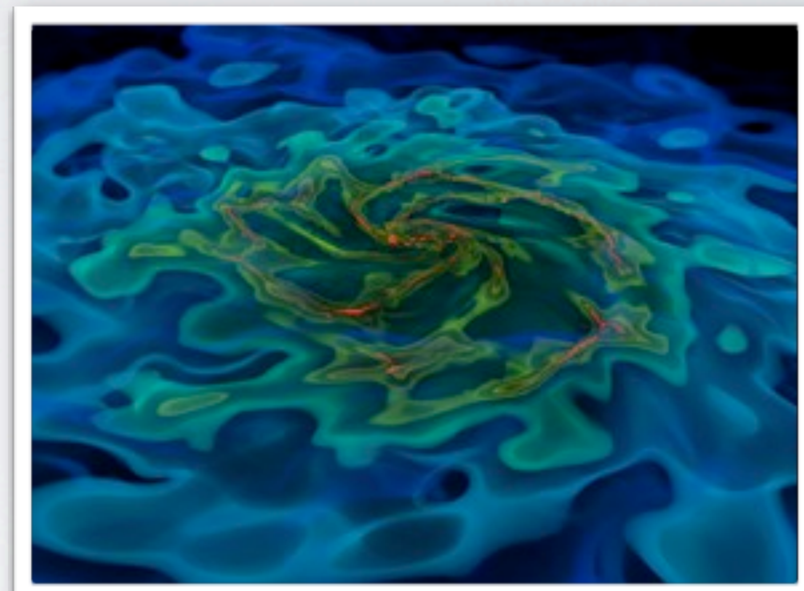
# Galaxy Formation with Properly Modeled Stars and MBHs

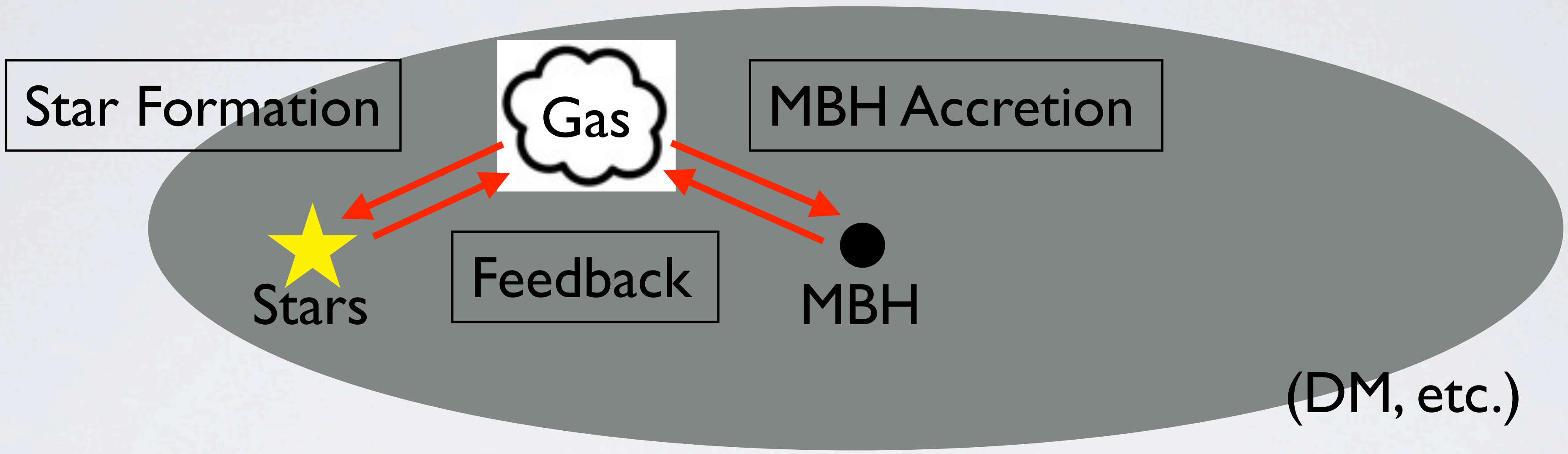


Ji-hoon Kim (KIPAC/Stanford)

Collaborators: John Wise(Princeton), Marcelo Alvarez(CITA),
Matthew Turk(UCSD), Tom Abel(Stanford)

# Outline

- Key Components to Understand and Simulate Galaxies



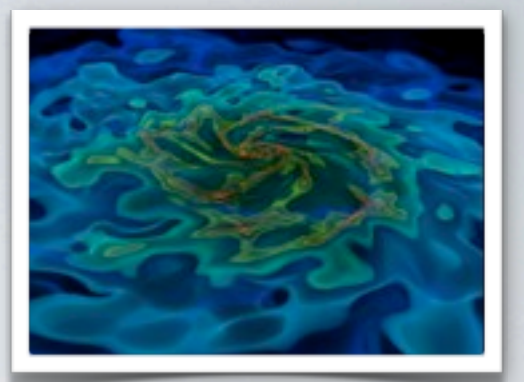

- Modeling the Physics of Galaxy Formation with Stars and MBHs As Best As You Can in AMR enzo-2.0

- Simulation Set-ups and Early Results

- Kim, Wise, Alvarez, & Abel (2010a, b) in prep.

- Kim, Wise, & Abel (2009) ApJL 694 L123

PART I



# [Star Formation and Feedback]

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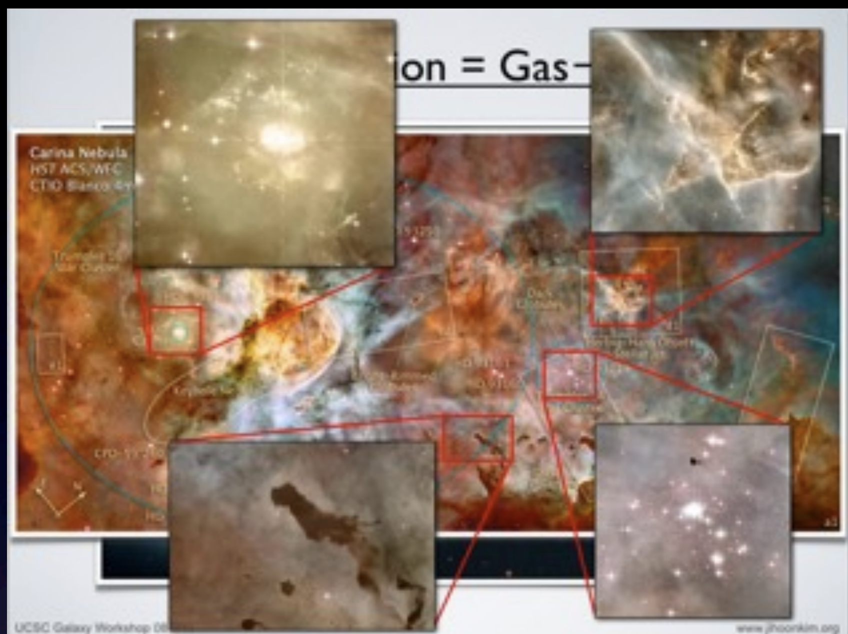
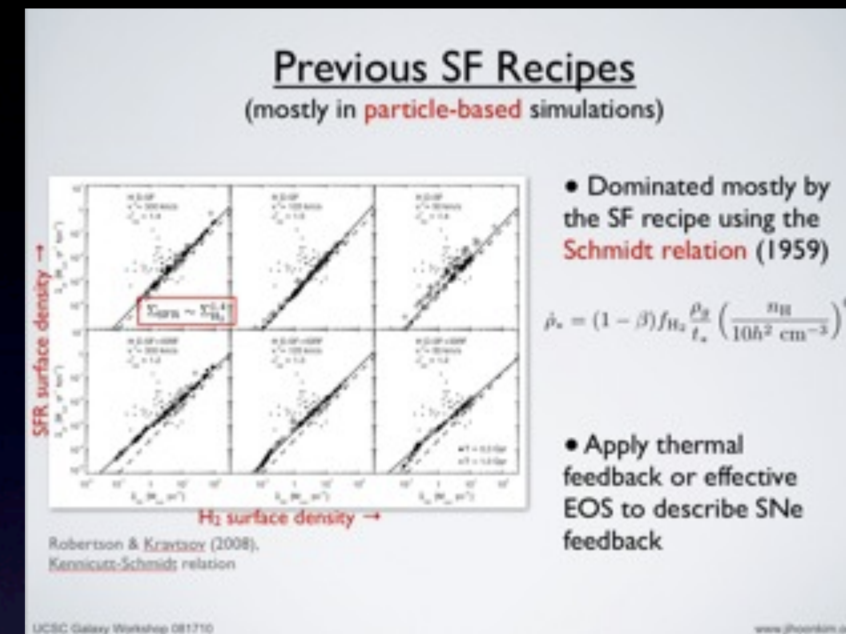
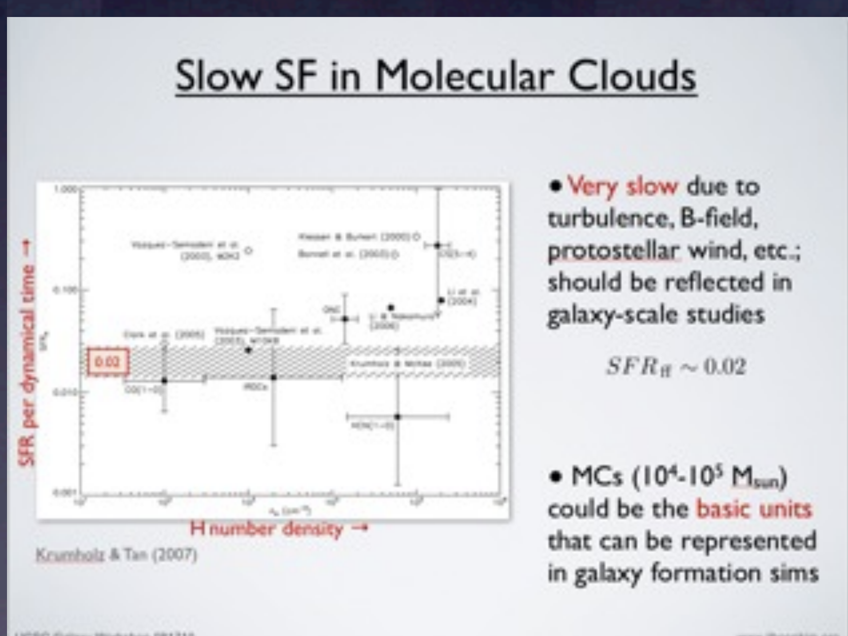
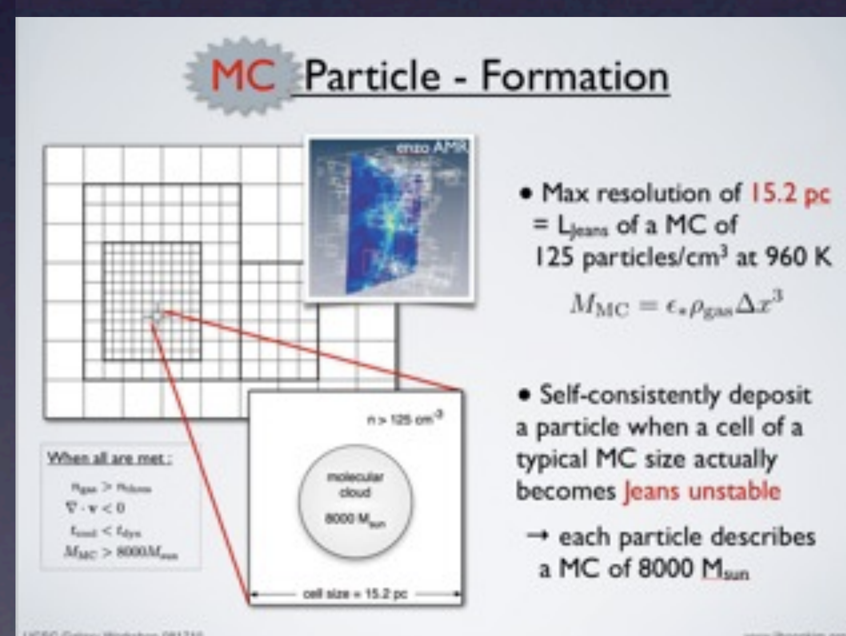
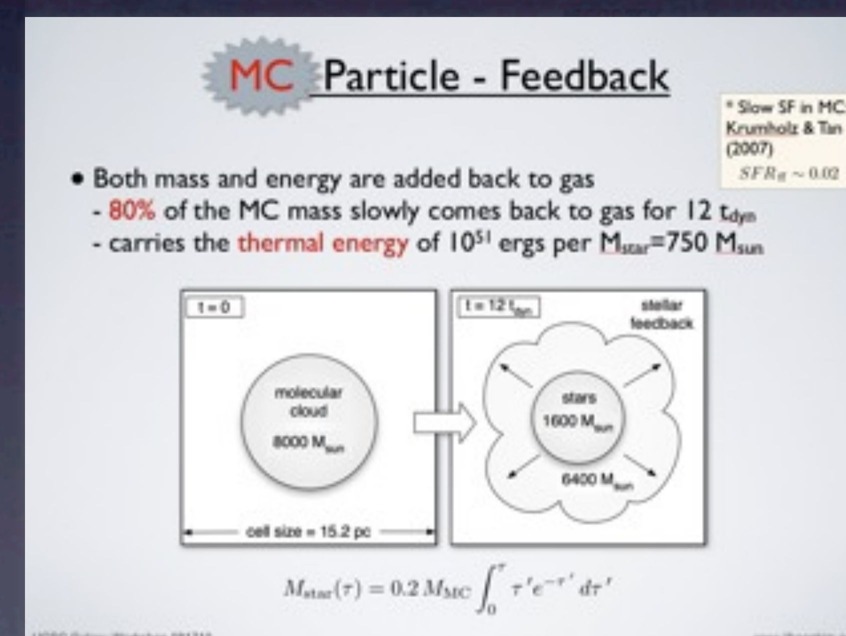




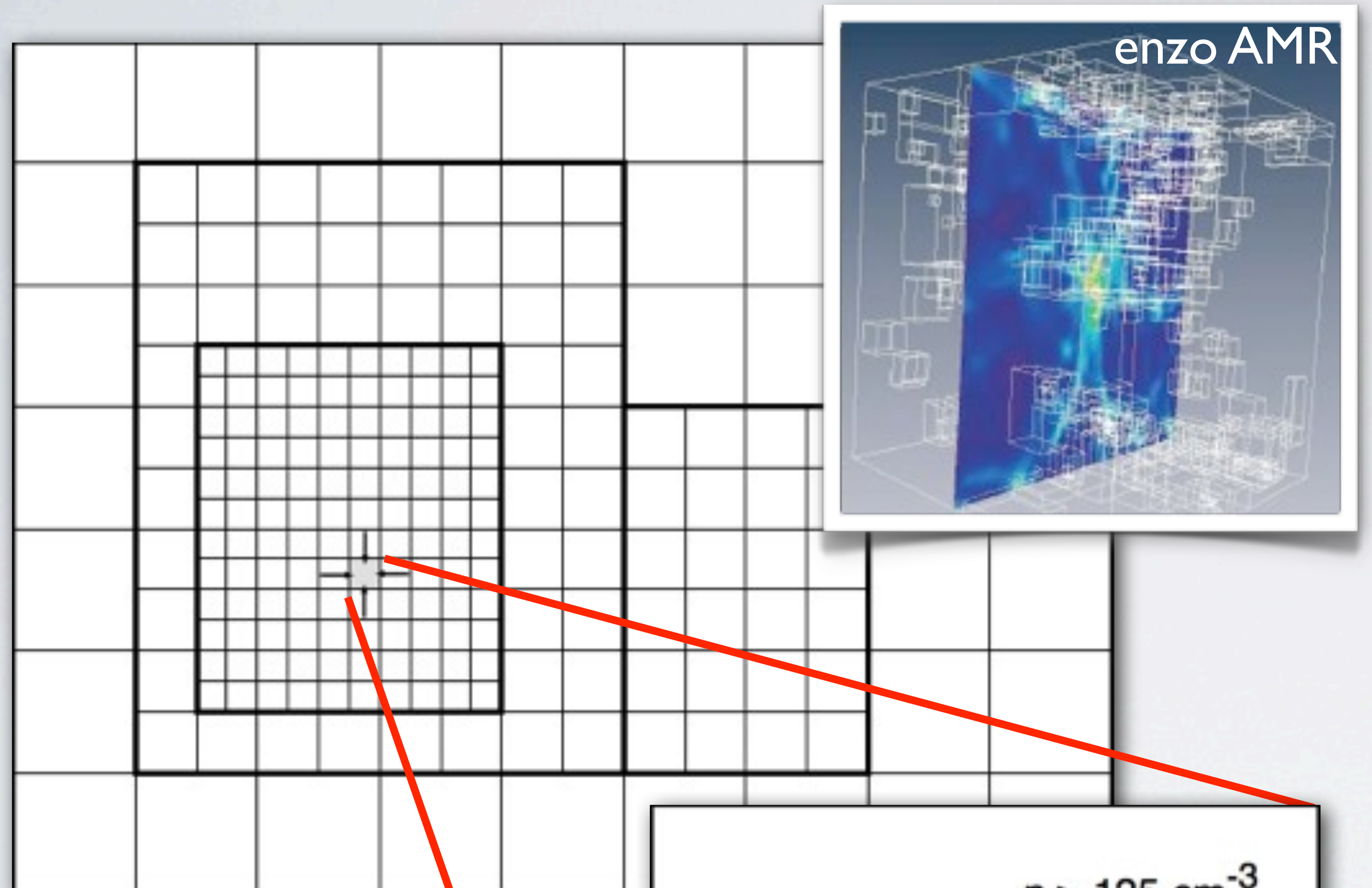


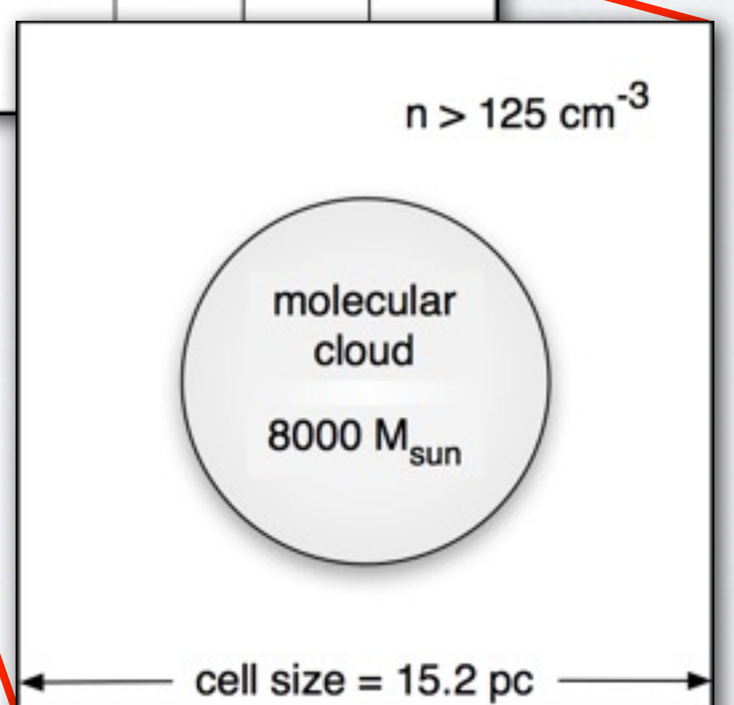



# MC ~~Star~~ Particle - Formation




When all are met :

