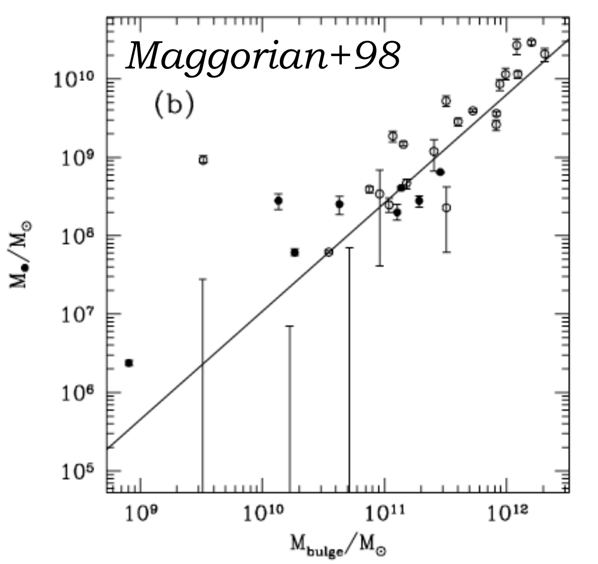
AGN vs Star formation -- The fate of gas in galaxies
28th July - 1st August 2014, University of Durham

Large-scale cosmological simulations of BH growth:

AGN luminosities & the connection with their host galaxies

Michaela Hirschmann (IAP Paris) with
Klaus Dolag *(USM)*, L. Bachmann *(USM)*, A. Saro *(USM)*,
S. Borgani *(OATS)* & A. Burkert *(USM) etc.*

Co-evolution of galaxies & BHs?

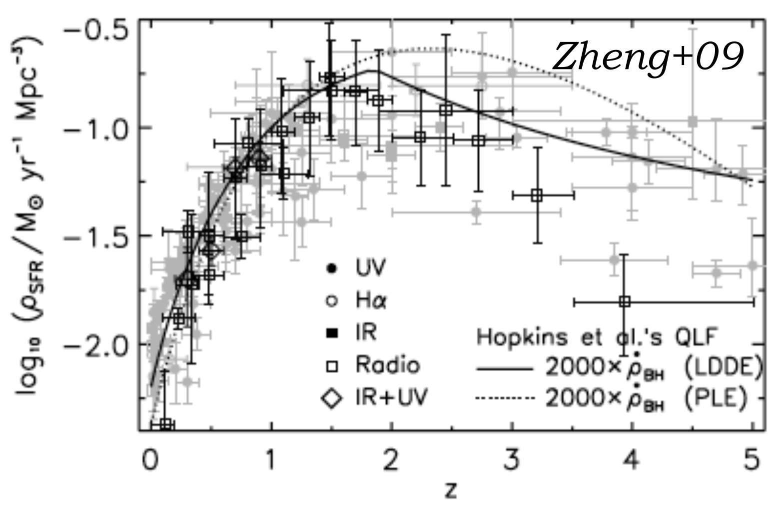


Spheroidal galaxy properties related to BH mass

Ferrarese & Merrit '00, Gebhardt+00, Magorrian+98, Kormendy&Bender12 etc

SFR density & BH accretion rate trace each other over cosmic time

Franceschini+99, Barger+01, Dickinson+03, Merloni04/06, Hopkins+07, Shankar +09, Brusa+09



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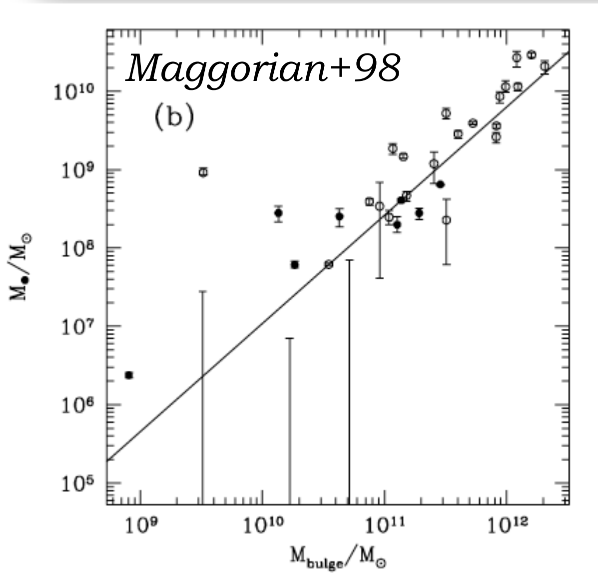

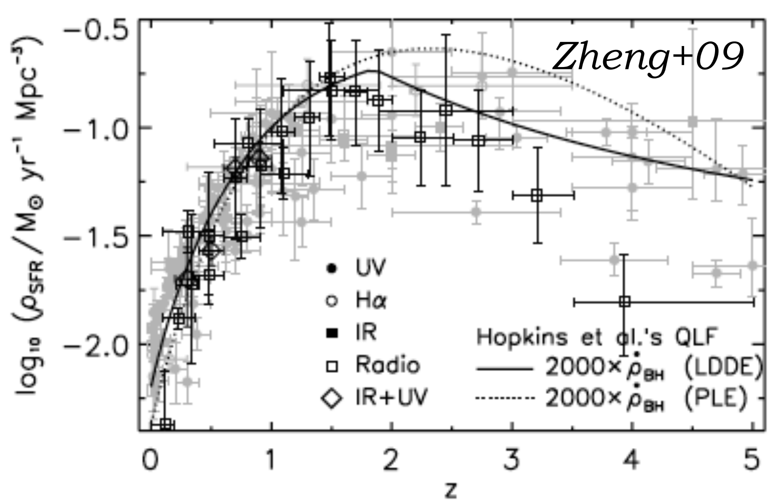

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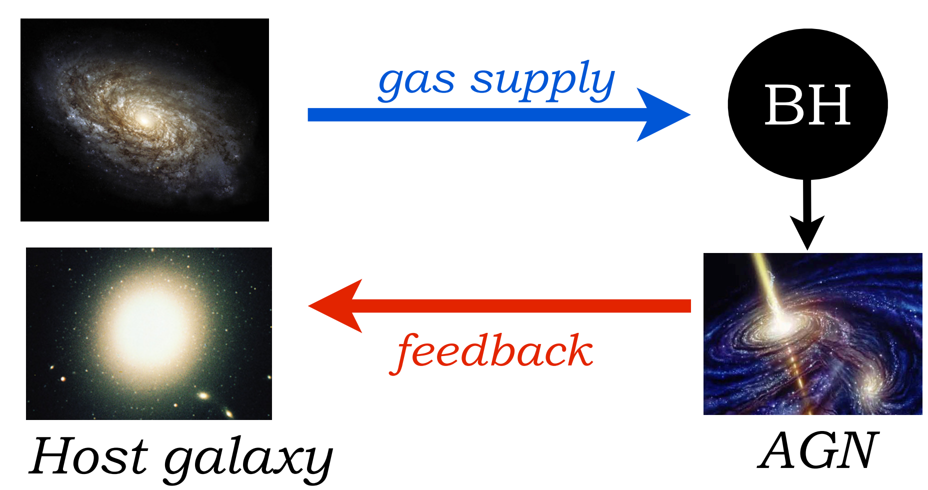
- *Statistical merging -- Central-Limit-Theorem* *(Peng+07, Hirschmann+10, Jahnke+10)*
- *"Physically coupled" evolution of galaxies & black holes* *(Robertson+06, Hopkins+08, Granato+04, Di Matteo+05, Croton+06 etc)*



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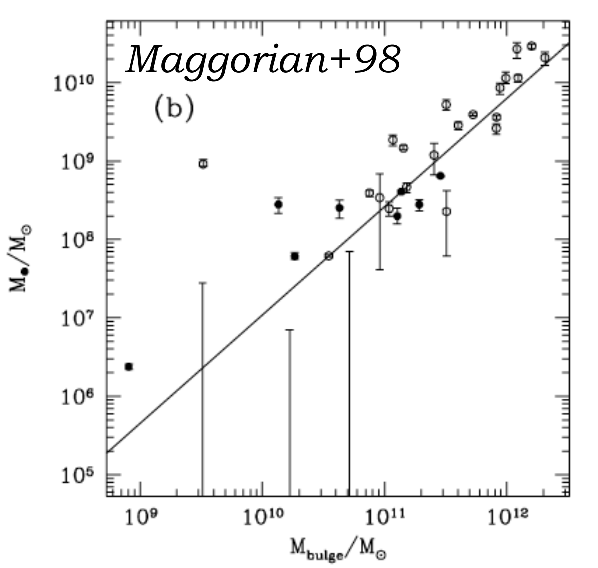

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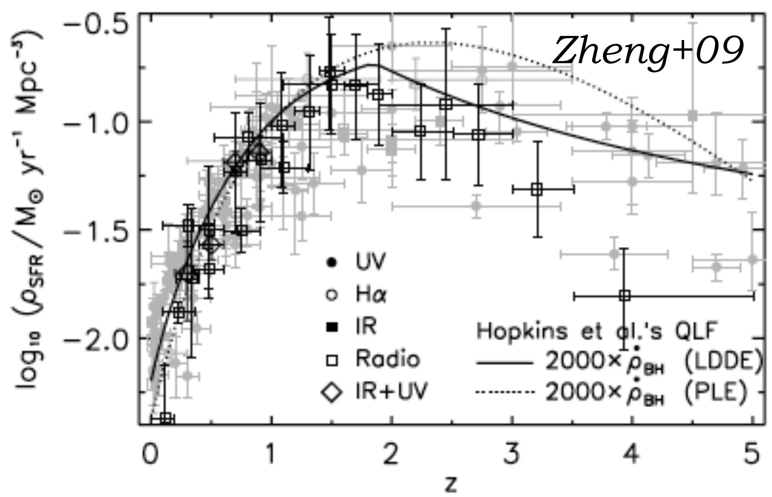

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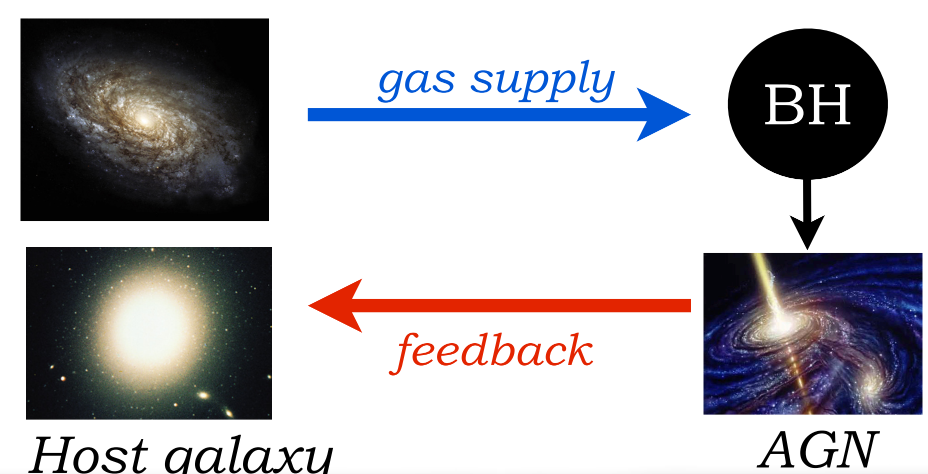

1. *What is the origin of the anti-hierarchical behaviour in the AGN evolution and how is it connected to the galaxy downsizing?*
   ...e.g. SAMs: Bonili+09, Fanidakis+12, Hirschmann+12
2. *How strongly is the SF coupled with AGN activity and what is the relative role of AGN feedback?*
3. *Which are the main trigger mechanisms for AGN activity?*

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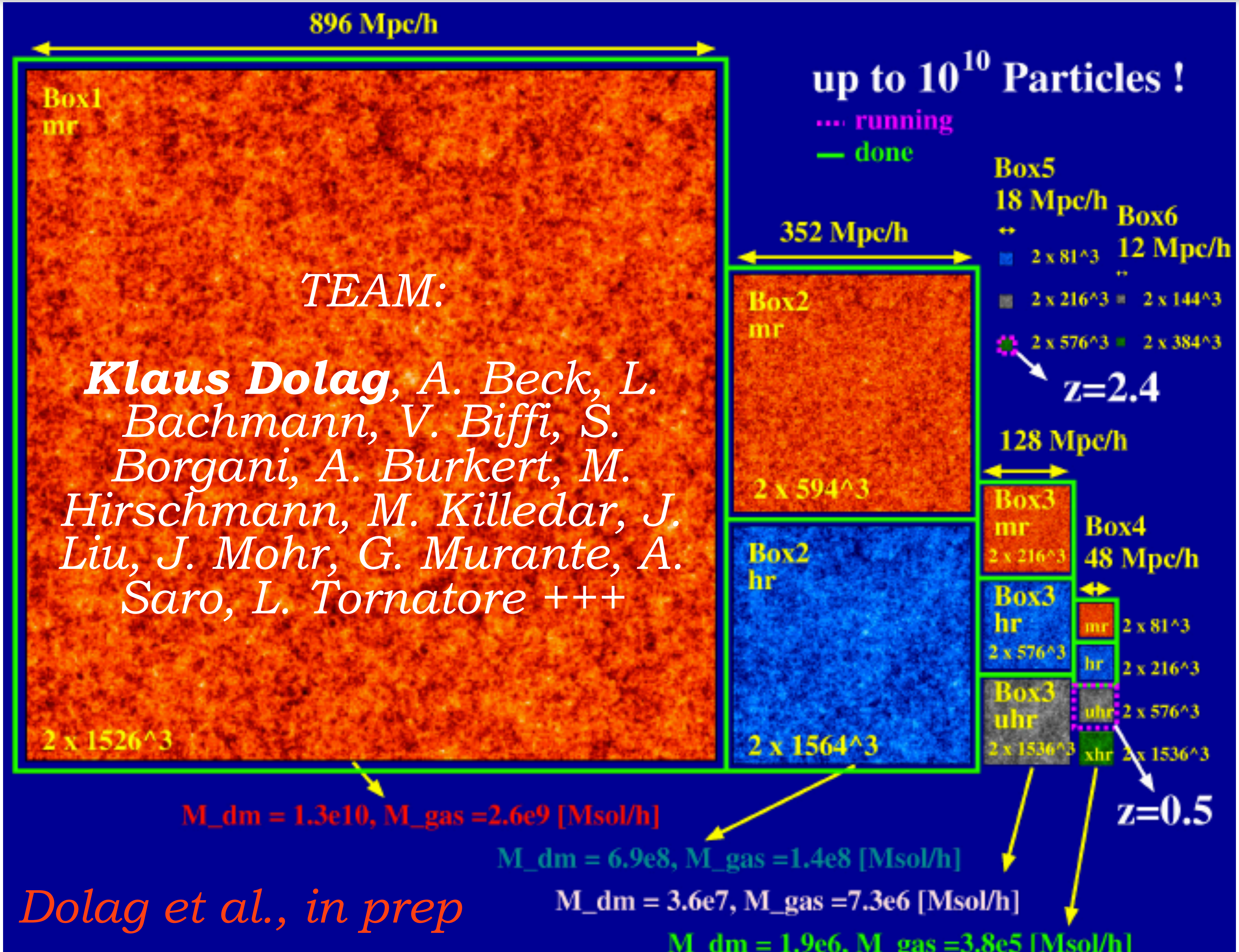
Magneticum simulations

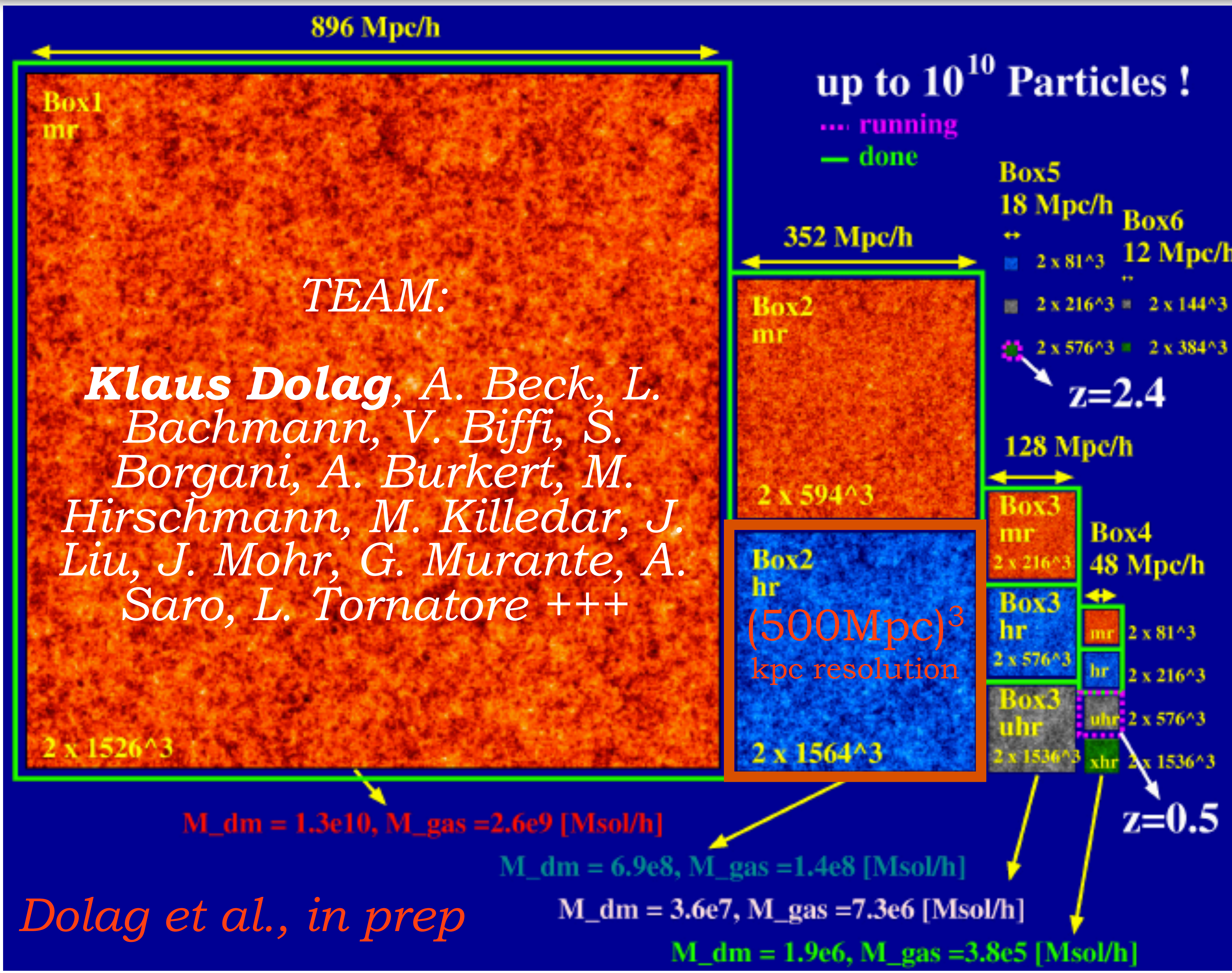


TEAM:

Klaus Dolag, *A. Beck, L. Bachmann, V. Biffi, S. Borgani, A. Burkert, M. Hirschmann, M. Killedar, J. Liu, J. Mohr, G. Murante, A. Saro, L. Tornatore +++*

