LCDM: Successes and Challenges

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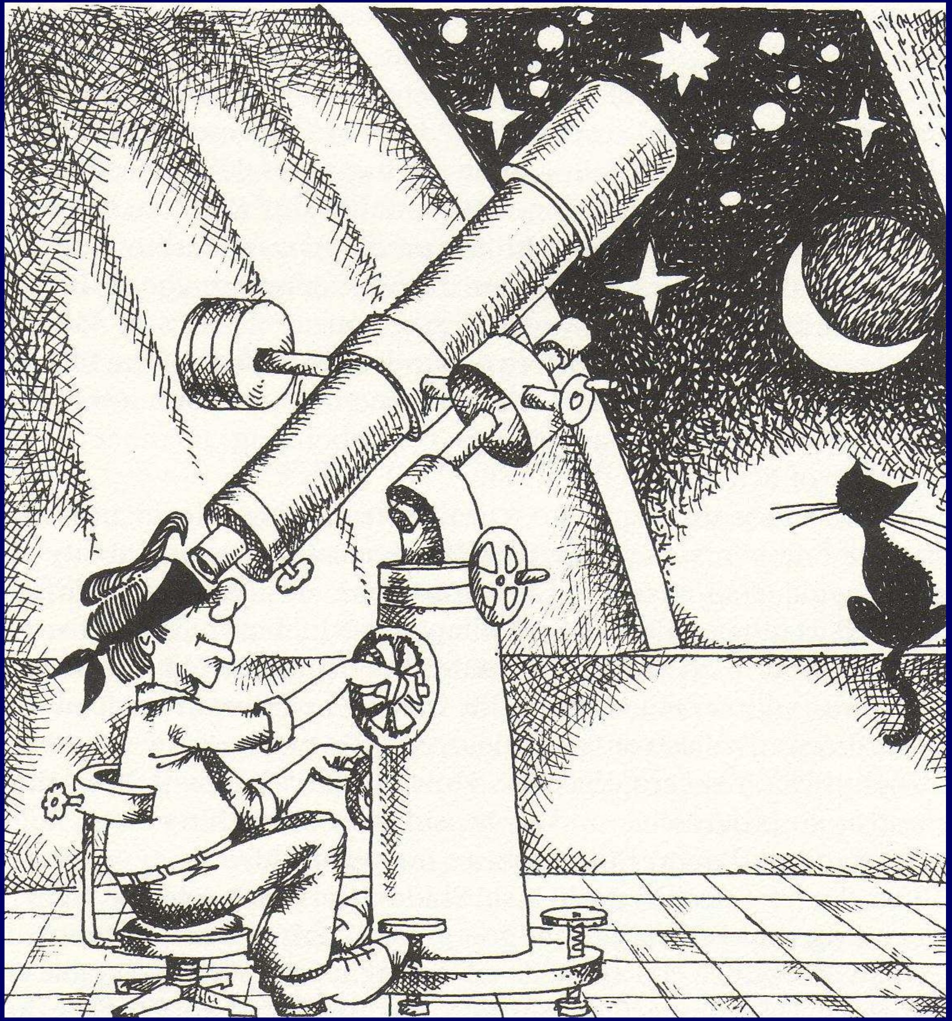
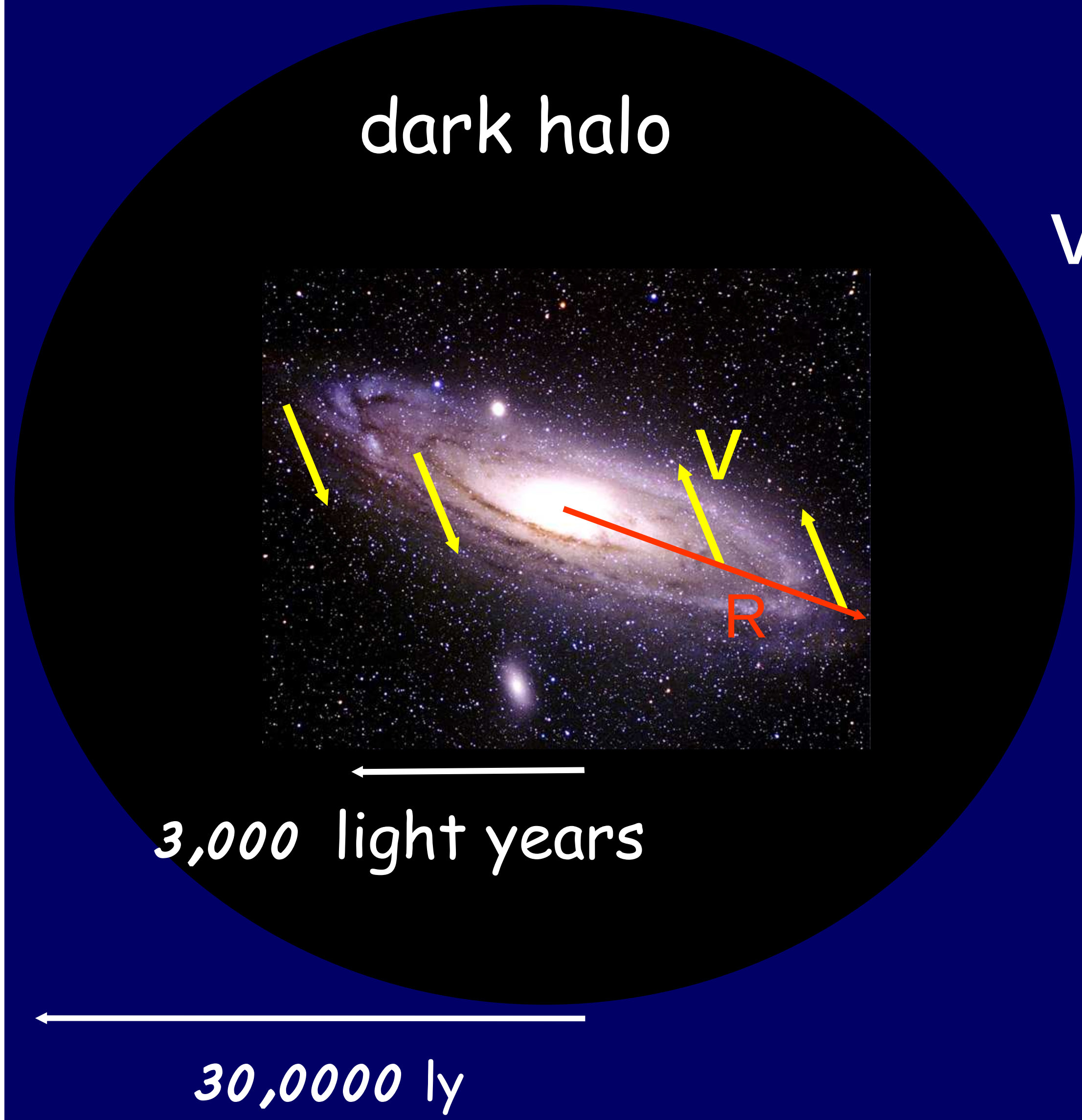
Beyond WIMPs: From Theory to Detection
June 2015

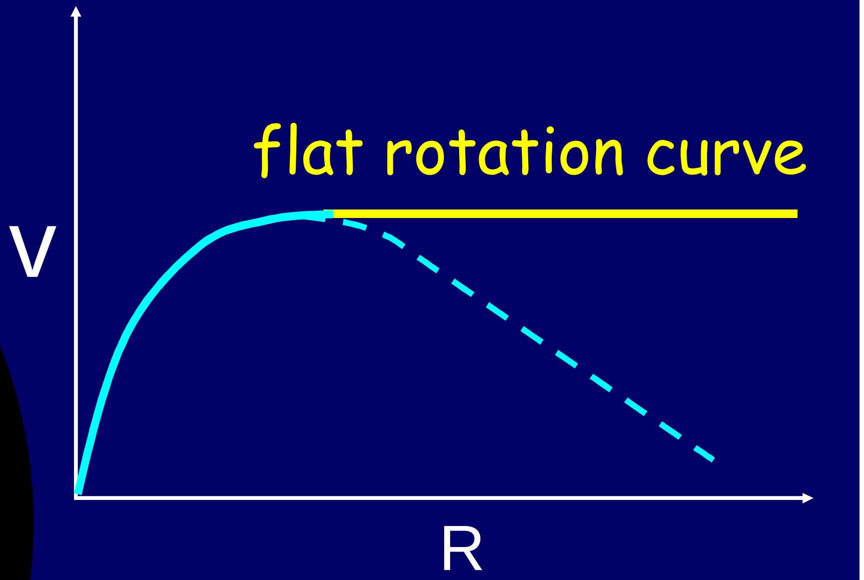
Astronomers have been measuring Dark Matter since 1933 (Zwicky – missing mass)



Novikov

Dark-Matter Halos in Galaxies

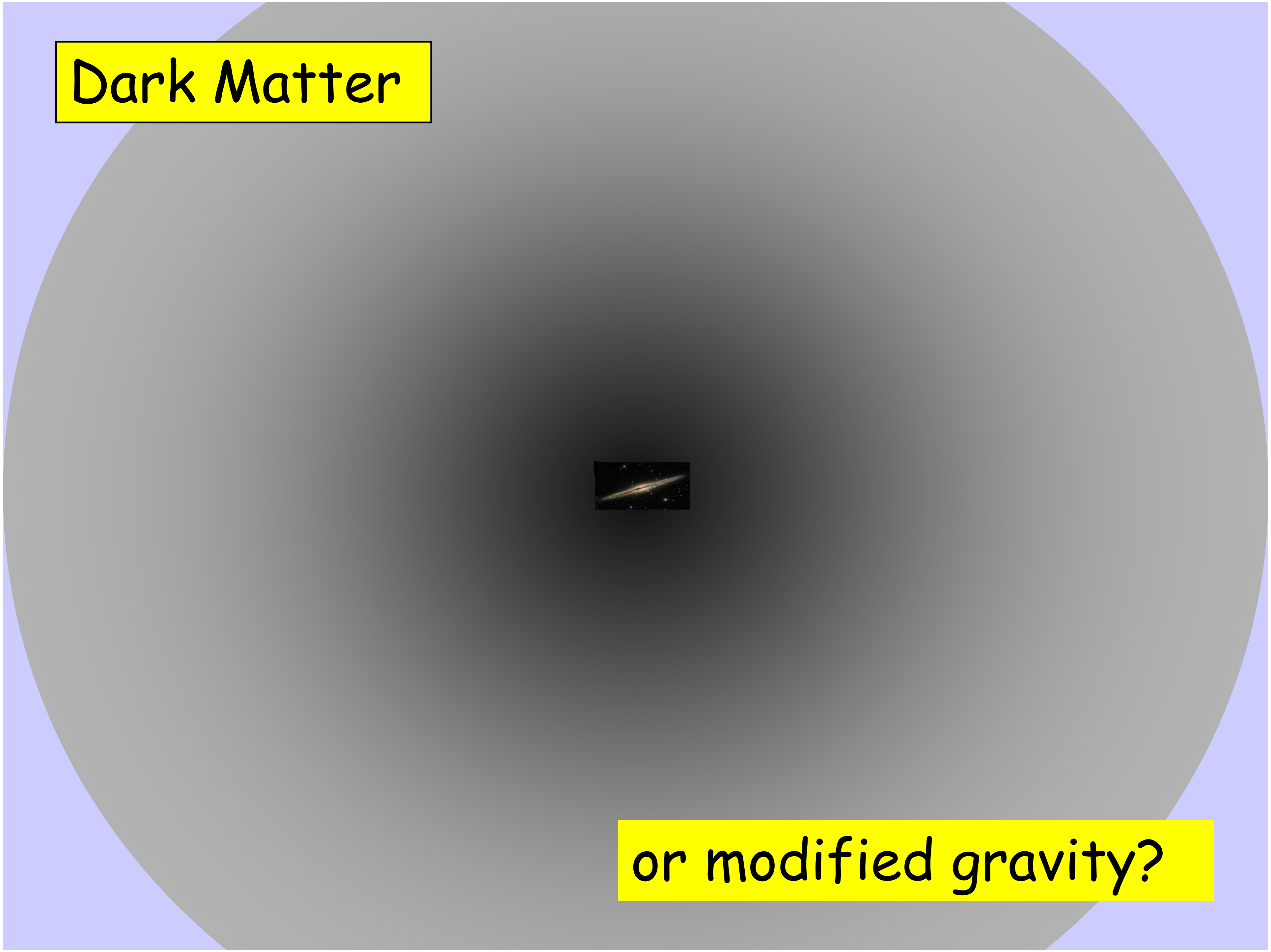




$$V^2 = \frac{GM(R)}{R}$$

$$\rightarrow M(R) \propto R$$

Dark Matter

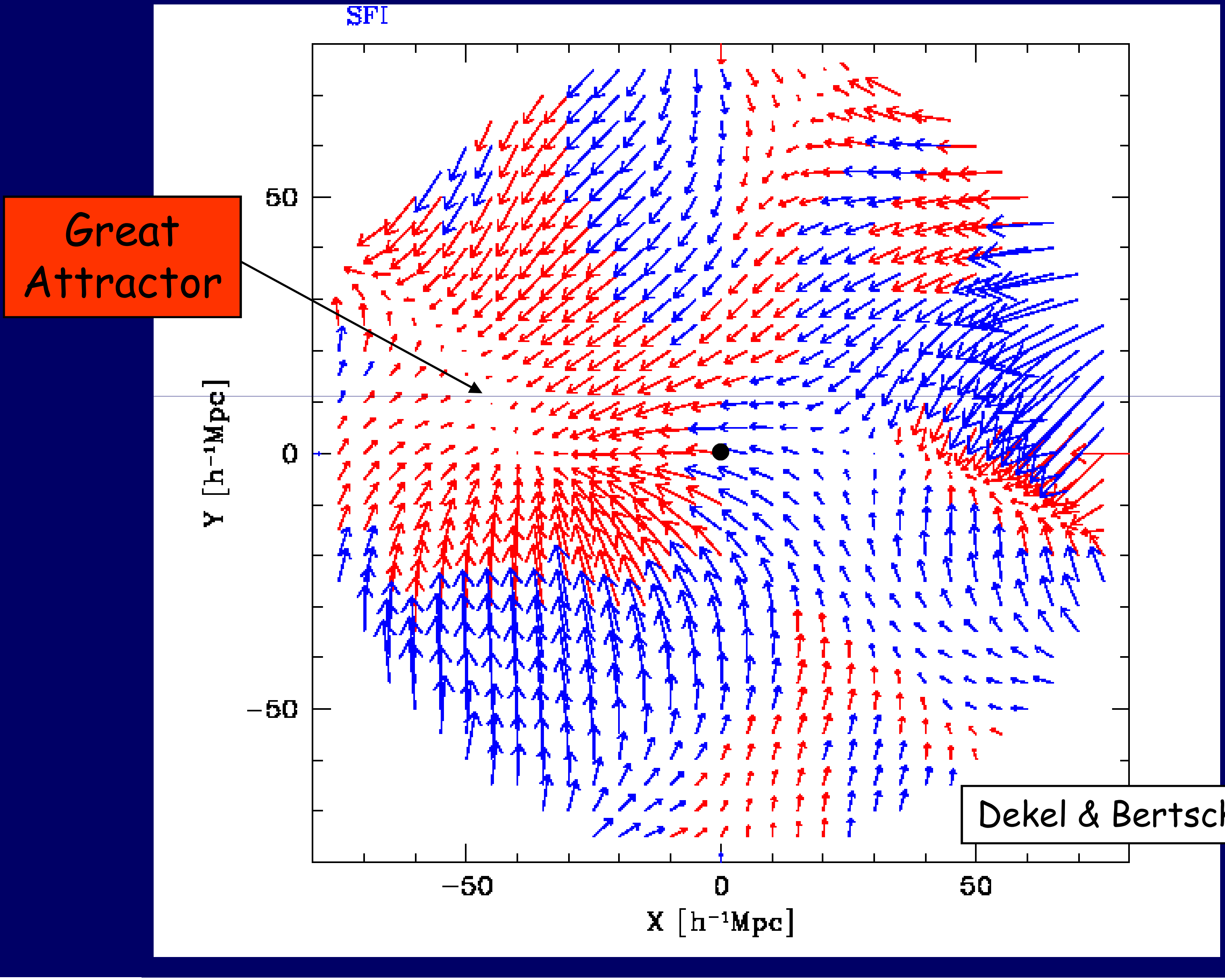


or modified gravity?

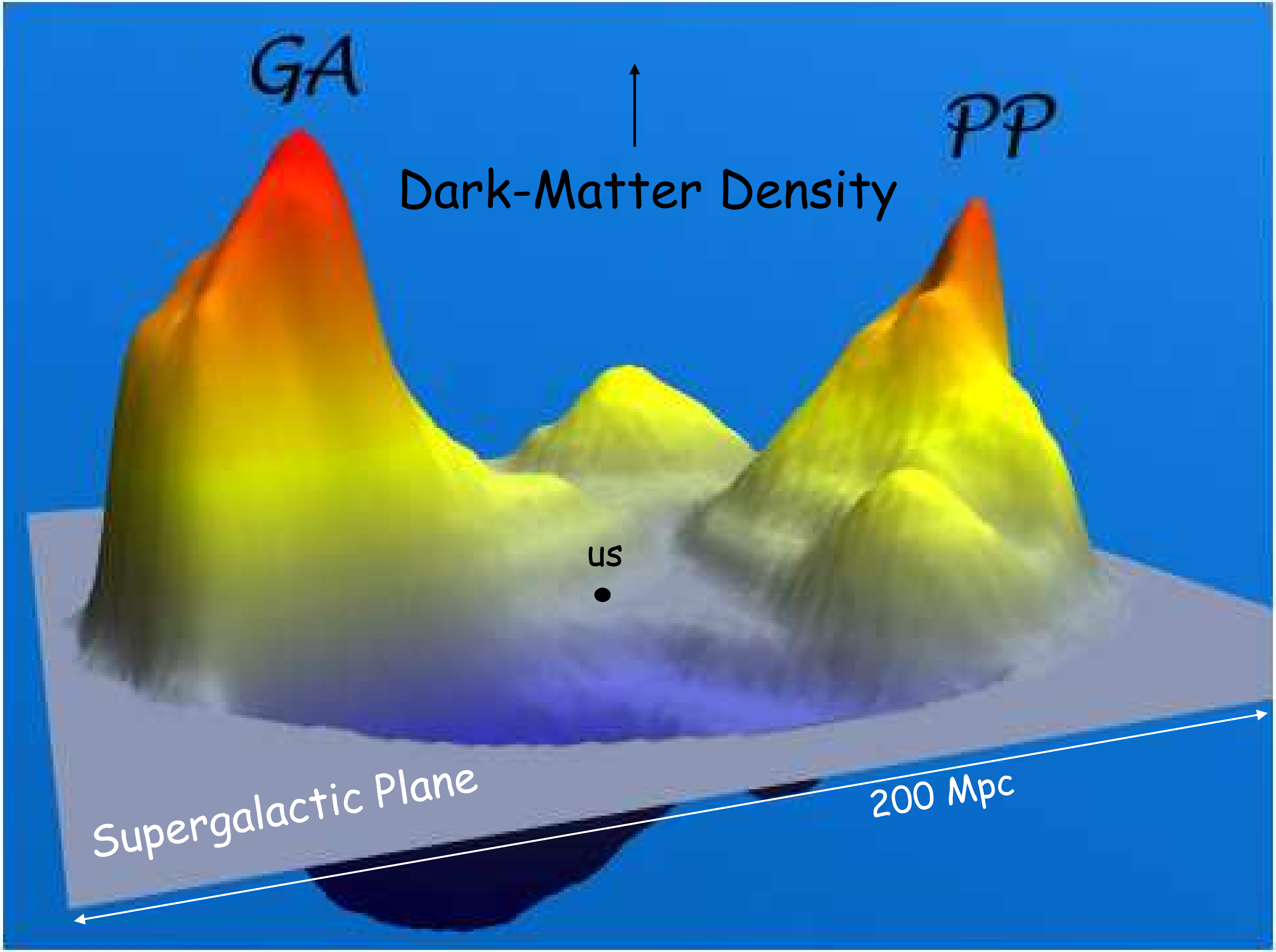
DM in Galaxy Clusters: Gravitational Lensing

HST

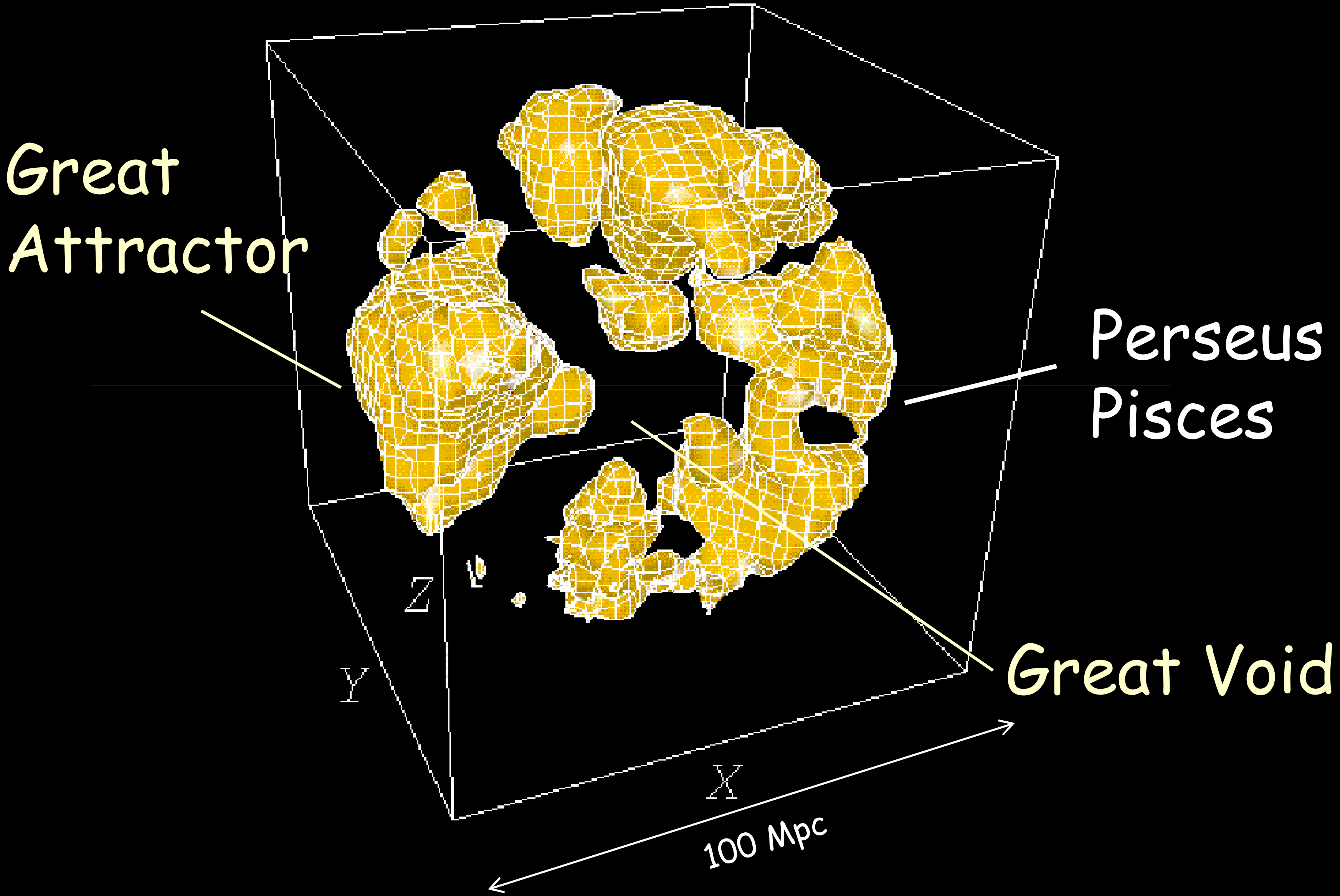
Large-Scale Cosmic Flows - POTENT



Dekel & Bertschinger 1990


GA
Dark-Matter Density
PP
us
Supergalactic Plane
200 Mpc

Large-Scale Mass Distribution



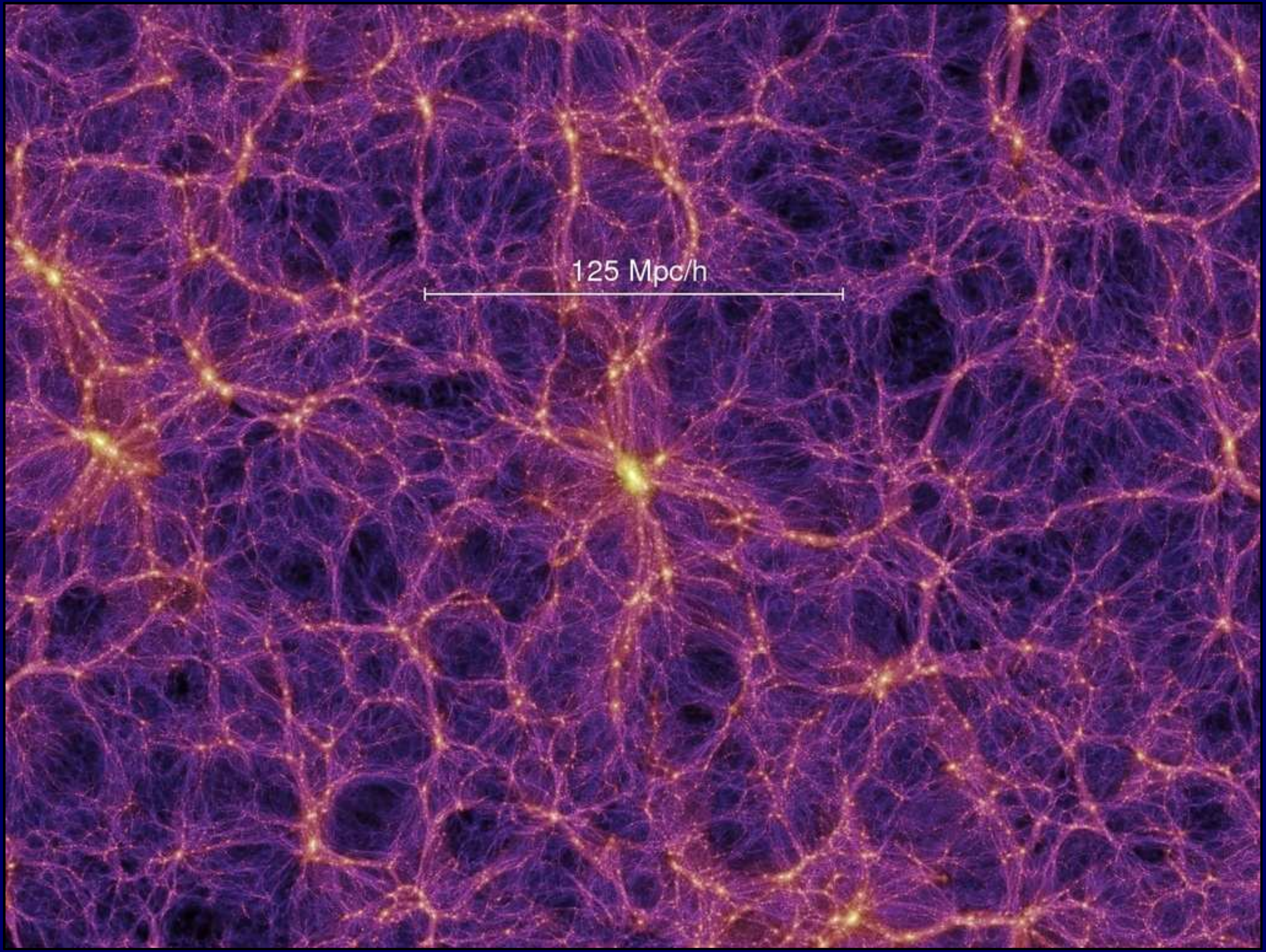
Most Mass is Non-baryonic Dark Matter

Planck+ 2015:

