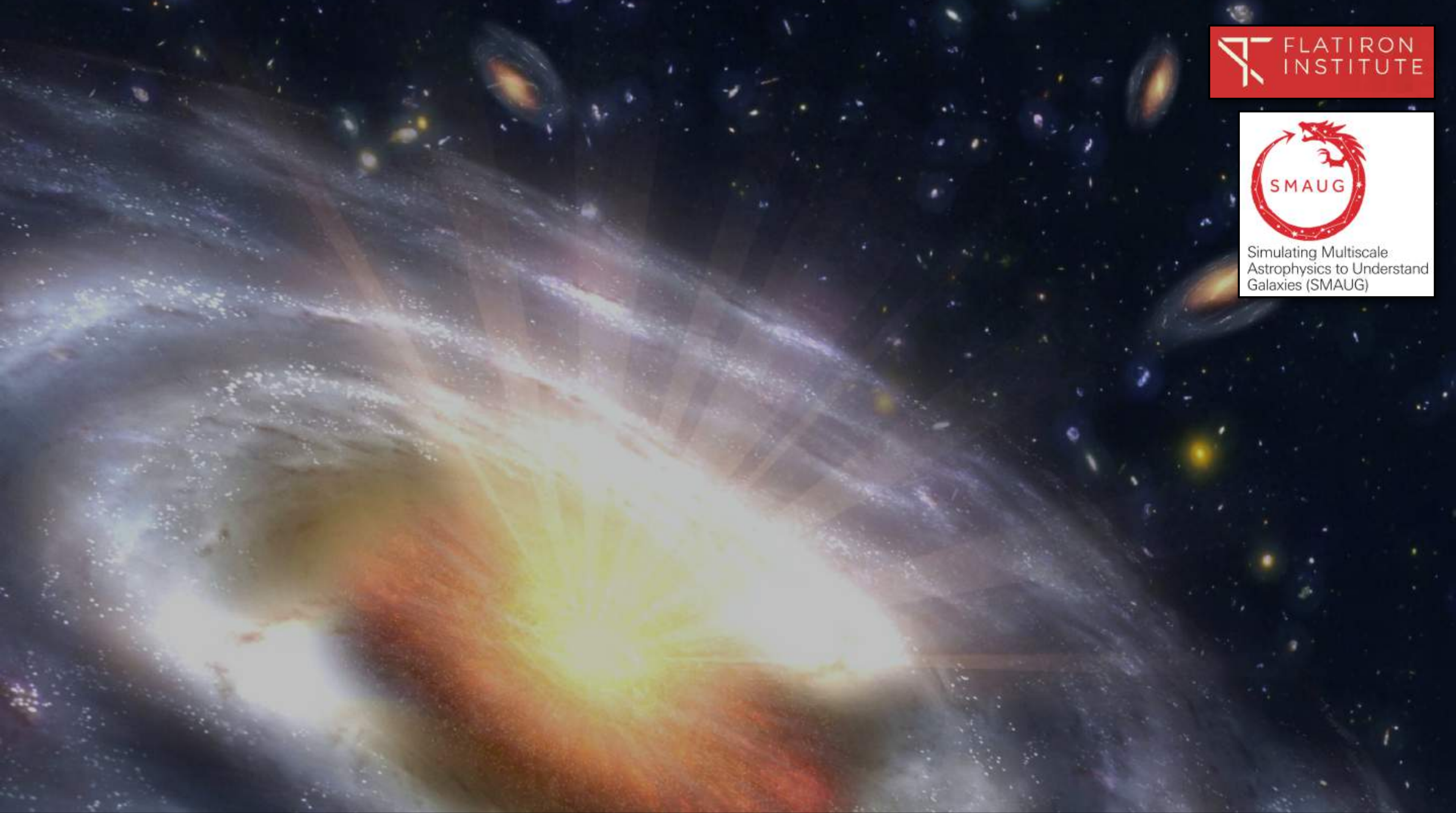


Formation and Evolution of Supermassive Black Holes

Melanie Habouzit, Flatiron Postdoc Fellow
Center for Computational Astrophysics

Collaborators: Rachel Somerville, Shy Genel, Marta Volonteri, Yohan Dubois, Yuan Li, the IllustrisTNG team.

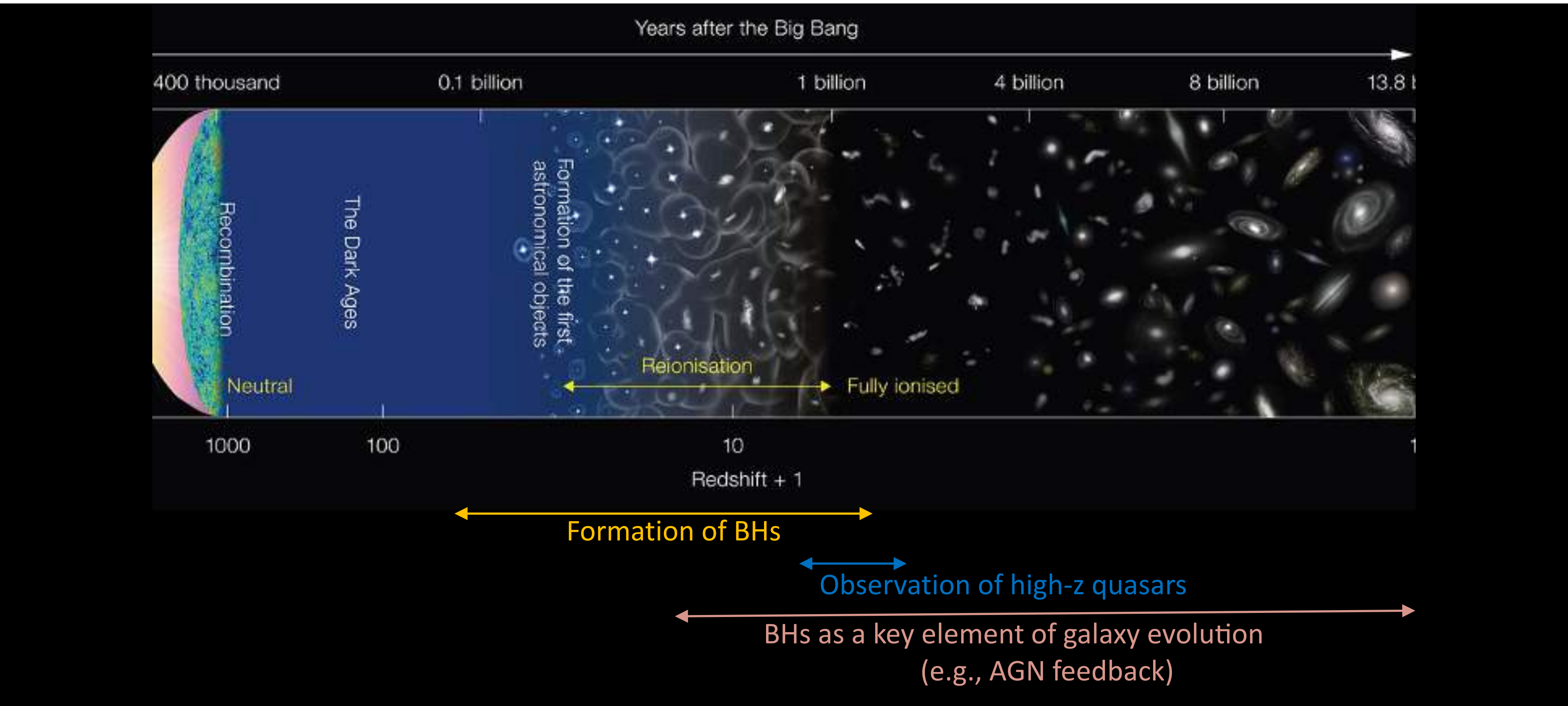
UC Berkeley, April 2019.

FLATIRON INSTITUTE

SMAUG
Simulating Multiscale Astrophysics to Understand Galaxies (SMAUG)

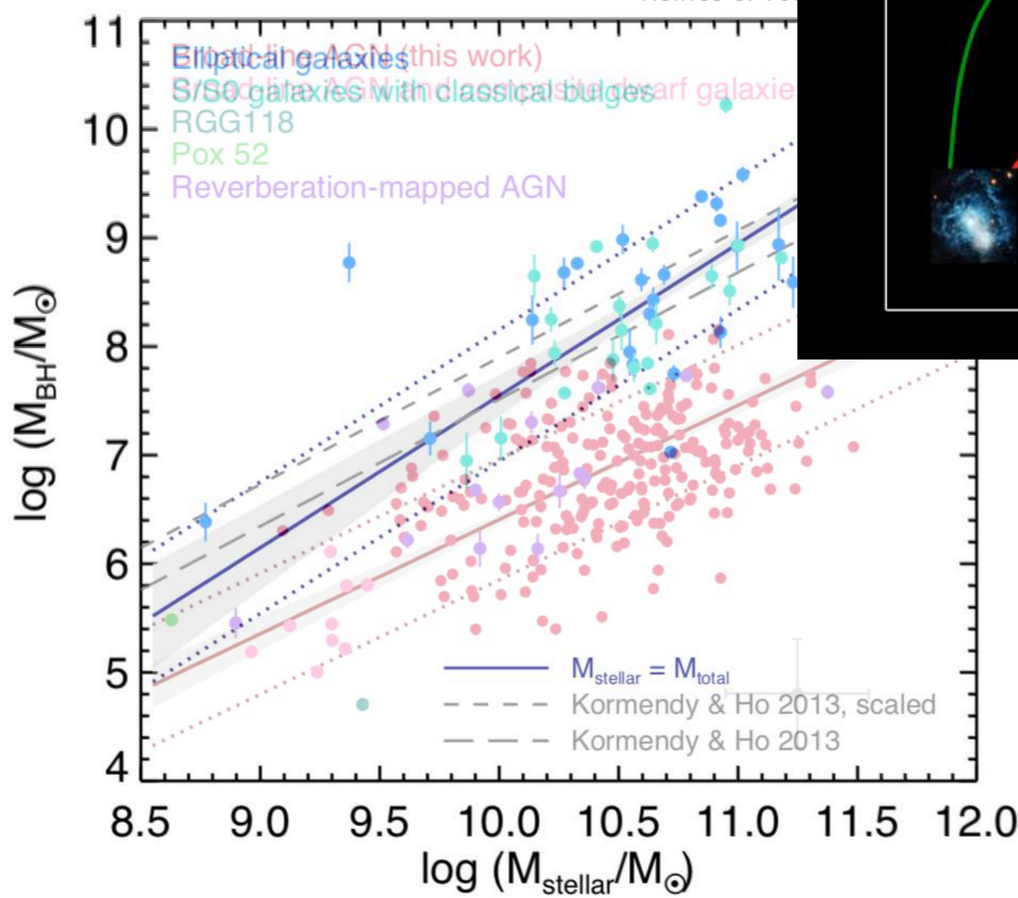
BHs are a key element of galaxies, and of galaxy evolution through cosmic times

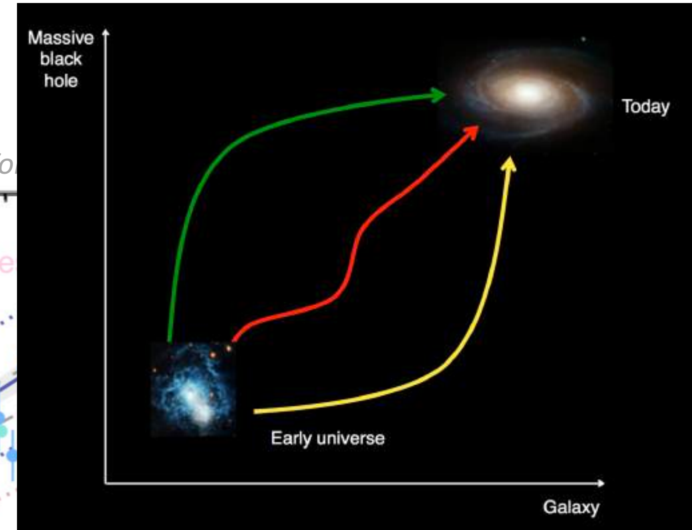
- BHs of 10^6-10^9 $M_\odot$ are observed in almost all nearby galaxies.
- BHs power active galactic nuclei (AGN) and quasars.
- Co-evolution between BHs and their host galaxies across cosmic times: scaling relations between M_{BH} and galaxy properties (mass, velocity dispersion), powerful outflows.



