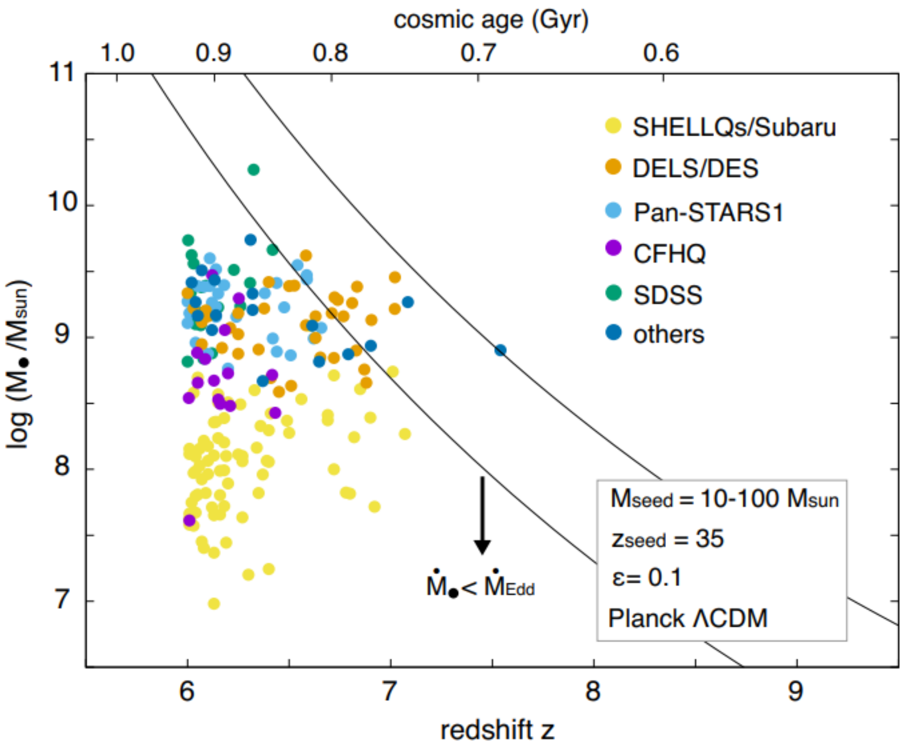
Supermassive Black Holes

2019 SNU-KIAS Physics Winter Camp

김정화, 배상민, 이제현, 이주현, 이호진

Supermassive Black Holes - Timescale Issues

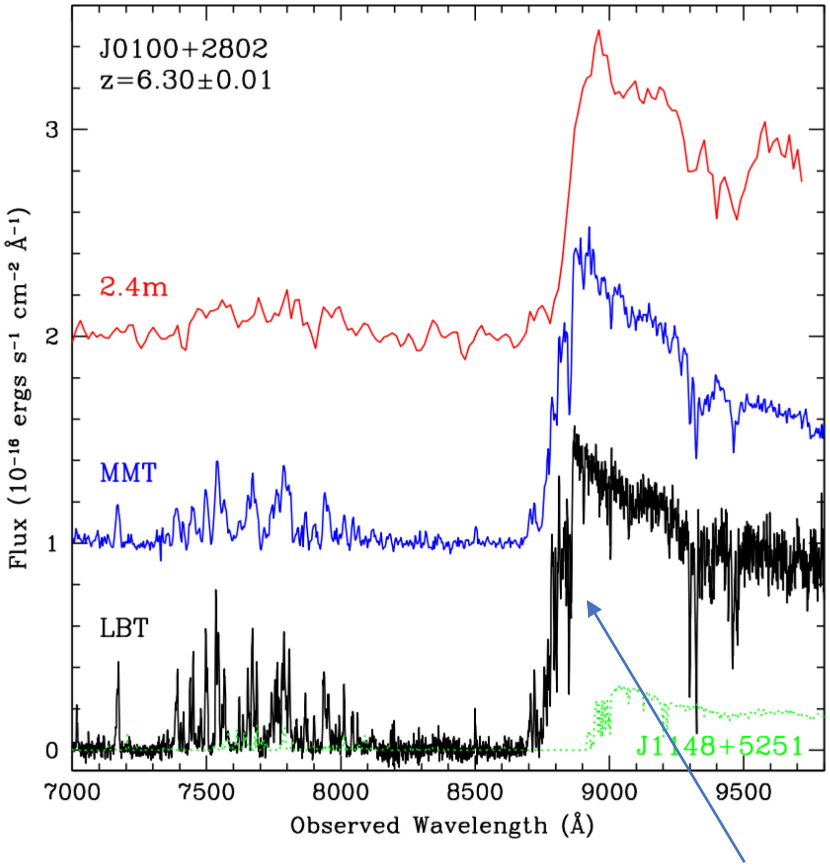


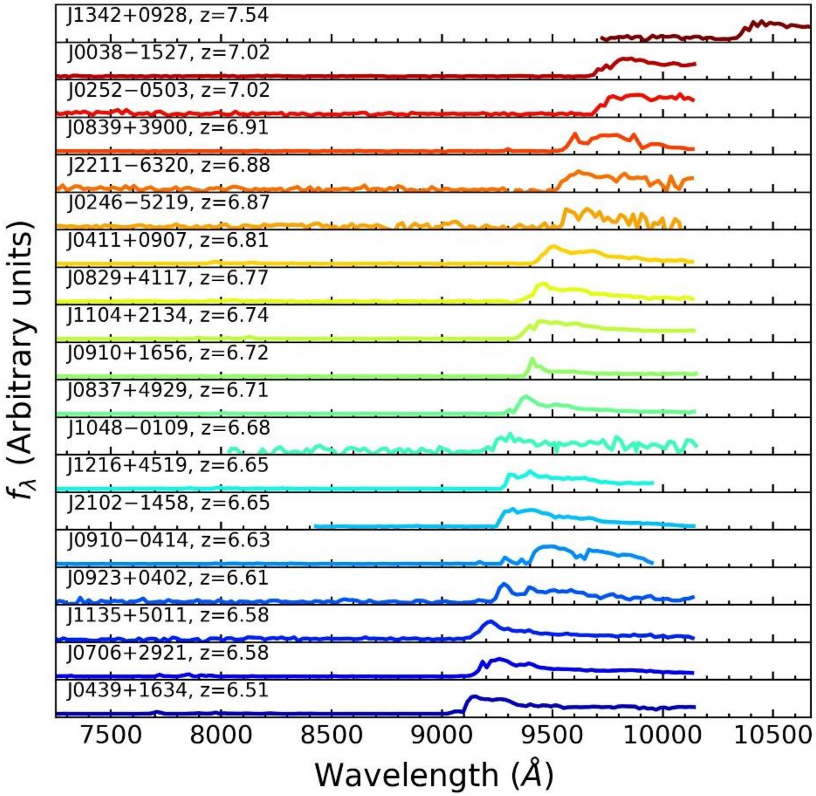
z ~ 7 -> 750Myr

$M_{BH} \sim 10^9 M_\odot$

How did the first SMBHs grow so large so fast?

