Astro/Physics 224 Winter 2008

Origin and Evolution of the Universe

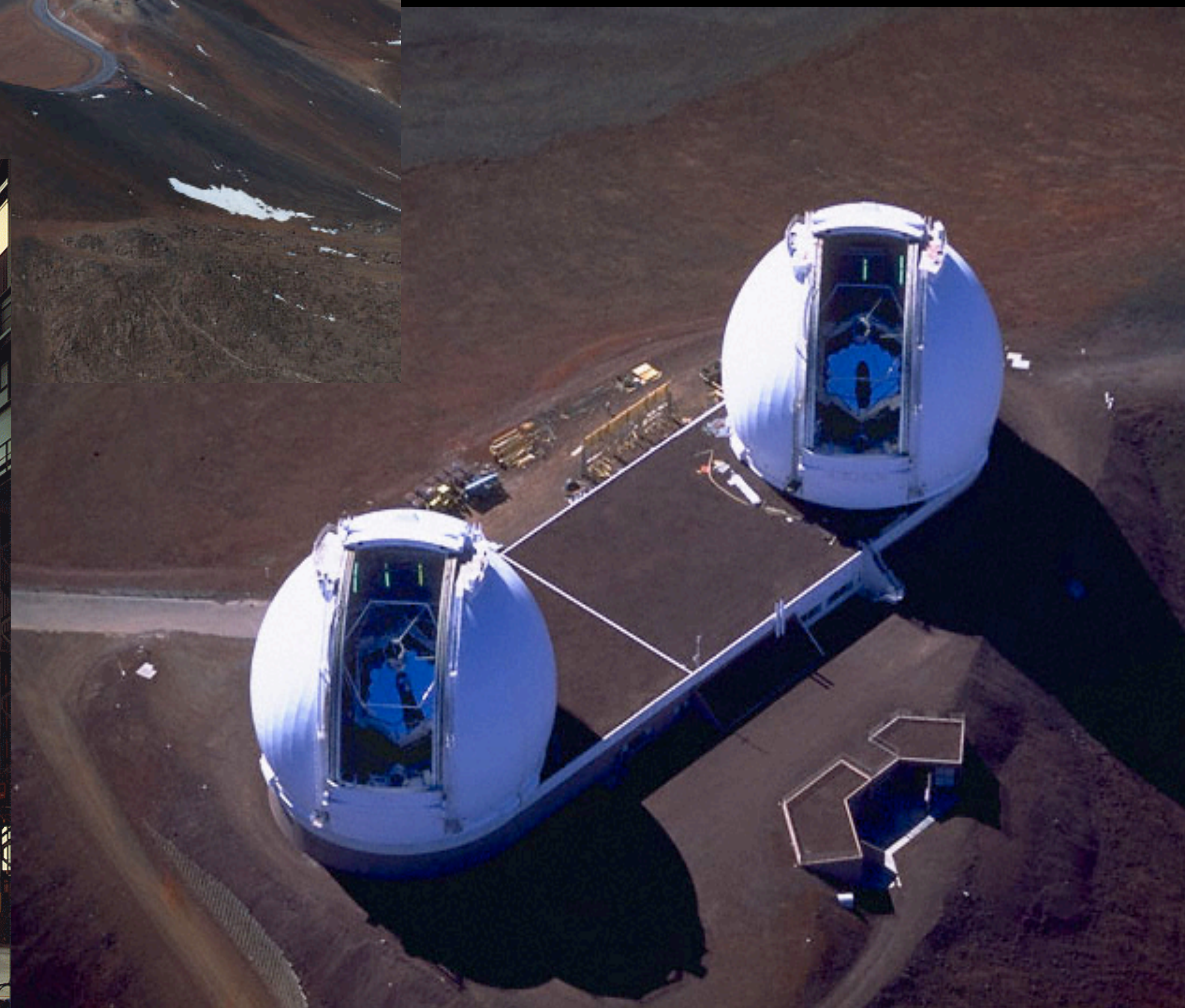
Galaxies and Semi-Analytic Models

Lectures 11&12 - Friday Feb 22 & Monday Feb 25

Joel Primack

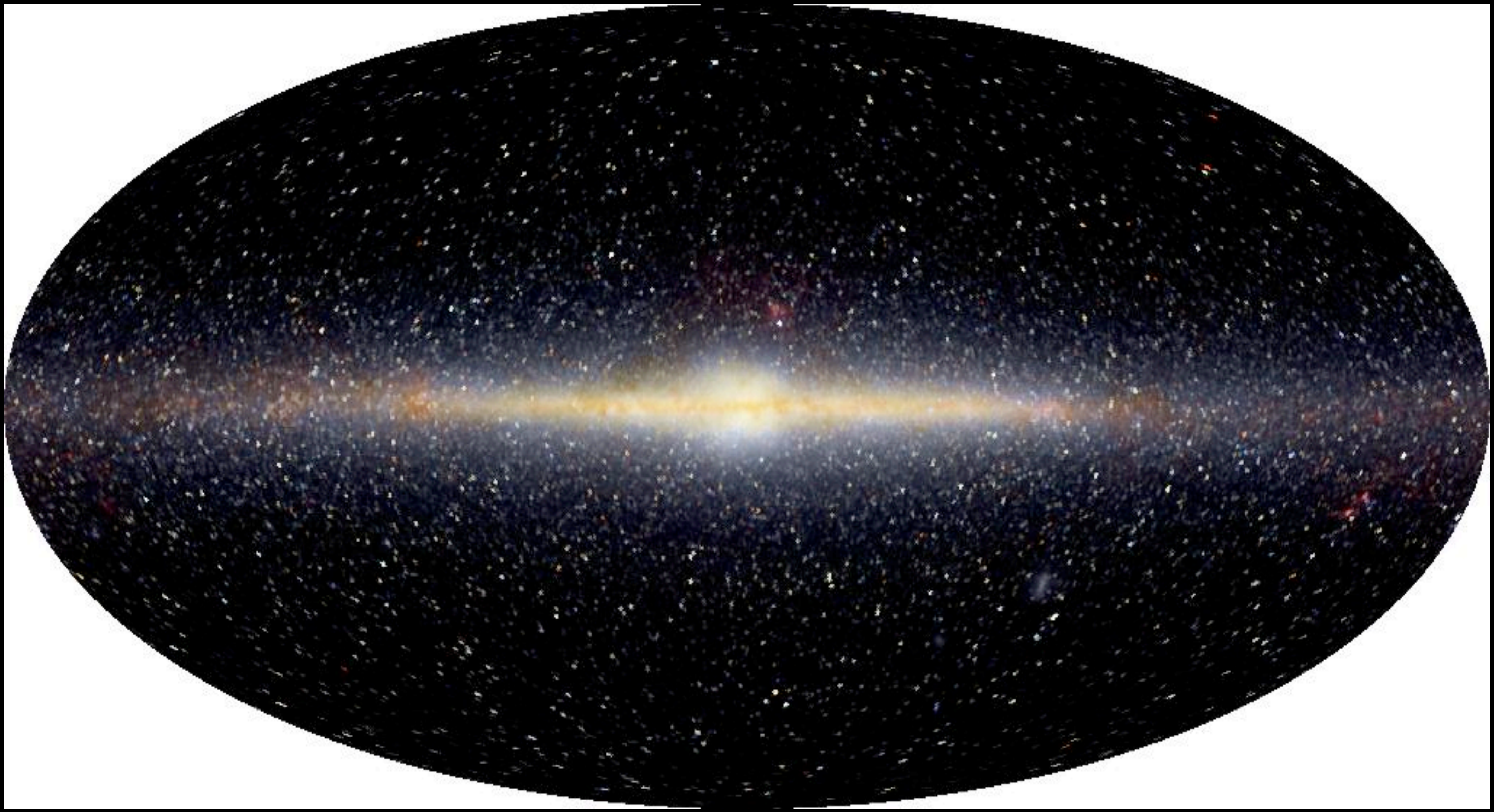
University of California, Santa Cruz

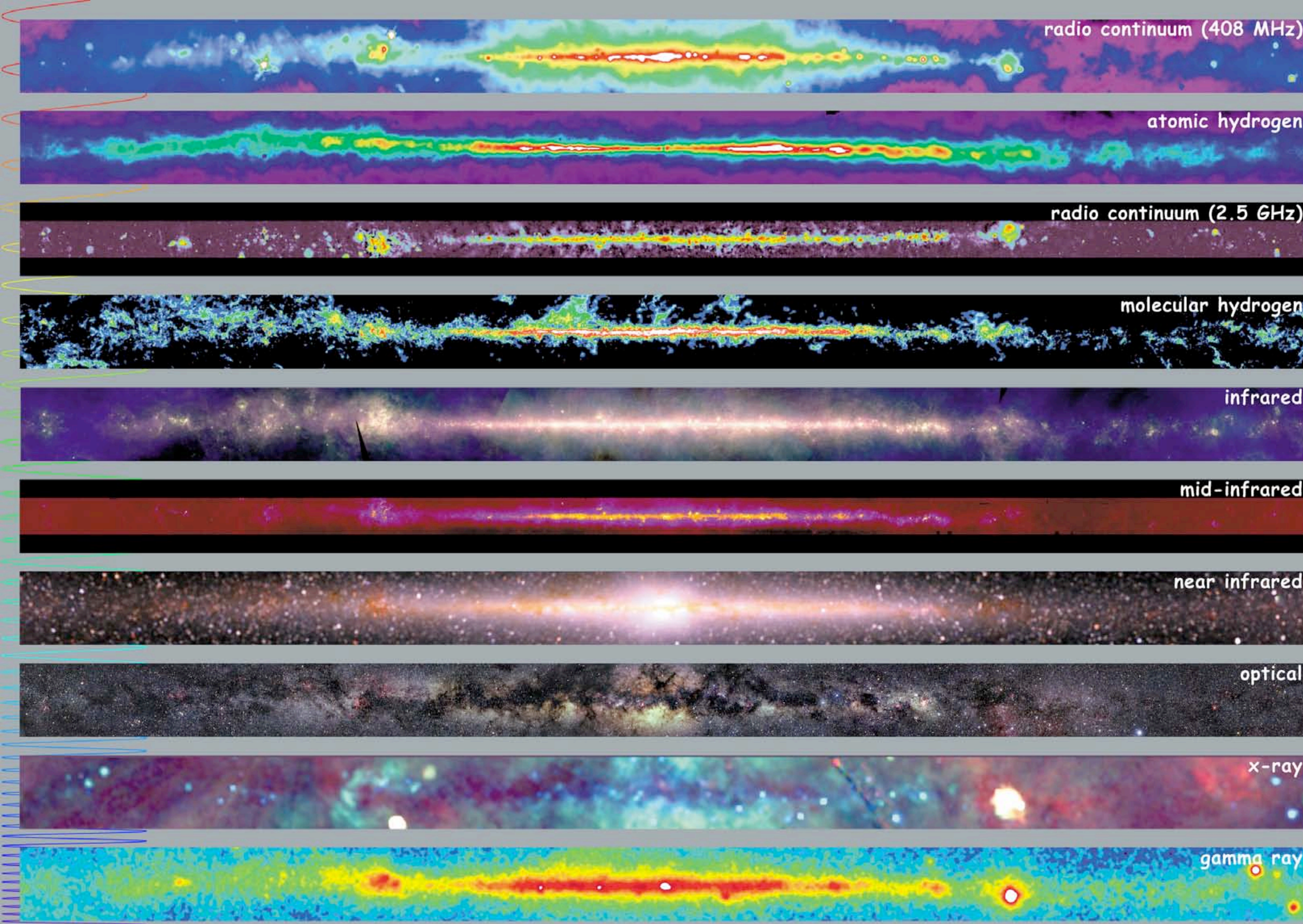
Keck Telescope
10 meter



Hubble Space Telescope

The Milky Way



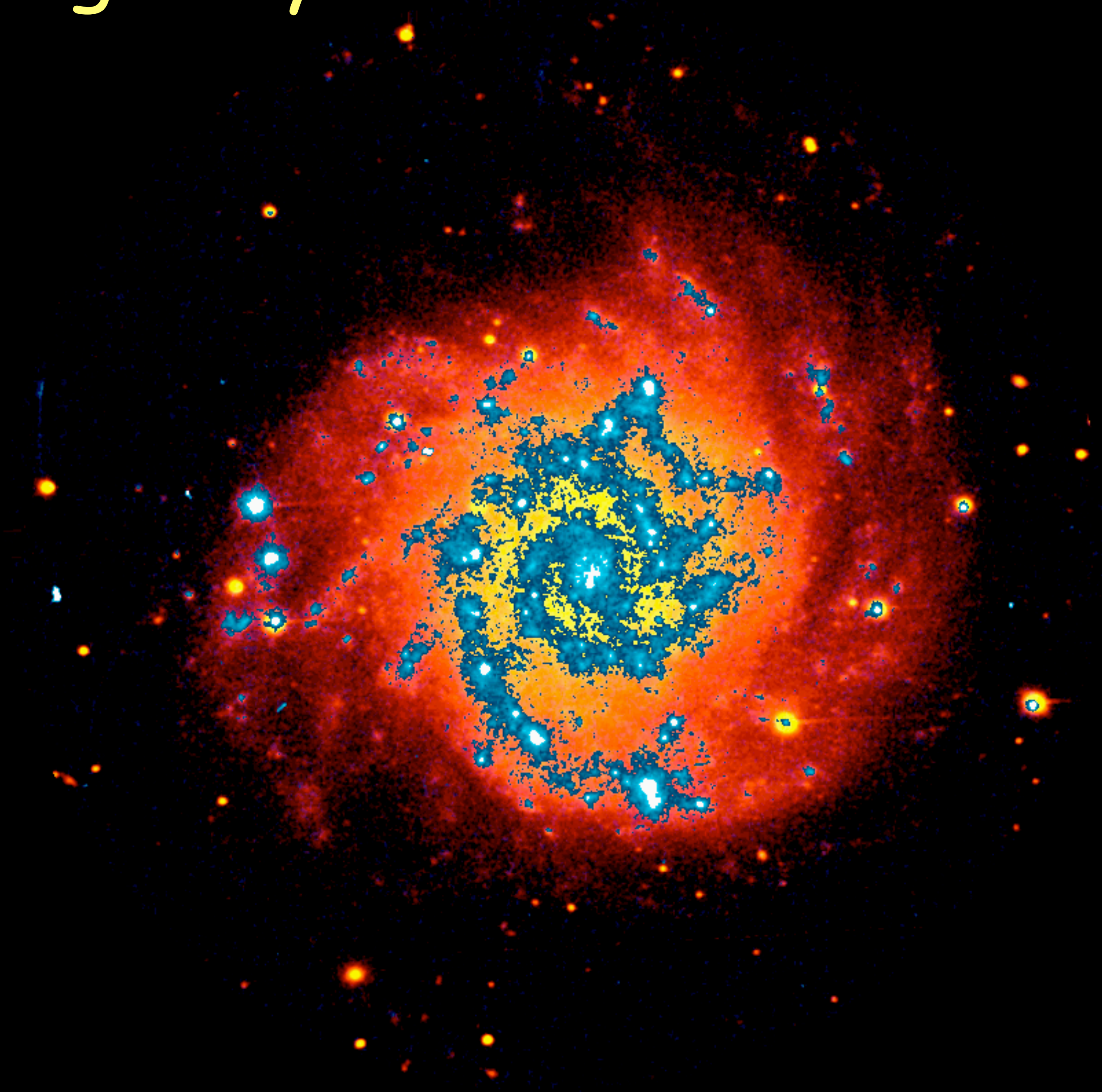


http://adc.gsfc.nasa.gov/mw

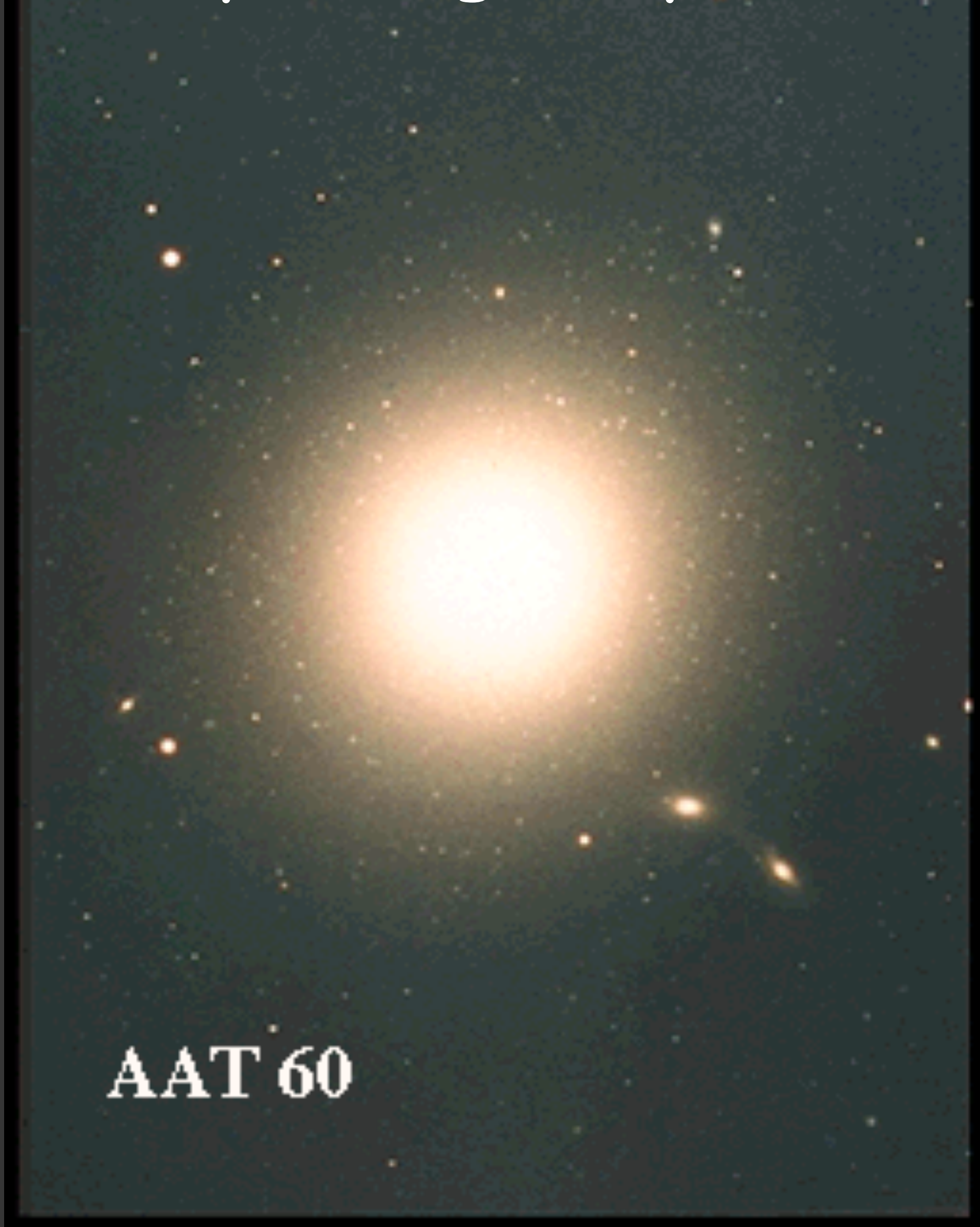
Multiwavelength Milky Way

A Spiral Galaxy

Spiral galaxy M74



Elliptical galaxy M87



Dwarf galaxy: LMC


Low-Surface-Brightness
& Dwarf Galaxies

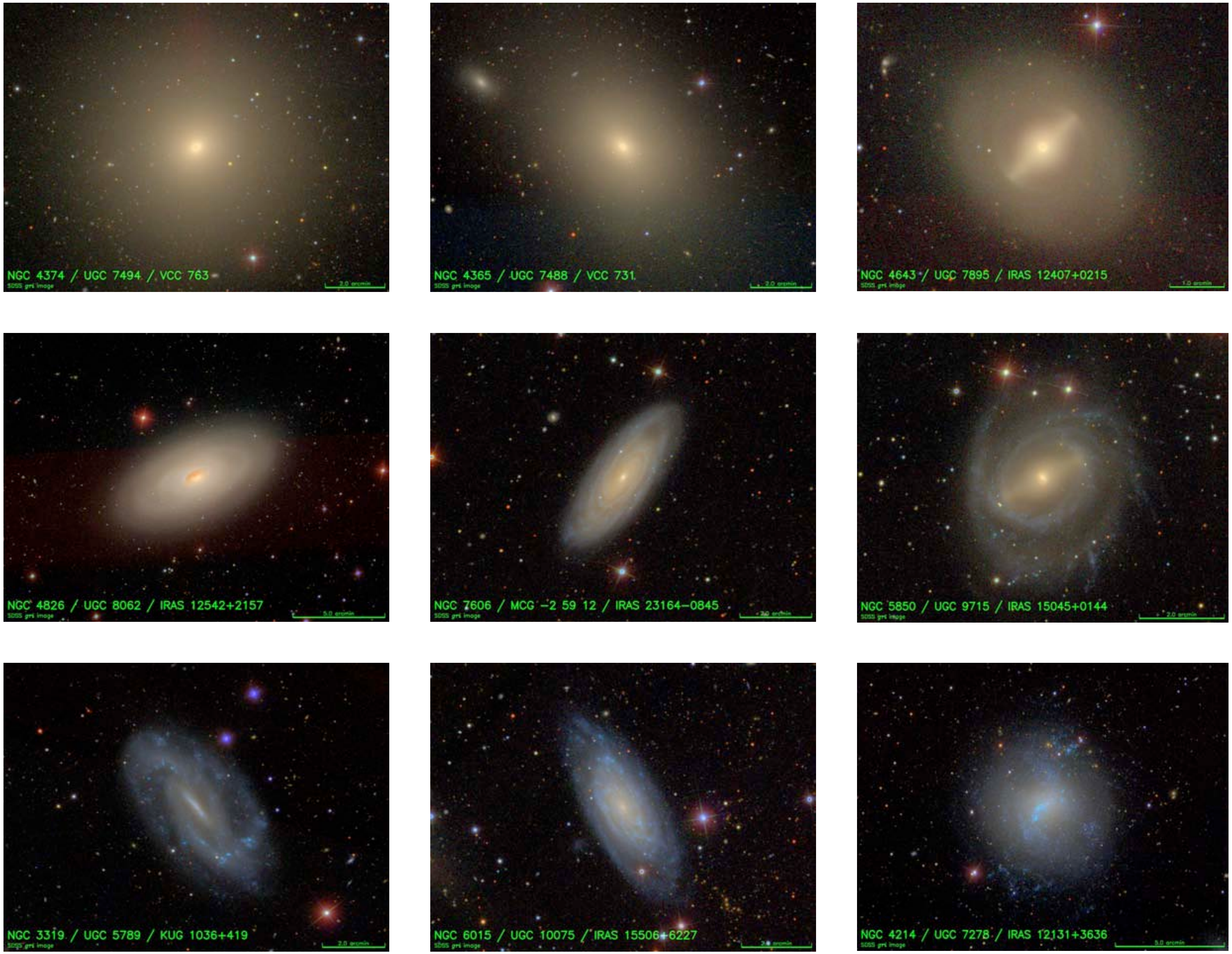
The Galaxy Catalog

by Zsolt Frei and James E. Gunn

This Galaxy Catalog is a collection of digital images of 113 nearby galaxies. Images taken in several passbands and a color-composite image are included for each galaxy.

http://www.astro.princeton.edu/~frei/catalog.htm

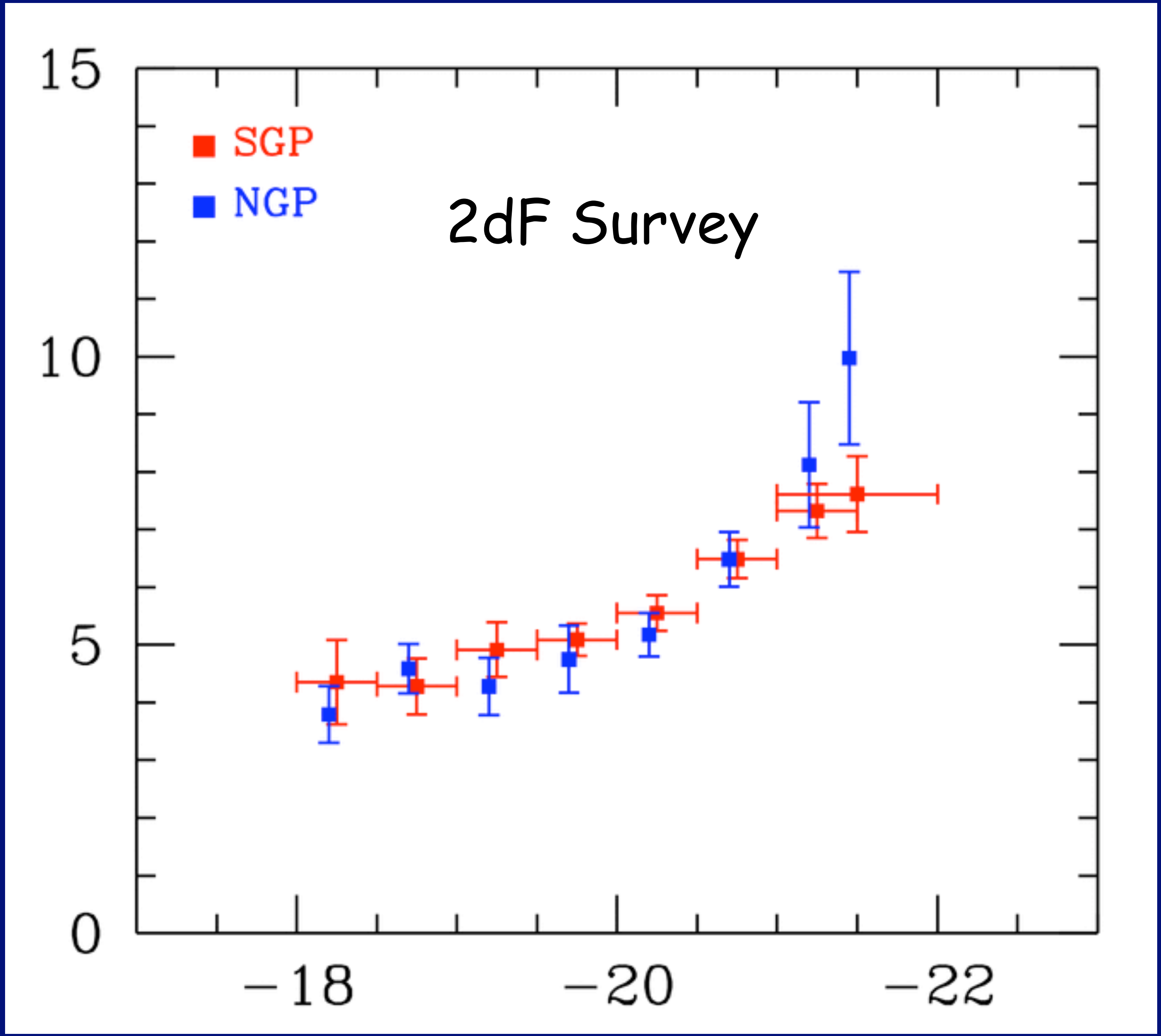
Motivation: How do Galaxies Form?



Images: David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration.

