A few examples of Dark matter models

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Chungnam National University

July 1, 2023 @ **2023 Cosmology Workshop on the Crossroad of Astrophysics and Particle physics: dark matter**

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

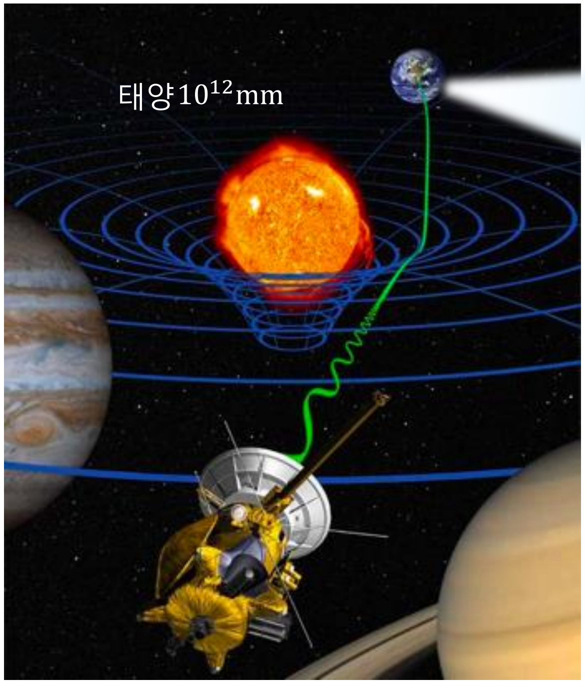


Image from NASA, Cassini spacecraft

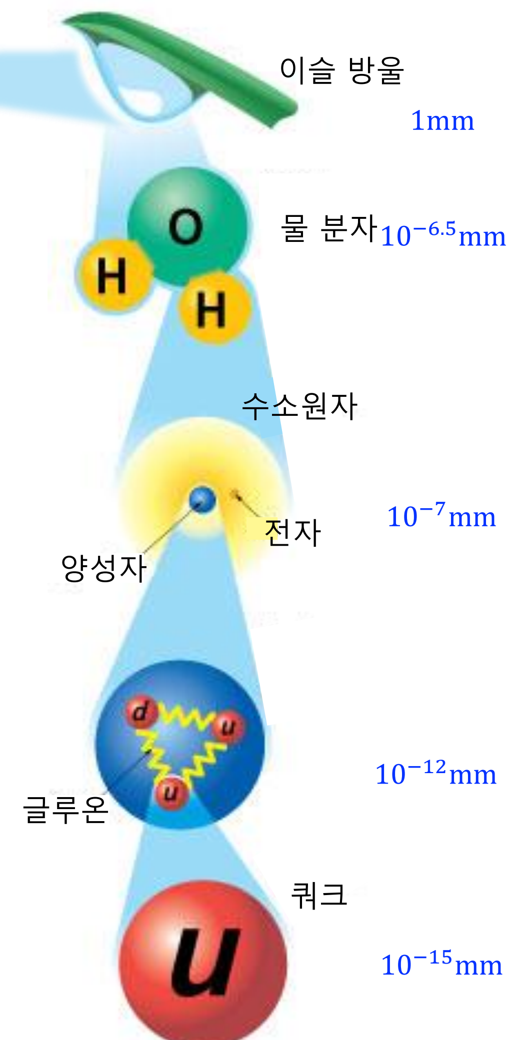
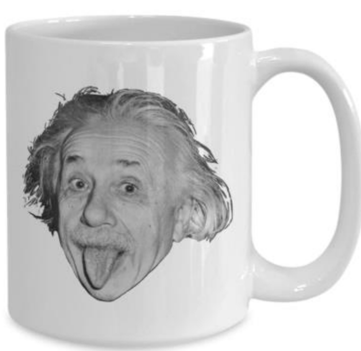
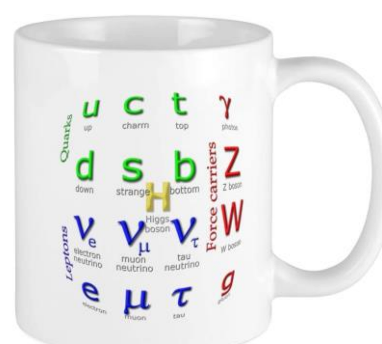


Image from CERN





gravity = curved spacetime

elementary particles = quark, lepton, gauge bosons, Higgs

Evolution of the Universe from GR + the SM

Successful in Hubble-Lemaitre law, Big Bang Nucleosynthesis, Stellar Evolution, and so on.

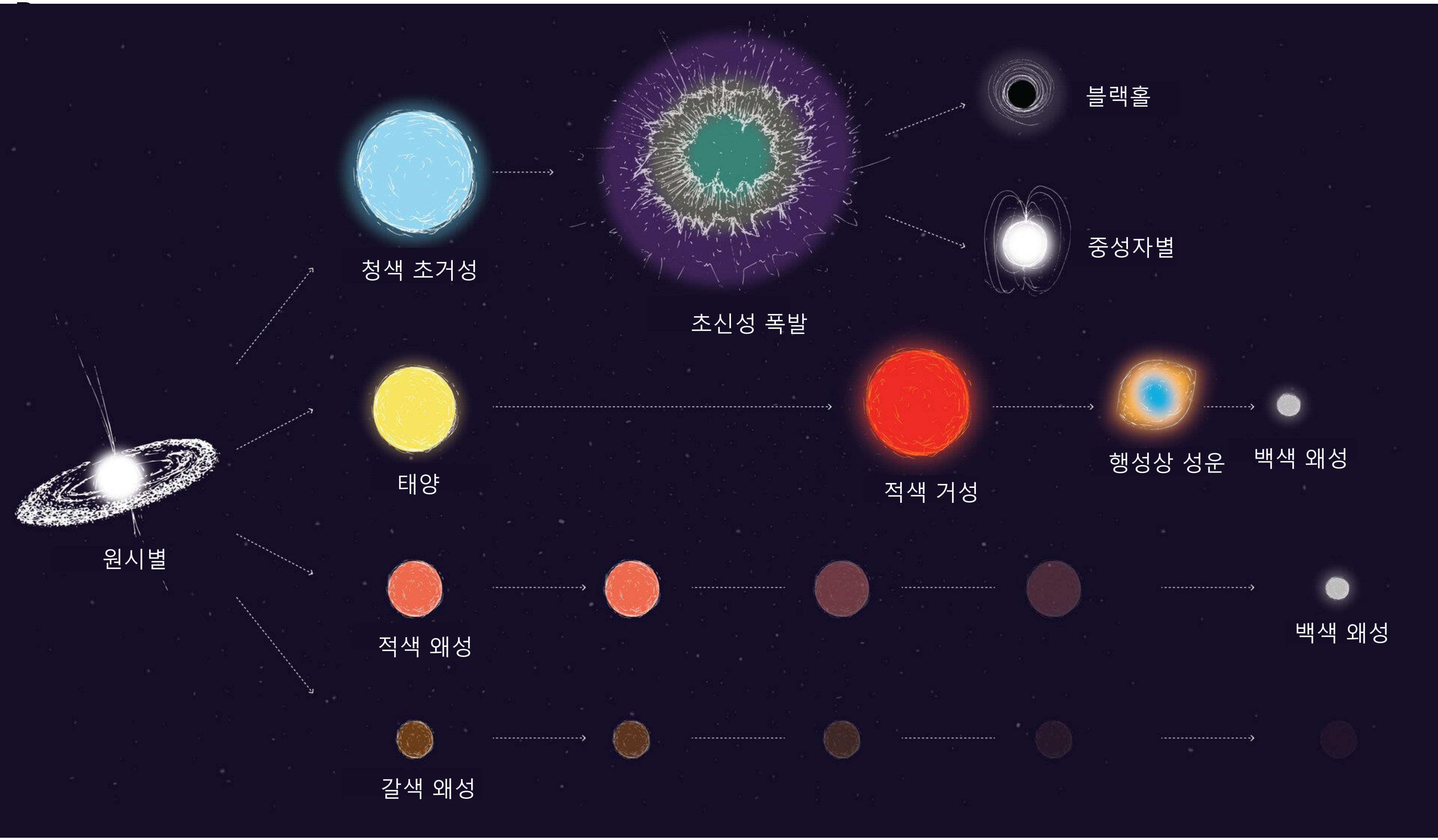
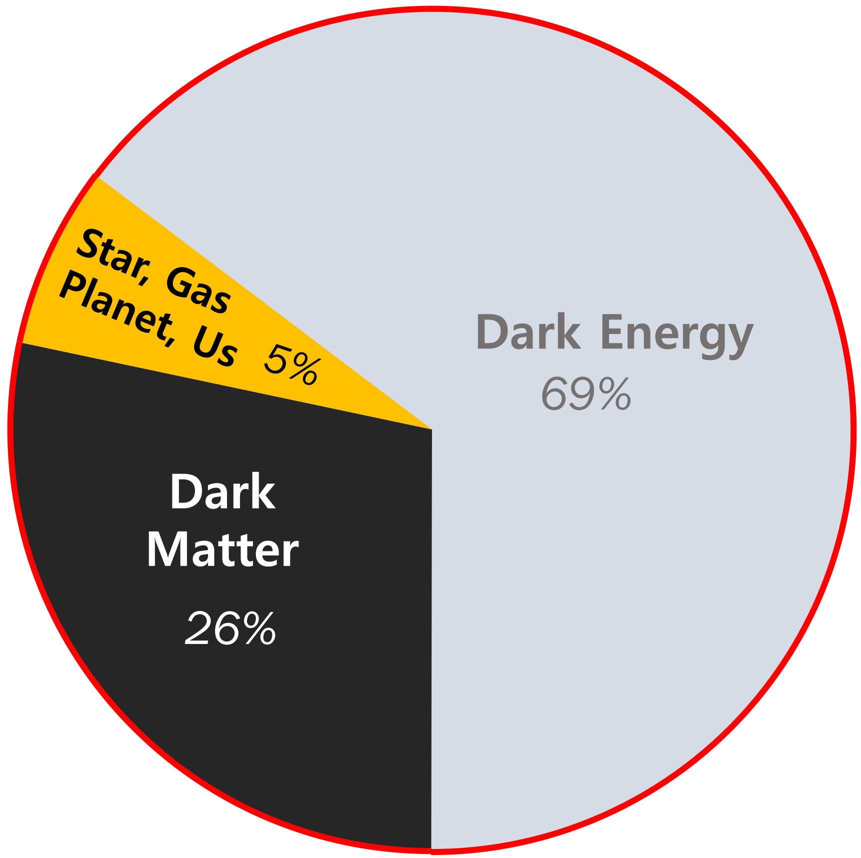


Image from ESA

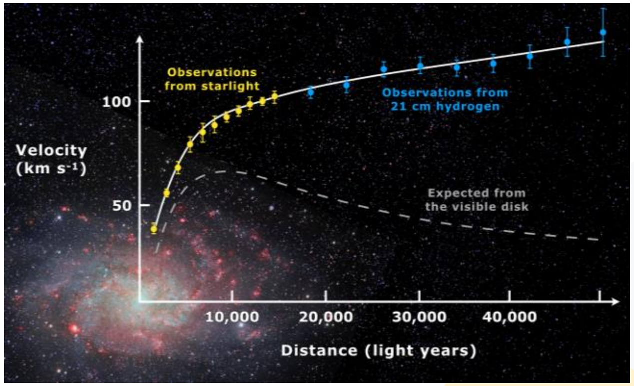
Content of the Universe



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

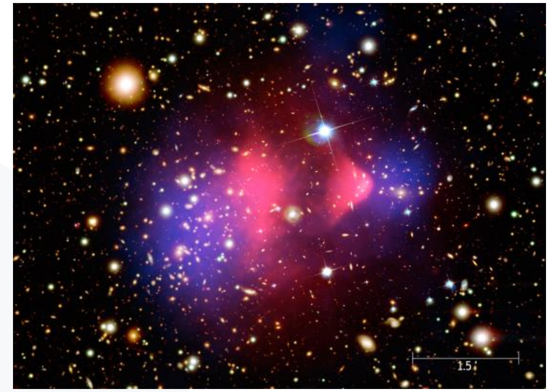
Content of the Universe - DM

Image of Galaxy Messier 33

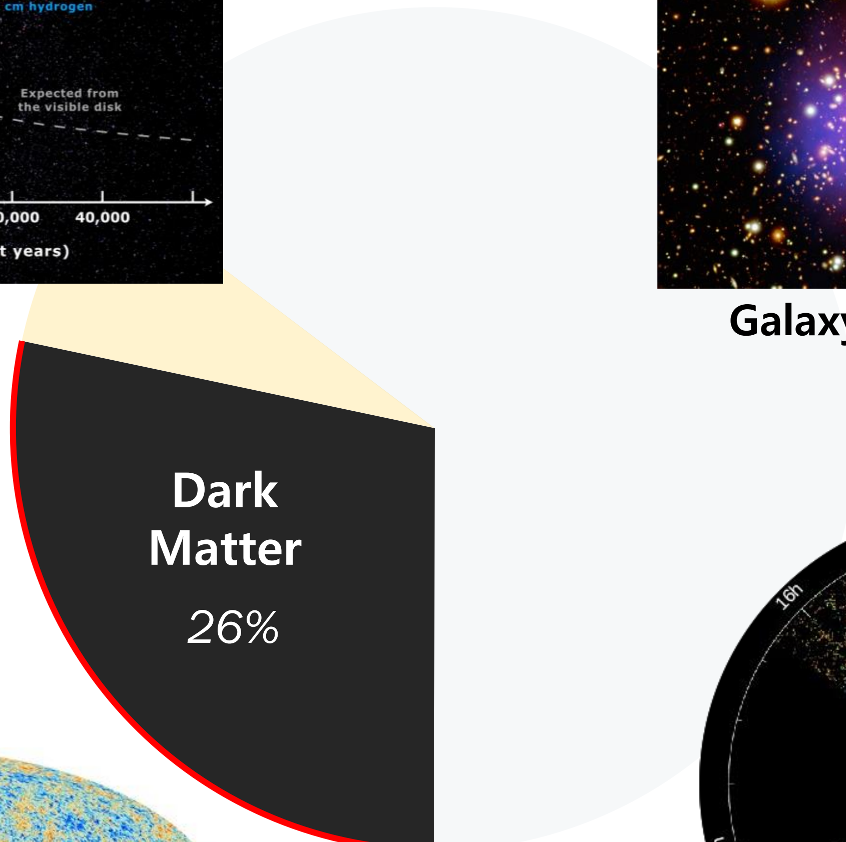


Galaxy Scale

Image of Bullet Cluster 1E 0657-558



Galaxy Cluster Scale



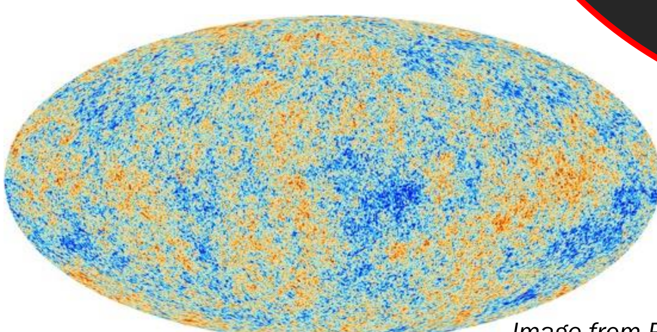


Image from PLACK

Cosmic Microwave Background

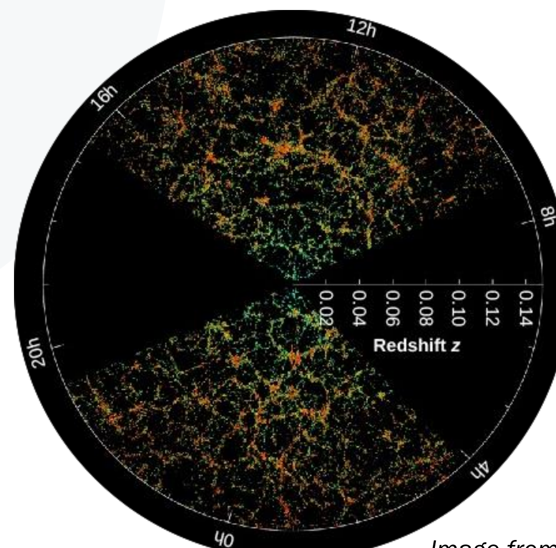


Image from SDSS

Large Scale Structure of the Universe

Content of the Universe - DM

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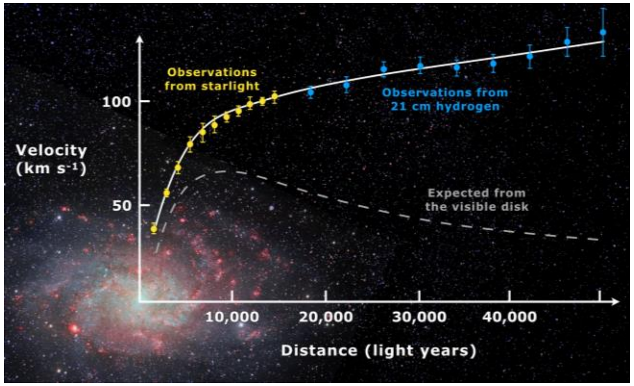

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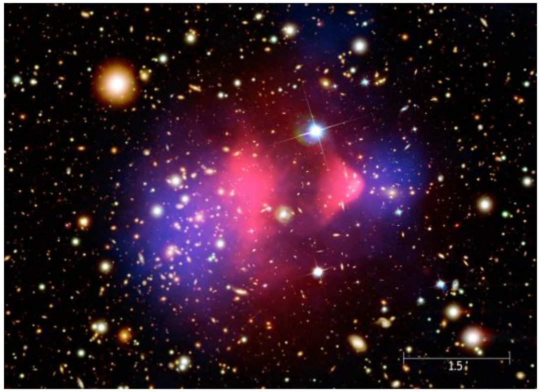
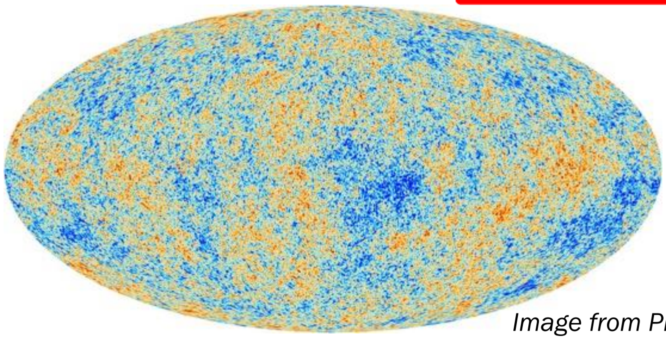


Galaxy Cluster Scale

<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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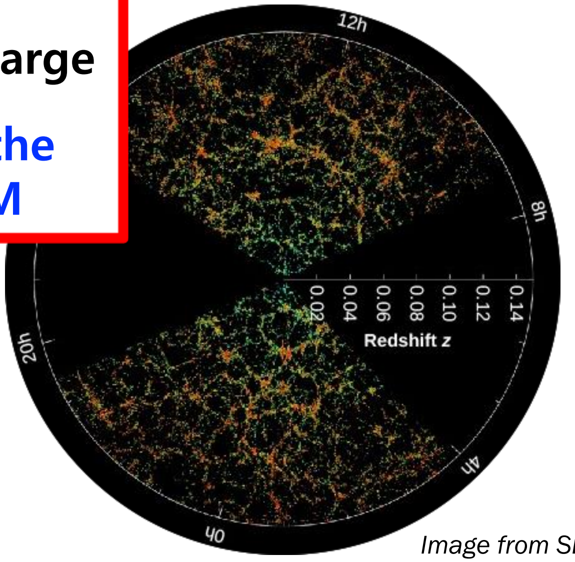
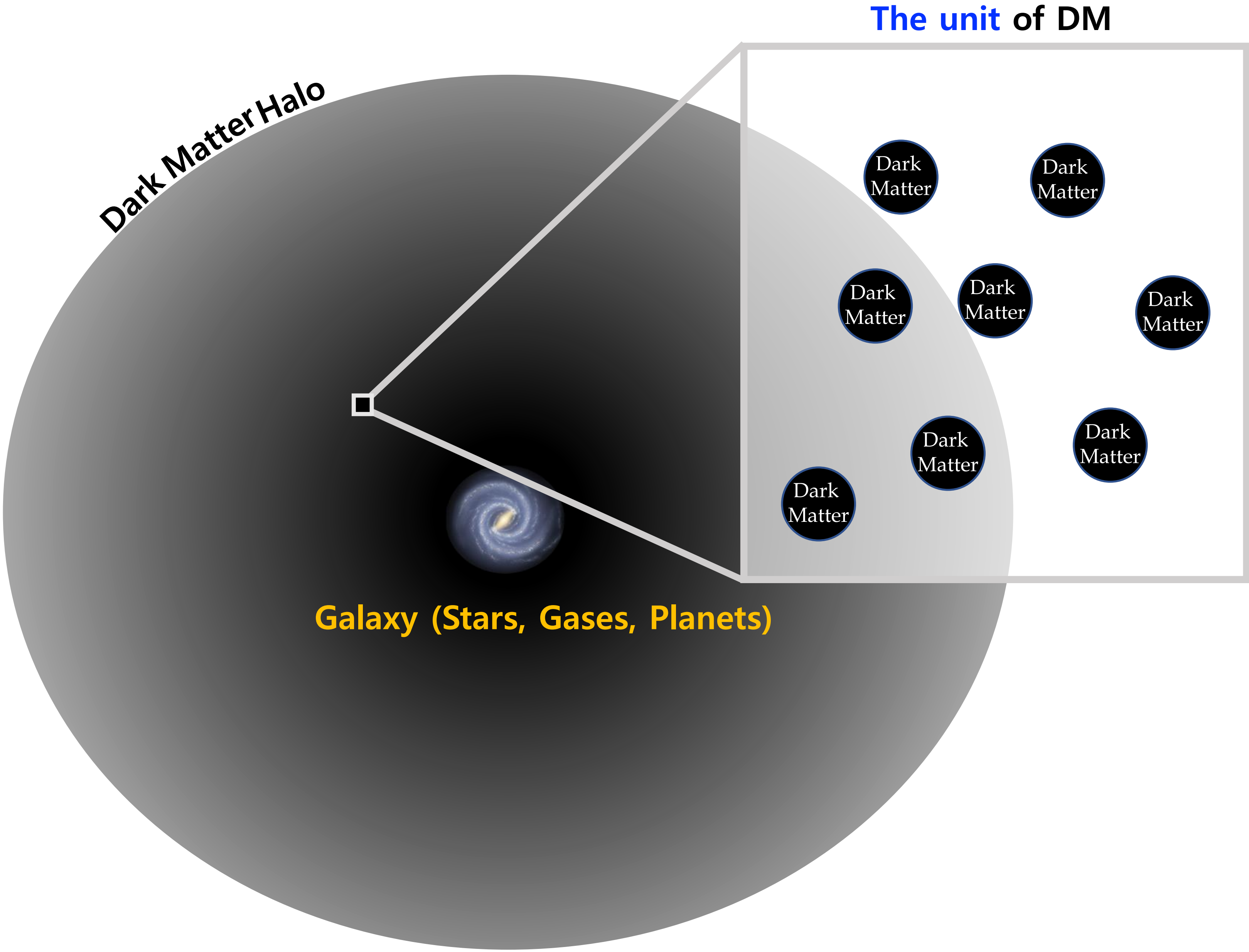


Image from SDSS

Large Scale Structure of the Universe

What is the nature of dark matter?