Dolag et al., in prep

Magneticum simulations



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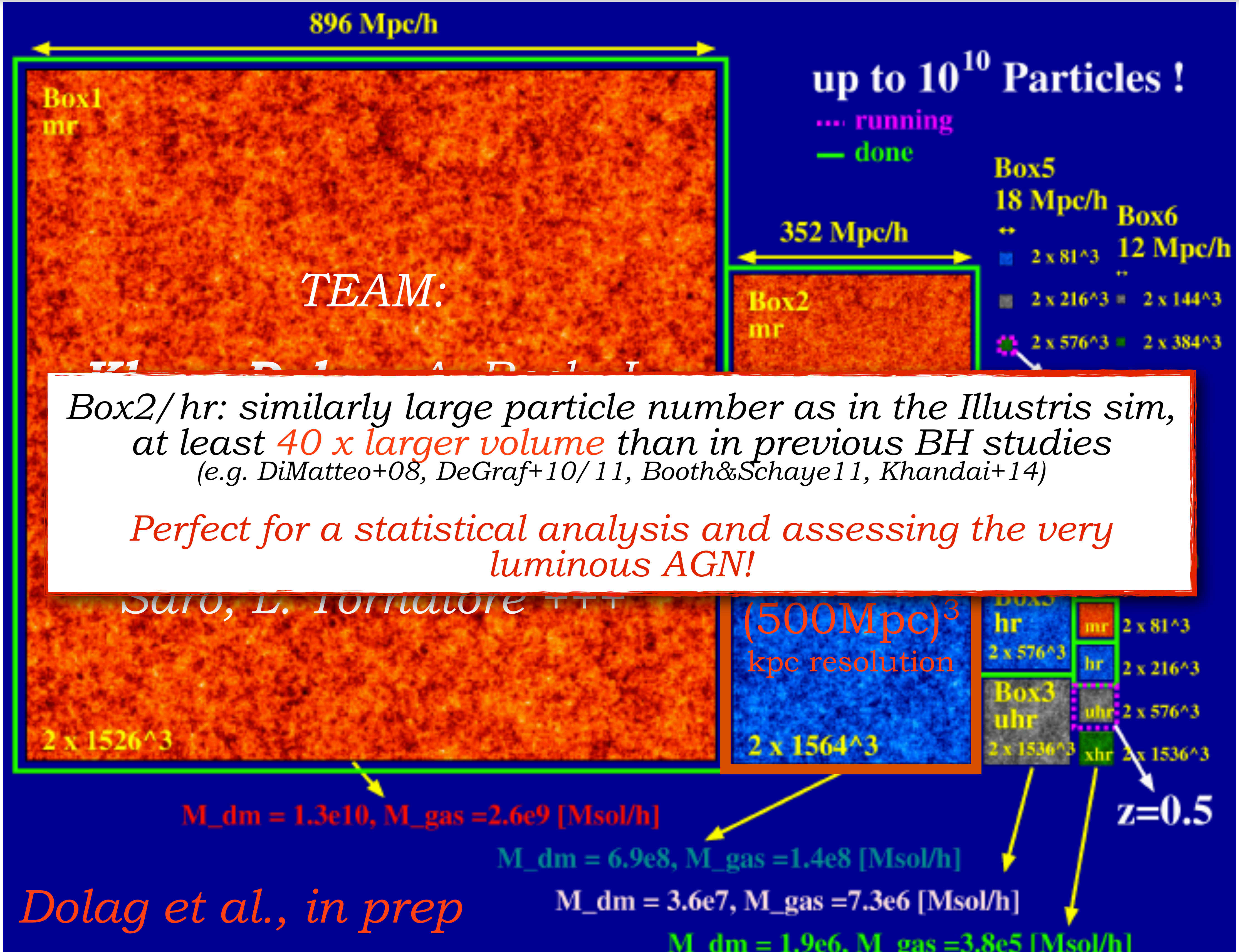

Box2/hr: similarly large particle number as in the Illustris sim, at least 40 x larger volume than in previous BH studies
(e.g. DiMatteo+08, DeGraf+10/11, Booth&Schaye11, Khandai+14)

Perfect for a statistical analysis and assessing the very luminous AGN!

Magneticum

including

- TreePM-SPH code *GADGET3* *(Springel+05)*
- Entropy conserving formulation *(Springel&Hernquist02)*
- *Higher order kernel* based on the bias-corrected, sixth-order Wendland kernel *(Dehnen&Aly12)* + 295 neighbours
- *Low viscosity scheme* to track turbulence *(Dolag+05)*
- Isotropic *thermal conduction* *(Dolag+04)*
- Modified SPH passes the “Blob” test and can reproduce Kevin-Helmholtz instabilities *(Beck+in prep.)*

- Radiative *cooling, star formation & stellar feedback* (v_{wind}=350km/s) *(Springel&Hernquist03)*
- *Chemical enrichment*, SNII, SNIa, AGB *(Tornatore +03/07)* & metal cooling *(Wiersma+09)*
- *BH growth* with thermal AGN fb *(Springel+05)* & Radio-mode fb *(Fabjan+10)* & further modifications *(Hirschmann+14, Bachmann+in prep.)*

Magneticum

BH model

- *BH seeds* (1e5$M_\odot$) in galaxies more massive than galaxy stellar masses of 1e10 $M_\odot$ *(Hirschmann+14)*
- BH growth: mergers & stochastic (Eddington-limited) gas accretion following the *Bondi-Hoyle formula:*

$$\dot{M}_\bullet = \frac{4\pi\alpha G^2 M_\bullet^2 \rho}{(c_s^2 + v^2)^2}$$

- *Thermal AGN feedback* *(Springel+05)*, by a factor of 4 increased efficiency for radiatively inefficient AGN (f_{edd}<0.01) *(Fabjan+10)*

$$\dot{E}_{\rm AGN} = \epsilon_r \ \eta_{\rm ff} \ \dot{M}_\bullet \ c^2$$

- *Improved scheme to follow BHs within galaxy clusters*: BHs are not pinned to the most bound particle anymore *(Hirschmann+14)*
- Dynamical friction force for low resolution sims (Chandrasekhar 1943) from properties of hosting SubHalo (updated on the fly)

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PhD student Lisa Bachmann is currently working on improving the sub-resolution models for BH accretion and AGN feedback!
Bachmann+in prep.,'14

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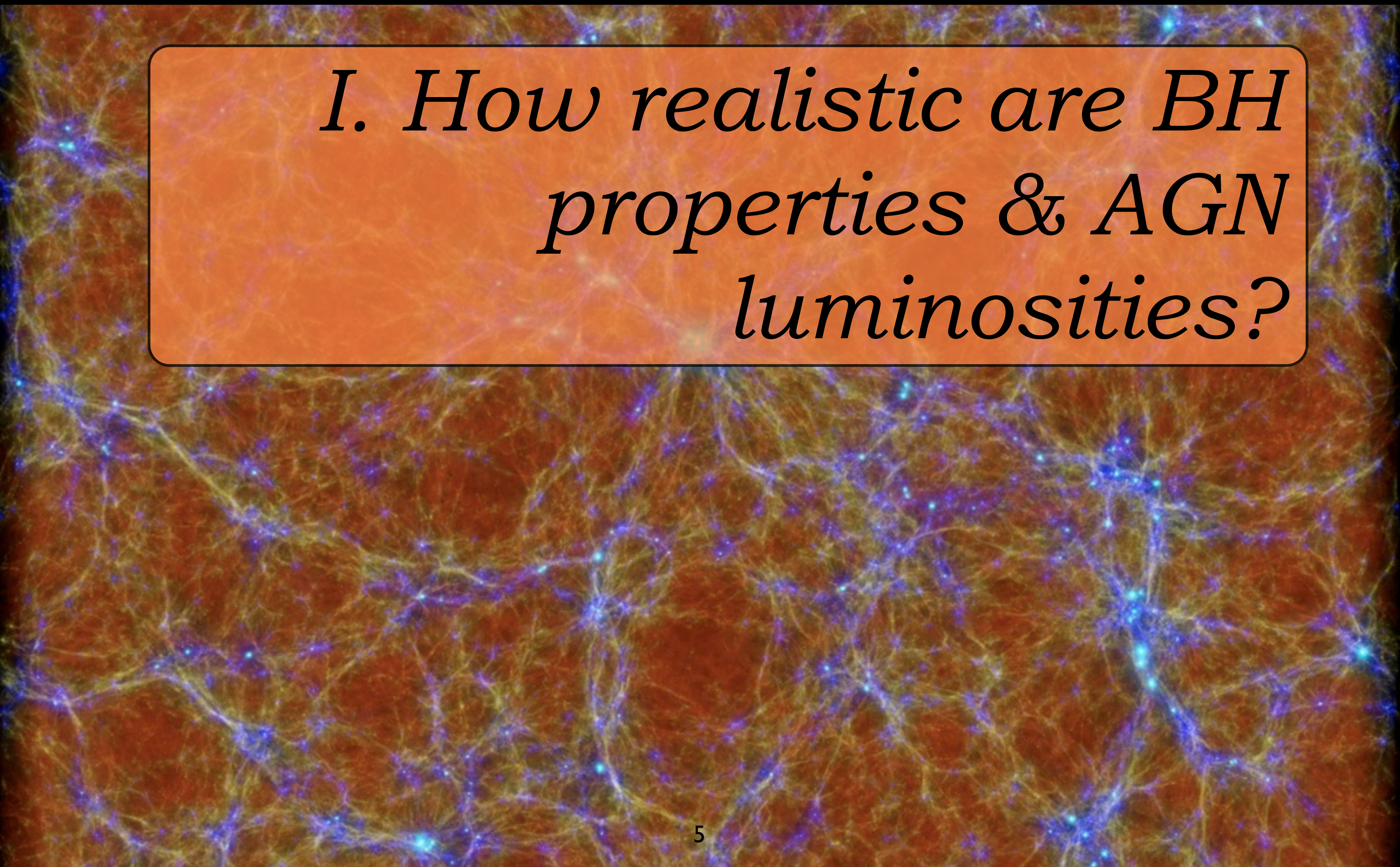
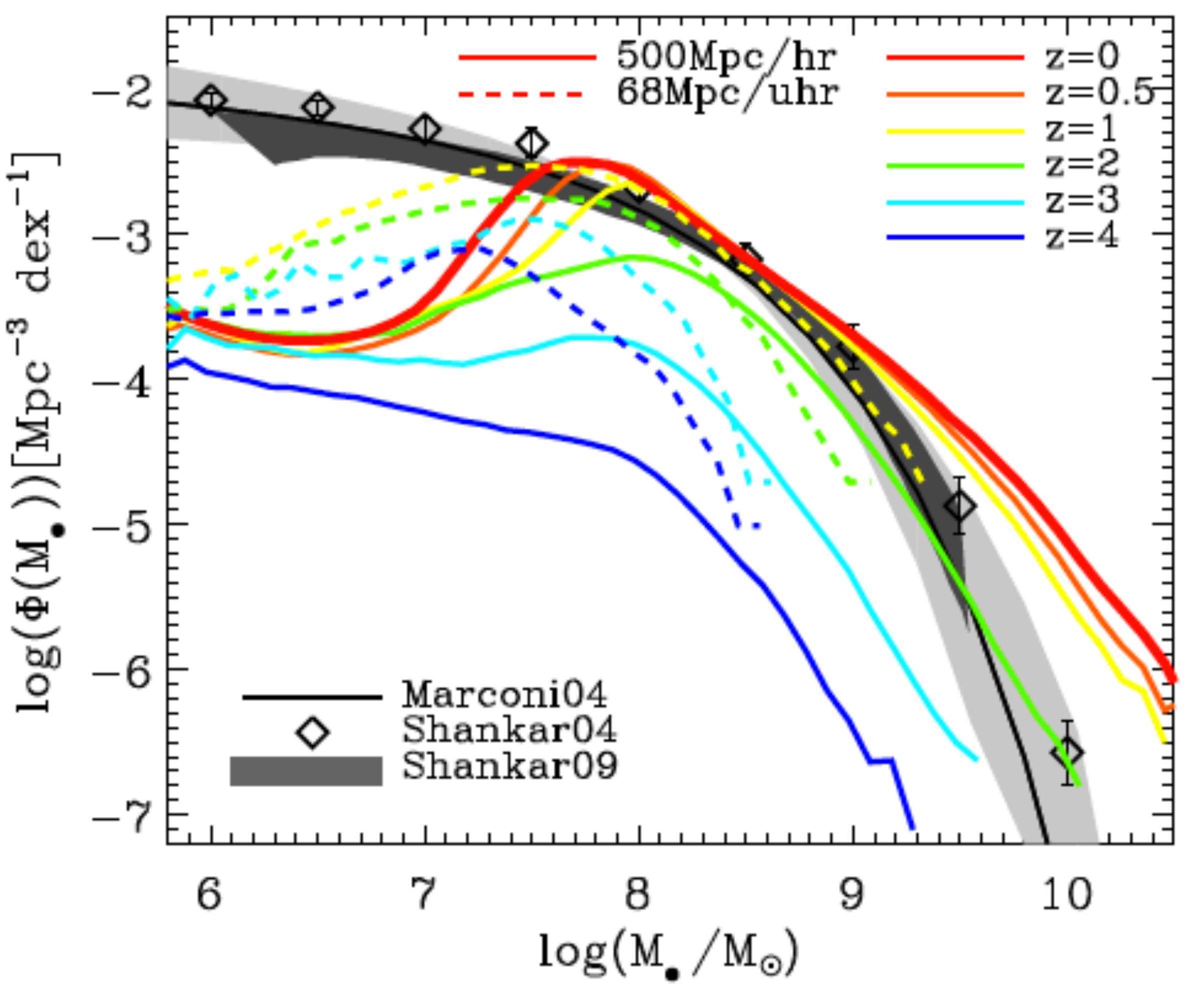
I. How realistic are BH properties & AGN luminosities?

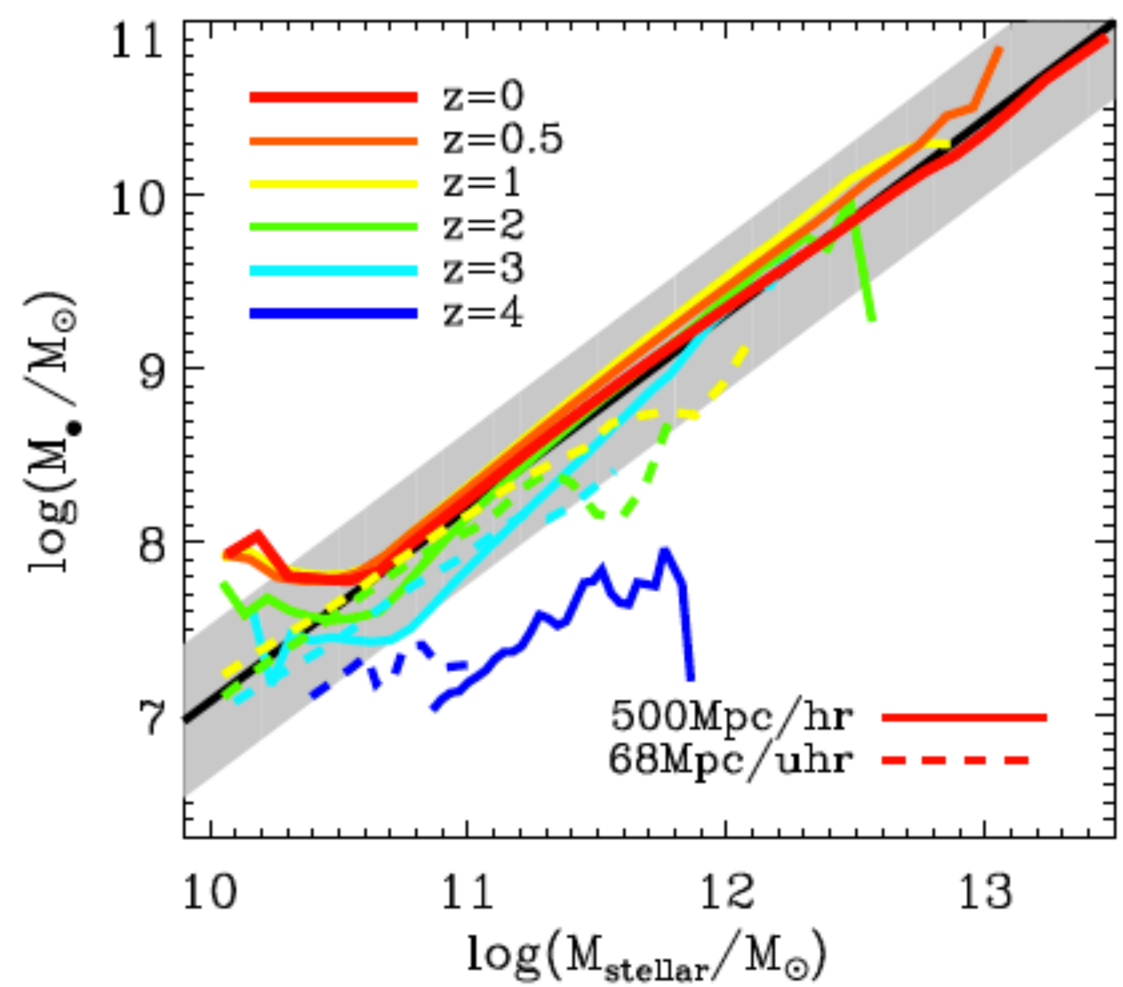


Evolution of BH properties

BH mass function



BH-stellar mass relation



Hirschmann+14

- Strong evolution until **z=1** (no significant BH growth afterwards)
- At **z=0**: massive BHs over-estimated, but...

