Galaxy Formation
The Big (and Little) Picture

Julianne Dalcanton
University of Washington

This is your Universe

This is your Universe on Dark Matter

Galaxies are our link to the dark sector

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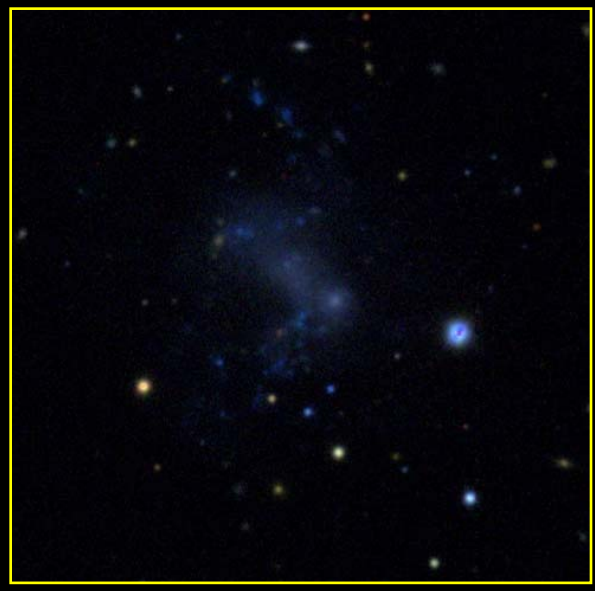
Galaxies:



Ellipticals

$M_{halo} > 10^{11} M_\odot$

V~350km/s

Highly Clustered

Old stars

Rare-ish

Spirals

$M_{halo} > 10^{10} M_\odot$

V~200km/s

Dwarfs

$M_{halo} > 10^{8} M_\odot$

V~30km/s

Weakly Clustered

Young stars

Numerous

Dark Matter

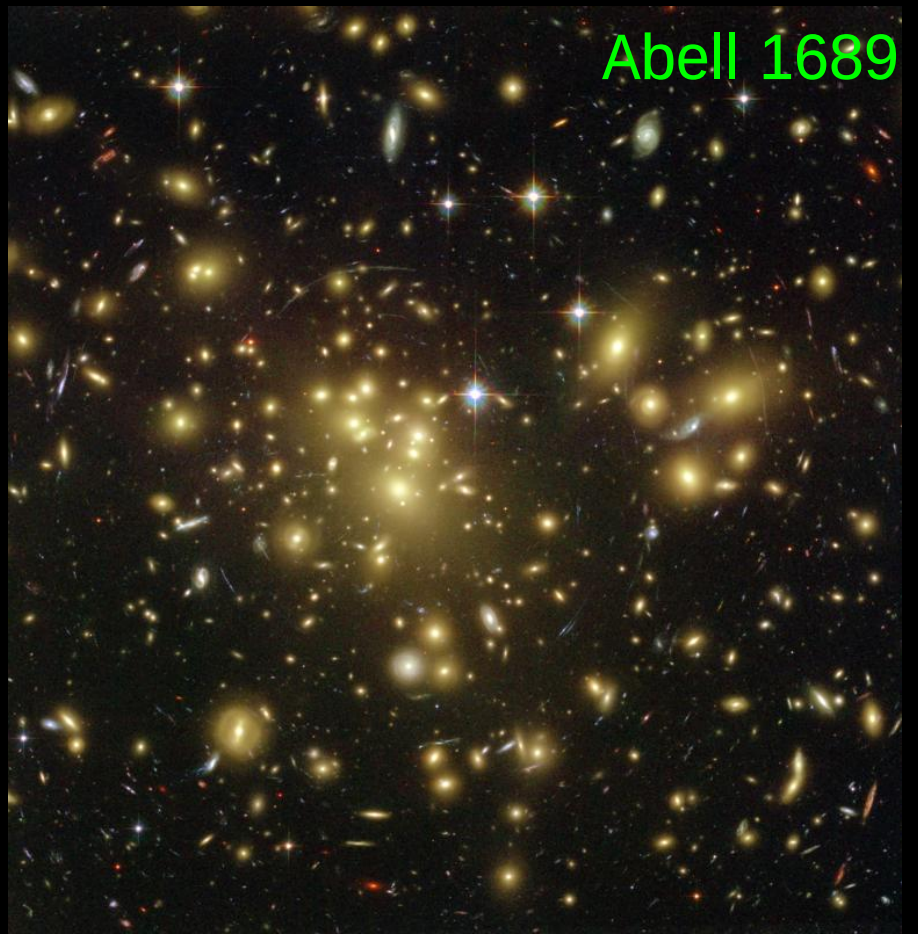
Large scale structure rotation

Structure forms hierarchically

- Dark matter collects into halos
- Small halos form first
- Lots of merging, especially at early times

Scale-free, so galaxy halo similar

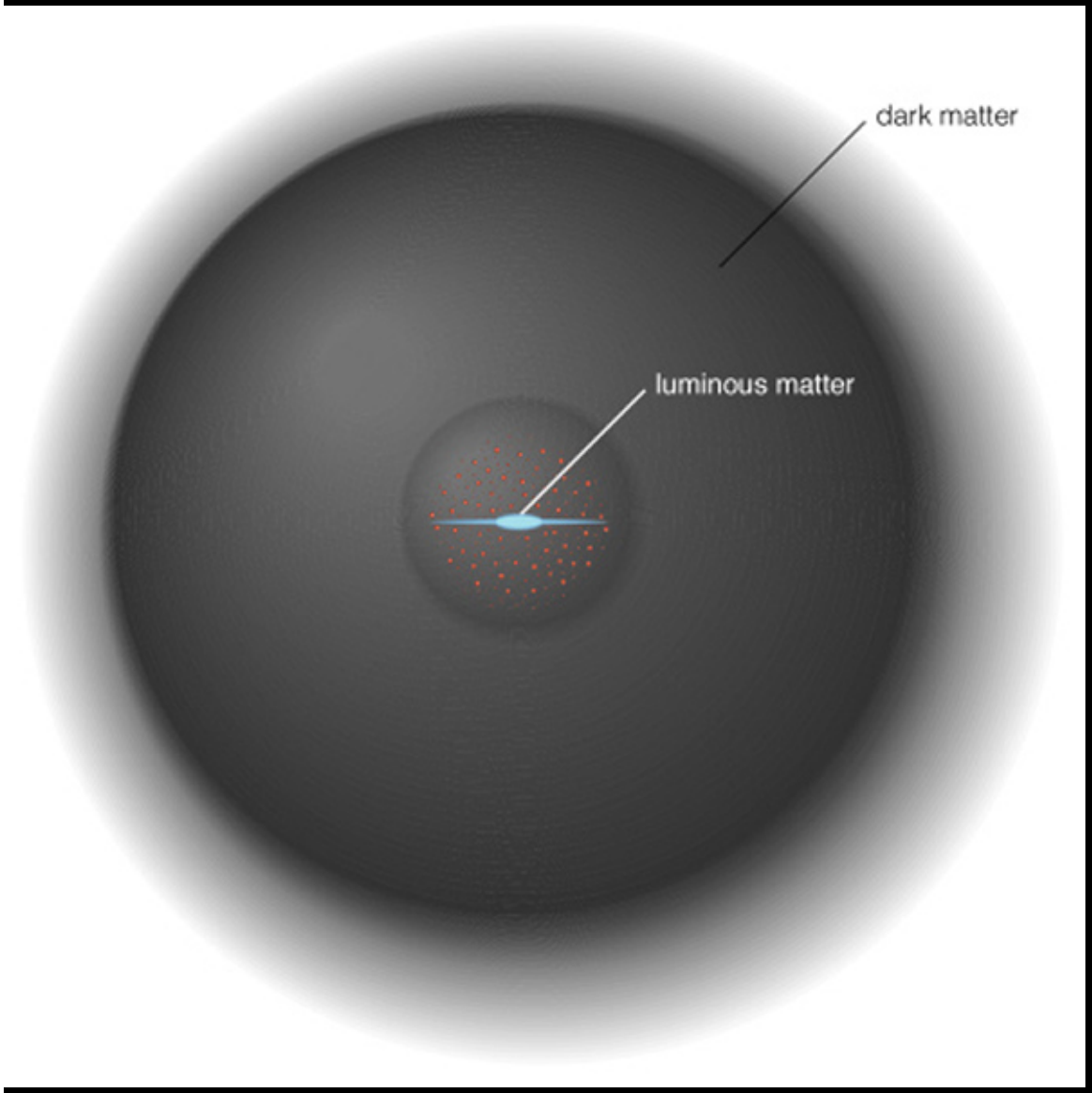
Galaxy Clusters



???

V. Springel

Galaxy Formation: The Short Course



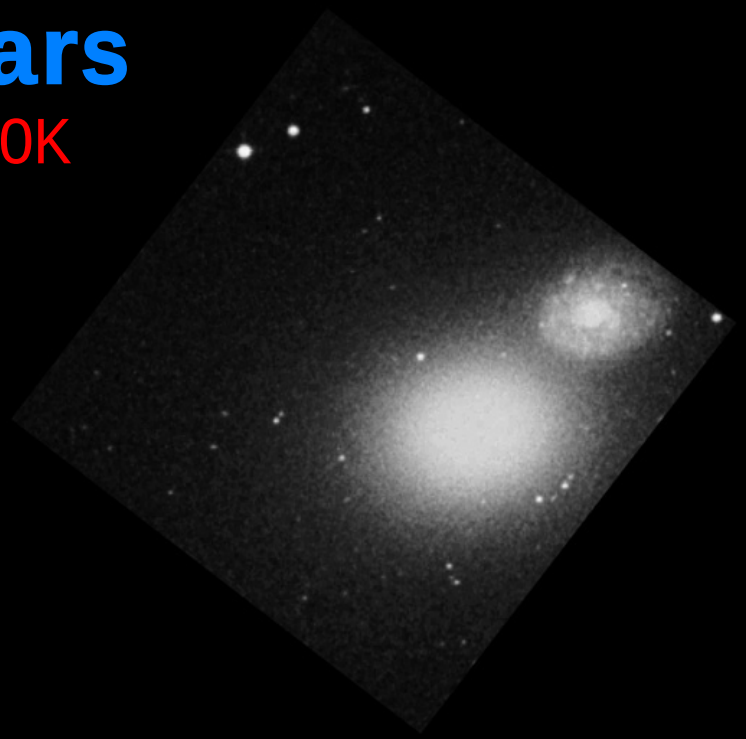
- Dark matter virializes.
- Gas heats & cools.
- Or it doesn't.
- Dense gas forms stars.

The slighly longer version:

- Infalling gas shock heats to the virial temperature of the dark matter halo.

