Supermassive BH Accretion and Feedback in SPH Simulation

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The Classical formula of Bondi Accretion

- The derivation of the Bondi accretion formula starts with the Bernoulli inegral:

$$\frac{v^2}{2} + \int_{P_\infty}^{P} \frac{dP}{\rho} - \frac{GM}{r} = 0$$

- Assumptions:
- Only gravity source is BH Mass $M = M_{BH}$
- The two only forces are BH gravity and gas pressure
- Homogeneous medium: Constant density and pressure at infinity.

$$\frac{v^2}{2} + \left(\frac{\gamma}{\gamma - 1}\right) \frac{P_\infty}{\rho_\infty} \left[\left(\frac{\rho}{\rho_\infty}\right)^{\gamma - 1} - 1 \right] - \frac{GM}{r} = 0$$

- Spherical symmetry

$$\dot{M} = \int r^2 \rho v \, d\Omega \qquad \dot{M} = 4\pi r^2 \rho v$$

The Classical formula of Bondi Accretion

Defining the speed of sound:

$$c_s = \sqrt{\gamma \frac{P_\infty}{\rho_\infty}} = \sqrt{\frac{\gamma K T_\infty}{\mu m_H}}$$

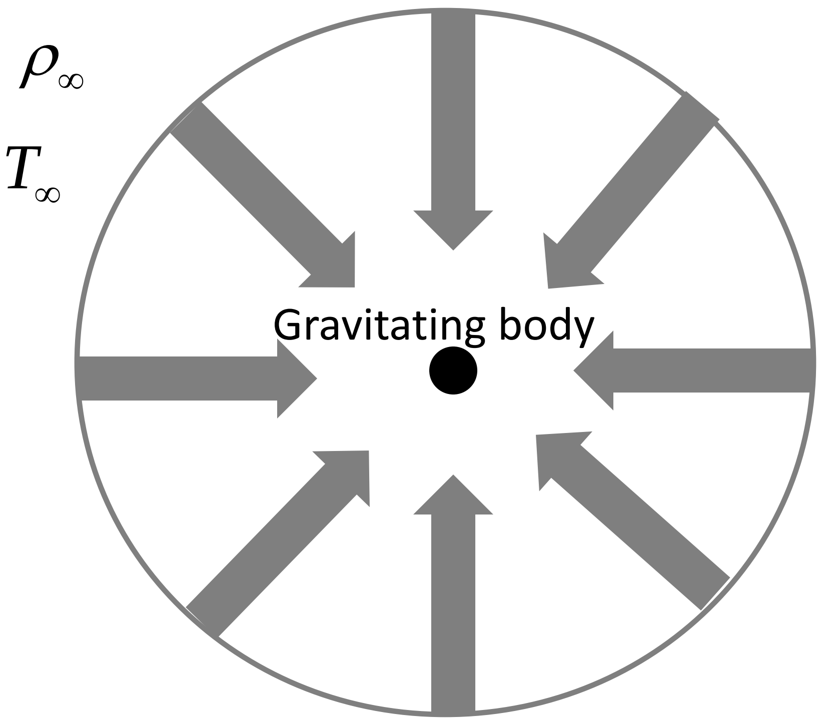
We get the Bondi Radius:

$$R = \frac{2GM_{BH}}{c_s^2 + v^2}$$

The Bondi Accretion Rate:

$$\dot{M}_B = \pi R^2 \sqrt{c_s^2 + v^2}\,\rho$$

$$\boxed{\dot{M}_B = \frac{4\pi\lambda G^2 M_{BH}^2 \rho}{\left(c_s^2 + v^2\right)^{3/2}}}$$



Implementation of Bondi-like accretion in cosmological simulations

- **A problem:** In cosmological simulations the hot phase result in a high temperature and therefore the Bondi radius is small.
- **The solution** (e.g., Di Matteo+ 2005): multiplying the Bondi accretion rate by a large factor **α=~100**.

