Challenges in Galaxy Formation: an exploration with numerical simulations

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SMU Physics Seminar
Dec. 12, 2017

Outline

I. Introduction to ΛCDM

II. Are the properties of galaxies consistent with LCDM?

III. Galactic winds

IV. Galaxy formation at the extreme: dwarf & satellite galaxies

V. Future Prospects: surveys, big data, and simulations

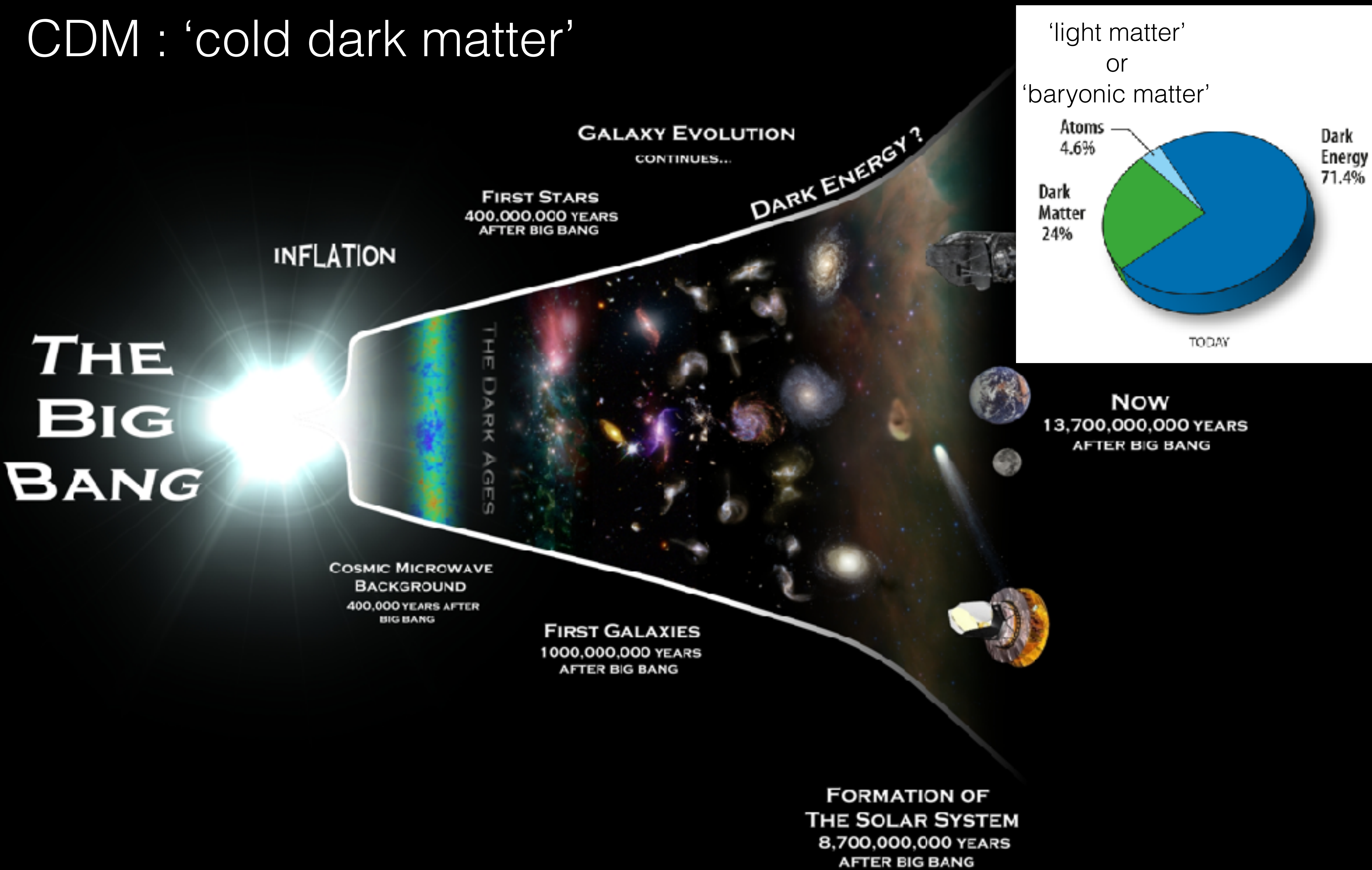
VI. Conclusions

Hubble Ultra Deep Field

‘ΛCDM’

Λ : cosmological constant, i.e. ‘dark energy’

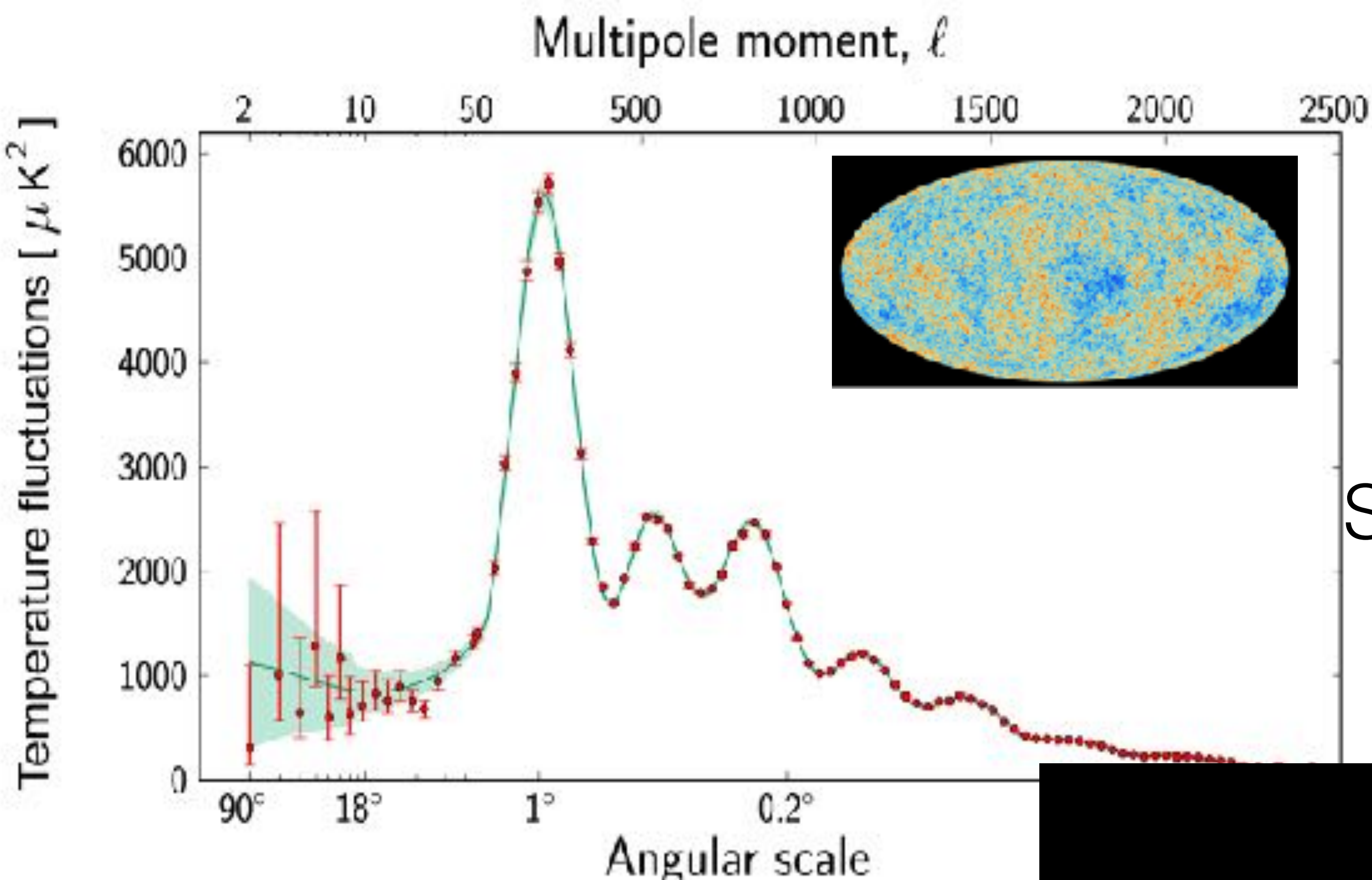
CDM : ‘cold dark matter’



Amazing observational progress has specified the initial conditions

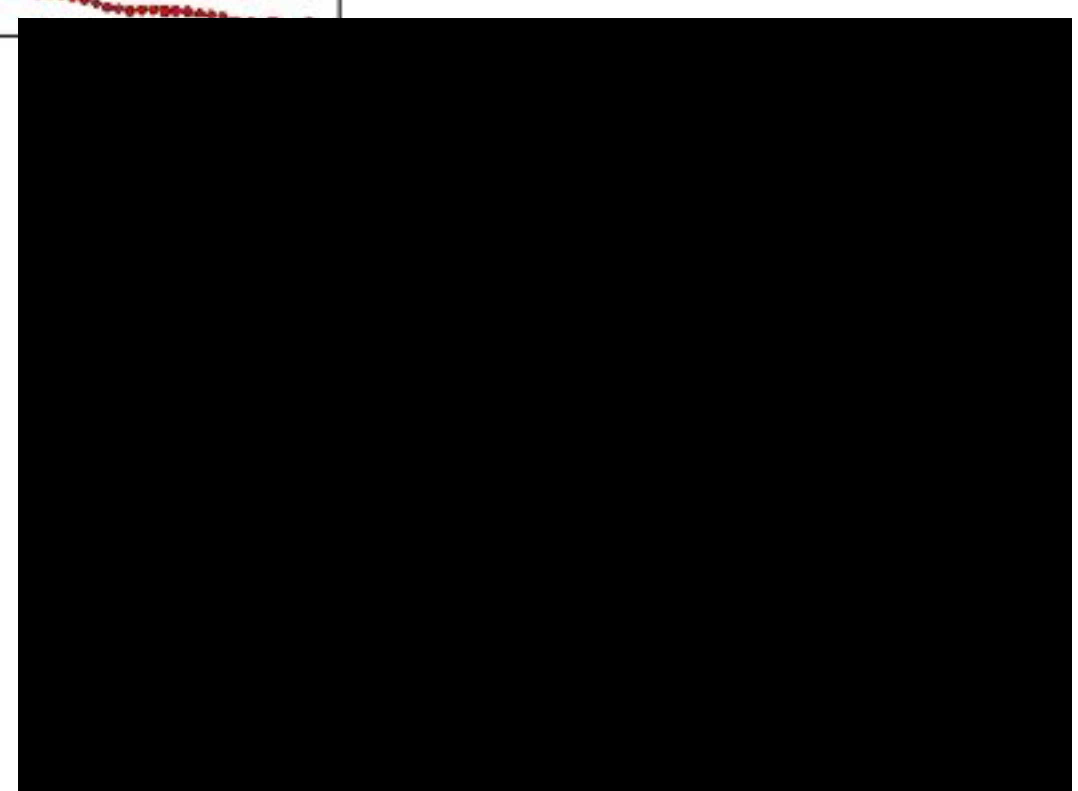
CMB CONSTRAINTS TODAY AS SEEN BY PLANCK (BUT ALSO WMAP & COBE)

Minimal, 6-parameter ΛCDM model is a great fit



Planck Collaboration (2013)

