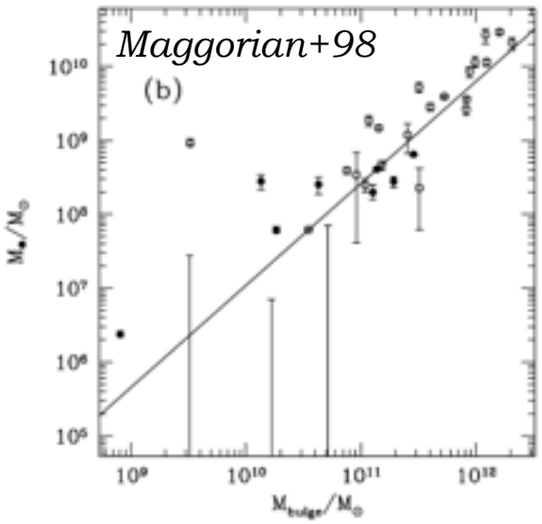
AGN 11 -- Where black holes & galaxies meet
23. - 26. September 2014, Trieste, Italy

Co-evolution of galaxies & black holes?

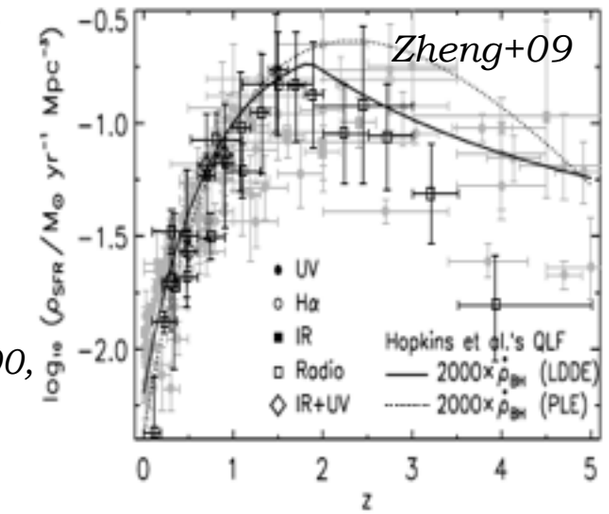
Insights from galaxy formation models & cosmological simulations

Michaela Hirschmann (IAP, France)
Main Collaborators:
K. Dolag *(USM)*, R. Somerville *(Rutgers)*, T. Naab *(MPA)*

Observational evidence...



- *SFR density & BHAR trace each other over cosmic time*
  Franceschini+99, Barger+01, Dickinson+03, Merloni04/06, Hopkins+07, Shankar+09, Brusa+09, Zheng+09, Merloni&Heinz12 etc.
- *Spheroidal galaxy properties related to BH mass*
  Ferrarese & Merrit '00, Gebhardt+00, Magorrian+98, Kormendy&Bender12 etc
- *Downsizing in BH growth* *Miyaji+00, Fiore+03, Ueda+03, Hasinger+05 etc*
  & galaxy evolution
  Cowie+96, Menci+08, Cimatti+06, Thomas+10
- *AGN-driven outflows* *Cicone+12, Cicone +14, Genzel+14*
- *Bubbles of X-ray emitting hot gas*
  (McNamara&Nulsen+07/12, Cattaneo+09, Fabian+12)



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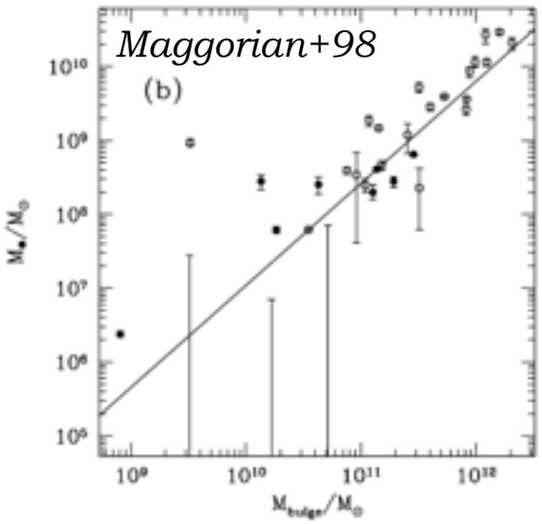

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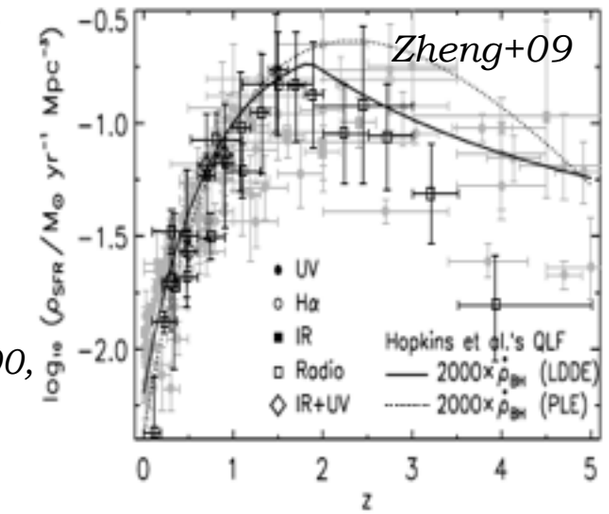
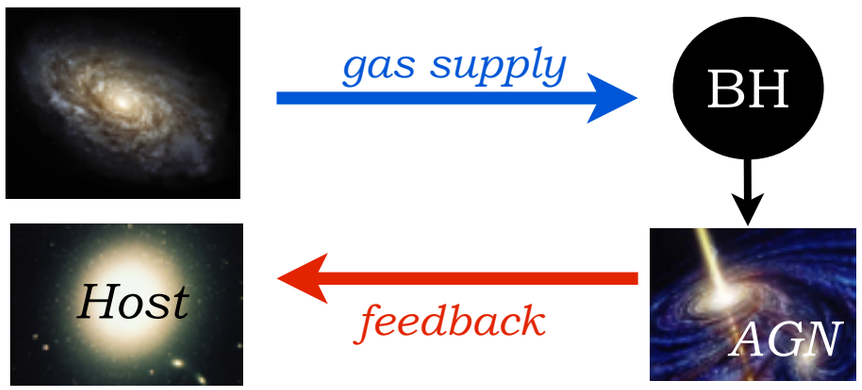


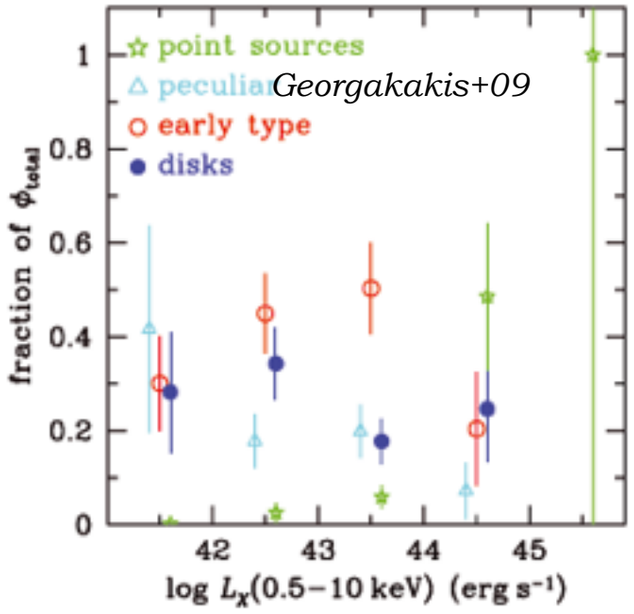
...interpreted as evidence for...

"Physically coupled" evolution of galaxies & black holes
(Robertson+06, Hopkins+08, Granato+04, Di Matteo+05, Croton+06 etc)

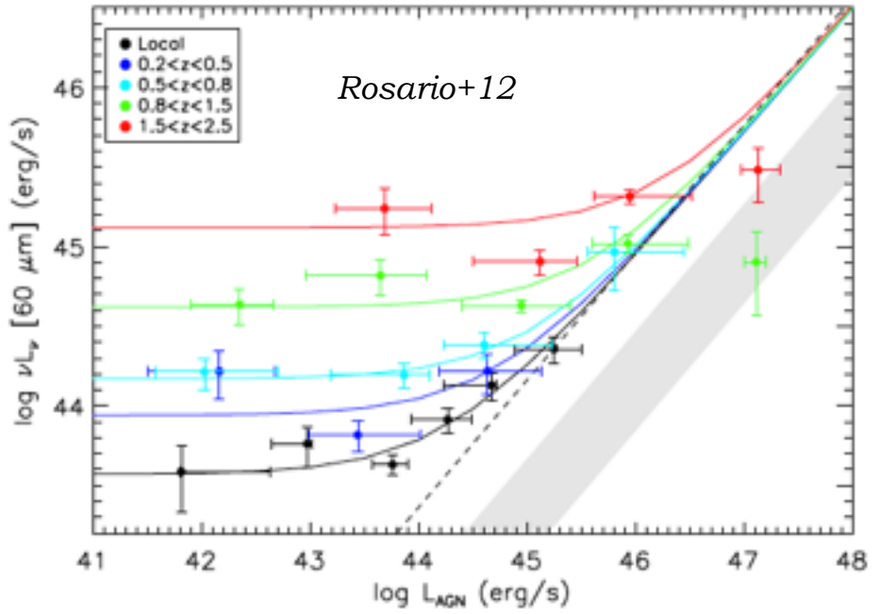


Rapid growth & SB due to *gas-rich major mergers* Naab+06, Robertson+06, Hopkins+08
Regulation of gas accretion & SF *by feedback* Granato+04, Di Matteo+05, Croton+06

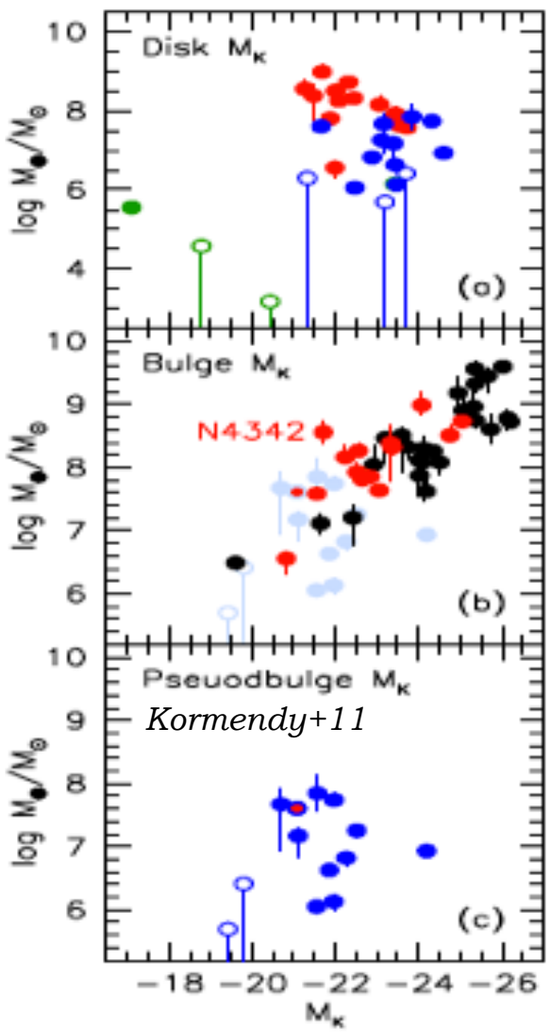
Observational disproof?



Georgakakis+09

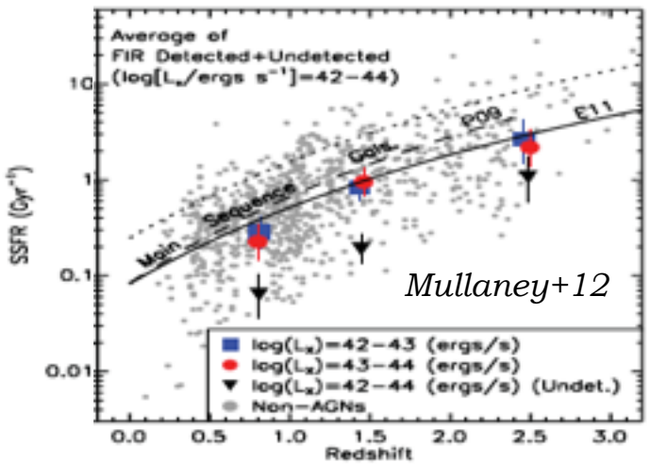


Rosario+12



Kormendy+11

- *No correlation between BHs and disk-like galaxies (with pseudo-bulges)*
  Kormendy+11 (Nature), Kormendy+13
- *Large fraction of AGN reside in undisturbed disk galaxies at low & high z*
  Cisternas+11, Grogin+05, Georgakakis+09, Schawinsky+12, Kocevski+12
- *Widely uncorrelated L_{bol} and SFR*
  Rosario+12, Rovilos+12, Mullaney+12, Harrrison+12, Page+12 (but see Hickox+12)
- *No "smoking gun" for a common trigger mechanism*
  Bongiorno+12, Merloni&Heinz+12
- *AGN seem to reside mainly in main sequence SF galaxies (still debated)*
  Silverman+09, Mullaney+12



Mullaney+12

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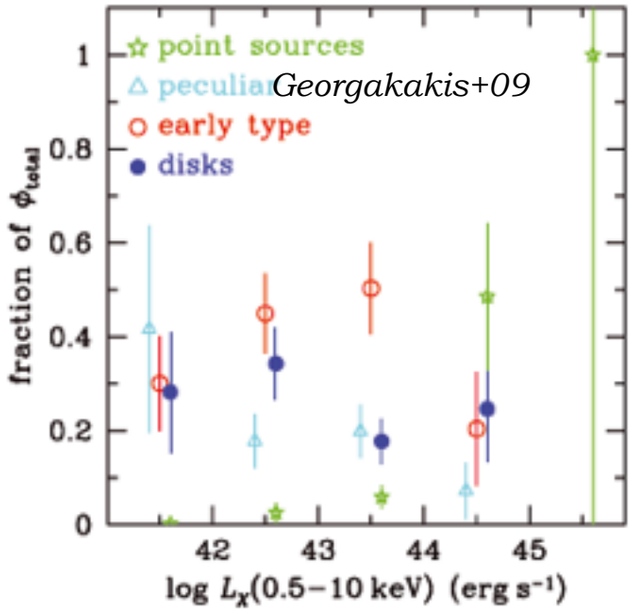

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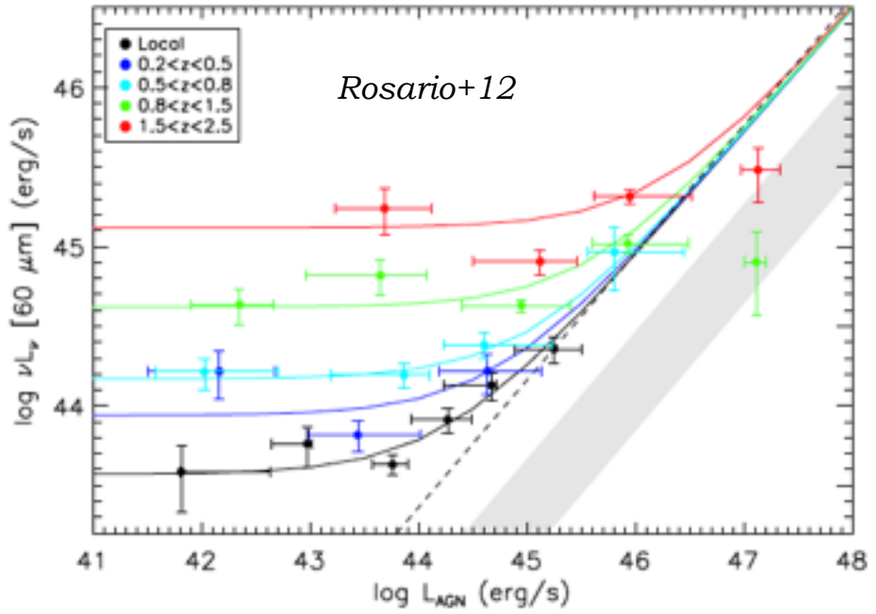

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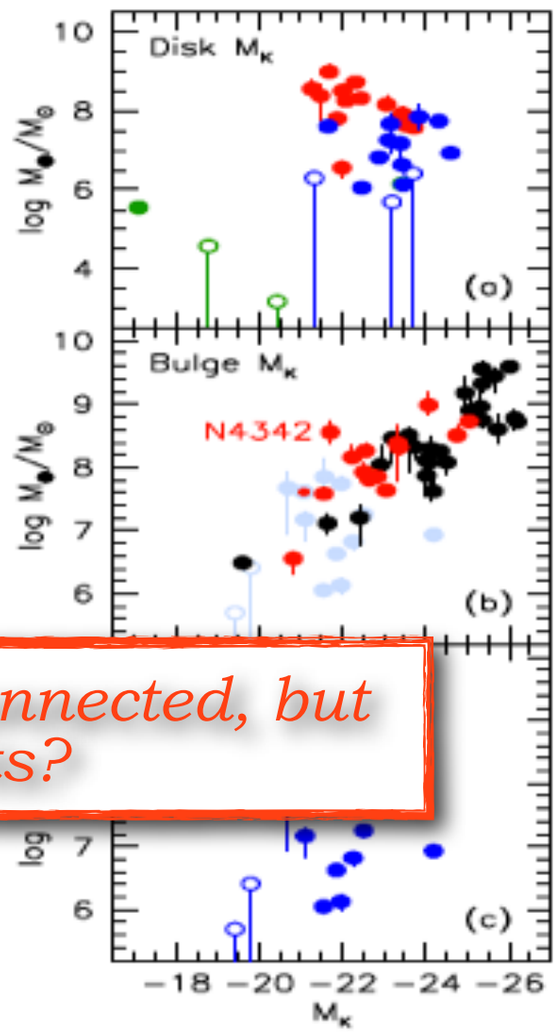

Globally BH growth and galaxy evolution is connected, but also on the basis of individual objects?

- *Large fraction of AGN reside in undisturbed disk galaxies at low & high z*
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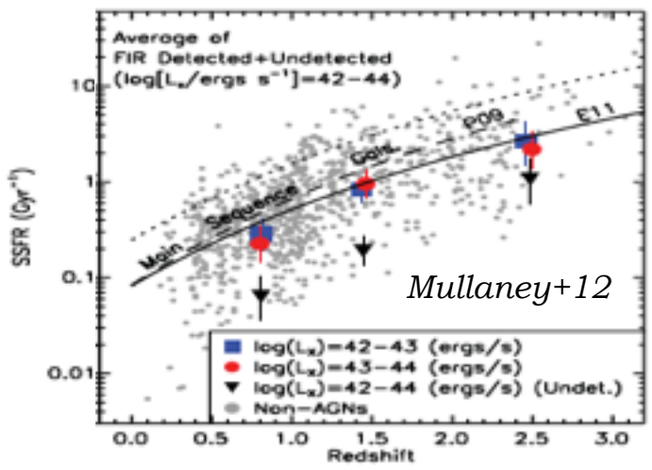

Mullaney+12

The need for theoretical models

Use predictions from
I. Galaxy formation models &
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to explore how we have to interpret observational results:

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Use predictions from
I. Galaxy formation models &
II. Cosmological hydrodynamic simulations
to explore how we have to interpret observational results:

1. Origin of BH scaling relations -> see Francesco's talk!

2. The (dis-?) connection between star formation and AGN activity in individual objects

3. The main trigger mechanisms for AGN activity

4. The relative effect of AGN feedback on their host galaxies

Under which conditions is the evolution galaxies and black holes causally connected and when is it physically de-coupled?

