Flatiron Institute
Center for Computational
Astrophysics

Formation and Growth of Supermassive Black Holes

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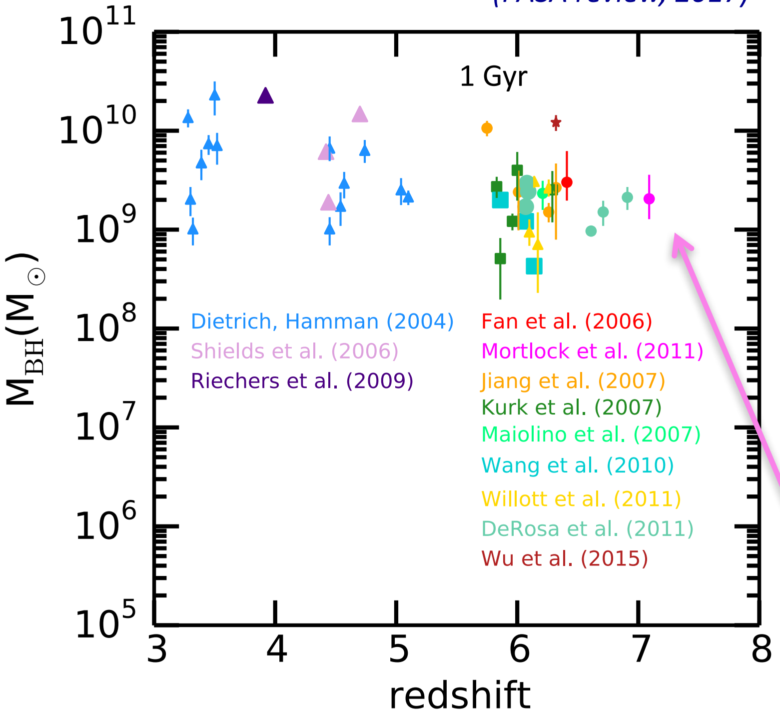
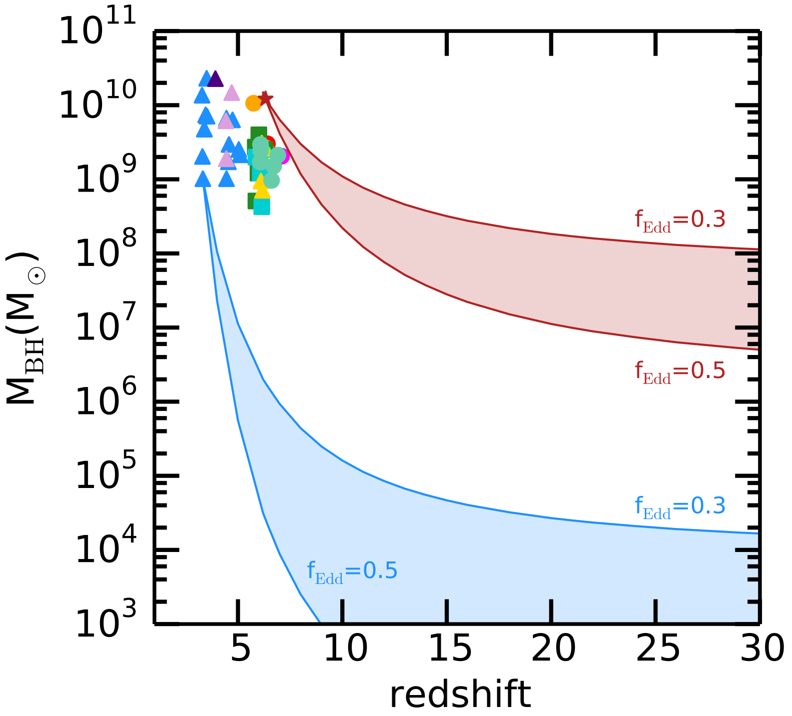
Constraint on BH formation from the population of quasars at high redshift

Valiante, Agarwal, MH, Pezzulli (PASA review, 2017)





ULAS J1120+0641 already in place only 770 Myr after the Big Bang *Mortlock et al. (2011)*

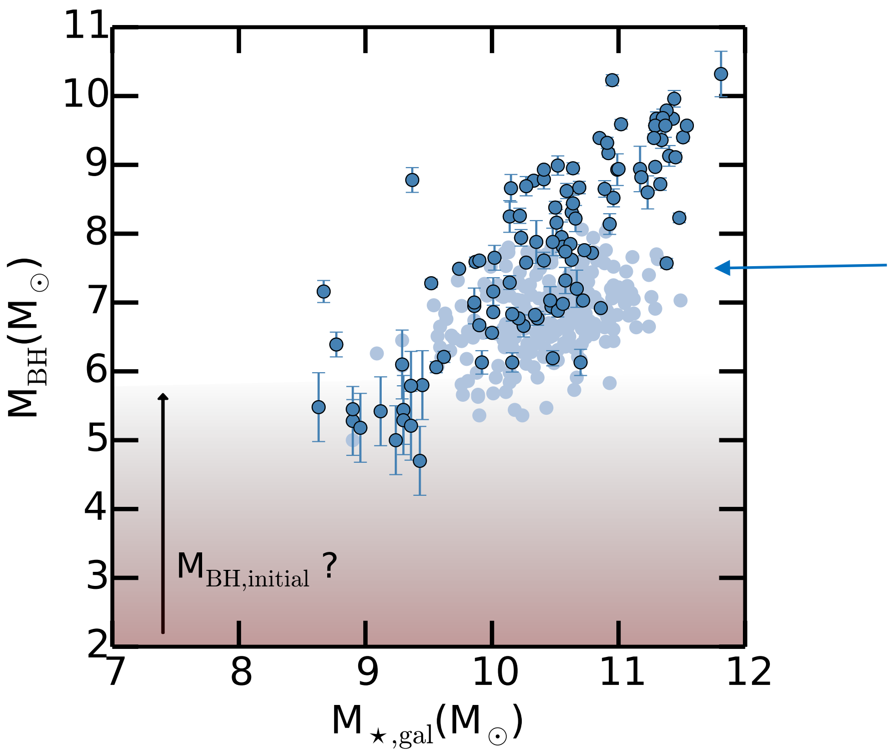
→ BHs must have formed in the early Universe in order to acquire 10^9 $M_\odot$ in less than 1 Gyr

