Seeding Supermassive Black Holes

Wei-Xiang Feng 06/20/2023

Pollica Summer Workshop on Self-Interacting Dark Matter

Feng, Yu & Zhong, Astrophys. J. Lett. **914**, L26 (2021); JCAP 05 (2022) 036

Outline

- ***Supermassive Black Hole (SMBH) Puzzle***
- ***SMBHs from Self-interacting Dark Matter (SIDM)***
- ***Dynamical (Relativistic) Instability***
- ***Summary & Future Plans***

SMBH Puzzle

M87 (Event Horizon Telescope)

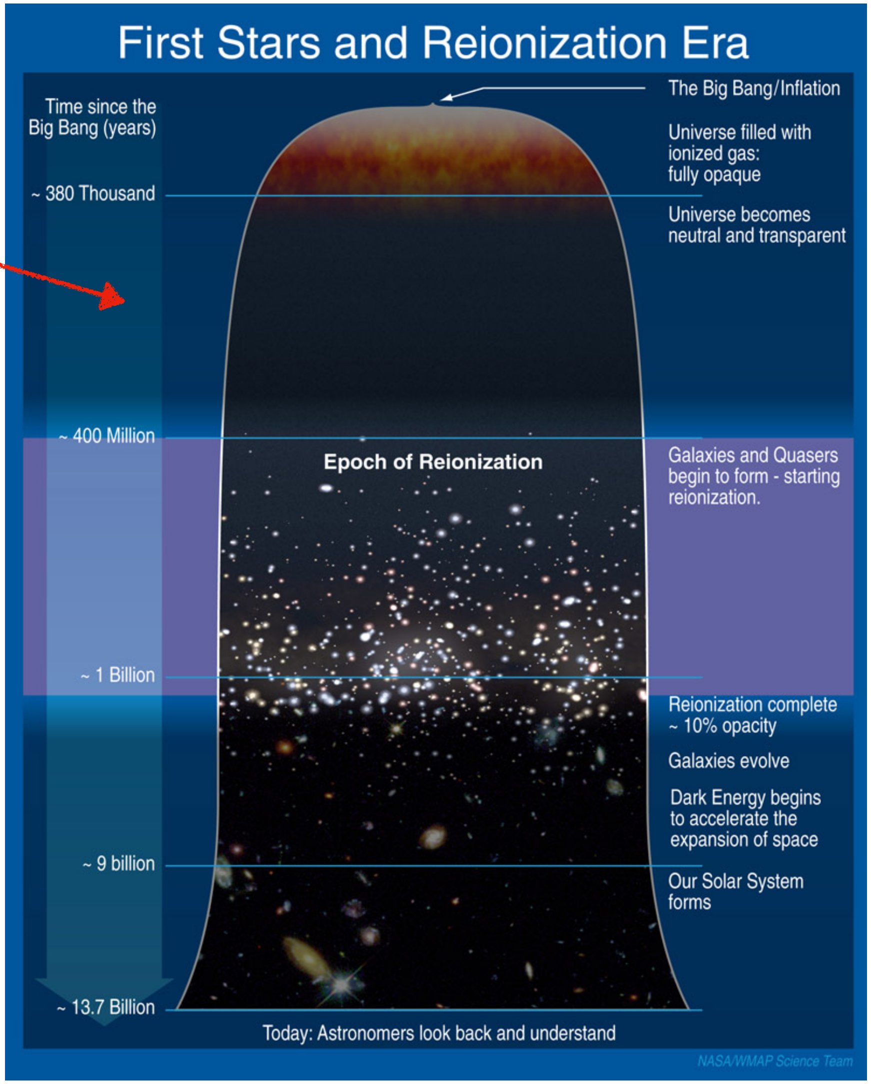
SMBH Puzzle

Cosmic History

Dark Age

- SMBHs with mass $\gtrsim 10^8 M_\odot$ are found at the centers of the most of massive galaxies.
- The early formation of SMBHs in re-ionization era ($6 < z < 20$) has puzzled astrophysicists for decades.
- More recently, around a hundred of distant SMBHs are found in ***800 Myr*** after the Big Bang (redshift $z \gtrsim 7$).

Banados et al., Nature, **553**, 473 (2018);
Wang et al., ApJ, **869**, L9 (2018);
Matsuoka et al., ApJ, **883**, 183 (2019); **872**, L2 (2019)