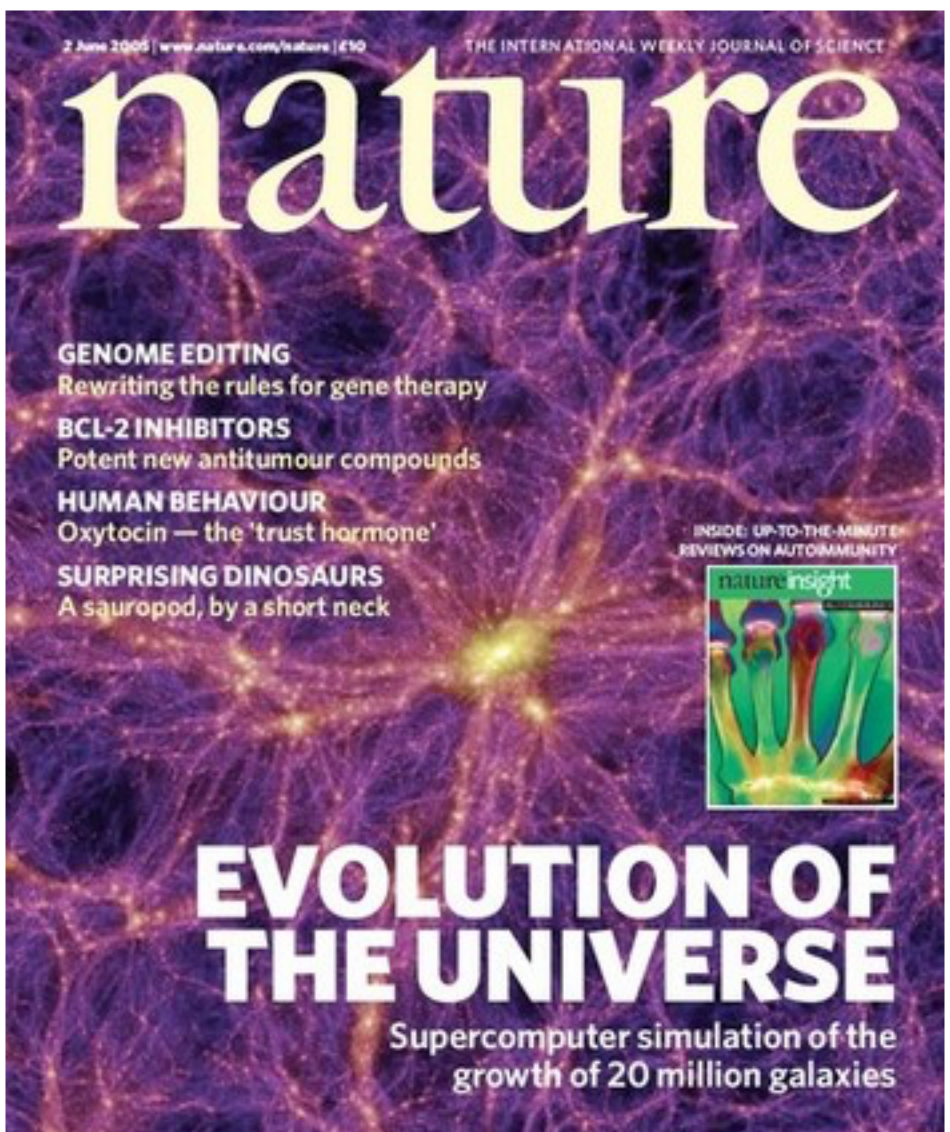
Simulations

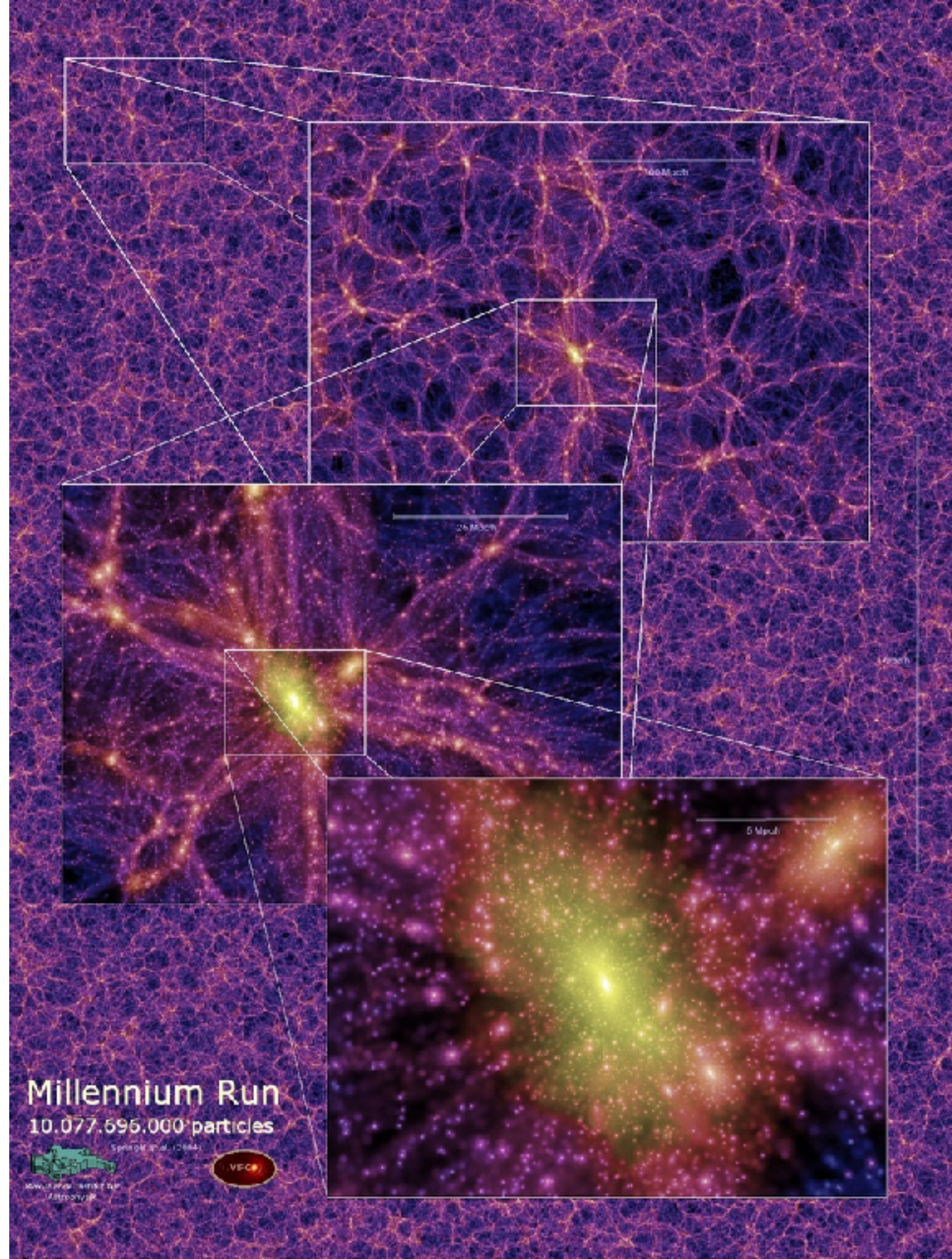


The Millennium Simulation captured the non-linear growth of small density perturbations into dark matter halos

COSMIC WEB IN MILLENNIUM

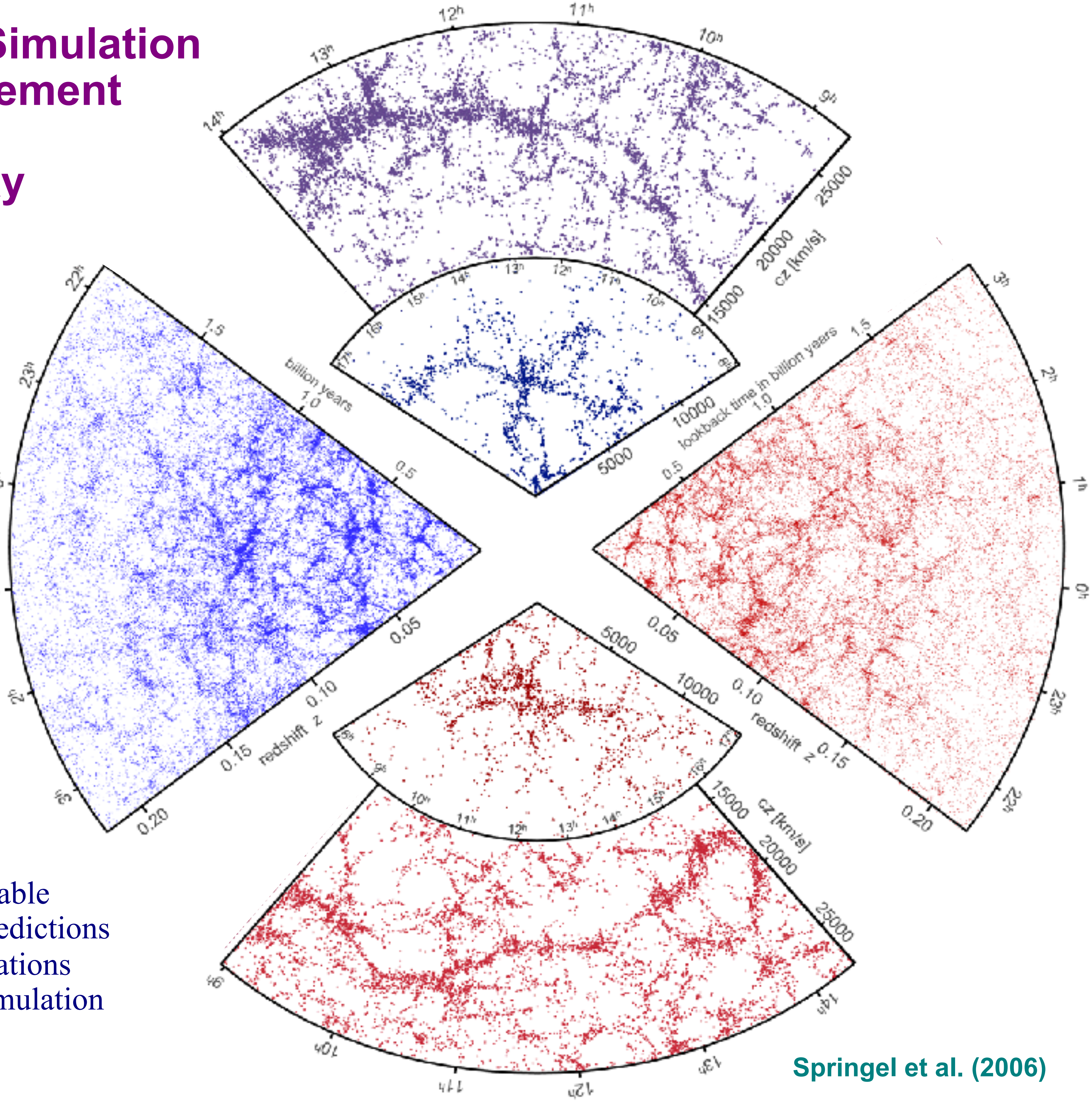
Includes over 10 billion particles





The Millennium Simulation found good agreement of the predicted large-scale galaxy distribution with observations

VIRTUAL VS OBSERVED PIE DIAGRAMS



public access to SQL-queryable database with simulation predictions led to more than 850 publications based on the Millennium simulation thus far

Springel et al. (2006)

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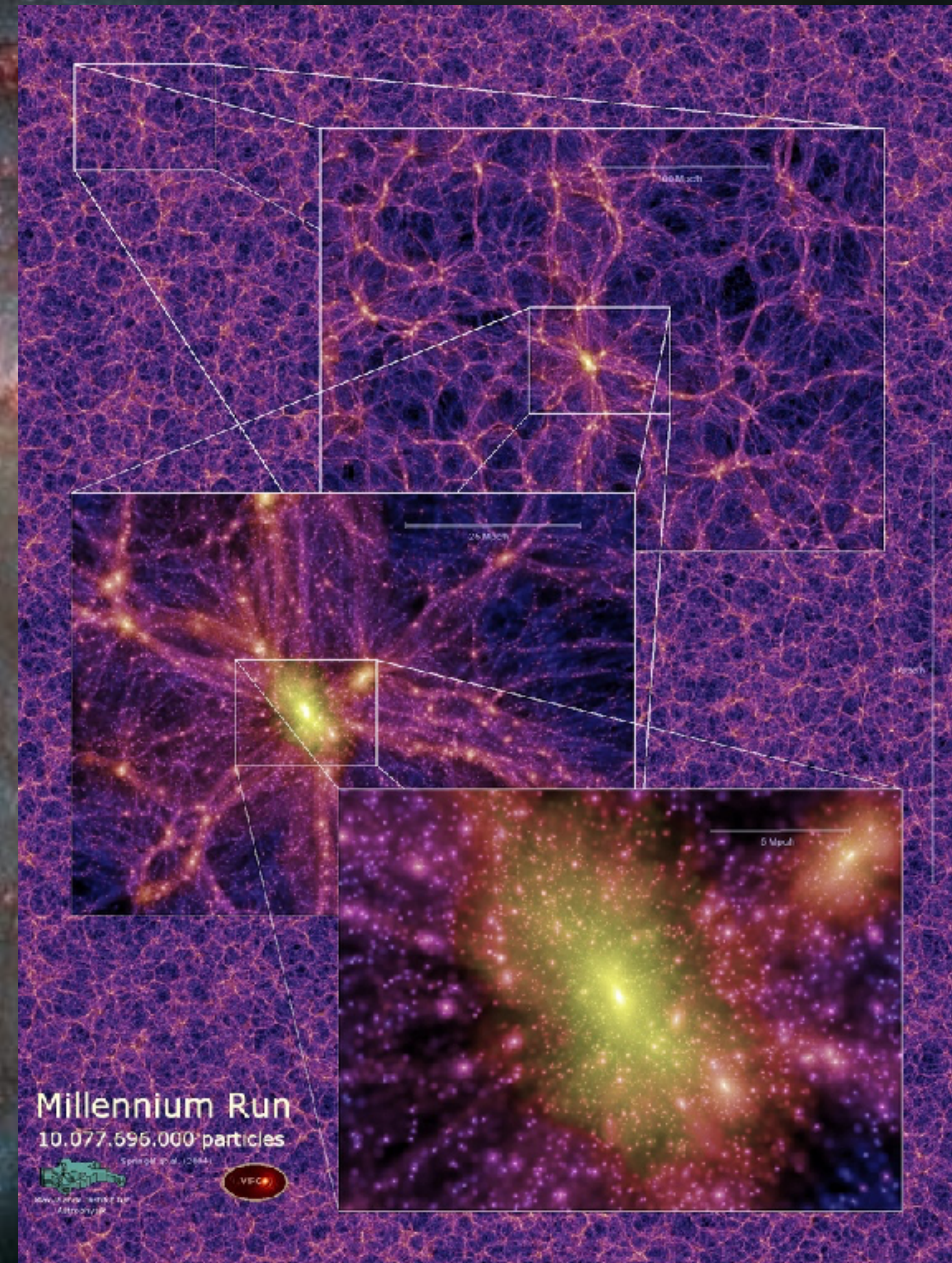
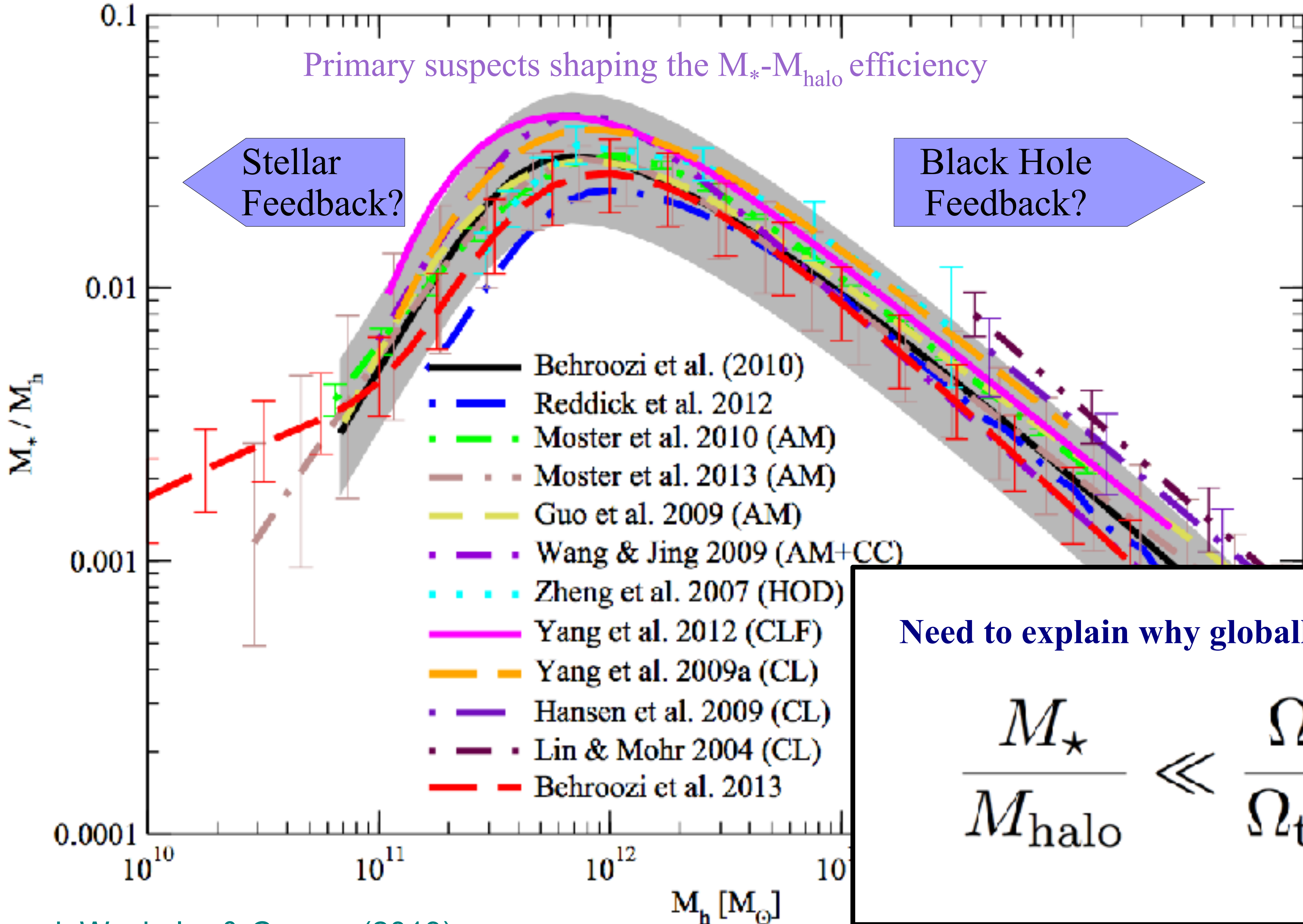


M51
Hubble Herritage Team (2005)

Abundance matching gives the expected halo mass – stellar mass relation in ΛCDM

MODULATION OF GLOBAL STAR FORMATION EFFICIENCY AS A FUNCTION OF HALO MASS



Need to explain why globally:

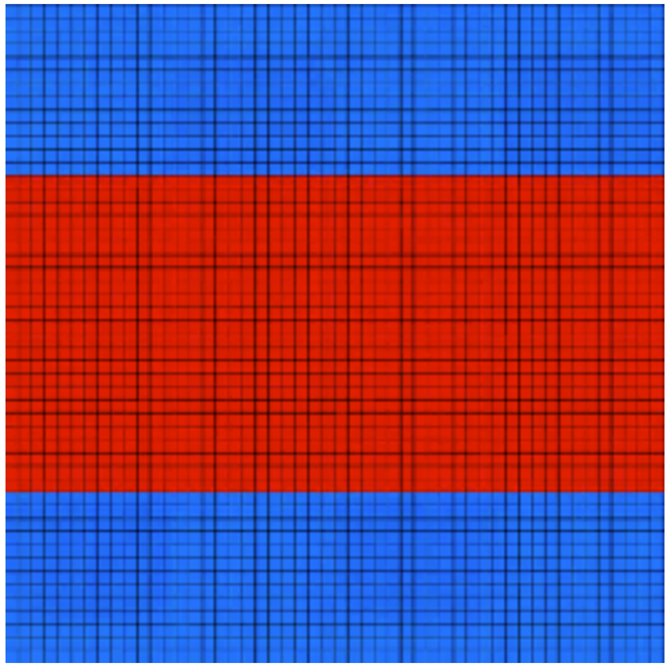
$$\frac{M_\star}{M_{\rm halo}} \ll \frac{\Omega_b}{\Omega_{\rm tot}}$$

Behroozi, Wechsler & Conroy (2013)

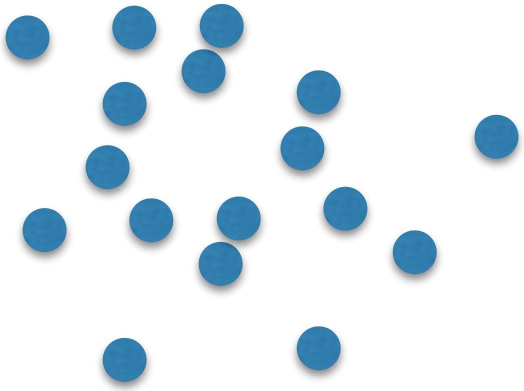
Much of astrophysics is described through systems of **Partial Differential Equations (PDEs)**

WE ALSO NEED TO DISCRETIZE THE PROBLEM

Discretize Gas on a Mesh



Discretize
Dark Matter & Stars
with Particles



Euler's Equations (Navier-Stokes, etc.)

