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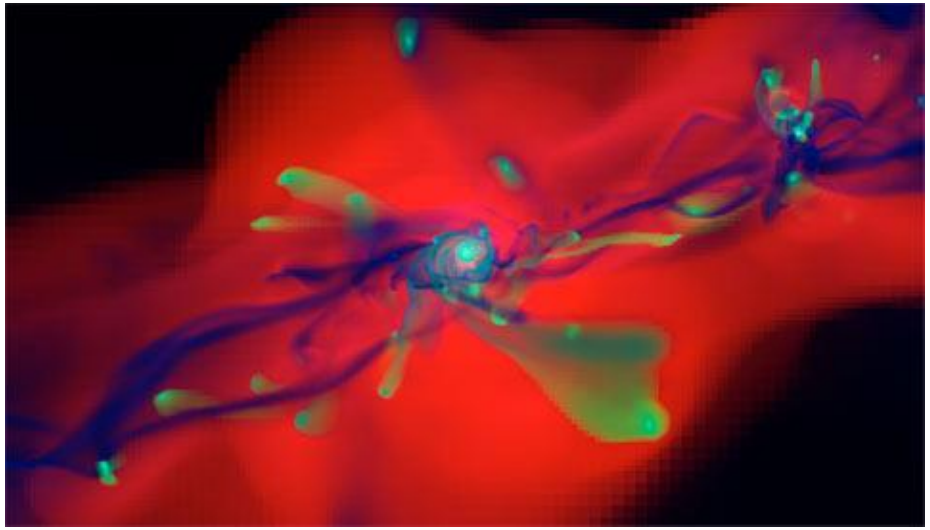
NCTS-TCA Summer Student Program



# *Circum-galactic Gas Dynamics and Fueling of Primordial Galaxies: The Impact of Cosmic Rays*

Steven Hsueh

Instructor: Ellis R Owen

# *Motivations*

- Investigating High-Energy Emission from Star-forming Galaxy
- Quenching Events in the Galaxy
- Primordial Galaxies Star Formation
- Goal: Investigating how cosmic rays can modify the supply of gas and star formation rate of primordial galaxy

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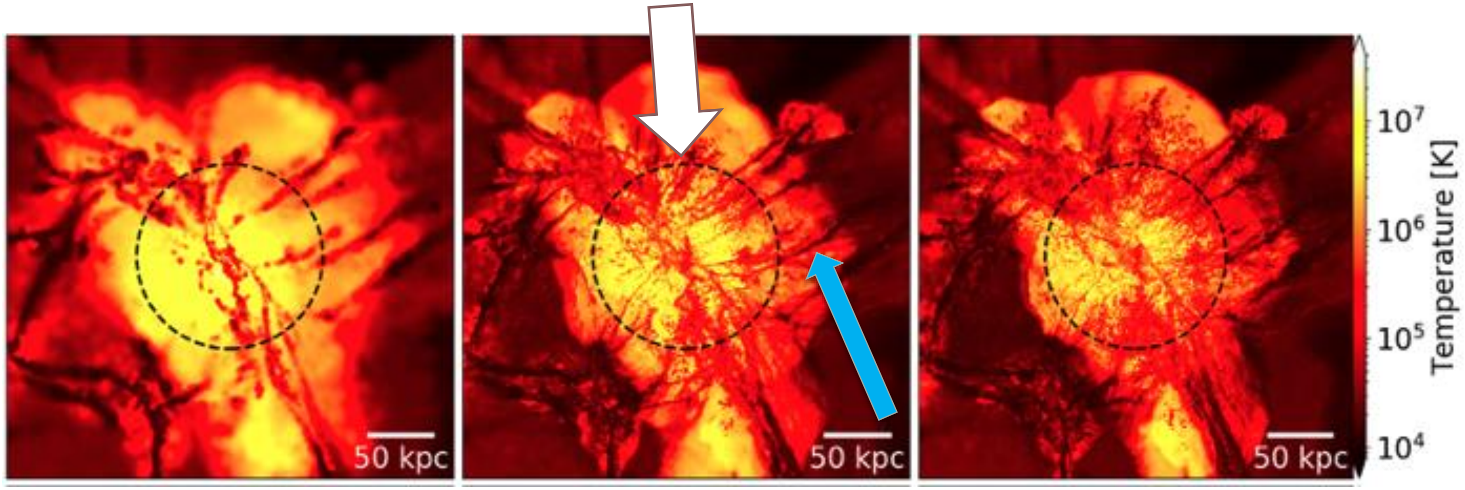
# *Backgrounds*

- What are cosmic rays?
- Star forming galaxy's link to cosmic rays
- Impact of Cosmic Rays