SMBH Puzzle

Cosmic History

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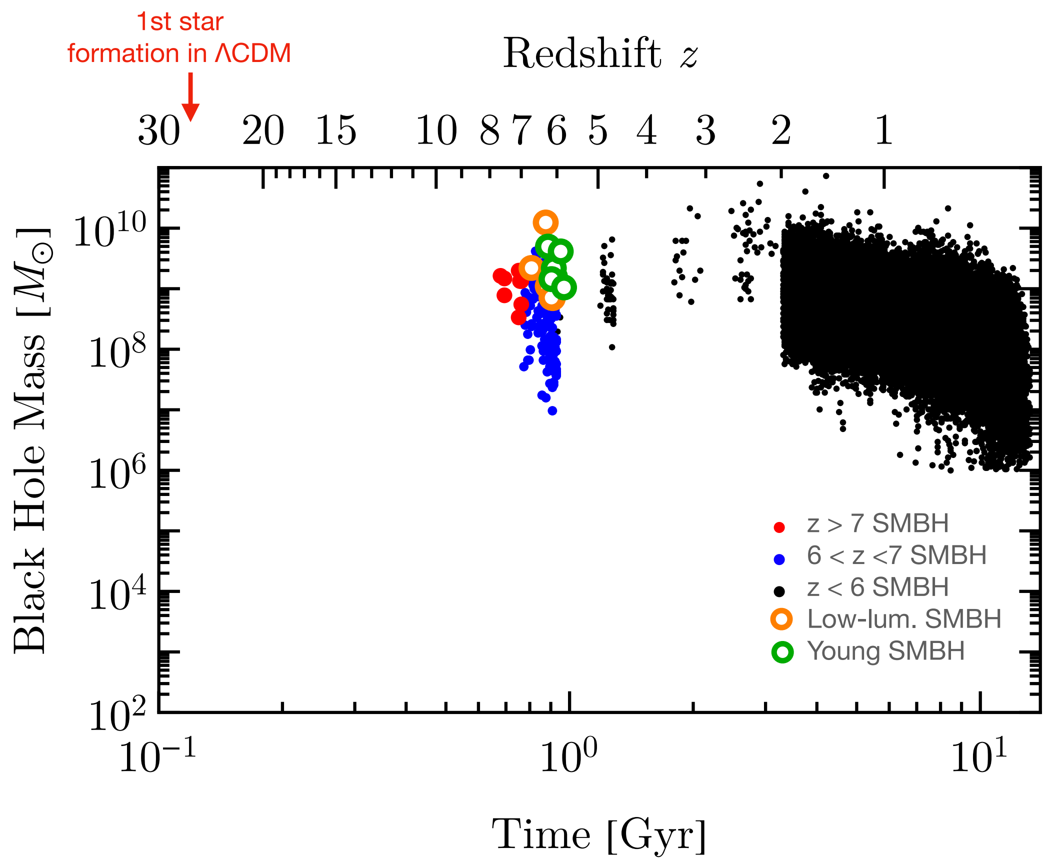
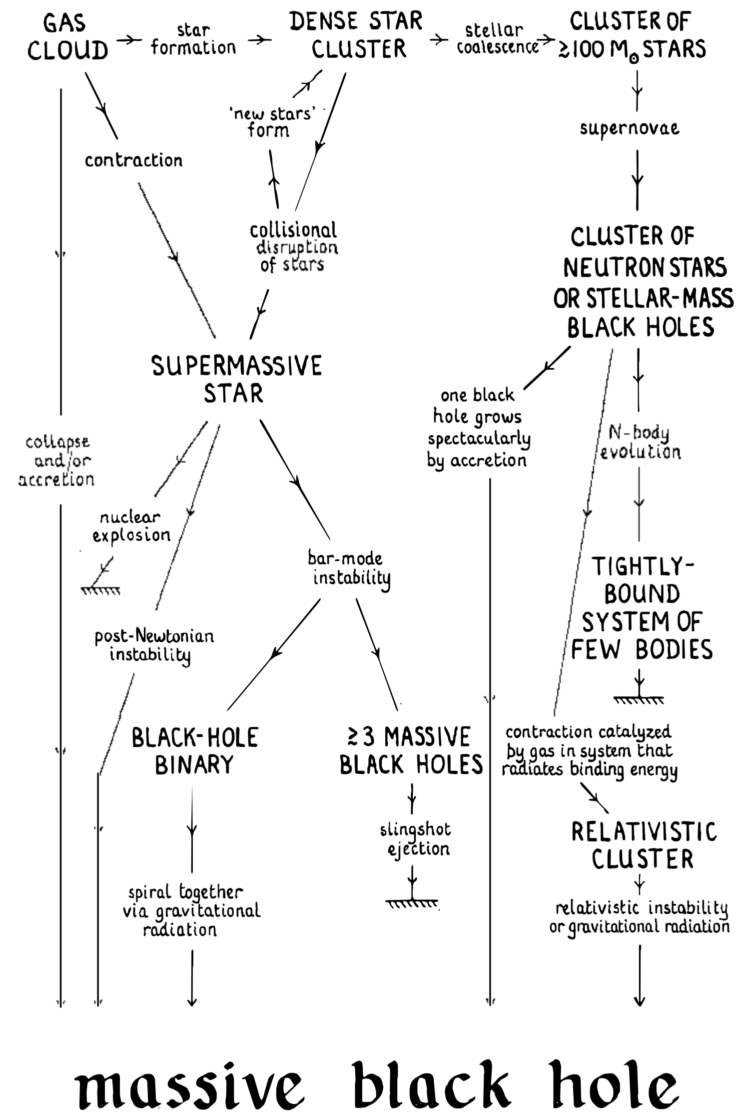


Banados et al., Nature, **553**, 473 (2018);
Wang et al., ApJ, **869**, L9 (2018);
Matsuoka et al., ApJ, **883**, 183 (2019); **872**, L2 (2019)

SMBH Puzzle

Merger Scenario

- ***Mergers*** of stellar-mass BHs from ***dead stars***.
- ***Super-Eddington accretion*** is required to reach SMBHs.
- Usually taking ***too long*** to reach SMBHs $\sim 10^8 M_\odot$.
- It is hard to explain the high redshift $z \gtrsim 7$ SMBHs.



Rees, ARA&A, **22**, 471 (1984)

