Galaxy formation in cold dark matter

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Main references:
Press & Schechter, 1974
White & Rees, 1978

Galaxy formation mechanism

Cosmological initial condition

Gravitational instability

Cosmic structure formation (dark haloes)

Gas cooling

Star formation

galaxies

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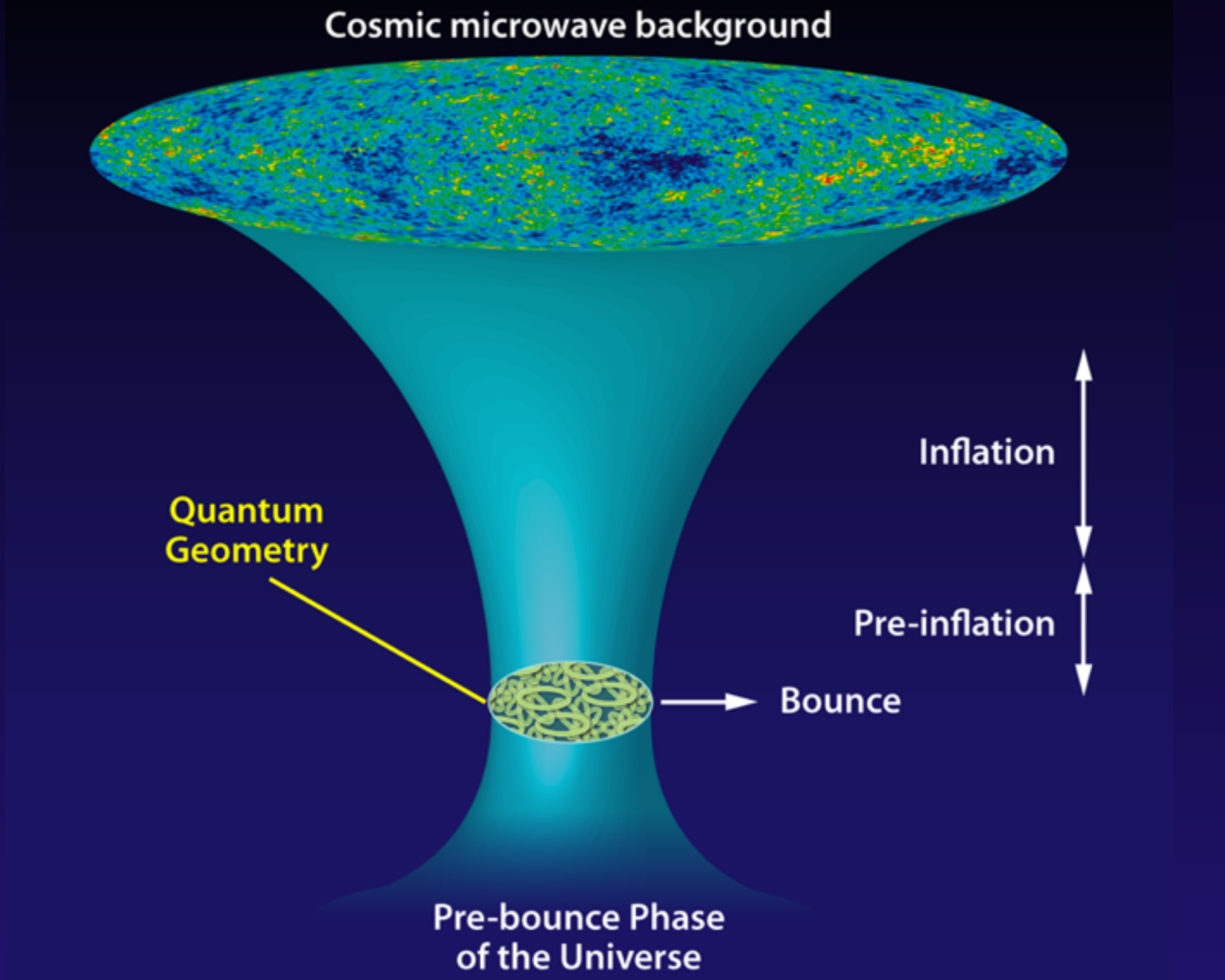

Credit: APS/Alan Stonebraker

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Gravitational instability

Newtonian dynamics

- Scale: much smaller than the Hubble radius (light horizon)

$$L \ll L_h \sim c/h$$

- Velocity: “cold” dark matter (non-relativistic)

$$v \ll c$$

- Density: no highly relativistic objects at early Universe

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Cosmic structure formation

Two dimensionless parameters

$$q = \frac{4}{3}\pi m_* n_* G/h^2$$

Gravity *vs.* expansion of the Universe

$$N_J = n(v/h)^3$$

Gravity *vs.* “pressure”

Validation of self-similarity

Macro-statistics

$$q = \frac{4}{3}\pi m_* n_* G/h^2$$

$$N_J = n(v/h)^3$$

- Dimensionless: two systems with the same q and N_J ought to condense similarly, regardless of the scale.
- Time evolution: possible self-similarity if q and N_J are constants in time.

