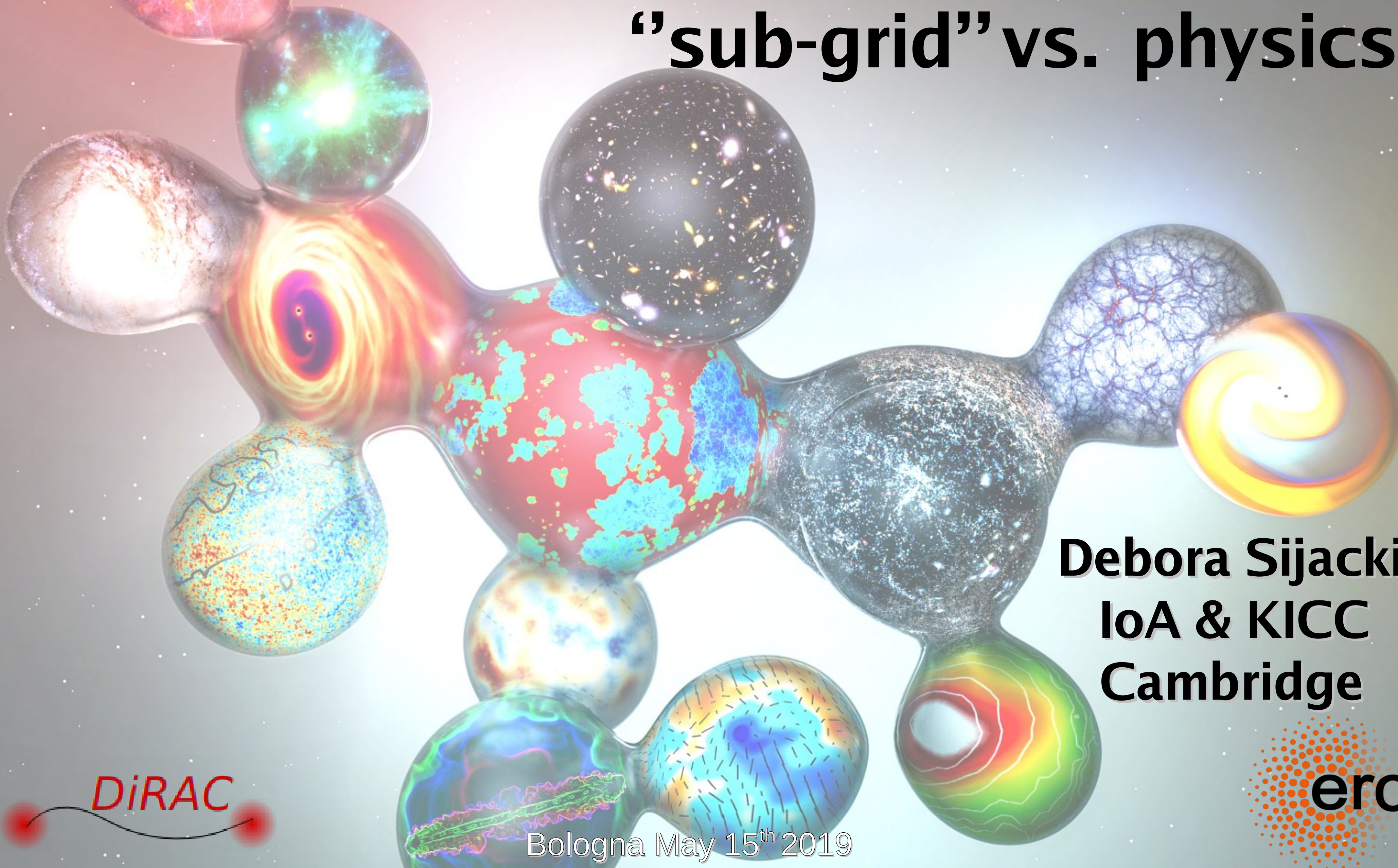
UNIVERSITY OF CAMBRIDGE

Galaxy formation simulations: ''sub-grid'' vs. physics



Debora Sijacki
IoA & KICC
Cambridge

Bologna May 15th 2019

Cosmological simulations of galaxy and structure formation

Provide ab initio physical understanding on all scales

Standard (and less standard) ingredients:

► “simple” ΛCDM assumption
(WDM, SIDM,…, evolving w,…, coupled DM+DE models,…)

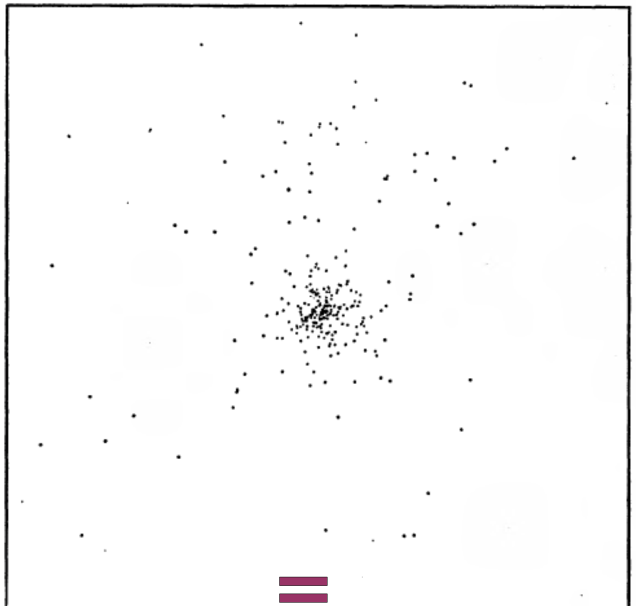
► Newtonian gravity (dark matter and baryons)
(relativistic corrections, modified gravity models,...)

► Ideal gas hydrodynamics + collisionless dynamics of stars
(conduction, viscosity, MHD,…, stellar collisions, stellar hydro)

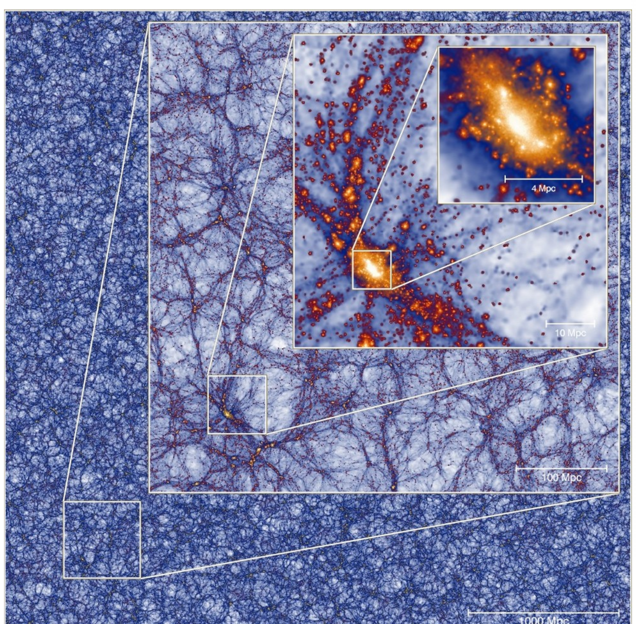
► Gas radiative cooling/heating, star & BH formation and feedback
(non equlibrium low T cooling, dust, turbulence, GMCs,…)

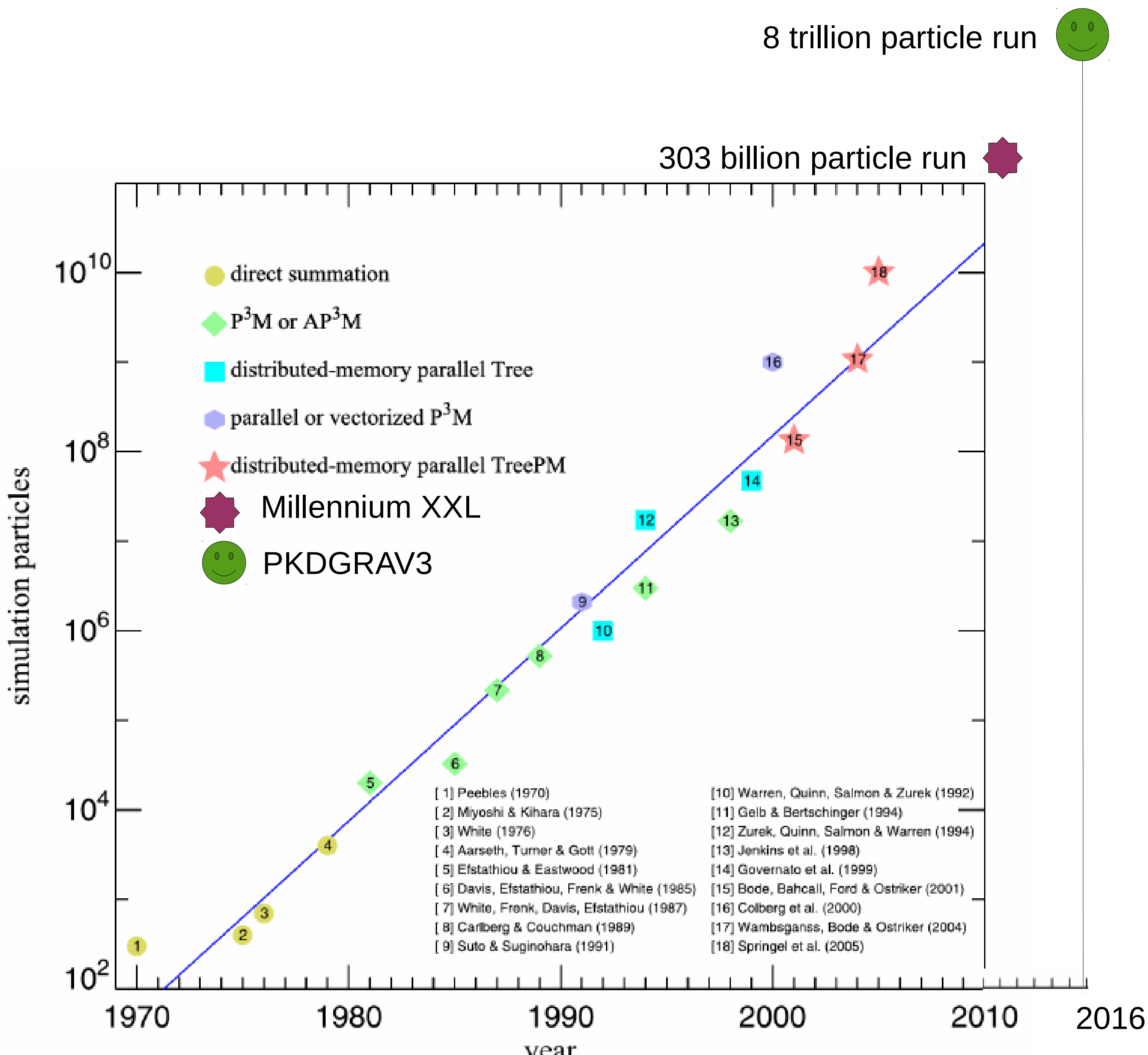
► Reionization in form of an uniform UV background
(simple accounting for the local sources,…, full RT on the fly)

Pure dark matter simulations in ΛCDM cosmology



40 yrs!

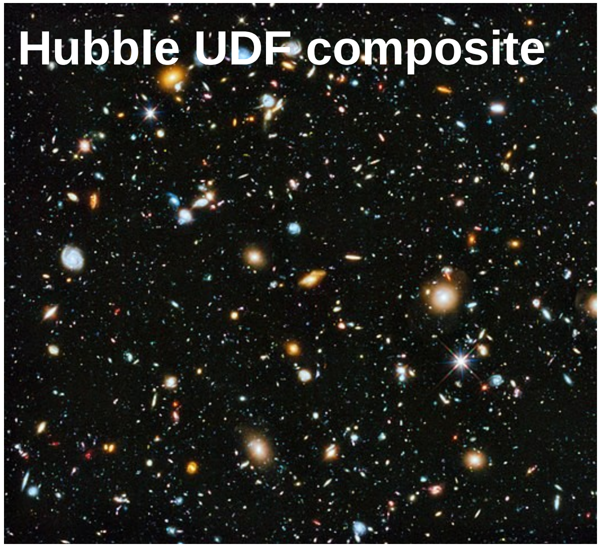


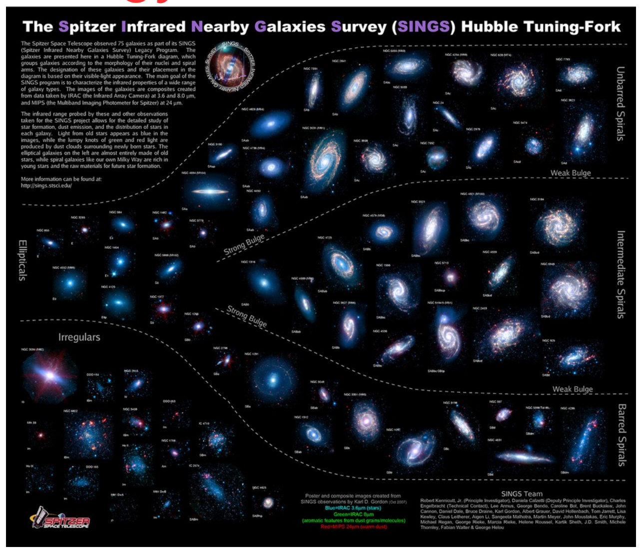


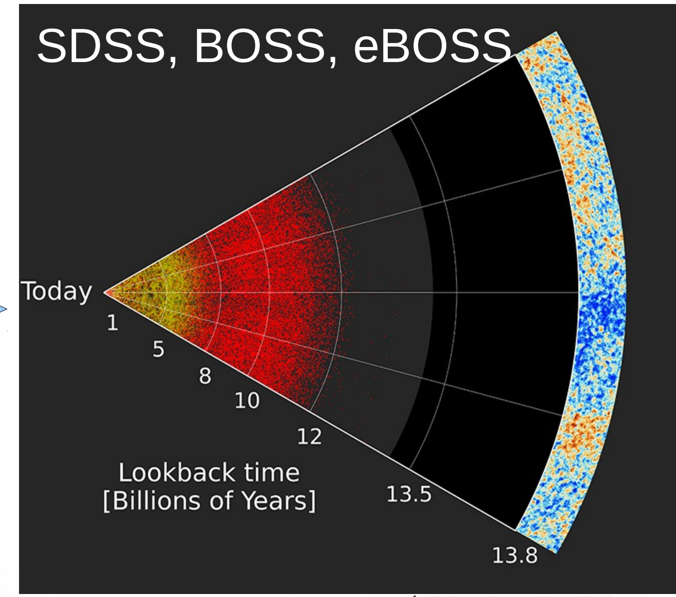
See also:
Horizon Run 3 (Kim 2011) MultiDark (Prada 2012)
DEUS (Alimi et al. 2012) Watson et al. 2013

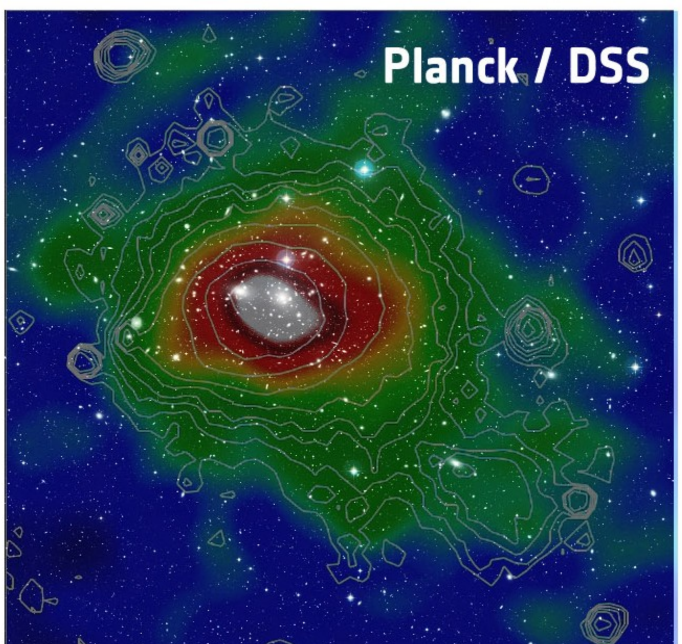
The importance of baryons

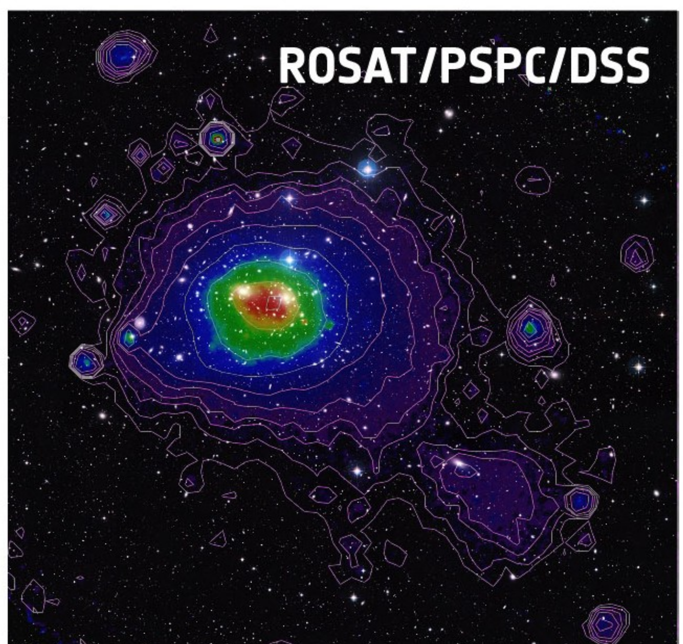
Baryons are directly observable and they affect the underlying dark matter distribution (contraction/expansion/shape/bias, WL,...) => profound implications for cosmology

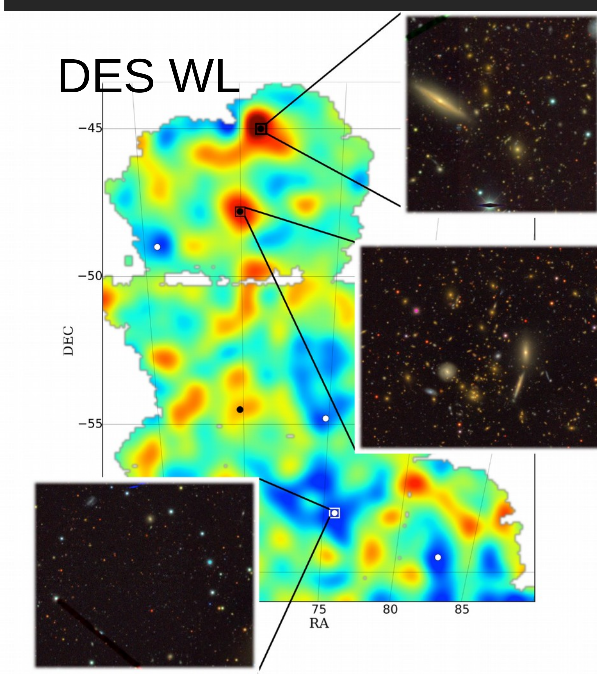






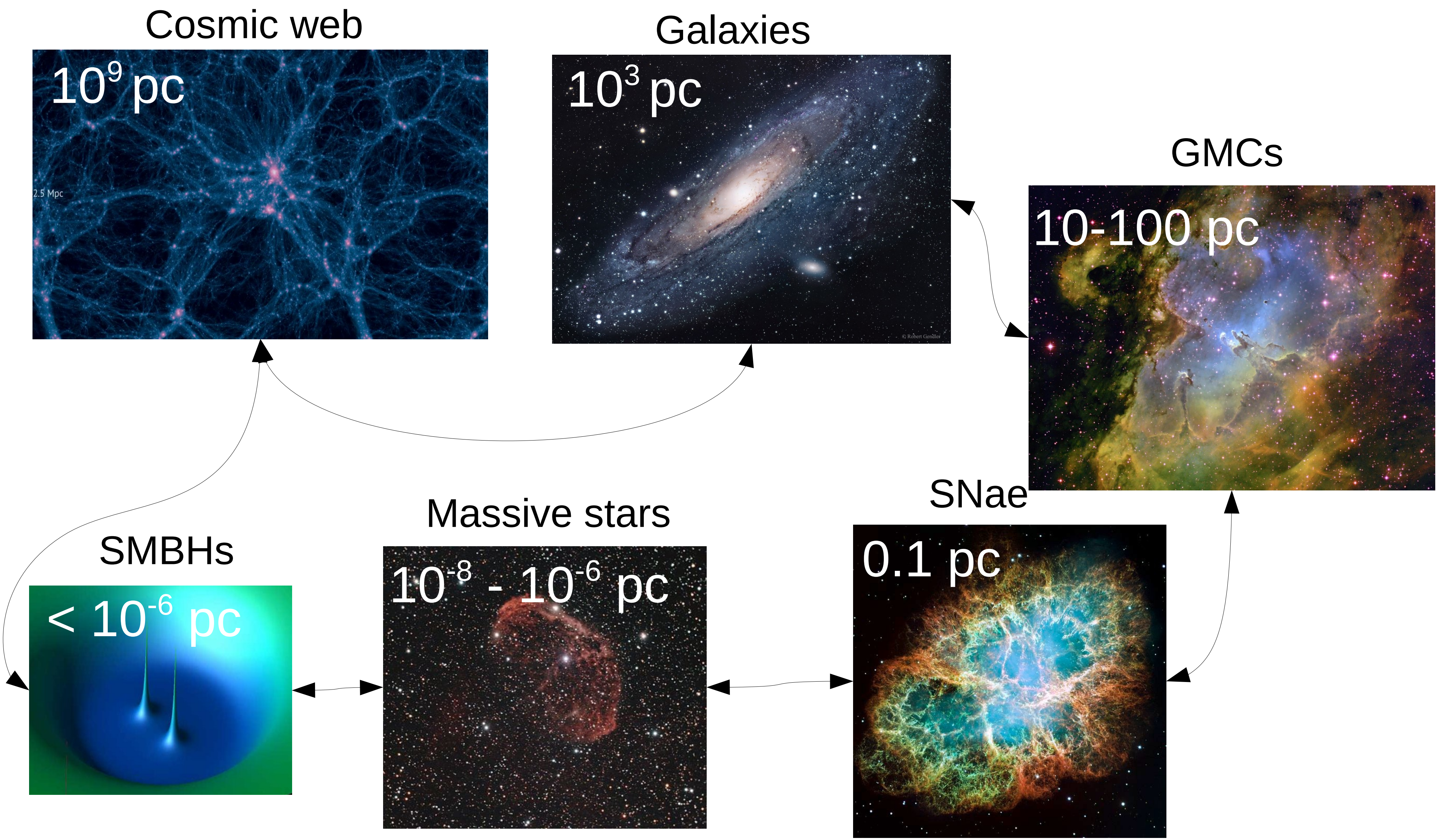






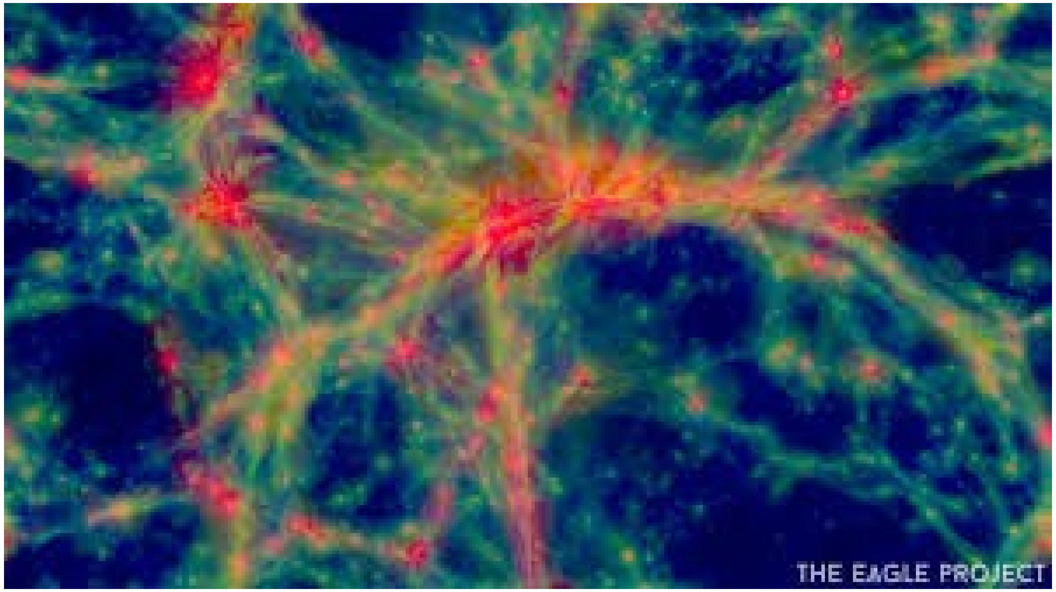
The importance of baryons

Vast range of spatial scales involved and very complex, non-linear physics → SUB-GRID models (“free parameters” constrained by obs)

