기초과학연구원
Institute for Basic Science

Exploring the Universe with Dark Light Scalars

Based on 2010.10880

Bugeon Jo, Hyeontae Kim, Hyung Do Kim, CSS

Chang Sub Shin (IBS-CTPU)

Dark Matter as a Portal to New Physics

Feb. 5, 2021

Outline

Motivation

- Origin of the light scalar DM
- Multi-component DM with very different features

Issues in Axion-Glueball DM Cosmology

- Gluo-thermodynamics with the axion
- Structure of the multi branched axion potential

Implications of Subcomponent Glueball Dark Matter

- Intro (SMBHs at z~7)
- Dark matter interpretation (gravo-thermal collapse)
- Our model and Caveats

Summary

Motivation

Motivation

The nature of dark matter is still shrouded in mystery

$$\bar{\rho}_{DM} \simeq 1.2\times10^{-6}\ \mathrm{GeV/cm^3} = m_{DM}\bar{n}_{DM}$$

$m_p = 1\ GeV$
$m_e = 0.5\ MeV$
$m_\nu = 0.1\ eV$

$10^{-22}eV$ — *Fuzzy DM*

μeV — *QCD axion*

keV — *Warm DM, Sterile neutrino*

$100\ GeV$ — *WIMP DM*

$M_P = 2\times10^{18}\ GeV$ — *Heavy DM*

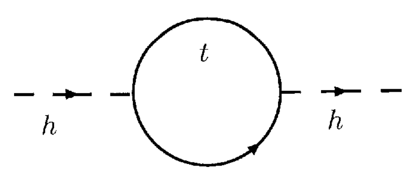
$M_\odot \simeq 10^{56}m_p$ — *Primordial Black Hole, Ultra Compact Mini Halo*

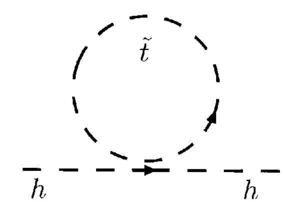
Wave-like ($n_{DM} \gg m_{DM}^3$) — *Particle-like (boson, fermion)* — *Macroscopic objects*

Unfortunately, there is no good guiding principle for the mass of dark matter these days

Origin of the scalar mass → Hints for new physics

Ex) Higgs boson (the weak scale is radiatively unstable)





$$\delta_{qc}m_H^2 \sim \Lambda_{UV}^2 \gg m_W^2$$

Supersymmetry, Composite Higgs, Relaxion, Scale invariance etc.

Motivation

Considering scalar dark matter: Need to explain the origin of its mass

→ *It also determines its interaction structure, too*

Natural scalar dark matter candidates

1) **Axion-like** particle (ϕ): *for the compact field* ($\phi \to \phi + 2\pi f_a$),

Approximate global symmetry: $\phi \to \phi + c$ is broken non-perturbatively

(by instanton, confinement, etc.)

e.g. $$\frac{\phi}{16\pi^2 f_a}\mathrm{Tr}\left[G_{\mu\nu}\tilde{G}^{\mu\nu}\right] \to V(\phi) = \sum a_n \Lambda^4 \cos\left(\frac{n\phi}{f_a}\right)$$

2) **Glueball-like** particle (φ_g): *At high scales, there is no scalar degree of freedom*

Confining gauge symmetry: $\mathrm{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right] \to \varphi_g$: $m_g \sim \sqrt{4\pi}\,\Lambda$ (confinement scale)

Both 1) & 2) (and their mixture) can make scalars light. What if we consider both mechanisms simultaneously as a dark sector?

$$L_{dark} = -\frac{1}{4g_h^2}G^a_{\mu\nu}G^{a\mu\nu} + \frac{1}{2}\left(\partial_\mu\phi\right)^2 + \frac{\phi}{32\pi^2 f_a}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

Dark Axion & Dark Glueball DM

$$L_{dark} = -\frac{1}{4g_h^2} GG + \frac{1}{2}(\partial_\mu \phi)^2 + \frac{\phi}{32\pi^2 f_a} G\tilde{G}$$

Confining phase transition at $T_g = T_{g,c} \simeq \Lambda$

** Taking SU(N) as the hidden gauge group*

** Decoupled from the SM from the beginning*

$$L_{eff} = \frac{1}{2}(\partial_\mu \varphi_g)^2 - \frac{1}{2} m_g^2 \varphi_g^2 + \frac{a_3}{3!}\frac{4\pi}{N} m_g \varphi_g^3 + \frac{a_4}{4!}\left(\frac{4\pi}{N}\right)^2 \varphi_g^4 + \frac{a_5}{5!}\frac{1}{m_g}\left(\frac{4\pi}{N}\right)^3 \varphi_g^5 + \cdots$$

$$+ \frac{1}{2}(\partial_\mu \phi)^2 - N^2\Lambda^4 \left(\frac{c_2}{2}\left(\frac{\phi}{N f_a}\right)^2 + \frac{c_4}{4!}\left(\frac{\phi}{N f_a}\right)^4 + \cdots\right)$$

$$+ \left(\frac{\phi}{N f_a}\right)^2 \left(\frac{g_1}{4\pi N} m_g^3 \varphi_g + \frac{g_2}{2!} m_g^2 \varphi_g^2 + \cdots\right) + \sum L_{eff}\left(\phi, \varphi_g(J^{PC})\right)$$

$$m_g \simeq 6\Lambda$$

$$m_a \sim 10^{-12}\mathrm{eV}\left(\frac{\Lambda}{\mathrm{MeV}}\right)^2\left(\frac{10^{15}\ \mathrm{GeV}}{f_a}\right)$$

$$\tau_{\varphi_g} \sim 10^{18}\mathrm{Gyr}\left(\frac{N}{3}\right)^6\left(\frac{f_a}{10^{13}\mathrm{GeV}}\right)^4\left(\frac{\mathrm{GeV}}{m_g}\right)^5$$

** Stability ensured by the lightness of scalars*

Dark Axion & Dark Glueball DM

$$L_{dark} = -\frac{1}{4g_h^2}GG + \frac{1}{2}\left(\partial_\mu \phi\right)^2 + \frac{\phi}{32\pi^2 f_a}G\tilde{G}$$

Confining phase transition
at $T_g = T_{g,c} \simeq \Lambda$

** Taking SU(N) as the hidden gauge group*
** Decoupled from the SM from the beginning*

Axion + Glueball
Multi-component dark matter

$$L_{eff} = \frac{1}{2}\left(\partial_\mu \varphi_g\right)^2 - \frac{1}{2}m_g^2\varphi_g^2 + \frac{a_3}{3!}\frac{4\pi}{N}m_g\varphi_g^3 + \frac{a_4}{4!}\left(\frac{4\pi}{N}\right)^2\varphi_g^4 + \frac{a_5}{5!}\frac{1}{m_g}\left(\frac{4\pi}{N}\right)^3\varphi_g^5 + \cdots$$

$$+\frac{1}{2}\left(\partial_\mu \phi\right)^2 - N^2\Lambda^4\left(\frac{c_2}{2}\left(\frac{\phi}{N f_a}\right)^2 + \frac{c_4}{4!}\left(\frac{\phi}{N f_a}\right)^4 + \cdots\right)$$

Self Interacting Dark Matter: φ_g

$m_g \simeq 6\Lambda$

$m_a \sim 10^{-12}\text{eV}\left(\frac{\Lambda}{\text{MeV}}\right)^2\left(\frac{10^{15}\text{ GeV}}{f_a}\right)$

Wave Dark Matter: ϕ

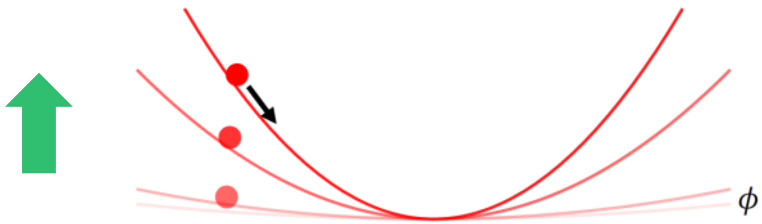
$\tau_{\varphi_g} \sim 10^{18}\text{Gyr}\left(\frac{N}{3}\right)^6\left(\frac{f_a}{10^{13}\text{GeV}}\right)^4\left(\frac{\text{GeV}}{m_g}\right)^5$

** Stability ensured by the lightness of scalars*

Issues in Axion-Glueball DM Cosmology

Axion Potential in the Deconfining Phase

Before the confining phase transition, the axion gets a scalar potential via instanton contributions



$$V(T_g, \phi) \simeq T_g^4 \, e^{-\frac{8\pi^2}{g_h^2(T_g)}} (1 - \cos\theta) \quad \text{for } T_g > T_{g,c}$$

$$= \frac{1}{2} m_a^2 \left(\frac{T_{g,c}}{T_g} \right)^{\frac{11}{3}N - 4} \phi^2 + \cdots \qquad \boxed{\theta \equiv \phi / f_a}$$

Energy flow from the gluons to the axions as the gluon temperature decreases ($\rho_g \to \rho_a$).

Naively, this implies $\rho_g = \rho_g(T_g) = \frac{\pi^2}{15}(N^2 - 1)\, T_g^4$ *decreases faster than* $1/a^4$

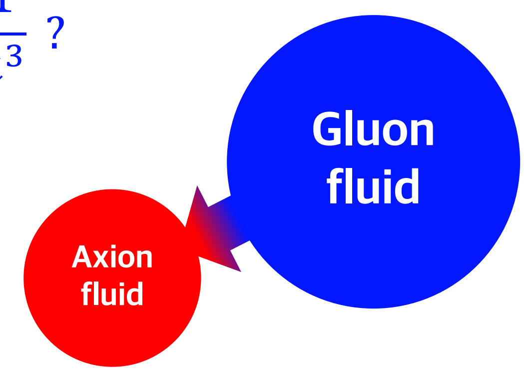
What about the entropy? $s_g = \dfrac{\rho_g + p_g}{T_g} = \dfrac{4\,\pi^2}{45}(N^2 - 1)\, T_g^3 \propto \dfrac{1}{a^3}$?

→ *Conceptual problems*

Is there also the flow of the entropy?

Is entropy conserved (i.e. $s_g \propto 1/a^3$*)?*

What is the correct form of the entropy for coupled fluids?



