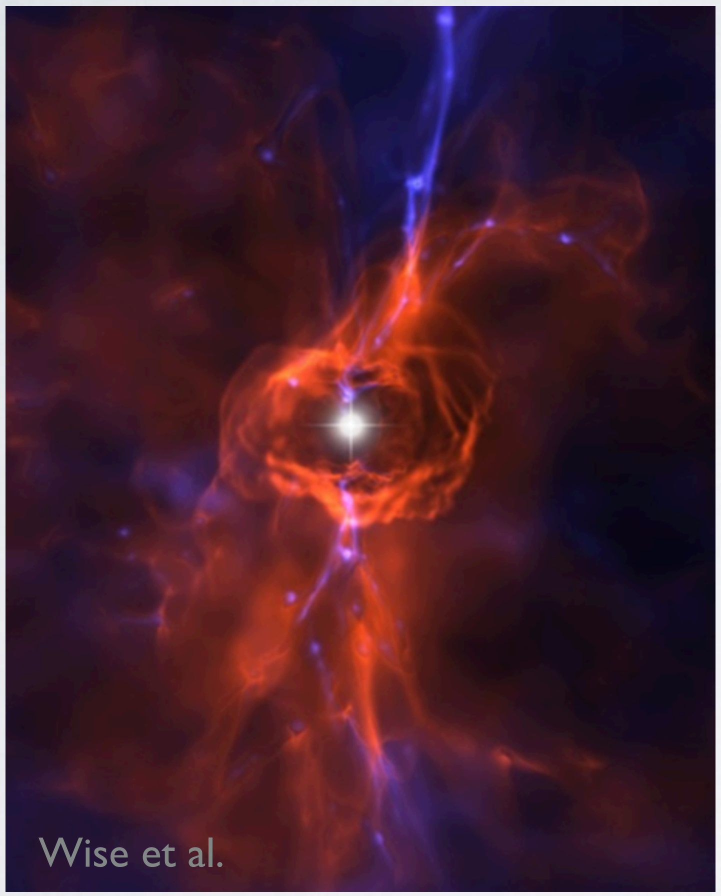
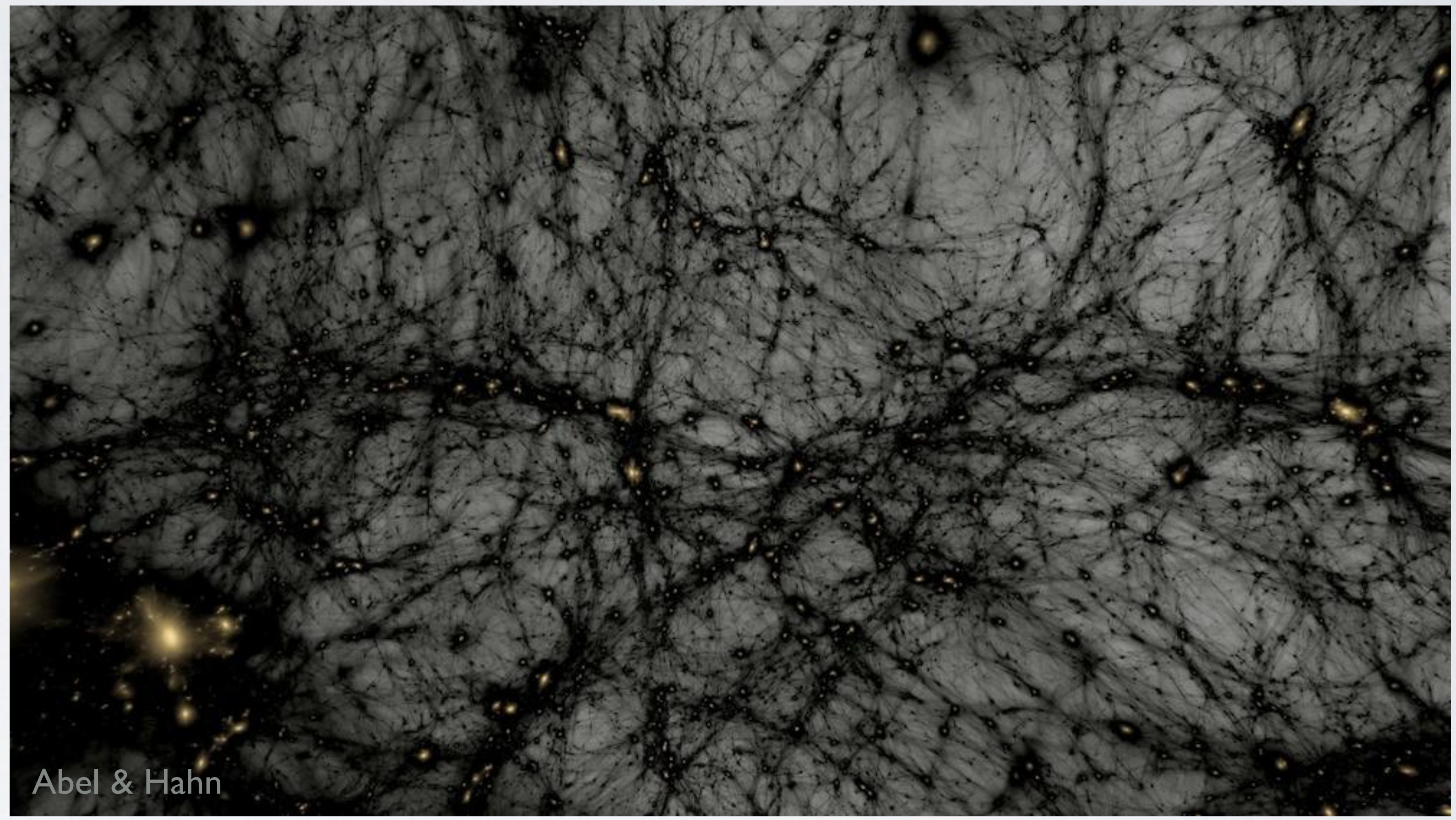
KIAS Astrophysics Summer School Lecture #1

Introduction to Computational Astrophysics

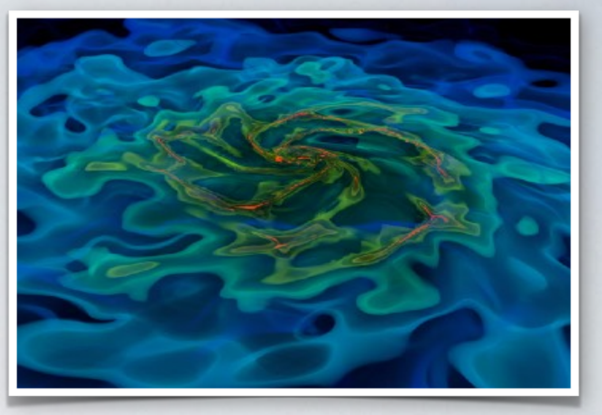




Ji-hoon Kim (Seoul National University)

Today's Lecture: Outline

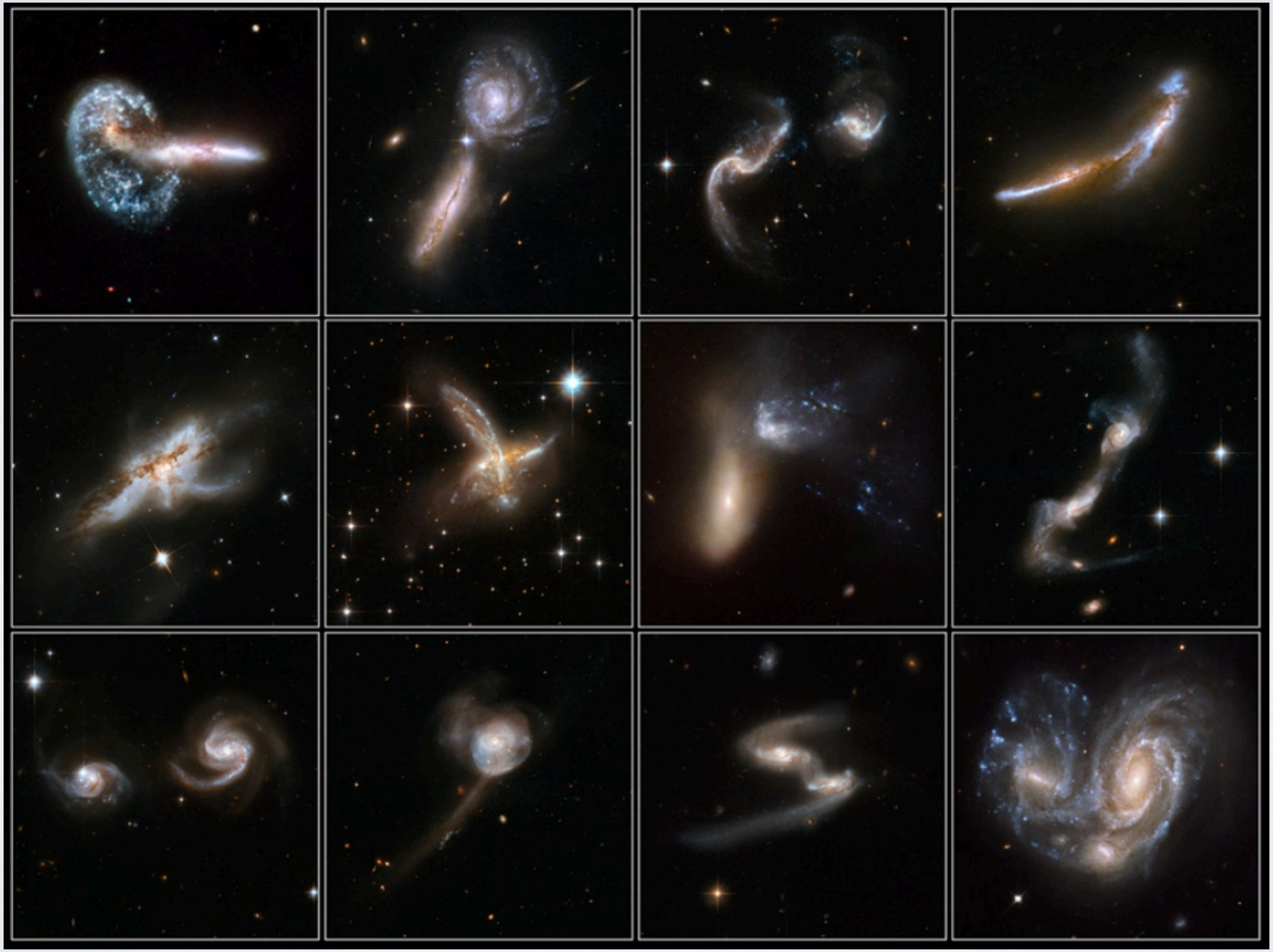
- Computational Astrophysics: Need and Examples
- Computational Astrophysics: Methodology
- Computational Astrophysics: Future Ahead



Computational Astrophysics: Why We Need It

Computational Cosmology: Need

- Observing the structure formation is humanly impossible, either.



HST

Computational Cosmology: Need

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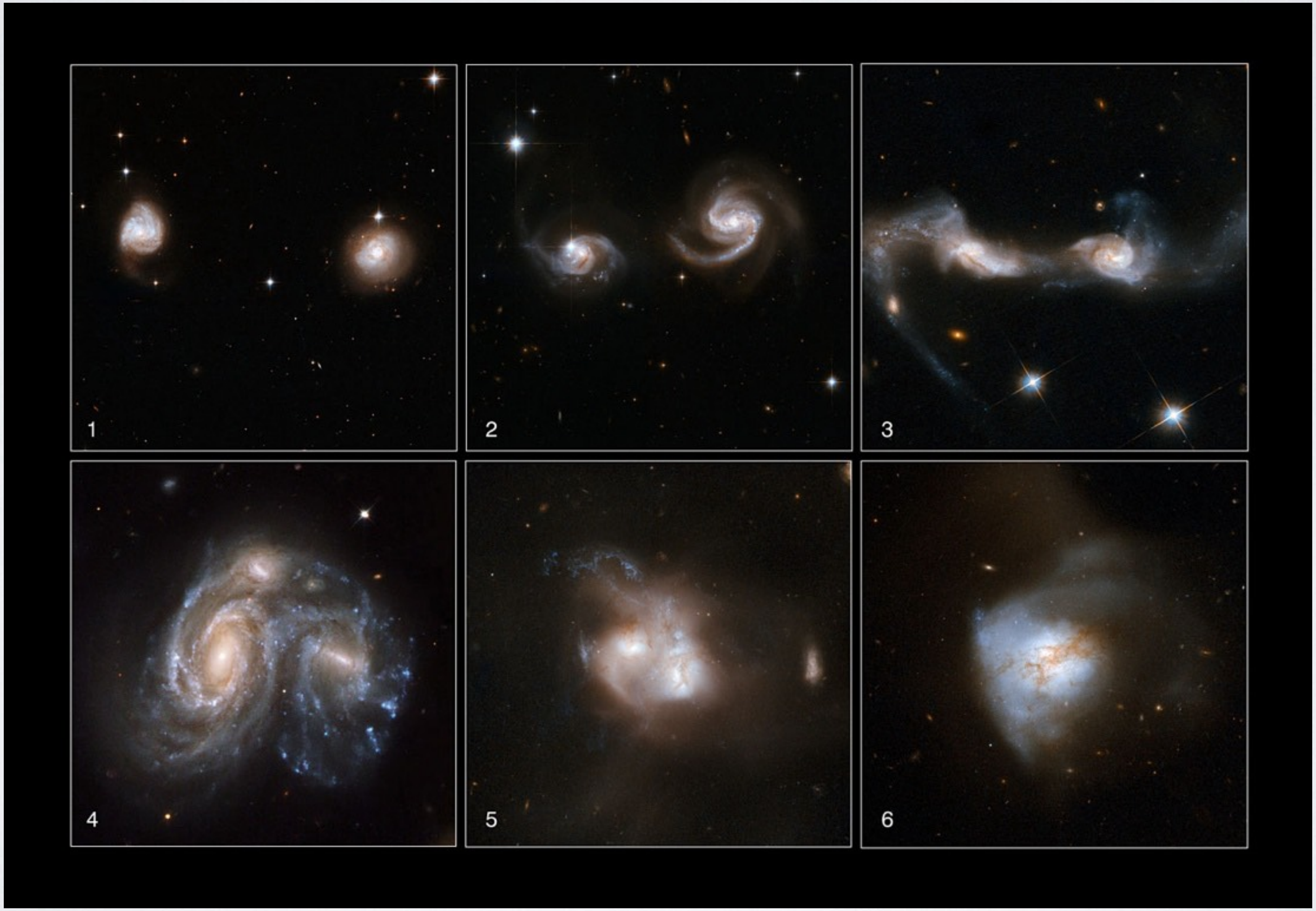
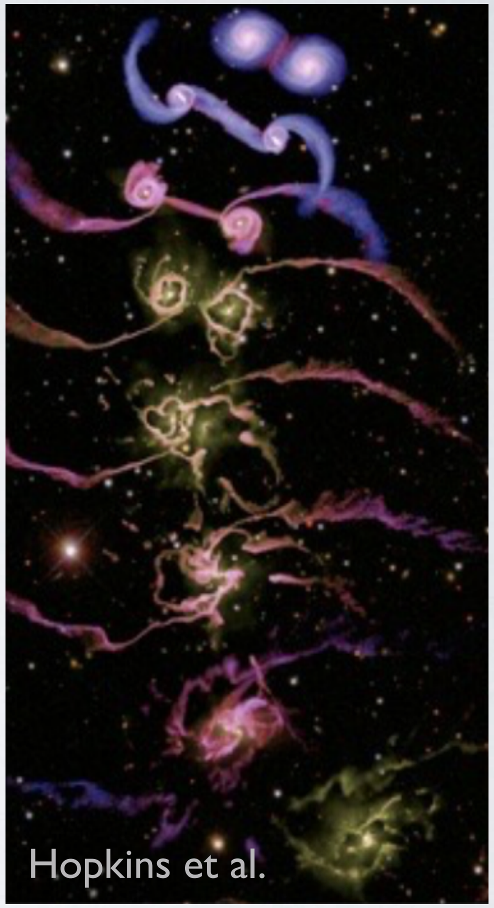


HST

Galaxy Merger Simulations

- If you want to see the whole process of galaxy mergers occurring in front of your eye, numerical simulation is the only way.

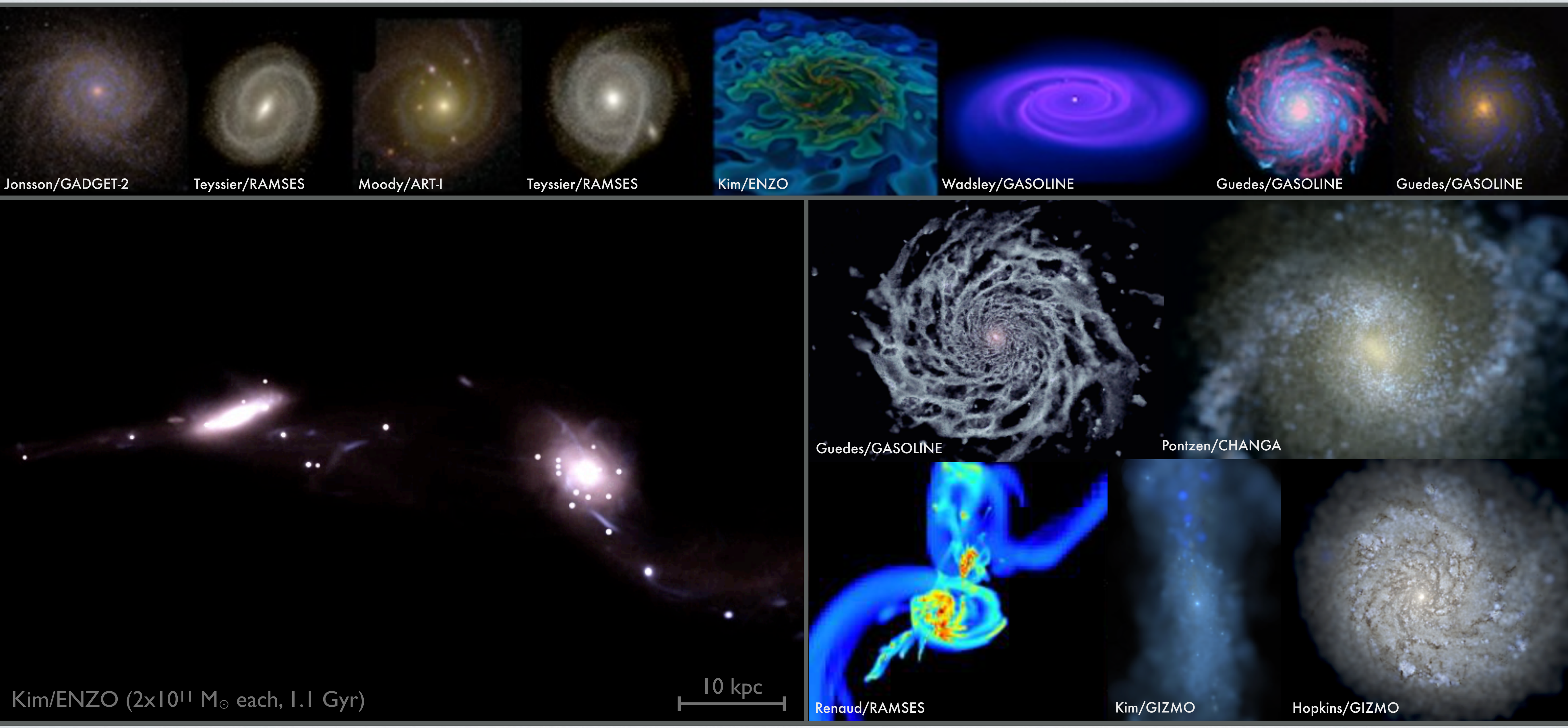
Merging of two galaxies 2x10^{11} M$_\odot$ each (Kim et al.)

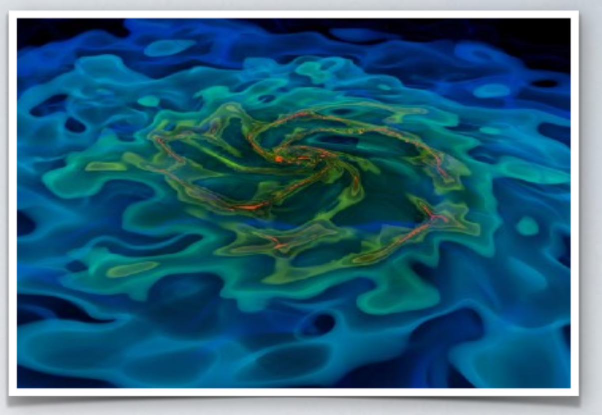


Hopkins et al.

Computational Cosmology: Need

- Numerical experiment essential due to nonlinear nature of structure formation → only tool to test theory against observations

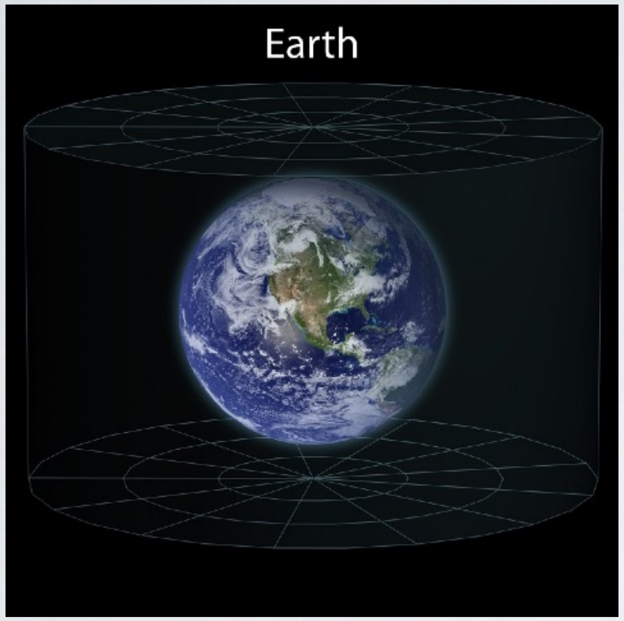




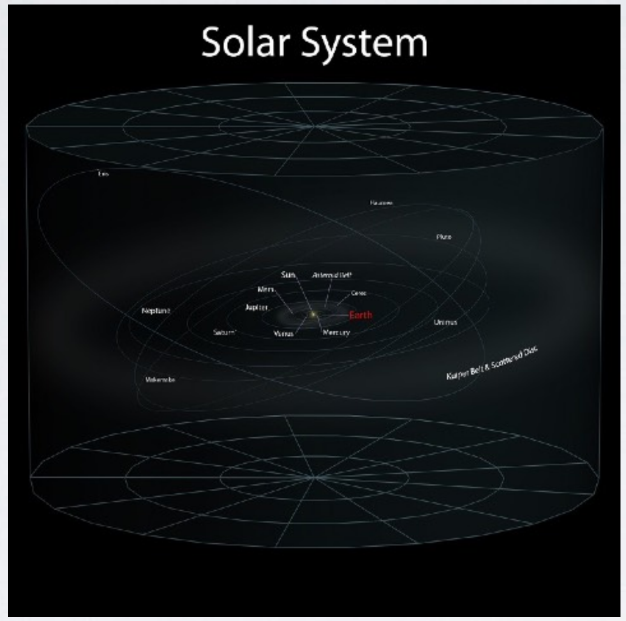
Computational Astrophysics: Examples

Scales of Cosmological Objects

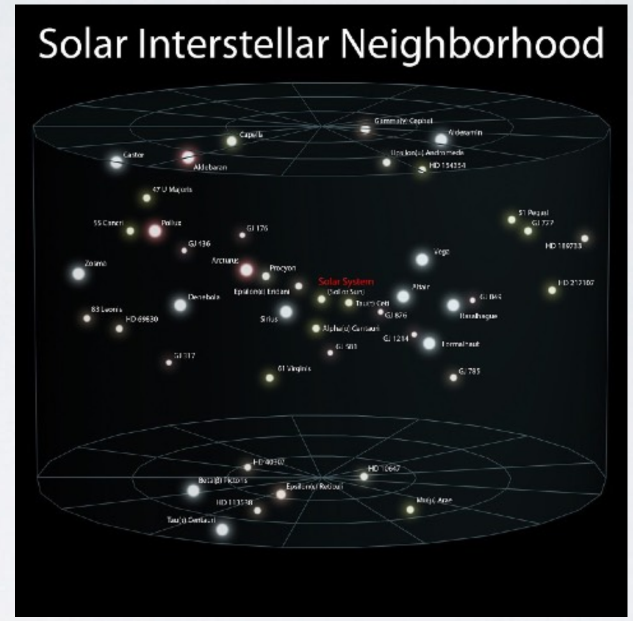
R_E



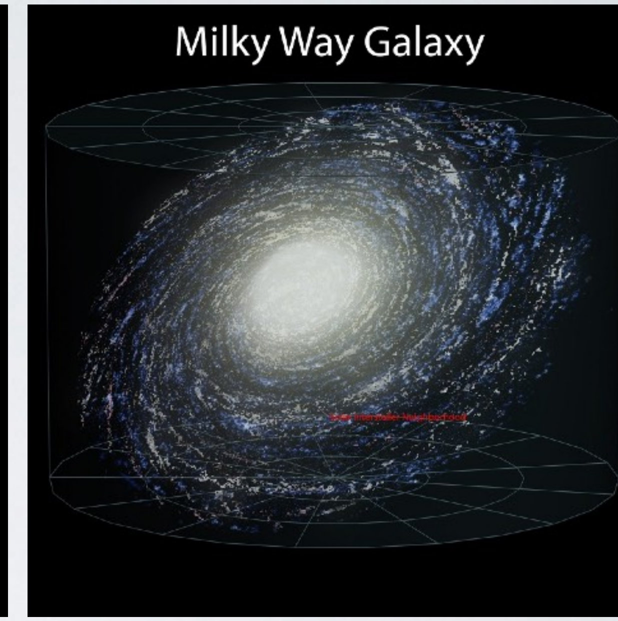
AU ~ $10^2 R_S \sim 10^4 R_E$



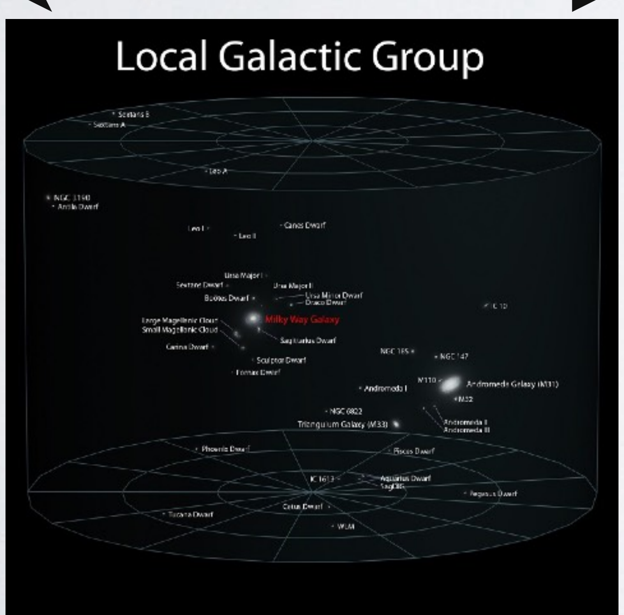
pc ~ 10^5 AU



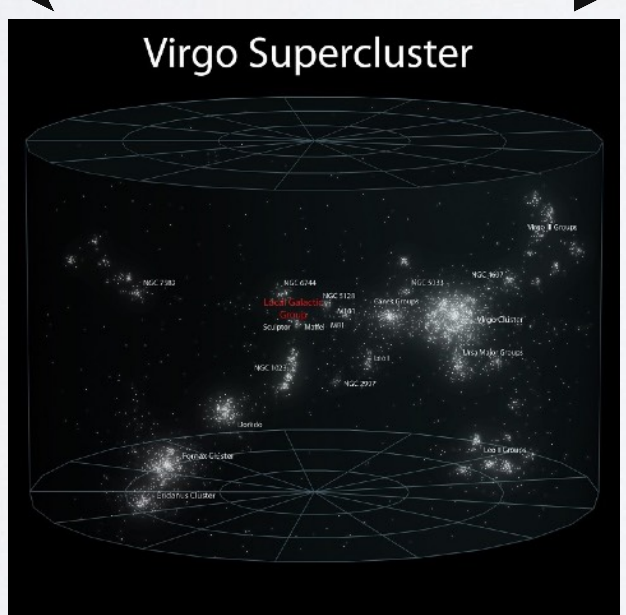
~ 10 kpc



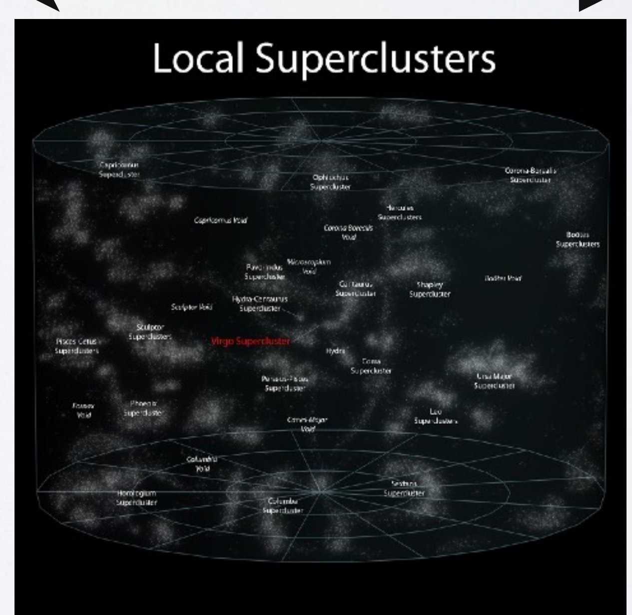
~ Mpc



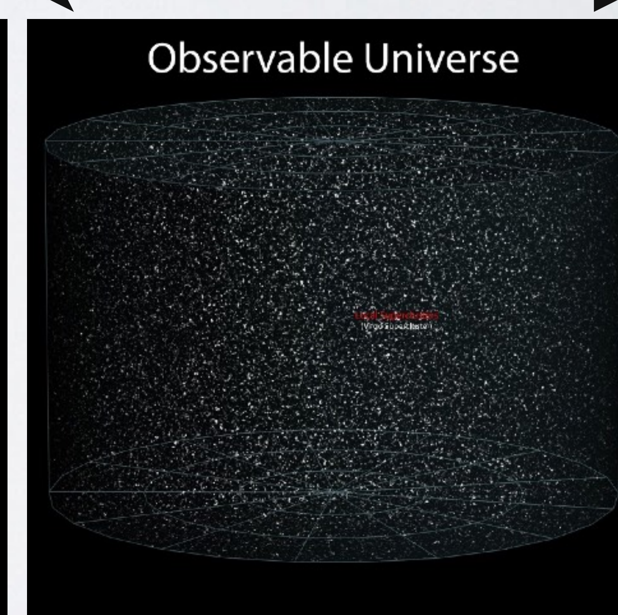
~ 10^2 Mpc



~ Gpc



~ 10 Gpc

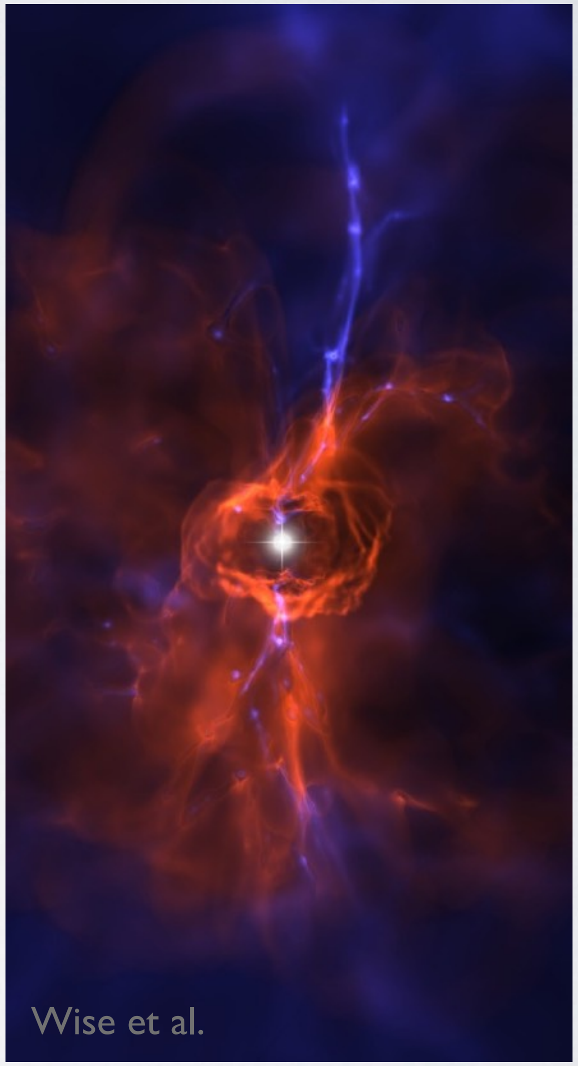


NASA/JPL/Colvin

First Stars and First Galaxies

- In the bottom-up structure formation scenario in which CDM produces small-scale powers, massive stars form first (~10^2 $M_\odot$).

Birth of a Population III star (Wise et al.)



Wise et al.

First Stars and First Galaxies

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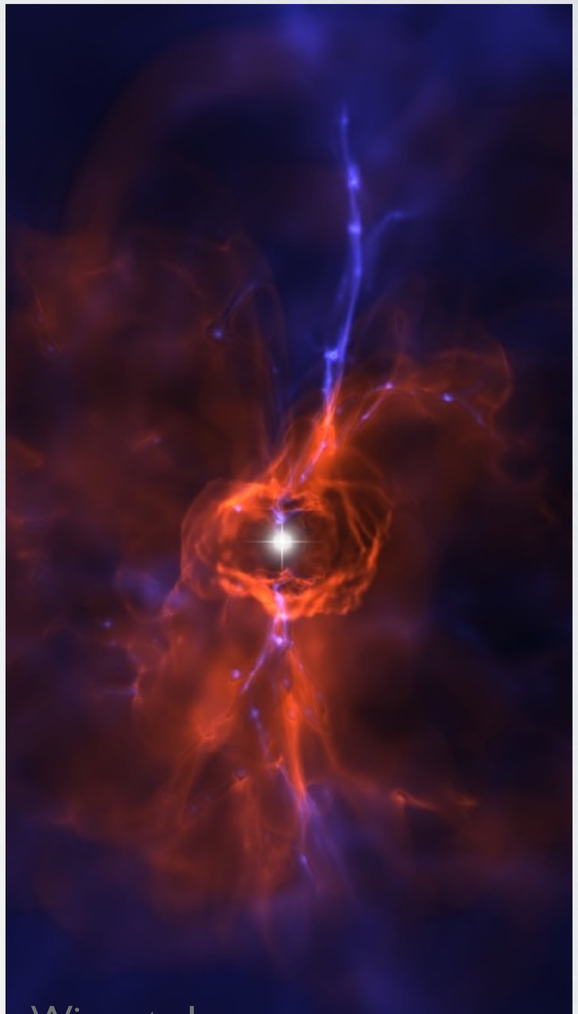
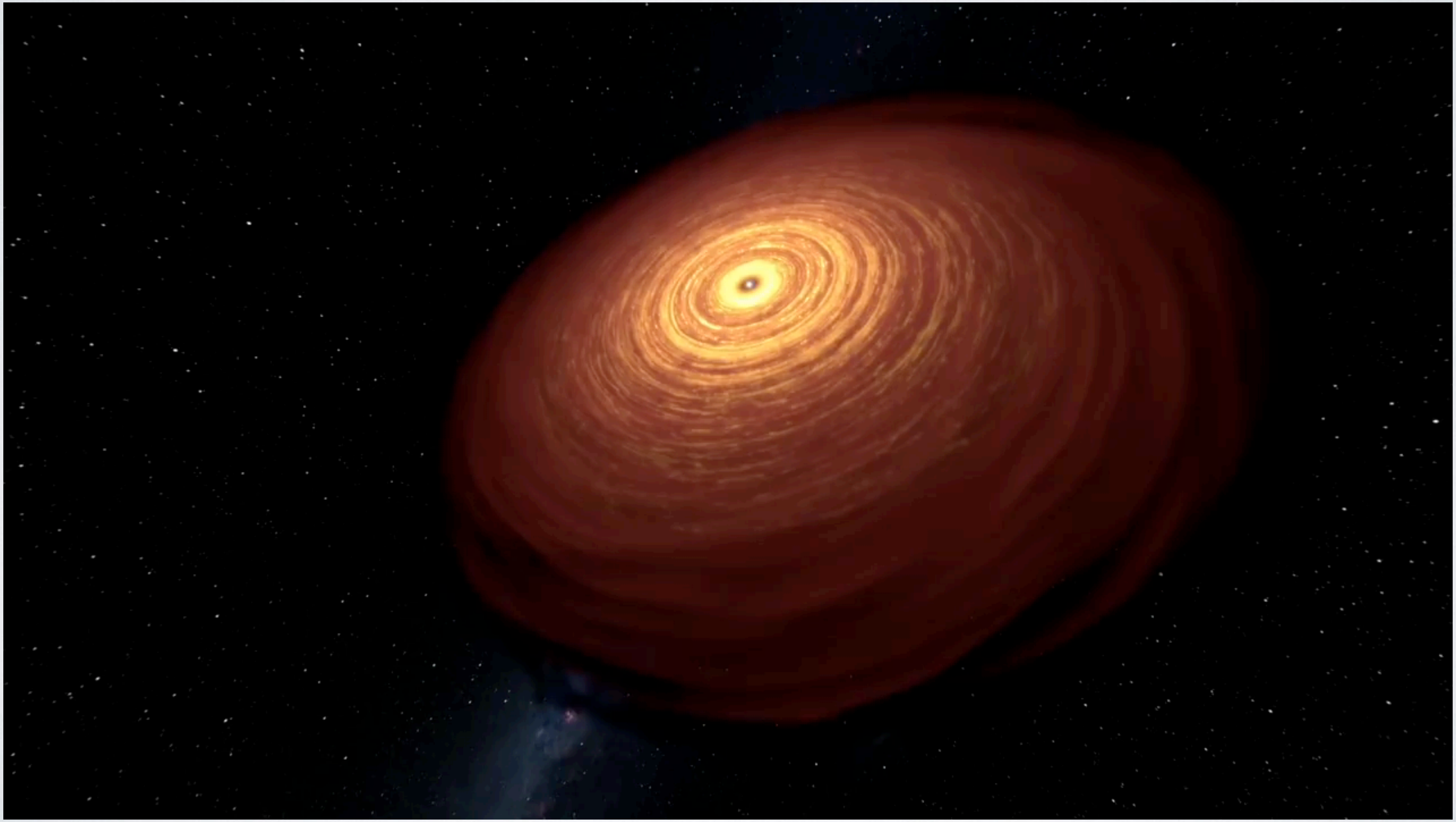


Wise et al.