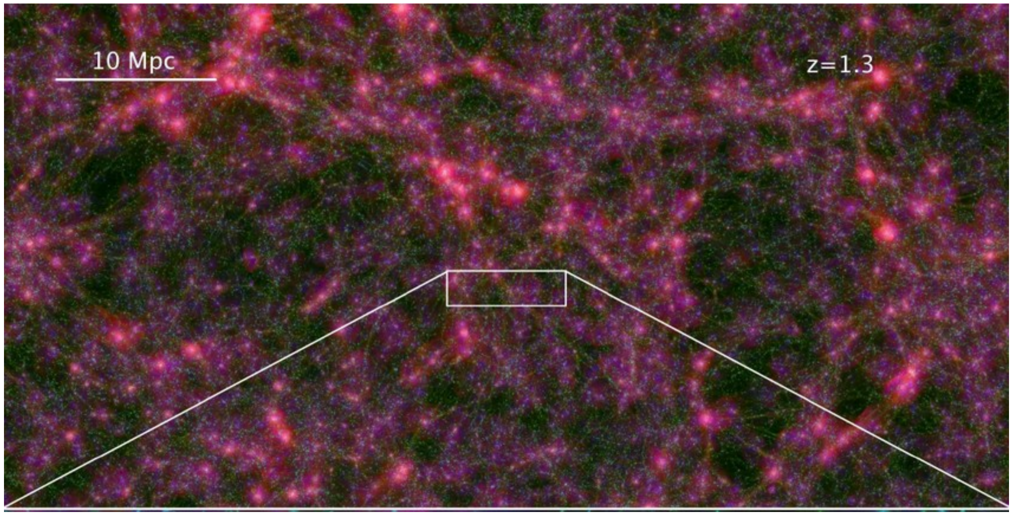


Current state-of-the-art in cosmological hydro simulations

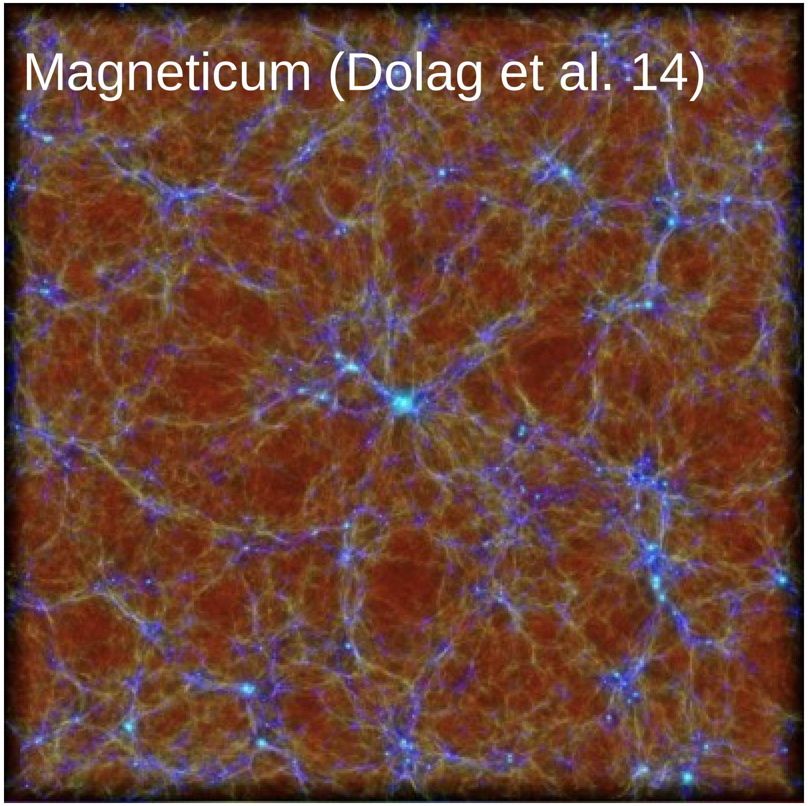
The Eagle Project (Schaye et al. 15)



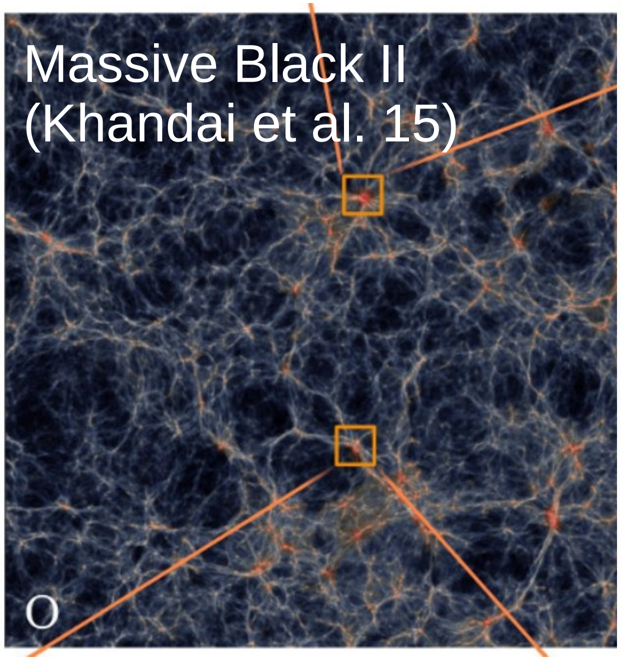
The Horizon AGN project (Dubois et al. 14)



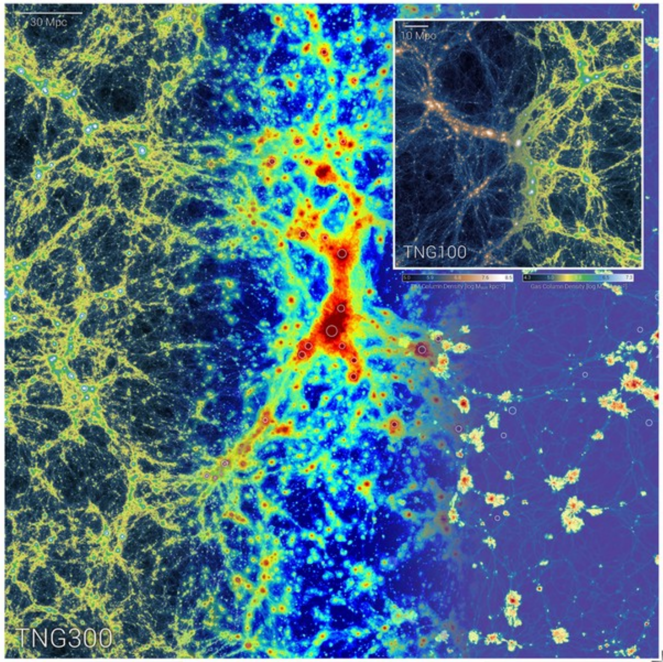
Magneticum (Dolag et al. 14)



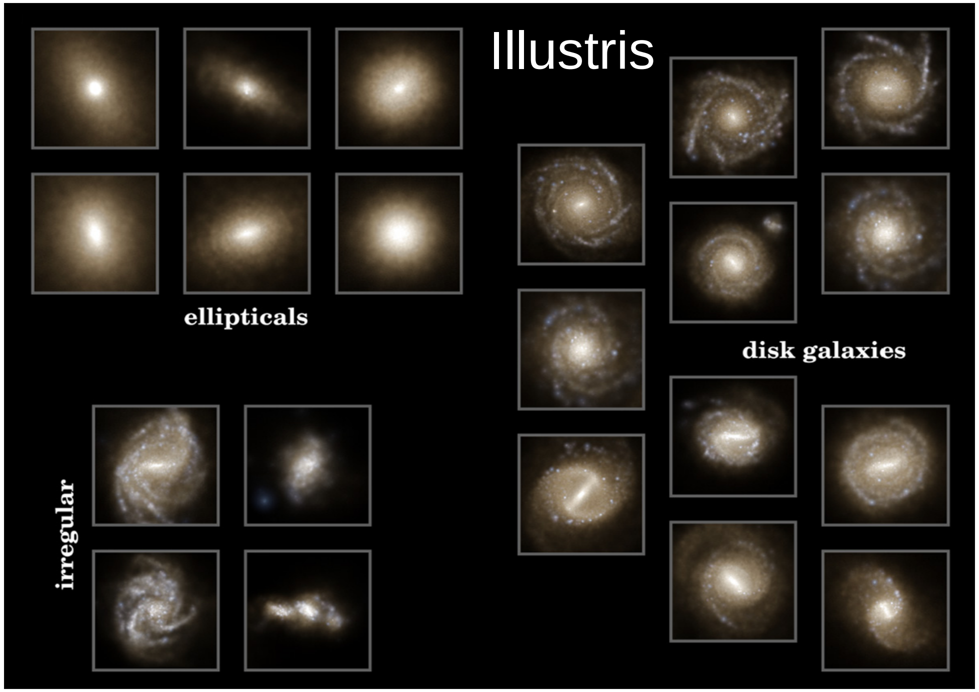
Massive Black II (Khandai et al. 15)

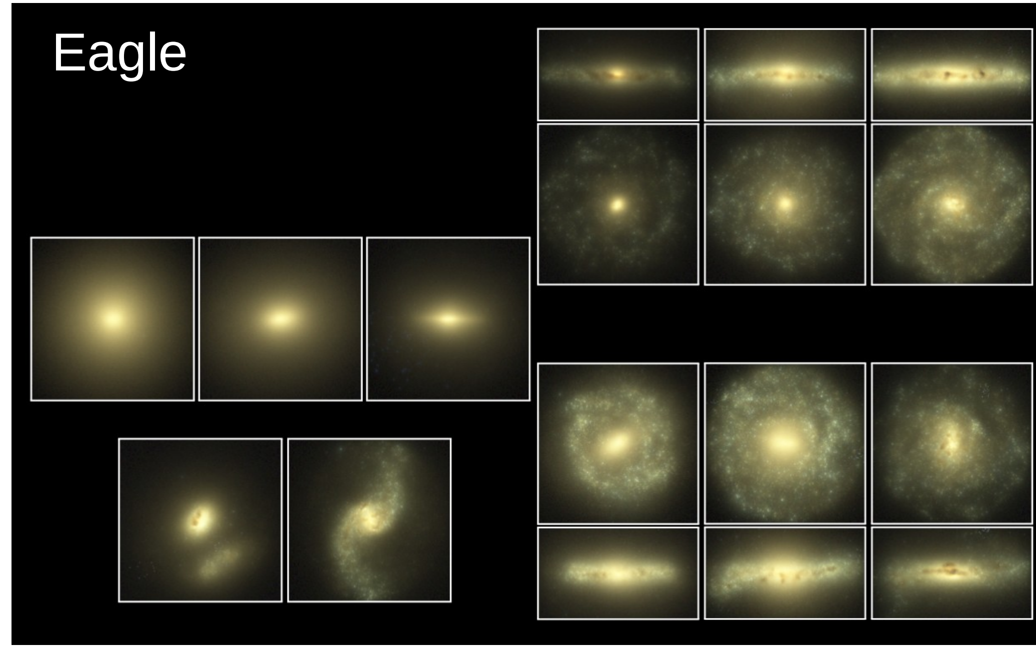


Illustris TNG (Springel et al. 17)



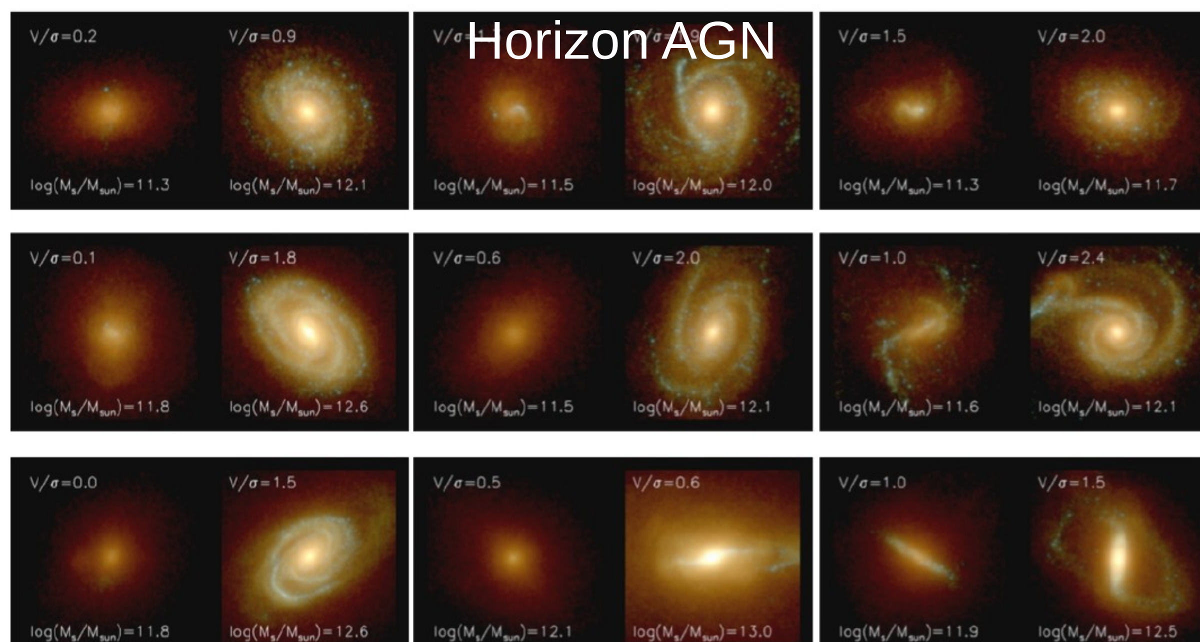
AGN feedback is the key for galaxy morphologies





Schaye et al. 2015

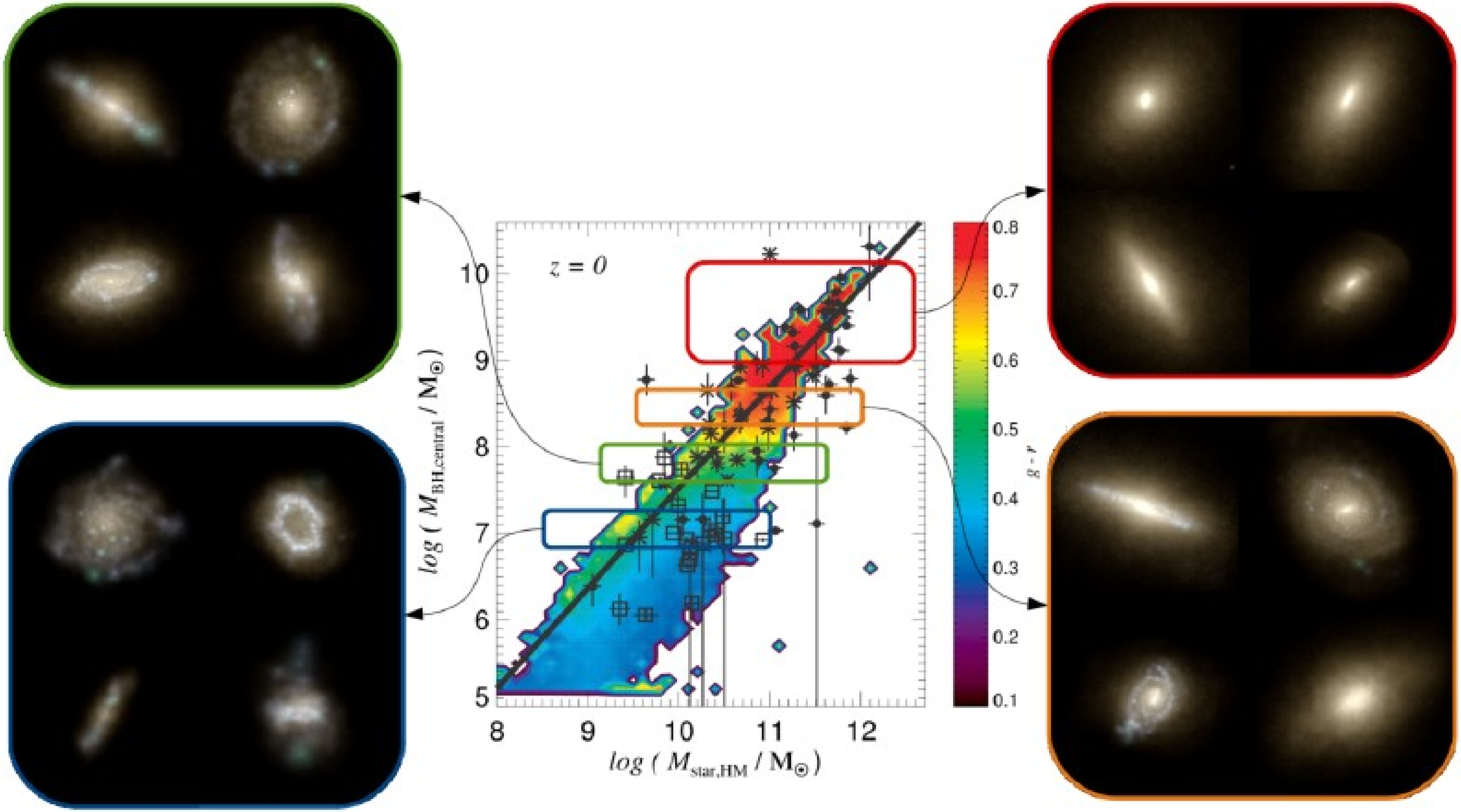
Vogelsberger et al. 2014
Genel et al. 2014
Sijacki et al. 2015



Dubois et al. 14

Black holes in Illustris

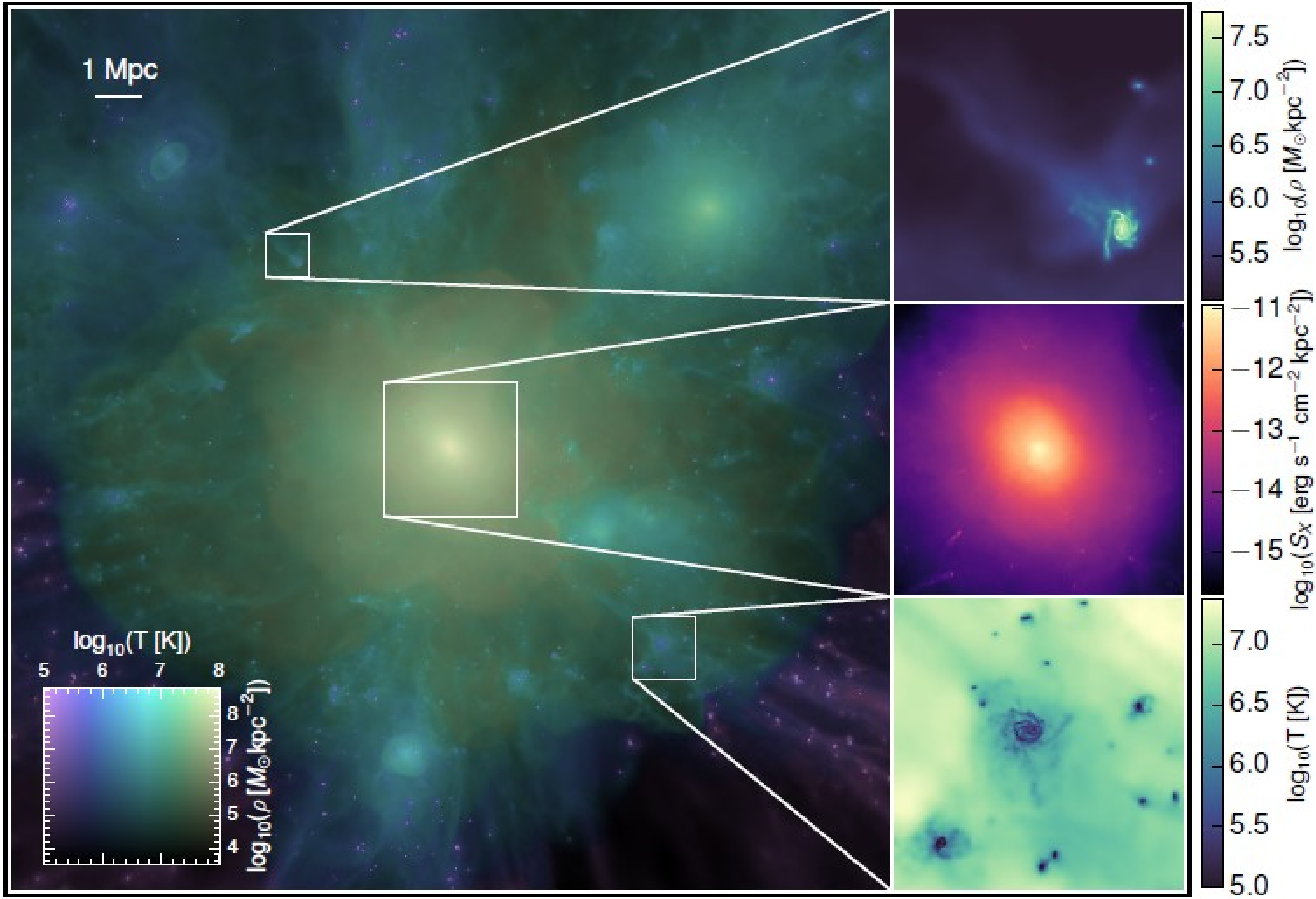
BH MASS – BULGE MASS RELATION



Kormendy & Ho, 2013: best fit
circles: ellipticals; stars: spirals with bulges; squares: pseudo bulges