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

Constraint on BH formation from present-day low-mass galaxies

→ Until recently, BHs were rarely looked for in low-mass galaxies, but observational evidence is accumulating showing that the population of massive BHs extends down to small galaxy masses

Greene & Ho (2004), Dong, Greene & Ho (2012), Reines, Greene, Geha (2013), Reines & Volonteri (2015), Baldassare et al. (2015)



Observational sample of local galaxies with z<0.055
Reines & Volonteri 2015

→ **Low-mass galaxies** are promising laboratories: the mass of the central BH does not differ much from its initial mass

Theoretical models for BH formation in the early Universe

BH seed mass

10^{4-6} $M_\odot$	10^3 $M_\odot$	100 $M_\odot$
Direct collapse	**Nuclear stellar clusters**	**Pop III remnants**

Direct collapse

- $M_{halo} > 10^{7-8}$ $M_\odot$
- Metal-free
- Cooling by H

=> very high Jeans mass
=> reduced winds loss

Loeb & Rasio (1994)
Bromm & Loeb (2003)
Spaans & Silk (2006)
Begelman et al. (2006)
Lodato &Natarajan (2006)
Latif et al. (2013)
Habouzit et al. (2016a, 2016b)

Nuclear stellar clusters

- $M_{cluster} \sim 10^5$ $M_\odot$
- Metal-poor
- Cooling by metals

=> low Jeans mass
=> reduced winds loss

Omukai, Schneider & Haiman (2008)
Devecchi & Volonteri (2009)
Regan & Haehnelt (2009)
Katz, Sijacki & Haehnelt (2015)
Habouzit et al. (2016c)

Pop III remnants

- $M_{minihalo} \sim 10^{5-6}$ $M_\odot$
- Metal-free
- Cooling by H_2

=> high Jeans mass
=> reduced winds loss

Madau, Rees (2001)
Volonteri, Haardt, Madau (2003)
Habouzit et al. (2016b,2016c)

Building a theoretical framework to study BH formation and growth

- **Code Ramses**: Grid-based hydro solver with adaptive mesh refinement *Teyssier (2002)*

- Cooling
- Star formation
- Supernova feedback *Dubois & Teyssier (2008), Teyssier et al. (2013), Dubois et al. (2015)*
- **BH formation with sink particles**

  MH, Volonteri, Dubois (2016)

  Regions to form BHs are identified on local gas and stellar properties
  See also Dubois et al. 2010, Bellovary et al. 2011
  BHs form in metal poor ($Z<10^{3.5}Z_\odot$), overdense, bound collapsing regions
  Theoretical Pop III stellar mass is proportional to the local gas density

- BH accretion: Bondi-Hoyle accretion, capped at the Eddington limit
- AGN feedback: isotropic injection of thermal energy *Dubois et al. (2012)*

Cosmological hydro. set of simulations
SuperCHUNKY

Box size 10 cMpc
Dark matter resolution 1.6×10^6 $M_\odot$
Spatial resolution 75 pc
Redshift 100 - 2
3 SN feedback simulations

3 different implementations of supernova feedback

MH, Volonteri, Dubois (2016)

