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

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Cosmic Mergers Workshop
Birmingham
Sept 22th 2017

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)

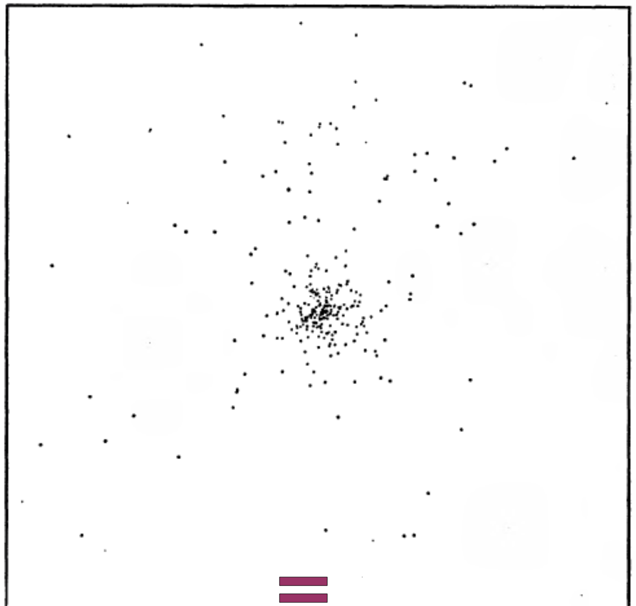
► Gas radiative cooling/heating, star & BH formation and feedback
(non equlibrium low T cooling, dust, turbulence, GMCs,…)

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

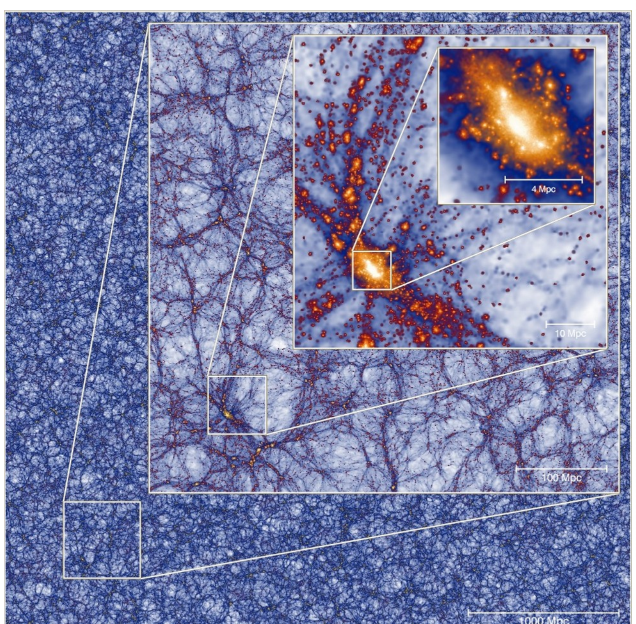
Time since the Big Bang: 3.7 billion years

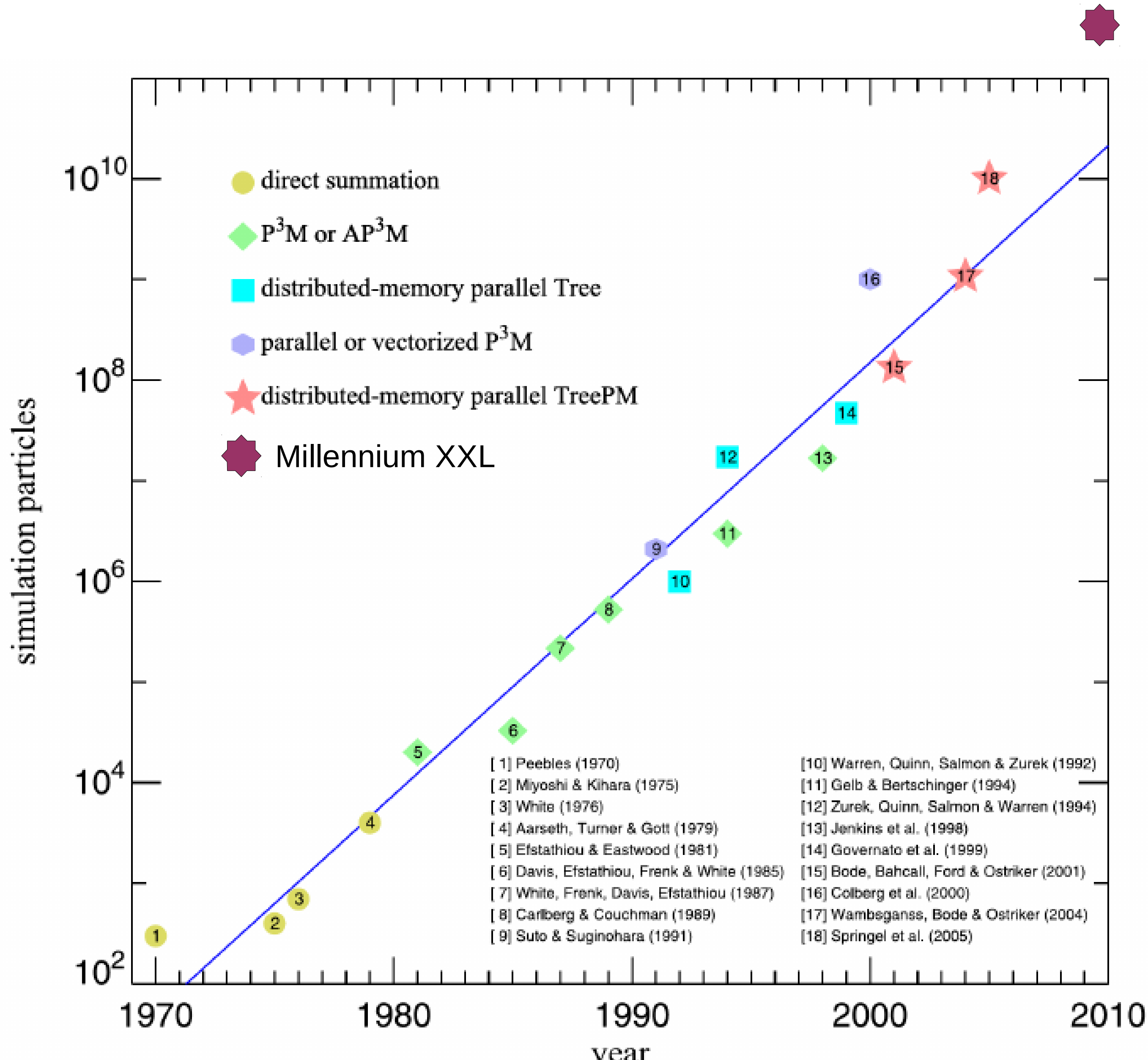
ILLUSTRIS

Pure dark matter simulations in ΛCDM cosmology



40 yrs!

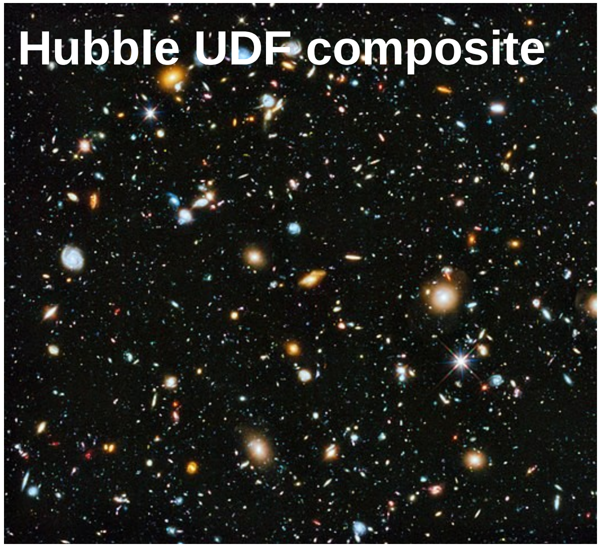


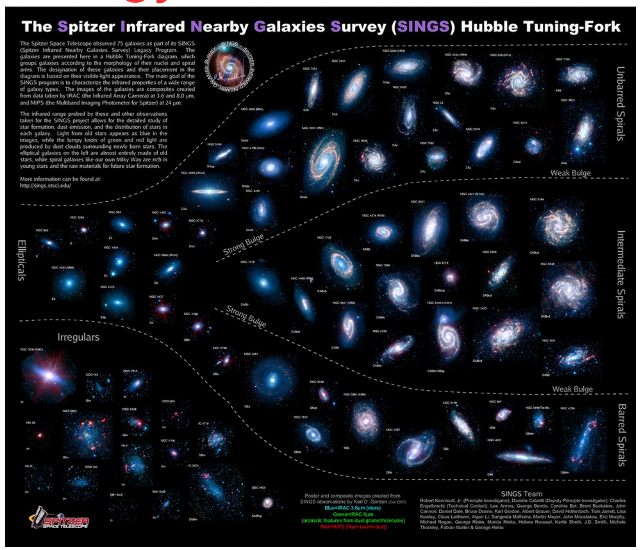


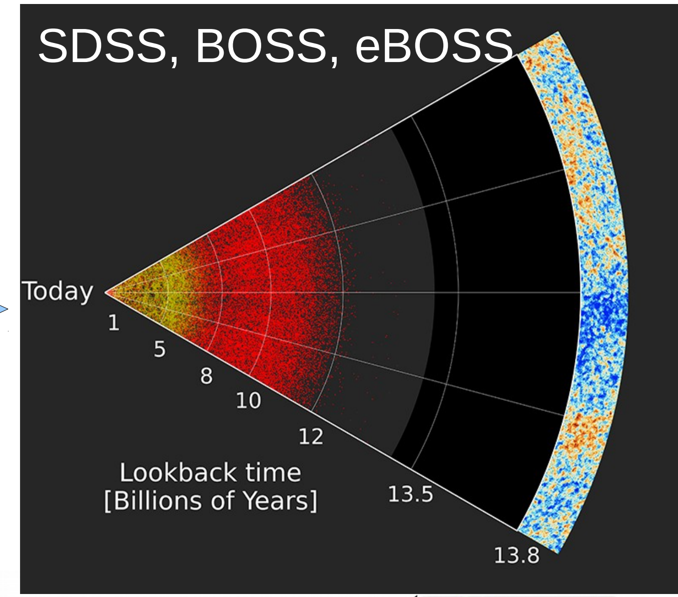
See also:
Horizon Run 3 (Kim 2011) MultiDark (Prada 2012)
DEUS (Alimi et al. 2012) Watson et al. 2013

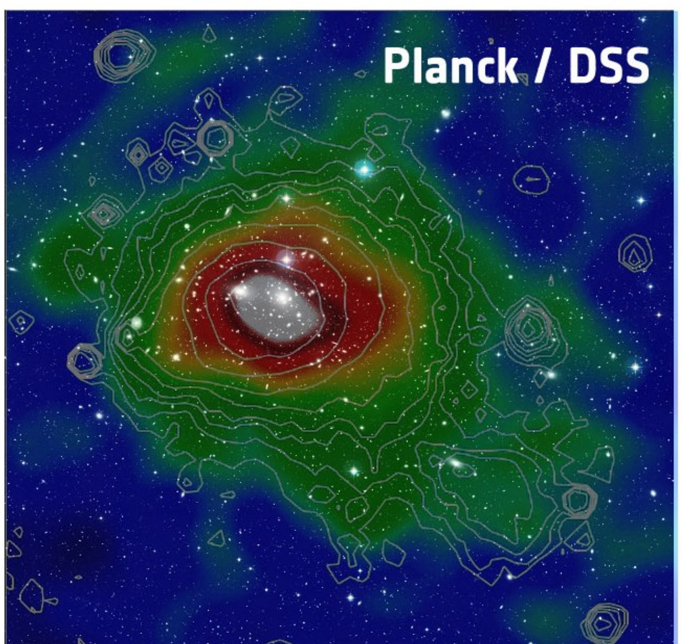
The importance of baryons

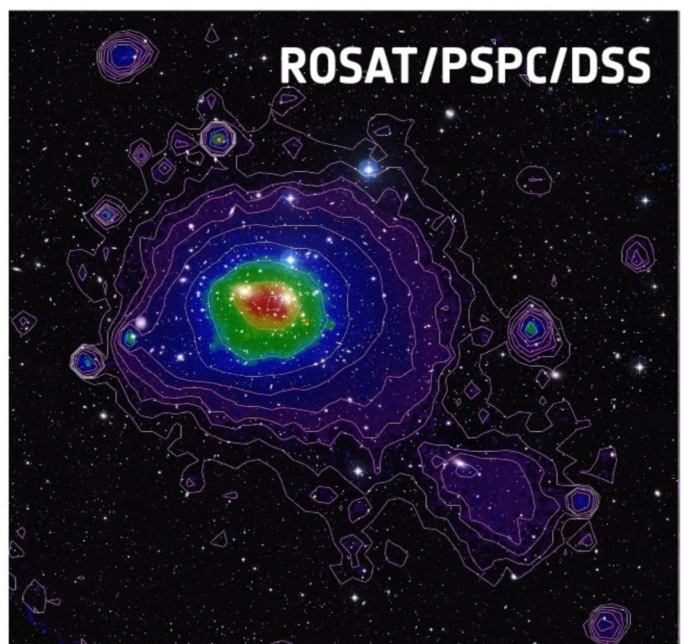
Baryons are directly observable and they affect the underlying dark matter distribution (contraction/expansion/shape/bias, WL,...) => profound implications for cosmology