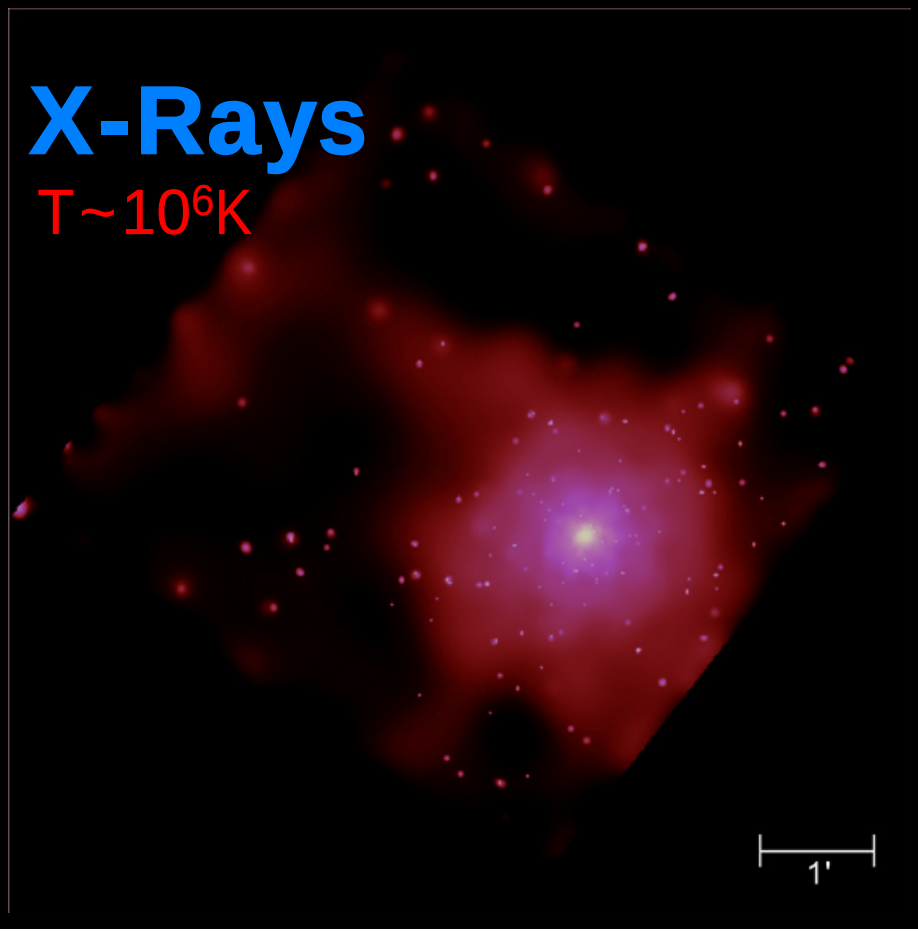
Stars

T~10K



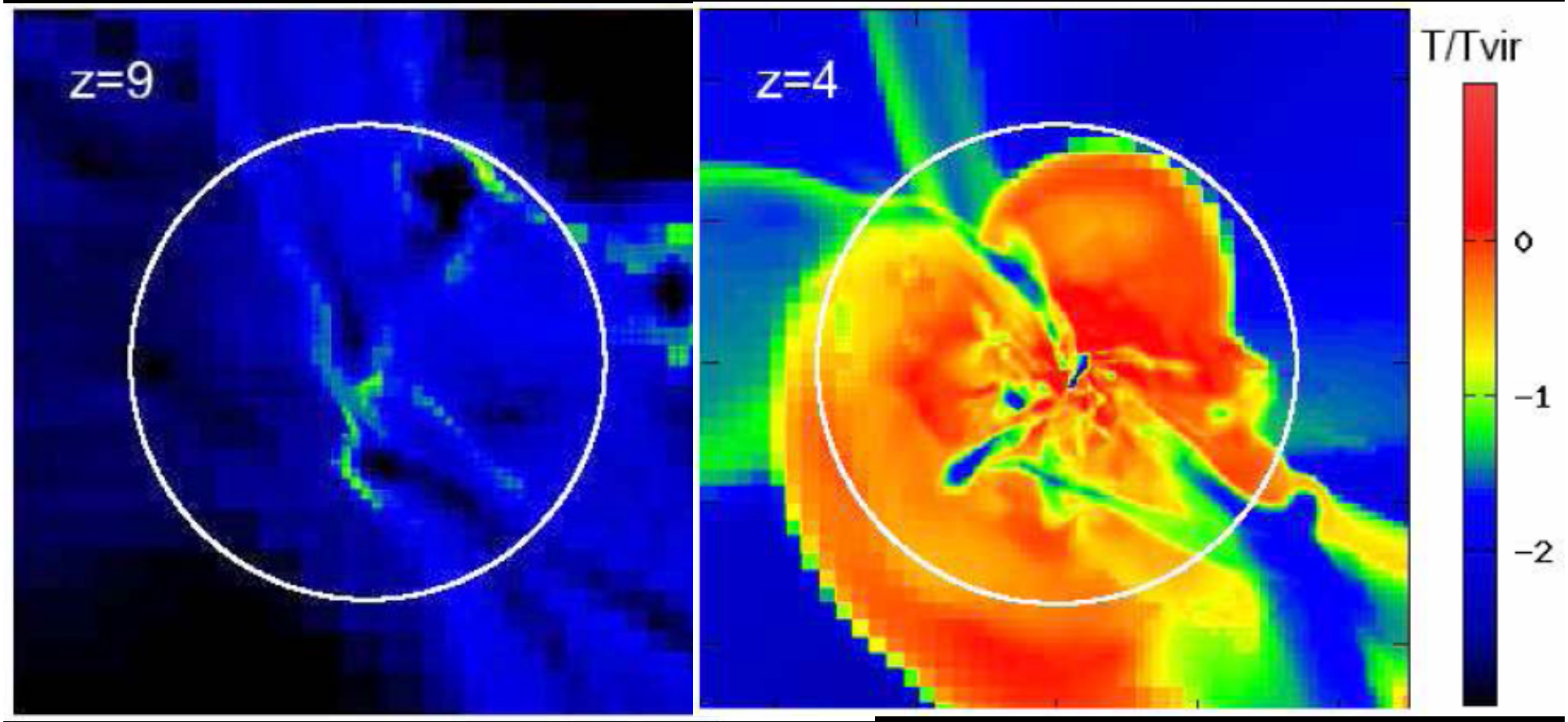
X-Rays

T~10^6K



NGC 4649

- ~~Infalling gas shock heats to the virial temperature of the dark matter halo.~~

