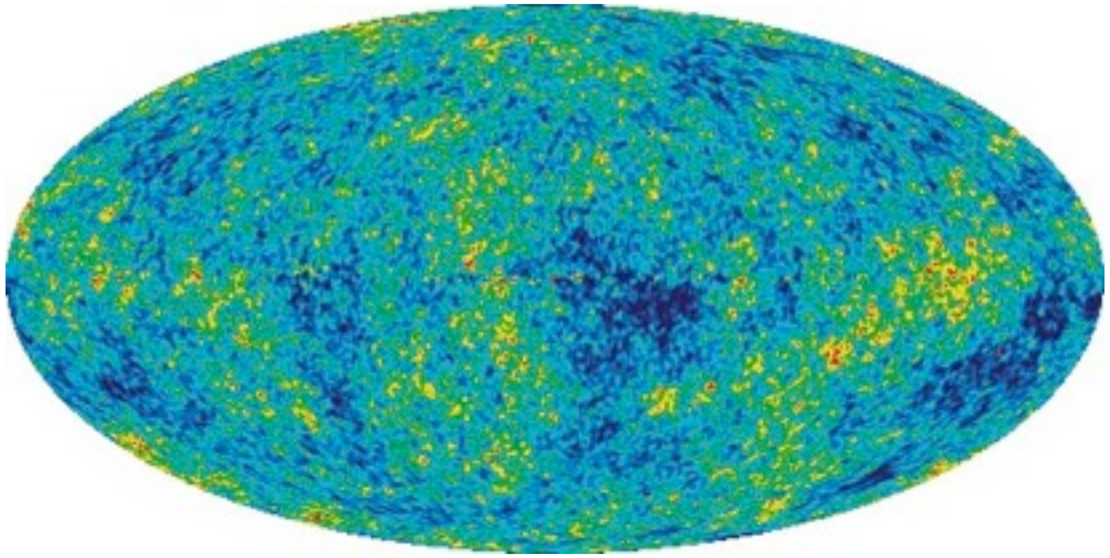
What is Galaxy Formation?

THE BIG PICTURE

Today



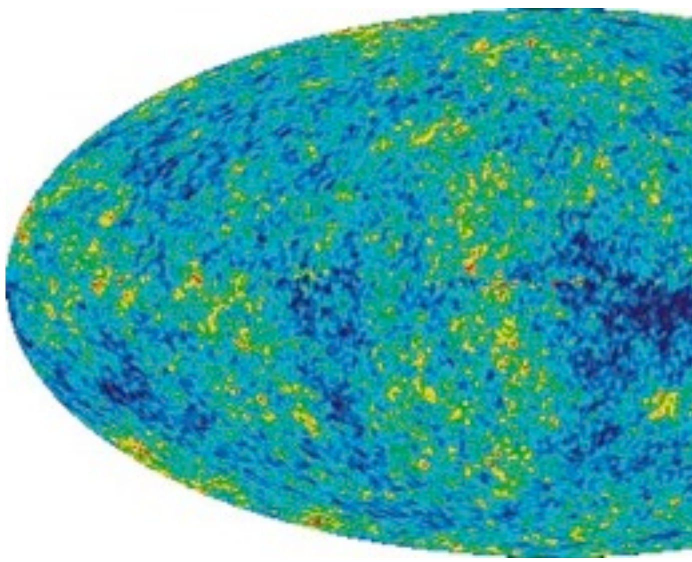
z~1090
(t~400,000 yr)

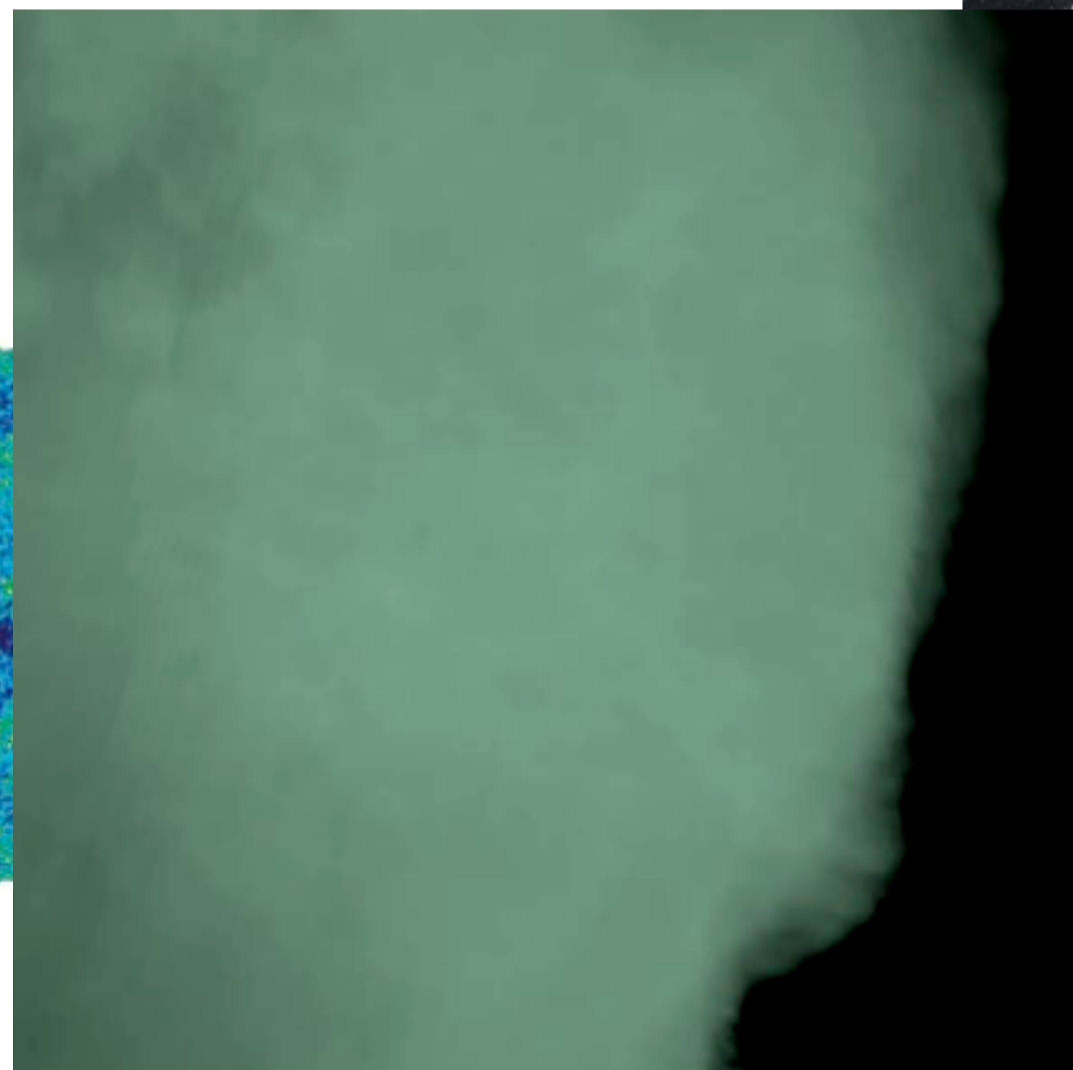
?

What is Galaxy Formation?

THE BIG PICTURE

Today





z~1090

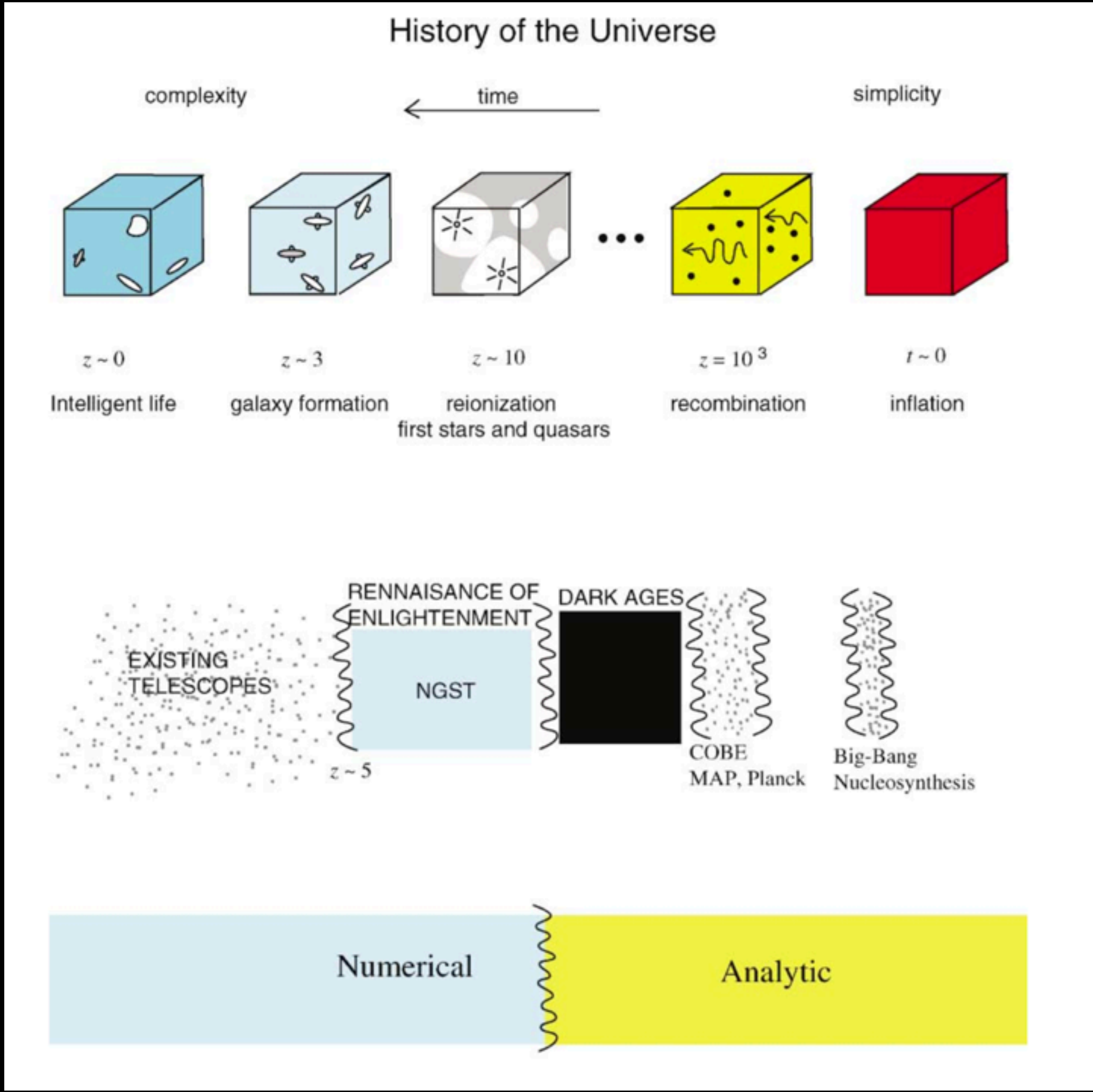
(t~400,000 yr)

A brief history of the theory of galaxy formation

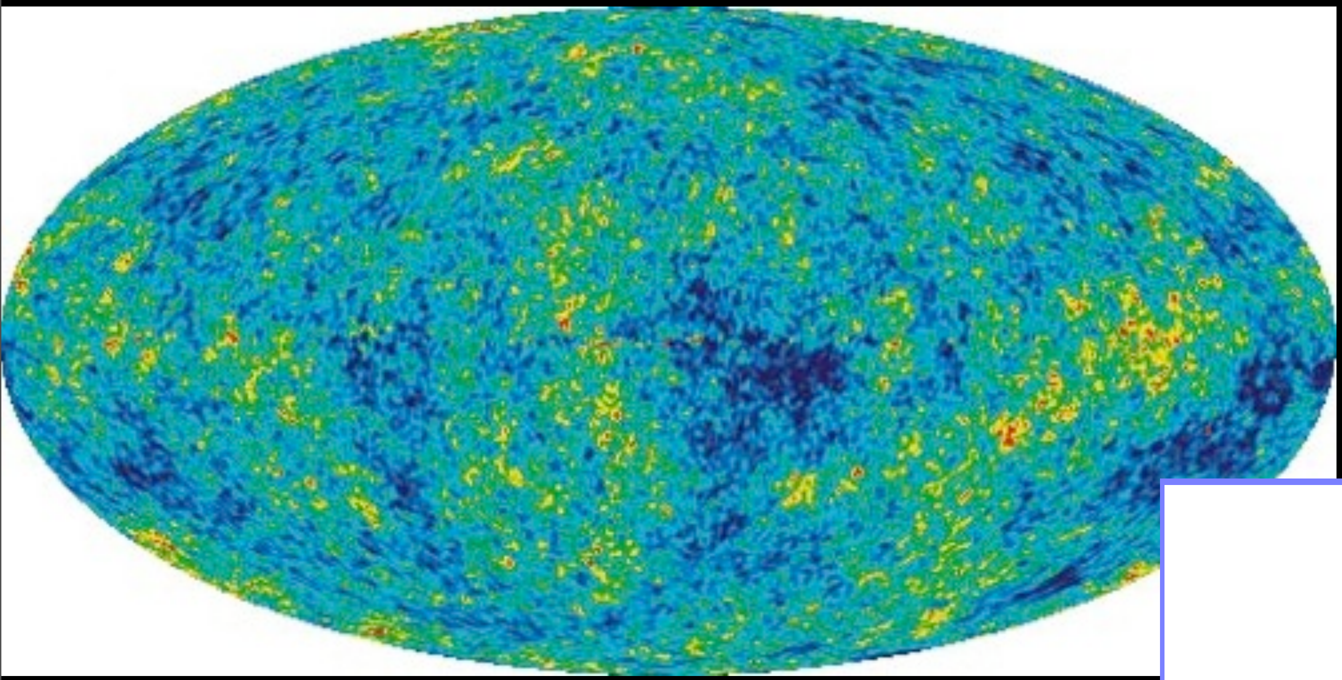
Milestones

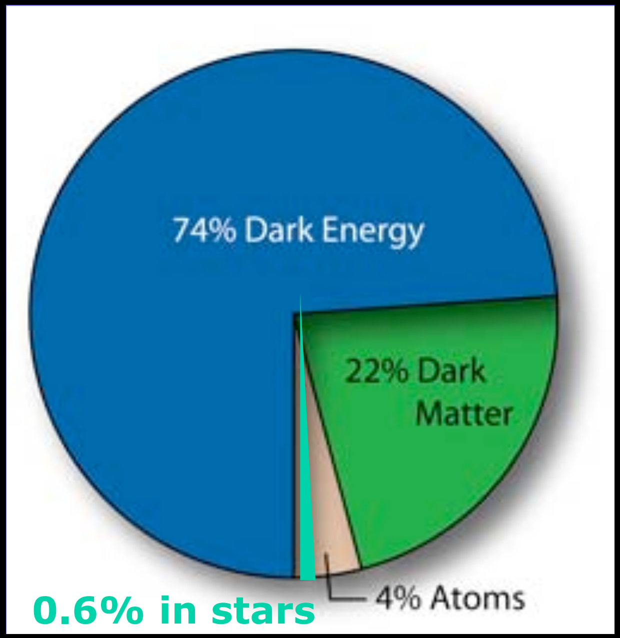
- Formation of cosmic structures - gravitational collapse (Gunn & Gott 1972, Press & Schechter 1974, Peebles 1982/89, Davis 1985, Bardeen et al. 1986)
- Galaxy rotation due to tidal torques present during collapse (Hoyle 1949, Peebles 1969, White 1984, Efstathiou & Jones 1979 [N-body simulations])
- Cooling argument for the observed ranges in galaxy masses (Hoyle 1953)
- Unification of Press & Schechter and gas cooling arguments - **foundation of today's models** (White & Rees 1978)
- Introduction of feedback in order to supress the number of faint galaxies (White & Rees 1978)

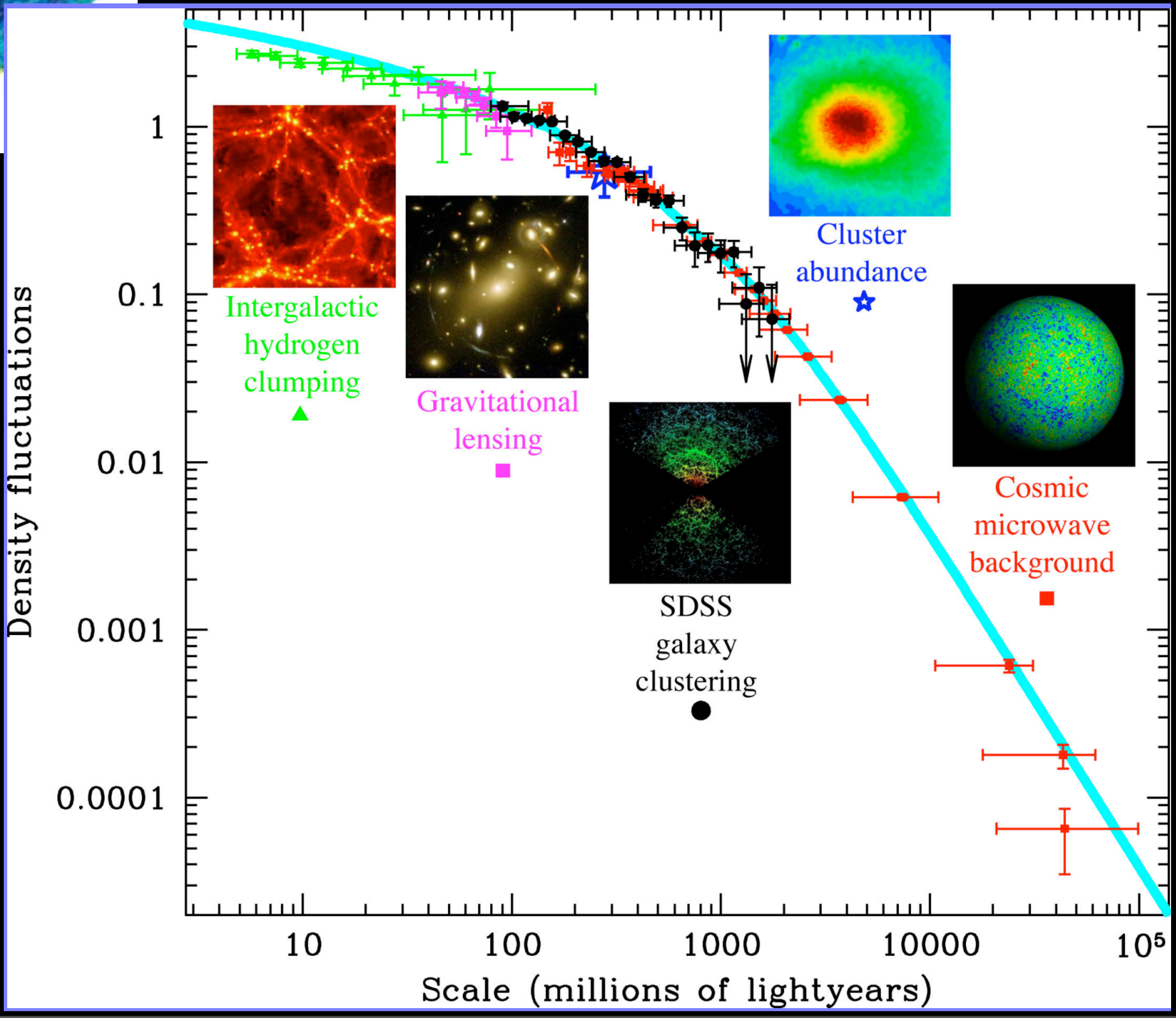
... start (not quite) at the beginning ...


