Cosmological Simulations to Study Galaxy Formation: High-z Quasar Outflows

INSTITUTO DE ASTRONOMIA, GEOFÍSICA E CIÊNCIAS ATMOSFÉRICAS

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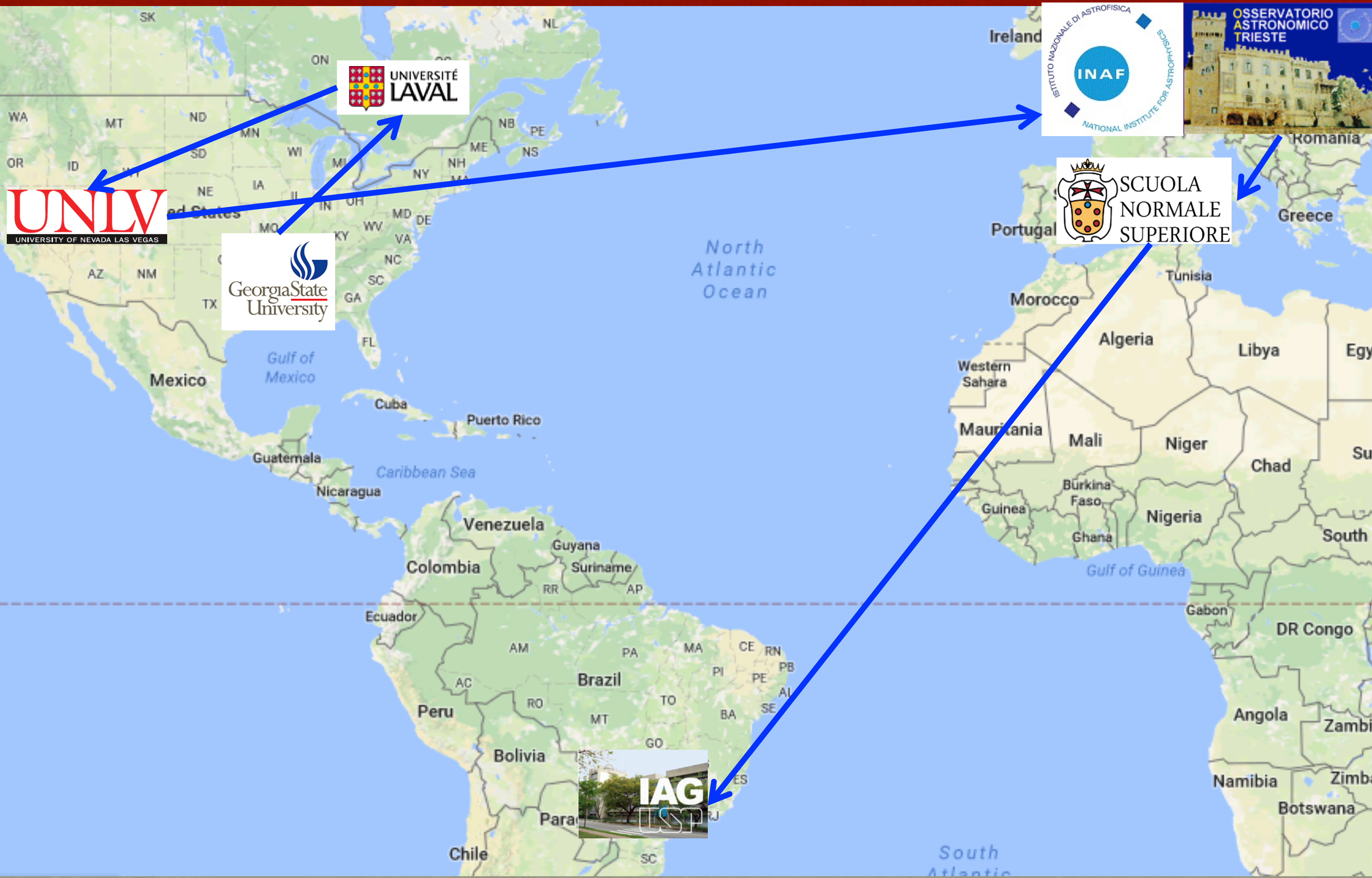
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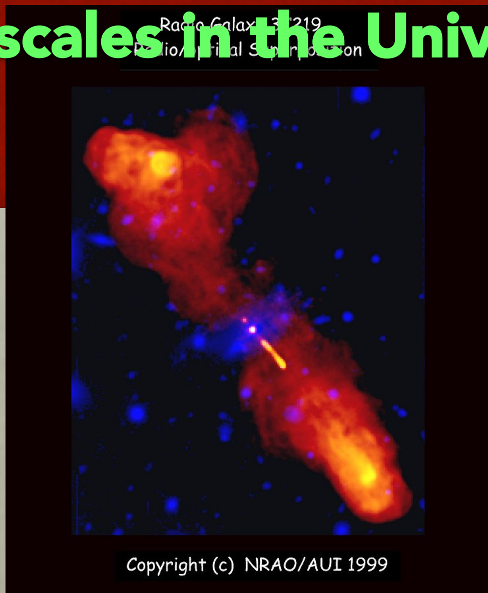
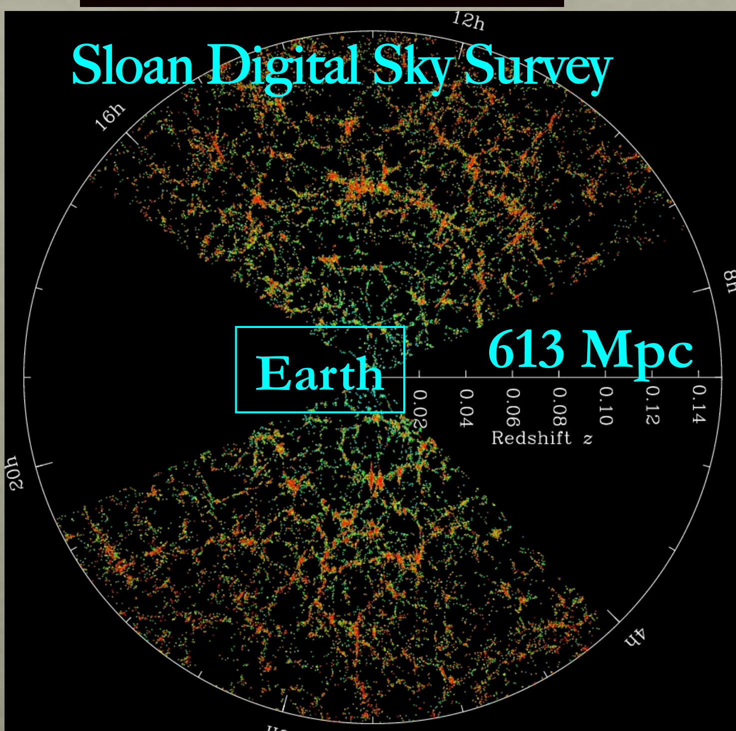
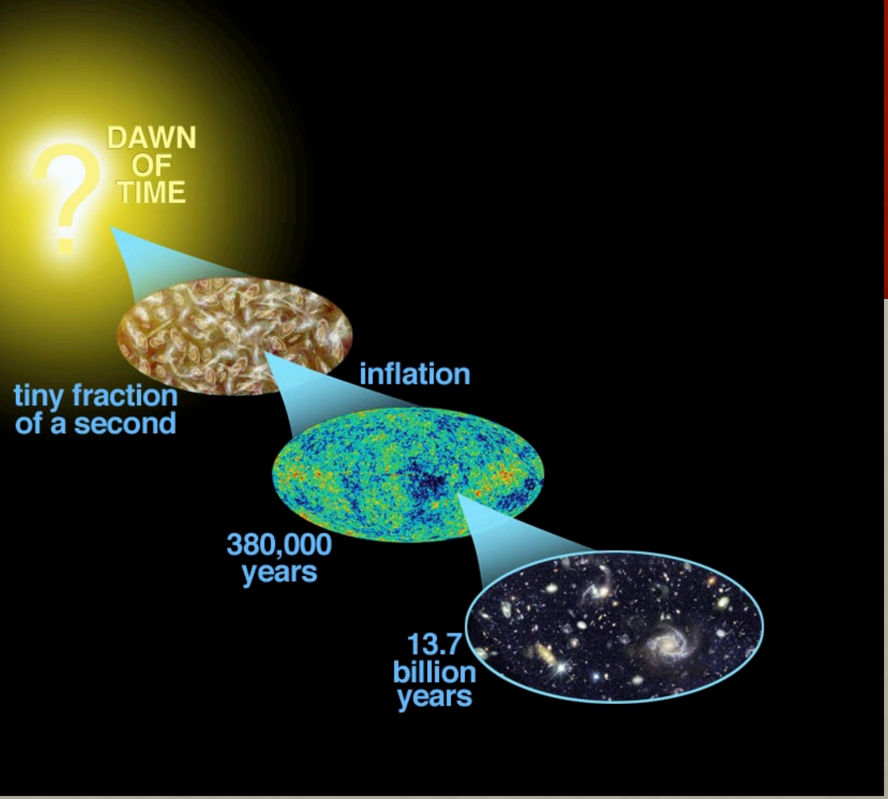
Matter observed to be distributed in various forms at different scales in the Universe: Galaxy, Cluster, Large-scale structure







Large Scale Structure Formation

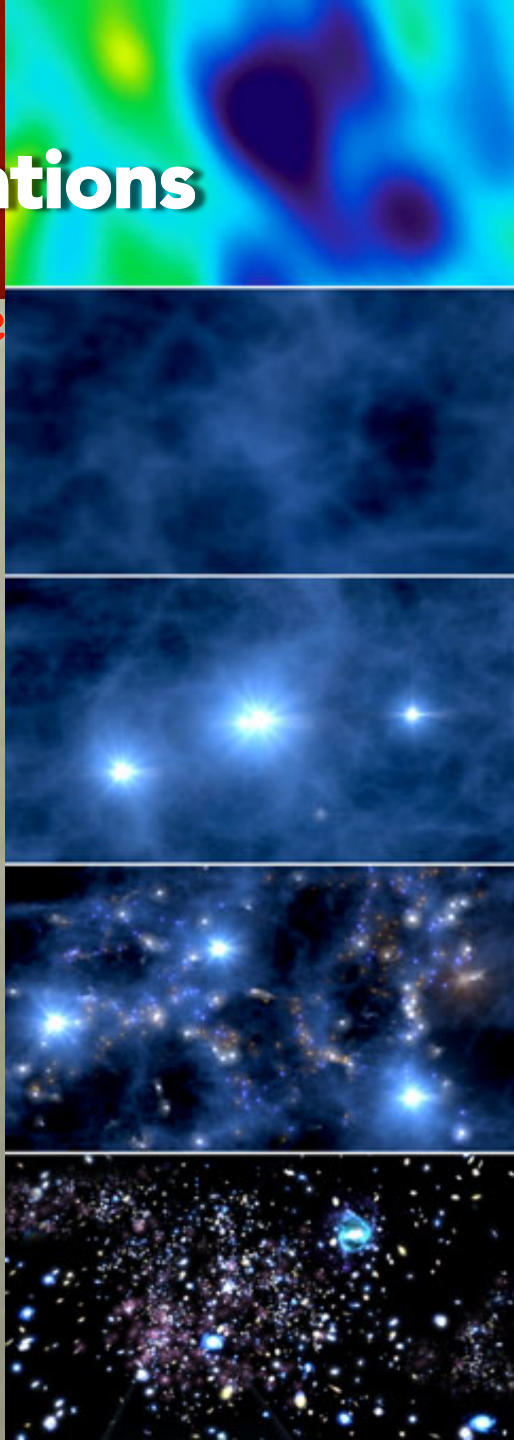
- Big Bang
  ⇒ (shortly after) Quantum fluctuations
  ⇒ Primordial density perturbations

- Inflation expands the perturbations

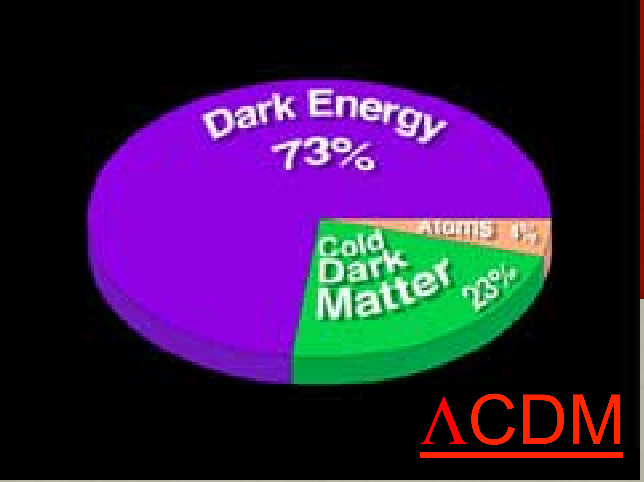
- Gravitational clumping of matter from these density fluctuations
  ⇒ Structures grow

- Main forces
  - Gravity : affects dark matter and baryons
  - Gas dynamics : only baryons