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

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

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

- Additional equations can describe
  - collisionless dynamics
  - magnetic fields
  - CRs
  - Radiation

What physics suppresses star formation in galaxies?

-

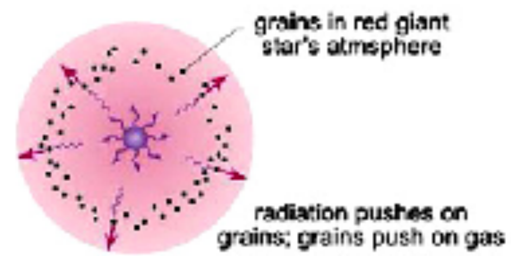
- **Supernova explosions (energy & momentum input)**

Kepler's Supernova

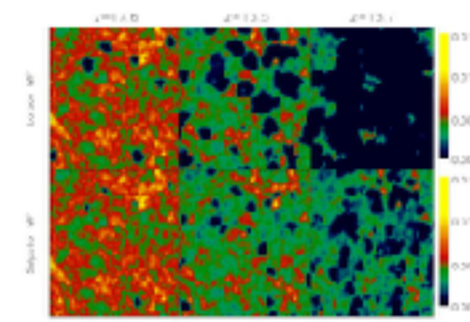
Bubble Nebula

- **Stellar winds**

- **Black Hole activity**

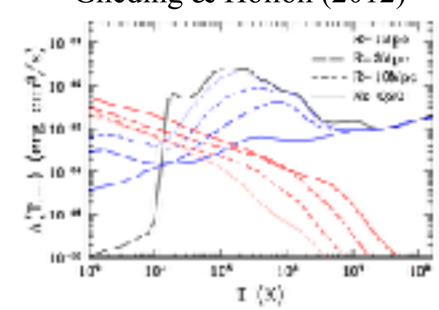


Ciardi al. (2003)

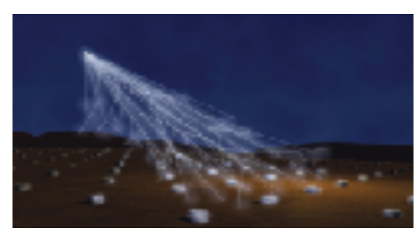


- **Radiation pressure on dust**
- **Photoionizing UV background and Reionization**

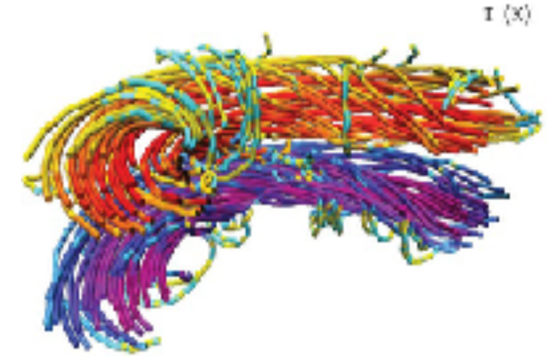
Gneding & Hollon (2012)



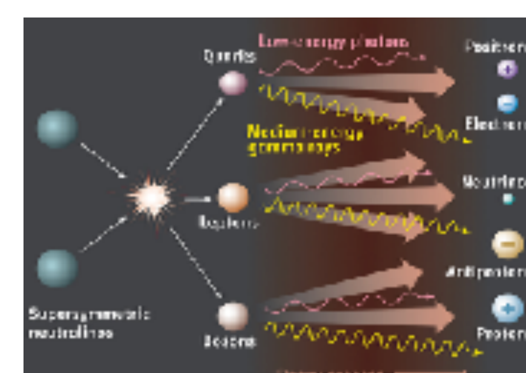
- **Modification of cooling through local UV/X-ray flux**
- **Photoelectric heating**



- **Cosmic ray pressure**



- **Magnetic pressure and MHD turbulence**
- **Exotic physics (decaying dark matter particles, etc.)**

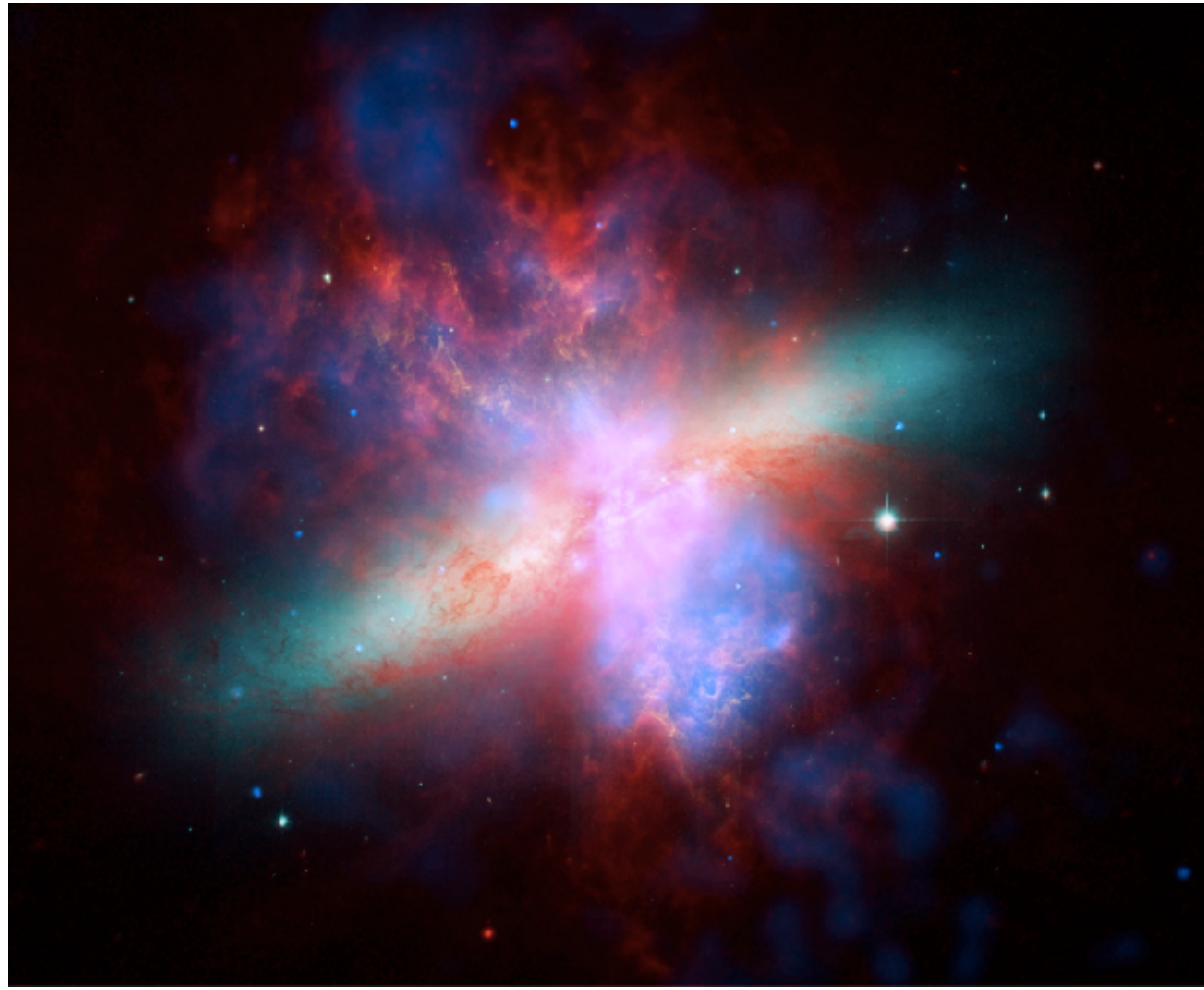


Galactic winds are a manifestation of stellar feedback and necessary to explain galaxy properties

EXAMPLE GALAXY M82

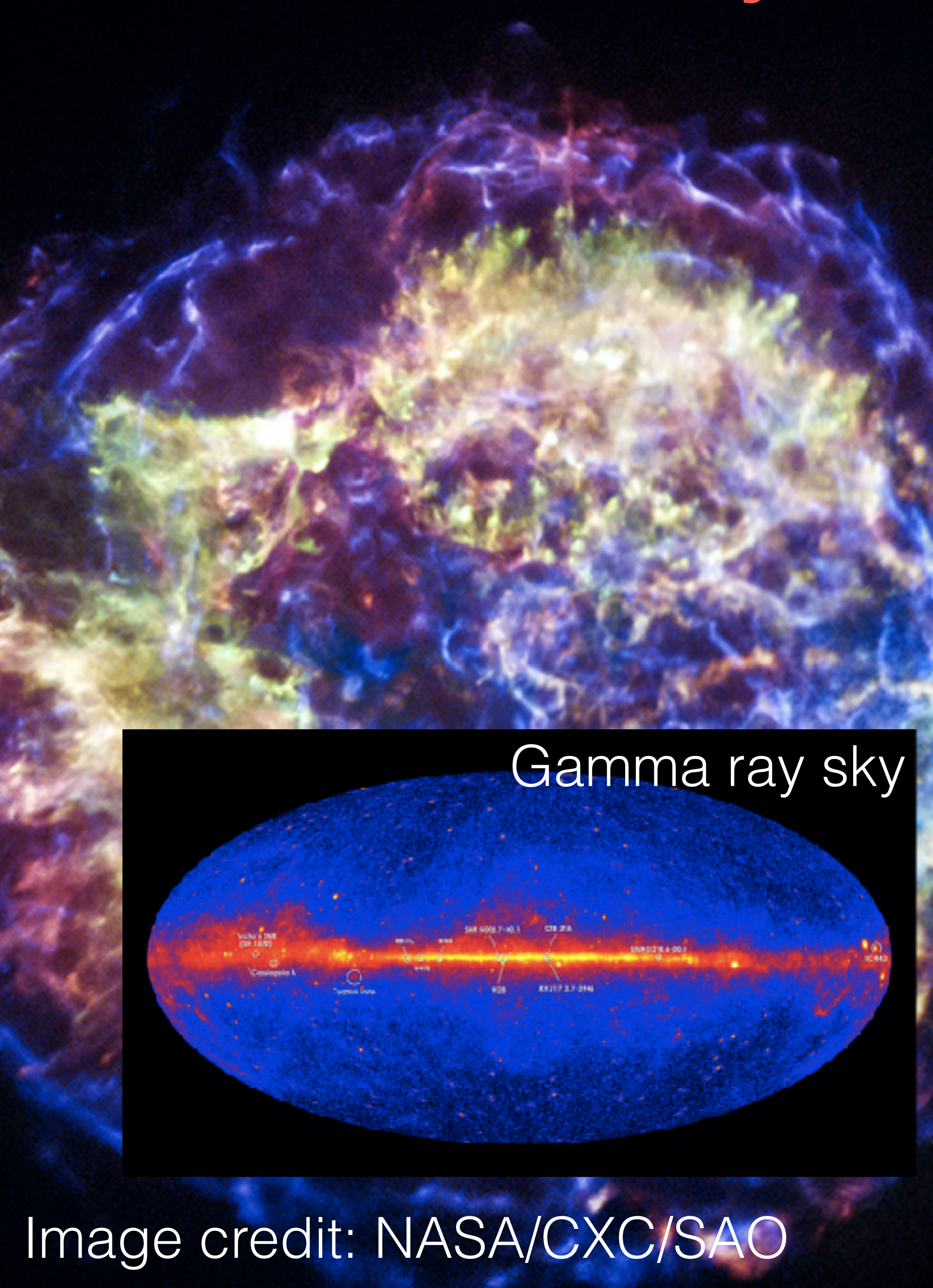
Galactic winds may impact global galaxy properties by:

- removing gas
- heating the gaseous halo
- driving turbulence within the ISM/CGM
- dynamically heat the dark matter



What drives galactic winds?

