Modeling the cosmological co-evolution of SMBHs and Galaxies:

models for BH accretion and AGN lightcurve

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Outline

- Astrophysical framework: BH and galaxy connections
- Description of the Tool
- Modeling the AGN lightcurve (Marulli, Bonoli et al. 2008)
- Work in progress...
  - New models for BH accretion
  - AGN clustering

Astrophysical Framework: BH-Ubiquity

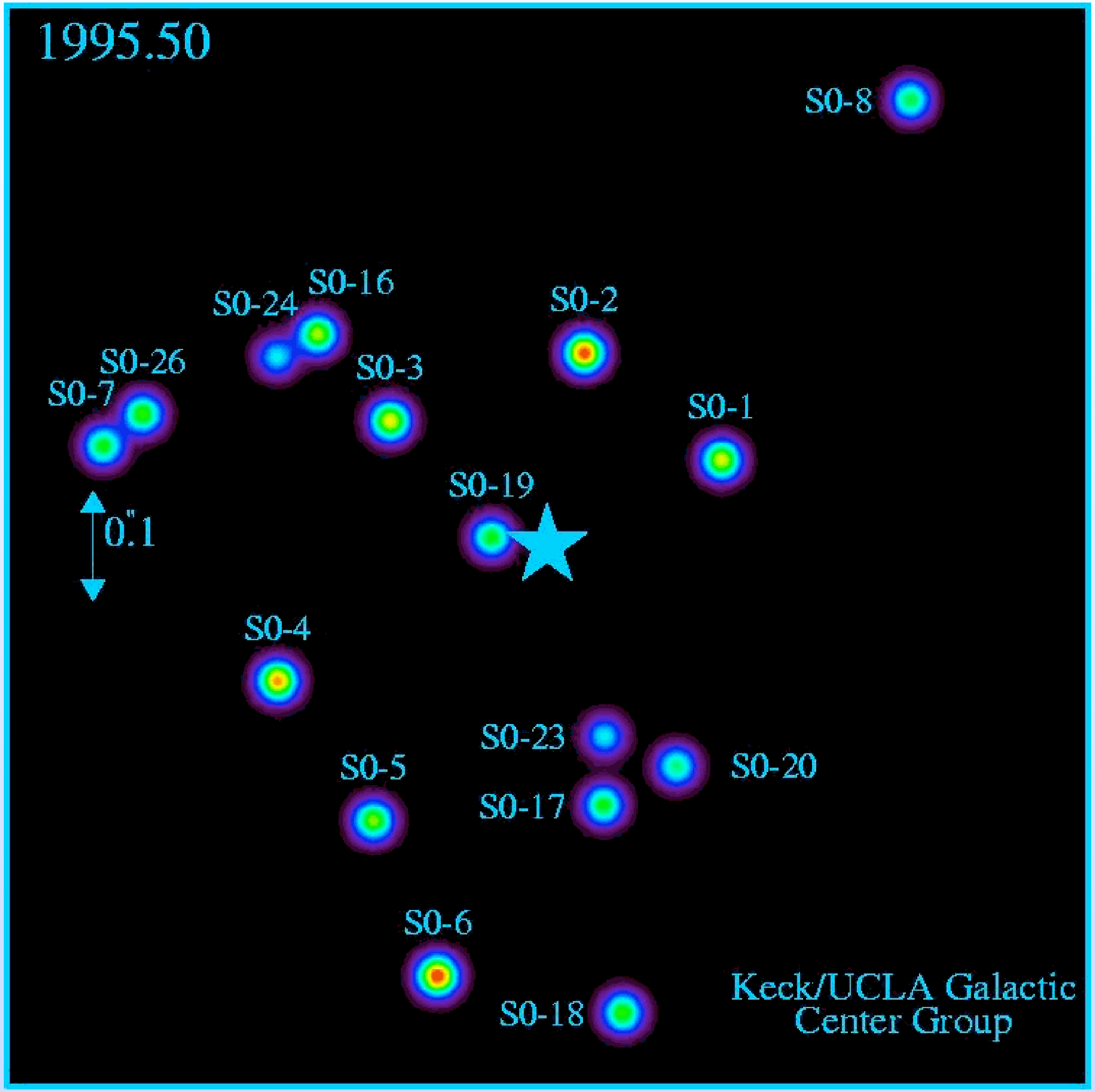
“SMBHs are ubiquitous at the center of all Spheroids”

Evidences:

- Active Galactic Nuclei
- Dynamics of the surrounding objects

Radius of influence: $$r_i = \frac{GM_{BH}}{\sigma} \approx 10.8pc \left(\frac{M_{BH}}{10^8 M_\odot}\right)\left(\frac{\sigma}{200km/s}\right)^{-2}$$

Astrophysical Framework: BH-Ubiquity



Sgr A*

$$M_{BH} \approx 4 \times 10^6 M_\odot$$

Ghez et al.

http://www.astro.ucla.edu/~ghezgroup/gc/pictures/index.shtml

Astrophysical Framework: A tight friendship

- The BH mass is connected to some physical properties of the host galaxy

Scaling relations:

~ M_{BH}-L_{Bulge} (Kormendy & Richstone 1995)

~ M_{BH}–M_{Bulge} (Magorrian et al. 1998)

~ M_{BH}–Sigma (Ferrarese & Merritt 2000, Gebhardt et al. 2000)

~ M_{BH}–M_{DM} (Ferrarese 2002)

.....

~ BH Fundamental Plane (Hopkins et al 2007)

BHs and their hosts must have formed from the same processes
and/or
they influence each other during their evolution

Astrophysical Framework: A tight friendship

- Nearly all mass in BHs has been accumulated during periods of bright AGN activity (Soltan 1982, Yu & Tremaine 2002, Merloni & Heinz 2008, ...)

Procceses that form spheroids and BHs, also trigger AGN activity

A friendship that started long ago...

Powerful quasars found at $z > 6$ with SDSS (Fan et al. 2000+)

- Powered by BHs with $M > 10^9\ M_{SUN}$

→ Massive BHs already in place at high z

Where do massive BHs come from?

Seed BHs from PopIII stars	Direct collapse of low-angular momentum gas
$M_{BH} \sim 10^{(2-3)}\ M_{SUN}$	$M_{BH} \sim 10^5 M_{SUN}$

(e.g., Volonteri, Madau...) (e.g., Koushiappas et al, ...)

The Goal

Study in a cosmological context:

- The main physical processes responsible for triggering the growth of BHs and AGN activity

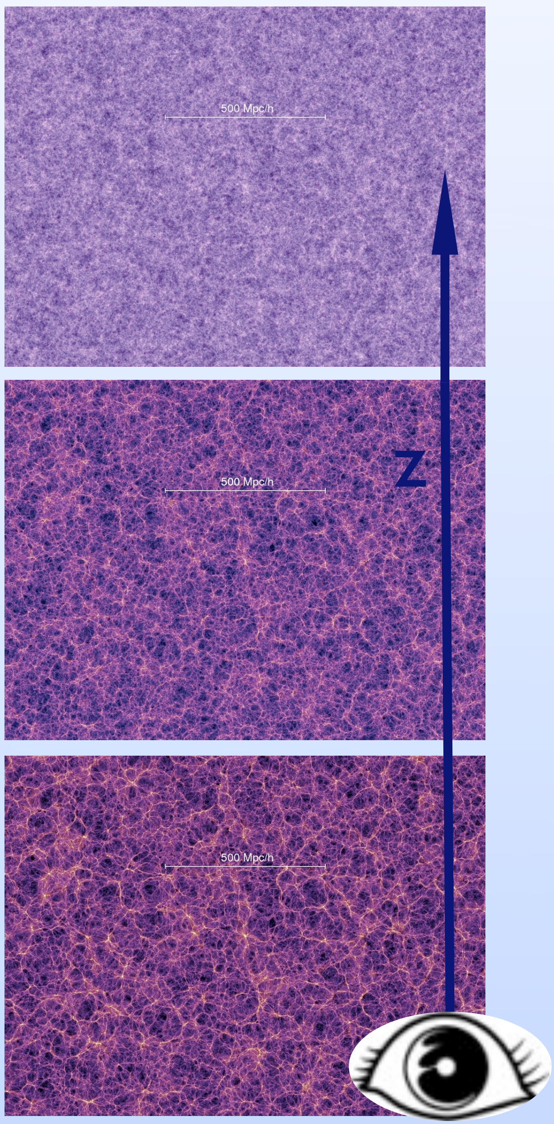
- How the BH population is connected to the environment

Our tool:

- Post-processing of the Millennium Simulation
(aka "Semi-analytical model" or "Hybrid simulation")

The Tool

DM merger trees from the Millennium Simulation ⟷ Analytical models for the evolution of the baryons



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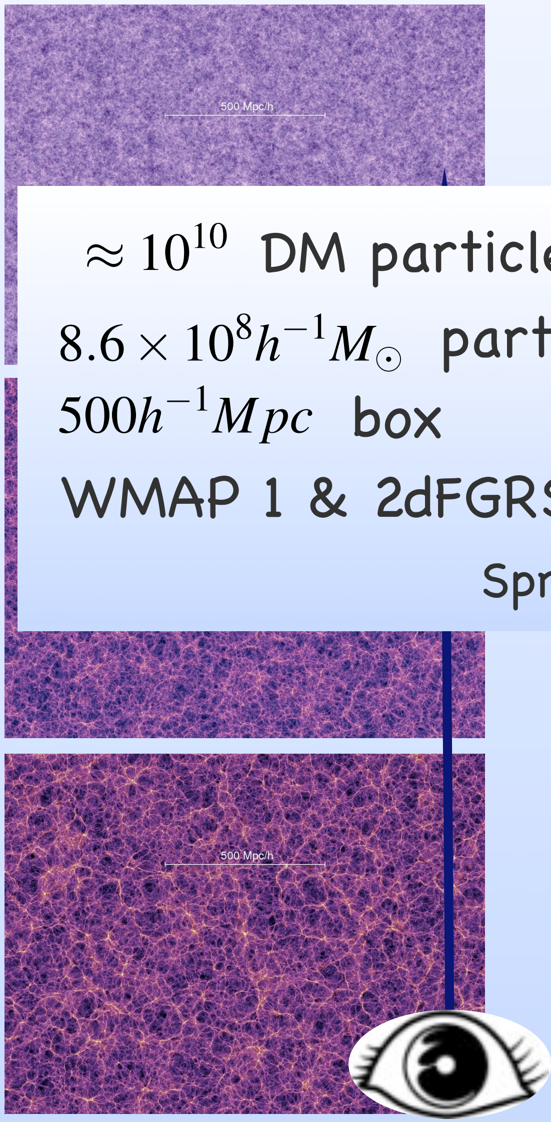


