Feedback From Supermassive Black Holes: Numerical Simulations

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Summary of Previous Talks

1. We have learned that there are definite issues in galaxy formation theories where we can show a connection between AGN and structure formation
2. Multi-wavelength observations show evidence of AGN-ICM interaction, co-evolution of AGNs with their host galaxies , impact of supermassive black holes on their environments.
3. Three Paths of AGN Feedback : Radiation mode , Relativistic Jets, Non-Relativistic outflows
4. Semi-Analytic models (Wyithe & Loeb 2002) do a good job in obtaining the AGN luminosity functions, interpreting the M_{BH}-σ relation.

Physics is not well understood, need to do cosmological simulations to understand the co-evolution and growth of black holes with their host galaxies

Simulations: Sijacki et al. 2007; DiMatteo et al. 2008, Thacker et al. 2006

Cosmological Simulations

- ❑In a cosmological simulation of AGN feedback a cosmological volume is taken
- ❑Simulation has dark matter dynamics
- ❑Simulation has hydrodynamics
- ❑Simulation may or may not have additional physics like cooling, star-formation, supernovae feedback.
- ❑AGN feedback run is in most case a subgrid model : The physics of the AGN is not resolved . Assumption is that we are looking at the large scale impact of some small scale physics which we do not resolve in the simulation.

Note : These are different from isolated AGN feedback simulation. They are more sophisticated models for the AGN physics but they do not study the co evolution.

(see Begelman & Ruszkowski 2002; Heinz et al. 2002; Reynolds et al. 2002)

Dark Matter and Gas Dynamics

Tree-Particle-Mesh (TreePM) (GADGET)

- Hybrid algorithm with a Tree code for high density regions and a Particle-Mesh algorithm otherwise (DiMatteo et al. 2008; Sijacki et al. 2007)

Adaptive Particle-Particle-Particle Mesh (AP3M) (HYDRA)

- Hybrid between direct particle-particle code and the particle mesh code (Thacker et al. 2006)

Adaptive Mesh Refinement (AMR) (see Douglas Rudd's talk)

- Particle Mesh code: Adaptive scheme

(We plan to use it for our AGN Feedback simulation)

Hydrodynamics is done in two ways

- **Particle based method**: averaging quantities over a smoothing length, Body fixed frame of reference (Lagrangian formalism) (the simulations described here are all SPH simulation)
- **Grid based method**: spatial grid (cells), space fixed frame of references (Eulerian Formalism) (Our current simulation; see Daisuke Nagai's talk; Douglas Rudd's talk)

Simulation Parameters

Run	Boxsize (h^{-1} Mpc)	N_P	m_{DM} ($h^{-1}M_\odot$)	m_{gas} ($h^{-1}M_\odot$)	ε (h^{-1} Kpc)	z_{end}
D4	33.75	2×216^3	2.75×10^8	4.24×10^7	6.25	0.00
D6 (BHCosmo)	33.75	2×486^3	2.75×10^7	4.24×10^6	2.73	1.00

Simulation	$L_{\rm box}$ $[h^{-1}{\rm Mpc}]$	$N_{\rm part}$	$m_{\rm DM}$ $[h^{-1}{\rm M}_\odot]$	$m_{\rm gas}$ $[h^{-1}{\rm M}_\odot]$	$z_{\rm start}$	$z_{\rm end}$	ϵ $[h^{-1}{\rm kpc}]$
R1	25	2×176^3	1.72×10^8	0.35×10^8	100	1	3.0
R2	25	2×256^3	5.58×10^7	1.14×10^7	100	1	2.0
R3	25	2×384^3	1.65×10^7	0.34×10^7	100	1	1.3

Run	Boxsize (h^{-1} Mpc)	N_P	m_{DM} ($M_\odot$)	ε (h^{-1} Kpc)	$Steps(z=1)$
0400	35	2×40^3	1.2×10^{10}	24	1340
0800	35	2×80^3	1.5×10^9	12	3678
1600	35	2×160^3	1.9×10^8	6	5420
3200	35	2×320^3	2.3×10^7	3	7381(z=2.5)
1020	146	2×640^3	2.2×10^8	9	10420(z=1.2)

Cosmological Simulations

- ❑**Initial mass function of black holes**
- ❑**Prescription of growth of black holes**
- ❑**Prescription of feedback**
  - ❖Mode of feedback
  - ❖Spatial scale of feedback
  - ❖Energy scale of feedback

Initial Mass Function of Black Holes

DiMatteo et al. 2008; Sijacki et al. 2007

❑Initial black holes are described in the simulation in the form of seed black holes.

❑Once a dark matter halo (mass $10^{10} M_{sun}$) is formed in the simulation, the simulation converts the densest SPH particle to a seed black hole of mass $10^{5}\, M_{sun}$.