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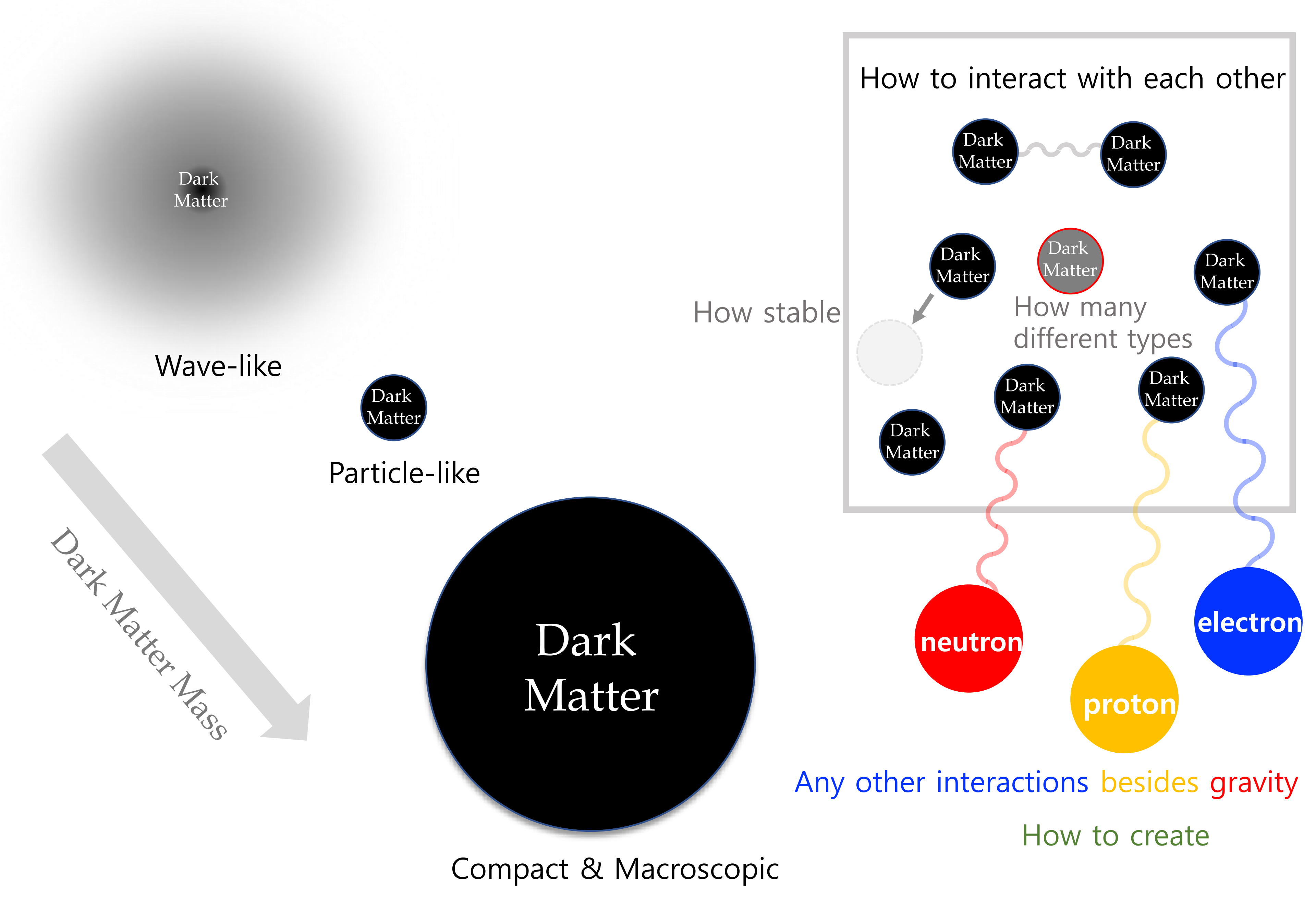
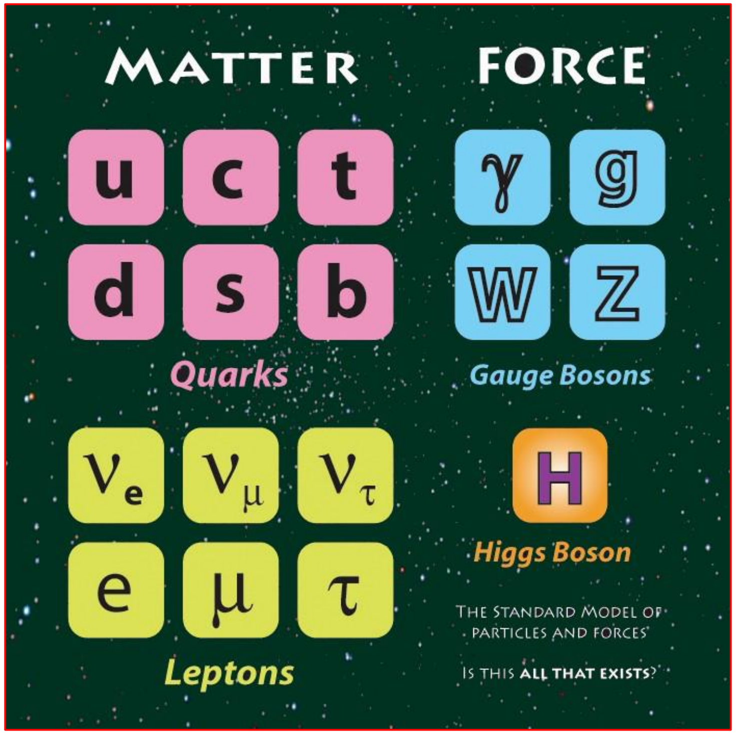


Particle physics approach for DM

Dark matter is a stable object from dark sector interactions and interactions with SM particles.

The Standard Model



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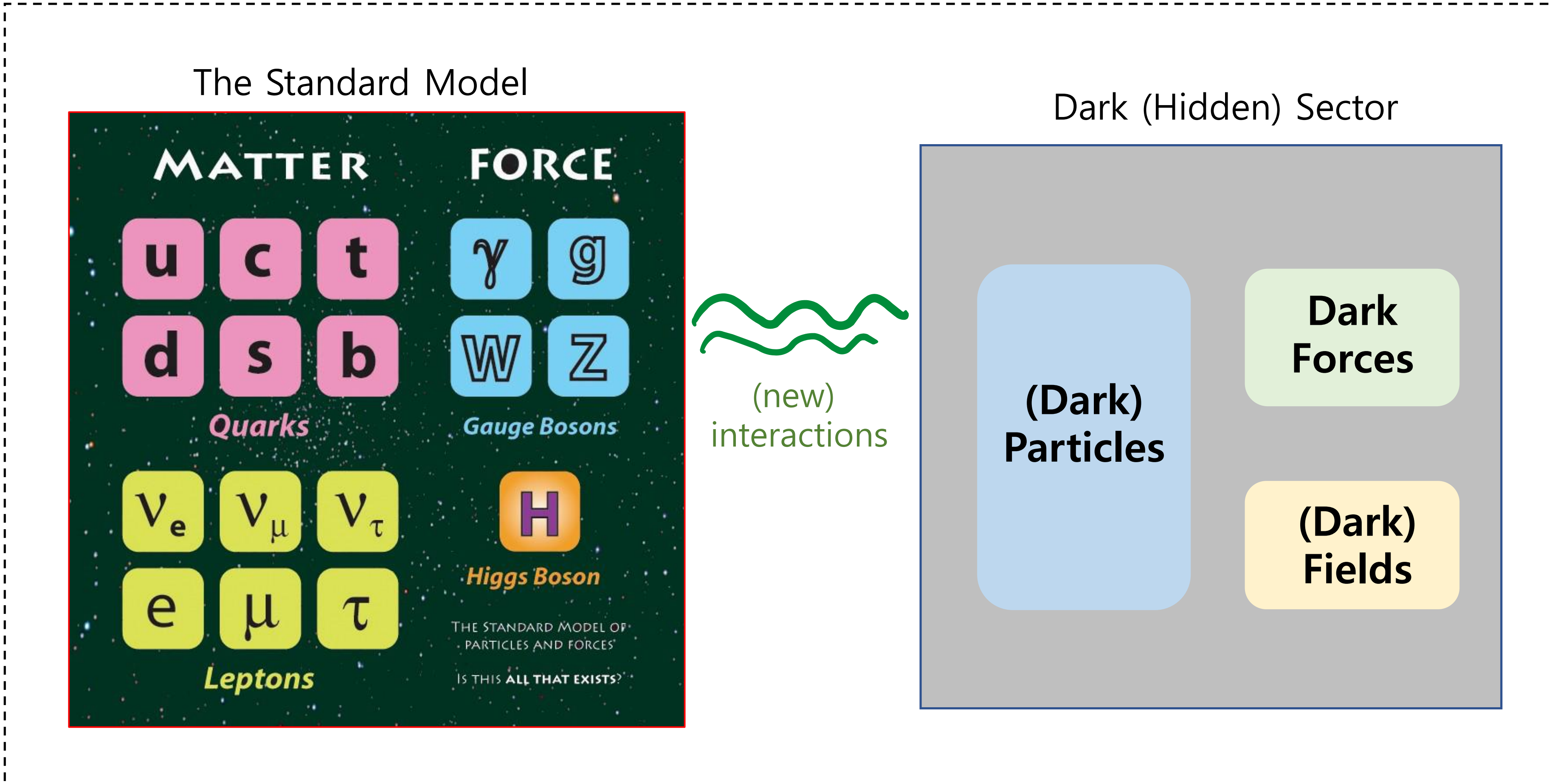

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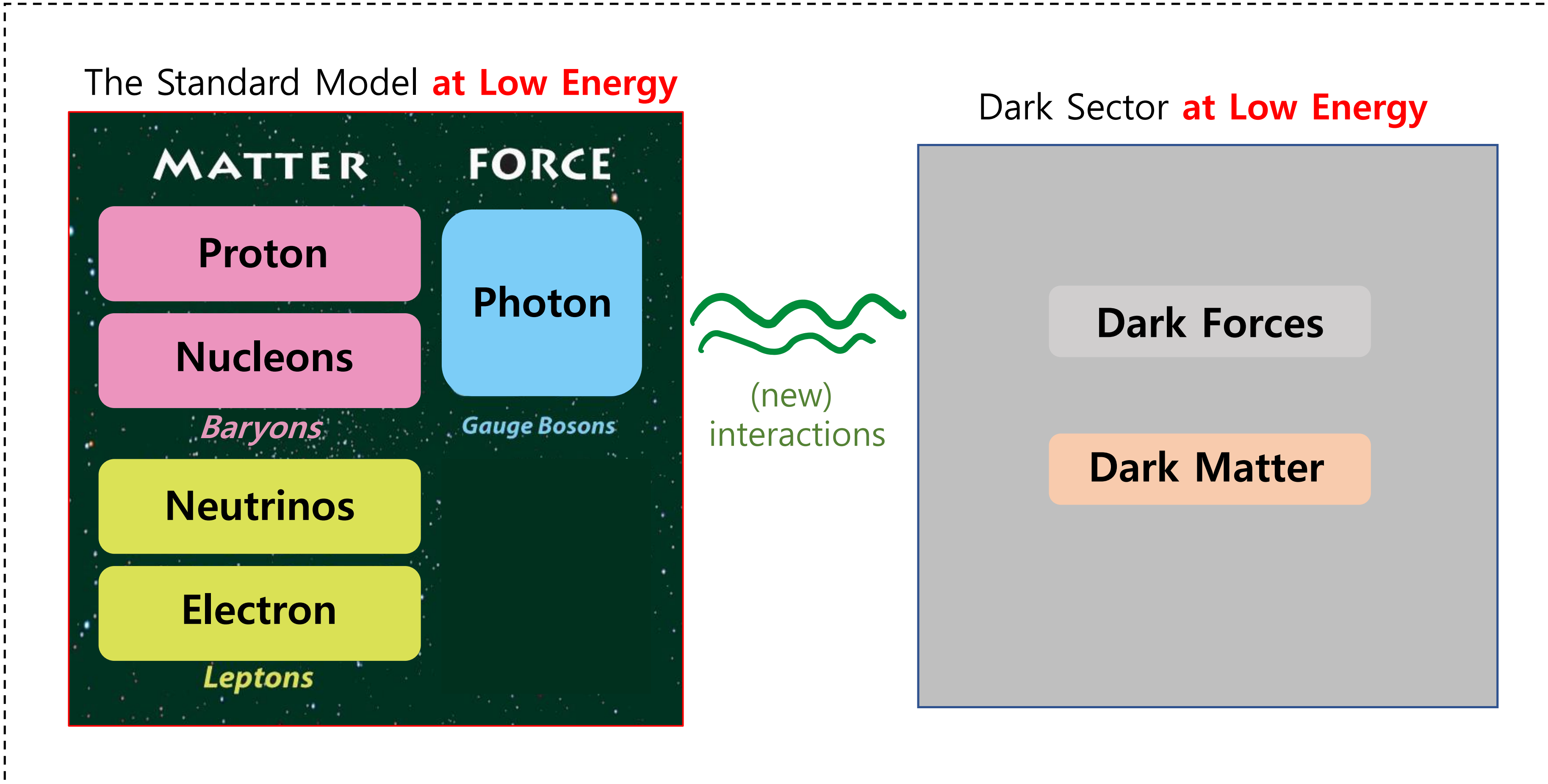
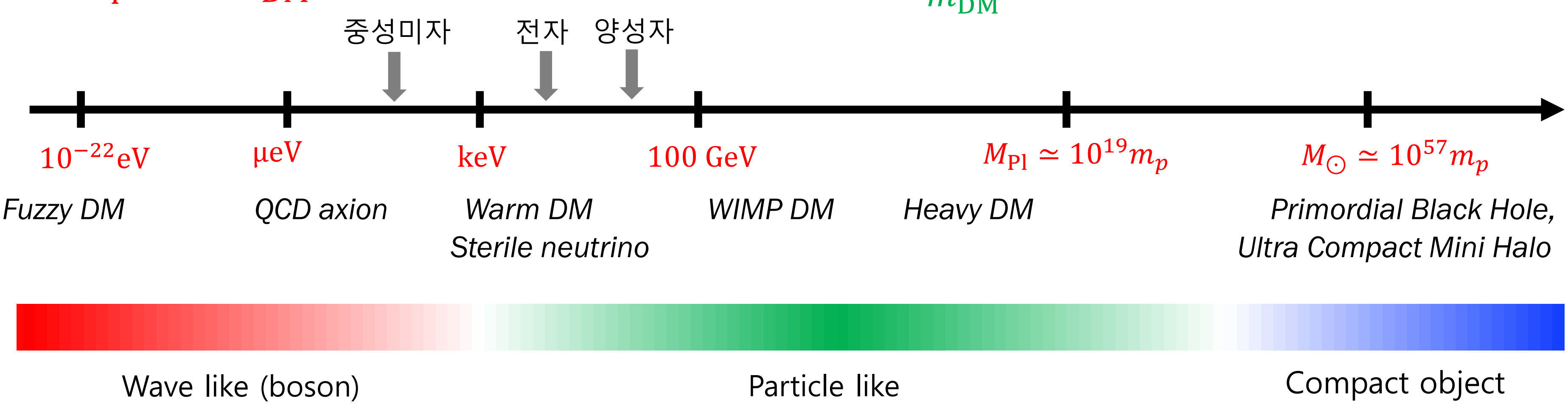


Candidates of DM for its mass

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

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

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



Candidates of DM for its mass and interactions

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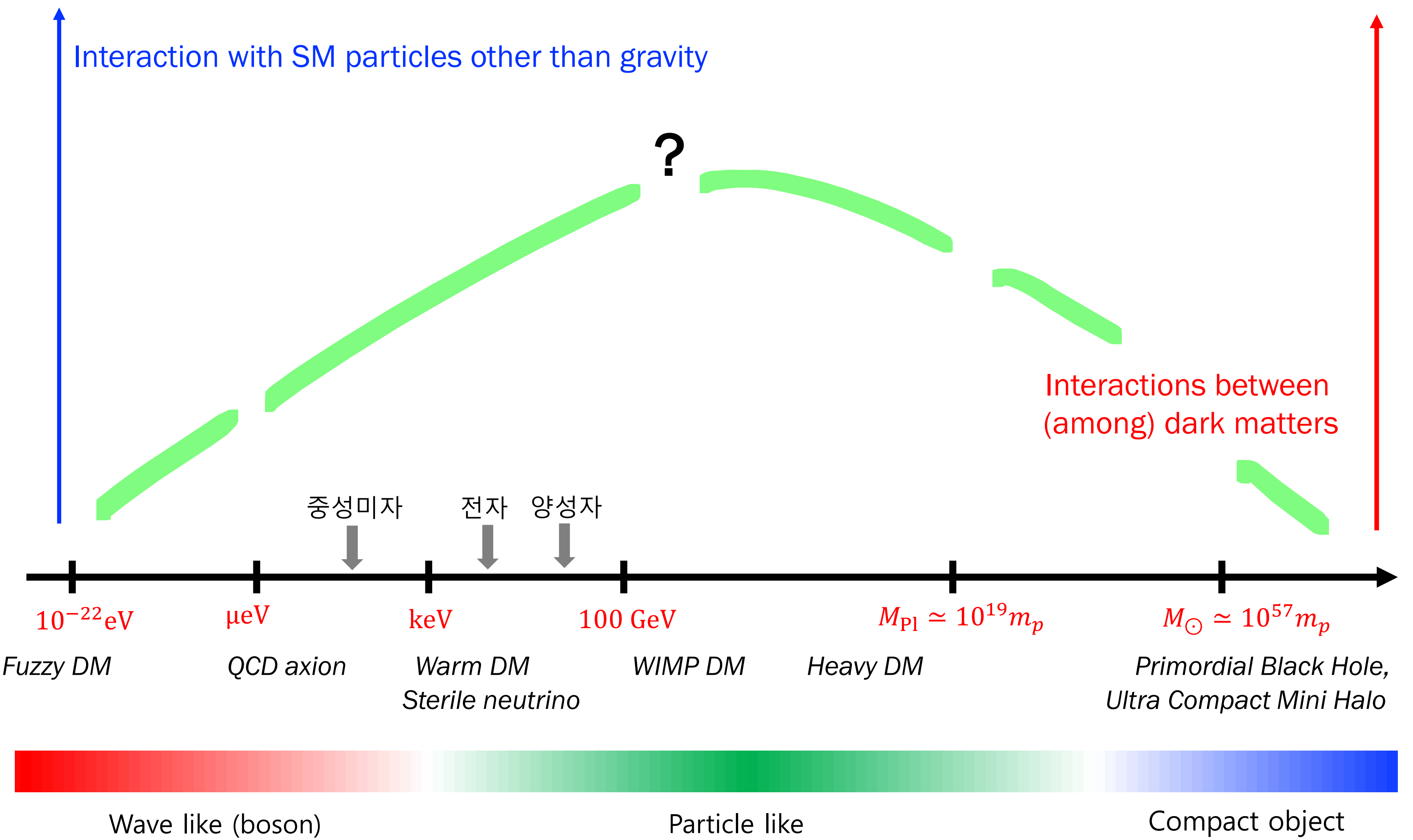