Cosmic Rays



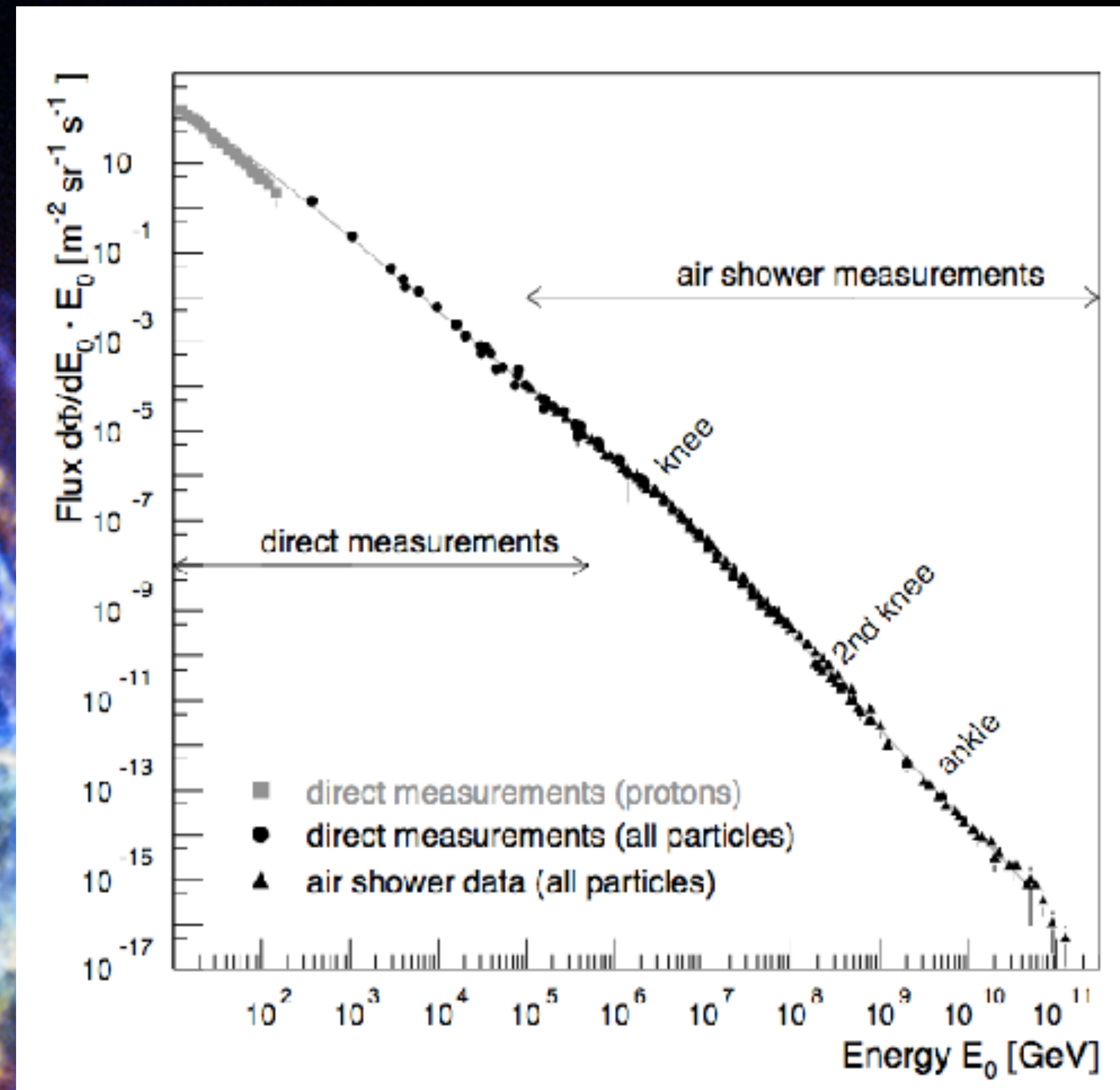


Image credit: NASA/CXC/SAO

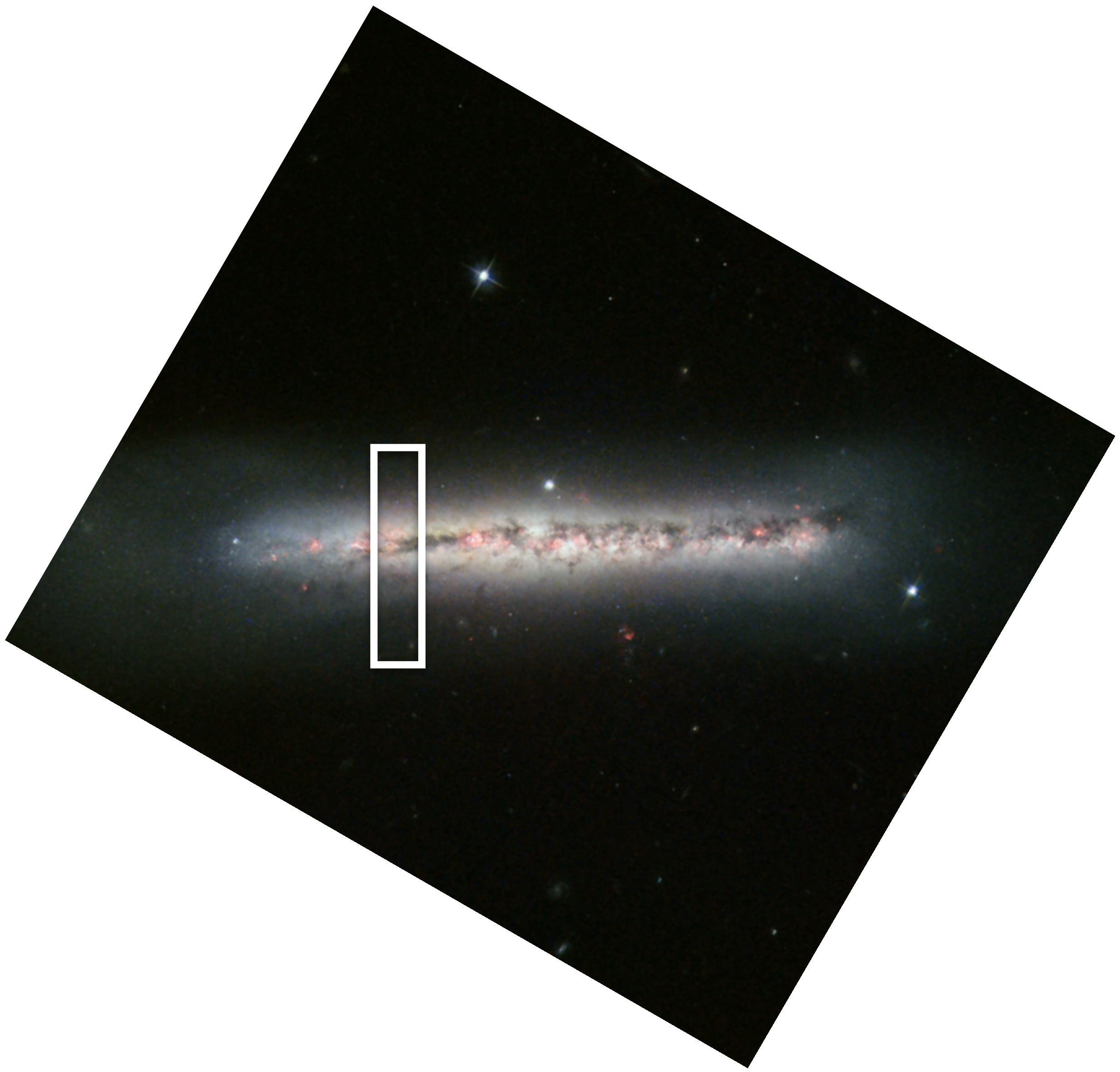
~10% of SN energy goes into CRs (Morlino & Caprioli 2012)

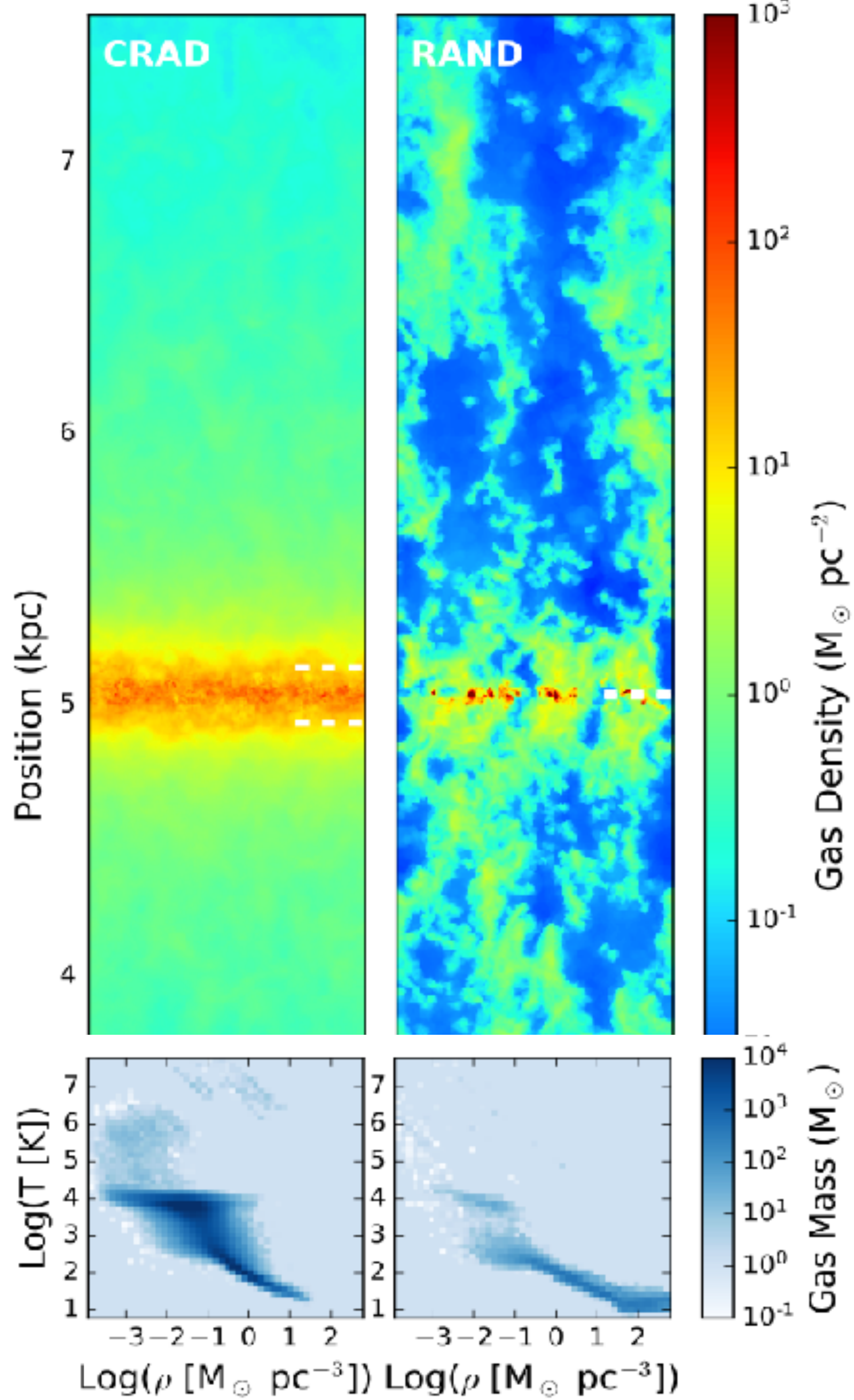
~ CR pressure in equipartition with thermal, magnetic & turbulent pressures in the ISM (Boulares & Cox 2000)

Stratified-box simulations of SN feedback demonstrate the importance of CRs for driving outlows

DIFFERENT MODES OF SUPERNOVA FEEDBACK

Simpson et al. (2016)