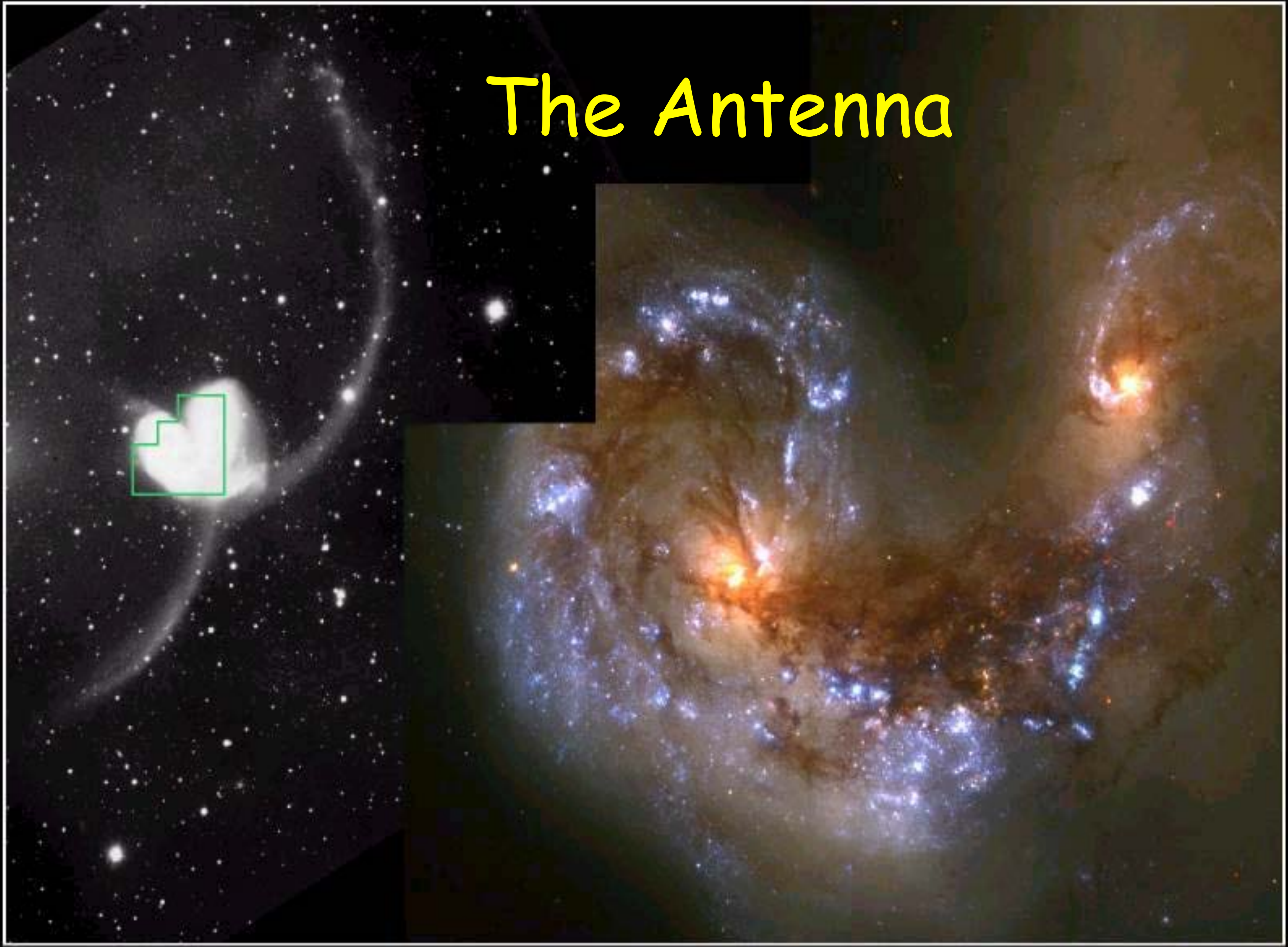
Luminosity Dependence of Galaxy Clustering

Correlation length (Mpc/h)



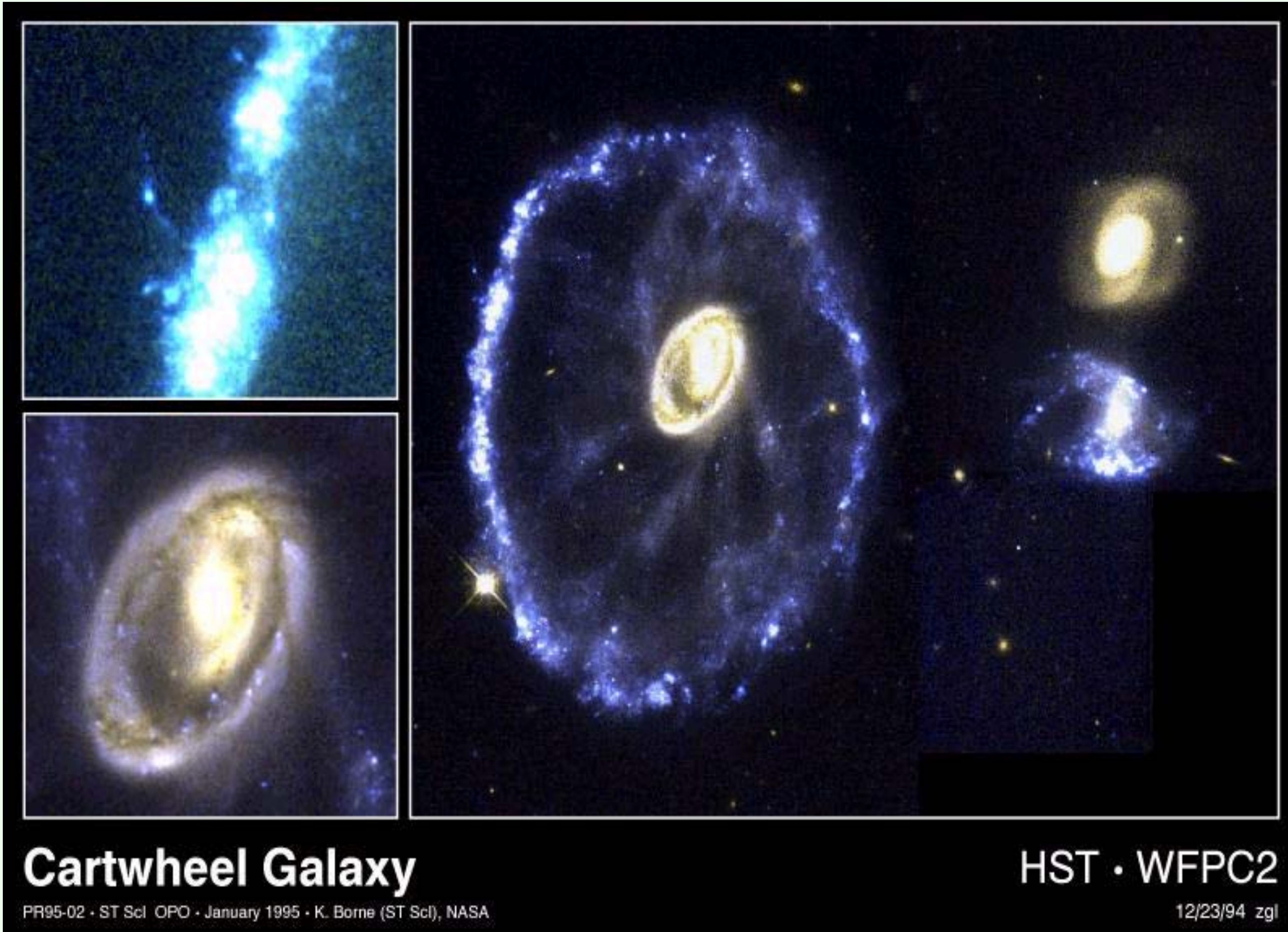
Luminosity ⟶

The Antenna

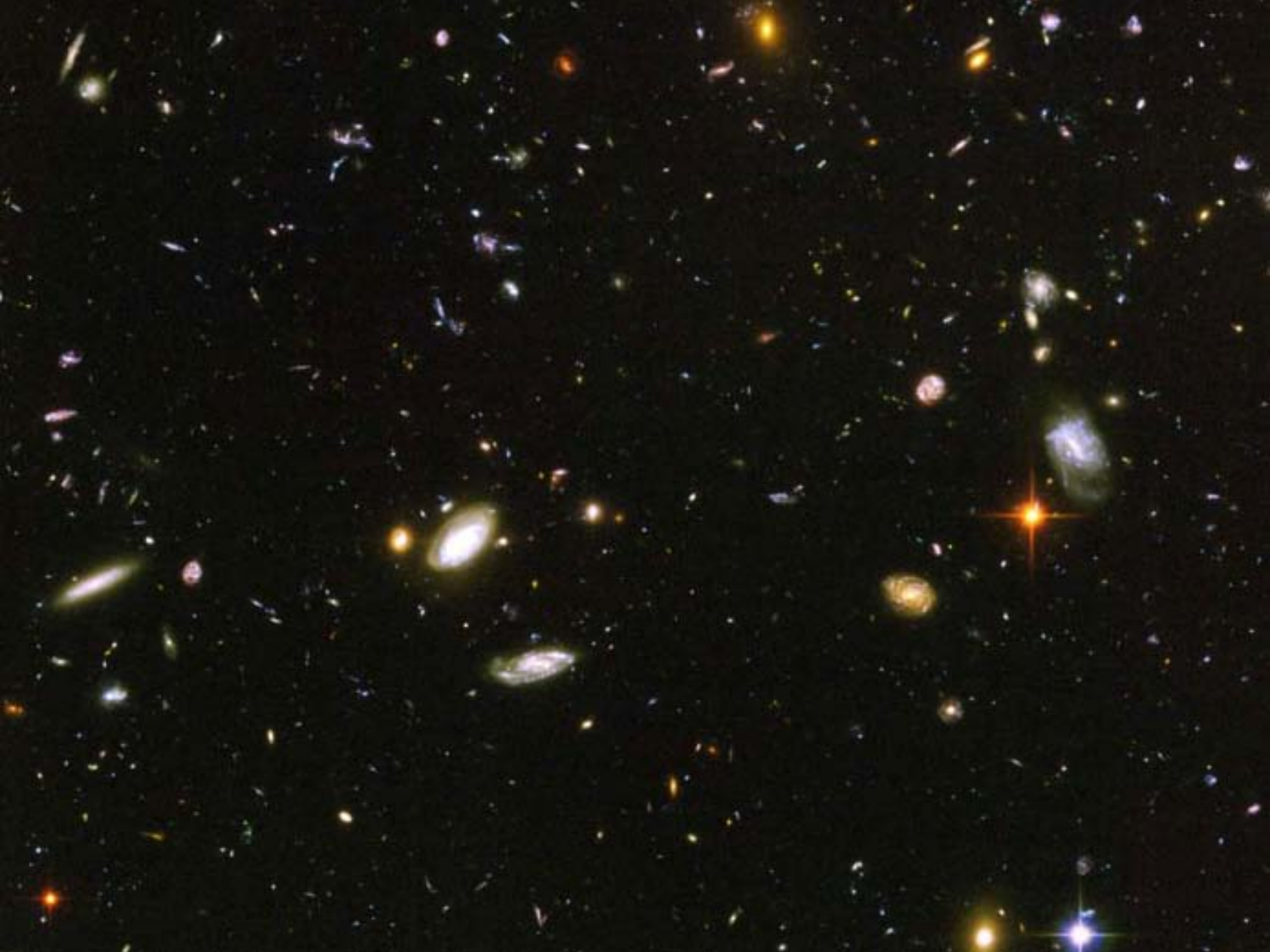


Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2

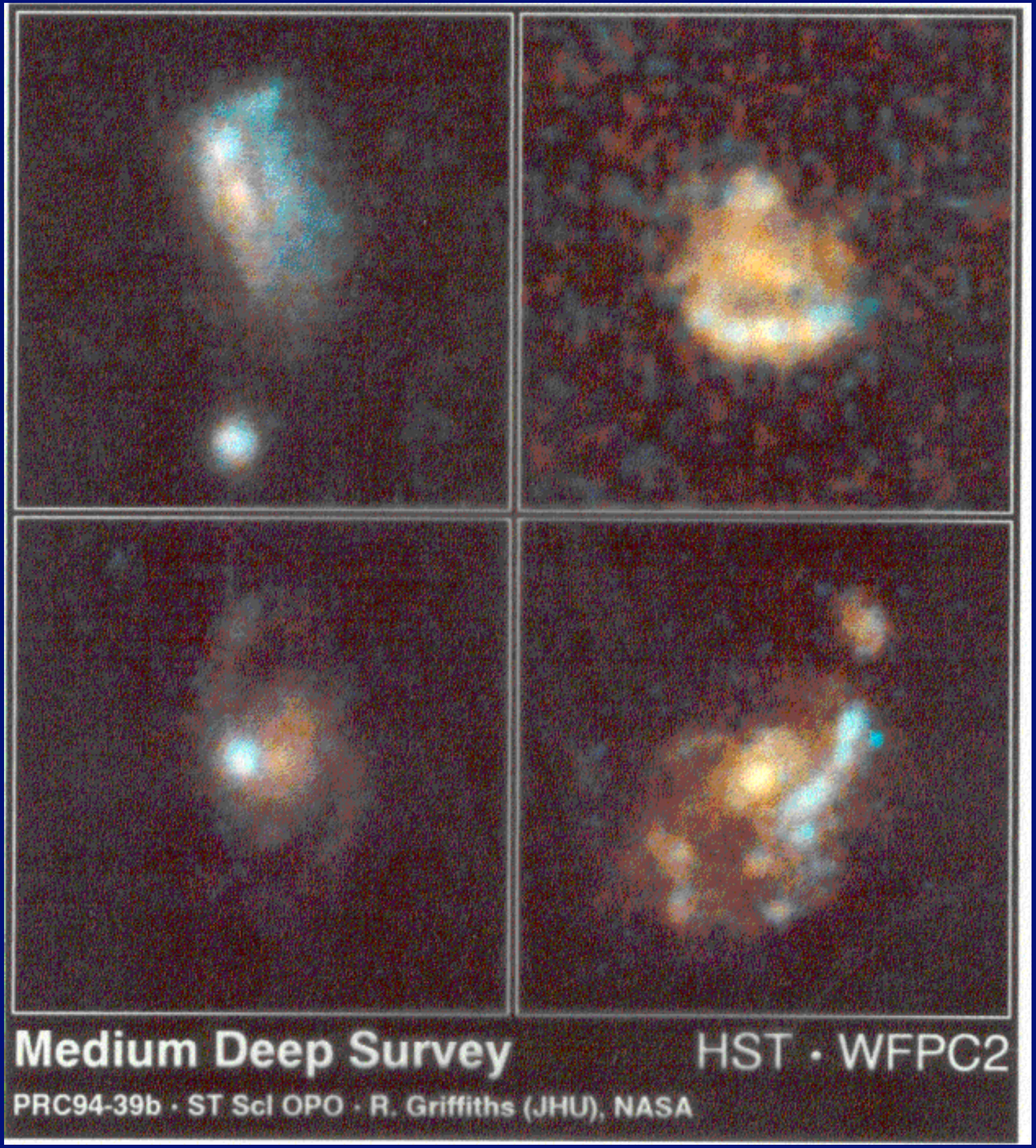
PRC97-34a • ST ScI OPO • October 21, 1997 • B, Whitmore (ST ScI) and NASA



Cartwheel Galaxy
HST • WFPC2
PR95-02 • ST ScI OPO • January 1995 • K. Borne (ST ScI), NASA
12/23/94 zgl



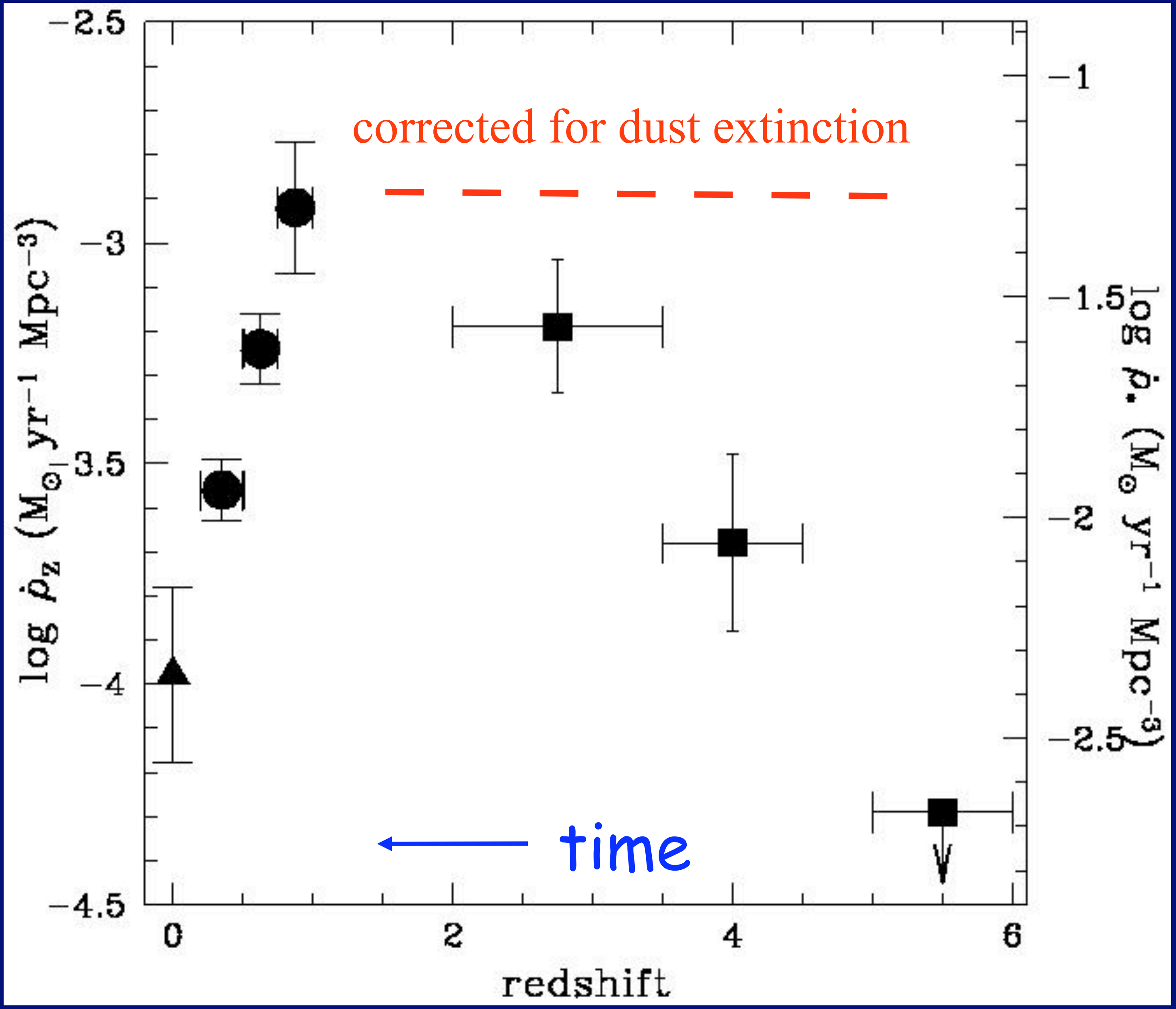
Baby galaxies in early universe



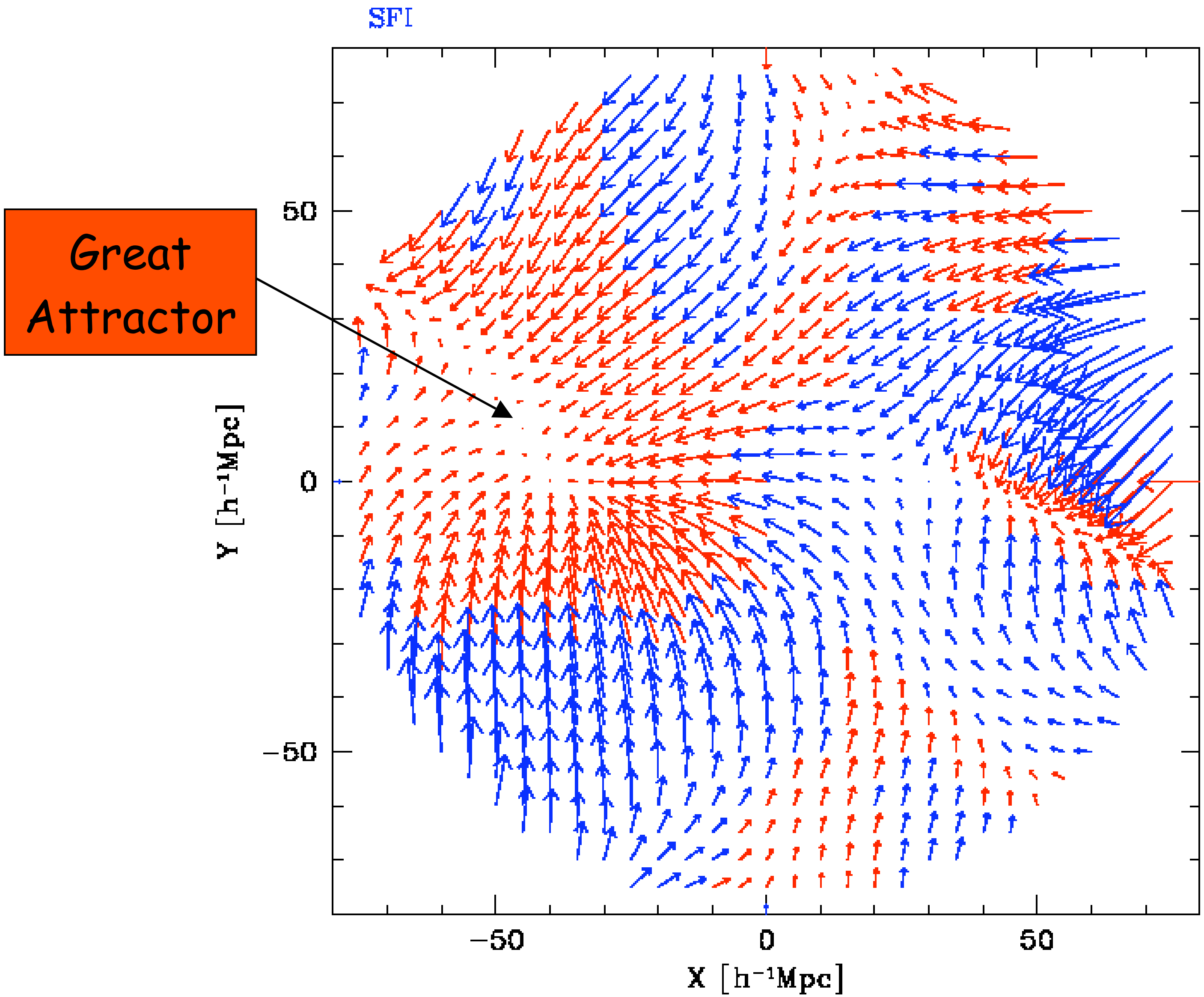
Star Formation History

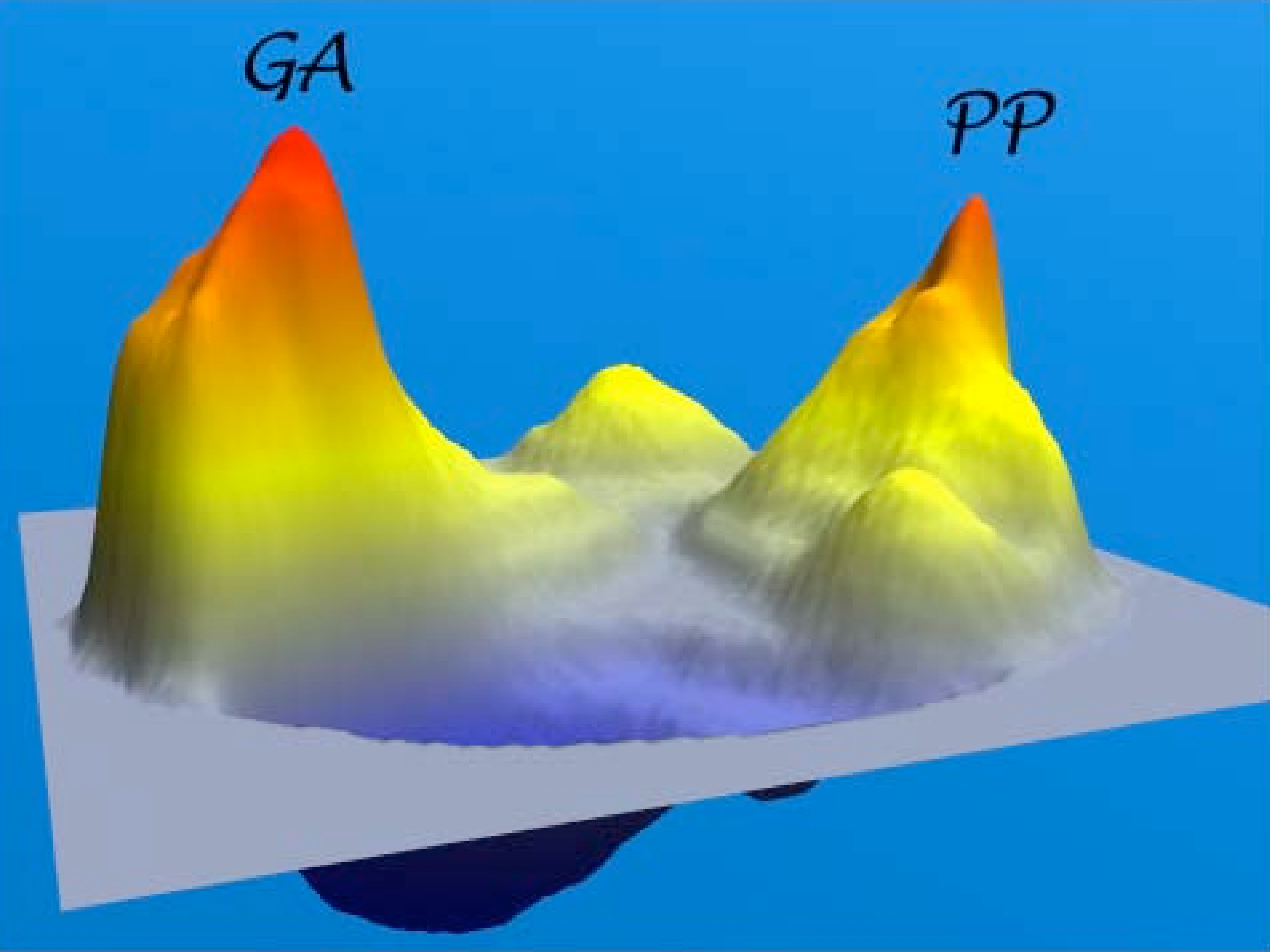
"Madau plot"