- Excellent match at **z=0** (consequence of the choice of fb eff)
- BH-stellar mass relation in place at **z=3**

Evolution of BH properties

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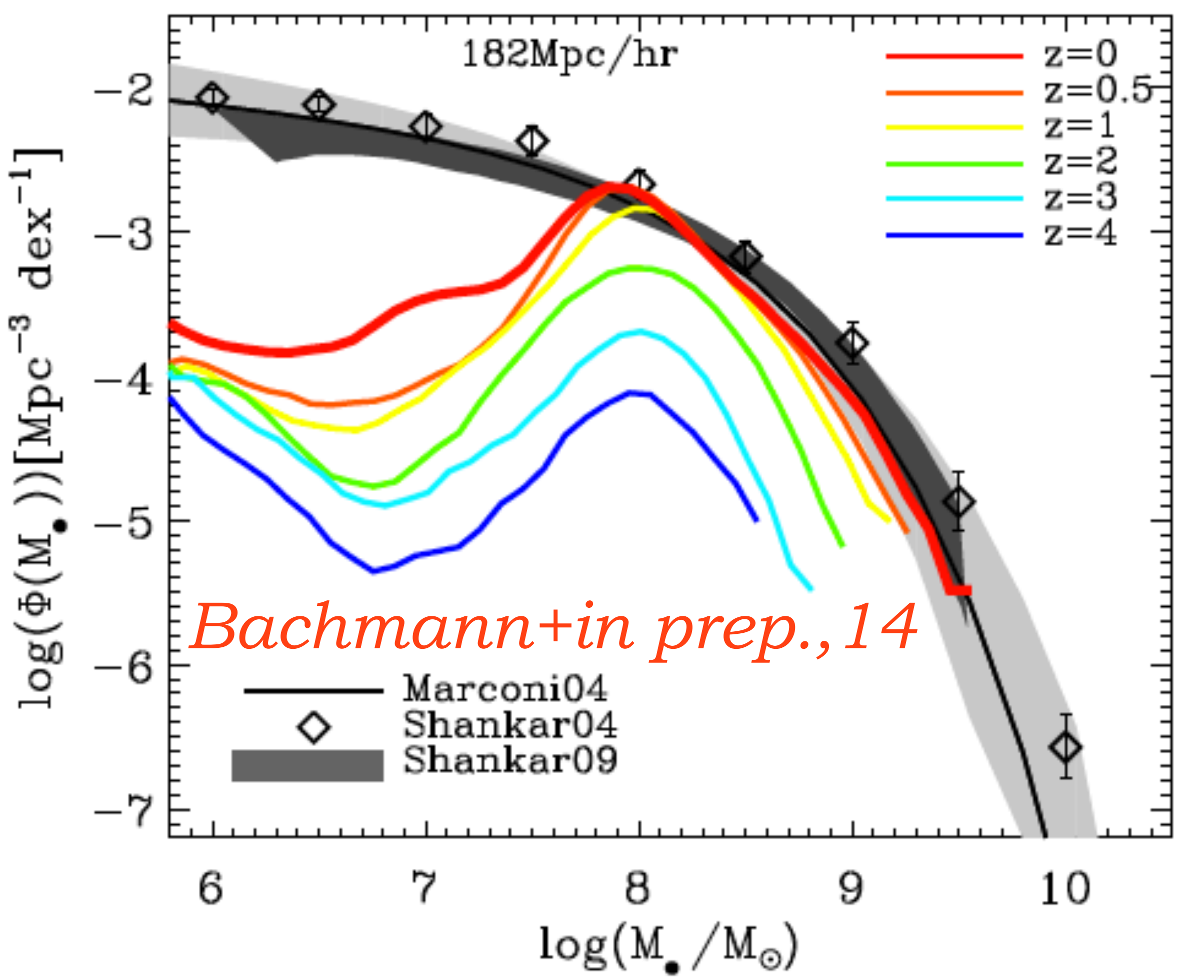
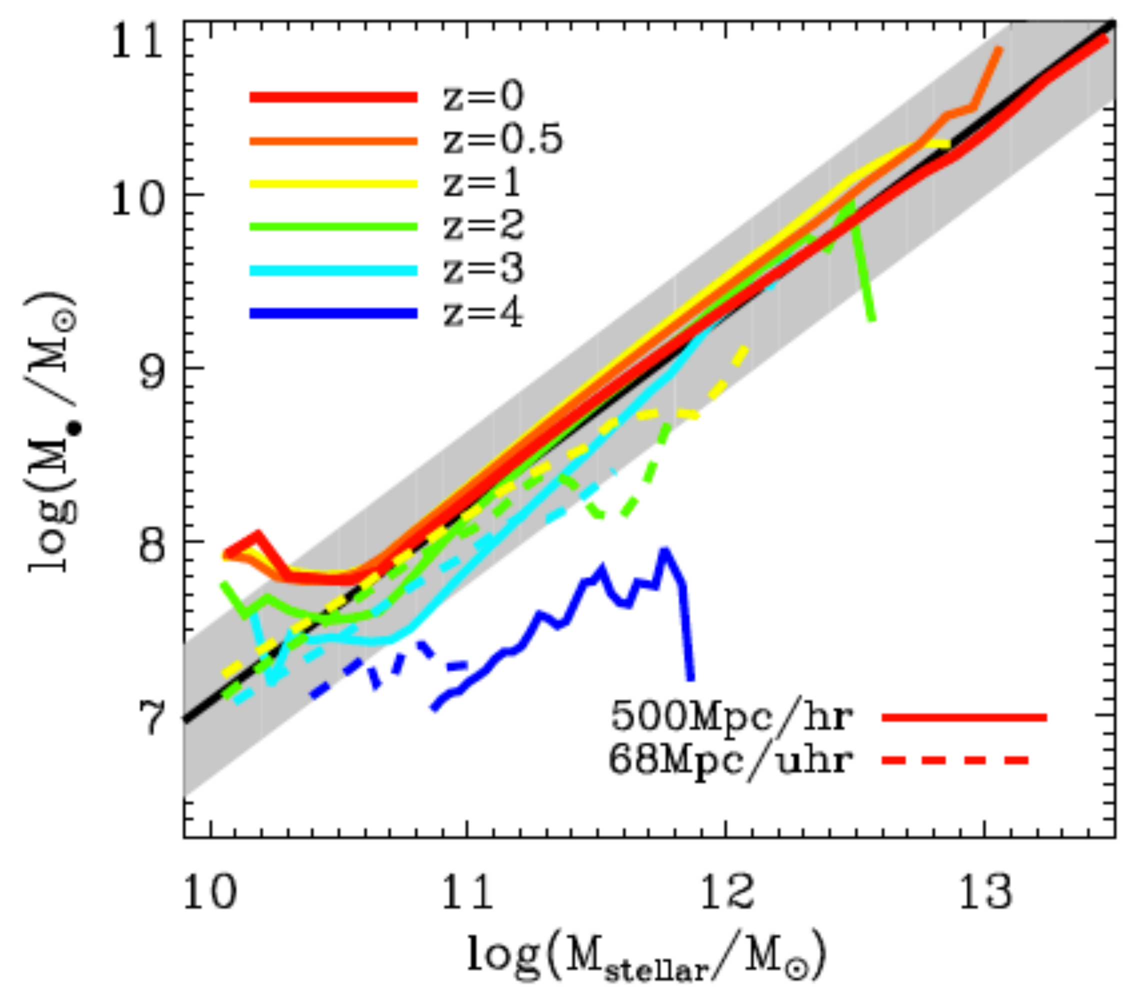


Different accretion model

BH-stellar mass relation



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Bolometric AGN luminosity fct.

Churazov, 2005:

Total released energy split into radiative & mechanical (outflow) component!

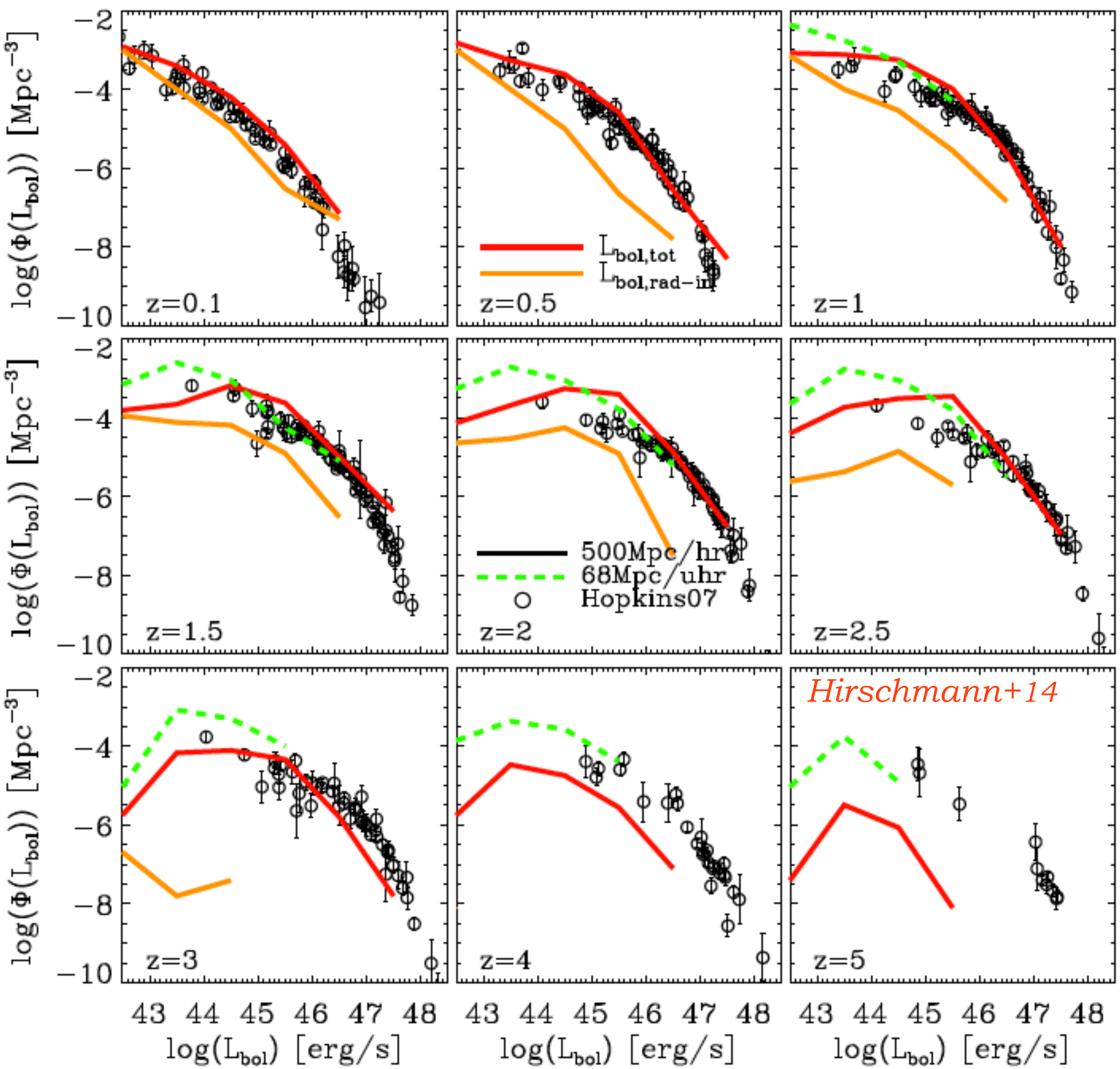
Radiatively efficient AGN:

$$f_{\rm Edd} = \dot{M}_\bullet / \dot{M}_{\bullet,\rm Edd} > 0.1$$
$$L_{\rm bol} = \frac{\epsilon_r}{1-\epsilon_r} \dot{M}_\bullet c^2$$

Radiatively inefficient AGN:

$$f_{\rm Edd} < 0.1$$
$$L_{\rm bol} = 0.1 \times L_{\rm Edd} \times \times (\dot{M}_\bullet / \dot{M}_{\bullet,\rm Edd} \times 10)^2$$

Bolometric AGN luminosity fct.



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- *General good match with obs.*
- *Box2/hr:* Too few AGN at z>3
- *Box4/uhr: convergence for AGN more luminous than 10^{44} erg/s*

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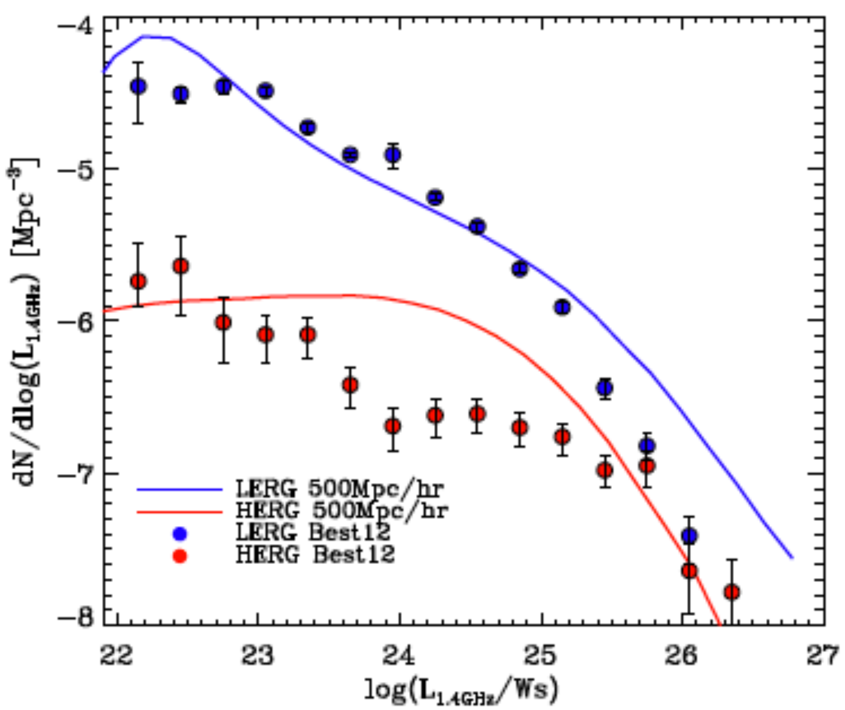
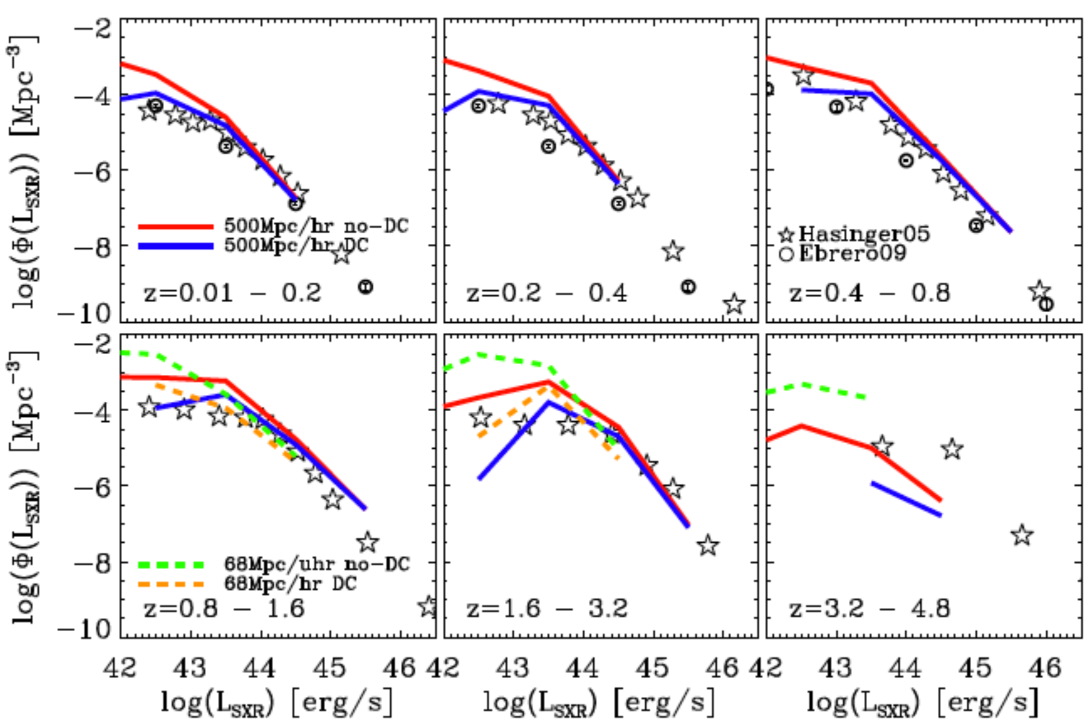
Radio - X-ray AGN luminosities

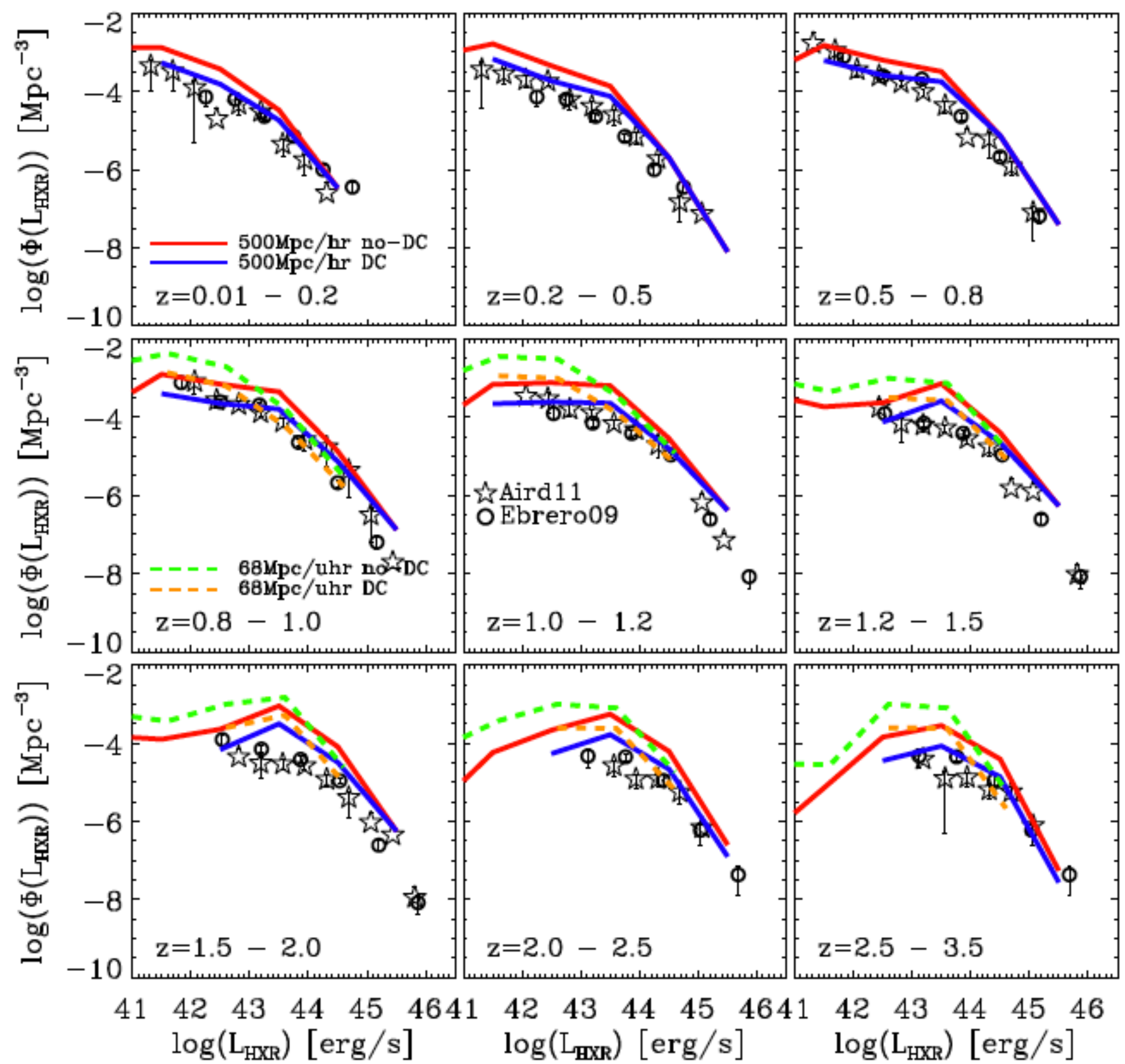
Radio luminosities



Soft X-ray luminosities



Hard X-ray luminosities



Hirschmann+14

X-ray luminosities include a correction for dust obscuration on a torus level (Hasinger08, Merloni+13)

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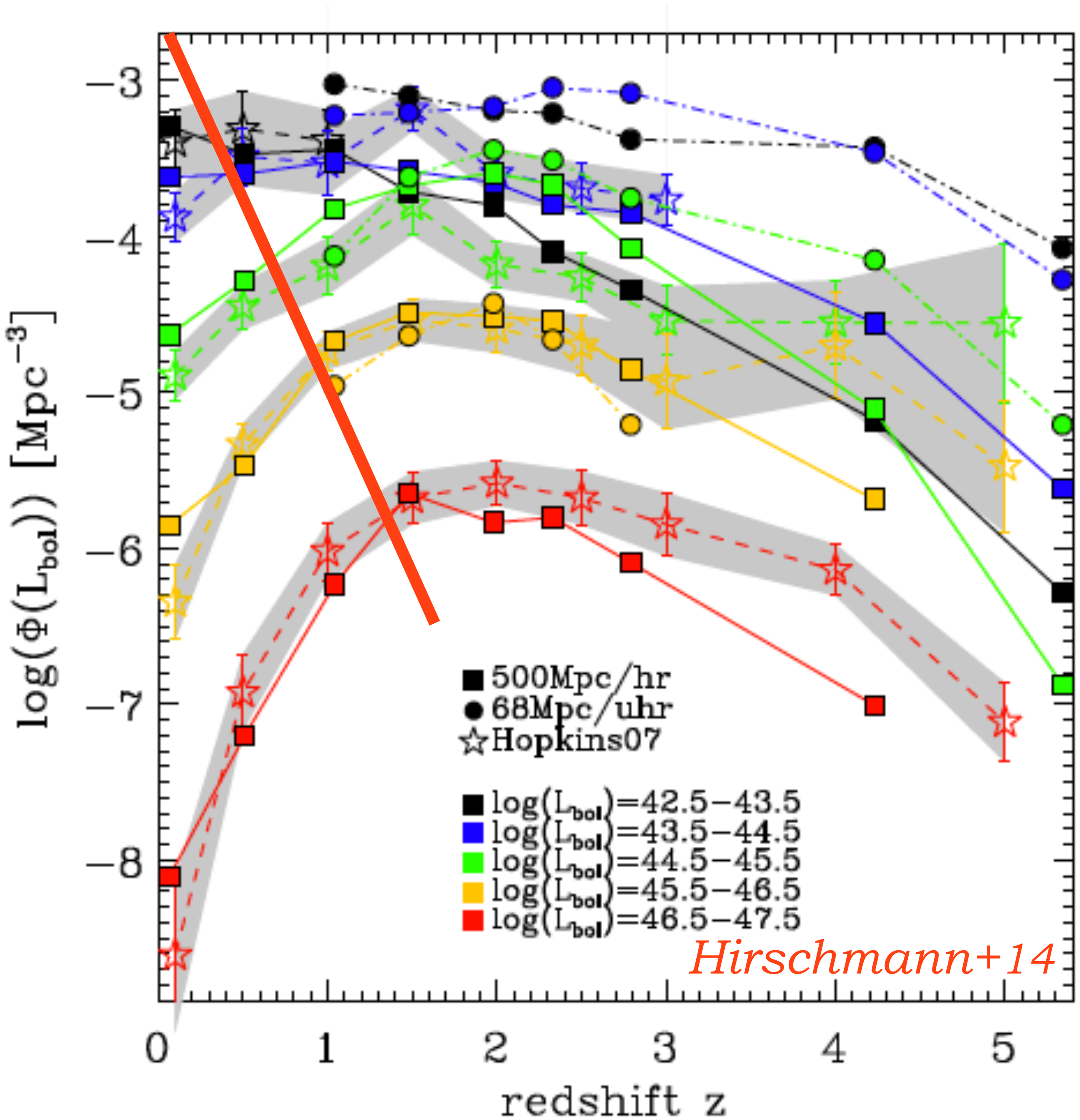
Anti-hierarchical trend

Magneticum simulations Box4/uhr & Box2/hr



- *Simulations self-consistently capture the downsizing trend!* *(see also SAMs: Bonoli+09, Fanidakis+12, Hirschmann +12)*
- *The simplified scheme of BH accretion is able to capture the essence of BH growth in reality*
- What is the origin of the downsizing trend?