Gluo-thermodynamics with the Theta term

Gluons in thermal equilibrium with T_g; Thermodynamic relations hold during the cosmic expansion.

$$f = -p \qquad s = -\frac{df}{dT} \qquad \rho = Ts - p$$

f = free energy density

When $\phi = 0$, the free energy density depends only on T_g:

$$f_g(T_g) = -\frac{T_g}{V}\ln Z_g = -\frac{T_g}{V}\ln\int dA_a \exp\left[-\int_0^{1/T_g} dt\, d^3\vec{x}\left(\frac{1}{4g_h^2}G^aG^a\right)\right]$$

Whereas for $\phi \neq 0$ ($\theta \neq 0$)

$$p_{g+\theta} = -f_{g+\theta} = \frac{T_g}{V}\ln\int dA_a \exp\left[\int_0^{1/T_g} dt\, d^3\vec{x}\left(\frac{1}{4g_h^2}G^aG^a + i\frac{\theta}{32\pi^2}G^a\tilde{G}^a\right)\right]$$

$$= -f_g(T_g) - V(T_g,\phi) \equiv p_g(T_g) - V(T_g,\phi)$$

$$s_{g+\theta} = -df_{g+\theta}/dT_g, \qquad \rho_{g+\theta} = T_g s_{g+\theta} - p_{g+\theta} \equiv \rho_g(T_g,\phi) + V(T_g,\phi)$$

$\rho_g(T_g,\phi)$ (depends not only on T_g but also on ϕ) and $p_g(T_g)$ are interpreted as the energy density and the pressure of the gluons only. Then, we confirm

$$s_{g+\theta} = \frac{dp_g}{dT_g} - \frac{\partial V(T_g,\phi)}{\partial T_g} = \frac{\rho_g + p_g}{T_g} = s_g \propto \frac{1}{a^3}! \qquad \textit{(entropy conservation)}$$

Axion Potential in the Confining Phase

Instanton approximation is no longer valid. Branch structure (k=1,…,N) emerges

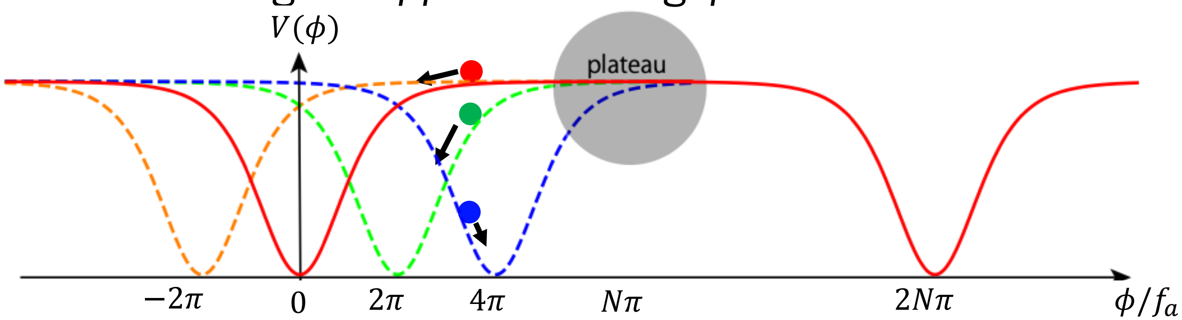
$$L = -\frac{1}{4g_h^2} GG + \frac{\theta}{32\pi^2} G\tilde{G}$$

$$e^{iS[\theta+2\pi]} = e^{iS+2in\pi} = e^{iS[\theta]}$$

$$E_k(\theta + 2\pi) \neq E_k(\theta)$$

Witten hep-th/9807109

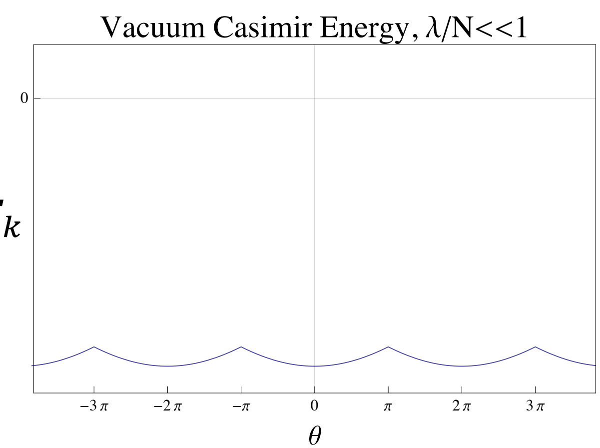
Phenomenological applications: e.g. pure natural inflation 1706.08522,1711.10490)

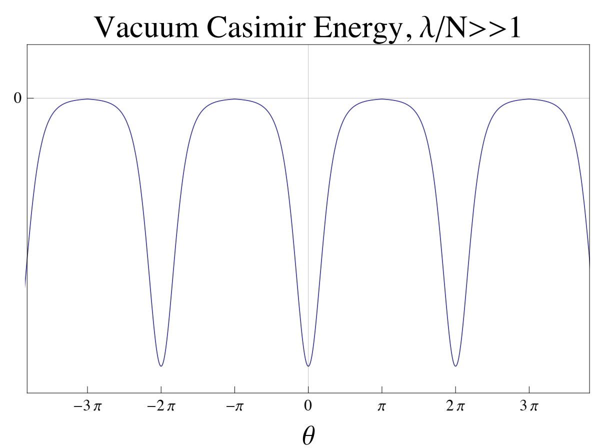


* Is there any nontrivial evolution of the axion DM?

* What is the tunneling rate between different branches?

min E_k





$$(\lambda = g_h^2 N)$$

$$E_{k+1} = \frac{-\Lambda_*^4}{\left(1 + \left(\frac{\lambda}{4\pi^2}\frac{\theta + 2\pi k}{N}\right)^2\right)^3}$$

Axion potential in holographic description: 1105.3740, Dubovsky, Lawrence, and Roberts

Dual Descriptions

Considering string theory realization of pure SU(N) gauge symmetry in 4D:

The world volume theory on N stacks of 4D branes wrapping a cycle with a radius β with a different boundary condition for fermions and bosons:

$$S_{D4} = -\mu_4 \int d^4x\, dy\, \mathrm{Tr}\, e^{-\phi}\sqrt{-\det\left(g_{\mu\nu} + B_{\mu\nu} + 2\pi\alpha' F_{\mu\nu}\right)} + \frac{1}{2}(2\pi\alpha')^2 \mu_4 \int C_1 \wedge \mathrm{Tr}\, F \wedge F + \cdots$$

$$\mu_4 = \frac{1}{(2\pi)^4 \alpha'^{5/2}}, \qquad g_s = \langle e^{\phi} \rangle, \qquad g_5^2 = 4\pi g_s \sqrt{\alpha'}, \qquad g_h^2 = \frac{g_5^2}{2\pi\beta}$$

$$\theta + 2\pi k = \frac{1}{\sqrt{\alpha'}} \int_{S_1} C_1$$

is dualized to the type IIA gravity action with N D4-branes (11 dim gravity action with N M5-branes) giving the nontrivial background metric solutions, *in the limit of large N & the 't Hooft coupling*

$$S = \frac{1}{(2\pi)^7 \alpha'^4} \int d^{10}x \sqrt{-g} \left(e^{-2\phi}\left(R + 4(\partial\phi)^2\right) - \frac{1}{2}|dC_1|^2 + \cdots \right)$$

$$ds^2 = f_{\alpha\beta}(C_\theta) dx^\alpha d^\beta \qquad\qquad C_1 = C_\theta dy$$

$$Z = e^{-V_4 E(\theta)} \simeq e^{-S_E(\text{renormalized onshell Eucleadian action})}$$

Matching between Lattice and Dual Descriptions

In lattice calculation from 1702.01049 (for N=3, 4, 6) Bonati, D'Elia, Rossi, Vicari

$$E(\theta) - E(0) = \frac{1}{2}\chi\theta^2(1 + b_2\theta^2 + b_4\theta^4 + \cdots)$$
$$= \frac{1}{2}\chi\theta^2\left(1 + \bar{b}_2\left(\frac{\theta}{N}\right)^2 + \bar{b}_4\left(\frac{\theta}{N}\right)^4 + \cdots\right)$$

$$\left(\frac{\chi}{\sigma^2}\right)_{N\to\infty} = 0.02, \qquad \bar{b}_2 = -0.23(3), \qquad |\bar{b}_4| \leq 0.1$$

In holographic dual description from 1105.3740 (β=the radius of extra dimension)

$$E_{k=1}(\theta) = -\frac{2}{3^7\pi^2}\left(\frac{\lambda N^2}{\beta^4}\right)\left(1 + \left(\frac{\lambda}{4\pi^2}\frac{\theta}{N}\right)^2\right)^{-3} = E(0) + \frac{1}{2}\chi_*\theta^2\left(1 + \bar{b}_{2*}\left(\frac{\theta}{N}\right)^2 + \cdots\right)$$

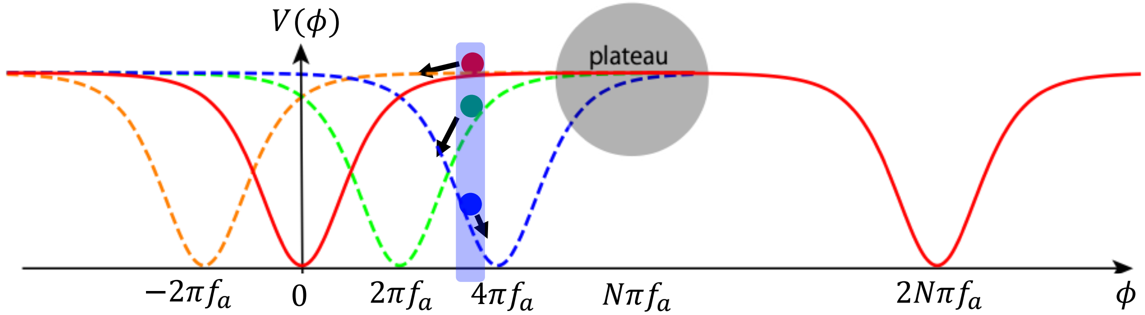
$$\frac{\chi_*}{(\pi/\beta)^4} \simeq 0.03\left(\frac{\lambda}{4\pi}\right)^3, \qquad \bar{b}_{2*} = -\frac{2}{\pi^2}\left(\frac{\lambda}{4\pi}\right)^2 \simeq -0.2\left(\frac{\lambda}{4\pi}\right)^2$$

Matching
$\lambda = g_h^2 N \simeq 4\pi$

Effective Axion Potential

The axion potential for kth branch (k=1,…,N) with $h(x) = h(x + 2\pi)$

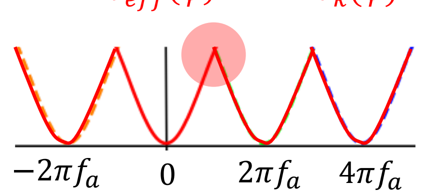
$$V_{k+1}(\phi) = N^2 \Lambda^4 h\left(\frac{\phi}{N f_a} + \frac{2\pi\, k}{N}\right)$$



Using the tunneling rate estimated in dual picture (1105.3740) with the relation $\lambda \sim 4\pi$*, we get*

$$\frac{\Gamma(k \to k-1)}{V_3} \sim c\,\Lambda^4\ \exp\left[-O(10^{-11}) N \frac{(N/k)^3}{(1+(k/N)^2)^2}\right]$$

$\Gamma_k / H \gg 1$ *around the phase transition unless* $N > 10^3$ → *The transitions between different branches happen* *<u>instantaneously</u>* *as the confining phase transition occurs.*