The Universe in a Box: Cosmological Hydrodynamical Simulations



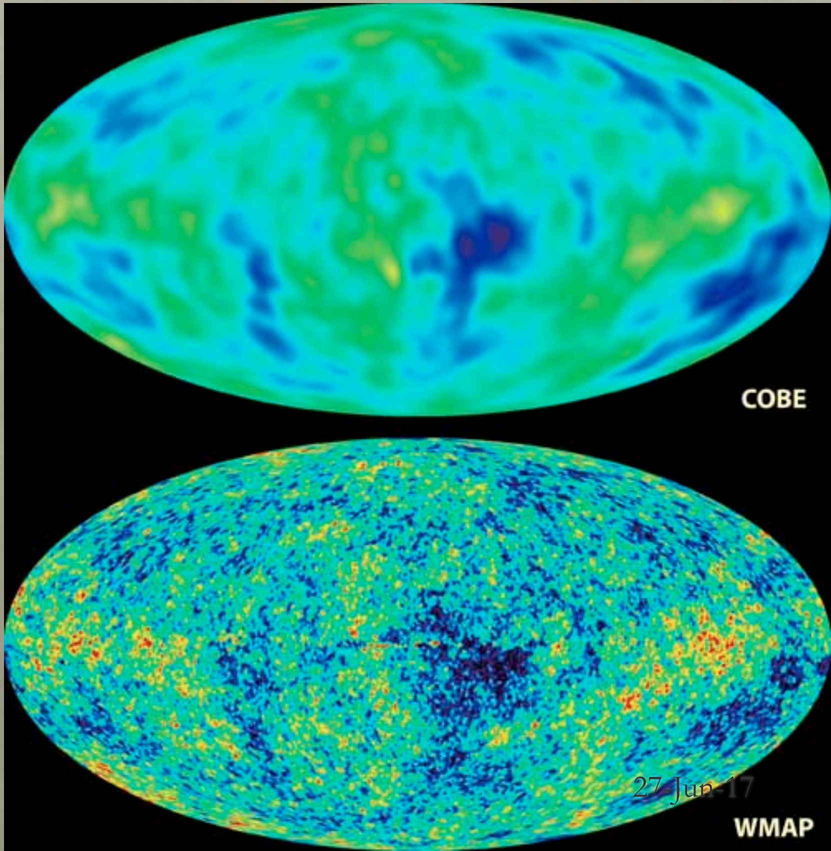
- Computational box ⇔ representative volume of Universe
- Resolution elements (particles or grid) in box ⇔ matter
- Steps:
  - Initial condition
  - Follow the non-linear evolution of IC density fields
- Bridge gap between observations of early epochs
  - Oldest stars: 10^9 yrs after Big Bang
  - CMBR: radiation from 3×10^5 yrs after
- Simulations are like experiments to verify theories of the evolution of the Universe
  - Can run many experiments in practical times



Initial Condition

- Cosmological model well constrained by observations
  - CMBR, SN, Galaxy clusters, Gravitational lensing

- Primordial density fluctuations
  - Gaussian
- Cosmological sim
  - Start with gaussian $\Delta\rho$ at CMB epoch (0.38 Myr after Big Bang, z~1100)
- Isolated galaxy, or, galaxy merger sim
  - Start with already formed galaxies



Tracking Gravitational Collapse

- Cosmological (over)density field, δ(x,t)

$$\delta \equiv \frac{\rho}{\bar{\rho}} - 1$$

- When δ << 1 : linear perturbation theory
  - Zeldovich approximation (Zeldovich 1970, A&A, 5, 84)
- Linear regime
  - Λ dominated
  - EdS/Matter dominated

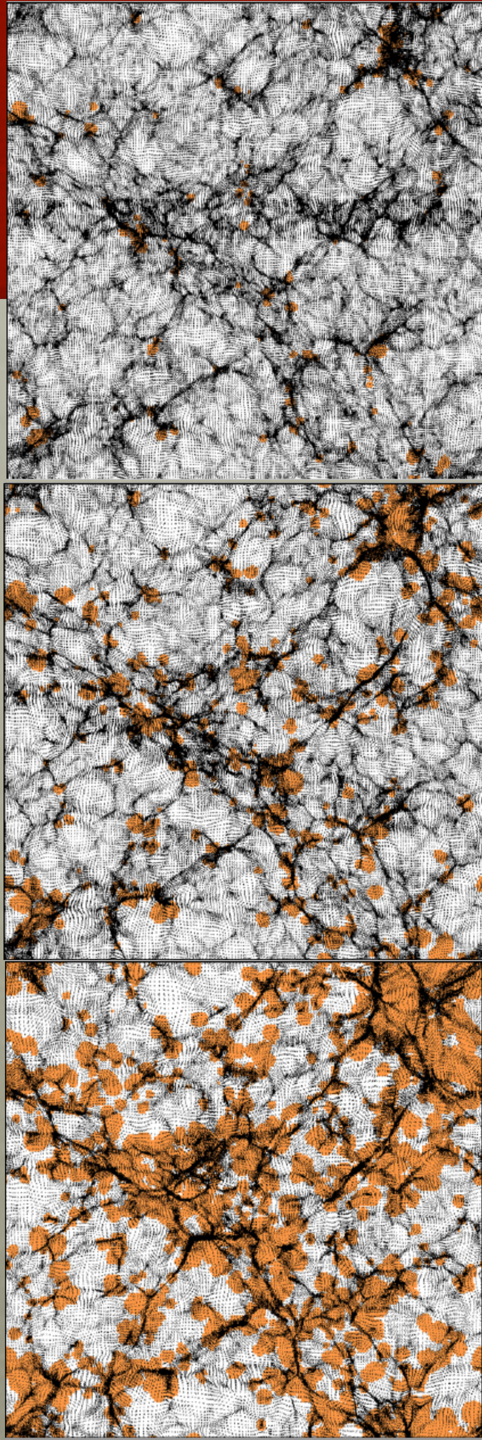
$$\delta_k(t) = A + Be^{-2Ht}$$

$$\delta_k(t) = At^{\frac{2}{3}} + Bt^{-1}$$

- Non-linear regime in galaxies, δ > 1 : linear approx. breaks down
- Need to run supercomputer simulations to track non-linear evolution
  - Days, weeks, months ...

N-body (Collision-less)

- Dark matter + Baryons



- Gravitational interactions only
- Equations of particle motion

$$\frac{d\vec{x}}{dt} = \vec{v} \qquad \frac{d\vec{v}}{dt} = -\nabla\Phi$$

- Poisson's equation for gravity

$$\nabla^2\Phi = 4\pi G\rho$$

- Non-relativistic velocities ⇒ Newtonian limit

Hydrodynamics (Baryons)

- Collisional particles with ideal gas properties

- Mass

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

- Momentum

$$\frac{\partial \vec{v}}{\partial t} + \left(\vec{v} \cdot \vec{\nabla}\right)\vec{v} = -\vec{\nabla}\Phi - \frac{\vec{\nabla} P}{\rho}$$

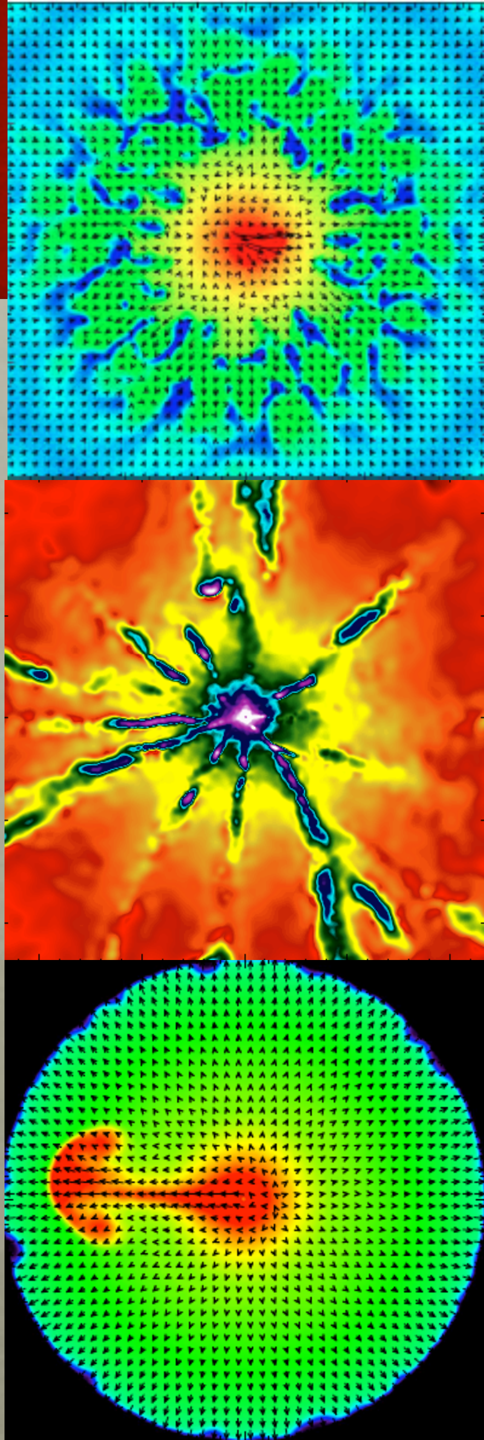
- Energy

$$\frac{\partial E}{\partial t} + \vec{\nabla} \cdot \left[(E + P)\vec{v}\right] = -\rho\vec{v} \cdot \vec{\nabla}\Phi$$

- Equation of state, $\varepsilon = f(\rho, P)$
  - Ideal gas
  - Polytropic

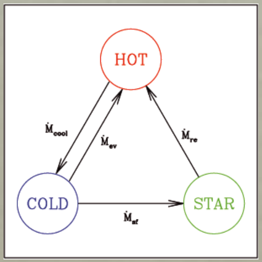
$$\varepsilon = \frac{1}{(\gamma - 1)} \frac{P}{\rho}$$

$$P = K\rho^{\gamma}$$



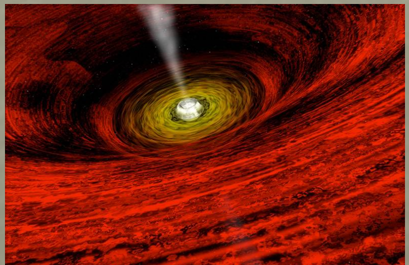
Modified-GADGET3 code: Sub-Resolution Physics

- GADGET3 : TreePM gravity + SPH hydro (Springel05)
- Metal-line cooling & radiative heating (Wiersma+09)
  - UV photoionizing background (Haardt&Madau01)
- Star-Formation
  - Effective model of multiphase ISM (Springel&Hernquist03)



- Stellar & Chemical Evolution (Tornatore+07)
  - Metal (C, Ca, O, N, Ne, Mg, S, Si, Fe) from SN type-II, type-Ia, & AGB stars
- SN Feedback (Tornatore+07, Tescari+09, Barai+13)
  - Kinetic feedback (↑ v)

- AGN accretion + feedback
  - (Rasia+16, Barai+14, Barai+16)



- Few (10 – 100)s Mpc side cosmological volume:
  - ✓ effect of Mpc-scale power fluctuations during structure formation
  - ✓ effect of cosmological large-scale events like galaxy mergers
  - ✓ statistics of galaxy populations over a mass range

(Barai+13)

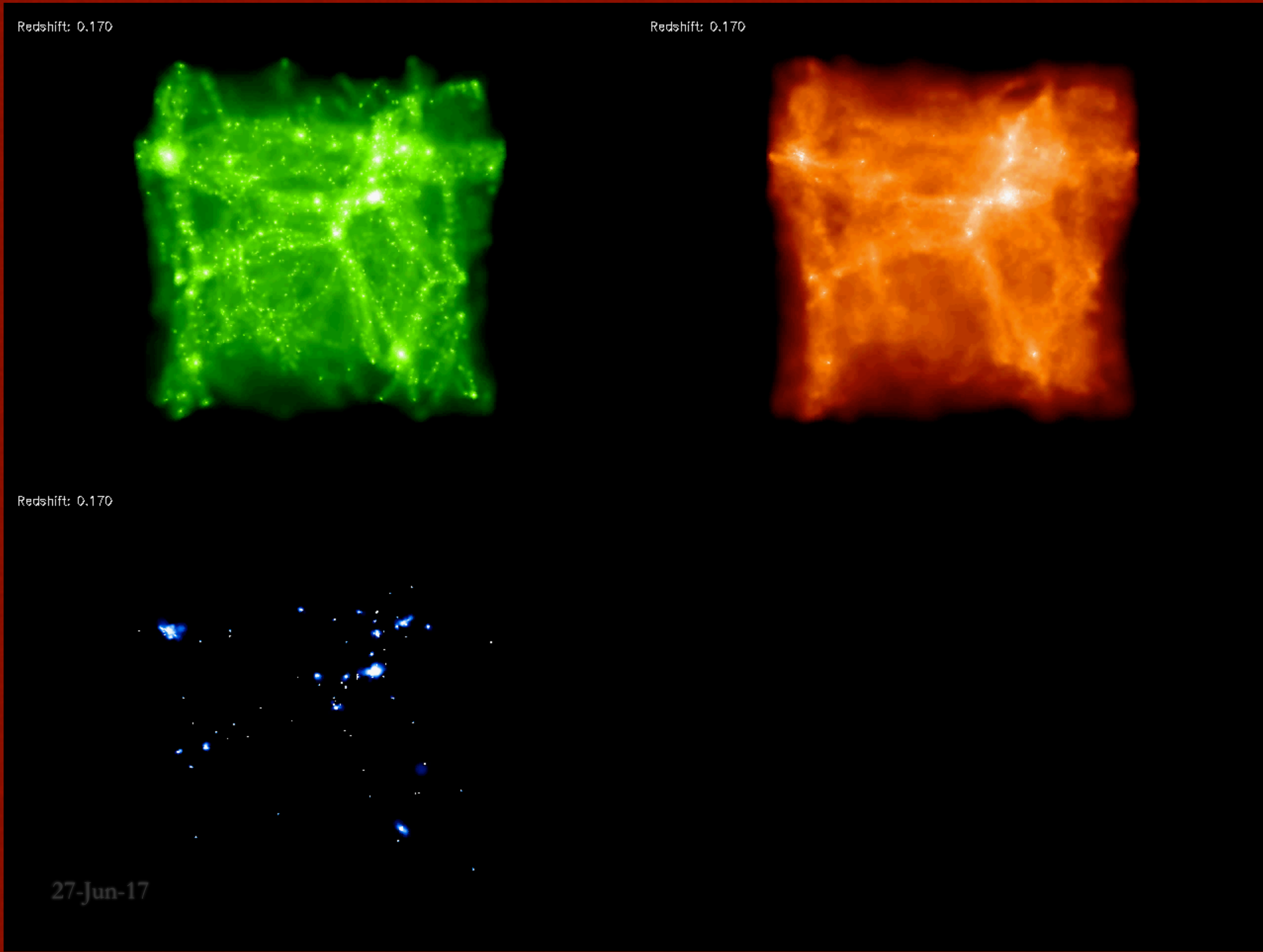
Large-scale filaments.