Validation of self-similarity

Micro-statistics

Micro-statistical properties may differ,
leading to different condensation

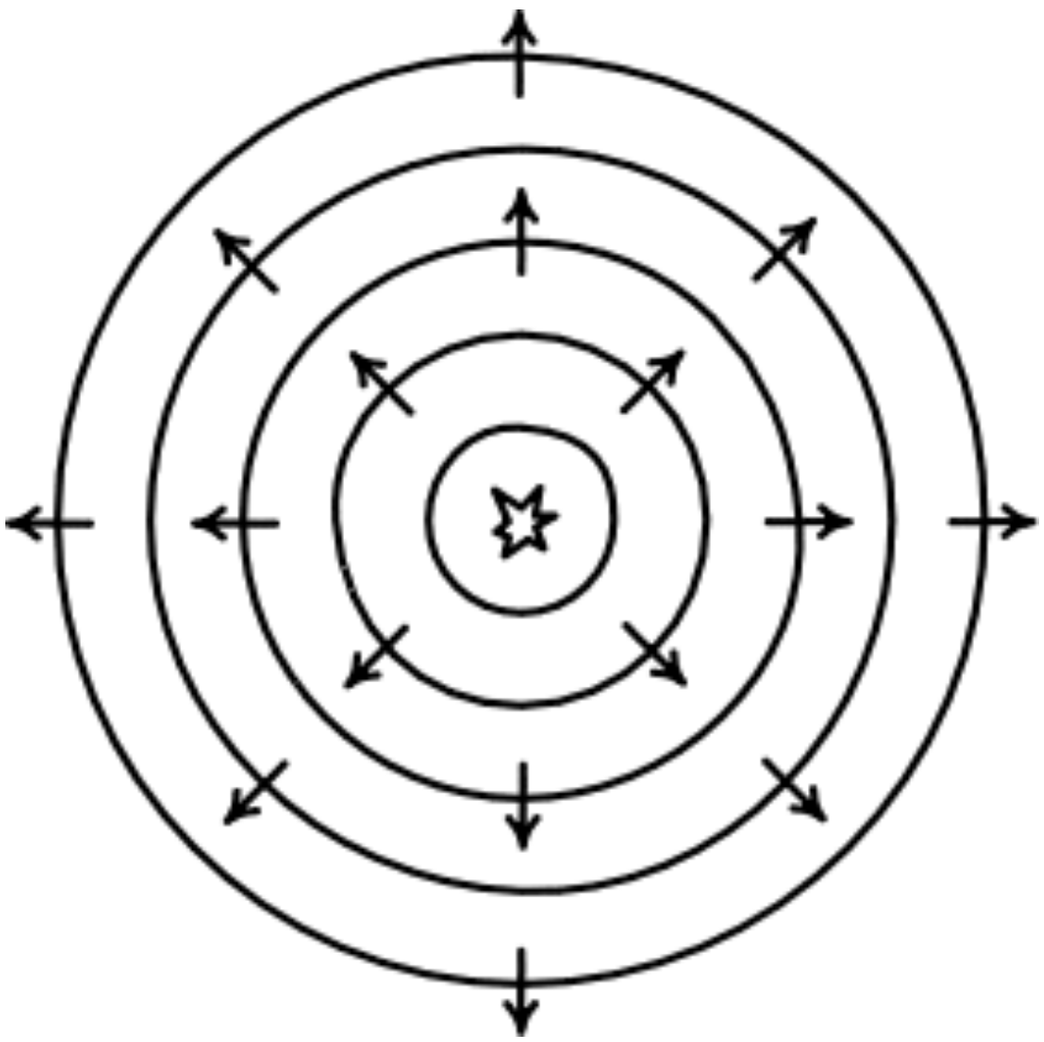
- mass function $n(m)$ may rely on the initial condition
- different internal correlation

Test on extreme cases

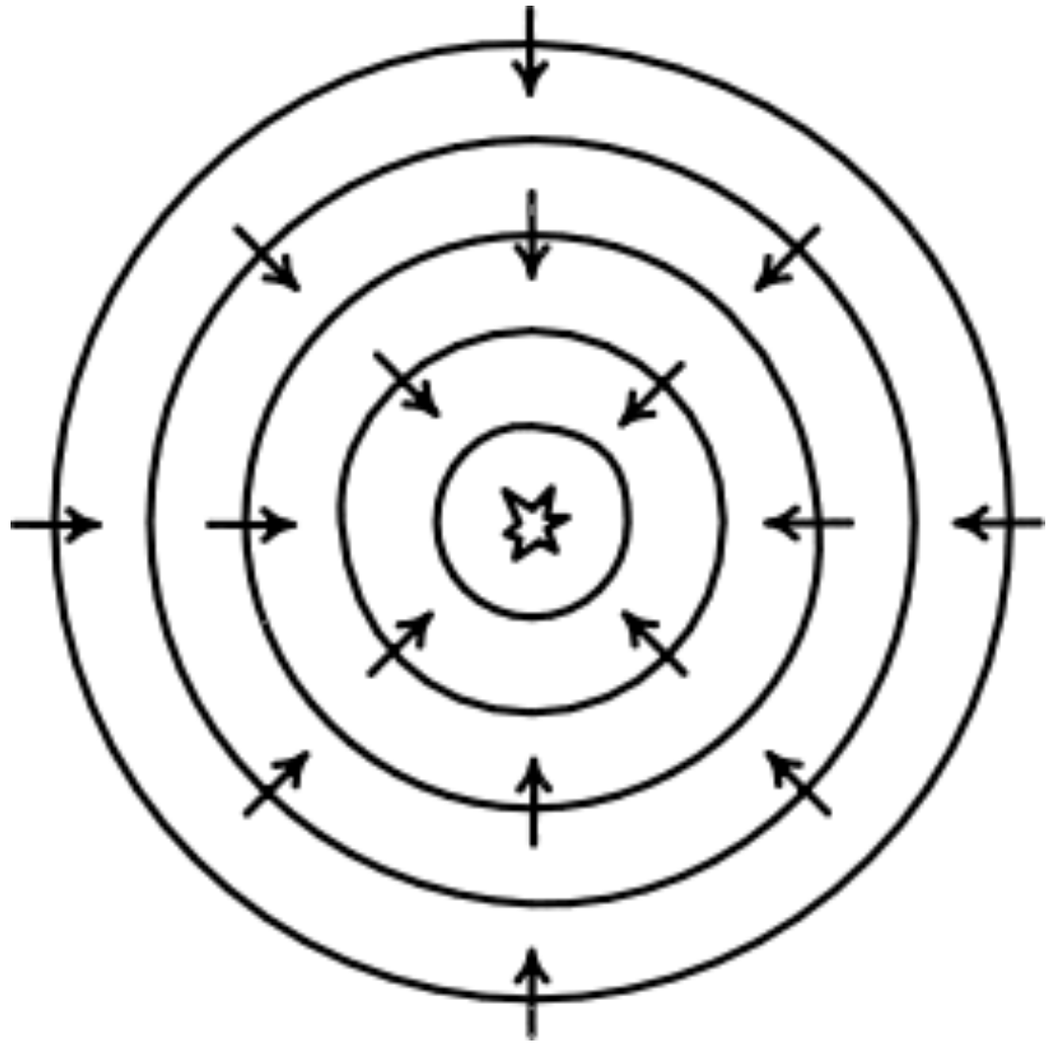
- Lower bound: particles are ordered in regular lattices.
- Upper bound: particles are statistically homogenous.