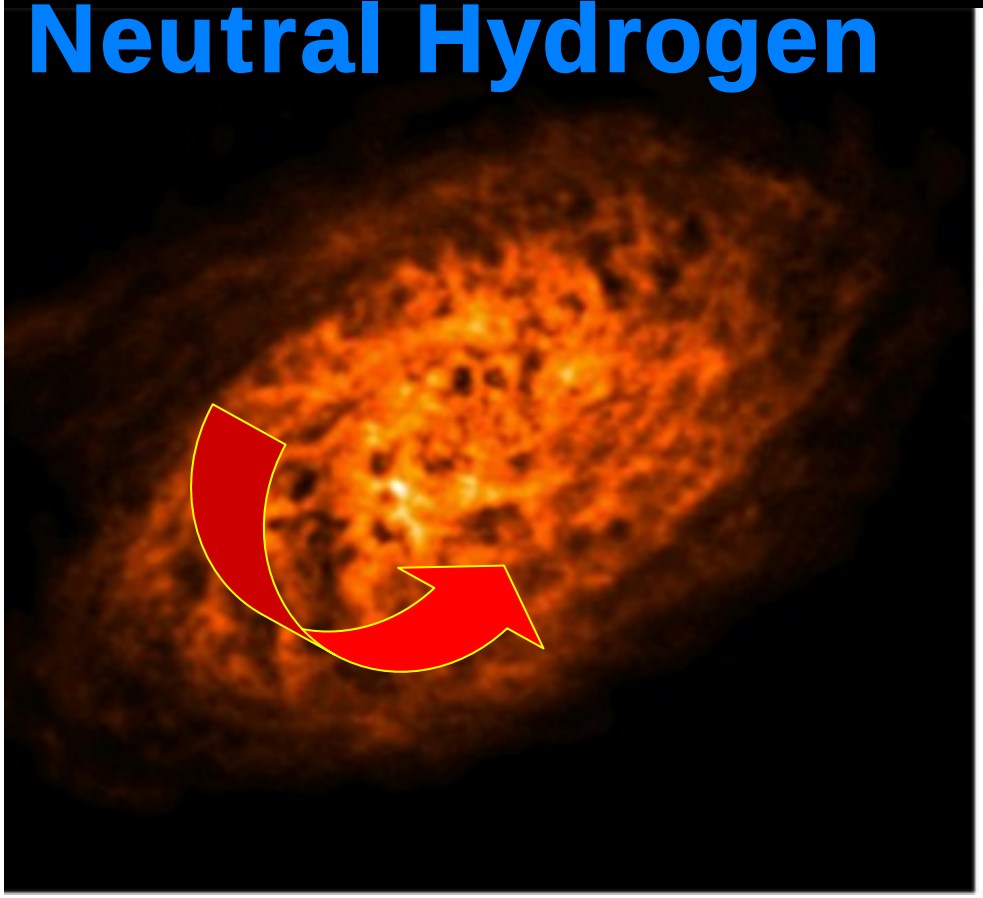


Simulation by Kravstov

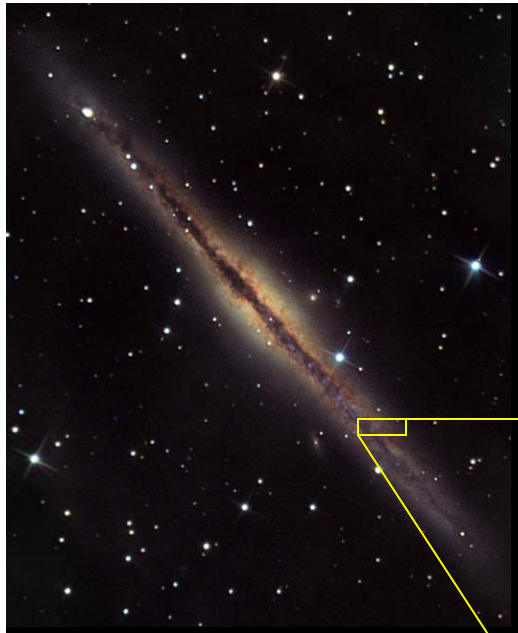
Dekel & Birnboim 2004

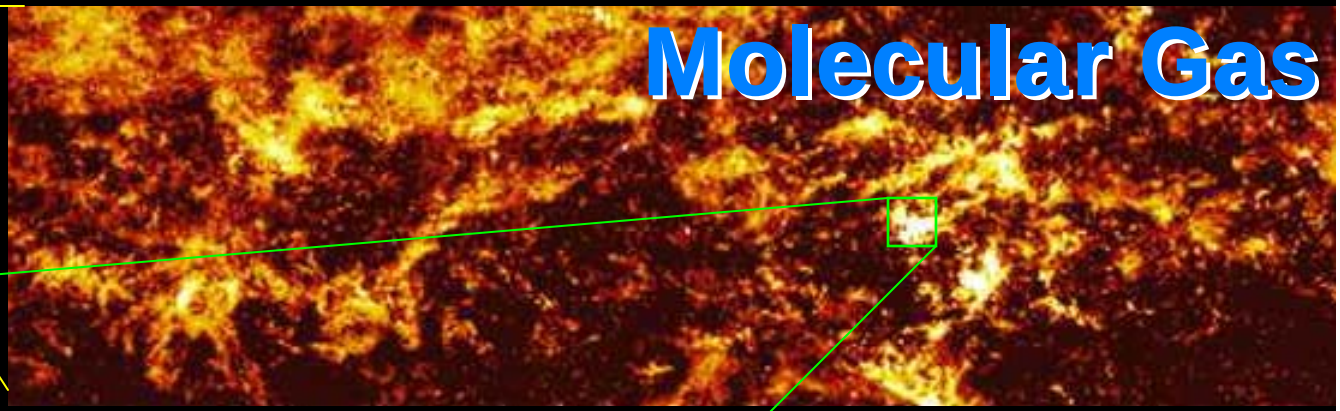
Some gas cools & contracts

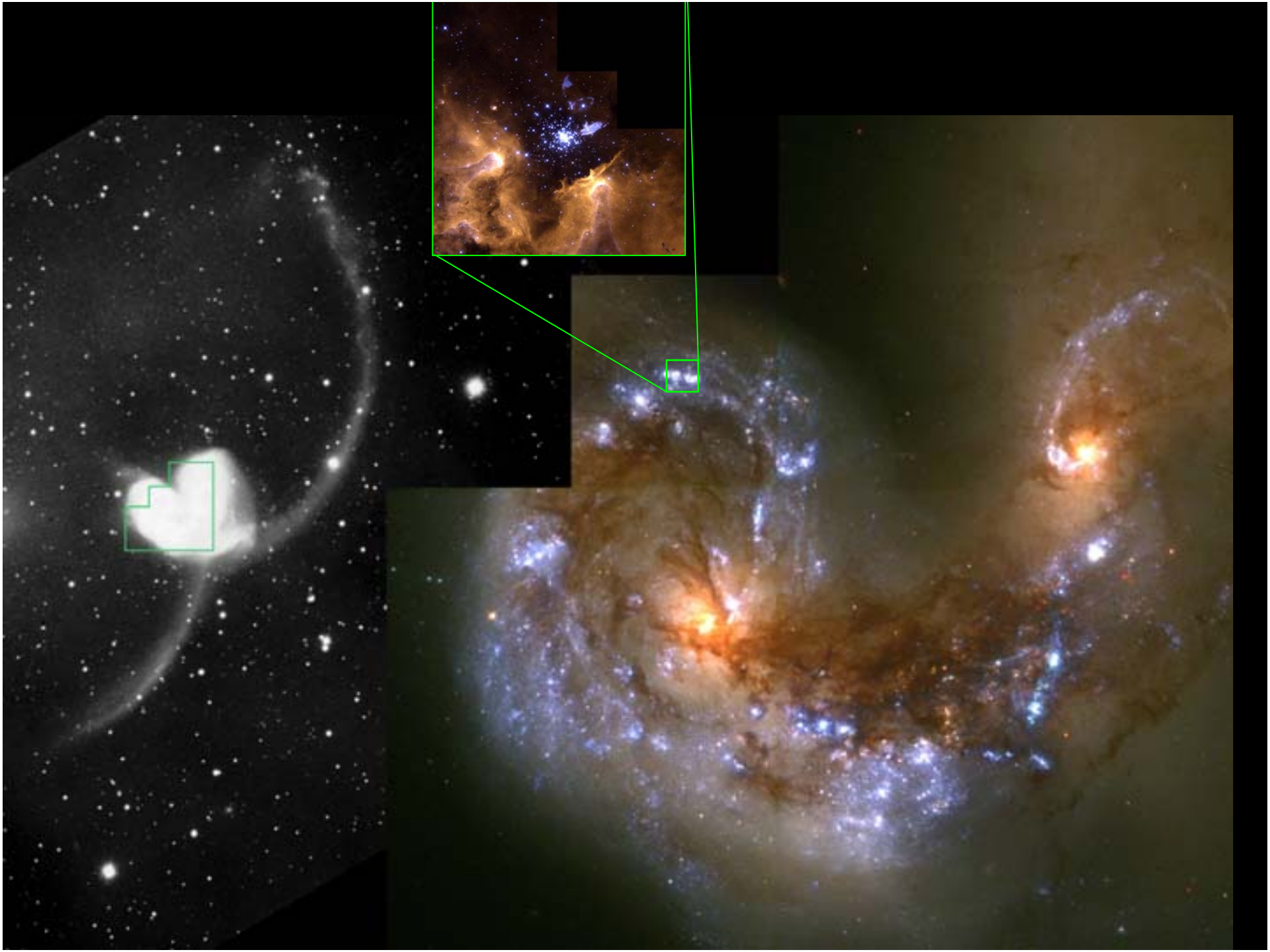
- Gas that comes in with high angular momentum forms a rotating disk.



When gas gets dense, it forms stars

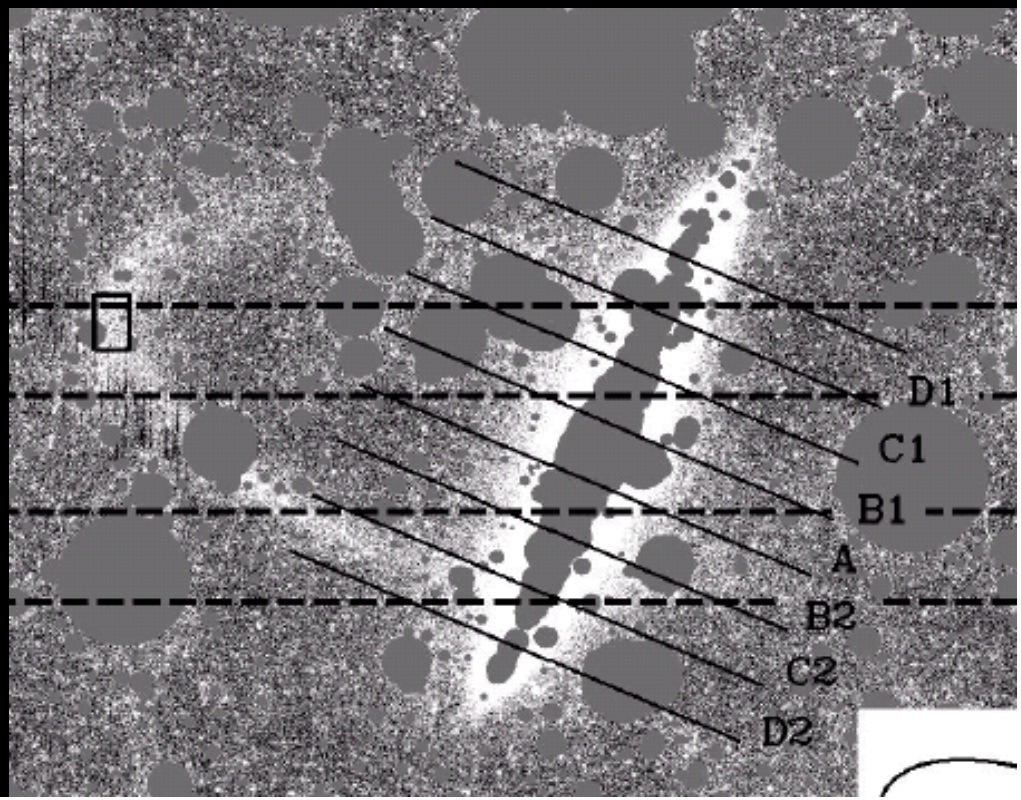




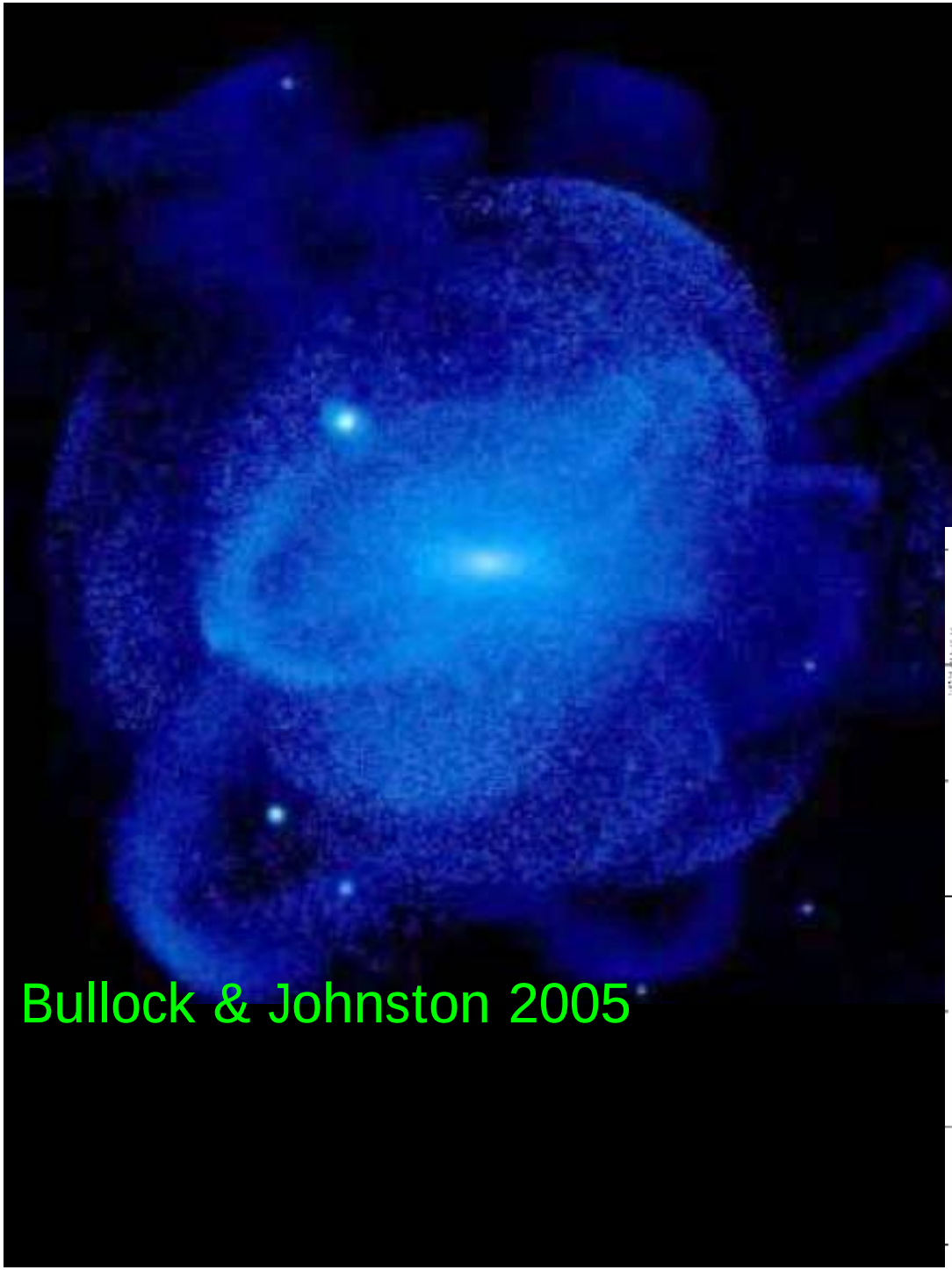


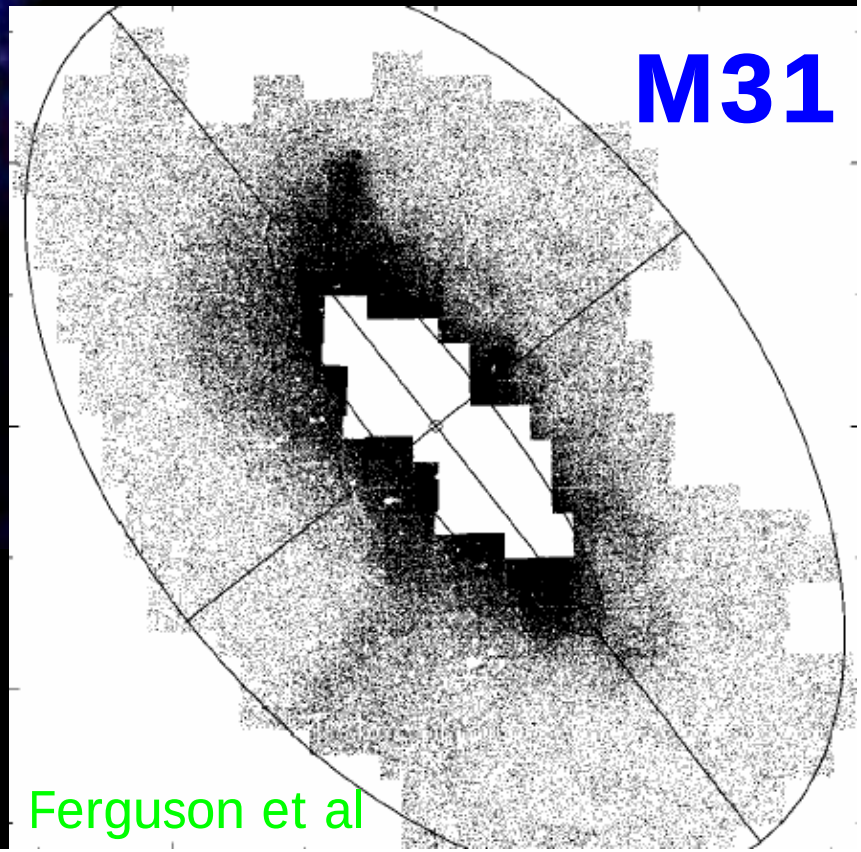
Stars are collisionless

- They tend to preserve the motion with which they were formed.

