Early structure formation in the dark universe with cosmological numerical simulations

Darren Reed

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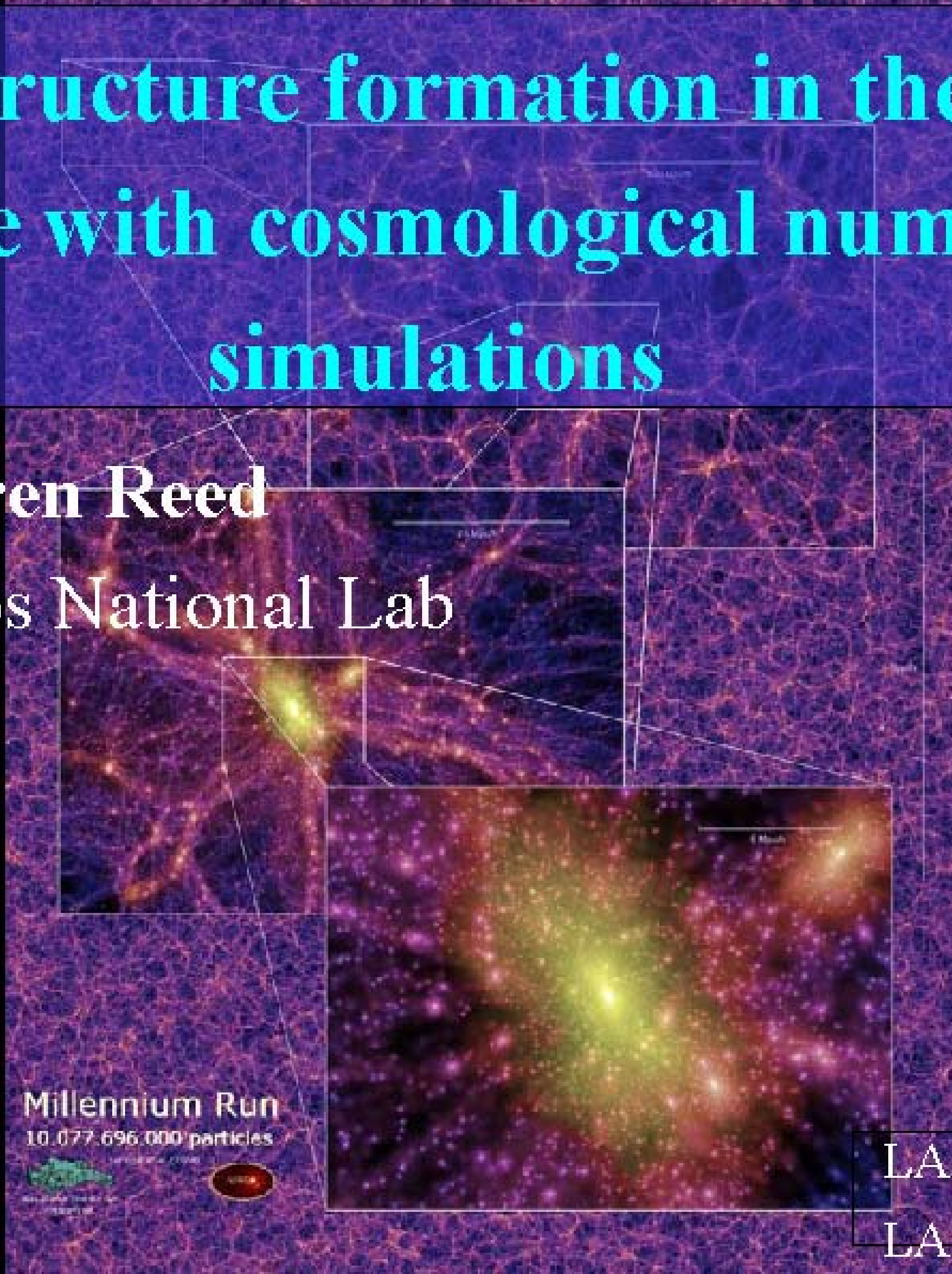

LA-UR 09-00005

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Early structure formation in the dark universe with cosmological numerical simulations

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Zarija Lukic (LANL)

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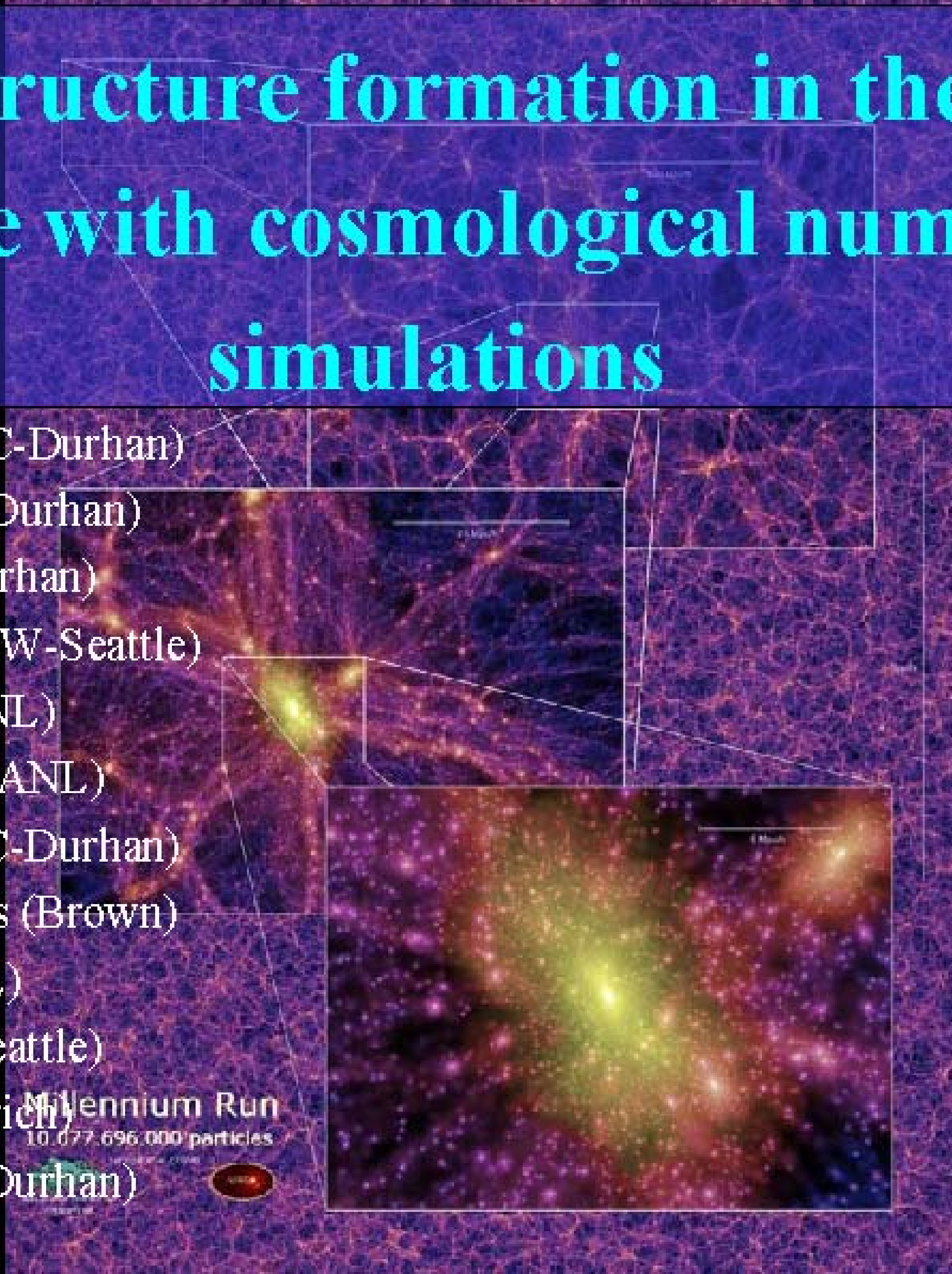
Joachim Stadel (Zurich)

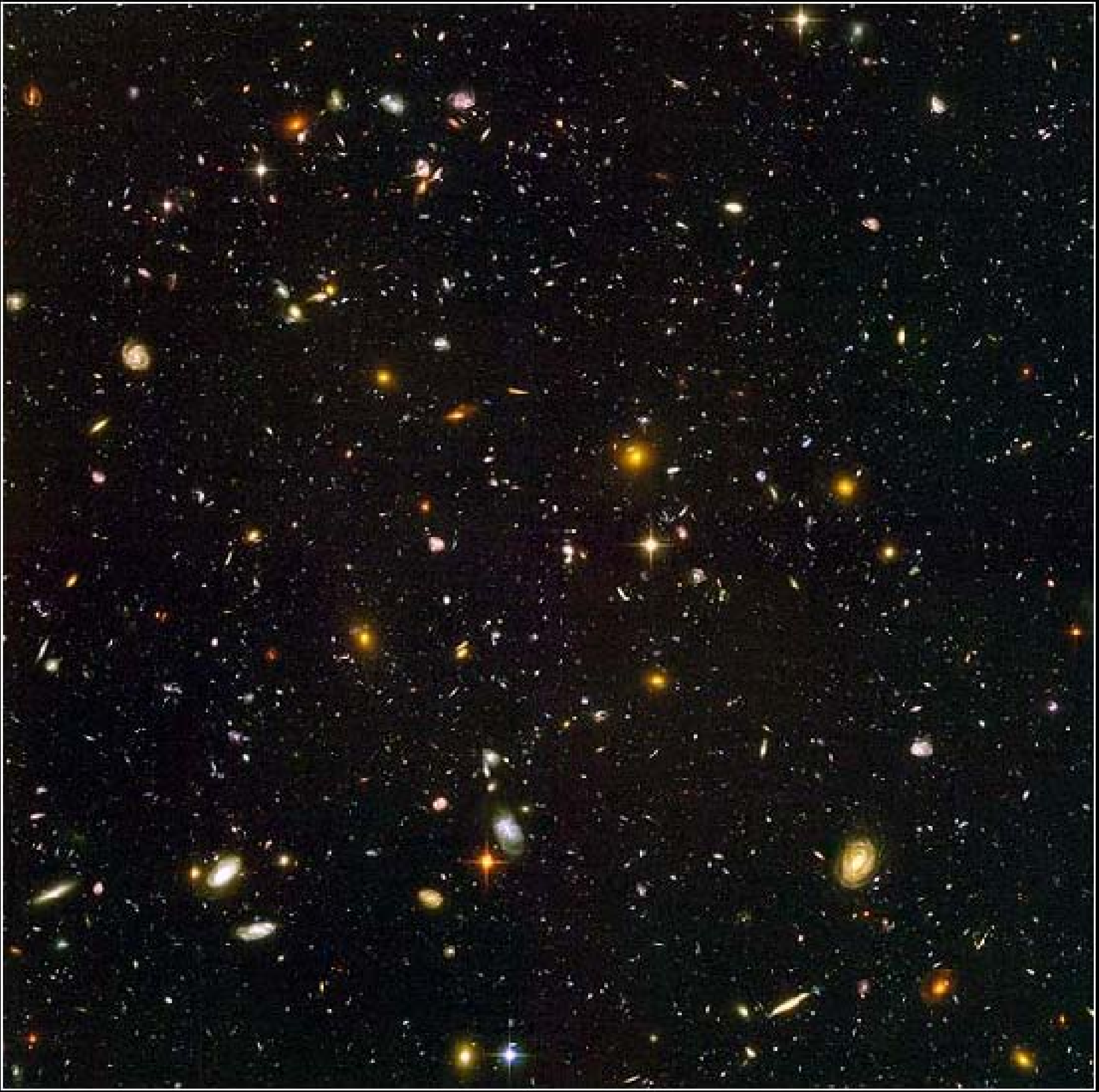
Tom Theuns (ICC-Durhan)



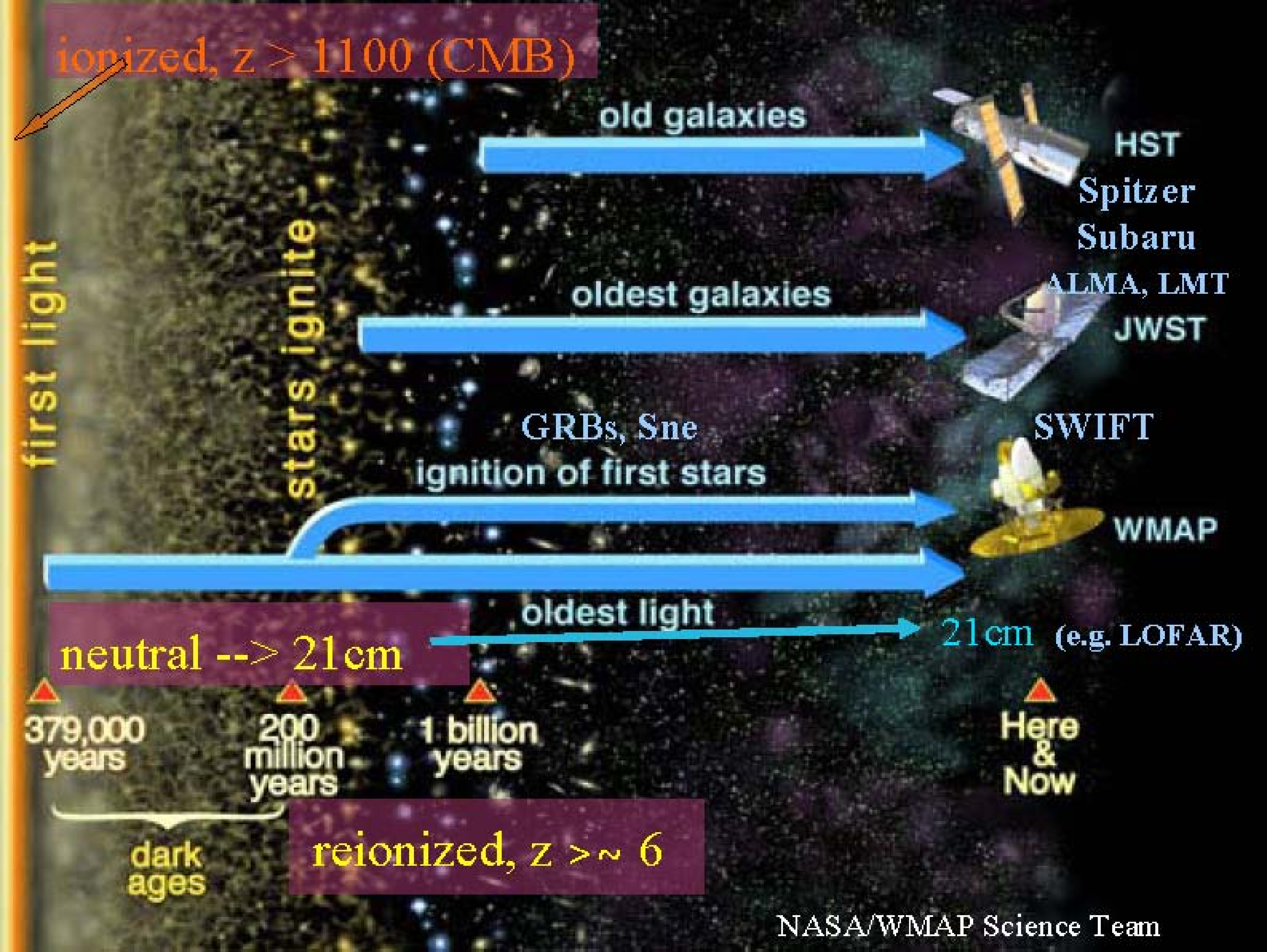
Overview:

- What is the universe made of?
- How numerical simulations model the universe
- Connecting simulations and observations
  - ***Galaxies live in halos***
  - ***Simulations link cosmology to:***
    - ***halo internal structure***
    - ***halo numbers (how many?)***
    - ***halo distribution (where?)***
  - –problems with the cosmological model
  - –model early structure formation
- Future directions – bigger & better simulations w/galaxy formation

Hubble Ultra Deep Field *HST* ▪ ACS



NASA, ESA, S. Beckwith (STScI) and The HUDF Team STScI-PRC04-07a


ionized, z > 1100 (CMB)
first light
stars ignite
old galaxies
HST
Spitzer
Subaru
ALMA, LMT
oldest galaxies
JWST
GRBs, Sne
SWIFT
ignition of first stars
WMAP
oldest light
21cm (e.g. LOFAR)
neutral --> 21cm
379,000 years
200 million years
1 billion years
Here & Now
dark ages
reionized, z >~ 6
NASA/WMAP Science Team

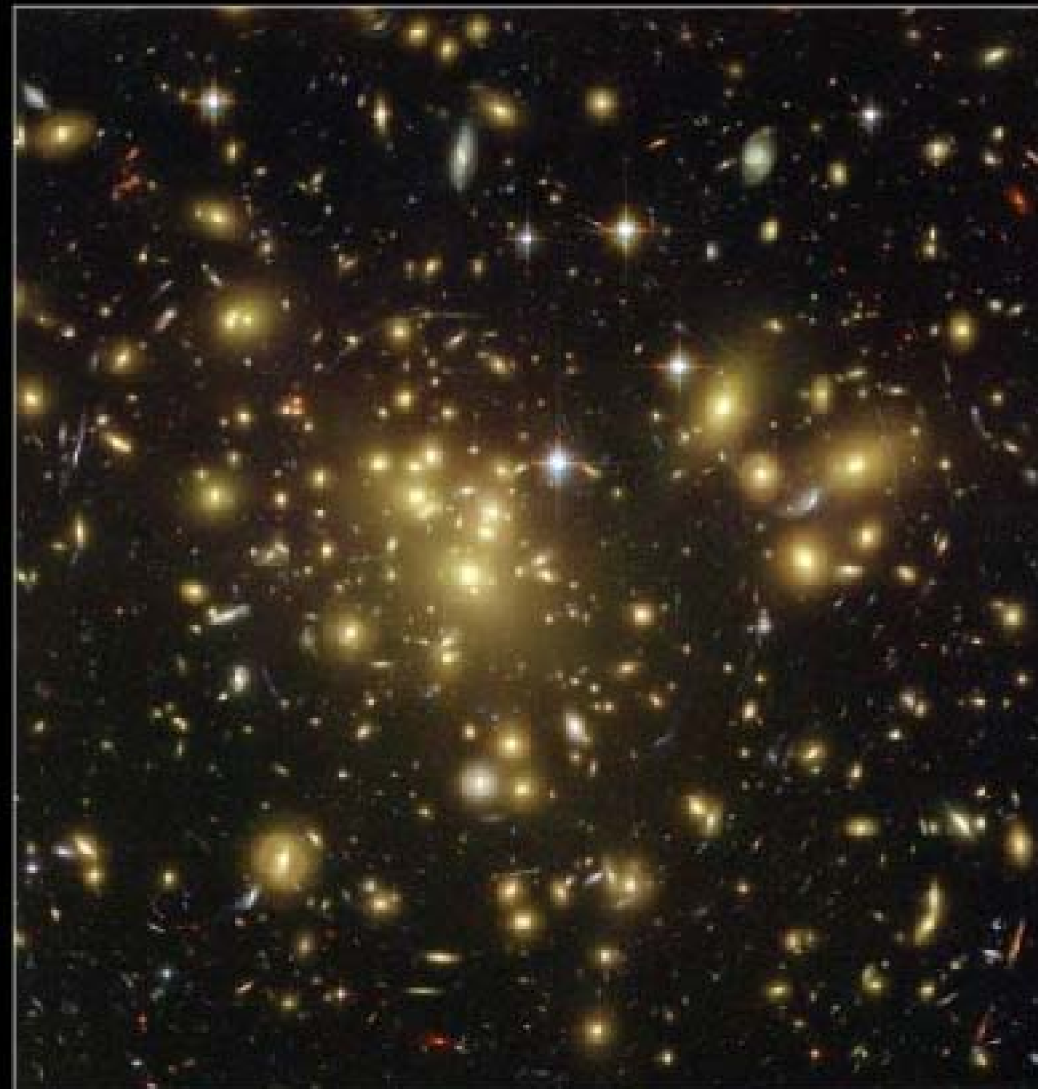
Dark matter evidence: Coma cluster, 1933

Fritz Zwicky

Measure galaxies velocities

virial mass estimate (KE=-PE/2)

