy Per Each Scattering: $\frac{\delta E_\chi}{E_\chi} \sim \frac{2m_{\mathrm{He}}}{m_\chi}$

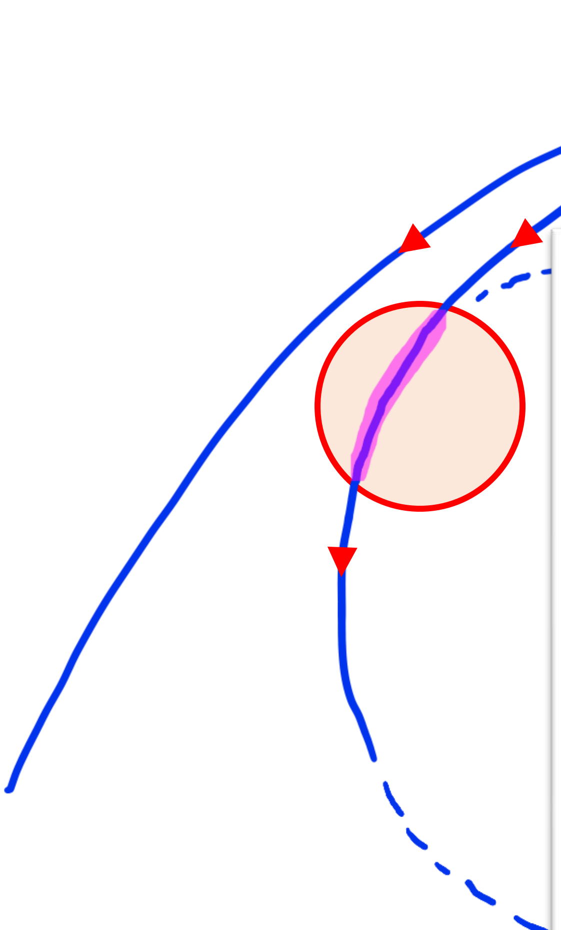
Dark Matter Captured When $\Delta E_\chi \sim m_\chi v_i^2$

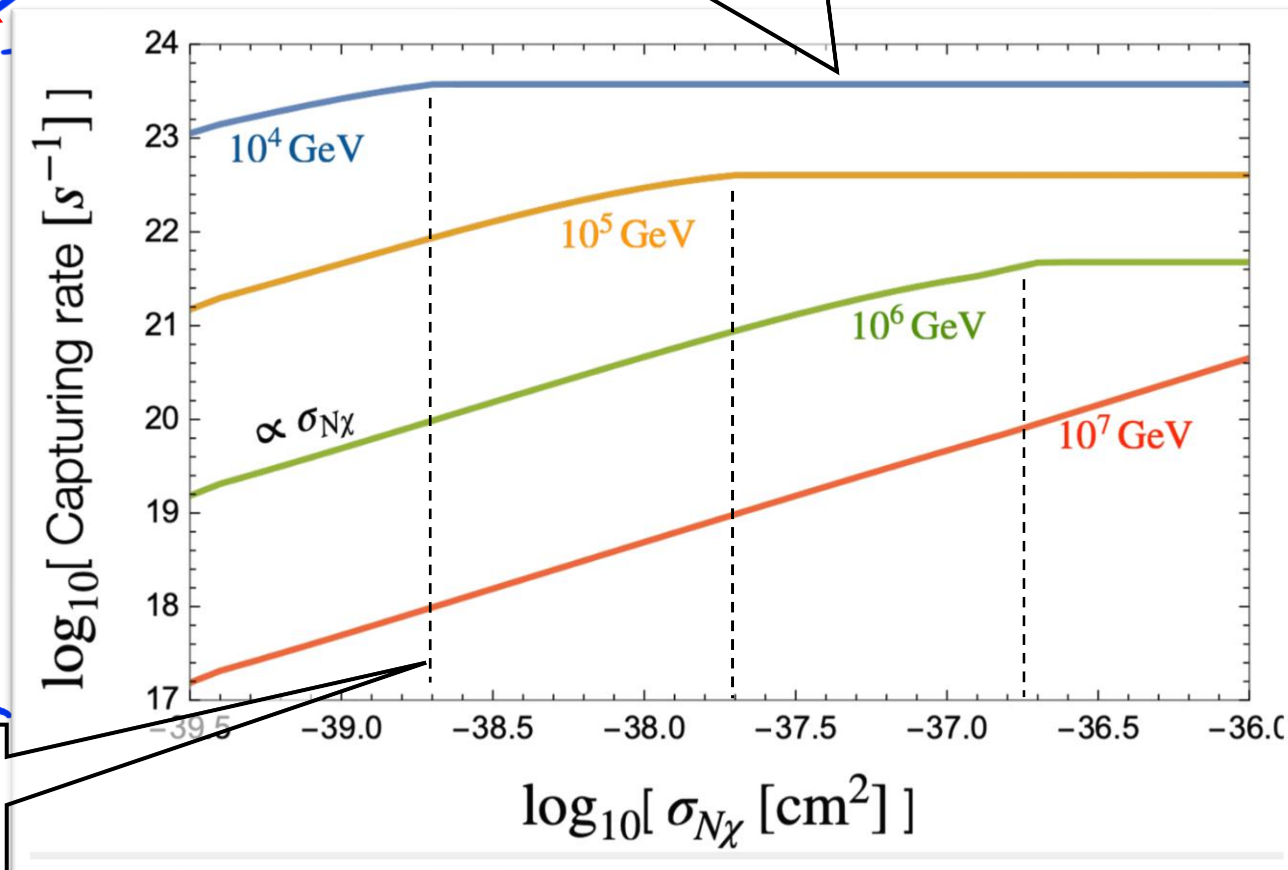
Negative Orbital Energy

$$E_\chi = \frac{1}{2} m_\chi v^2 - \frac{G M_{\mathrm{RG}} m_\chi}{r} < 0$$

Dark Matter Capture

Almost all incident DM captured
Geometric capturing rate $\sim 4\pi R_{\mathrm{RG}}^2 n_\chi v_i$