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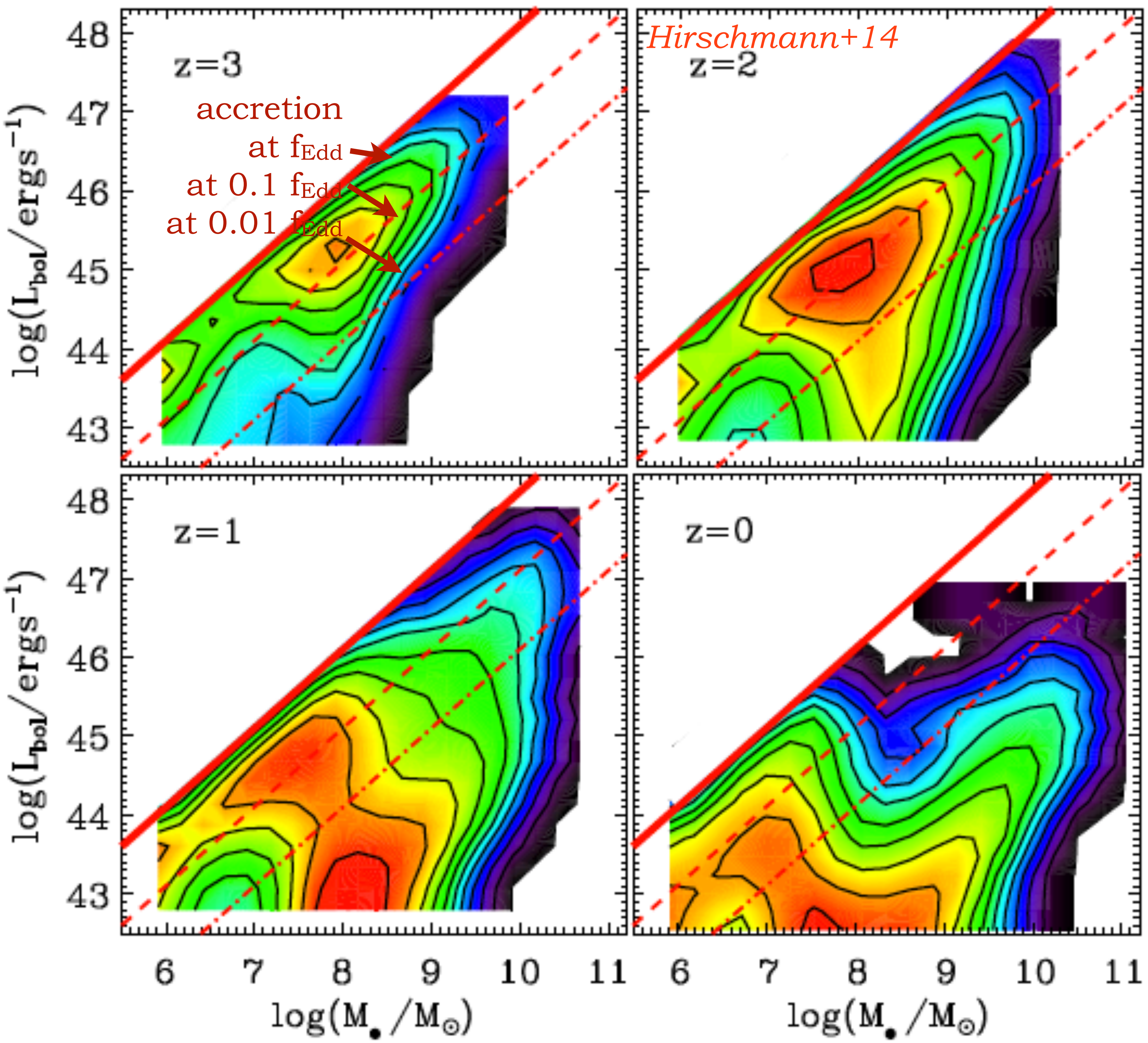
BH mass-luminosity plane



Moderately luminous AGN at low z have large contribution from massive BHs accreting way below their peak luminosities -- WHY?

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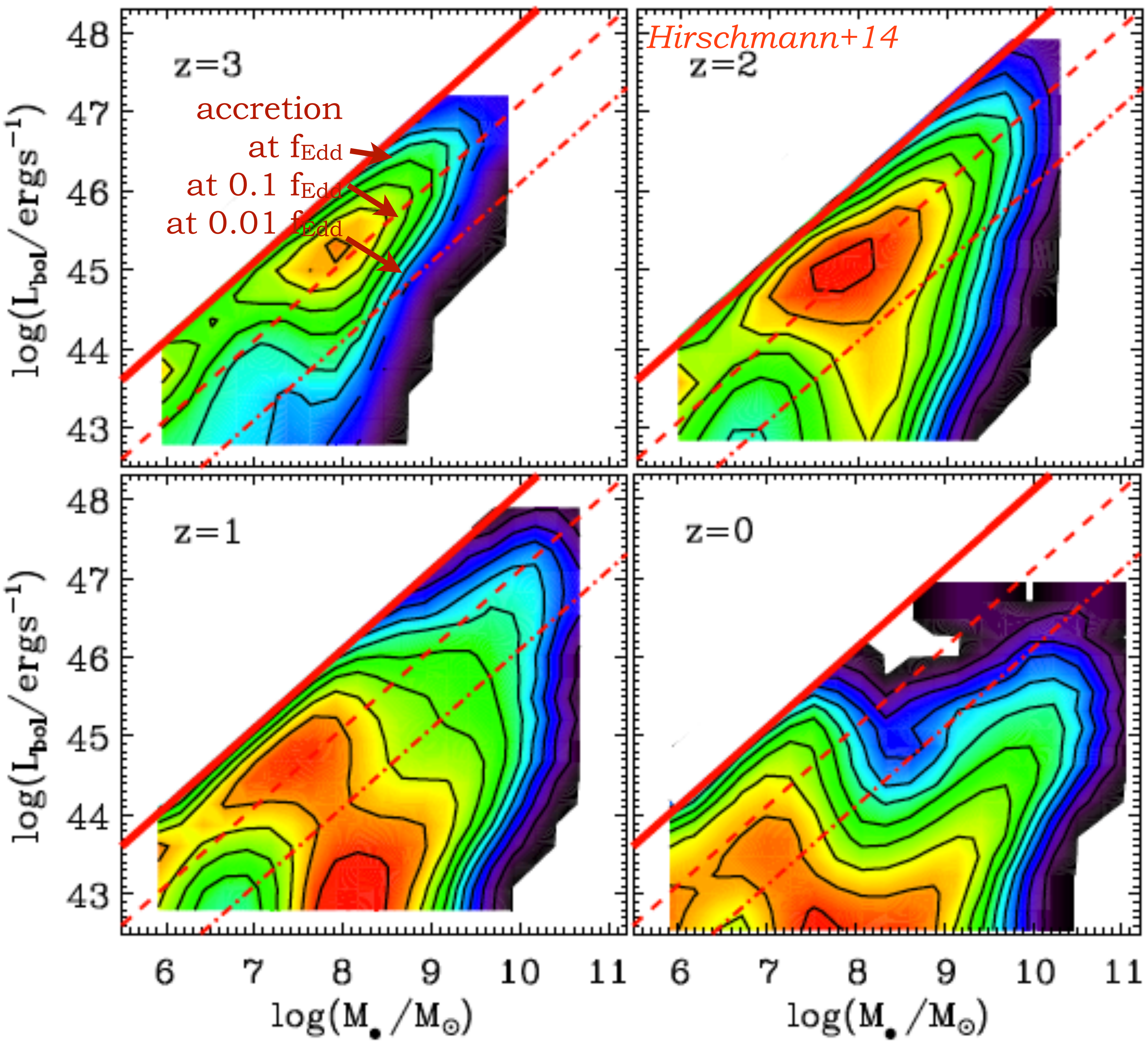
BH mass-luminosity plane



Moderately luminous AGN at low z have large contribution from massive BHs accreting way below their peak luminosities -- WHY?

Mainly gas density around the BHs matters: *Decreasing ϱ_{gas} with decreasing z & increasing M_{BH} due to SF and AGN fb*

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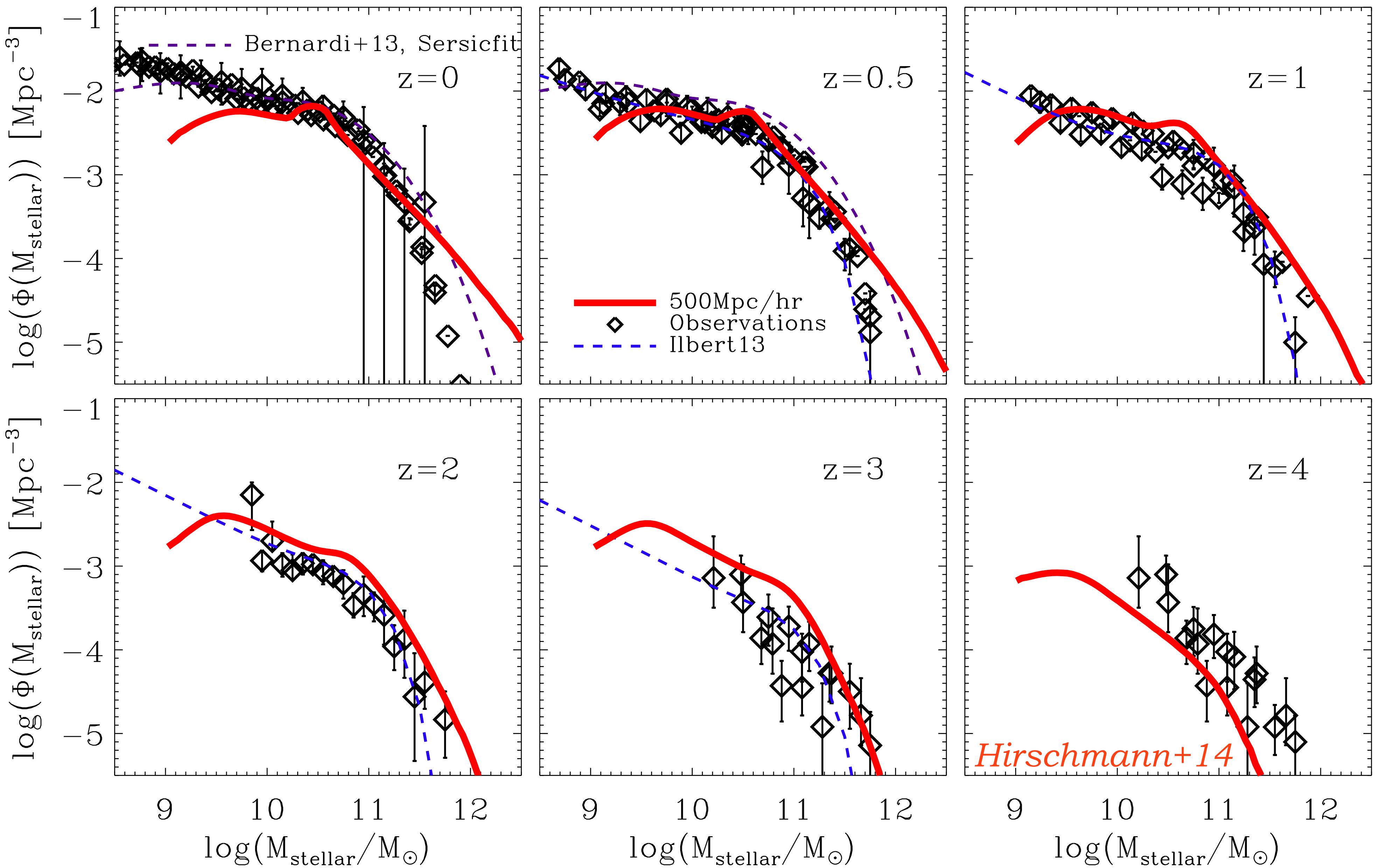
II. Connection between AGN and their host galaxies

Galaxy properties

Evolution of the stellar mass function of all galaxies



- Agreement with observations at z>=1
- Too many massive galaxies at z<1 (too inefficient AGN fb)
- PhD student Lisa Bachmann is working on improving the accretion & fb scheme

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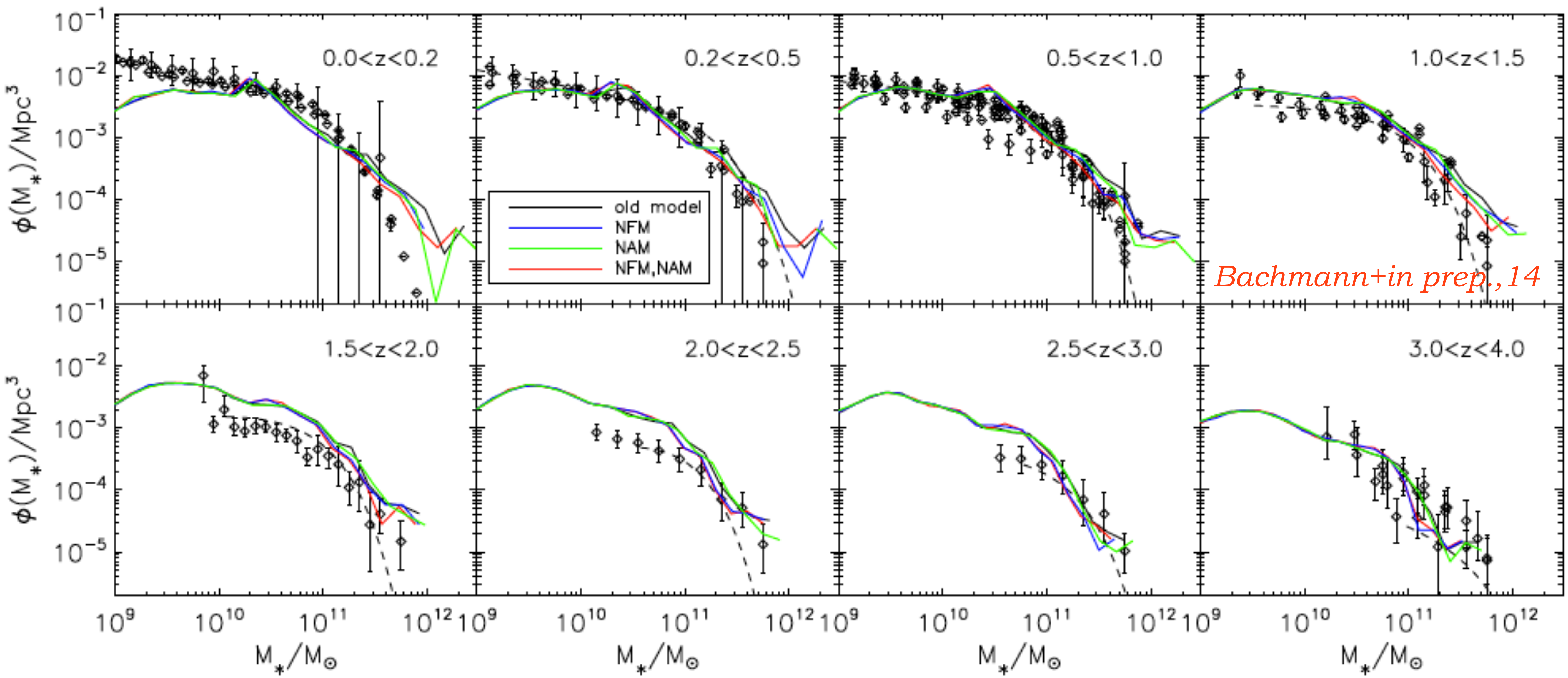
Galaxy properties

Evolution of the stellar mass function of all galaxies



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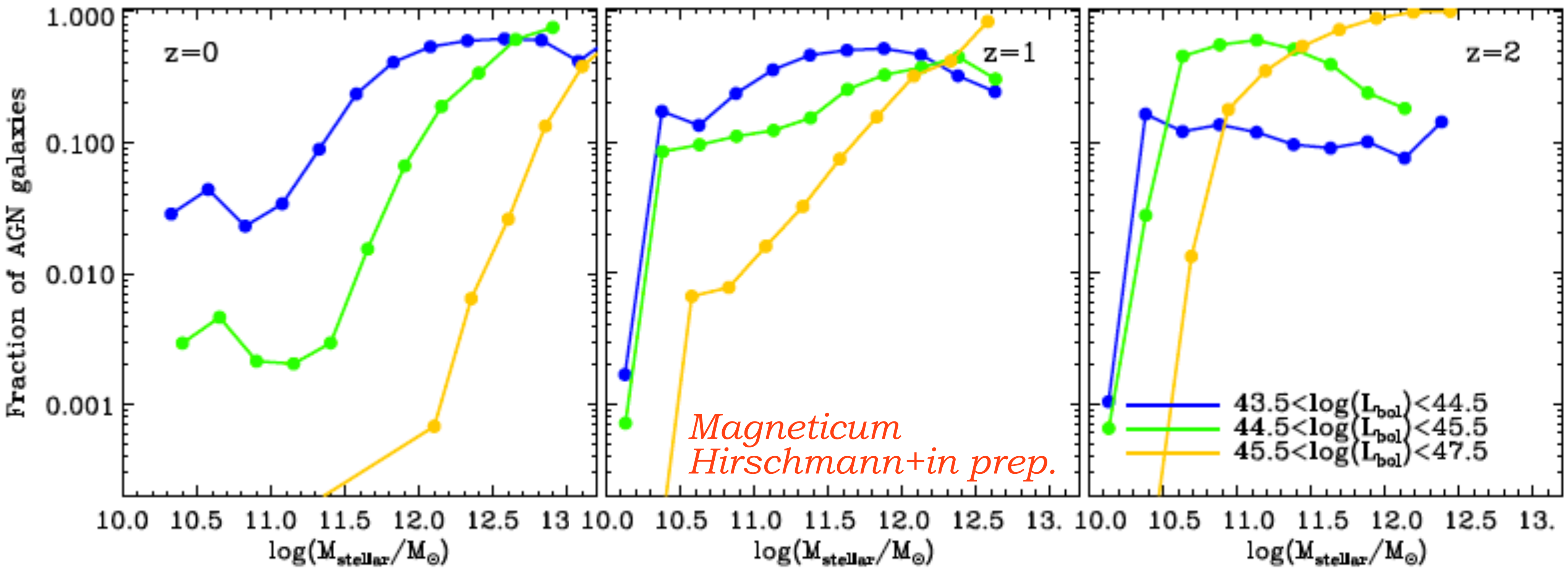
Probability for hosting AGN