Sijacki et al, 2015

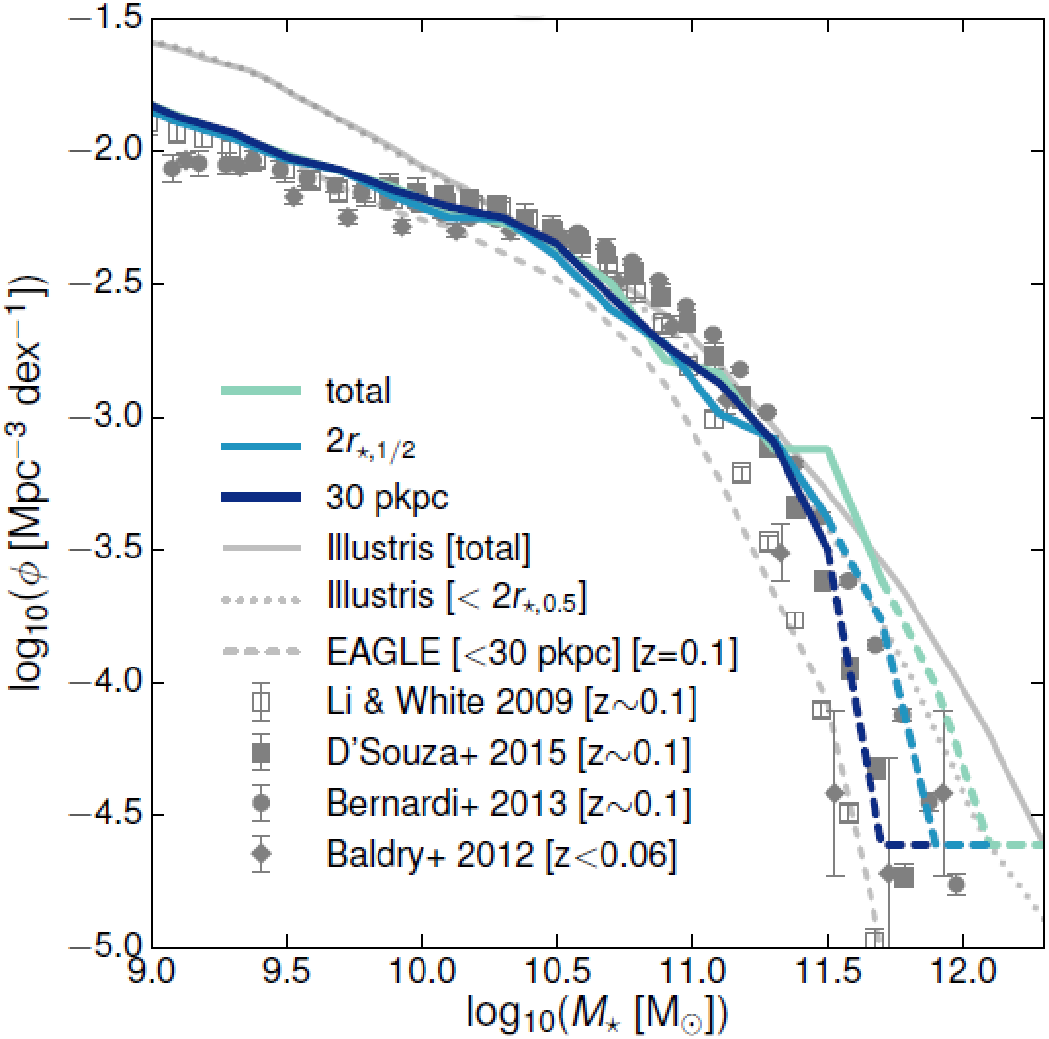
AGN feedback in galaxy clusters: the FABLE project



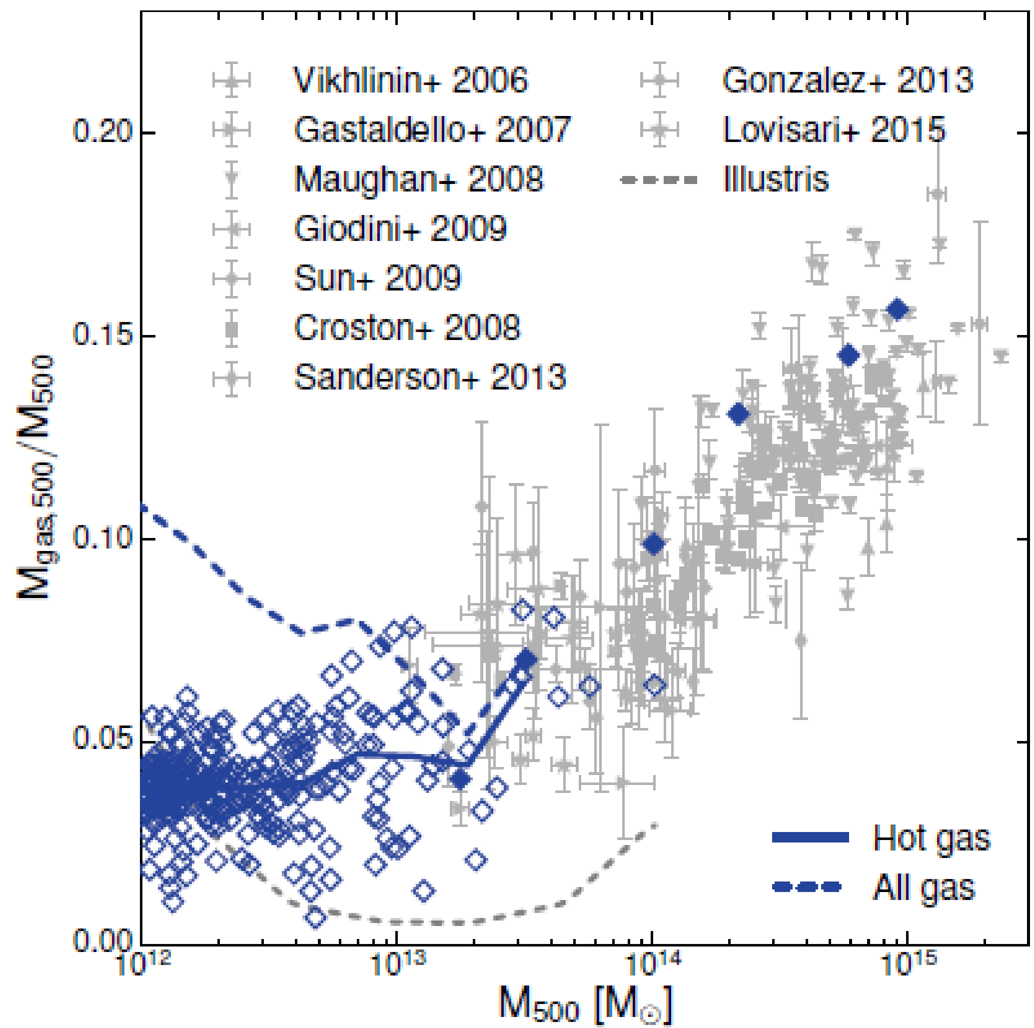
Henden, Puchwein, Shen & Sijacki, 2018 27 high resolution cluster zoom-in simulations

AGN feedback in galaxy clusters: the FABLE project

STELLAR MASS FUNCTION



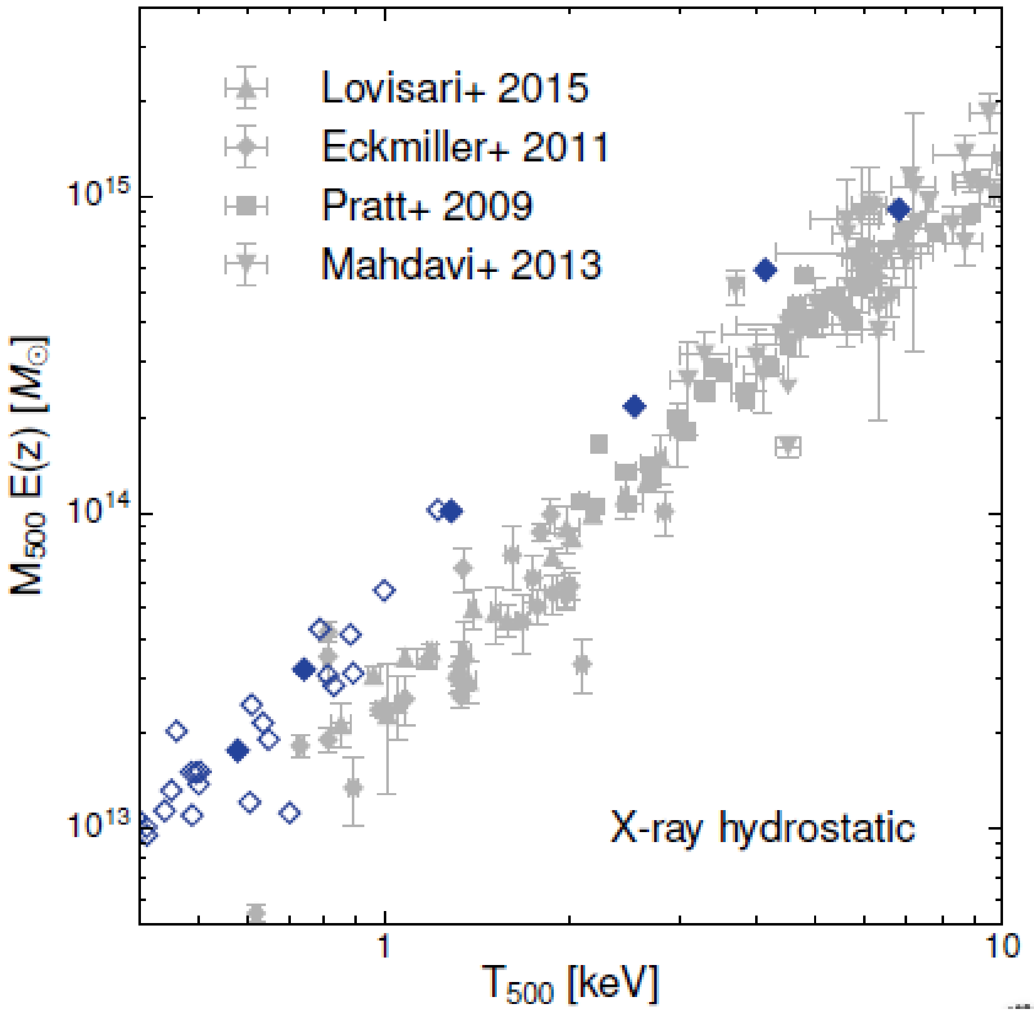
GAS MASS FRACTION

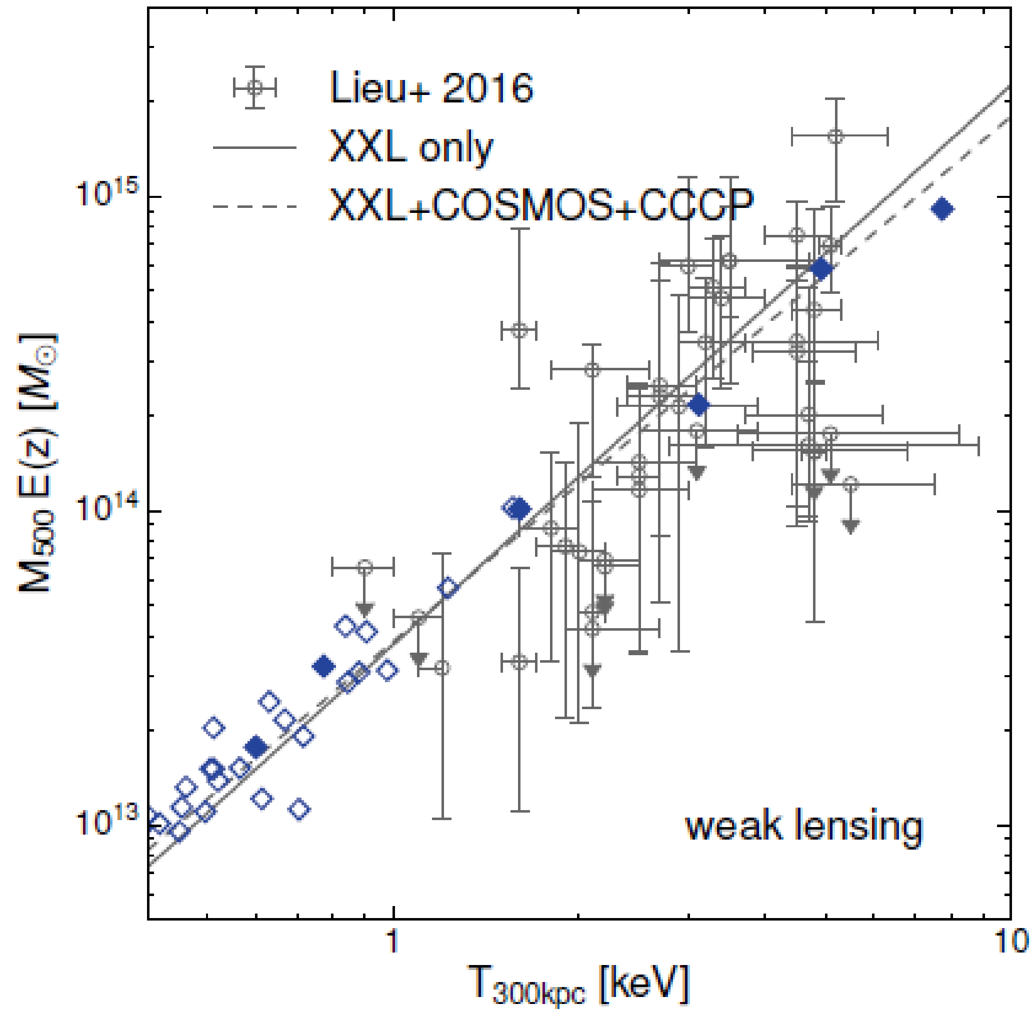


Henden, Puchwein, Shen & Sijacki, 2018

AGN feedback in galaxy clusters: the FABLE project

MASS-TEMPERATURE RELATION: large hydro-static mass bias?
IMPLICATIONS FOR COSMOLOGY!



