Perturbed Universe

Kandaswamy Subramanian

Inter-University Centre for Astronomy and Astrophysics

and

Ashoka University

Plan

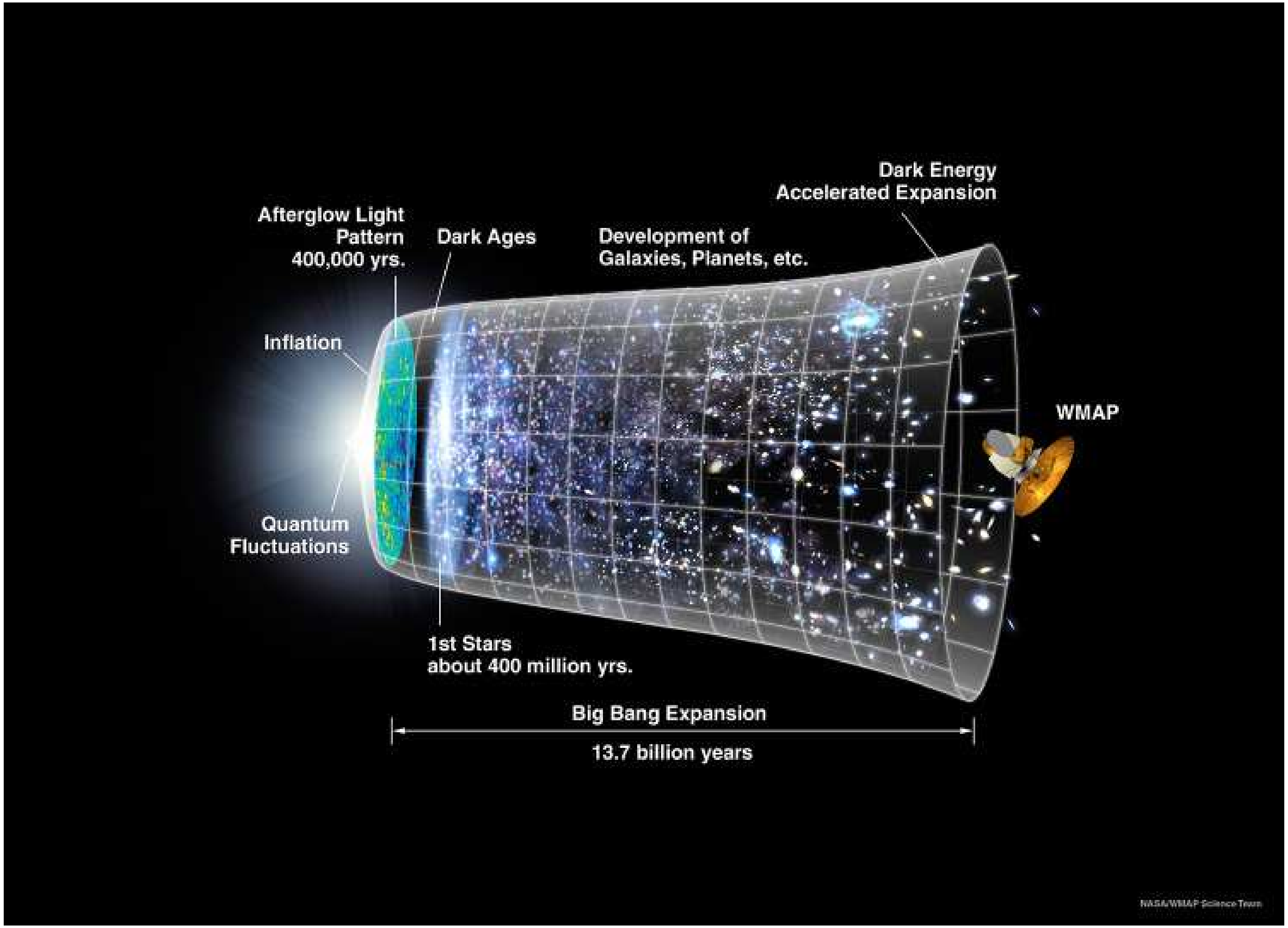
- **Introducing the Universe of Strucutures**
- **Gravitational Instability paradigm**
- **Physics ("Dirty buisness") of Galaxy Formation**
- **Probes of structure formation**
- **Open questions**

Literature

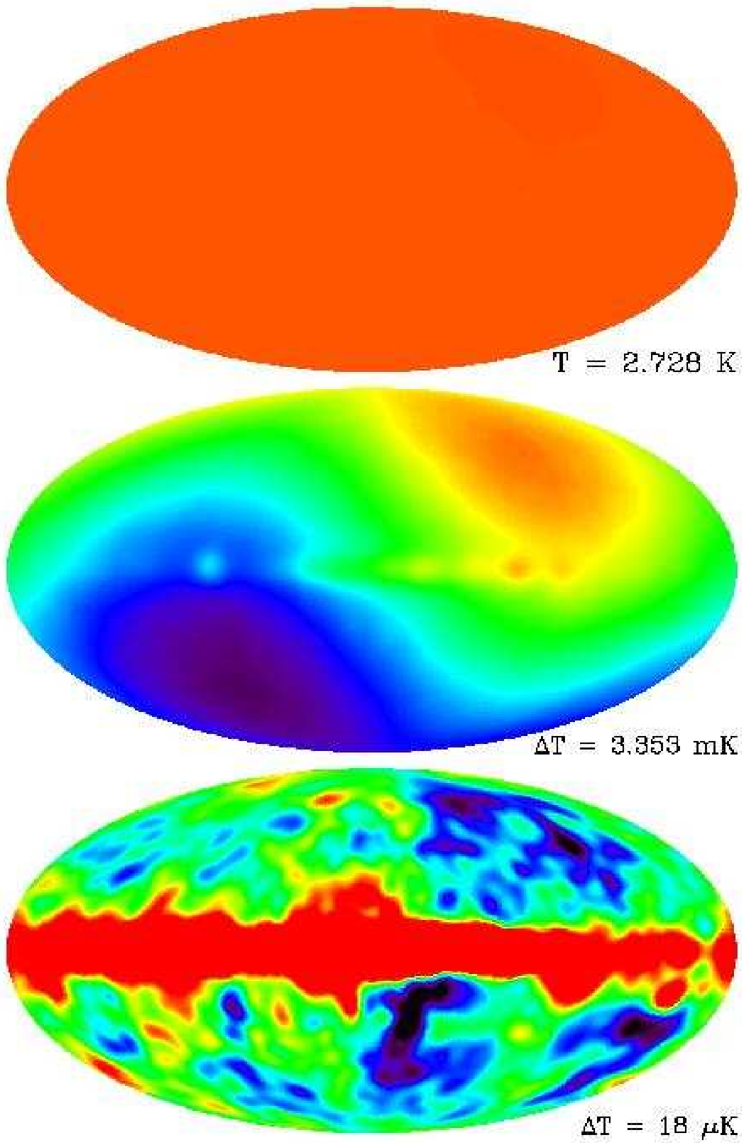
- P. J. E. Peebles, Large scale structure of the Universe (1980)
- T. Padmanabhan and K. Subramanian, Galaxy formation, 1992, Bulletin of the Astronomical Society of India, 20, 1-155.
- T.Padmanabhan, Structure formation in the Universe
- T. Padmanabhan, Theoretical Astrophysics Vol III
- Scott Dodelson, Modern Cosmology
- K. Subramanian, Physics of CMBR anisotropies, 2005, Current Science, 88, 1068 (astro-ph/0411049)
- H. Mo, F. Van den Bosch and S. White, Galaxy formation and Evolution

Smooth Universe to Structures

How does the smooth universe develop into present day structures?

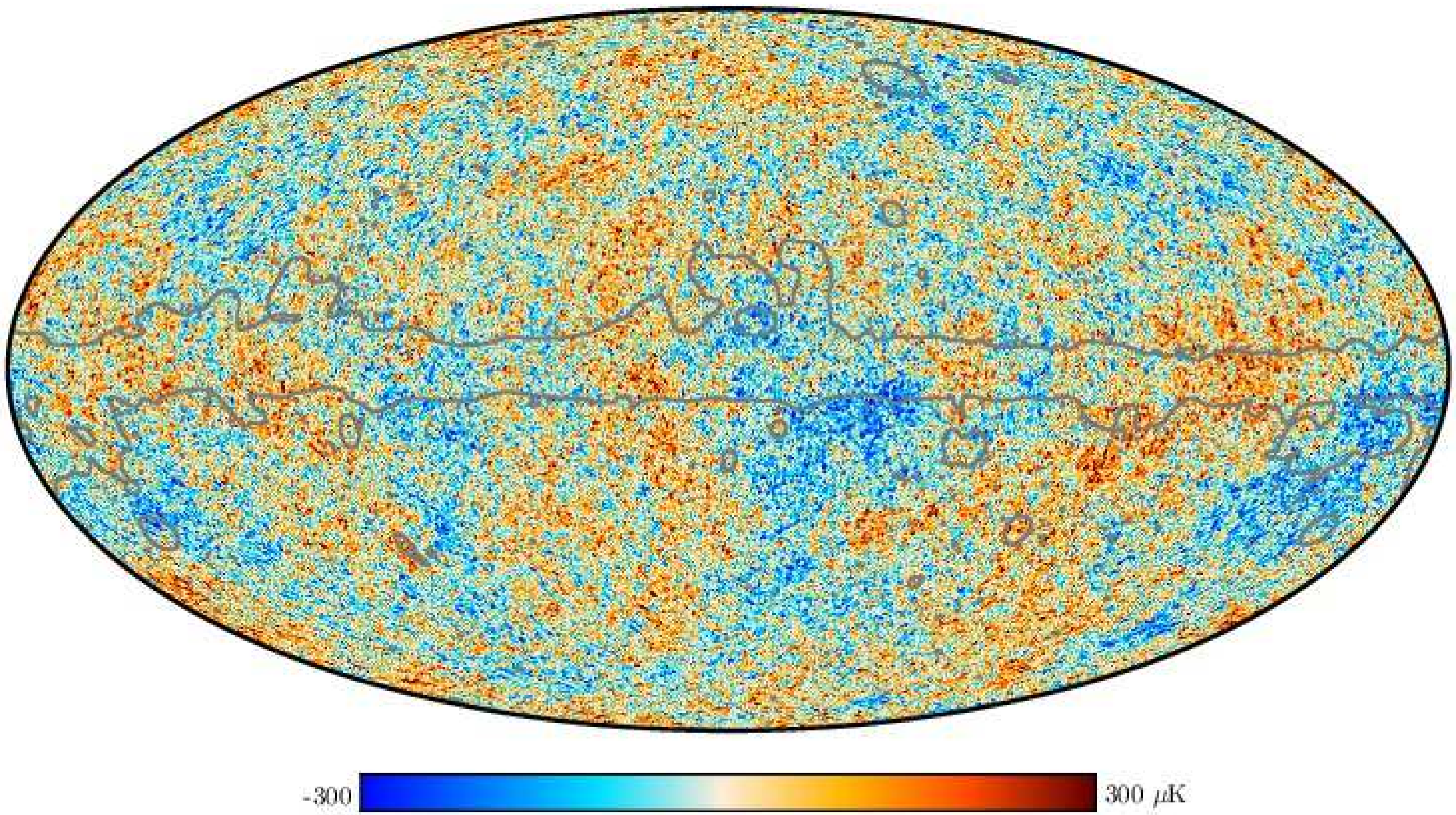


CMB from COBE



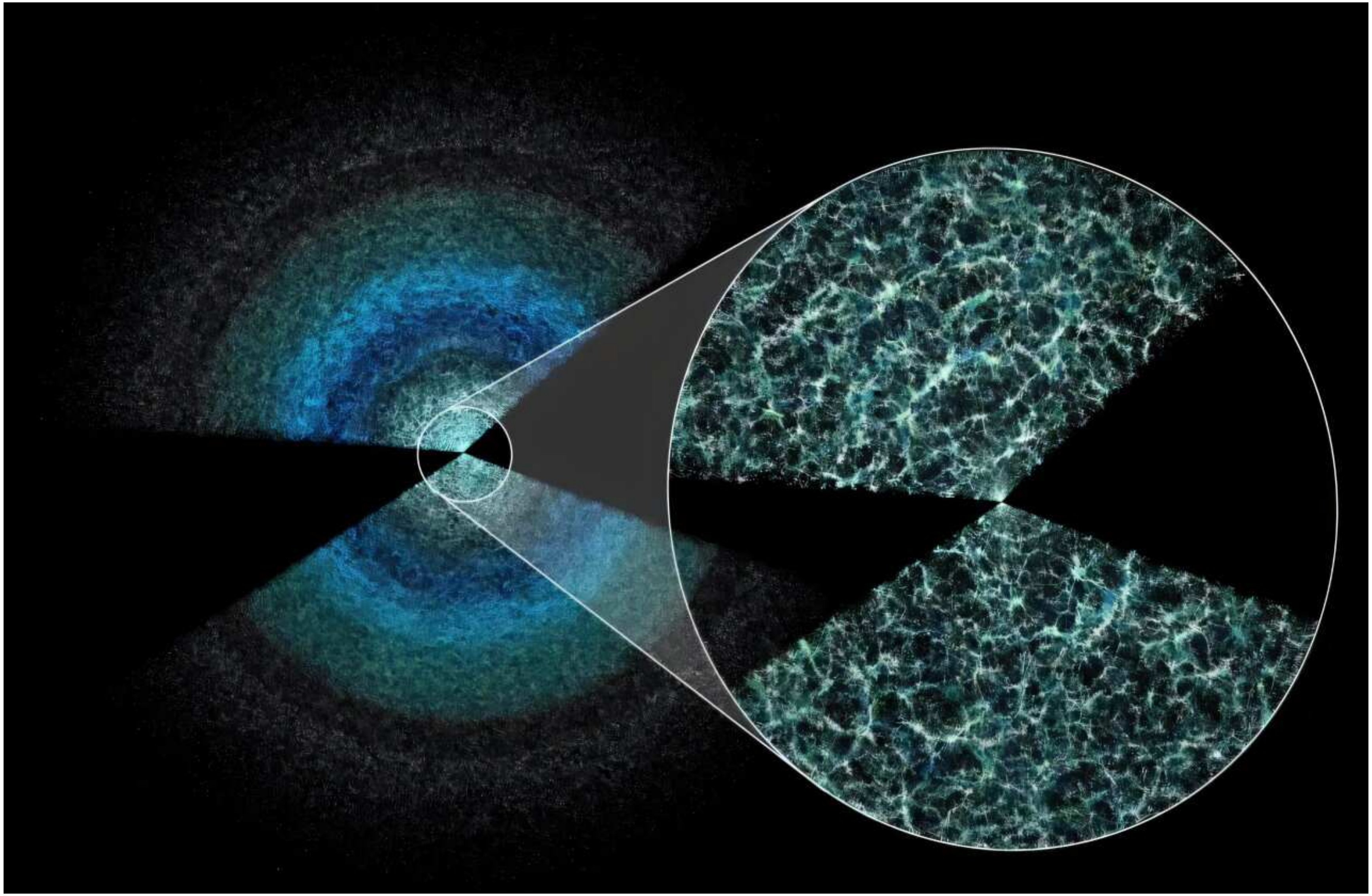
CMB Anisotropy from Planck

Planck 2018 results I, A&A, 2019



Anisotropies indicate existence of seeds for Structure formation!

Large Scale structures: DESI

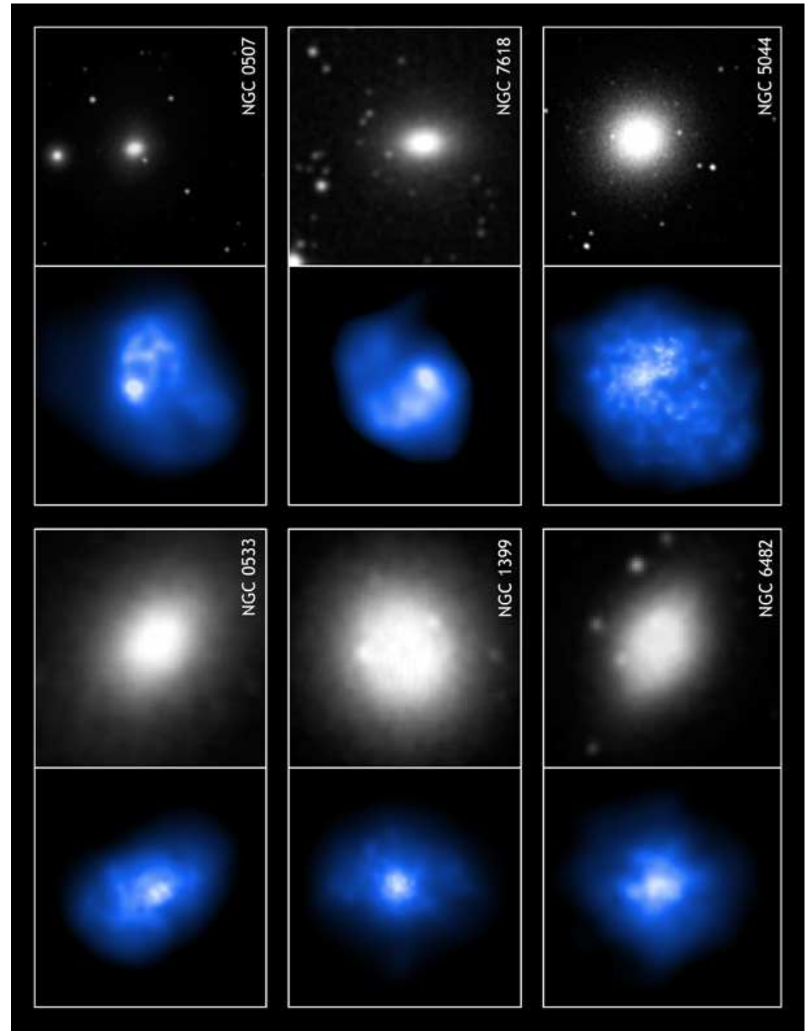


Galaxies:Spirals and Ellipticals

M31: Andromeda

M51: Whirlpool

Ellipticals: Optical and X-ray



Galaxy formation in a nutshell

- Universe smooth but not quite; Small fluctuations imprinted on the smooth universe
- These grew due to SELF GRAVITATIONAL INSTABILITY; Over dense regions lagged behind Hubble expansion
- Turned around and eventually collapsed to form structures.
- Dark matter (collisionless) 'virialized to form a dark matter Halo
- Baryons locked to radiation before recombination; after recombination stream with respect to dark matter.
- Baryon density fluctations eventually catch up with dark matter, collapsed with DM, heated up through shocks and 'virializes'
- If the heated gas can cool efficiently (by atomic/molecular lines) within a dynamical time, collapse, become self-gravitating, form stars, a visible Galaxy results.

Jeans instability in expanding universe

- **Fluid equations (Baryons, Dark matter)**

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0; \quad \rho\left[\frac{\partial\mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right] = -\nabla p - \rho\nabla\phi$$

$$p = K\rho^{\gamma}; \quad \nabla^2\phi = 4\pi G\rho \quad \text{(Newtons law)}$$

- **Background evolution** $\rho = \bar{\rho}(t), \mathbf{v} = H(t)\mathbf{r} = \frac{\dot{a}}{a}\mathbf{r}, p = \bar{p}(t), \bar{\phi}(t)$

$$\frac{d\bar{\rho}}{dt} + 3\frac{\dot{a}}{a}\bar{\rho} = 0 \rightarrow \bar{\rho}(t) = \frac{\rho_0}{a^3}$$

$$\mathbf{r}\left[\dot{H} + H^2\right] = -\nabla\bar{\phi} = \mathbf{r}\frac{\ddot{a}}{a} \Rightarrow \frac{\ddot{a}}{a} = -\frac{1}{3}\nabla^2\bar{\phi} = -\frac{4\pi G\bar{\rho}}{3}$$

- **Exactly Einstein equation for background except that pressure also gravitates :** $\rho \rightarrow (\rho + 3p)$**.**
- **Can also choose** $a(t)$ **from Einstein with pressure, but neglect pressure perturbations. DM in RD era.** (see Peebles 1980).