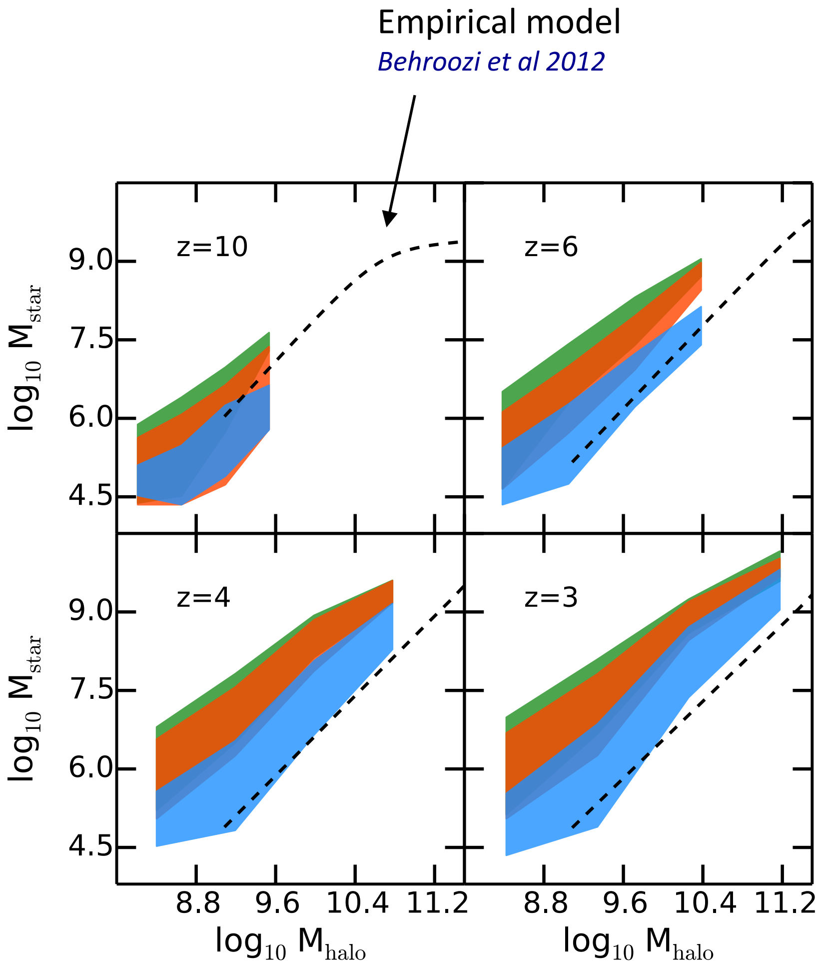
Thermal SN feedback
releases only internal energy
Dubois & Teyssier (2008)

Kinetic SN feedback
reproduces a Sedov blast wave
Dubois & Teyssier (2008)

WEAK
SN
FEEDBACK

Delayed cooling SN feedback
Prevents cooling after a SN explosion
Teyssier et al. (2013)
Dubois et al. (2015)