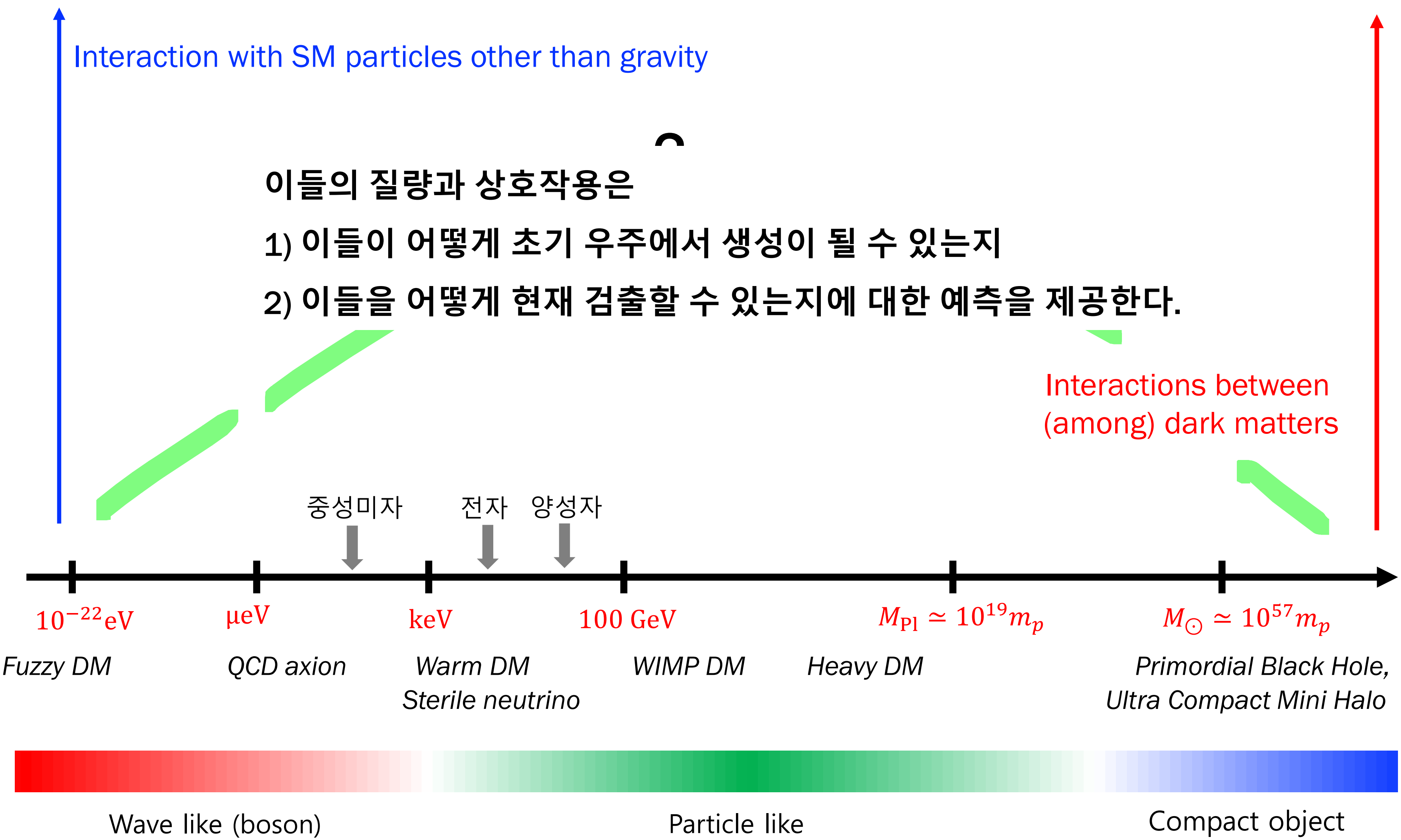
Candidates of DM for its mass and interactions

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

이들의 질량과 상호작용은

1) 이들이 어떻게 초기 우주에서 생성이 될 수 있는지

2) 이들을 어떻게 현재 검출할 수 있는지에 대한 예측을 제공한다.

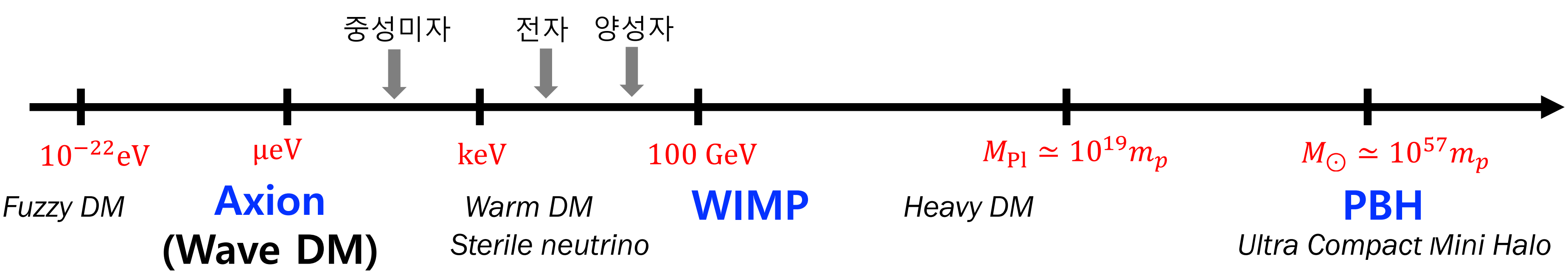


Well known candidates for each mass range

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

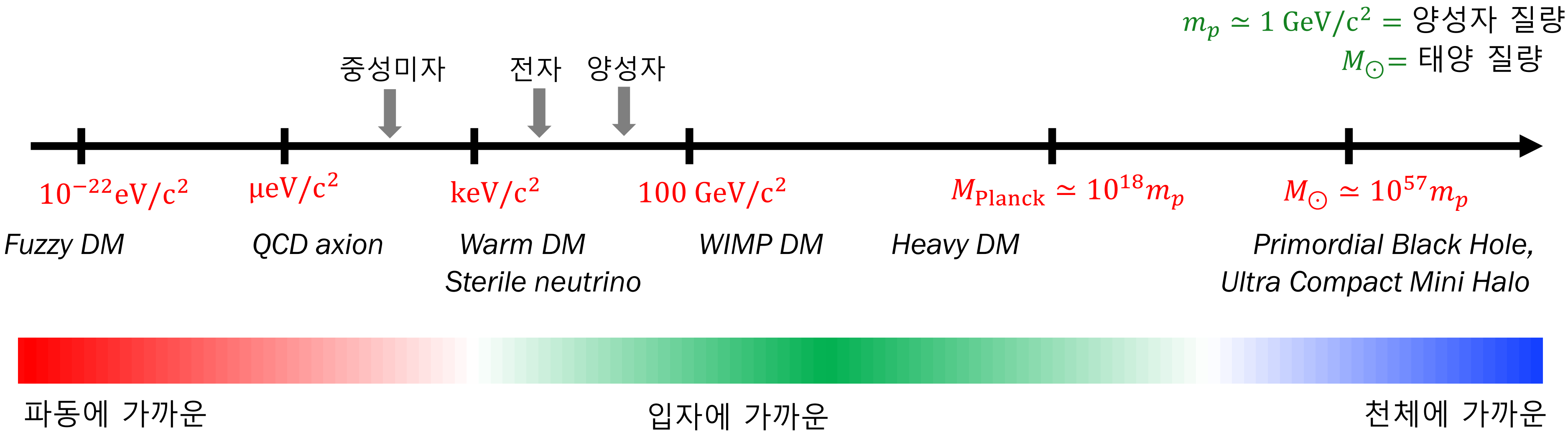
QCD Axion (Axion) : $(\mathbf{0.0001} \sim \mathbf{10})\ \mu\mathrm{eV}$

Primordial Black Hole (PBH) : $\left(\mathbf{10^{-17}} \sim \mathbf{100}\right) M_{\odot} = \left(\mathbf{10^{-40}} \sim \mathbf{10^{59}}\right) \mathrm{GeV}$



Probing the Nature of Dark Matter

Candidates of DM for its mass



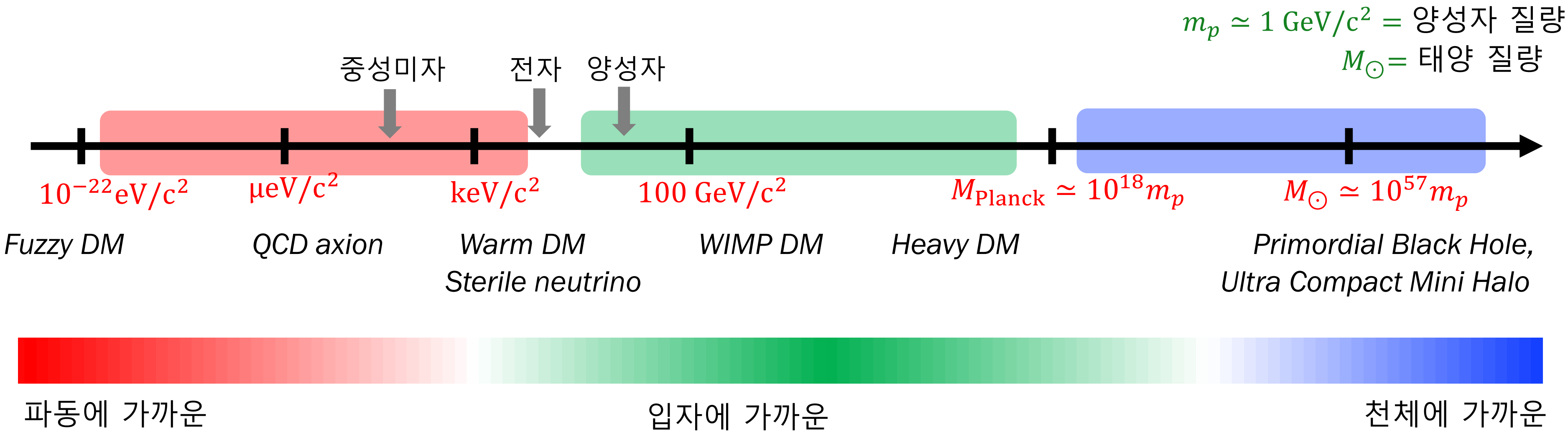
Approach for DM studies in particle physics

(A) Taking a specific DM mass range

(B) Taking a specific symmetry

(C) Any new possibilities that can be probed by observations, etc.

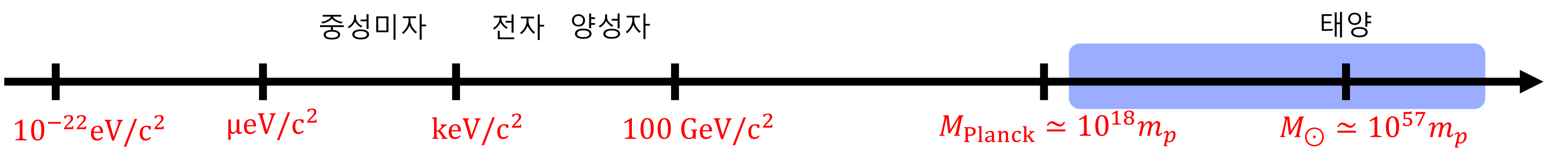
Candidates of DM with respect to its mass



My Approach

DM physics related with scalar field dynamics for various mass range

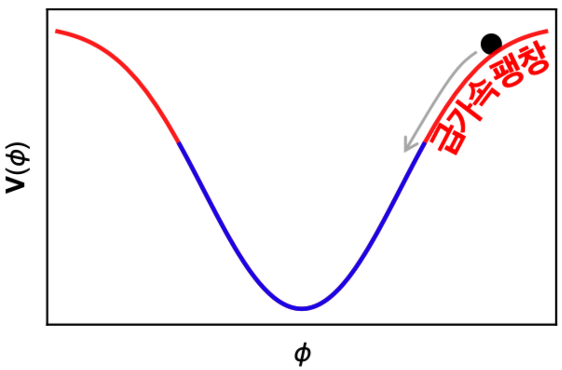
(1) Compact Dark Matter

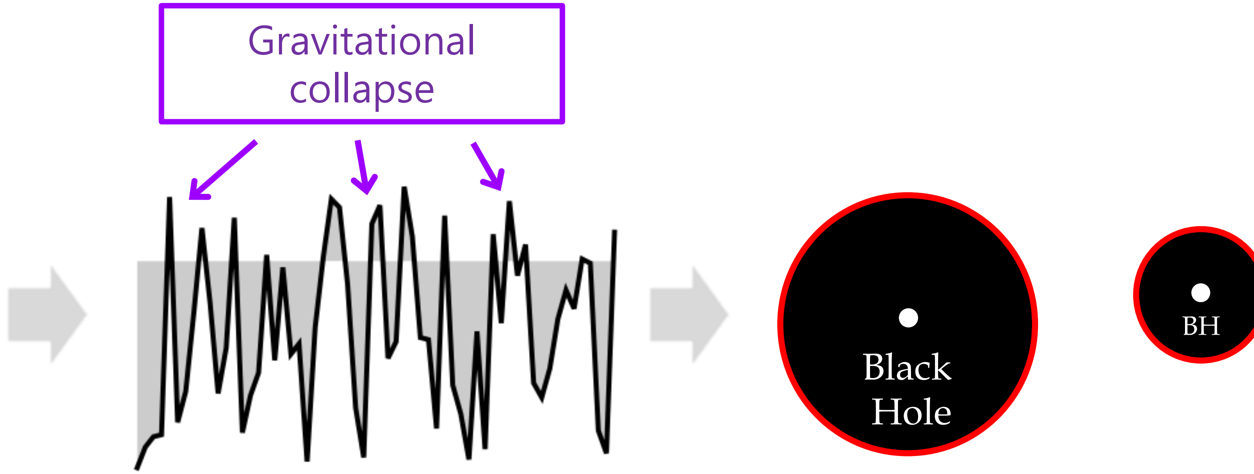


(1) Compact Dark Matter

In the early Universe, inflating period

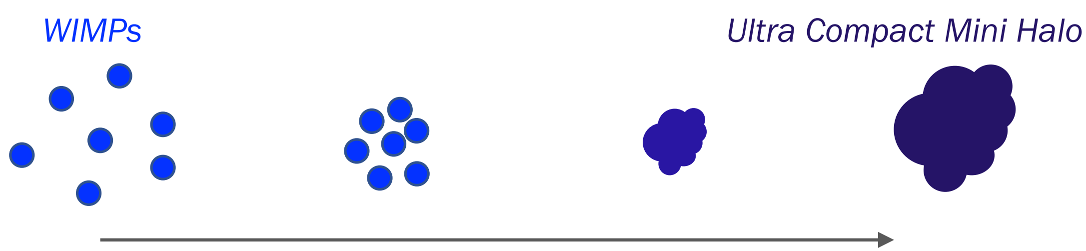
Inflaton scalar field dynamics





Density fluctuation → **Primordial Black Holes**

Stable Scalar dynamics
In the early Universe
Early matter domination



K.-Y. Choi, J.-O. Gong, ***CSS***
Phys. Rev. Lett. 115, 211302 (2015)

Searching for Compact Dark Matter

See compact dark matter through LIGO GW observatory

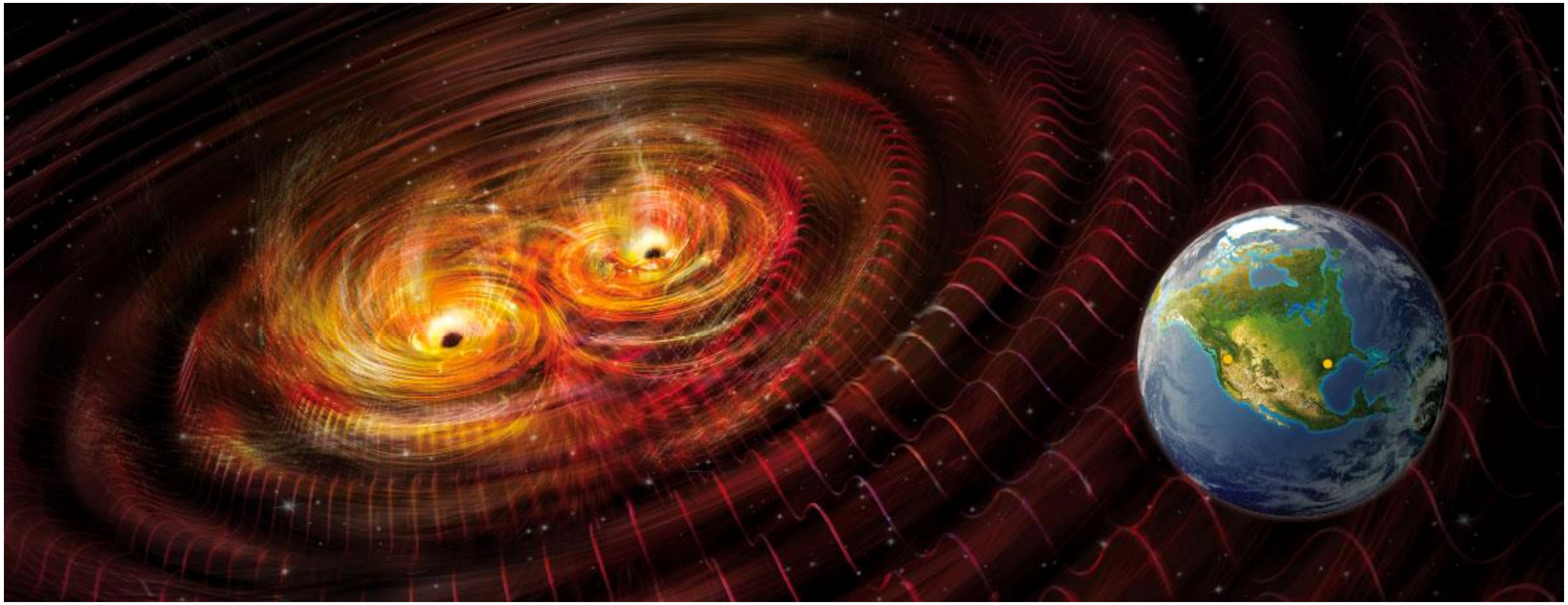


Image from sciencenews.org

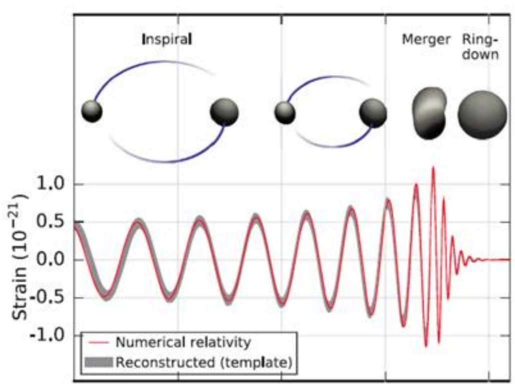
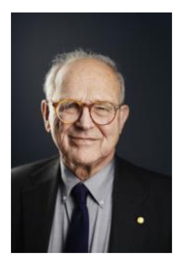


Image from LIGO

The Nobel Prize in Physics 2017



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Rainer Weiss

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Barry C. Barish

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Kip S. Thorne

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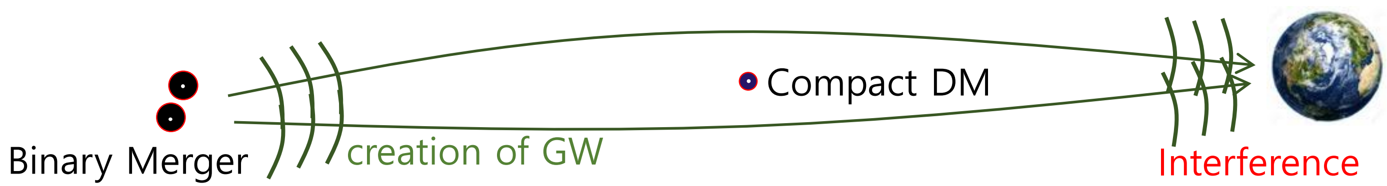
Gravitational Wave: Telescope for DM