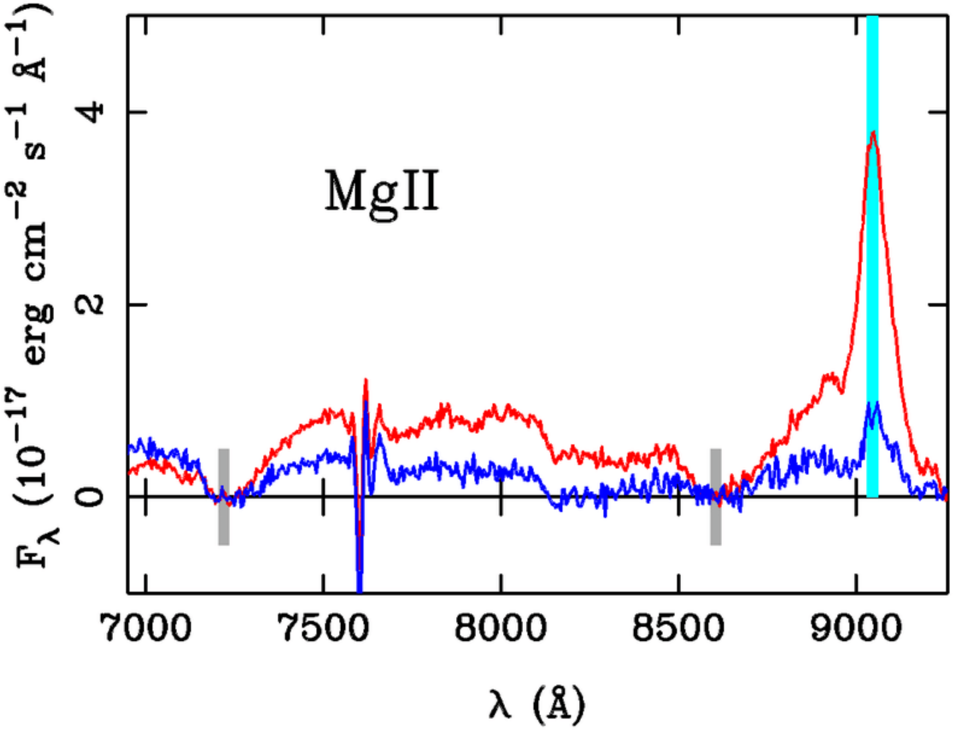
High-Redshift (z ~ > 6) Quasar Surveys





Lyman-α break (912 Å)

High-Redshift (z ~ > 6) Quasar Surveys



MgII Line width

$$\Delta v^2 \sim GM/r$$

Mass prediction

Eddington Limit

Assumptions

1. Spherical symmetry of Radiation & Gravity

2. Radiation pressure = Gravitational force
(Inward) (Outward)

$$L_{Edd} = \frac{4\pi c G M_\bullet}{\kappa_{es}}$$

κ_{es} : Opacity for Thompson scattering

$M_\bullet$: Black hole mass

Limitations

1. Not spherical case?

2. Depends on opacity κ

Growing BHs by Accretion – Eddington Limit

$$\dot{M}_{\rm Edd} \equiv \epsilon L_{\rm Edd}/c^2$$

$$L_{\rm Edd} = 4\pi c G M_\bullet/\kappa_{\rm es}$$

$$t_{\rm grow} \approx \frac{0.45\ \epsilon}{(1-\epsilon)f_{\rm duty}} \ln\left(\frac{M_\bullet}{M_{\rm seed}}\right)\ {\rm Gyr}$$