History of the Universe
complexity
time
simplicity
$z \sim 0$
Intelligent life
$z \sim 3$
galaxy formation
$z \sim 10$
reionization
first stars and quasars
$z = 10^3$
recombination
$t \sim 0$
inflation
EXISTING
TELESCOPES
RENNAISANCE OF
ENLIGHTENMENT
NGST
$z \sim 5$
DARK AGES
COBE
MAP, Planck
Big-Bang
Nucleosynthesis
Numerical
Analytic

Standard ("Concordance") Cosmological Model







~10% Errors in description of expansion history

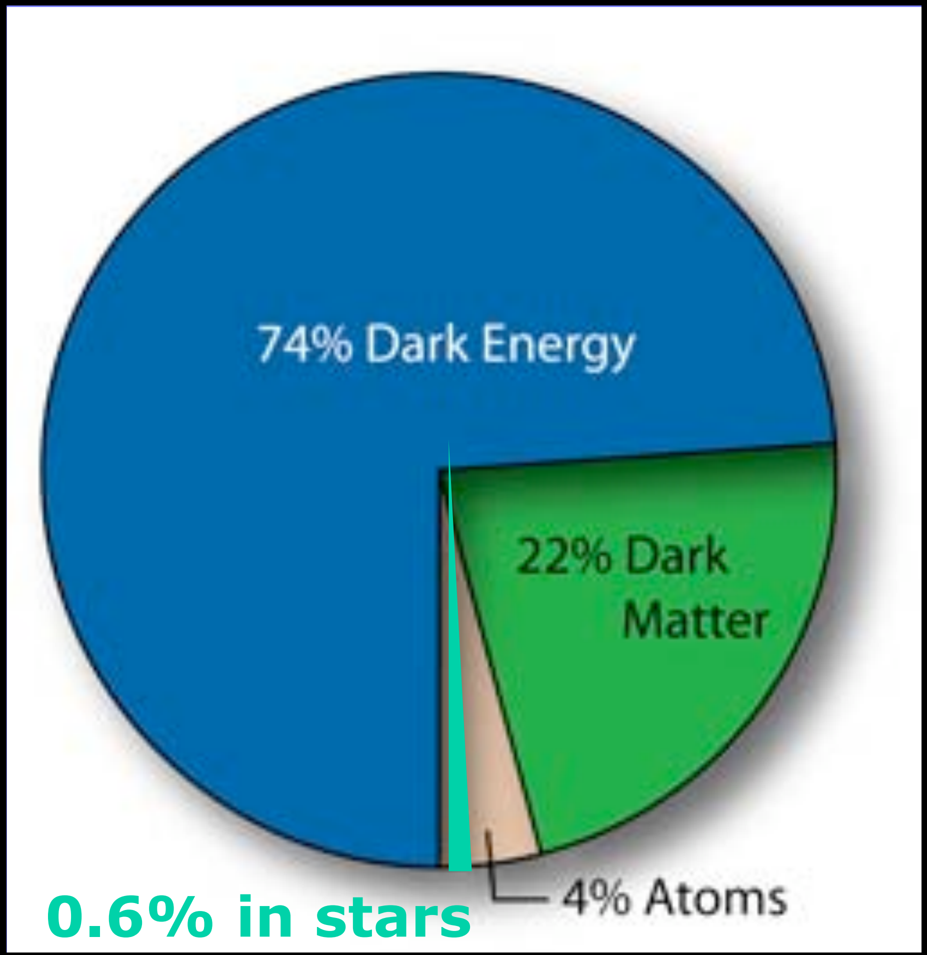
Basic and Derived Cosmological Parameters: Running Spectral Index Model

Parameters	Mean and 68% Confidence Errors
Basic	
Amplitude of fluctuations, A	$0.83^{+0.09}_{-0.08}$
Spectral index at $k = 0.05$ Mpc^{-1}, n_s	0.93 ± 0.03
Derivative of spectral index, $dn_s/d\ln k$	$-0.031^{+0.016}_{-0.018}$
Hubble constant, h	$0.71^{+0.04}_{-0.03}$
Baryon density, $\Omega_b h^2$	0.0224 ± 0.0009
Matter density, $\Omega_m h^2$	$0.135^{+0.008}_{-0.009}$
Optical depth, τ	0.17 ± 0.06
Derived	
Matter power spectrum normalization, σ_8	0.84 ± 0.04
Characteristic amplitude of velocity fluctuations, $\sigma_8 \Omega_m^{0.6}$	$0.38^{+0.04}_{-0.05}$
Baryon density/critical density, Ω_b	0.044 ± 0.004
Matter density/critical density, Ω_m	0.27 ± 0.04
Age of the universe, t_0	13.7 ± 0.2 Gyr
Reionization redshift,[a] z_r	17 ± 4
Decoupling redshift, z_{dec}	1089 ± 1
Age of the universe at decoupling, t_{dec}	379^{+8}_{-7} kyr
Thickness of surface of last scatter, Δz_{dec}	195 ± 2
Thickness of surface of last scatter, Δt_{dec}	118^{+3}_{-2} kyr
Redshift of matter/radiation equality, z_{eq}	3233^{+194}_{-210}
Sound horizon at decoupling, r_s	147 ± 2 Mpc
Angular size distance to the decoupling surface, d_A	$14.0^{+0.2}_{-0.3}$ Gpc
Acoustic angular scale,[b] ℓ_A	301 ± 1
Current density of baryons, n_b	$(2.5 \pm 0.1) \times 10^{-7}$ cm^{-3}
Baryon/photon ratio, η	$(6.1^{+0.3}_{-0.2}) \times 10^{-10}$

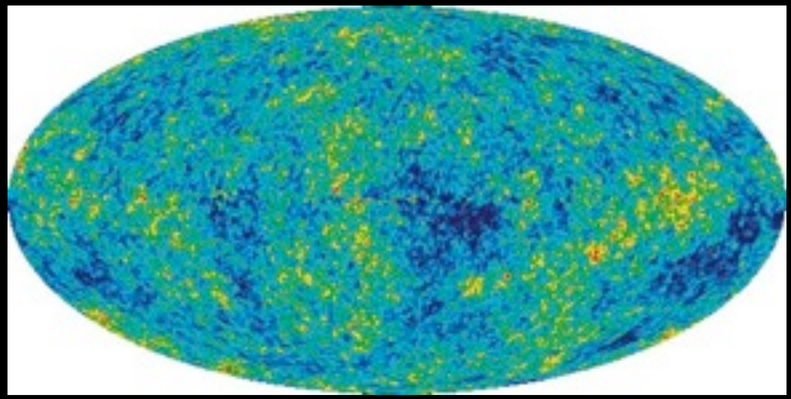
Note.—Fit to the *WMAP*, CBI, ACBAR, 2dFGRS, and Lyα forest data.
[a] Assumes ionization fraction, $x_e = 1$.
[b] $l_A = \pi d_C / r_s$.

See also Spergel et al 2007 (WMAP 3yr data)

Forget baryons (for now)



- Start with small, random perturbations:



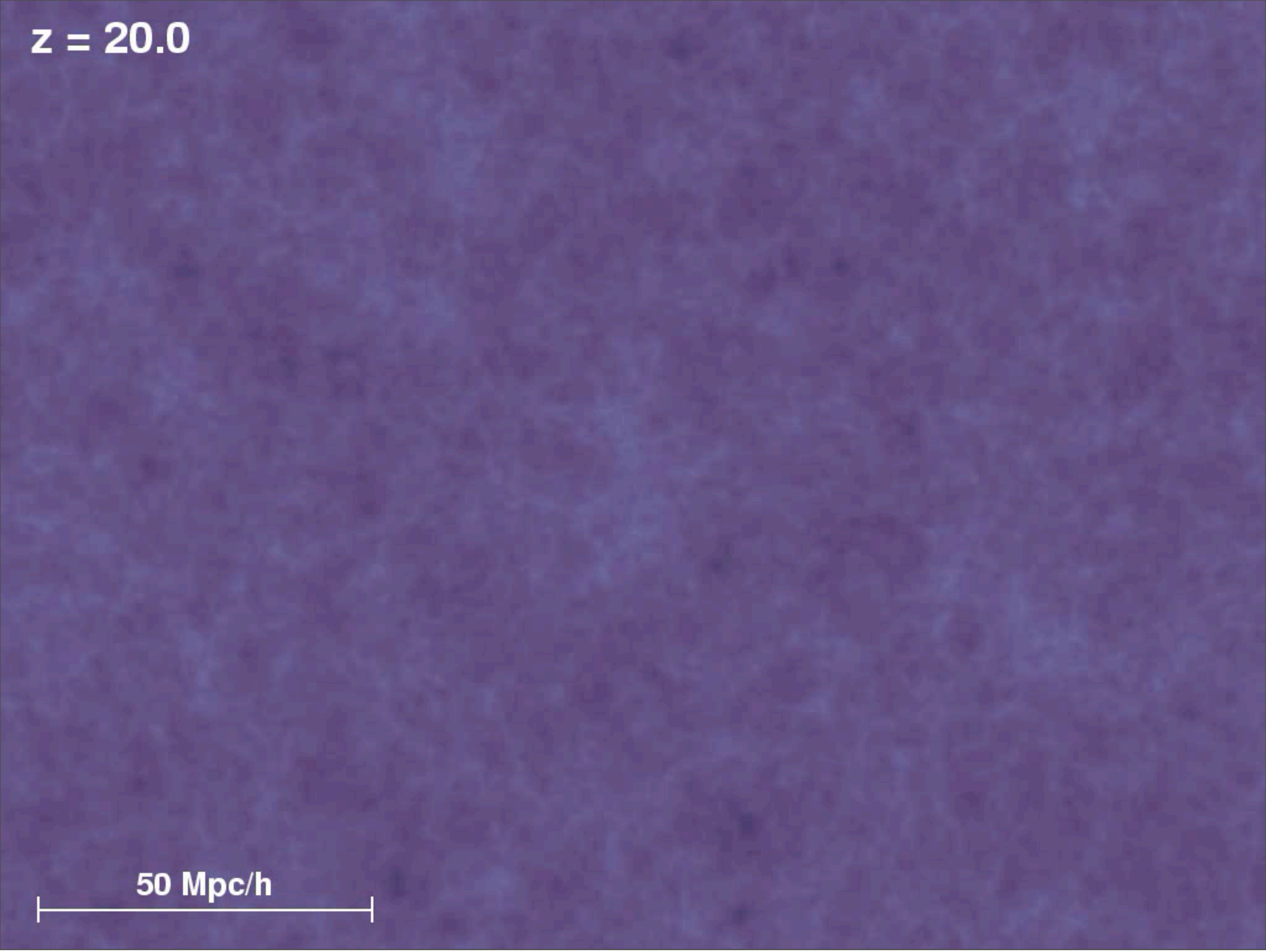
- Add gravity!

Expansion:

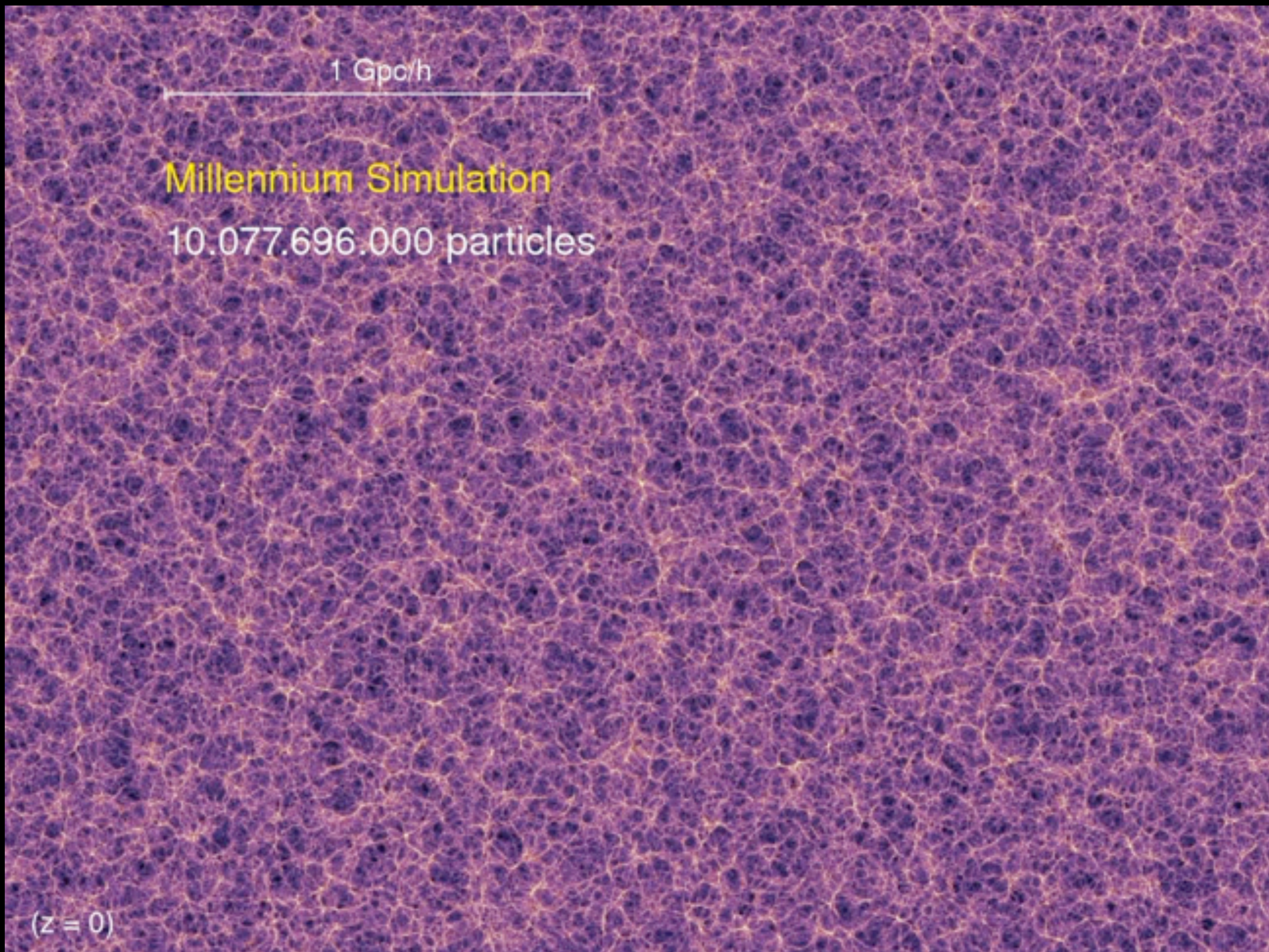
$$\frac{\dot{a}}{a} = H_0\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda}$$

"Everything else":

$$F_{\rm grav} = \frac{G\,M_1\,M_2}{r_{12}^2}$$


z = 20.0
50 Mpc/h

Dense regions “turn around” (detach from Hubble flow) and collapse



Each collapsed region is a “halo”

Collapse by z=0:

$$\rho_i > 1.86\,\rho_0$$

“Virialize”
(can’t radiate!)