Scaling relation between BHs and their host galaxies

Reines & Vo





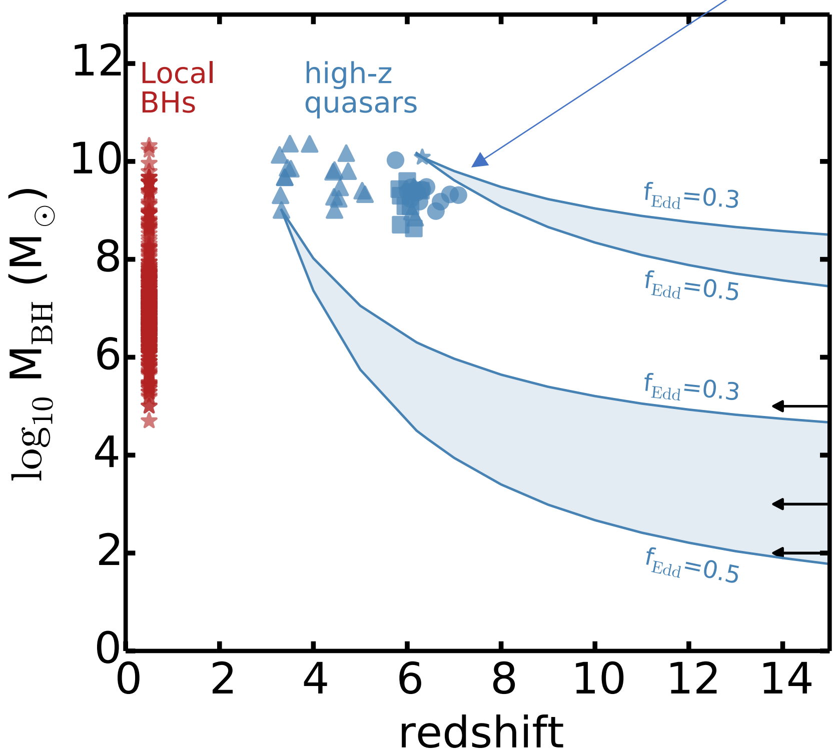
Volonteri

Co-evolution between BHs and galaxies → Role of AGN feedback ?

BHs in dwarf galaxies, and some galaxies without BH → BH formation ?

See aslo Ferrarese, Merrit+00, Gebhardt+00, Kormendy+01, Merrit+01, Haring & Rix04, Kormedy & Ho13, McConnell&Ma13.

The challenges of BH formation mechanisms



High redshift quasars

$L_{\rm bol} = 10^{46-48}\,{\rm erg/s}$

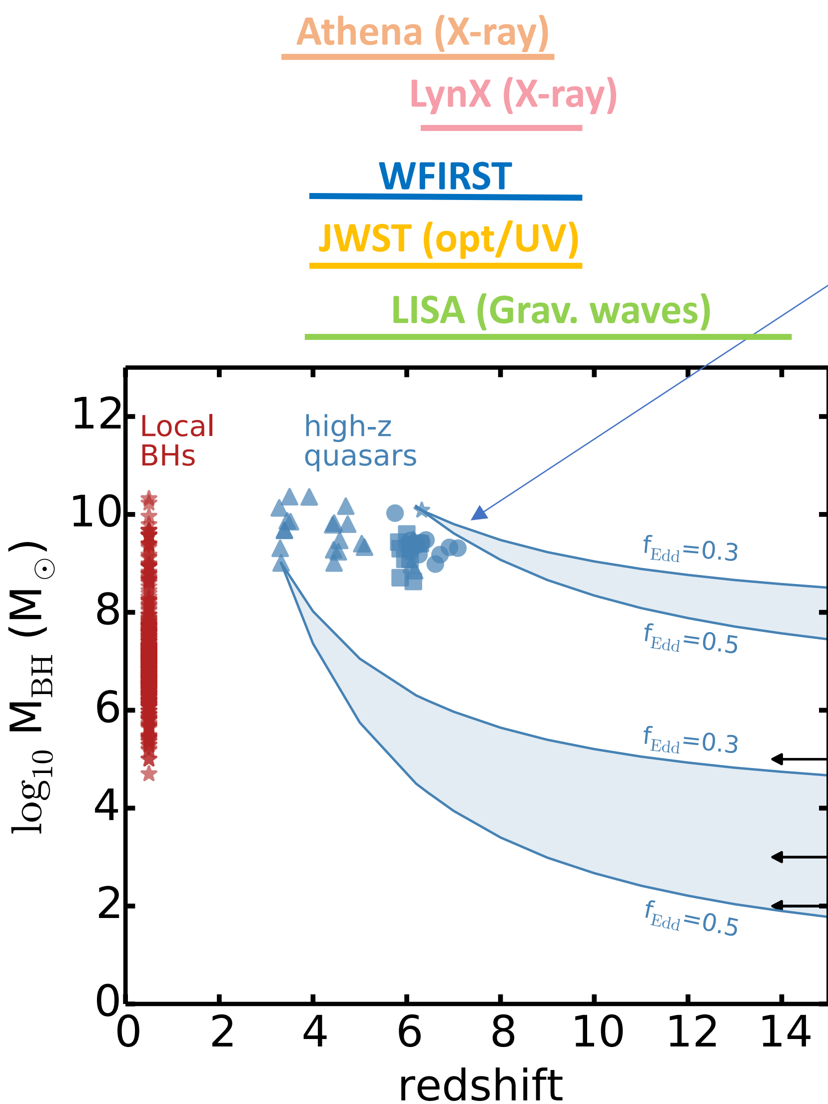
ULAS J1120+0641 already in place only 770 Myr after the Big Bang *Mortlock+11*

Dietrich, Hamman04
Shields+06, Riechers+09,
Fan+11, Jiang+07,
Mortlock+11, Kurk+07,
Maiolino+07, Wang+10,
Willott+11, DeRosa+11,
Wu+15

BHs must have **formed in the early Universe** in order to acquire 10^9 $M_\odot$ in less than 1 Gyr.

Quasars are only the tip of the iceberg, **very rare objects** (1 Gpc^{-3}), and do not contribute the most to the build up of galaxy population, cosmic reionization, etc.

The challenges of BH formation mechanisms



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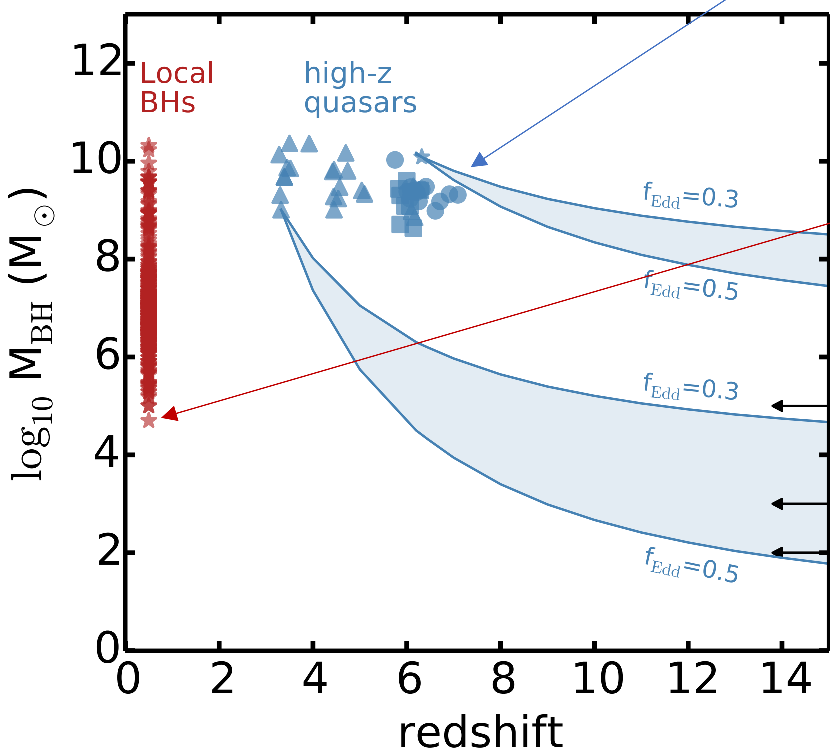

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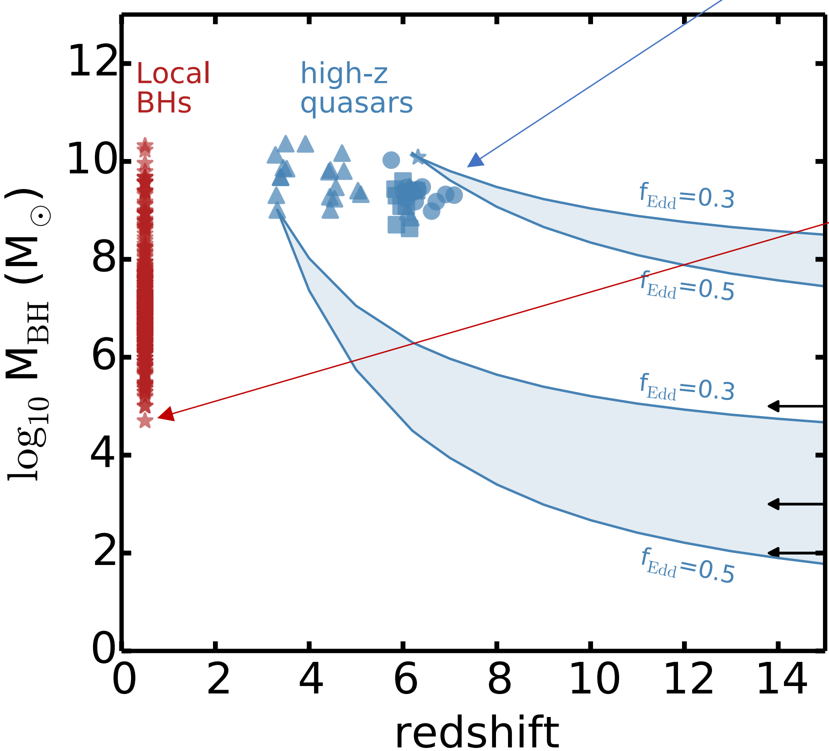
Wu+15

Local low-mass galaxies

RGG 118
Galaxy of 2×10^9 M_{sun}
BH of 5×10^4 M_{sun}
Baldassare+15

Greene & Ho04,
Dong, Greene & Ho12,
Reines, Greene, Geha13,
Reines+15, Baldassare+15,
Mezcua+18

The challenges of BH formation mechanisms



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Mezcua+18

The physics of BH formation determines the masses and abundance of BHs in galaxies.

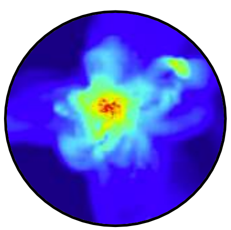
The physics of BH formation in the high redshift Universe.

PopIII remnant model (light seeds)

Madau& Rees 01,
Volonteri, Haardt, Madau 03
Habouzit+16a,+17

Pristine H_2 cooling mini-halo

- Fragmentation of the gas
- High Jeans mass
- Reduced winds loss



Massive PopIII stars of 10-1000 $M_\odot$
Hirano+14, Greif+12, Schneider+06,12, Omukai+05

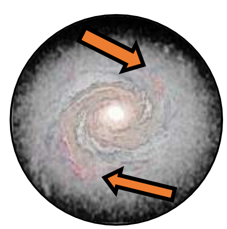
$M_{BH} \sim 100\ M_\odot$

Direct collapse model (heavy seeds)

Loeb & Rasio 94, Bromm & Loeb 03, Spaans & Silk 06, Begelman+06, Lodato & Natarajan+06,07, Shang, Bryan, Haiman 10, Latif+13, Agarwal+12,14, Visbal+14, Inayoshi++, Habouzit+16a,16b

Pristine atomic cooling halo

- No efficient coolants (metals, H_2).
- Suppression of H_2 by high Lyman-Werner radiation from nearby star-forming galaxies.
- Very high Jeans mass.
- Reduced winds loss.
- Large inflows (1-100 Myr).