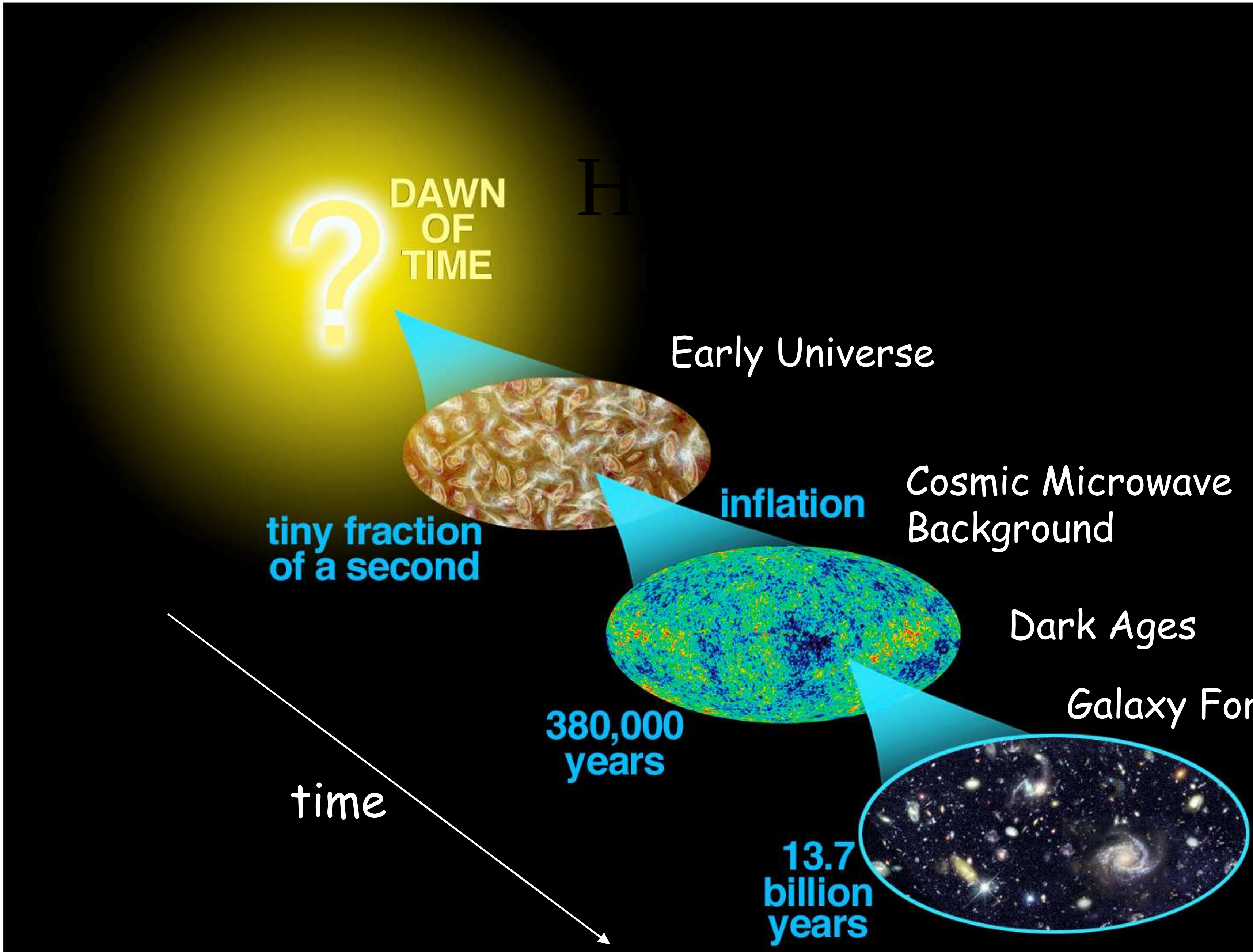
Total Mass $\Omega_m = 0.308 \pm 0.012$

Baryons $\Omega_b = 0.0478 \pm 0.0004$

Formation of Structure



H



Early Universe

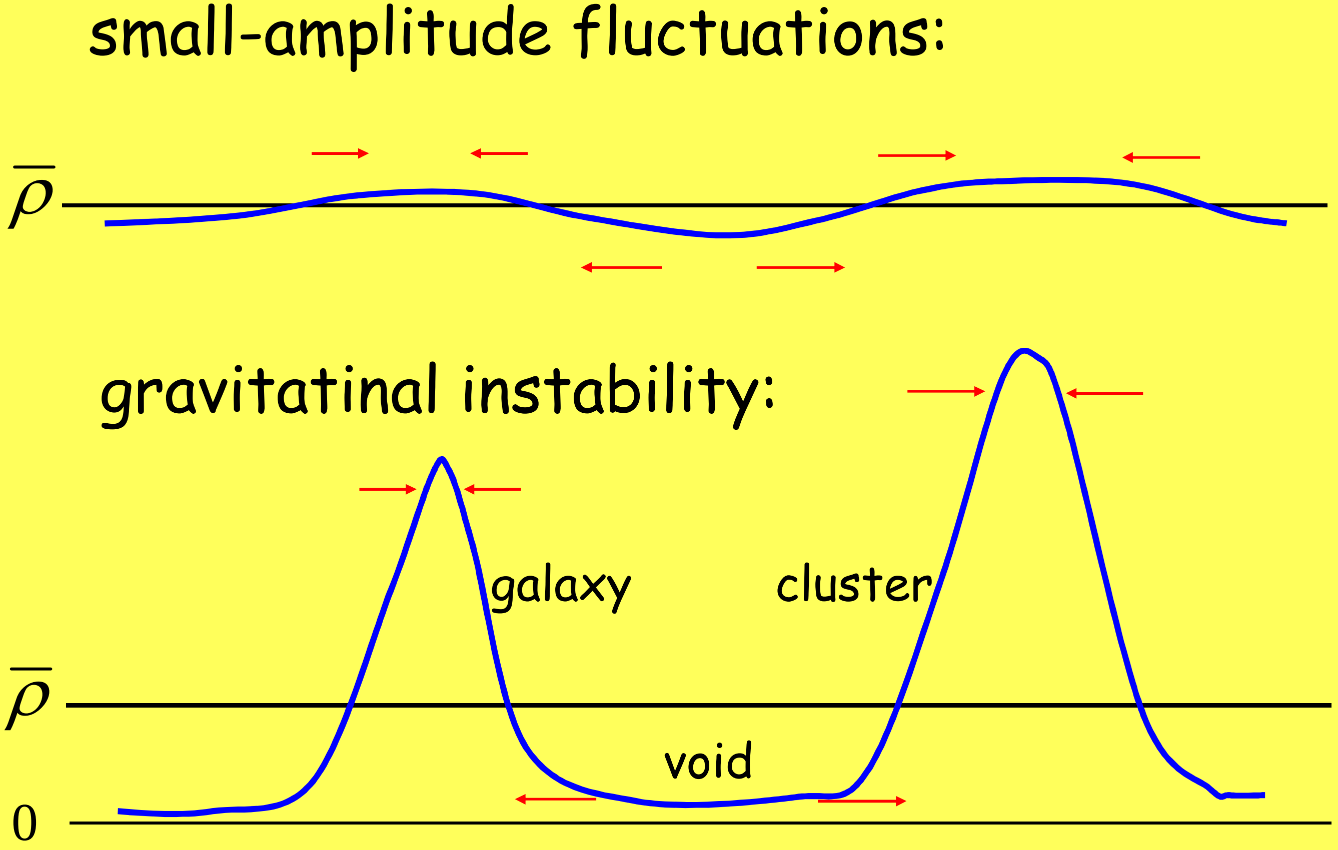
Cosmic Microwave Background

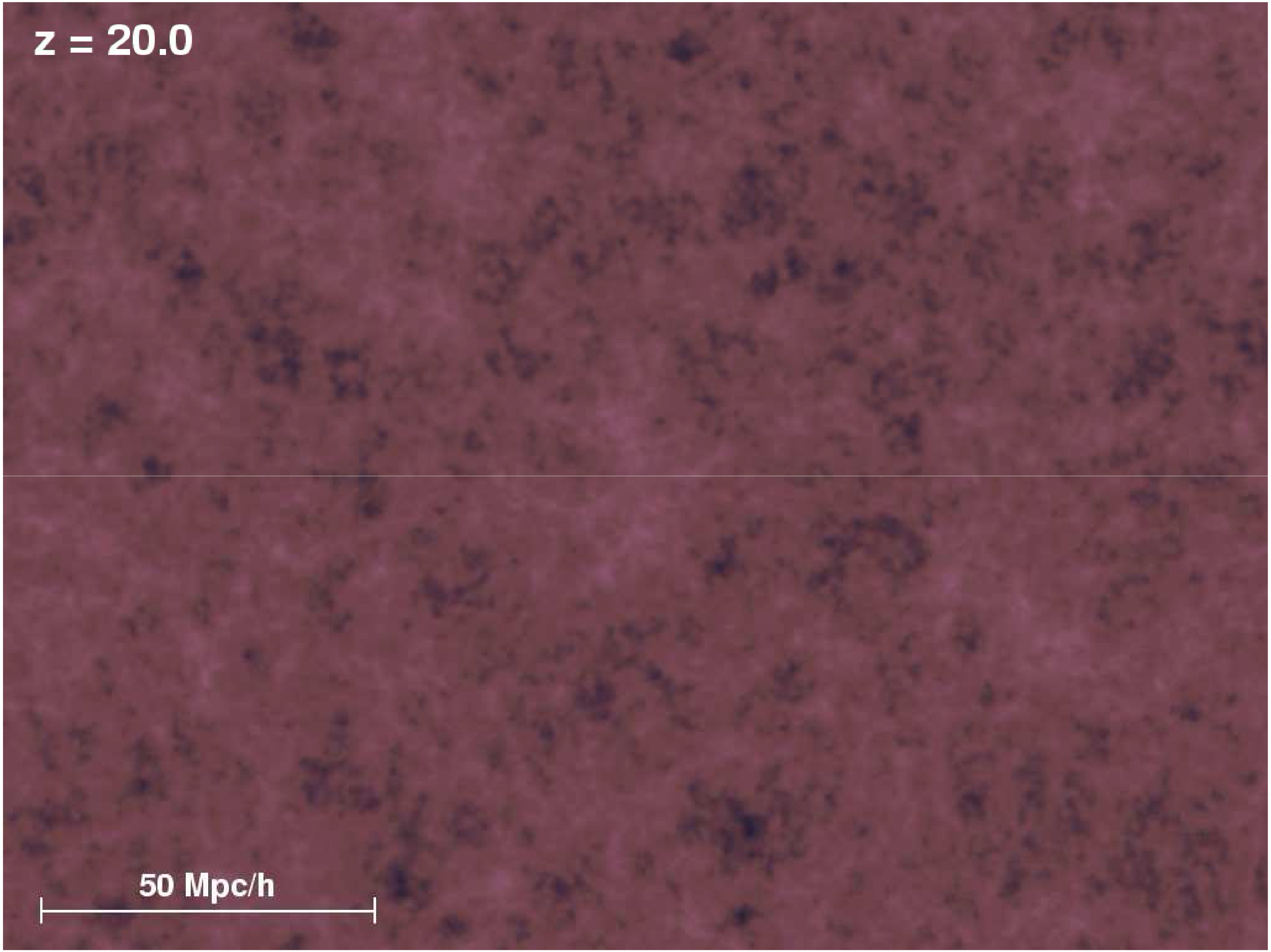
Dark Ages

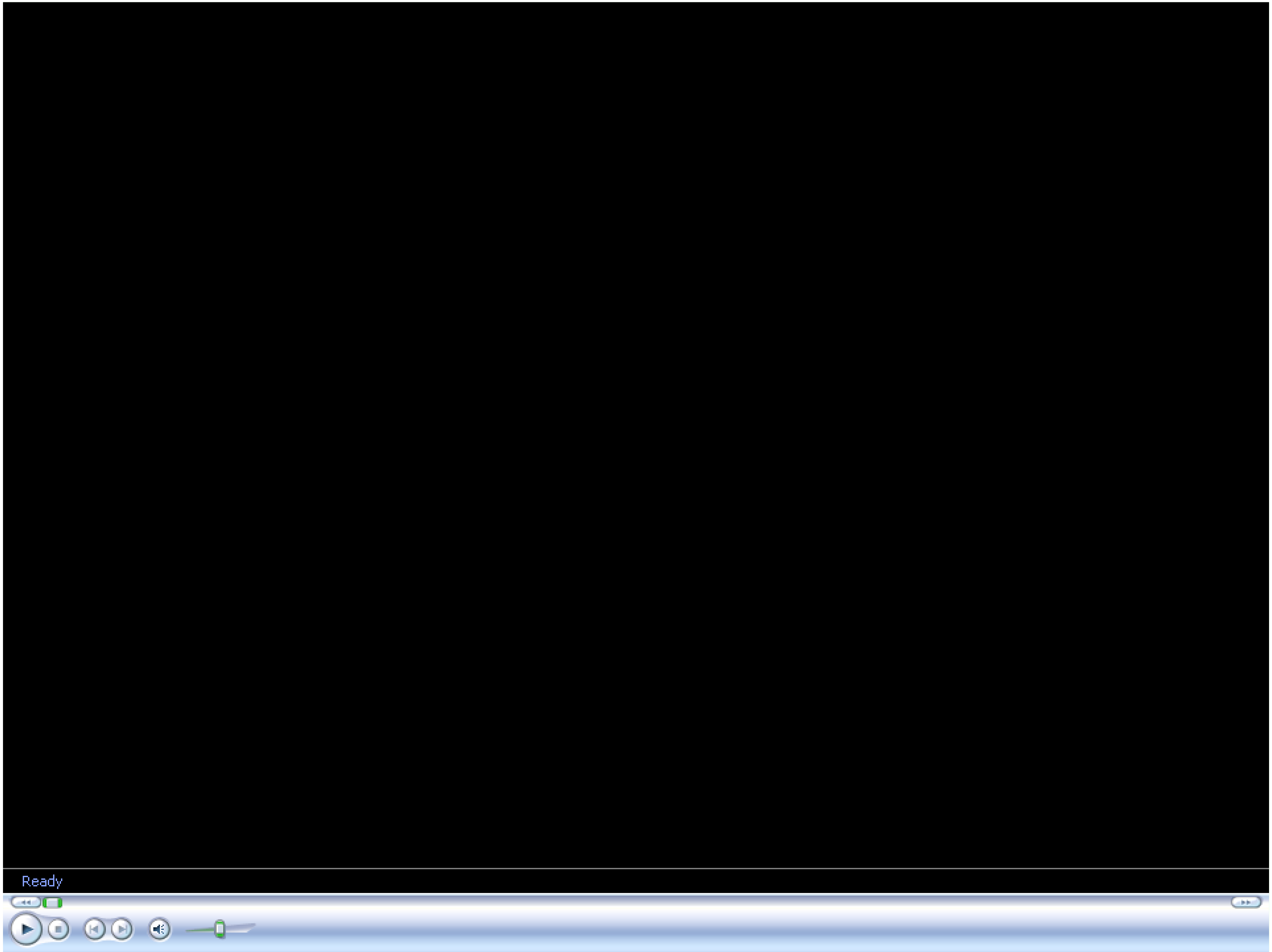
Galaxy Formation

time

Gravitational instability




z = 20.0
50 Mpc/h



Ready

The Initial Fluctuations

At Inflation: Gaussian, adiabatic

Fourier transform:

$$\delta(\vec{x}) = \sum_{\vec{k}} \delta_{\vec{k}}\, e^{i\vec{k}\cdot\vec{x}}$$

Power Spectrum:

$$P(k) \equiv <|\tilde{\delta}(\vec{k})|^2> \;\propto k^n$$

rms perturbation:

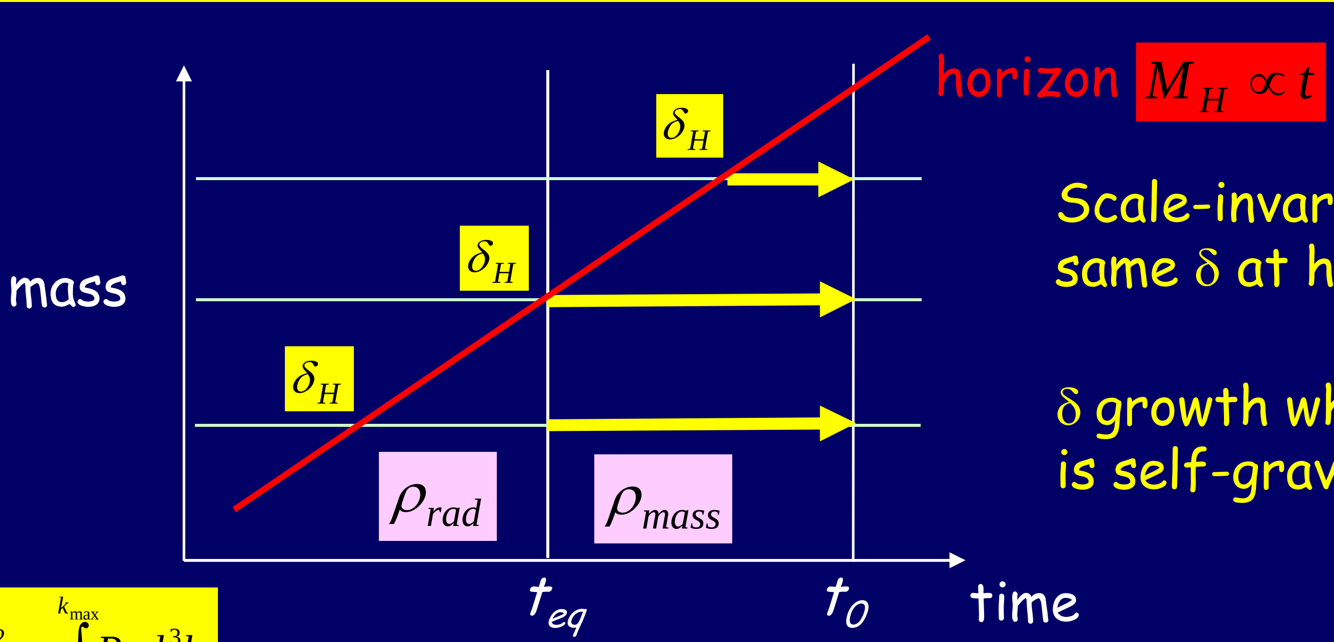
$$\delta_{rms} = <\delta^2>^{1/2} \propto \int_{k=0}^{k_{\max}} P_k\, d^3k \quad \propto M^{-(n+3)/6}$$

Correlation function:

$$\xi(r) \equiv <\delta(\vec{x})\delta(\vec{x}+\vec{r})> \;\propto \int |\tilde{\delta}(\vec{k})|^2\, e^{-i\vec{k}\cdot\vec{r}}\, d^3k \;\propto r^{-(n+3)}$$

$$dP = [1+\xi(r)]\, n\, dV$$

CDM Power Spectrum of linear fluctuations

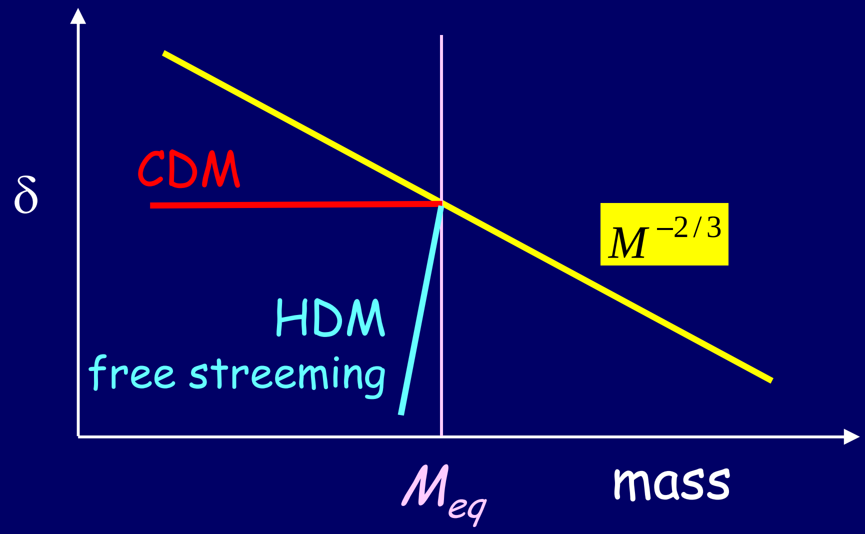


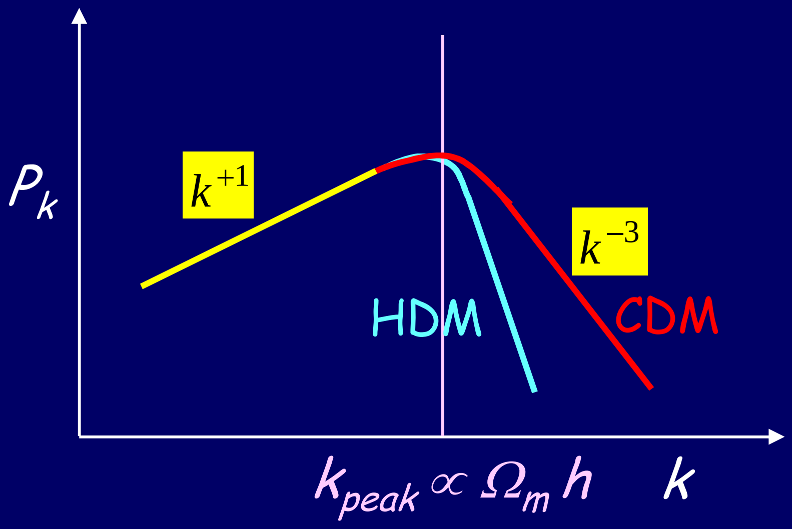
Scale-invariance:
same δ at horizon

δ growth when matter
is self-gravitating

$$< \delta^2 >^{1/2} \propto \int_{k=0}^{k_{\max}} P_k \; d^3k$$

$$\delta \propto (t/t_H)^{2/3} \propto t^{2/3} M^{-2/3}$$



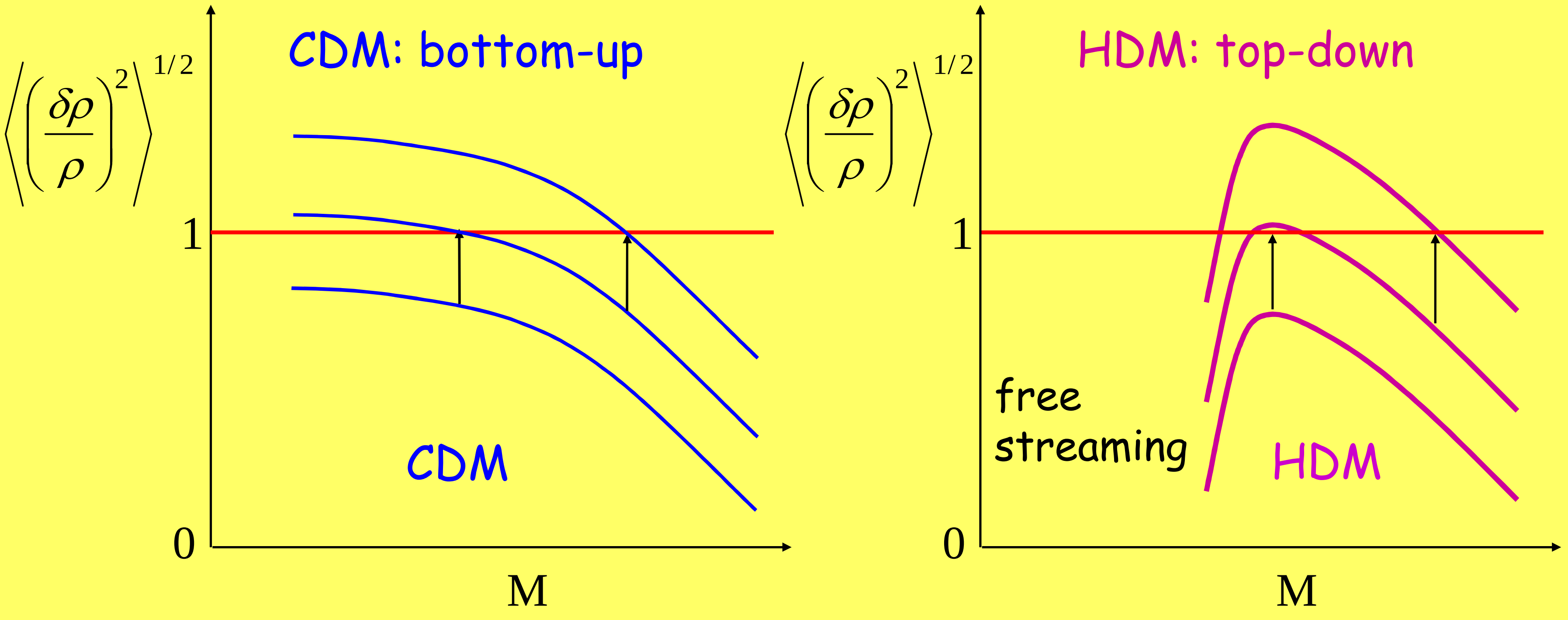


Formation of Large-Scale Structure

Linear fluctuation growth $\delta << 1 \quad \rightarrow \quad \delta \propto a \propto t^{2/3}$

rms fluctuation at mass scale M $P_k \propto k^n \;\rightarrow\; \delta \propto M^{-\alpha} \quad 0 < \alpha = \frac{n+3}{6} \leq 2/3$

Typical objects forming at a: $1 \sim \delta \propto M^{-\alpha} a \quad \rightarrow M_* \propto a^{1/\alpha}$



DM Particle Mass

HDM: relativistic till z_{eq}~10^4, T~10^4K -> m ~ ev,
M_H~$10^{15}M_\odot$ (clusters-superclusters)

WDM: M_H~$10^9M_\odot$ (small galaxies) -> m ~ kev

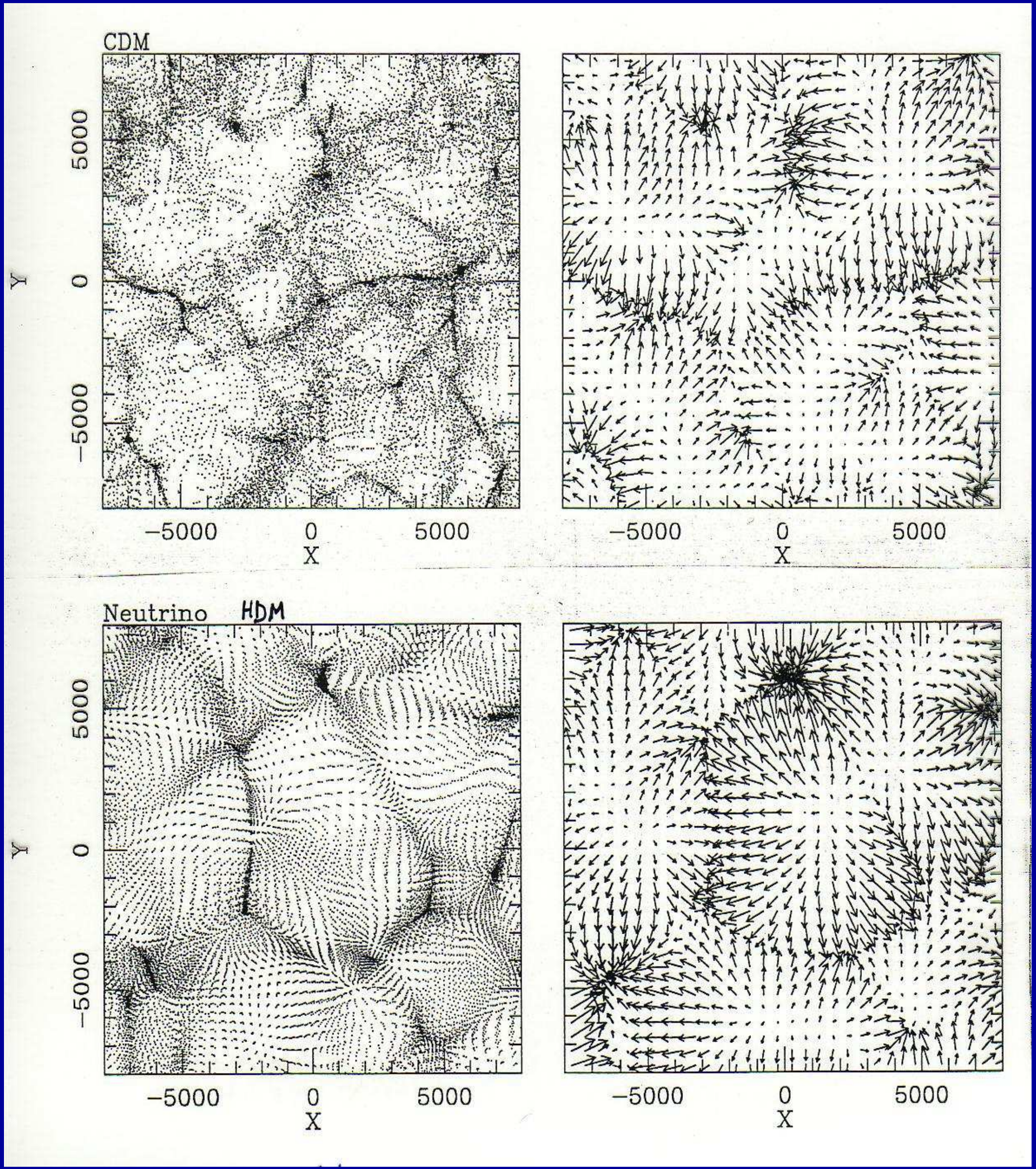
CDM: M_H~$10^6M_\odot$ (dwarf galaxies) -> m ~ Gev

Micro-Macro Connection

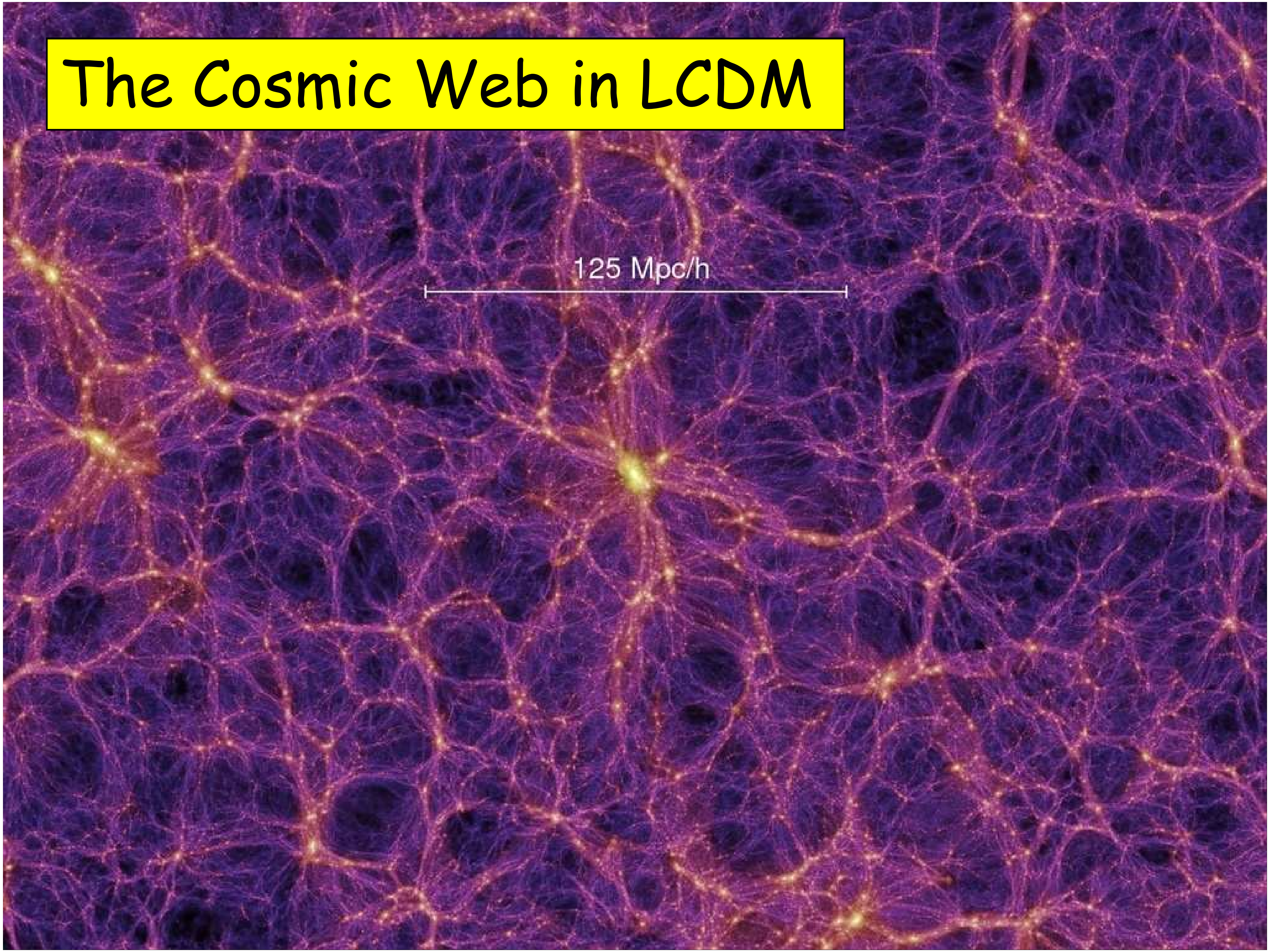
Cold Dark Matter

Hot Dark Matter

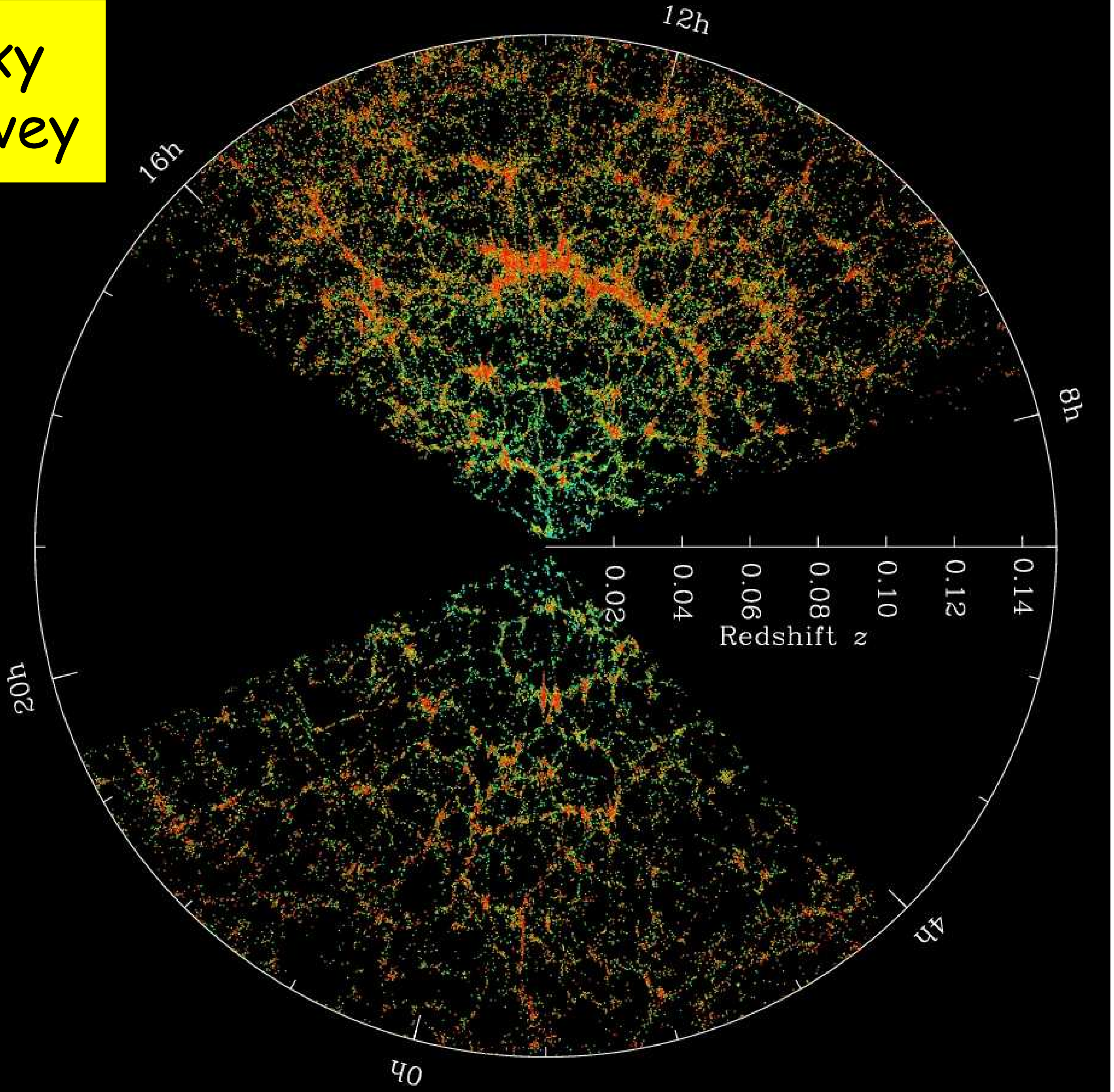
(ν)