❑Motivated from expected mass scales of seed supermassive black holes from theories of formation of supermassive black holes (see DiMatteo et al. 2008 for details)

Thacker et al. 2006

Formation of black hole is entangled with mergers. Following a galaxy merger it is assumed that black holes are formed in the simulation (see lecture 2 notes)

Growth of Black Hole

DiMatteo et al. 2008; Sijacki et al. 2007

Bondi- accretion is assumed for growth of the black hole. Black holes also grow by merging with other black holes
(see lecture notes for derivation of Bondi-accretion)

$$\dot{M}_{BH} = 4\pi[G^2 M_{BH}^2 \rho]/(c_s^2 + v^2)^{3/2}$$

$$r_B = 50pc \left(\frac{M_{BH}}{10^7 M_\odot}\right) \left(\frac{c_\infty}{30km/s}\right)^{-2}$$

Subgrid model

Black Holes do not grow with the simulation and is an instantaneous process. The mass of the black hole is calculated using the M_{BH}-σ relation (Thacker et al. 2006)
(See Lecture 2 on how we get the mass of the black hole)

Recall Lecture 2

Mode of Feedback

- Radiative feedback only (DiMatteo et al. 2008)
- Both radiative/kinetic feedback (kinetic: radio jets); No jet in the simulation ; a primitive model of radio bubble
- Two mode feedback model below and above a certain threshold accretion efficiency. Choice of efficiency 0.01 .
- Model assumes that radiatively efficient feedback follows rapid accretion phases of a black hole (quasar mode), mostly operative at high redshifts
- Radiatively inefficient feedback follows the jet mode in the forms of radio bubble in clusters. (Sijacki et al. 2007)

Quasar winds (Kinetic) (Thacker et al. 2006) (Radio quiet)
Uses a Sedov-Taylor model (see lecture 2) to model a point like explosion following a merger event

Energy Scale of Feedback

- A certain fraction of the mass energy goes into feedback energy
- This fraction is assumed to be 0.5% (motivated by the self-regulatory growth scenario and by matching with the normalisation of the observed M_{BH}-σ relation)
- Energy is distributed within the gas particles isotropically (DiMatteo et al. 2008)
- Energy is distributed within the radius of the bubble . Mechanical efficiency is assumed to be 0.2% (Sijacki et al. 2007)

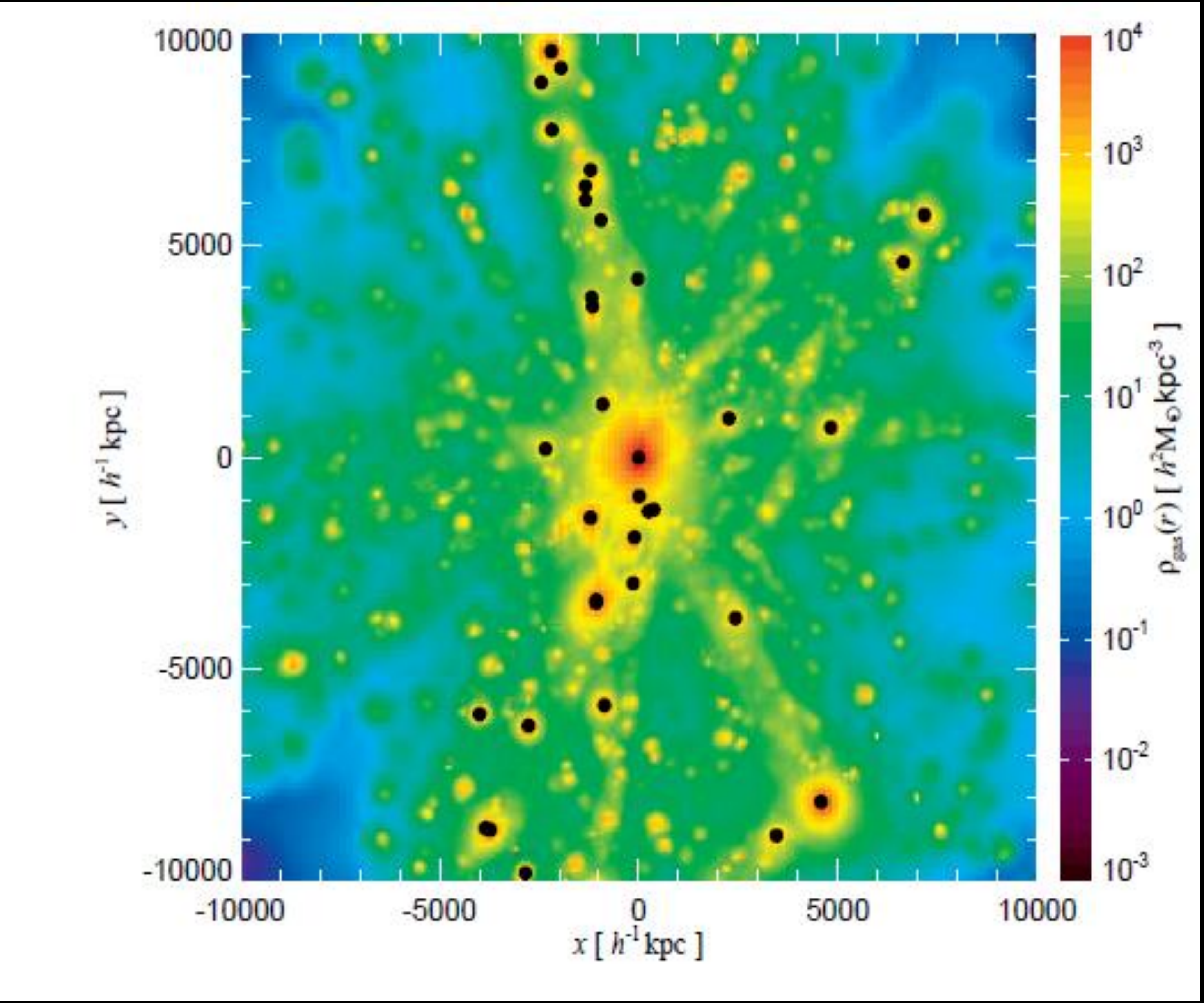
- Following a merger in the simulation the black hole shines at its Eddington luminosity and returns a fraction of its mass energy to the galactic gas.
- The fraction is taken t be 0.5%. (Thacker et al. 2006)