--> **most mass not in galaxies**



Galaxy Cluster Abell 1689

Hubble Space Telescope • Advanced Camera for Surveys

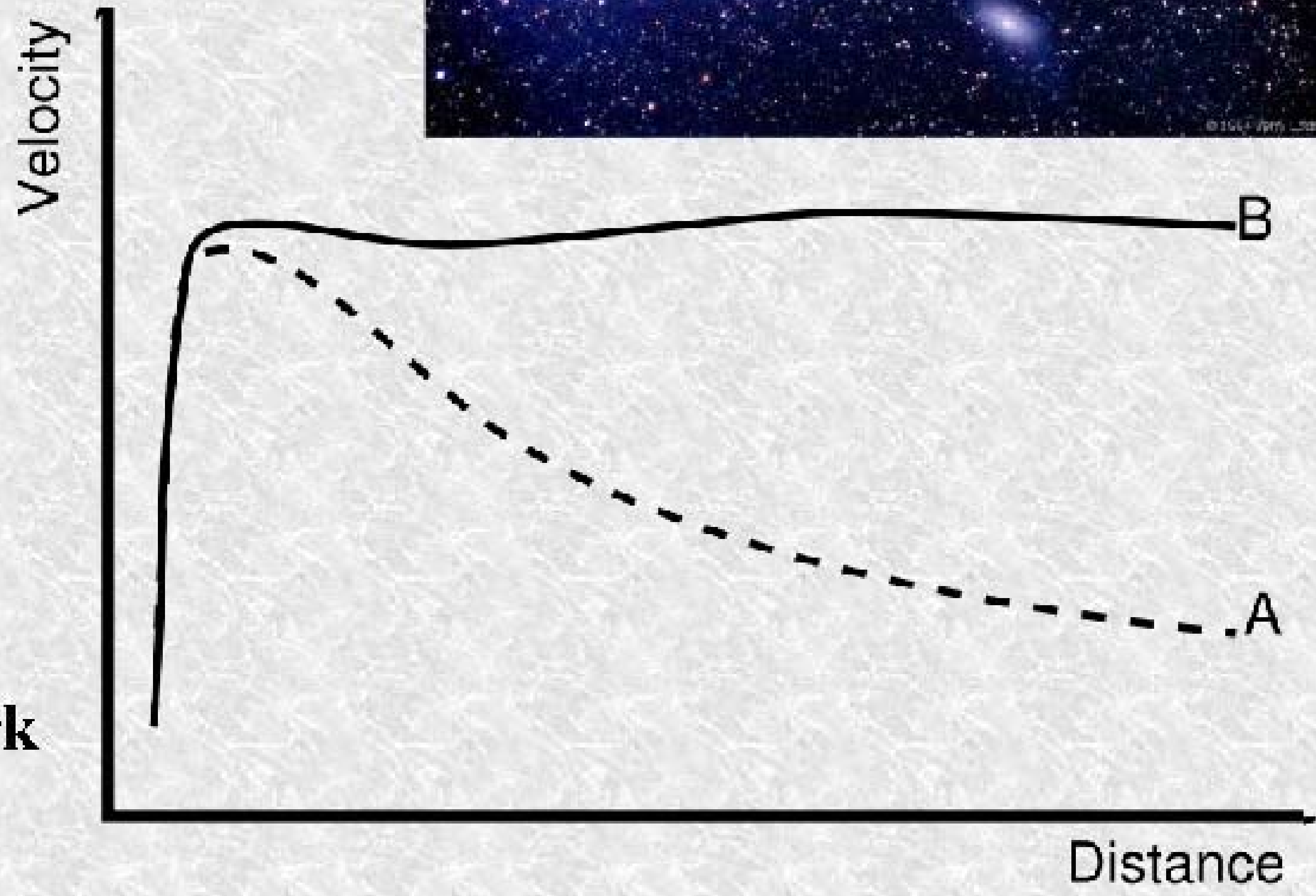
NASA, N. Benítez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin (STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA

STScI-PRC03-01a

Dark matter evidence: Spiral galaxy rotation curves

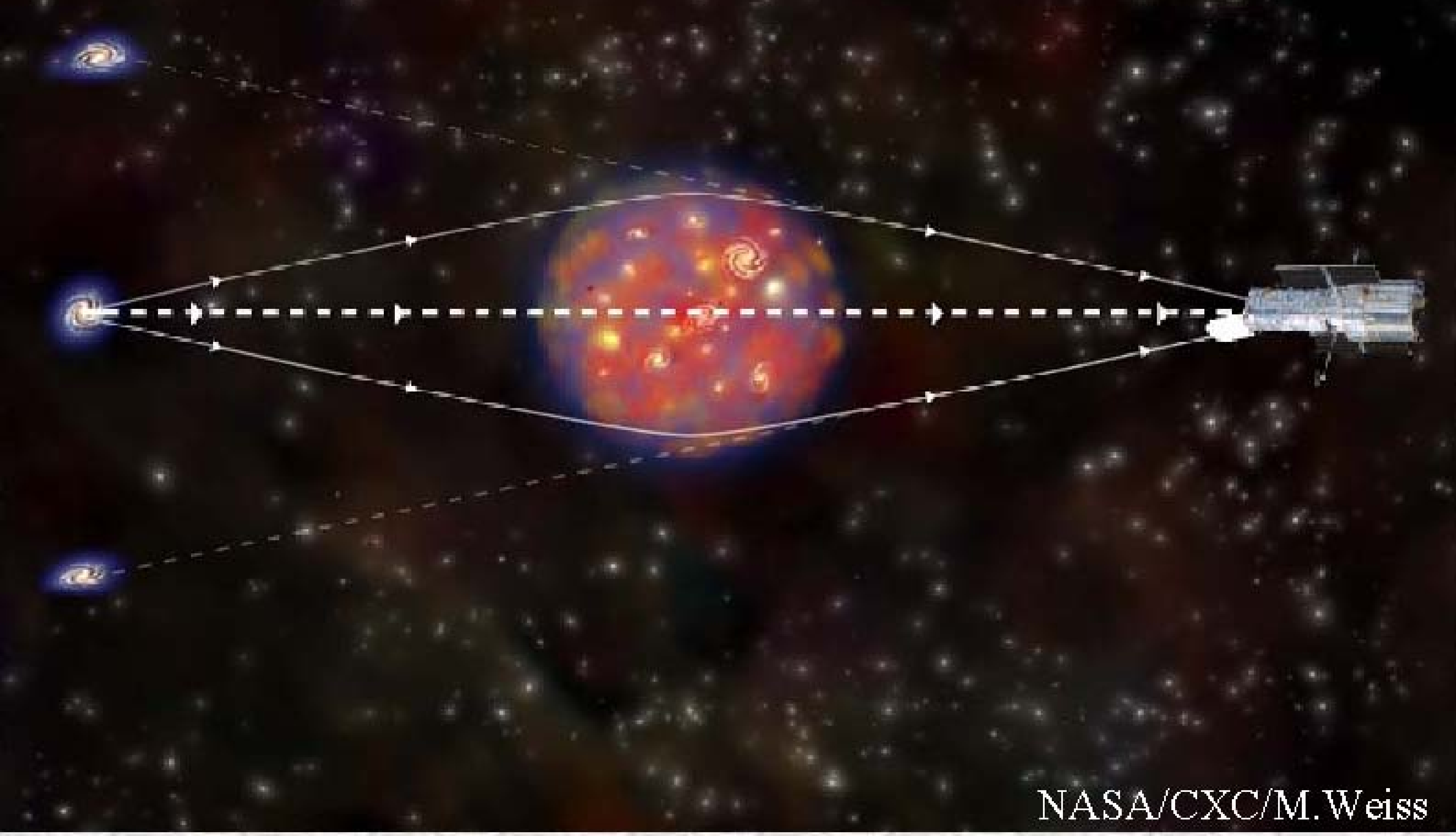
Vera Rubin

stellar velocities

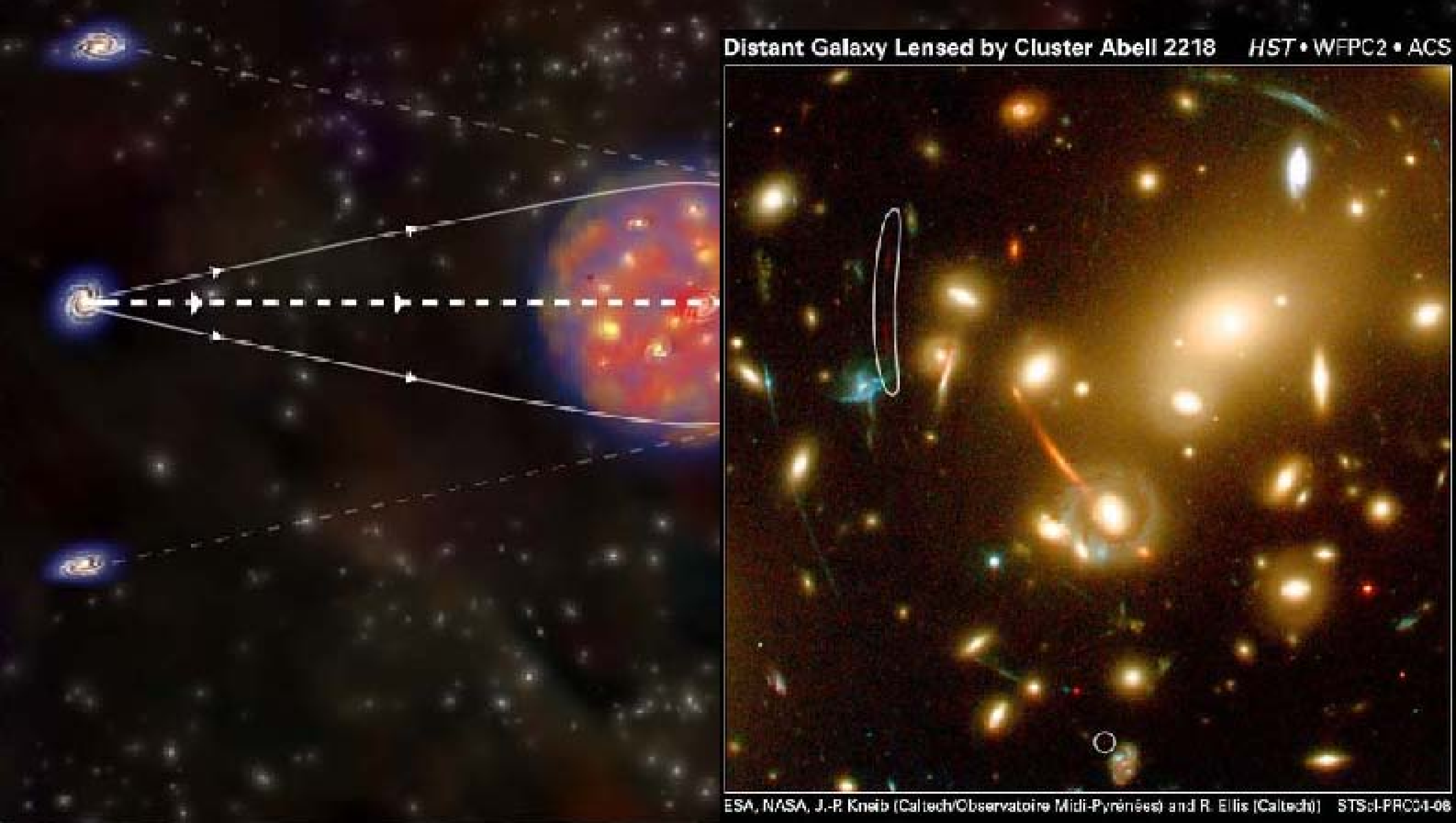


⇨ **most mass in galaxies is dark**

gravitational lensing → mass distribution



gravitational lensing → mass distribution



Dark matter evidence: Bullet cluster, 2006

Red = hot gas

(≅ baryon mass)

x-ray (thermal bremsstrahlung)

Blue = mass (total)

gravitational lensing of

background galaxies

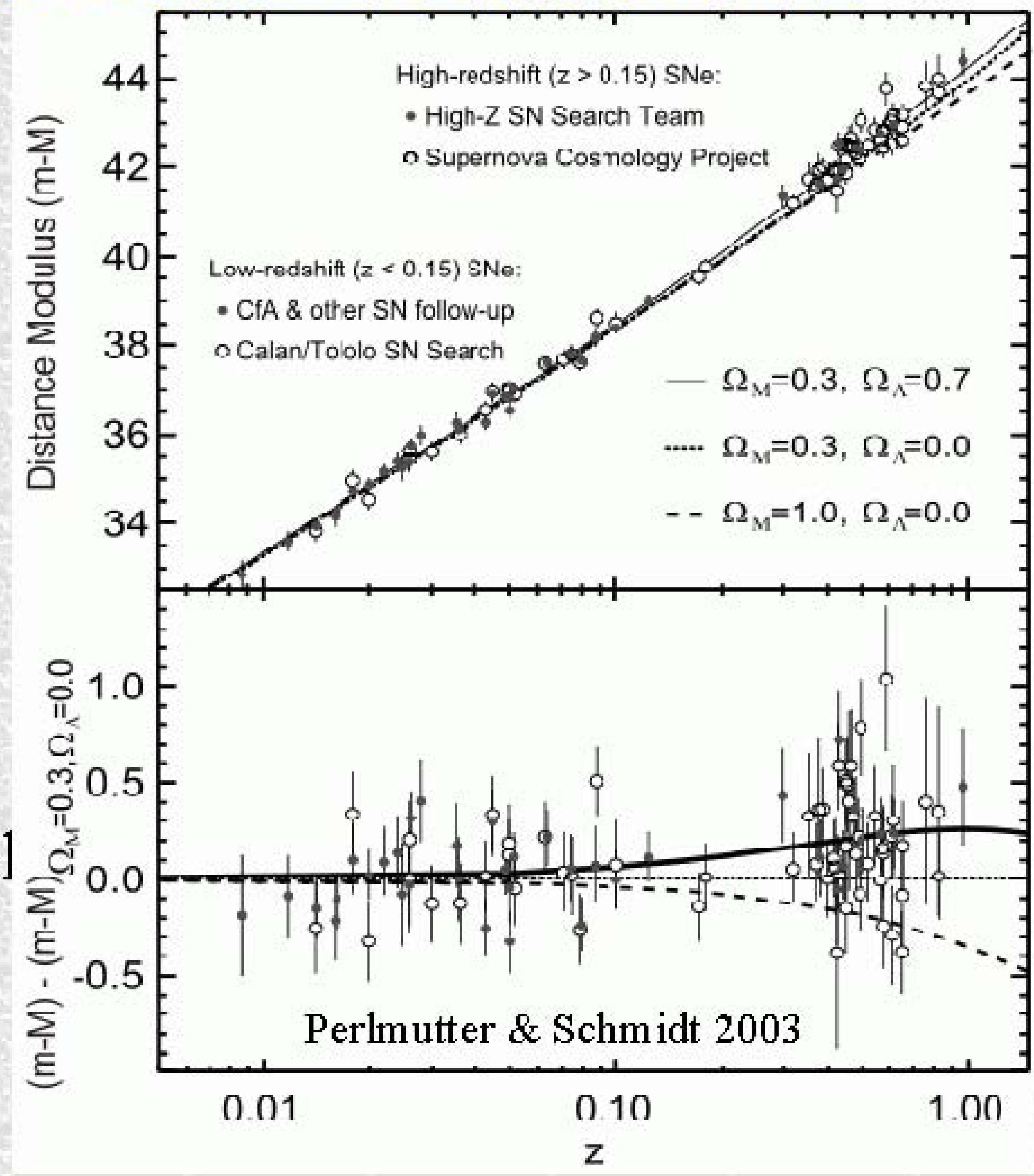
NASA/Clowe et al. (2006)

non-baryon (dark matter)

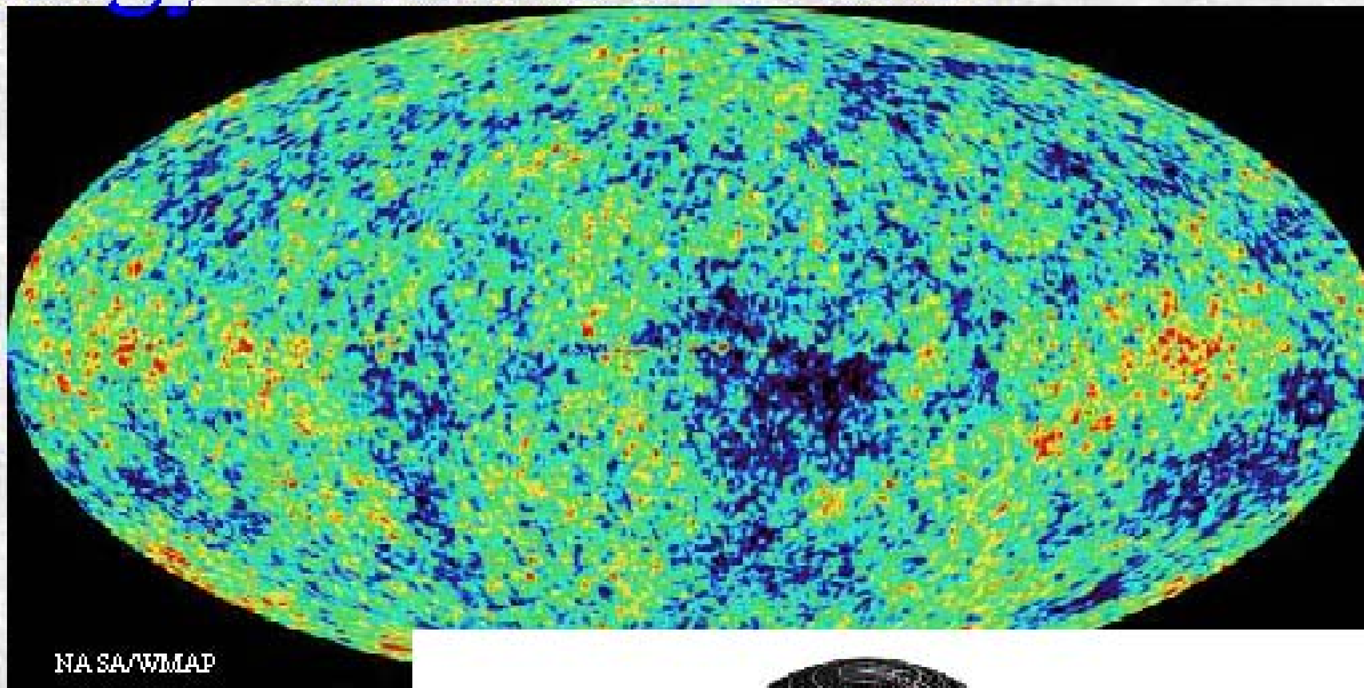
dominates mass distribution

Dark energy evidence: supernovae

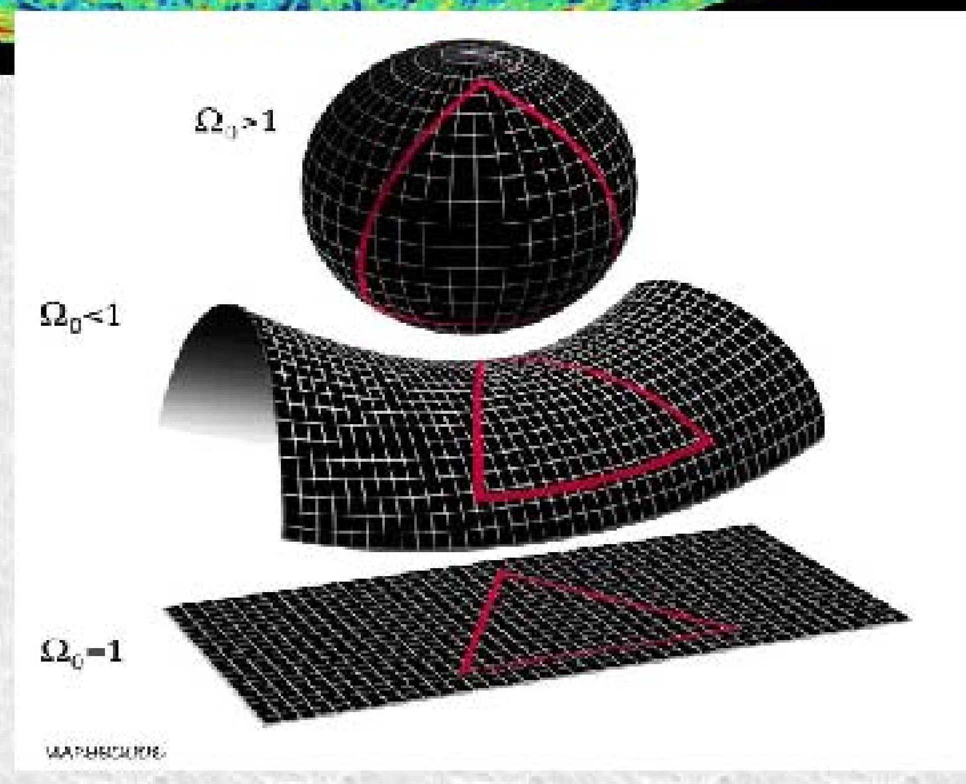
- Riess et al. 1998, Perlmutter et al.
- Distant supernova too faint
- Consistent with Einstein's cosmological constatnt



Dark energy evidence: CMB

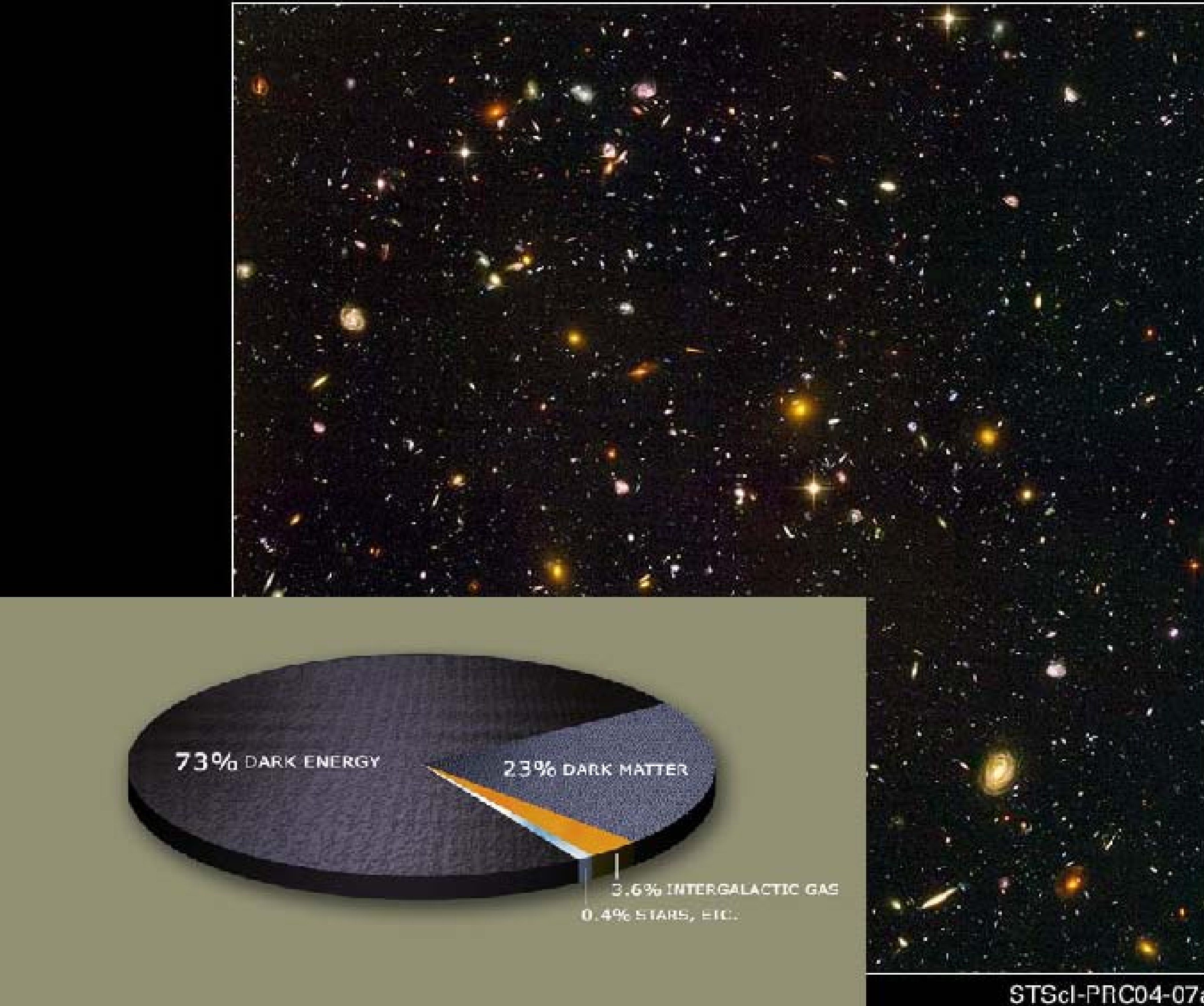


- Fluctuation scale sensitive to geometry
- CMB: universe is "flat", $\Omega_m + \Omega_{d.e.} = 1$



Hubble Ultra Deep Field

HST ▪ ACS

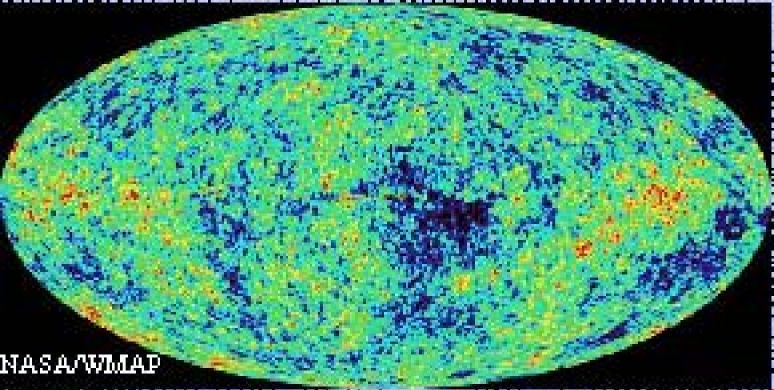


STScI-PRC04-07a

What is the dark matter?