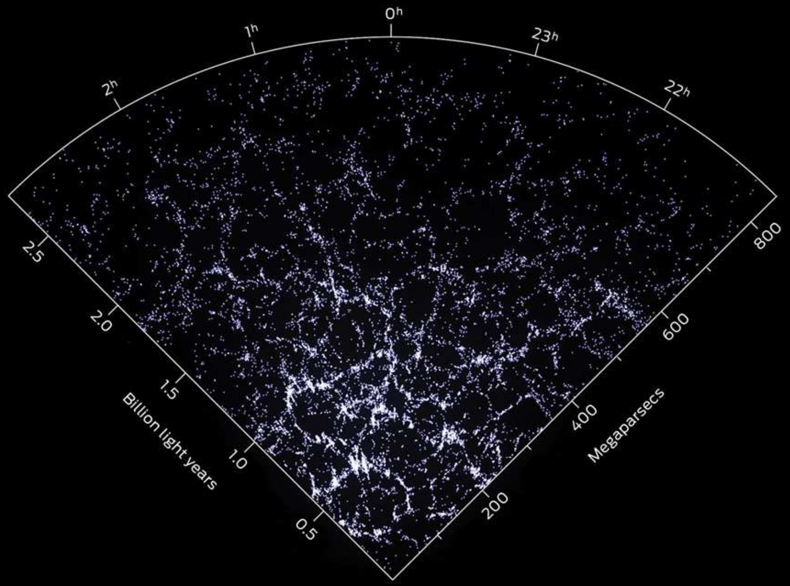
The Cosmic Web in LCDM



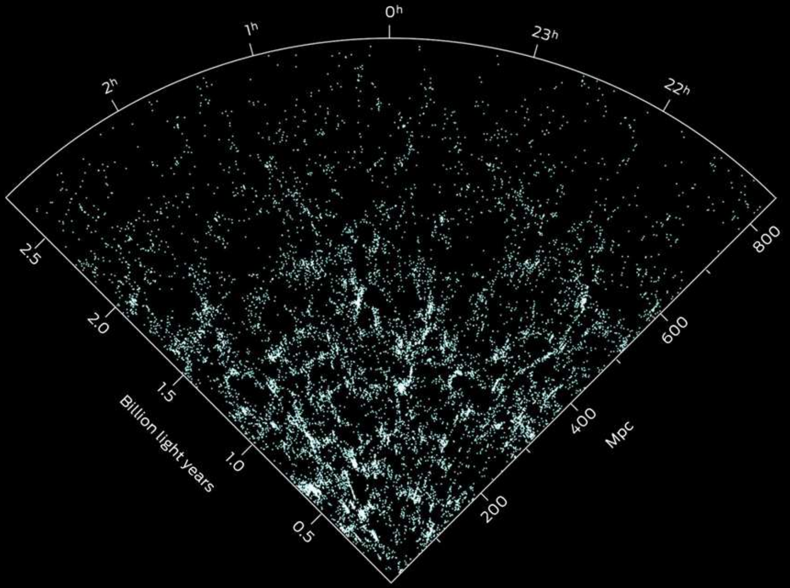
SDSS Galaxy Redshift Survey



Sloan Digital Sky Survey

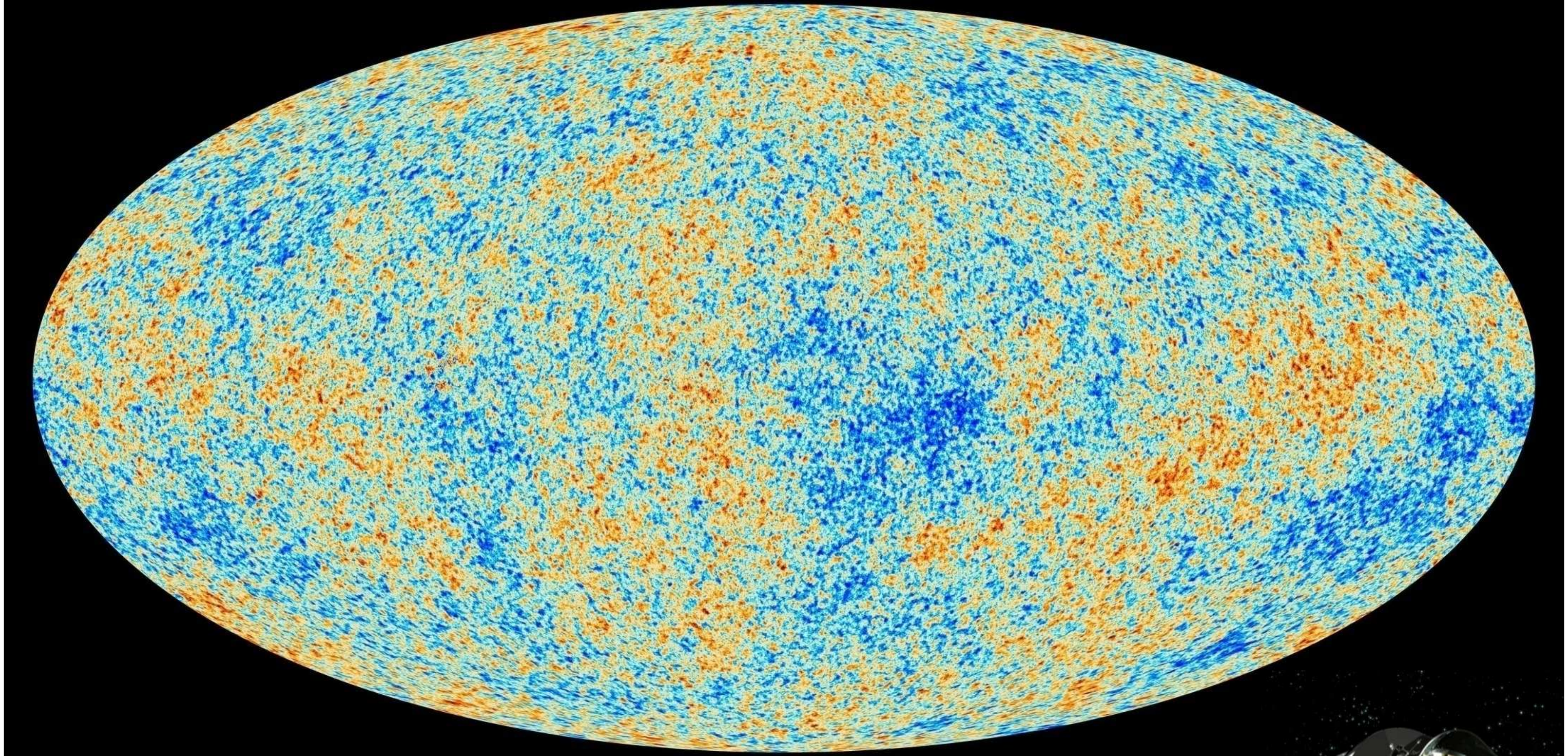


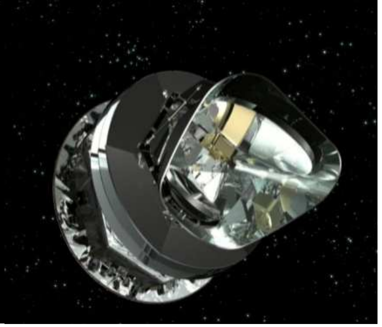
Bolshoi Simulation



Cosmic Microwave Background

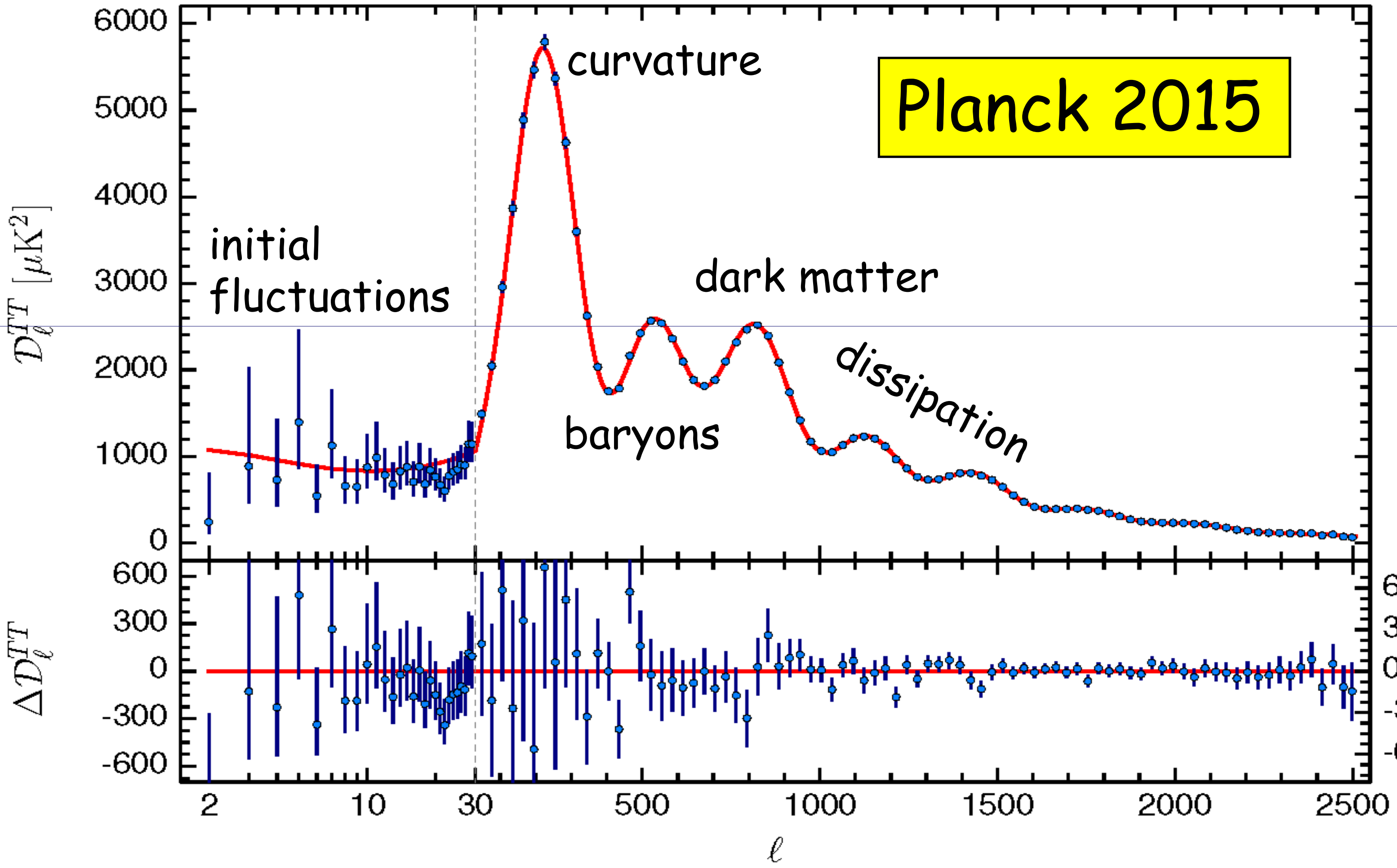
Planck 2015: CMB Temperature Map





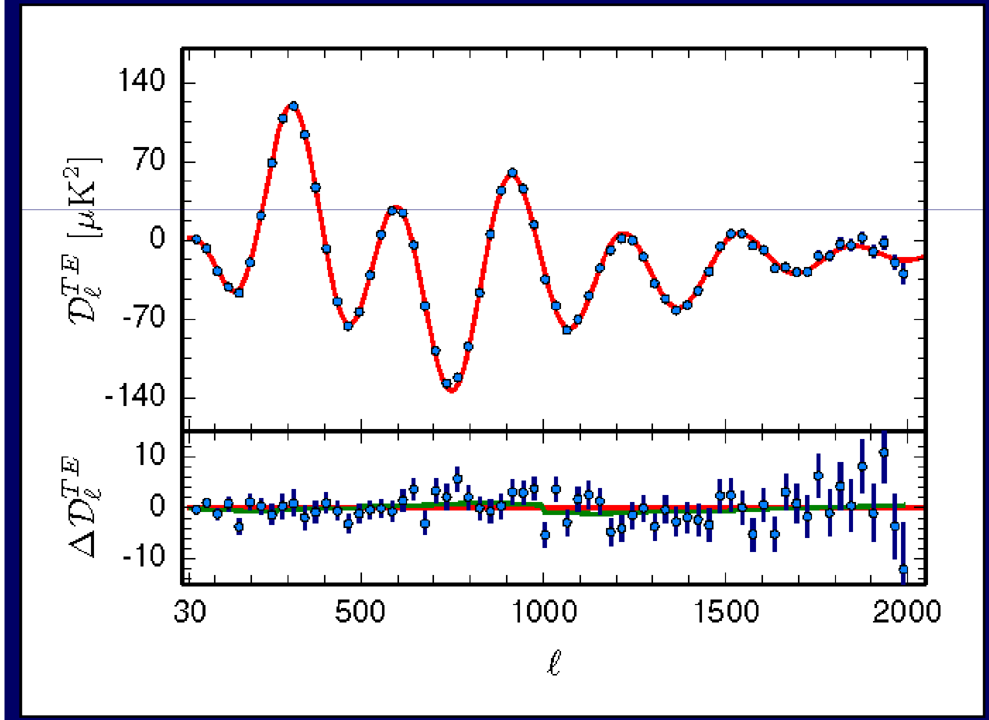
$\delta T/T \sim 10^{-5}$ arcmin

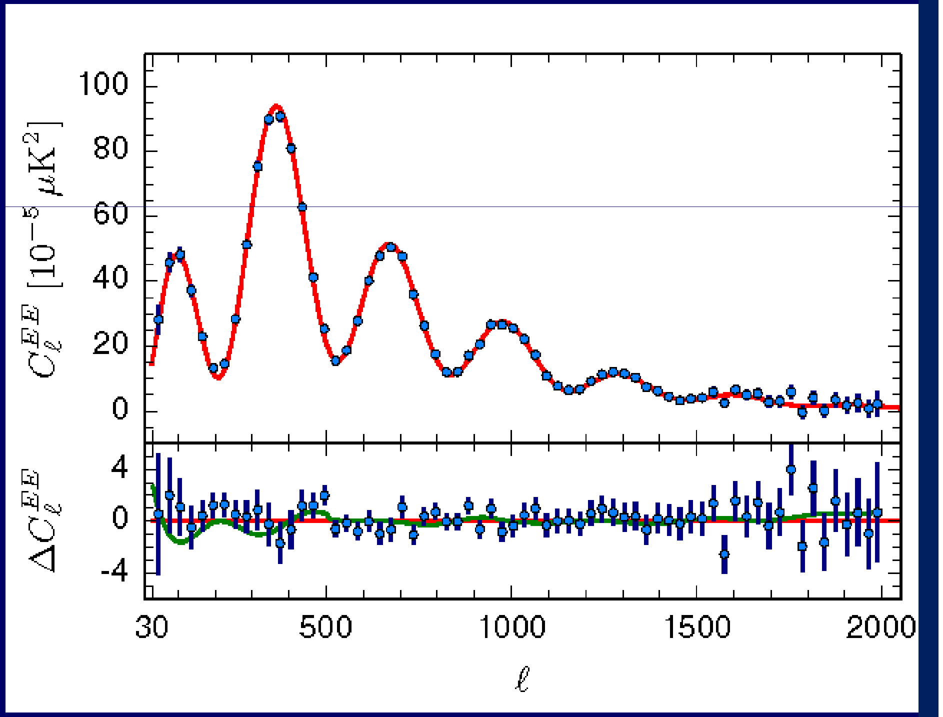
ΛCDM matches in detail the CMB TT fluctuations It allows accurate parameter determination



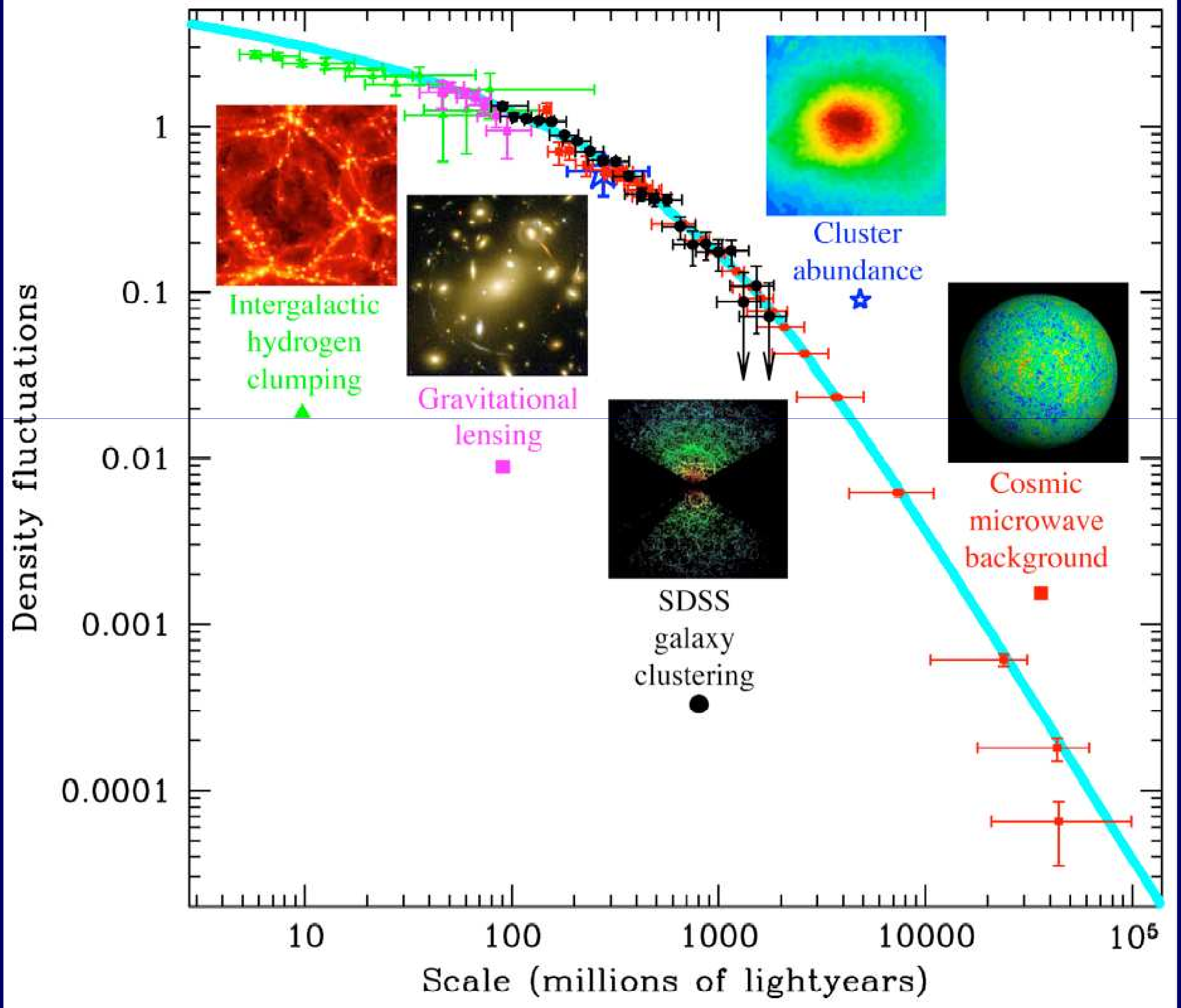
Polarization by scattering off electrons; re-ionization by stars & quasars at z~10

Planck 2015

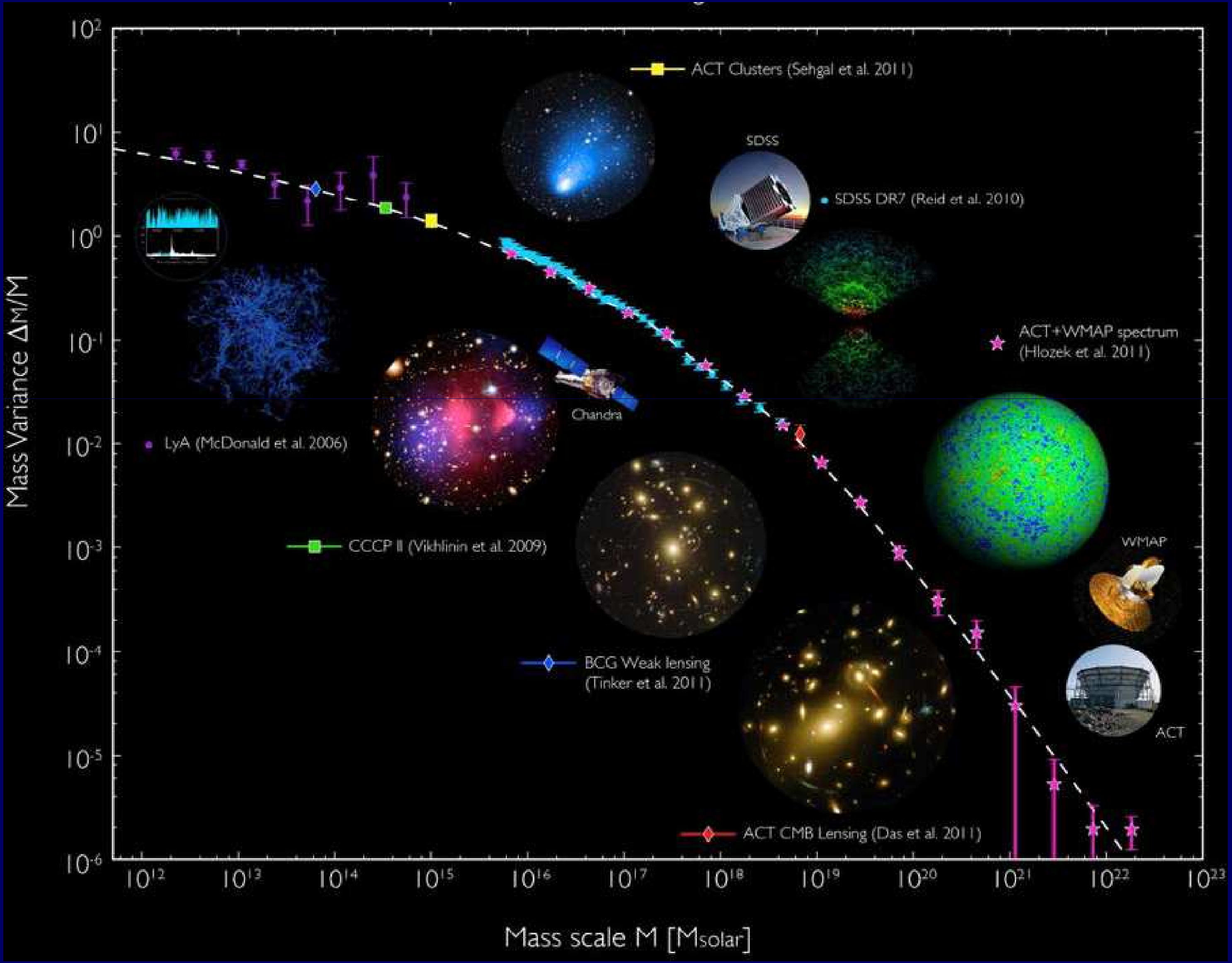




Success of the LCDM Power Spectum



Success of the LCDM Power Spectum



Standard ΛCDM Model Parameters

2015: Planck (+BAO+SN)

Total density	$\Omega_{m+\Lambda} = 1.000 \pm 0.005$
Dark energy density	$\Omega_\Lambda = 0.692 \pm 0.012$
Mass density	$\Omega_m = 0.308 \pm 0.012$
Baryon density	$\Omega_b = 0.0478 \pm 0.0004$
Hubble constant	$H_0 = 67.8 \pm 0.9$ km s^{-1} Mpc^{-1}
Age of universe	$t_0 = 13.80 \pm 0.02$ Gyr
Fluctuation spectral index	$n_s = 0.968 \pm 0.006$
Fluctuation amplitude	$\sigma_8 = 0.830 \pm 0.015$
Optical depth	$\tau = 0.066 \pm 0.016$

Beyond the Standard ΛCDM Model

2015: Planck (+BAO+SN)

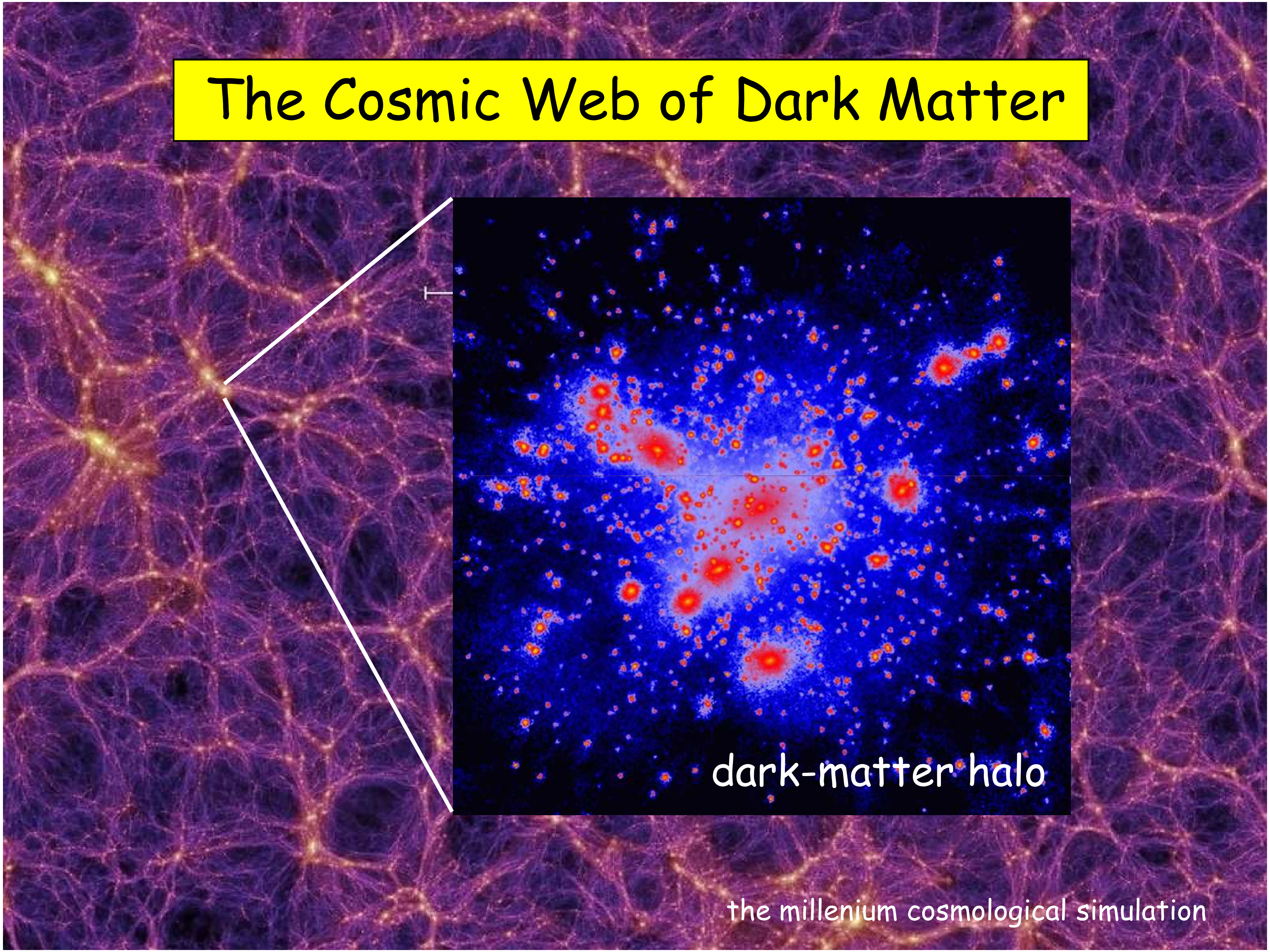
Total density	$\Omega_{tot} = 1-\Omega_k = 1.000 \pm 0.005$
Equation of state	$w = -1.006 \pm 0.045$

Tensor/scaler fluctuations	$r < 0.11$ (95% CL)
Running of spectral index	$dn/d\ln k = -0.03 \pm 0.02$

Neutrino mass	$\sum m_\nu < 0.23$ eV (95% CL)
# of light neutrino families	$N_{eff}=3.15 \pm 0.23$