Spatial Scale of Feedback

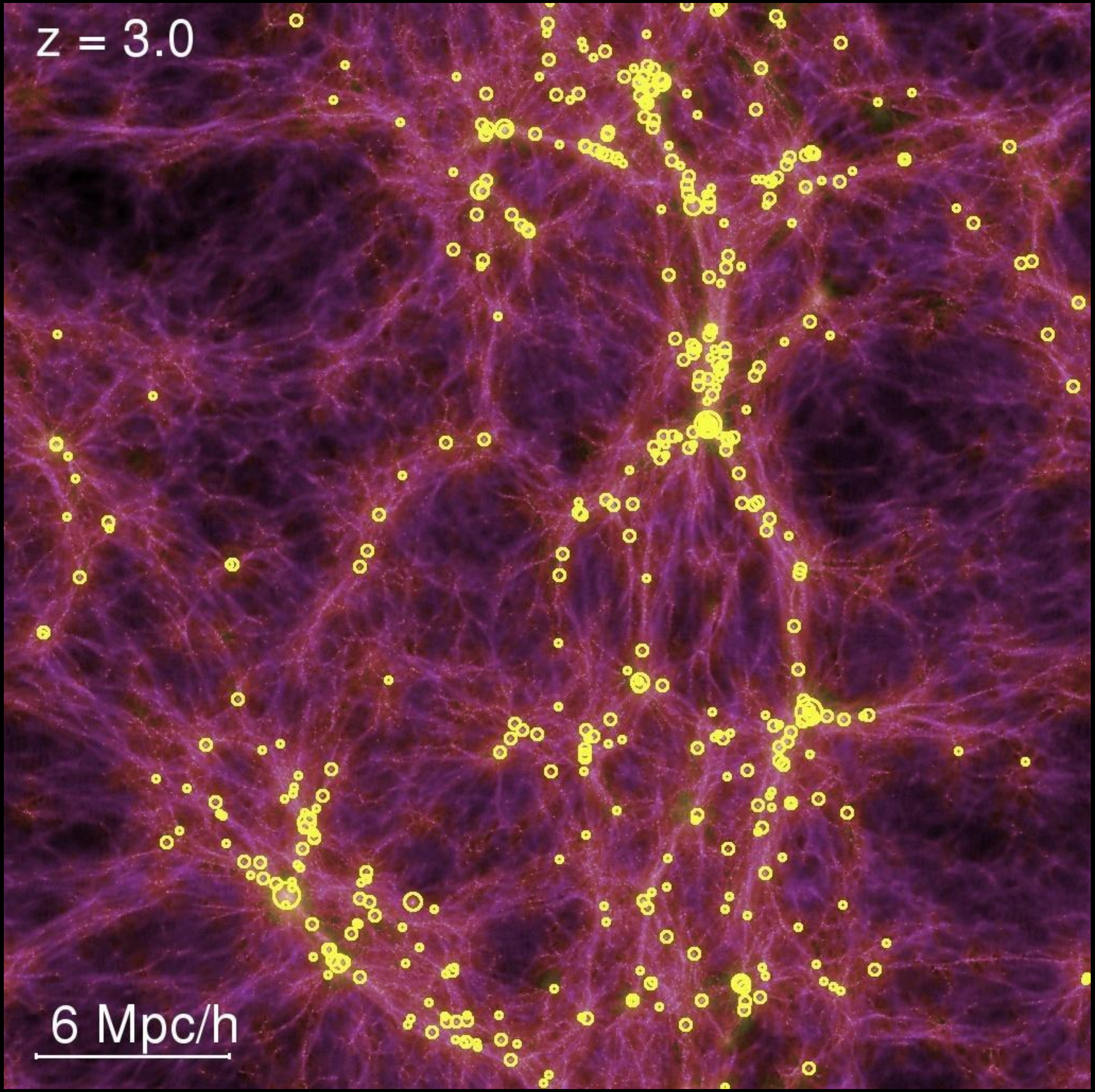
❑The feedback energy from the black hole is distributed within the gas smoothing kernel. The scale turns out to be about couple hundreds of kpc (DiMatteo et al. 2008)