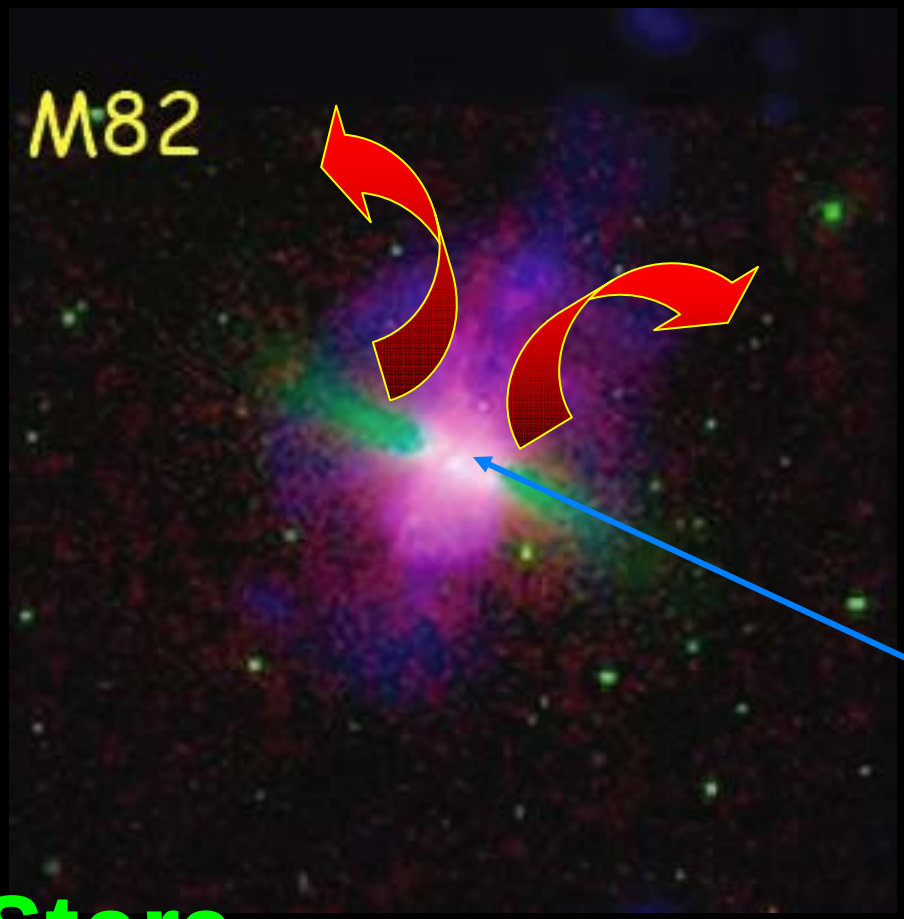


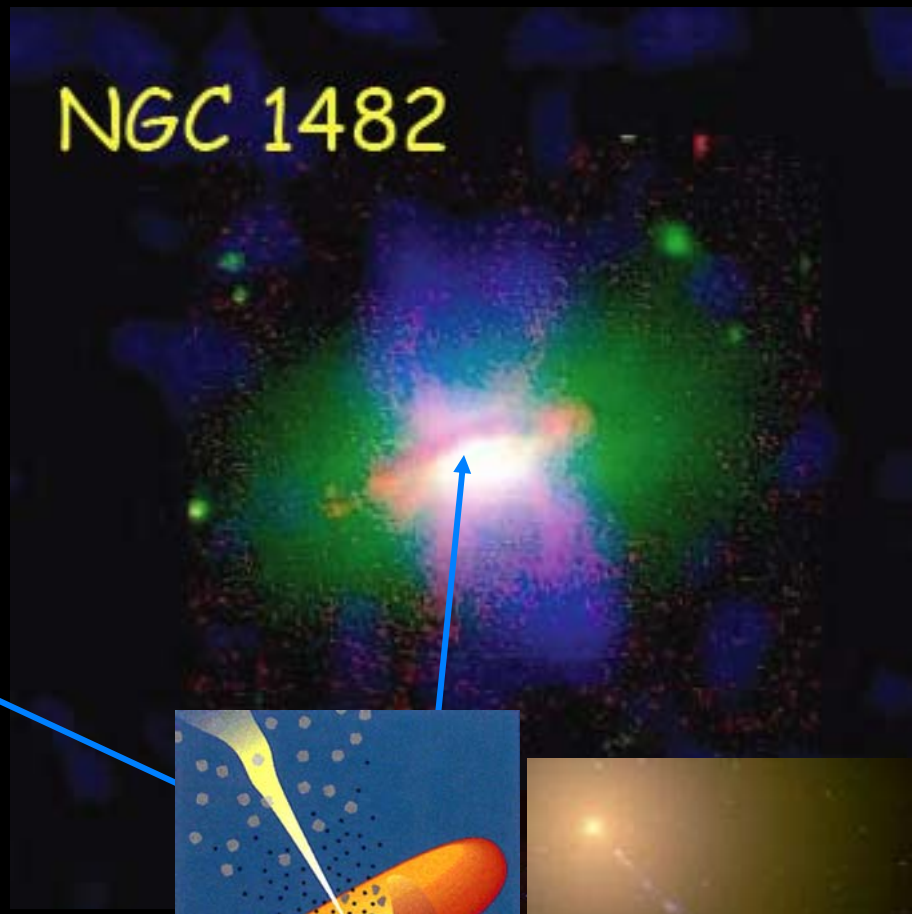
Courtesy K. Johnston

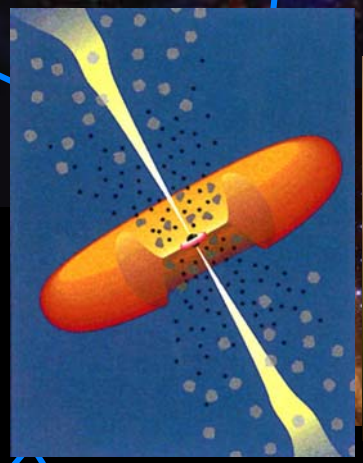

Bullock & Johnston 2005


M31
Ferguson et al

Gas can be ejected: "Feedback"







Stars

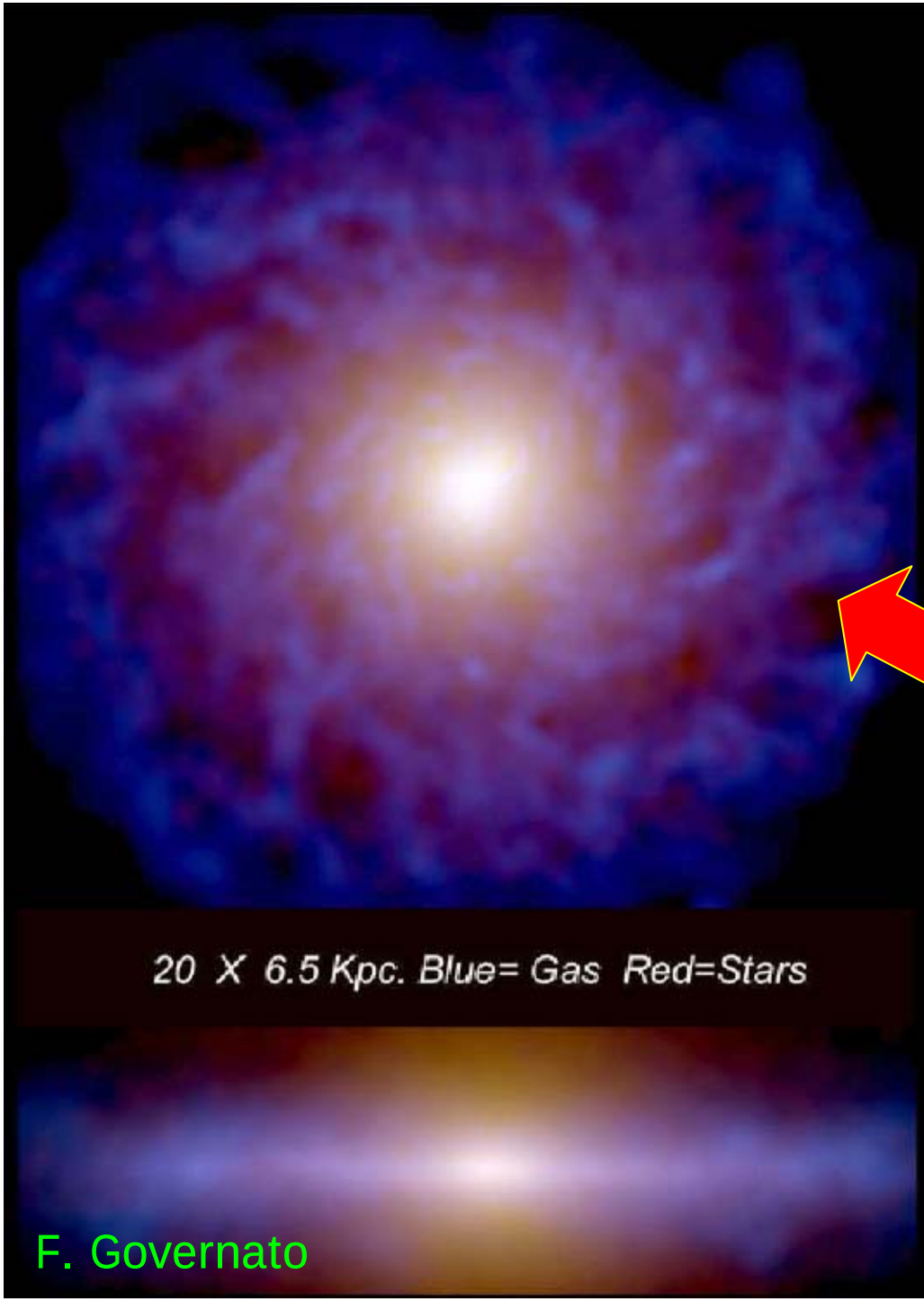
Ionized Gas (10^4K)

Really Ionized Gas (5×10^6K)

Strickland et al 2004

Simulated galaxies are starting to look really promising!

- rotation
- ages
- sizes



F. Governato

Is CDM compatible with our understanding of galaxy formation?