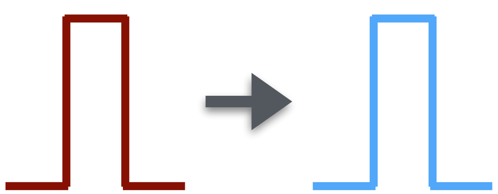




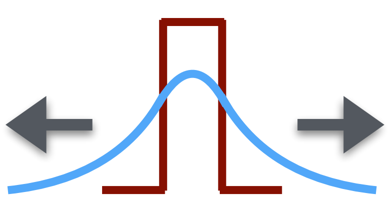
Gas Density Evolution

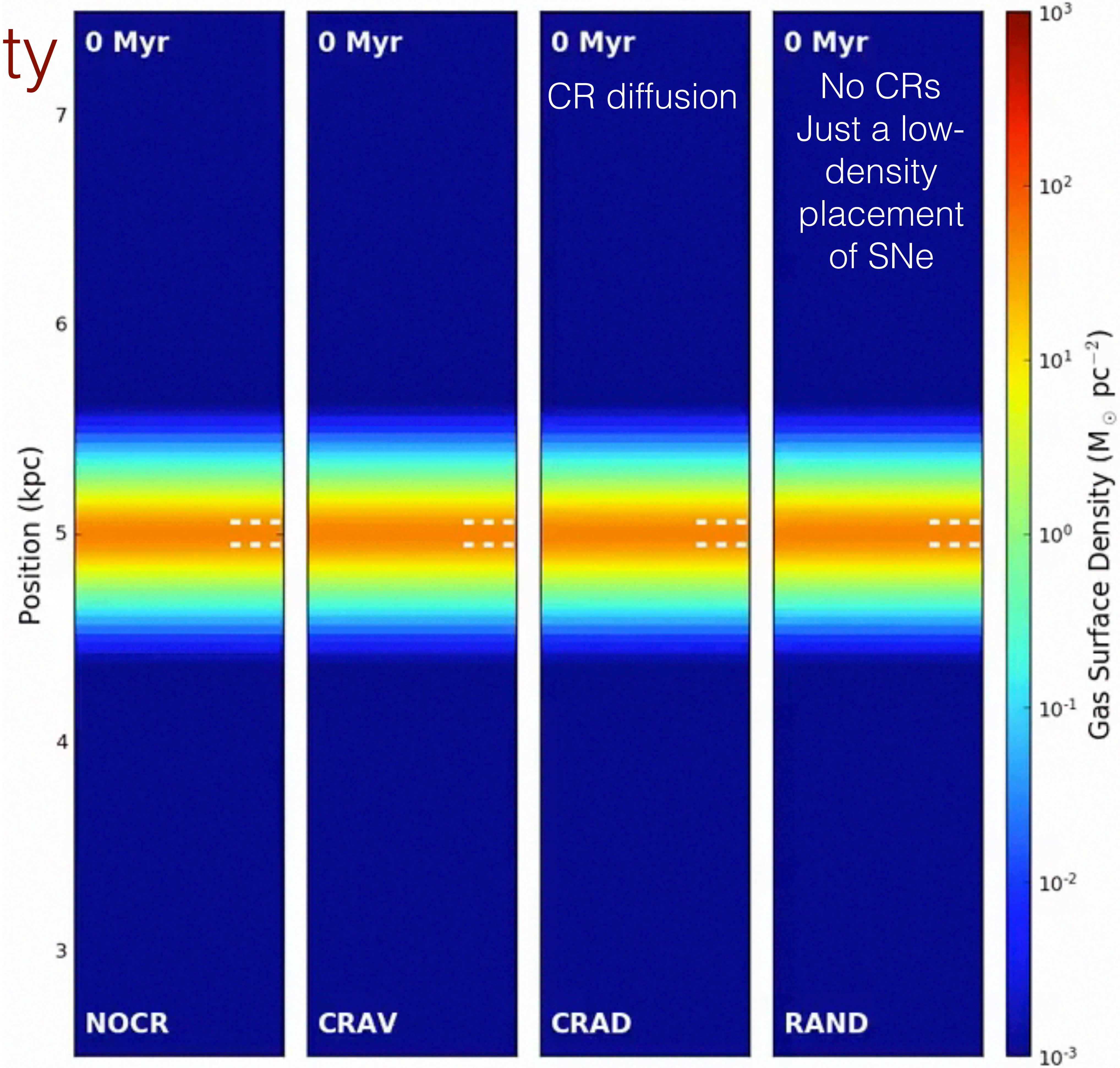
CR transport

advection

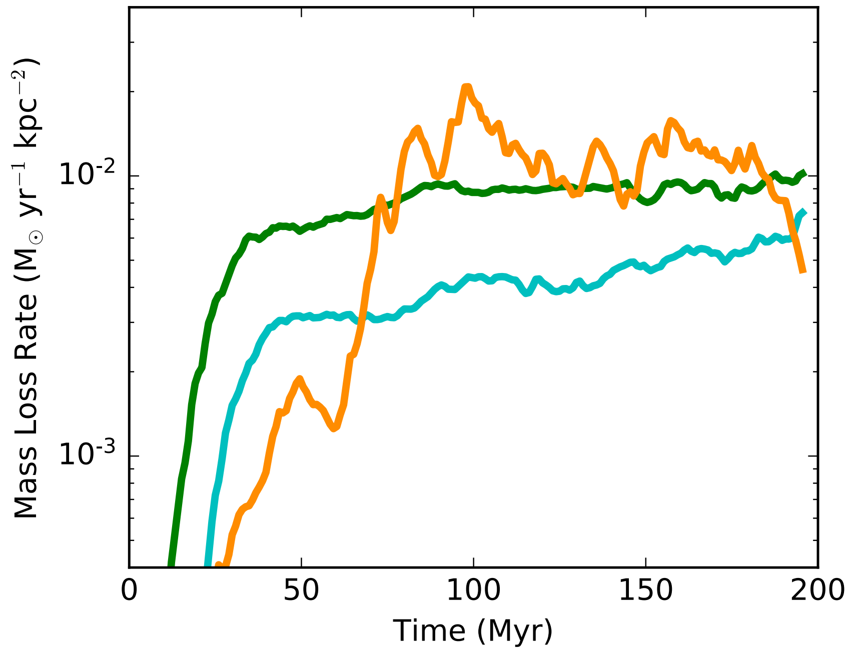


diffusion

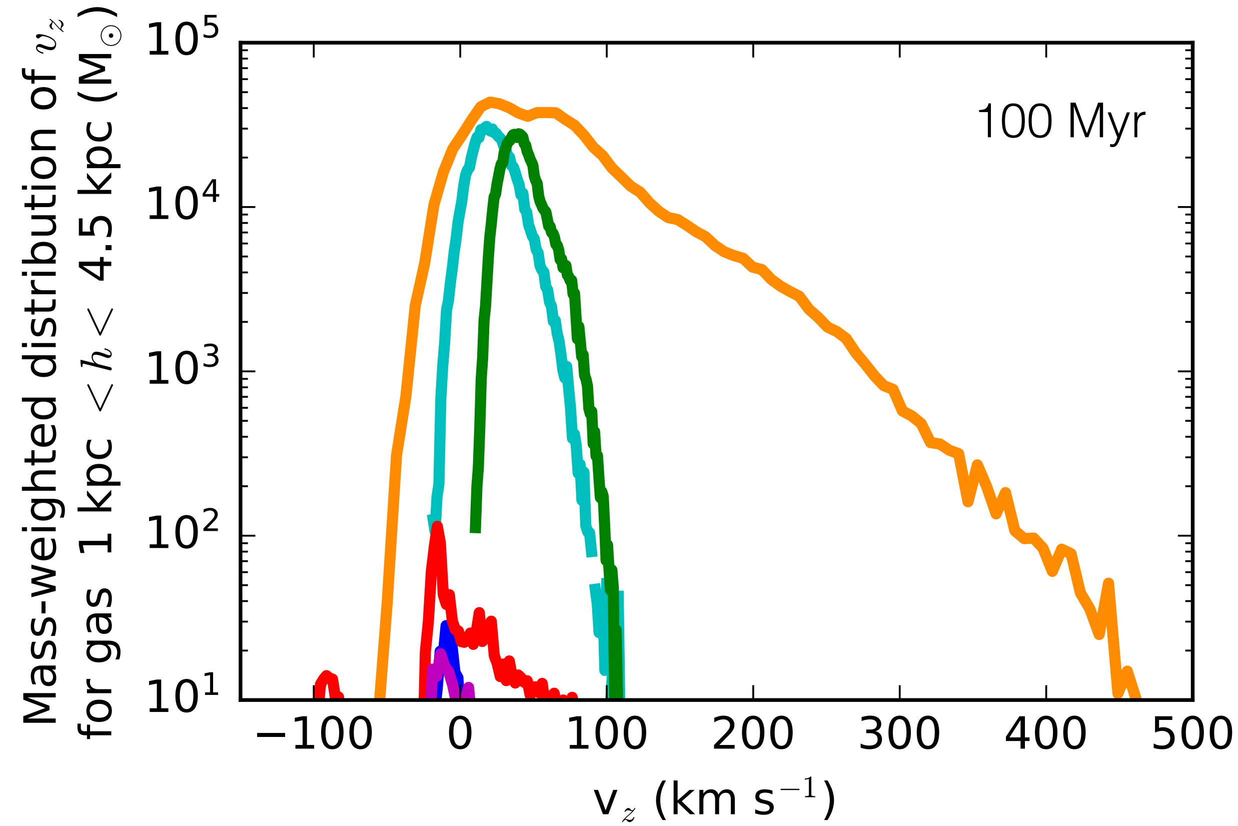




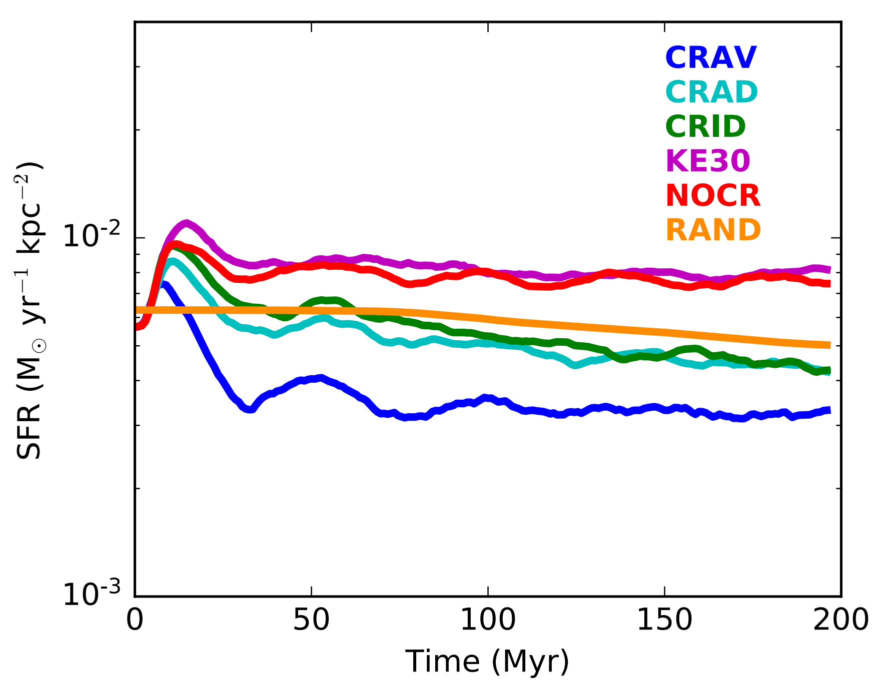
Outflow Properties



Mass loss rate ~equals star formation rate



CRs are a viable mechanism for driving outflows, yet give different predictions for temperature & velocity of outflows



Simpson et al. (2016)

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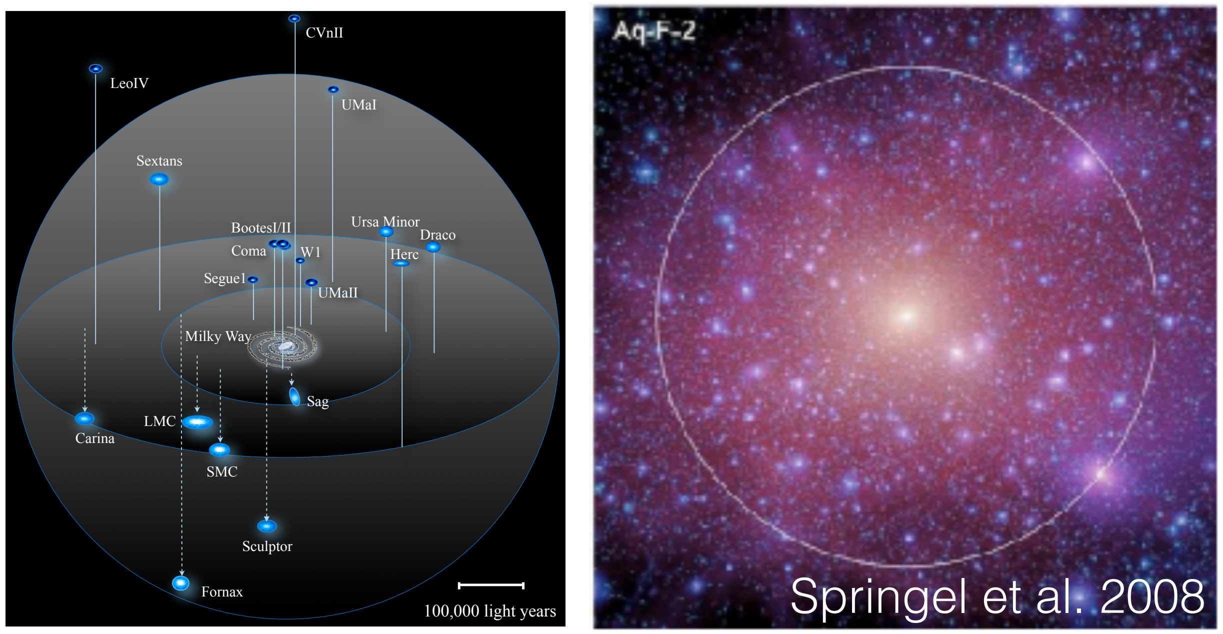
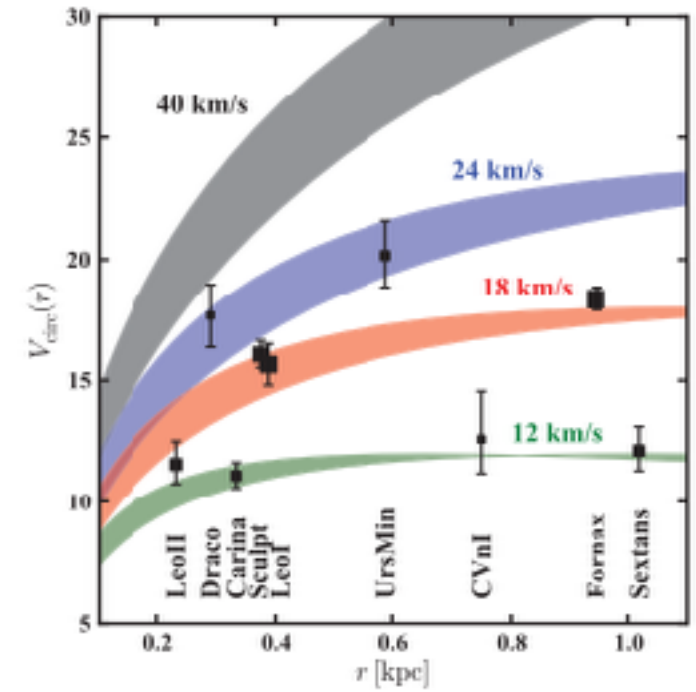
Inconsistencies between pure CDM predictions & observations especially acute at low masses

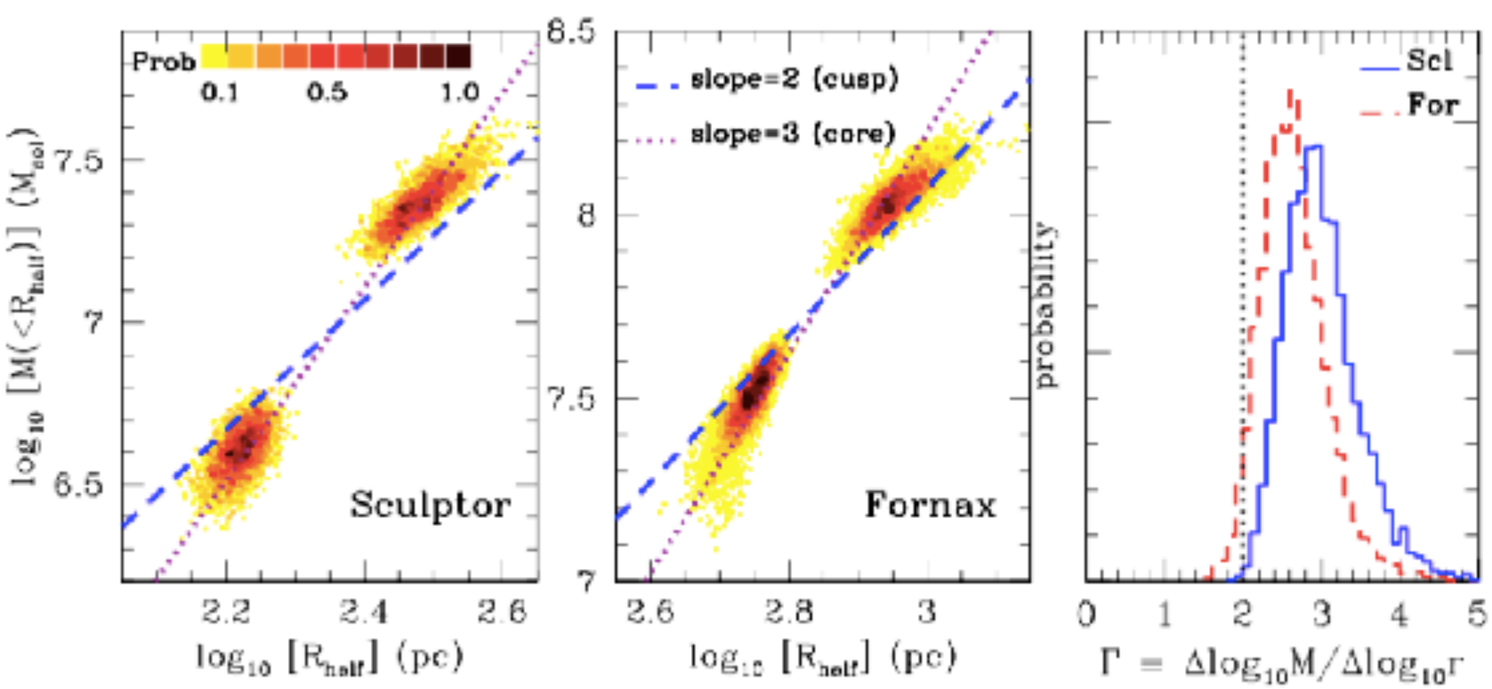
'Missing' Satellites
(e.g. Moore et al. 1999)



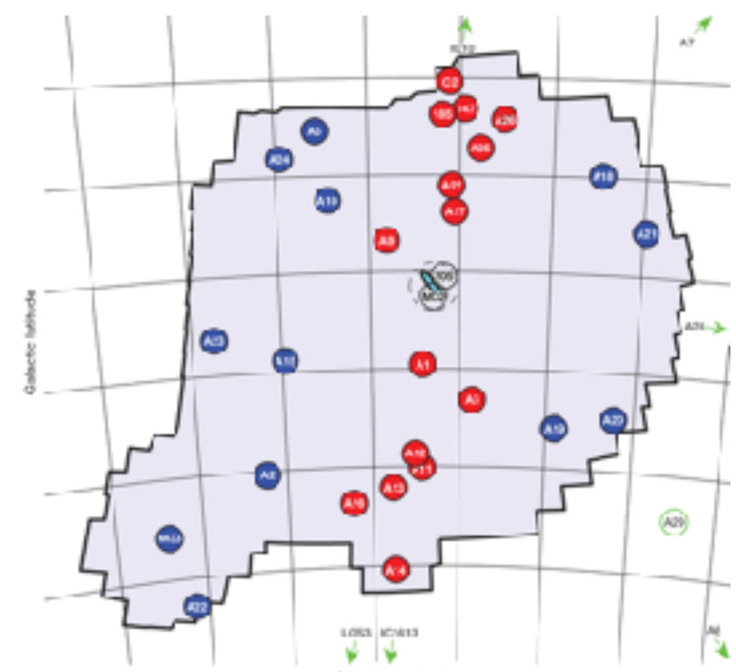
'Too big to fail'
(Boylan-Kolchin et al. 2012)