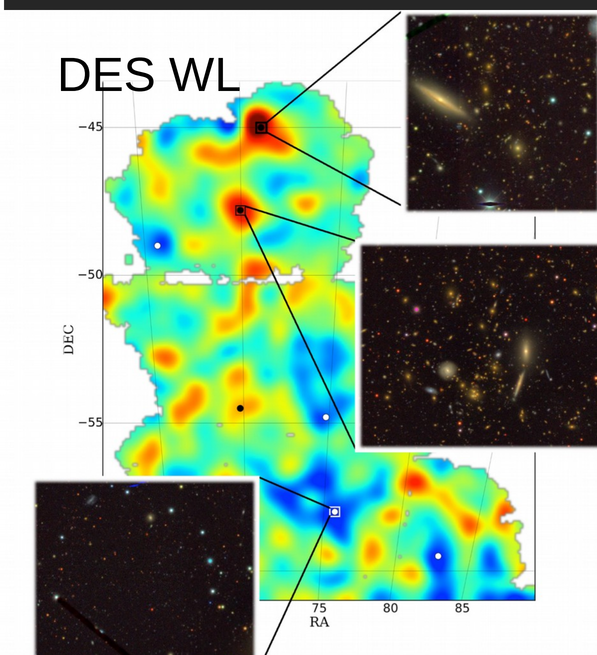






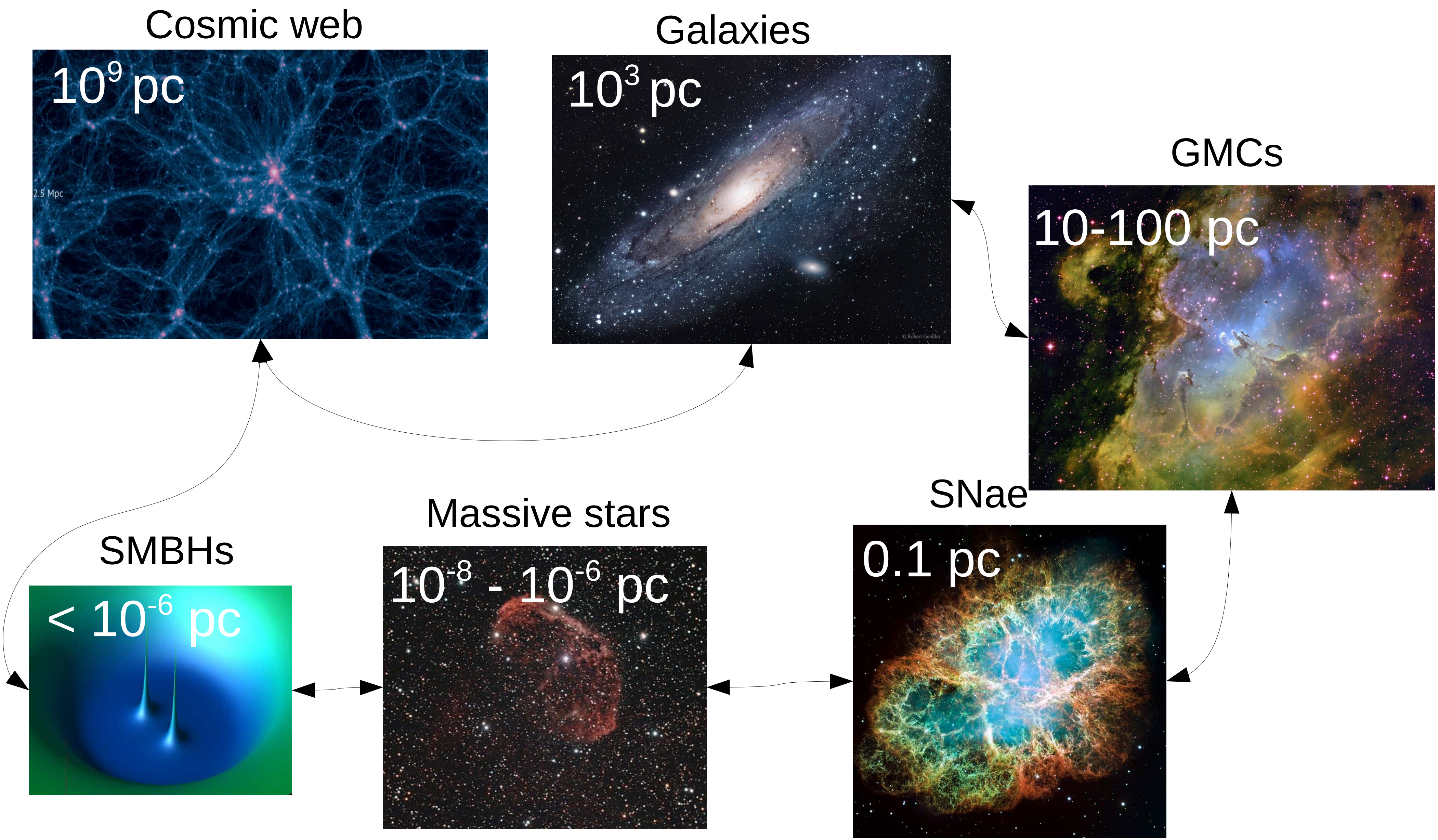






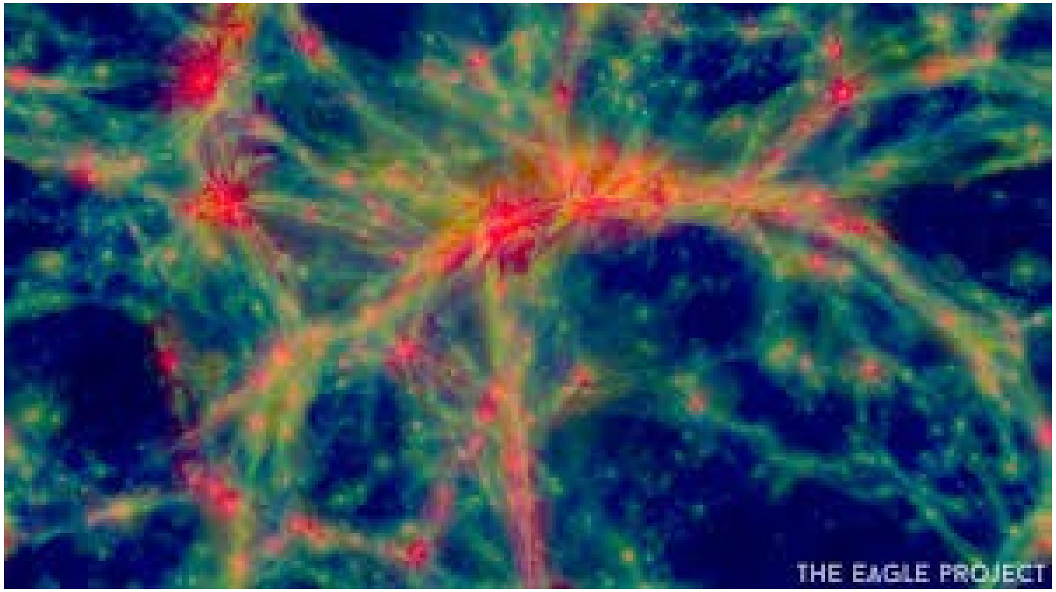
The importance of baryons

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

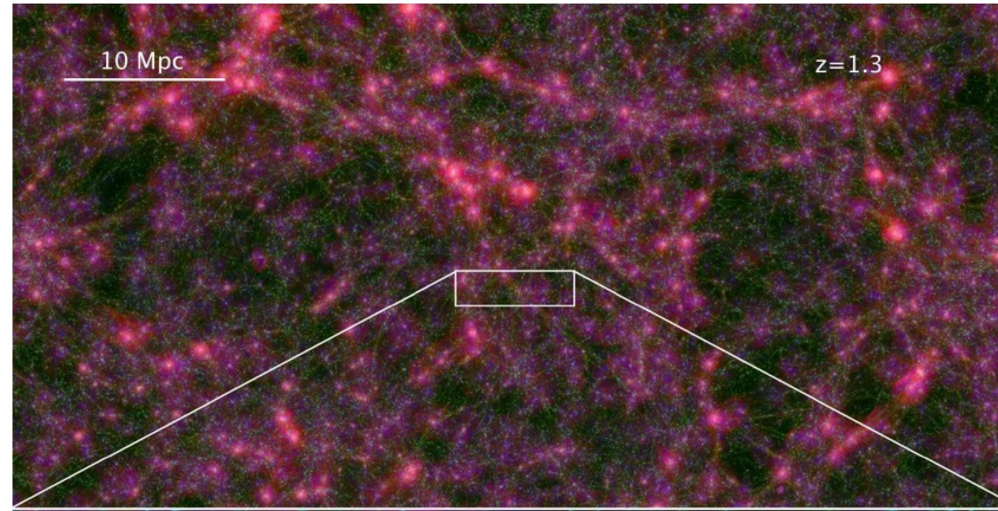


Current state-of-the-art in cosmological hydro simulations

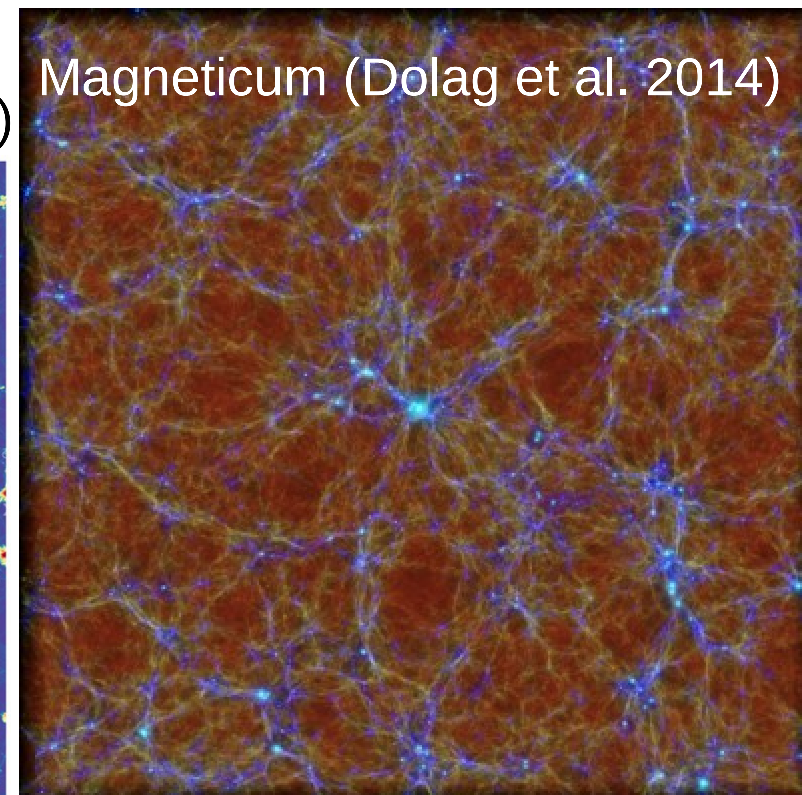
The Eagle Project (Schaye et al. 2015)



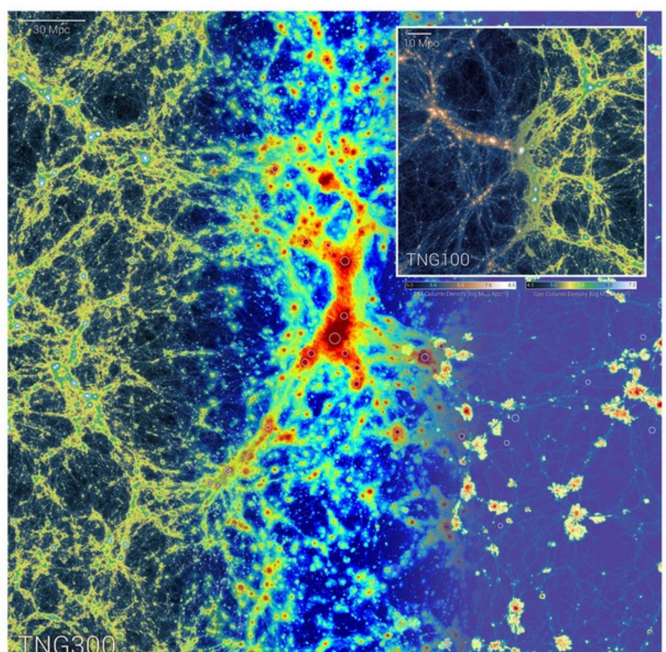
The Horizon AGN project (Dubois et al. 14)