Planet and Planetary System Formation

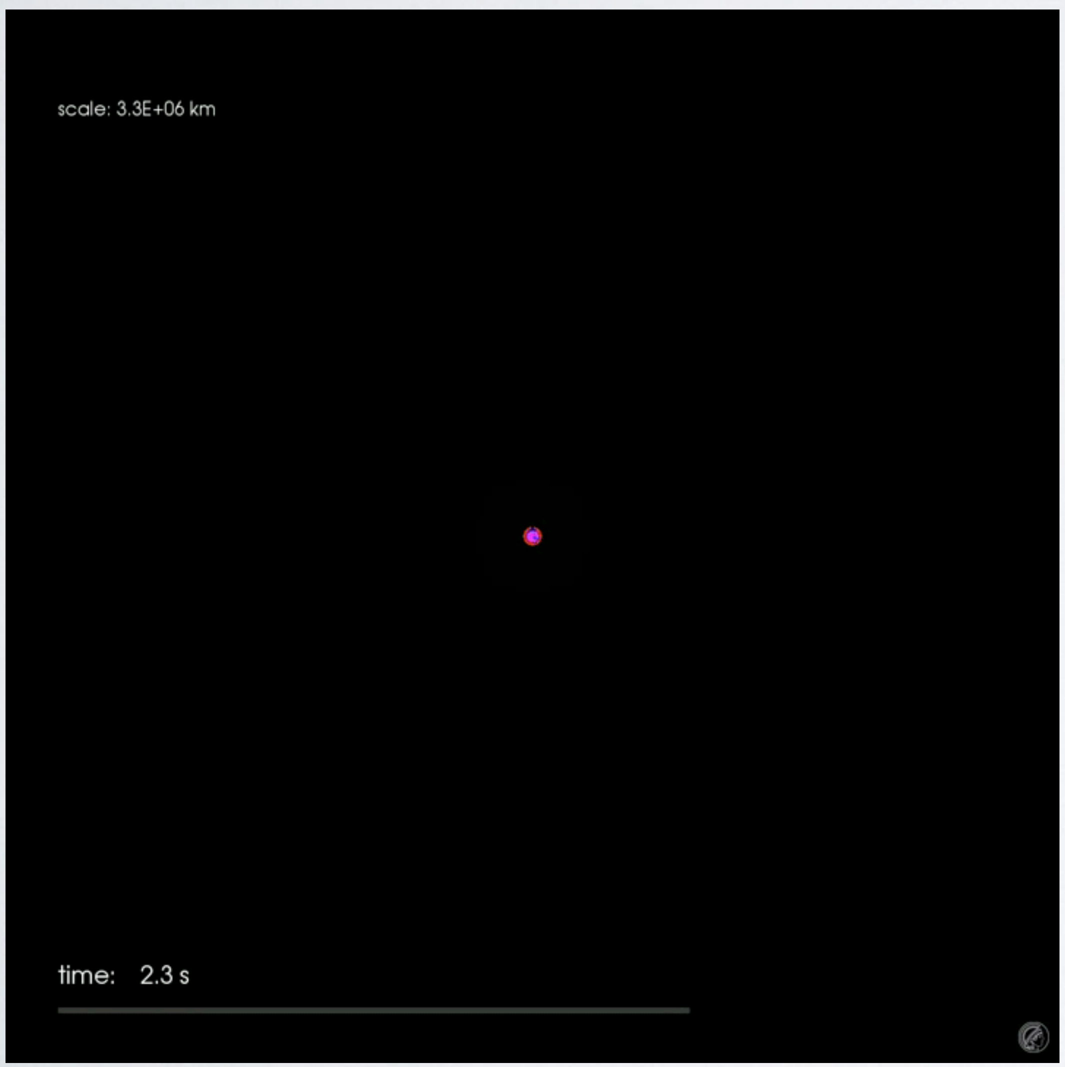
- A dense gas disk fragments to form a planetary system.



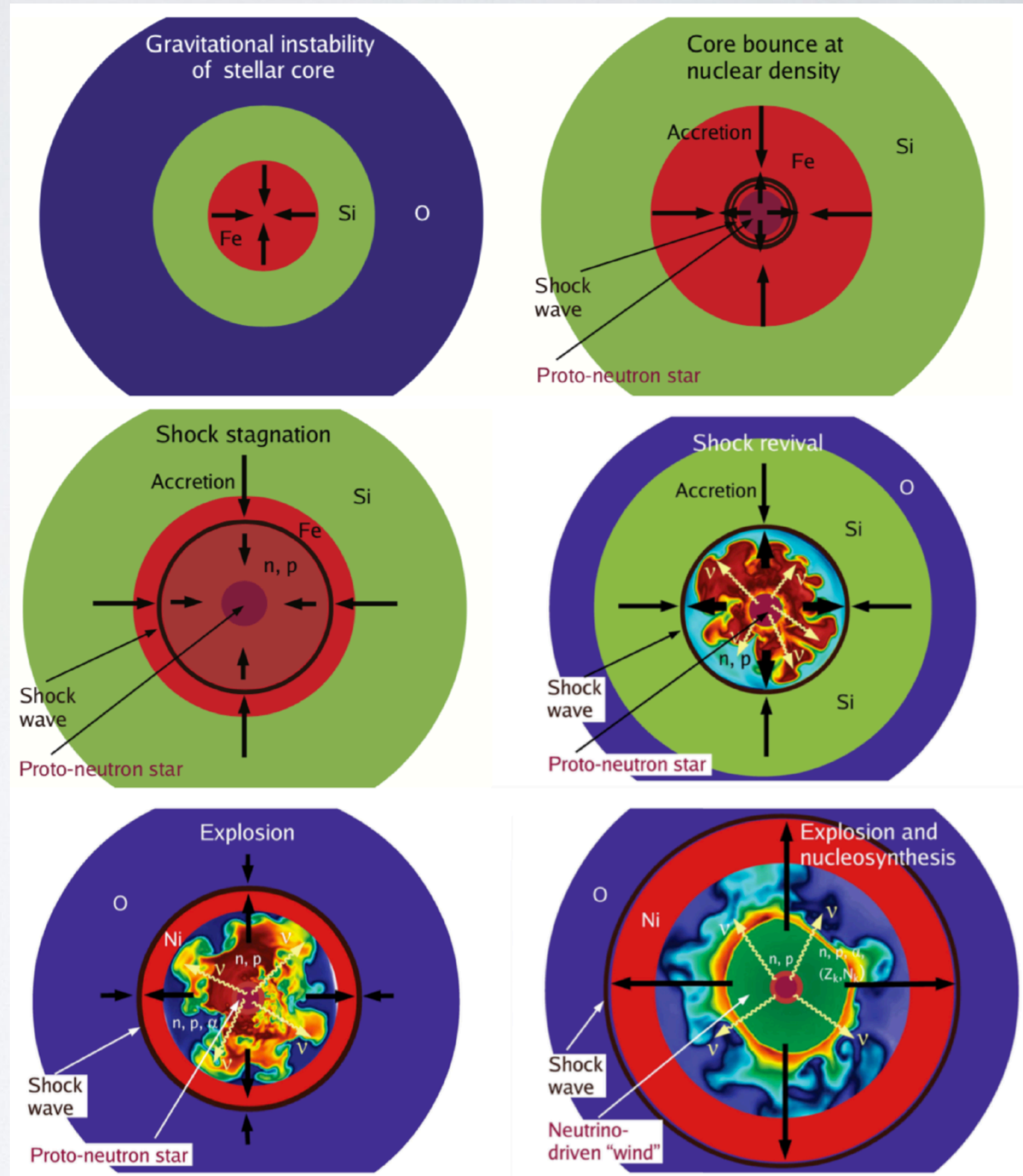
California Academy of Science

Igniting Core-Collapse Supernova (CCSN)

- Neutrino plays an major role as it carries 99% of the total SN energy.



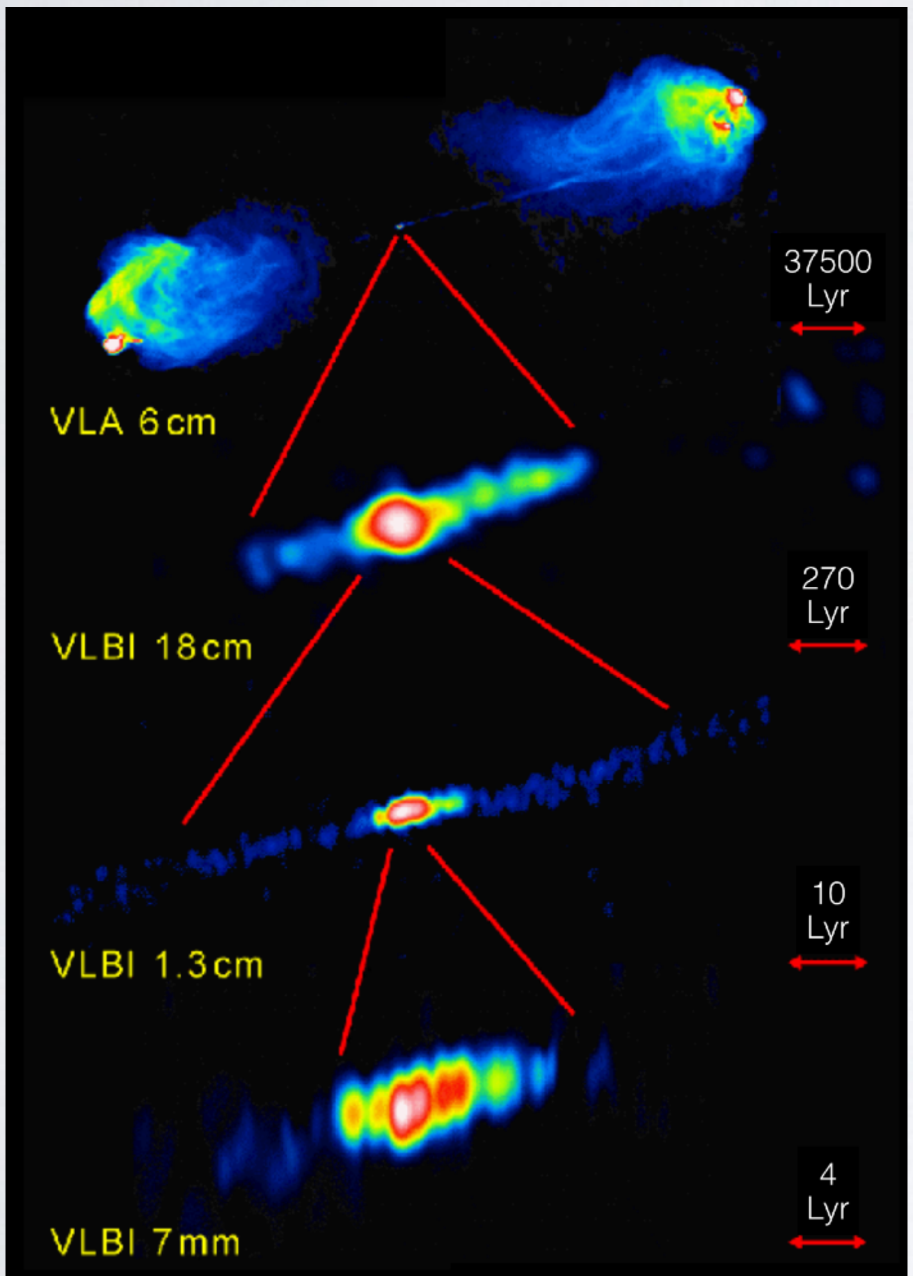
Hammer, Janka et al. (2010)



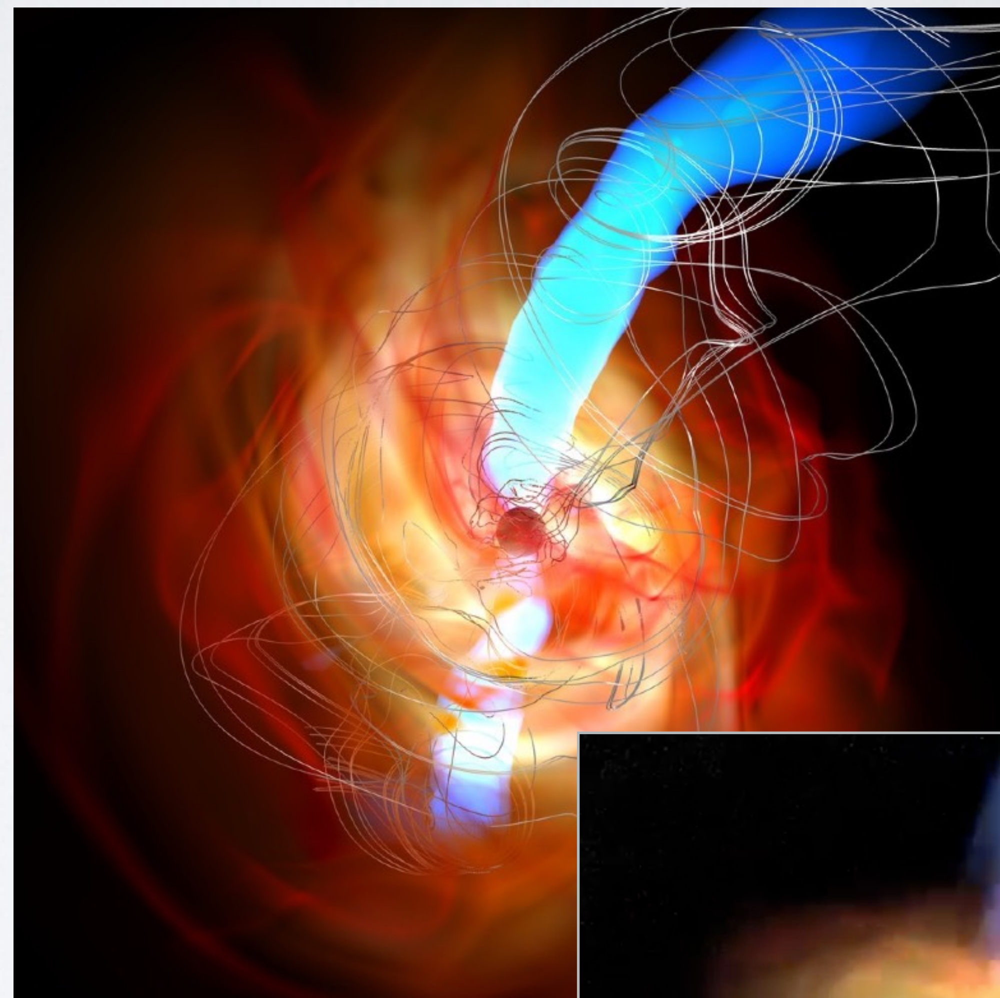
Janka et al. (2012)

Strong Jets From the Galactic Center

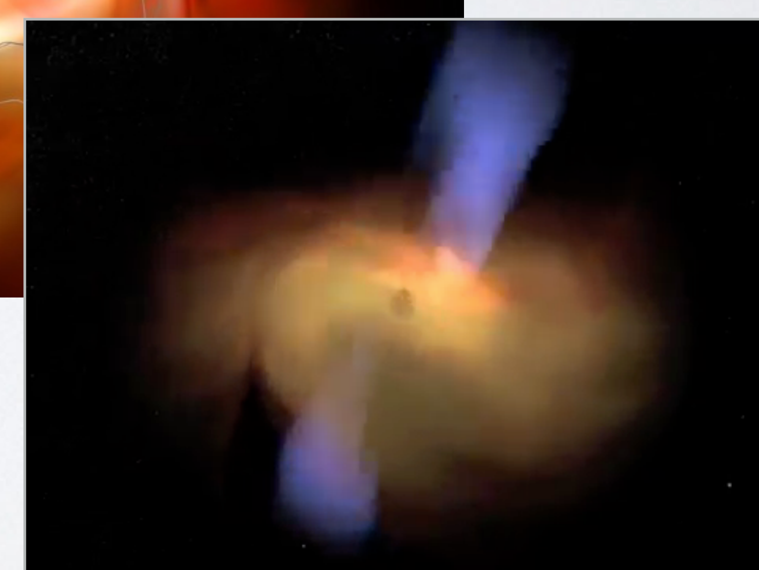
- Indicates a supermassive black hole or active galactic nucleus.



5 orders of magnitude zoom-in of Cyg A (MPIfR)

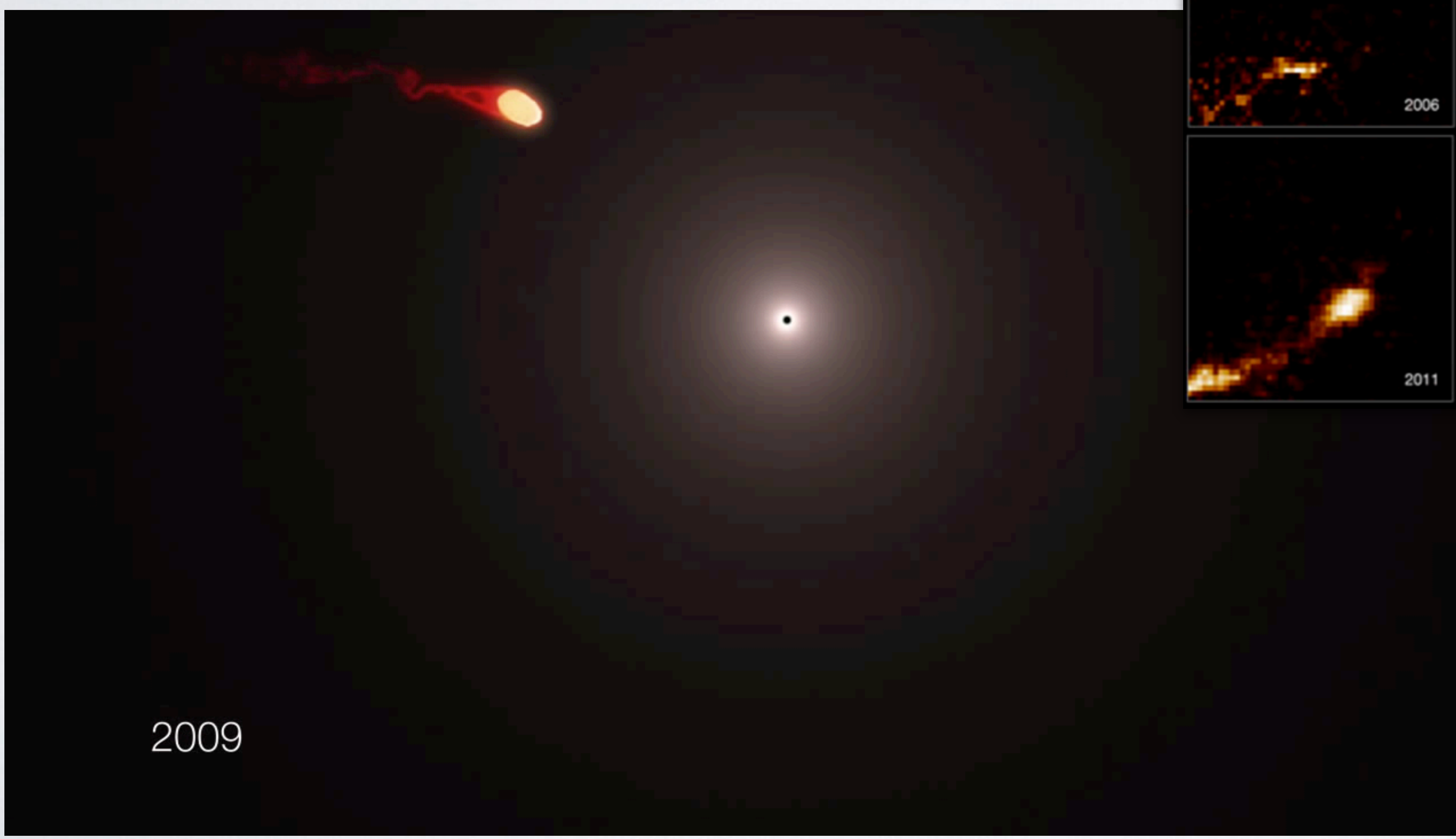


3D-GRRMHD run of Kerr BH (McKinney et al. 2014)

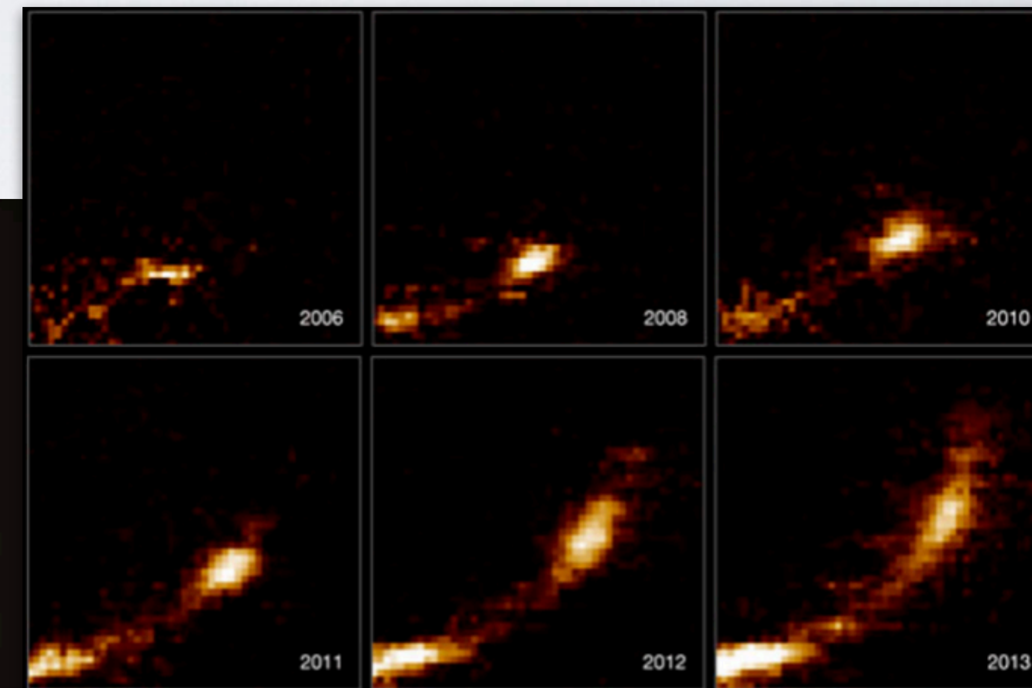


Tidal Disruption Event of A Gas Cloud

- A gas cloud ("G2 Cloud") approaching Milky Way's massive BH discovered in 2011. Pericentric approach in 2013.



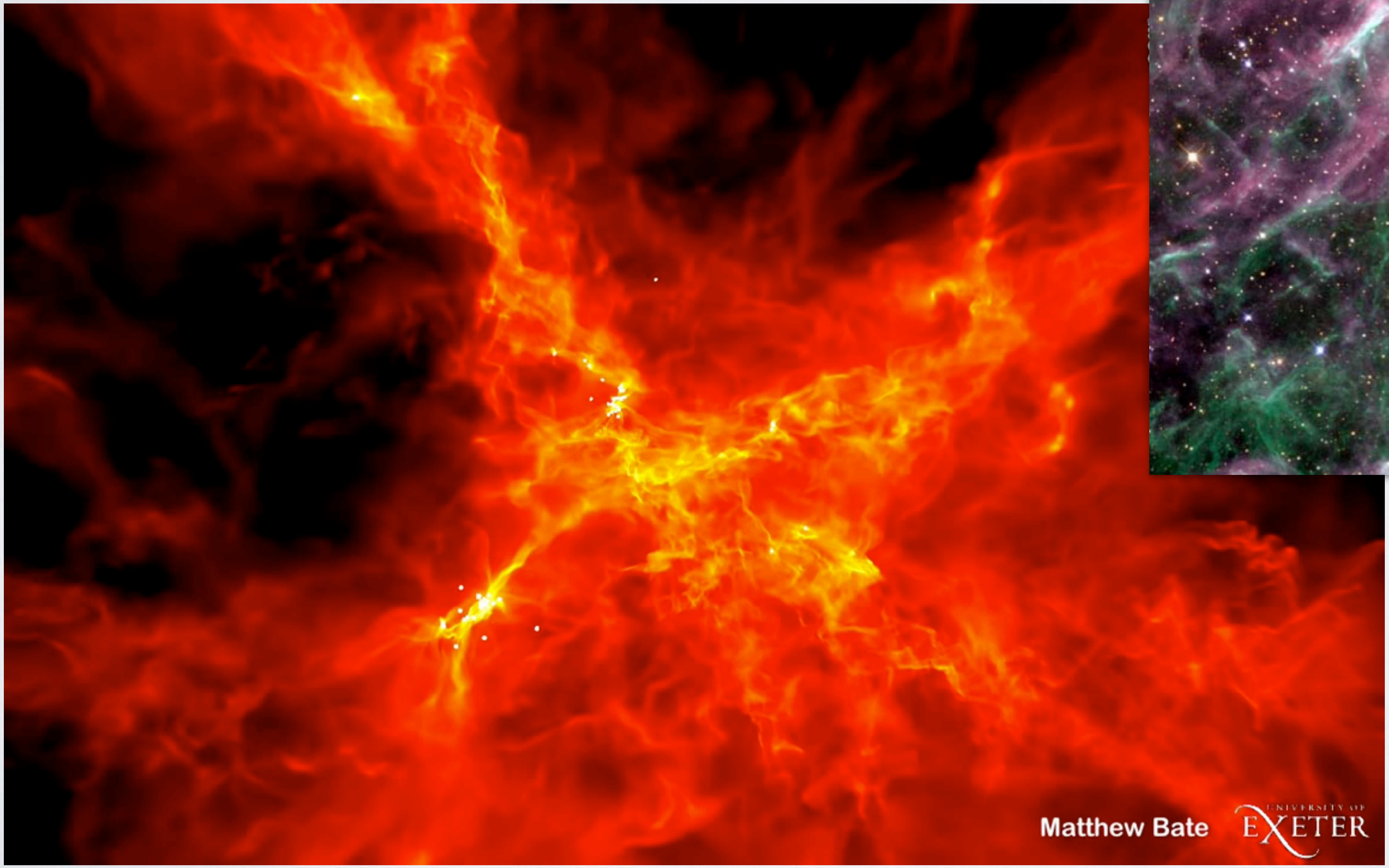
ESO/MPE

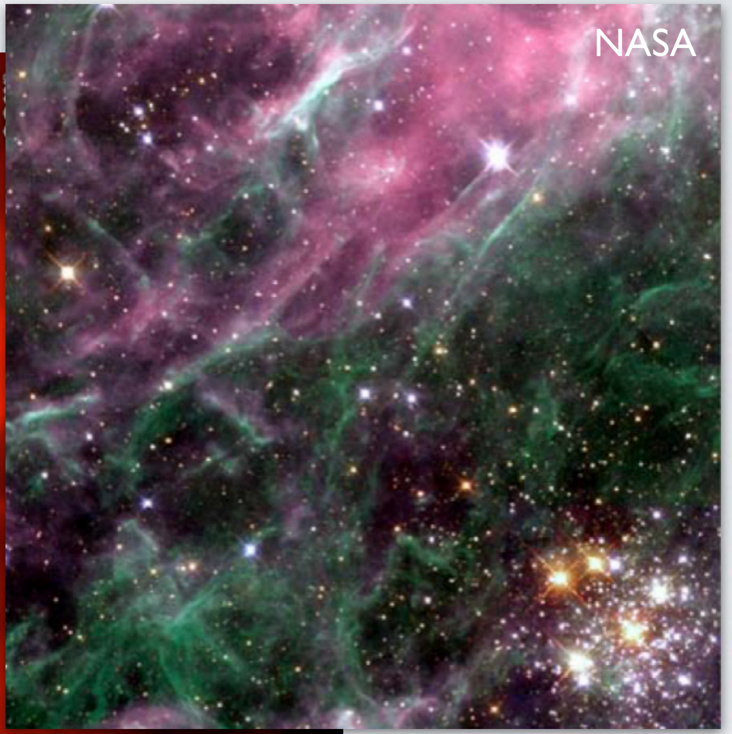


ESO/VLT

Star Cluster Formation

- In the bottom-up structure formation scenario in which CDM produces small-scale powers, small structures form first.

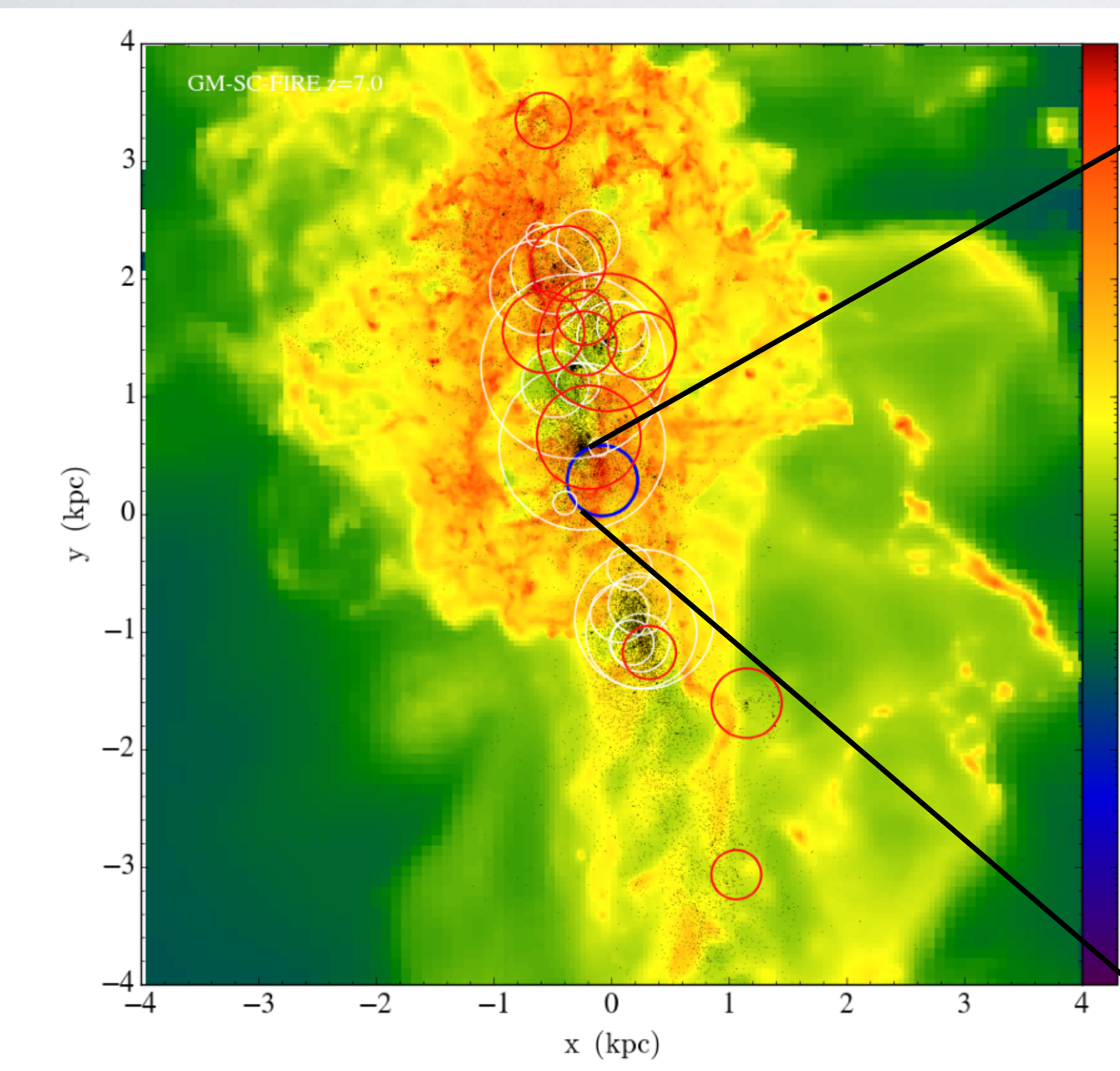




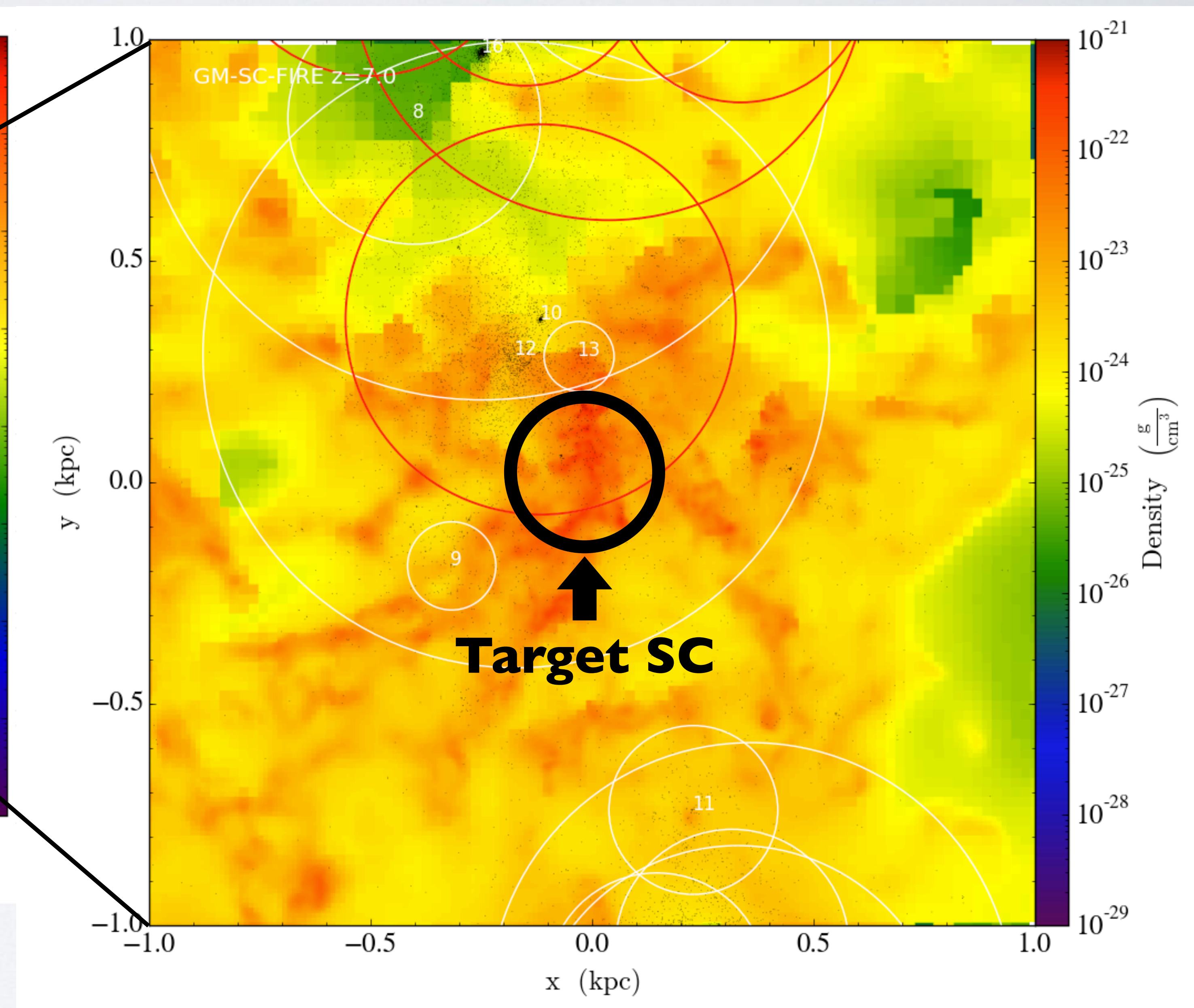
Bate et al.

Merger-driven Globular Cluster Formation

- Realistic descriptions of interstellar medium (e.g., Hopkins et al.) are keys to describe SC formation in high-z merging proto-galaxies.



1.3×10[10] M☉ halo, 1100 M☉ resolution, Kim et al. (2018)



2 kpc width, density projection, centered on target SC

Mihos & Hernquist, NASA/STScI

Early Numerical Experiments: Holmberg

- Used 37 lightbulbs to represent a “nebula”, and a photocell to measure simulated gravitational force (1941).