https://arxiv.org/pdf/2006.10058.pdf

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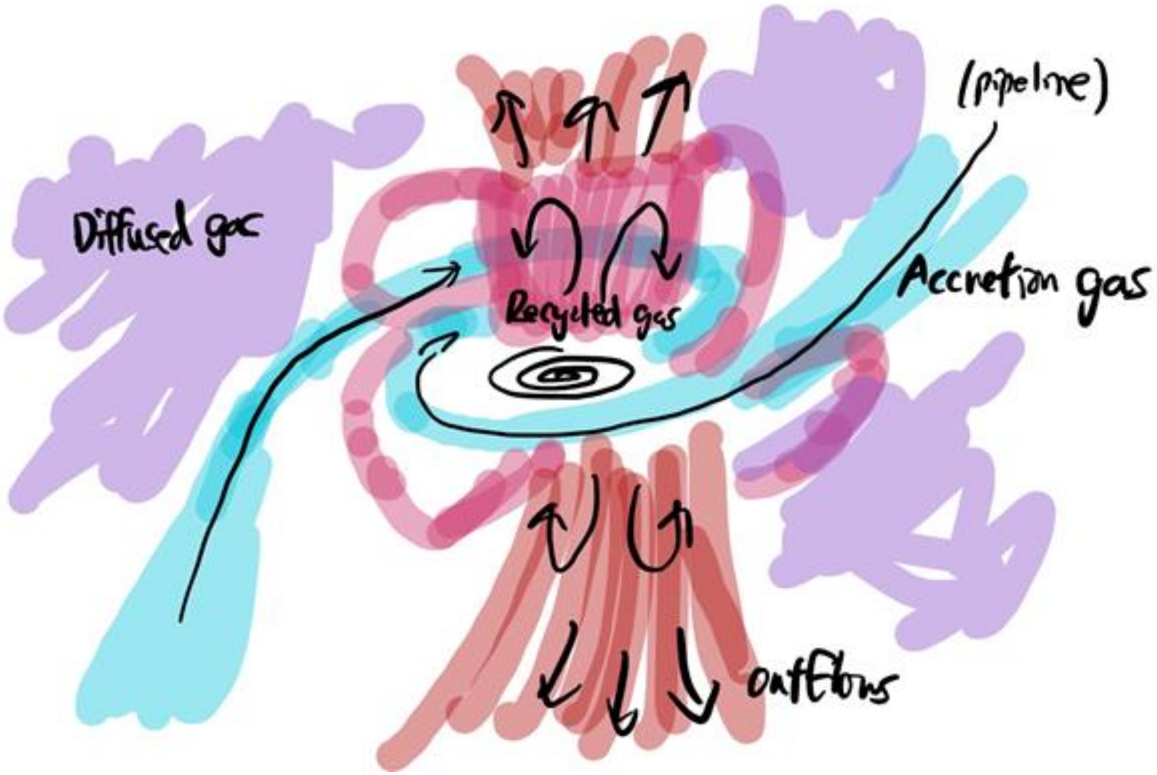
# *Outline*

- Methods
- Results
  - Different galaxy mass
  - Different CR pressure wrt thermal gas
- Further discussions

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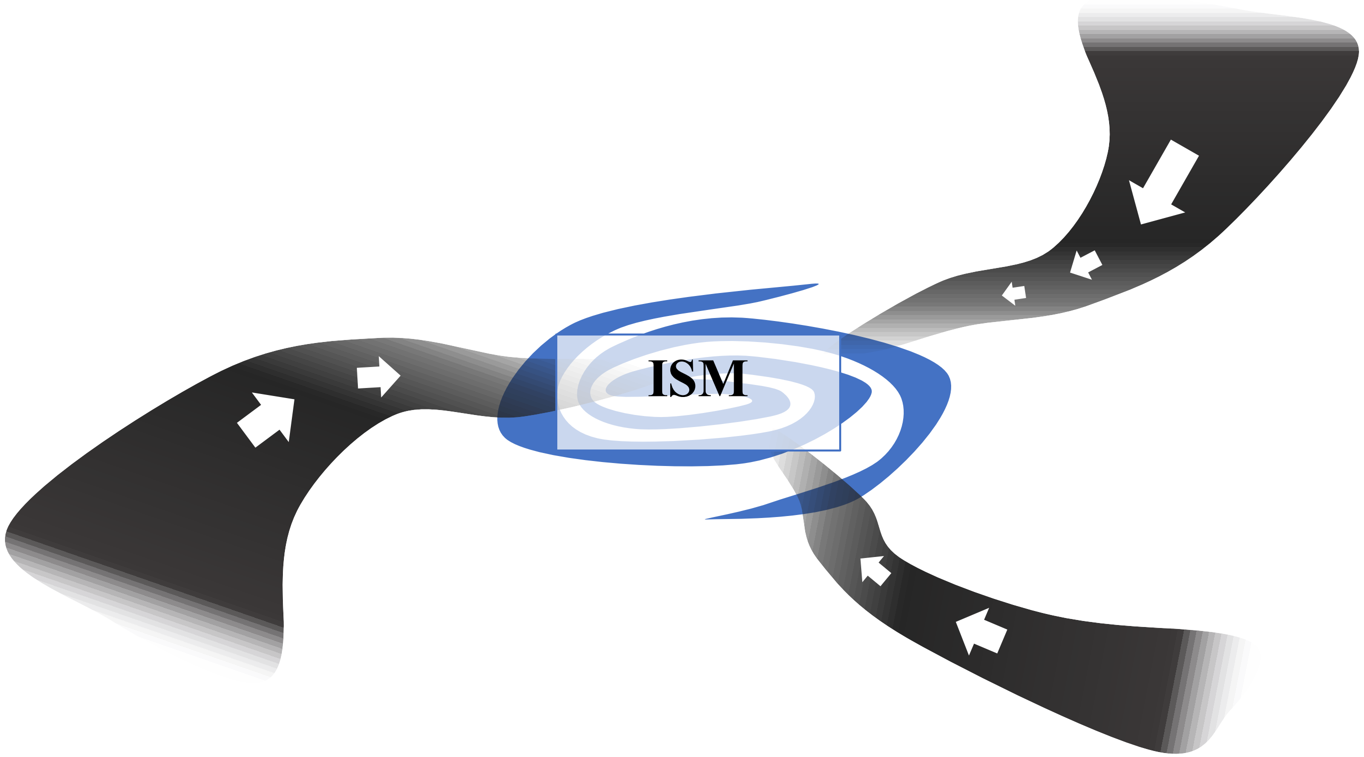
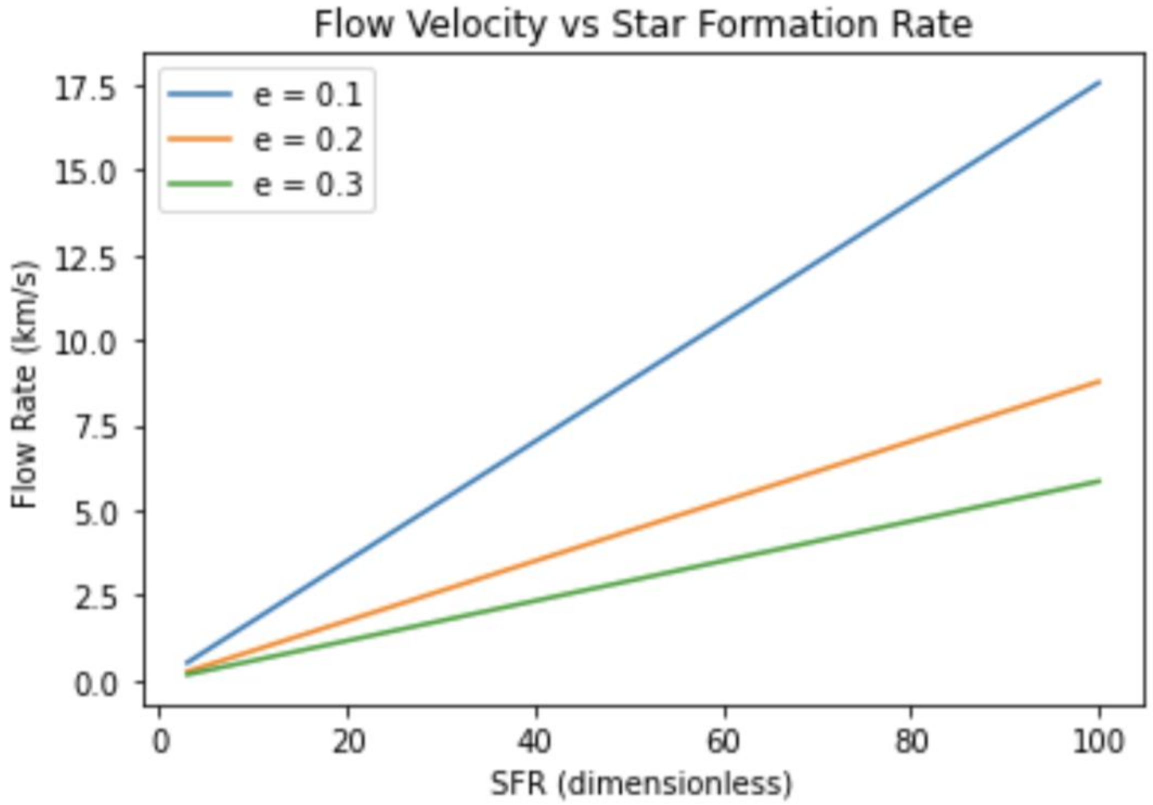
# *Filamentary Inflow*