Dark matter profiles may be cored
(Walker & Penarrubia 2011)

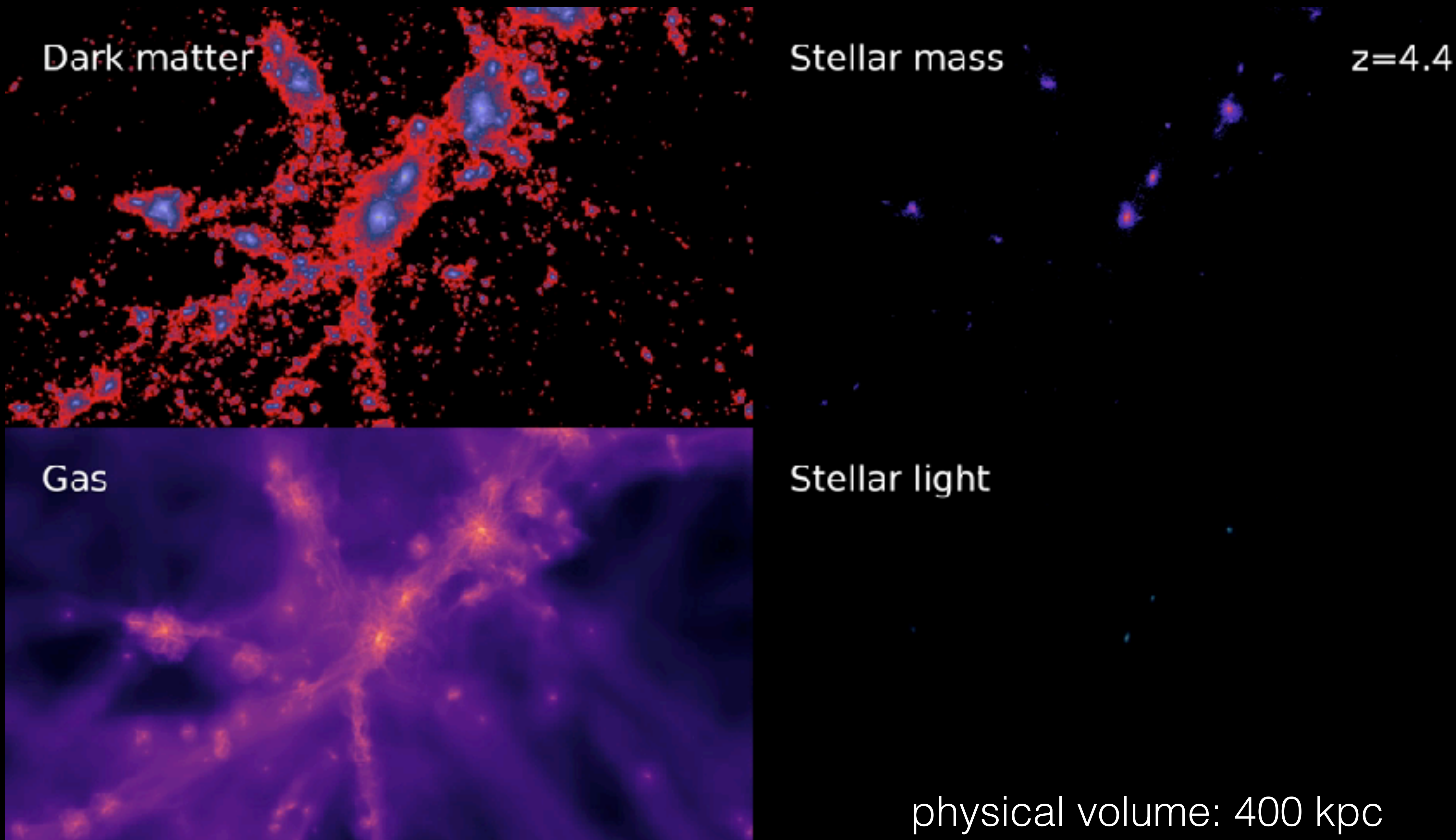


Planes of satellites?
(Ibata et al. 2013)



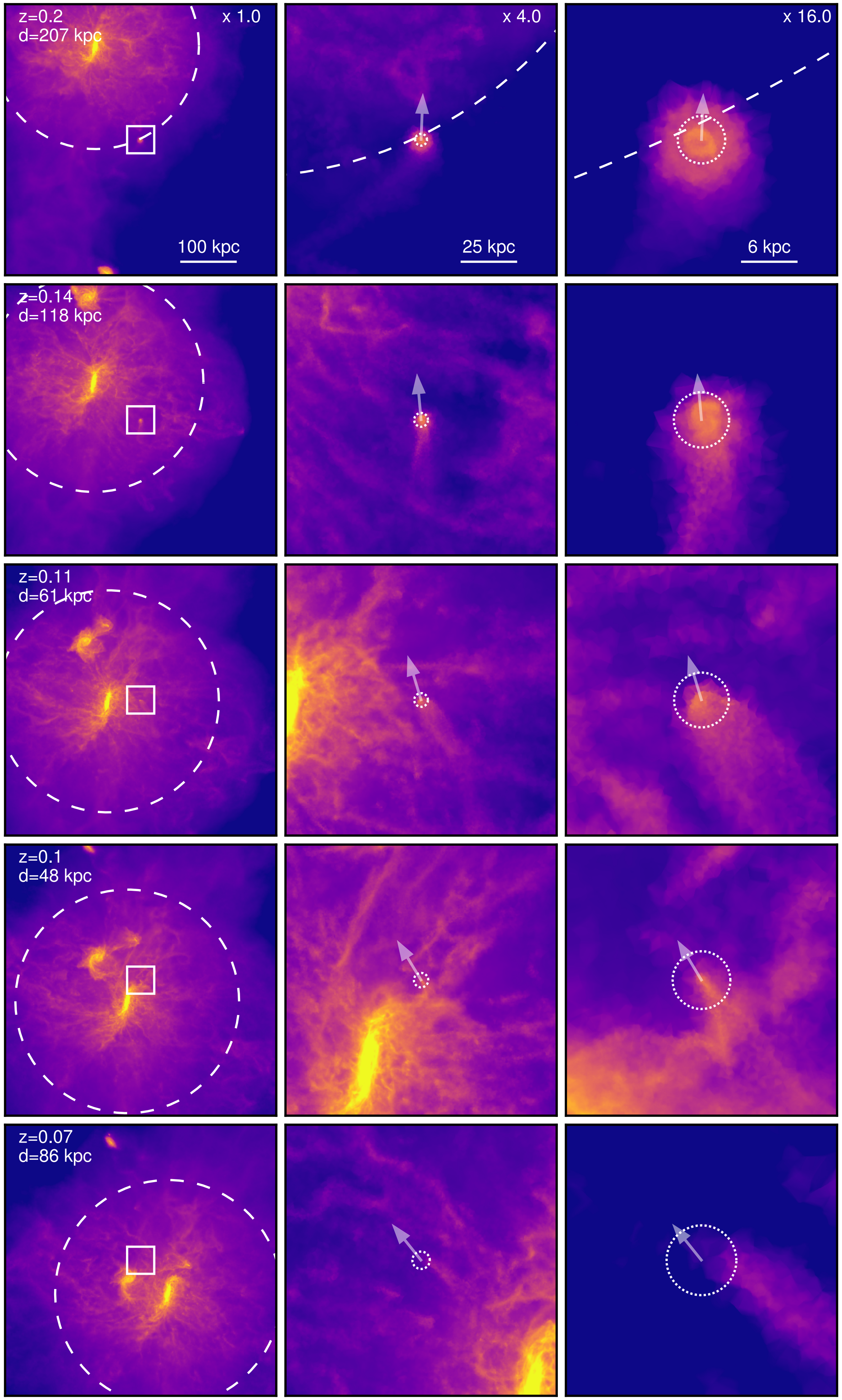
The Auriga Project

Grand et al. 2017



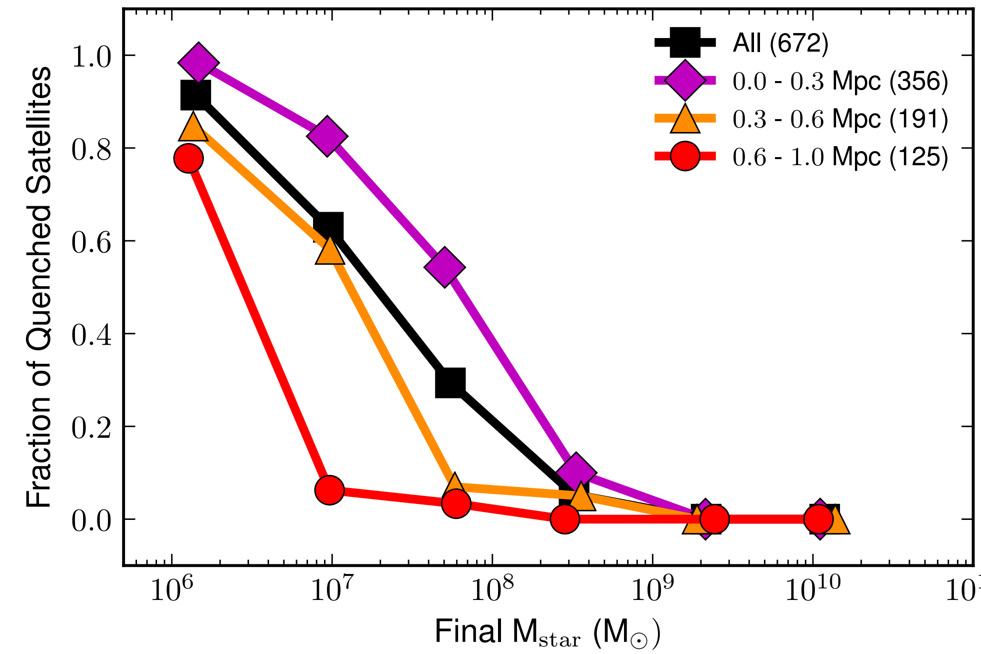
The Set-up & Physics

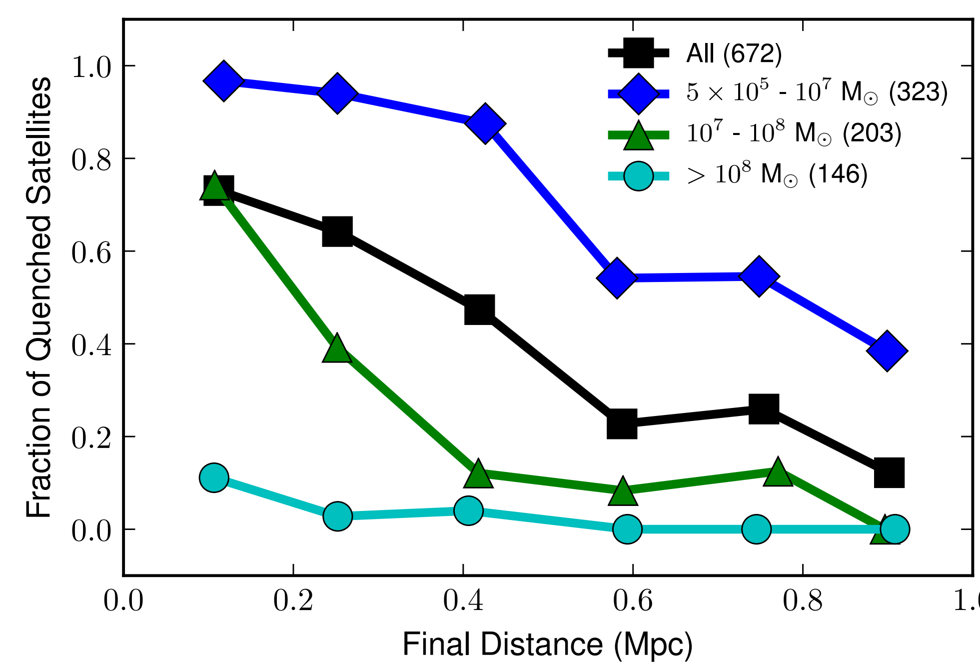
- Thirty cosmological zoom simulations of 10^{12} $M_\odot$ halos
- DM particle mass ~ 3 x 10^5 $M_\odot$; baryon cell/particle mass ~ 5 x 10^4 $M_\odot$
- Second-order hydrodynamics on a moving mesh (AREPO)
- MHD, SF & stellar feedback, AGN feedback, UV background, atomic & metal line cooling



Ram pressure is the dominant quenching mechanism

EVIDENCE FROM THE AURIGA SIMULATIONS





Simpson et al. 1705.03018

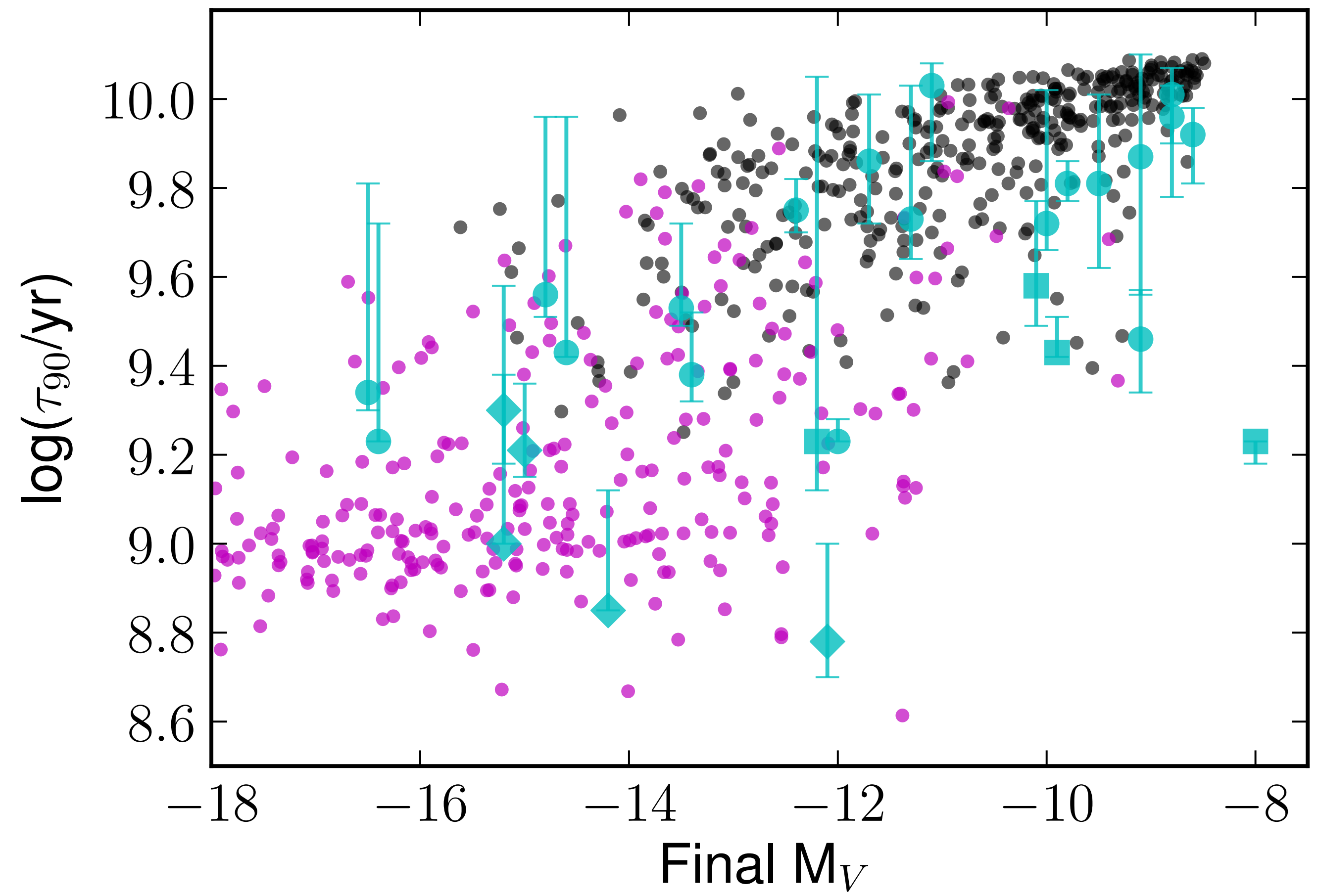
Can we explain the observed quenching times of MW satellite galaxies?

