Approaching a theory of galaxy formation

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Approaching a theory…

- There is not an established theory of galaxy formation
- Cosmology as a framework
- “Concordance cosmology” was established in the last decades of the XX century

ΛCDM cosmology

What makes a galaxy?

Hubble Heritage Team (AURA/STScI/NASA/ESA)

galaxy constituents

- dark matter, stars, gas, and dust

- galaxies are complex, multi-component systems

galaxy diversity

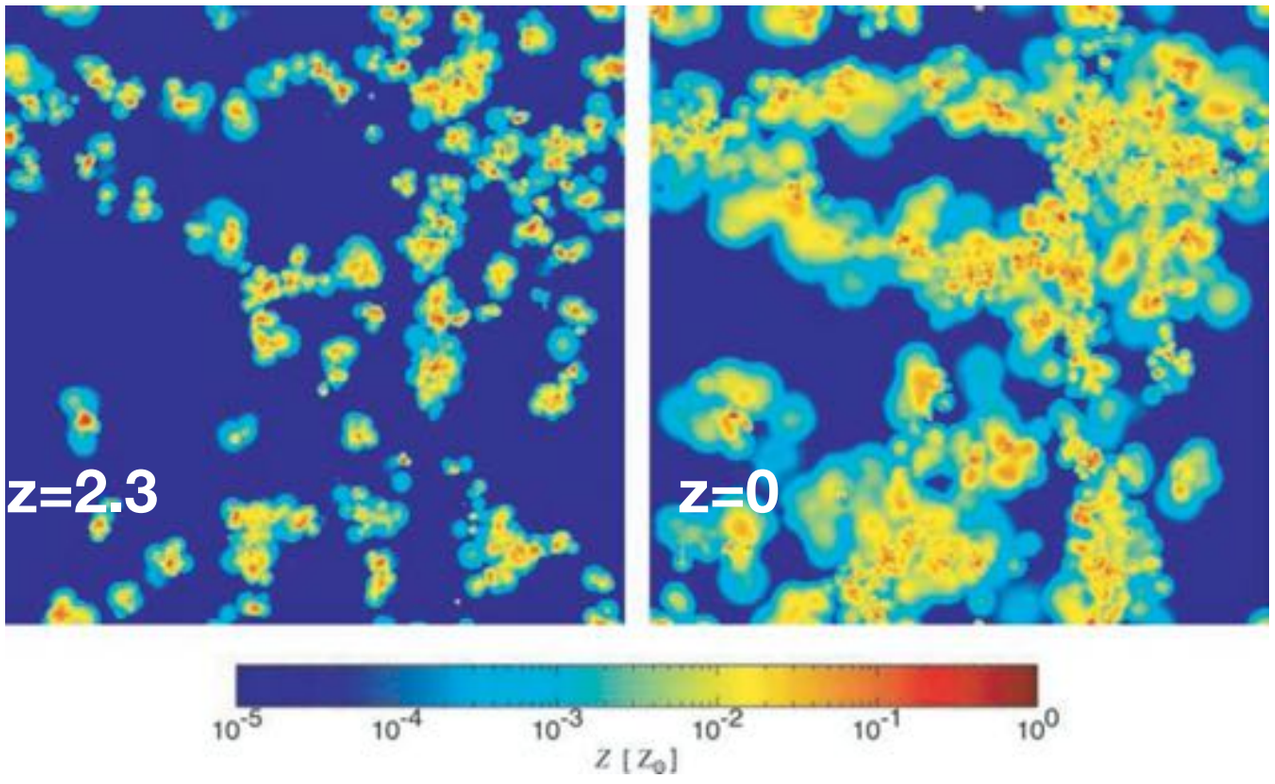
Hubble Heritage Team (AURA/STScI/NASA/ESA)

Galaxy Astrophysics

- Gas and dark-matter gravitational dynamics
- interactions between gas and radiation
- star formation

galaxy formation is a hard problem, but

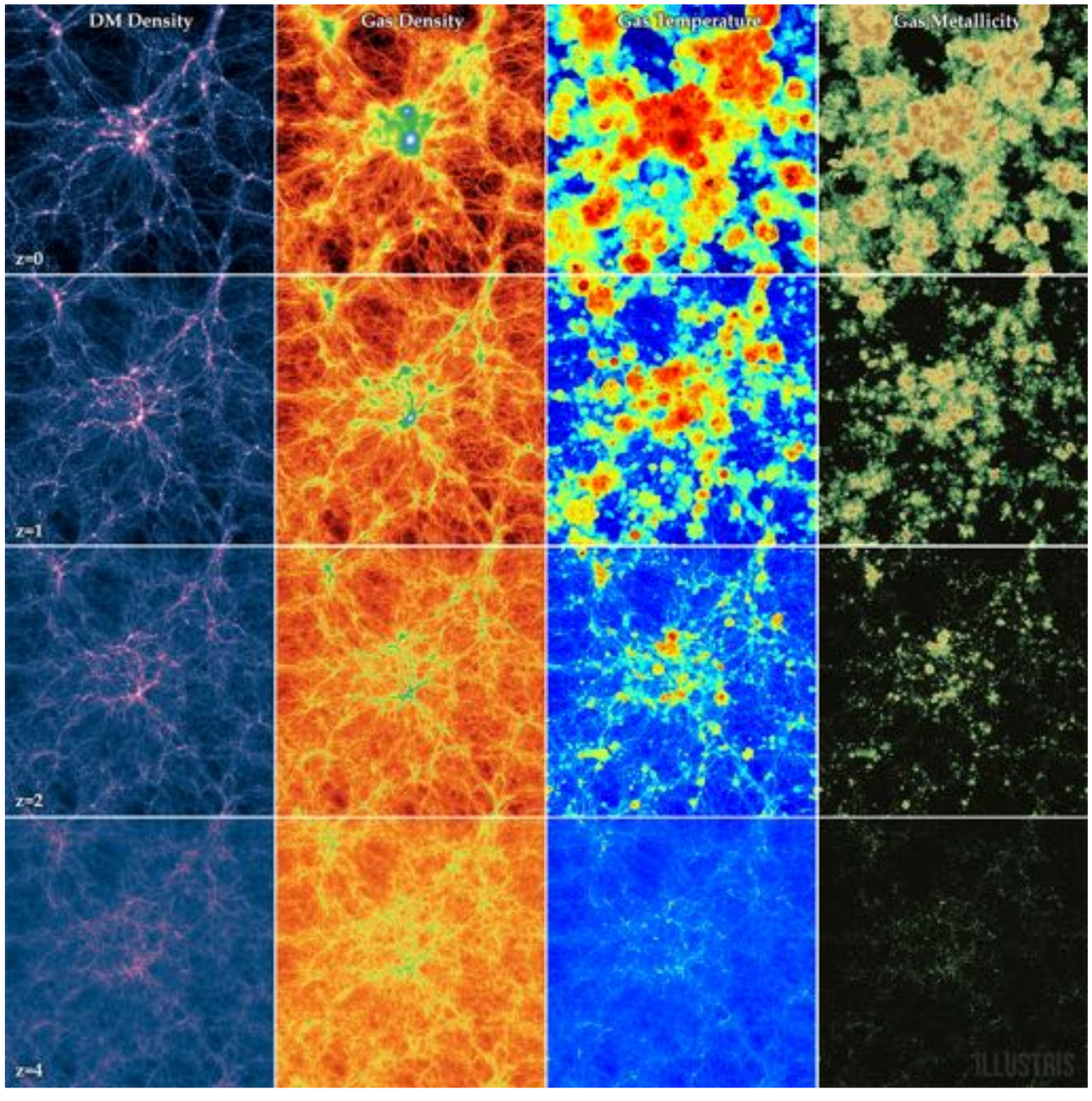
Fast developments (2003)



Projected mean metallicity of the gas in a 2×50^3 simulation.
The map is 11.3 h^{-1} Mpc
m_{dm}=8 10^8 h^{-1} Msun

Springel & Hernquist (2003)

Fast developments (2014)



ILLUSTRIS has 2×1820^3 particles
in a 100 Mpc box
$m_{dm}=6\ 10^6$ Msun

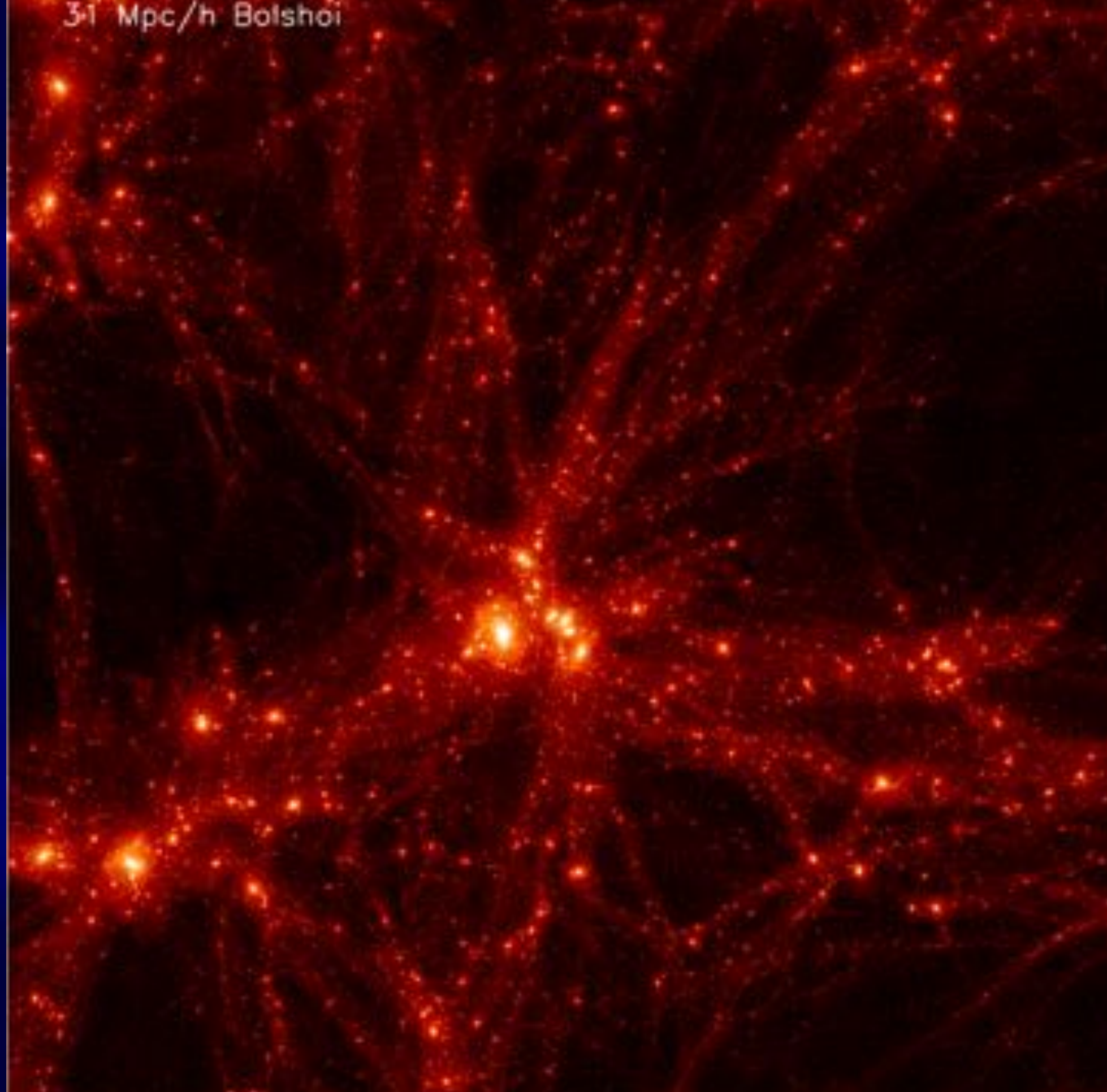
Outline of lectures

- Galaxies as crossroads between astrophysics and cosmology
- Cosmological simulations of galaxy formation
- The physics of star formation and feedback

