Cosmological simulations of our Universe

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Cosmo – 17 Paris
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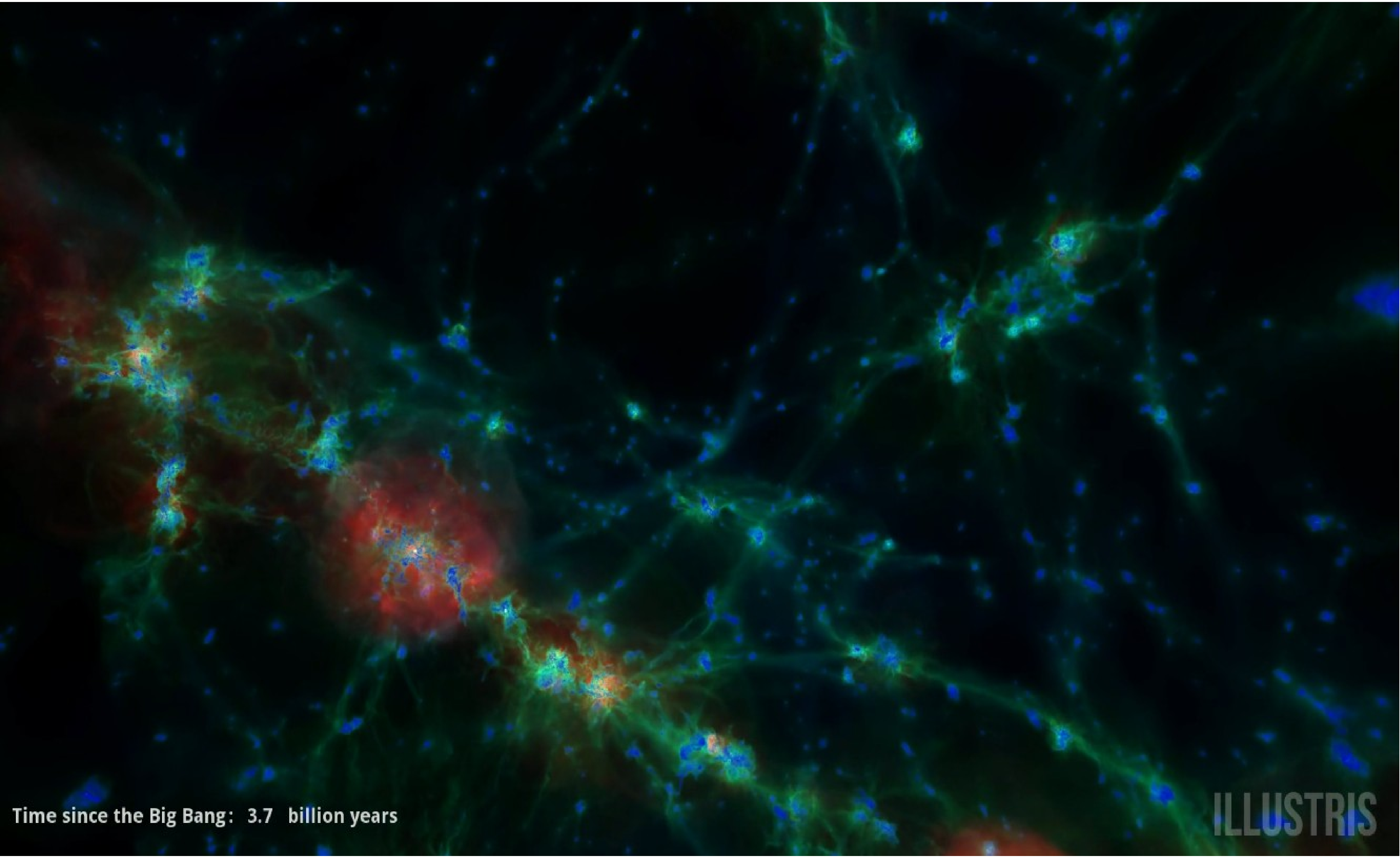
Cosmological simulations of galaxy and structure formation



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,…)

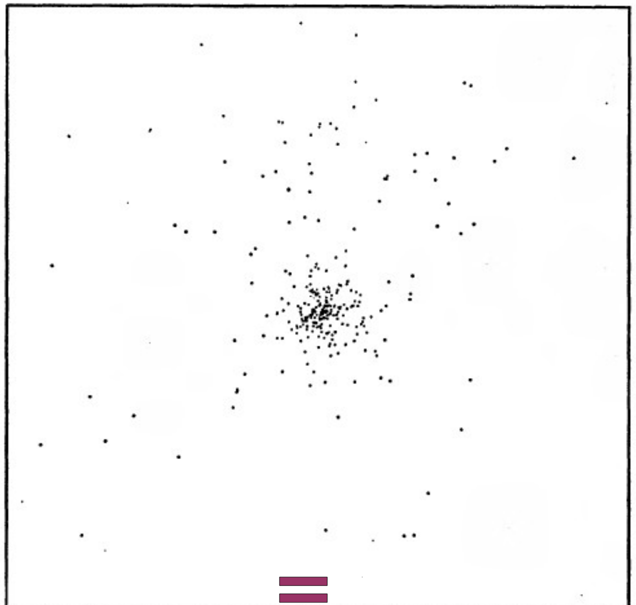
► **Newtonian gravity (dark matter and baryons)**
(relativistic corrections, modified gravity models,...)

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

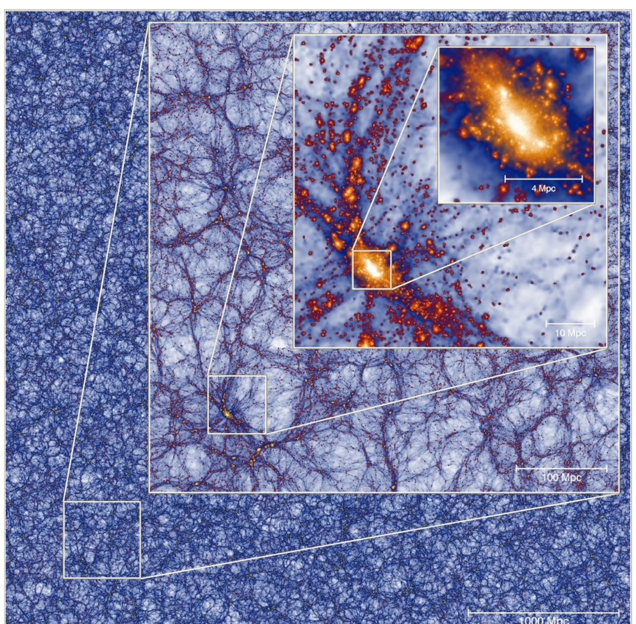
► **Gas radiative cooling/heating, star & BH formation and feedback**
(non equlibrium low T cooling, dust, turbulence, GMCs,…)

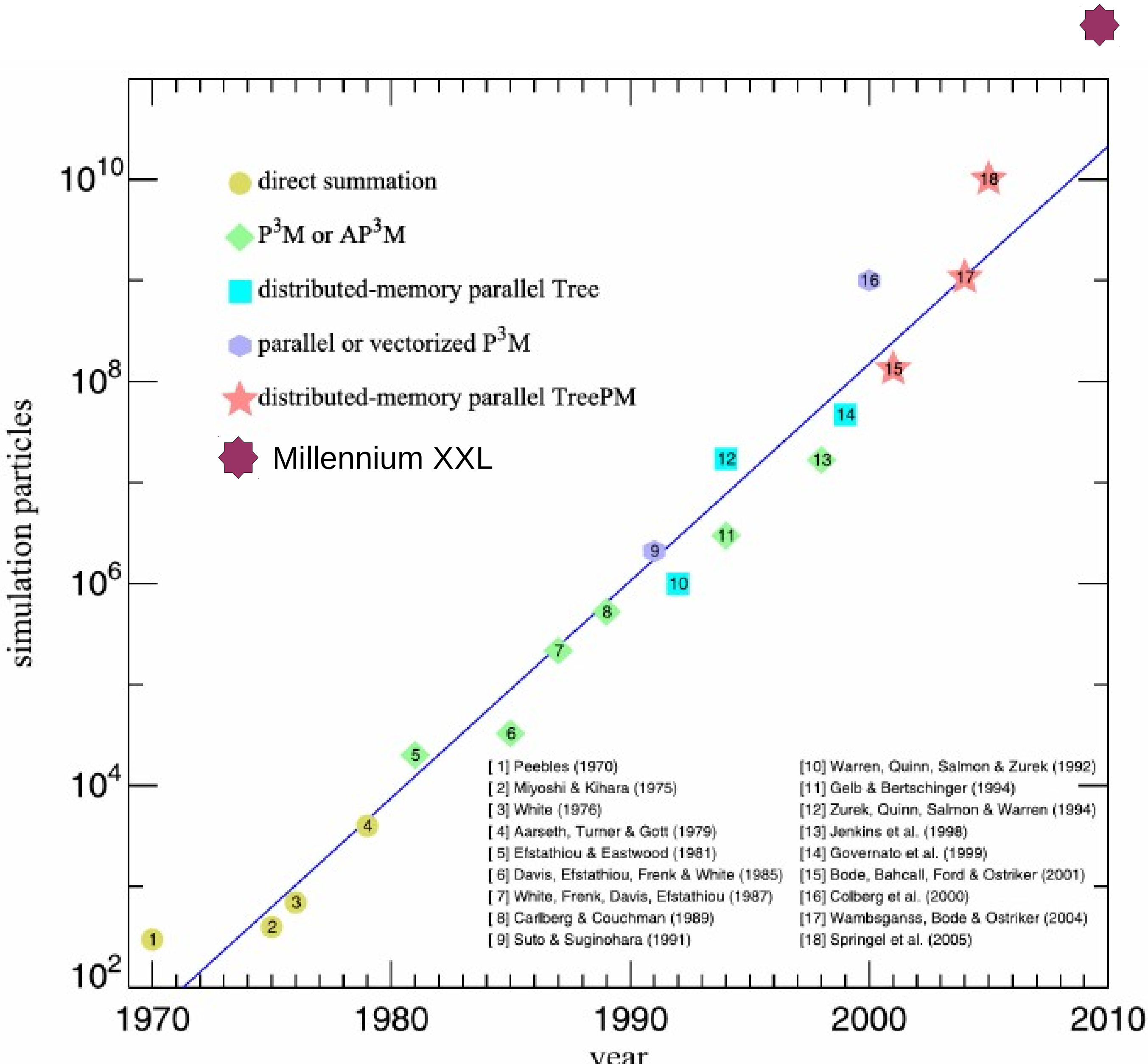
► **Reionization in form of an uniform UV background**
(simple accounting for the local sources,…, full RT on the fly)

Pure dark matter simulations in ΛCDM cosmology



40 yrs!