- Luminous AGN reside preferentially in more massive galaxies
- The same for moderately luminous AGN at low z

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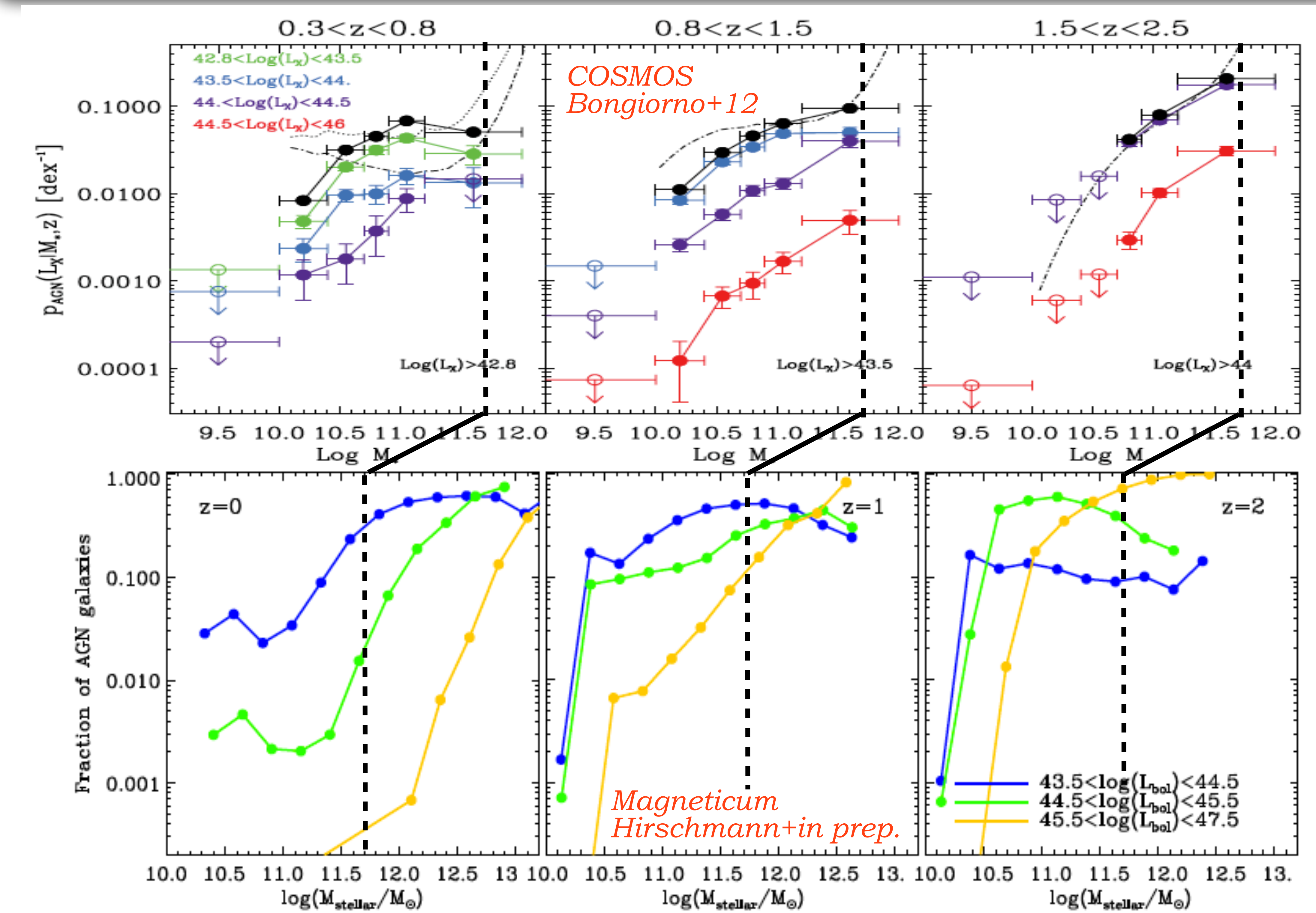
Probability for hosting AGN



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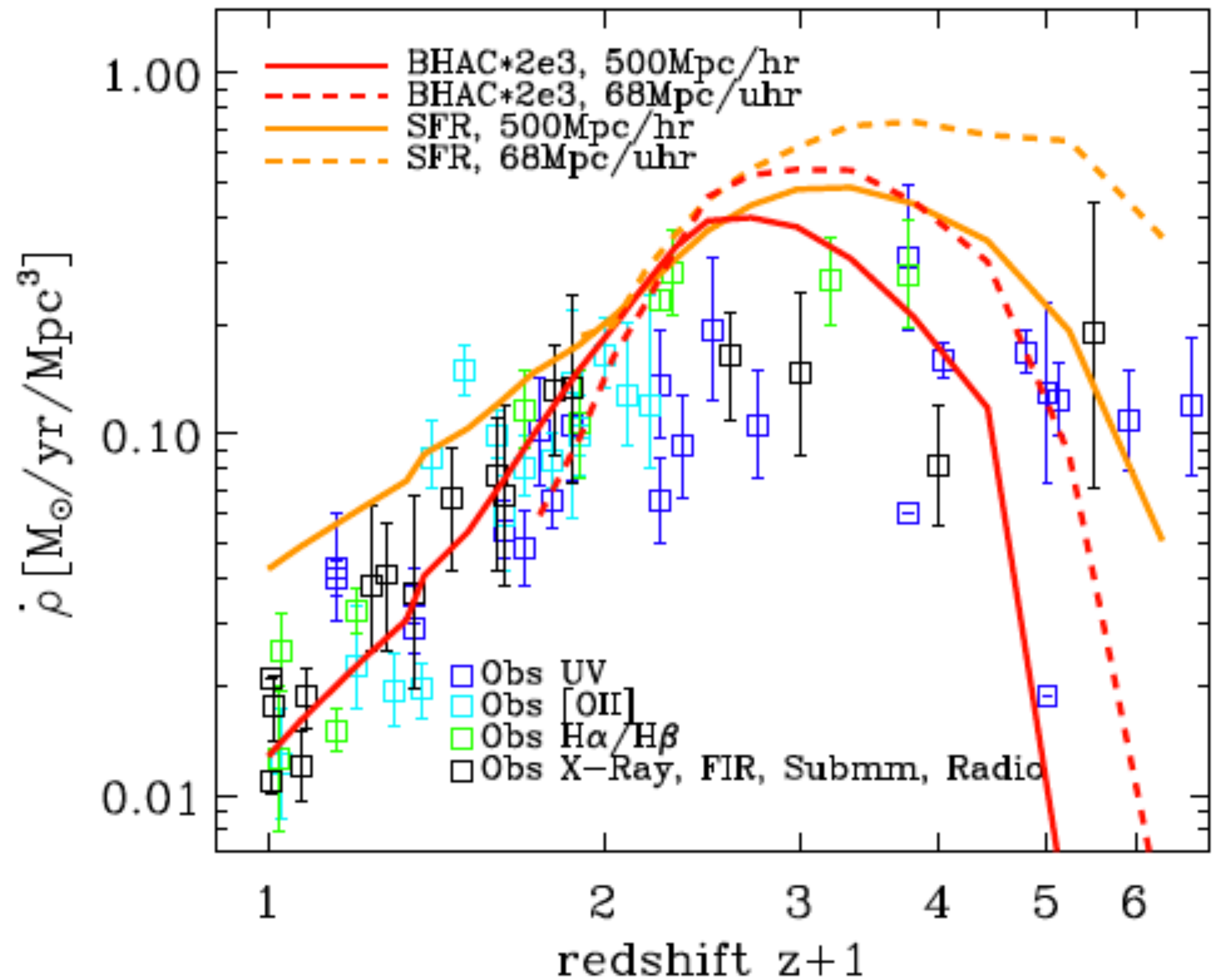
Global evolution of SFR & BH accretion



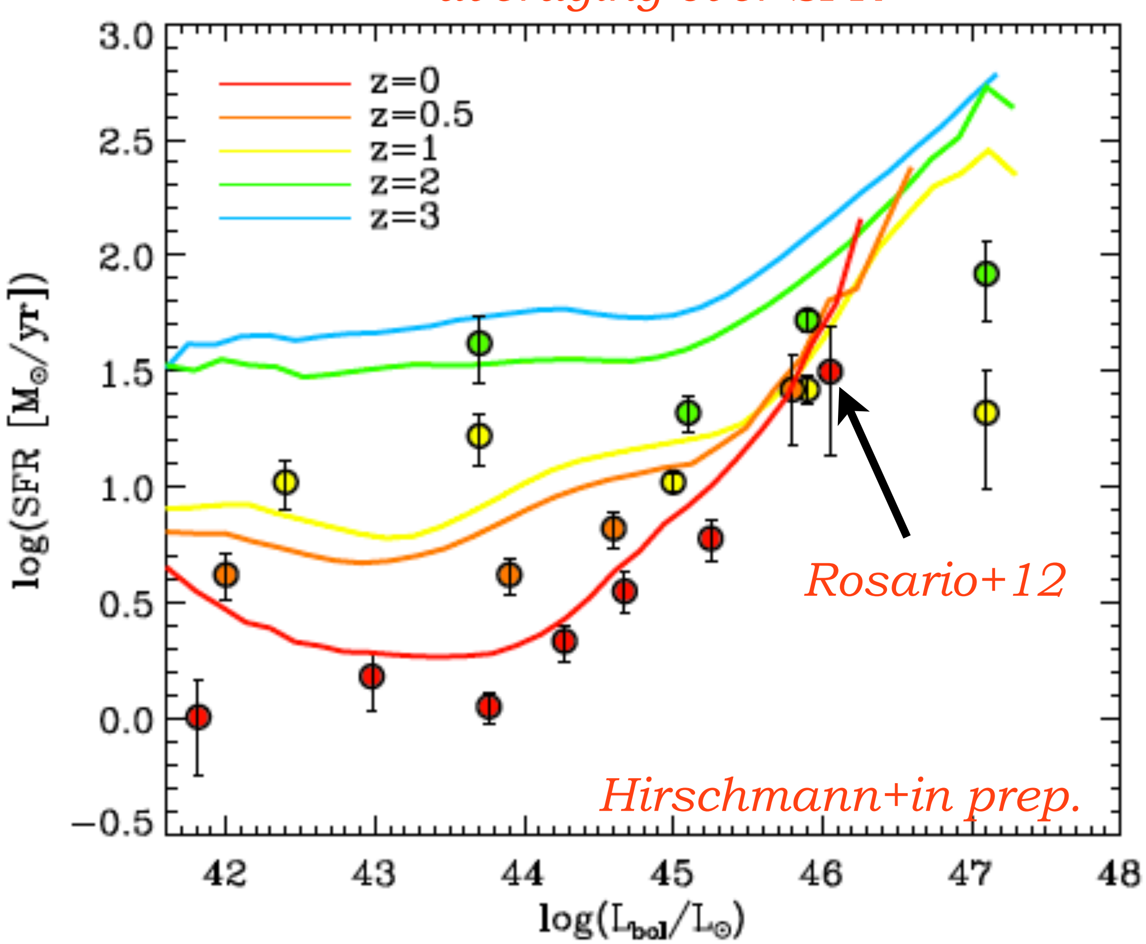
- Consistent with observations: global SFR and BH accretion rate densities peak at z~1-2 and decline at lower and higher z
- But is there a correlation between SFR and L_{bol} at a given redshift?

AGN luminosity vs. SFR

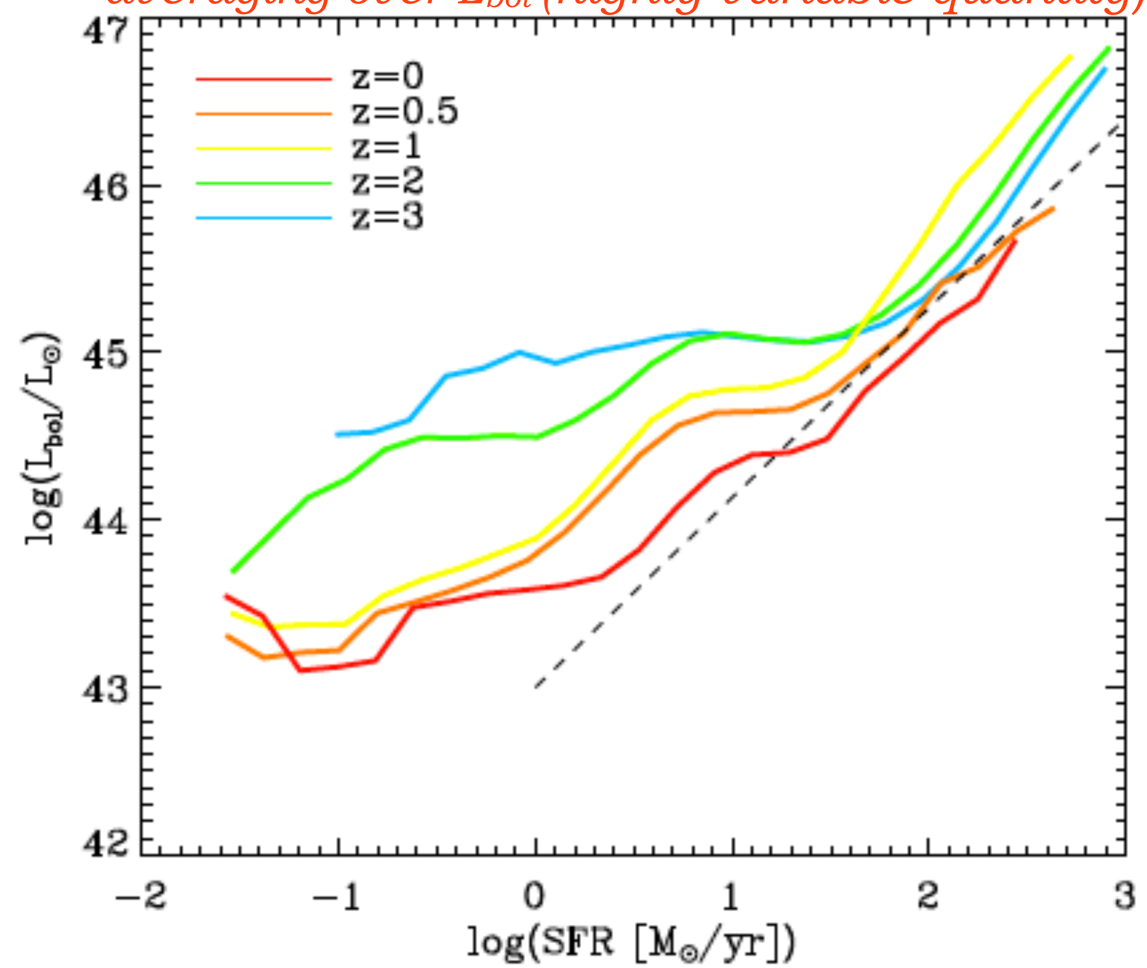
Observational situation unclear and partly contradictory:

- Correlation: *e.g. Netzer+09*
- Deviation from correlation: *Lutz+08, Shao+10, Mullaney+12, Page+12, Santini+12/14, Rosario+12, Rovilos+12*

averaging over SFR



averaging over L_{bol} (highly variable quantity)



- Strong correlation for luminous AGN $L_{bol}>10^{45}$ erg/s --> AGN & SF most likely triggered by a common mechanism, a merger
- Weaker-No correlation for less luminous AGN

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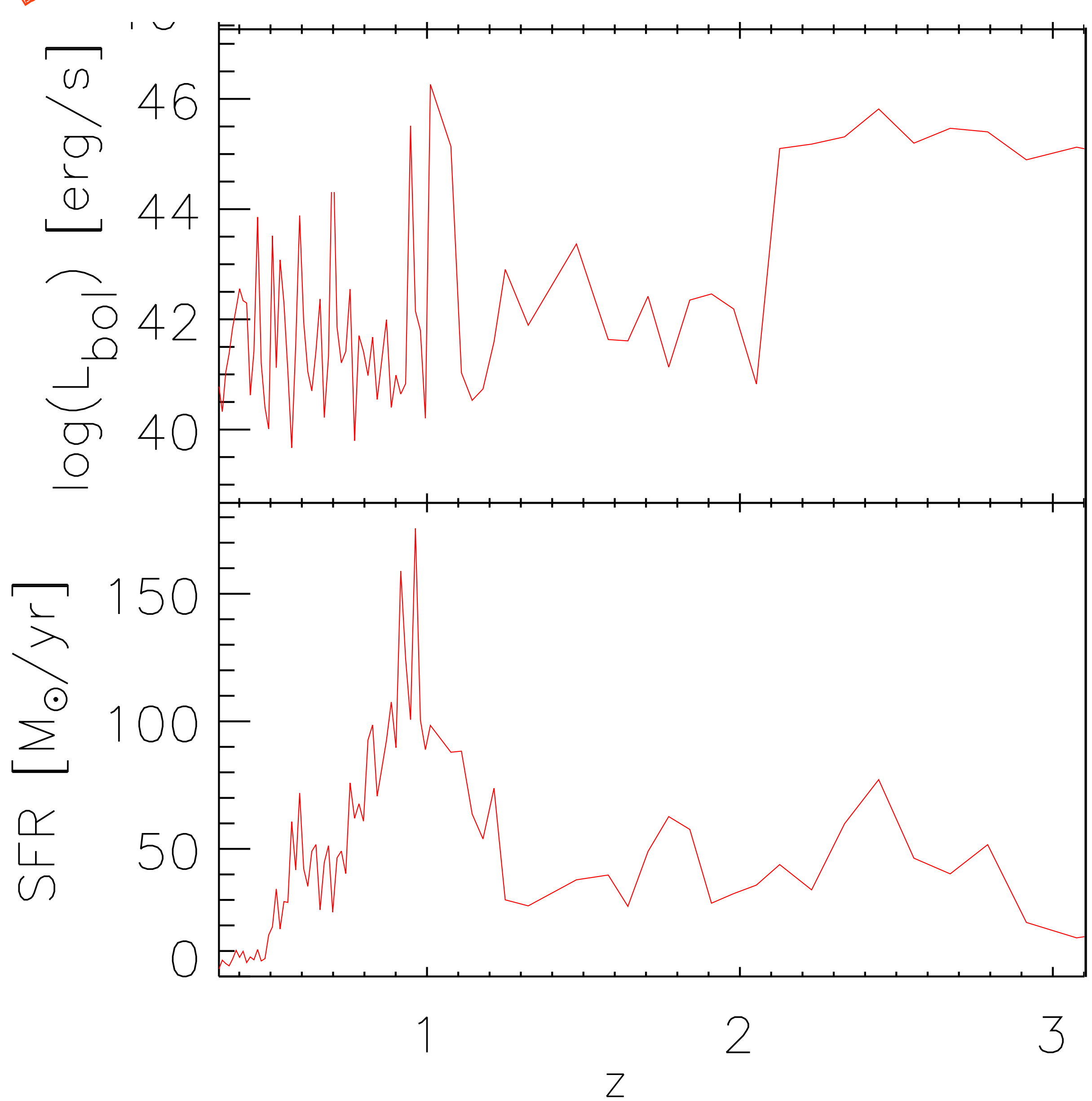
AGN trigger mechanisms

Light curves of individual AGN (higher res. run)

done by L. Bachmann

preliminary

1e9 M☉- black hole



Fully statistical analysis in progress!