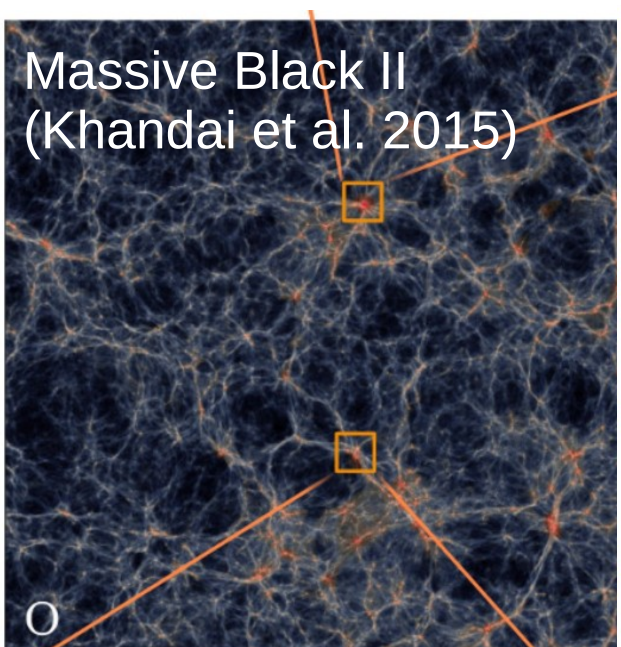
Magneticum (Dolag et al. 2014)



Illustris TNG (Springel et al. 17)

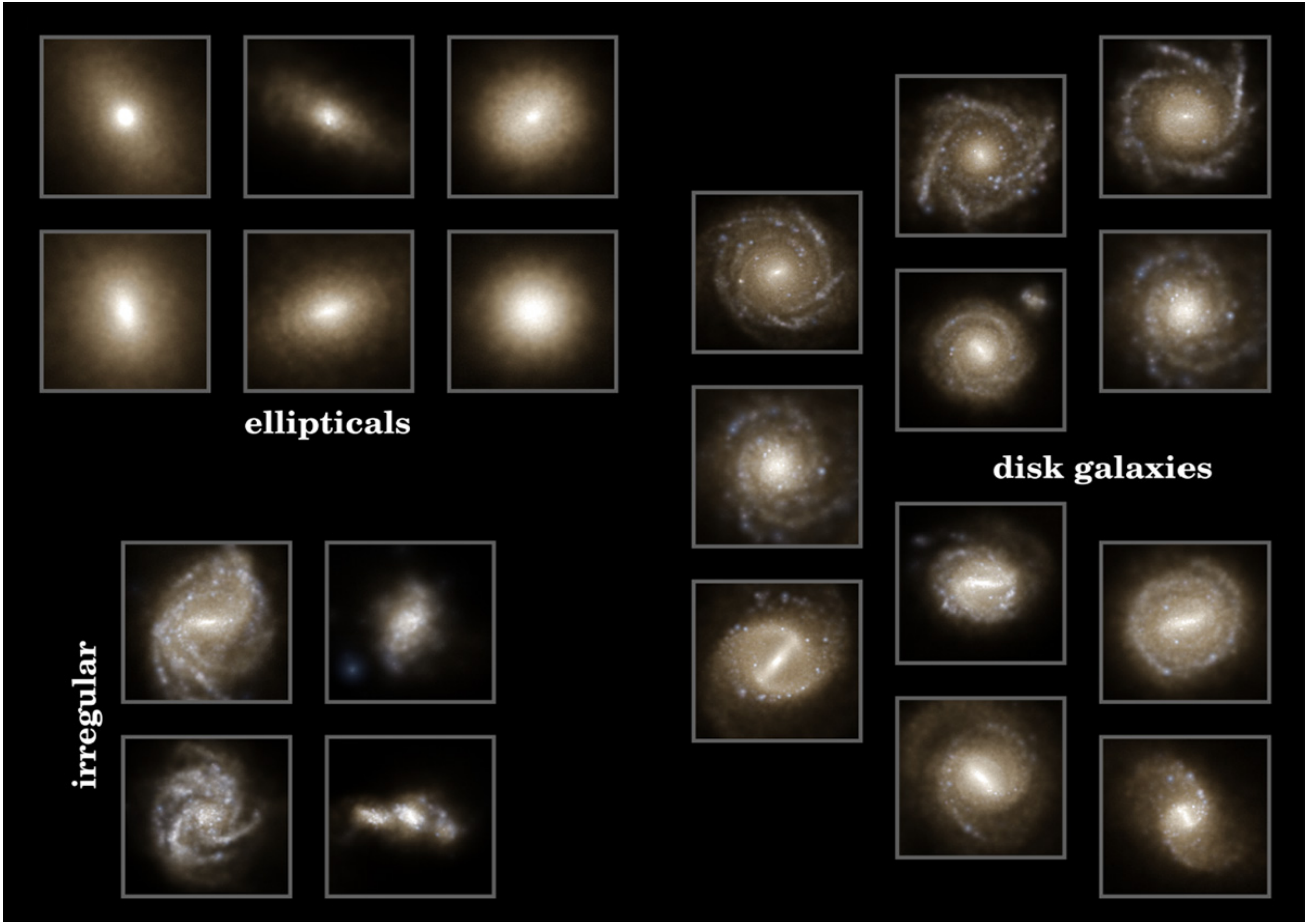


Massive Black II (Khandai et al. 2015)



The Illustris project

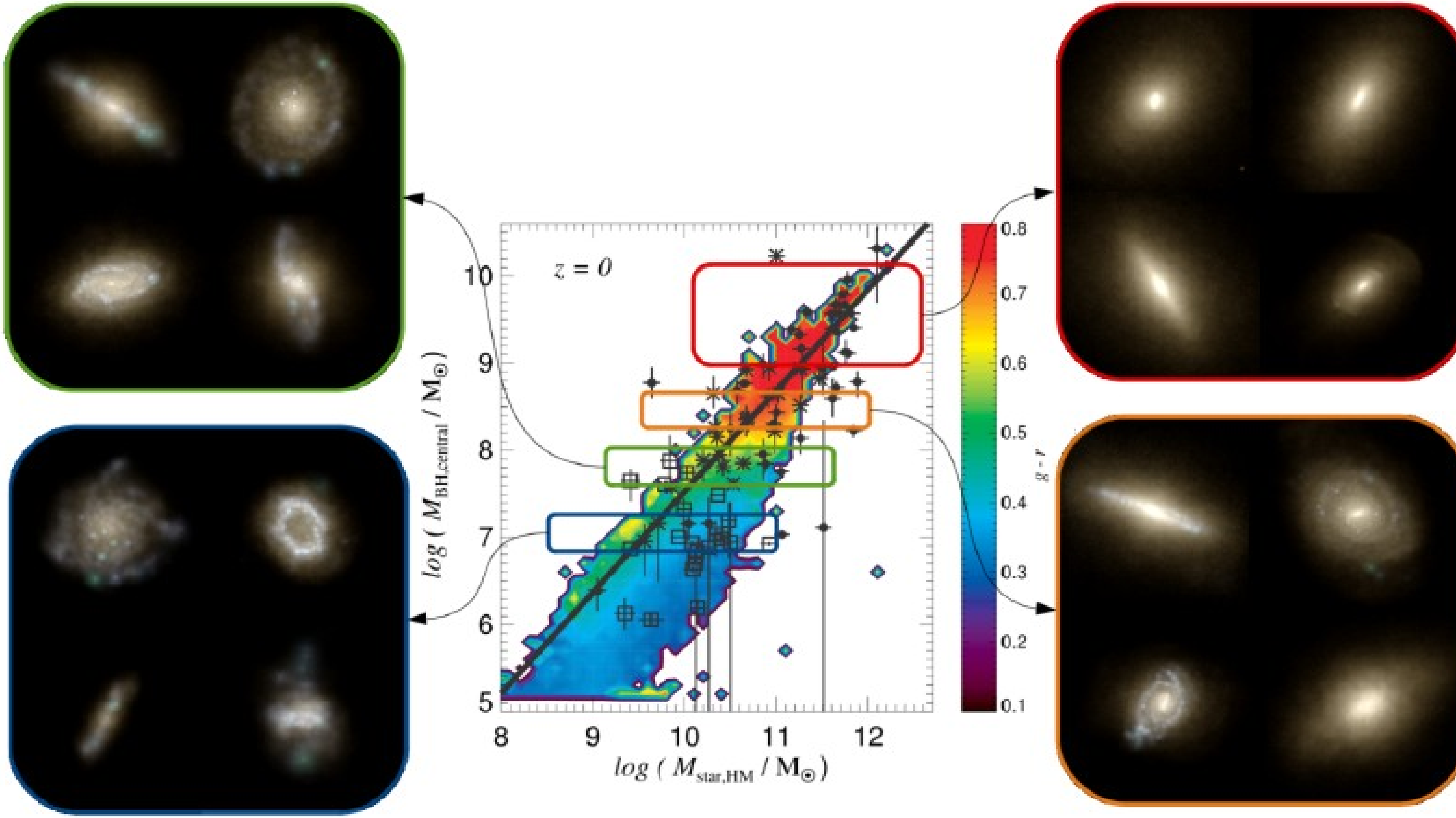
GALAXY MORPHOLOGIES



Vogelsberger et al., Nature, 2014, Vogelsberger et al., MNRAS, 2014
Genel et al., MNRAS, 2014
Sijacki et al., MNRAS, 2015

Black holes in Illustris

BH MASS – BULGE MASS RELATION



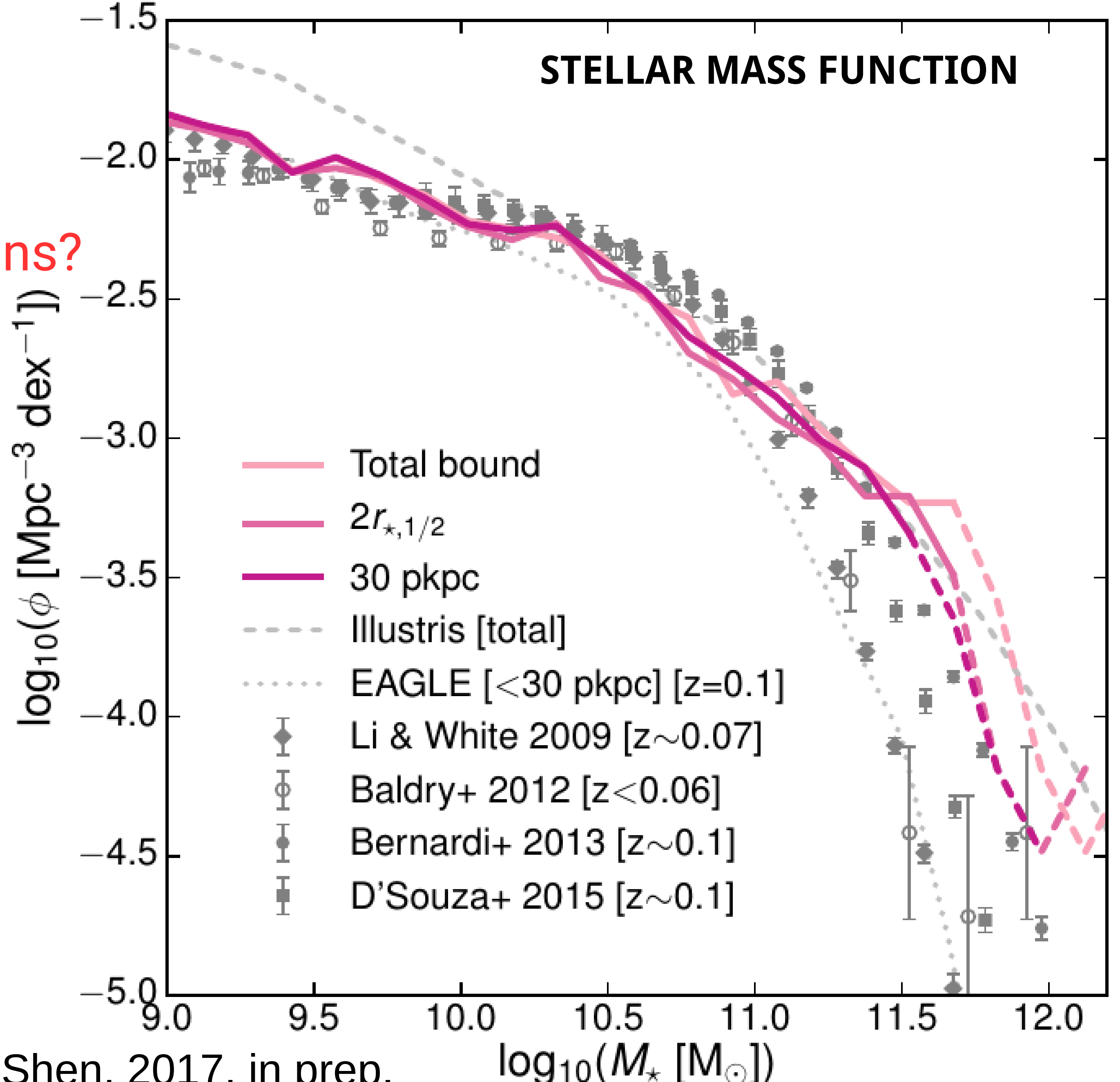
Kormendy & Ho, 2013: best fit
circles: ellipticals; stars: spirals with bulges; squares: pseudo bulges

Sijacki et al, 2015

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

Different sub-grid models achieve similar results!