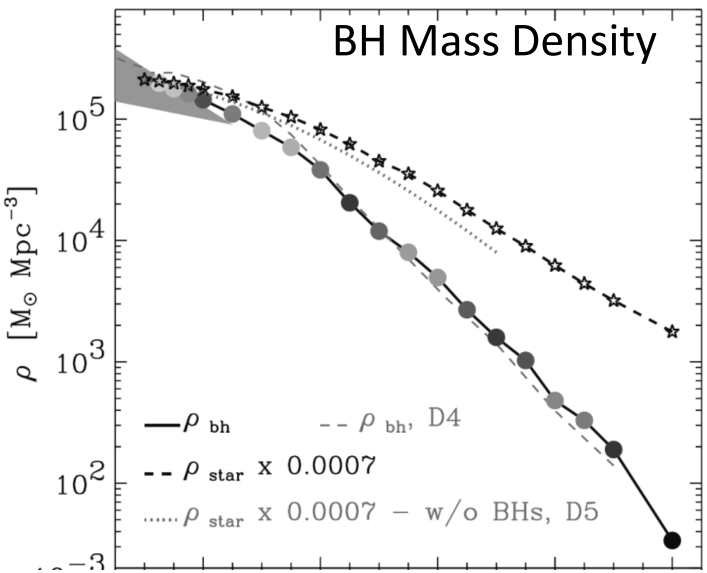
$$\dot{M}_{\mathrm{BH}} = \min(\alpha \dot{M}_{\mathrm{B}}, f_{\mathrm{Edd}} \dot{M}_{\mathrm{Edd}}) \qquad \dot{M}_{\mathrm{Edd}} = \frac{4\pi G M_{\mathrm{BH}} m_{\mathrm{p}}}{\epsilon_{\mathrm{r}} \sigma_{\mathrm{T}} c}$$

- Other suggestions were taking a varying factor rather than a constant (Booth & Schaye 2006)

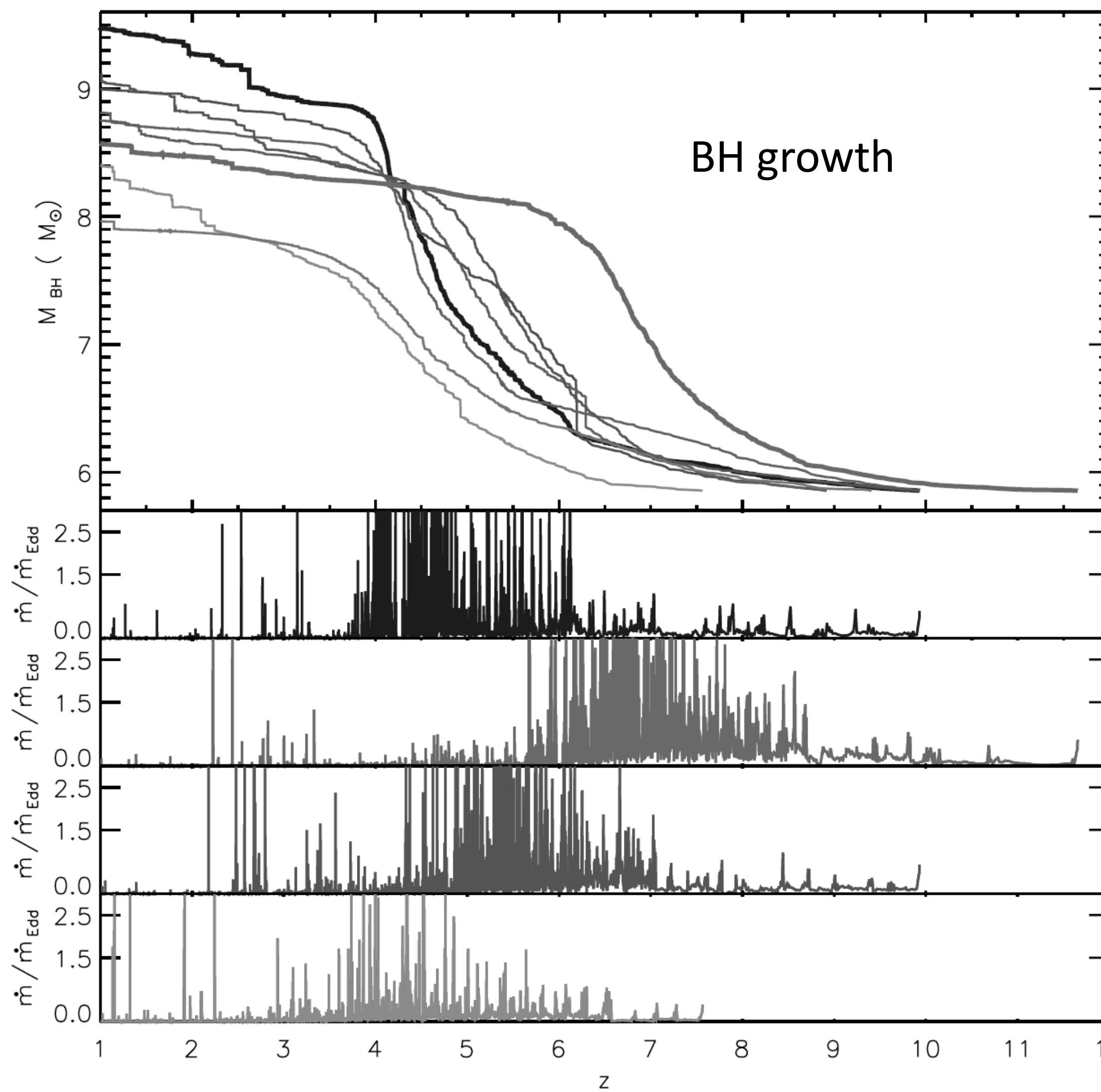
$$\alpha = \begin{cases} 1 & n_{\mathrm{H}} < n_{\mathrm{H}}^* \\ (n_{\mathrm{H}}/n_{\mathrm{H}}^*)^\beta & n_{\mathrm{H}} \geq n_{\mathrm{H}}^* \end{cases} \qquad n_{\mathrm{H}}^* = 0.1\mathrm{cm}^{-3}$$

