Galaxy Formation with Properly Modeled *Stars and MBHs*

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Outline

- Key Components to Understand and Simulate Galaxies

- Modeling the Physics of Galaxy Formation with Stars and MBHs As Best As You Can in AMR enzo-2.0

- Simulation Set-ups and Early Results

- Kim, Wise, Alvarez, & Abel (2010a, b) in prep.
[Star Formation and Feedback]
**[Star Formation and Feedback]**

**First Goal**

- **GOAL**: Include the physics of star formation and feedback in the numerical studies of galaxy formation!

**Previous SF Recipes**

(mostly in particle-based simulations)

- Dominated mostly by the SF recipe using the Schmidt relation (1959)
  \[ \rho_\text{gas} = (1 - \beta) \rho_\text{crit} \left( \frac{\rho_\text{gas}}{10^{-16} \text{ cm}^{-3}} \right)^{\beta} \]
- Apply thermal feedback or effective EOS to describe SNe feedback

**Slow SF in Molecular Clouds**

- Very slow due to turbulence, B-field, protostellar wind, etc.; should be reflected in galaxy-scale studies
  \[ SFR_{\text{II}} \sim 0.02 \]
- MCs (10^4-10^5 M_\odot) could be the basic units that can be represented in galaxy formation sims

**MC Particle - Formation**

- Max resolution of 15.2 pc
  \[ L_{\text{ Jeans}} = \sqrt{25 \text{ particles/cm}^3 \text{ at } 960 \text{ K} \text{ } M_{\text{MC}} = \epsilon_s p_{\text{gas}} \Delta x^3} \]
- Self-consistently deposit a particle when a cell of a typical MC size actually becomes Jeans unstable
  → each particle describes a MC of 8000 M_\odot

**MC Particle - Feedback**

- Both mass and energy are added back to gas
  - 80% of the MC mass slowly comes back to gas for 12 t_{\text{dyn}}
  - carries the thermal energy of 10^{51} ergs per M_{\text{star}}=750 M_\odot

\[ M_{\text{star}}(t) = 0.2 M_{\text{MC}} \int_0^t e^{-r^2} dr \]

[Image of galaxy formation]
Star Particle - Formation

- Max resolution of $15.2 \text{ pc}$
  
  $= L_{\text{Jeans}}$ of a MC of 125 particles/cm$^3$ at 960 K

$$M_{\text{MC}} = \epsilon \rho_{\text{gas}} \Delta x^3$$

- Self-consistently deposit a particle when a cell of a typical MC size actually becomes Jeans unstable

$\rightarrow$ each particle describes a MC of $8000 M_{\text{sun}}$

When all are met:

- $n_{\text{gas}} > n_{\text{thres}}$
- $\nabla \cdot \mathbf{v} < 0$
- $t_{\text{cool}} < t_{\text{dyn}}$
- $M_{\text{MC}} > 8000 M_{\text{sun}}$

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Both mass and energy are added back to gas.
- 80% of the MC mass slowly comes back to gas for $12 t_{\text{dyn}}$
- carries the thermal energy of $10^{51}$ ergs per $M_{\text{star}}=750 M_{\odot}$

\[
M_{\text{star}}(\tau) = 0.2 M_{\text{MC}} \int_{0}^{\tau} e^{-\tau'} d\tau'
\]
[MBH Accretion and Feedback]
Coevolution of Galaxies and MBHs

- Have galaxies and MBHs grown at the same time under each other’s influence?

Magorrian et al. (1998)

Zheng et al. (2009)

Study the coevolution of galaxies and MBHs in one comprehensive self-consistent framework!
MBH Particle - Accretion

- Eddington-limited Bondi estimate with no prefactor; subtraction from a sphere of radius $R_{\text{Bondi}}$

$$\dot{M}_{\text{BH}} = \min \left( \frac{4\pi G^2 M_{\text{BH}}^2 \rho_B}{c_s^3}, \frac{4\pi GM_{\text{BH}} m_p}{\epsilon_r \sigma_T c} \right)$$

- Getting close to resolving $R_{\text{Bondi}}$ of MBHs in galaxy-scale simulations

$$R_{\text{Bondi}} = \frac{2GM_{\text{BH}}}{c_s^2} \approx 8.6 \text{ pc} \left( \frac{M_{\text{BH}}}{10^5 M_\odot} \right) \left( \frac{10 \text{ km/s}}{c_s} \right)^2$$
MBH Particle - Feedback

- Designed **three** different feedback channels; **two** currently in use

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**Fig. 2.** Two-dimensional schematic views of the different modes of massive black hole feedback. (A) radiative feedback model described in Section 2.7: photon packages carrying the energy is adaptively traced via full radiative transfer, (B) mechanical feedback model described in Section 2.8: a momentum is given to the cells around the MBH along a pre-calculated jet direction, and (C) thermal feedback model dominantly used in particle-based galaxy-scale simulations: energy is thermally deposited kernel-weighted to the neighboring gas particles around the MBH.