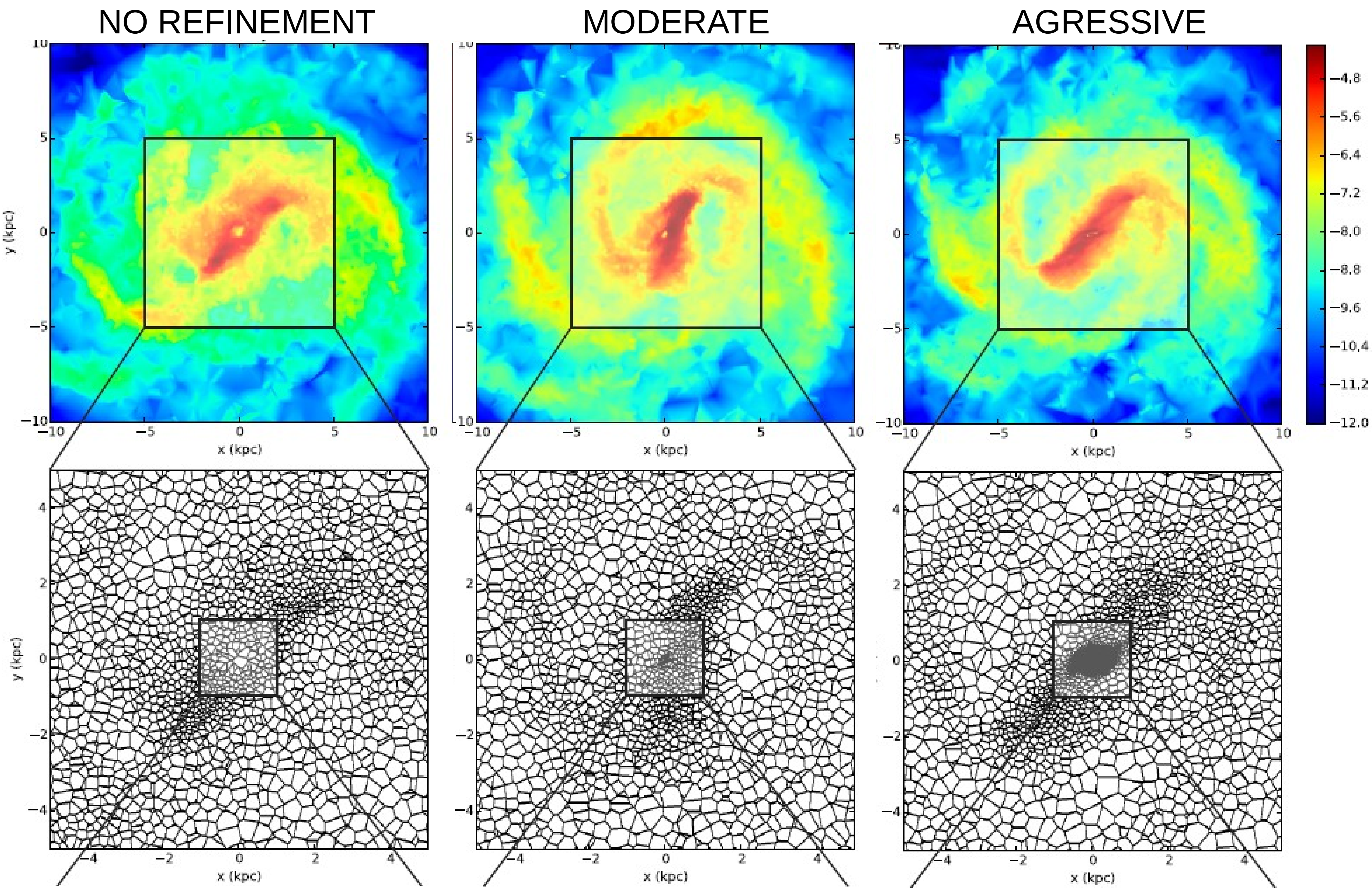
- ➢ Predictive power?
- ➢ Fine tuning?
- ➢ Purpose of simulations?
- ➢ Learning about the underlying physics?



Henden, Puchwein, Sijacki & Shen, 2017, in prep.

