Numerical Simulations of physical processes driving galaxy evolution

Lecture 3: Simulation Types

Rhea-Silvia Remus

Canary Islands Winter School, 26.11.2021

Disclaimer

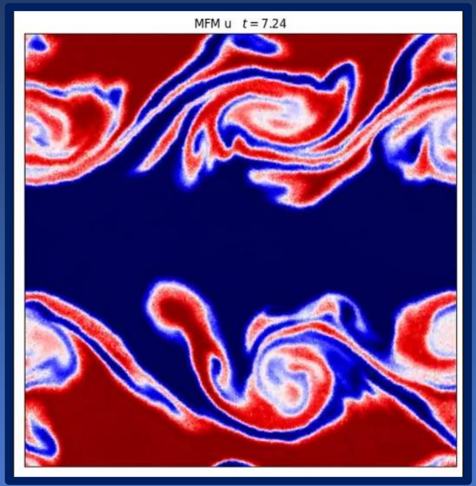
This lecture was designed for presentation with movie media. If no specific URL is provided, movies can be found at

www.usm.uni-muenchen.de/~rhea/teaching/movies

Movies are marked by a *

Summary: Computational Methods

Smooth Particle Hydrodyn.

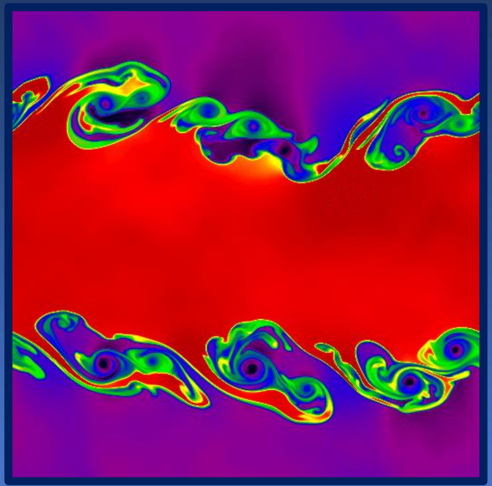


Courtesy
M. Niemeyer, K. Dolag

- ✓ Very good conservation properties (mass, momentum, total energy, angular momentum, entropy)
- ✓ shape invariant

- Instabilities do not grow sufficiently
- Mixing behind shocks not sufficient
- Shocks captured by artificial viscosity

Adaptive Mesh Refinement

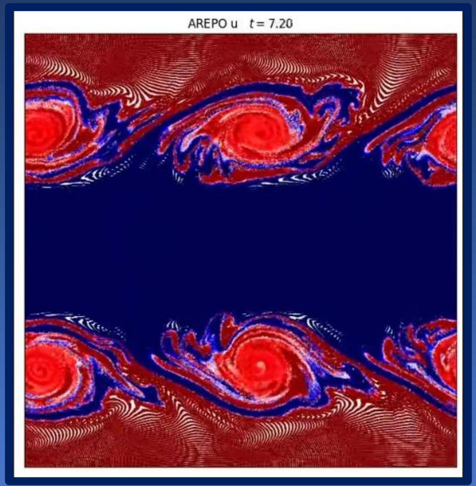


https://www.astro.princeton.edu/~jstone/Athena/tests/kh/kh.html

- ✓ Instabilities nicely grow
- ✓ Mixing between phases works well

- Energy conservation issues (especially for fast moving elements)
- Flow over cell boundaries becomes an issue for adaptive meshs
- Not shape invariant

Moving Mesh



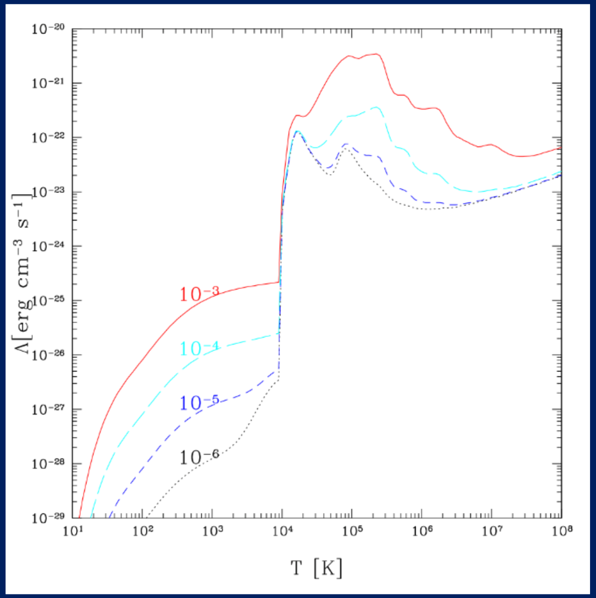
Courtesy
M. Niemeyer, K. Dolag

- ✓ All good things from the other two

- Flow over cell boundaries (only pseudo-Lagrangian)

Summary: Including Physics

Cooling



Maio et al., 2007

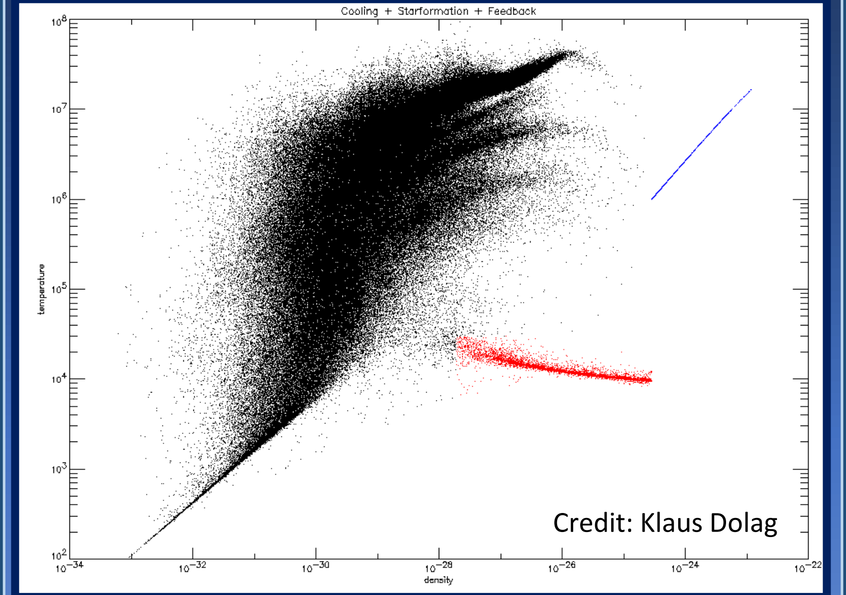
Basic Assumption:

- Optically thin
- Ionization equilibrium (H, H^+, He, He^+, He^{++},e^-)
- 2-body processes ($\sim n^2$)

$\Lambda(T)/n^2$

BUT: Cooling Catastrophe

Star Formation

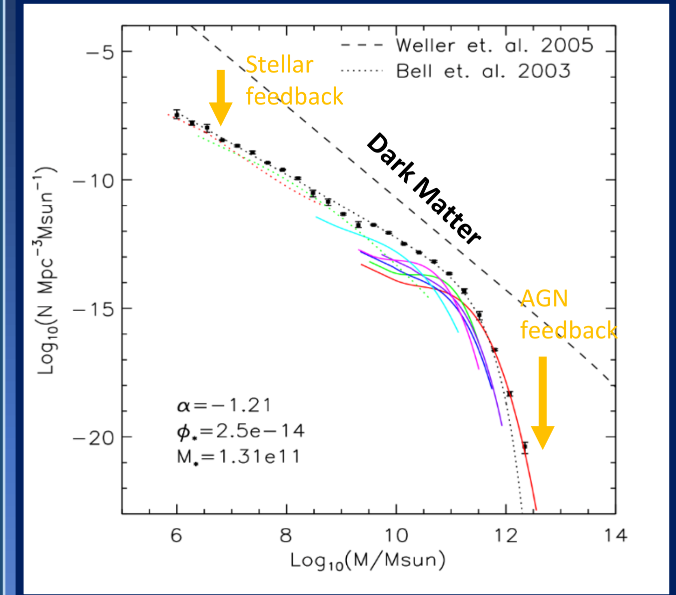


Star formation subgrid model:

- Self-regulated star formation
- Set of differential equations needs to be solved.
- Produces reasonable galaxies at low z

BUT: star formation rates at high z not captured

Feedback



Read & Trentham 2005

Feedback comes from two different sources:

- Massive Stars and Supernovae
- Supermassive Black Holes (AGN)

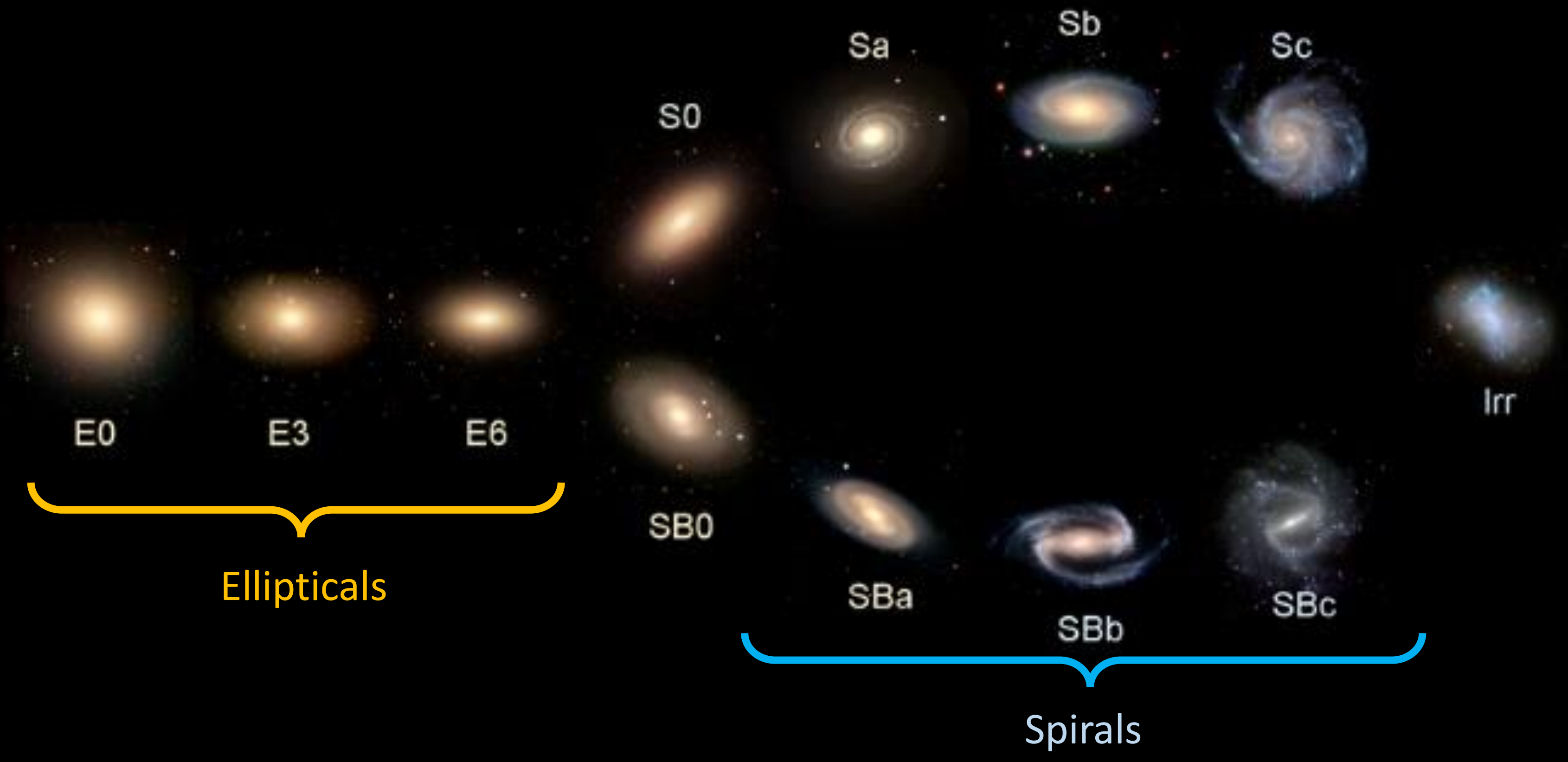
Stops the Overcooling Catastrophe

BUT: Burns holes into disks

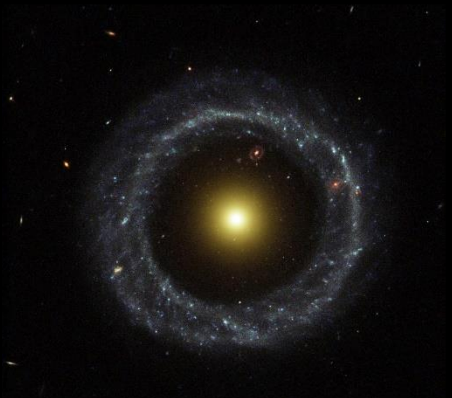
Making Galaxies
(and (Proto)-Clusters)

Introduction: why do we care about galaxies?

Galaxies come in many different flavours, not just the well known regular shapes but a multitude of distorted features that need to be explained



NASA, ESA & The Hubble Heritage Team (STScI/AURA)



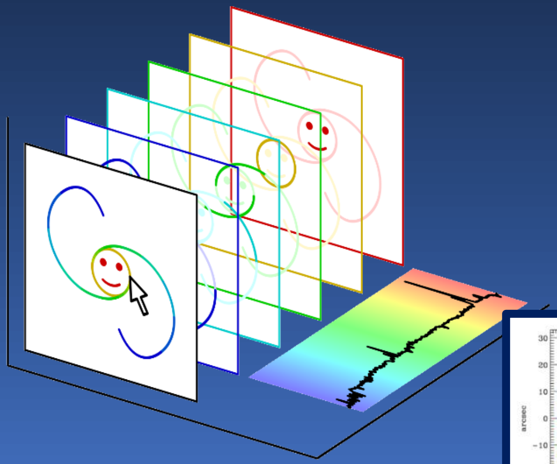
P.-A. Duc (CEA,CFHT) & Atlas3D

ESO/VMC Survey

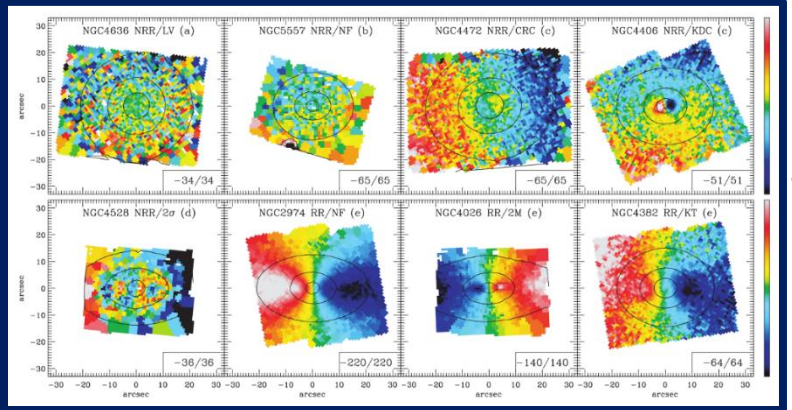
NASA, ESA & The Hubble Heritage Team

Edwin Hubble’s Galaxy Classification

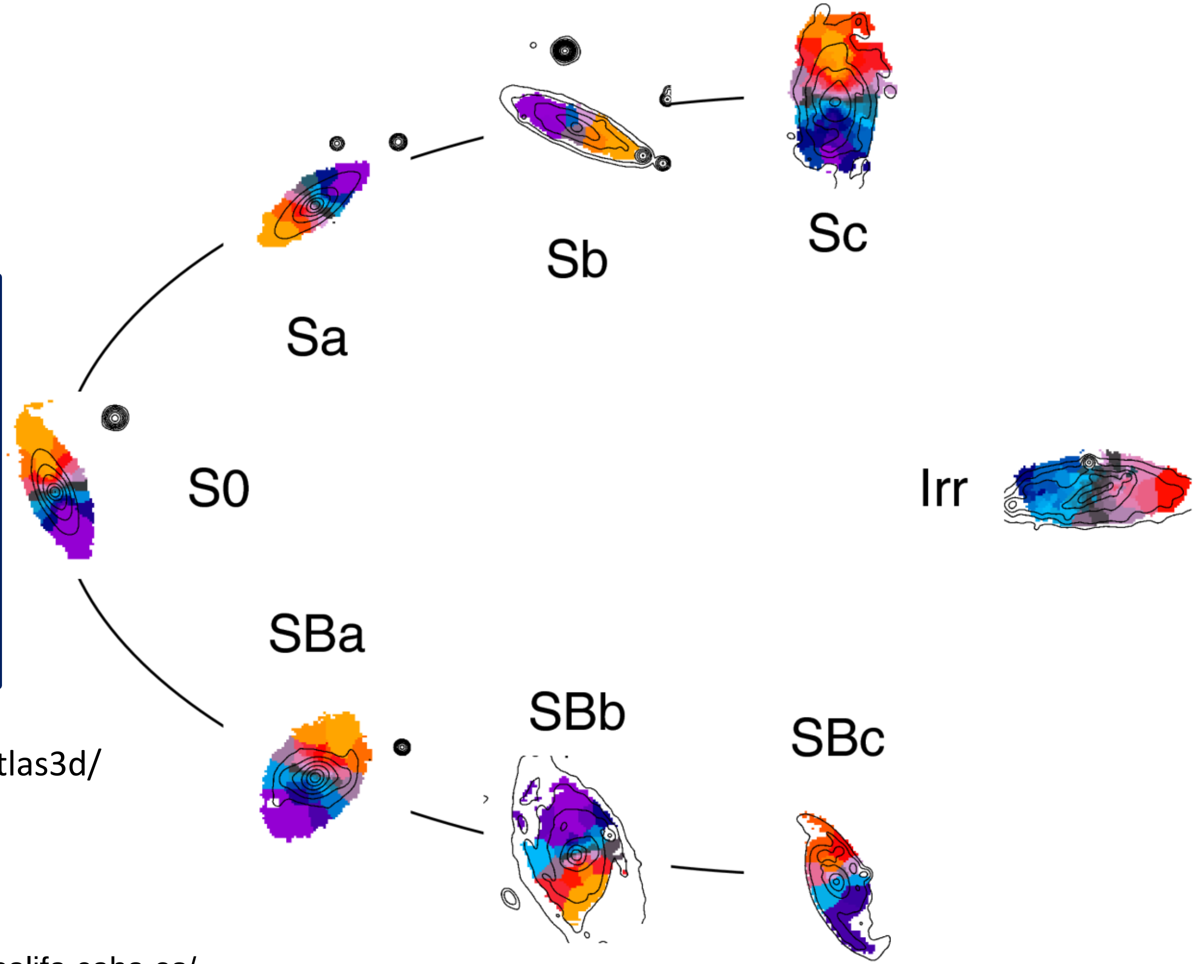
Introduction: why do we care about galaxies?



With the advent of Integral Field Spectroscopy, the features known to exist in galaxies were multiplied especially in the realm of quiescent galaxies

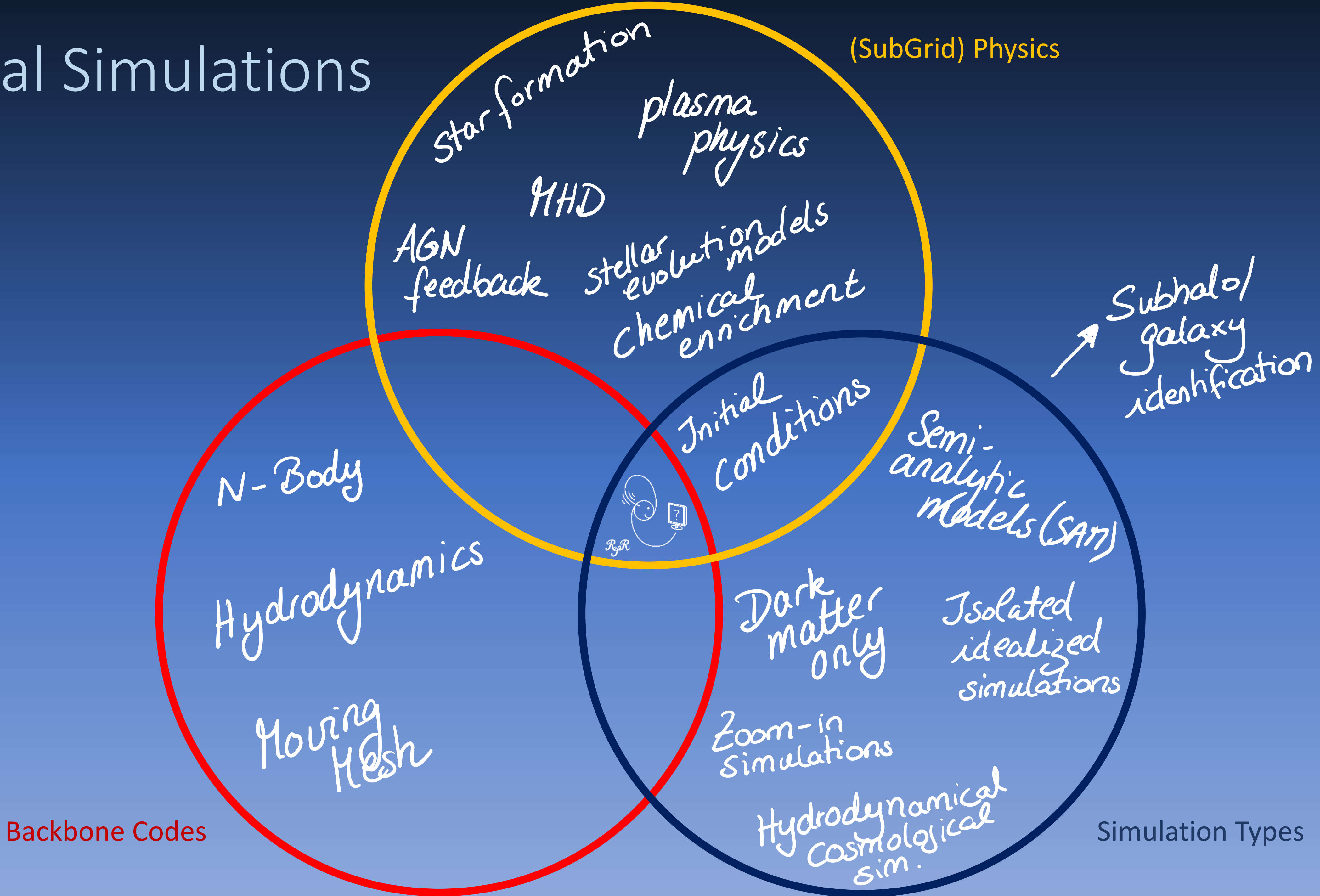


Atlas^{3D} Survey: https://www-astro.physics.ox.ac.uk/atlas3d/



Pictures from the CALIFA survey: http://califa.caha.es/

Numerical Simulations



Quiz

When was the first simulation of two merging galaxies performed?

1. 1941
2. 1972
3. 1985
4. 2001

Quiz

When was the first simulation of two merging galaxies performed?

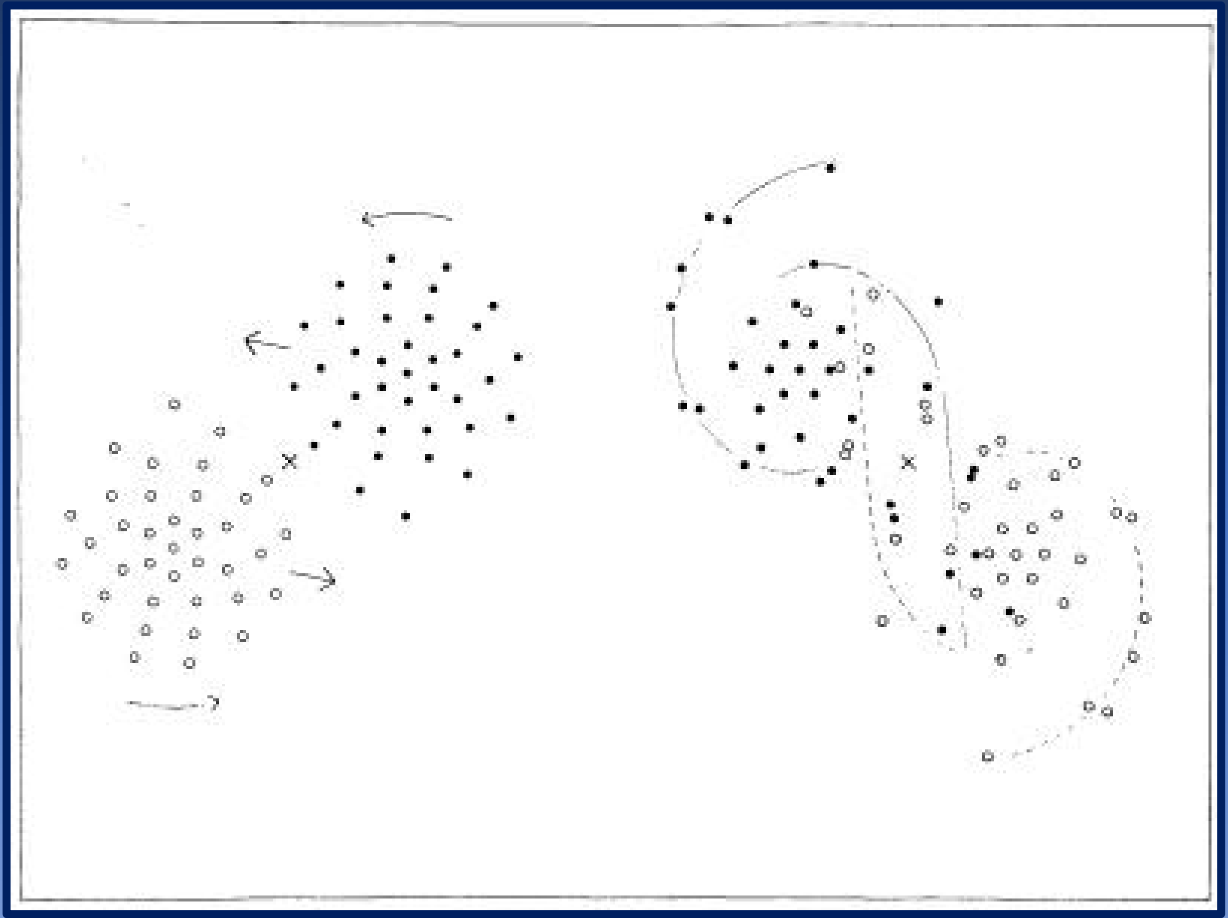
1. 1941
2. 1972
3. 1985
4. 2001

First Simulation

1941: Erik Holmberg performed a merger of two galaxies using Light Bulbs. He calculated the acceleration by integrating the light at a given position with a photocell.