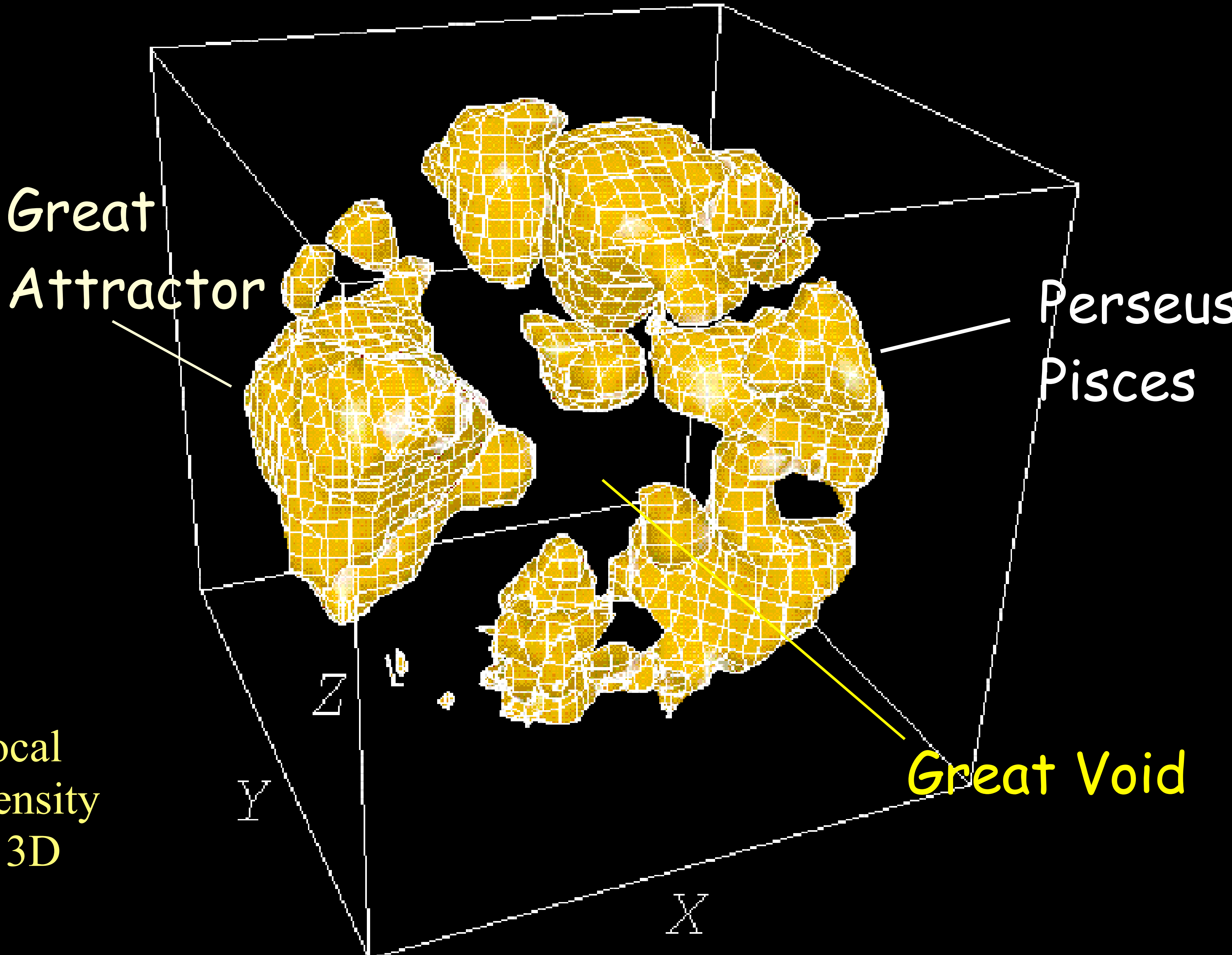
star formation rate density



Cosmic Flows - POTENT

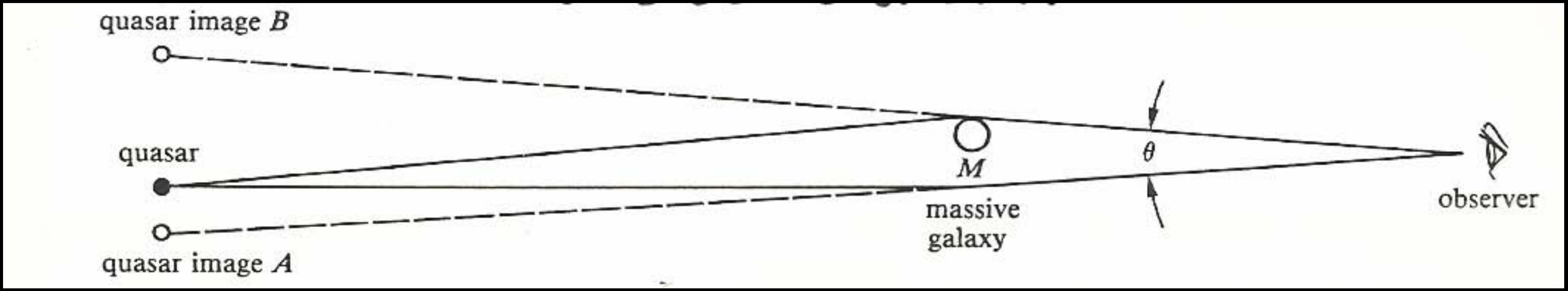


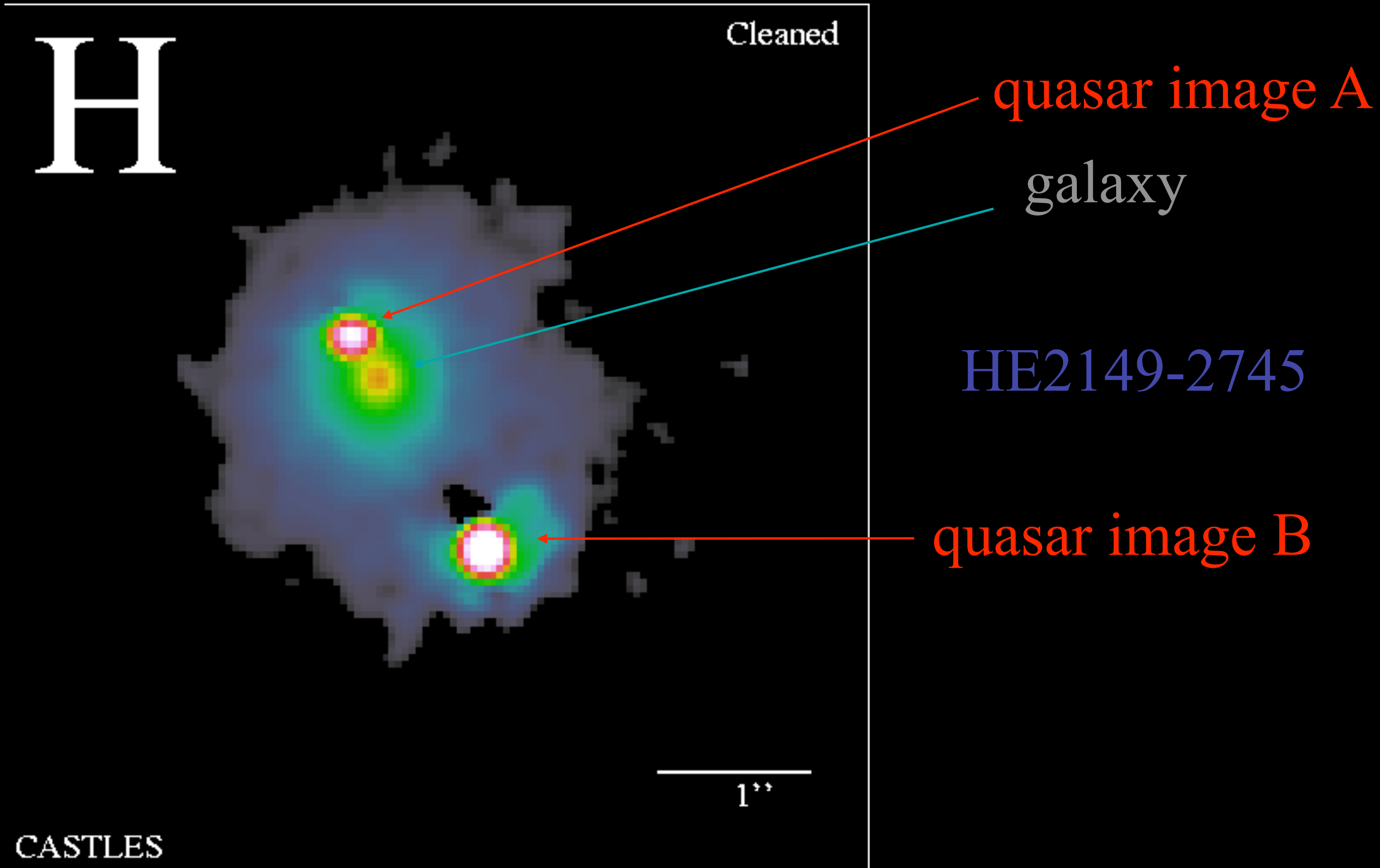

GA
PP



Local Density in 3D

GRAVITATIONAL LENSING





HE2149-2745

The Smithsonian "Castle" on the Mall in Washington, and

strongly lensed

from the CASTLES website

http://cfa-www.harvard.edu/castles

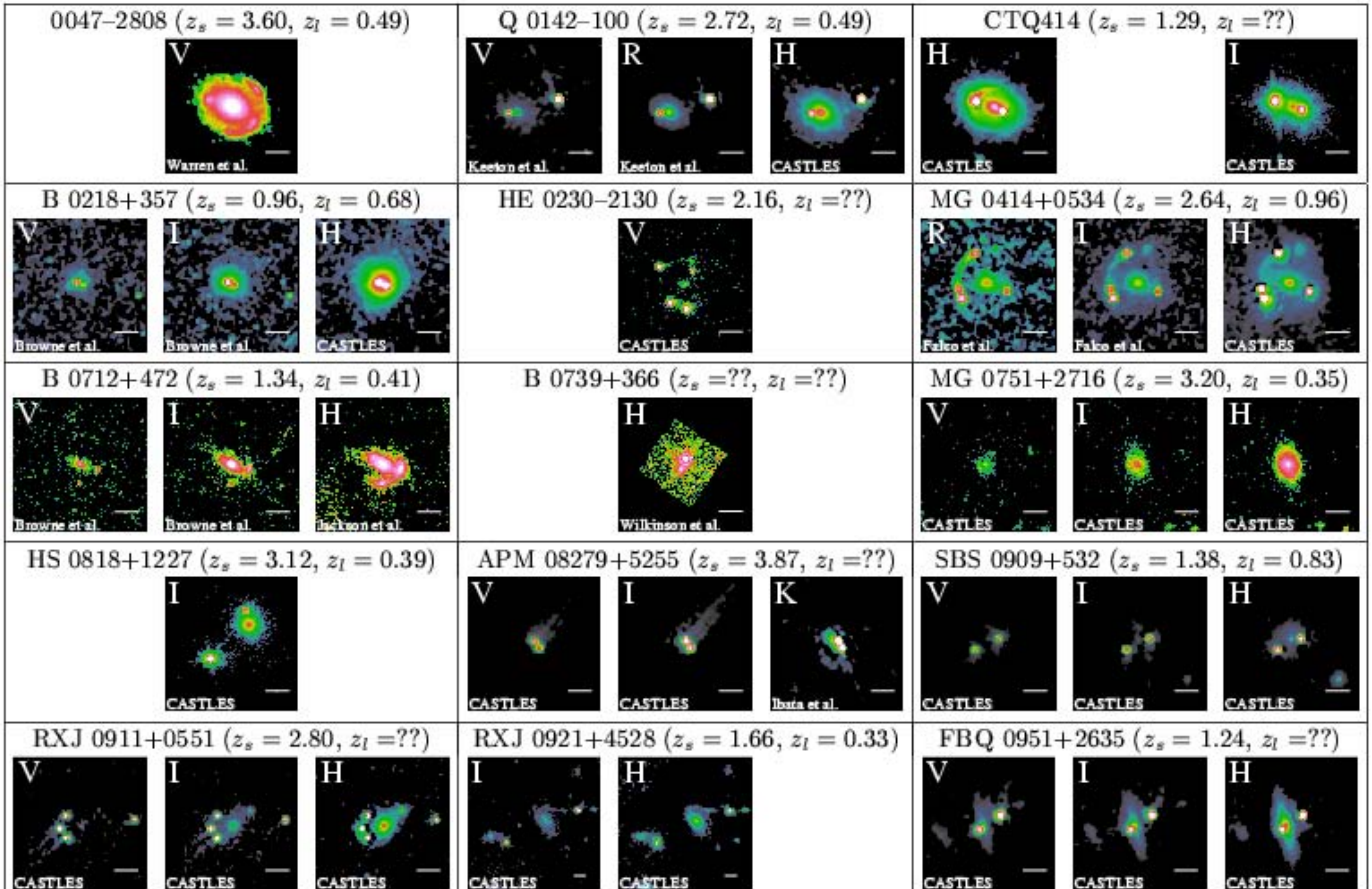
see also http://astron.berkeley.edu/~jcohn/lens.html

CASTLES

CfA/Arizona HST Gravitational Lens Survey

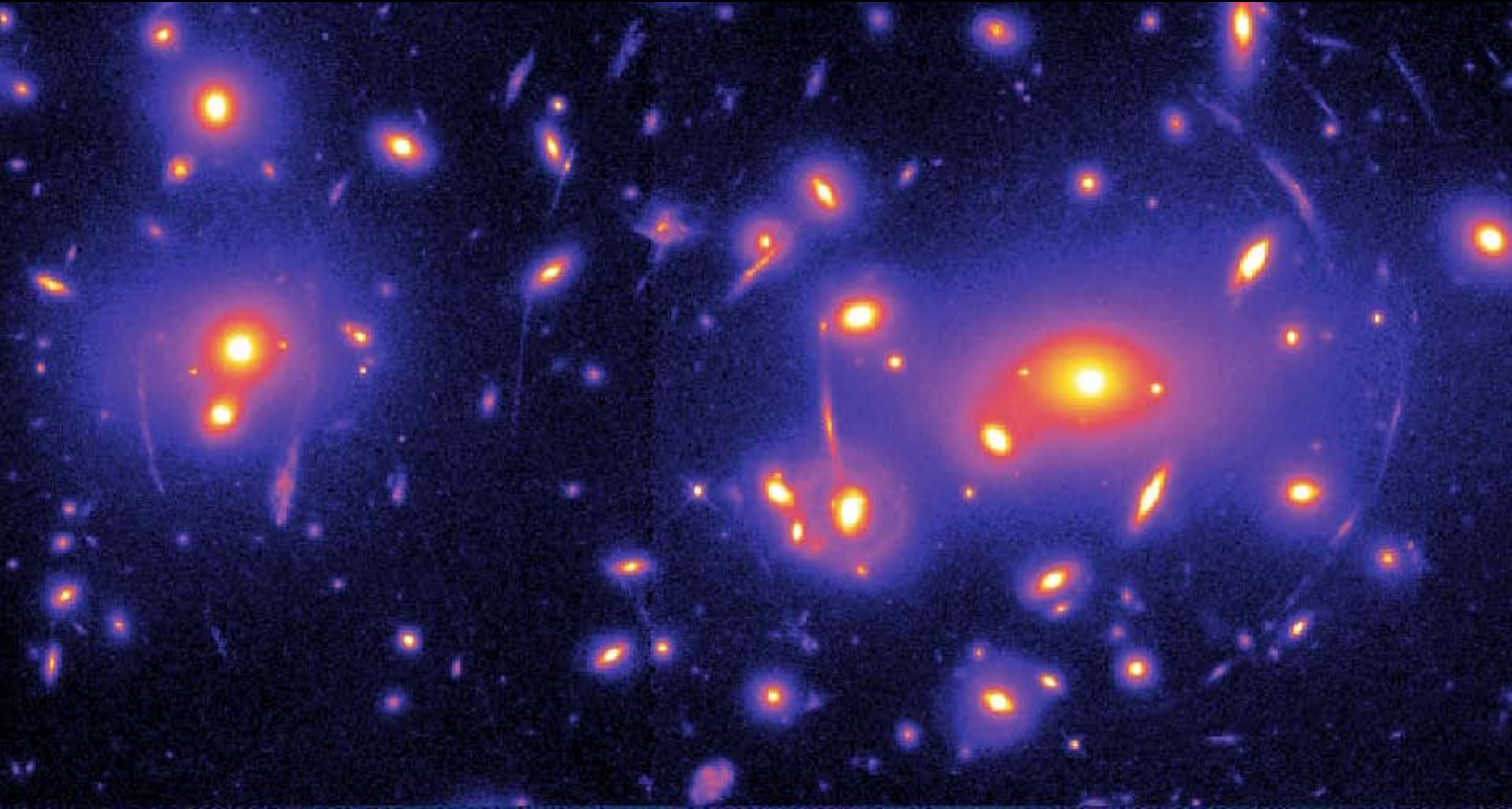
E.E. Falco, C.D. Impey, C.S. Kochanek, J. Lehár,
B.A. McLeod, H.-W. Rix, C.R. Keeton, J.A. Muñoz & C. Peng

http://cfa-www.harvard.edu/castles/



GRAVITATIONAL LENSING BY A CLUSTER OF GALAXIES

Abell 2218



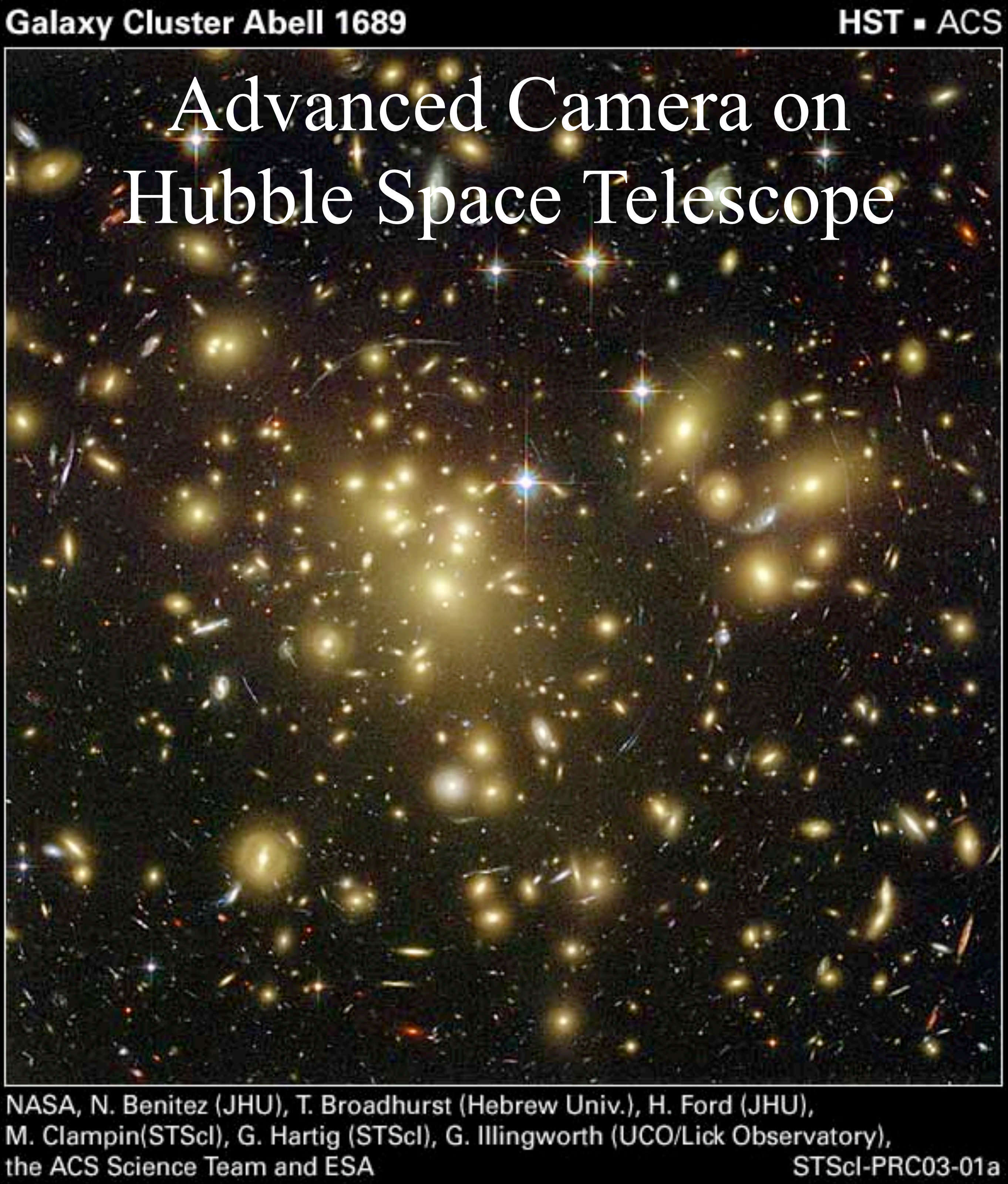
Gravitational Lens
Galaxy Cluster 0024+1654

HST • WFPC2

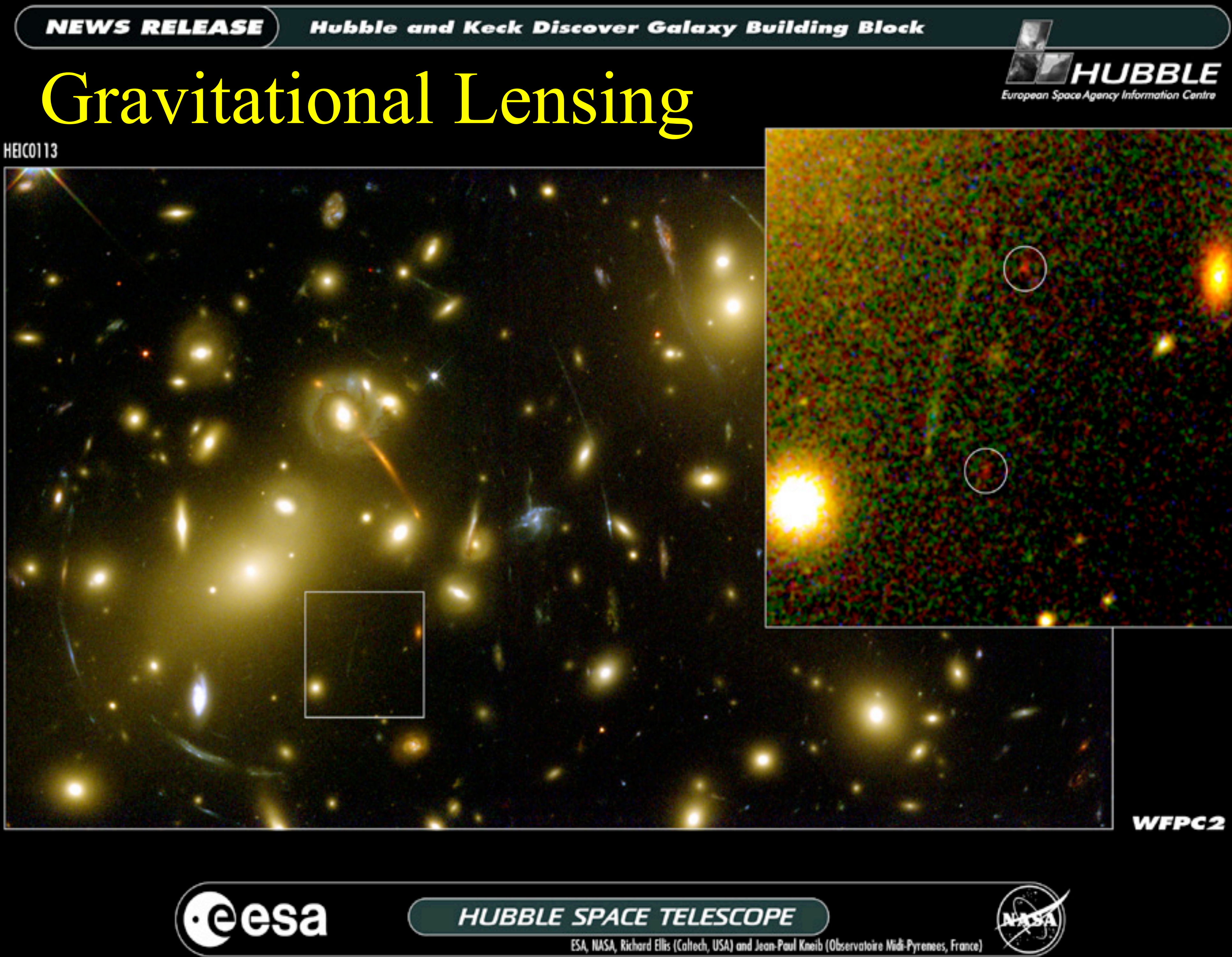
PRC96-10 • ST ScI OPO • April 24, 1996

W.N. Colley (Princeton University), E. Turner (Princeton University), J.A. Tyson (AT&T Bell Labs) and NASA