$f_{\rm duty} = 1$

Maximum

$\epsilon = 0.1$

From low-z quasars

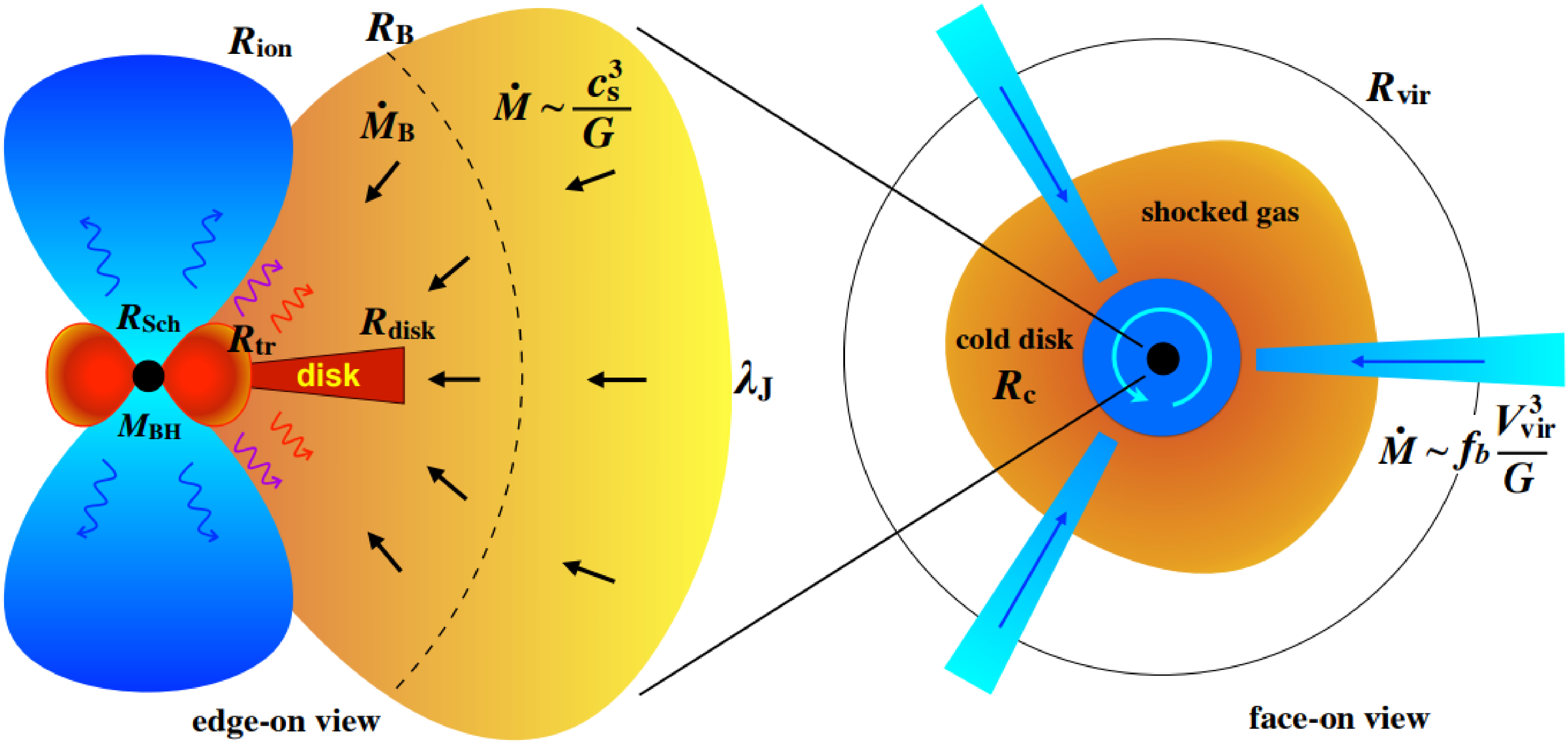
$M_{\rm seed} = 100\ {\rm M}_\odot$

Maximum
Stellar-BH mass

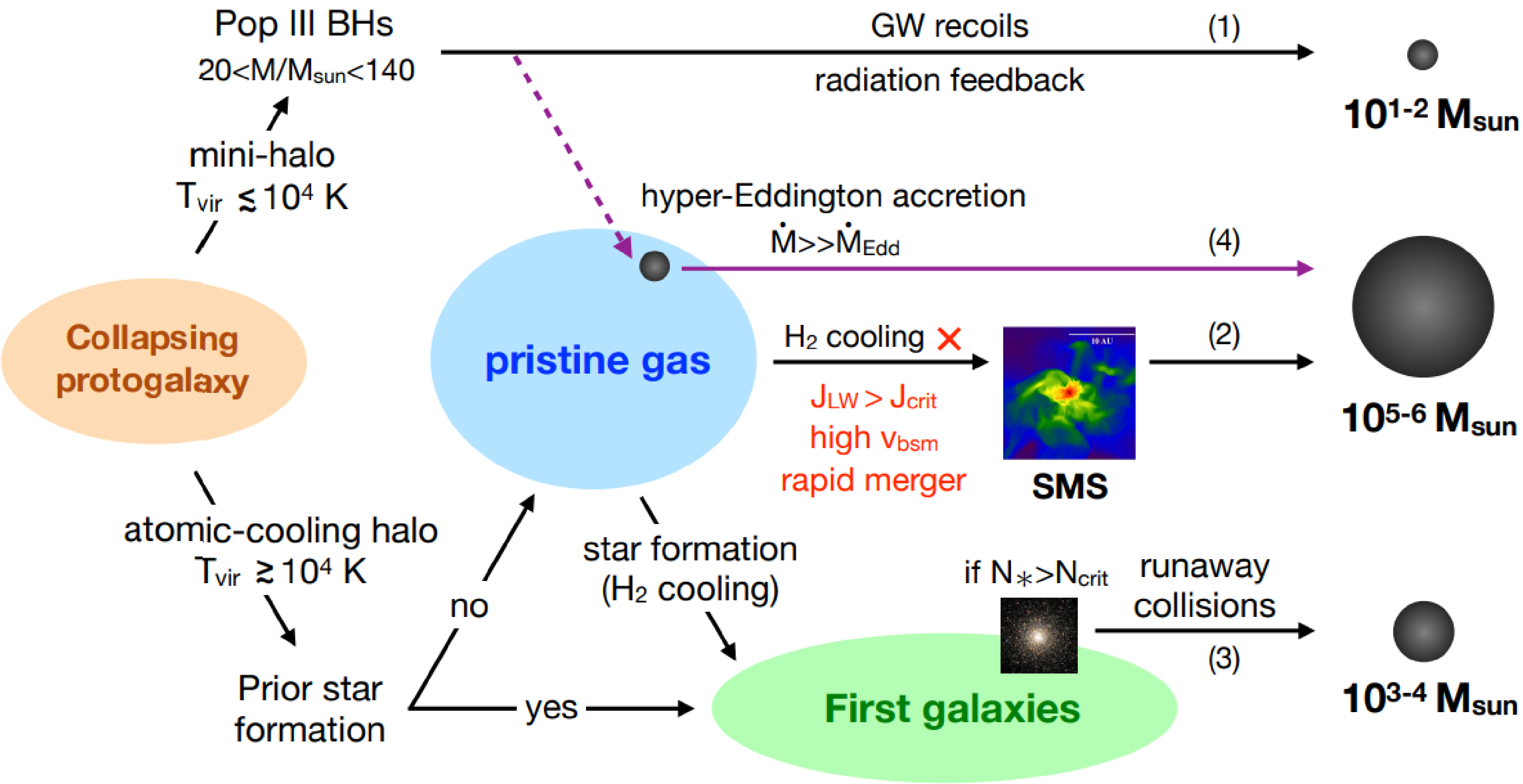
$M_\bullet = 10^9\ {\rm M}_\odot$

Target mass

Possible Solutions – Hyper Eddington Accretion



Possible Solutions – Larger Seed Mass



Pop III BHs

$20<M/M_{sun}<140$

mini-halo

$T_{vir} \lesssim 10^4$ K

GW recoils

(1)

radiation feedback

10^{1-2} M_{sun}

hyper-Eddington accretion

$\dot{M}>>\dot{M}_{Edd}$

(4)

Collapsing protogalaxy

pristine gas

H_2 cooling ✗

$J_{LW} > J_{crit}$

high v_{bsm}

rapid merger

SMS

(2)

10^{5-6} M_{sun}

atomic-cooling halo

$T_{vir} \gtrsim 10^4$ K

Prior star formation

no

yes

star formation (H_2 cooling)

if $N_*>N_{crit}$

runaway collisions

(3)

First galaxies

10^{3-4} M_{sun}

Non-Interacting Cold Dark Matter (CDM)