Perturbed evolution

- **Perturbed state**: $\rho = \bar{\rho} + \rho_1$, $\mathbf{v} = H\mathbf{r} + \mathbf{v}_1$, $\phi = \bar{\phi} + \phi_1$, $\delta = \rho_1/\bar{\rho}$
- **Linearly perturbed equations:** $p_1 = c_s^2 \rho_1$, $\nabla^2 \phi_1 = 4\pi G \rho_1$
  $\left(\frac{\partial}{\partial t} + H\mathbf{r} \cdot \nabla\right)\rho_1 + \bar{\rho}\nabla \cdot \mathbf{v}_1 + \rho_1 \nabla \cdot (H\mathbf{r}) = 0$
  $\bar{\rho}\left(\frac{\partial}{\partial t} + H\mathbf{r} \cdot \nabla\right)\mathbf{v}_1 + \bar{\rho}\mathbf{v}_1 \cdot \nabla(H\mathbf{r}) + \rho_1 \mathbf{r}[\dot{H} + H^2] =$
  $-\nabla p_1 - \bar{\rho}\nabla\phi_1 - \rho_1 \nabla\bar{\phi}$
- **Change to comoving co-ordinates :** $(\mathbf{x} = \mathbf{r}/a(t), t)$**, Then** $(\partial/\partial t)|_{\mathbf{x}} = (\partial/\partial t)|_{\mathbf{r}} + H\mathbf{r} \cdot \nabla$
- **Define** $\delta = \rho_1/\bar{\rho}$**. Perturbed eqns become:**

$$\frac{\partial \delta}{\partial t} + \frac{1}{a}\nabla_{\mathbf{x}} \cdot \mathbf{v}_1 = 0; \quad \nabla^2_{\mathbf{x}}\phi_1 = 4\pi G a^2 \bar{\rho}\delta$$

$$\frac{\partial \mathbf{v}_1}{\partial t} + H\mathbf{v}_1 = -\frac{c_s^2}{a}\nabla_{\mathbf{x}}\delta - \frac{1}{a}\nabla_{\mathbf{x}}\phi_1$$

Perturbed evolution

$$\frac{\partial\delta}{\partial t} + \frac{1}{a}\nabla_{\mathbf{x}}\cdot\mathbf{v}_1 = 0; \quad \nabla^2_{\mathbf{x}}\phi_1 = 4\pi G a^2\bar{\rho}\delta$$

$$\frac{\partial\mathbf{v}_1}{\partial t} + H\mathbf{v}_1 = -\frac{c_s^2}{a}\nabla_{\mathbf{x}}\delta - \frac{1}{a}\nabla_{\mathbf{x}}\phi_1$$

- Take divergence of v_1 eqn., substitute in δ eqn.

$$\frac{\partial^2\delta}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial\delta}{\partial t} - \frac{c_s^2}{a^2}\nabla^2\delta - 4\pi G\bar{\rho}\delta = 0$$

- **Expand in terms of Fourier modes** $\delta(\mathbf{x},t) = \sum\delta_k(t)\exp(i\mathbf{k}\cdot\mathbf{x})$

$$\frac{d^2\delta_k}{dt^2} + 2\frac{\dot{a}}{a}\frac{d\delta_k}{dt} + \left[\frac{k^2c_s^2}{a^2} - 4\pi G\bar{\rho}\right]\delta_k = 0$$

- $G = 0$, $\dot{a} = 0 \Rightarrow$ Sound waves **with speed of sound** c_s

Perturbing the expanding universe

$$\frac{d^2\delta_k}{dt^2} + 2\frac{\dot{a}}{a}\frac{d\delta_k}{dt} + \left[\frac{k^2c_s^2}{a^2} - 4\pi G\bar{\rho}\right]\delta_k = 0$$

- **Expansion damping (2nd), pressure support (3rd), gravitational instability (4th)**
- **Jeans Instability if**: $k < k_J$ or $M > M_J$: **Jeans Mass**
  $k_J/a = \sqrt{4\pi G\bar{\rho}}/c_s; \quad M_J = (4\pi/3)\bar{\rho}\left((2\pi a)/k_J\right)^3$
- **Also valid for CDM with $c_s = 0$:**
- **Spatially flat Matter dominated, $a \propto t^{2/3}$, $\bar{\rho} = 1/(6\pi G t^2)$.**
  $\ddot{\delta}_k + (4/3t)\dot{\delta}_k - (2/3t^2)\delta_k = 0 \rightarrow \delta \propto t^n$, with $n = 2/3$, $n = -1$.
- $\delta_k \propto a(t) \propto t^{2/3}$ **in matter dominated era**
- **Power law growth NOT exponential growth**
- **Need finite seed fluctuations, which must be seen in CMBR**

Damping of perturbations

- In radiation dominated era expansion damping too strong
  $\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G\bar{\rho}_m\delta_m = 0$, (H dominated by $\bar{\rho}_{rad}$)

- $\ddot{\delta}_m + (1/t)\dot{\delta}_m \approx 0 \Rightarrow \delta_m \propto \ln(t) \propto \ln(a)$: Grows only logarithmically during radiation domination. Potential decays.

- Introduces a feature in density power spectrum at scale which enters Hubble radius at Radiation matter density equality

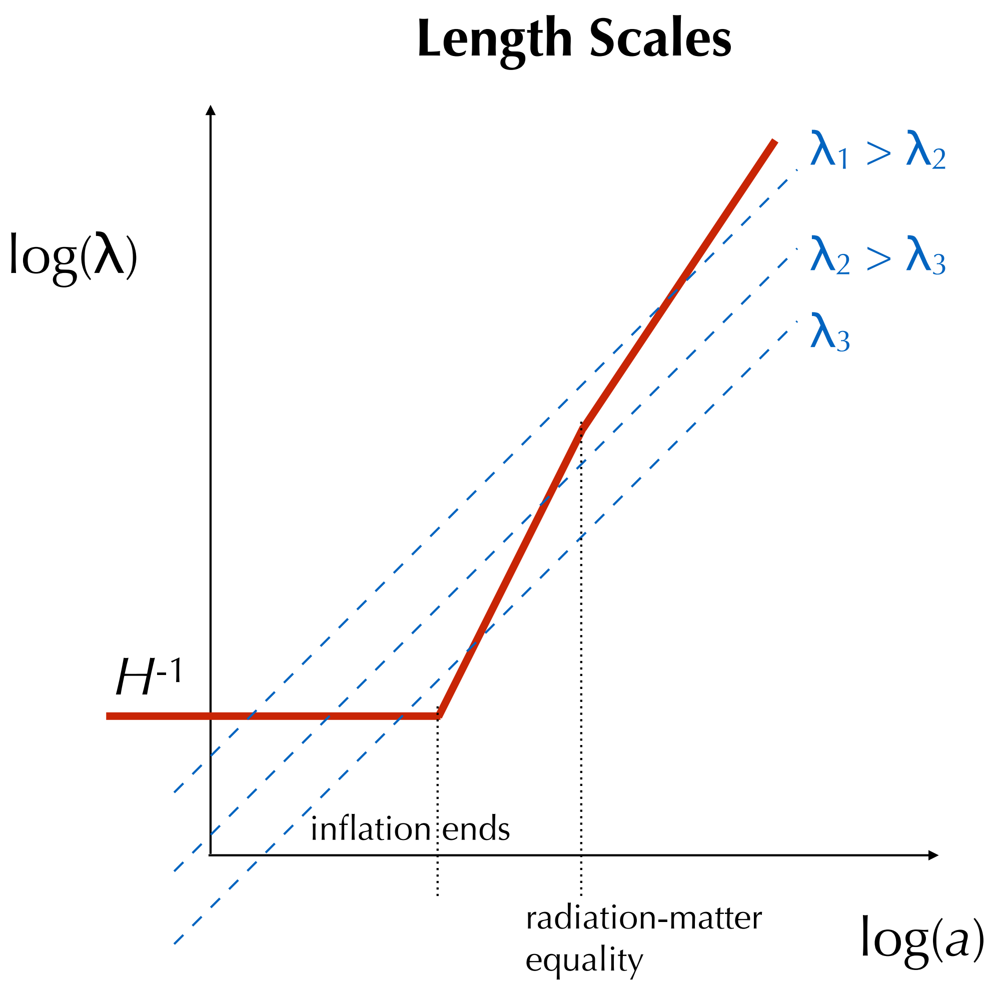
- Also if DM has large random velocities, "Free streaming" of DM smooths density perturbations on small scales

- Baryon-photon perturbation oscillates as sound wave, small scales damped by radiative viscosity, fall into DM potential after recombination and catch up with δ_m.

- At late time DE dominates universe expansion $\rightarrow$ expansion damping freezes growth of δ_m

Inflation and perturbations

Courtesy Prof. Aseem Paranjape



Inflation and Perturbations

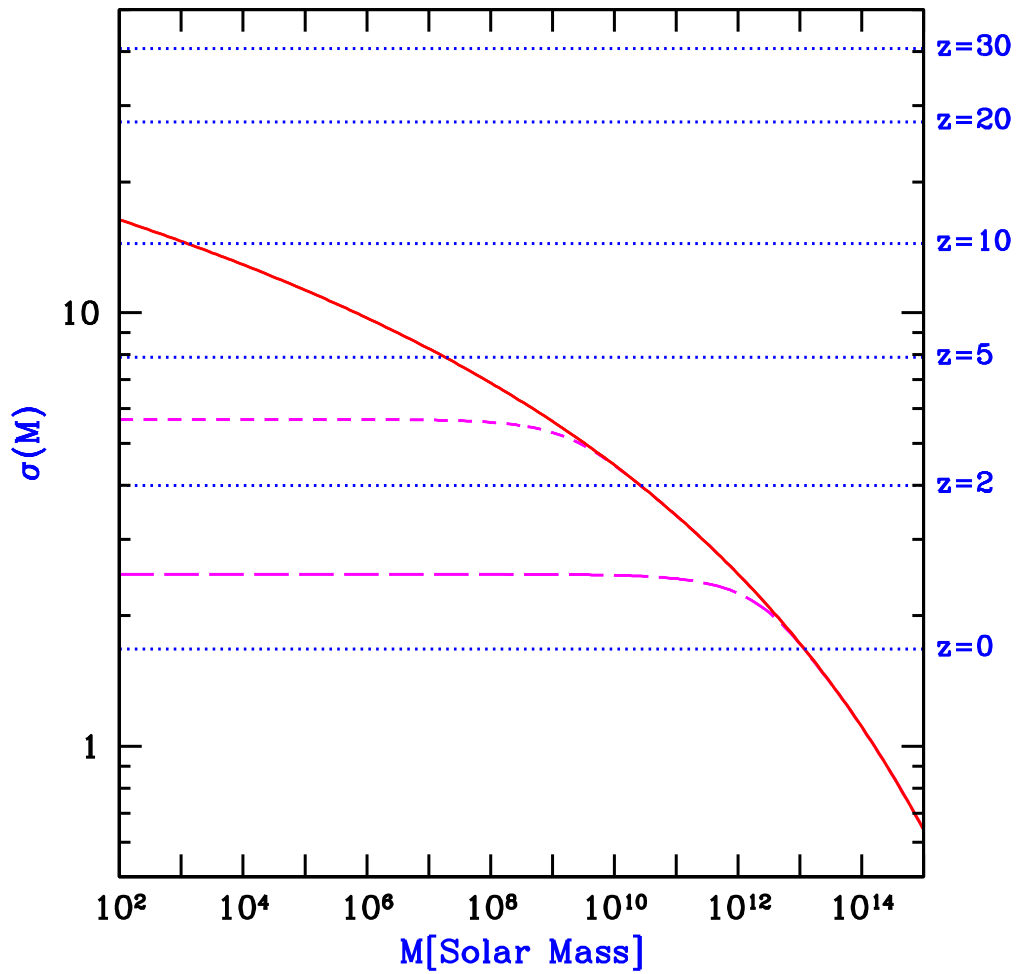
- Define Hubble radius $d_H = c/H(t)$, compare with any length scale $\lambda = a(t)\lambda_0$.
- Matter dominated, $d_H \propto t \propto a(t)^{3/2}$. Radiation dominated $d_H \propto t \propto a^2$ and inflationary era $a(t) \propto e^{H_0 t}$ and so $d_H \propto 1/H_0$.
- Any $\lambda < d_H$ at present, becomes larger than d_H in past. And will again be smaller than d_H during Inflation.
- Curvature fluctuations arise as quantum fluctuations during the inflationary era and then transit to classical density fluctuations as any scale exits the Hubble radius during inflationary era.
- 'Curvature' flictuations almost scale independent at Hubble exit, do not change outside d_H, are then independent of scale again at Hubble re-entry.

The transfer function

- **Each mode re-enters Hubble radius when Physical waveleghth a/k is smaller than Hubble radius H^{-1}: $k/(aH) > 1$ or $k\eta > 1$ (Conformal time, η defined by $dt = ad\eta$)**
- **Larger wavelengths enter at later epochs (conformal times η).**
- **In RD era, $a \propto t^{1/2} \propto \eta$, scale factor at entry $a_e \propto \eta_e \propto 1/k$.**
- **For entry in RD era, perturbation amplitude at present is** $\delta_m(a_0) = \delta_e \ln(a_{eq}/a_e)(a_0/a_{eq}) \propto \delta_e(a_0/a_{eq})\ln(k/k_{eq}) \to$ $\delta_m(a_0) \propto \delta_e(a_0/a_{eq})\ln(M_{eq}/M)$, **for $M < M_{eq}$.**
- **In MD era, $a \propto t^{2/3} \propto \eta^2$, scale factor at entry $a_e \propto \eta_e^2 \propto 1/k^2$**
- $\delta_m(a_0) = \delta_e(a_0/a_e) \propto \delta_e(a_0/a_{eq})(k/k_{eq})^2 \propto \delta_e(a_0/a_{eq})(M_{eq}/M)^{2/3}$
- **For a scale invariant spectrum δ_e is constant at Hubble entry:** **Harrison-Zeldovich spectrum** $\phi_k = 4\pi G\bar{\rho}(a/k)^2\delta_k \propto (H/(k/a))\delta_k \propto \delta_k$, when $k/a = H$

Fluctuation amplitude today

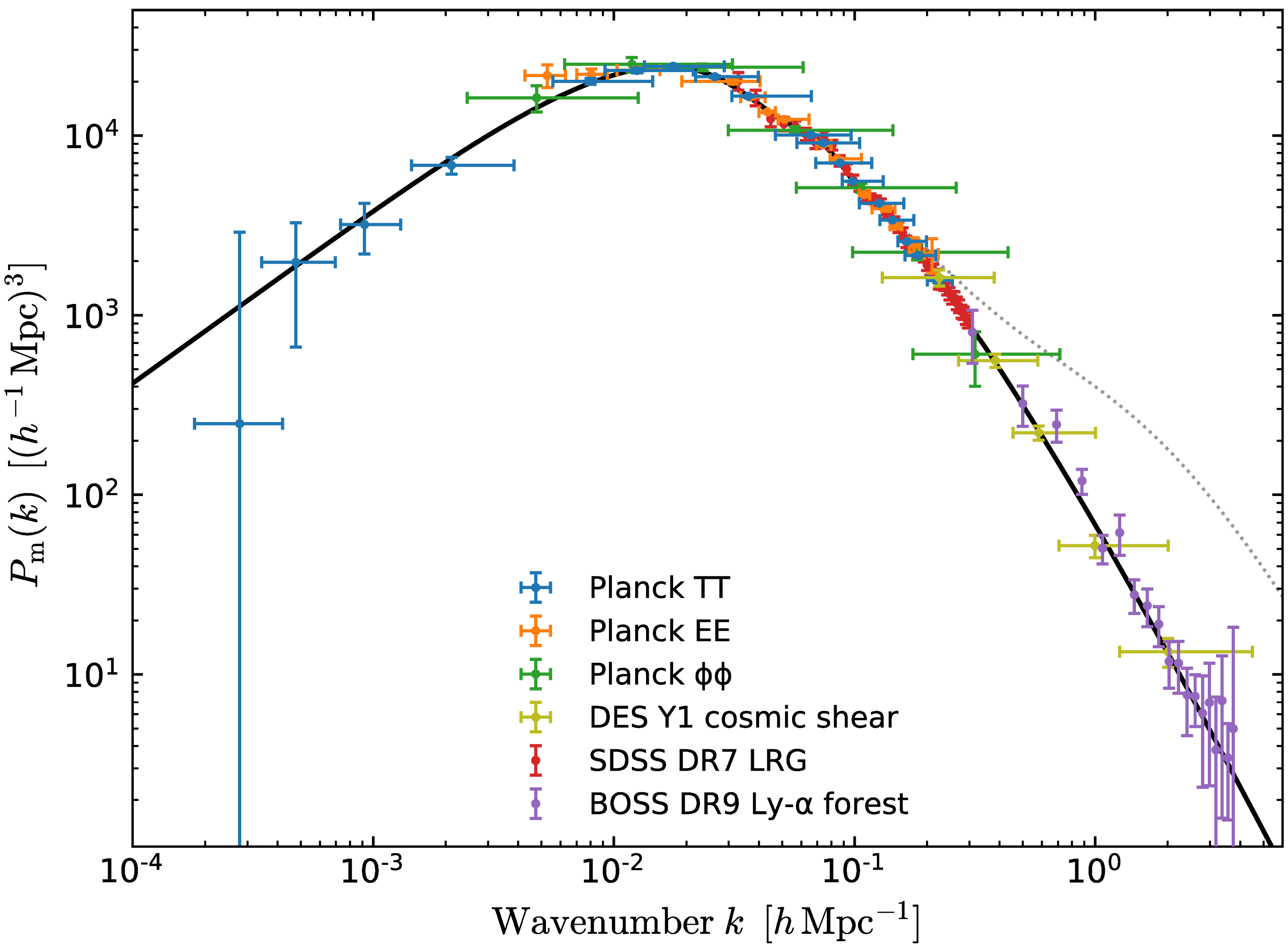
δ_m **has Gaussian PDF,** $\langle \delta_m \rangle = 0$ **and** $\langle \delta^2(M) \rangle = \sigma^2(M)$**.**