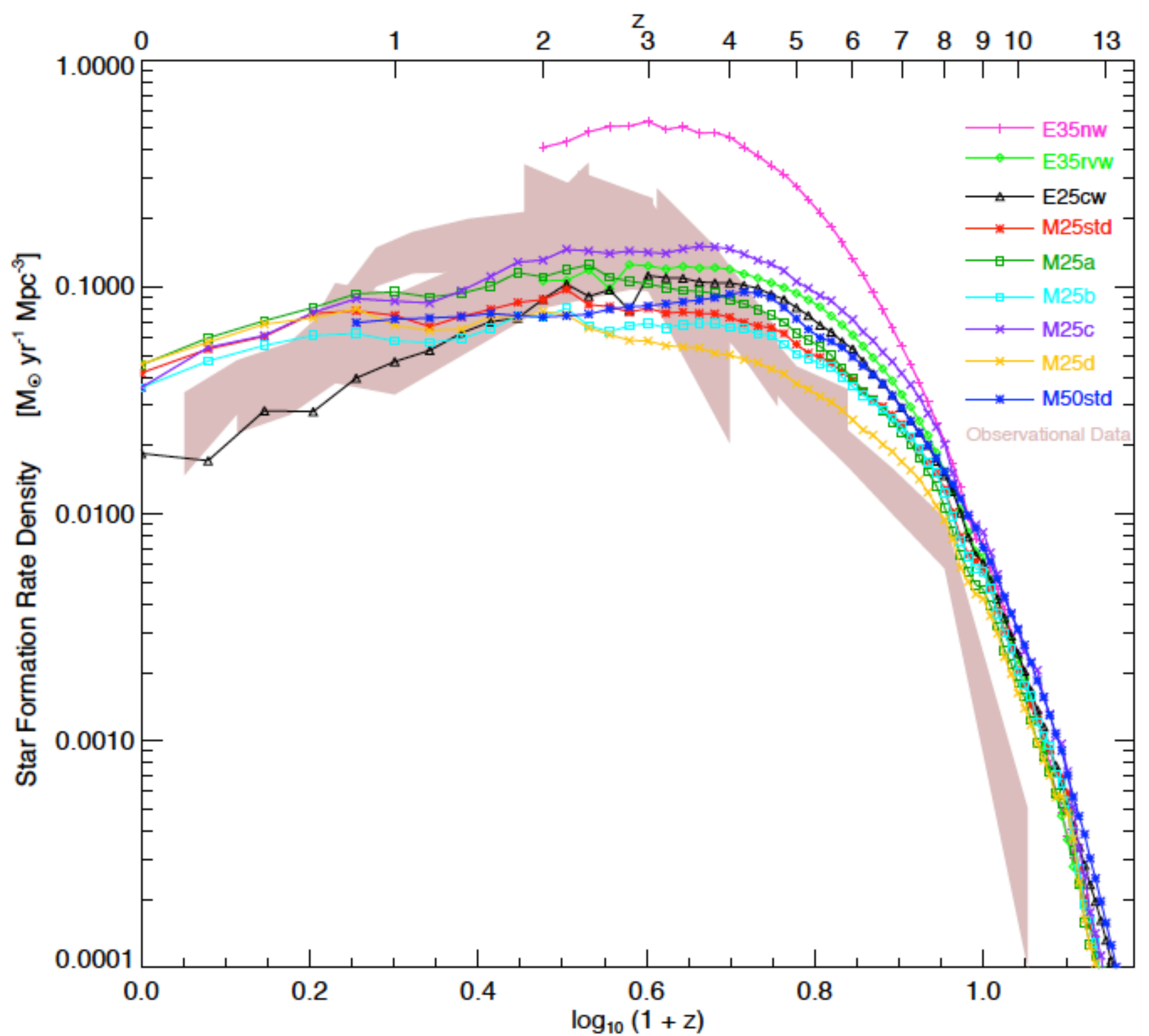
(5 Mpc)^3 box at low-z.

Dark matter - green,

Gas - red,

Stars - blue

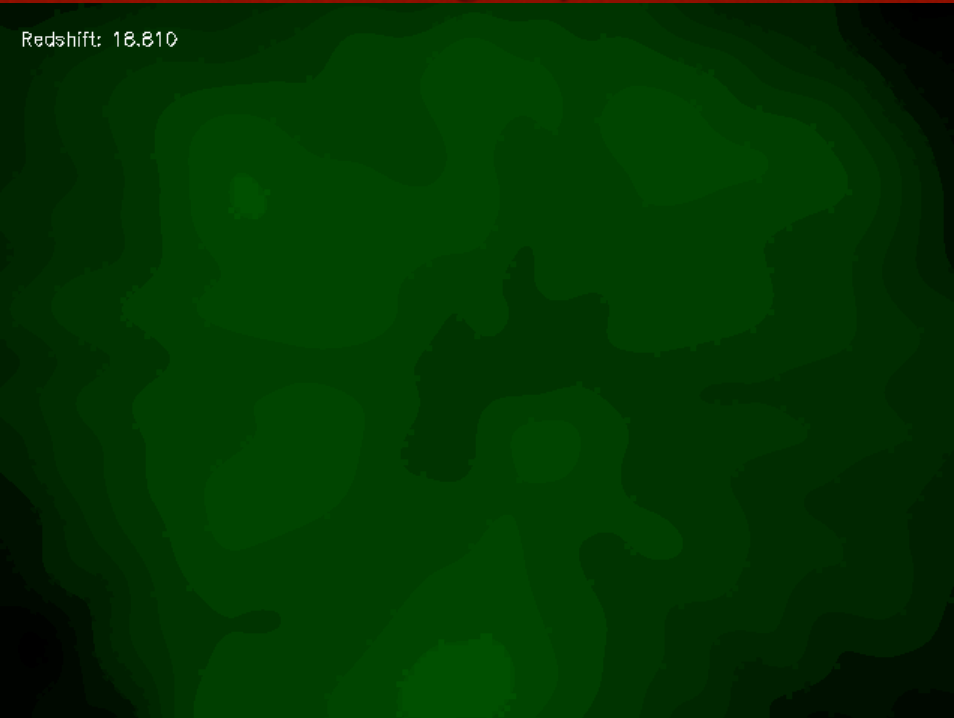


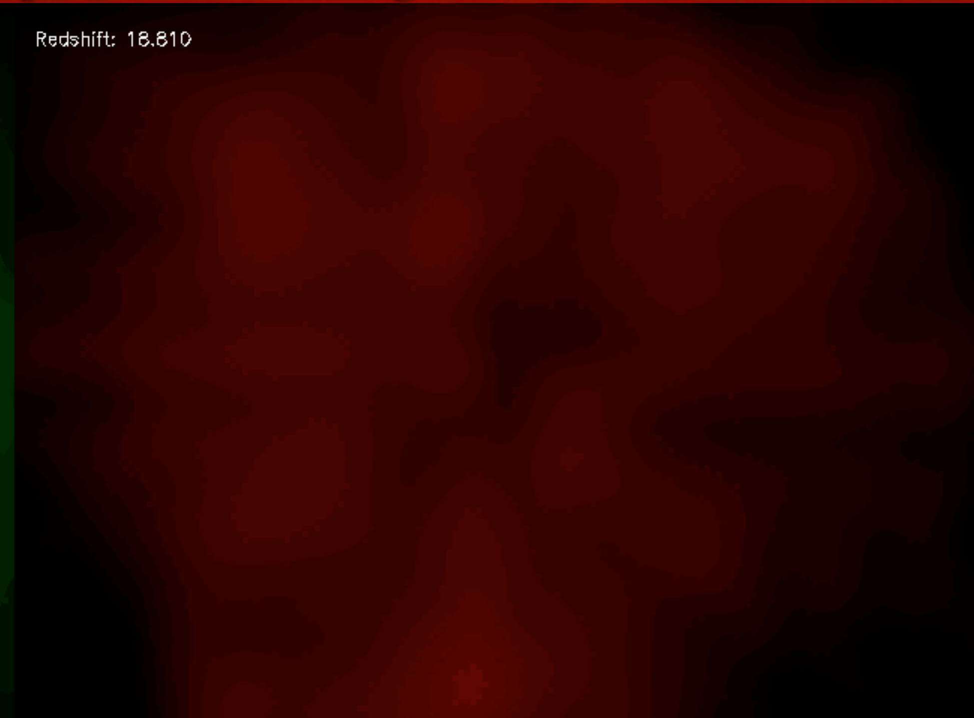


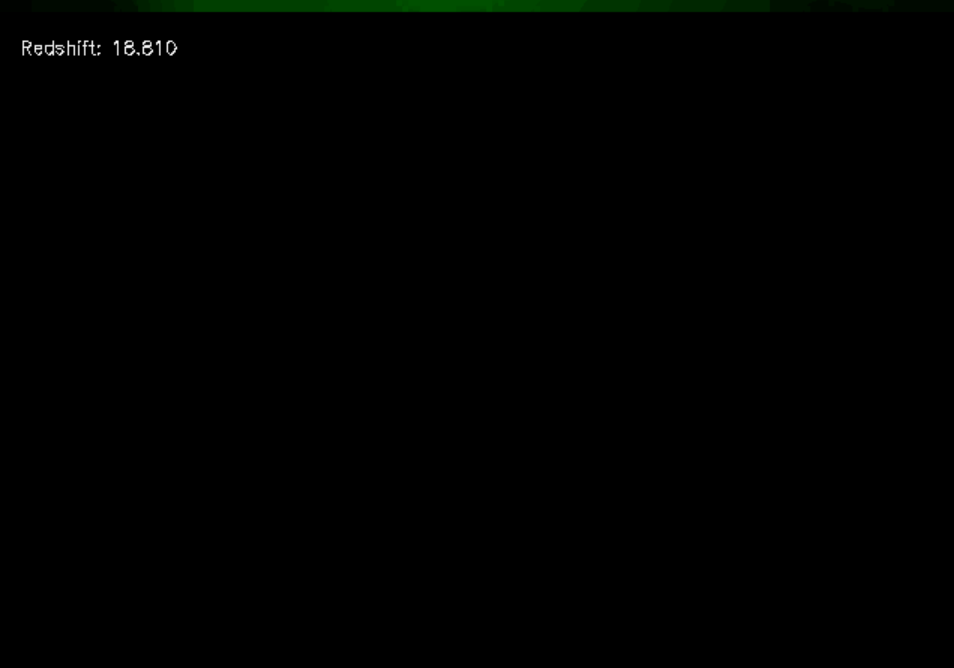
Star Formation Rate Density Evolution

(Barai+15)

Formation of a disk galaxy at z=2. (Barai+13) Dark matter, gas, stars. Face-on view.

