SPHerical Dynamics of Miniquasars and Dark Matter Minihalos

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In collaboration with: Finn Karstens, Aster Schnell, Prof. Dr. Laura Sagunski, and Dr. Sean Tulin

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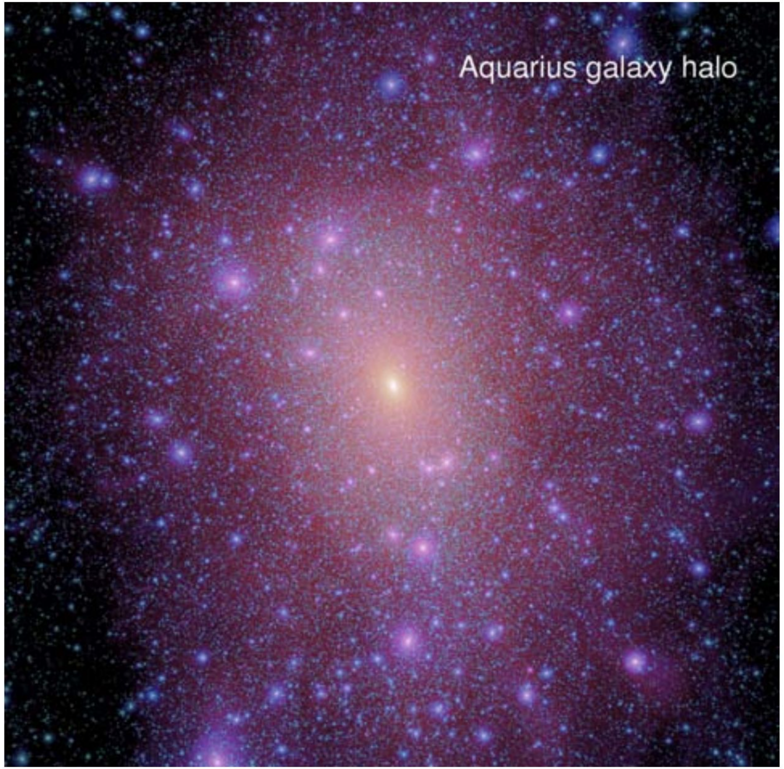


Image credit: Frenk & White, 2012

What are Minihalos and Miniquasars?

- **Minihalos** are small Dark Matter (DM) halos that are the birthplace for the first stars (Population III)
  - Mass 10^5 - 10^6 Msol
  - Predicted to exist but *no observational evidence*
- **Miniquasars** are Quasar-like objects on an incredibly small scale
  - Predicted to form on Intermediate Mass Black Holes (IMBH) with accreting gas
  - *Radiative feedback:* energy released impacts surroundings

Image credit: NASA, ESA and J. Olmsted (STScI)