Barkana and Loeb, 2001

Probing Power spectrum today

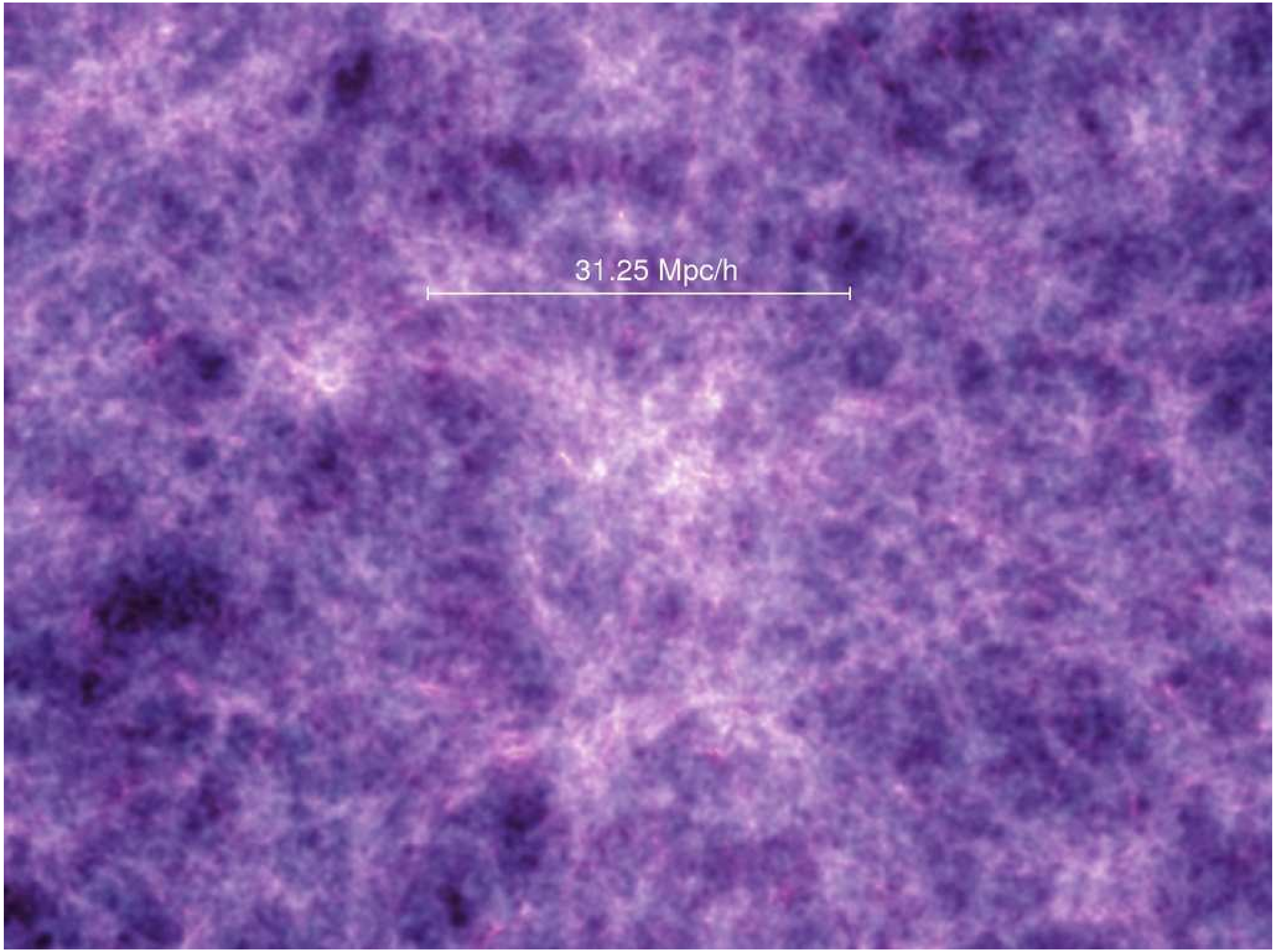
Planck 2018 results I, A&A, 2019



$$(k^3 P(k)/2\pi^2 = \delta_m^2)$$

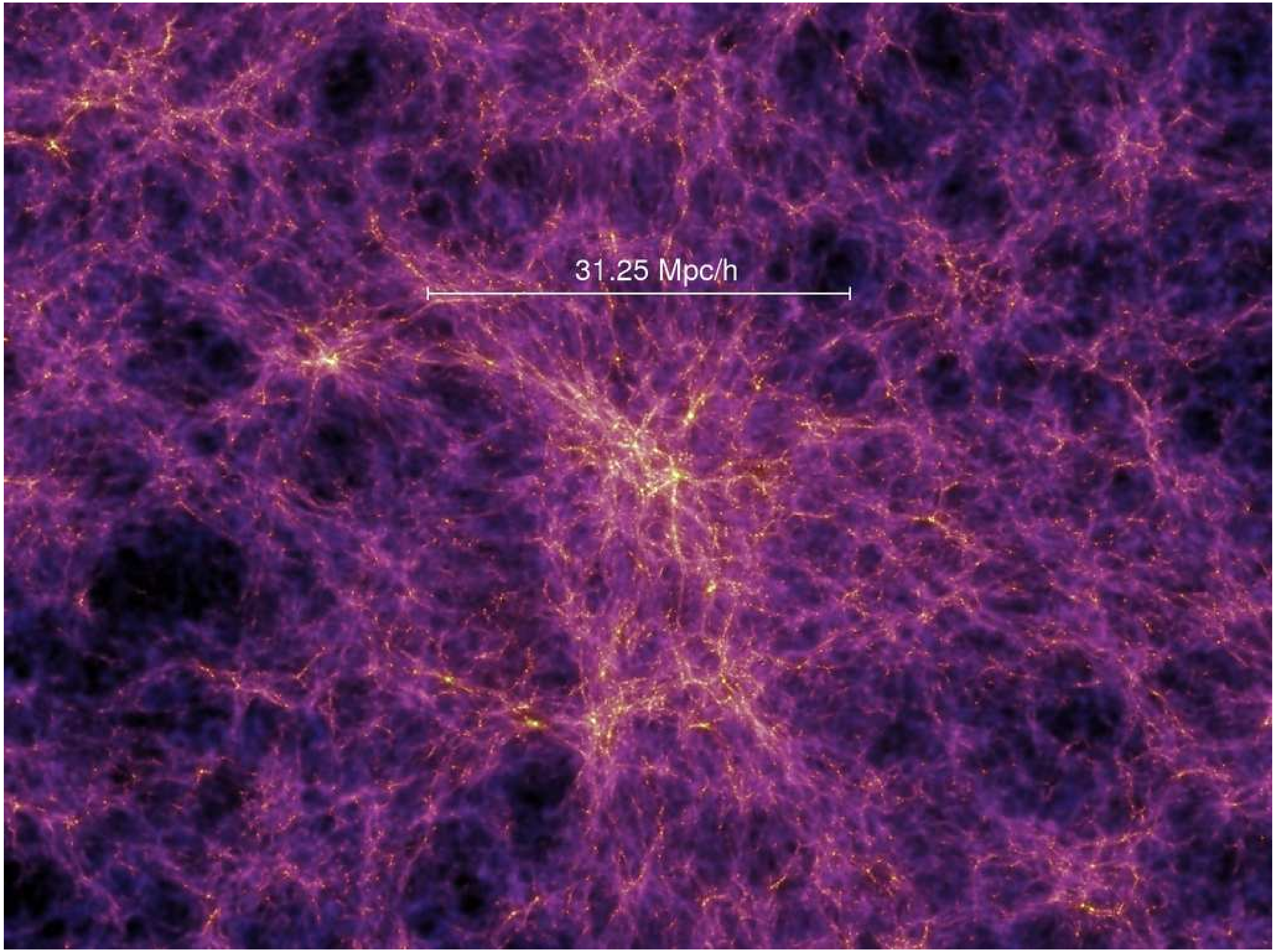
Millenium Simulation: Springel/White

Redshift $= 18.3$ **or** $t = 0.21$ **Gyr,** $15h^{-1}$ **Mpc thick slice**



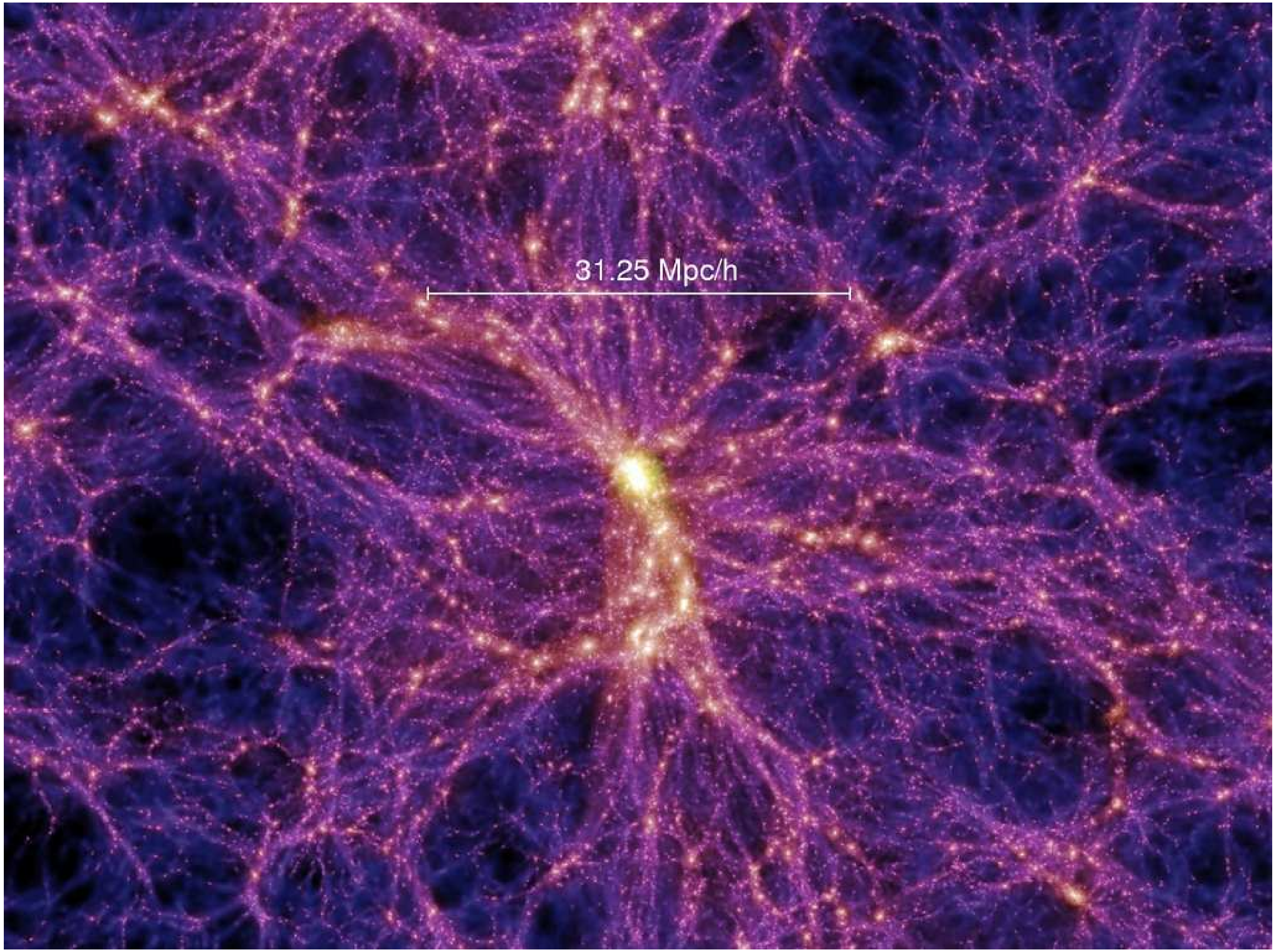
Structure formation: Millenium Simulation

Redshift $= 5.7$ **or** $t = 1$ **Gyr**



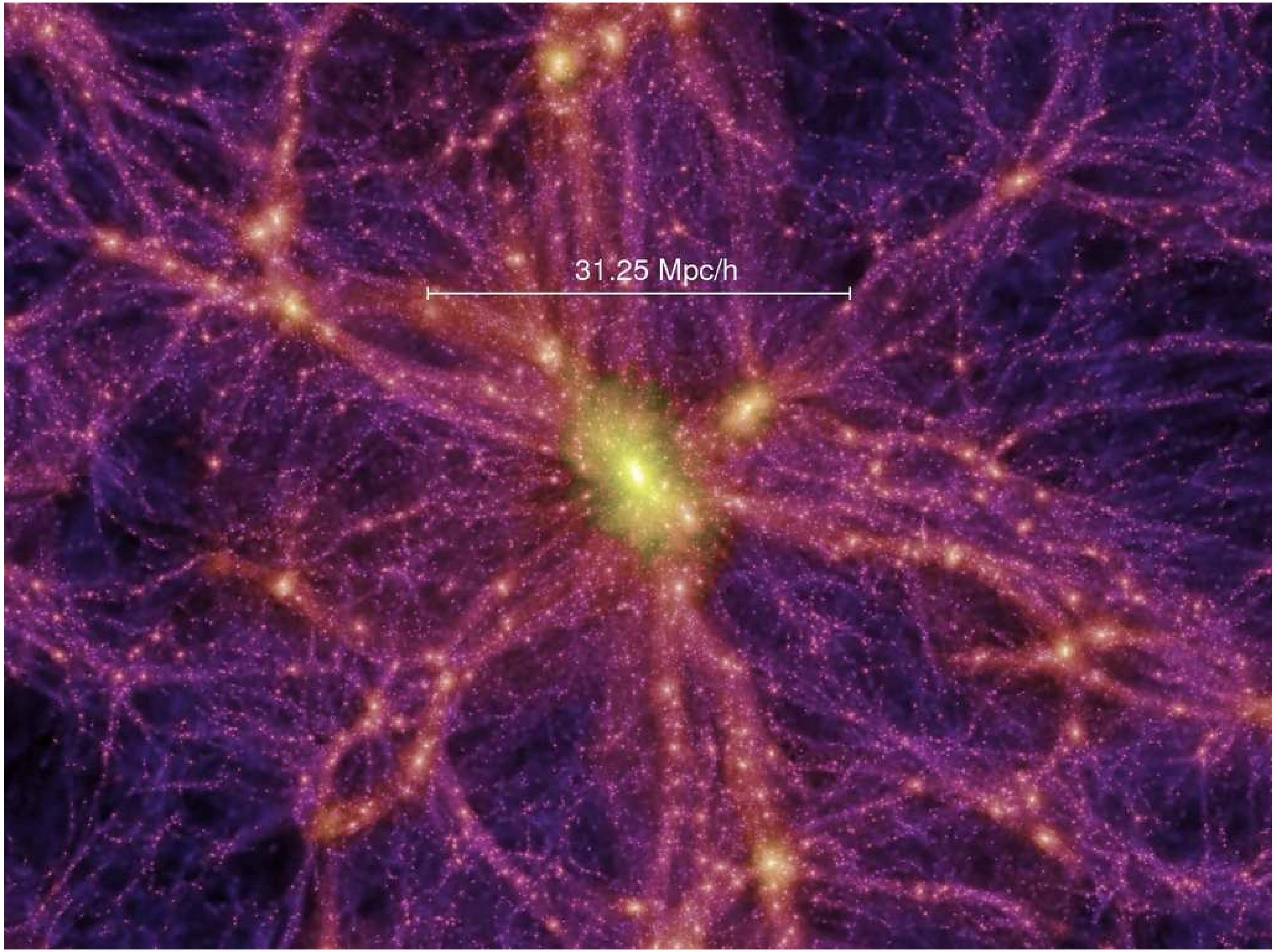
Structure formation: Millenium Simulation

Redshift $= 1.4$ **or** $t = 4.7$ **Gyr**



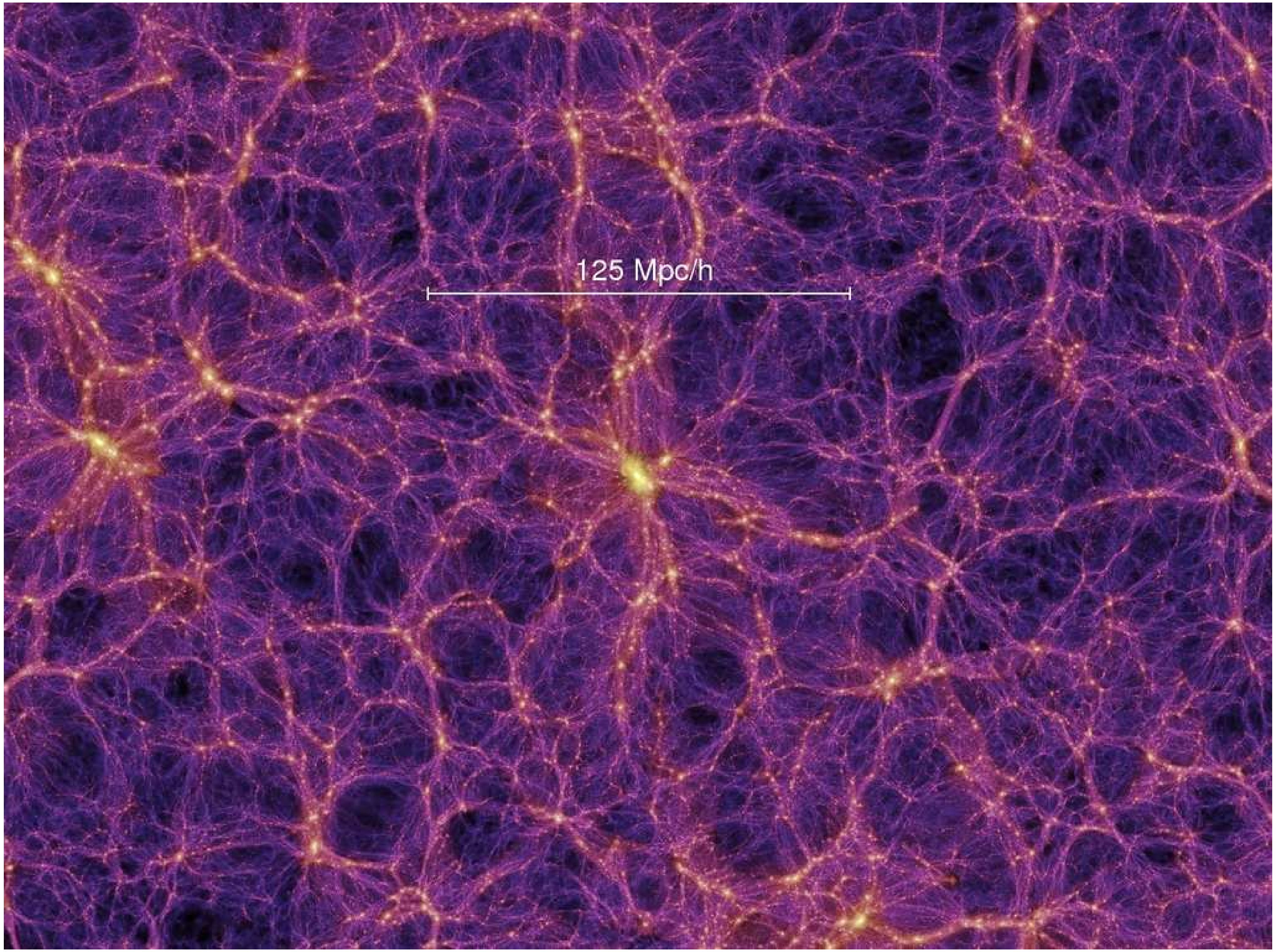
Structure formation: Millenium Simulation

Redshift $= 0$ **or** $t = 13.6$ **Gyr**



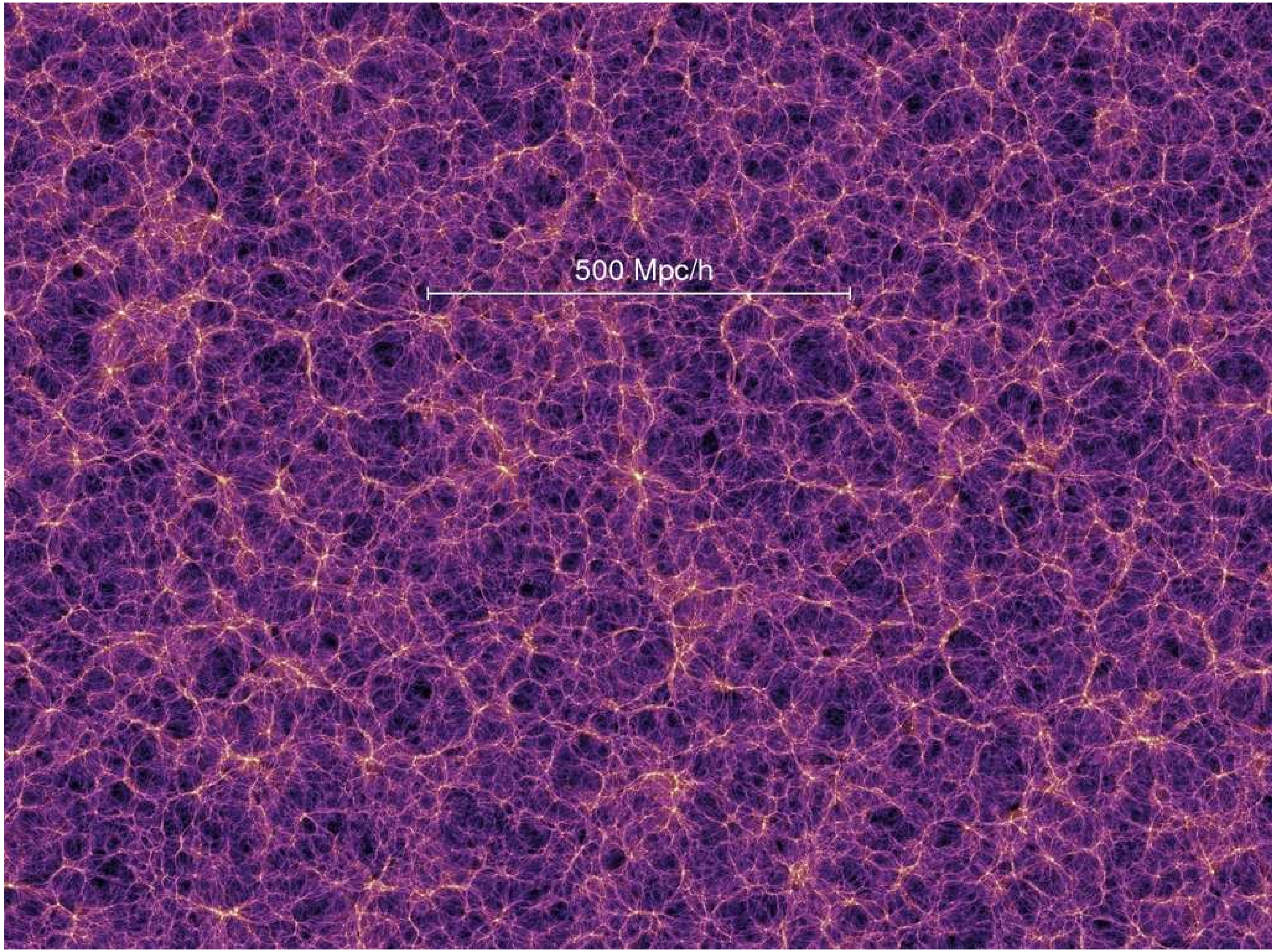
Structure formation: Millenium Simulation