Owen, Ellis. (2019). Hadronic Processes of Energetic Particles in Star-Forming Galaxies and High-Redshift Protogalactic Environments.

# Filamentary Inflow

$$v(\epsilon_{SF}) = (\frac{1}{N_F \epsilon_{SF}}) * (\frac{M_F}{\rho_F A_F t_{dyn}}) = (\frac{1}{N_F \epsilon_{SF}}) * (\frac{R_{SF}}{\rho_F A_F})$$

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# *Inflow With CRs*

$$\frac{1}{r^2}\frac{d}{dr}(r^2\rho v) = 0$$

Mass Continuity

$$\rho v\frac{dv}{dr} = -\frac{dP}{dr} - \frac{dP_C}{dr} - \rho\frac{GM}{r^2}$$

Momentum(General)

$$\frac{1}{r^2}\frac{d}{dr}[\rho(v + v_A)r^2\frac{\gamma_C}{\gamma_C - 1}\frac{P_C}{\rho}] = -I$$

Cosmic Ray Energy Equation

$$\frac{1}{r^2}\frac{d}{dr}[\rho v r^2(\frac{v^2}{2} + \frac{\gamma_g}{\gamma_g - 1}\frac{P}{\rho})] = -\rho v\frac{GM}{r^2} + I$$

Thermal Gas Energy Equation

$$I = -(v + v_A)\frac{dP_C}{dr}$$

Energy Transfer Rate Equation

$$v_A = \tilde{v_A} = \frac{r_s^2\sqrt{< B^2 >}}{r^2\sqrt{4\pi\rho}}$$

Alfven Velocity

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# *Inflow With CRs*

- Studying inflow solution in two different cases:
  - Cosmic ray to thermal gas pressure ratio as 1, varying galaxy mass
  - Galaxy mass fixed at 10E11 $M_{\odot}$, varying CR pressure value

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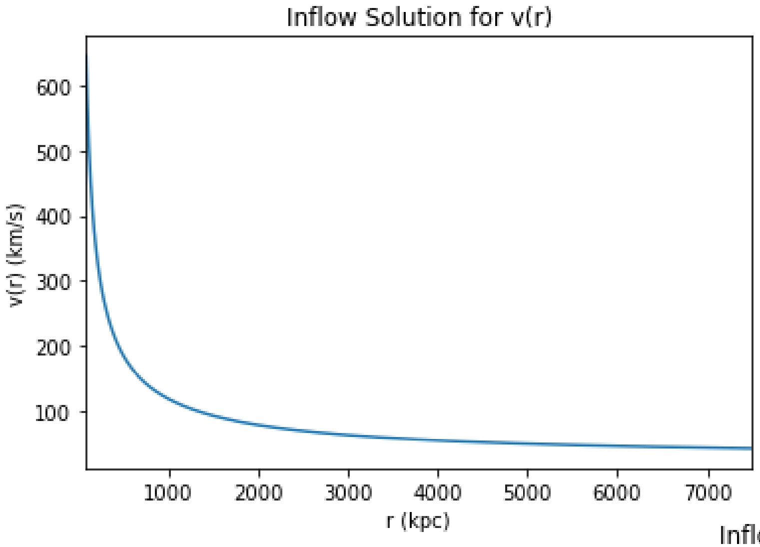
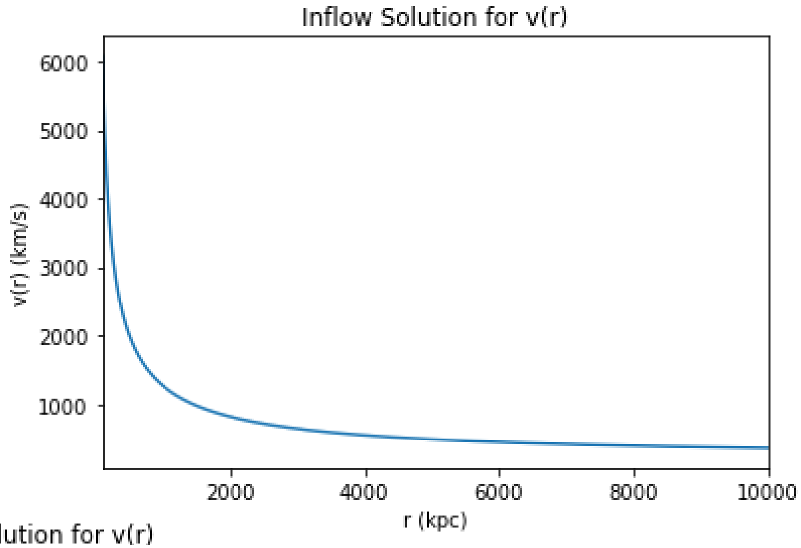
# *Case 1: Cosmic Ray to Thermal Gas Pressure Ratio as 1, Varying Galaxy Mass*