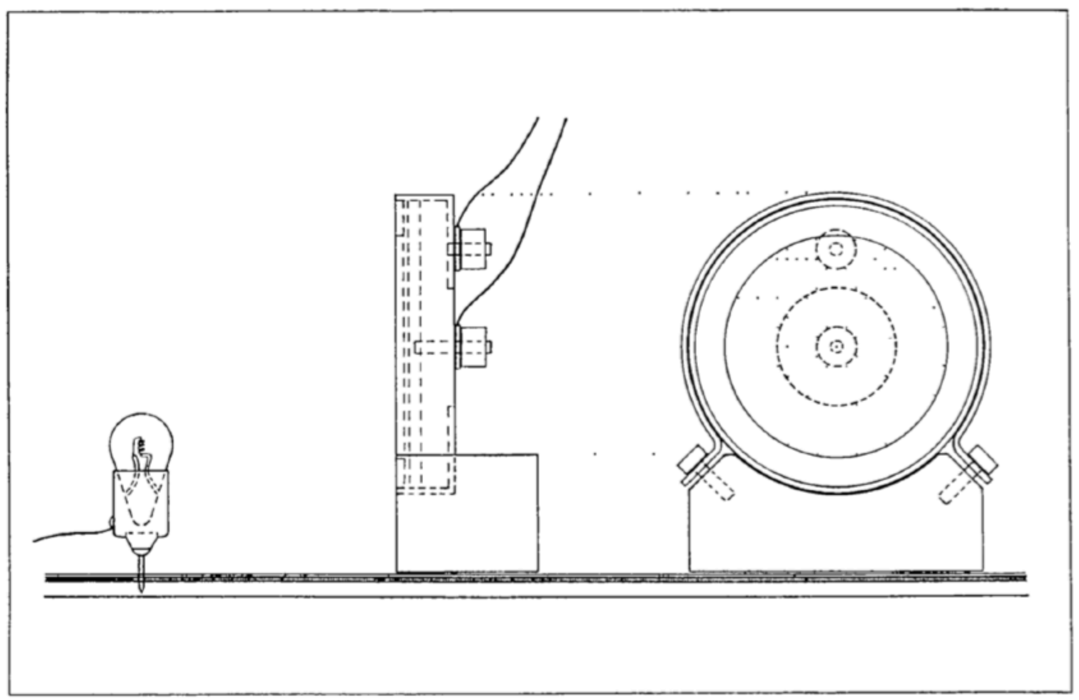


FIG. 1.—Cross-section of light-bulb and photocell (half-size)

Holmberg (1941)

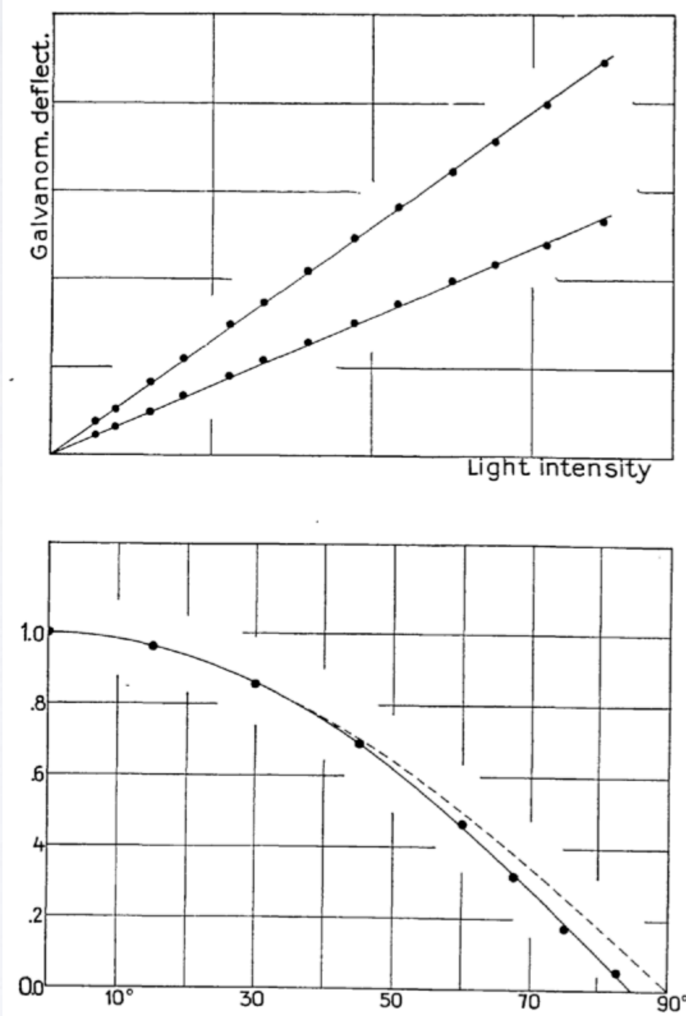


FIG. 2

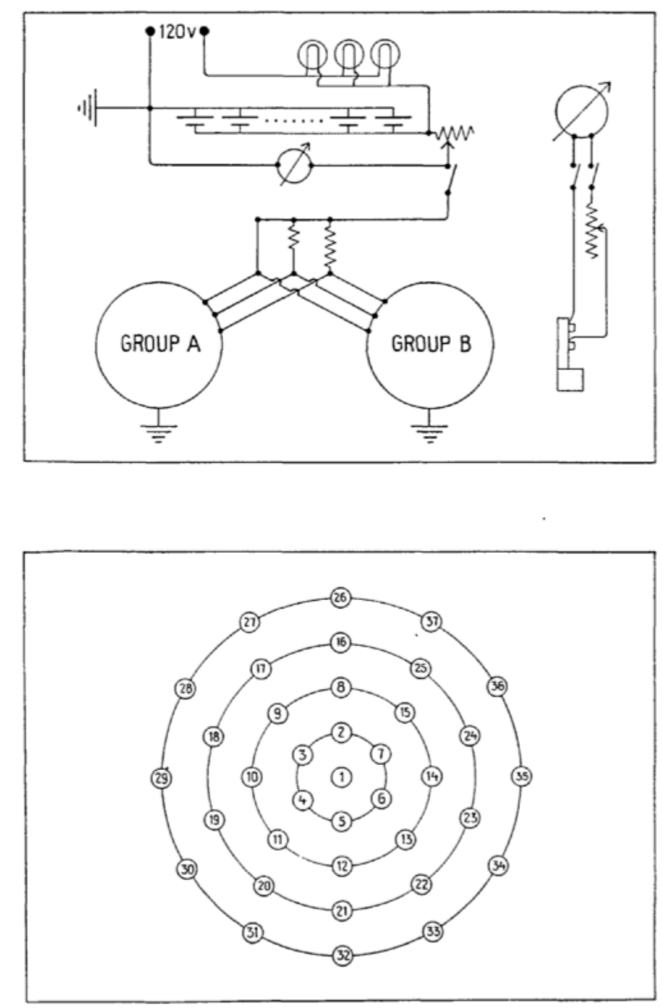


FIG. 3

FIG. 2.—(a) Relation between galvanometer deflection and light-intensity (resistance of 0 and 10,000 ohms). (b) Relation between galvanometer deflection and angle of incidence of light (*dotted line* = theoretical cosine law).

FIG. 3.—(a) Coupling scheme. (b) Arrangement of the 37 light-bulbs in groups A and B

Holmberg (1908-2000)

Early Numerical Experiments: Holmberg

- Used 37 lightbulbs to represent a "nebula", and a photocell to measure simulated gravitational force (1941).

FIG. 4a FIG. 4b

FIG. 4a.—Tidal deformations corresponding to parabolic motions, clockwise rotations, and a distance of closest approach equal to the diameters of the nebulae. The spiral arms point in the direction of the rotation.

FIG. 4b.—Same as above, with the exception of counterclockwise rotations. The spiral arms point in the direction opposite to the rotation.

Holmberg (1941)

Early Experiments: Toomre & Toomre

- Showed that bridges and tails in peculiar/multiple galaxies are tidal relics of close encounters.

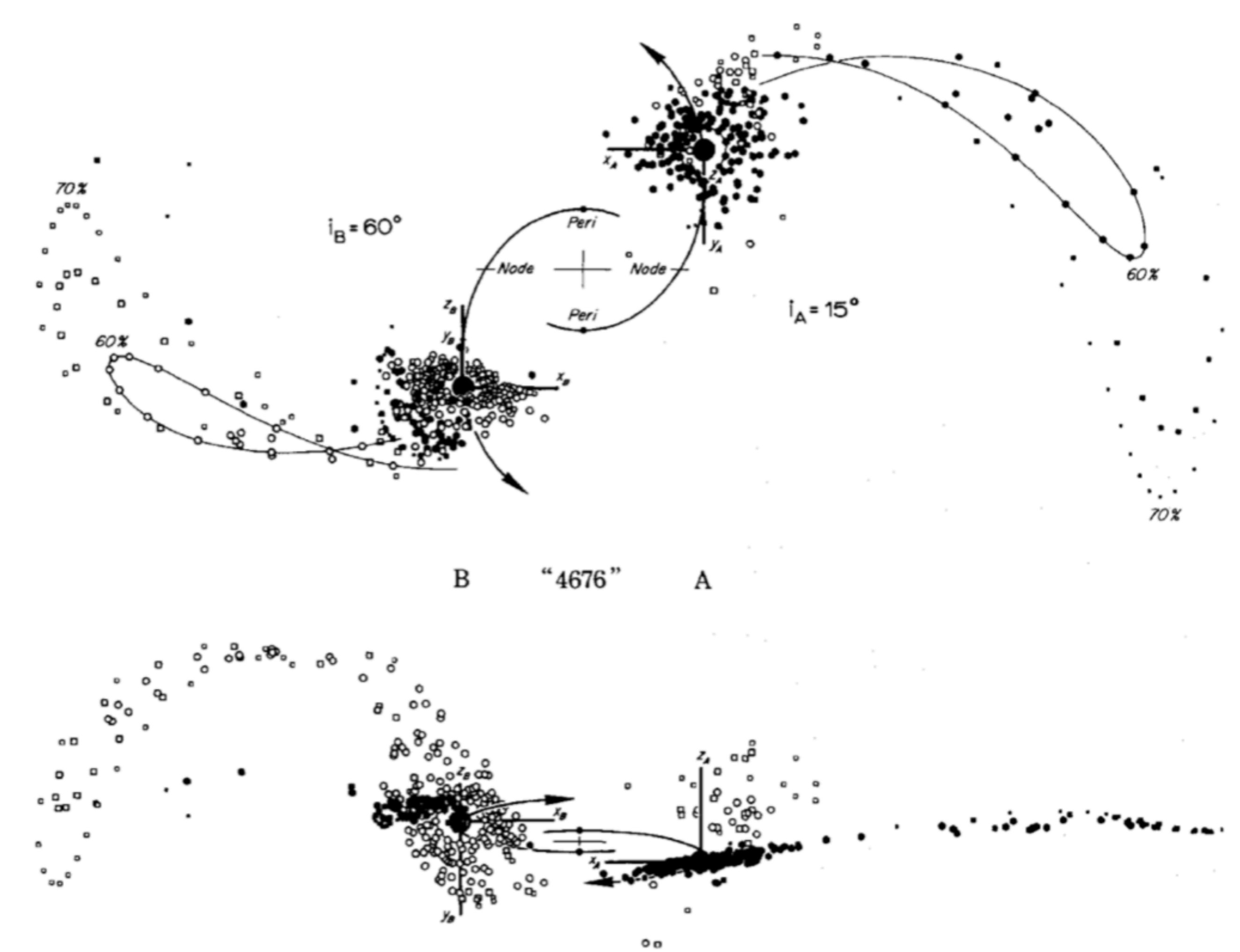


FIG. 22.—Model of NGC 4676. In this reconstruction, two equal disks of radius $0.7R_{min}$ experienced an $e = 0.6$ elliptic encounter, having begun flat and circular at the time $t = -16.4$ of the last apocenter. As viewed from either disk, the adopted node-to-peri angles $\omega_A = \omega_B = -90°$ were identical, but the inclinations differed considerably: $i_A = 15°$, $i_B = 60°$. The resulting composite object at $t = 6.086$ (cf. fig. 18) is shown projected onto the orbit plane in the upper diagram. It is viewed nearly edge-on to the same—from $\lambda_A = 180°$, $\beta_A = 85°$ or $\lambda_B = 0°$, $\beta_B = 160°$—in the lower diagram meant to simulate our actual view of that pair of galaxies. The filled and open symbols distinguish particles originally from disks A and B, respectively.

Toomre & Toomre (1972)

Early Experiments: Toomre & Toomre

- Showed that bridges and tails in peculiar/multiple galaxies are tidal relics of close encounters.

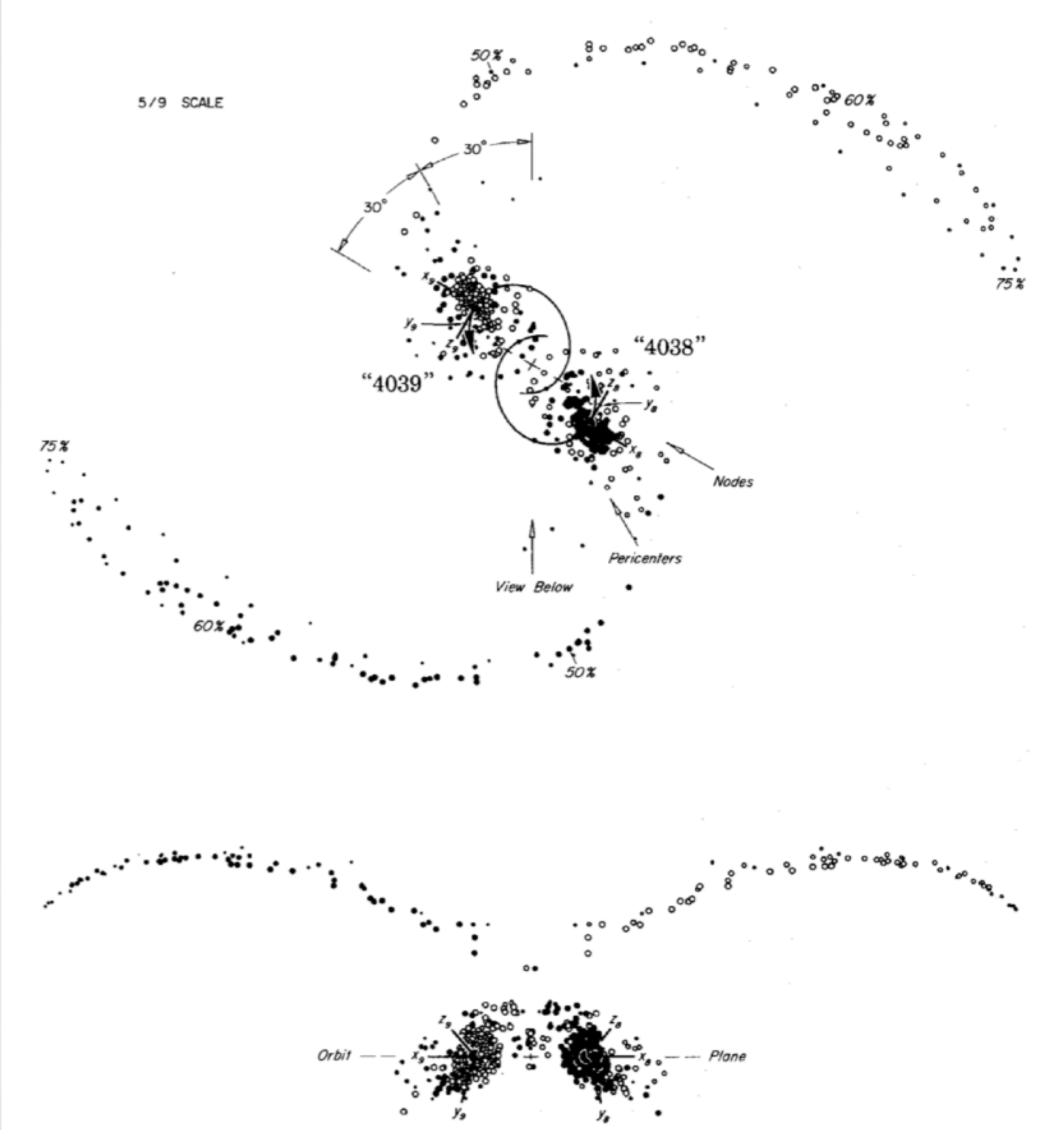
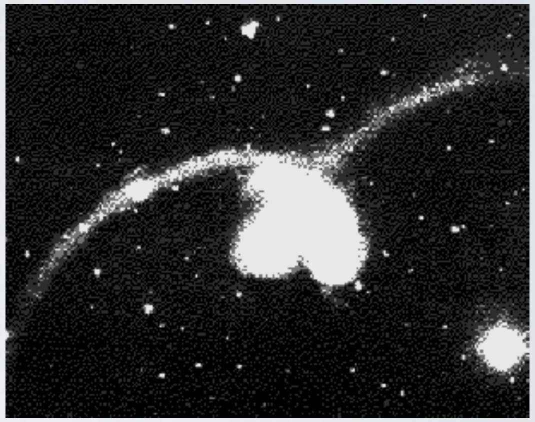
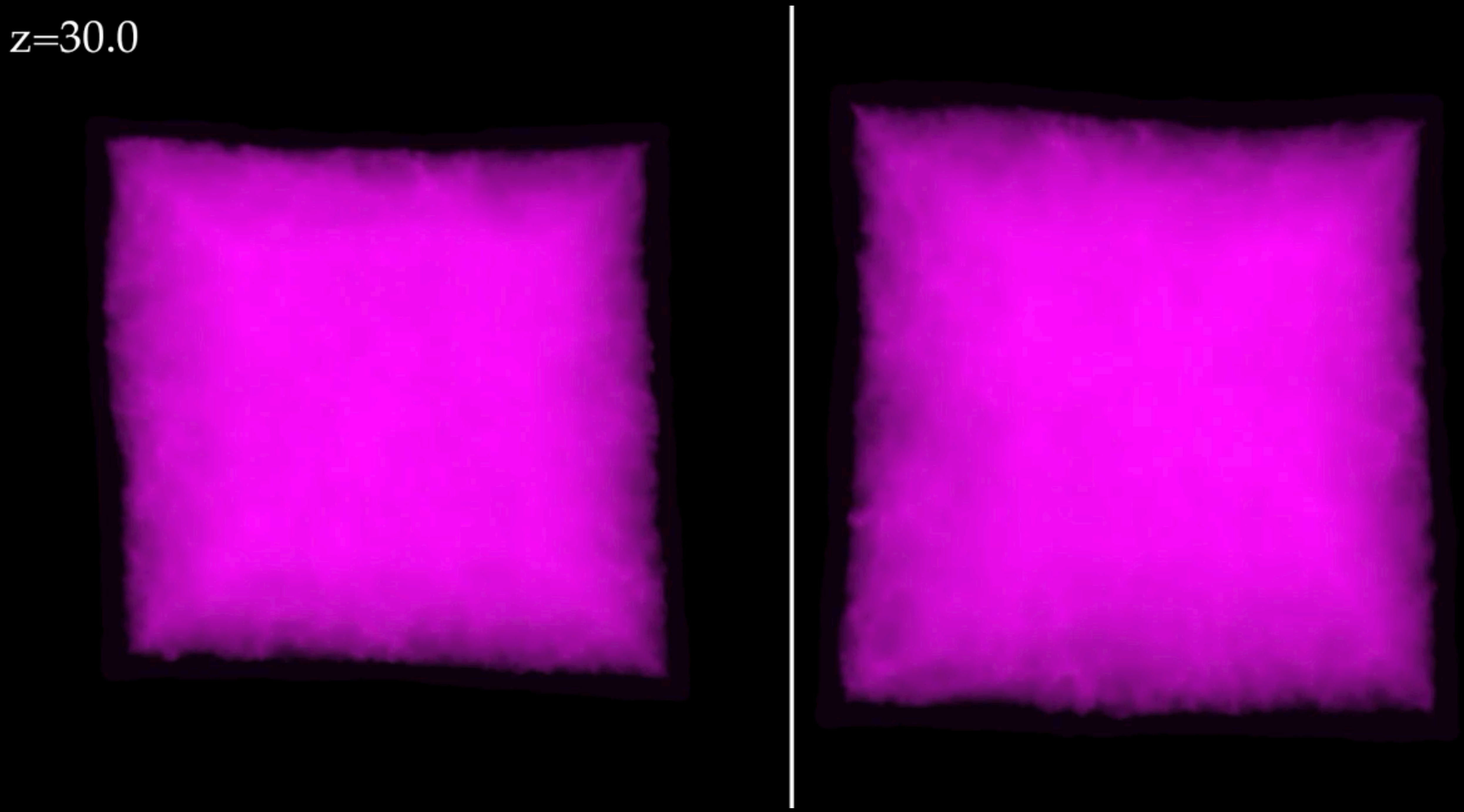


FIG. 23.—Symmetric model of NGC 4038/9. Here two identical disks of radius $0.75R_{\min}$ suffered an $e \approx 0.5$ encounter with orbit angles $i_8 = i_9 = 60°$ and $\omega_8 = \omega_9 = -30°$ that appeared the same to both. The above all-inclusive views of the debris and remnants of these disks have been drawn exactly normal and edge-on to the orbit plane; the latter viewing direction is itself 30° from the line connecting the two pericenters. The viewing time is $t = 15$, or slightly past apocenter. The filled and open symbols again disclose the original loyalties of the various test particles.



Toomre & Toomre (1972)

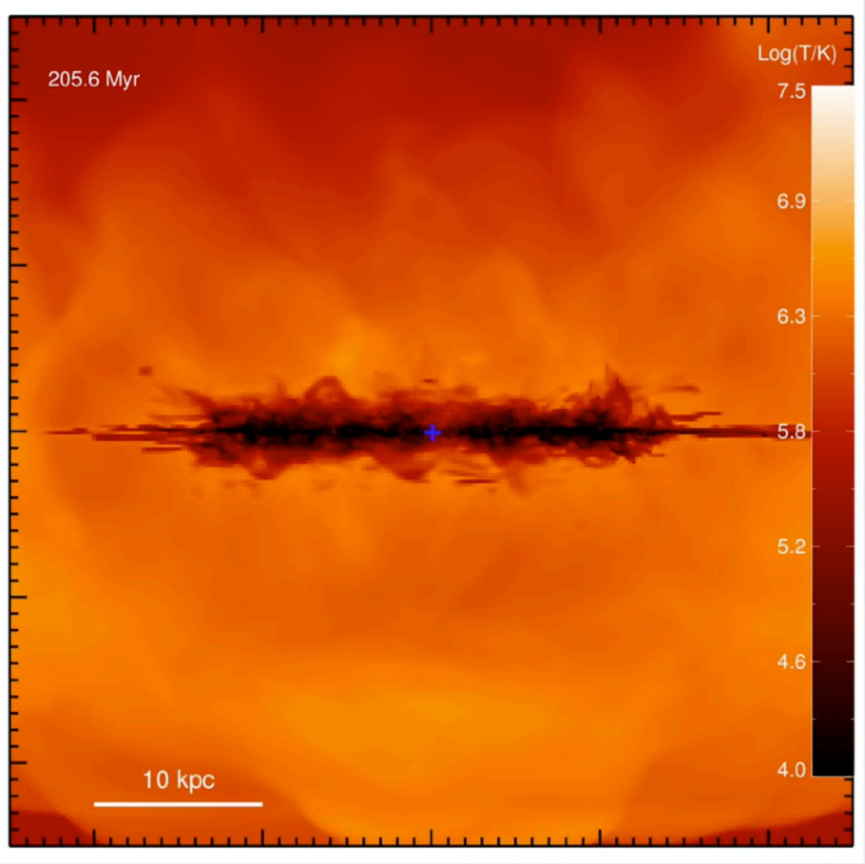


Hopkins et al./FIRE, face-on and edge-on view of a MW-size galaxy in a zoom-in simulation

Strong Jets From the Galactic Center

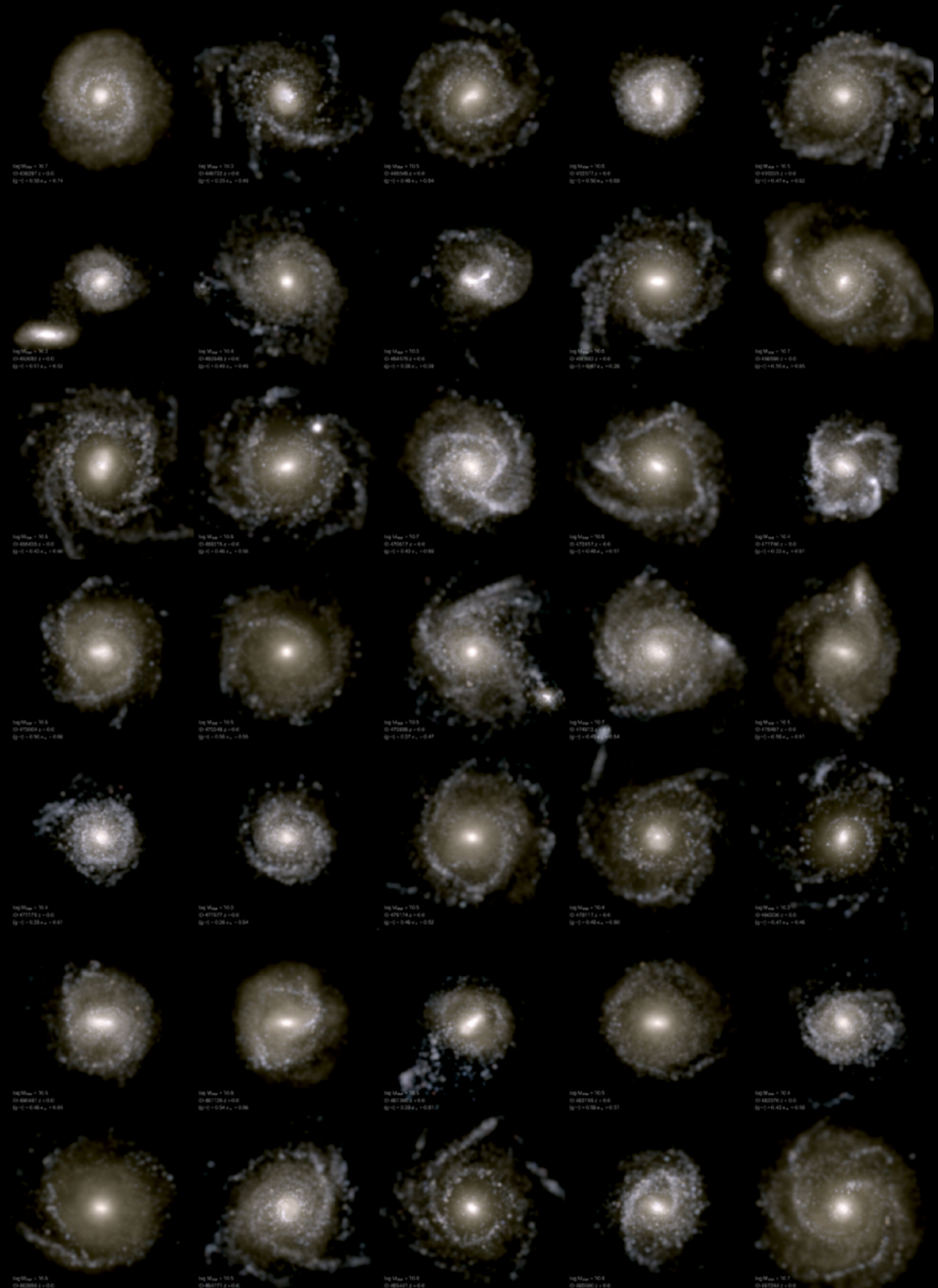
- Mechanical feedback creates lobes and bubbles in X-ray images.

Per A Cluster, NASA/CXC/SAO

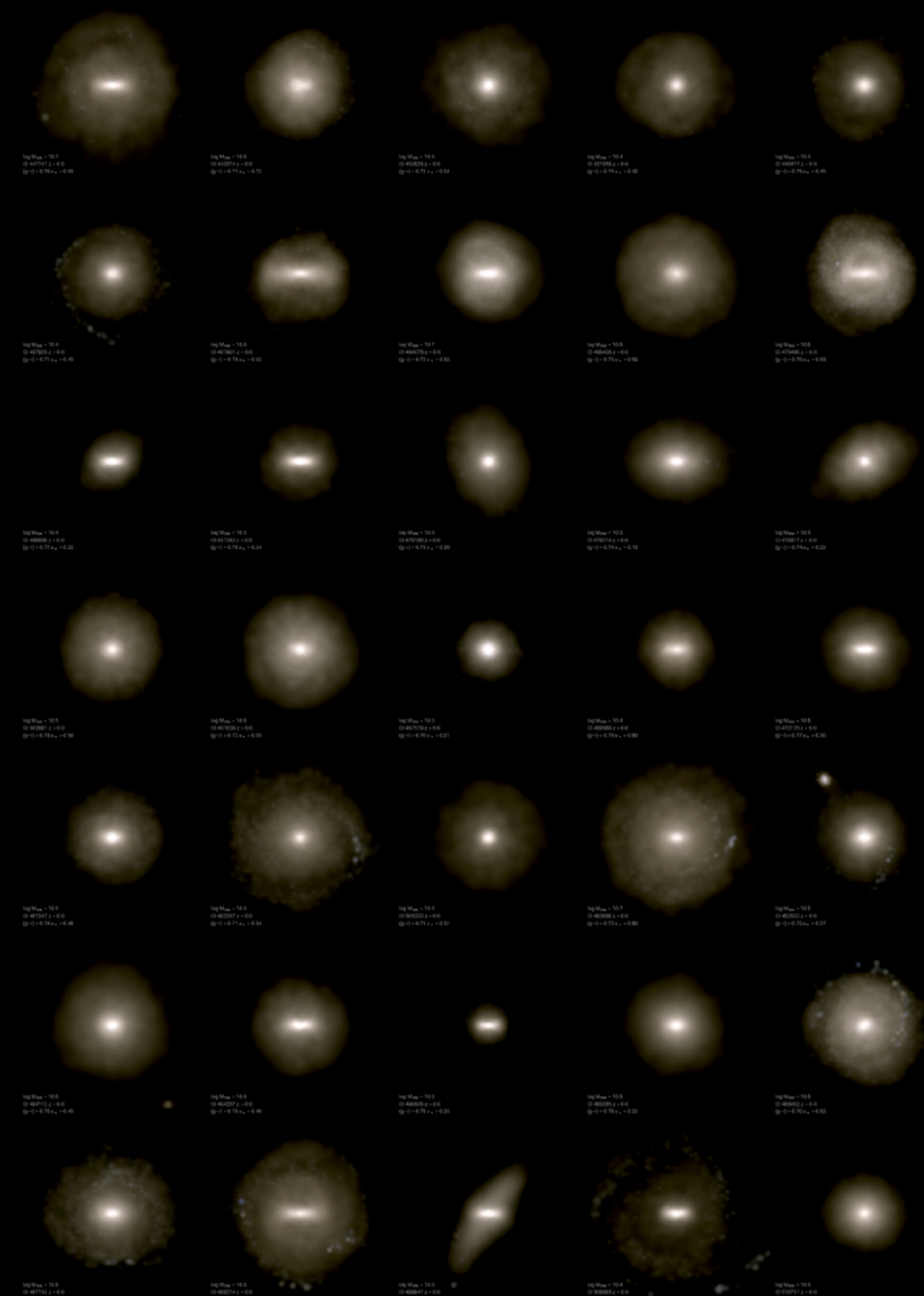


Gabor et al.

Mock JWST Observations

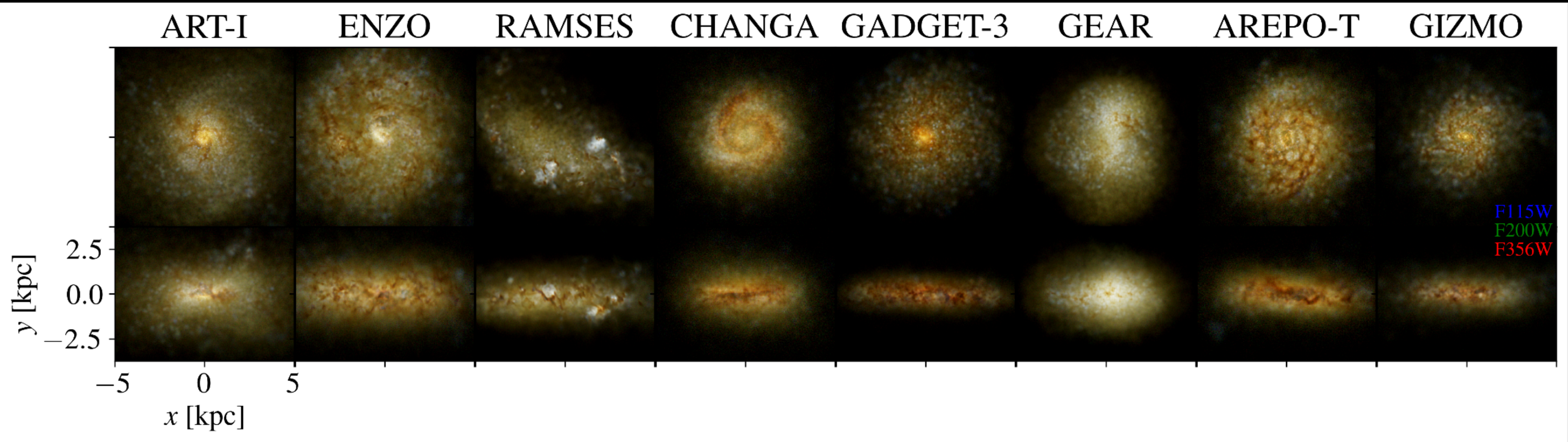


Star-forming galaxies, Illustris-TNG Collaboration



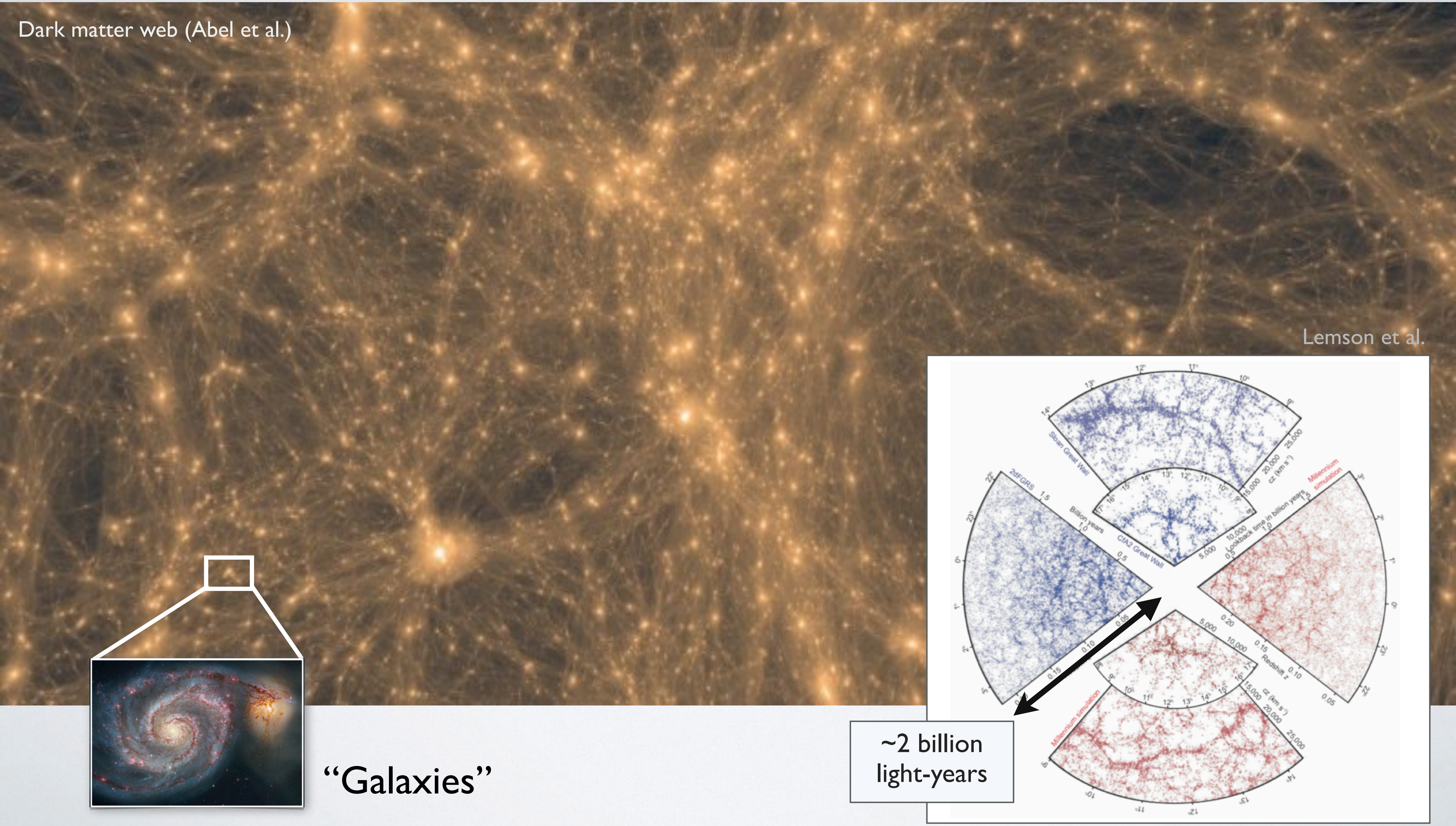
Star formation quenched galaxies, Illustris-TNG Collaboration

Mock JWST Observations



Jung et al. for the AGORA Collaboration (2025)