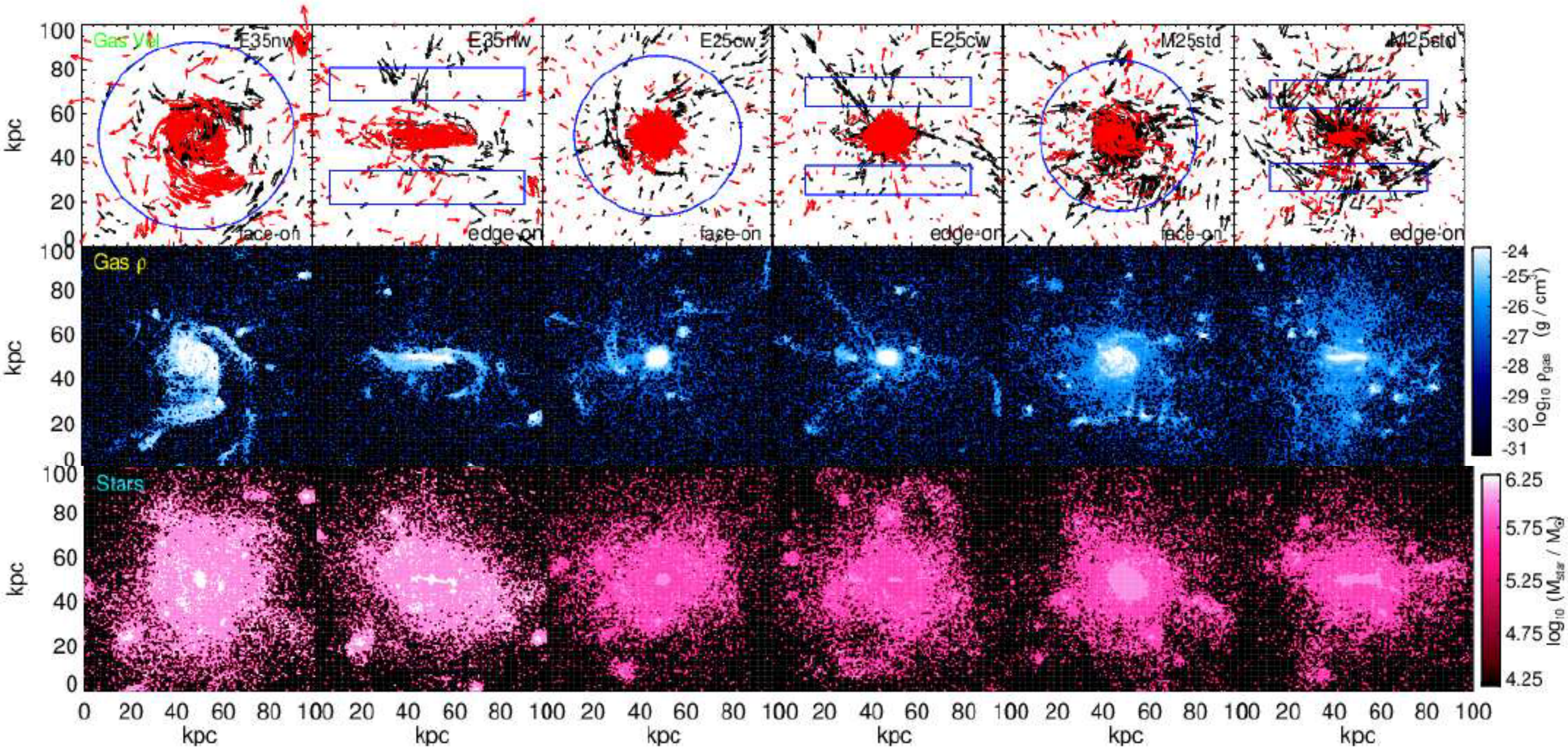




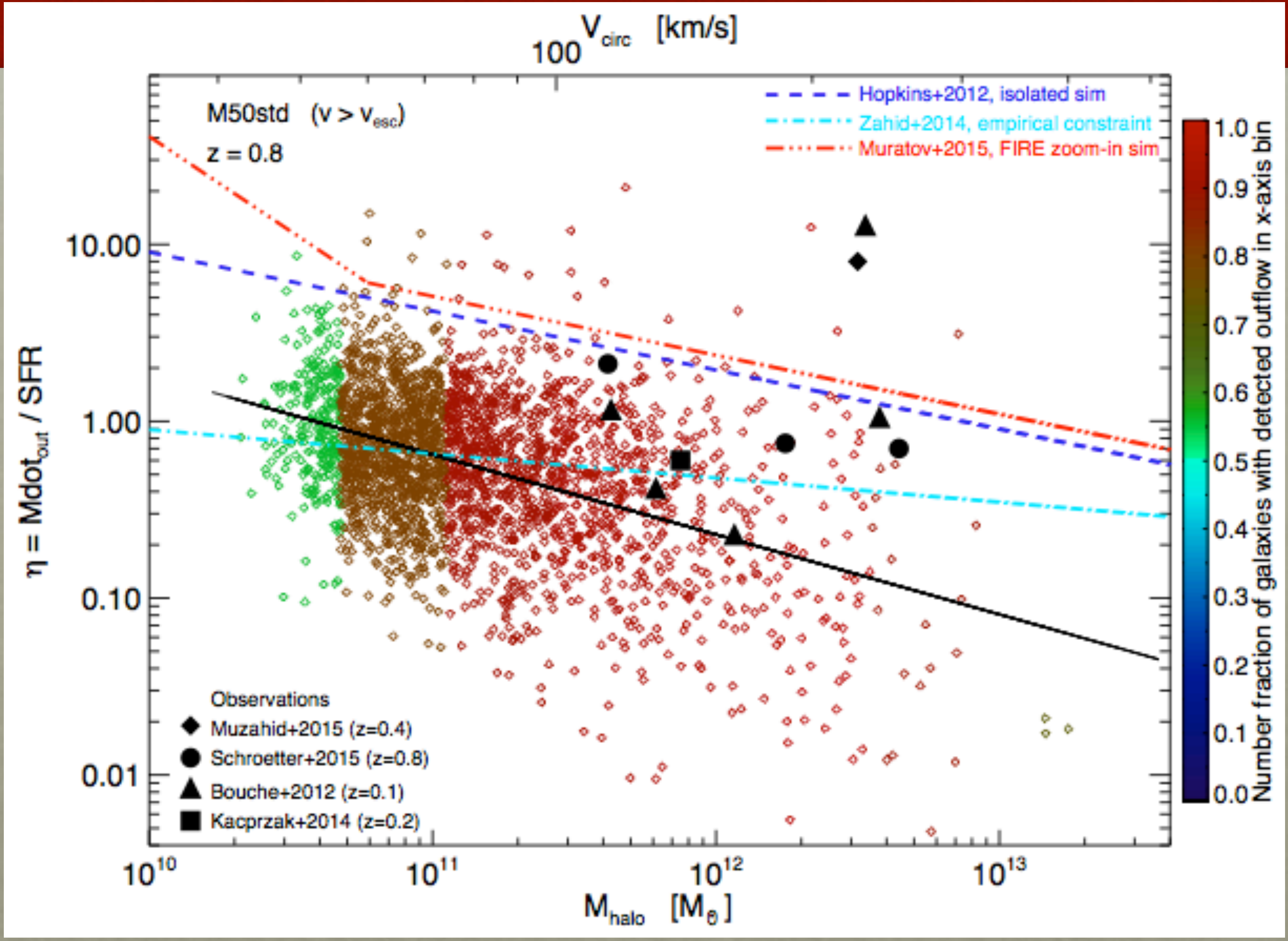


Galaxies with Different Morphologies

(Barai et al. 2015, MNRAS, 447, 266)

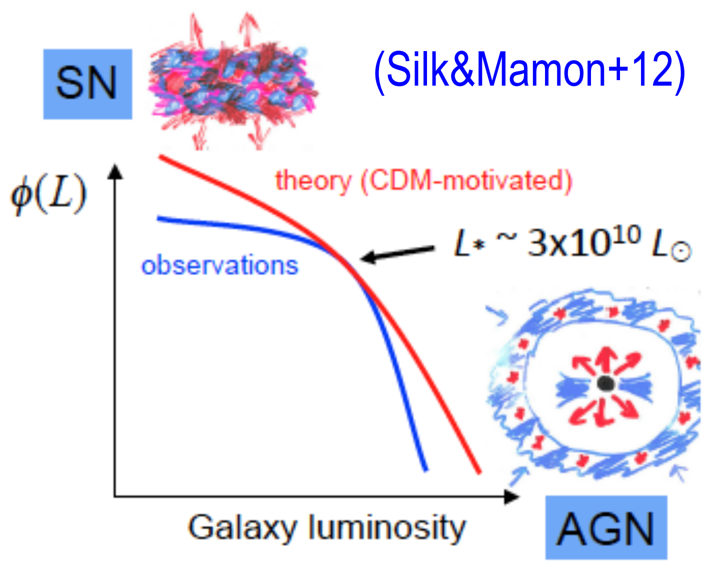


Galactic Outflow Mass-Loading Factor (Barai+15 --- comparison with other studies)



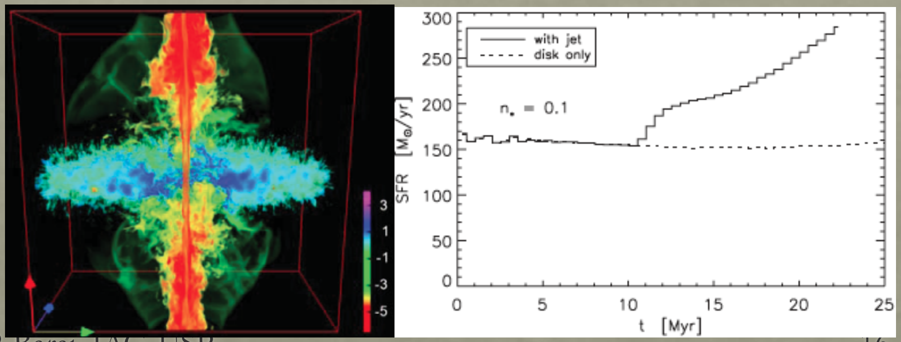
AGN Feedback

- Energy output from central SMBHs affecting host galaxies

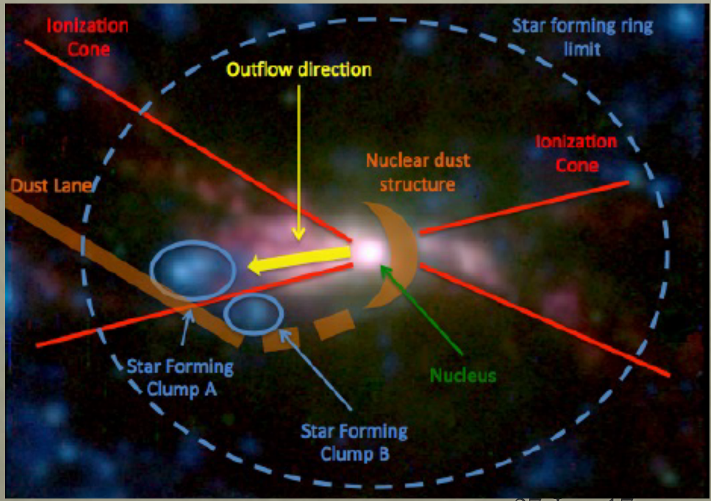


- Negative feedback
  - Quench star-formation
  - Reduce the number of massive galaxies

- Positive feedback
  - SF induced by compression of cold clouds in multi-phase ISM with AGN-driven jets



(Gaibler+12)



(Cresci+15)

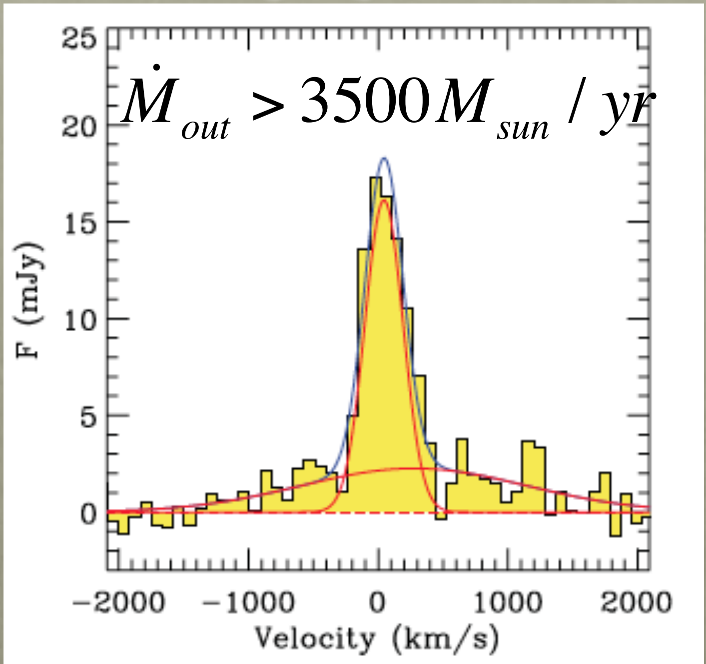
AGN Outflows

- Observed in different forms
  - Jets & cocoons: radio (Nesvadba+08)
  - Blue-shifted broad absorption lines: UV & optical (Rupke&Veilleux11)
  - Warm absorbers (Krongold+07) & ultra-fast outflows: X-rays (Tombesi+13)
  - Molecular gas: far-IR (Feruglio+10)

- This work

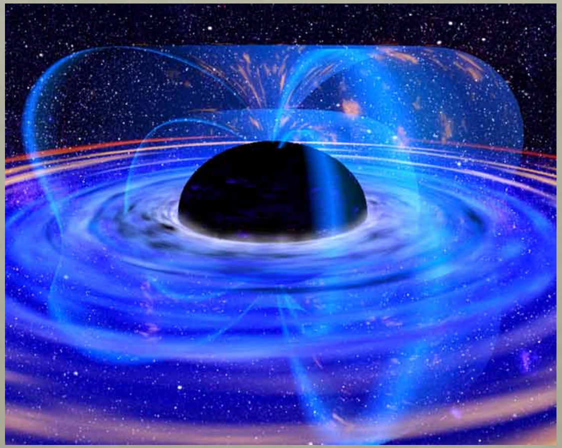
  ➔ Simulate massive, powerful gas outflows in quasars > 12.5 Gyr ago

- Observation SDSS J1148+5251, z = 6.4
  - (Maiolino+12, Cicone+15)
    - [CII] emission line at 158 μm
    - Detected broad wings tracing outflow
  - (Willott+03) $M_{BH} = 3 \times 10^9 M_{sun}$



Modeling AGN Feedback in Galaxy Formation Simulations: the sub-resolution physics

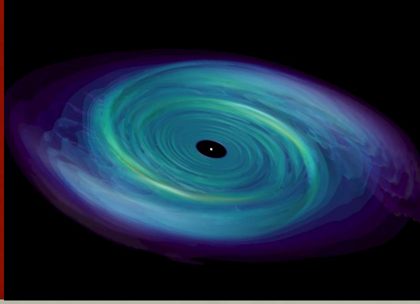
- Generation of seed BH ($10^5\ M_{sun}$) at:
  - Center of galaxy ($M_{halo} > 10^9\ M_{sun}$)
  - Minimum gravitational potential

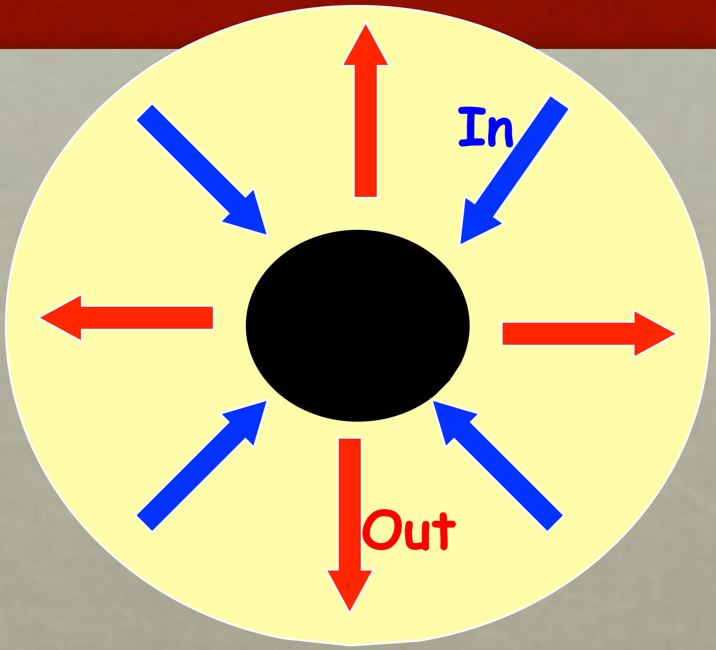


- BH growth
  - Accretion of gas
  - Merger with other BHs

- Feedback
  - Transfer of energy (kinetic) from BH to surrounding gas

Accretion & Energy Feedback





$$\dot{M}_{\rm Bondi} = \alpha \frac{4\pi G^2 M_{\rm BH}^2 \rho}{(c_s^2 + v^2)^{3/2}}.$$

$$\dot{M}_{\rm BH} = \min\left(\dot{M}_{\rm Bondi}, \dot{M}_{\rm Edd}\right).$$

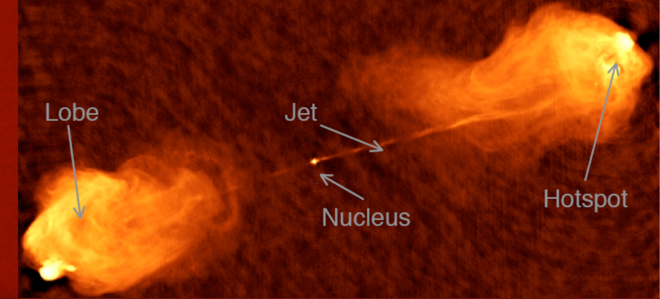
- Bondi-Hoyle-Lyttleton accretion rate (Bondi52)
  - Limited to the Eddington rate
- Fraction of the accreted mass energy is radiated away
- Radiatively efficient accretion (Shakura&Sunyaev73)
- Some of the radiated energy is fed back & coupled to the surroundings

$$L_r = \epsilon_r \dot{M}_{\rm BH} c^2$$

$$\epsilon_r = 0.1$$

$$\dot{E}_{\rm feed} = \epsilon_f L_r = \epsilon_f \epsilon_r \dot{M}_{\rm BH} c^2$$