Advanced Camera on Hubble Space Telescope



Gravitational Lensing

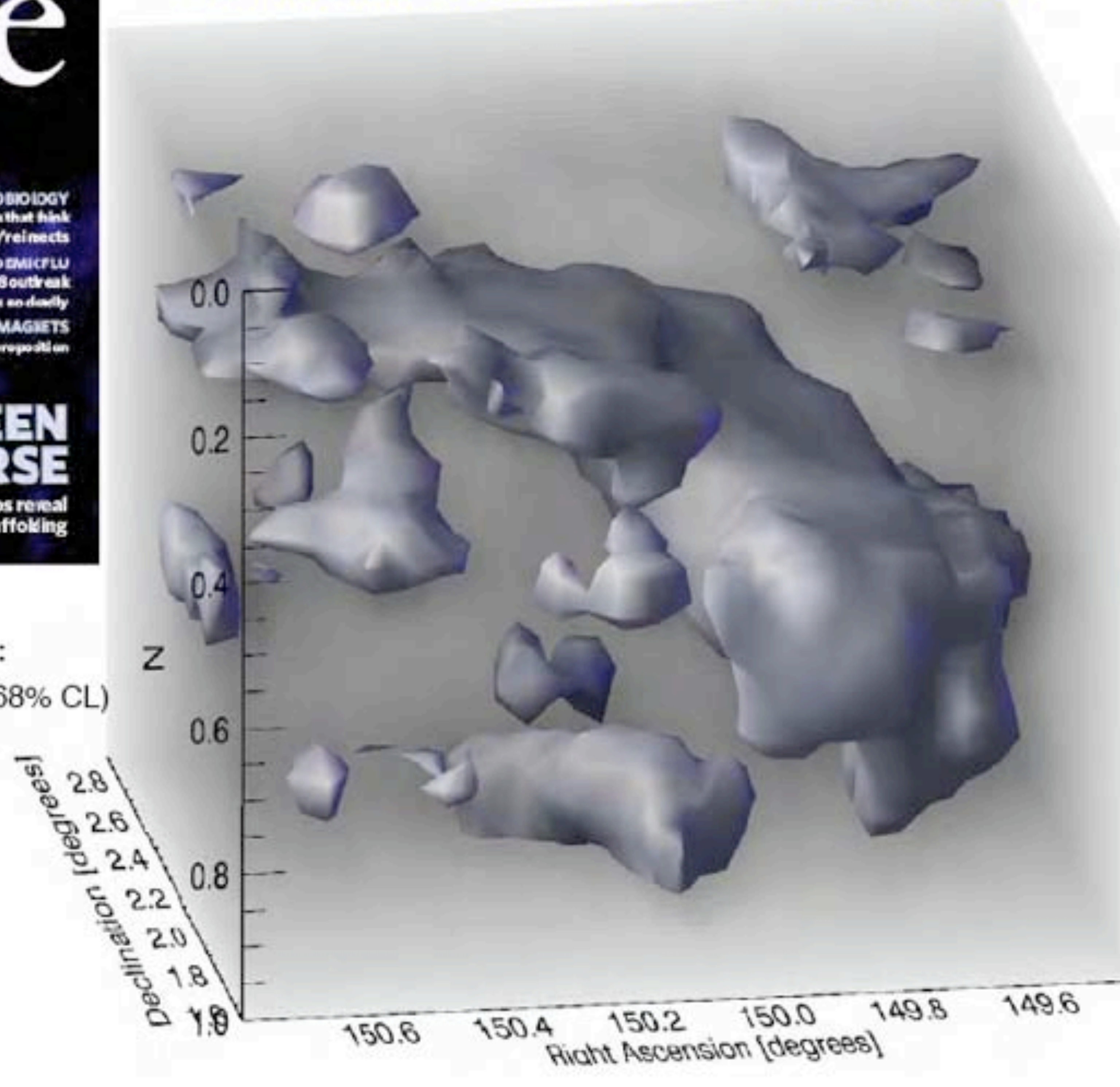


COSMOS WEAK LENSING MAPS OF THE DARK MATTER

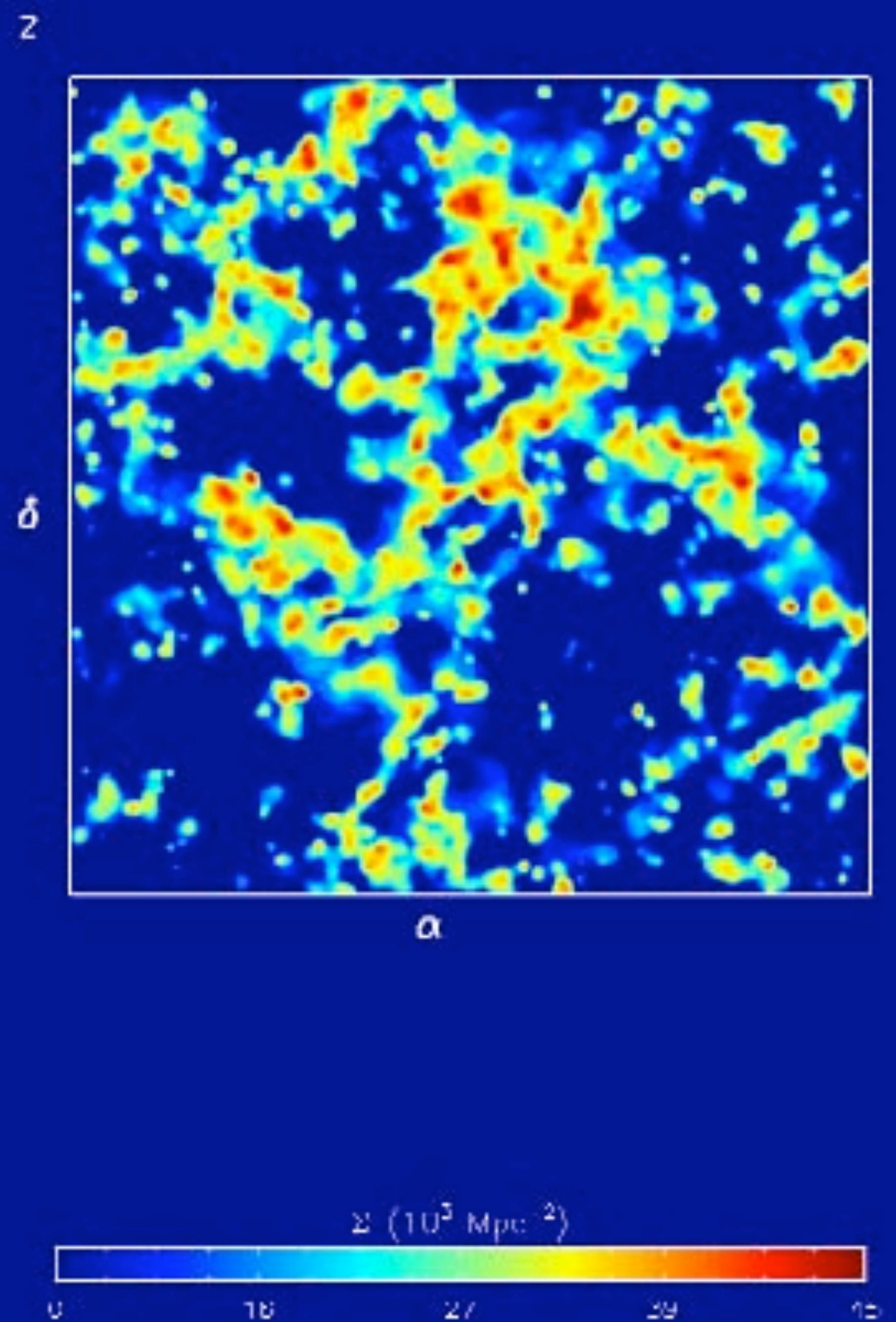
18 January 2007

Massey et al. COSMOS ApJS:

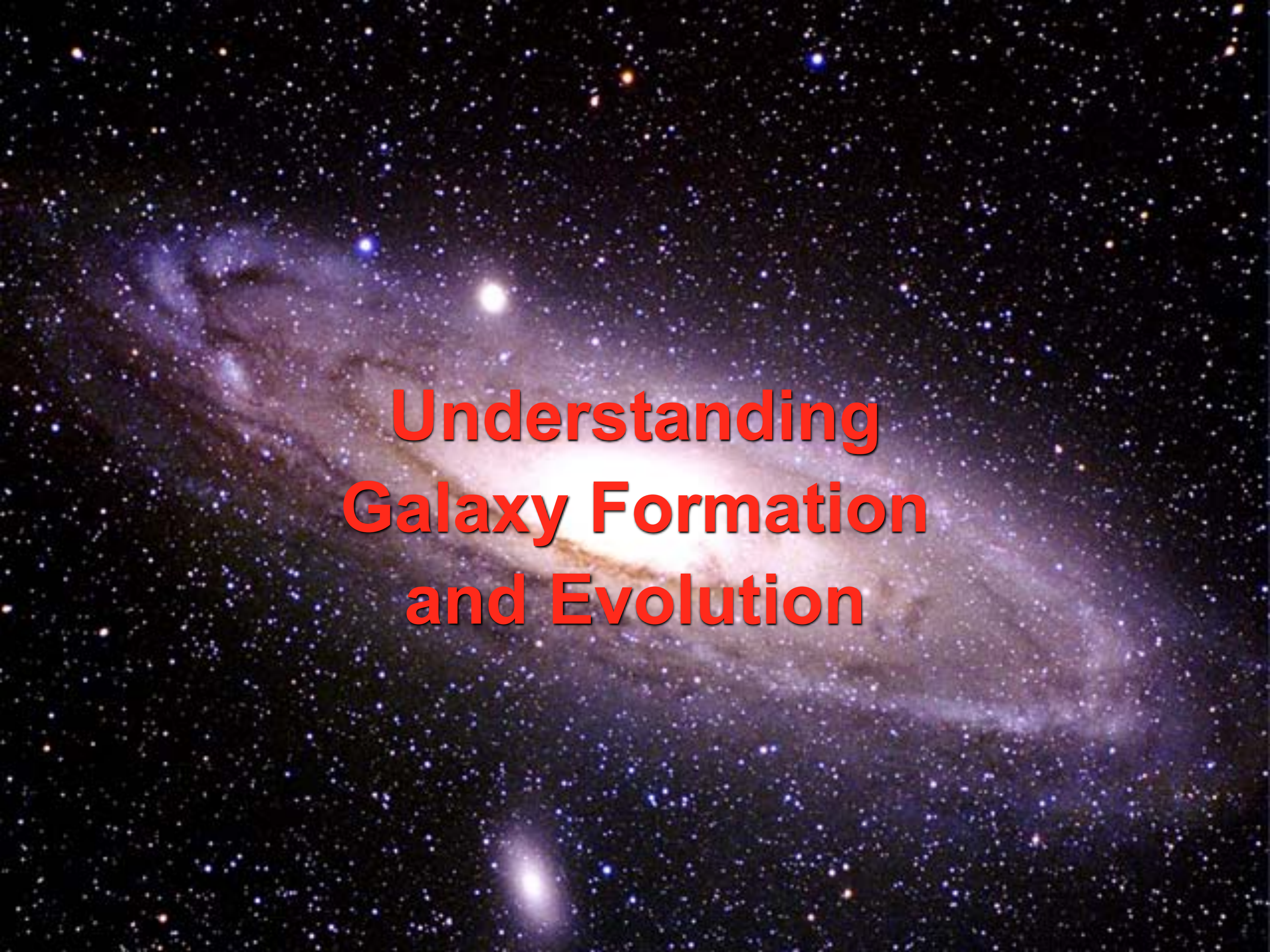
$\boldsymbol{\sigma}_8(\Omega_m/0.3)^{0.44}=\mathbf{0.866}^{+0.085}_{-0.068}$ (68% CL)



COSMOS 3D weak lensing density map



from
Nick
Scoville


Understanding
Galaxy Formation
and Evolution

Challenge: predict properties of galaxies and their correlations today, and their evolution over time

Nature, **311**, 517-525 (1984)

Formation of galaxies and large-scale structure with cold dark matter

George R. Blumenthal* & S. M. Faber*

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† Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA

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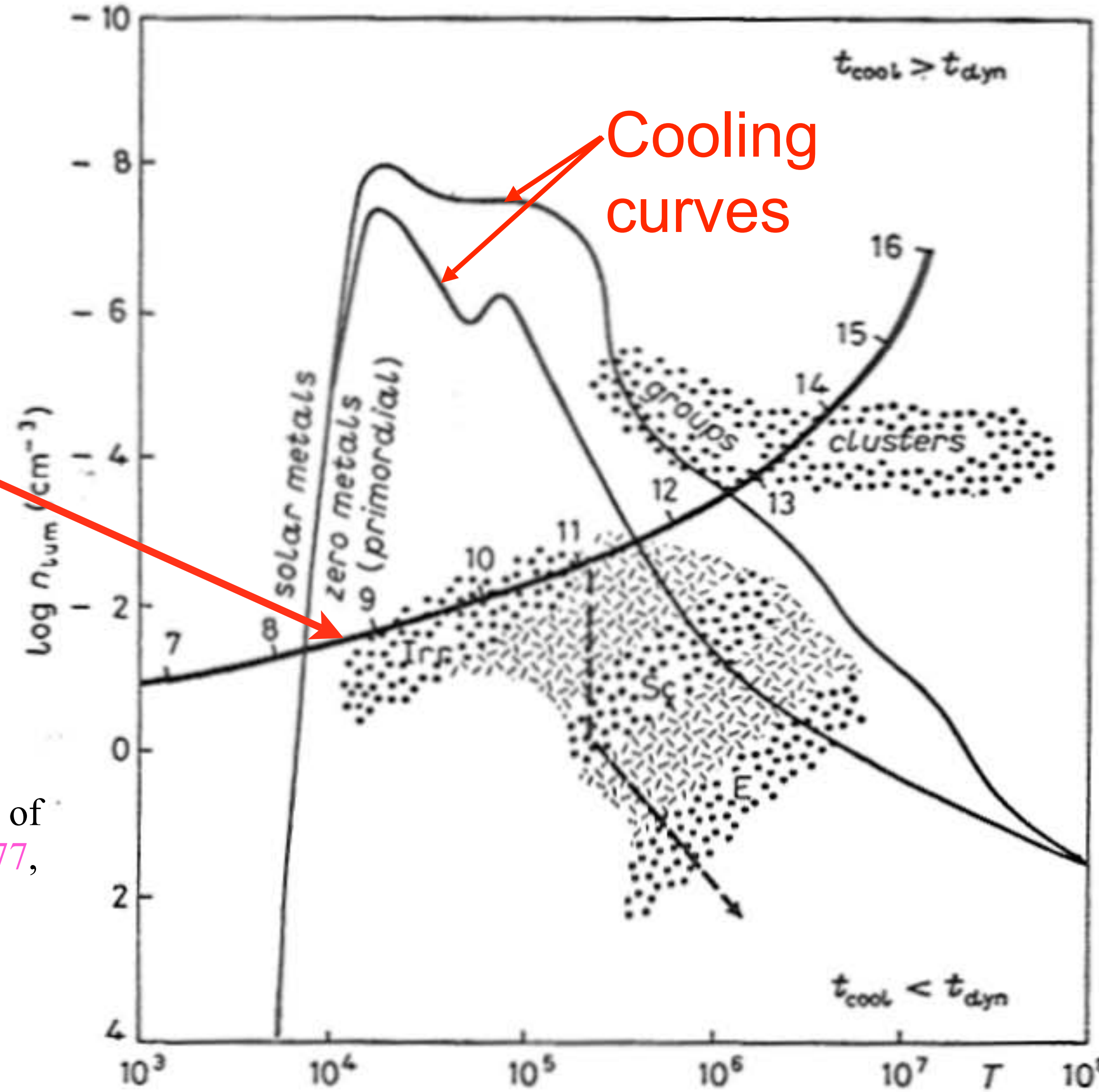
The dark matter that appears to be gravitationally dominant on all scales larger than galactic cores may consist of axions, stable photinos, or other collisionless particles whose velocity dispersion in the early Universe is so small that fluctuations of galactic size or larger are not damped by free streaming. An attractive feature of this cold dark matter hypothesis is its considerable predictive power: the post-recombination fluctuation spectrum is calculable, and it in turn governs the formation of galaxies and clusters. Good agreement with the data is obtained for a Zeldovich ($|\delta_k|^2 \propto k$) spectrum of primordial fluctuations.

tions[96,97]. We conclude that a straightforward interpretation of the evidence summarized above favours $\Omega \approx 0.2$ in the cold DM picture, but that $\Omega = 1$ is not implausible.

Conclusions

We have shown that a Universe with ~10 times as much cold dark matter as baryonic matter provides a remarkably good fit to the observed Universe. This model predicts roughly the observed mass range of galaxies, the dissipational nature of galaxy collapse, and the observed Faber–Jackson and Tully–Fisher relations. It also gives dissipationless galactic haloes and clusters. In addition, it may also provide natural explanations for galaxy-environment correlations and for the differences in angular momenta between ellipticals and spiral galaxies. Finally, the cold DM picture seems reasonably consistent with the observed large-scale clustering, including superclusters and voids. In short, it seems to be the best model available and merits close scrutiny and testing.

CDM Spherical Collapse Model

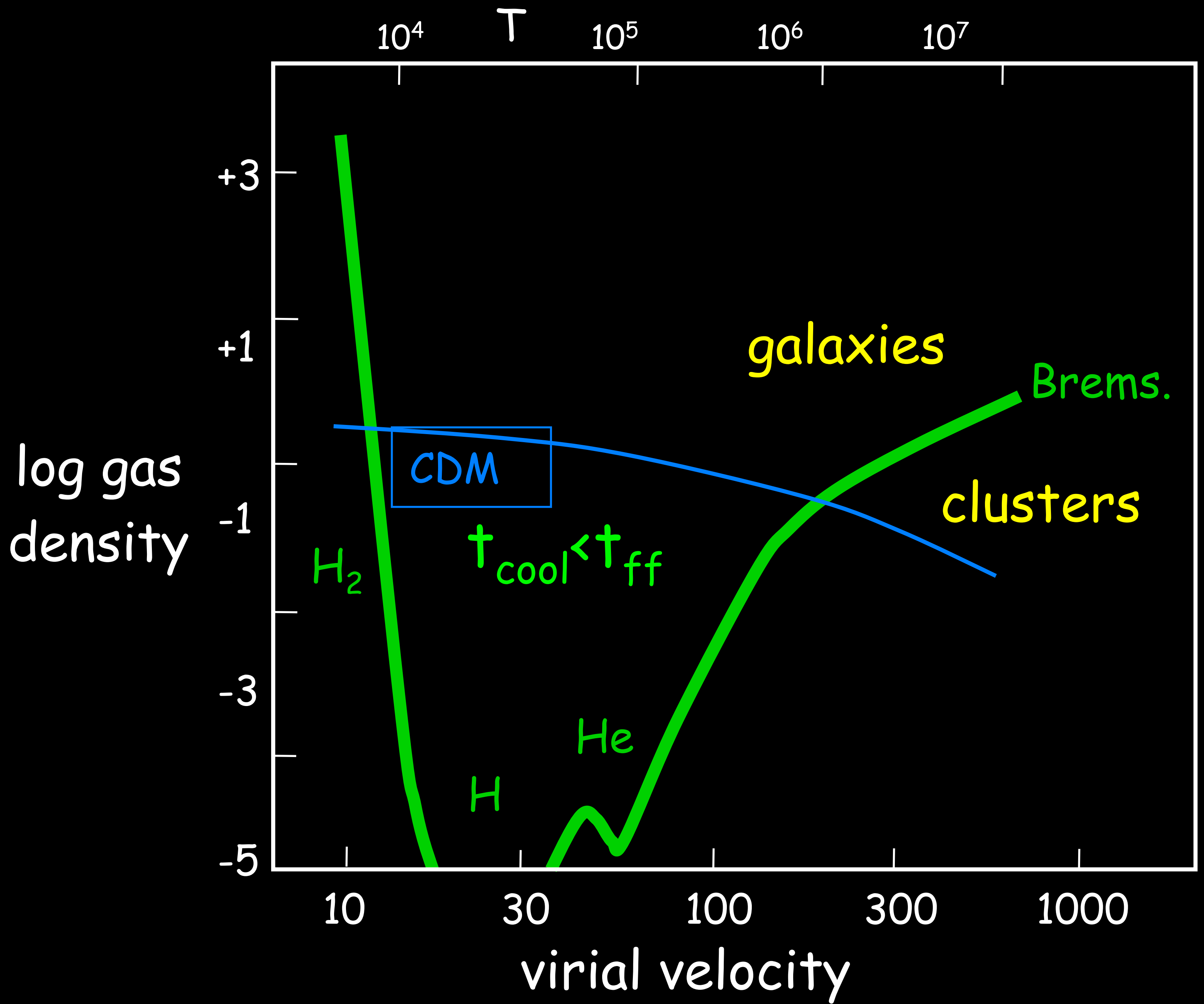


Primack & Blumenthal 1983 based on CDM, cooling theory of Rees & Ostriker 1977, Silk 1977, Binney 1977 and baryonic dissipation within dark halos White & Rees 1978

The baryonic density *vs.* temperature as root-mean-square perturbations having total mass M become nonlinear and virialize. The numbers on the tick marks are the logarithm of M in units of $M_\odot$. This curve assumes $n = 1$, $\Omega = h = 1$ and a baryonic to total mass ratio of 0.07. The region where baryons can cool within a dynamical time lies below the cooling curves. Also shown are the positions of observed galaxies, groups and clusters of galaxies. The dashed line represents a possible evolutionary path for dissipating baryons.

Rees & Ostriker 77, Silk 77, Binney 77, White & Rees 1978

CDM: Blumenthal, Faber, Primack, & Rees 1984



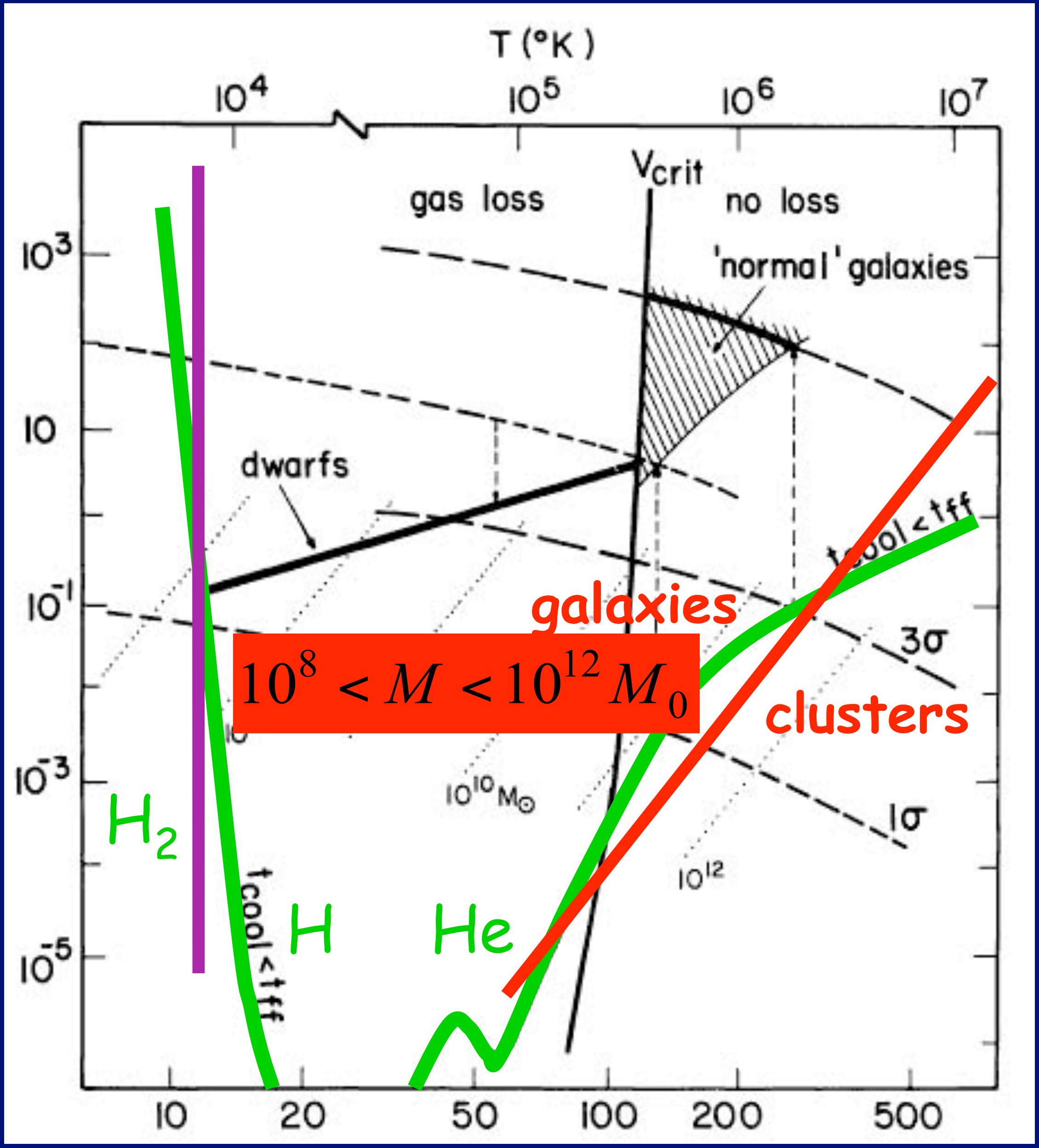
Dekel

Upper & Lower Bounds: $t_{cool} = t_{dyn}$

H_2
dissociate

Haiman,
Rees &
Loeb 96

gas
density



Rees &
Ostriker 77

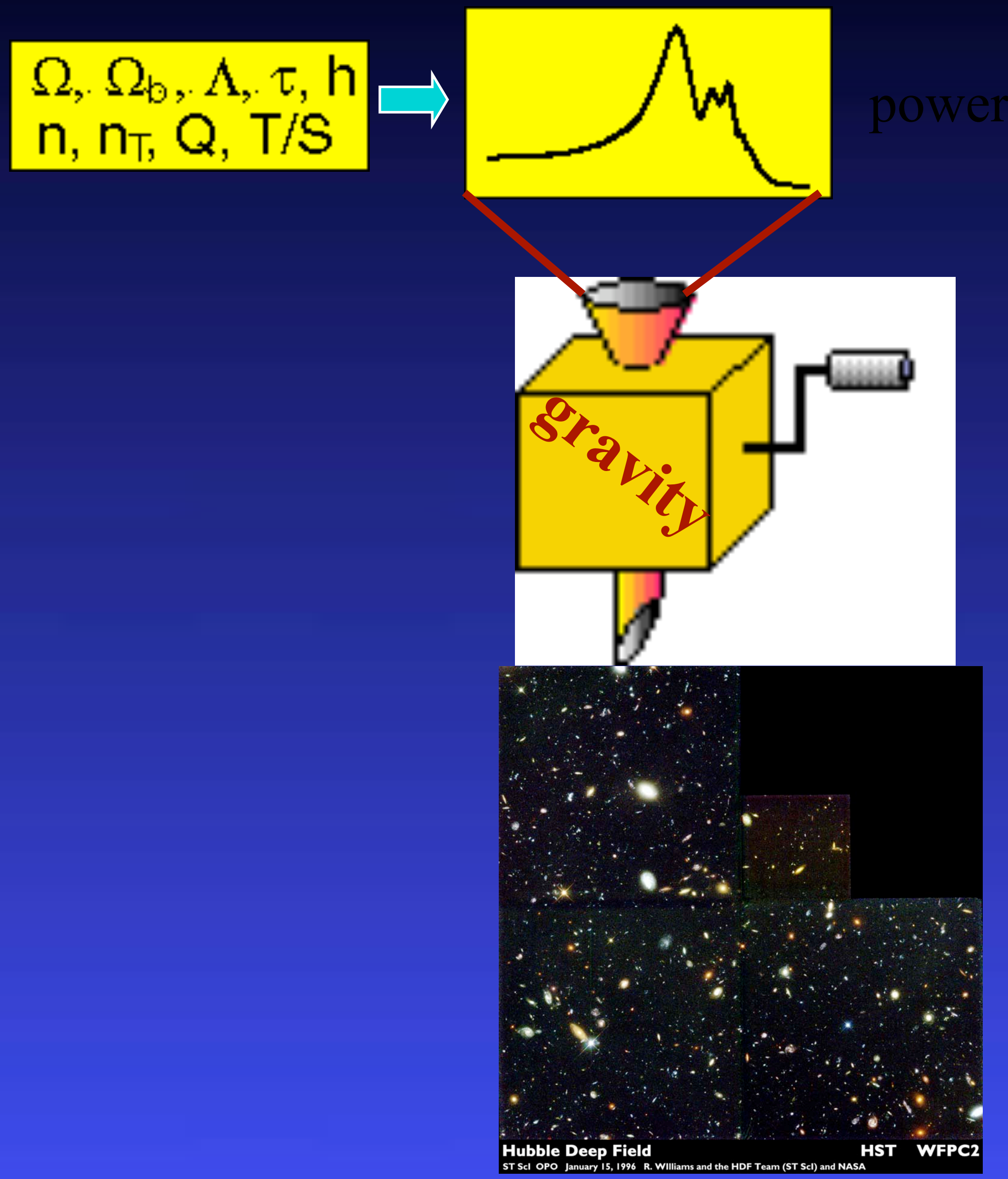
Silk 77

White & Ress 78

bremstralung

virial velocity

Semi-Analytic Models



simulation by the VIRGO consortium

Semi-Analytic Models

gravity

collisional heating/radiative cooling of gas

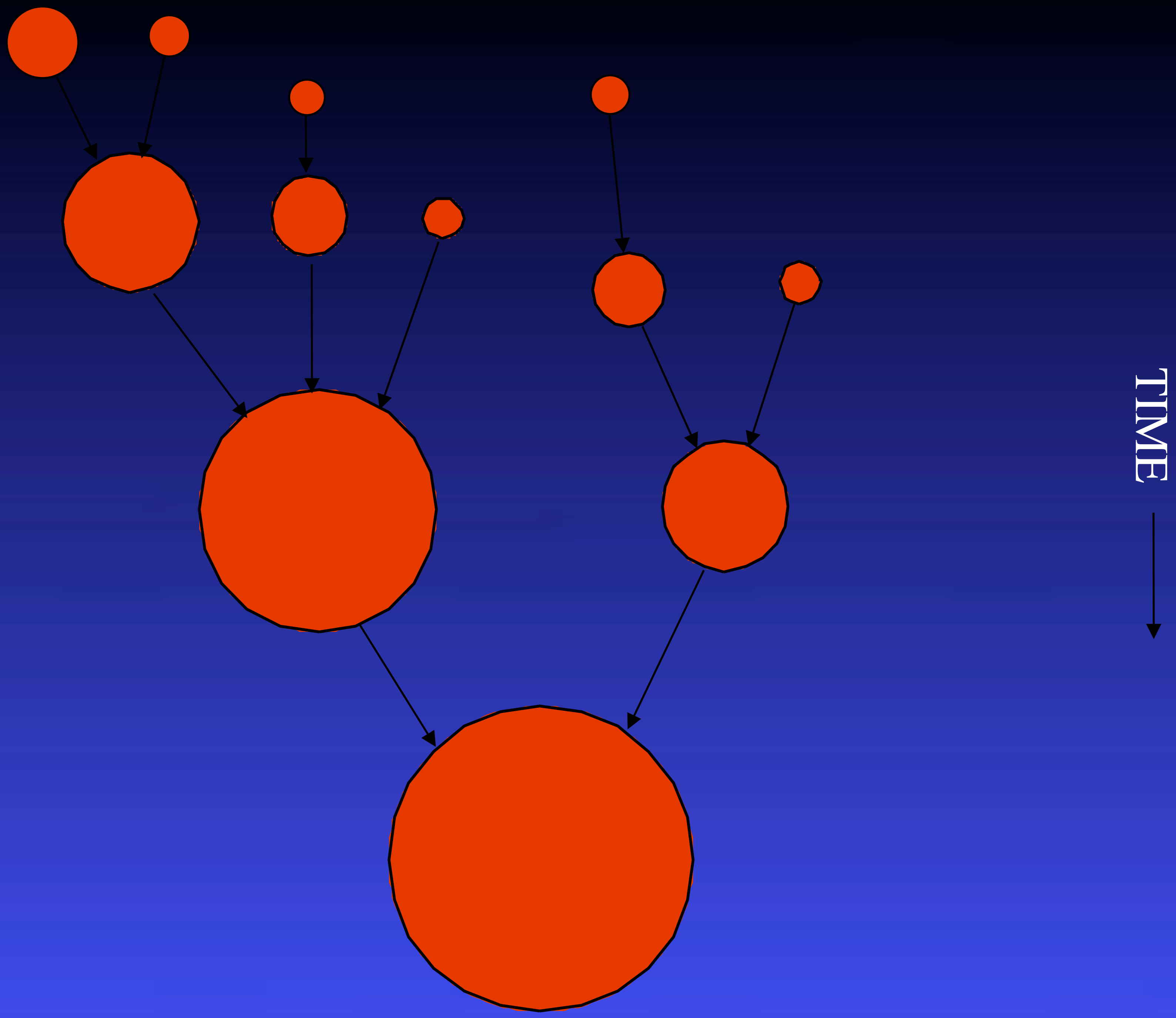
star formation/SN feedback/chemical enrichment

stellar evolution/dust absorption and emission

the challenge:

tools:

- collisionless N-body simulations
  - solve equations of gravity for particles of dark matter (& sometimes stars)
- hydrodynamic N-body simulations
  - solve equations of gravity and hydrodynamics/thermodynamics for particles of dark matter and gas
- semi-analytic models (SAMs)
  - treat gravity and “gastrophysics” via analytic approximations (bulk properties)



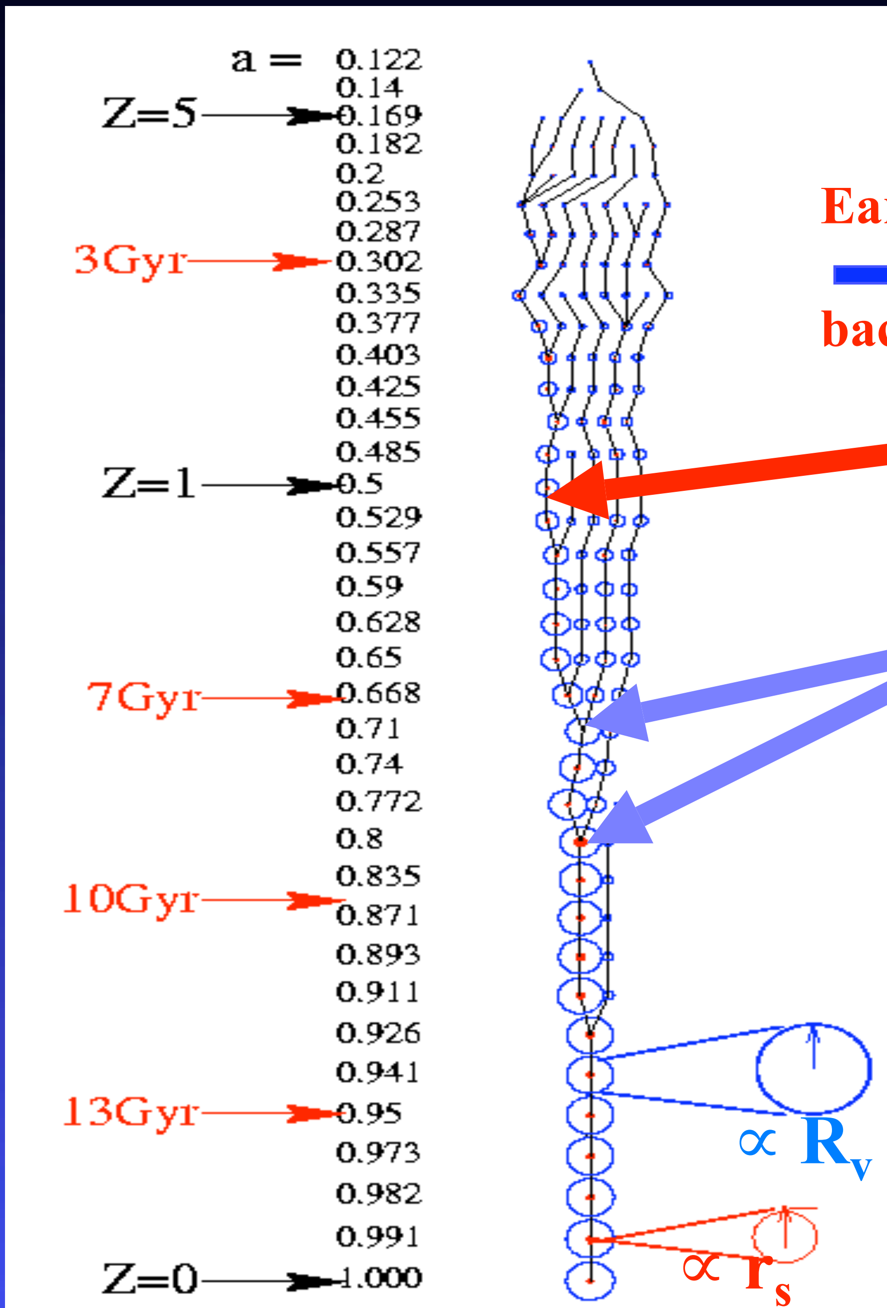
dark matter merging hierarchy

alternative merger tree treatments

- pure SAM
  - –dark matter merger tree constructed using extended Press-Schechter (EPS)*
- hybrid SAM+N-body, a posteriori
  - –galaxies associated with halos in N-body at output redshift
  - –merging histories obtained using EPS
- hybrid SAM+N-body, a priori
  - –halo merger histories extracted from N-body
  - –SAM galaxies based on structural merger trees

*See White & Frenk 1991, Somerville & Kolatt 1999

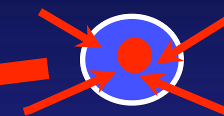
Halo Mass Accretion Histories



$t_0 \approx 13.6$ Gyr

Galaxy halo densities reflect the density of the universe at the formation epoch.

Early epoch of rapid mass accretion by major mergers: ⇒ central region obtains density similar to the background density.



Subsequent epoch of slow mass accretion by minor mergers builds outer part of dark matter halo with $r > r_s$, increasing the concentration of the halo:

$$C_v \equiv R_v/r_s$$

Wechsler, Bullock, Primack, Kravtsov, Dekel 2002

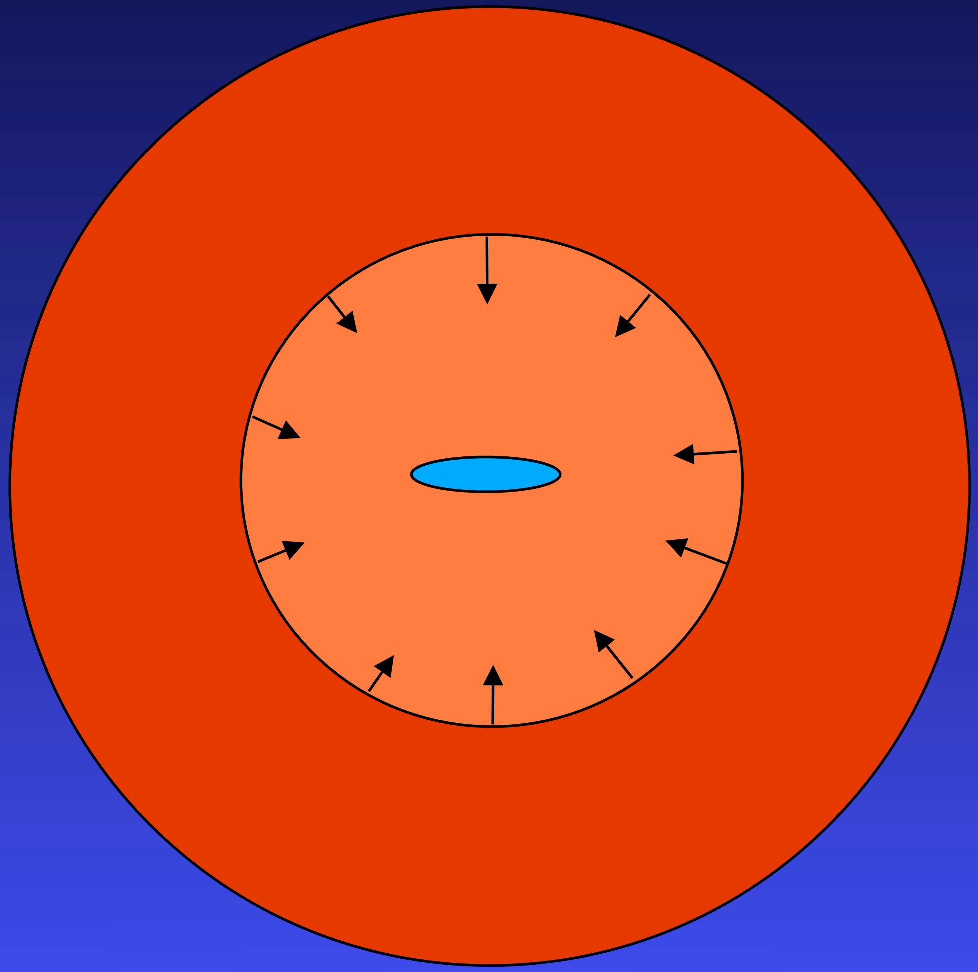
Spin parameter λ typically shows big jumps due to major mergers, and slow decline during slow mass accretion epoch due to random orientations of orbital angular momenta of accreted satellites.

Vitvitska et al. 2002

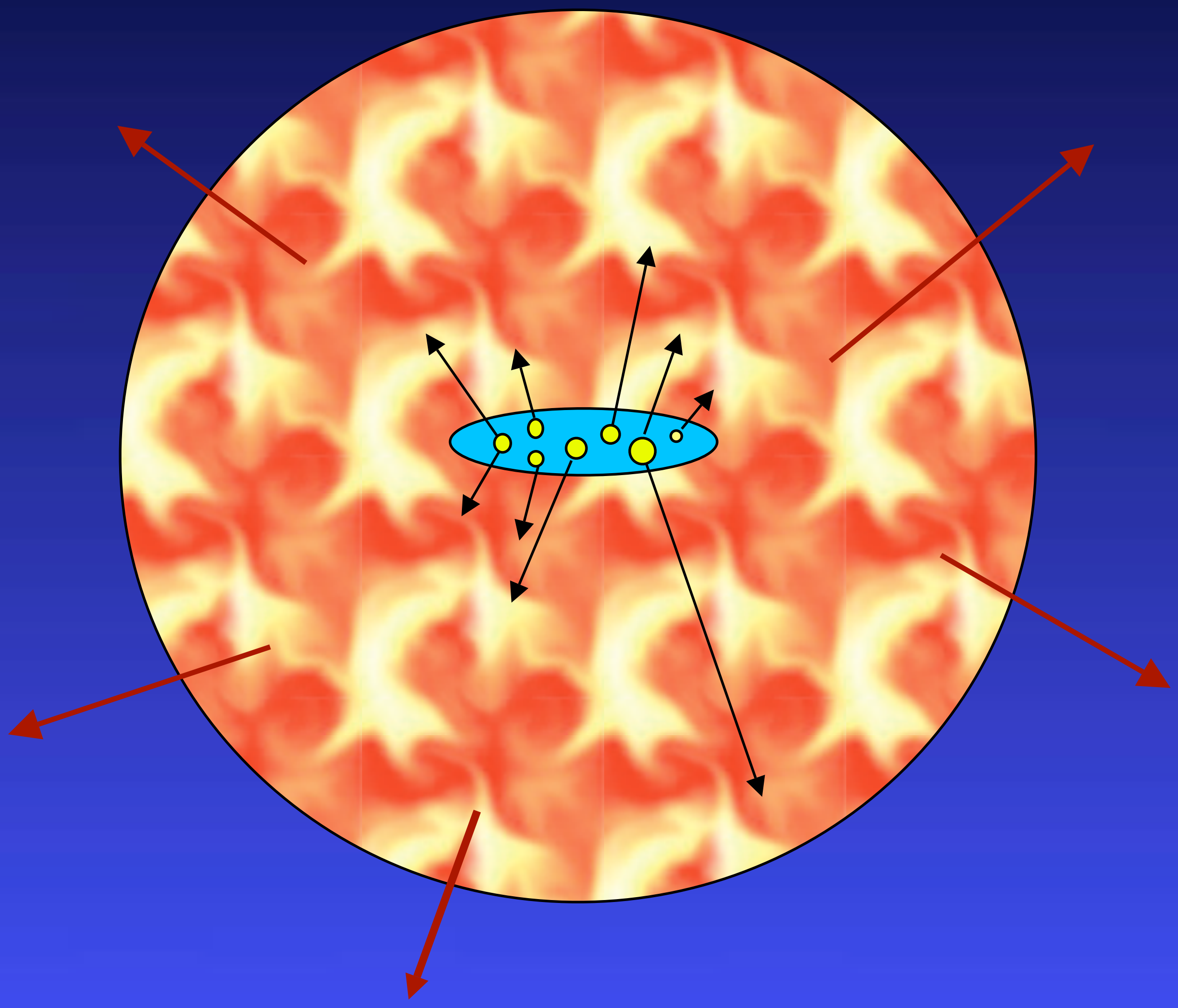
Ingredients of Galaxy Formation

1. gravitational formation of dark halos via collapse & mergers
2. gas cooling → contraction to a disk, centrifugally supported
3. star formation in a disk
4. collisions → star bursts
5. mergers of stellar disks → spheroids
6. feedback

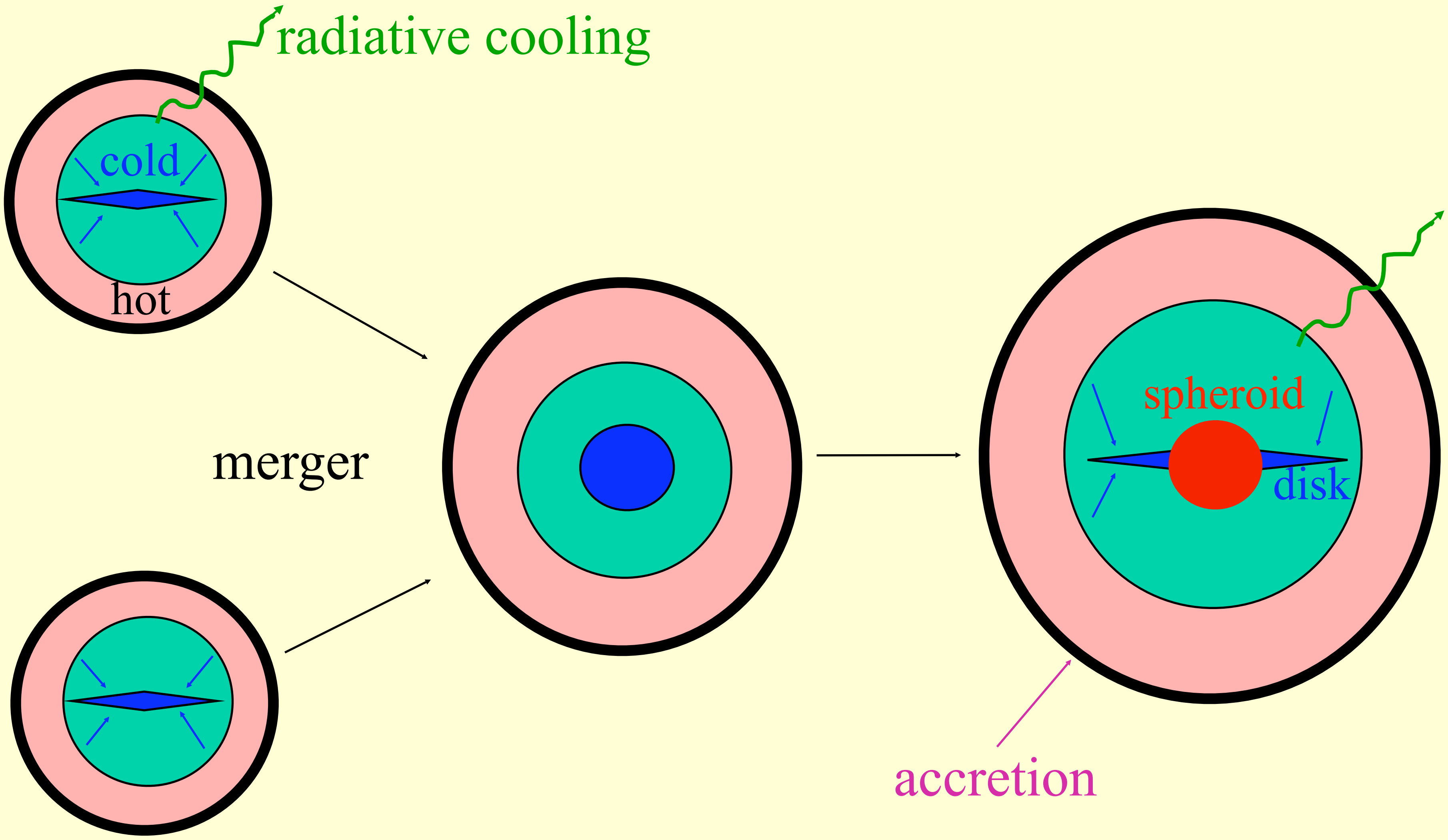
cooling and disk formation



star formation and supernovae feedback



Galaxy Formation in halos



halos

cold gas → young stars → old stars

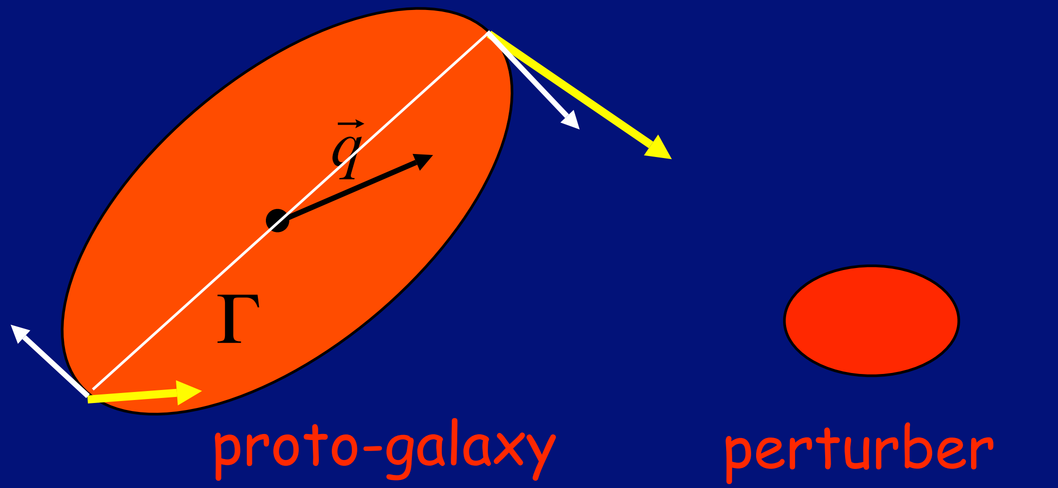
Issue: Including Spheroids Formed by Disk Instability

The stardard SAM assumption is that all galactic spheroids form in major mergers of (proto-)galaxies. This leads to a density-morphology relationship much like that observed. But central regions of baryonic disks are likely to be gravitationally unstable, forming bars that evolve into bulges. This process must be understood better and included in more realistic models. However, the formation and evolution of disk galaxies is not yet understood since even the best simulations generally do not (yet) give galaxies with realistic disks. It is not clear whether this is because of a failure of the underlying CDM assumptions or merely because of insufficient resolution and astrophysics in the simulations.

Angular Momentum & Disk Size

Tidal Torque Theory:

$$J_i \propto t\, \varepsilon_{ijk} T_{jl} I_{lkj}$$



Tidal: $$T_{ij} = -\frac{\partial^2 \phi}{\partial q_i\, \partial q_j}$$

Inertia: $$I_{ij} = \rho_0 a_0^3 \int_\Gamma q_i\, q_j\, d^3 q$$

Spin parameter: $$\lambda \equiv \frac{J/M}{R_{vir} V_{vir}} \approx 0.05$$

If angular-momentum is conserved

Disk radius: $$J/M = R_{disk} V = \lambda R_{vir} V$$

$$\rightarrow R_{disk} \approx 0.05\, R_{vir}$$

ANGULAR MOMENTUM ISSUES

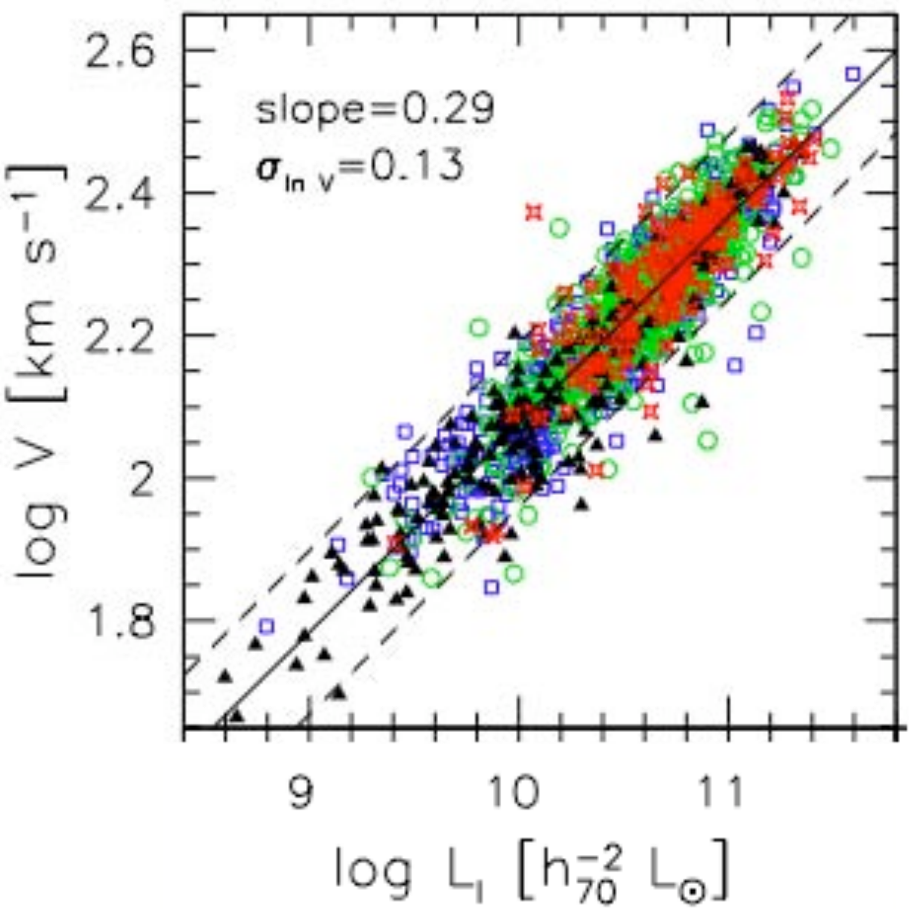
Catastrophic loss of angular momentum (Navarro & Benz 91, Navarro & Steinmetz 00) due to overcooling in hydrodynamic simulations (Maller & Dekel 02). Spiral galaxies would be hard to form if ordinary matter has the same specific angular momentum distribution as dark matter (Bullock+01). How do the disk baryons get the right angular momentum?

Mergers give halos angular momentum – too much for halos that host spheroids, too little for halos that host disks (D'Onghia & Burkert 04)? Role of AGN and other energy inputs? Role of cold inflows (Birnboim & Dekel 03, Keres+05, Dekel & Birnboim 06)?

Can simulated disks agree with observed Tully-Fisher relation and Luminosity Function? Recent high-resolution simulations (Governato+07, Ceverino & Klypin 08) are encouraging.

The Tully-Fisher Relation

- A correlation between the rotation velocity, V, and luminosity, L, of disk galaxies (Tully & Fisher 1977).
- Small intrinsic scatter 0.05dex in V|L (cf 0.15 dex in R|L)
- Scatter is independent of surface brightness (e.g. Courteau & Rix 1997).