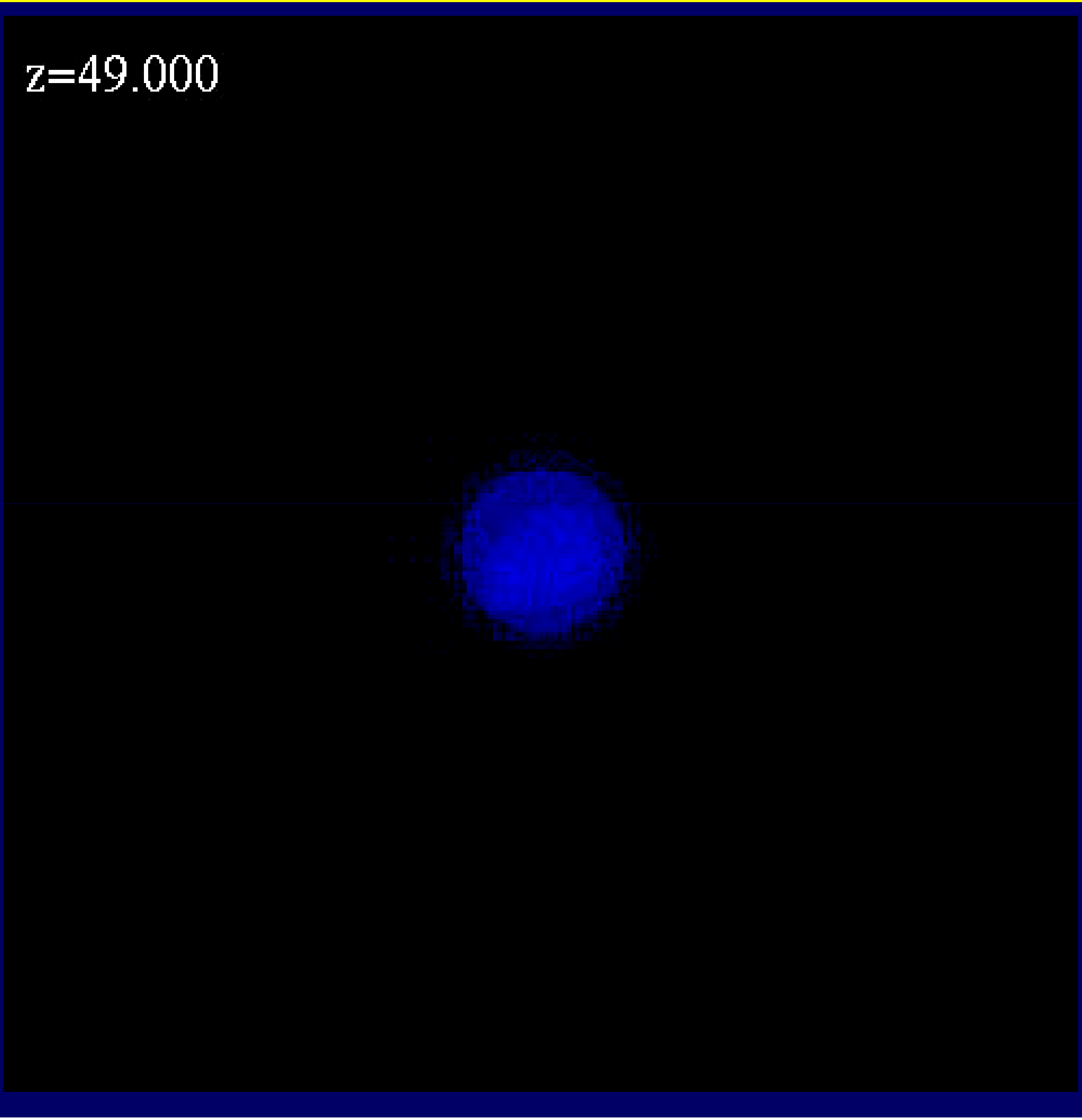
Dark-Matter Halos

The Cosmic Web of Dark Matter

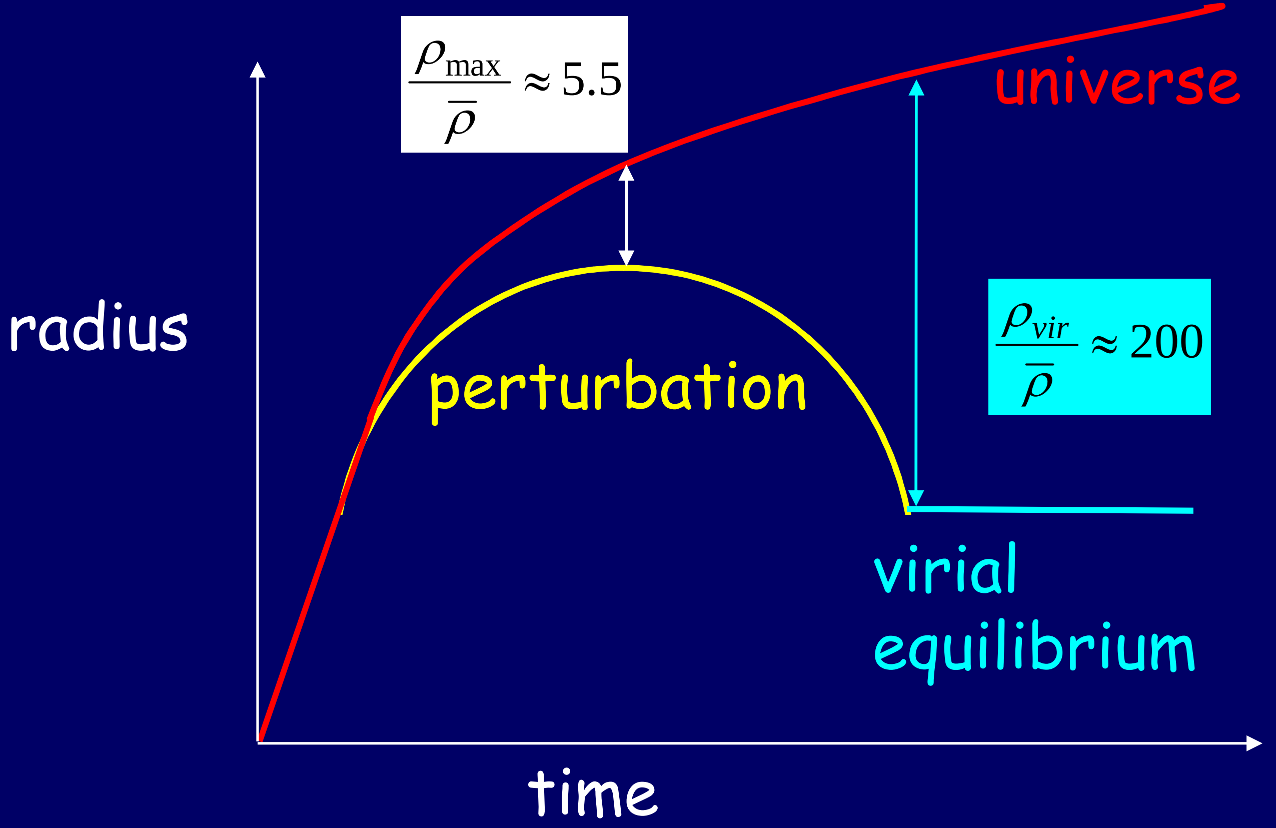


the millenium cosmological simulation

N-body simulation of Halo Formation



Spherical Collapse



$$\frac{\rho_{\max}}{\bar{\rho}} \approx 5.5$$

universe

radius

perturbation

$$\frac{\rho_{vir}}{\bar{\rho}} \approx 200$$

virial equilibrium

time

virial equilibrium:

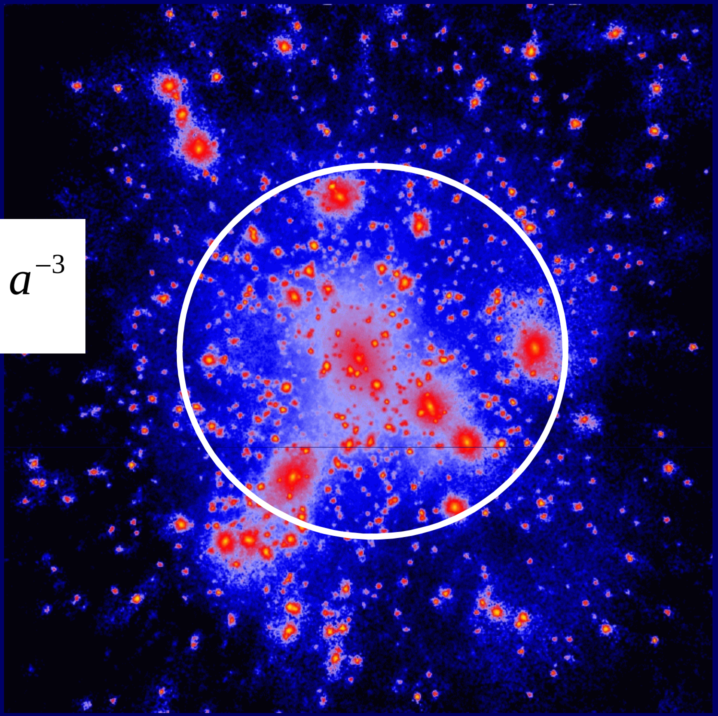
$$E = -\frac{1}{2}\frac{GM}{R_{vir}} = -\frac{GM}{R_{\max}}$$

Halo Virial Scaling Relations

Virial equilibrium: $V_{\mathrm{v}}^2 = \dfrac{GM_{\mathrm{v}}}{R_{\mathrm{v}}}$

Spherical collapse: $\dfrac{M_{\mathrm{v}}}{(4\pi/3)\,R_{\mathrm{v}}^3} = 200\,\rho_u = 200\,\rho_{u0}\,a^{-3}$

$$\rightarrow \quad \boxed{M_{\mathrm{v}} \propto V_{\mathrm{v}}^3\, a^{3/2} \propto R_{\mathrm{v}}^3\, a^{-3}}$$

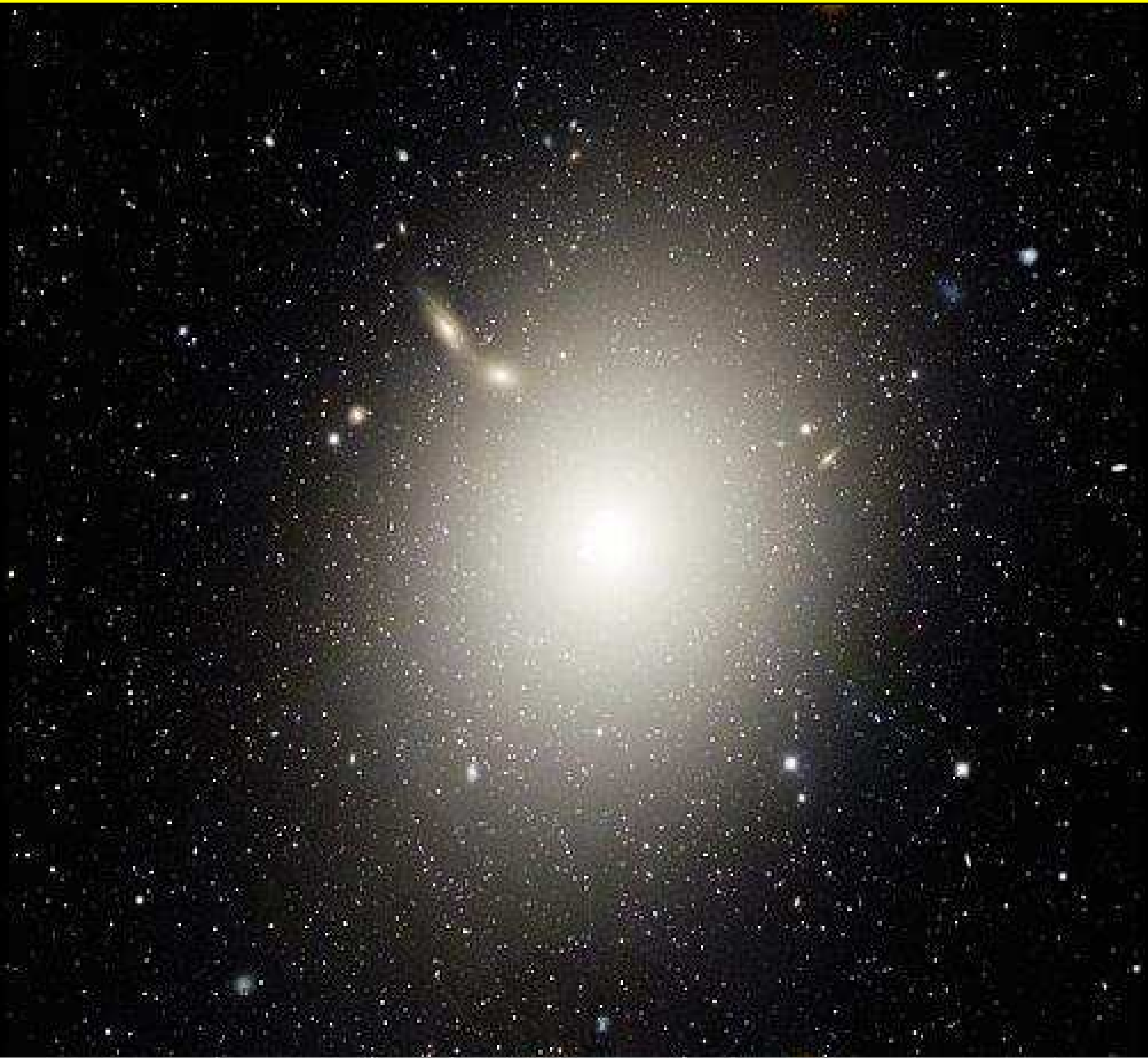


To get the observed Tully-Fisher Relation: $L \sim V_{\mathrm{disk}}^4$
need only small adjustments

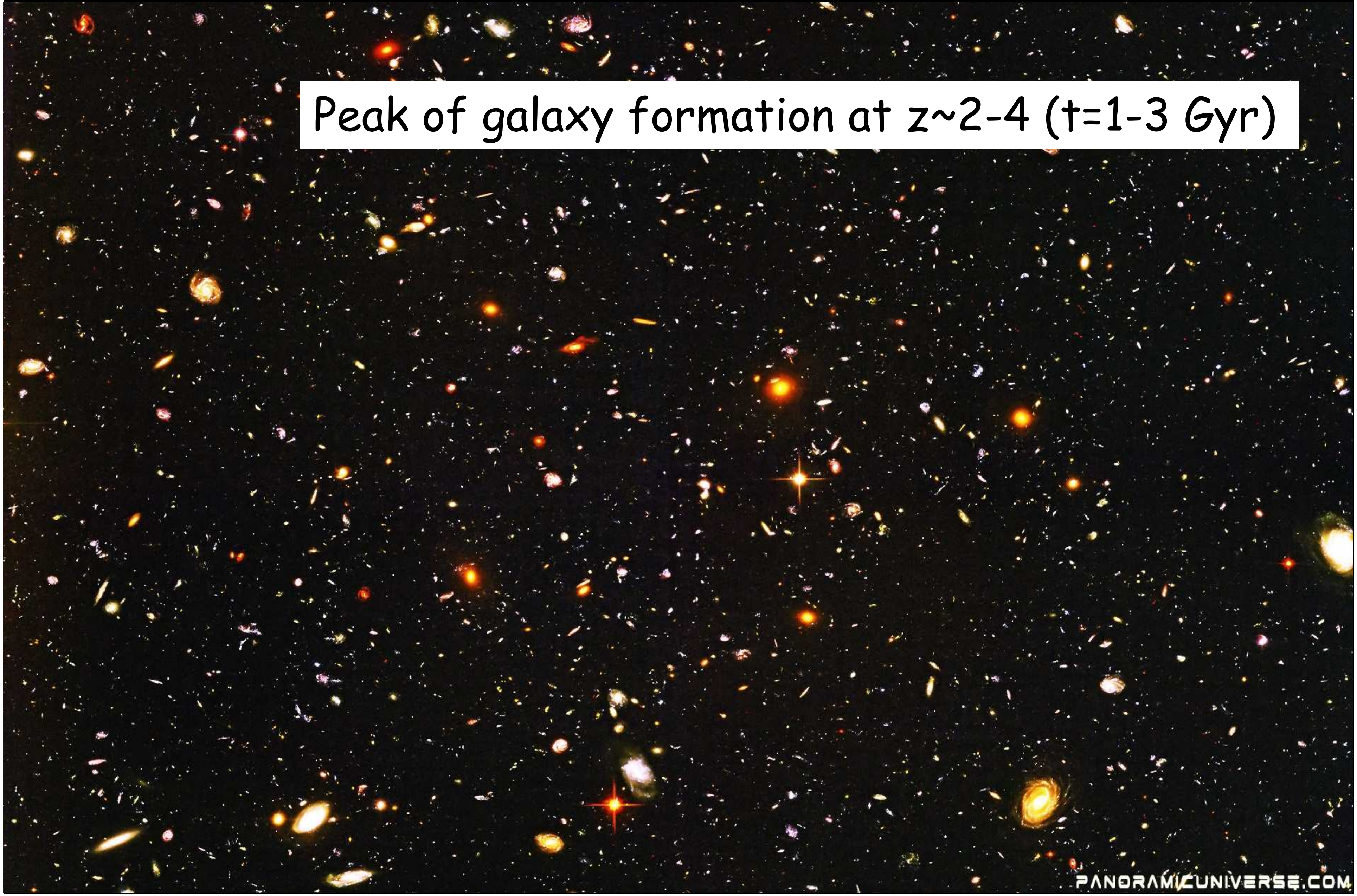
Galaxy Formation
A Recent Paradigm Shift

Disks: rotating, gas and young stars, blue

Spheroids: pressure-support, old stars, red



Hubble Deep Fields: Time Evolution



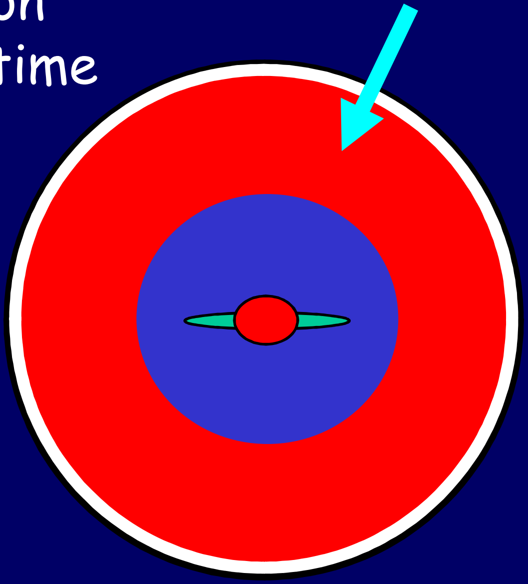
Peak of galaxy formation at z~2-4 (t=1-3 Gyr)

Standard Picture: Spherical Collapse

Rees & Ostriker 77, Silk 77, White & Rees 78, Fall & Efstathiou 80 ...

Proto-halo expansion, turnaround,
collapse to a virialized DM halo – at overdensity ~ 200

AM by tidal torques prior to maximum expansion
Spin $\lambda\sim(J/M)/RV\sim0.04$ independent of mass and time



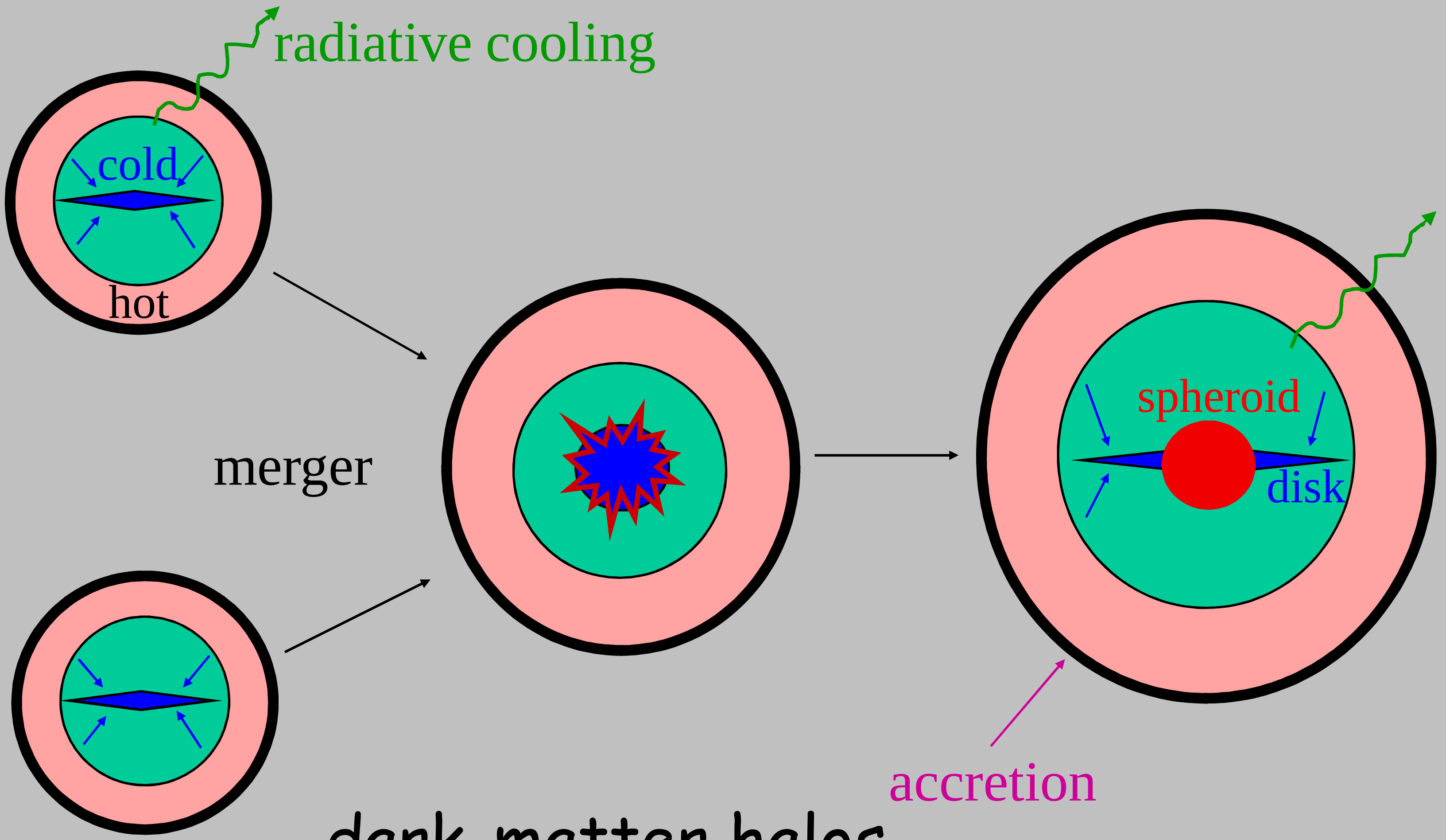
Spherical gas infall into the halo
Virial shock heating to $T_v\sim10^6$K

Radiative cooling, cylindrical accretion to disk

AM is conserved. Halo AM determines disk
size and structure: $R_{disk} \sim \lambda\, R_{halo}$

Bulge by mergers & disk instability

Standard Paradigm: Mergers



dark-matter halos

cold gas - disk - starburst, spheroid - old stars

Stellar+AGN feedback leads to red-and-dead Ellipticals

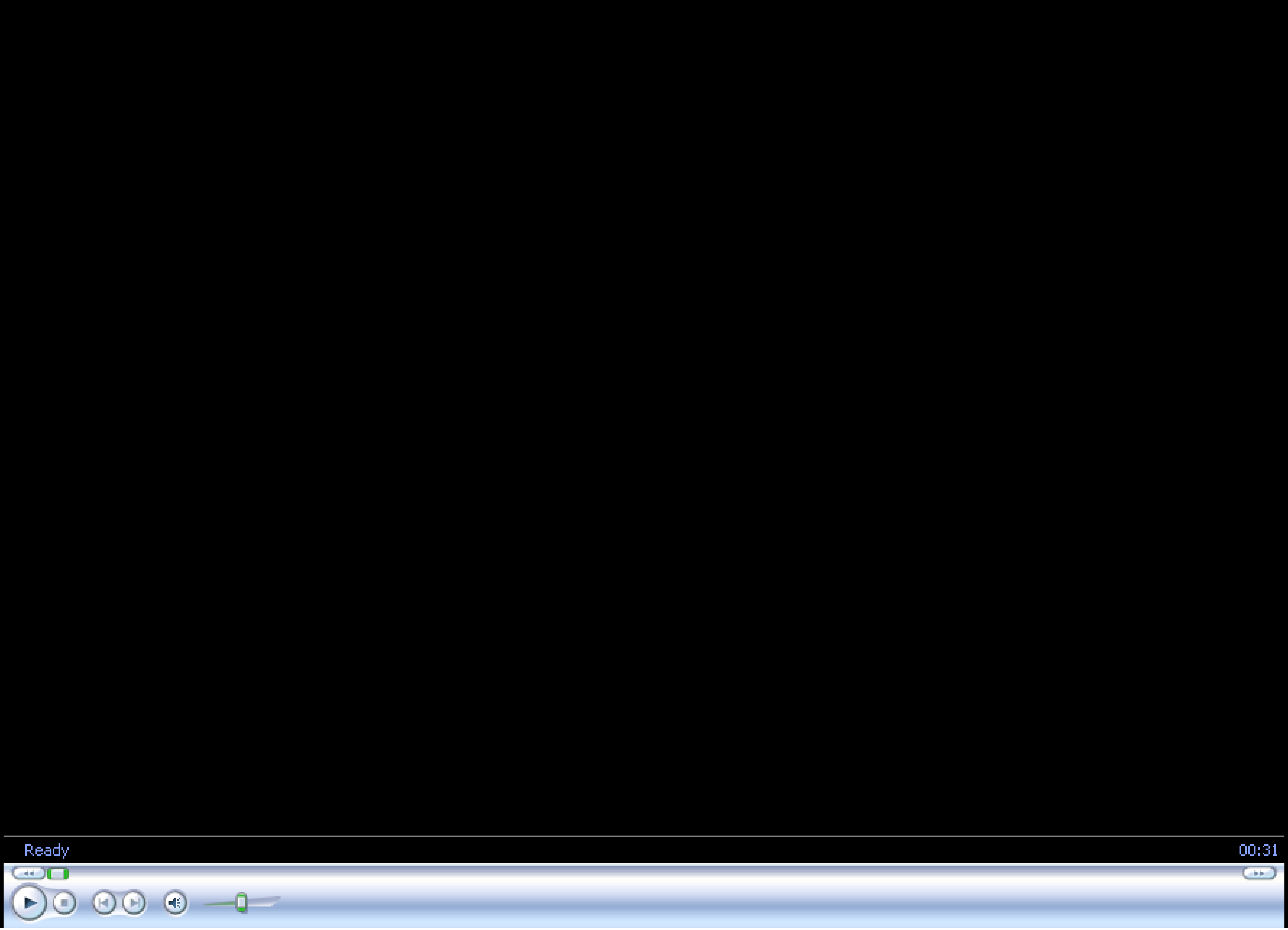
A Galaxy Merger

The Mice • Interacting Galaxies NGC 4676

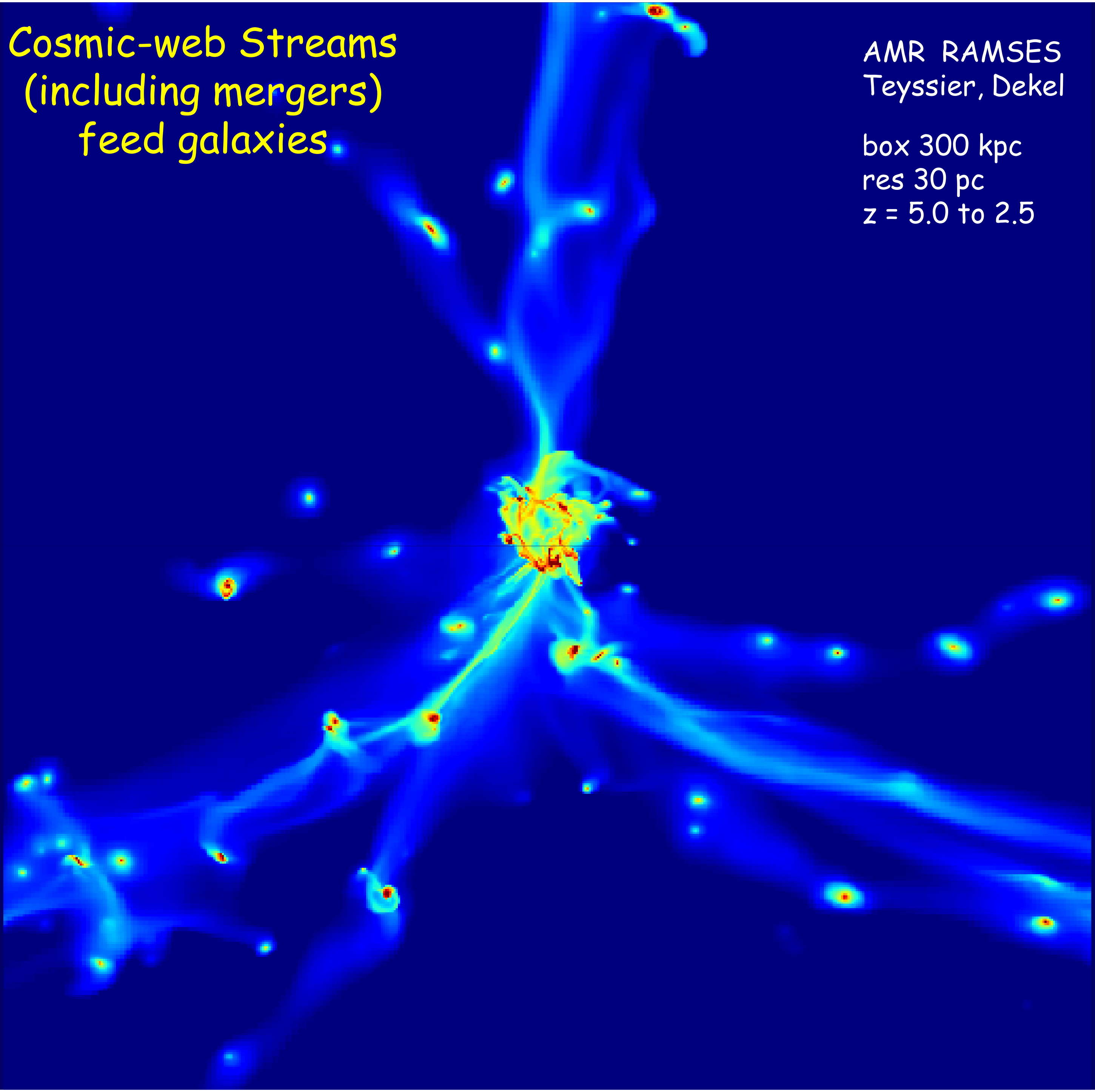
Hubble Space Telescope • Advanced Camera for Surveys

NASA, H. Ford (JHU), G. Illingworth (UCSC/LO), M. Clampin (STScI), G. Hartig (STScI) and the ACS Science Team • STScI-PRC02-11d