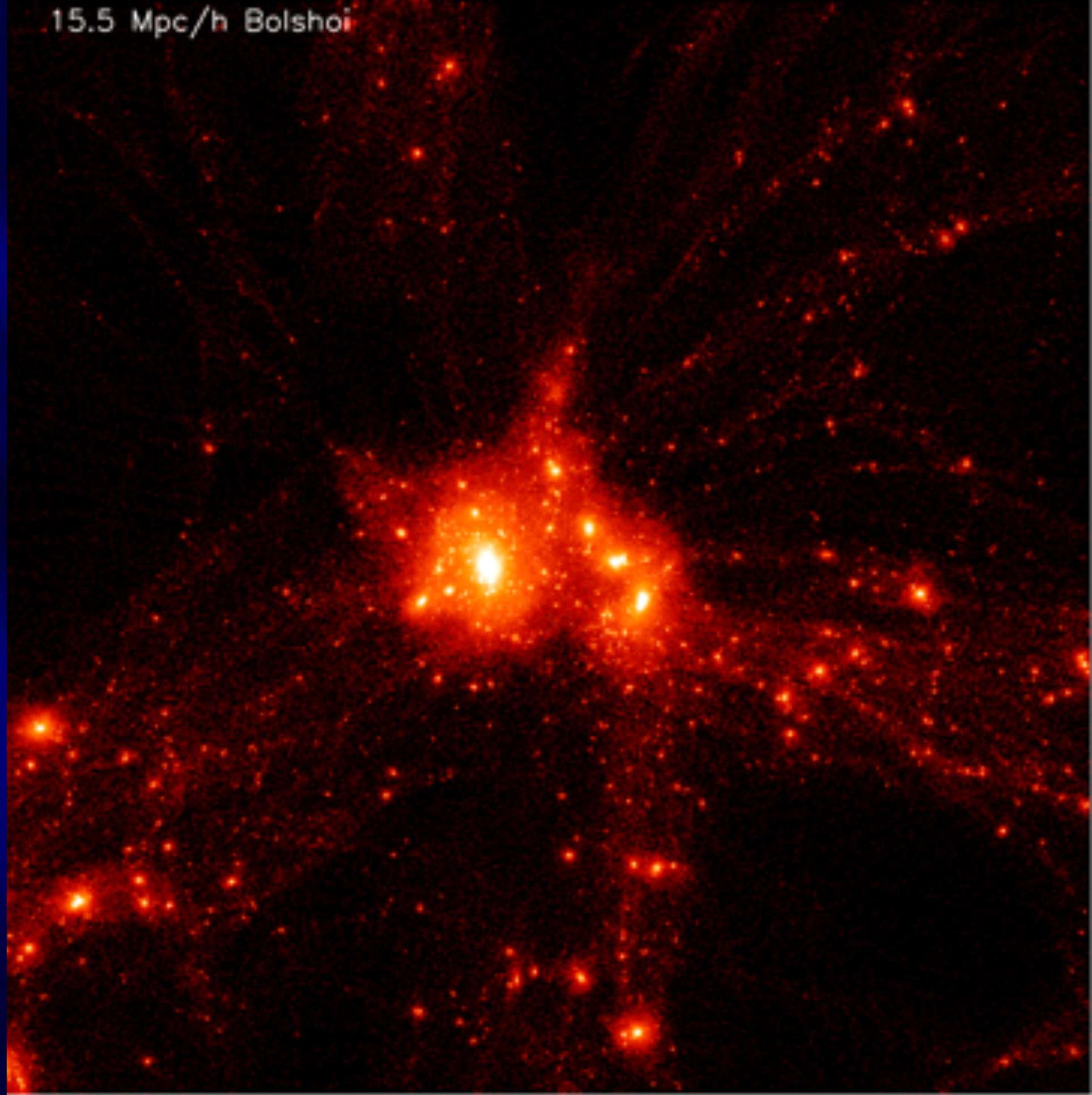
1. Galaxies as crossroads between astrophysics and cosmology

bigBolshoi 1Gpc 8G particles

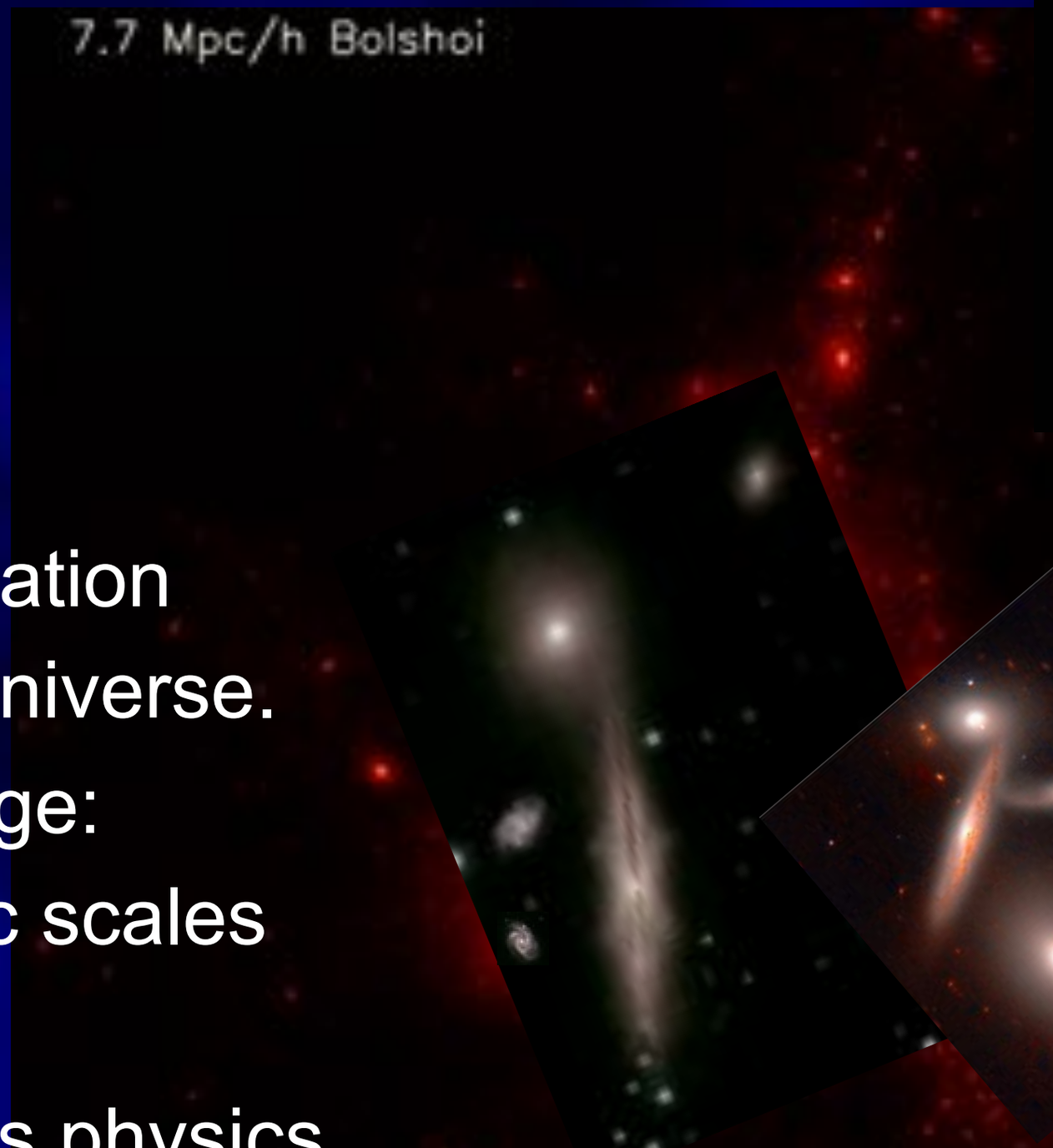
62 Mpc/h Bolshoi


3.1 Mpc/h Bolshoi

15.5 Mpc/h Bolshoi



Small Galaxy Group



- Galaxy Formation in a ΛCDM Universe.
- Dynamic range:

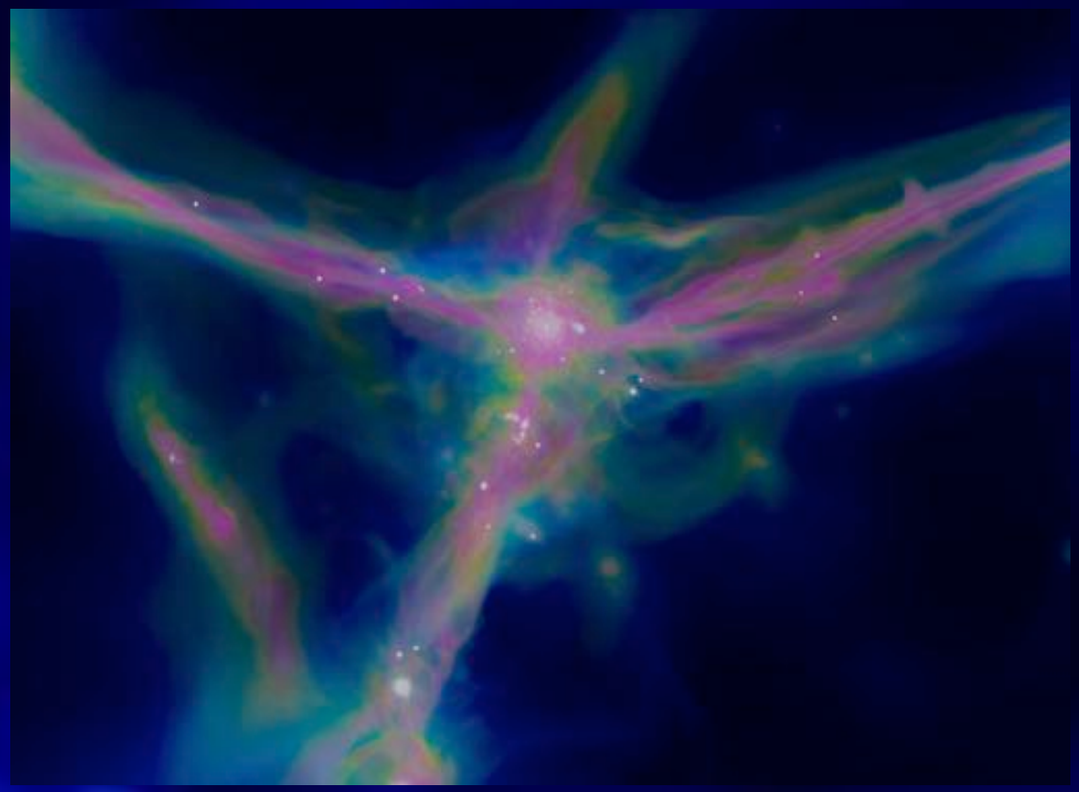
From Mpc to pc scales

- Physics:

Gravity plus gas physics

Our tool: Cosmological Simulations of Galaxy Formation

Galaxies as crossroads



- Different scales are related
- Different astrophysical processes are linked through non-linear mechanisms
- The evolution of the Universe matters for the formation of a single star
- Stars and galaxies are not isolated objects

First application: Dwarf Galaxies as challenges to cosmology

Annual Review of Astronomy and Astrophysics

Small-Scale Challenges to the ΛCDM Paradigm

James S. Bullock[1] and Michael Boylan-Kolchin[2]

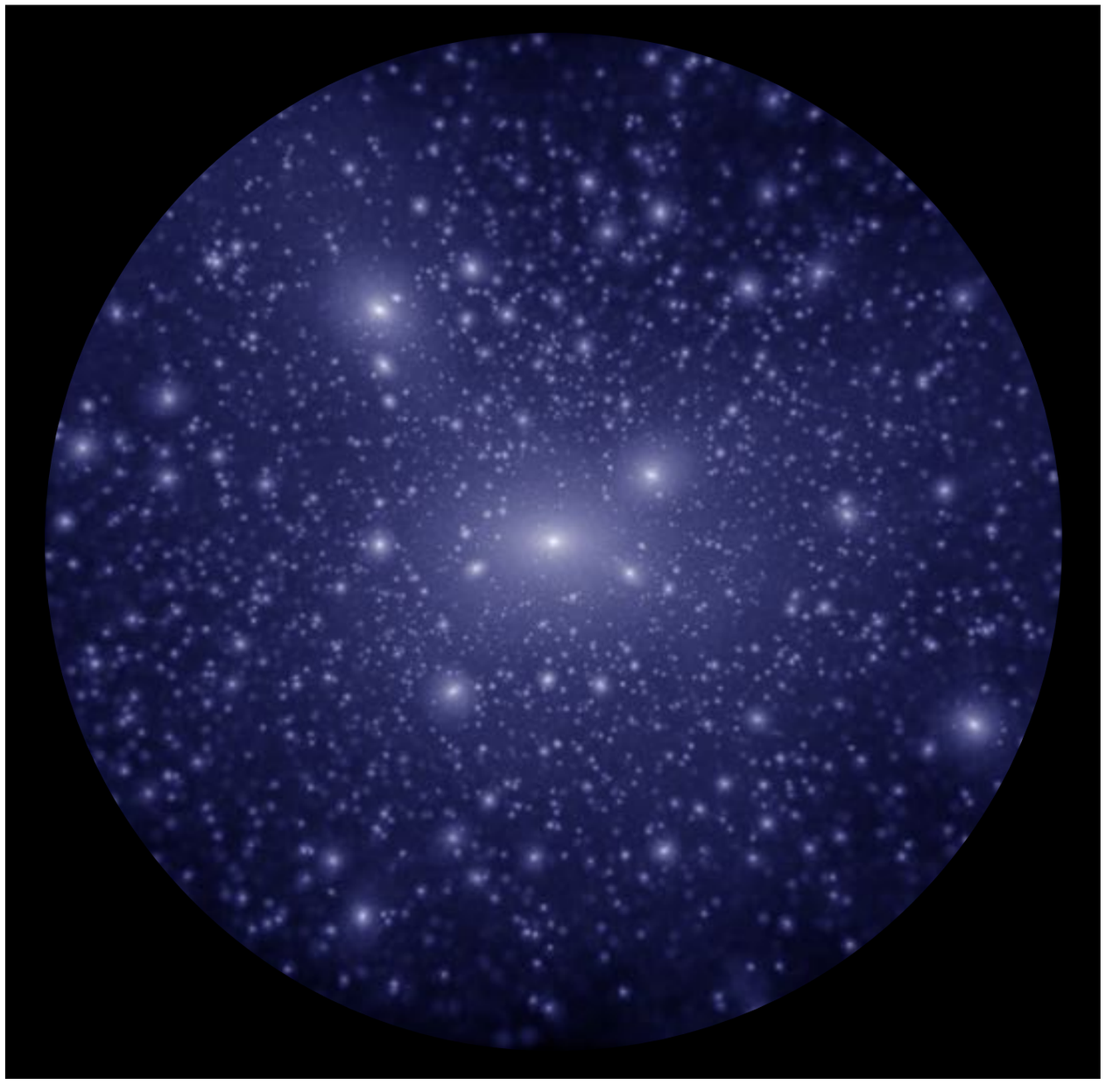
Annu. Rev. Astron. Astrophys. 2017. 55:343–87

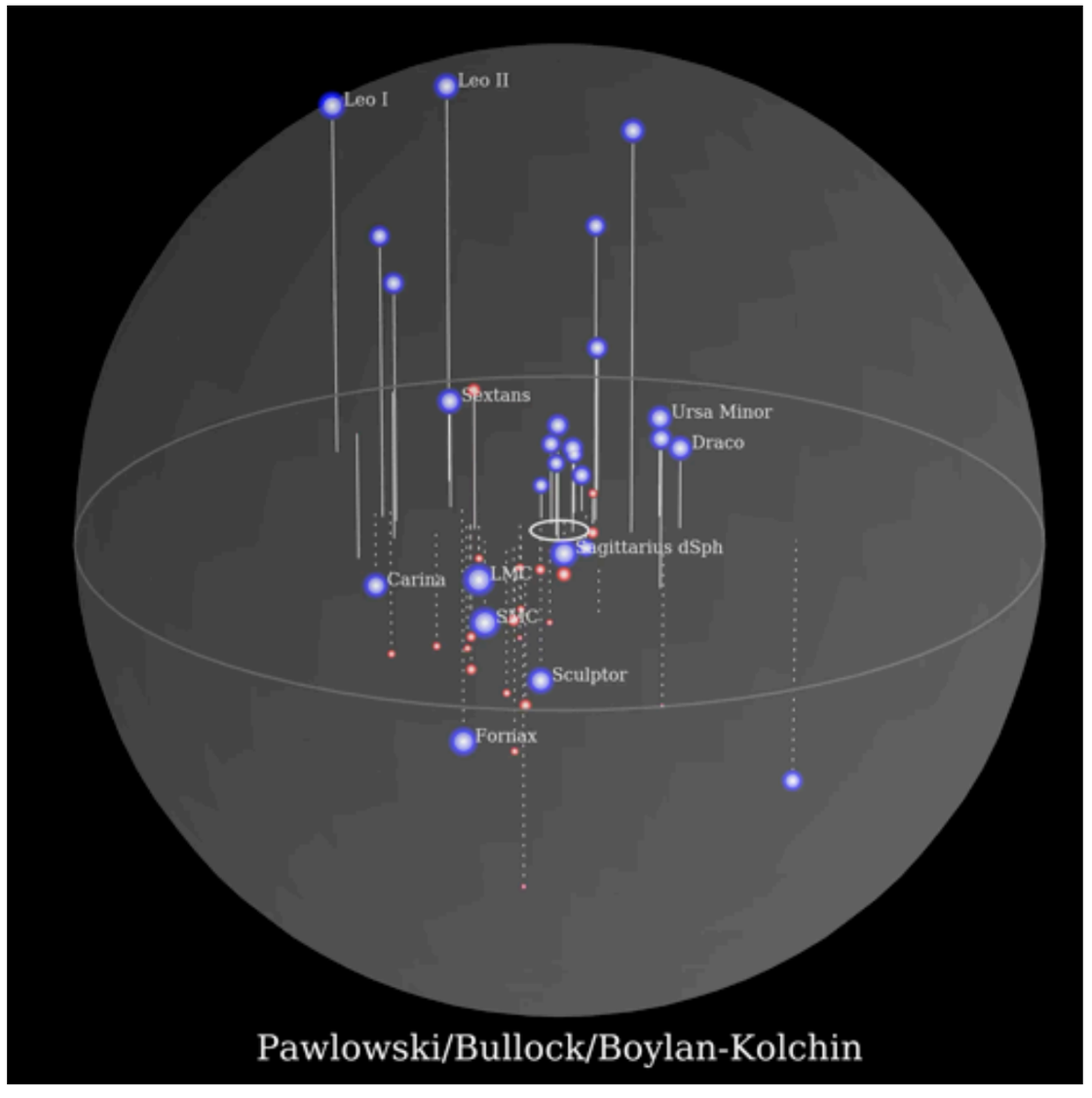
First published as a Review in Advance on June 28, 2017

The *Annual Review of Astronomy and Astrophysics* is online at astro.annualreviews.org

https://doi.org/10.1146/annurev-astro-091916-055313

low number of satellites





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WHERE ARE THE MISSING GALACTIC SATELLITES?

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DARK MATTER SUBSTRUCTURE WITHIN GALACTIC HALOS

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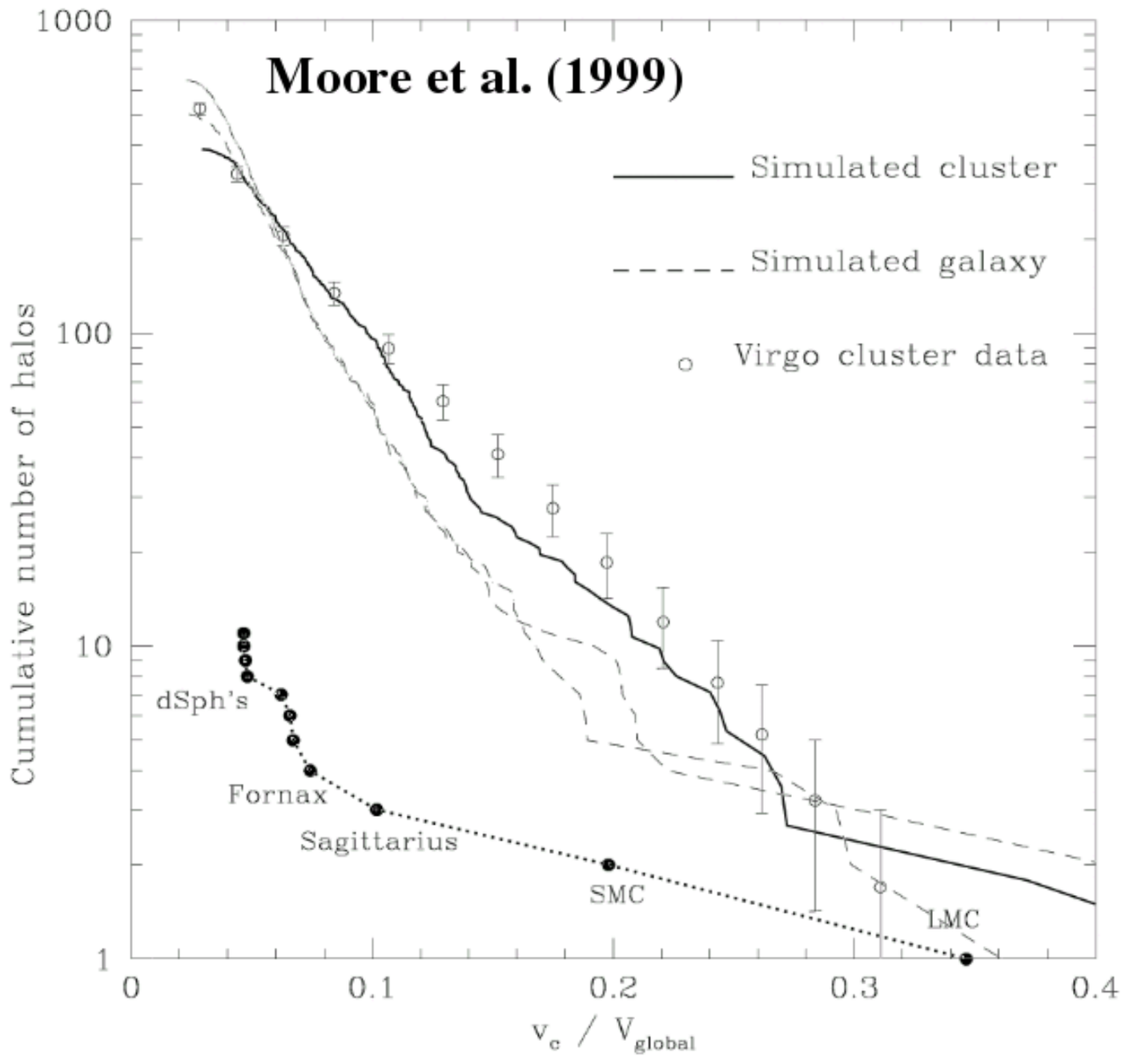
Quantifying the Missing Satellites Problem