Gravity: Acceleration $a = \frac{G\,M}{r^2} \propto \frac{1}{r^2}$

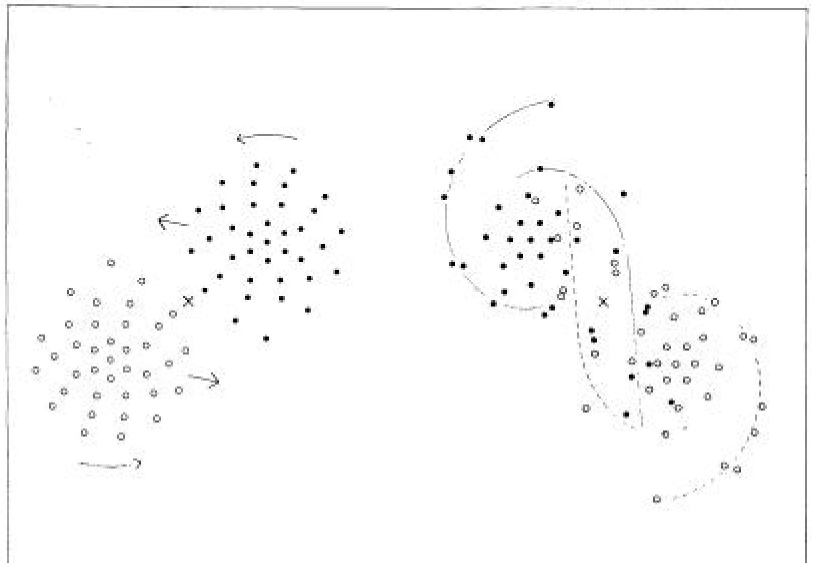
Light: Flux $F = \frac{L}{4\pi r^2} \propto \frac{1}{r^2}$



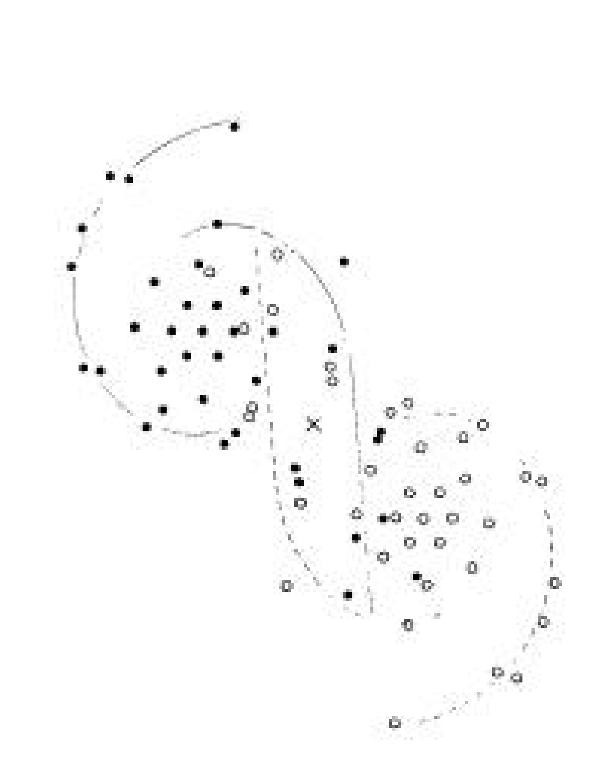
Holmberg 1941

First Simulation

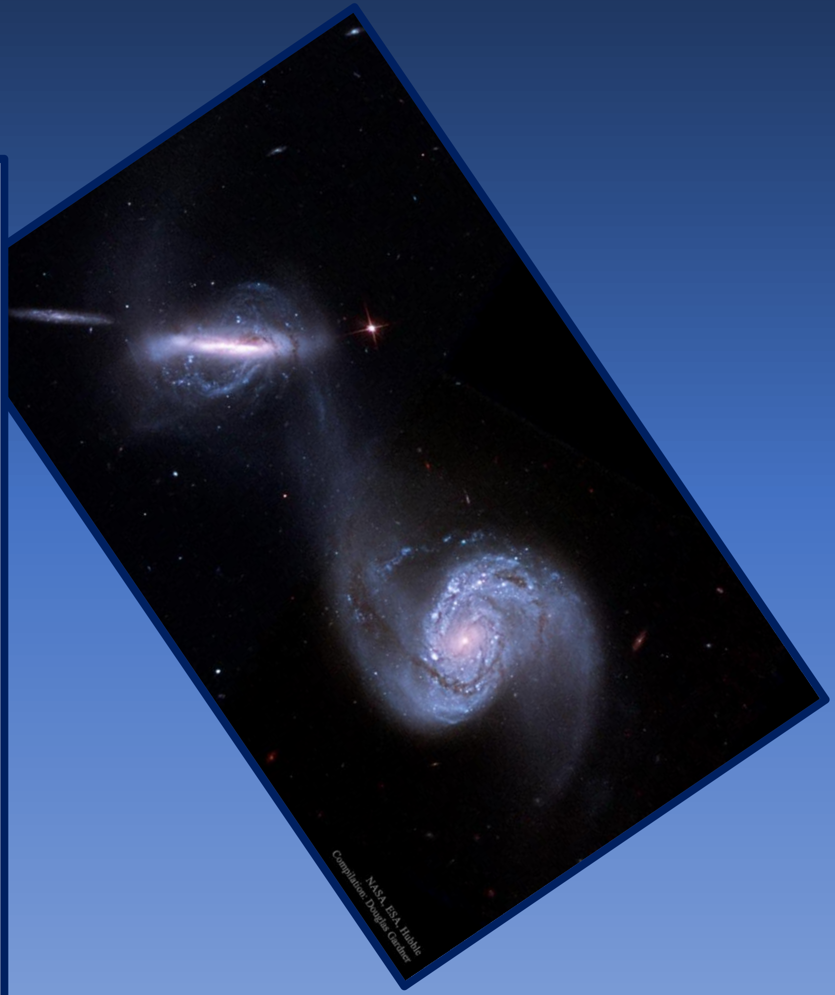
1941: Erik Holmberg performed a merger of two galaxies using Light Bulbs. He calculated the acceleration by integrating the light at a given position with a photocell



Holmberg 1941



Holmberg 1941

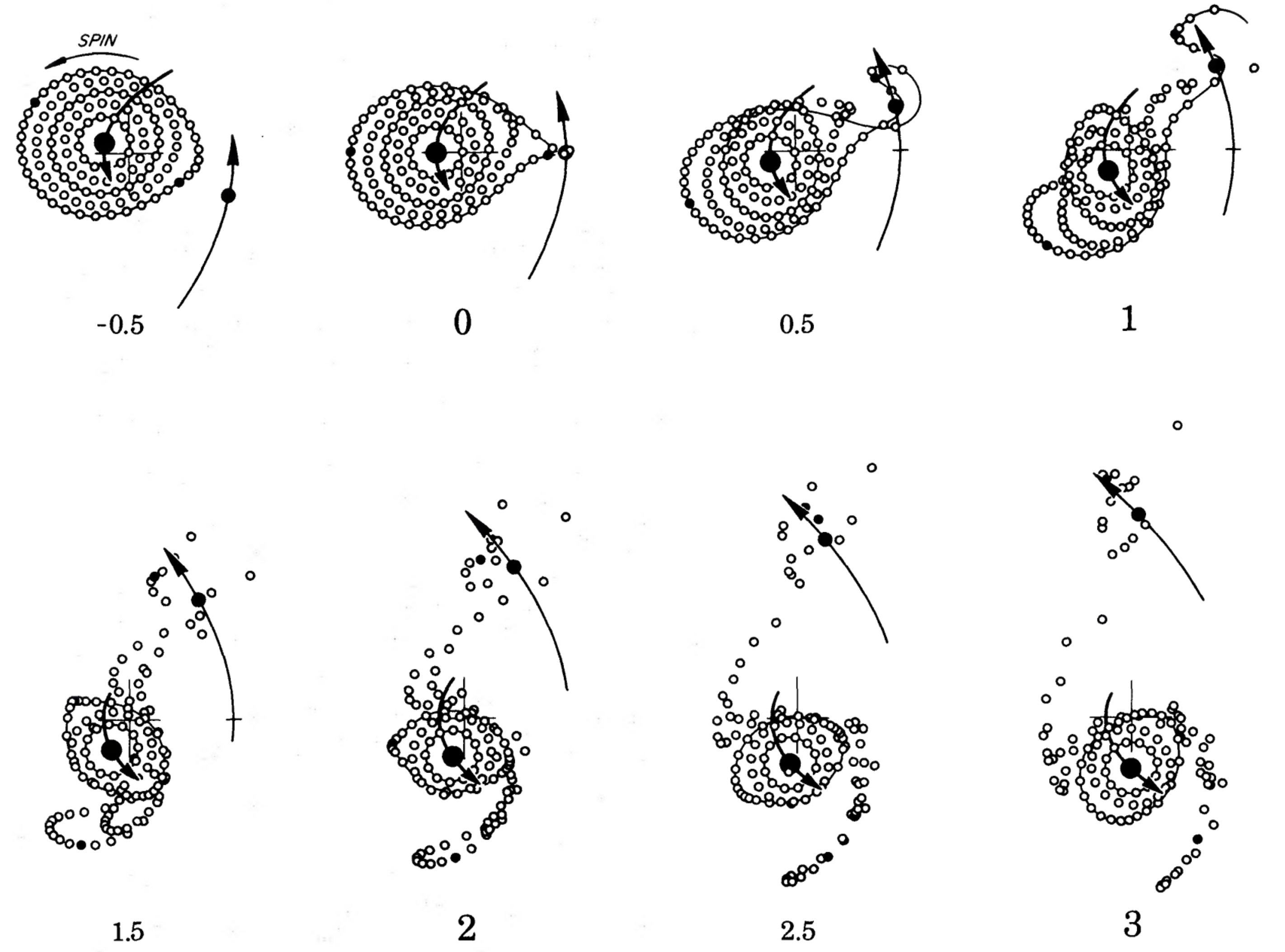


Next one: Toomre and Toomre

30 years later….

Galactic Bridges and Tails
by Toomre & Toomre, 1972

A simple fly-by already can make arms and tidal tails



Toomre & Toomre 1972

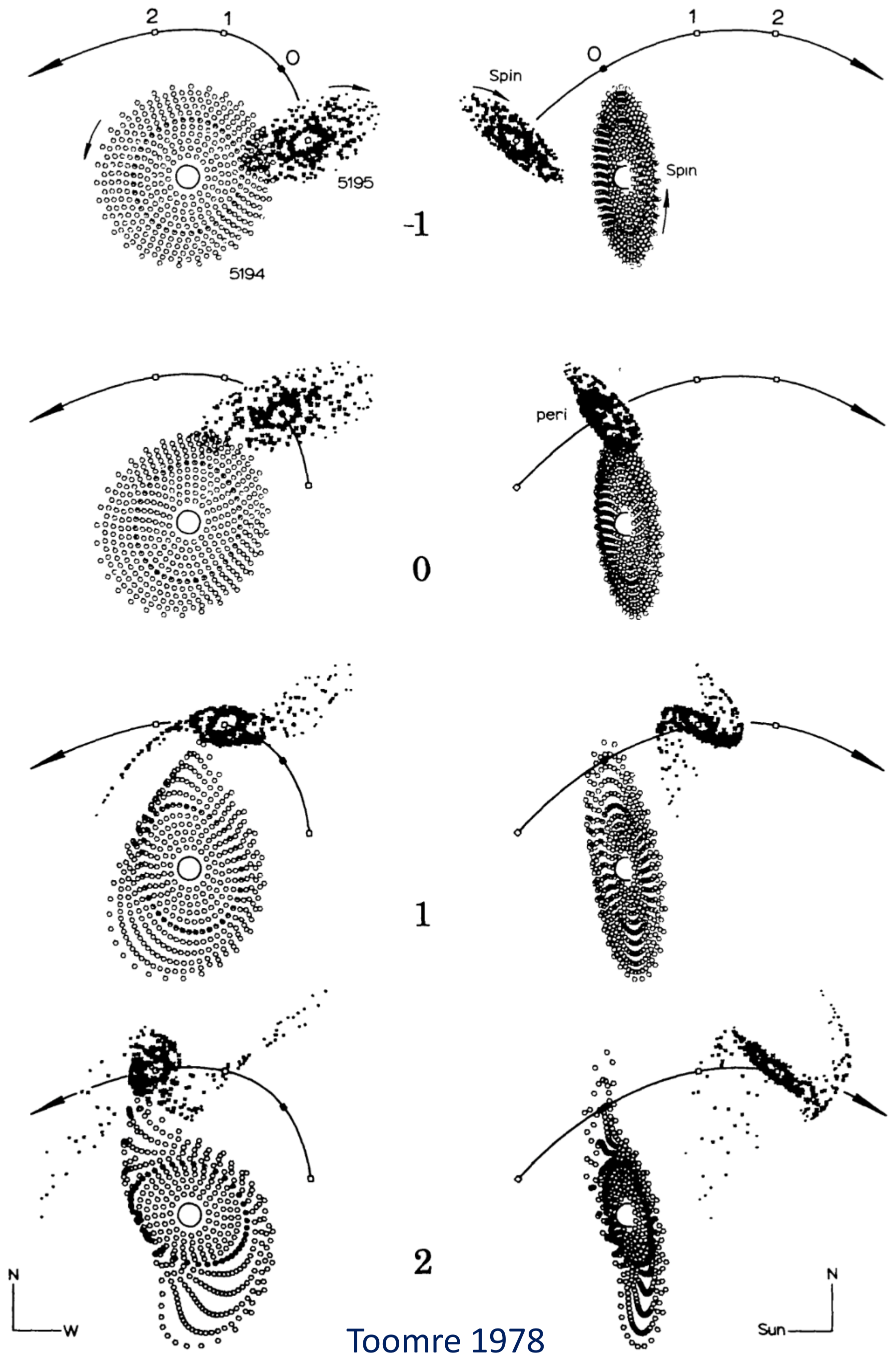
N-Body Simulations

30 years later….

Galactic Bridges and Tails

by Toomre & Toomre, 1972

M51: Image credit: X-ray: NASA/CXC/SAO; Optical: Detlef Hartmann; Infrared: NASA/JPL-Caltech



Toomre 1978

N-Body Simulations

30 years later….

Galactic Bridges and Tails

by Toomre & Toomre, 1972

N-Body Simulations

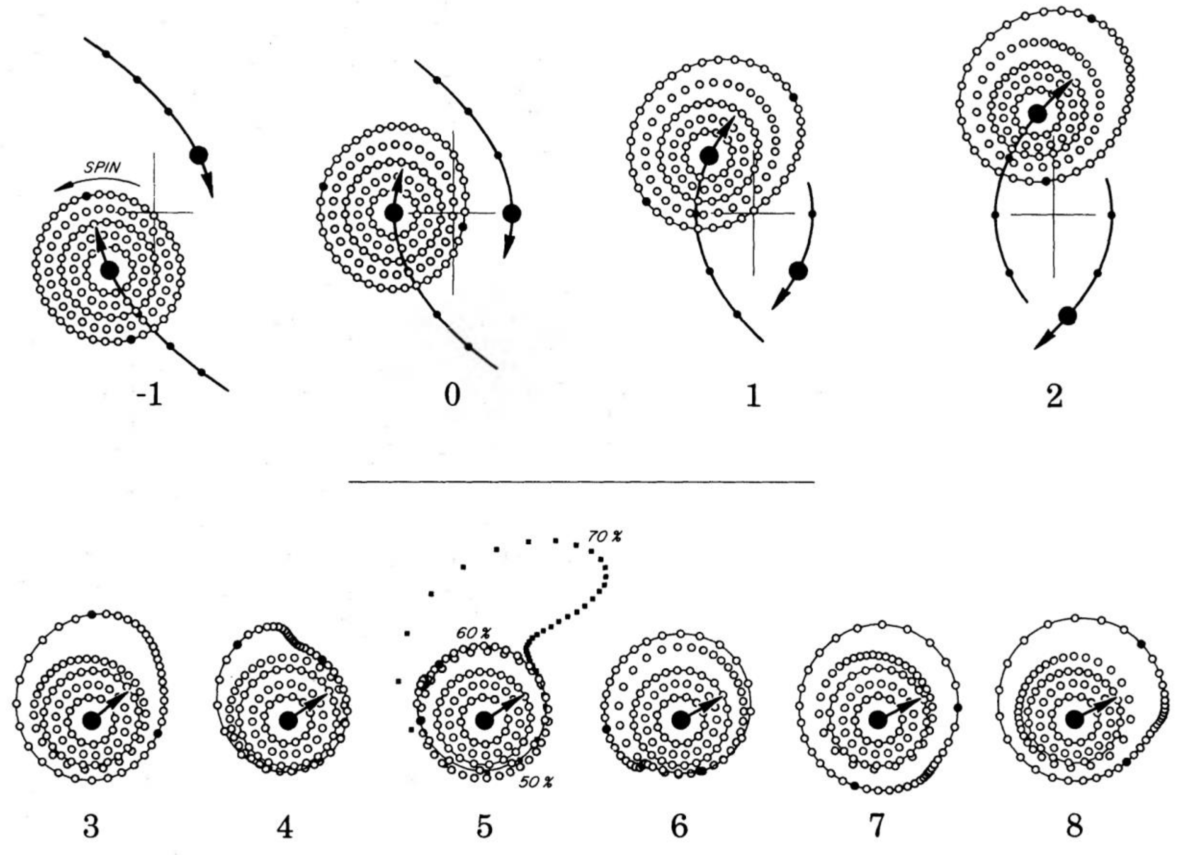
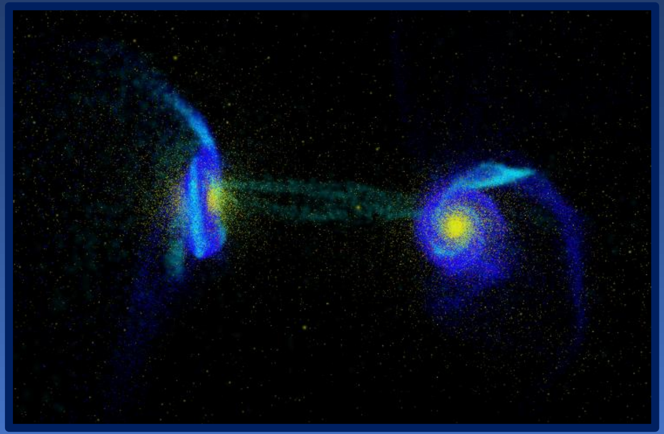


FIG. 1.—A flat retrograde ($i = 180°$) parabolic passage of a companion of equal mass. The two small filled circles denote test particles from the $0.6R_{min}$ ring which, in the absence of the encounter, would have reached positions exactly to the right and left of the victim mass at $t = 0$. The filled squares at $t = 5$ depict additional test particles from $0.7R_{min}$. (Note the partial interpenetrations of the outermost rings at $t = 4$, 5, and 6, and their continuing oscillations thereafter.)

Toomre & Toomre 1972

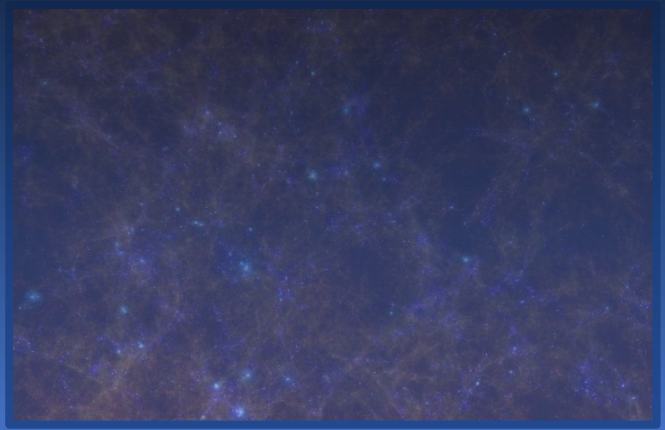
Overview: Galaxy Formation Simulations

Isolated Merger Simulations



Cosmological Zoom-Simulations

Cosmological Box Simulations



Isolated (Binary Merger) Simulations

Artificially set up galaxies with defined mass distributions.

Set two (or more) on a collision orbit with clearly defined orbital parameters (controlled initial conditions).

Isolated (Binary Merger) Simulations

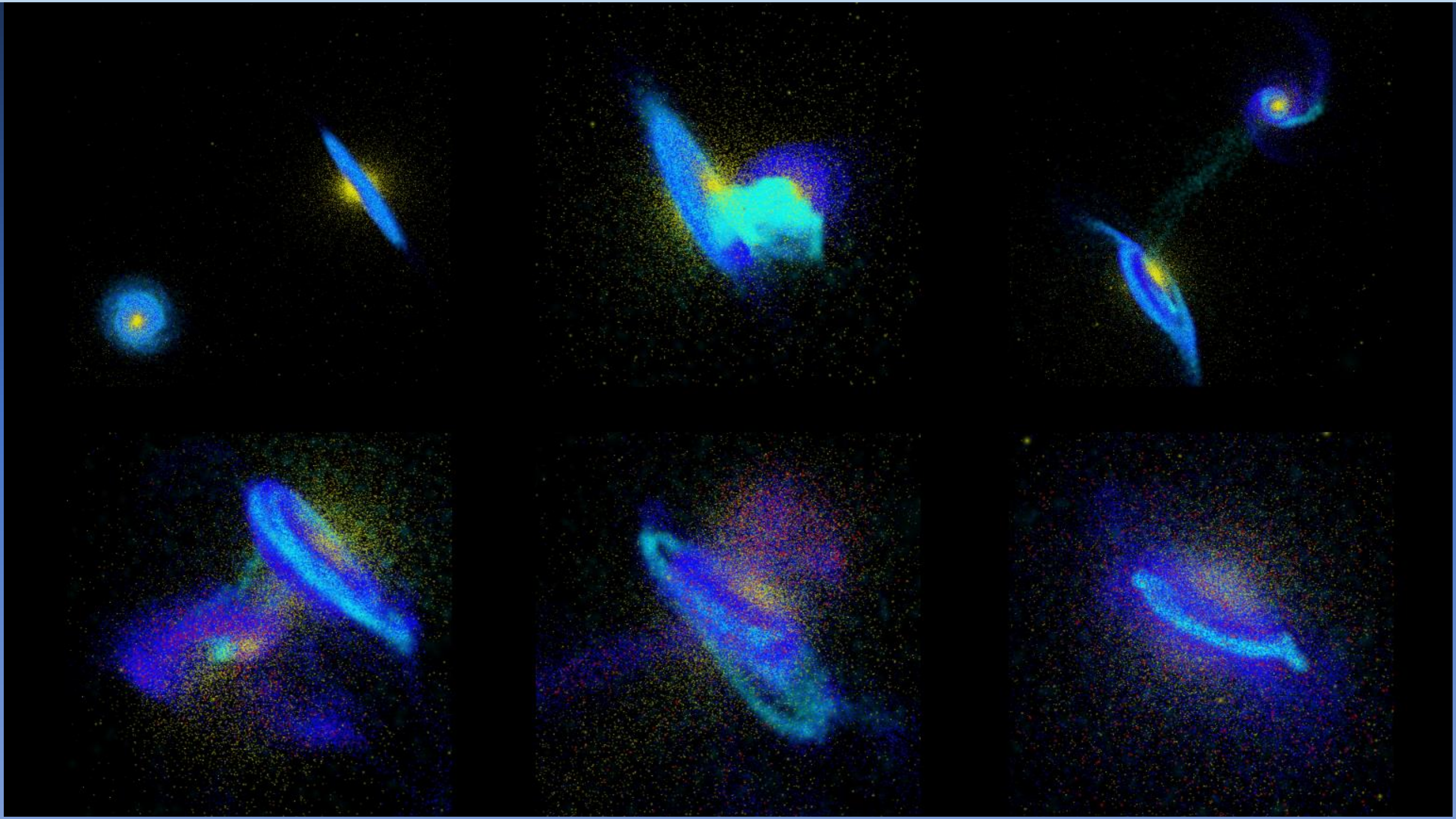


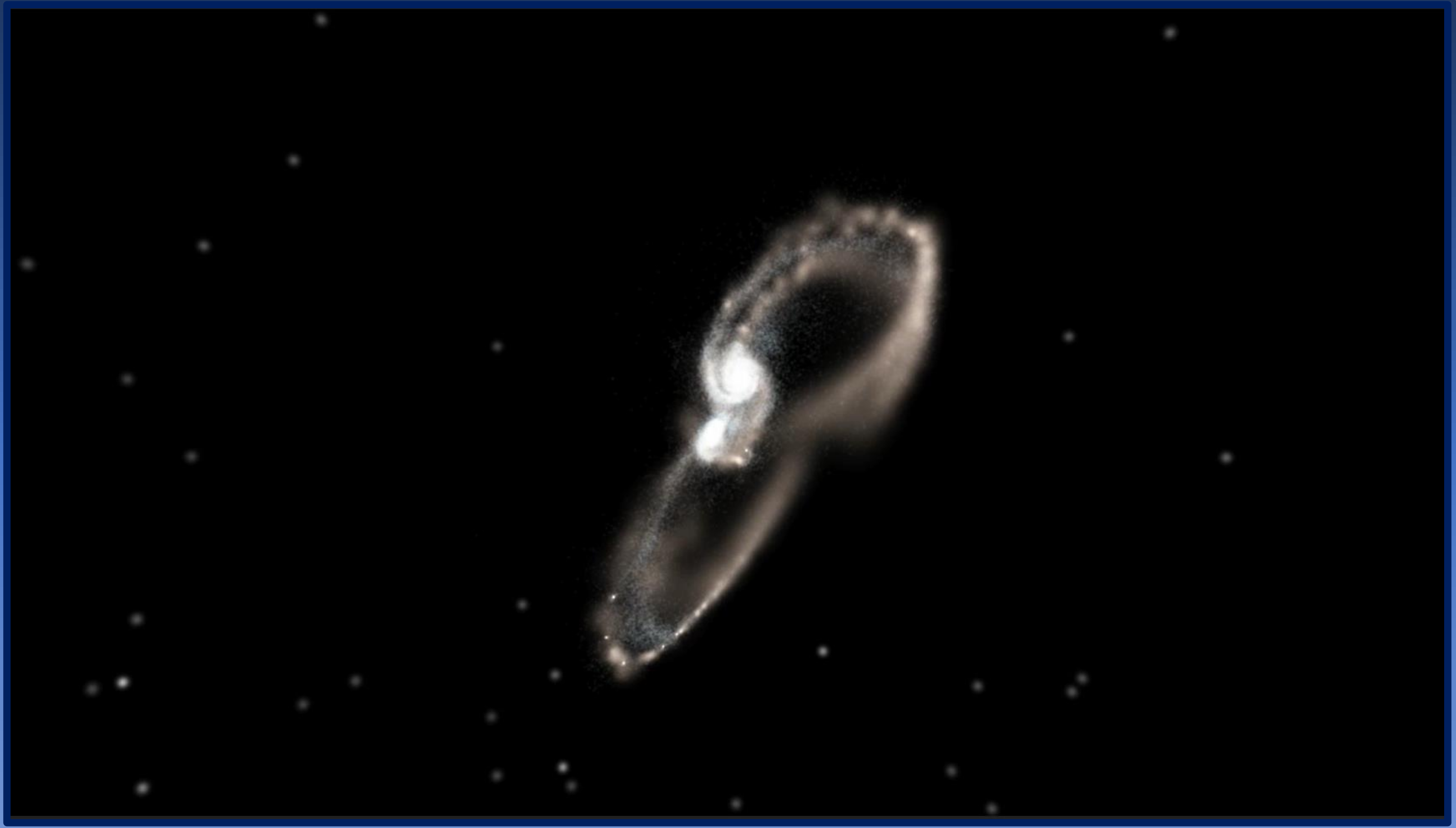
Image: Rhea-Silvia Remus

Isolated (Binary Merger) Simulations

*

Artificially set up galaxies with defined mass distributions.