CDM

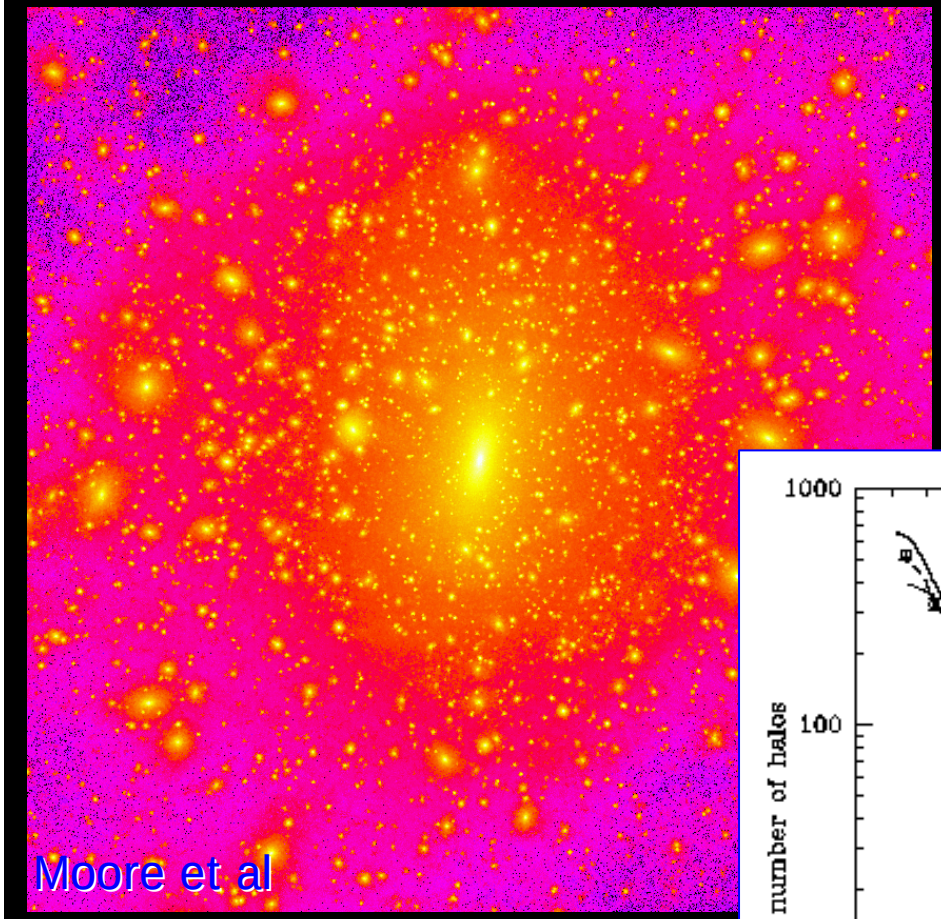
- Heirarchical
- Lots of small scale power
- Small stuff first
- Large stuff last

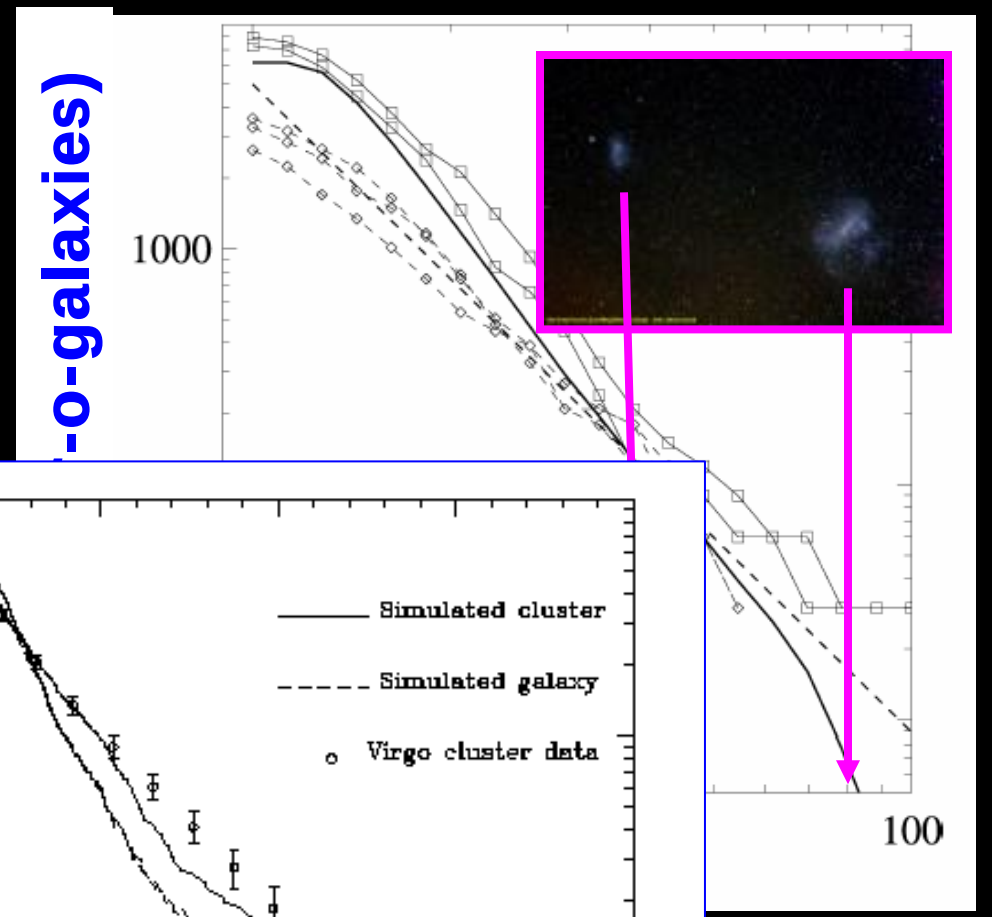
Nature

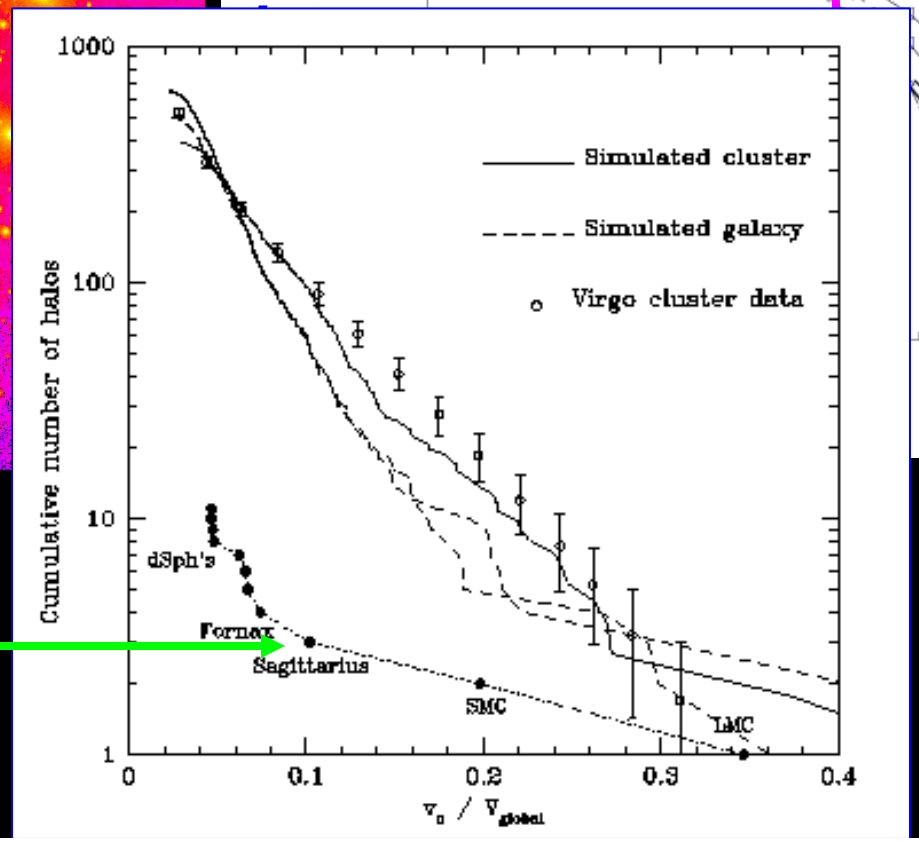
- *Too Few* low mass galaxies
- Young low mass galaxies & *old* high mass galaxies
- Massive objects at high redshift.
- Anti-Heirarchical?

Surprisingly, yes

Hiding Low Mass Halos:







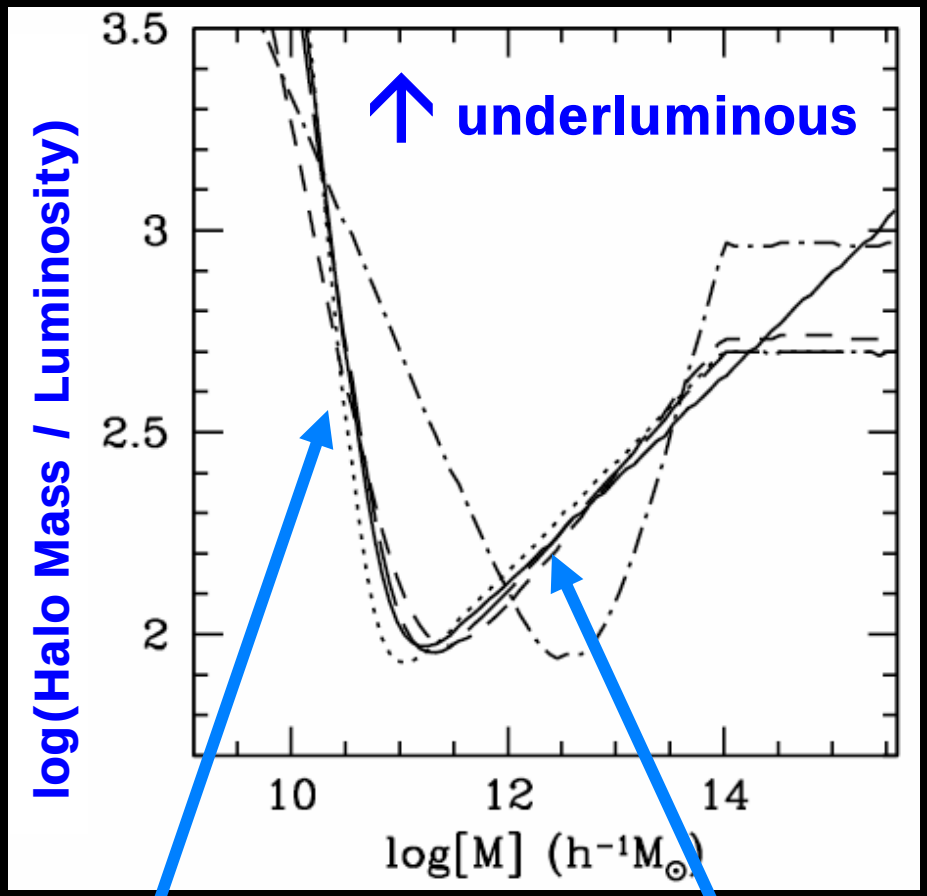
Milky Way data is "missing" galaxies if ΛCDM is correct

Making dwarf galaxies disappear:

- "Feedback"
  Supernova blowout
  $E_{thermal}$;E_{KE} >E_{grav}
- "Squelching"
  Reionization
  $E_{thermal}$>E_{grav}
- "Tidal Disruption"
  $E_{grav,host}$>E_{grav}

Dwarf galaxies have small gravitational potentials

Similar problems for *massive* galaxies:



SN Feedback from disks

?