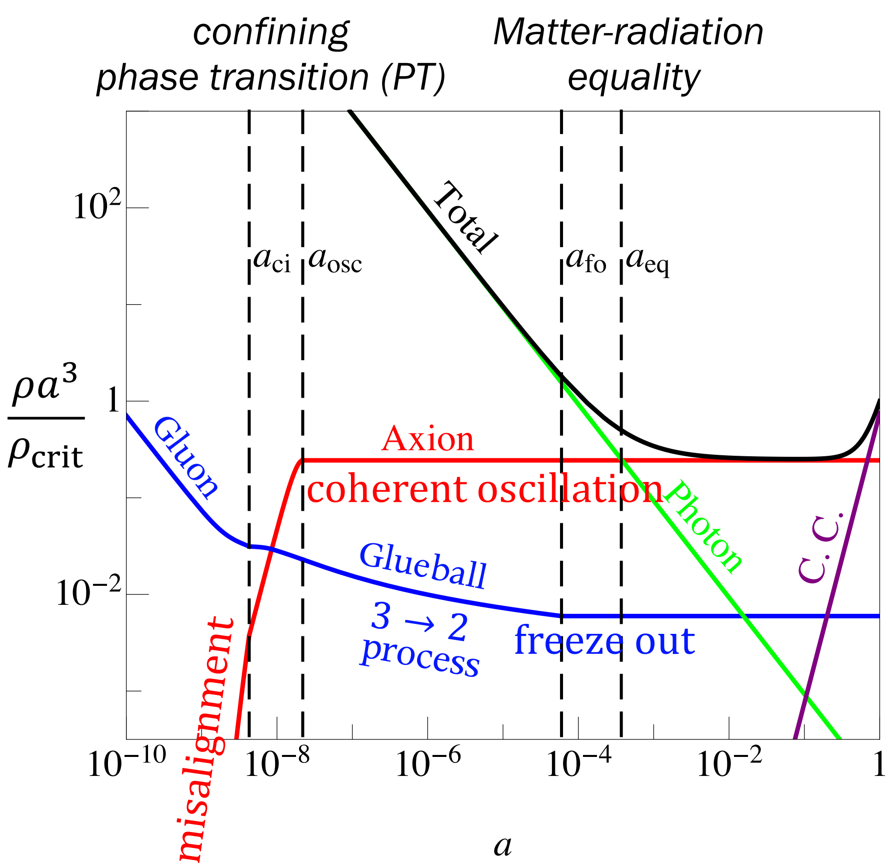
$$V_{eff}(\phi) \sim \frac{\Lambda^4}{f_a^2}\phi^2\left(1 + O\left(\frac{\phi^2}{N^2 f_a^2}\right)\right)$$

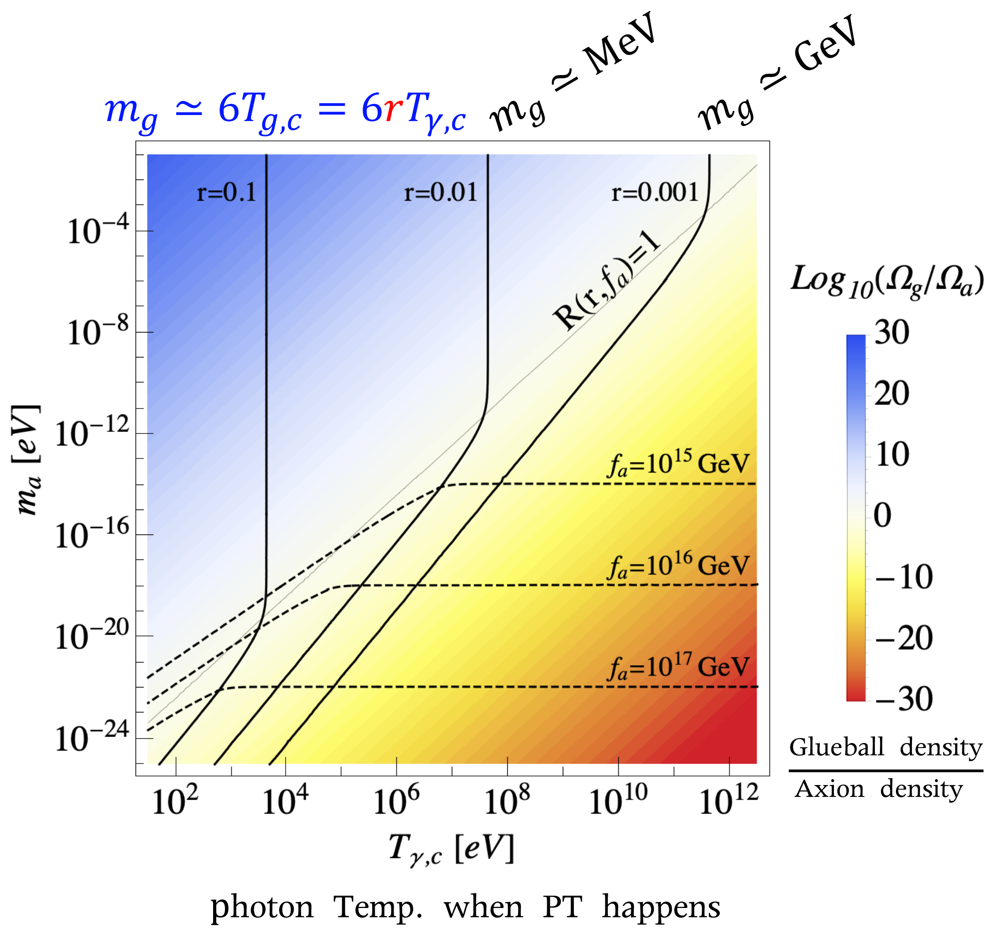
for $\phi < \pi f_a$

Background Density Evolution

$$L_{dark} = -\frac{1}{4g_h^2}GG + \frac{1}{2}\left(\partial_\mu \phi\right)^2 + \frac{\phi}{32\pi^2 f_a}G\tilde{G}$$

$$r = \left(\frac{T_g}{T_\gamma}\right)_{BBN}$$





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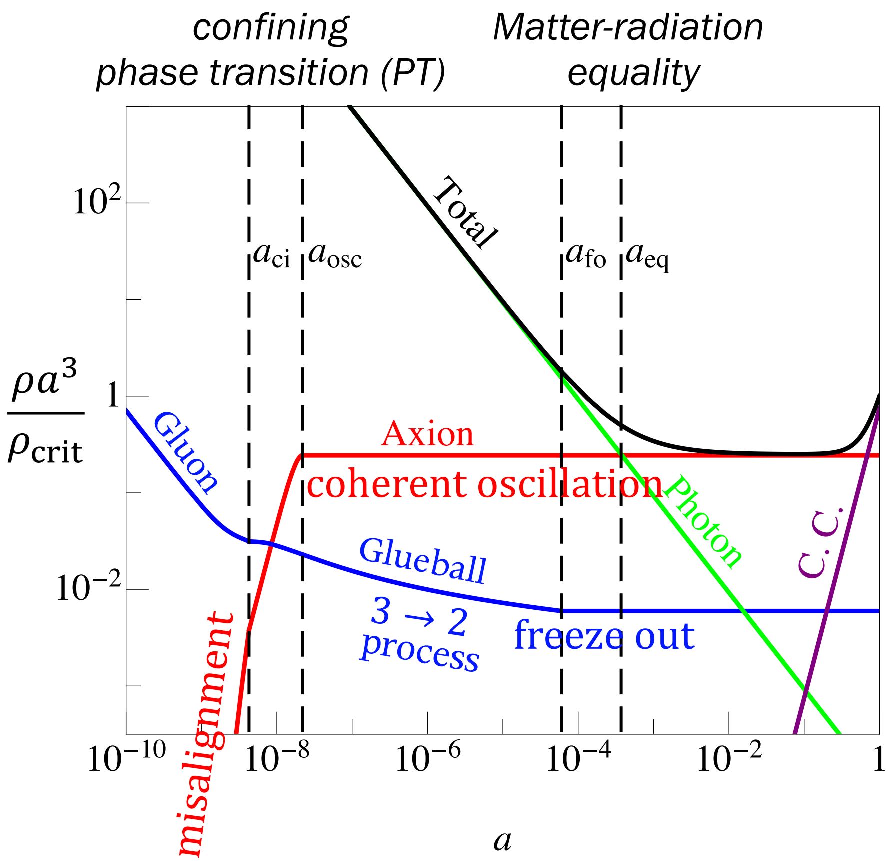
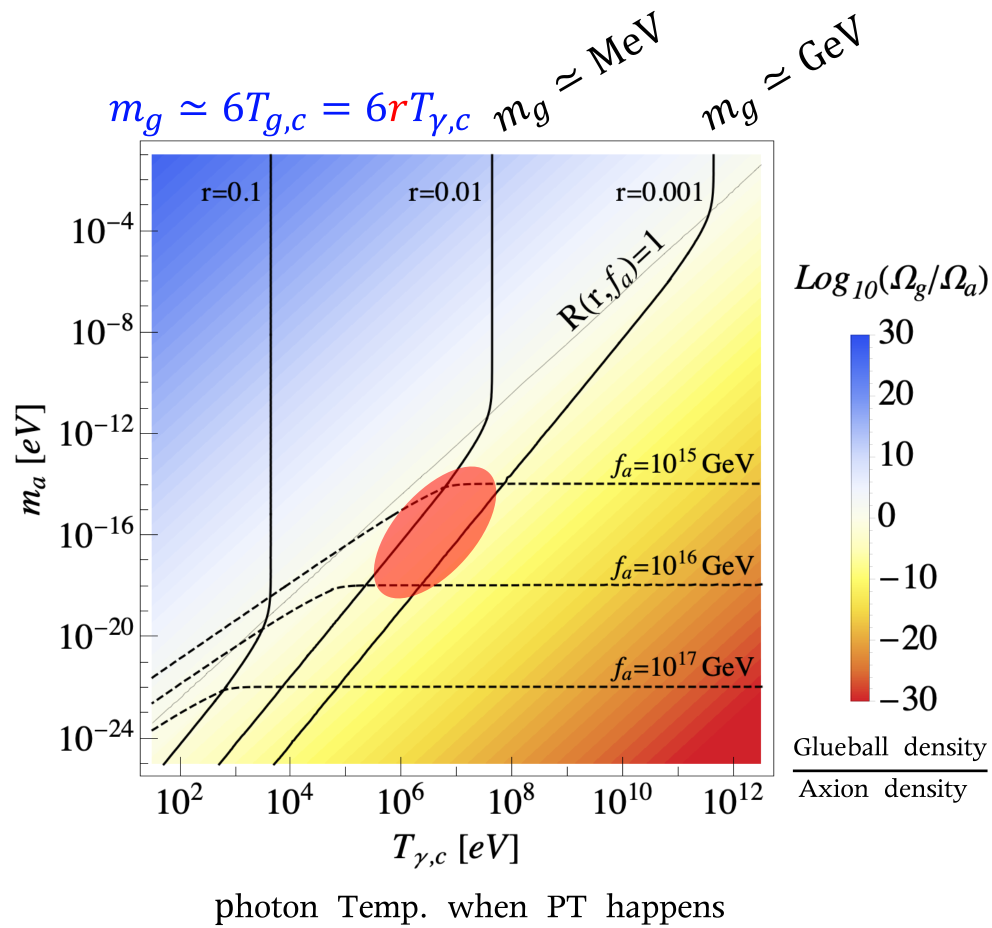


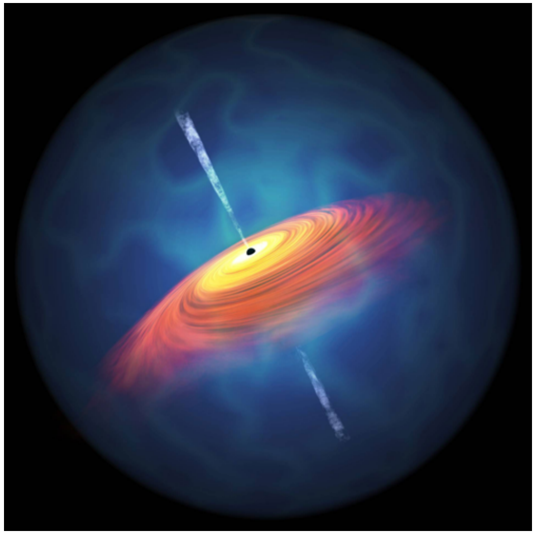


is our interest: dominant axion DM & sub-comp. strongly interacting glueball DM

Implications of
Subcomponent Glueball Dark Matter

Supermassive Black Holes (SMBH) at High z

In the 2010s, new observations of the quasars lead to the discovery of SMBHs around z = 7.