I. Semi-analytic galaxy formation models

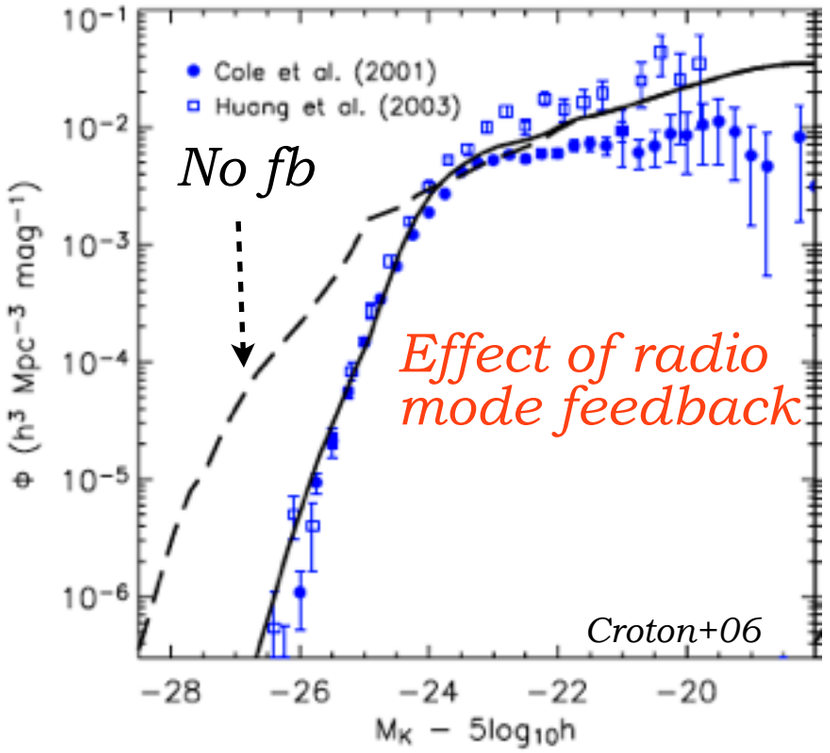
Galaxy formation models

Approximation with physically motivated analytic laws

e.g. Bower+06, Croton+06, Somerville+08, Fontanot+06, Fanidakis+12, Hirschmann+12, Menci+13

Models for BH growth:

- Distinction between cold and hot gas accretion
- For hot gas accretion, fraction of gas is heated, *radio-mode fb is solving the over-cooling problem*
- For cold gas accretion, an a priori connection between starbursts and AGN activity is adopted driven by a common mechanism, mostly major mergers (or DI's)
- Many details different
- Successful in reproducing a statistically realistic population of BHs & AGN



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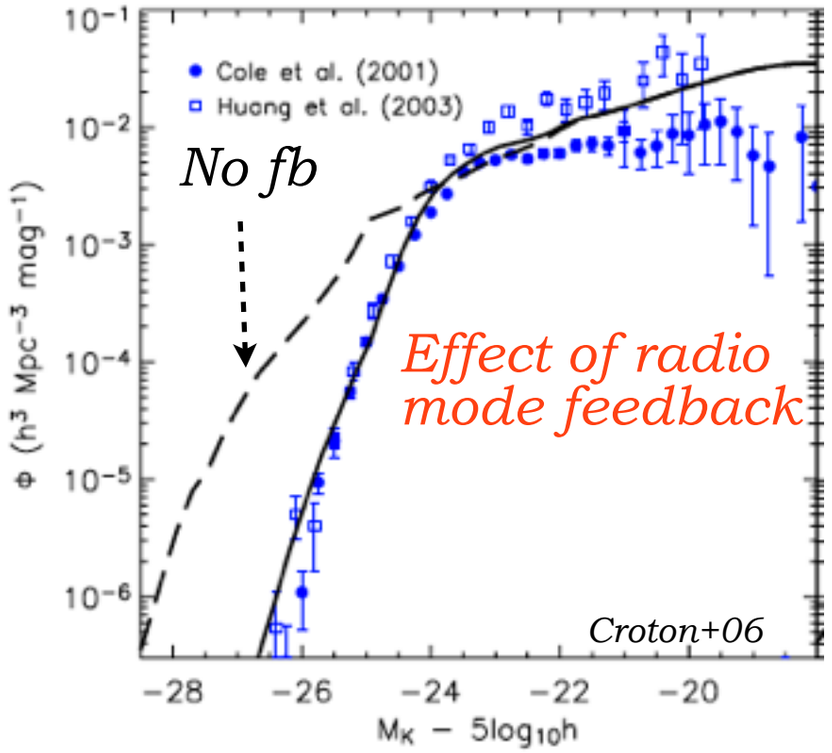
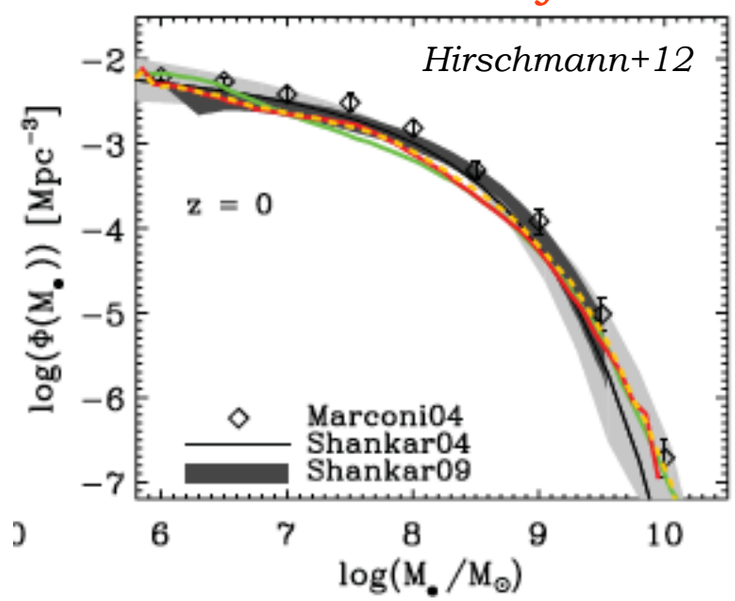
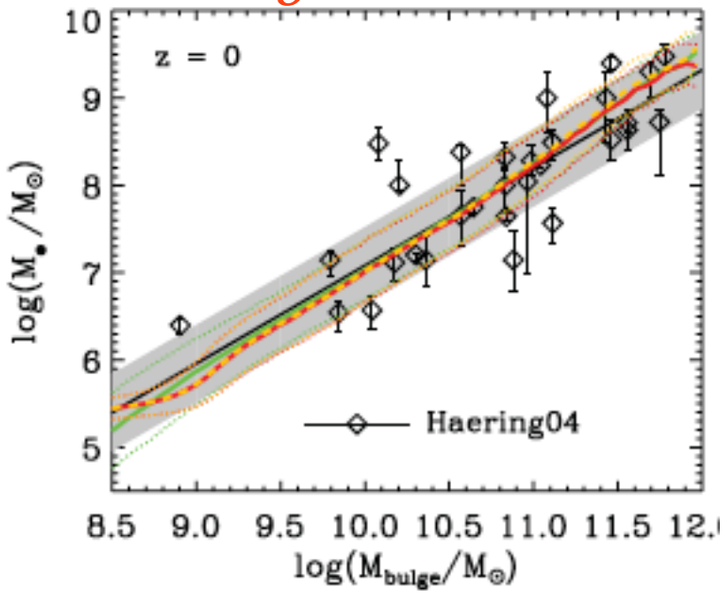


BH mass fct



BH-bulge mass relation



Anti-hierarchical BH growth

...in semi-analytic galaxy formation models...

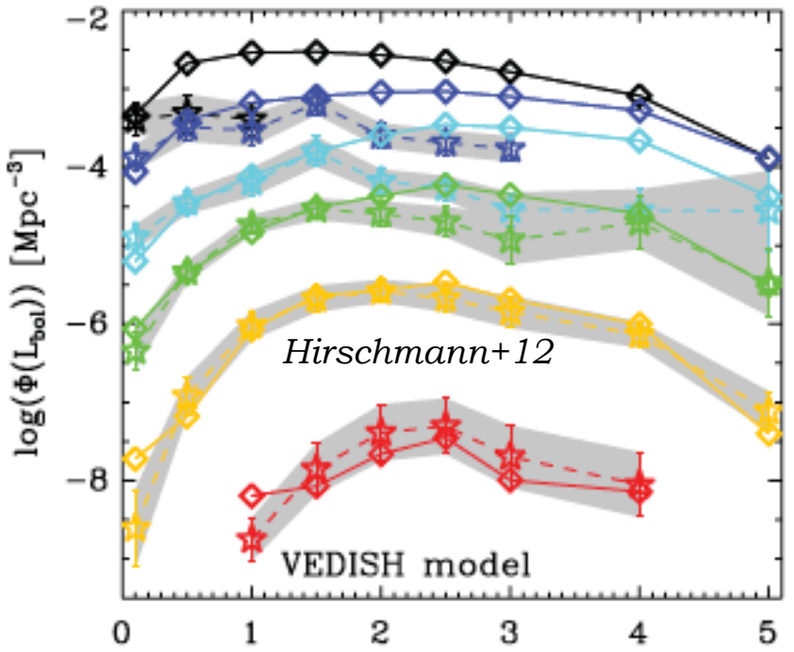
e.g. Marulli+07, Bonoli+09, Fanidakis+12, Hirschmann+12, Menci+13

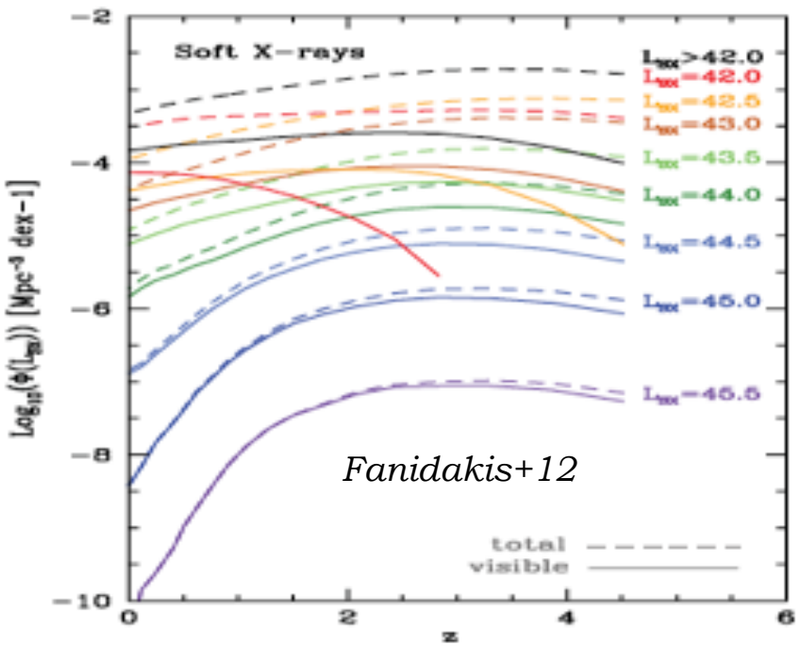
Consensus:

- *Downsizing due the available cold gas*
- *Most luminous AGN are driven by major merger events (see however Fanidakis+12)*
- *Dust obscuration important for less luminous AGN at high z*
- *Further trigger/accretion mechanism is necessary for moderately luminous AGN*

Differences:

- *Physical driving mechanisms for moderately luminous AGN:*
  - *Disk instabilities (Hirschmann+12),*
  - *Hot gas accretion -ADAF model (Fanidakis +12)*
  - *Minor mergers (Neistein+13)*
- *Degeneracy for trigger mechanisms of moderately luminous AGN*



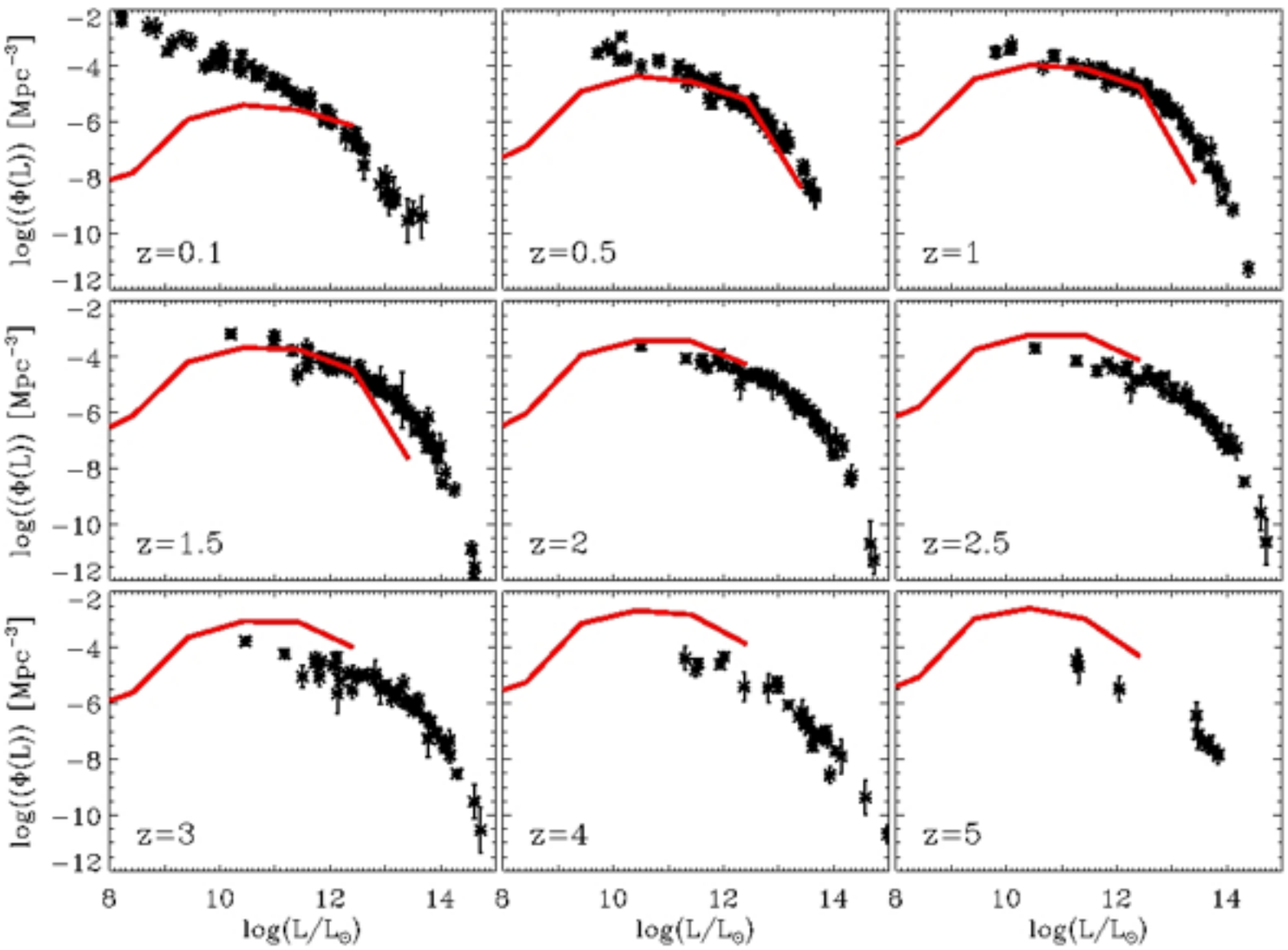


AGN trigger mechanisms

...AGN activity only due to disk instabilities...

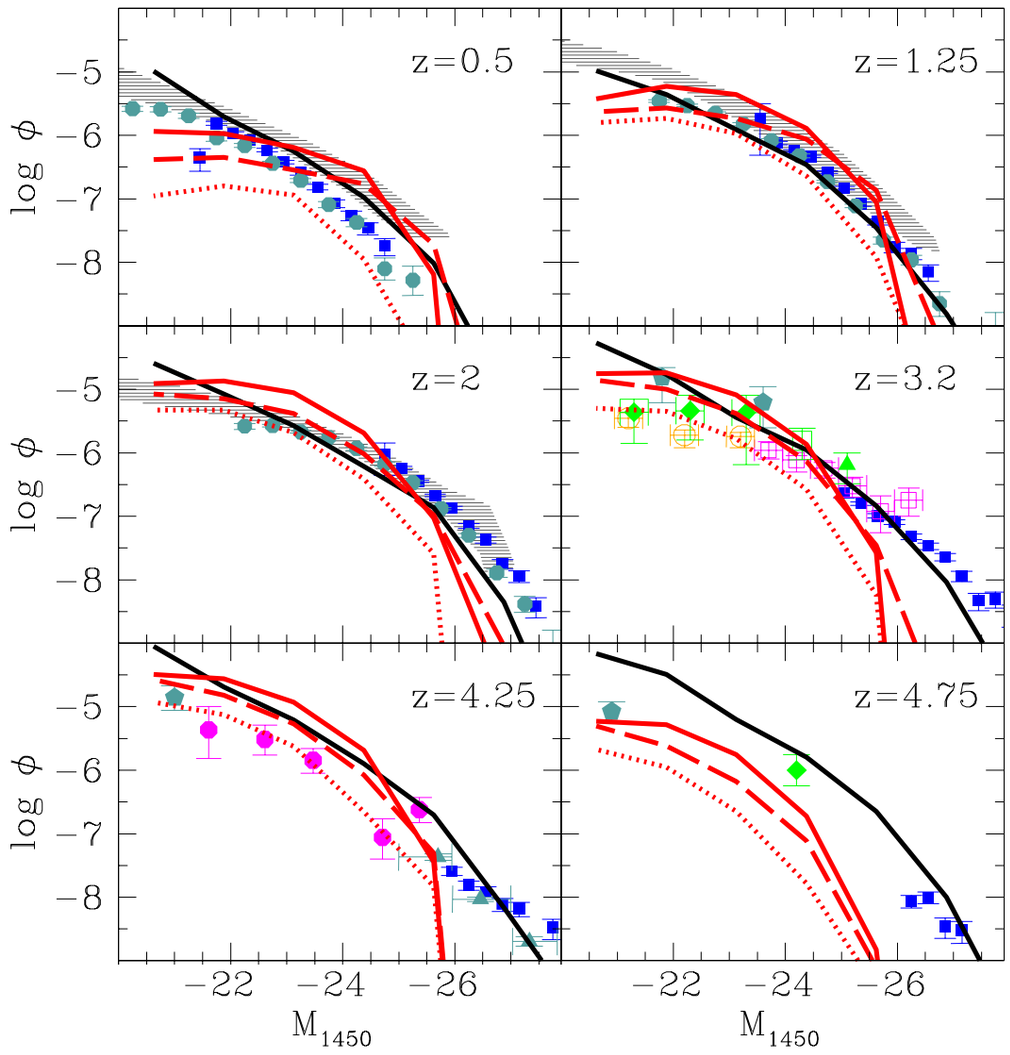
Menci+14, Hirschmann&Somerville in prep.

Full disk destroyed & gas accreted at high Eddington-ratios *Hirschmann&Somerville in prep*



Gas accretion according to simulations in Hopkins+11

Menci+14



DI's cannot trigger enough luminous AGN at z>1.5!

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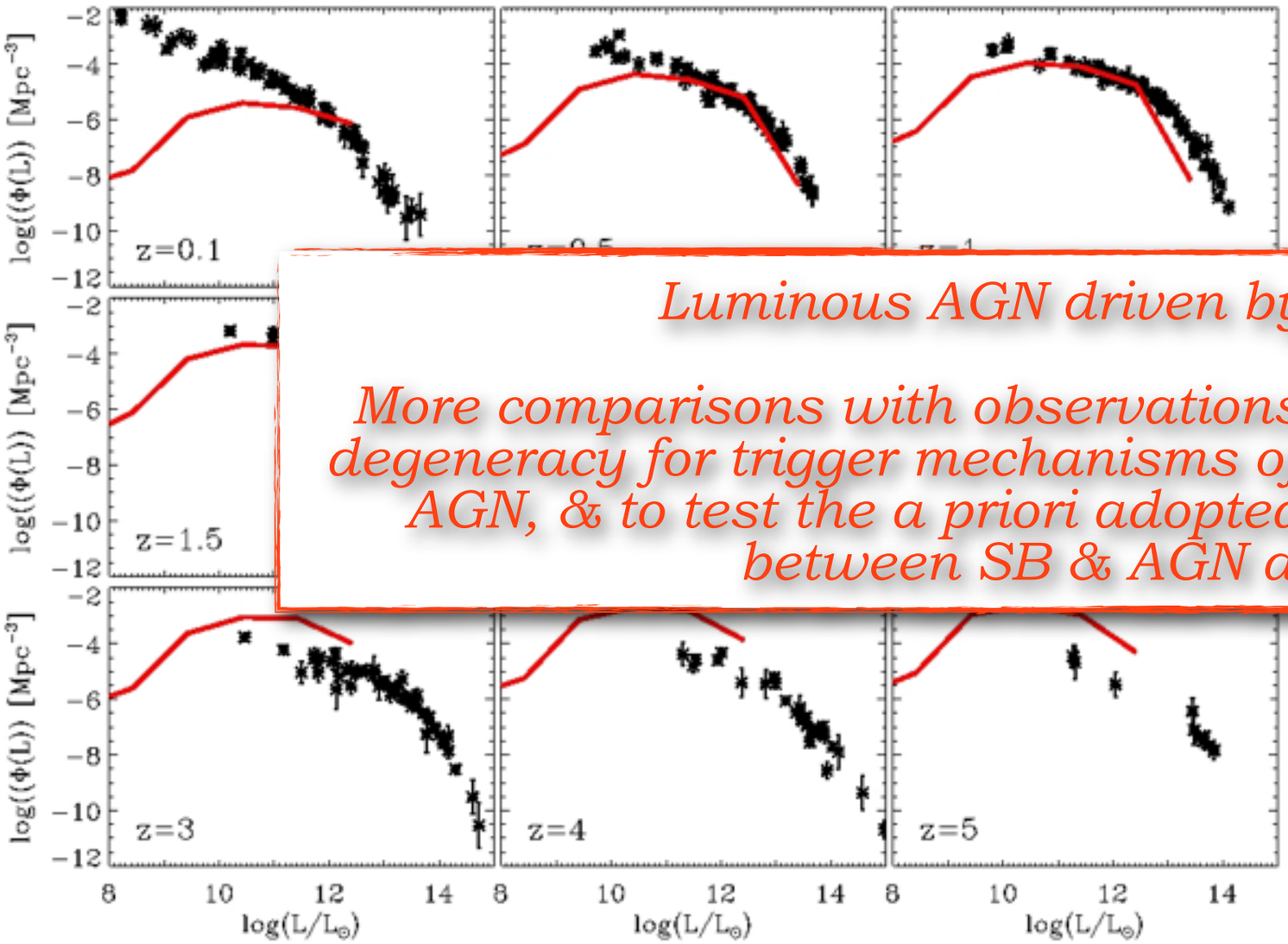

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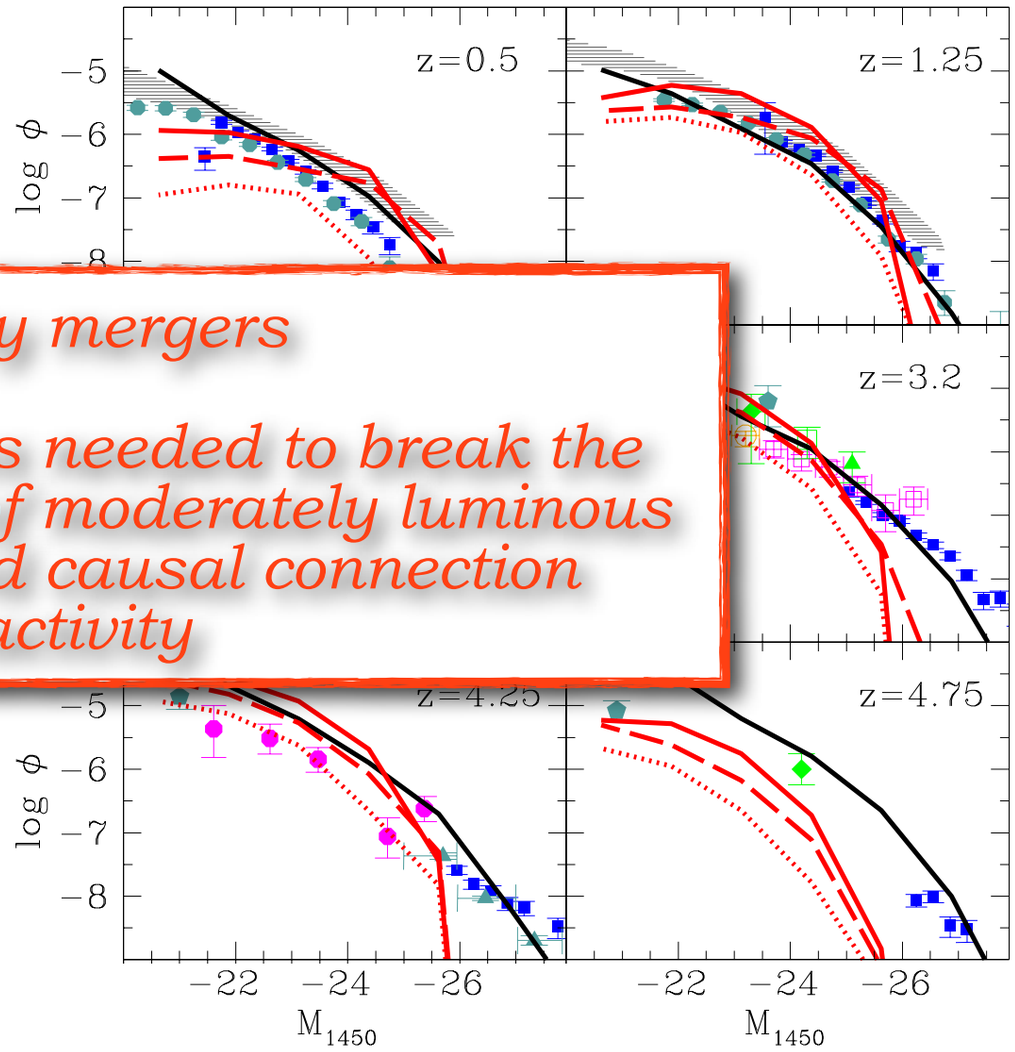


Luminous AGN driven by mergers

More comparisons with observations needed to break the degeneracy for trigger mechanisms of moderately luminous AGN, & to test the a priori adopted causal connection between SB & AGN activity

DI's cannot trigger enough luminous AGN at z>1.5!