Mergers: Simulations versus Observations



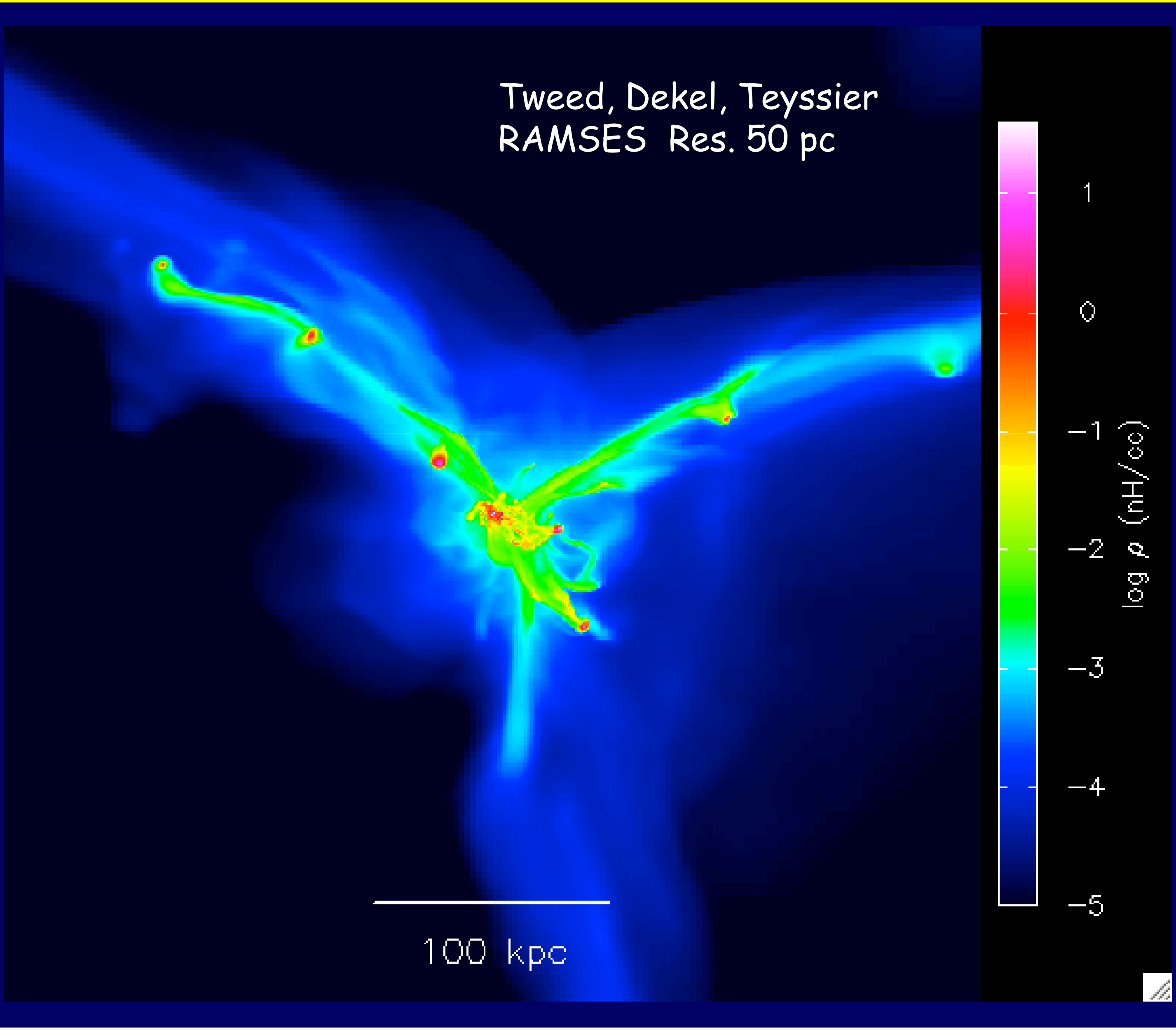
Cosmic-web Streams (including mergers) feed galaxies

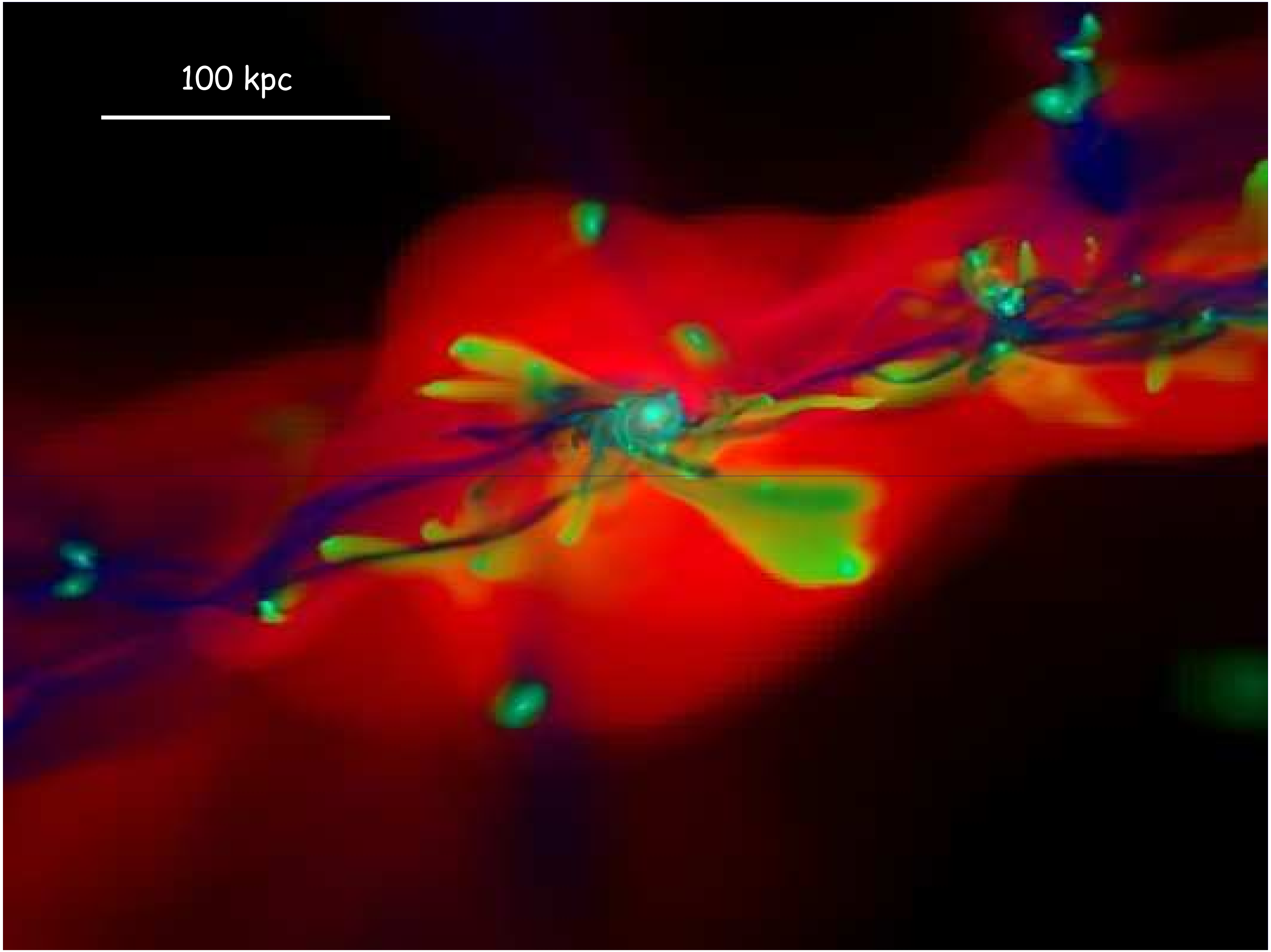


AMR RAMSES
Teyssier, Dekel

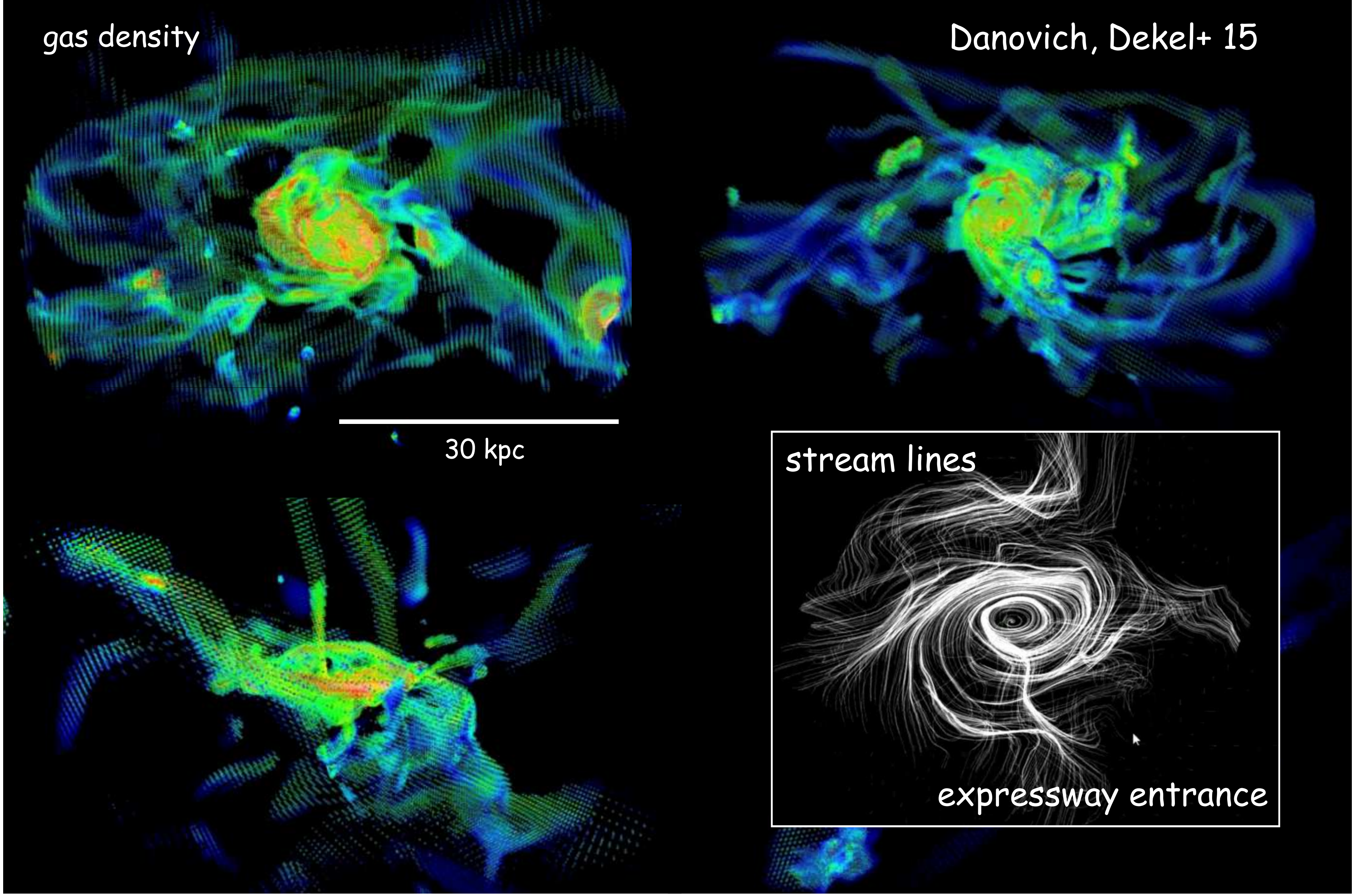
box 300 kpc
res 30 pc
z = 5.0 to 2.5

Streams Feeding a High-z Galaxy




100 kpc

An Extended Tilted Ring about the Disk



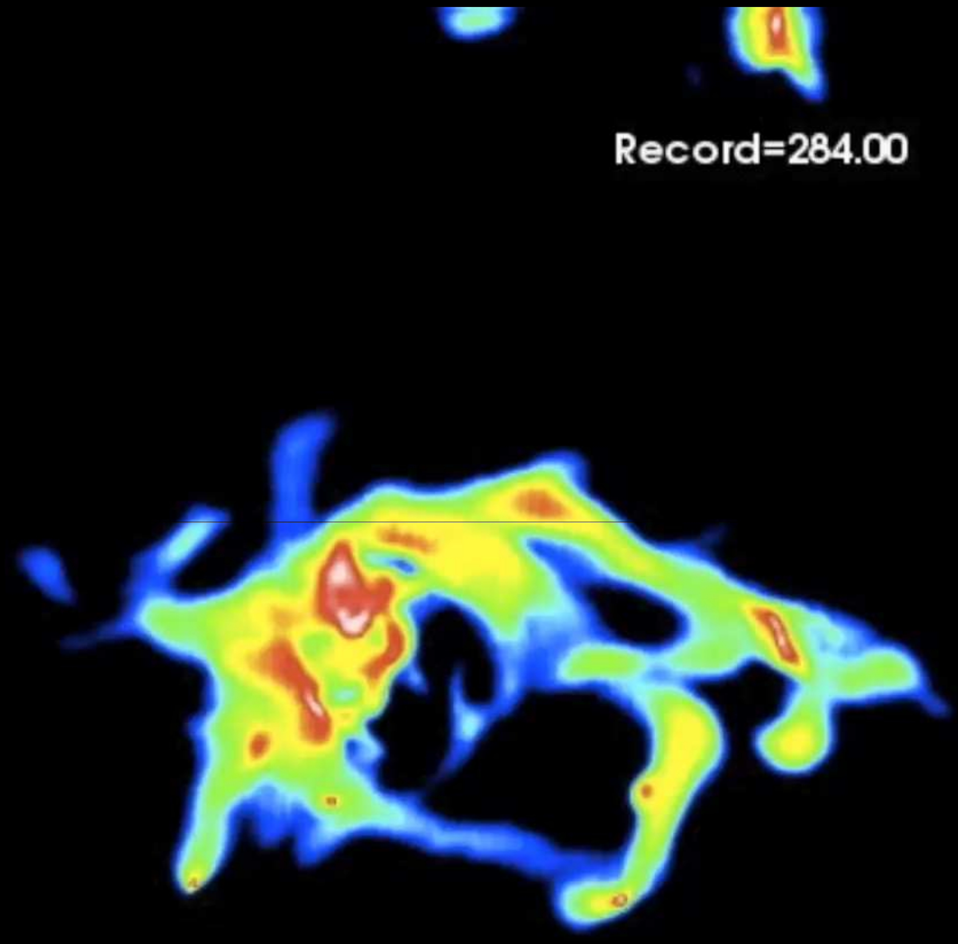
Danovich, Dekel+ 15

Clumpy Disk

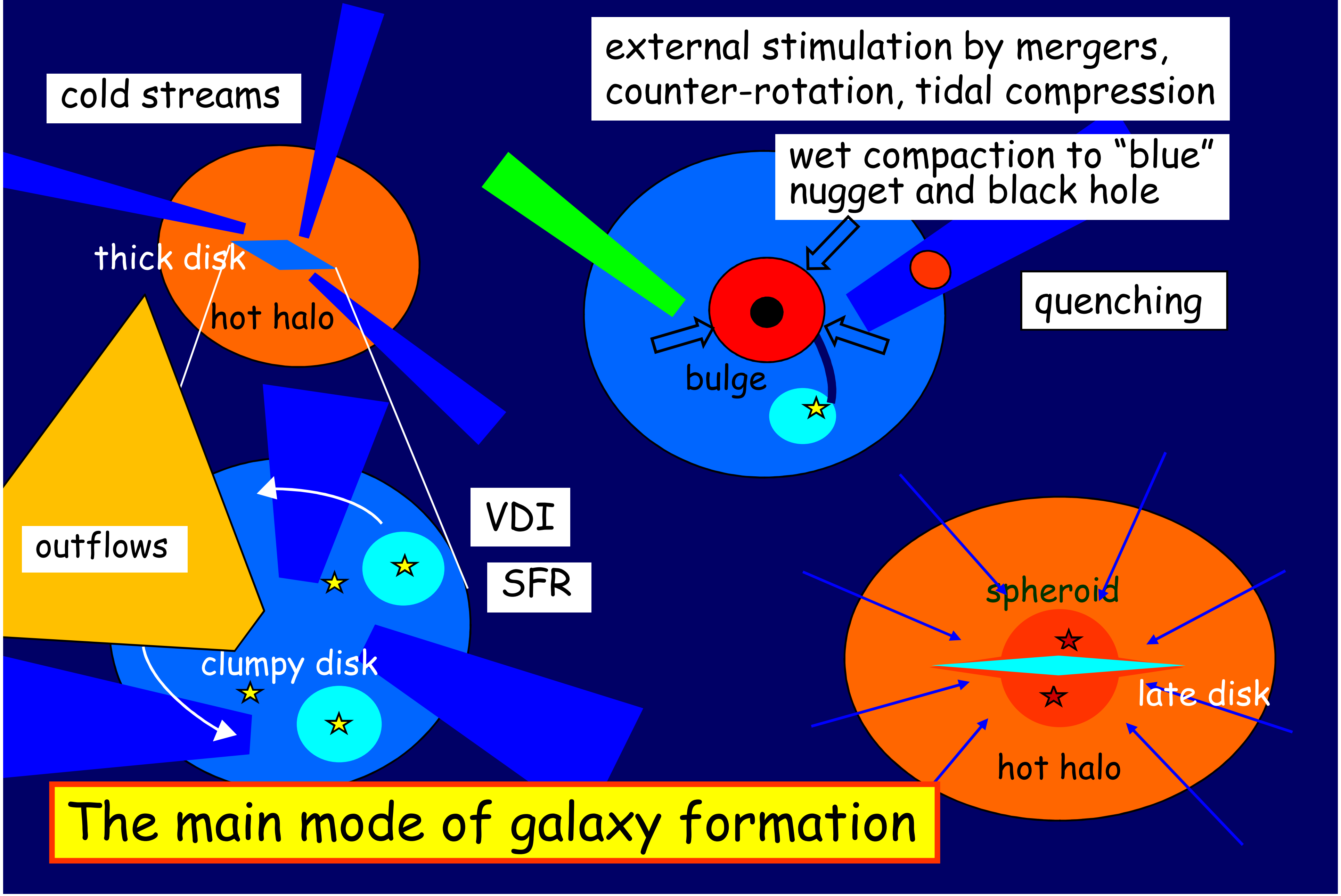
Ceverino, Dekel et al.

10 kpc

z=4-2.1



Stream-Fed Galaxies at High z



cold streams

thick disk

hot halo

outflows

VDI

SFR

clumpy disk

external stimulation by mergers, counter-rotation, tidal compression

wet compaction to "blue" nugget and black hole

bulge

quenching

spheroid

late disk

hot halo

The main mode of galaxy formation

Challenges to LCDM

The Tully-Fisher Relation

From Halo Virial Relations to Observed TF

$$\boxed{M_{\rm v} \propto V_{\rm v}^{3} a^{3/2}} \longrightarrow \boxed{L \propto V_{\rm disk}^{4}}$$

Massive galaxies

no outflows $M_* \propto M_{\rm v}$ $L \propto M_*$

rotation curve shape $V_{\rm disk} / V_{\rm v} \propto V_v^{-0.5}$

$$\longrightarrow \boxed{L \propto V_{\rm disk}^{4}}$$

Low-mass galaxies

strong outflows $M_* / M_{\rm v} \propto V_{\rm v}^{2}$

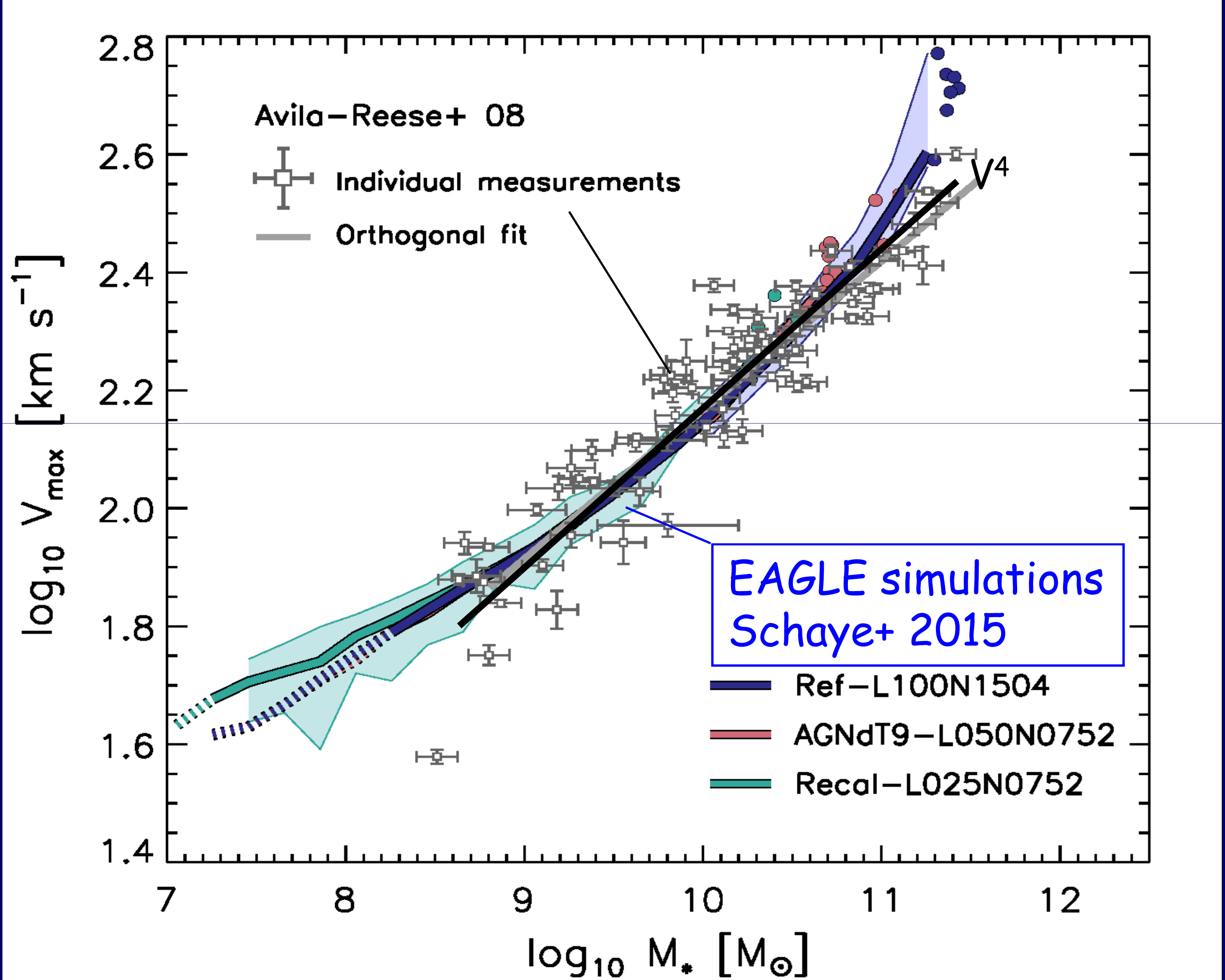
low-mass gals are blue $L / M_* \propto M_*^{-0.2}$

$V_{\rm disk} \approx V_{\rm v}$

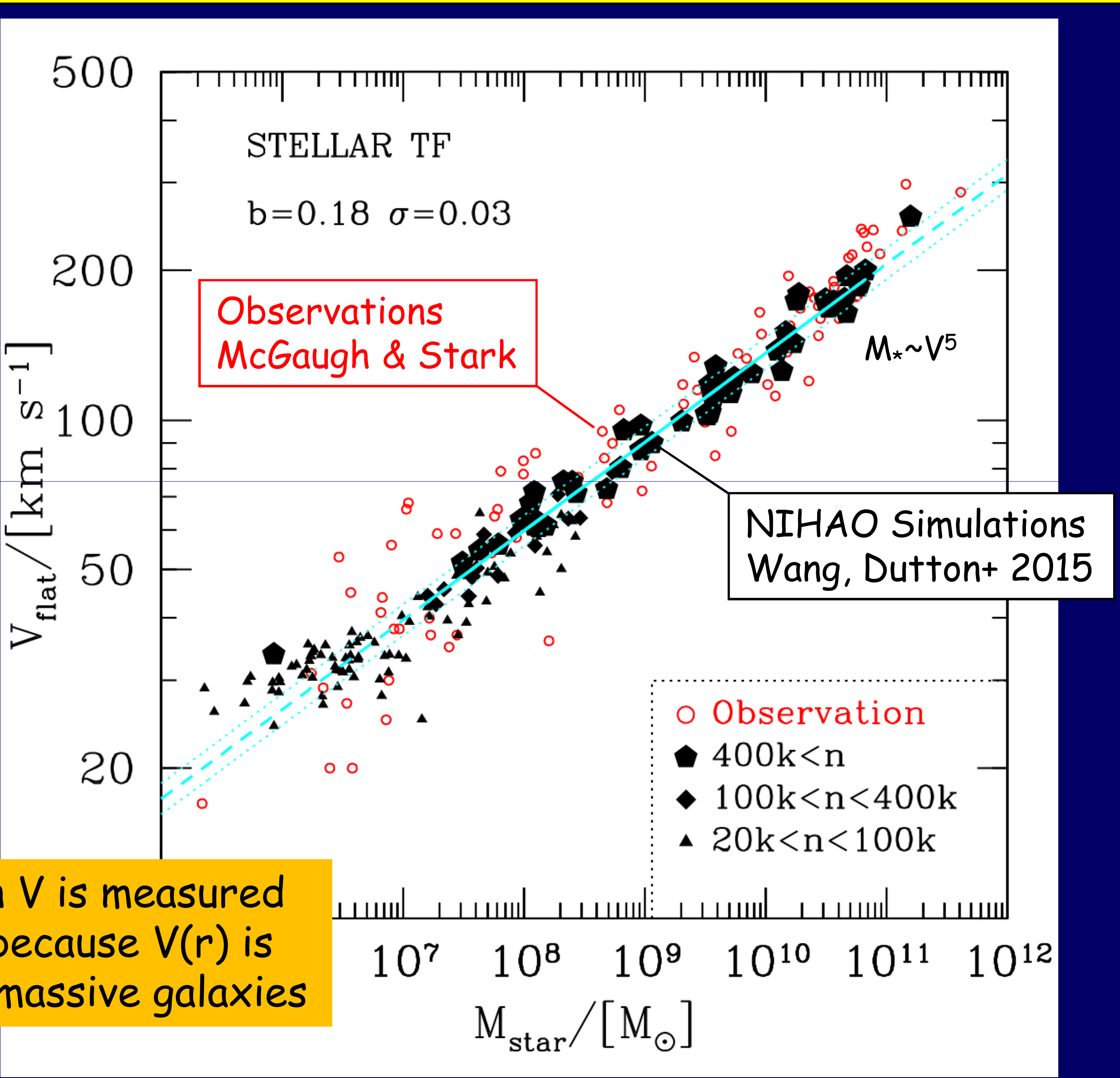
$$\longrightarrow \boxed{L \propto V_{\rm disk}^{4}}$$

Challenge: reproduce simultaneously the slope, zero-point, scatter, and the luminosity function

TF Relation: Simulations vs Observations



TF Relation: Simulations vs Observations



Observations
McGaugh & Stark

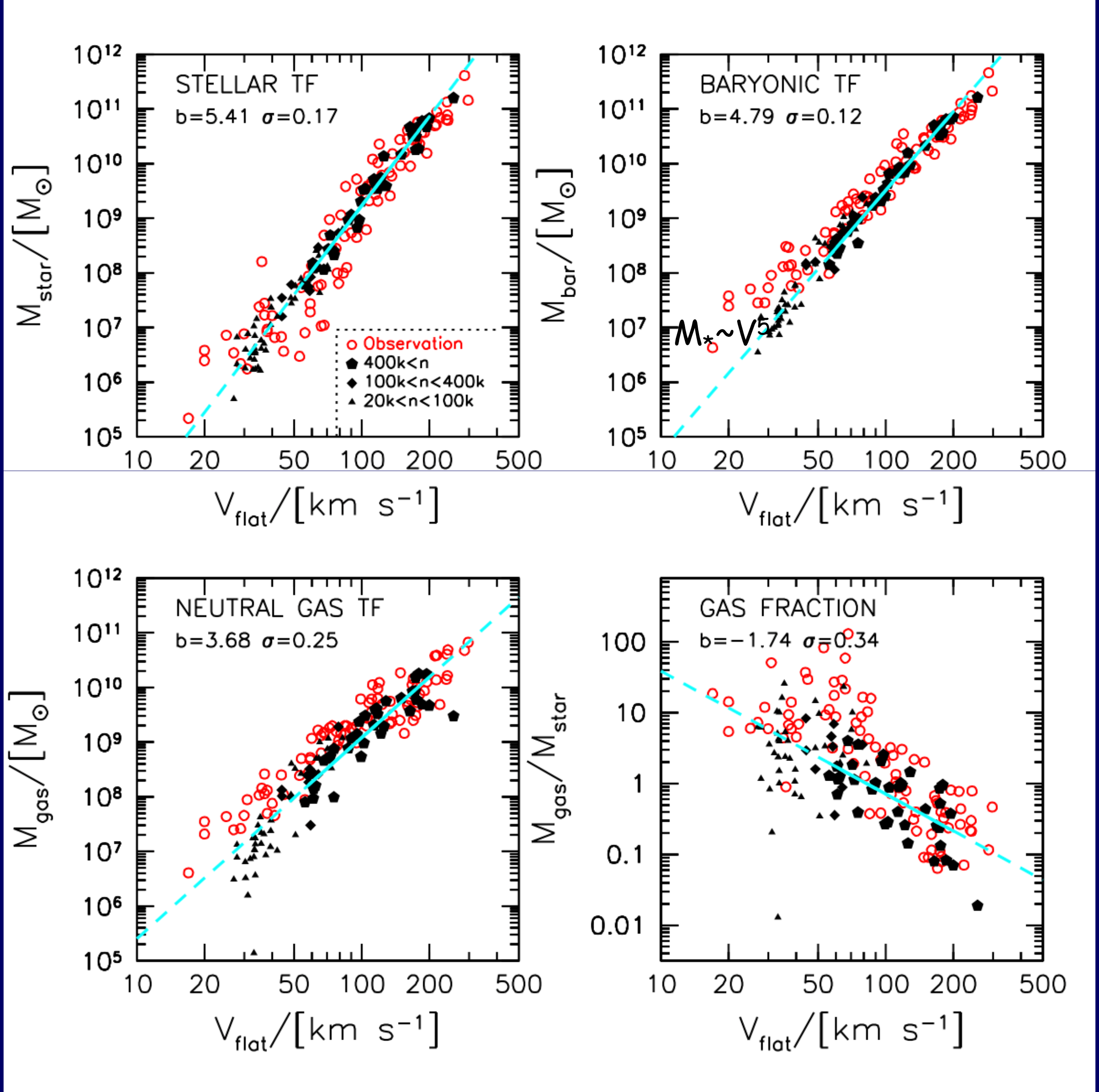
NIHAO Simulations
Wang, Dutton+ 2015

Steeper when V is measured at a larger r because V(r) is declining for massive galaxies

TF Relation: Simulations vs Observations

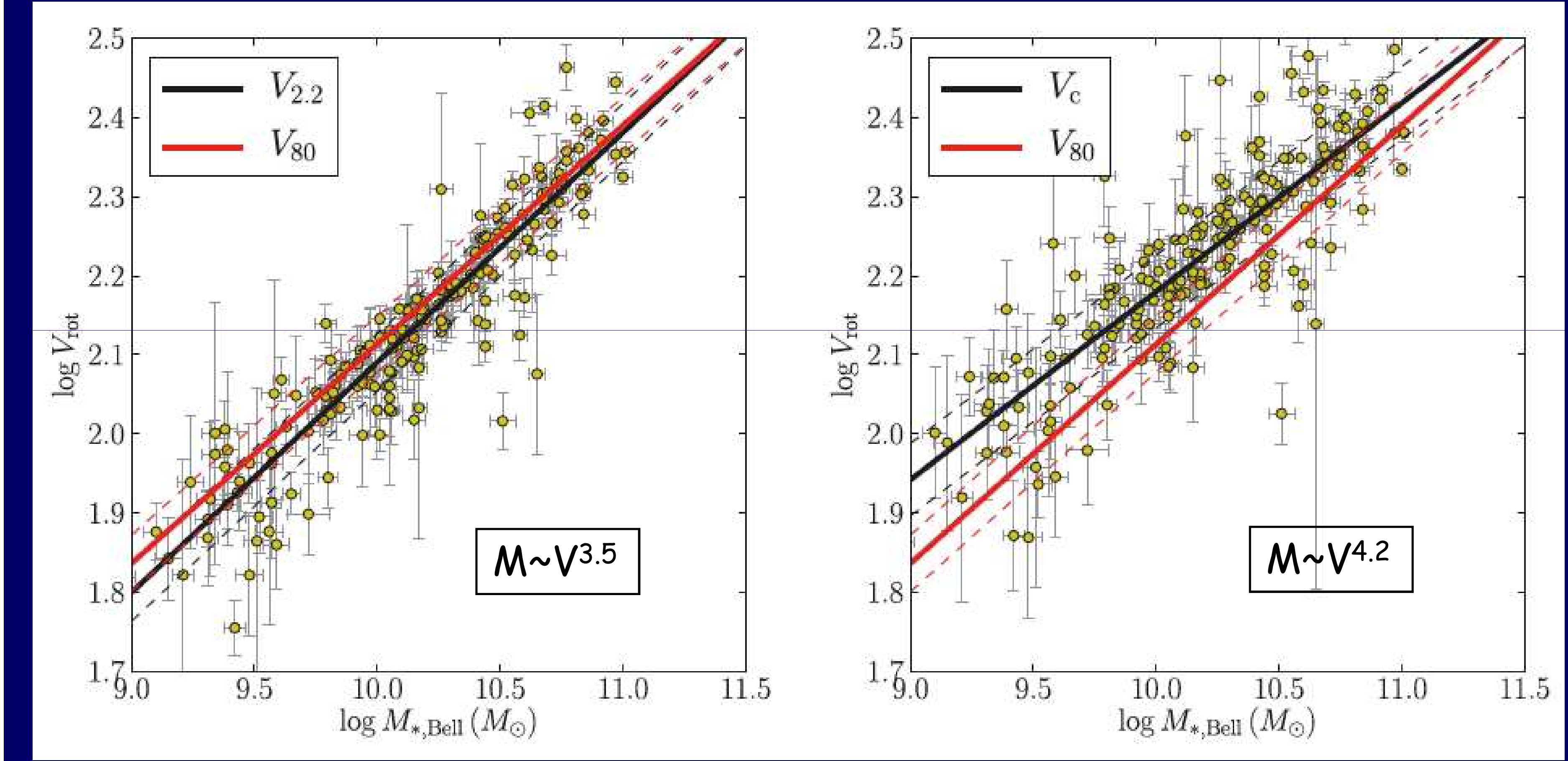
Observations
McGaugh & Stark

NIHAO Simulations
Wang, Dutton+ 2015



The TF slope depends on which V is used

Reyes+ 2011



The Challenge in the TF Relation

Need to reproduce simultaneously the
- slope ~3-5
- zero-point
- small scatter ±0.2 dex

and
- the galaxy luminosity function

Given the DM virial relations, the key for the adjustments is the systematic variations of V_{disk}/V_{vir} and M_*/M_{vir} (or M_{bar}/M_{vir})

These variations depend on halo properties, gas inflow, SFR, and especially on feedback!