Assumption

Steady state condition& spherical symmetry

mass flux conservation & Energy-momentum conservation

$$J^{k}_{;k} = 0\,, \qquad T^{k}_{0;k} = 0$$

$$nur^{2} = C_{1} \qquad \frac{(P+\varepsilon)}{n}\left(1-\frac{r_g}{r}+u^{2}\right)^{1/2} = k_{1}$$

Wind equation

$$\frac{d(logu)}{d(logr)}\left[u^{2}-V^{2}\left(1-\frac{r_g}{r}+u^{2}\right)\right]+\left[\frac{r_g}{2r}-2V^{2}\left(1-\frac{r_g}{r}+u^{2}\right)\right]=0$$

$$r_g = \frac{2GM_{bh}}{c^{2}} \qquad V^{2} = \frac{d(log(P+\varepsilon))}{d(logn)} - 1$$

Non-Interacting Cold Dark Matter (CDM)

Critical point

$$\frac{d(logu)}{d(logr)}\left[u^2 - V^2\left(1-\frac{r_g}{r}+u^2\right)\right]+\left[\frac{r_g}{2r}-2V^2\left(1-\frac{r_g}{r}+u^2\right)\right]=0$$

$$r_g = \frac{2GM_{bh}}{c^2}$$

$$V^2 = \frac{d(log(P+\varepsilon))}{d(logn)} - 1$$

$$u_c^2 = \frac{r_g}{4r_c}, \qquad V_c^2 = \frac{u_c^2}{(1-3u_c^2)}$$