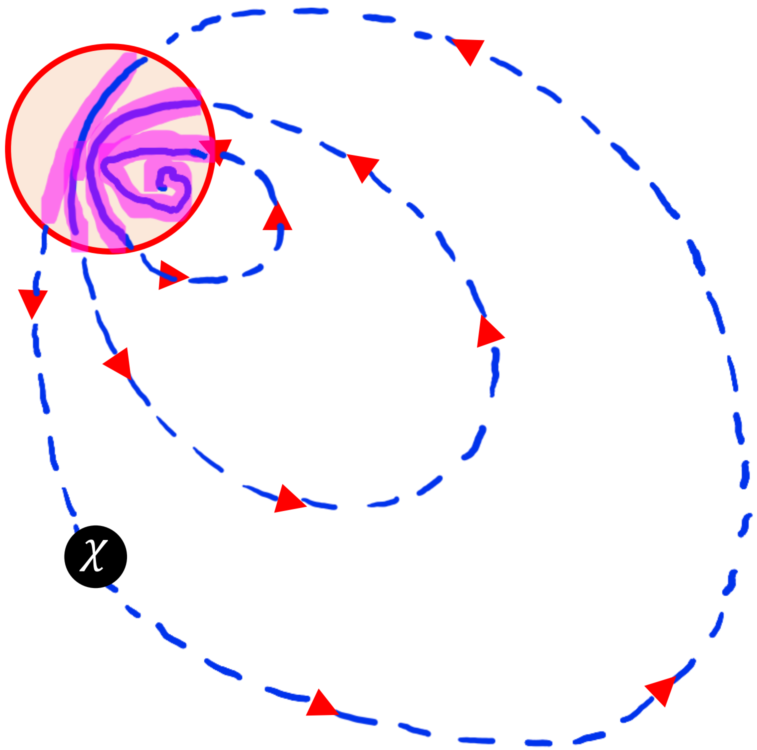
$$n_{\mathrm{He}}\sigma_{\mathrm{He}\chi}R_{\mathrm{RG}} \sim \frac{m_\chi}{m_{\mathrm{He}}}\frac{v_i^2}{v_{esc}^2}$$

Ingress Transition

- The Orbital Energy = Kinetic + Potential Energy < 0

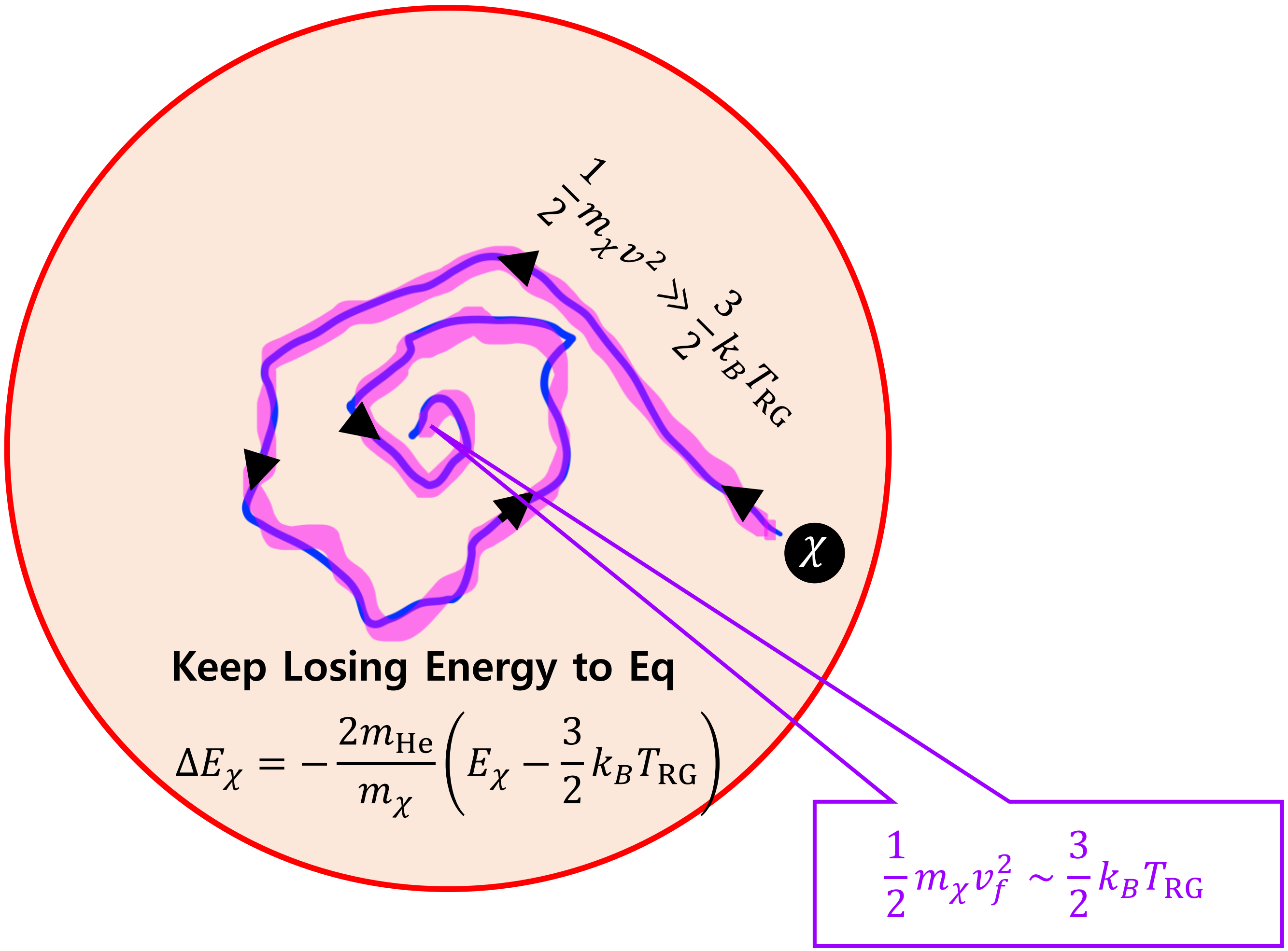
- Losing Energy Per Each Scattering: $\frac{\delta E_\chi}{E_\chi} \sim \frac{2m_{\mathrm{He}}}{m_\chi}$