- Dark
- $\Omega_{d.m} \simeq 0.25 \quad \Omega_{baryon} \simeq 0.04$
- ~Collisionless
- Cold (or warm), non-relativistic at freeze-out
- WIMP, axion, sterile neutrino.......

Simulation Techniques



\+ Hi-z SNe, CMB, etc

Cosmological parameters:
($\Omega \simeq 0.25$, $\Lambda \simeq 0.75$, $\sigma_8 \simeq 0.8$, $H_0 \simeq 72$, $n_s \simeq 1$)

σ_8: amplitude of power spectrum,
(rms mass fluctuation of 8 Mpc/h spheres)

Initial conditions:
High z
(early, linear)
gaussian
random
realization

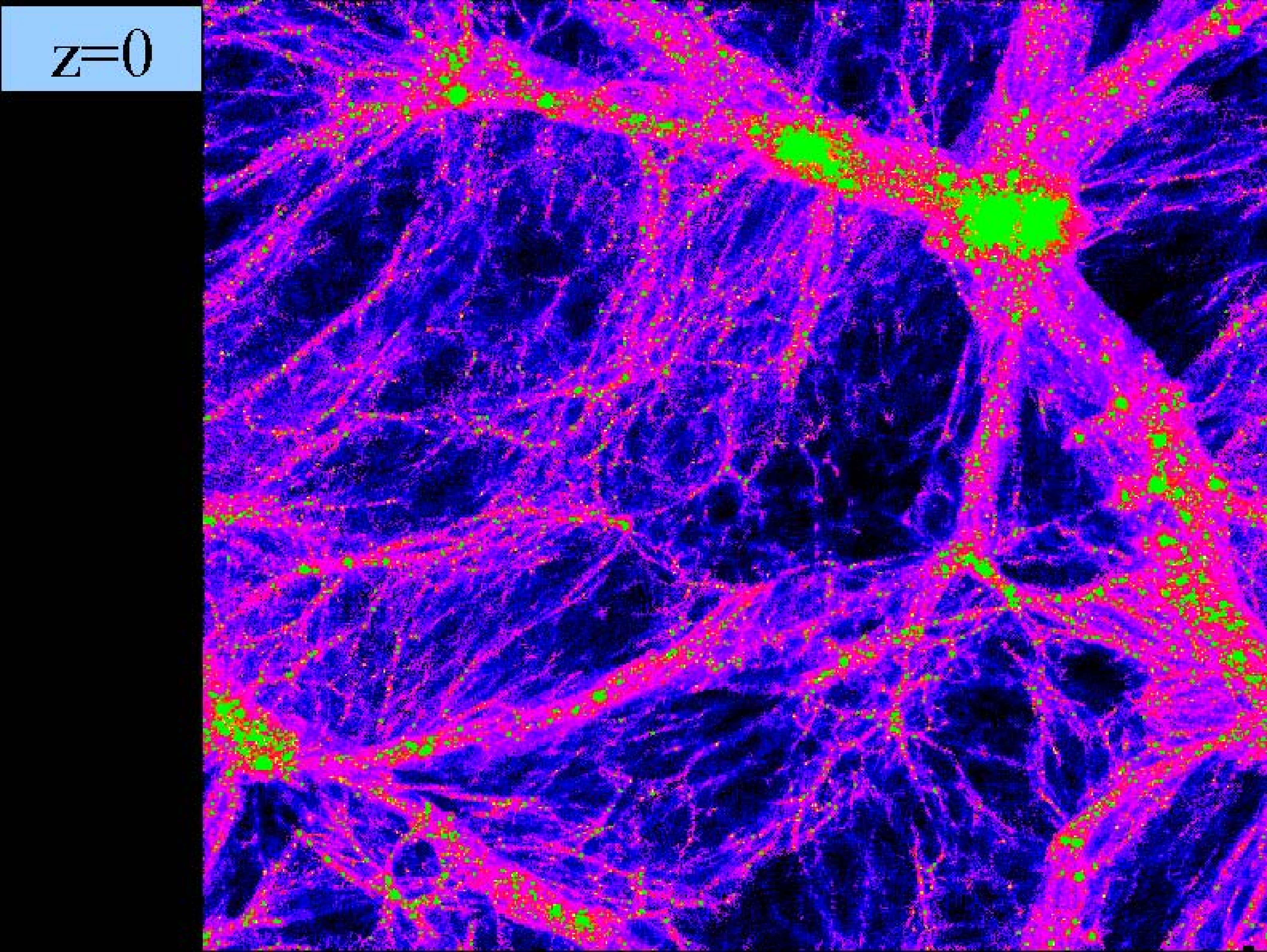
Evolve particles
(gravity)
L-GADGET2
(PM-tree code V. Springel)
GASOLINE
(Stadel, Wadsley, Quinn)

- *Simulation:*

  An imitation; a sham.

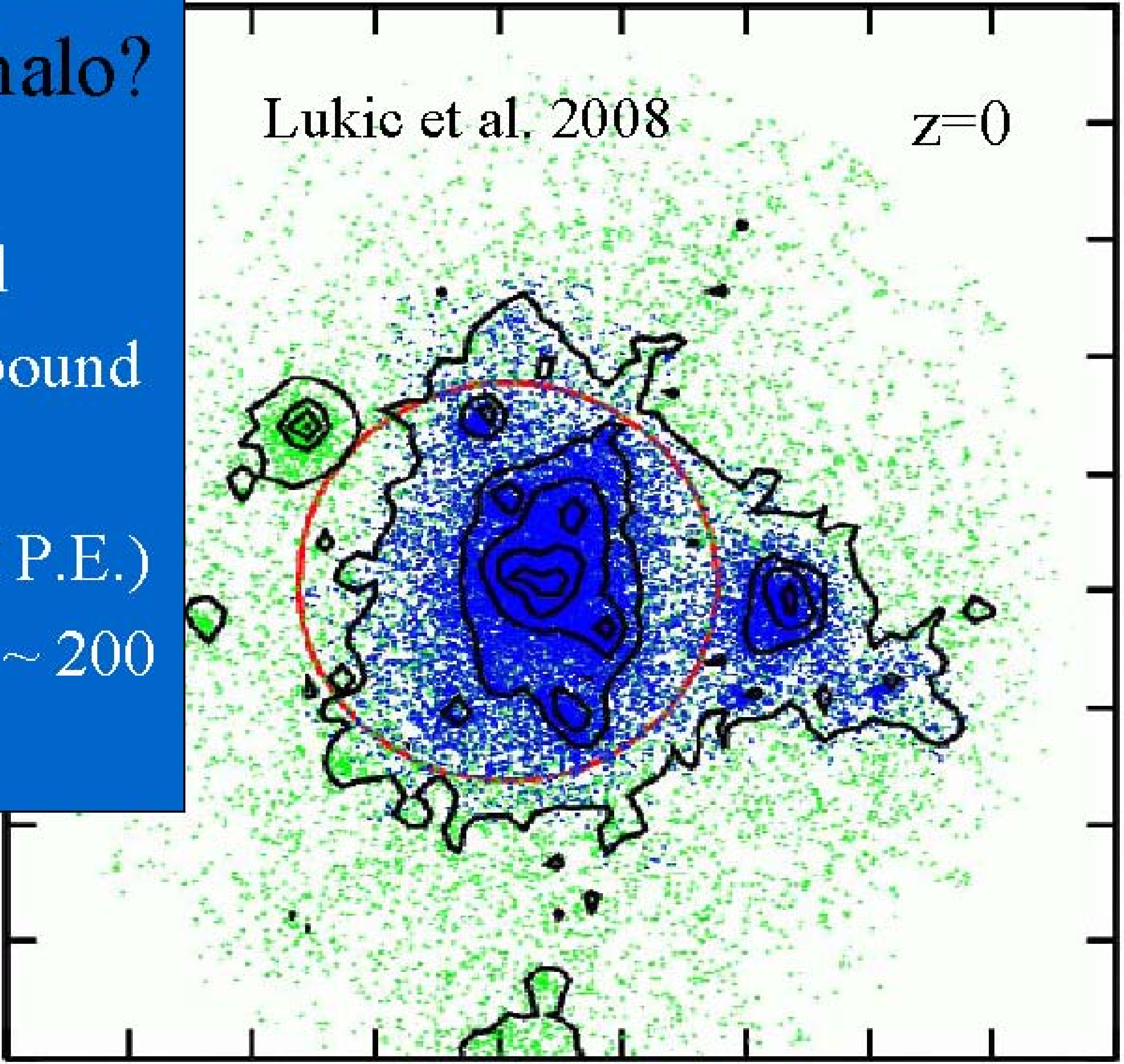
  Assumption of a false appearance.

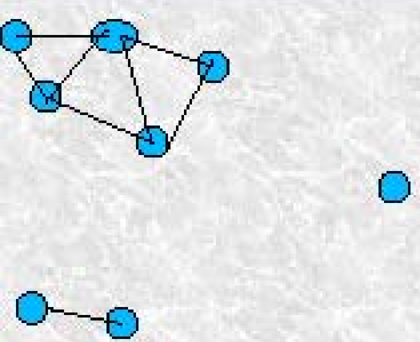
  (American Heritage Dictionay)

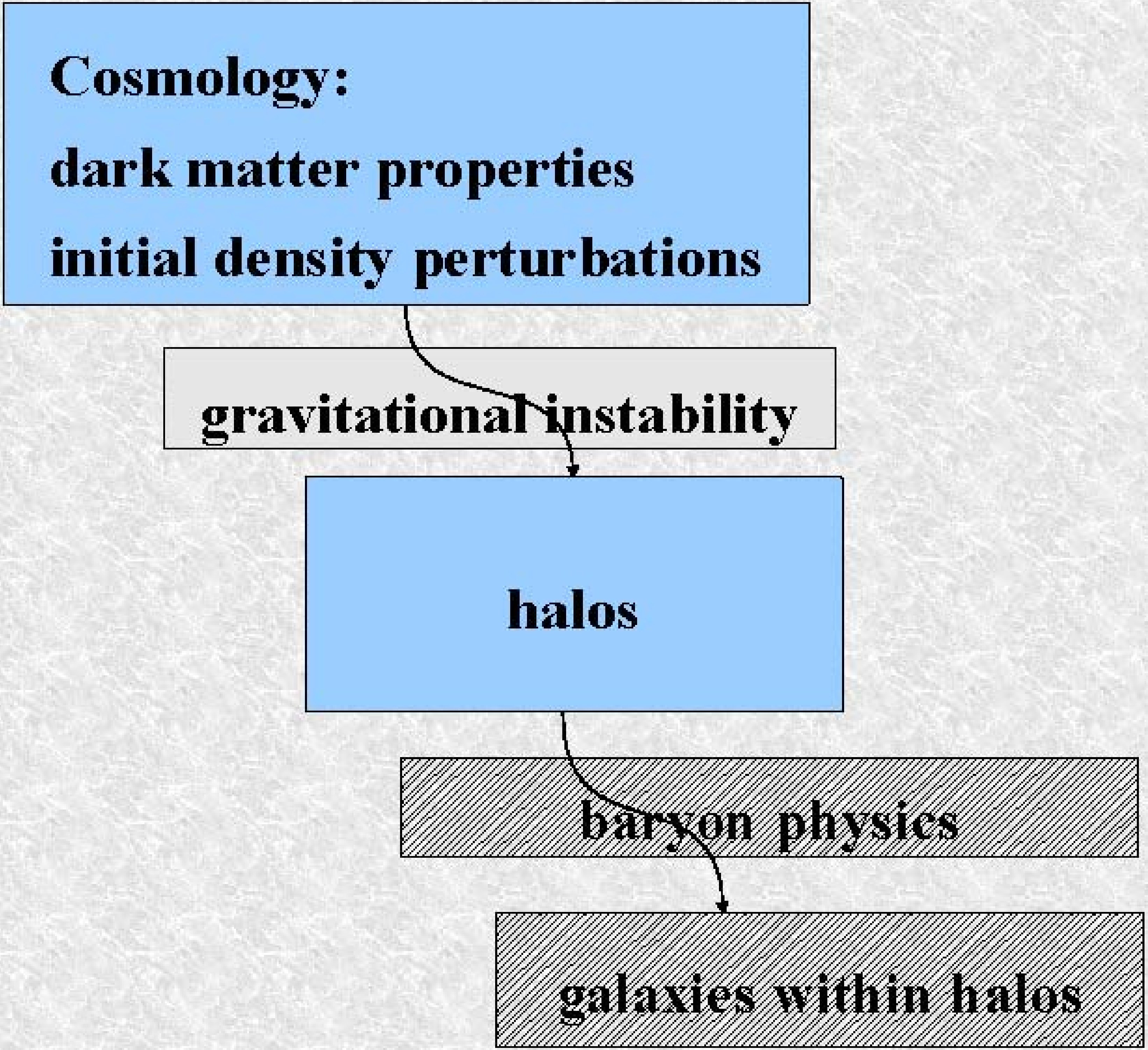

z=0

What is a halo?

- Grow from gravitational instability, bound
- Viralized (K.E. = -1/2 P.E.)
- overdensity ~ 200






Cosmology:
dark matter properties
initial density perturbations
gravitational instability
halos
baryon physics
galaxies within halos

Halos as a cosmological probe

internal structure: satellite numbers, density profiles

numbers: e.g. halo numbers vs. cluster numbers

clustering: halo bias relates observable galaxies to underlying mass distribution (p(k))

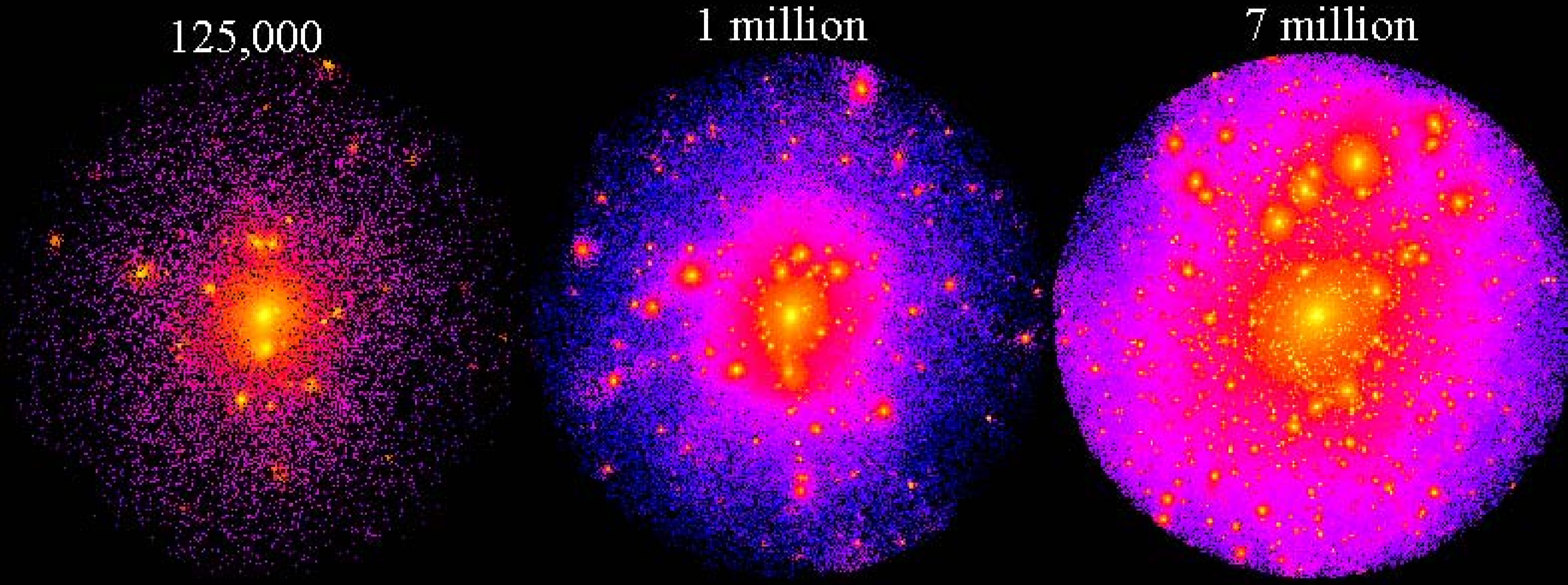
Internal halo structure: motivations

- -Probe fluctuation spectrum on ***small scales***
- ***Dark matter probe***
  - Subhalos- satellites, gravitational lensing
  - Density profiles-- rotation curves, grav. lensing, X-ray

Dark matter annihilation(?)