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

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

$$M_{\rm MC} = \epsilon_* \rho_{\rm gas} \Delta x^3$$

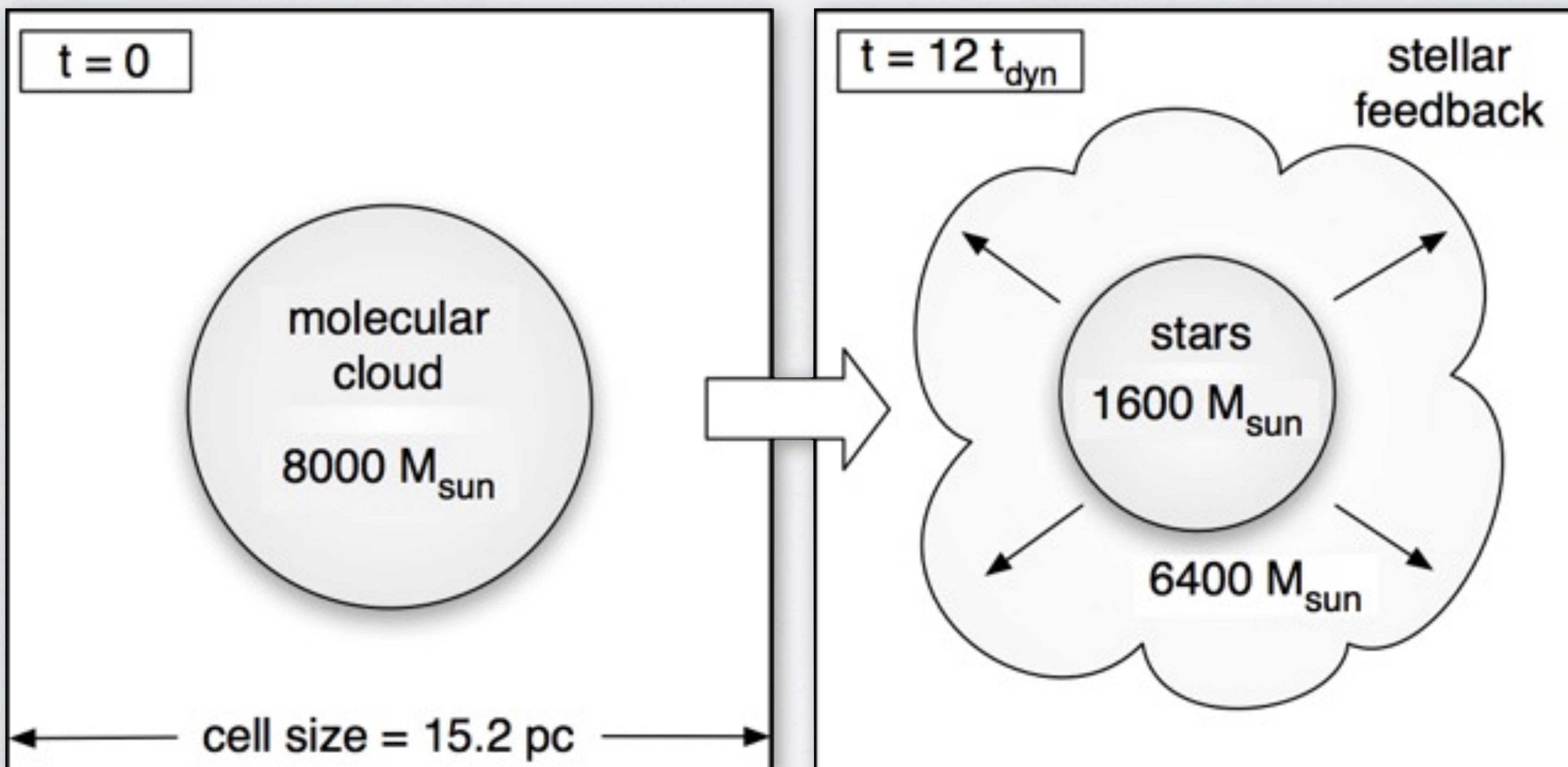
- Self-consistently deposit a particle when a cell of a typical MC size actually becomes Jeans unstable

  → each particle describes a MC of 8000 $M_{\rm sun}$

# MC ~~Star~~ Particle - Feedback

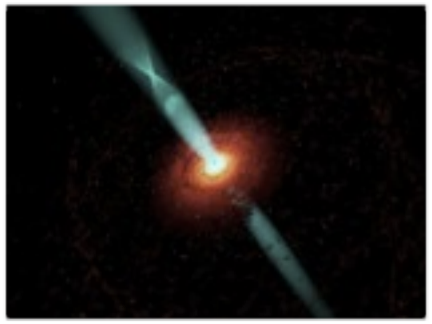
* Slow SF in MC: Krumholz & Tan (2007)
$SFR_{\rm ff} \sim 0.02$

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




$$M_{\rm star}(\tau) = 0.2\, M_{\rm MC} \int_0^{\tau} \tau' e^{-\tau'}\, d\tau'$$

PART II

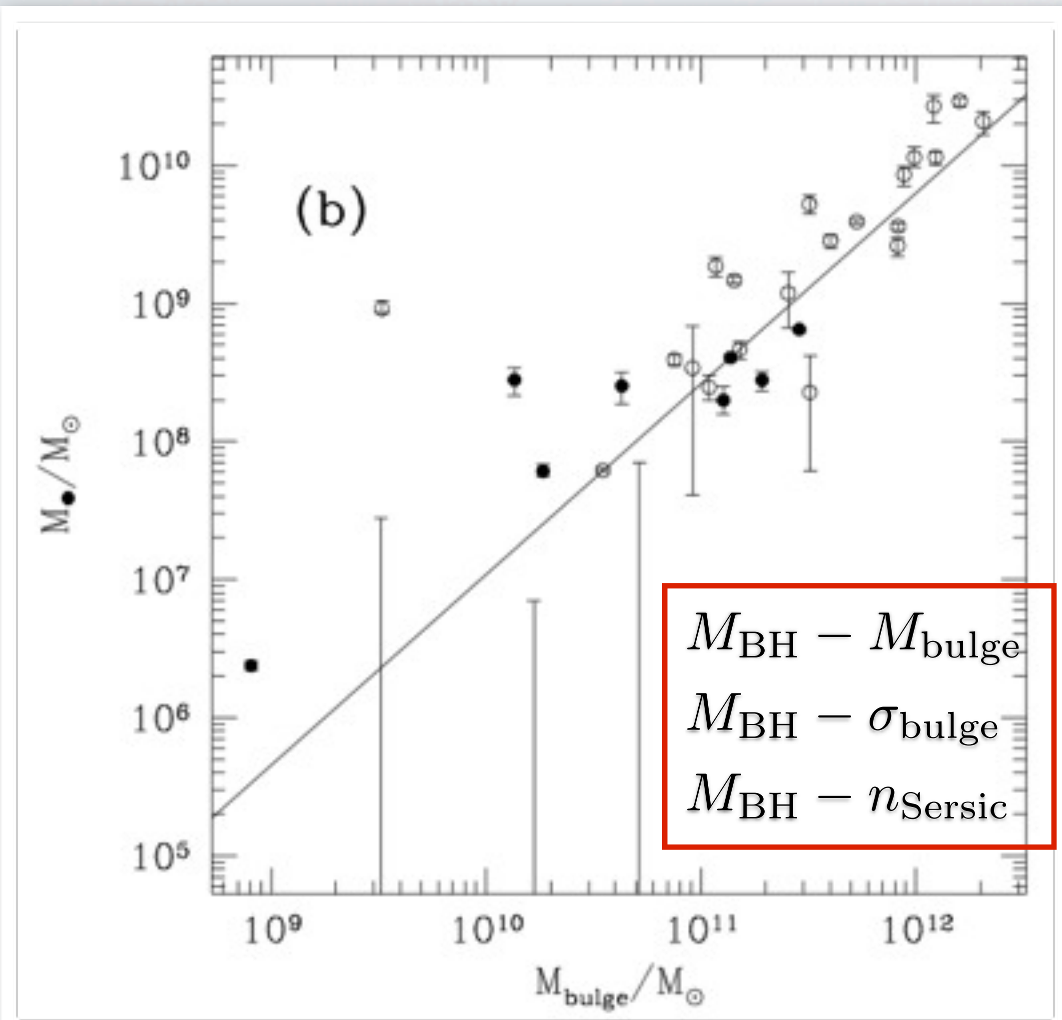


# [MBH Accretion and Feedback]

# Coevolution of Galaxies and MBHs

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

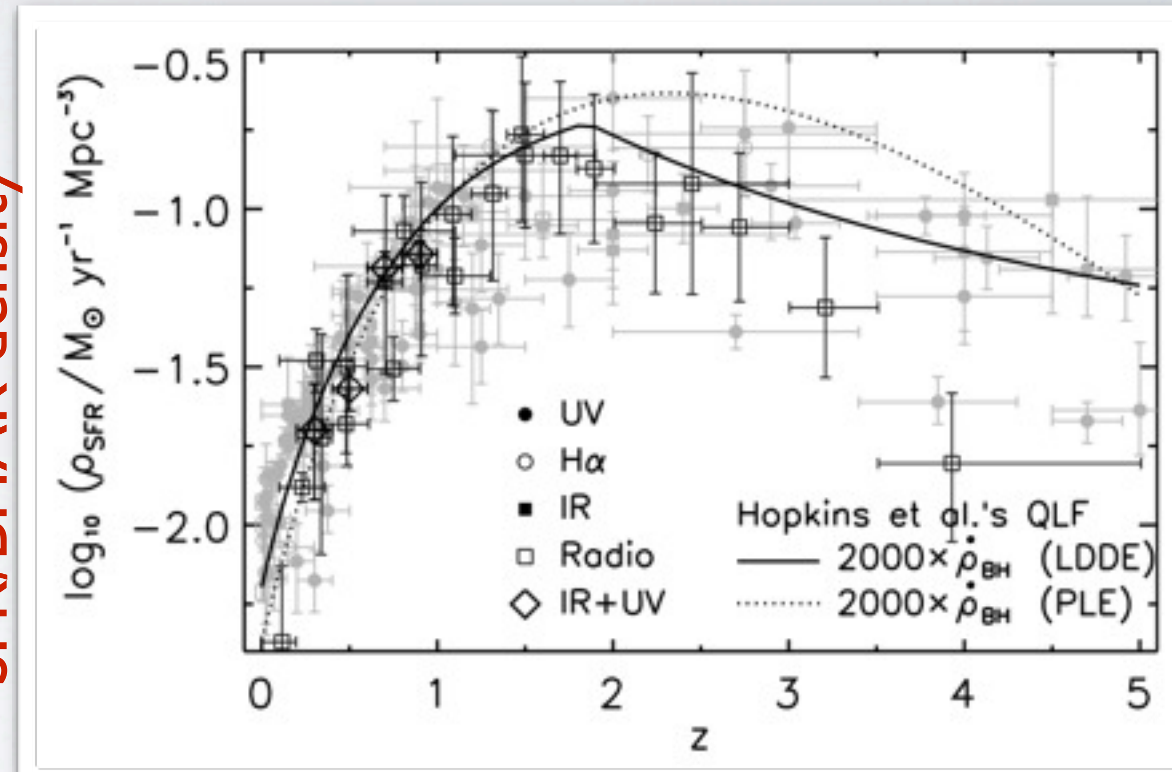
massive dark object (MDO) mass →




bulge mass →

Magorrian et al. (1998)

SFR/BHAR density →




redshift →

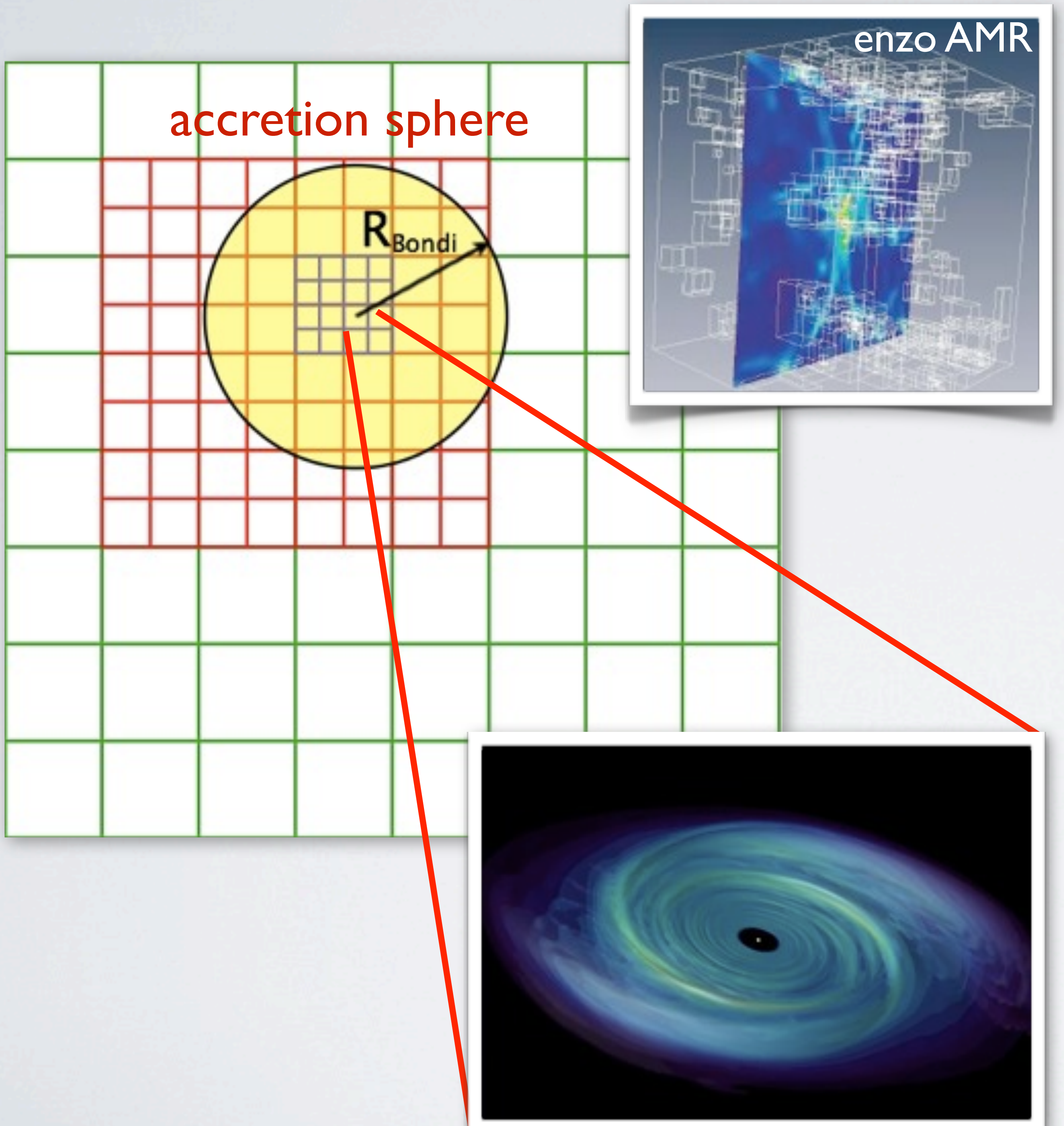
Zheng et al. (2009)

* Unified model: Silk & Rees (1998), Kauffmann & Haehnelt (2000), etc.