Kinetic Feedback from AGN
(Barai+16)



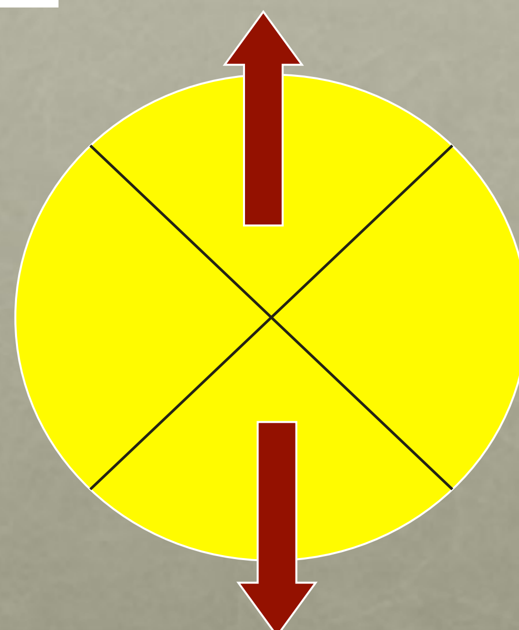
- Energy-driven wind $\frac{1}{2}\dot{M}_w v_w^2 = \dot{E}_{\rm feed}$

$$\dot{M}_w = 2\epsilon_f \epsilon_r \dot{M}_{\rm BH} \frac{c^2}{v_w^2}.$$

- Free parameters:

$$\epsilon_f = 0.05,\ v_w = 10,000\ {\rm km/s}$$

- Probabilistic method for kicking gas particles around BH



$$p_i = \frac{\dot{M}_w \Delta t}{M_{\rm gas}^{\rm cone}}.$$

- New particle velocity
  - Radially away from SMBH

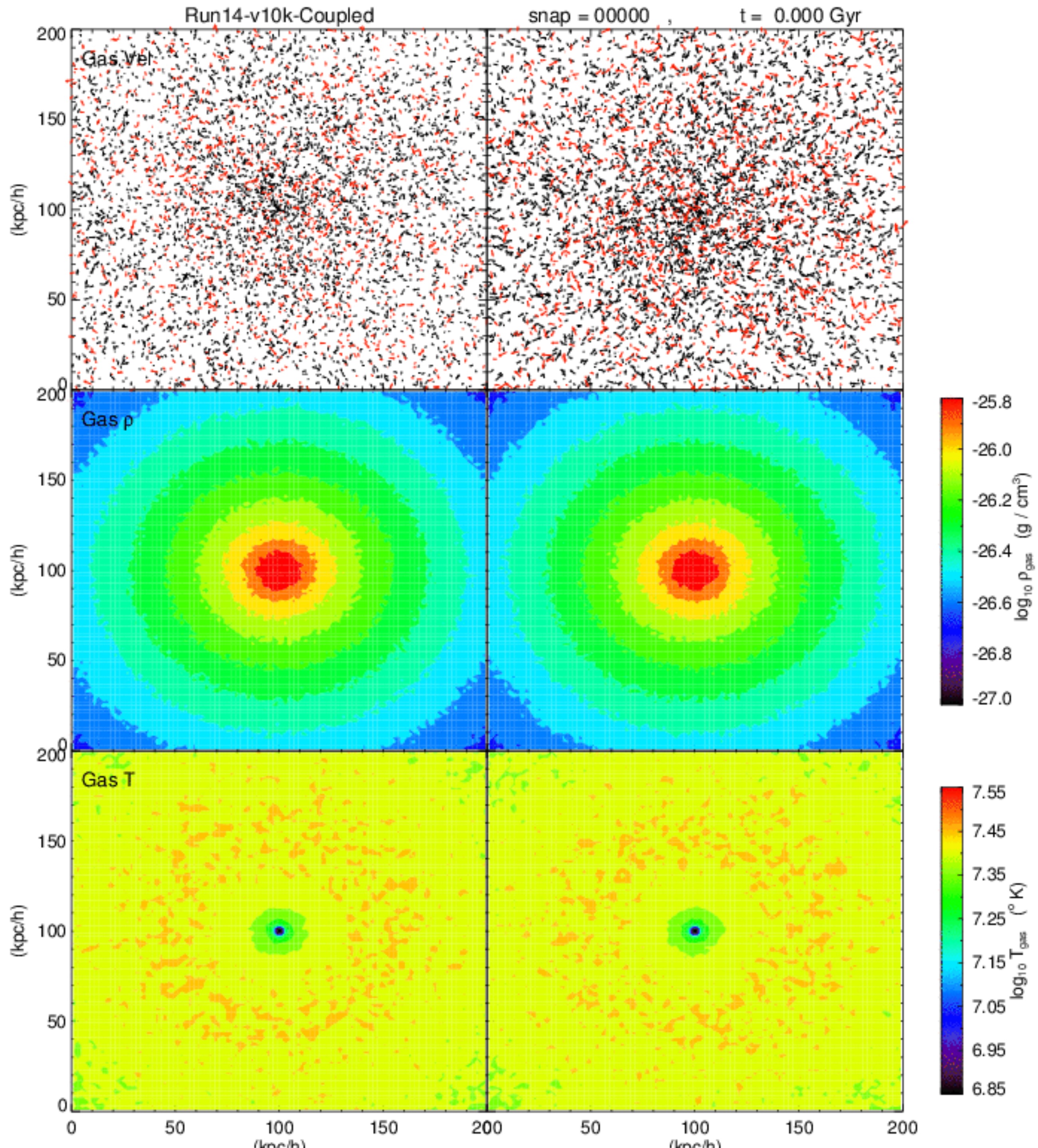
$$\vec{v}_{\rm new} = \vec{v}_{\rm old} + v_w \hat{n}$$

- Wind particles always coupled to hydrodynamical interactions

AGN feedback heating up galaxy cluster cool-core.

Isolated cluster run (constant energy output from AGN, fixed duty cycle).

(Barai+16)



Zoom-In Cosmological Hydro Simulation

IC with MUSIC (Hahn&Abel+11)

1) Perform dark-matter only run of a periodic cosmological volume, starting from z=100

2) Select massive DM halo at z=6

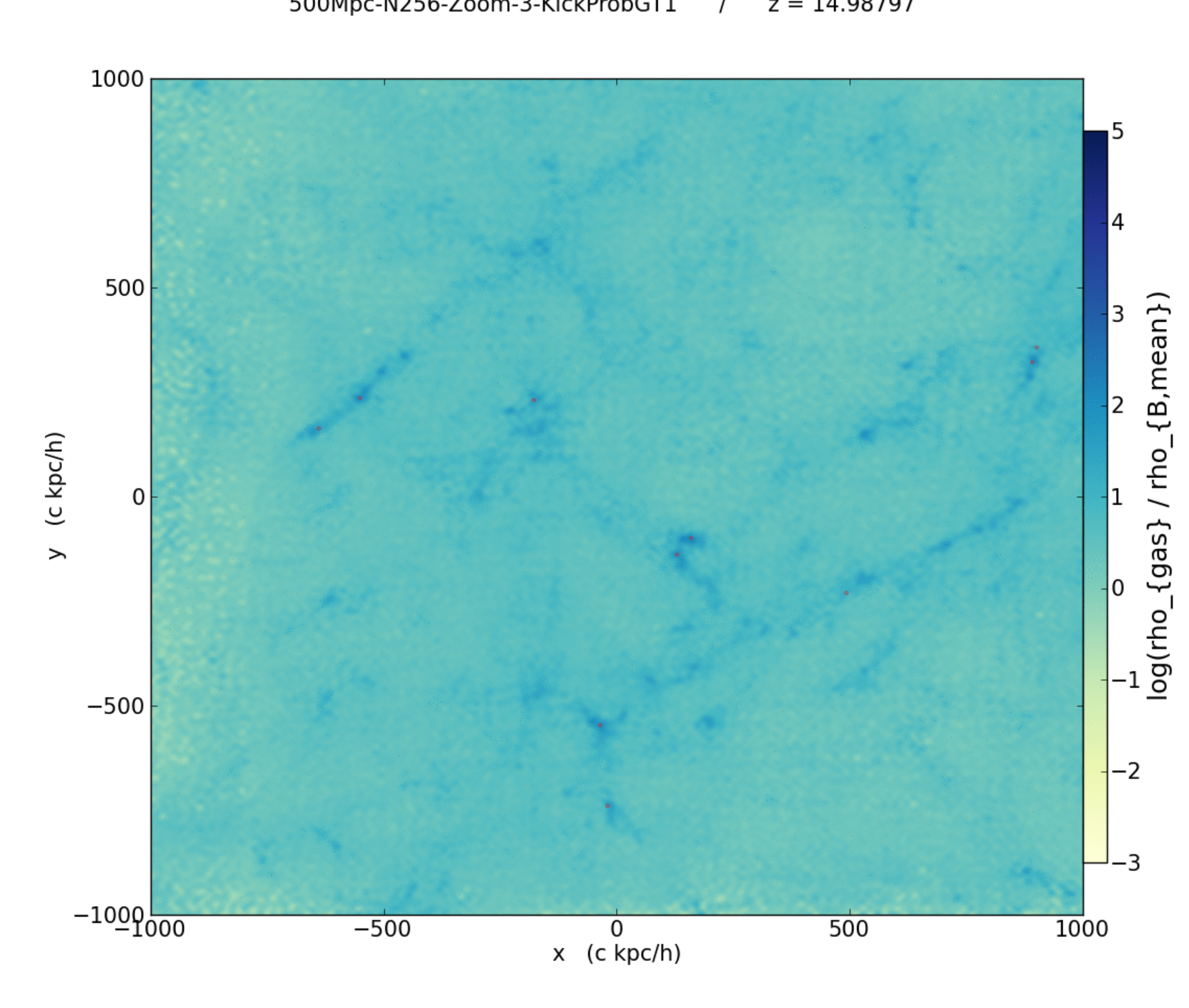
3) Track-back $r<2R_{200}$ DM particles to z=100, & identify Lagrangian region

4) Generate Zoom-In IC, including baryons

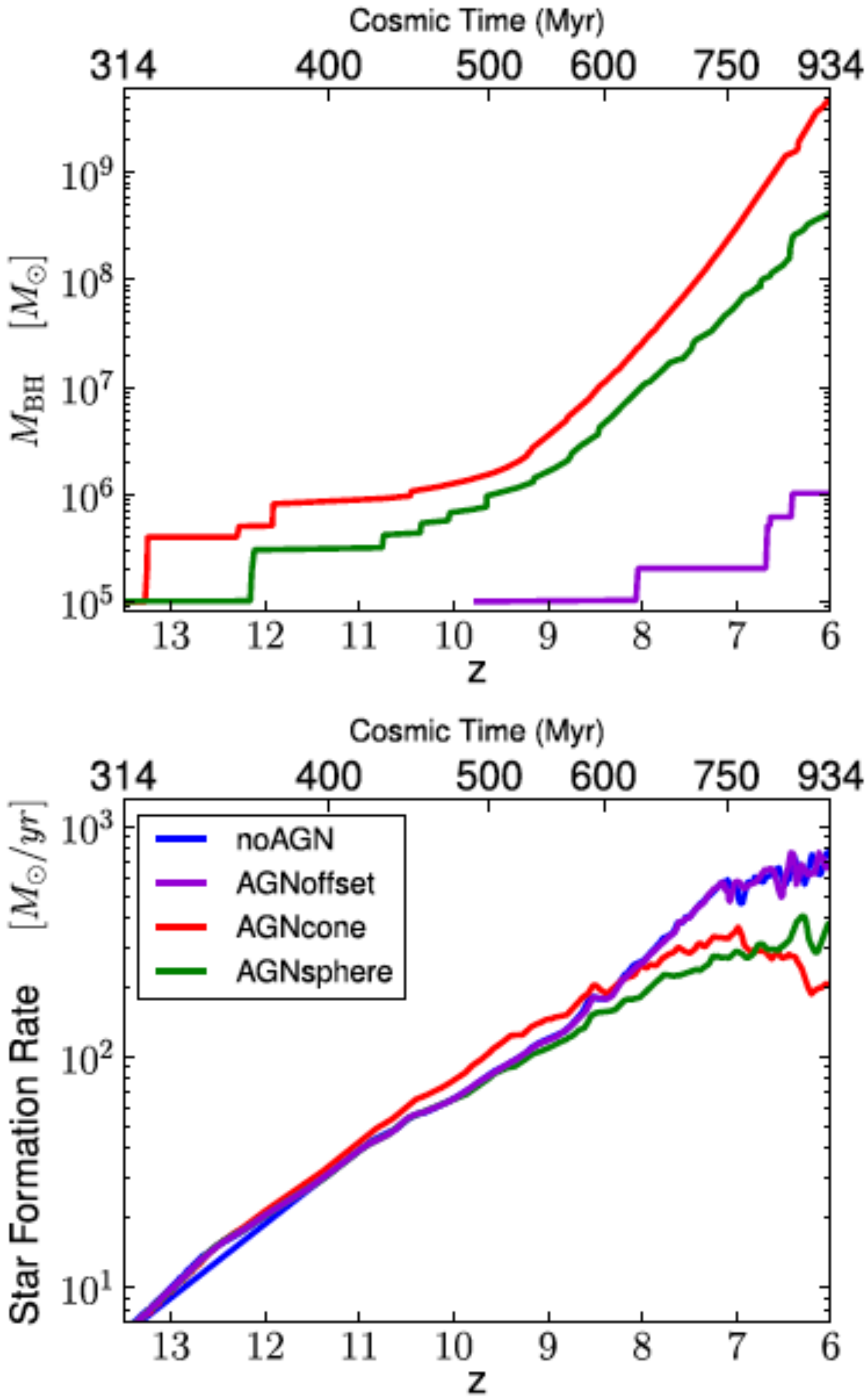
5) Perform Zoom-In sim from z=100

$L_{\rm box}$ [Mpc]	$N_{\rm DM}$	$N_{\rm gas}$	$m_{\rm DM}$ $[M_\odot]$	$m_{\rm gas}$ $[M_\odot]$	$L_{\rm soft}$ [/h kpc]	Model	$M_{\rm halo,max}$ $[M_\odot]$
500	17224370				33	Coarse	4.4×10^{12}
5.21	591408	591408	7.54×10^6	1.41×10^6	1	Hydro	