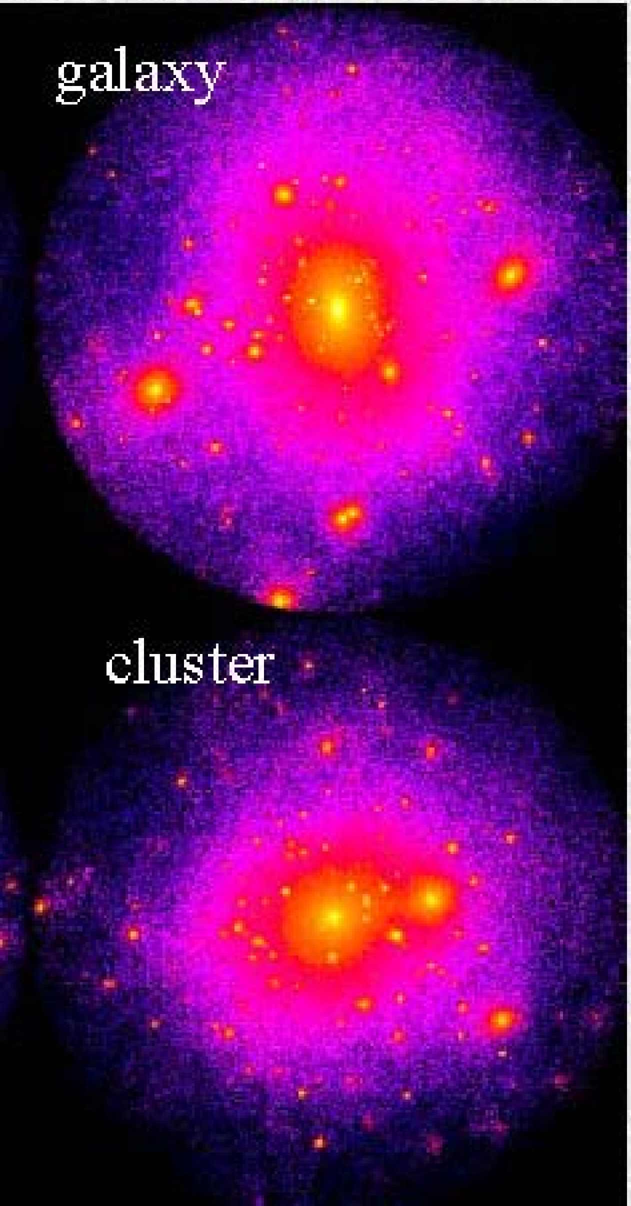
Effects of halo to halo variations

Resolution Issues:

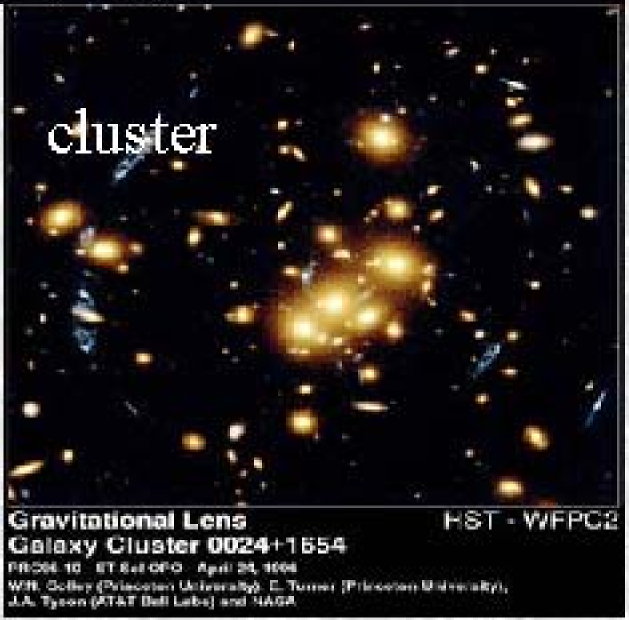


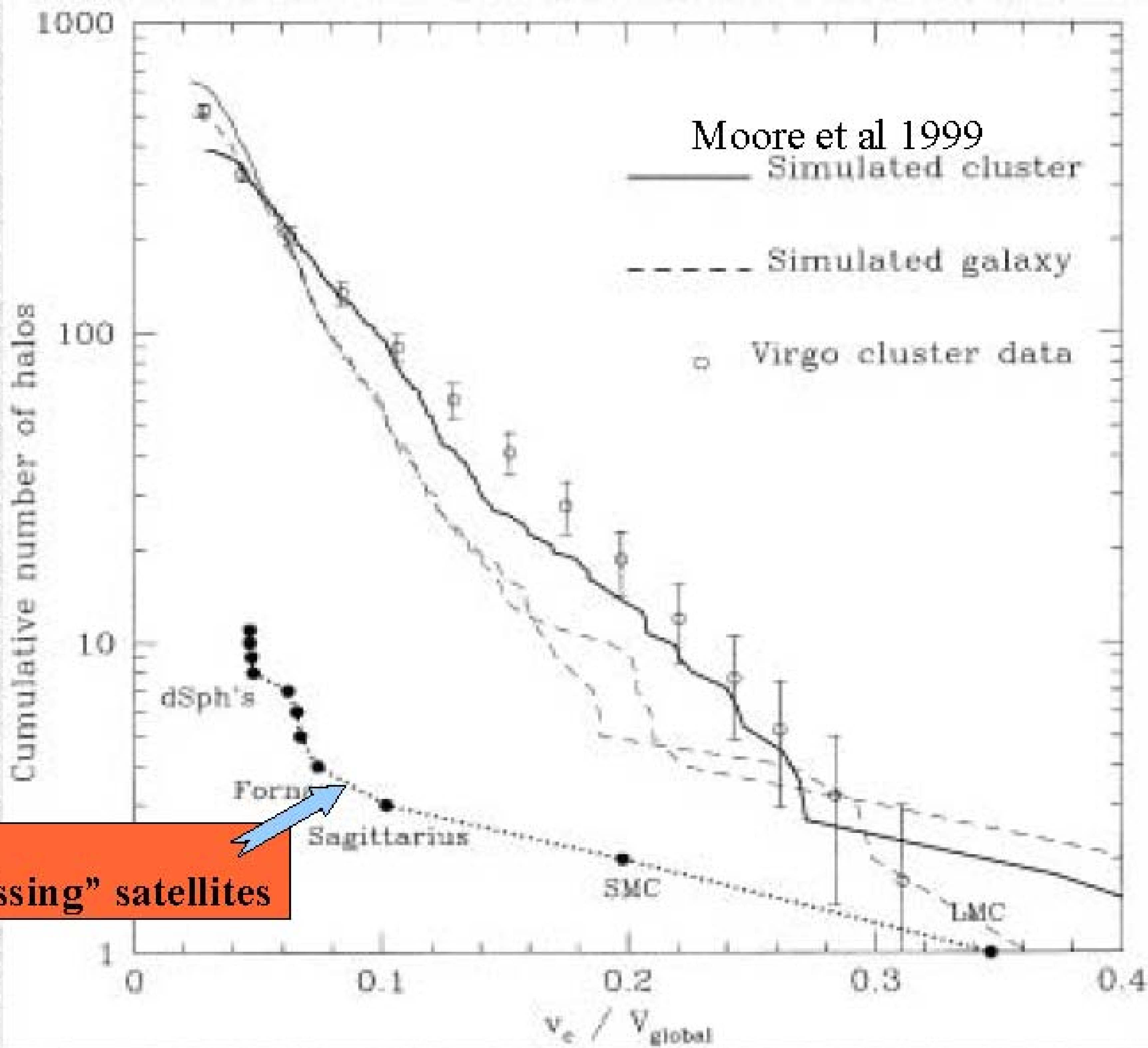
a CDM crisis
"missing" local group satellite galaxies

Simulated Halos

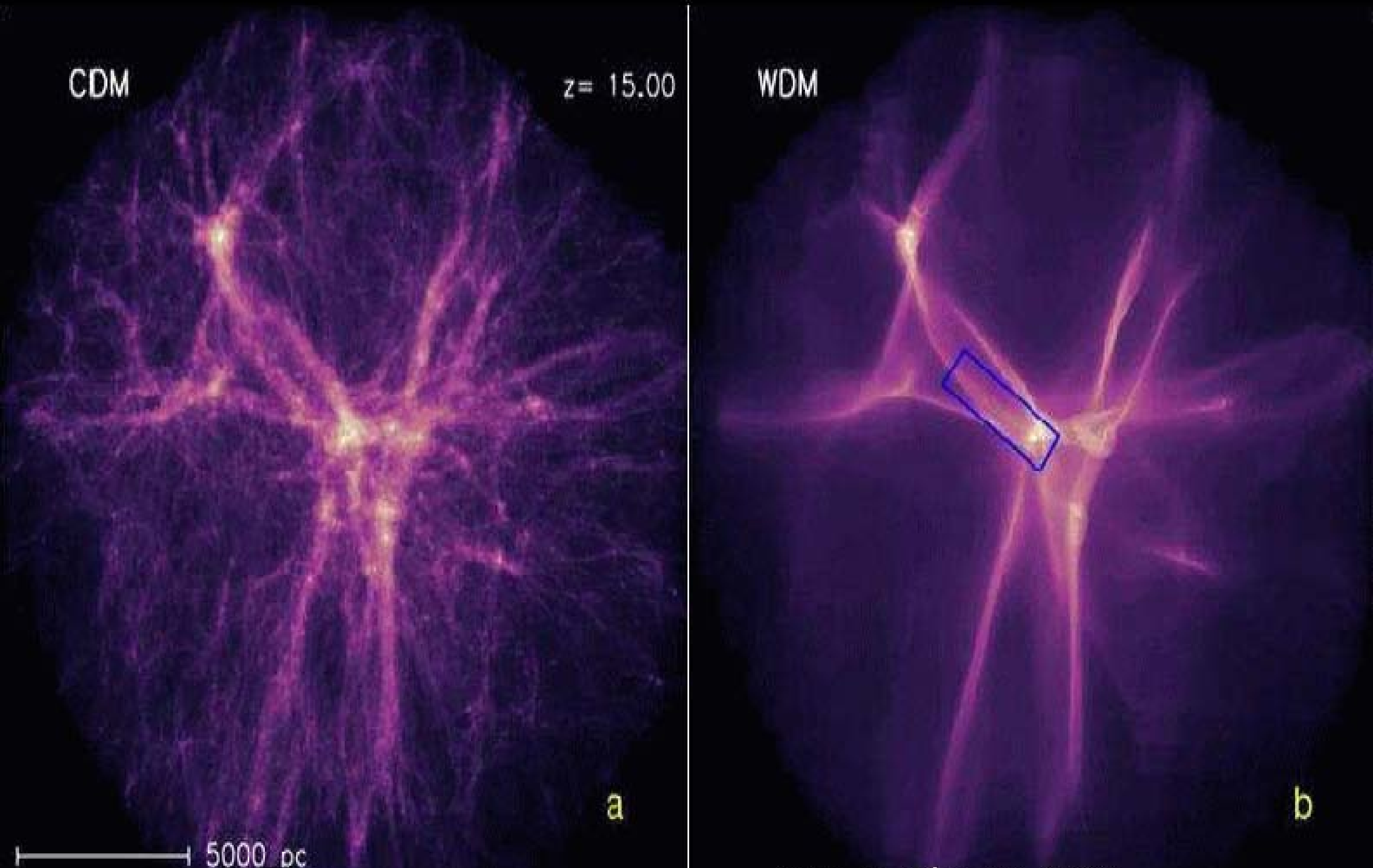


Real Halos




Moore et al 1999
Simulated cluster
Simulated galaxy
Virgo cluster data
dSph's
Forna
Sagittarius
SMC
LMC
"missing" satellites
Cumulative number of halos
1000
100
10
1
0
0.1
0.2
0.3
0.4
v_c / V_{global}

Cold Dark Matter   Warm Dark Matter



Gao & Theuns 2007

2 possible solutions to missing satellites

1-Warm dark matter

2-Most subhalos did not form stars due to "gas heating"

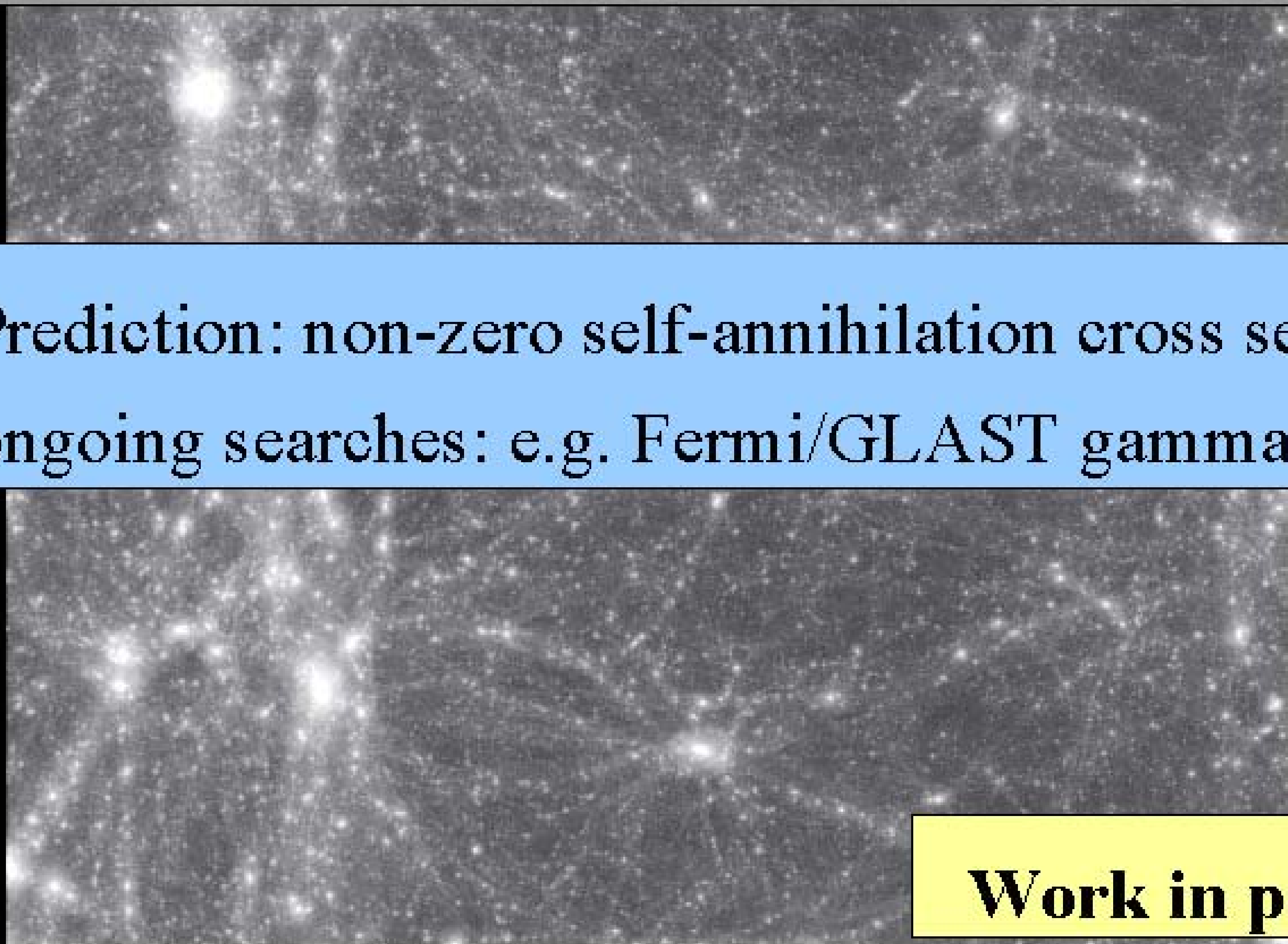
Early times

Reionization/ UV background

Supernovae

➡ Need to understand star/galaxy formation especially at early stages (out to reionization era)

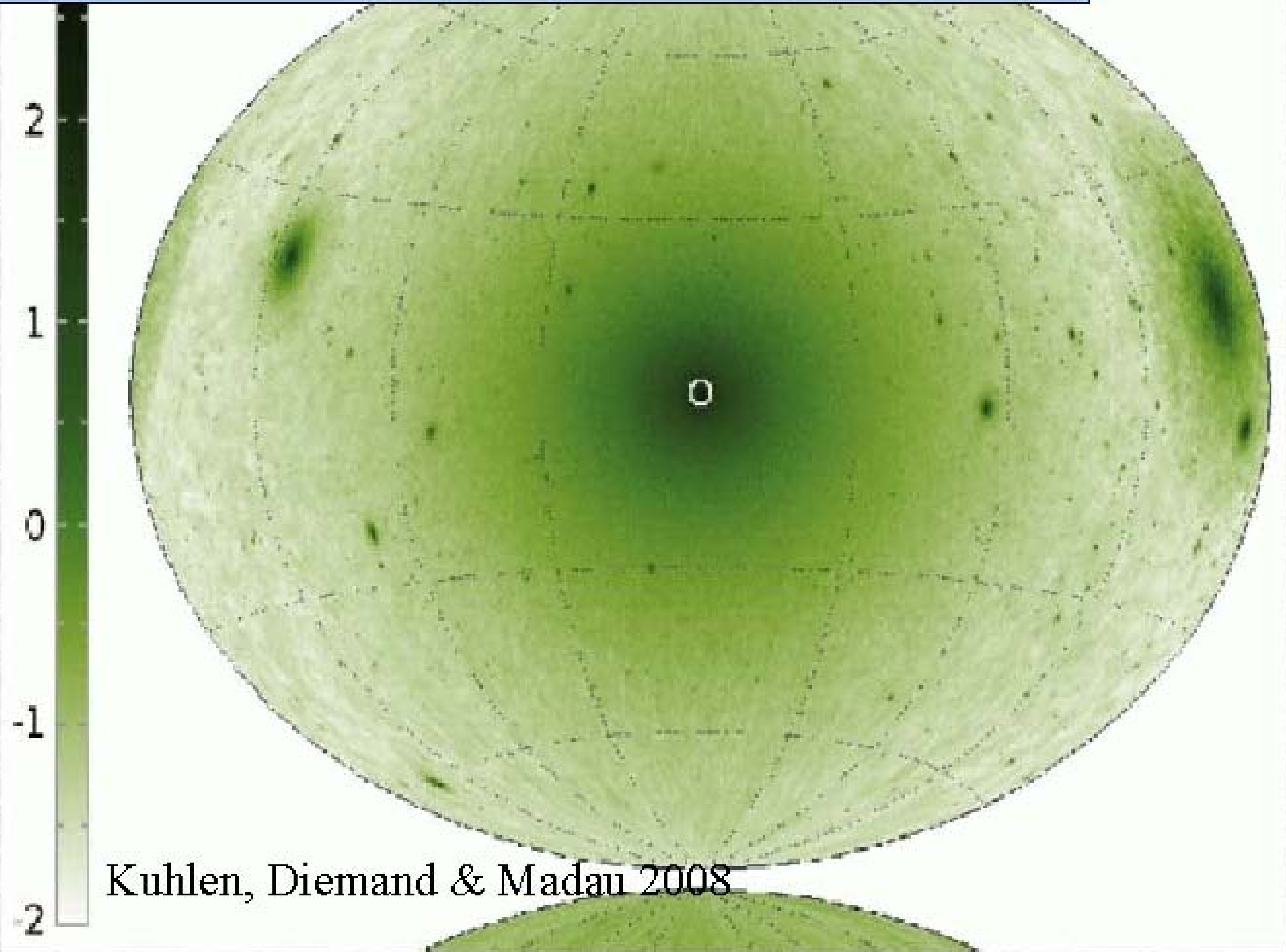
Non-universality of halo mass profile & implications for dark matter self-annihilation detection



Prediction: non-zero self-annihilation cross section
ongoing searches: e.g. Fermi/GLAST gamma-ray