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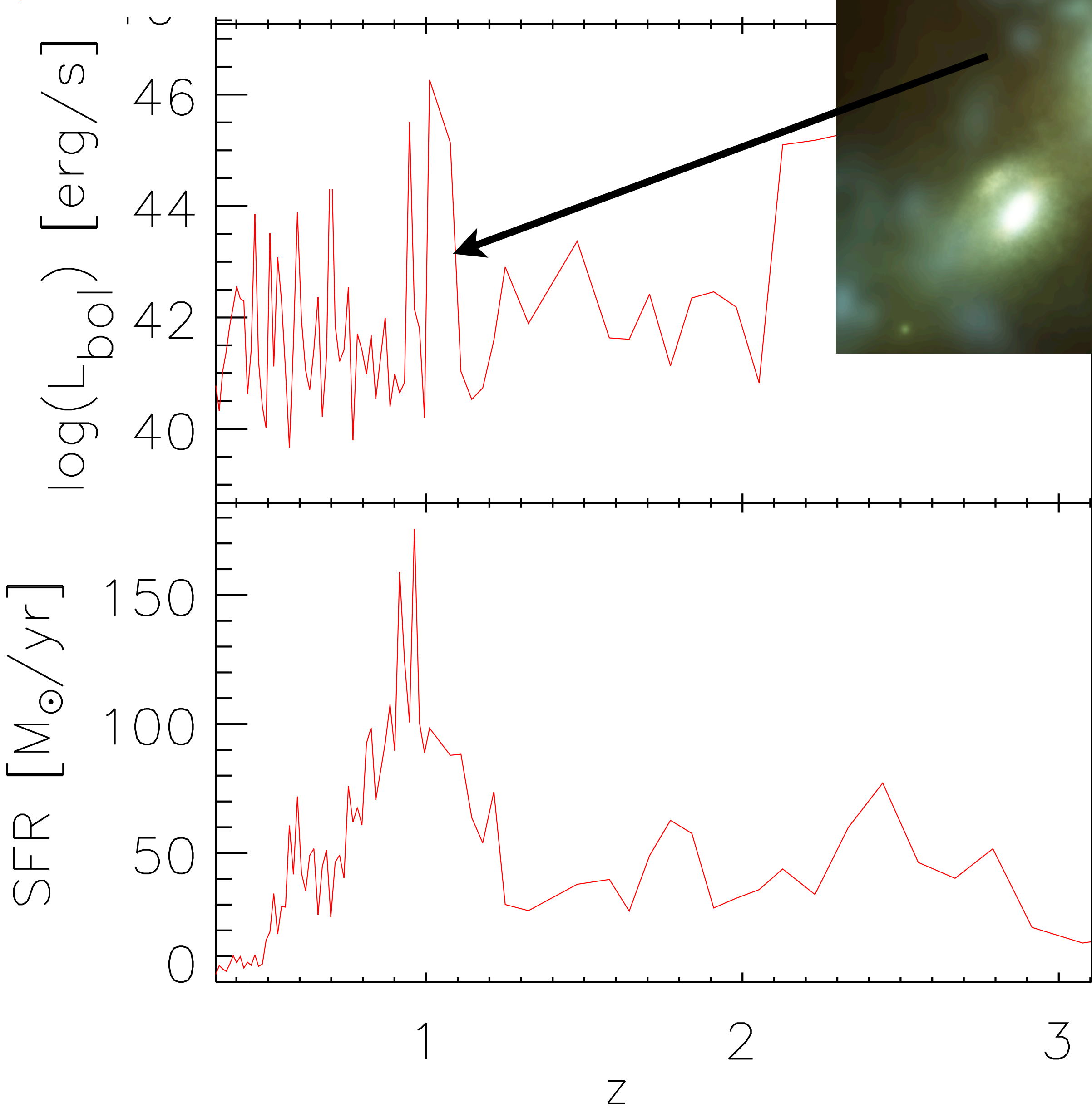

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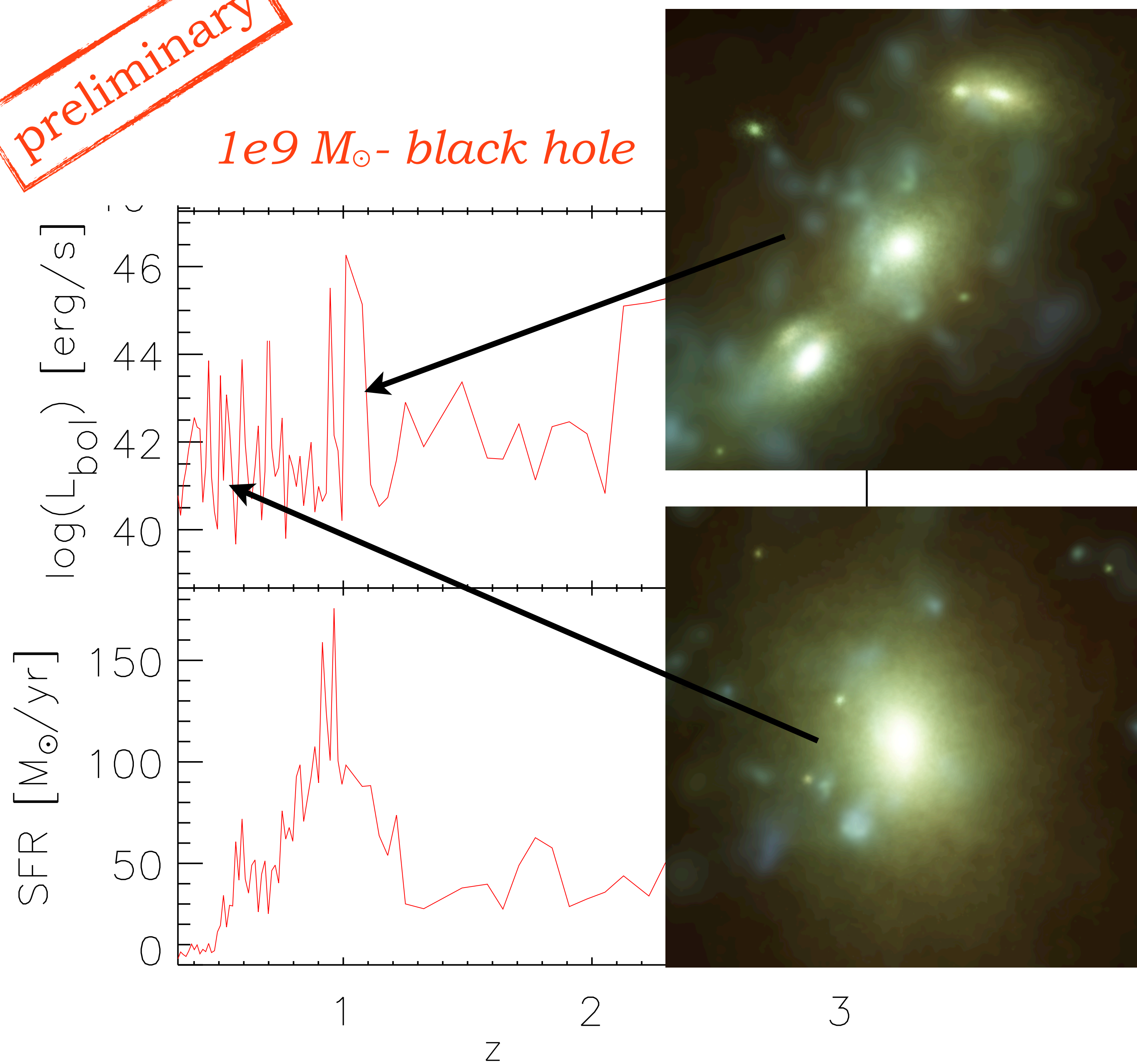


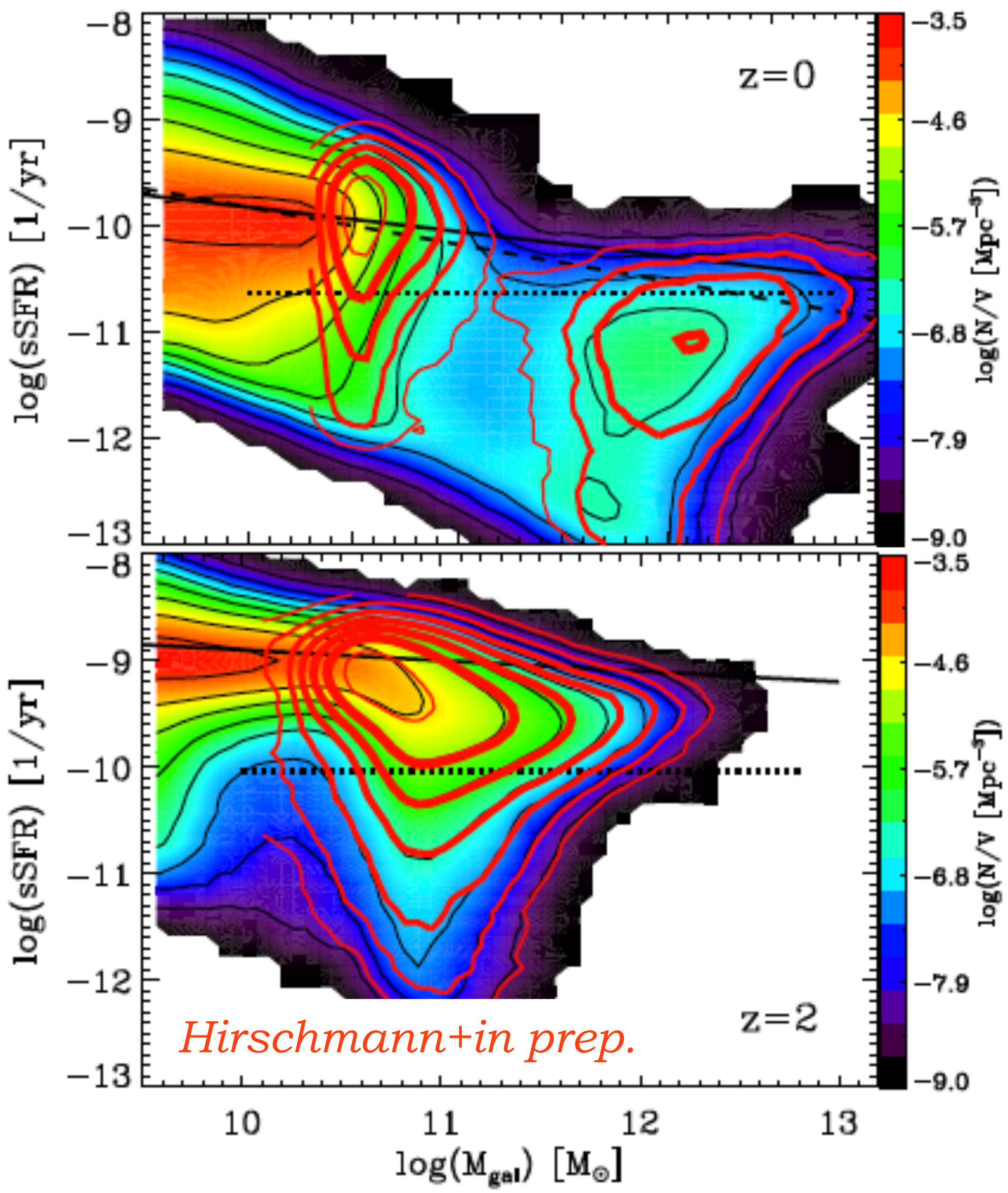
✶ *Luminous AGN (L_{bol}>10^{45} erg/s) triggered by merger, typical for z<=2*

✶ *Less luminous AGN not necessarily triggered by mergers*

Fully statistical analysis in progress!

How quiescent are AGN hosts?

Relation between specific SFR and stellar mass



Bongiorno+12 (including luminous AGN):
58-66% quiesc. AGN hosts
27-37% MS AGN hosts

Mullaney+12 (moderately lum AGN):
79% MS AGN hosts
15% quiescent AGN hosts

- About 40% of AGN (>10^{43} erg/s) live in quiescent hosts
- AGN hosts are more quiescent than all gal's (>1e10$M_\odot$), *consequence of mass bias*

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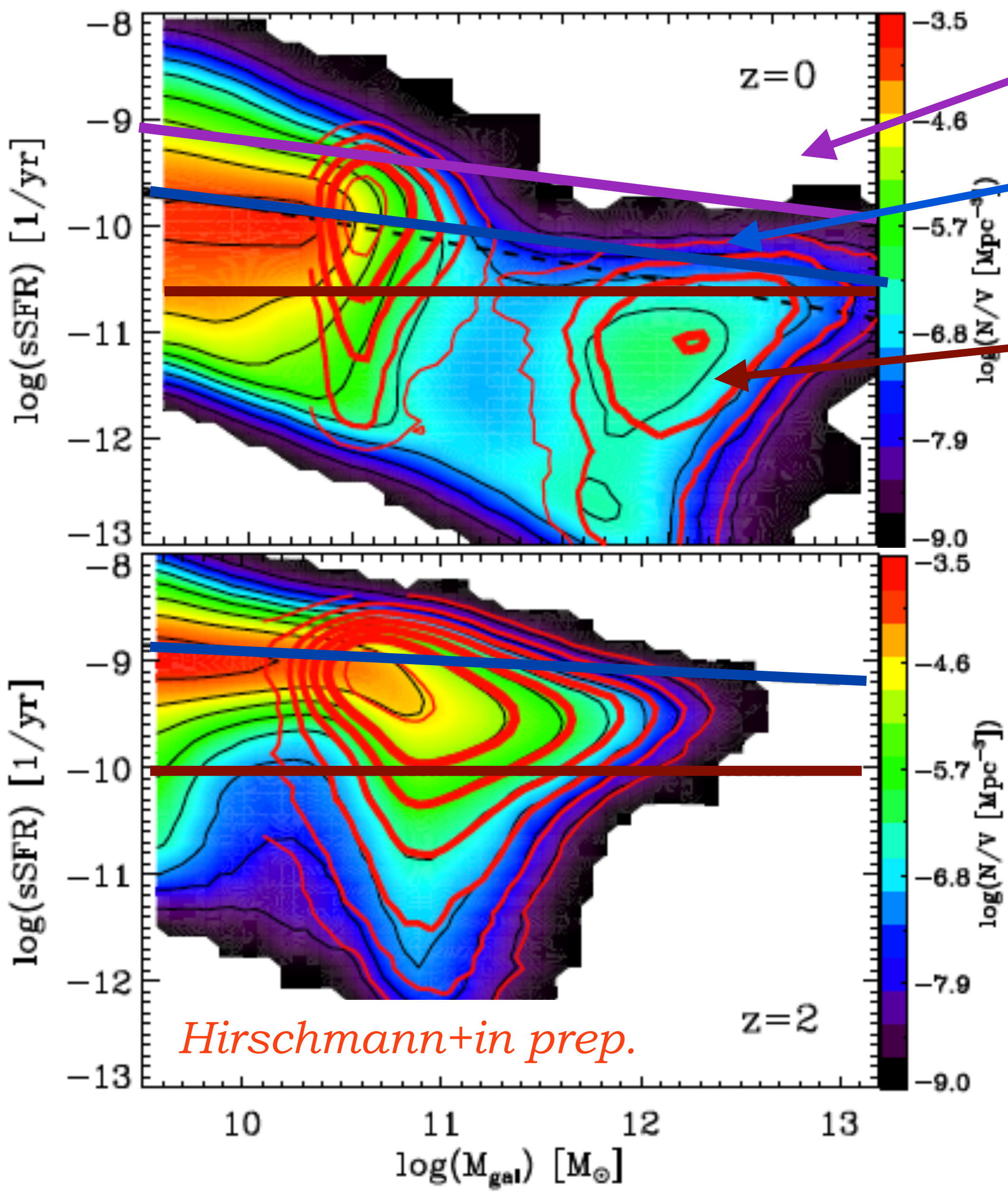

z=0

Star-bursting:
< 10 % in both AGN hosts & all gal's

Main sequence:
58% of all g's
52% of AGN hosts

Quiescent:
34% of all g's
39% of AGN hosts

z=2

Star-bursting:
< 10 % in both AGN hosts & all gal's

Main sequence:
76% of all g's
68% of AGN hosts

Quiescent:
15% of all g's
22% of AGN hosts

Bongiorno+12 *(including luminous AGN):*
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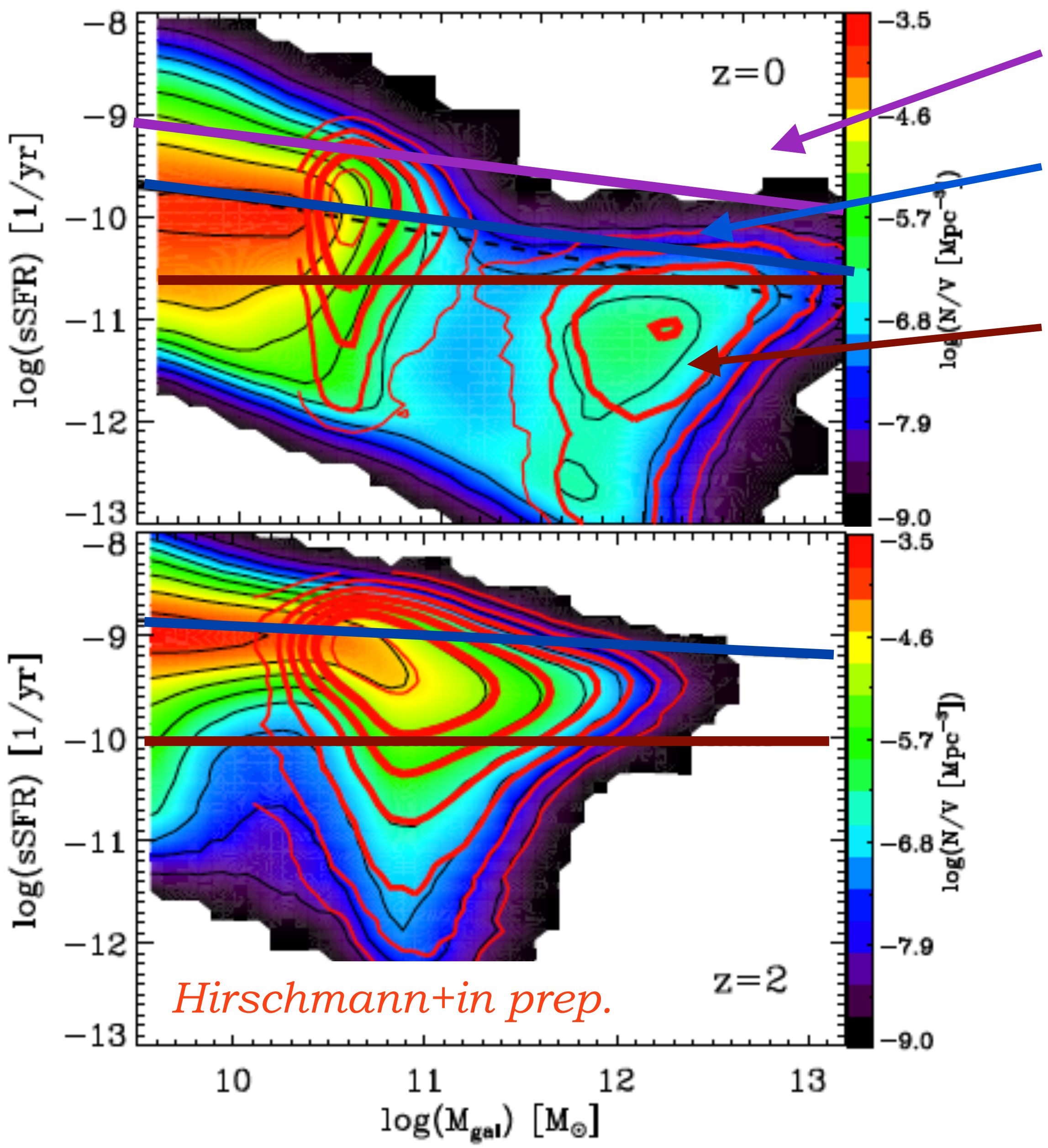