Redshift $= 0$ **or** $t = 13.6$ **Gyr**



Structure formation: Millenium Simulation

Redshift $= 0$ **or** $t = 13.6$ **Gyr**

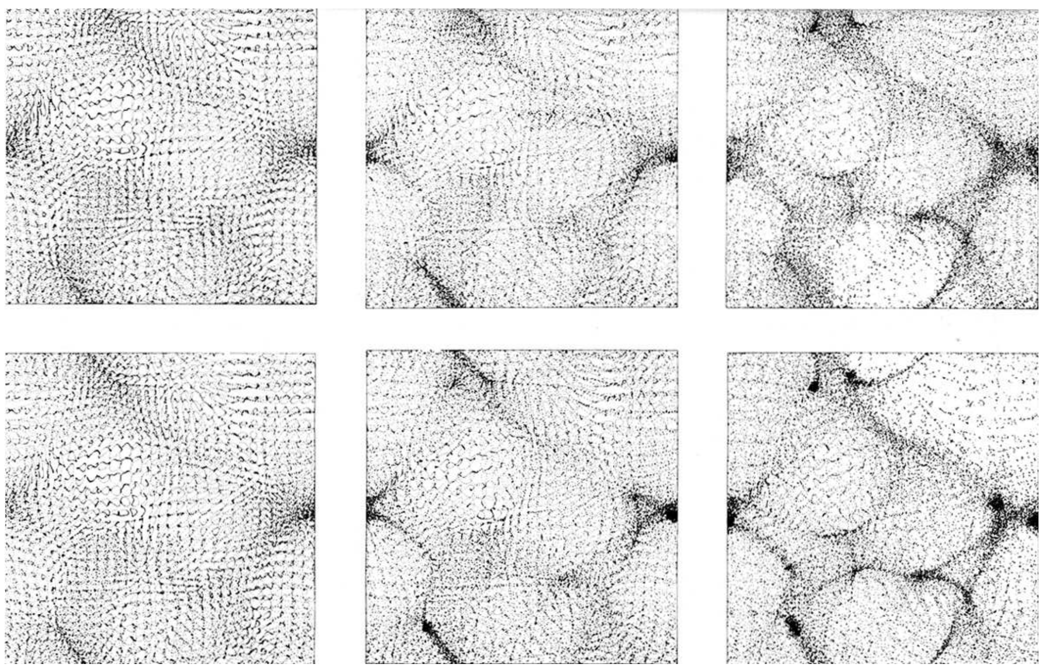


http://www.mpa-garching.mpg.de/galform/virgo/millennium/

Zeldovich approximation

$$\mathbf{r}(t) = a(t)\,\mathbf{x}(t) = a(t)\left[\mathbf{q} + D(t)\mathbf{f}(\mathbf{q})\right], \quad \text{where} \quad D(t)\nabla\cdot\mathbf{f} = \delta$$

$$\rho(\mathbf{r},t) = \frac{\bar{\rho}}{Det(\partial r_i/\partial q_j)} = \frac{\bar{\rho}/a^3}{Det(\partial x_i/\partial q_j)} = \frac{\bar{\rho}/a^3}{Det(\delta_{ij} + D(t)\partial f_i/\partial q_j)}$$

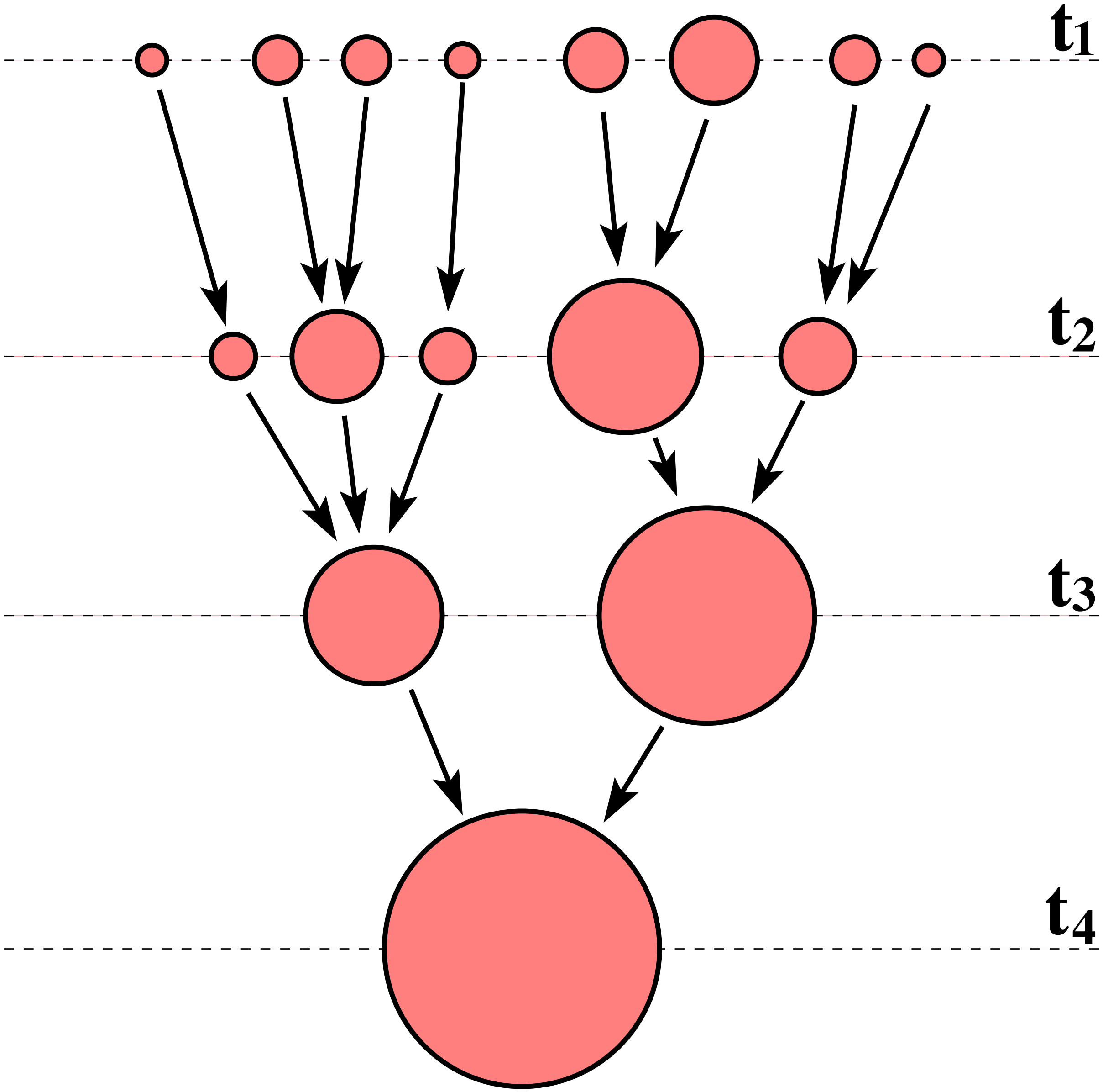


http://ned.ipac.caltech.edu/level5/March02/Efstathiou/

Some issues in Galaxy formation

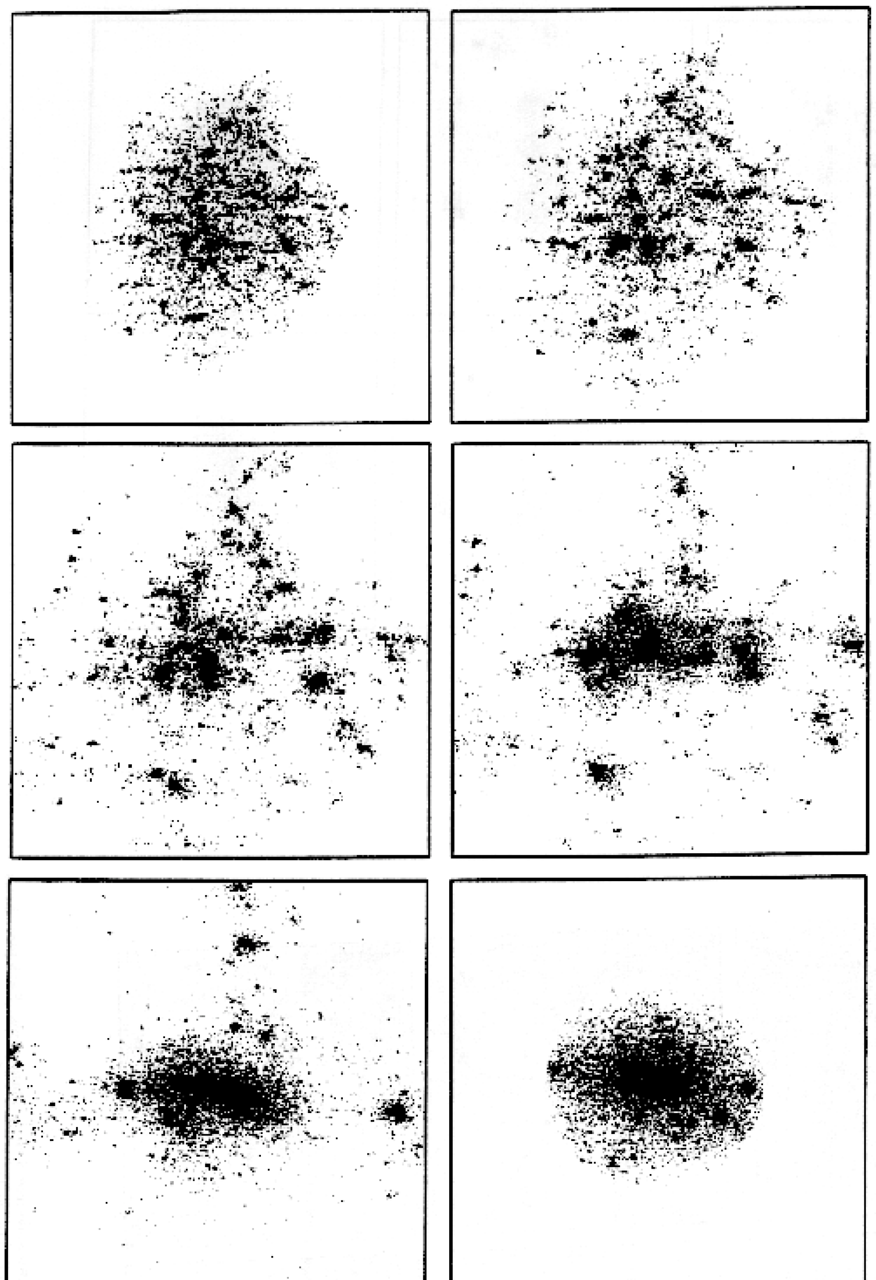
- Formation of dark matter halos.
- Cooling of Gas and galactic masses.
- Collapse/accretion mode: Hot versus Cold mode
- Star formation: IMF, Rate, Sensitivity to Physical conditions
- Feedback from Stars: On star/galaxy formation and IGM
- AGN co-evolution with galaxies and feedback
- The role of evolving magnetic fields and cosmic rays
- Formation of disk and elliptical galaxies
- Applications to understanding high-z galaxies; abundance/clustering

Merger tree



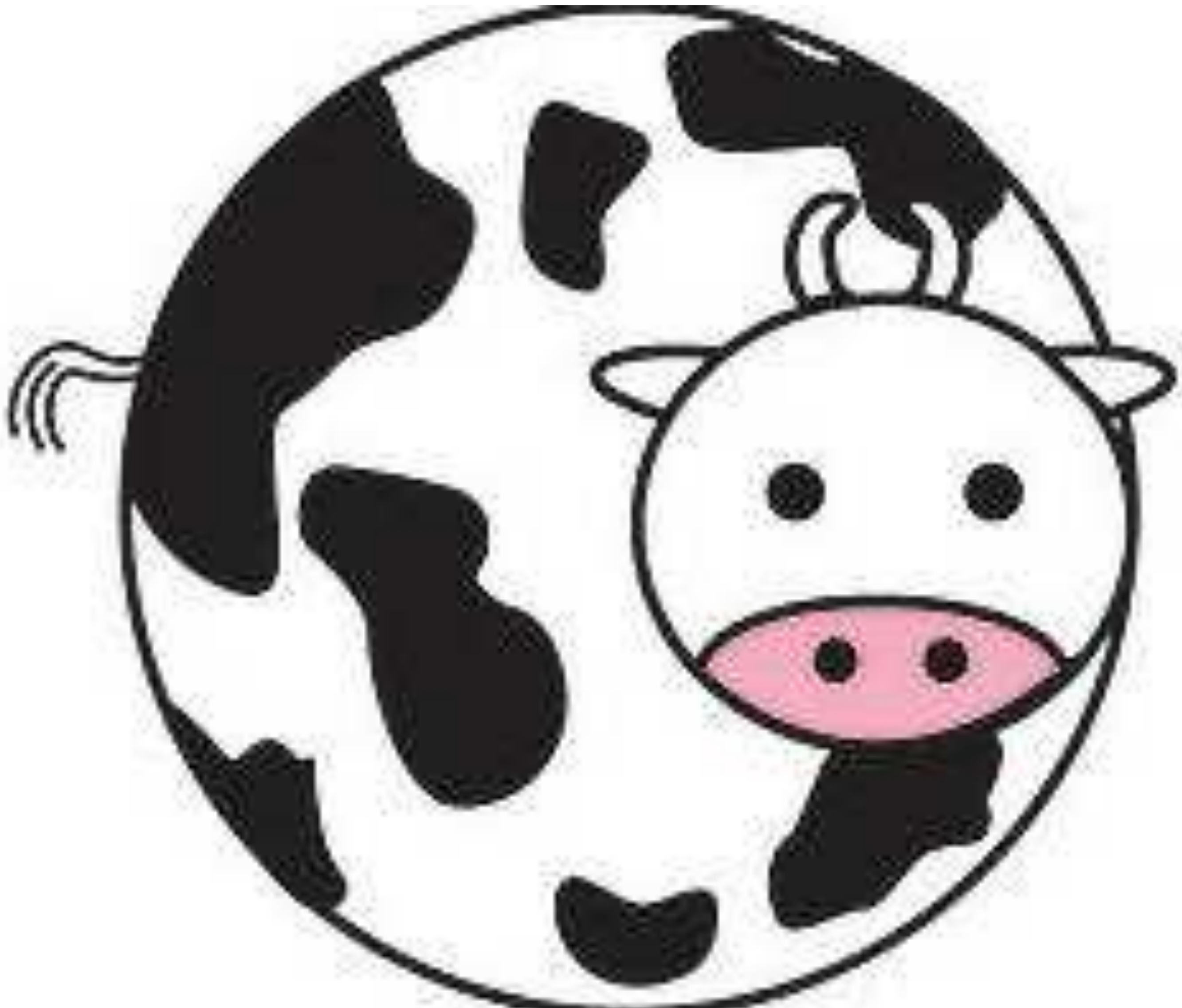
Mo, Van den Bosch, White

Dark matter halo formation



Spherical (cow) Collapse Model

Model collapsing overdense region as a sphere



Spherical Model for nonlinear evolution

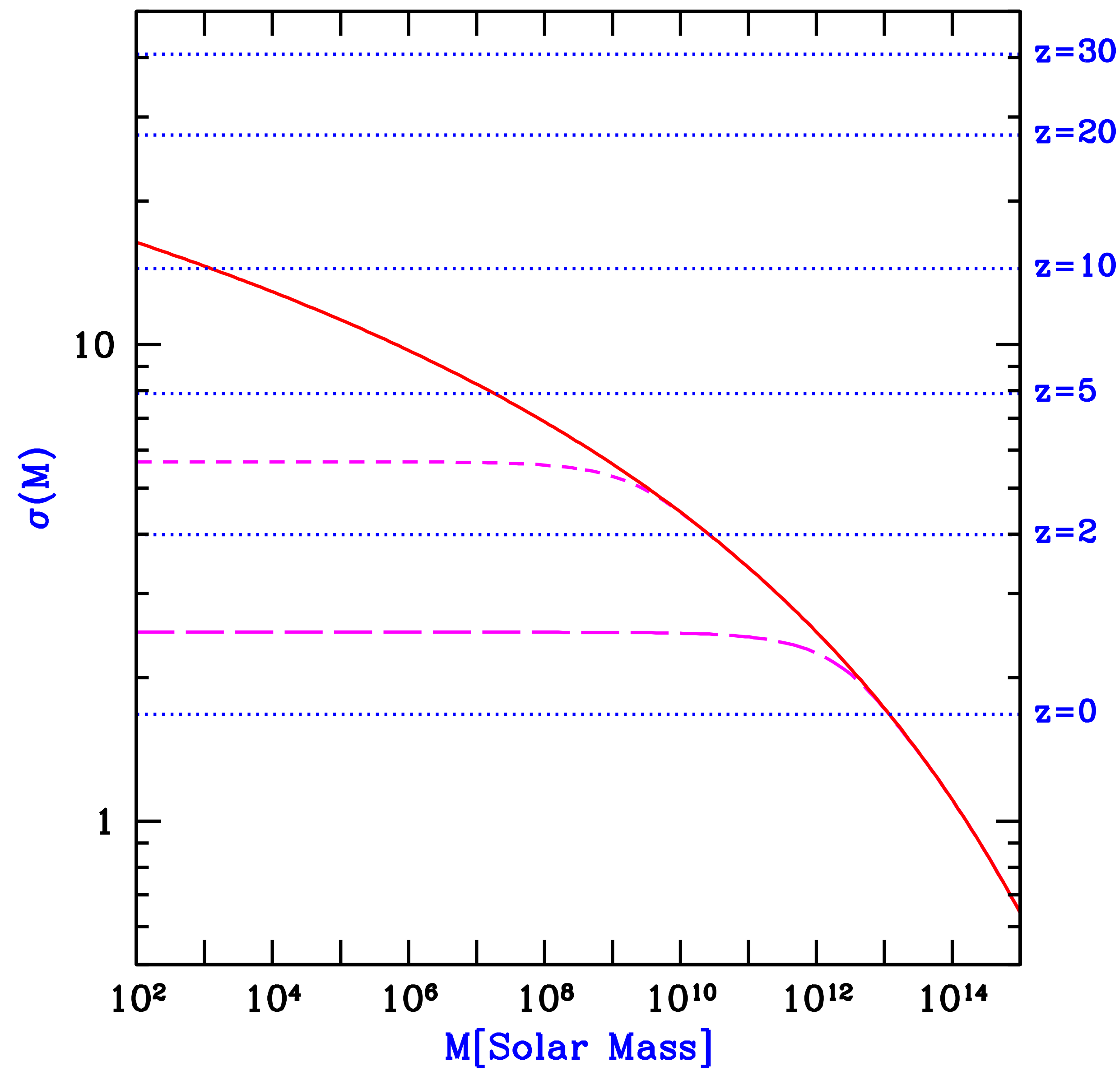
- **Spherical collapse model:** $\ddot{r} = -GM/r^2$**. Multiply both sides by** $\dot{r}$ **and integrate to get** $\dot{r}^2/2 - GM/r = -E$**. Integrate** $\int \frac{dr}{\sqrt{2(GM/r-E)}} = \int dt$
- **by substituting** $r = 2A\sin^2(\theta/2) = A(1-\cos\theta)$**, to get**

$$r = A(1-\cos\theta), \quad t = B(\theta - \sin\theta), \quad A^3 = GMB^2$$

$$1+\delta(t) = \frac{\bar{\rho}}{\rho_b(t)} = \frac{(3M/4\pi r^3)}{(1/6\pi G t^2)} = \frac{9(\theta-\sin\theta)^2}{2(1-\cos\theta)^3}$$