Set two (or more) on a collision orbit with clearly defined orbital parameters



Credit: Credit: Frank Summers
http://www.tapir.caltech.edu/~phopkins/Site/animations/Mergers/sims-versus-observations.html

Evolution of simulating the Antennae Galaxies

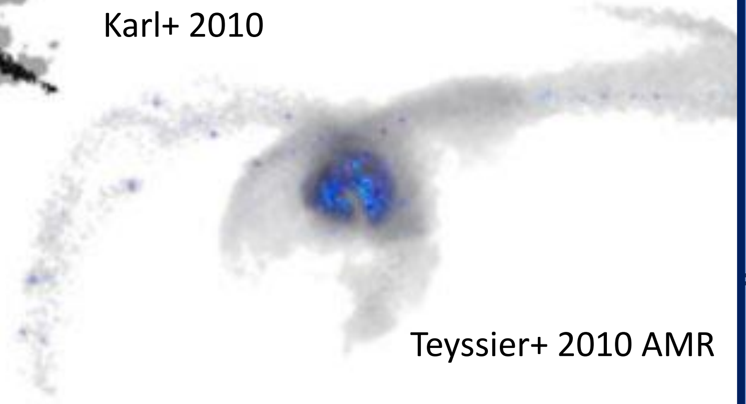
Image Data: Subaru, NAOJ, NASA/ESA/Hubble, R.W. Olsen - Processing: Federico Pelliccia and Rolf Wahl Olsen (APOD)

Toomre & Toomes 1972

Barnes 1988

Mihos+ 1993

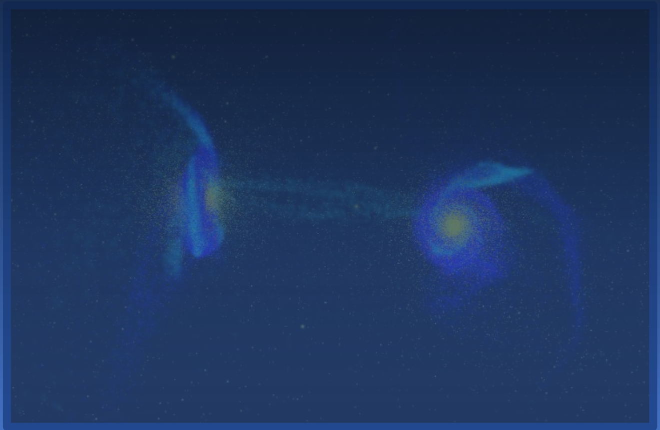
Karl+ 2010



Teyssier+ 2010 AMR

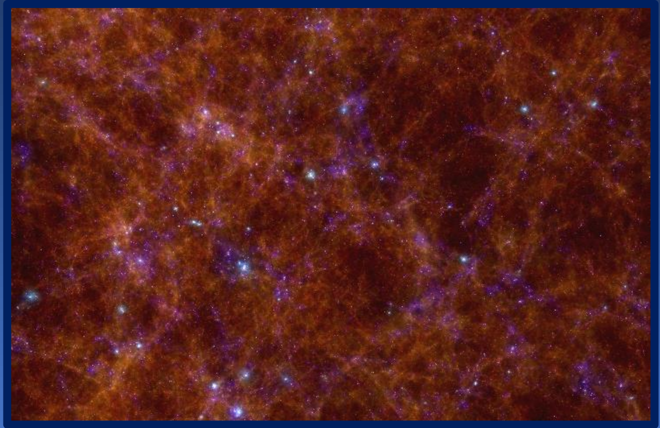
Overview: Galaxy Formation Simulations

Isolated Merger Simulations



Cosmological Zoom-Simulations

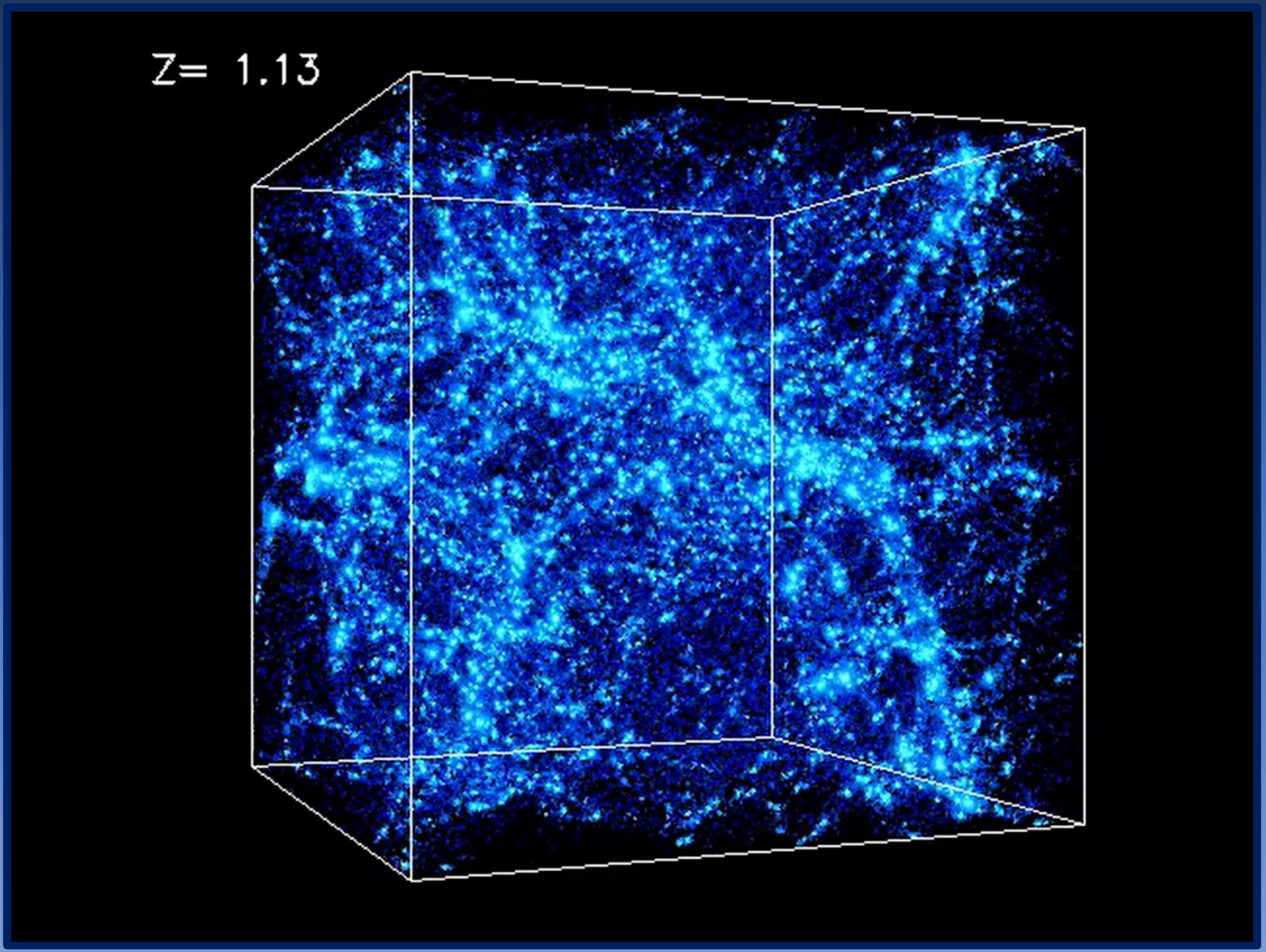
Cosmological Box Simulations



Cosmological Simulations

Simulate a full universe starting with dark matter and gas in a cubic volume.

Galaxies form due to initial perturbations – you have to take what you get.



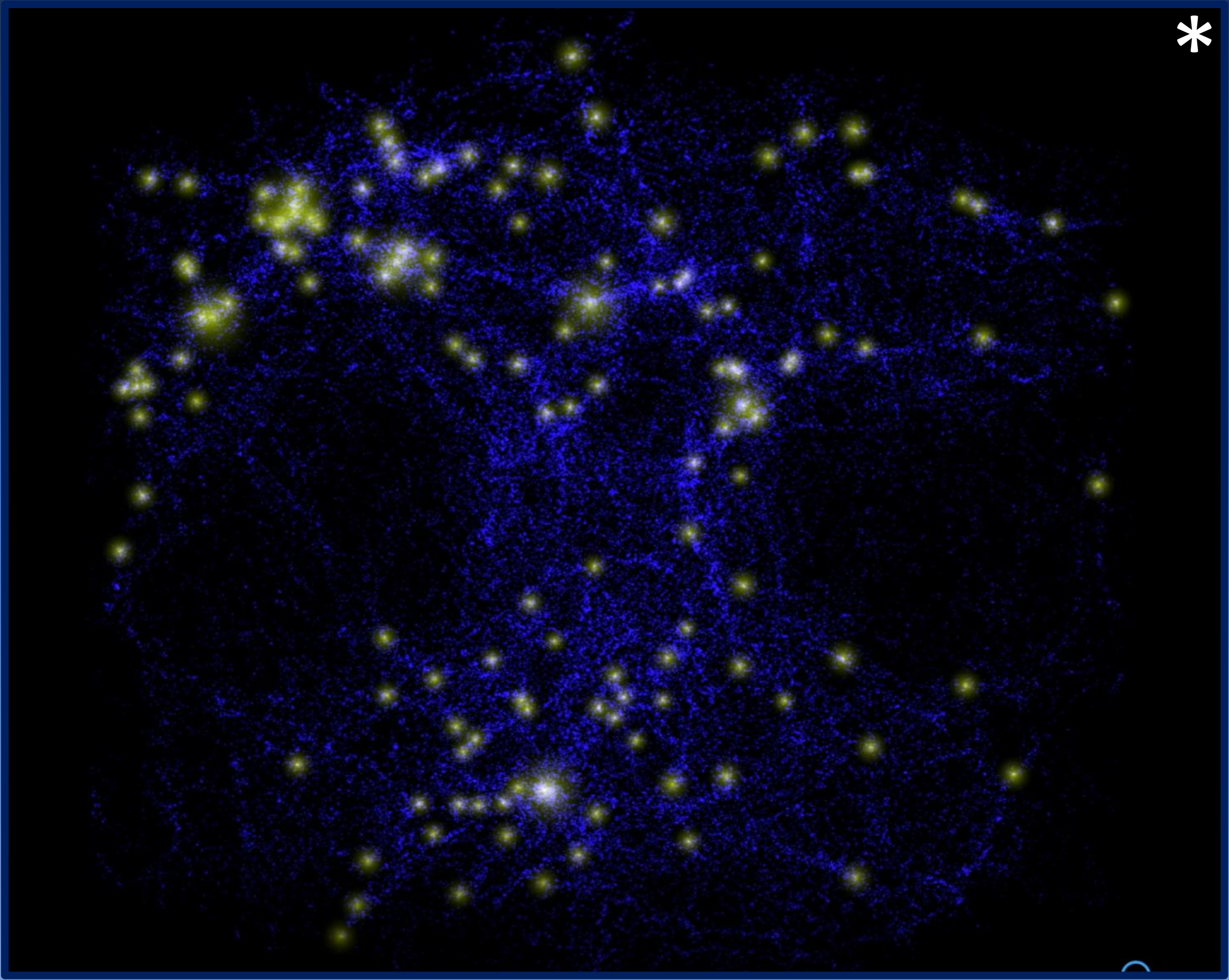
Simulations were performed at the National Centre for Supercomputer Applications by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University). Visualizations by Andrey Kravtsov.

http://cosmicweb.uchicago.edu/filaments.html

Cosmological Simulations

The most massive structures are formed in the crossings of filaments

Note: small boxes always show a cross-like structure in the cosmic web due to the larges mode in growth

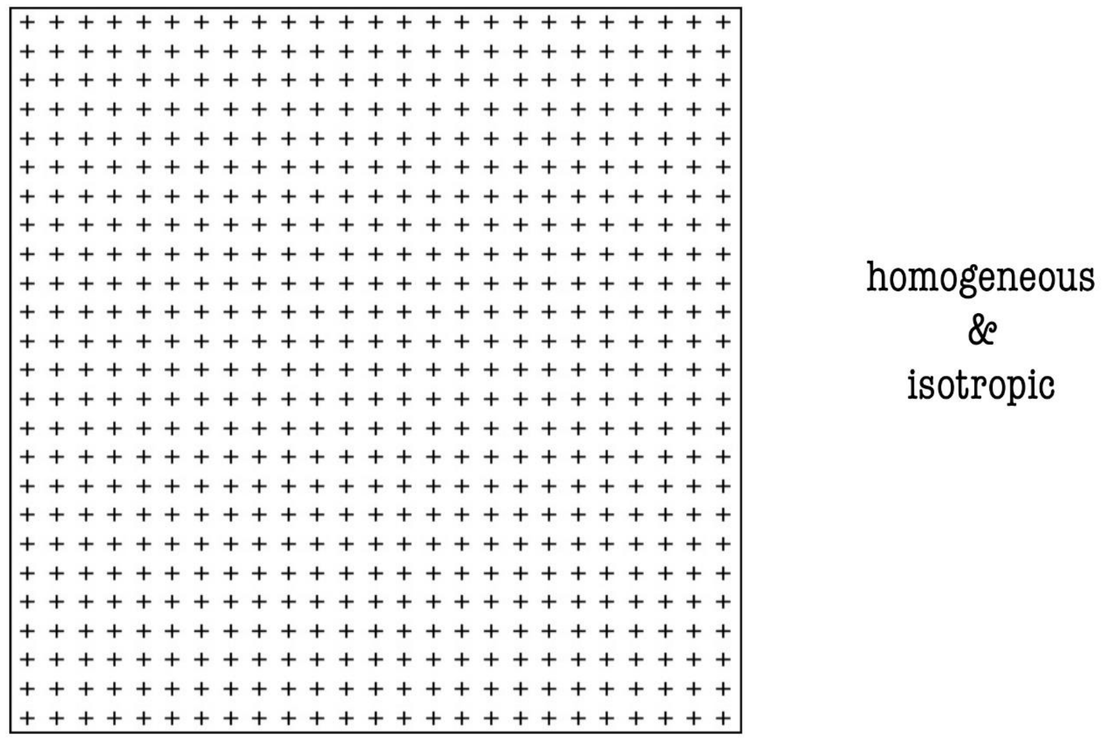


Movie credit: Rhea-Silvia Remus

Cosmological Simulations

Initial Conditions:

Box volume with periodic boundary conditions, particles set up homogeneous and isotropic.



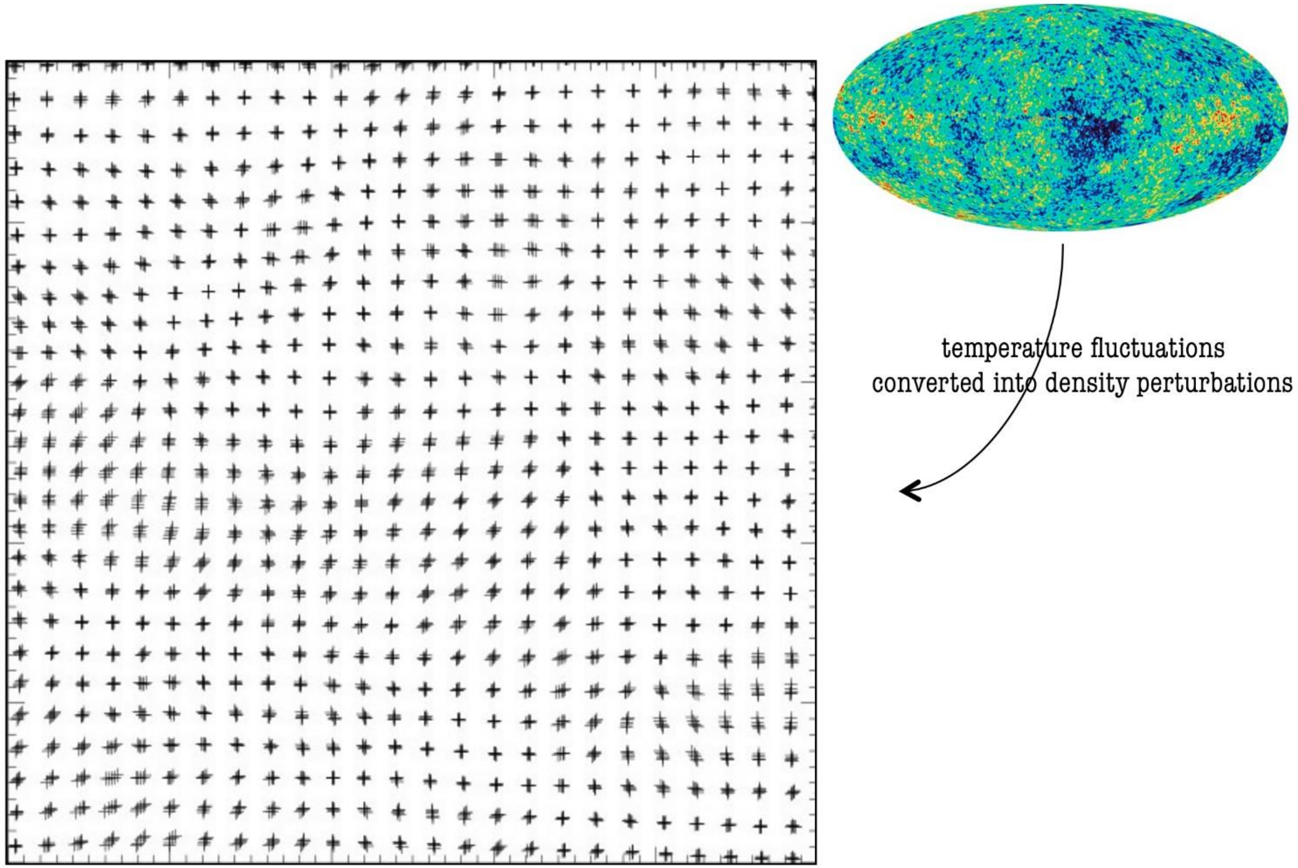
From A. Knebe: http://popia.ft.uam.es/aknebe/page3/files/ComputationalCosmology/05ICs.pdf

Cosmological Simulations

Initial Conditions:

Box volume with periodic boundary conditions, particles set up homogeneous and isotropic.

Then perturb the initial distribution due to chosen cosmology.

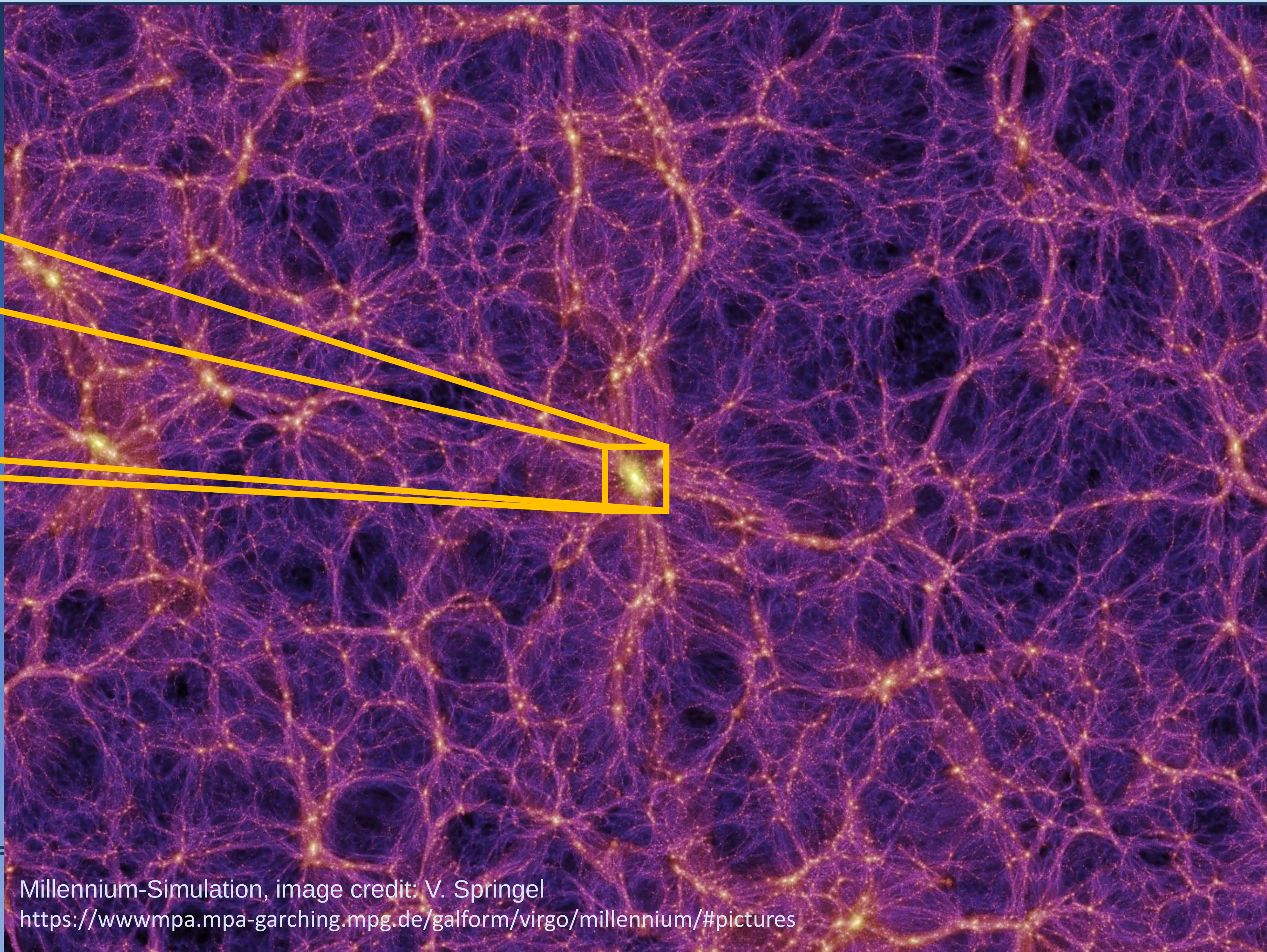


From A. Knebe: http://popia.ft.uam.es/aknebe/page3/files/ComputationalCosmology/05ICs.pdf

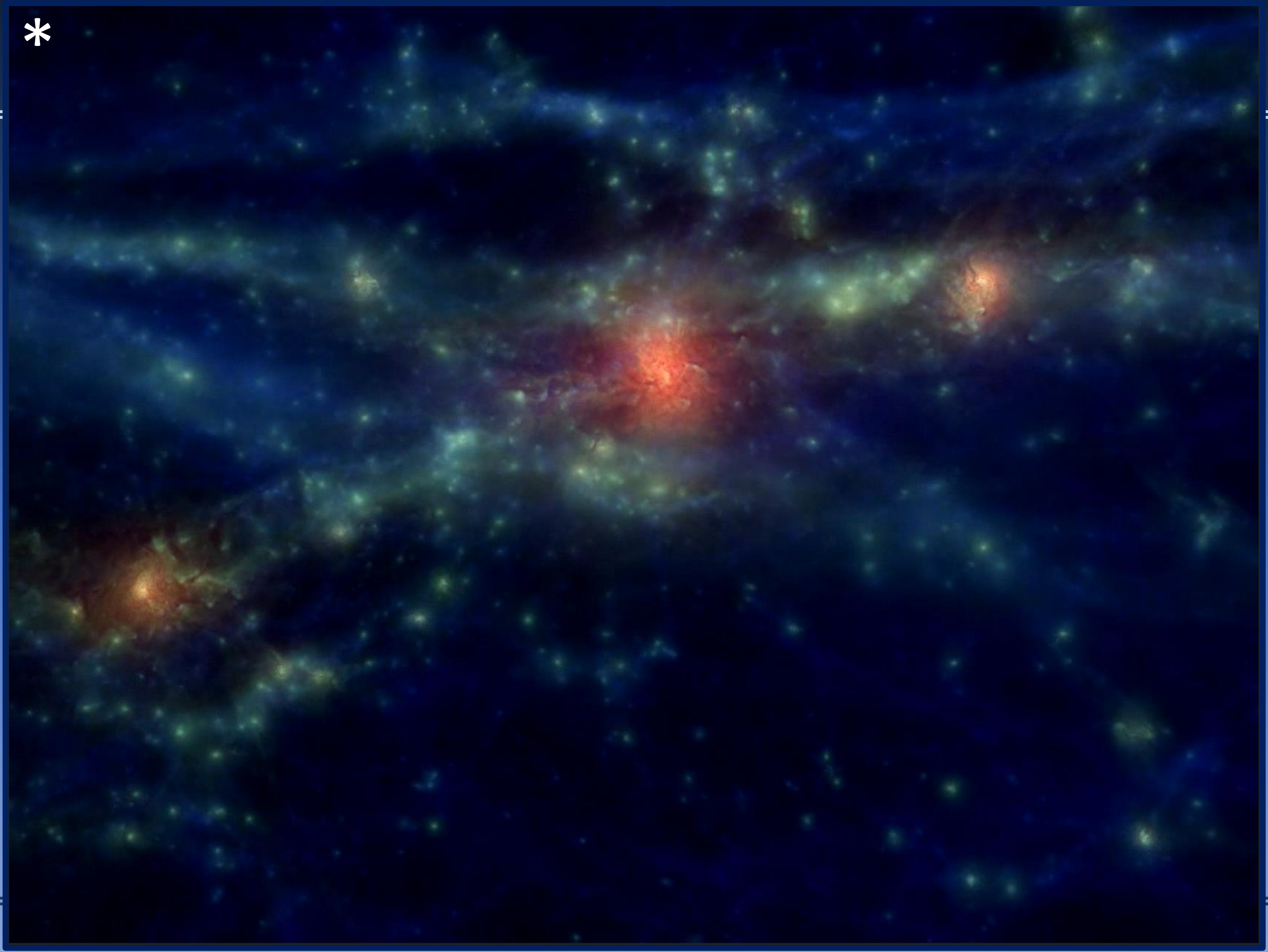
Sidestep: Semi-Analytic Models

Semi-Analytic Models and Empirical Models

Image Credit: NASA, ESA, Jennifer Lotz and the HFF Team (STScI)



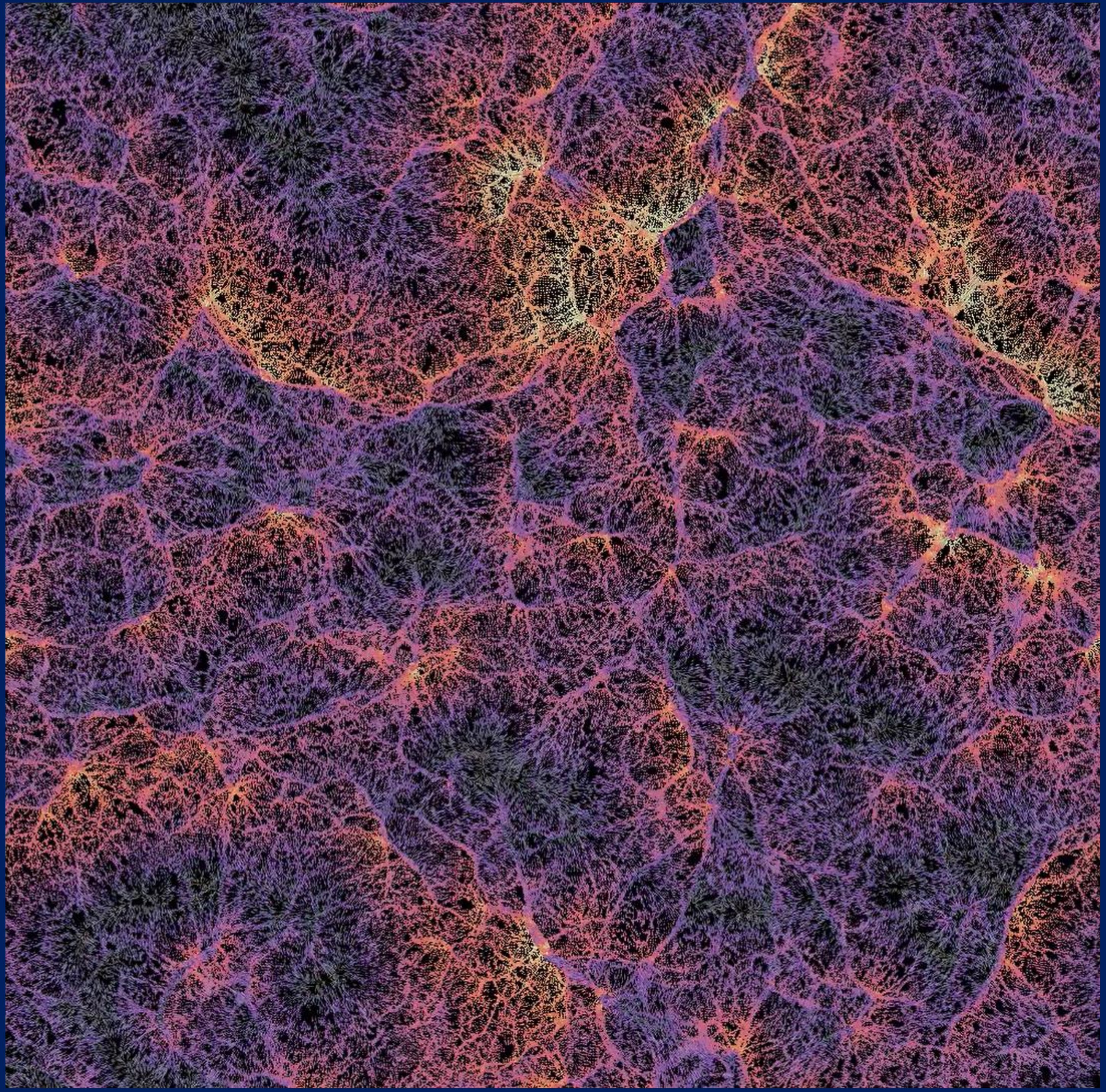
Millennium-Simulation, image credit: V. Springel
https://wwwmpa.mpa-garching.mpg.de/galform/virgo/millennium/#pictures