Spherical collapse model

Spherical perturbation + collisionless dark matter



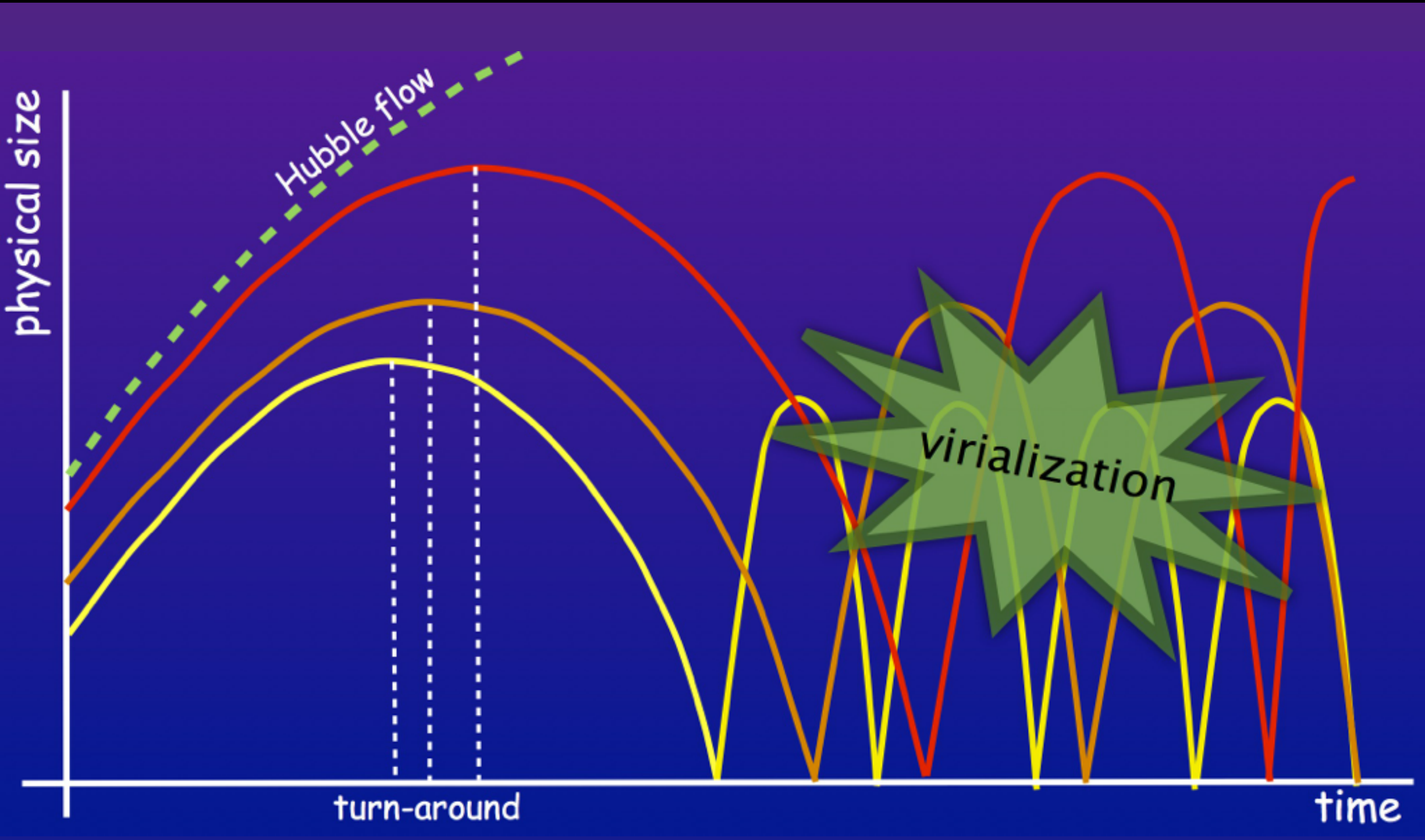
Background expansion



Gravitational collapse

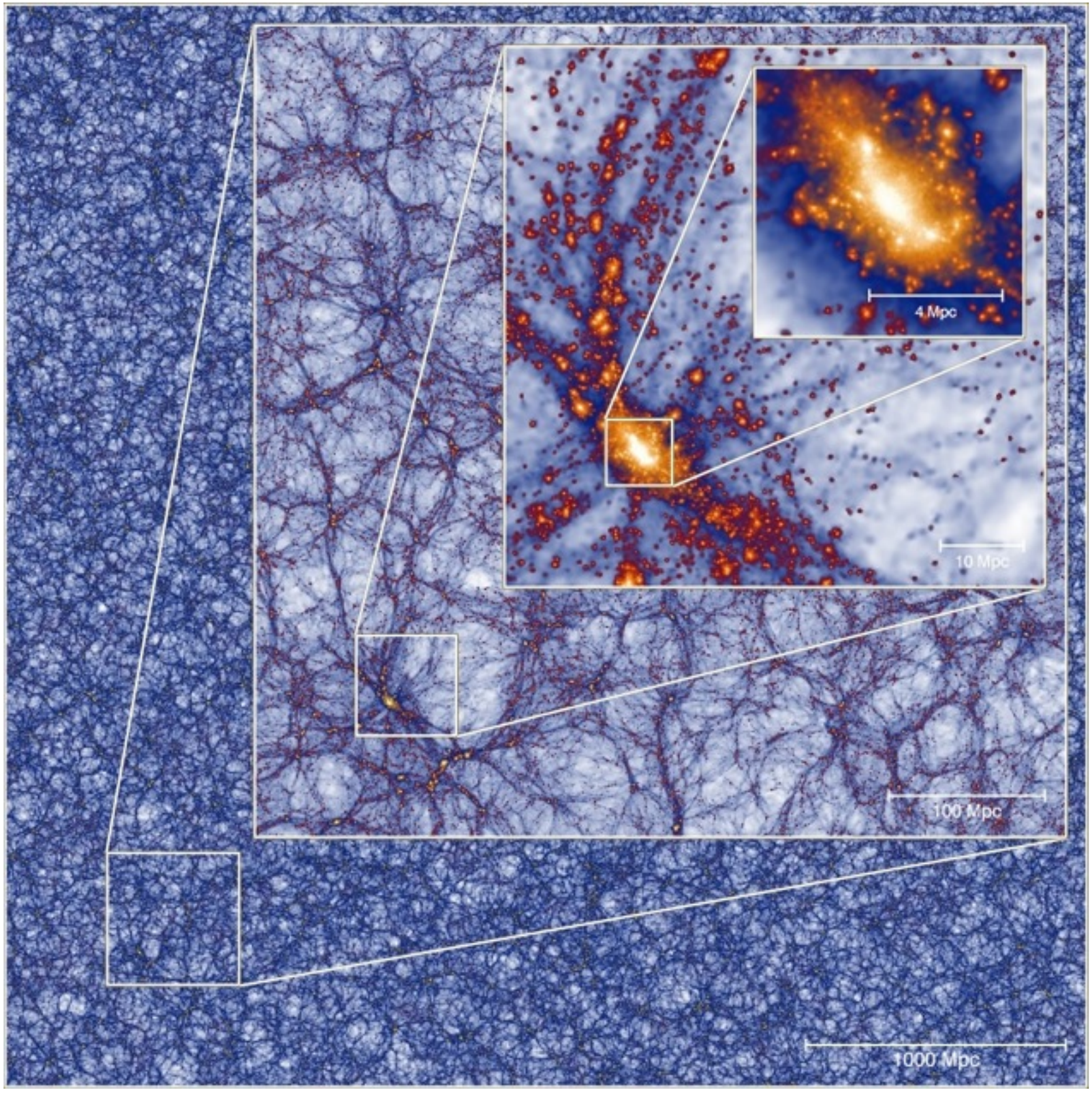
Credit: John D. Norton's web

Spherical collapse model



Credit: Frank van den Bosch

Cosmic web structures



Millennium-XXL simulation

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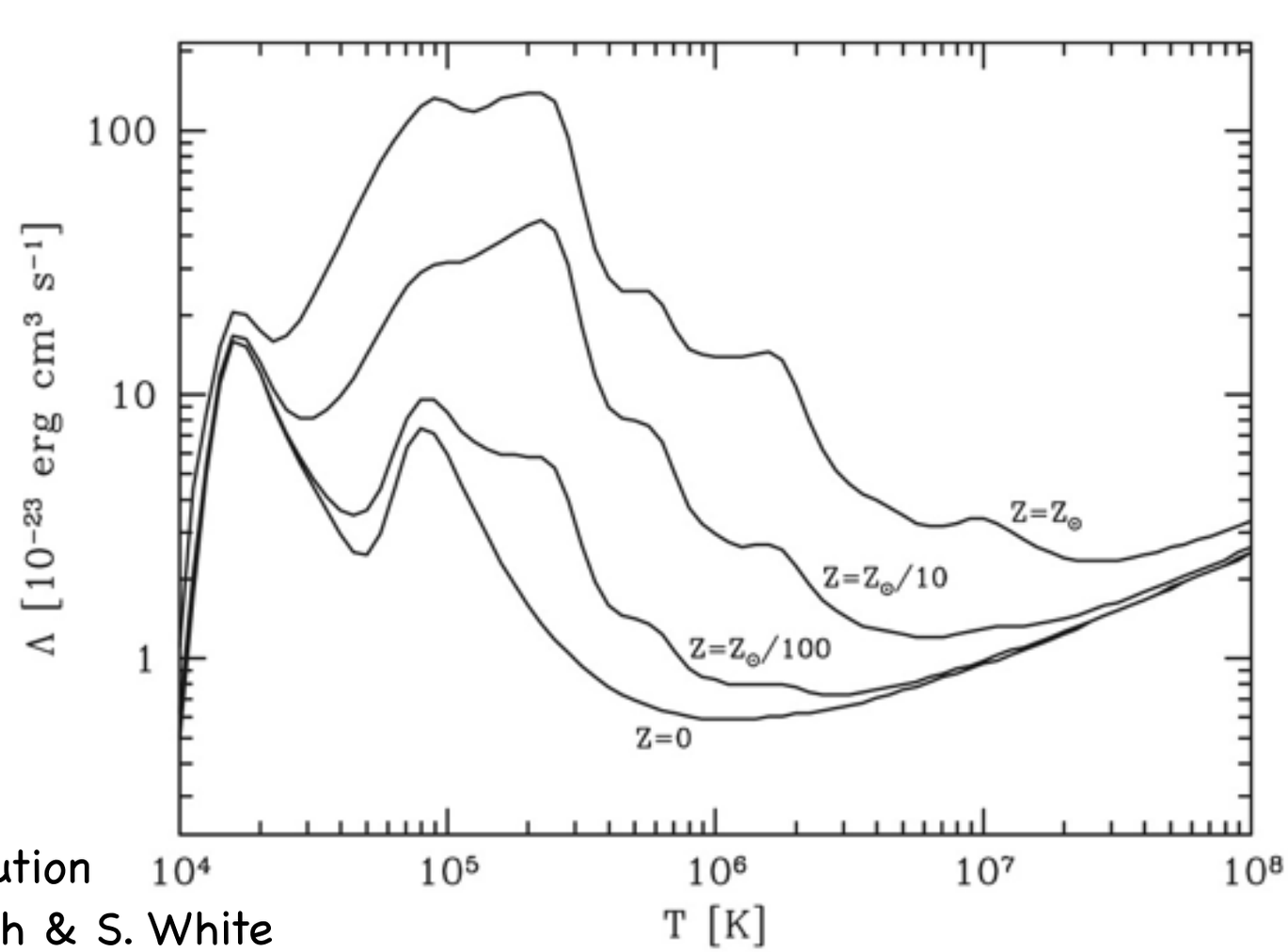
Gas cooling

- Compton cooling (inverse Compton scattering with CMB photons at early Universe)
- Radiative cooling (rely on chemical composition, density, temperature…)



Galaxy Formation & Evolution
by H. Mo, F. van den Bosch & S. White

Gas cooling time scale

$$t_{\rm cool} \lesssim H^{-1}$$

Cooling *vs.* age of the Universe

$$t_{\rm cool} \lesssim t_{\rm dyn}$$

Cooling *vs.* “pressure”