$\approx 10^{10}$ DM particles

$8.6 \times 10^{8} h^{-1} M_{\odot}$ particle mass

$500 h^{-1} Mpc$ box

WMAP 1 & 2dFGRS cosmology

Springel et al (2005)

- Fix a cosmic baryon fraction
- Gas infall and cooling
- Star Formation (Chabrier IMF)
  - Metals
  - SNe feedback
  - Recycled gas
- Disk instability
- Galaxy mergers
- BH growth
- AGN heating

Croton et al. 2006

DeLucia & Blaizot 2007

The life of a BH

1. When galaxies are formed, we put a **BH seed** (1.e3 Msun)

2. During mergers, the mass of the final BH is the **sum** of the mass of the progenitors

3. **"Quasar mode"** - During mergers, the final BH accretes a fraction of the cold gas of the host galaxy

$$\Delta m_{BH} = \frac{f_{BH} m_{cold}}{1 + (280 Kms^{-1}/V_{vir})^2}$$

(Kauffmann & Haehnelt 2000)

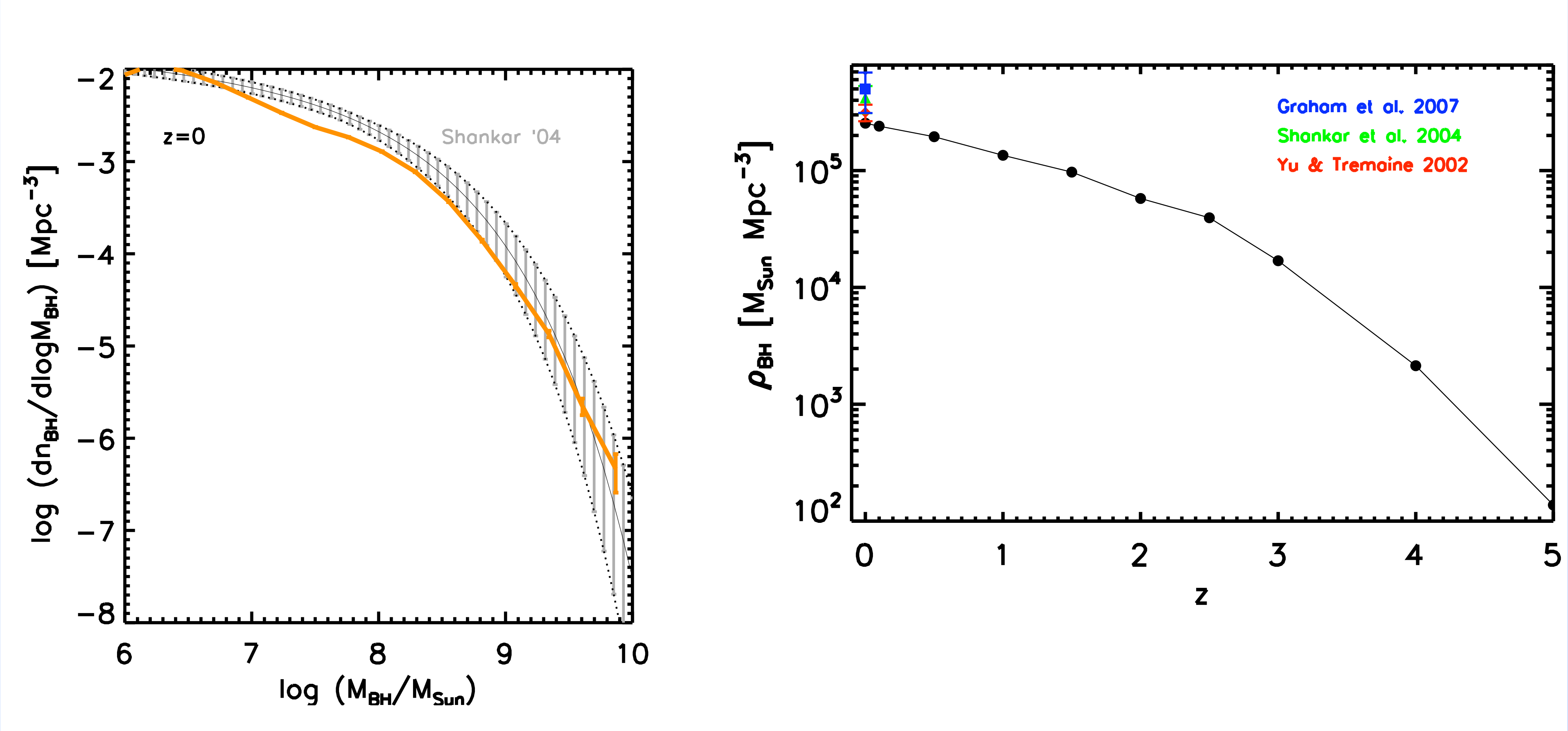
4. **"Radio mode"** - the BH accretes hot gas when a static hot halo has formed around the host galaxy

$$\dot{m}_{BH} \propto m_{BH} f_{hot} V_{vir}^3$$

(Croton et al. 2006)