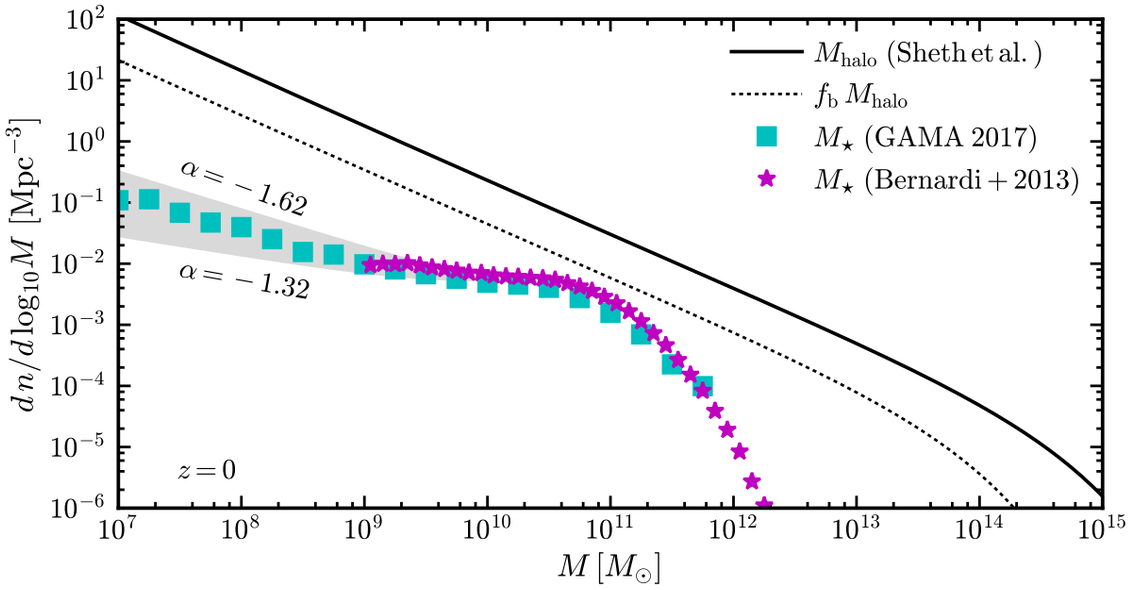
Cumulative peak circular velocity function (CVF)

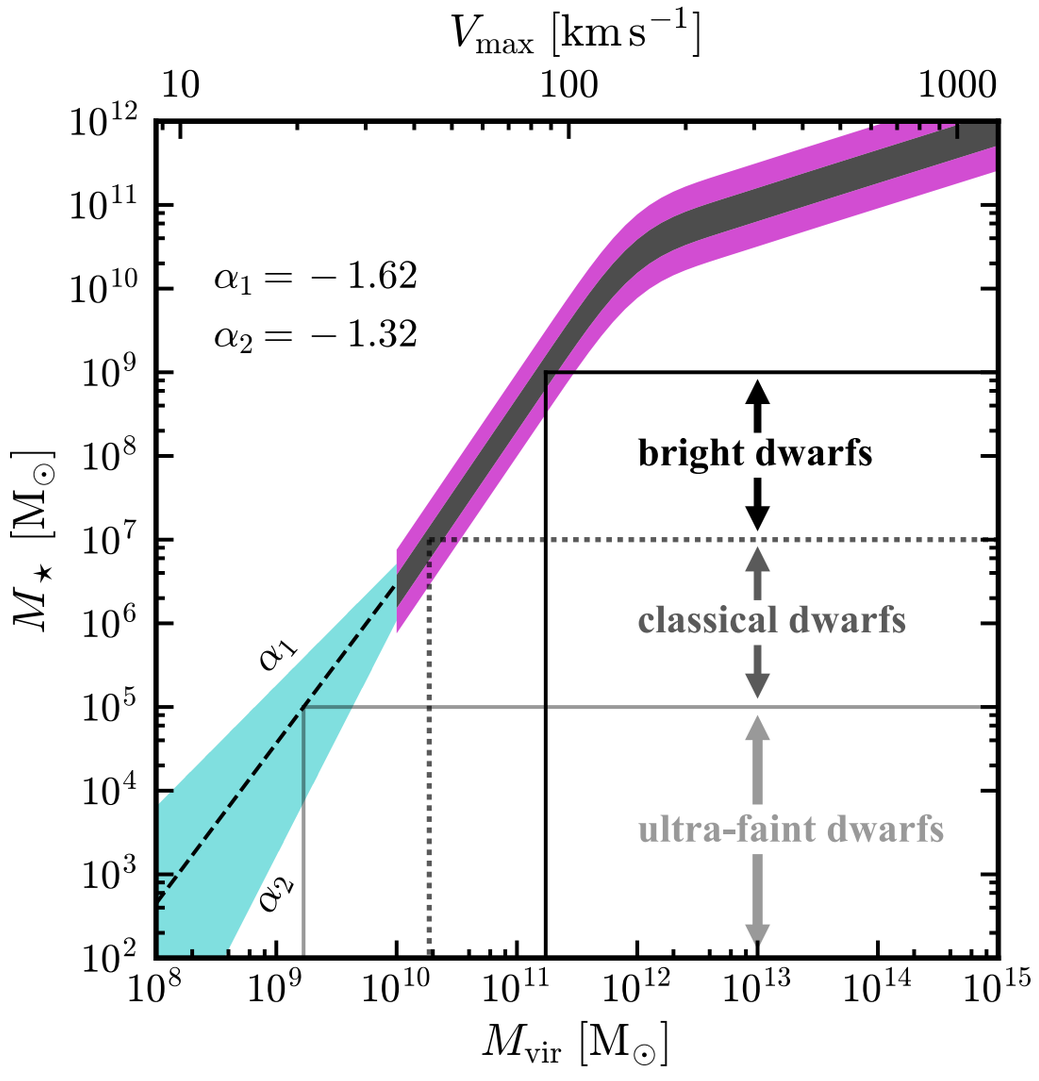


Vmax of satellites normalized to the Vvir of the parent halo

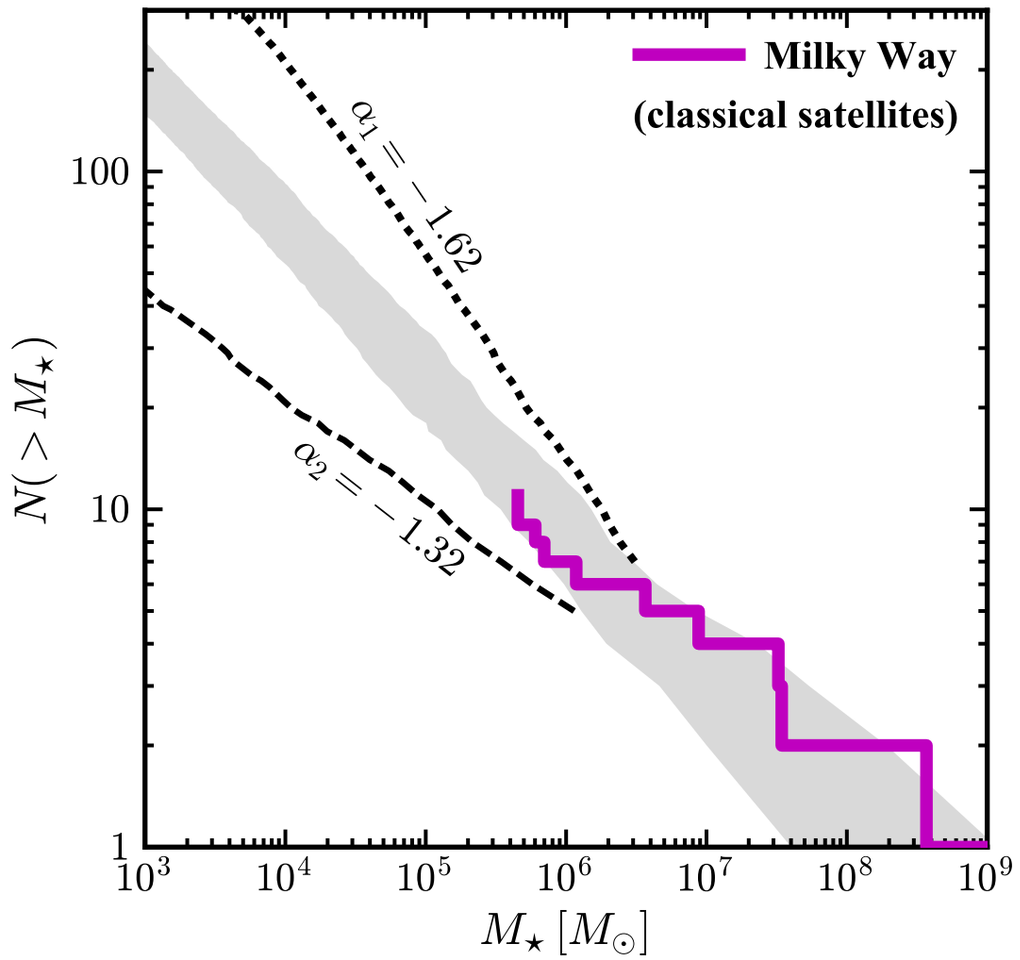
Discrepancy of ~ 2 orders of magnitude between the number of satellites predicted by numerical simulations of galactic systems and the Local Group.