- **The sphere expands, turns around at** $\theta = \pi$**, when** $1+\delta_m \approx 5.6$**,** $\delta_0 = 1.062(1+z_m)$**, collapses at** $\theta = 2\pi$**, when** $\delta_0 = 1.686(1+z_{coll})$**.**
- **The sphere settles down to about** $1/2$ **the turn around radius by which time the density contrast is** $\bar{\rho}/\rho_b \sim 5.6 \times 8 \times 4 \sim 180$**.**
- $\delta_0(M)$ **is a stochastic random variable with dispersion** $\sigma(M)$

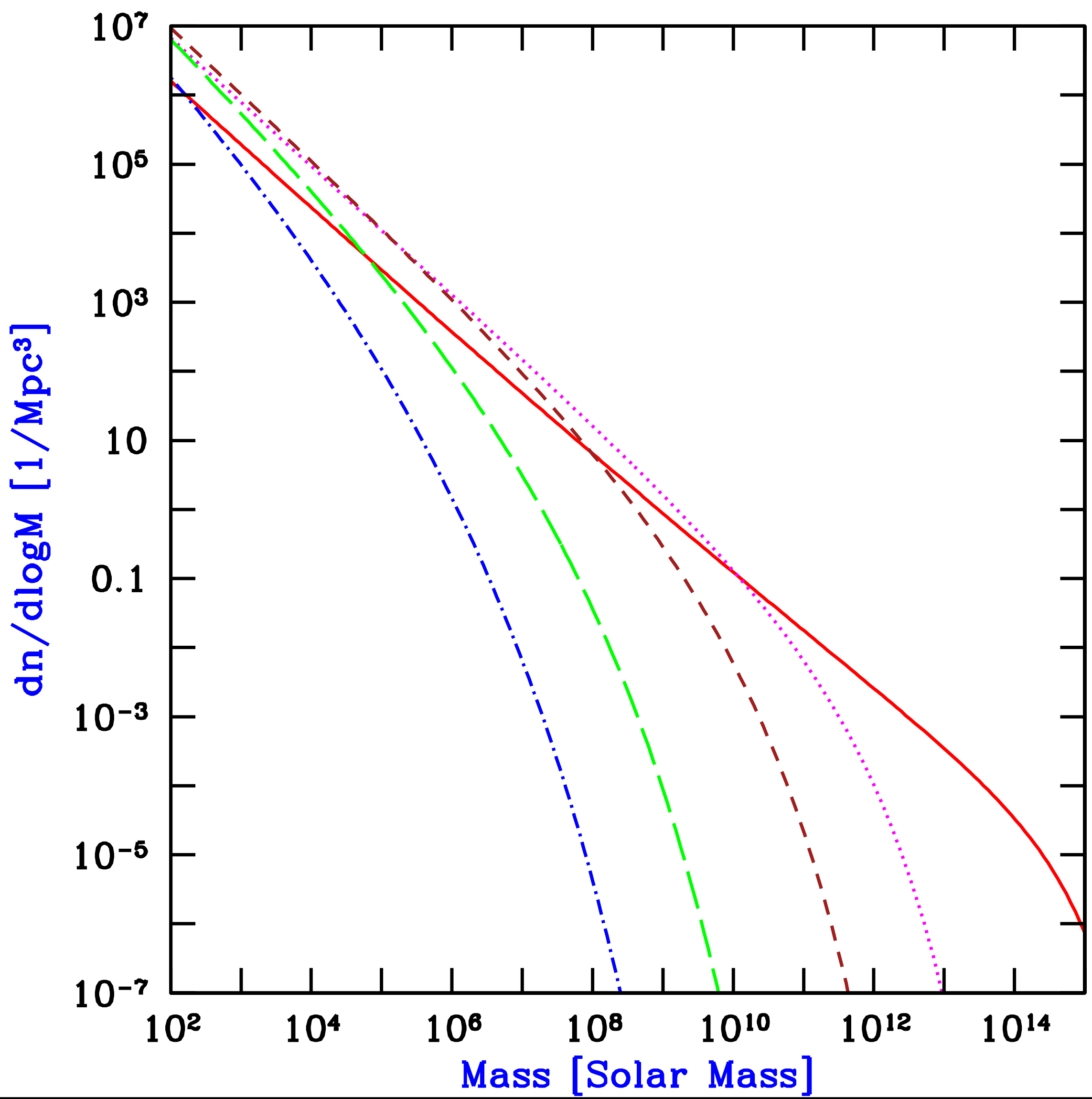
Galaxy formation



Barkana and Loeb, PhR, 2001.

Galaxy formation

Halo mass function at z =0, 5, 10, 20, 30.



Barkana and Loeb, PhR, 2001

Spherical model: Numbers

- **Using Virial them** $2T + U = 0$, $T + U = E \rightarrow U/2 = E$, $GM^2/2r_{vir} = GM^2/r_m \rightarrow r_{vir} = r_m/2$, $Mv^2 \approx GM^2/r_{vir}$, $T_{vir} = \mu v^2/3k_B$, $\bar{\rho} = 8\rho_m = 44.8\rho_b(t_m) \approx 180\rho_b(t_{coll})$

$$r_{\rm vir} = 80.4 \left(\frac{M}{10^{12}\ h^{-1}\ M_\odot}\right)^{1/3} \left(\frac{1+z}{3}\right)^{-1} h_{0.7}^{-1}{\rm kpc}$$

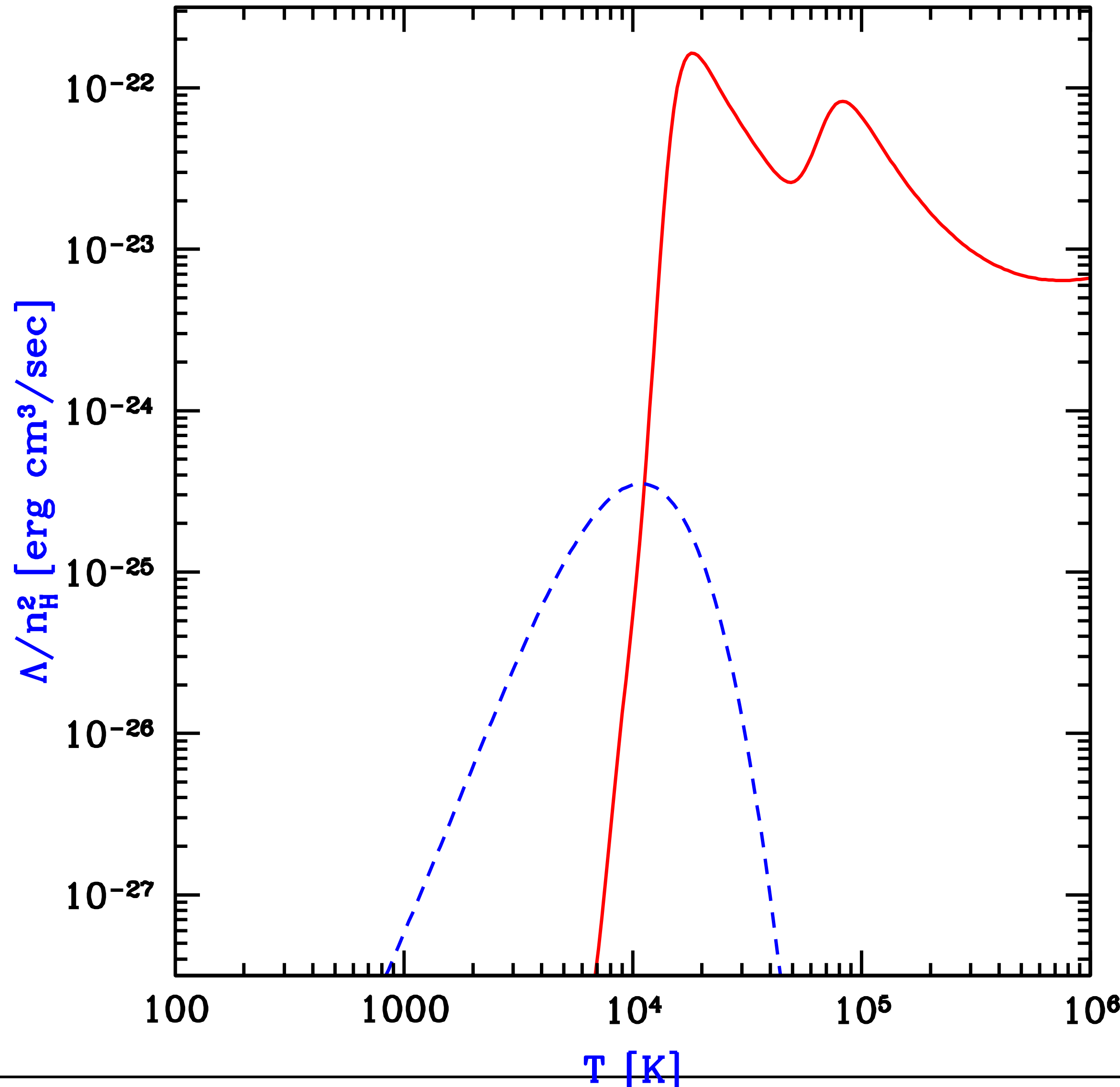
$$V_c = \left(\frac{GM}{r_{\rm vir}}\right)^{1/2} = 276.1 \left(\frac{M}{10^{12}\ h^{-1}\ M_\odot}\right)^{1/3} \left(\frac{1+z}{3}\right)^{1/2} {\rm km\ s}^{-1}$$

$$T_{\rm vir} = \frac{\mu m_p V_c^2}{2k_B} = 2.76 \times 10^6 \left(\frac{\mu}{0.6}\right) \left(\frac{M}{10^{12}\ h^{-1}\ M_\odot}\right)^{2/3} \left(\frac{1+z}{3}\right) {\rm K}$$

- **Heated gas cools by Brehmstraulung, Hydrogen/Helium recombination lines, compton cooling and possibly molecular line cooling**
- **Visible galaxy mass set by ability to cool within dynamical timescale?**

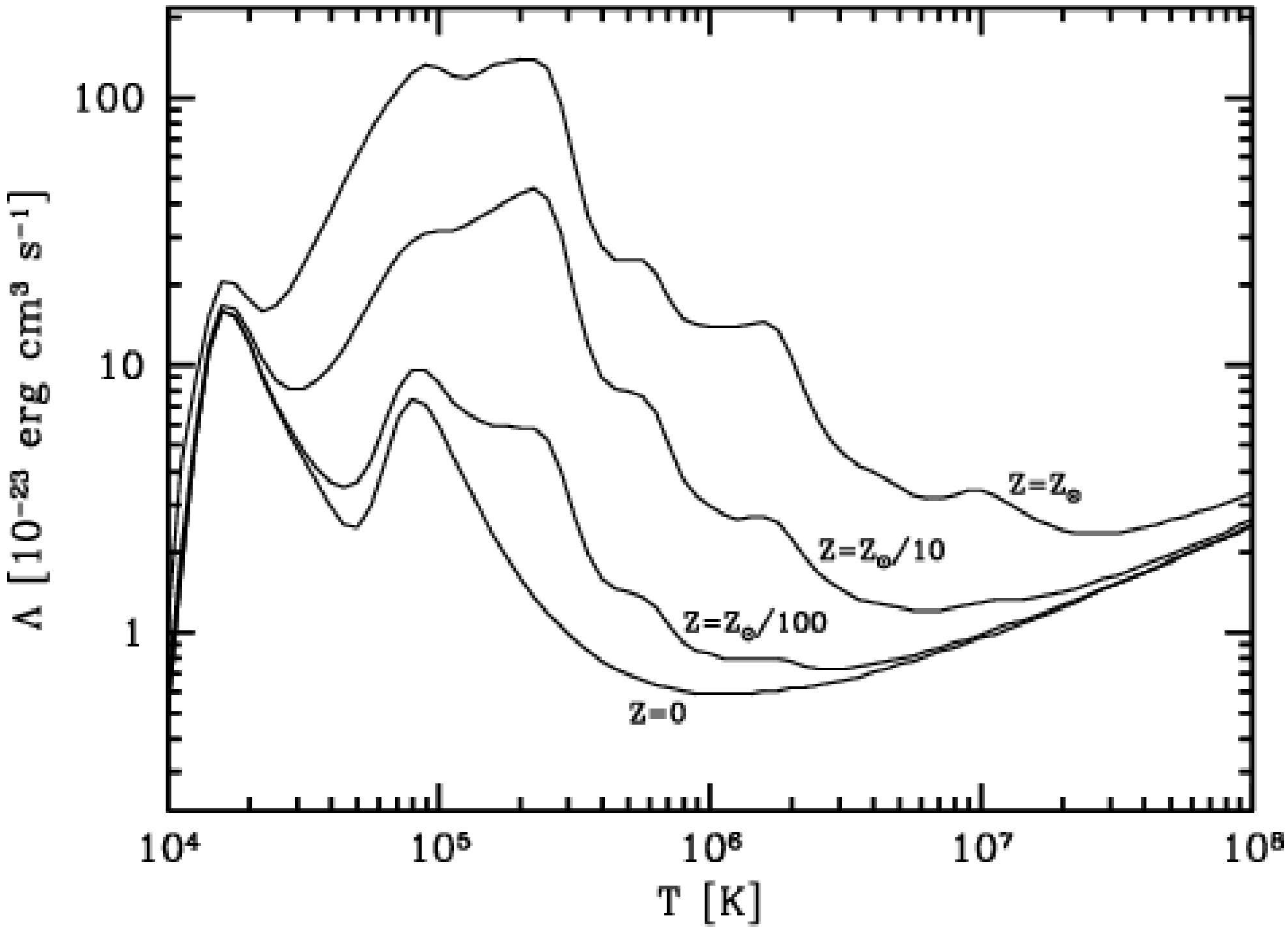
Galaxy formation

Visible galaxy scale set by Cooling



$n(H_2) = 10^{-3} n(H)$; Barkana and Loeb, PhR, 2001

Cooling of gas



Mo, Van Den Bosch, White, 2010

Dynamical vs cooling time

$$\Lambda(T,\rho) \approx \left[A_B T^{1/2} + A_R T^{-1/2}\right] \rho^2 erg\ s^{-1}\ cm^{-3}$$

- **Assume only recombination cooling**

$$t_{cool} = \frac{3\rho k_B T}{\mu \Lambda(\rho, T)} \approx 2.6{\times}10^9 \left(\frac{f_b}{0.1}\right)^{-1} \left(\frac{M}{10^{12} M_\odot}\right)^{1/2} \left(\frac{r_m}{200 kpc}\right)^{3/2} \ \mathrm{yr}$$

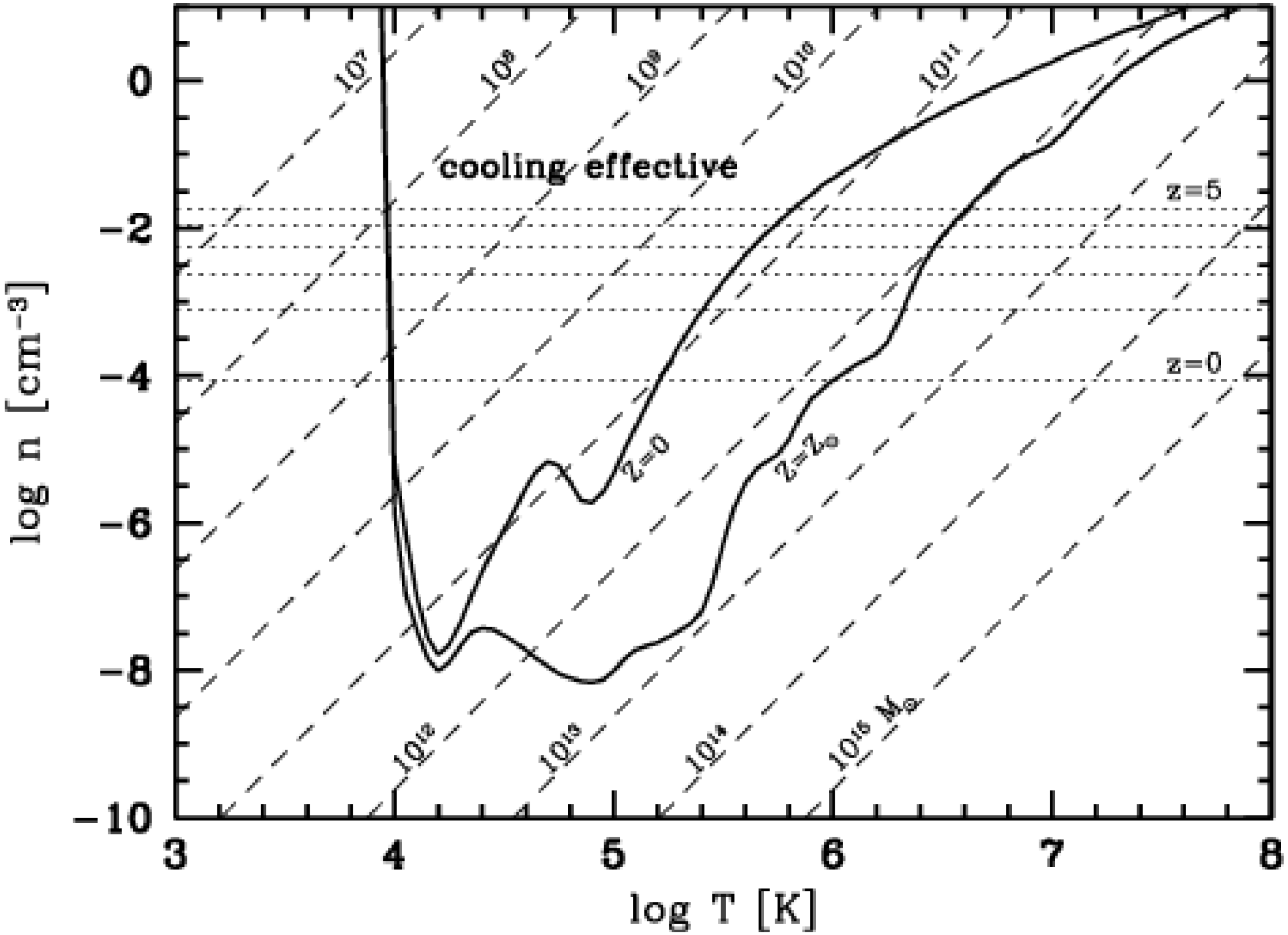
$$t_{dyn} = \frac{t_{coll}}{2} \approx 1.5 \times 10^9 \left(\frac{M}{10^{12} M_\odot}\right)^{-1/2} \left(\frac{r_m}{200 kpc}\right)^{3/2} \ \mathrm{yr}$$

$$\frac{t_{cool}}{t_{dyn}} \approx 1.7 \left(\frac{f_b}{0.1}\right)^{-1} \left(\frac{M}{10^{12} M_\odot}\right)$$

- **Cooling efficient for galaxy scale masses** $\sim 10^{12} M_\odot$
- $GM/r = 3k_B T/\mu$, $M = 4\pi\rho r^3/3 \rightarrow M_{gas} \propto T^{3/2} n^{-1/2}$