❑For radio bubbles the scale is the radius of the bubble (~50 kpc) (Sijacki et al. 2007)

❑The Sedov solution gives the scale of the bubble depending on the energy of the outflow.
(~1 Mpc) (Thacker et al. 2006) (see lecture 2)

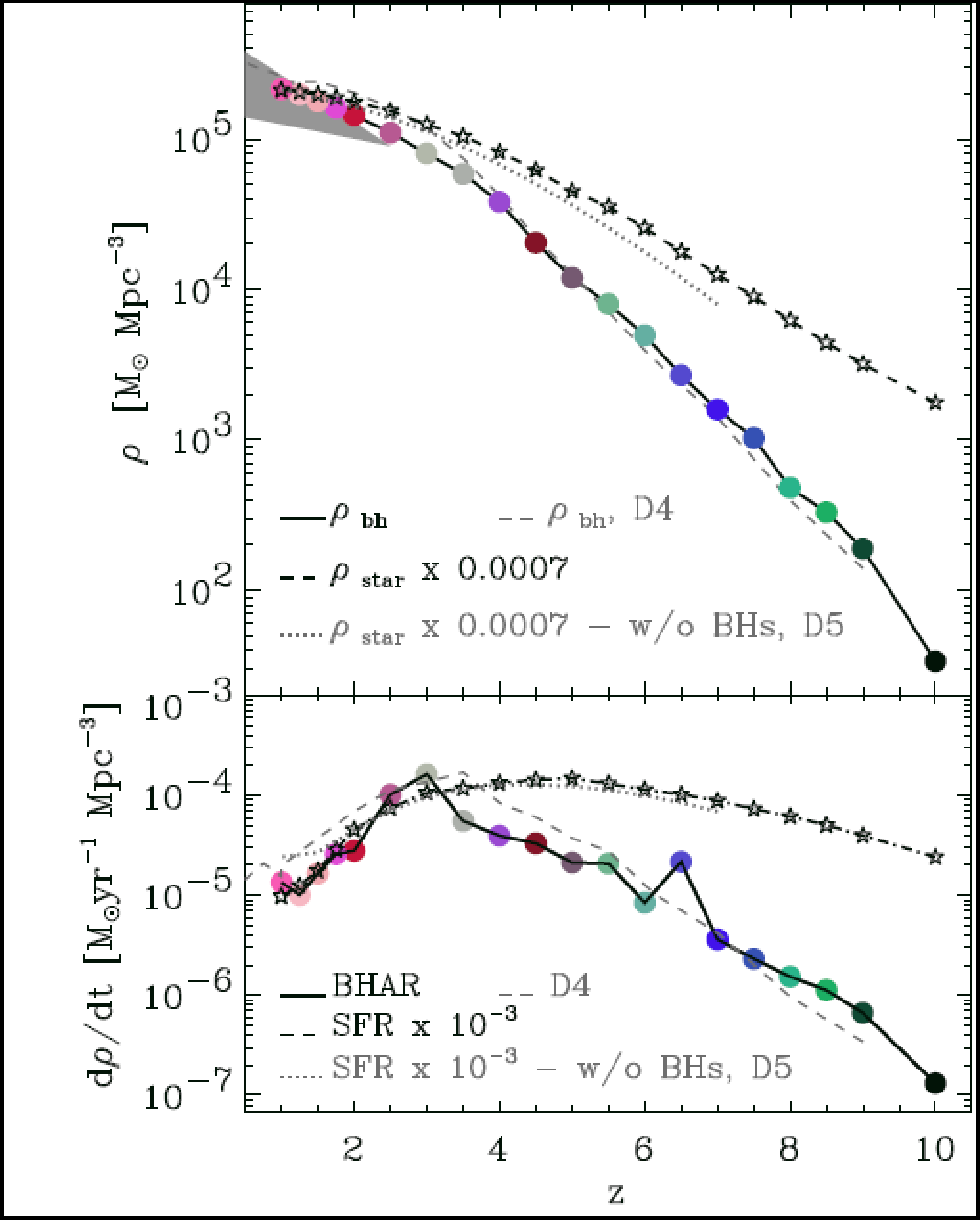


Sijacki et al. 2007