Resolving flows onto BHs

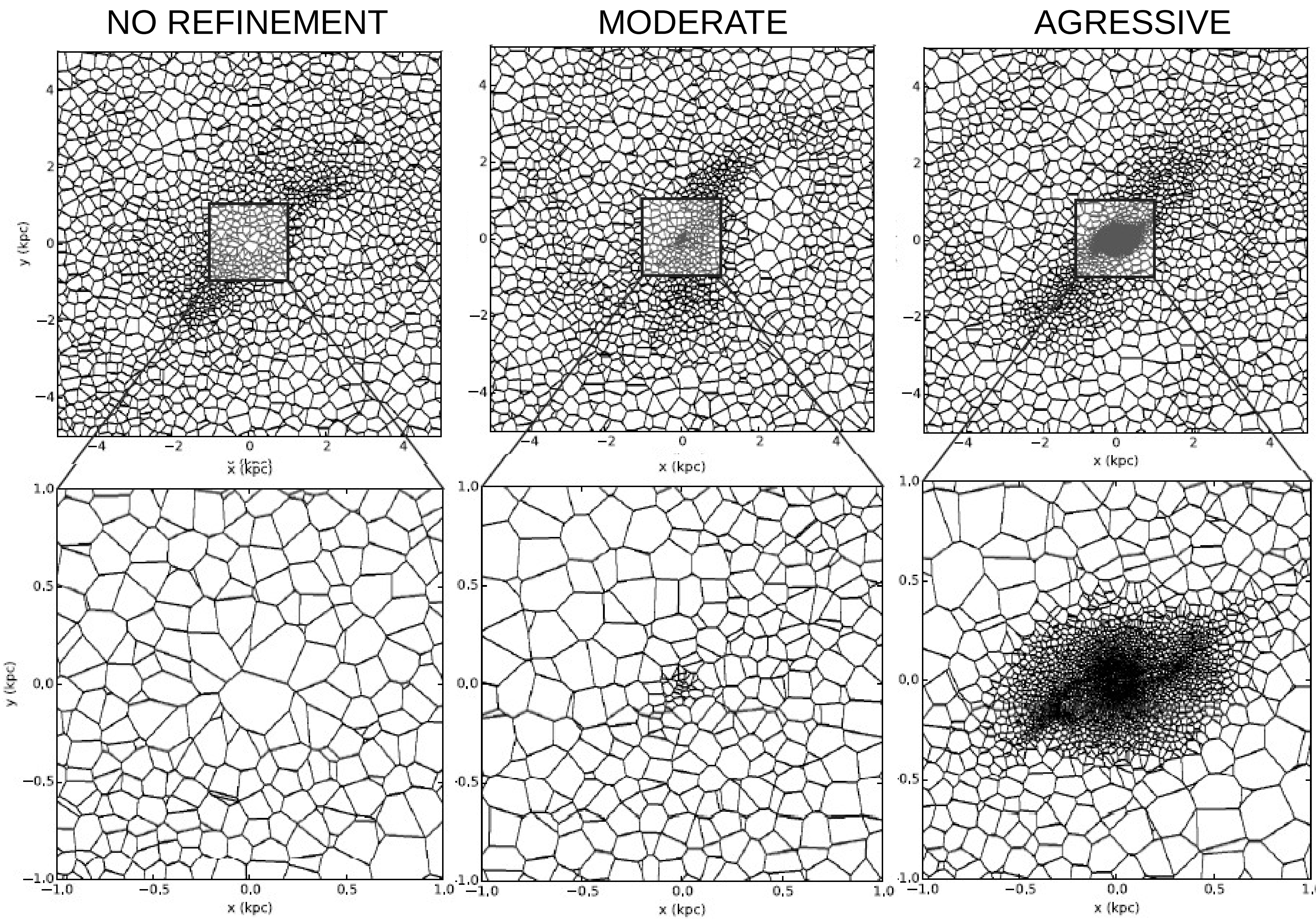
GAS DENSITY MAPS + VORONOI MESH



Curtis & Sijacki, MNRAS, 2015

Resolving flows onto BHs

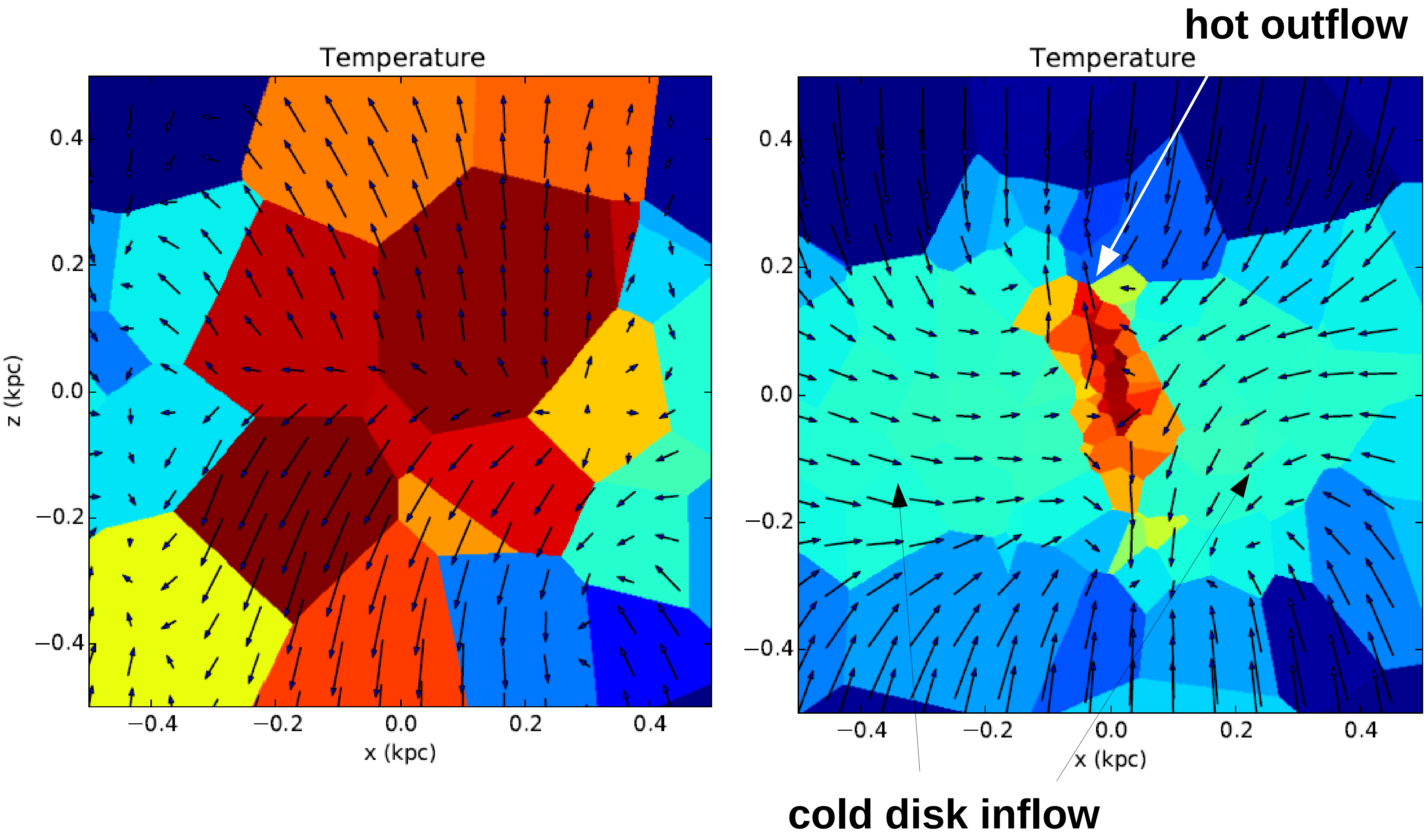
VORONOI MESH



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

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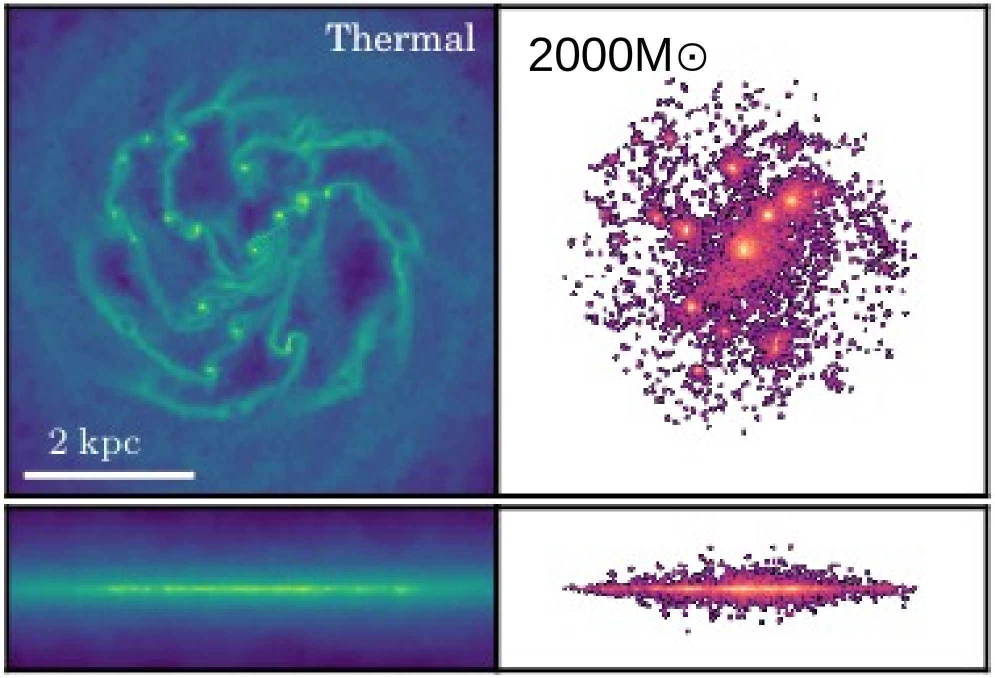
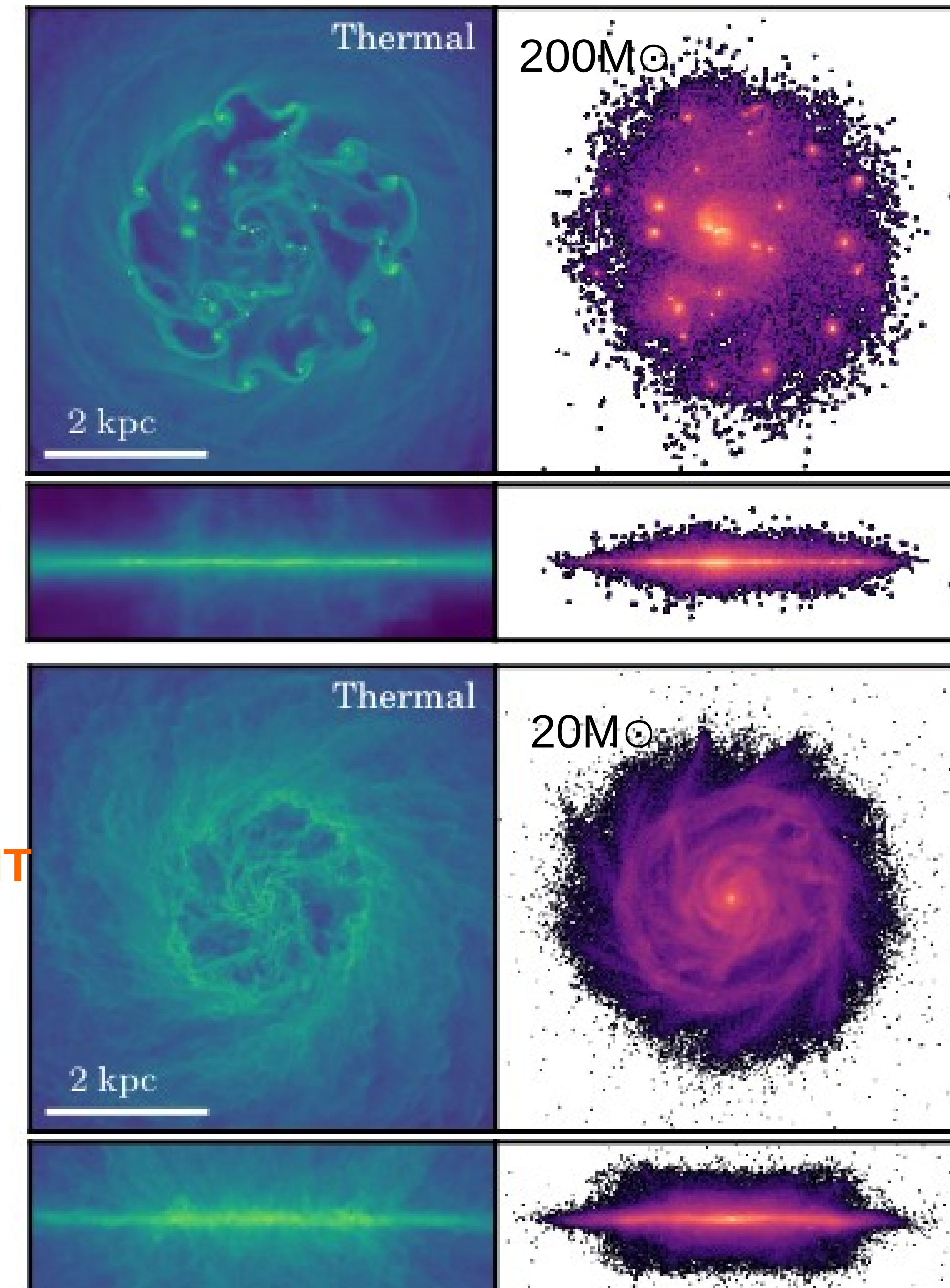




SAME SUPERNOVA FEEDBACK AT DIFFERENT RESOLUTIONS LEADS TO COMPLETELY DIFFERENT GALAXY MORPHOLOGIES

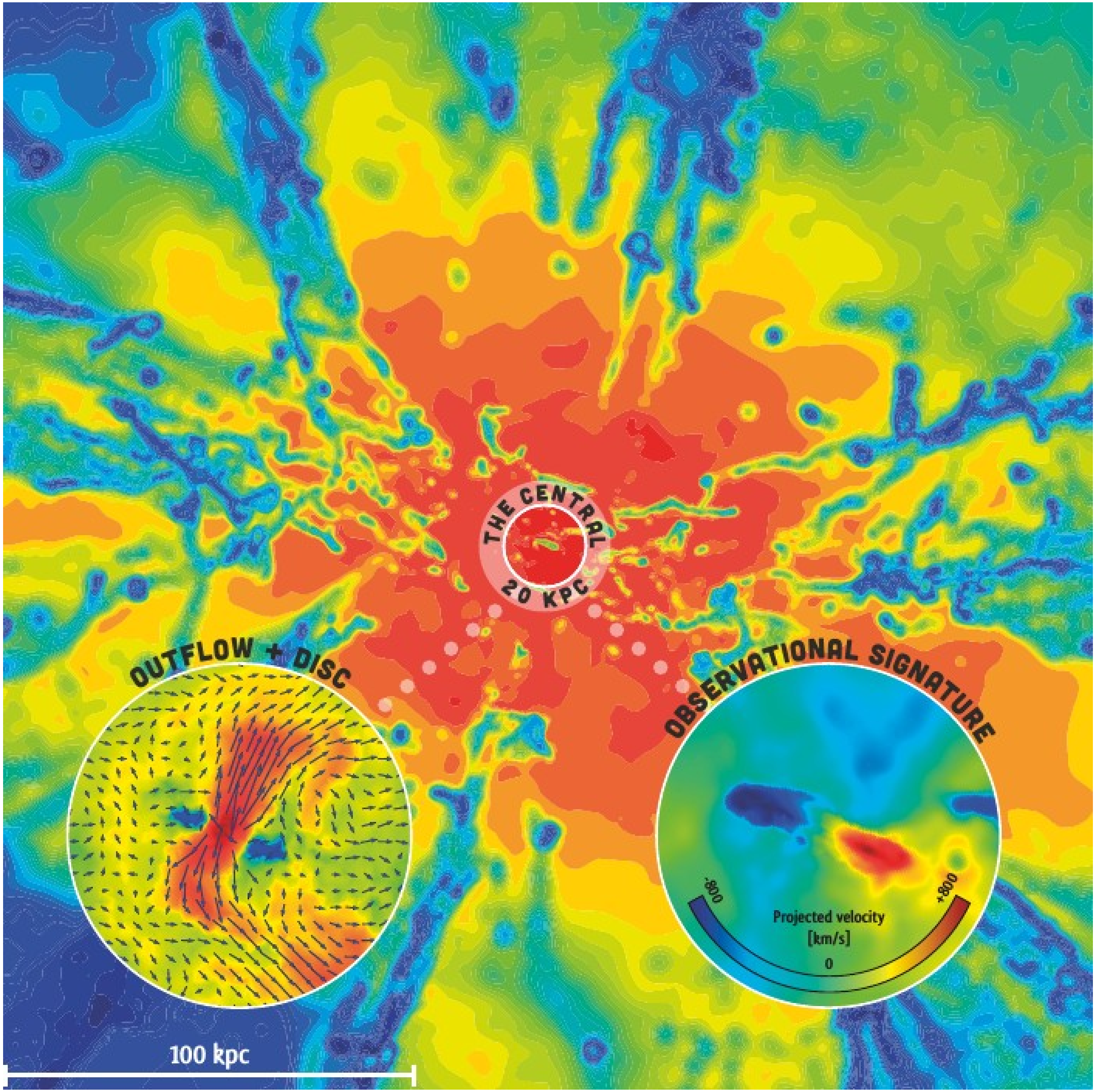
Smith, Sijacki & Shen, arXiv:1709.03515

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?)