# *Pressure Ratio = 1, Varying Galaxy Mass*

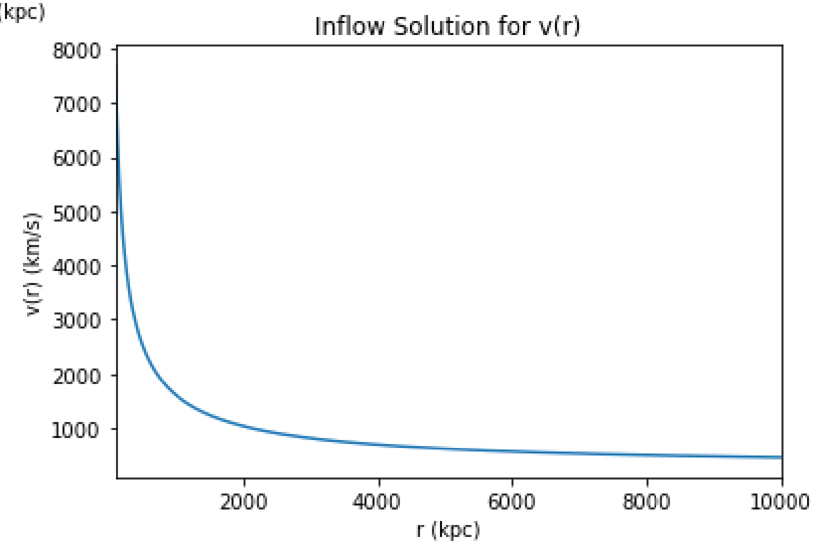
Dwarf: 10E9 $M_\odot$




Normal: 10E11 $M_\odot$

Massive: 10E12 $M_\odot$

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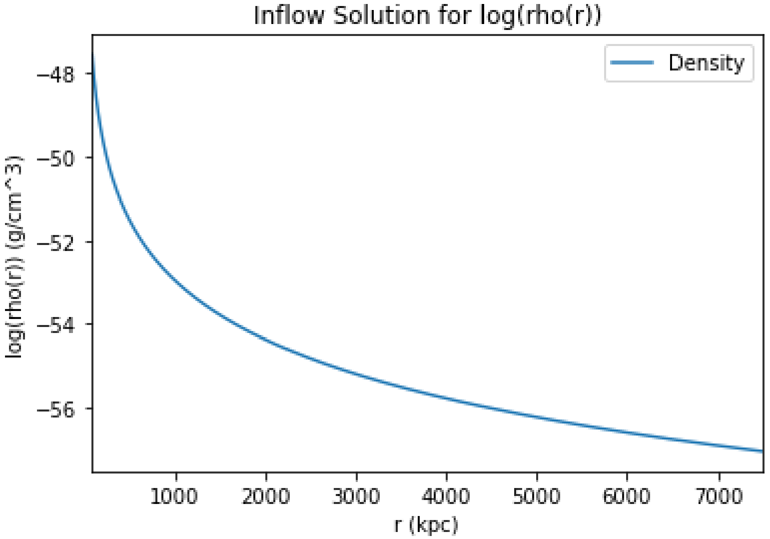
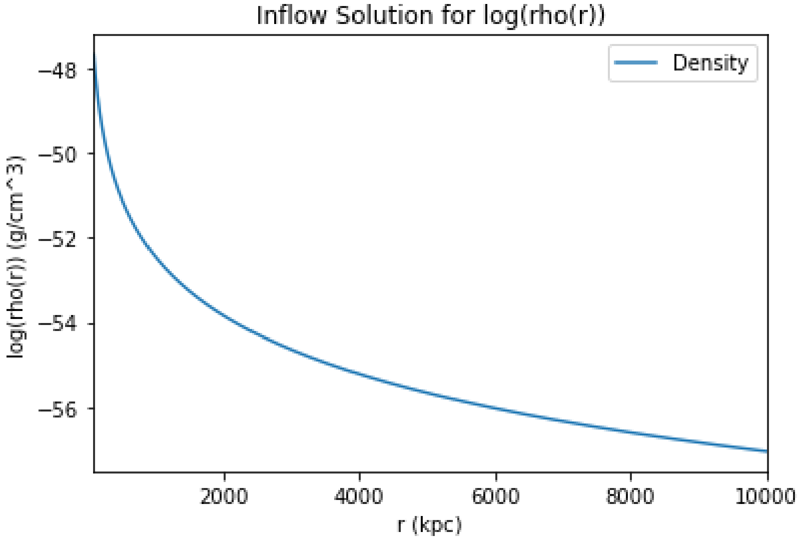
# *Pressure Ratio = 1, Varying Galaxy Mass*