Magneticum Pathfinder Simulations by Klaus Dolag

www.magneticum.org

*



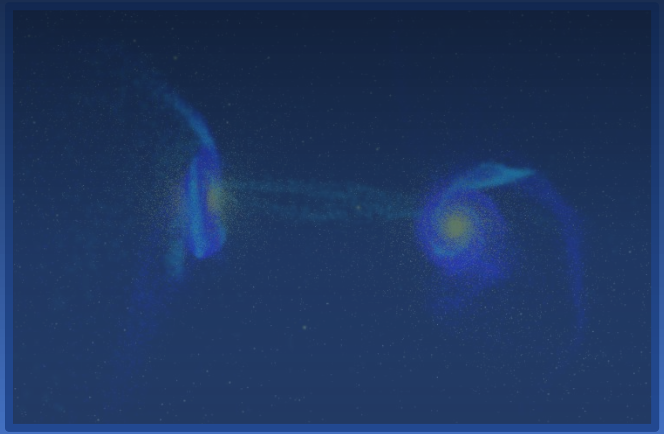
Magneticum Pathfinder
Simulations by Klaus Dolag

www.magneticum.org

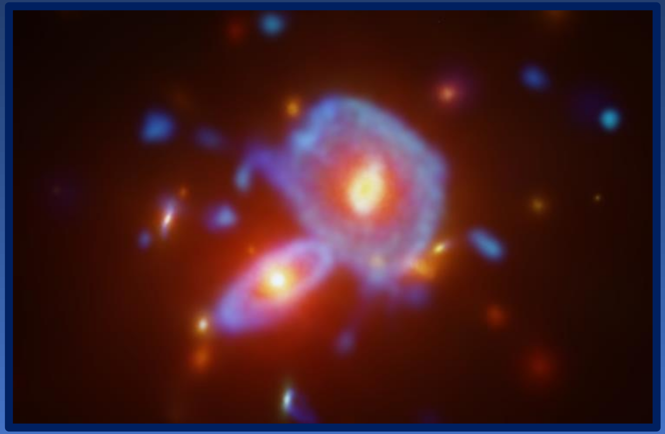
Credit: Benjamin Seidel

Overview: Galaxy Formation Simulations

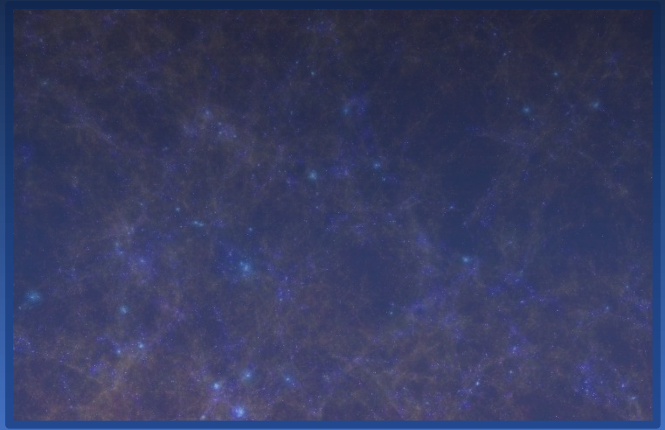
Isolated Merger Simulations



Cosmological Zoom-Simulations



Cosmological Box Simulations

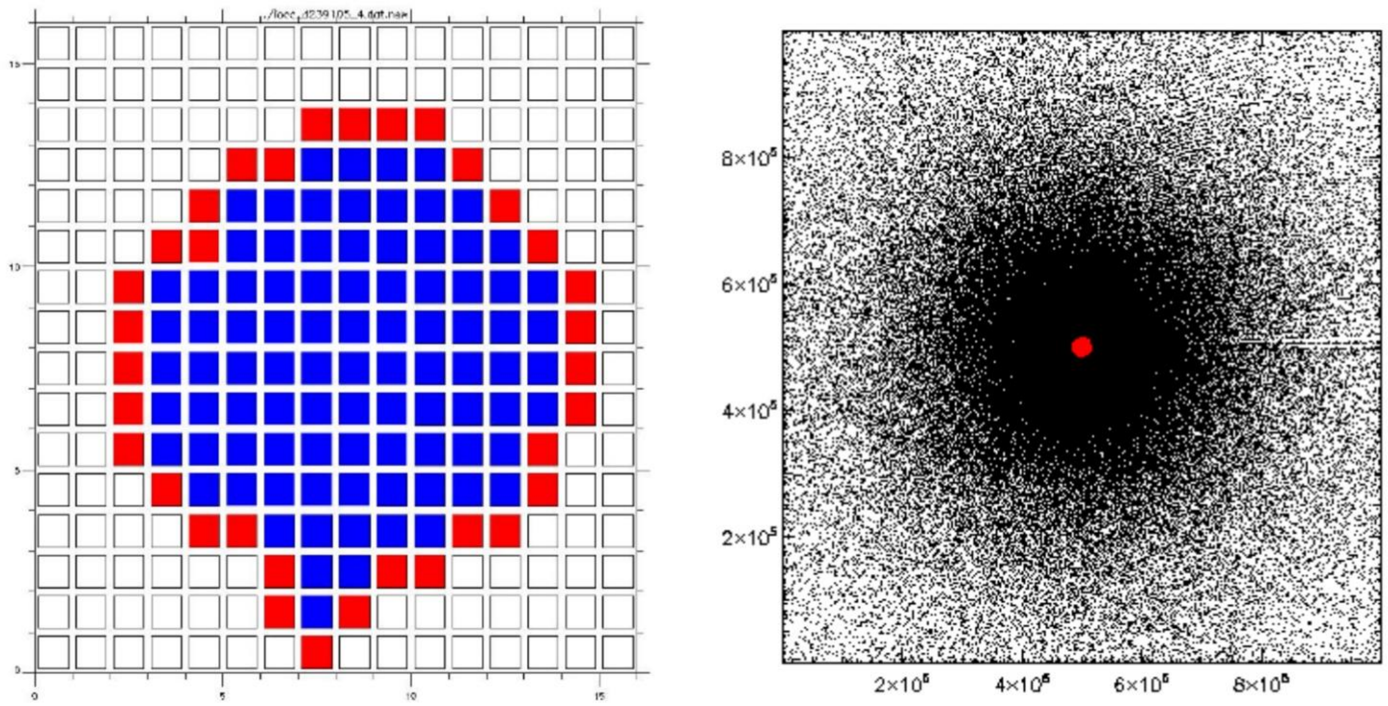


Cosmological Zoom Simulations

Initial Conditions:

Chose a galaxy of interest from a cosmological dark matter box volume.

Then split the dark matter particles into dark matter and gas in the region of interest, while the remaining box volume stays on low resolution dark matter only



From D. Schlachtberger, Master's Thesis

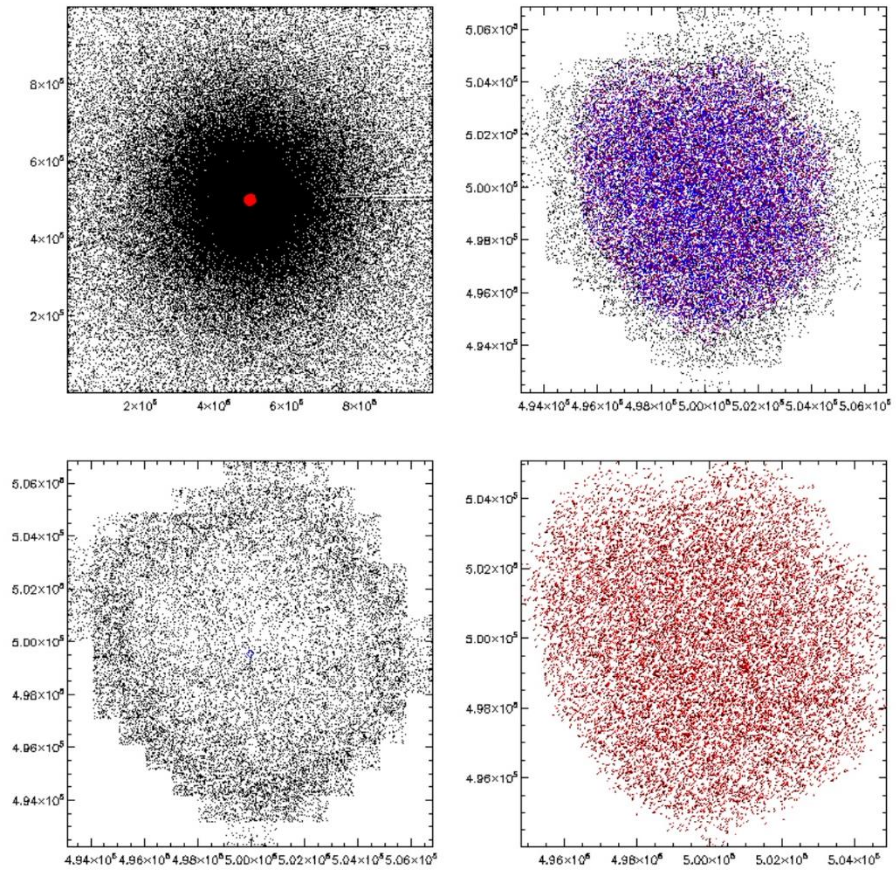
Cosmological Zoom Simulations

Initial Conditions:

Chose a galaxy of interest from a cosmological dark matter box volume.

Then split the dark matter particles into dark matter and gas in the region of interest, while the remaining box volume stays on low resolution dark matter only.

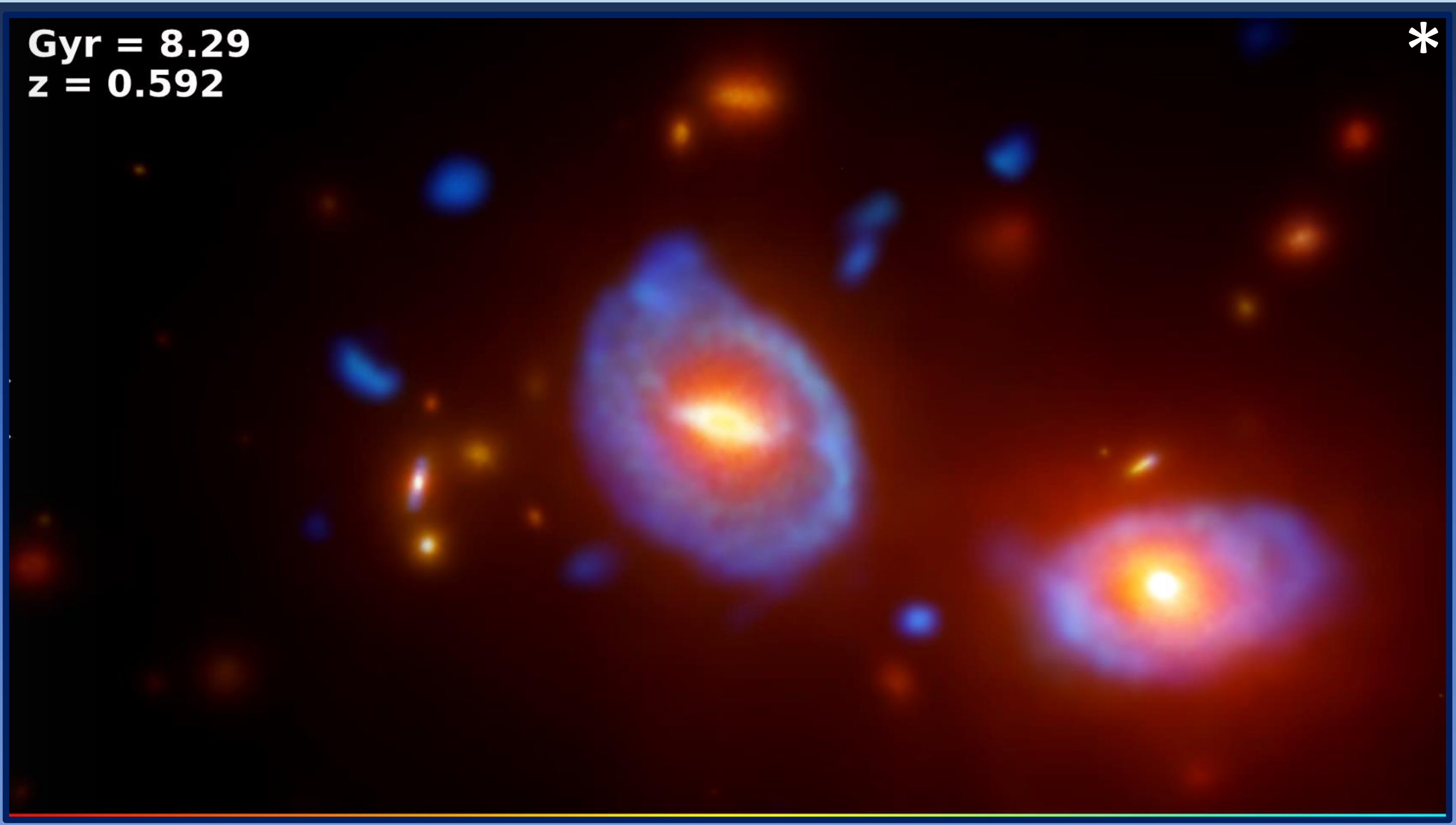
Only a small part of the cosmological box is simulated in high resolution.



From D. Schlachtberger, Master's Thesis

Cosmological Zoom Simulations

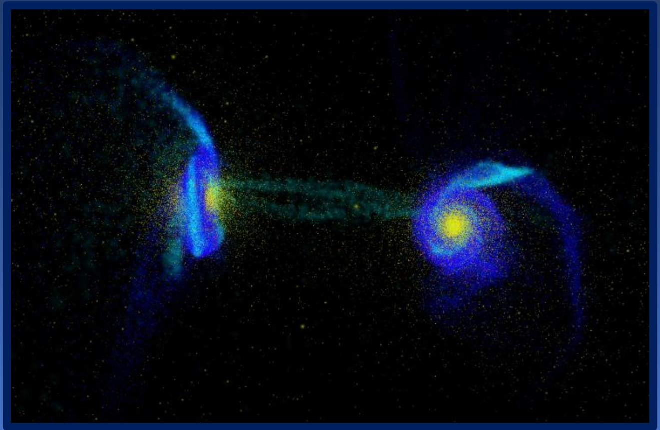
C·O·M·P·A·S·S



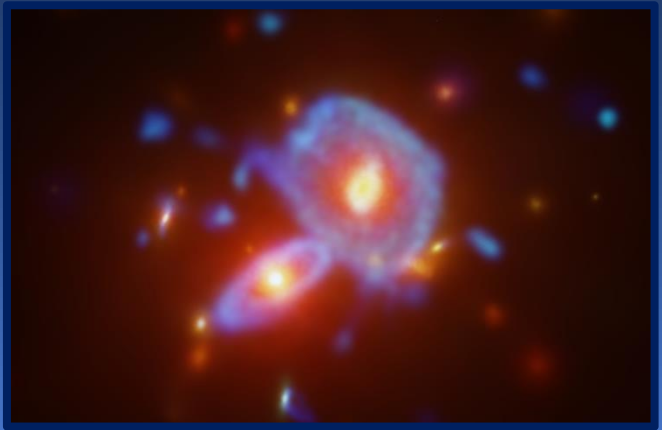
COMPASS ZOOM SIMULATIONS. Image Credit: D. Schlachtberger

Overview: Galaxy Formation Simulations

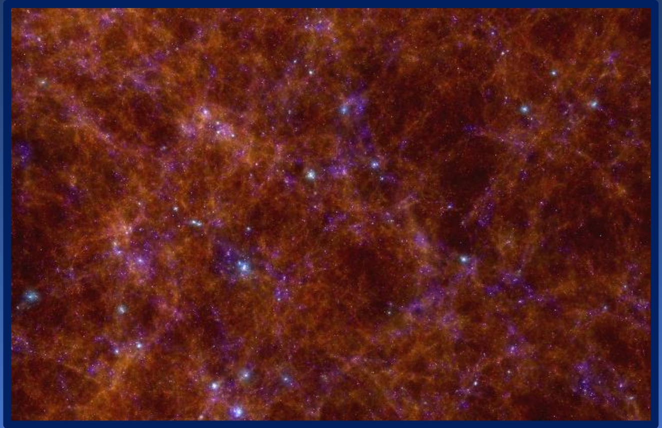
Isolated Merger Simulations



Cosmological Zoom-Simulations

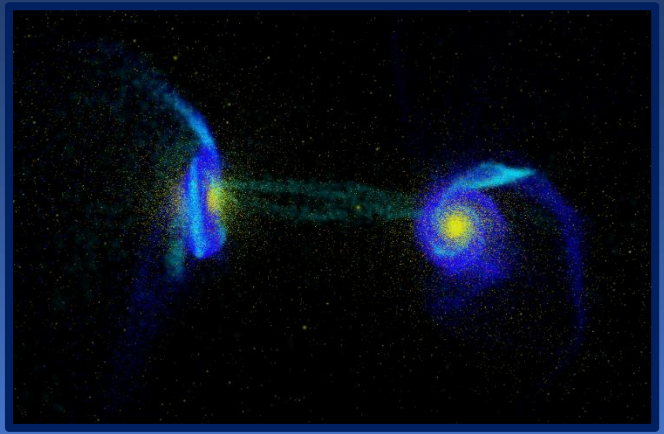


Cosmological Box Simulations



Overview: Galaxy Formation Simulations

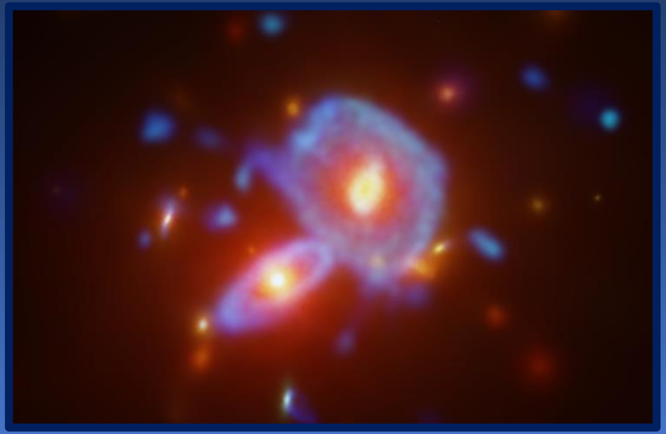
Isolated Merger Simulations



+ high resolution (temporal & spatial)
+ controlled conditions
+ parameter study (orbits, masses...)

- no cosmological formation
- not statistical representative
- no redshift evolution

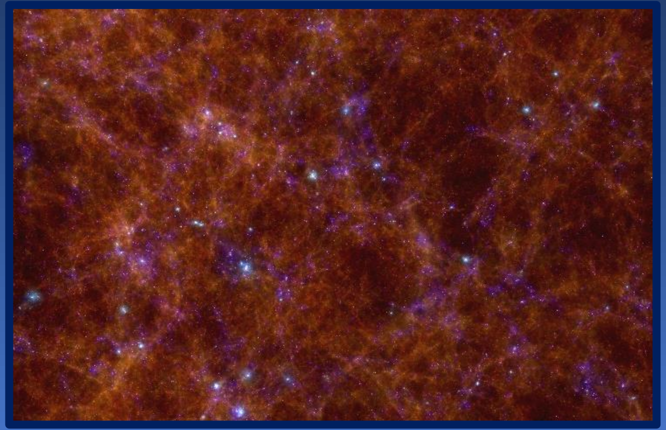
Cosmological Zoom-Simulations



+ high resolution (temporal & spatial)
+ cosmological formation
+ target objects (special environment...)

- biased selection of targets
- not statistical representative
- no parameter control

Cosmological Box Simulations

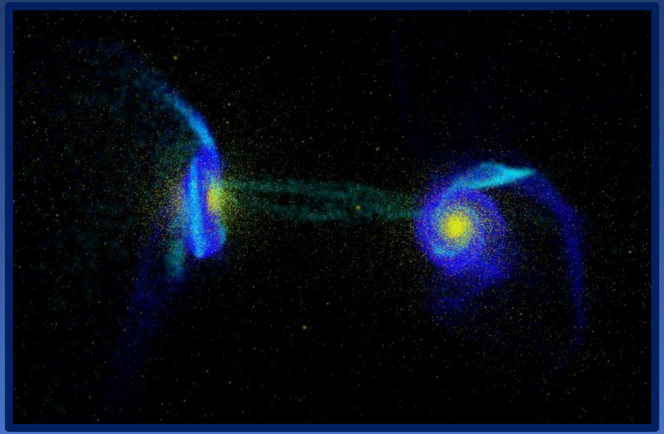


+ cosmological formation
+ statistical representative
+ no selection bias

- low resolution
- no parameter control
- computationally expensive

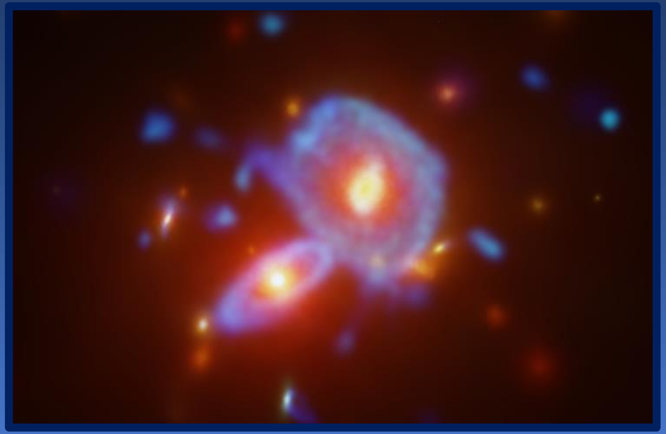
Overview: Galaxy Formation Simulations

Isolated Merger Simulations



There are a lot of different idealized merger simulations, but most of them do not have a fancy name

Cosmological Zoom-Simulations



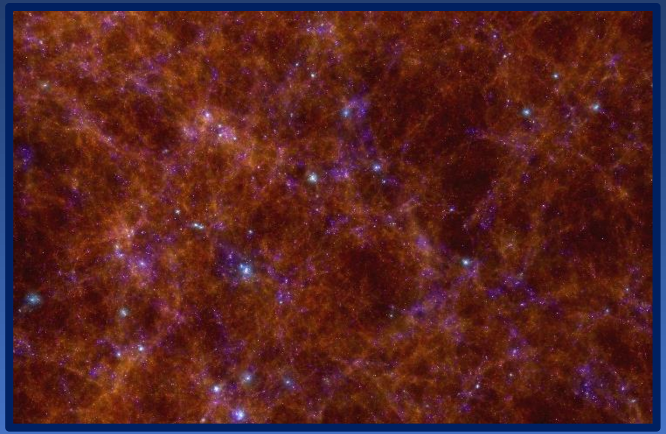
Galaxies (Dwarf to Groups)

- Oser/Naab
- NiHAO
- Fire
- Aquarius
- E-Mosaics

Clusters:

- The 300 Project
- CEagle/Hydrangea
- Romulus-C

Cosmological Box Simulations



Fully Hydrodynamical

- Eagle
- Magneticum
- HorizonAGN
- Illustris/IllustrisTNG
- MassiveBlack

Overview: Galaxy Formation Simulations

Disclaimer: This is by no means a complete list!

Isolated Merger Simulations

There are a lot of different idealized merger simulations, but most of them do not have a fancy name

Cosmological Zoom-Simulations

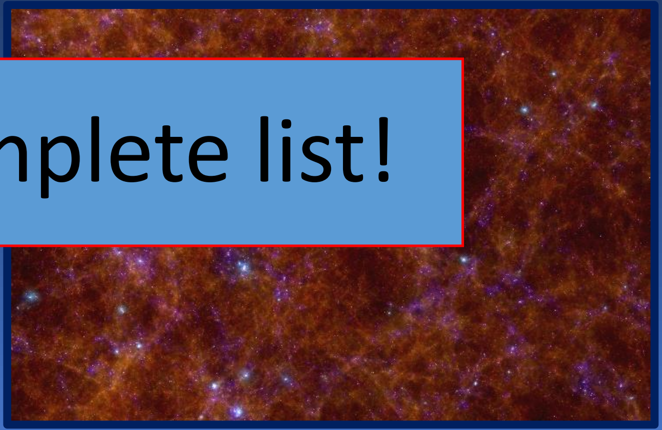
Galaxies (Dwarf to Groups)

- Oser/Naab
- NiHAO
- Fire
- Aquarius
- E-Mosaics

Clusters:

- The 300 Project
- CEagle/Hydrangea
- Romulus-C

Cosmological Box Simulations



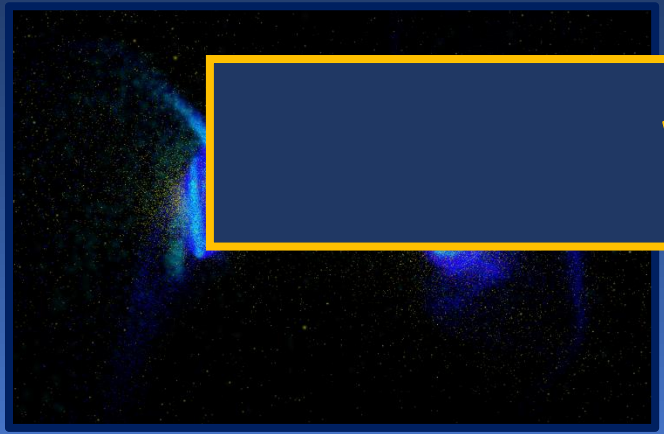
Fully Hydrodynamical

- Eagle
- Magneticum
- HorizonAGN
- Illustris/IllustrisTNG
- MassiveBlack

Overview: Galaxy Formation Simulations

Why do we need them all?

Isolated Merger Simulations



There are a lot of different idealized merger simulations, but most of them do not have a fancy name

Cosmological Zoom-Simulations

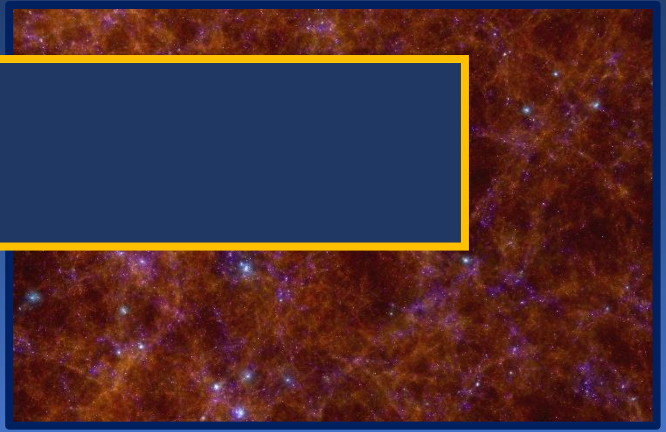
Galaxies (Dwarf to Groups)

- Oser/Naab
- NiHAO
- Fire
- Aquarius
- E-Mosaics

Clusters:

- The 300 Project
- CEagle/Hydrangea
- Romulus-C

Cosmological Box Simulations

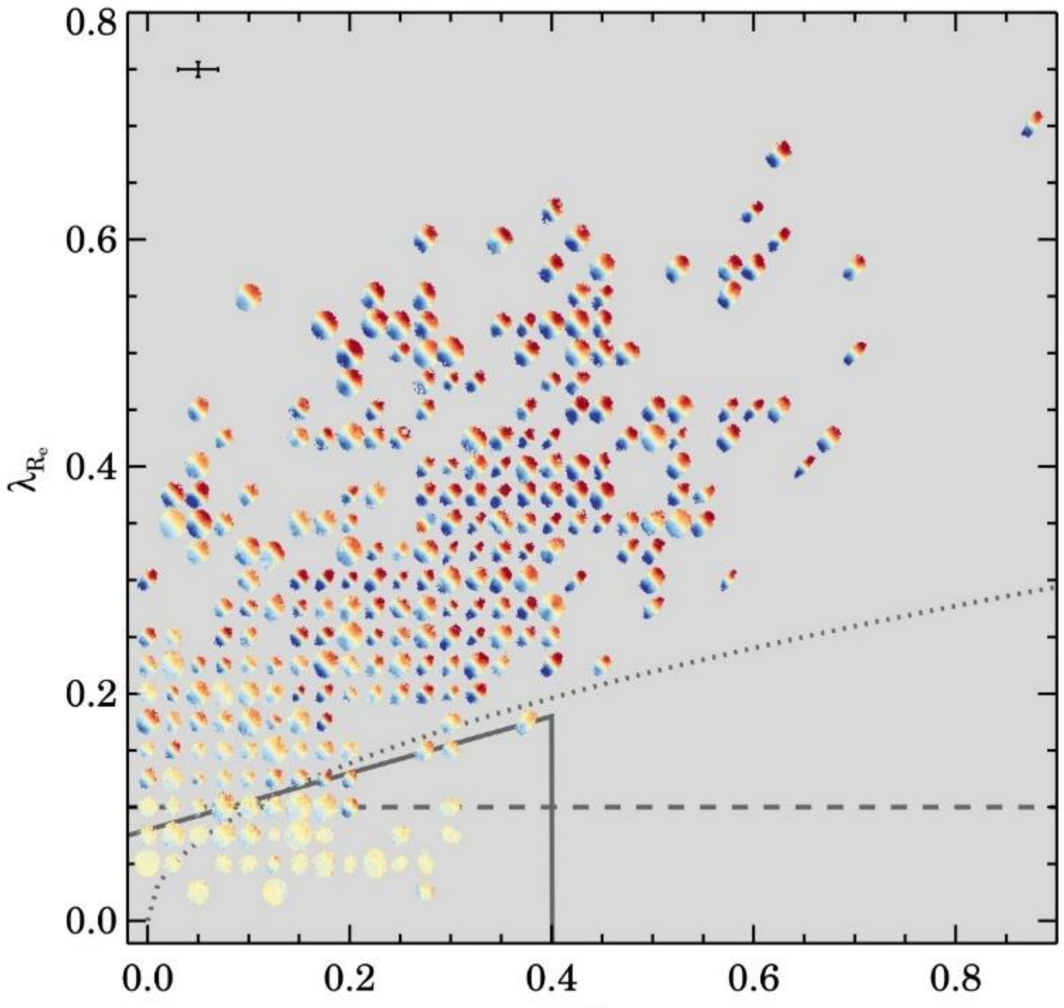


Fully Hydrodynamical

- Eagle
- Magneticum
- HorizonAGN
- Illustris/IllustrisTNG
- MassiveBlack

Why so many different simulation types?