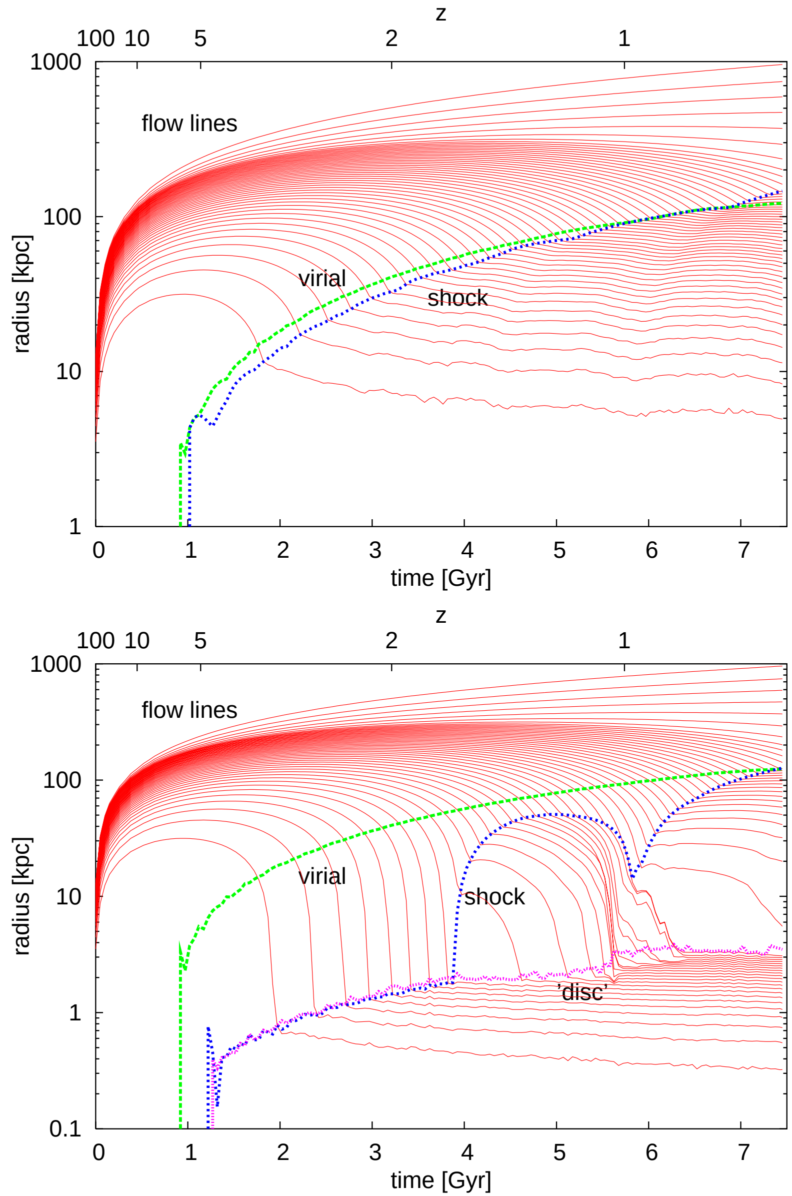
Cooling diagram

solid: $t_{cool} = t_{dyn}$, **dashed:** $M_{gas} = const$, **dotted:** $\delta(z) = 200$



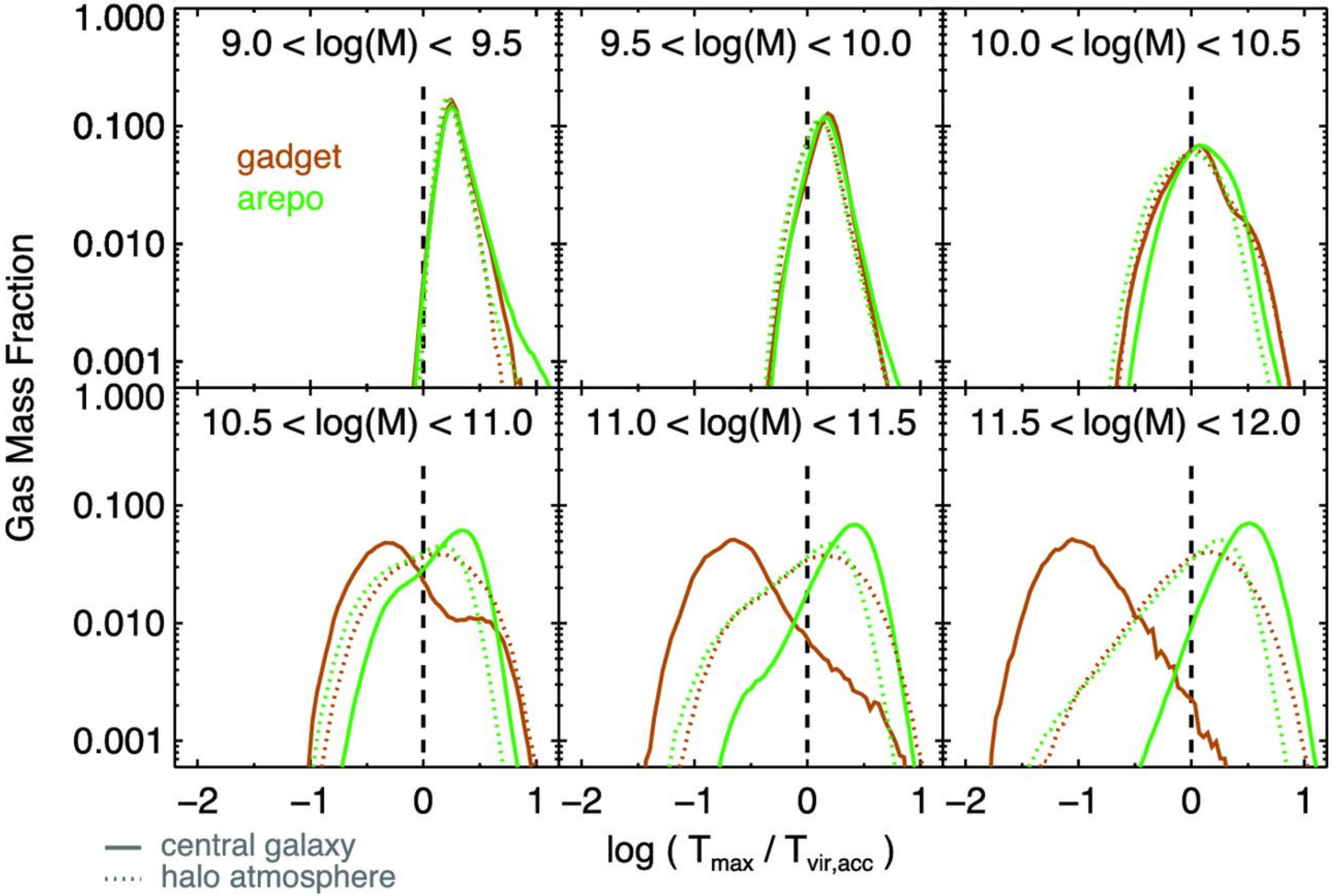
Mo, Van Den Bosch, White, 2010

Accretion mode in Galaxy formation



- Birnboim and Dekel, 2003
- Top: adiabatic collapse; bottom: with cooling
- small/large galaxies predominantly cold/hot mode accretion
- Dividing line where $t_{cool} < t_{dyn}$

Cold versus hot mode

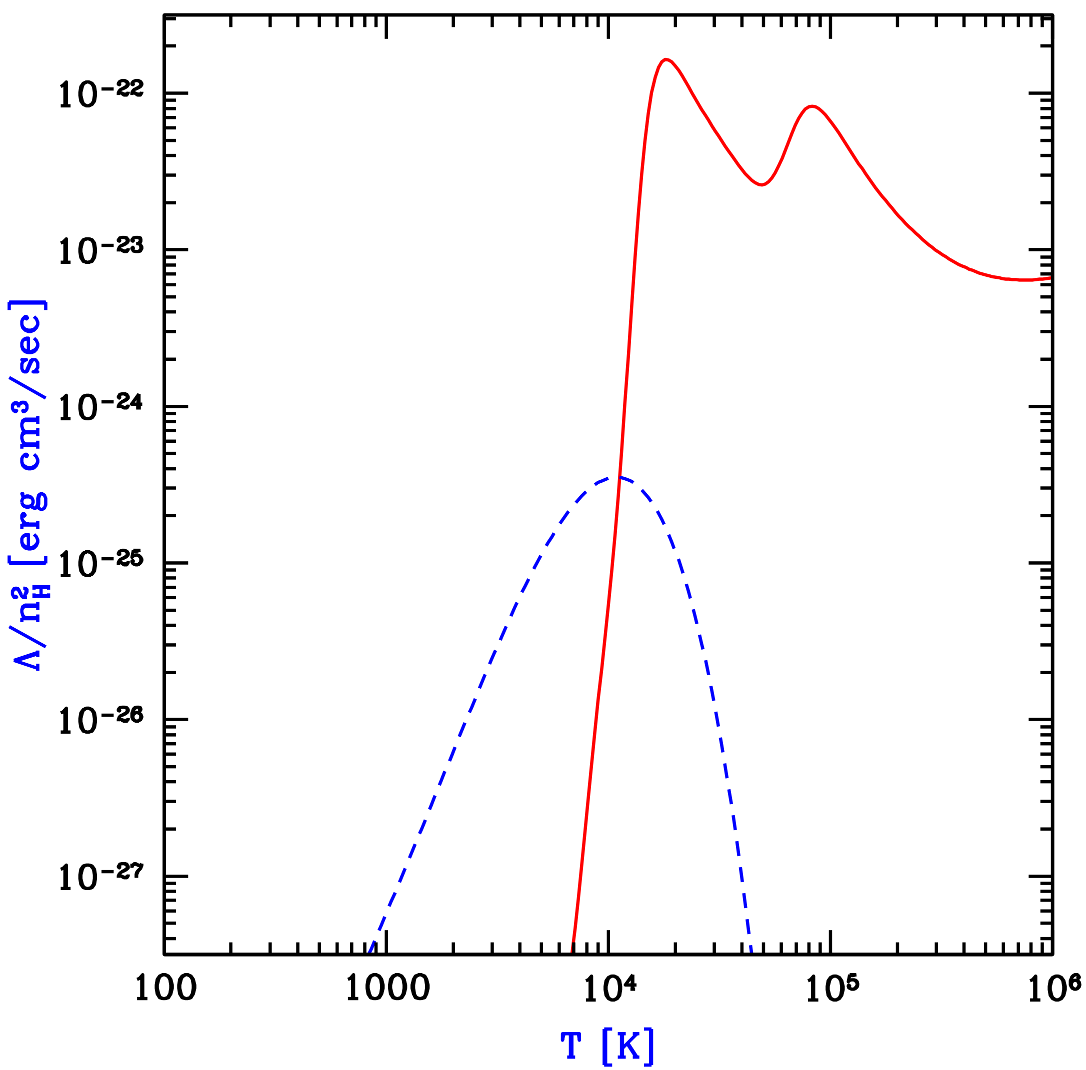


Nelson et. al,MNRAS, 2013

Formation of the first stars

- **Initial and physical conditions possibly simpler for first star formation**
- **Structures grow heirarchically – While Jeans mass goes down**
- **First nonlinear halos collapse and capture gas at** $z \sim 20 - 30$ **and have** $M \sim 10^6 M_\odot$, $T_{vir} < 10^4 K$ **(No metals).**
- **No atomic cooling; need** H_2 **molecule formation to cool**
- **Catalysed by free electrons:** $H + e^- \rightarrow H^- + \gamma$;
  $H^- + H \rightarrow H_2 + e^-$
- H_2 **cooling by collisional excitation of rotational levels** $+$ **radiative decay**
- **First stars massive; their radiative, chemical feedback kills this mode!**
- **Turbulent collapse to form first stars can generate magnetic fields by super exponential amplification!** (Irshad et al 26, PRL)

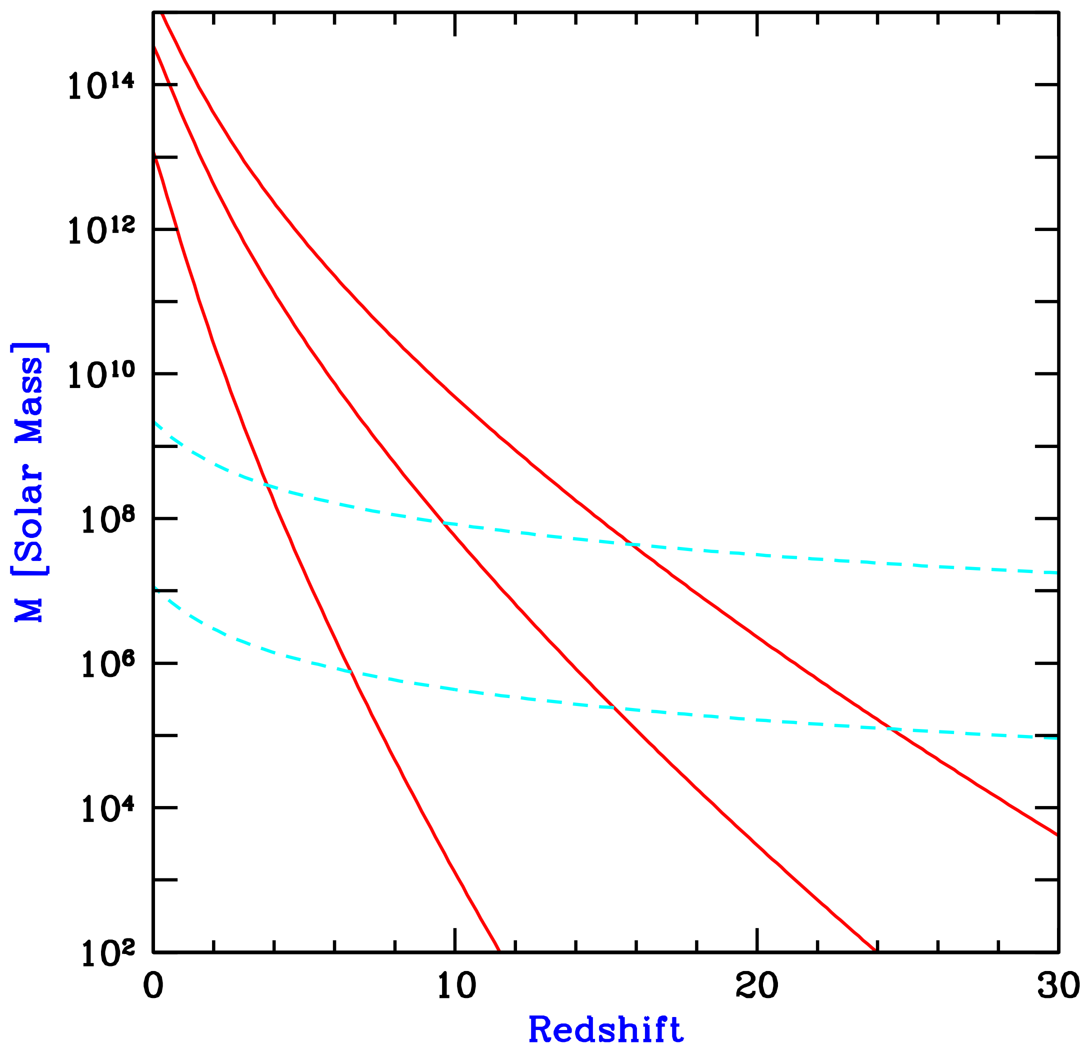
Cooling of primordial gas



$n_H = 0.045$, $f_{H2} = 10^{-2}$ (Loeb, 2006)

Collapsed mass versus redshift

1, 2, 3 σ fluctuations; limits imposed by atomic and H2 cooling



What about later star formation?

From gas to later stars

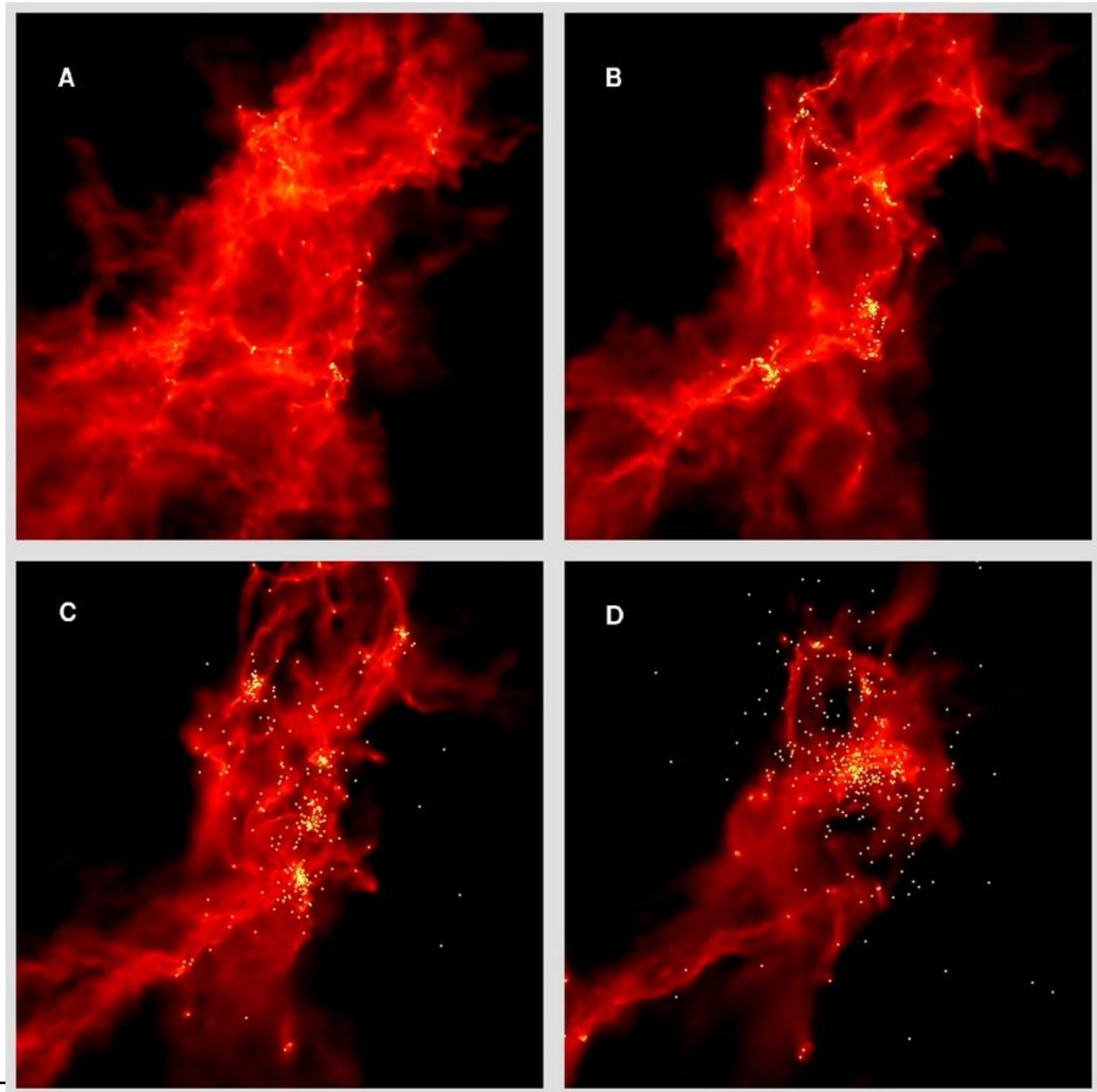
- **What drives SF? Rate? Efficiency? IMF?**
- **Stars form in Giant Molecular clouds; H2 forms on dust grains**
- $M \sim 10^5 - 10^6 M_\odot$, $n_{H2} \approx 100 - 500$ cm^{-3}, $T \sim 10$K,
  $\tau_{ff} \sim 3.6 \times 10^6 (n_{H2}/100\ cm^{-3})^{-1/2}$ yr,
  $M_J = 40 M_\odot (c_s/0.2 kms^{-1})^3 (n_{H2}/100\ cm^{-3})^{-1/2}$
- **Observations show efficiency of starformation is low** $\sim 2\%$
- **Explaining this efficiency and the initial mass function challenging!**
- **Modern theories of star formation involve not only gravity but crucially supersoninc turbulence, magmetic fields and feedback in jets radiation!**