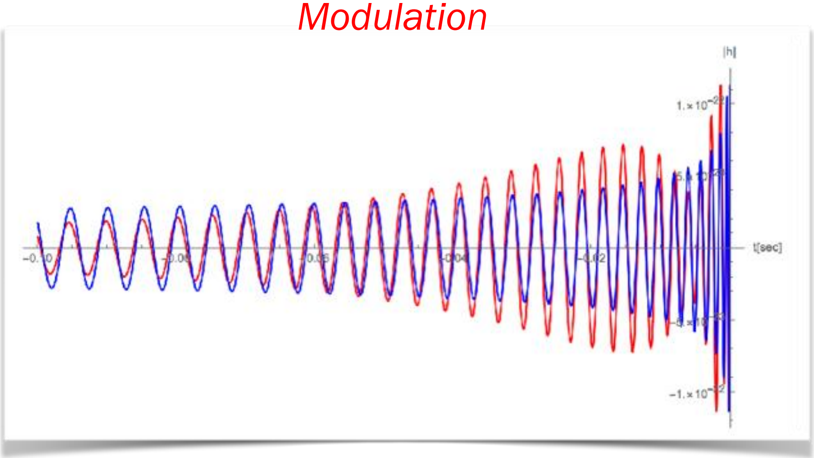


Femto-Lensing effect by compact DM →

Deformation of waveform at LIGO

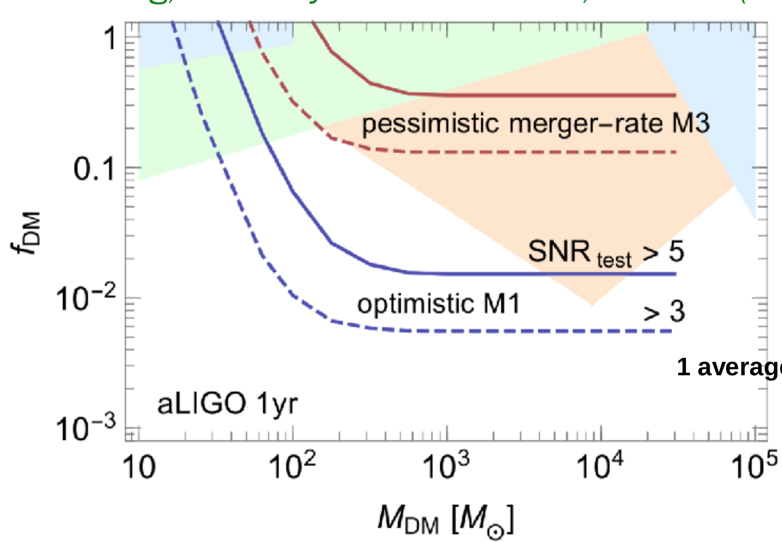
→ **Evidence of Compact DM**

Modulation



chirp signal with fringes

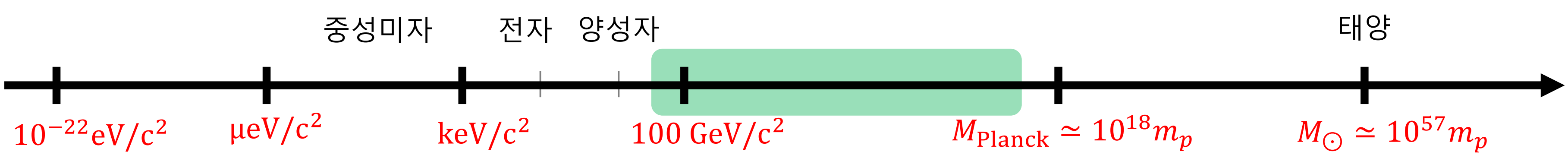
*S. Jung, **CSS** Phys. Rev. Lett. 122, 041103 (2019)*



1 average detection

(2) Particle Dark Matter: Source of GW

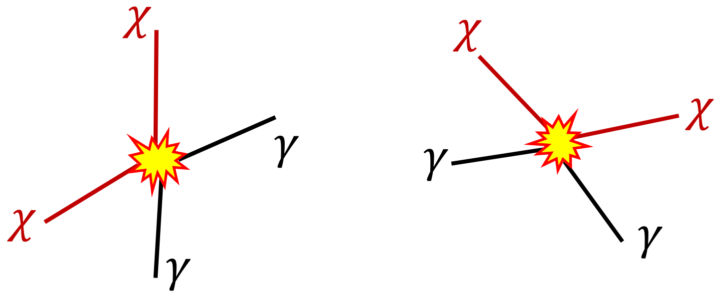
(A deeper connection between Gravitational Wave and Dark Matter)



Particle-like Dark Matter

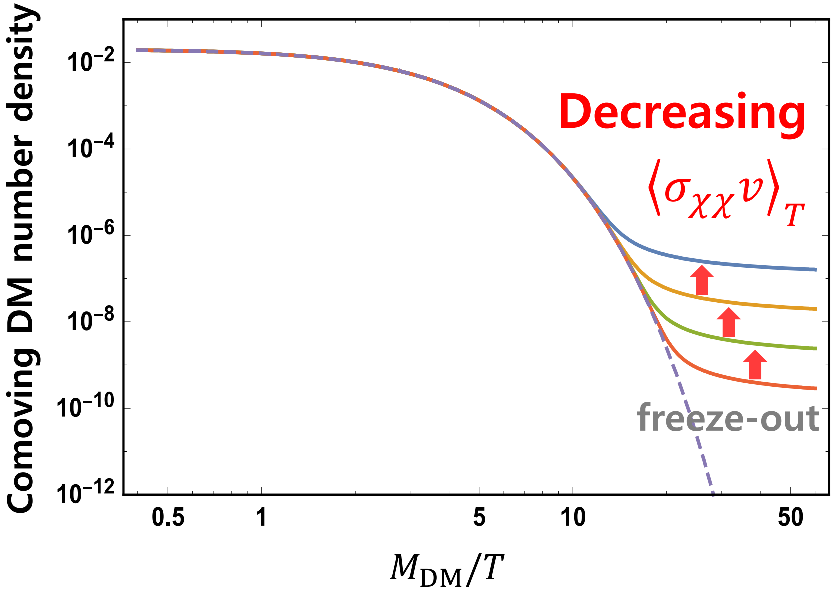
Thermal Dark Matter

Dark matter density is determined by its annihilation cross-section



$$\Omega_{DM}h^2 = 0.1\left(\frac{3\times10^{-26}\text{cm}^3/\text{s}}{\langle\sigma_{\chi\chi}v\rangle_T}\right)$$

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



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

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

The Unitarity bound: $\langle\sigma_{\chi\chi}v\rangle_T \le \frac{4\pi}{M_{DM}^2\langle v\rangle_T}$

Thermal DM Beyond the Unitarity Bound

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

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

- **WIMPZilla, Superheavy DM, gravitational production etc.**

- **One can think the origin or dark matter mass tightly related with production mechanism : These days, various approaches along this direction are actively studied**

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!**

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

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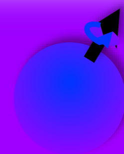


Higgs field (giving mass to the elementary particles)

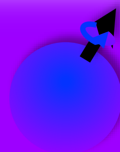
Nonzero expectation value of the scalar field imposes DM mass

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



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 fill the Universe**
→ **Cosmic 1st order phase transition**

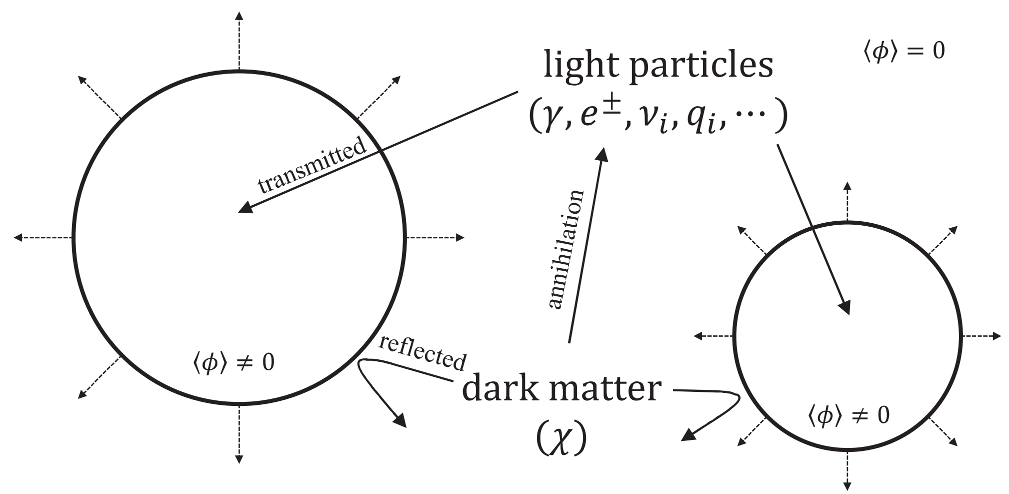
Origin of DM mass & its abundance

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

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



Cosmic 1st order phase transition
→ Production of Gravitational Waves

Simulation from D. Cutting et al. 1802.05712

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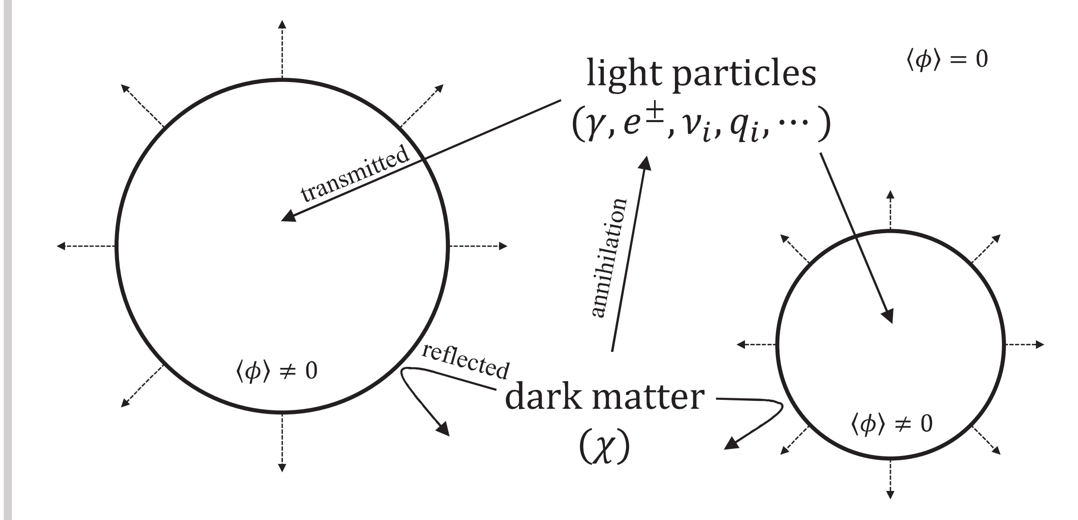
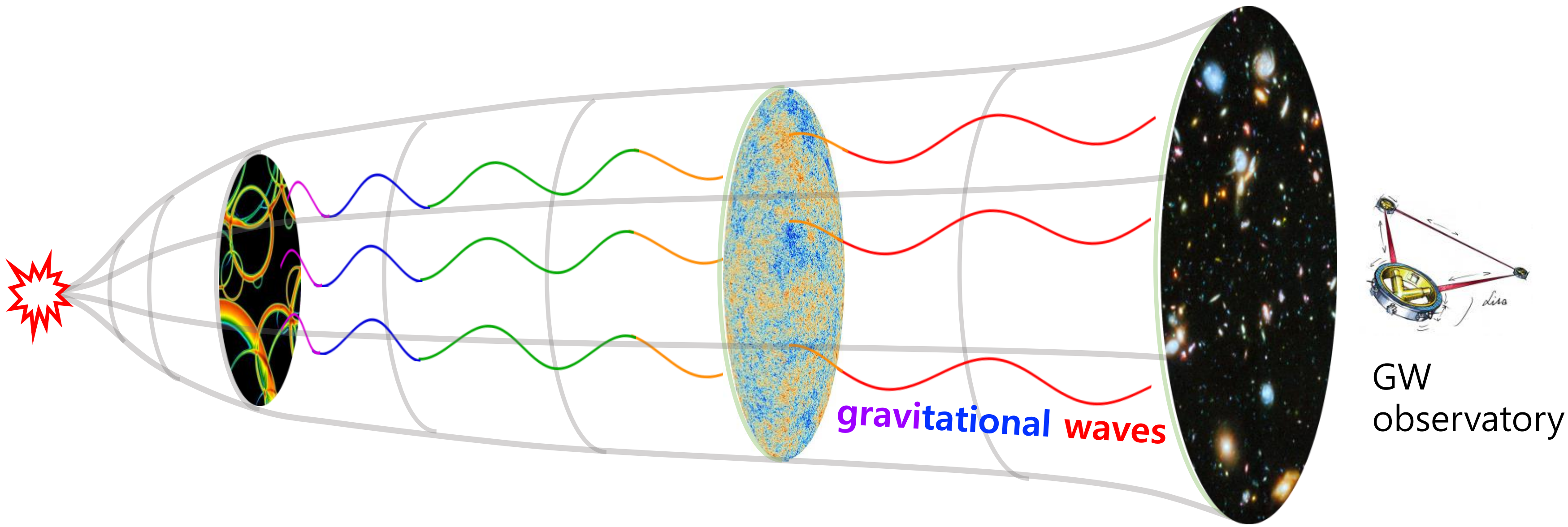


Cosmic 1st order phase transition
→ Production of Gravitational Waves

2) Understanding the origin of DM by GW observations

Stochastic Gravitational Waves

Proposing the mechanism working in a wide range of DM mass

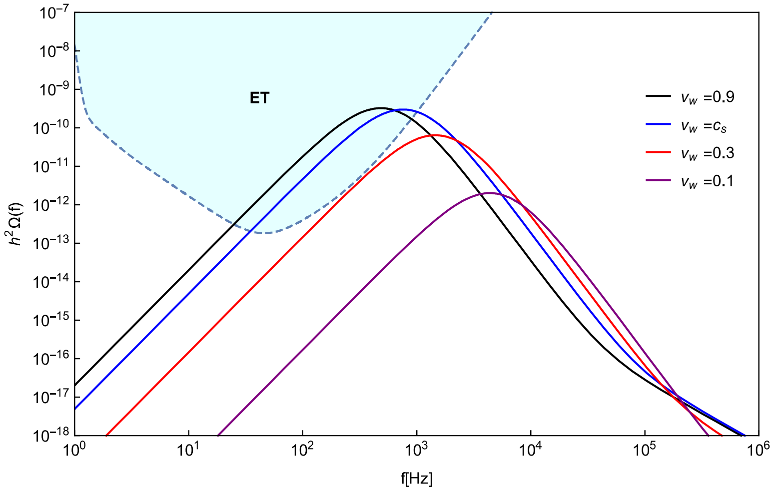


2) Understanding the origin of DM by GW observations

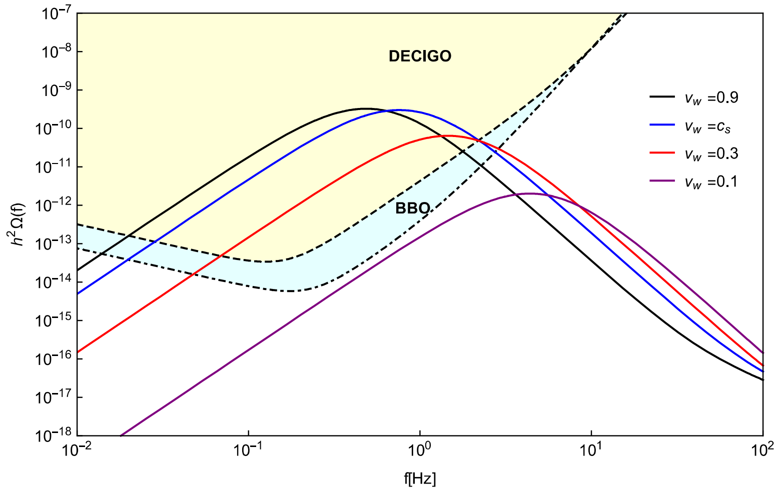
Origin of DM mass & GW observations

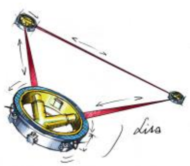
Proposing the mechanism working in a wide range of DM mass

Mass=100PeV



Mass=100TeV



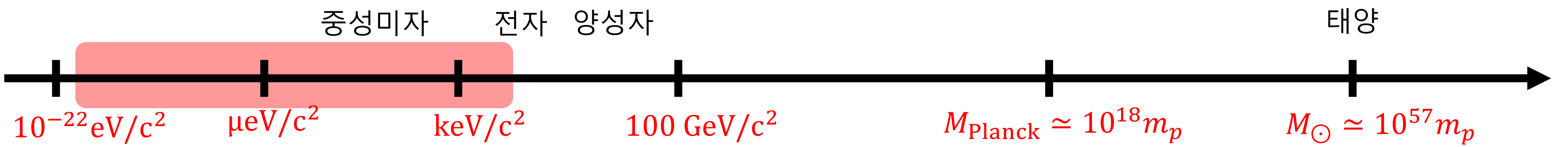


중력파 관측소

M. Ahmadvand 2108.00958

2) Understanding the origin of DM by GW observations

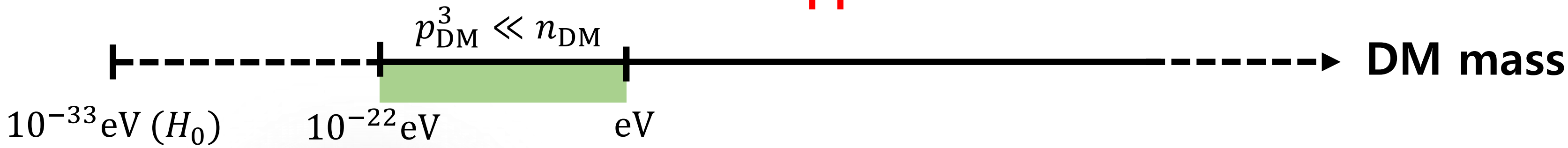
(3) Wave Dark Matter



Wave Dark Matter

Ultra-light scalar dark matter: High occupation number ➔ Wave feature

➔ Suppression of small scale structure

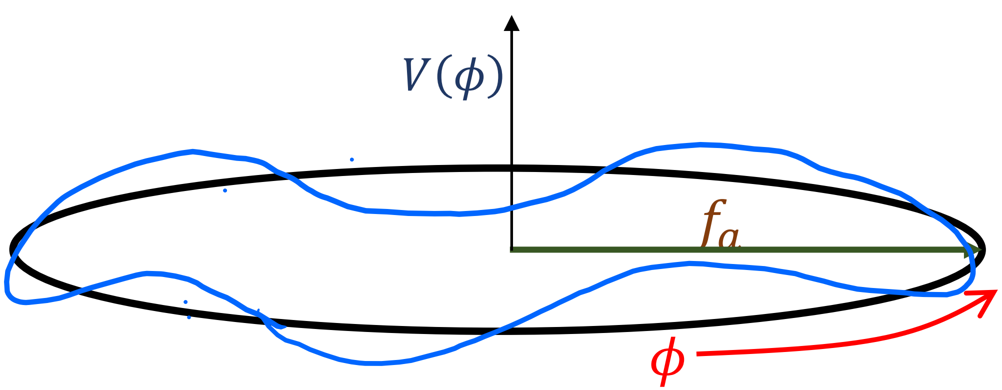


$$\lambda_{\mathrm{dB}} = \frac{2\pi}{M_{\mathrm{DM}} v_{\mathrm{vir}}} \sim \mathrm{kpc}\left(\frac{10^{-22}\mathrm{eV}}{M_{\mathrm{DM}}}\right)$$

Coherent Waves ($p_{\mathrm{DM}}^3 \ll n_{\mathrm{DM}}$)

- **One of the well known example of wave dark matter is**

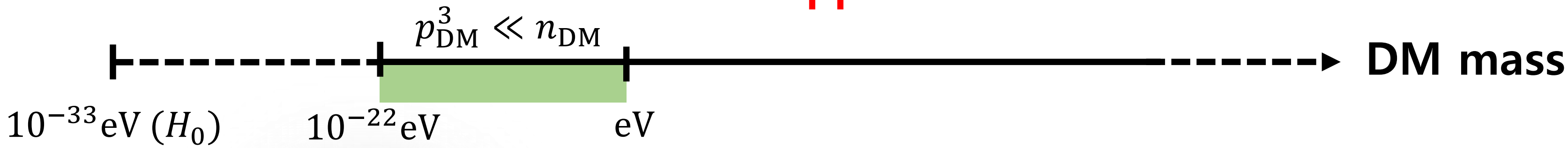
(QCD) Axion



Wave Dark Matter

Ultra-light scalar dark matter: High occupation number ➔ Wave feature

➔ Suppression of small scale structure

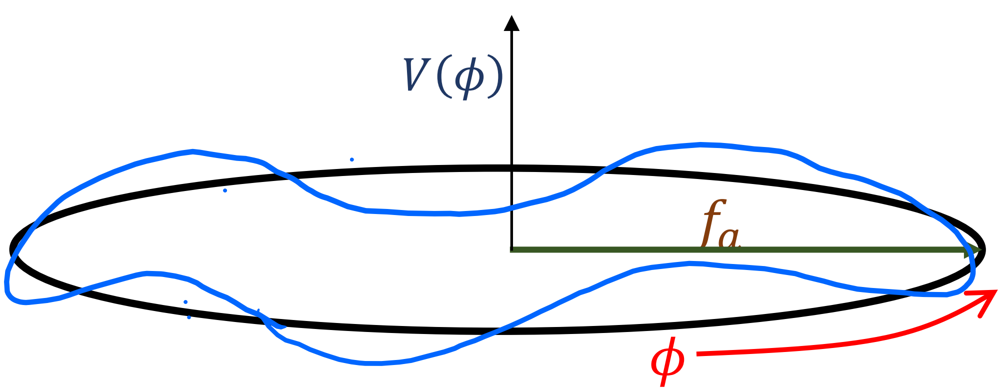


$$\lambda_{\rm dB} = \frac{2\pi}{M_{\rm DM} v_{\rm vir}} \sim {\rm kpc}\left(\frac{10^{-22}{\rm eV}}{M_{\rm DM}}\right)$$