S. Tulin & L. Sagunski (2023)

DM Halo on Galactic Scales

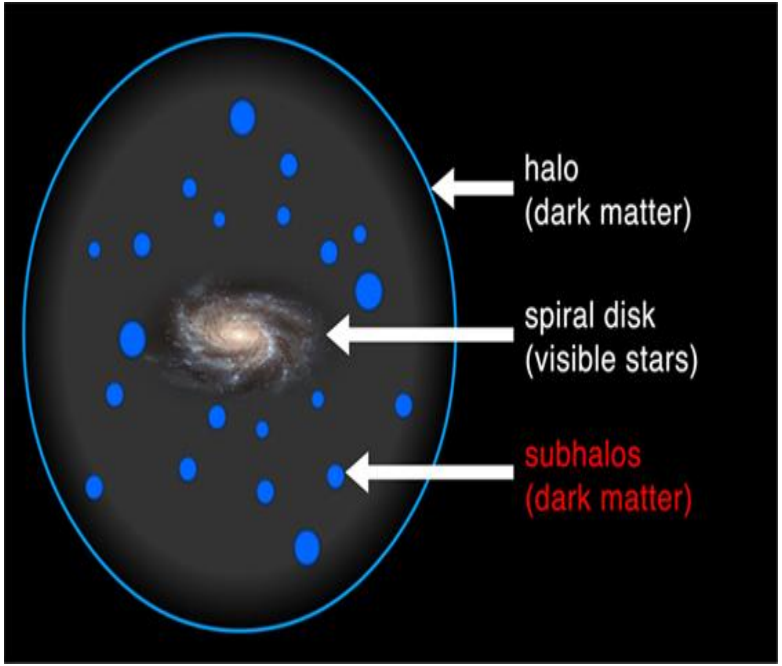


Image credit: Astrobites.org

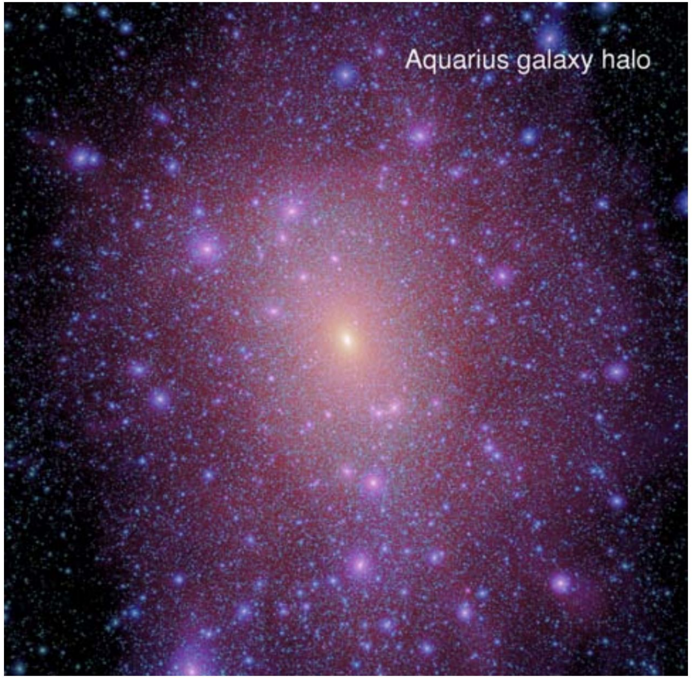


Image credit: Frenk & White, 2012

Our Models

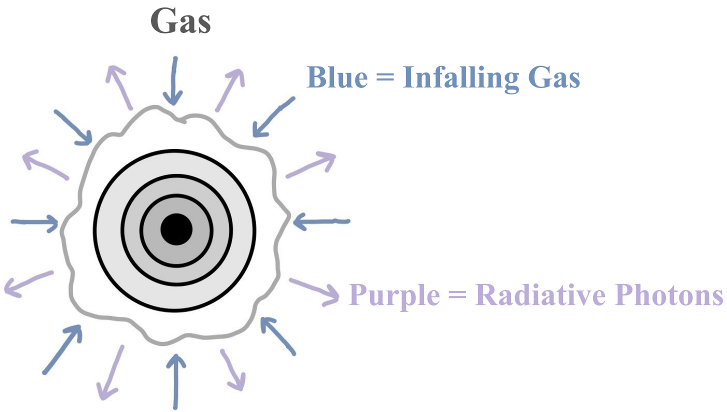
- ➔ **Self-Interacting Dark Matter (SIDM)**
  - ◆ Proposed to solve the *core-cusp problem*
  - ◆ Particles interact with each other through forces **other than gravity.**
  - ◆ Could be elastic (non dissipative) or inelastic (dissipative)

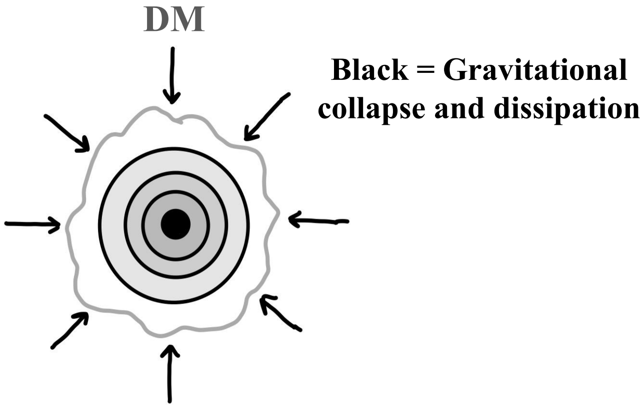
- ➔ **Role of SIDM in Minihalos**
  - ◆ Puzzled on how Supermassive Black Holes (SMBH) grow so fast
  - ◆ IMBH predicted to exist as intermediate step in growing SMBH
  - ◆ Our Idea: from collapsing DM, not gas

S. Tulin, H. Yu (2017)

Our Theoretical Model

- Simulating dynamics of DM halo with gas as a series of **concentric shells**
  - Includes spherical symmetry
- **SPHerical** Python Package was utilized
  - Includes DM interactions, gas interactions, and radiative feedback





Motivation + Main Goals

➔ Motivation

- Want to test how formation of Pop III stars reacts with different DM parameters
  - What happens if both gas and DM collapse at epoch?
- Suspect system won't form Pop III stars, instead will form IMBH

➔ Overall Goals

- Model dynamics of gas and DM at epoch of Pop III formation
- Cooling and heating rates via radiative heating
- Understand concepts of DM and its impact
- Connect with observations

Introduction to the Teams

- ➔ Research group from EXPLORE IV (January 2024 - April 2024)
- ➔ Split big research group into **two smaller groups**
- ➔ Work individually then come together and interface our results.