Example: Why different Cosmological Simulations



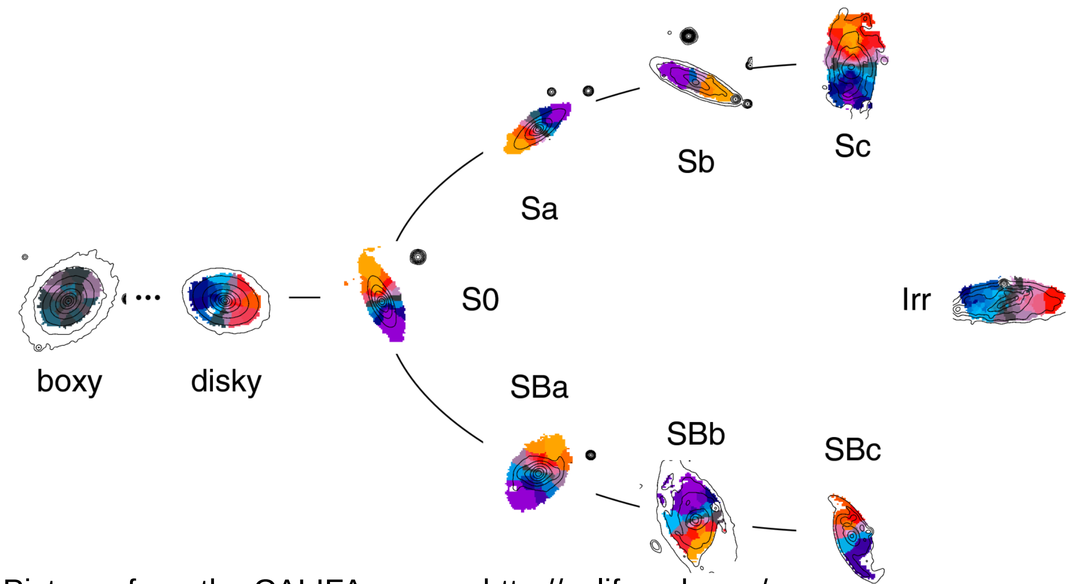
SAMI, van de Sande et al., 2017

Fast rotating ETGs

Slow rotating ETGs

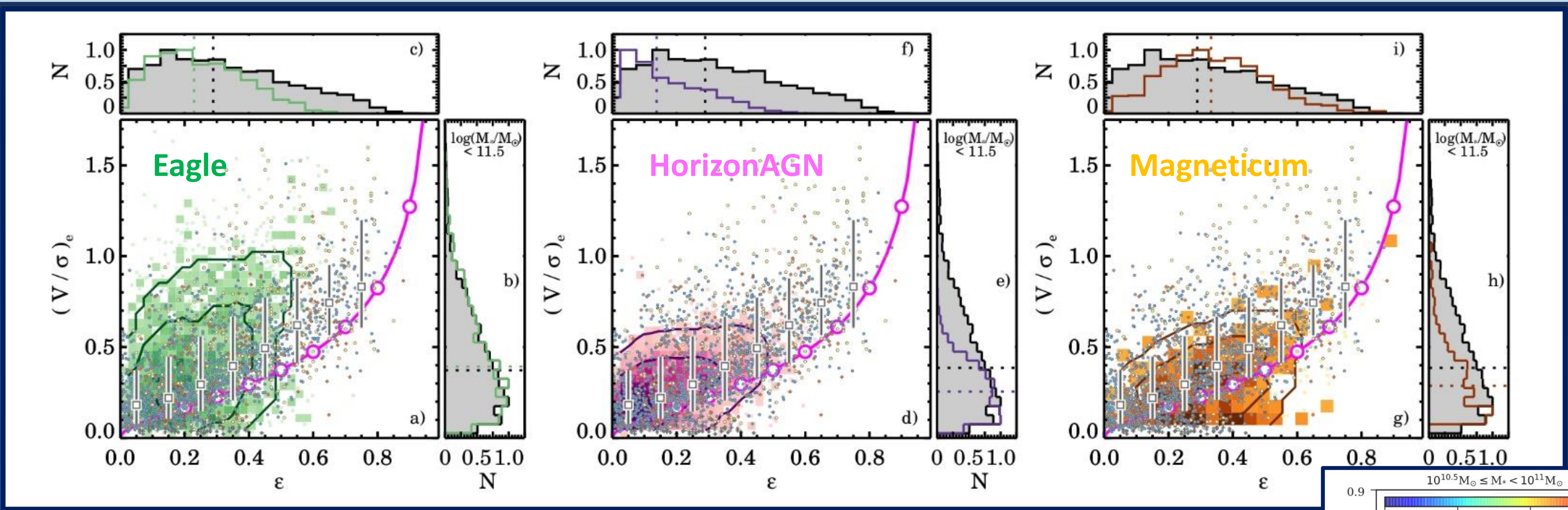
$$\lambda_R \equiv \frac{\langle R\,|V|\rangle}{\langle R\sqrt{V^2+\sigma^2}\rangle}$$

Emsellem et al., 2007; 2011

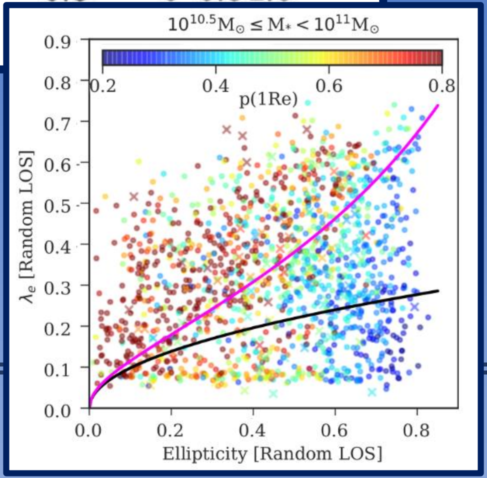


Pictures from the CALIFA survey: http://califa.caha.es/

Simulations versus Observations

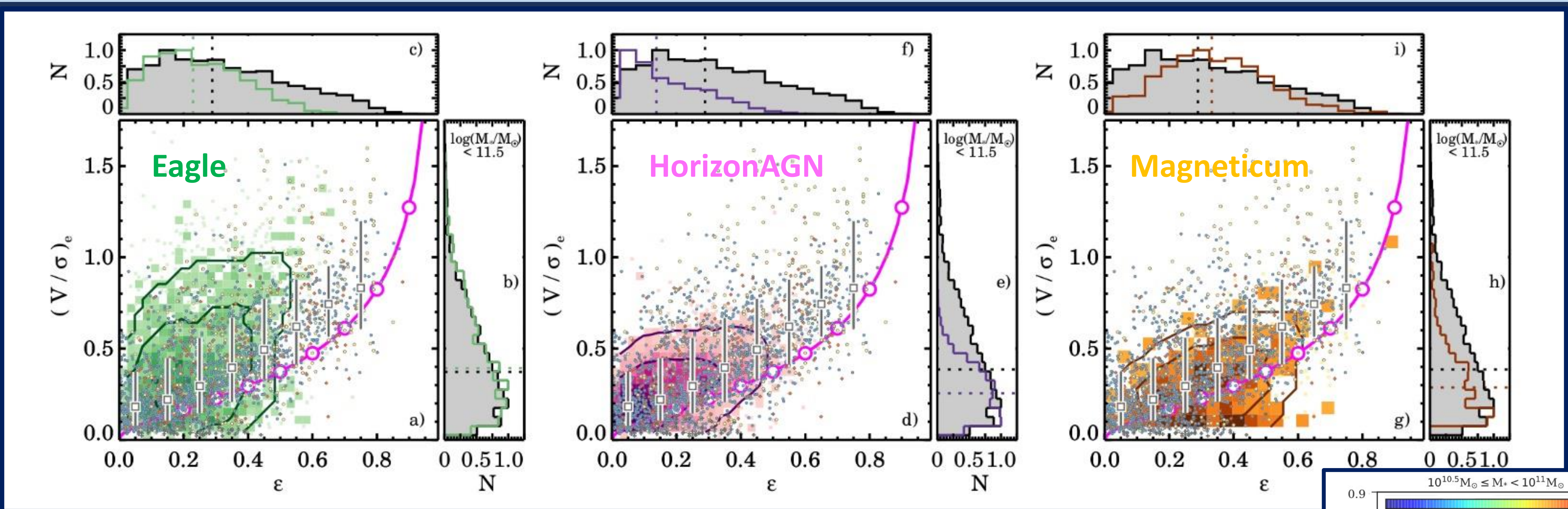


Van de Sande et al., 2019



TNG: Pulsoni et al., 2020

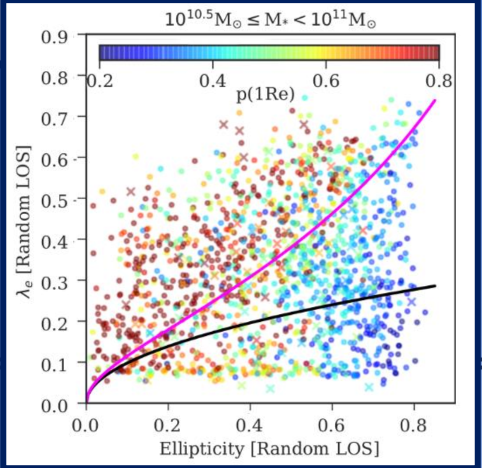
Simulations versus Observations



Van de Sande et al., 2019

Differences between cosmological simulations are not from the different Codes but from the SubGrid Physics

TNG: Pulsoni et al., 2020



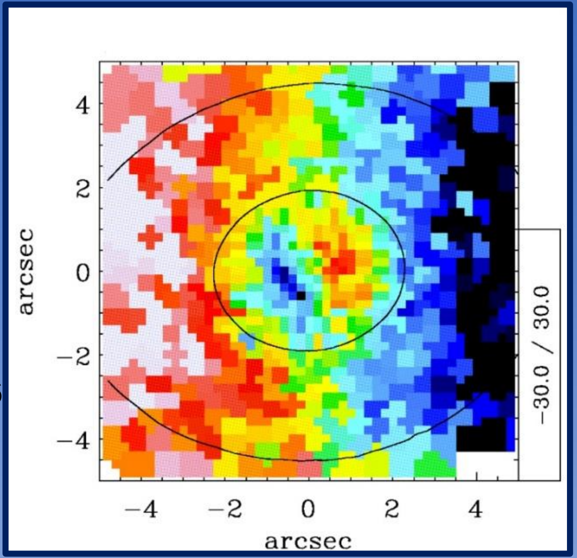
Example: Why different Galaxy Simulations?

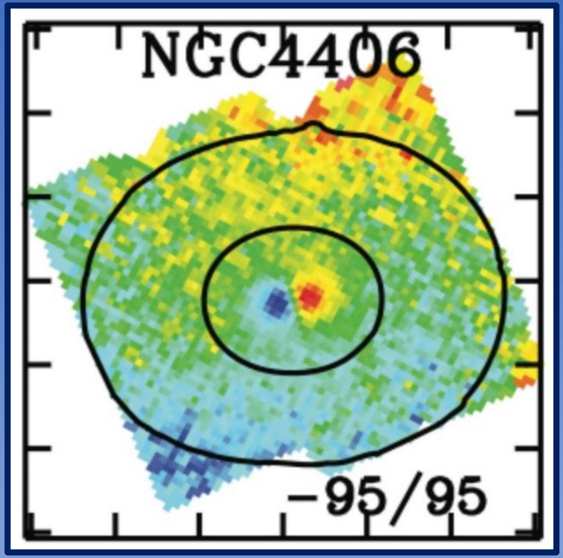
Kinematically Distinct Cores in ETGs come in two flavors:

Small (<1kpc) core with a young stellar population, mostly inside fast rotators

Large core with an old stellar population, usually in massive slow rotators

McDermid et al., 2006 but also in dwarf galaxies (Rys et al., 2013)

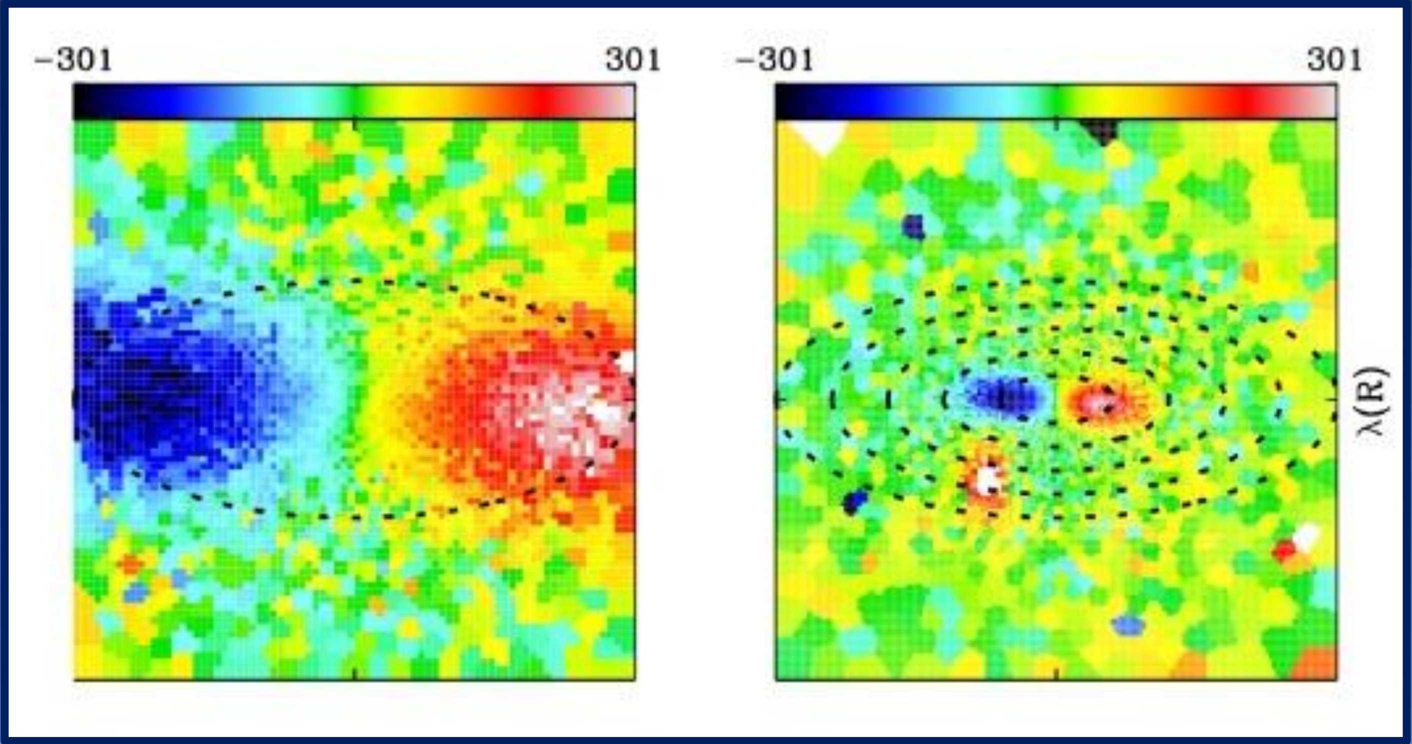




Kranjovic et al., 2013

Old KDCs: Cosmological Simulation

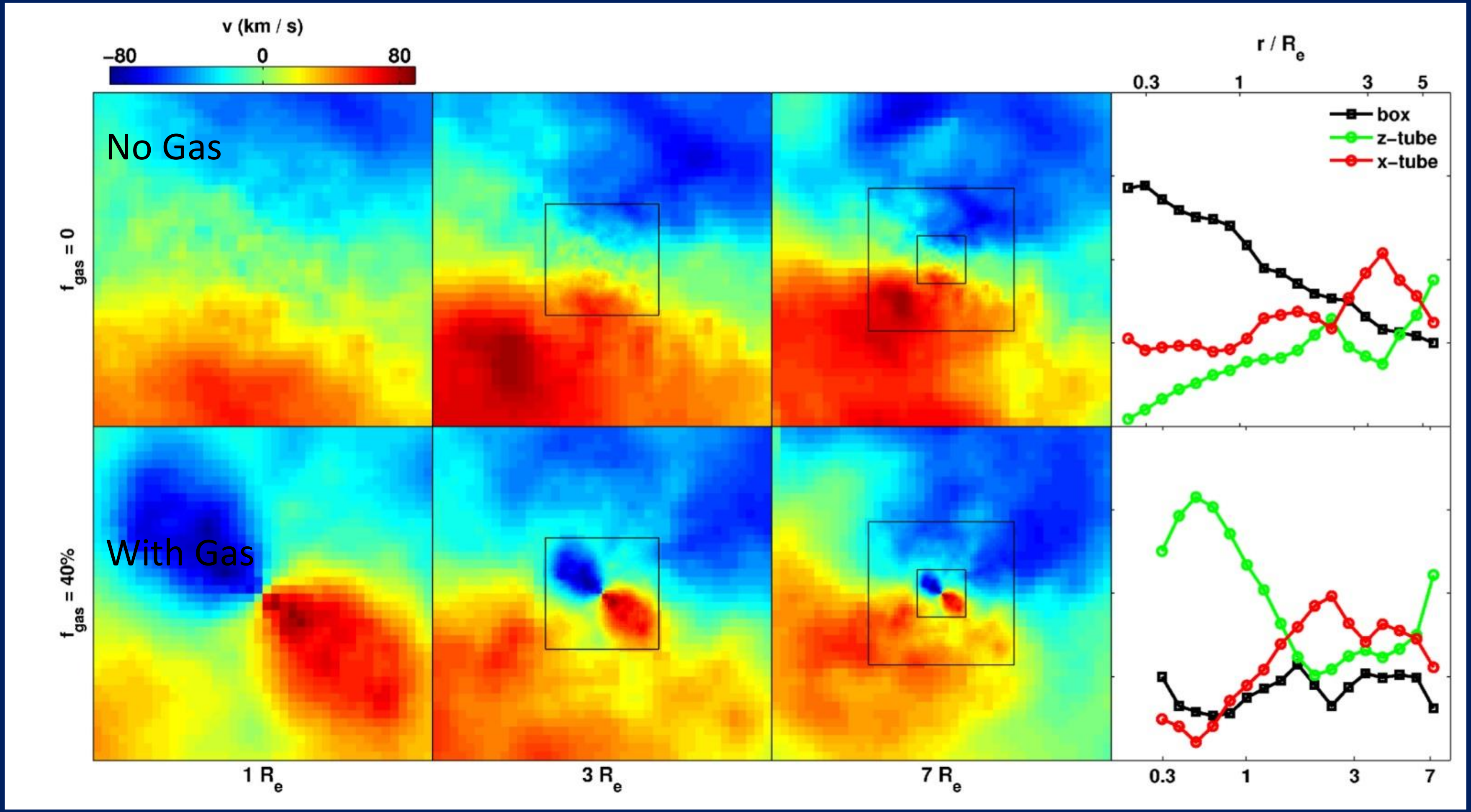
Large KDCs are found in cosmological simulations to be made from an old rotating disks already build up at z=2, which then only accreted minor or mini mergers with ratios smaller than 1:10. These mergers destroy the rotation in the outskirts, but cannot reach the central areas of a galaxy (see Schulze et al., 2020 and Karademir et al., 2019)



Schulze et al., 2020; see also Schulze et al., 2018 for kinematic maps within $1R_{half}$ and correlations with kinematic type

Young KDCs: Isolated Merger Simulations

Young, small KDC are formed in gas-rich major merger events, and they are dominated by z-tube orbits. They are only formed by mergers with gas fractions of 15-40%

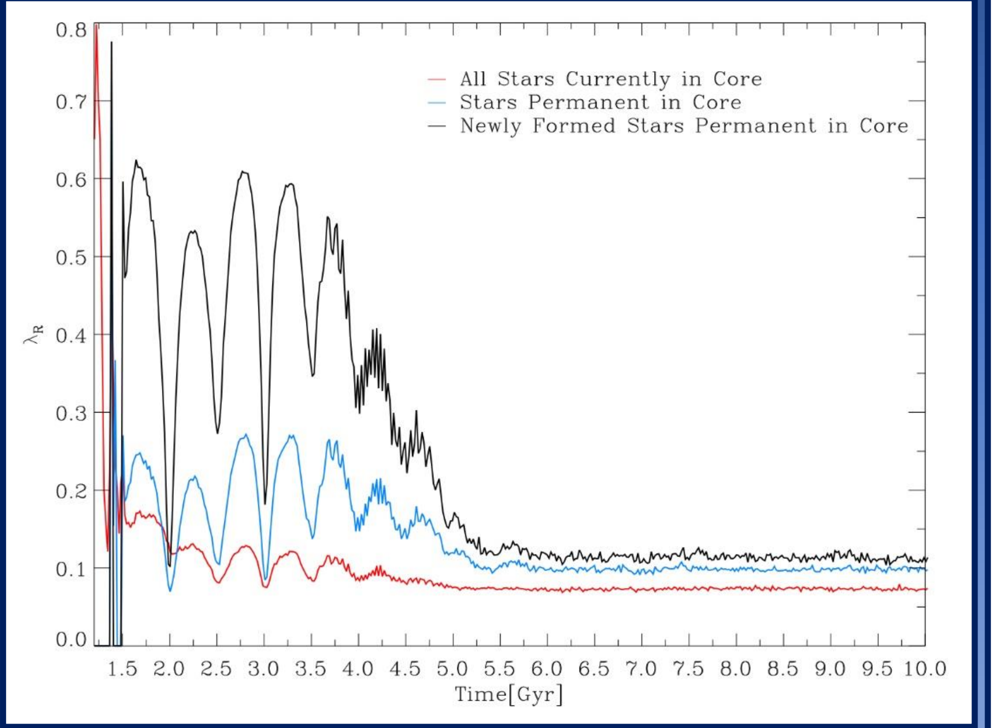


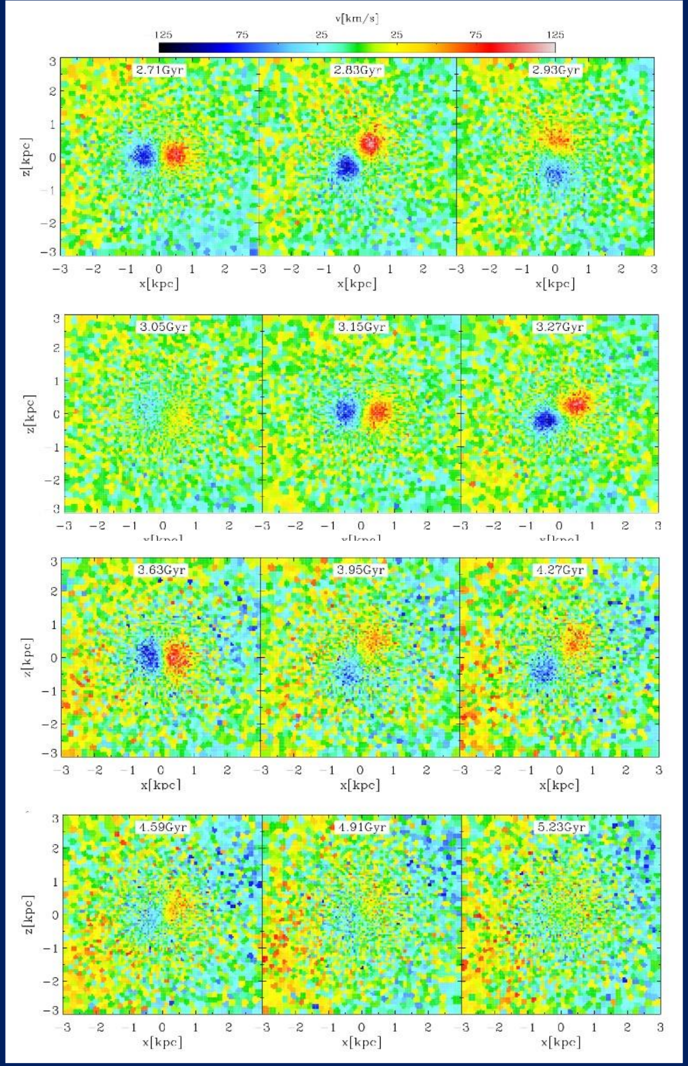
Hoffman et al., 2010

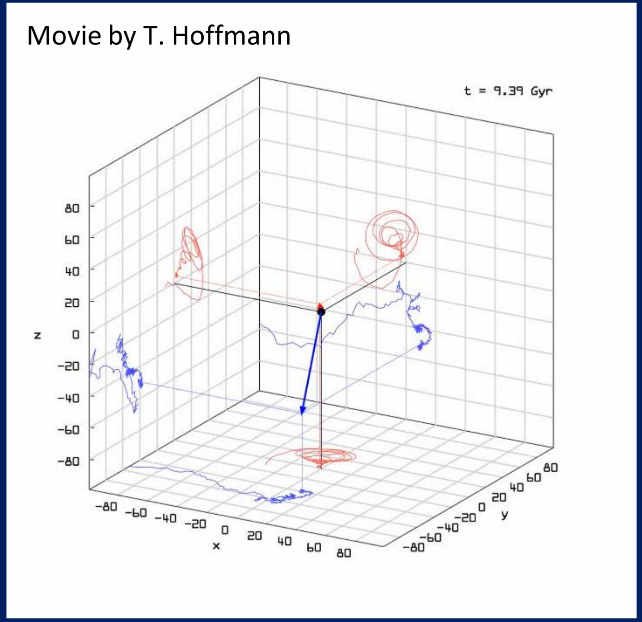
Young KDCs: Isolated Merger Simulations

*

KDC made from mostly newly-formed stars that keep the memory of the angular momentum of the merger: performs a motion comparable to the precession of a gyroscope in a gravitational potential; superposition of an intrinsic rotation and a global precession that gets gradually damped over cosmic time.







Lifetime of a young KDC: stable for ≈3Gyrs after the merger, damped over ≈ 1.5Gyrs.

Schulze et al., 2017

Chose the right simulation type for your question!