- But in any case, the Bondi rate is multiplied by some large number.

Results from studies that assumed (100X) Bondi accretion



DI MATTEO ET AL.



We ask ourselves:

Does the Bondi equation have all the physics we need in order to understand accretion to SMBHs?

Can we come to wrong understanding of the accretion process by adopting the strong assumptions?

Is there a better treatment for accretion?

We suggest a new accretion model:

- No spherical symmetry assumed.
- No homogeneous medium assumed.
- No averaging of hot and cold temperatures that gives high T and low accretion rate.
- The gas gravity is taken into account in the Bernoulli function.

- There is no one accretion radius for each SMBH but rather a different accretion radius for each gas particle.

Our Suggested solution: Using the basic hydrodynamic equations instead of Bondi.

- We calculate for each gas particle the Bernoulli function:

$$Be(t) = e_k + h - \Phi$$
$$= \frac{(\mathbf{v} - \mathbf{v}_{BH})^2}{2} + \frac{\gamma - 1}{\gamma}\frac{P}{\rho} - \frac{G(M_{BH} + M_{\mathrm{gas}})}{r}$$

- $Be(t) < 0$ is a required condition for accreting particles.
- Colder gas has smaller enthalpy (*h*~*T*) → greater chance for being accreted.

Accretion

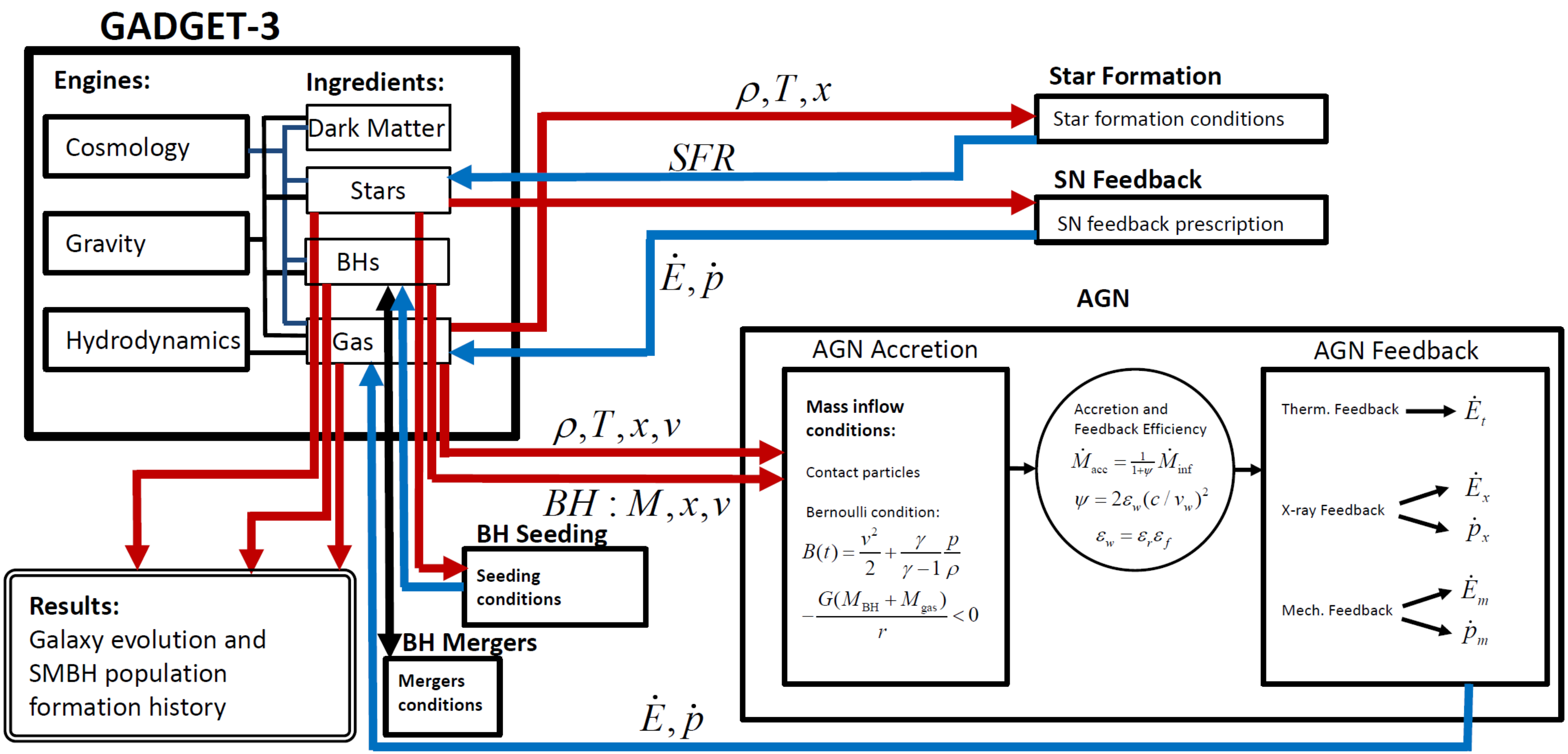
Feedback

AGN Feedback included in the model

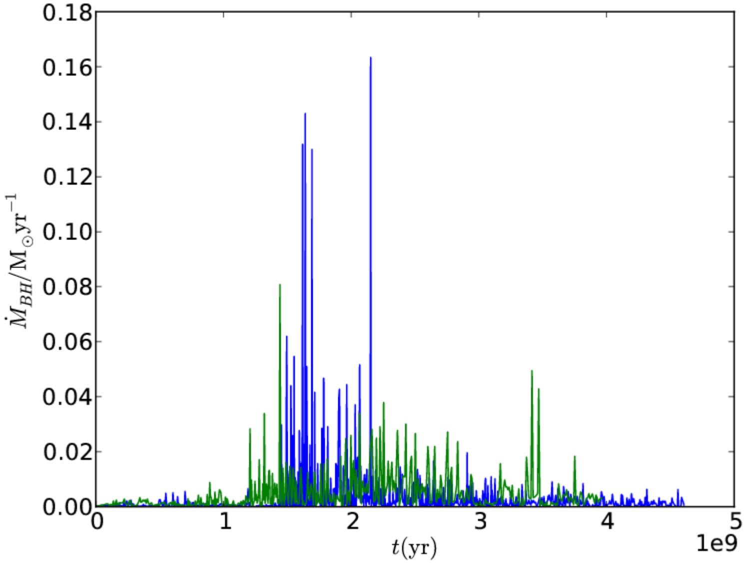
- **Thermal feedback (energy)**
- **X-ray feedback** (momentum + energy; Based on Sazonov+ 2005)
- **Mechanical feedback by AGN winds** (momentum + energy ; based on Choi & Ostriker 2012, Ostriker+ 2010)

➔ The pervious two are new implementations in cosmological simulations.