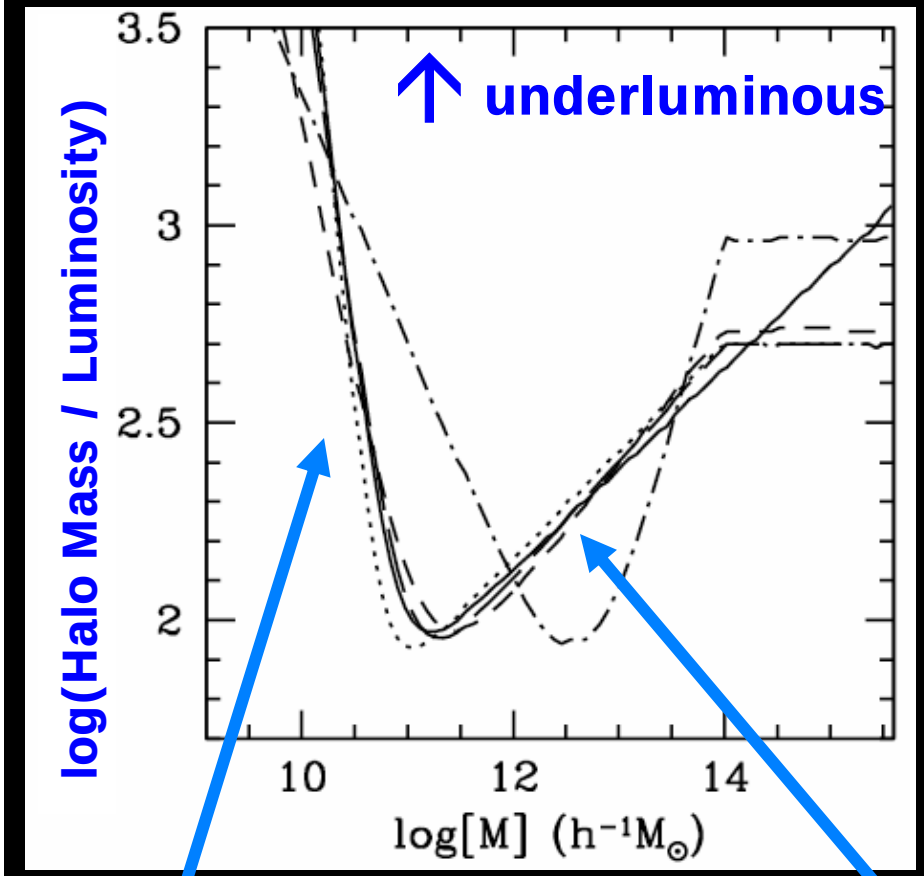
van den Bosch et al 2004

- Smaller fraction of baryons wound up in massive galaxies
- Star formation feedback & reionization won't work for deep potential wells

Merging = Gas→BH = Outflow

V. Springel et al

AGN Feedback:

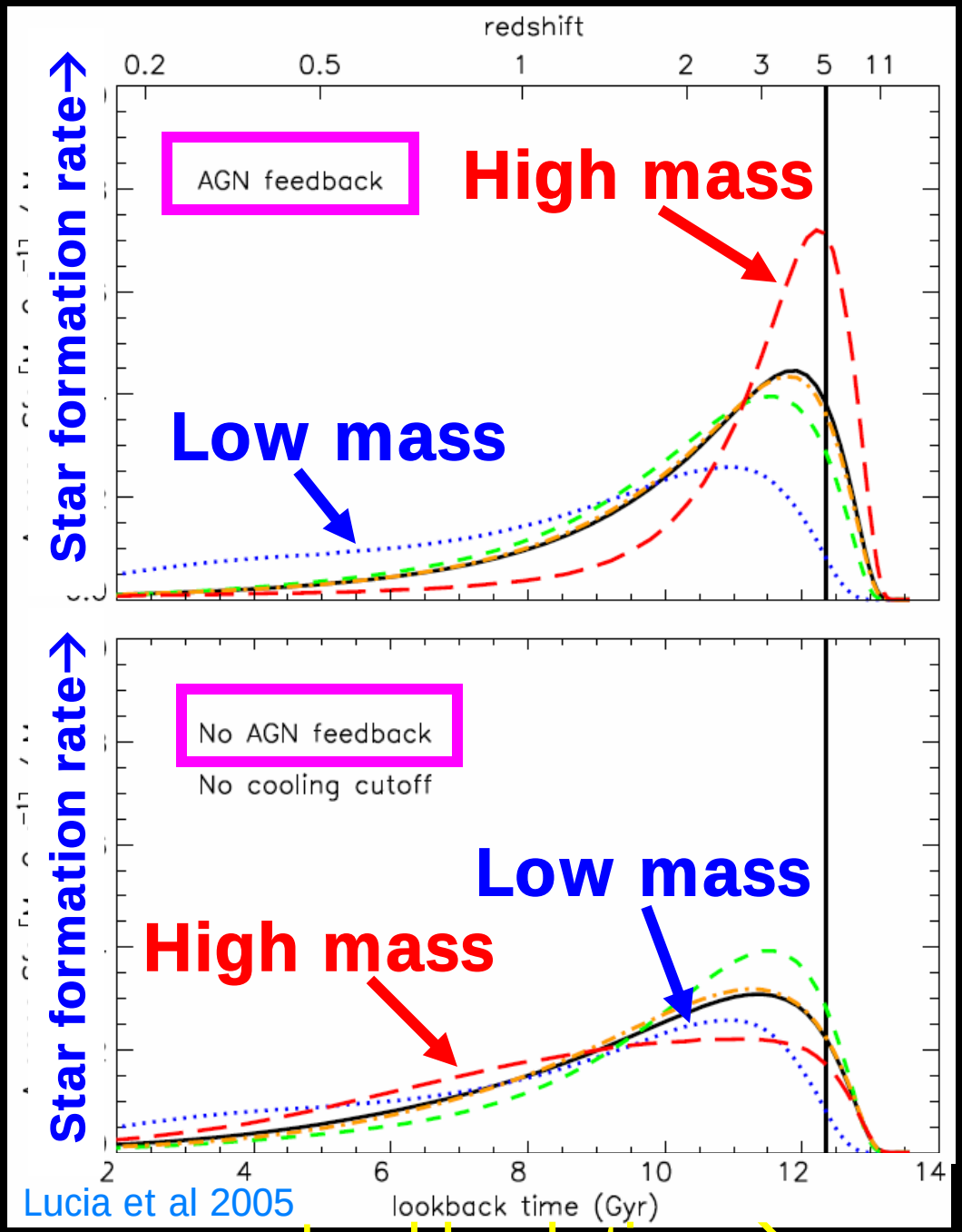


SN Feedback from disks

AGN Feedback from spheroids

van den Bosch et al 2004

- Bigger spheroid = Bigger Black Hole
- Feedback *stronger* in more *massive* galaxies
- Star formation shuts down earlier and more completely in massive galaxies



Lucia et al 2005

Lookback time→

AGN Feedback makes galaxies *appear* "anti-hierarchical"

In massive galaxies:

- Stars form early
- Mass assembles late

Putting it all together:

Courtesy G. Stinson & F. Governato

Problems remain

- Predicting internal structure




- Internal kinematics
- Numbers/Masses at high redshift?
- Compatibility with reionization?

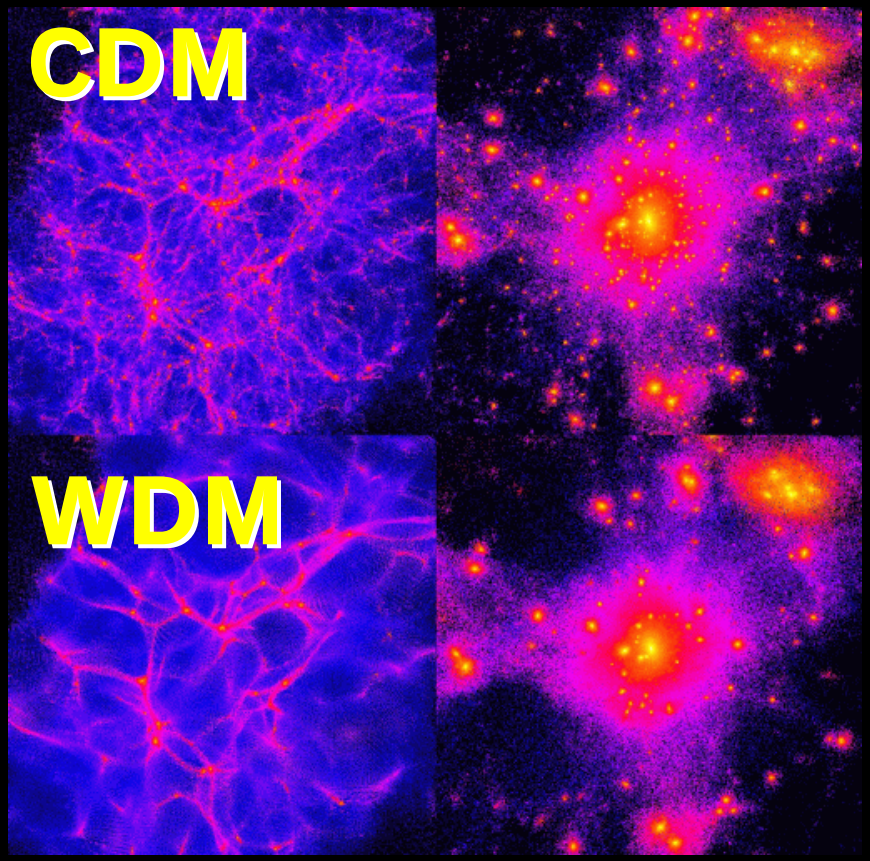
But, given our success of making the impossible possible, I'd be optomistic.

But really, this is all a fairy tale.

We've proven that ΛCDM is ***not necessarily wrong***.

This doesn't mean it's ***right***!