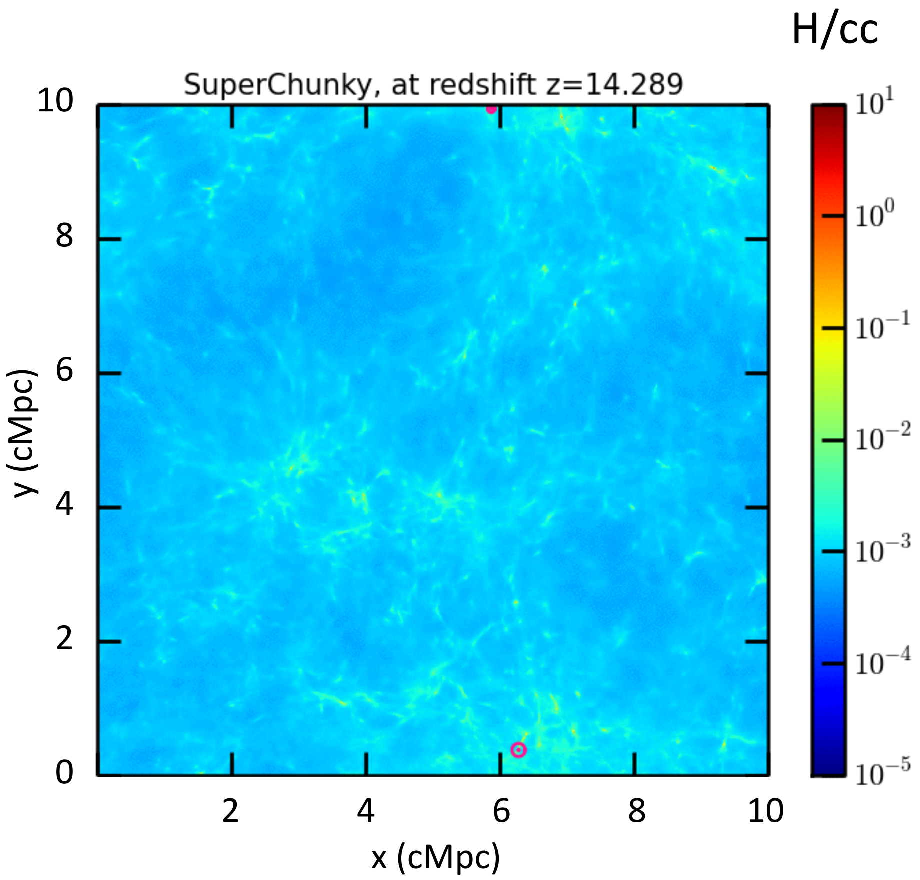
STRONG
SN
FEEDBACK



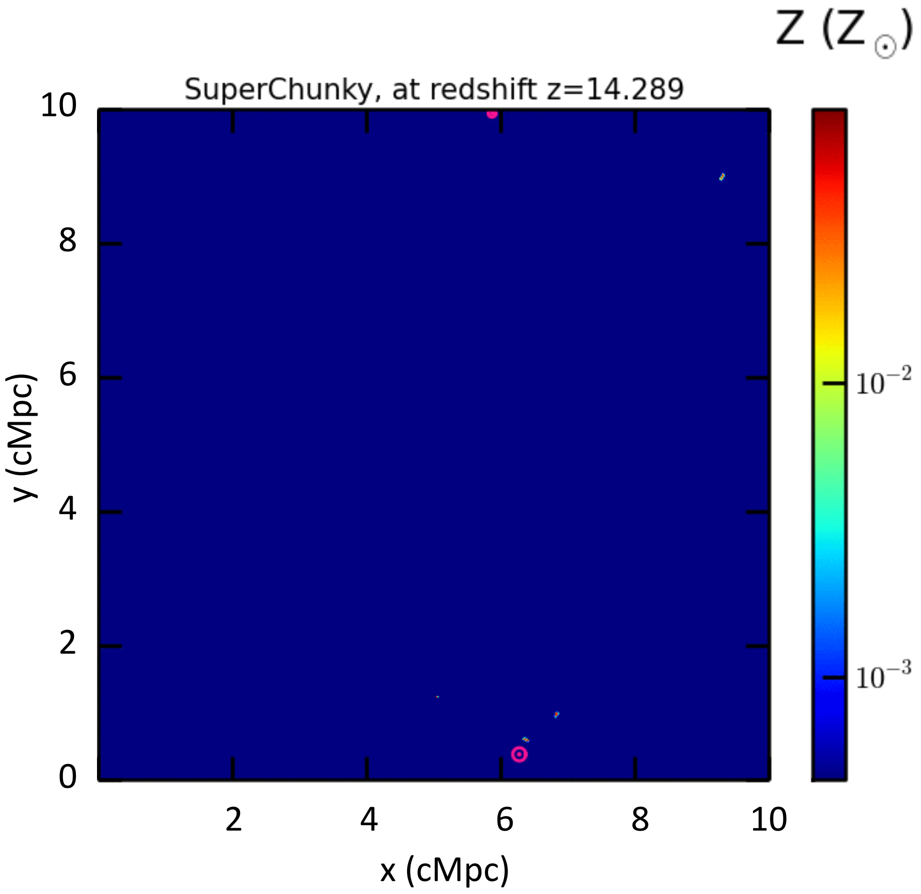
BH formation

MH, Volonteri, Dubois (2016)

Gas density map



Metallicity map



→ BHs form in dense and metal poor regions according to theoretical prescriptions

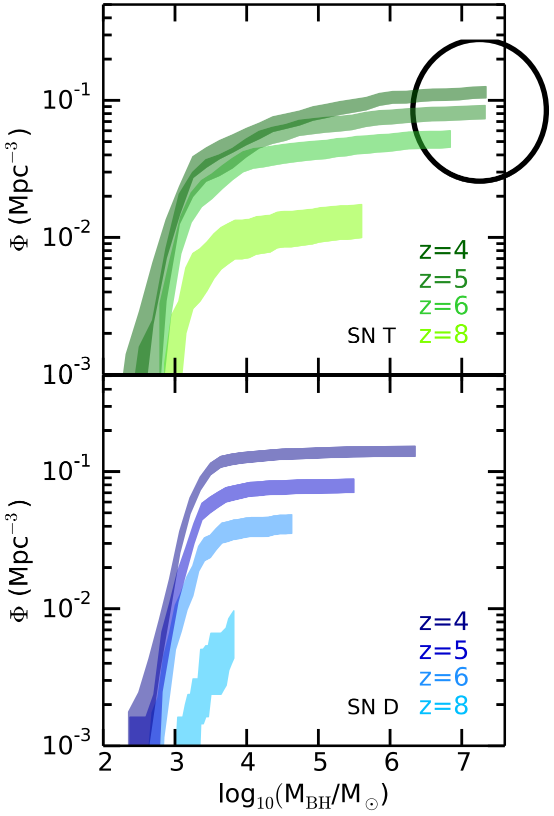
Time evolution of BHs

MH, Volonteri, Dubois (2016)