Possible Solutions





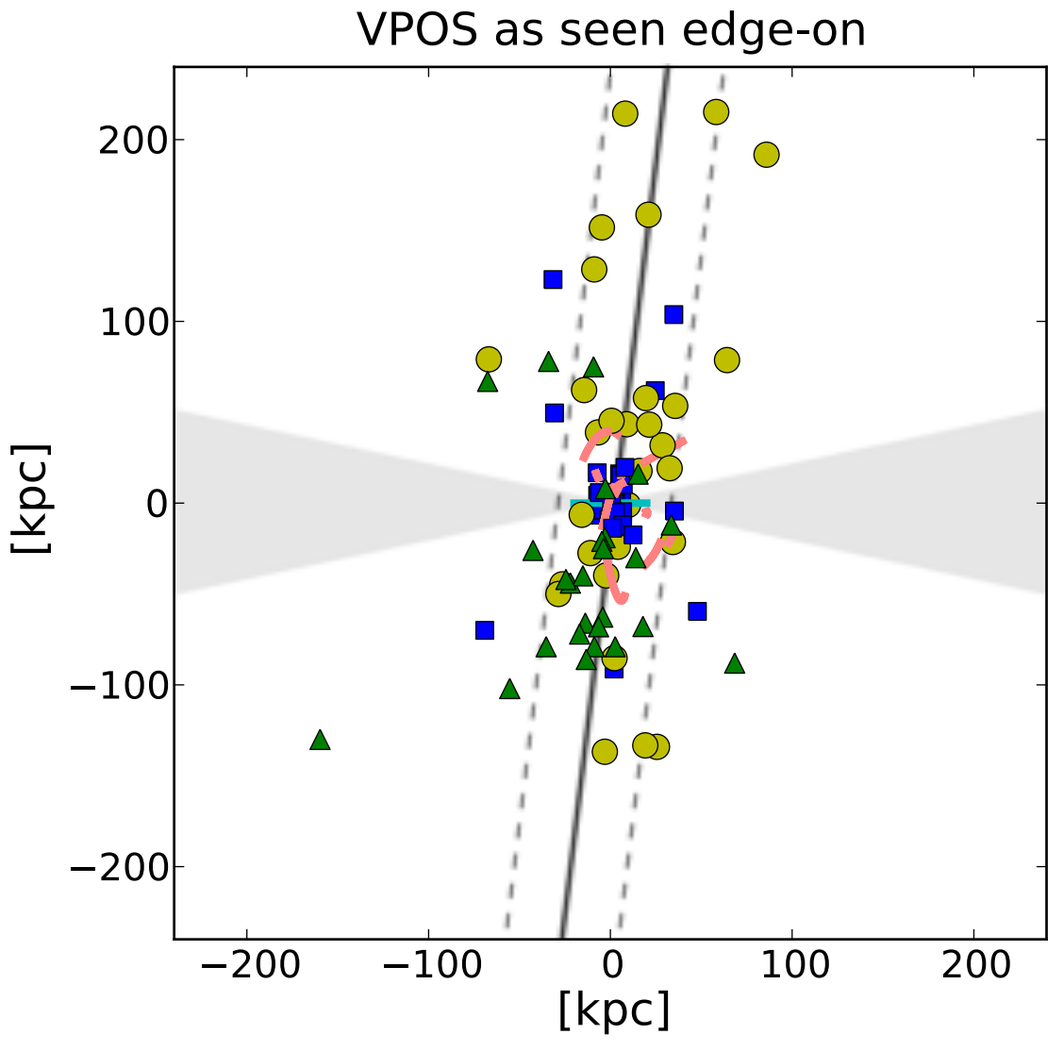
Possible Solutions

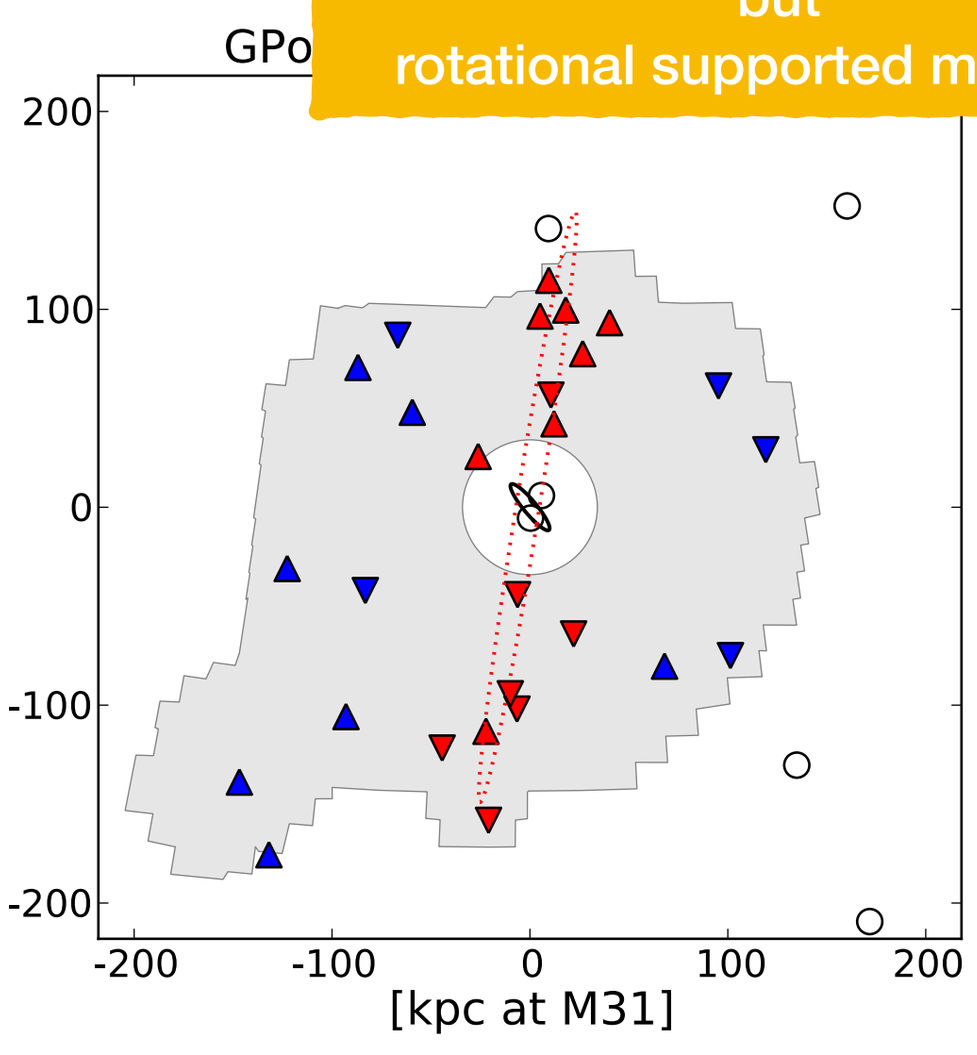


Which physical process drive this?

Planes of Satellites

Posible Solutions:
filamentary accretion within ΛCDM
limited coverage in observations
but
rotational supported motions?





First Tutorial Section

PROJECTS

- Main Goal: Get experience and skills with simulations data
- Beyond simple homeworks
- Scientifically relevant (and open) projects.