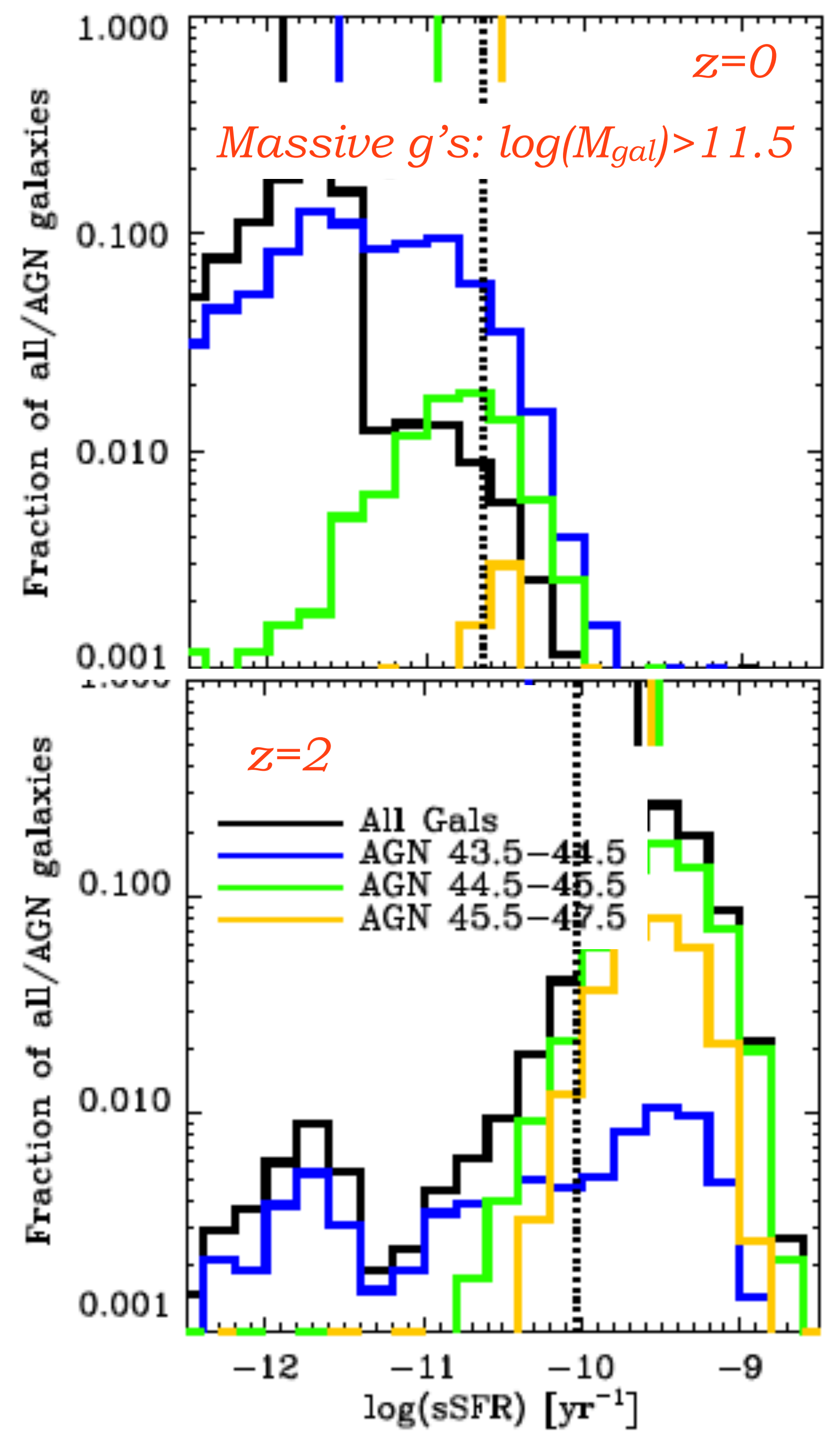

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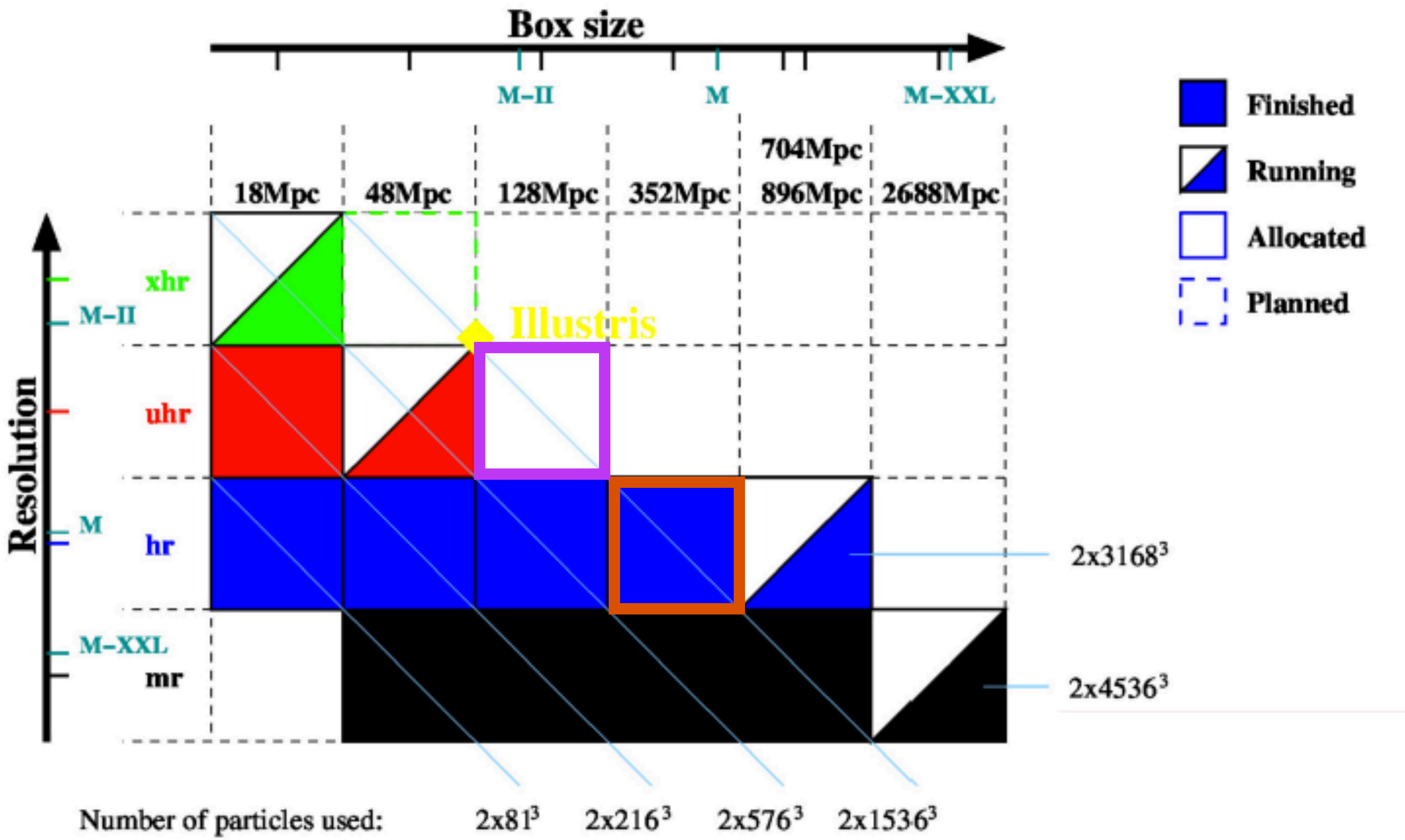
Summary

500Mpc-box Magneticum simulation run down to z=0 allow for a statistical analysis of BH growth and AGN!

- Simulations *predict a fairly realistic population of BHs and AGN* and naturally capture the *downsizing trend due to large-scale gas density (~1-2kpc)* around massive BHs
- *Galaxy properties reasonable*, but too many massive galaxies which are too star-forming -> L. Bachmann working on improving the AGN fb model
- *AGN preferentially live in massive host galaxies* which are slightly *less star-forming than average "normal" galaxies*, eventual additional effect of AGN fb
- *Preliminary: At z<=2, luminous AGN and SF in the host gal's seem to be connected and triggered mainly by merger events*, less luminous not necessarily (stochastic gas accretion) driven by merger or connected to peak in the SFR history

Outlook...



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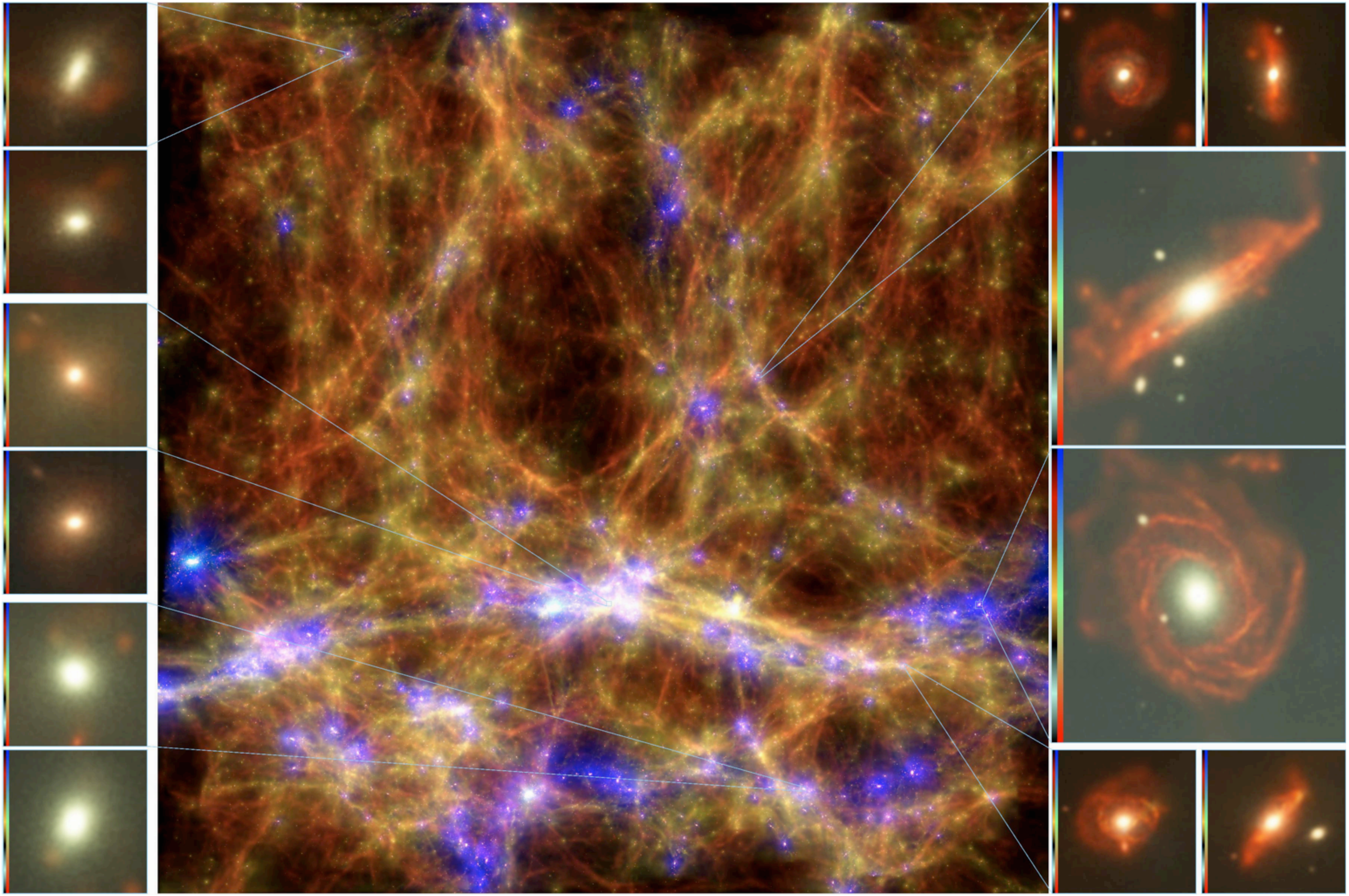

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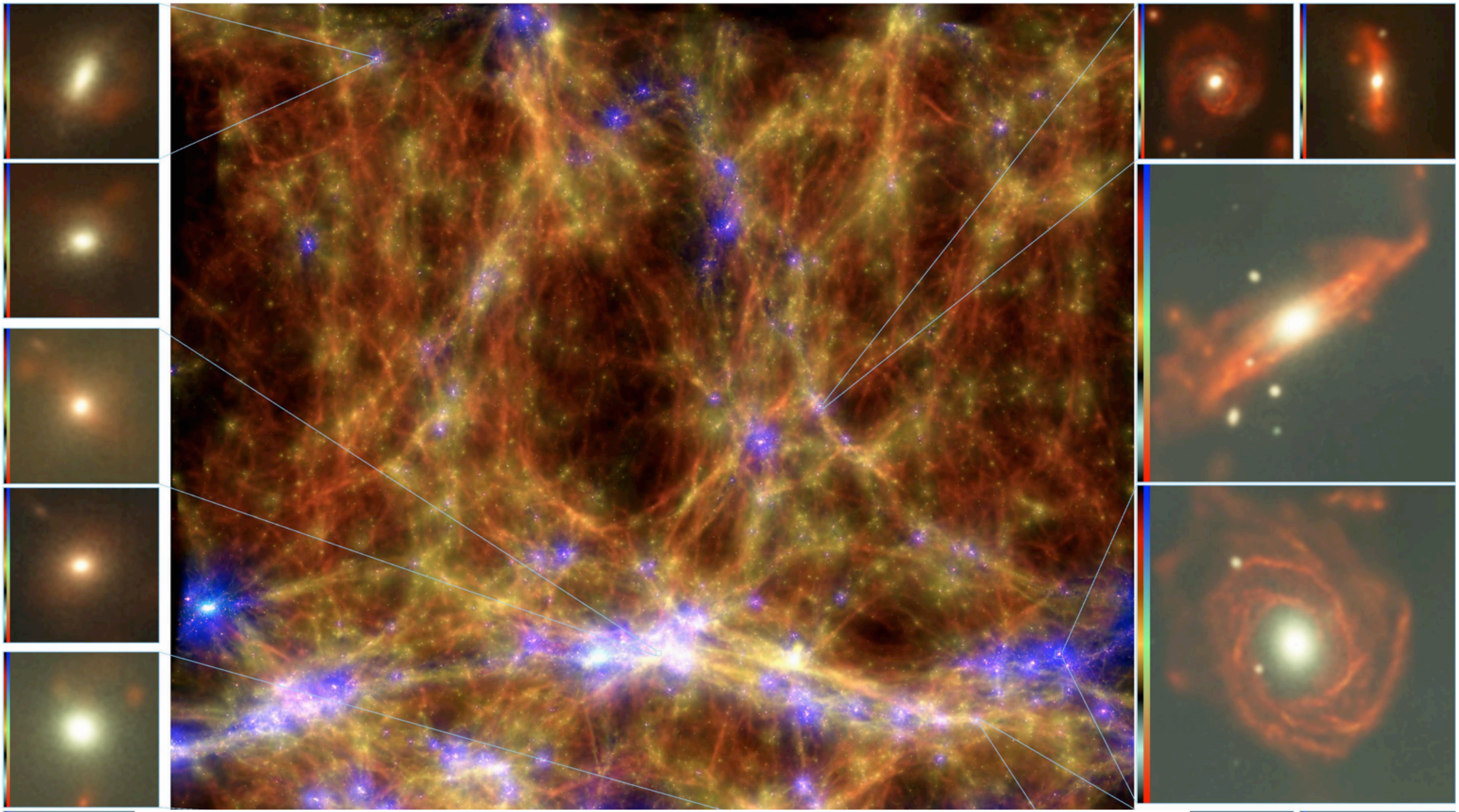
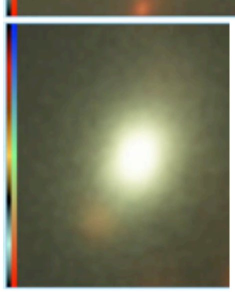
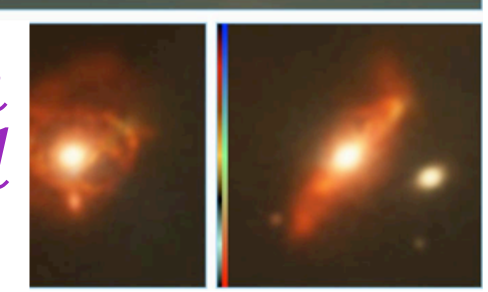




A statistical approach for linking AGN with the host morphology (disky and spheroidal hosts) will be possible!



M. Hirschmann

Magneticum: Box2/hr, $(500 Mpc)^3$ & $2x1564^3$ part.