# GOAL

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 $R_{\rm Bondi}$

$$\dot{M}_{\rm BH} = \texttt{min}\left(\frac{4\pi G^2 M_{\rm BH}^2 \rho_{\rm B}}{c_{\rm s}^3}\,,\ \frac{4\pi G M_{\rm BH} m_{\rm p}}{\epsilon_{\rm r}\sigma_{\rm T} c}\right)$$

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

$$R_{\rm Bondi} = \frac{2GM_{\rm BH}}{c_{\rm s}^2} \simeq 8.6\ {\rm pc}\left(\frac{M_{\rm BH}}{10^5 M_\odot}\right)\left(\frac{10\,{\rm km/s}}{c_{\rm s}}\right)^2$$

# MBH Particle - Feedback

- Designed three different feedback channels; two currently in use

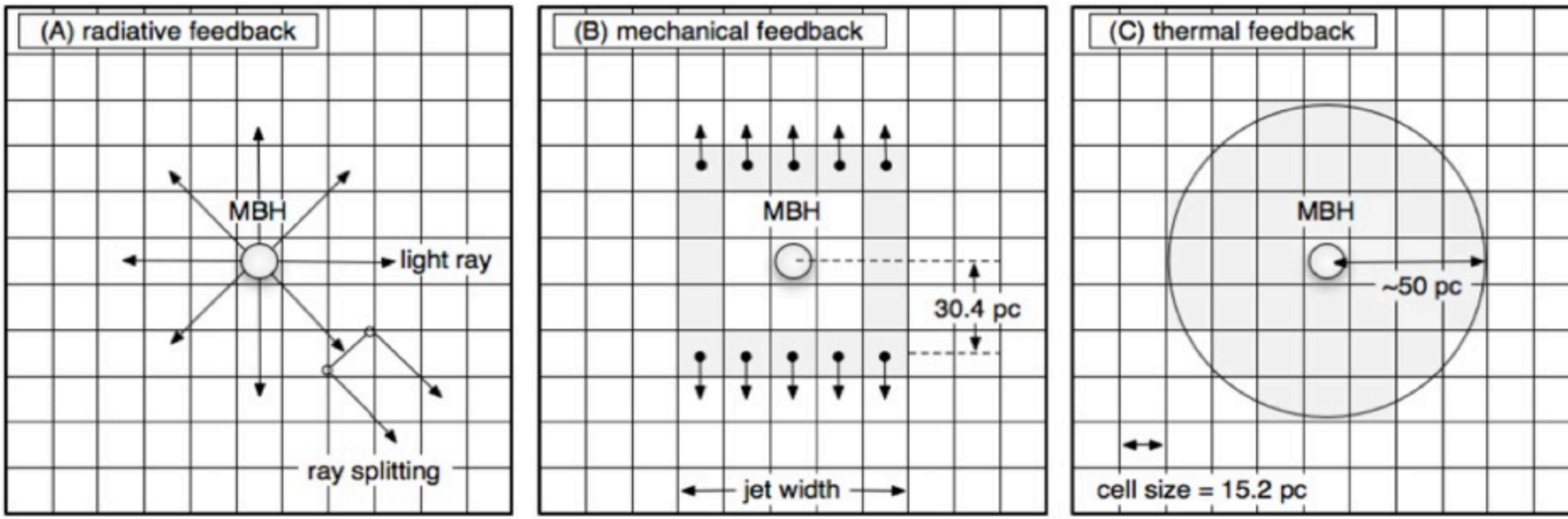
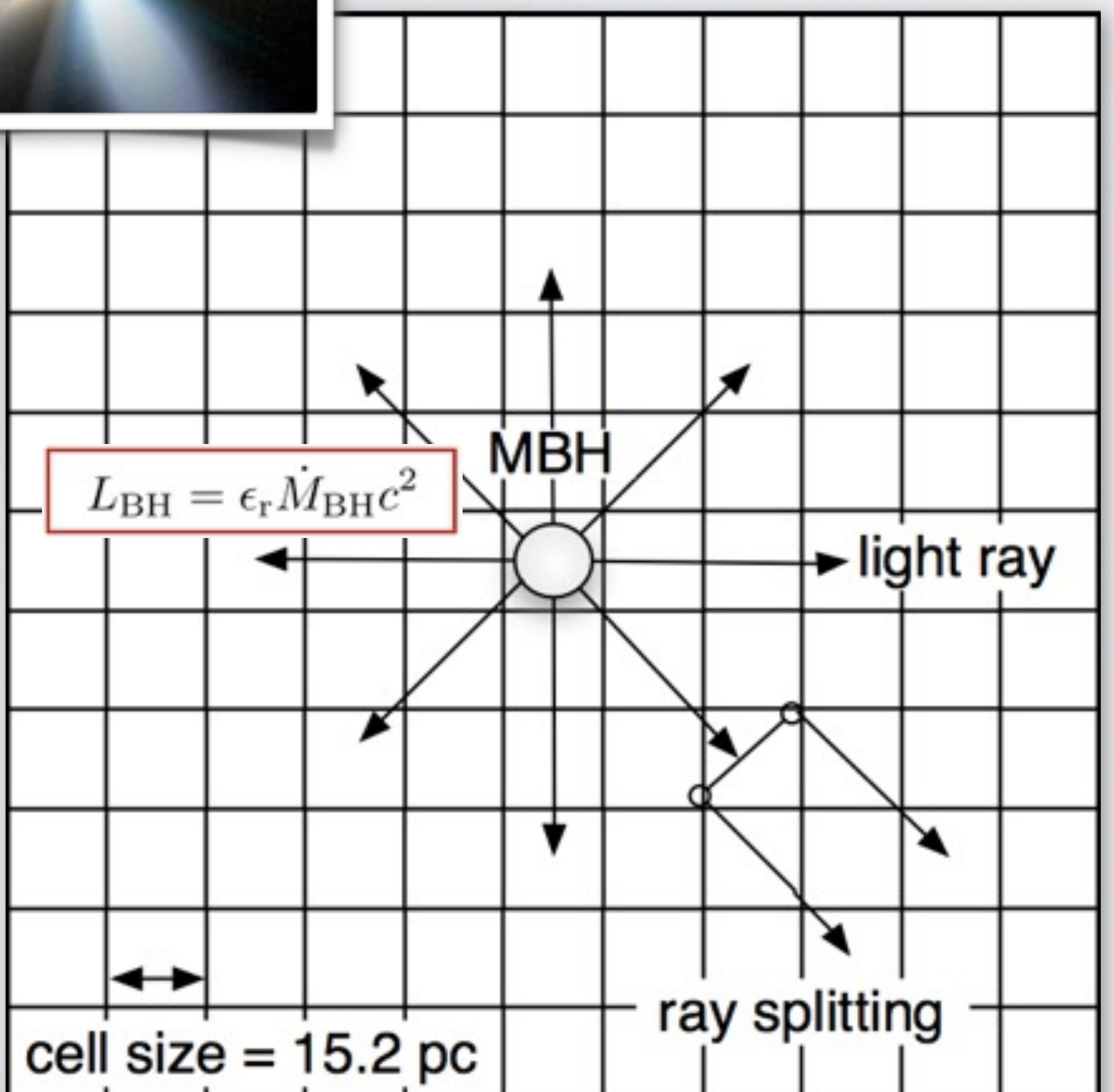


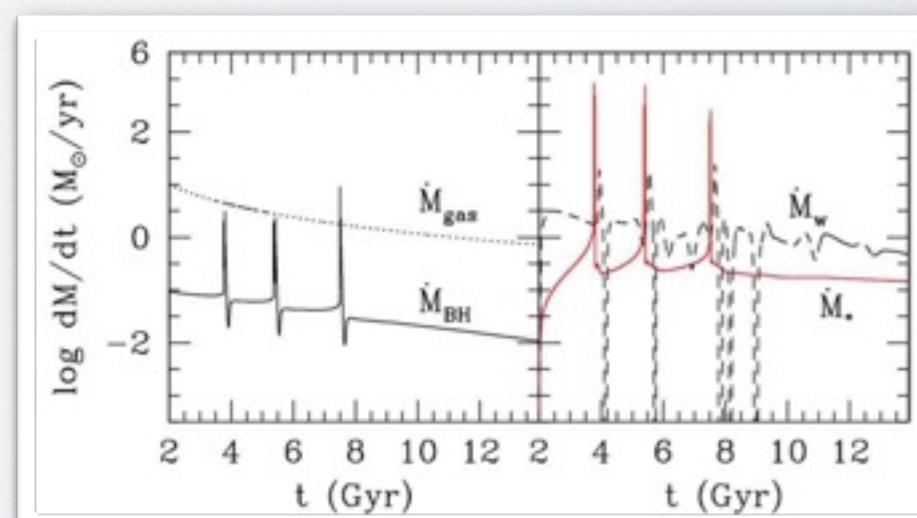

FIG. 2.— Two-dimensional schematic views of the different modes of massive black hole feedback. (A) radiative feedback model described in Section 2.7: photon packages carrying the energy is adaptively traced via full radiative transfer, (B) mechanical feedback model described in Section 2.8: a momentum 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.

- Kim, Wise, Alvarez, & Abel (2010a, b) in prep.

# (1) MBH Radiative Feedback

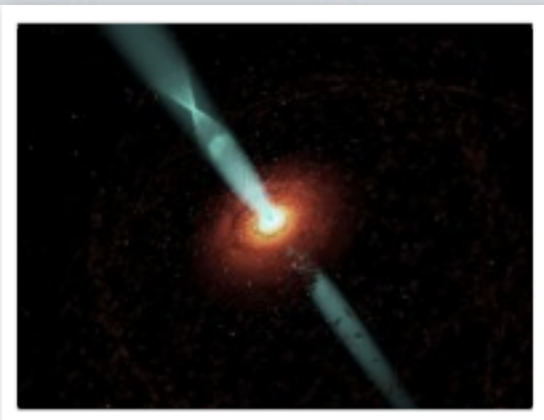



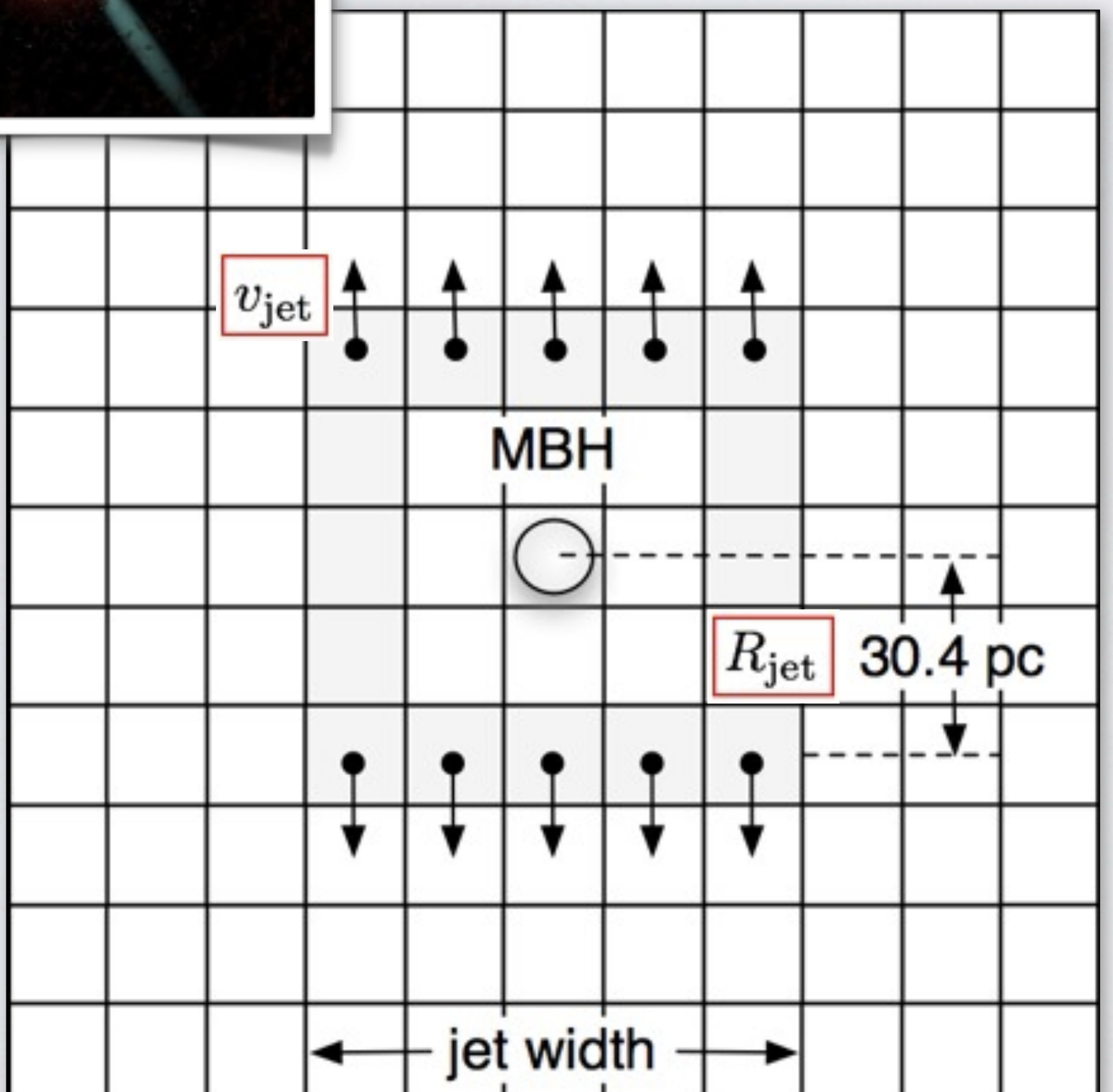

- Full 3D radiative transfer: monochromatic 2 keV X-ray photon packages do
  - photoionization (H,He,$He^+$)
  - photoheating
  - Compton heating ($e^-$)
  - radiation pressure




Ciotti et al. (2010): 1D-model

# (2) MBH Mechanical Feedback






- Mechanical Energy
  = Potential Energy
  (jets introduced at $R_{jet}$)
  + Kinetic Energy
  (jets launched with $v_{jet}$)

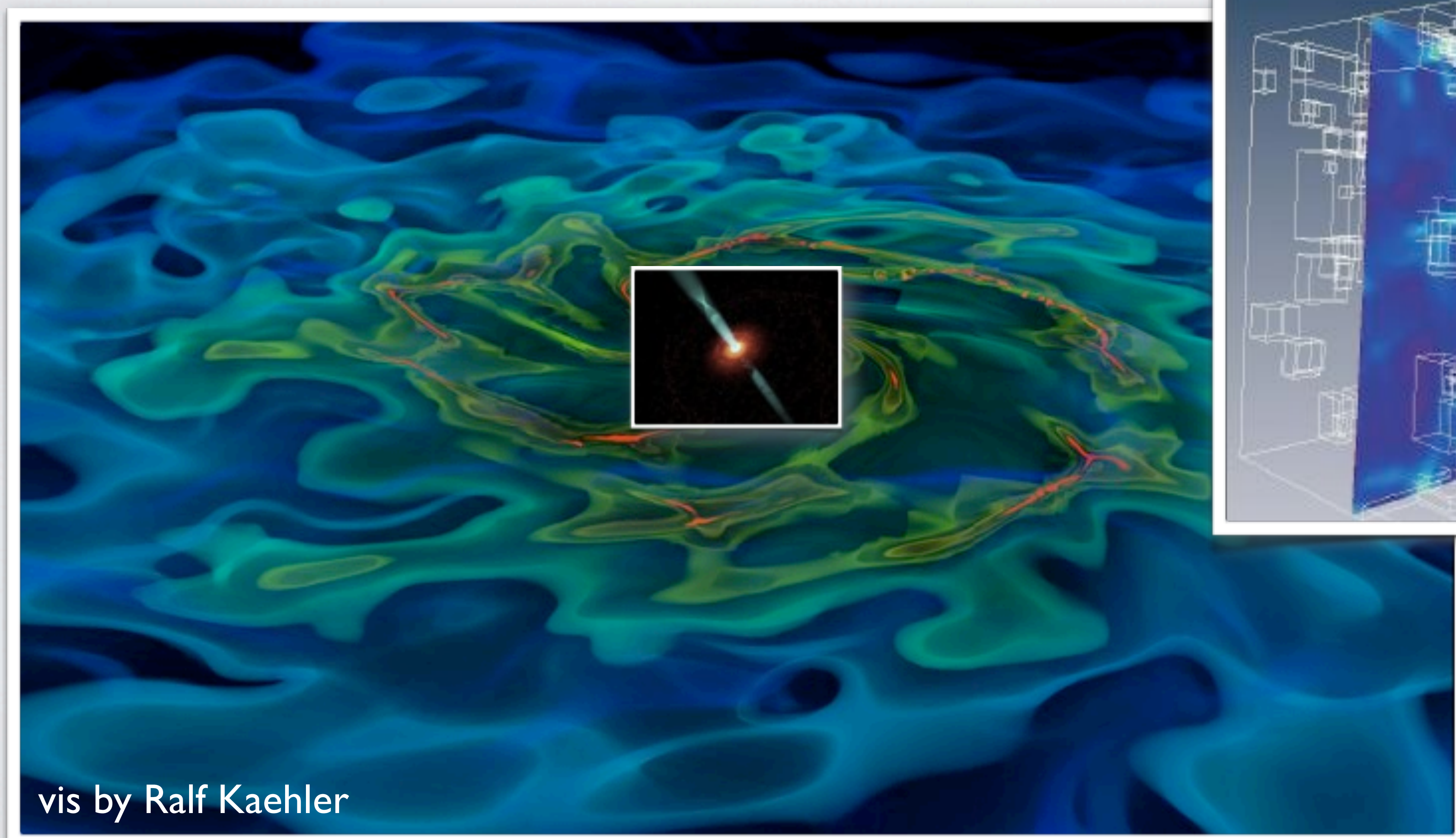
$$\epsilon_{\rm kin} \equiv \frac{P_{\rm kin}}{L_{\rm BH}} = 10^{-4} \quad \text{and} \quad \eta_{\rm jet} \equiv \frac{\dot{M}_{\rm jet}}{\dot{M}_{\rm BH}} = 0.05$$

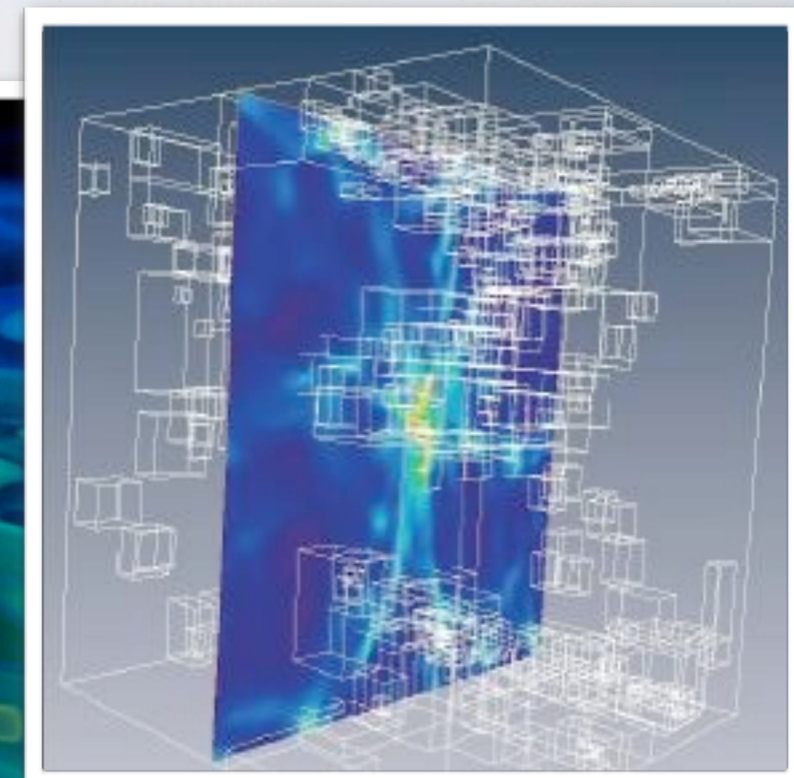
$$\rightarrow \quad v_{\rm jet} = c \left( \frac{2\epsilon_{\rm kin}\epsilon_{\rm r}}{\eta_{\rm jet}} \right)^{1/2}$$