II. Cosmological hydrodynamic simulations

1. Basic BH and AGN properties
2. AGN trigger mechanisms
3. Connection between L_{bol} & SFR
4. Effect of AGN feedback

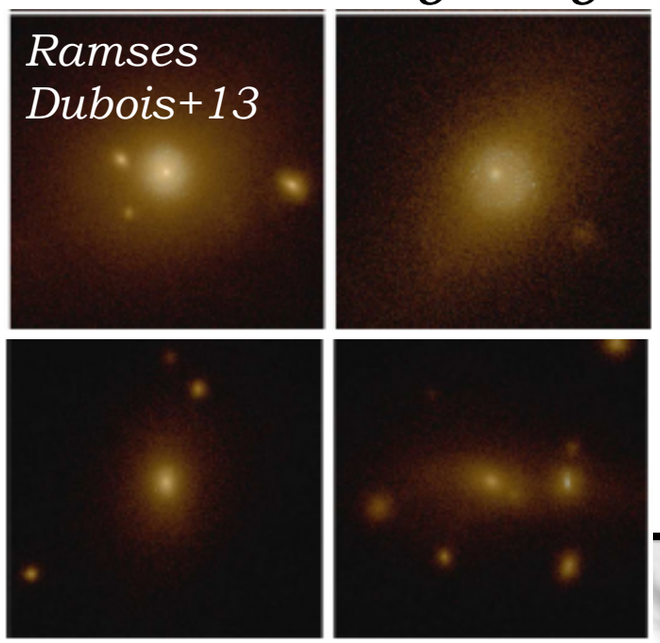
Cosmological simulations

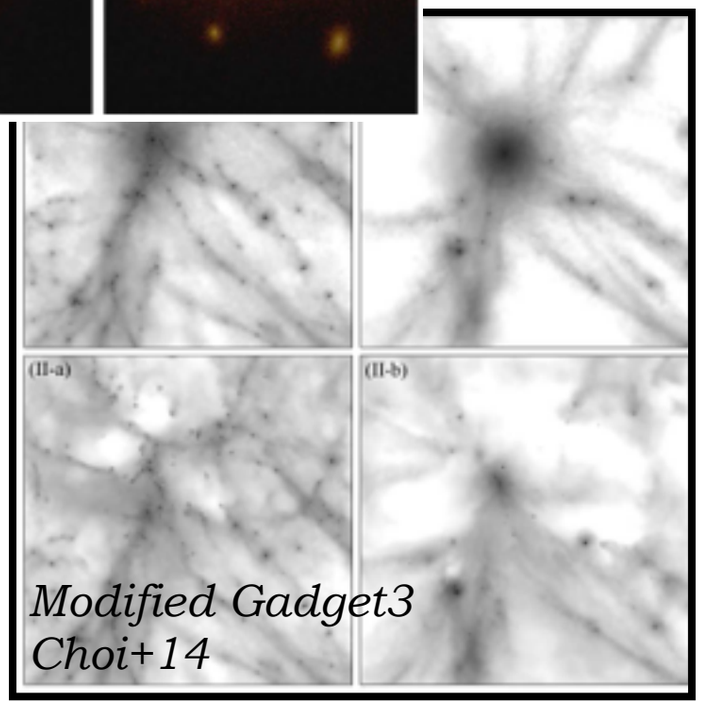
Explicitly solving gas dynamical equations, spatial information accessible

Zoom simulations

(e.g. Dubois+13, Angles-Alcazar+13, Marinacci+13, Choi+14, Cluster zooms: Martizzi+13/14, Planelles+14, Ragone+14)

High spatial & mass resolution possible, excellent information on internal galaxy structure

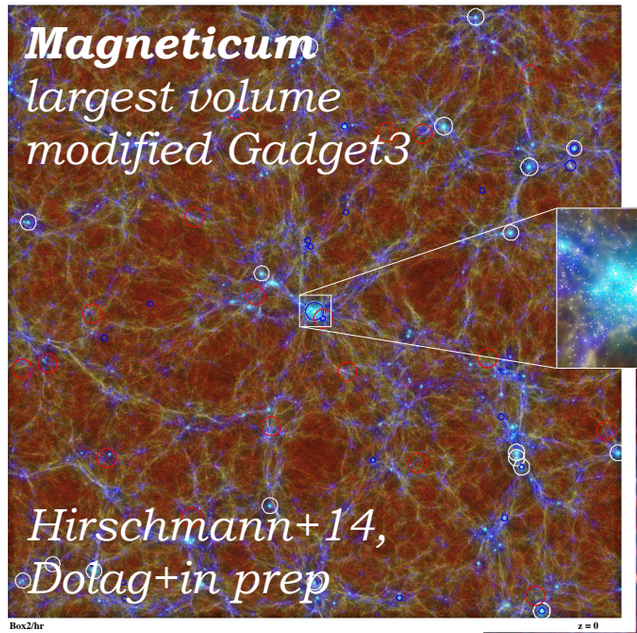


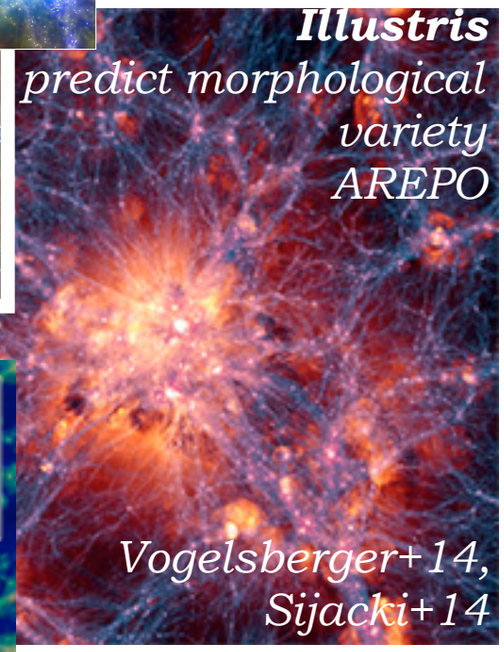


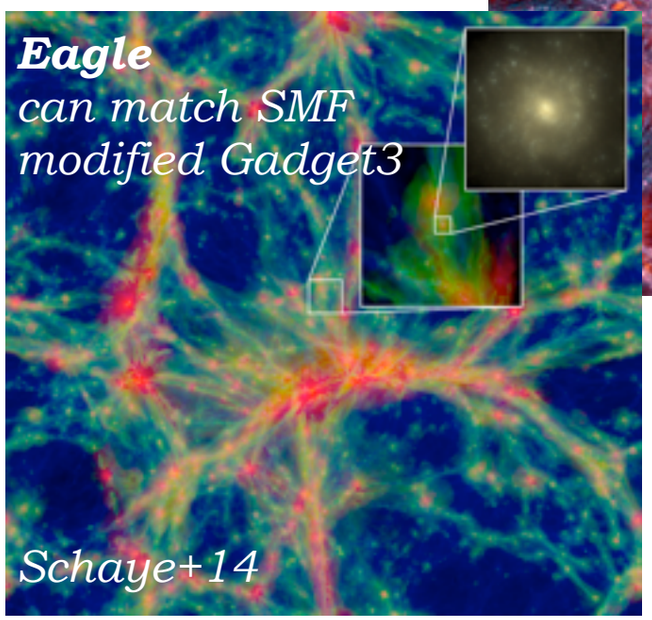
Large simulation boxes

(e.g. DiMatteo+08, DeGraf+10, McCarthy+10/11, Booth&Schaye09/11, Puchwein&Springel+13, Hirschmann +14, Khandai+14,, Sijacki+14, Schaye+14, Dolag+in prep.)

Statistical information accessible







BH model

...in cosmological simulations...

- Mostly (for Gadget/Arepo codes) *variations of Springel+05*
- *BH seeds* in galaxies/halos more massive than a certain limit
- *BH growth*: mergers & stochastic gas accretion following the *Bondi-Hoyle formula* (differences in treating alpha):

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

- *AGN feedback implementation varies*:
  - thermal energy injection

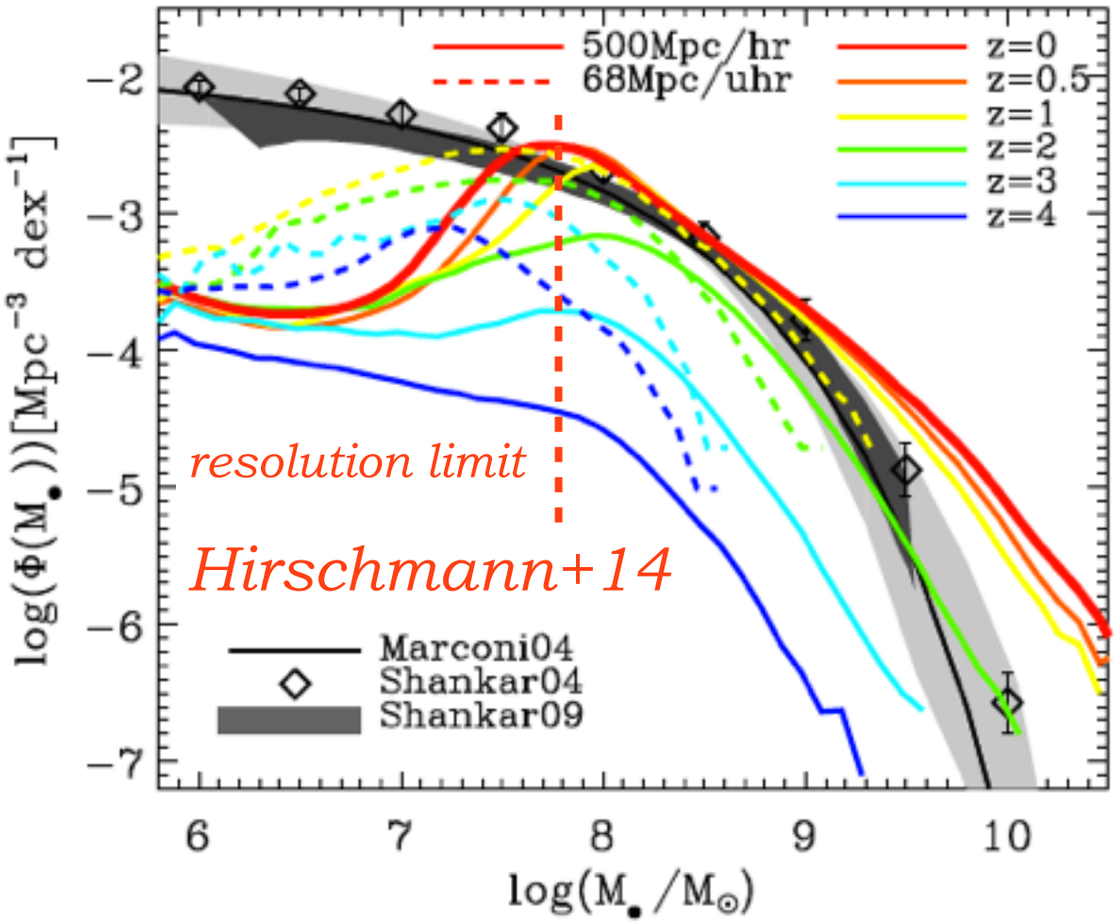
$$\dot{E}_{\rm AGN} = \epsilon_r \ \eta_{\rm ff} \ \dot{M}_\bullet \ c^2$$

  - increased efficiency in radiatively inefficient AGN *(Sijacki+07, Fabian+10, Hirschmann+14, Bachmann+14, Sijacki+14)*
  - AGN-driven winds (mechanical fb) *(Choi +14, Dubois+13, Barai+in prep.)*
- *Differences in many other details (e.g BH pinning, accretion limit etc)*

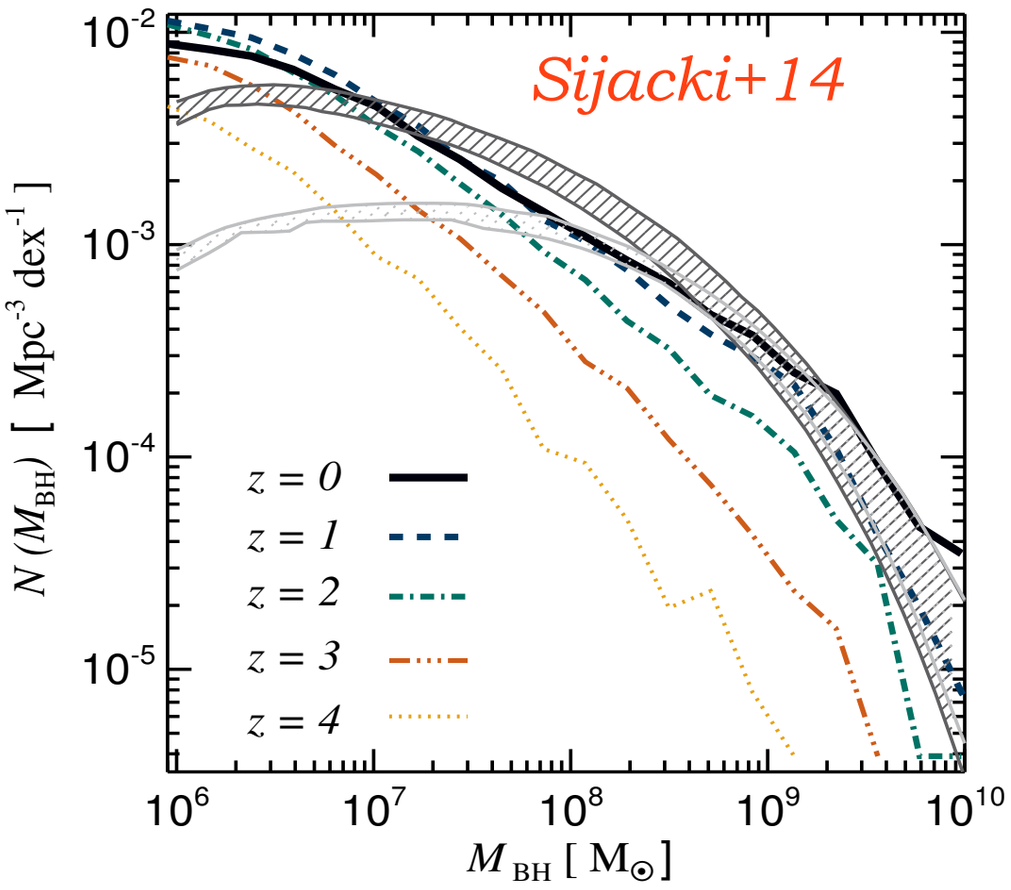
Realistic population of BHs

BH mass function

Magneticum



Illustris



- Strong evolution until **z=1** (no significant BH growth afterwards)
- At **z=0**: massive BHs over-estimated, but...
- see also *Khandai+14*, *DiMatteo+08*

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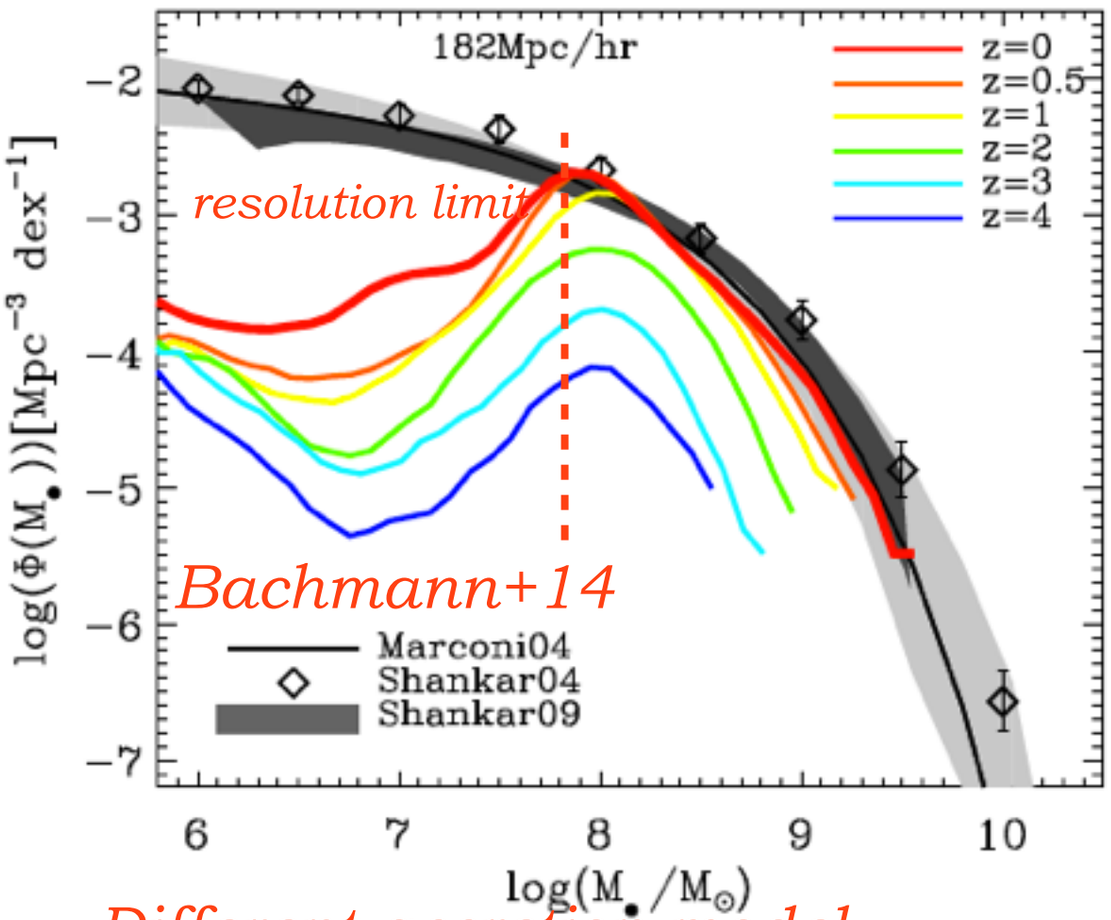

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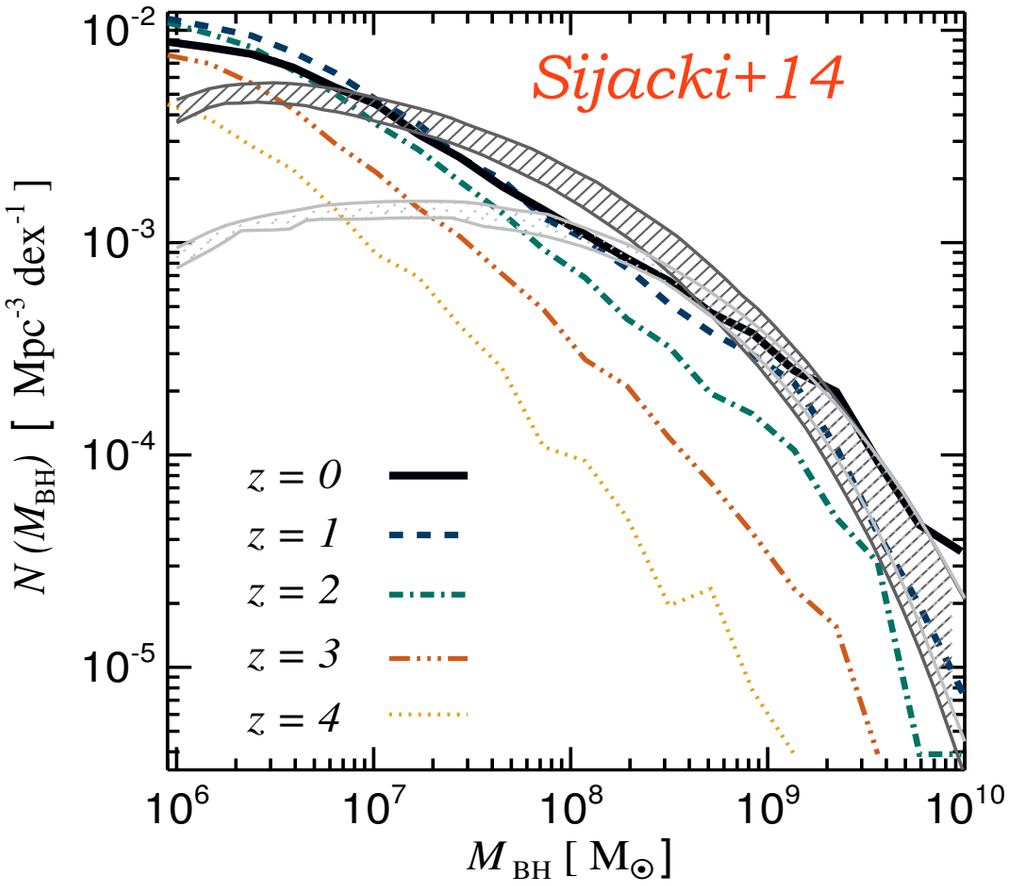

Different accretion model following the results of Gaspari+13

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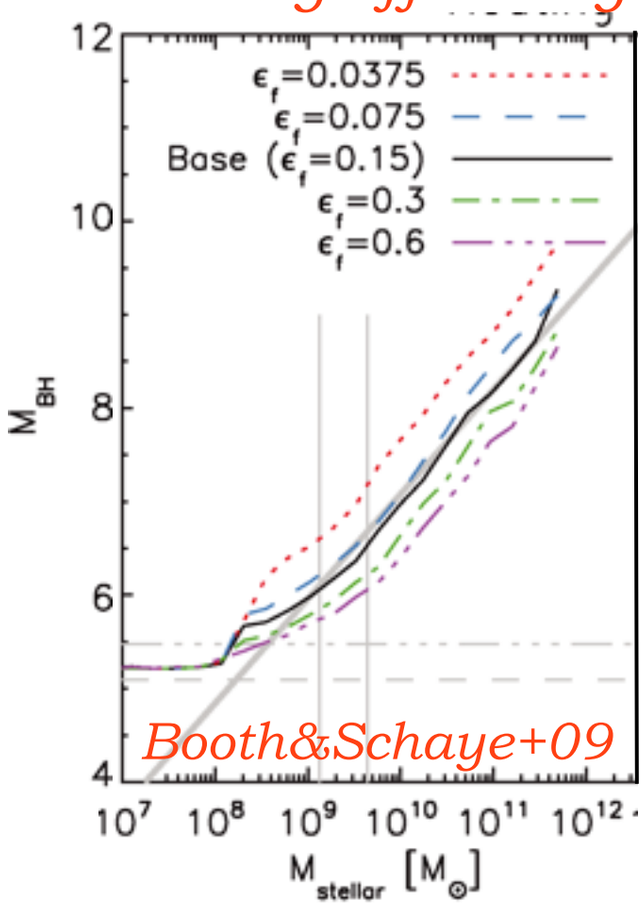
Realistic population of BHs