region



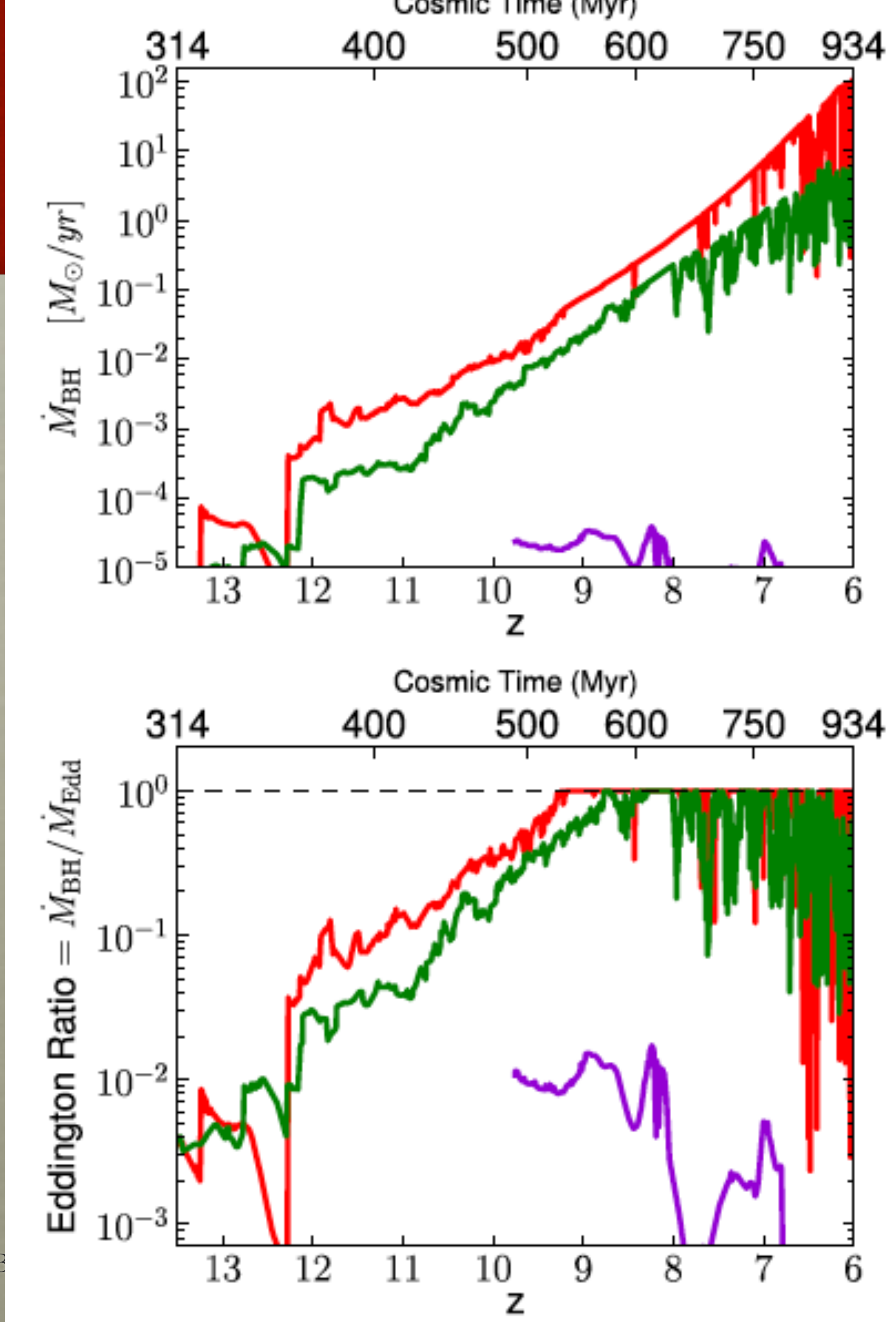
500Mpc-N256-Zoom-3-KickProbGT1 / z = 14.98797
y (c kpc/h)
x (c kpc/h)
1000
500
0
−500
−1000
−1000
−500
0
500
1000
log(rho_{gas} / rho_{B,mean})
5
4
3
2
1
0
−1
−2
−3



Growth of most-massive BH

(in each simulation)

impact on Star Formation Rate

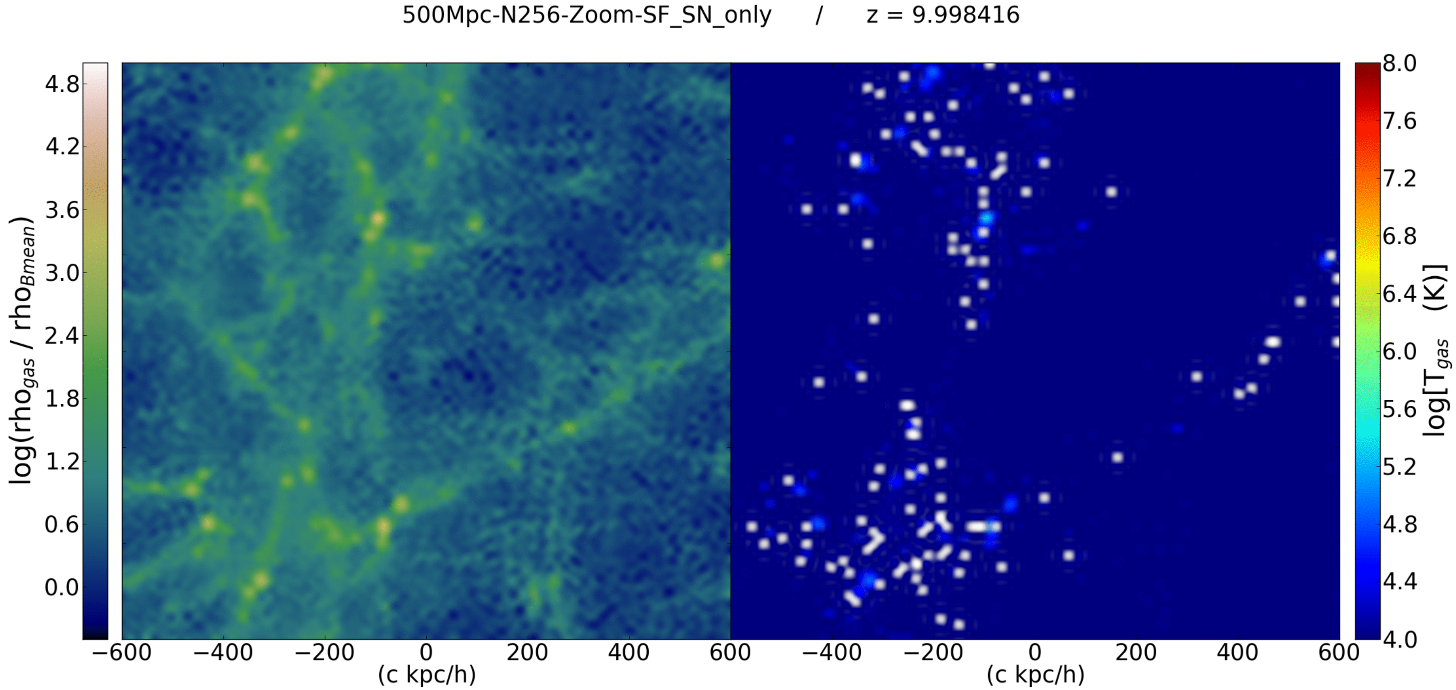


BH Accretion Rate

Eddington Ratio

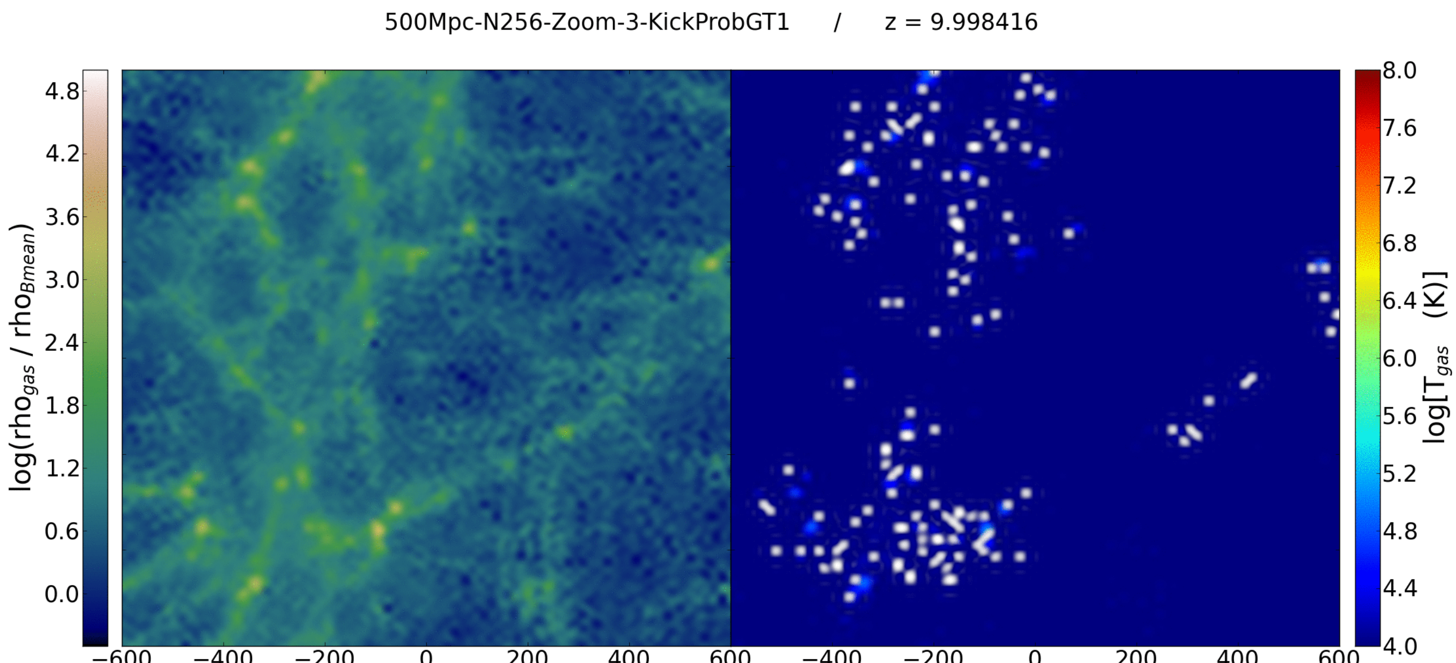
2D maps of Gas Density & Temperature

SF & SN-feedback only run



vs.