Unstable disk with inflows

Supermassive star or quasi-star

$M_{BH} \sim 10^{4-6}\ M_\odot$

Compact stellar cluster (light seeds)

Omukai, Schneider & Haiman 08, Devecchi & Volonteri 09, Regan & Haehnelt 09, Katz, Sijacki & Haehnelt 15, Habouzit+17

Metal-poor gas proto-galaxy

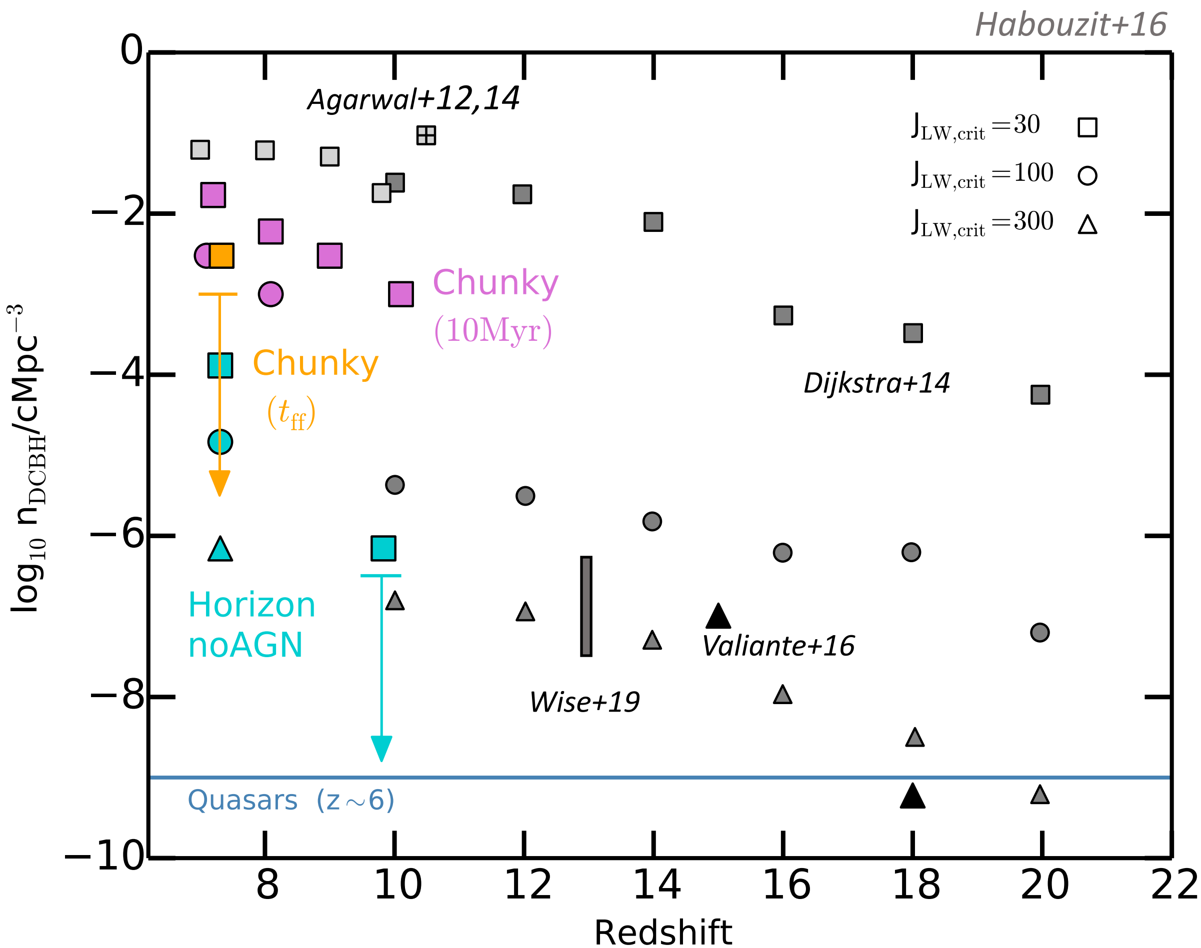
- Cooling by H_2
- Lower Jeans mass
- Reduced winds loss
- Compact cluster of low-mass stars

Runaway collisions between stars form a Very Massive Star

$M_{BH} \sim 10^3\ M_\odot$

Number density of *direct collapse* BH candidates (*heavy seeds*)

Post-processing study based on the largest cosmo. simulations used so far.



→ Low number density of direct collapse BHs, may be sufficient to explain the population of high-z quasars, but not the presence of BHs in more *normal* galaxies.

See also Dijkstra+14, Ahn+09, Wolcott-Green+11, Agarwal+12,14, Johnson+14, Visbal+14, Decerra+15, Chon+16, Valiante+16, Regan+14,18, Wise+19…

A physical model of BH formation in cosmological simulations (*light seeds*)

Cosmological simulations (EAGLE, Illustris, …)

Seeding based on dark matter halo mass.

Fixed initial BH mass: $M_{\rm BH} = 10^{5-6}\,{\rm M_\odot}$

Large volume (100-300 cMpc on a side).
Lower resolution, do not resolve the low-mass galaxy regime.

→

My cosmological simulations

Follow theoretical prescriptions from the *light seeds* models (PopIII remnants and compact stellar clusters), based on local gas properties.

BHs form in metal poor, overdense, bound, collapsing regions.

BH initial mass computed individually.

$$M_{\rm BH} = f_{\rm BH,\,IMF\,PopIII} \times \epsilon_{\rm BH} \times M_\star$$
$$= 0.48 \times 0.50 \times M_\star$$
$$M_{\star,\rm PopIII} = \int_{m_1}^{m_2} m \frac{{\rm d}N}{{\rm d}m} dm$$

Smaller volume (10-30 cMpc on a side)
Higher resolution, resolve the low-mass galaxy regime.

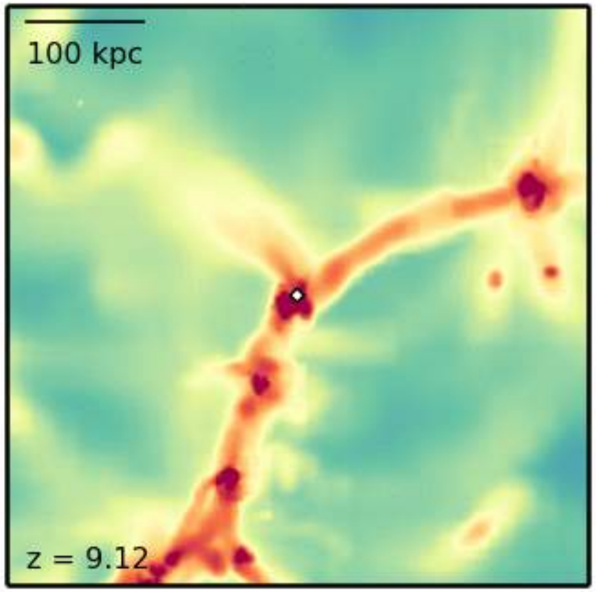
Habouzit+17

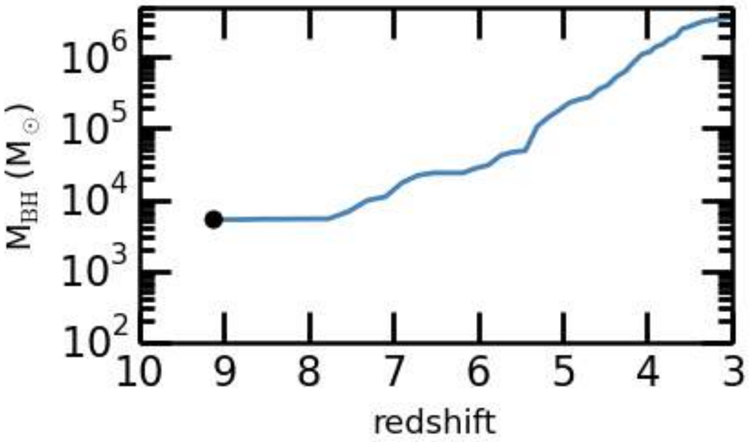
A physical model of BH formation in cosmological simulations (*light seeds*)

Adaptive Mesh Refinement (AMR) **Ramses**

Box length 10 cMpc
Spatial resolution 70 pc
Dark matter resolution 1.6×10^6 M_{sun}

- **Cooling + UV background**
- **Star formation + 3 versions of SN feedback**
  Metal enrichment
- **BH formation *light seed* model**
  PopIII remnant / Stellar compact cluster
- **Bondi accretion**
- **AGN feedback (injection of thermal energy)**





Habouzit+17

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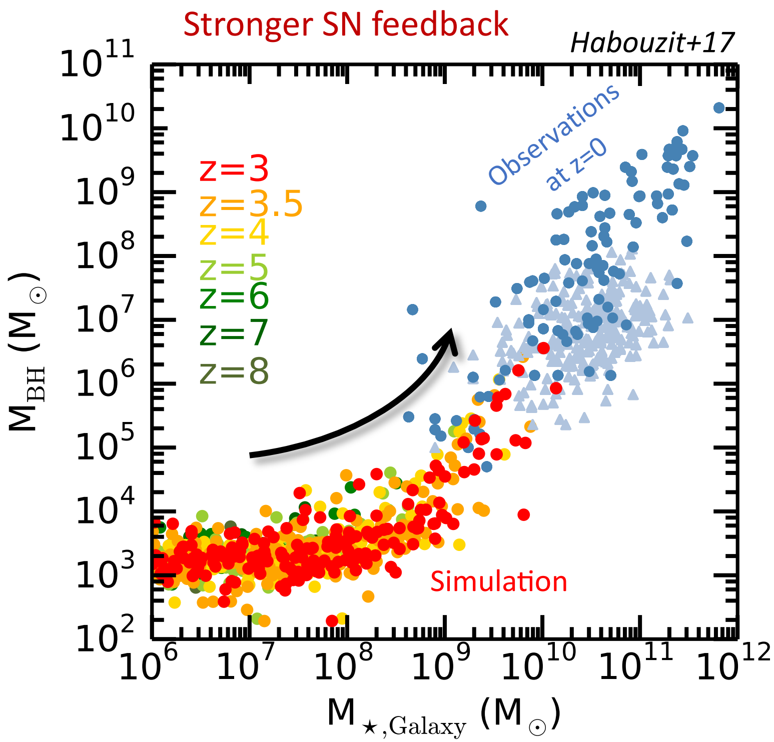
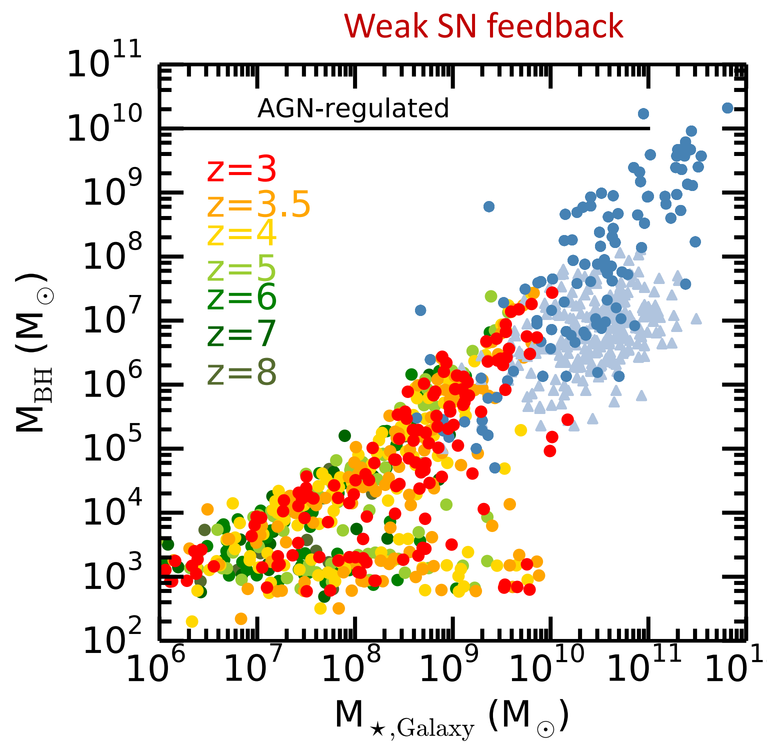
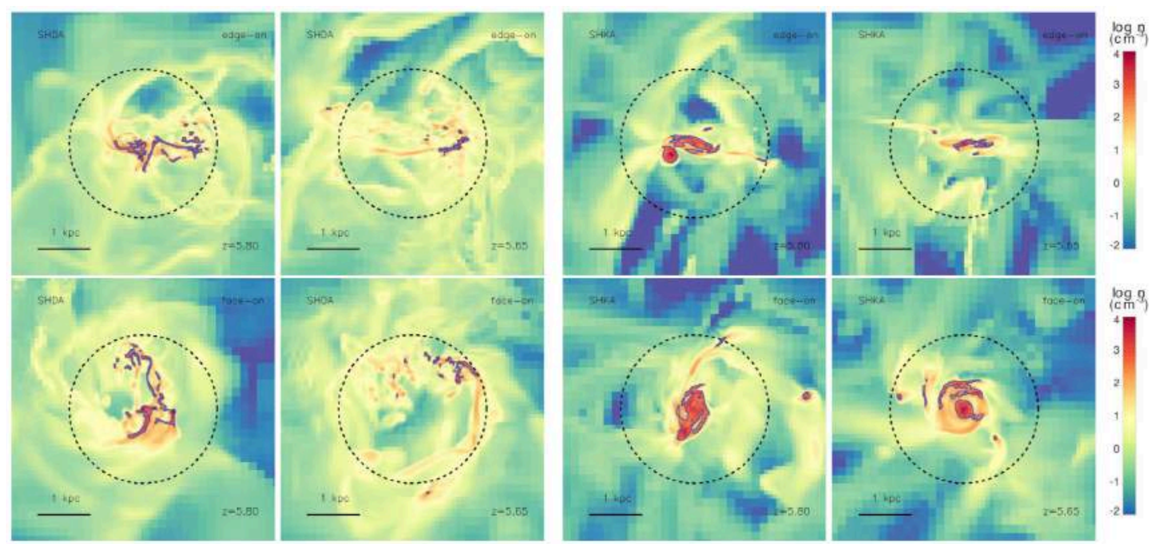