Minihalos and Miniquasars

Grackle Team

- ➔ Finn Karstens
- ➔ Aster Schnell
- ➔ Dr. Laura Sagunski

Quasar Team

- ➔ Lauren Morley
- ➔ Dr. Sean Tulin

The Grackle Team

- ➔ Grackle is an **open-sourced library** designed for simulating chemical and thermal processes.
- ➔ Main goals
  1. Improve on the current SPHerical *cooling rate* using Grackle
  2. Determine new *radiative heating* rate

- ➔ Luminosity is the main connecting factor between the two teams

```
my_chemistry = chemistry_data()
my_chemistry.use_grackle = 1
my_chemistry.primordial_chemistry = 1
```

The Quasar Team

- ➔ Main Goals
  1. Calculate *Accretion Luminosity* and *Radiation Pressure*.
  2. Calculate the Luminosity at *different shell positions*.
  3. Confirm *BH formation* in simulation
  4. Run *high-end simulations* on Canadian Supercomputer.
- ➔ EXPLORE project: previously completed Goal 1
- ➔ GREP project: aim to complete Goals 2-4

Theoretical Formula and Result - Luminosity

Dissipation ⟶ Shell Collapse ⟶ BH Formation

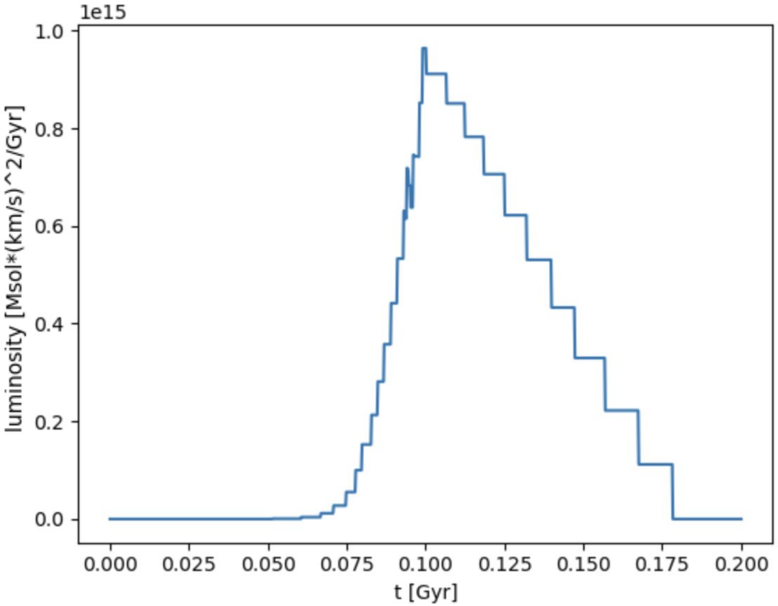
➔ Accretion luminosity

$$L_{BH}(t) = \epsilon \dot{M}_{BH}(t) c^2$$

➔ Need to convert *discrete shell collapse* into *continuous* luminosity

➔ ϵ = radiative efficiency

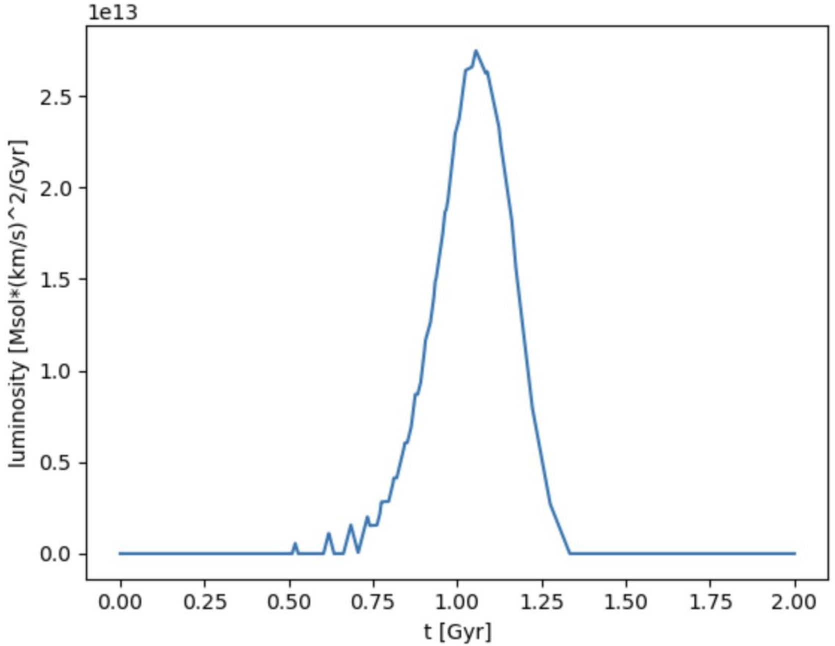
➔ c = speed of light



L. Ciotti, J.P. Ostriker (2007)

Adding in DM interactions + Updating functions

- ➔ DM interactions can be added in preparation of full simulations
- ➔ Improvement of the Luminosity function.
  - ◆ Allows for improved numerical performance when the luminosity is continuous

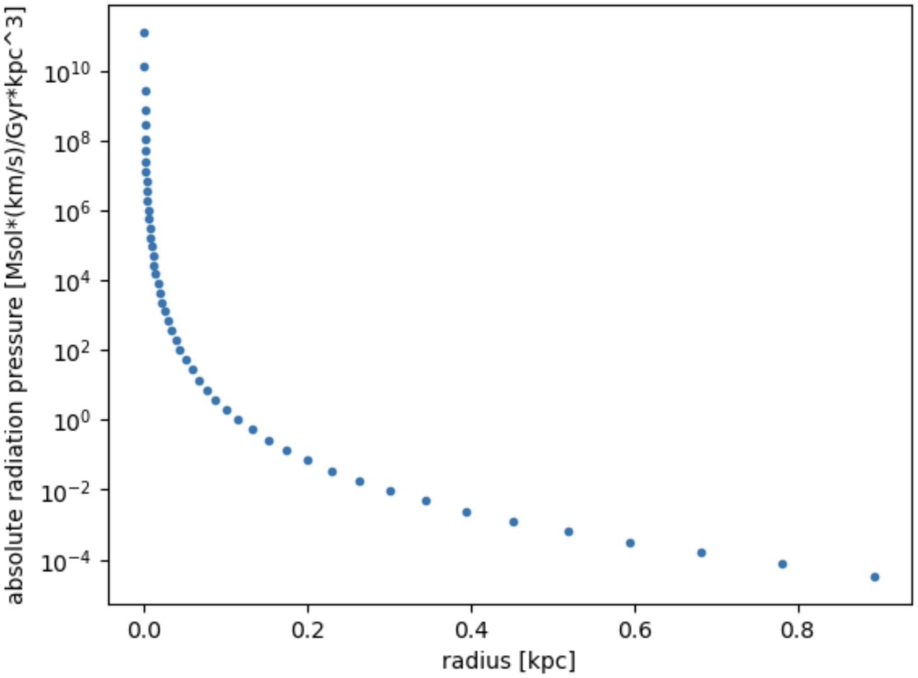


Theoretical Formula and Result - Radiation Pressure Acceleration

➔ Radiation pressure comes from ionization opacity.

$$\frac{(\nabla p_{rad})_{photo}}{\rho} = -\frac{\kappa_{photo}}{c}\frac{L^{eff}_{BH,photo}(r)}{4\pi r^2}$$