- Dark Metter Ingress When The Orbital Energy < $-\frac{1}{2}m_\chi v_{esc}^2$



Thermalization

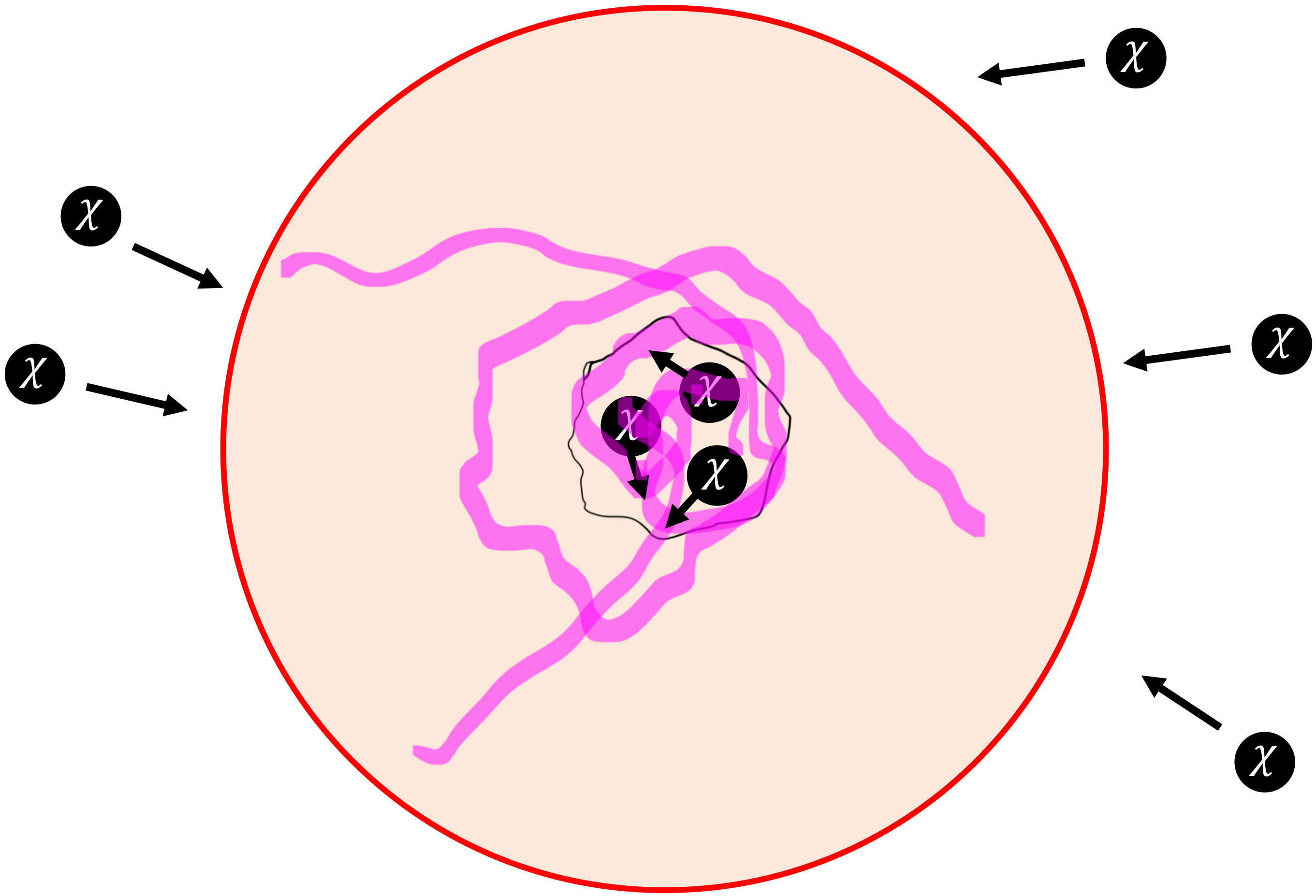
As the DM falls into the core, the initial kinetic energy around the core is much greater than the background temperature. Therefore, DM constantly interacts with background nuclei to **achieve thermal equilibrium.**



Thermalization

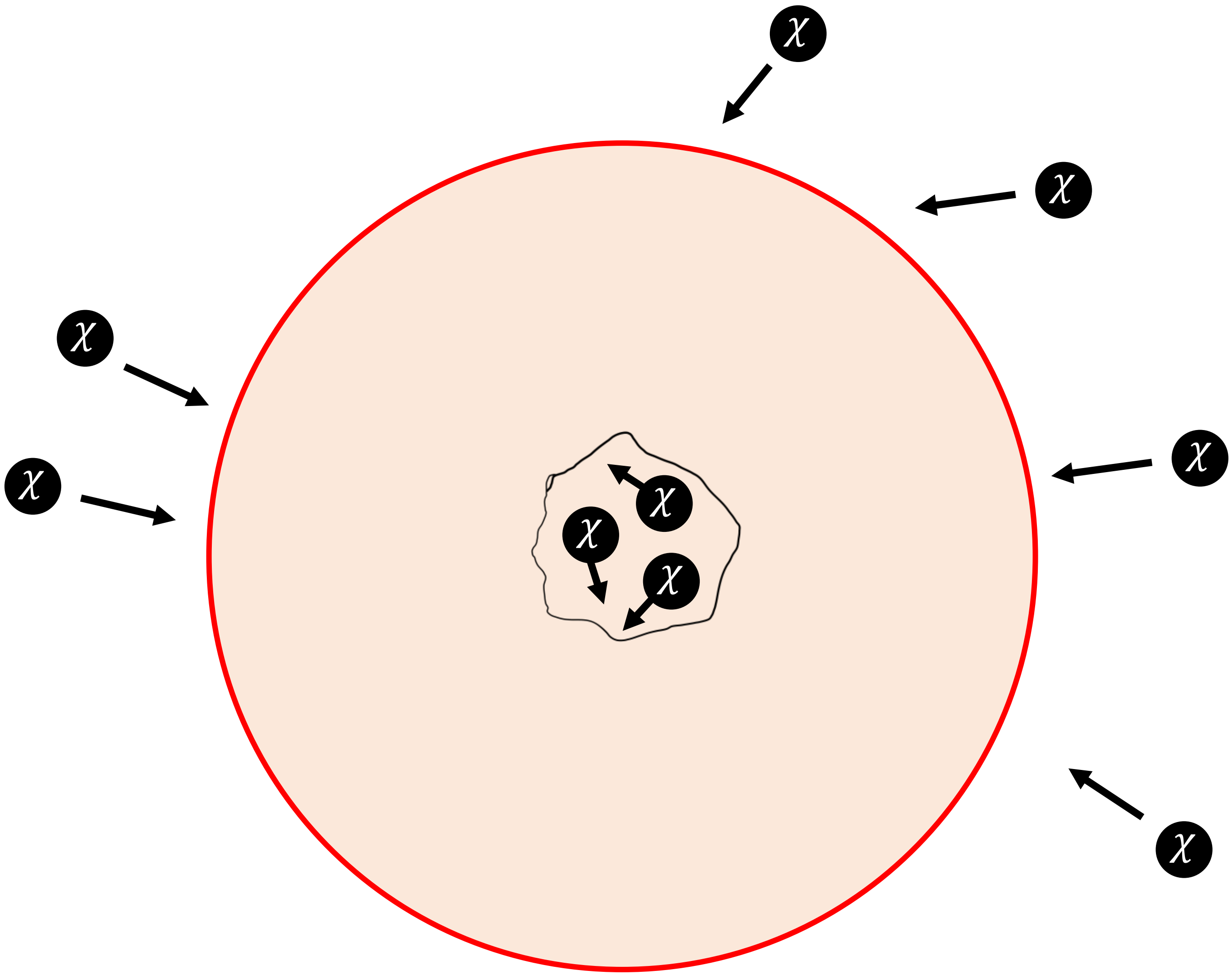
Dark Matters are gradually accumulated at the core. Dark Matter clump has the virial radius as