Why galaxy formation is *not* constraining cosmological models*

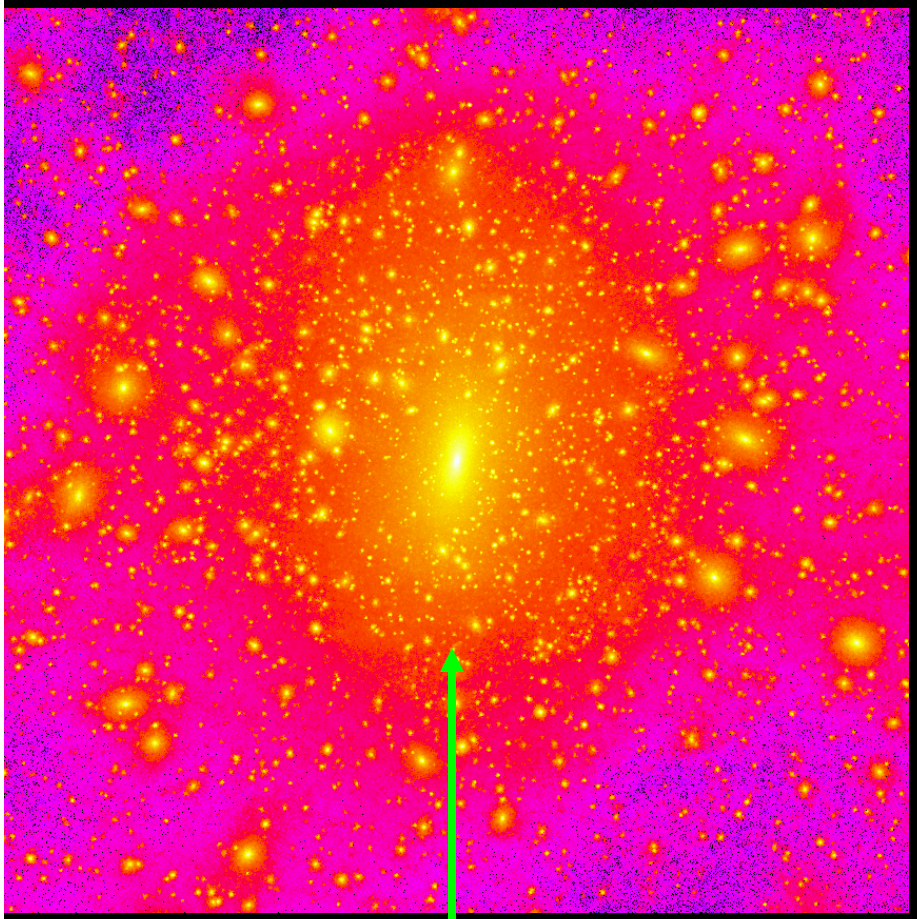


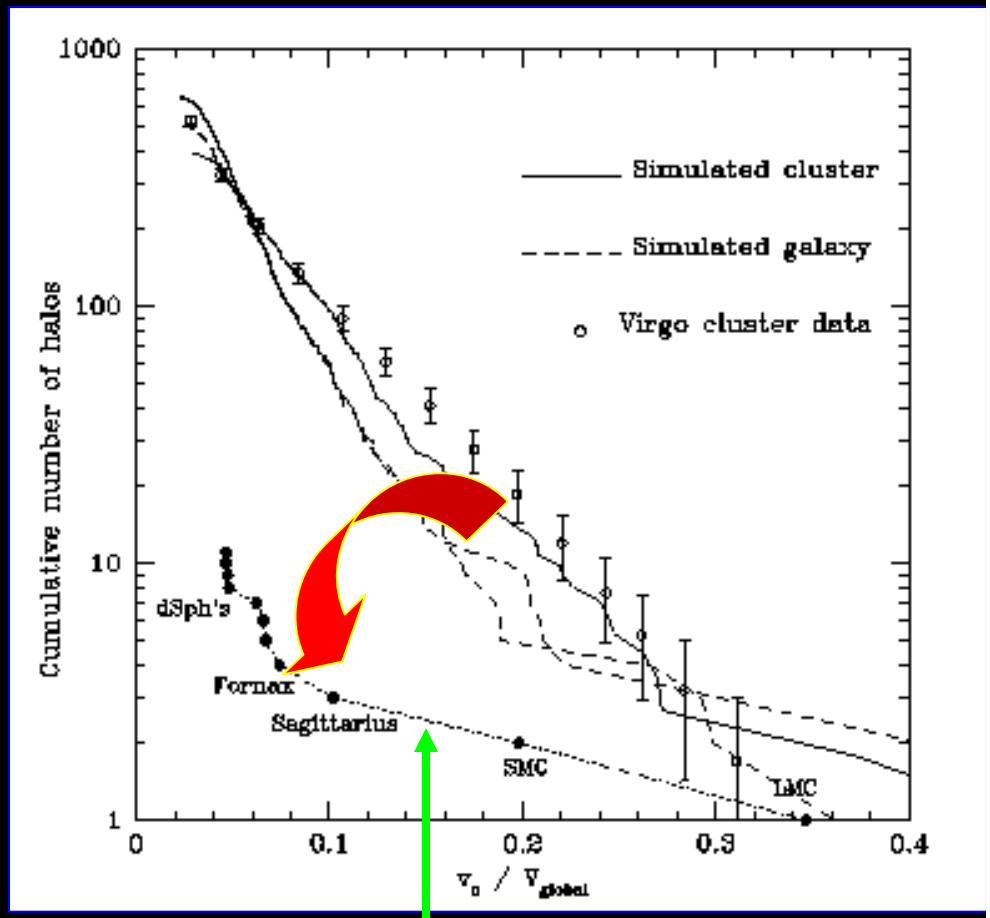
Theory starts with ΛCDM as an *a priori* assumption

Tunes "gastrophysics" to match observations

Moore et al

*in the era of precision cosmology

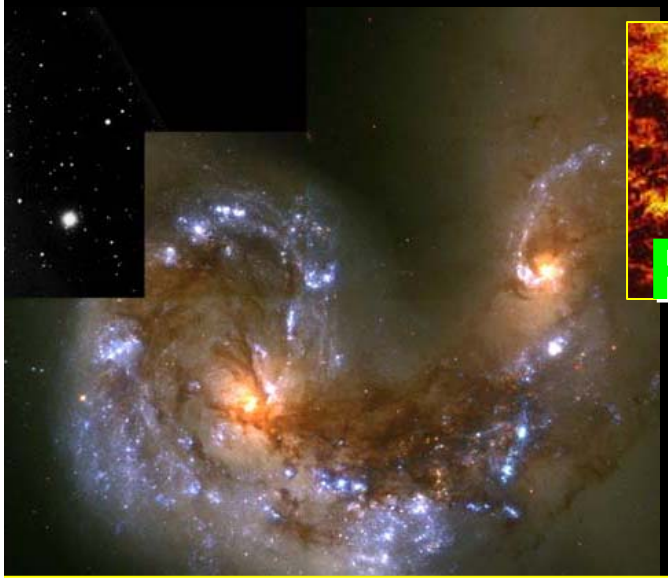


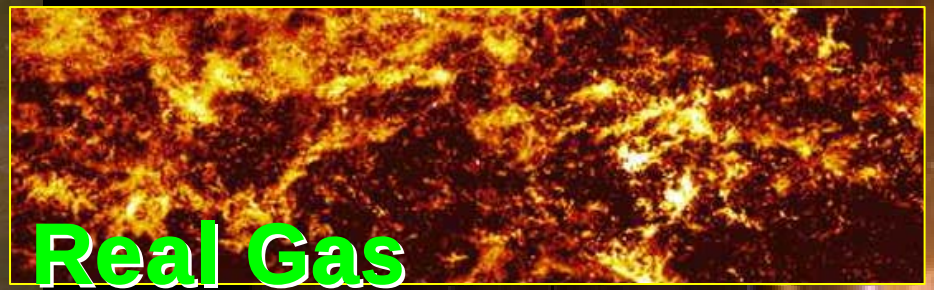


Start with predicted dark matter distribution

Adust star formation and SN “feedback” to suppress the “right number” of galaxies

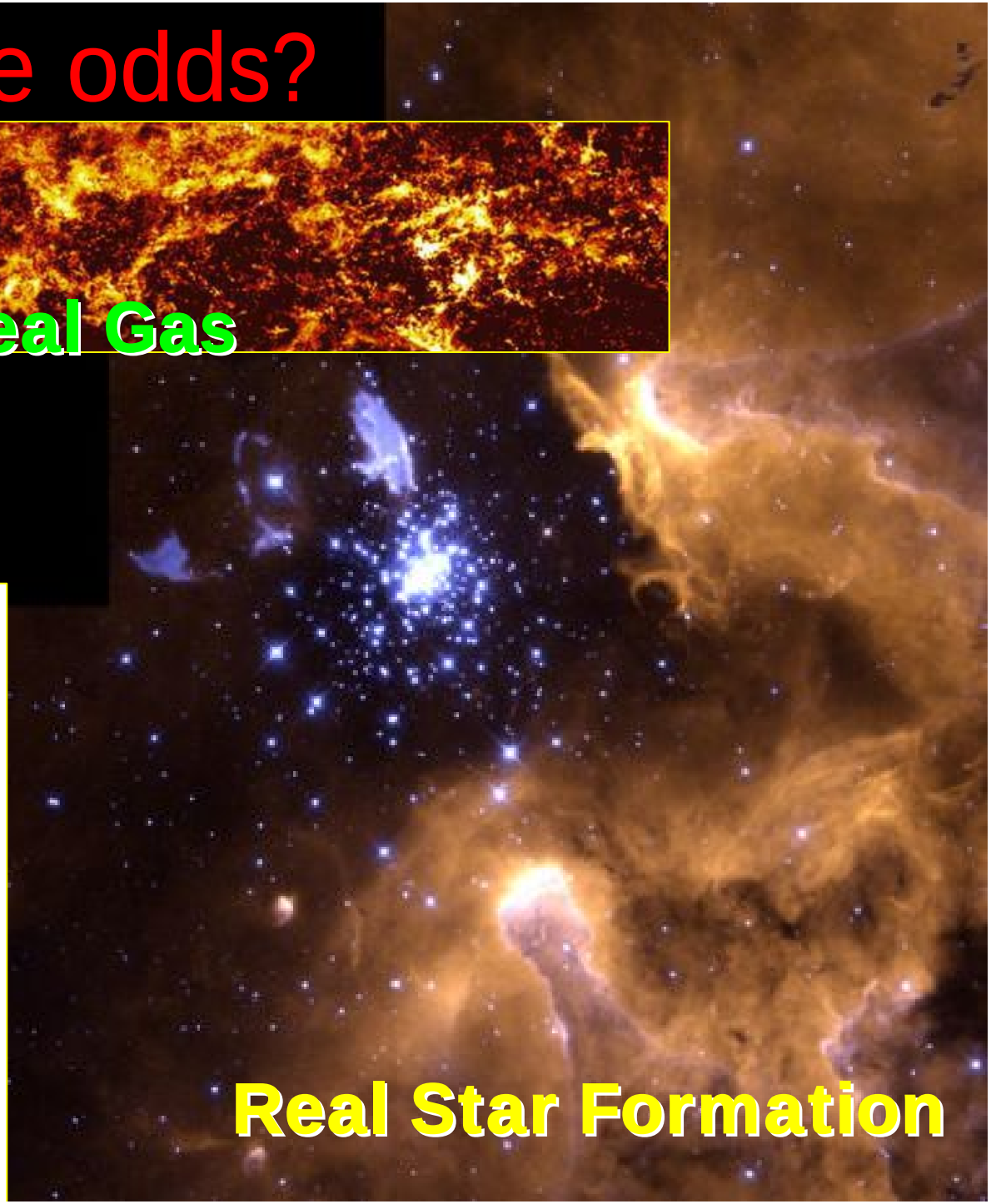
What are the odds?