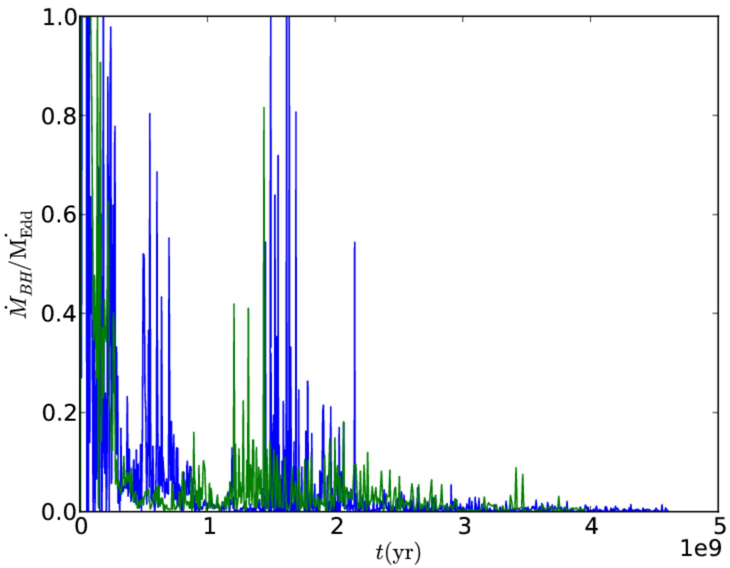
Model Flow Chart



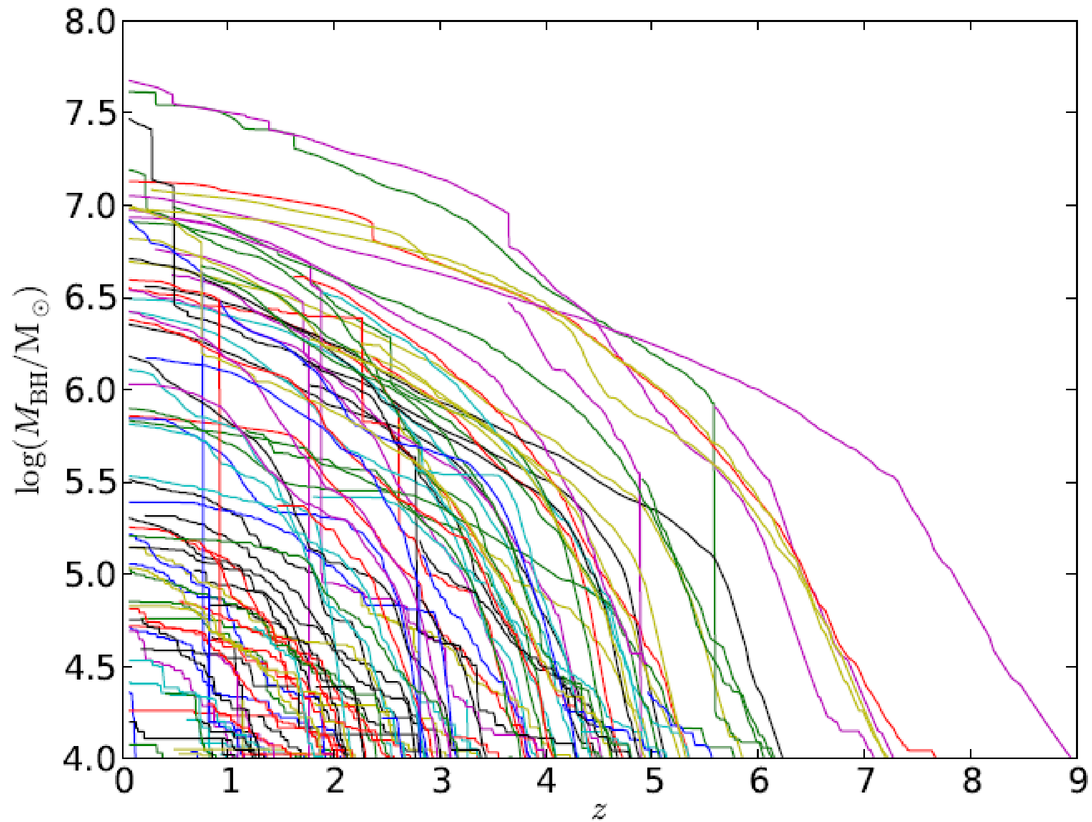
BH growth



0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
$\dot{M}_{BH}/\mathrm{M}_{\odot}\mathrm{yr}^{-1}$
0
1
2
3
4
5
1e9
$t(\mathrm{yr})$