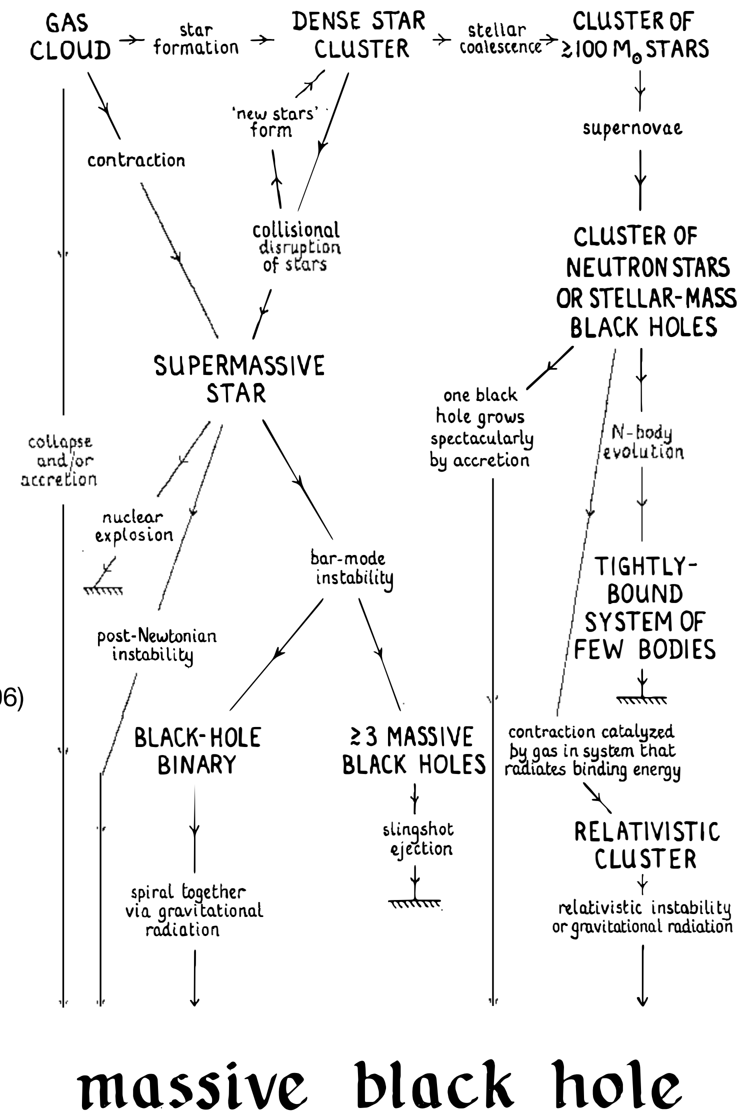
SMBH Puzzle

Direct Collapse Scenario

- An ***efficient*** way is through the ***direct collapse*** from ***dense gas cloud***.
- ***Temperature*** should be sufficiently ***high*** to prevent the gas cloud from ***fragmentation***.

Begelman, Volonteri & Rees, MNRAS, **370**, 289 (2006)

- The main challenge for these models is the ***disposal of angular momentum***.



Rees, ARA&A, **22**, 471 (1984)

SMBHs from SIDM

Wikipedia

SMBHs from SIDM

Observational Constraints of SIDM

- What if DM has self-interaction? Spergel & Steinhardt, PRL, **84**, 3760 (2000) Tulin & Yu, Phys. Rept. **730**, 1-57 (2018)
- Core-cusp, diversity,… Kamada, Kaplinghat, Pace & Yu, PRL, **119**, 111102 (2017) Ren, Kwa, Kaplinghat & Yu, PRX, **9**, 031020 (2019) Kaplinghat, Ren & Yu, JCAP, **06**, 027 (2020)
- Observational constraints on self-interaction strength $\sigma/m \sim \mathcal{O}(1)\ \mathrm{cm}^2/\mathrm{g}$ from dwarf galaxies Kaplinghat, Tulin & Yu, PRL, **116**, 041302 (2016)
- Elastic collisions or with dissipations… Essig, Mcdermott, Yu & Zhong, PRL, **123**, 121102 (2019)

SMBHs from SIDM

Direct Collapse from SIDM

- Early works by Ostriker (2000), Balberg & Shapiro (2002)…

Ostriker, PRL, **84**, 5258 (2000)
Balberg & Shapiro, PRL, **88**, 101301 (2002);
Balberg, Shapiro & Inagaki, ApJ, **568**, 475 (2002)

- Gravitationally bound & thermodynamic system → ***Gravothermal*** evolution

- Gravitationally bound system → ***Negative*** heat capacity

→ Getting hotter & hotter as heat is transported out !

- Gravothermal contraction → Catastrophic ***core collapse*** !

Sameie, Yu, Sales, Vogelsberger & Zavala, PRL, **124**, 141102 (2020)

- ***Too slow*** to have early SMBHs given $\sigma/m \sim \mathcal{O}(1)\ \mathrm{cm^2/g}$

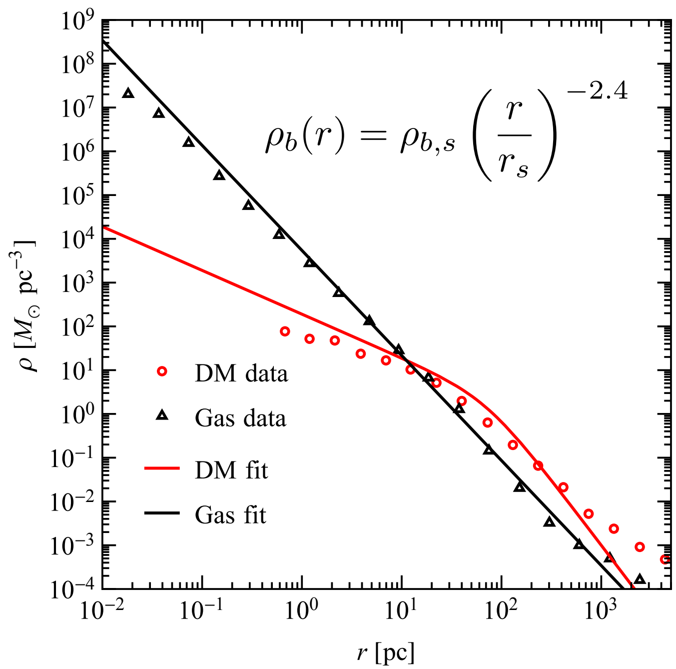
Gravothermal Evolution of SIDM Dark Halos

Baryon Distribution for Protogalaxies

- We adopt a ***single power law*** of baryonic gas from simulation by Wise et al.

$$M_b(r) = 1.67 \times \frac{\rho_{b,s}}{\rho_s}(4\pi\rho_s r_s^3)\left(\frac{r}{r_s}\right)^{0.6}$$