➔ $\boldsymbol{\kappa} = \sigma_{thomson} / m_p$

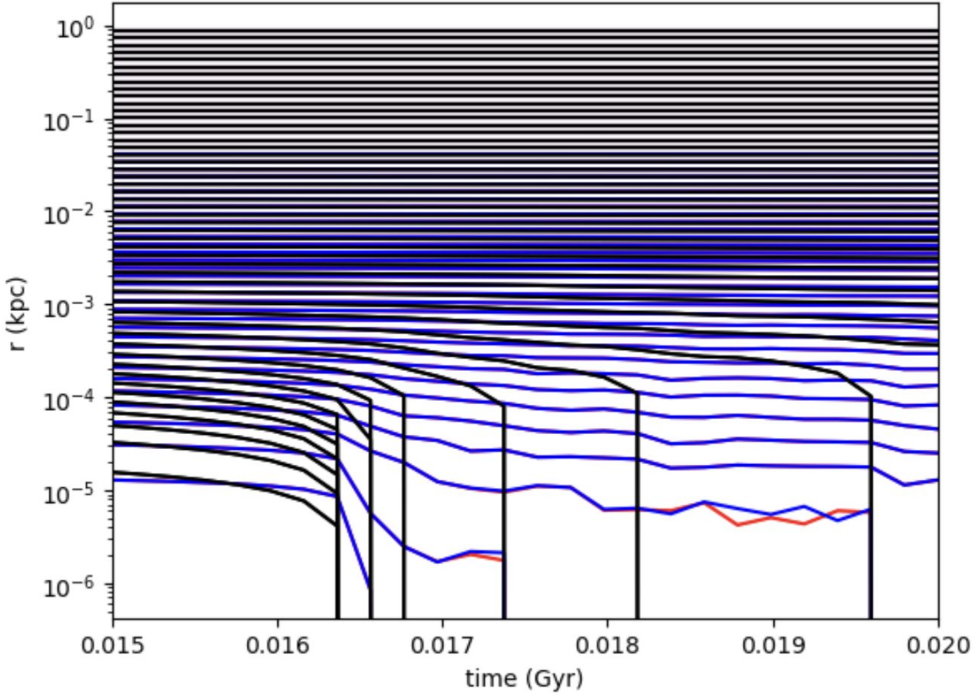


L. Ciotti, J.P. Ostriker (2007)

Confirmation that Radiation Pressure Acceleration works

- ➔ Black = DM shells
- ➔ Blue = gas shells **with** radiation pressure
- ➔ Red = gas shells **without** radiation pressure

- ➔ Luminosity and Radiation Pressure are working!



Luminosity at different shell positions

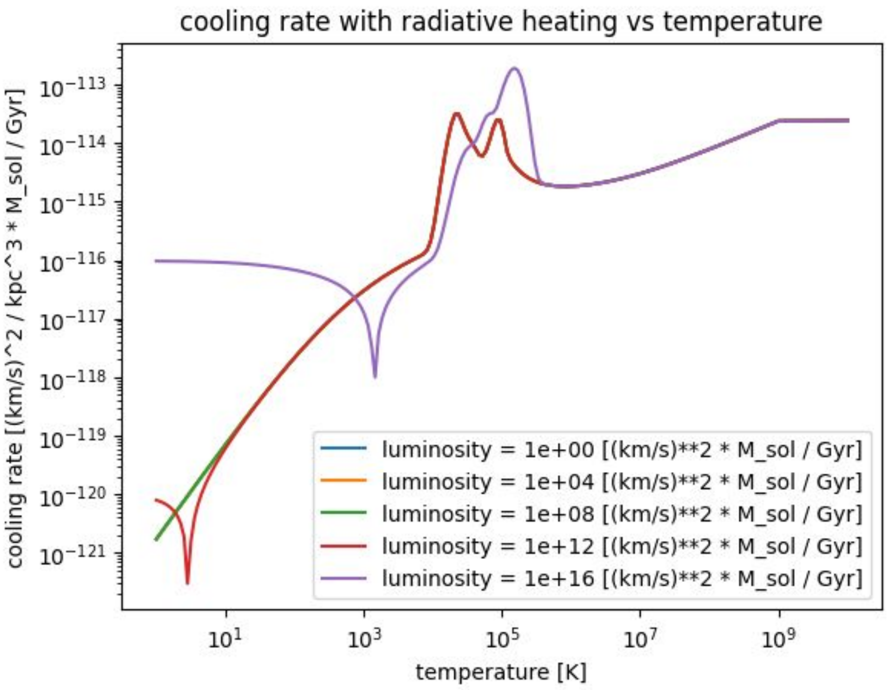
- ➔ Luminosity can be considered and its effects on radiative heating and cooling
- ➔ Calculate luminosity at each shell position using formula below
  - ◆ $H \propto L^{eff}_{BH,photo}(r)$

$$\frac{L^{eff}_{BH,photo}(r)}{dr} = -4\pi r^2 H \longleftarrow H \propto 10^{-24} n \epsilon G_0 \, ergs \; cm^{-3} \; s^{-1}$$