AGN run



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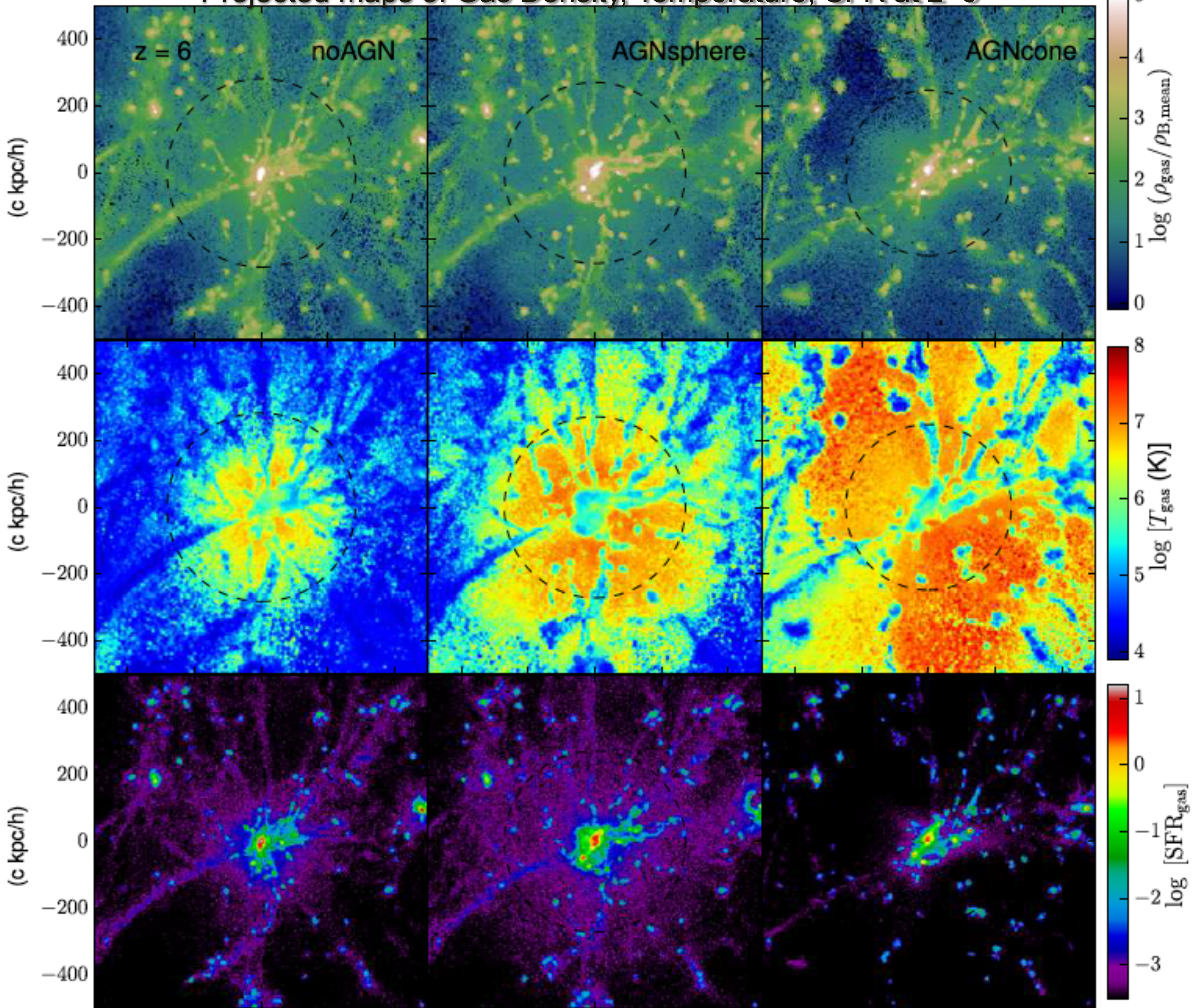
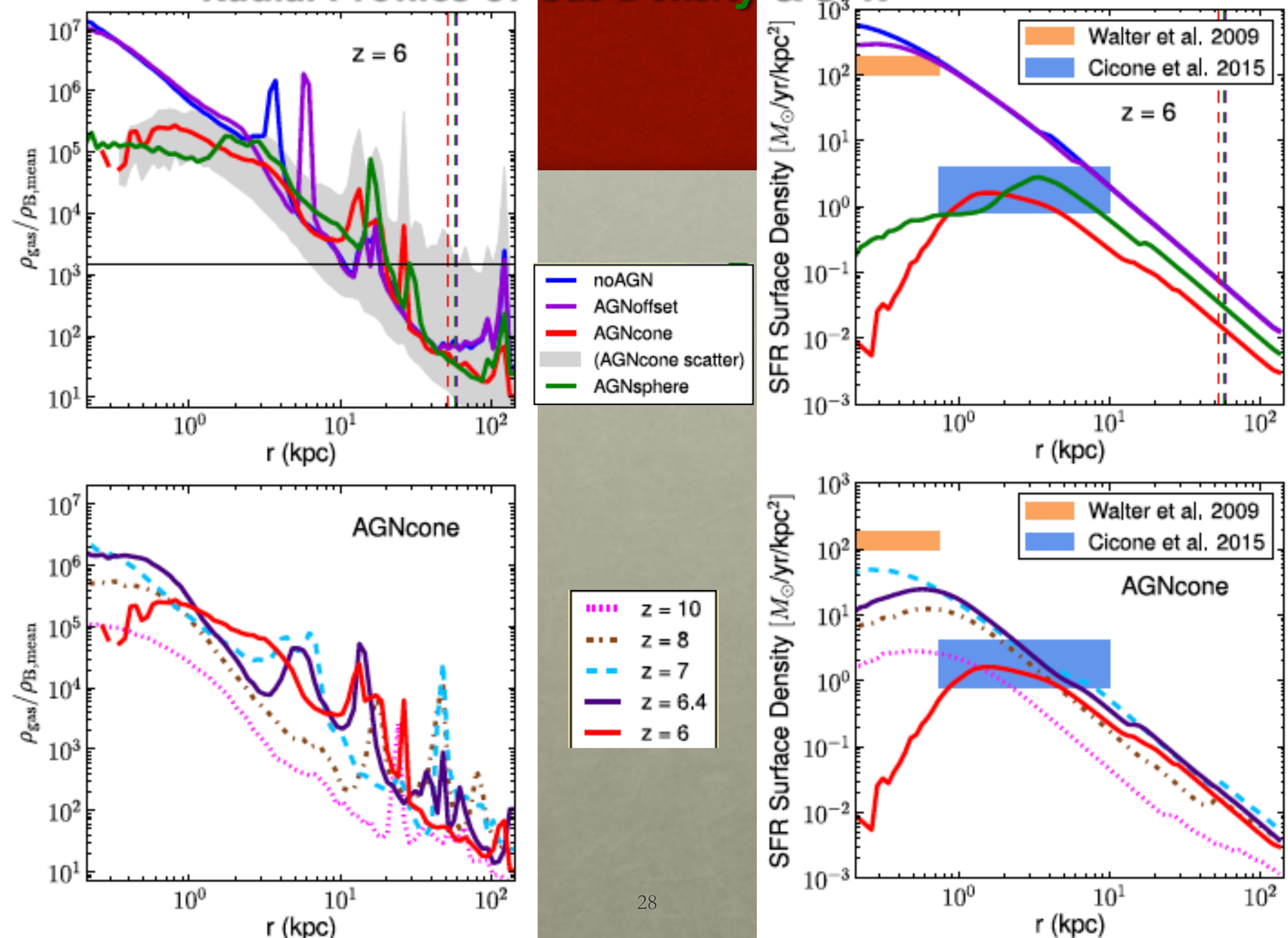
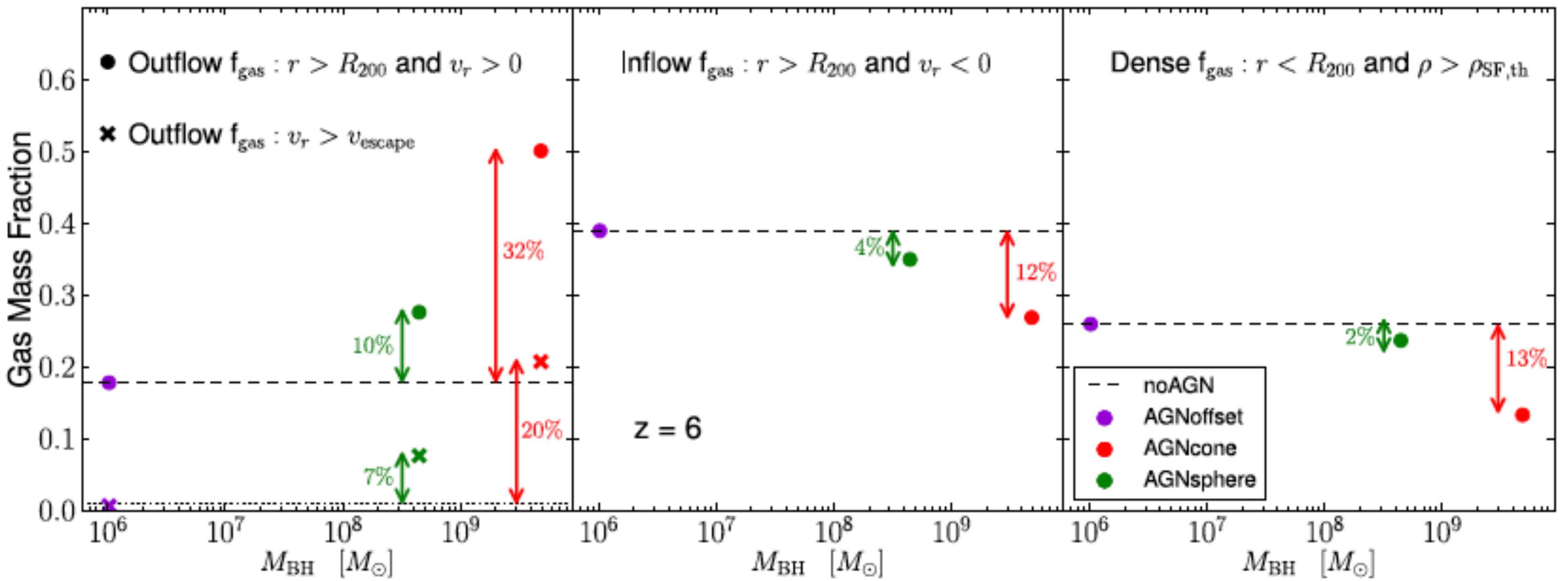
Projected maps of Gas Density, Temperature, SFR at z=6



Radial Profiles of Gas Density & SFR



Outflowing, Inflowing, Dense Gas Mass Fraction



Summary

- Cosmological Hydrodynamic Simulations are powerful tool
  - Reproduce the observed large-scale structures
  - Study origin & evolution of structures over Hubble time

- Starting from 10^5 M_{sun} seeds, can grow BH to 10^9 M_{sun} in a cosmological environment
  - Need growth at Eddington accretion rate over z=9-6 (for 100s Myr)

- Massive BHs generate powerful outflows
  - Outflow mass is increased (& inflow is reduced) by 20%

Future:

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High-energy astrophysics of galaxies and AGN in the cosmological context by connecting numerical simulations and observations with the CTA and ASTRI Mini-Array

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Duration: December 01, 2016 - November 30, 2020
Field of knowledge: Physical Sciences and Mathematics - Astronomy

Principal Investigator: Paramita Barai
Grantee: Paramita Barai

Home Institution: Instituto de Astronomia, Geofísica e Ciências Atmosféricas (IAG). Universidade de São Paulo (USP). São Paulo, SP, Brazil

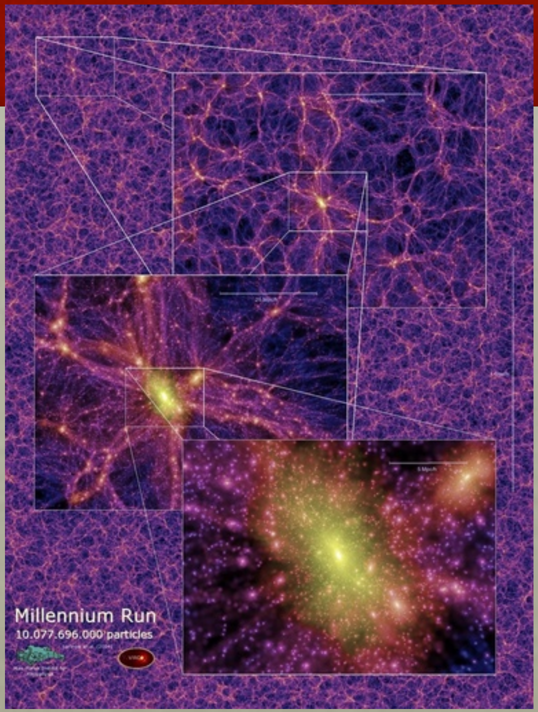
Assoc. researchers: Elisabete Maria de Gouveia Dal Pino

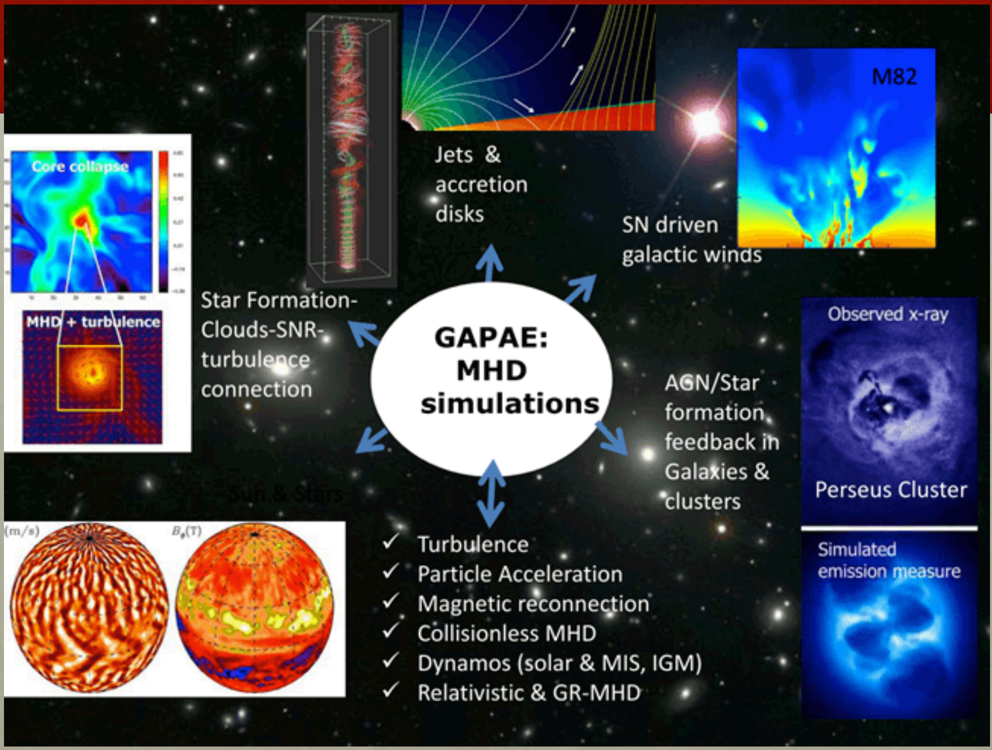
Associated scholarship(s): 16/22183-8 - High-energy astrophysics of galaxies and AGN in the cosmological context by connecting numerical simulations and observations with the CTA and ASTRI Mini-Array, BP.JP