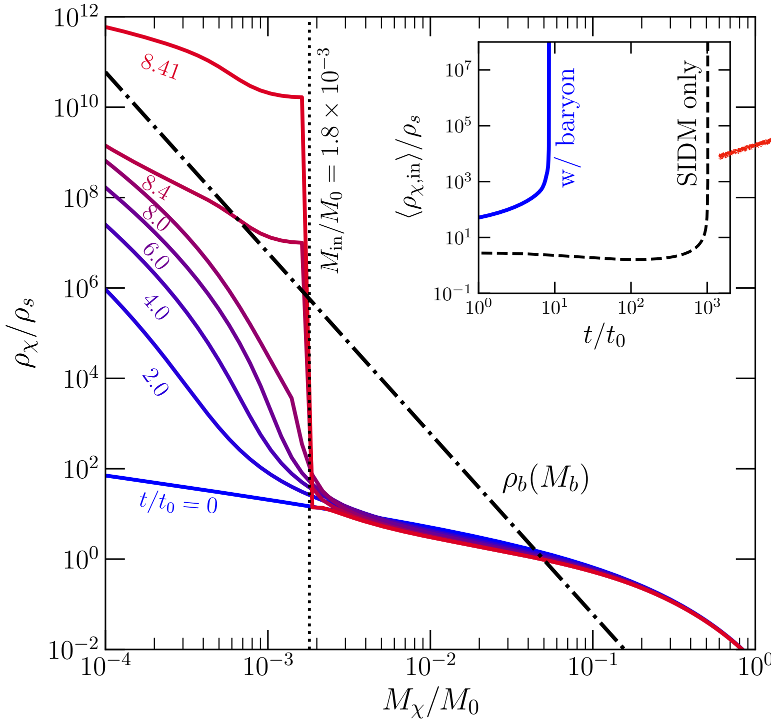
Wise et al., ApJ **682** 745 (2008)



- $\rho_{b,s} = 0.19 M_\odot/\mathrm{pc}^3, \rho_s = 2.6 M_\odot/\mathrm{pc}^3$ and $r_s = 73\mathrm{pc} \Rightarrow M_b(r) \simeq 0.1 M_0 \left(r/r_s\right)^{0.6}$

Gravothermal Evolution of SIDM Dark Halos

Baryonic Content Speeds up the Collapse



With and without baryons, $t_c = 8.4t_0$ and $t_c \simeq 10^3 t_0$, respectively

FIG. 1: Gravothermal evolution of the dark matter density vs. enclosed mass in the presence of the baryonic potential (solid), as well as the fixed baryon profile (dash-dotted). Each dark matter profile is labeled with its corresponding evolution time, and the vertical dotted line indicates the mass of the central halo that would eventually collapse into a seed black hole. The *insert* panel illustrates the evolution of the averaged dark matter density of the central halo with (solid) and without (dashed) including the baryons.

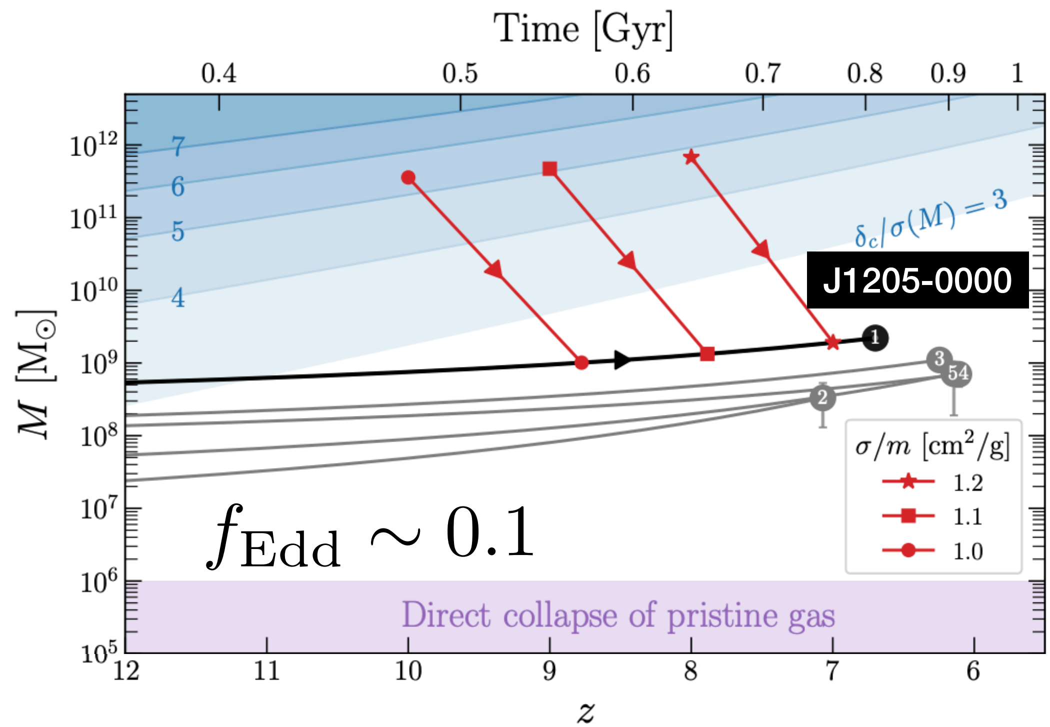
Feng, Yu & Zhong, Astrophys. J. Lett. **914**, L26 (2021)

The ***central density diverges*** in finite time (***gravotheramal catastrophe***) !