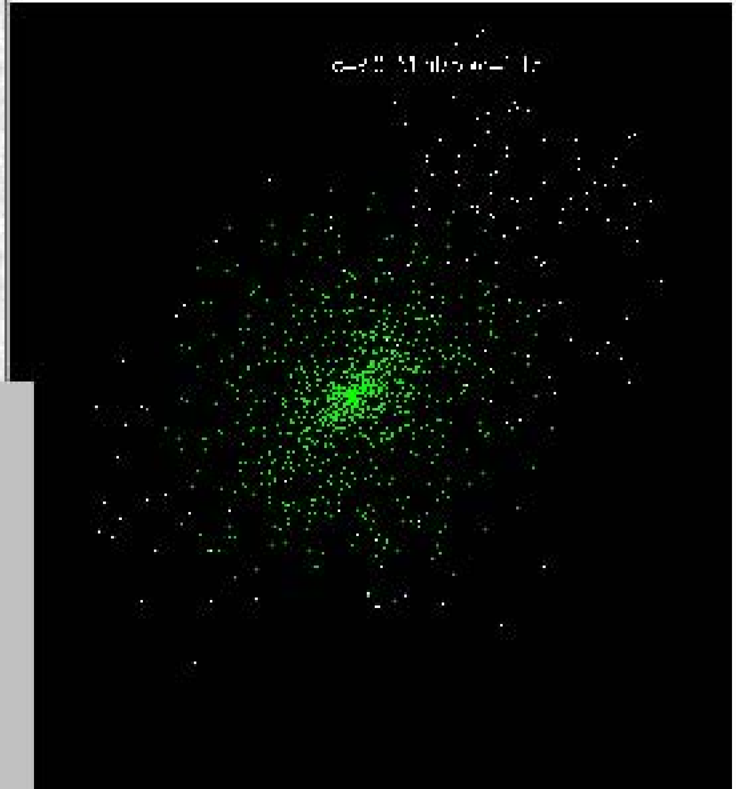
Work in progress

Predicted annihilation signal from Milky Way assuming Luminosity α ρ^2

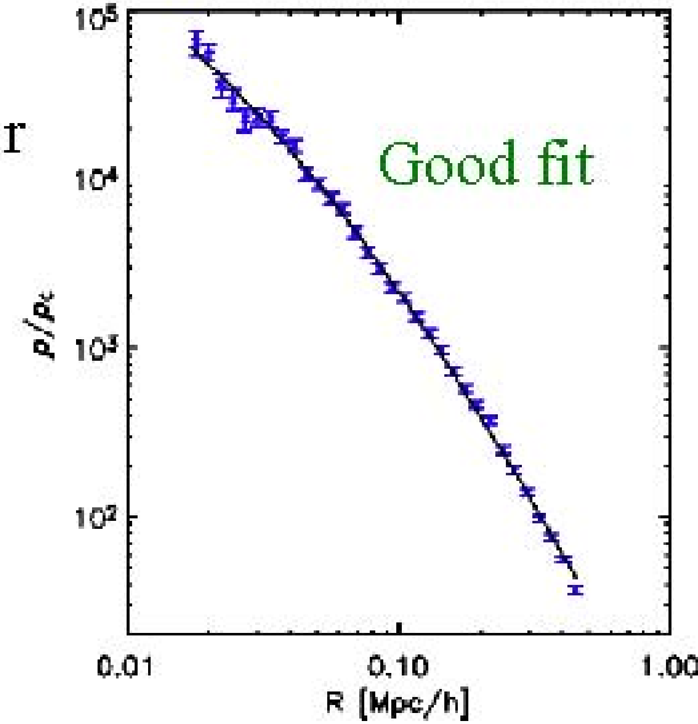


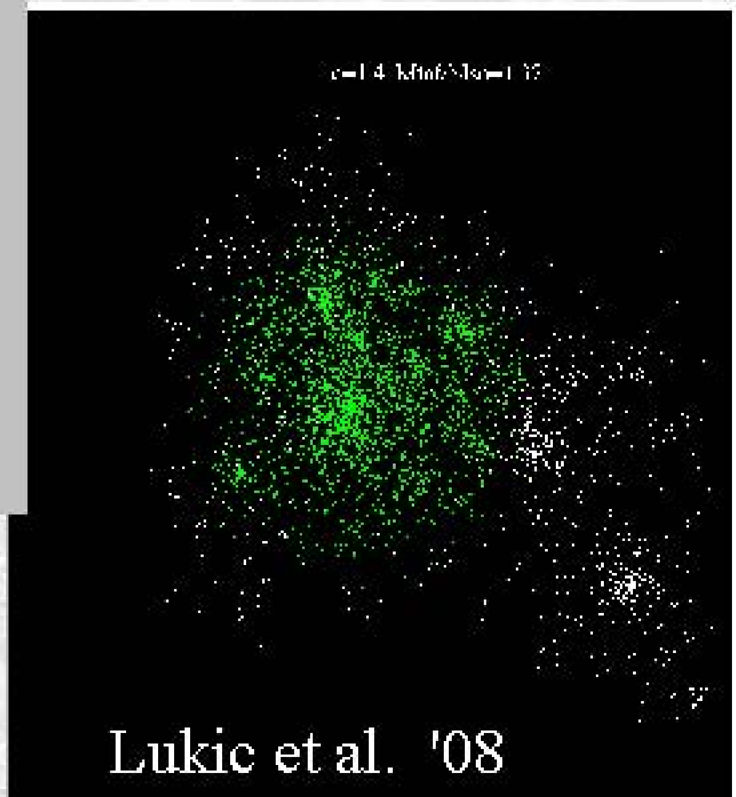
Halo to halo scatter

--> strong variation in d.m. annihilation

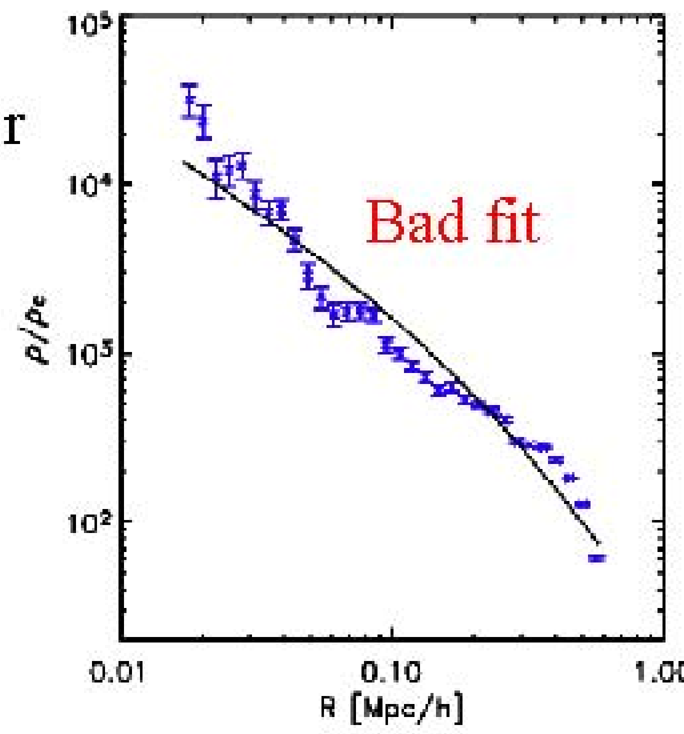


ρ vs r





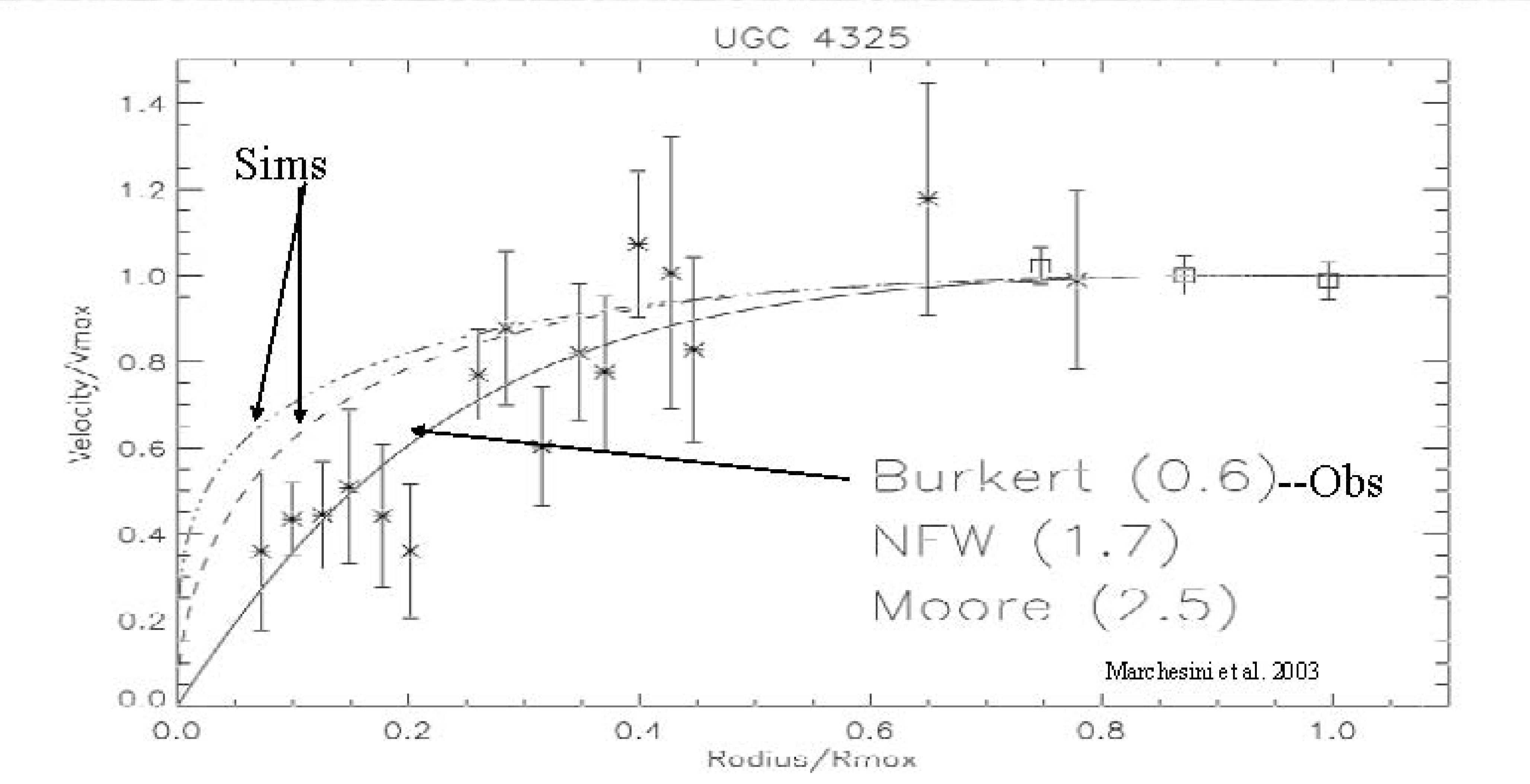
ρ vs r



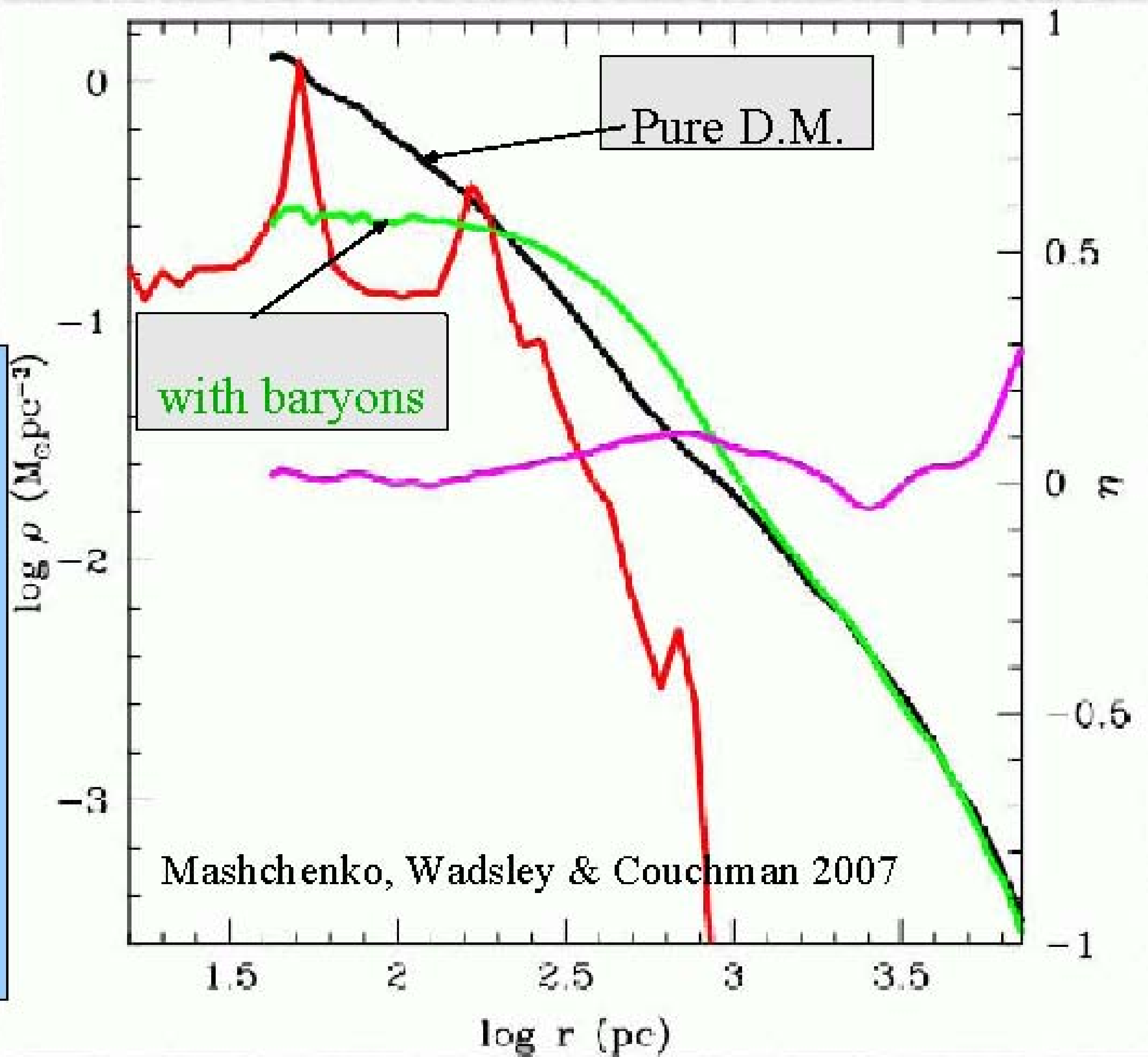
Another **CDM crisis**

low density "cores" in many small galaxies

vs CDM simulation high density "cusps": $V_c = (GM/R)^{1/2}$



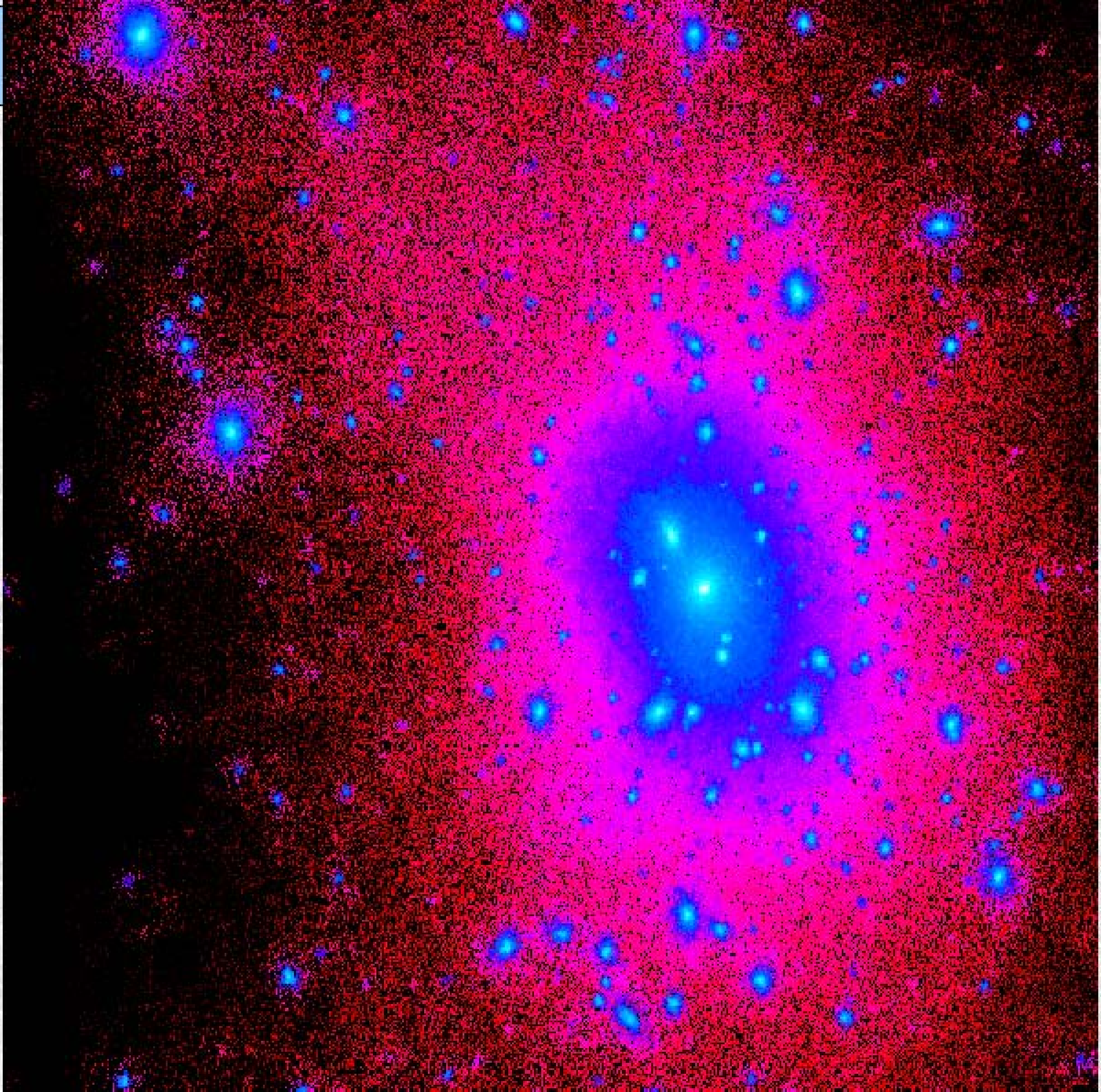
Can early star formation lower central density?



Solution?

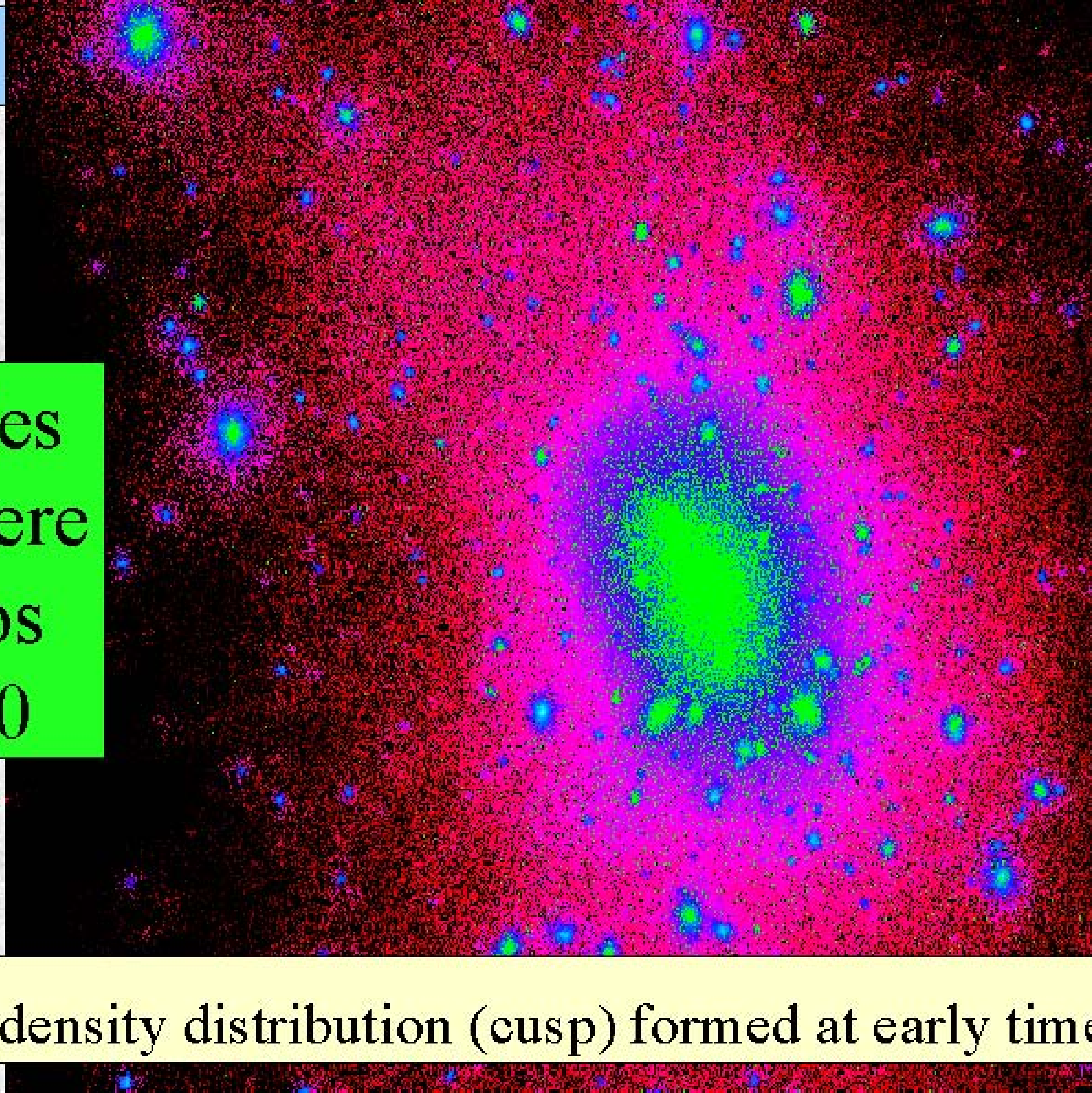
Star/galaxy formation "sloshing" by supernova "feedback" transforms cusps into cores?

z=0



z=0

particles that were in halos at z=10



central density distribution (cusp) formed at early times

Utilizing the high redshift dark universe [z >~ 5]

-compare galaxy numbers to halo numbers

-compare galaxy clustering with halo clustering

--probe **cosmology** (e.g. D.M. type)

--probe **galaxy formation physics** (e.g. Sne)