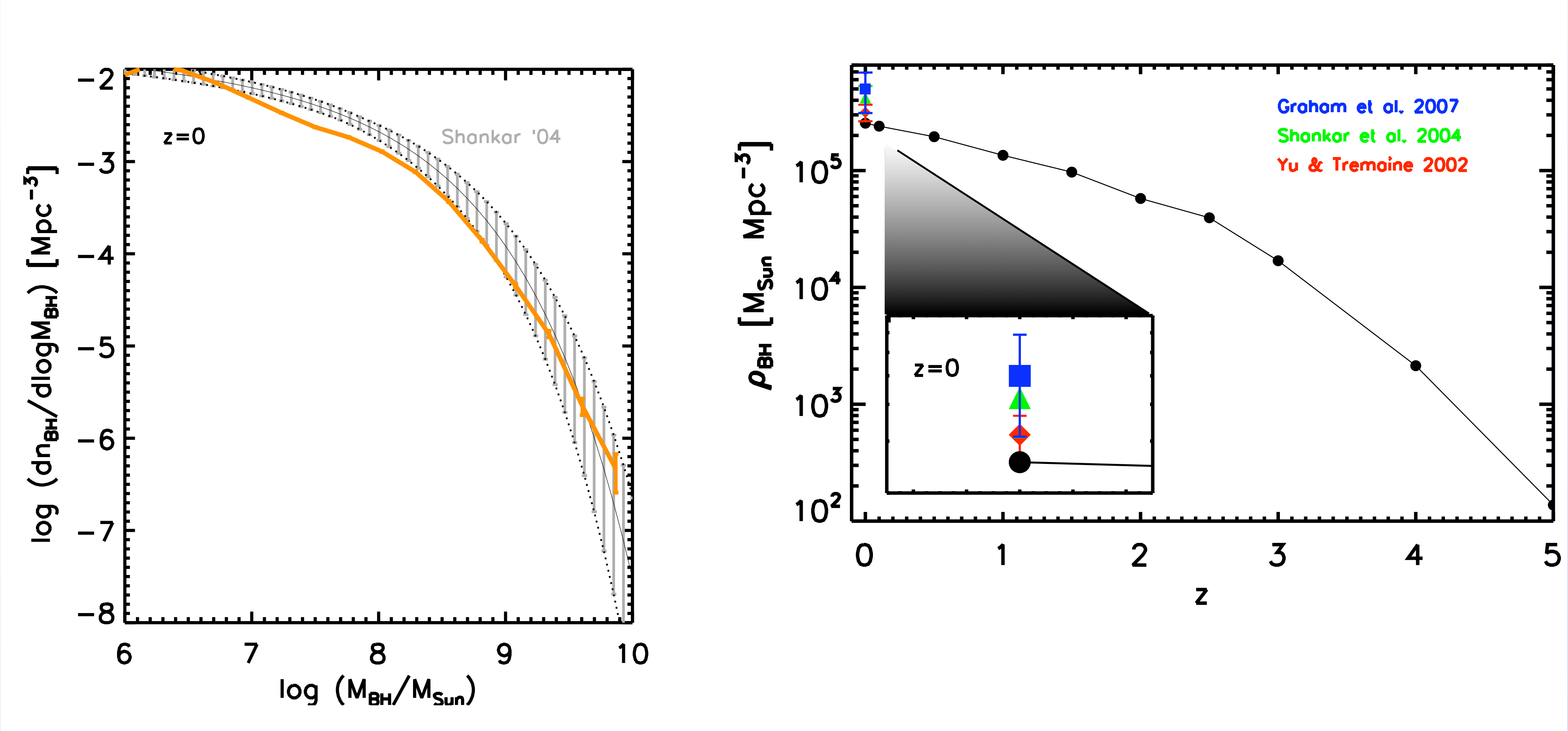
First Tests

Mass function
and
mass-density evolution



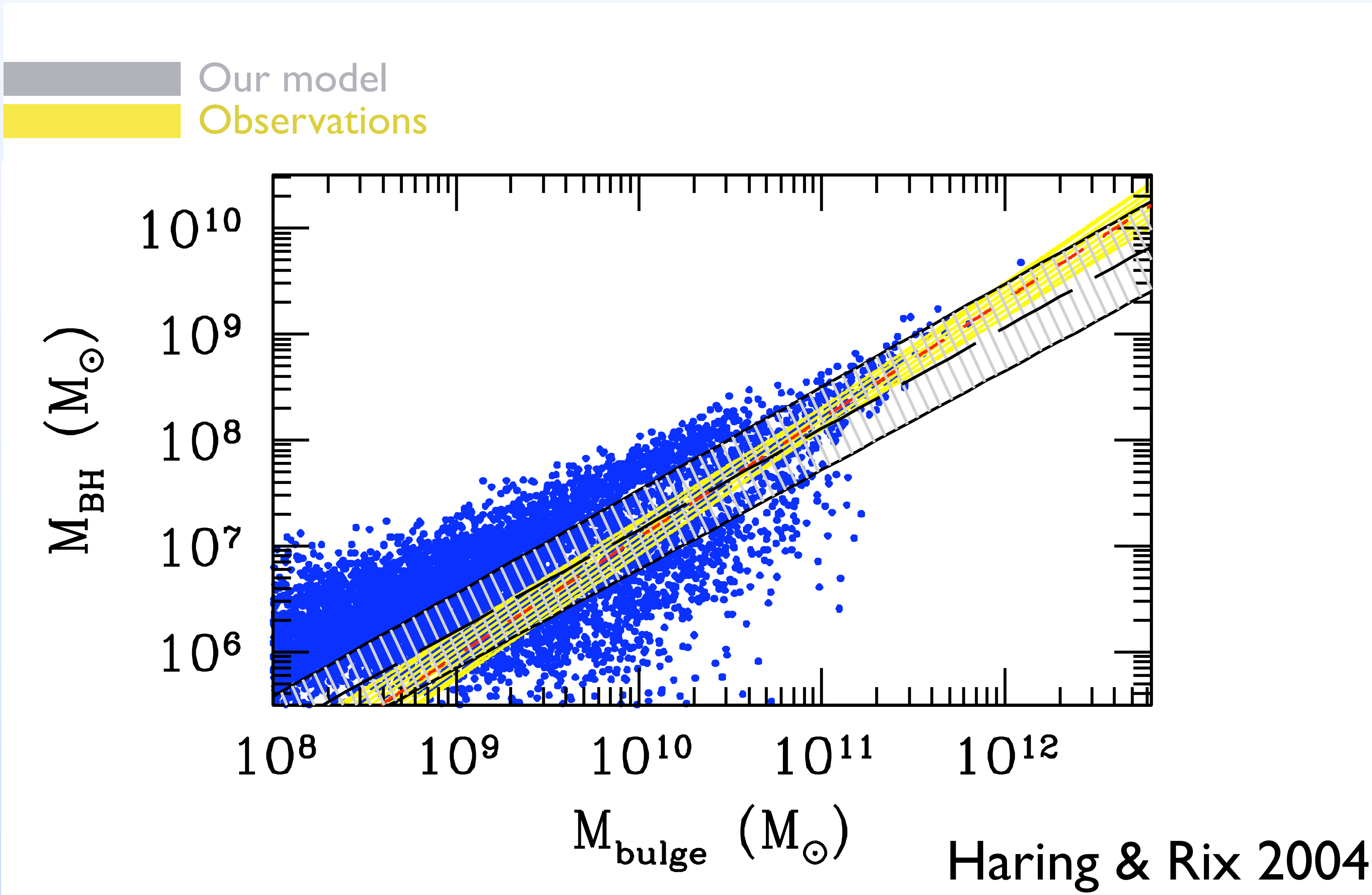
First Tests

Mass function and mass-density evolution



First Tests

Scaling relations at z=0



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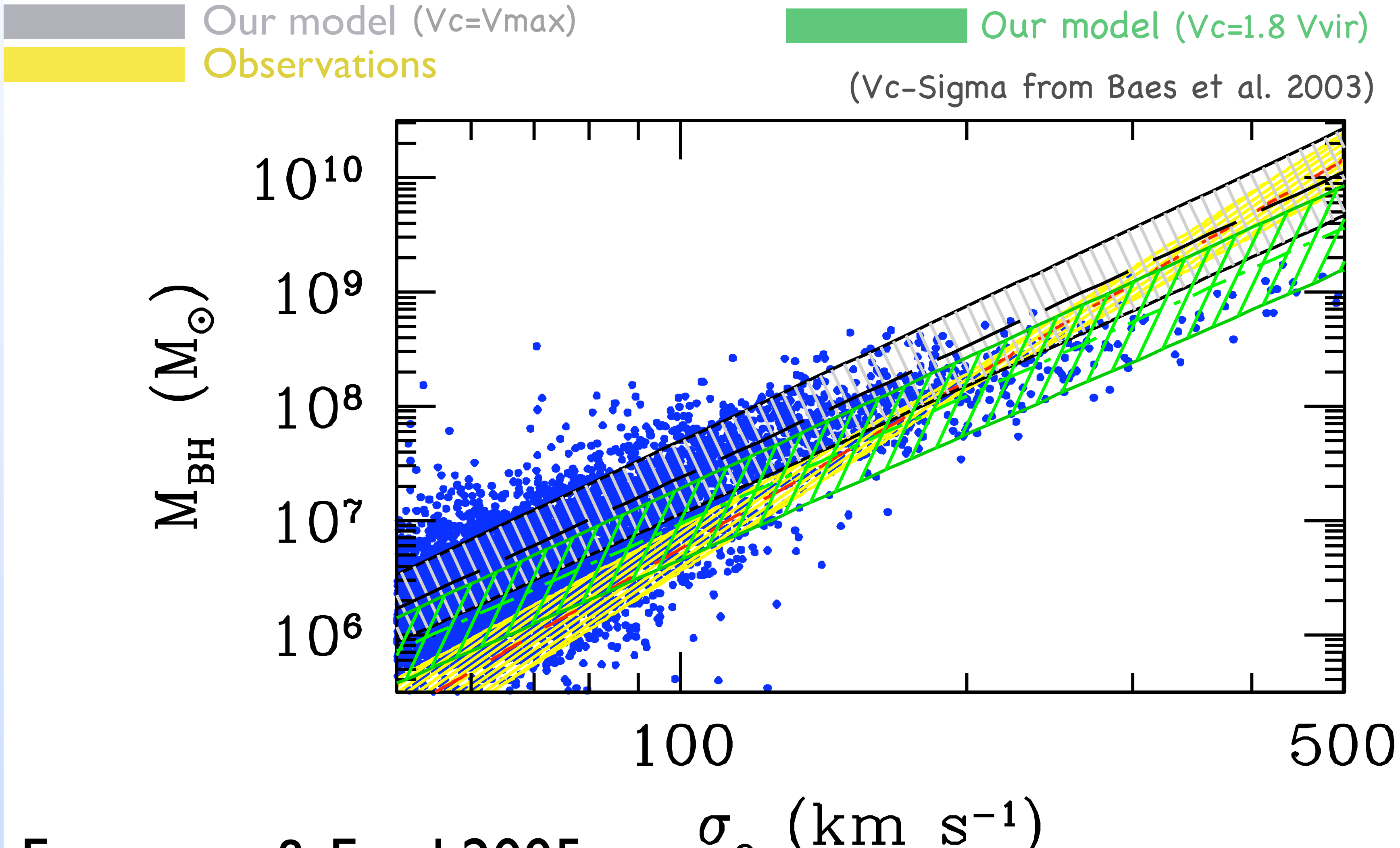

Ferrarese & Ford 2005

Modeling the AGN lightcurve

Mass-dependent AGN lifetimes

$$L_{Bol} = \frac{\varepsilon}{(1-\varepsilon)}\dot{M}_{BH}c^2$$

$$L_{Bol} = f_{Edd} \times L_{Edd}$$

$$\dot{M}_{BH} = \frac{(1-\varepsilon)}{\varepsilon c^2} f_{Edd} L_{Edd}$$

$$t_{acc} = \frac{\varepsilon}{1-\varepsilon}\frac{t_{Edd}}{f_{Edd}} \ln\left(1 + \frac{\Delta M}{M_{BH}(t_0)}\right)$$

$$M_{BH}(t) = M_{BH}(t_0) e^{\frac{1-\varepsilon}{\varepsilon}\frac{t}{t_{Edd}} f_{Edd}}$$

$$L_{Bol}(t) = f_{Edd} \times L_{Edd}(M(t))$$

$\varepsilon = 0.1$

$t_{Edd} = 0.45 Gyr$

$$L_{Edd} = \frac{4\pi G m_p c}{\sigma_T} M_{BH} \approx 1.3 \times 10^{38} \left(\frac{M_{BH}}{M_\odot}\right) erg/s$$

Modeling the AGN lightcurve

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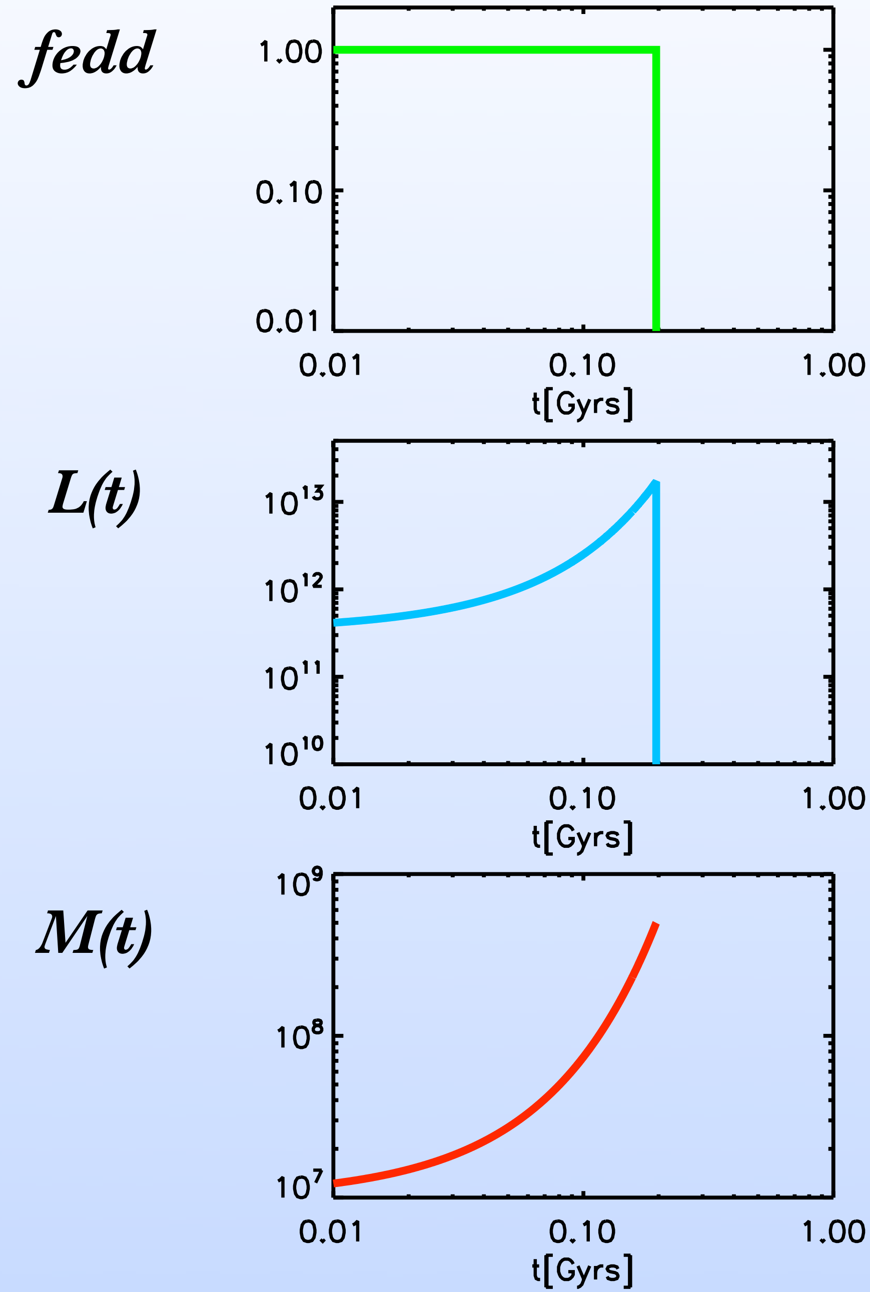
Modeling the AGN lightcurve