Gravothermal Evolution of SIDM Dark Halos

Solving High Redshift SMBH Puzzle

- **Press-Schechter** formalism for halo mass function $\frac{dn(M,z)}{dM} \propto \exp\left[-\frac{\delta_c^2(z)}{2\sigma^2(M)}\right]$
- SIDM halos with redshift $z \gtrsim 10$ and $\sigma/m \sim \mathcal{O}(1)\ \mathrm{cm}^2/\mathrm{g}$
- With baryons, it takes $\simeq 126\ \mathrm{Myr}$; in contrast, it takes $\gtrsim 10\ \mathrm{Gyr}$ for pure SIDM halos. ($t_0 = 15\mathrm{Myr}$)



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assuming Salpeter time $t_{Sal} = 50$ Myr for Eddington accretion

Dynamical (Relativistic) Instability

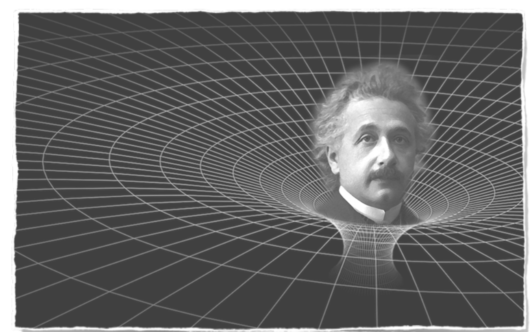
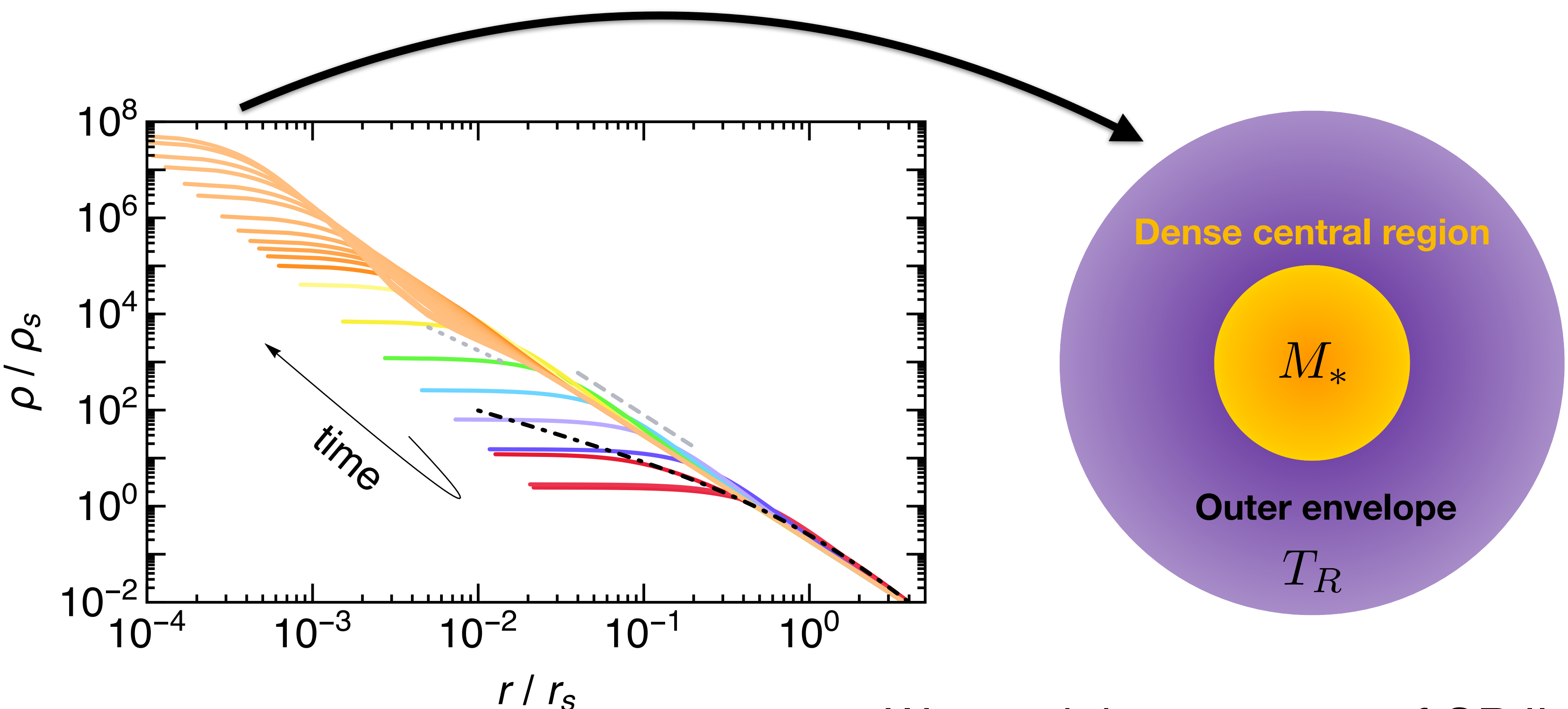


Image by Matt Payne

Direct Collapse of the Inner Core?



$\rightarrow$ We need the treatment of GR !!

Dynamical Instability

Truncated MB - Distribution with Cutoff $w = \beta\epsilon_c$

- For a ***gravitationally bound system***, the DM particles with sufficient high energy will evaporate and leave the core.

- The energy of particles in the distribution function cannot extend indefinitely, a ***radially dependent cutoff energy*** $\epsilon_c(r)$ is required to describe the equation of state of the gaseous sphere.

- This cutoff energy $\epsilon_c(r)$ is thus correlated with the ***gravitational potential***.

- This type of model has been applied to ***globular clusters***.