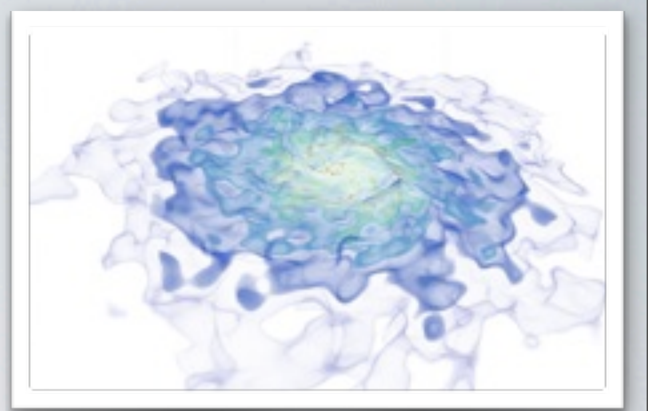
- Directed along $\vec{L}_{\text{gas-accreted}}$; injected at every 300 $M_{sun}$

# Multi-scale Physics

- Resolving things from $R_{Bondi}$ to $R_{galaxy}$, from $10^2$ K to $10^7$ K
  → AMR enzo-2.0 poised to do a better job than ever



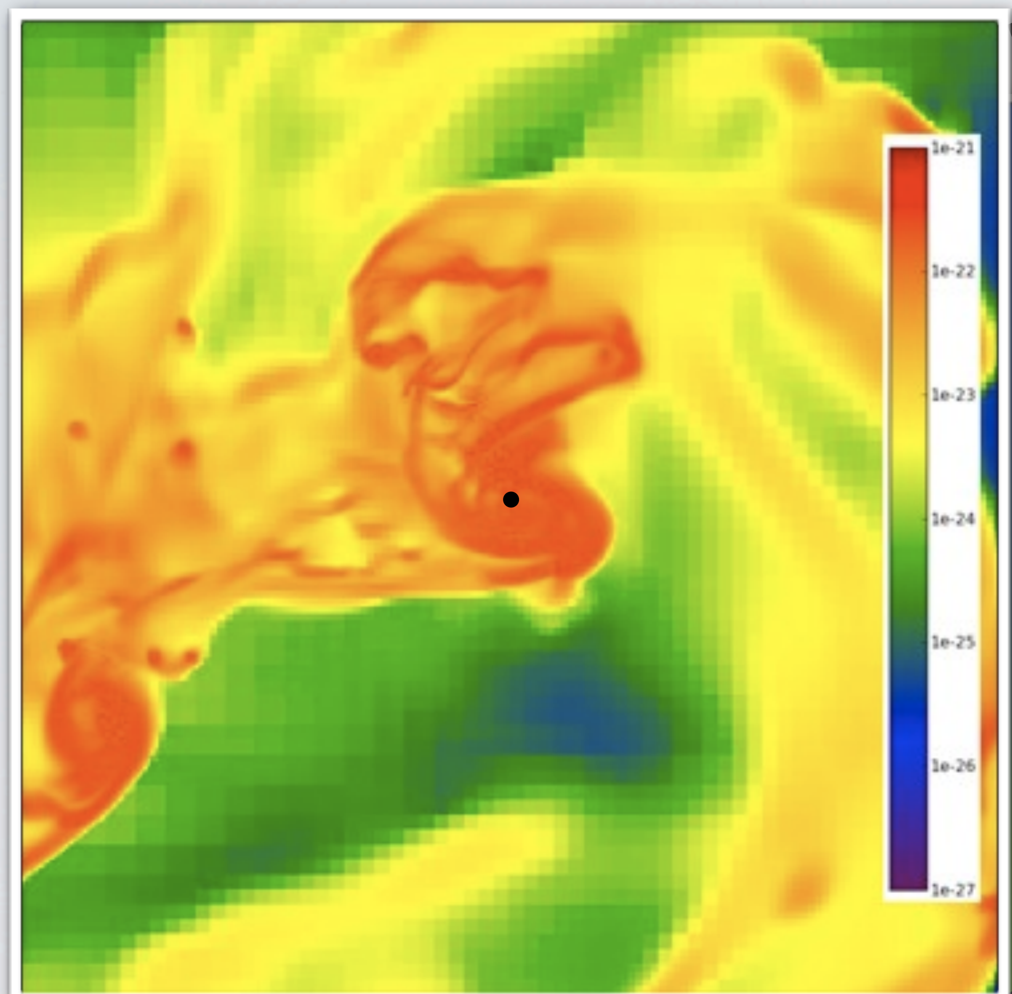





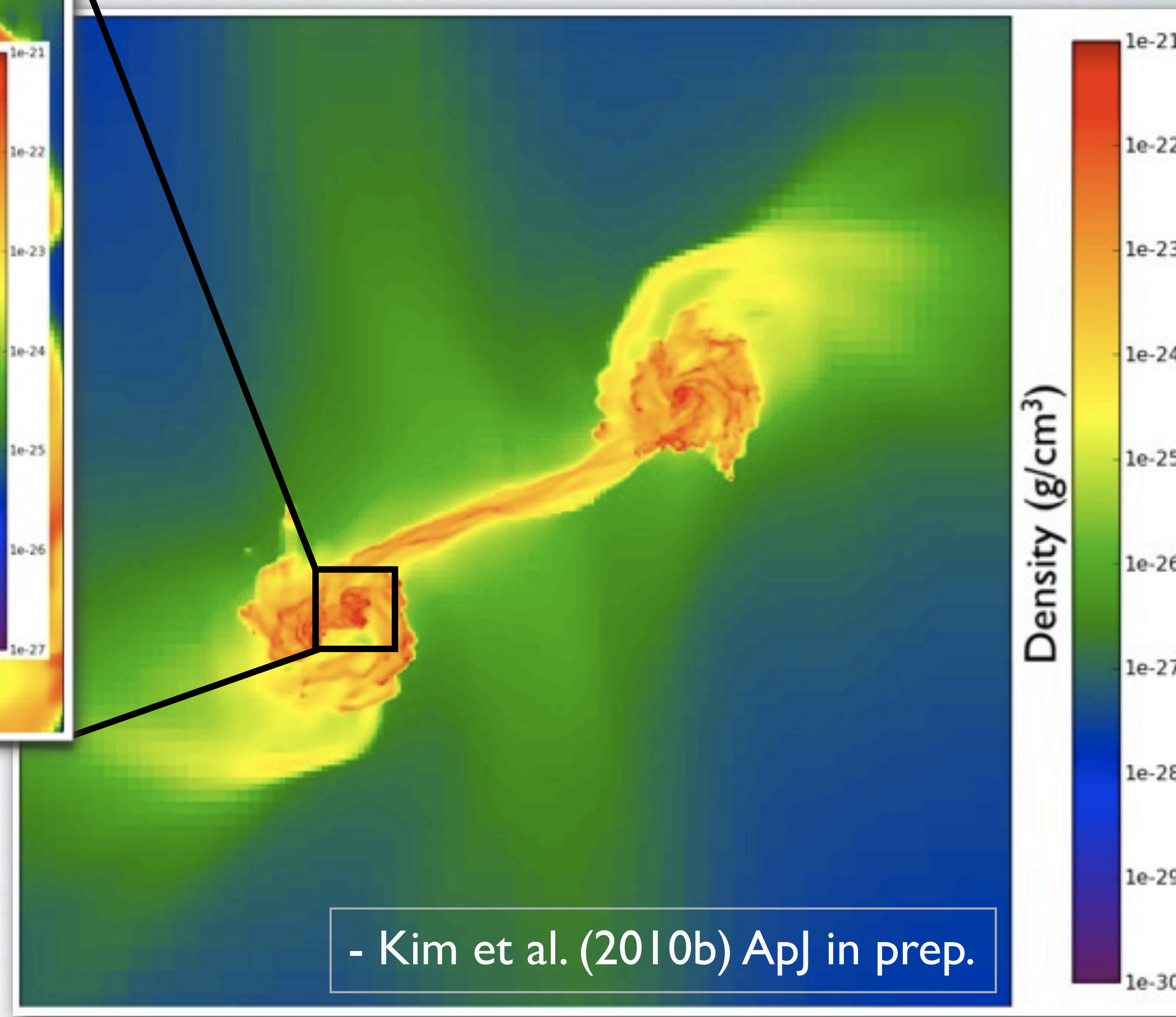
# [Setting Up An Experiment & Early Results]

# I. Galaxy Mergers

- Two 2x10$^{11}$ M$_{sun}$ galaxies with embedded 10$^{5}$ M$_{sun}$ MBHs set on a collisional orbit (60° tilted, initially separated by ~80 kpc)

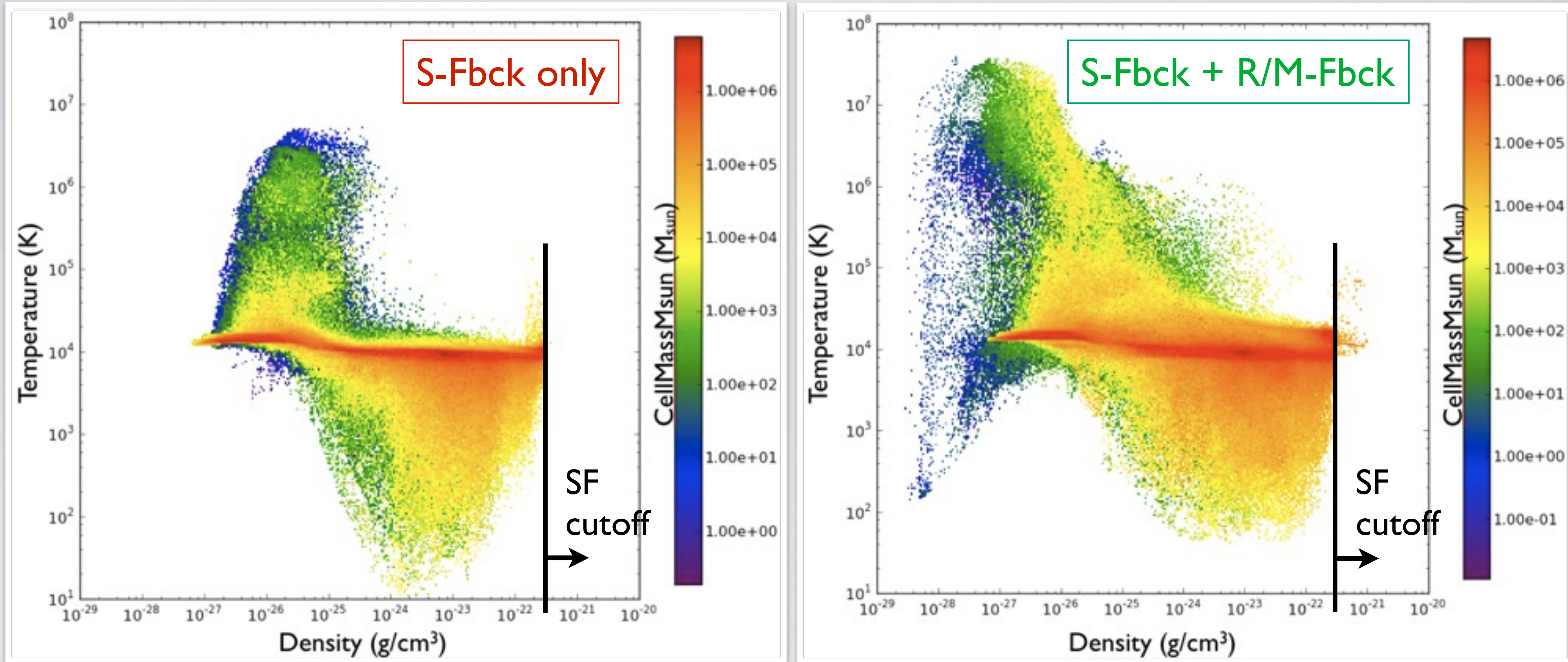


4 kpc centered on a MBH




Density-weighted density proj., 40 kpc, 200 Myrs

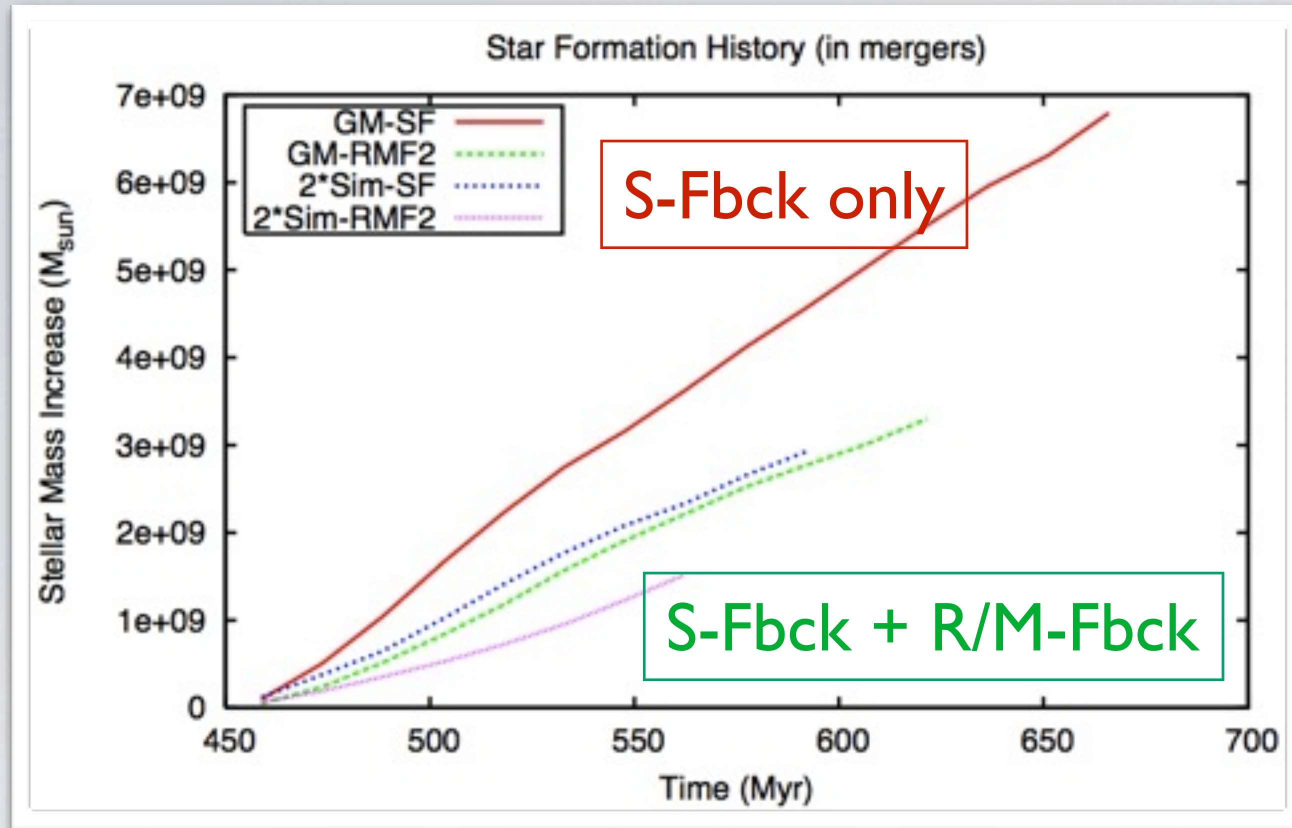
# Density-Temperature PDF



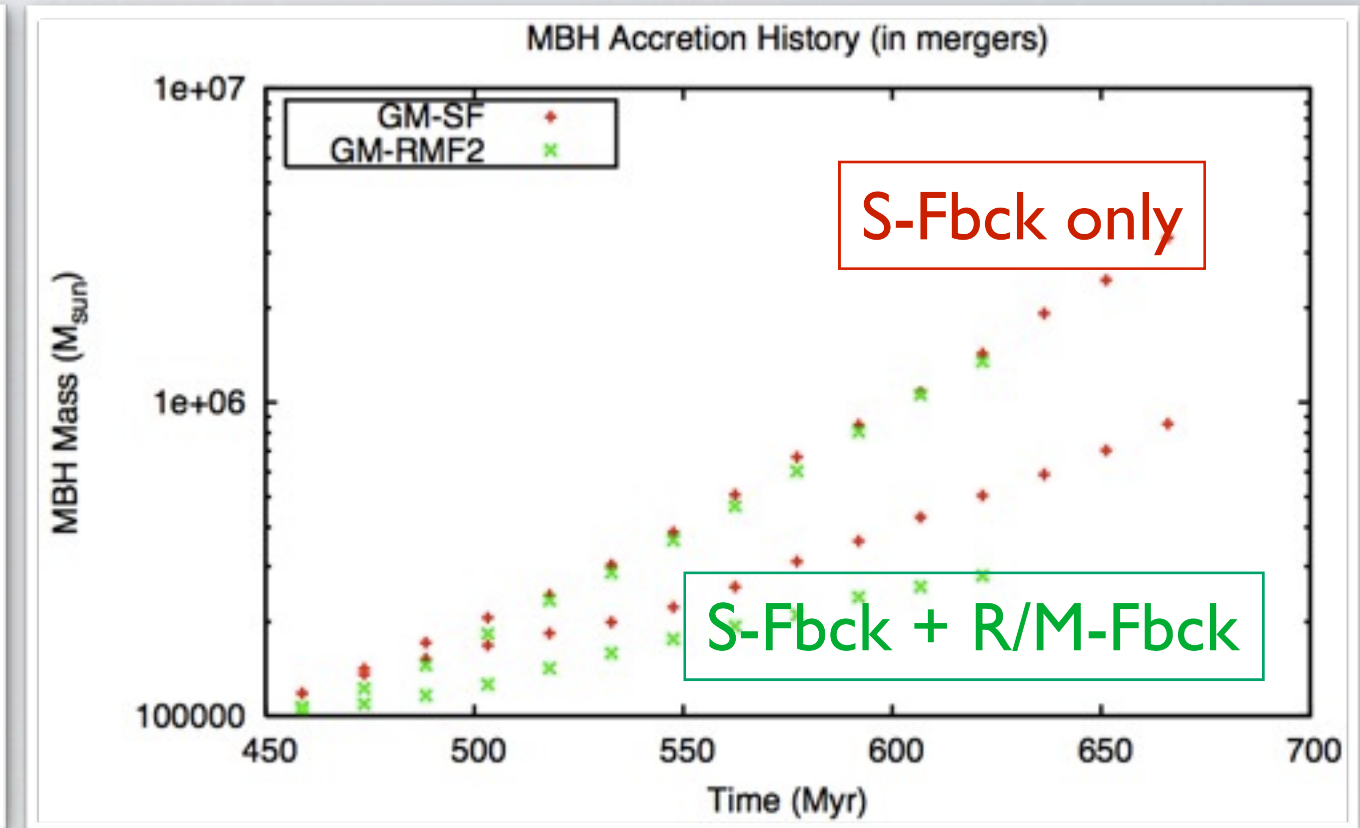

PDF in a 10 kpc sphere centered on one of MBHs

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

# SF and BH Accretion History




SFH (total stellar mass increase)