Evolution of the BH-stellar mass relation

heating efficiency



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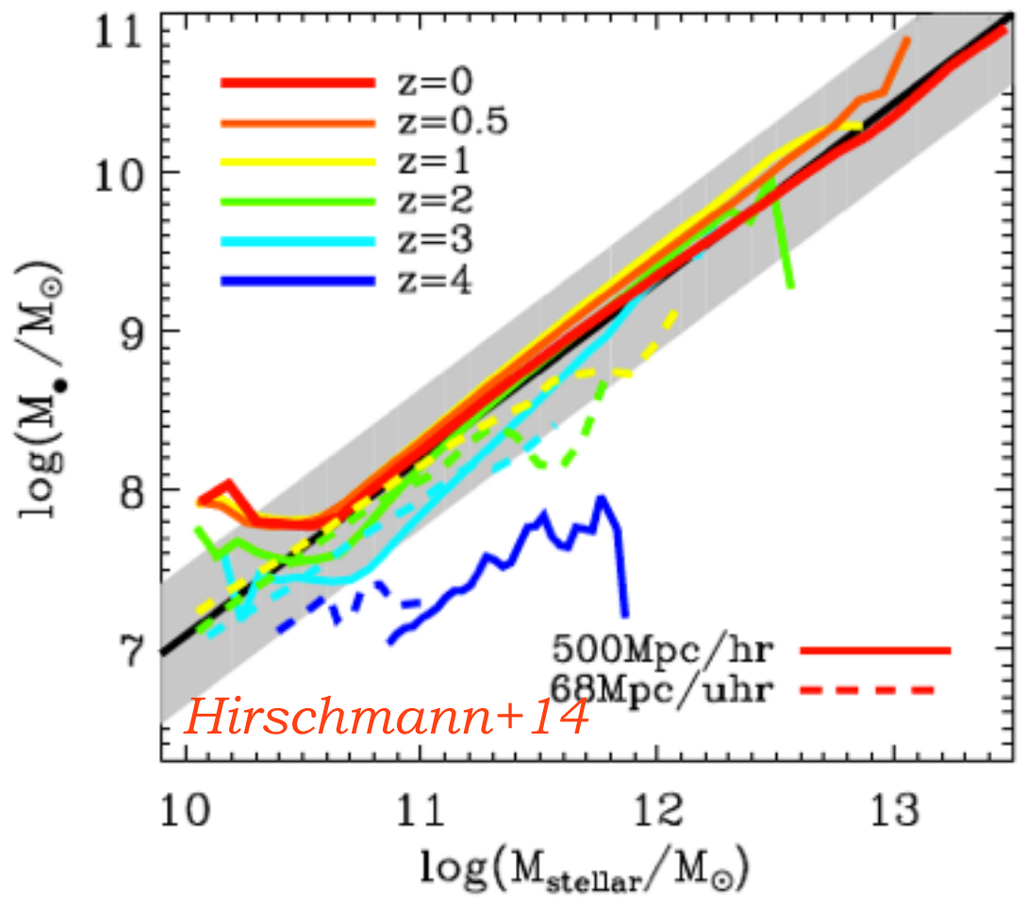
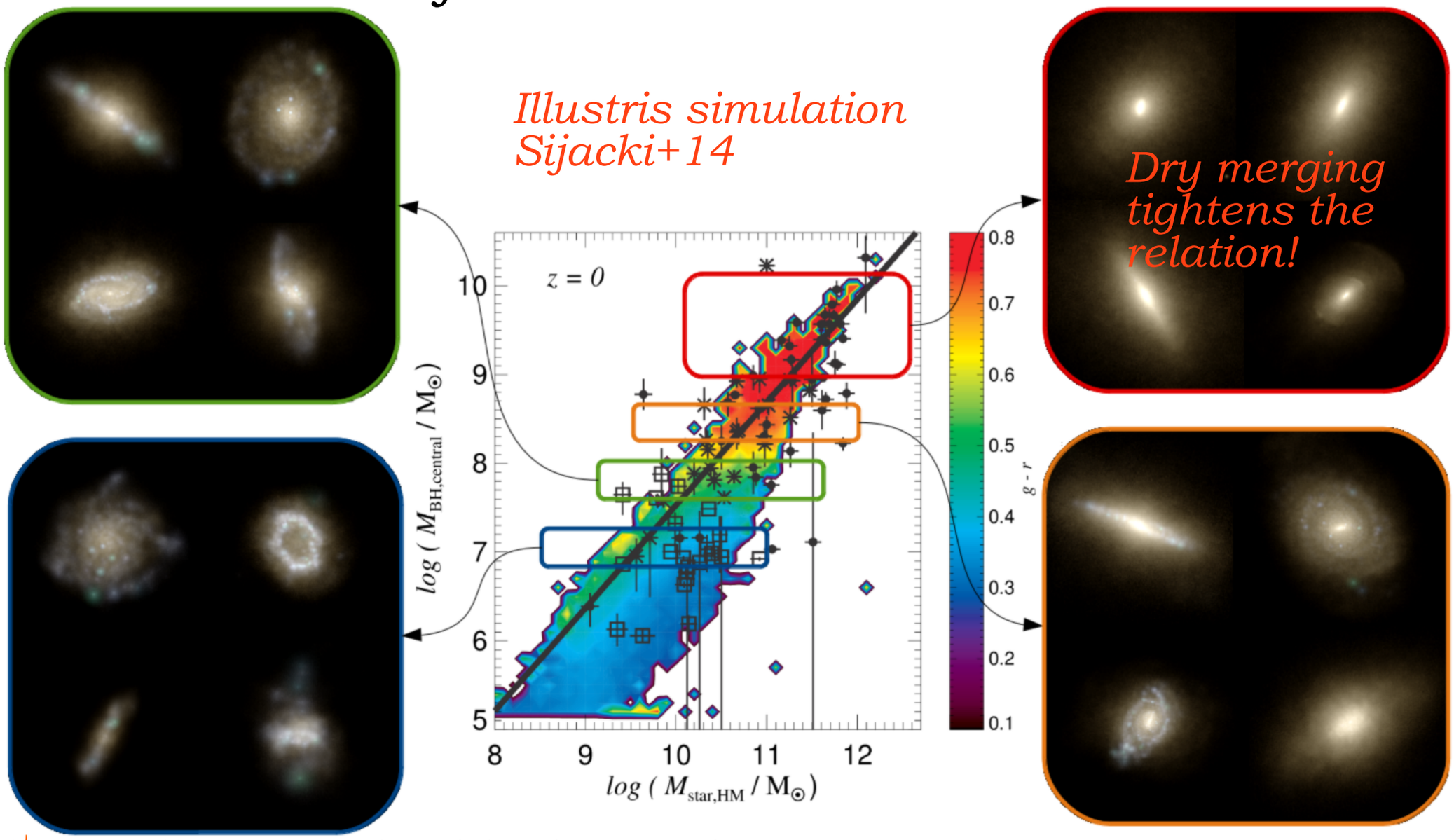


- Excellent match with observations (slope originates from self-regulated BH growth due to feedback, and normalisation due the choice of fb eff)
- BH-stellar mass relation in place at **high z**

Realistic population of BHs

Evolution of the BH-stellar mass relation



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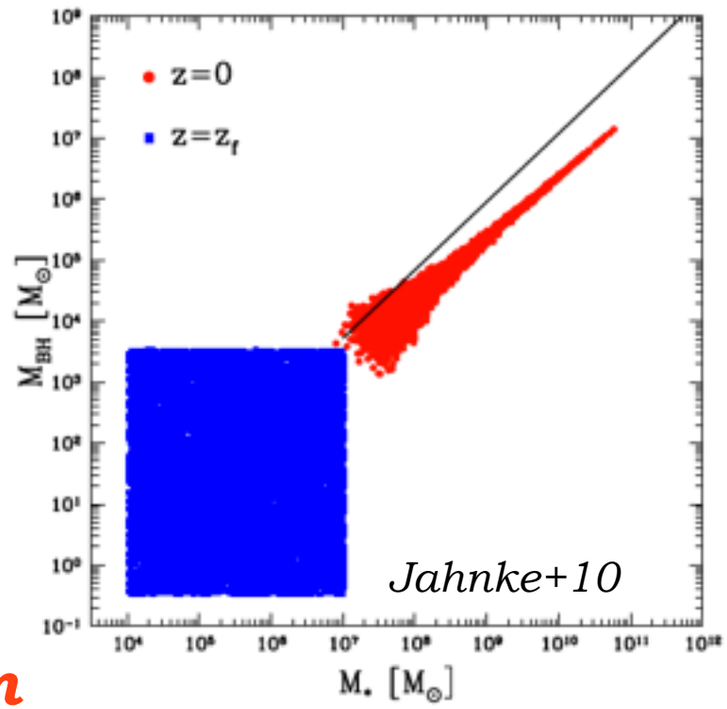
Non-causal origin of BH scaling relations?

Subsequent merging *(random or cosmological) of initially uncorrelated galaxies and black holes (no growth by gas accretion)...*

✴*...automatically produces a correlation between bulges & BHs* *(Peng+07, Hirschmann+10, Jahnke+10)*

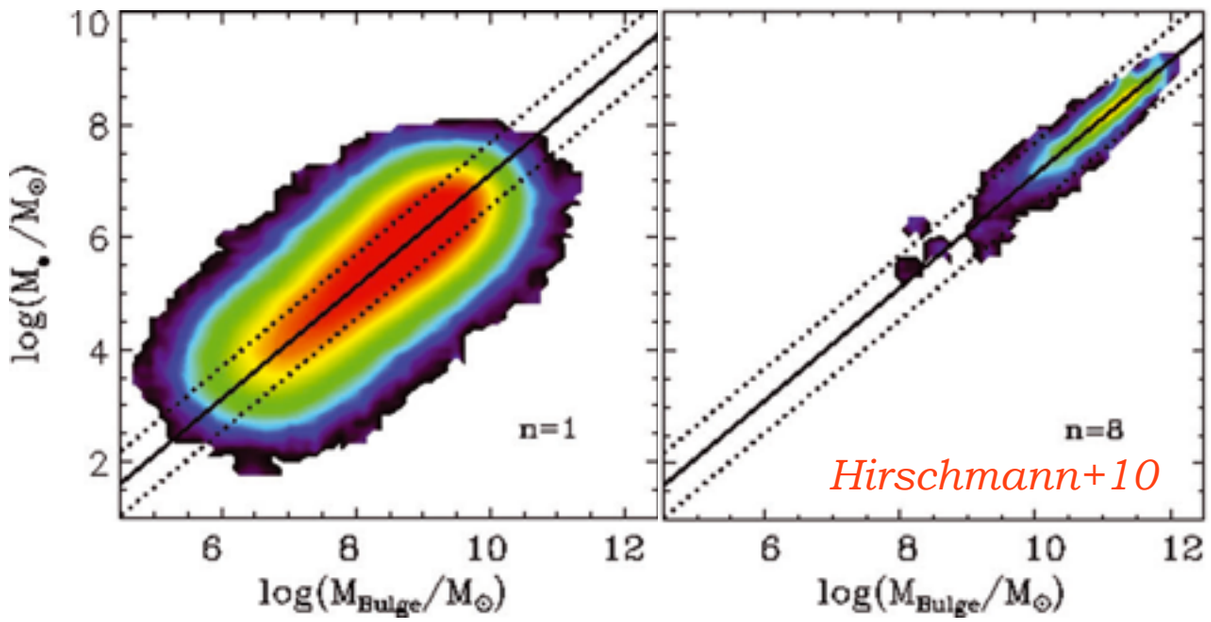
✴*...reduces the scatter with decreasing redshift & increasing BH mass* *(Hirschmann+10)*



...thanks to the Central-Limit-Theorem

Reasonable scenario for dry minor mergers of massive galaxies & BHs at low redshift

At higher redshift or for less massive objects, gas accretion dominates BH growth



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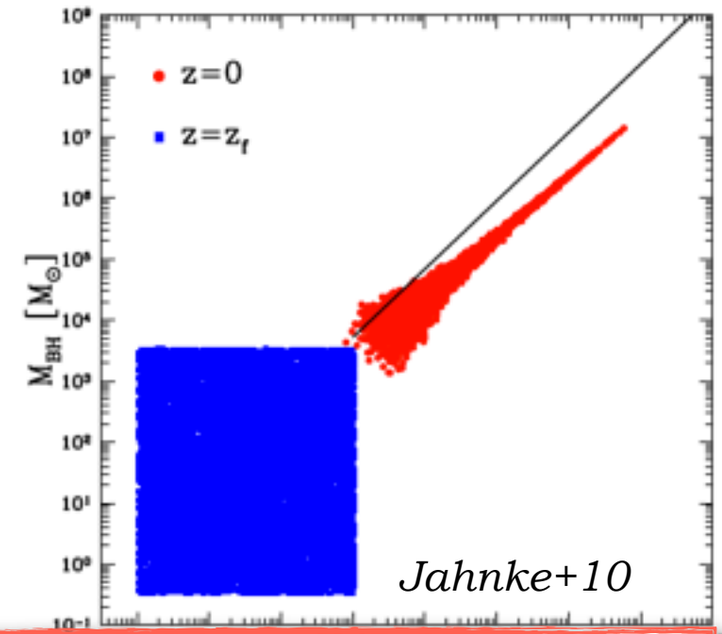
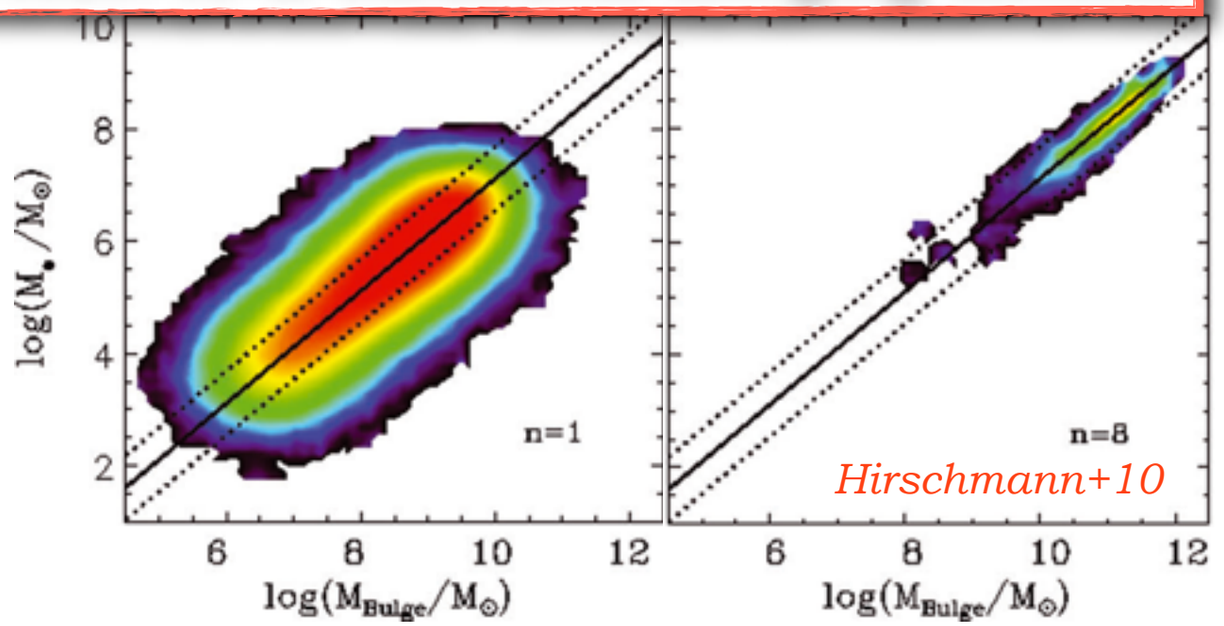


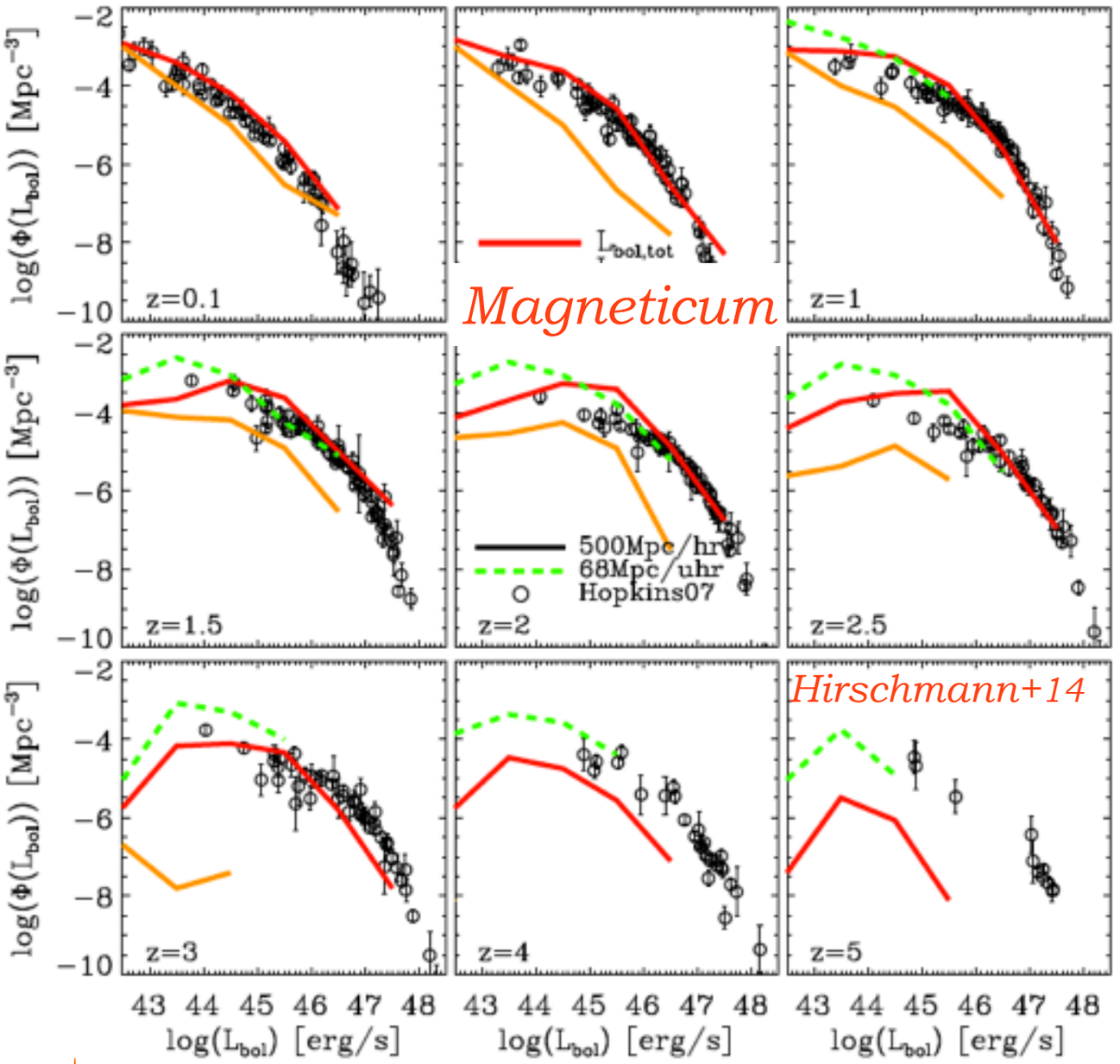
- Relative importance of AGN fb & statistical merging unclear

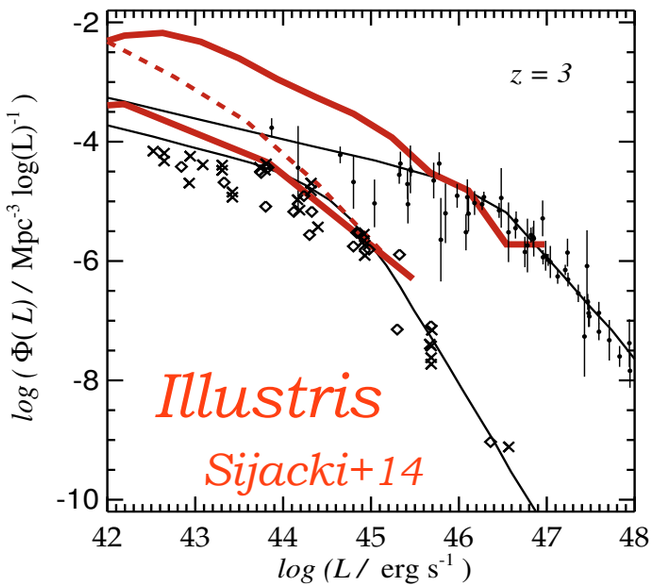
Reasonable scenario for dry minor mergers of massive galaxies & BHs at low redshift

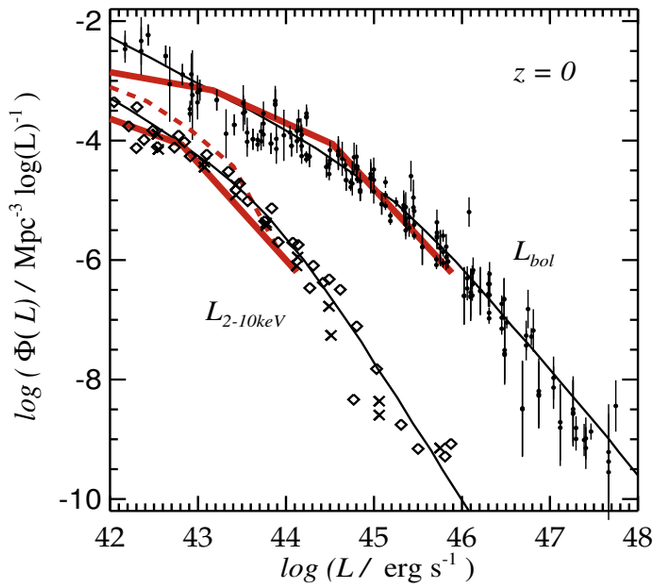
At higher redshift or for less massive objects, gas accretion dominates BH growth