Derived from GR,

$$(P+\varepsilon) = mnc^2 + \frac{5}{6}mn\sigma^2 = mnc^2 + \frac{5}{6}m\frac{n^{5/3}}{Q_n^{2/3}}$$

σ : velocity dispersion of the peculiar velocity

$Q = \dfrac{mn}{\langle\sigma^2\rangle^{3/2}}$: indicator of the phase space density → Conserved!

$$Q_n = \frac{Q}{m} = \frac{n}{\sigma^3}$$

Non-Interacting Cold Dark Matter (CDM)

$$V^2 = \frac{d(log(P+\varepsilon))}{d(logn)} - 1 \simeq \frac{5}{9}\frac{n_c^{2/3}}{Q_n^{2/3}c^2} \qquad \frac{\sigma}{c} \ll 1$$

$$u_c^2 \simeq \frac{5}{9}\frac{n_c^{2/3}}{Q_n^{2/3}c^2} \qquad u_c^2 \ll \frac{1}{3} \Leftrightarrow r_g \ll r_c$$

$$r \gg r_g \ \rightarrow \ u = 0$$

$$k_1 = mc^2 + \frac{5}{6}m\left(\frac{n_\infty}{Q_n}\right)^{2/3} \simeq mc^2$$

Accretion rate

$$\frac{dM_{bh}}{dt} = 4\pi r_c^2\left(\frac{T_{0,c}^1}{c}\right) = \frac{27\pi}{4\sqrt{125}}r_g^2c^4Q = \frac{27\pi}{\sqrt{125}}(GM_{bh})^2Q$$