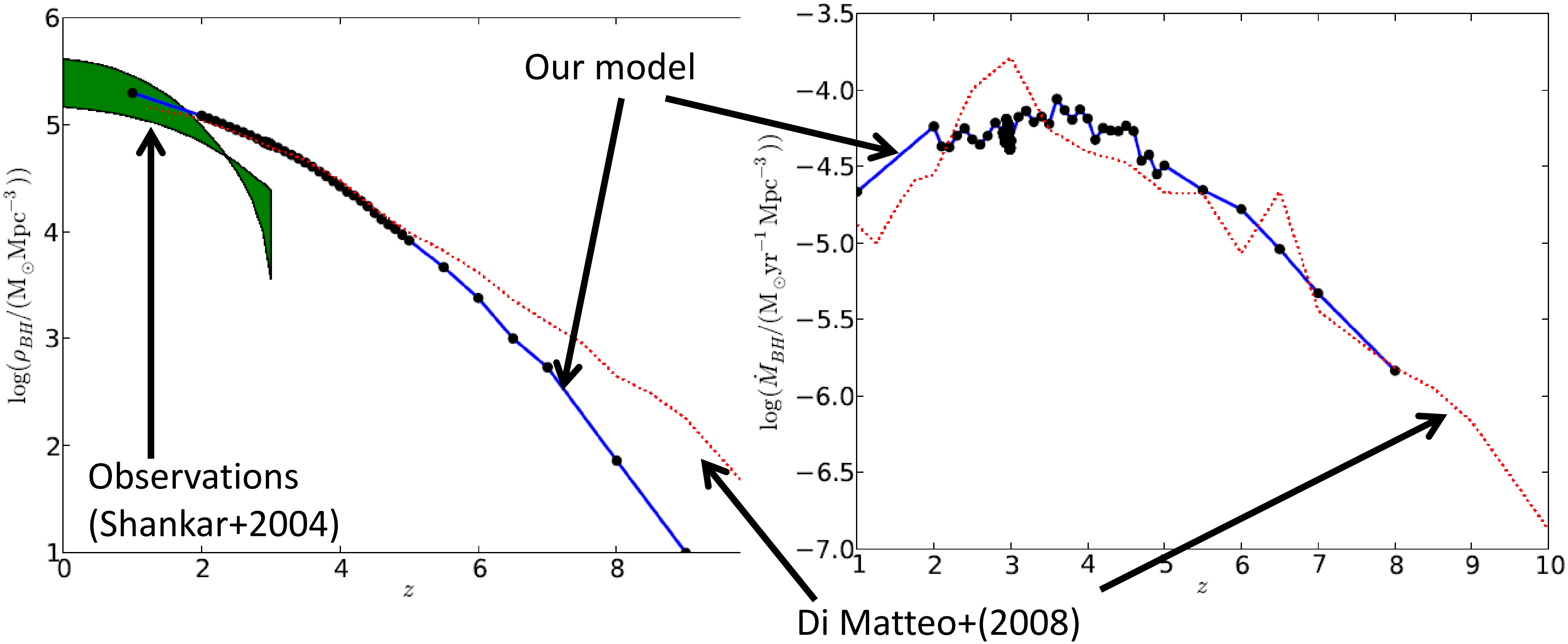


1.0
0.8
0.6
0.4
0.2
0.0
$\dot{M}_{BH}/\dot{\mathrm{M}}_{\mathrm{Edd}}$
0
1
2
3
4
5
1e9
$t(\mathrm{yr})$