Large-Scale Structure (LSS) of Universe



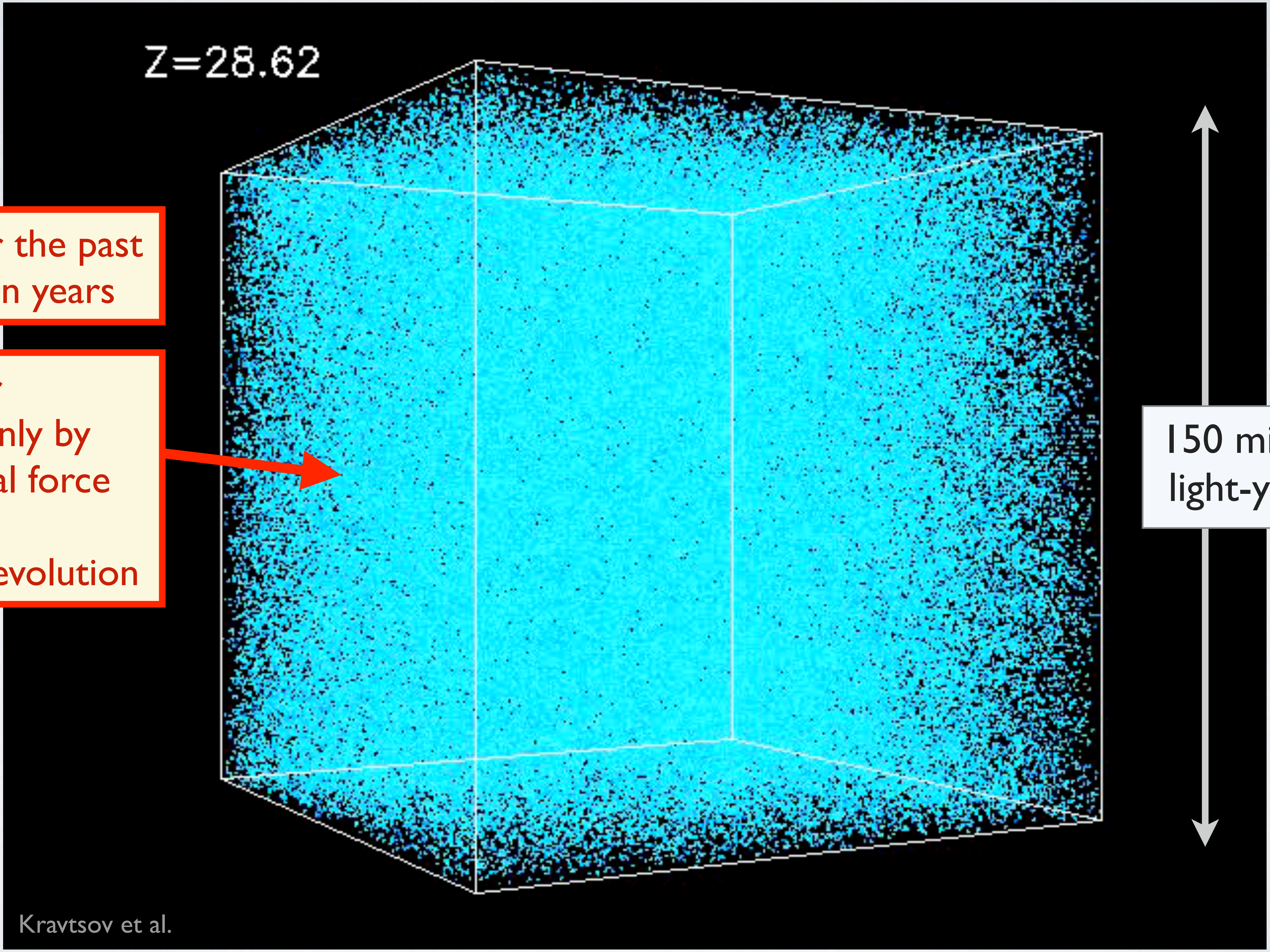
"Galaxies"

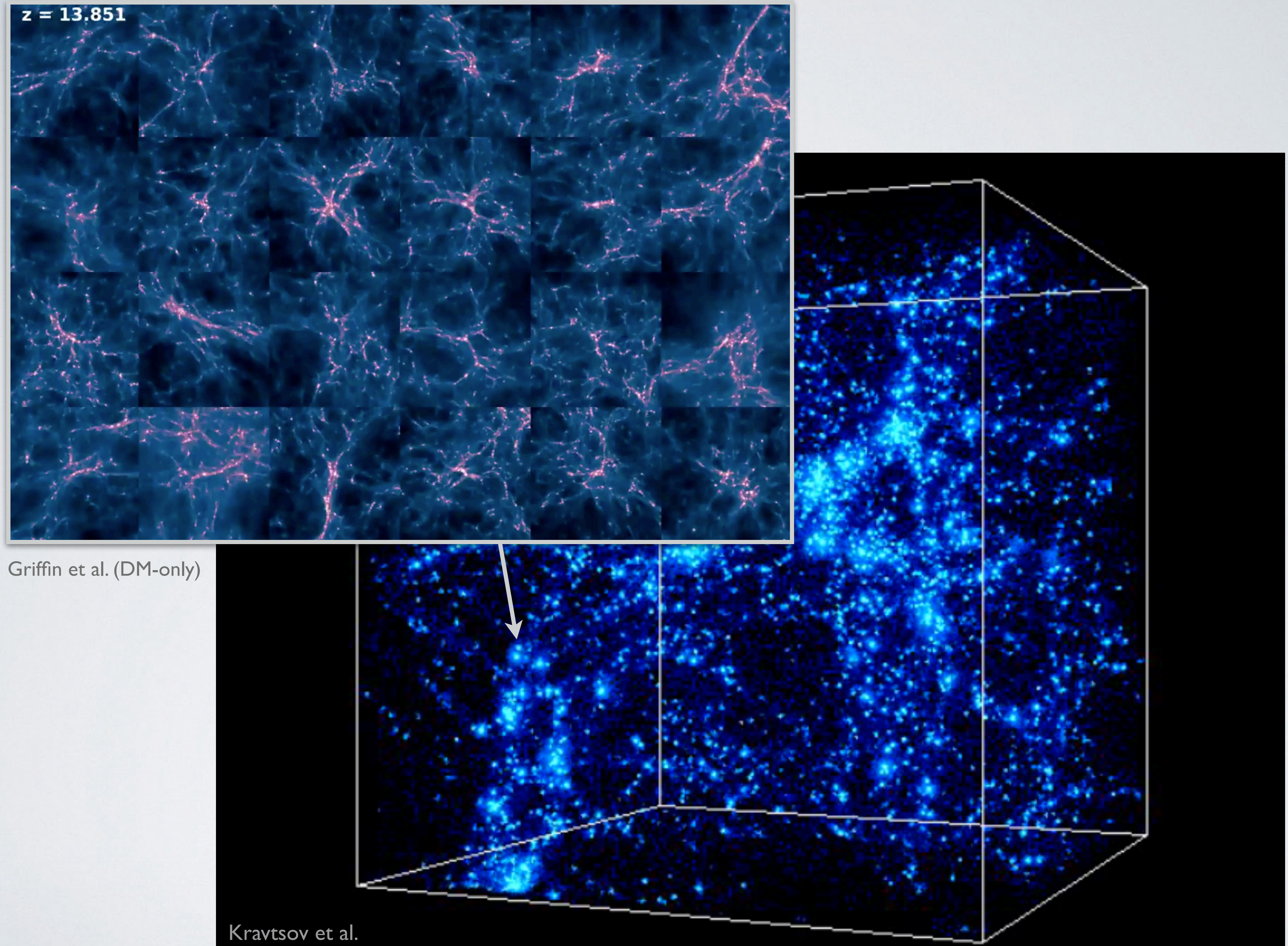
Lemson et al.

Numerical Cosmology: Structure Formation

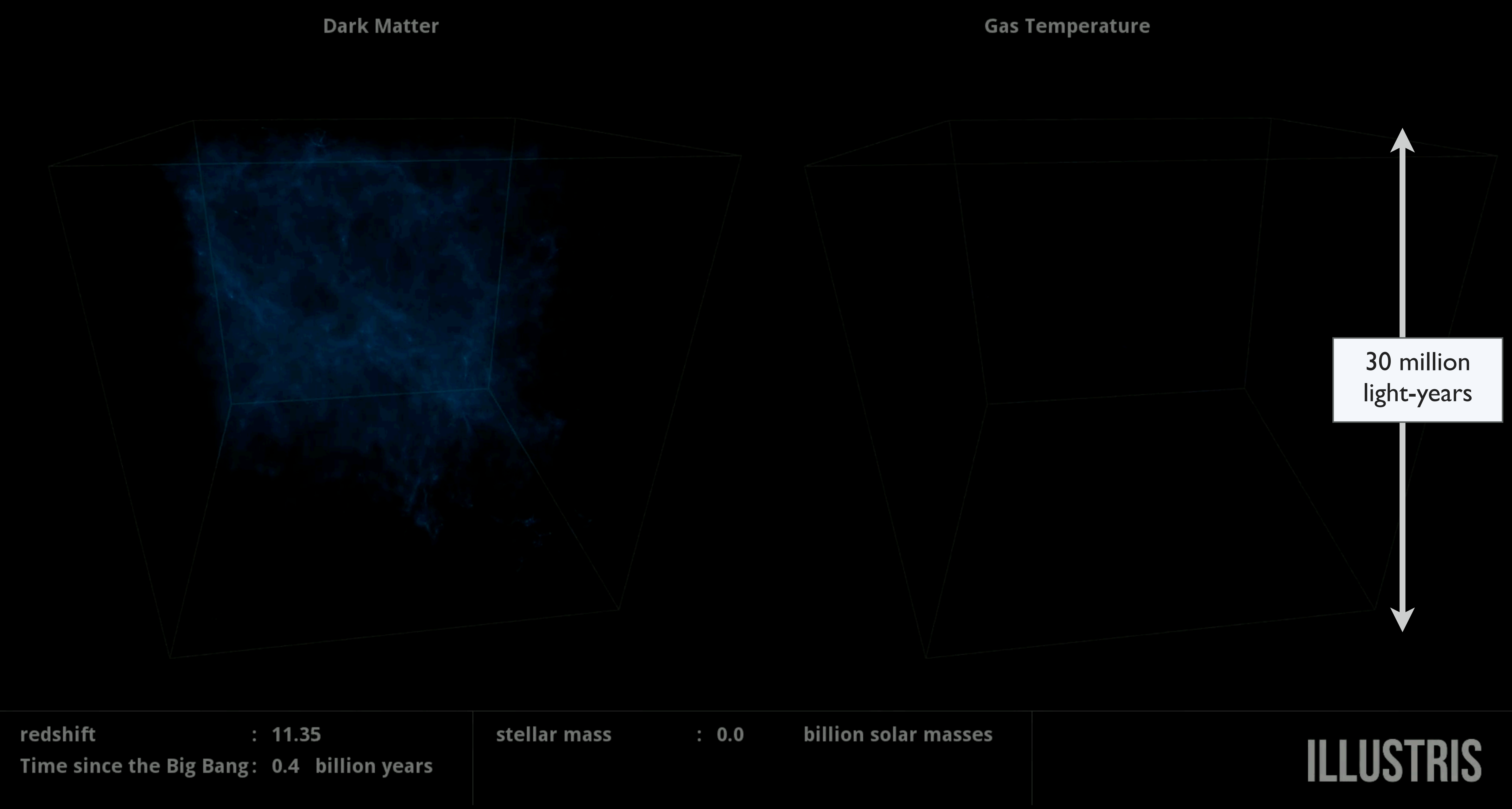
Evolution for the past ~13.6 billion years

Dark matter
- interacts only by gravitational force
- dominates structural evolution



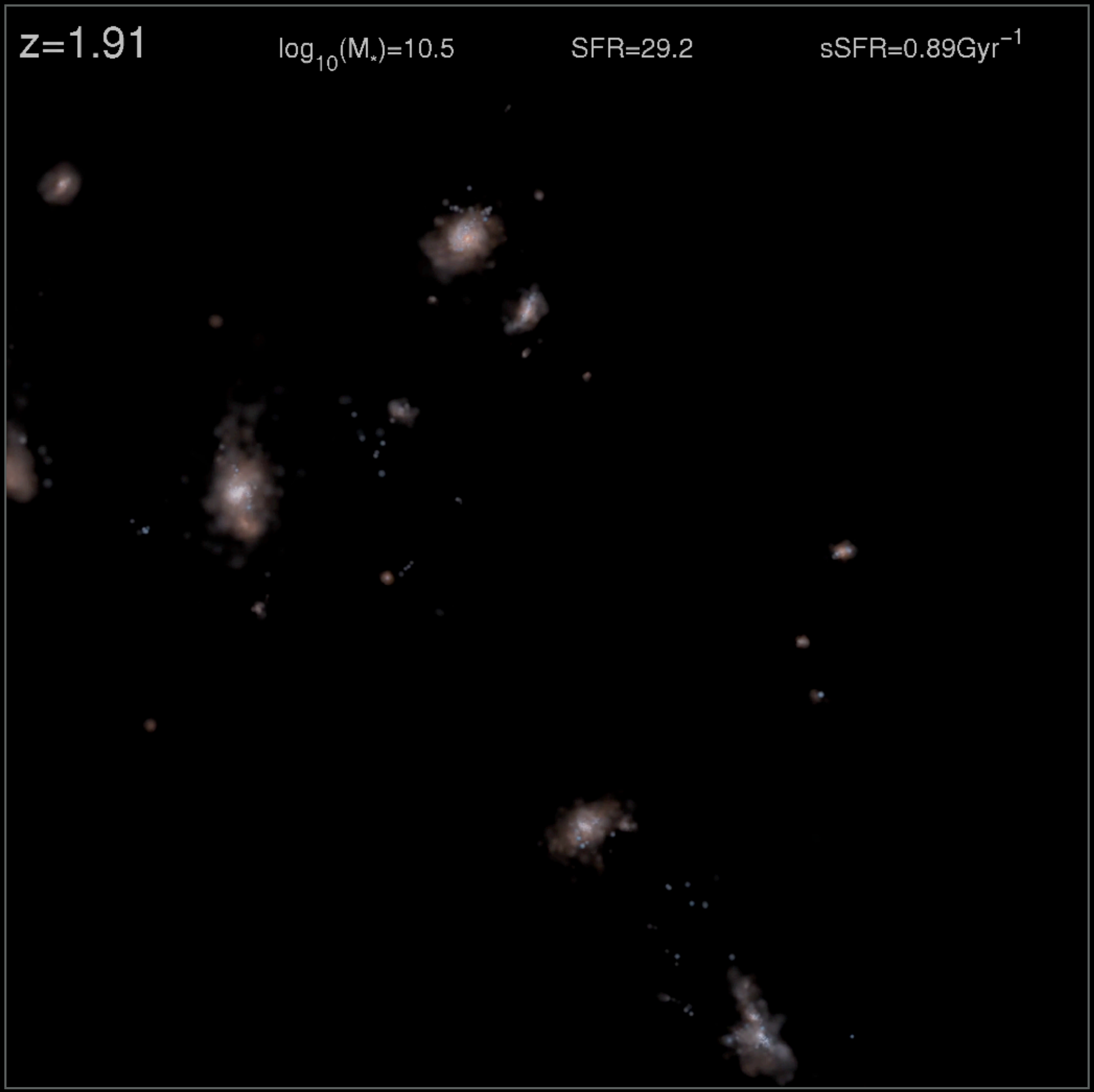


Griffin et al. (DM-only)

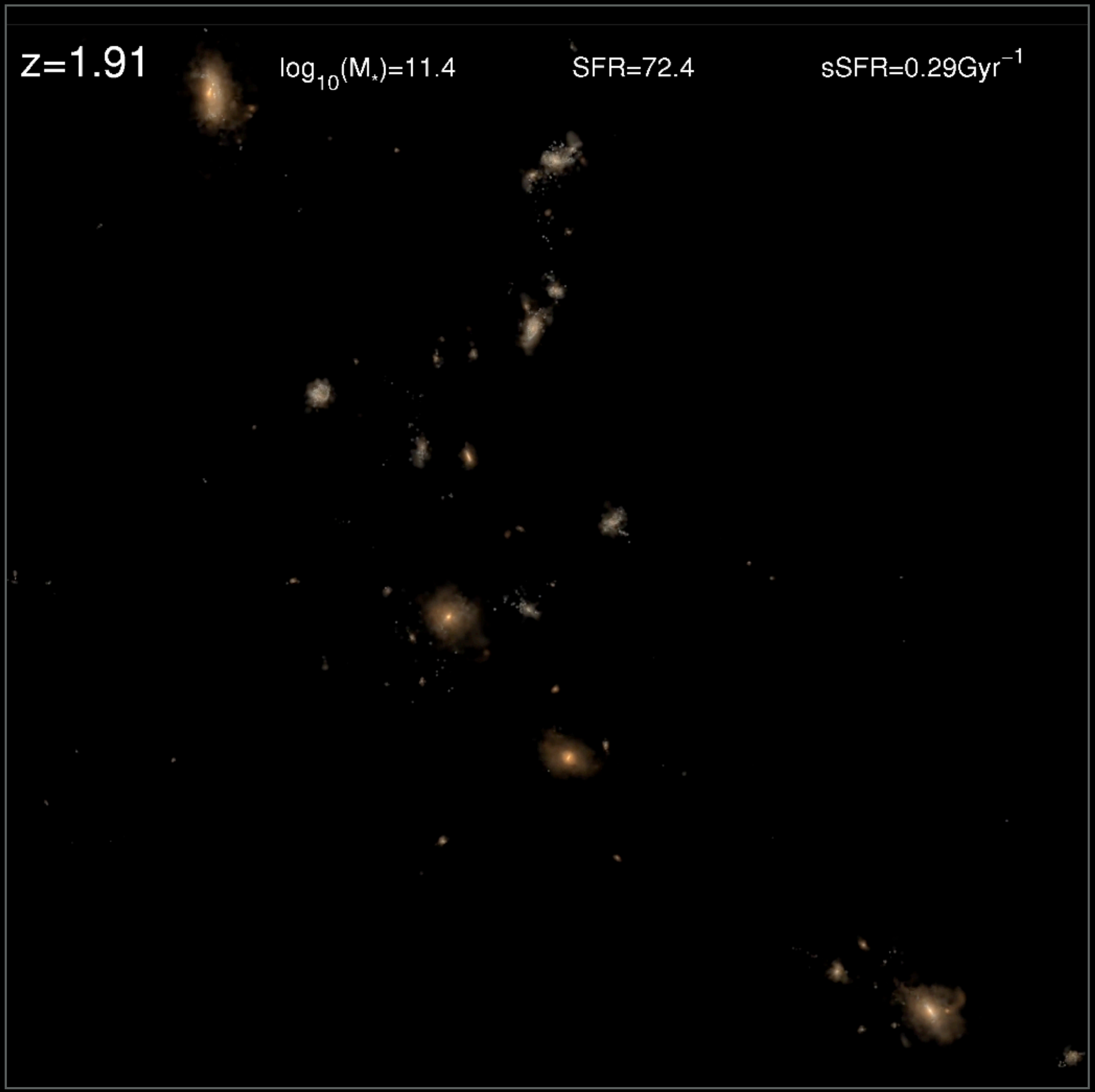


DM density and gas temperature, 10 Mpc, Illustris Collaboration

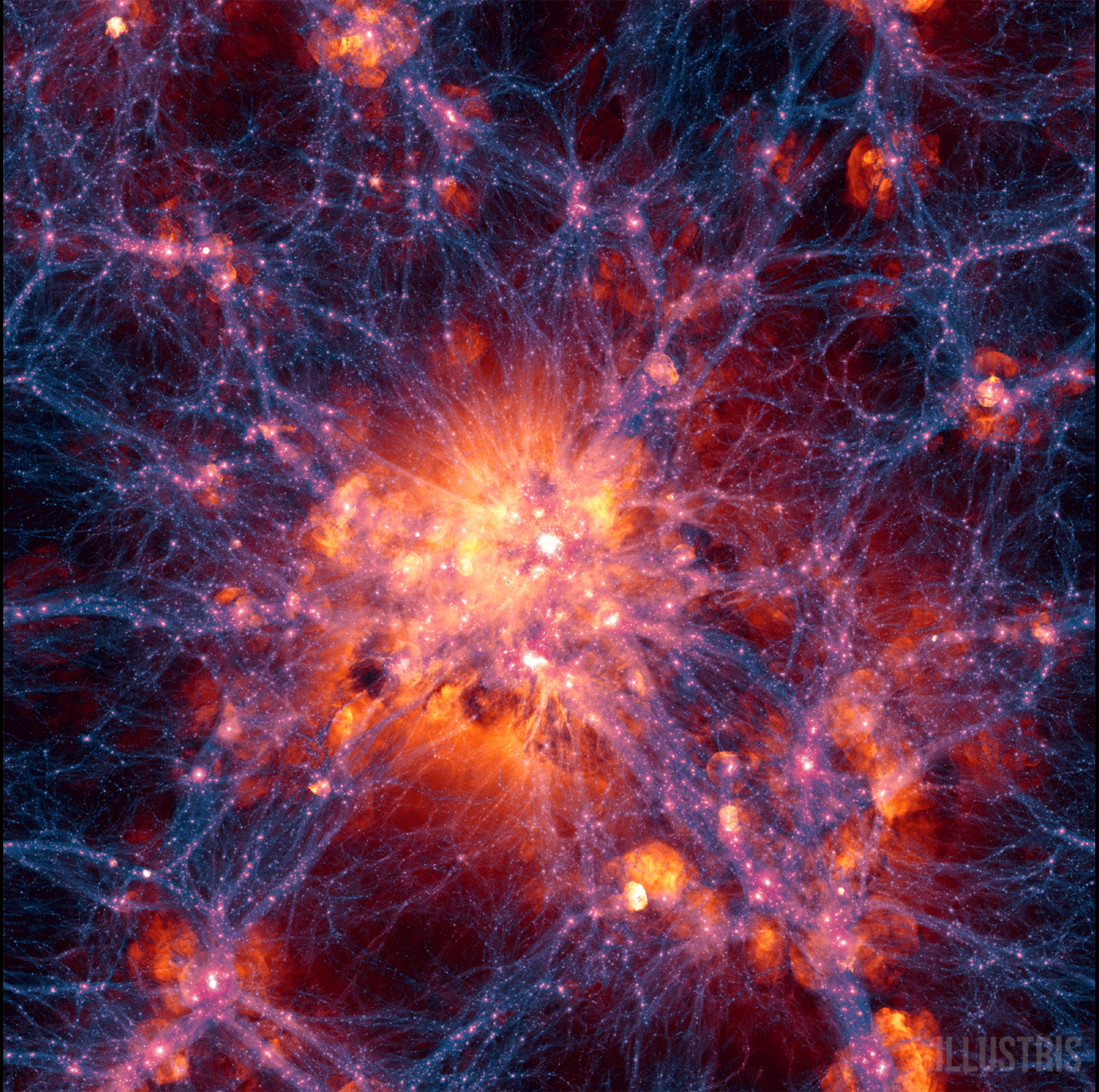
Individual Galaxy Evolution History



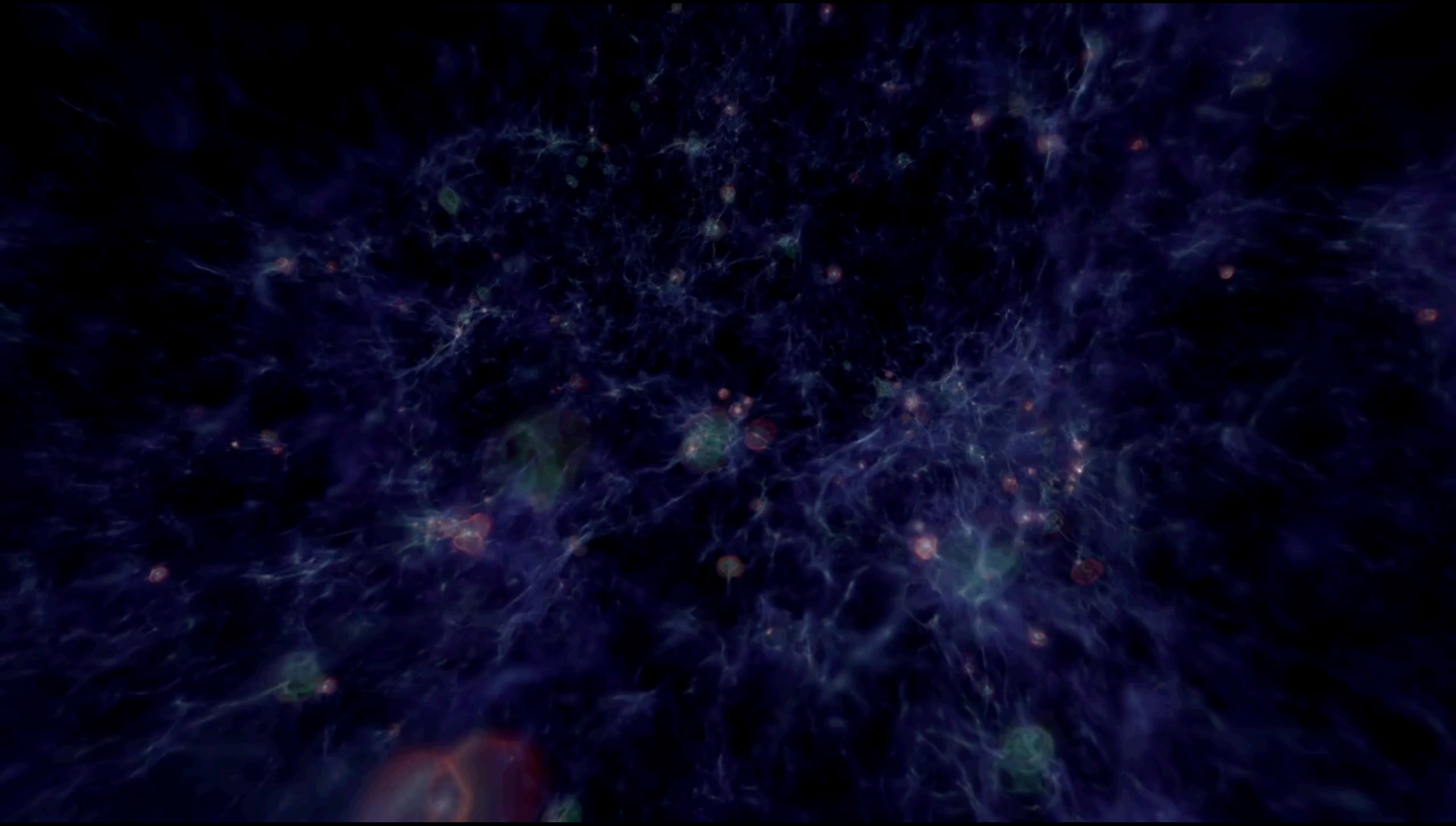
Star-forming late-type galaxy, Illustris-TNG Collaboration



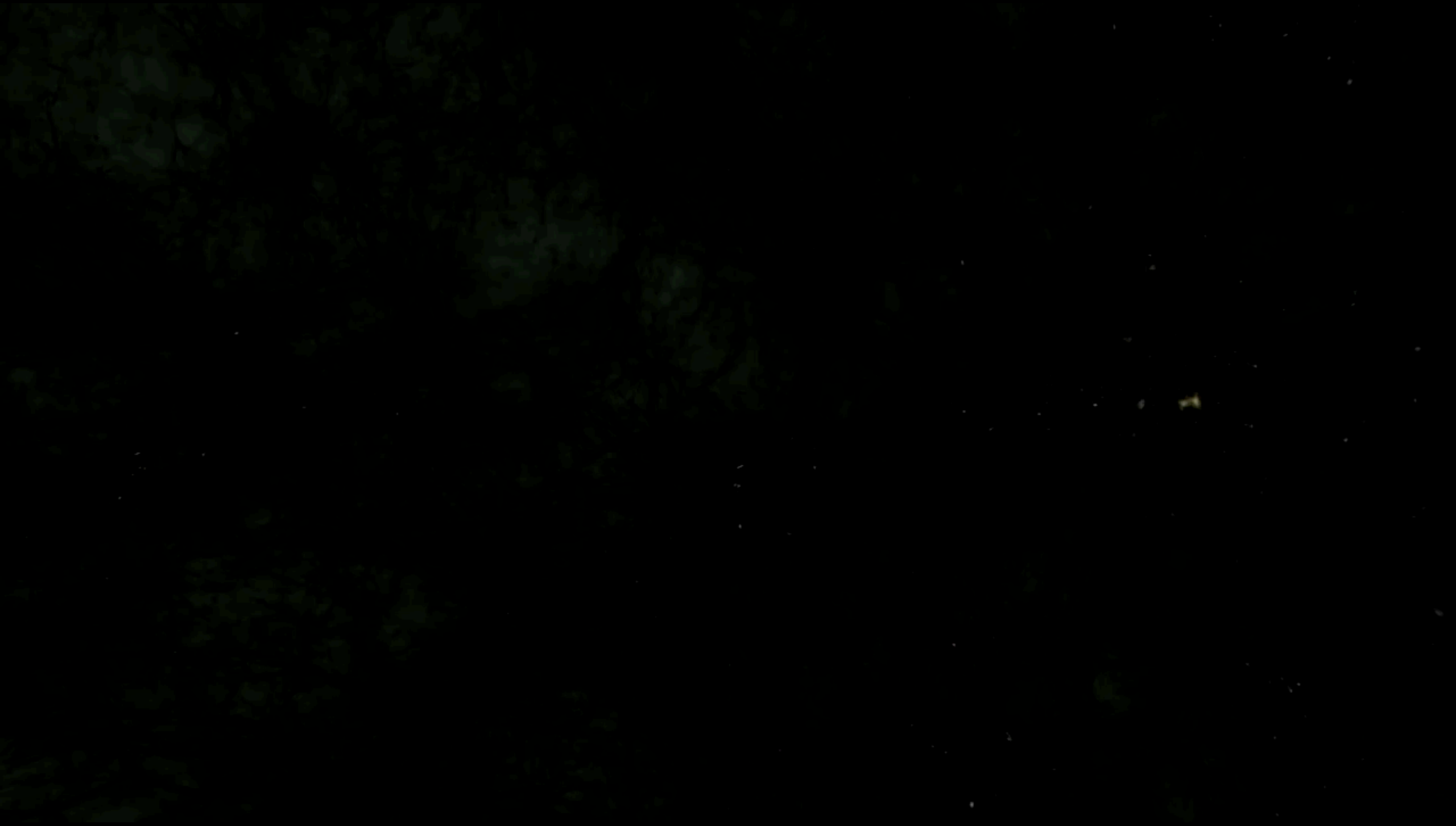
Star formation quenched, early-type galaxy, Illustris-TNG Collaboration



Illustris
Collaboration

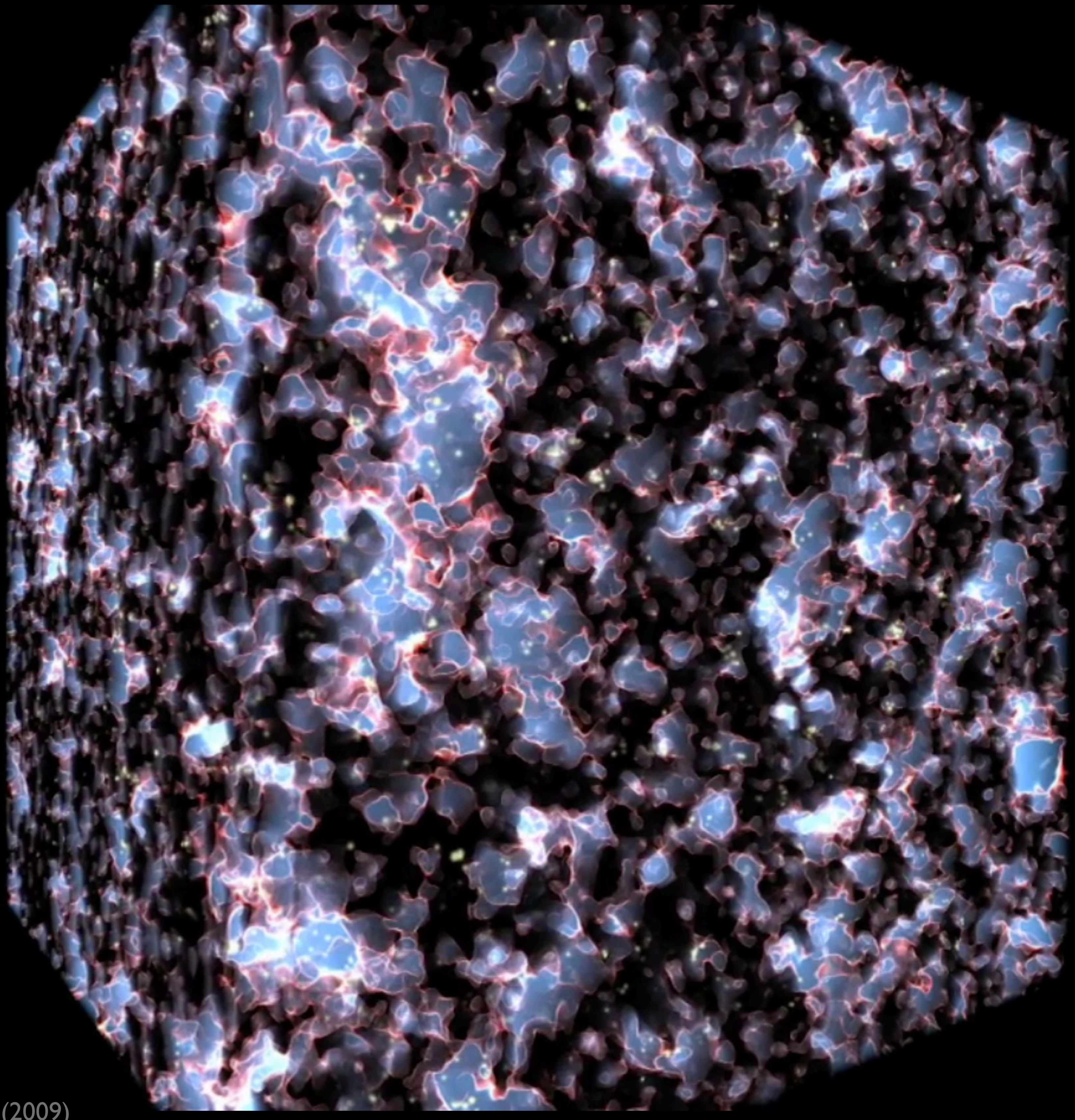


Renaissance simulation (400 Myrs after Big Bang), Norman, Xu, O'Shea et al., visualization by AVL@NCSA/UIUC

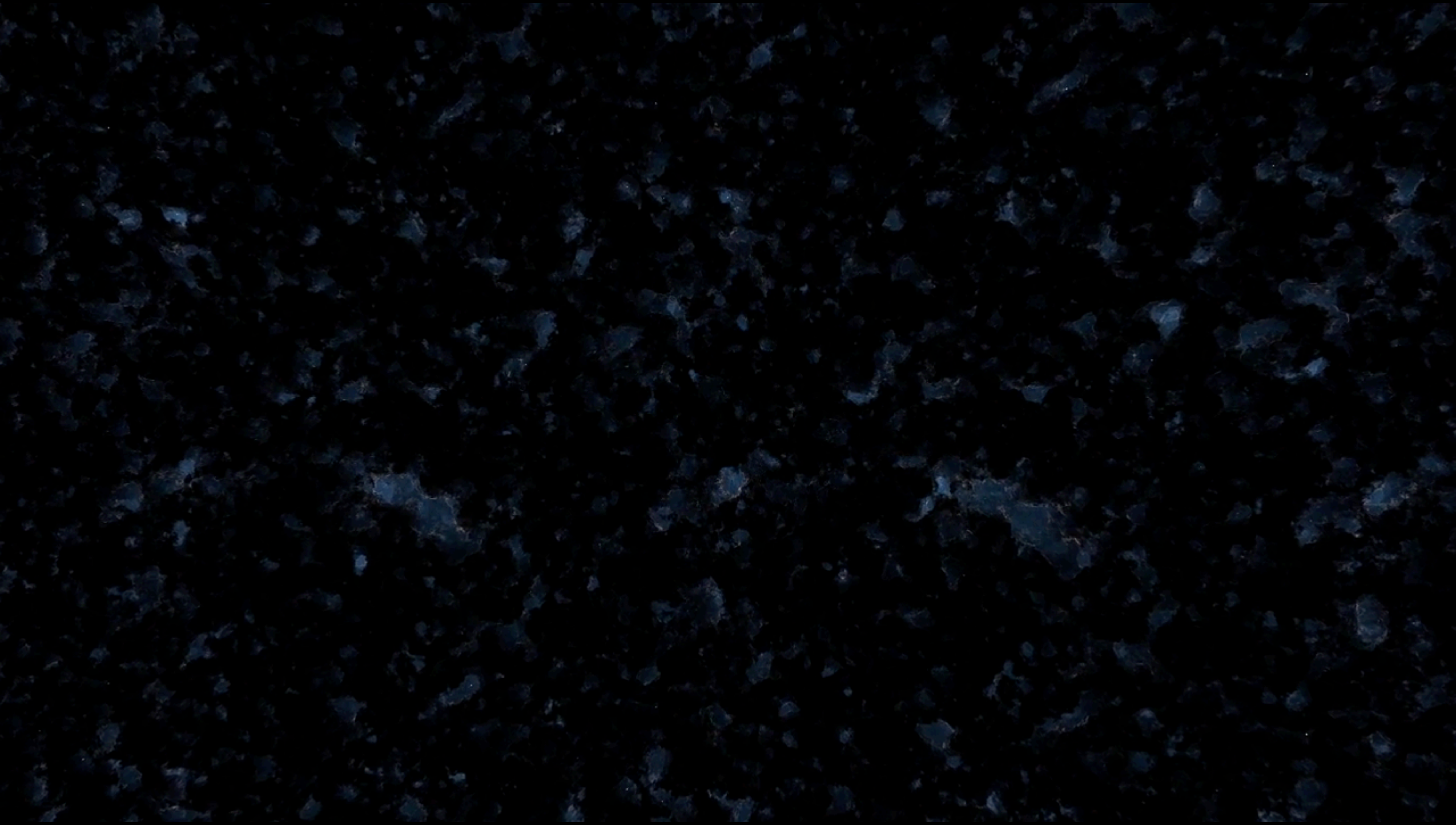


~Gpc across, Abel & Hahn

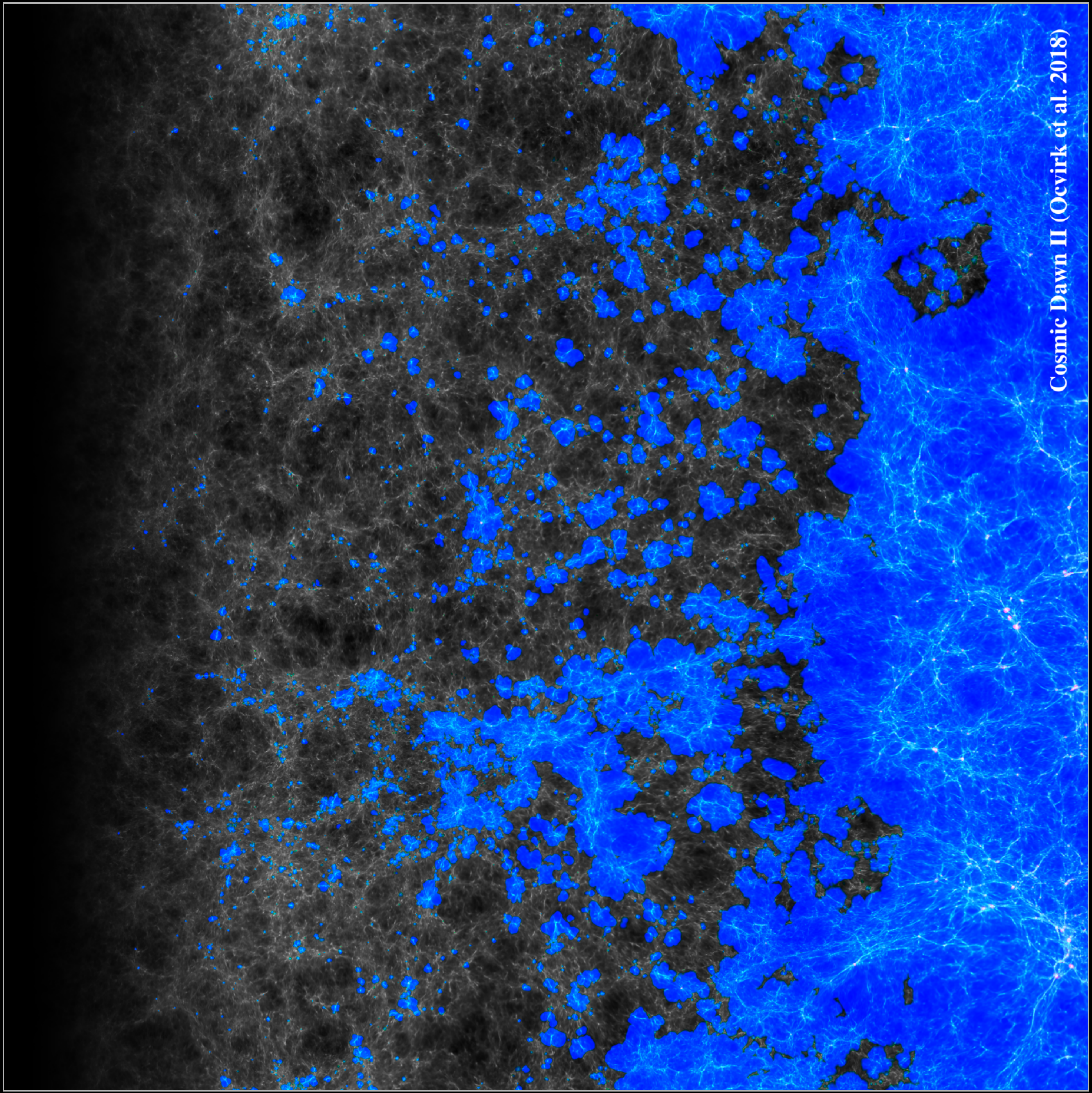
“Swiss Cheese” Reionization



Alvarez et al. (2009)