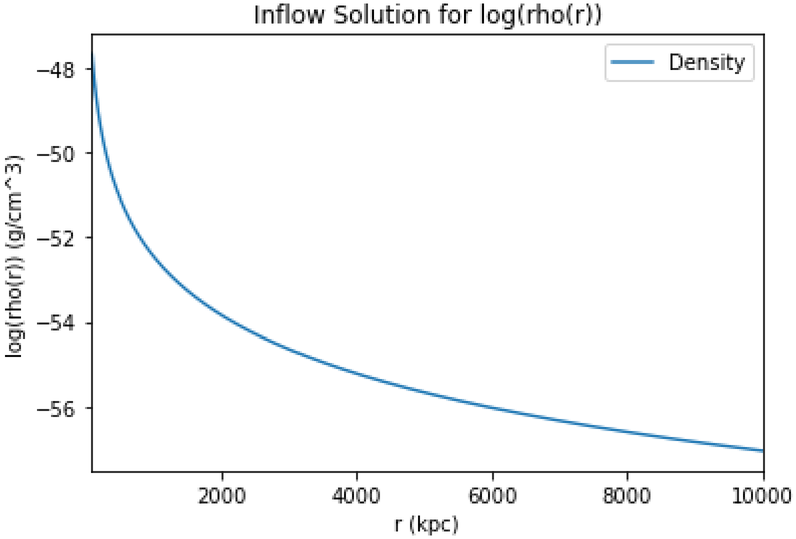
Dwarf: 10E9 $M_{\odot}$




Normal: 10E11 $M_{\odot}$




Massive: 10E12 $M_{\odot}$

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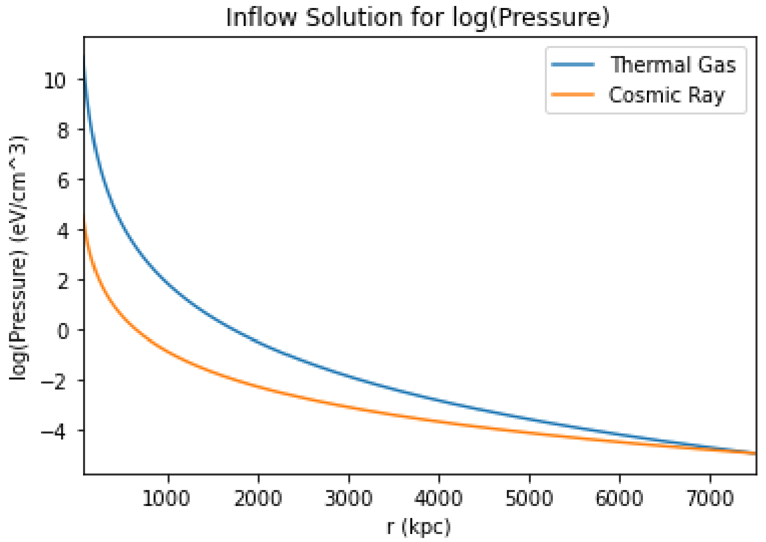
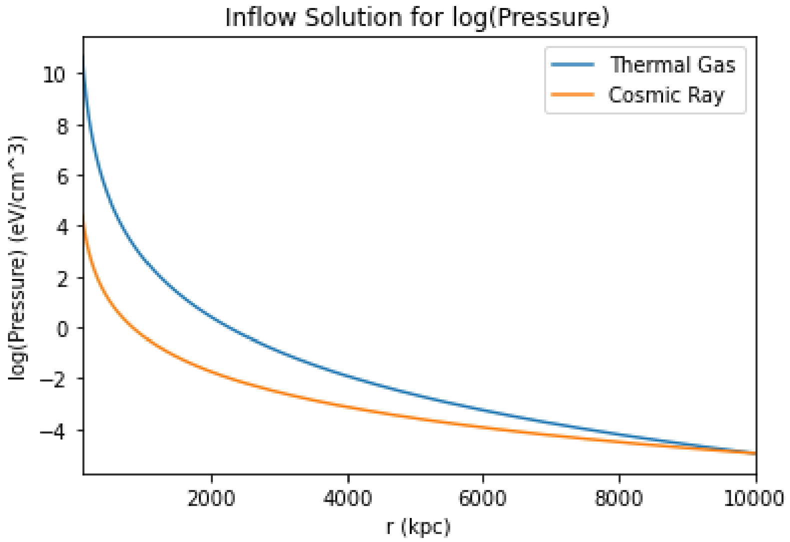
# *Pressure Ratio = 1, Varying Galaxy Mass*

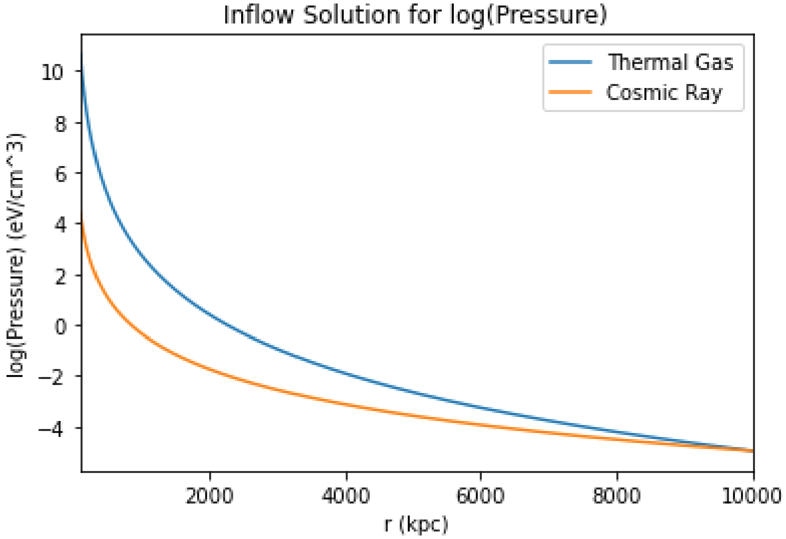
Dwarf: 10E9 $M_{\odot}$




Normal: 10E11 $M_{\odot}$

Massive: 10E12 $M_{\odot}$

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# *Ratio = 1, Varying Galaxy Mass*