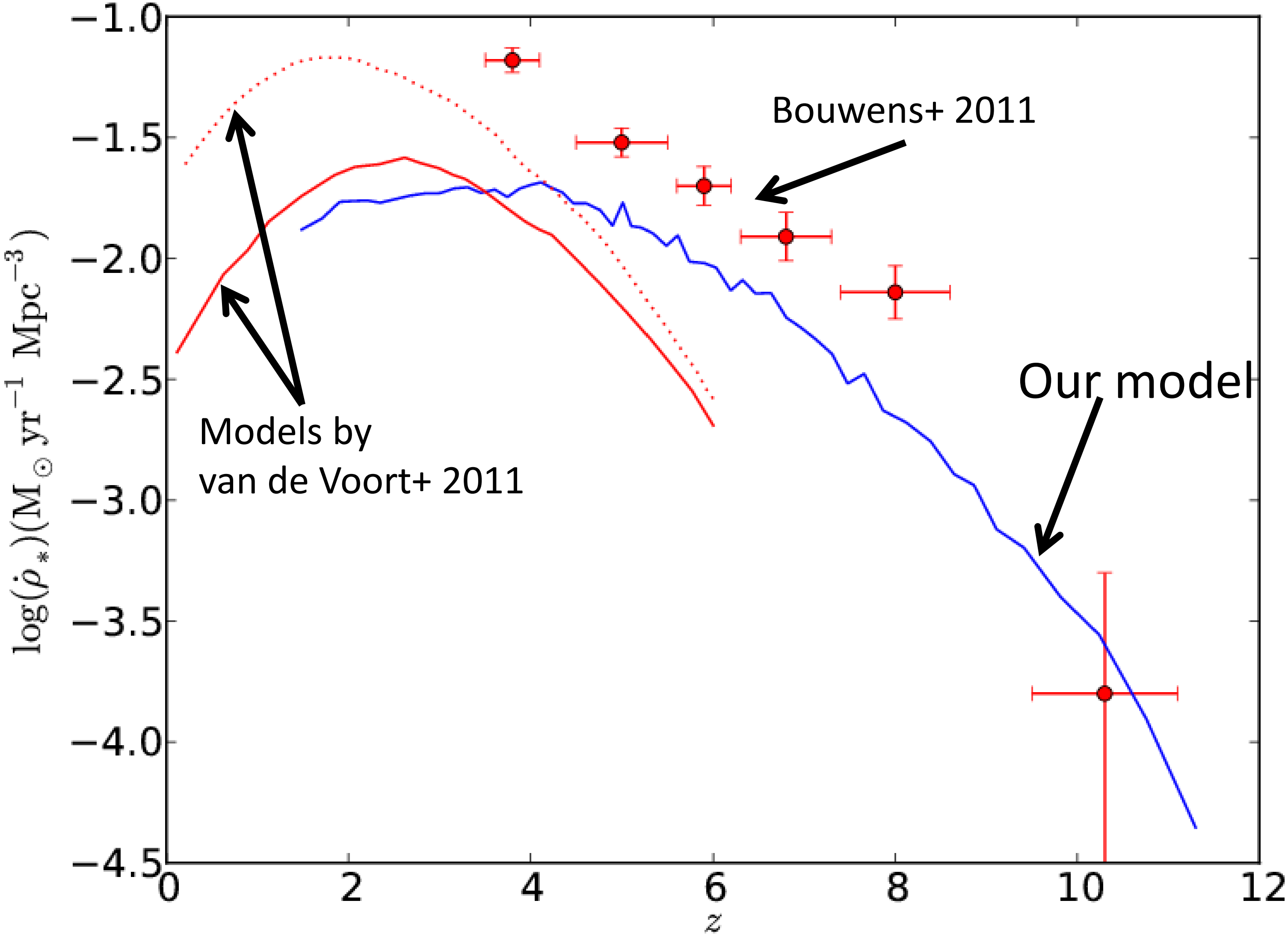


8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
$\log(M_{\mathrm{BH}}/\mathrm{M}_{\odot})$
0
1
2
3
4
5
6
7
8
9
z