Courteau et al. 2007

slide: Aaron Dutton

The Tully-Fisher Zero Point Problem

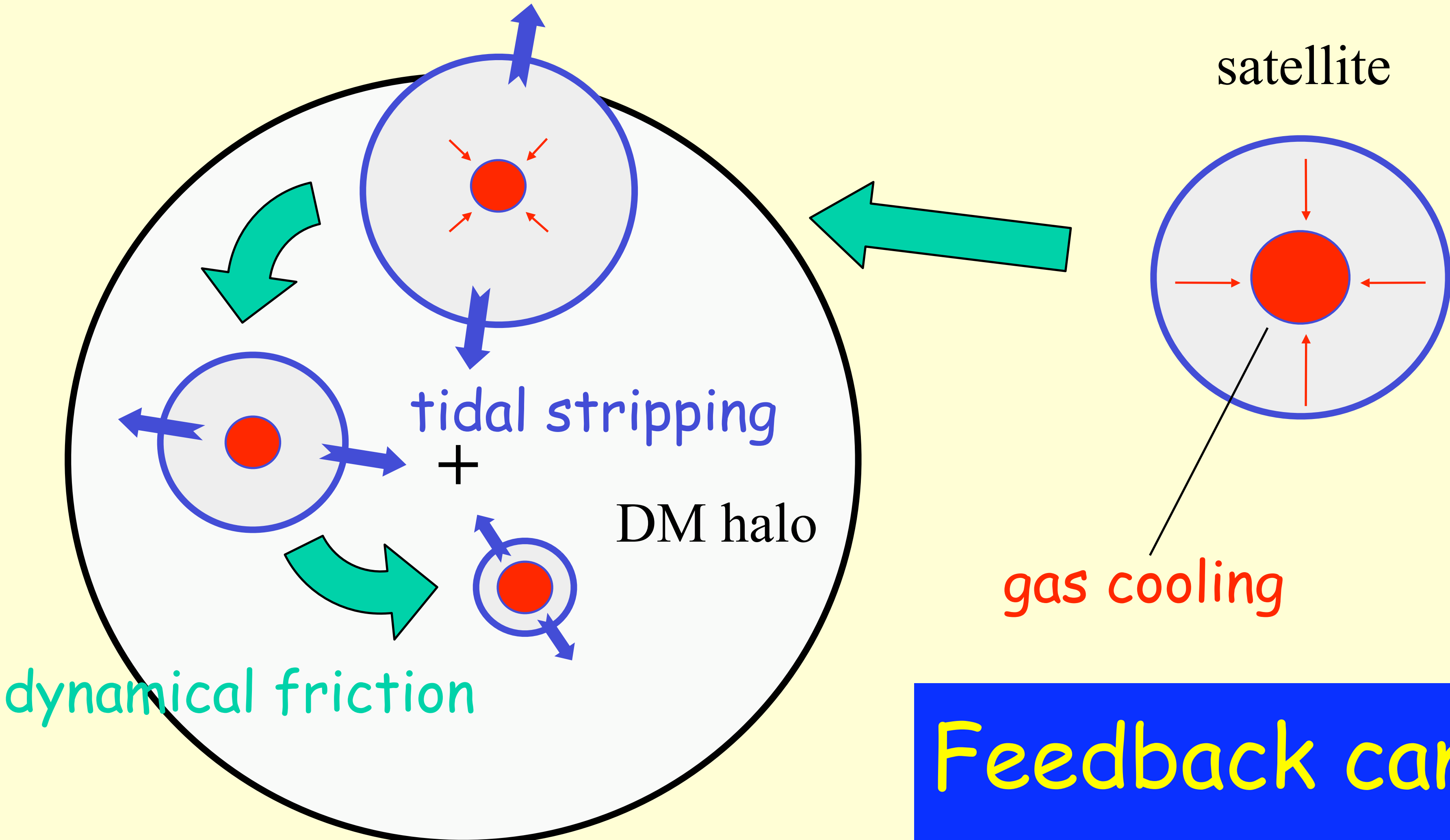
- Reproducing the zero point of the TF relation has been a long standing problem for CDM based galaxy formation models (e.g. Van den Bosch 2000; Mo & Mao 2000; Cole et al 2000; Eke, Navarro & Steinmetz 2001).

- Semi-Analytic models can reproduce the TF relation and galaxy luminosity function ONLY IF Vobs=Vvir (e.g. Somerville & Primack 1999) or **Vobs=Vmax,h** (e.g. Croton et al. 2006).

- Measurements of halo masses from groups and isolated galaxies/halos also supports **Vobs=Vmax,h** (Eke et al 2006; Blanton et al. 2007)

slide: Aaron Dutton

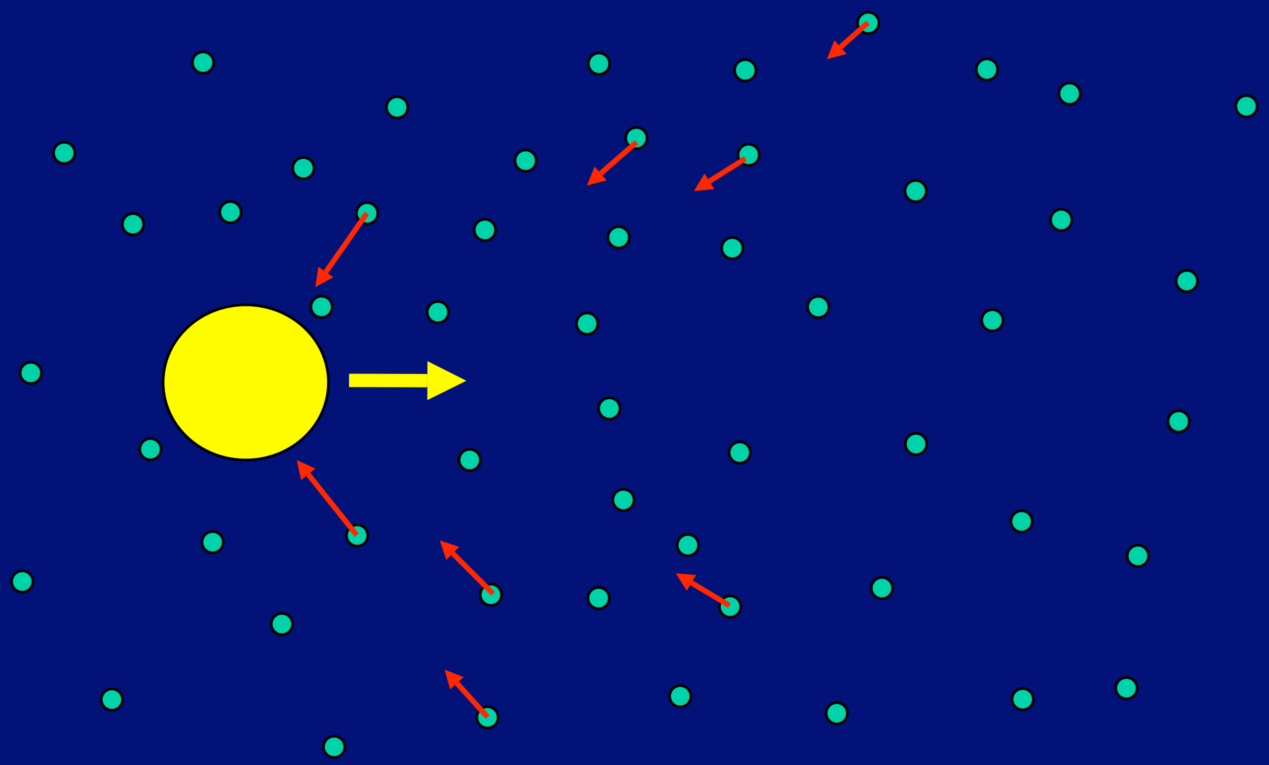
Avoiding the spin catastrophe: over-cooling and feedback



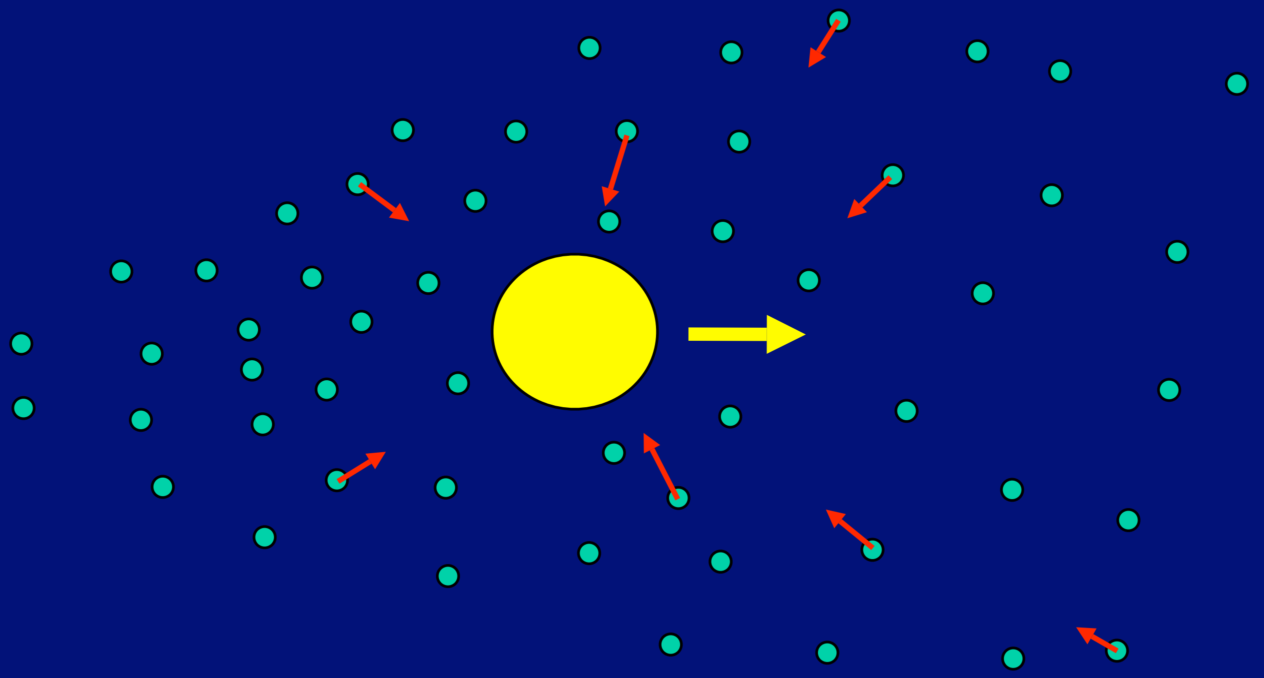
Maller & Dekel 2002

Feedback can save the day!

Dynamical Friction



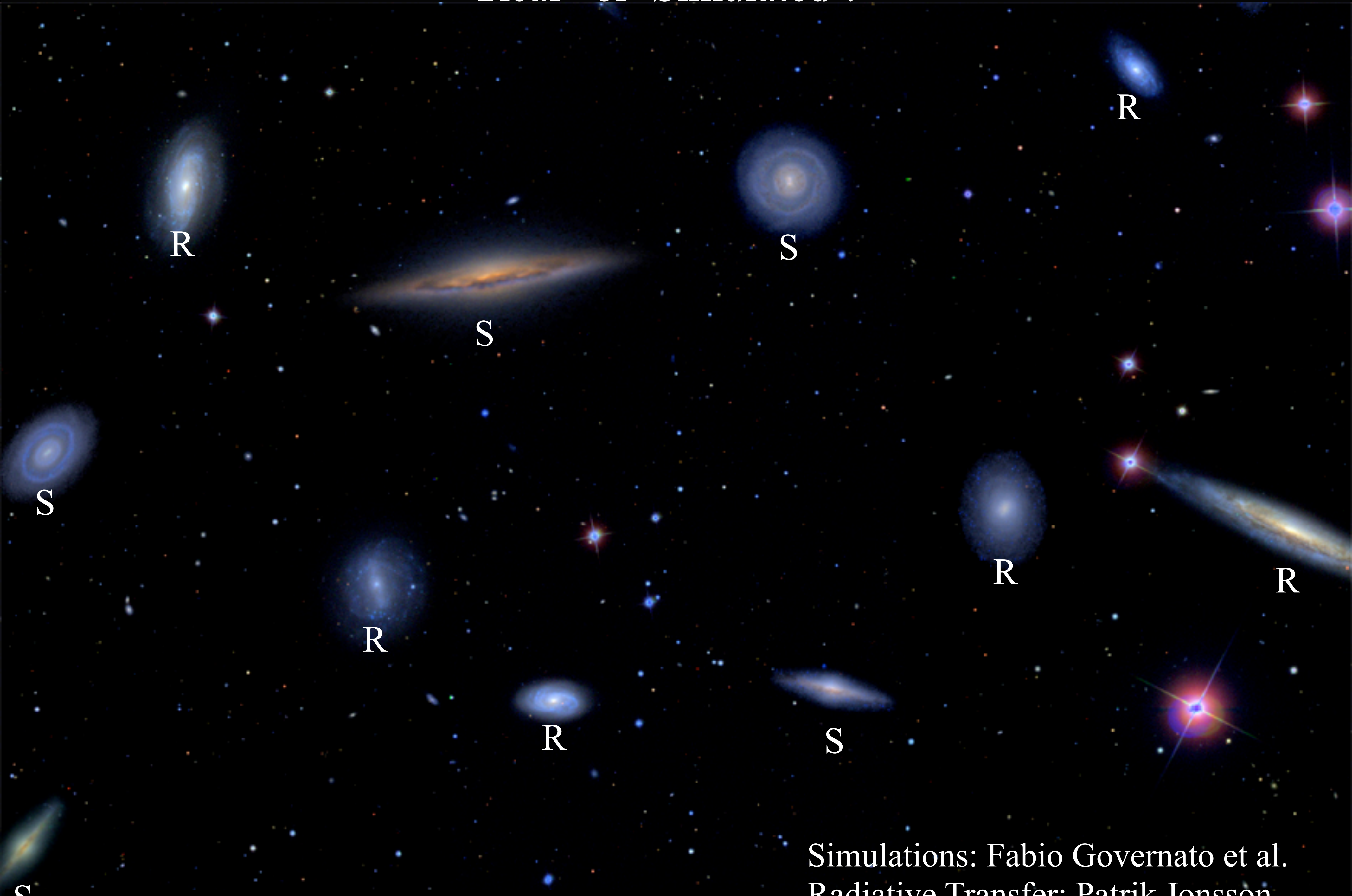
Dynamical Friction



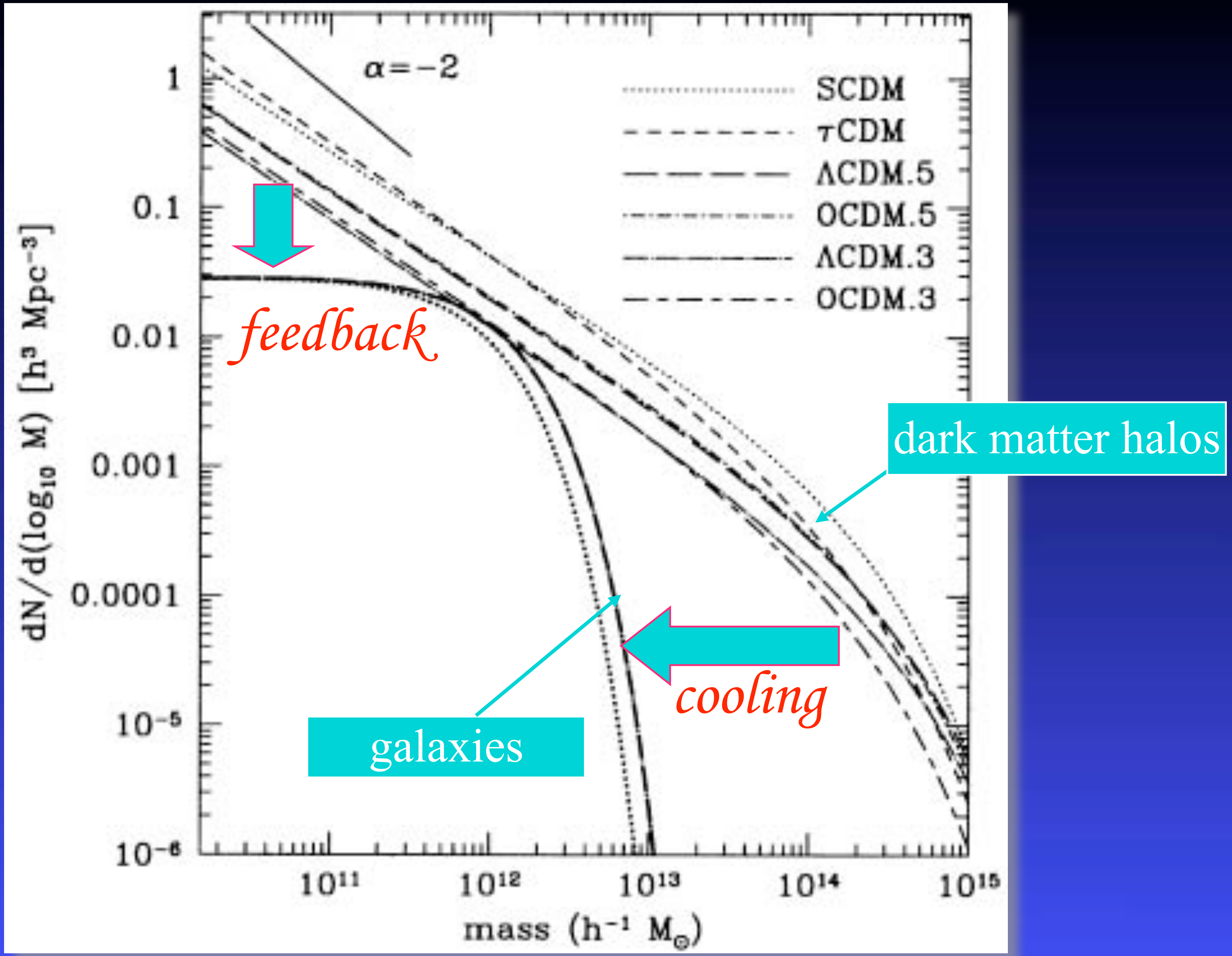
The ab-initio formation of a realistic rotationally supported disk galaxy with a pure exponential disk in a fully cosmological simulation is still an open problem. We argue that the suppression of bulge formation is related to the physics of galaxy formation during the merger of the most massive protogalactic lumps at high redshift, where the reionization of the Universe likely plays a key role. A sufficiently high resolution during this early phase of galaxy formation is also crucial to avoid artificial angular momentum loss.

Lucio Mayer, Fabio Governato, Tobias Kaufman 2008

Real or **S**imulated ?

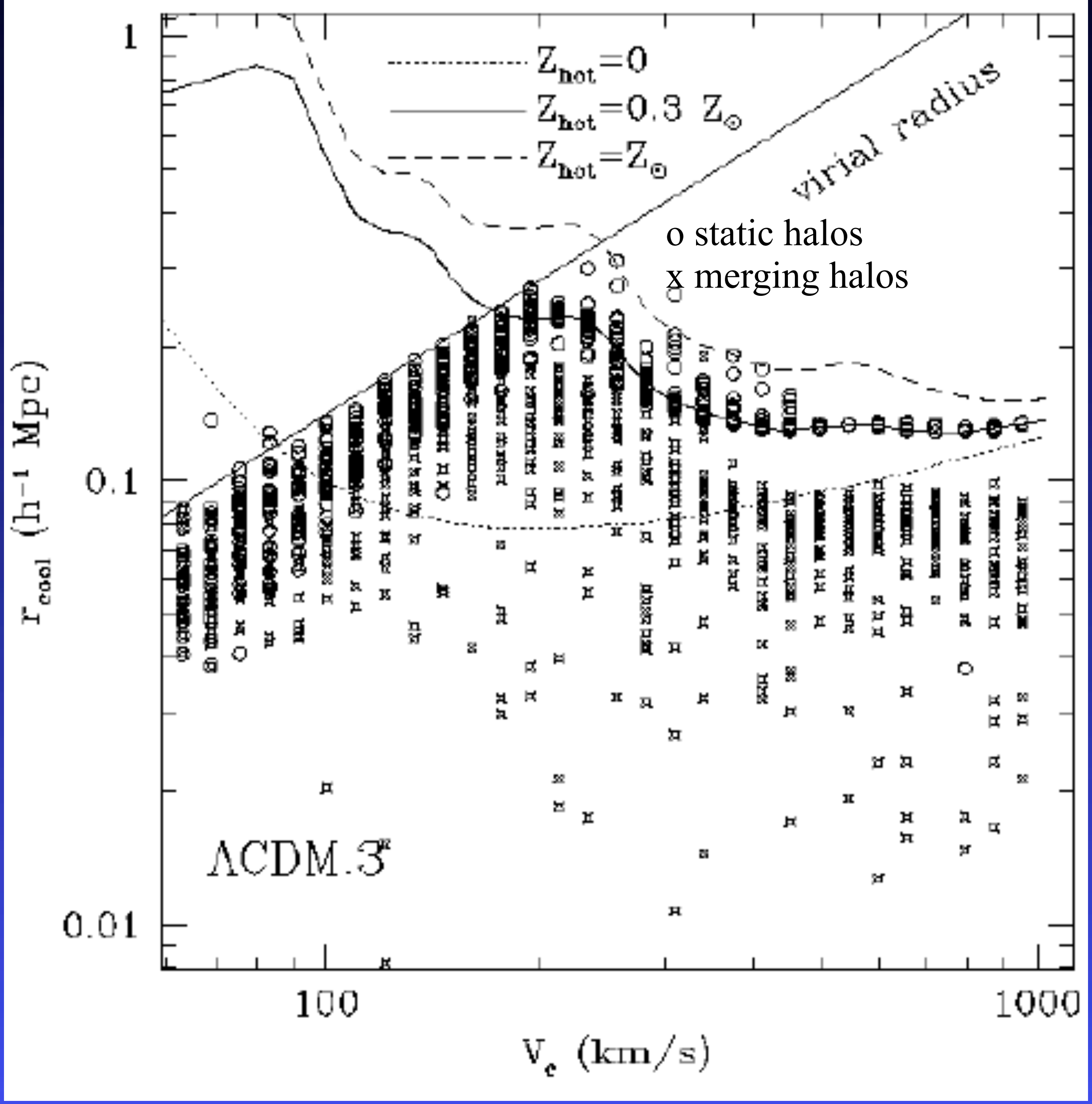


Simulations: Fabio Governato et al.
Radiative Transfer: Patrik Jonsson



Somerville & Primack 1999

cooling is efficient in small halos



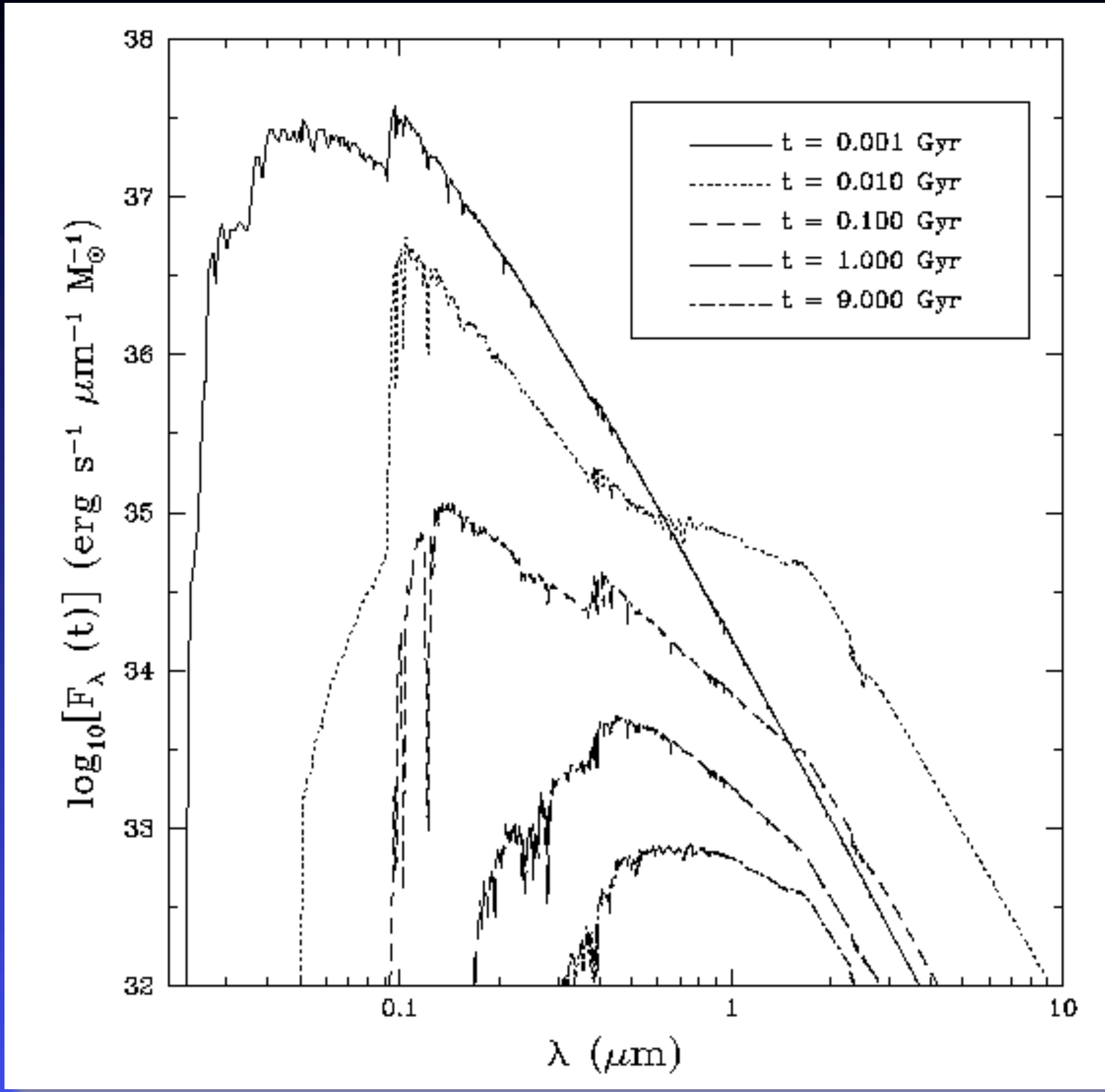
Somerville & Primack 1999

Issue: Is Halo Gas Heated to T_{vir}?

Hydrodynamic simulations (Katz et al. 2002, Birmboim & Dekel 2003) suggest that halo gas is heated to the virial temperature of the halo only for halos with $M > 10^{11}$, contrary to the standard assumption in SAMs. Cool gas entering halos could change the angular momentum distribution in galaxies, for example. This needs to be investigated by higher resolution simulations including more relevant astrophysics, such as merger-driven starbursts, AGN, and stellar and supernova feedback.