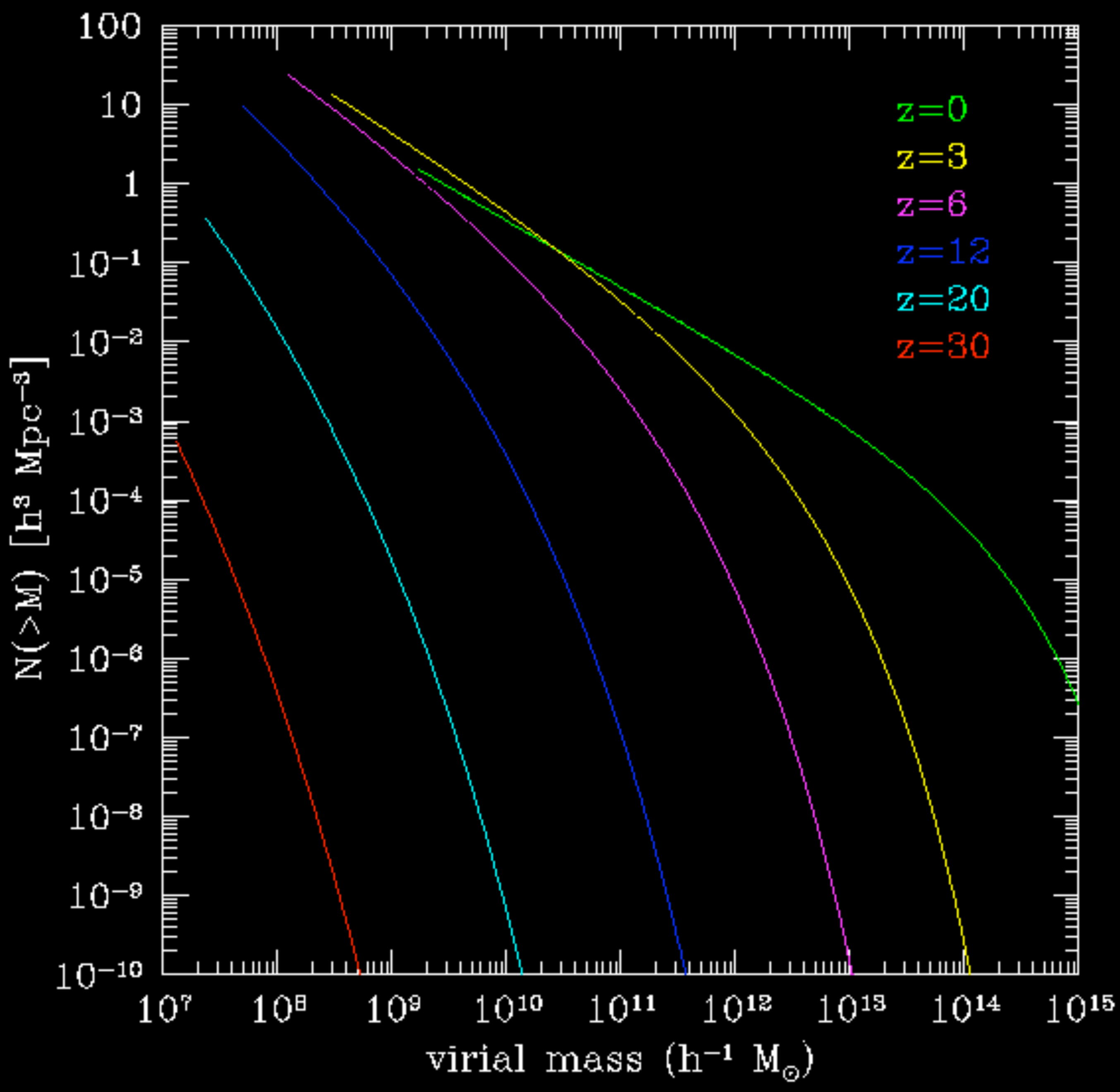
$$-\frac{1}{2}\,PE_{\rm vir} = E$$

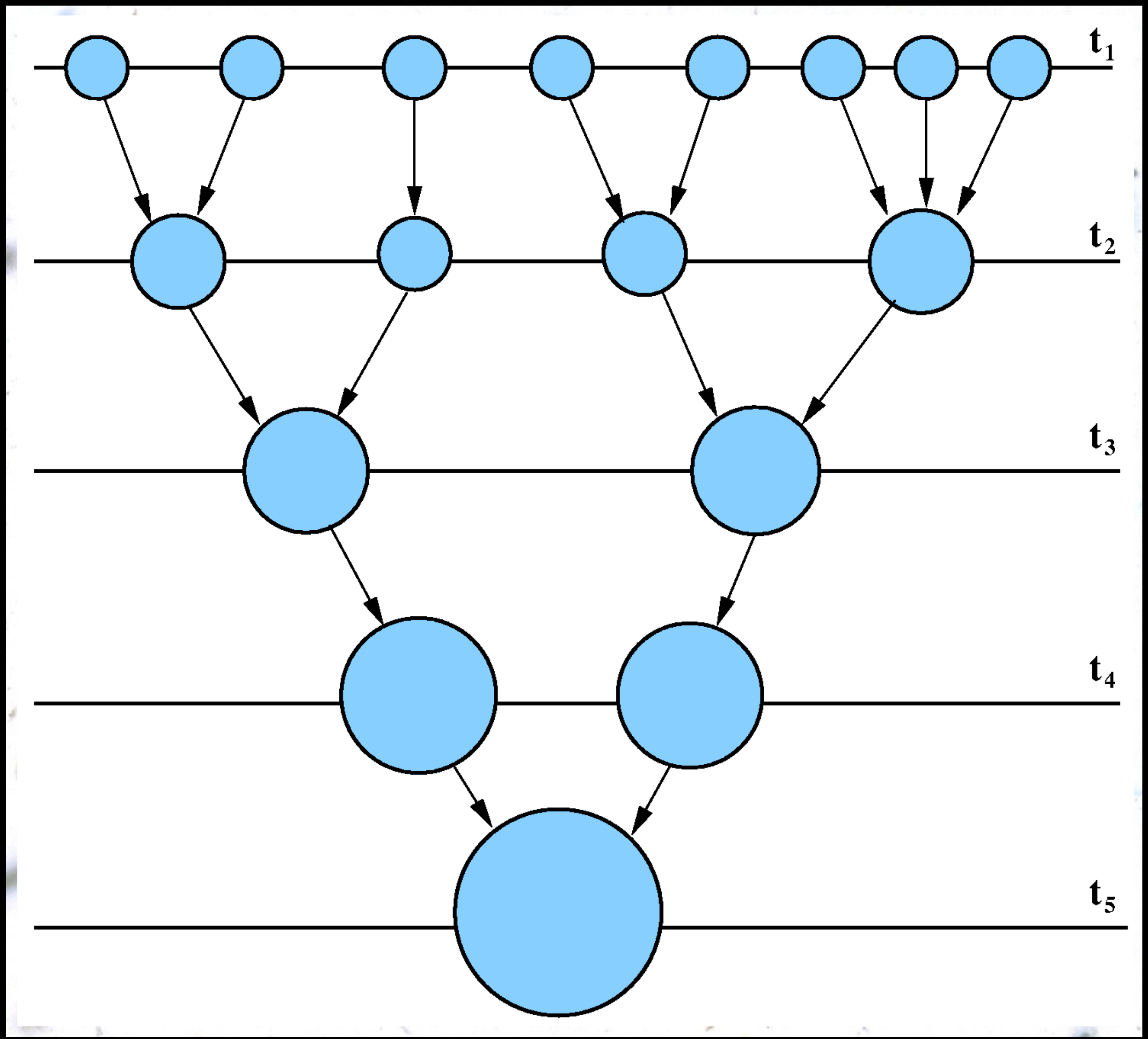
$$\langle\rho\rangle_{\rm vir} \sim 200\,\rho_0$$

$$V_{\rm vir}^2 \sim \frac{G\,M_{\rm vir}}{R_{\rm vir}}$$

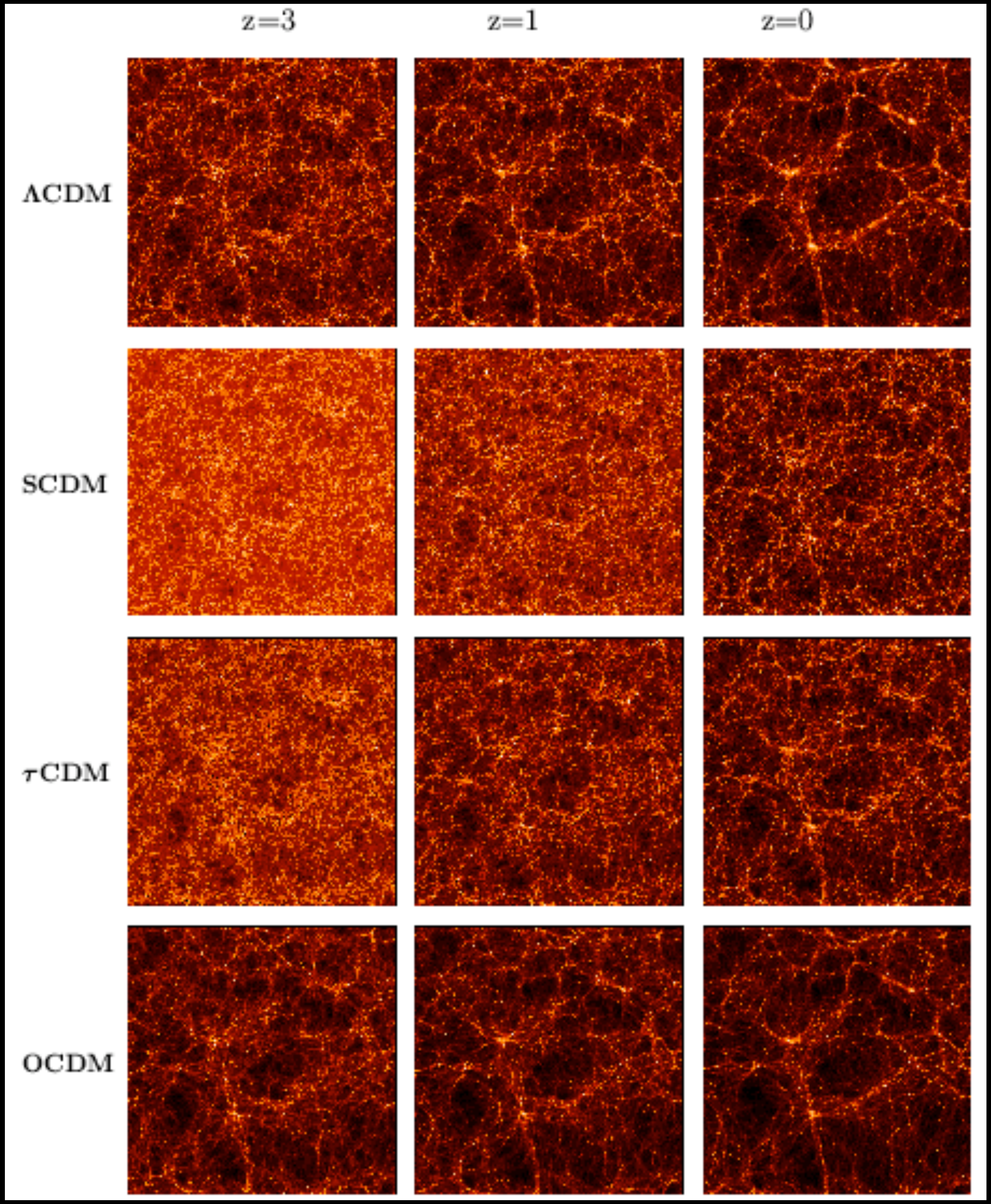
Millenium simulation: Flythrough

Analytically approximate “halos”:

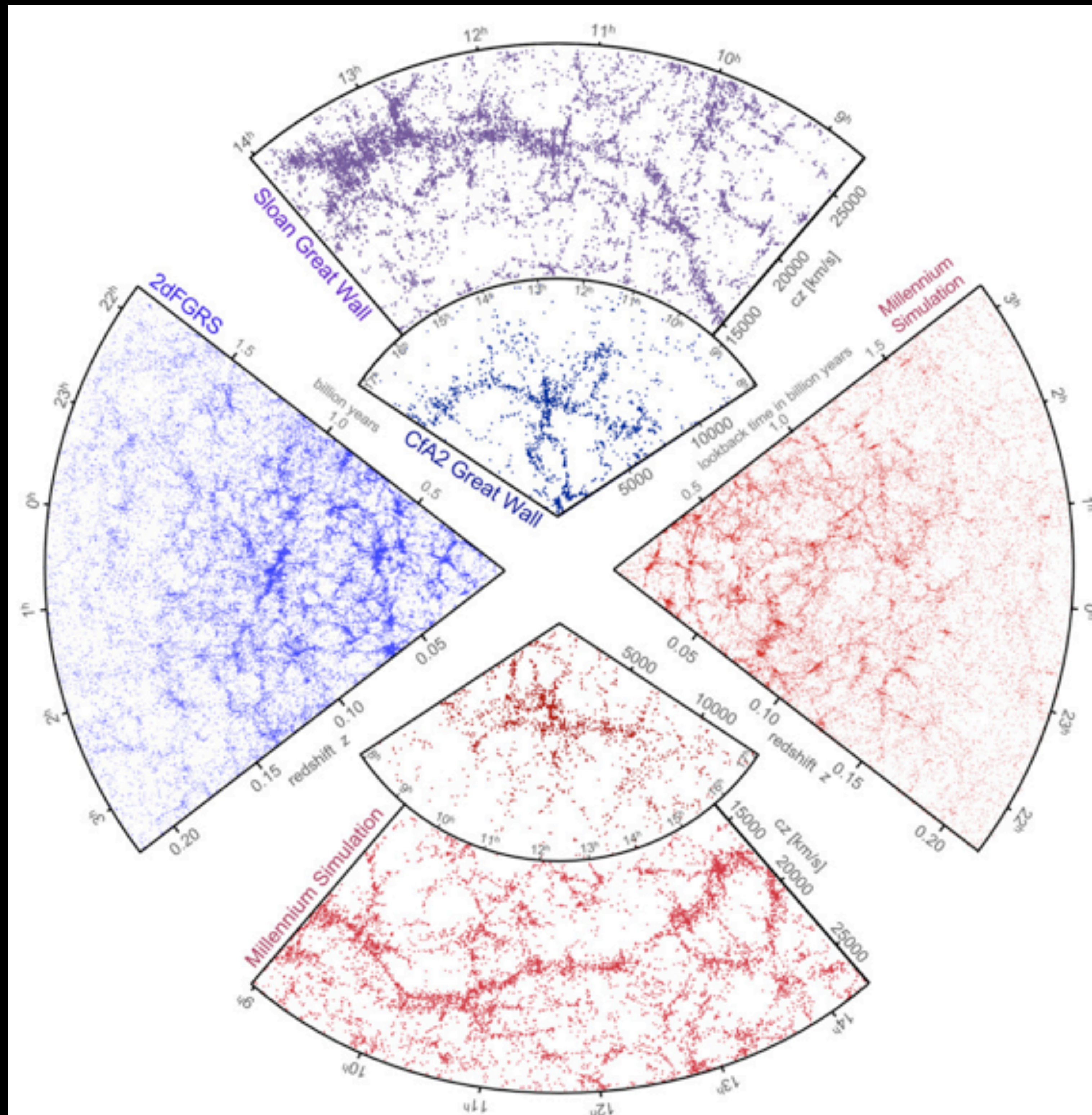




Expansion history determines growth of structure

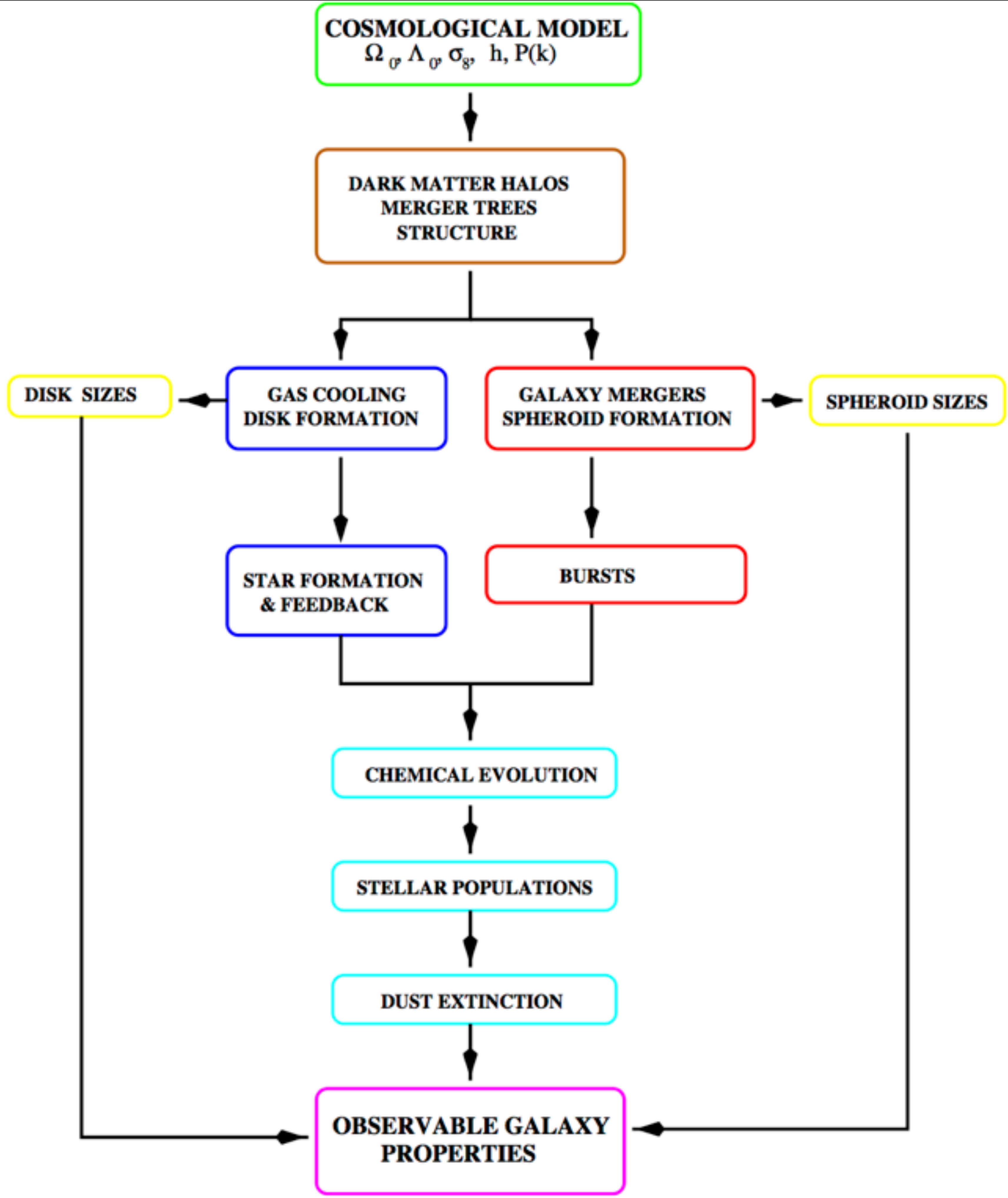


Not much wiggle room here!