- Star formation rate:
    - Dwarf: ≈ 2 $M_{\odot}$ / year
    - Normal: ≈ 21 $M_{\odot}$ / year
    - Massive: ≈ 65 $M_{\odot}$ / year
- Galaxies with larger mass can sustain larger inflow rate which are inflowing with higher velocity

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# *Case 2: Varying Cosmic Ray to Thermal Gas Pressure Ratio, Fixed Galaxy Mass*

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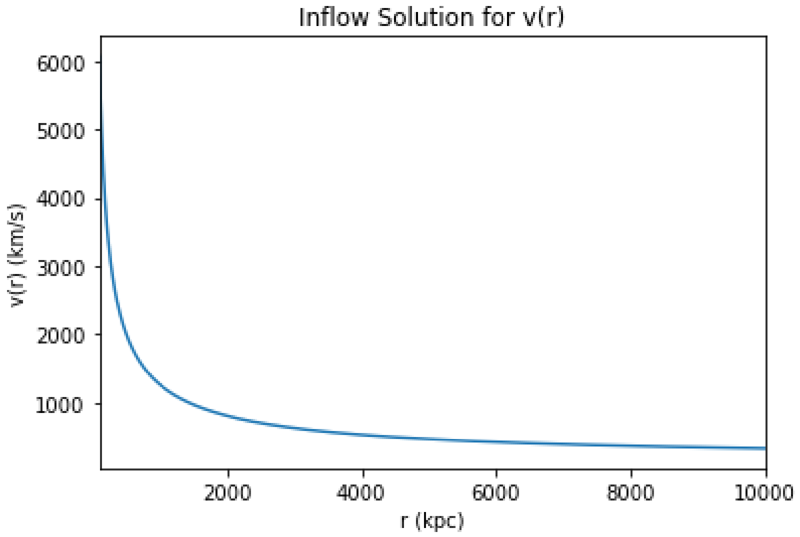
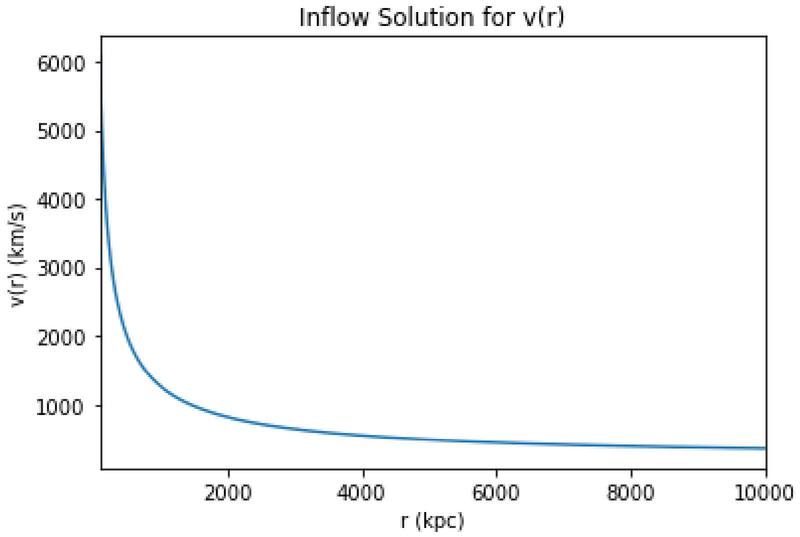
# *Fixed Mass, Varying Pressure*