$$r_\chi \sim \sqrt{\frac{k_B T_{\mathrm{RG}}}{G \rho_{\mathrm{RG}} m_\chi}}$$



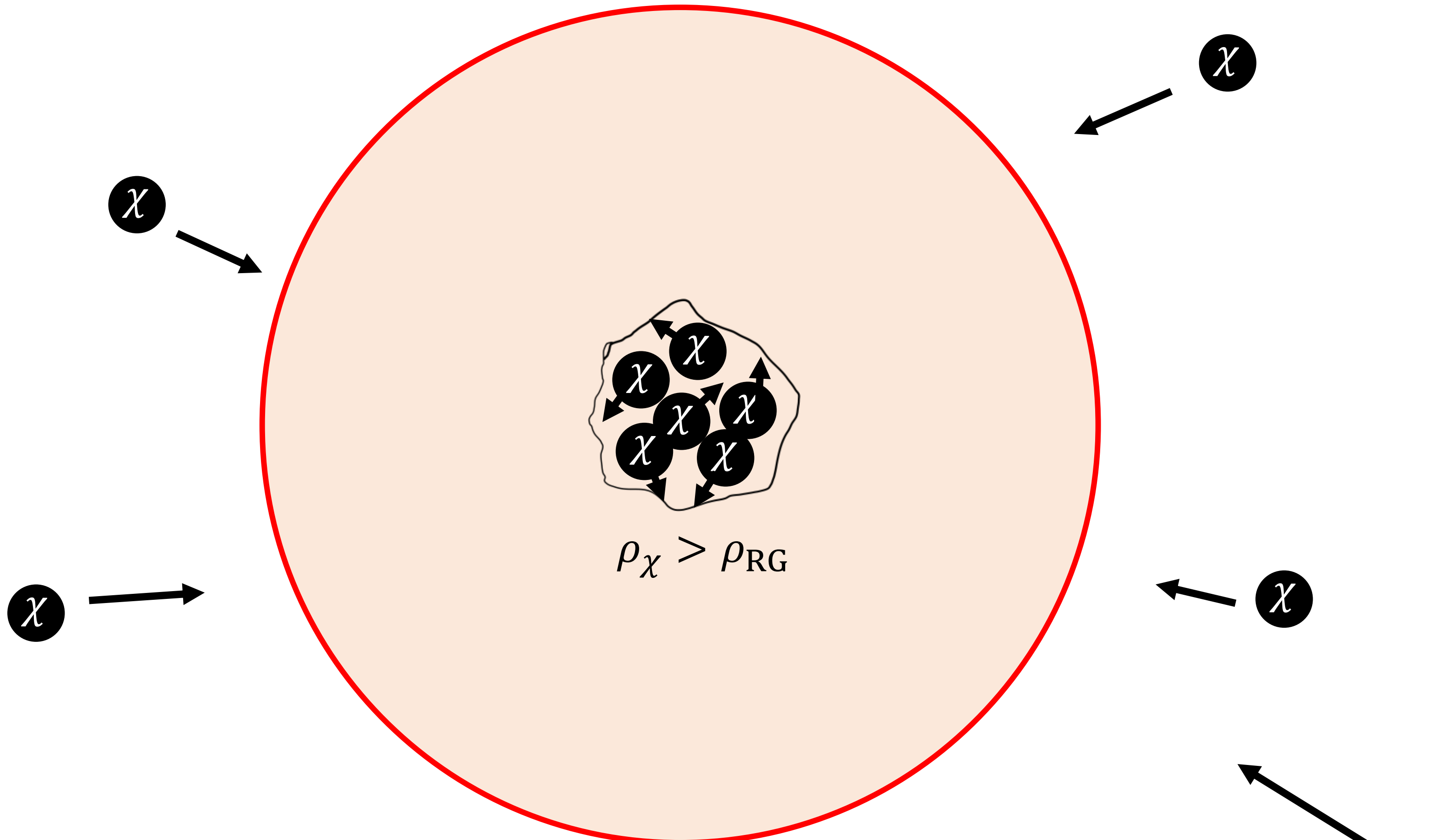
Gravothermal Collapse and Heating of RG

DM density increases over time.



Gravothermal Collapse and Heating of RG

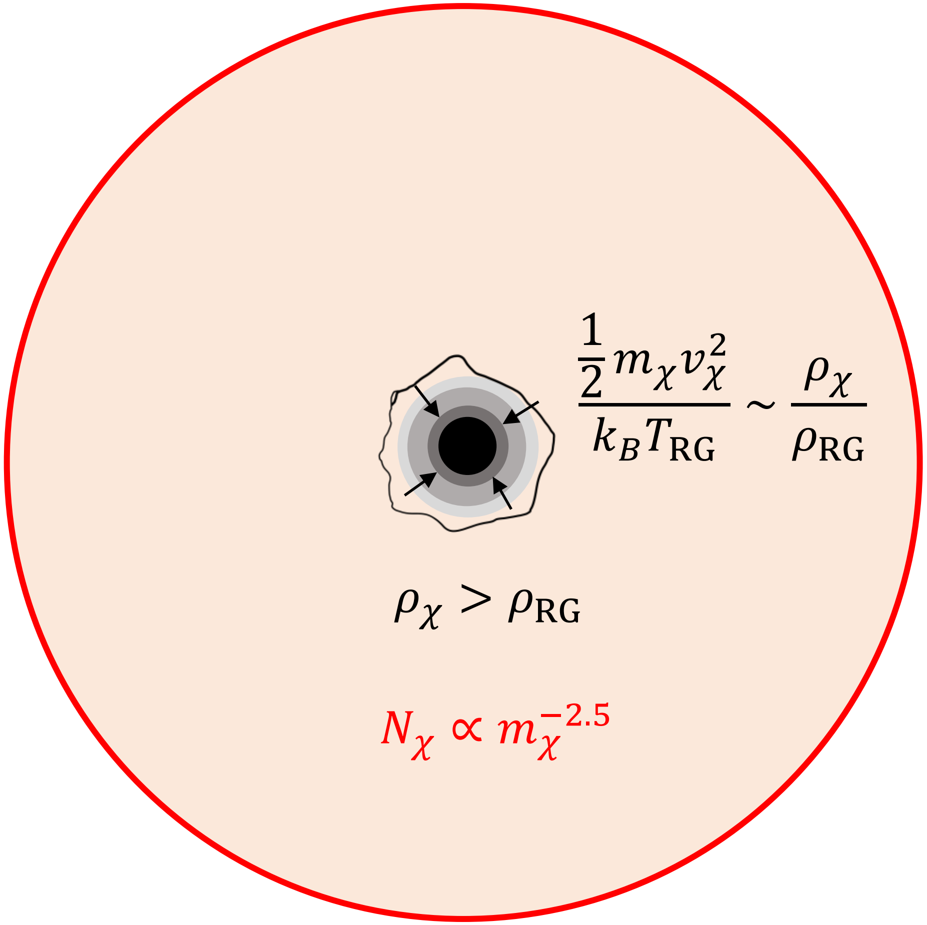
DM density increases over time. Eventually the DM density can be bigger than the background RG density: $\boldsymbol{\rho_\chi > \rho_{\mathrm{RG}}}$.