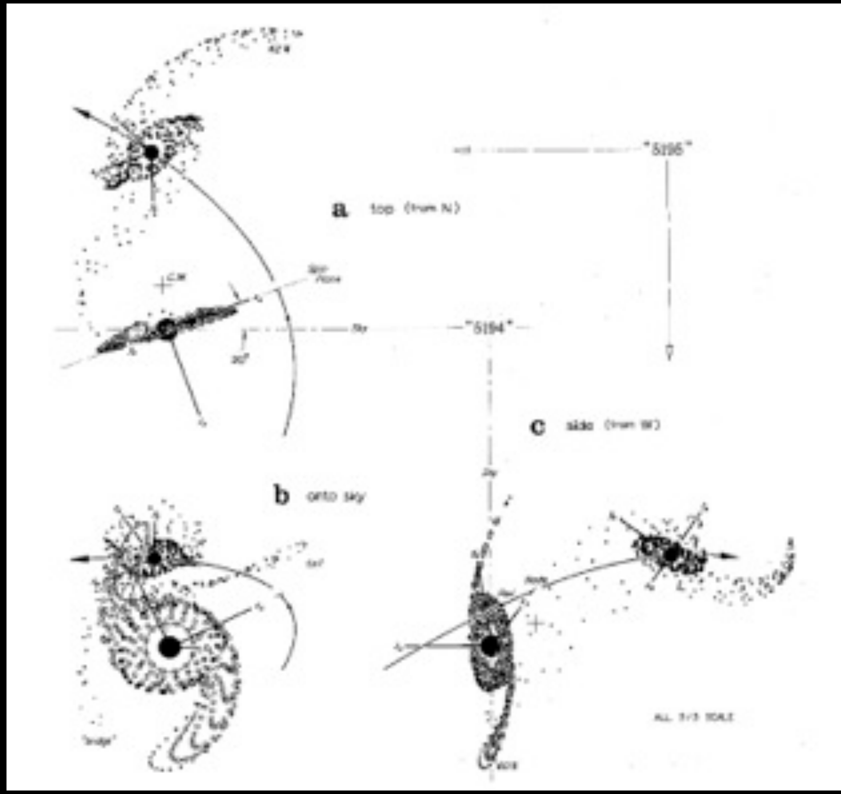


http://space.mit.edu/home/tegmark/movies.html

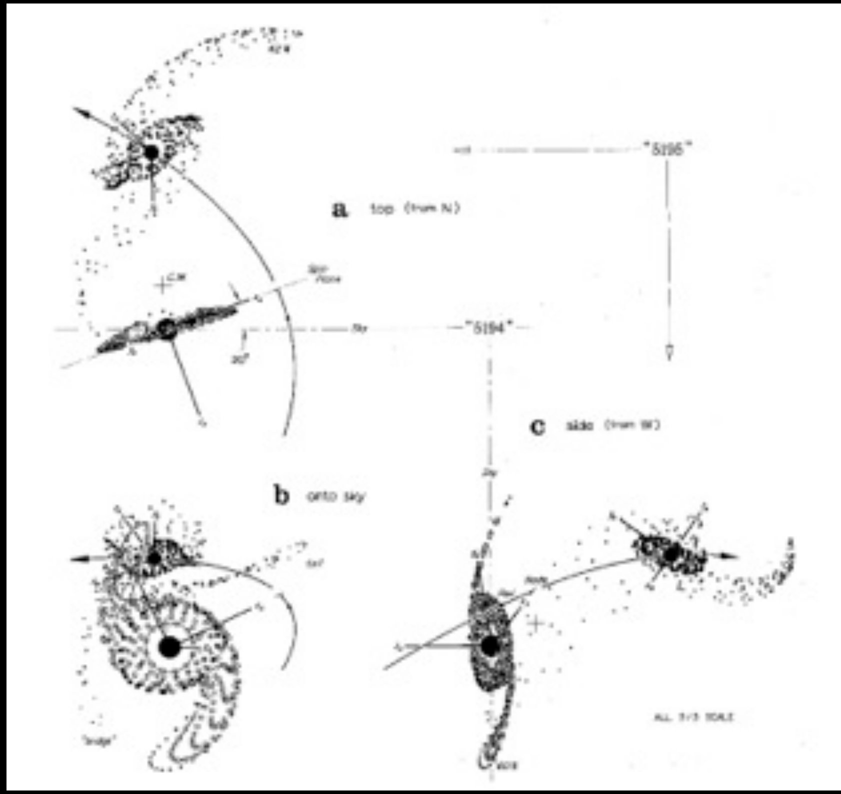
... what about the baryons? ...


COSMOLOGICAL MODEL
$\Omega_0, \Lambda_0, \sigma_8$, h, P(k)
DARK MATTER HALOS
MERGER TREES
STRUCTURE
DISK SIZES
GAS COOLING
DISK FORMATION
GALAXY MERGERS
SPHEROID FORMATION
SPHEROID SIZES
STAR FORMATION
& FEEDBACK
BURSTS
CHEMICAL EVOLUTION
STELLAR POPULATIONS
DUST EXTINCTION
OBSERVABLE GALAXY
PROPERTIES

Simulate Directly:

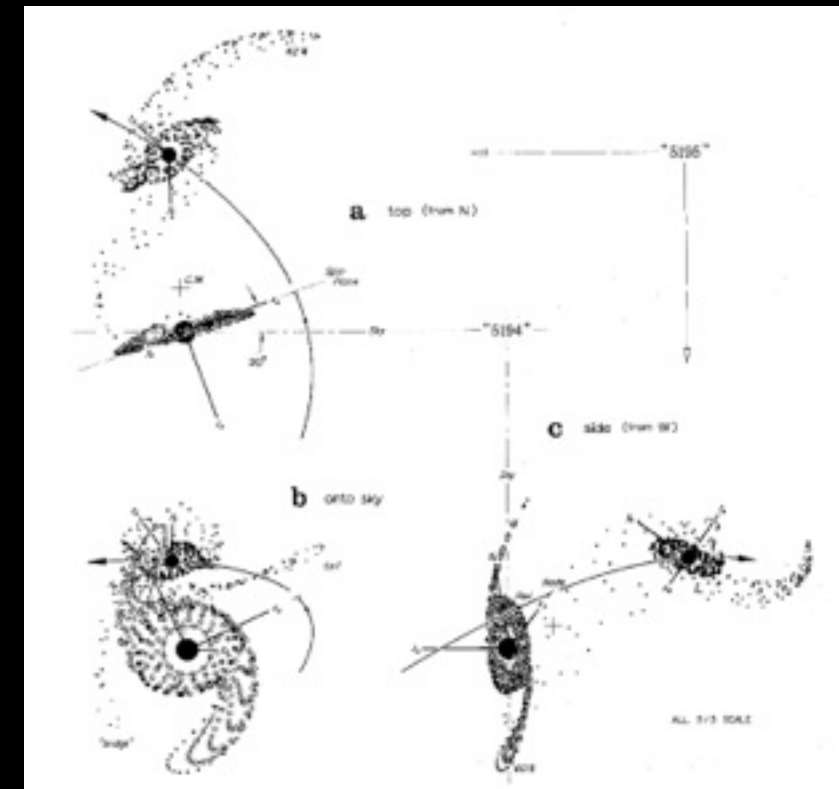


Simulate Directly:

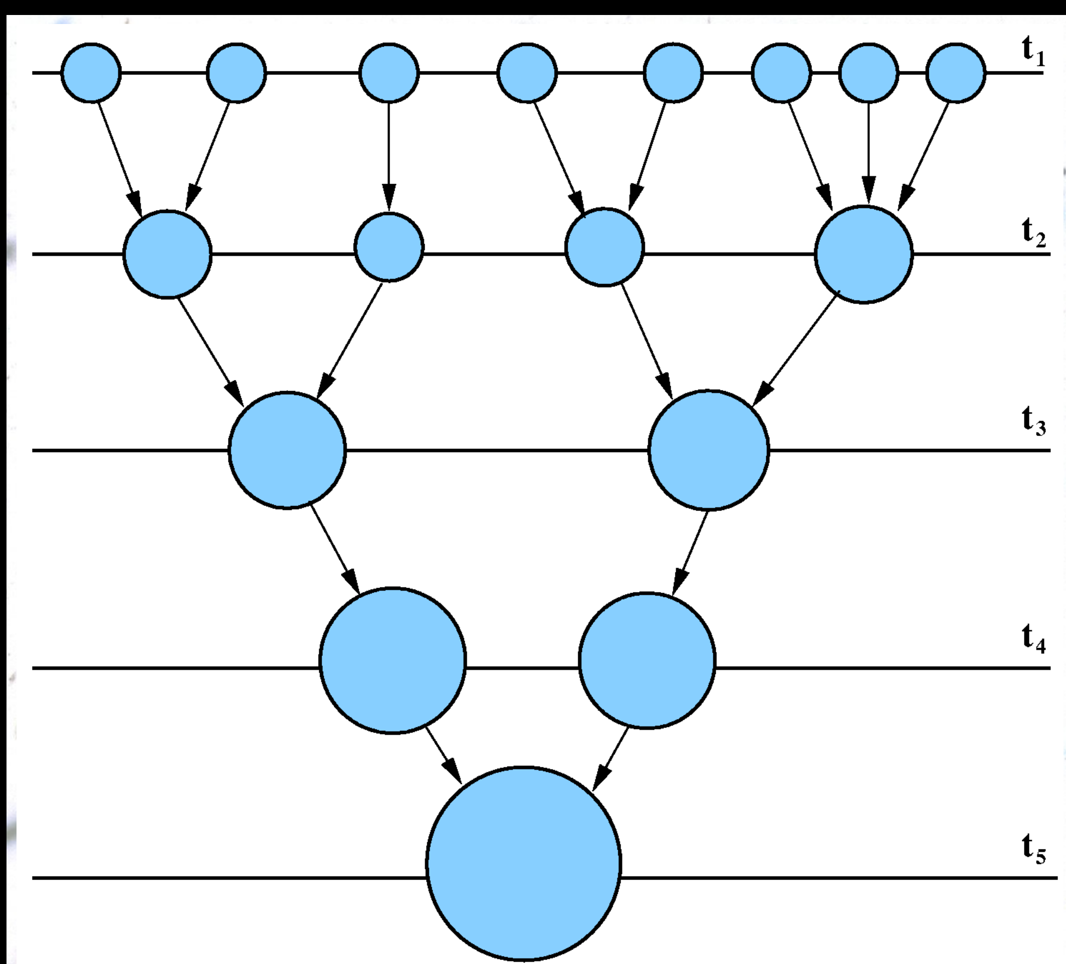


OR, Semi-Analytic Model:

Simulate Directly:

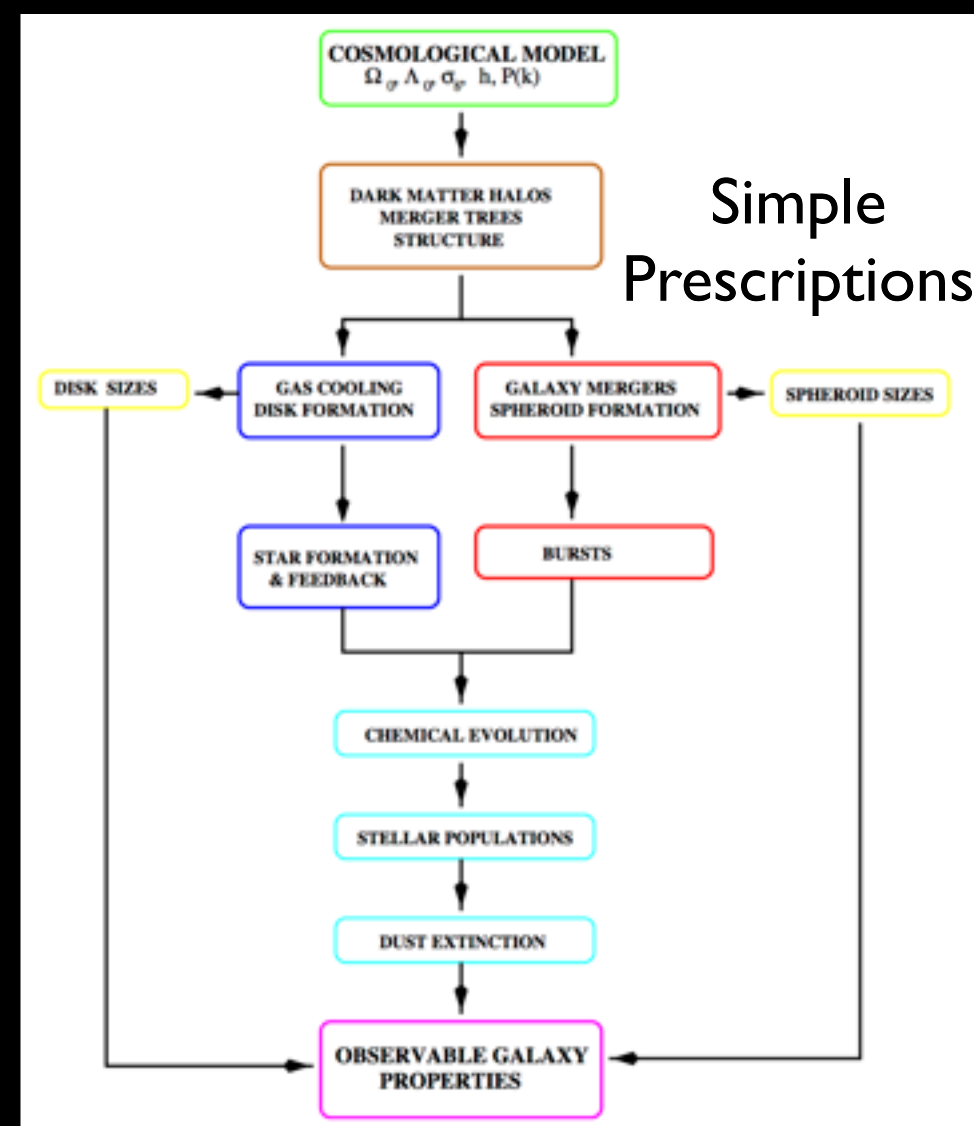


OR, Semi-Analytic Model:



+

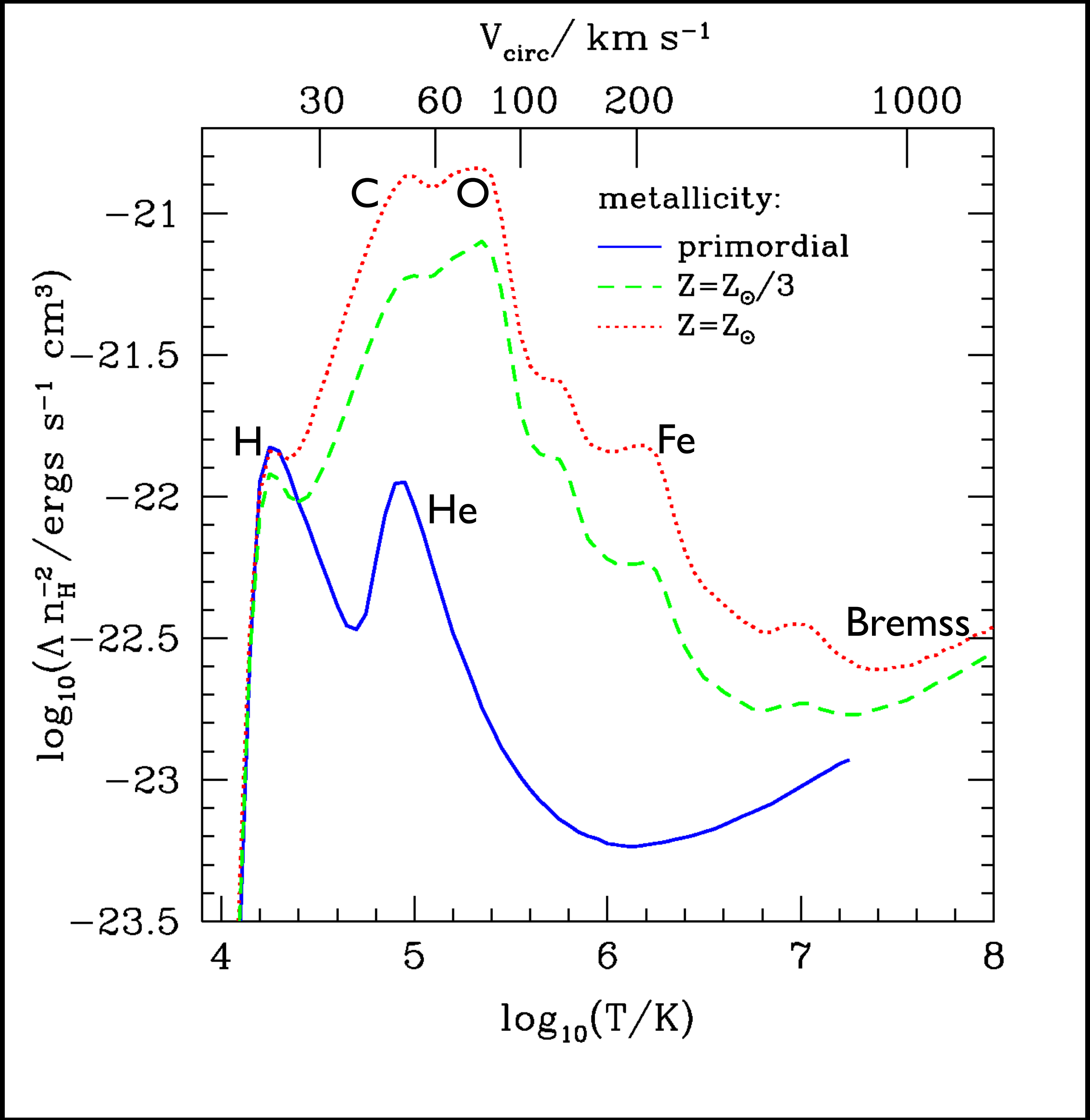
Simple Prescriptions



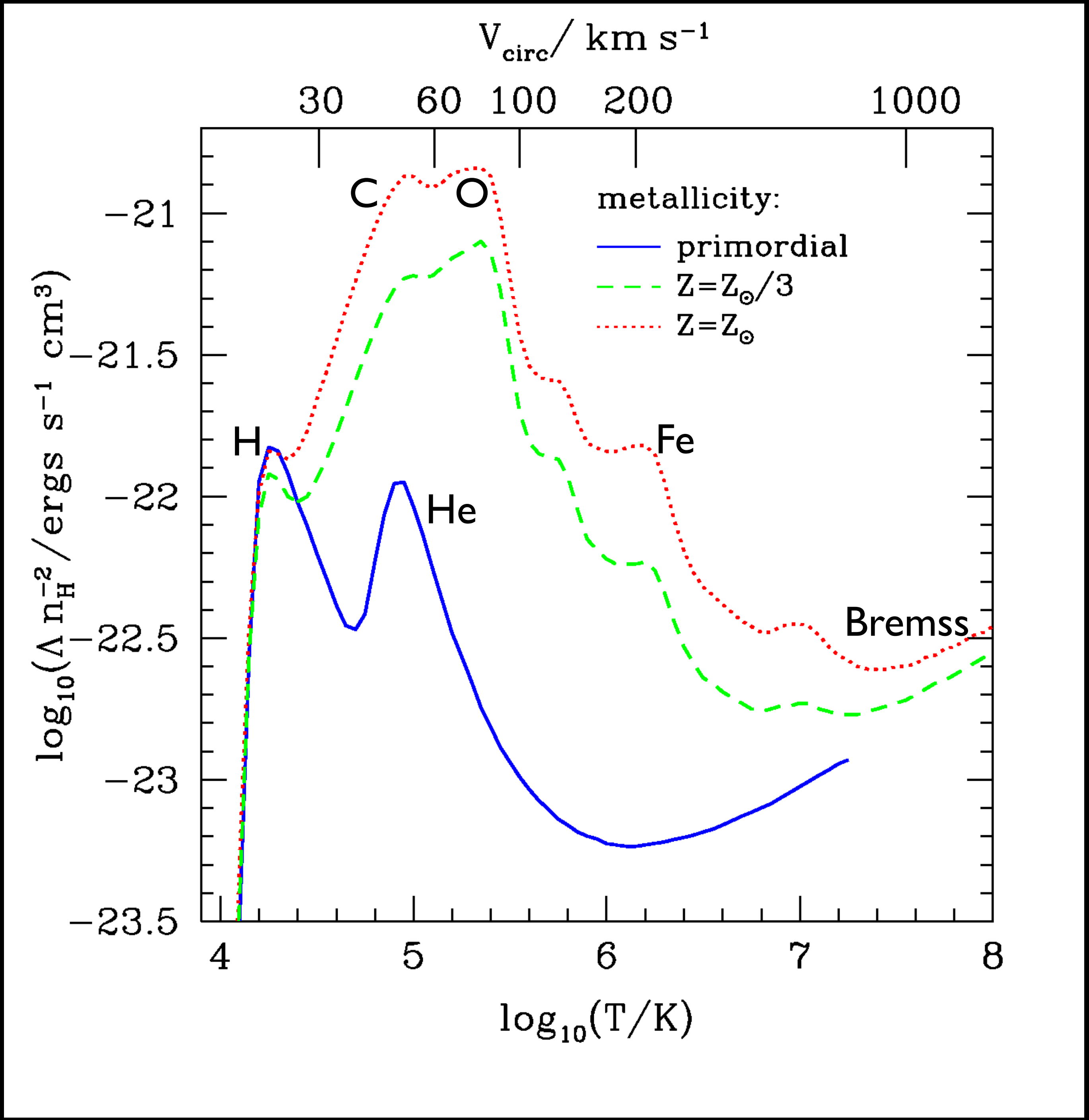
KE >> PE, nothing happens

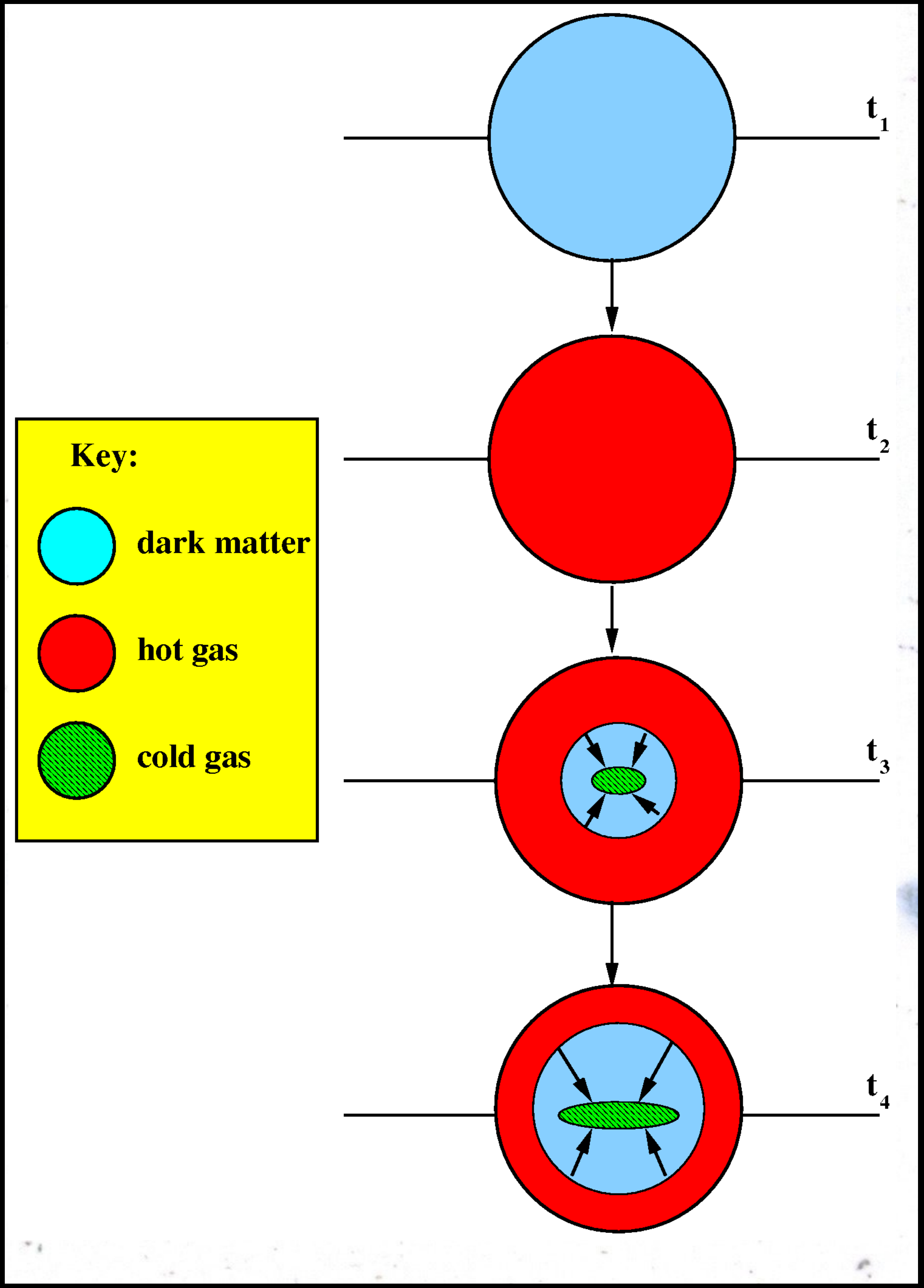
$$c_s \gtrsim V_{\rm vir}$$

$$V_{\rm vir} > 10\,{\rm km\,s^{-1}} \rightarrow M_{\rm vir} \gtrsim 10^8\,M_{\rm sun}$$

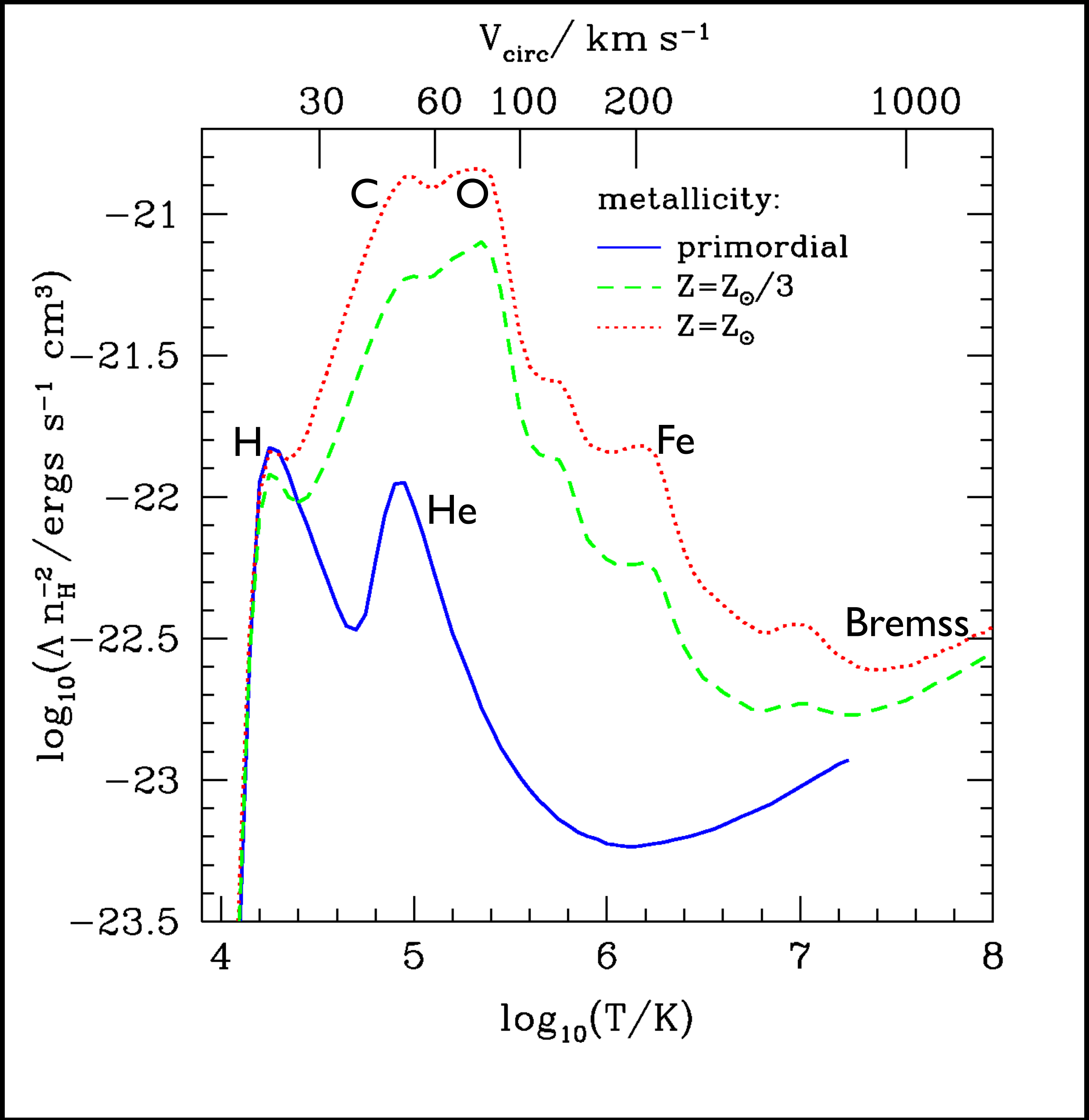


- Inverse Compton (CMB vs hot halo, z>10)
- Bremsstrahlung + Metal-Lines ($T>10^6$)
- Atomic/Recombination ($10^4 < T < 10^6$)
- Molecular + Fine Structure ($T < 10^4$)