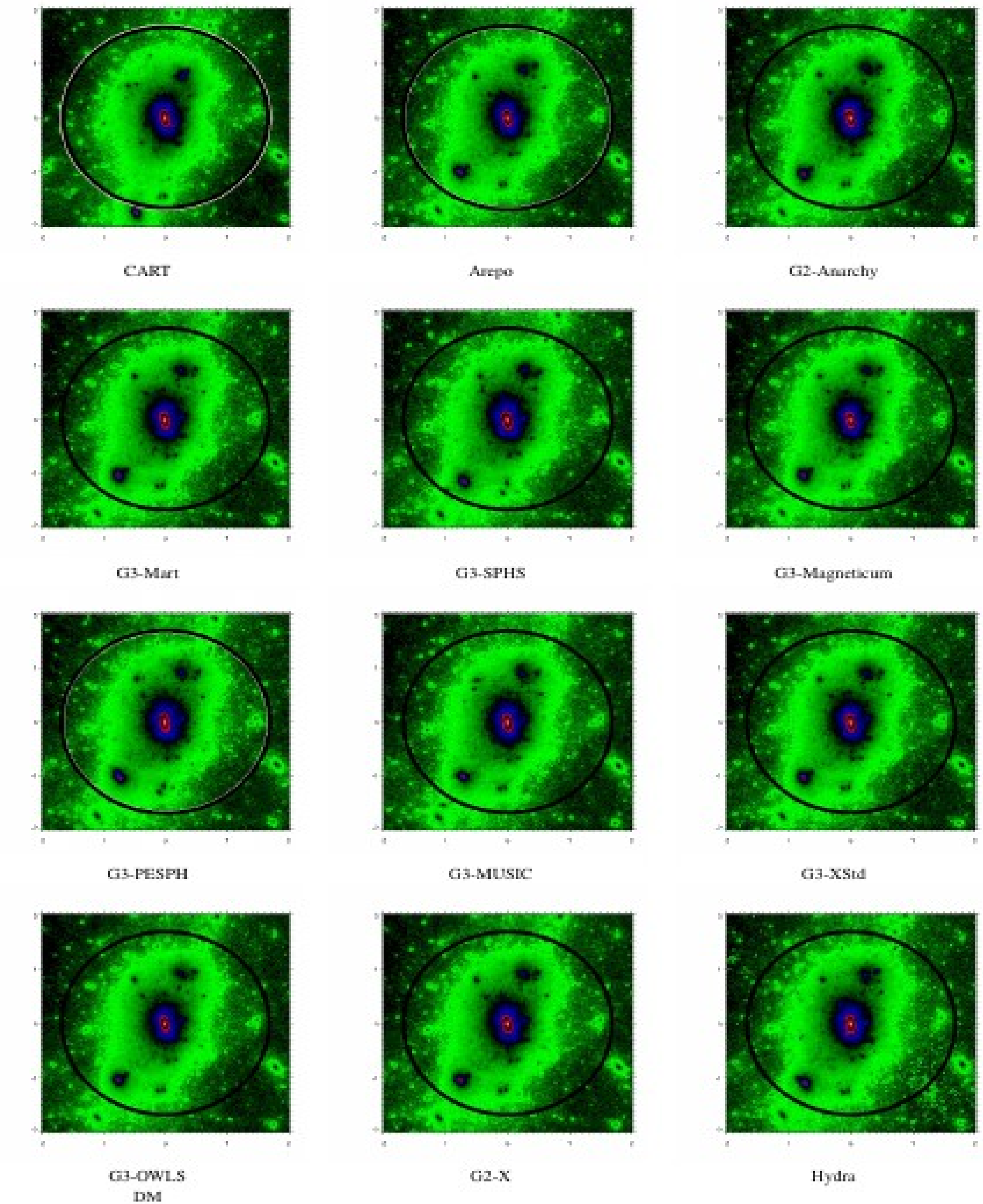




See also:
Horizon Run 3 (Kim 2011) MultiDark (Prada 2012)
DEUS (Alimi et al. 2012) Watson et al. 2013

Pure dark matter simulations in ΛCDM cosmology

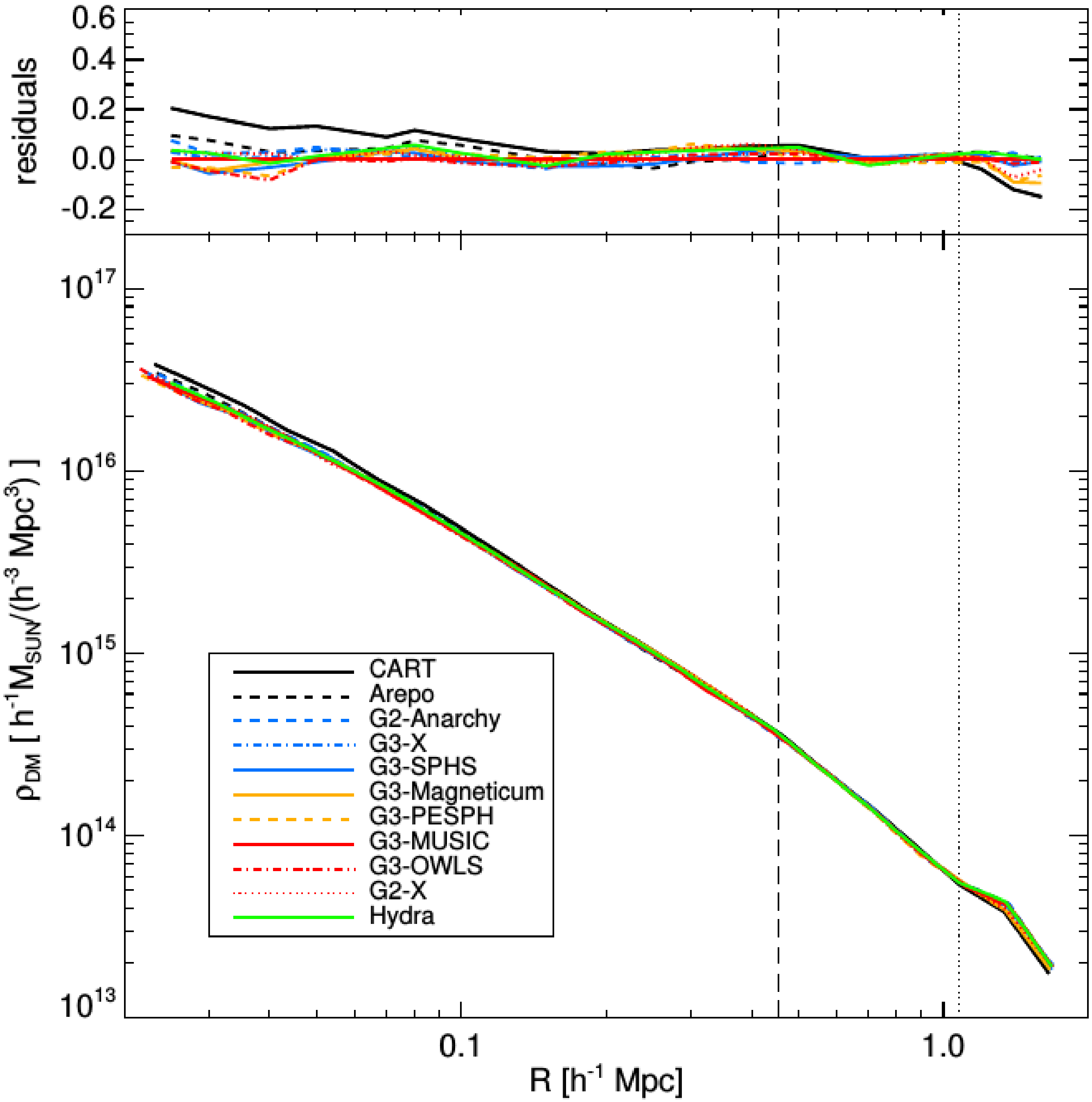
Cosmological simulation of a galaxy cluster



Sembolini et al. 2016 (Nifty)

Pure dark matter simulations in ΛCDM cosmology

Cosmological simulation of a galaxy cluster

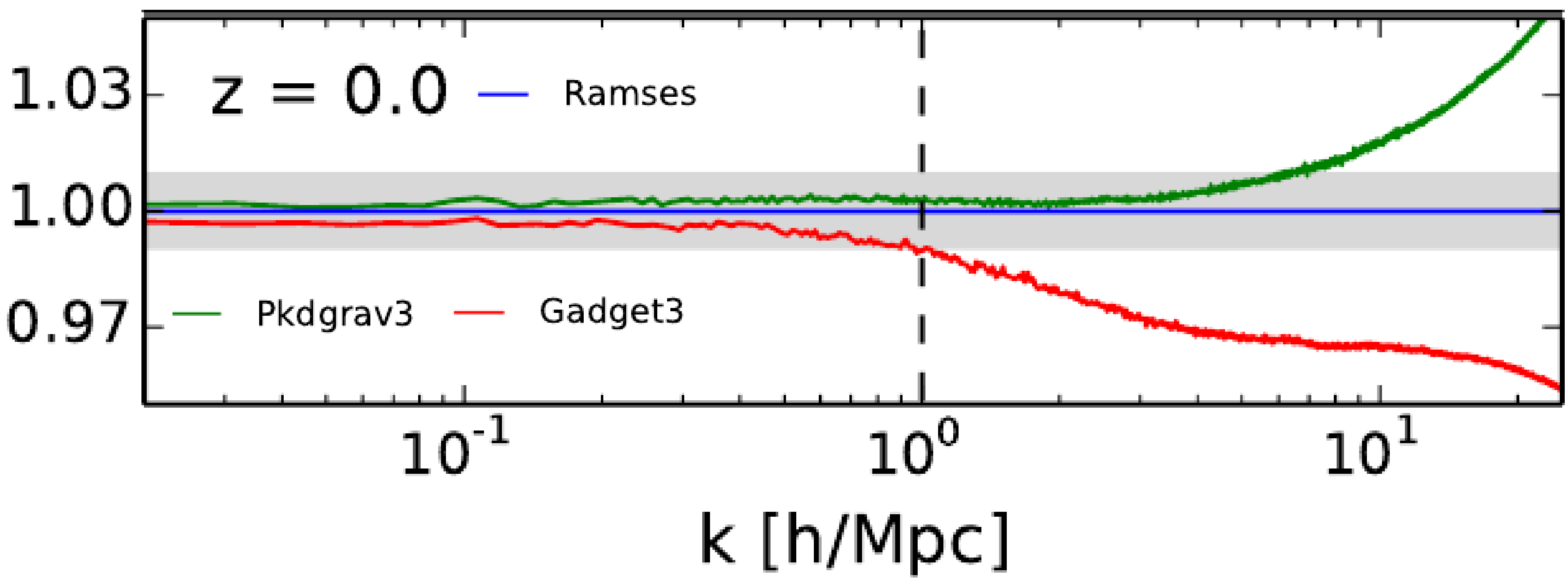


Sembolini et al. 2016

Pure dark matter simulations in ΛCDM cosmology

State-of-the-art:

- codes well tested and consistent results of independent groups
- accuracy in predicting matter power spectrum a few %



Schneider et al. 2015

Pure dark matter simulations in ΛCDM cosmology

State-of-the-art:

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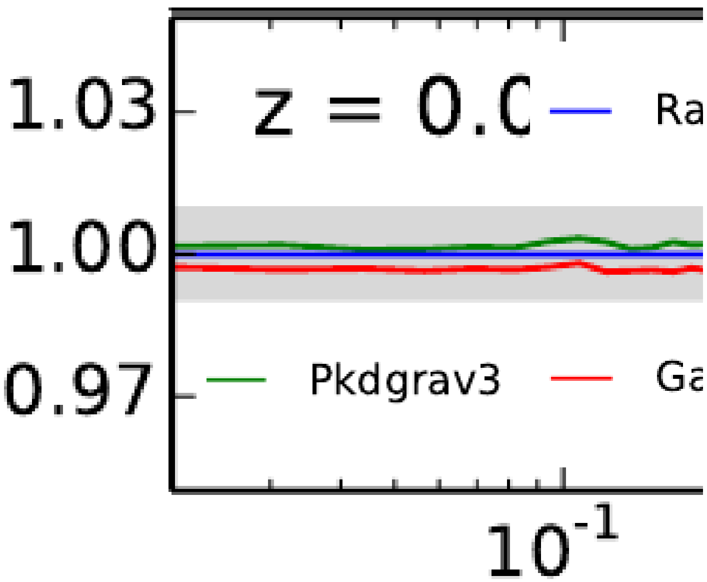
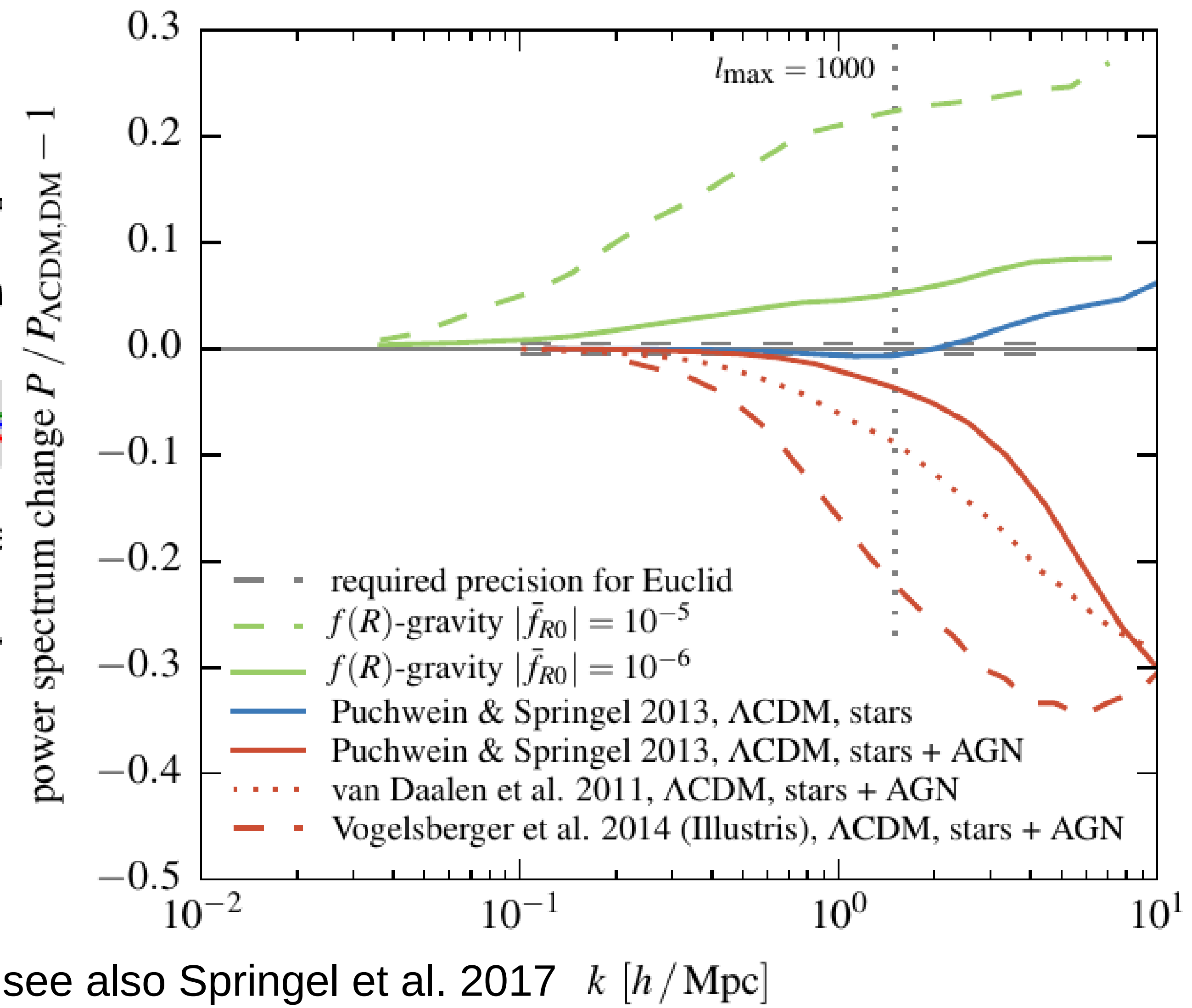
- accuracy in predicting matter power spectrum a few %

But not with baryons!



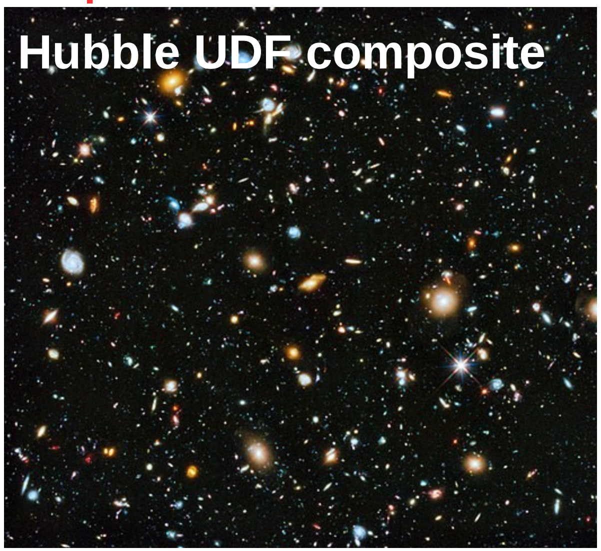
Schneider et al. 2015

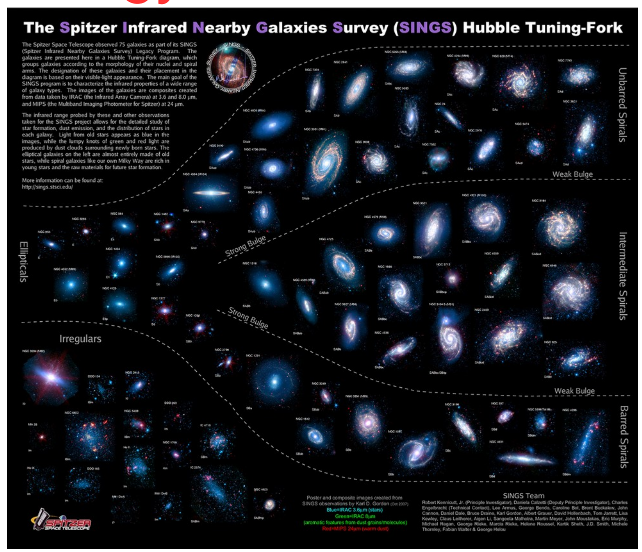


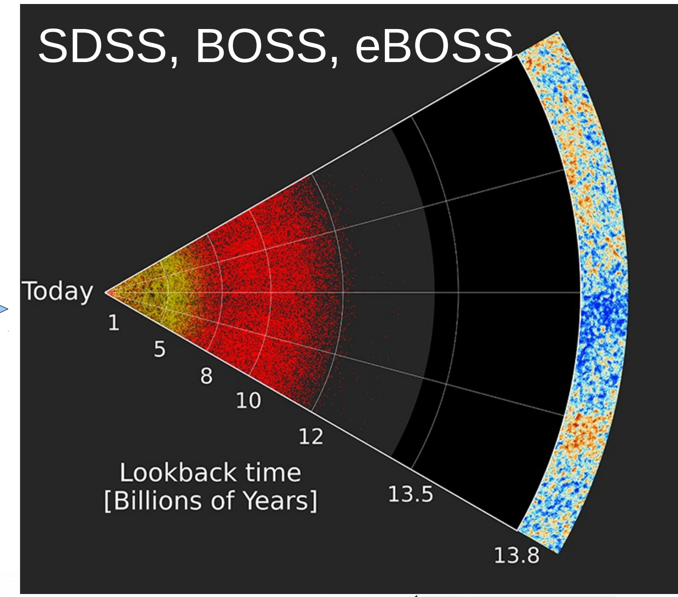
see also Springel et al. 2017

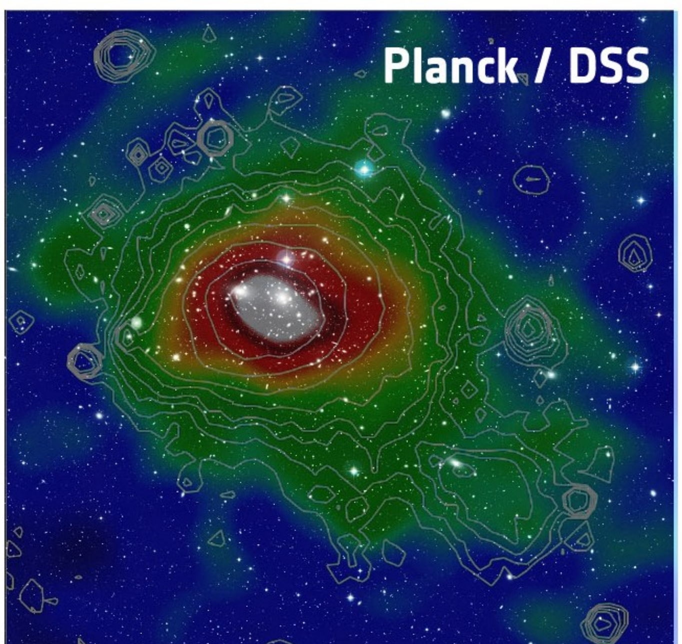
The importance of baryons

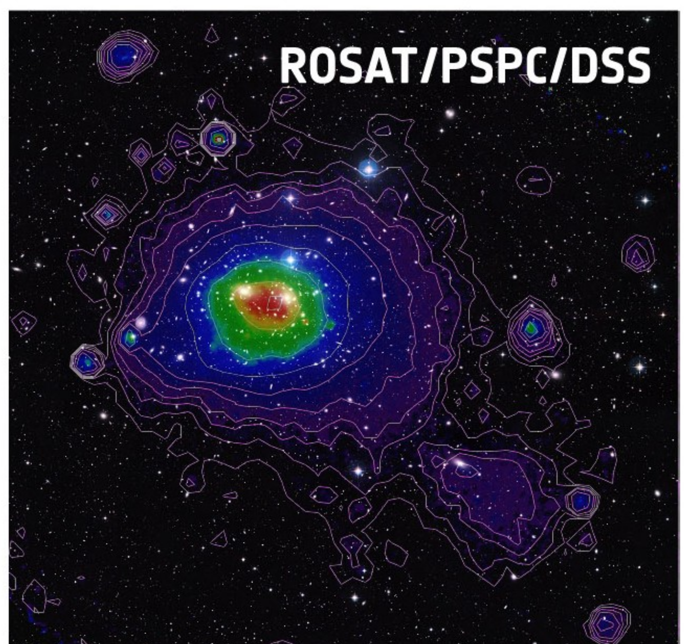
Baryons are directly observable and they affect the underlying dark matter distribution (contraction/expansion/shape/bias, WL,...) => profound implications for cosmology