Michie, MNRAS, **125**, 127; **126**, 331 (1963)
King, AJ, **67**, 471 (1962); **70**, 376 (1965); **71**, 64 (1966)
Ruffini & Stella, A&A, **119**, 35 (1983)
Merafina & Ruffini, A&A, **221**, 4 (1989); **227**, 415 (1990)
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Dynamical Instability

Truncated MB - Distribution with Cutoff $w = \beta\epsilon_c$

- For a general quantum phase-space distribution function

$$f_\eta(\epsilon \le \epsilon_c) = \frac{1 - e^{\beta\epsilon - w}}{e^{\beta\epsilon - \alpha} - \eta}, \quad f_\eta(\epsilon > \epsilon_c) = 0, \qquad \begin{array}{lcl} \alpha & = & \beta\mu \\ \beta & = & 1/k_B T \end{array}$$

(μ: chemical potential)
(T: temperature)

$\epsilon = \sqrt{p^2c^2 + m^2c^4} - mc^2$ (kinetic energy of a particle)

$\eta = \pm 1$ (+1 for bosons ; 1 for fermions; 0 for classical particles)

- In classical limit $e^{\beta\epsilon} \gg e^{\alpha}$ (or $\epsilon - \mu \gg k_B T$), it tends to the truncated MB distribution $\quad f_0(\epsilon \le \epsilon_c) = e^{\alpha}(e^{-\beta\epsilon} - e^{-w}), \quad f(\epsilon > \epsilon_c) = 0.$

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Dynamical Instability

Adiabatic Index (NG)

- A Newtonian star is balanced by pressure-buoyancy & counterbalancing gravity

$$\langle f_p \rangle = \langle p \rangle / R \text{ (up to some unimportant const factor)} = \langle f_g \rangle = \langle \rho \rangle \mathcal{M}/R^2 = \frac{4\pi}{3} \langle \rho \rangle^2 R.$$

- By ***linear perturbation*** of a Newtonian star of radius R, we have

$$\delta \ddot{R} = -3 \left(\langle \gamma \rangle - \frac{4}{3} \right) \left(\frac{4\pi}{3} \right) \langle \rho \rangle \delta R = -\omega^2 \delta R.$$

MTW, "Gravitation" (2017)

- The dynamical instability in Newtonian gravity requires the (pressure-averaged) adiabatic index of the core $\langle \gamma \rangle \leq \gamma_{cr.} = 4/3$, whereas $4/3 \leq \gamma \leq 5/3$ for an ideal gas.

- For ***ideal gas***, it could ***hardly*** occur in the ***Newtonian scenario***!

Dynamical Instability

Adiabatic Index (GR)

- By linear perturbation of a perfect fluid in Schwarzschild spacetime

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = -e^{2\Phi(r)}dt^2 + e^{2\Lambda(r)}dr^2 + r^2(d\theta^2 + \sin^2\theta\ d\phi^2).$$

- In GR, the ***pressure*** plays a role in ***gravitational energy*** such that

$$\gamma_{\rm cr} \equiv \frac{4}{3} + \frac{1}{36}\frac{\int_0^R e^{3\Phi+\Lambda}[16p + (e^{2\Lambda}-1)(\rho+p)](e^{2\Lambda}-1)r^2 dr}{\int_0^R e^{3\Phi+\Lambda} p r^2 dr} + \frac{4\pi}{9}\frac{\int_0^R e^{3(\Phi+\Lambda)}[8p + (e^{2\Lambda}+1)(\rho+p)]pr^4 dr}{\int_0^R e^{3\Phi+\Lambda} p r^2 dr} + \frac{16\pi^2}{9}\frac{\int_0^R e^{3\Phi+5\Lambda}(\rho+p)p^2 r^6 dr}{\int_0^R e^{3\Phi+\Lambda} p r^2 dr} > \frac{4}{3}$$

and

$$\langle\gamma\rangle \equiv \frac{\int_0^R e^{3\Phi+\Lambda}\gamma p r^2 dr}{\int_0^R e^{3\Phi+\Lambda} p r^2 dr} \quad \rightarrow \langle\gamma\rangle < \gamma_{cr.}$$ ***is possible !***

Chandrasekhar, ApJ, **140**, 417 (1964)
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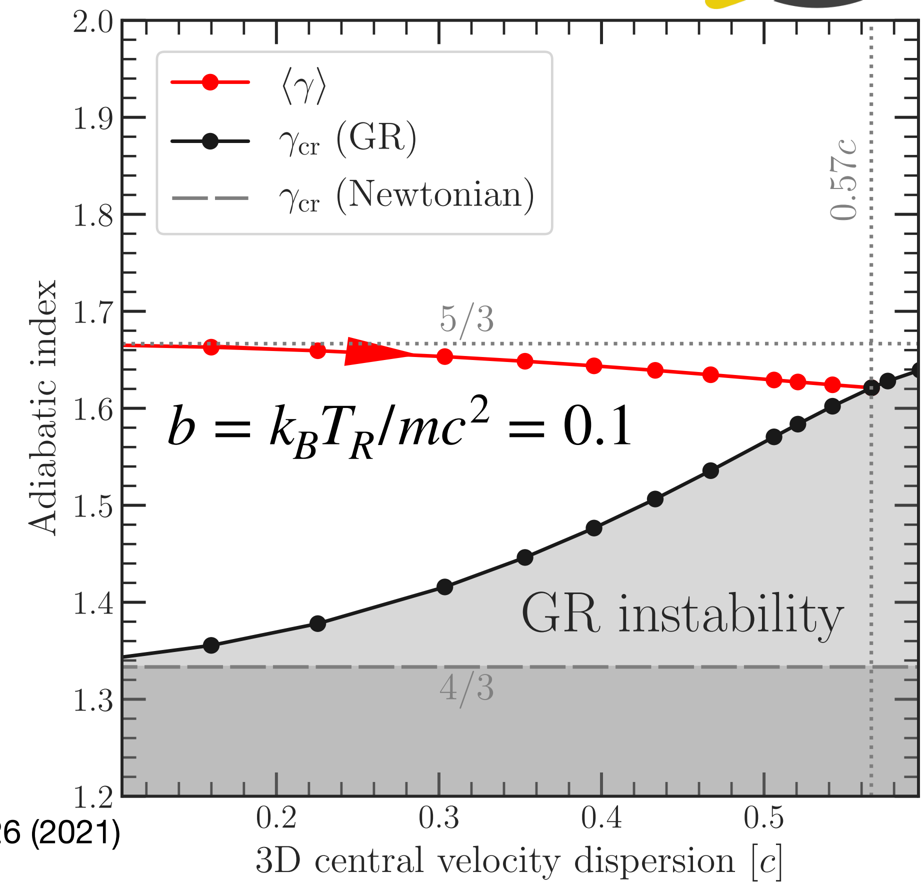
Dynamical Instability