Star forming regions

Horse head nebula: NASA/ESA/Hubble Heritage Team

Turbulence and star formation

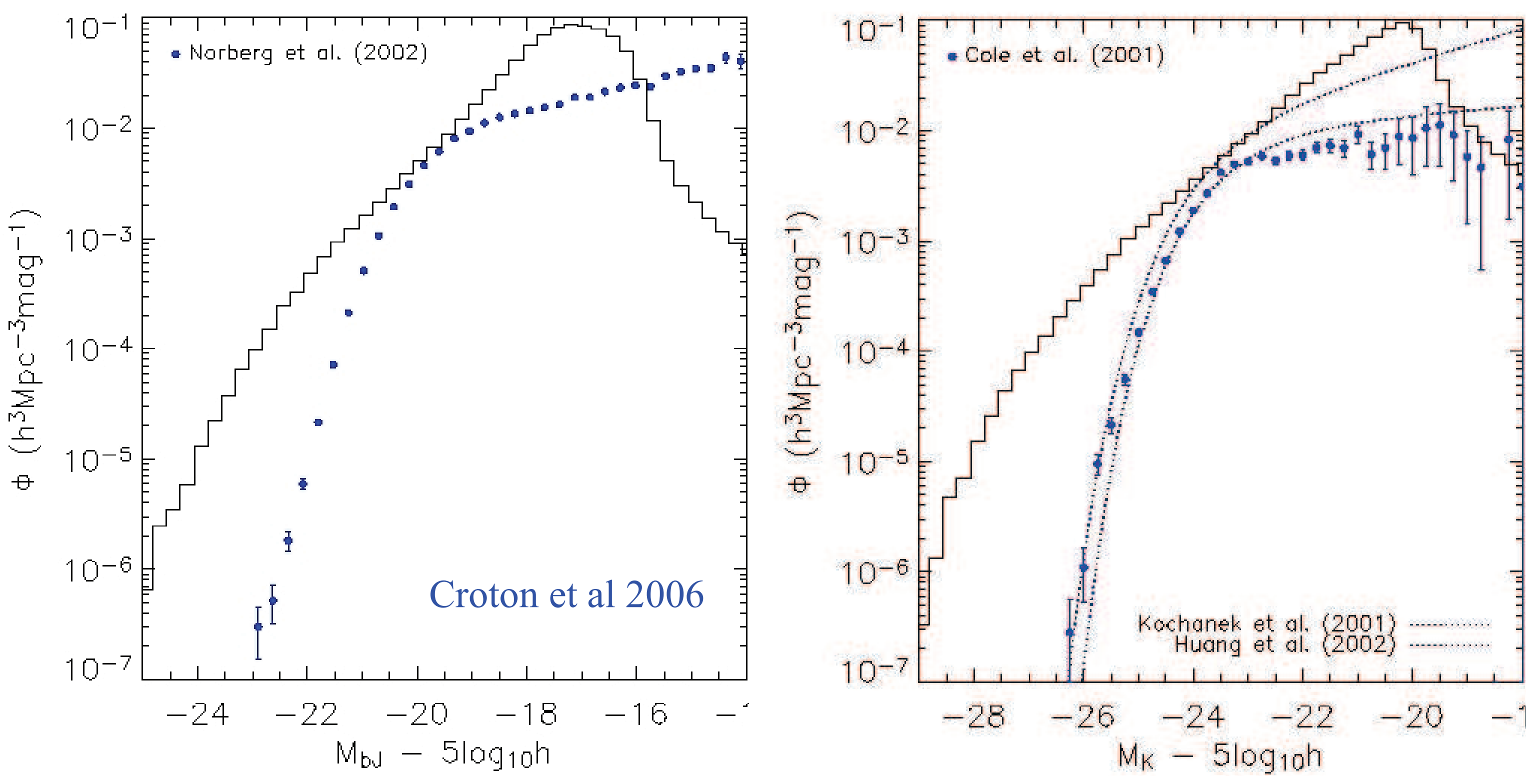
Fragmentation of $1000 M_{\odot}$ turbulent molecular clud; Bonnell et al, 2003



Galaxy formation

Cooling and Feedback Important (White 2006 Talk)

Luminosity Function in a ΛCDM model w/o Feedback



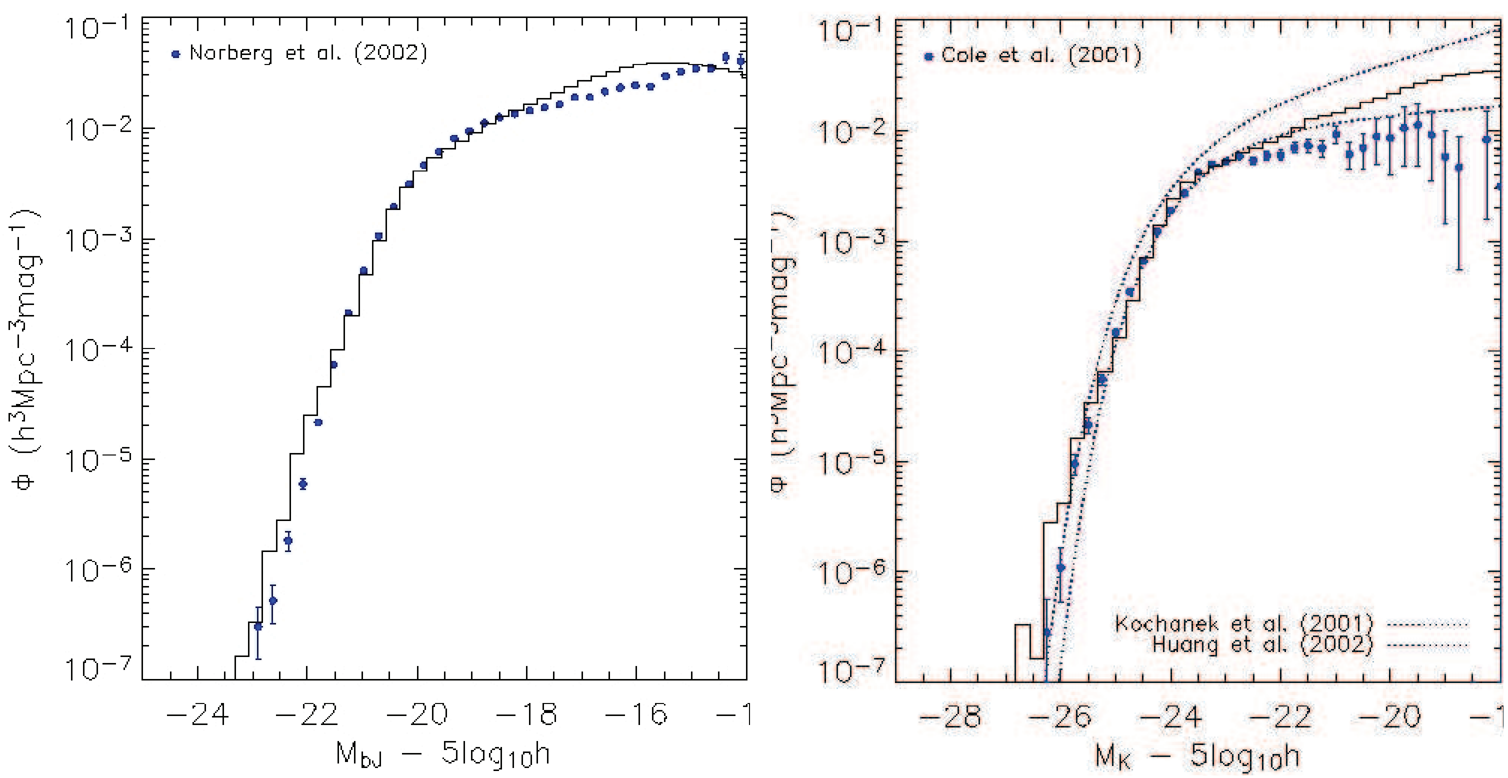
Concordance model with cooling and star formation but no feedback

--- too many stars --- wrong shape --- cD's too massive

Galaxy formation

Cooling and Feedback Important

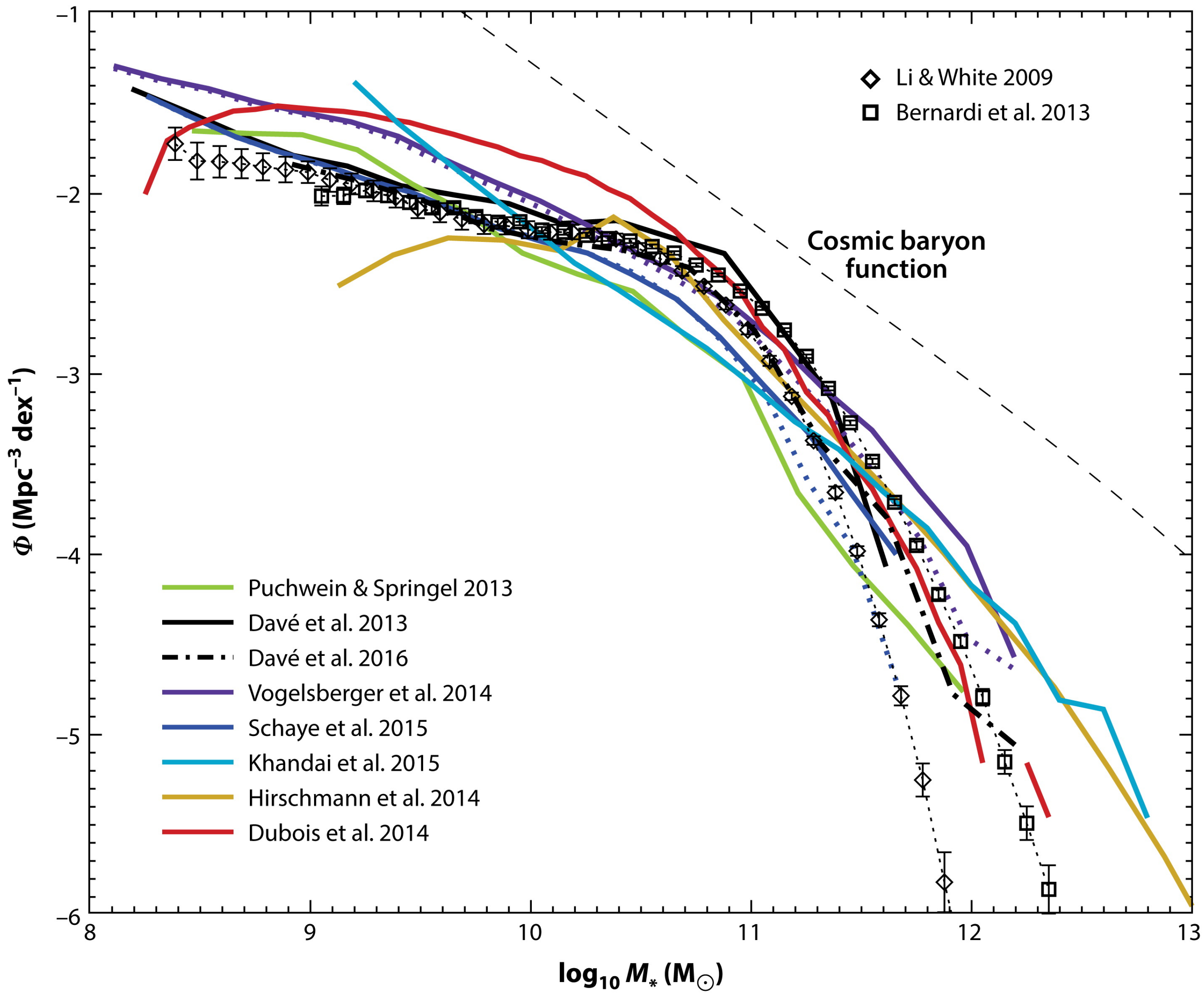
Effect of feedback on the Luminosity Function



Full model with reionisation, AGN and SN feedback   Croton et al 2006

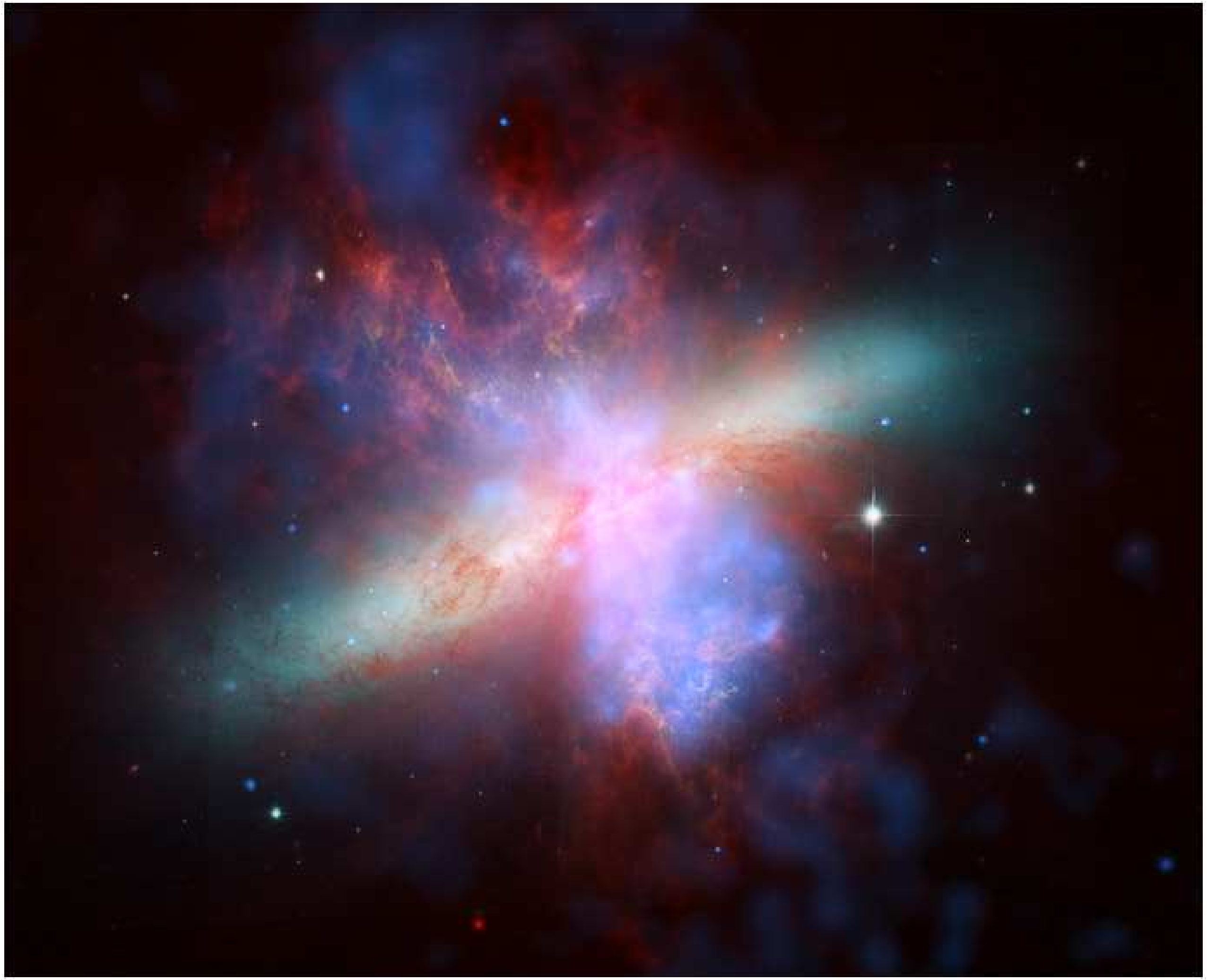
z=0 LF : Feedback in the local universe

Naab and Ostriker, ARAA, 55, 59 (2017)



Naab T, Ostriker JP. 2017.
Annu. Rev. Astron. Astrophys. 55:59–109

Outflow from Starburst galaxy M82



NASA website

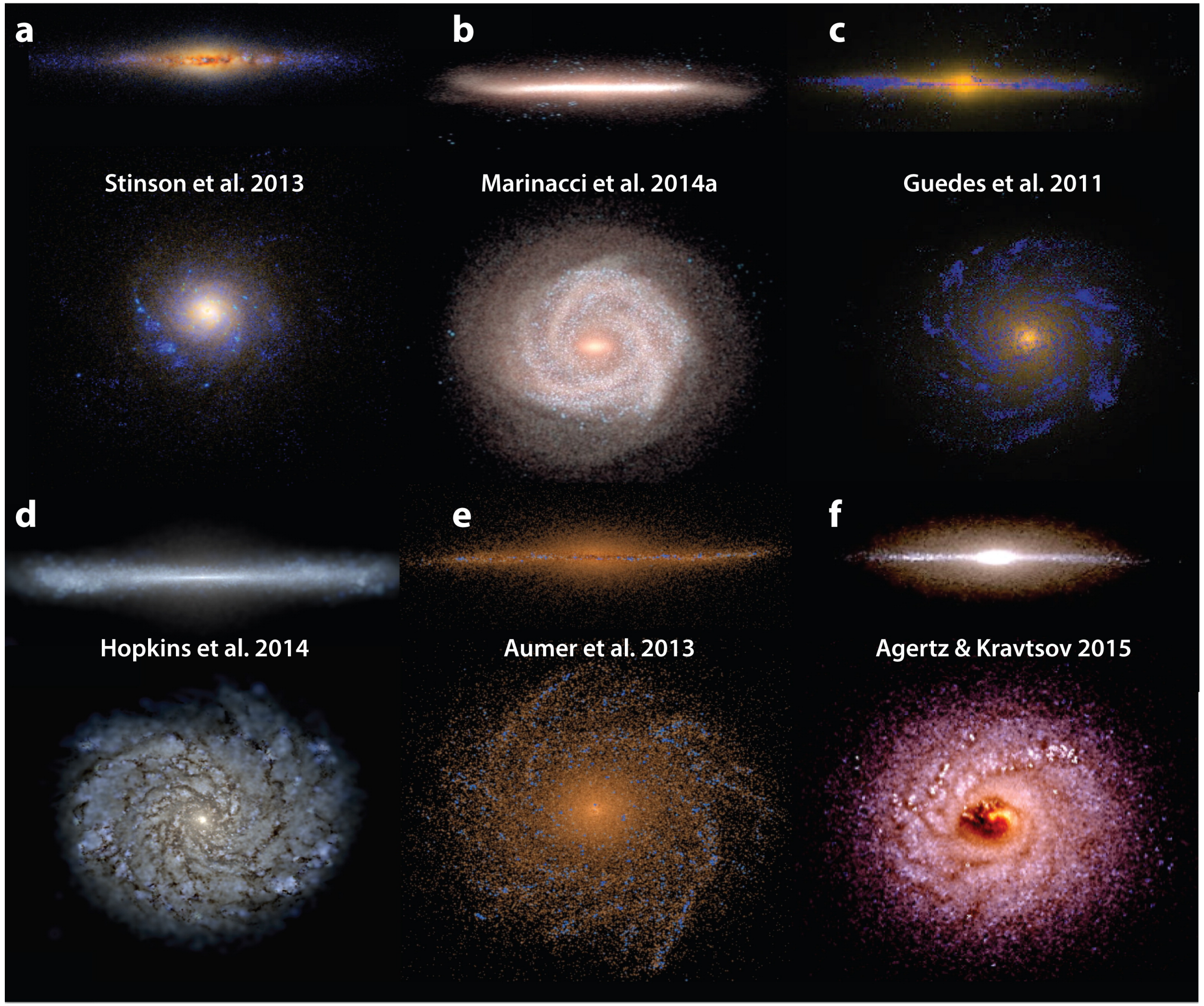
Supernovae Feedback

- **SNe creates hot bubble of shock heated gas**
- **Clustered SNe leads to formation of super bubble**
- **Galaxy blows a wind of hot gas, cool clouds, into halo**
- **Luminosity** $L(t) = 10^{51} \times \epsilon_w \nu \dot{M}_{SF}$
- $\nu = 1/130 M_\odot^{-1}$ **for Salpeter,** $1/50 M_\odot^{-1}$ **if** $M_{low} = 1 M_\odot$
- **If the energy given to gas in SNe overlap time equal to gas binding energy, gas will be stripped (Dekel, Silk, 1986)**
- **Typically halos with** $V_c < 100$ **km s**$^{-1}$ **affected**