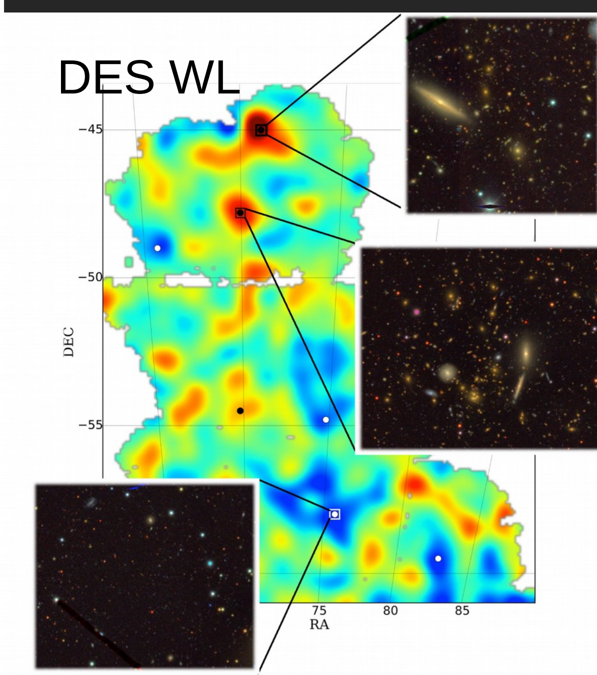






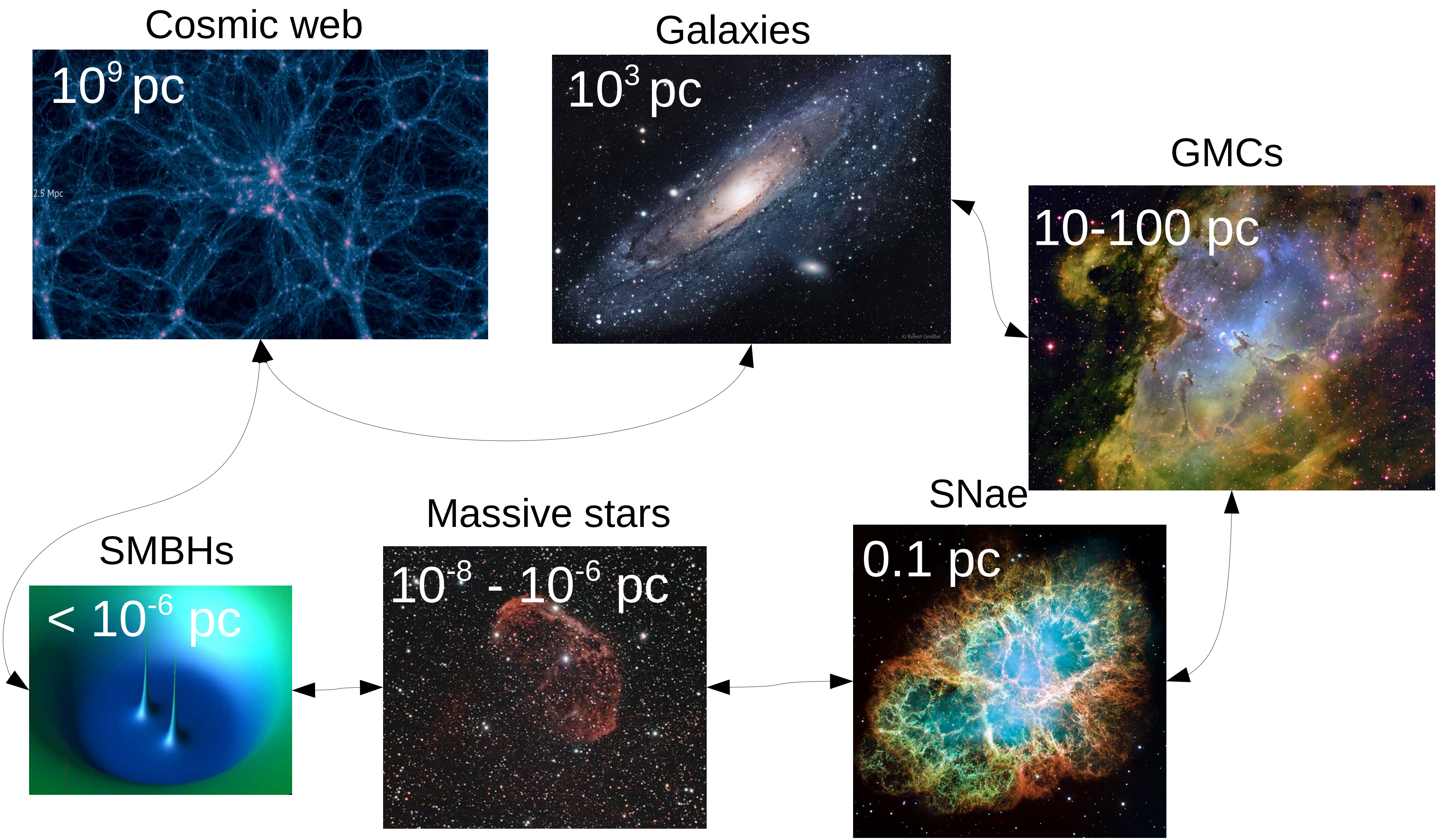






The importance of baryons

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



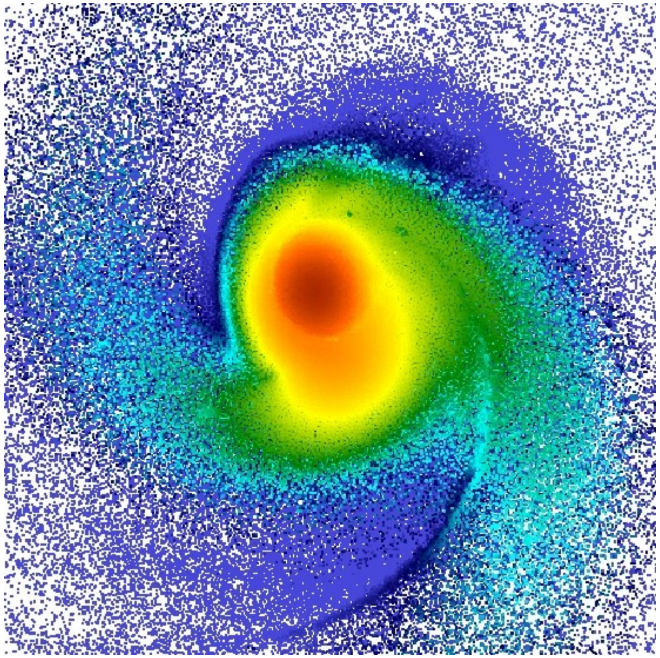
The importance of baryons

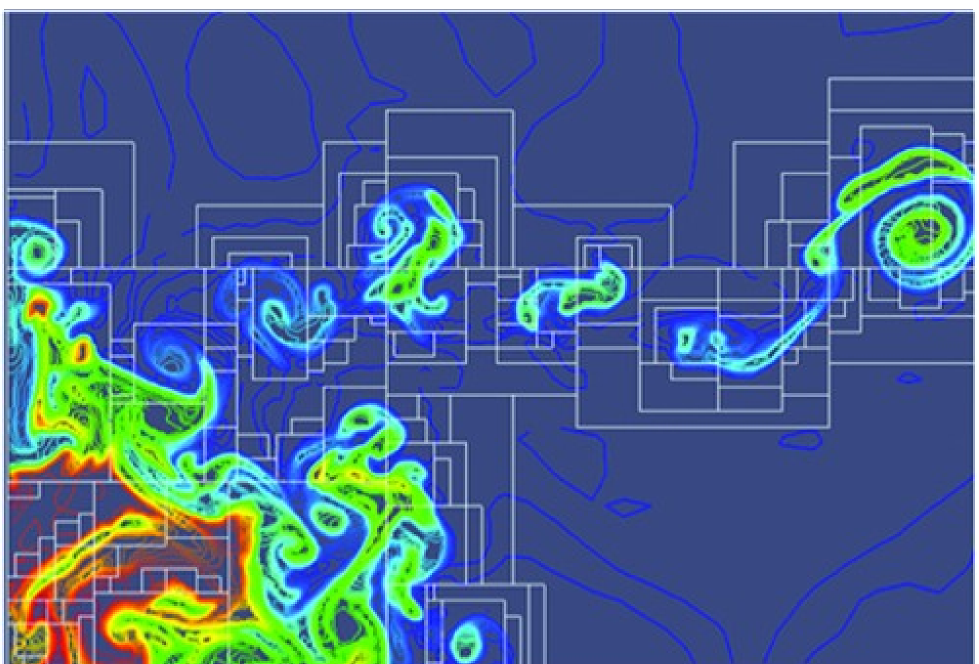
Hydrodynamical modelling

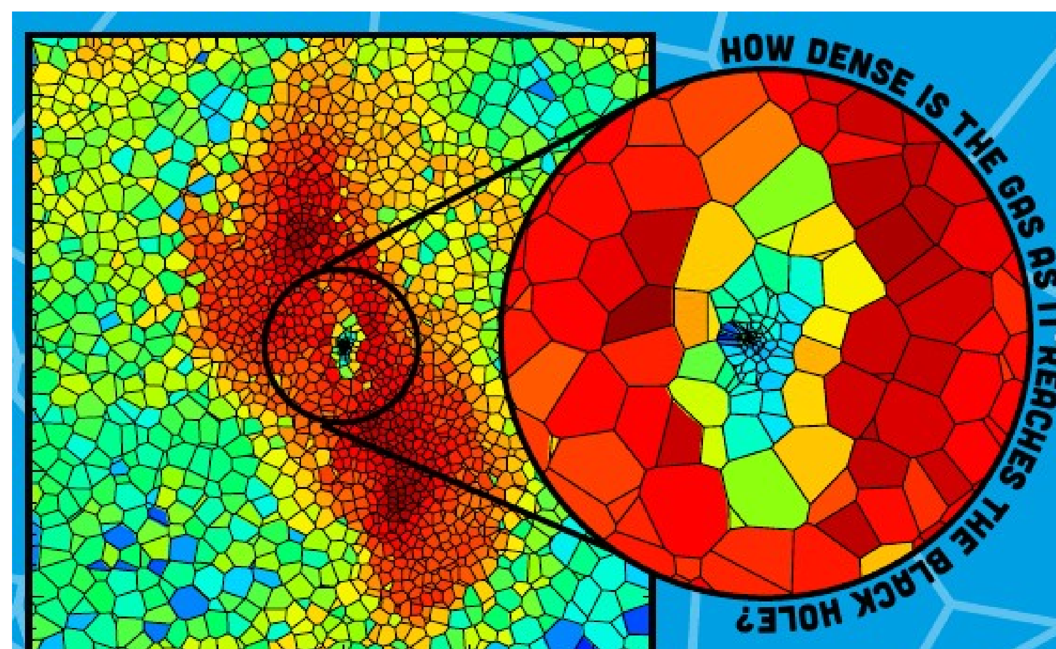
$$\frac{\partial \boldsymbol{U}}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{F} = 0$$

$$\boldsymbol{U} = \begin{pmatrix} \rho \\ \rho \boldsymbol{v} \\ \rho e \end{pmatrix} = \begin{pmatrix} \rho \\ \rho \boldsymbol{v} \\ \rho u + \frac{1}{2}\rho \boldsymbol{v}^2 \end{pmatrix}$$

$$\boldsymbol{F}(\boldsymbol{U}) = \begin{pmatrix} \rho \boldsymbol{v} \\ \rho \boldsymbol{v}\boldsymbol{v}^T + P \\ (\rho e + P)\boldsymbol{v} \end{pmatrix} \quad P = (\gamma - 1)\rho u$$