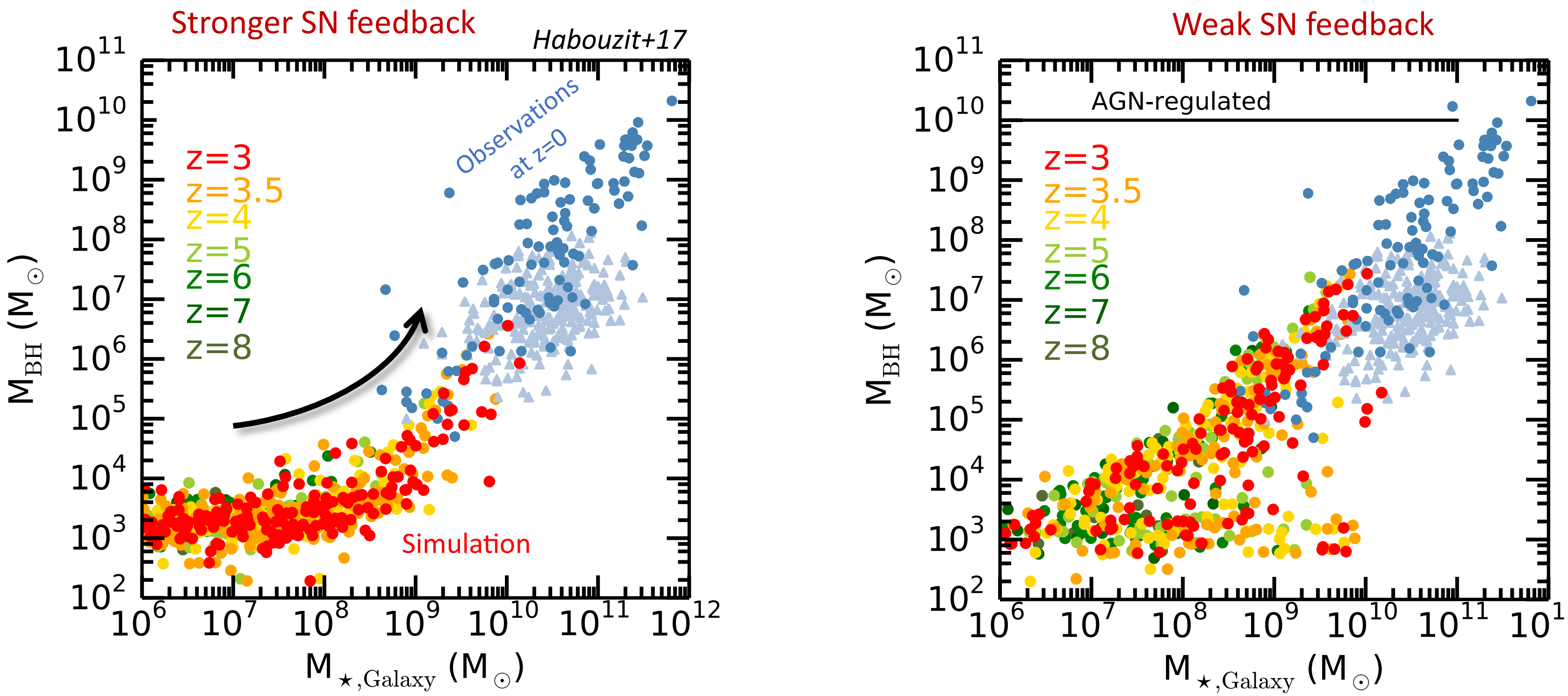
Dubois et al. (2015)

Set of zoom-in cosmological simulations with high resolution.

Dark matter resolution 2 x 10^5 $M_\odot$.
Spatial resolution ~10-35 pc.



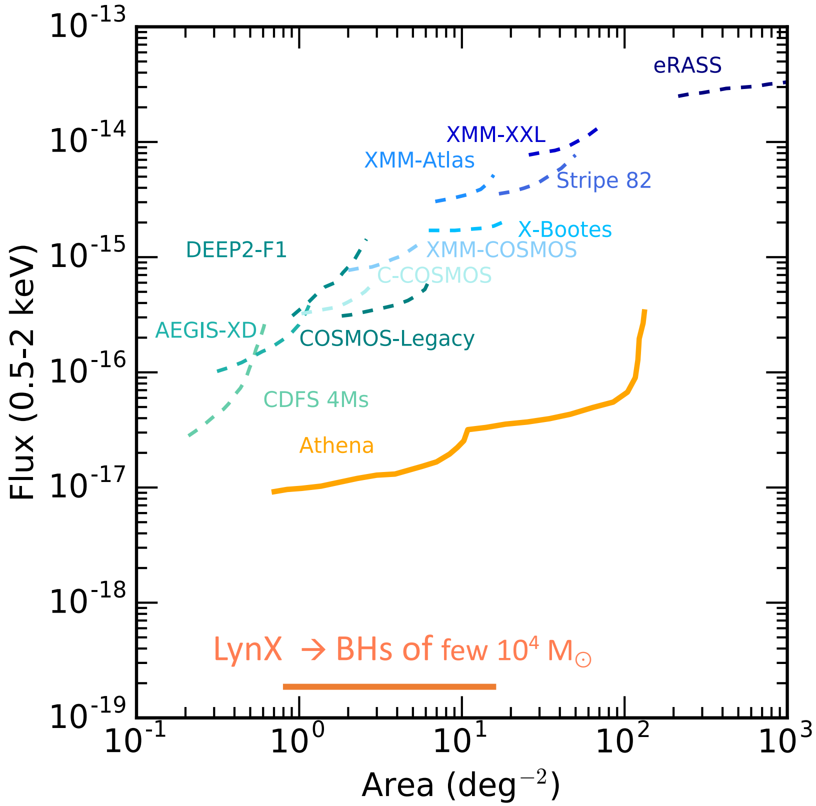
A physical model of BH formation in cosmological simulations (*light seeds*)

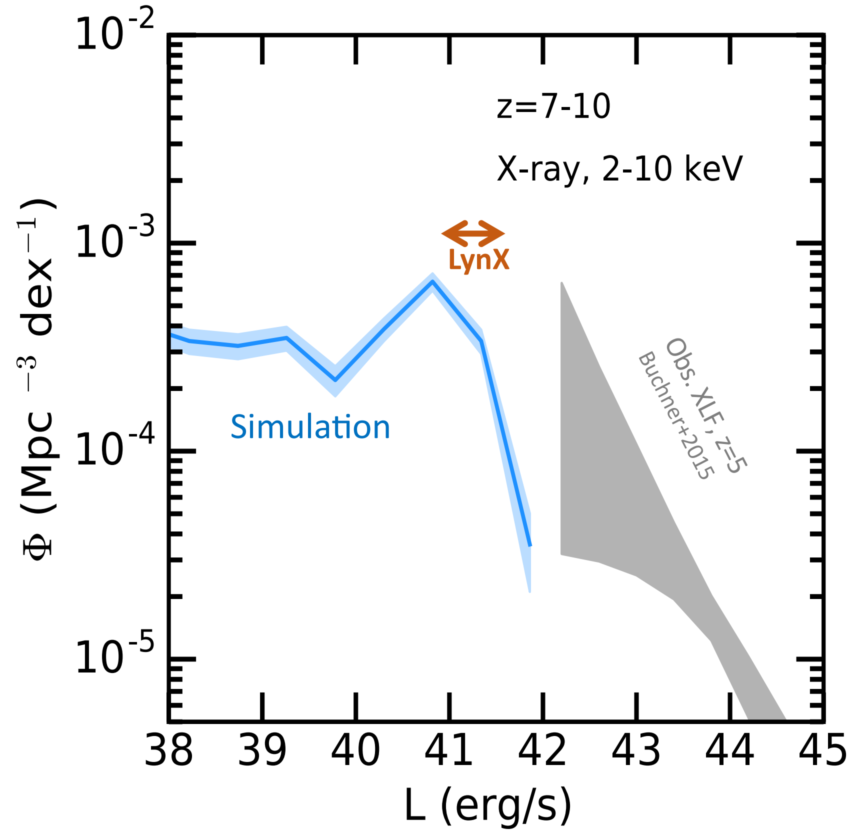


- BHs are regulated by SN feedback at early times:
  BHs have a hard time to grow because their galaxies have shallow potential wells as a result of SN winds, which are sufficient to remove the dense cold gas and suppress BH accretion.

- Our simulation reproduces/predicts:
  - the M_{BH}-M_* relation,
  - the BH hard X-ray luminosity function from high to low redshift (*Buchner+15*),
  - the low number of high-z AGN: only 3 candidates in LBGs in CDF-S at z>6, *Giallongo+15*,
  - the probability for galaxies to host a BHs (*galaxy occupation fraction*).

Predictions for the *Interim Report* of the LynX concept mission *(Habouzit+ in prep).*



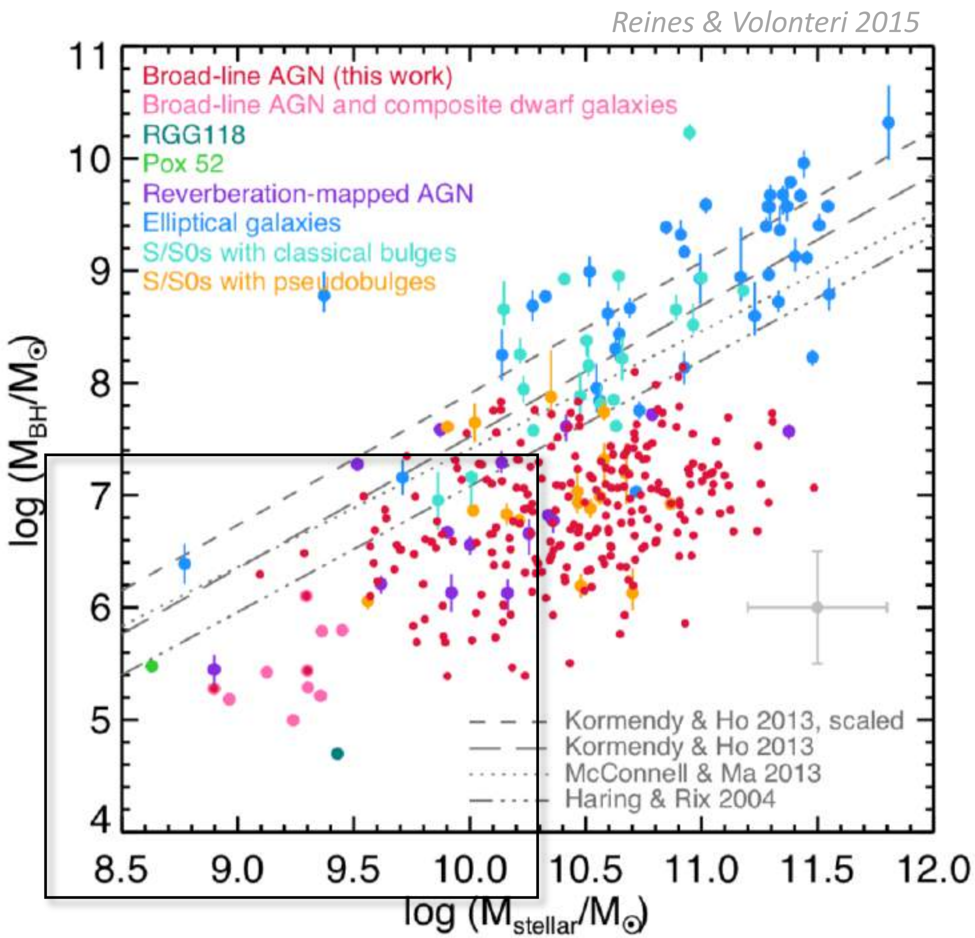


The BH X-ray luminosity function constrains a combination of BH parameters: **BH mass**, **BH accretion rate**, **galaxy occupation fraction**.

- $L_{x,\ Athena}$ = 3 x 10^{43} erg/s, M_{BH} = $10^{6\text{-}7}$ M_{sun}
- $L_{x,\ LynX}$ = 1.5 x 10^{41} erg/s, M_{BH} = 2 x 10^4 M_{sun}

Predicted BH density on the sky ~ 500-1000 deg^{-2} for z=7-10, with large uncertainties.