Formation of disk and elliptical galaxies

- **Galaxies (both DM and gas) acquire anuglar momentum by tidal torques: Only $\sim 5\%$ of that required for rotational support**
- **Gas cools and collapses in the DM potential and can spin up conserving L to form rotationally supported disks**
- **Disks that form in heirarcical clustering simulations were too compact**
- **No Feed Back: Gas condenses into clumps, forms stars, loses angular momentum $\rightarrow$ too much stars, disk too compact and low L.**
- **Feed back allows less stars, more L being retained by gas, better disk galaxies**
- **Also allows more extended star formation**
- **Elliptcals could form by mergers of disk galaxies**

Disk galaxies need feedback

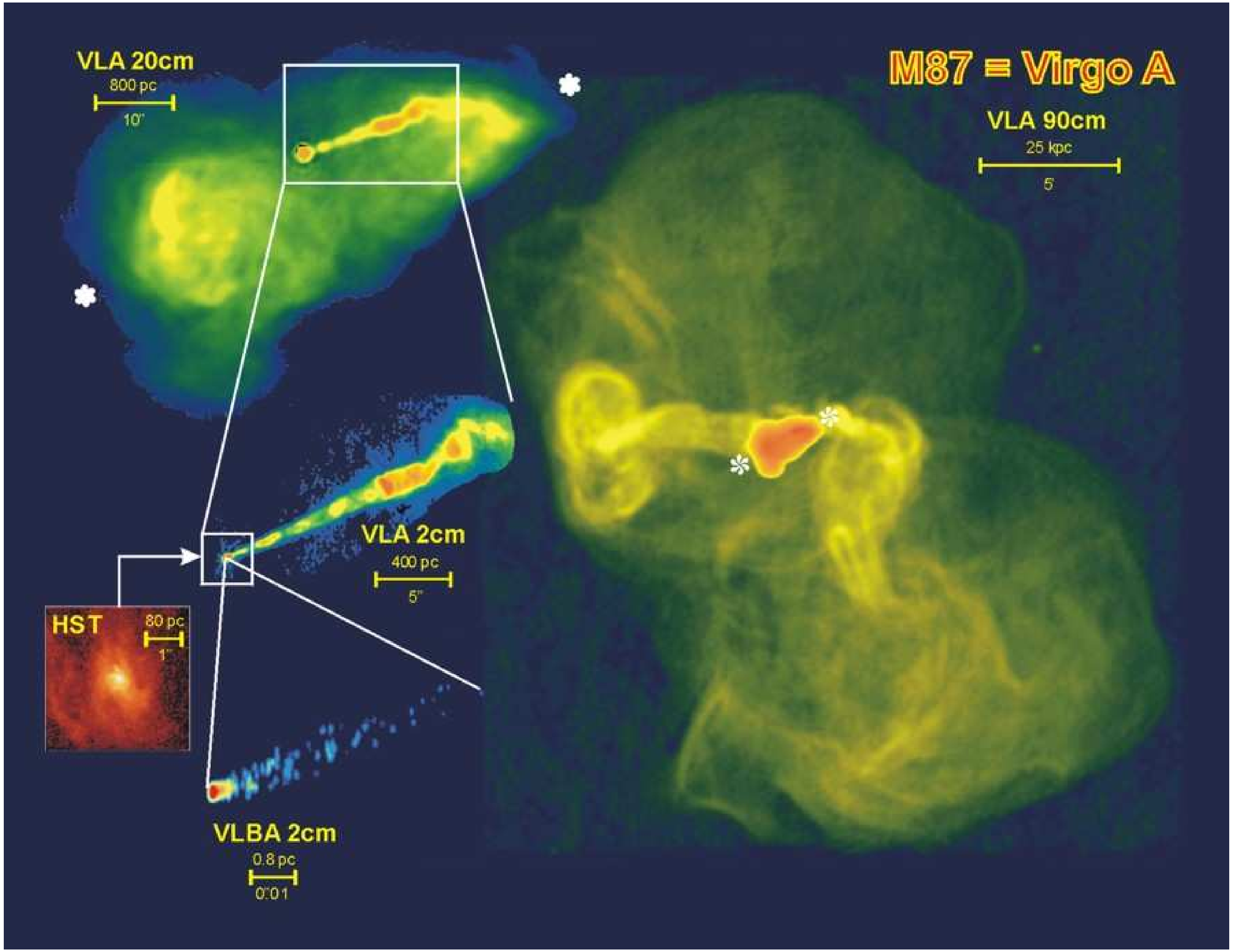


Naab T, Ostriker JP. 2017.
Annu. Rev. Astron. Astrophys. 55:59–109

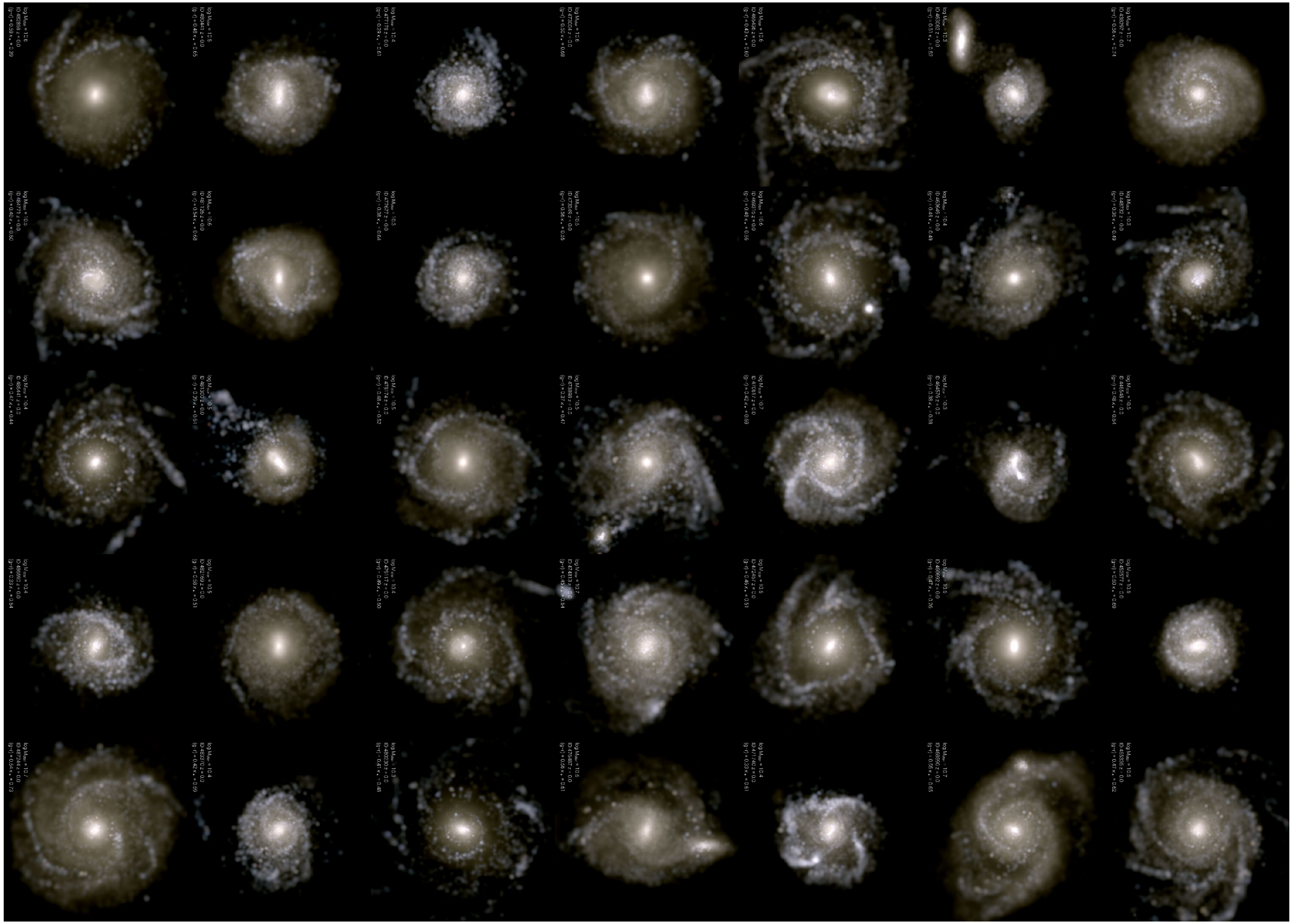
- **No FB: Gas condenses into clumps, forms stars, loses angular momentum $\rightarrow$ too much stars, disk too compact and low L. FB $\rightarrow$ better disks!**

AGN Feedback

Image courtesy of NRAO/AUI: http://images.nrao.edu/270

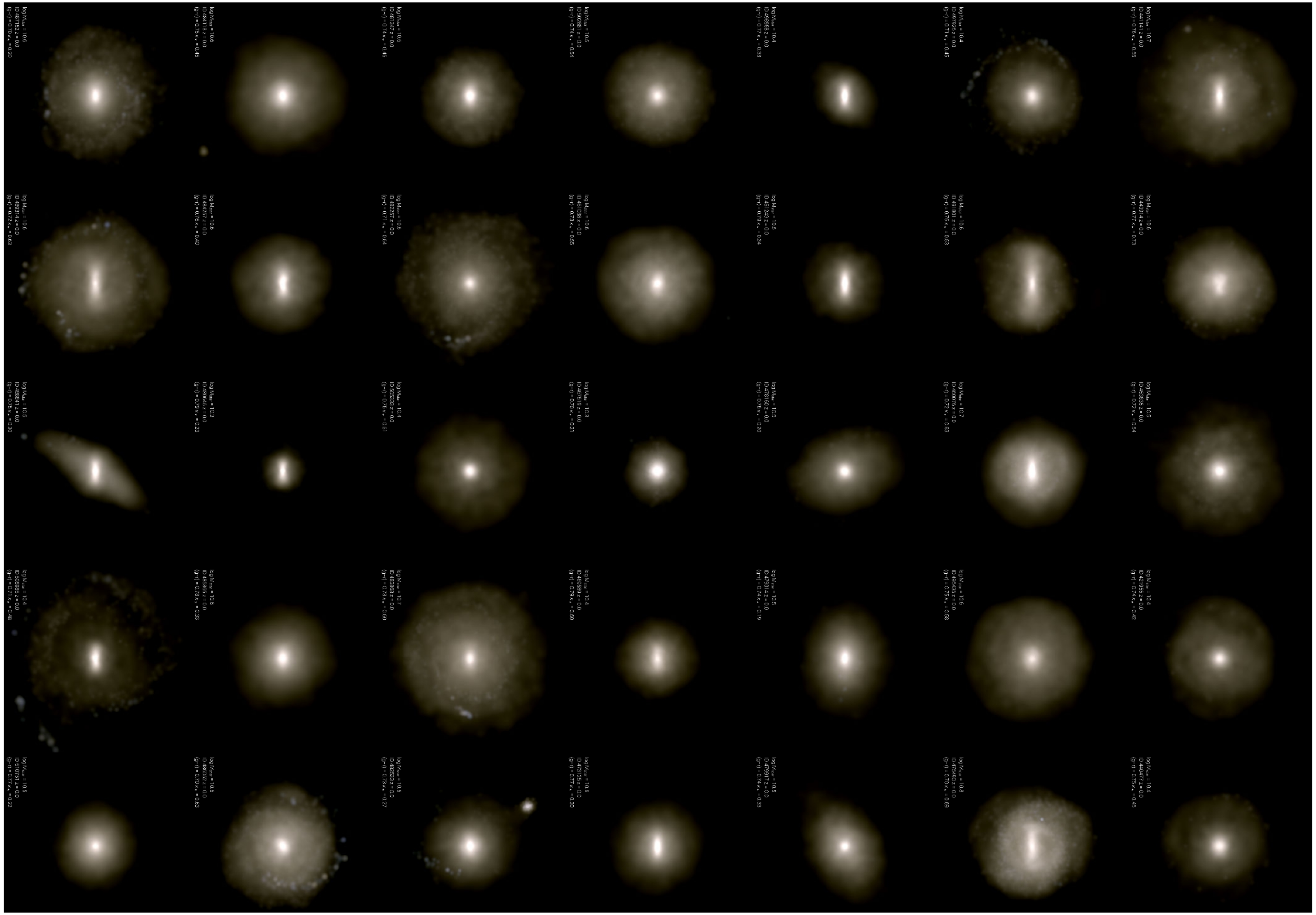


Disk galaxies with feedback in TNG



Nelson et. al. , MNRAS, 2018 (Illustris-The Next Gneration)

Early type galaxies with feedback in TNG



Nelson et. al. , MNRAS, 2018

High z galaxies with JWST

Figure 7. from
Guido Roberts-Borsani et al 2025 Astrophys. J. 983 doi:10.3847/1538-4357/adba60
https://dx.doi.org/10.3847/1538-4357/adba60
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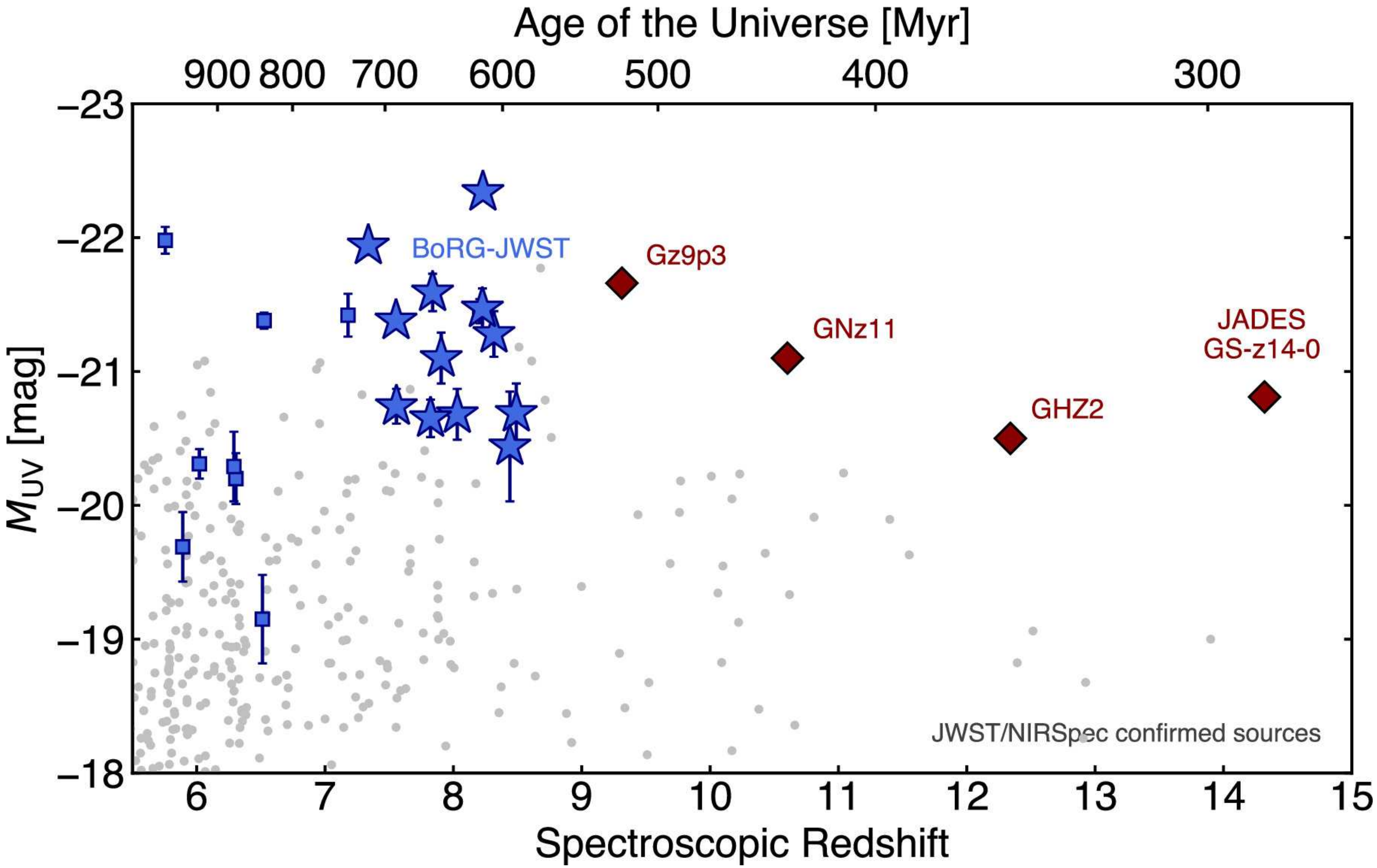
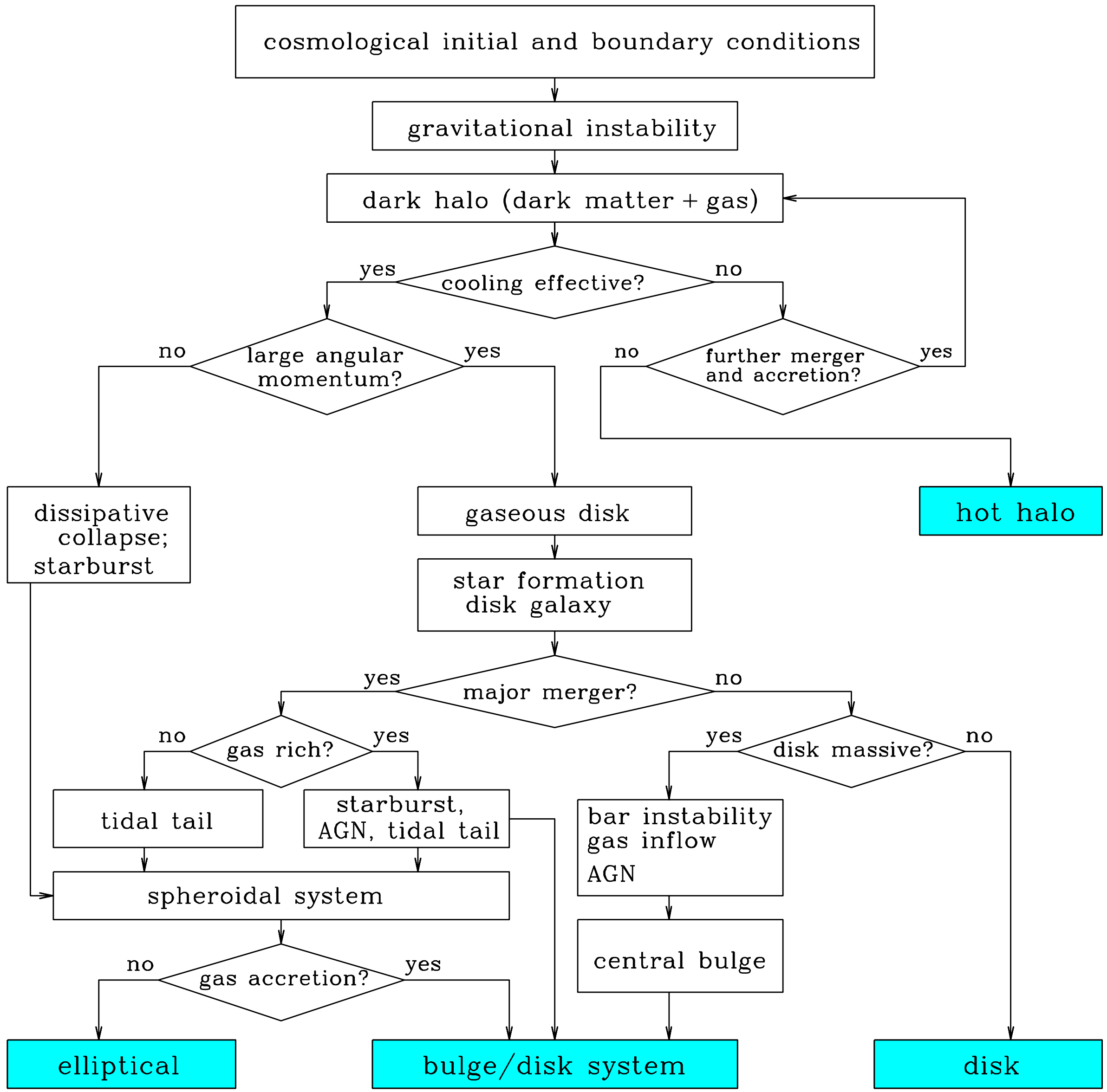


Some issues in Galaxy formation



Mo, Van den Bosch, White