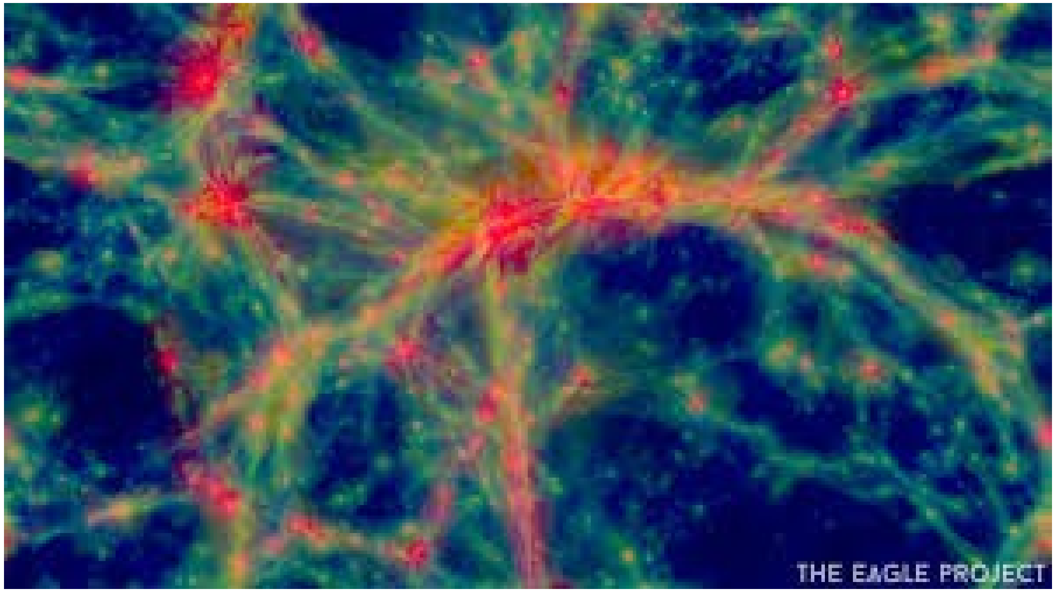




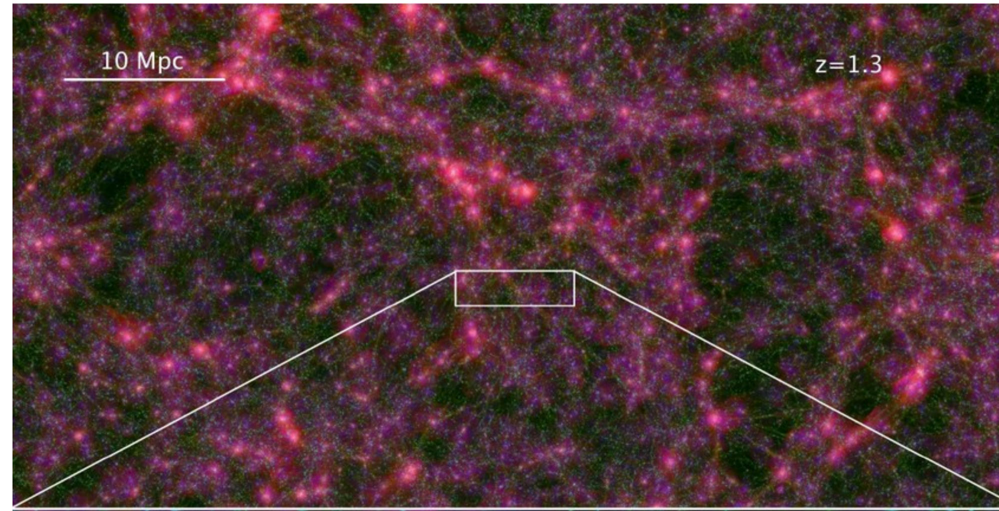


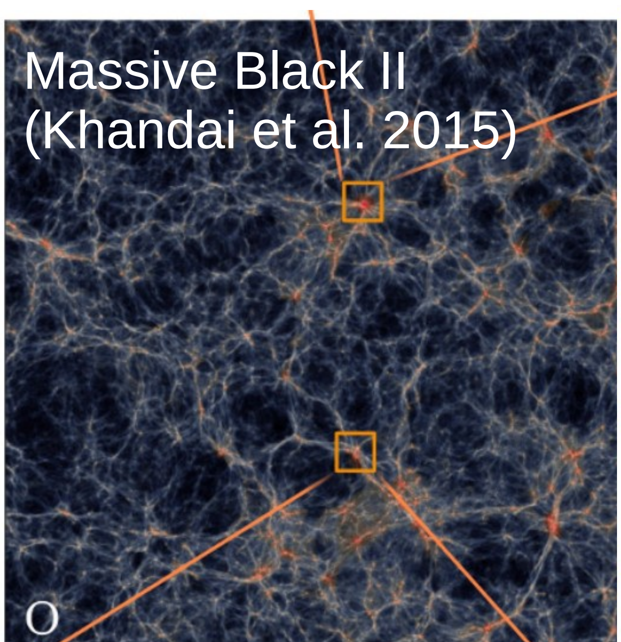
Current state-of-the-art in cosmological hydro simulations

The Eagle Project (Schaye et al. 2015)

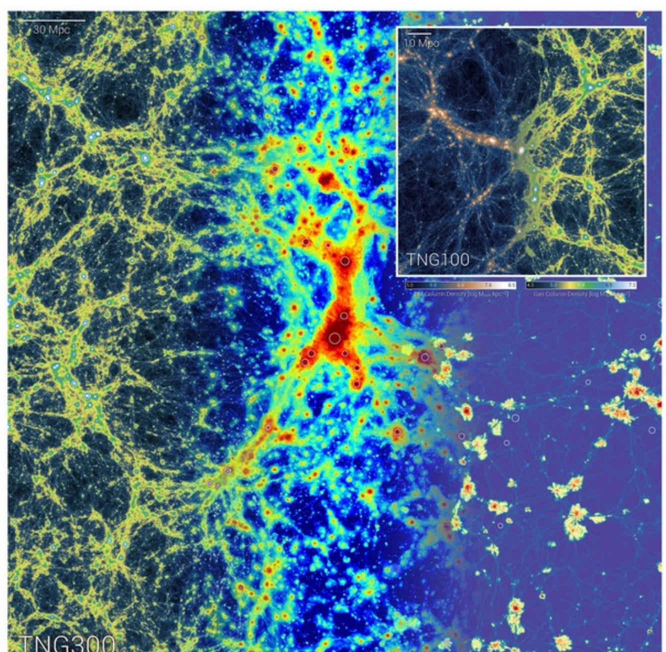


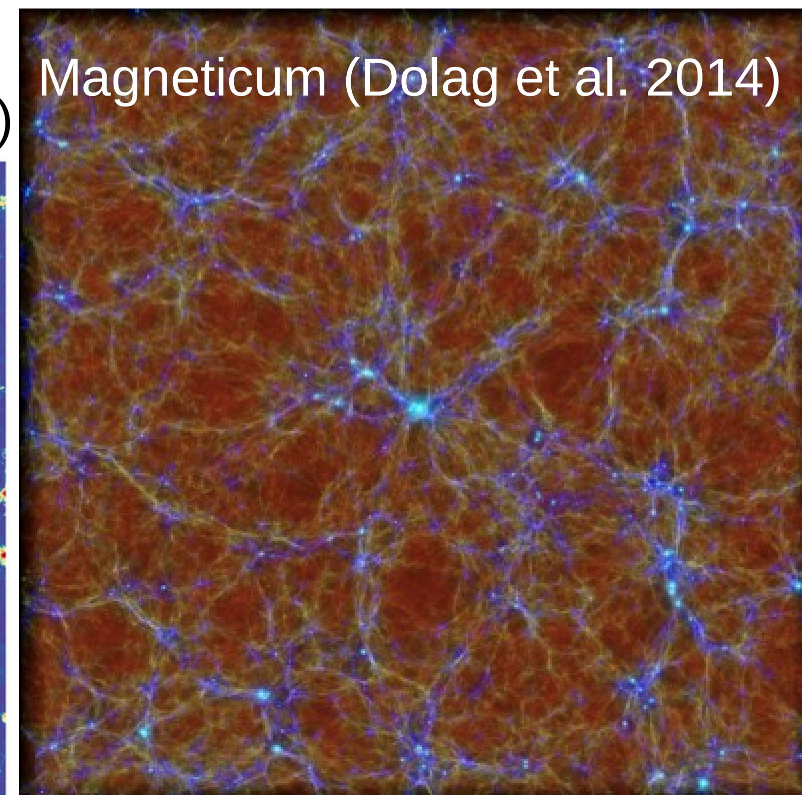
The Horizon AGN project (Dubois et al. 14)





Illustris TNG (Springel et al. 17)





The Illustris project

HUBBLE DEEP FIELD

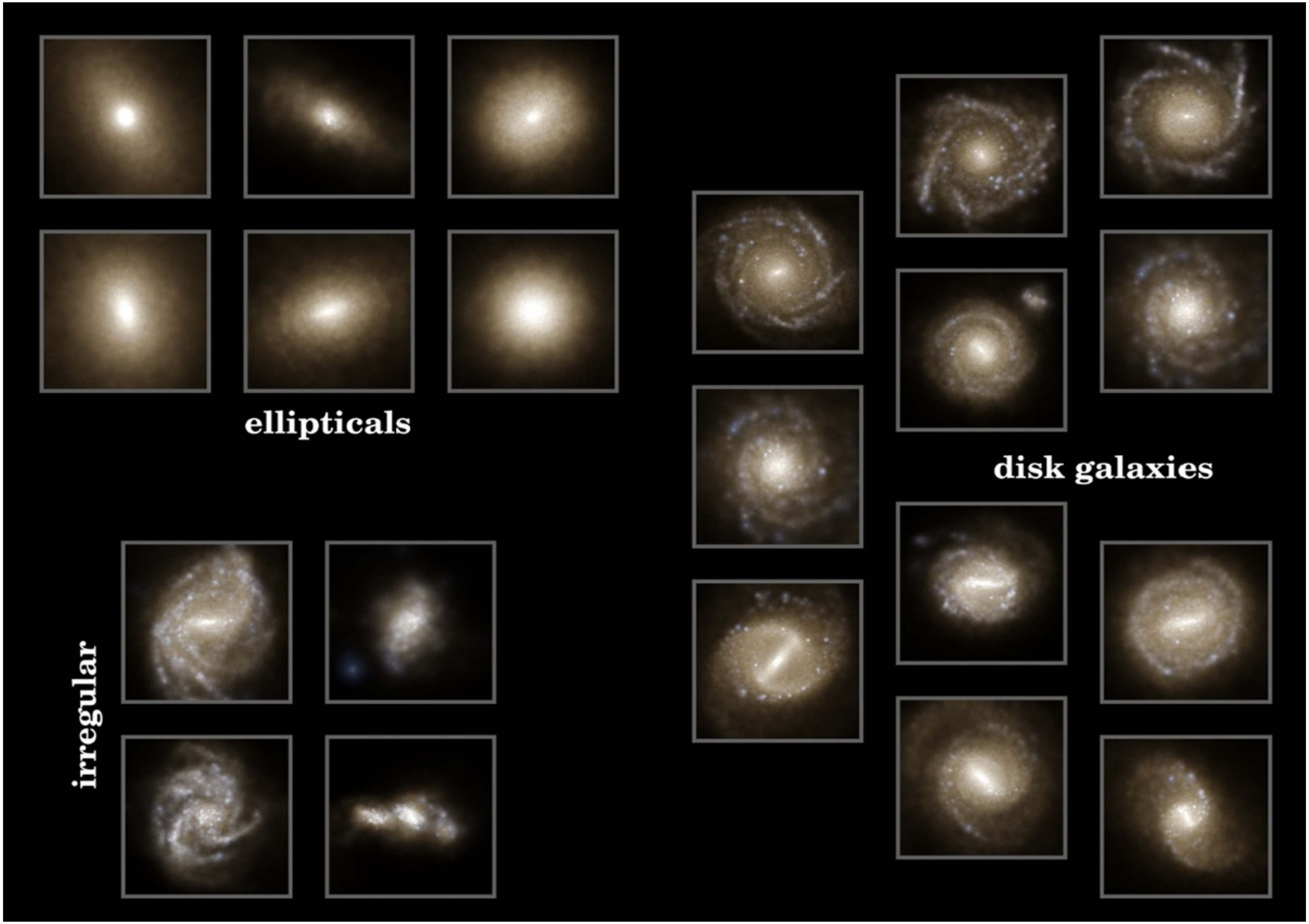
Vogelsberger et al., Nature, 2014
Vogelsberger et al., MNRAS, 2014
Genel et al., MNRAS, 2014
Sijacki et al., MNRAS, 2015