Abstract

Feedback from star-formation, supernovae explosions, and active galactic nuclei (AGN) accretion, are some of the most-energetic events in the Universe. These are observed to generate powerful galactic outflows, influence galaxy evolution on cosmological scales. This project aims to explore problems of high-energy astrophysical phenomena in galaxies and AGN, in the cosmological context over the past 12 Gyr, which form unsolved questions of Astronomy. There will be close collaboration with expert researchers at Instituto de Astronomia, Geofisica e Ciencias Atmosfericas, of the Universidade de Sao Paulo (IAG-USP): the group of Prof. Elisabete de Gouveia Dal Pino and her collaborators. One main aim is to make predictions for the upcoming gamma-ray observing instruments: Cherenkov Telescope Array (CTA), and its precursor - the ASTRI MINI-ARRAY. The scientific objectives are to characterize energetic events of the following 4 broad categories, and how to observe them at earlier epochs using gamma-rays: (1)

Integration of my research within the High Energy & Plasma Astrophysics Group of Prof. Elisabete de Gouveia Dal Pino





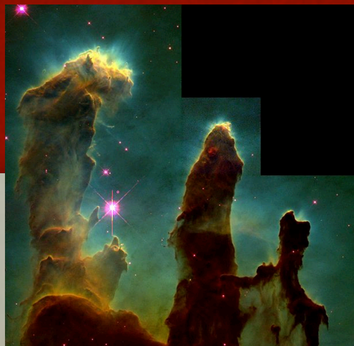
- Investigate high-energy phenomena in the cosmological context
  - SN/AGN winds
  - Non-thermal acceleration of particles and emission

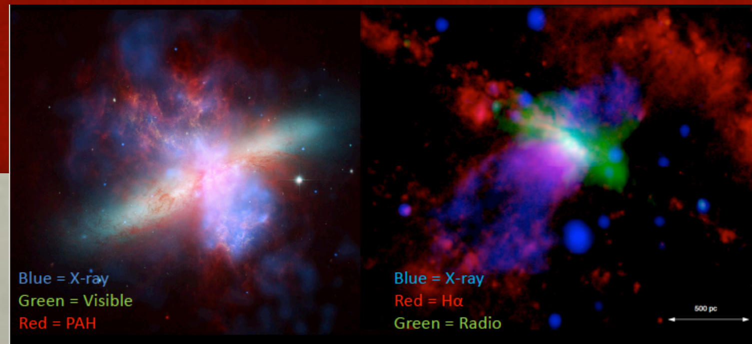
- Explore:
  - Intergalactic magnetic field
  - Extragalactic backgroud light

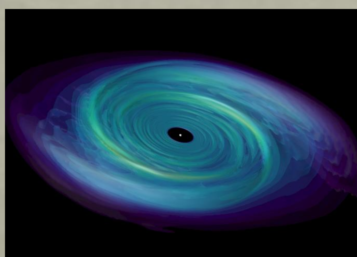
- Science for ASTRI Mini-Array and CTA

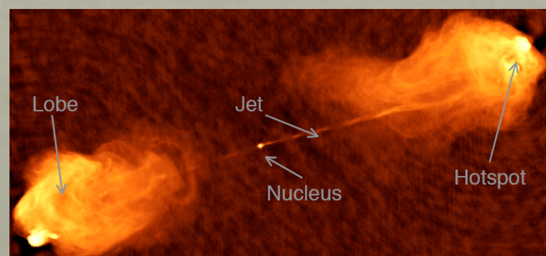
Extra Slides

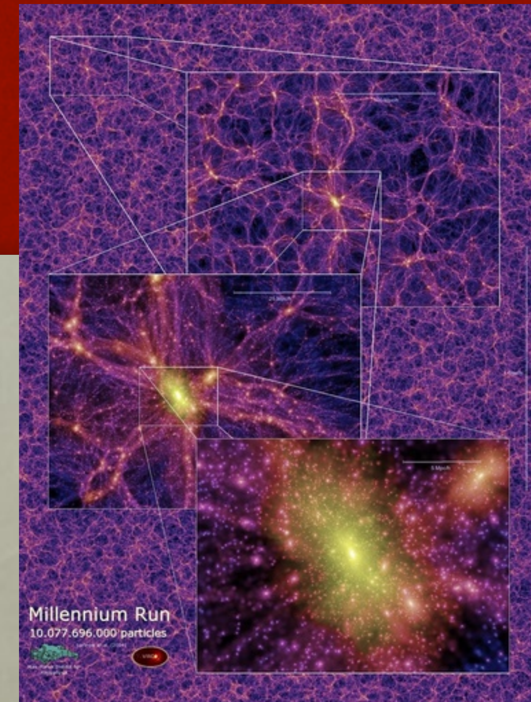
Why Sub-Resolution Models ?











Physics of baryons

- Radiative cooling and (photo + collisional) ionization heating of gas
- Fragmentation, clumping, multiphase ISM
- Star formation
- Metal production & chemical enrichment
- SN feedback, galactic wind
- AGN accretion + feedback
- …

In cosmological hydrodynamical simulations

(few - 10's Mpc) box : Resolution ~ $10^6 M_{Sun}$, 1 kpc

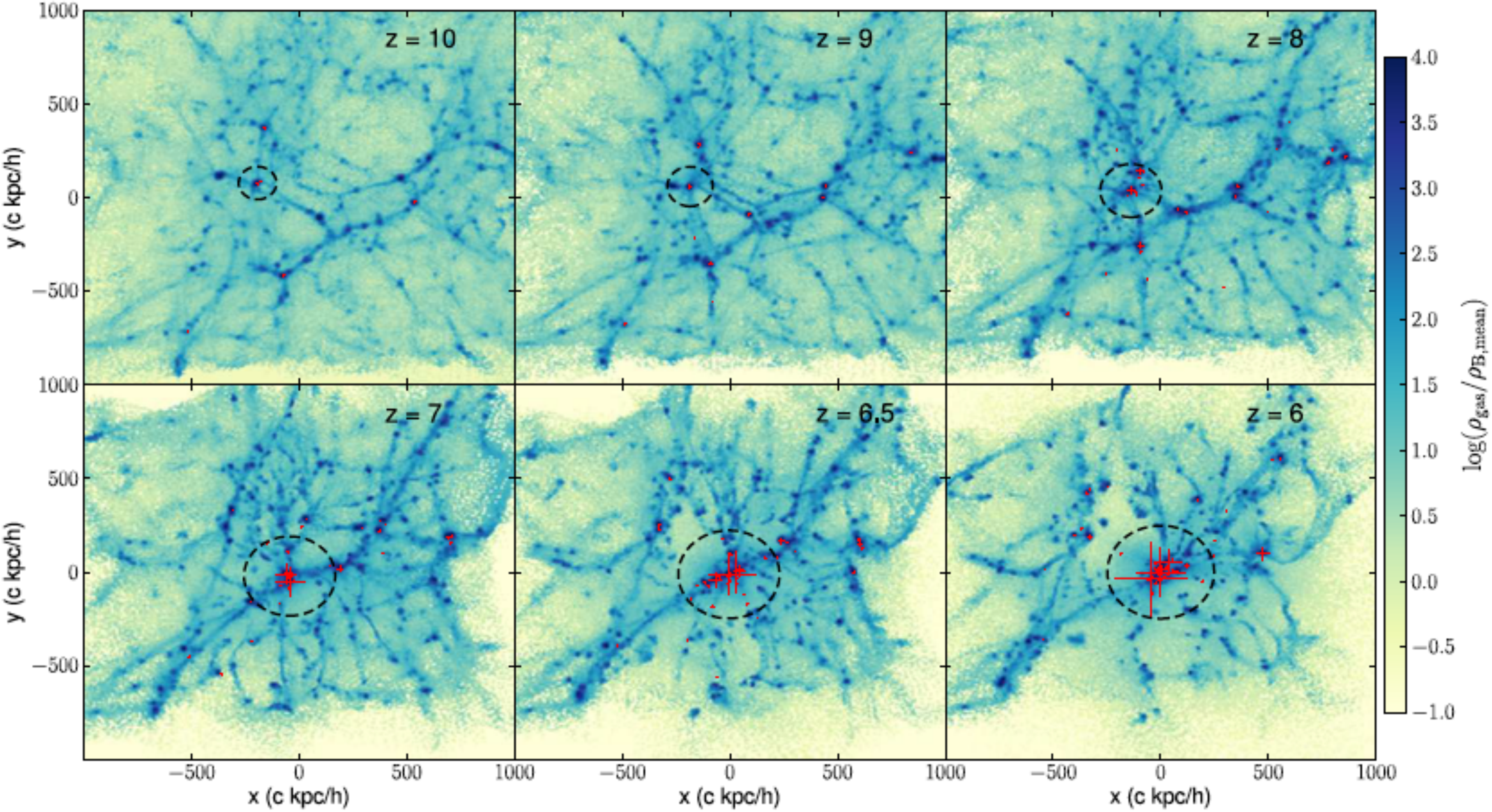
- Baryonic physics occur on much smaller scales
- Implemented as sub-resolution models

Simulation Parameters (Barai et al. submitted)

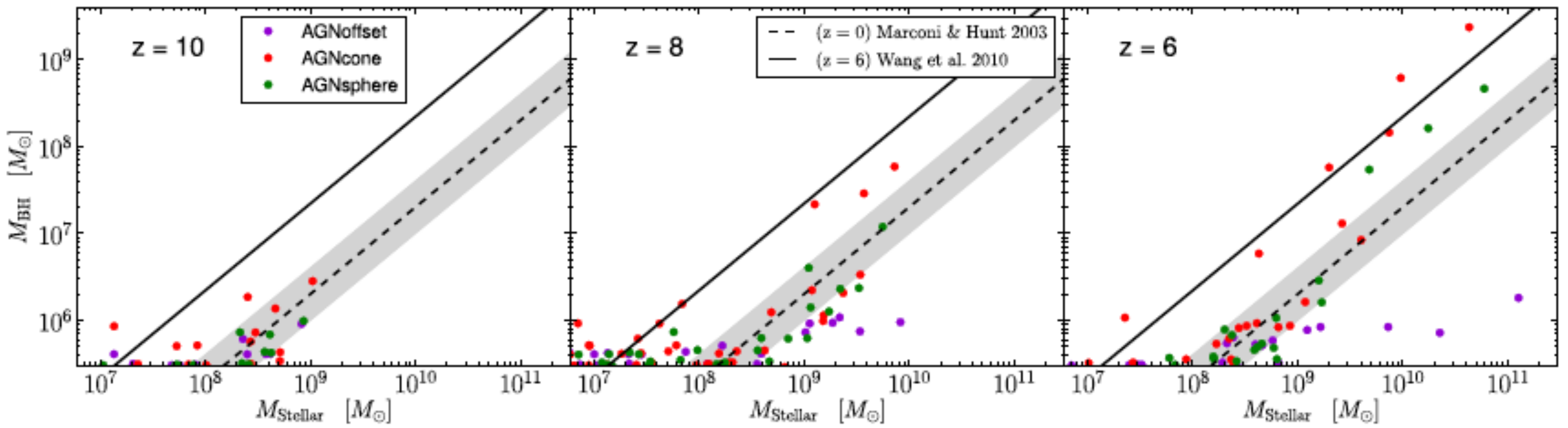
Table 1. Simulation runs and parameters.

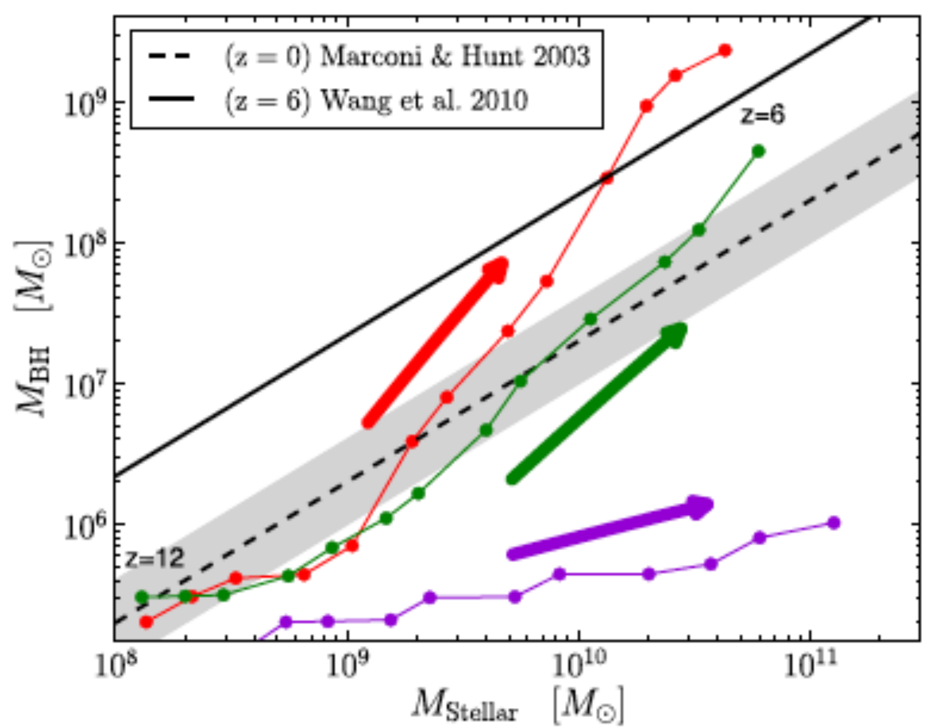
Run name	AGN feedback algorithm	Reposition of BH to potential-minimum	Geometry of region where feedback energy is distributed	Half opening angle of effective cone
noAGN	No BH	–	–	–
AGNoffset	Kinetic	No	Bi-Cone	45°
AGNcone	Kinetic	Yes	Bi-Cone	45°
AGNsphere	Kinetic	Yes	Sphere	90°

BH locations & Gas Overdensity in 2-Mpc zoomed region



(BH – Galaxy Stellar) Mass correlation





Radial Velocity Histogram (around most-massive galaxy at z=6)