Comparison to Observations

I. Abell 2744: Substructures in Clusters

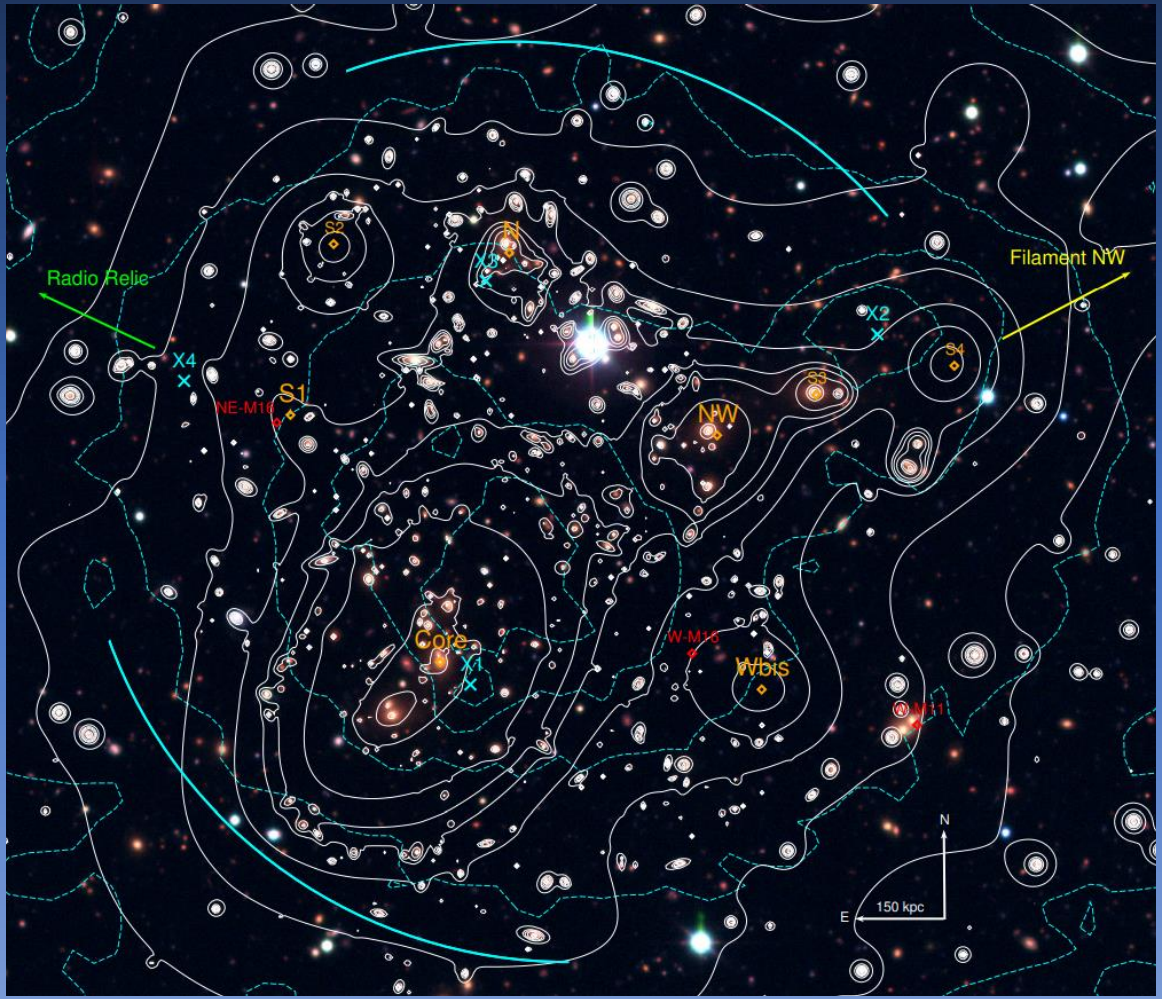


Image credit: Jauzac et al. 2016

Abell 2744

- z = 0.308
- Dynamically active
- In 1.3Mpc aperture:

$$M_{tot}(< 1.3\text{Mpc}) = 2.3 \cdot 10^{15} M_{\odot}$$

I. Abell 2744: Substructures in Clusters

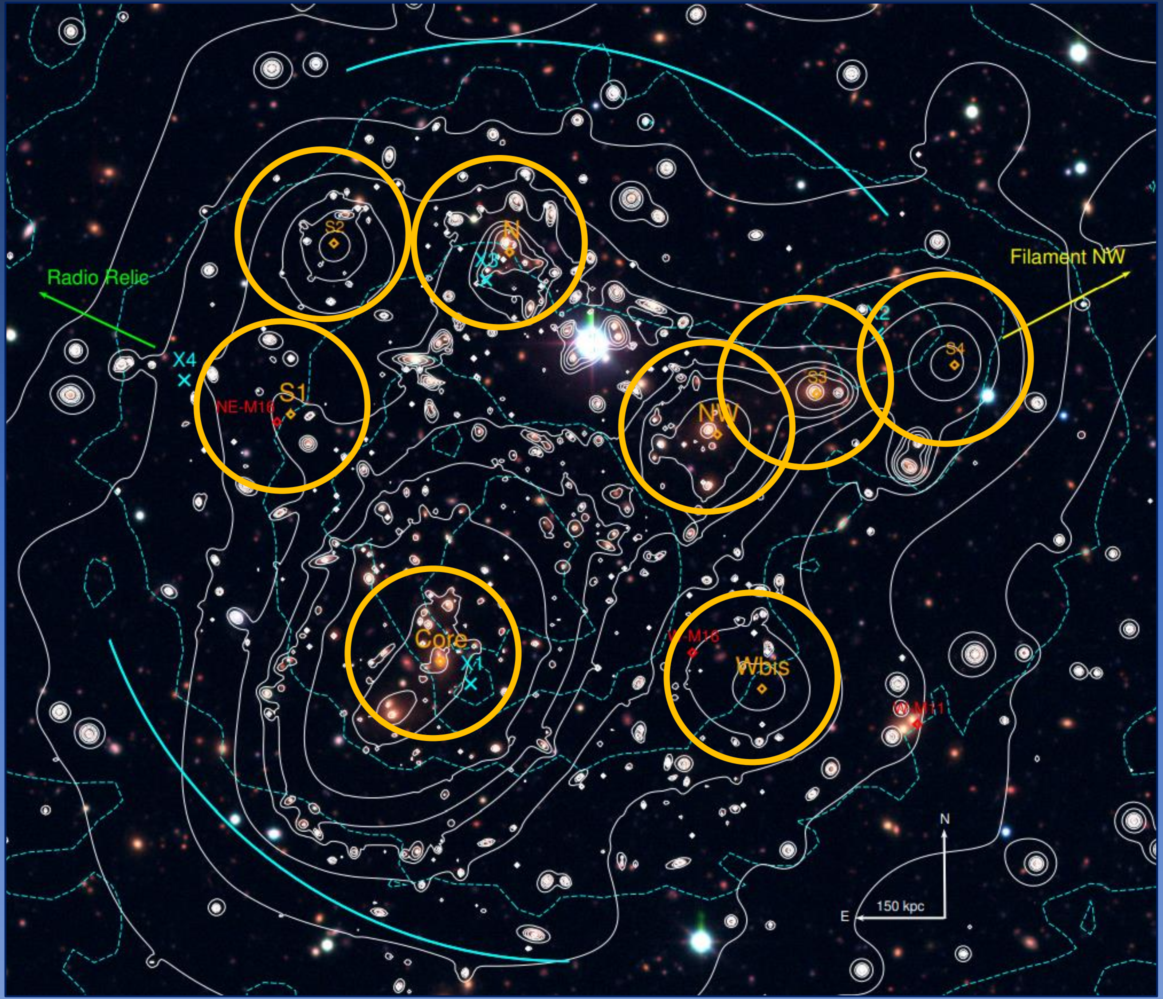


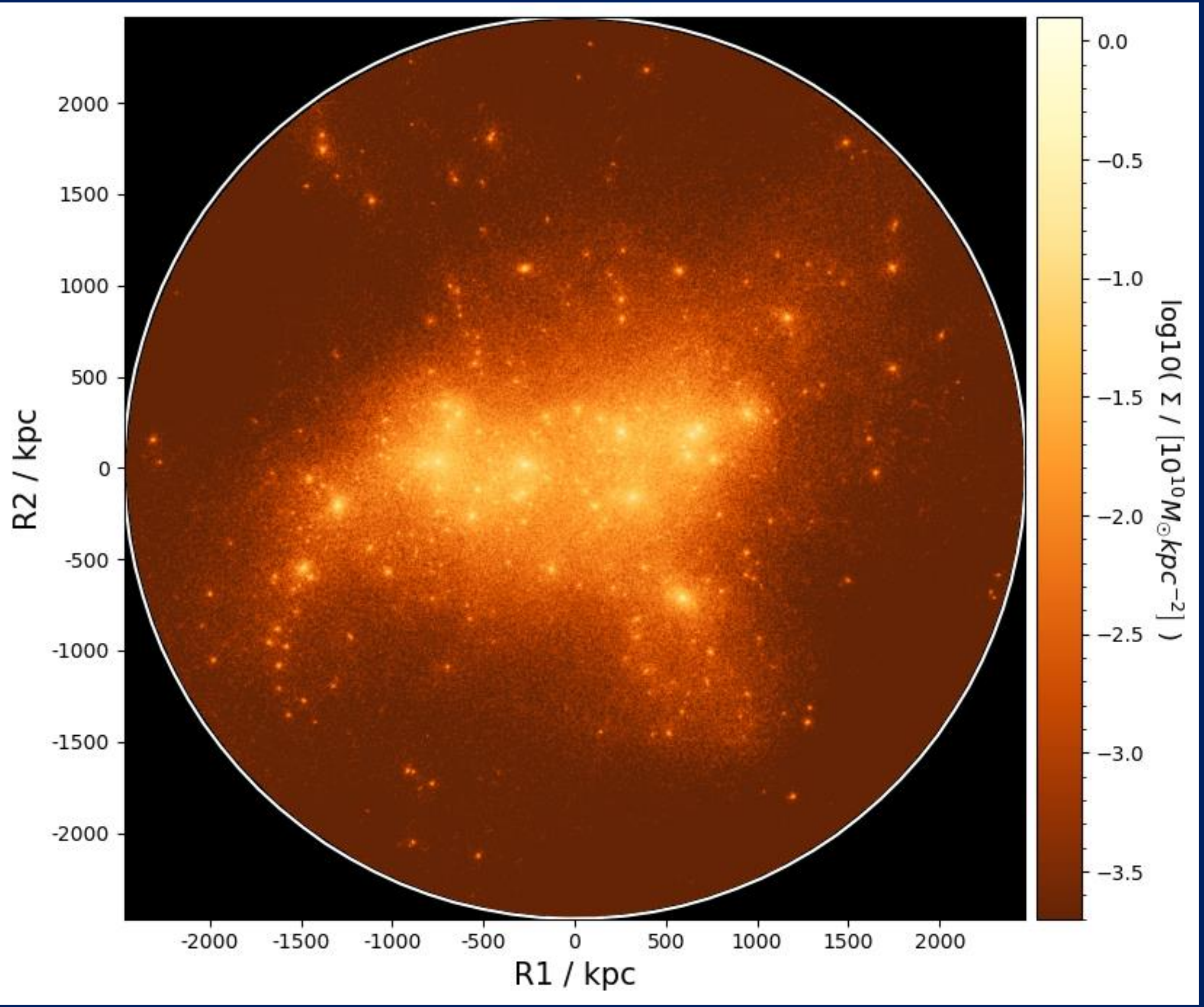
Image credit: Jauzac et al. 2016

Abell 2744

- z = 0.308
- Dynamically active
- In 1.3Mpc aperture:

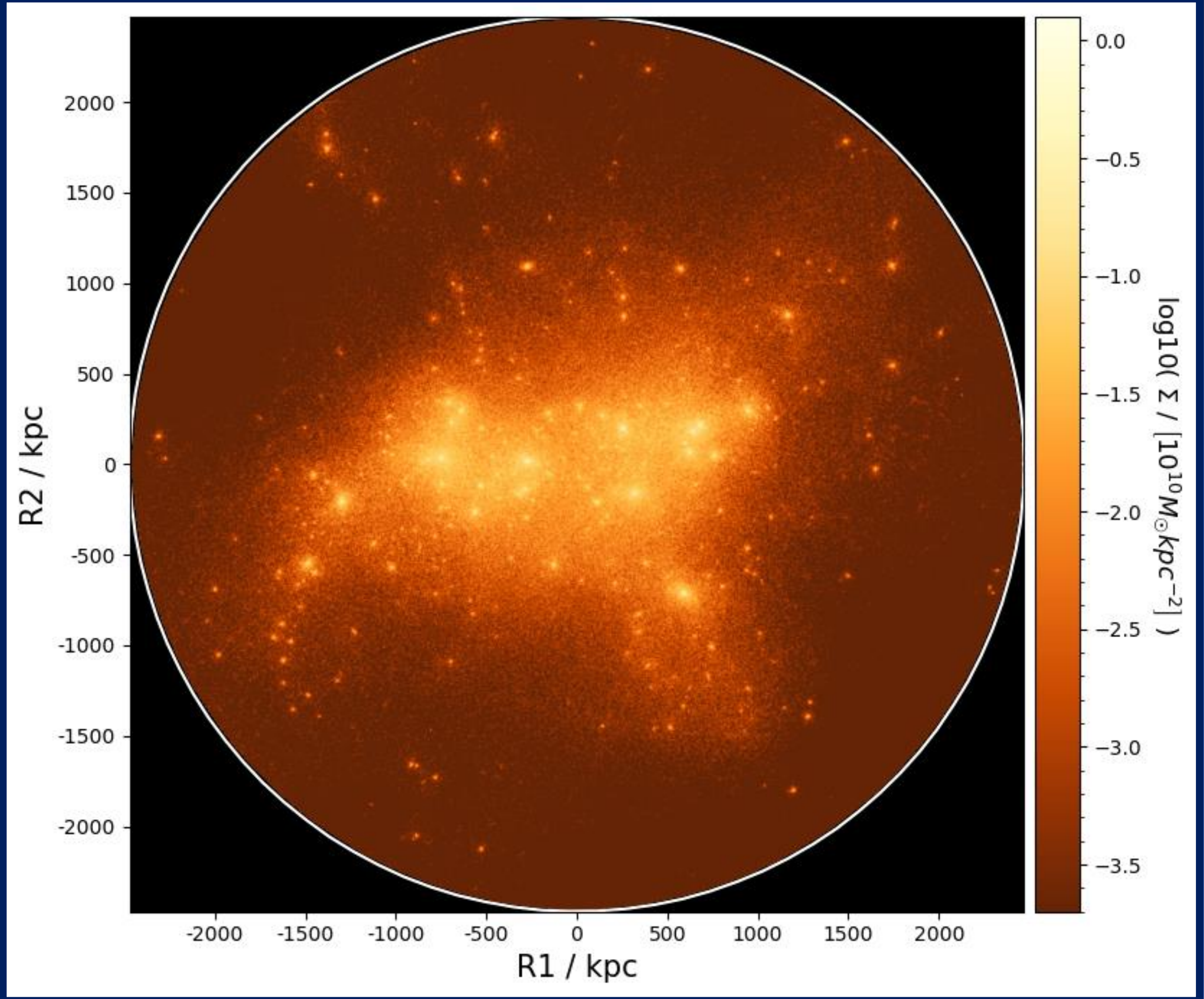
$$M_{tot}(< 1.3\text{Mpc}) = 2.3 \cdot 10^{15} M_{\odot}$$

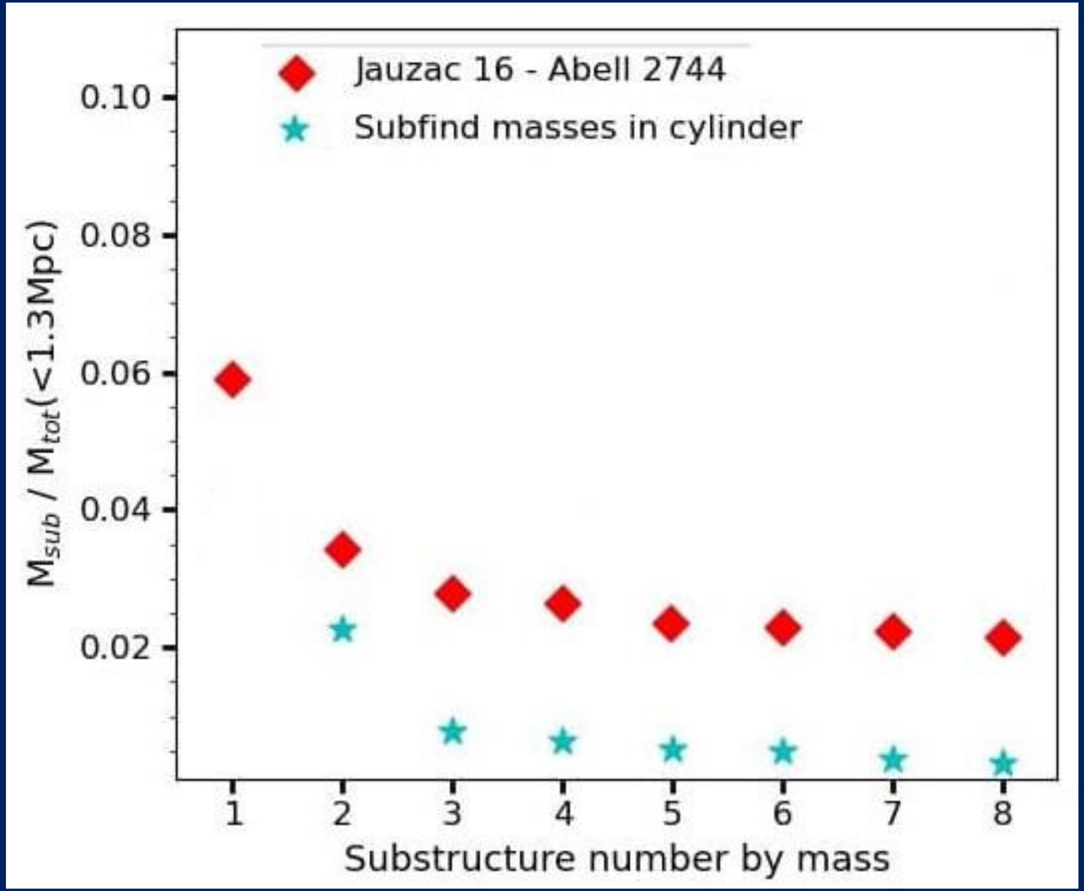
I. Abell 2744: Substructures in Clusters



Kimmig et al., in prep.

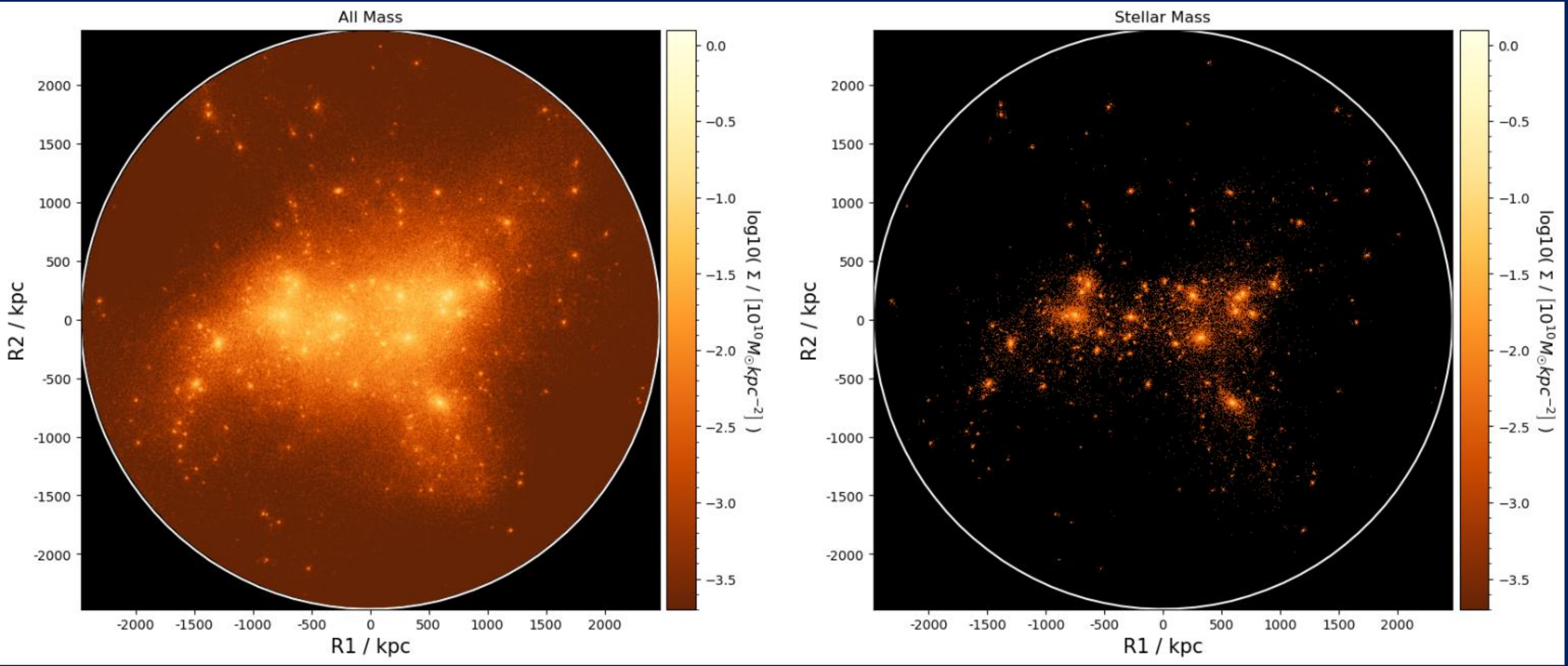
I. Abell 2744: Substructures in Clusters





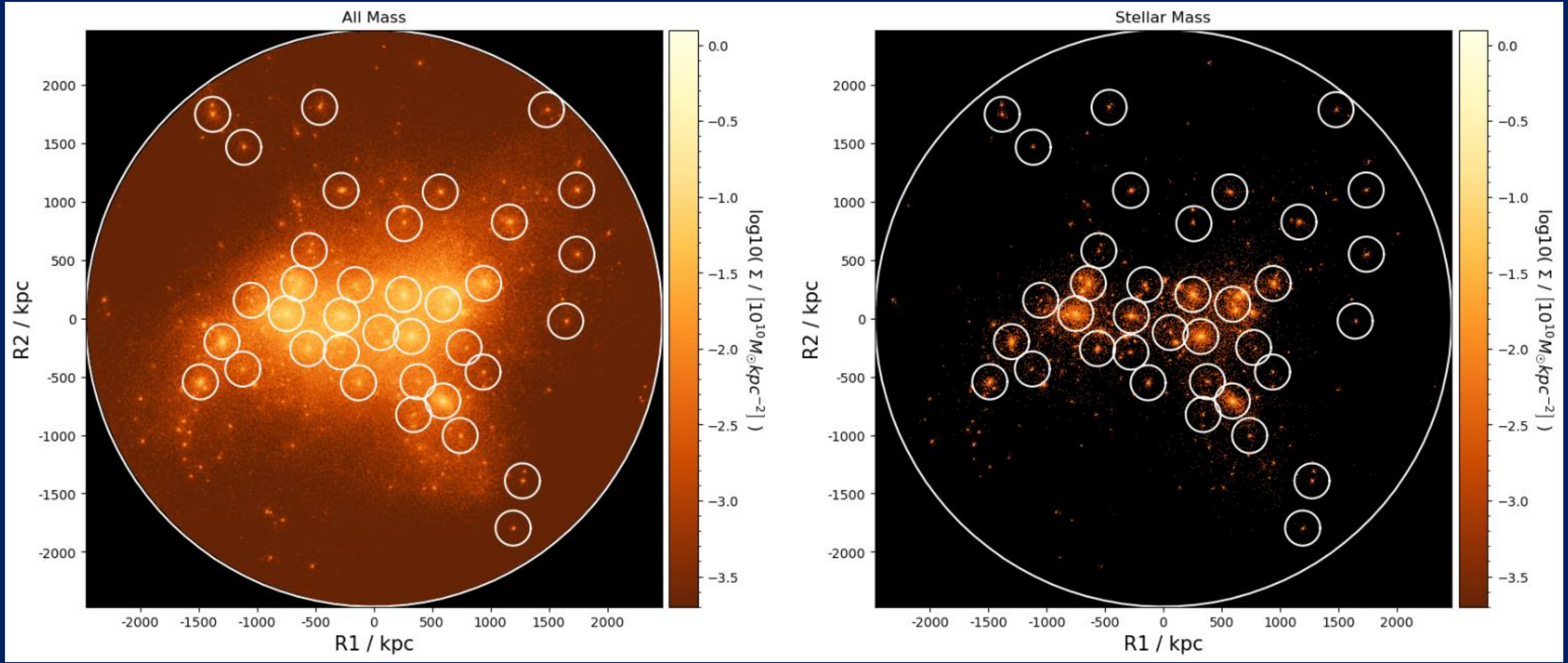
Kimmig et al., in prep.

I. Abell 2744: Substructures in Clusters



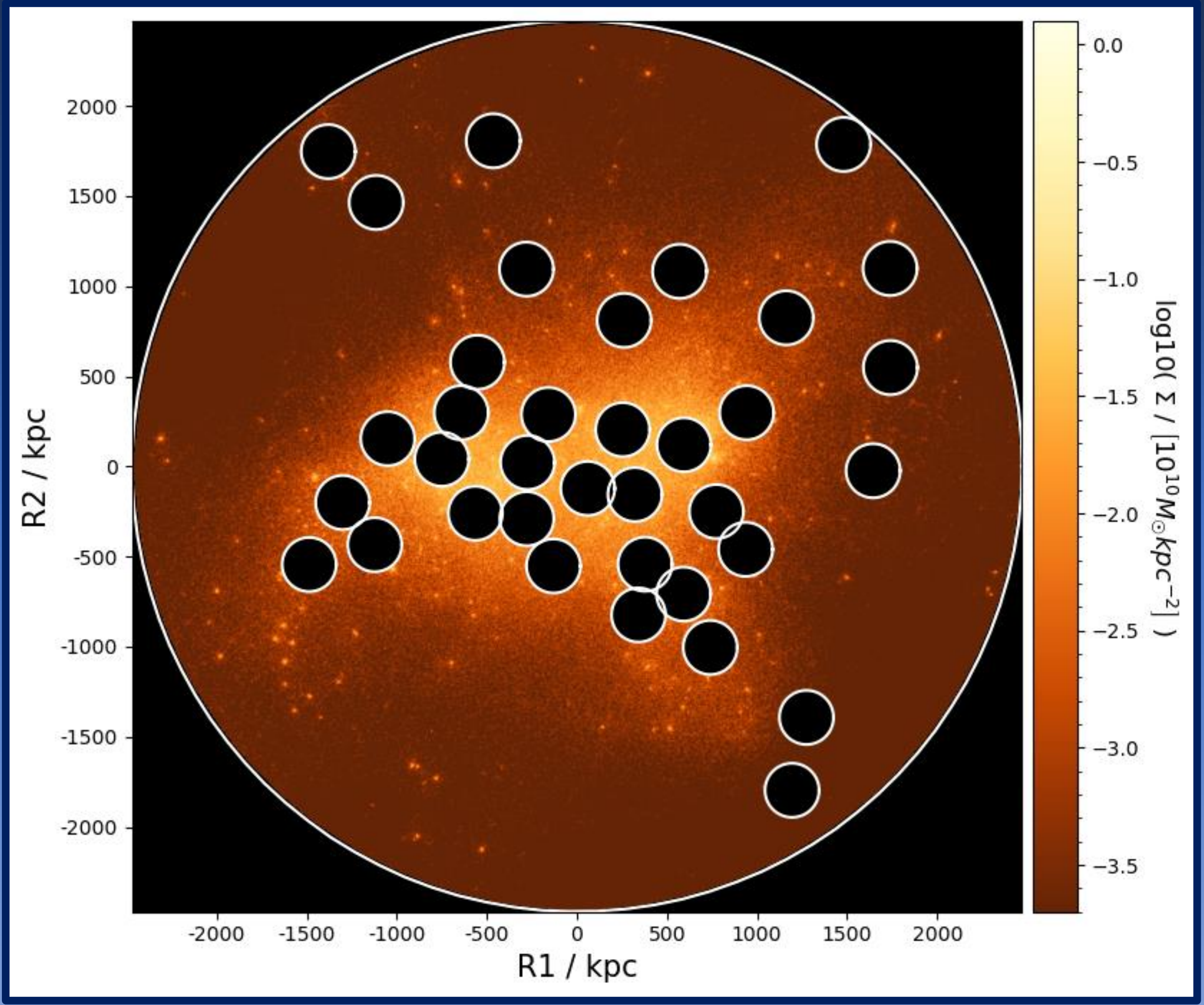
Kimmig et al., in prep.