PARTNERSHIP FOR ADVANCED COMPUTING IN EUROPE

XSEDE Extreme Science and Engineering Discovery Environment

The Illustris project

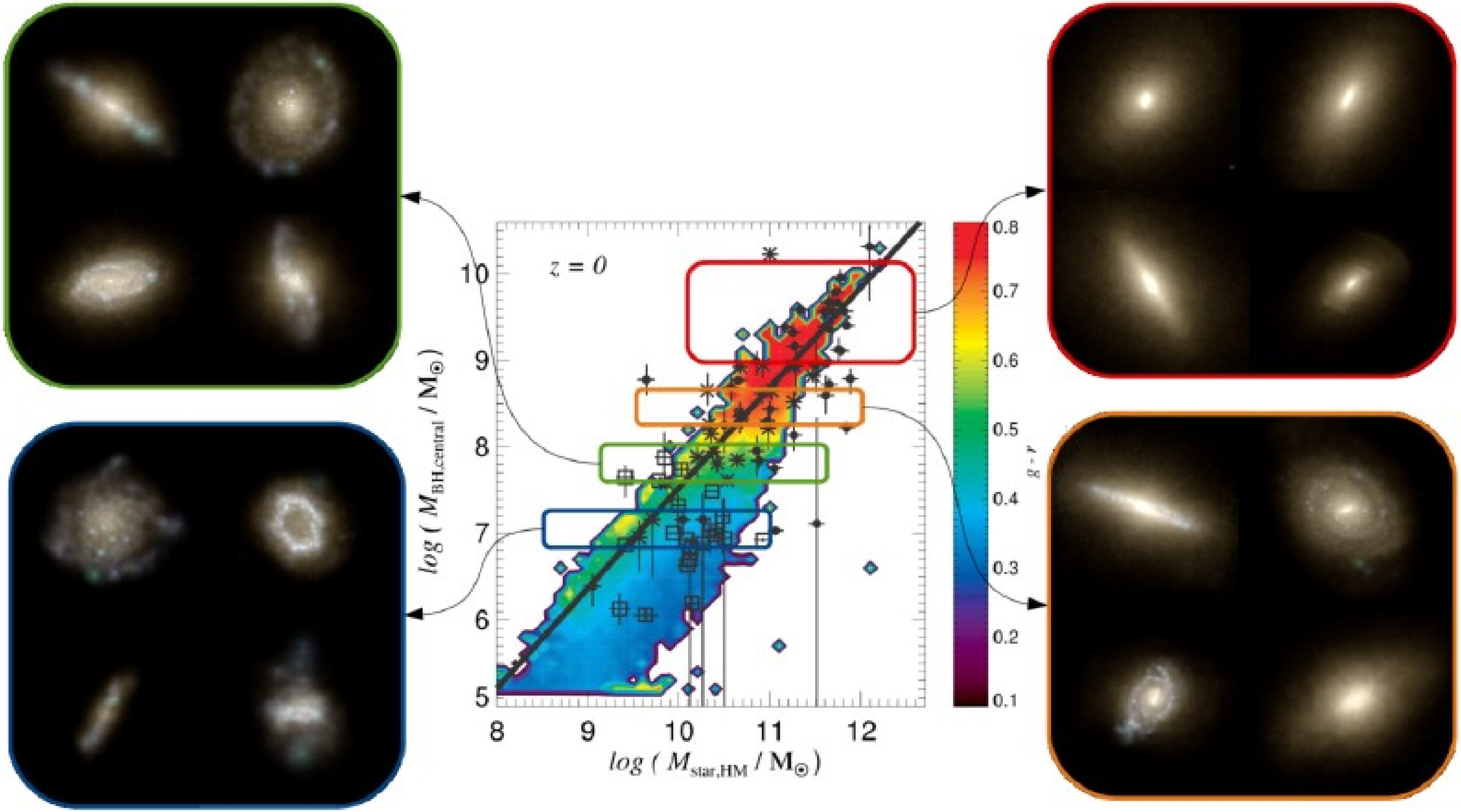
GALAXY MORPHOLOGIES



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



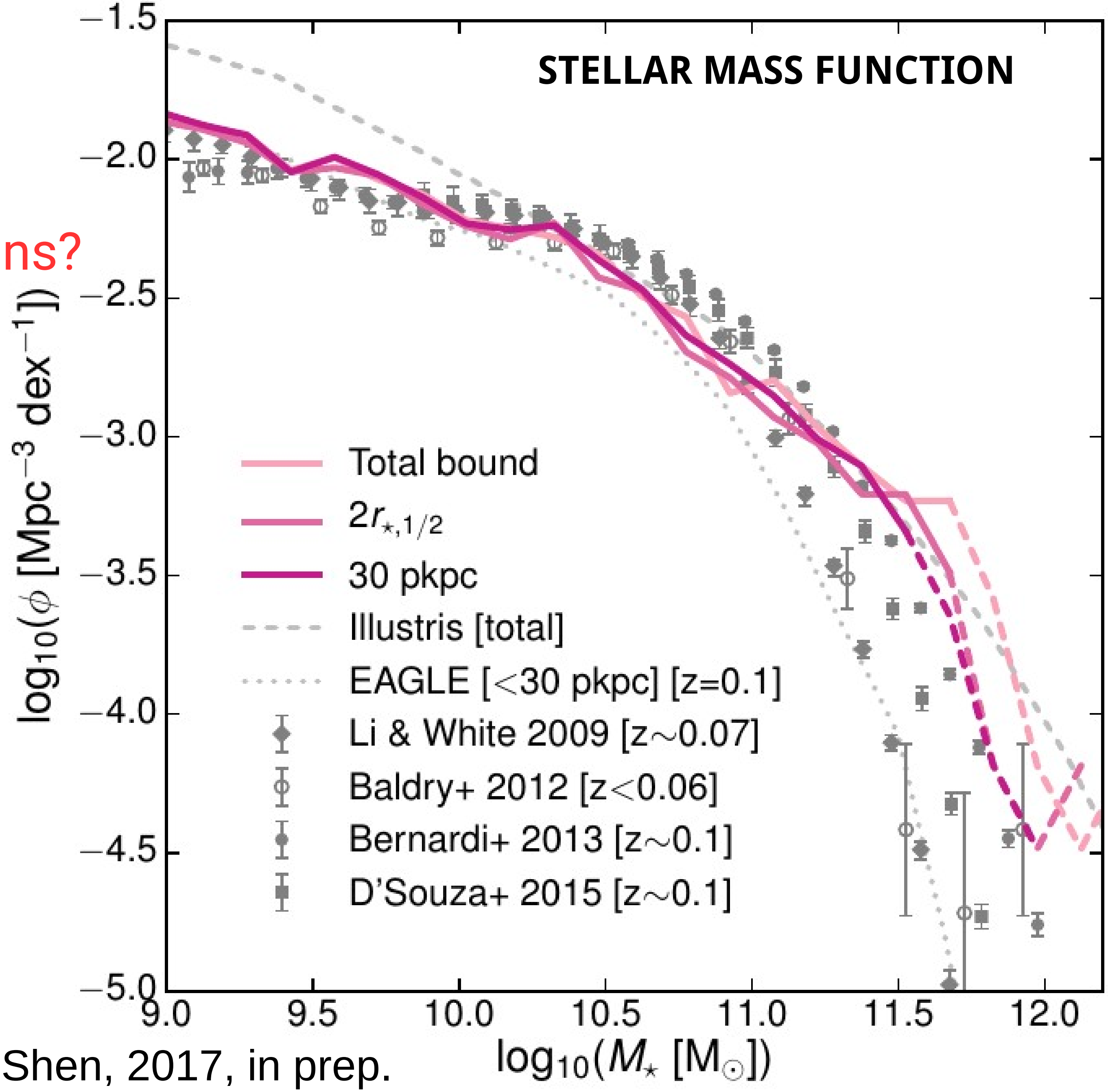
Kormendy & Ho, 2013: best fit
circles: ellipticals; stars: spirals with bulges; squares: pseudo bulges

Sijacki et al, 2015

Current state-of-the-art in cosmological hydro simulations[16]

Different sub-grid models achieve similar results!

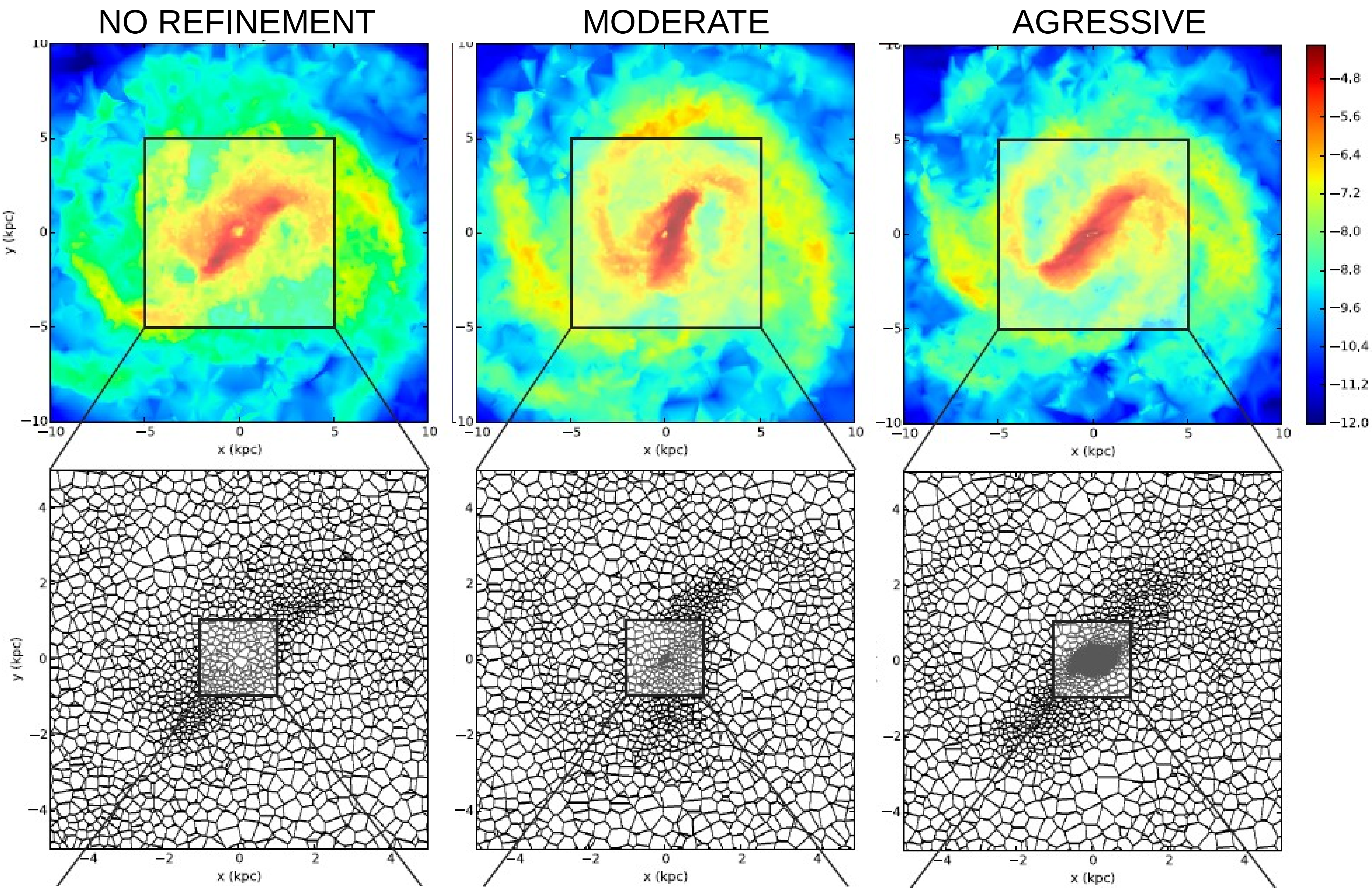
- ➢ Predictive power?
- ➢ Fine tuning?
- ➢ Purpose of simulations?
- ➢ Learning about the underlying physics?