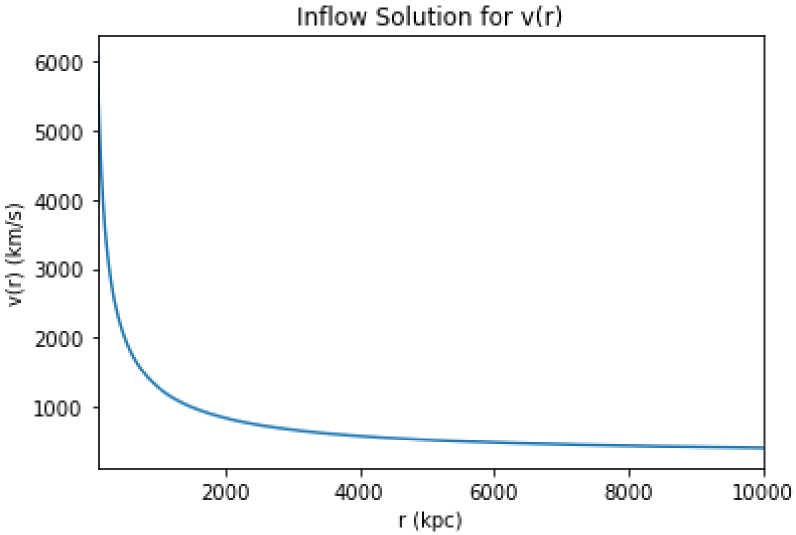
0.0004 eV/cm^3




0.007 eV/cm^3

0.11 eV/cm^3

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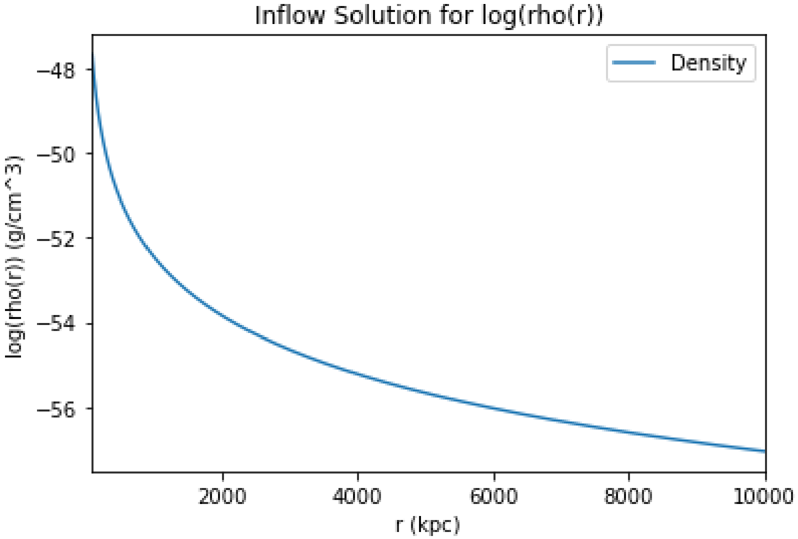
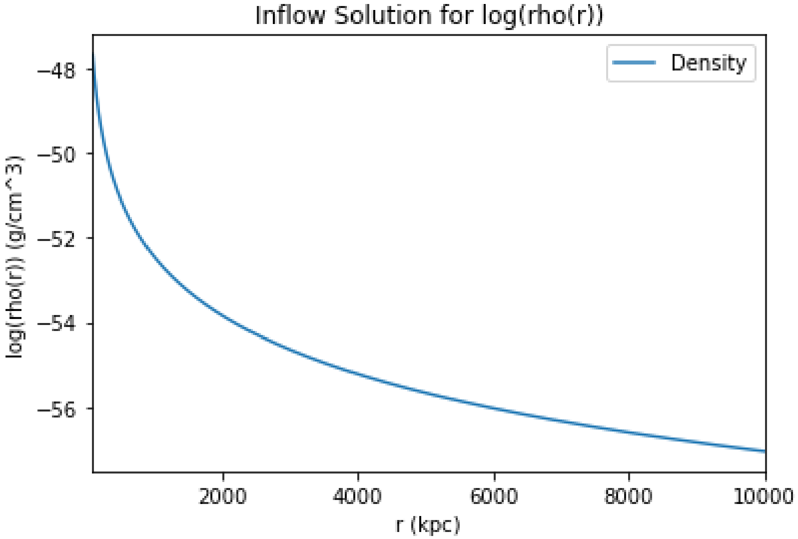
# *Fixed Mass, Varying Pressure*

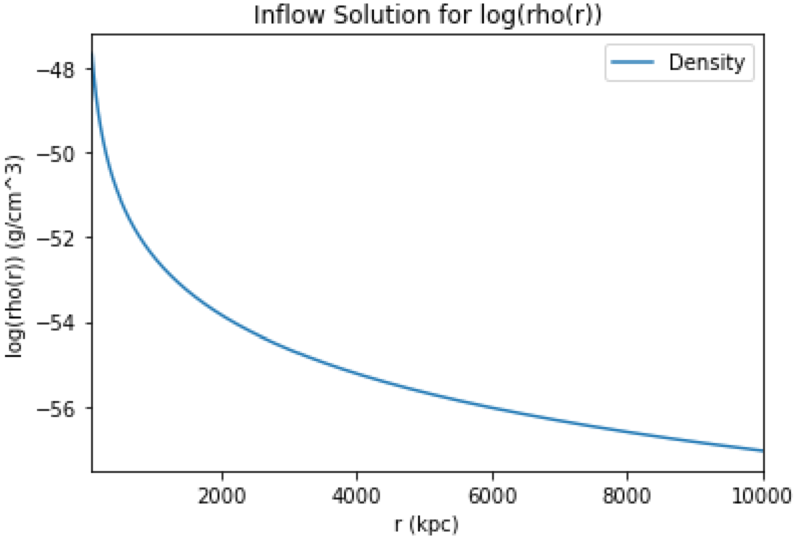
0.0004 eV/cm^3




0.007 eV/cm^3

0.11 eV/cm^3

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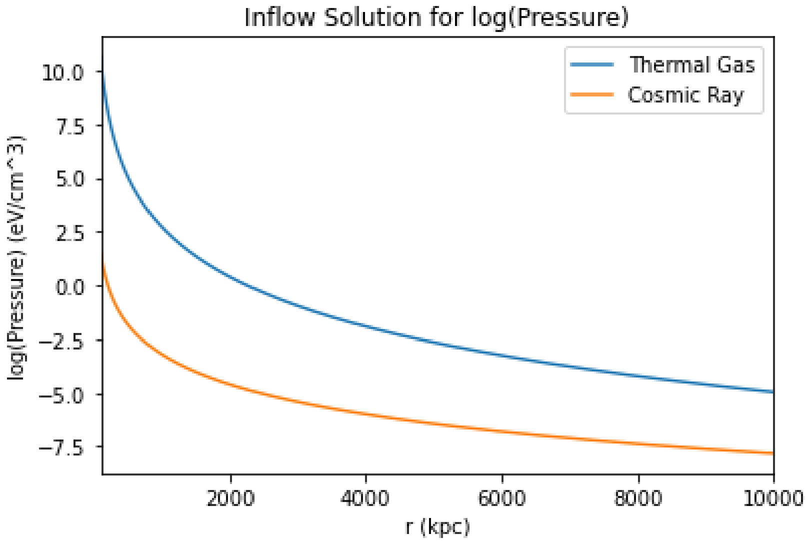
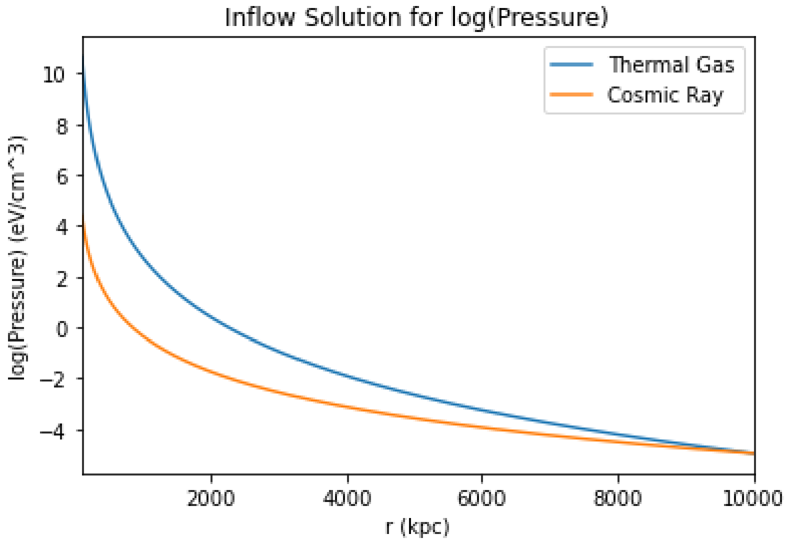
# *Fixed Mass, Varying Pressure*