Scaling relation between BHs and their host galaxies



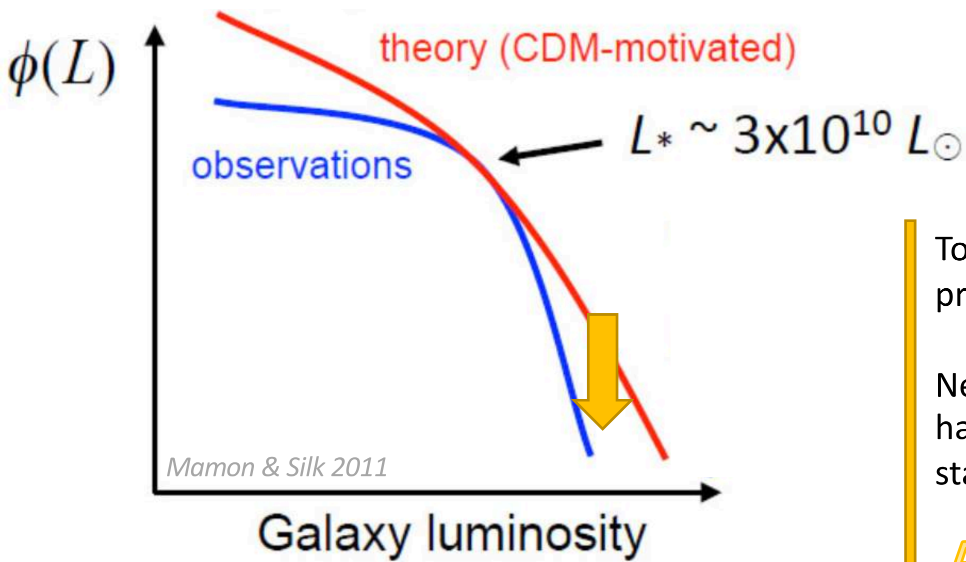
Co-evolution between BHs and galaxies → Role of AGN feedback ?

BHs in dwarf galaxies, and some galaxies without BH → BH formation ?

See aslo Ferrarese, Merrit+00, Gebhardt+00, Kormendy+01, Merrit+01, Haring & Rix04, Kormedy & Ho13, McConnell&Ma13.

AGN feedback to solve the overcooling problem in massive galaxies.

Galaxy luminosity function



Too many bright galaxies are predicted.

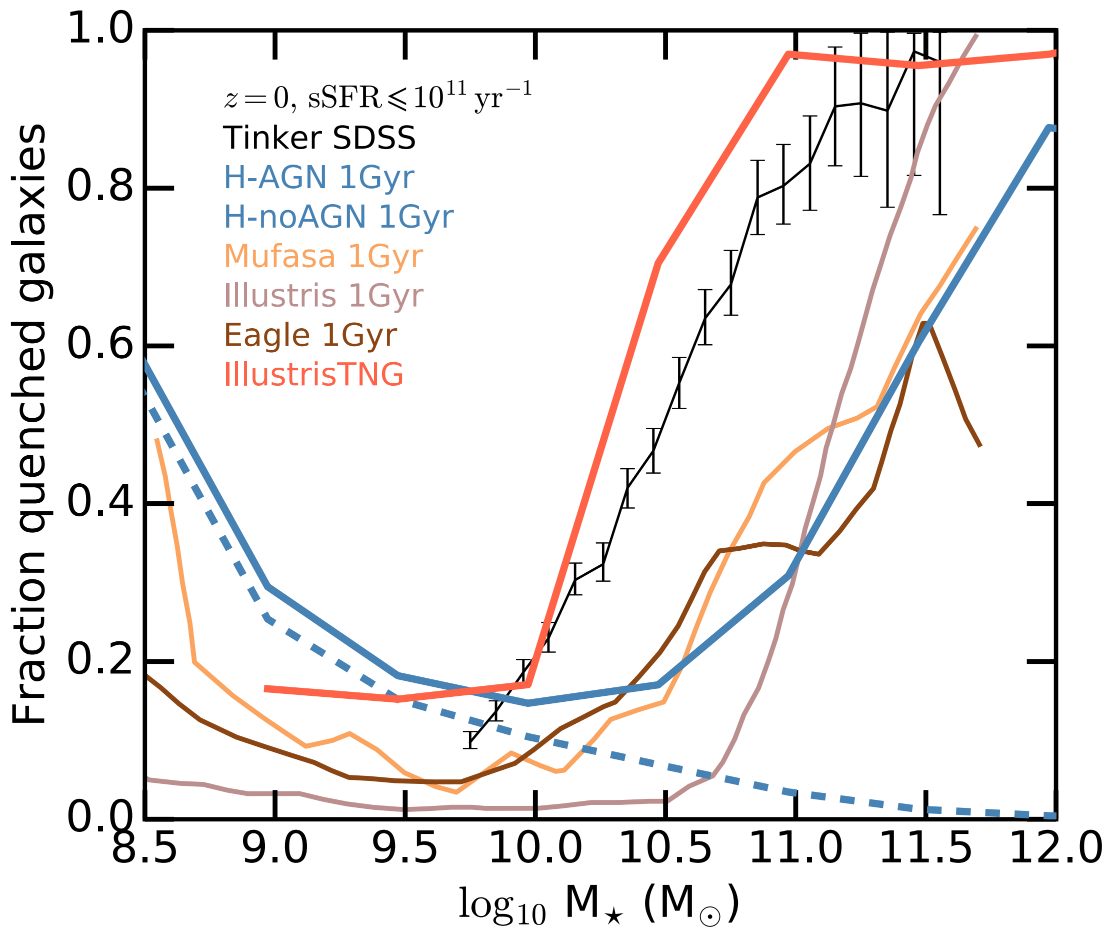
Need to prevent gas cooling in large halos, and to sustain suppression of star formation in time.

AGN feedback

All cosmological hydrodynamical simulations rely on AGN feedback to suppress SFR in massive galaxies and produce the population of quiescent massive galaxies.

To what extent the simulations are able to recover observational trends of the galaxy and BH populations ?

Fraction of galaxies with suppressed star formation rate (*quenched* galaxies).



See also Bonnari et al. 2018 for IllustrisTNG and the IQ collaboration at the CCA.

All simulations have their own recipe for AGN feedback, but same idea !

Rate of energy injected in BH surroundings

$$\dot{E}_{\rm AGN} = \epsilon_{\rm f}\epsilon_{\rm r}\dot{M}_{\rm BH}c^2$$

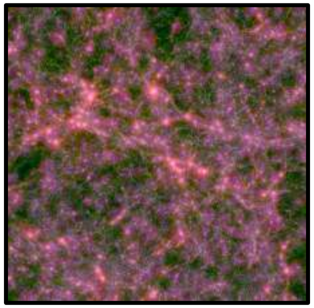
Eddington ratio

$$f_{\rm Edd} = \dot{M}_{\rm BH}/\dot{M}_{\rm Edd}$$

Simulation
EAGLE
Schaye+14

Single mode feedback: injection of thermal energy into BH surroundings (stochastically)

Simulation
Horizon-AGN
Dubois+14,15



2 mode feedback: thermal for $\dot{M}_{\rm BH}/\dot{M}_{\rm Edd} > 0.01$

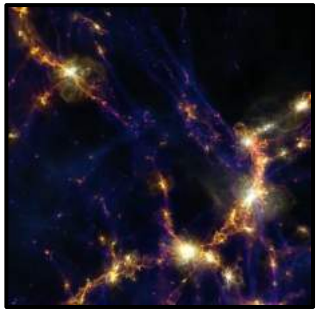
kinetic bipolar outflows for $\dot{M}_{\rm BH}/\dot{M}_{\rm Edd} < 0.01$

Simulation
Illustris
Sijacki+07,15

2 mode feedback: thermal for $\dot{M}_{\rm BH}/\dot{M}_{\rm Edd} > 0.01$

bursty thermal energy into hot bubbles (r=50 kpc) displaced away from the galaxies for $\dot{M}_{\rm BH}/\dot{M}_{\rm Edd} < 0.01$

Simulation
IllustrisTNG
Weinberger+17



2 mode feedback: thermal for $\dot{M}_{\rm BH}/\dot{M}_{\rm Edd} > X$

bursty kinetic wind $\dot{M}_{\rm BH}/\dot{M}_{\rm Edd} < X$

transition between modes depends on Eddington ratio and BH mass

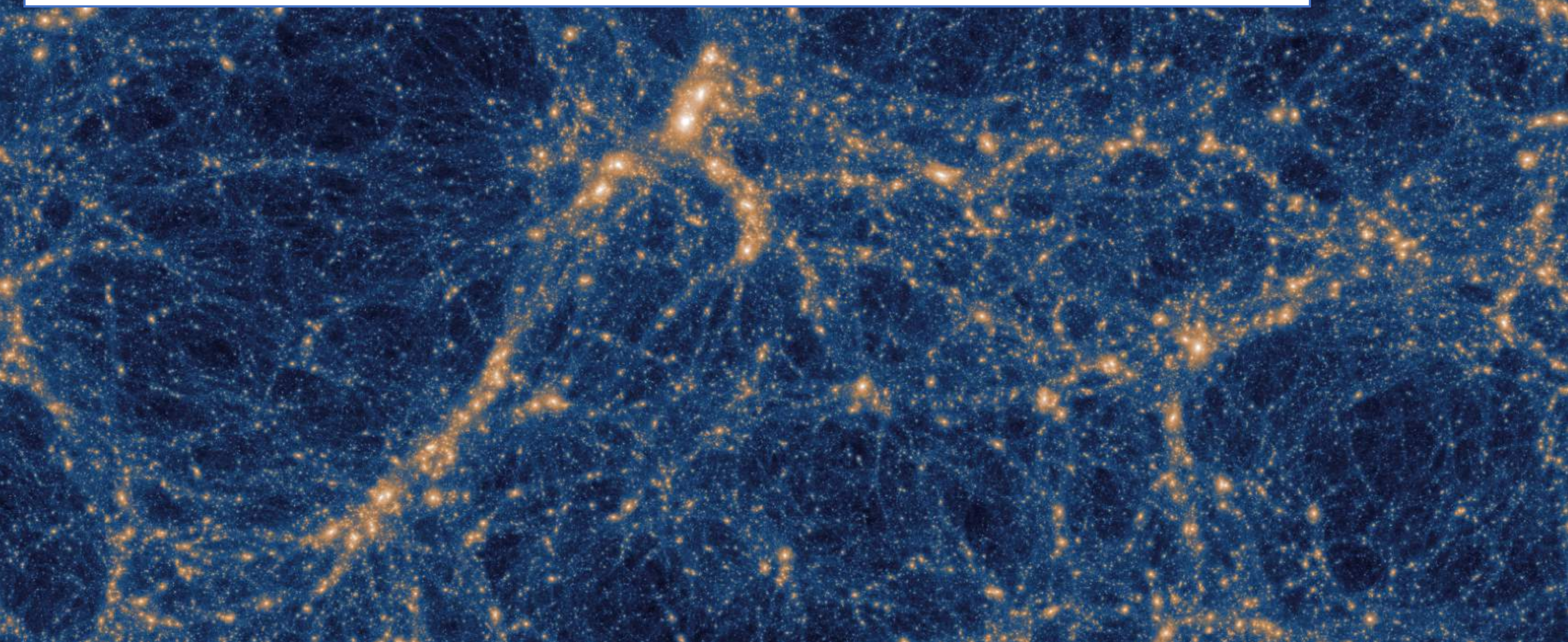
Cosmological hydro simulations IllustrisTNG100 and IllustrisTNG300

More details in Pillepich+17b, Weinberger+17,18

$m_{DM} = 7.5 \times 10^6\, M_\odot$, $m_{DM} = 60 \times 10^6\, M_\odot$
$m_{gas} = 11 \times 10^6\, M_\odot$, $m_{gas} = 1.4 \times 10^6\, M_\odot$

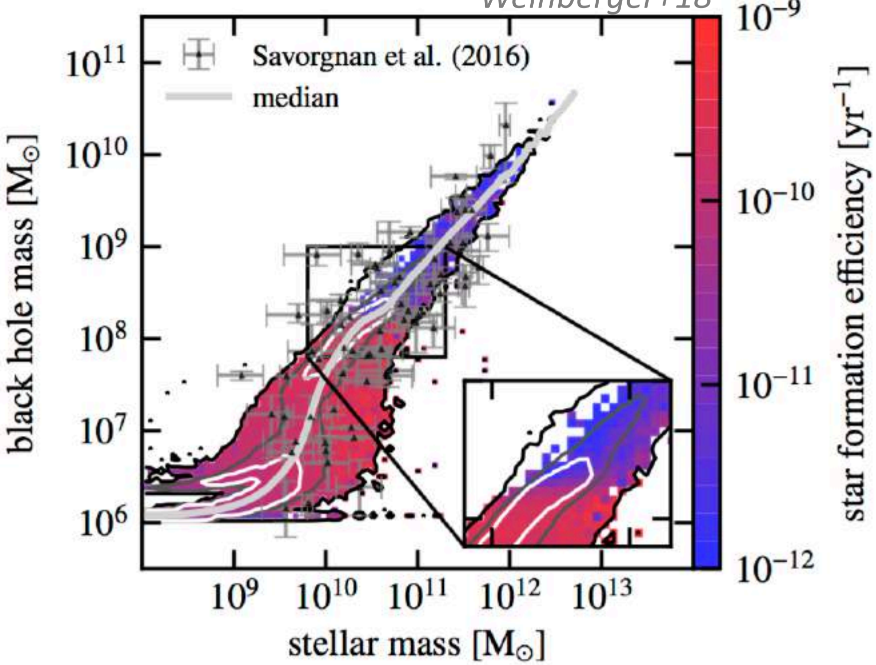
Radiative cooling.
Photoheating by UV background.
Star formation and SN feedback, metal enrichment.