Adiabatic Index (truncated MB in GR)

- When the pressure starts to dominate the energy density, $p \sim 0.1\rho c^2$, it tends to destabilize the core and the dynamical instability can be triggered.
- This occurs well before the gas becomes ultra-relativistic, $\langle\gamma\rangle \to 4/3$
- When $b \gtrsim 0.1$, if central velocity dispersion of the gas system reaches $(0.56 - 0.57)c$, the core becomes dynamically unstable and evolves adiabatically to a BH.



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Angular Momentum Loss

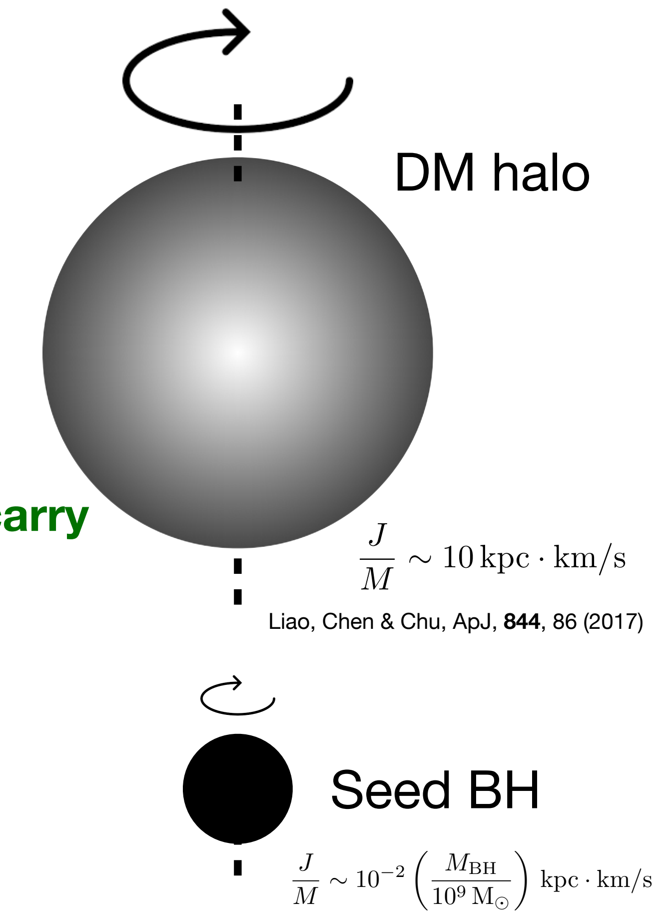
Angular Momentum of the Inner Core

- To reach the direct collapse into a BH, the angular momentum of the inner core must satisfy

$$J < (G/c)M^2$$

maximal angular momentum a BH can carry

- For a typical halo, the specific angular momentum of the halo central region is $10^2 - 10^5$ times larger than the max value of the corresponding BH



Angular Momentum Loss

Angular Momentum Dissipations through LMFP Viscosity

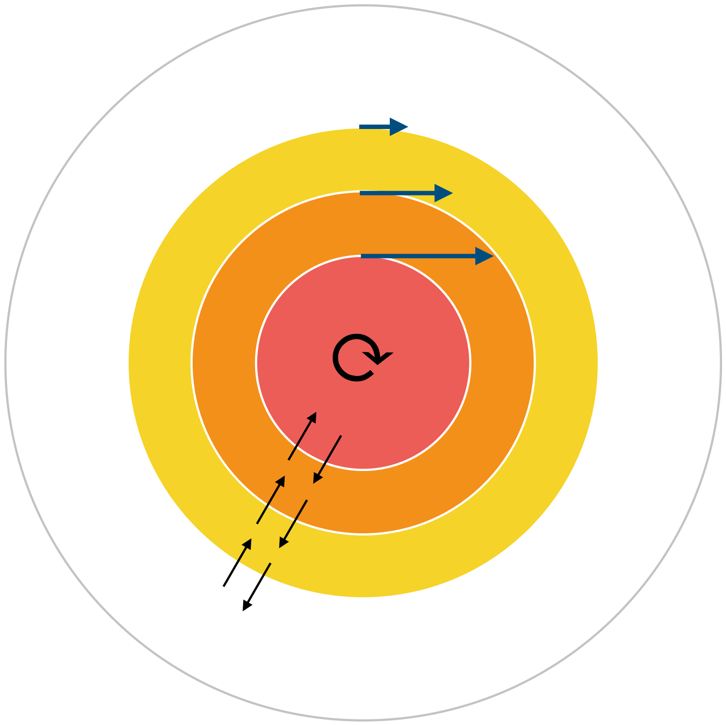
- DM self-interactions introduce viscosity between the halo shells,

$$\eta \sim \frac{m}{k_B}\kappa$$

- The bulk angular momentum can be transported out through the shear pressure due to viscosity

- The central region becomes non-rotational soon after the gravothermal evolution starts

$$t_{\mathrm{dis}} \sim \mathcal{O}(1\%)t_c$$



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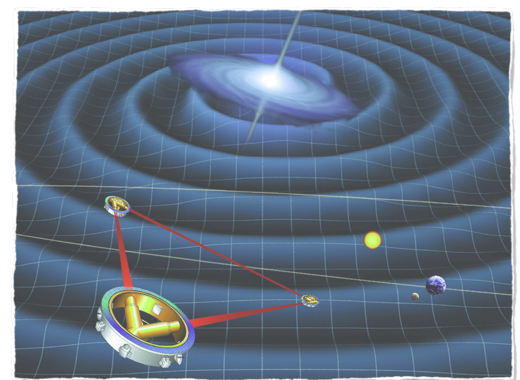
Summary & Future Plans



NASA

Summary

- The origins of SMBHs & the nature of DM are two important problems in physics.