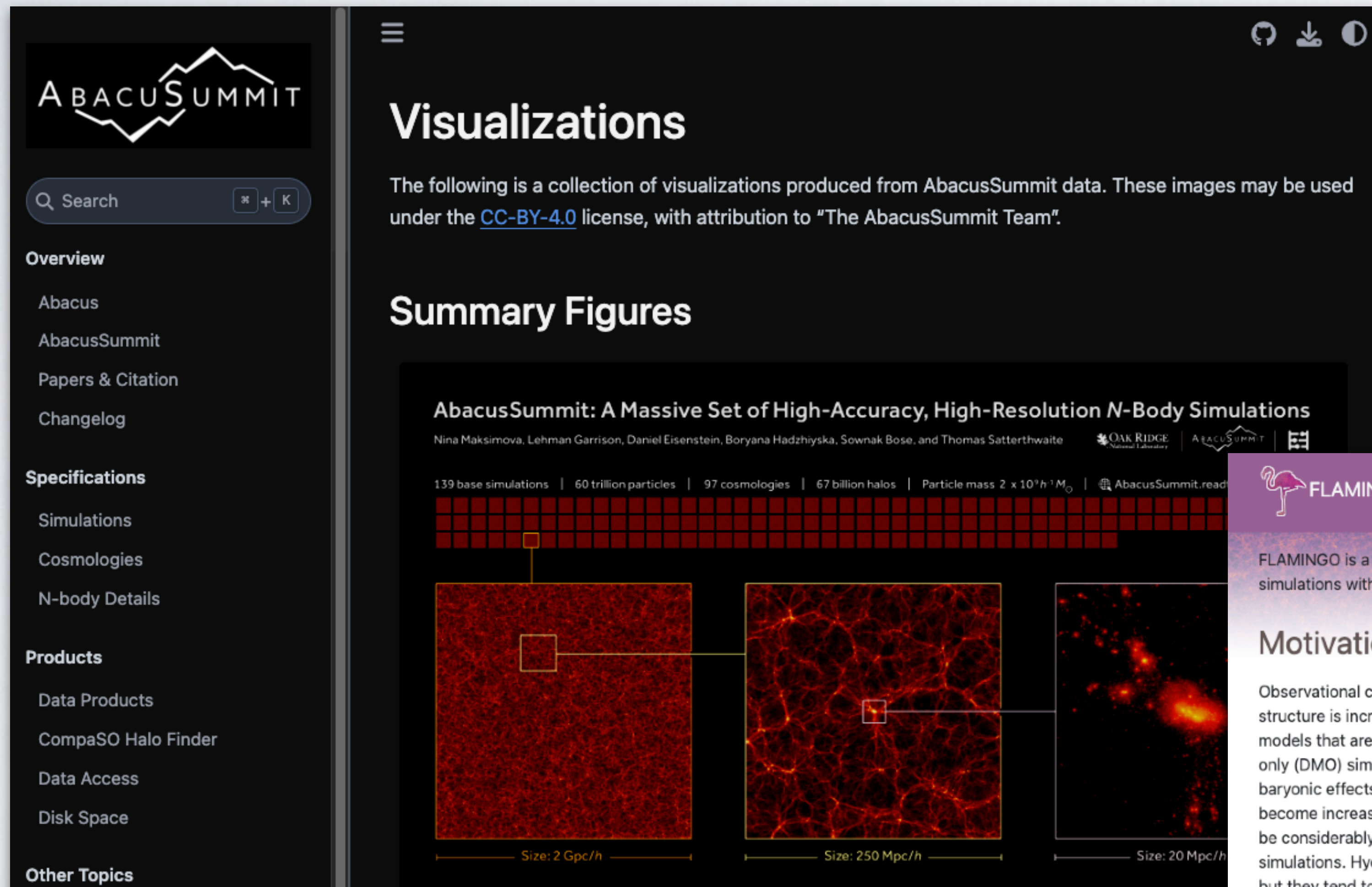
Epoch of reionization, Alvarez et al,



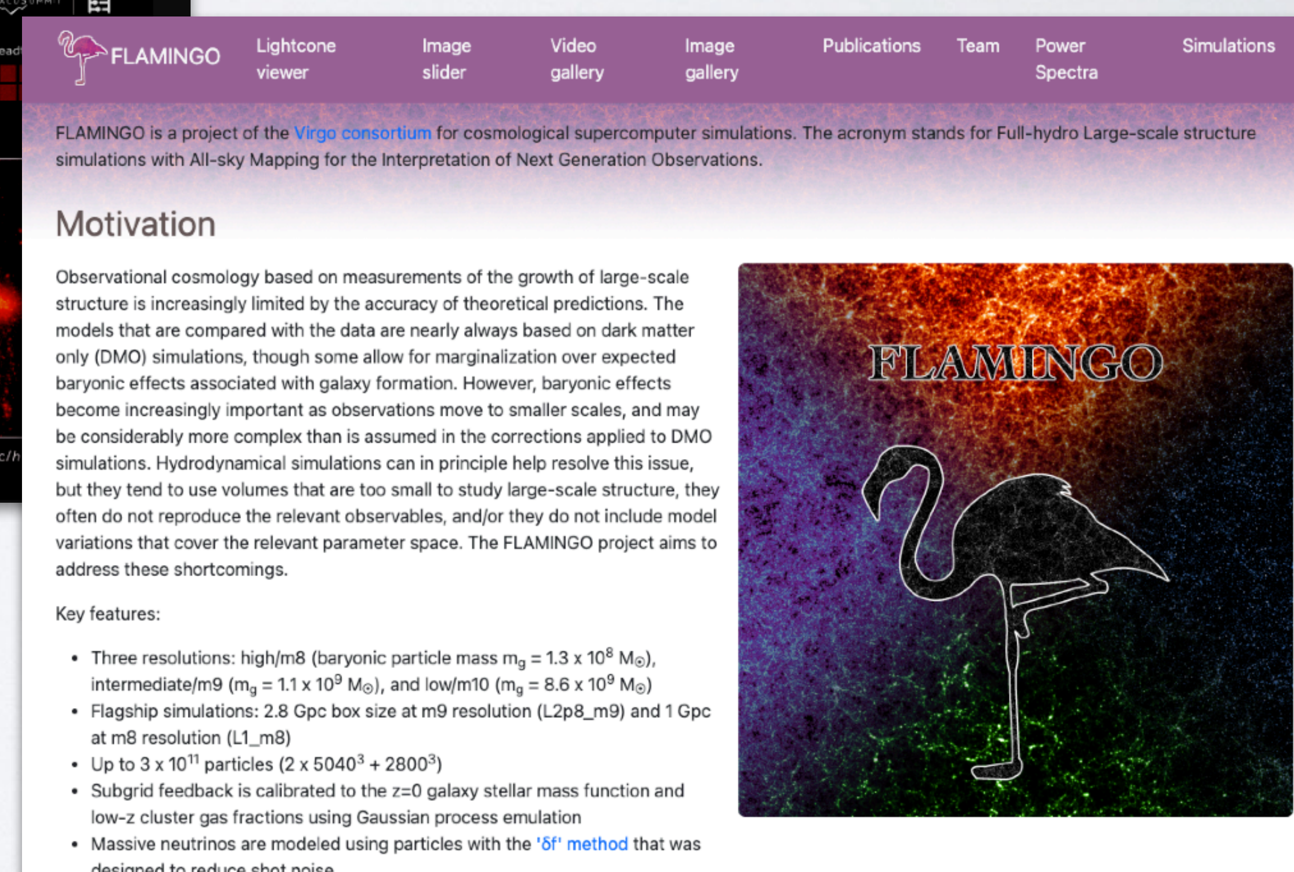
Ocvirk et al. (2018)

Generating "Large" Universes

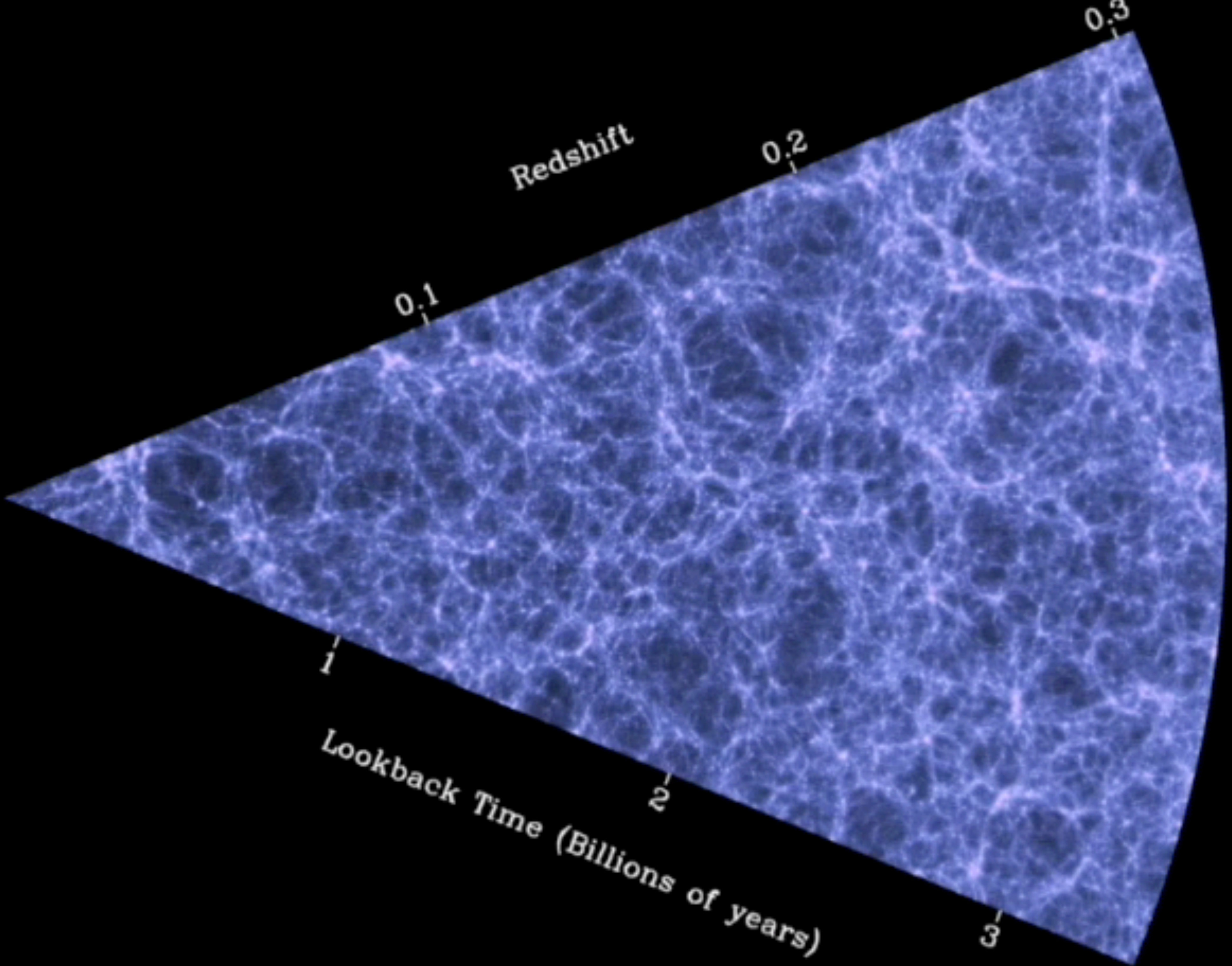
- Large-box simulations try to cover the volumes comparable to the "observable" universe.



AbucusSummit simulation, abacussummit.readthedocs.io



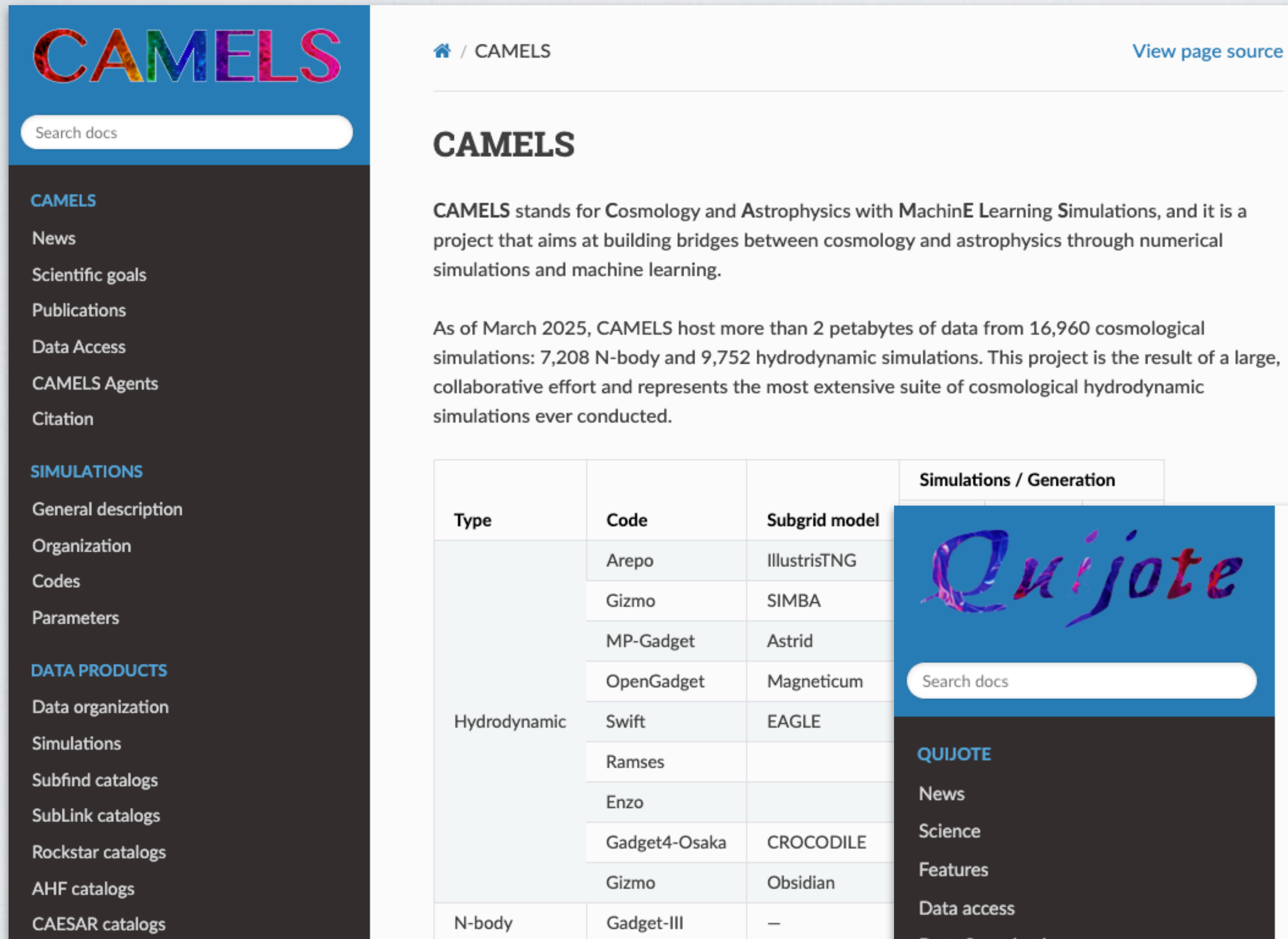
FLAMINGO simulation, flamingo.strw.leidenuniv.nl



http://sdss.kias.re.kr/astro/Horizon-Runs/

Generating "Many" Different Universes

- Can be used to train a machine that infers physics parameters or cosmological parameters of our universe.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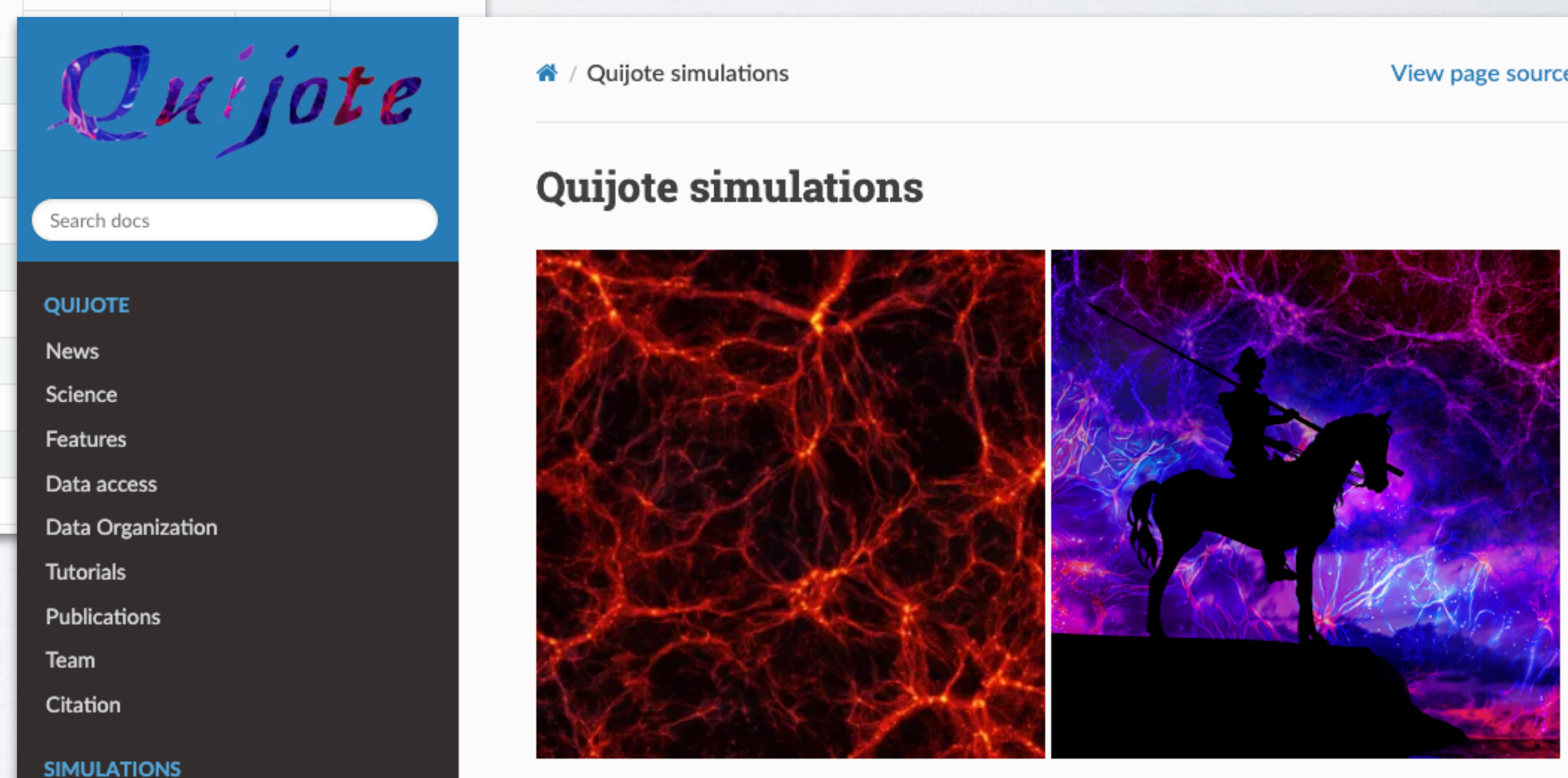
CAMELS

CAMELS stands for **C**osmology and **A**strophysics with **M**achin**E** **L**earning **S**imulations, and it is a project that aims at building bridges between cosmology and astrophysics through numerical simulations and machine learning.

As of March 2025, CAMELS host more than 2 petabytes of data from 16,960 cosmological simulations: 7,208 N-body and 9,752 hydrodynamic simulations. This project is the result of a large, collaborative effort and represents the most extensive suite of cosmological hydrodynamic simulations ever conducted.

Type	Code	Subgrid model	Simulations / Generation
Hydrodynamic	Arepo	IllustrisTNG	
	Gizmo	SIMBA	
	MP-Gadget	Astrid	
	OpenGadget	Magneticum	
	Swift	EAGLE	
	Ramses		
	Enzo		
	Gadget4-Osaka	CROCODILE	
	Gizmo	Obsidian	
N-body	Gadget-III	–	

CAMELS Collaboration, camel-simulations.org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SIMULATIONS

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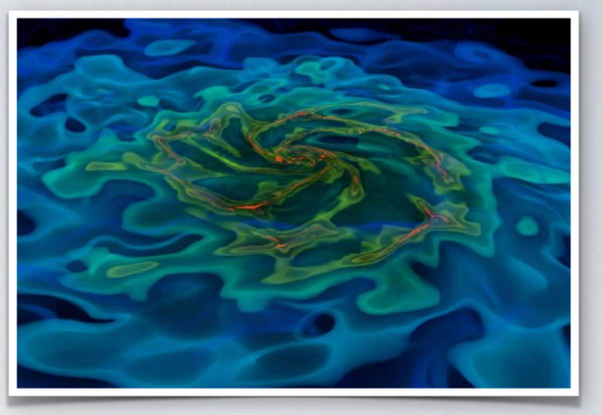
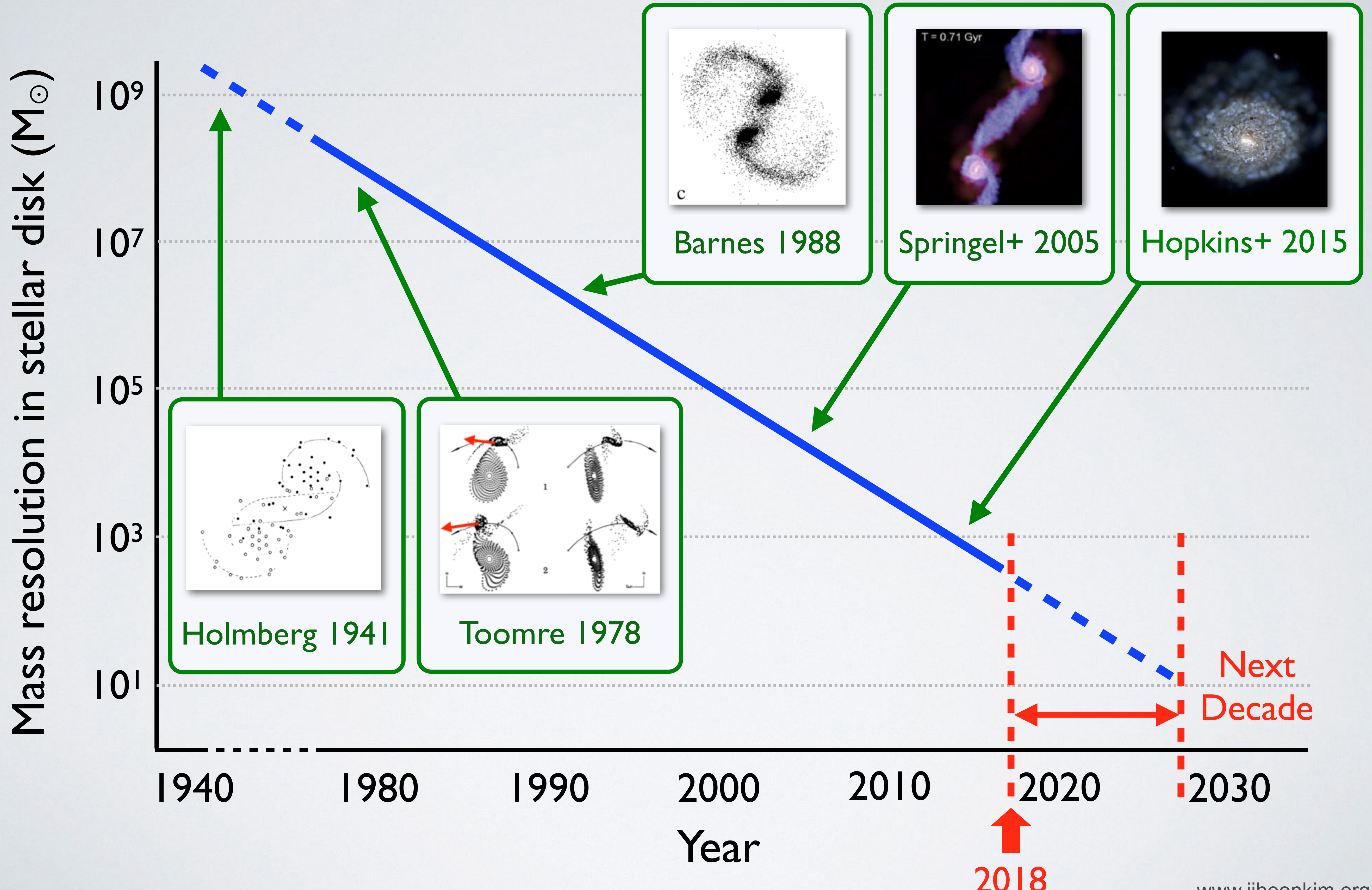
Quijote simulations

Quijote Collaboration, quijote-simulations.readthedocs.io



Computational Astrophysics: Methodology

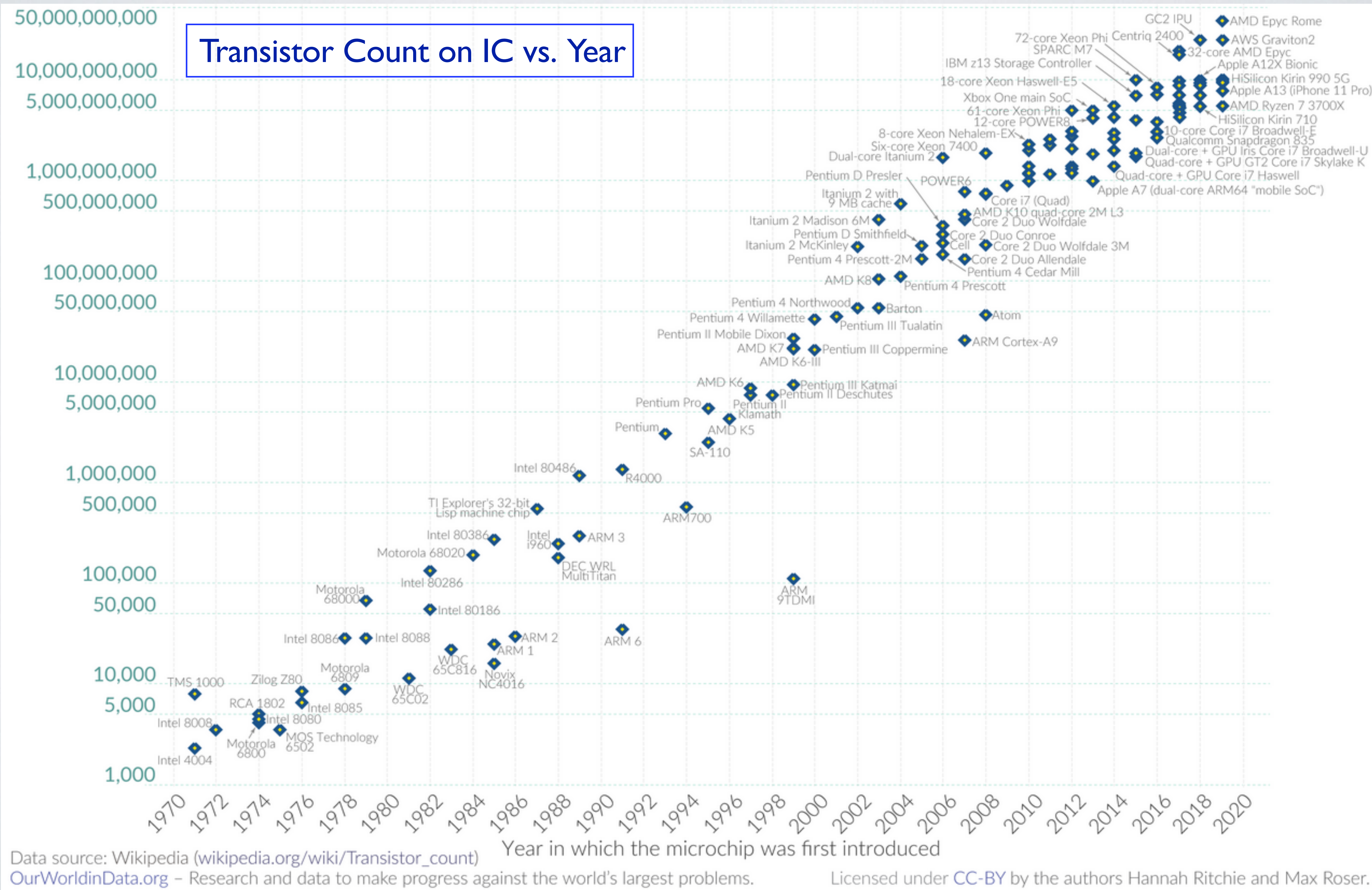
Computational Cosmology: Resolution



www.jihoonkim.org

Computational Cosmology: Tools

- Tools of numerical experiments have evolved exponentially.



Computational Cosmology: Tools

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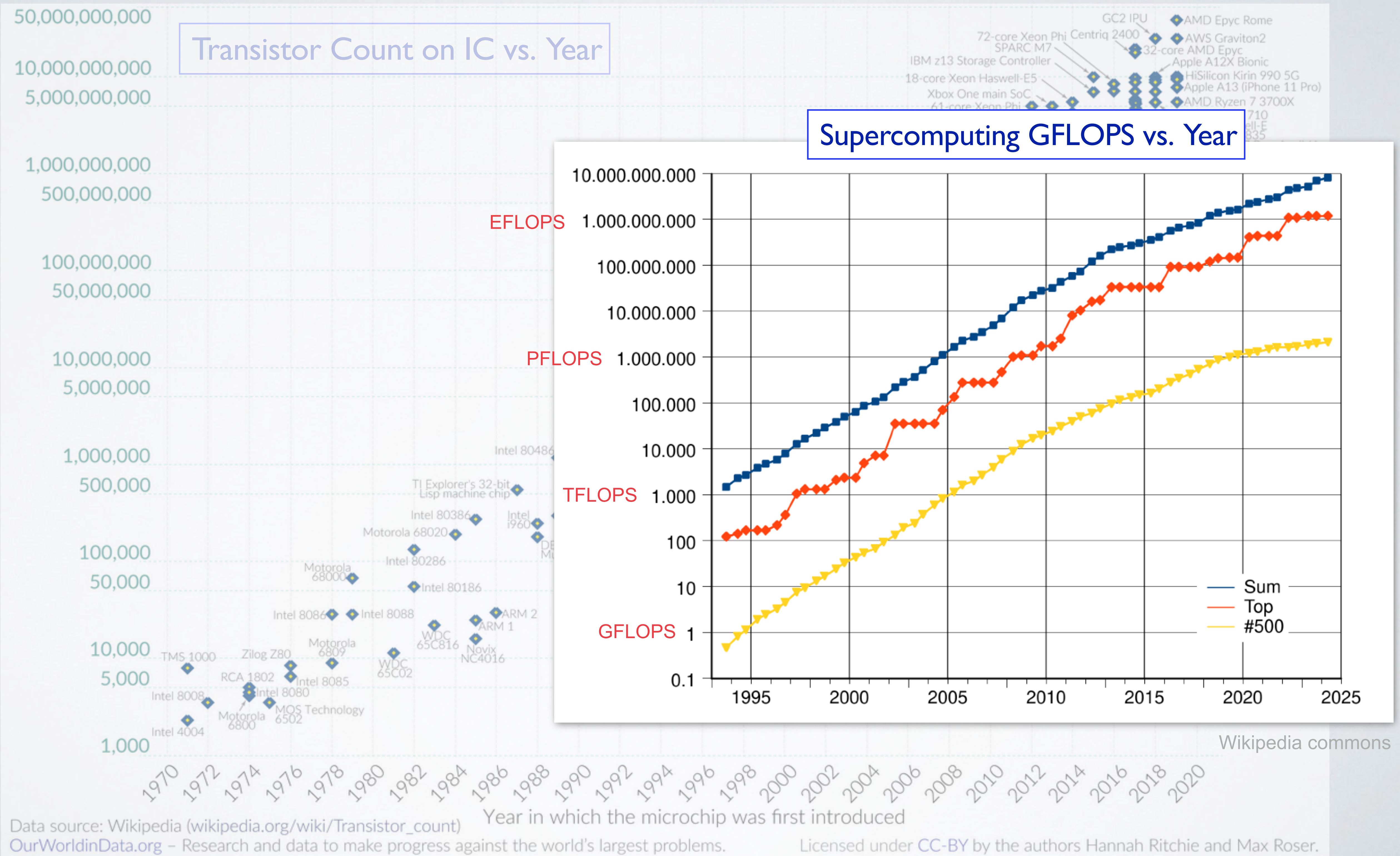
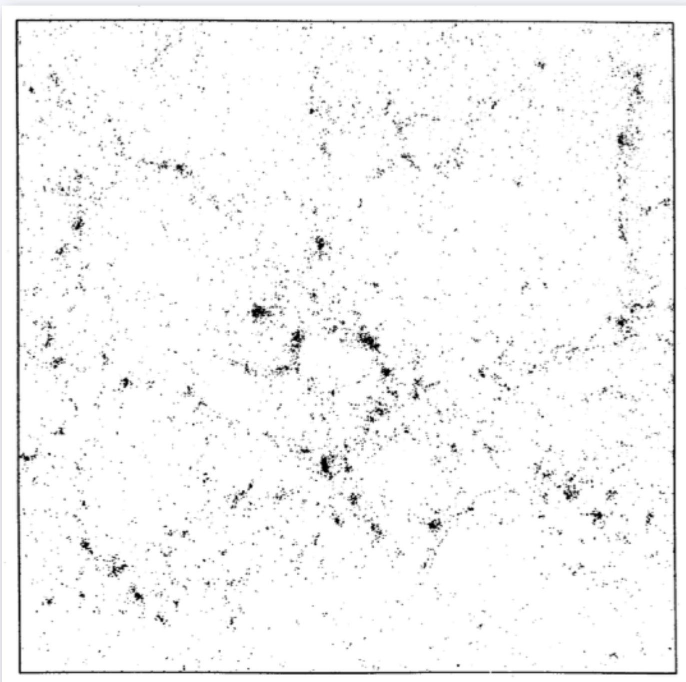
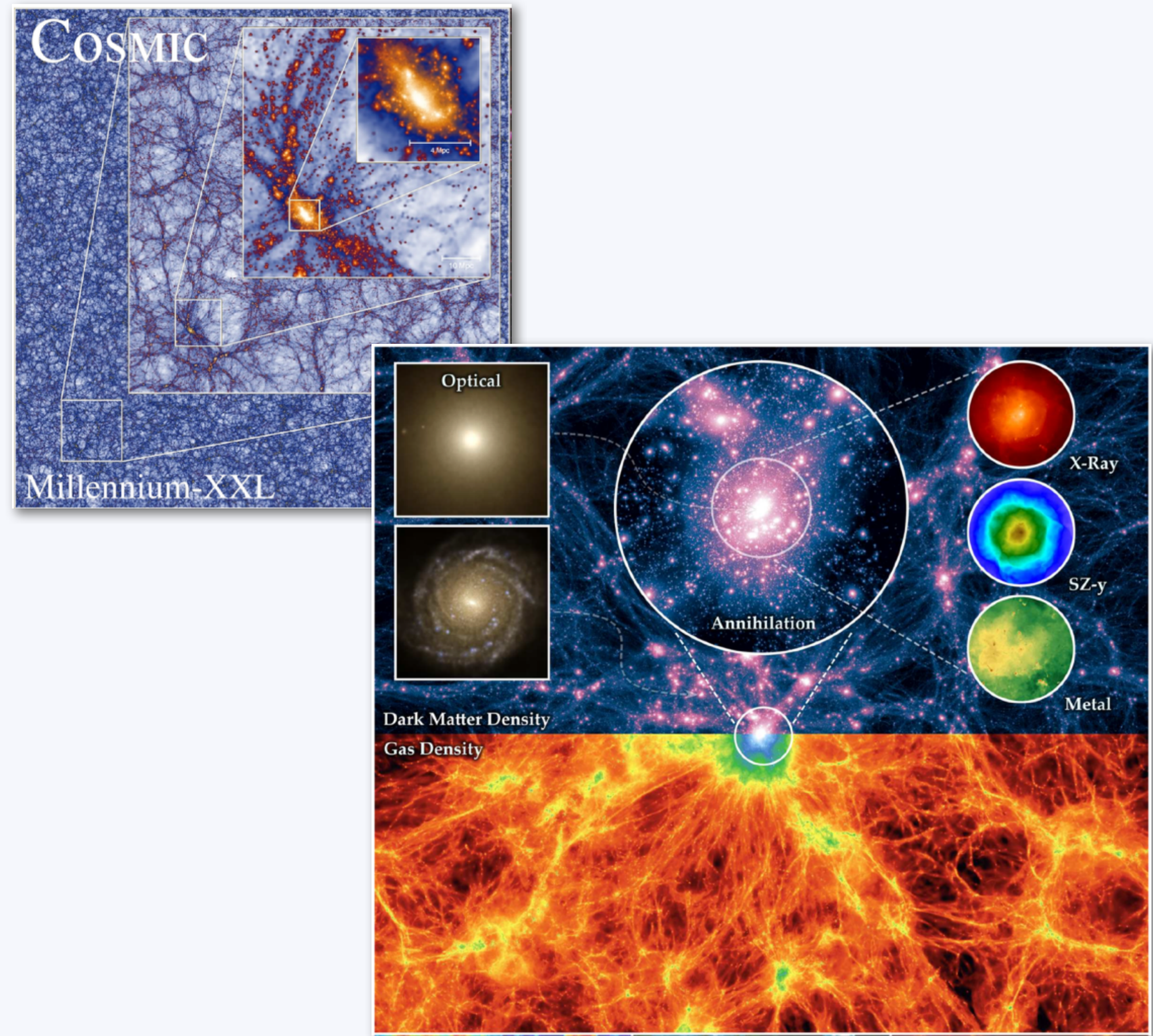