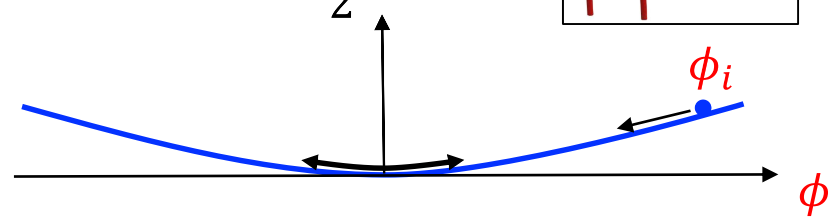
Coherent Waves ($p_{\rm DM}^3 \ll n_{\rm DM}$)

- **One of the well known example of wave dark matter is**

(QCD) Axion



$$V(\phi) = \frac{1}{2} m_a^2 \phi^2$$

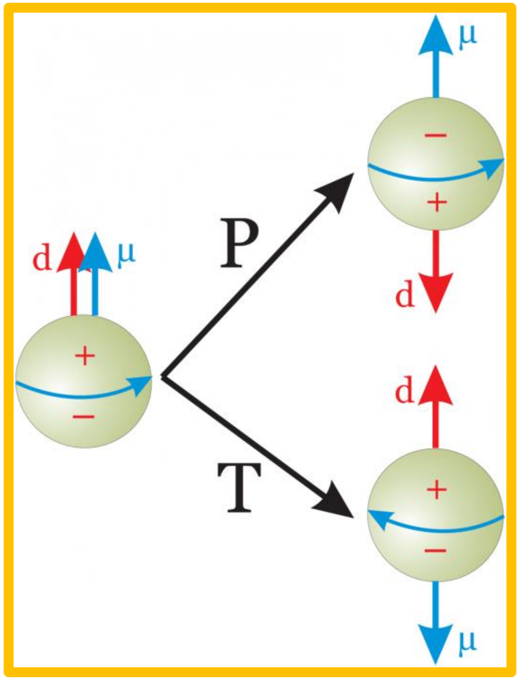


QCD Axion

QCD 액시온은 표준모형의 강한 CP 문제를 해결하기 위해 도입된 가상의 Pseudo-Scalar 보존이다.

$$L = \frac{1}{2}(\partial_\mu \phi)^2 + \frac{g_s^2}{32\pi^2}\frac{\phi}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu} + \frac{c_\gamma e^2}{16\pi^2}\frac{\phi}{f_a}\vec{E}\cdot\vec{B}$$

글루온 **전기장, 자기장**



$$H_{eff} \ni -\vec{S}_N \cdot \left(g_N \frac{e}{2m_N}\vec{B} + d_N \vec{E}\right)$$

$\mu_N = \frac{g_N e}{2m_N}$ = 중성자 자기쌍극자 모멘트

d_N = 중성자 전기쌍극자 모멘트

$d_N \approx 0$ ($|d_N| < 1.8 \times 10^{-26} e$ cm) 왜 강한 상호작용은 (약작용과 달리) CP 대칭적인가?

QCD Axion

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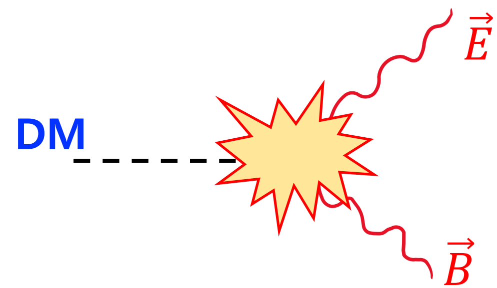
글루온 **전기장, 자기장**

$$L_{eff} = \frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m_a^2 \phi^2 + \frac{\tilde{c}_\gamma e^2}{16\pi^2}\frac{\phi}{f_a}\vec{E}\cdot\vec{B}$$

$$m_a \simeq \mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$



비록 액시온은 절대적으로 안정적이지 않고 두 광자로 붕괴할 수 있지만 가벼운 질량과 매우 약한 상호작용으로 인해 입자의 수명이 우주의 나이보다 훨씬 길다.

$$\tau_a \sim \left(\frac{m_a^3}{f_a^2}\right)^{-1} \sim 10^{47}\text{sec}\left(\frac{f_a}{10^{12}\text{GeV}}\right)^5 \gg \tau_U = 4.4\times 10^{17}\text{sec}$$

QCD Axion

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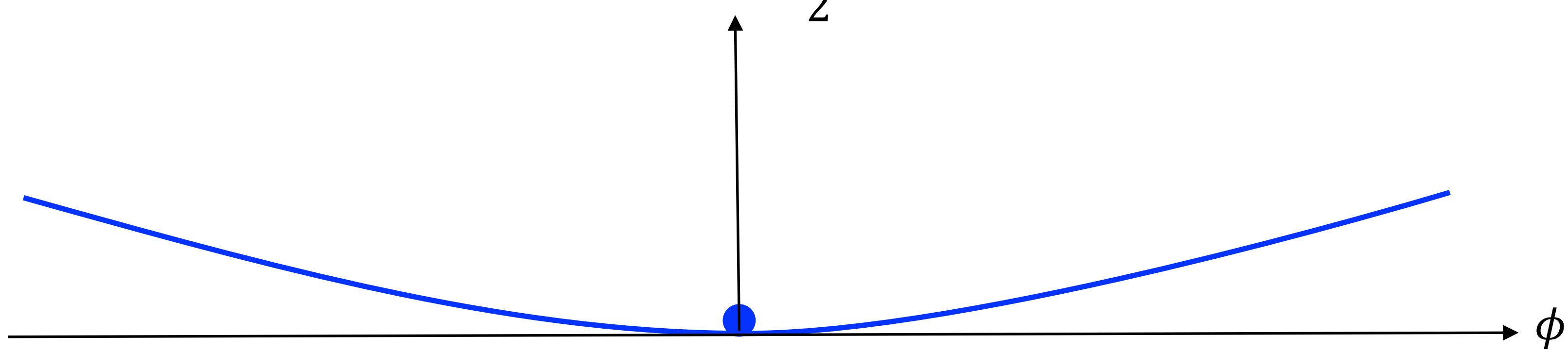

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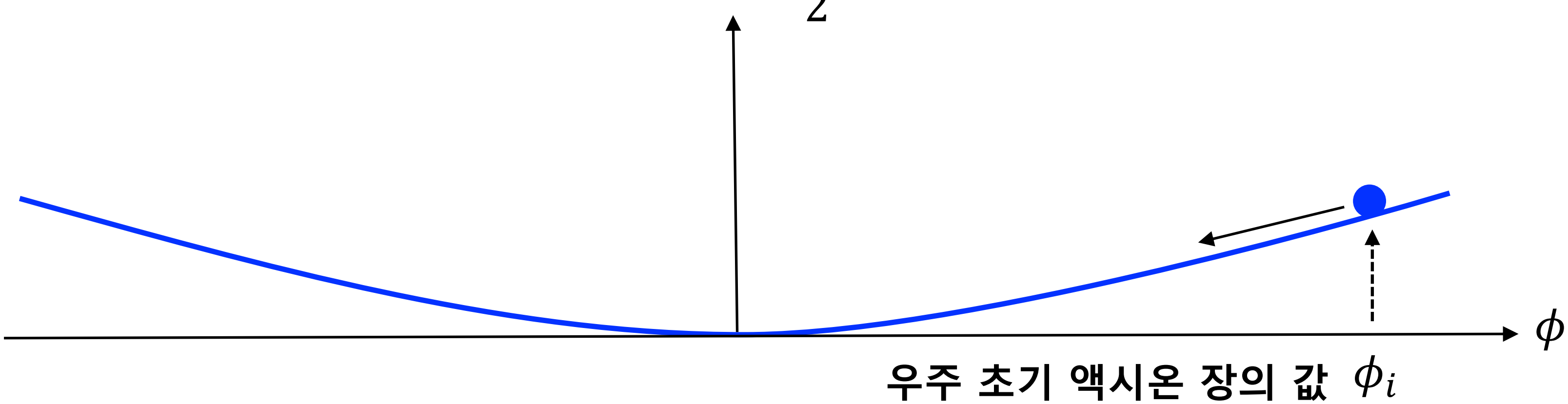
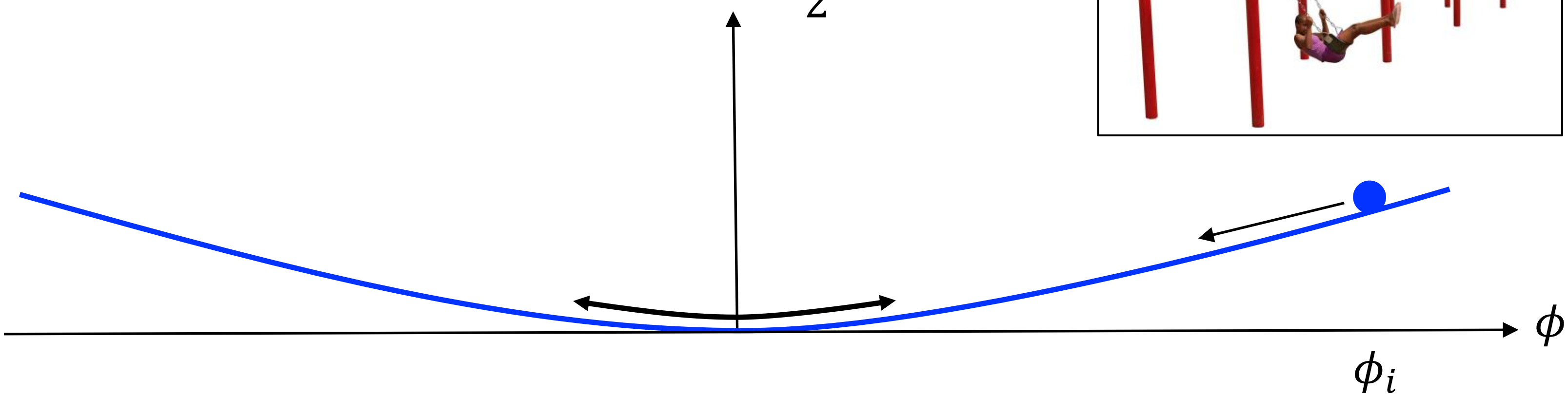


QCD Axion

초기 액시온 장이 공간적으로 매우 균일하게 분포하고, Coherent 한 Oscillation 이 이뤄지는 경우, 비록 액시온의 질량이 매우 작더라도 큰 스케일에서 차가운 암흑물질과 같은 형태로 움직임을 확인할 수 있다.

$$\ddot{\phi}(t) + 3H(t)\dot{\phi}(t) + m_a^2\phi(t) = 0 \qquad (H(t) = \text{주어진 시간에서의 허블 파라메터})$$



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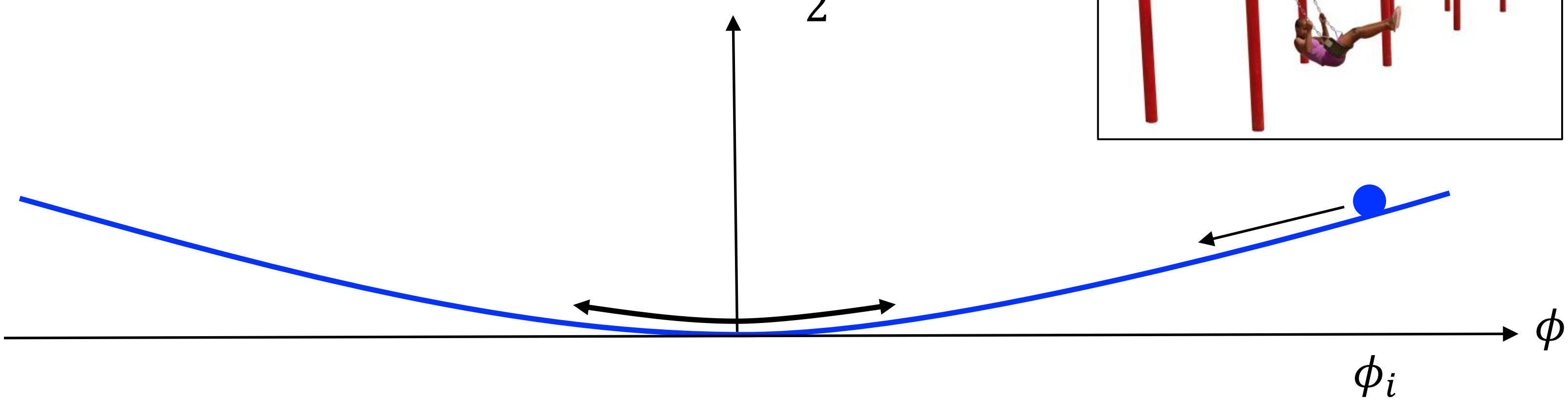
이러한 이유로 액시온 혹은 ultralight boson field 는 well motivated 된 암흑물질후보로 다뤄진다.

$$\left(\frac{\rho_{\mathrm{DM}}}{\rho_{tot}}\right) \simeq 0.25\left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{\frac{7}{6}}\left(\frac{\phi_i}{f_a}\right)$$

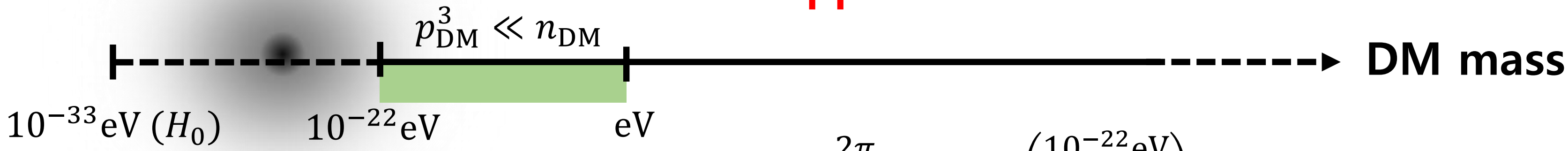
$$V(\phi) = \frac{1}{2}m_a^2\phi^2$$



Ly-alpha & 21cm Forest For Wave Dark Matter

Ultra-light scalar dark matter: High occupation number ➔ Wave feature

➔ Suppression of small scale structure



$$\lambda_{\rm dB} = \frac{2\pi}{m_{\rm DM} v_{\rm vir}} \sim {\rm kpc}\left(\frac{10^{-22}\,{\rm eV}}{m_{\rm DM}}\right)$$

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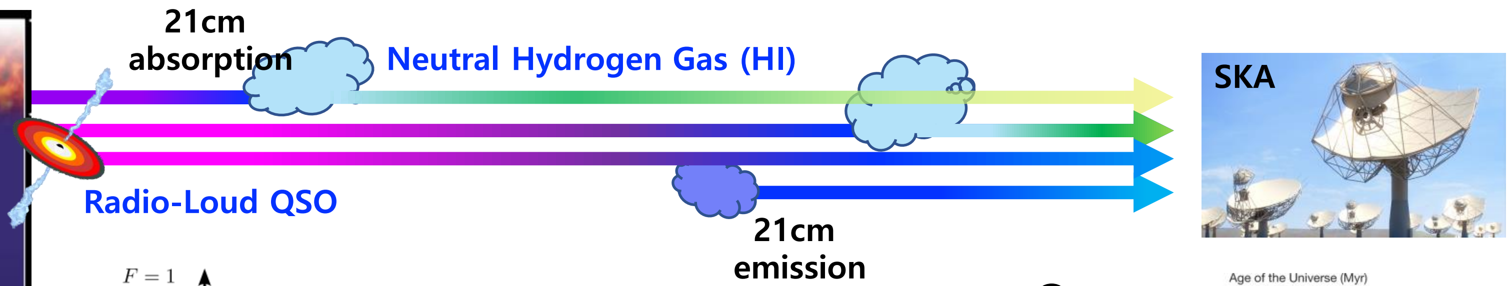
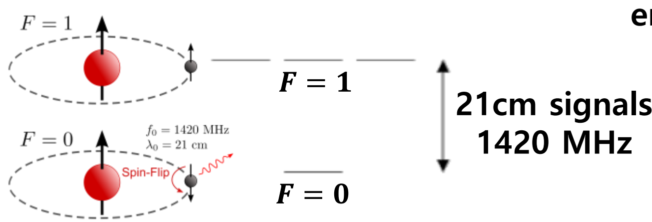
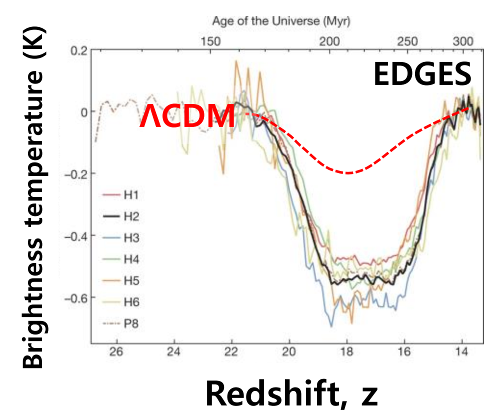






Taken from Nature 555, 67–70 (2018)

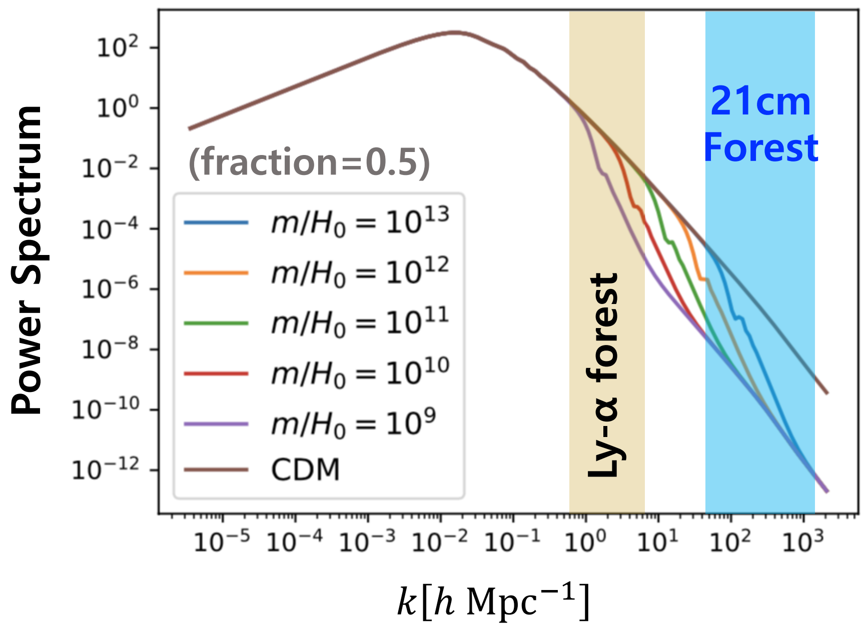
Ly-alpha & 21cm Forest For Wave Dark Matter

The Ly-alpha forest gives the strong constraint on wave DM for a certain mass range

The 21cm forest could be more powerful to constrain wave dark matter with a higher mass range than using the Lyman alpha forest [Shimabukuro, Ichiki, Kadota Phys. Rev. D 101 (2020) 4, 03516]

Ly-α forest: $M_{\rm DM} \gtrsim 10^{-21}{\rm eV}$

21cm forest: $M_{\rm DM} \gtrsim 10^{-18}{\rm eV}$



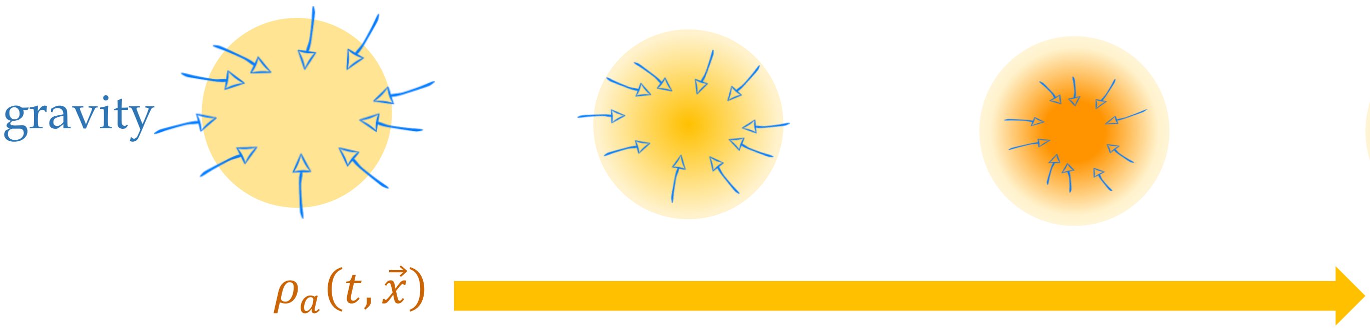
Wave dark Matter: Soliton core, quasiparticles