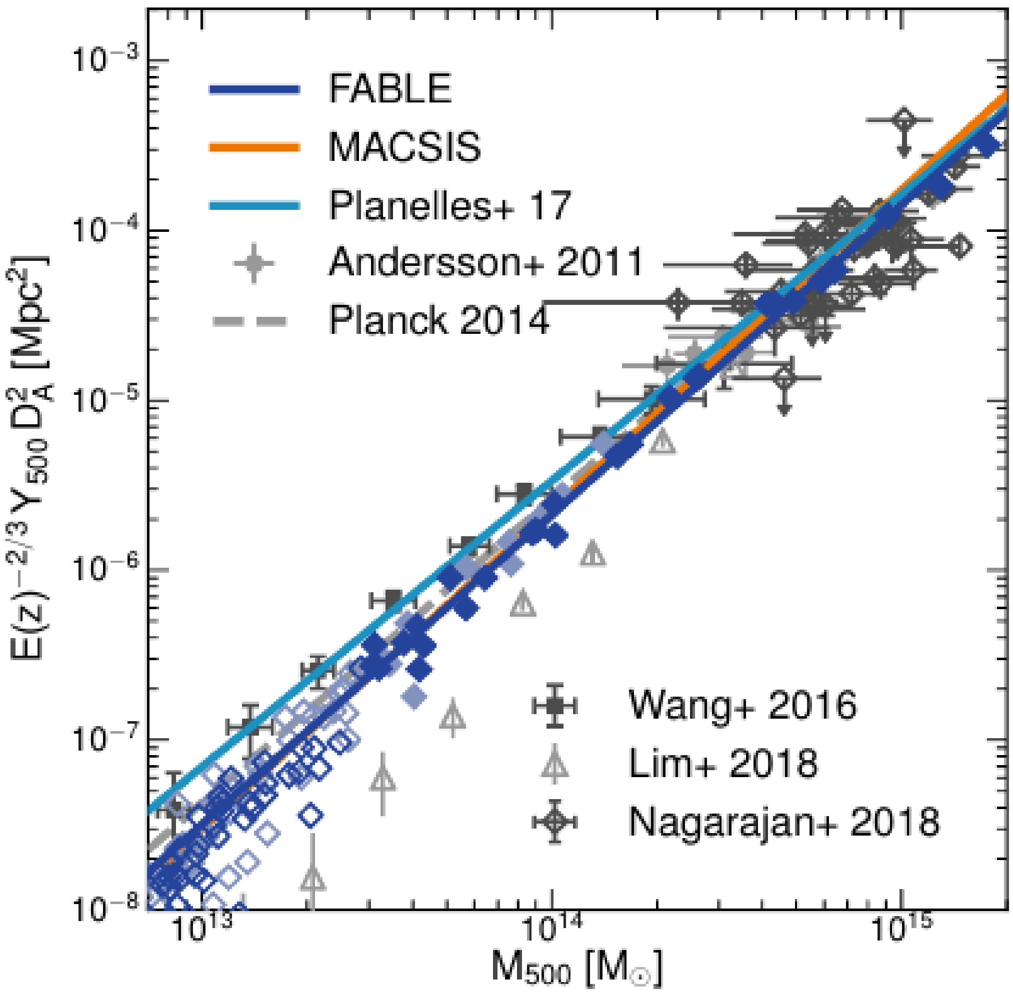


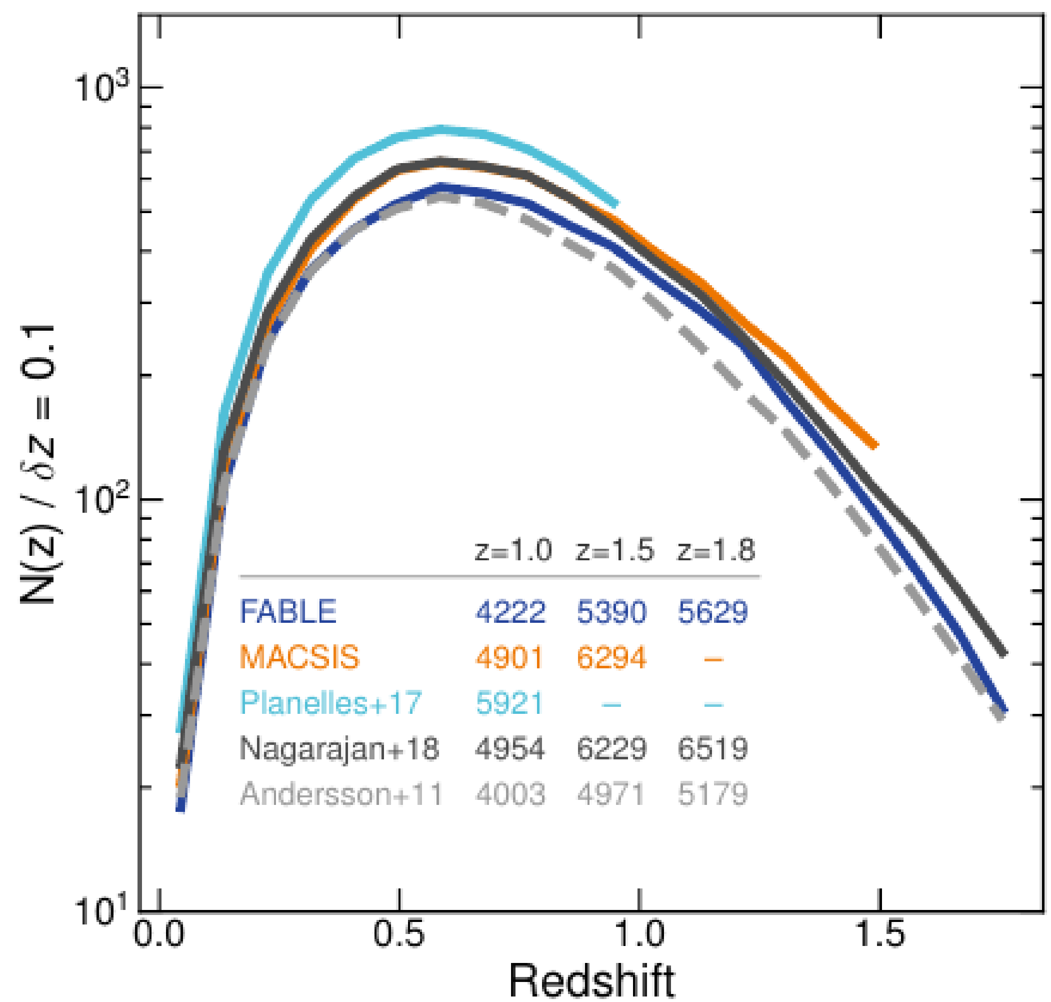
Henden, Puchwein, Shen & Sijacki, 2018

AGN feedback in galaxy clusters: the FABLE project

Y500-M500 THEORETICAL RELATION UNCERTAINTY: PREDICTED SZ CLUSTER COUNTS FOR SPT-3G LIKE SURVEY DIFFER SIGNIFICANTLY

$$Y_{500,\mathrm{lim}}\,\mathrm{D_A^2} = 10^{-5}\ E(z)^{-0.25}\,\mathrm{Mpc}^2$$



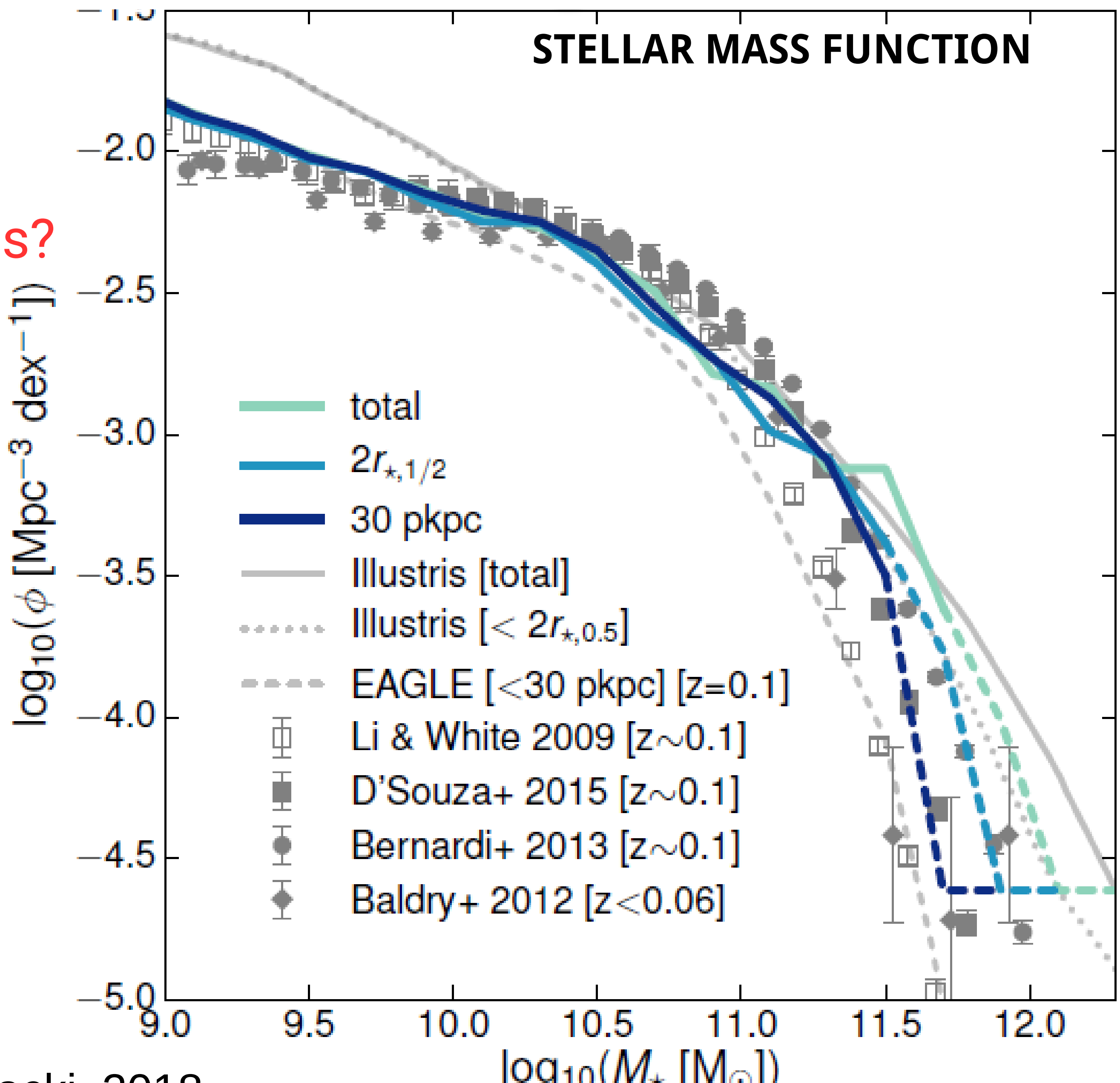


Henden, Puchwein, Sijacki, 2019, to be submitted

Current state-of-the-art in cosmological hydro simulations

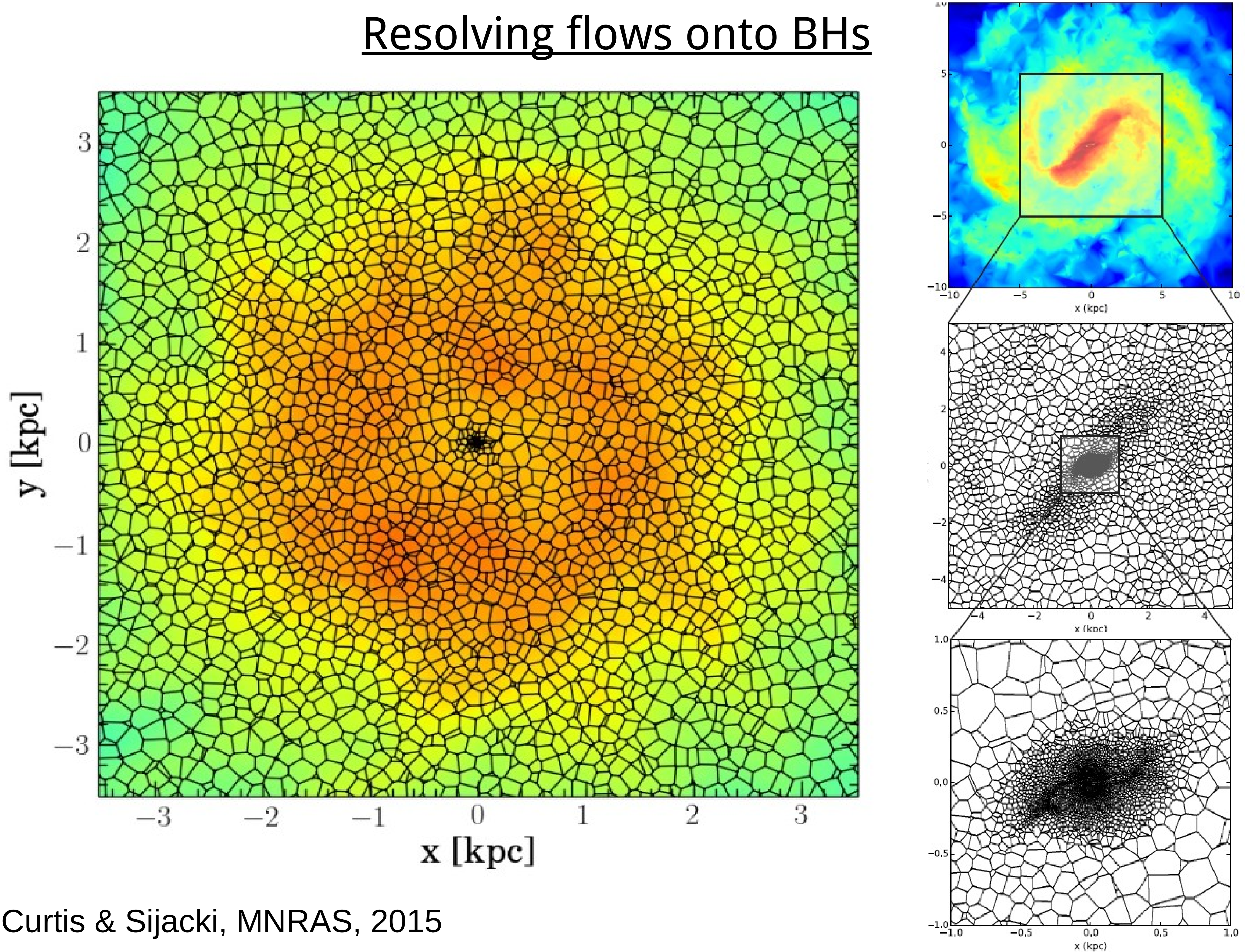
Different sub-grid models achieve similar results!

- ➢ Predictive power?
- ➢ Fine tuning?
- ➢ Purpose of simulations?
- ➢ Learning about the underlying physics?



Henden, Puchwein, Shen & Sijacki, 2018

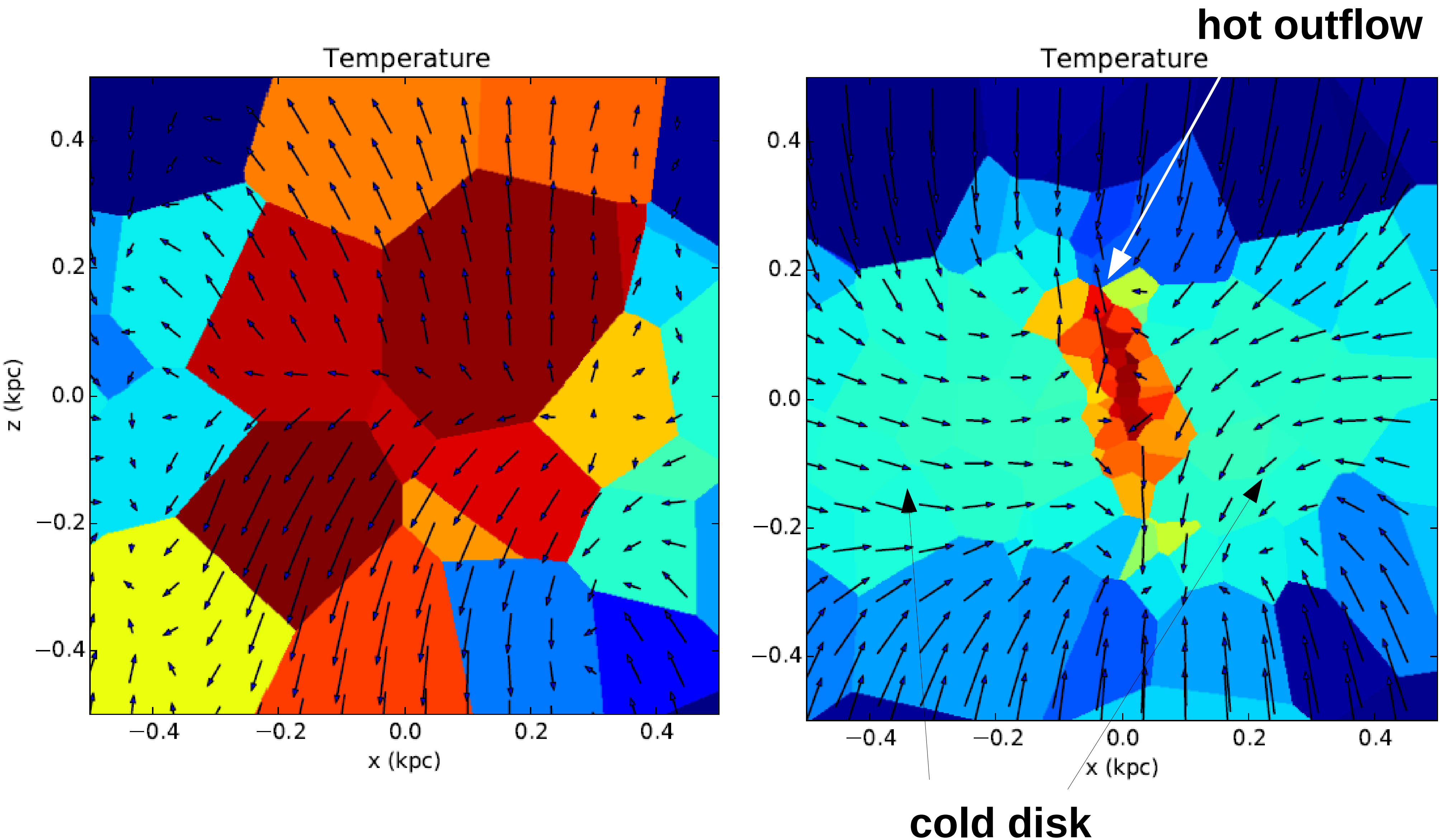
Resolving flows onto BHs



Curtis & Sijacki, MNRAS, 2015

How (dramatic) change in resolution affects the physics?

SAME BH FEEDBACK AT DIFFERENT RESOLUTIONS LEADS TO COMPLETELY DIFFERENT INNER GALAXY PROPERTIES



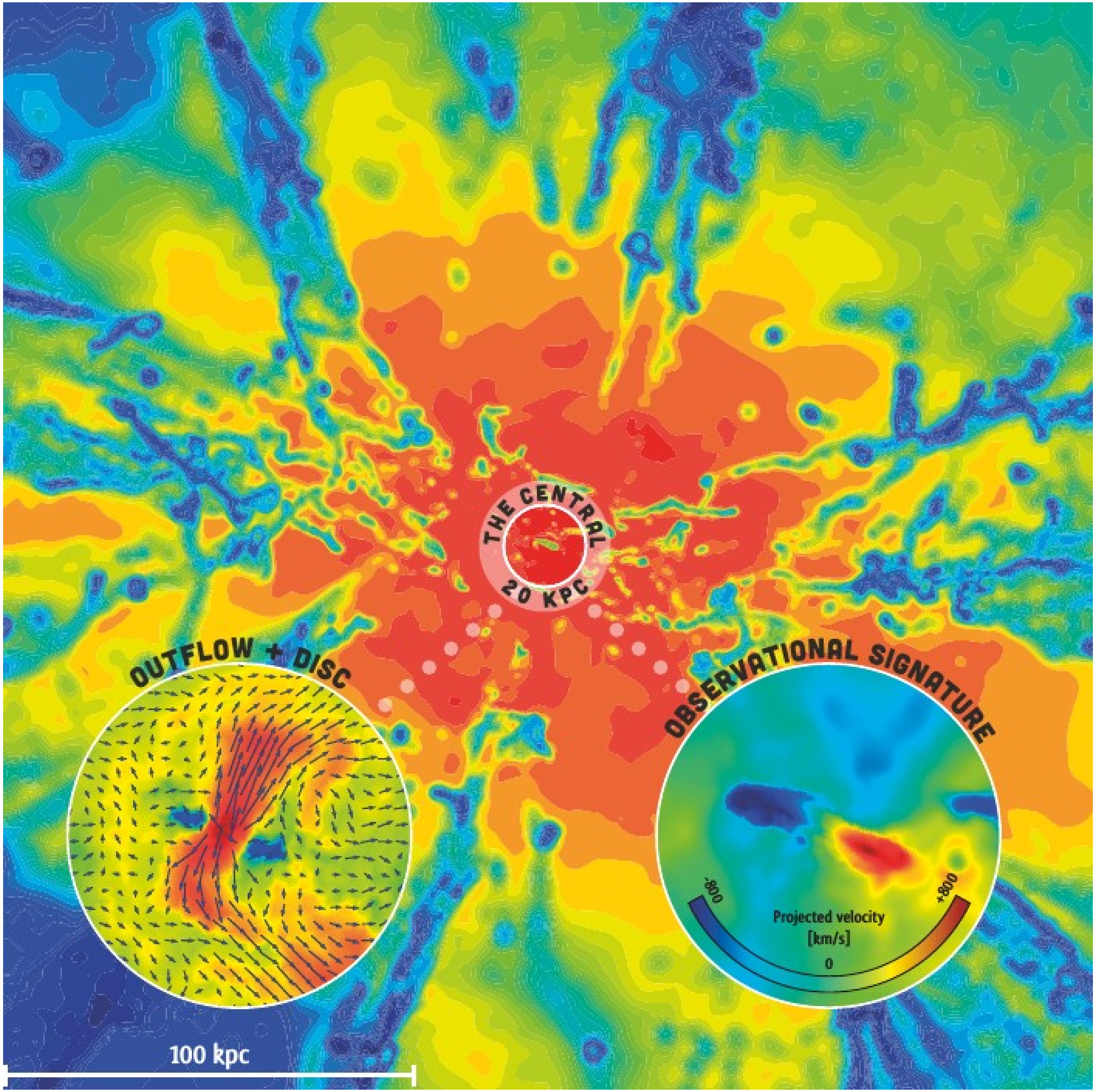
Curtis & Sijacki, MNRAS, 2015

Powerful QSO outflow in a massive disk galaxy at high z

Curtis & Sijacki, MNRAS Letter 2016

SAME BH FEEDBACK AT DIFFERENT RESOLUTIONS LEADS TO VERY DIFFERENT GALAXY MORPHOLOGY

(have we understood morphological evolution of galaxies and quenching?)

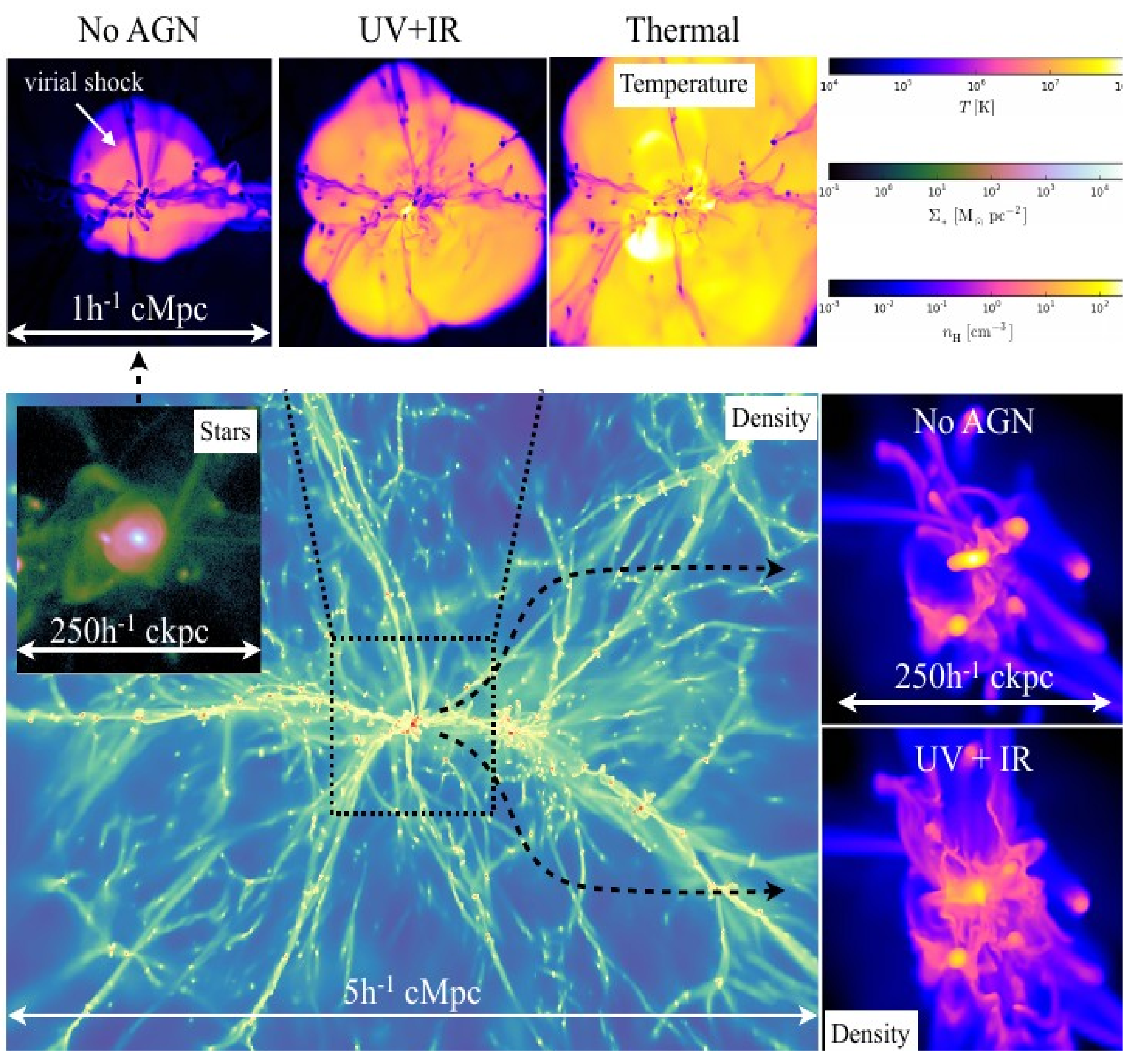


Powerful QSO outflow in a massive disk galaxy at high z

Costa, Rosdahl, Sijacki, Haehnelt, 2018

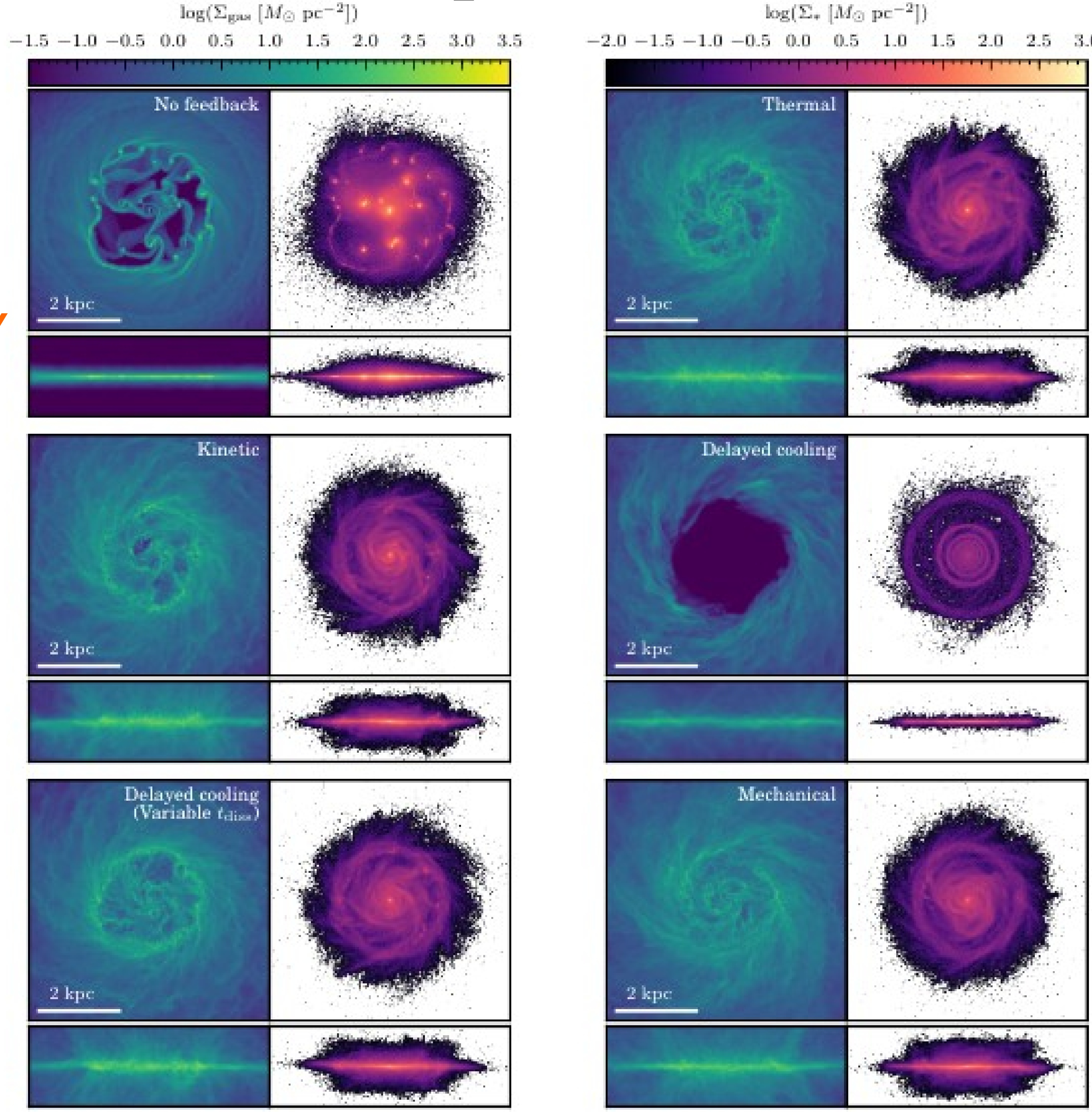
DIFFERENT BH FEEDBACK AT A SAME RESOLUTION LEADS TO VERY DIFFERENT GALAXY MORPHOLOGY

(have we understood morphological evolution of galaxies and quenching?)



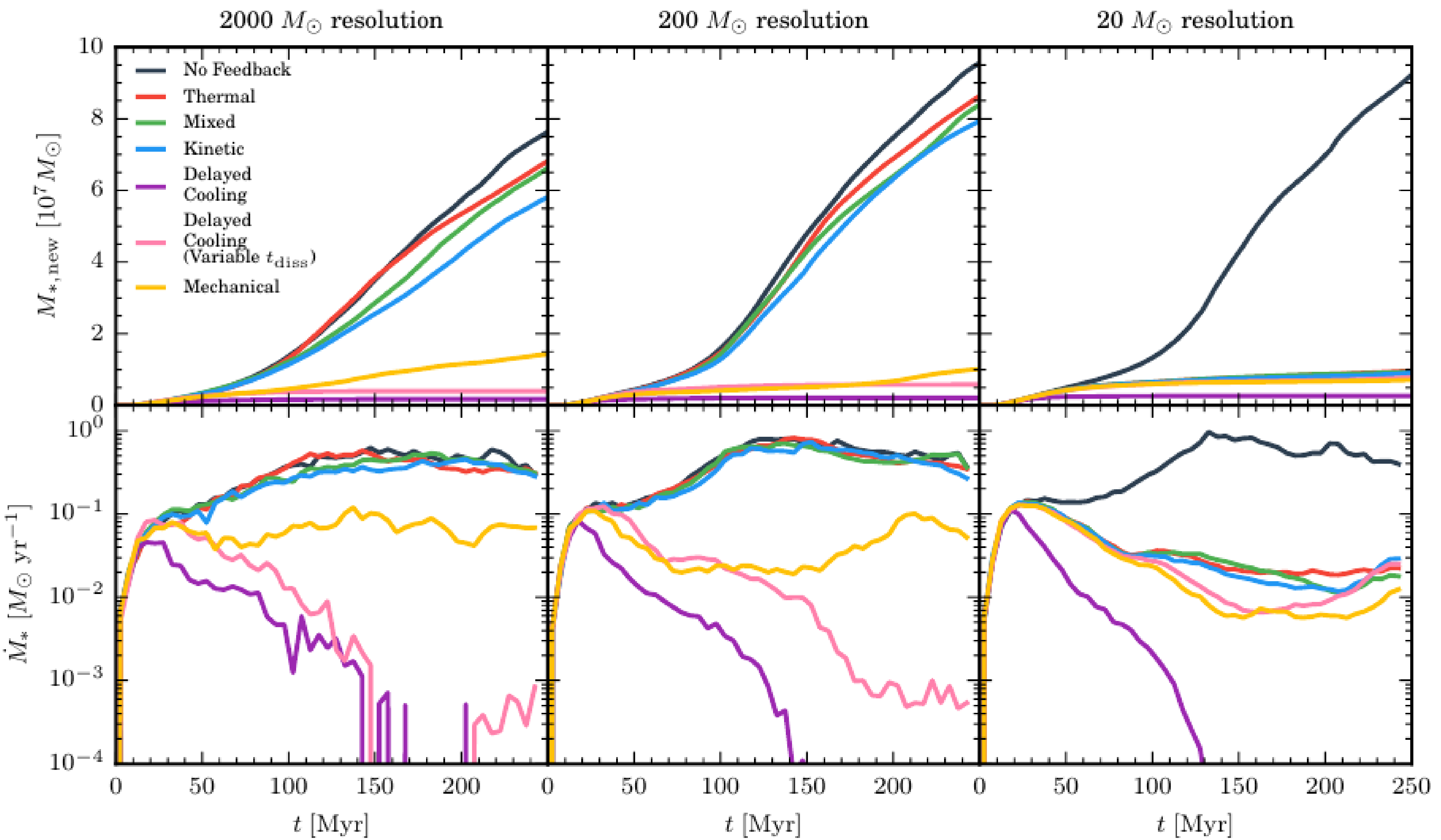
SN feedback in dwarf galaxies?