Computational Cosmology: Resolution



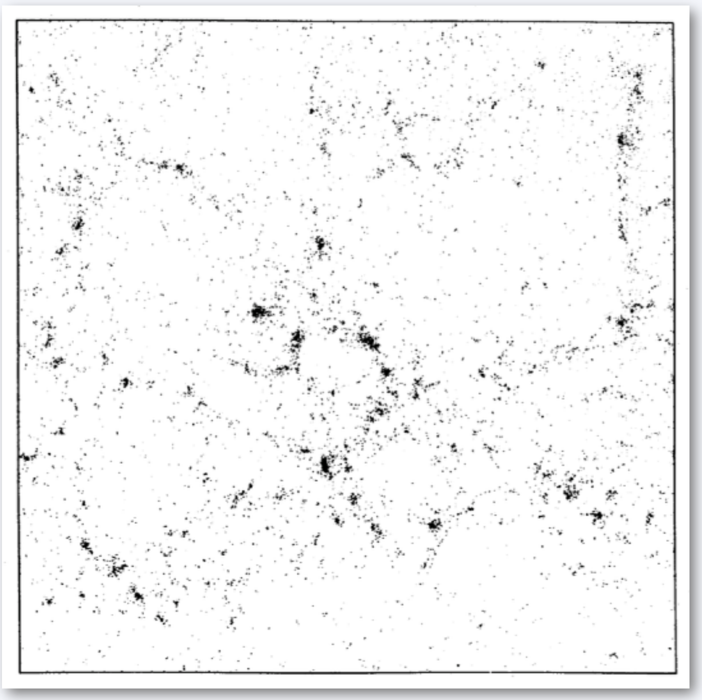
Davis et al. 1985

32^3 particles in $(32.5\ h^{-2}\ \mathrm{Mpc})^3$



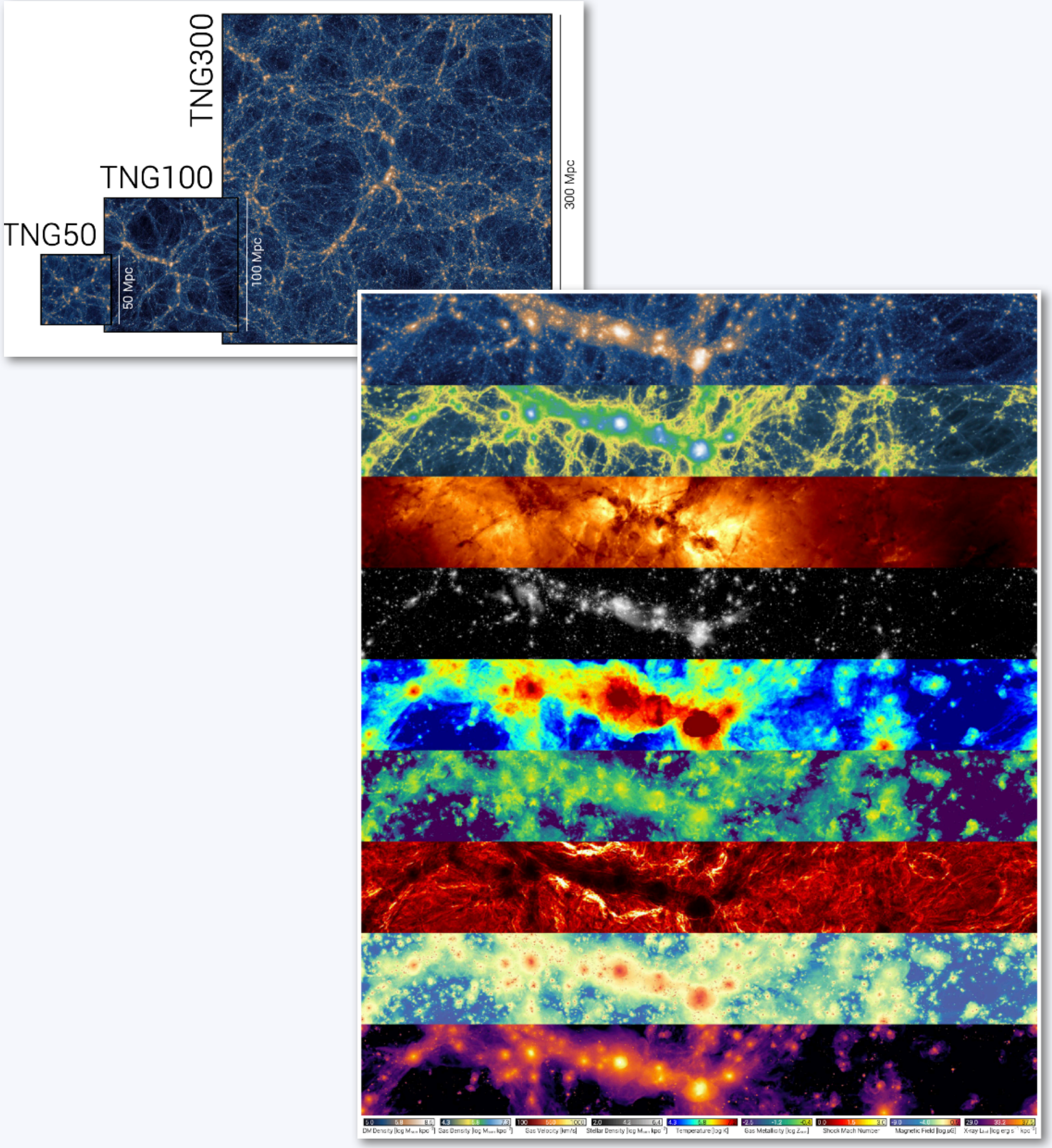
Vogelsberger et al. 2014 (“Illustris”)

2×1820^3 particles/cells in $(75\ h^{-1}\ \mathrm{Mpc})^3$



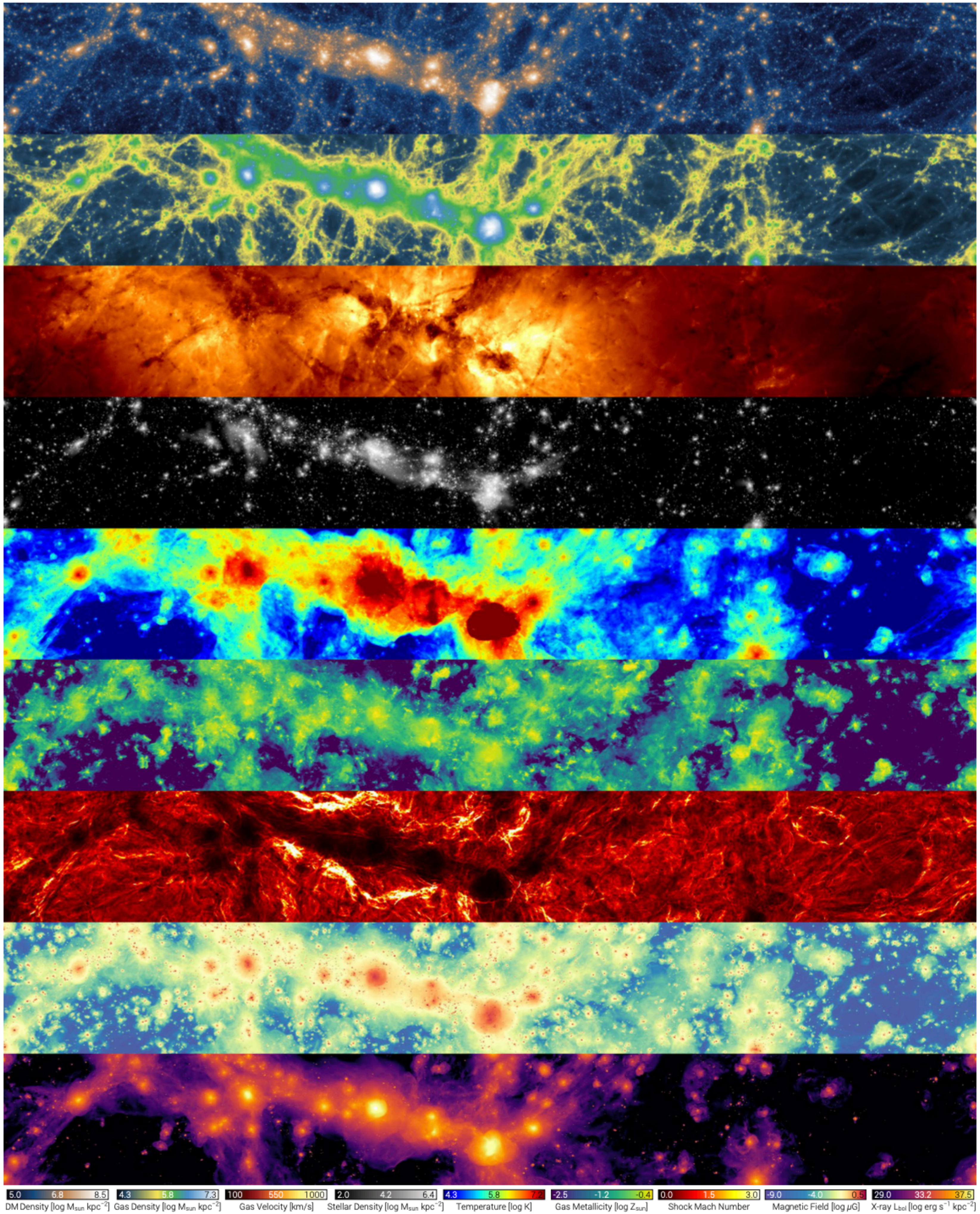
Davis et al. 1985

32^3 particles in $(32.5\ h^{-2}\ \mathrm{Mpc})^3$



Nelson et al. 2019 ("IllustrisTNG")

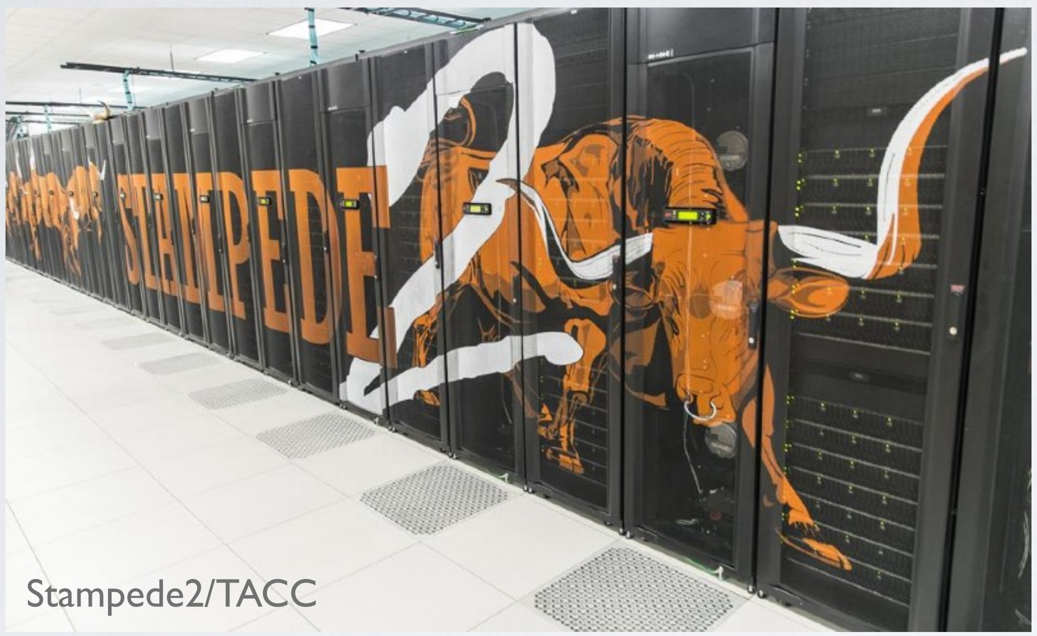
2500^3 particles/cells in $(205\ h^{-1}\ \mathrm{Mpc})^3$



Nelson et al. (2019)

Supercomputing Facilities

- Supercomputing resources provided by e.g., national labs.



Stampede2/TACC


Cambridge

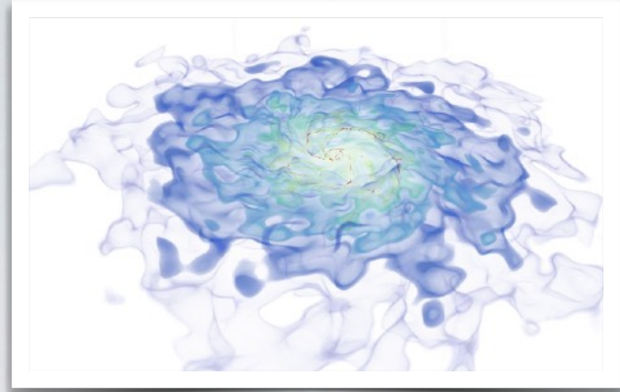
Pleiades/NASA

Nurion/KISTI

Supercomputing Facilities

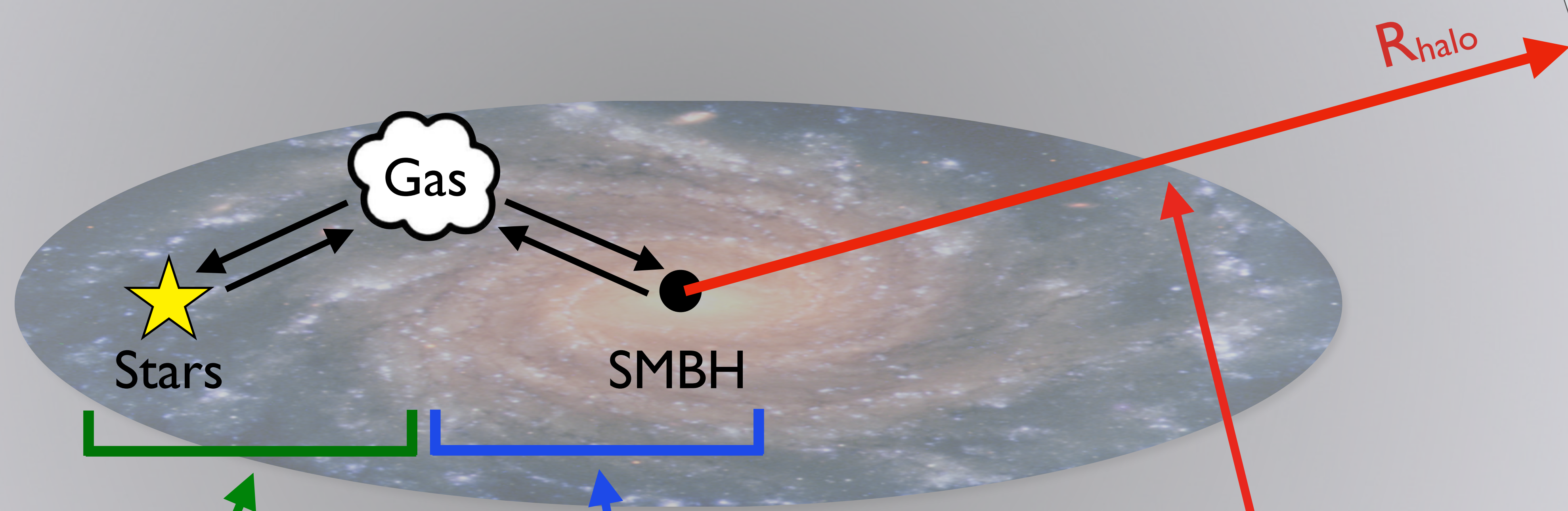
- Supercomputing resources provided by e.g., national labs.

Nurion(5th gen)/KISTI



Components of Simulations

Multi-scale, Nonlinear Interactions

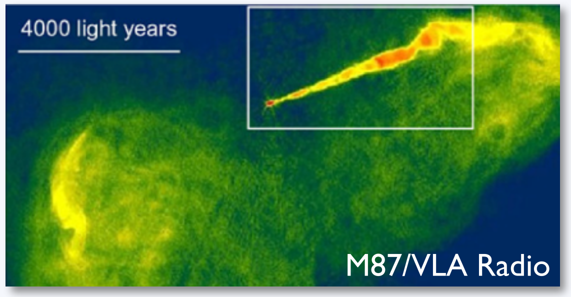


Stars or Molecular Clouds
Formation & Feedback

$R_{GMC} \sim 10$ pc

Massive Black Hole
Accretion & Feedback

$R_{Bondi} \sim$ pc
$R_{Schw.} \sim 10^{-5}$ pc

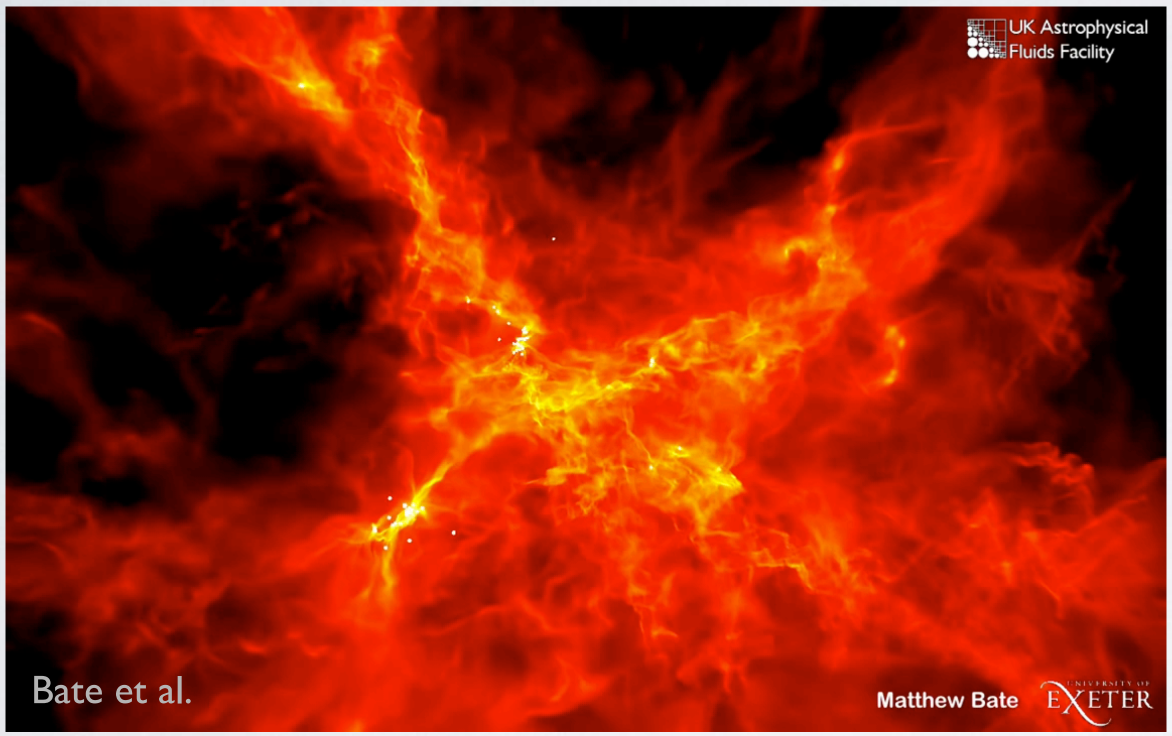


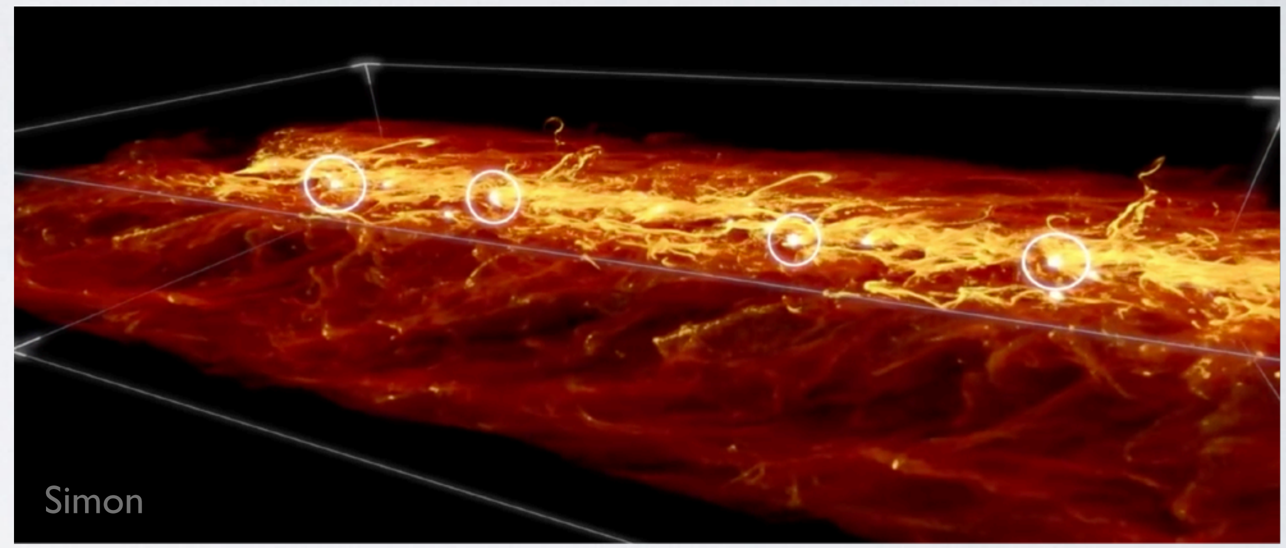
(Inter-)Galactic
Dynamics & Interaction

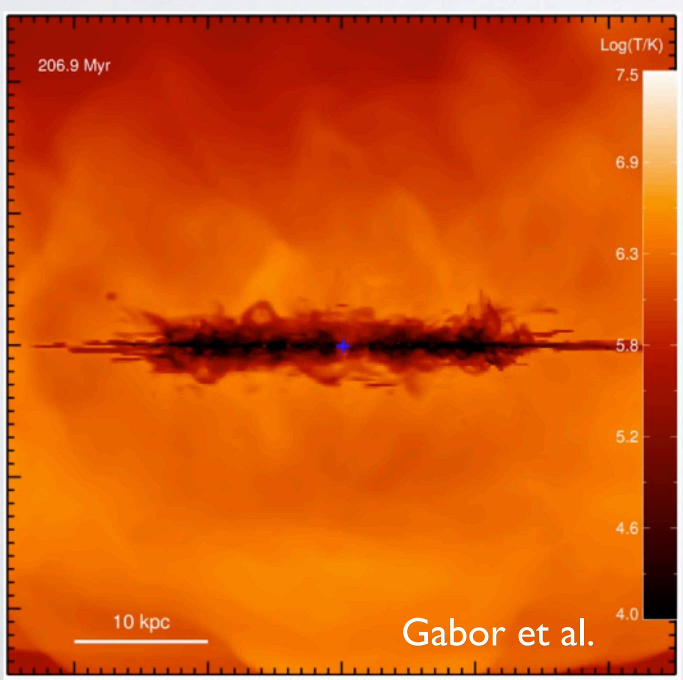
$R_{halo} \sim 100$ kpc

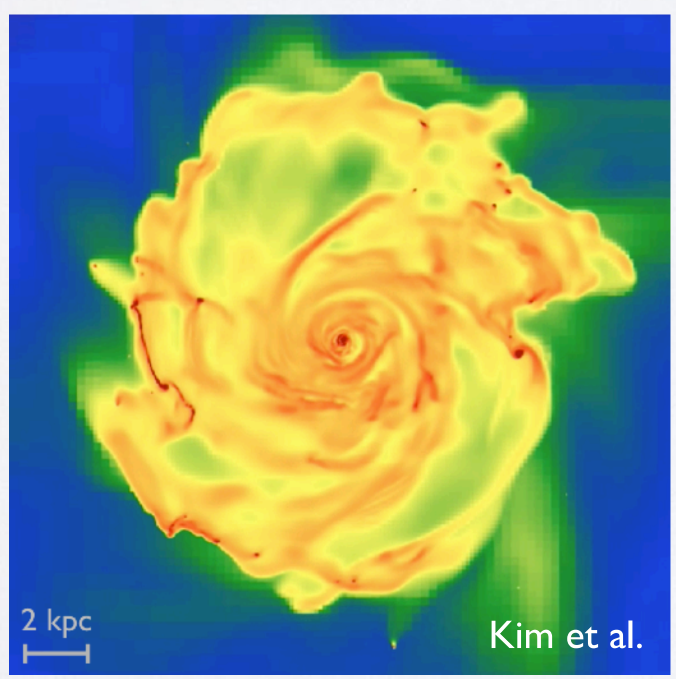
“Idealized” Initial Conditions

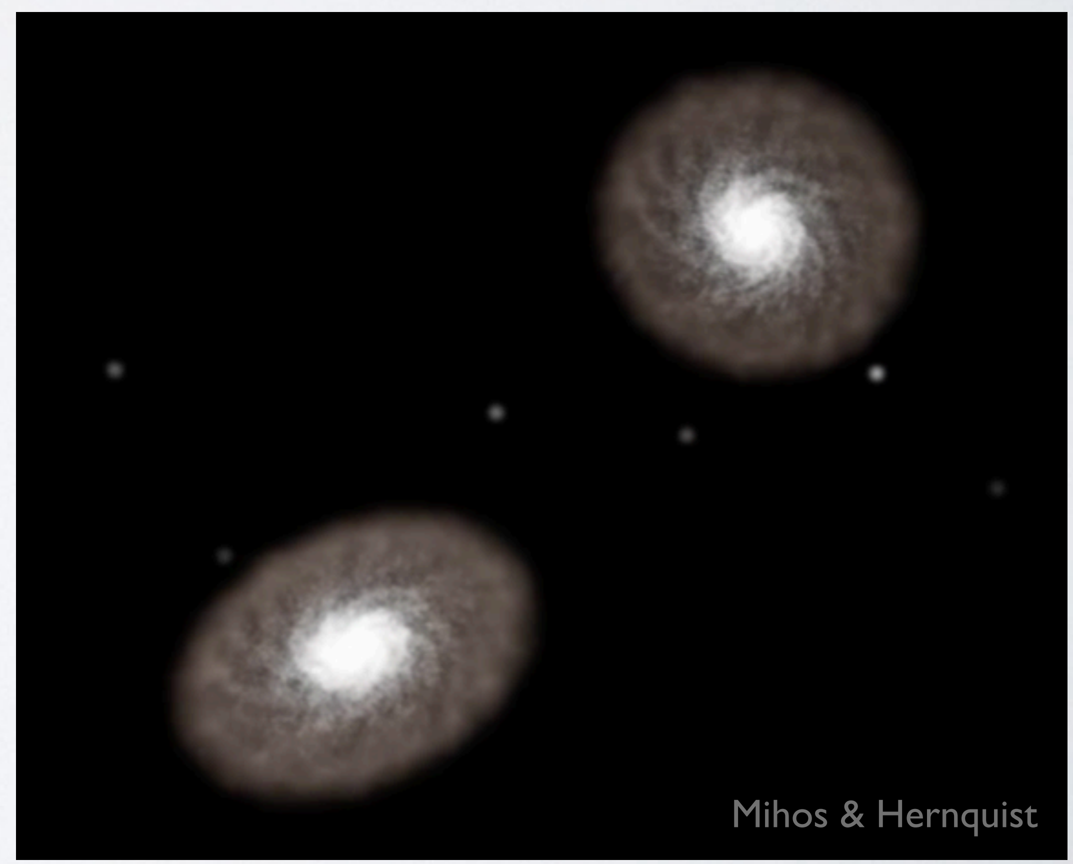
- Start from physically-motivated, yet idealized, often isolated ICs.





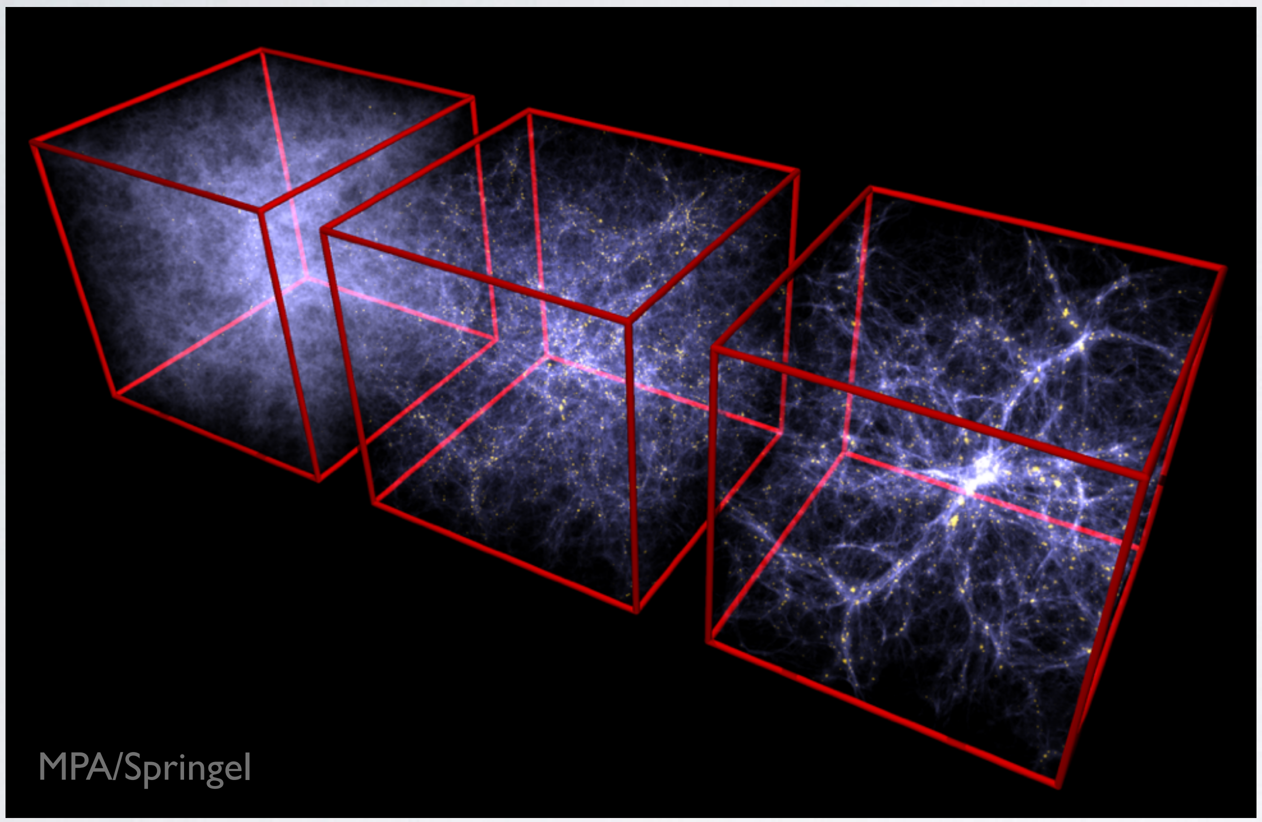


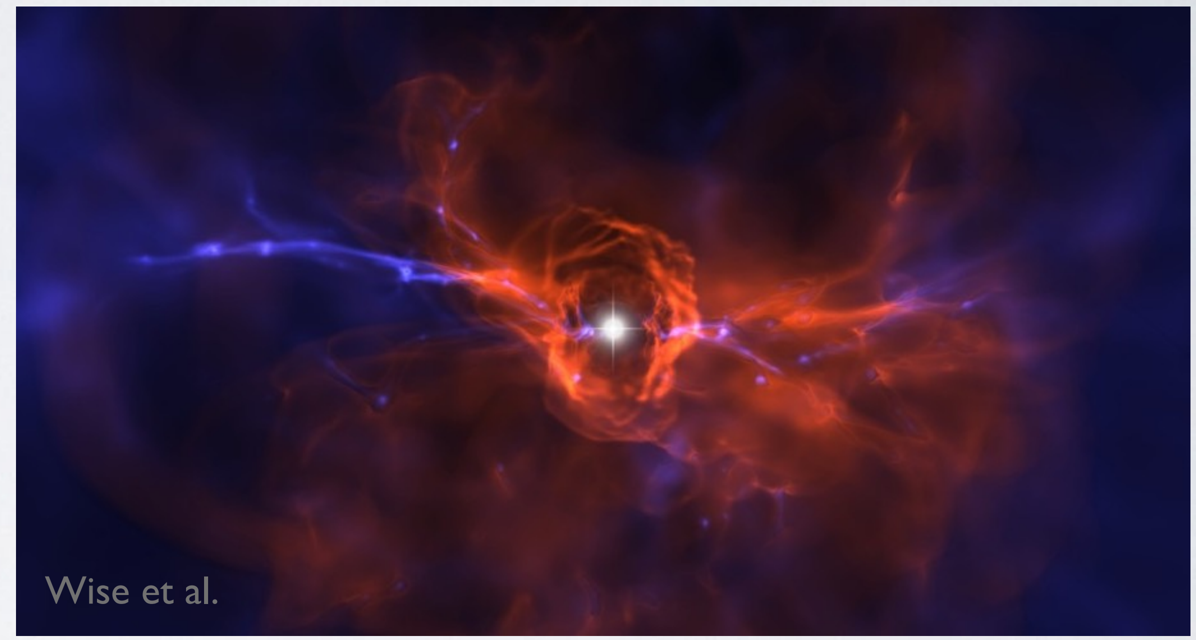


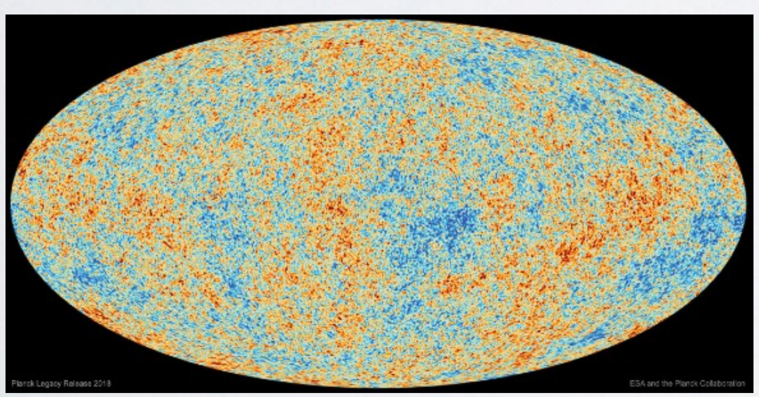


“Cosmological” Initial Conditions

- Start from perturbed density distribution motivated by CMB.