Mod I

Eddington-limited accretion

fedd=1



Modeling the AGN lightcurve

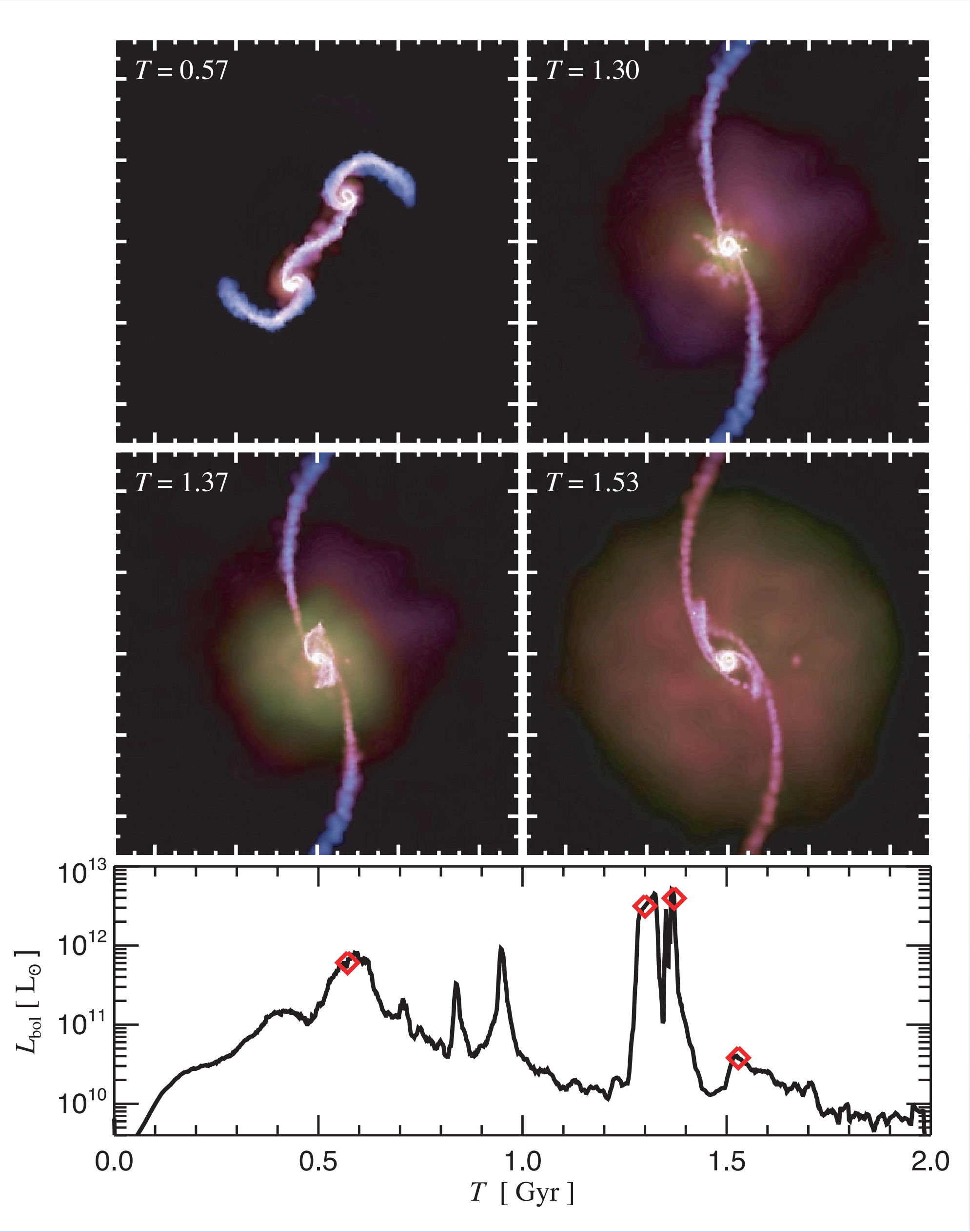
Hopkins et al. 2005
From hydrodynamical simulations of galaxy mergers

↓

phase of bright activity followed by quiescent phase

$$\frac{dt}{d\ln L} = |\alpha|\, t_9 \left(\frac{L}{10^9 L_\odot}\right)^{\alpha}$$

$$\alpha = -0.95 + 0.32 \log \frac{L_{peak}}{10^{12} L_\odot}$$



Modeling the AGN lightcurve

Mod II

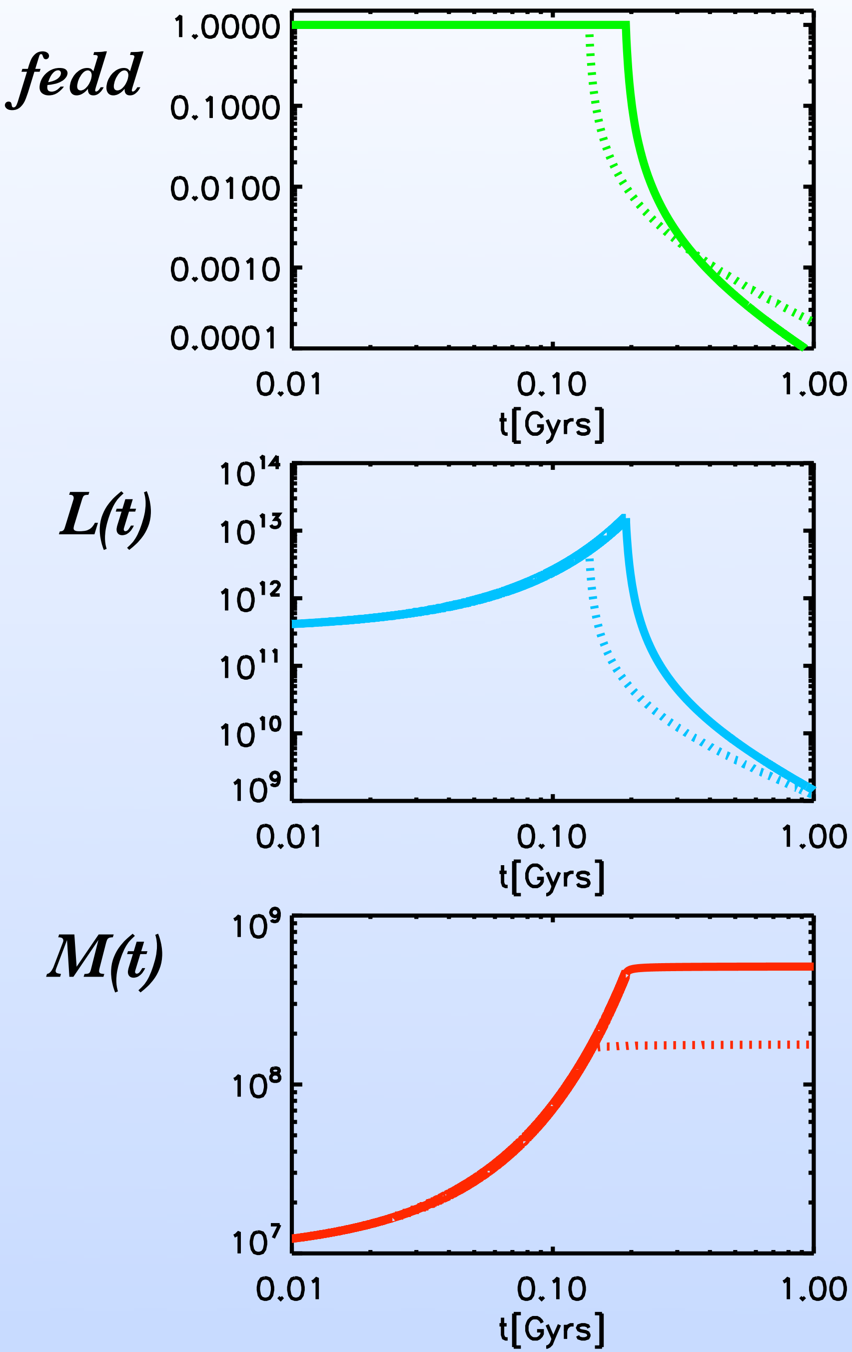
2-phase accretion:

1. Eddington limited
2. Long quiescent phase (Hopkins et al. 05)

$$\frac{dt}{d\ln L} = |\alpha| t_9 \left(\frac{L}{10^9 L_\odot}\right)^\alpha$$

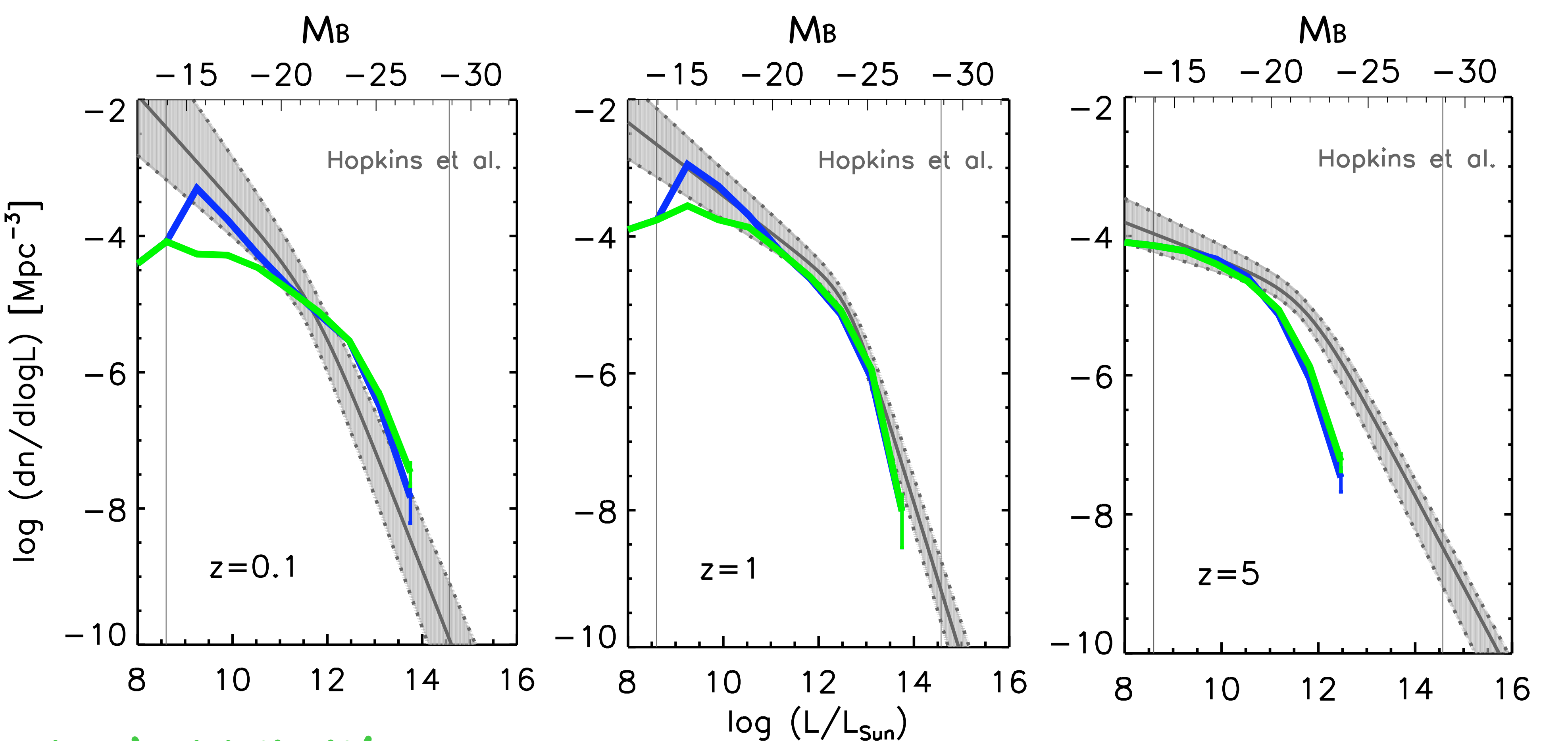
$$\alpha = -0.95 + 0.32 \log \frac{L_{peak}}{10^{12} L_\odot}$$

$$L_{peak} = L_{Edd}(M + \mathcal{F}\Delta M)$$



Modeling the AGN lightcurve

Evolution of the AGN bolometric luminosity function

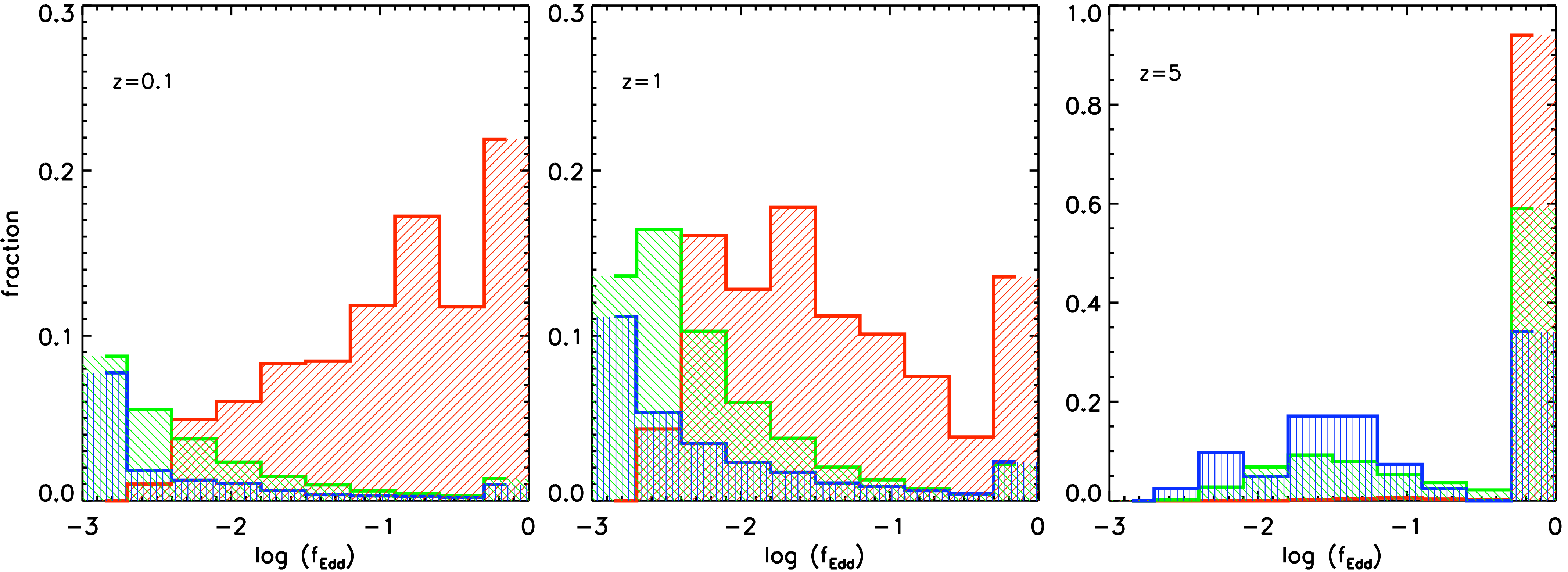


Mod I 'Edd limit'

Mod II 'Hopkins'

Modeling the AGN lightcurve

Distribution of fEdd for Mod II



1.e6 MSUN < MBH < 1.e7 MSUN

1.e7 MSUN < MBH < 1.e8 MSUN

MBH > 1.e8 MSUN

See, e.g, Heckman et al. 2004

First Summary

We tested a model in which BHs-growth and AGN activity are triggered by galaxy mergers

We tested different theoretical models for the AGN lightcurve

The BH population at z=0 is well-sampled, except:
- The BH mass density is too low
- We lack luminous AGN at high-z

We ruled out AGN lifetimes that do not depend on the BH-mass

Marulli, Bonoli et al. 2008, MNRAS 385, 1846

New Models

1. Simply accrete more cold gas during mergers

$$\Delta m_{BH} = \frac{f_{BH} m_{cold}}{1 + (280 Kms^{-1}/V_{vir})^2}$$

2. The amount of cold gas accreted during mergers depends on the redshift of the merger
"Dynamic model" (Croton 2006)

$$\Delta m_{BH} = \frac{f_{BH} m_{cold}}{1 + (280 Kms^{-1}/V_{vir})^2}(1+z)$$

3. Accretion of cold gas also during disk instabilities
Condition for instability (Mo, Mao & White '98):

$$\frac{V_C}{(GM_{disk}/r_{disk})^{1/2}} \leq 1$$

$$\Delta m_{BH} = \frac{f_{disk} m_{cold}}{1 + (280 Kms^{-1}/V_{vir})^2}$$

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New Models

Mass function
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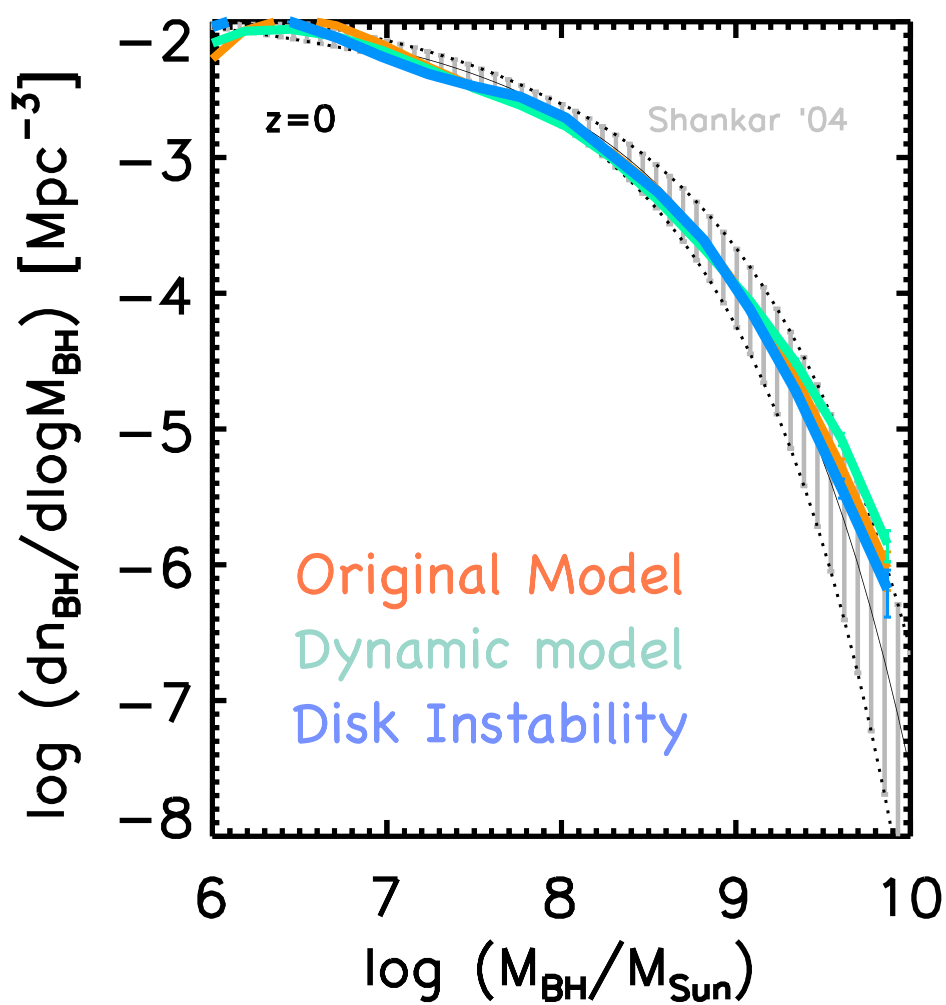
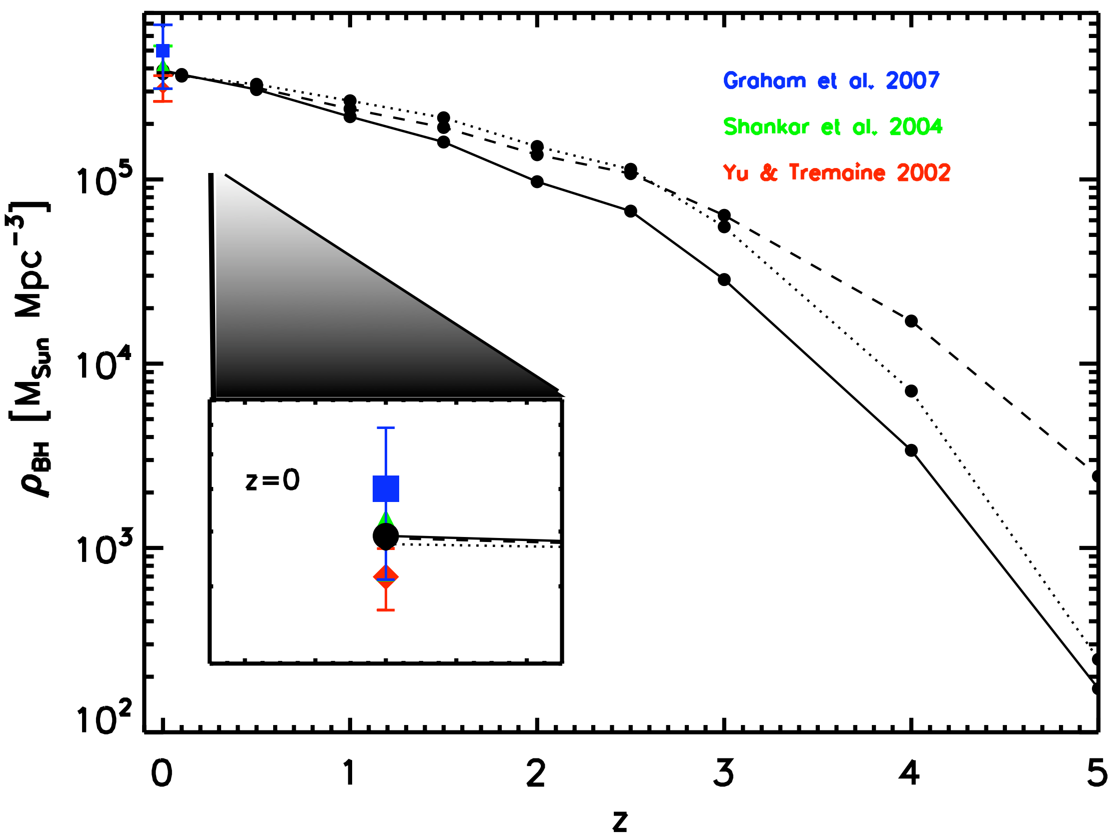