- ➔ Boundary condition where when r = 0, $L^{eff}_{BH,photo}(r) = L_{BH}$

L. Ciotti, J.P. Ostriker (2007); M. Wolfire et al (1994)

Grackle Team Results and Summary

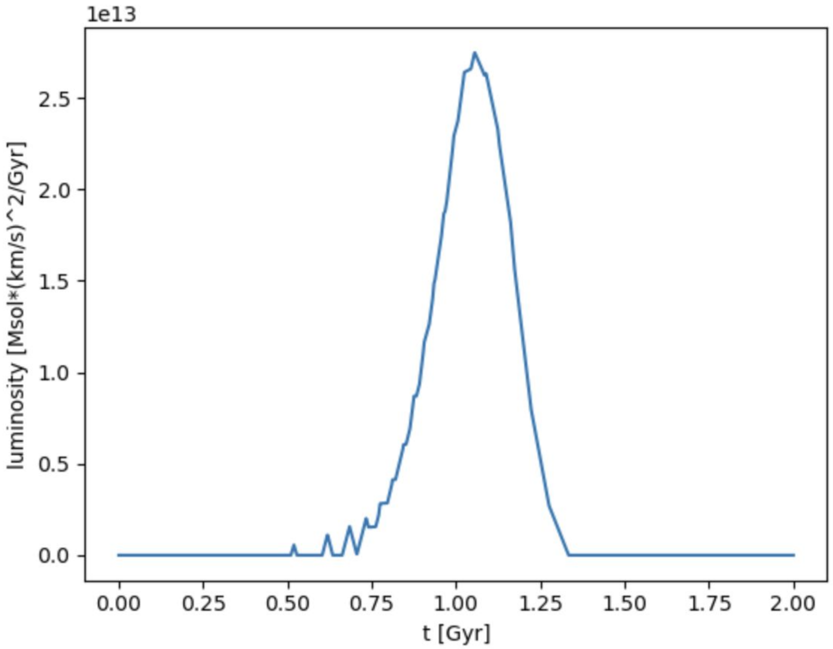


- ➔ Cooling rates used to determine shell energy lost due to radiative processes
- ➔ Depends on gas density, temperature or energy, and any heating

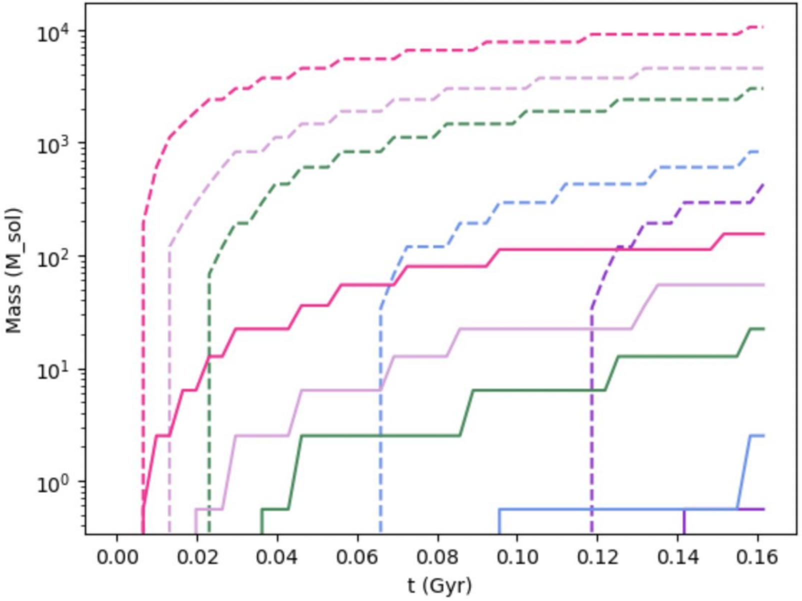
- ➔ Constant at low luminosity
- ➔ As luminosity increases, cooling rate increases at lower temperatures

Summary

- ➔ Revisiting Goals 1 & 2:
  1. Calculate **Accretion Luminosity** and **Radiation Pressure**.
  2. Calculate the Luminosity at **different shell positions**.
- ➔ Luminosity and Radiation Pressure were **successfully calculated** and implemented into the SPHerical code.
- ➔ Luminosity at different shell positions was successfully calculated and implemented into Grackle Code



Summary



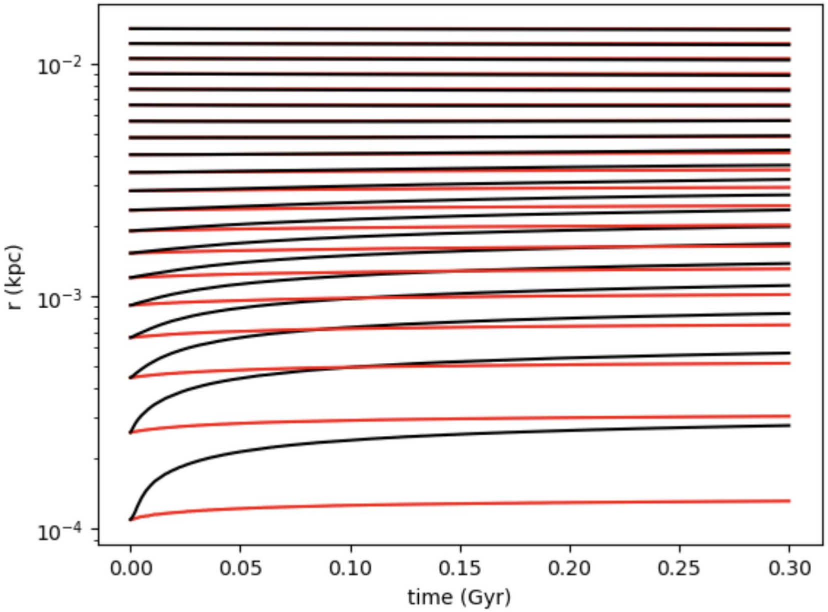
➔ Revisiting Goals 3 & 4:

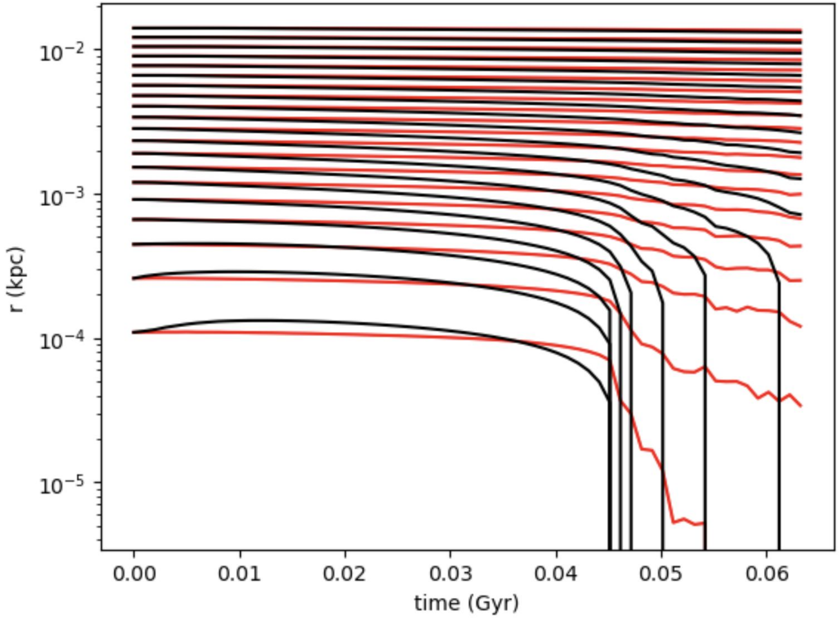
3. Confirm **BH formation** in simulation
4. Run **high-end simulations** on Canadian Supercomputer.

➔ BH formation was confirmed

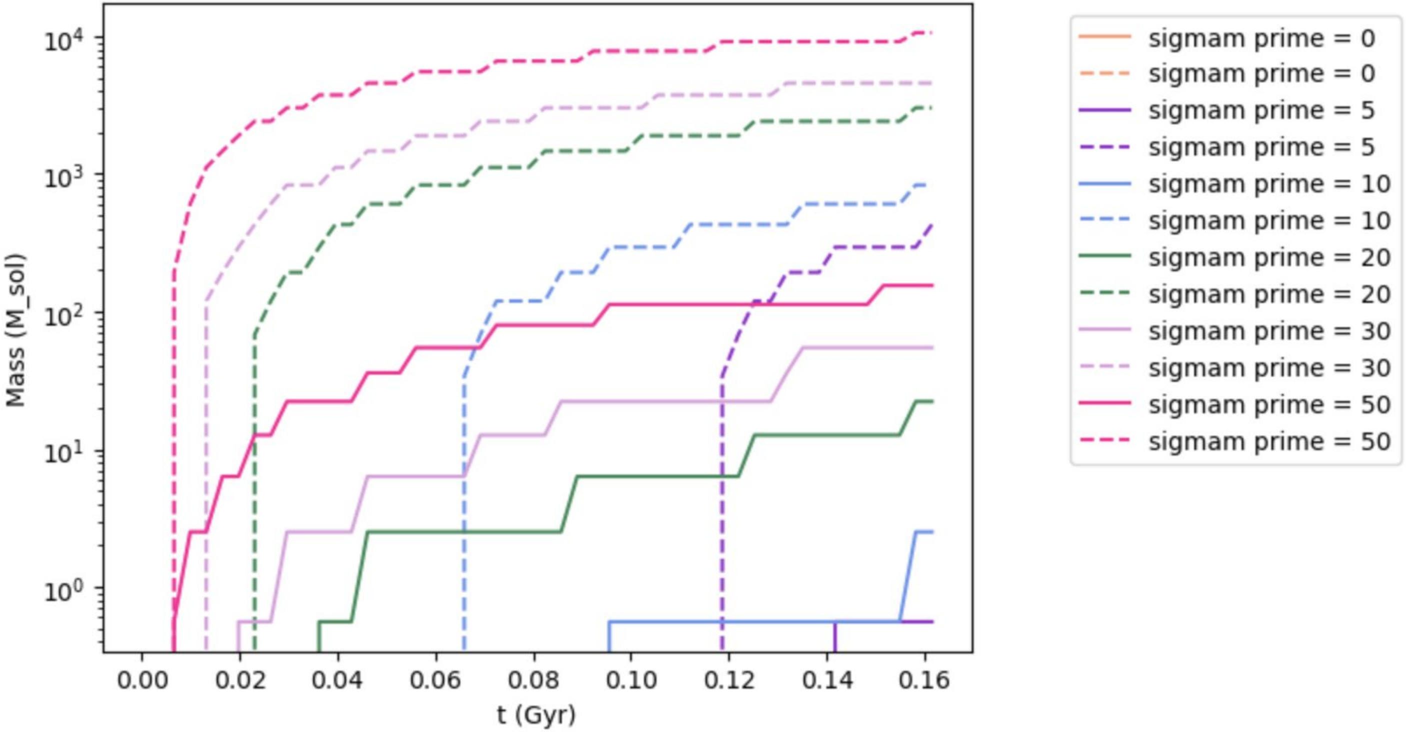
➔ Simulations were ran with varying parameters on Canadian Supercomputer