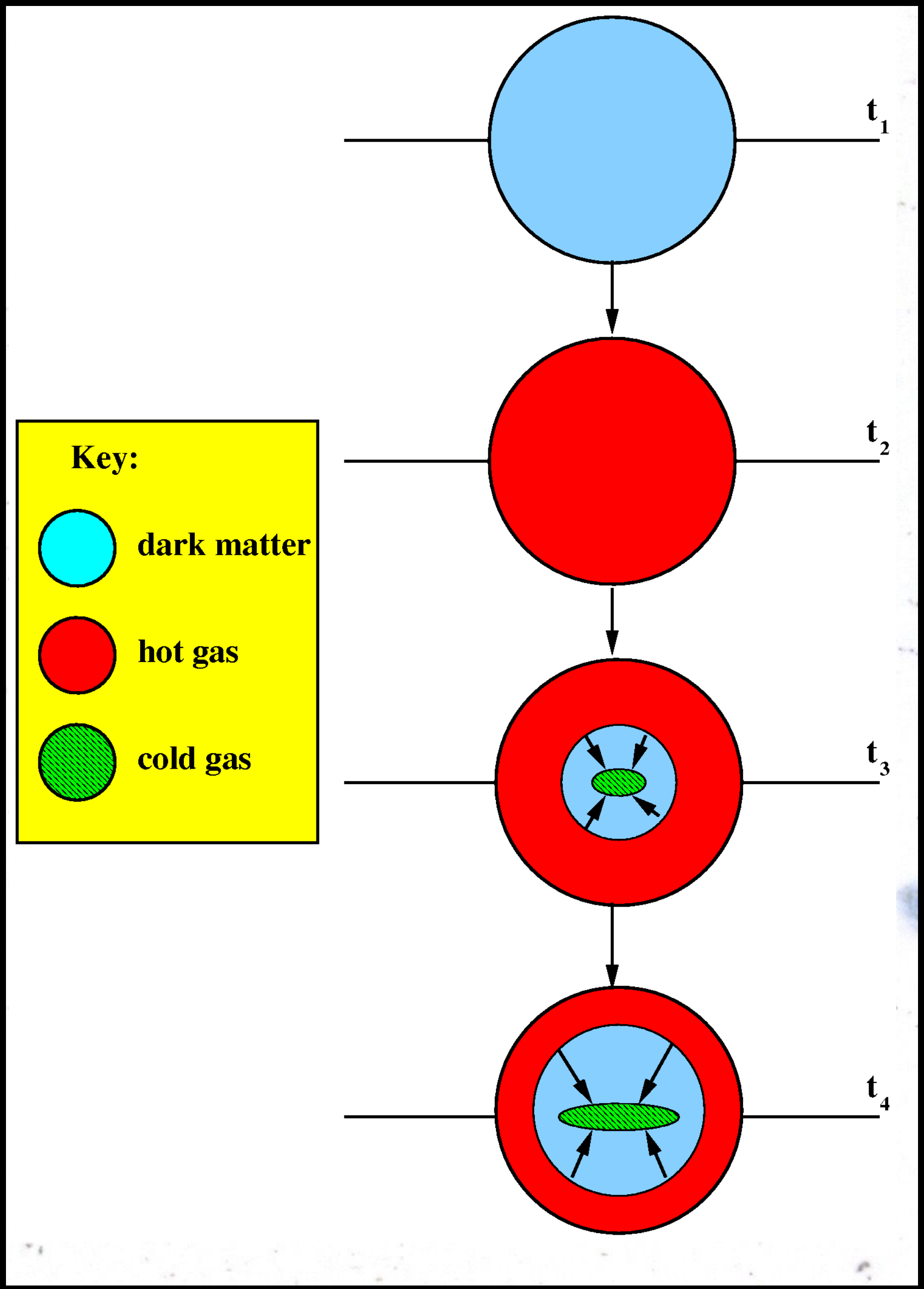




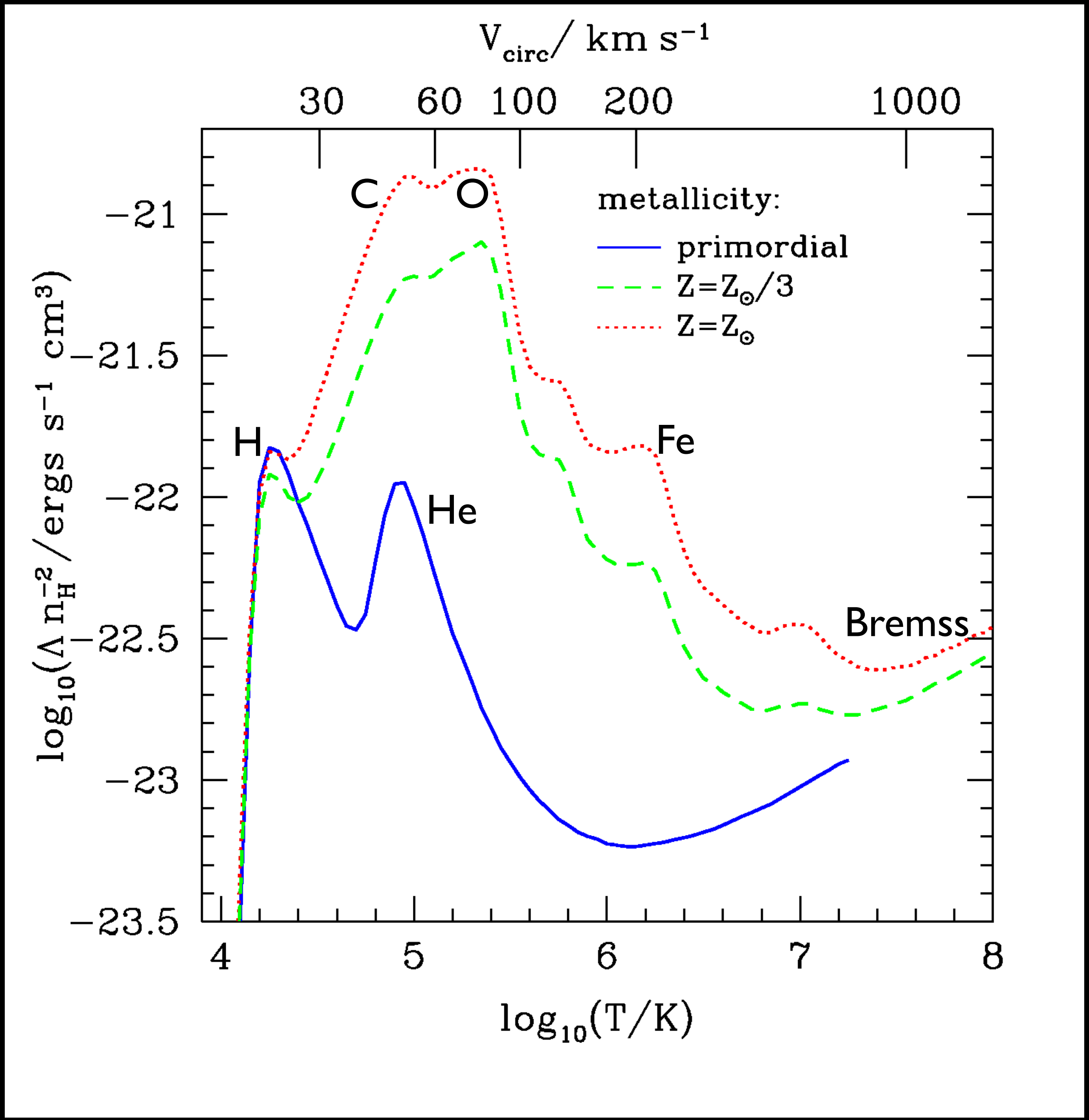
- Inverse Compton (CMB vs hot halo, z>10)
- Bremsstrahlung + Metal-Lines ($T>10^6$)
- Atomic/Recombination ($10^4 < T < 10^6$)
- Molecular + Fine Structure ($T < 10^4$)

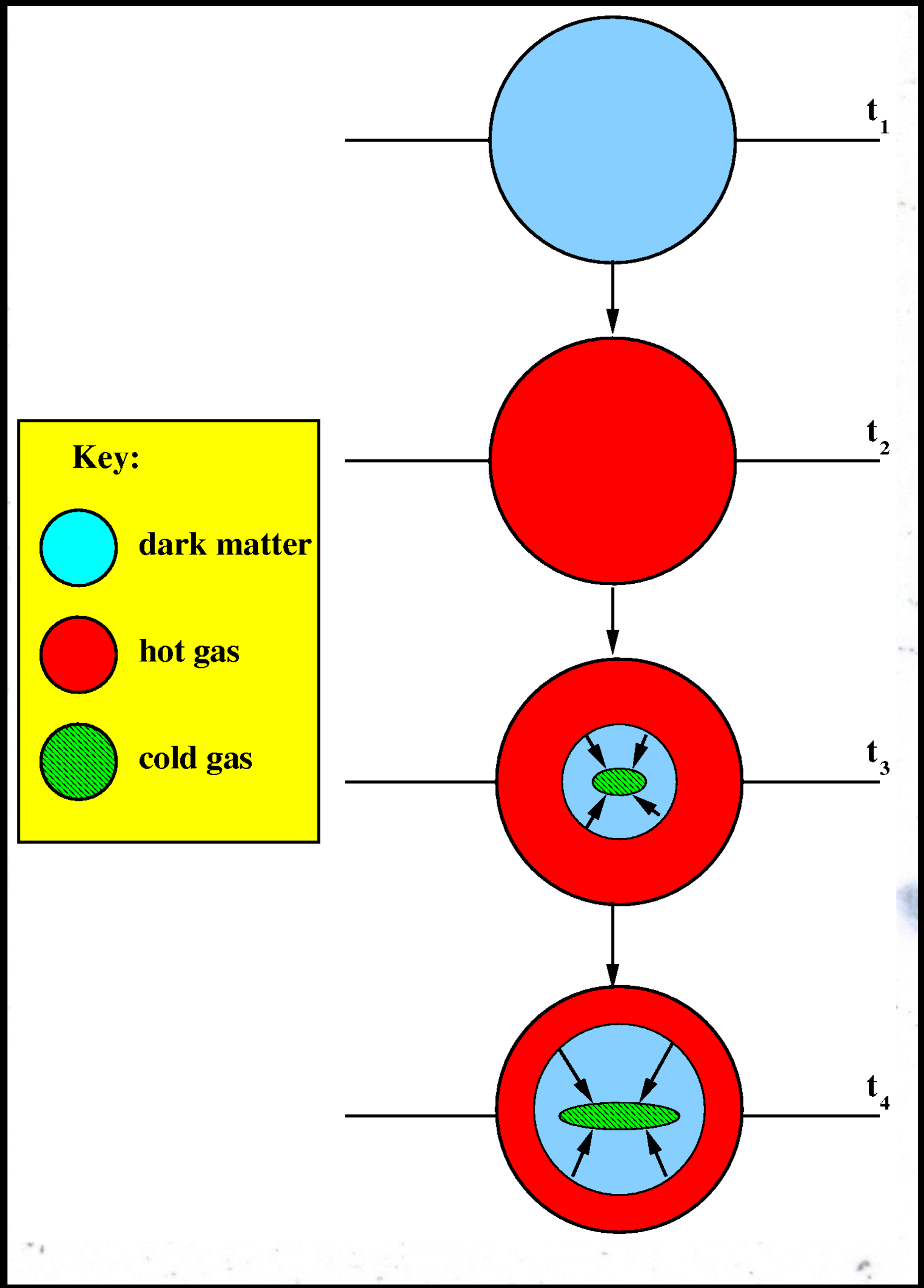


V_{circ}/ km s^{-1}
30
60
100
200
1000
C
O
metallicity:
primordial
$Z=Z_\odot/3$
$Z=Z_\odot$
H
He
Fe
Bremss
$\log_{10}(\Lambda n_H^{-2}/\mathrm{ergs\ s^{-1}\ cm^3})$
−21
−21.5
−22
−22.5
−23
−23.5
4
5
6
7
8
$\log_{10}(T/K)$

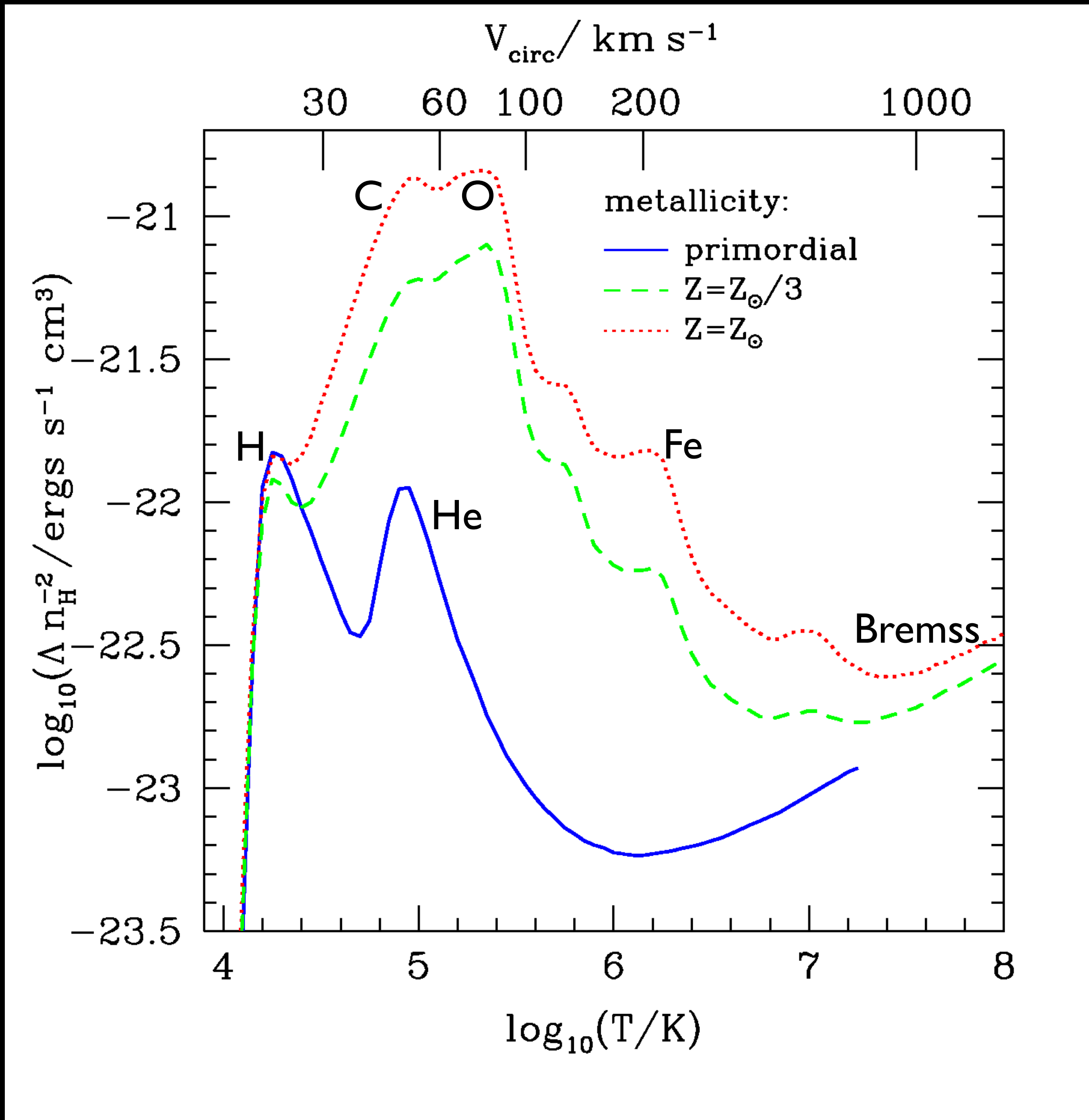


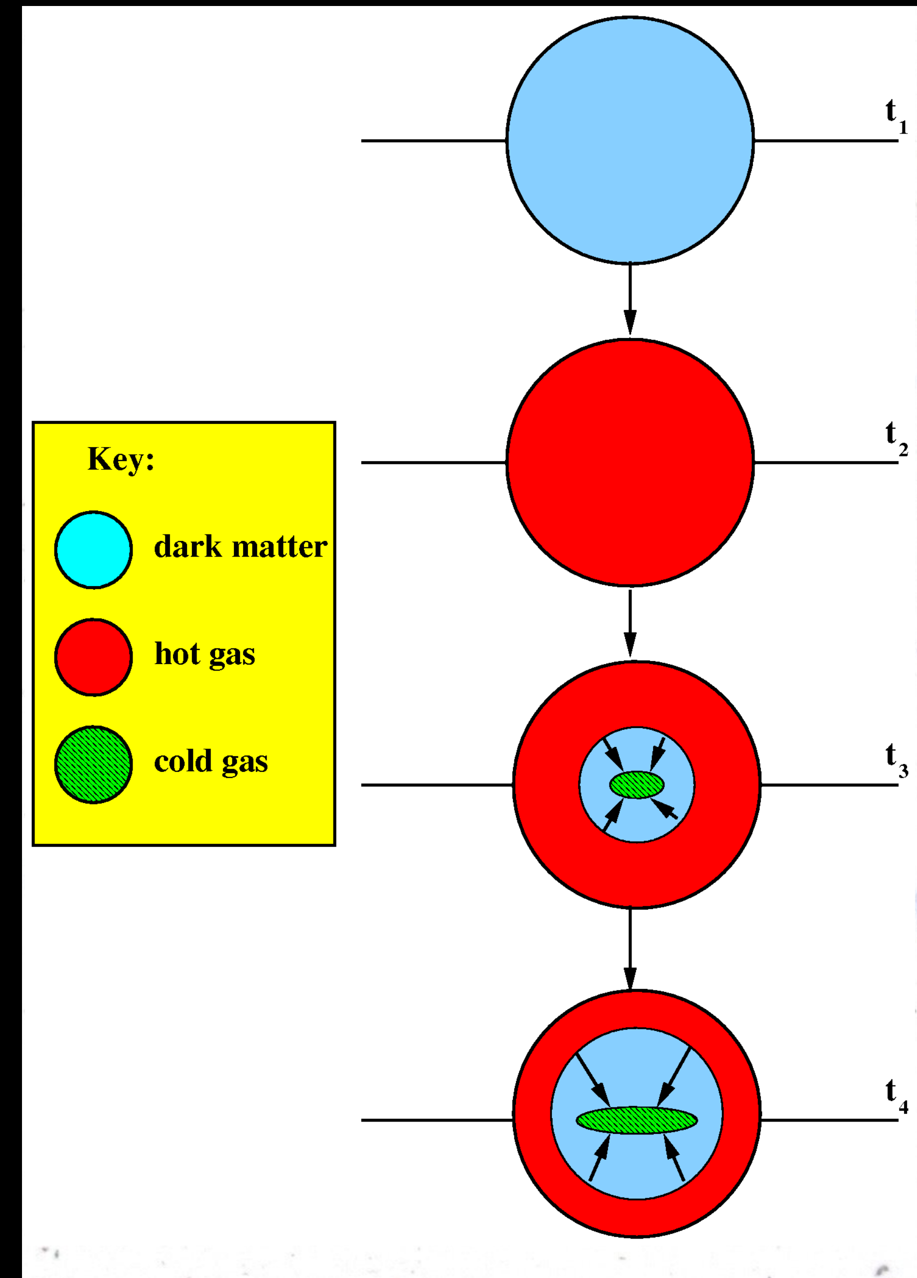
t_1
t_2
t_3
t_4
Key:
dark matter
hot gas
cold gas