Adiabatic contraction of DM must be avoided – otherwise V_{disk} gets too high (zero-point). Feedback!

The small scatter is because galaxies evolve along the relation: more gas -> higher SFR -> larger M_* -> higher V

Mass Function: Galaxies vs DM Halos

Halos (Press-Schechter)

Scale of non-linear fluctuations

$$M_{PS}(a) \text{ by } \left\langle \delta^2 \right\rangle^{1/2}(M_{PS},a) = \delta_{\text{collapse}} \approx 1.7$$

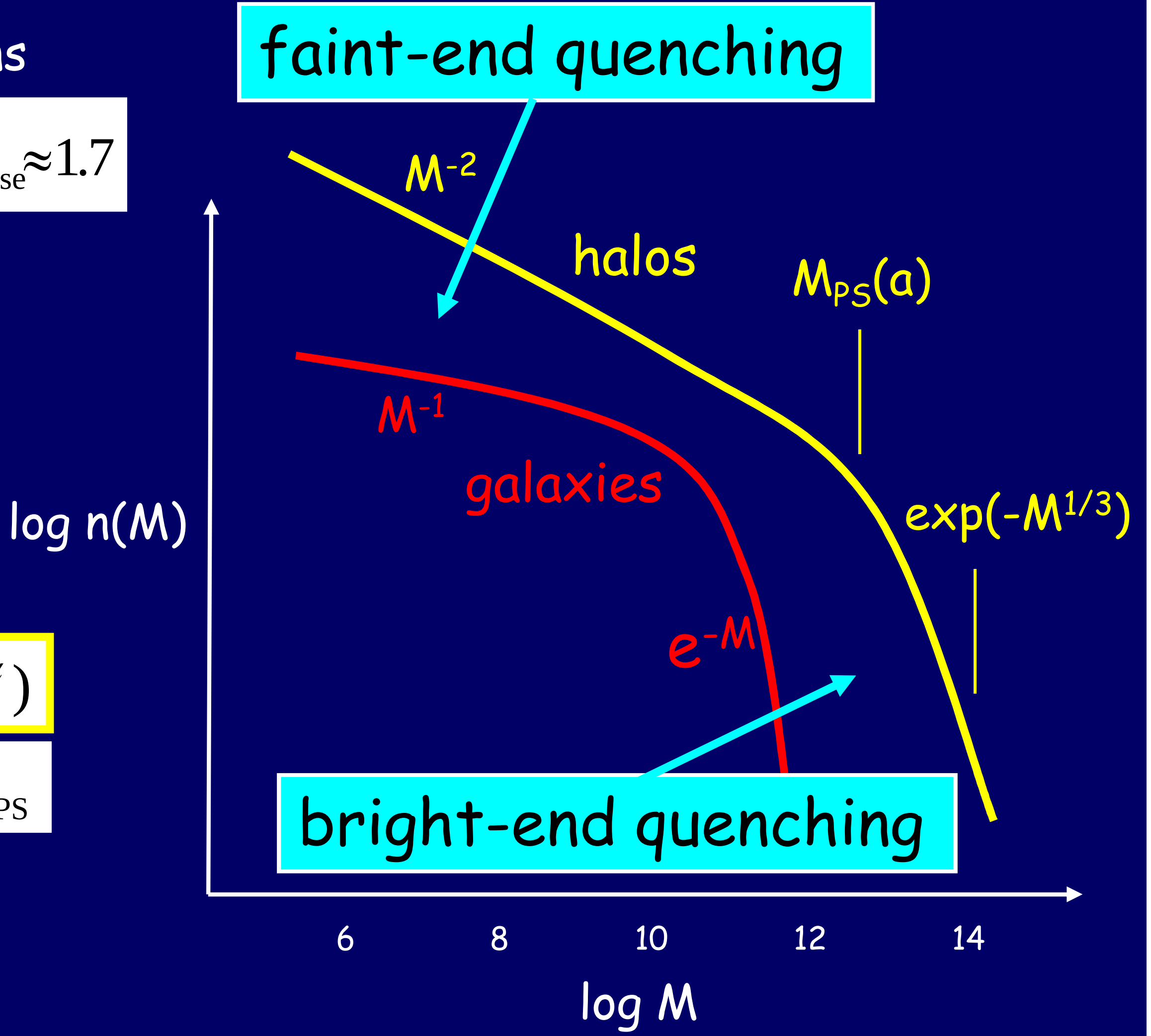
A power-law power spectrum

$$P_k \propto k^n \qquad \alpha = (3+n)/6 \approx 1/6$$

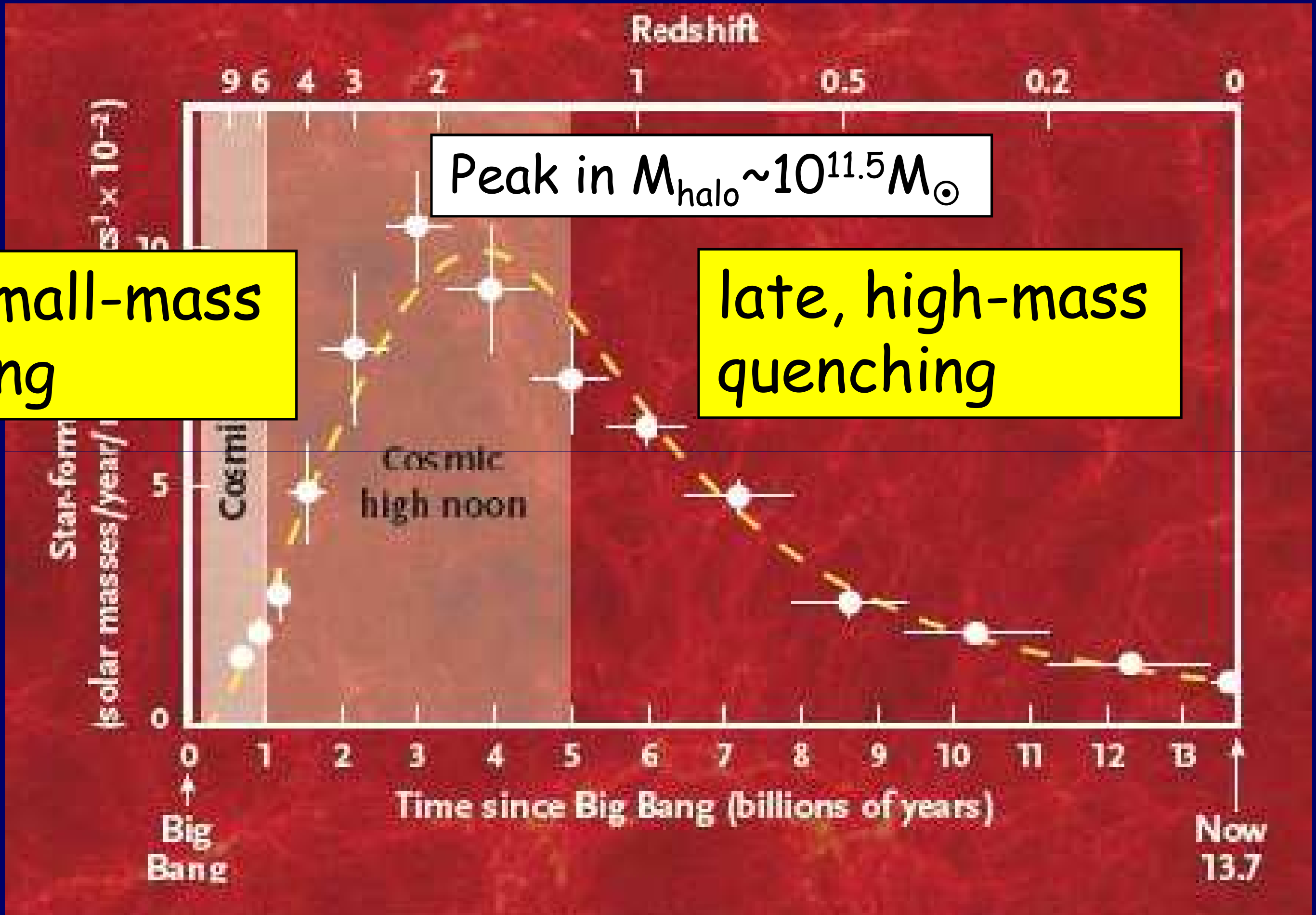
$$M_{PS} \approx 10^{13} M_{\Theta}\, a^{1/\alpha}$$

$$n(M) \propto \tilde{M}^{-2+\alpha} \exp(-0.5\tilde{M}^{2\alpha})$$

$$\tilde{M} \equiv M / M_{\text{PS}}$$



Evolution of Star-Formation Rate Density



Peak in M_{halo}~$10^{11.5}M_{\odot}$

early, small-mass quenching

late, high-mass quenching

STARBIRTH RATE Using data from many surveys, including CANDELS, astronomers have plotted the rate of star formation through cosmic history. The rate climbed rapidly at cosmic dawn and peaked at cosmic high noon.

Quenching of Star Formation in Massive Galaxies

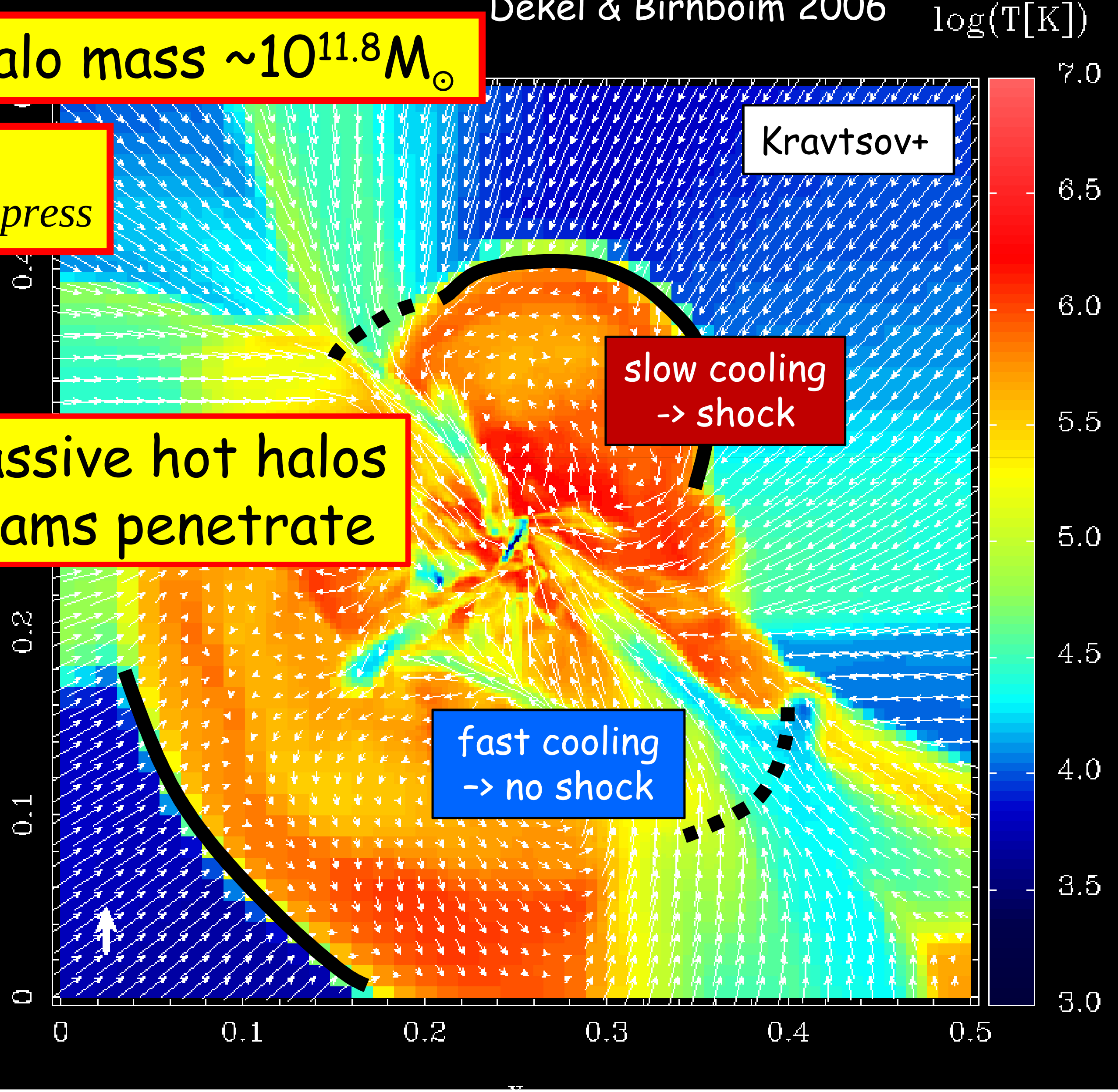
Virial Shock Heating

critical halo mass ~$10^{11.8} M_\odot$

$t_{cool}^{-1} < t_{compress}^{-1}$

in hi-z massive hot halos
cold streams penetrate

Dekel & Birnboim 2006

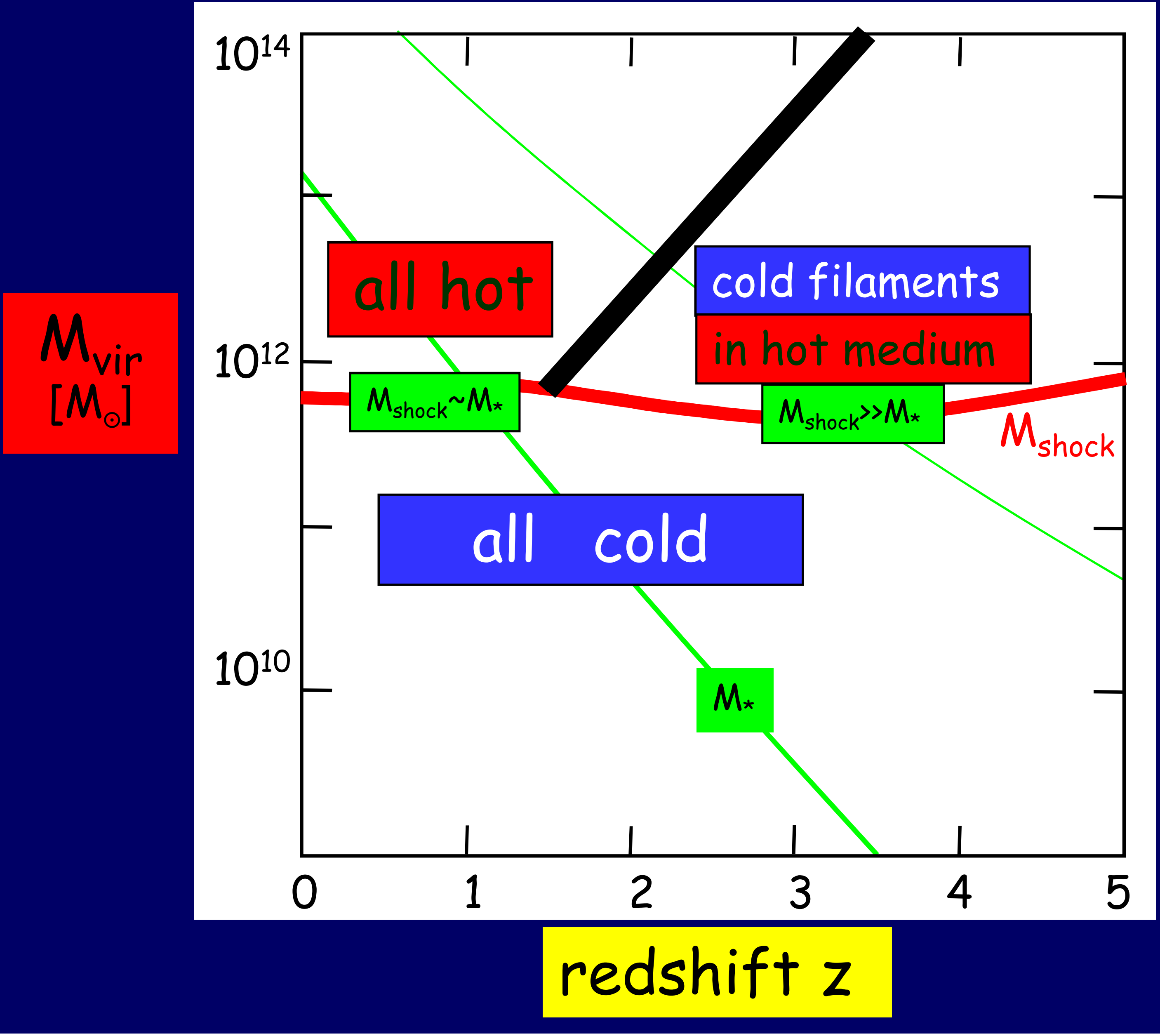


Kravtsov+

slow cooling
-> shock

fast cooling
-> no shock

Cold Streams in Big Galaxies at High z



Dekel &
Birnboim 06

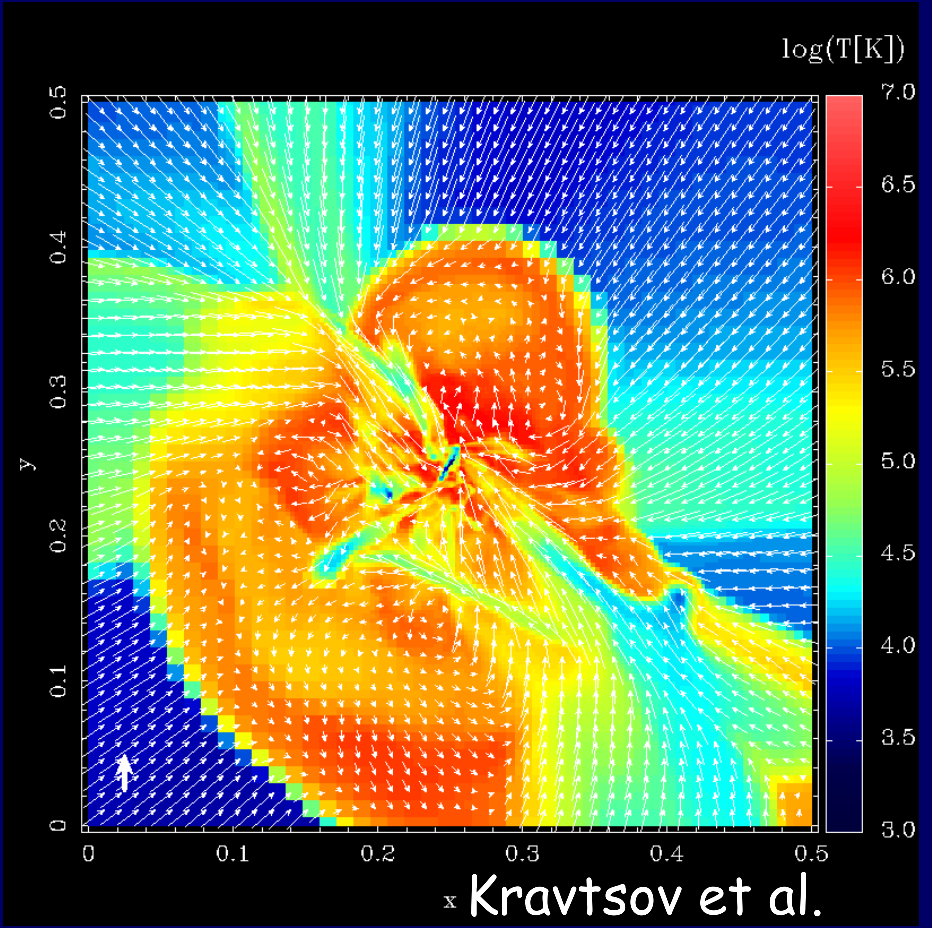
Shock Heating Triggers AGN Feedback

$M > M_{shock}$

More than enough energy is available in AGNs

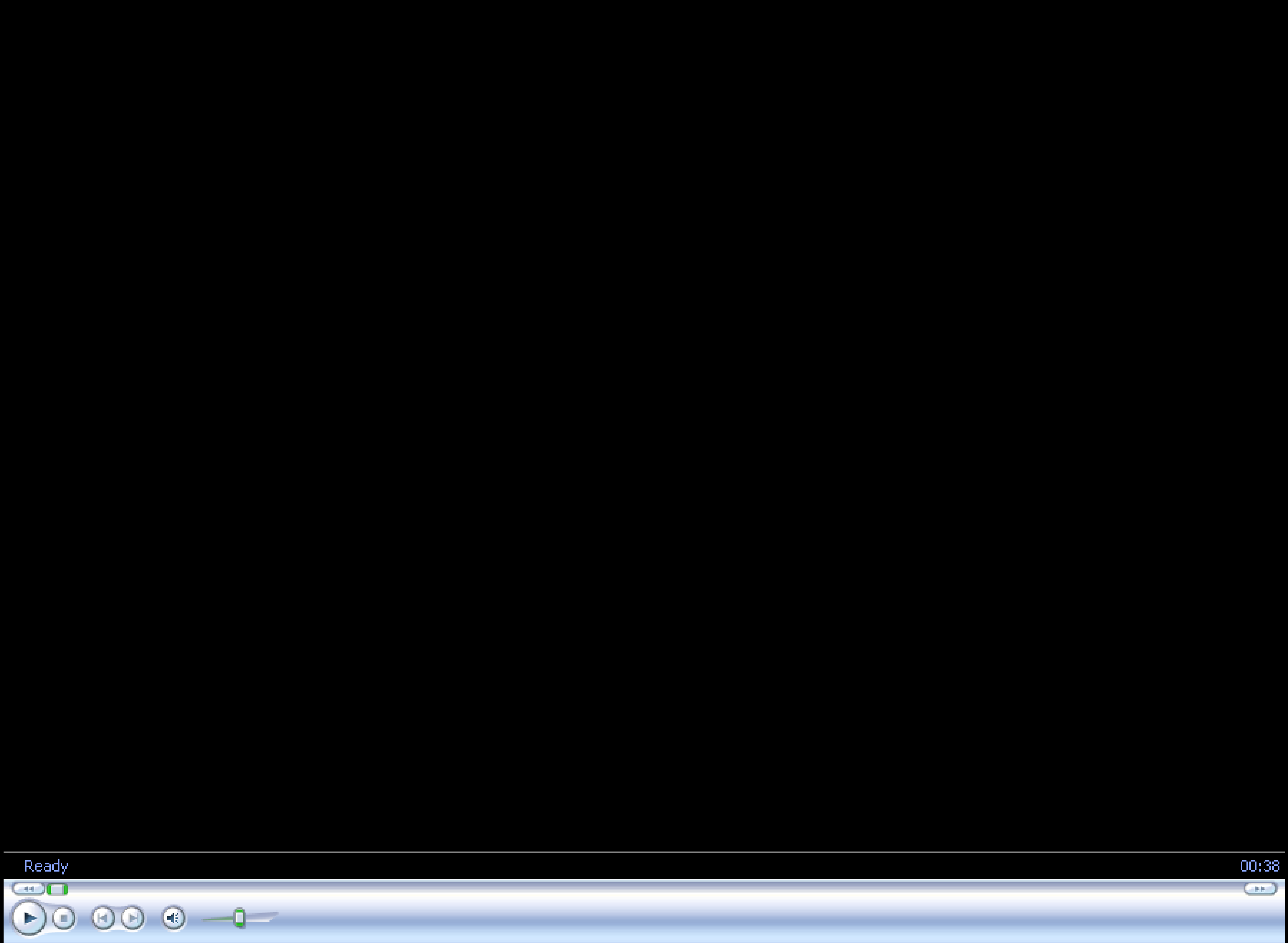
Hot gas is vulnerable to AGN feedback, while cold streams are shielded

→Shock heating is the trigger for AGN feedback in massive halos

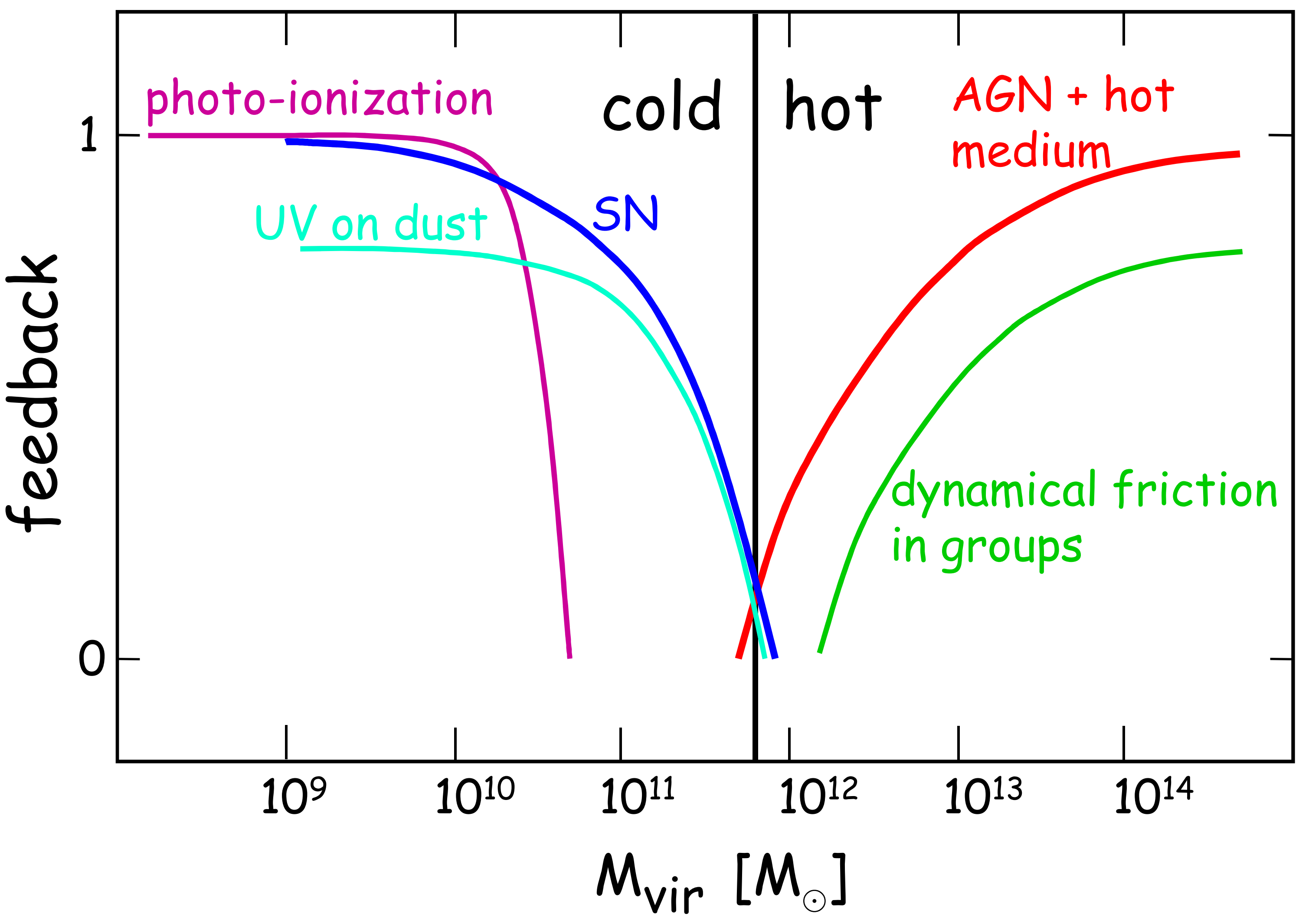


Kravtsov et al.