AGN luminosity function

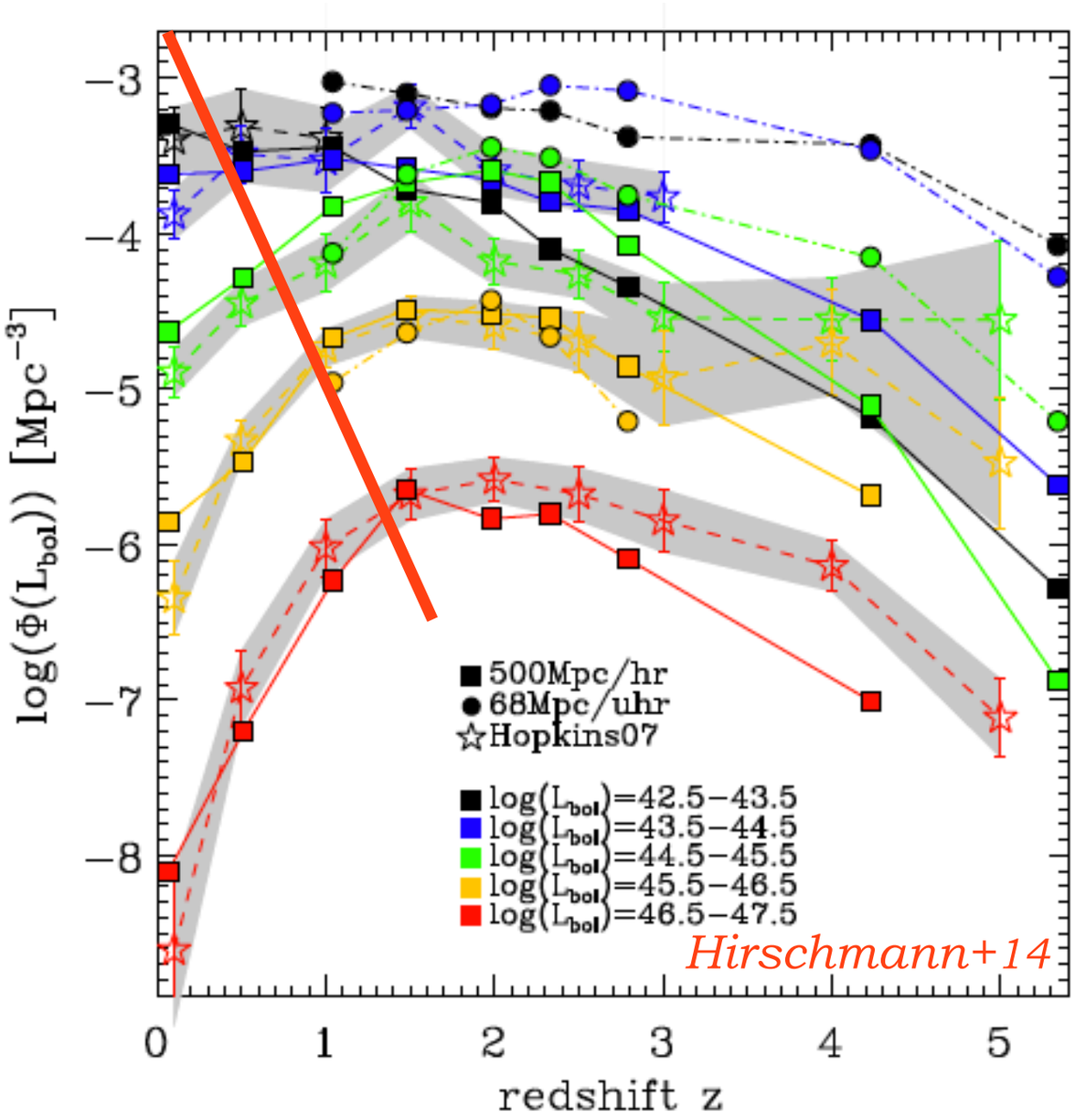






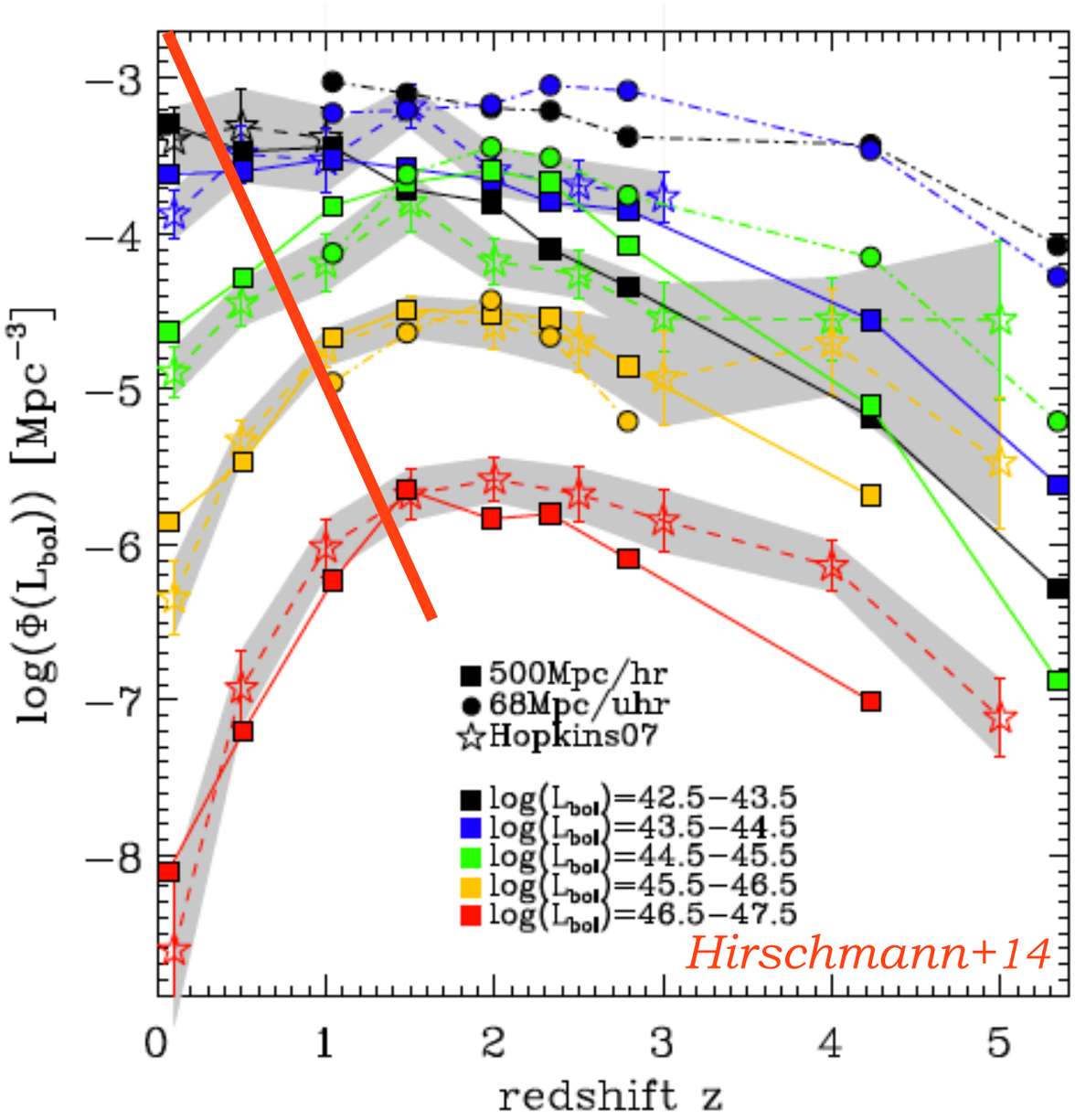
- *Magneticum has currently the best statistics for assessing the high luminous end*
- *500Mpc/hr: Too few AGN at z>3*
- *68Mpc/uhr: convergence for AGN more luminous than 10^{44} erg/s*
- *See also Khandai+14, DeGraf+10*

Anti-hierarchical trend



- *Simulations can self-consistently capture the downsizing trend!*
  (DeGraf+10, Khandai+14, Sijacki+14)
- *The simplified schemes of BH accretion are able to capture the essence of BH growth in reality*
- *Moderately luminous AGN at low z have large contribution from massive BHs accreting way below their peak luminosities -- WHY?*

Anti-hierarchical trend



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- *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 & AGN fb

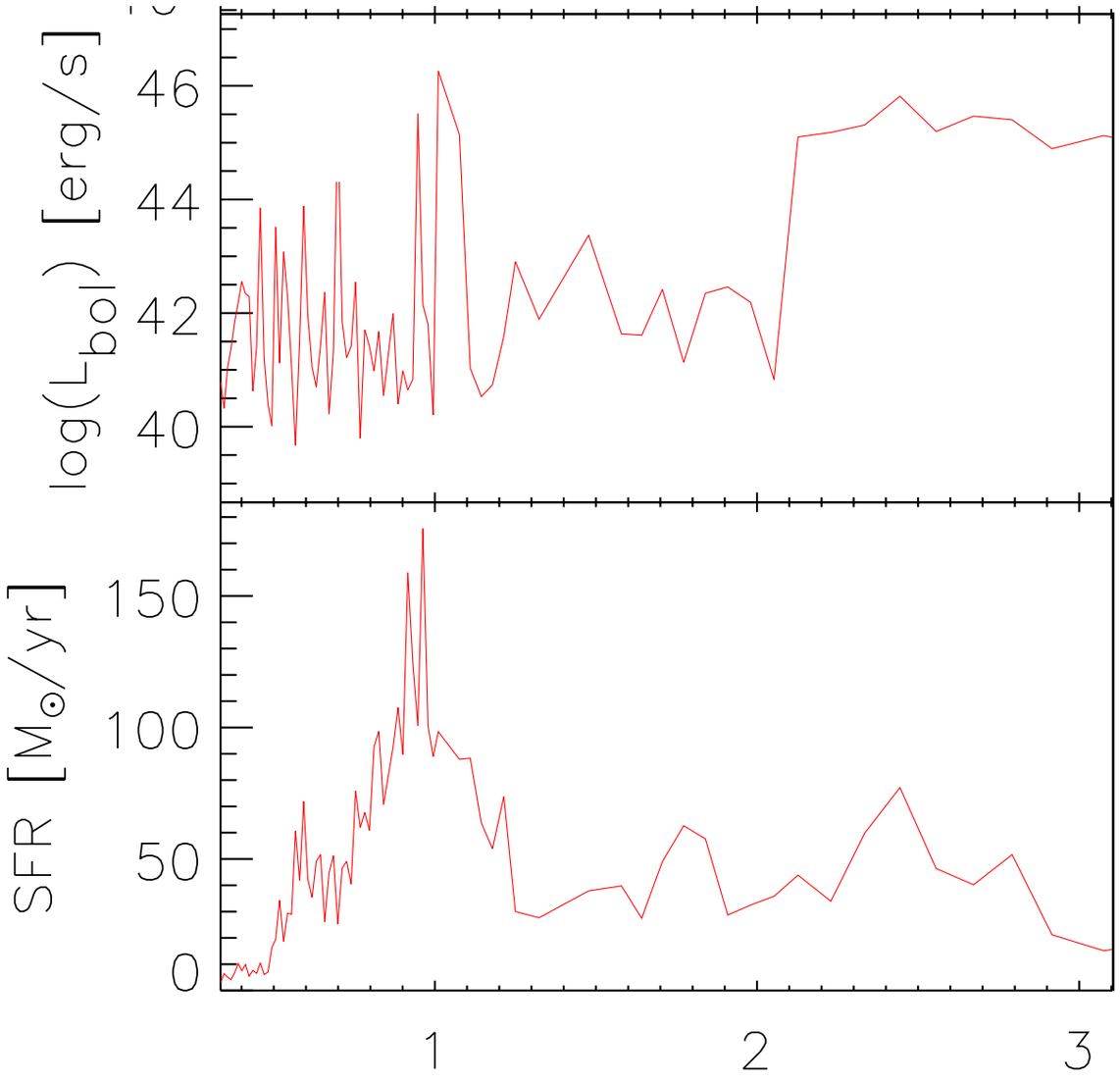
AGN trigger mechanisms

Light curves of individual AGN (higher res. run)

done by L. Bachmann

preliminary

1e9 $M_\odot$- black hole



Fully statistical analysis in progress!

AGN trigger mechanisms

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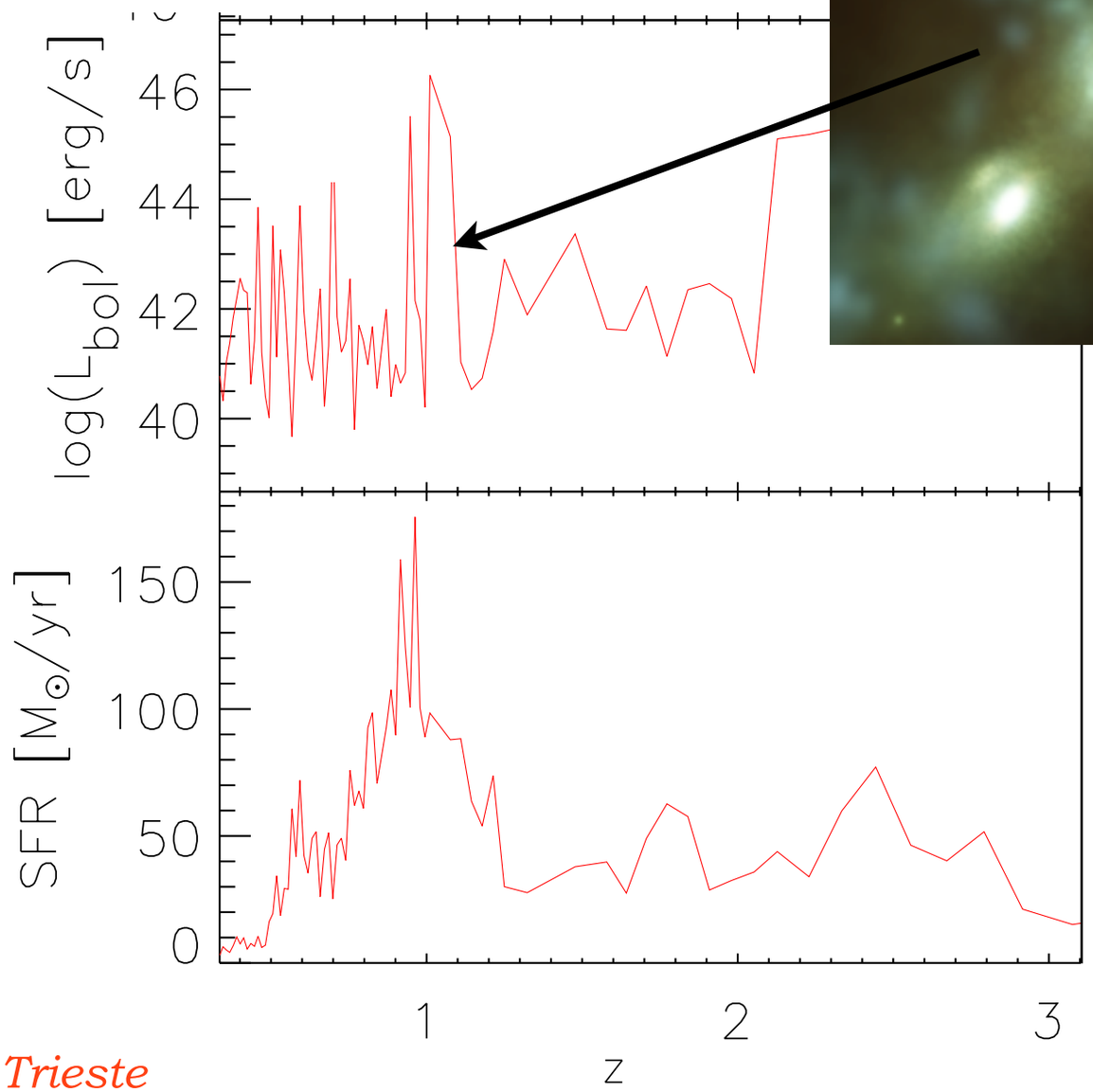

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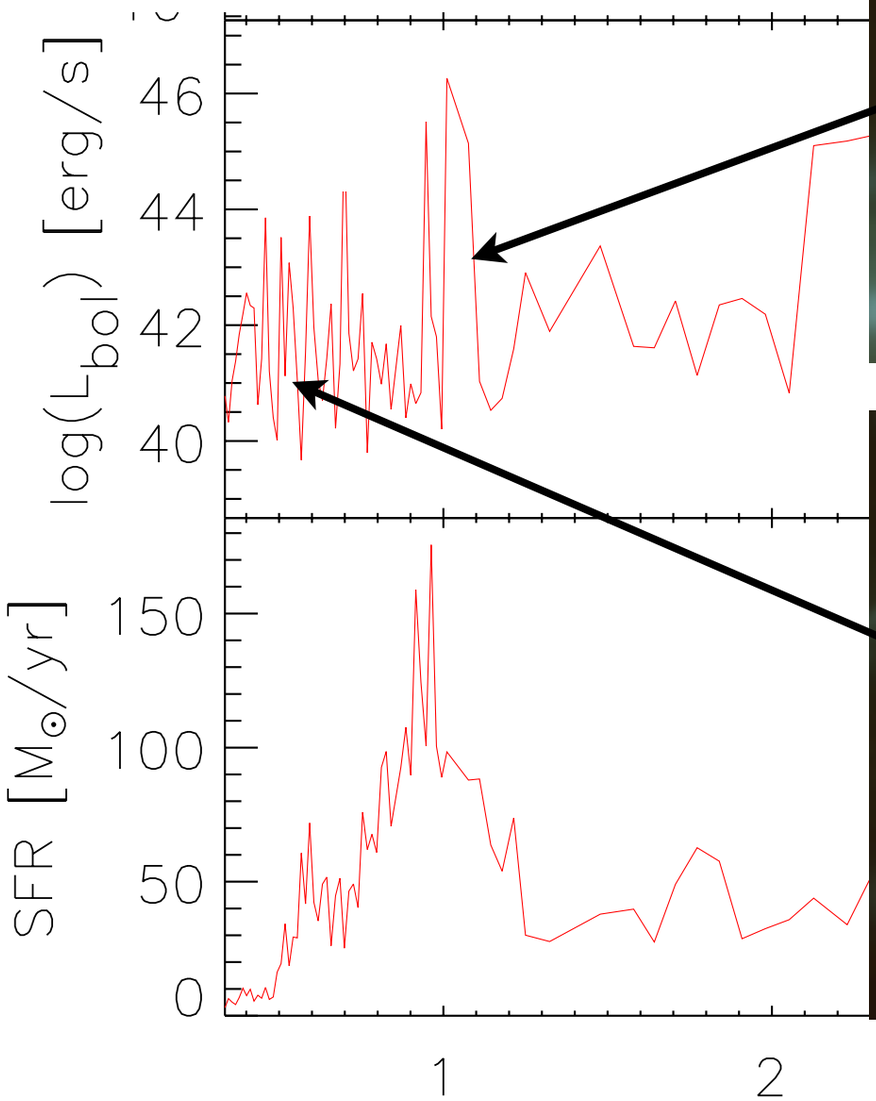

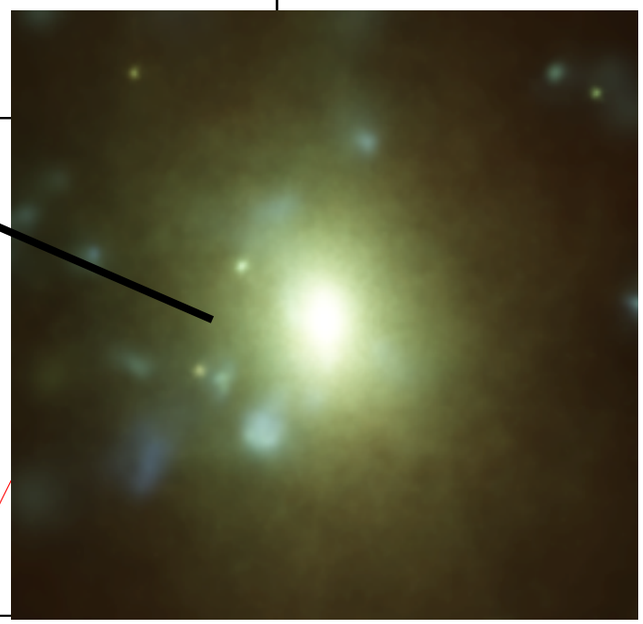

✶*Less luminous AGN not necessarily triggered by mergers*

Fully statistical analysis in progress!