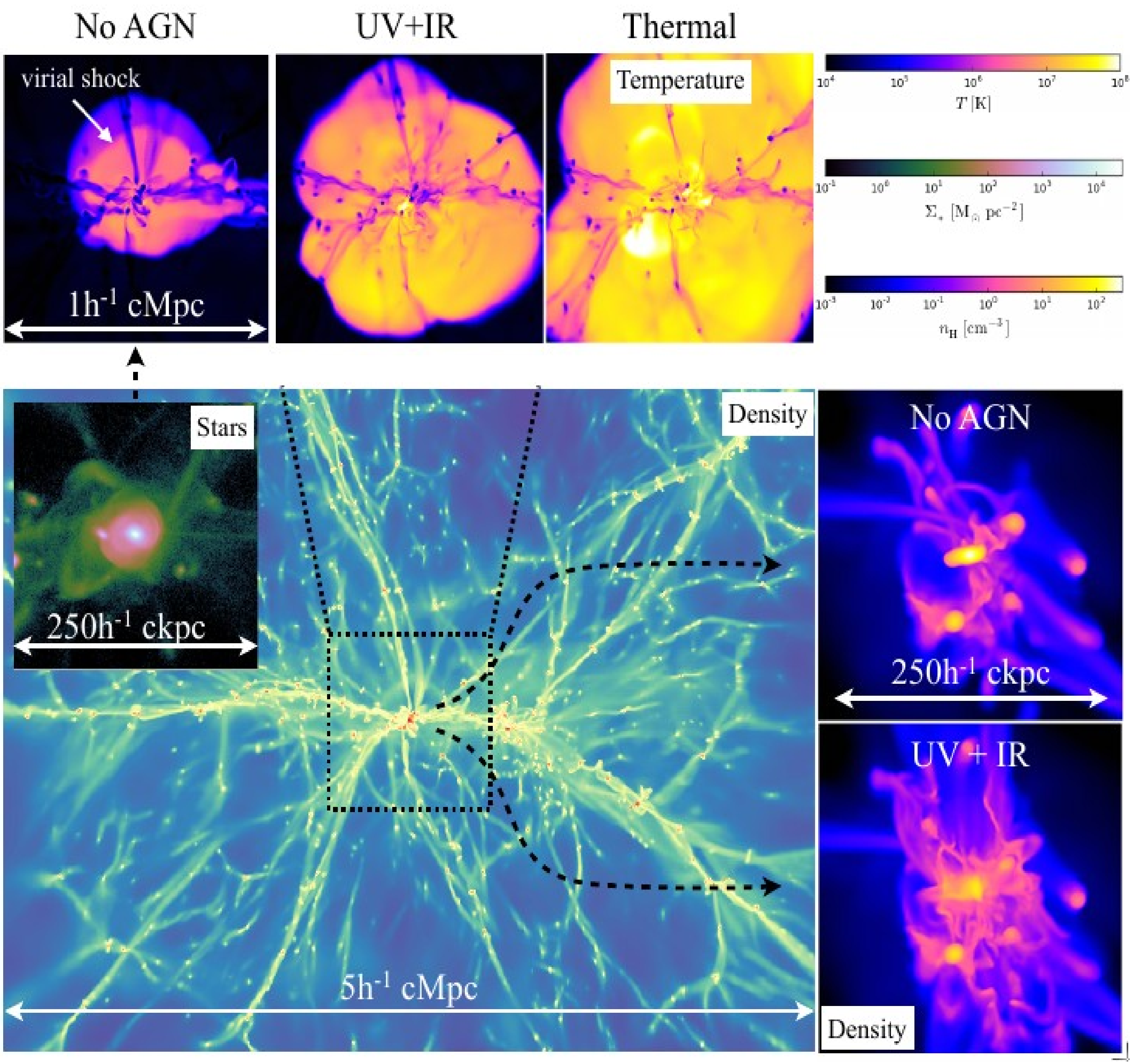


Powerful QSO outflow in a massive disk galaxy at high z

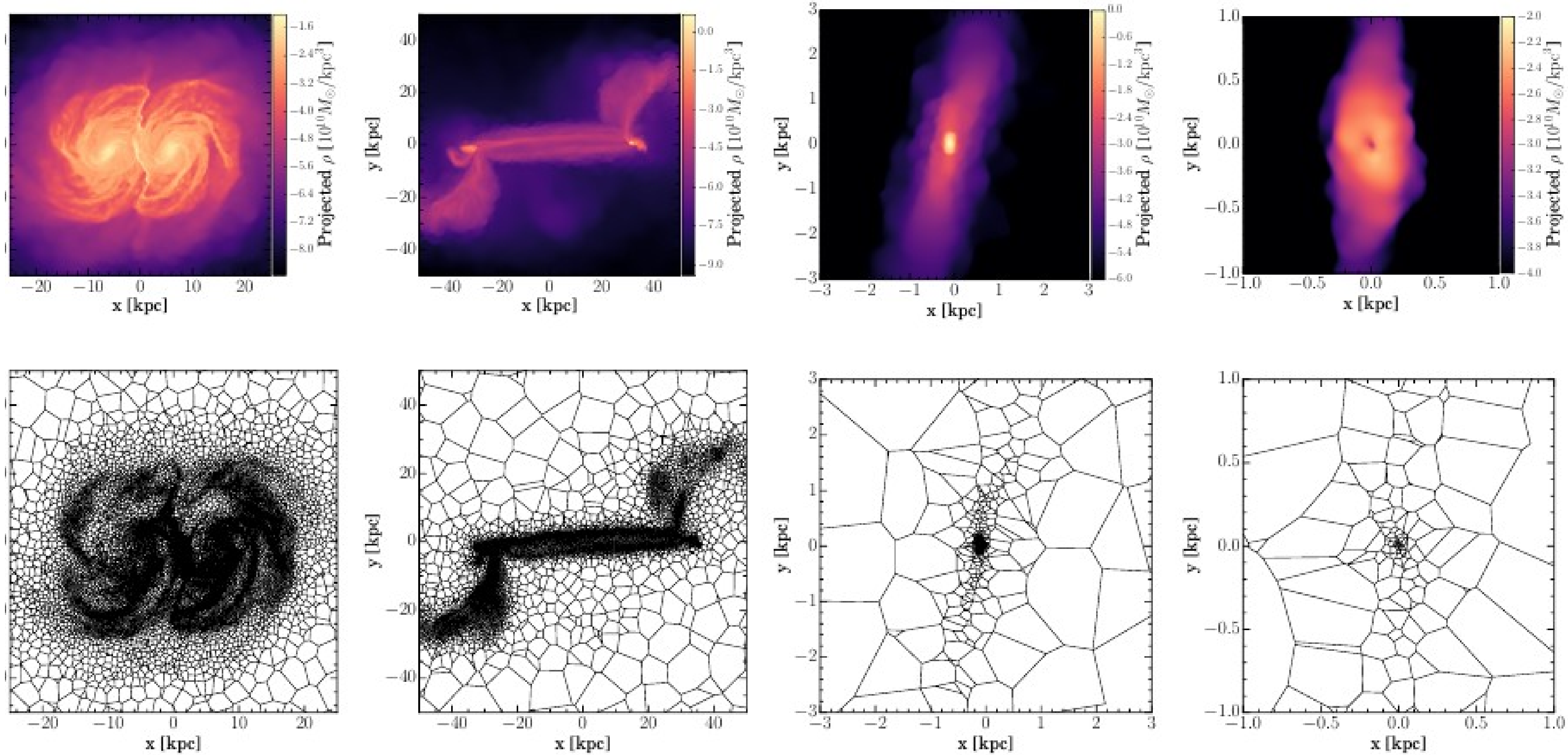
Costa, Rosdahl, Sijacki, Haehnelt, 2017, in prep.

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

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



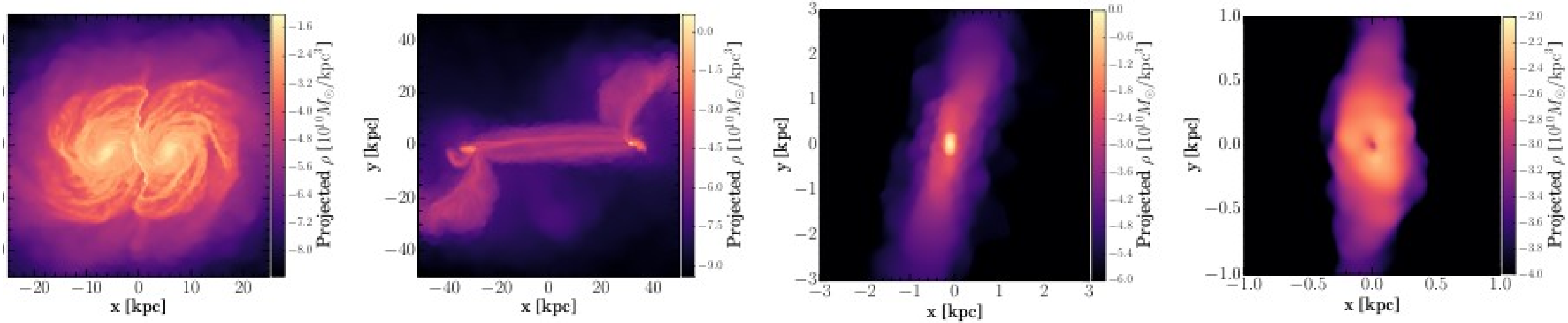
Resolving flows onto BHs: impact of gas angular momentum

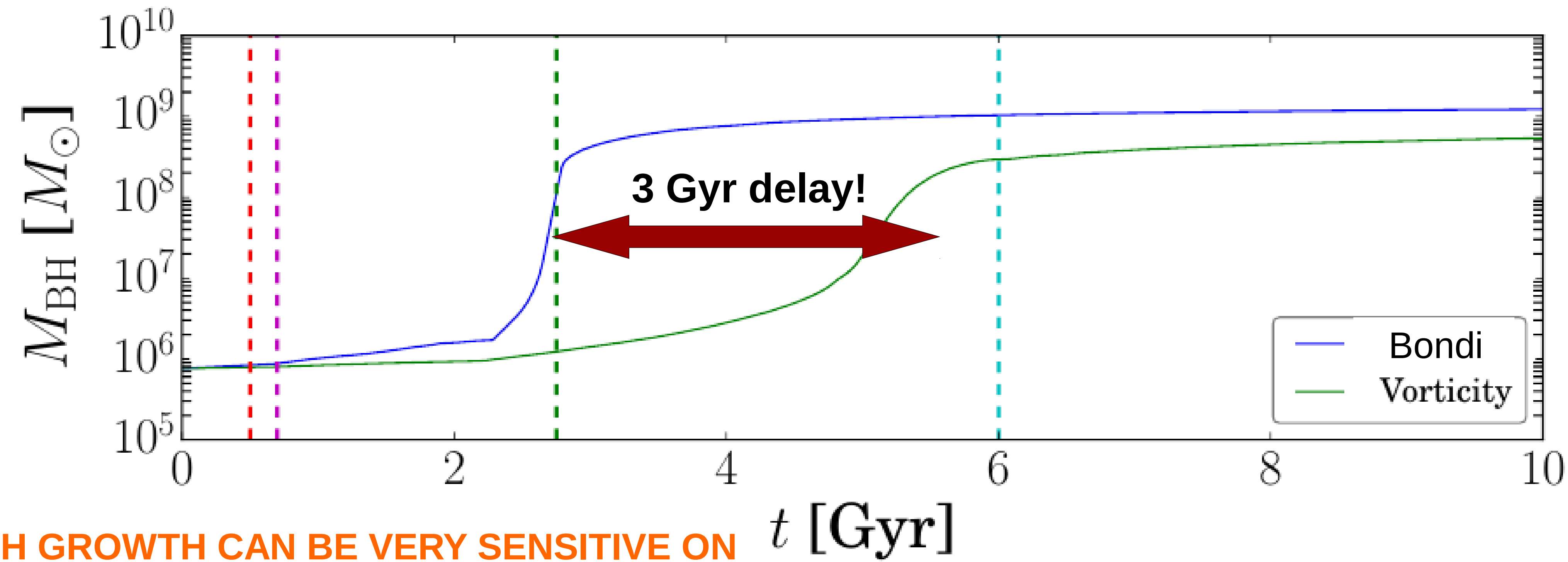


VERY HIGH RESOLUTION SIMULATIONS OF MERGING GALAXIES WITH SMBHs

Curtis & Sijacki, MNRAS, 2016

Resolving flows onto BHs: impact of gas angular momentum





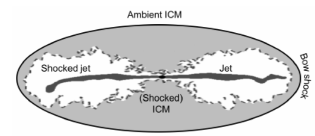
BH GROWTH CAN BE VERY SENSITIVE ON THE ACCRETION MODEL ADOPTED (even with self-regulation!)

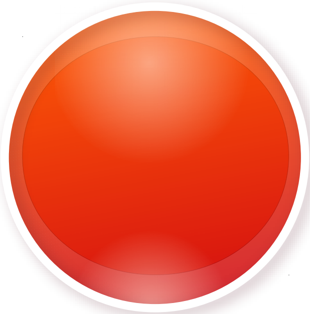
$$\dot{M}_{\rm Vort} = \frac{4\pi G^2 M_{\rm BH}^2 \rho_\infty}{c_\infty^3} \times \begin{cases} 0.34 & \omega_\star < 0.1 \\ 0.34\,\frac{2}{3\pi\omega_\star}\ln(16\omega_\star) & \omega_\star > 0.1. \end{cases}$$

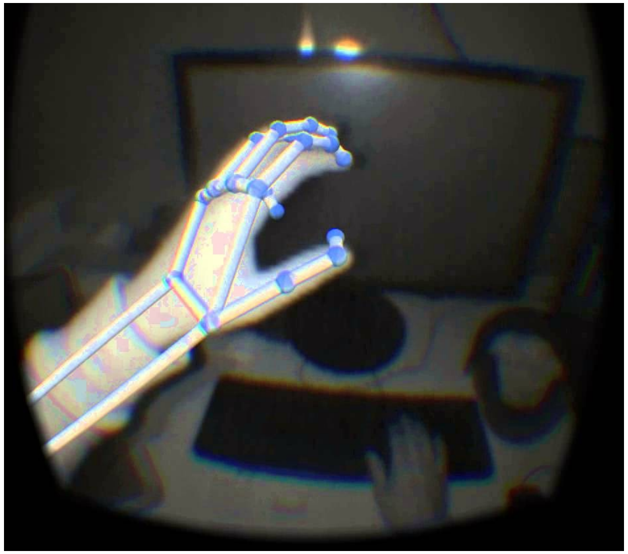
Curtis & Sijacki, MNRAS, 2016 (Krumholz 2005)

AGN jet feedback: cocoon inflation and turbulence

(not to scale)