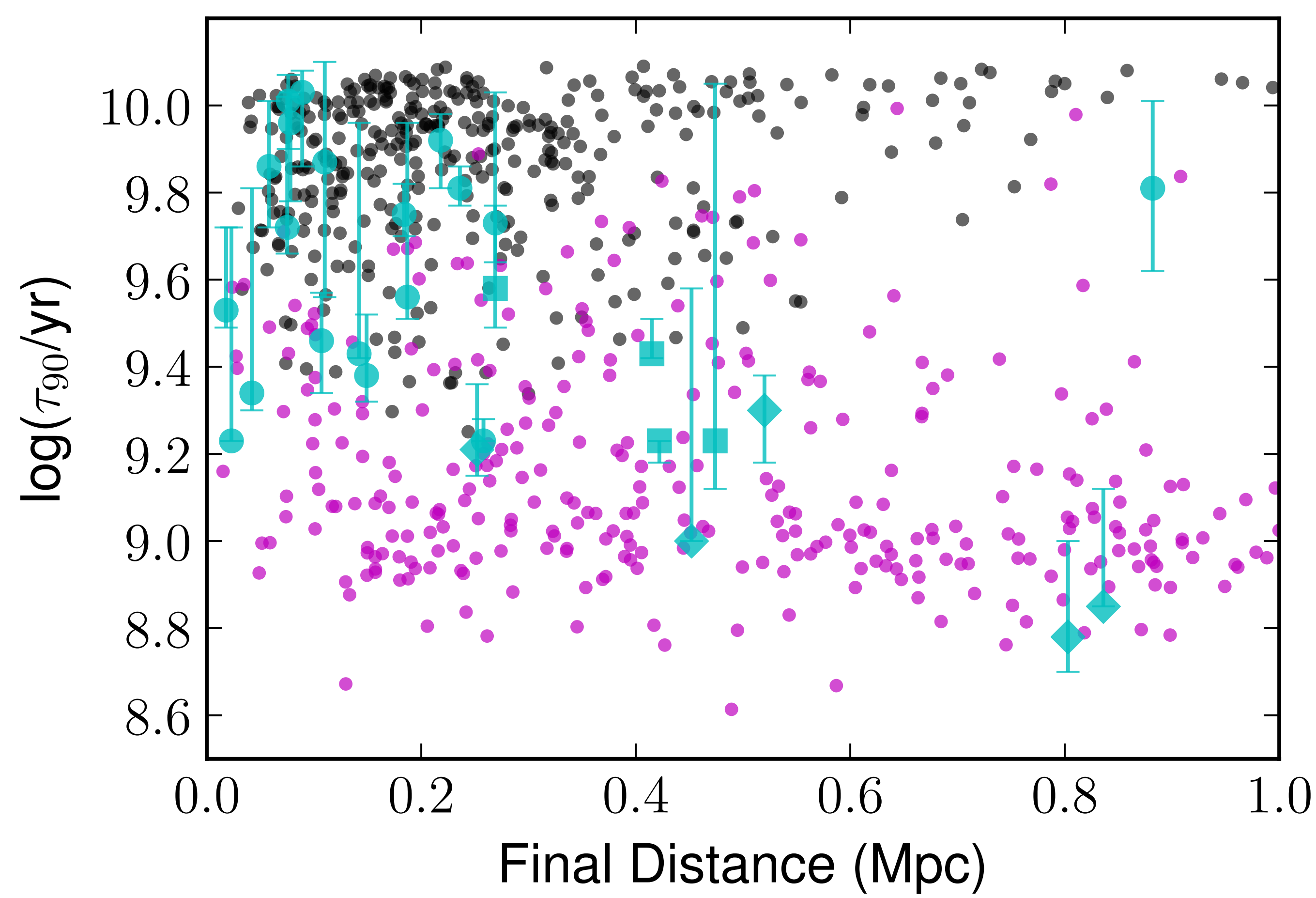
A COMPARISON TO THE ANGST SAMPLE

τ_{90} is the time by which 90% of a system's stellar mass formed

- cyan points from ANGST sample (Weisz et al. 2015)
- black and magenta points Auriga satellites (quenched & star forming)

Simpson et al. 1705.03018





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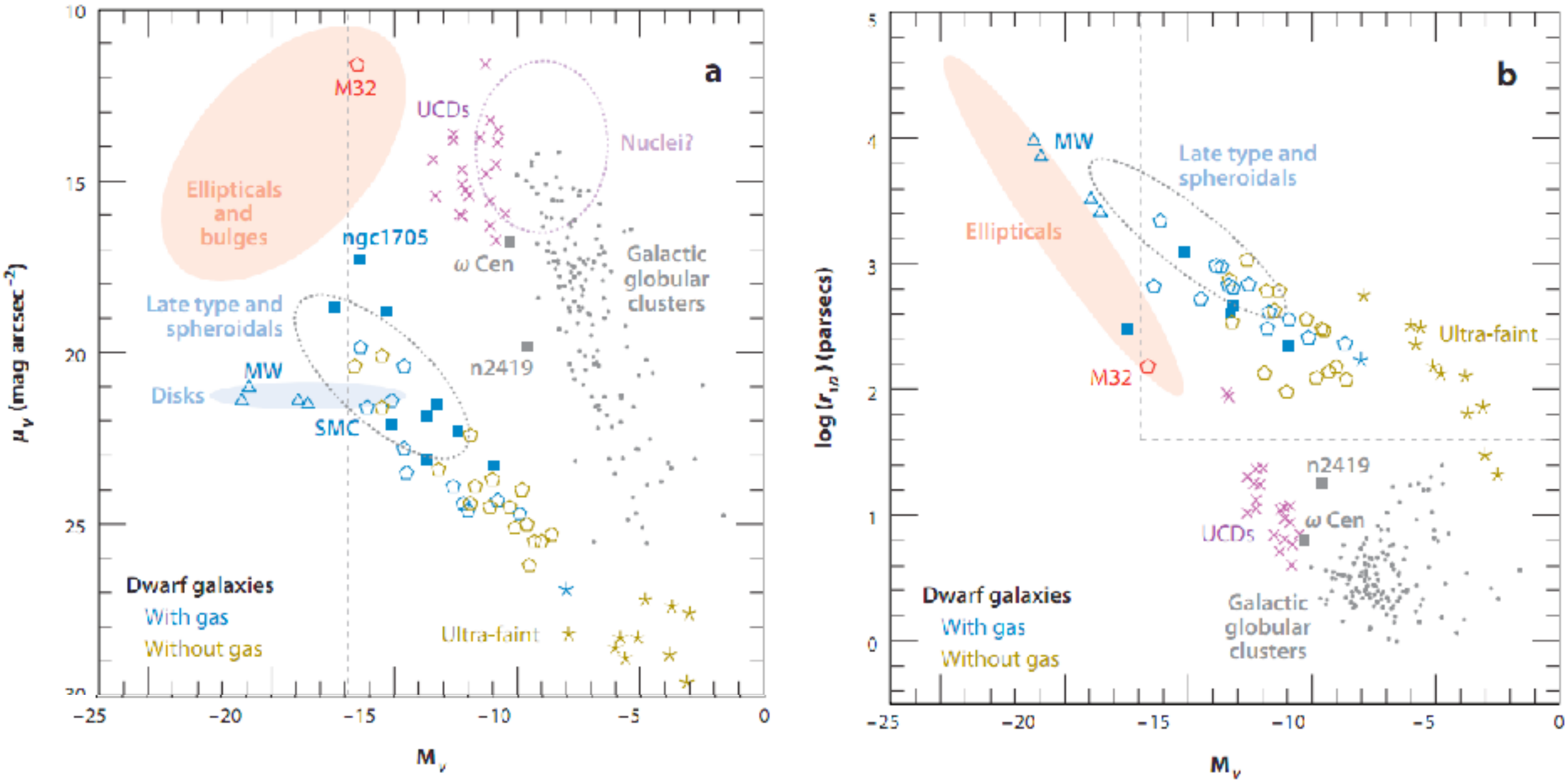
An open question: what is the lowest mass galaxy?

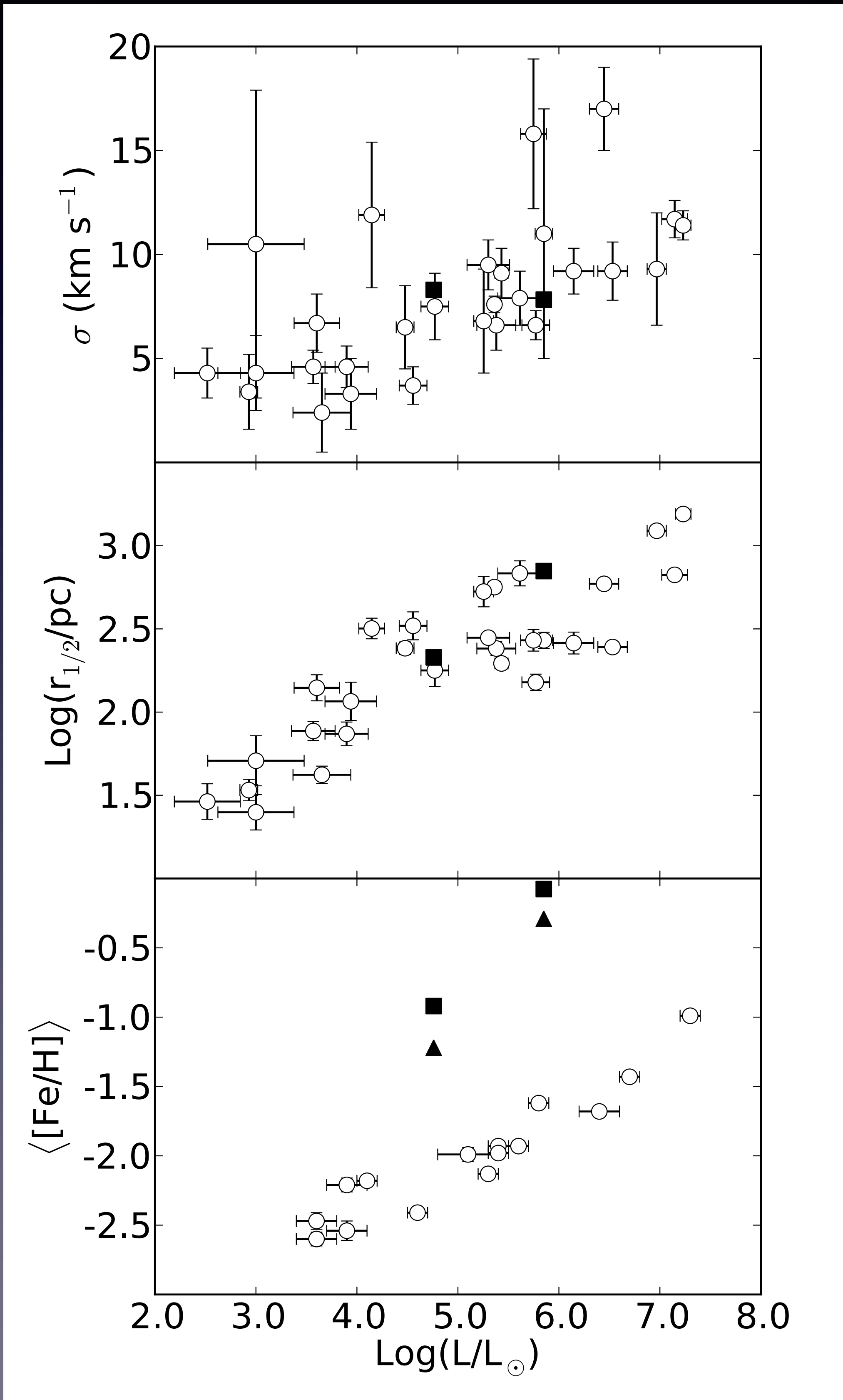
AN OPPORTUNITY FOR NEW SURVEYS



Is there a limit to galaxy formation? Is this limit determined by dark matter or some other effect?

Reionization and MW dSphs

Simpson et al. 2012



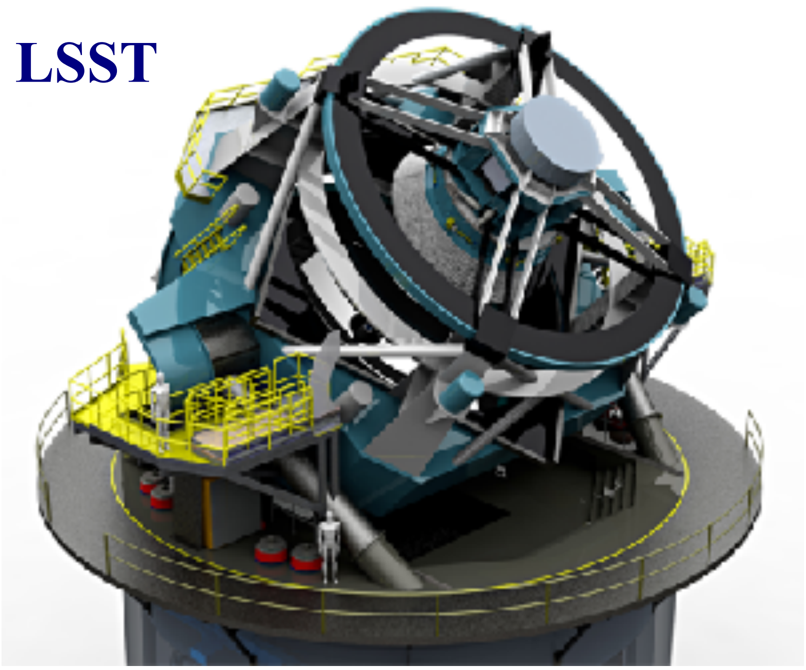
	Reionization z=6-7	Reionization z=8-8.9
	R10	R10-earlyUV
$M_{tot}/M_\odot$	1.55×10^9	1.55×10^9
$M_*/M_\odot$	1.43×10^6	1.16×10^5
r_{200} (kpc)	23.7	23.9
$r_{1/2}$ (pc)	704	213
$M_{1/2}/M_\odot$	3.05×10^7	3.86×10^6
$M_{300}/M_\odot$	7.53×10^6	7.41×10^6
$\sigma_{1/2}$ (km/s)	7.83	8.30
$\langle Z/Z_\odot \rangle$ (median)	0.51	0.06