AGN trigger mechanisms

Light curves of individual AGN (higher res. run)

done by L. Bachmann

preliminary

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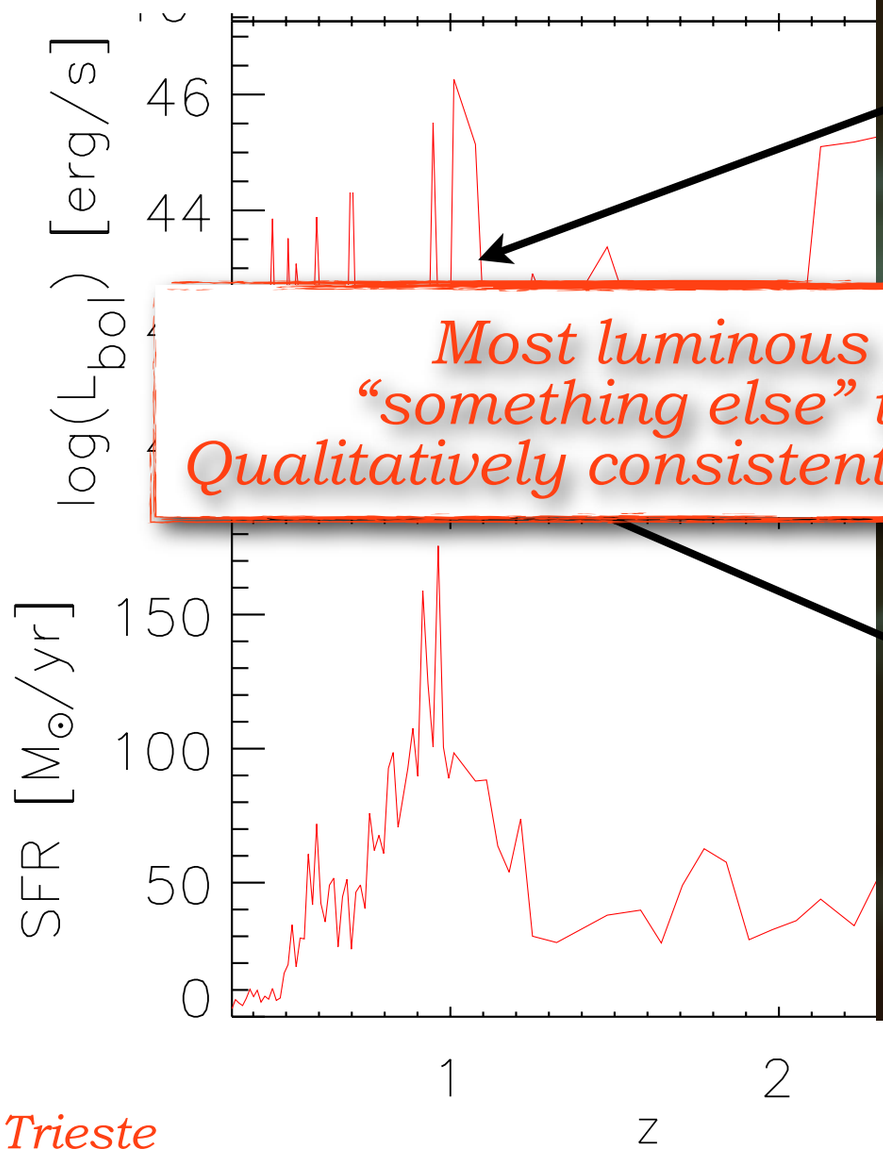
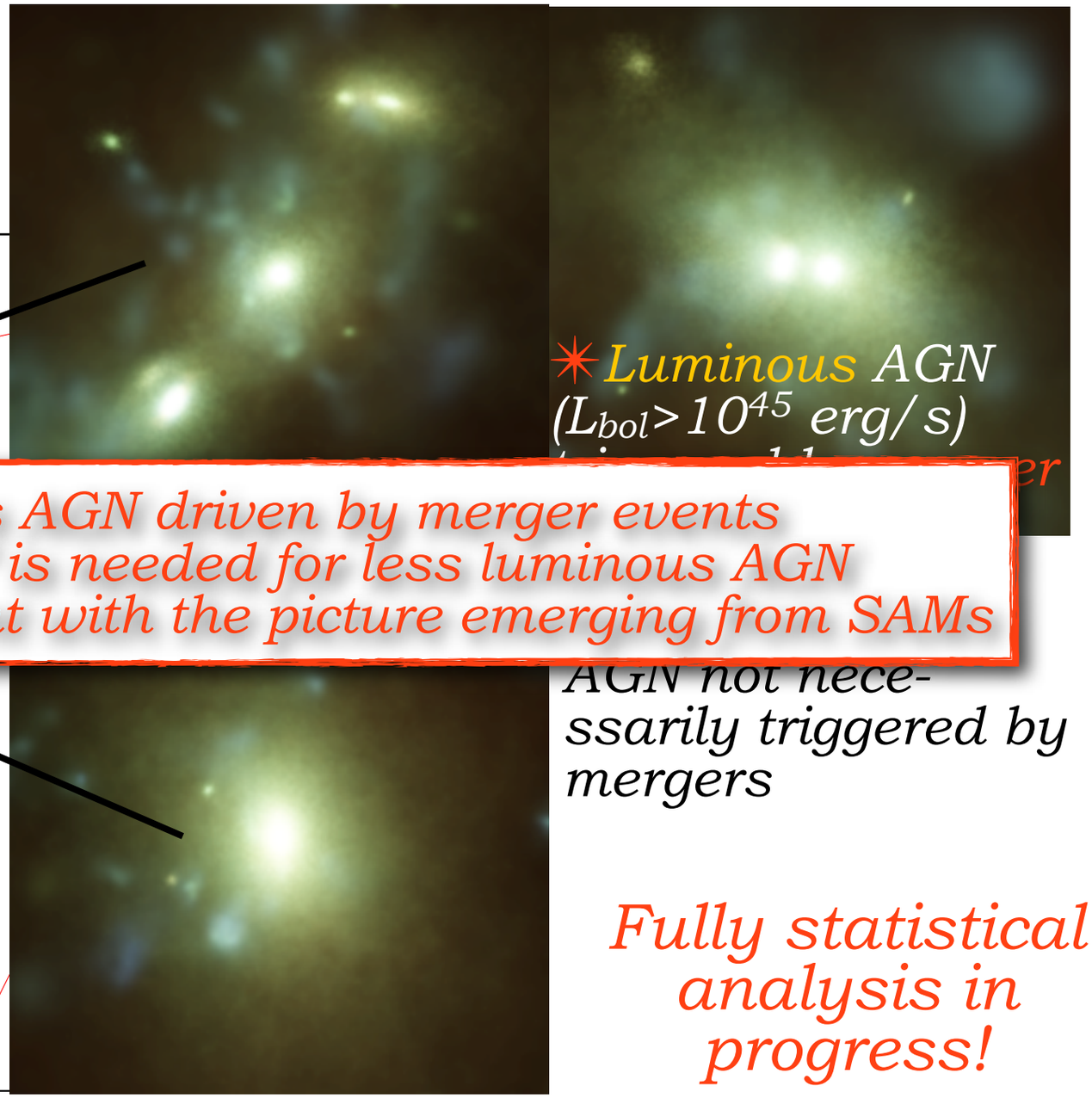




✳*Luminous AGN ($L_{bol}>10^{45}$ erg/s)*

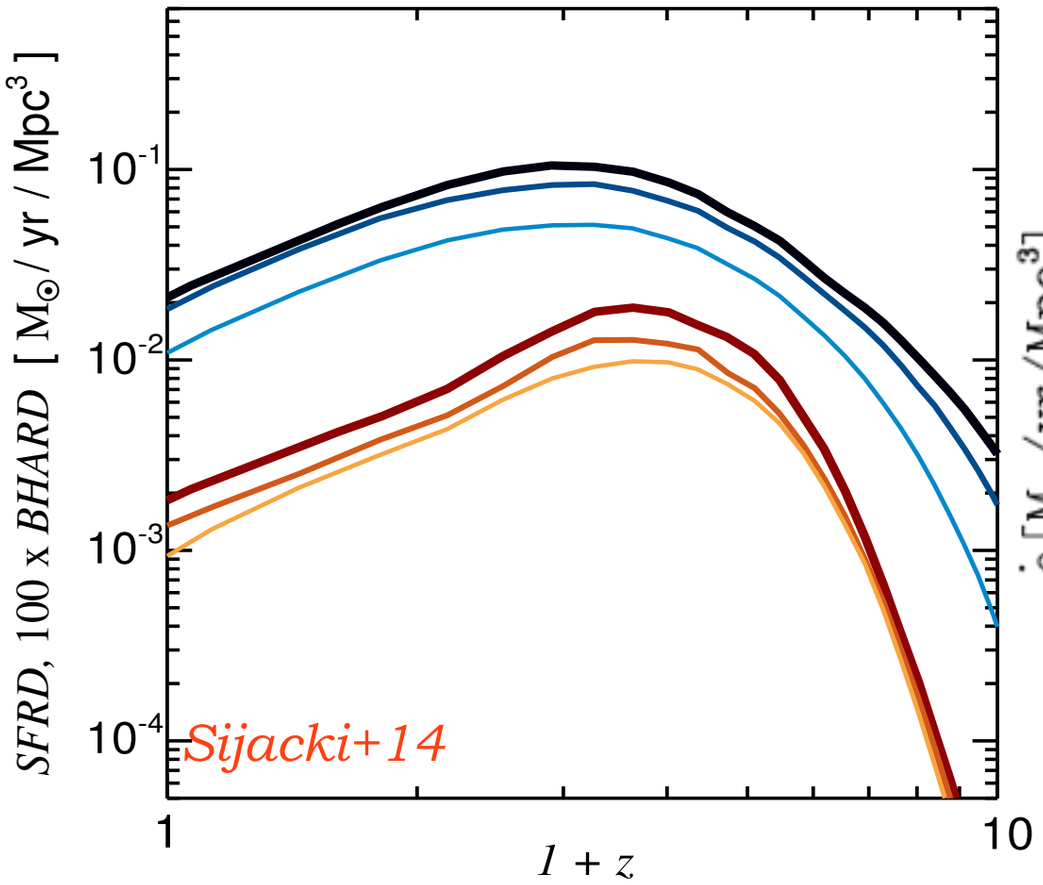
AGN not necessarily triggered by mergers

Most luminous AGN driven by merger events
"something else" is needed for less luminous AGN
Qualitatively consistent with the picture emerging from SAMs

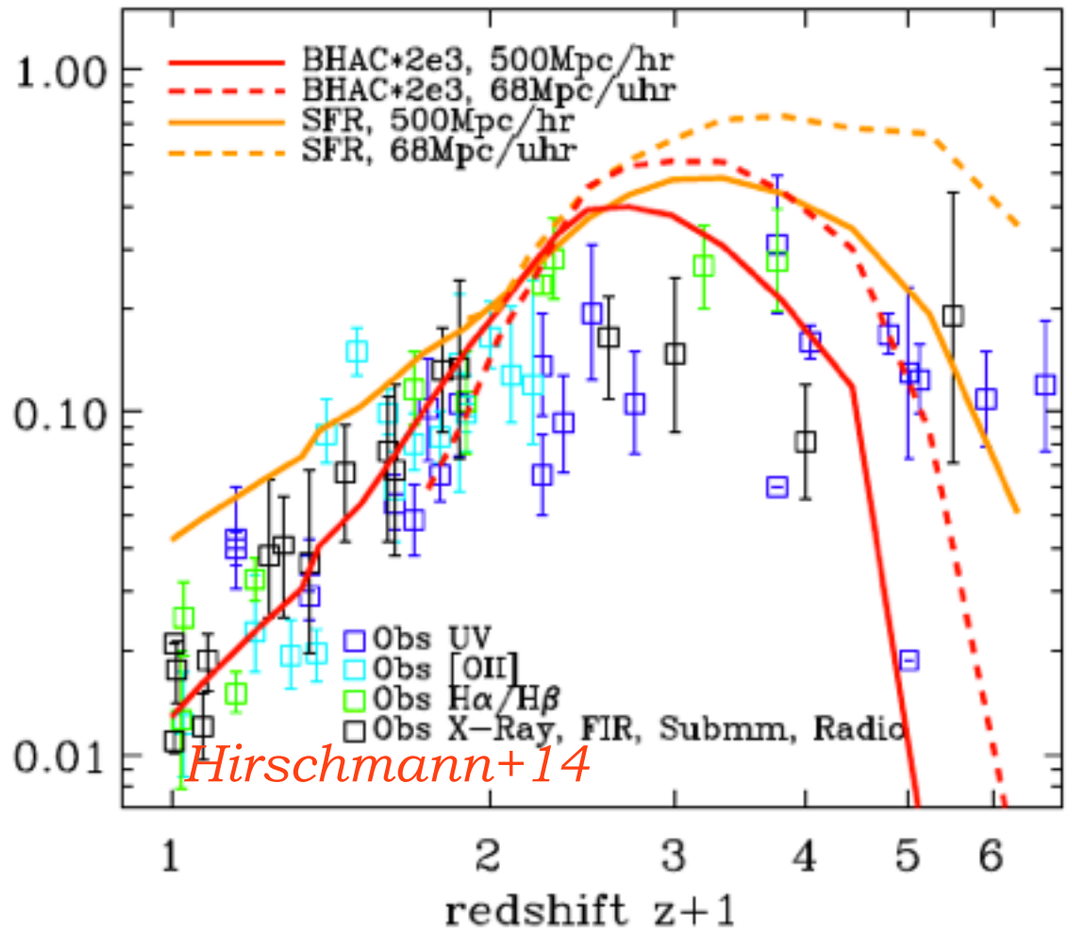
Fully statistical analysis in progress!

Global connection between SFR & BHAR

Illustris



Magneticum

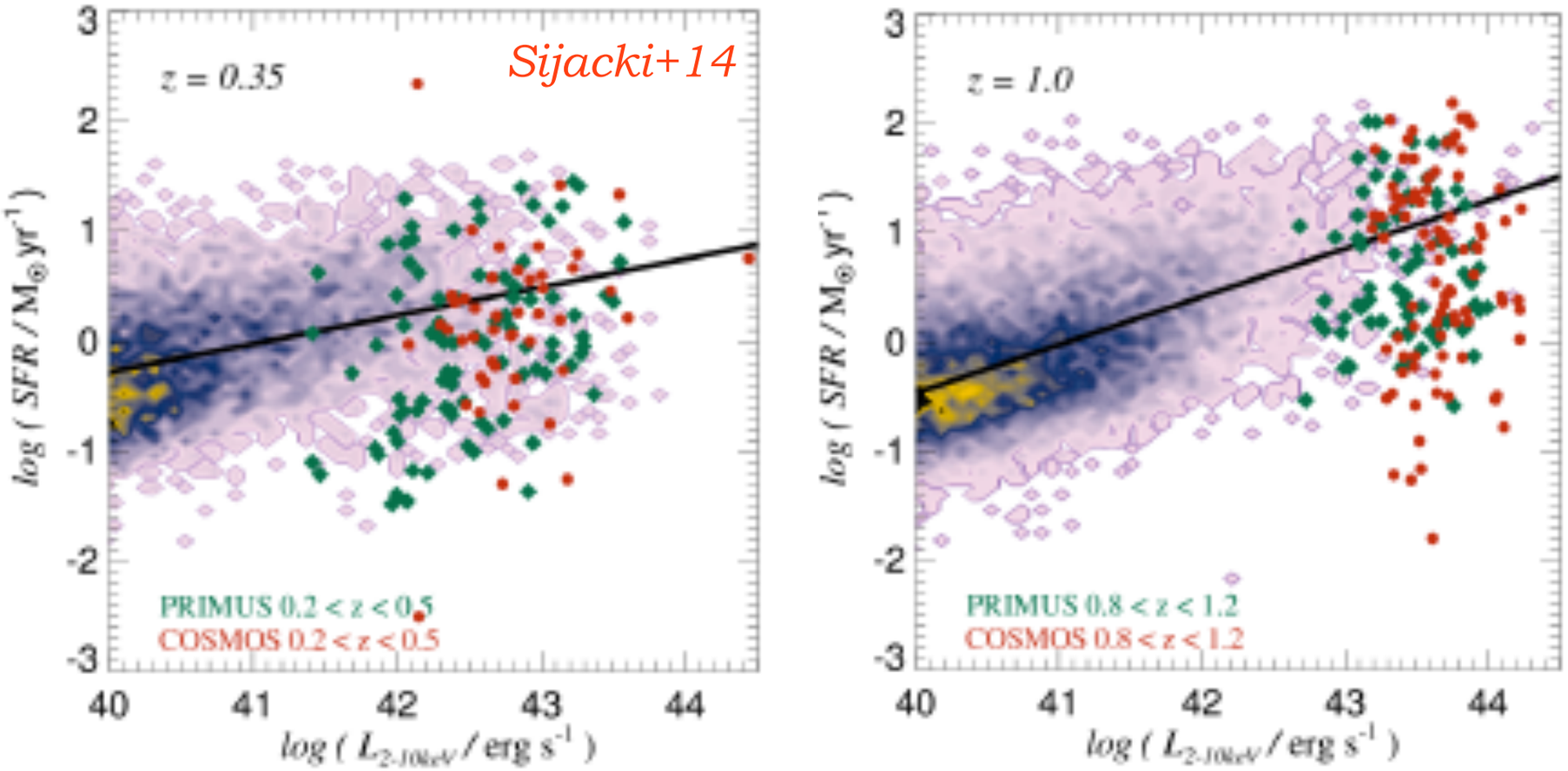


- Consistent with observations: global SFR and BH accretion rate densities peak at z~1-2 and decline at lower and higher z
- But is there a correlation between SFR and L_{bol} at a given redshift?

AGN luminosity vs. SFR

Observational situation unclear and partly contradictory:

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



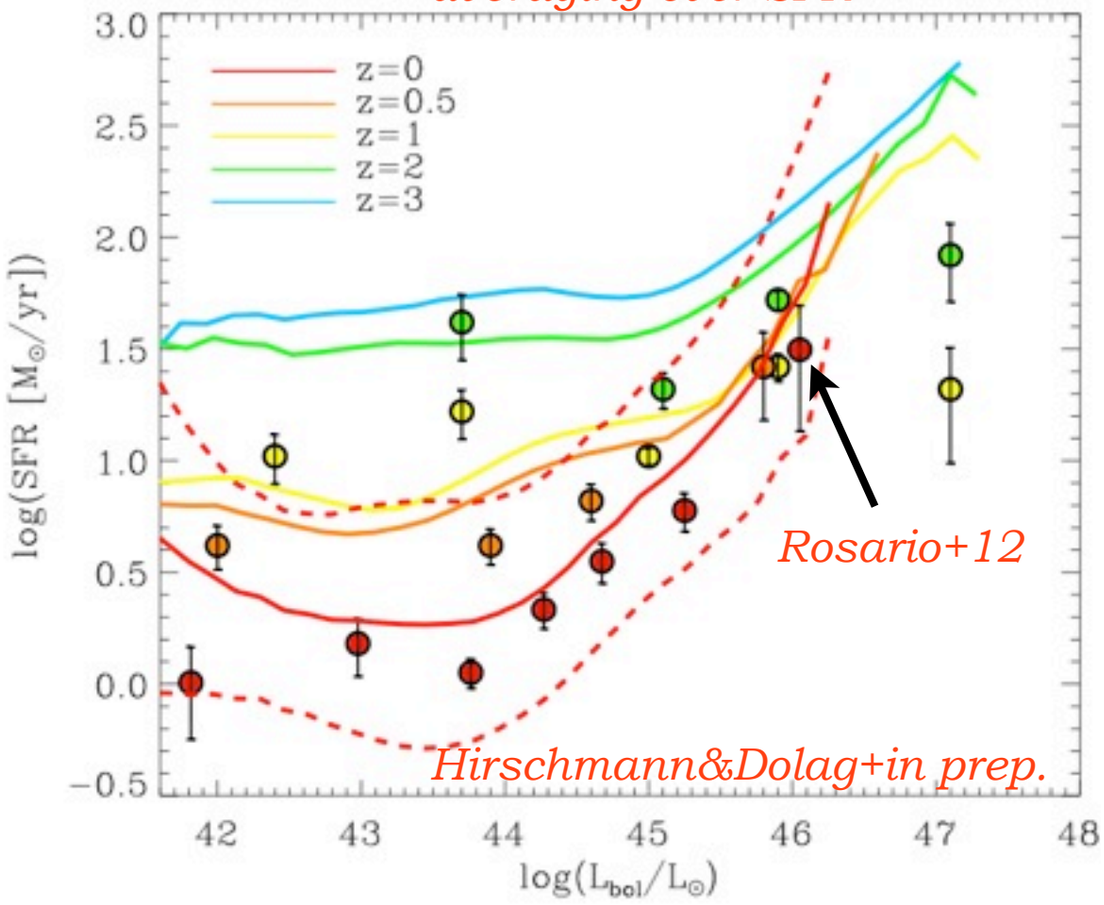
- Weak correlation, but large scatter at a given AGN luminosity
- Complex connection on an individual object basis
- L_{bol} more highly variable quantity?

AGN luminosity vs. SFR

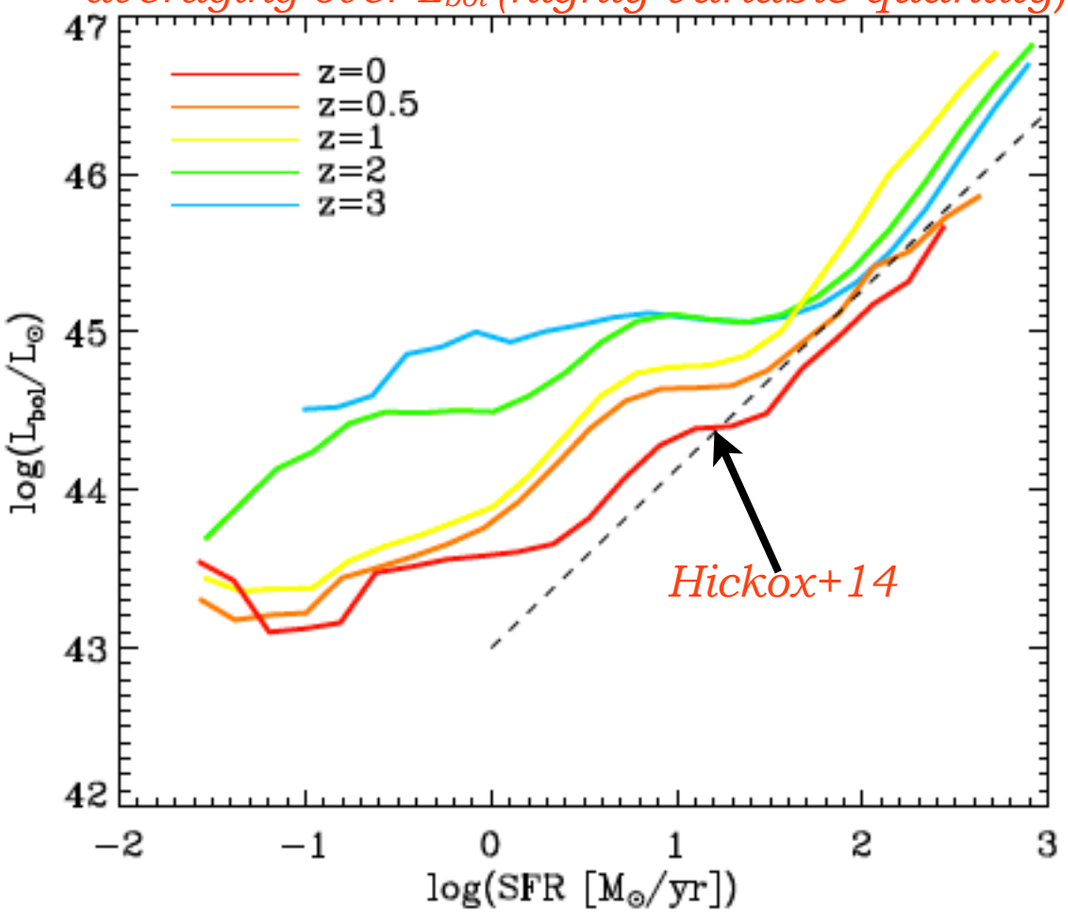
Observational situation unclear and partly contradictory:

- Correlation: *e.g. Netzer+09, Hickox+14*
- 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 moderately luminous AGN

AGN luminosity vs. SFR

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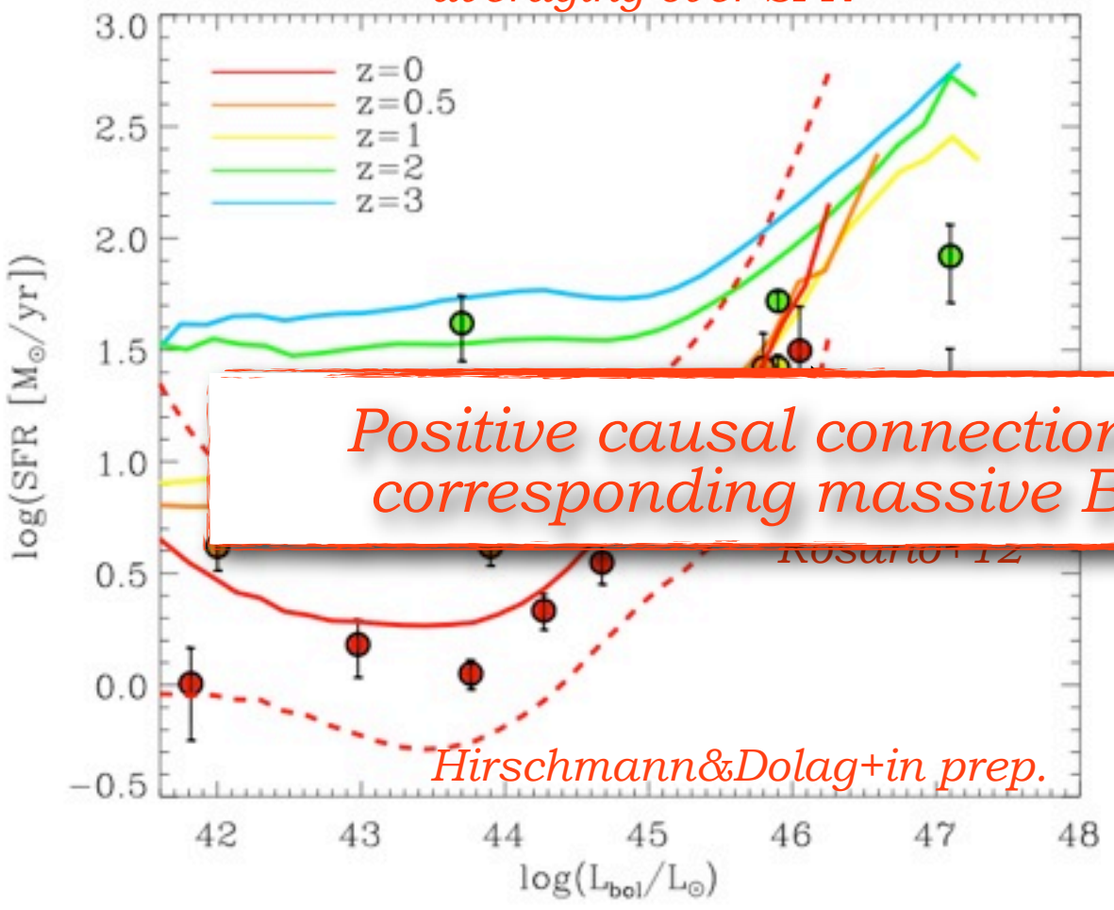