Gravothermal Collapse and Heating of RG

DM density increases over time. Eventually the DM density can be bigger than the background RG density: $\boldsymbol{\rho_\chi > \rho_{\mathrm{RG}}}$. Then the Dark Matter sphere becomes unstable:

Gravothermal Collapse → DM Virial Radius decreases → DM Kinetic Energy Increases



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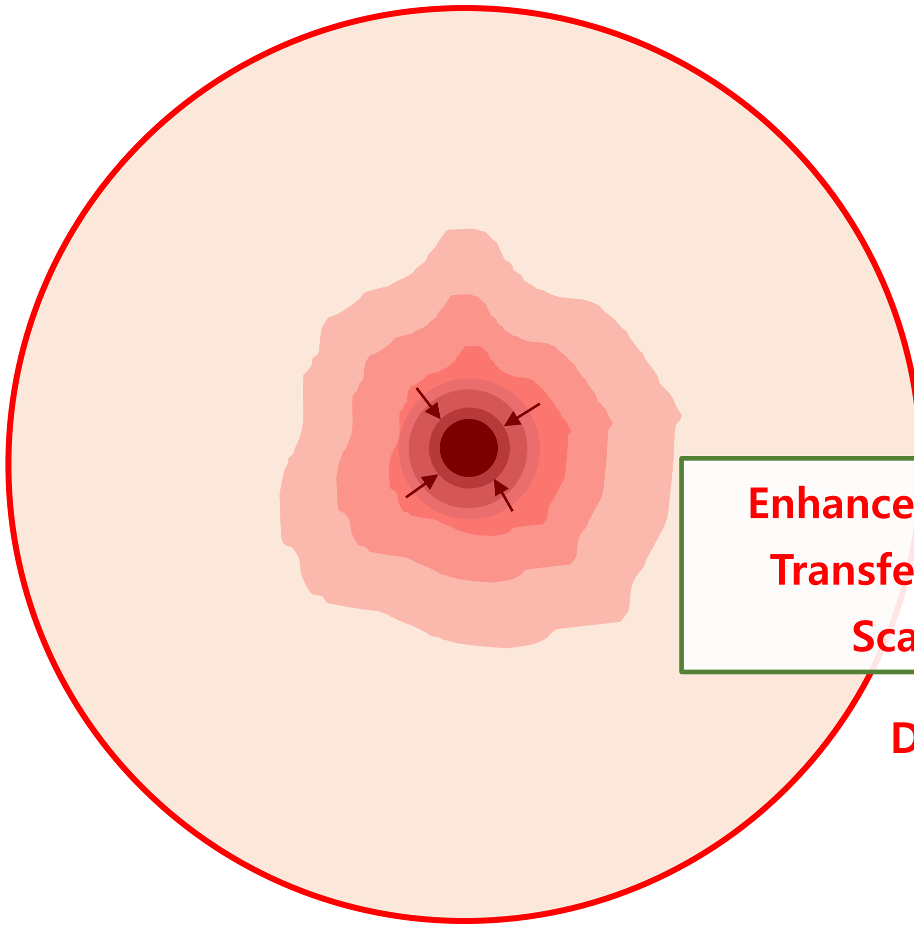


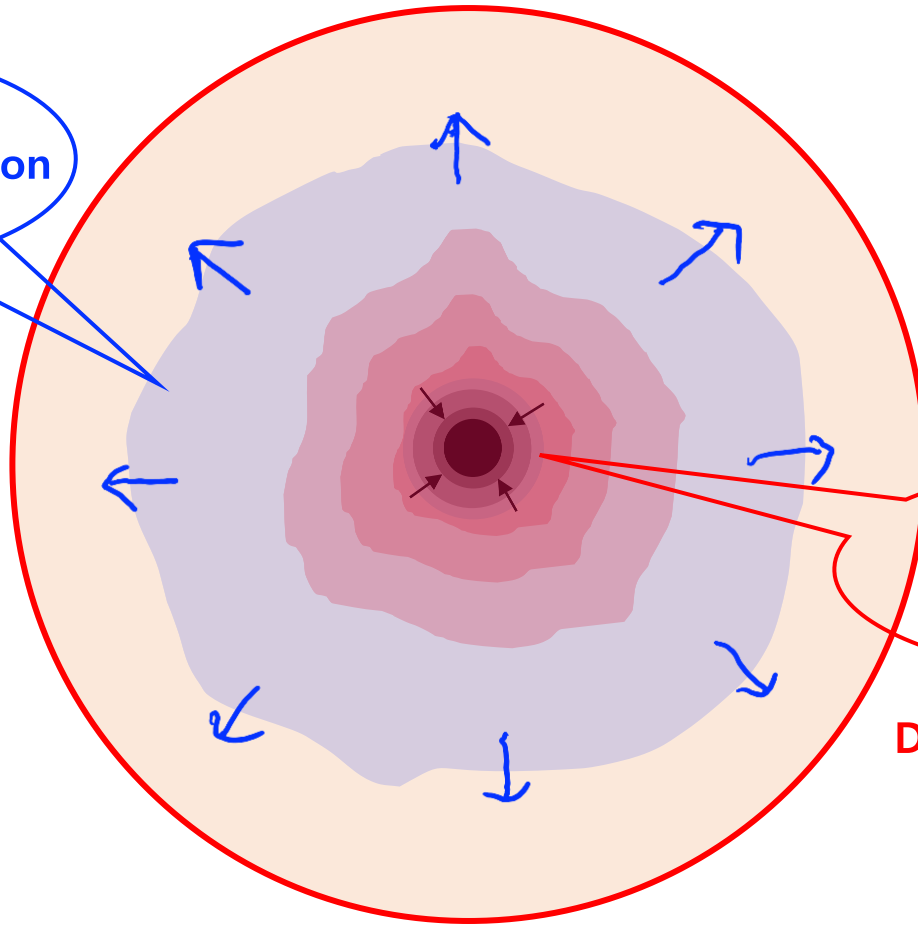
Enhanced DM Kinetic Energy is Transferred to the Nuclei by Scatterings: Heating

DM Energy Transfer Rate

$$\dot{Q}_\chi \sim N_\chi n_{\mathrm{He}} \sigma_{\mathrm{He}\chi} v_\chi m_{\mathrm{He}} v_\chi^2$$

Cooling vs Heating

Diffusion is important for runway fusion. **However, if the diffusion is so efficient compared to the DM heating effect, the nuclear fusion will not be efficiently triggered**. This is because the locally enhanced temperature is quickly decreasing to the background value before the fusion happens.