Around the redshift $z = 7$ ($t \simeq 770$ Myr $\sim 0.05\, t_U$),

J1342+0928 ($z = 7.54, M_{BH} = 0.8{\times}10^9 M_\odot$, *1712.01860*)

J1120+0641 ($z = 7.09, M_{BH} = 2.0{\times}10^9 M_\odot$, *1106.6088*)

J2348-3054 ($z = 6.89, M_{BH} = 2.1{\times}10^9 M_\odot$, *1311.3260*)

J0109-3047 ($z = 6.75, M_{BH} = 1.5{\times}10^9 M_\odot$, *1311.3260*)

J0305-4150 ($z = 6.61, M_{BH} = 1.0{\times}10^9 M_\odot$, *1311.3260*)

J0100+2802 ($z = 6.3, M_{BH} = 1.2{\times}10^{10} M_\odot$, *1502.07418*)

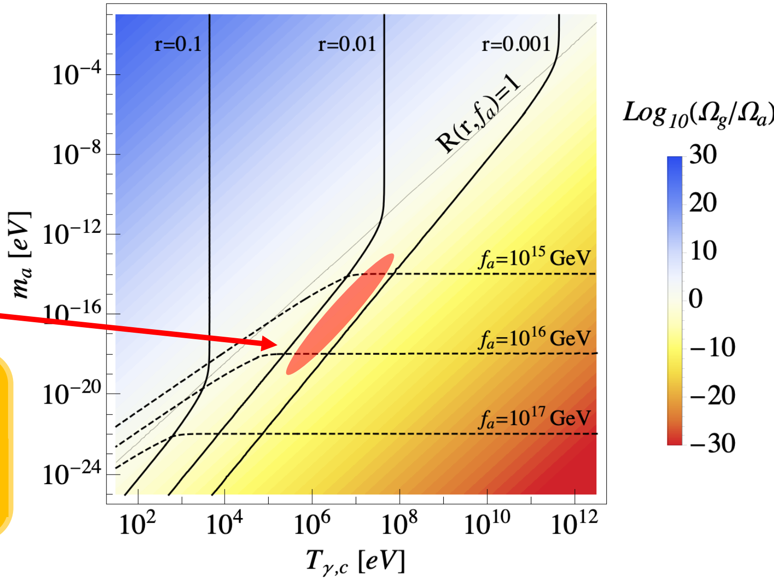
The origins of these SMBHs are not clear. It may originate from strongly self-interacting subcomponent DM

1501.00017 Pollack, Spergel, Steinhardt

(dark glueball subcomponent DM)

$$\sigma_{g2\to2} \sim \frac{1}{16\pi}\left(\frac{4\pi}{N}\right)^4 \frac{1}{m_g^2}$$

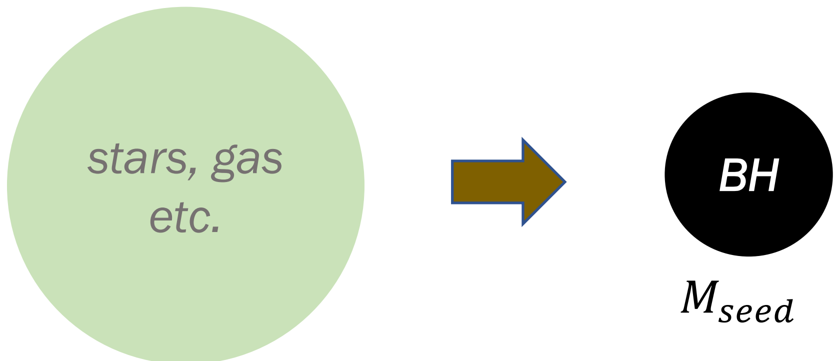
$$m_g \sim 0.01 - 1 \text{ MeV}$$
$$m_a \sim 10^{-18} - 10^{-14} \text{ eV}$$



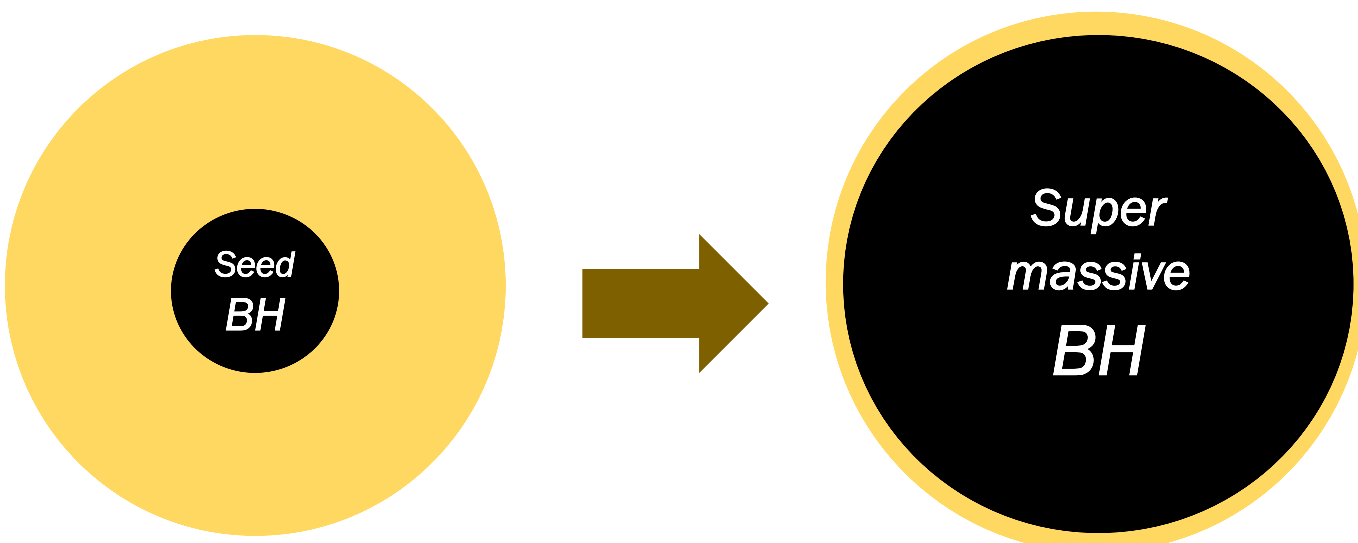
Formation and Growth of BHs

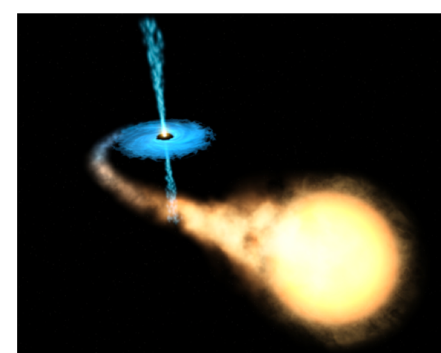
Basic process

1) *Formation of the seed black hole (e.g. stellar evolution, direct formation from gas collapse)*



2) *Growth by accretion of baryons (and dark matters) or mergers with other black holes*





$$M_{BH}(t_{col}) = M_{seed} \rightarrow M_{BH}(t_{obs}) = M_{SMBH} \gg M_{seed}$$

Accretion rate is enough for SMBHs at High z?

If the seed black hole is formed inside the virialized massive halo, it is reasonable that it happens $z < 20 - 30$

From the Eddington limit, $M_{BH}(t_{obs}) \leq M_{seed} \exp\left(\frac{t_{obs} - t_{col}}{t_{Sal}}\right) \equiv M_{seed}\, \mathcal{A}_{acc}$

$(t_{Sal} = 45 \text{ Myr})$

During matter domination, the age of the Universe, $t(z) = 550 \text{ Myr} \left(\frac{10}{1+z}\right)^{3/2}$

For $z_{obs} = 7,\ \ z_{col} = 15,\ \ \mathcal{A}_{acc} \sim (2-6)10^4$ → $M_{seed} \sim 10^5\, M_\odot$ *at* $z_c = 15$

For $z_{obs} = 7,\ \ z_{col} = 30,\ \ \mathcal{A}_{acc} \sim (6-10)10^5$ → $M_{seed} \sim 10^4\, M_\odot$ *at* $z_c = 30$

Within the CDM framework

As the remnants of the Pop III stars ($z \sim 20$), $M_{seed} = O(100)\, M_\odot$ *(Madau & Rees 2001, Heger et al. 2003, Wise & Abel 2005)*

The larger growth rate within a certain period? (super-Eddington accretion)