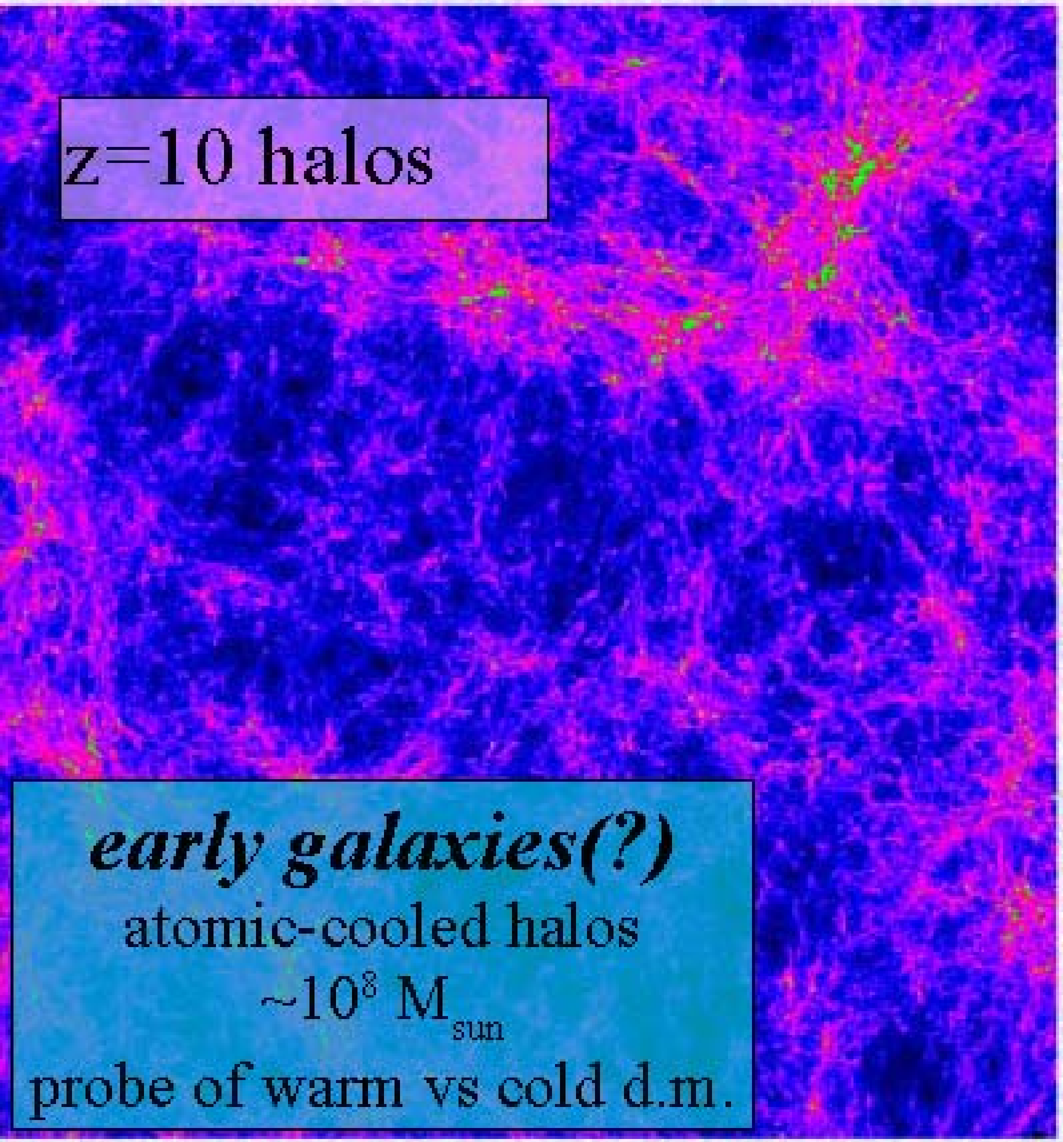
Halos as a cosmological probe

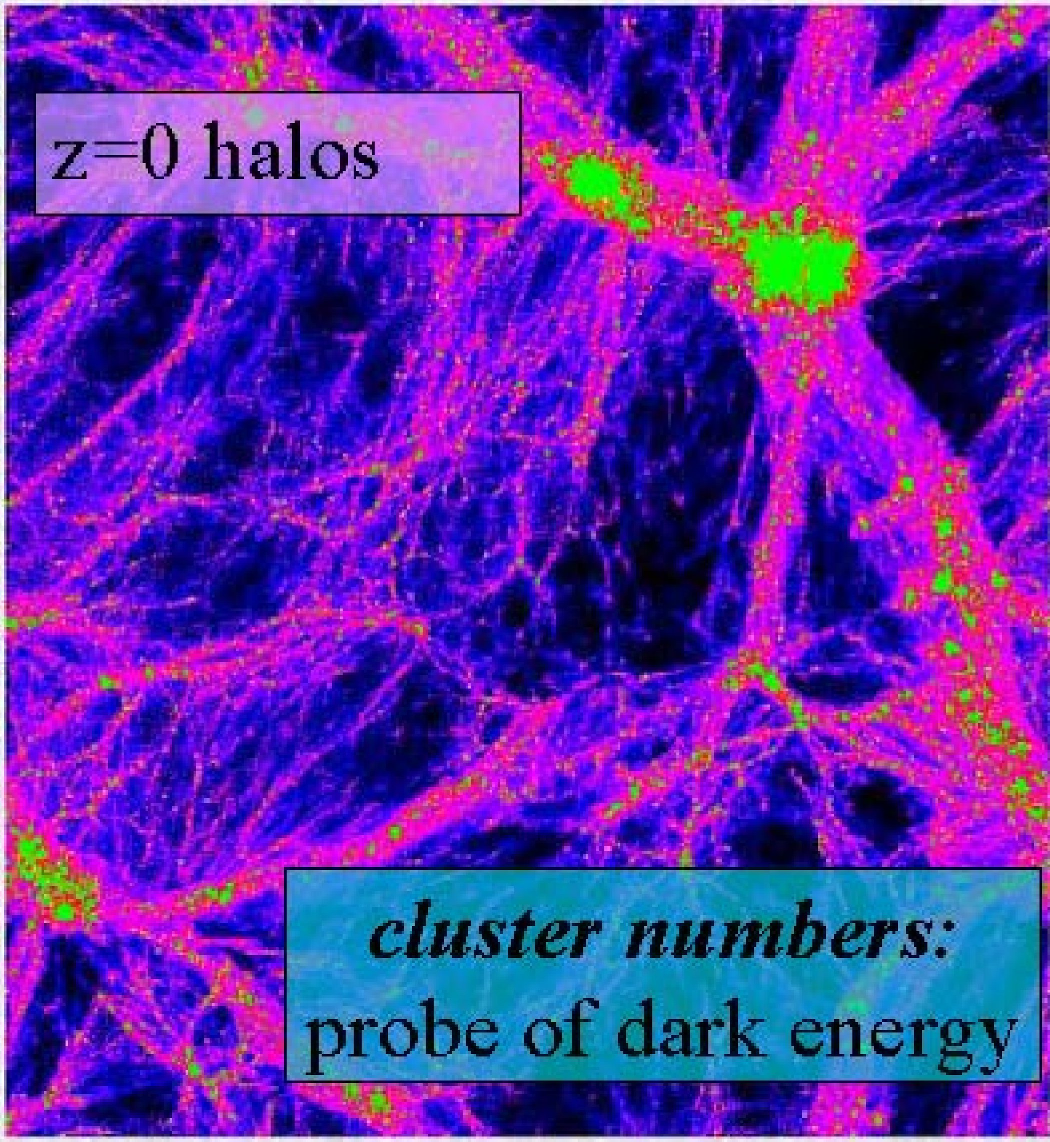
internal structure: satellite numbers, density profiles

numbers: e.g. halo numbers vs. galaxy numbers

clustering: halo bias relates observable galaxies to underlying mass distribution (p(k))

halo mass function: n(m,z)

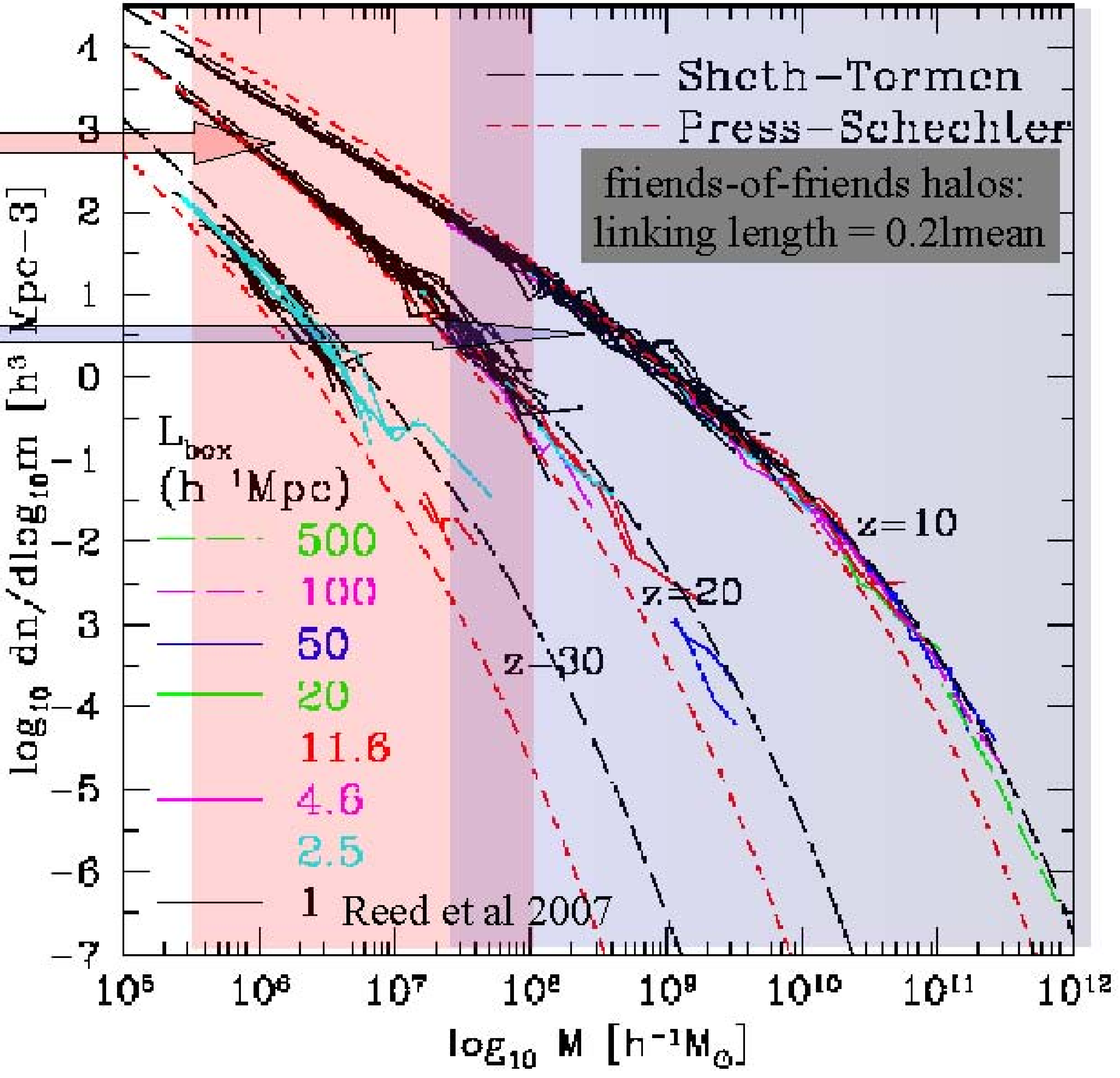


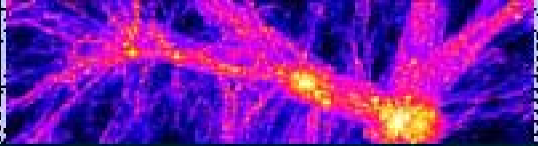


1st stars
H_2-cooled halos

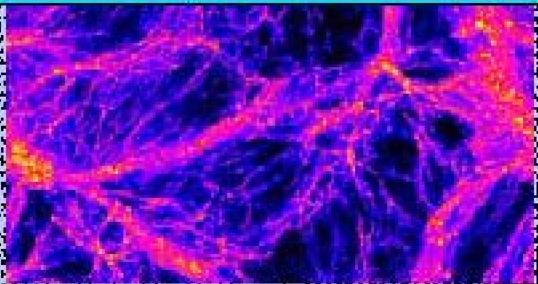
1st galaxies
atomic-cooled halos

comoving abundance

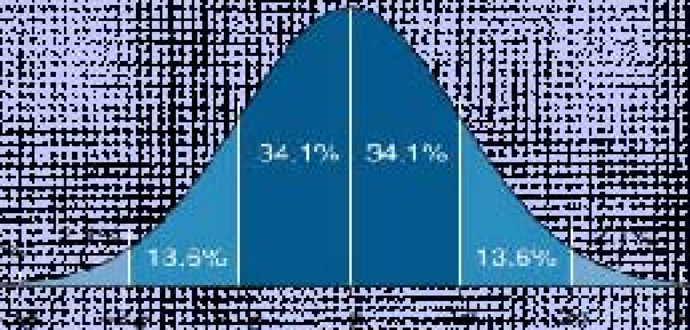




Simulations: convert linear density field to (non-linear) halos

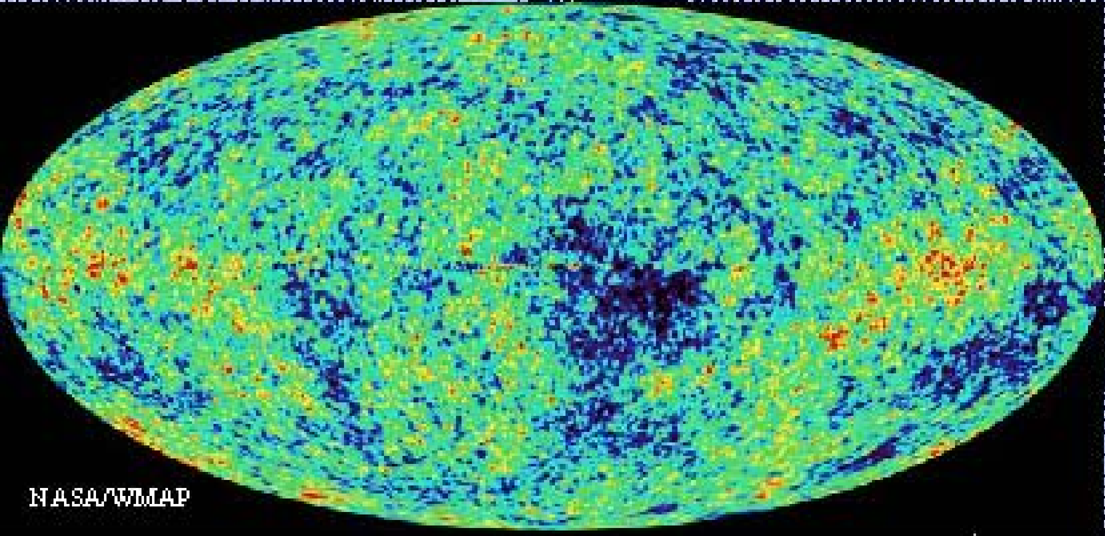


cosmology → linear gaussian random fluctuation field



"predict" halo numbers, clustering as function of cosmology

"universal":
all redshifts, all masses
(Jenkins et al 2001)



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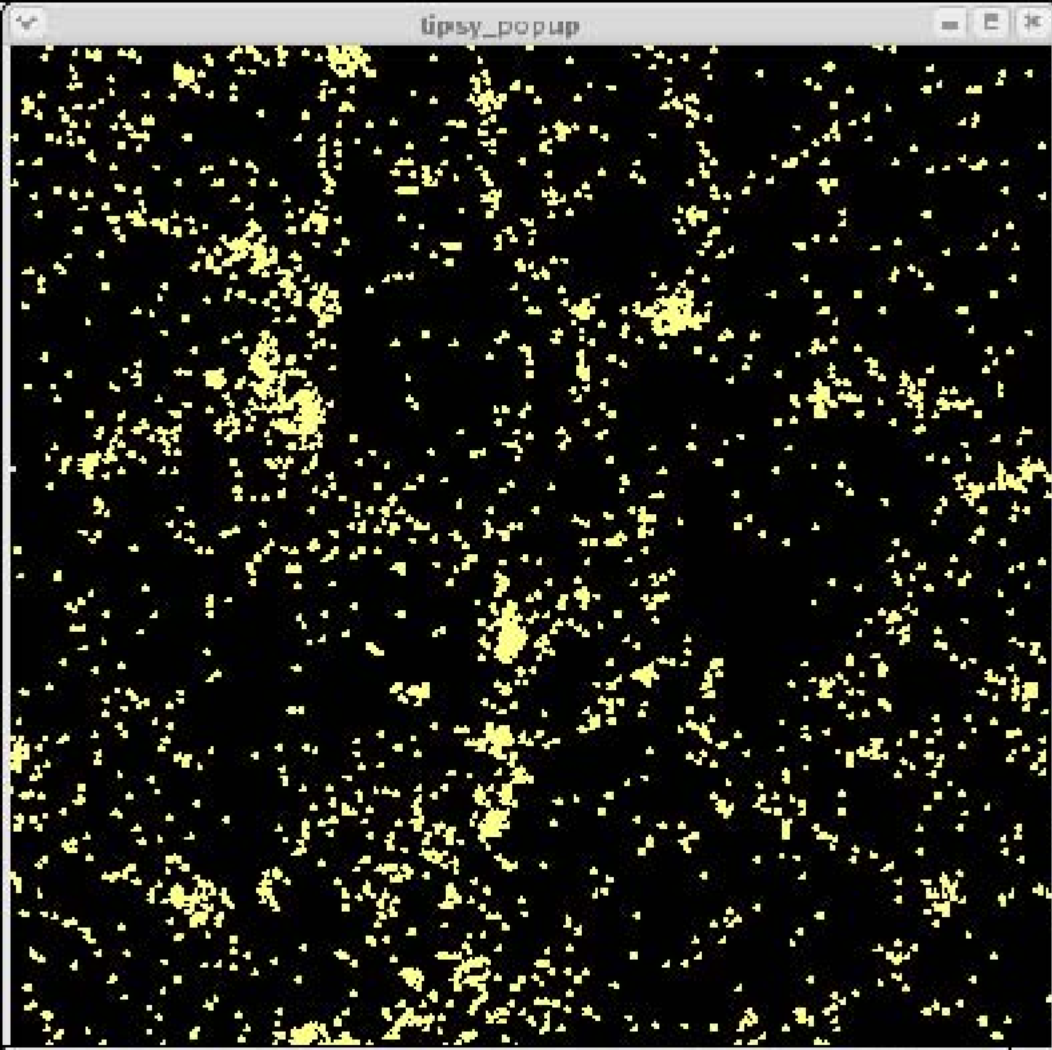
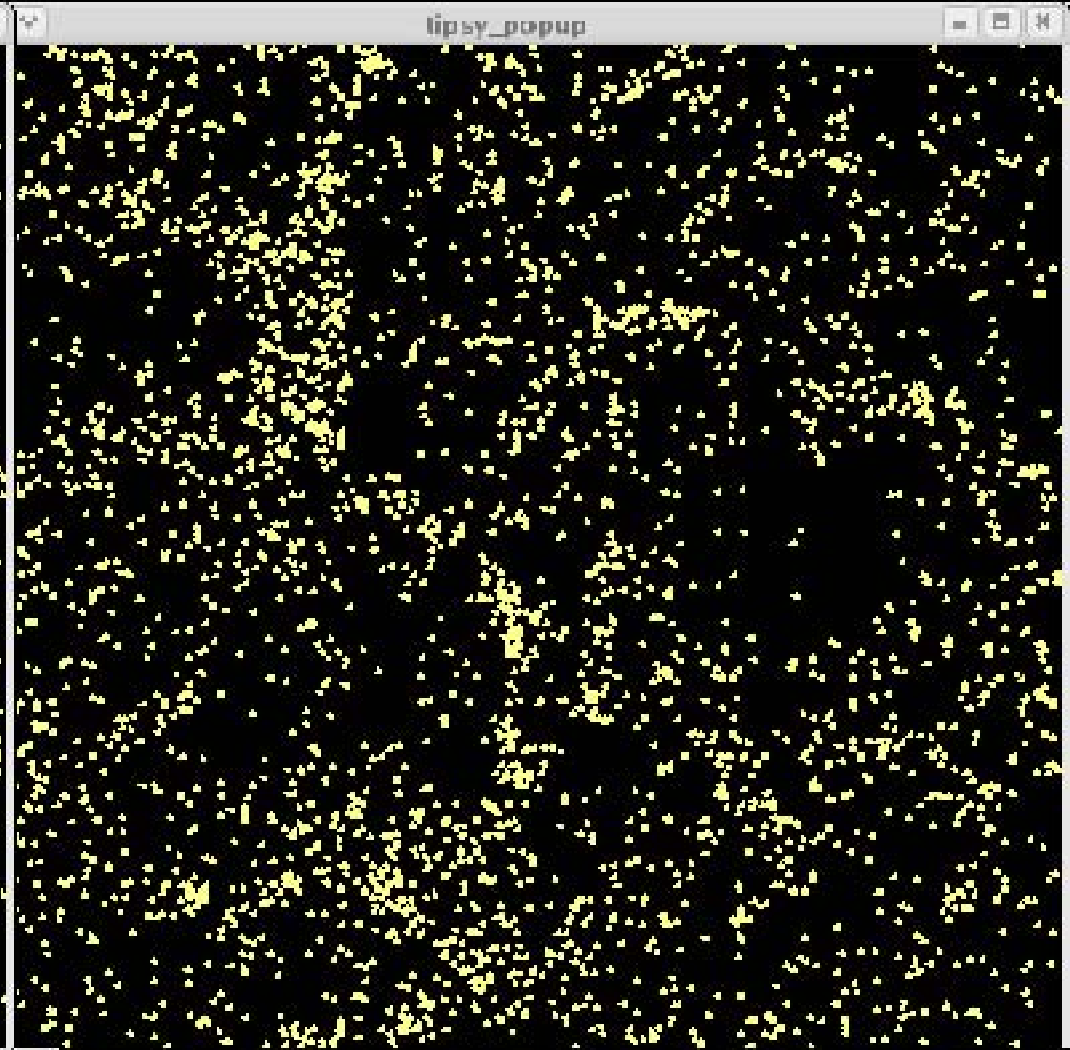


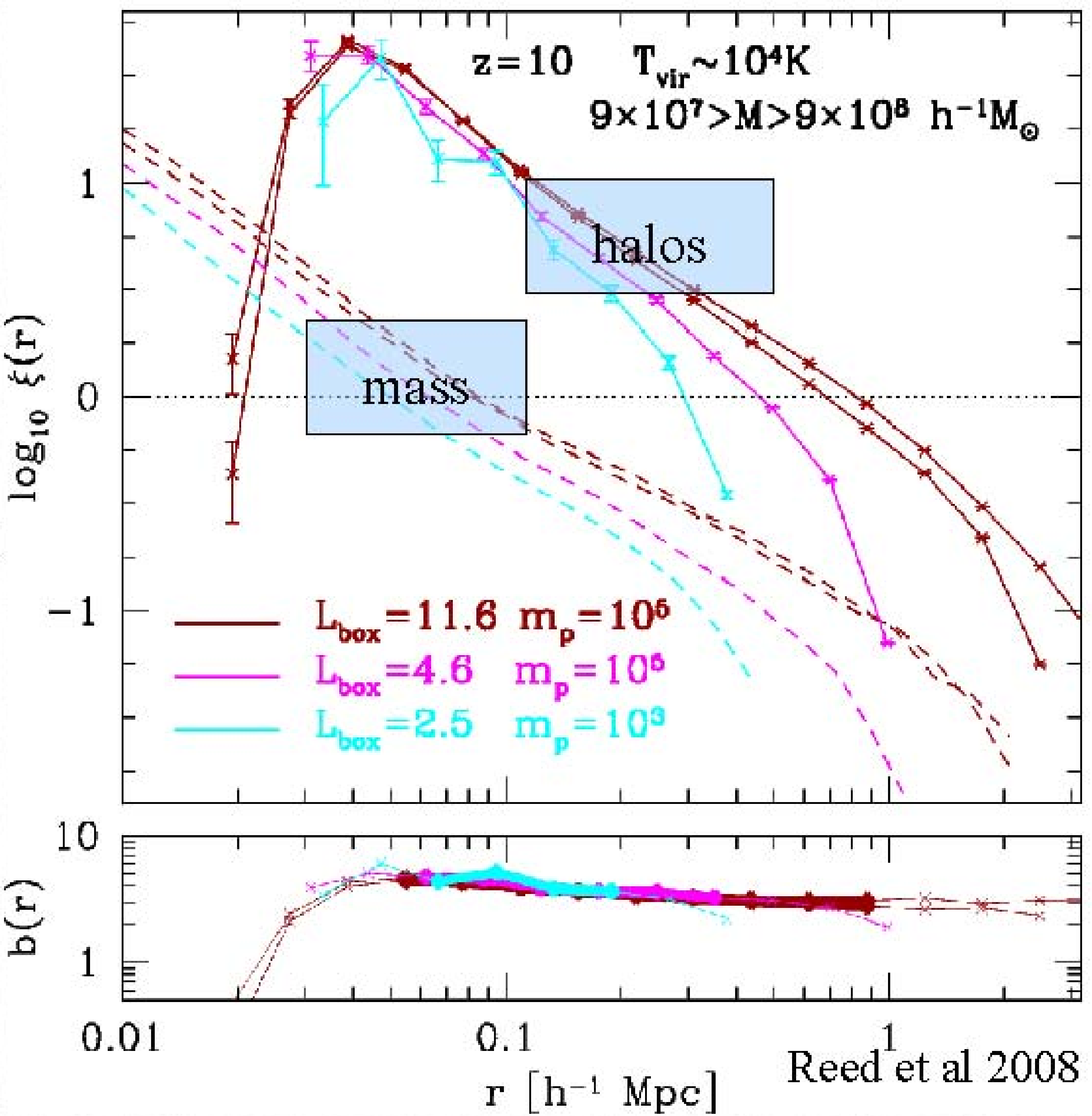
highly clustered



weakly clustered

Pair correlation function

$\xi(r) = N_{pair}/N_{pair\_random} - 1$



Halo bias:

$b = (\xi_{halos}/\xi_{mass})^{1/2}$

Universality of large-scale bias

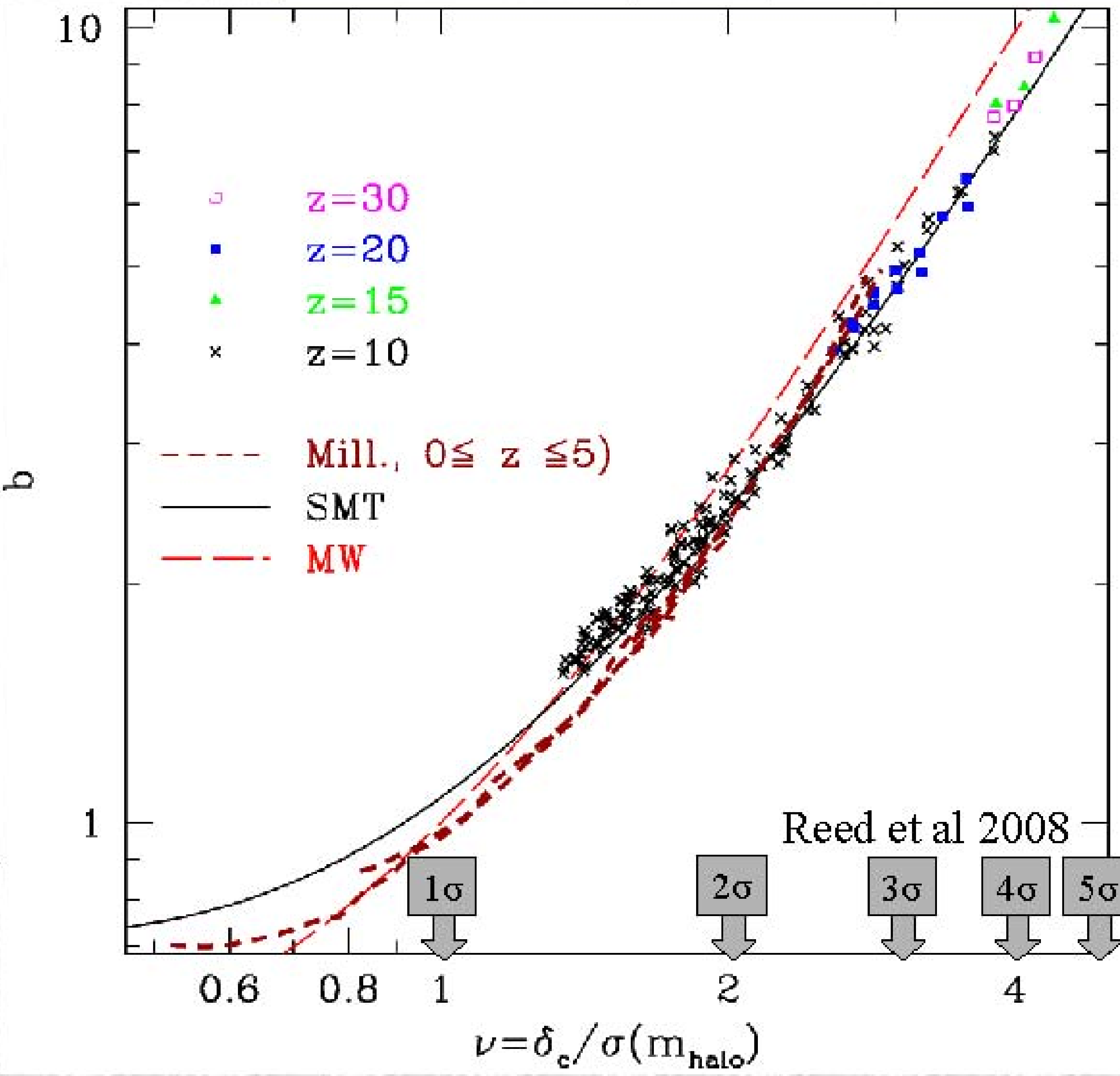
"universal" mass variable, ν,

$b = (\xi_{halos}/\xi_{mass})^{1/2}$

MW=predictions of Mo & White (1996)

SMT=Sheth, Mo & Tormen (2001)

Millennium run data from Gao et al. (2005).



Utilizing the high redshift dark universe [z >~ 5]

-compare galaxy numbers to halo numbers

-compare galaxy clustering with halo clustering

--probe **cosmology** (e.g. D.M. type)

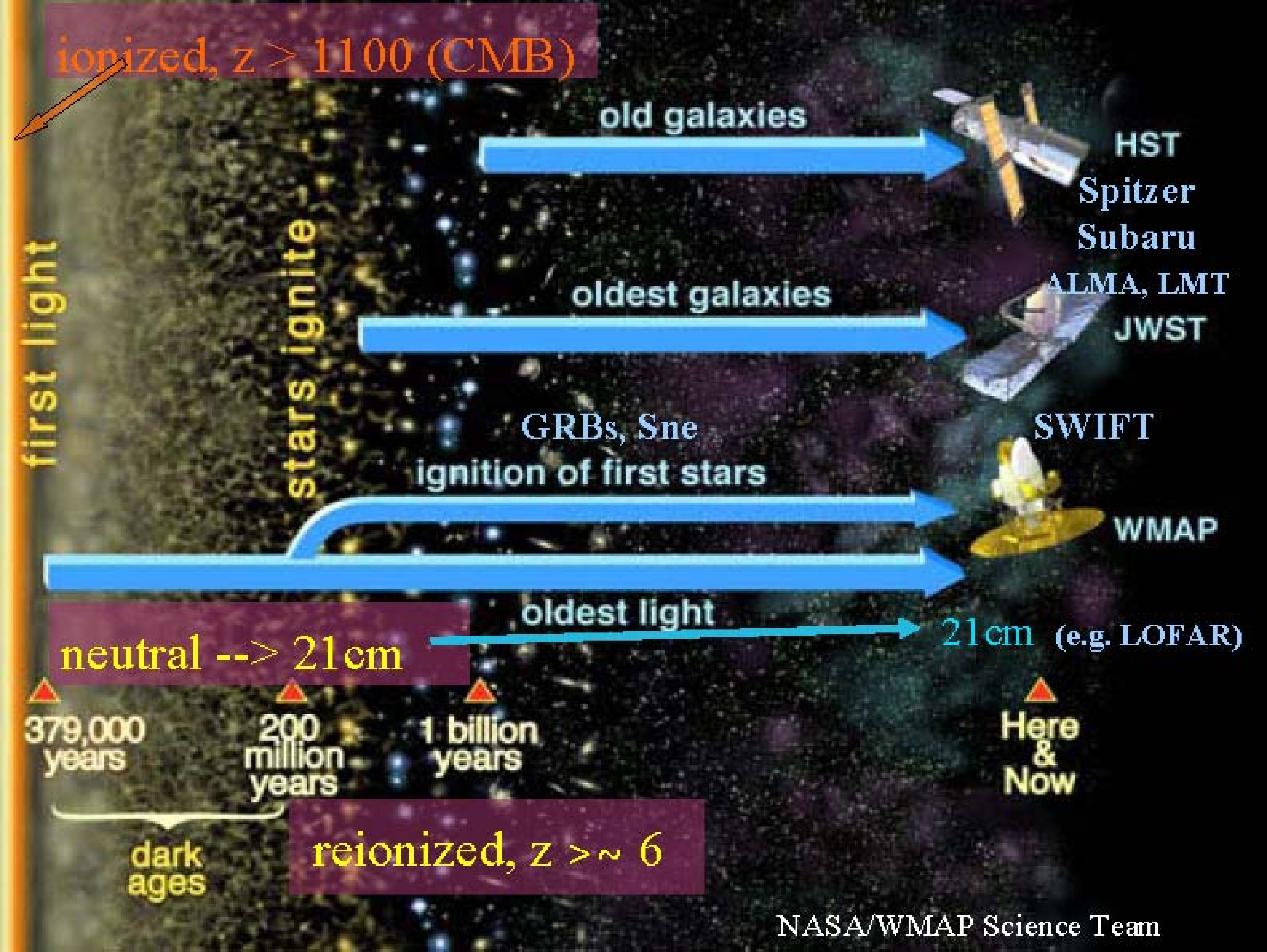
--probe **galaxy formation physics** (e.g. Sne)

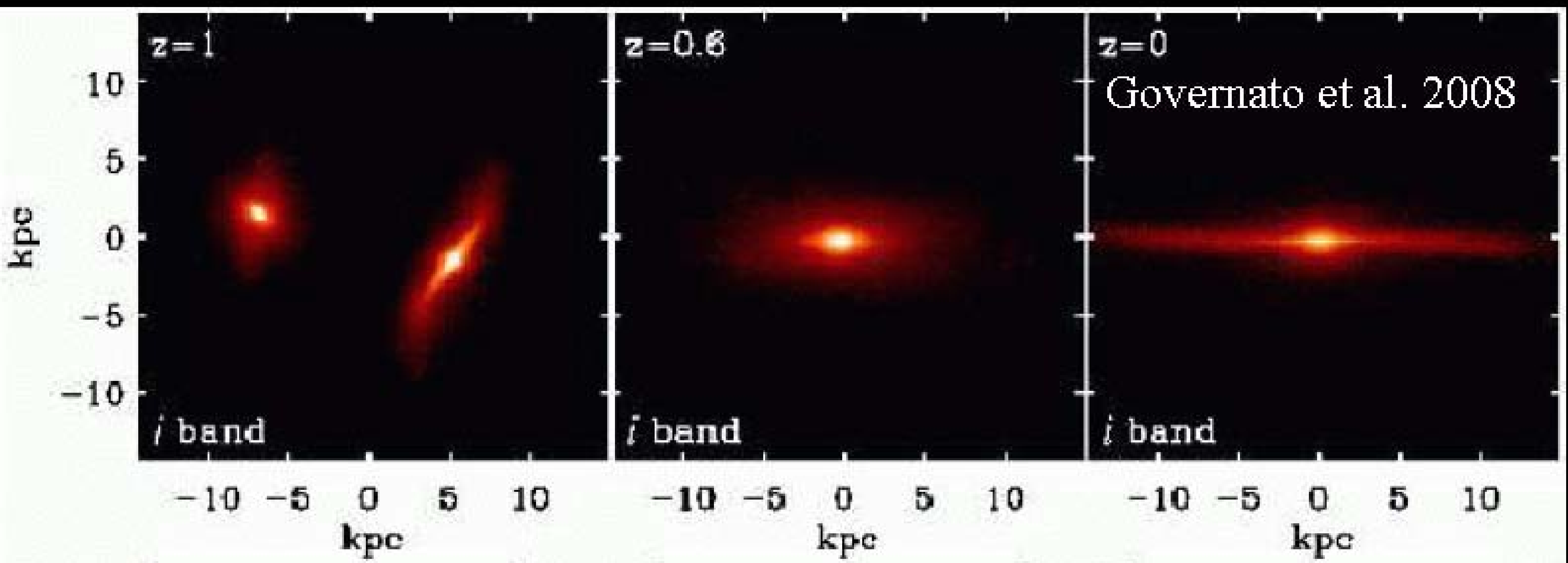
-Need to model ***early galaxy formation***

*how do early galaxies populate halos

*history of present day galaxies

*model (gravitational) response of d.m. to baryons


ionized, z > 1100 (CMB)
old galaxies
HST
Spitzer
Subaru
ALMA, LMT
oldest galaxies
JWST
GRBs, Sne
SWIFT
ignition of first stars
WMAP
oldest light
21cm (e.g. LOFAR)
neutral --> 21cm
first light
stars ignite
379,000 years
200 million years
1 billion years
Here & Now
dark ages
reionized, z >~ 6
NASA/WMAP Science Team


z=1
z=0.6
z=0
Governato et al. 2008
10
5
0
−5
−10
kpc
i band
i band
i band
−10 −5 0 5 10
kpc
−10 −5 0 5 10
kpc
−10 −5 0 5 10
kpc

simulating early galaxy formation

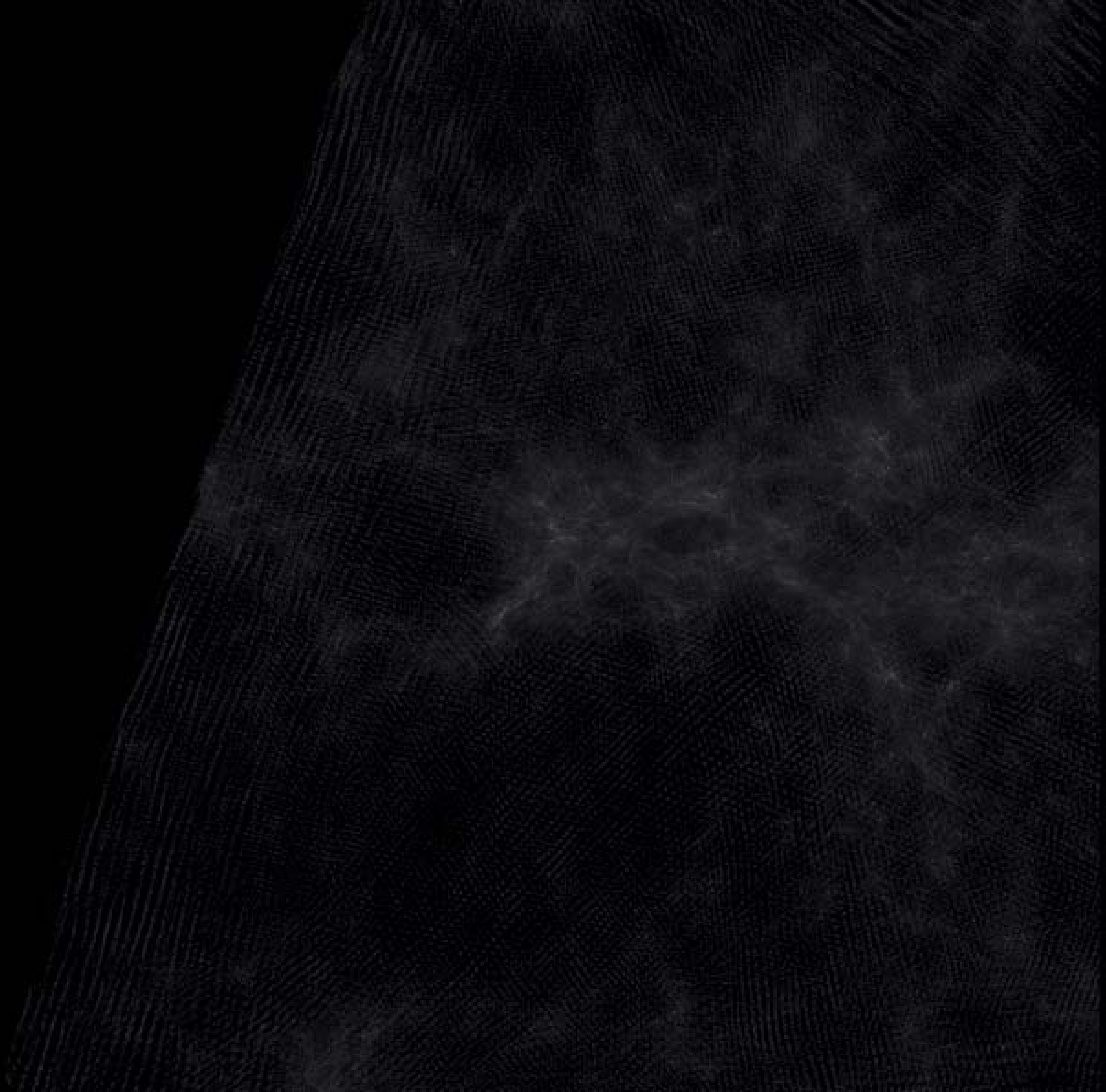
Work in progress

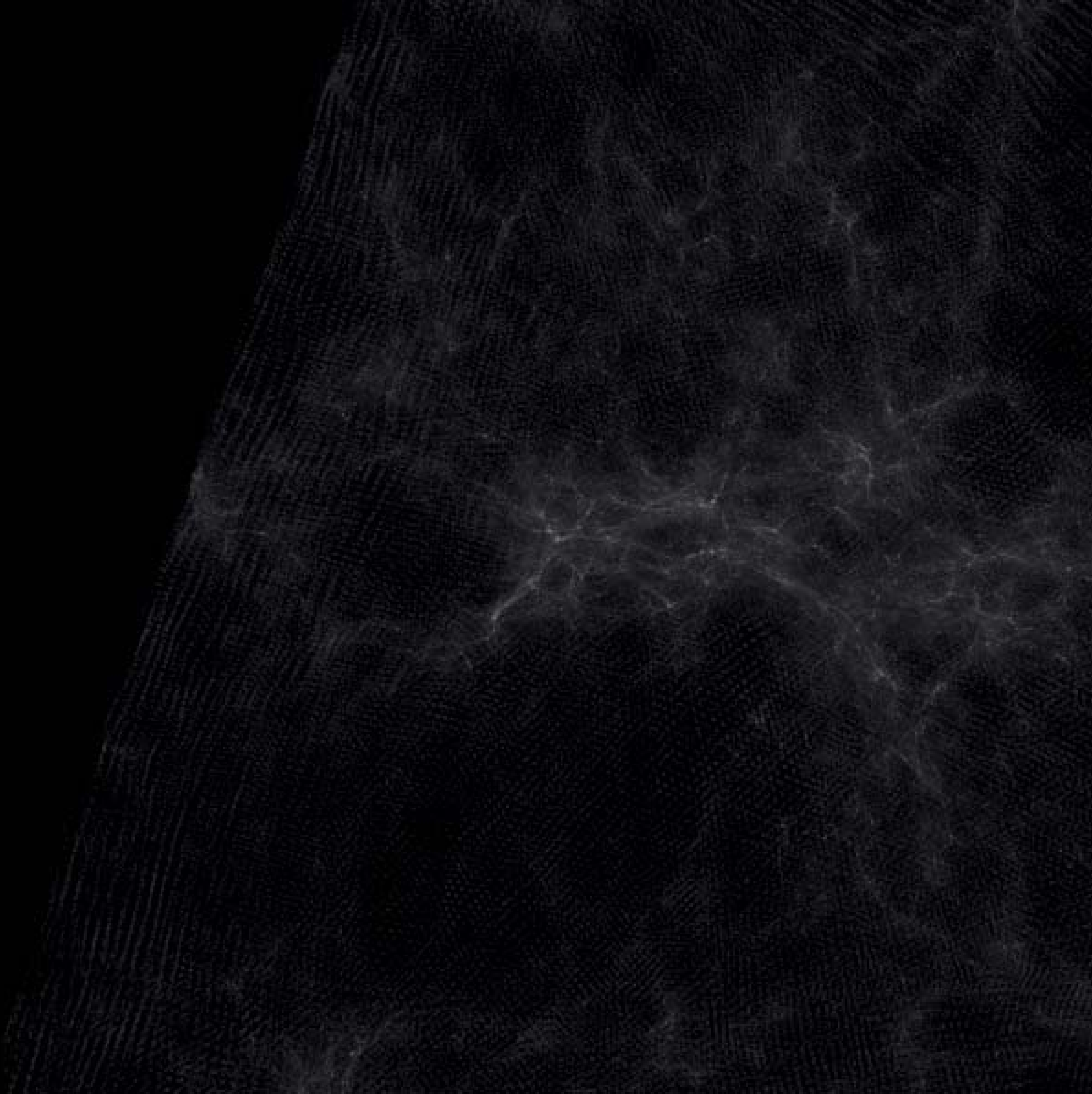
- Smoothed particle hydrodynamic simulations
  - code GASOLINE (Stadel, Wadsley, Quinn……)
    - Gas cooling
    - Star formation
    - Supernova energy injection, chemical enrichment
  - (with Governato et al.)