Self-Interacting Dark Matter (SIDM)

Elastic scattering (without any other interactions)

SIDM $\sigma/m \sim 1cm^2g^{-1}$ $f = 1$

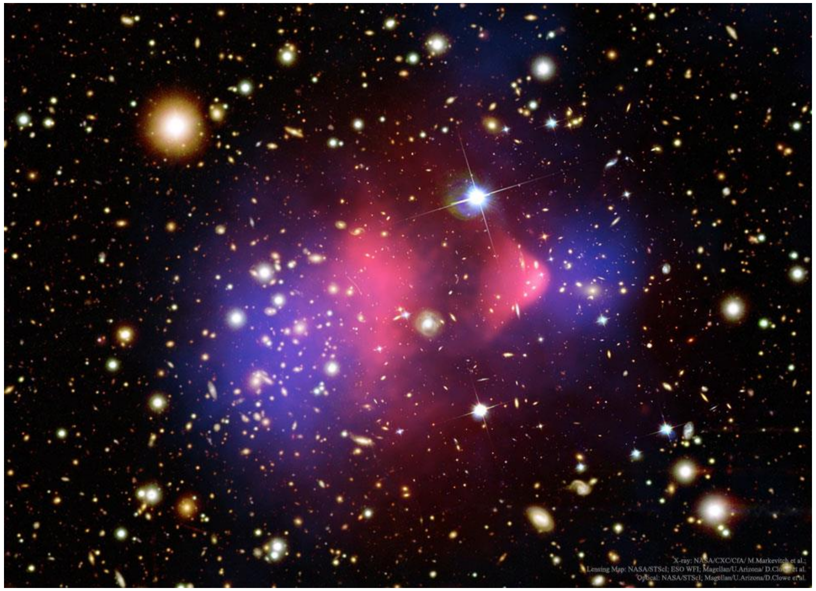
uSIDM $\sigma/m \gg 1cm^2g^{-1}$ $f \ll 1$

σ/m : cross section per mass

f : fraction

$\sigma/m \sim 1cm^2g^{-1}$ estimated from

Bullet Cluster observation



X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

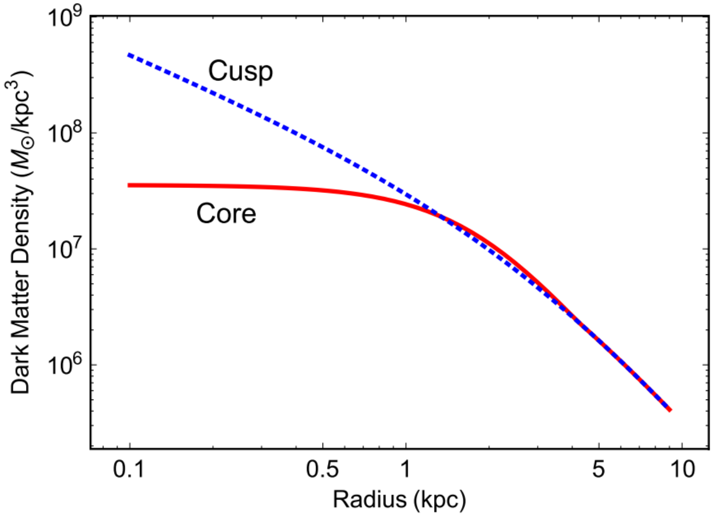
SIDM – Possible Solution of LCDM Problems