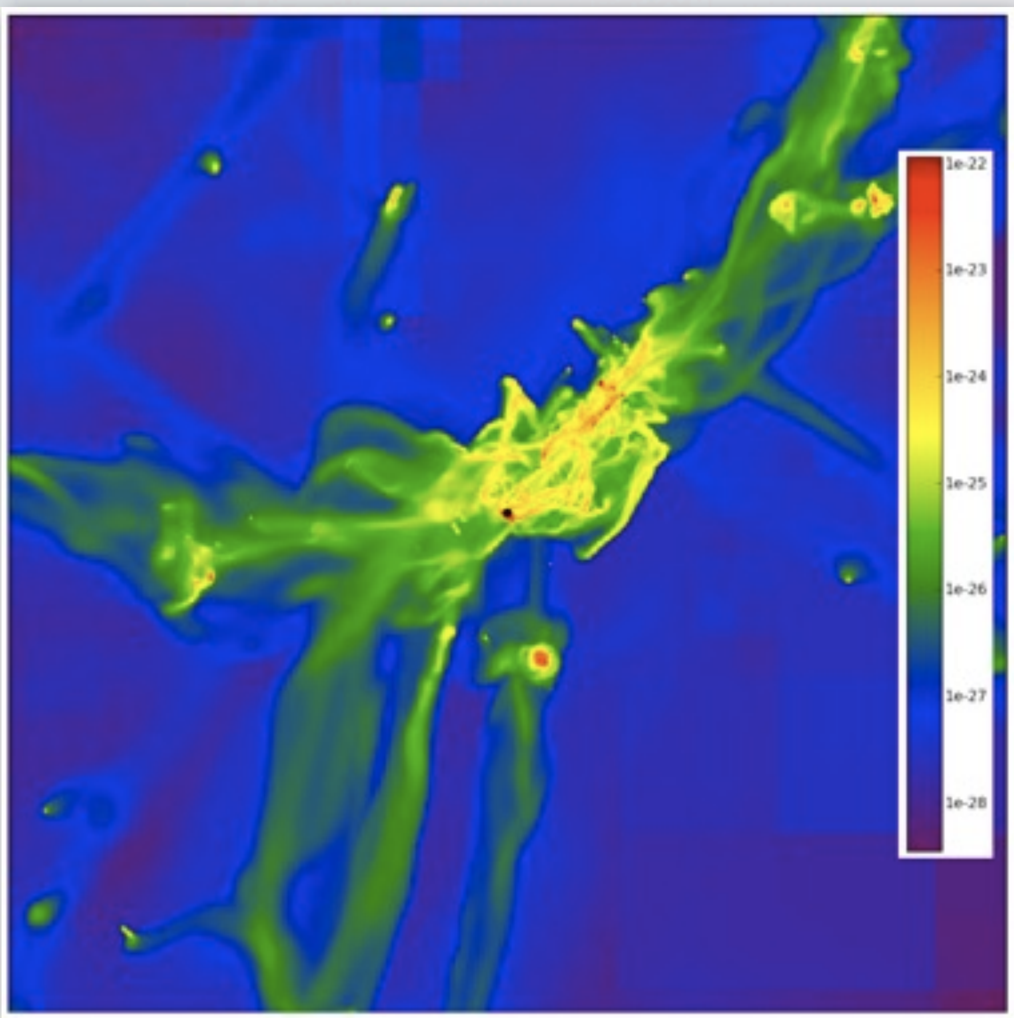



BHAH

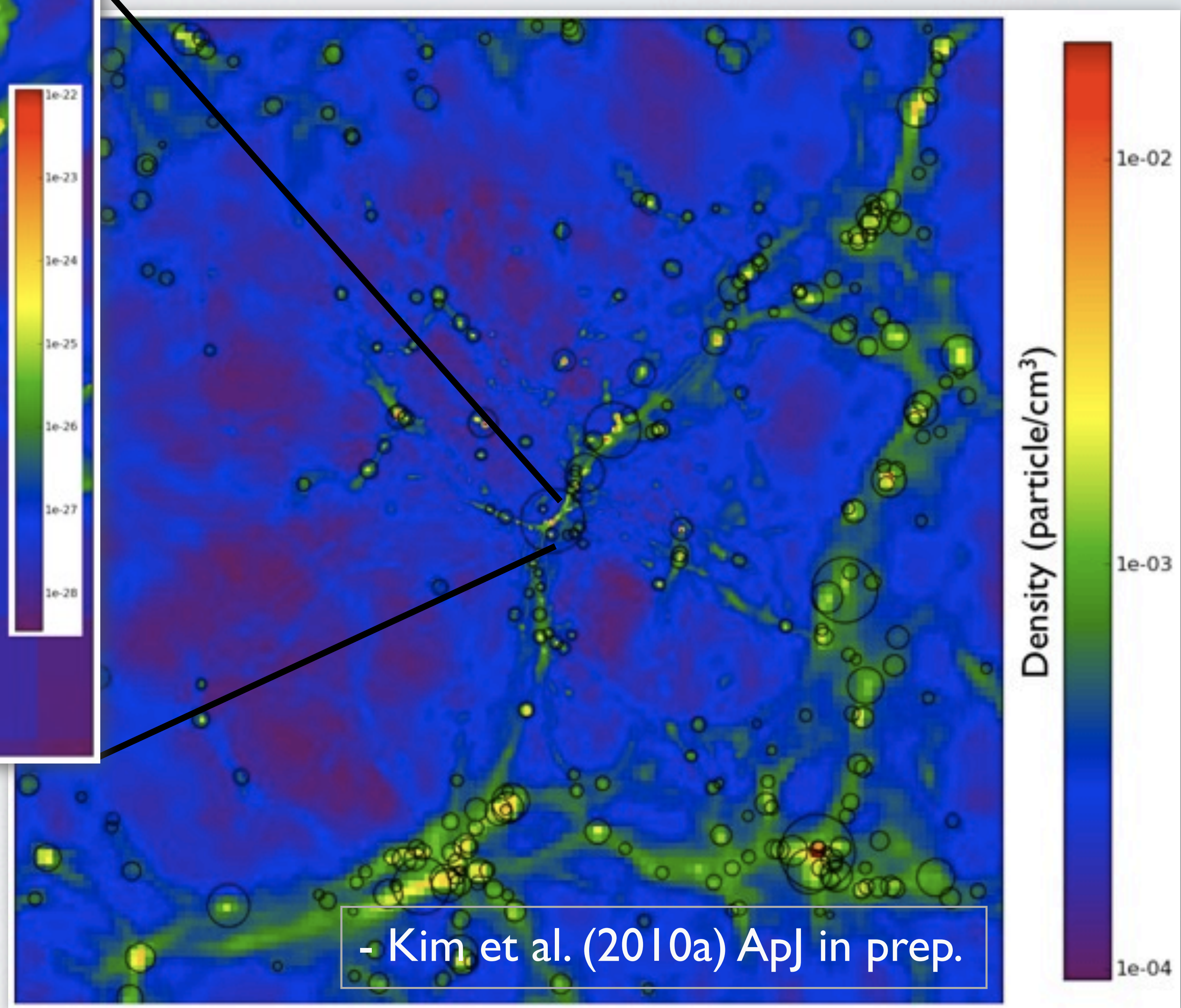
- Star formation rate suppressed by soft X-ray radiation from MBH; more to see as two galaxies start to merge
- Jets do not impact much in regulating accretion as they are mostly perpendicular to gas disks

# II. Cosmological Galaxy Formation at z=3

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

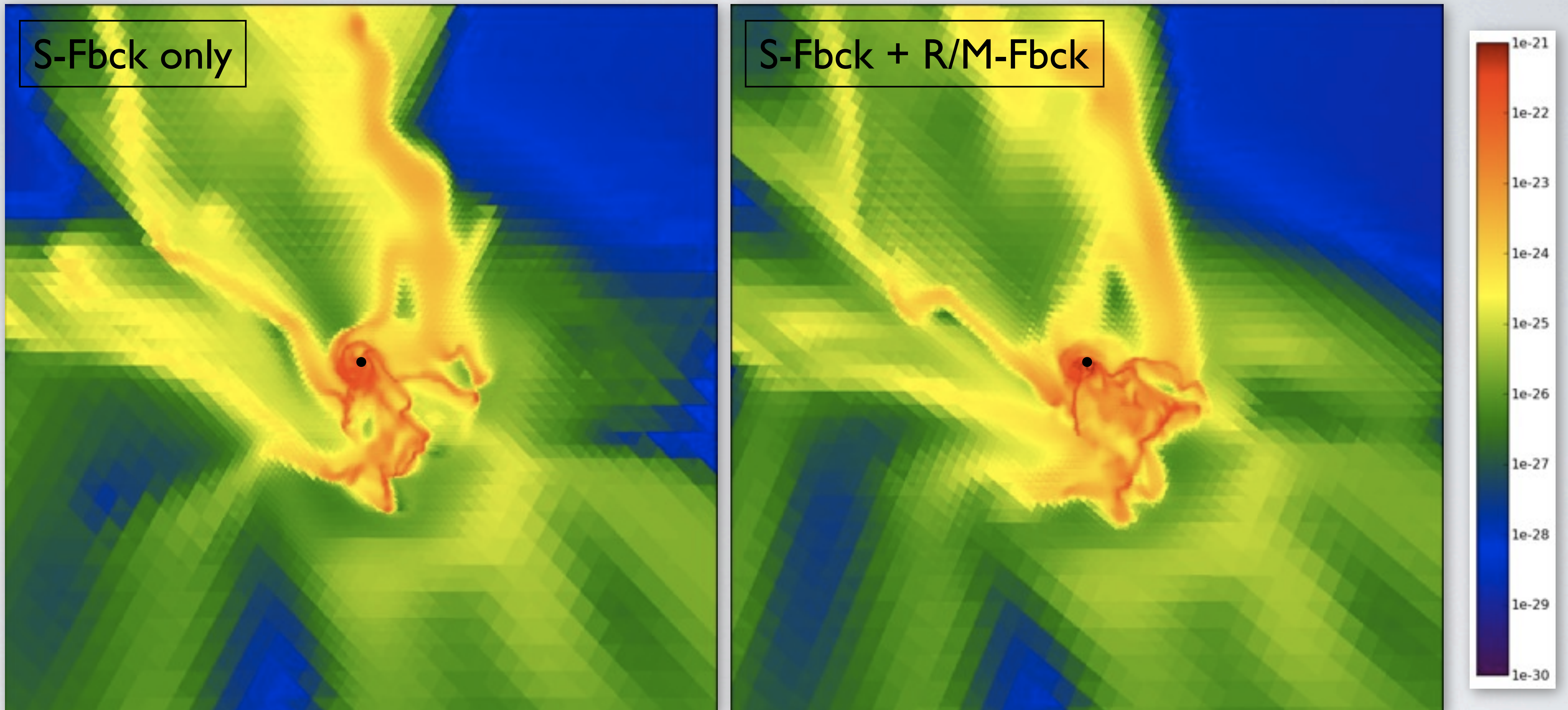



200 kpc centered on a MBH




z=3, Density projection,16 comoving Mpc

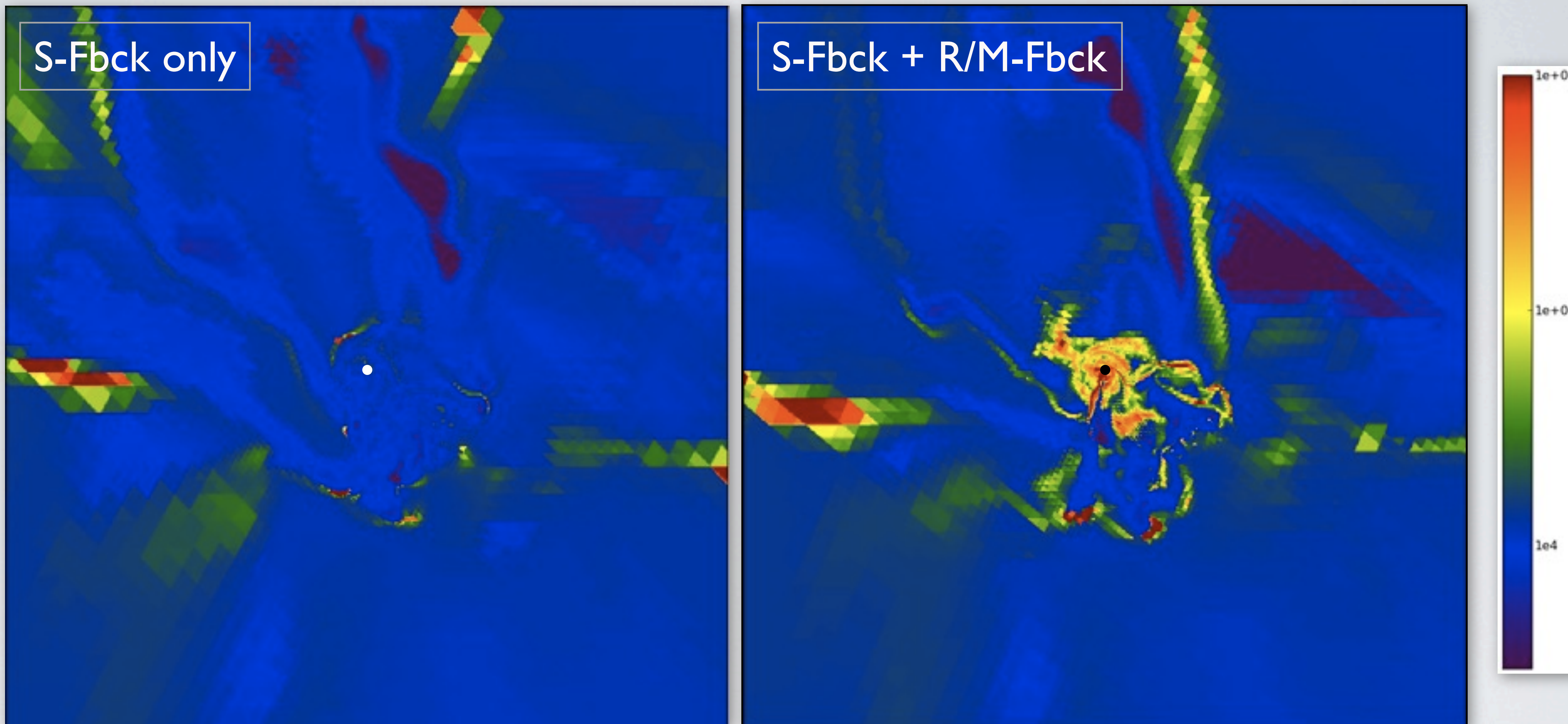
# Density Slice (Face-on)




Slice perpendicular to L, ~200 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