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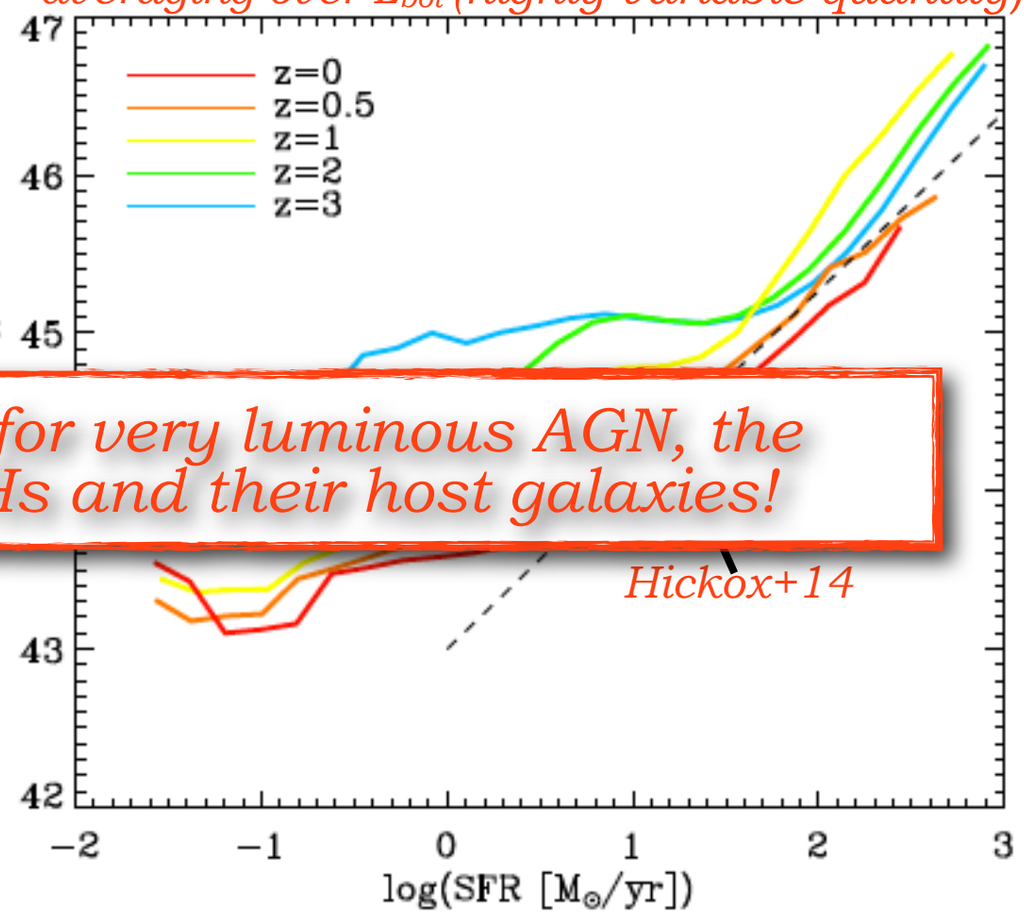
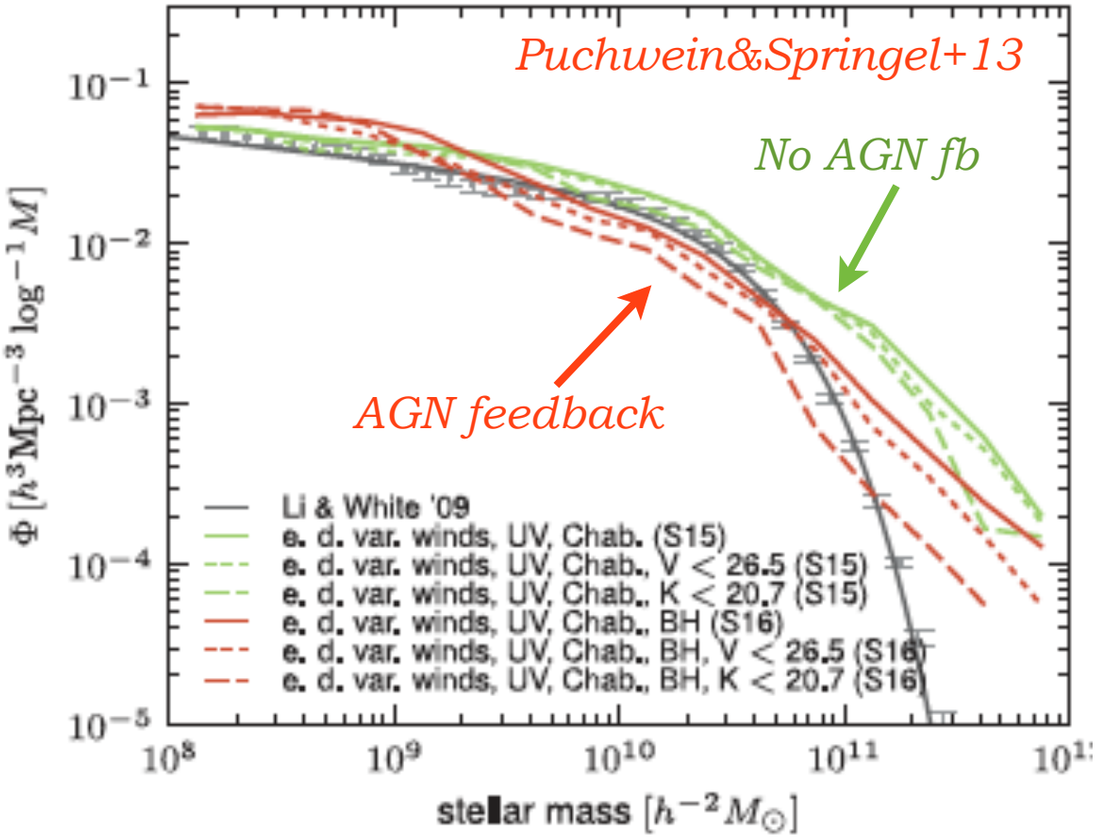


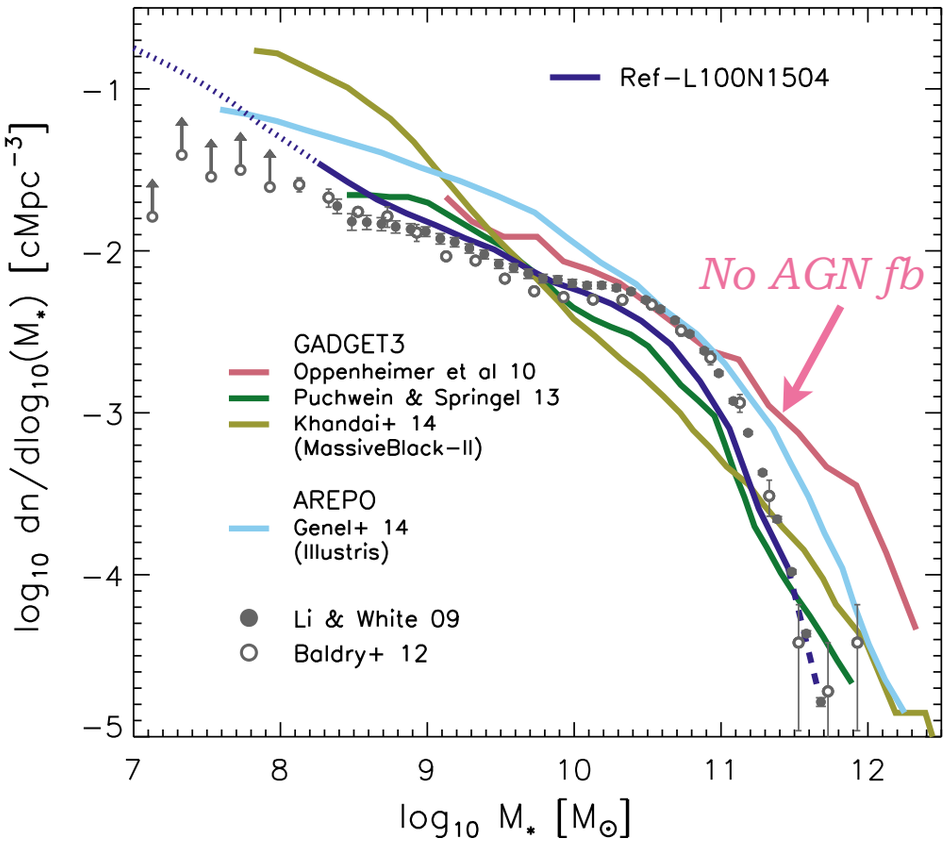
Positive causal connection for very luminous AGN, the corresponding massive BHs and their host galaxies!

- 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 moderately luminous AGN

Effect of AGN feedback

...on the stellar mass function

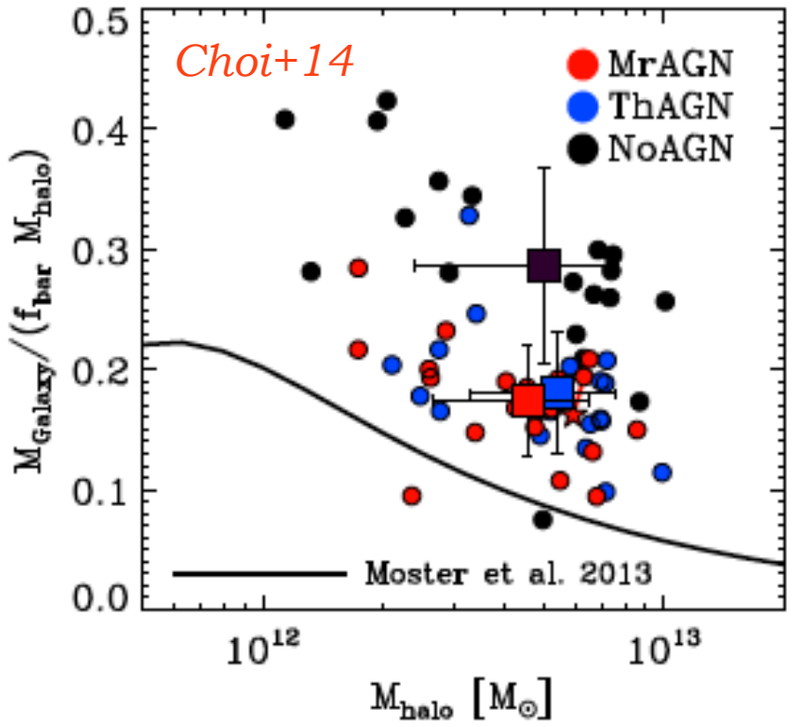


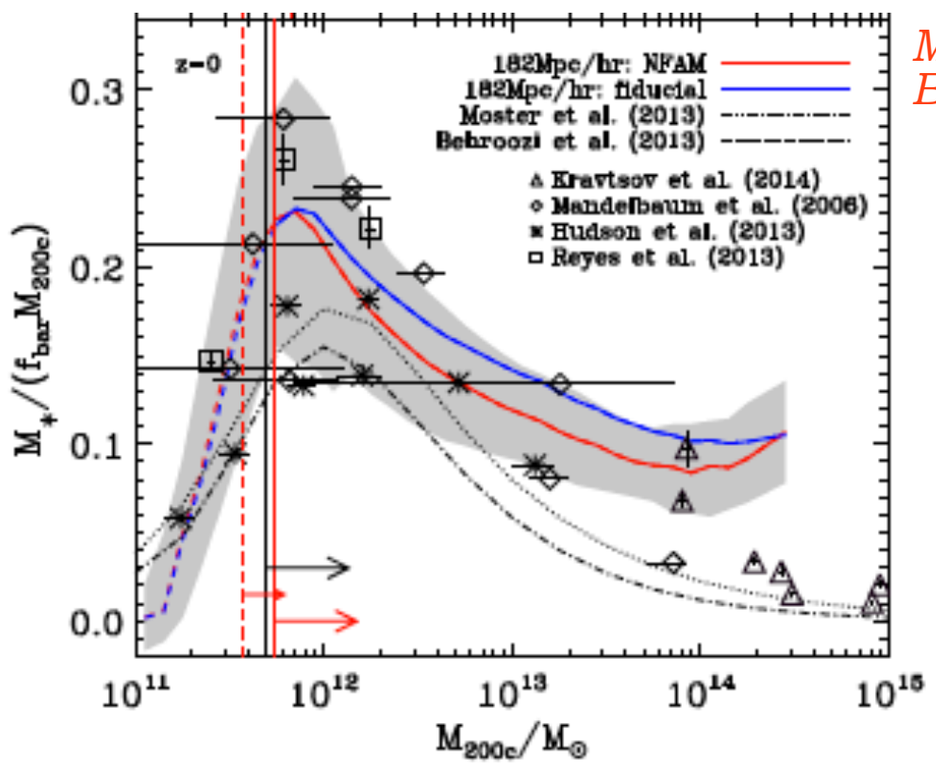


- AGN feedback shapes the massive end of the stellar mass function, *it affects primarily massive galaxies*
- Often models for AGN (radio-mode) feedback too inefficient in suppressing SF in massive galaxies

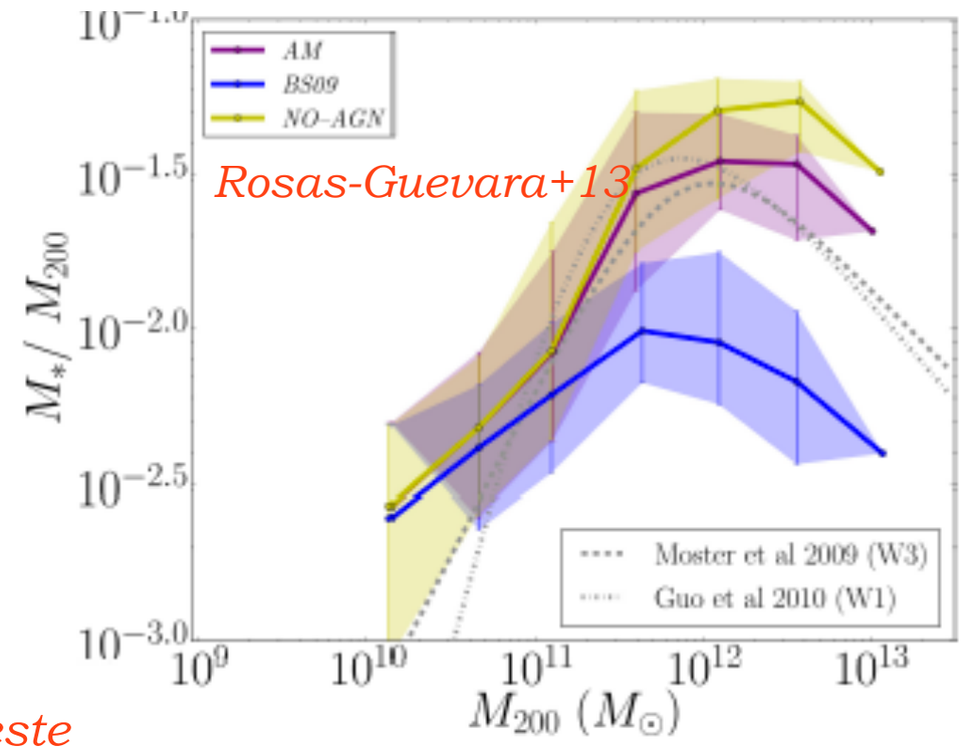
Effect of AGN feedback

...on baryon conversion efficiencies





Magneticum
Bachmann+14

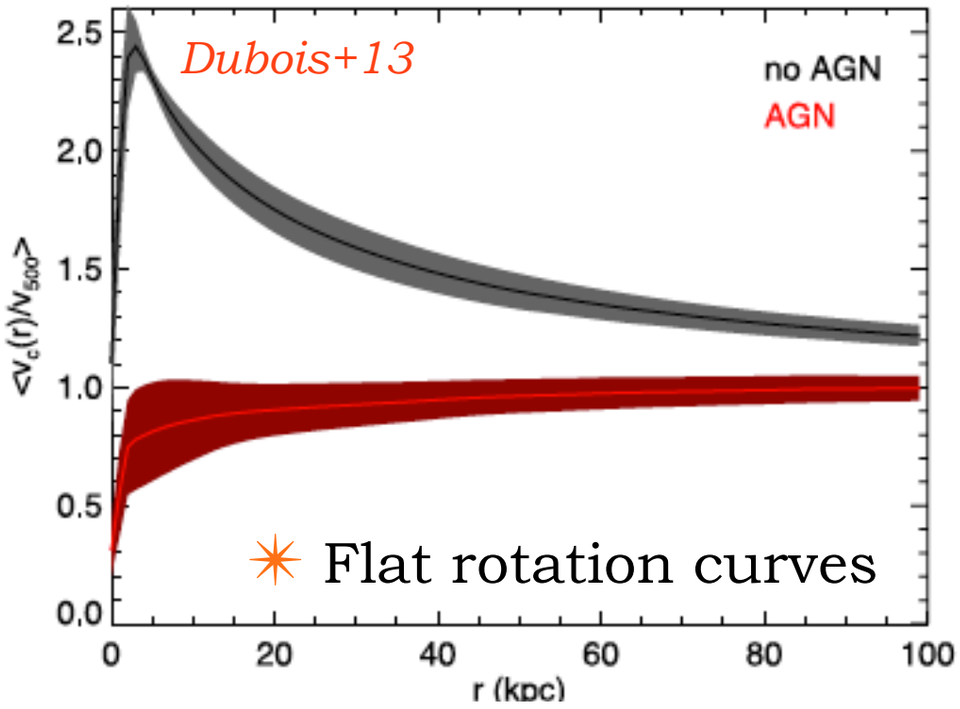


- Reduction of baryon conversion effs by a factor of 1.5-2
- AGN fb reduces SF in halos more massive than 5e11 M