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MBH Radiative Feedback

- Full 3D radiative transfer: monochromatic 2 keV X-ray photon packages do
  - photoionization (H, He, He$^+$)
  - photoheating
  - Compton heating (e$^-$)
  - radiation pressure

$L_{BH} = \epsilon_{r} \dot{M}_{BH} c^2$

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Ciotti et al. (2010): 1D-model
(2) MBH Mechanical Feedback

- Mechanical Energy
  \[ \text{Potential Energy} \]
  (jets introduced at \( R_{\text{jet}} \))
  + \text{Kinetic Energy} 
  (jets launched with \( v_{\text{jet}} \))

\[ \epsilon_{\text{kin}} \equiv \frac{P_{\text{kin}}}{L_{\text{BH}}} = 10^{-4} \quad \text{and} \quad \eta_{\text{jet}} \equiv \frac{\dot{M}_{\text{jet}}}{\dot{M}_{\text{BH}}} = 0.05 \]

\[ \rightarrow v_{\text{jet}} = c \left( \frac{2\epsilon_{\text{kin}}\epsilon_{r}}{\eta_{\text{jet}}} \right)^{1/2} \]

- Directed along \( \mathbf{L}_{\text{gas-accreted}} \);
  injected at every 300 \( M_{\odot} \)
Multi-scale Physics

- Resolving things from $R_{\text{Bondi}}$ to $R_{\text{galaxy}}$, from $10^2$ K to $10^7$ K
  $\rightarrow$ AMR enzo-2.0 poised to do a better job than ever
[Setting Up An Experiment & Early Results]
I. Galaxy Mergers

- Two $2 \times 10^{11} M_{\text{sun}}$ galaxies with embedded $10^5 M_{\text{sun}}$ MBHs set on a collisional orbit ($60^\circ$ tilted, initially separated by $\sim 80$ kpc)
Density-Temperature PDF

PDF in a 10 kpc sphere centered on one of MBHs

- X-ray radiation significantly changes the ISM, and thus SF
- Hot temperature near a MBH prohibits nuclear star formation
SF and BH Accretion History

- Star formation rate **suppressed** by soft X-ray radiation from MBH; more to see as two galaxies start to merge

- Jets do not impact much in regulating accretion as they are mostly perpendicular to gas disks
II. Cosmological Galaxy Formation at $z=3$

- A $\sim 10^{12} \, M_{\odot}$ galaxy selected at $z=3$ in a low-resolution run
  → insert a $10^5 \, M_{\odot}$ MBH and restart with 15.2 pc resolution

200 kpc centered on a MBH


z=3, Density projection, 16 comoving Mpc
• X-ray radiation heats up gas clumps and suppresses SF (probably more efficiently because there is no well-defined disk)
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Temperature Slice

S-Fbck only

S-Fbck + R/M-Fbck

Temperature profile, 20 kpc sphere
Radial Density Profile

S-Fbck only

S-Fbck + R/M-Fbck

Mass profile, 20 kpc sphere
SF and BH Accretion History

- Radiation also **regulates** the accretion on to the MBH
- Jets should make more impact with **no well-defined gas disk**
Towards An Unabridged Understanding of Galaxy Formation

- Various components for understanding the physics of galaxy formation are pieced together:
  - Proper treatment of **MC formation & feedback**
  - Proper treatment of **MBH accretion & feedback**

- Stellar and MBH processes in **one self-consistent framework**
  - MBH feedback regulates SF and its own growth
  - With tools at hand, many future projects are being designed

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Thank you!

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Morphology: Face-on Projection

- MBH feedback makes the disk hot and turbulent preventing gravitational collapse
Face-on Projection (Earlier)

- Too early to compare morphological differences, yet
X-ray radiation *heats up* gas clumps and suppresses SF (probably more efficiently because there is no well-defined disk)
Temperature Slice (Earlier)

Slice perpendicular to L, 100 Myrs, 20 kpc

- X-ray radiation heats up gas clumps and suppresses SF (probably more efficiently because there is no well-defined disk)
Temperature Slice (Earlier)

S-Fbck only

S-Fbck + R/M-Fbck

Temperature profile, 20 kpc
MBH Thermal Feedback

(C) thermal feedback

MBH

~50 pc

cell size = 15.2 pc

Sedov Test (Radius calibrated to $R_{\text{shock}} = 1.0$)

103 kyrs (DD0023)
200 kyrs (DD0036)
600 kyrs (DD0090)
950 kyrs (DD0138)
Sedov solution

Log Density (amu. cm$^{-3}$)

-4.75 -2.70 -0.65 1.41

$y$-slice: 40.00 kpc wide

time: 738.31 kyr, remaining: 41.34 Myr
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Density-Temperature PDF

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SF and BH Accretion History
Merger Sequence

Galaxy = Gas + Stars + MBH + DM, etc.