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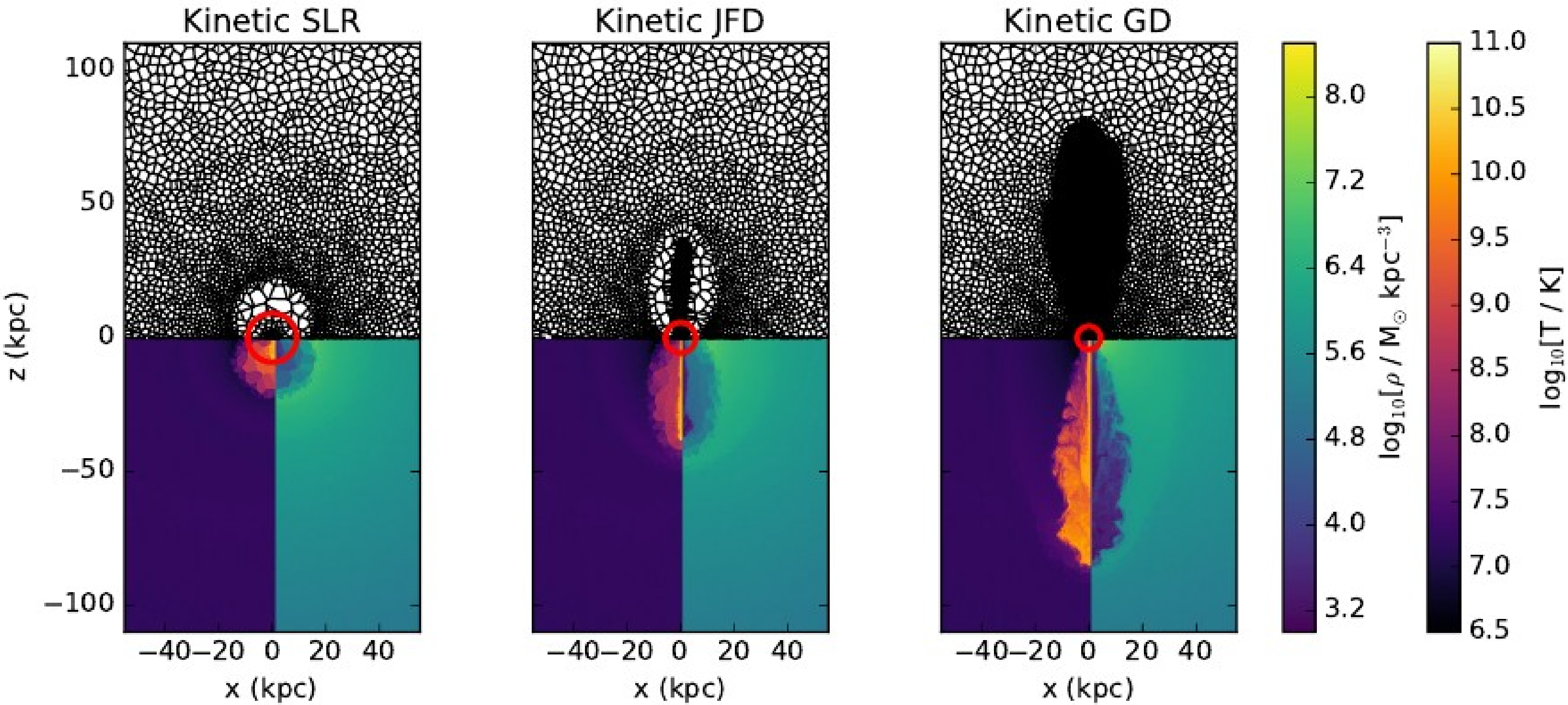
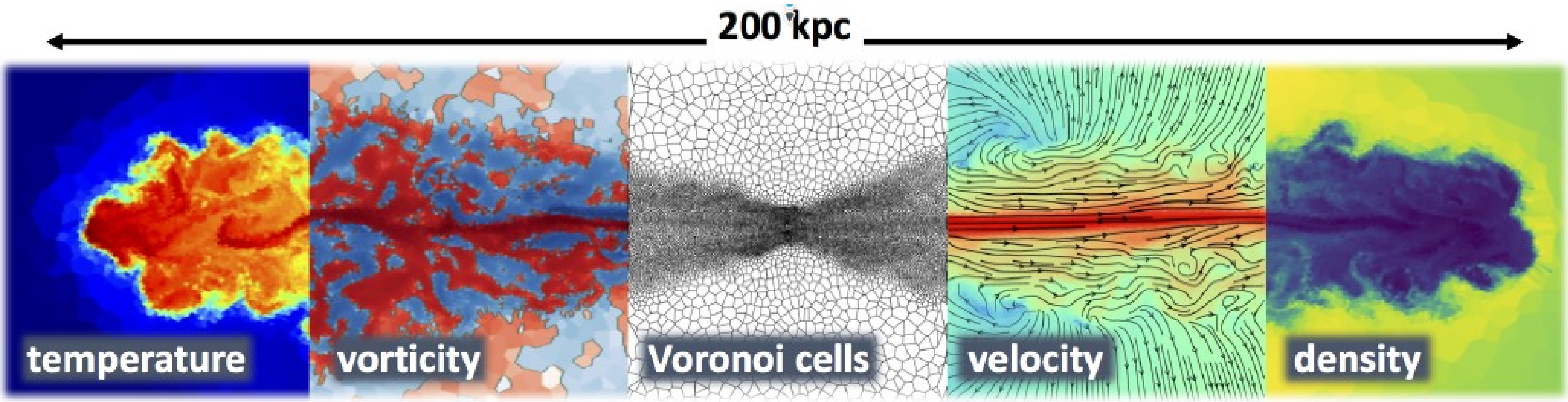


FOR RESOLVING JETS, INSTABILITIES AND TURBULENCE NUMERICAL TECHNIQUE MATTERS!

Bourne & Sijacki, MNRAS, 2017

AGN jet feedback: cocoon inflation and turbulence



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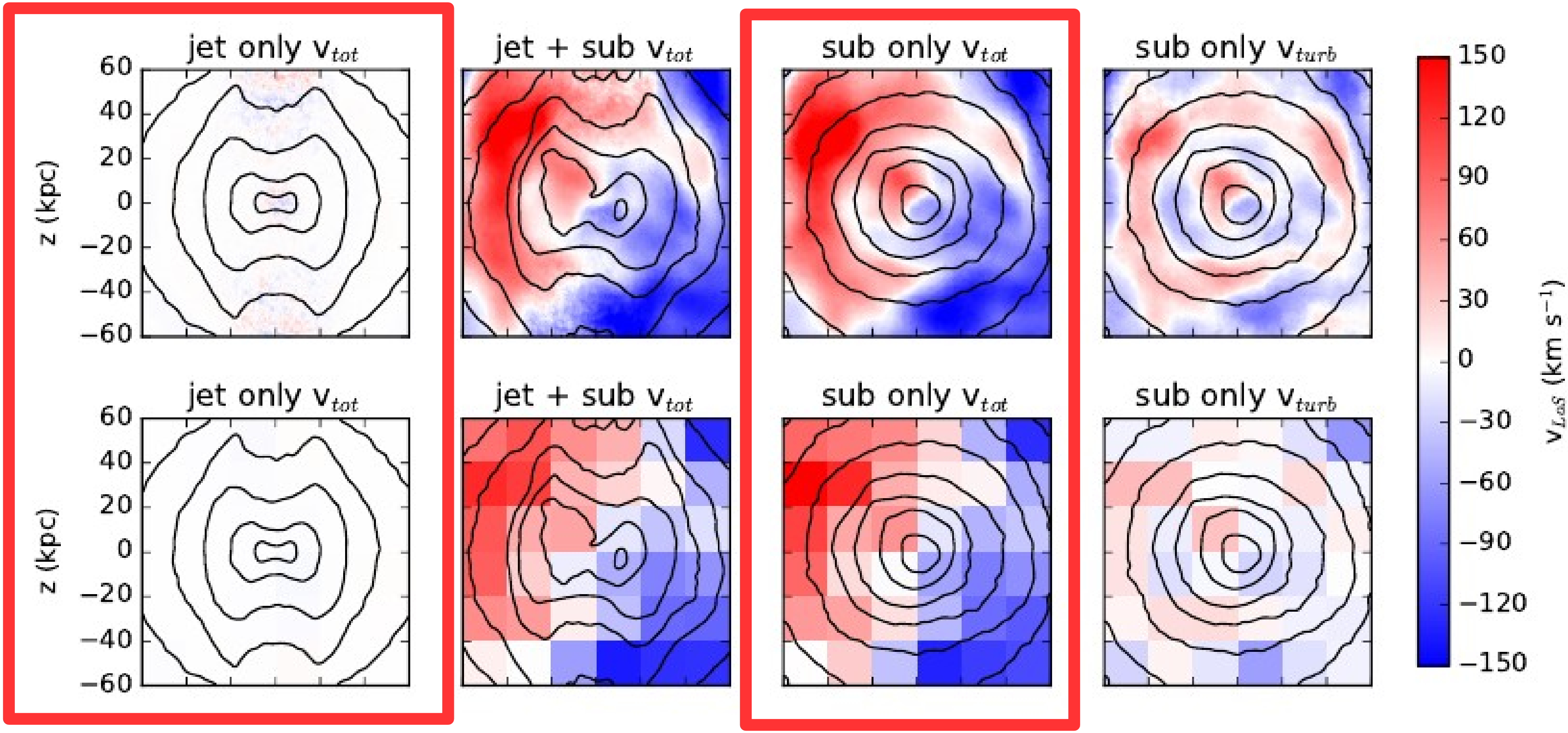
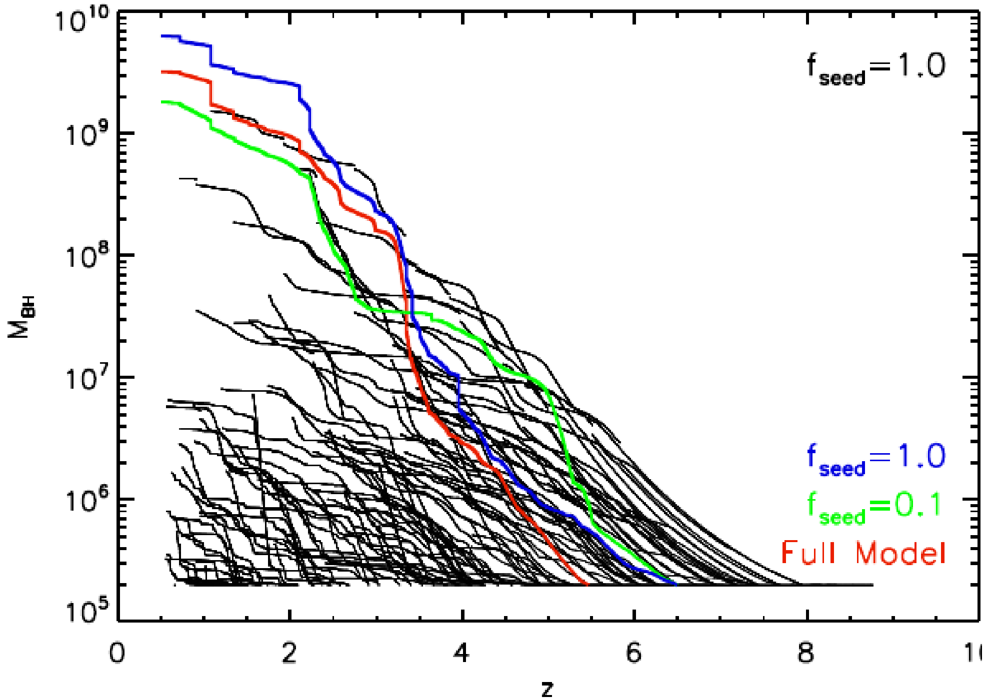
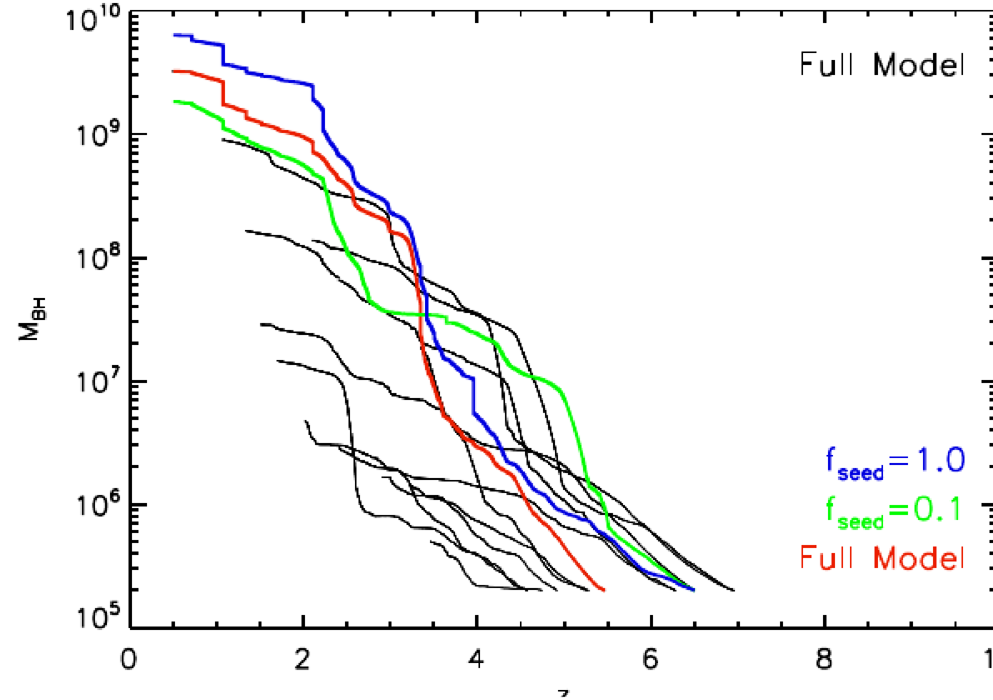