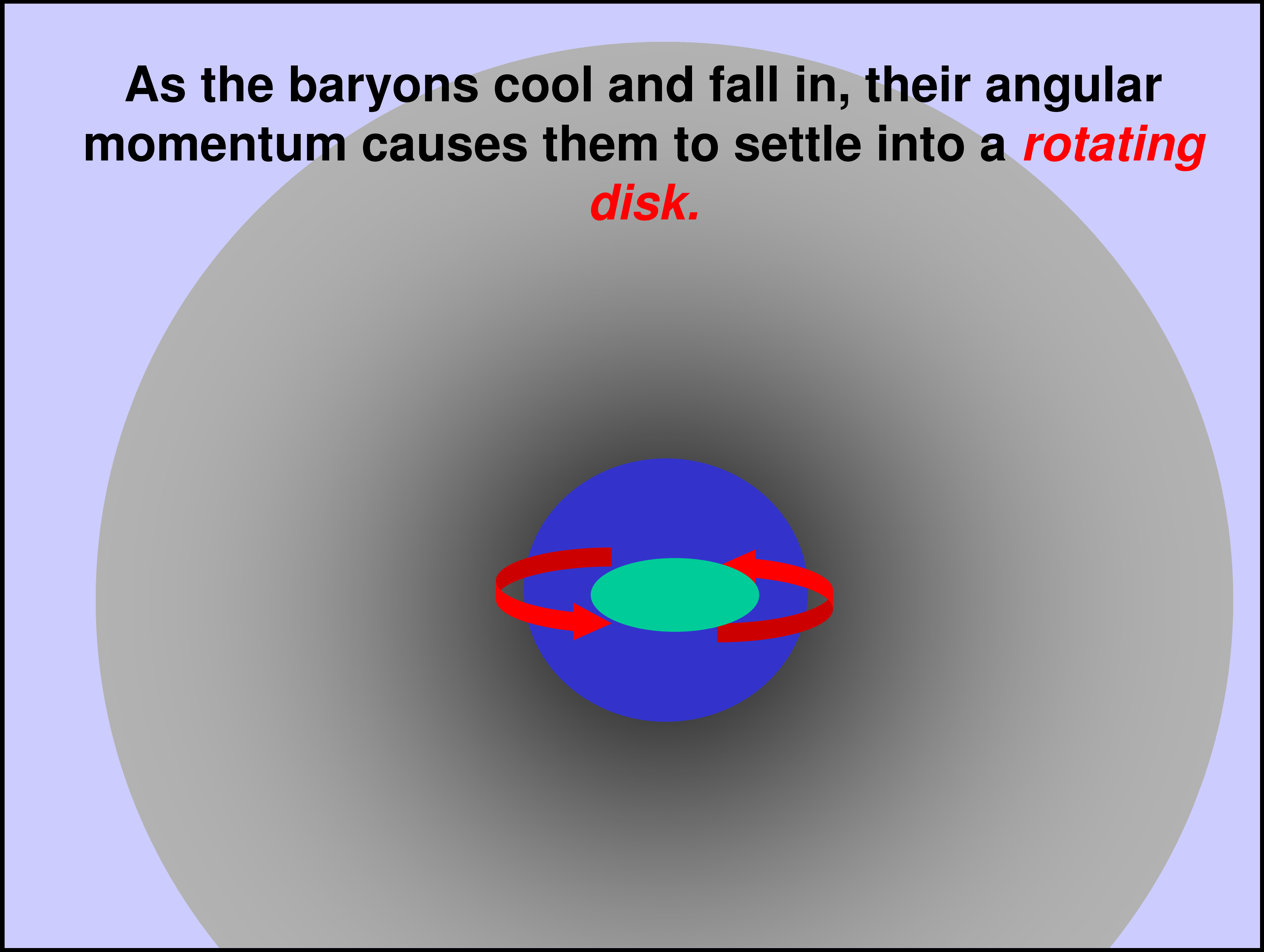
$$t_{\rm cool} = \frac{E}{\dot{E}} = \frac{\left(\frac{3}{2}\,\frac{\rho_{\rm gas}\,k\,T_{\rm vir}}{\mu m_{\rm H}}\right)}{\rho_{\rm gas}^2\,\Lambda(T_{\rm vir},\ Z_{\rm gas})}$$





$$t_{\rm cool} = \frac{E}{\dot{E}} = \frac{\left(\frac{3}{2}\,\frac{\rho_{\rm gas}\,k\,T_{\rm vir}}{\mu m_{\rm H}}\right)}{\rho_{\rm gas}^2\,\Lambda(T_{\rm vir},\ Z_{\rm gas})}$$

$$t_{\rm dyn} = \frac{R}{V_{\rm grav}} \approx \frac{1}{\sqrt{G\rho}}$$

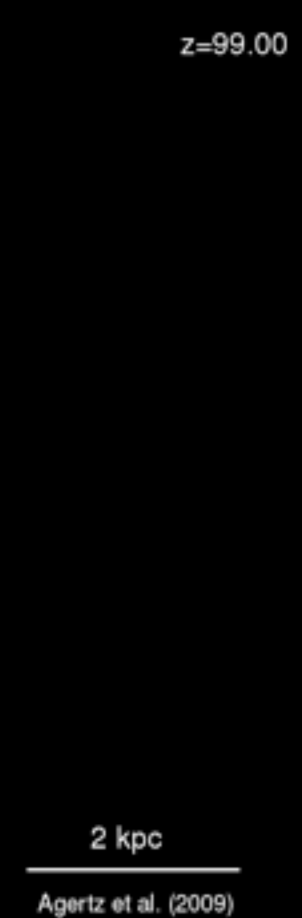


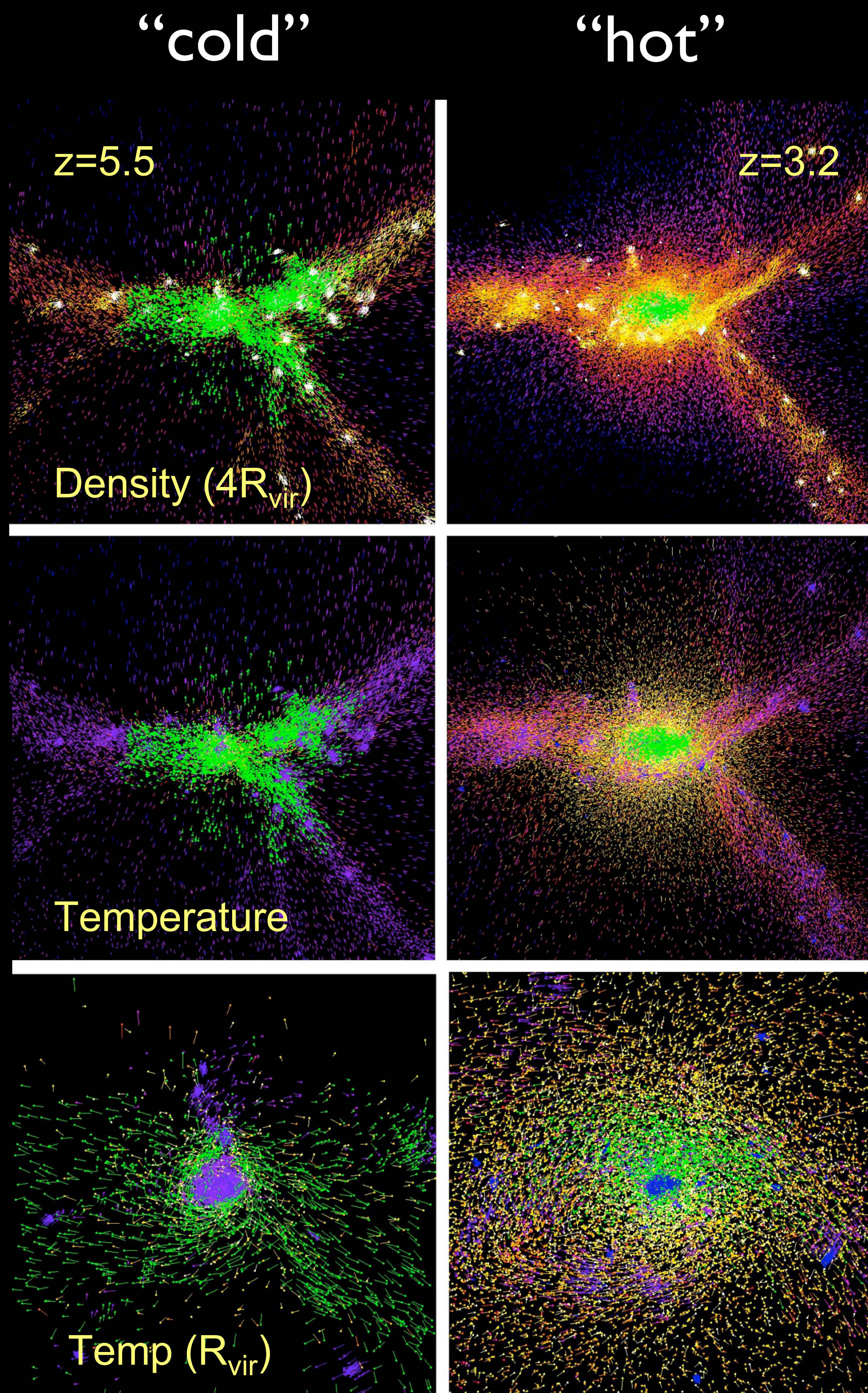
$$j = \frac{J}{M} \sim R_{\rm disk}\, V_{\rm disk} \sim \frac{\langle J_{\rm halo} \rangle}{M_{\rm halo}} = \lambda\, R_{\rm vir}\, V_{\rm vir}$$

$$\text{sims} : \lambda \sim 0.05$$

How Gas Gets Into Galaxies

- Modes of Gas Accretion (Keres et al 05):
  - Hot Mode: (White&Rees 78) Gas shock heats at halo's virial radius up to T_{vir}, cools slowly onto disk. Limited by t_{cool}. Hydrostatic eqm $kT/m \sim v^2$
  - Cold Mode: (Binney 77) Gas radiates its potential energy away in line emission at $T << T_{vir}$, and never approaches virial temperature. Limited by t_{dyn}. $kT/m << v^2$

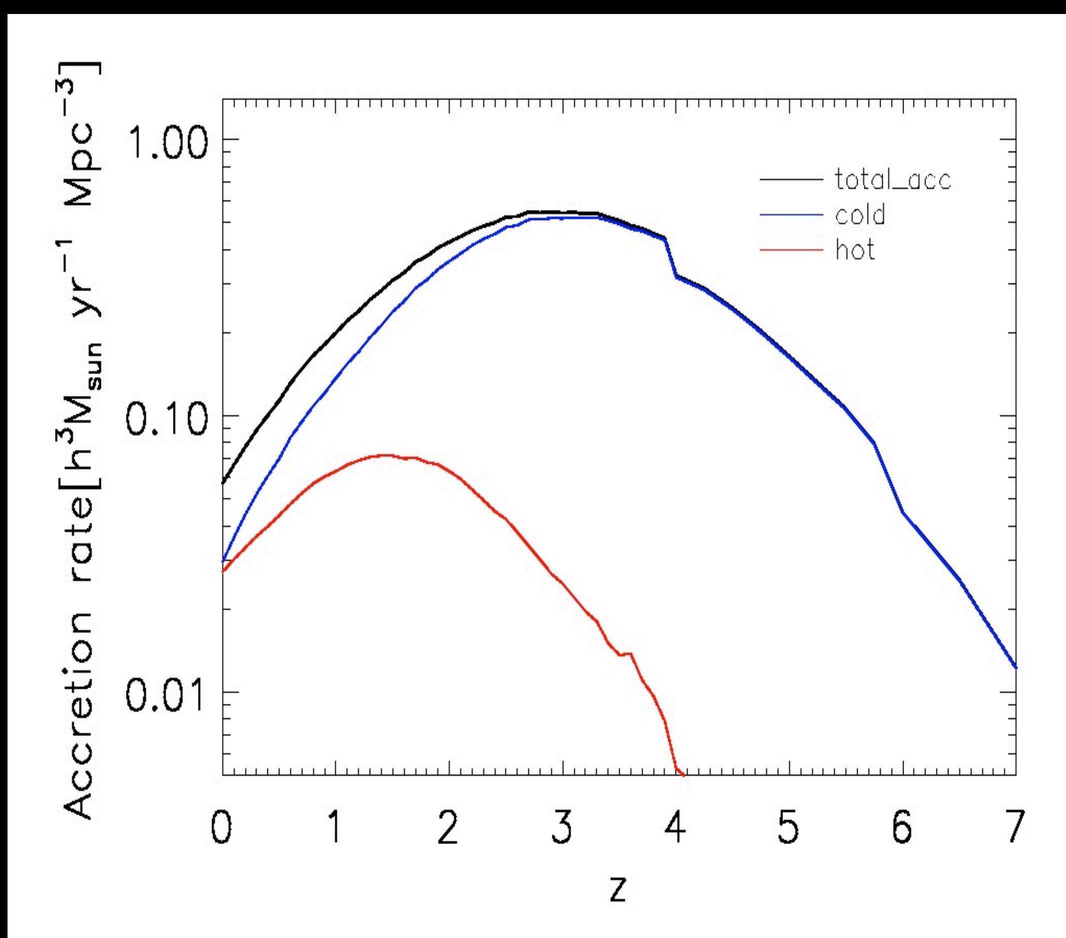




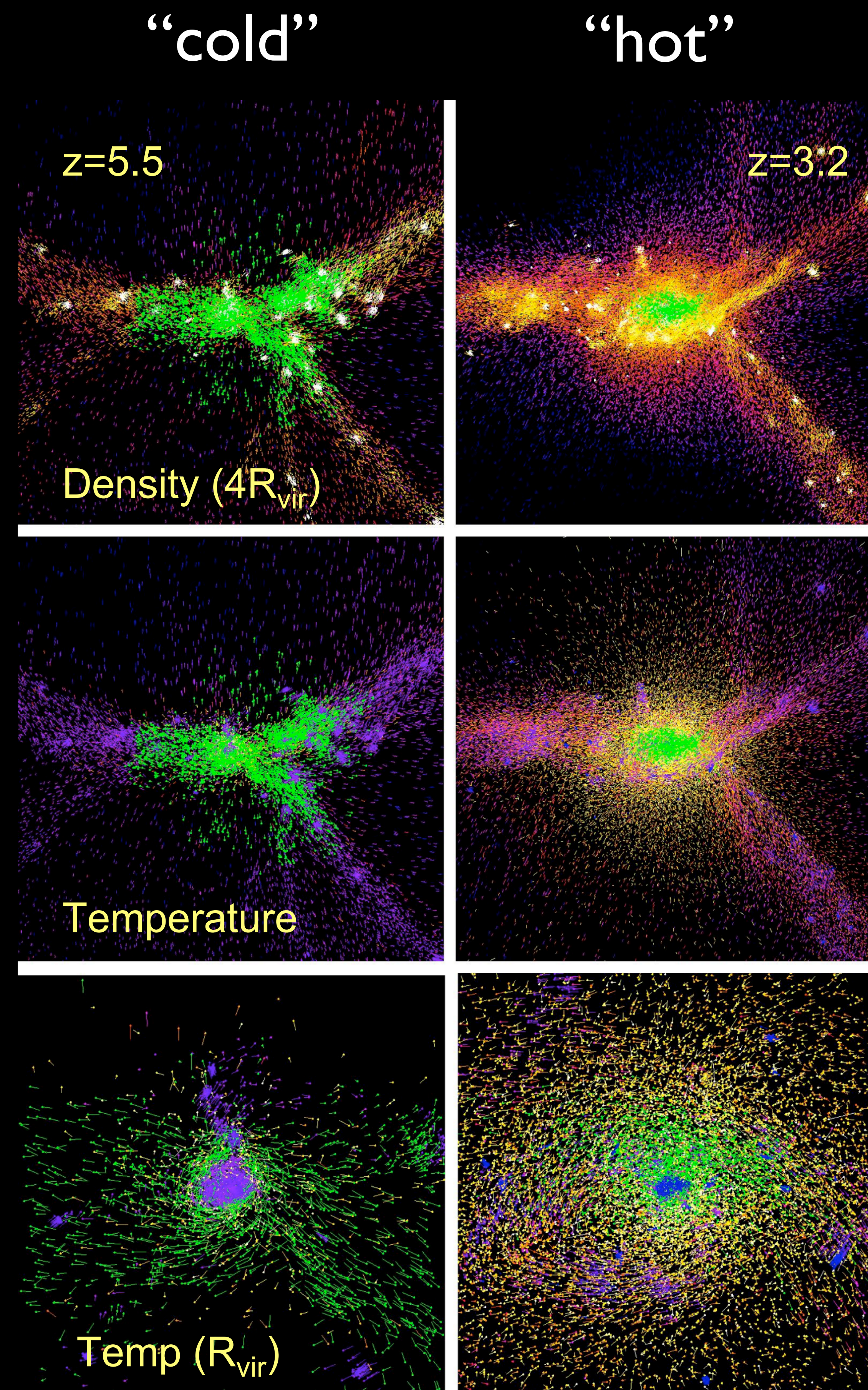
Keres et al 2005

How Gas Gets Into Galaxies

- Modes of Gas Accretion (Keres et al 05):
  - Hot Mode: (White&Rees 78) Gas shock heats at halo's virial radius up to T_{vir}, cools slowly onto disk. Limited by t_{cool}. Hydrostatic eqm $kT/m \sim v^2$
  - Cold Mode: (Binney 77) Gas radiates its potential energy away in line emission at $T<<T_{vir}$, and never approaches virial temperature. Limited by t_{dyn}. $kT/m << v^2$