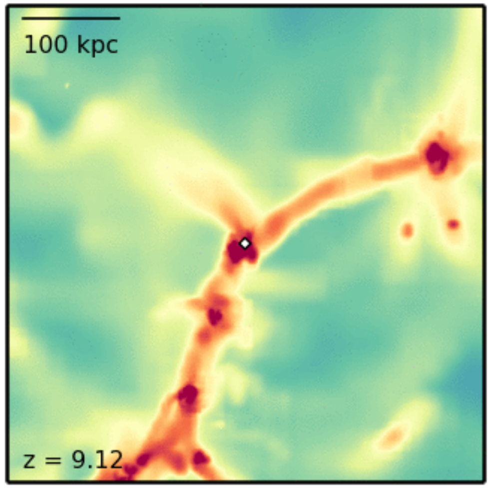
Cumulative BH mass function

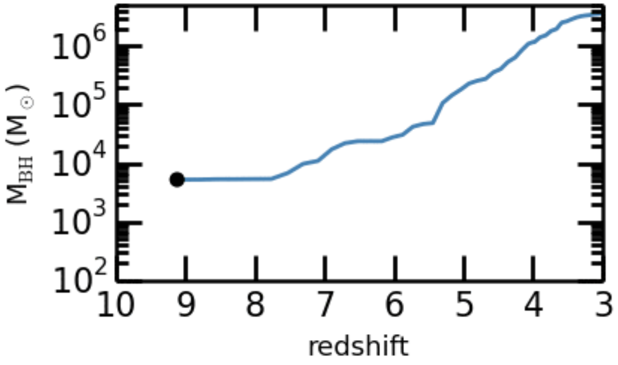
WEAK
SN
FEEDBACK

STRONG
SN
FEEDBACK



Time evolution of BH mass



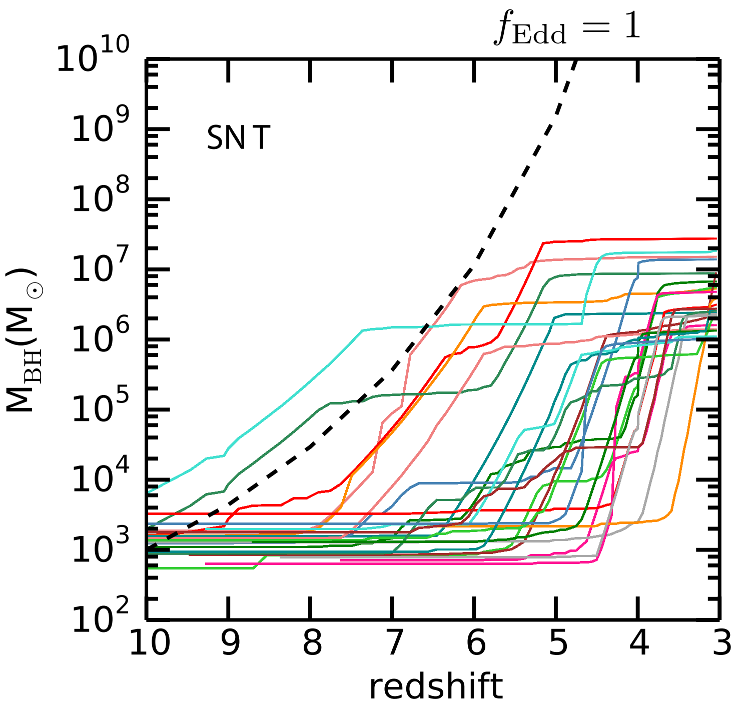


→ Strong SN feedback leads to lower BH accretion rates, and to a less massive population of BHs.

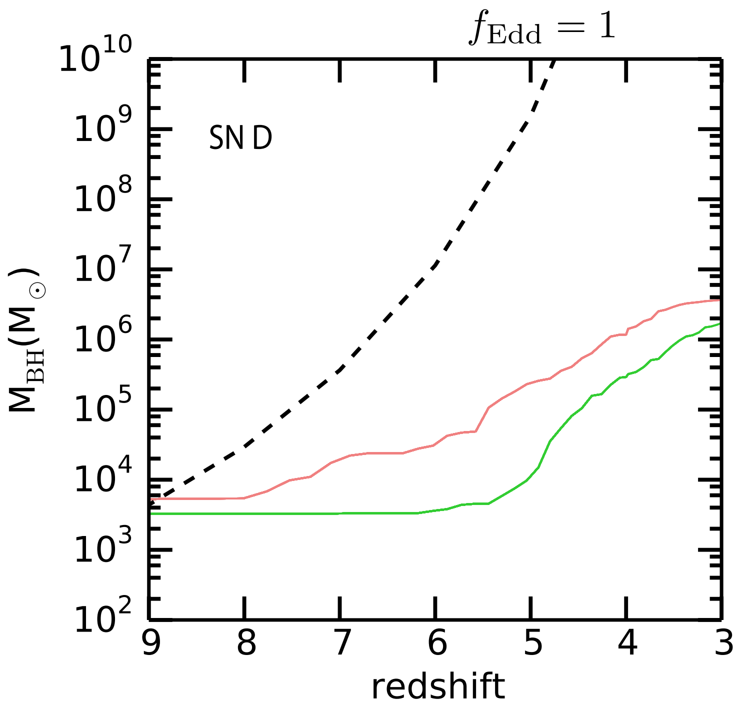
Time evolution of BHs

MH, Volonteri, Dubois (2016)

Weak SN feedback



Strong SN feedback



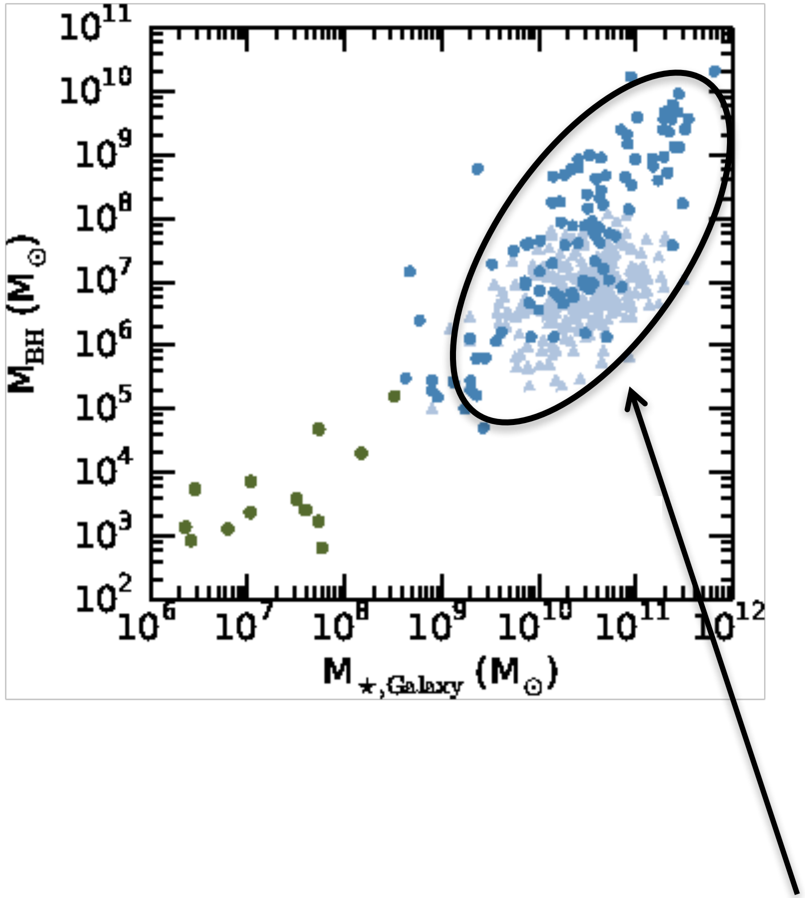
→ Growth of BHs that reach 10^6 $M_\odot$ by z=3