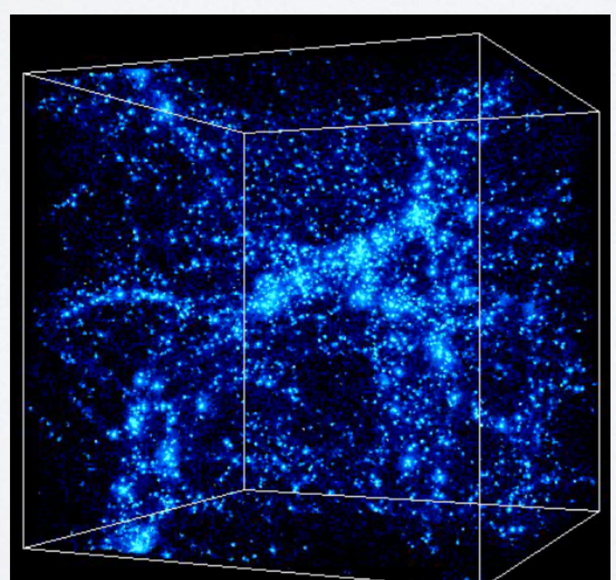


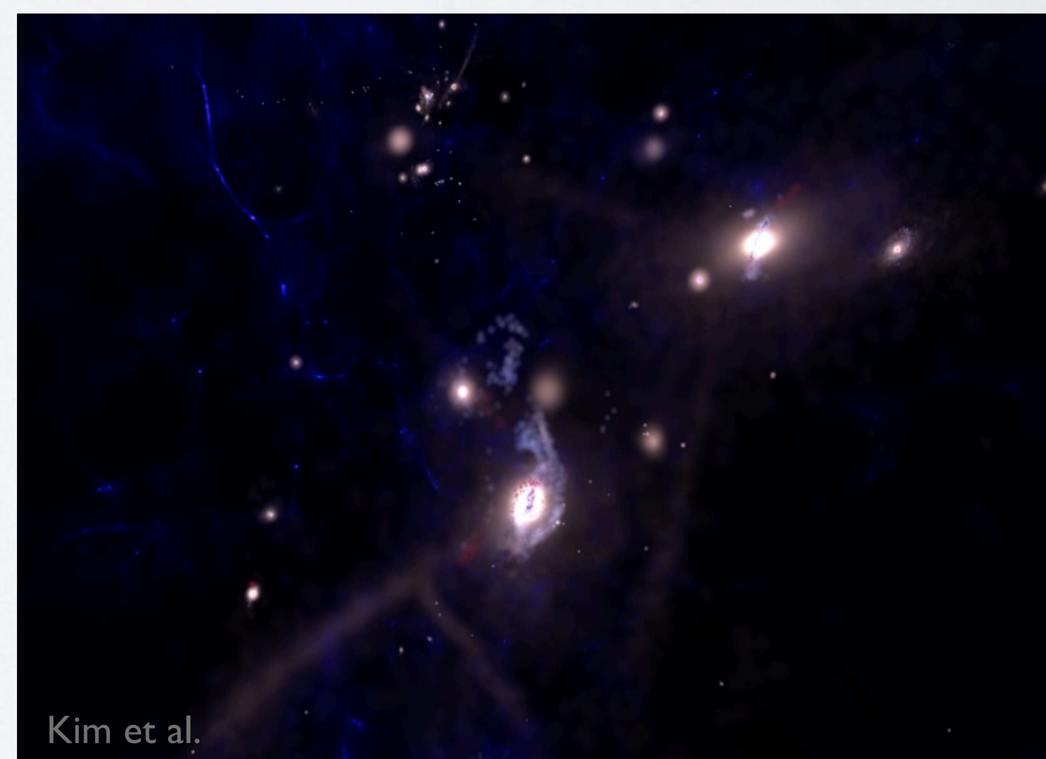




ESA/Planck

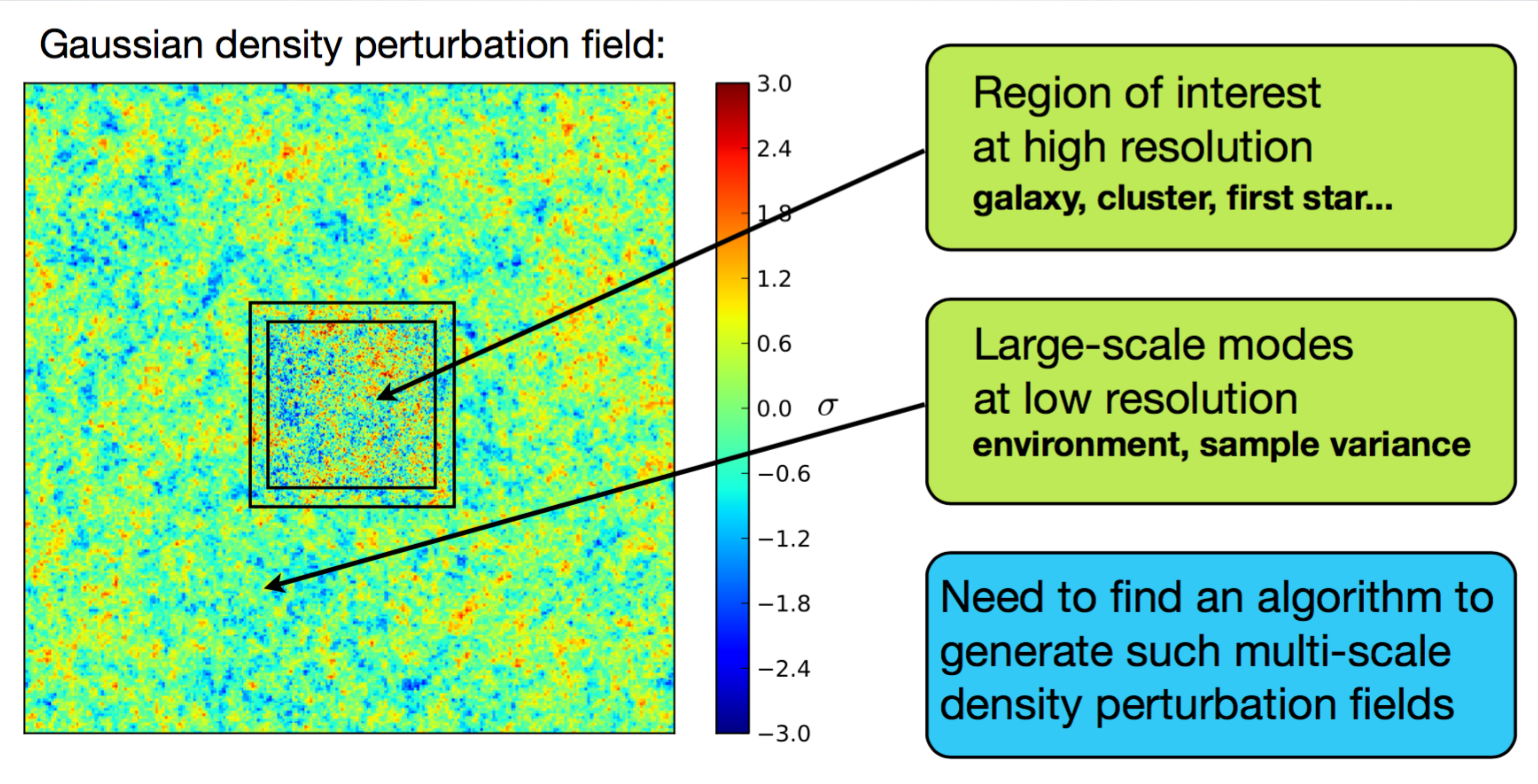
Kravtsov et al.





“Zoom-in” Cosmological ICs

- Strategy to best utilize your resources on regions of interest.
- Nested zoom-in IC to capture both large- and small-scale power.



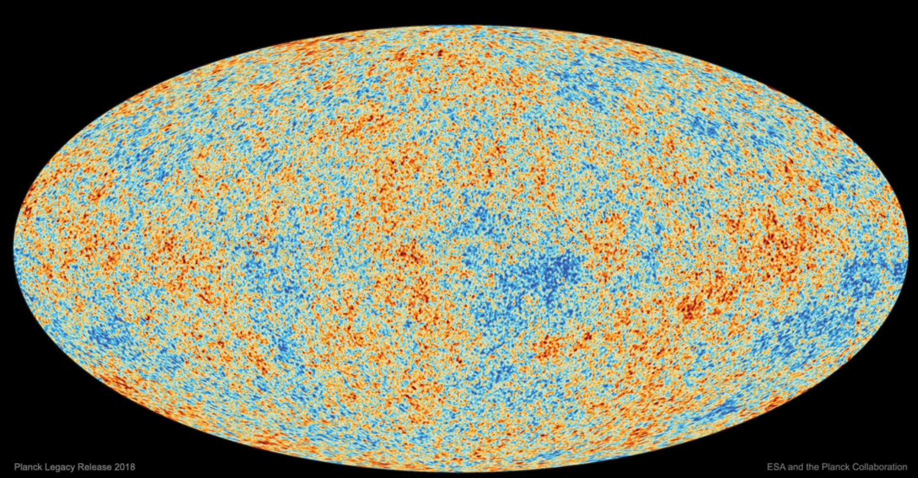
Hahn

Linear and Nonlinear Growth

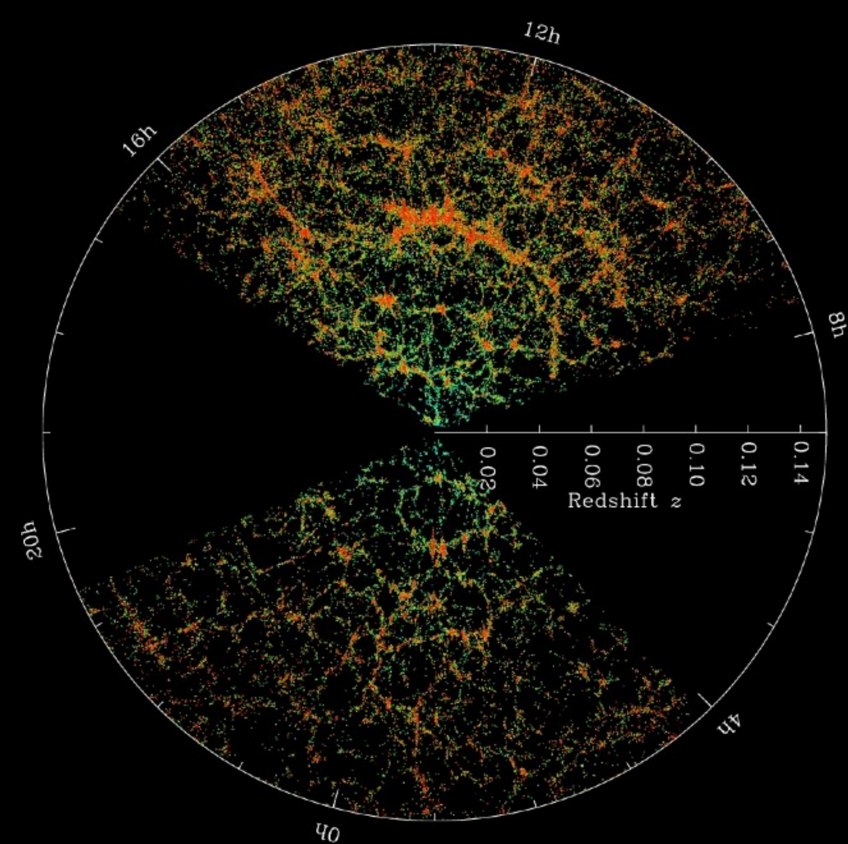
- If $|\delta\rho/\bar{\rho}| = |\delta(x)| \ll 1$, $\delta(x)$'s evolves linearly (right after CMB).
- The Universe at ~Mpc scale has entered the nonlinear regime.

$\langle(\delta\rho/\bar{\rho})^2\rangle^{0.5} \sim 10^{-5}$

$\langle(\delta\rho/\bar{\rho})^2\rangle^{0.5} \gg 1$

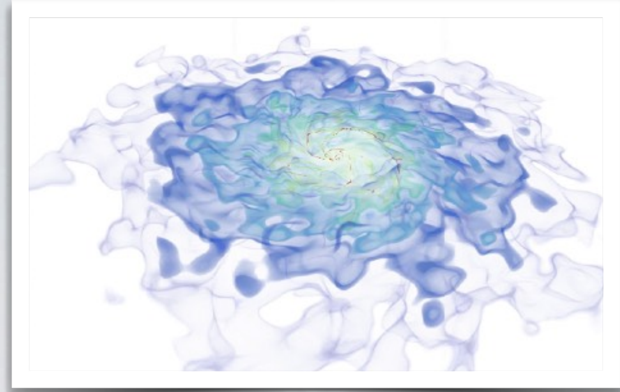


Planck



SDSS


Hydra Cluster



Physics Processes in Simulations

most important astrophysical processes

gas cooling	inter-stellar medium	star formation	stellar feedback	super-massive black holes	active galactic nuclei	magnetic fields	radiation fields	cosmic rays
atomic/ molecular/ metals/ tabulated/ network	effective equation of state/ multi-phase	initial stellar mass function/ probabilistic sampling/ enrichment	kinetic/ thermal/ variety of sources from stars, supernovae	numerical seeding/ growth by accretion prescription/ merging	kinetic/ thermal/ radiative/ quasar mode/ radio mode	ideal MHD/ cleaning schemes/ constrained transport	ray tracing/ Monte Carlo/ moment-based	production/ heating/ anisotropic diffusion/ streaming

numerical discretization of matter components

Collisionless Gravitational Dynamics

- *N*-body methods based on integral Poisson's equation (e.g. tree, fast multipole)
- *N*-body methods based on differential Poisson's equation (e.g. particle-mesh, multigrid)
- *N*-body hybrid methods (e.g. TreePM)
- Beyond *N*-body methods (e.g. Lagrangian tesselation)

dark matter

Hydrodynamics

- Lagrangian methods (e.g. smoothed particle hydrodynamics)
- Eulerian methods (e.g. adaptive-mesh-refinement)
- Arbitrary Lagrangian-Eulerian methods (e.g. moving mesh)
- Mesh-free / mesh-based

gas

generating initial conditions

Volume — sample of galaxies ← linear perturbation theory → Zoom — individual galaxy

Gravity

- Newtonian gravity in an expanding background
- modified gravity as dark matter alternative
- modified gravity as dark energy alternative
- ...

Dark Matter

- cold dark matter
- warm dark matter
- self-interacting dark matter
- fuzzy dark matter
- ...

Dark Energy

- cosmological constant
- dynamical dark energy
- inhomogeneous dark energy
- coupled dark energy
- ...

Initial Conditions

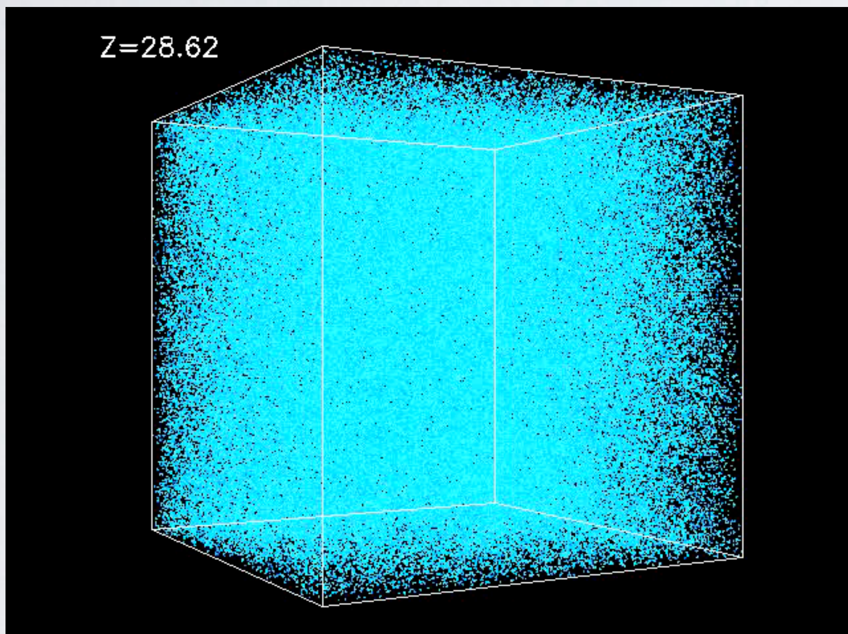
- inflation generated initial perturbations on top of homogeneous Friedmann model
- ...

cosmological framework

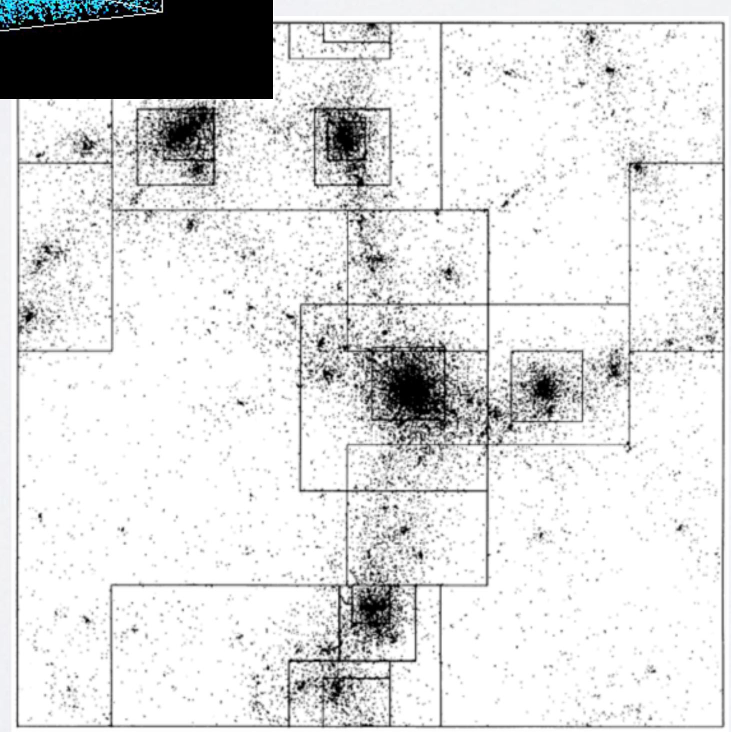
Vogelsberger et al. (2019)

Gravity: Poisson's Equation

- Gravity is the main driver for structure formation in Universe.



Kravtsov et al.



P3M-SPH,
Couchman et al. (1995)

Poisson's equation for gravity:

$$\nabla^2 \Phi = 4\pi G \rho$$

Its solution has the form:

$$\Phi(\mathbf{x}) = \int g(\mathbf{x} - \mathbf{x}')\, \rho(\mathbf{x}')\, \mathrm{d}\mathbf{x}',$$

with $g(\mathbf{x}) = -\frac{G}{|\mathbf{x}|}$

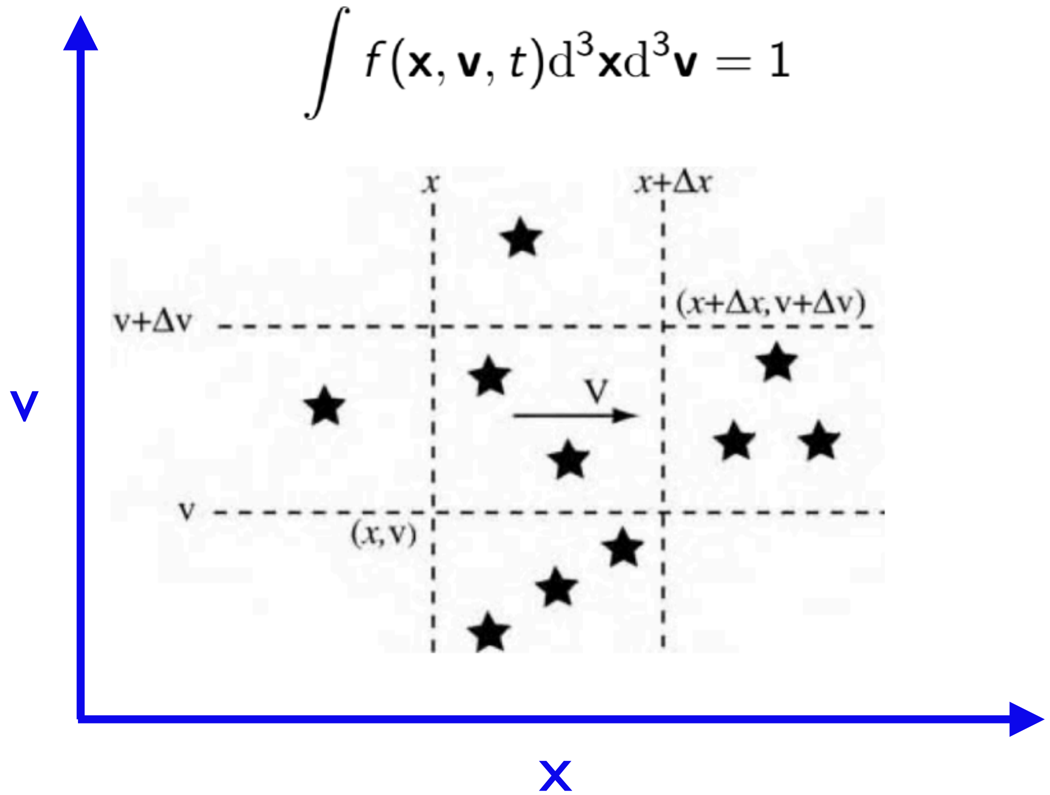
The convolution in x-space is simply a multiplication in k-space:

$$\hat{\Phi}(\mathbf{k}) = \hat{g}(\mathbf{k}) \cdot \hat{\rho}(\mathbf{k})$$

Collisionless Boltzmann Equation

- Let us consider a stellar/galactic system of a large number of identical bodies moving in a smooth potential $\Phi(\mathbf{x}, t)$.
- Galactic dynamics is all about deriving the probability $f(\mathbf{x}, \mathbf{v}, t)$ of finding a star in a 6-dimensional phase space volume $d^3\mathbf{x}d^3\mathbf{v}$.

$$\int f(\mathbf{x}, \mathbf{v}, t)\mathrm{d}^3\mathbf{x}\mathrm{d}^3\mathbf{v} = 1$$



Then, 6-dim continuity equation: $$\frac{\partial f}{\partial t} + \sum_{i=1}^{6} \dot{w}_i \frac{\partial f}{\partial w_i} = 0$$

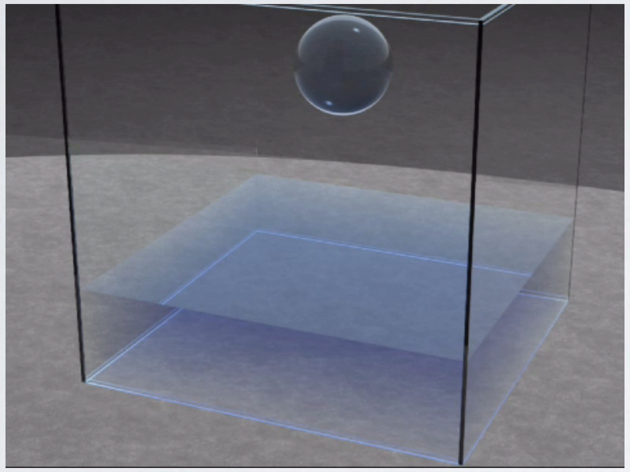
$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla f - \nabla \Phi \cdot \frac{\partial f}{\partial \mathbf{v}} = 0$$

Euler equation in fluid dynamics: $$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \mathbf{v}) = 0$$

www.ast.cam.ac.uk/~vasily, Sparke & Gallagher

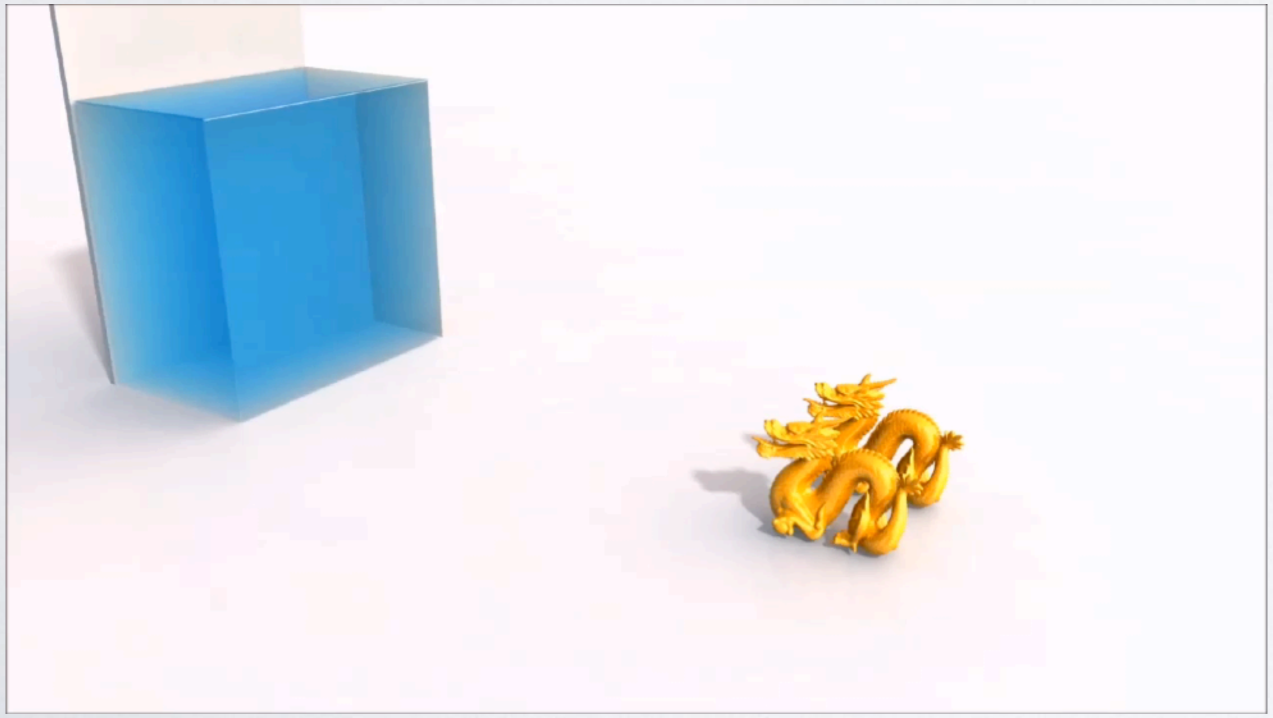
Fluid Dynamics: Euler Equations

- At small scales, hydrodynamics of the baryonic components turns out to be important (e.g., star formation, supernovae).



Fedkiw et al.

Fedkiw et al.



Bender & Koschier

Three conservation equations:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{v}) = 0,$$

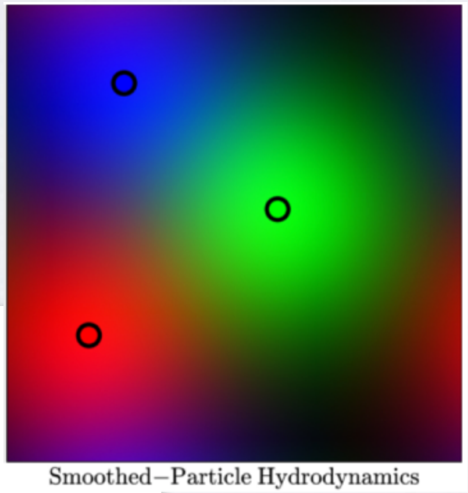
$$\frac{\partial}{\partial t}(\rho \mathbf{v}) + \nabla(\rho \mathbf{v}\mathbf{v}^T + P) = 0,$$

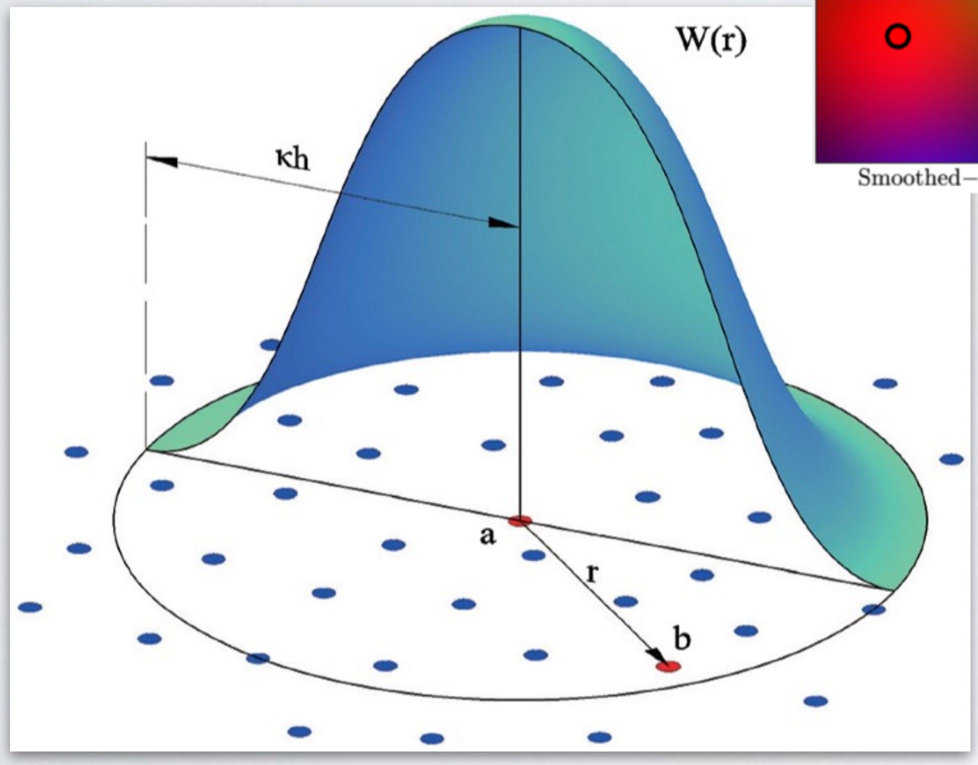
$$\frac{\partial}{\partial t}(\rho e) + \nabla[(\rho e + P)\mathbf{v}] = 0$$

Smoothed Particle Hydrodynamics (SPH)

- Describe the continuum media with discrete particles.
  - originally for astrophysics (1970s), but now for many other fields with fluids

Hopkins (2014)





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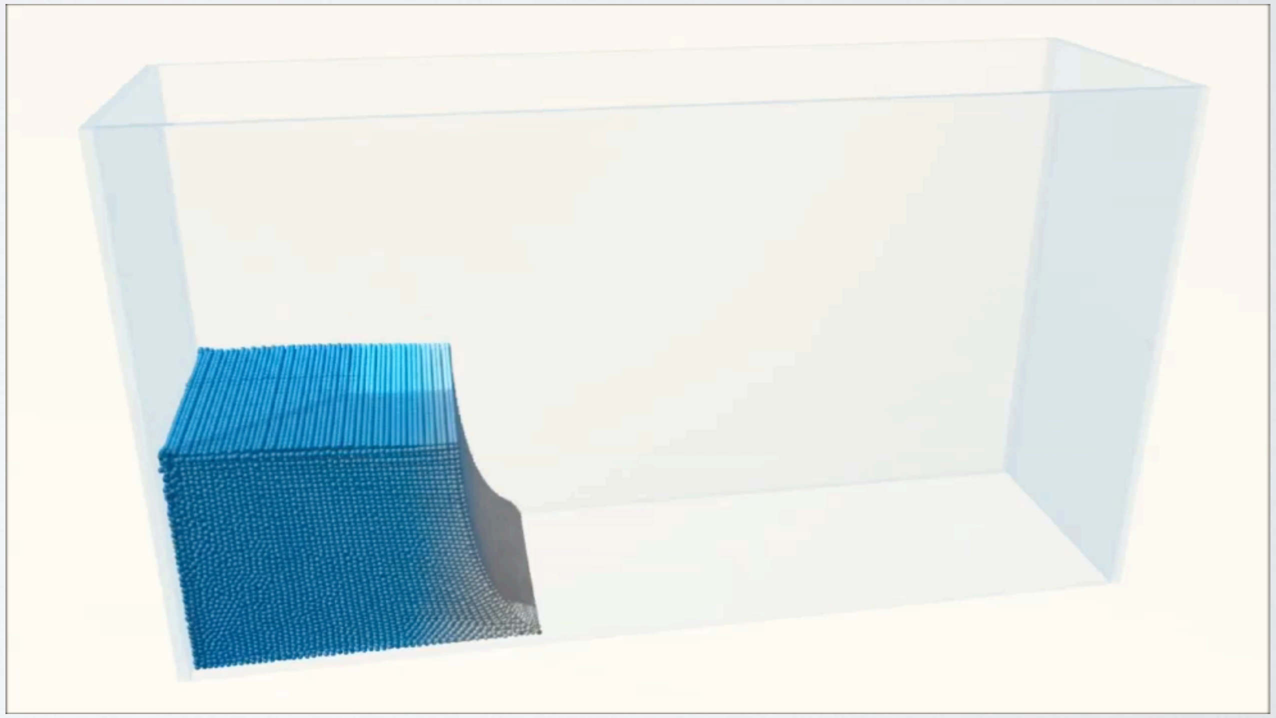
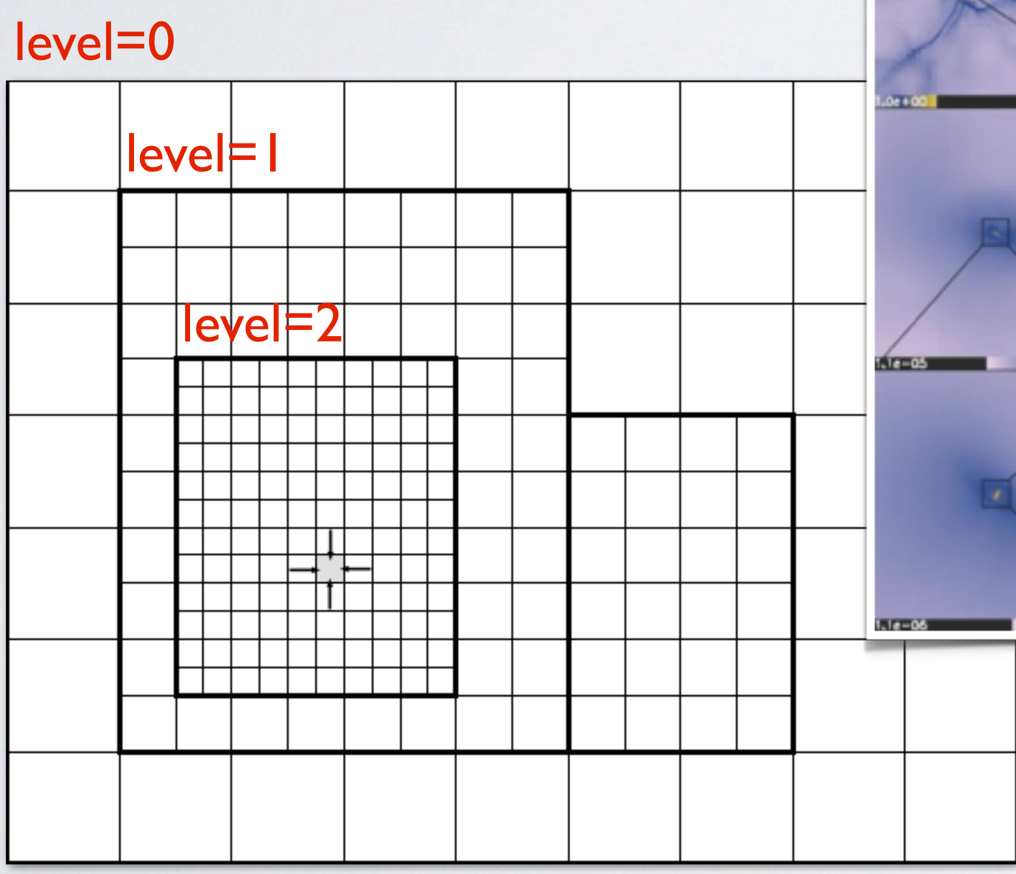
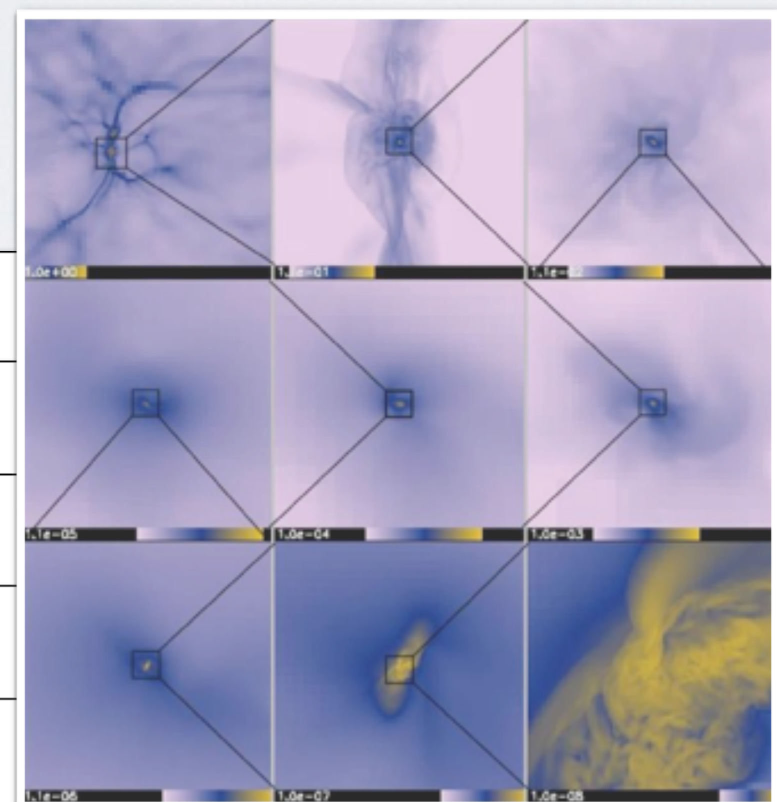


Bender & Koschier

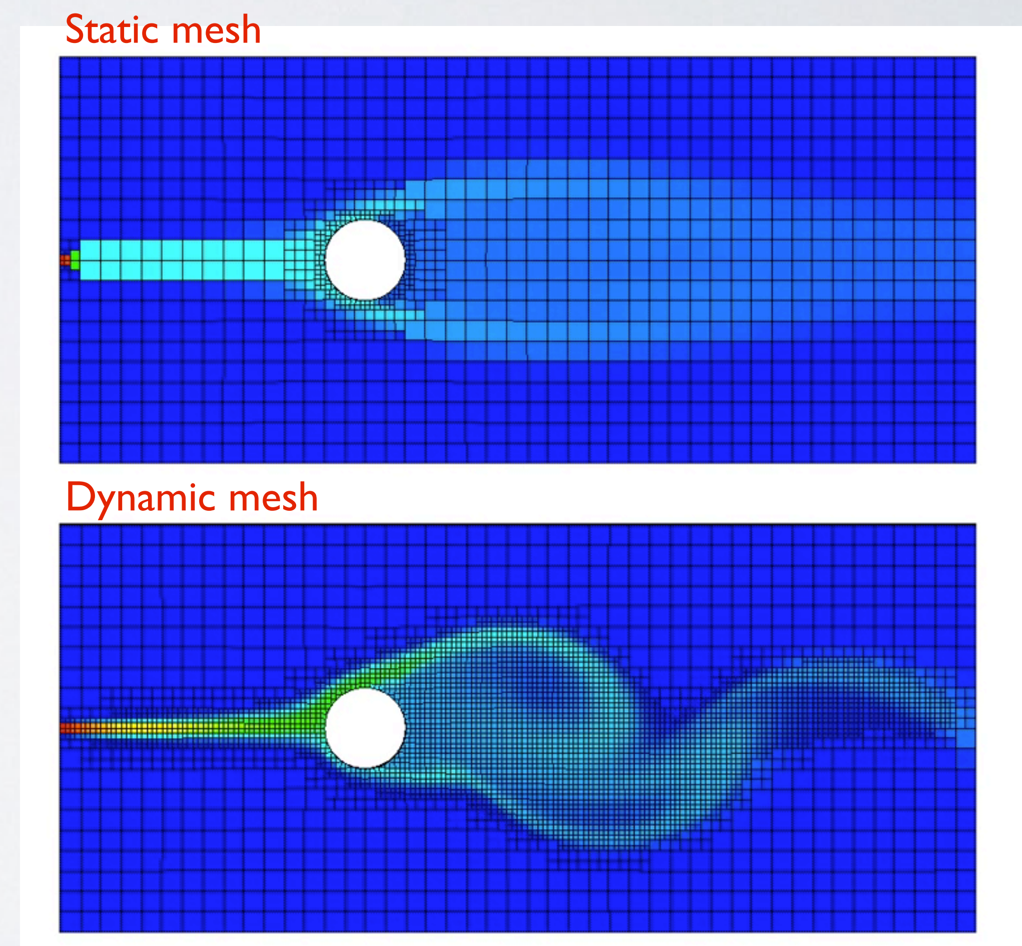
Adaptive Mesh Refinement (AMR)