Results - Radius vs Time

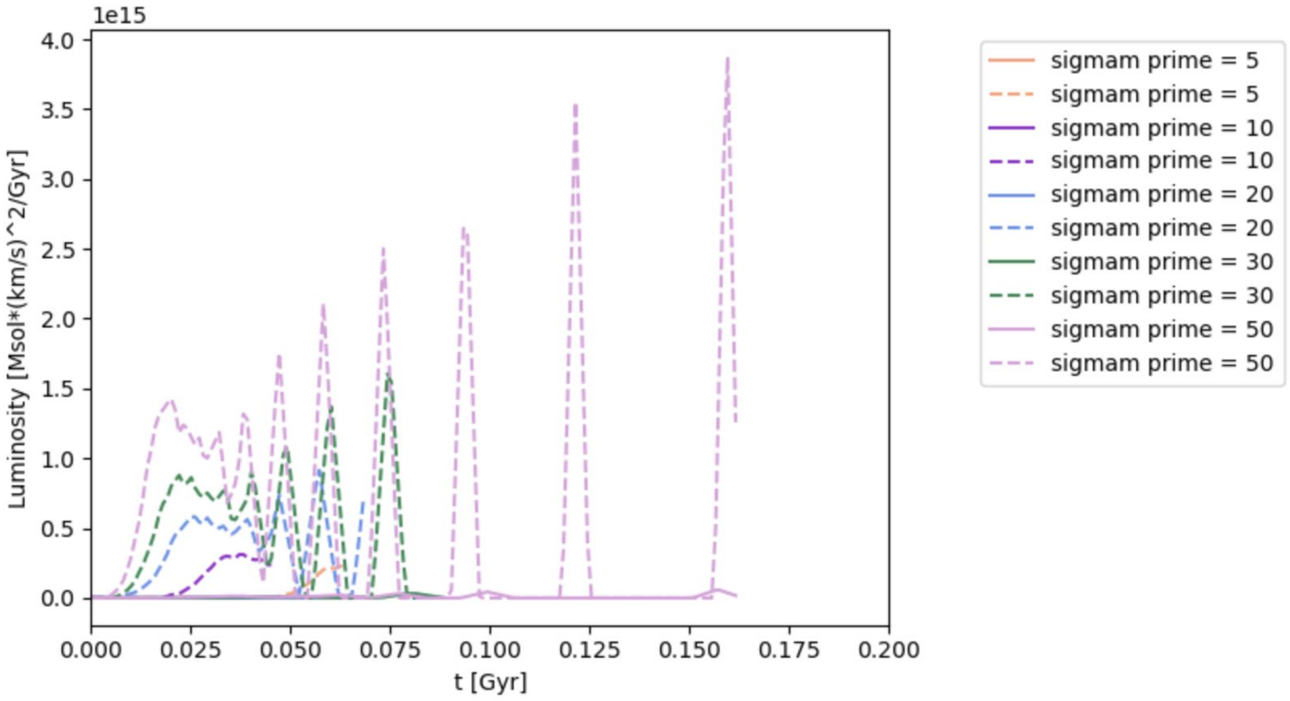




Results - Collapsed Mass Vs Time



Results - Luminosity Vs Time



Next Steps

- Improve on current simulation results
  - Run for longer and collapse more shells
  - Smooth out Luminosity function
- Combine results together and run full simulation on Canadian Supercomputer
  - Vary DM parameters
- Analyze plots and see effect of DM on evolution
- Compare with Observations