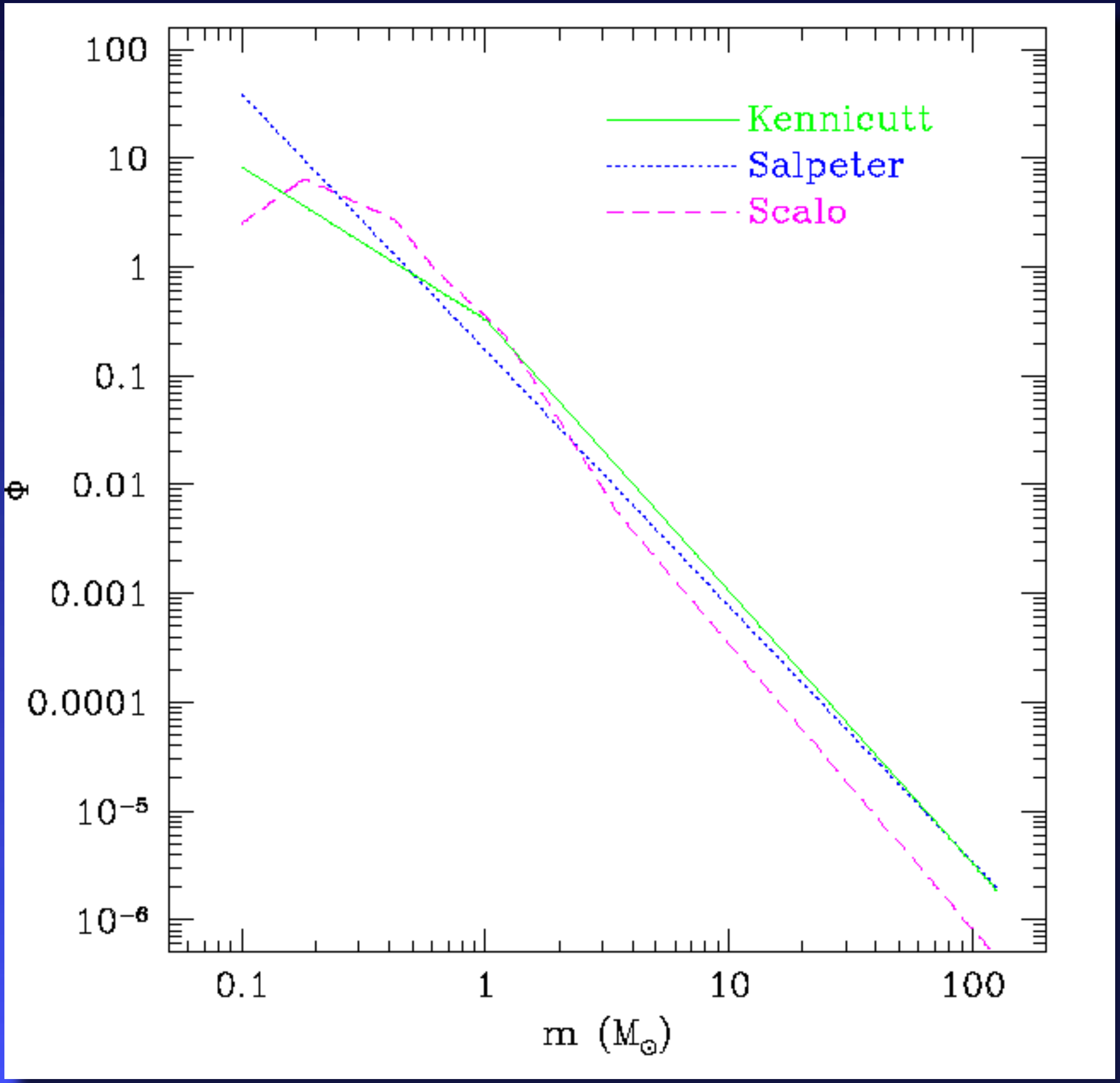
spectral energy distribution

distribution of stellar ages and metallicities is convolved with many “single burst” stellar population models to represent many generations of stars



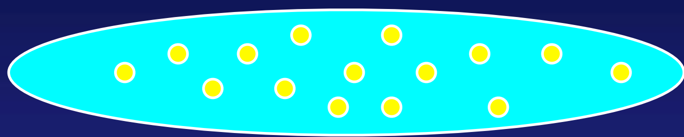
Devriendt, Guiderdoni & Sadat 1999

Issue: Does the IMF Change?



In constructing stellar spectral energy distributions, it is necessary to assume a stellar initial mass function (IMF). What is the IMF? Does it depend on redshift, gas density, metallicity, environment, or other circumstances and parameters?

dust absorption and emission



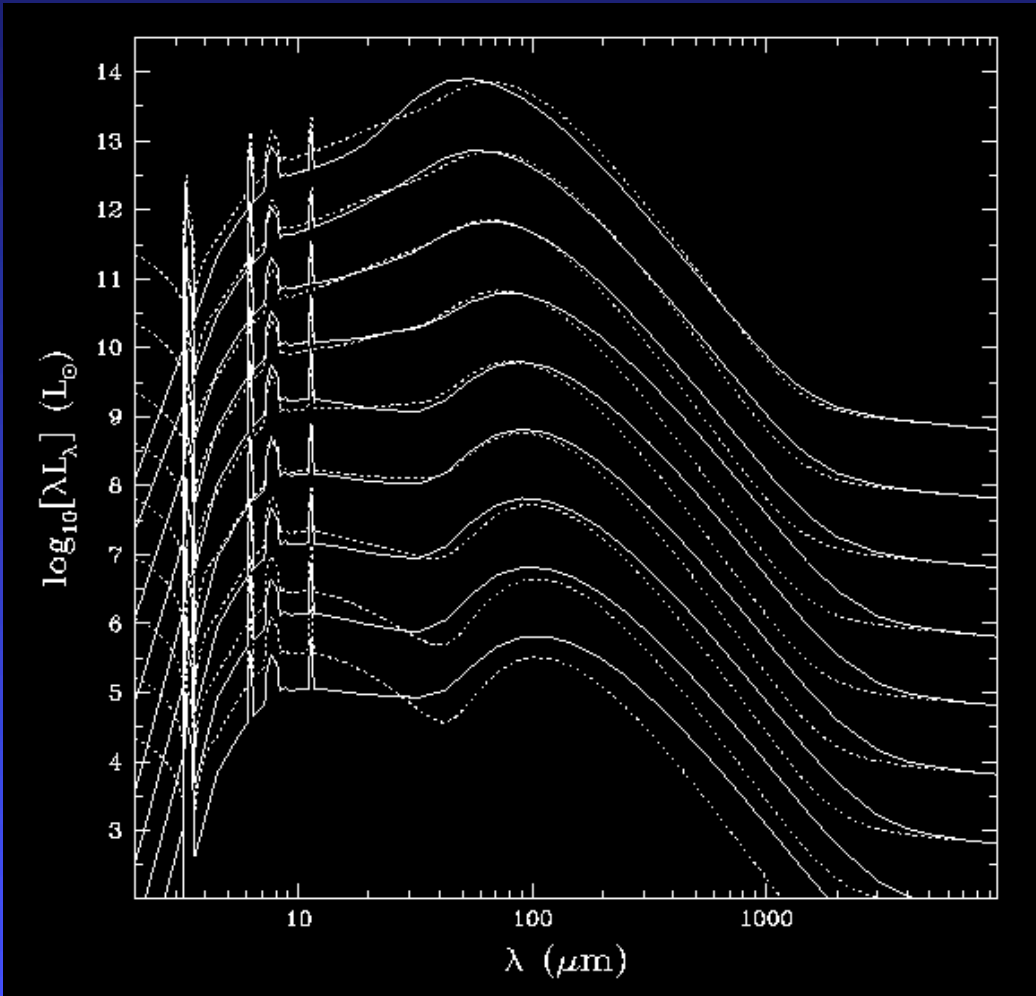
optical depth of dust proportional to

a. (star formation rate)$^{1/2}$ OR

b. column density of metals $Z_{gas}\ N_H$

energy absorbed
= energy emitted

empirical template
dust emission spectra
(Devriendt & Guiderdoni)
VSGs, BGs, and PAHs

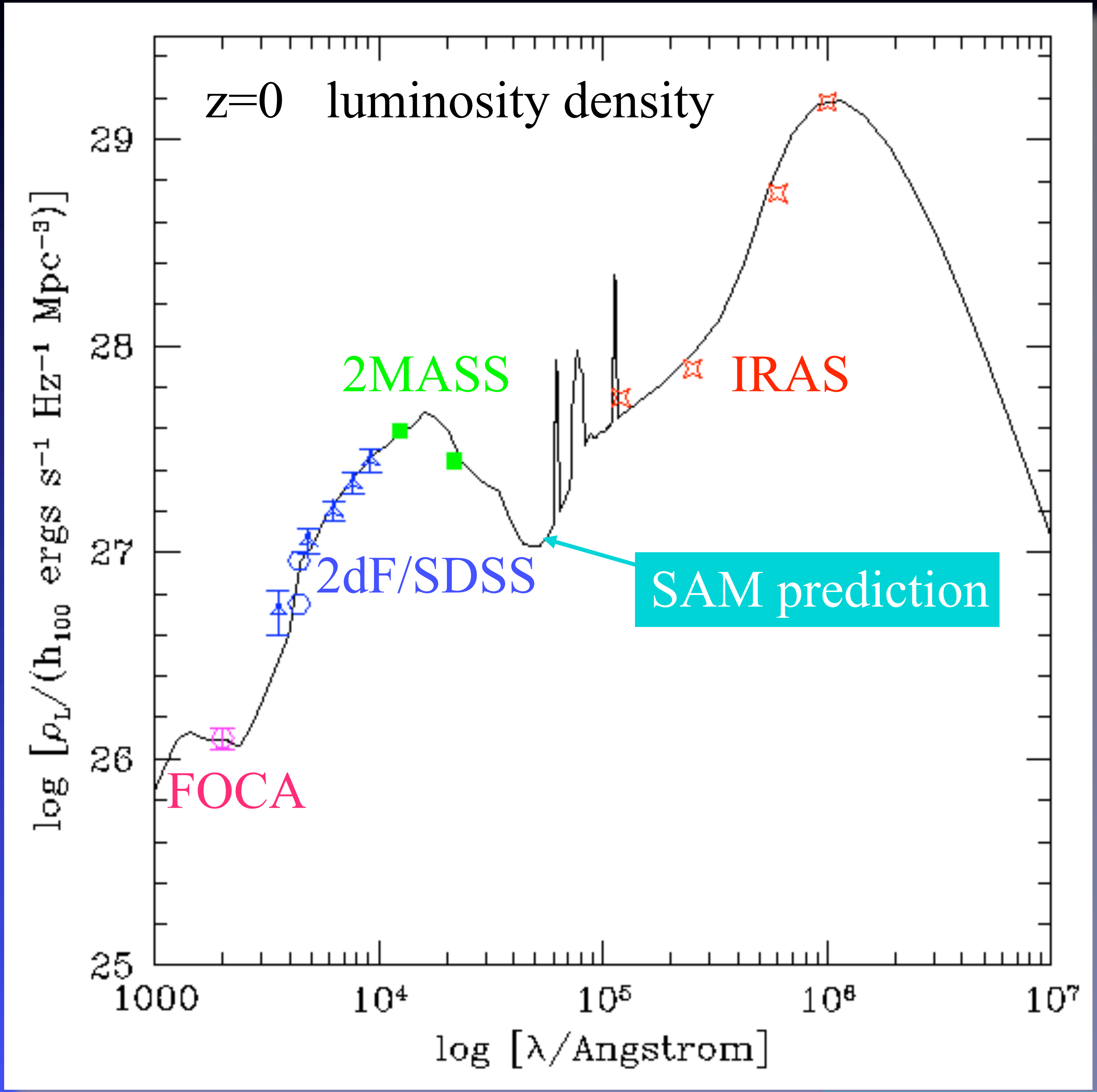


Devriendt & Guiderdoni. 1999

free parameters

- star formation efficiency α
- SN feedback efficiency β
- chemical yield y
- dust normalization τ^0_{dust}
- dust composition
- IMF

adjusted to fit a set of redshift zero observations
– then left fixed



Primack et al. 2005

Things that work pretty well

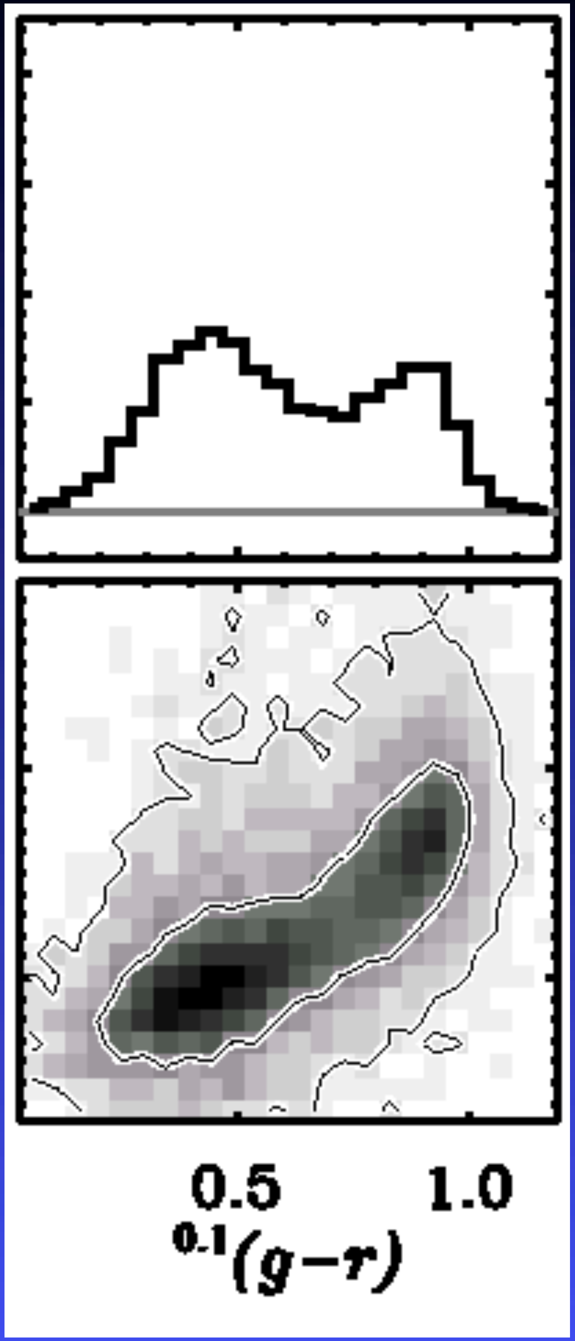
- global properties of “normal” galaxies (optical counts, luminosity functions, luminosity density, etc.) over the redshift range probed by observations ($z = 0 - 4$)
- clustering on large scales; dependence of galaxy bias on redshift, luminosity, color, type, etc.
- structural/dynamical properties of HSB galaxies like the Milky Way and M31

Problems for standard LCDM SAMS

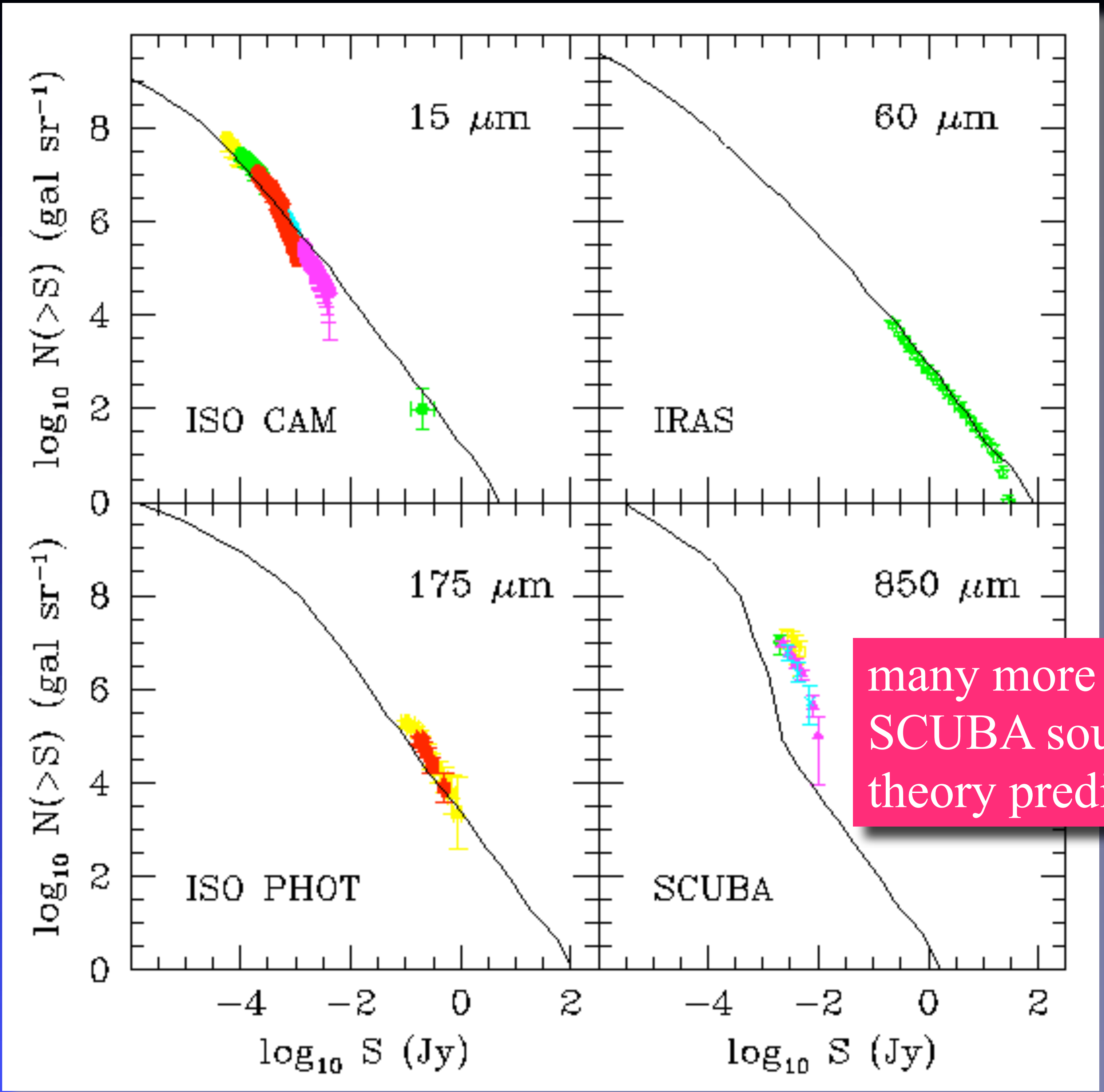
- SAMs need to predict bimodal color distribution of galaxies (nearby to z~1.5)
- SAMs underpredict number of bright dusty galaxies at z~0.7 compared to ISOCAM
- SAMs underpredict number of "extremely red" (ERO) galaxies at z=1-1.5
- SAMs underpredict number of bright sub-mm sources (z~2?) unless they are low T

We're not predicting enough red objects!

bimodal
color
distribution

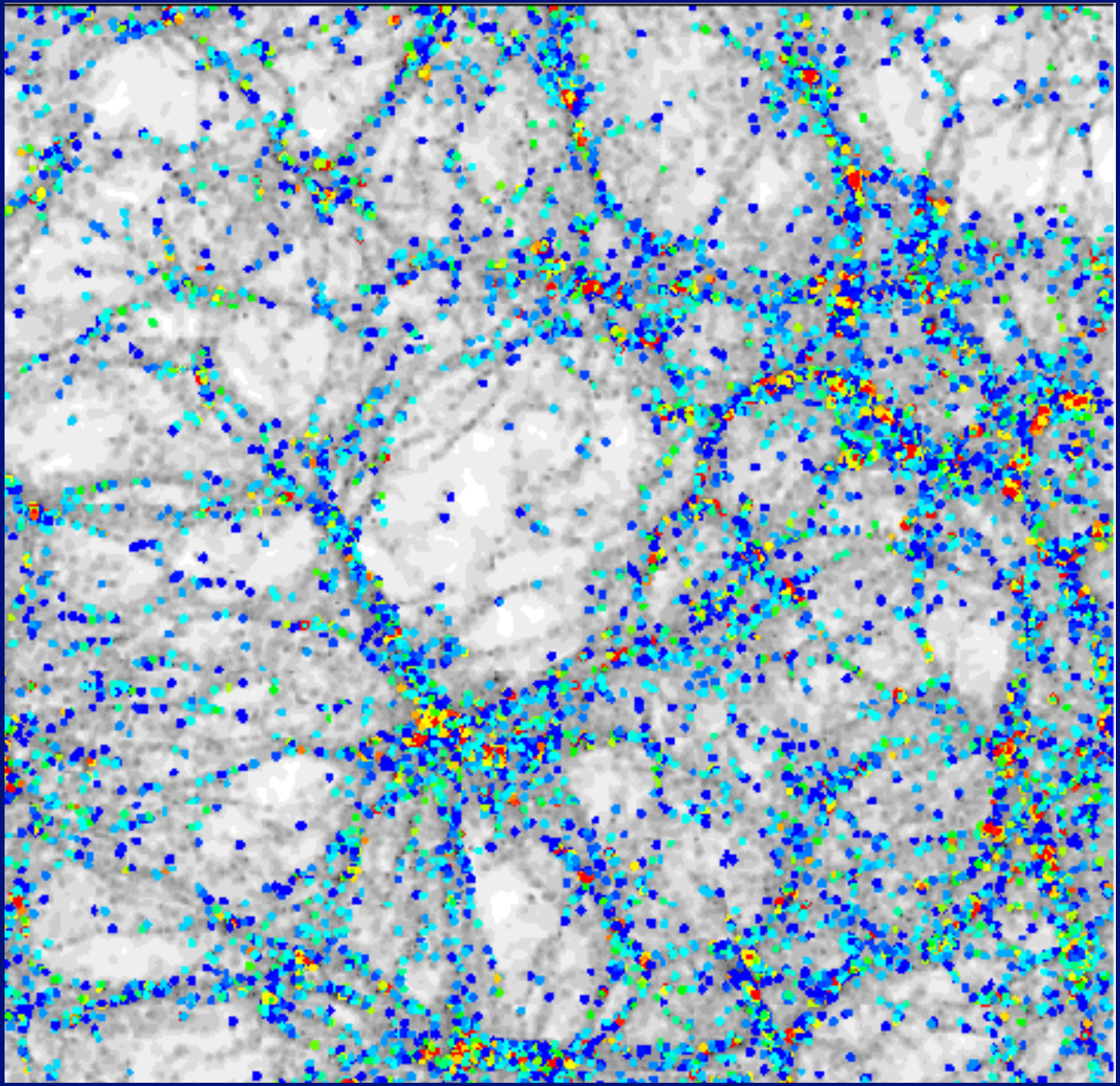


SDSS:
Blanton et al. 2002



many more bright SCUBA sources than theory predicts

Galaxy type correlated with large scale structure



elliptical

elliptical

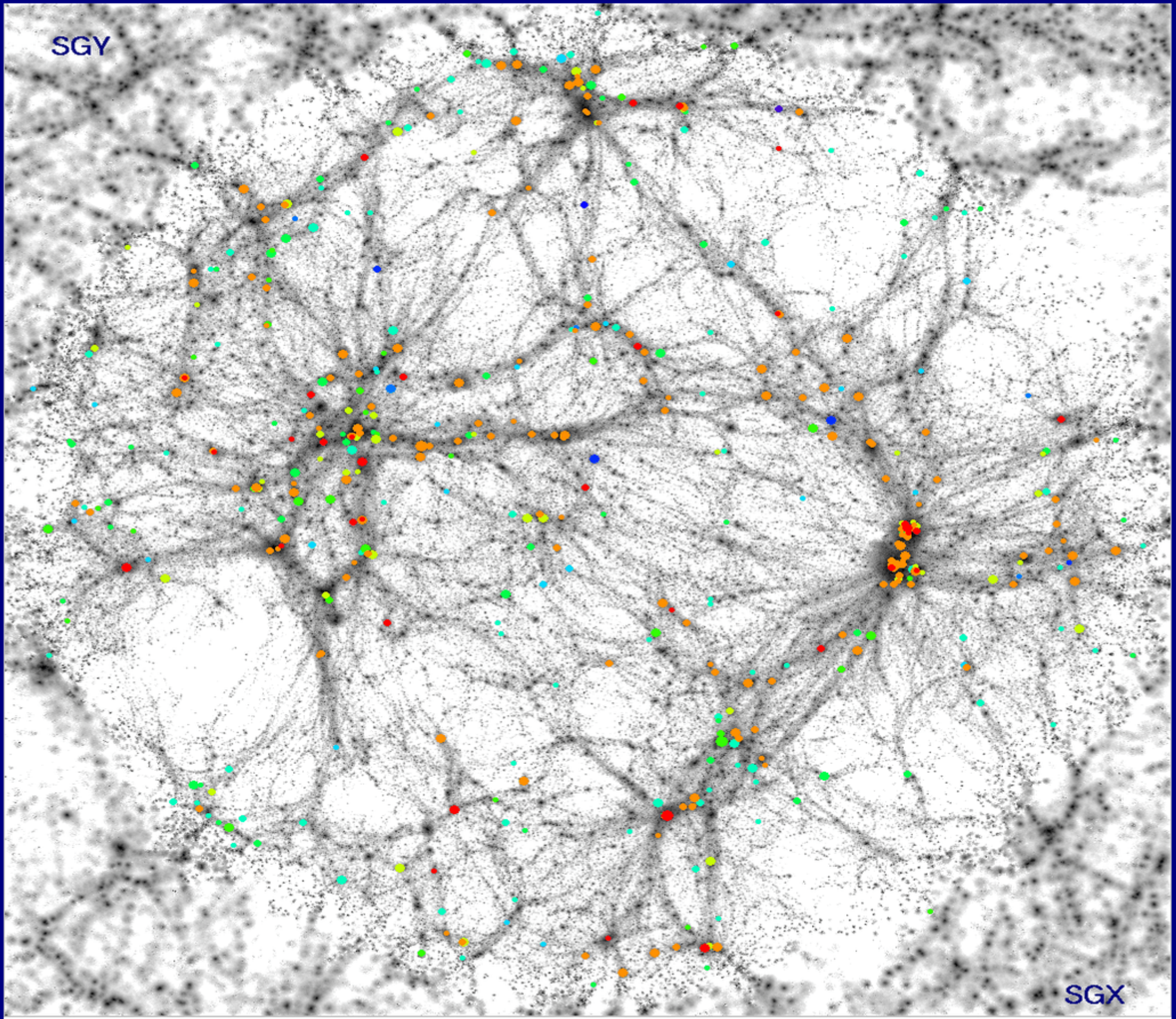
bulge+disk

disk

Semi-Analytic Modeling

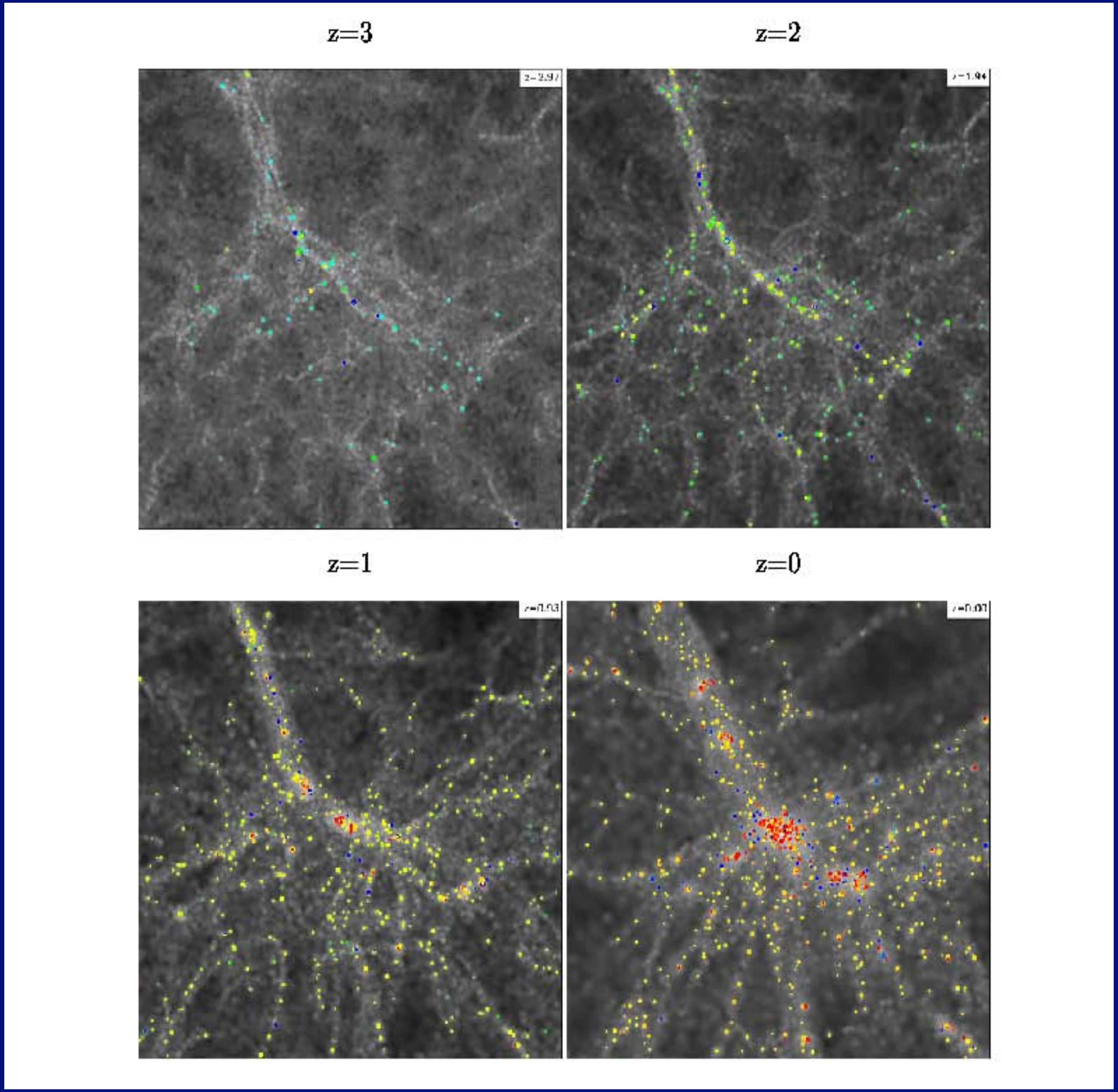
Kauffmann et al.