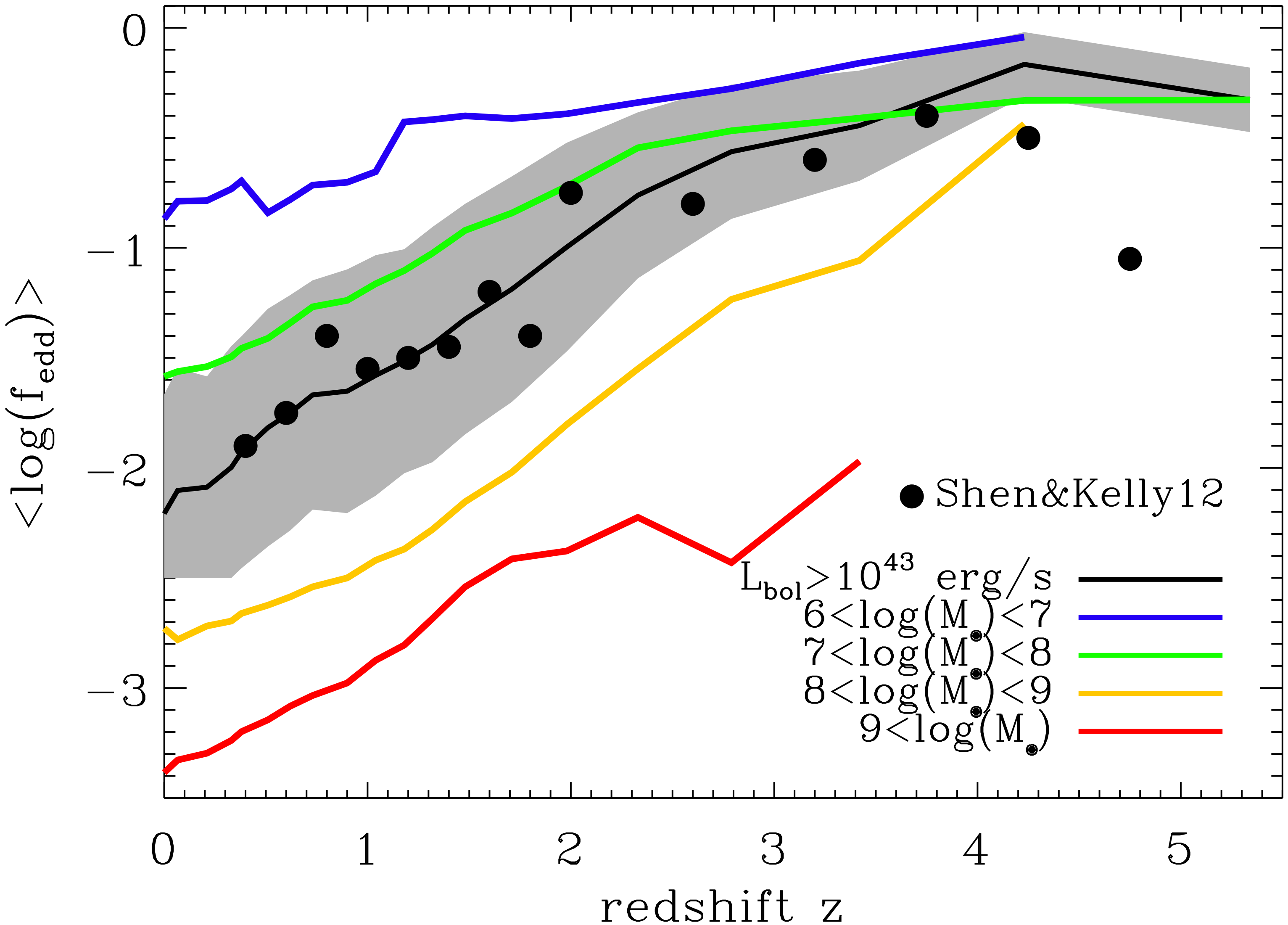
AGN vs Star formation -- The fate of gas in galaxies
28th July - 1st August 2014, University of Durham

Supplementary material

AGN luminosities & the connection with their host galaxies

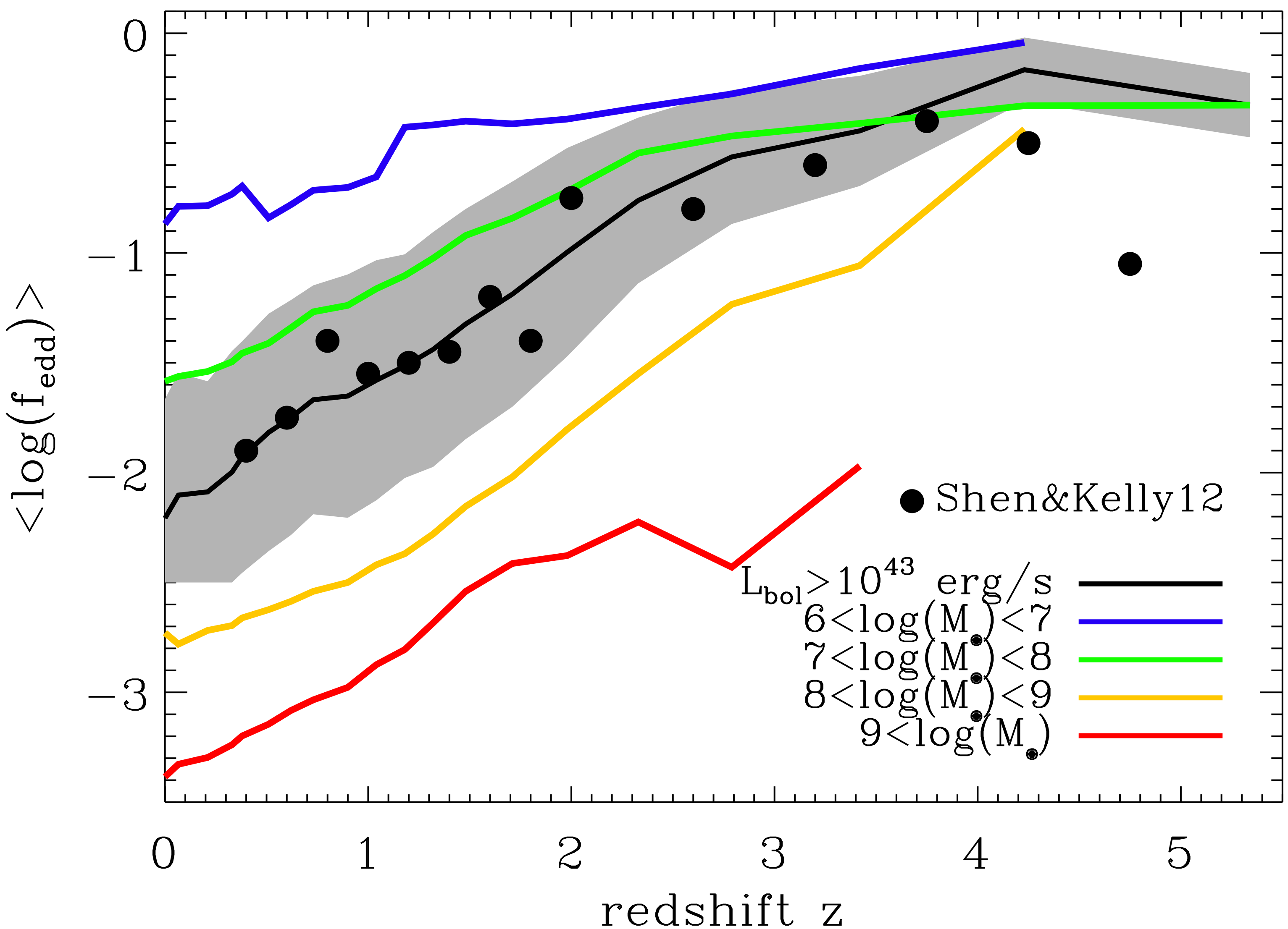
Eddington-ratio evolution

Different BH mass bins



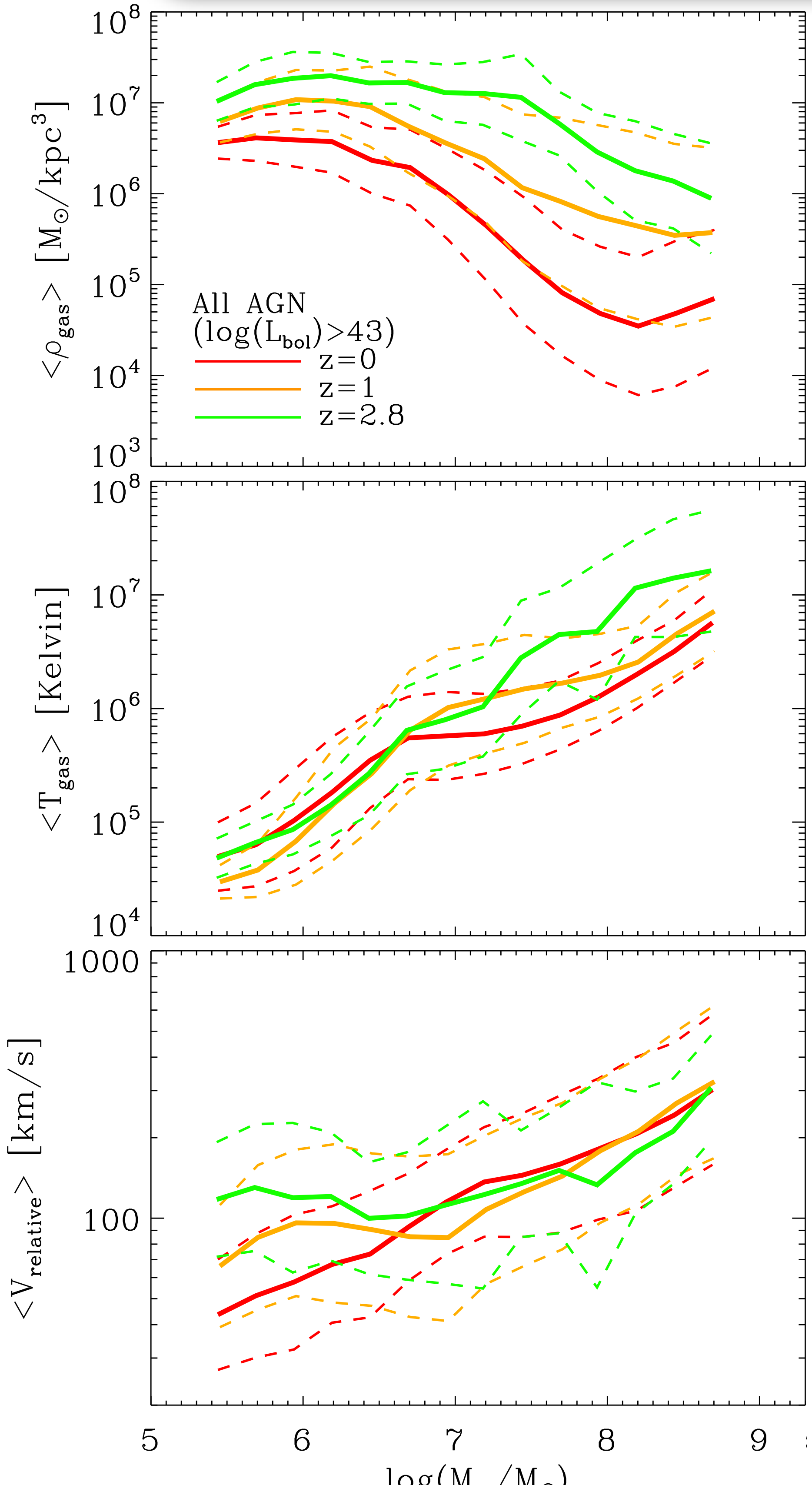
Eddington-ratio evolution

Different BH mass bins



- *Decreasing mean Eddington-ratio with z matching observations*
- *Low mass black holes have on average the highest Eddington-ratios*

Origin of downsizing



Bondi-accretion: $\dot{M}_\bullet = \frac{4\pi G^2 M_\bullet^2 \rho}{(c_s^2 + v^2)^2}$

(within resolved accretion region)

- *More massive BHs have lower ϱ_{gas}, higher T_{gas} and v_{rel} → lower accretion rates*
- *BHs more massive than 10^7 $M_\odot$: lower ϱ_{gas} at lower z → lower accretion rates*

Gas density around the BHs matters!
Gas depletion due to SF and AGN fb
(in agreement with Hopkins et al. 2006)

The radio luminosity function

Following *Best et al. 2012*

HERGs: radiatively efficient

$f_{Edd} > 0.01$

$$\log\left(\frac{L_{\rm rad}+L_{\rm mech}}{L_{\rm edd}}\right) = -1.6$$

LERGs: radiatively inefficient

$f_{Edd} < 0.01$

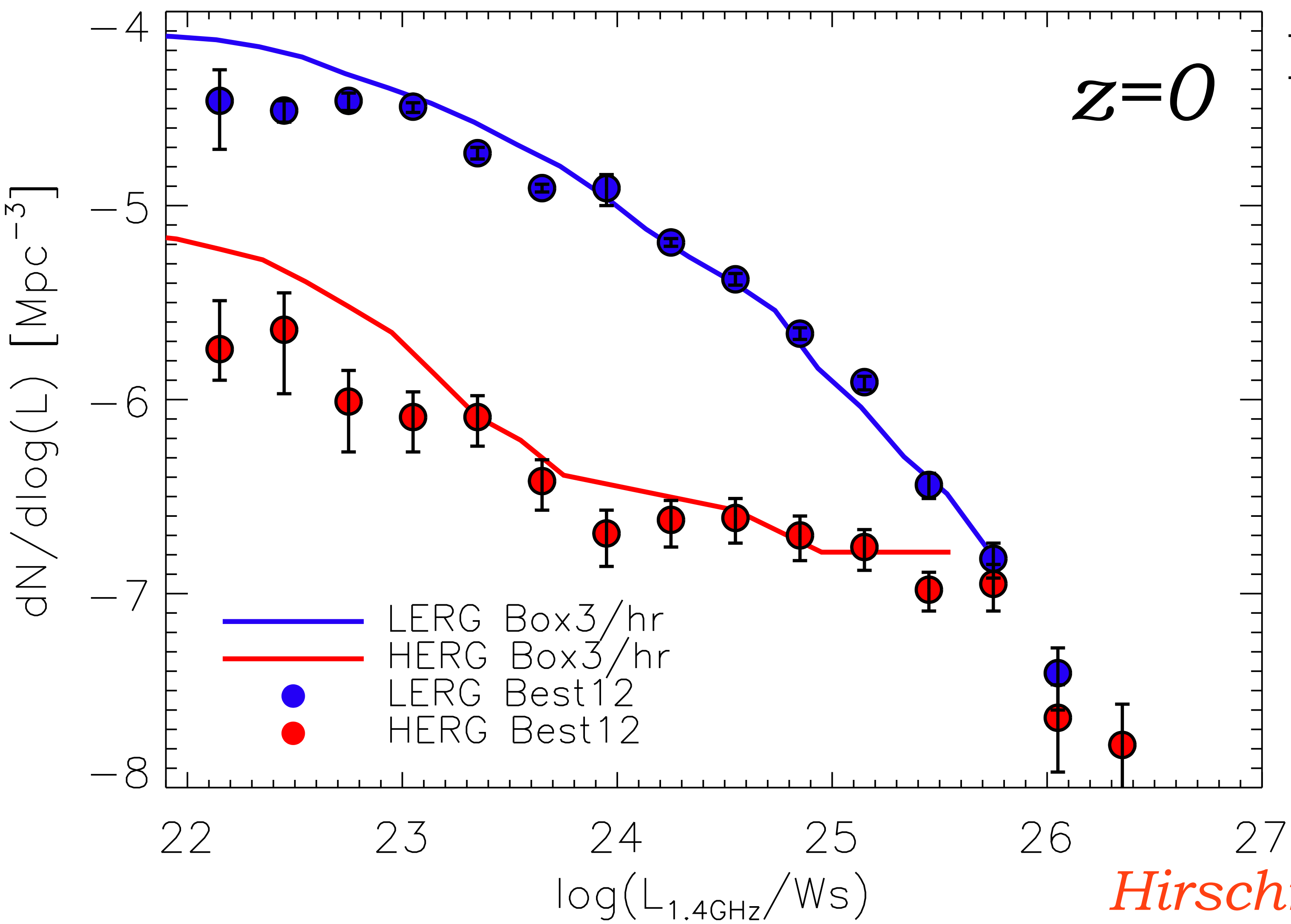
$$\log\left(\frac{L_{\rm rad}+L_{\rm mech}}{L_{\rm edd}}\right) = -3$$

Hirschmann et al. 2013

Jet mechanical luminosity: $L_{\rm mech} = 7.3 \times 10^{36}\ (L_{1.4{\rm GHz}}/10^{24}{\rm W\ Hz}^{-1})^{0.7}\ {\rm W}$

Cavagnolo et al. 2010

The radio luminosity function



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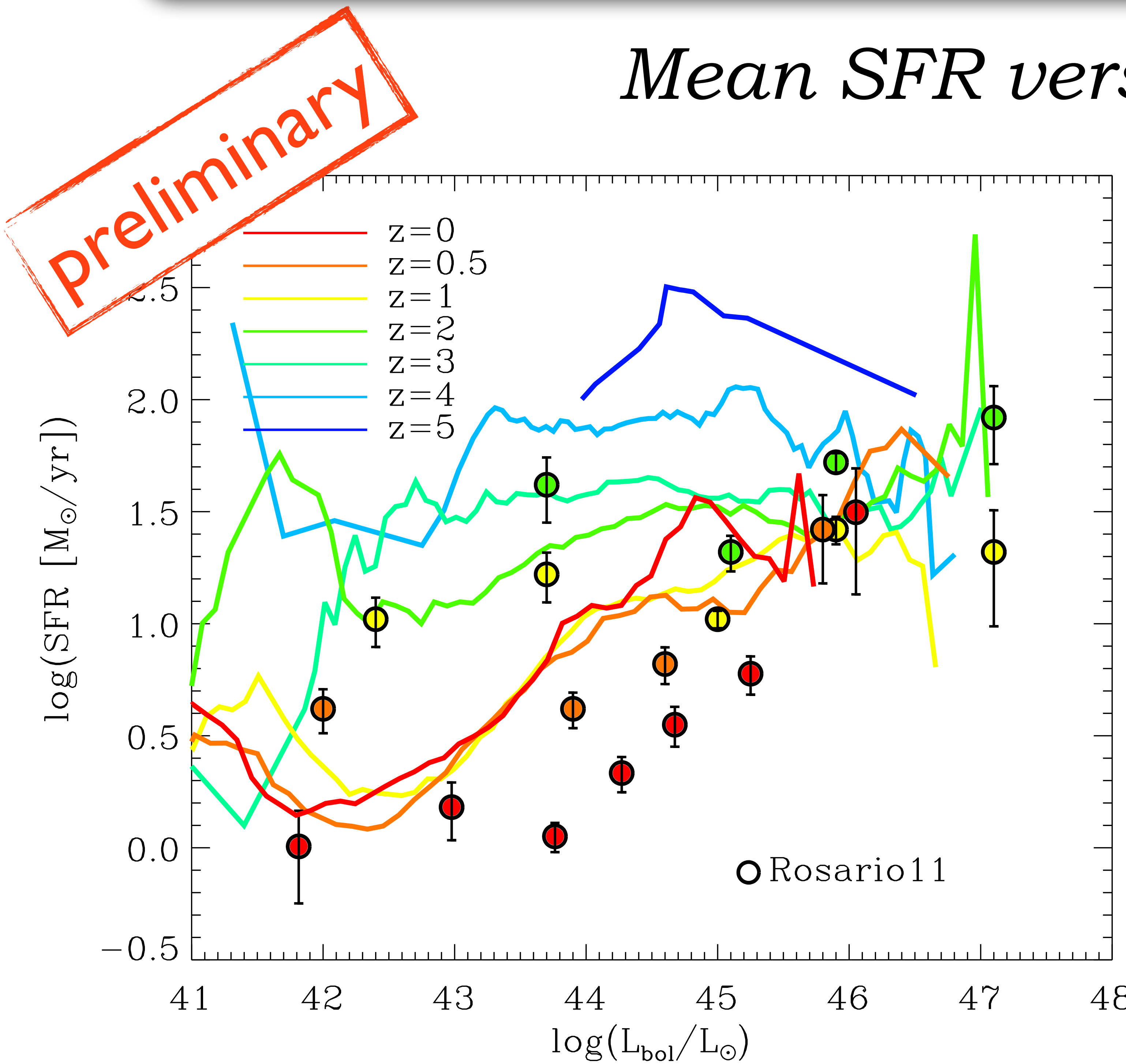
Cavagnolo et al. 2010

Perfect agreement with observational data at z=0!

AGN-host galaxy connection

Mean SFR versus L_{bol}



Constant SFR at high z:

- *No merger-triggered* AGN?
- SB episode short & AGN in blow-out phase?

Relation at low z:

- Preferentially *merger-triggered* AGN, merger trigger also starburst?
- Effect of *AGN fb* gets more important at low z?

Hirschmann & Dolag, in prep.

z>2: Constant SFR
z<2: Relation between SFR & L_{bol}