DIFFERENT SN FEEDBACK AT A SAME RESOLUTION LEADS TO VERY DIFFERENT GALAXY MORPHOLOGY



Smith, Sijacki et al. 2018

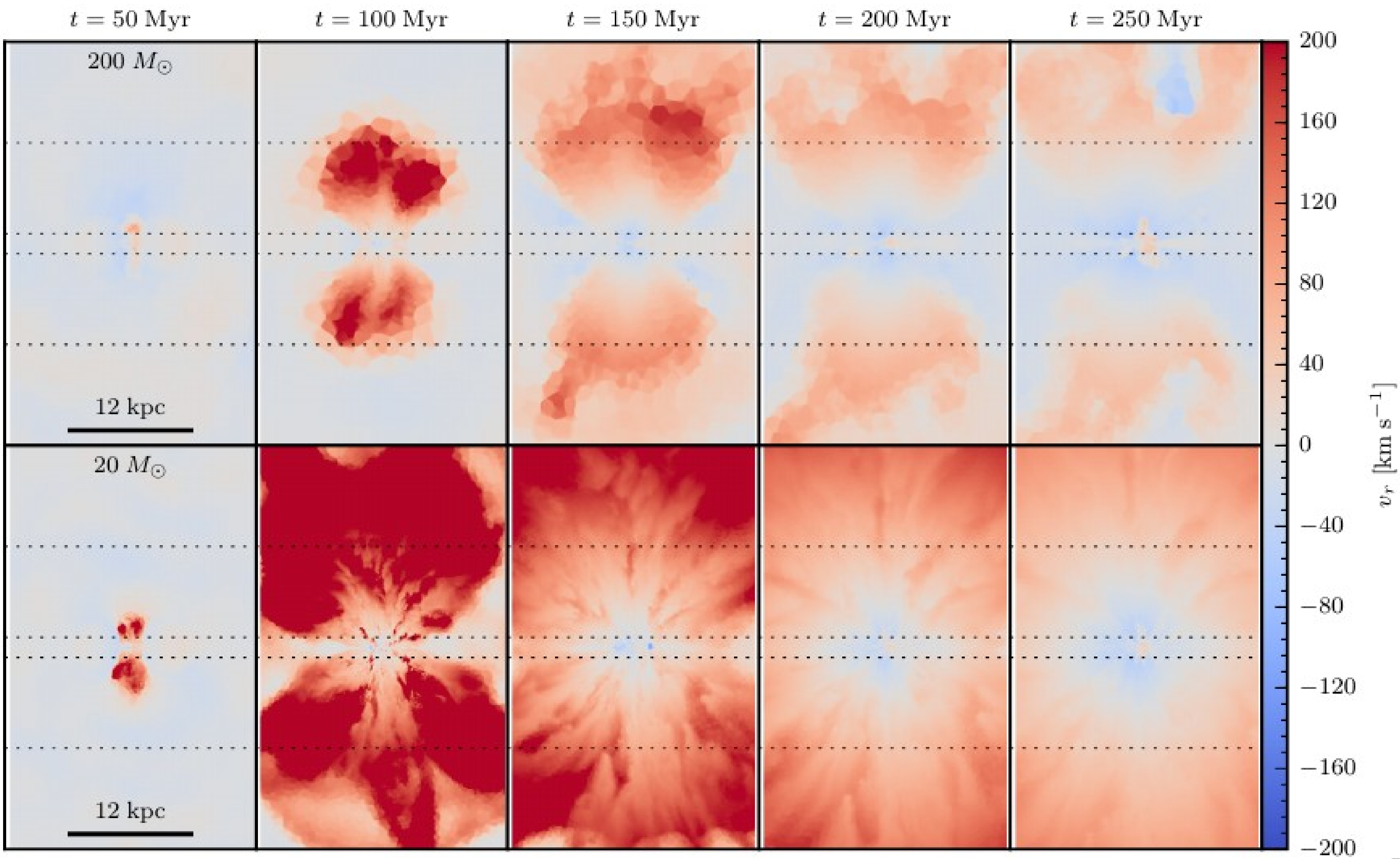
SN feedback in dwarf galaxies?



Smith, Sijacki et al. 2018

MECHANICAL FEEDBACK LEADS TO LARGELY CONVERGED SFRs

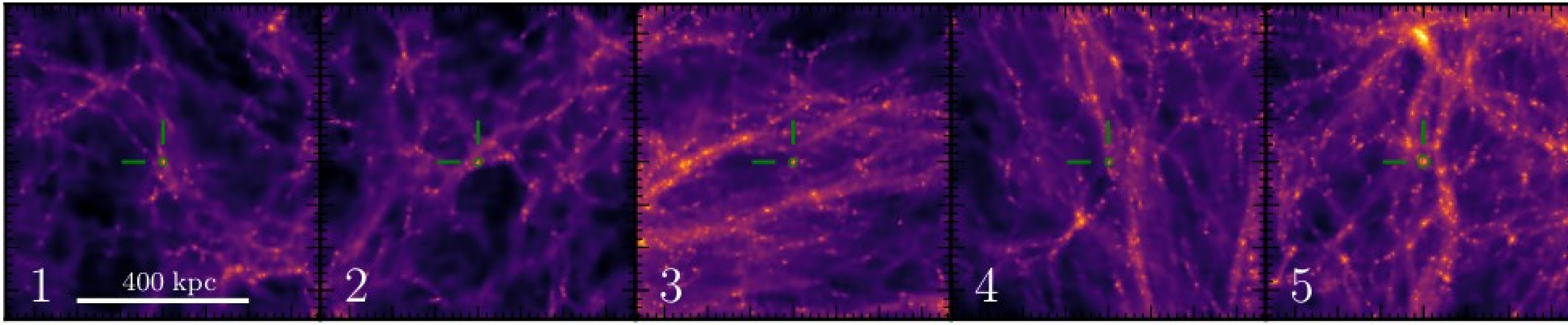
SN feedback in dwarf galaxies?



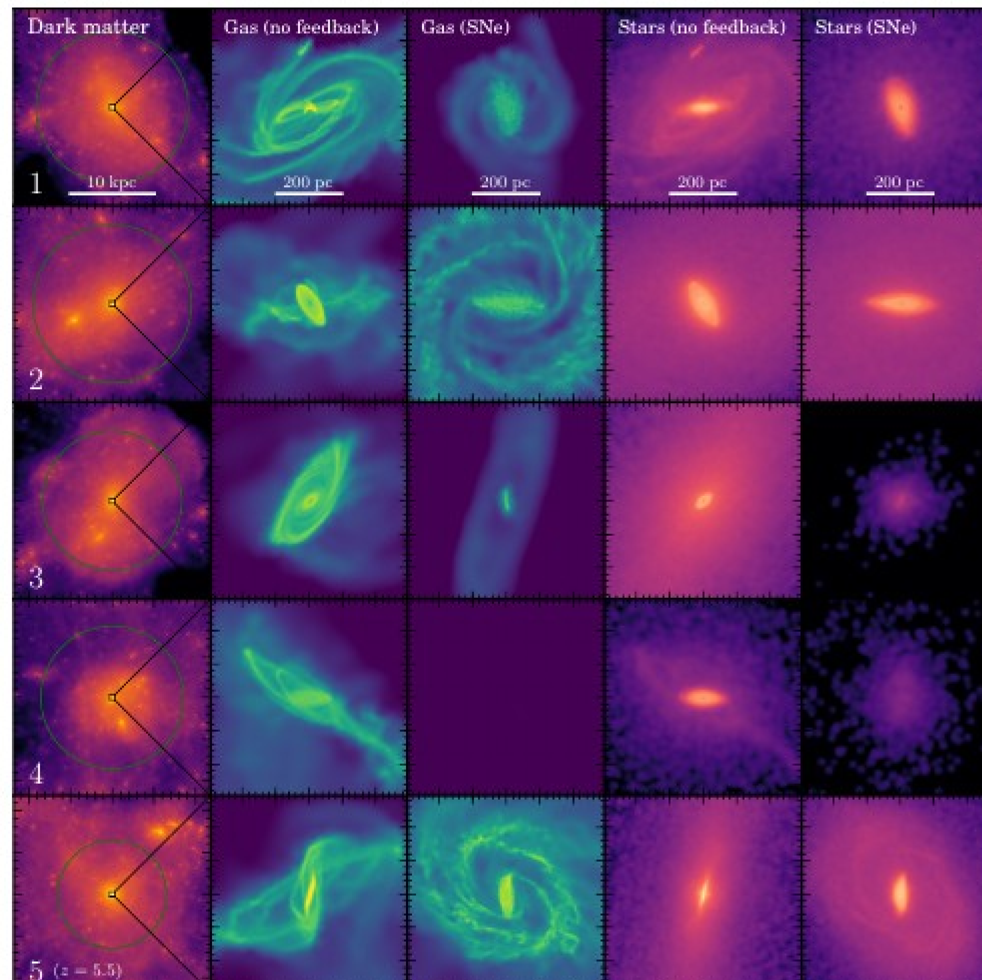
Smith, Sijacki et al. 2018

BUT THE OUTFLOW PROPERTIES ARE NOT CONVERGED!

SN feedback in cosmological dwarfs?

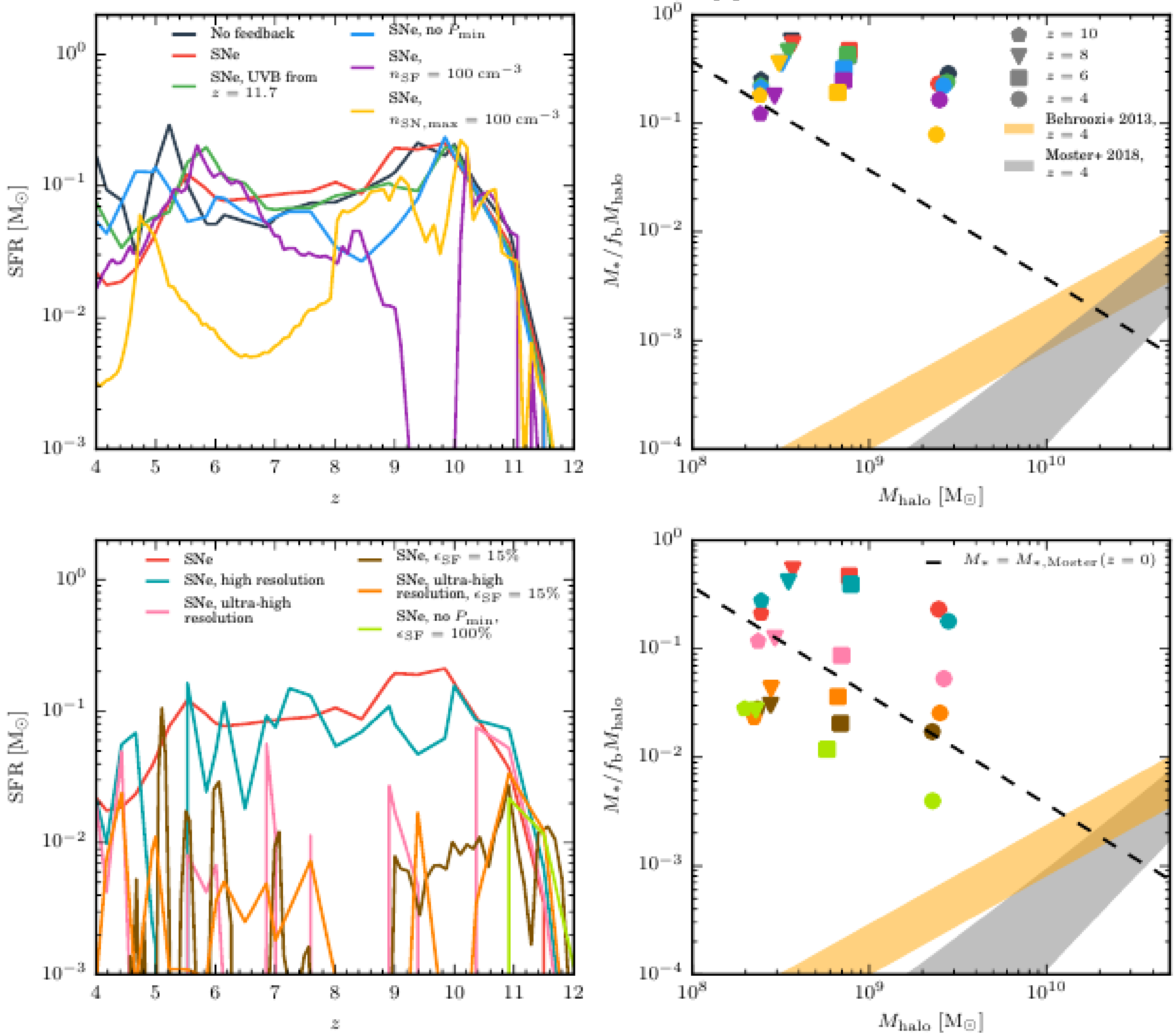


SN FEEDBACK NOT SUFFICIENT TO SUPPRESS GAS INFLOWS AND CENTRAL DENSE GAS CONCENTRATIONS IN MAJORITY OF CASES



Smith, Sijacki et al. 2019

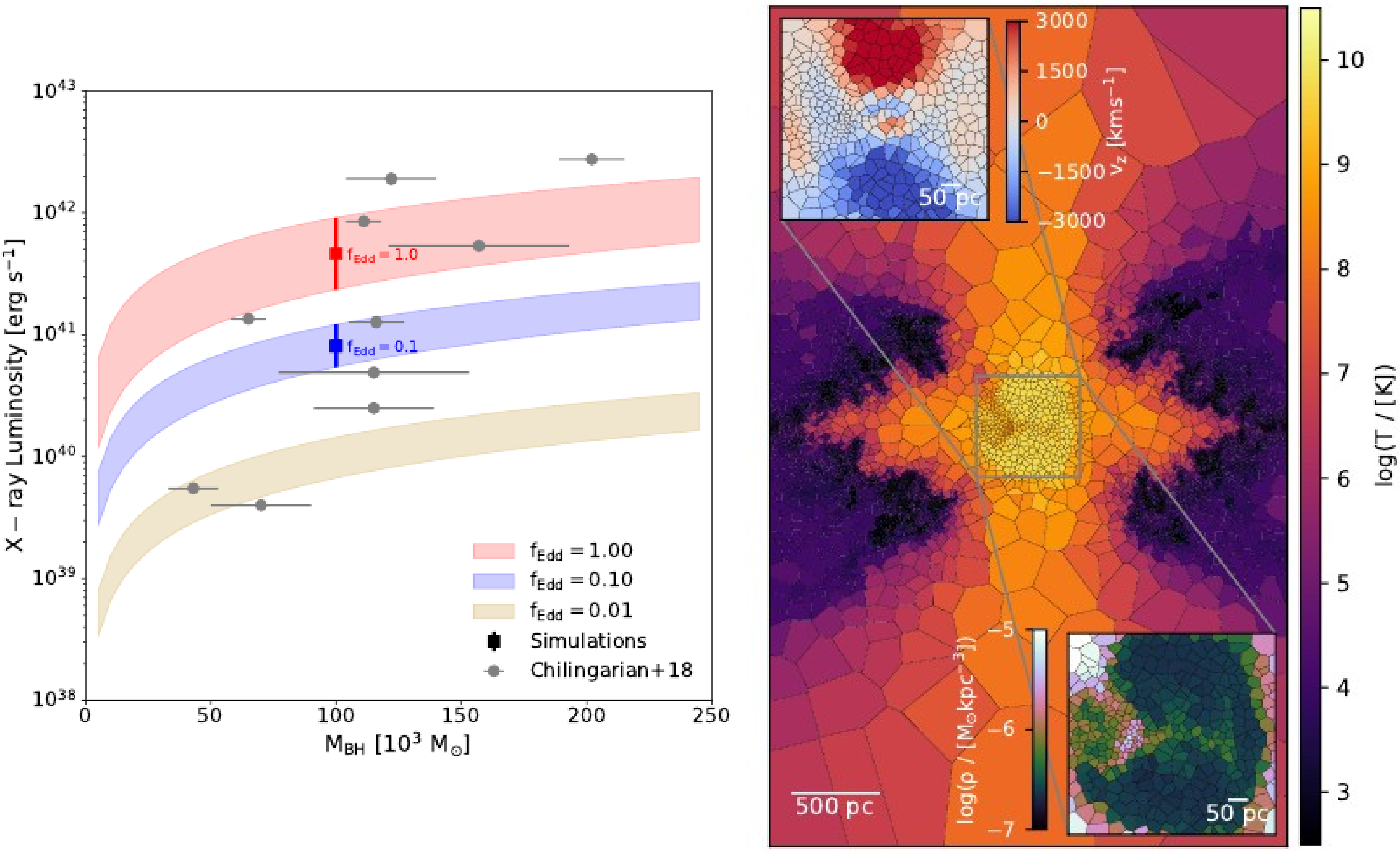
SN feedback in cosmological dwarfs?



Smith, Sijacki et al. 2019

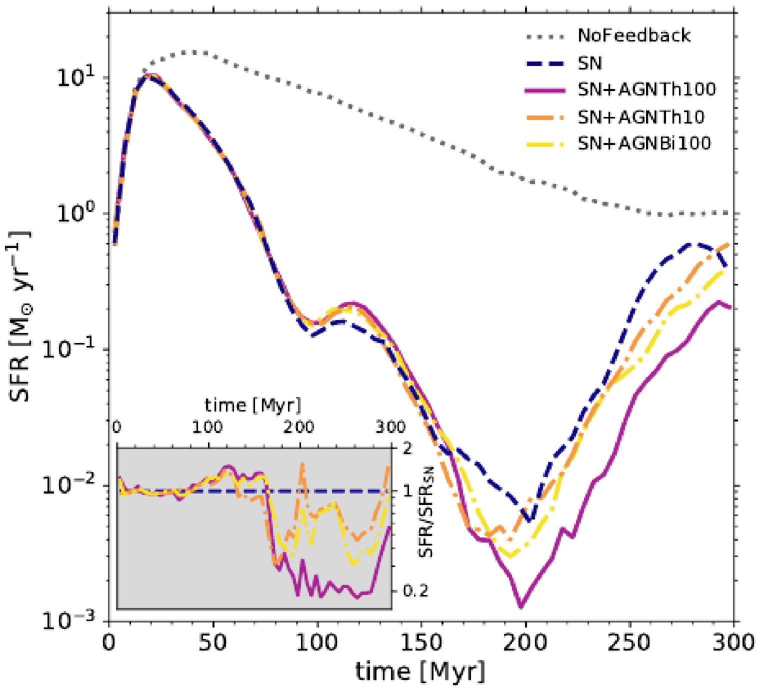
NEED FOR (ISM) PHYSICS BEYOND SN ALONE

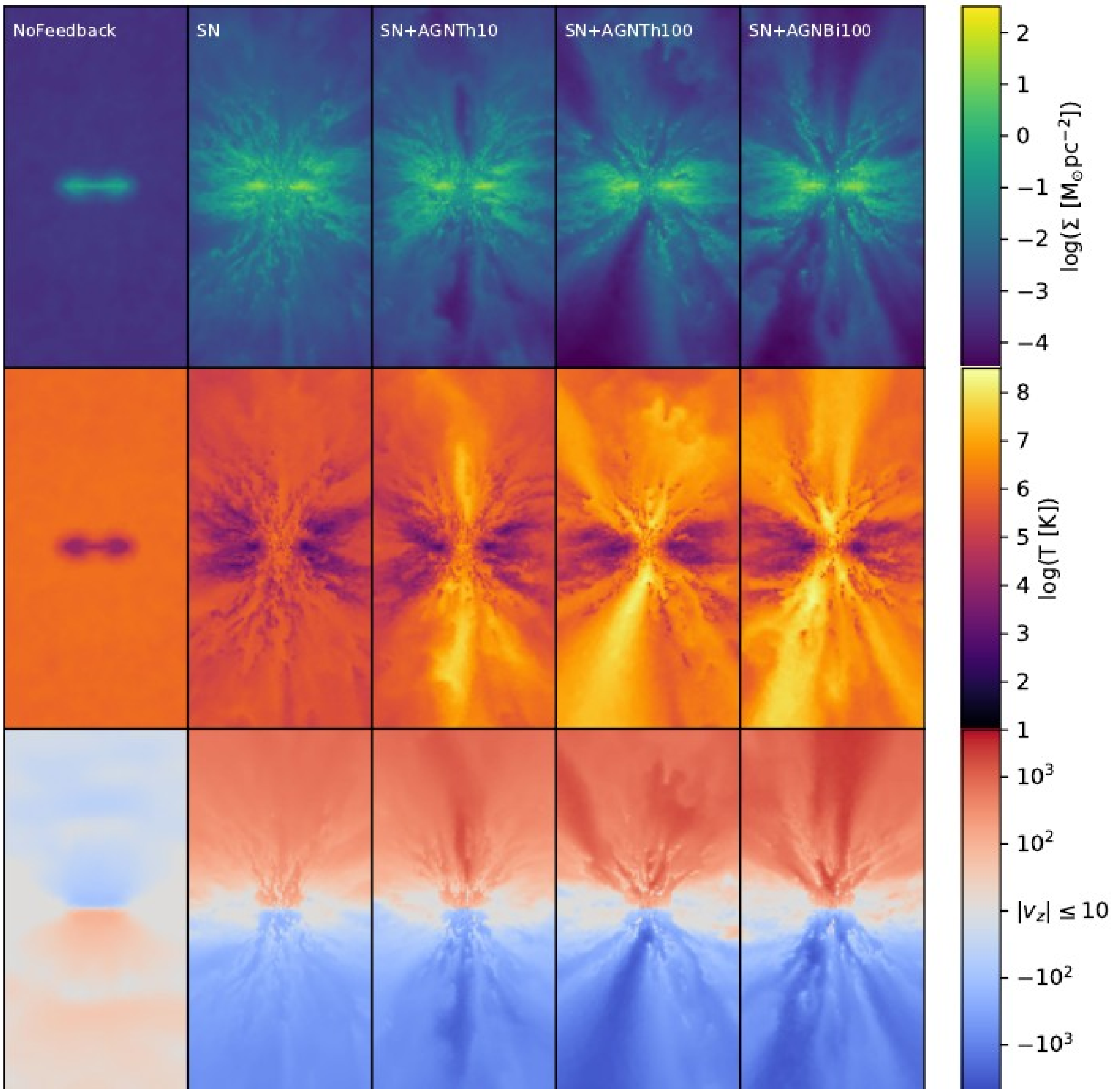
AGN feedback in dwarf galaxies?