→ BHs in the weak SN feedback simulation are more numerous, and reach higher masses

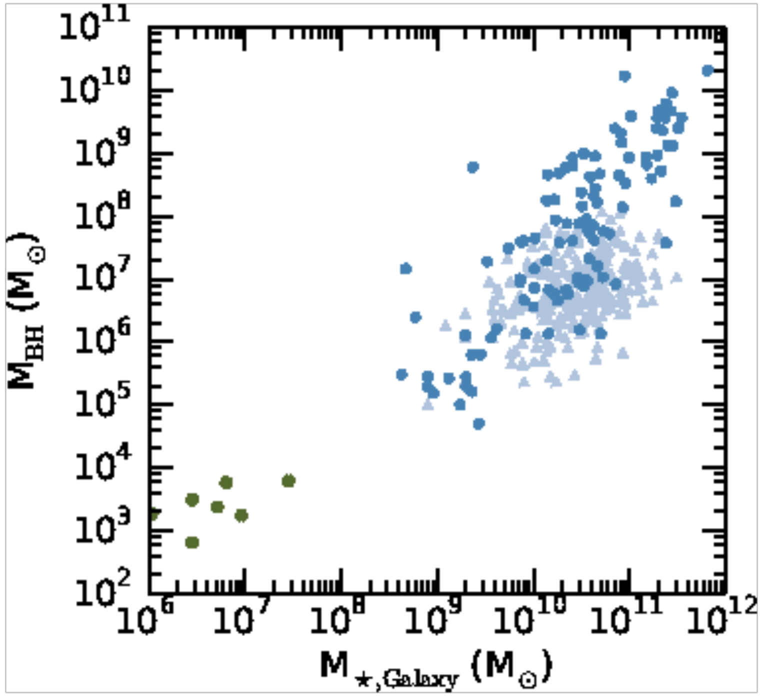
Comparison with observations

MH, Volonteri, Dubois (2016)