Cooling from Diffusion

Conductive Diffusion Rate

$$\dot{Q}_{\rm dff} \sim \frac{\Delta E}{t_{\rm dff}}$$

$$\boxed{\dot{Q}_\chi > \dot{Q}_{\rm dff}}$$

Heating from DM-Nucleus Scattering

DM Energy Transfer Rate

$$\dot{Q}_\chi \sim N_\chi n_{\rm He} \sigma_{\rm He\chi} v_\chi m_{\rm He} v_\chi^2$$

Burning vs Diffusion

Assuming that triple alpha fusion is induced by a local heating effect, runway Helium fusion is achieved when the "burning time scale" is shorter than the "diffusion time scale".

** Burning Time Scale (Heating Time Scale by Triple alpha Nuclear Reaction)

$$t_{\mathrm{burn}} \sim \frac{\epsilon_{th}}{\dot{S}_{3\alpha}}$$

ϵ_{th} = Generated energy per unit mass by burning maintaining heated regime ~ Capacity × $(T_{\mathrm{burn}} - T_{\mathrm{RG}})$

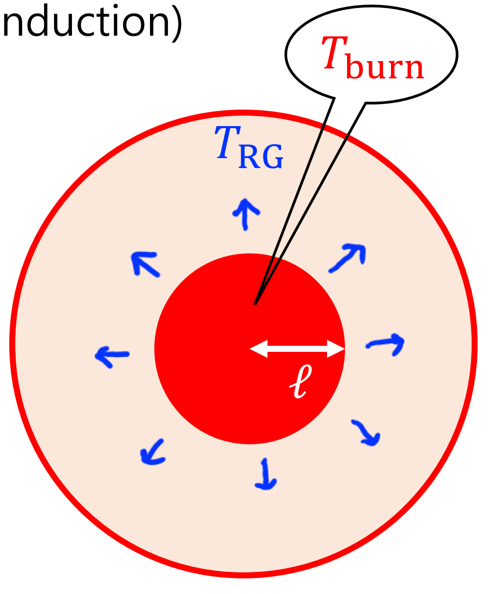
$\dot{S}_{3\alpha}$ = 3alpha nuclear reaction rate for heating ~ $Q_{3\alpha} \times r_{3\alpha}/\rho_{\mathrm{RG}}$

** Diffusion Time Scale (Cooling Time Scale by Electronic/Radiation Conduction)

$$t_{\mathrm{dff}} \sim \frac{\ell^2}{D}$$

ℓ = The width of heated region

D = Thermal Diffusivity ~ $\lambda_{eff} \times v_e$



***** Sparkled frame persists and expands when $t_{\mathrm{burn}} < t_{\mathrm{dff}}$**

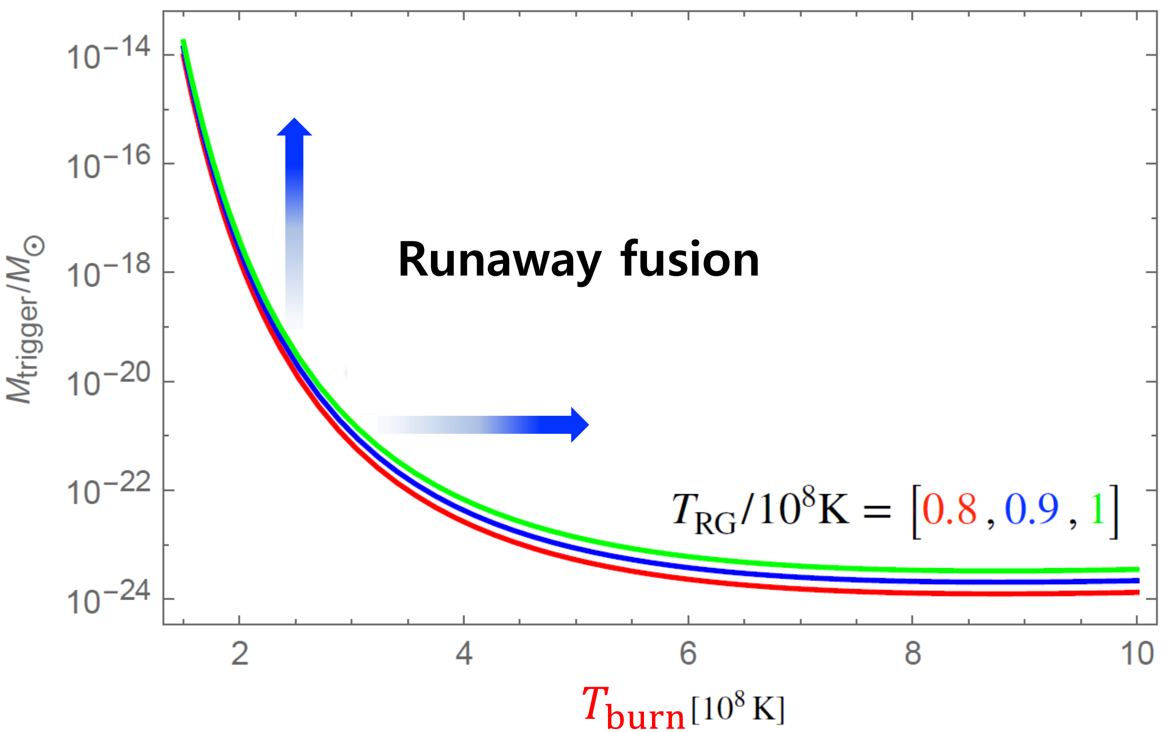
Trigger Mass for Helium Burning

The condition

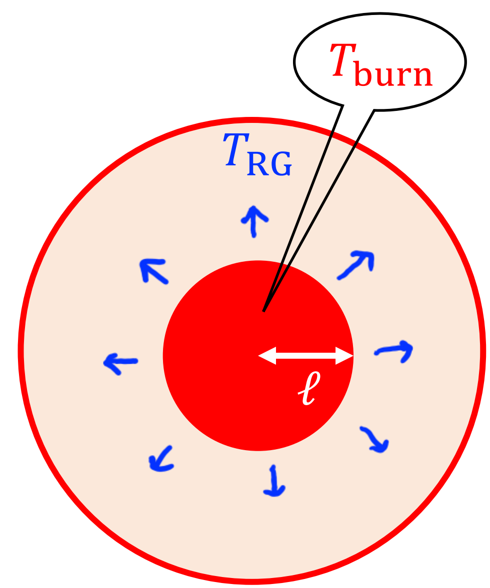
$$\boldsymbol{t_{\mathrm{burn}}} = \boldsymbol{t_{\mathrm{dff}}} \quad \Rightarrow \quad \ell_{\mathrm{trigger}} = \sqrt{\frac{D\epsilon_{th}}{\dot{S}_{3\alpha}}}$$