Koudmani, Sijacki et al. 2018

AGN feedback in dwarf galaxies: outflows



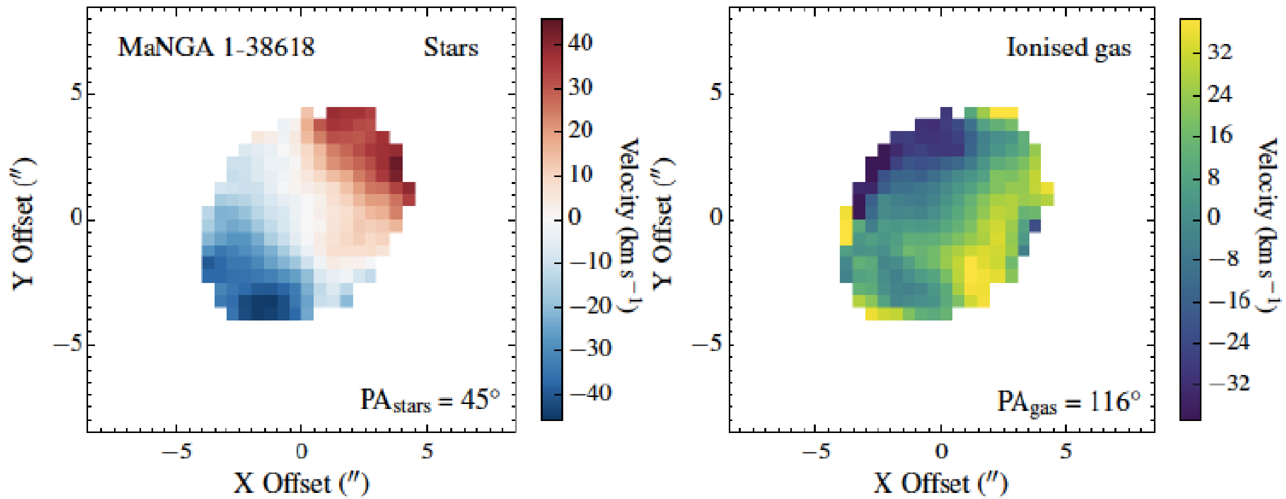


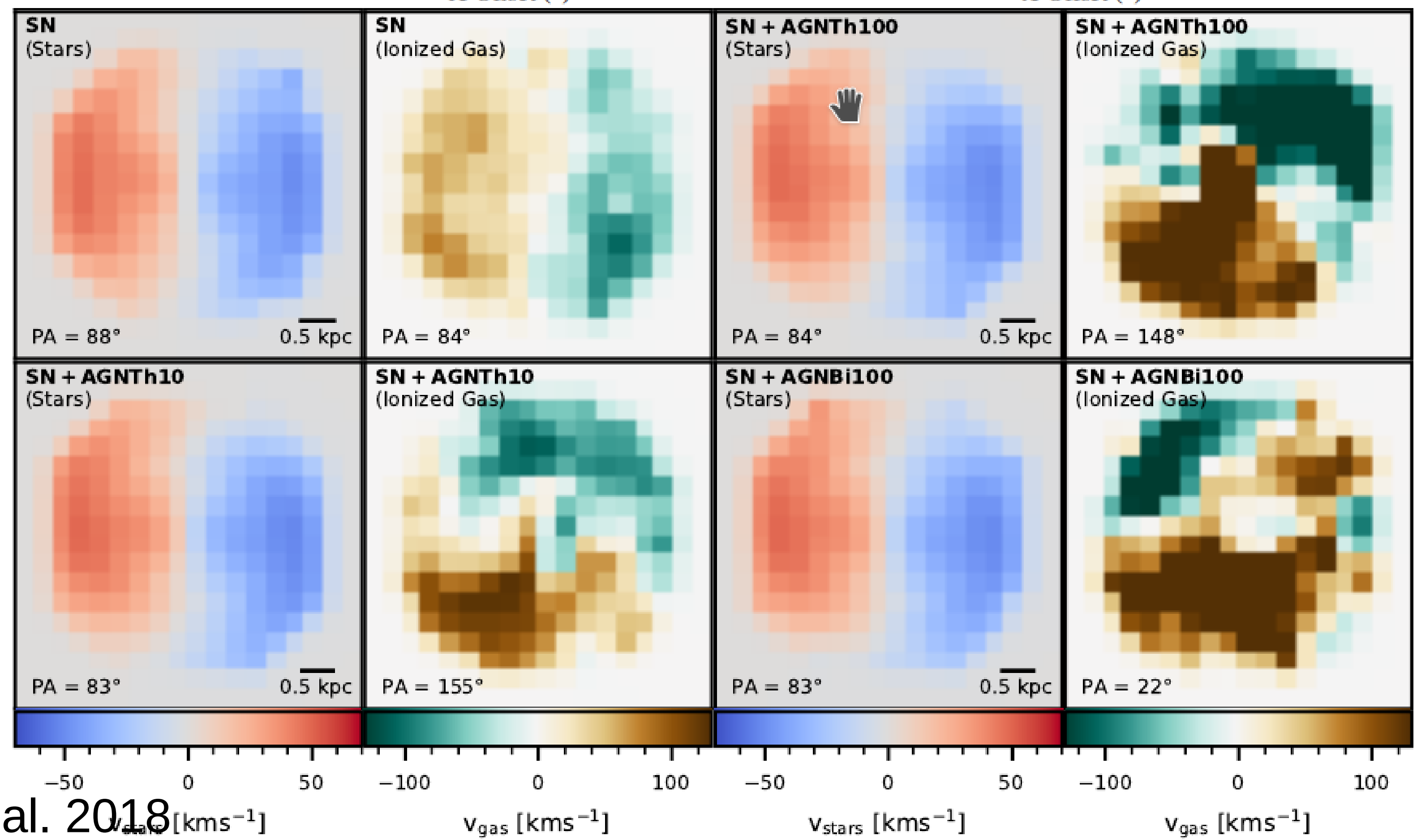
GLOBAL SFR NOT MUCH AFFECTED HOWEVER OUTFLOWS MUCH FASTER AND HOTTER

Koudmani, Sijacki et al. 2018

AGN feedback in dwarf galaxies: outflows

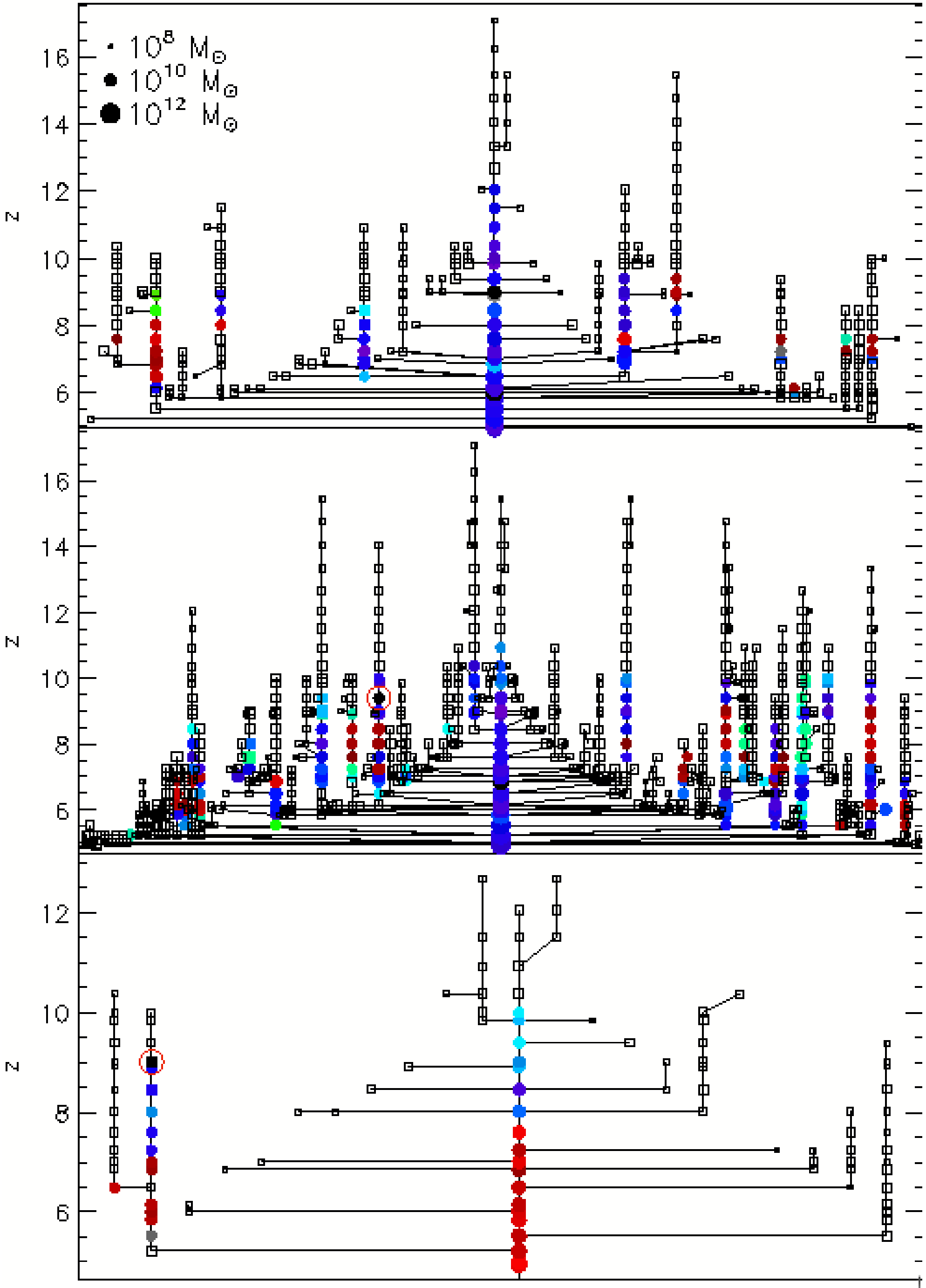
KINEMATIC OFFSETS BETWEEN STARS AND IONIZED GAS (MaNGA)

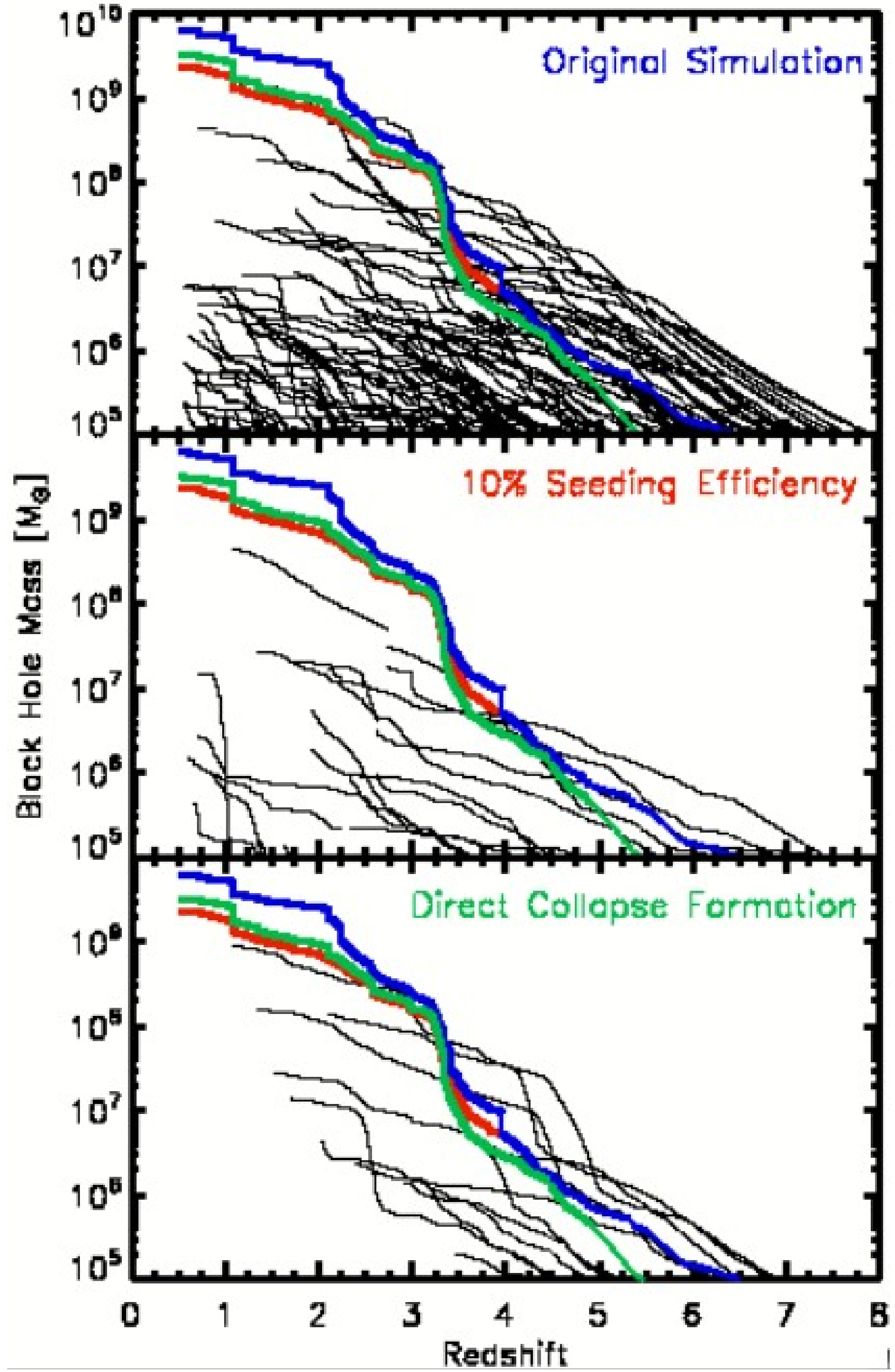




Koudmani, Sijacki et al. 2018

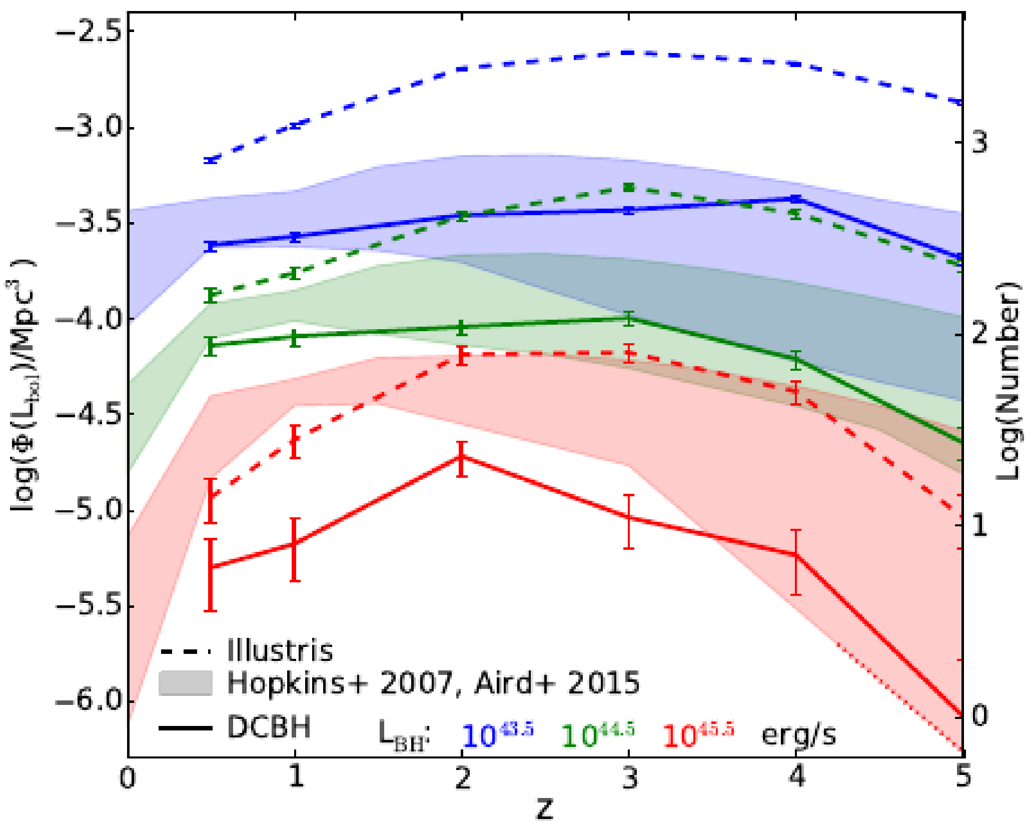
BH seeding: implications for BH growth

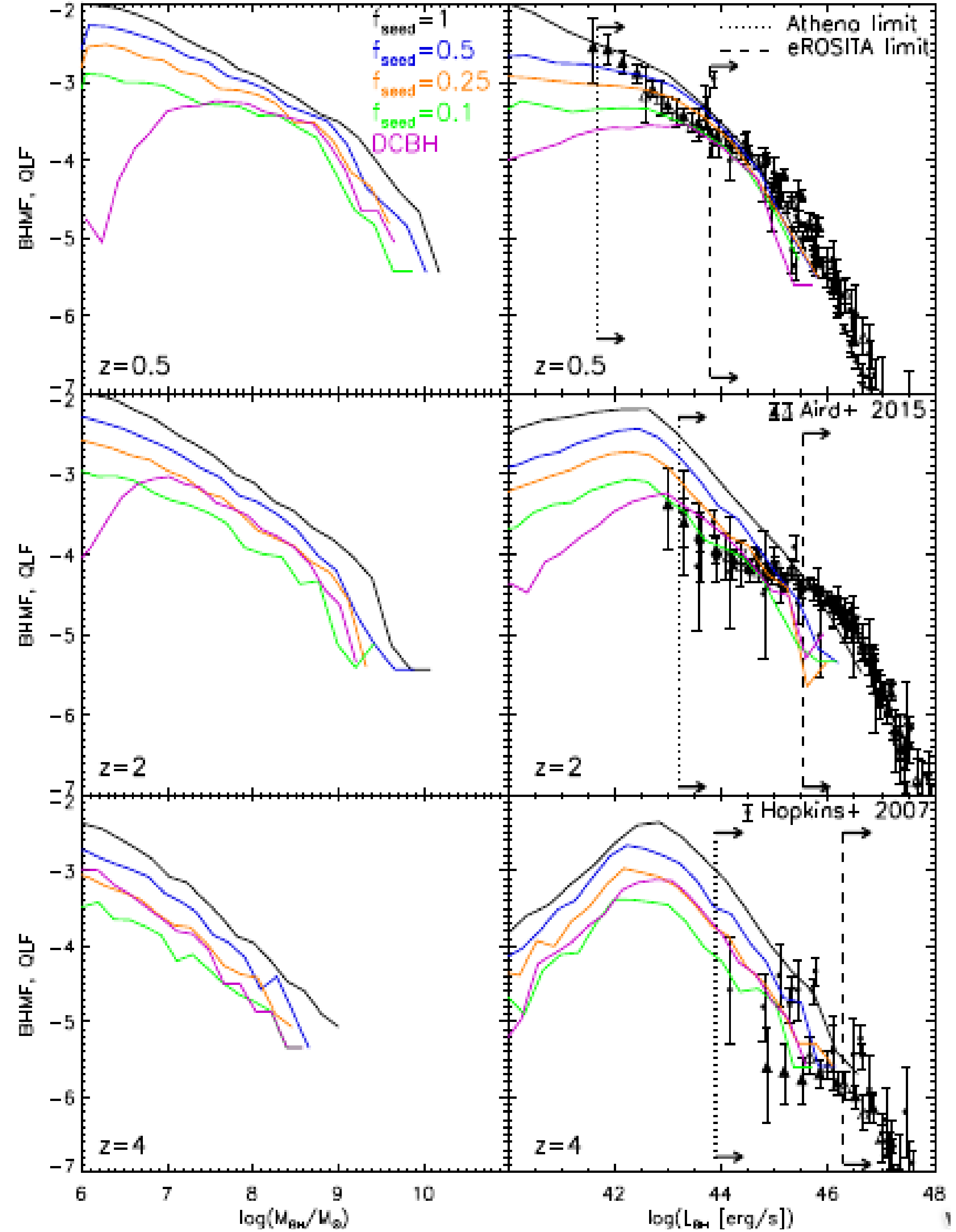




DeGraf & Sijacki, 2019, to be submitted

BH seeding: implications for BH growth

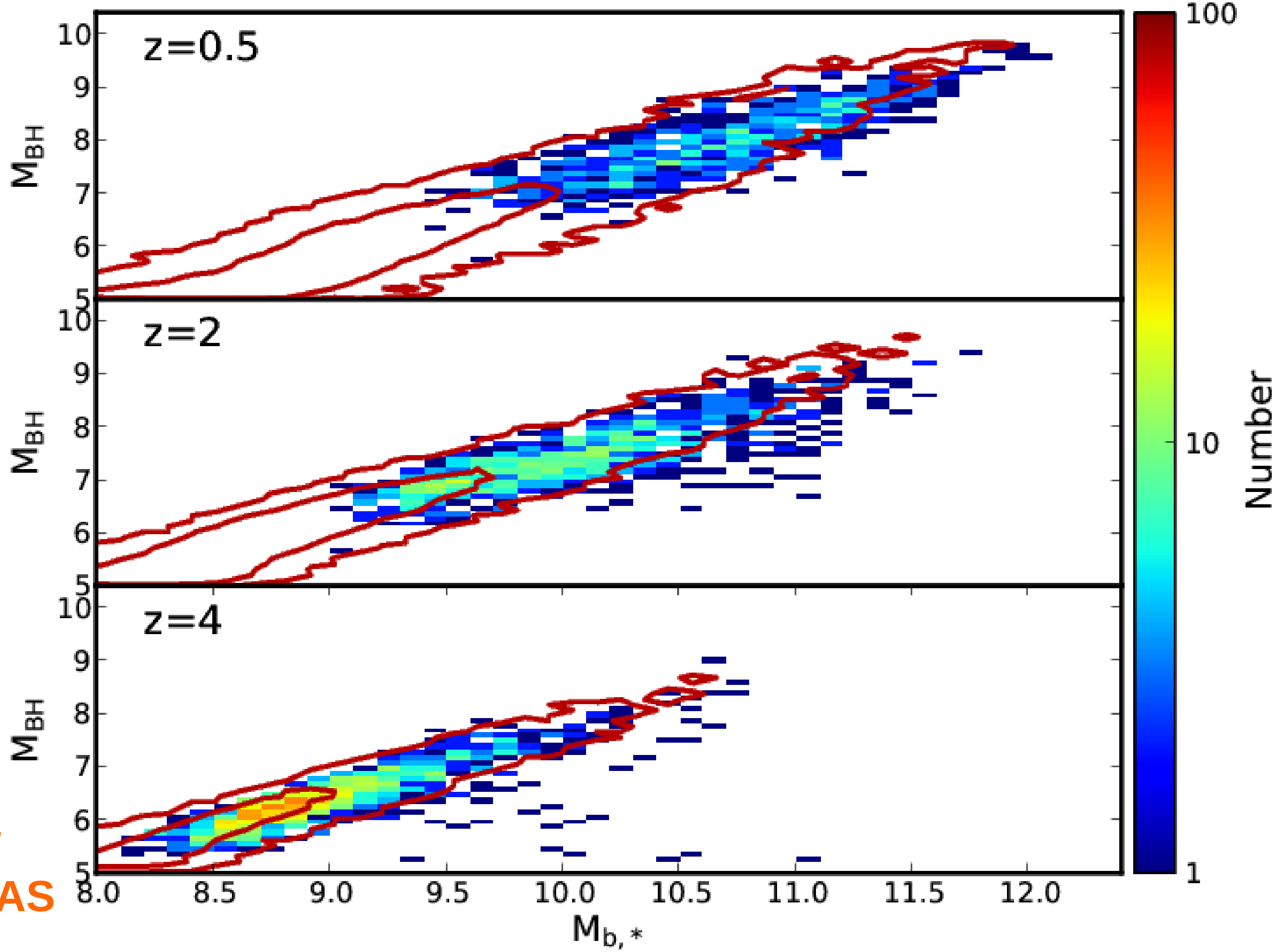




DIFFERENT SEEDING MODELS CAN CHANGE DRAMATICALLY THE BHMF AND THE BHLF AT THE LOW MASS END PREDICTIONS FOR ATHENA

DeGraf & Sijacki, 2019, to be submitted

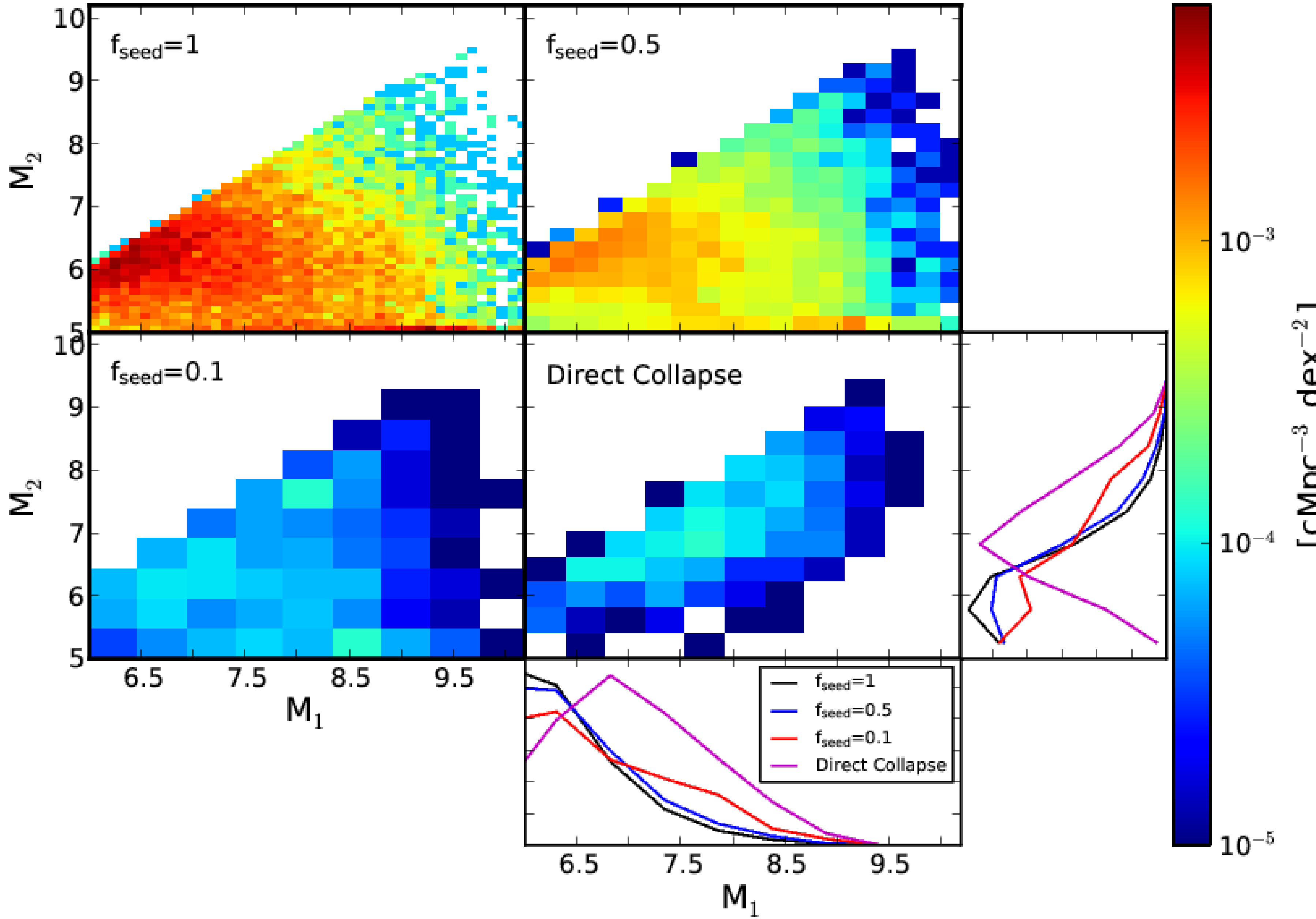
BH seeding: implications for BH scaling relations