Data from Walker et al. 2009,
Kirby et al. 2008 & Kirby et al. 2011

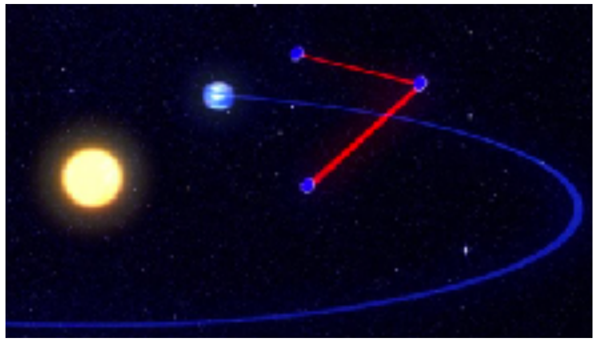
New and upcoming observational facilities will expand our understanding of galaxy formation

OBTAIN TESTABLE PREDICTIONS FOR NEW UND UPCOMING LARGE OBSERVATIONAL FACILITIES

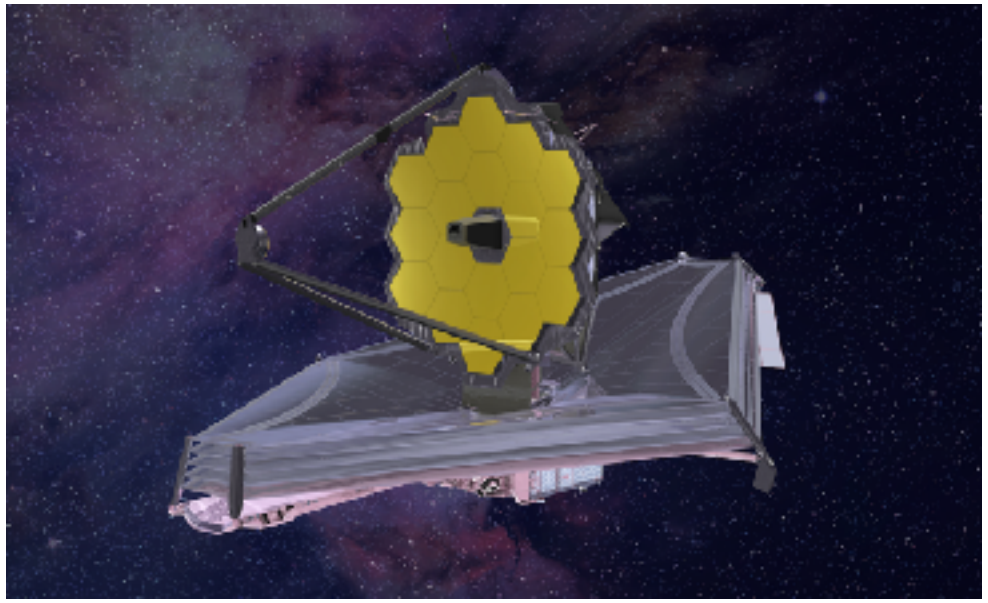
LSST



eLISA



James Webb Space Telescope



Dark Energy Spectroscopic Instrument

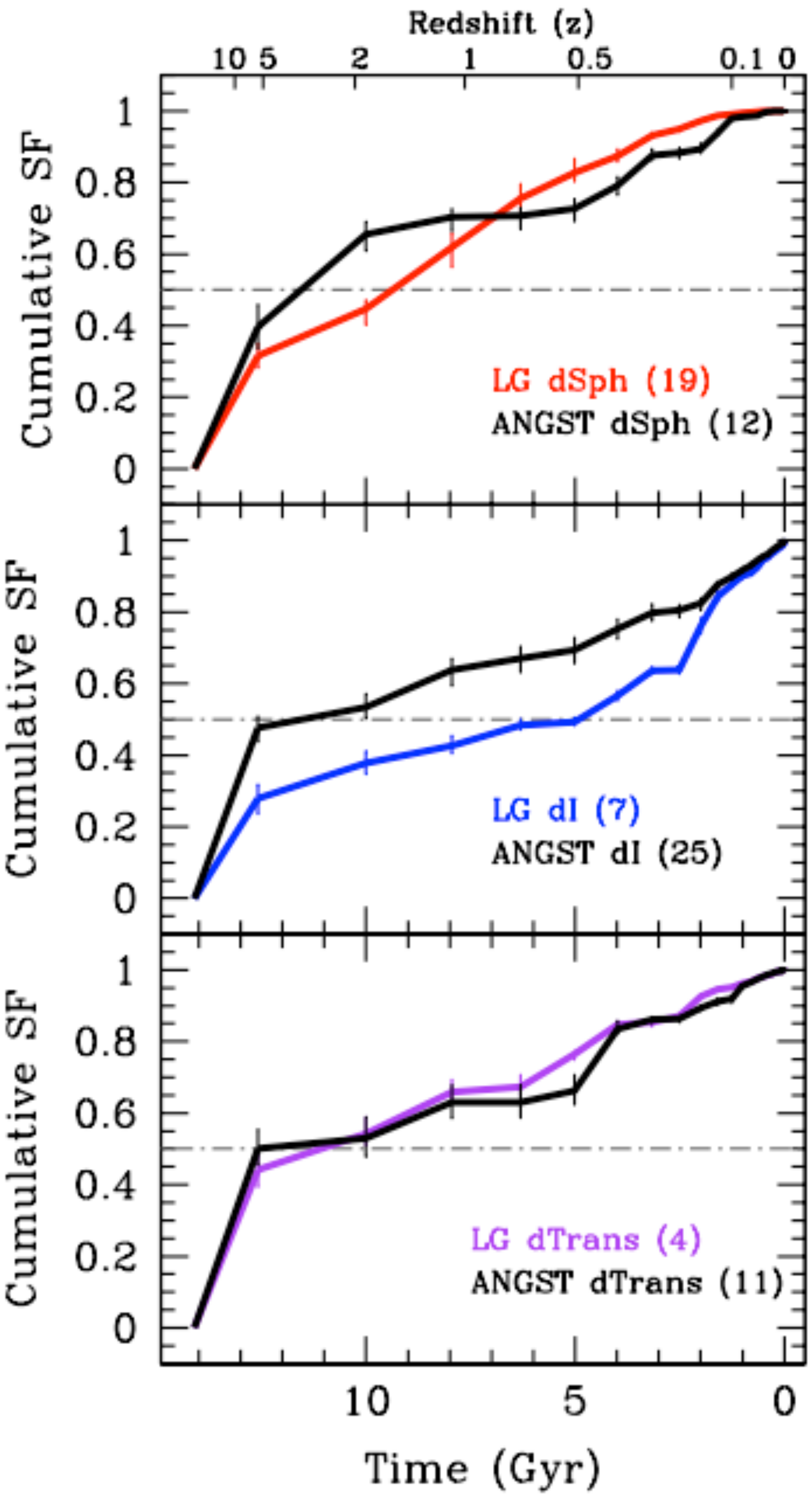
Atacama Large Millimeter Array

Square Kilometer Array

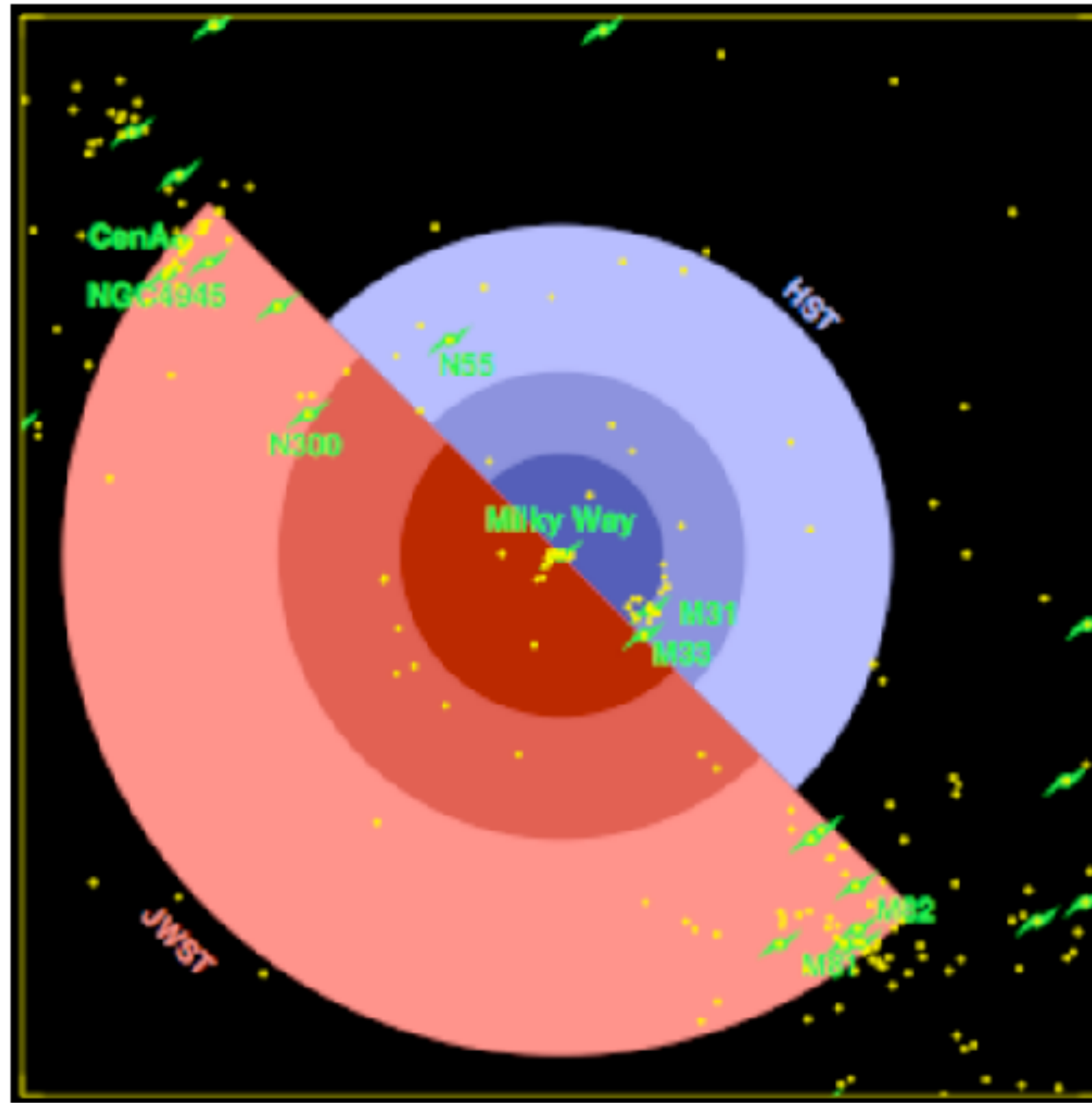
ANGST

JWST and near field cosmology

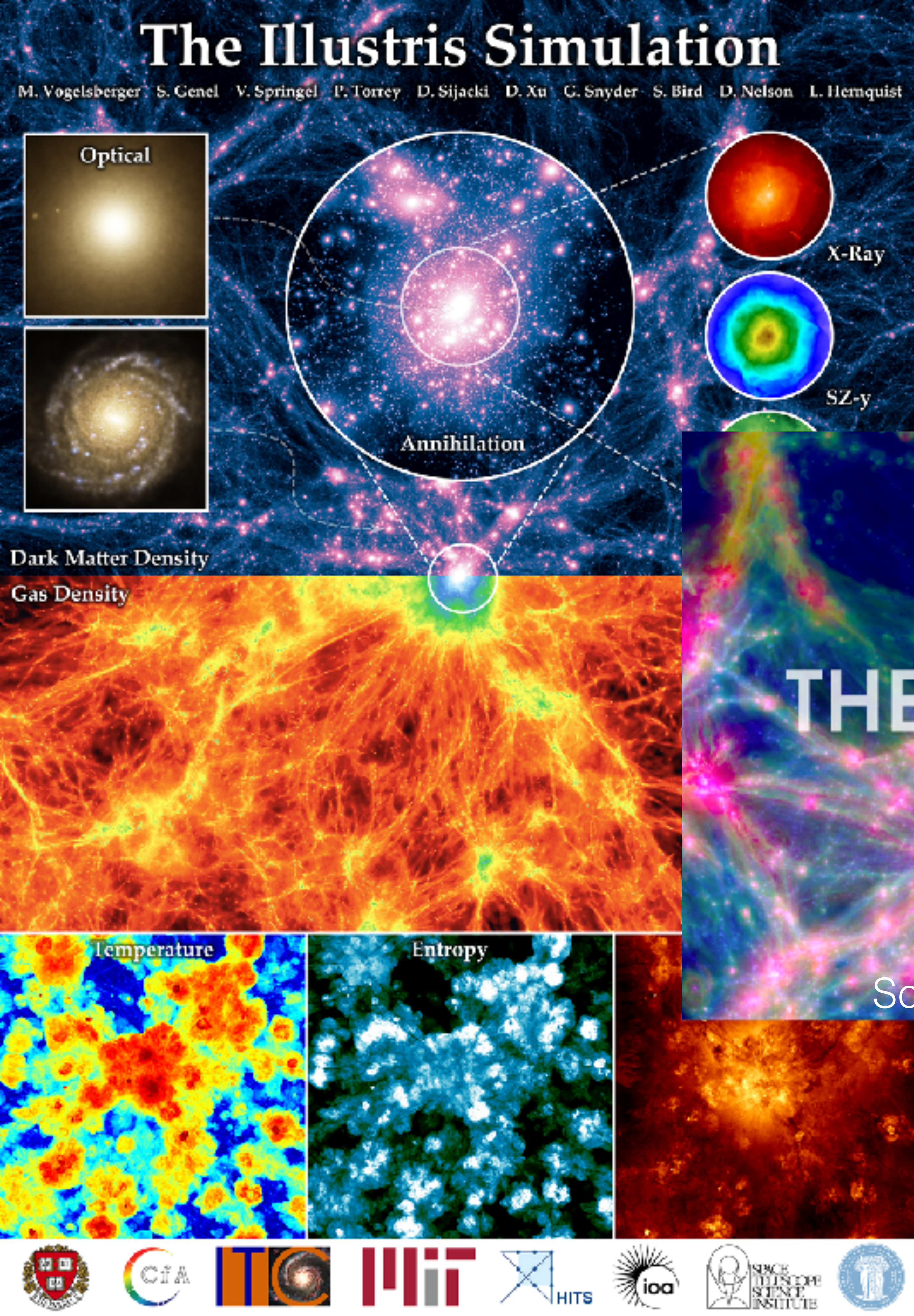
RESOLVED SFH IN A LARGER VOLUME



Weisz et al. 2011



Brown+ 2008


The Illustris Simulation
M. Vogelsberger S. Genel V. Springel P. Torrey D. Sijacki D. Xu G. Snyder S. Bird D. Nelson L. Hernquist
Optical
X-Ray
SZ-y
Annihilation
Dark Matter Density
Gas Density
Temperature
Entropy
HITS


THE EAGLE PROJECT
Schaye et al. (2014) and the Virgo Consortium

V. Conclusions

- One of the fundamental tests of ΛCDM is observations of galaxies and their properties
- Numerical simulations are necessary to make predictions for these data
- Modeling baryonic effects (e.g. stellar feedback) is an important component of predictive simulations
- As data become bigger, so too must simulations - leaps forward in computing speed and algorithm development will help us to develop next generation simulations