Black hole formation, Bondi accretion.
2 mode AGN feedback: thermal mode, and **efficient** kinetic mode.



M_{BH}-M_* relation

Weinberger+18

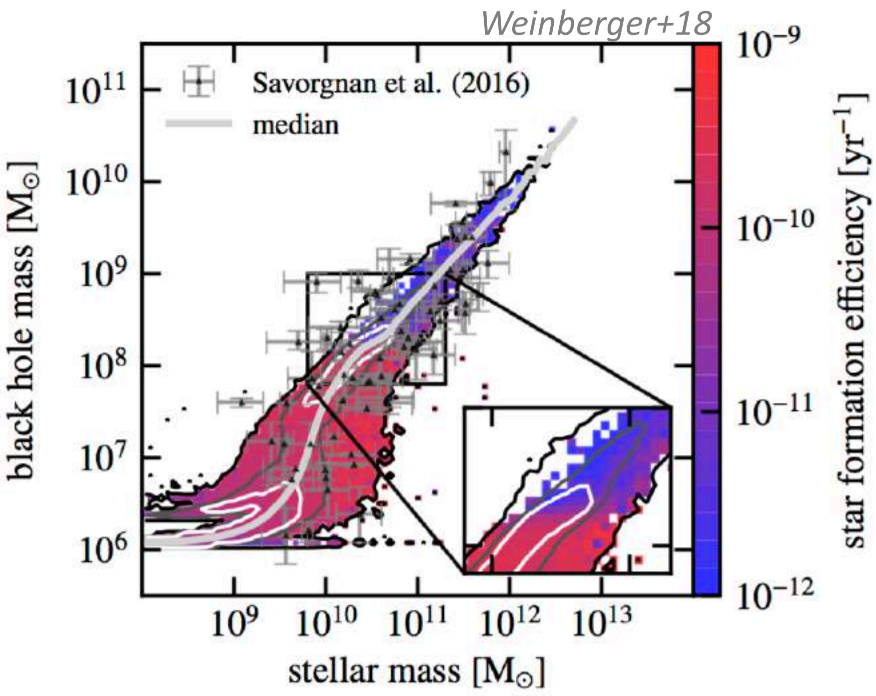


Overall good agreement between TNG300 and the observational sample of *Savorgnan+16*.

Very tight correlation in TNG100 and TNG300.
The broad line AGN region is not reproduced in TNG100.

The BH population of IllustrisTNG

M_{BH}-M_* relation



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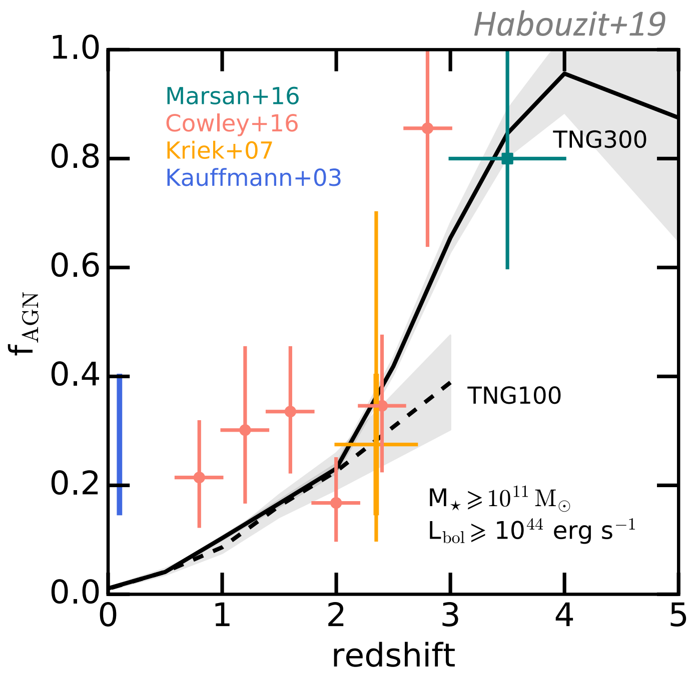
AGN in massive galaxies

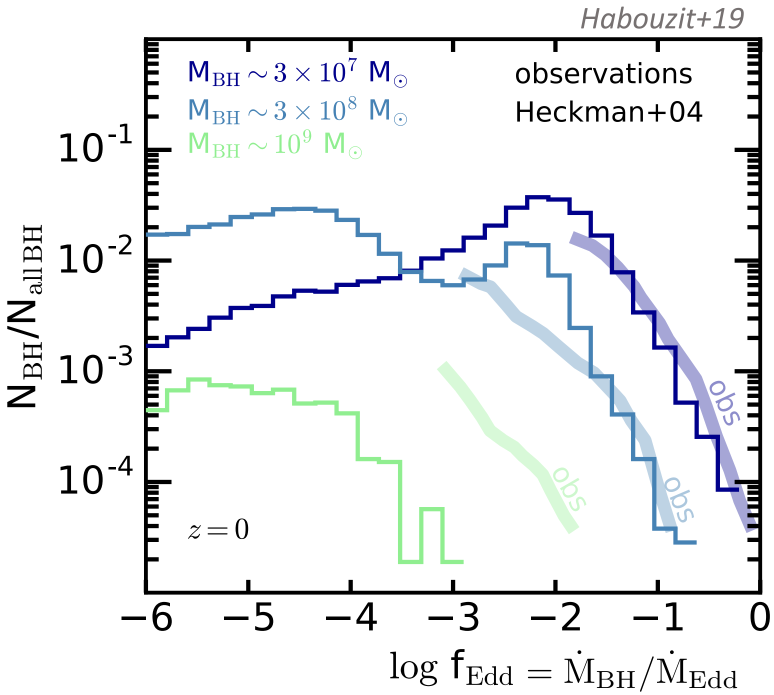


For the first time: statistics with the large volume of TNG300.

Good agreement at high redshift.
Lack of bright AGN in massive galaxies at *low redshift*.

Eddington ratio distribution of IllustrisTNG

Eddington ratio distribution

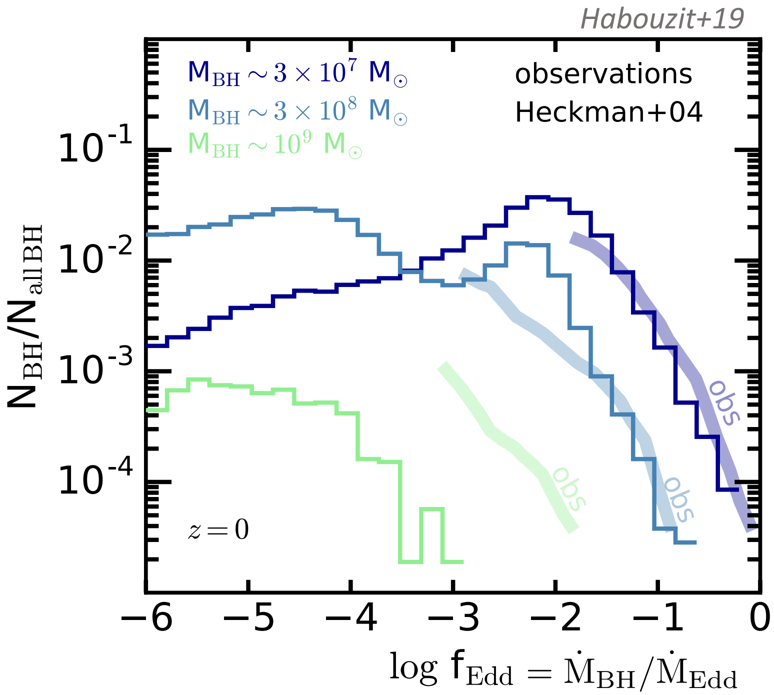


Good agreement for M_{BH}< a few 10^8 M_{sun}

Massive BHs of M_{BH}>10^9 M_{sun} have lower Eddington ratios than the observed ones.

Eddington ratio distribution of IllustrisTNG

Eddington ratio distribution



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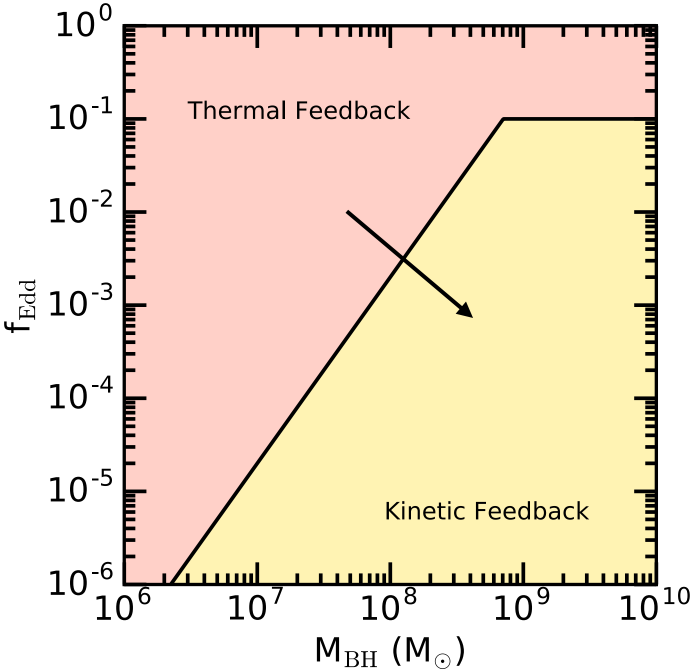
2 mode AGN feedback



Massive BHs of ~10^8 $M_\odot$ transition from the thermal mode to the very efficient kinetic mode.

Thermal feedback mode: continuous injection of thermal energy into BH surroundings.
Kinetic feedback mode: pulsed and directed injection of momentum.

To what extent the llustrisTNG simulations produce a population of galaxies in good agreement with observations?

Formation of the population of massive quiescent galaxies $M_{\star} \geqslant 10^{10}\,\mathrm{M}_{\odot}$ $1 \leqslant z \leqslant 3$

$\log_{10}$ sSFR (Gyr^{-1})

Extended star-forming galaxies (eSF)

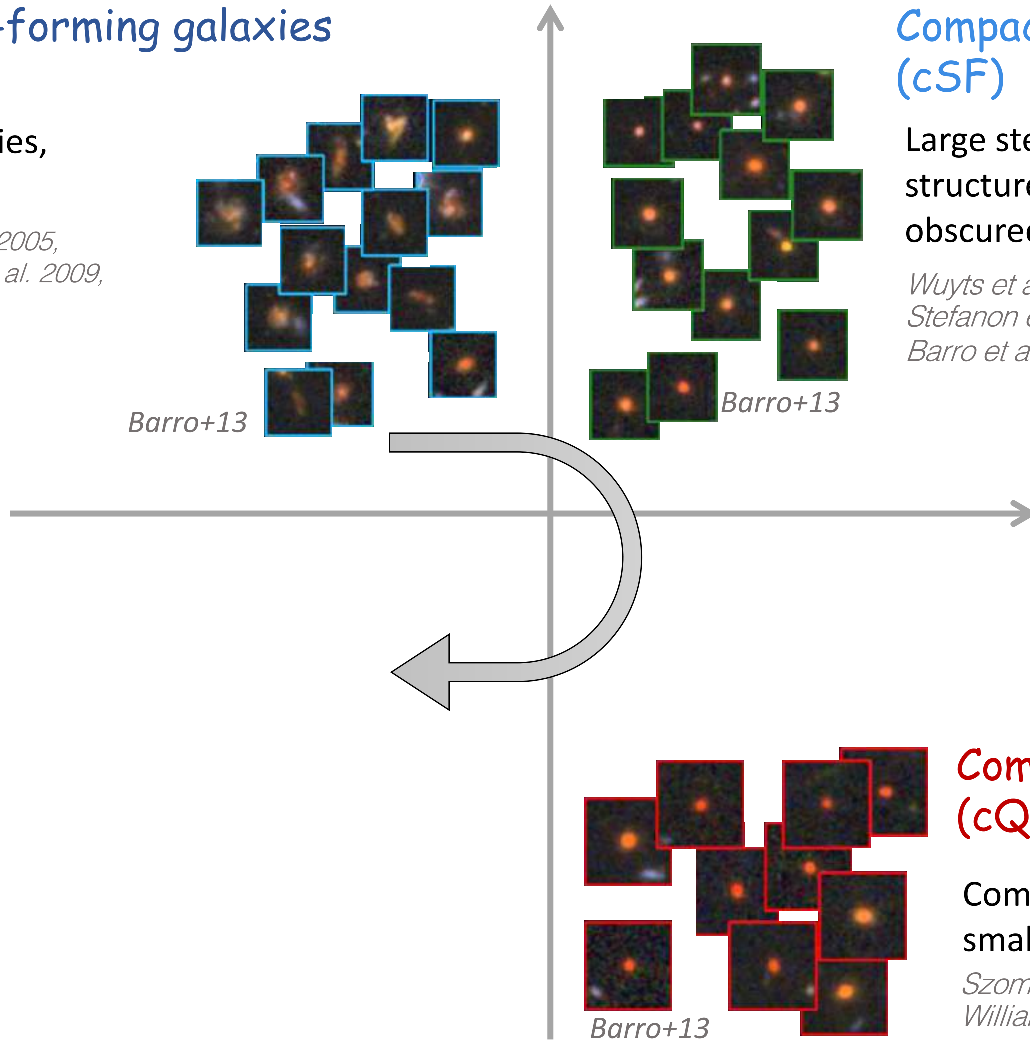
Disk-like morphologies, irregular, clumpy.