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

Resolving flows onto BHs

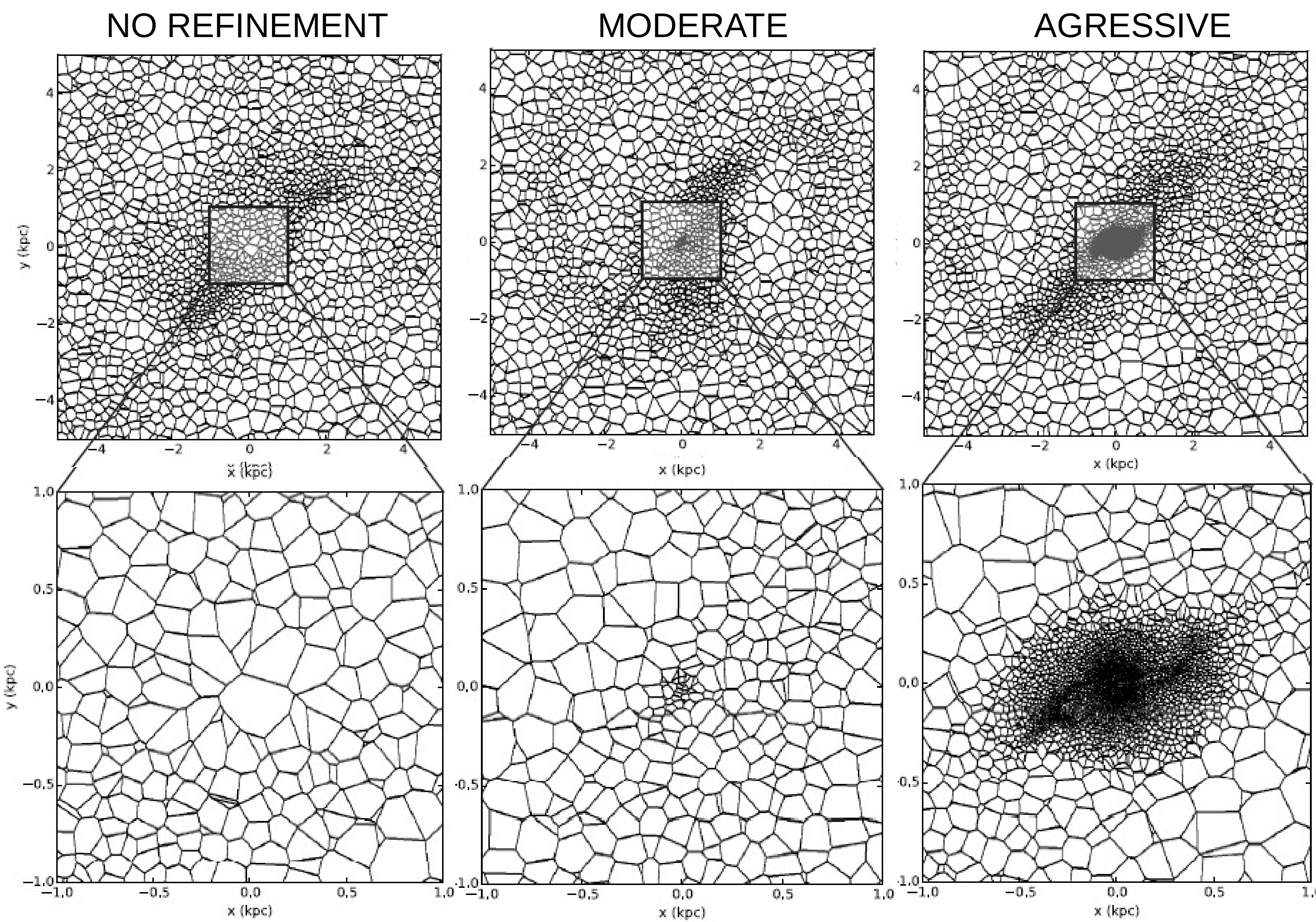
GAS DENSITY MAPS + VORONOI MESH



Curtis & Sijacki, MNRAS, 2015

Resolving flows onto BHs

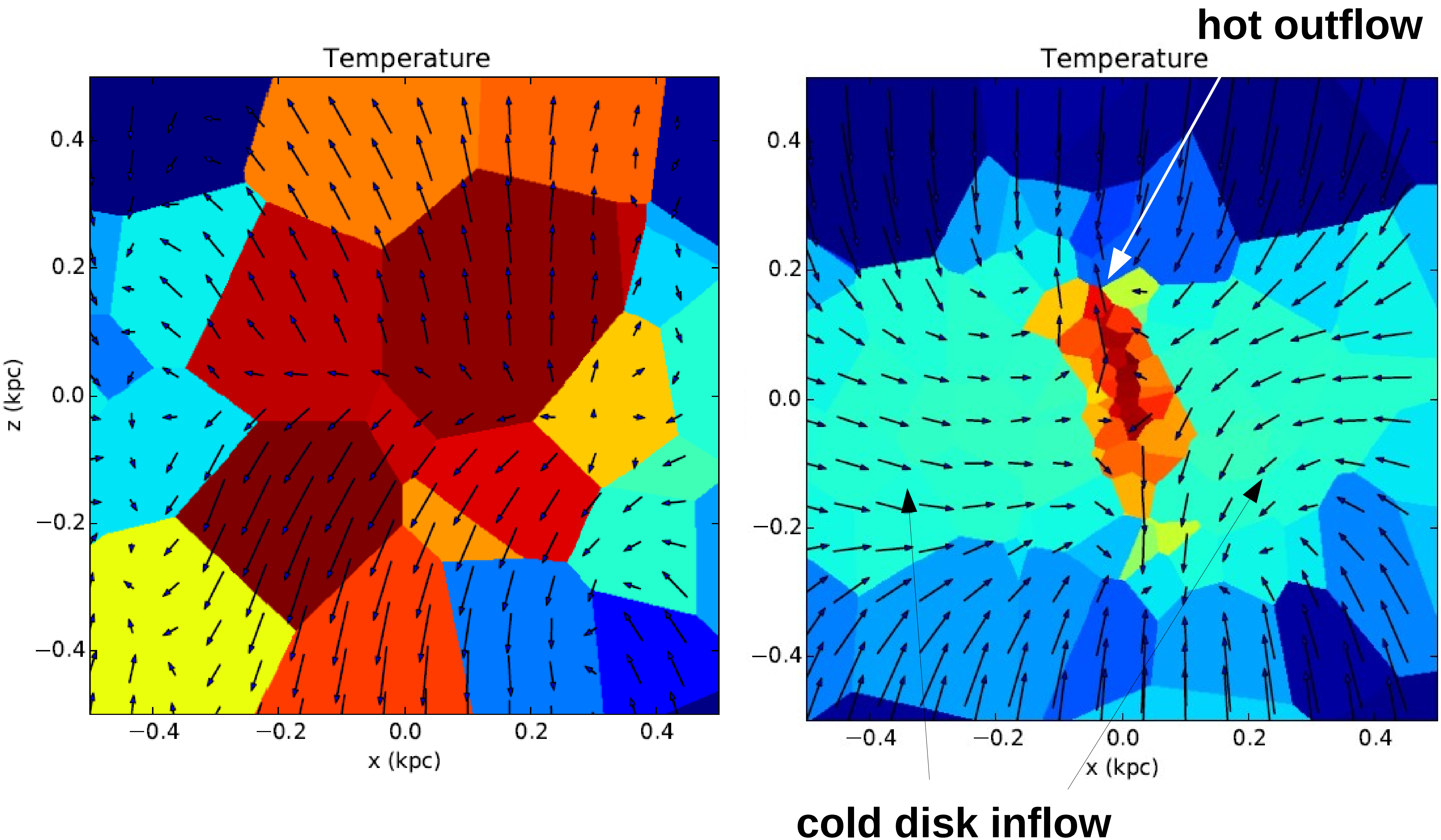
VORONOI MESH



Curtis & Sijacki, MNRAS, 2015

Resolving flows onto BHs

GAS TEMPERATURE MAPS (edge on)