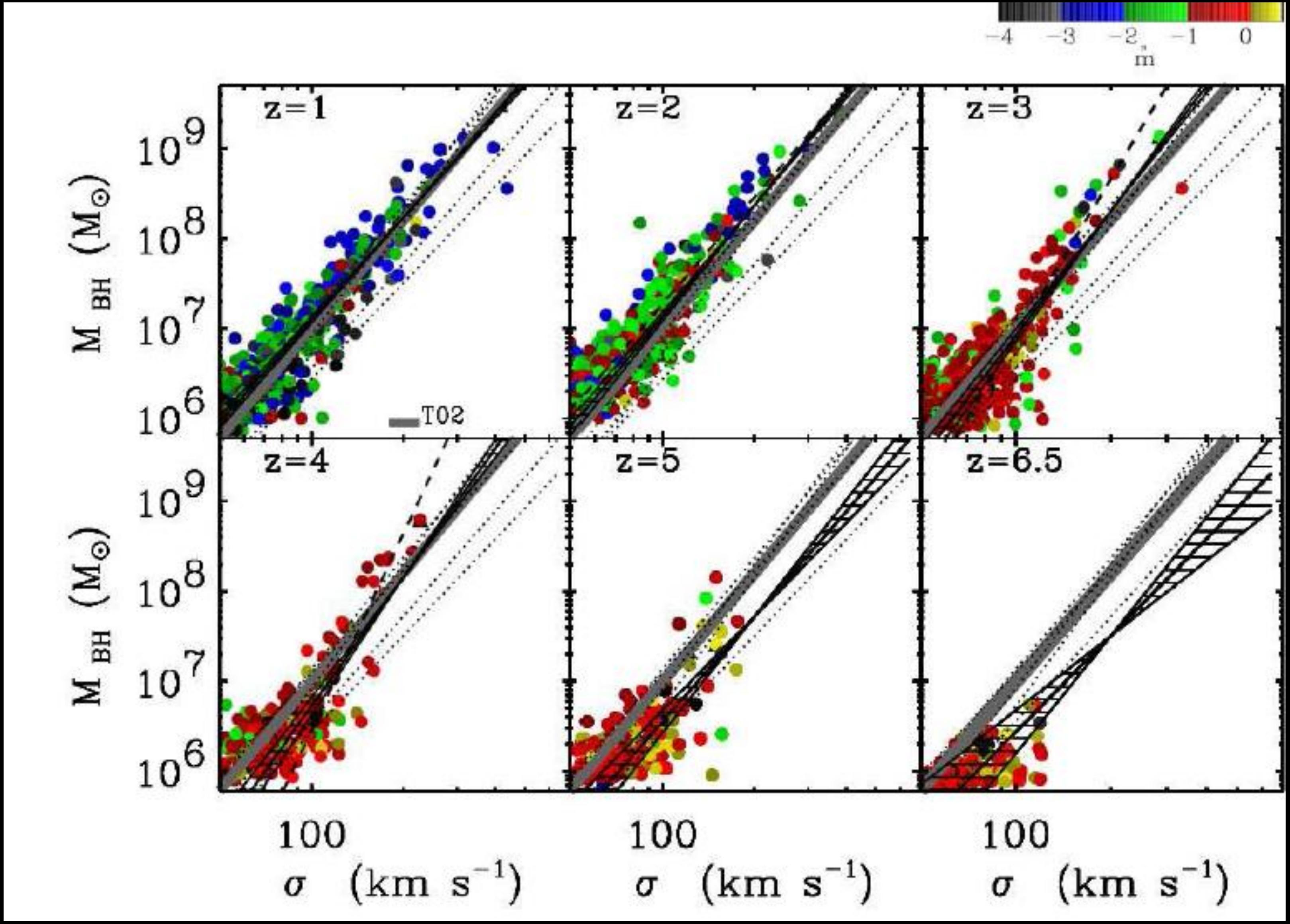
DiMatteo et al. 2008

Star formation and black hole formation rate

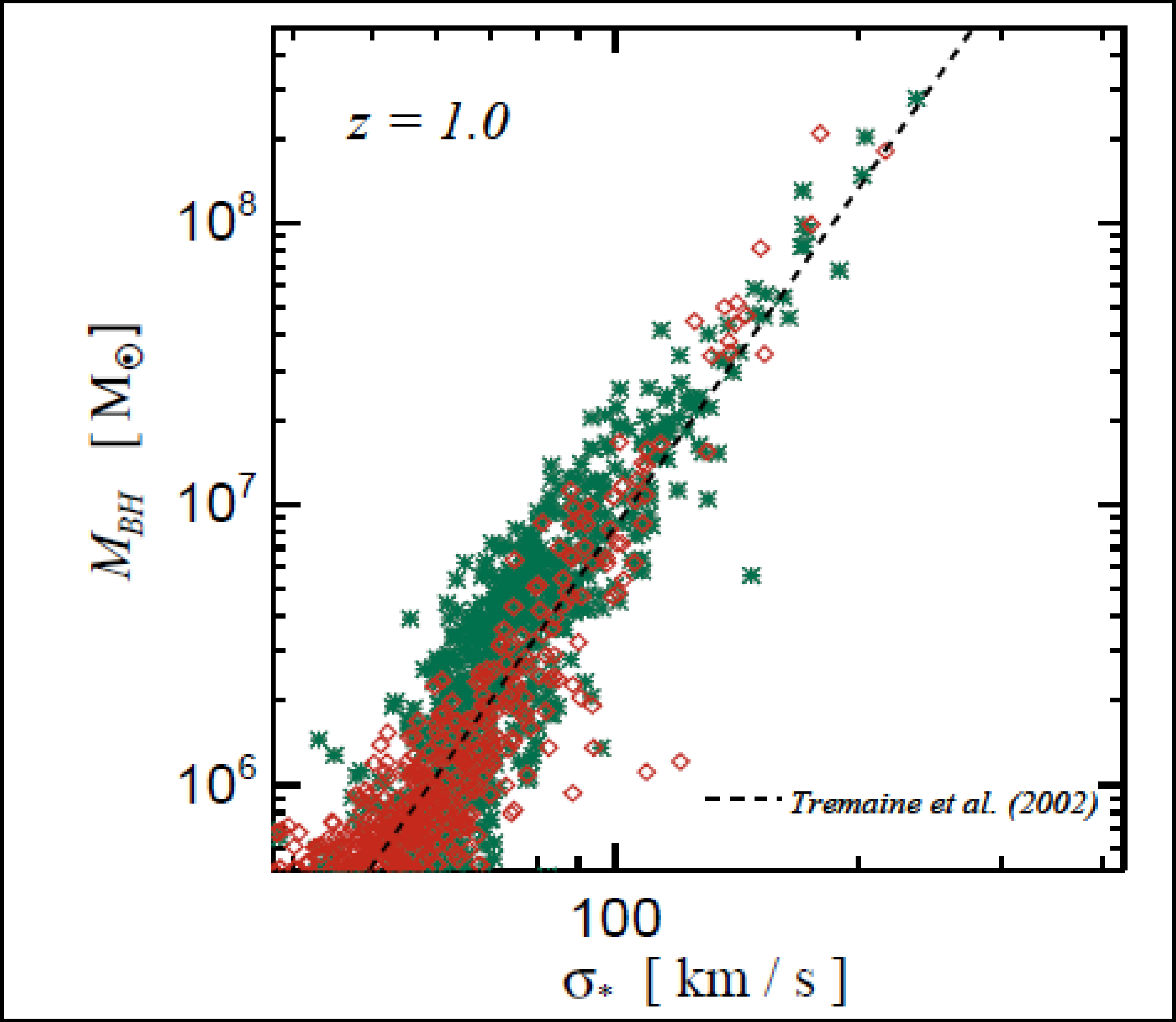


DiMatteo et al. 2008

M_{BH}-σ relation

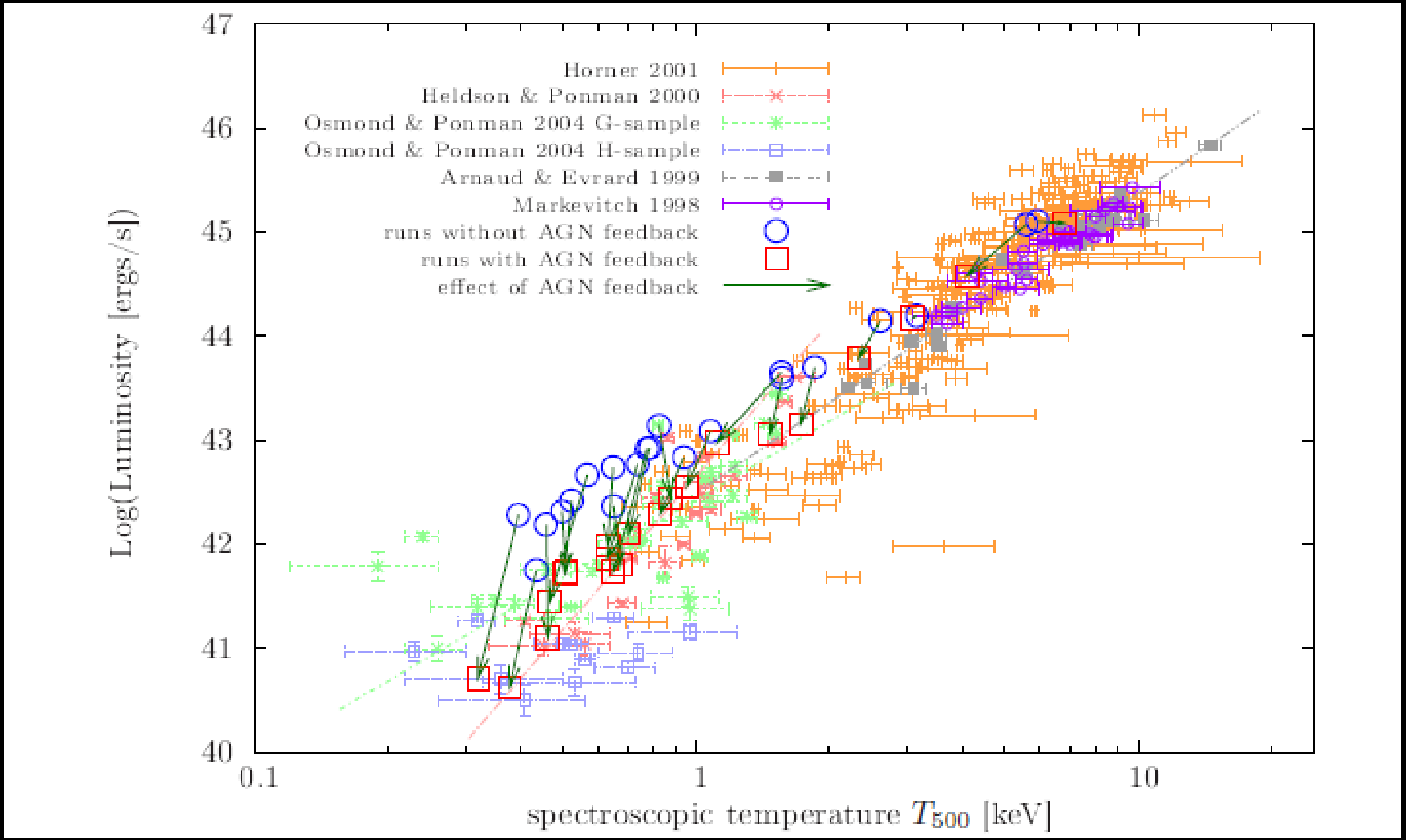


DiMatteo et al. 2008



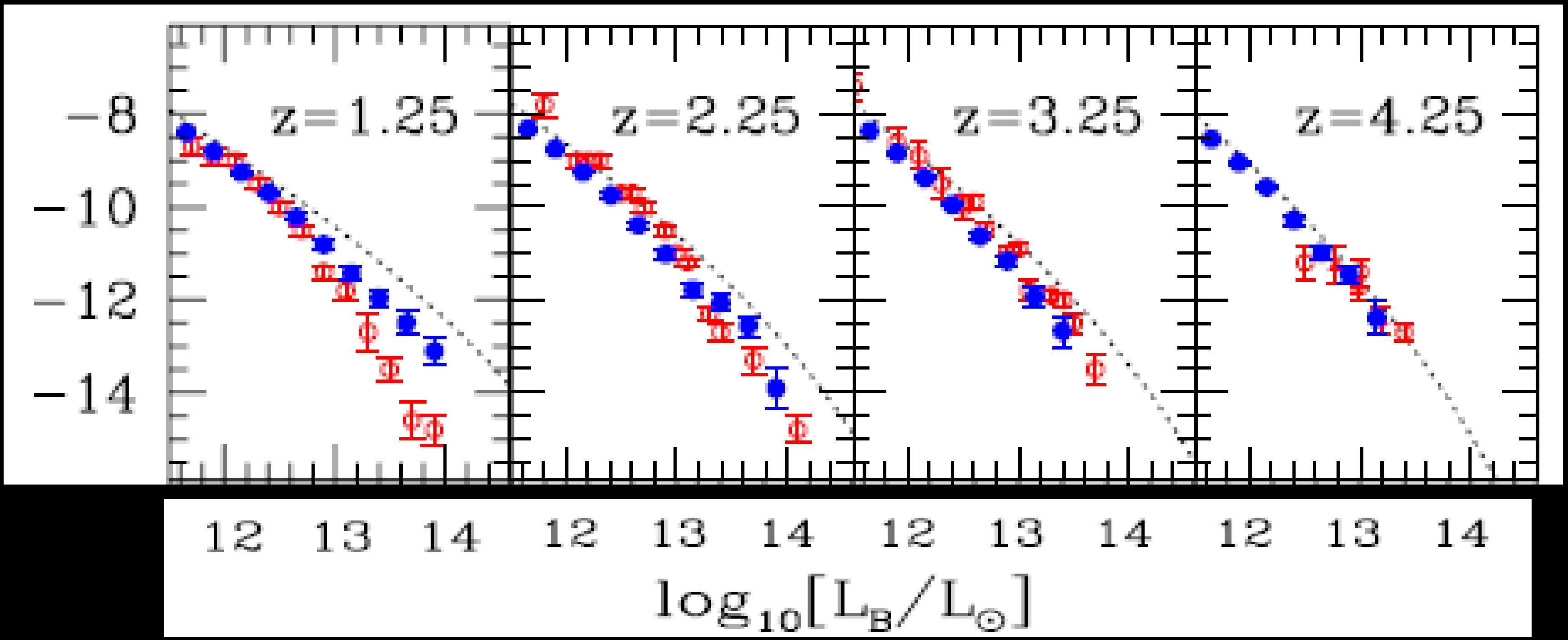