Core-Cusp Problem

In comparison with observation,

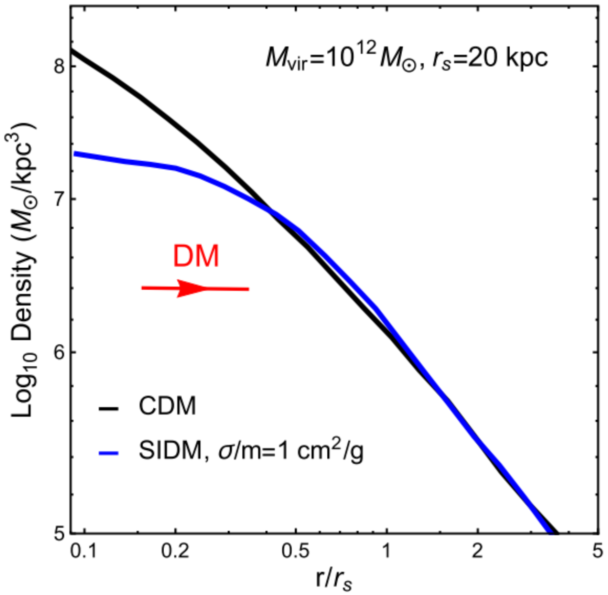
DM halo density profile from

N-body simulation is too cuspy



Core ↔ Cusp

(observation) (simulation)



Choquette et al. 2019

But, SIDM can solve Core-Cusp Problem!

SMBH Seed – Gravothermal Collapse of SIDM Halo

Assumption

1. Cooling by conduction (due to scattering)
2. Collapse occurs before dynamically relaxed

$$t_{\mathrm{dyn}}(r_s) \ll t_{\mathrm{rel}}(r_s)$$

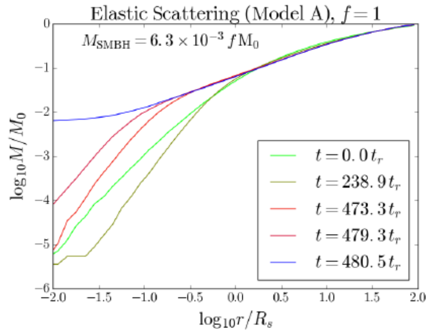
SMBH Seed

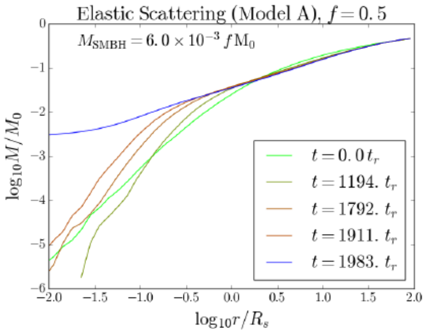
At $z \sim 13.5 \quad M_o = 10^5 M_\odot$

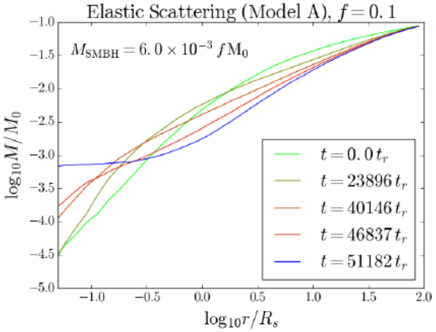
Possible parameter from simulation

$$\sigma/m = 380 cm^2 g^{-1},\ f = 0.1$$

: not likely!







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Mirror World

A duplicate of the Standard Model(SM) matter

A Cold Dark Matter(CDM) candidate

$$\Omega_m = (\Omega_c + \Omega'_b) + \Omega_b \qquad x = \frac{T'_\gamma}{T_\gamma}\ , \qquad \beta = \frac{\Omega'_b}{\Omega_b}$$

For simplicity, $\beta = 1$ is taken

In order to avoid the CMB(Cosmic Microwave Background) &

BBN(Bing Bang Nucleosynthesis)

$$x \lesssim 0.3$$

In this case mirror matter behaves like CDM at the time of CMB last

scattering

Thermal History

Free electron number fraction

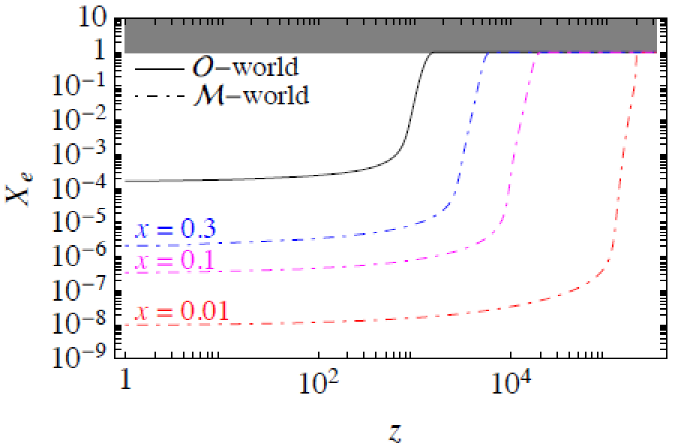
$$\frac{dX_e}{dz} = \frac{\mathcal{P}_2}{(1+z)H(z)}\left(\alpha_H(T_g)n_H X_e^2 - \beta_H(T_g)e^{-\frac{E_\alpha}{T_g}}(1-X_e)\right)$$