SUBSTRUCTURES RATHER THAN AGN JETS DRIVE LARGE SCALE TURBULENCE. HITOMI OBSERVATIONS CONSISTENT WITH ICM BULK VELOCITIES

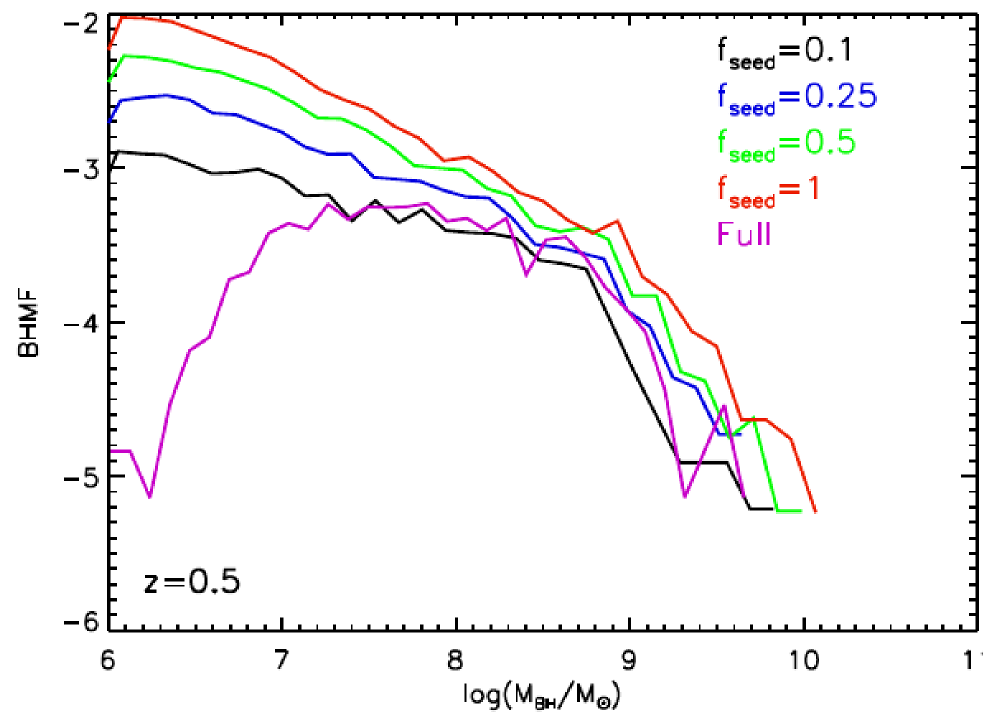
Bourne & Sijacki, MNRAS, 2017

BH seeding: implications for merger rates





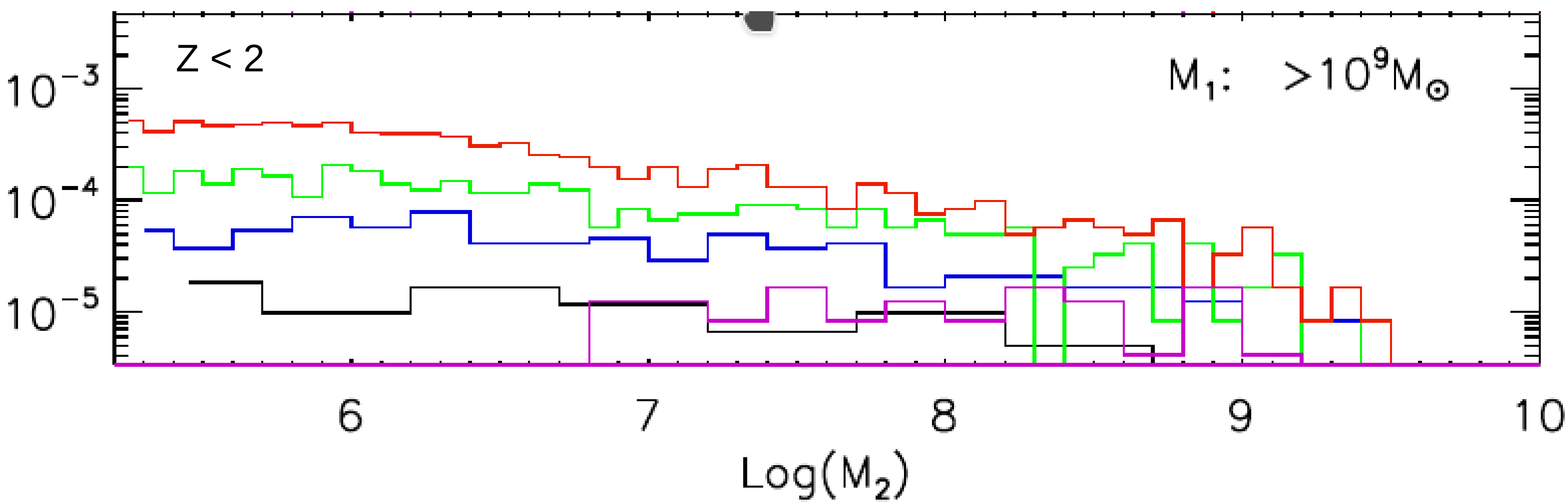
DIFFERENT SEEDING MODELS CAN CHANGE DRAMATICALLY THE BHMF AT THE LOW MASS END (OBS. NOT CONSTRAINED) WITHOUT AFFECTING THE HIGH MASS END (OR THE BHLF)



DeGraf & Sijacki, 2017, in prep.

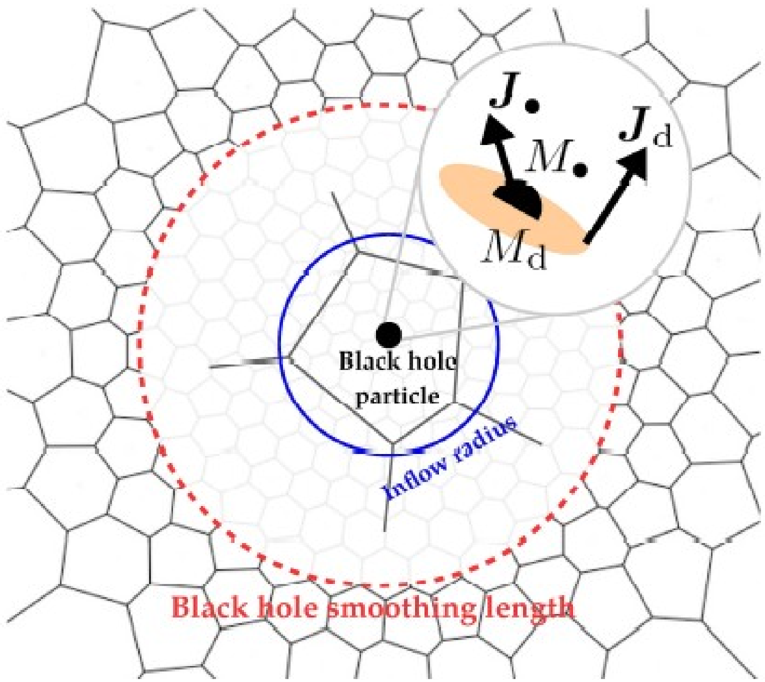
BH seeding: implications for merger rates

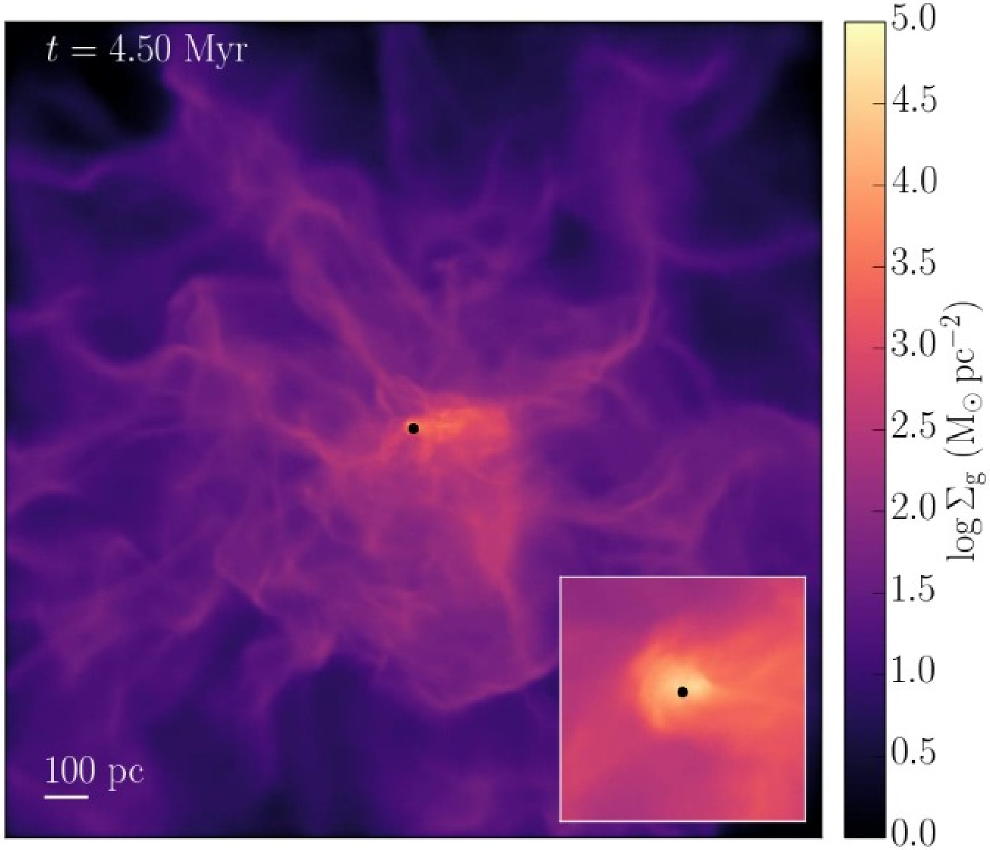
NUMBER DENSITY OF MERGERS

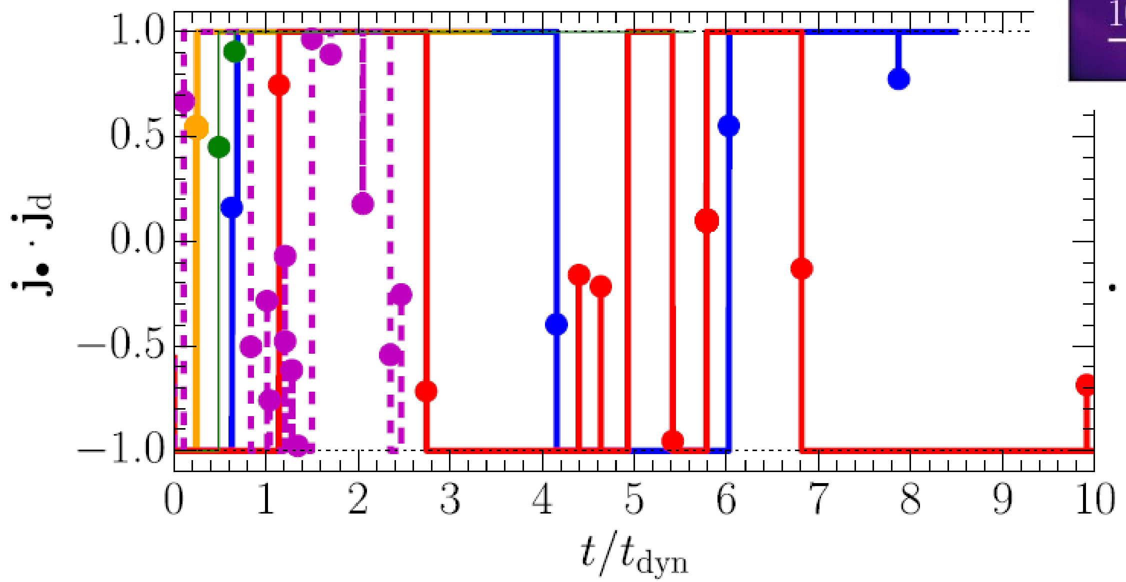


DeGraf & Sijacki, 2017, in prep.

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, 2017, in prep.

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