slice through galaxy plane

Radial momentum

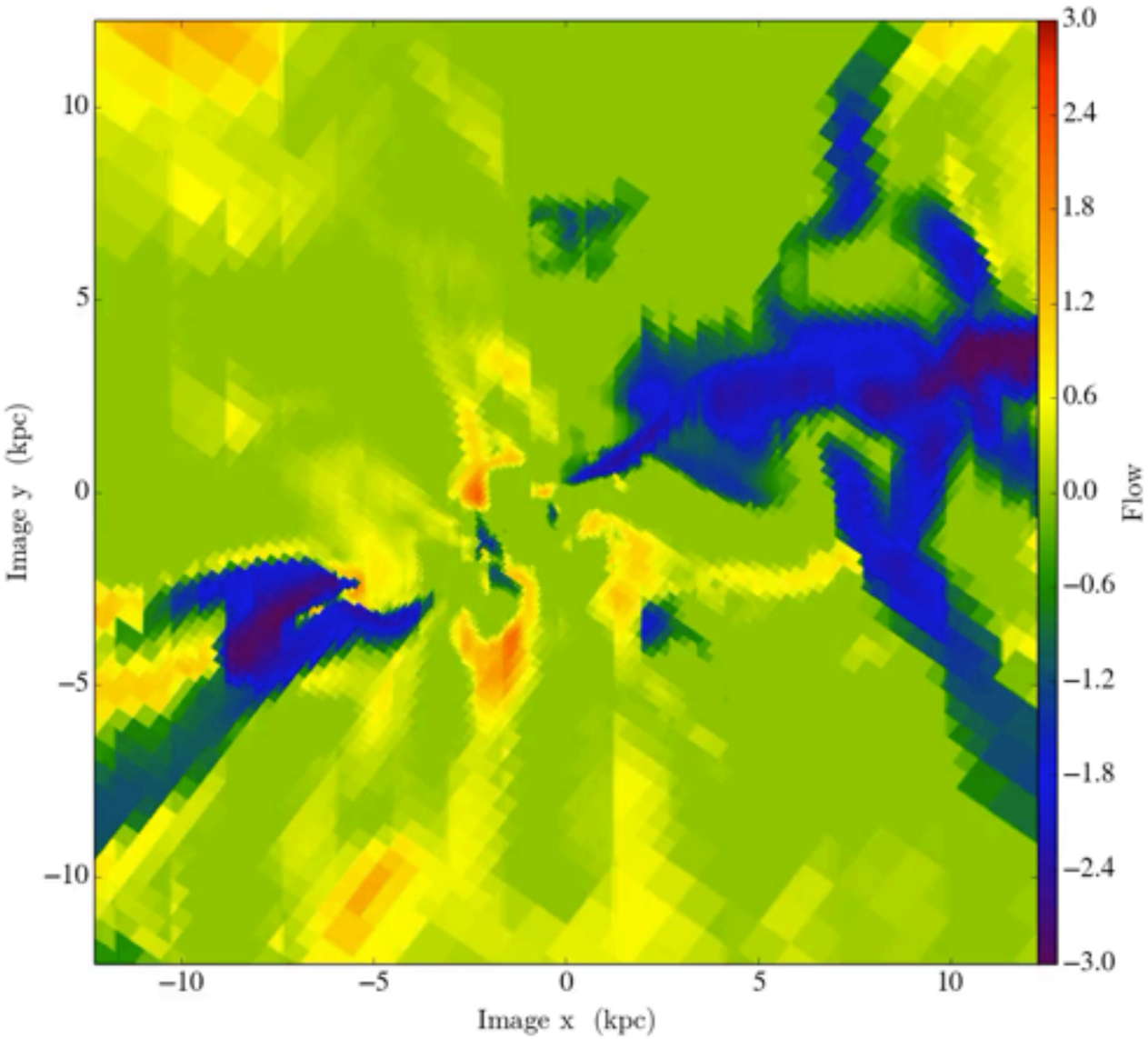
Gas density

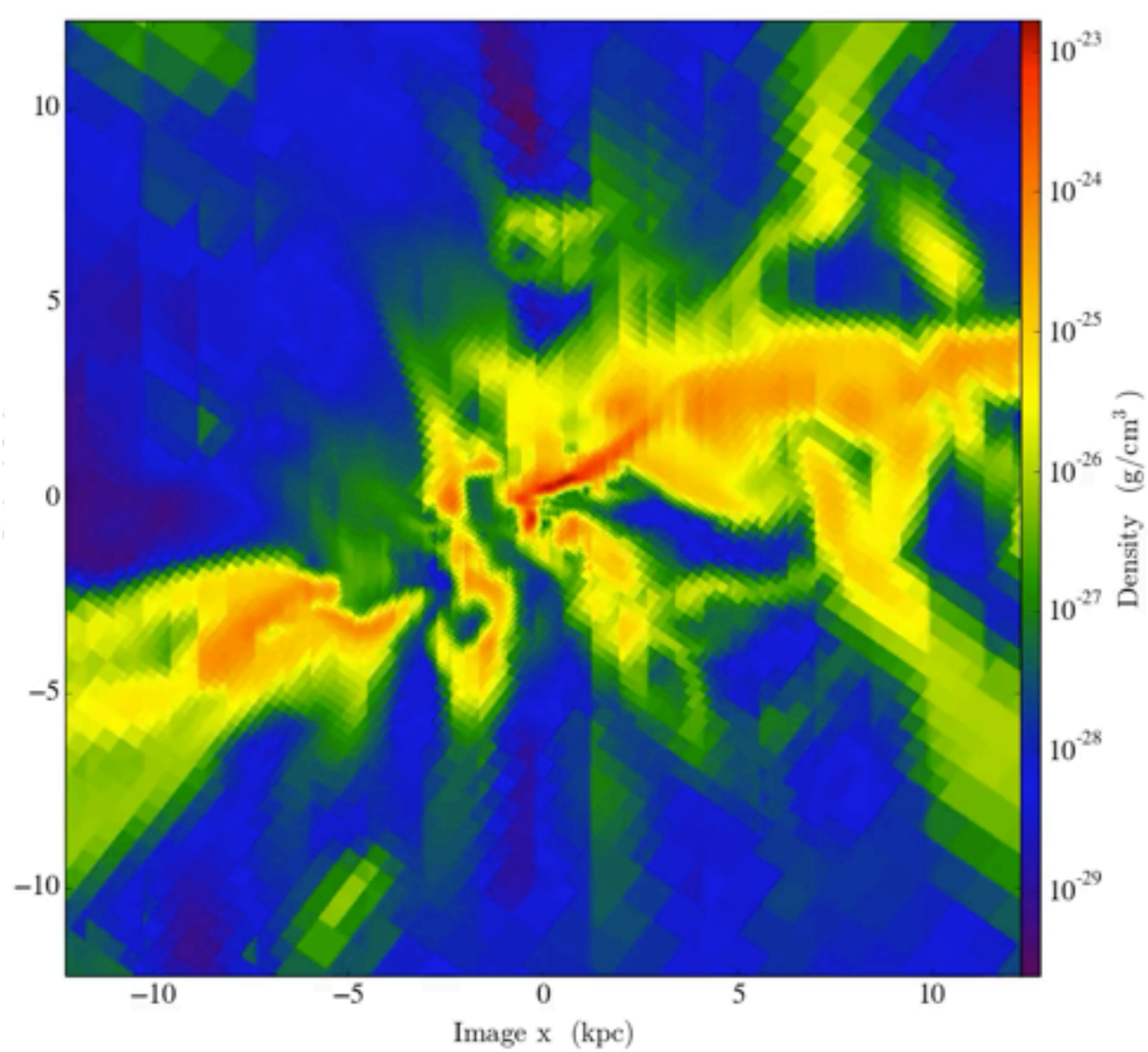
DeGraf et al.