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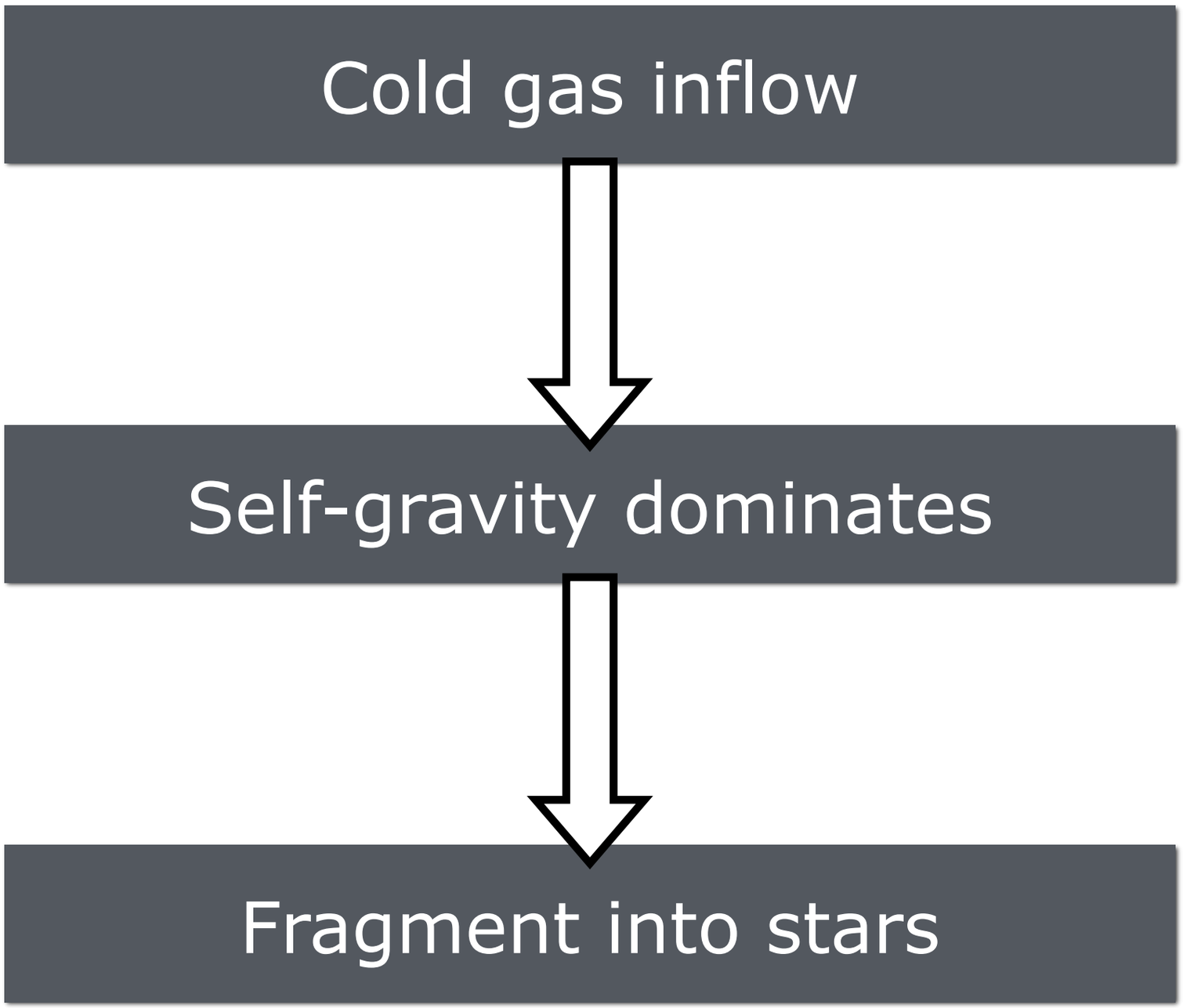

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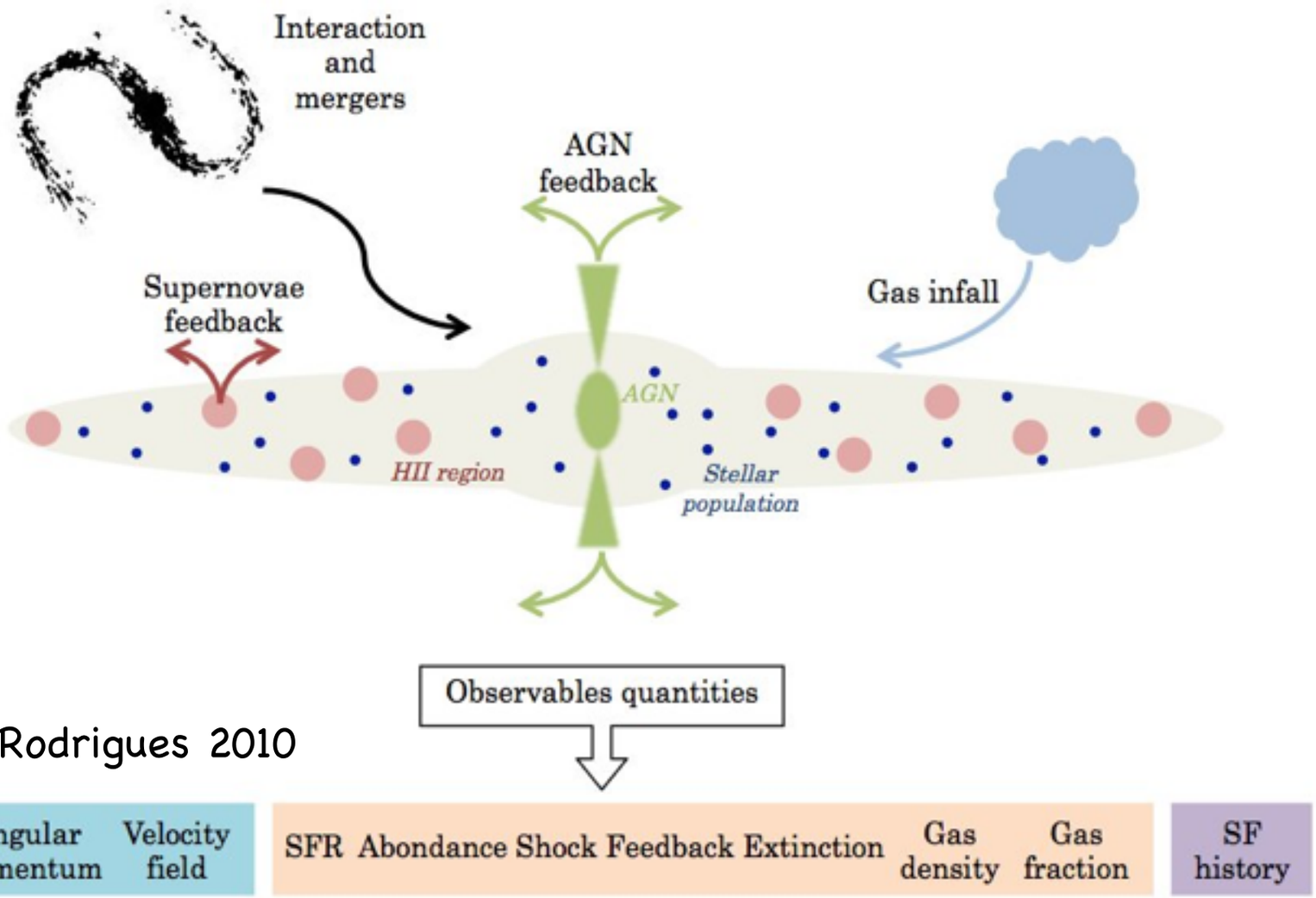
More ...