The homogenous evolution of the axion will eventually be destroyed by gravity:

Starting from $\rho_a(t,\vec{x}) \simeq \frac{1}{2}\left(\dot{\phi}^2 + (\nabla\phi)^2 + m_a^2\phi^2\right) = \bar{\rho}_a(t)\left(1 + \delta_a(t,\vec{x})\right)$

$(\delta_a(t,\vec{x}) \ll 1)$

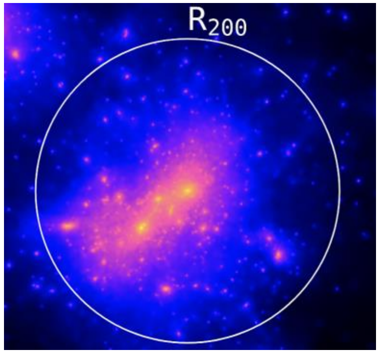
$\delta_a(t,\vec{x})$ can grow by self-gravity and becomes $\delta_a(t,\vec{x}) = O(1)$ → nonlinear evolution



For usual cold dark matter case, clump does not directly collapse to black hole

Instead, it is virialized as $2\langle K\rangle \simeq -\langle V\rangle$ for

$$K = \sum \frac{1}{2} m_i v_i^2 , \qquad V = -\sum \frac{G m_i m_j}{r_{ij}}$$



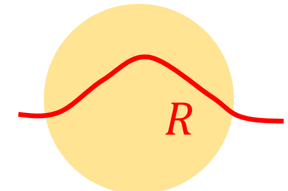
Roughly for a halo mass M_h, with a size R, virial velocity:

$$v_{vir}^2 \sim \frac{G M_h}{R}$$

Wave dark Matter: Soliton core, quasiparticles

For a gravitationally bound object made by axion field with a mass M_h and a size R, there is one more ingredient: irreducible gradient energy by its size

$$\rho_a \simeq \frac{1}{2}\left(\dot{\phi}^2 + (\nabla\phi)^2 + m_a^2\phi^2\right) \sim \frac{1}{2}m_a^2\phi^2 + O\left(m_a^2 a^2 v_{vir}^2\right) + \frac{\phi^2}{2R^2}$$



Including gravity, total energy becomes

$$E_h = \left(\int d^3x\, \rho_a\right) - \frac{GM_h^2}{R} = M_h + M_h\left(O(v_{vir}^2) + \frac{1}{2m_a^2R^2} - \frac{GM_h}{R}\right)$$

rest mass energy

Wave dark Matter: Soliton core, quasiparticles

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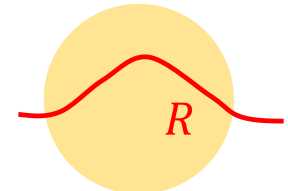

$$\rho_a \simeq \frac{1}{2}\left(\dot{\phi}^2 + (\nabla\phi)^2 + m_a^2\phi^2\right) \sim \frac{1}{2}m_a^2\phi^2 + O\left(m_a^2 a^2 v_{vir}^2\right) + \frac{\phi^2}{2R^2}$$

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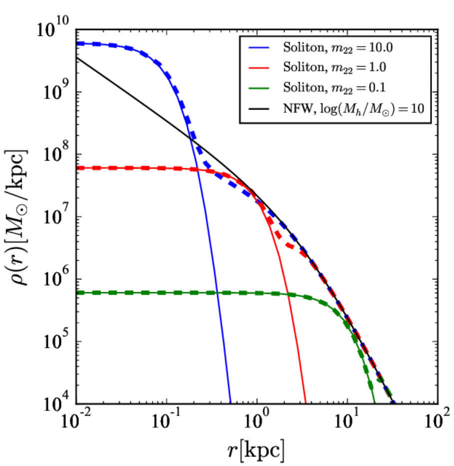
rest mass energy

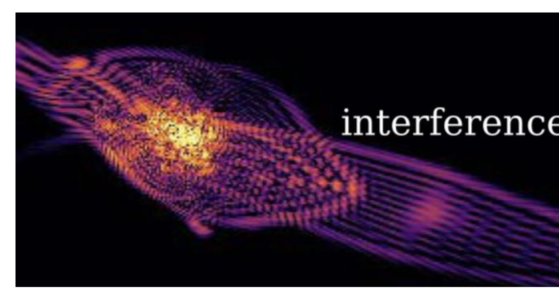
Like a hydrogen atom, the pressure by the gradient energy ("quantum pressure by uncertainty principle") provide the minimum size of the halo: Solitonic bound state



$$\frac{1}{m_a^2R^2} \lesssim v_{vir}^2 \sim \frac{GM_h}{R} \rightarrow R_{soliton} = \frac{1}{m_a^2 GM_h} \lesssim R \quad \left(M_h \sim \frac{M_{\rm Pl}^2}{m_a}v_{vir}\right)$$

Astrophysical "de Broglie wavelength"

$$\lambda_{dB} = \frac{2\pi}{m_a v_{vir}} \sim kpc\left(\frac{10^{-22}eV}{m_a}\right)$$

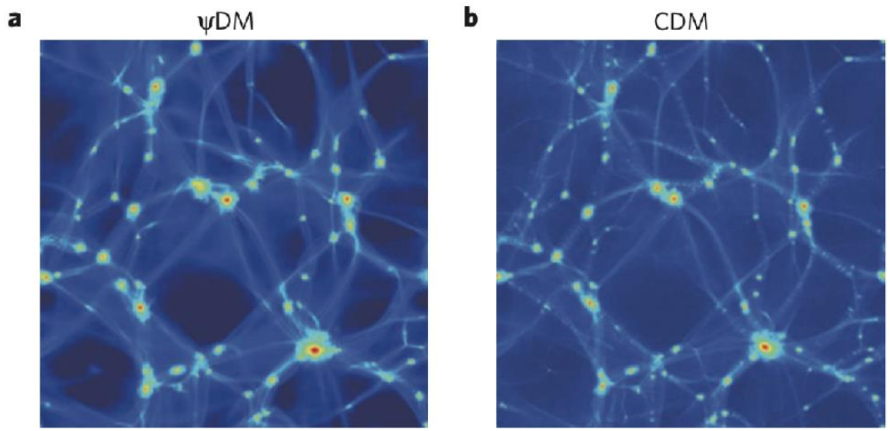


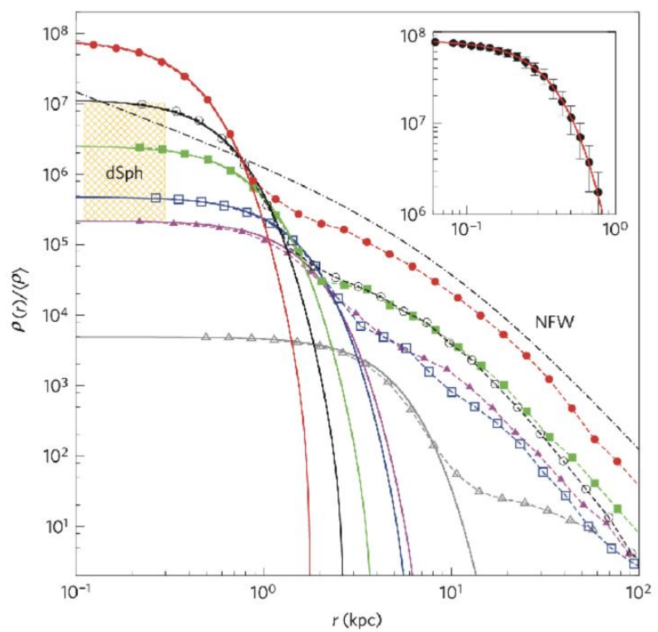
From Safarzardeh, Spergel 1906.11848

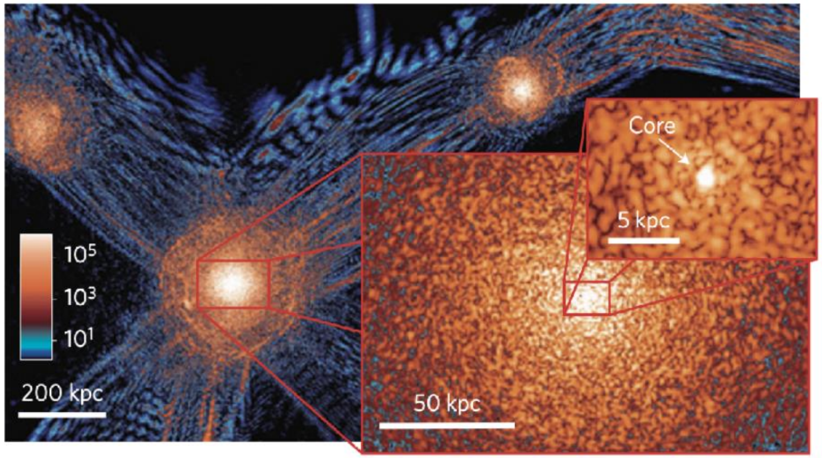
From Mocz et.al. PRL 123, 141301

Wave DM simulation

Schive, Chiueh, Broadhurst (14)





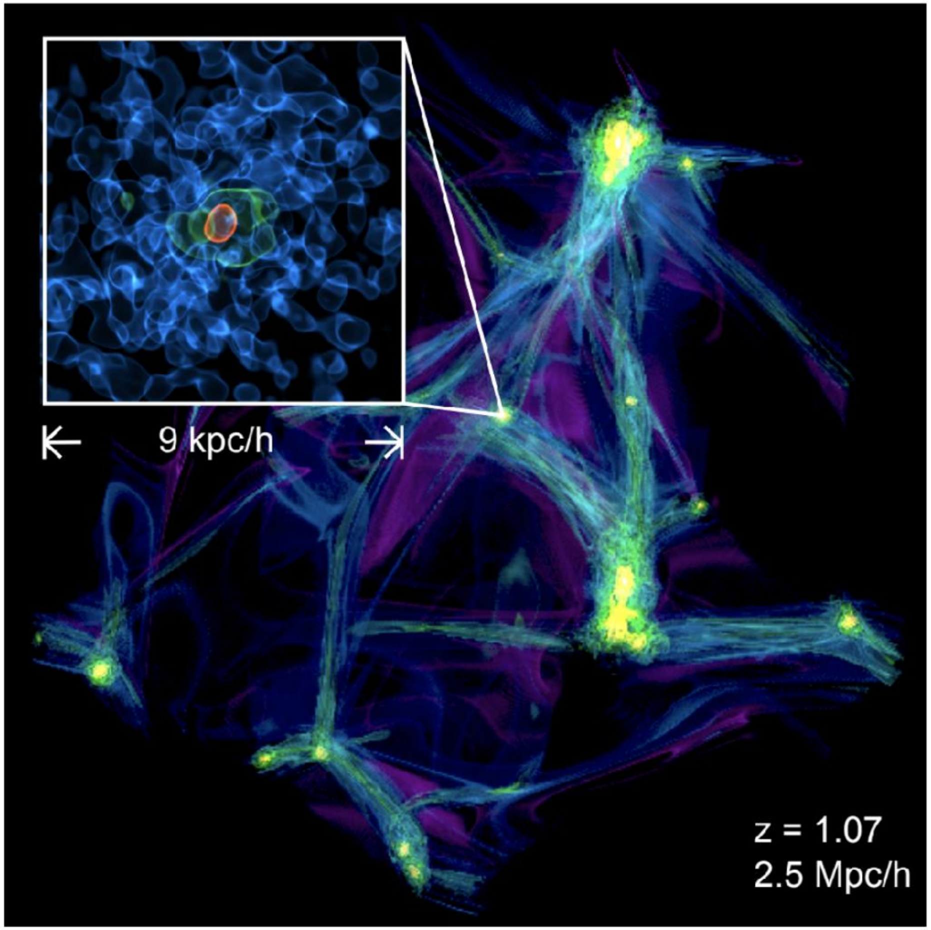


* characteristic *soliton* at the center has been observed

* small scale structures are erased

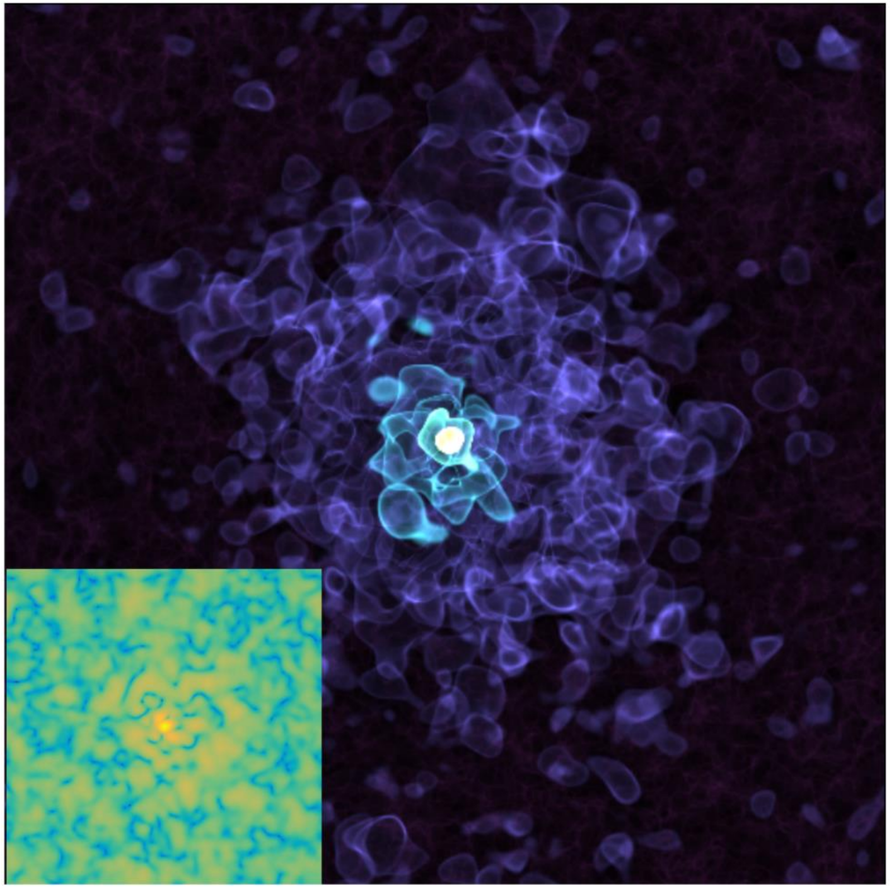
From H. Kim's slide in NPKI workshop

Wave DM simulation



Veltmaat, Niemeyer, Schwabe (18)

Mocz et al (17)



From H. Kim's slide in NPKI workshop

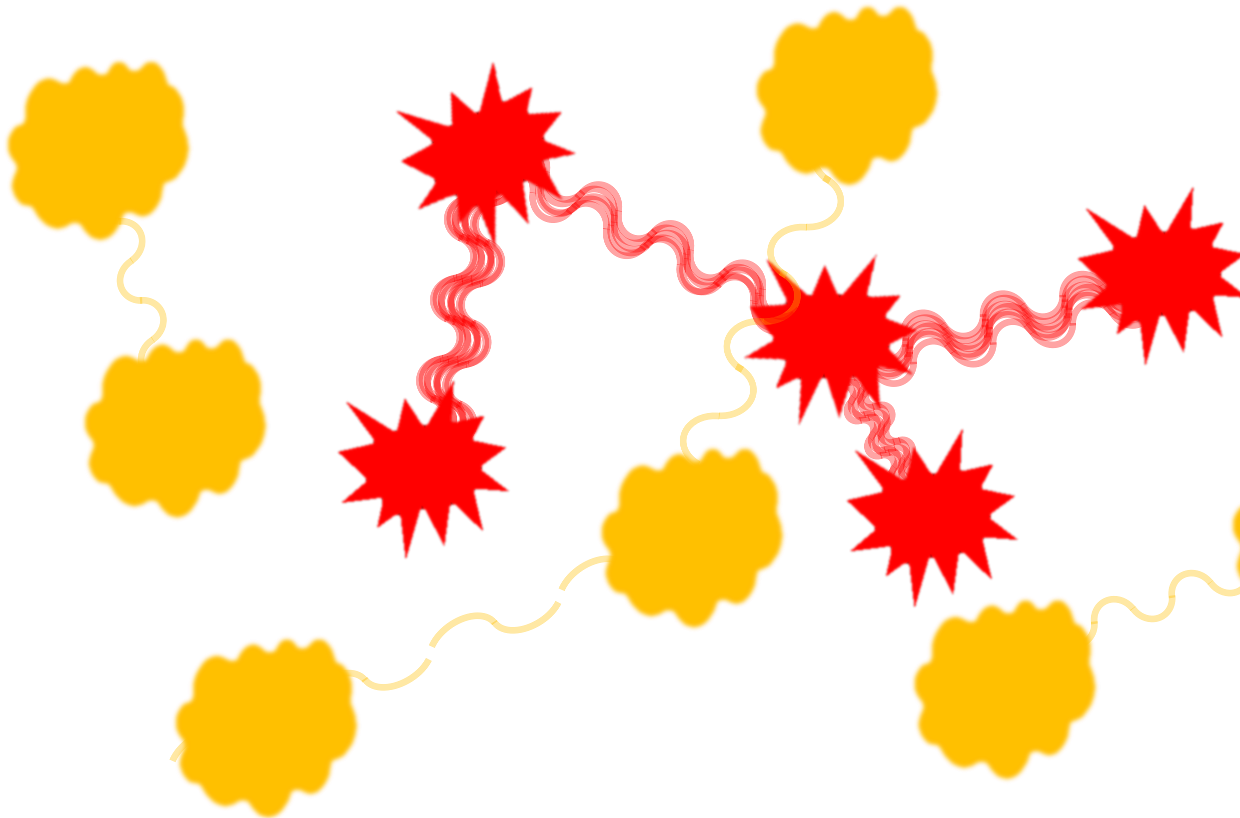
Wave DM + Self interacting Sub DM

Naturally light scalar dark matter

Axion 타입 : 가벼울수록 약하게 서로 상호작용

Glueball 타입 : 가벼울수록 강하게 서로 상호작용

Bugeon Jo, Hyeontae Kim, Hyung Do Kim, **CSS**
Phys. Rev. D 103, 083528 (2021)



Multi component (매우 약한 상호작용 + 매우 강한 상호작용) scalar dark matter scenario

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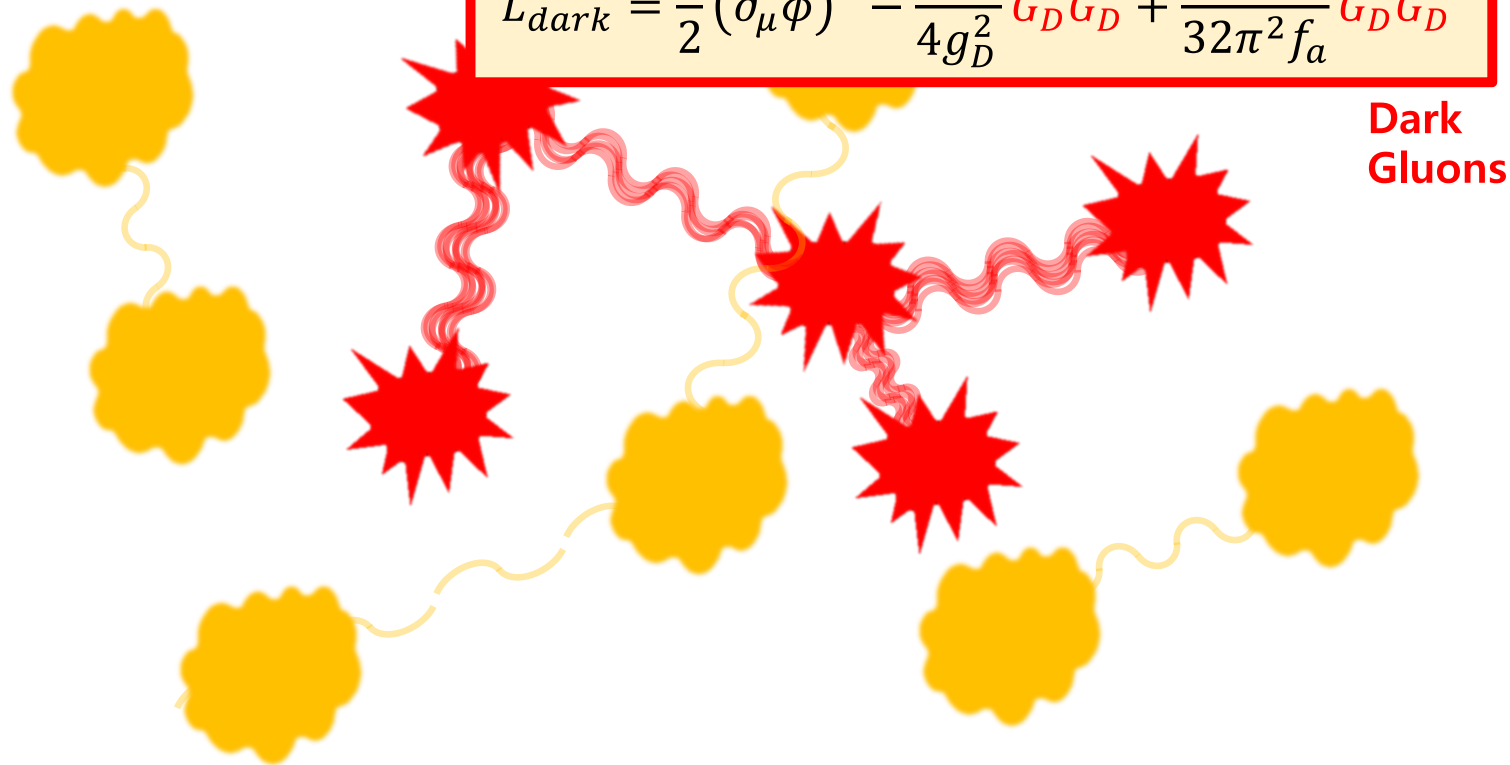