- Eulerian mesh adaptively focused on regions of high interests.
  - refines cells if found interesting; e.g., dense, collapsing, unstable, shocked





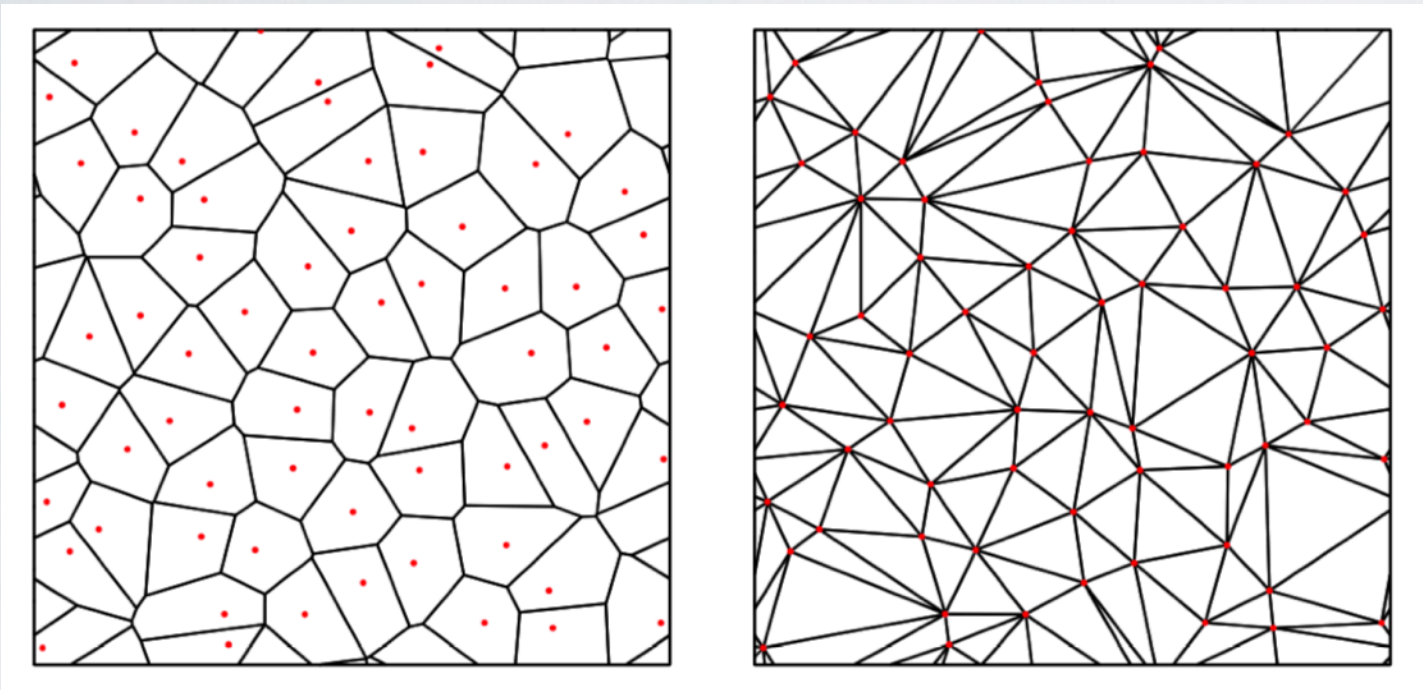
Abel et al. (2002)



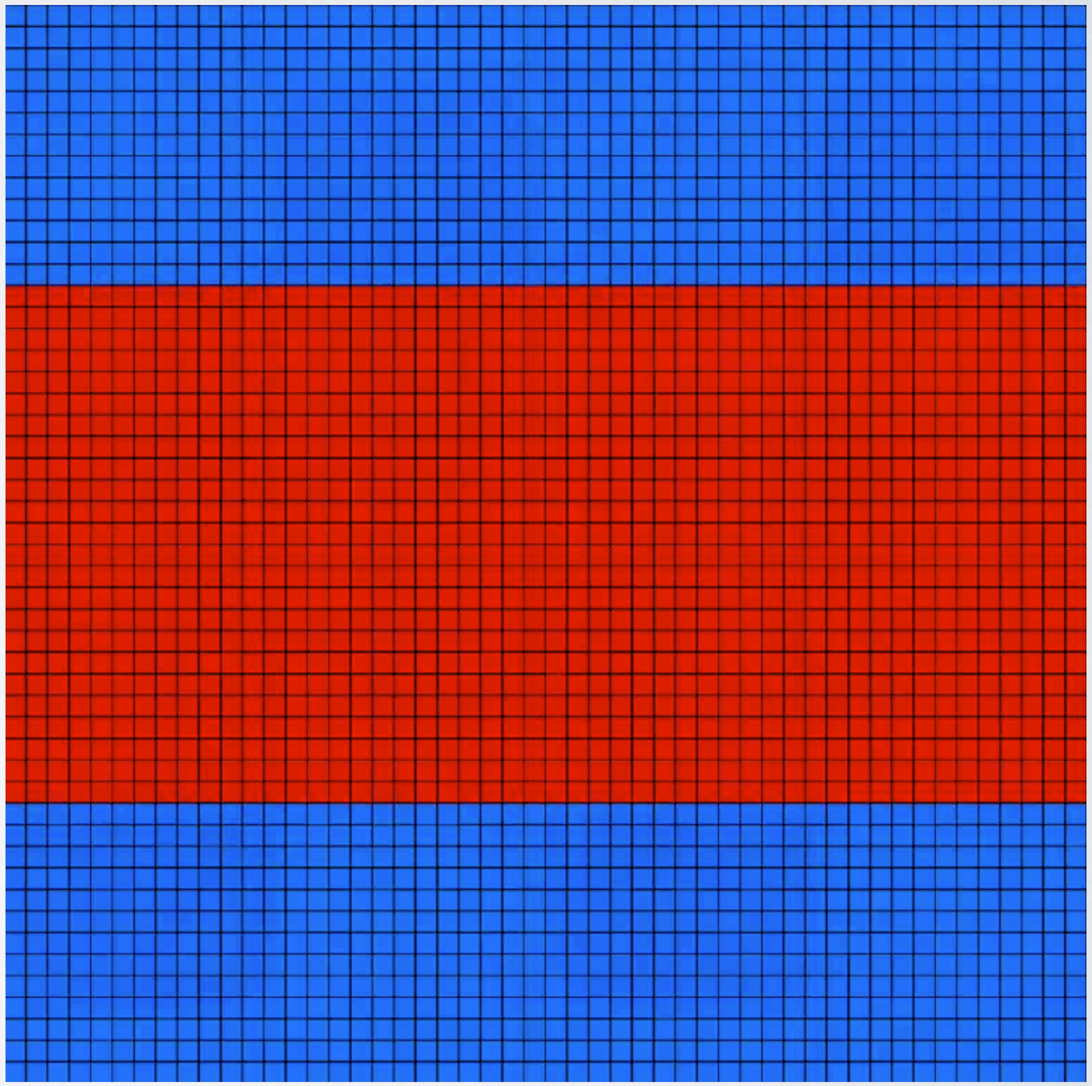
Holzmann CFD, OpenFOAM

Moving Mesh

- Based on a moving, unstructured mesh defined by the Voronoi tessellation of space using a set of discrete points.



Springel (2009), Voronoi & Delaunay tesselation

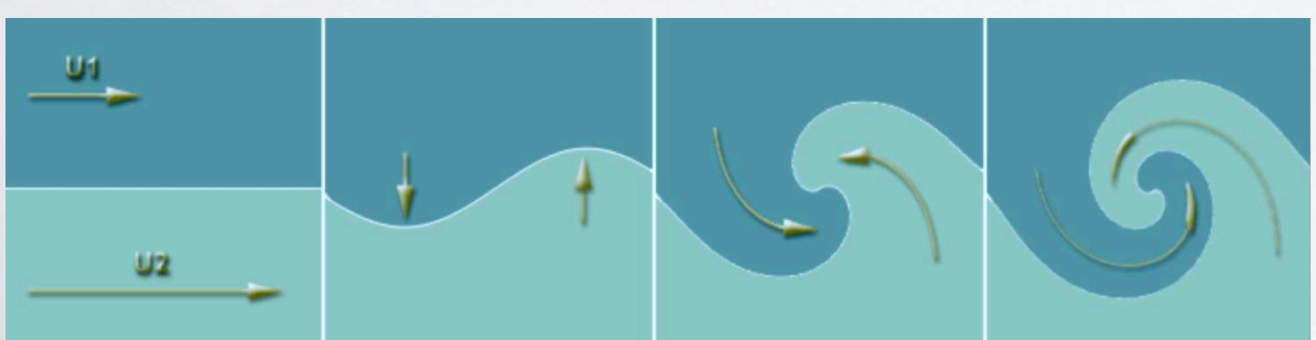


Springel, AREPO

Fluid Instability (I): Kelvin-Helmholtz

- If there is a velocity difference across the interface between two fluids (e.g., Jupiter's great red spot).

karlgaff.wordpress.com/kelvin-helmholtz-instability

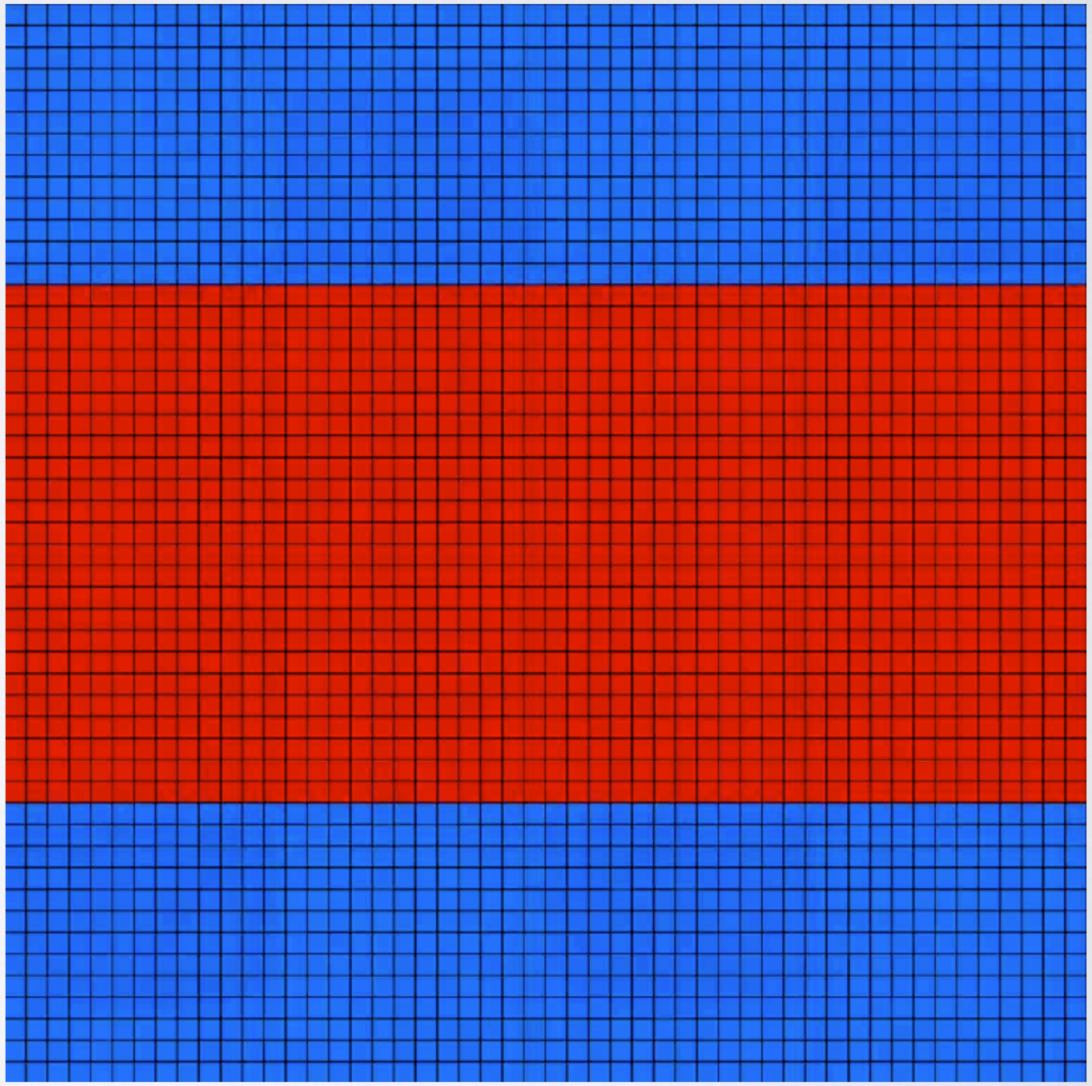


van den Bosch

Fluid Instability (I): Kelvin-Helmholtz

- If there is a velocity difference across the interface between two fluids (e.g., Jupiter's great red spot).

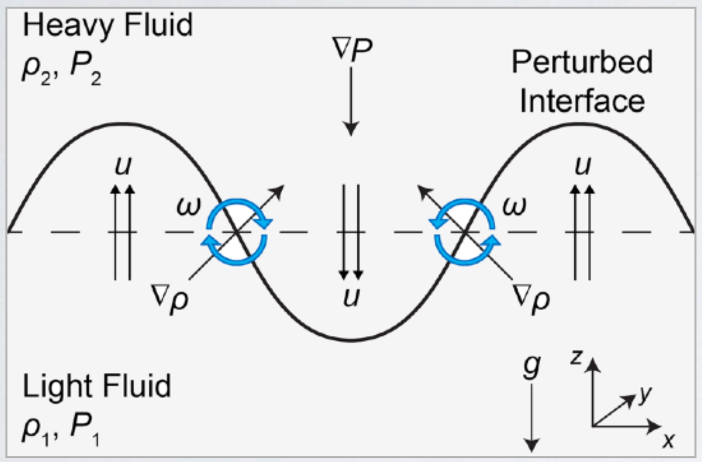
Springel, AREPO (moving mesh, seeded by random noise)



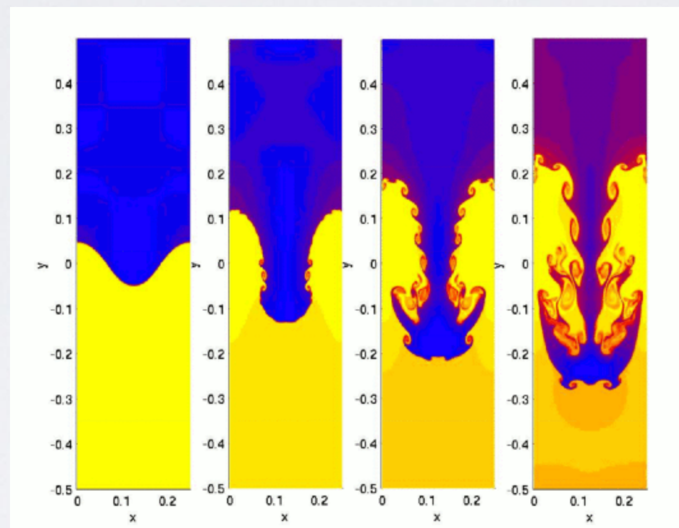
Springel, AREPO (one excited mode)

Fluid Instability (II): Rayleigh-Taylor

- If there is a density difference across the interface between two fluids (e.g., dense shell pushed by SN into lighter ISM).

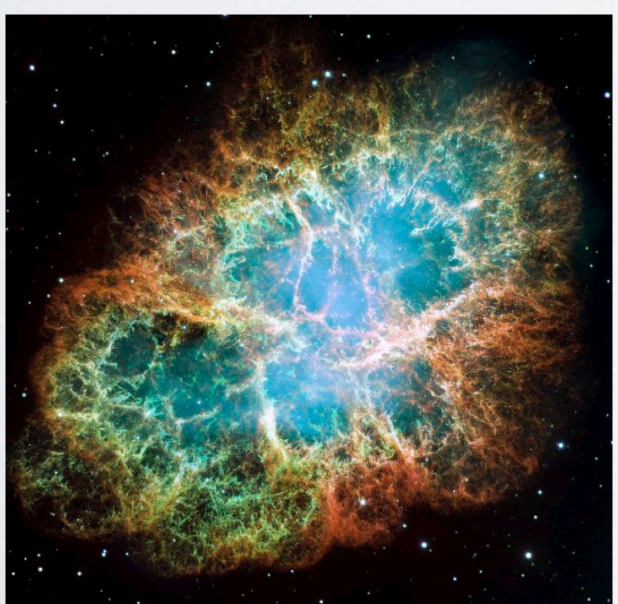


mohammadalkhadra.com

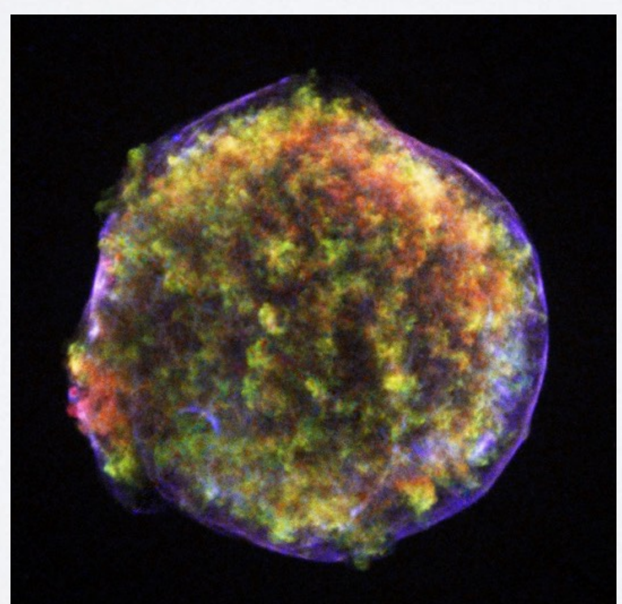


Li & Li

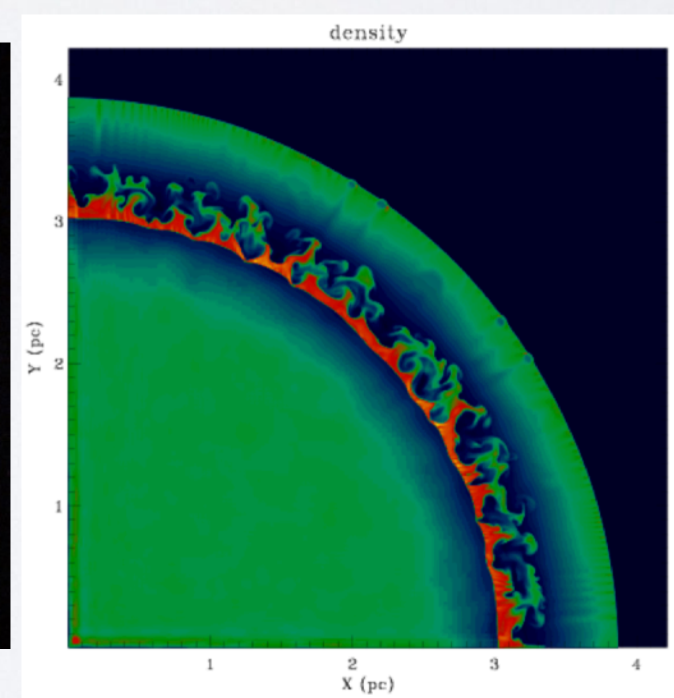
Riordon, AIP



SN1054 (Crab), NASA/ESA/HST



SN1572 (Tycho's), NASA/CXC



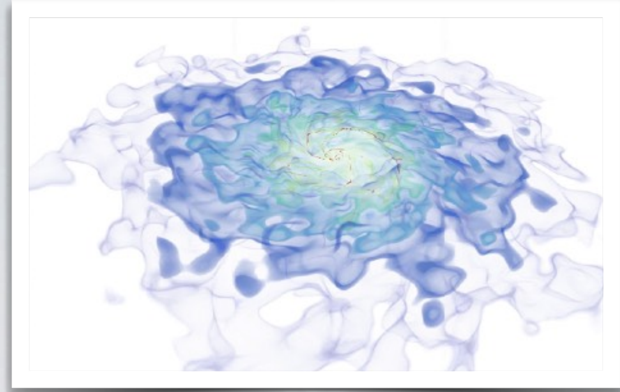
Fraschetti et al. (2010)

Fluid Instability (II): Rayleigh-Taylor

- If there is a density difference across the interface between two fluids (e.g., dense shell pushed by SN into lighter ISM).

Springel, AREPO (moving mesh, seeded by random noise)

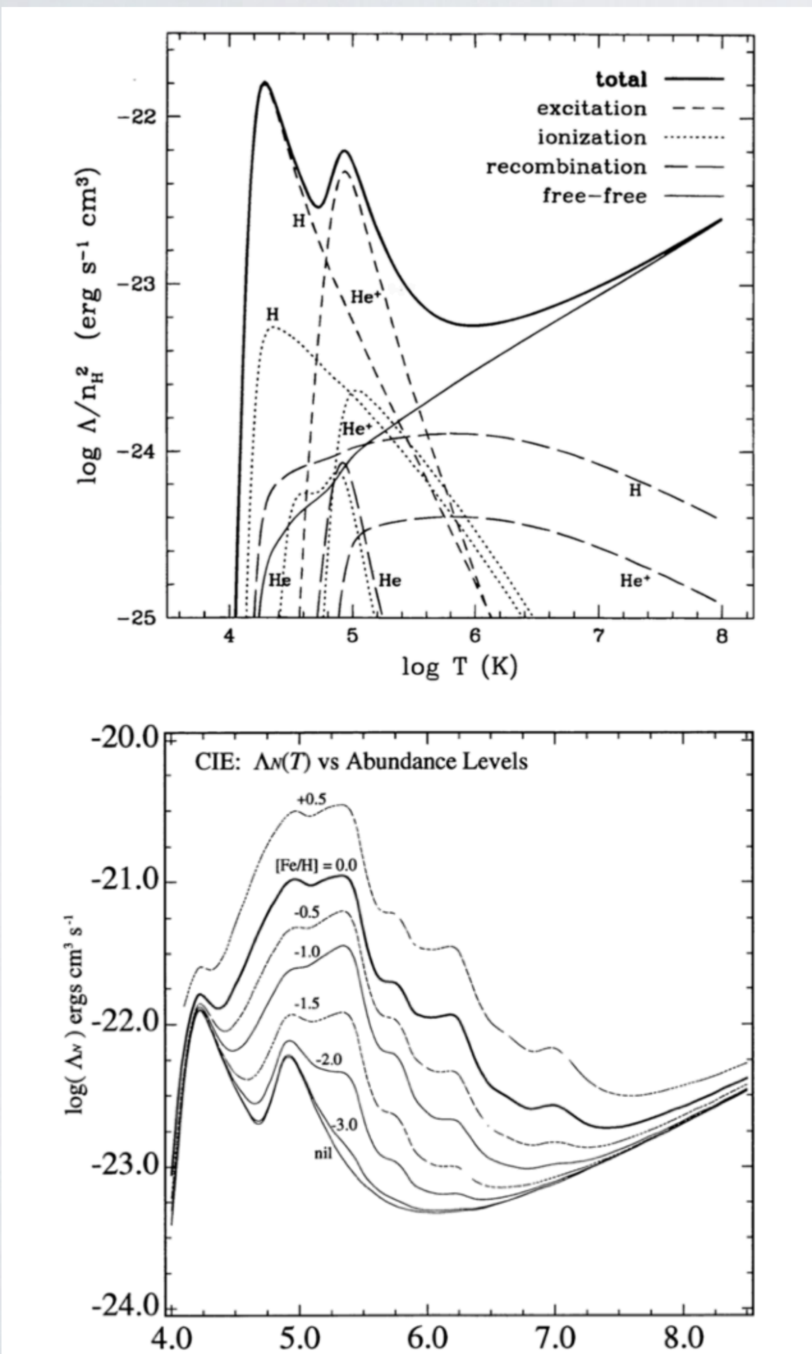
Riordon, AIP



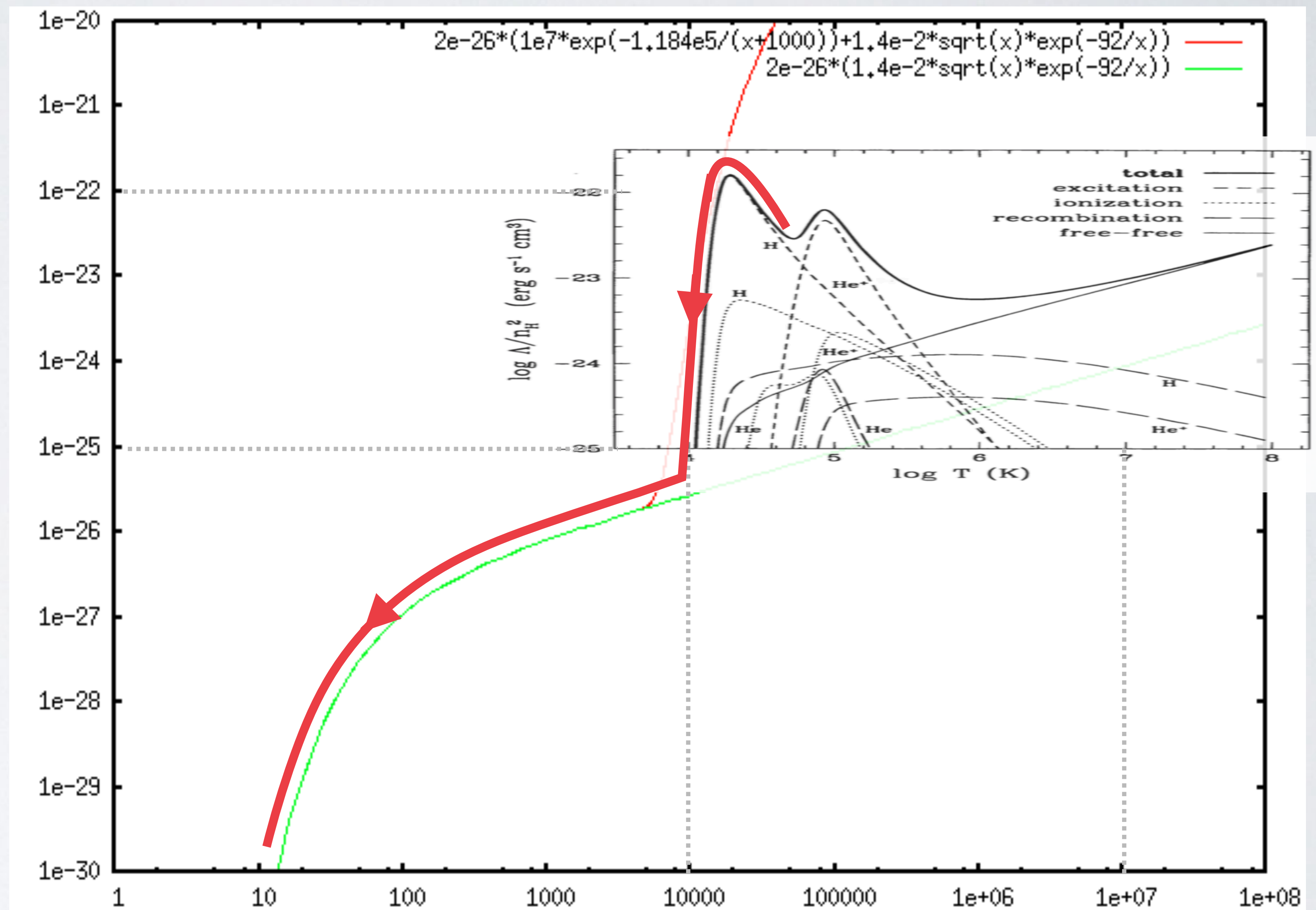
Physics Processes in Simulations Continues

“Radiative Cooling”

- Baryons cool by radiating photons (atomic processes).



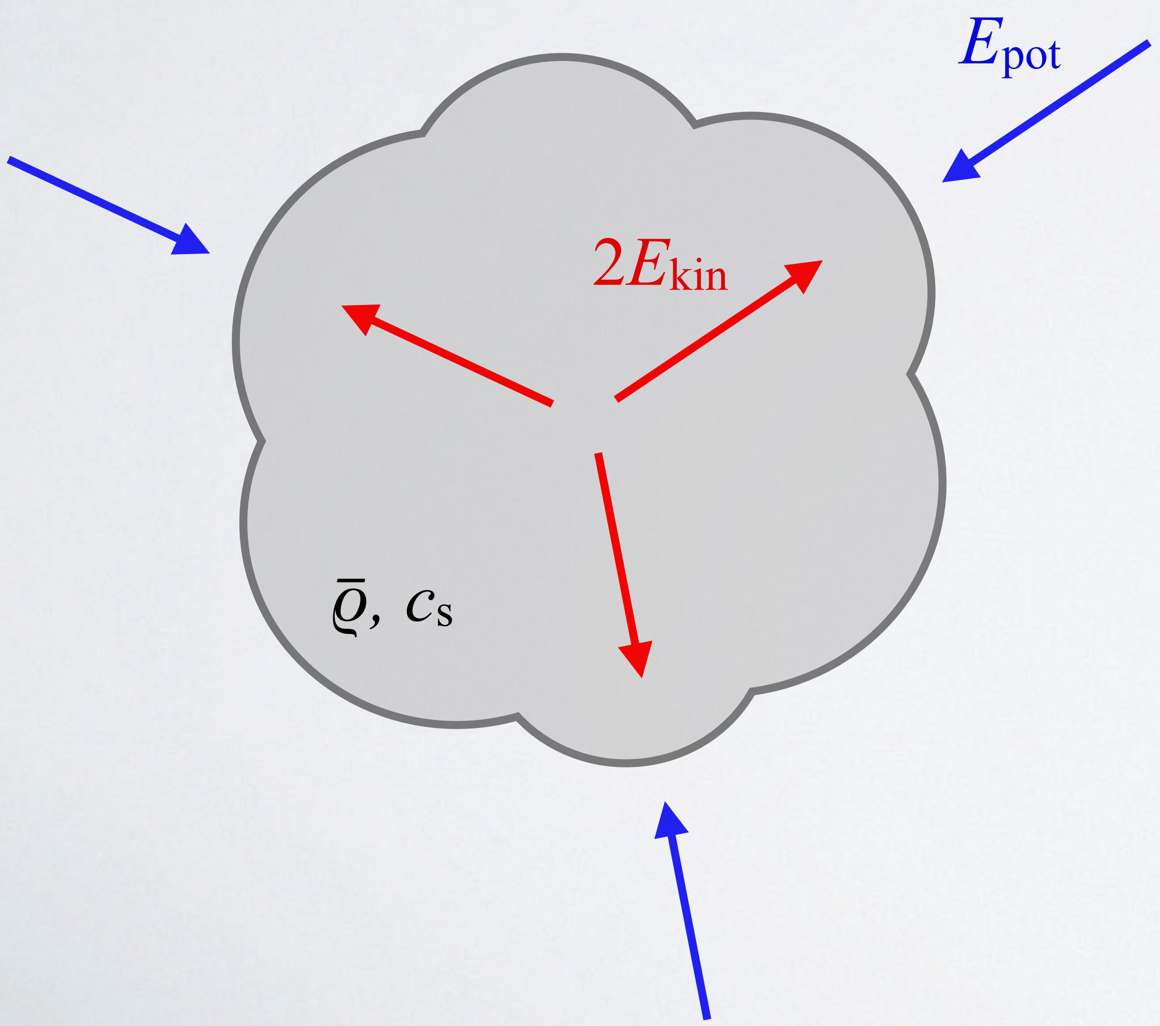
Sutherland & Dopita (1993)



$$t_{\rm cool} = \frac{3n\,k_{\rm B}T}{2\,n_{\rm H}^2\,\Lambda(T)} \simeq 3.3\times10^9\,{\rm yr}\left(\frac{T}{10^6\,{\rm K}}\right)\left(\frac{n}{10^{-3}\,{\rm cm}^{-3}}\right)^{-1}\left(\frac{\Lambda(T)}{10^{-23}\,{\rm erg\,s^{-1}\,cm^3}}\right)^{-1}$$

"Jeans Instability"

- If the gas pressure of a cloud can no longer balance the self-gravity, the cloud becomes gravitationally unstable and collapses.



Jeans unstable if virial equilibrium breaks down with the gas pressure that is not strong enough:

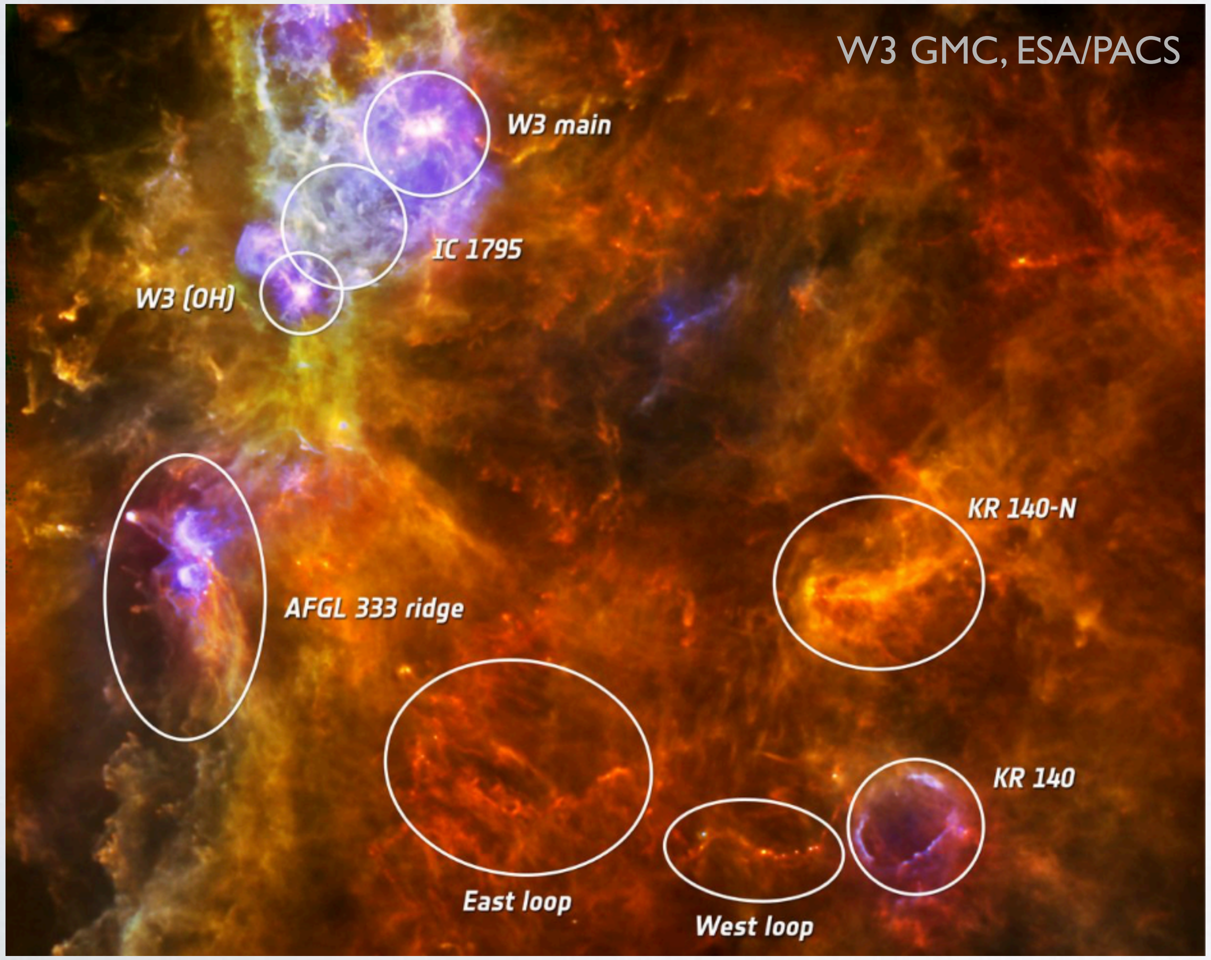
$$2\langle E_{kin}\rangle < -\langle E_{pot}\rangle$$

$$\rightarrow M\langle v^2\rangle < GM^2/R$$

$$\rightarrow M > M_{Jeans} \simeq \frac{c_s^3}{G^{3/2}\bar{\rho}^{1/2}}$$

Jeans Mass and Fragmentation

- Jeans mass (M_{Jeans}) is the minimum mass of a gravitationally unstable cloud. Once M_{Jeans} is exceeded, runaway collapse occurs.
- Increase in $\bar{\rho}$ (or decrease in c_s) reduces M_{Jeans}. This means that as the cloud collapses, it will fragment into even smaller clouds.



When the gas is gravitationally compressed, it takes t_{sc} for pressure waves to cross the region and restore the pressure-gravity balance.

But, if the cloud collapses quicker than the pressure waves can respond, then the balance breaks down.

$$t_{\rm ff} = \left(\frac{3\pi}{32G\bar{\rho}}\right)^{1/2} \quad < \quad t_{\rm sc} = \frac{R}{c_{\rm s}}$$

$$\rightarrow \quad M \quad > \quad M_{\rm Jeans} \simeq \frac{c_{\rm s}^3}{G^{3/2}\bar{\rho}^{1/2}}$$