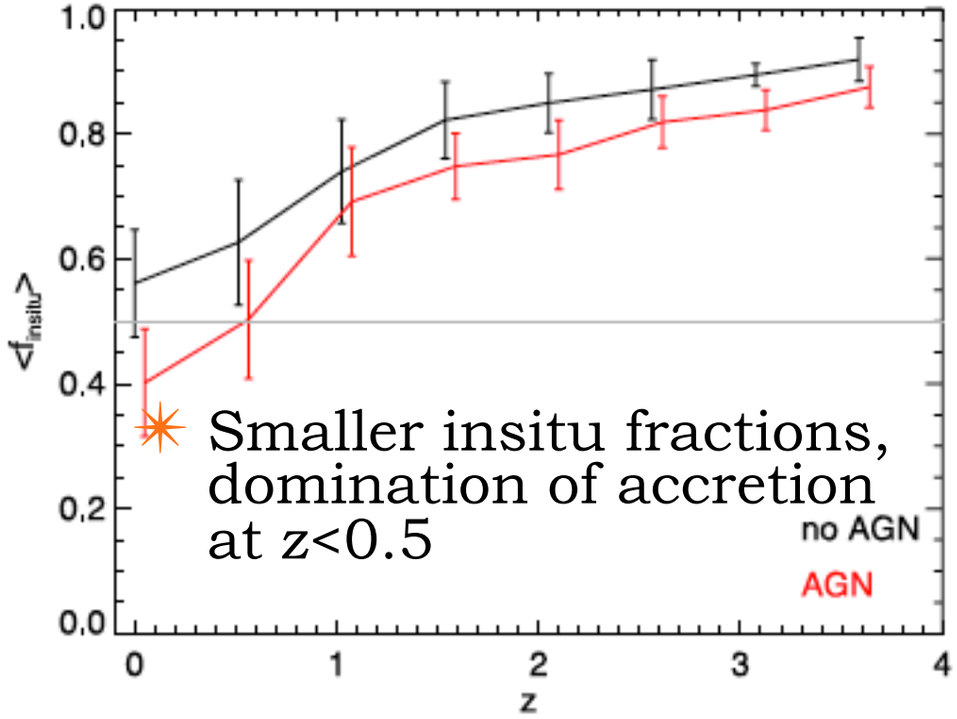
Effect of AGN feedback

...on morphology, kinematics, sizes, insitu/accreted fractions

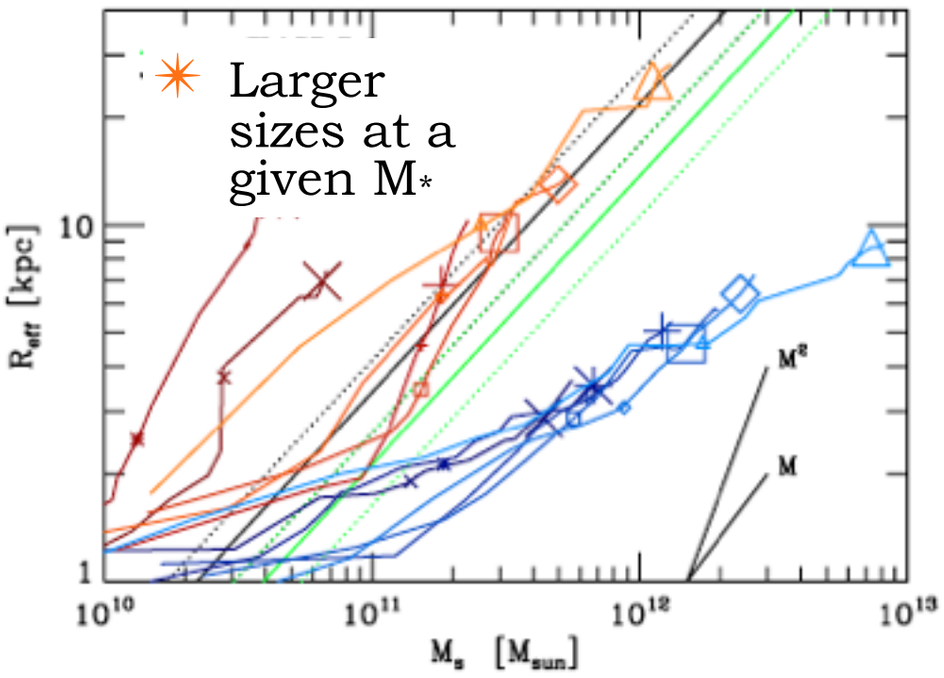
Probed mass range 4e12-8e13 $M_\odot$



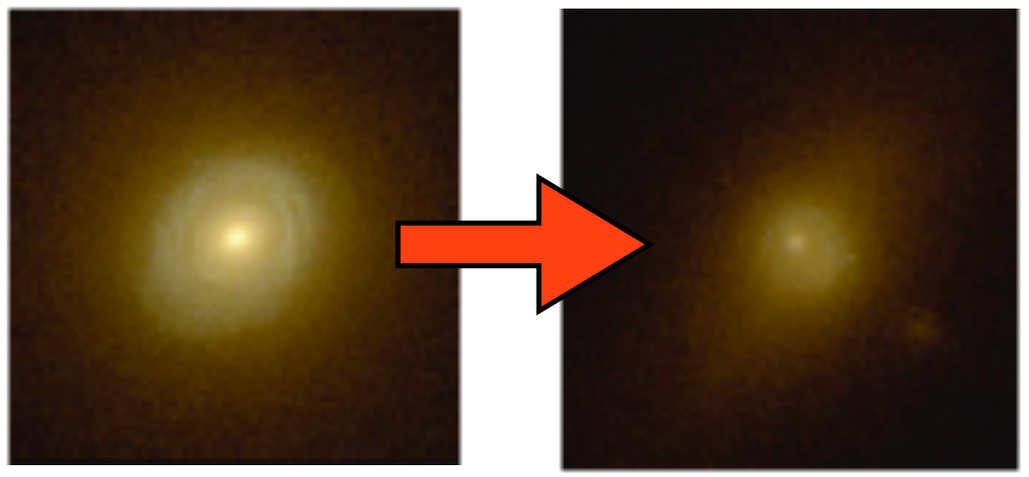
✶ Flat rotation curves



✶ Smaller insitu fractions, domination of accretion at z<0.5



✶ Larger sizes at a given M*



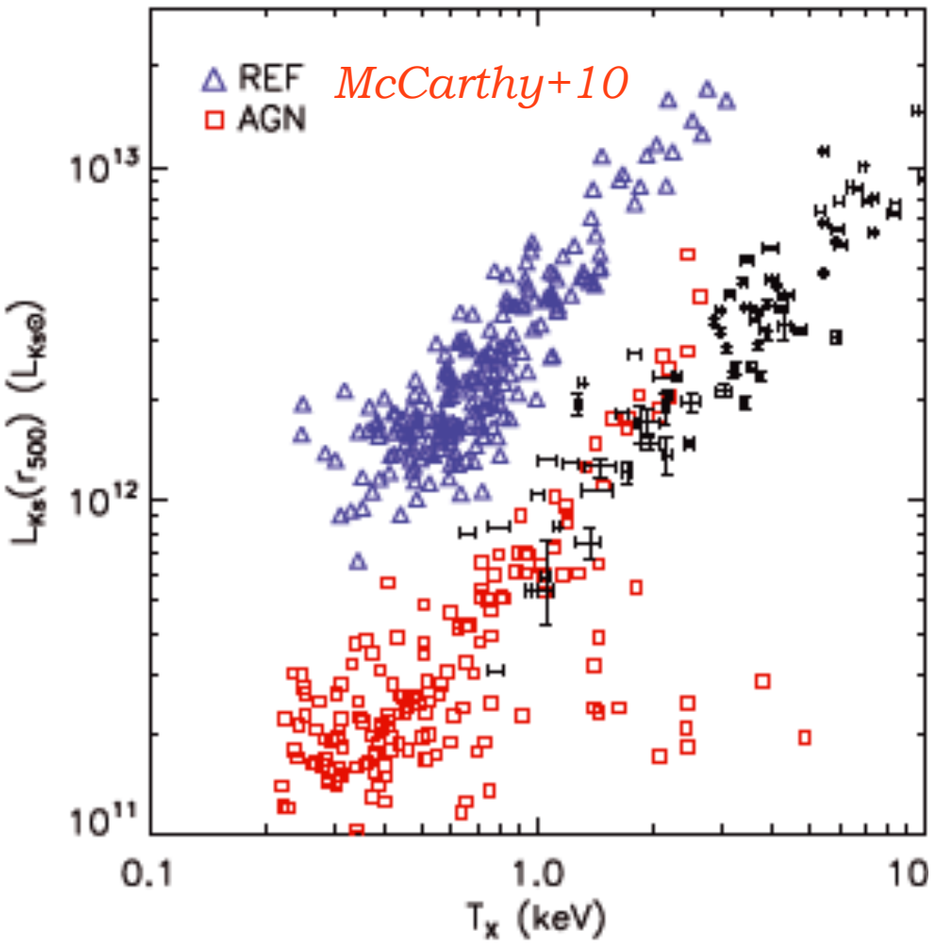
✶ Morphological transition from disk galaxies to elliptical galaxies

Effect of AGN feedback

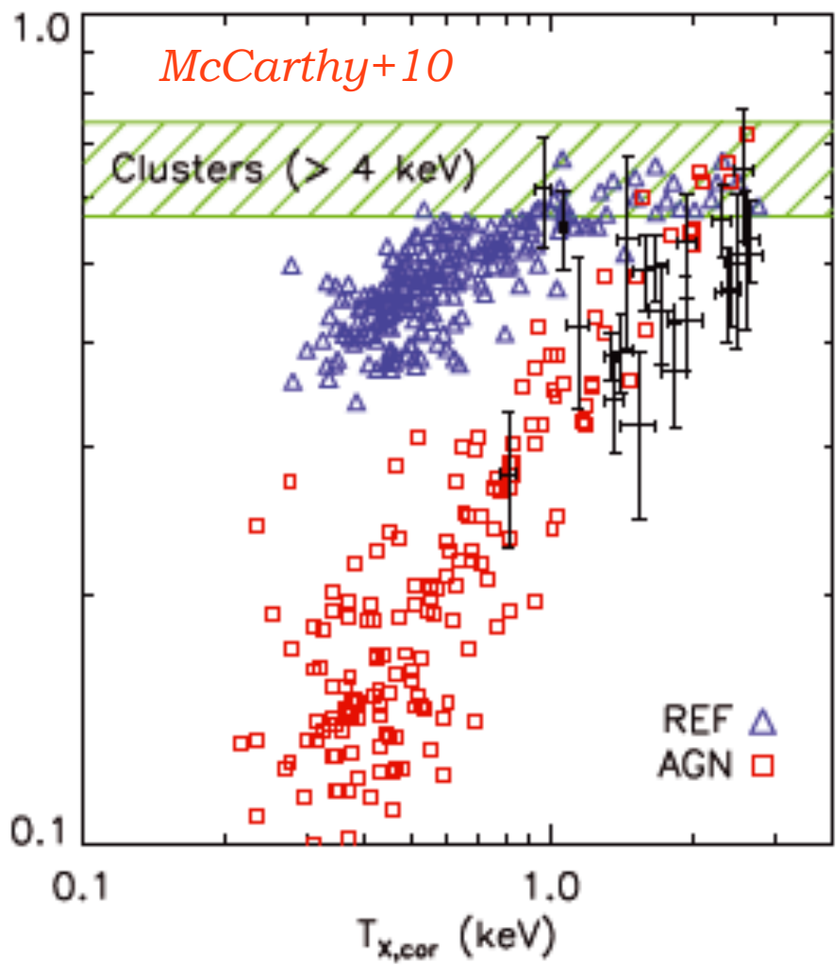
on galaxy groups

e. g. McCarthy+10/11

L-T relation



Gas fractions



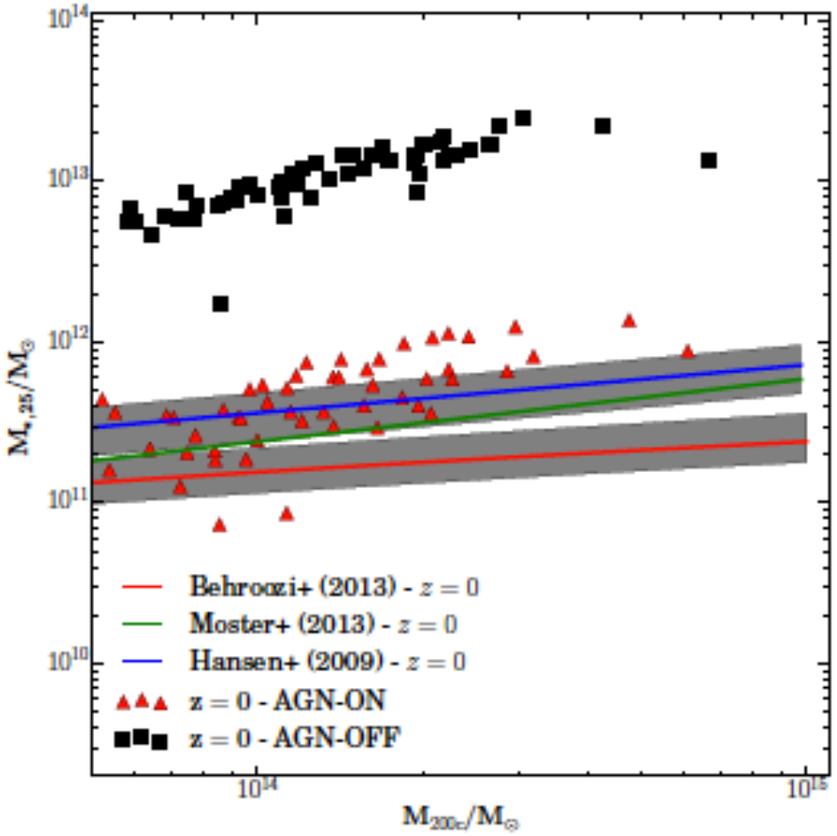
- AGN fb reduces the SF efficiency by a factor of ~4
- Agreement with observed L-T relation
- AGN fb reduces the gas fractions, also consistent with observations

Effect of AGN feedback

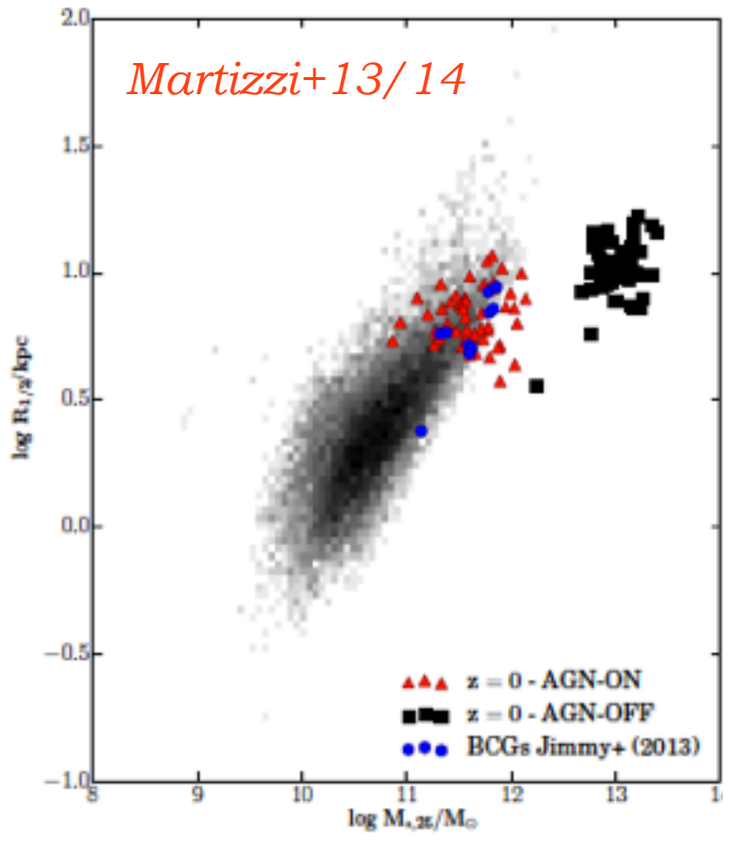
on the brightest cluster galaxies

Planelles+14, Ragone+14, Martizzi+13/14

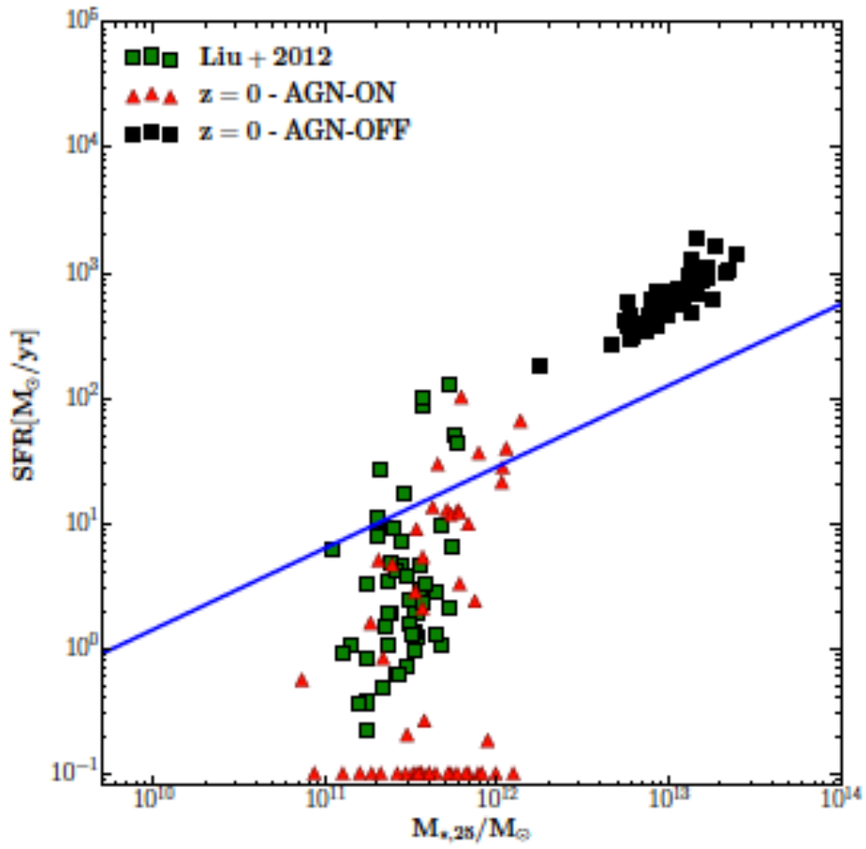
Stellar-halo mass relation



Mass-size relation



SFR-mass relation



- AGN fb affects stellar mass, sizes, SFR & kinematics resulting in a more realistic population of BCGs
- But see *Ragone+14* for some limitations of current models

Emerging picture…

low-mass — *Black hole mass* — *high-mass*

Redshift: *high* … *low*

- *Weak correlation with host galaxy properties*
- *Stellar fb may also affect BH growth?!*

Hardly any causal connection

- *Additional trigger mechanisms, secular evolution DI's/ stochastic gas accretion?*
- *Weak correlation with host galaxy properties*
- *AGN fb hardly any effect on the host galaxies*

Hardly any causal connection

- *Very luminous AGN mainly driven by merger events*
- *Connected with SF (starbursts)*
- *AGN feedback (quasar-mode) regulates BH growth & SF helping to establish BH scaling relations*

Causal connection

- *Appear as less luminous AGN, accretion at low Edd-ratios*
- *Dry merging tightens black hole relations*
- *AGN fb (radio-mode) locks baryons in hot gas -> suppresses SF*

(Negative) causal connection

Challenges…

- *Improve sub-resolution models for BH accretion and feedback, try to rely on high-resolution simulations of isolated galaxies*

- *AGN feedback models hardly understood, try to distinguish between different flavours (radiative vs mechanical) by comparison with observations (2D maps)*

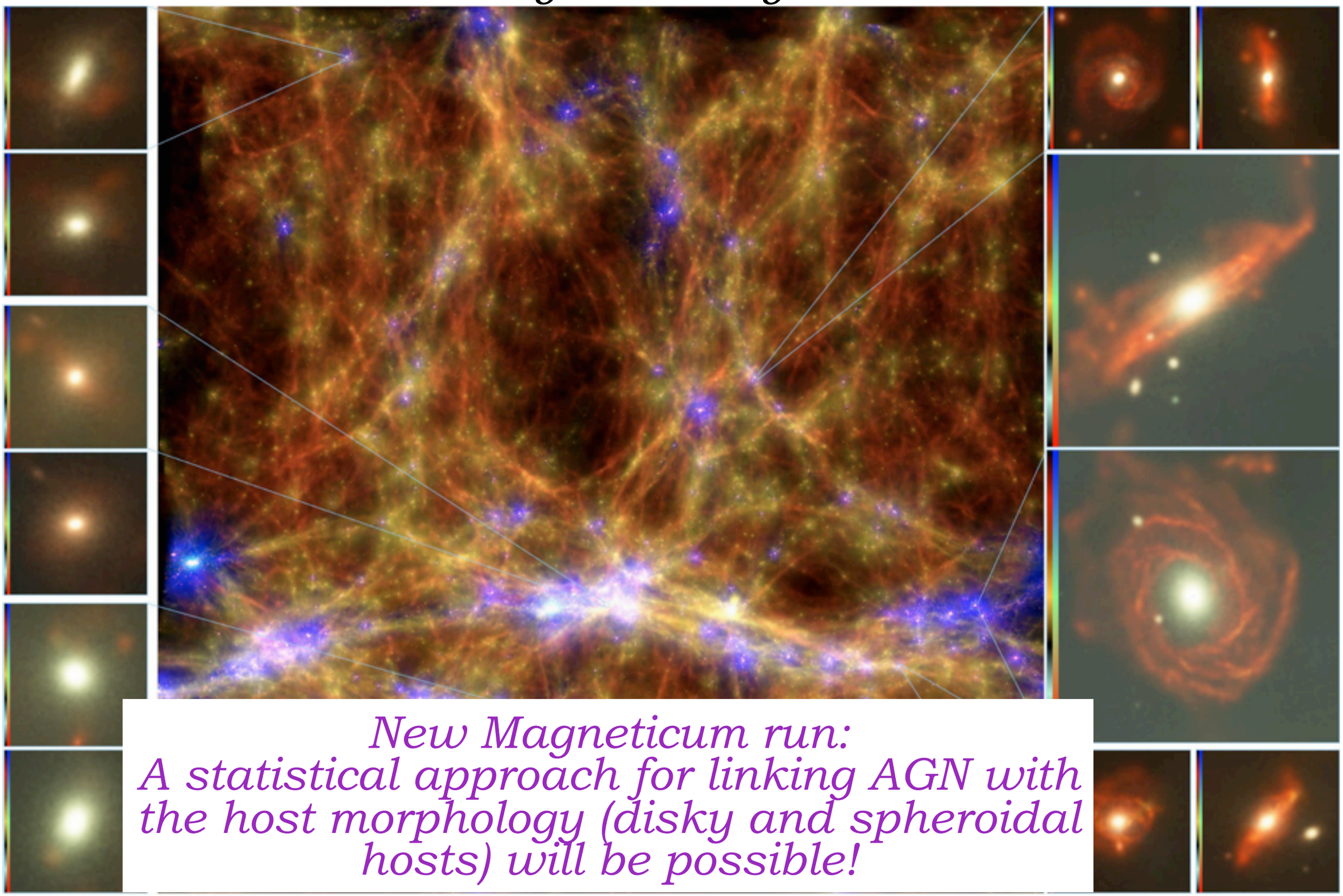
- *Increase the resolution in cosmological (zoom) simulation to better resolve the accretion region around the BH (Bondi-radius!) and to capture physical processes as violently instable disks and/or secular evolution processes (DI's)*

- *Improve comparison with observations, account for selection effects, output directly observable quantities*

- *BH seeding? High-z evolution of first BHs?*

Short-term aim

with K. Dolag & the Magneticum team

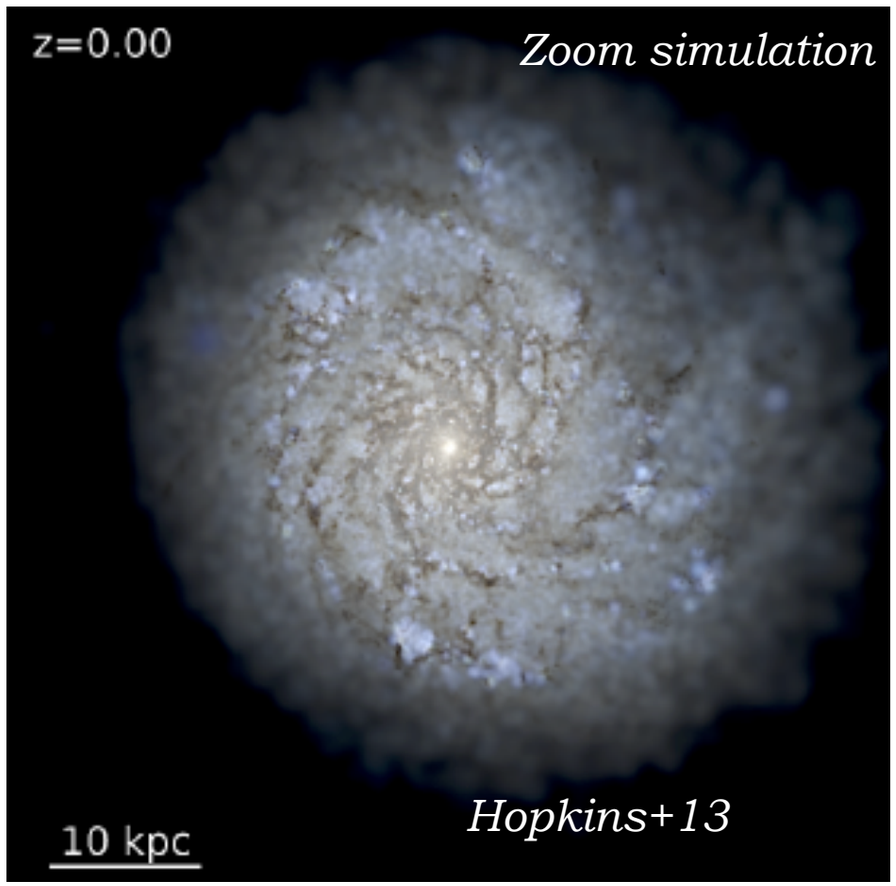


New Magneticum run:
A statistical approach for linking AGN with the host morphology (disky and spheroidal hosts) will be possible!

Long-term project...

with T. Naab, J. Ostriker and others...

Statistically complete sample of cosmological zoom simulations of massive galaxies



- Statistically complete sample of cosmological zoom simulations of massive galaxies
- Effectively resolving the ISM (like in the FIRE simulation set) and resolving the Bondi-accretion radius
- Including different flavours for AGN feedback
- Allows for unprecented exact investigations of structural & kinematical properties on a statistical basis