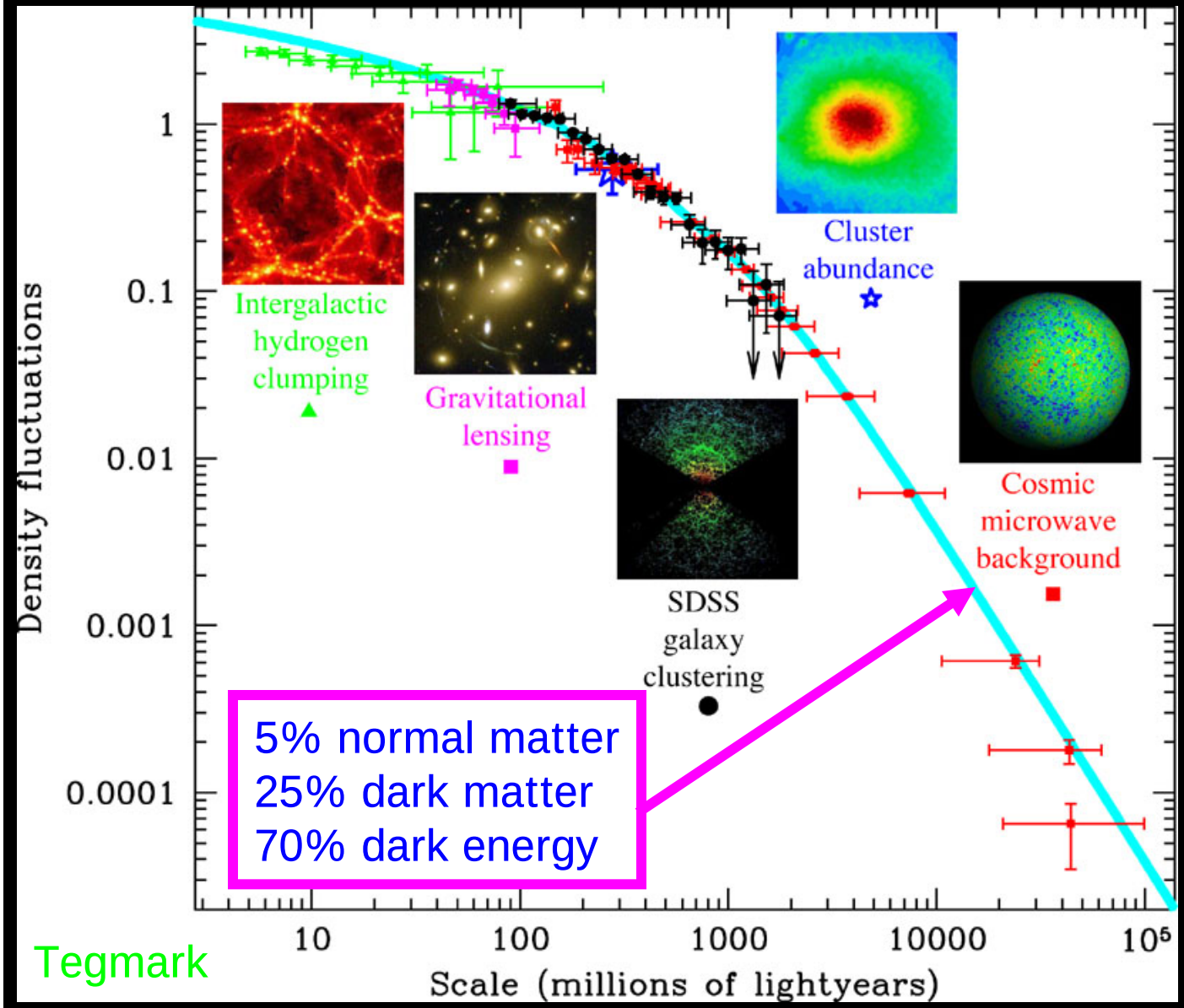
Real Outflows

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



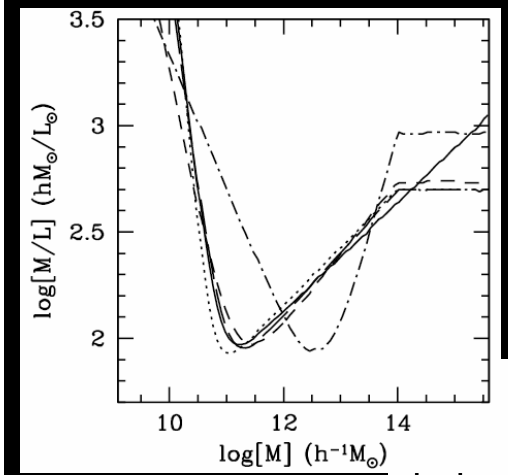
Red = ionized

Where could non-ΛCDM physics be lurking?



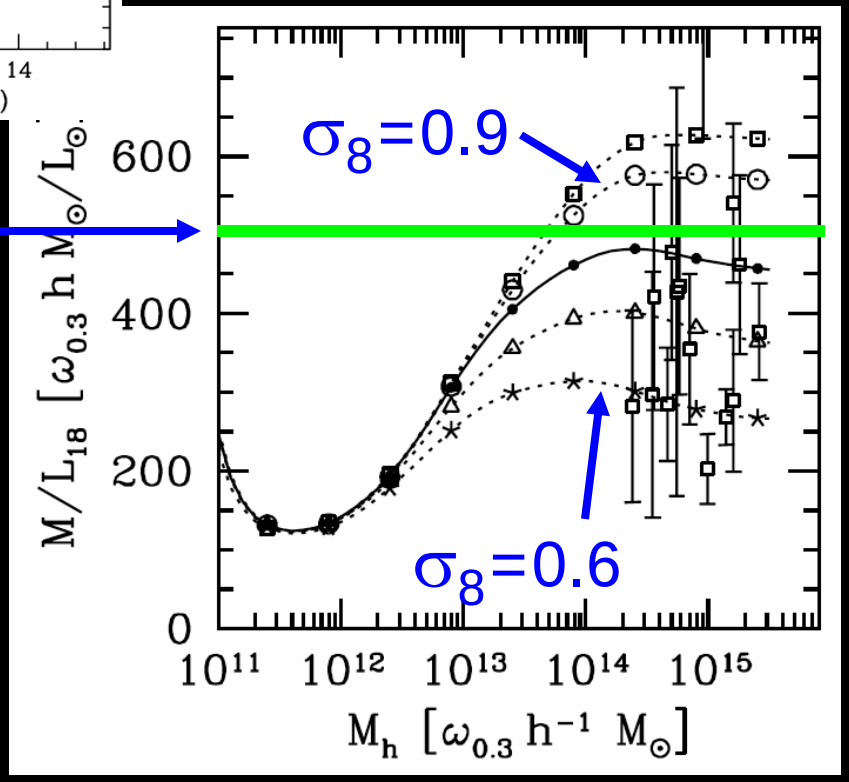
Not on large (>Mpc) scales

On intermediate (~1-10Mpc) scales?



- Fix shape of the linear power spectrum
- $\sigma_8 \Omega_m^{0.6}$ is lower when measured on small scales, than for CMB+SN

True average M/L



Tinker et al 2005

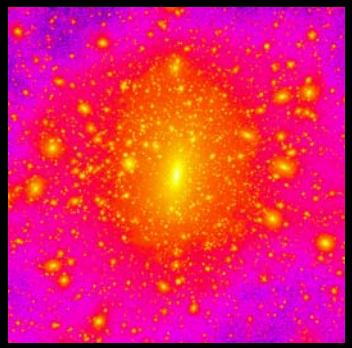
(Note: derived behavior of baryons vs mass is qualitatively similar)

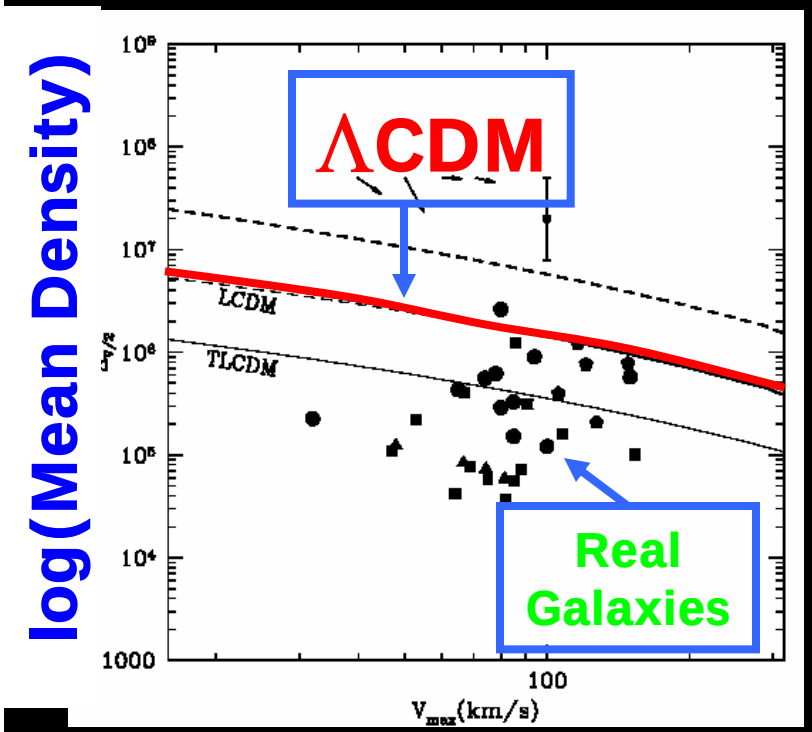
On smaller (~1 kpc) scales?

Compared to the *real* universe

ΛCDM simulations have:

- Too many small lumps
- Too high a central density

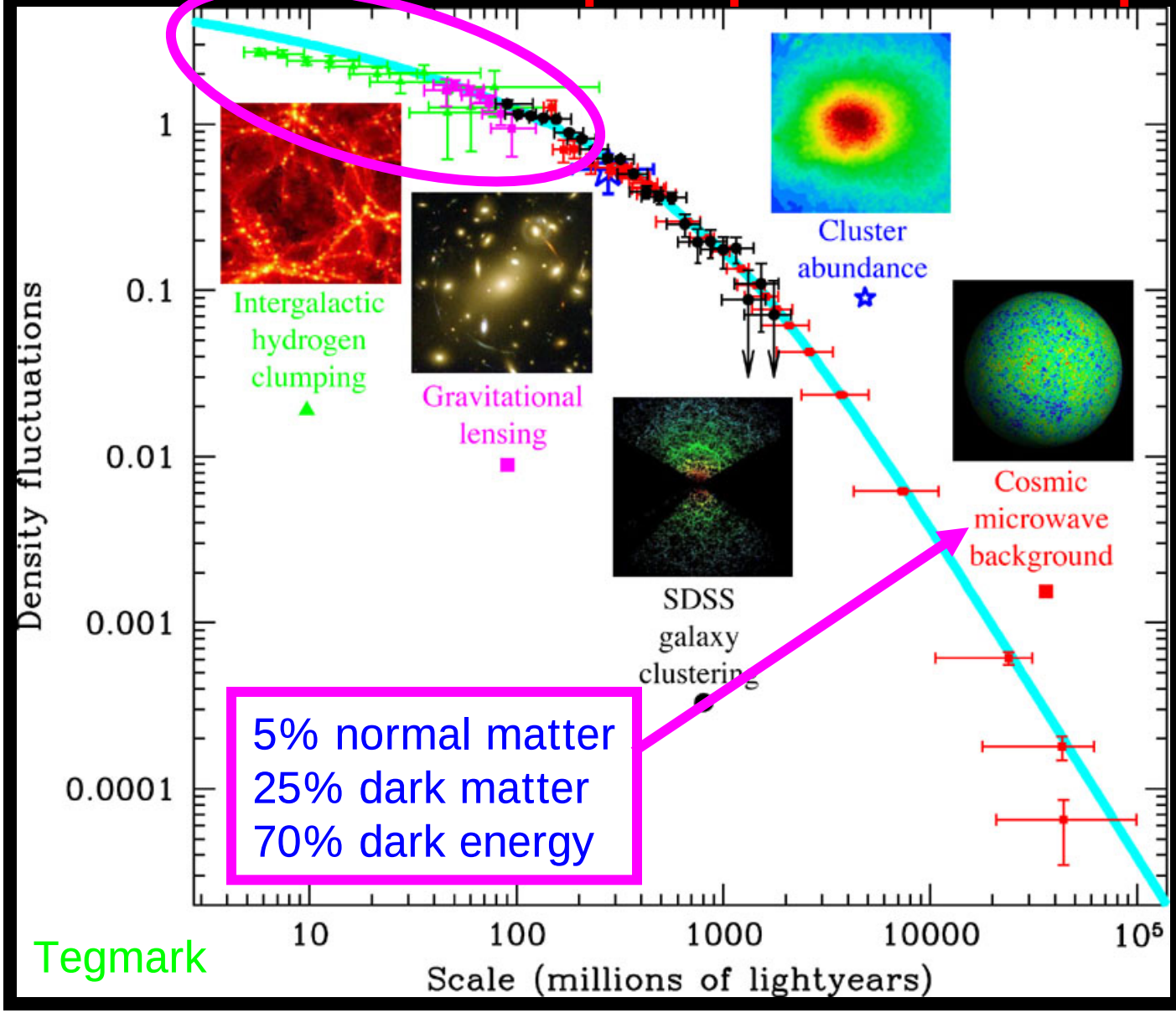




$$\rho(<R) \propto \frac{M}{R^3} \propto \left(\frac{V(R)}{R}\right)^2$$

- Too much small scale power
- Too high initial phase space density

Galaxy formation provides far more freedom than people are exploiting



Tegmark

CDM is an absurdly minimal description of dark matter

What to do?

- Don’t ignore theories whose power spectra deviate at small scales.
- Improve constraints on gastrophysics.
- Look for better observational tests.
- Increase dynamic range of simulations.
- Aggressively pursue dark-dark halos