Feedback

Feedback mechanism for reheating

- Supernova feedback
- AGN feedback



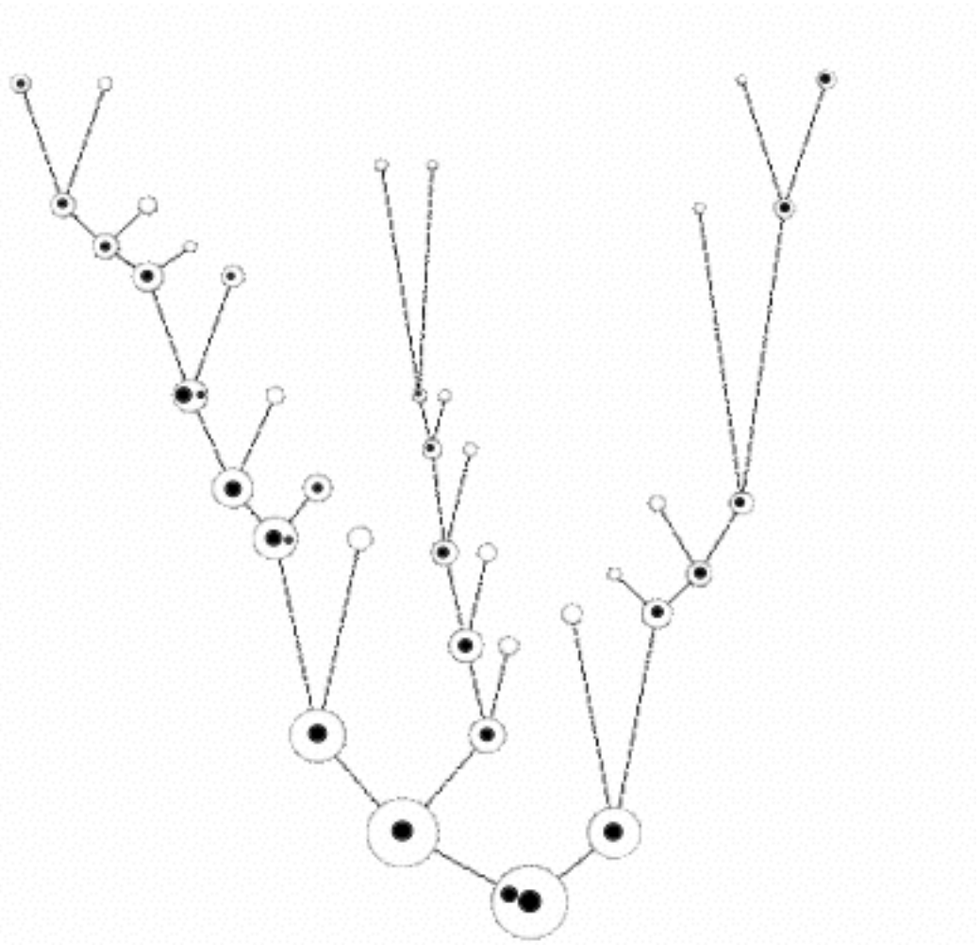
Rodrigues 2010

More ...

Mergers

Mergers of haloes: a bottom-up manner

- More massive galaxies have higher metallicity
- Formation of elliptical galaxies
- More satellites
- Star bursts
- …

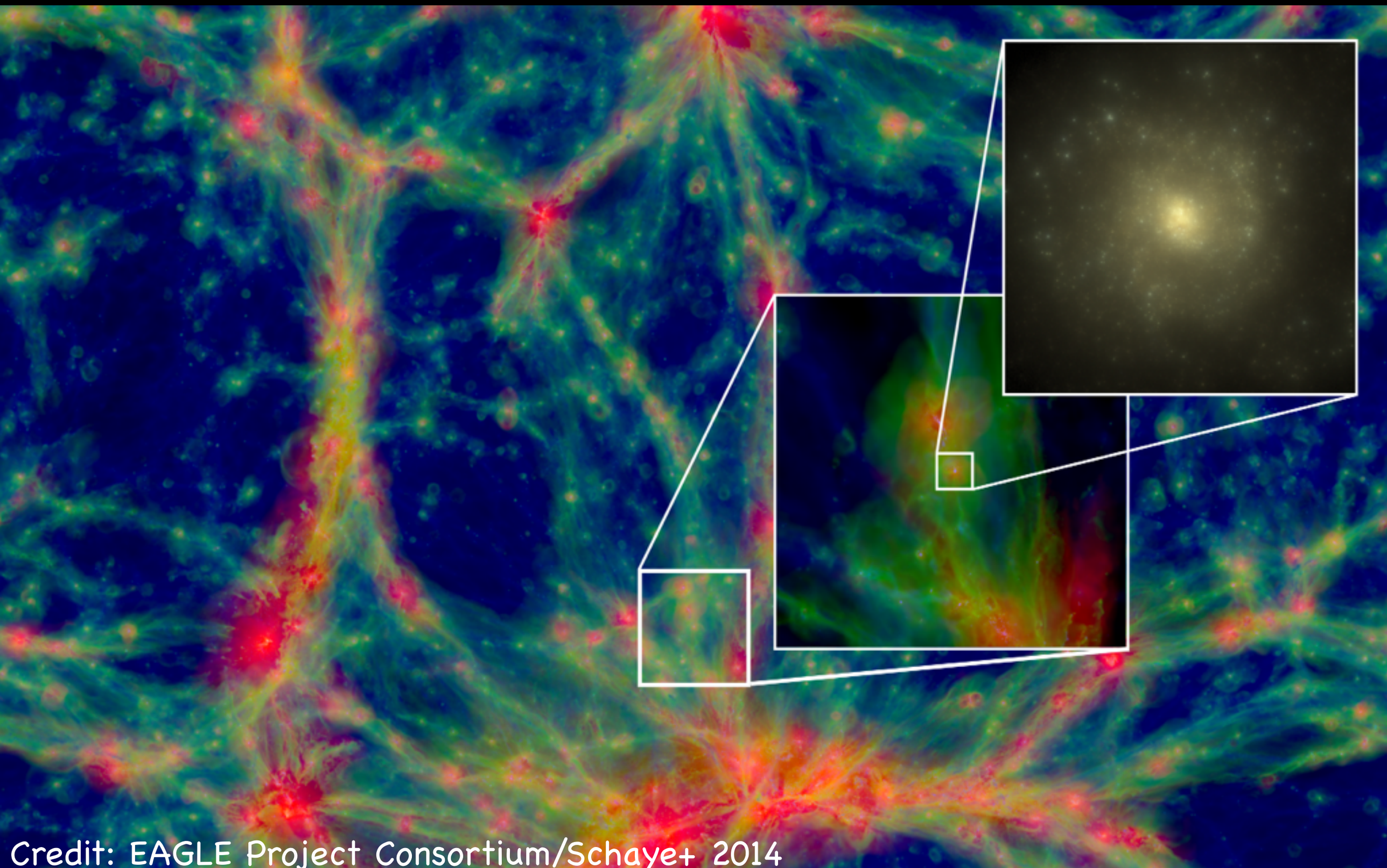


Credit: Marta Volonteri

Unknowns

- Gas mass fraction
- Time scale of different mechanisms
- Initial mass function
- Feedback efficiency
- …