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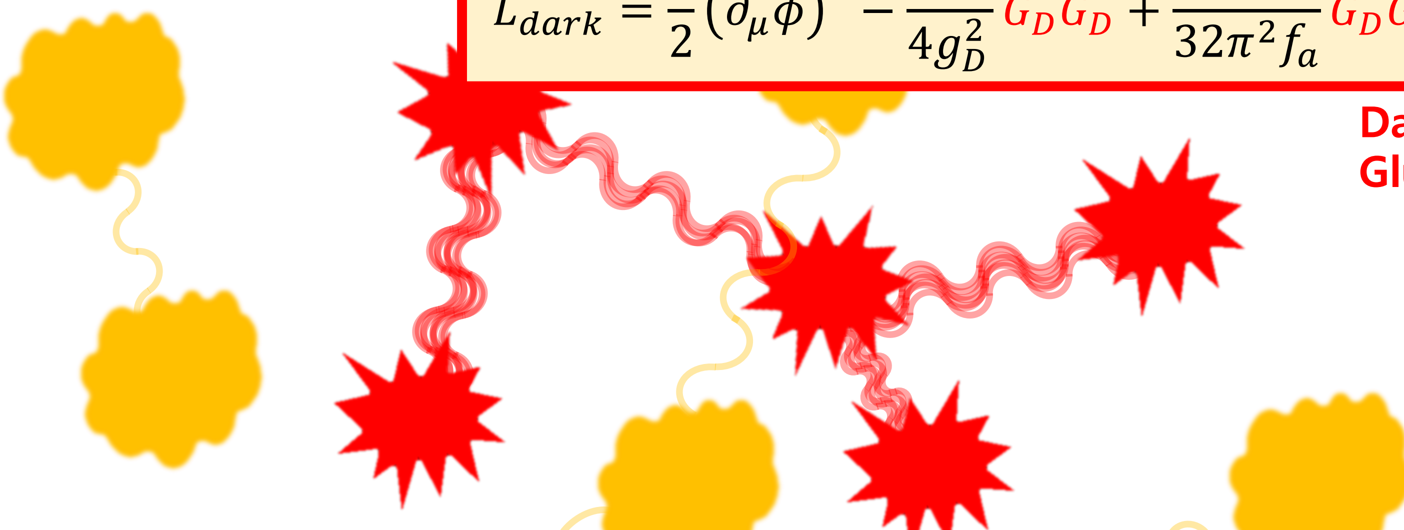


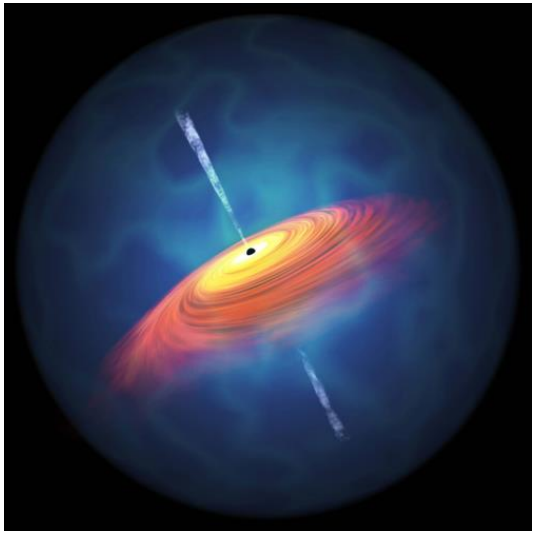
$$L_{eff} = \frac{1}{2}\left(\partial_\mu \varphi_g\right)^2 - \frac{1}{2} m_g^2 \varphi_g^2 + \frac{a_3}{3!}\frac{4\pi}{N} m_g \varphi_g^3 + \frac{a_4}{4!}\left(\frac{4\pi}{N}\right)^2 \varphi_g^4 + \frac{a_5}{5!}\frac{1}{m_g}\left(\frac{4\pi}{N}\right)^3 \varphi_g^5 + \cdots$$
$$+ \frac{1}{2}\left(\partial_\mu \phi\right)^2 - N^2 \Lambda^4 \left(\frac{c_2}{2}\left(\frac{\phi}{N f_a}\right)^2 + \frac{c_4}{4!}\left(\frac{\phi}{N f_a}\right)^4 + \cdots\right)$$

Dark Glueball

Multi component (매우 약한 상호작용 + 매우 강한 상호작용) scalar dark matter scenario

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*)

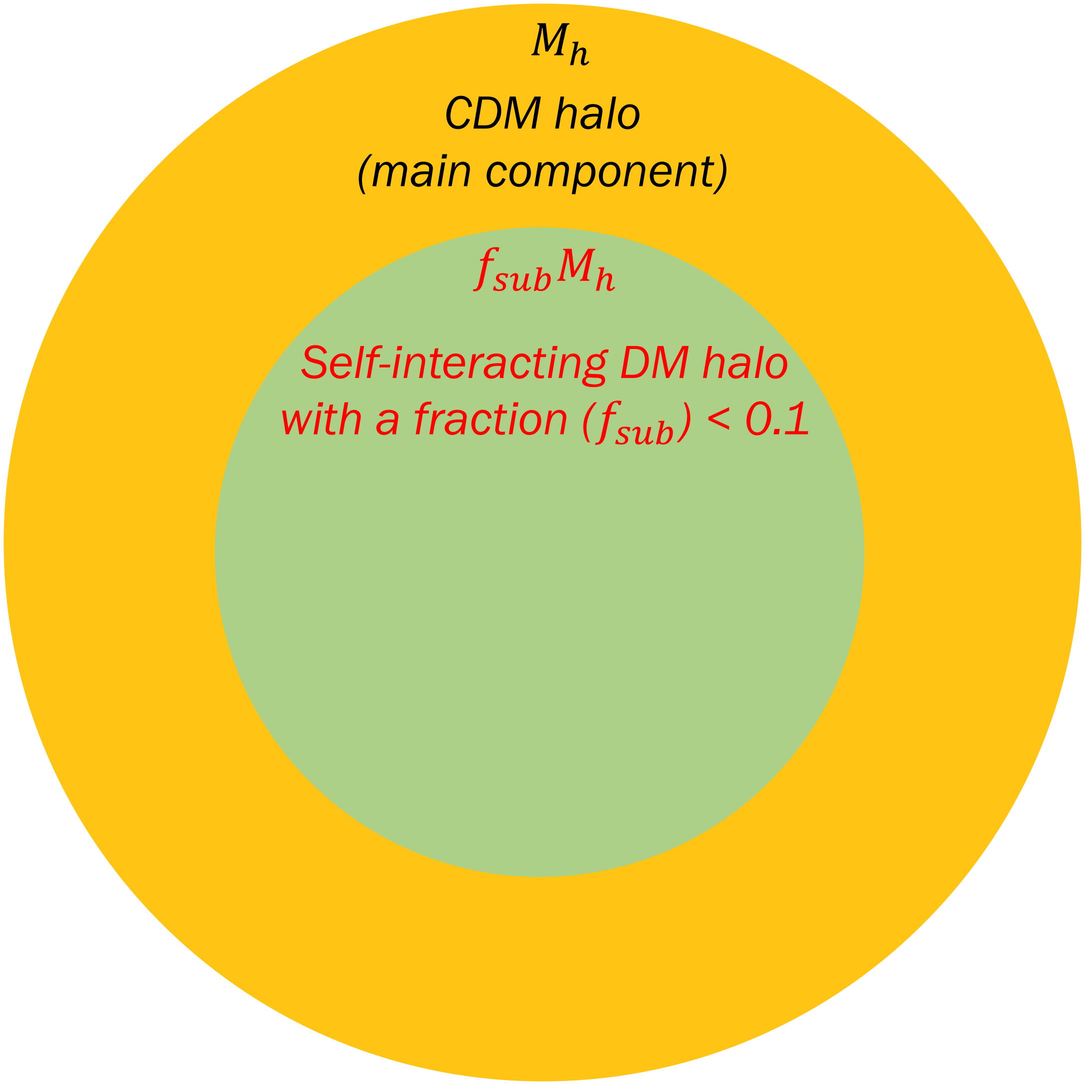
J0305-4150 ($z = 6.61, M_{BH} = 1.0 \times 10^9 M_\odot$, *1311.3260*)

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 : **dark glueball (strongly self-interacting) subcomponent DM**

Effect of Subcomponent Self-interacting DM

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



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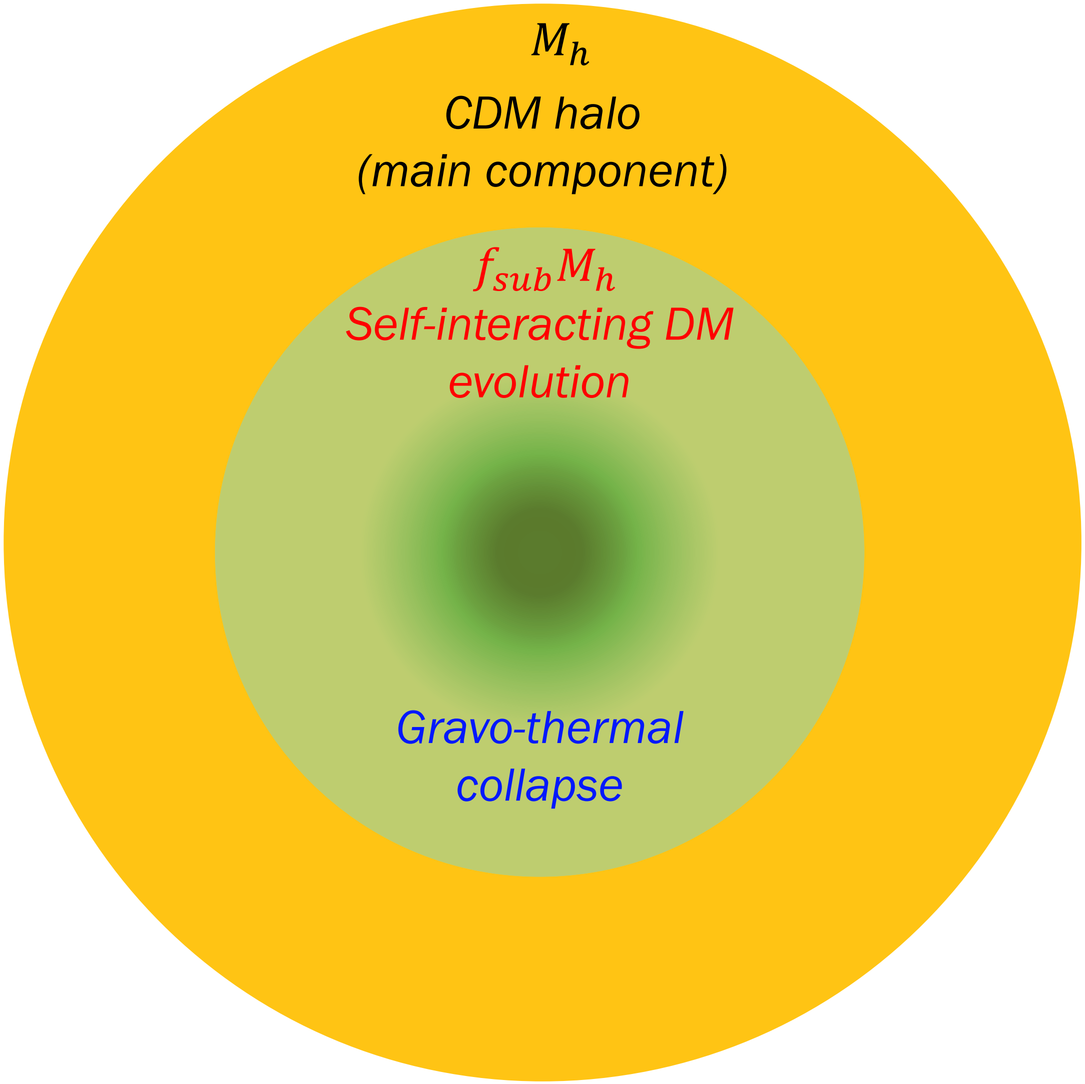

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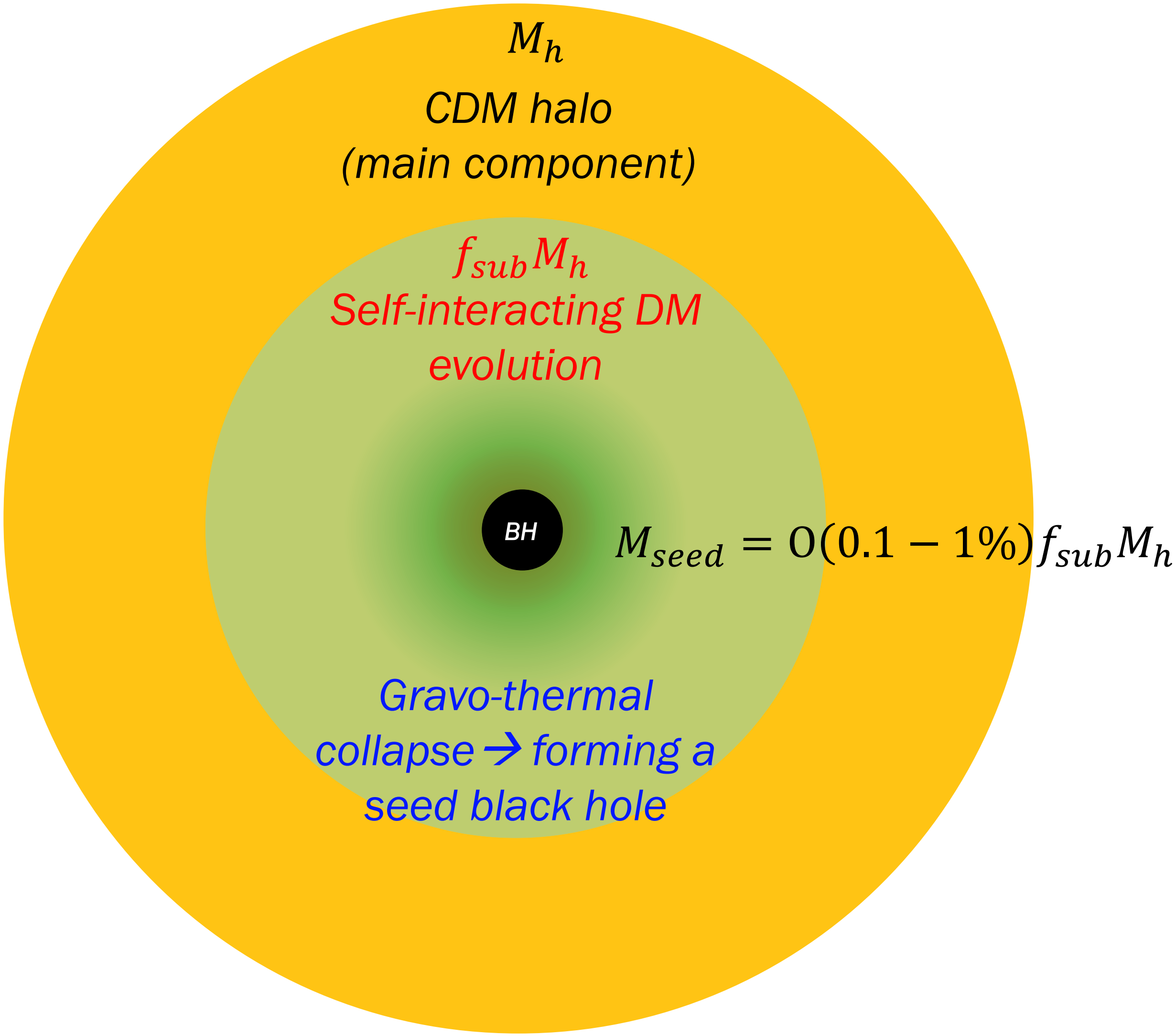
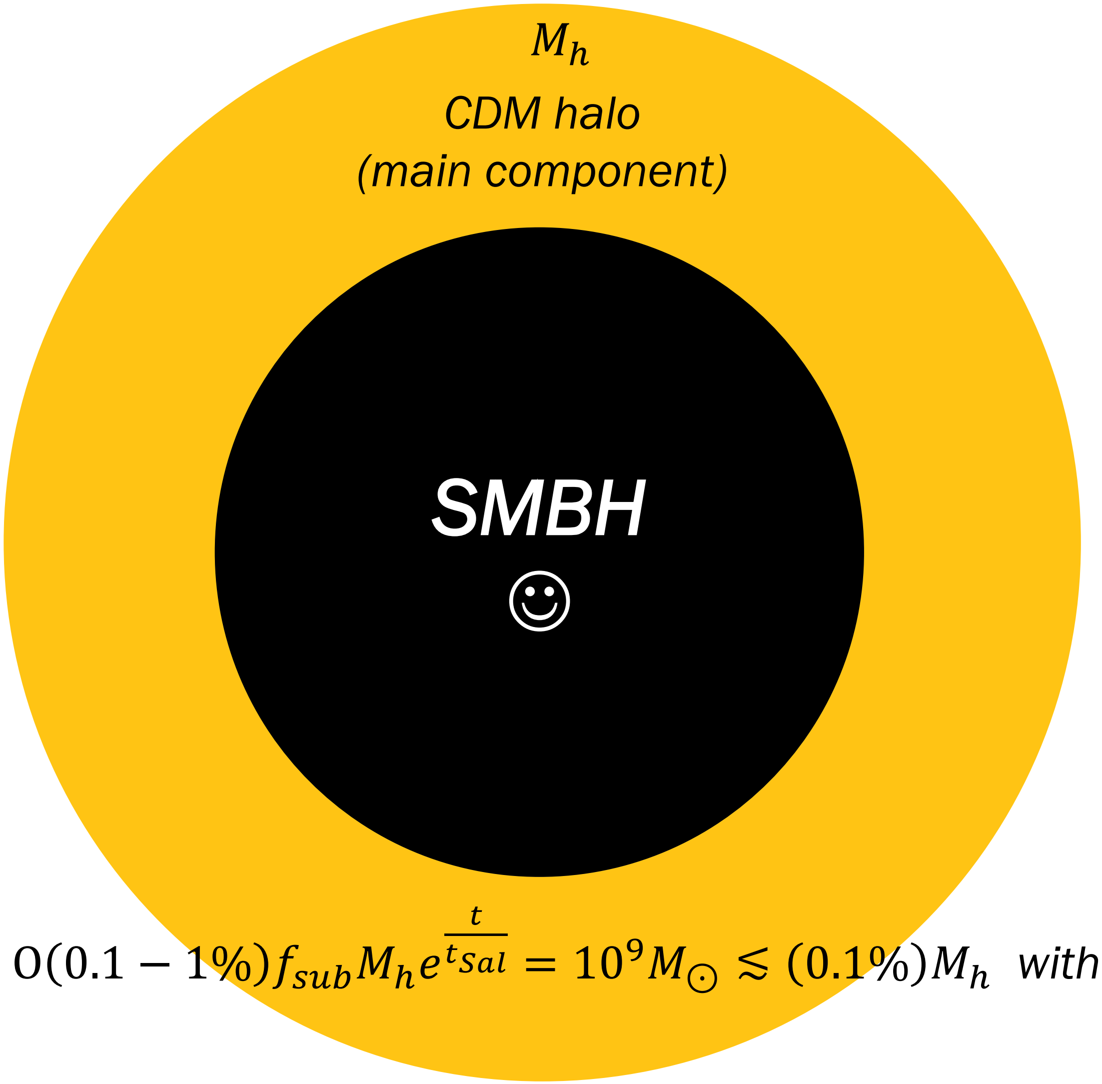


Effect of Subcomponent Self-interacting DM

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

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

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

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

Negative heat capacity → instability

Considering the bound system with

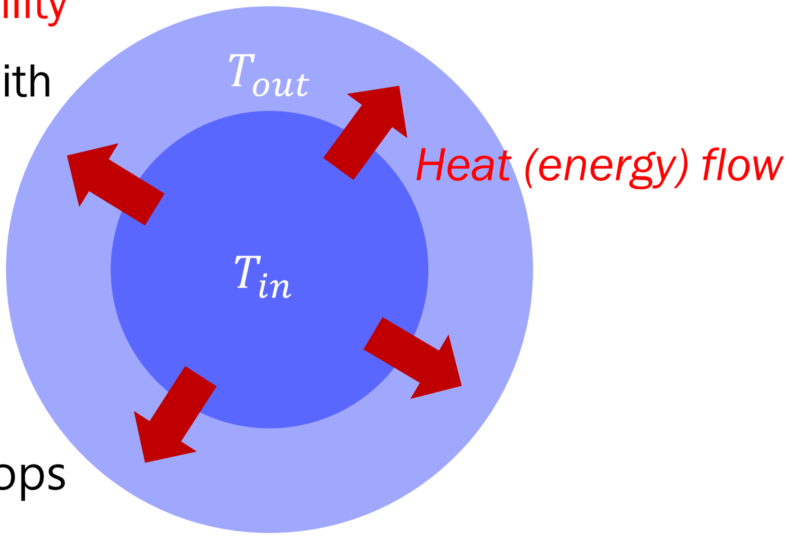
initial temperature gradient

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

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

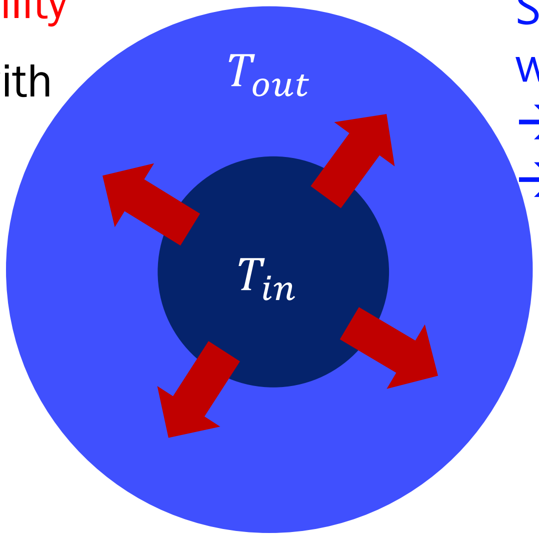
Considering the bound system with

initial temperature gradient

For the negative c_T case

Heat (energy) flow continues!