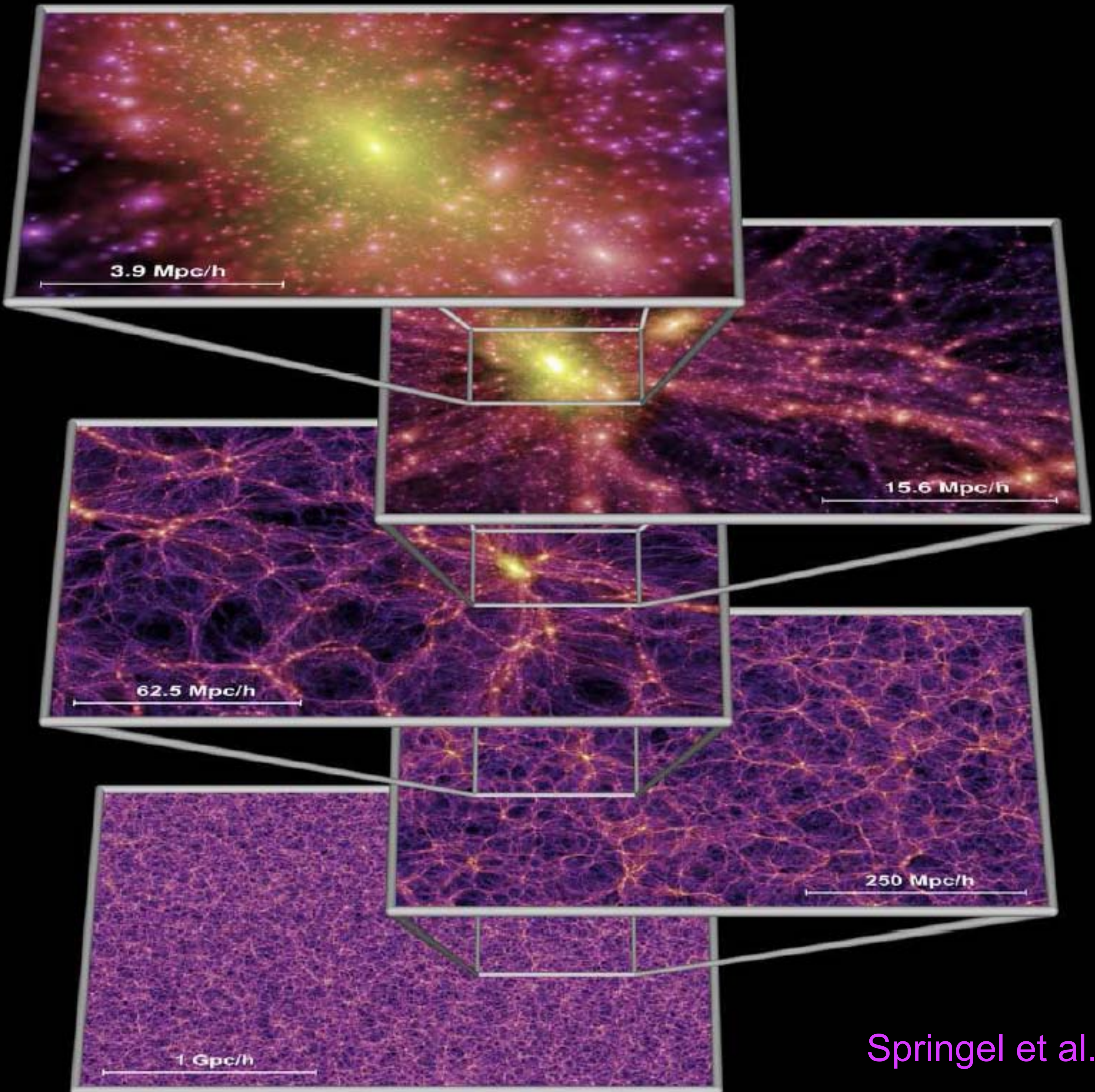
Elliptical galaxies in clusters in the local universe



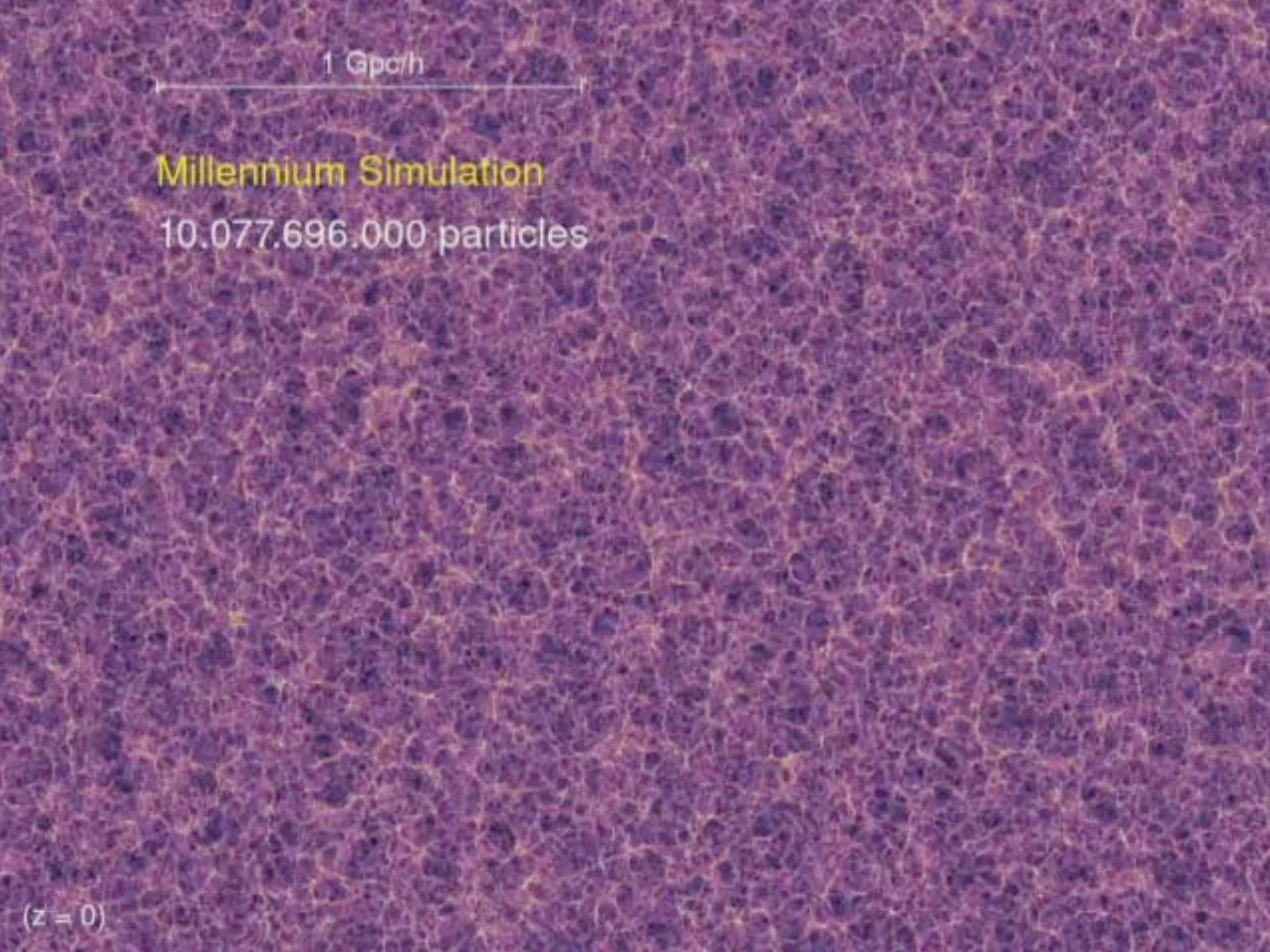
ΛCDM CR : E and S0 galaxies
Credits : Mathis, Lemson, Springel, Kauffmann, White and Dekel.

Formation of galaxies in a cluster



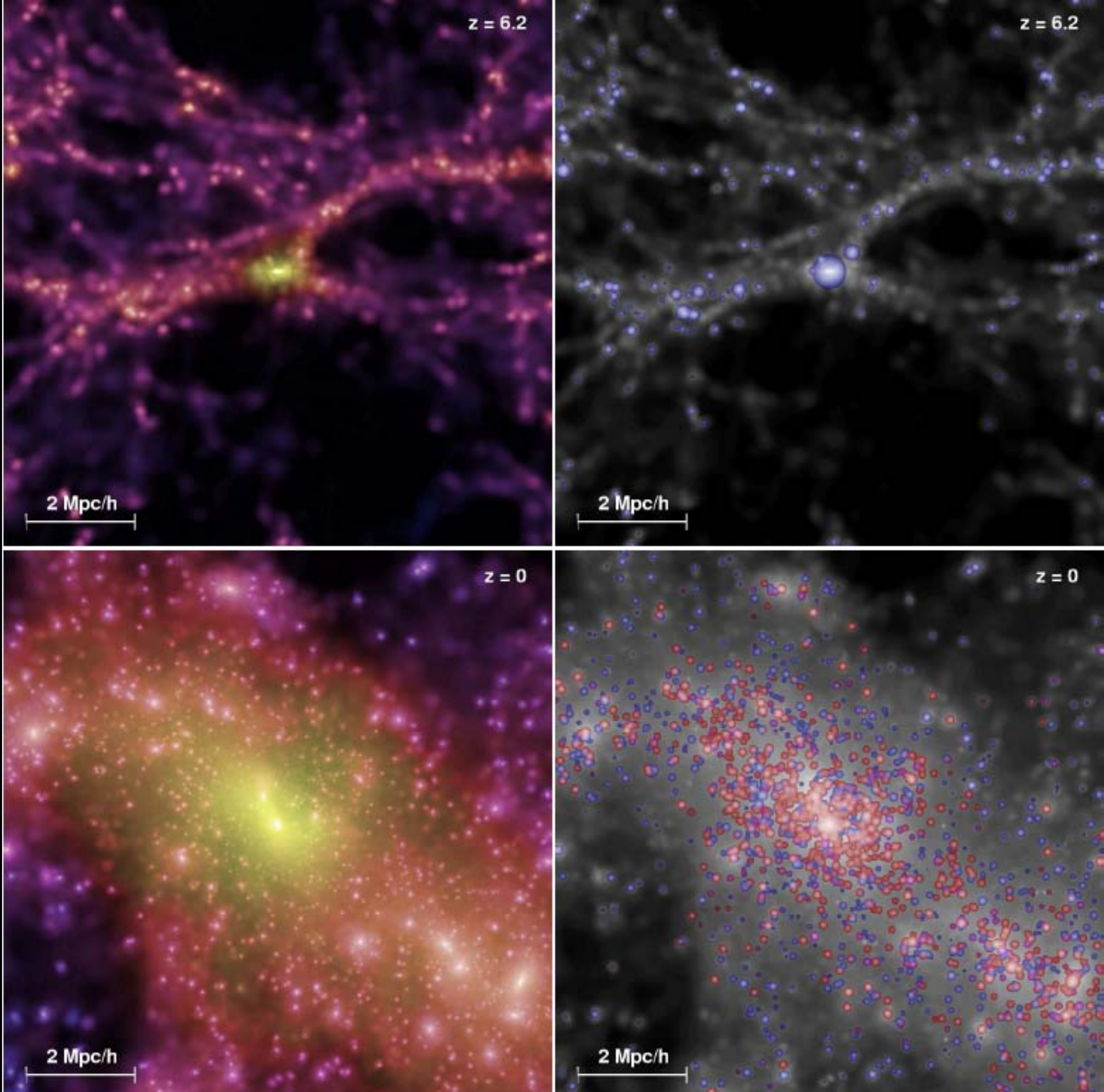


Springel et al. 2005


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

Environment of a 'first quasar candidate' at high and low redshifts. The two panels on the left show the projected dark matter distribution in a cube of comoving sidelength $10h^{-1}$ Mpc, colourcoded according to density and local dark matter velocity dispersion. The panels on the right show the galaxies of the semi-analytic model overlayed on a gray-scale image of the dark matter density. The volume of the sphere representing each galaxy is proportional to its stellar mass, and the chosen colours encode the restframe stellar $B-V$ colour index. While at z = 6.2 (top) all galaxies appear blue due to ongoing star formation, many of the galaxies that have fallen into the rich cluster at z = 0 (bottom) have turned red.

Springel et al. 2005



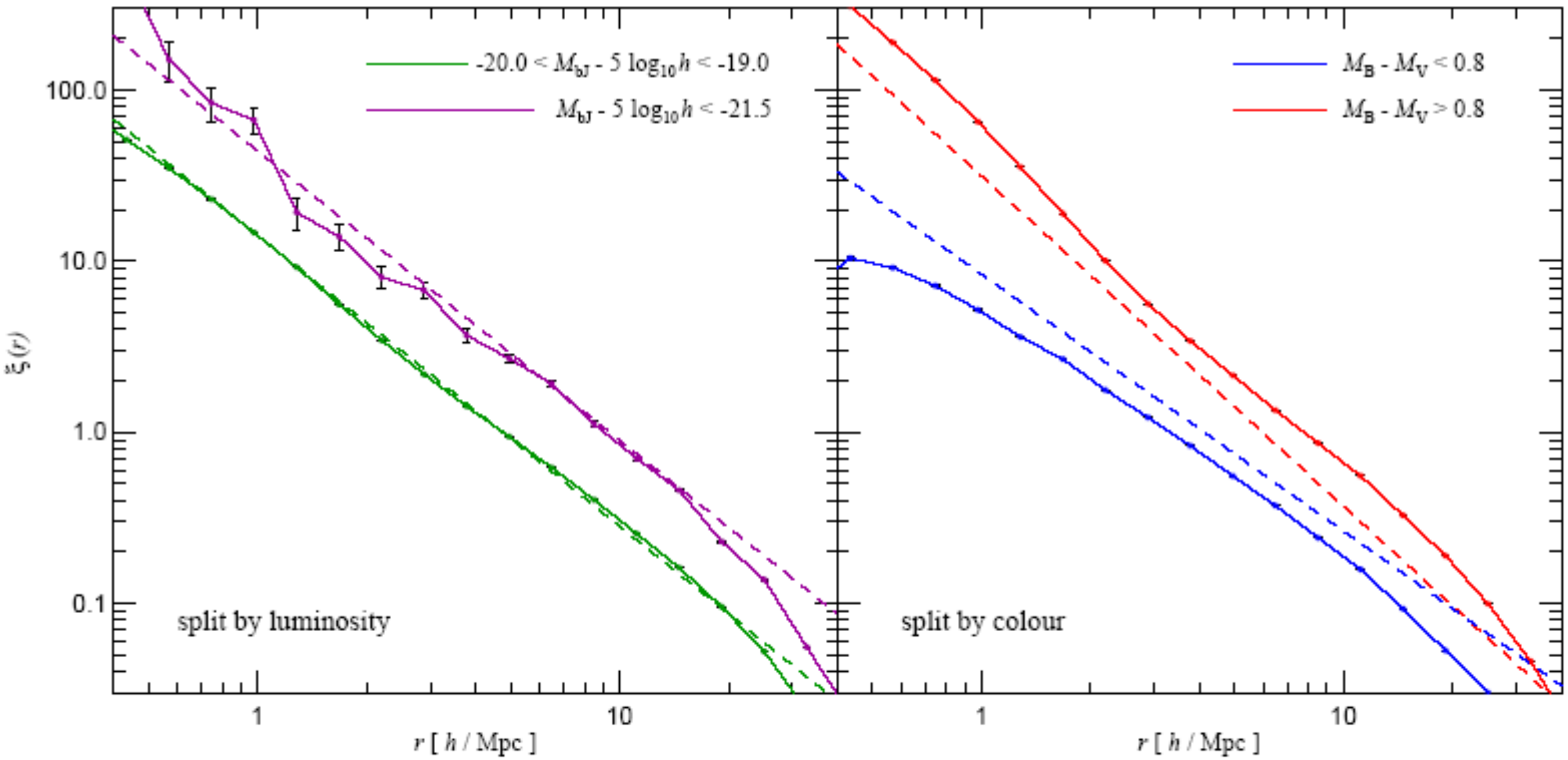


Figure 5: Galaxy clustering as a function of luminosity and colour. In the panel on the left, we show the 2-point correlation function of our galaxy catalogue at $z = 0$ split by luminosity in the bJ-band (symbols). Brighter galaxies are more strongly clustered, in quantitative agreement with observations[33] (dashed lines). Splitting galaxies according to colour (right panel), we find that red galaxies are more strongly clustered with a steeper correlation slope than blue galaxies. Observations[35] (dashed lines) show a similar trend, although the difference in clustering amplitude is smaller than in this particular semi-analytic model.

Springel et al. 2005

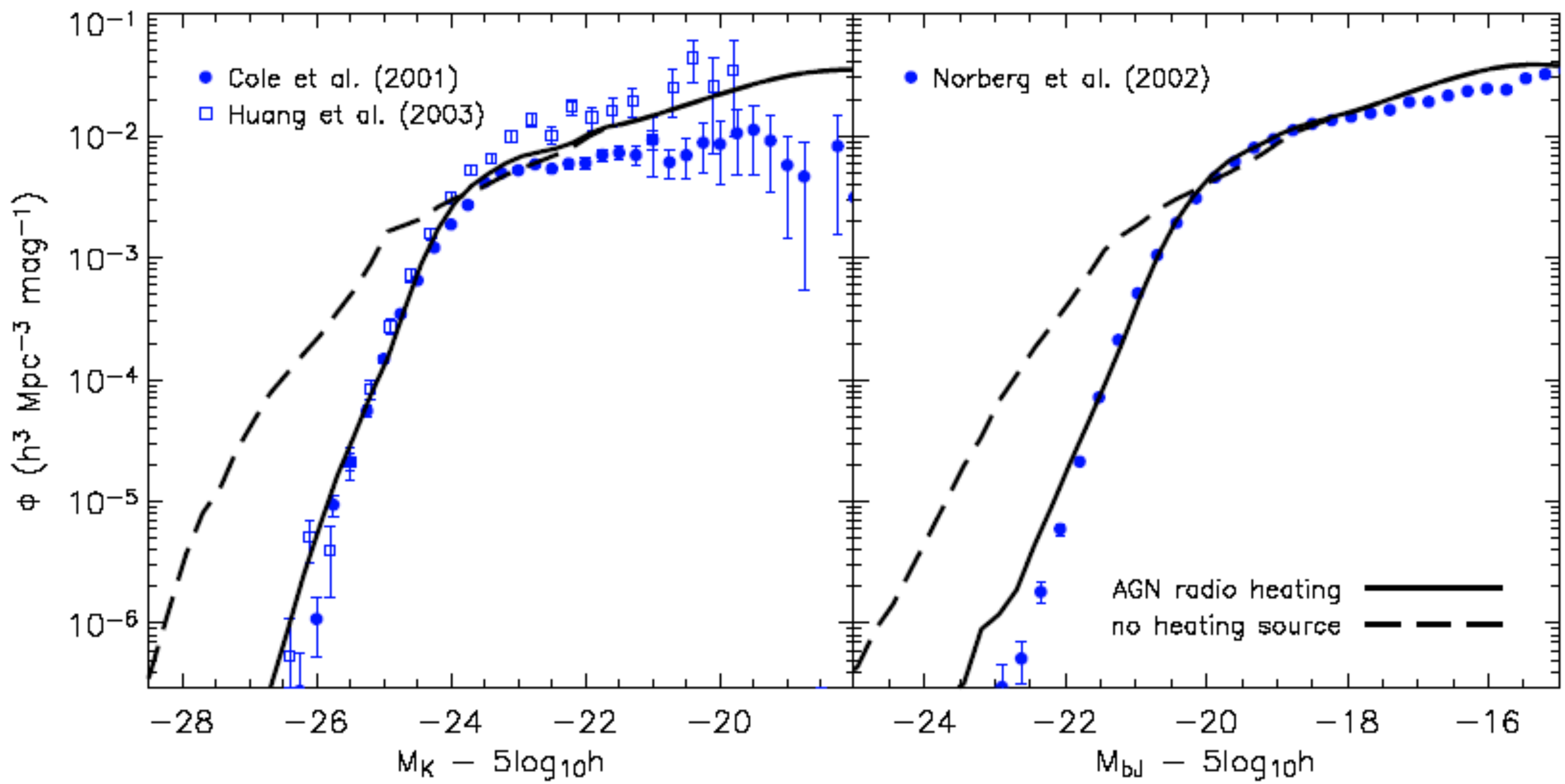
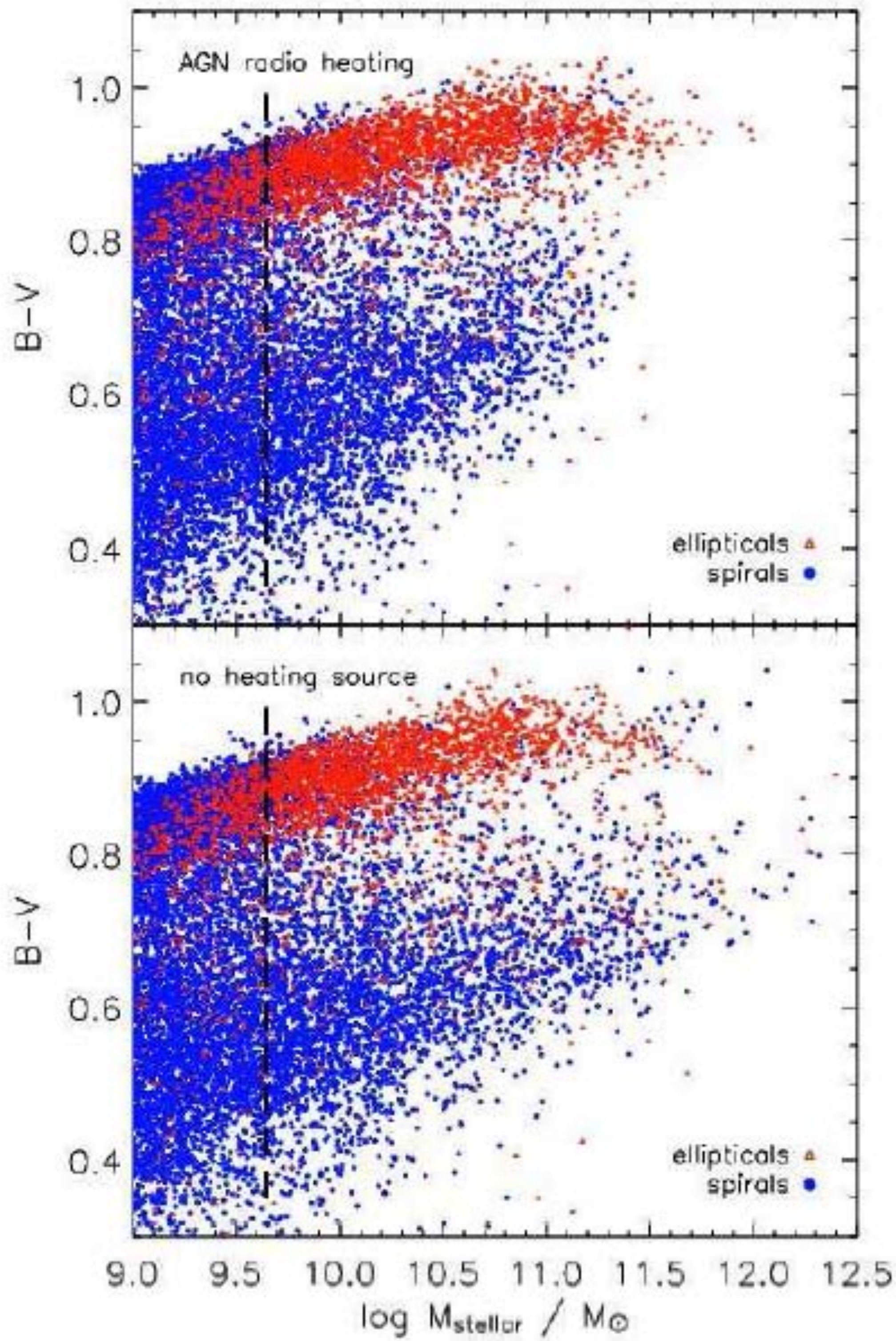


Figure 8. Galaxy luminosity functions in the K (left) and b_J (right) photometric bands, plotted with and without 'radio mode' feedback (solid and long dashed lines respectively – see Section 3.4). Symbols indicate observational results as listed in each panel. As can be seen, the inclusion of AGN heating produces a good fit to the data in both colours. Without this heating source our model overpredicts the luminosities of massive galaxies by about two magnitudes and fails to reproduce the sharp bright end cut-offs in the observed luminosity functions.

Croton et al. 2006



Color Magnitude Diagram

With heating – brightest galaxies are red, as observed

Without heating – brightest galaxies are blue

Croton et al. 2006

(see also Cattaneo et al. 2006)

Continue with my lecture at the Dark Matter 2008 meeting at Marina del Rey:

DM2008-Primack.pdf