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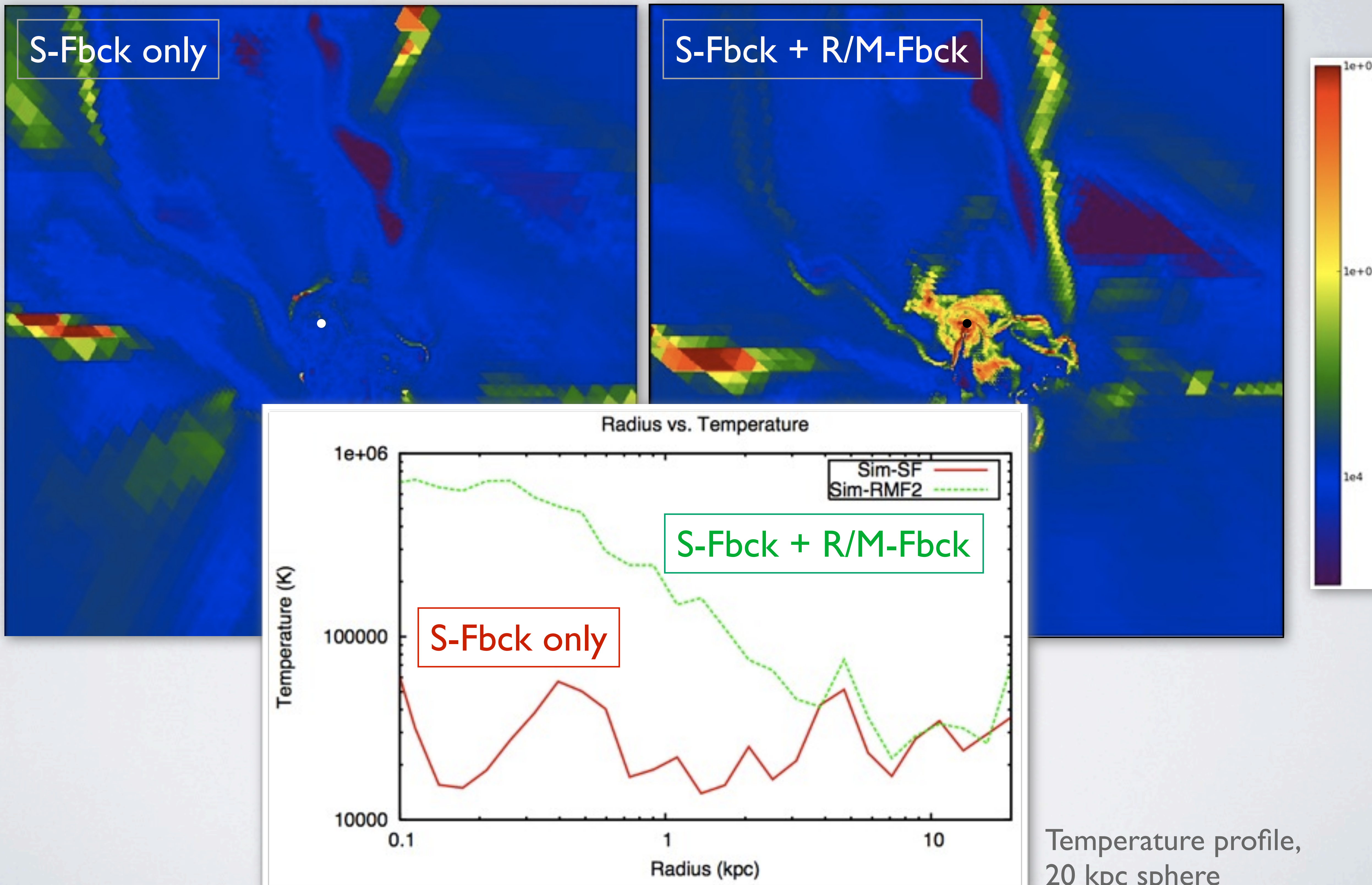
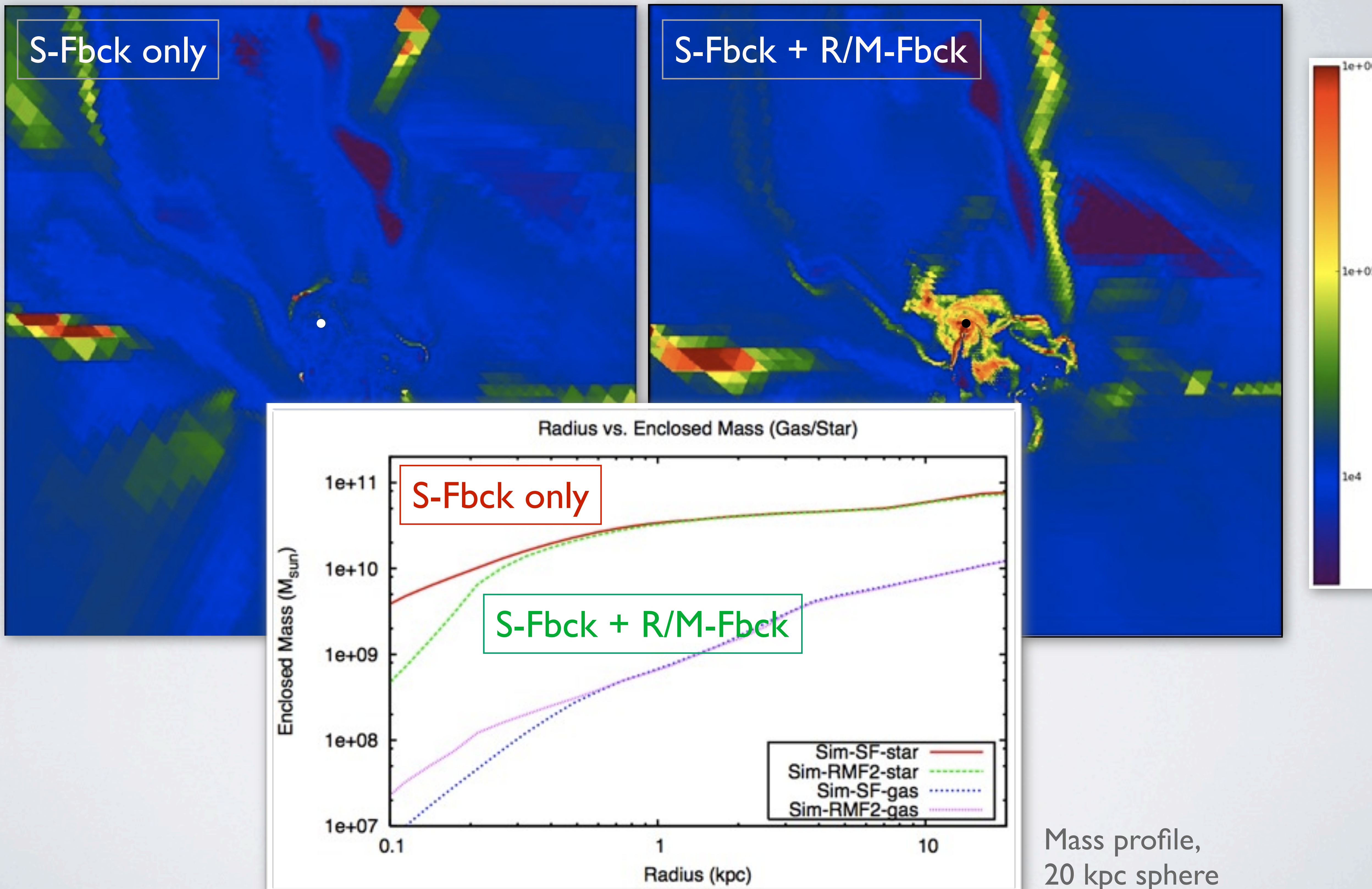


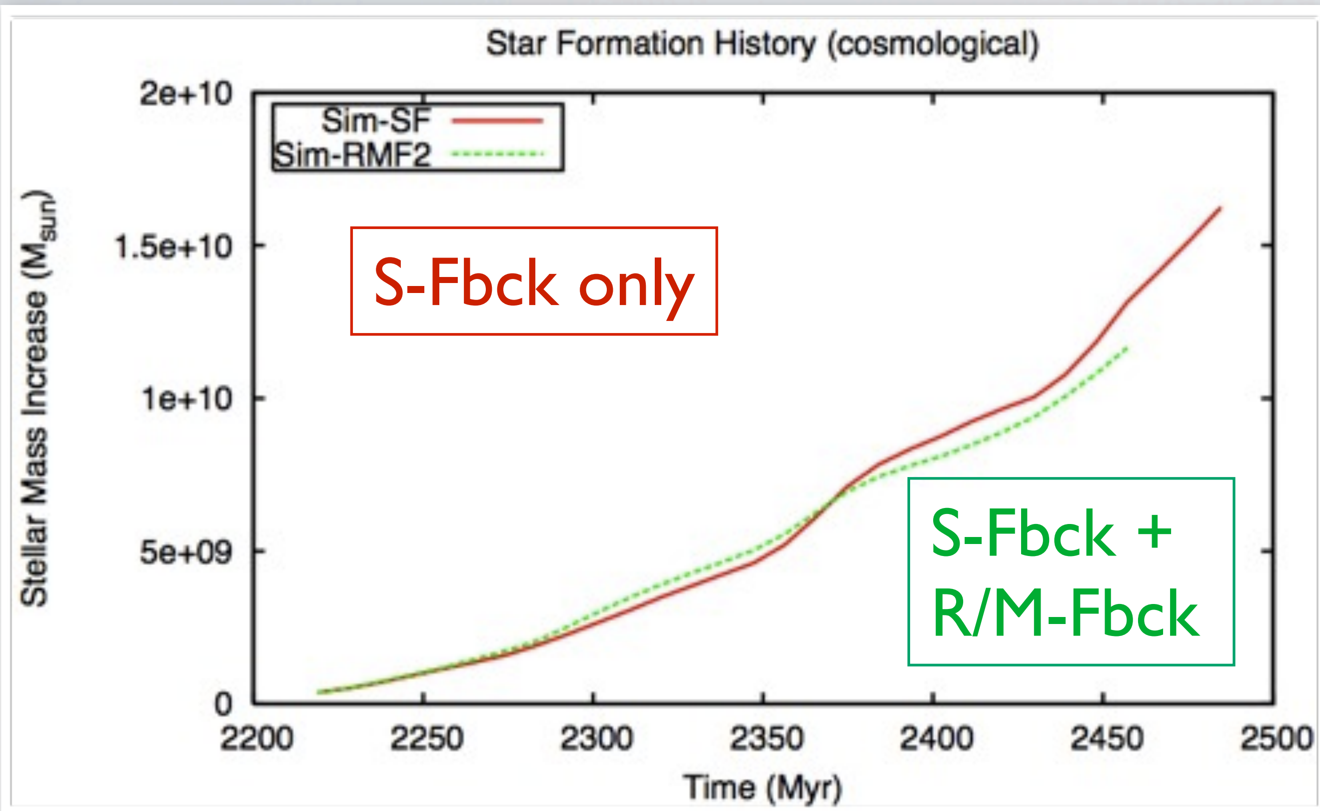

Temperature profile, 20 kpc sphere

# Radial Density Profile

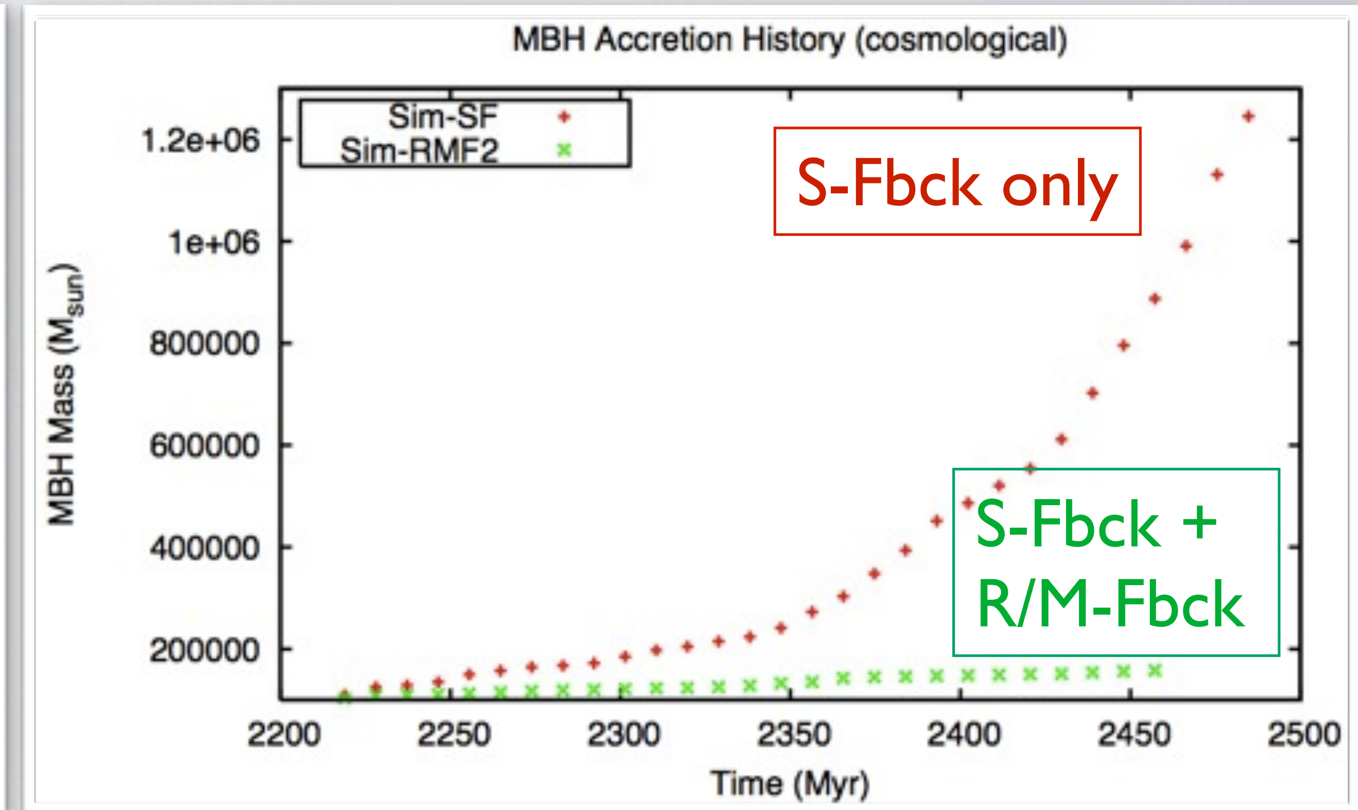



Mass profile,
20 kpc sphere

# SF and BH Accretion History




SFH (in the entire volume)




BHAH

- 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:

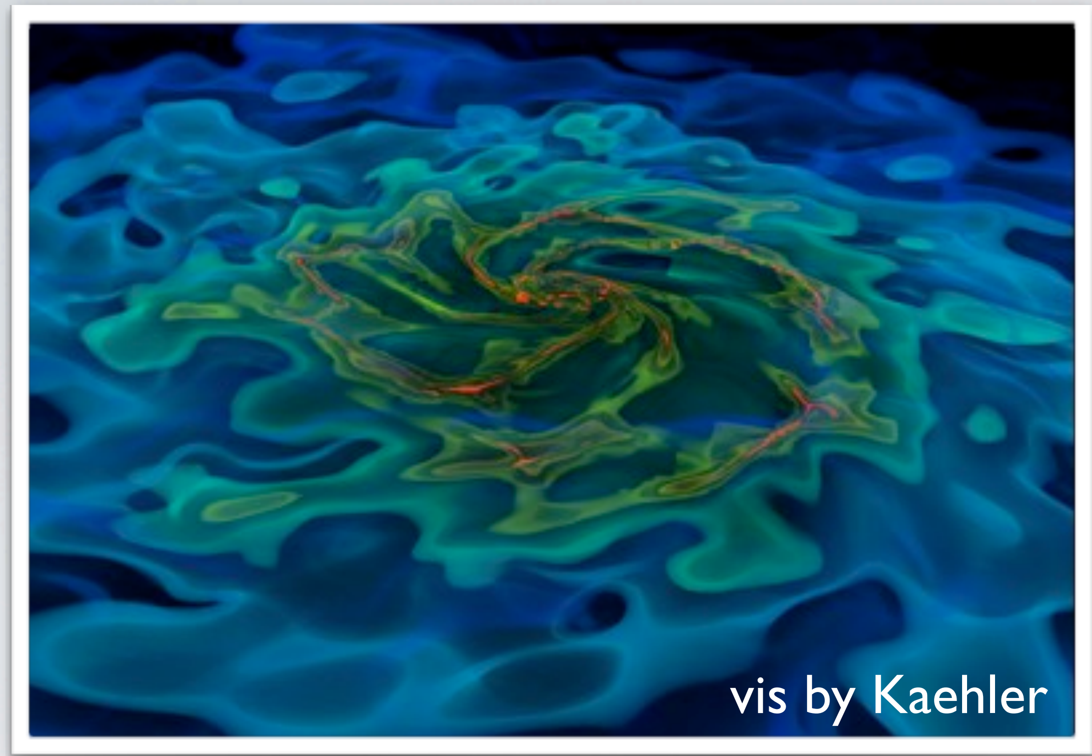
  - Proper treatment of MC formation & feedback
  - Proper treatment of MBH accretion & feedback

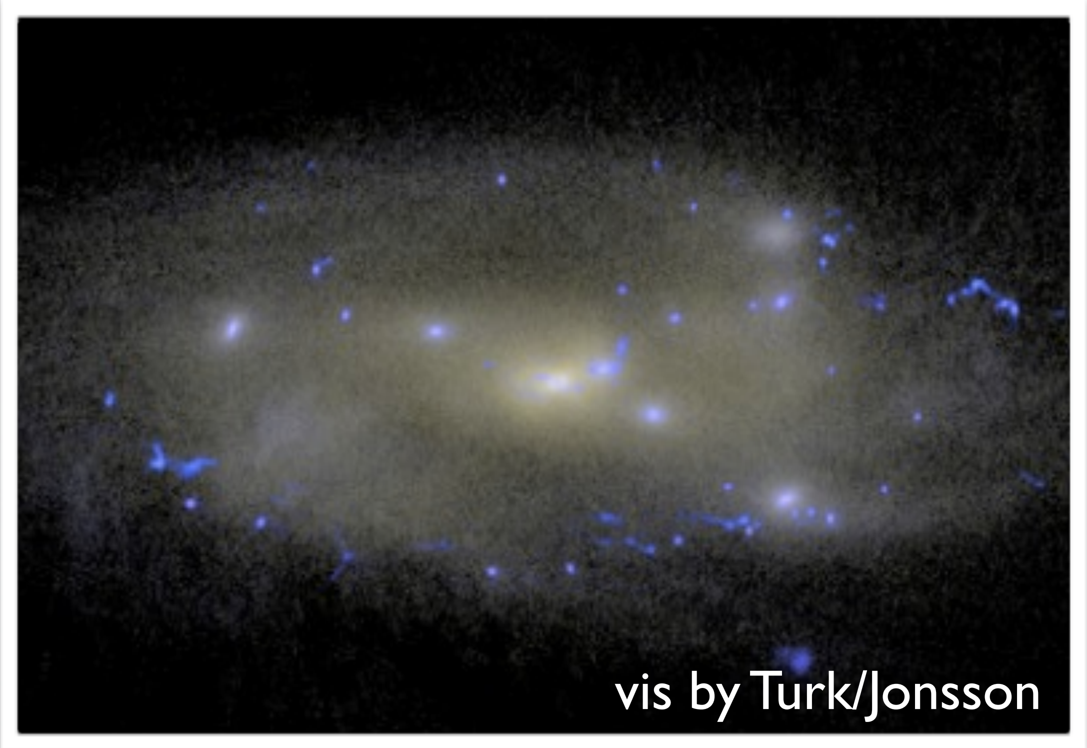
- Stellar and MBH processes in one self-consistent framework

  - MBH feedback regulates SF and its own growth
  - With tools at hand, many future projects are being designed

- Kim, Wise, Alvarez, & Abel (2010a, b) in prep.