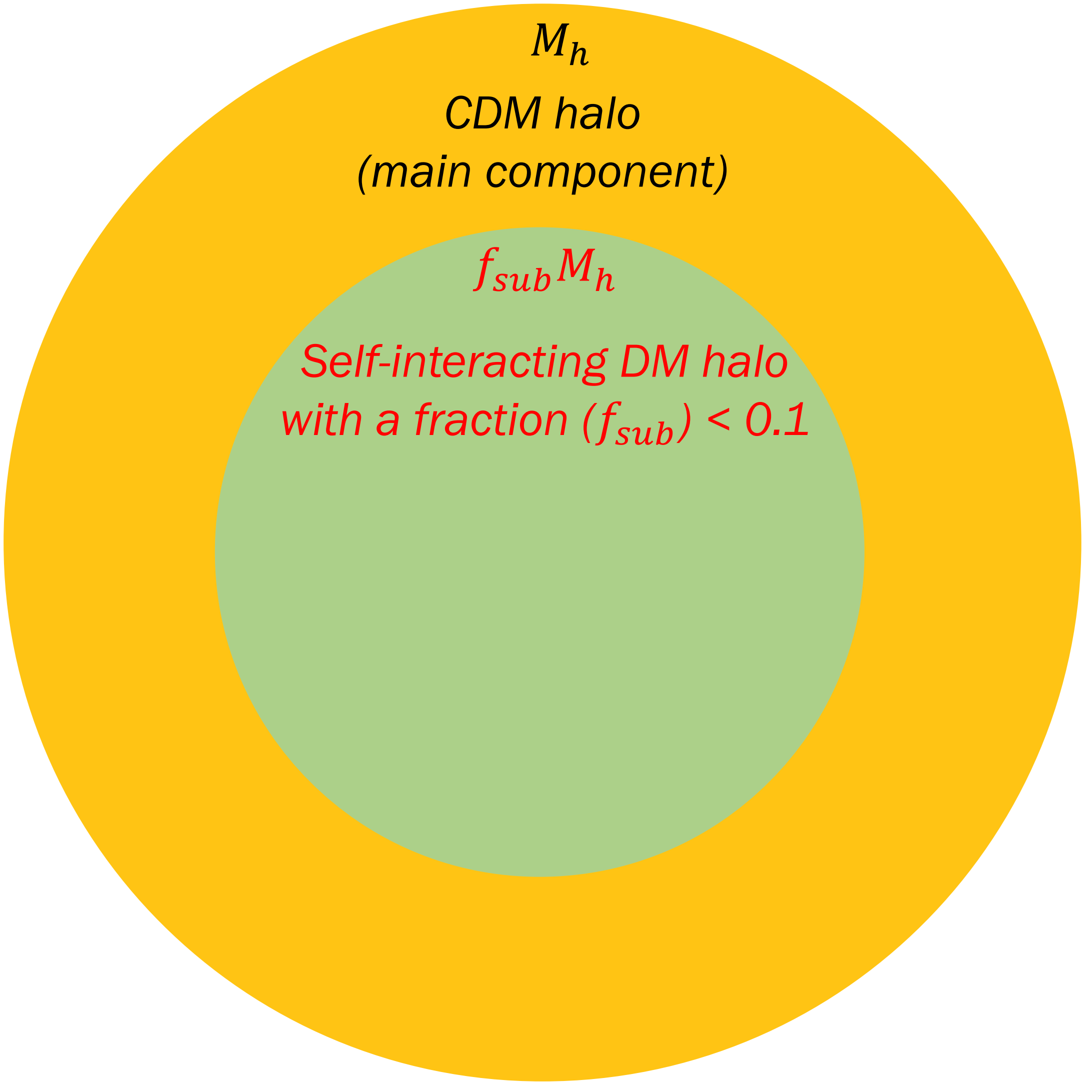
$$M_{BH}(t) = M_{seed}\, e^{f_{Edd}\, t/\tau_{Sal}}, \qquad (f_{Edd} > 1)$$

Direct collapse of gas into the BH ? $M_{seed} = O(10^{4-6})\, M_\odot$ *but should prevent fragmentation, star formation before the collapse* *(Loeb & Rasio 1994, Eisenstein & Loeb 1995, …)*

Collapsing star cluster? From mergers of Pop II stars, $M_{seed} = O(10^3)\, M_\odot$ *but maybe useful only for explaining observed quasars at z<5* *(Devecchi & Volonteri 2009)*

Beyond the CDM framework 1501.00017

Beyond the CDM framework : multi-component with strongly interacting sub-comp. DM



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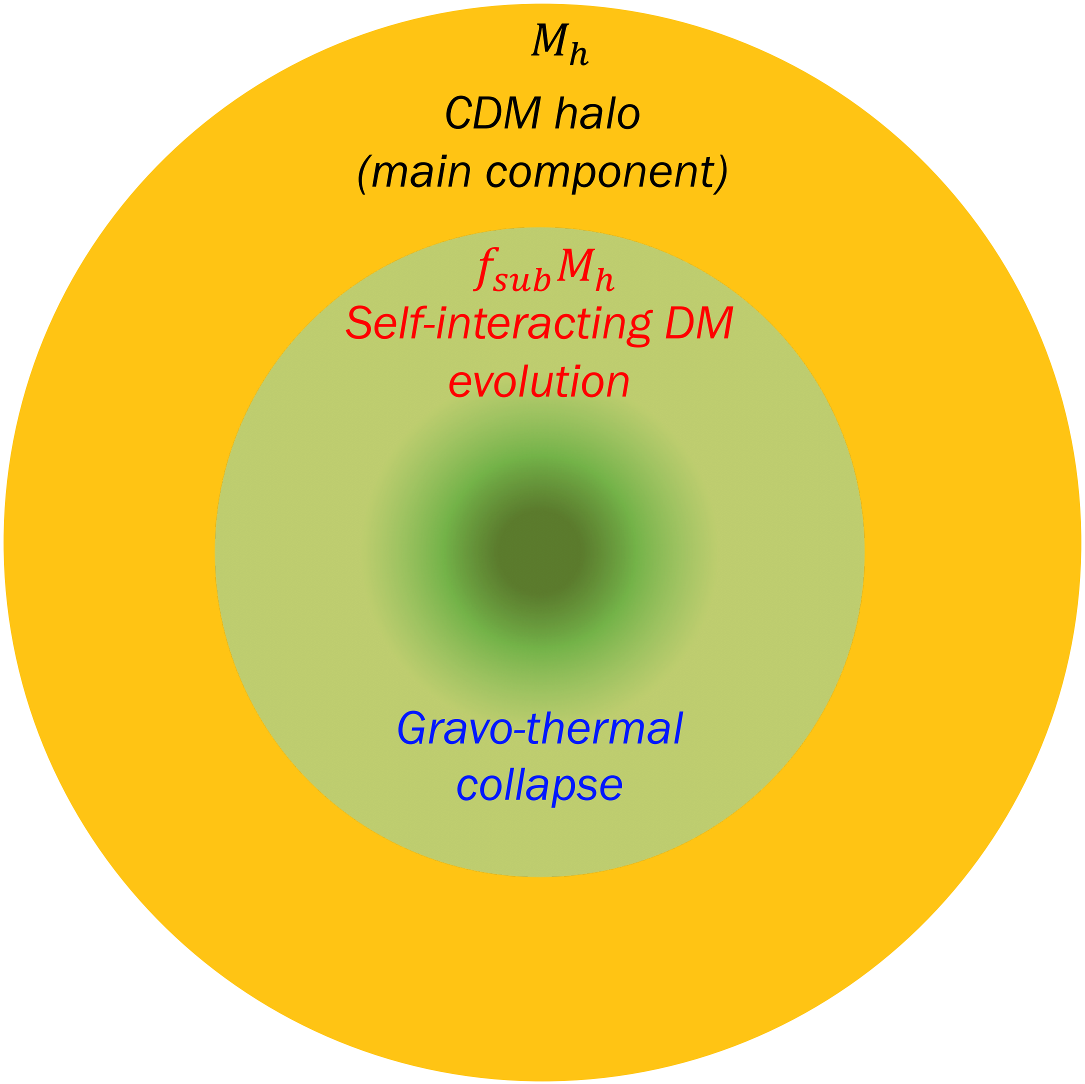

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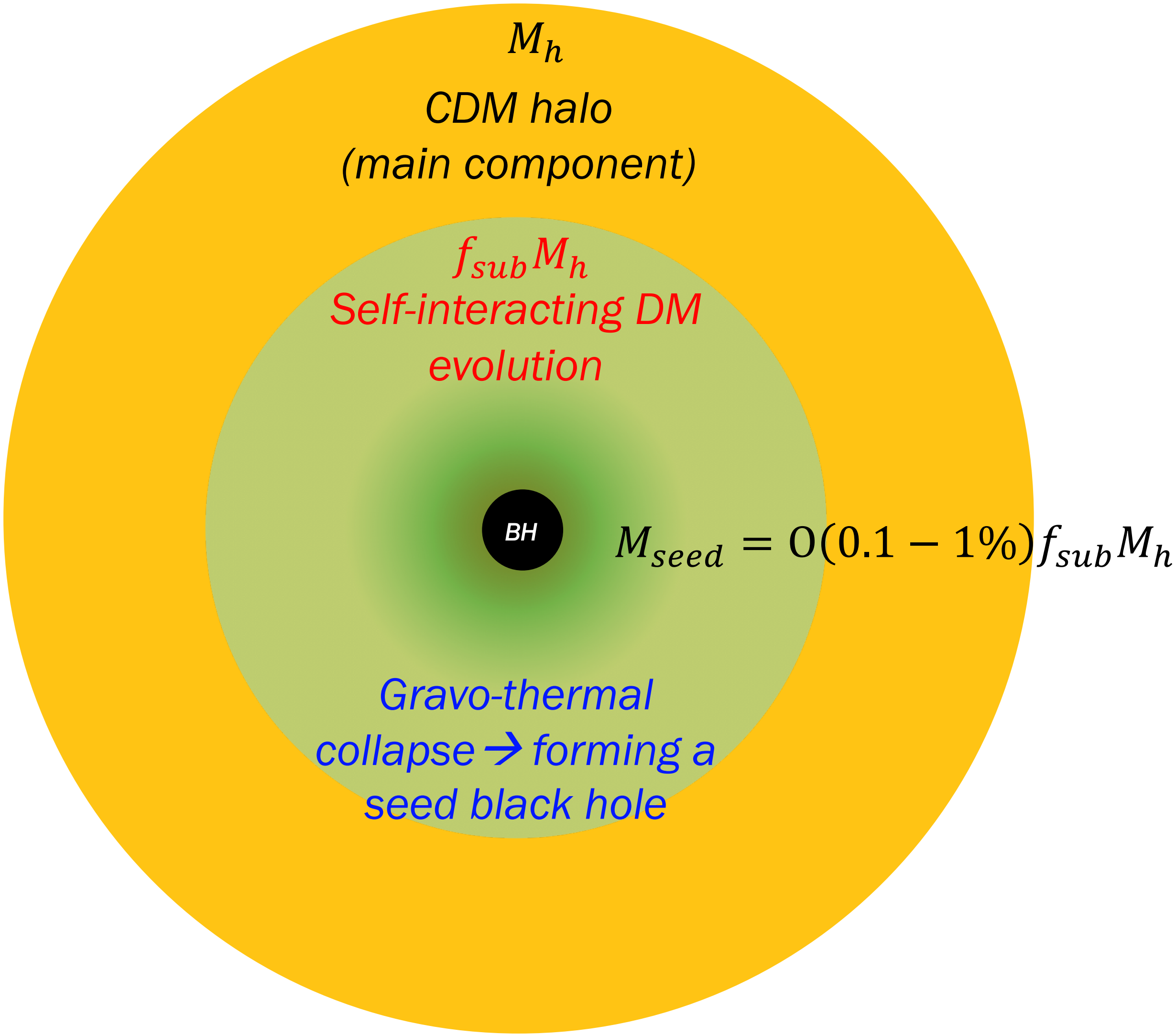