BH OCCUPATION FRACTION OF LOW MASS GALAXIES HAS A POTENTIAL TO CONSTRAIN SEEDING MODELS

DeGraf & Sijacki, 2019, to be submitted

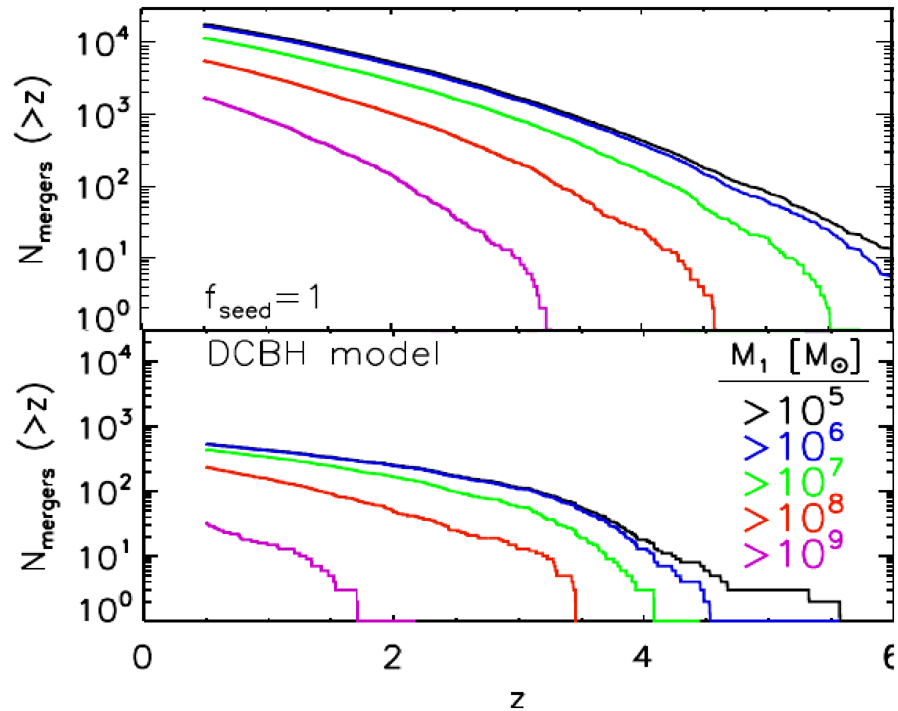
BH seeding: implications for merger rates

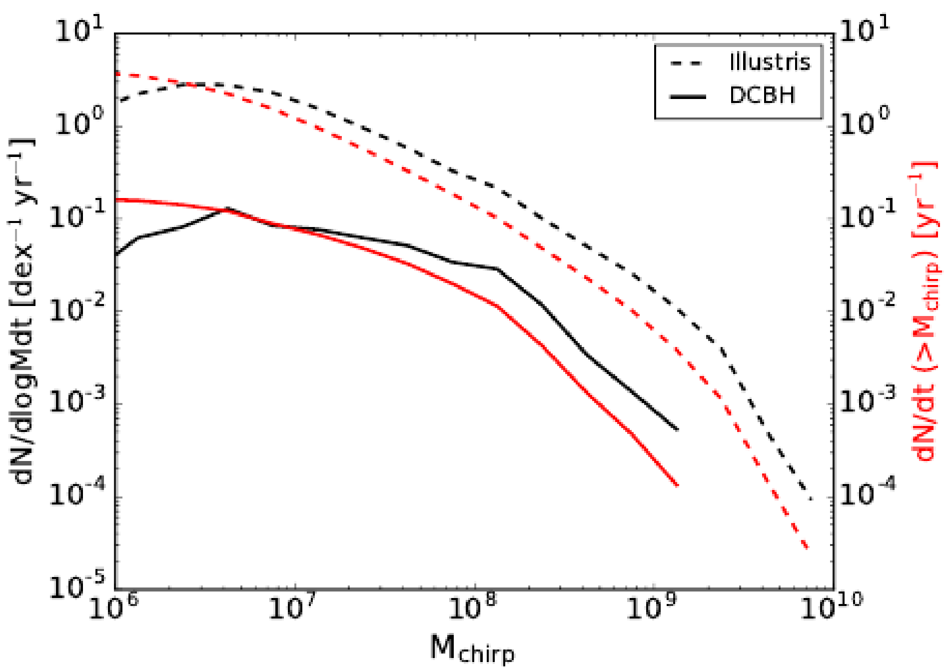


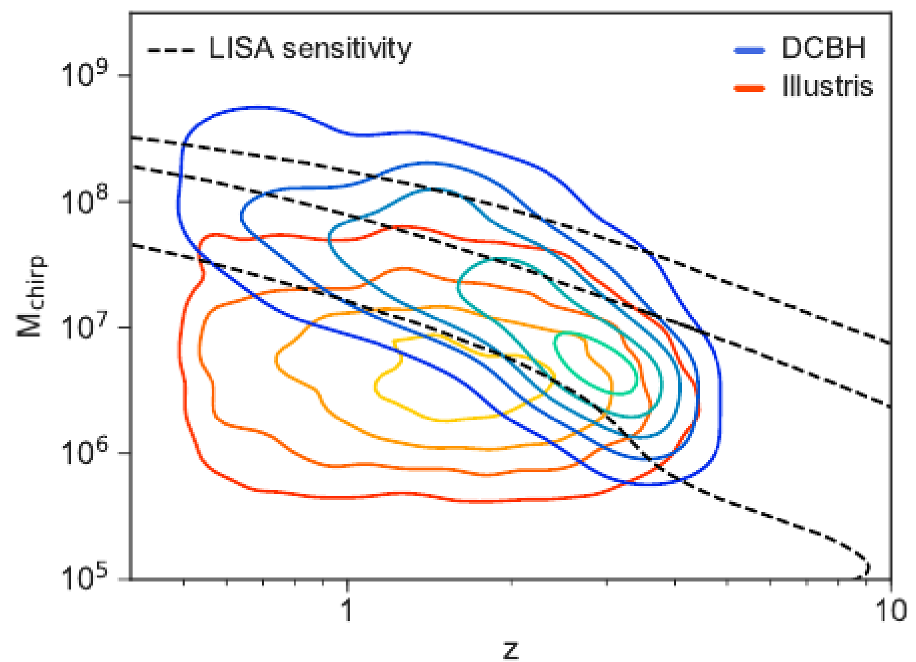
DeGraf & Sijacki, 2019, to be submitted

BH seeding: implications for merger rates

BH MERGER RATE AND REDSHIFT EVOLUTION OF CHIRP MASS VERY SENSITIVE ON THE SEEDING PRESCRIPTION: PREDICTIONS FOR LISA

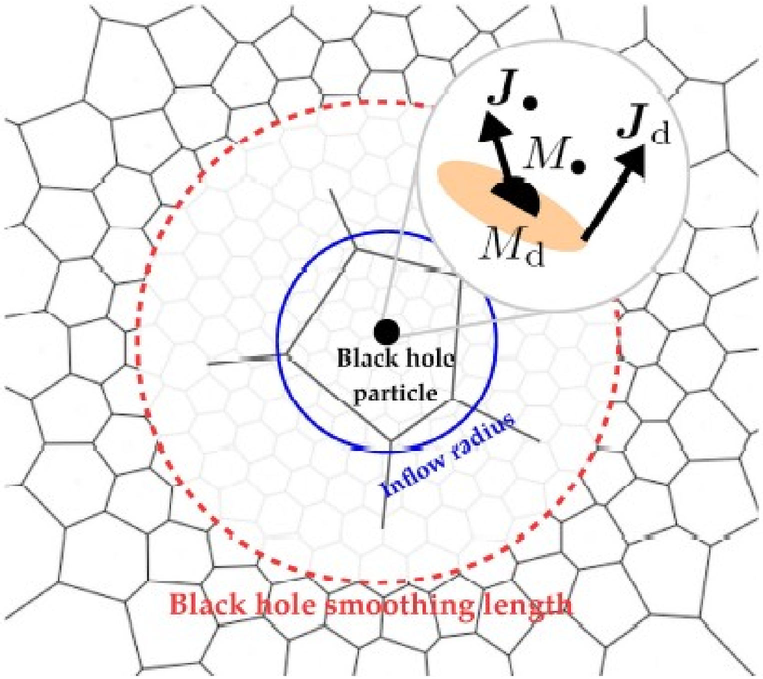


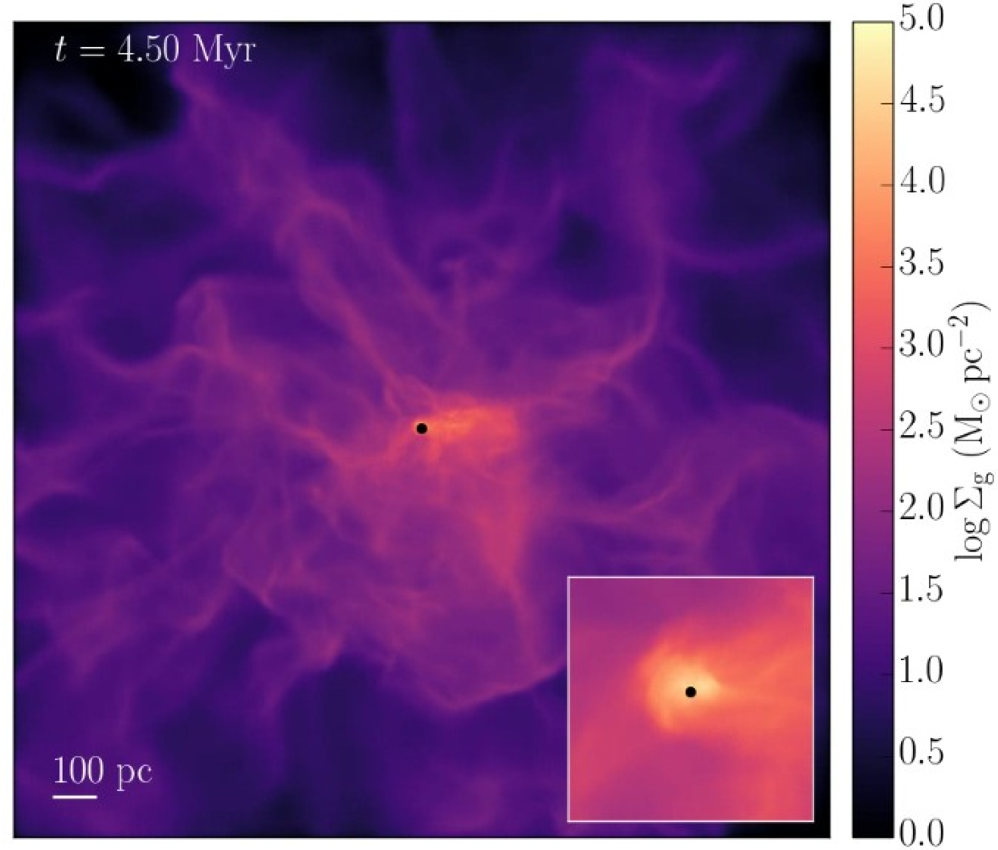


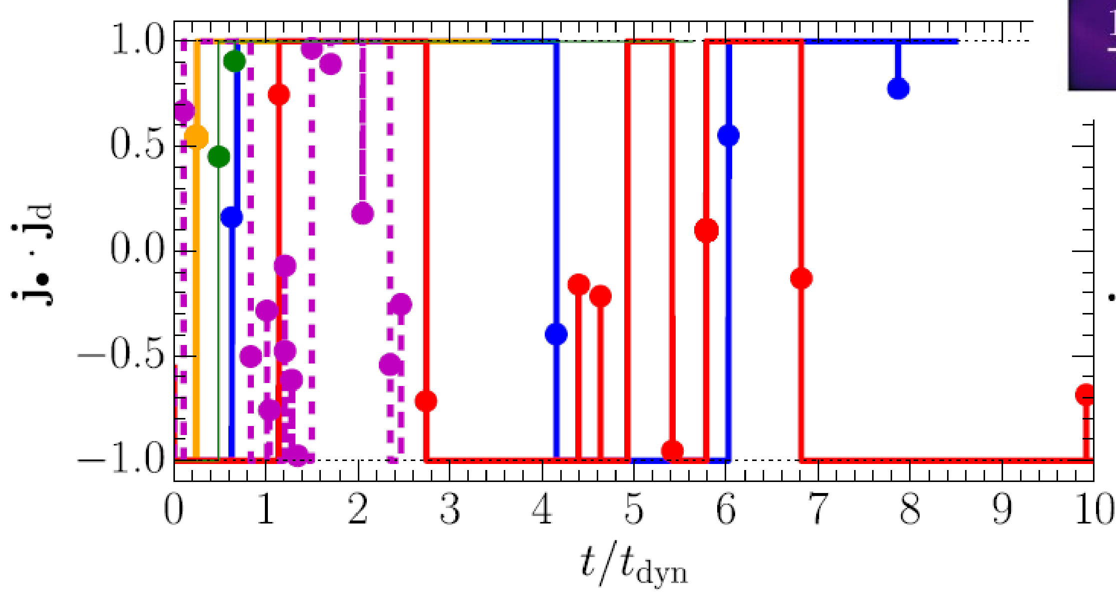


DeGraf & Sijacki, 2019, to be submitted

BH spins: coherent vs. chaotic accretion models



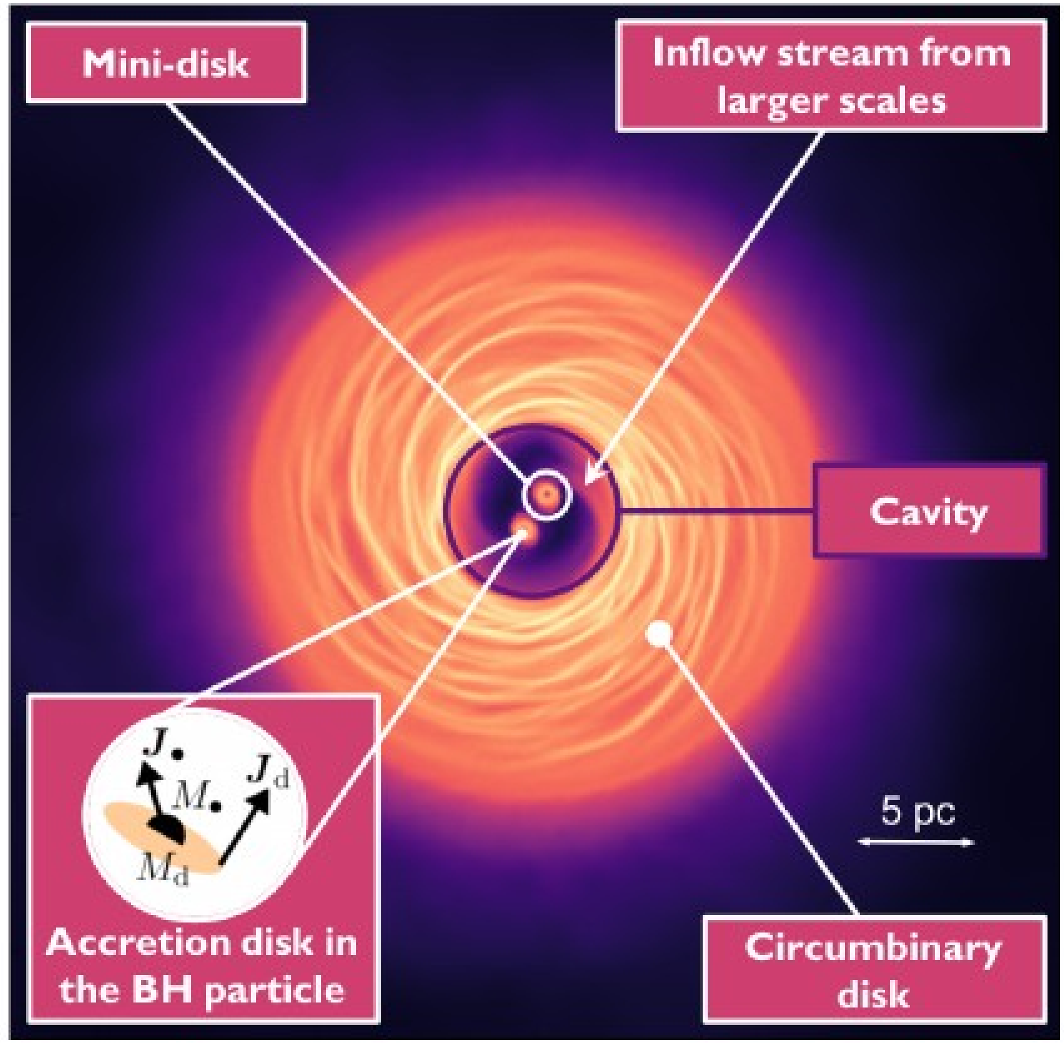




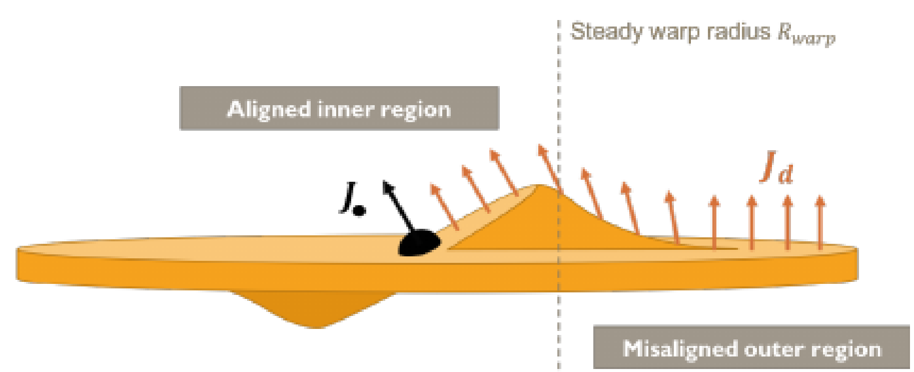
A SIMPLE MODEL FOR BH MASS AND SPIN EVOLUTION ASSUMING THIN, STEADY SS DISK COUPLED TO FULL HYDRO ON LARGER SCALES

Fiacconi, Sijacki & Pringle, 2018

Merging supermassive black hole binaries



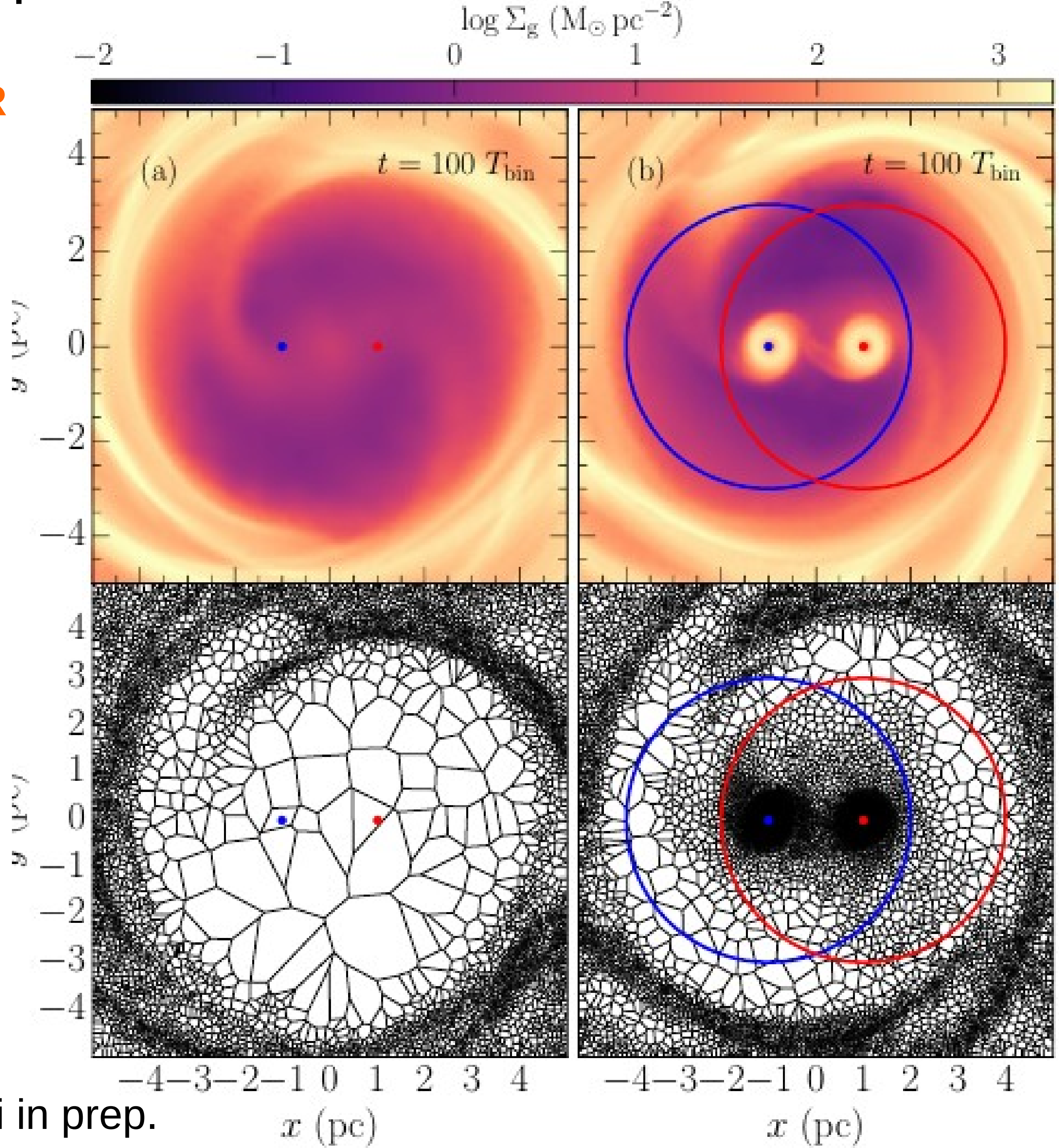
FROM GALAXY TO BLACK HOLE MERGER



Fiacconi, Piotrowska & Sijacki in prep.