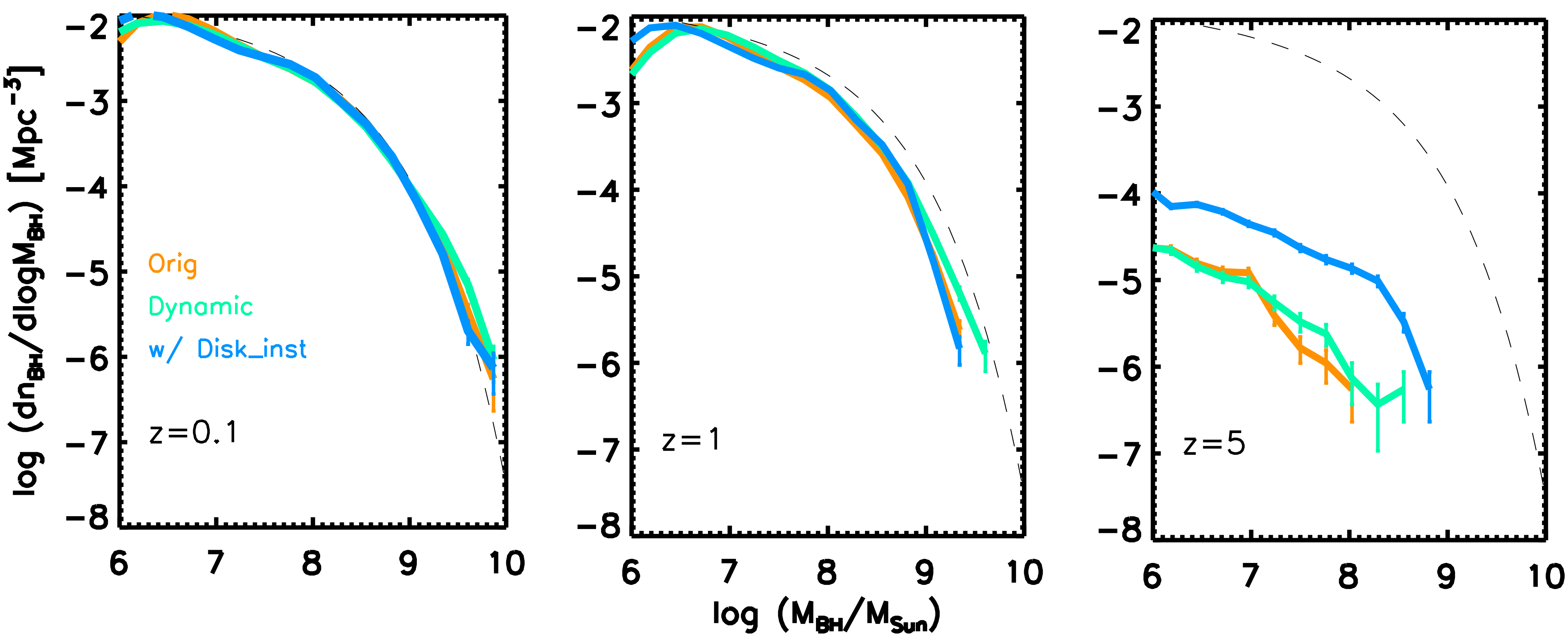
____ Original Model

.... Dynamic model

– – –Disk Instability

New Models

Evolution of the mass function

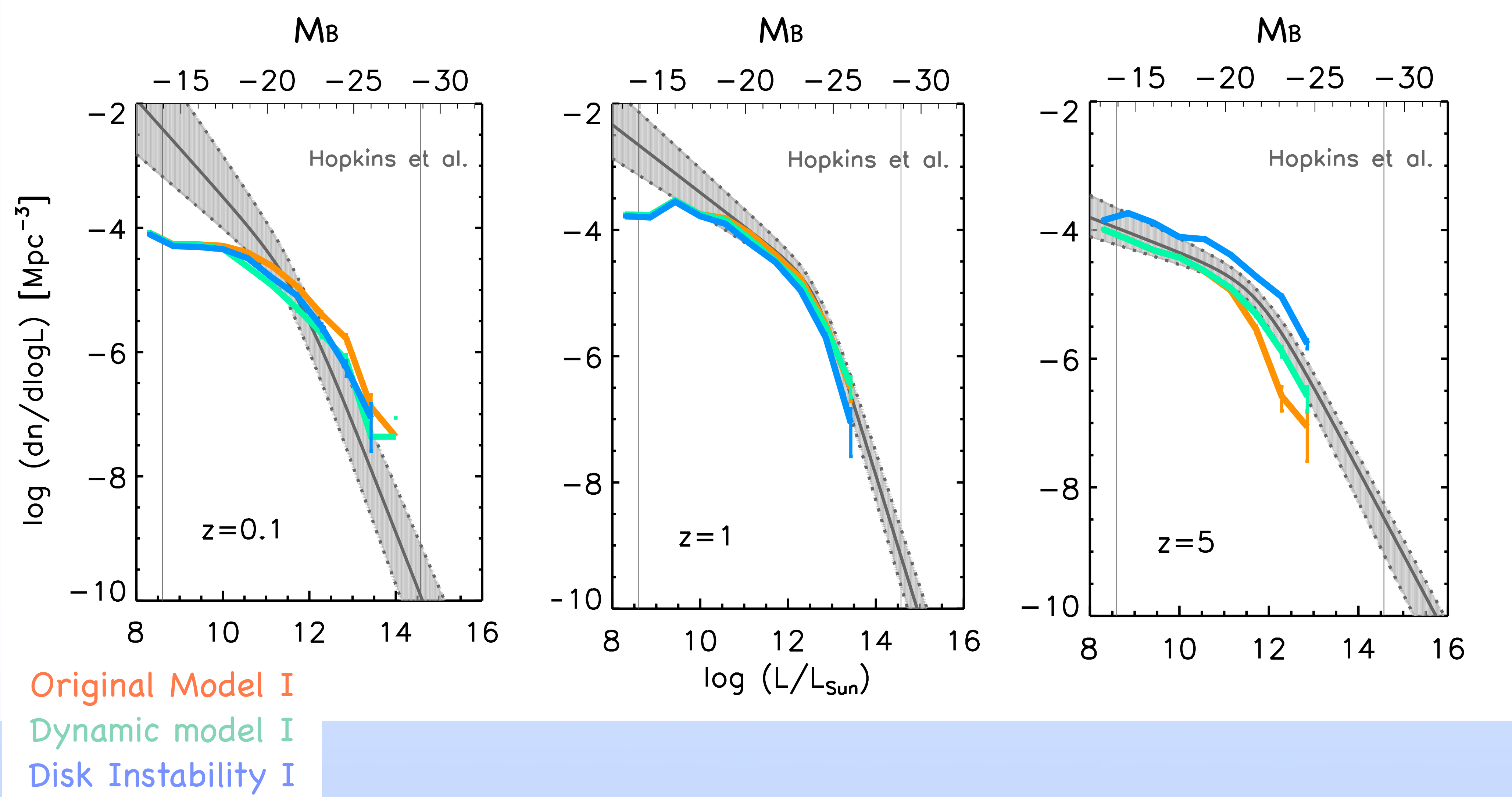


Original Model
Dynamic model
Disk Instability

New Models

The AGN bolometric luminosity function

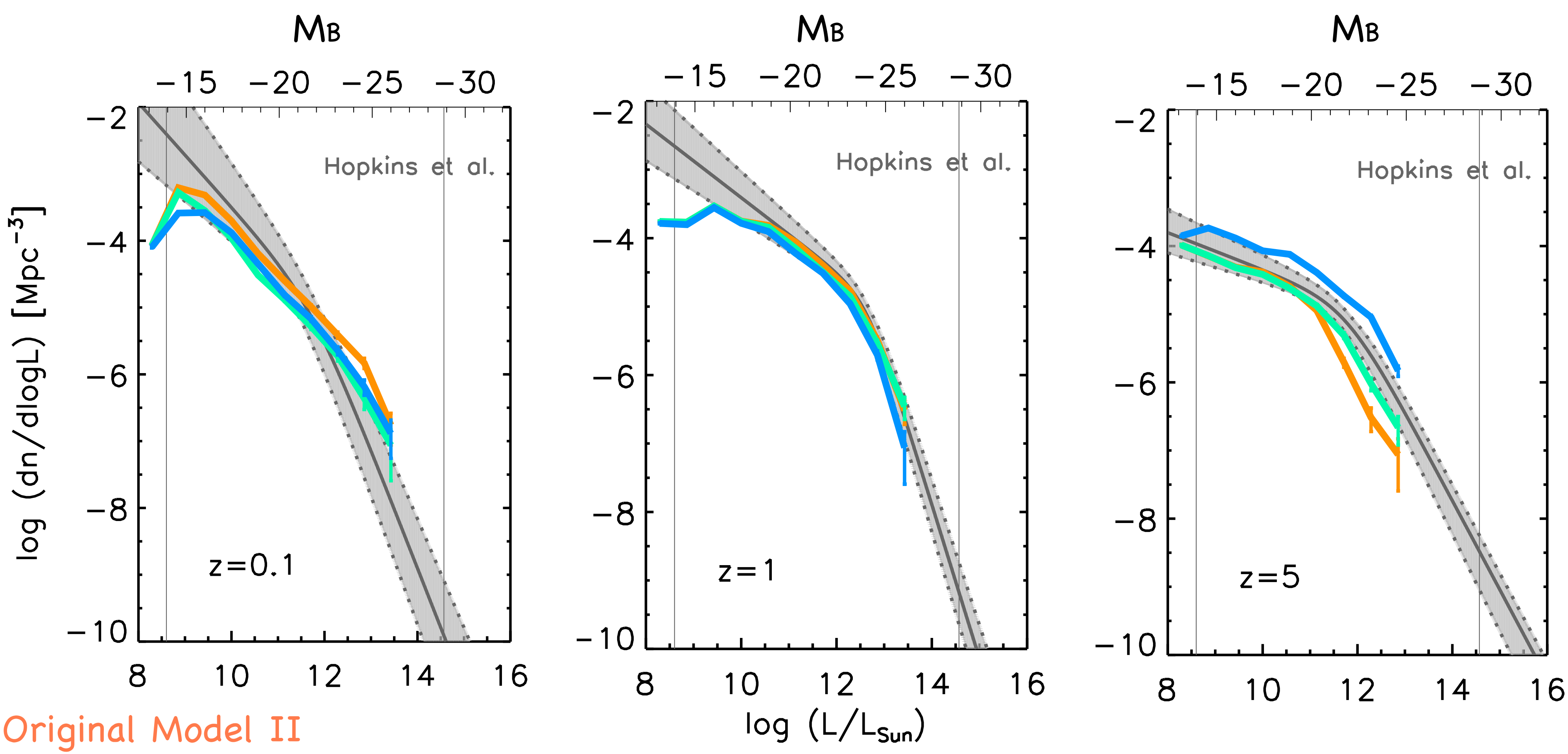
With Mod I - Eddington-limited model



New Models

The AGN bolometric luminosity function

With Mod II - Hopkins model



Original Model II
Dynamic model II
Disk Instability II

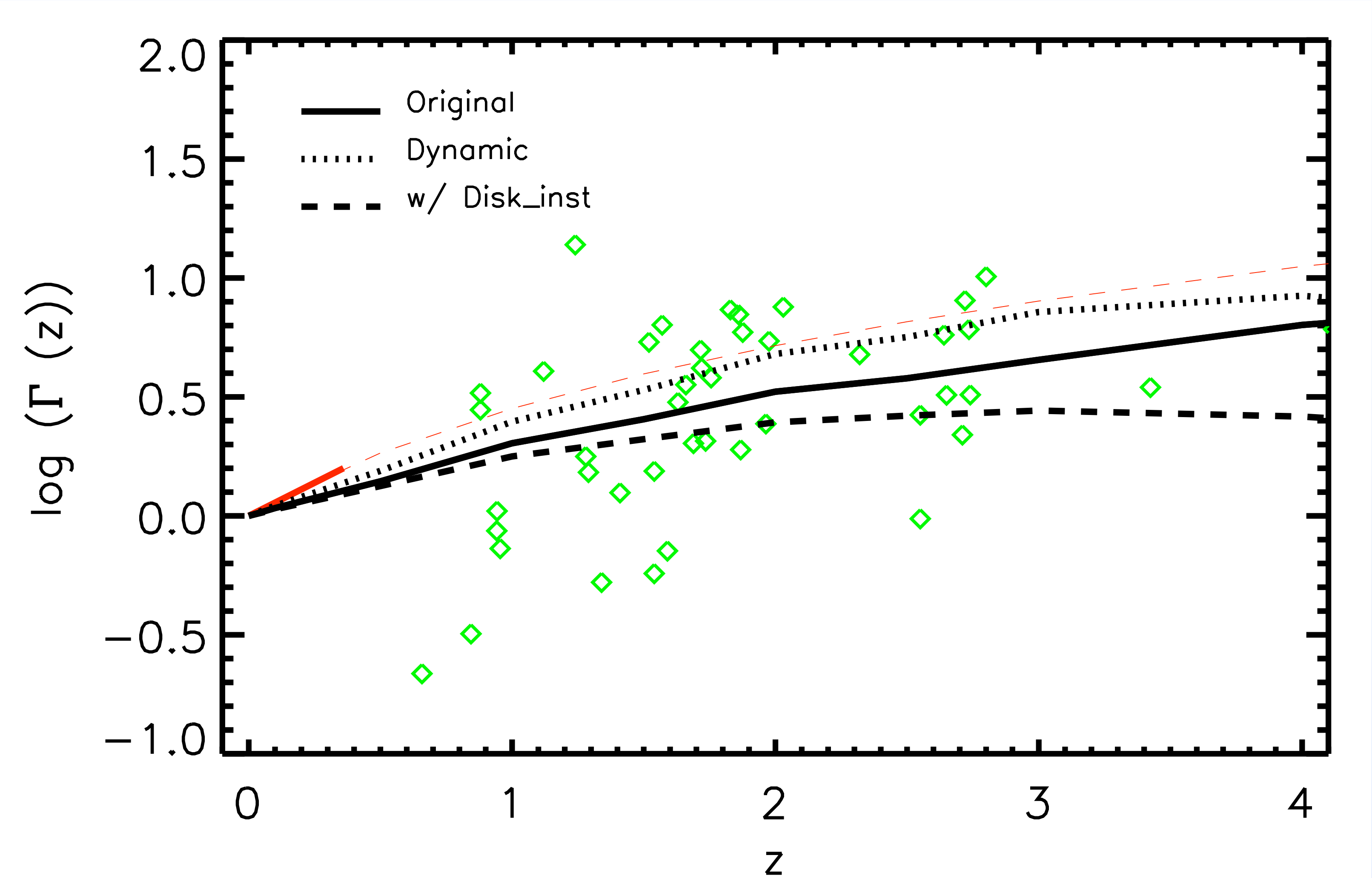
Work in progress...

What can we do with those models?