Weak SN feedback



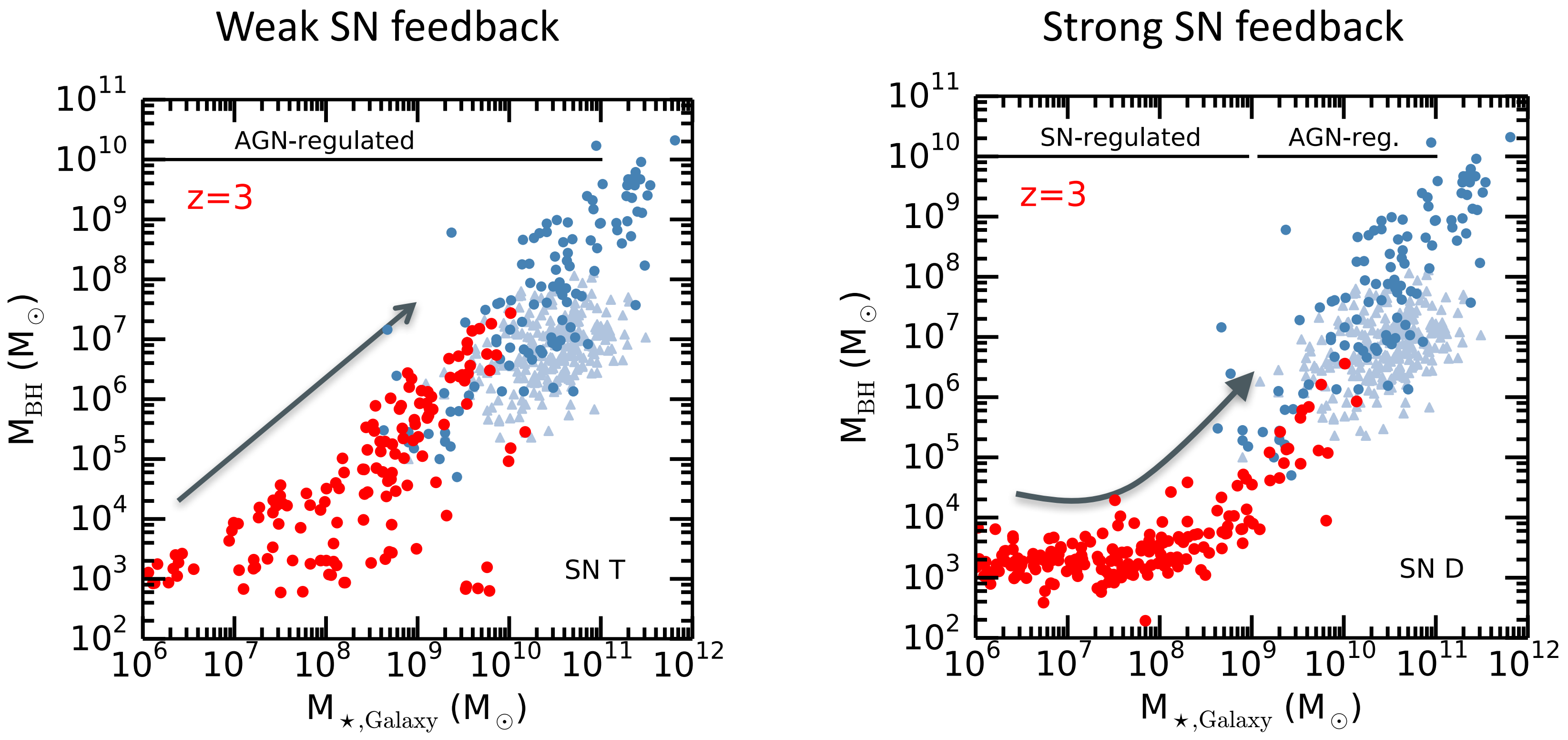
Strong SN feedback



Observational sample of
local galaxies with z<0.055
Reines & Volonteri 2015

Comparison with observations

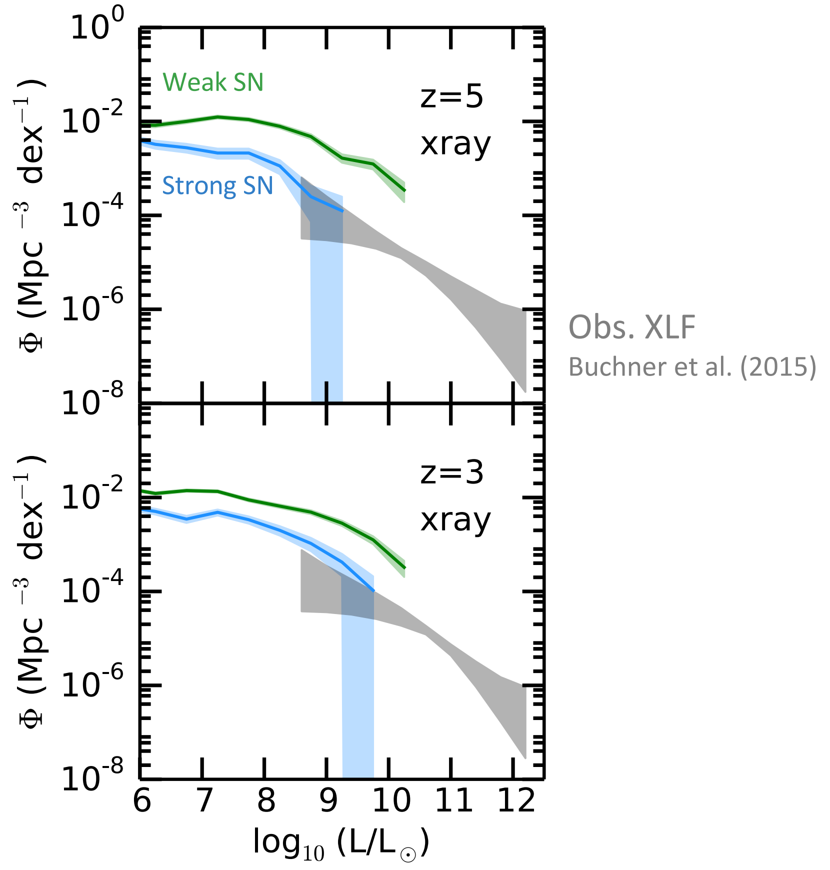
MH, Volonteri, Dubois (2016)



- Our high-z predictions connect the low-z observations
- Linear co-evolution between BHs and their host galaxies
- BH growth is regulated by AGN feedback

- Our high-z predictions connect the low-z observations
- Non linear co-evolution between BHs and their host galaxies
- BH growth is regulated by SN feedback, and AGN feedback at later time
- BHs at stuck at low-mass
- Ungrown BHs are most common in low-mass galaxies

Validation of the BH model with observations



BH luminosity function

- Simulations with weak SN feedback produce a number of AGN that is more than one order of magnitude higher than what is expected from observations
- Better agreement for the strong SN feedback simulation

Number of high redshift AGN candidates

Only 3 AGN candidates in CDF-S, $6<z<7$, $L_x>10^{42.9}$ erg/s, ~150 arcmin^2

Giallongo et al. 2015 , Treister et al. 2013, Weigel et al. 2015, Cappelluti et al. 2016, Vito et al. 2016

In the simulation, including duty cycle and Compton thick AGN correction:

- Weak SN feedback: several tens or hundreds of candidates
- Strong SN feedback: 3-5 AGN, in better agreement with the observations

Two complementary methods to understand BH formation and growth

Today's low-mass galaxies
to look at pristine BHs

- Reveal BH initial properties such as initial seed mass
- Discriminate between BH formation models, e.g. with galaxy occupation fraction

  Greene 2012, Reines, Greene, Geha (2013), Miller et al. (2015), Reines & Volonteri (2015)

High-redshift galaxies
to look at the early stages of BH evolution

- Upcoming missions *JWST, WFIRST,* will give us an unprecedented view on high-z galaxies and BHs