Sijacki et al. 2007

LX-T relation in clusters



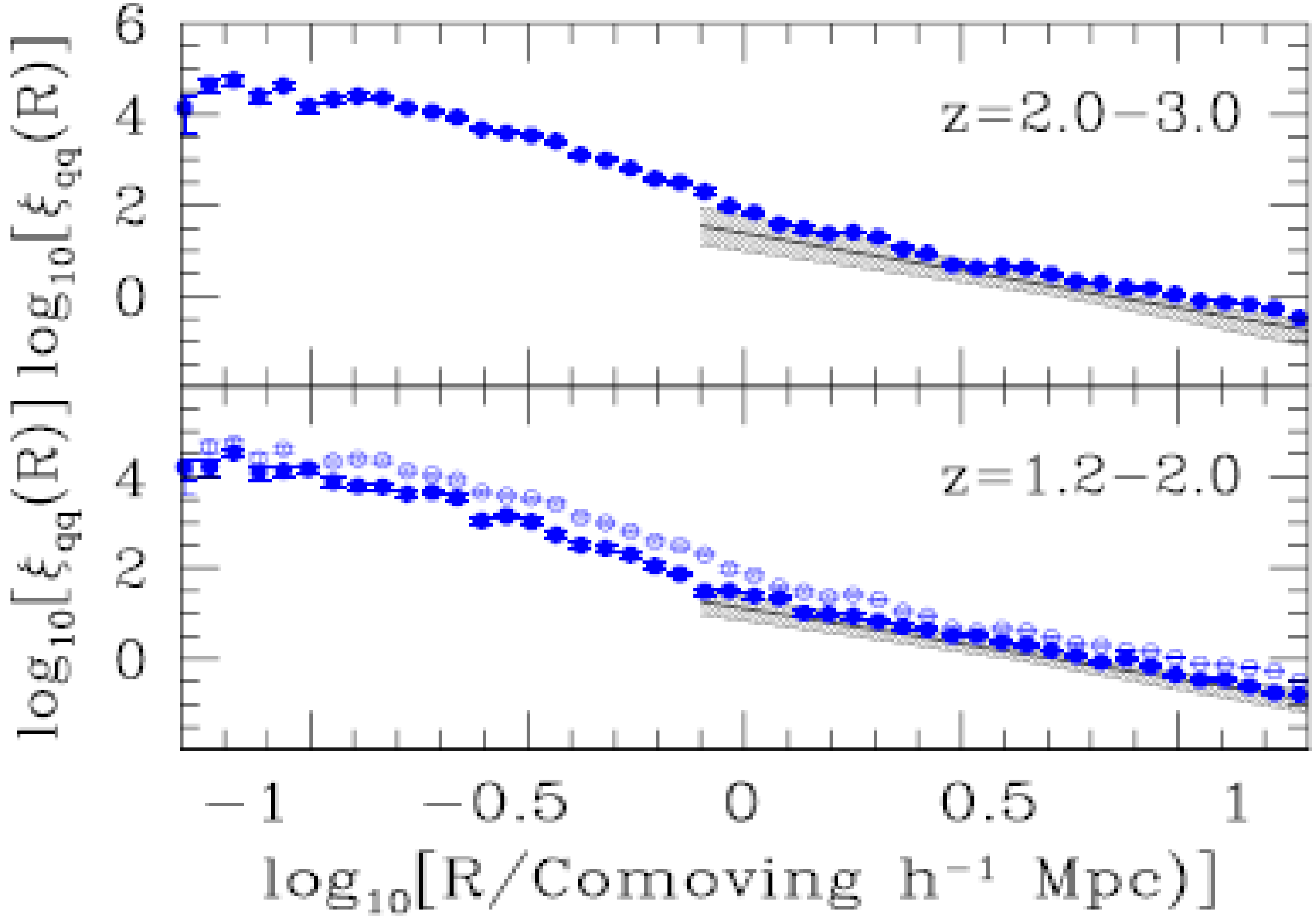
Puchweinn et al. 2008

AGN Luminosity Functions



Thacker et al. 2006

Correlation Function of AGNs



Thacker et al. 2006

One can also do the quasar-galaxy cross-correlation

Summary

- ❑AGN Feedback has important impact on structure formation (e.g., cooling flow problem in clusters)
- ❑Observational Evidence through Multi-Wavelength Observations
- ❑Theoretically feedback can be in three modes: Radiative, Relativistic Jets, non-relativistic winds
- ❑Current semi-analytic models and numerical simulations have been successful in reproducing several observational signatures (e.g., M_{BH}-σ relation, AGN luminosity functions)
- ❑Several unanswered questions: (e.g., Coupling mechanism unknown!)
- ❑Fine Tuning of Parameters
- ❑**Exciting field** (many problems to solve)

THANK YOU