- Kim, Wise, & Abel (2009) ApJL 694 L123



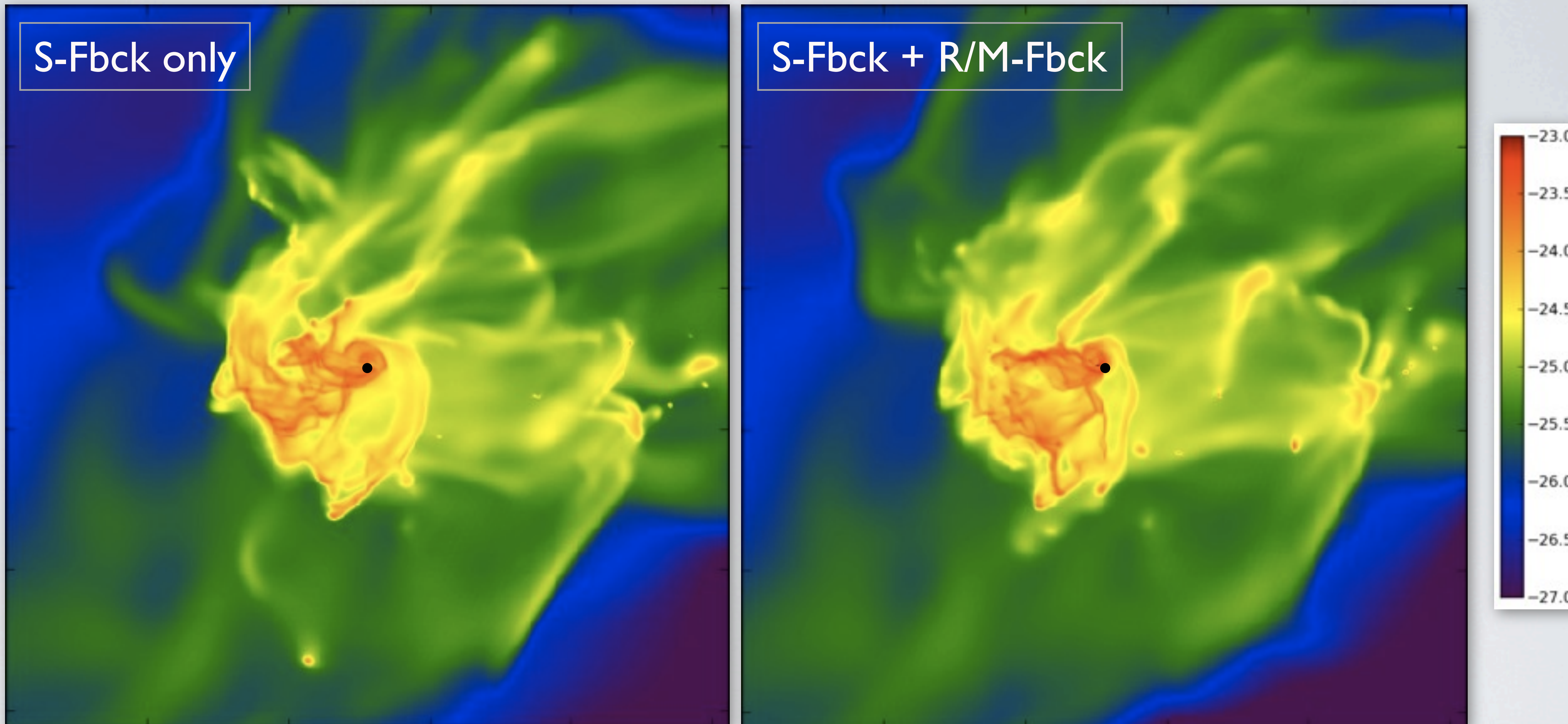




# Thank you!

- Kim, Wise, Alvarez, & Abel (2010a, b) in prep.
- Kim, Wise, & Abel (2009) ApJL 694 L123

# [Supplemental Slides]

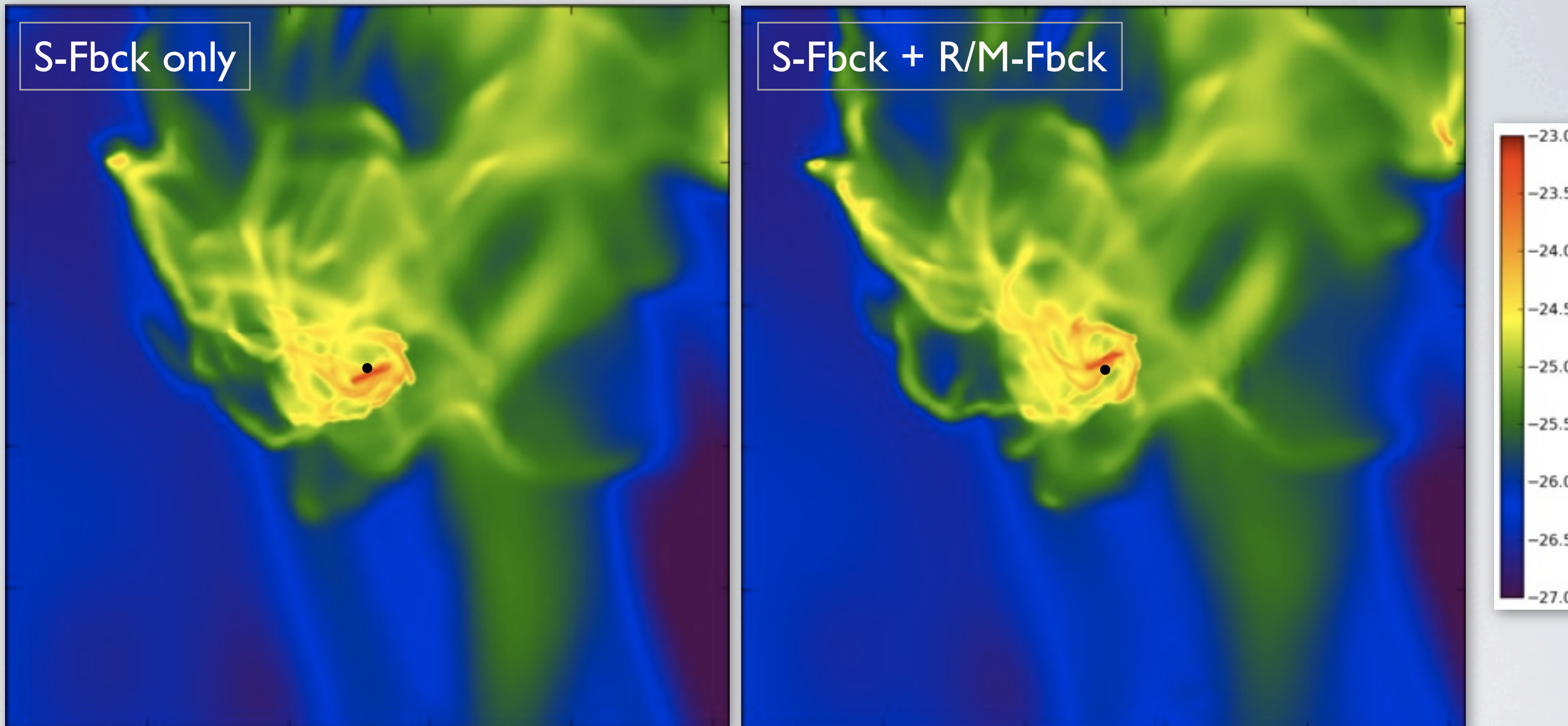
# Morphology:  Face-on Projection




Projection along L, ~220 Myrs, 20 kpc

- MBH feedback makes the disk hot and turbulent preventing gravitational collapse

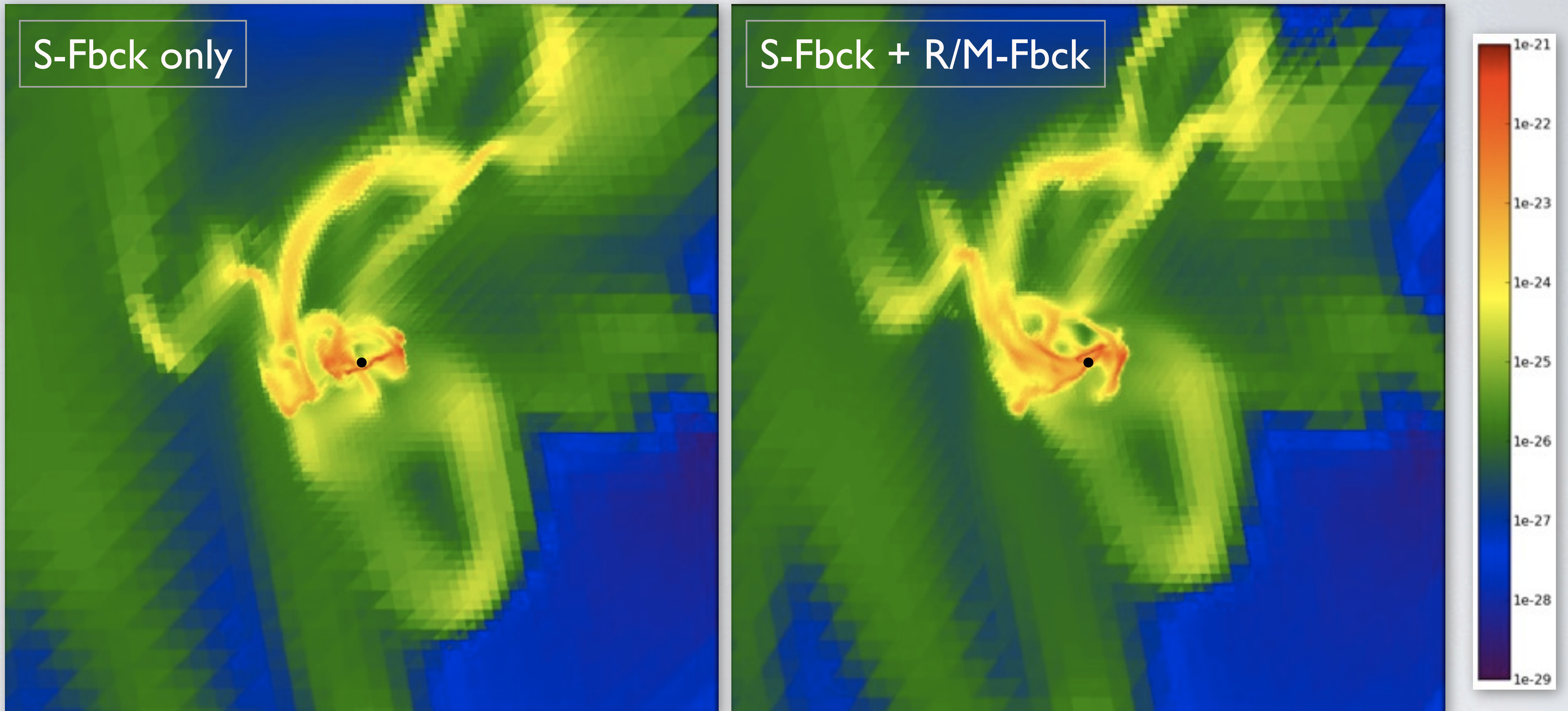
# Face-on Projection (Earlier)




Projection along L, 100 Myrs, 20 kpc

- Too early to compare morphological differences, yet

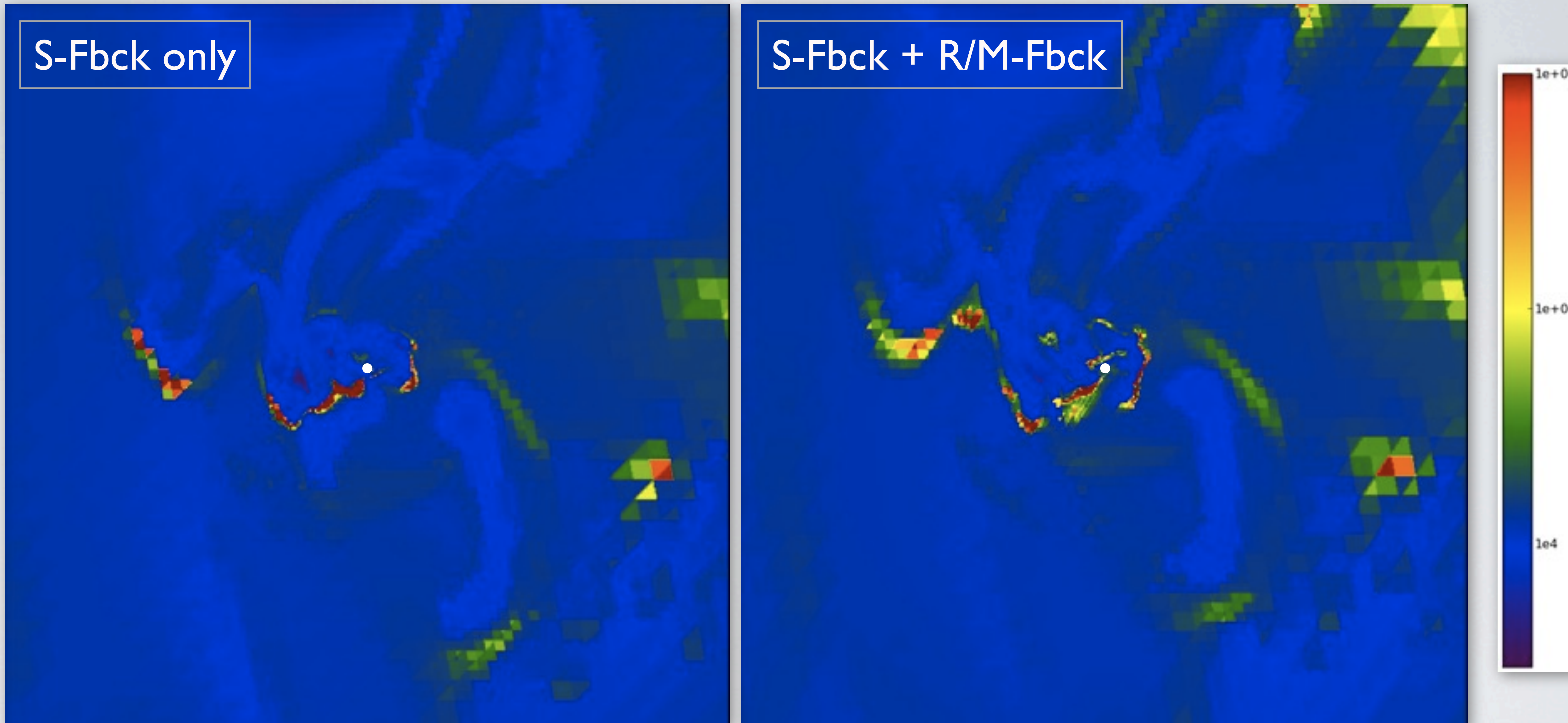
# Density Slice (Earlier)




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)