Merger: Galaxies with a Central Black Hole



Strong Feedback on Small and Large Scales

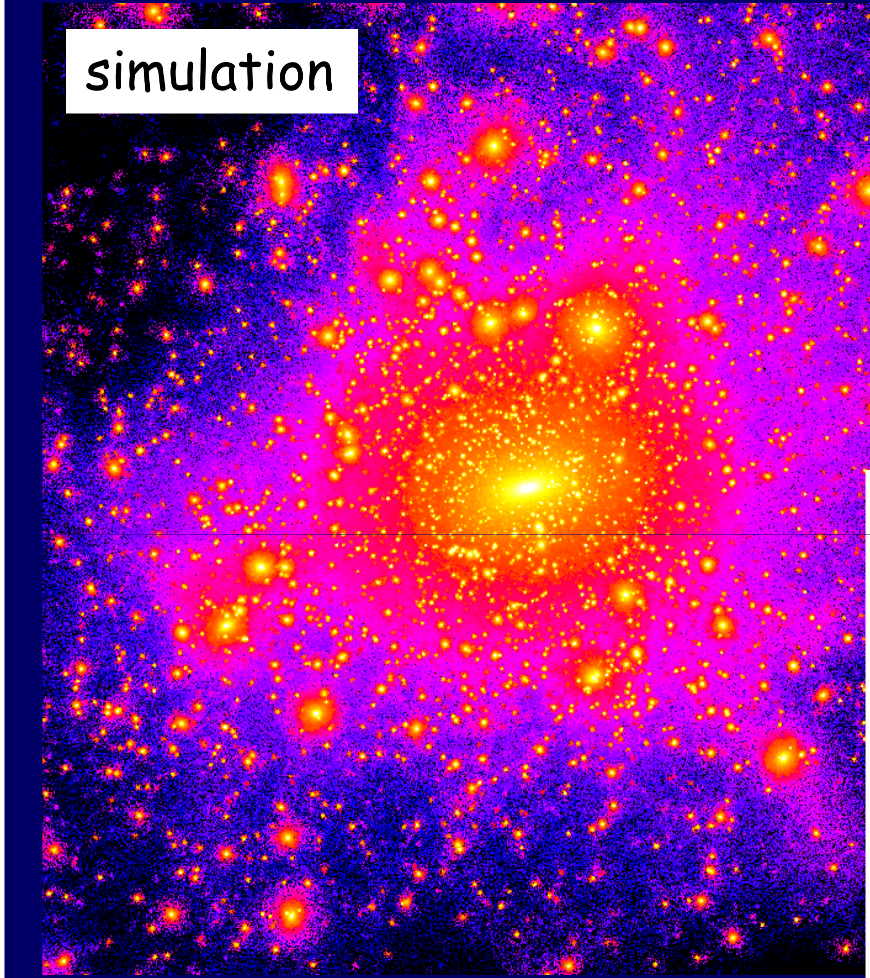


Small Scale Issues

- Missing dwarfs / Too big to fail

- Cusp-core

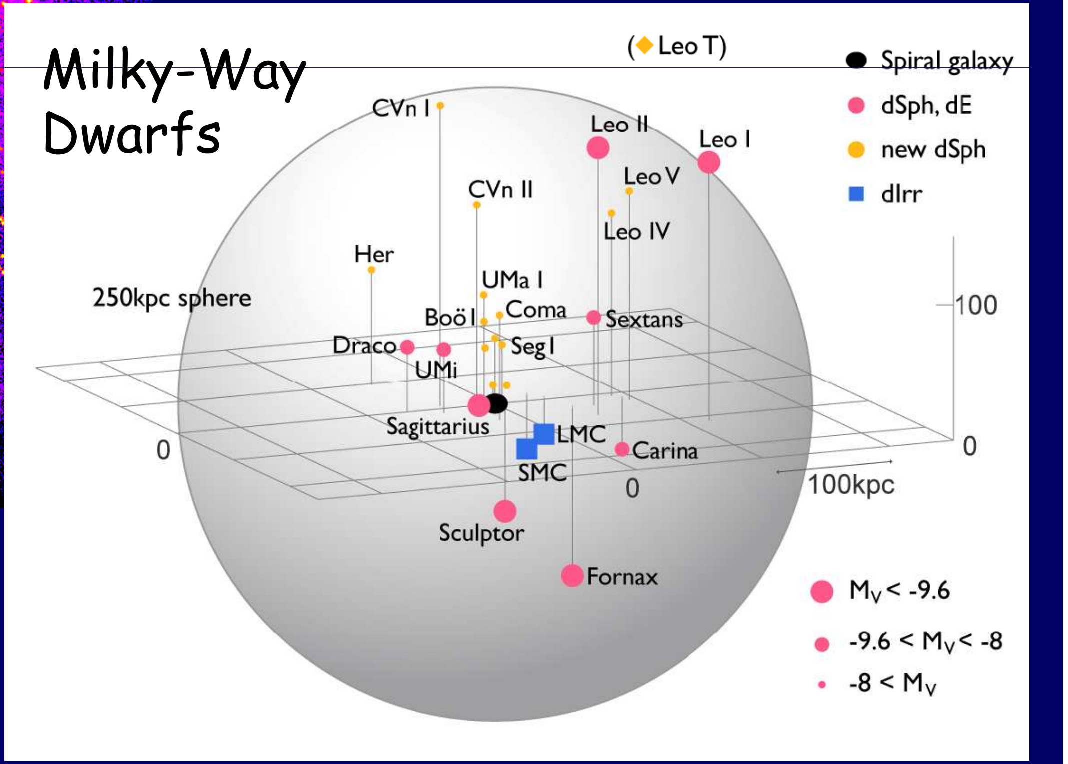
Missing Dwarfs in a Milky-Way Halo



simulation

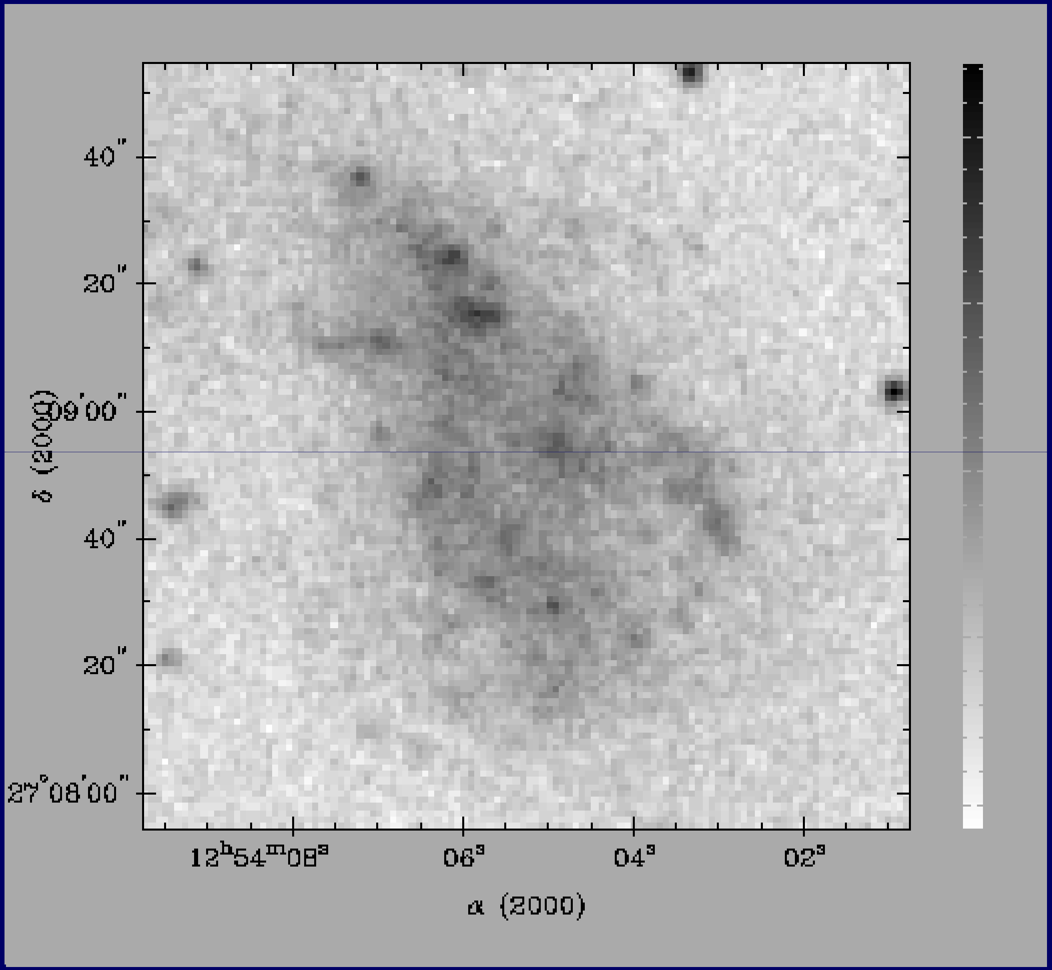
V>30 km s^{-1}: ~10 subhalos, 2 dwarfs

V>10 km s^{-1}: ~10^5 subhalos, ~20 dwarfs



Milky-Way Dwarfs

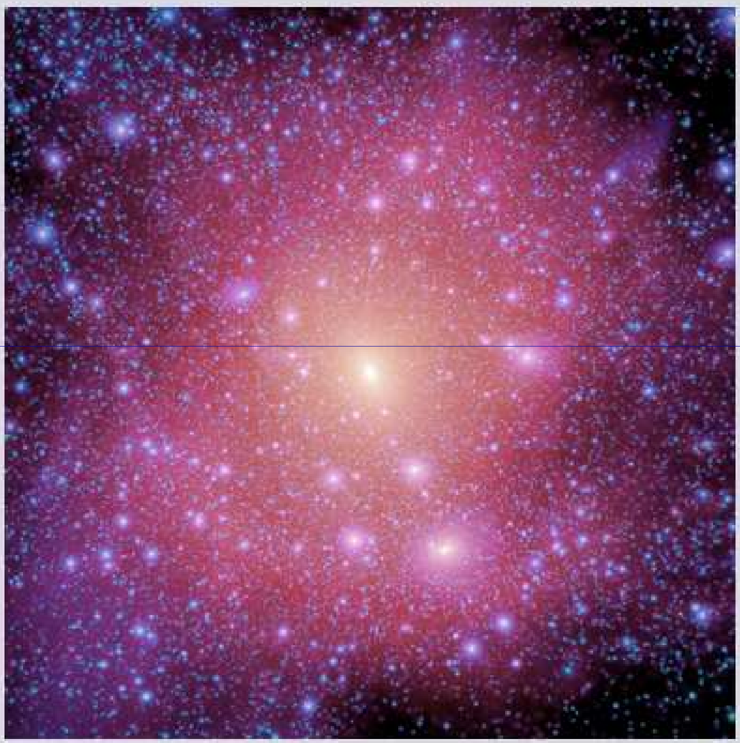
Low-mass Galaxies are of Low Surface Brightness

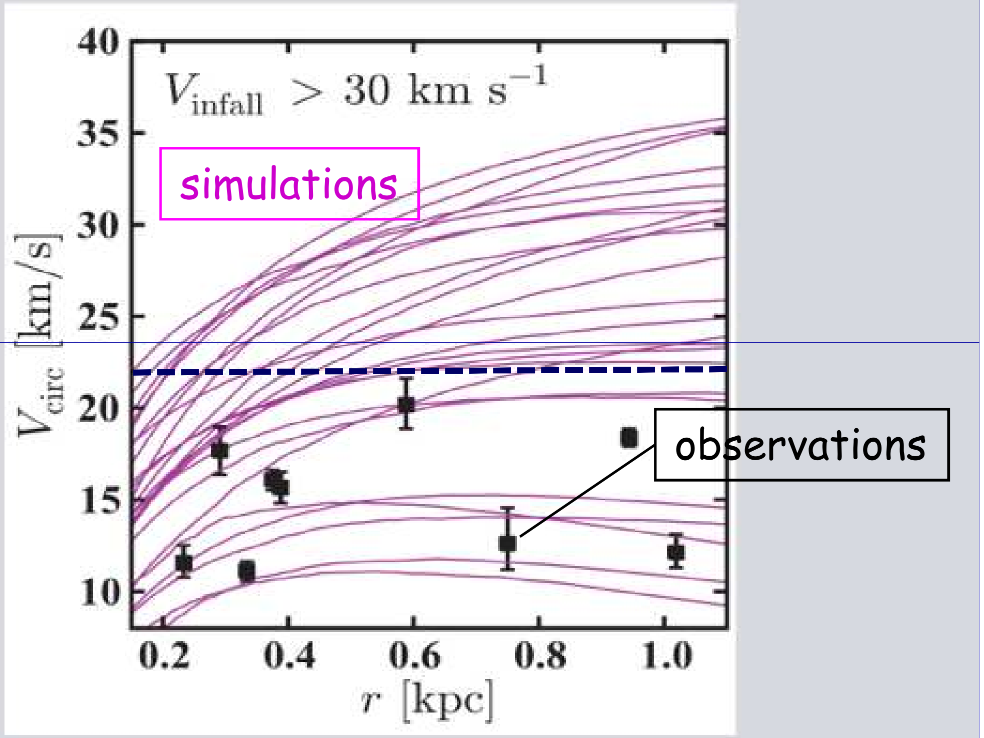


DDO154

DM dominated:
Low M_{star}/M_{DM}

Too Big To Fail: Where are the massive/dense subhalos of MW?

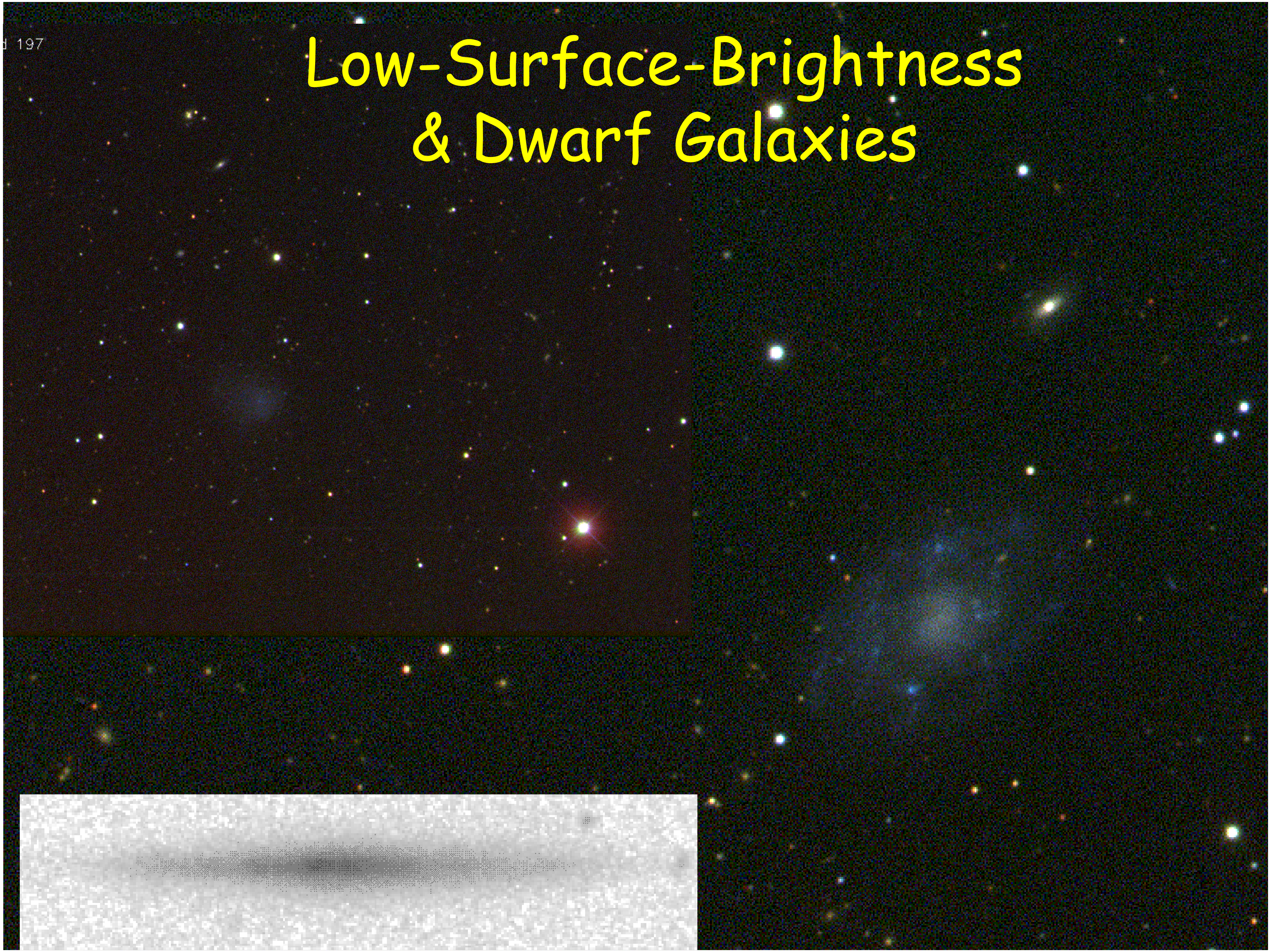




Lots of massive subhalos: denser than known satellites

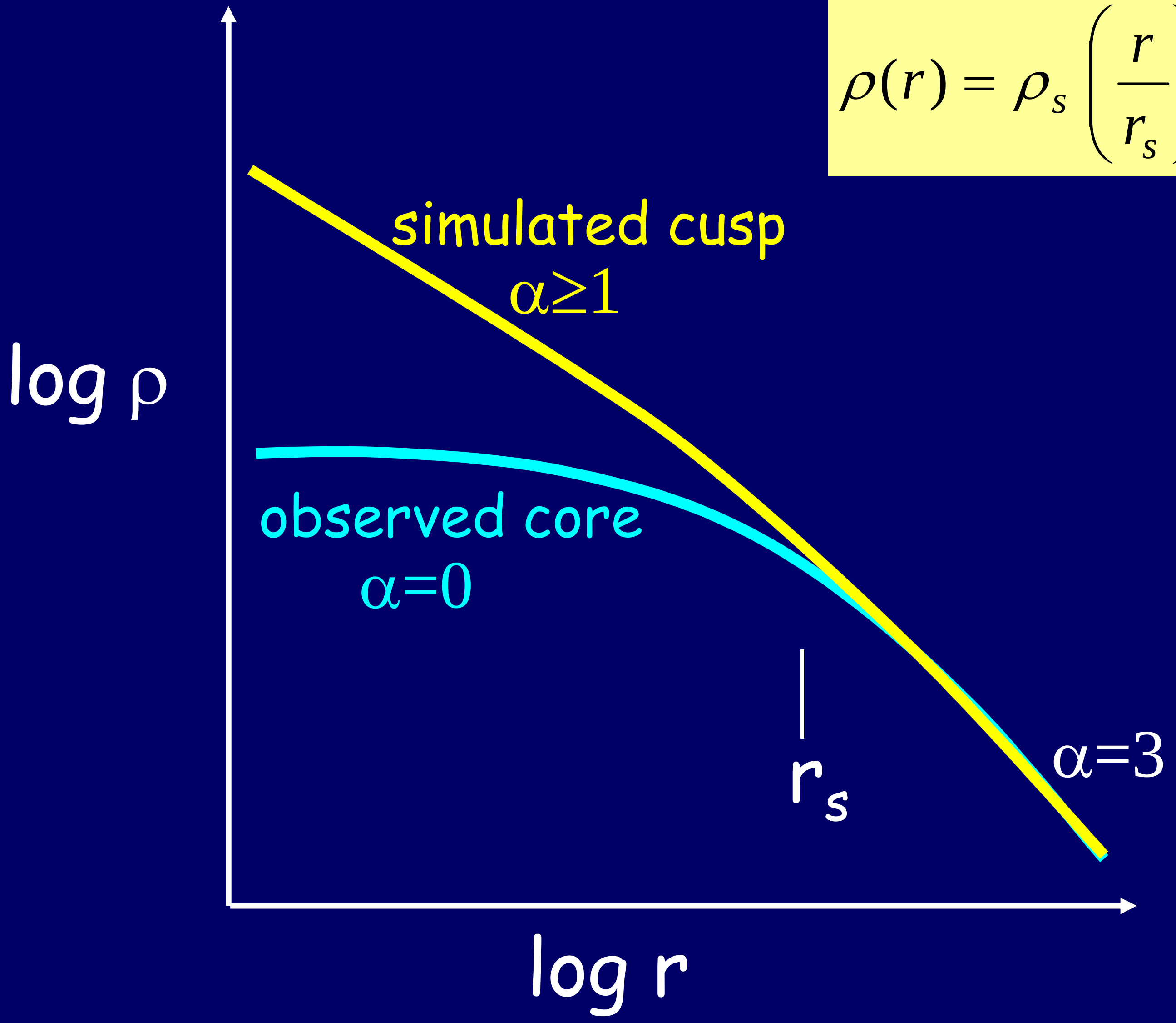
Boylan-Kolchin, Bullock, Kaplinghat 2011,2012

Low-Surface-Brightness & Dwarf Galaxies



The dark-halo cusp/core problem

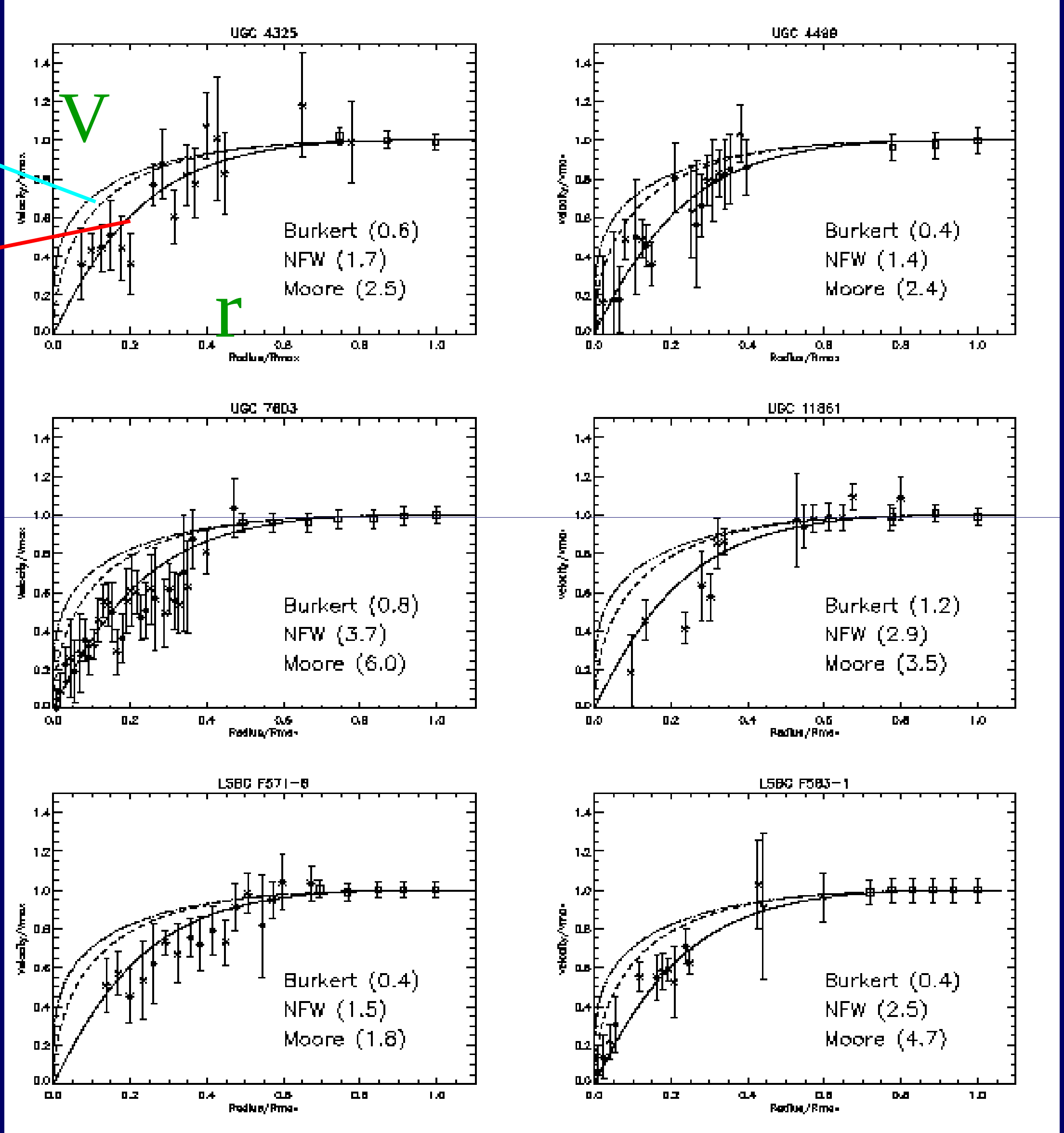
$$\rho(r) = \rho_s \left(\frac{r}{r_s}\right)^{-\alpha_0} \left(1 + \frac{r}{r_s}\right)^{-3+\alpha_0}$$



Observed Cores vs. Simulated Cusps

cusp $\alpha \geq 1$

core $\alpha = 0$



$$V^2 = \frac{GM(r)}{r}$$

$$\rightarrow V \propto r^{1-\alpha/2}$$

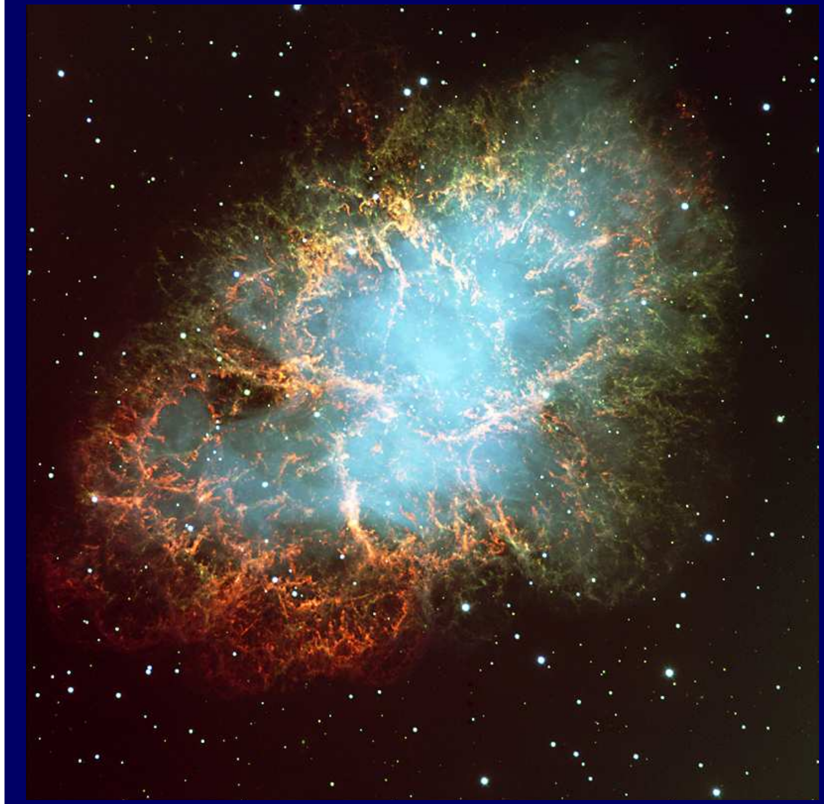
Marchesini, D'Onghia, et al.