Elmegreen & Elmegreen 2005, Elmegreen 2007, Kriek et al. 2009, Guo et al. 2012

Compact star-forming galaxies (cSF)

Large stellar mass, spheroid-like structures, more compact, heavily obscured SF.

Wuyts et al. 2011, Petel et al. 2012, Stefanon et al. 2013, Williams et al. 2013, Barro et al. 2013



$\log_{10}\Sigma_e$ ($M_{\odot}$/pkpc^{-2})

with $\Sigma_e = 0.5\, M_*/\pi r^2$

compactness

Compact quiescent galaxies (cQ)

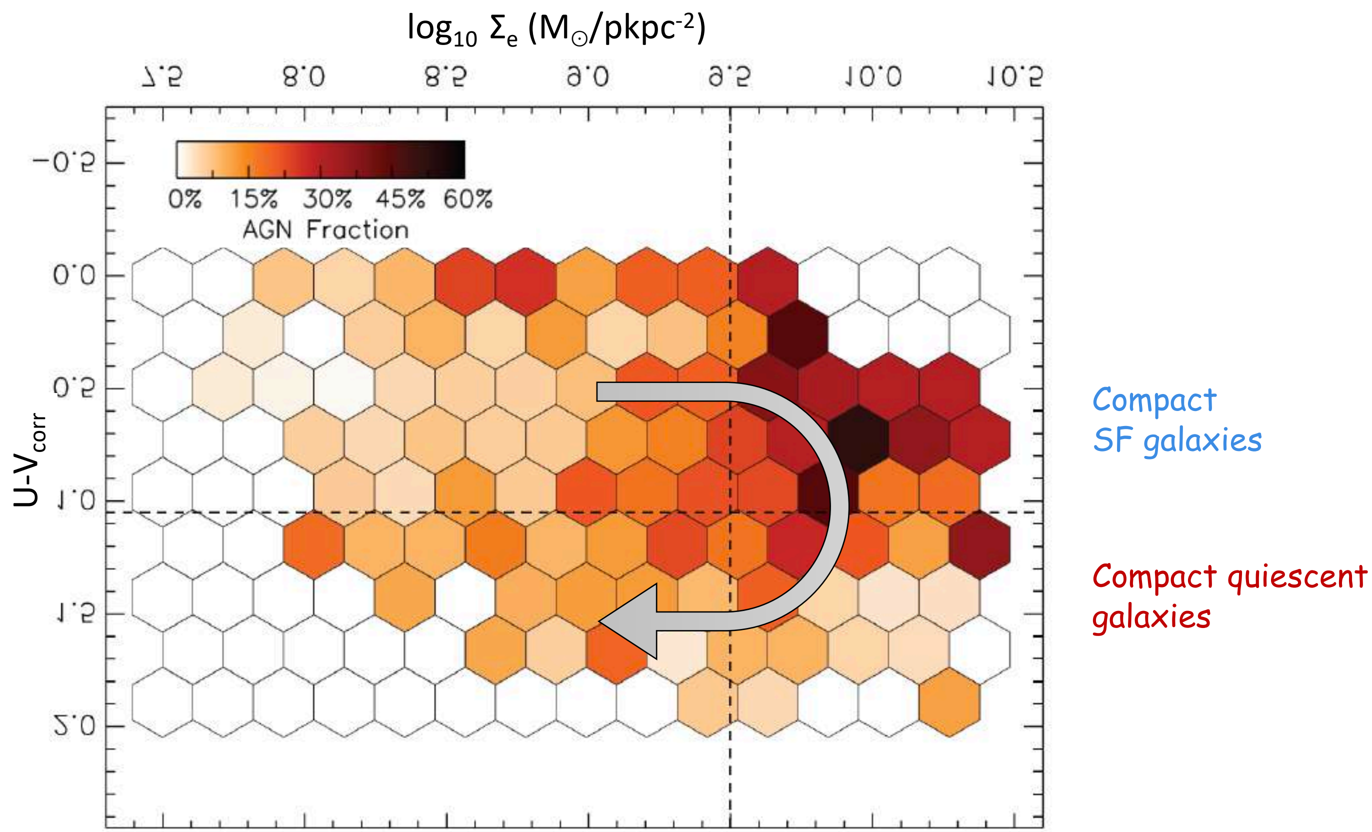
Compact elliptical, suppressed SFR, small sizes.

Szomoru et al. 2011, Bell et al. 2012, Williams et al. 2010, Wuyts et al. 2011

See also Zolotov+15, Tachella+16, Dubois+16, Choi+18, for the quenching of massive galaxies.

Observational evidence for a high fraction of AGN among compact star-forming galaxies

- Clumpy and compact galaxies at z~0.11 harbor a high AGN fraction in SDSS *Trump+13*
- Compact star-forming galaxies in GOODS-S at z~2 more likely to host bright AGN *Barro+14*
- 40% of compact star-forming galaxies in 1.4⩽z⩽3 in the candels fields host an AGN *Kocevski+17*



Kocevski+17

What is the dependence of the AGN fraction on a galaxy's location in the sSFR-compactness diagram?

Cosmological hydro simulations IllustrisTNG100 and IllustrisTNG300

More details in Pillepich+17b, Weinberger+17,18

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Radiative cooling.
Photoheating by UV background.
Star formation and SN feedback, metal enrichment.

Black hole formation, Bondi accretion.
2 mode AGN feedback: thermal mode, and **efficient** kinetic mode.

Galaxy sizes in r-band (projected) from *Genel+17*

Observations from the candels fields

(GOODS-S, UDS, EGS, GOODS-N, *Grogin+11*)

Galaxies with $10^{10}\ M_\odot$ selected in H_{160} band, sizes measured with GALFIT *(Peng+02)* and the HST/WFC3 H-band images. K correction to correct to rest-frame r band.

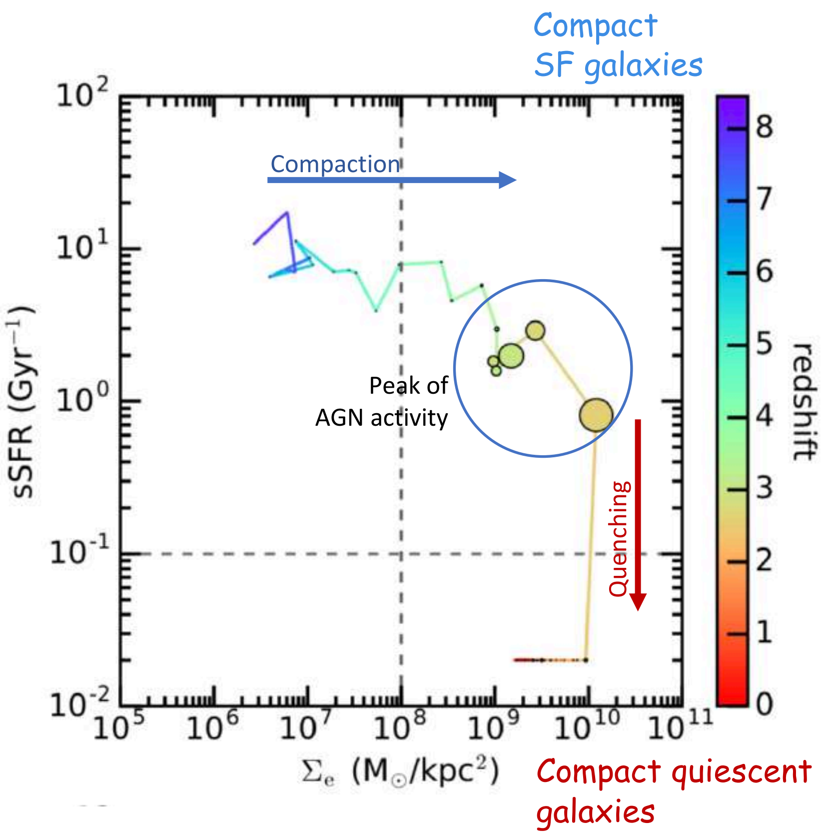
AGN sample from *Kocevski+17 (Xue+11, Xue+16, Nandra+15).*

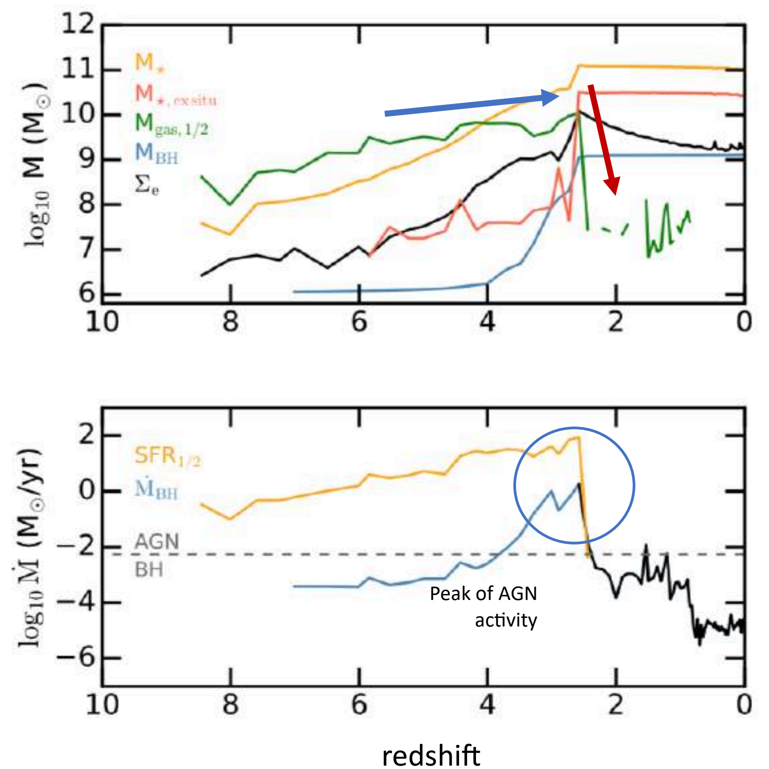
→ 3208 galaxies in $1.4 \leqslant z \leqslant 3$, among which 313 X-ray selected AGN with $Lx \geqslant 10^{42}$ erg/s.

The full story for an individual TNG galaxy

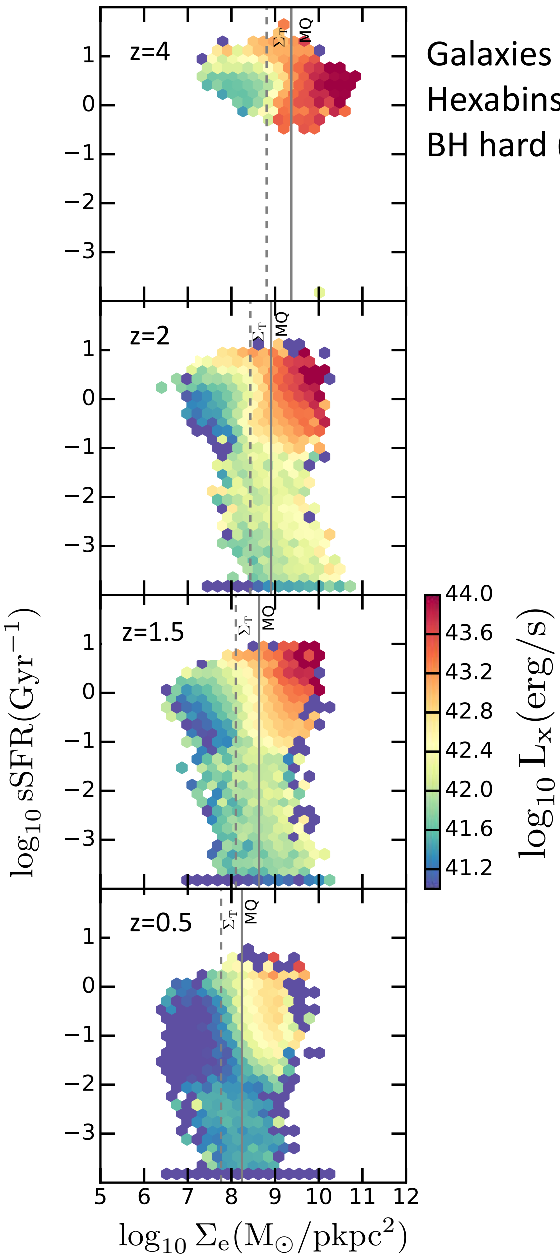
→ We identify 4500 massive quiescent galaxies at z=0, and trace them back in time.