Slice perpendicular to L, 100 Myrs, 20 kpc

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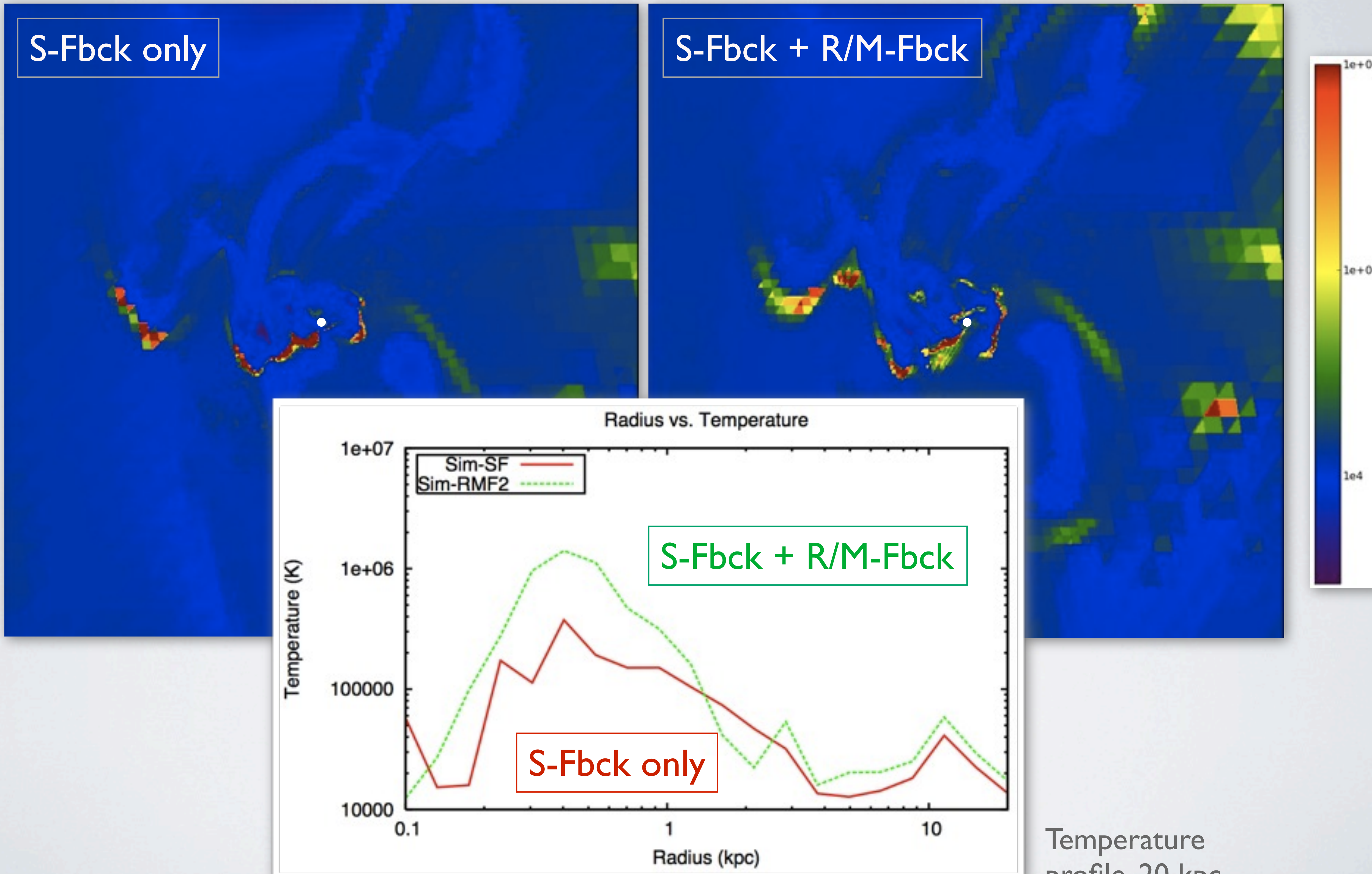
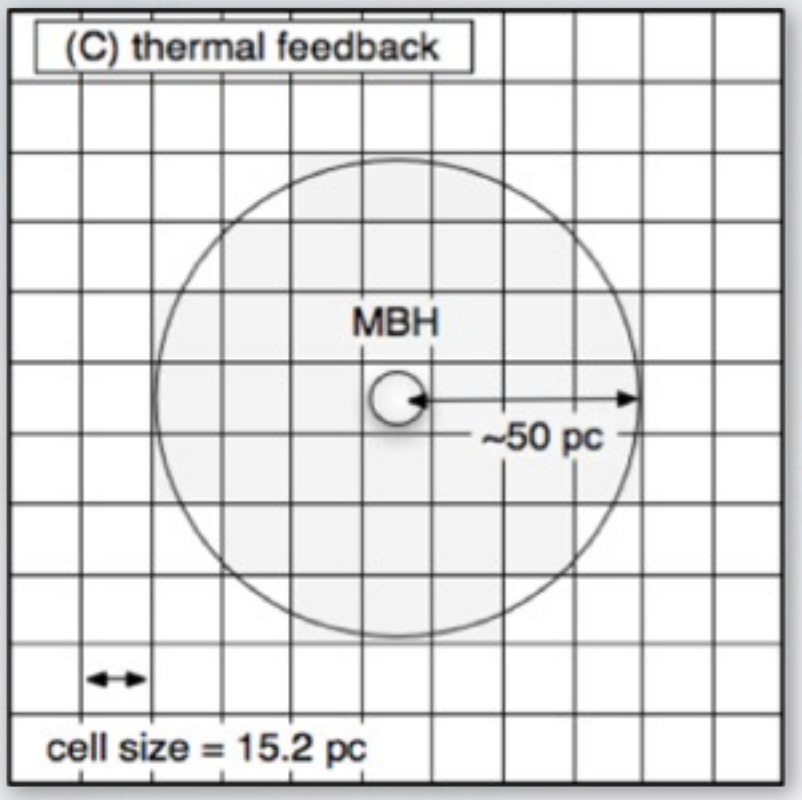
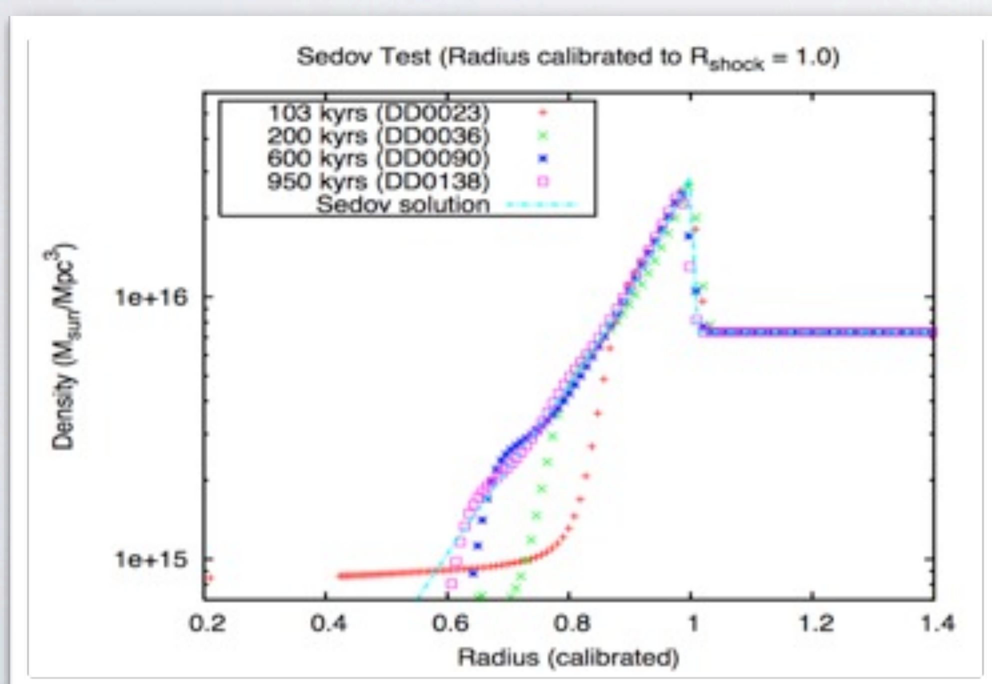
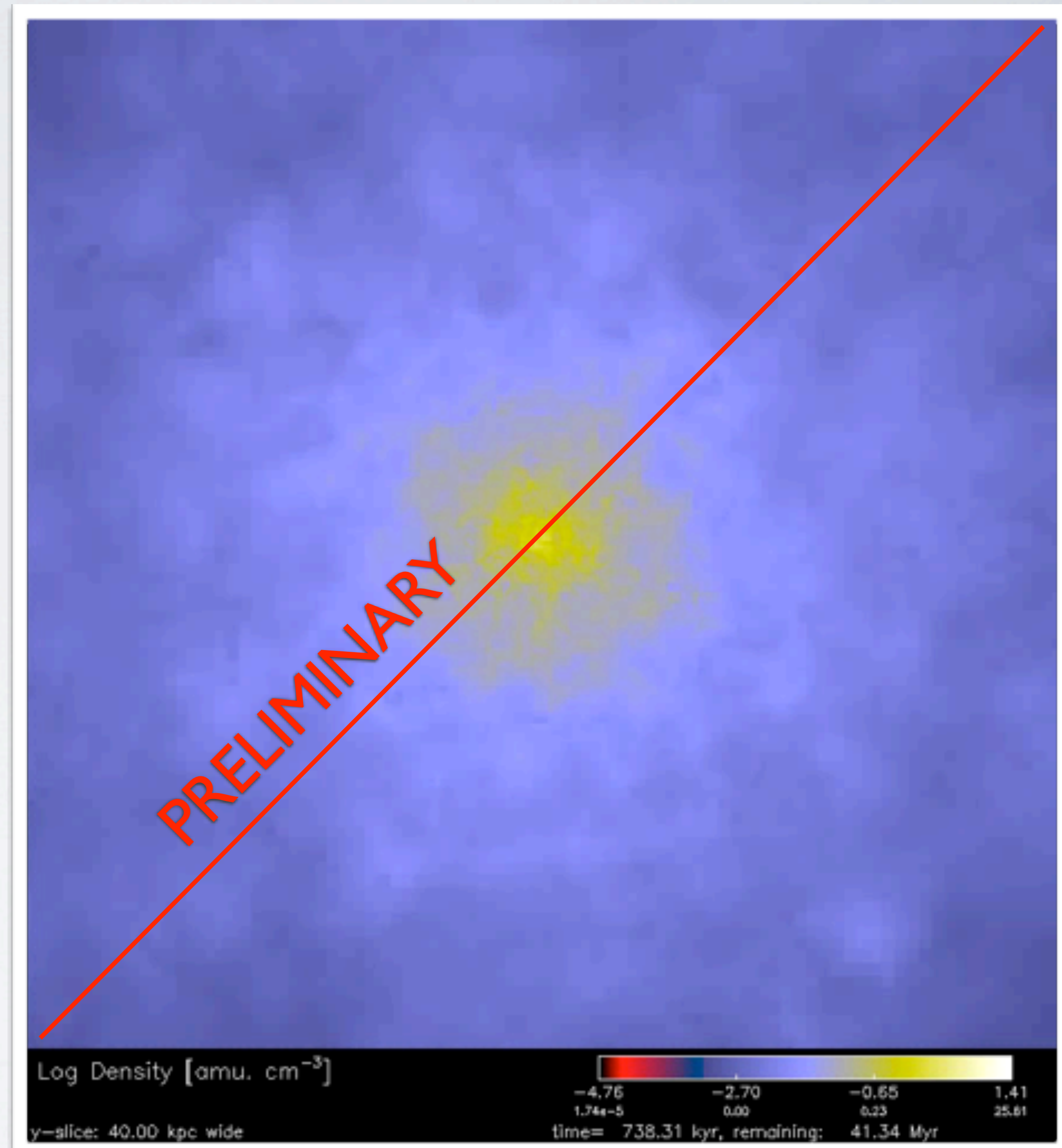



Temperature profile, 20 kpc

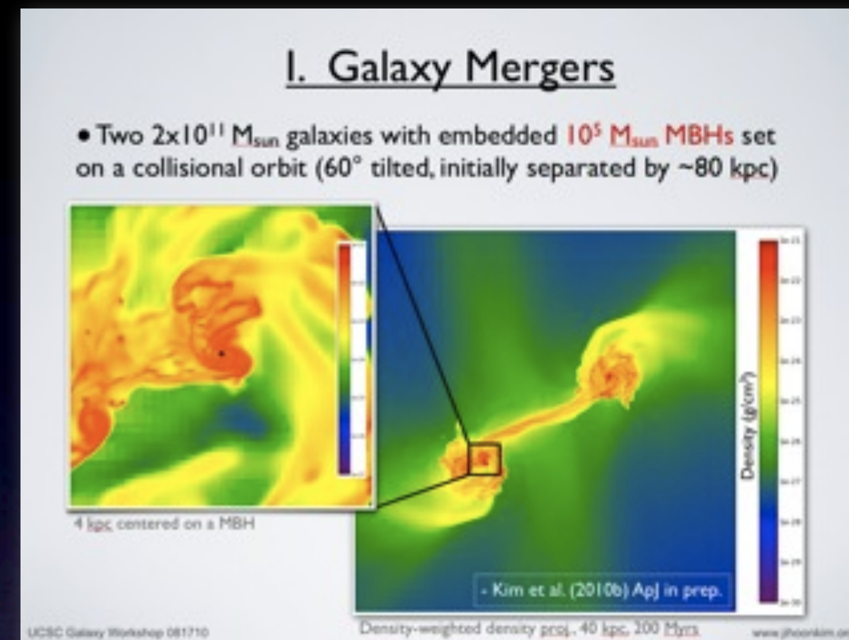
# MBH Thermal Feedback

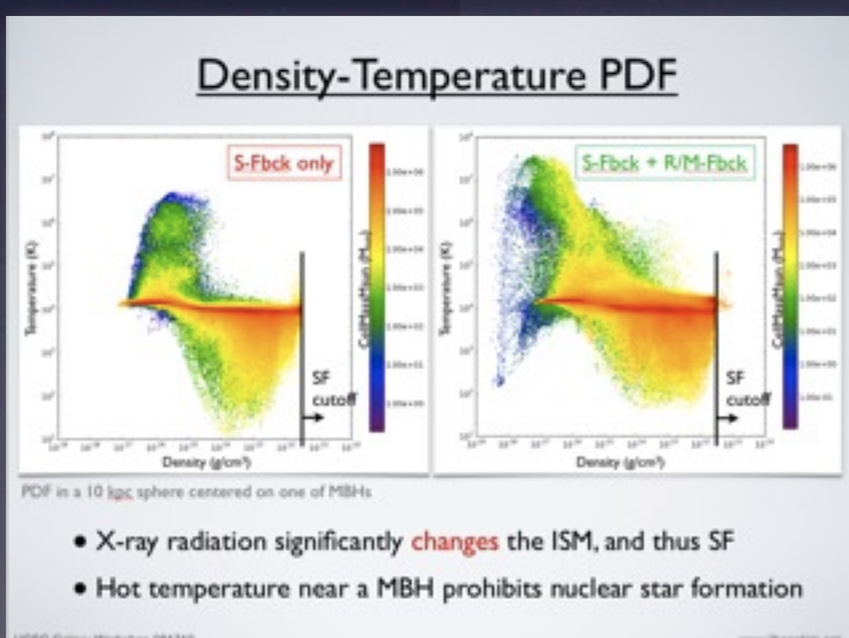


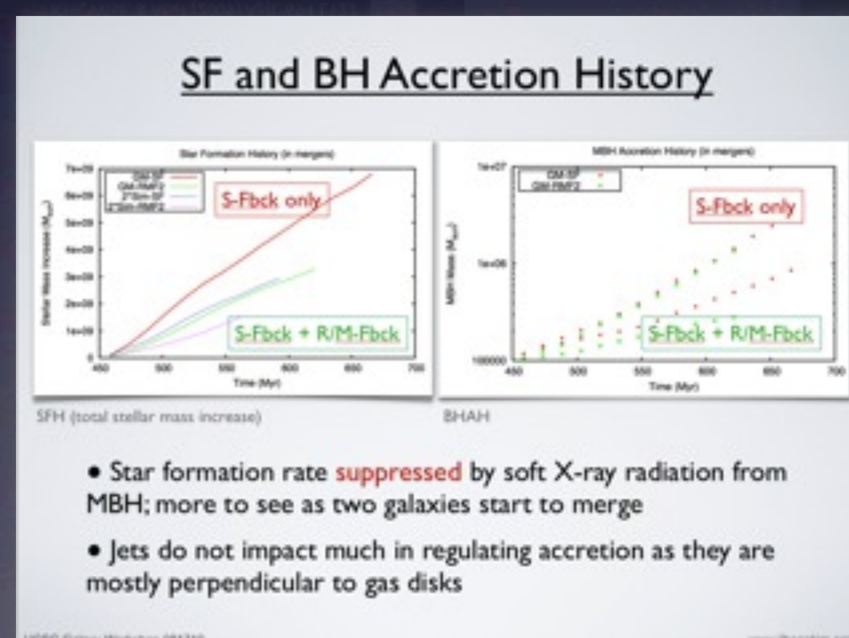



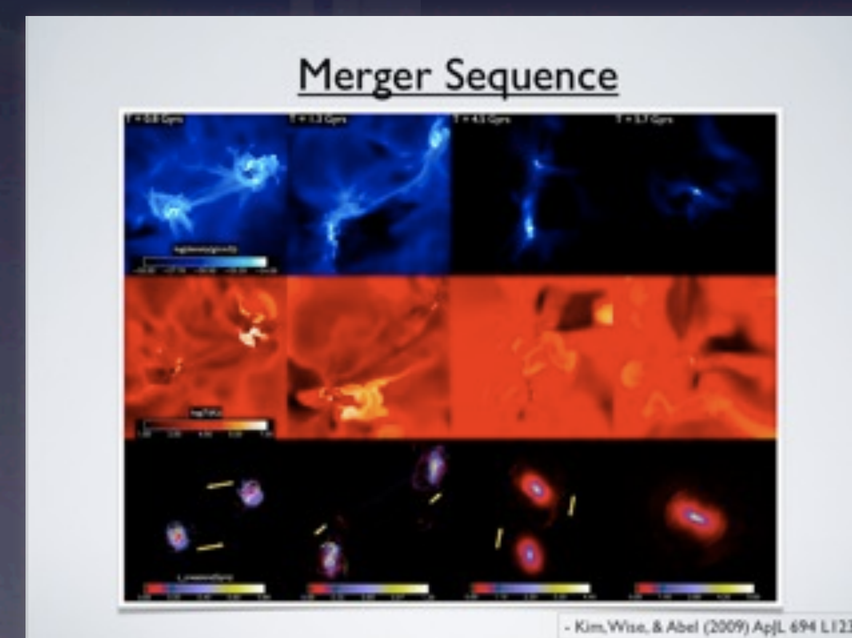



# [I. Galaxy Mergers]

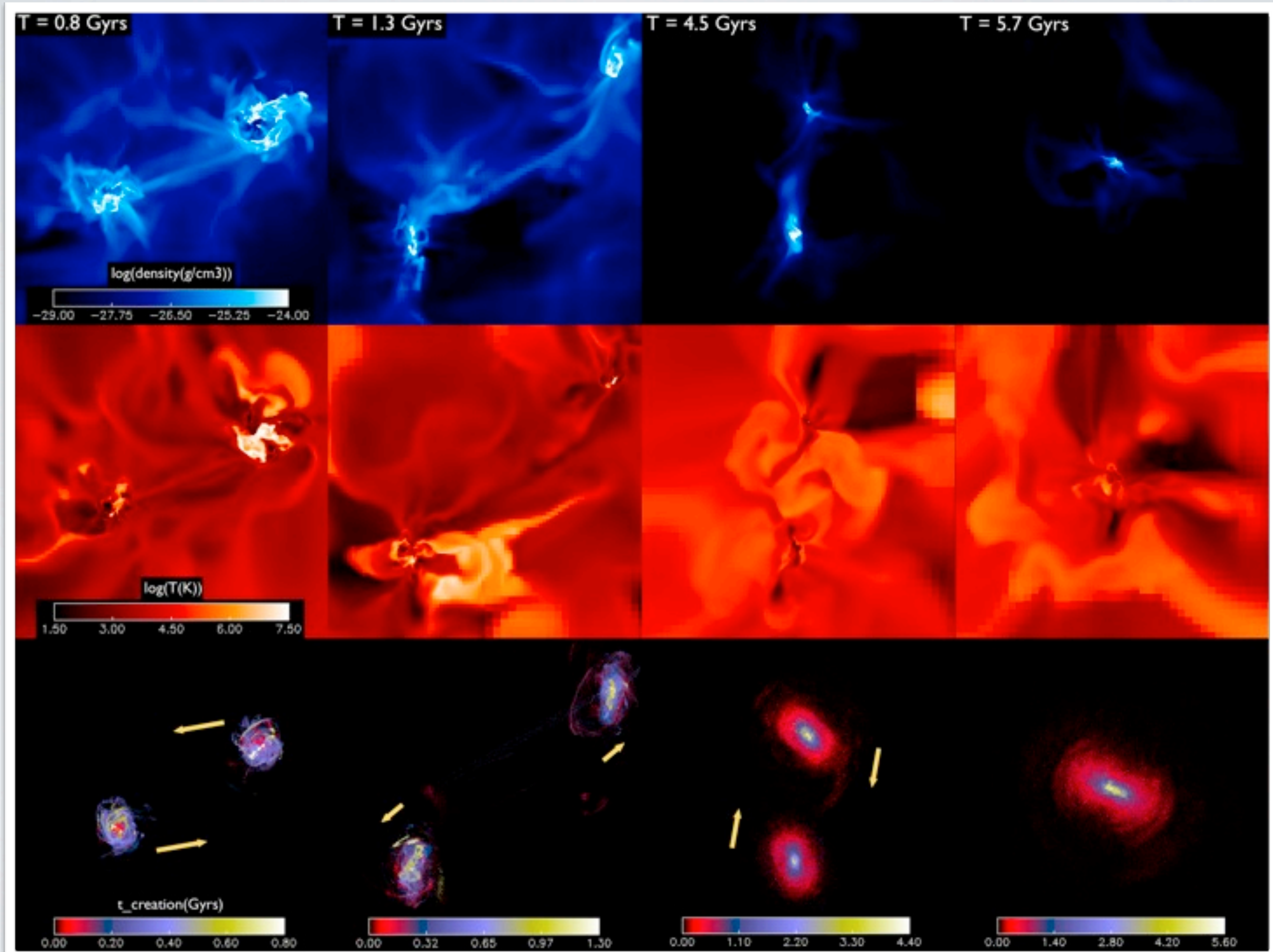



# Merger Sequence




- Kim, Wise, & Abel (2009) ApJL 694 L123

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