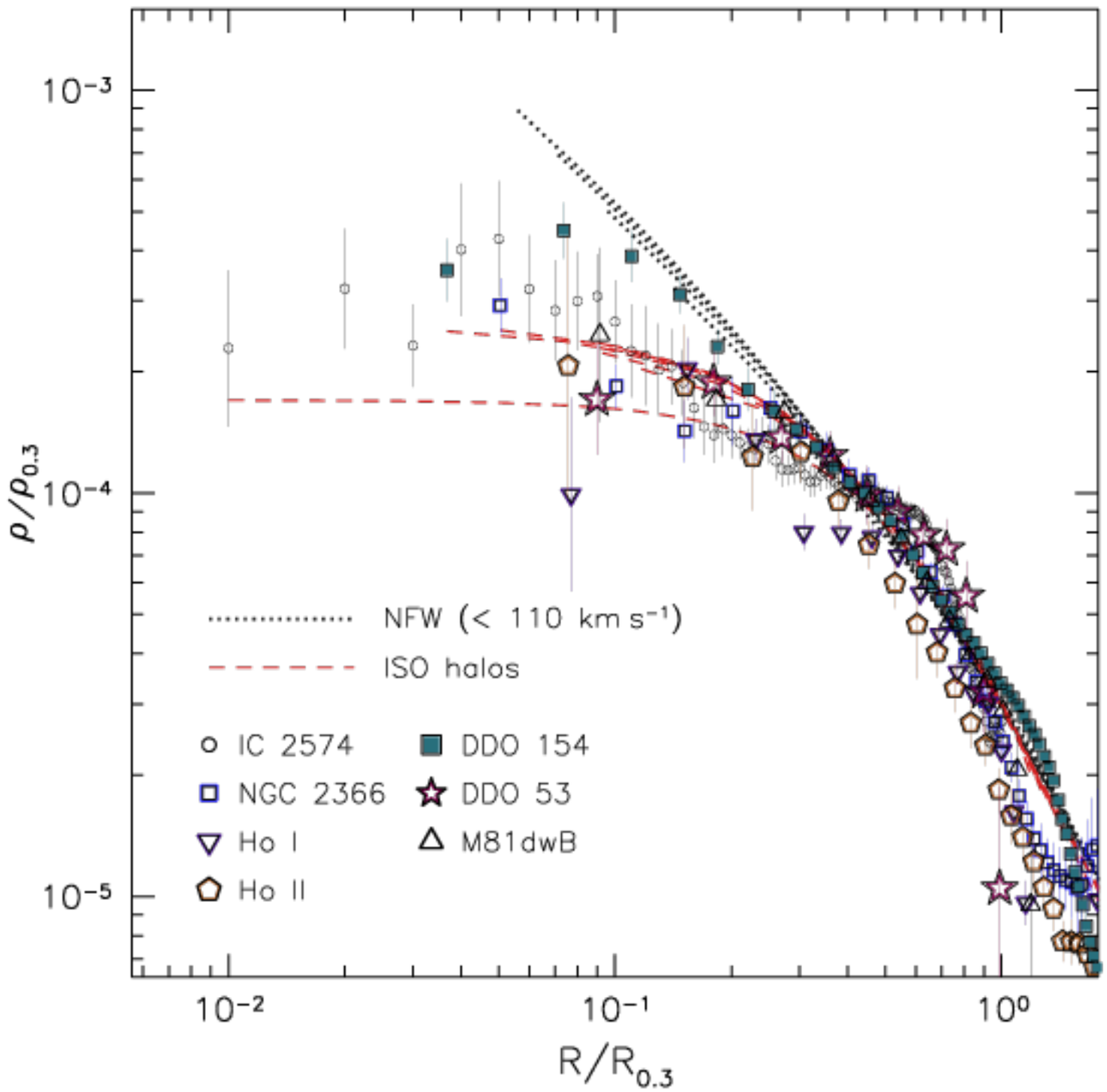
Hydro-dynamical simulations



Credit: EAGLE Project Consortium/Schaye+ 2014

Unresolved problems

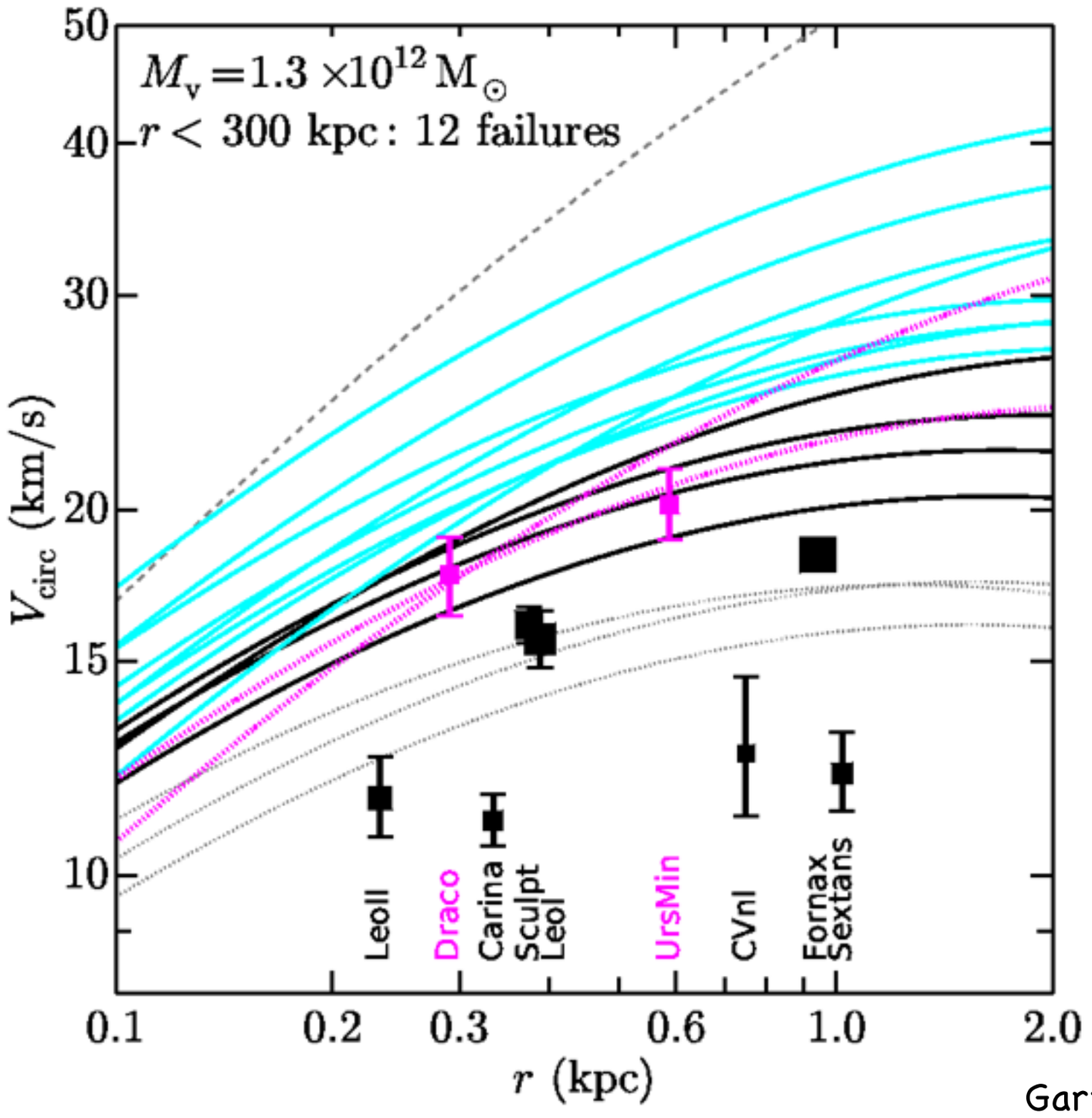
Core or cusp



Walker & Loeb 2014

Unresolved problems

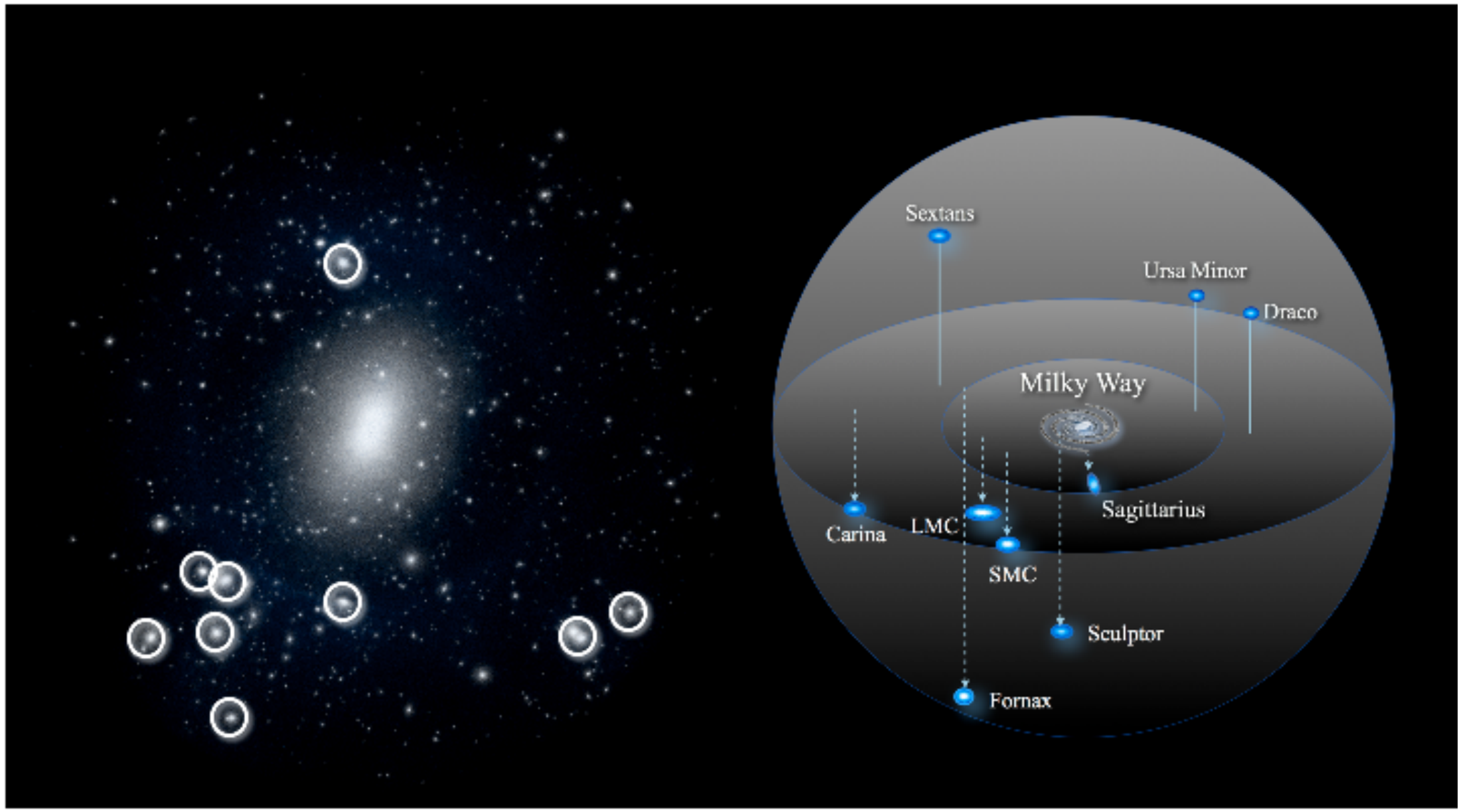
"Too big to fail"



Garrison-Kimmel+ 2014

Unresolved problems

Missing satellite



Weinberg+ 2015

Summary

- Structure formation in CDM cosmology.
- Gas cooling and collapse in dark haloes.
- Gas fragmentation and formation of stars/galaxies.
- Merger/feedback processes.
- Problems due to CDM or baryonic effects?