1. *Compaction* while the galaxy is still forming stars.
2. Peak of SFR and AGN activity during the *star-forming compact* galaxy phase, corresponding to a minimum of the galaxy size.
3. BH enters the efficient kinetic mode of AGN feedback.
4. *Quenching*: SFR and BH activity are suppressed.





Dependence of AGN fraction on a galaxy's location of the sSFR-Σ_e diagram



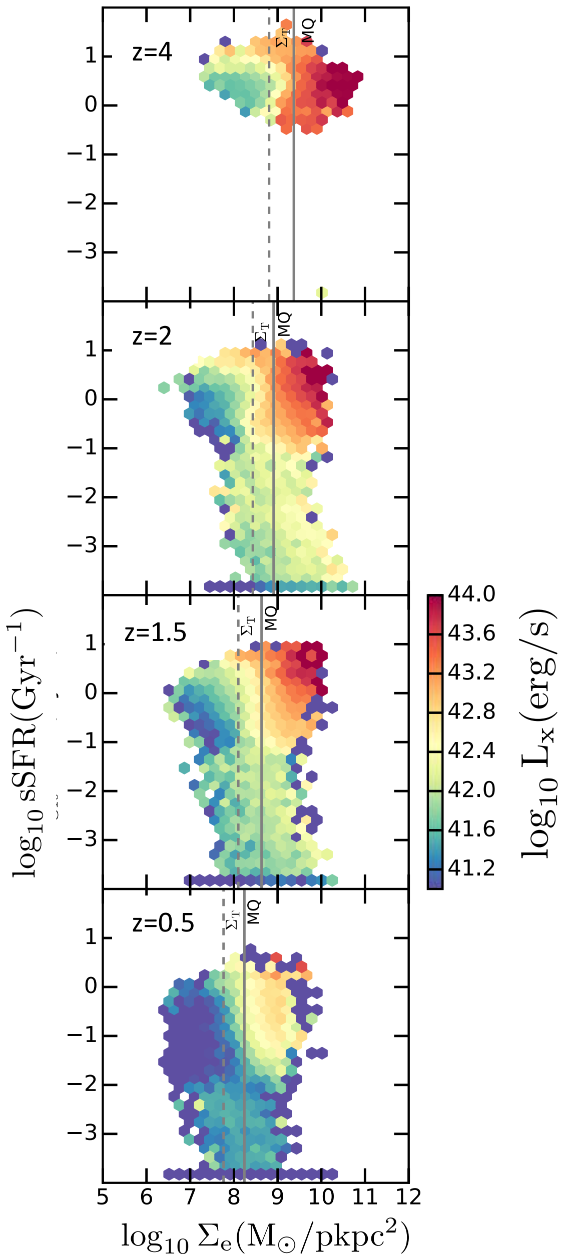
Galaxies with $M_\star \geqslant 10^{9.5}\,\mathrm{M}_\odot$
Hexabins color coded by
BH hard (2-10 keV) X-ray luminosity.

Compact star-forming galaxies host BHs with higher X-ray luminosity.

Compact quiescent galaxies host very faint AGN, or quiescent BHs.

Dependence of AGN fraction on a galaxy's location of the sSFR-Σ_e diagram

Habouzit+19

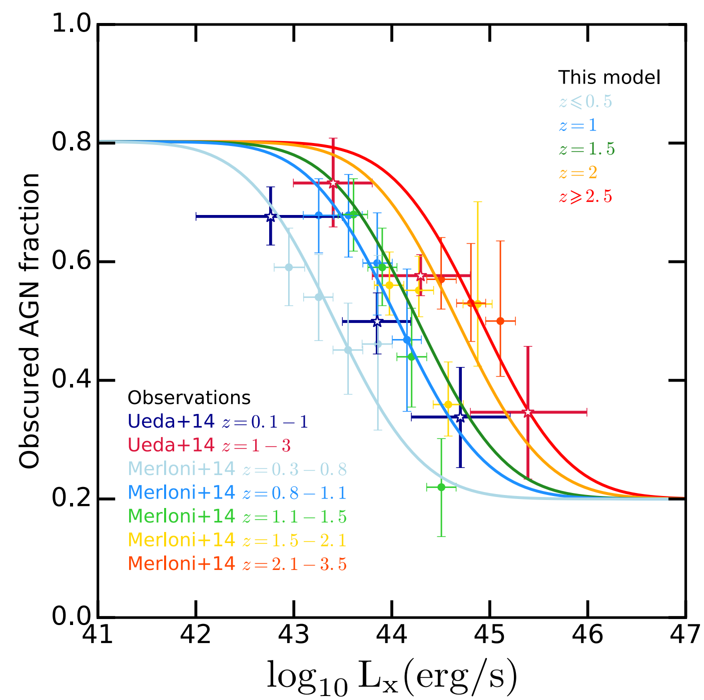


Correction for Obscured AGN

→ We follow *Ueda et al. 2014, Merloni et al. 2014*

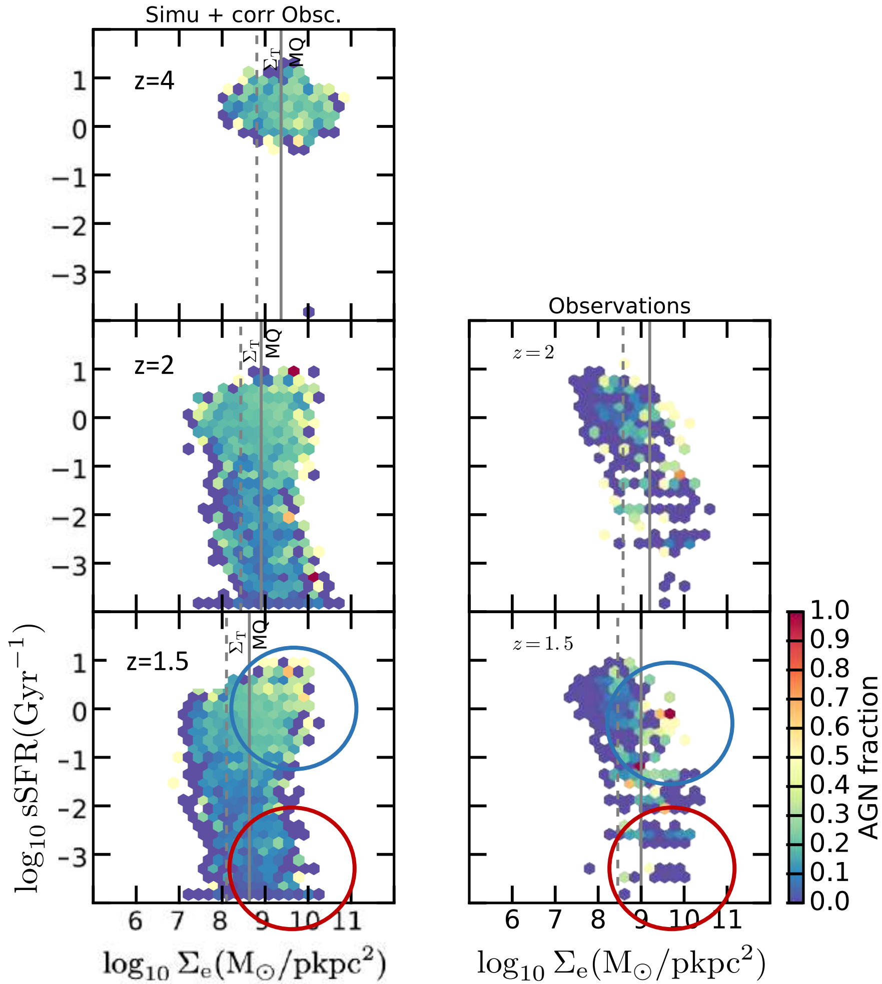
→ Build a redshift-dependent model with anti-correlation between the obscured AGN fraction and BH X-ray luminosity.

→ Most likely also depends on galaxy structural properties.
See Chang+17, galaxies with obscured AGN are more compact.



Dependence of AGN fraction on a galaxy's location of the sSFR-Σ_e diagram

Habouzit+19

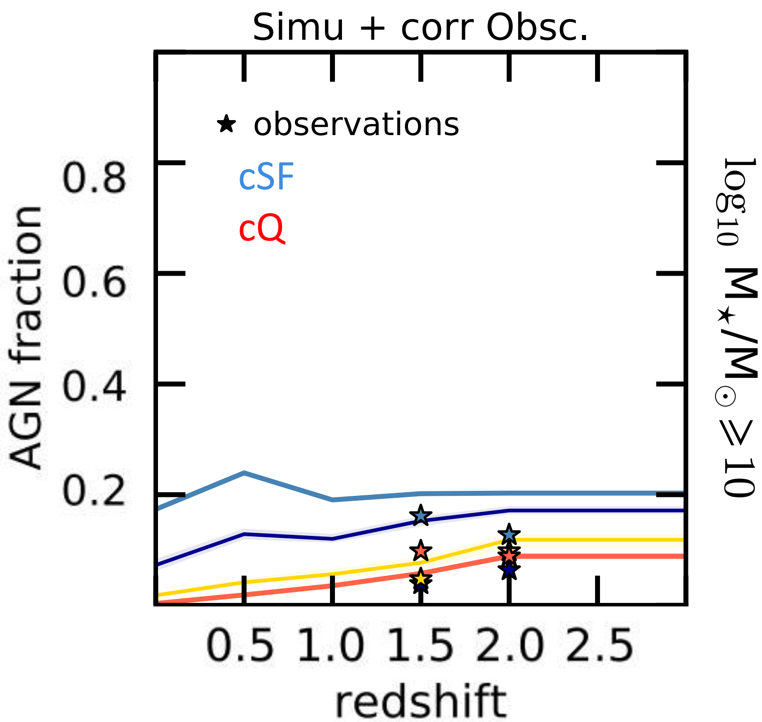


→ *Compact SF* galaxies host more and brighter AGN than the *compact quiescent* galaxies.

→ Qualitatively in good agreement with observations. Trump+13, Barro+14, Kocevski+17

Dependence of AGN fraction on a galaxy's location of the sSFR-Σ_e diagram

Habouzit+19



→ 20% of the **cSF** host a X-ray AGN in the simulation, 13-16% in the observations.

→ Only 6-9% of the simulated **cQ** do so, 9-10% in the observations.

The AGN fraction as a function of galaxy structural and star-forming properties in TNG is in good qualitative agreement with the candels observations.

Good quantitative agreement for $M_\star \geqslant 10^{10}\,\mathrm{M_\odot}$, but strongly depends on the fraction of obscured AGN.

The AGN feedback model in IllustrisTNG produces a population of massive galaxies in good agreement with observations (from candels).
However, the kinetic wind feedback mode may be too efficient for BHs of $M_{\rm BH} \geqslant \mathrm{a\,few}\,10^8\,\mathrm{M_\odot}$.

Formation, Growth, and Feedback of Supermassive Black Holes.

Formation and early growth of BHs

Direct collapse: unlikely to explain the presence of BHs in all normal galaxies, but could explain the population of rare high-z quasars.

PopIII remnants/Stellar clusters: BH growth is stunt by SN feedback in low galaxies of $<10^9$ M_{sun}. Our model reproduces the M_{BH}-M_* relation, good agreement for the hard X-ray and bolometric luminosity functions, and the observed lack of AGN in z=6 galaxies.

We need to keep improving BH formation modeling in simulations to build a comprehensive view of BH signatures in the early Universe, to maximize the scientific return of the observational missions Athena, LynX, LISA, WFIRST, JWST.

Understand the role of AGN feedback in regulating (massive) galaxies.

All cosmological simulations rely on AGN feedback modeling to sustain star-formation in time in massive galaxies.

Analysis of the new efficient pure kinetic AGN feedback mode of the IllustrisTNG simulations.
Good agreement between TNG and candels galaxies for the fraction of AGN in compact star-forming galaxies, which are the progenitors of the compact quiescent galaxies.

However, some discrepancies emerge for the population of BHs: massive BHs are too regulated.