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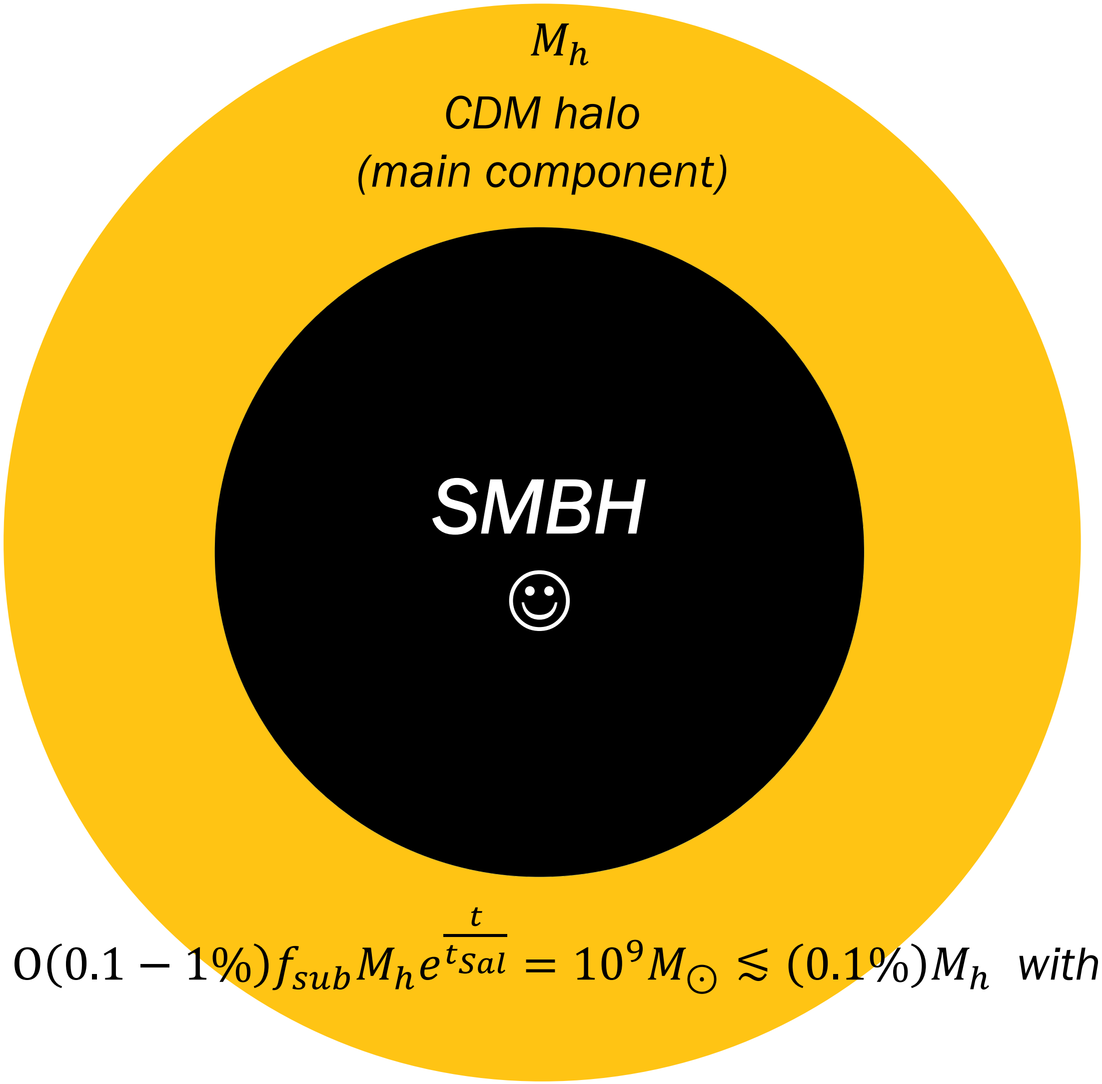
Beyond the CDM framework : multi-component with strongly interacting sub-comp. DM



$$M_{BH}(t) = O(0.1 - 1\%) f_{sub} M_h e^{\frac{t}{t_{Sal}}} = 10^9 M_\odot \lesssim (0.1\%) M_h \ \text{with}\ M_h = 10^{12} M_\odot$$

Gravo-Thermal Collapse 1

Thermally equilibrated system which is bound by gravity

If the system is in equilibrium with gravity, the system has a negative specific heat capacity

$$c_T = \frac{dE}{dT} < 0$$

Why? Thermal equilibrium → thermal energy (kinetic energy) is virialized by potential energy

$$\langle V \rangle = -2\langle K \rangle \to E = Nm + \langle V \rangle + \langle K \rangle = Nm - \langle K \rangle = Nm - NT \to \frac{dE}{dT} = -N \simeq -\frac{E}{m}$$

(c.f. black hole: $E = M_{BH}$, $T = \frac{M_P^2}{M_{BH}} = \frac{M_P^2}{E} \to \frac{dE}{dT} = -\frac{E}{T} < 0$ *)*

Negative heat capacity → instability

Considering the bound system with

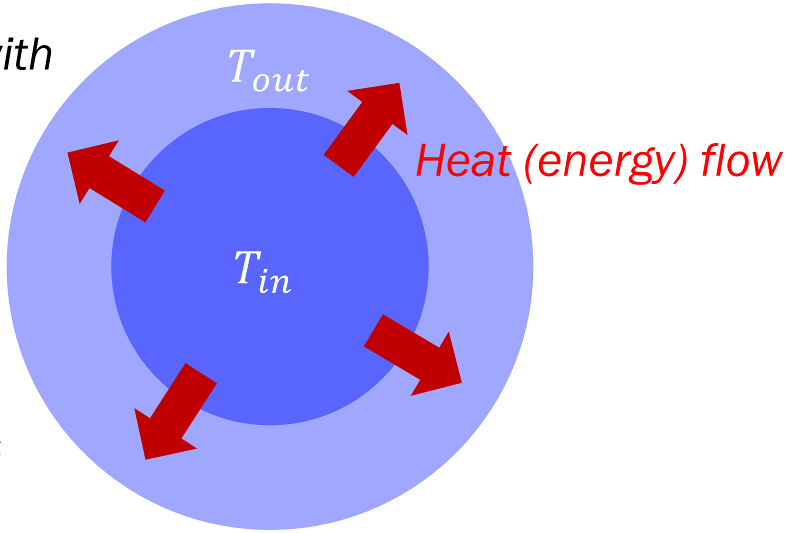
initial temperature gradient

$$T_{in} > T_{out}$$

For the <u>*positive*</u> c_T *case,*

T_{in} *decreases,* T_{out} *increases*

and meet at T_{eq}*. Heat flow stops*



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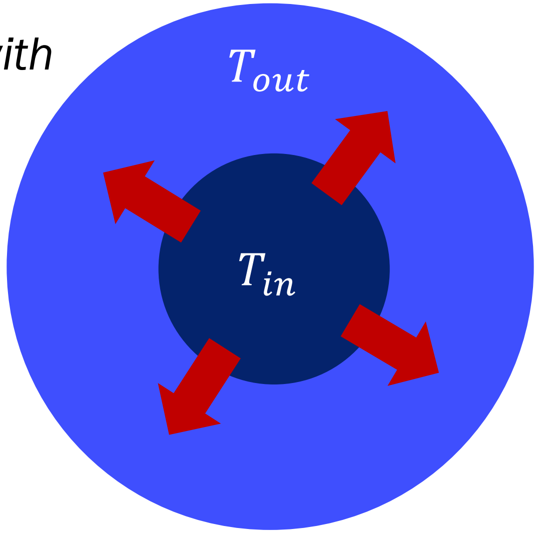
Negative heat capacity → instability

Considering the bound system with initial temperature gradient

For the negative c_T case

Heat (energy) flow continues!

$T_{in} > T_{out}$ maintains forever!



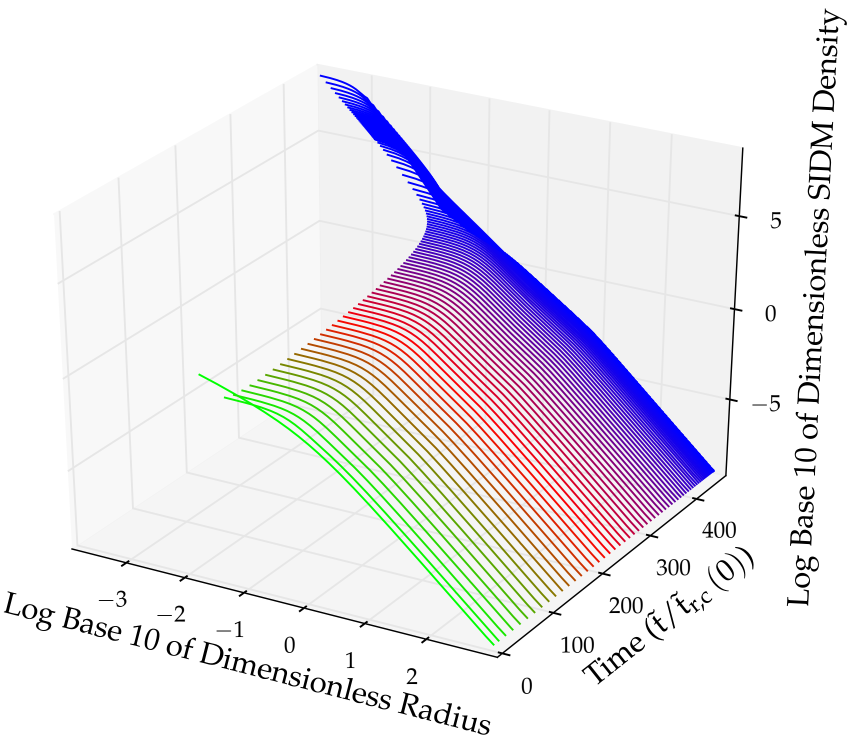
Strongly bound system with high virial velocity
→ leads to gravitational collapse
→ forming a black hole

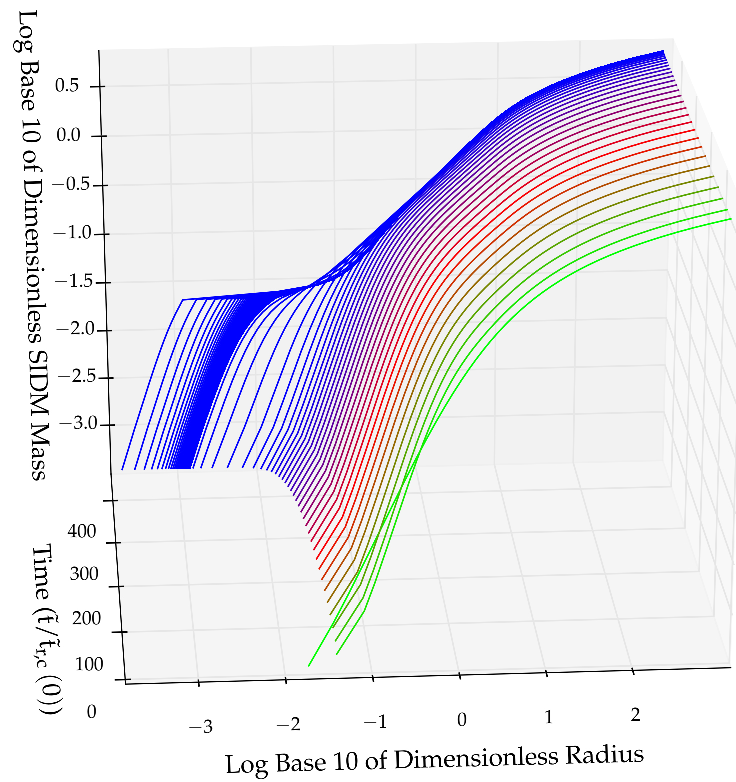
Gravo-Thermal Collapse 2

For the gravo-thermal collapse, maintaining thermal equilibrium is an important condition.