I. Abell 2744: Substructures in Clusters



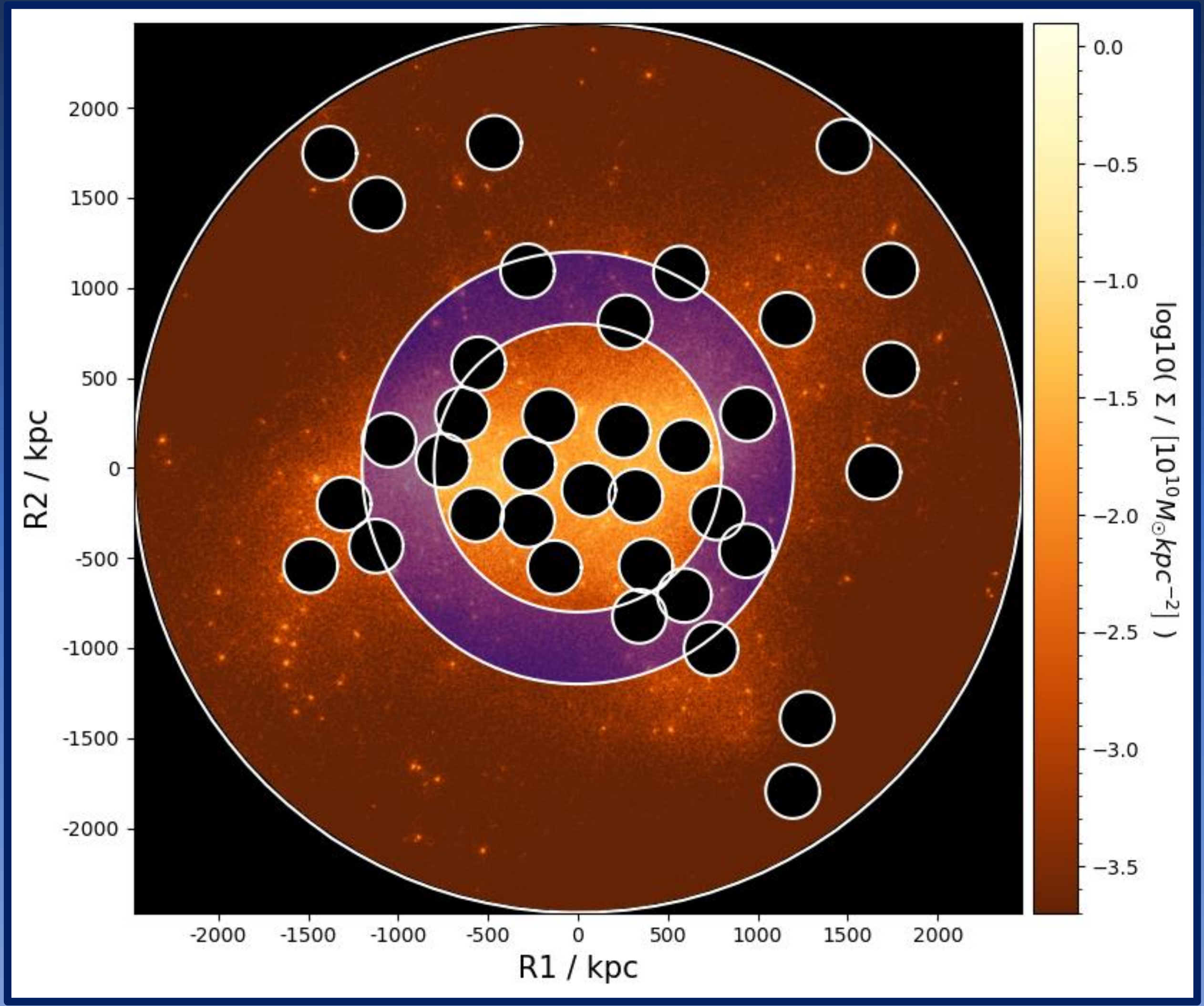
Kimmig et al., in prep.

I. Abell 2744: Substructures in Clusters



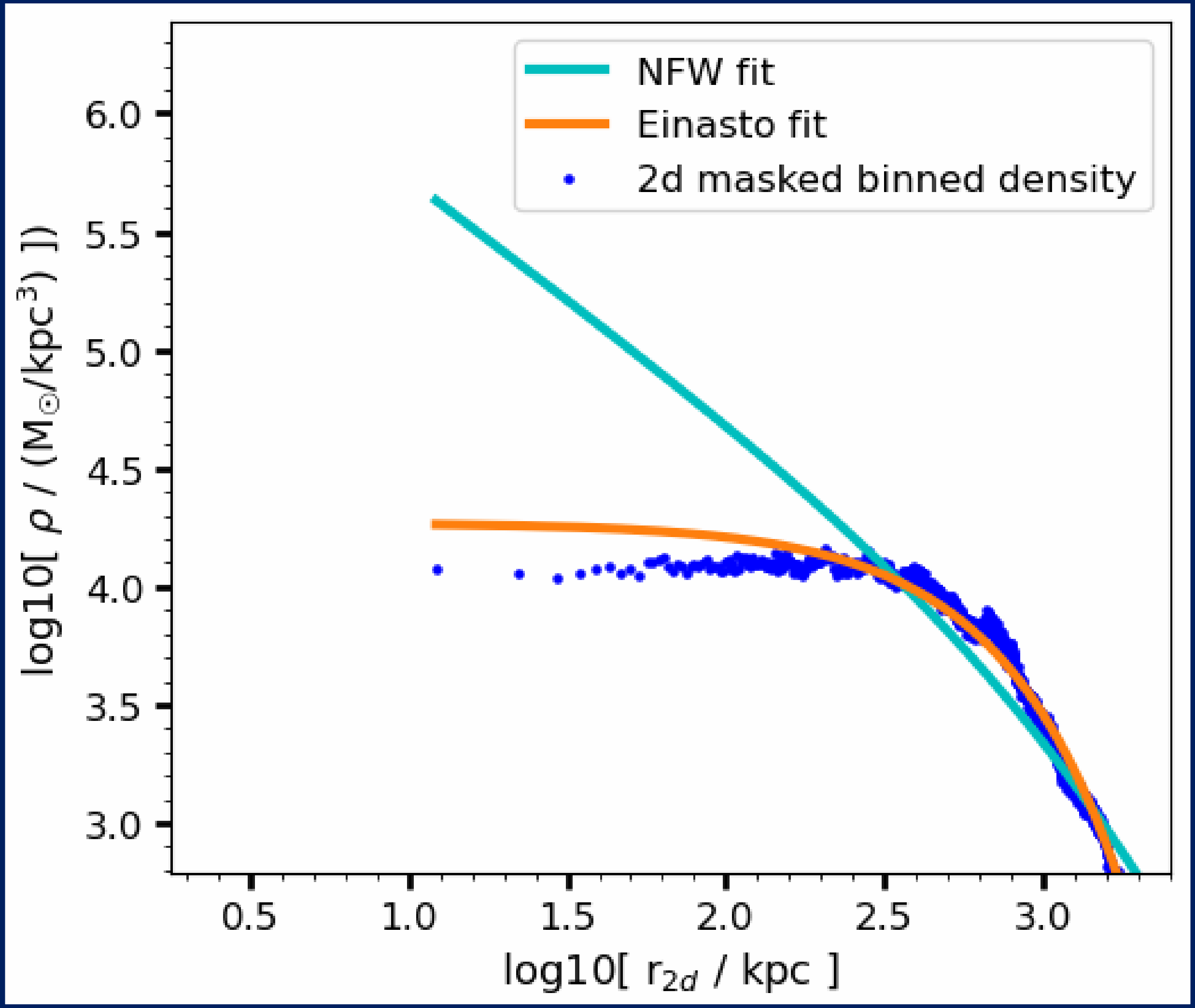
Kimmig et al., in prep.

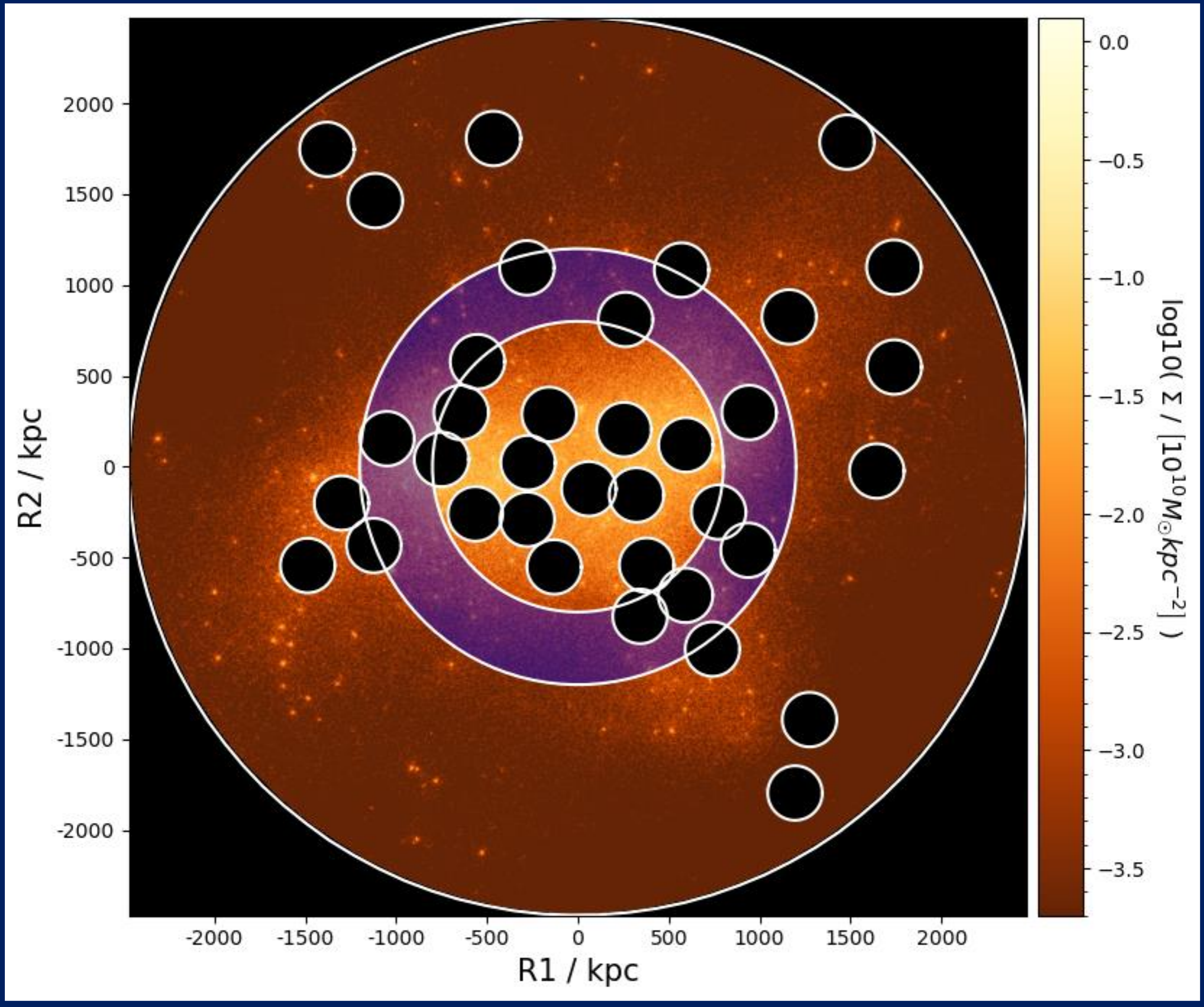
I. Abell 2744: Substructures in Clusters



Kimmig et al., in prep.

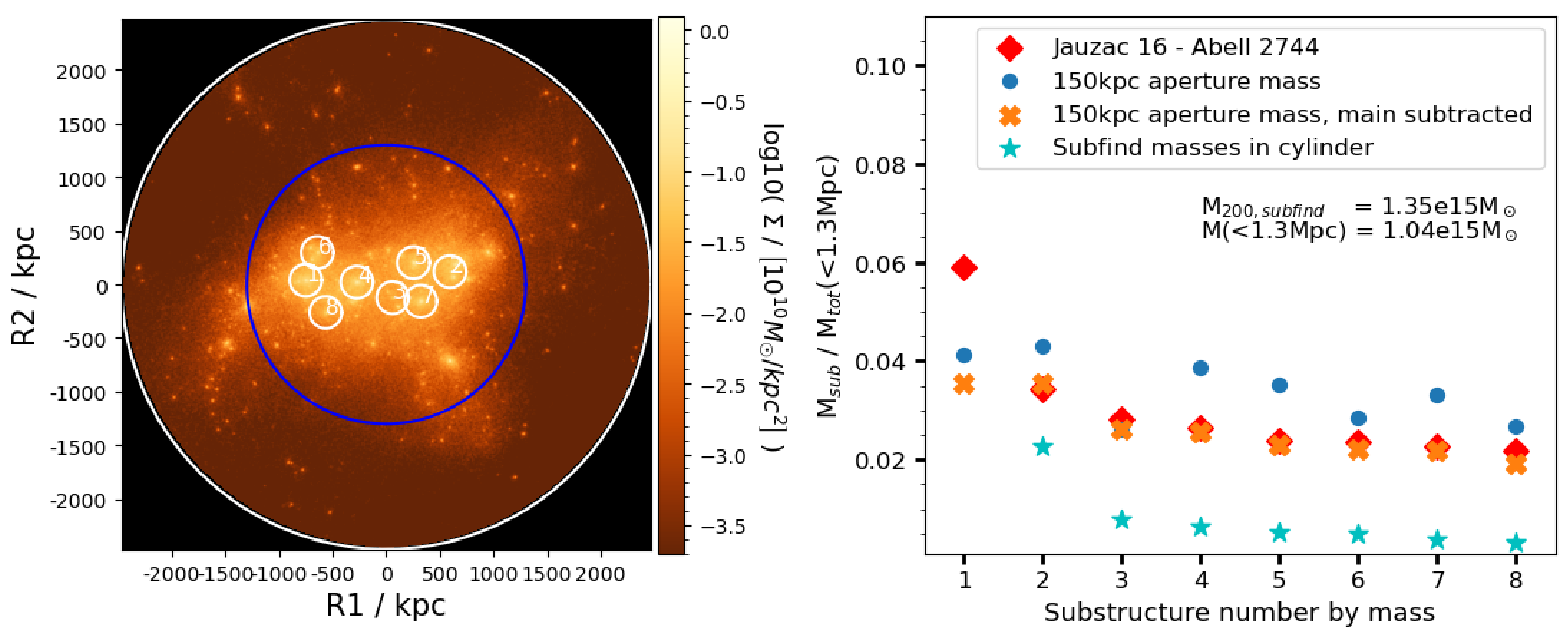
I. Abell 2744: Substructures in Clusters





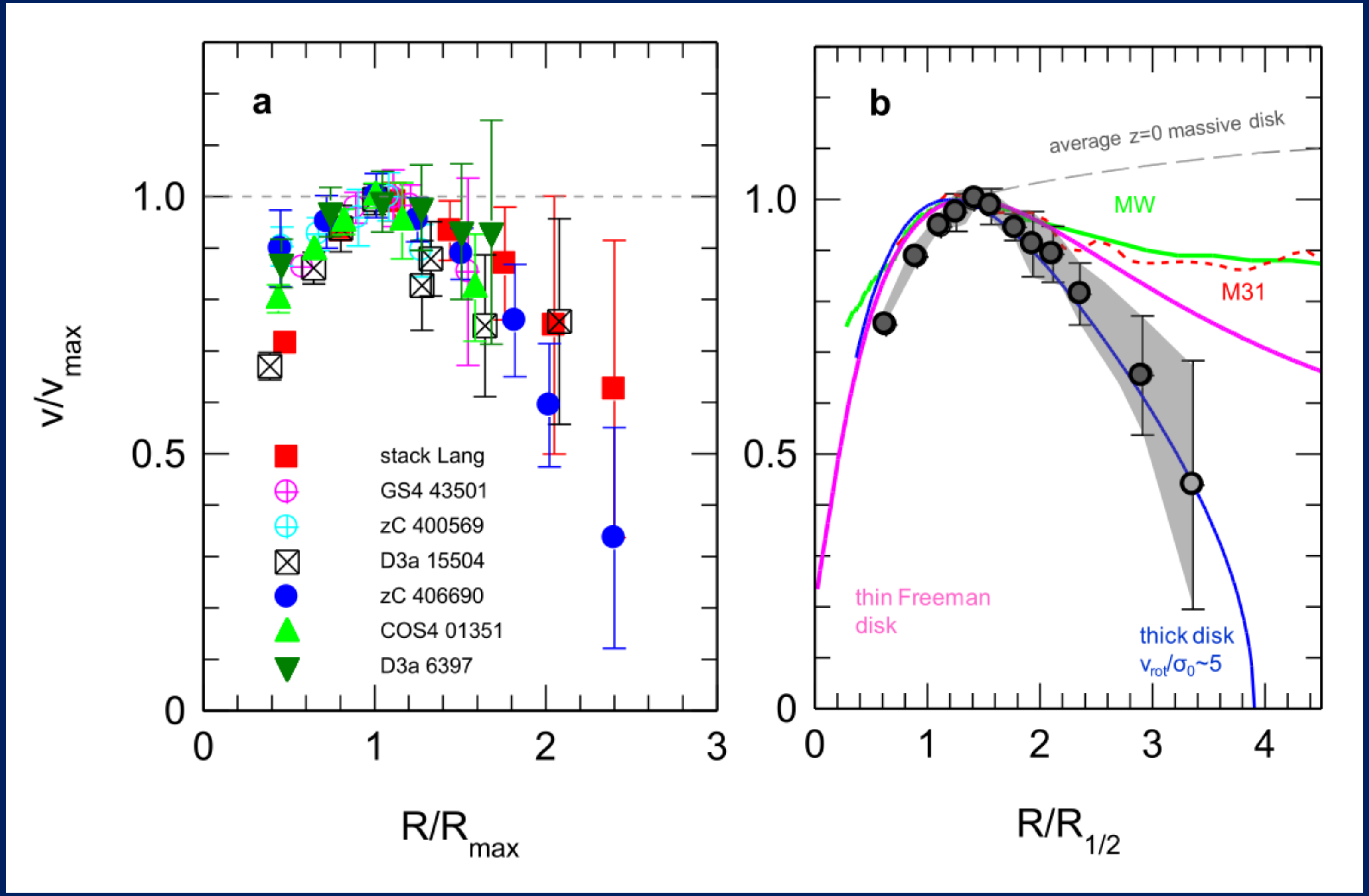
Kimmig et al., in prep.

I. Abell 2744: Substructures in Clusters



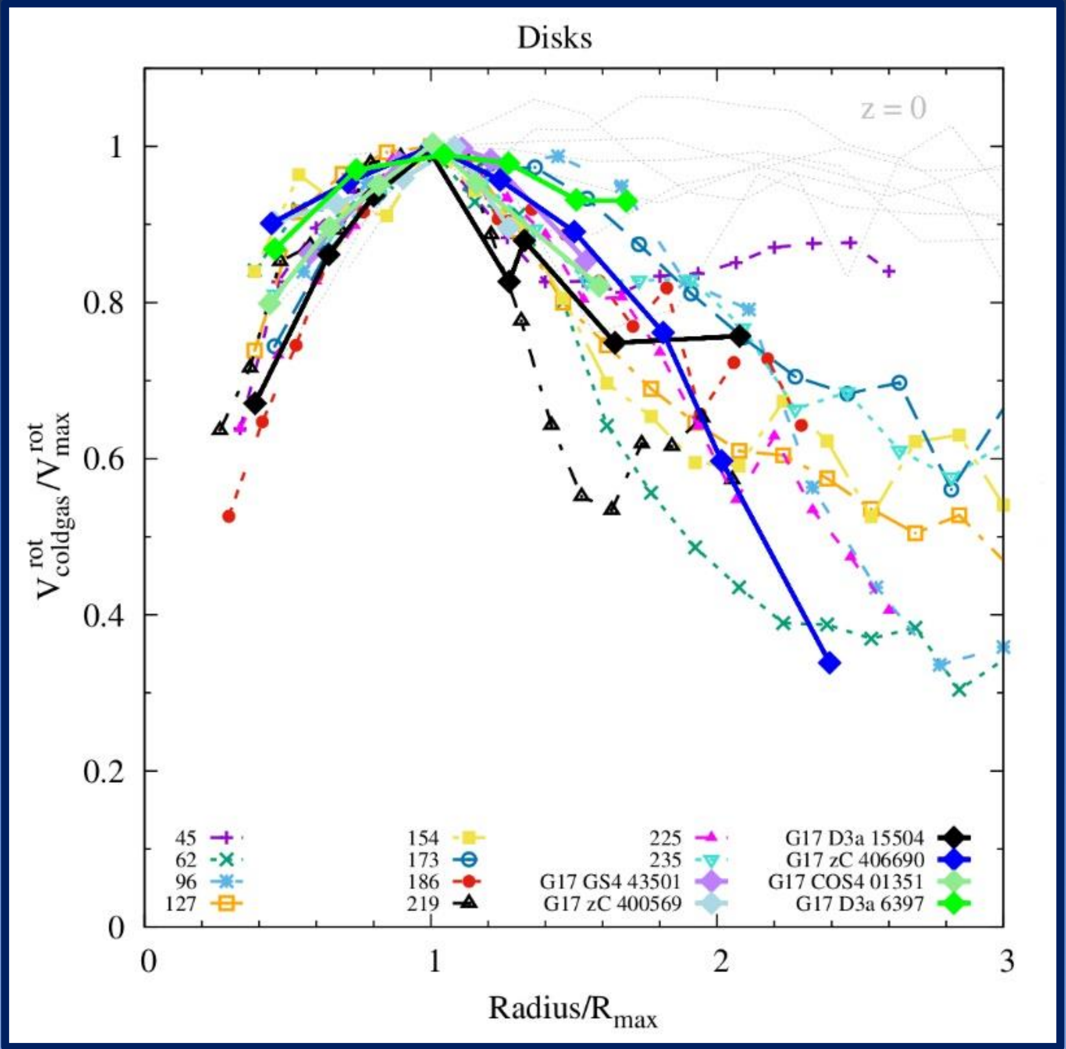
Kimmig et al., in prep.

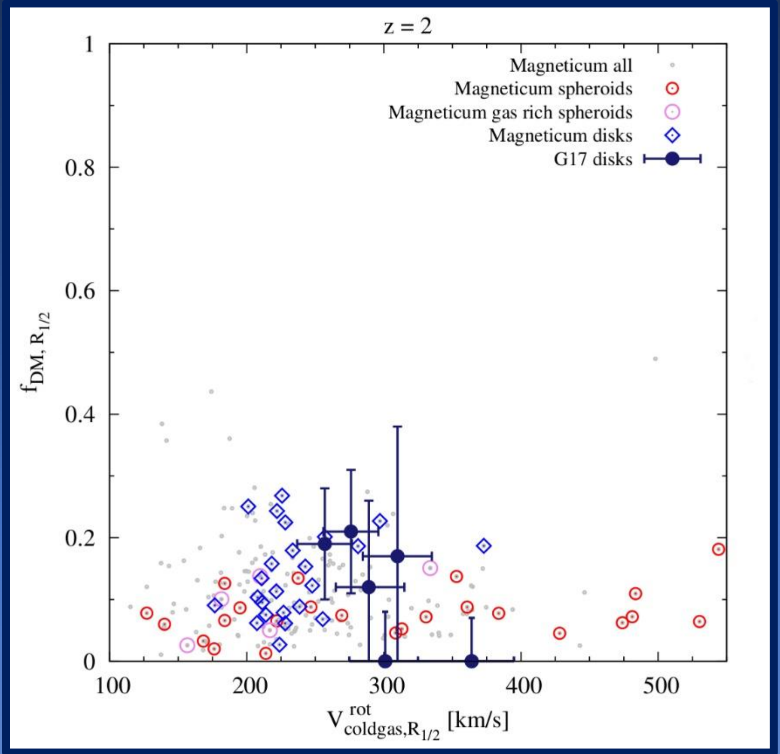
II. No Dark Matter in Disks at z=2?



Genzel et al., 2017

II. No Dark Matter in Disks at z=2?

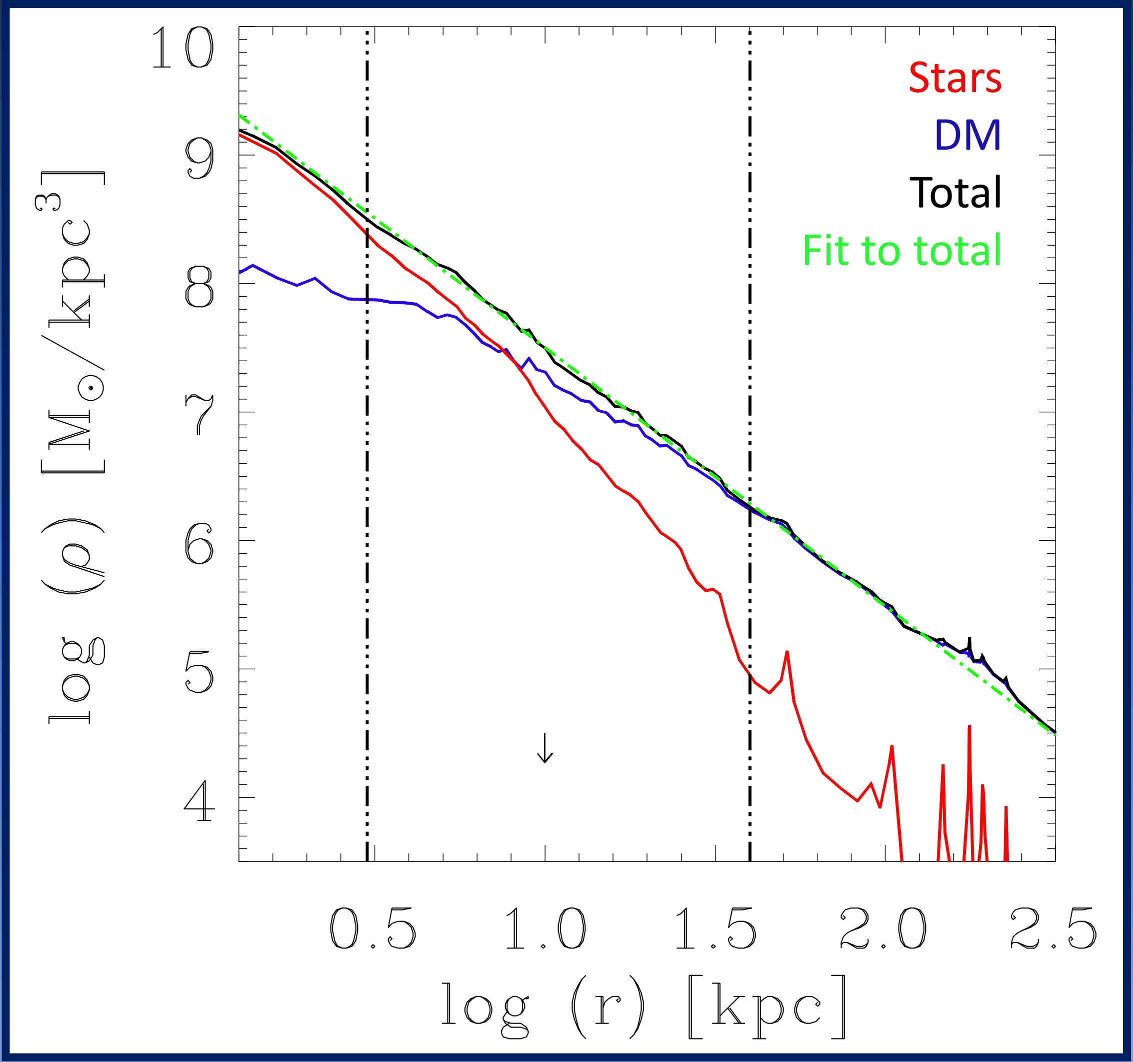




At z=2, approximately half of the Magneticum disk galaxies have declining rotation curves in agreement with observations by Genzel et al., 2017, and similar central dark matter fractions.

Teklu et al., 2018

III. Total Density Slopes with Redshift



Total radial density profiles can be fit by a single power law.

Inner part: Stars dominate the total profiles.

Outer part: Dark Matter dominates the total profiles.