- ***Gravothermal evolution*** of SIDM dark halos ($\sigma/m \sim \mathcal{O}(1)$ cm²/g) usually takes $\gtrsim 10$ Gyr to reach a ***singular state (gravothermal catastrophe)***.

- ***Baryonic potential*** can reduce the collapse time by a factor of $10 \sim 10^3$.

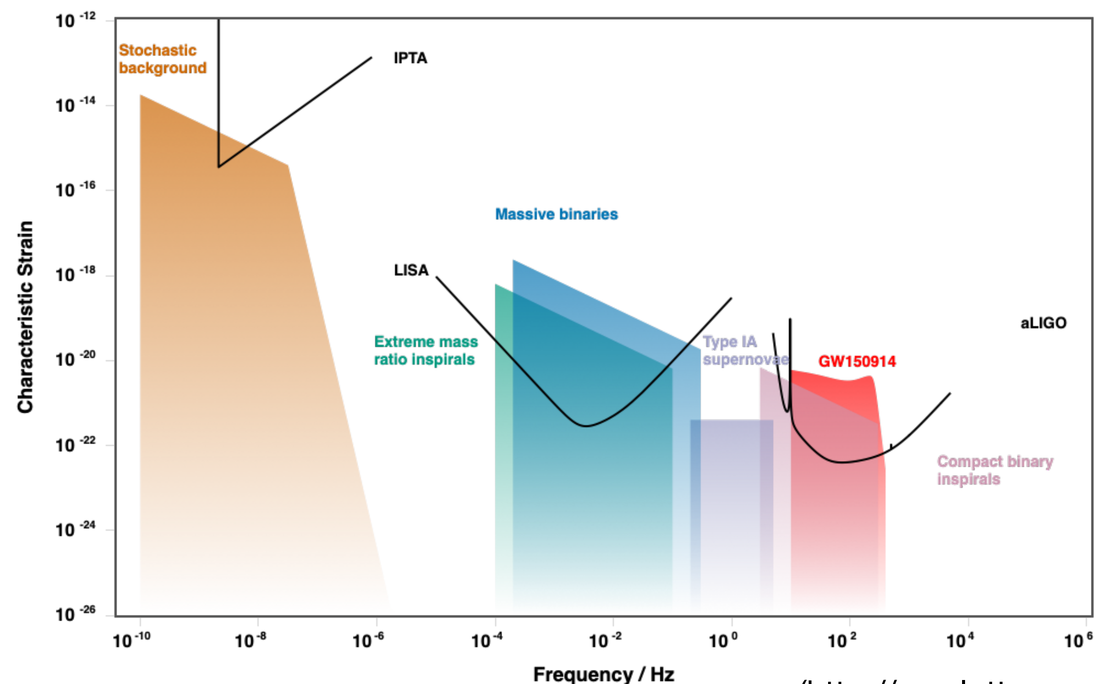
- ***Direct collapse*** of SIDM core halos of $10^4 - 10^9 M_\odot$ by redshift $z = 7$ is possible !

- The ***sufficient condition*** for the inner core to collapse into a BH is $v(0) = (0.56 - 0.57)c$.

- The ***angular momentum*** of SIDM halos can be transported out within the collapse time.

Future Plans

- ***Low frequency*** ($10^{-4} - 1$***Hz***) GWs of SMBH binary mergers back to $z \simeq 15$ is detectable from ***Laser Interferometer Space Antenna (LISA)***.
- How does the ***quantum statistics*** ($\alpha > 0$) change the instabilities ?
- How do the ***DM pair production & annihilation*** ($b \gtrsim 1$) affect the instabilities ?
- ***Co-evolution*** of galaxies & SMBHs in this scenario is worth examining from ***James Webb Space Telescope (JWST)***



(http://gwplotter.com)

Article | Published: 22 February 2023

A population of red candidate massive galaxies ~600 Myr after the Big Bang

Ivo Labbé, Pieter van Dokkum, Erica Nelson, Rachel Bezanson, Katherine A. Suess, Joel Leja, Gabriel Brammer, Katherine Whitaker, Elijah Mathews, Mauro Stefanon & Bingjie Wang

Nature (2023) | Cite this article

Massive galaxies exist in the early Universe at z~8!

Abstract

Galaxies with stellar masses as high as ~ 10^{11} solar masses have been identified[1–3] out to redshifts z ~ 6, approximately one billion years after the Big Bang. It has been difficult to find massive galaxies at even earlier times, as the Balmer break region, which is needed for accurate mass estimates, is redshifted to wavelengths beyond 2.5 μm. Here we make use of the 1-5 μm coverage of the *JWST* early release observations to search for intrinsically red galaxies in the first ≈ 750 million years of cosmic history. In the survey area, we find six candidate massive galaxies (stellar mass > 10^{10} solar masses) at $7.4 \le z \le 9.1$, 500–700 Myr after the Big Bang, including one galaxy with a possible stellar mass of ~10^{11} solar masses. If verified with spectroscopy, the stellar mass density in massive galaxies would be much higher than anticipated from previous studies based on rest-frame ultraviolet-selected samples.

The expected halo mass ~10^{11}-10^{12} $M_\odot$ at z~8

Thanks for your attention!

see, e.g., Boylan-Kolchin (2022); Nadler, Benson, Driskell, Du, Gluscevic (2022)