Therefore the "relaxation time" should be shorter than the age of the Universe for a given z.

How short? Numerical calculation is necessary





1501.00017 for the isolated halo with f_{sub}=1

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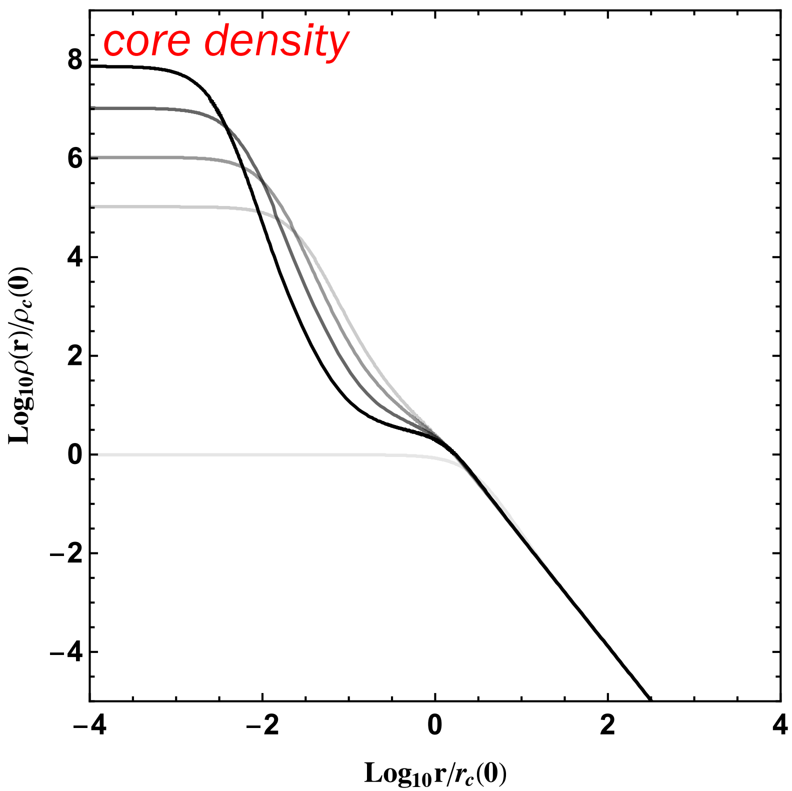
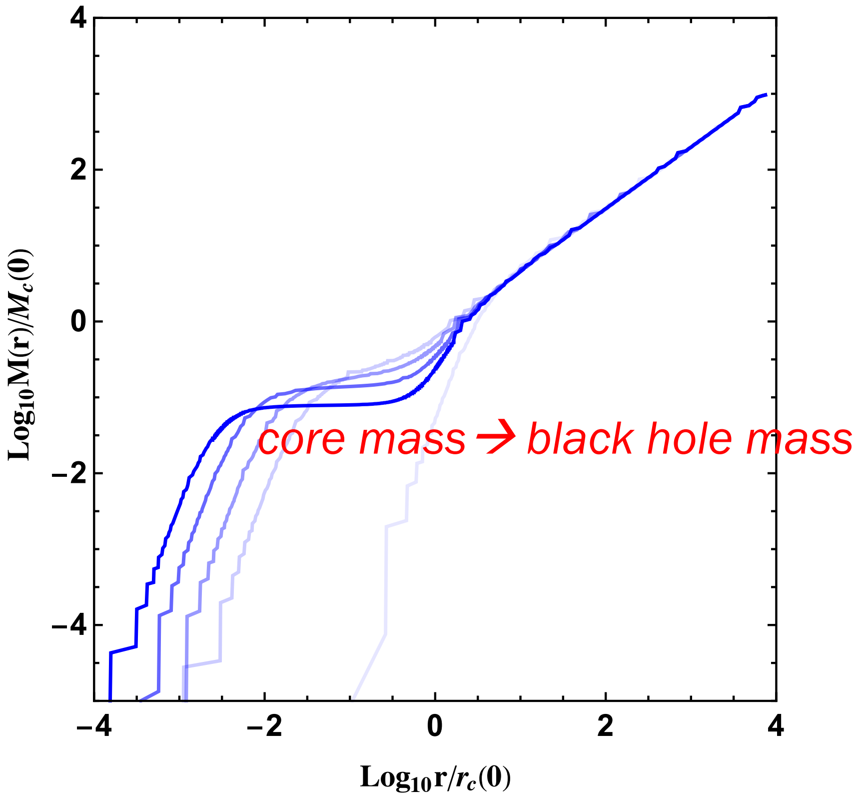




Balberg et.al. 0110561 for the isolated halo with f_{sub}=1

Gravo-Thermal Collapse for sub component DM

Numerical calculations estimate the collision time as

$$\Delta t_{col} \simeq 480\, t_{relax}(t_i)$$

$$t_{relax}(t_i) = \frac{m_{DM}}{\sigma_{el}\rho_s(t_i)v_s(t_i)}$$

It is non-trivial to estimate the collision time for the collapse of sub-component dark matter.

There are two papers to estimate the collision time and the seed black hole mass for the isolated halo with a small fraction (f_{sub}) of self-interacting DM

$$\Delta t_{col} \simeq 480\, t_{relax}(t_i), \qquad M_{seed} \simeq \frac{0.02}{\ln c} f_{sub} M_h$$

1501.00017, fluid approximation

$$t_{relax}(t_i) = \frac{m_{subDM}}{\sigma_{el}\, f_{sub}\rho_s(t_i)v_s(t_i)}$$

$$\Delta t_{col} \simeq \frac{480}{f_{sub}^2}\, t_{relax}(t_i), \qquad M_{seed} \simeq 0.006 f_{sub} M_h$$

1812.05088 Choquette, Cline, Cornell, N-body simulation up to f_{sub}=0.1

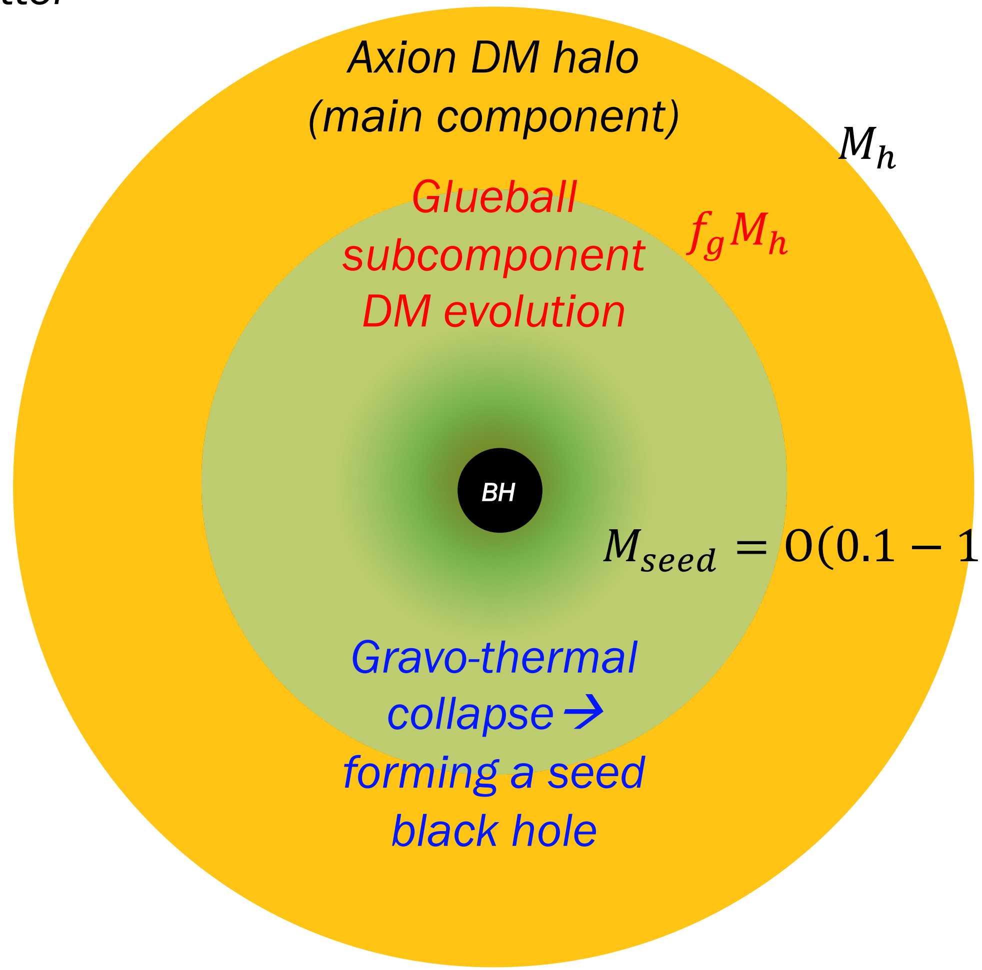
In order to explain the SMBH at z=7, ($\Delta t_{col} < t(z_{col}) < t(z=7)$)

$$f_{sub}\sigma_{el}/m_{subDM} \sim 1 - 10\ \mathrm{cm}^2/\mathrm{g}$$

$$f_{sub}^3\sigma_{el}/m_{subDM} \sim 1 - 10\ \mathrm{cm}^2/\mathrm{g}$$

Seed Black Hole Formation in Our Model

The large seed black hole can be made by the gravo-thermal collapse of the subcomponent glueball dark matter