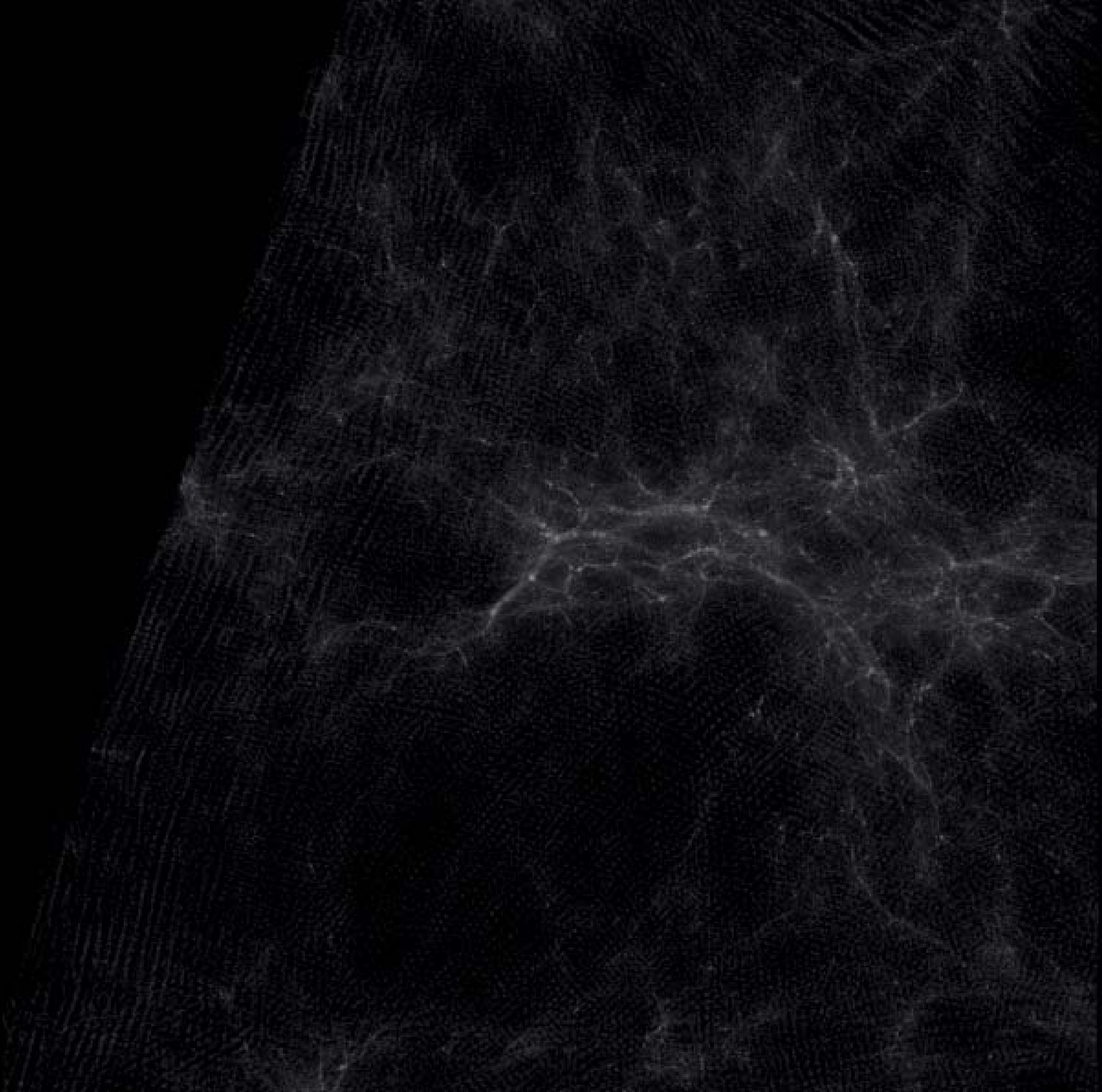
–Model cosmological volume (~50 Mpc):

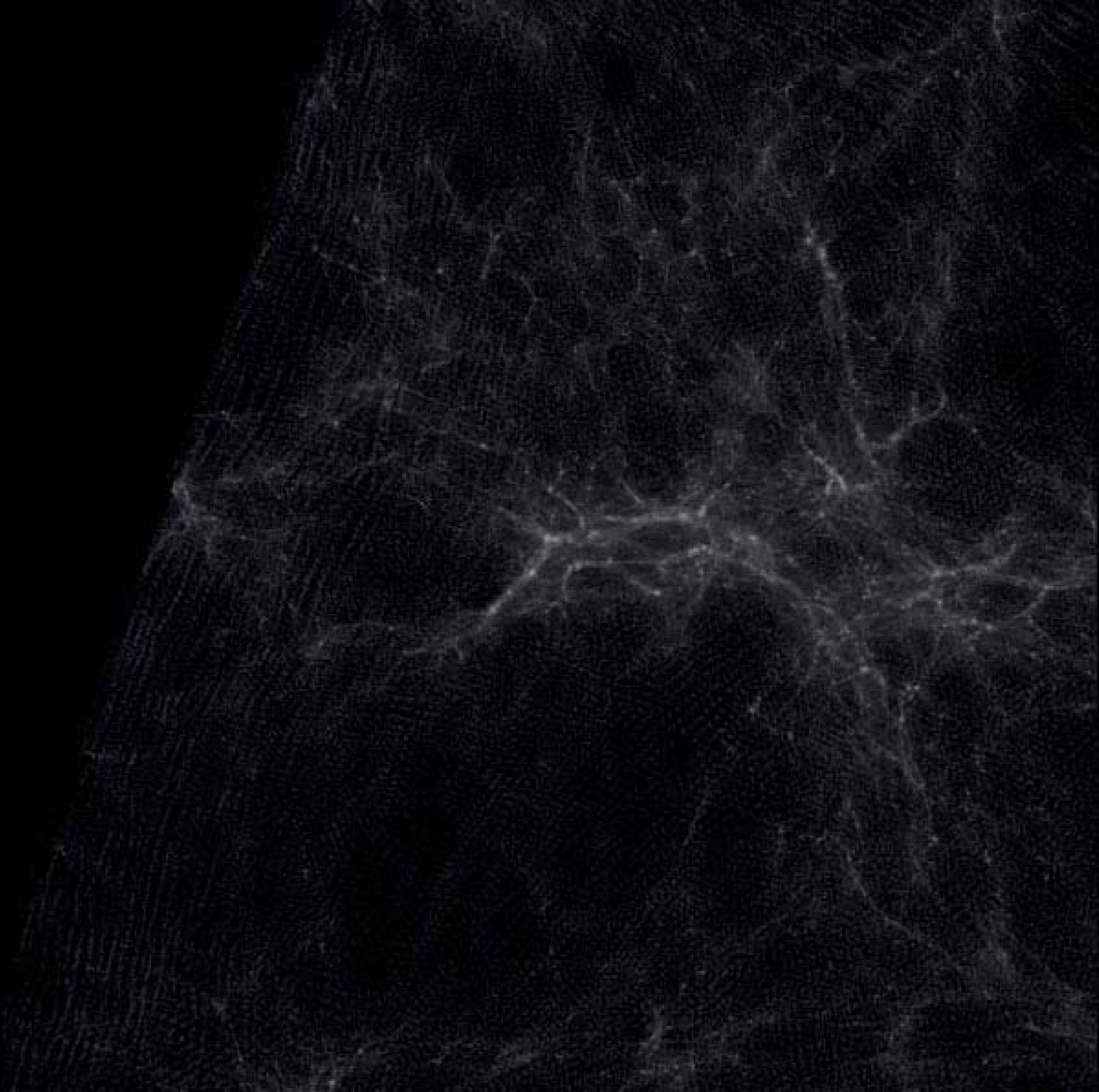
–stop at high redshift before physics too complex

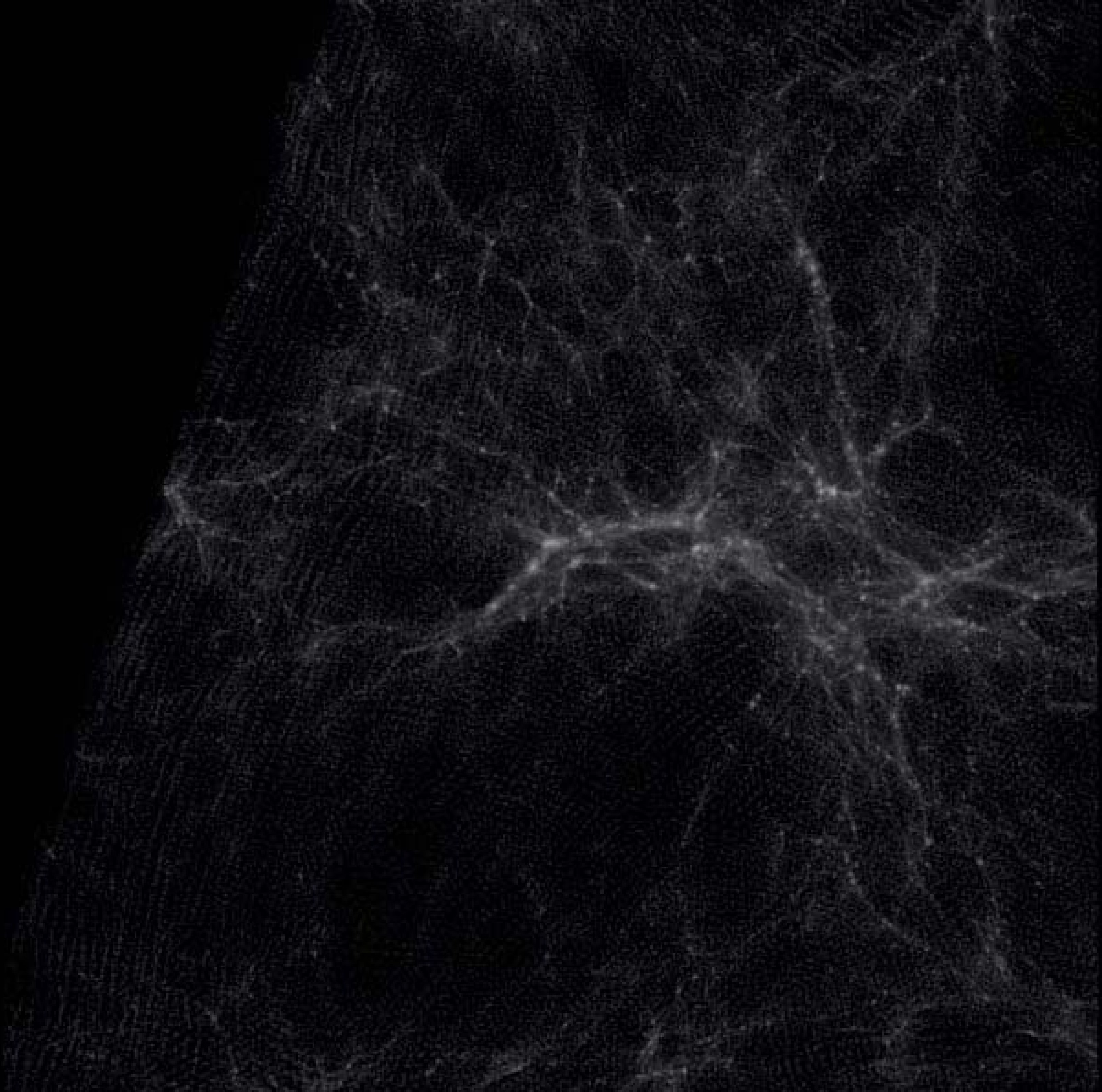
–but within observable range (redshift ~5)

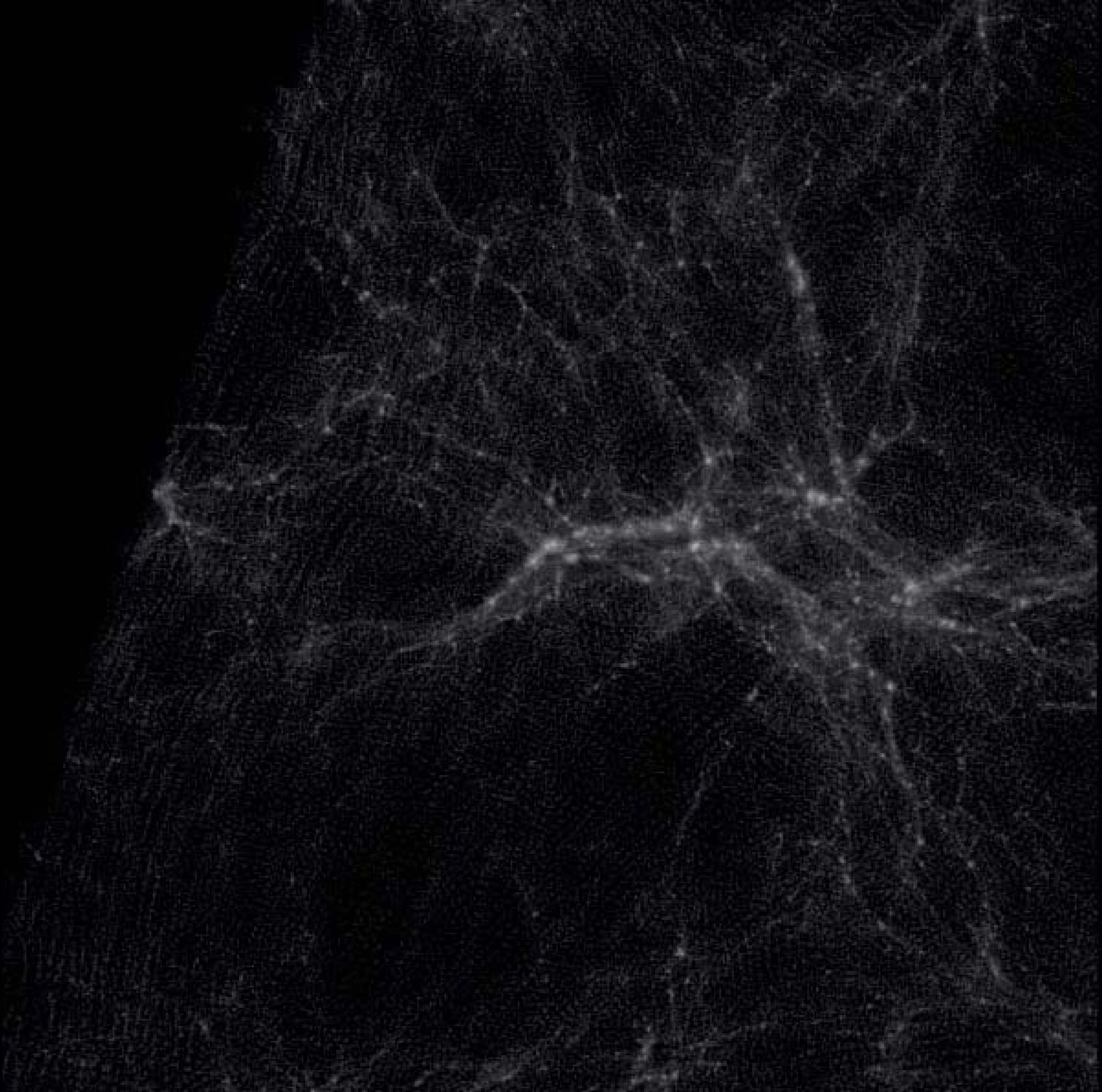


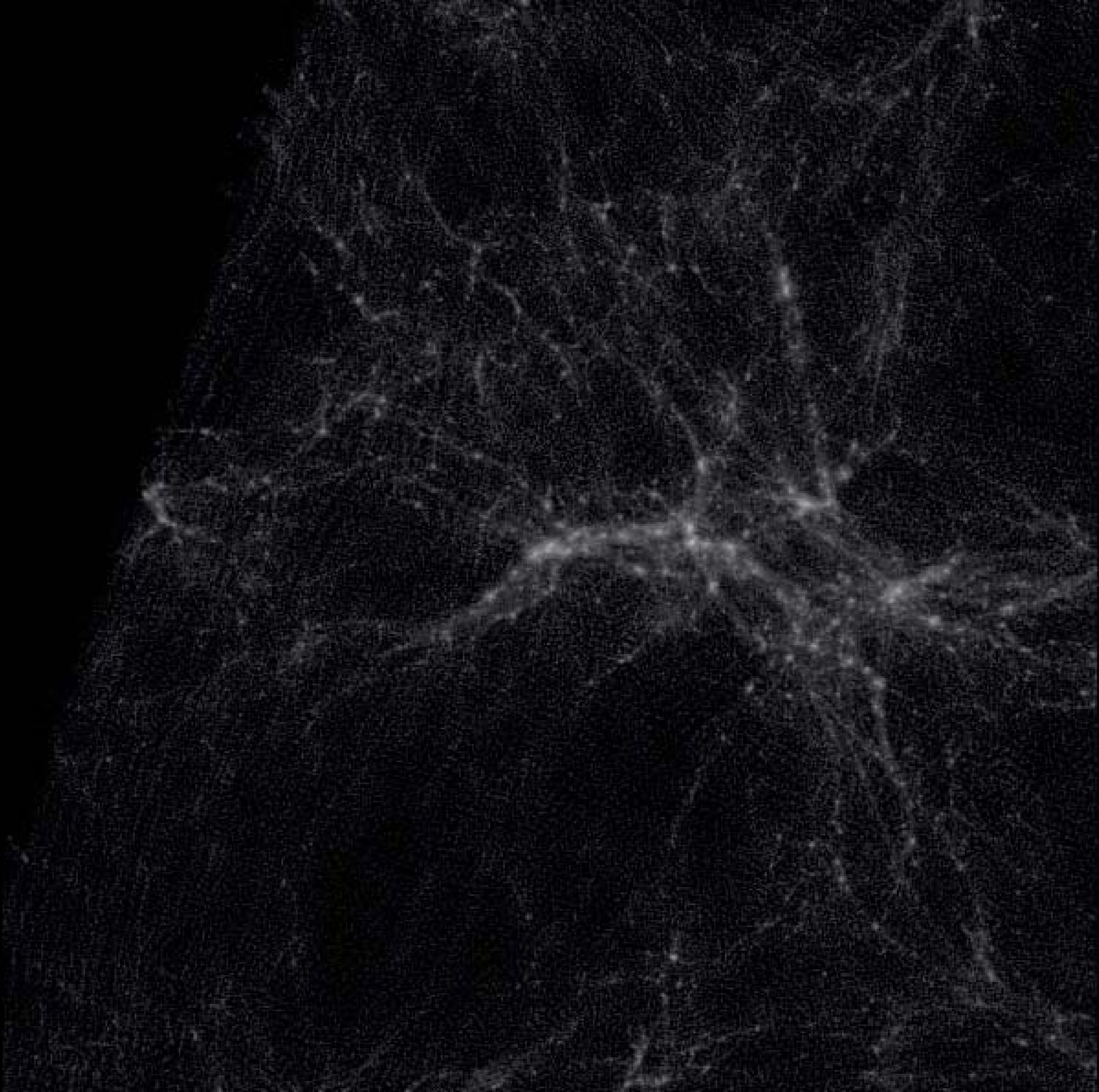


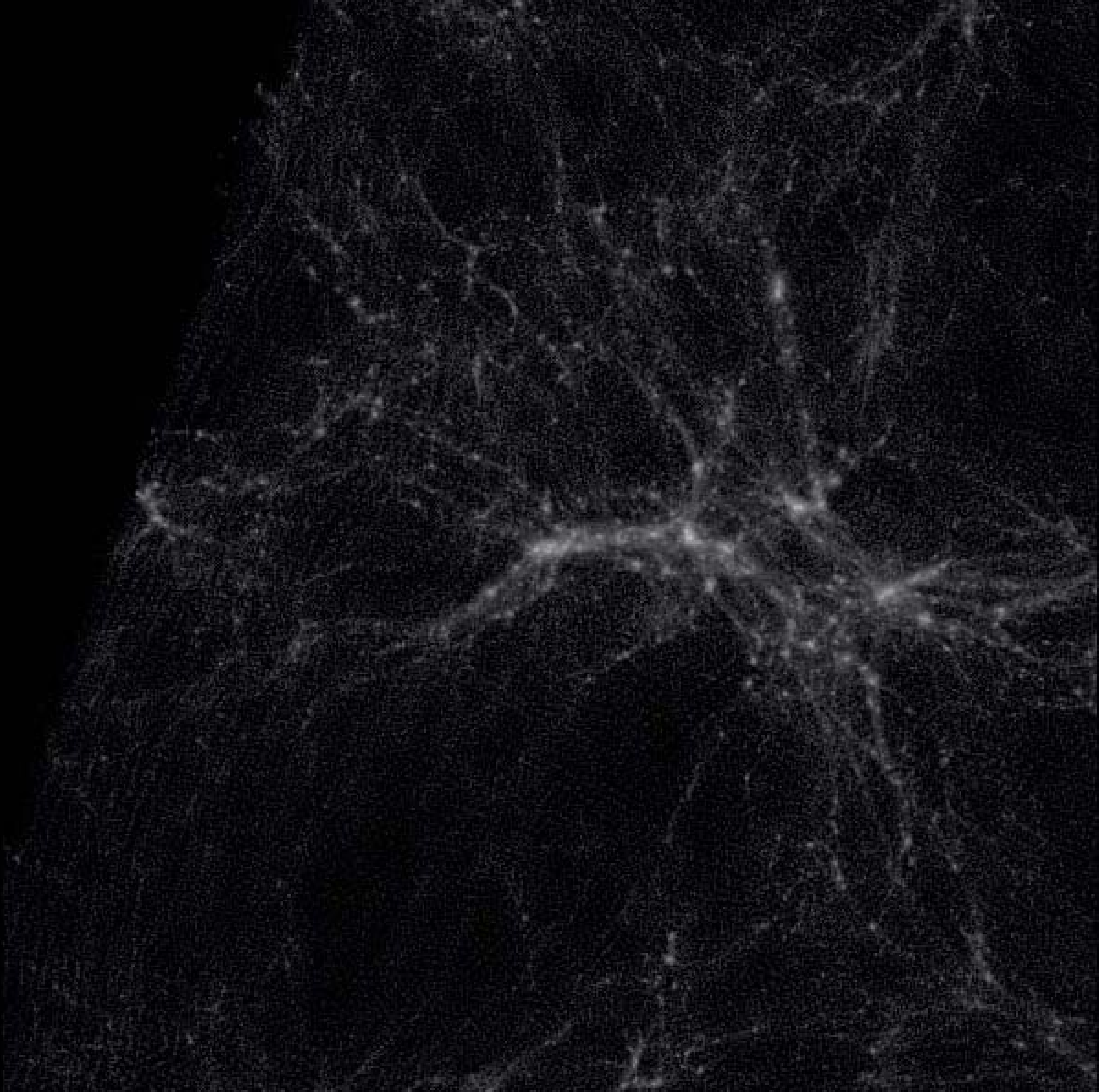












Future Simulations --> more particles, more physics, higher redshifts

- ***Galaxy Formation*** – High redshift, high densities
  - Accurate baryon (gas + stars) physics
  - Interplay between dark matter and baryons
- ***Small scales***
  - "Cold" vs "Warm" dark matter

Conclusions

- Universe is mostly dark matter (+ dark energy)
- Simulation vs. observations comparisons:
  - Halo structure
  - Halo numbers
  - Halo distribution
- To understand cosmology & galaxy formation:
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  - better baryon physics (star/galaxy formation)

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