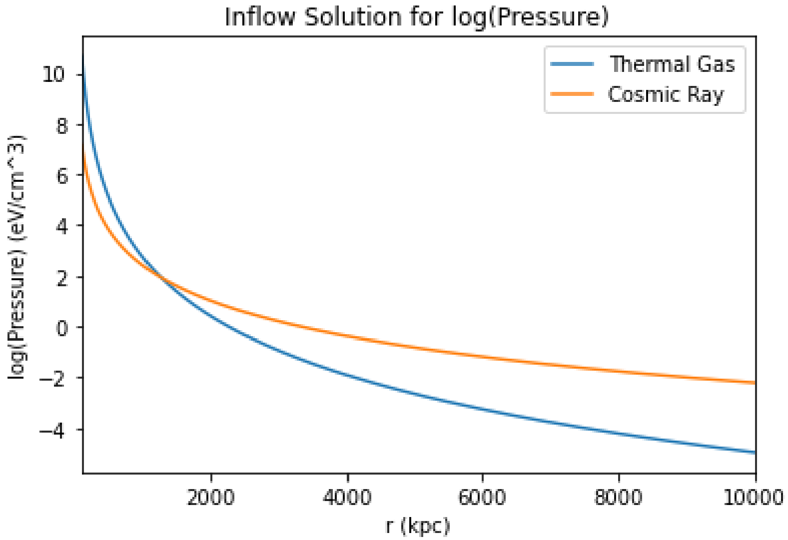
0.0004 eV/cm^3




0.007 eV/cm^3

0.11 eV/cm^3

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# *Fixed Mass, Varying Pressure*

- Star formation rate:
  - Less:16 $M_{\odot}$ / year
  - Equal: 21 $M_{\odot}$ / year
  - More: 56 $M_{\odot}$ / year
- Systems where inflows are more impacted by the dynamical effects of cosmic rays seem to sustain higher rates of gas supply to the host galaxy, and higher SFR

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# *Discussion*

- Star formation rate is sensitive to CR pressure, and their dynamical impacts on the supply of gas to a galaxy through inflow
- Result SFR reasonably consistent with observational data
- Limitation:
  - Very idealized model set-up used as a first study
  - Sensitive to boundary conditions

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*Thank You for Listening!*

# *Sources*


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# *Accretion With CRs*

$$\frac{dv}{dr} \Rightarrow \frac{du}{dx} = \frac{2u - (\frac{V_c}{c_s})^2 \frac{u}{x}}{x(u^2 - 1)}$$

$$v_A = \tilde{v_A} = \frac{r_s^2 \sqrt{< B^2 >}}{r^2 \sqrt{4\pi\rho}} \Rightarrow v_A^2 = \frac{8\pi U_{B,0}}{4\pi\rho_s} \frac{1}{x^4 y} = \frac{v_{A,0}^2}{x^4 y}$$

$$v + v_A = uc_s + \frac{v_{A,0}}{x^2\sqrt{y}} = v_{eff}$$

$$\frac{dP_C}{dr} \Rightarrow \frac{d\theta_C}{dx} = \frac{\theta_C}{y} \frac{uc_s + v_{eff}}{2v_{eff}} \frac{dy}{dx}$$

$$\frac{dP}{dr} \Rightarrow \frac{d\theta}{dx} = \left(\frac{5\theta}{3y} - \frac{4\theta_C}{9y} R_{CT} \frac{\frac{v_{A,0}}{x^2\sqrt{y}}(uc_s + v_{eff})}{uc_s v_{eff}}\right) \frac{dy}{dx}$$

$$R_{CT} = \frac{P_{C,0}}{P_0}$$

$$\frac{d\rho}{dr} \Rightarrow \frac{dy}{dx} = \frac{1}{u^2 c_s^2}\left(R_{T\rho} \frac{d\theta}{dx} + R_{C\rho} \frac{d\theta_c}{dx} + \frac{yV_c{}^2}{x^2}\right) - \frac{2y}{x}$$

$$R_{T\rho} = \frac{P_0}{\rho_s}, R_{C\rho} = \frac{P_{C,0}}{\rho_s}$$

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# Accretion With CRs

$$\frac{dv}{dr} = \frac{2vc_s^2 - \frac{GM}{r}v}{r(v^2 - c_s^2)}$$

$$\frac{dM}{dt} = 4\pi\rho v r^2 = const$$

$$\frac{d\rho}{dr} = \frac{1}{v^2}(\frac{dP}{dr} + \frac{dP_C}{dr} + \rho\frac{GM}{r^2}) - \frac{2}{r}\rho$$

$$\frac{dP_C}{dr} = \frac{\gamma_C P_C}{\rho}\frac{2v + v_A}{2(v + v_A)}\frac{d\rho}{dr}$$

$$\frac{dP}{dr} = (\frac{\gamma_g P}{\rho} - \frac{\gamma_C P_C}{\rho}\frac{\gamma_g - 1}{2}\frac{v_A(2v + v_A)}{v(v + v_A)})\frac{d\rho}{dr}$$

$$c_s^2 = \frac{\gamma_g P_C}{\rho} + \frac{\gamma_C P_C}{\rho}\frac{(2v + v_A)(v - (\gamma_g - 1)v_A)}{2v(v + v_A)}$$

$$v_A = \tilde{v_A} = \frac{r_s^2\sqrt{< B^2 >}}{r^2\sqrt{4\pi\rho}}$$

$$x = \frac{r}{r_s}$$

$$u = \frac{v}{c_s}$$

$$y = \frac{\rho}{\rho_s}$$

$$\theta = \frac{P}{P_0}$$

$$\theta_C = \frac{P_C}{P_{C,0}}$$

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