$$M_{seed} = O(0.1 - 1\%) f_g M_h$$

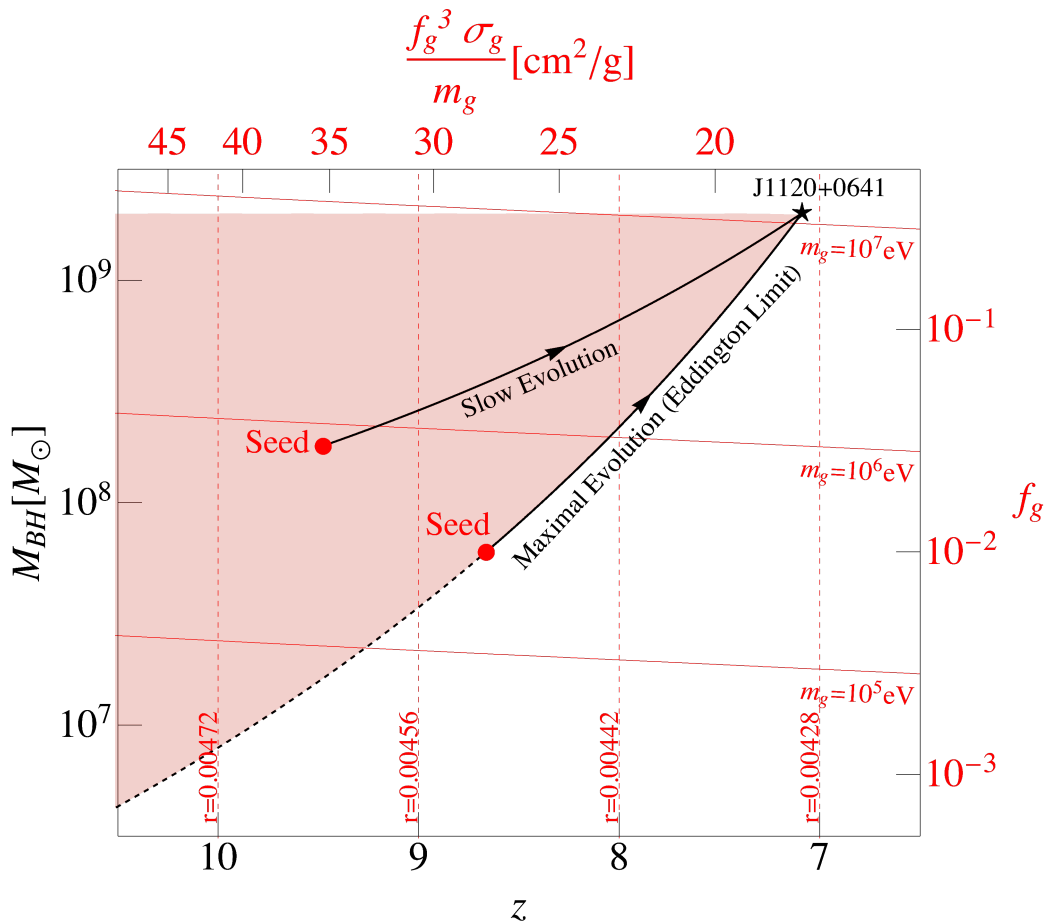
$$M_{BH}(t) = M_{seed} e^{\frac{t-t_i}{t_{Sal}}}$$

$$\Delta t_{col} \simeq \frac{480}{f_g^2}\, t_{relax}(t_i), \qquad M_{seed} \simeq 0.006 f_g M_h$$

$$t_{relax}(t_i) = \frac{m_g}{\sigma_g\, f_g \rho_s(t_i) v_s(t_i)}$$

SMBH at High z for an Isolated Host Halo

The large seed black hole can be made by the gravo-thermal collapse of the subcomponent glueball dark matter



for $M_h = 10^{12} M_\odot$

Caveats: History of the Host Halo Mass

The assumption of the isolated host halo with a mass $M_h = 10^{12} M_\odot$ for $z \geq 10$ is not realistic:
the problem of SMBH → the problem of supermassive dark matter halo.

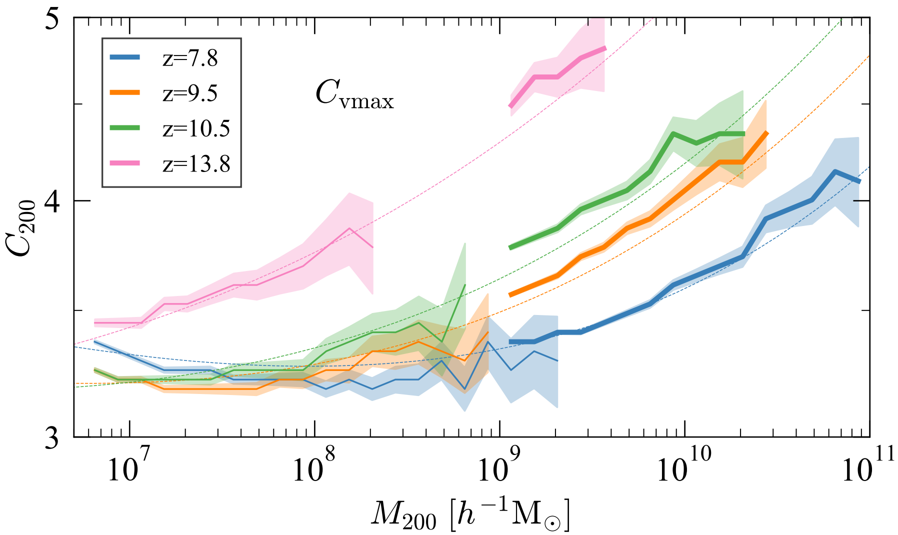
The merger history of the host halo (e.g. the history of heaviest halo) and its profile should be considered: $\{M_h(z), \rho_s(z), c(M_h, z), v_s(z)\}$

Our approach: at $z = z_i$*, a seed black hole forms with* $M_{seed} = 0.006\, f_g\, M_h(z_i)$

Both the black hole and the host halo grow such that $M_h(z = 7) \gtrsim 10^{12} M_\odot$ *and*

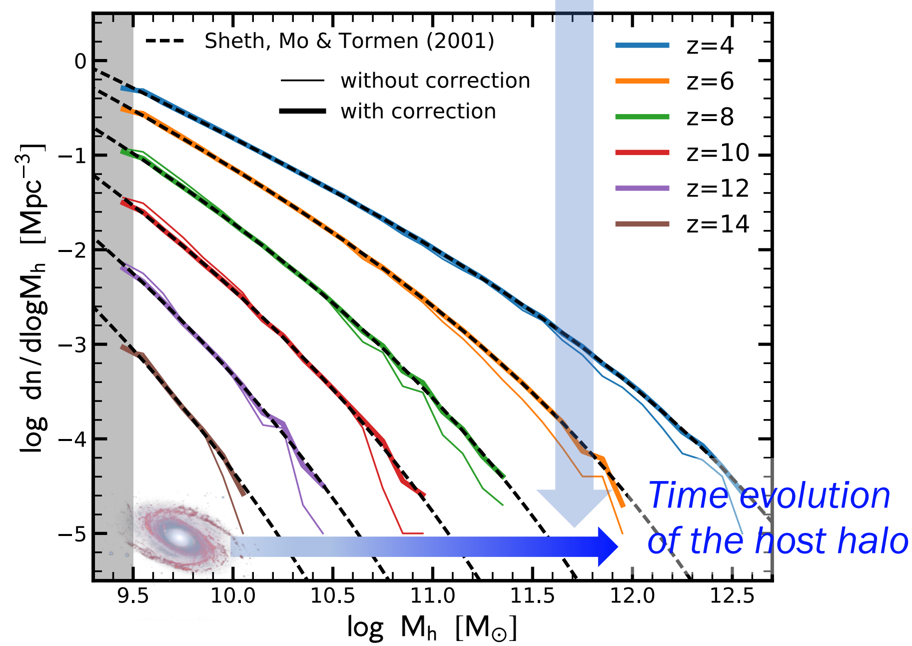
$$M_{BH}(z = 7) = M_{seed}\, e^{\frac{t(7) - t(z_i)}{t_{Sal}}} \sim 10^9 M_\odot$$

Concentration parameter for given M_h, z



Ishiyama et al. 2007.14720

halo mass function (z)



Tacchella et al. 1806.03299

Caveats: Evolution of the Glueballs inside the Core

As the core becomes extremely dense after the gravo-thermal collapse accelerates, the temperature of the core also increases as $T_c \propto \rho_c^{1/3}$. This could provide nontrivial effects for the evolution of DM (e.g. formation of BEC, $T_{BEC} \propto \rho_c^{2/3}$).

For the glueball DM case, the number-changing interaction is also crucial for $m_g \lesssim \mathrm{keV}$ → prevent the gravo-thermal collapse

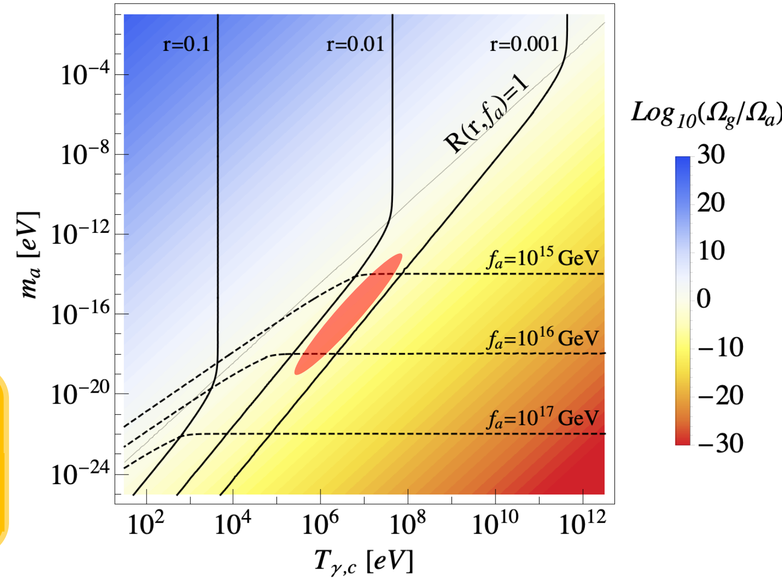
$$\Delta t_{col} \left(\frac{1}{T_g} \frac{dT_g}{dt} \right)_{3\to2} \simeq 0.06 \left(\frac{10^{-3}}{f_g} \right) \left(\frac{10^{-3}}{v_s(t_i)} \right)^2 \left(\frac{\mathrm{keV}}{m_g} \right)^4 \left(\frac{\rho_s(t_i)}{10^{12} M_\odot/\mathrm{kpc}^3} \right)$$

Even for $m_g \gg \mathrm{keV}$, it becomes gradually important ($\Gamma_{3\to2} \propto \rho_c^2$) during the gravo-thermal collapse. Its effect on the final formation of the BH is not clear yet.

From the cosmological history, the mass of the glueball is also bounded by its effective free-streaming length.

If $m_g \lesssim 100$ eV, the glueball DM will not form a halo because it is too warm

$$m_g \sim 0.01 - 1\ \mathrm{MeV}$$
$$m_a \sim 10^{-18} - 10^{-14}\ \mathrm{eV}$$



Summary

The origin of the lightness of the scalar is directly related to its cosmological evolution. Two well-known mechanisms provide opposite behavior for the relation between the interaction strength and the mass of the dark matter.

We studied the minimal nontrivial model of the dark sector that comprises the coupled scalar dark matters: dark axion and dark glueball. Some nontrivial features are clarified.

Strongly interacting subcomponent glueball dark matter can provide a hint on the origin of supermassive black holes at high redshifts.

The possible observations of black hole superradiance by the dark axion & glueball bose stars and other substructures can provide the complementary hints