Gives the Trigger radius ℓ_{trigger}, or Trigger Mass defined as

$$M_{\mathrm{trigger}} = \frac{4\pi}{3}\rho_{\mathrm{RG}}\ell_{\mathrm{trigger}}^{3}$$



Burning temperature



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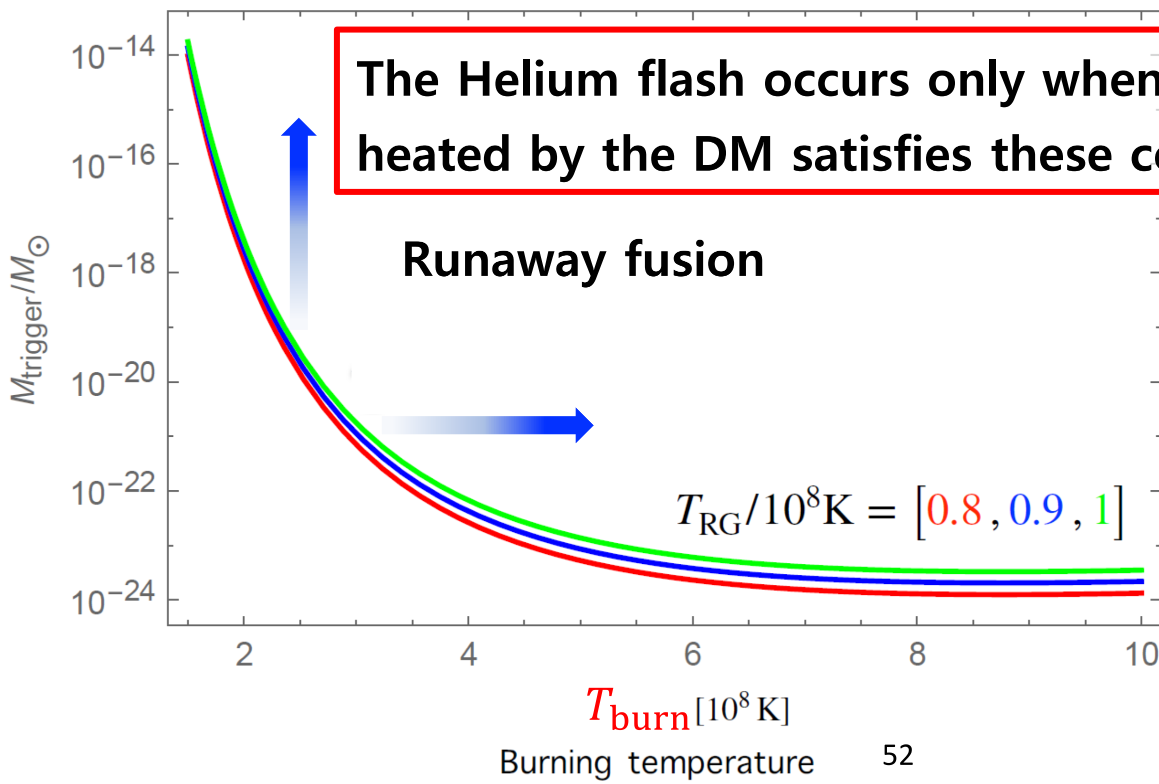
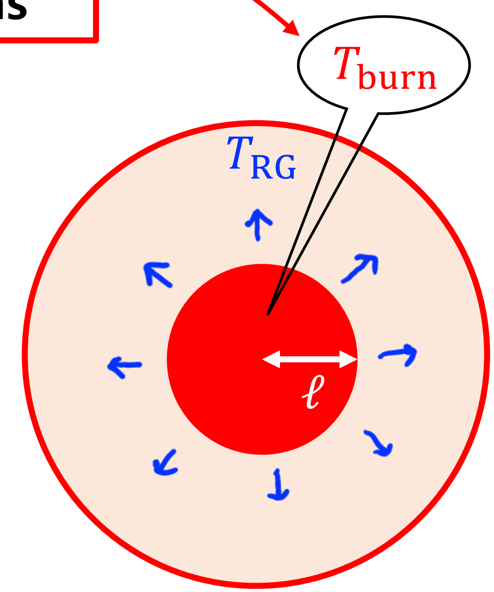
The Helium flash occurs only when the area heated by the DM satisfies these conditions