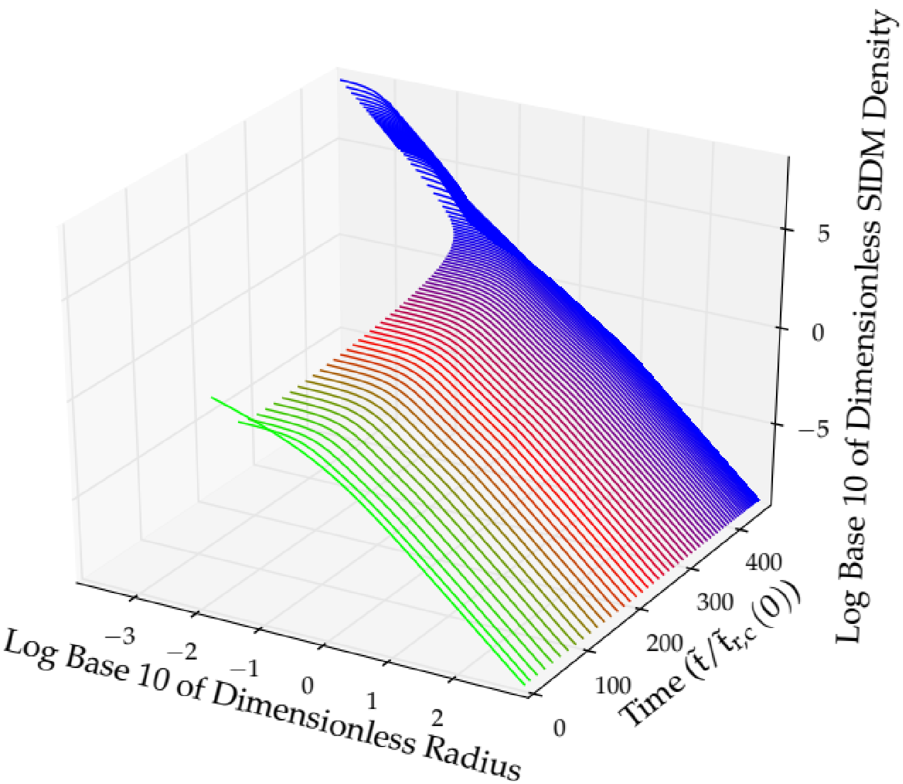
$T_{in} > T_{out}$ maintains forever!

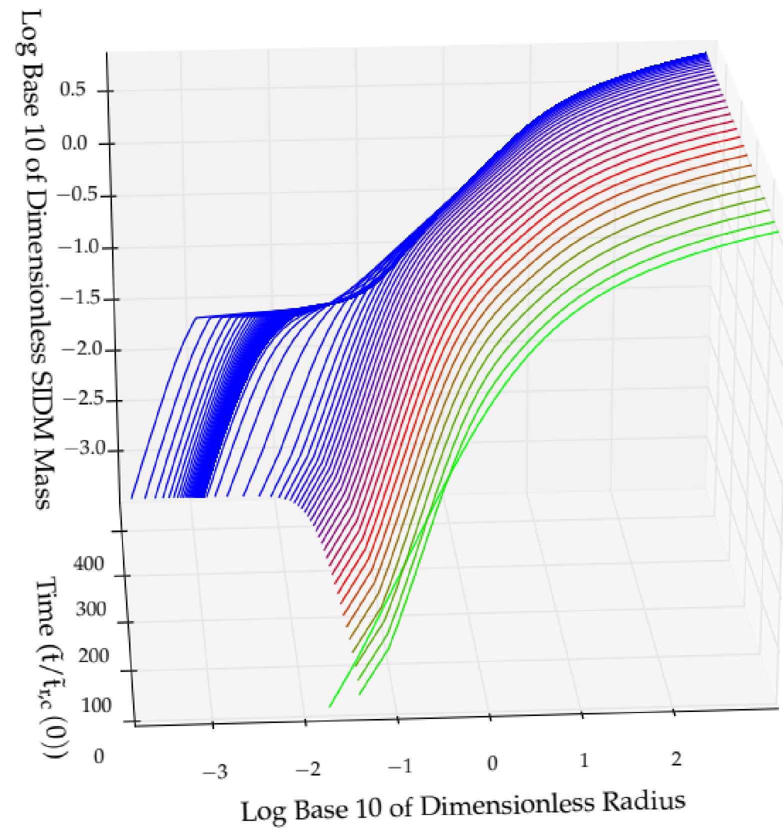


Strongly bound system
with high virial velocity
→ leads to gravitational collapse
→ forming a black hole

Gravo-Thermal Collapse

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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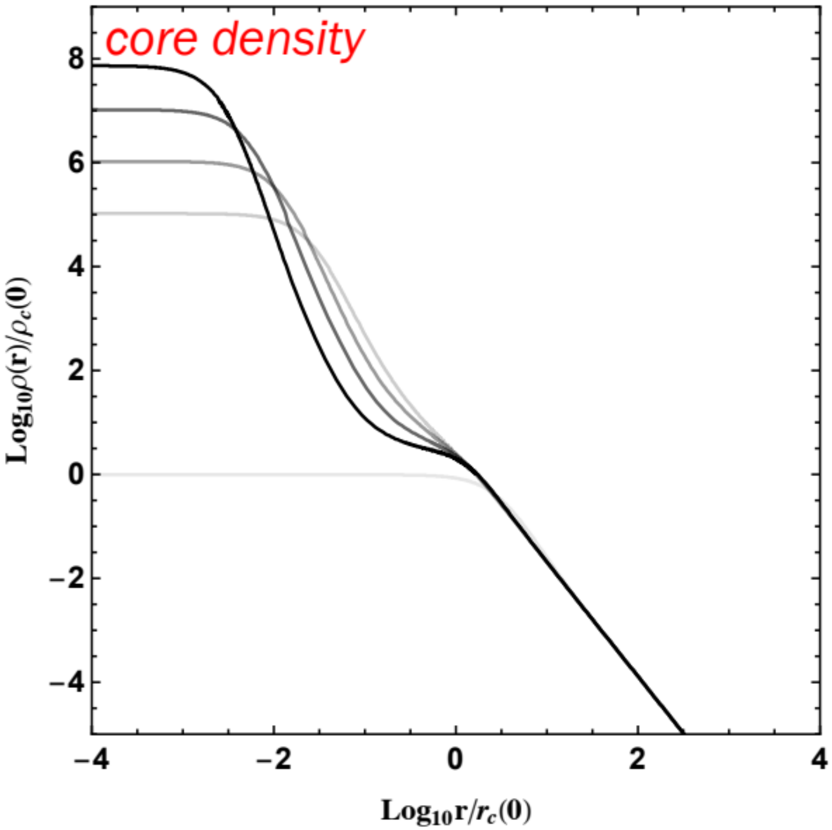
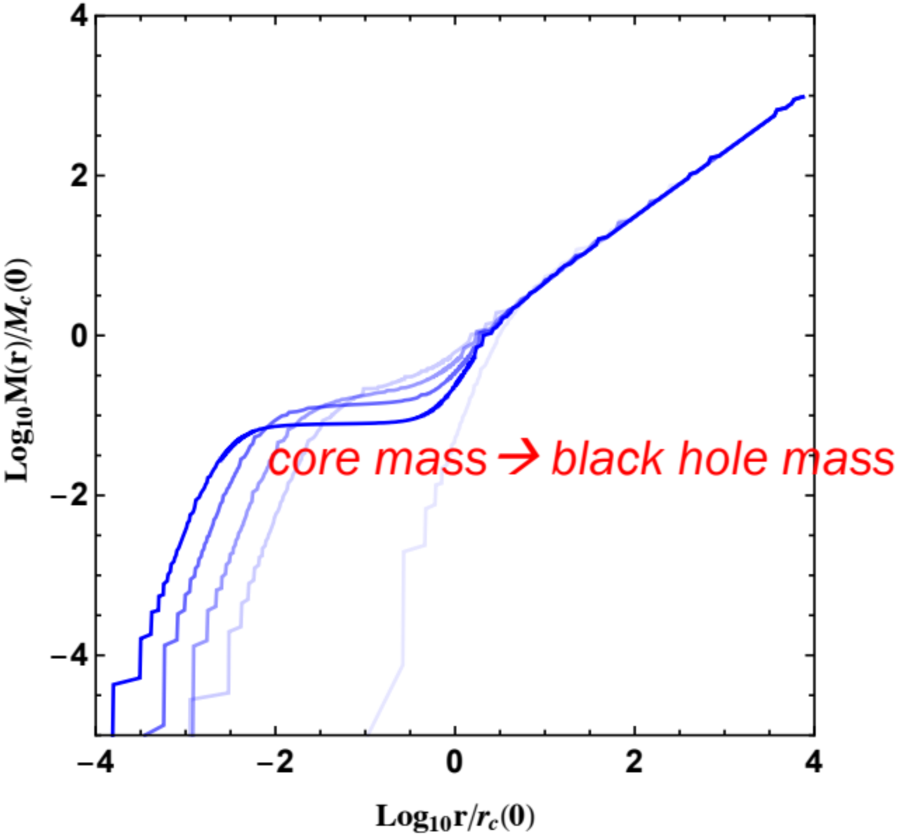
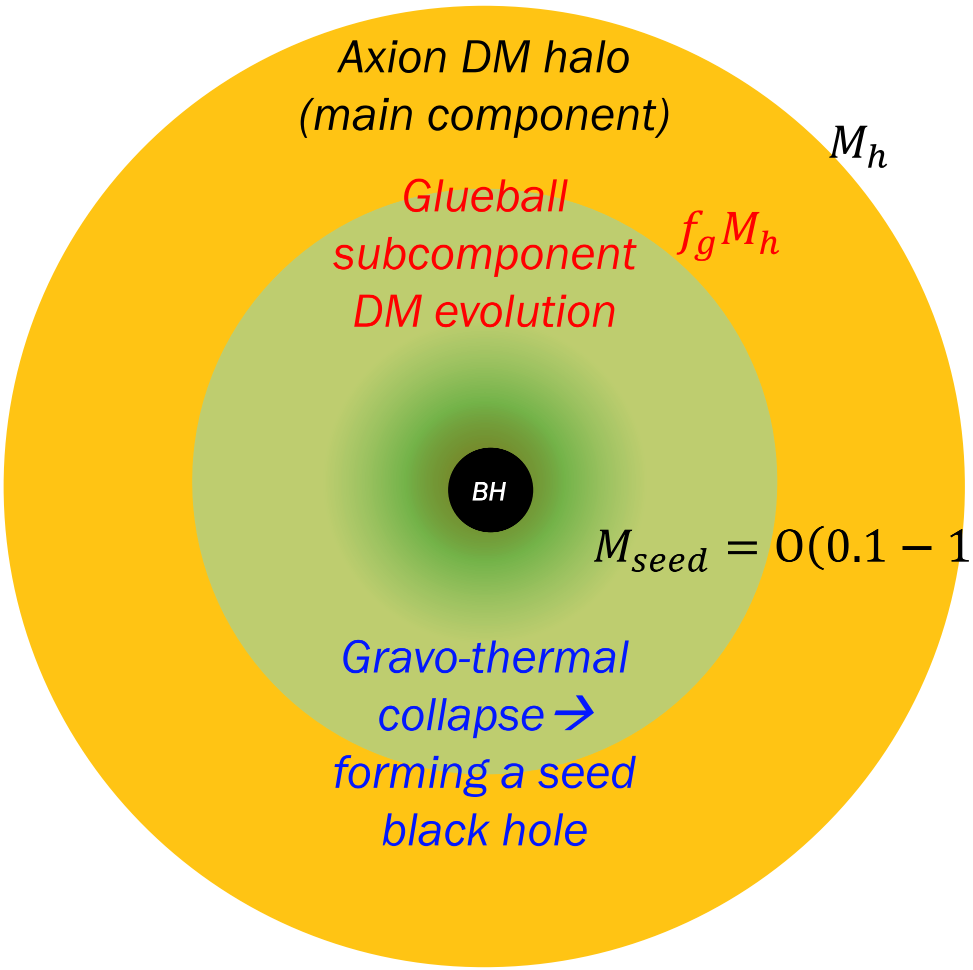




Balberg et.al. 0110561 for the isolated halo with f_{sub}=1

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.



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

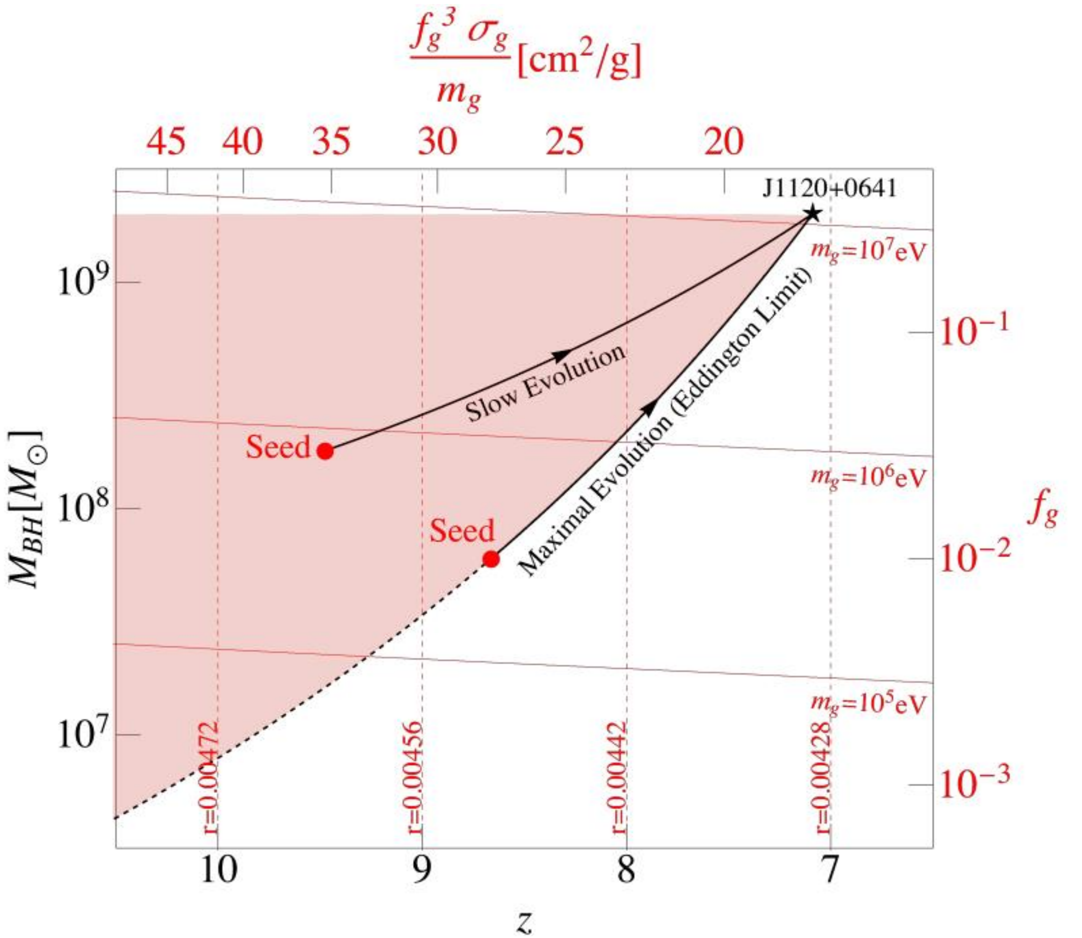
$$M_{BH}(t) = M_{seed} e^{\frac{t-t_i}{t_{Sal}}}$$

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

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

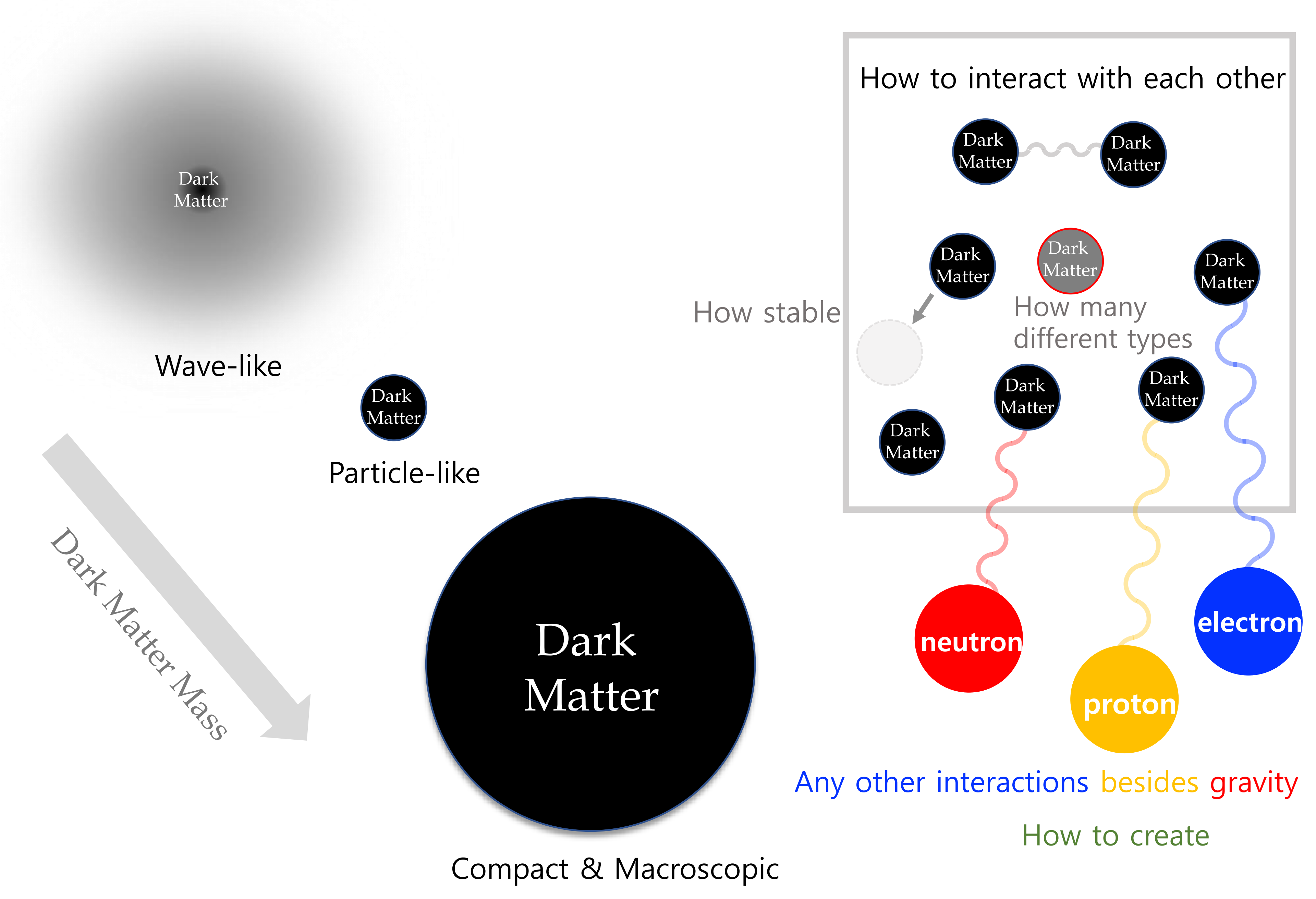
SMBH at High z for an Isolated Host Halo

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



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

What is the effect of the nature of dark matter?



감사합니다.