BH mass density

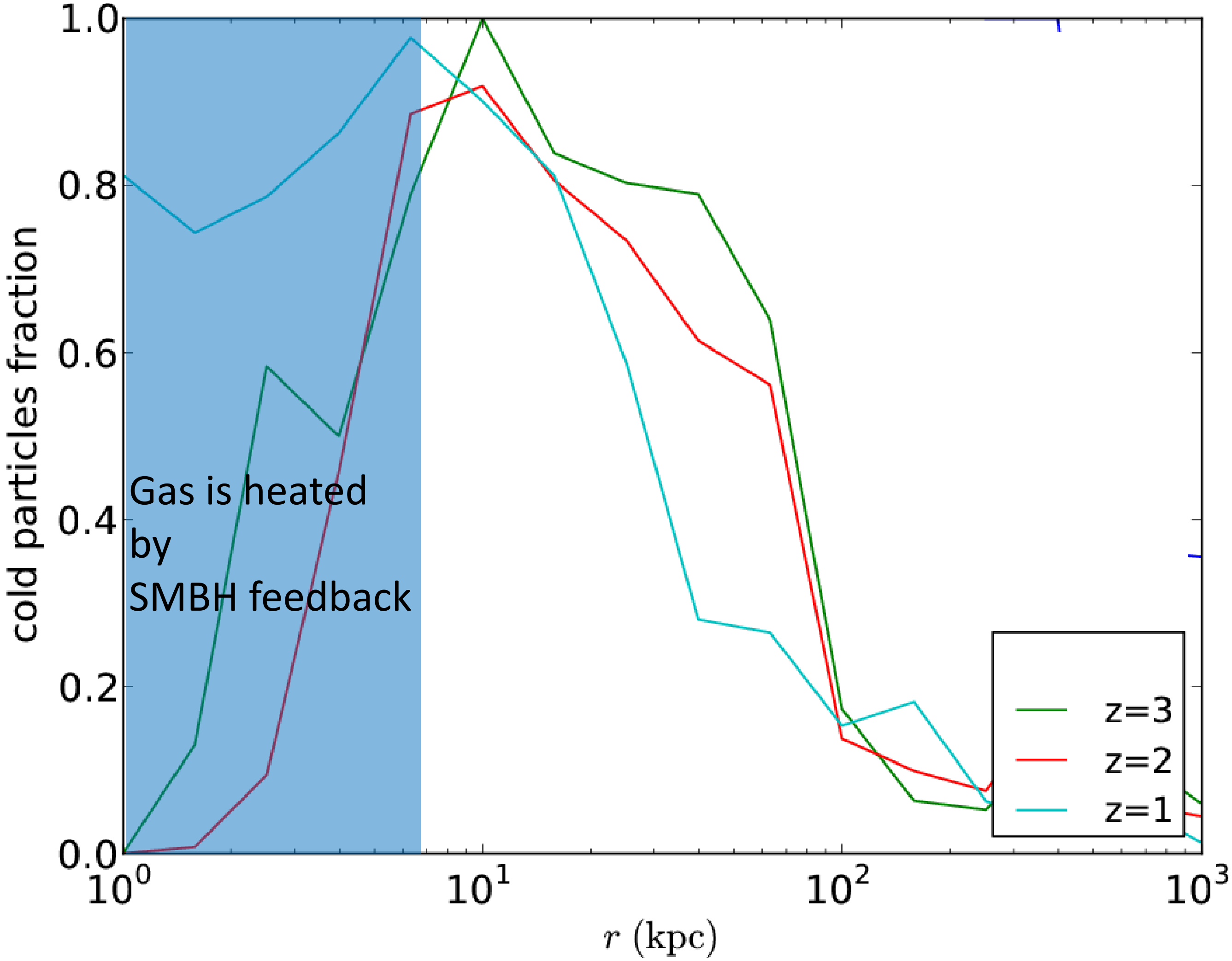


SFR



-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
0
2
4
6
8
10
12
z
$\log(\dot{\rho}_*)(\mathrm{M}_\odot\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3})$
Bouwens+ 2011
Our model
Models by
van de Voort+ 2011

Cold gas (T<10kK) mass fraction



Additional code ingredients:

- **Metal line cooling (Choi & Nagamine 2009)**
  – enhancement of SFR by 10-30%
- **Multicomponent Variable Velocity (MVV) galactic wind model (Choi & Nagamine 2011)**
  – energy + momentum driven winds,
  – galaxy V_w is a function of M_* ,no overheating of IGM
- **Currently SF model : “Pressure” based (Schaye & Dalla Vecchia 2008; Choi & Nagamine 2010)**
  – shift of SF threshold density, pressure and EoS based SF law
- **Coming soon: H2-based SF model (Thompson & Nagamine 2012)**
  – SFR based on computed H2 mass fraction with Krumholz+ 2009 model

Summary

Our suggested model:

- Using the basic hydrodynamic equations instead of Bondi.
- + Detailed feedback model (energy + momentum) with the important physical processes.

- We find that the accretion is dominated by cold gas.
- Our model overcomes problems with Bondi accretion.
- We manage to account for observed quantities: BH mass density, BH mass function, SFR, $M_{BH} - M_*$ relation.