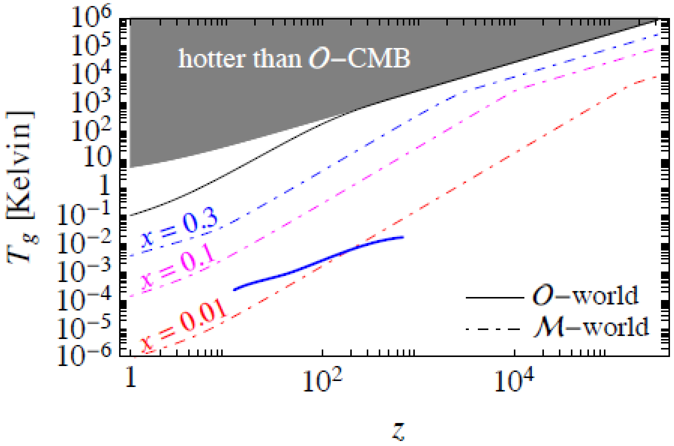
Gas temperature

$$\frac{dT_g}{dz} = \frac{1}{1+z}\left[2T_g - \gamma_C\left(T_\gamma(z) - T_g\right)\right]$$

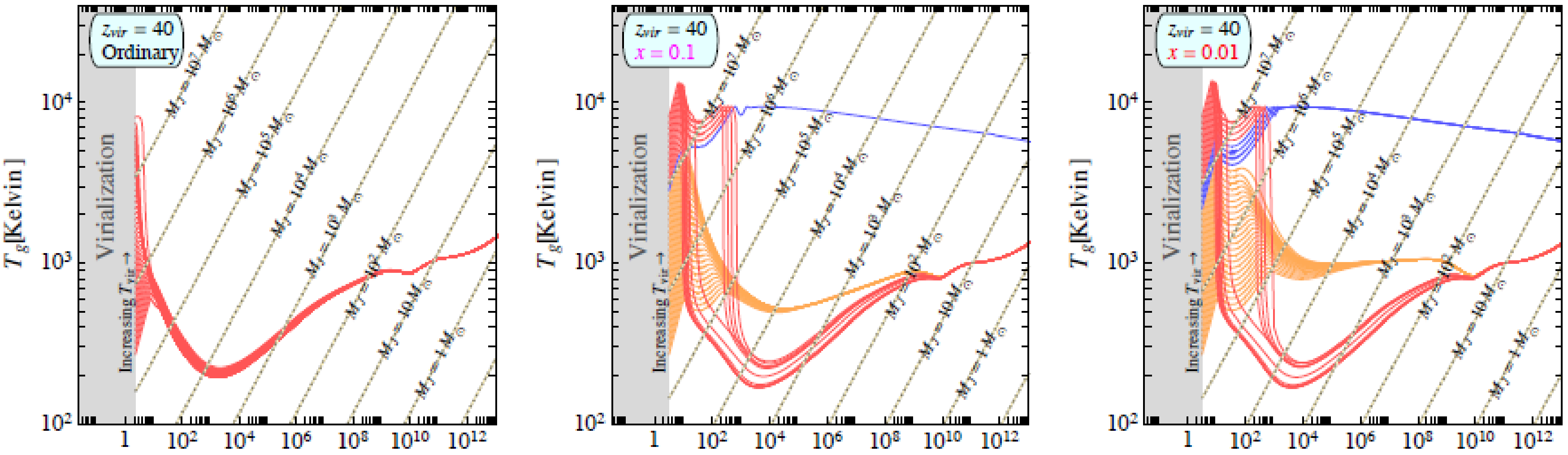
For mirror world

$$X_e \to X_e', \qquad T_g \to T_g', \qquad n_H \to n_{H'}, \qquad \gamma_C \to \gamma_C', \qquad T_\gamma(z) \to xT_\gamma(z)$$





Structure formation



Accretion of BH seeds

$$M(t) = M_0 e^{\frac{t-t_0}{t_{Sal}}}$$

$$t_{Sal} = \frac{\epsilon M c^2}{(1-\epsilon)L} \simeq 400Myr\,\frac{\epsilon}{1-\epsilon}\,\frac{L_{Edd}}{L}$$

Thank you!

Q&A