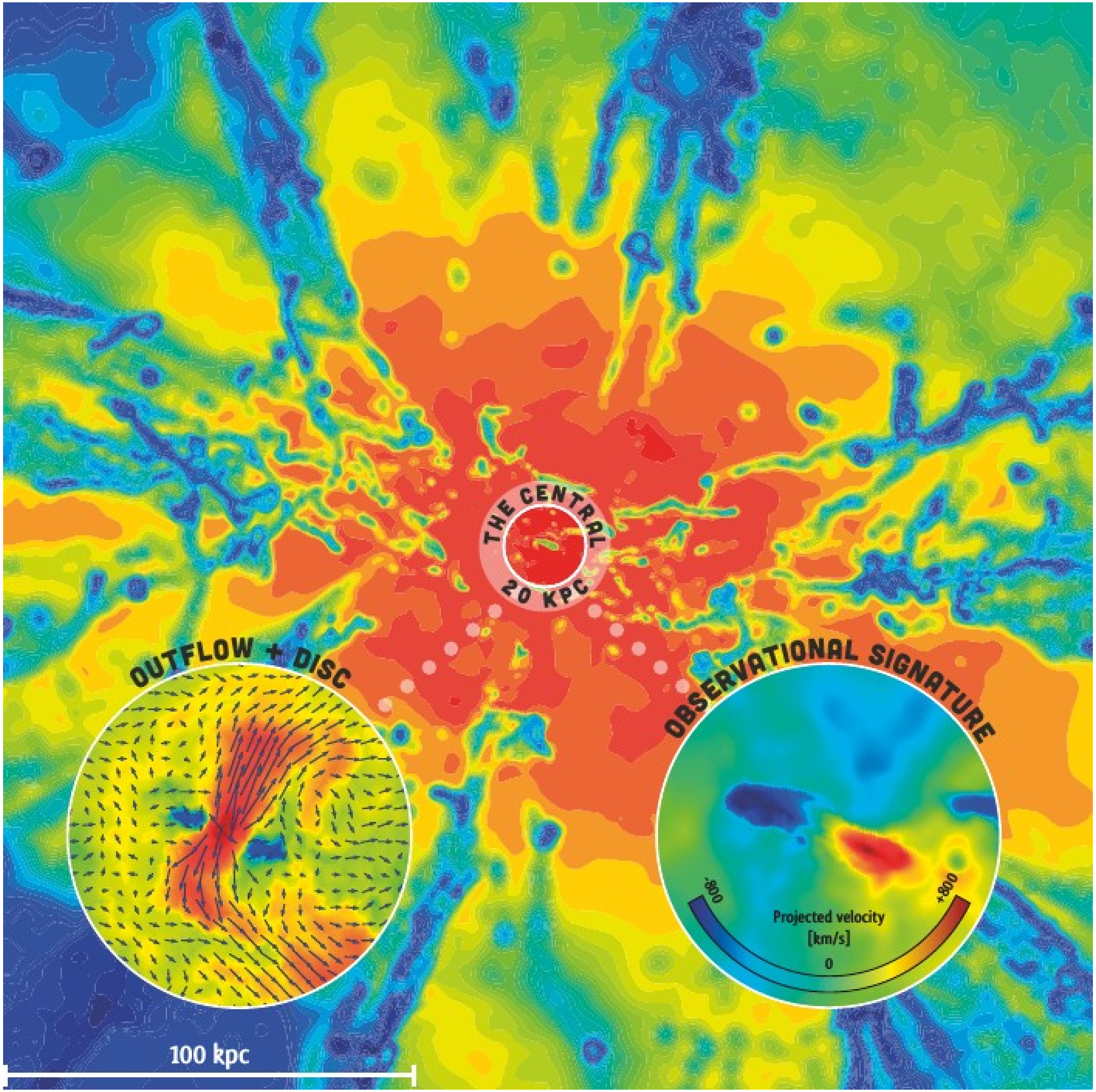
Curtis & Sijacki, MNRAS, 2015

Powerful QSO outflow in a massive disk galaxy at high z

Curtis & Sijacki, MNRAS Letter 2015

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

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

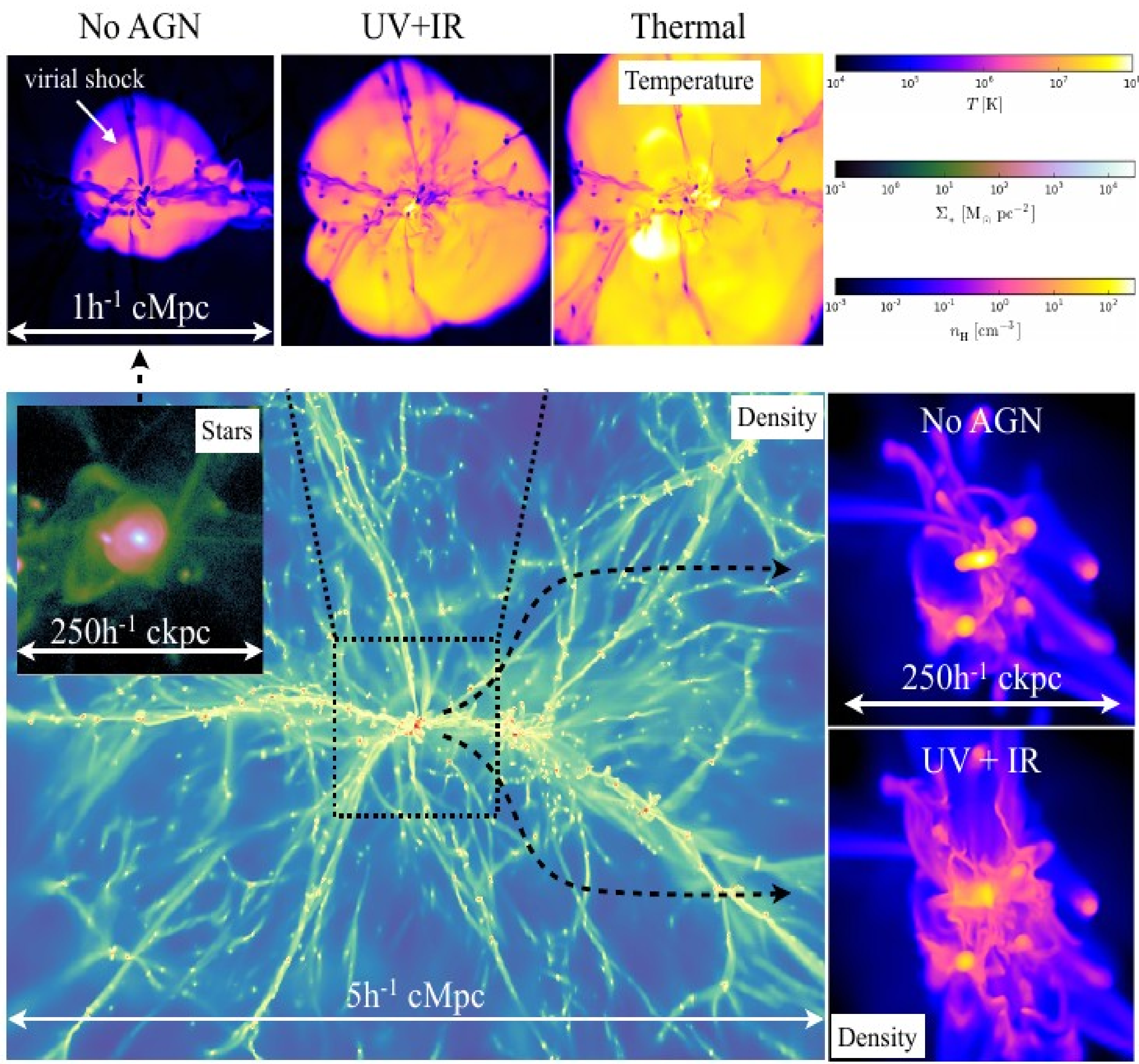


Powerful QSO outflow in a massive disk galaxy at high z

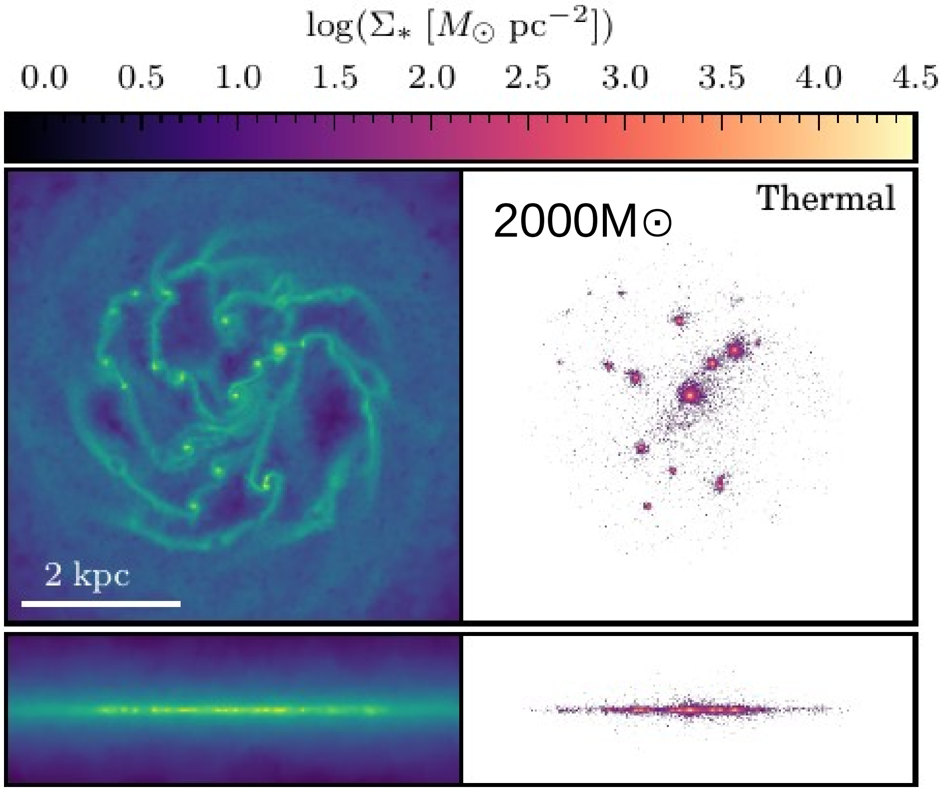
Costa, Rosdahl, Sijacki, Haehnelt, 2017, in prep.

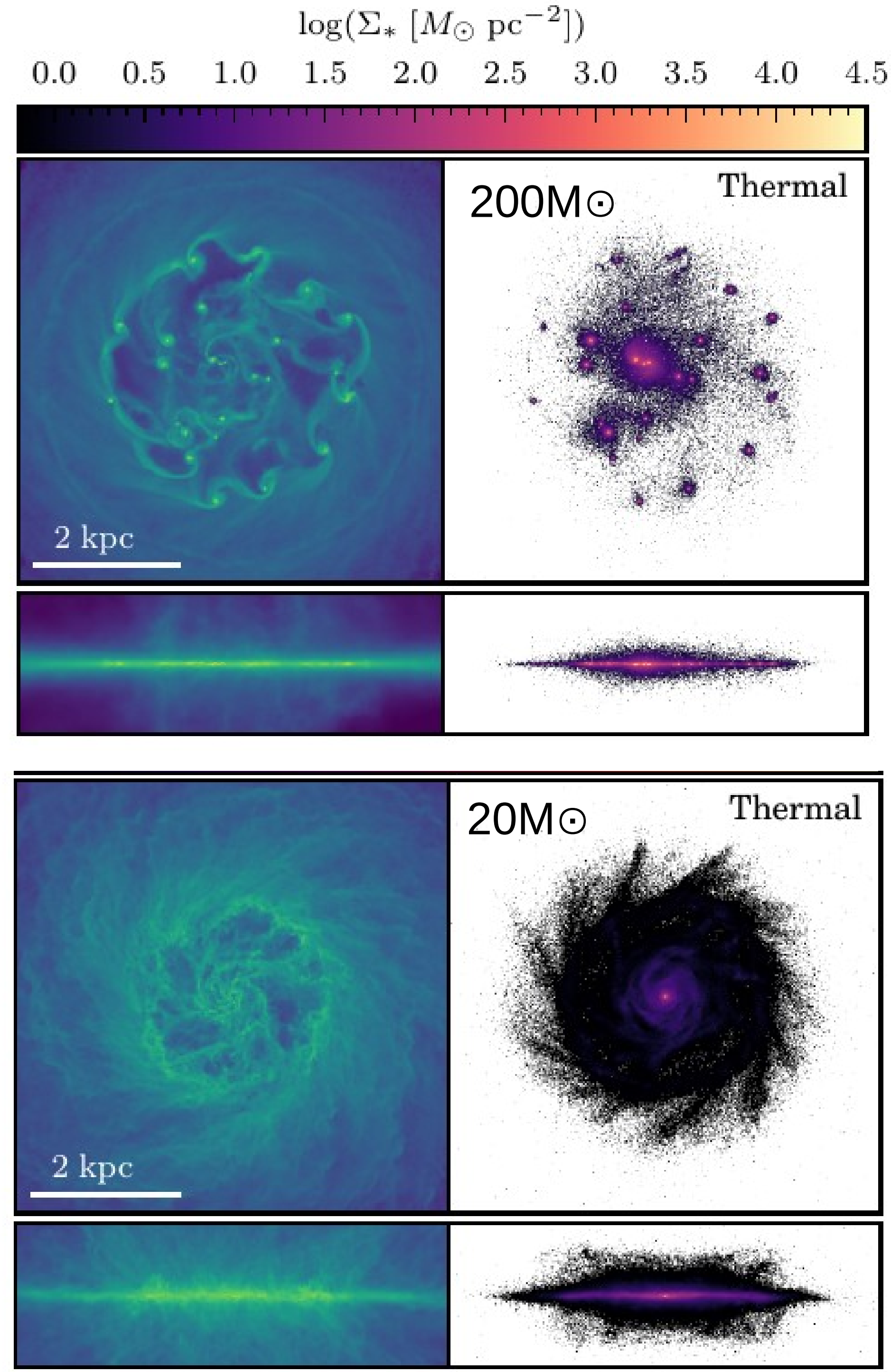
DIFFERENT BH FEEDBACK AT A SAME RESOLUTION LEADS TO VERY DIFFERENT GALAXY MORPHOLOGY

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



How (dramatic) change in resolution affects the physics?





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

Smith, Sijacki & Shen, 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