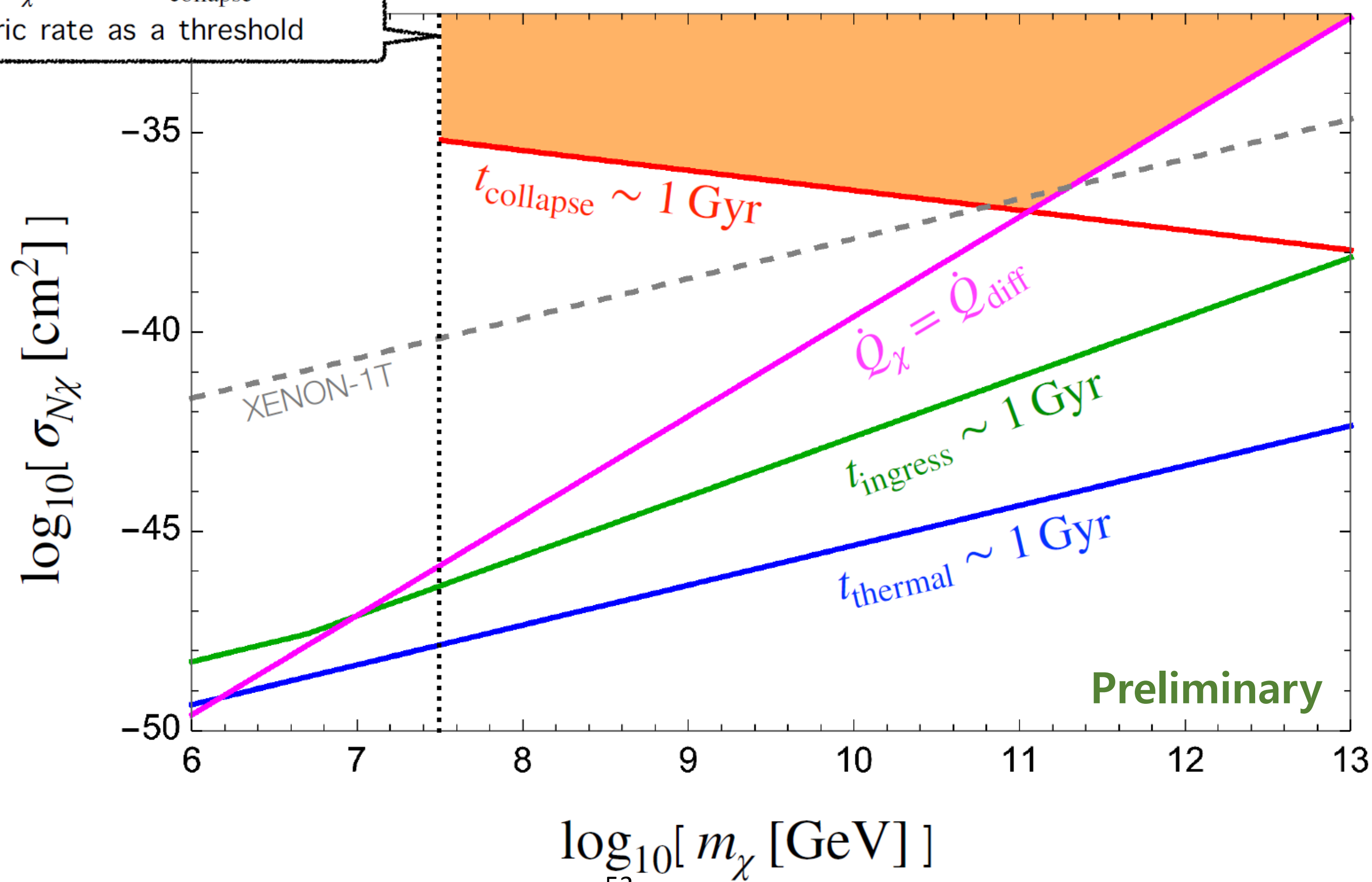


Constraints on Heavy Dark Matter

Simplified example with fixed the density $\rho_{\mathrm{RG}} \sim 10^6\,\mathrm{g/cm^3}$, and radius of $R_{\mathrm{RG}} \sim 10^4\mathrm{km}$.

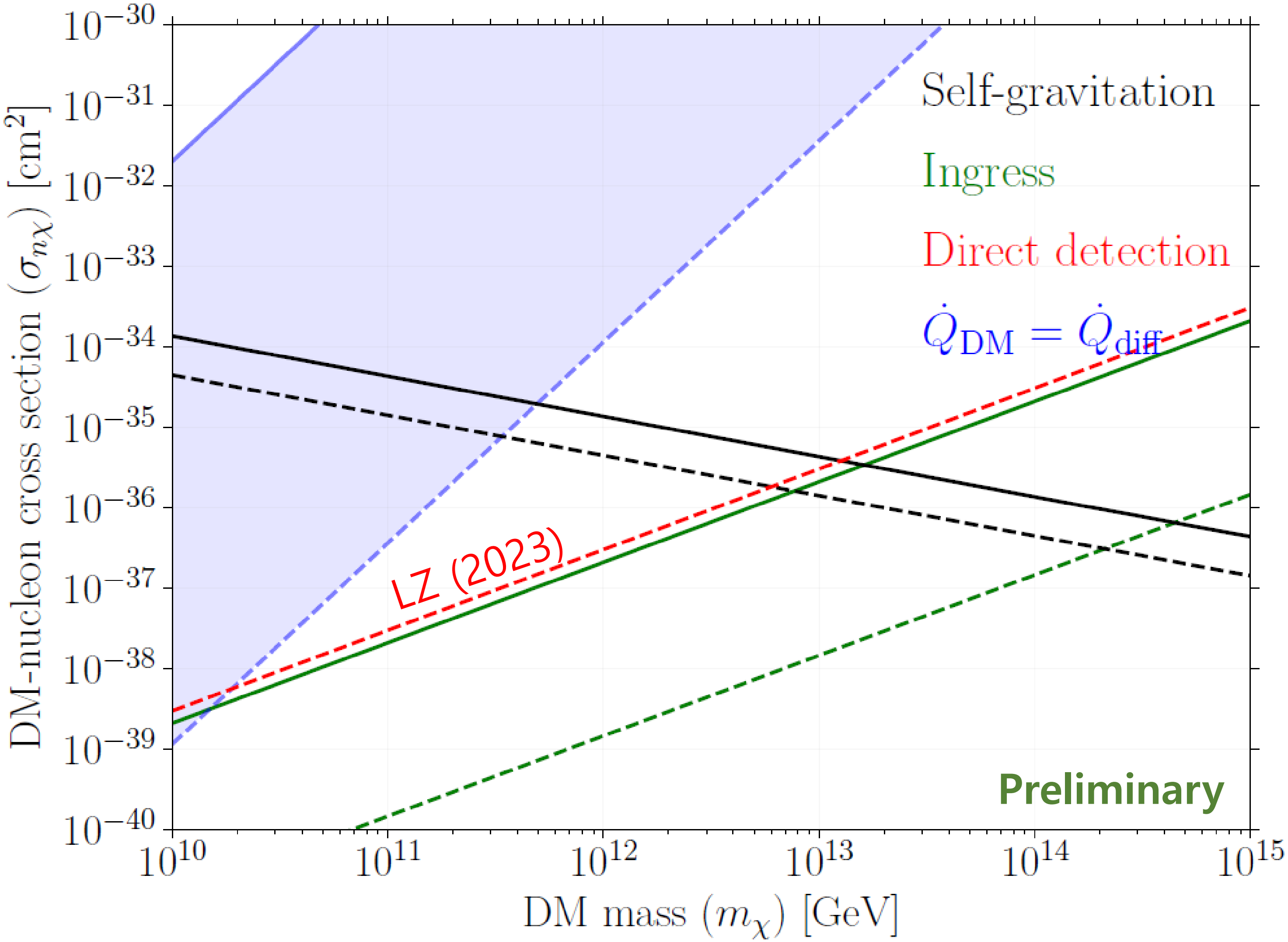
Heaviness of DM is relevant for reducing the time scale of DM self-gravitational collapse.

- Smaller m_χ, larger N_{collapse} required
- Geometric rate as a threshold



Constraints on Heavy Dark Matter

Considering **the full evolution of RG from its birth to 1Gyr**, we can refine the constraints



Summary

Heavy dark matter and its phenomenological implications are well-motivated these days. We provide the example of heavy dark matter that can have sizable interactions with the SM particles and observational consequences

The stellar evolution can be altered by the surrounding dark matter. This talk focused on the tip of the Red Giants just before the Helium Flash. Their dynamics can be highly affected by the Dark Matter heating.

We examine the effect of heavy dark matter capturing and its evolution inside the core of the Red Giants. A detailed study based on the statistics of Horizontal vs RG branches and the data of the luminosity of TRGB is necessary to provide more concrete predictions.