  Natarajan et al. 2017, Volonteri et al. 2017

- Studied mission, e.g. *LynX*, could provide a strong constraint on the xray BH luminosity function (BH seed mass, Edd ratio distribution, occupation fraction)

  Vito et al. 2017 and talk

Cosmological hydro. simulation
APPLE

Box size 30 cMpc
Dark matter resolution 10^7 $M_\odot$
Spatial resolution 60 pc
Redshift 100-6
BH formation *Habouzit et al. 2016*

Preliminary

Observing and understanding the high-redshift Universe

Cosmological hydro. simulation
APPLE

Box size 30 cMpc
Dark matter resolution 10^7 $M_\odot$
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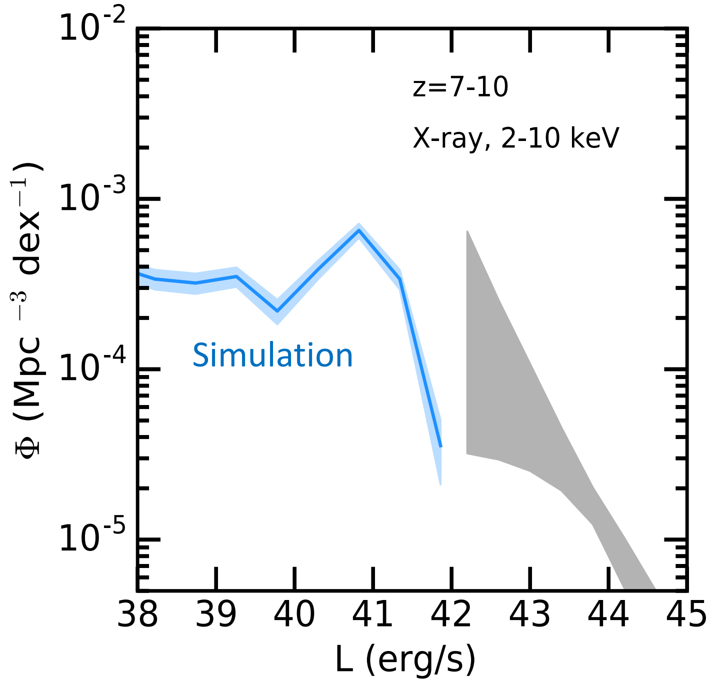
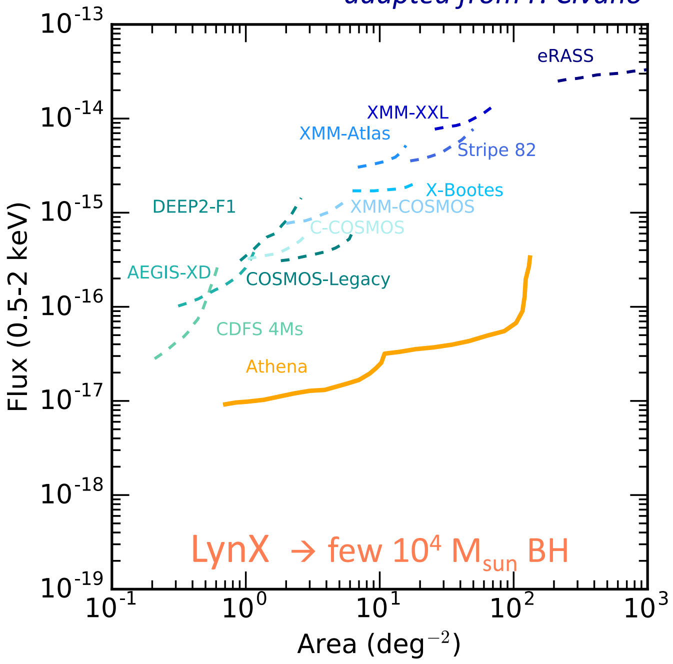
Redshift 100-6
BH formation *Habouzit et al. 2016*

Hard xray luminosity function at z>7



Obs. XLF, z=5
Buchner et al. (2015)

adapted from F. Civano



→ Xray luminosity function could strongly constrain a combination of BH properties
→ For a flux limit of 10^{-19} cgs, LynX mission could expect detecting ~ 800 deg^{-2} objects

Conclusion

New BH seeding model in large-scale cosmological hydro simulation, based on the **Pop III remnant and nuclear stellar cluster models**. *Habouzit et al. 2016c*
Based on local gas and stellar properties instead of halo properties.
Self-consistent BH initial mass distribution, instead of fixed mass BHs.
Provide a galaxy occupation fraction for lower resolution simulations.

Stronger SN feedback
- leads to galaxies with stellar masses closer to those predicted by the relation with halo mass
- is able to stunt/regulate BH growth

Validation of the BH model
- Simulated BHs connect the local (z=0) BH sample of *Reines & Volonteri (2015)*
- Good agreement with BH bolometric (*Hopkins et al. 2007*) and xray (2-10 keV) luminosity functions (*Buchner et al. 2015*)
- Good agreement with the number of high-z AGN candidates in CDFS (*Giallongo et al. 2015*)

Understanding the first galaxies and BHs is one of the current challenges in galaxy formation, both theoretically, and observationally. *Habouzit et al. 2017 in prep*
The simulation provides a suitable theoretical framework to prepare studied mission (e.g. LynX), and predict what we will be able to observe with upcoming mission (e.g. JWST).