- Look at host galaxy properties (e.g., mass, colors...) and study their redshift evolution

Work in progress...

Evolution of M_{BH}/M_{Bulge}



$$\Gamma(z) = \frac{M_{BH}/M_{Bulge}(z)}{M_{BH}/M_{Bulge}(z=0)}$$

____ Original Model
.... Dynamic model
- - -Disk Instability

____ Treu et al.2007
◇ ◇ Peng et al. 2006

Work in progress...

What can we do with those models?

- Look at host galaxy properties (e.g., mass, colors...) and study their redshift evolution

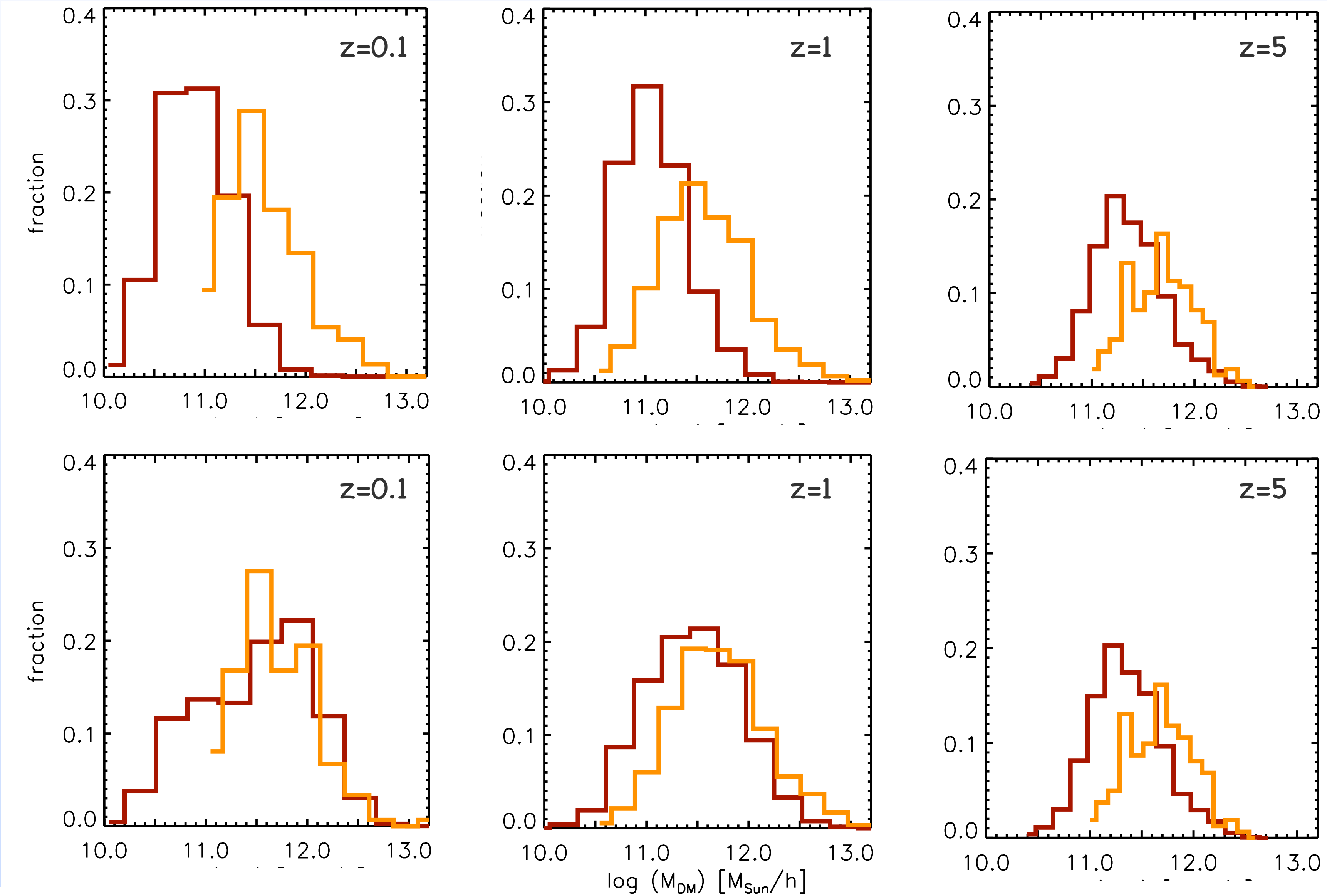
- Study the clustering properties of our AGN sample

Work in progress...