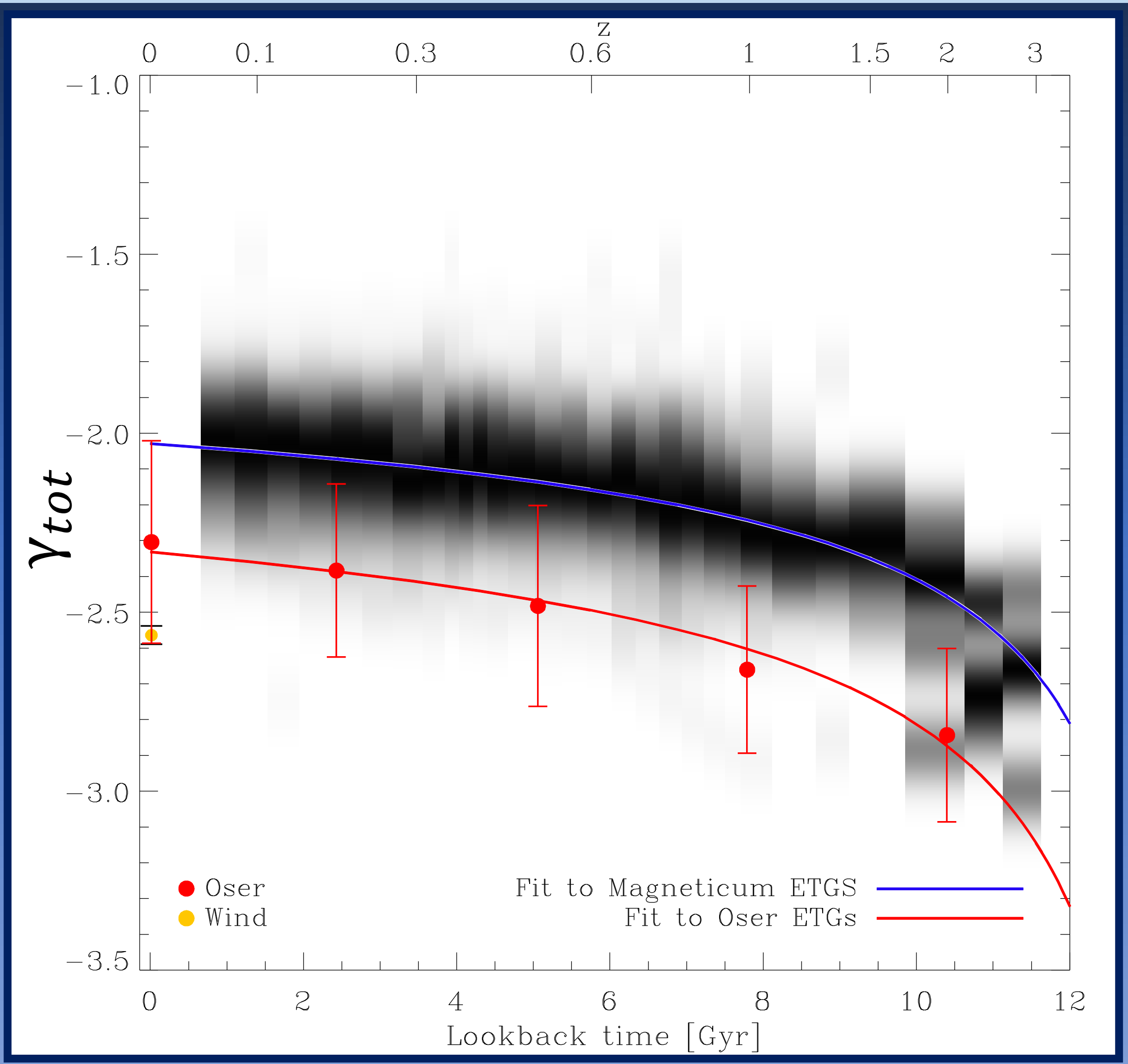
$$\gamma = \frac{\mathrm{d}\log(\rho)}{\mathrm{d}\log(r)}$$

Most ETGs have slopes close to isothermal, i.e. $\gamma_{tot} \approx -2$, but they can be as steep as $\gamma_{tot} \approx -3$.

➡ This is independent of the included feedback models

Remus et al., 2013, 2017

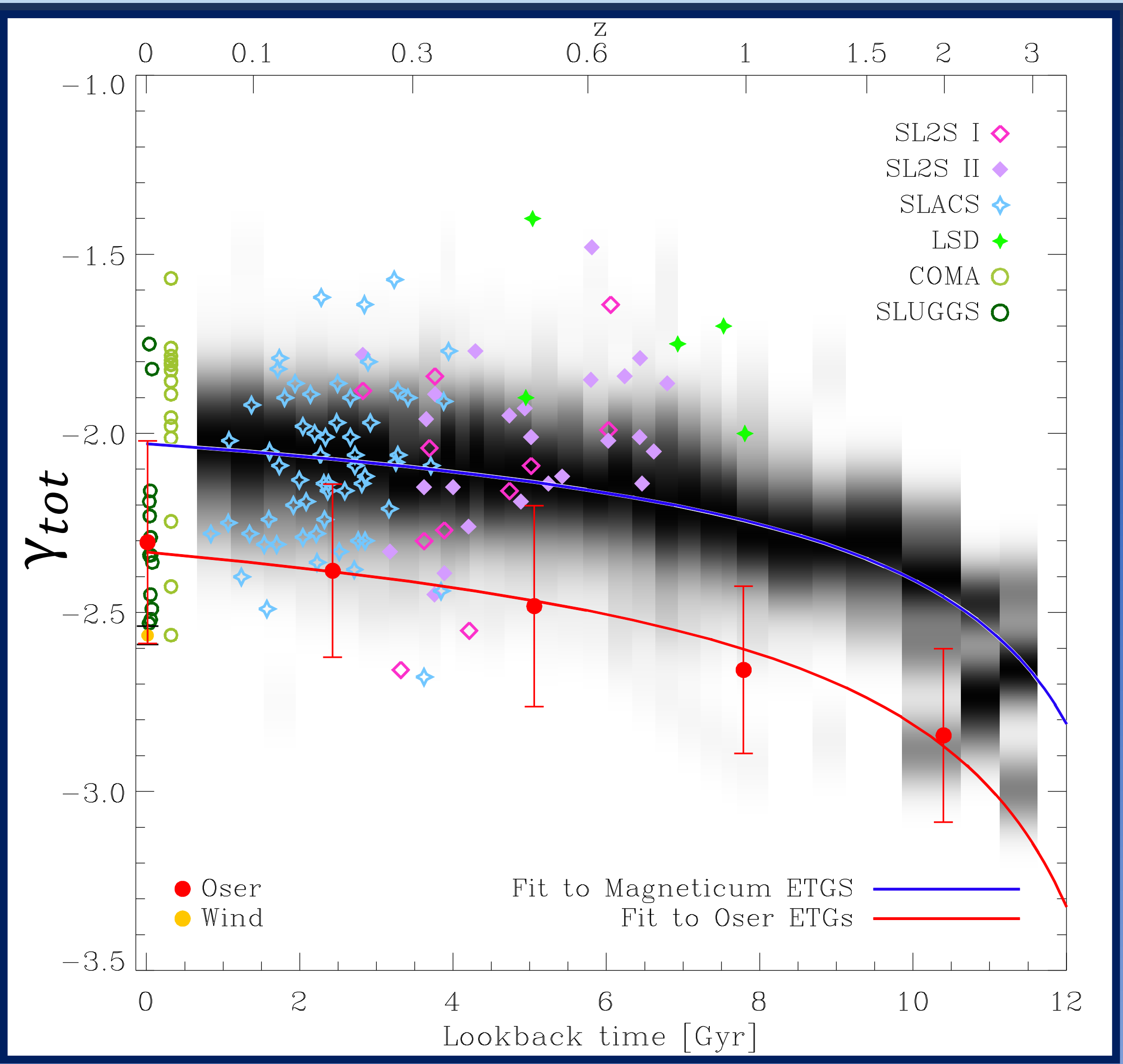
III. Total Density Slopes with Redshift



The power-law slope becomes generally steeper with time

Remus et al., 2017

III. Total Density Slopes with Redshift



Strong Lensing Observations:

- SL2S:
  - Ruff et al. 2011
  - Sonnenfeld et al. 2013
- SLACS: Auger et al. 2010
- LSD: Treu & Koopmans 2004

Strong Lensing indicates an opposite trend to simulations

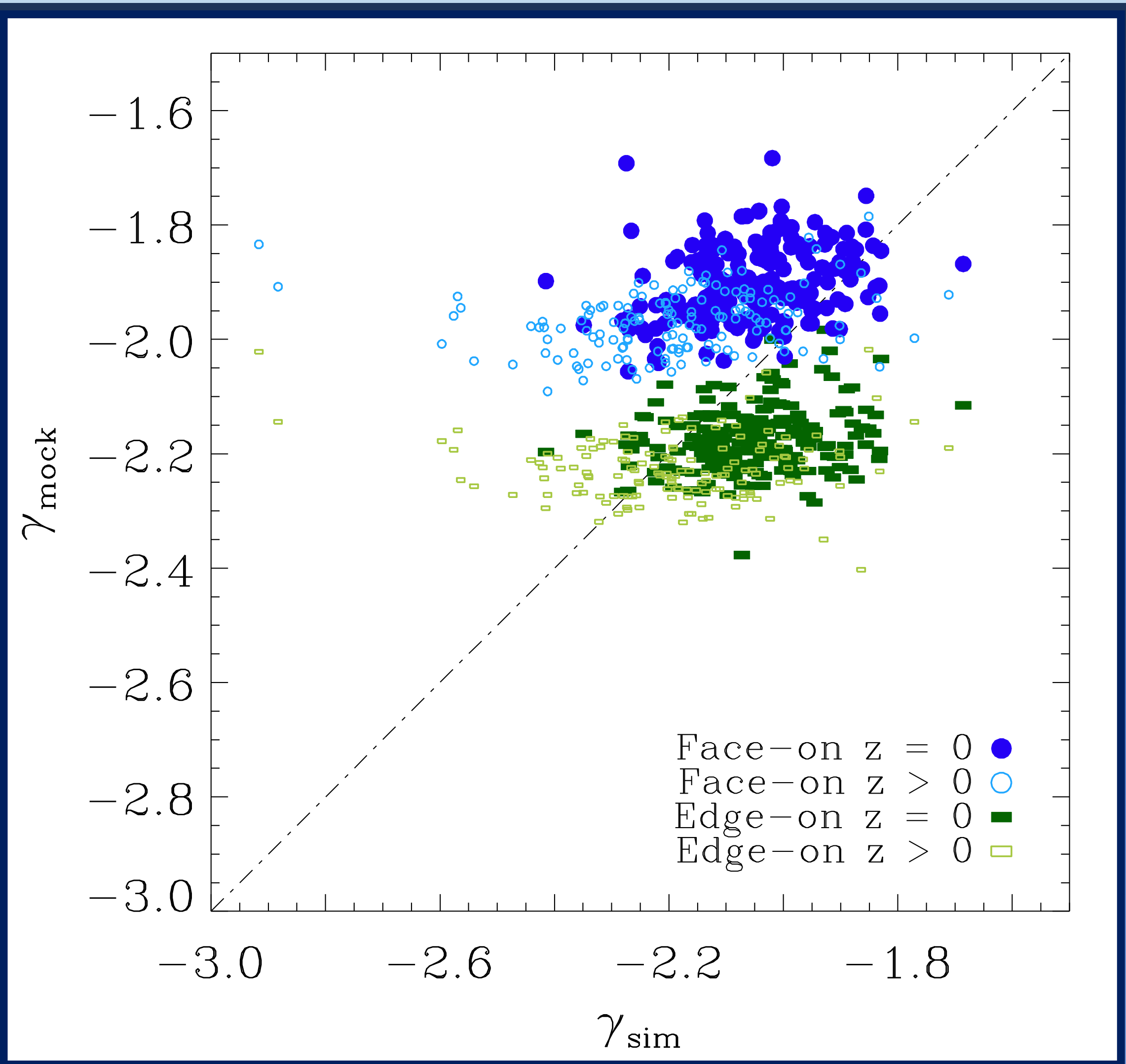
Dynamical Modelling:

- Coma Cluster: Thomas et al. 2007
- SLUGGS: Cappellari et al. 2015

Dynamical Modelling is in good agreement, but only available at low redshift

Remus et al., 2017

III. Total Density Slopes with Redshift



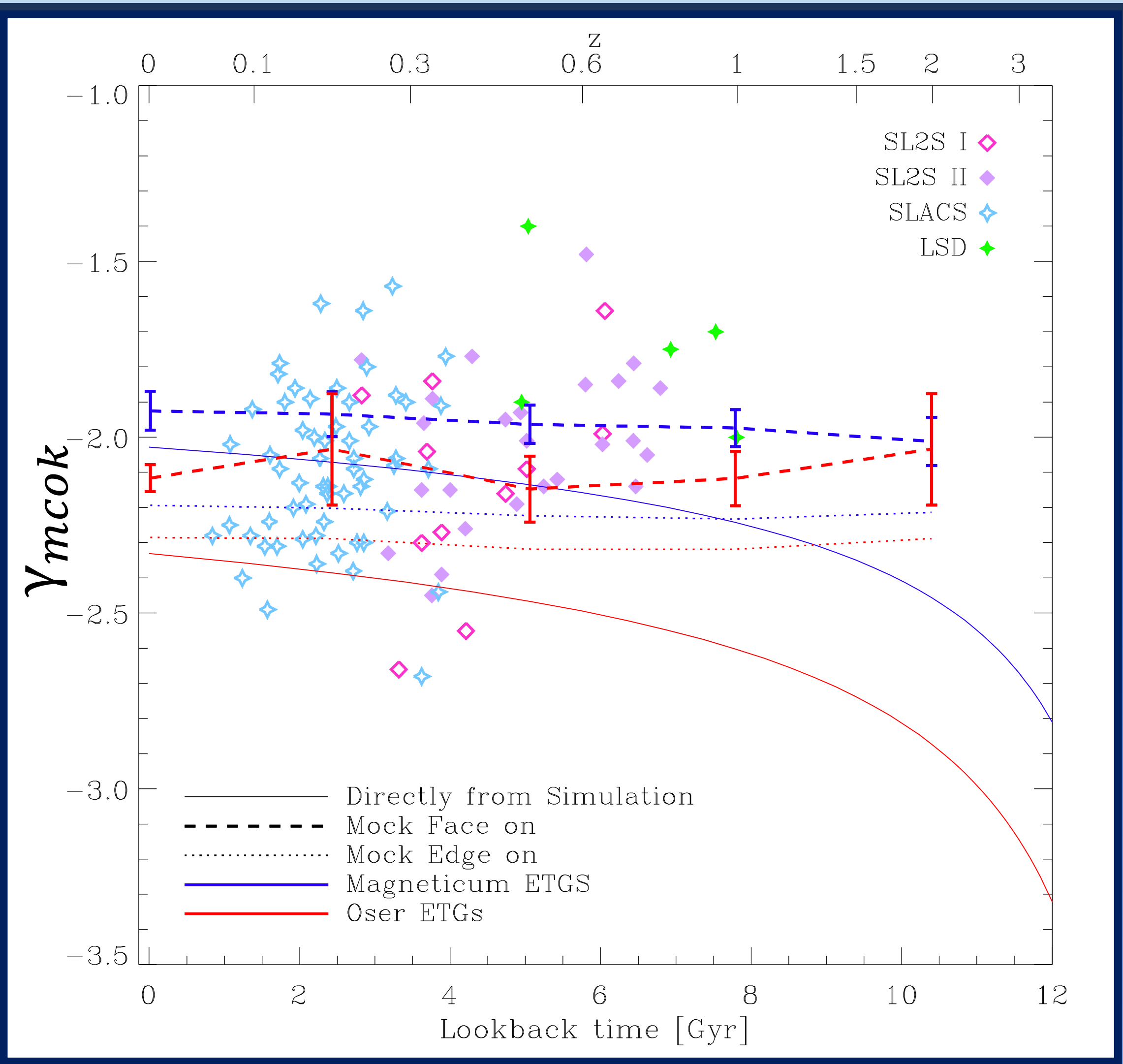
Remus et al., 2017

"Mocking" the simulated ETGs:

- $M_{tot}(R_{Ein})$
- $R_{eff} \rightarrow R_{1/2}$
- R_{Ein} = 1.5 $R_{1/2}$ following Sonnenfeld et al., 2013
- $\sigma_{LOS}(R_{1/2}/2)$

Program kindly provided by A. Sonnenfeld, see Sonnenfeld et al., 2013,2015a,b

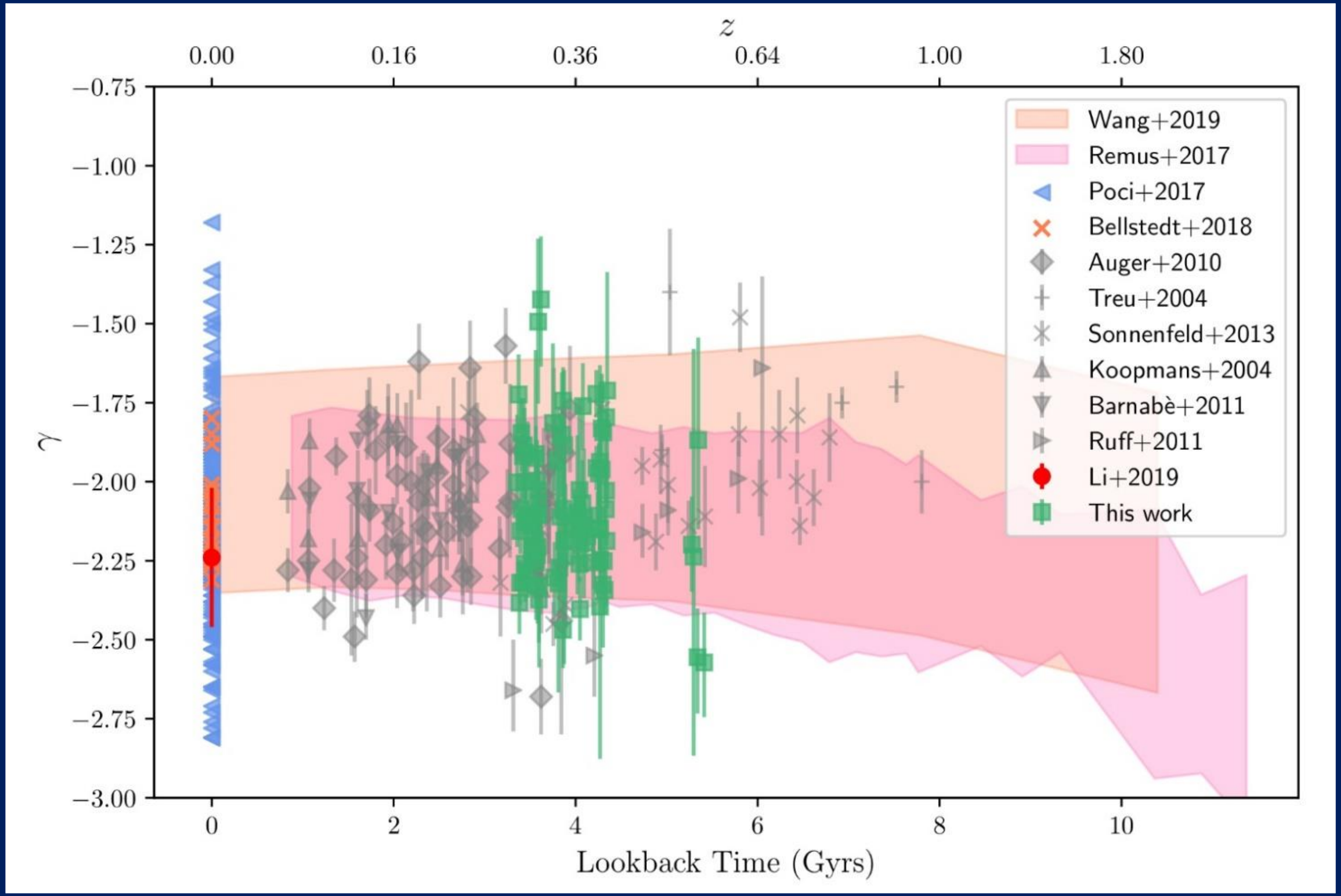
III. Total Density Slopes with Redshift



We find the same redshift evolution trend as the strong lensing observations if we use the observers' program to mock our simulated ETGs

Remus et al., 2017

III. Total Density Slopes with Redshift

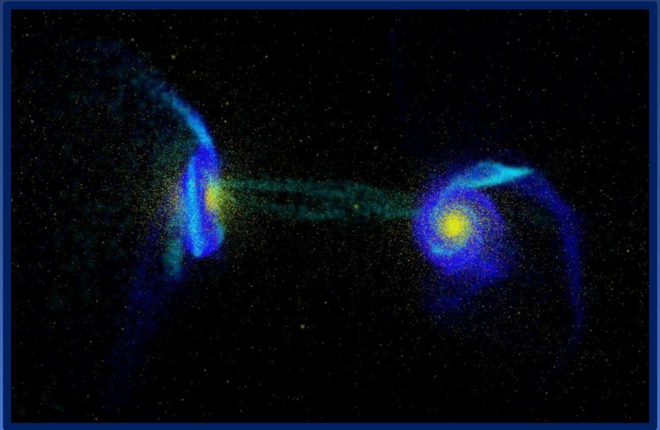


Kinematic measurements now confirm simulation trends

Derkenne et al., 2021

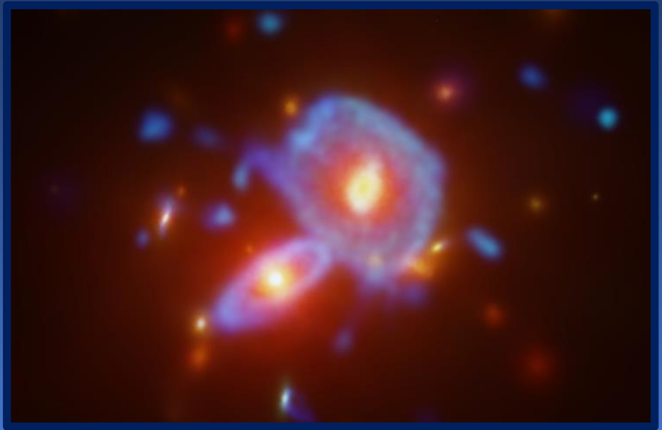
Overview: Galaxy Formation Simulations

Isolated Merger Simulations



There are a lot of different idealized merger simulations, but most of them do not have a fancy name

Cosmological Zoom-Simulations



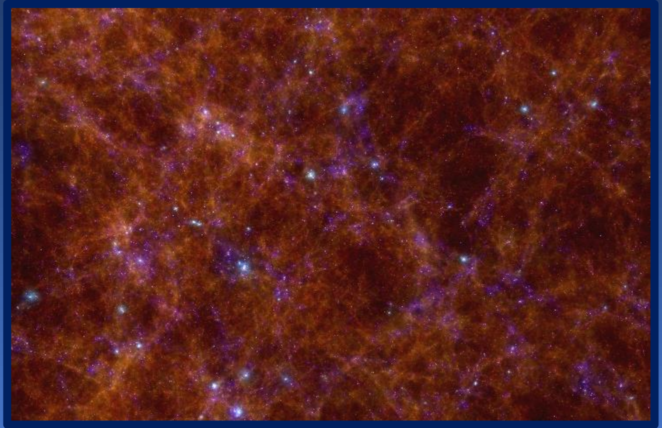
Galaxies (Dwarf to Groups)

- Oser/Naab
- NiHAO
- Fire
- Aquarius
- E-Mosaics

Clusters:

- The 300 Project
- CEagle/Hydrangea
- Romulus-C

Cosmological Box Simulations

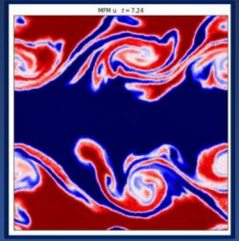


Fully Hydrodynamical

- Eagle
- Magneticum
- HorizonAGN
- Illustris/IllustrisTNG
- MassiveBlack

Summary

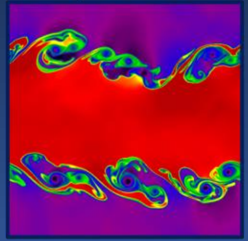
Smooth Particle Hydrodyn.



- ✓ Very good conservation properties (mass, momentum, total energy, angular momentum, entropy)
- ✓ shape invariant

- Instabilities do not grow sufficiently
- Mixing behind shocks not sufficient
- Shocks captured by artificial viscosity

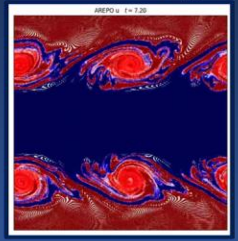
Adaptive Mesh Refinement



- ✓ Instabilities nicely grow
- ✓ Mixing between phases works well

- Energy conservation issues (especially for fast moving elements)
- Flow over cell boundaries becomes an issue for adaptive meshs
- Not shape invariant

Moving Mesh



- ✓ All good things from the other two

- Flow over cell boundaries (only pseudo-Lagrangian)

Isolated Merger Simulations

+ high resolution (temporal & spatial)
+ controlled conditions
+ parameter study (orbits, masses...)

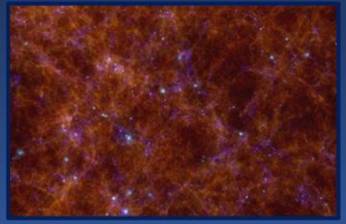
- no cosmological formation
- not statistical representative
- no redshift evolution

Cosmological Zoom-Simulations

+ high resolution (temporal & spatial)
+ cosmological formation
+ target objects (special environment...)

- biased selection of targets
- not statistical representative
- no parameter control

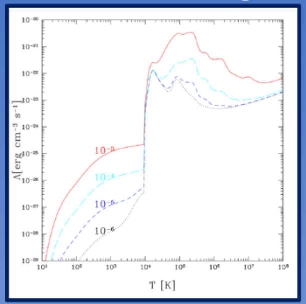
Cosmological Box Simulations



+ cosmological formation
+ statistical representative
+ no selection bias

- low resolution
- no parameter control
- computationally expensive

Cooling



Maio et al., 2007

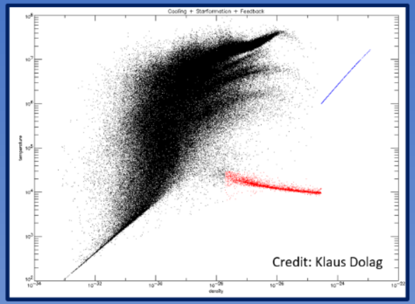
Basic Assumption:

- Optically thin
- Ionization equilibrium ($H, H^+, He, He^+, He^{++}, e^-$)
- 2-body processes ($\sim n^2$)

$\Lambda(T)/n^2$

BUT: Cooling Catastrophe

Star Formation

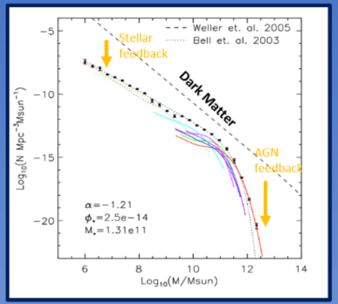


Star formation subgrid model:

- Self-regulated star formation
- Set of differential equations needs to be solved.
- Produces reasonable galaxies at low z

BUT: star formation rates at high z not captured

Feedback



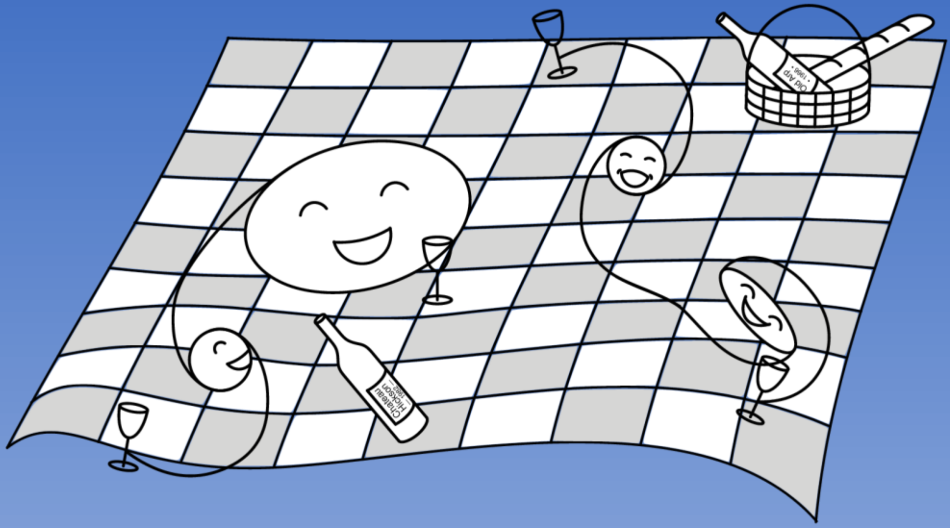
Read & Trentham 2005

Feedback comes from two different sources:

- Massive Stars and Supernovae
- Supermassive Black Holes (AGN)

Stops the Overcooling Catastrophe

BUT: Burns holes into disks



RgR