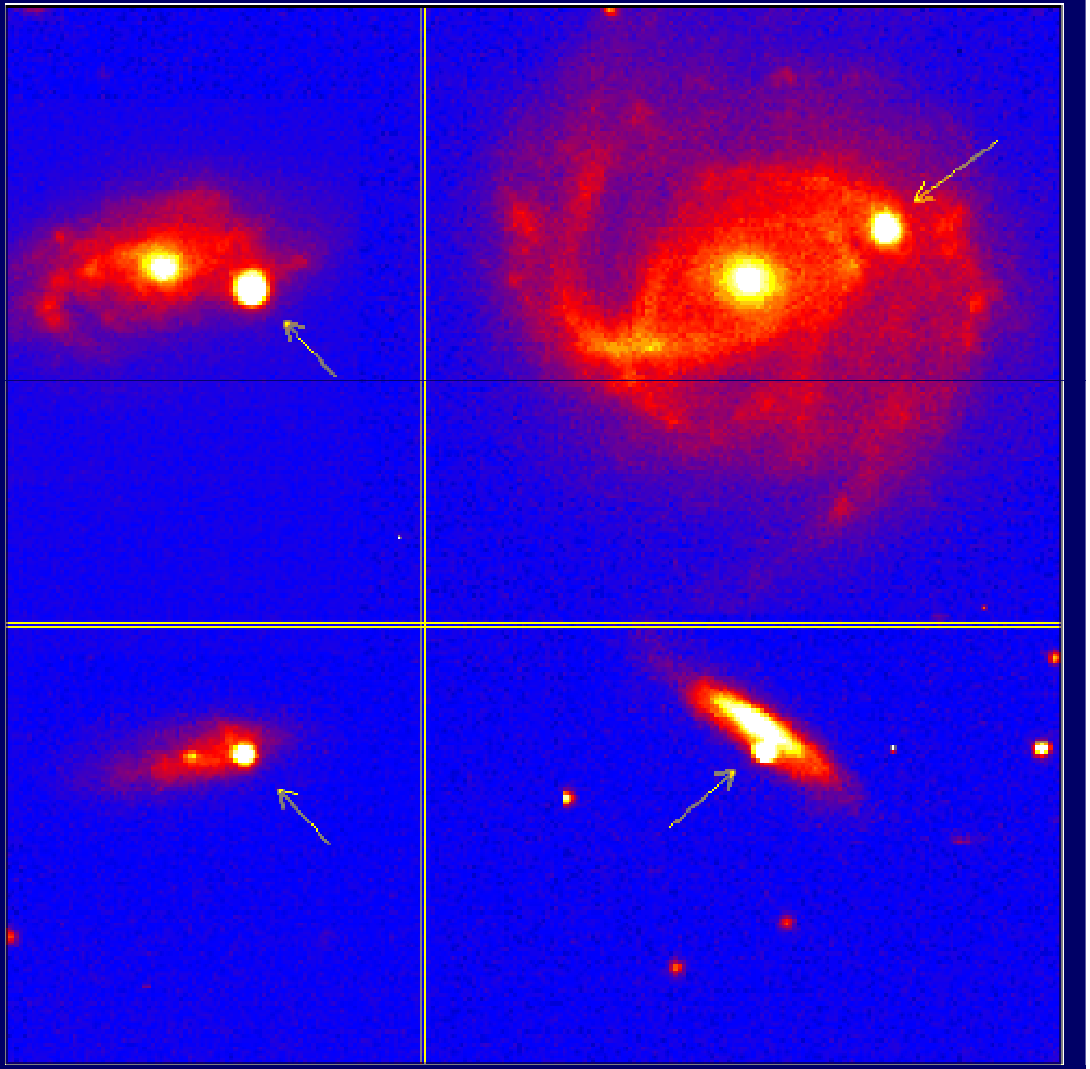
The Astrophysical Solution:
Feedback

The baryonic mass in galaxies is ~20% of the cosmic baryon fraction

Outflows are observed

Supernovae Feedback



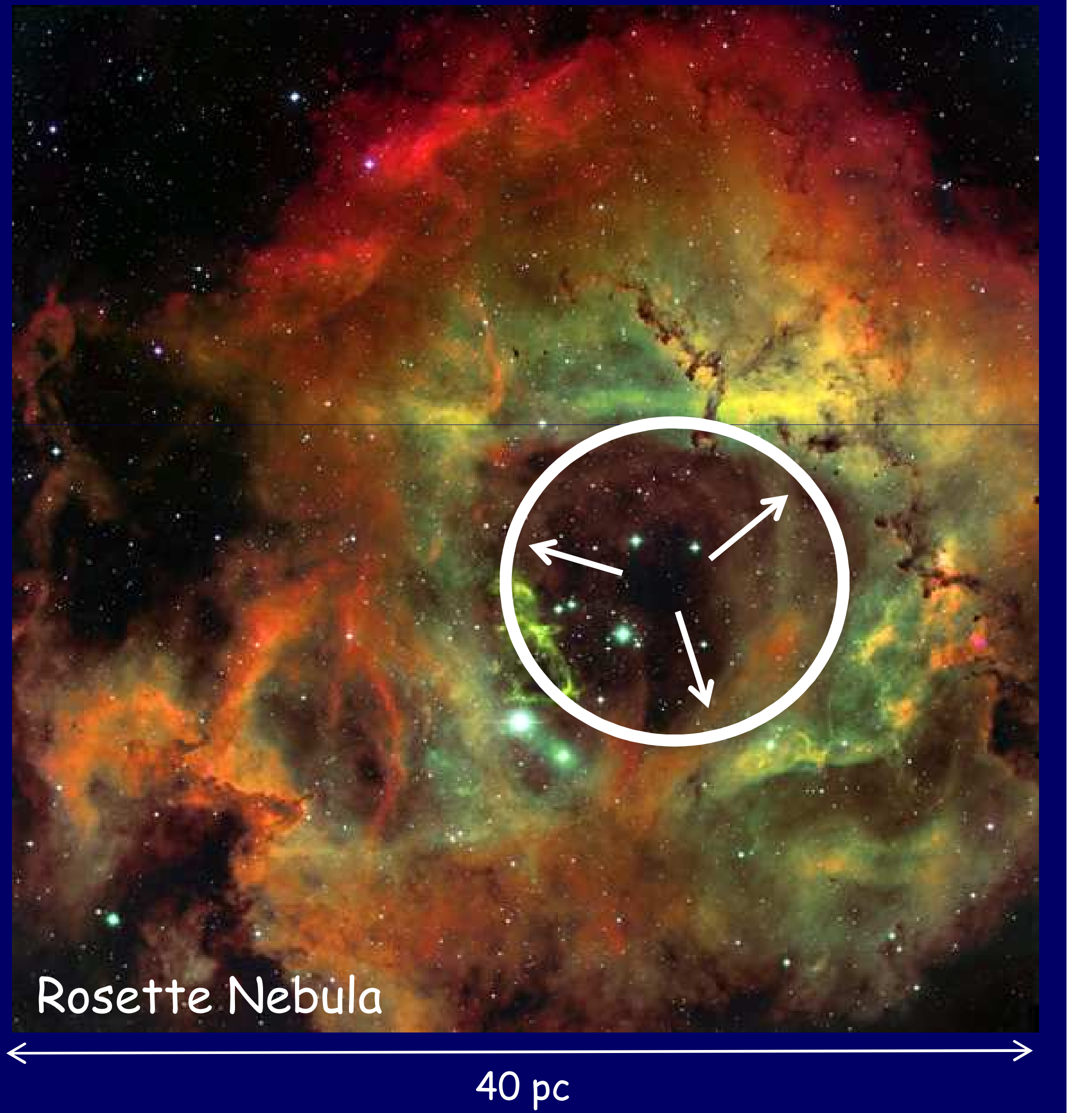


Radiative Feedback

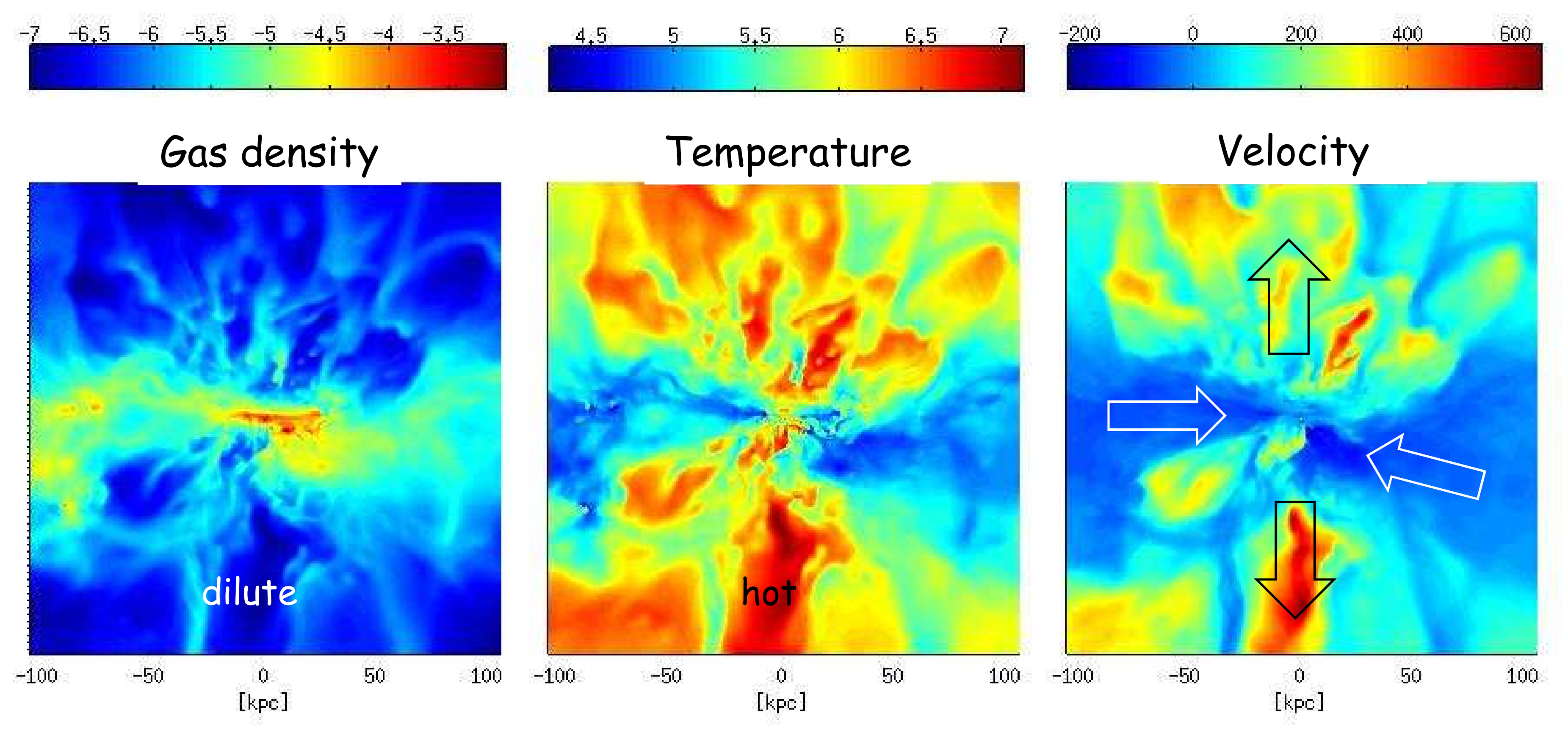
No supernovae

- Radiative pressure by UV ionizing photons from massive young stars
- Acting on dense gas and dust
- Some IR trapping

$P=(L/c)/R^2$ for 5 Myr



Inflows and Outflows



DeGraf, Ceverino + 15

cosmological simulations 25pc

$z=2.6$ $M_v=7\times10^{11}$
radiative fdbk $\eta\sim3$

Outflows remove most of the gas

Supernova-Driven Outflow

Dekel & Silk 1986 +

Energy fed to the ISM during the “adiabatic” phase:

$$E_{\rm SN} \approx \nu\varepsilon\, \dot{M}_*\, t_{\rm rad} \quad \propto M_* (t_{\rm rad}/t_{\rm ff})$$

$$\dot{M}_* \approx M_*/t_{\rm ff}$$

$$\approx 0.01$$

Energy required for blowout:

$$E_{\rm SN} \approx M_{\rm gas} V^2$$

$$V_{\rm crit} \approx 100\ \ km\, s^{-1} \quad \rightarrow \quad M_{*{\rm crit}} \approx 3\times 10^{10} M_\Theta$$

$$M_*/M_{\rm v} \propto V^2 \quad (M_* << M_{\rm outflow} \quad V << 100\, km\, s^{-1})$$

Maximum Effect on DM if Instant Blowout

$$E_{before} = -\frac{GM^2}{R} + \frac{1}{2}MV^2$$

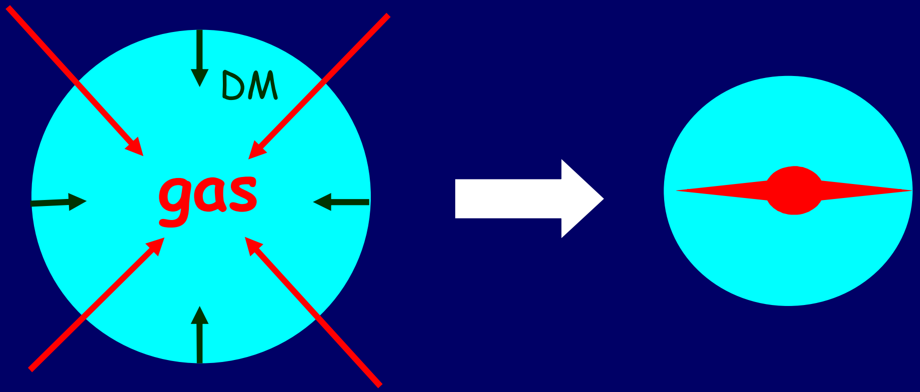
Lose M/2 while V^2 is unchanged:

$$E_{after} = -\frac{G(M/2)^2}{R} + \frac{1}{2}(M/2)V^2 = 0$$

unbound!

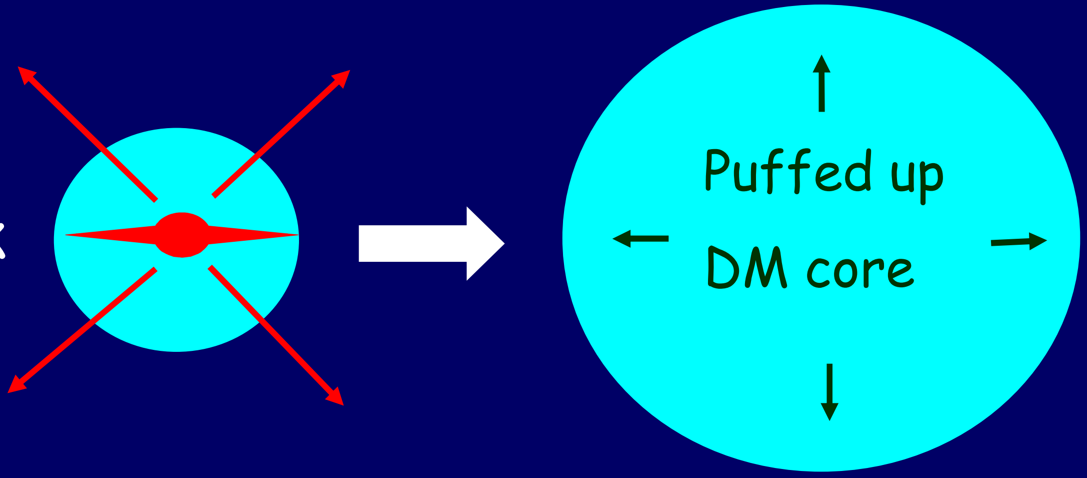
Reaction of DM-Halo to Gas Blowouts

Adiabatic contraction

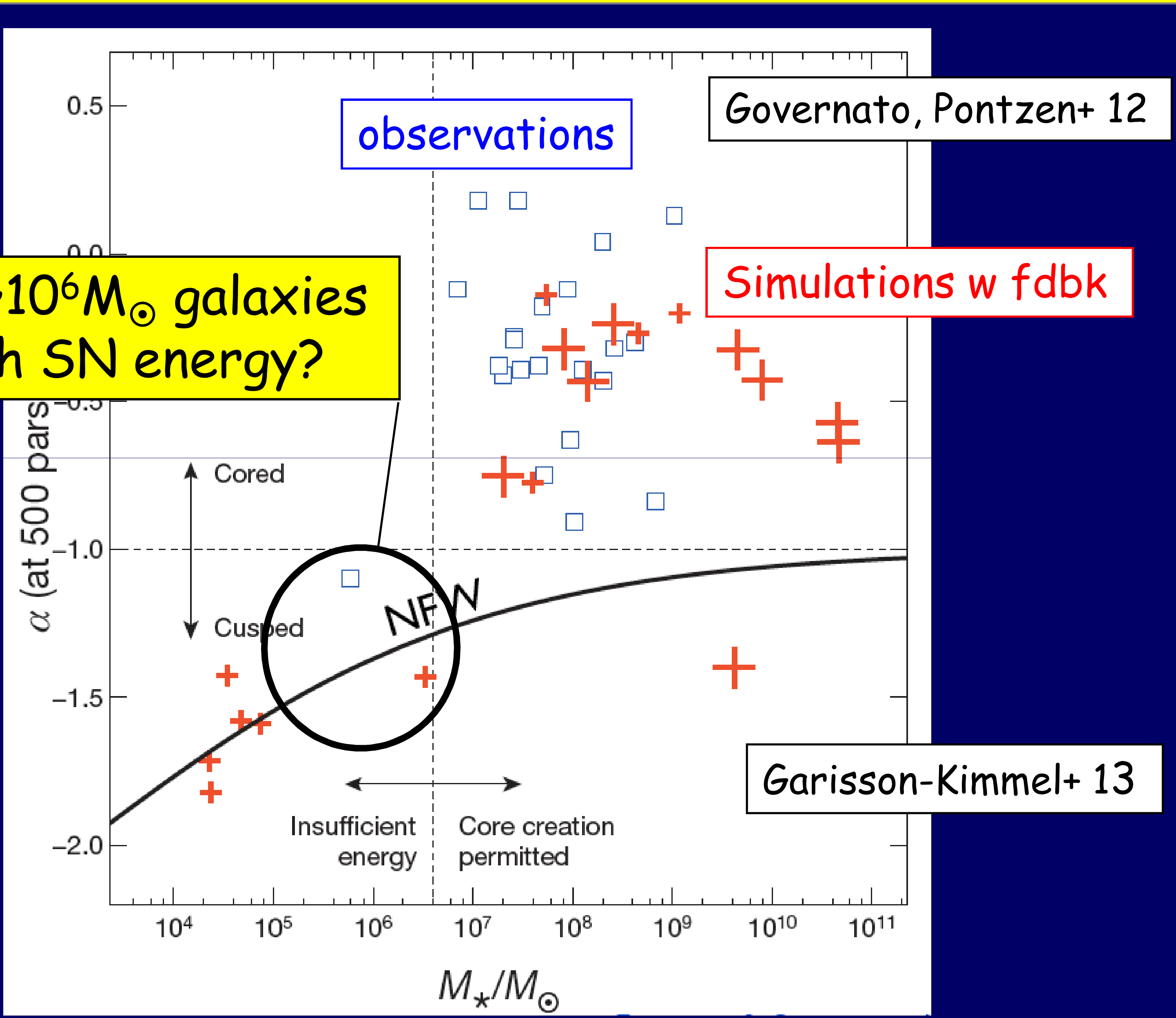


Instant gas blowouts

by supernova feedback



Can TBTF be solved with supernova feedback?



observations

Governato, Pontzen+ 12

Simulations w fdbk

Garisson-Kimmel+ 13

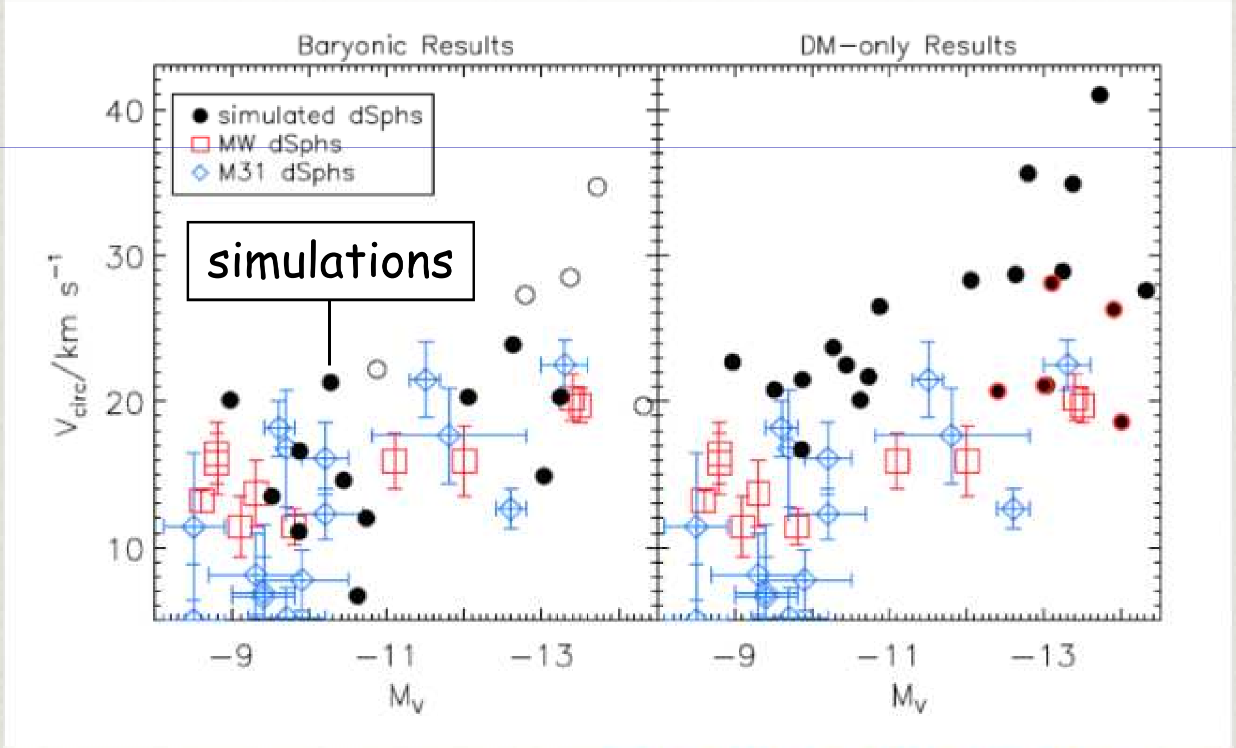
Small $M_* \sim 10^6 M_\odot$ galaxies not enough SN energy?

Slope of density profile at r=50pc

Proposed Solution: tides from disk stripping make massive subhalos less dense

Mass loss due to tidal stripping in presence of disk

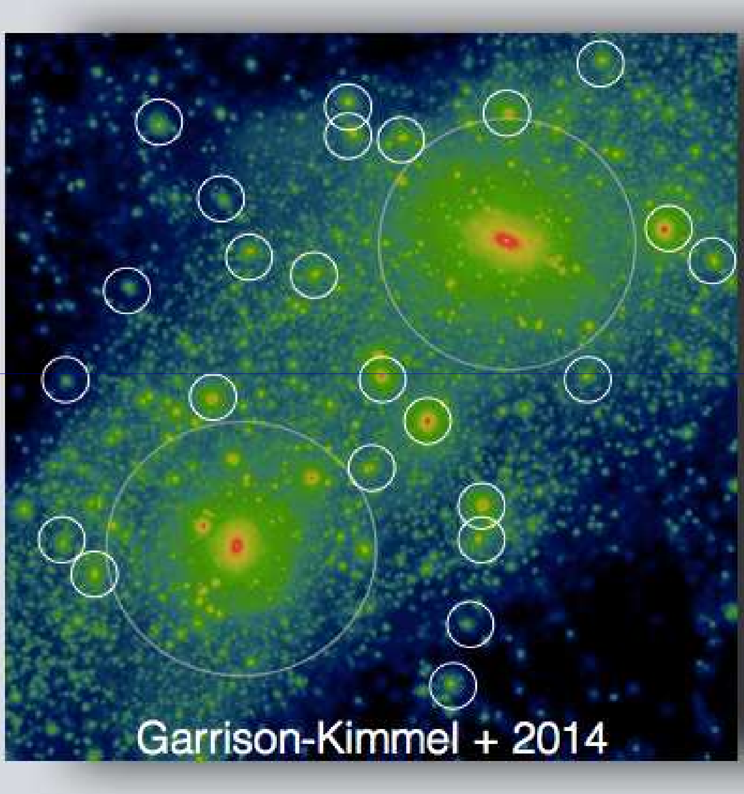
Large DM cores in satellites brighter than M_V = -12;
cores + tides = even greater mass loss

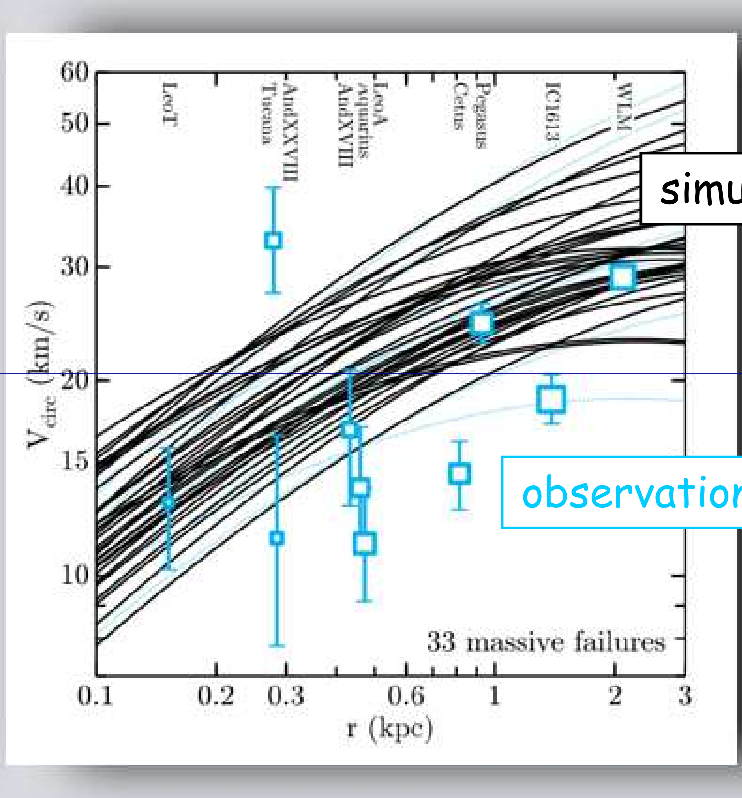


Slide from A. Brooks

BROOKS & ZOLOTOV (2013)

Problem with tidal solution: TBTF persists beyond influence of disk/tides!





simulations

observations

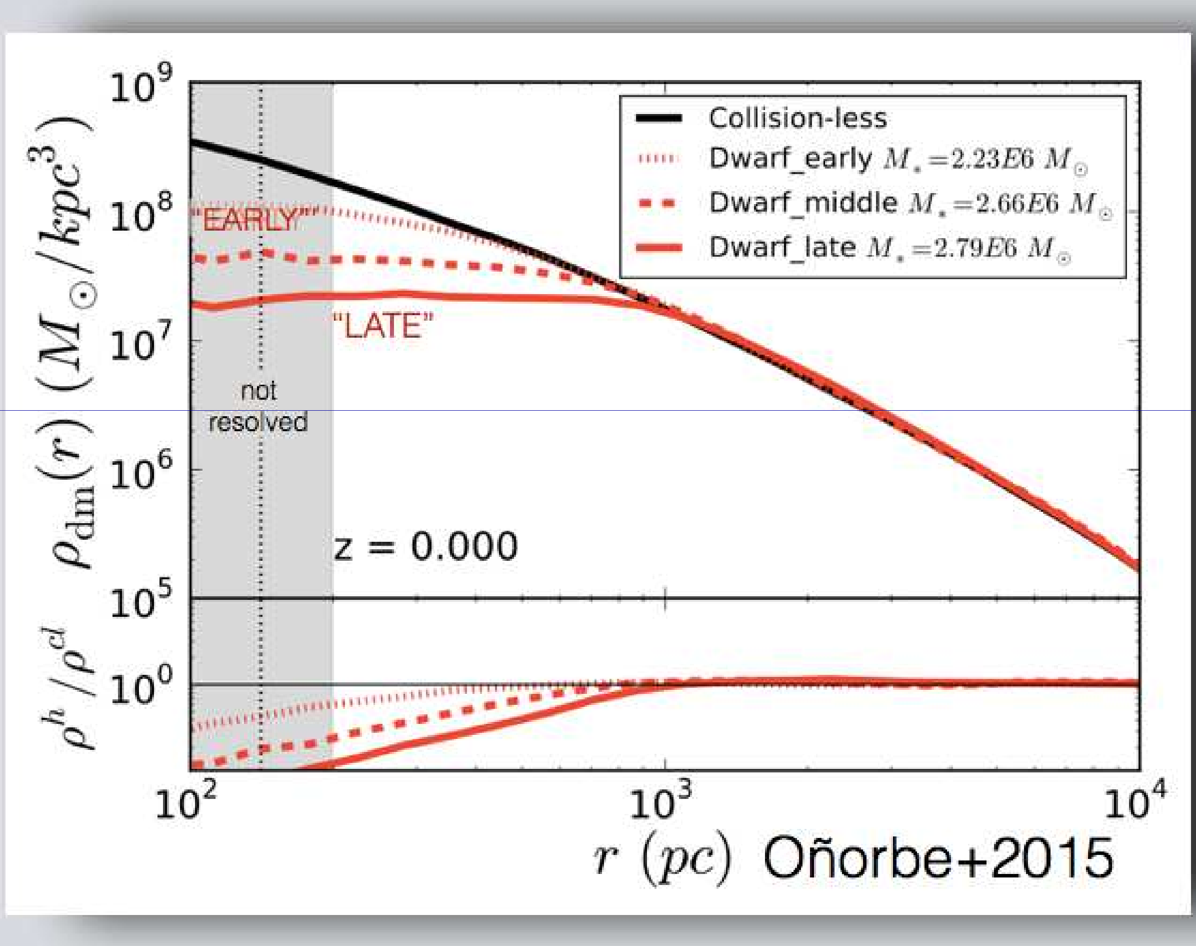
Lots of massive halos should exist within Local Group

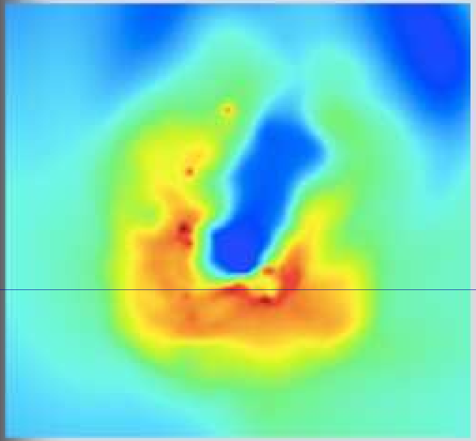
Outer Local Group: Garrison-Kimmel+2014

TBTF in the Field: Papastergis+2014

Need the SN feedback to be more effective than previously modeled

Newer Simulations: Feedback might just barely be able to do it. Still not clear.





FIRE/Gizmo:
Oñorbe, Bullock
et al. 2015

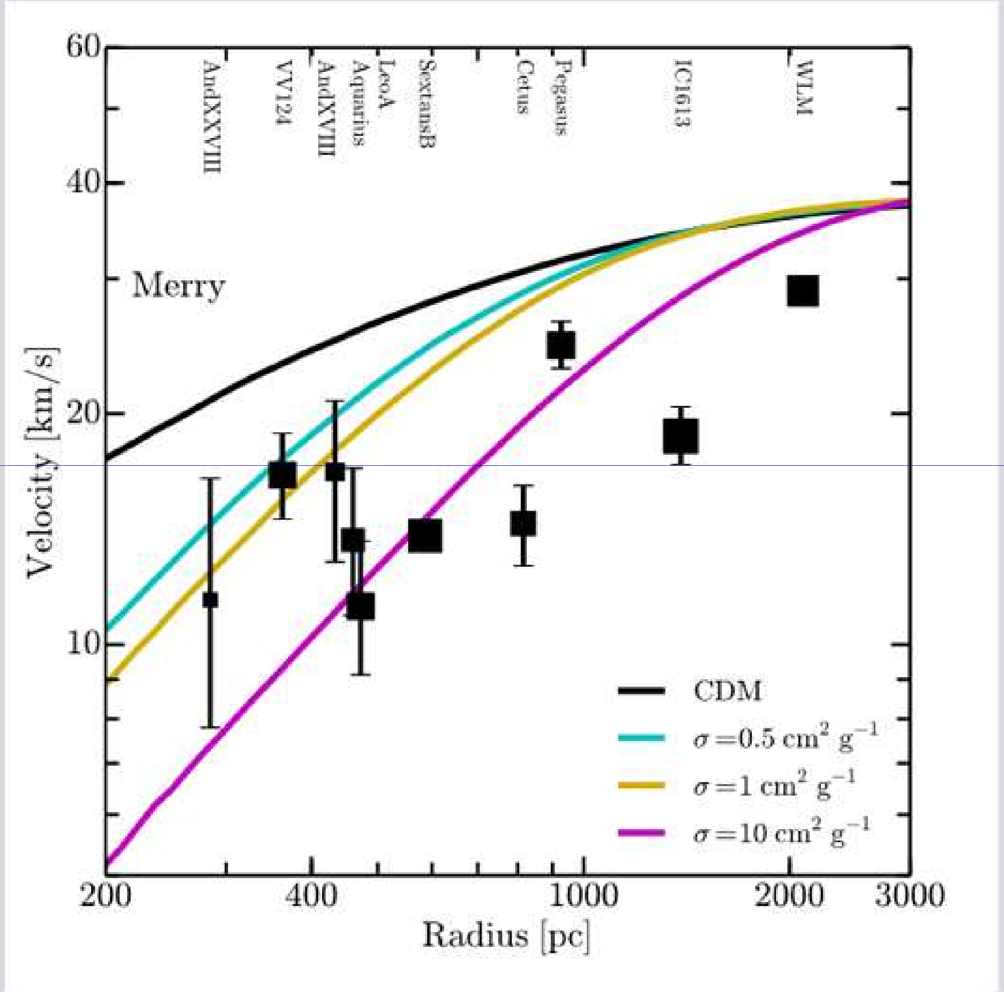
$M_{HALO}=10^{10}\ M_\odot$ $M_\star=2.5\times10^6\ M_\odot$

Do we need a different kind of DM to reduce the small-scale power?

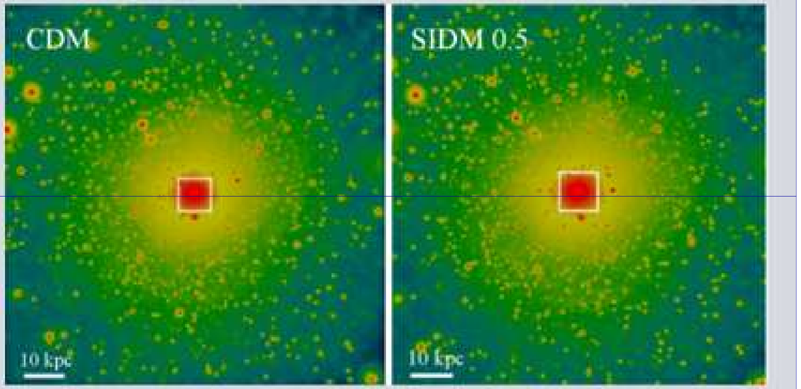
Warm DM?

Self-interacting (repulsive) DM?

Alternative: Change DM physics
- self-interacting DM with ~nuclear cross sections



Elbert+2015



SIDM looks exactly like CDM except DM halos have low-density cores rather than cusps

Summary

LCDM is extremely successful in matching the CMB and large-scale structure

Robust predictions for global properties of cosmic web and DM halos

Rapid progress in implementing baryonic processes, within the cosmic web, to explain the evolution of galaxy properties: mass, size, morphology, SFR and quenching

Challenges: TF relation, missing dwarfs and cusp/core.
Astrophysical answer: stellar and supernova feedback
(yet to be modeled in proper detail)

Conclusion

Do we desperately need non-CDM dark matter?

I don't think so

Do we know the full answers within CDM and baryonic physics

Not yet, but we are on our way

Will it be interesting for particle physicists to come up with non-CDM DM candidates that may help with the small-scale issues?

Absolutely yes