Masses of DM halos hosting AGNs for "Dynamic model"

Mod I
'Edd limit'

Mod II
'Hopkins'



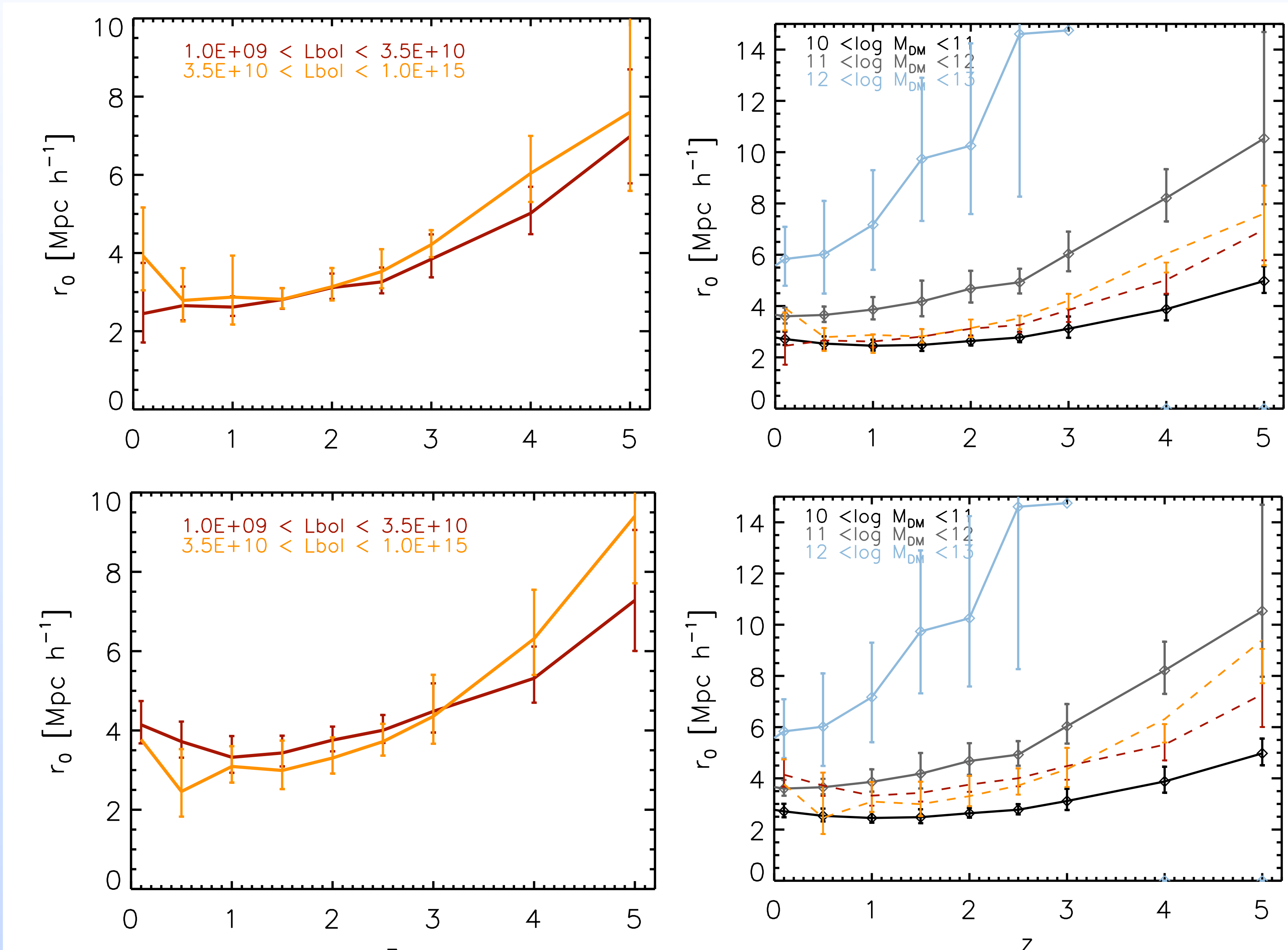
1.e9 < L_{bol} < 3.5e10 L_{bol} > 3.5e10

Work in progress...

Correlation length r_0 $$\xi(r) = \left(\frac{r}{r_0}\right)^{-\gamma}$$

Mod I
'Edd limit'

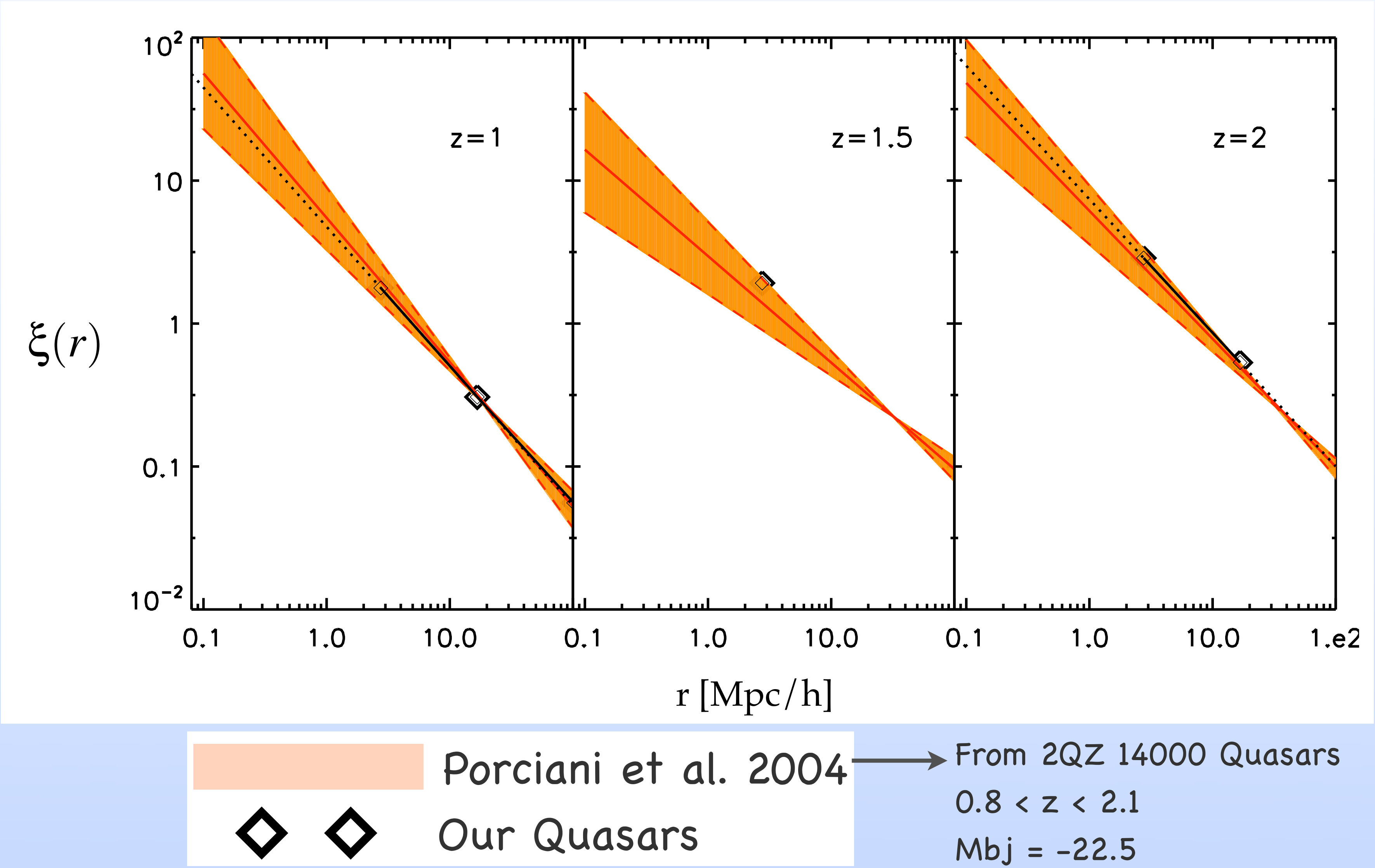
Mod II
'Hopkins'



Work in progress...

Comparison with optical observations - an example

"Observable fraction" and Bolometric correction from Hopkins et al 2007



From 2QZ 14000 Quasars

0.8 < z < 2.1

Mbj = -22.5

Summary

We tested a model in which BH-growth and AGN activity are triggered by galaxy mergers:

- We found good agreement with local scaling relations, but the existing model needed to be modified to accrete more mass, in particular at high-z.

We tested different theoretical models for the AGN lightcurve:

- We ruled out lightcurve models that do not depend on BH mass.
- We found that a model based on Hopkins et al. 2005 gives a better description of the faint end of the AGN luminosity function.

We tested new models for BH accretion, including a model with disk instability.

We are now studying in detail the **properties of the host galaxy** and the **clustering properties** of our simulated AGNs