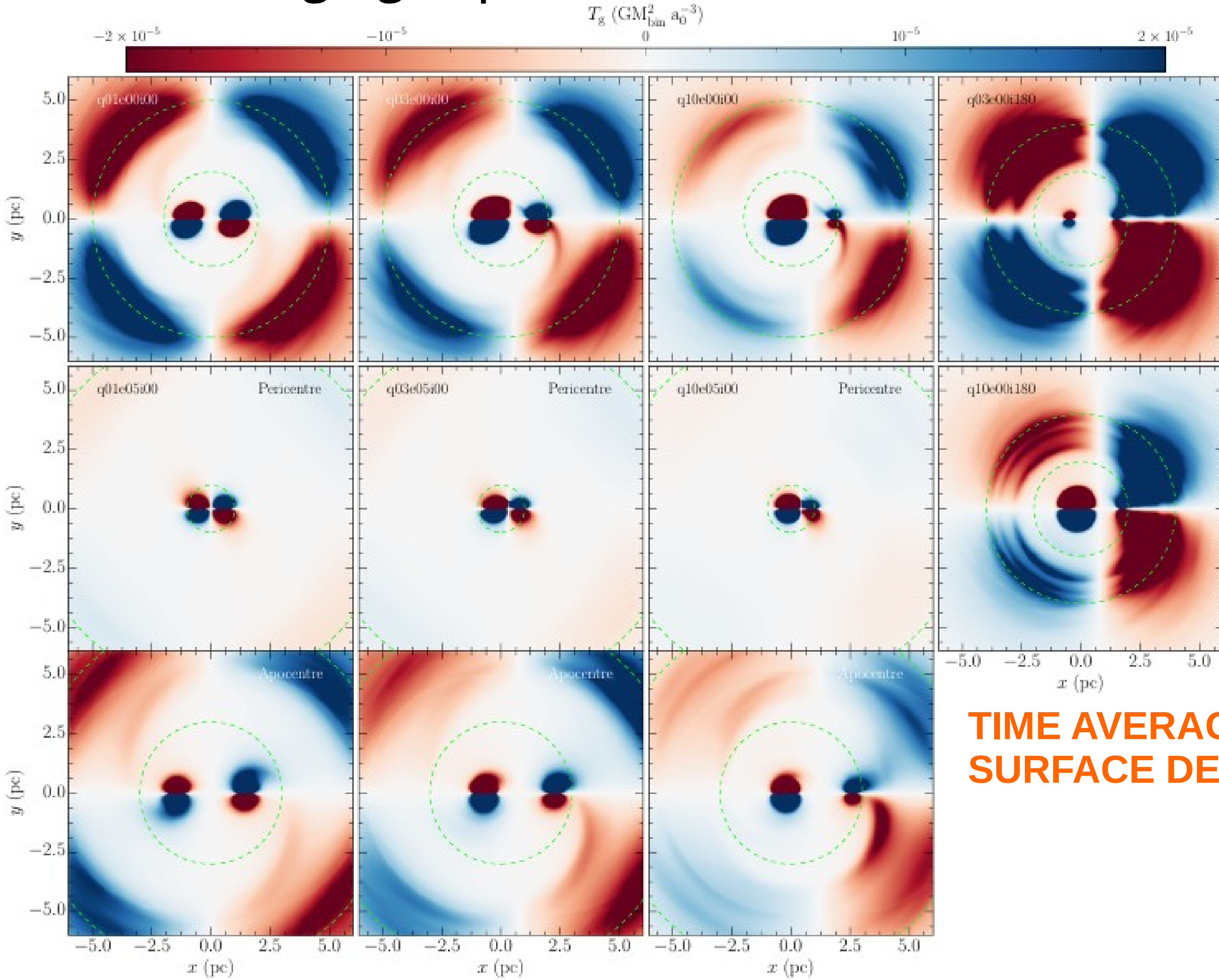
Merging supermassive black hole binaries

MINI DISKS CRUCIAL FOR BINARY DYNAMICS & SPIN EVOLUTION



Fiacconi, Piotrowska & Sijacki in prep.

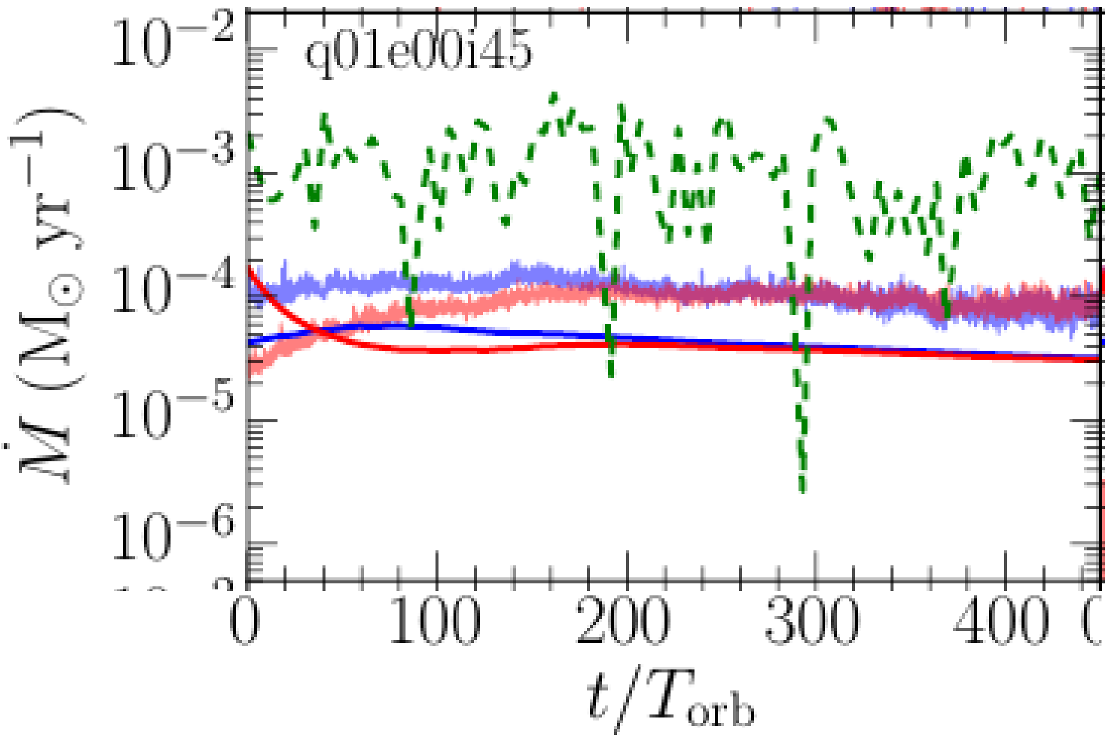
Merging supermassive black hole binaries



TIME AVERAGED TORQUE SURFACE DENSITY MAPS

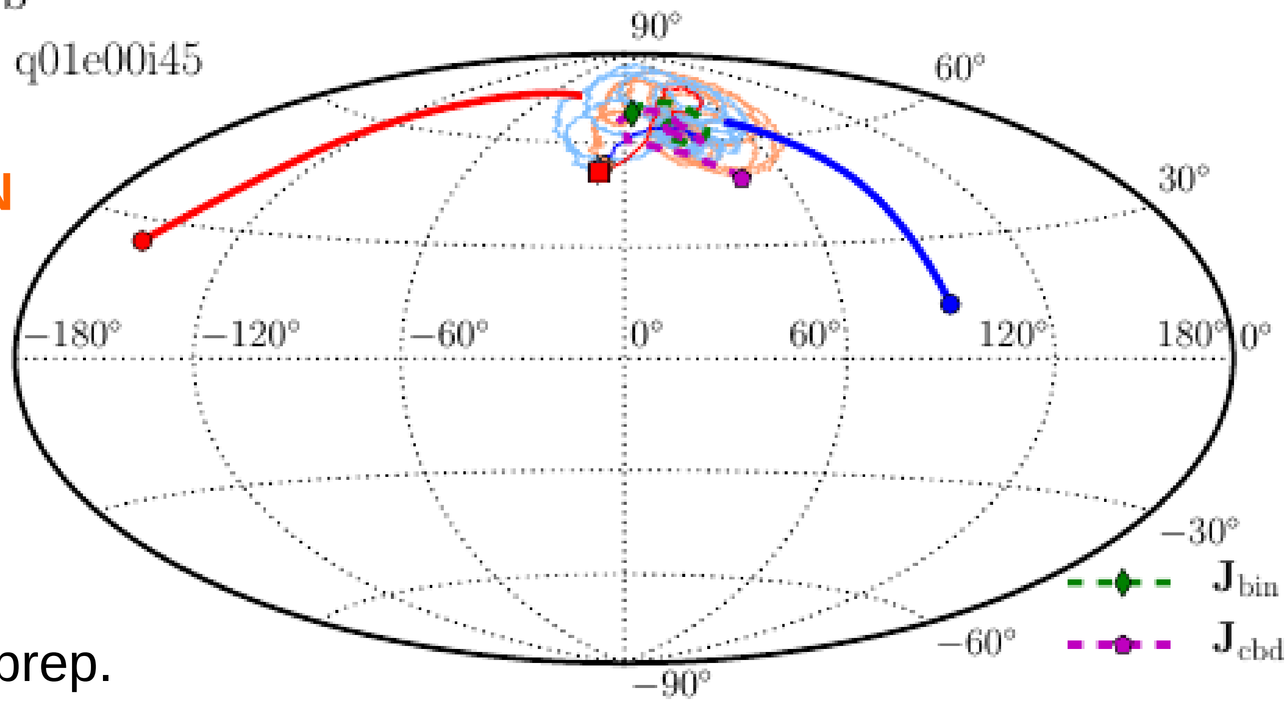
Fiacconi, Piotrowska & Sijacki in prep.

Merging supermassive black hole binaries



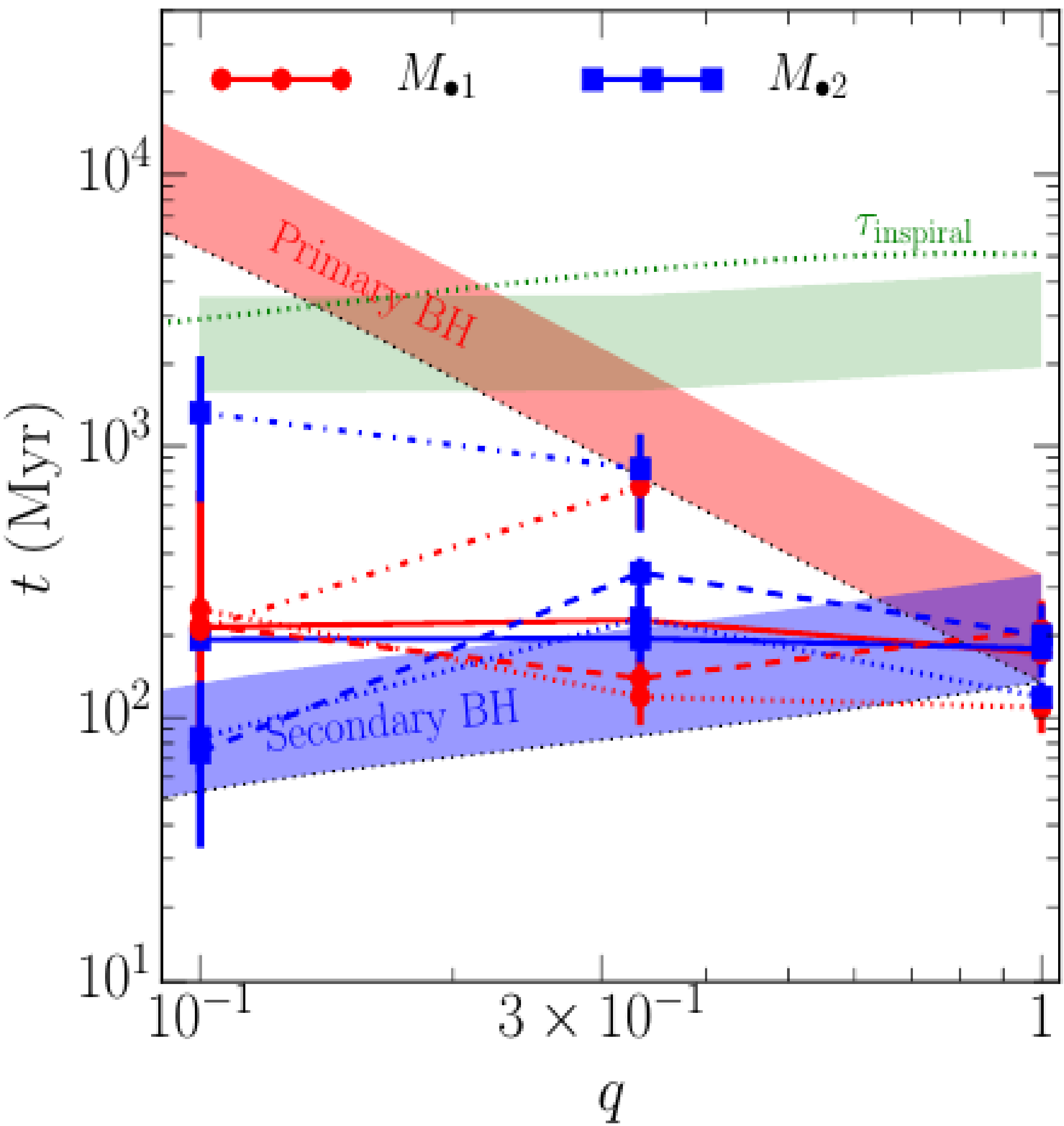
MASS ACCRETION RATES ONTO BLACK HOLES → SPIN MAGNITUDE EVOLUTION

SPIN DIRECTION EVOLUTION



Fiacconi, Piotrowska & Sijacki in prep.

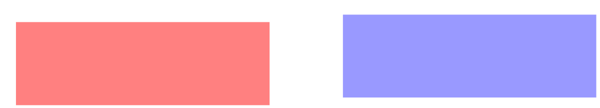
Merging supermassive black hole binaries



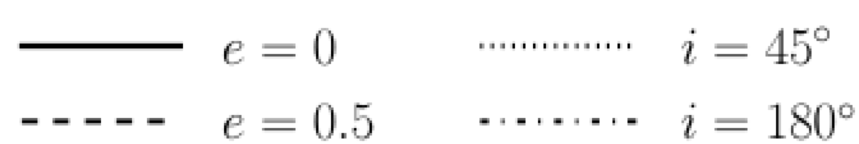
SPIN ALIGNMENT TIMESCALE MUCH SHORTER THAN THE INSPIRAL TIMESCALE

→ LOW RECOIL VELOCITY OF MERGER REMNANT
→ HIGHER BH RETENTION RATE IN GALACTIC NUCLEI

Analytical predictions
(Gerosa et al. 2015)



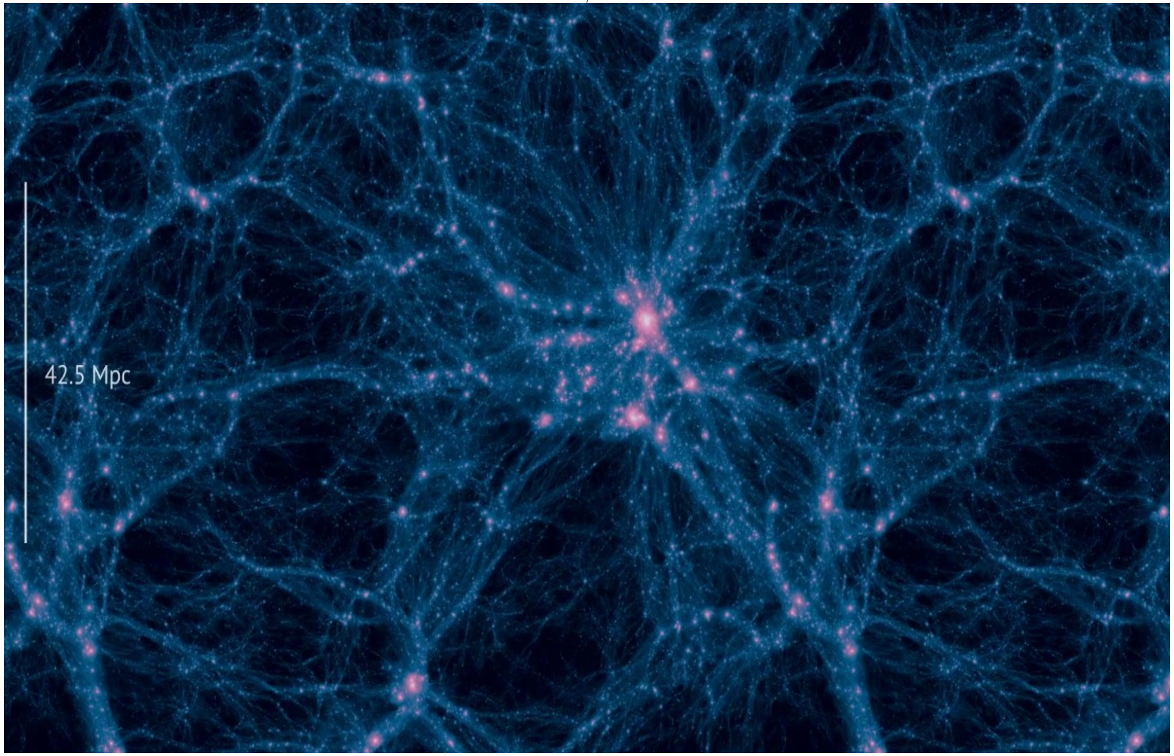
Our simulations



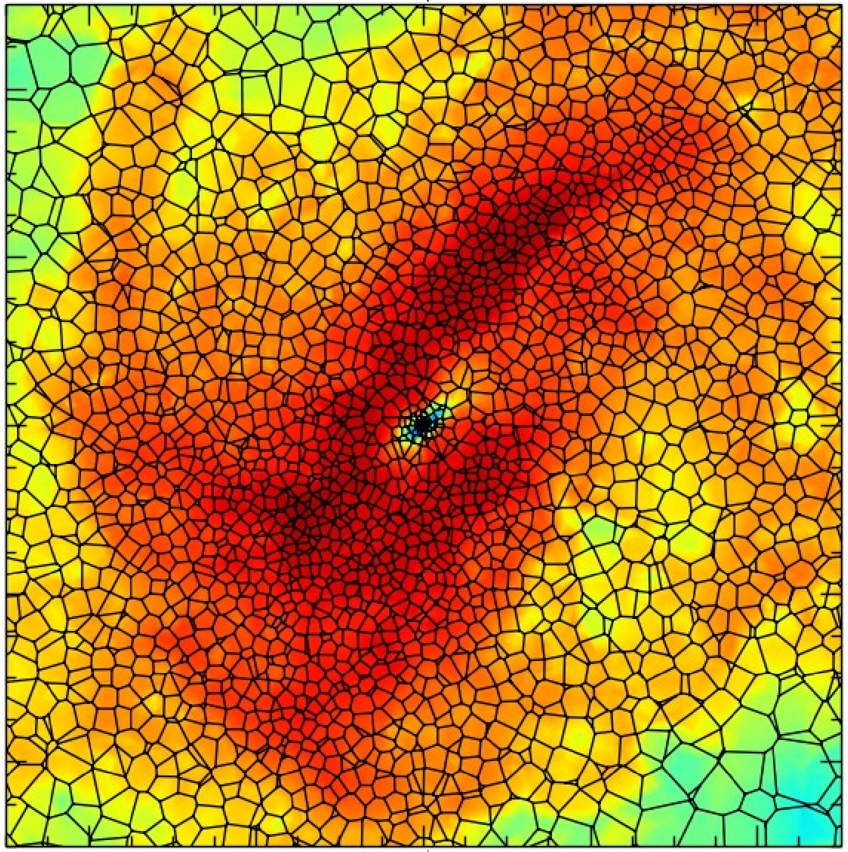
Fiacconi, Piotrowska & Sijacki in prep.

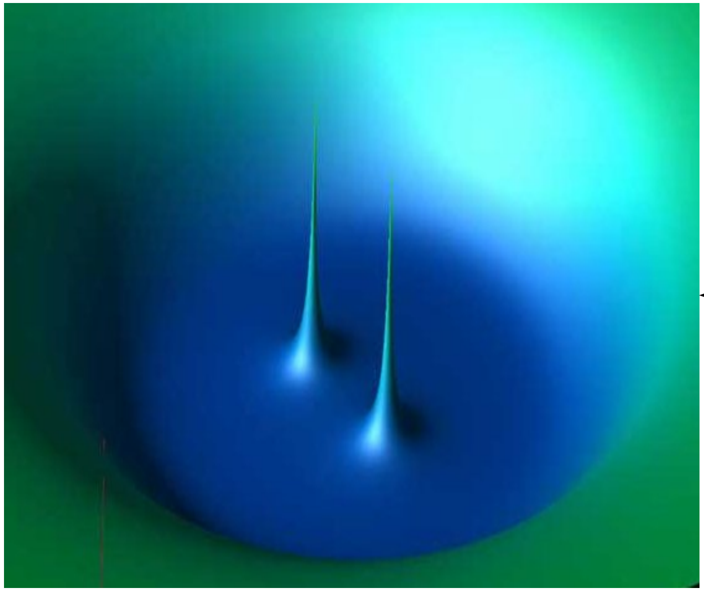
The Future

10^9 pc



10^3 pc





10^{-6} pc

GR simulations

Conclusions

Lessons learned:

1. Calibrating galaxy formation physics in simulations requires careful study of numerics and unbiased comparison with large observational datasets

2. Sub-grid physics uncertainties still very large!
→ Free parameters of sub-grid models "fine tuned" for specific observables
→ Other results are in principle predictions, but....

a) Different set of baryonic physics can lead to similar z = 0 results (redshift evolution is different) → DEGENERACIES

b) Same baryonic physics at different resolutions may lead to different results → WHAT DO WE LEARN ABOUT PHYSICS?

3. Next generation sub-grid models for SF and BH physics needed in large cosmological simulations
→ spatial resolution requirements daunting
→ more cross-talk with "small-scale" community