slice through galaxy plane

Radial momentum

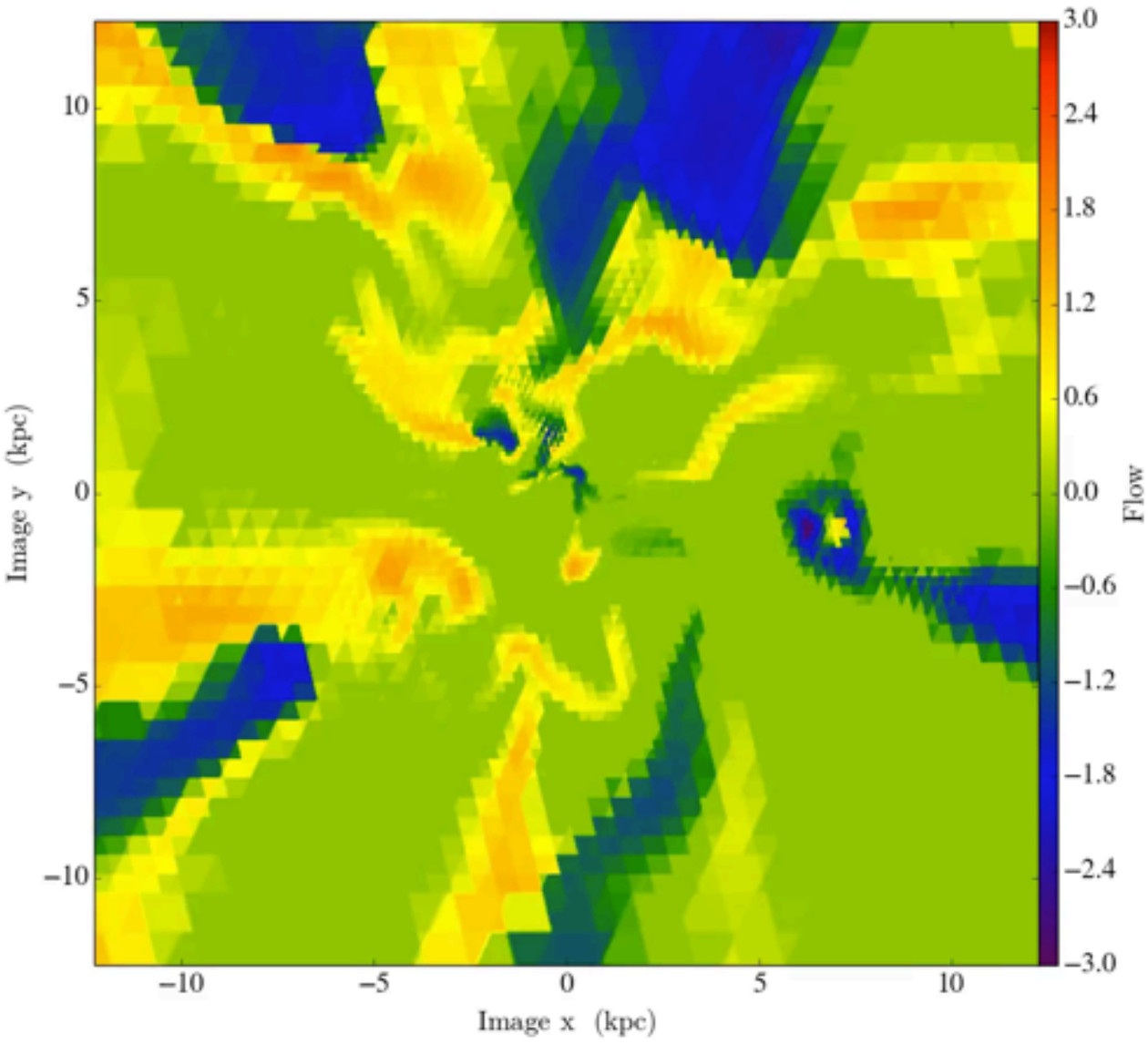
Gas density



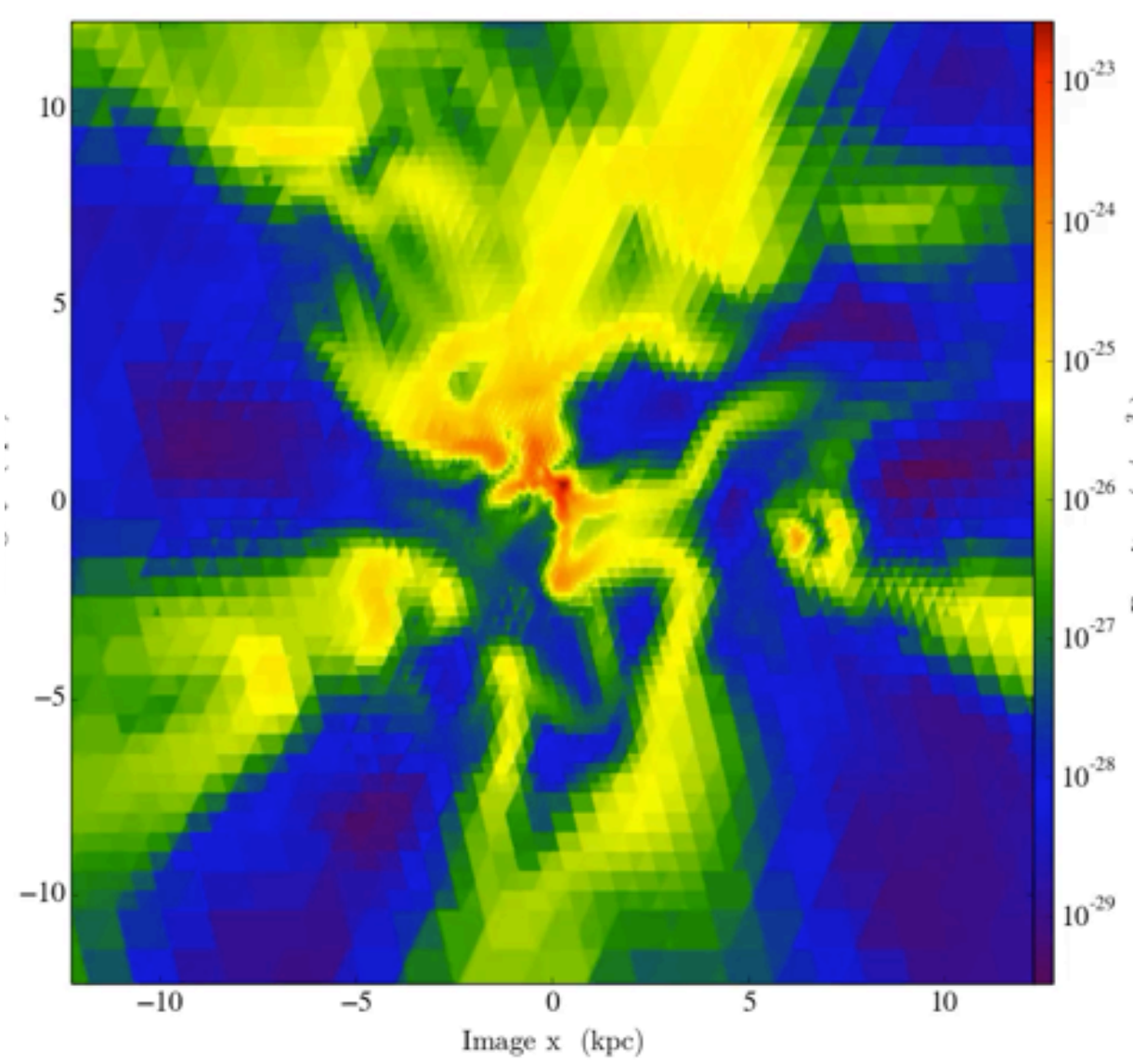


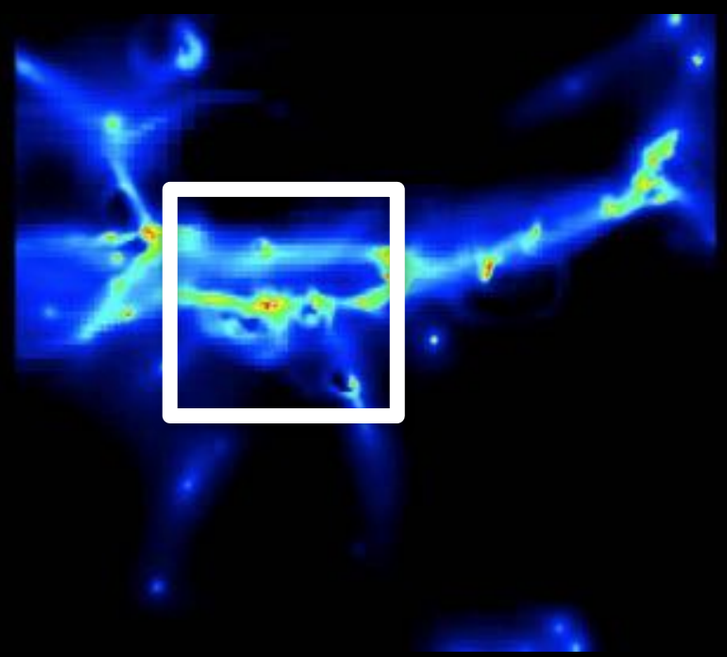
slice perpendicular galaxy

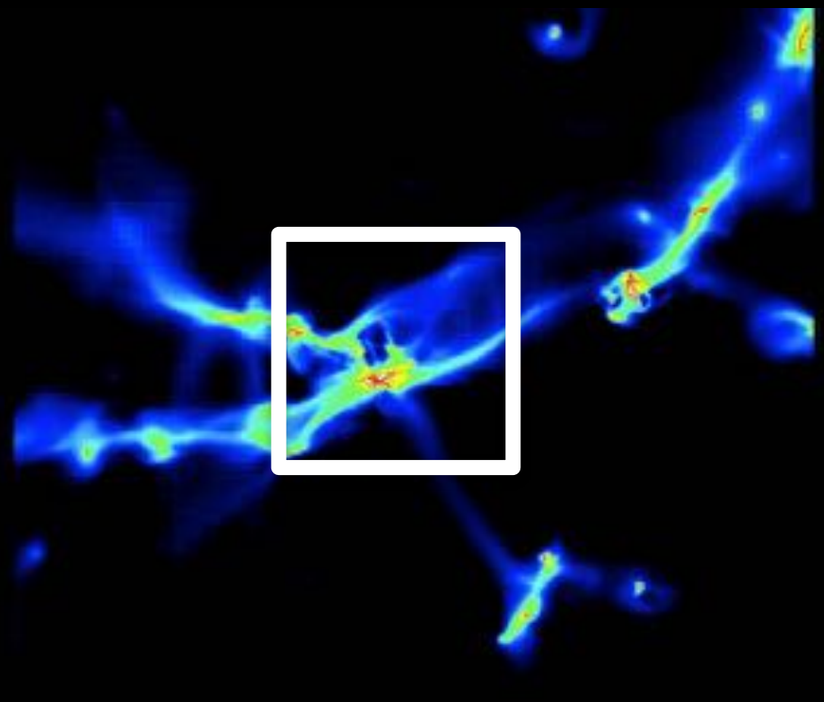
Radial momentum

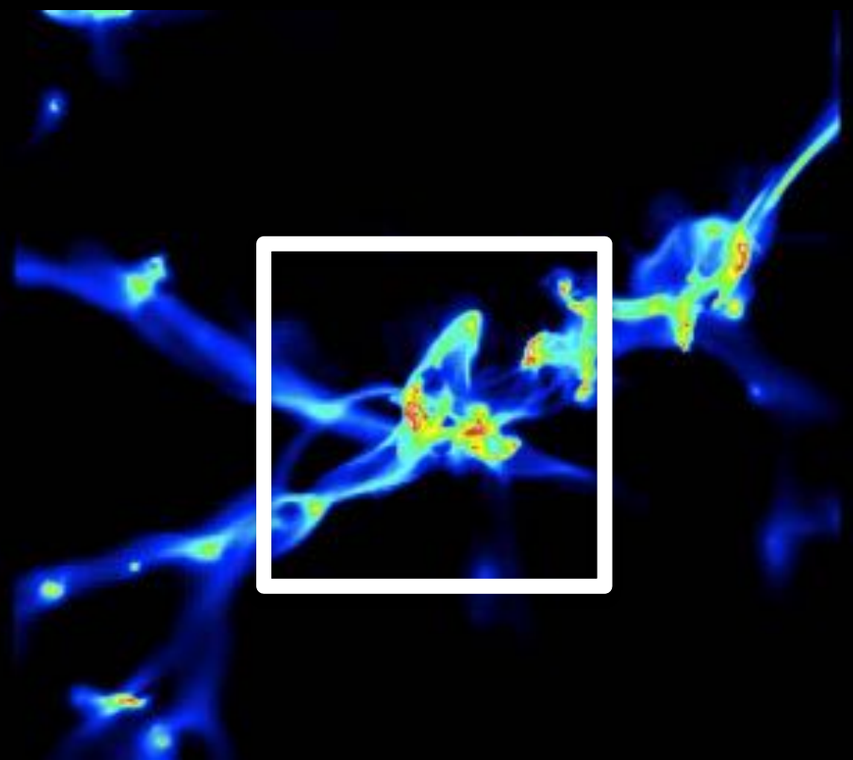


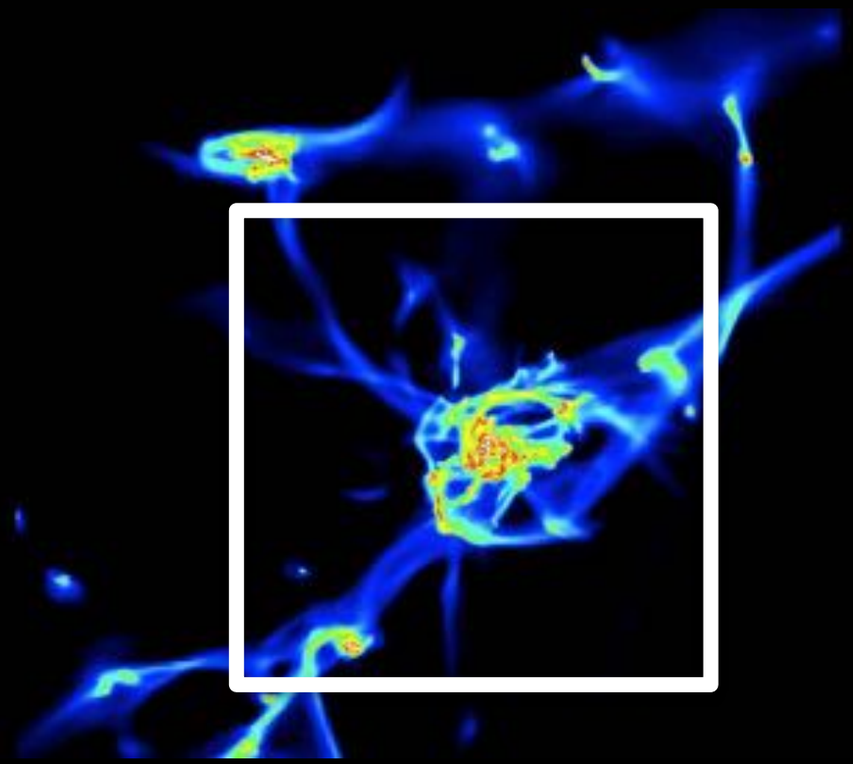
Gas density





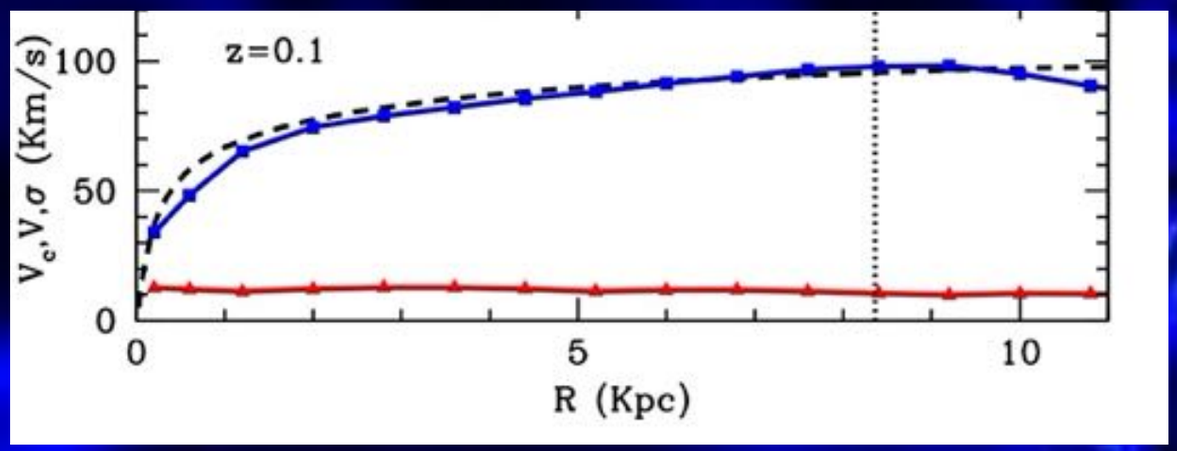






Data: Disc-dominated galaxy at z~0

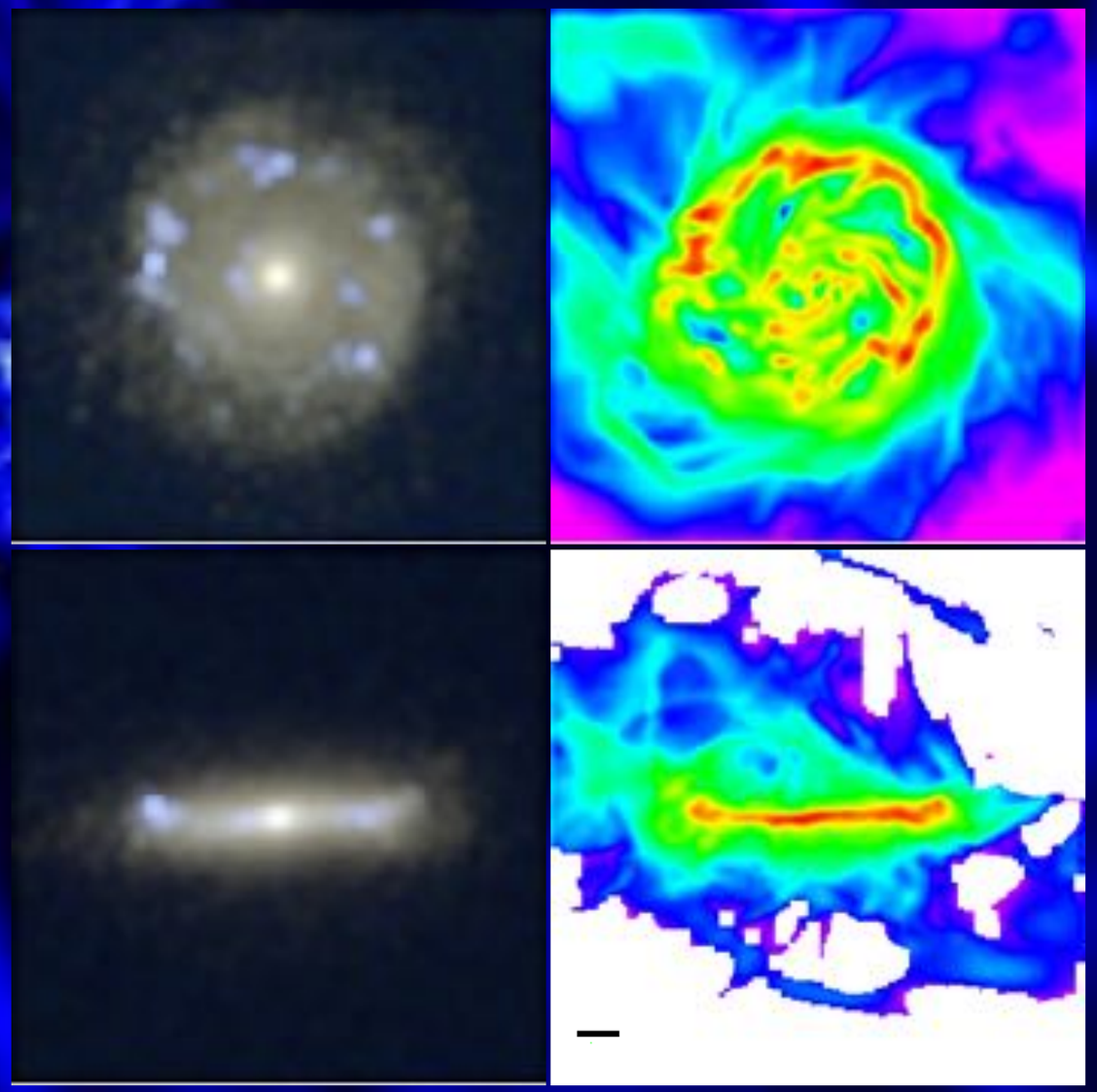
Rotation curve:



Ceverino et al. 2017a

stellar light

gas



40 kpc

List of projects

- 1. Accretion rate onto halos and onto galaxies: DM, gas, stars
- 2. Interaction of cold flows and Disk.
- 3. Angular momentum: in cold flows vs disk
- 4. Basic Structure of galaxies: Density profiles of gas, stars, DM. f_b?
- 5. Kinematics of gas: disk rotation curve, velocity dispersion
- 6. Kinematics of stars: bulge/disk decomposition
- 7. Gas outflows

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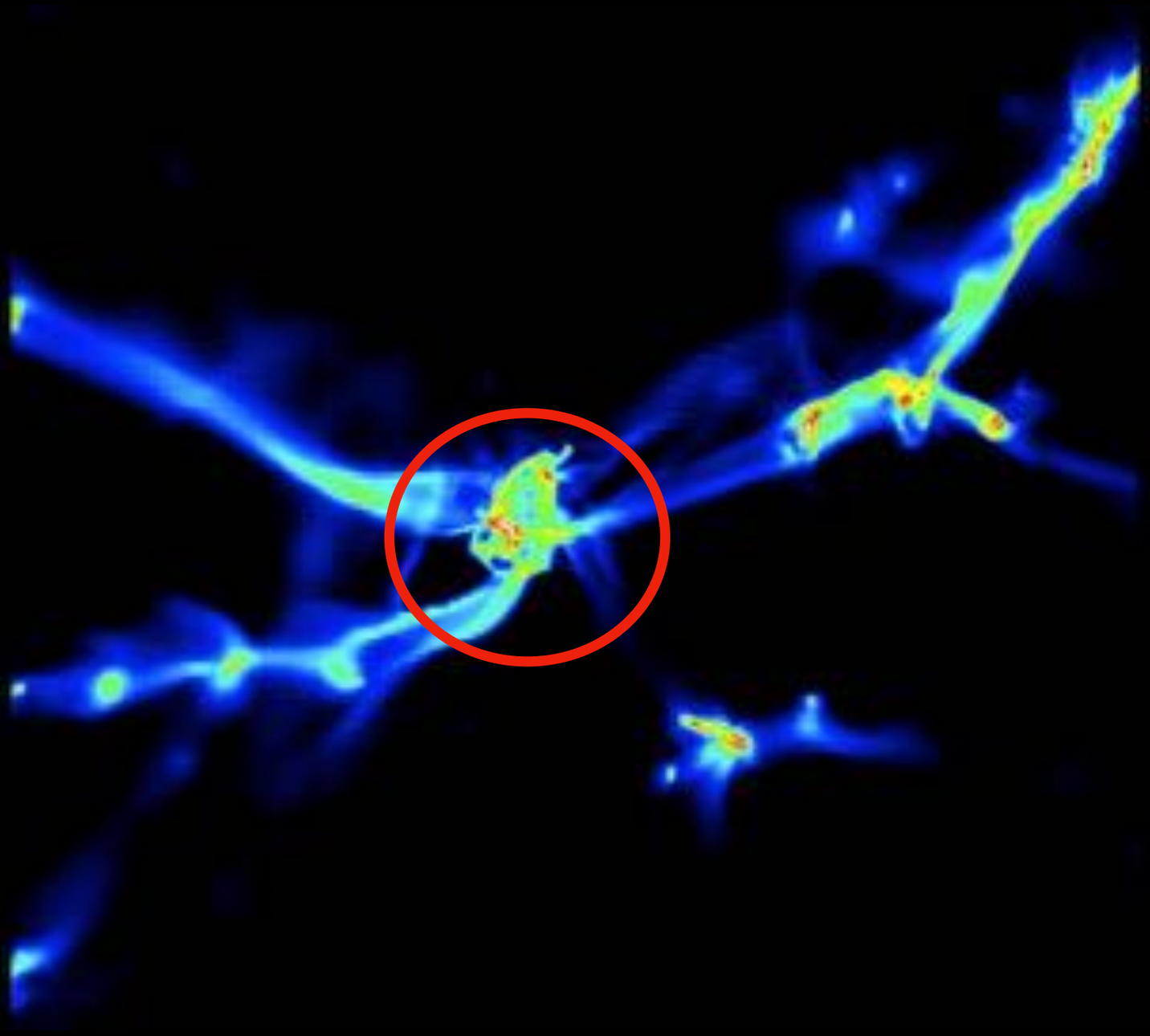

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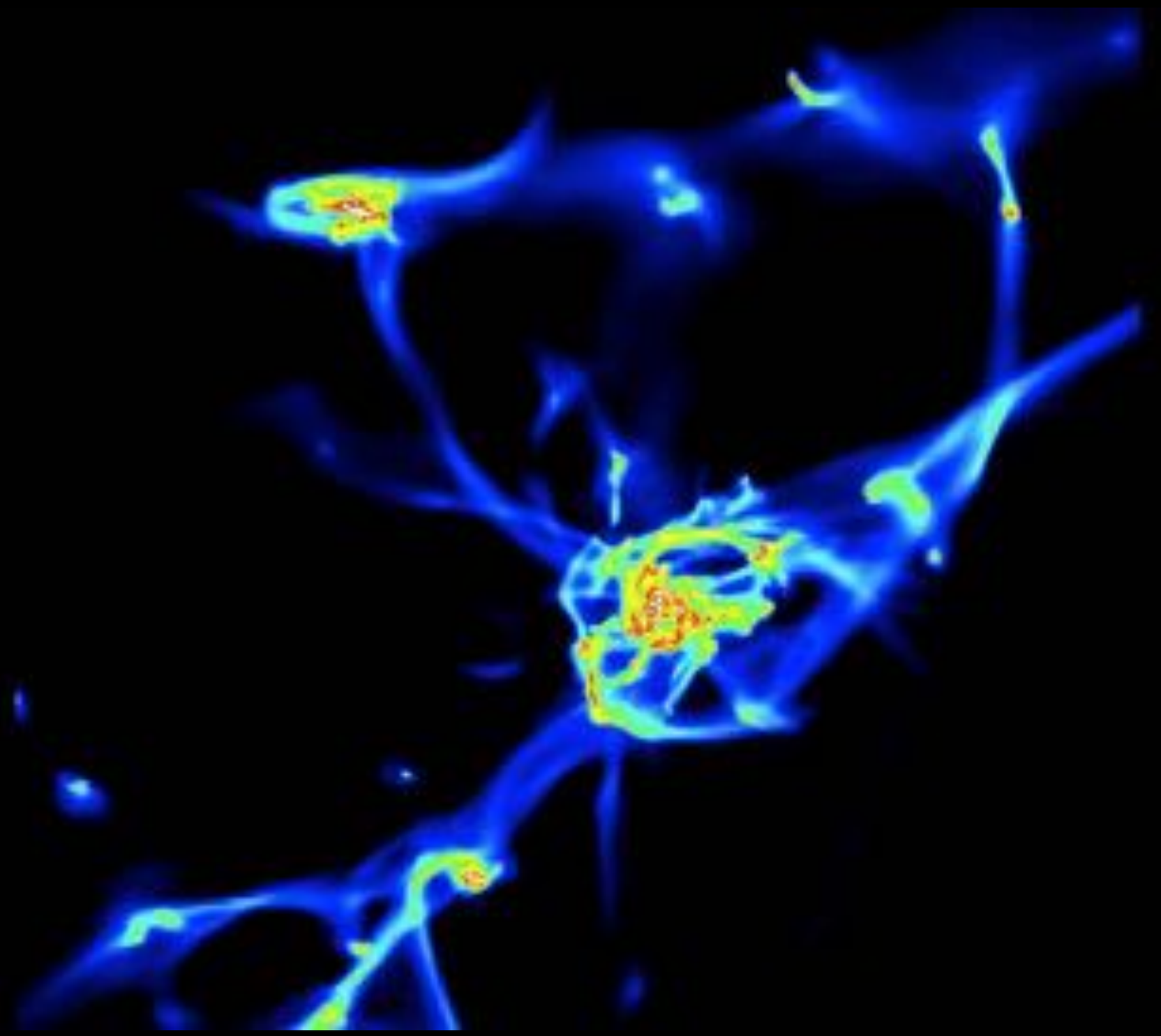

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Angular-momentum buildup in 4 phases

III. inner halo – outer tilted ring
non-linear torques, dissipation
AM loss $\lambda_{cold} \rightarrow 0.04$ & alignment

II. outer halo
AM transport j~const
$\lambda_{cold} \sim 3\lambda_{dm} \sim 0.1$ DM mix

I. cosmic web
linear tidal torques
→ impact parameter
$\lambda_{cold} \sim 1.7\lambda_{dm} \sim 0.3$

IV. inner disc (+bulge)
VDI, outflows
$\lambda_{baryons} \sim 0.03$

spin parameter
$\lambda = (J/M)/(V\sqrt{2}\, R_v V_v)$

Danovich et al. 2015

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```
ceverino@carina:~/MW3> more DataSet_README
Brief description of the outputs from cosmological simulations of galaxy formation
================================================================================
by Daniel Ceverino, Jerusalem, February 2010
================================================================================

These outputs files are binary fortran files that contains all the information inside a box of 4Rvir centered in th
e major progenitor in cosmological simulations of galaxy formation.

Name of the files:
==================

The first part is the name of the simulation.
Next, there are one or two letters that determine the type of data in the file:

*_D* --> ID, Position, velocity and mass for DM particles (8 fields)
*_S* --> ID, Position, velocity, mass and age for stellar particles (9 fields)
*_Si*--> ID, Position, velocity, initial mass and age for stellar particles  (9 fields)
*_SZ*--> ID, Position, velocity, mass, age and SNII, SNIa metals mass fraction for stellar particles (11 fields)
*_G* --> Cell size, position, velocity, density and temperature for gas cells (9 fields)
*_GZ*--> Cell size, position, velocity, density, temperature and SNII, SNIa mass metals fraction for gas cells (11
fields)

Next, there is a number that corresponds to the size of the cutout box. It is always equal to 4 times the virial ra
dius (4Rvir).
Finally, the file ends with the expansion parameter, a=1/(1+z), of the snapshot.
For example, the file 'MW2_0120.a0.200.dat' contains the dark matter information of the major progenitor in simulat
ion 'MW2' at a=0.200 (redshift z=4) inside a box of 120 proper kpc centered in that galaxy.

Physical units:
---------------
Units are always in proper (not comoving) units:

Cell size --> pc
Position --> kpc
Velocity --> km/s
mass --> Msun
age --> Gyr
metals mass fraction --> dimensionless
density --> H atoms / cm^3
temperature --> K

Files format:
-------------
These files are written in fortran binary format (big endian). All fields are single precision floating numbers, wi
th the exception of the fields of positions, velocities and masses for stars and dark matter: They have double-prec
ision. The particle ID number is the only integer field.
```

Three take-home messages

- We are witnessing a rapid development towards a theory of galaxy formation
- Galaxies are crossroads for physics at different scales
- Research is fun

THANKS