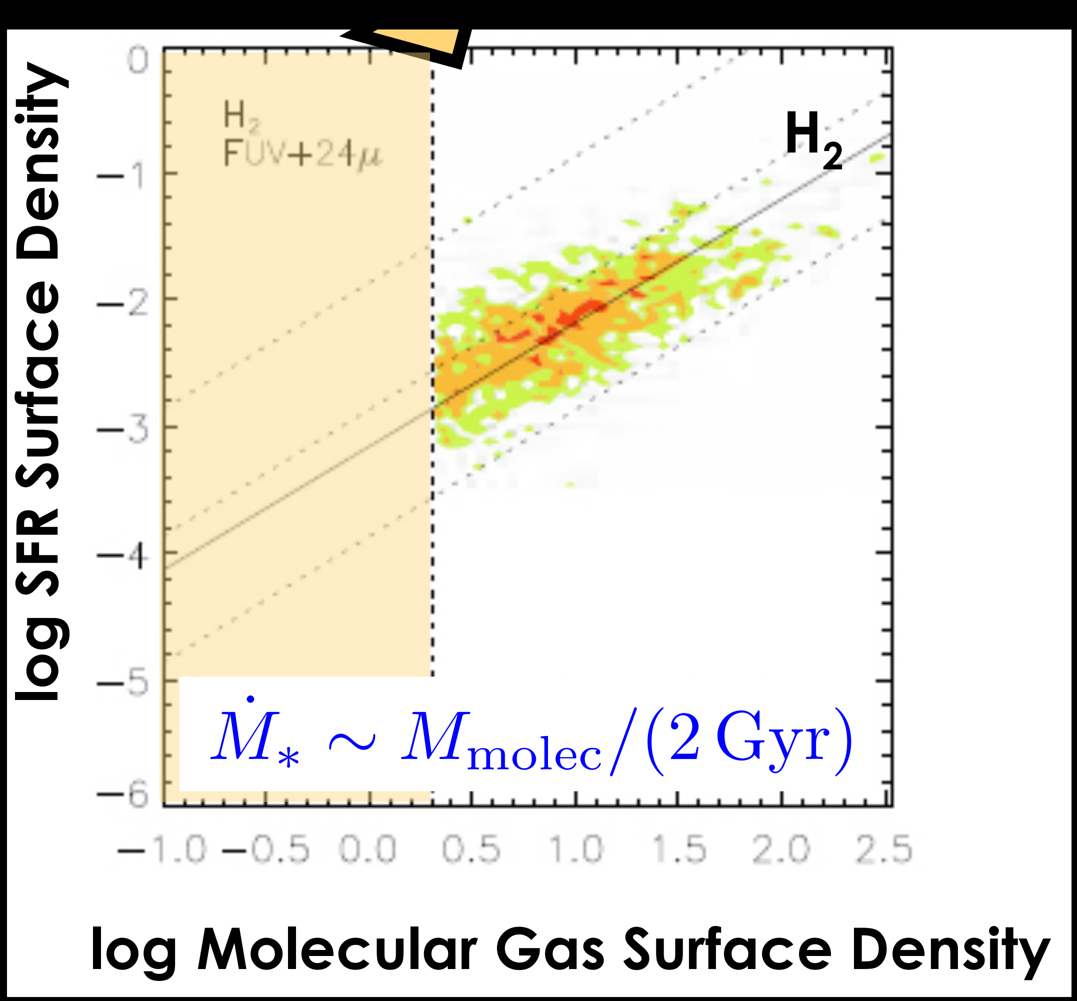
Kereš et al. 2009

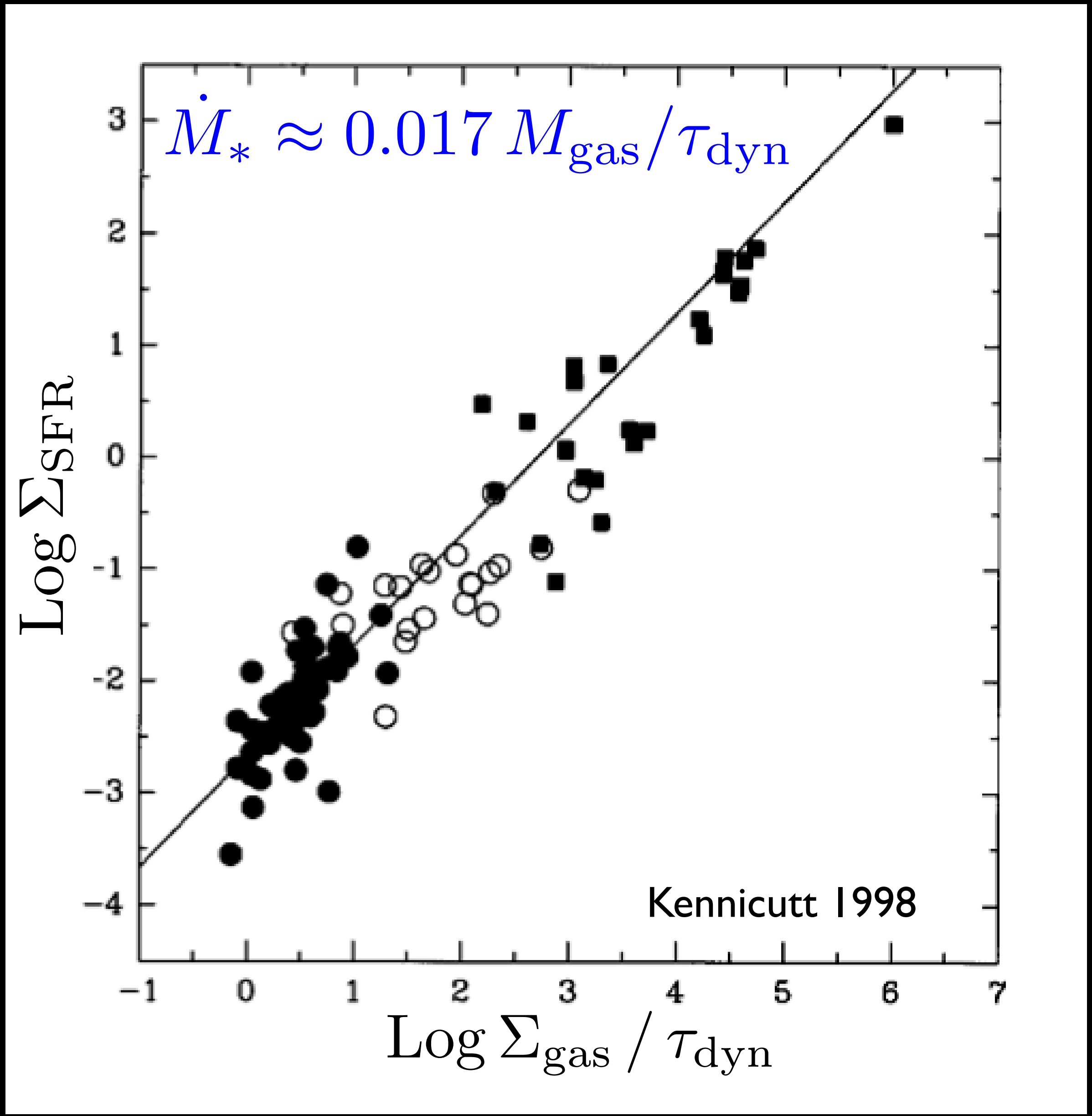


Keres et al 2005

Star Formation?

$$\dot{M}_* \sim \frac{M_{\rm gas}}{\langle \tau(\Sigma_{\rm gas},\, Z,\, f_{\rm molec},\, t_{\rm dyn}, \ldots) \rangle}$$

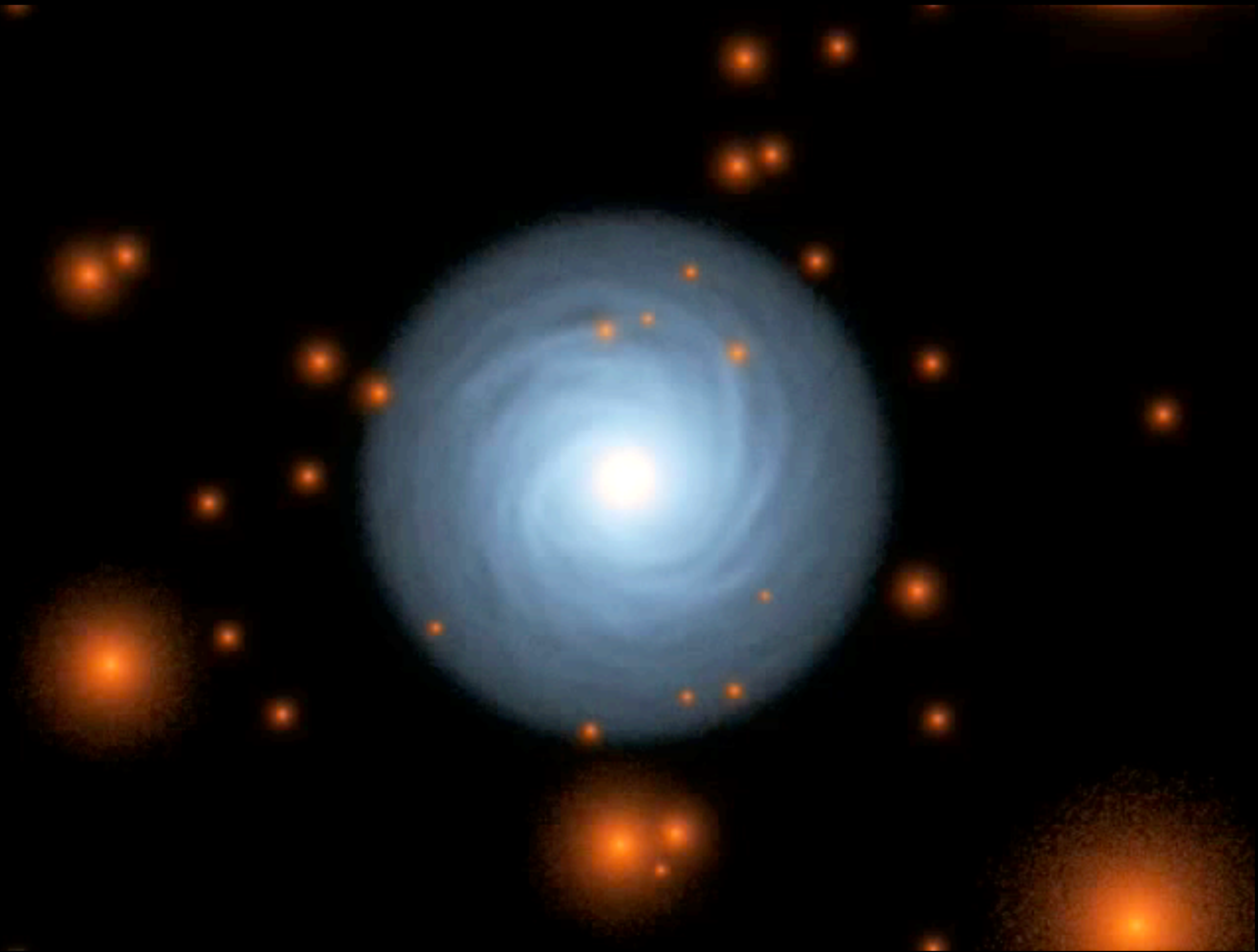




Mergers: Major (~1/Dz)

- violent relaxation destroys disks
- phase space conserved: Tully-Fisher > Faber-Jackson
- scramble into r^1/4-law, randomize orbits

Mergers: Minor (~10s/Dz)

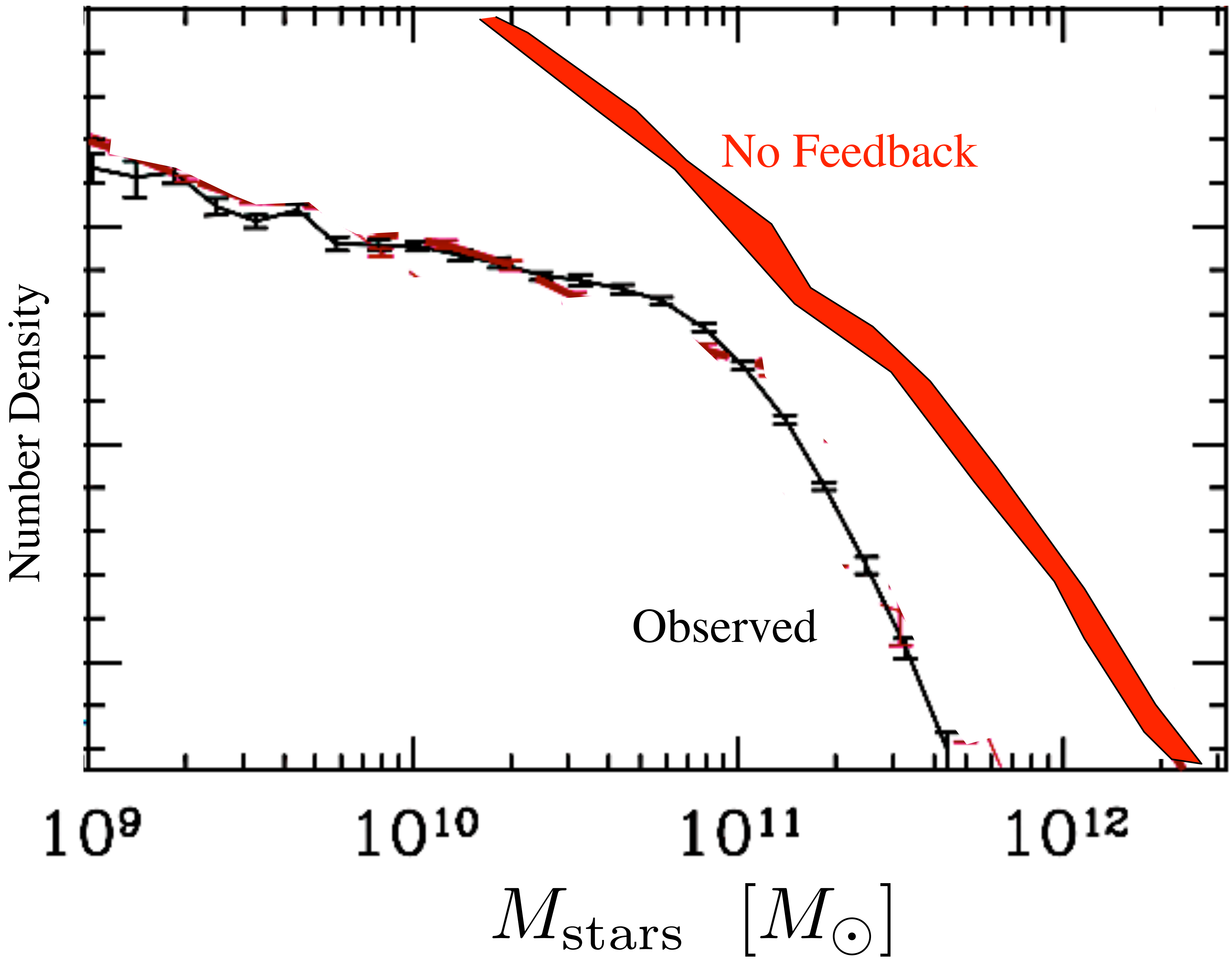


- "heats" disk (thin to thick)
- excite spirals & bars ("secular" structure)
- shred the small galaxies into the halo

... So, do we understand it? ...

Problem:

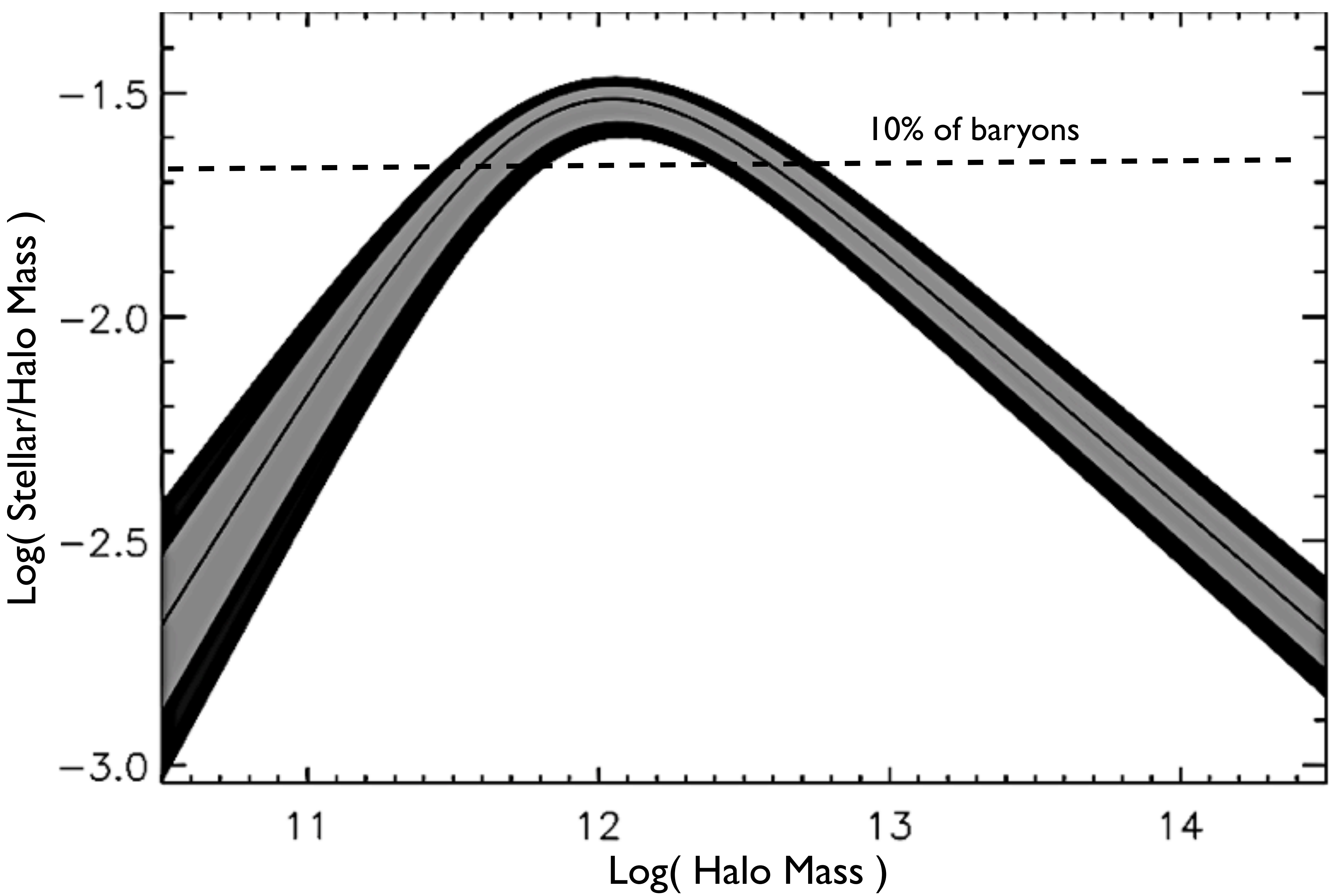
Q: WHY IS STAR FORMATION SO INEFFICIENT?



Problem:

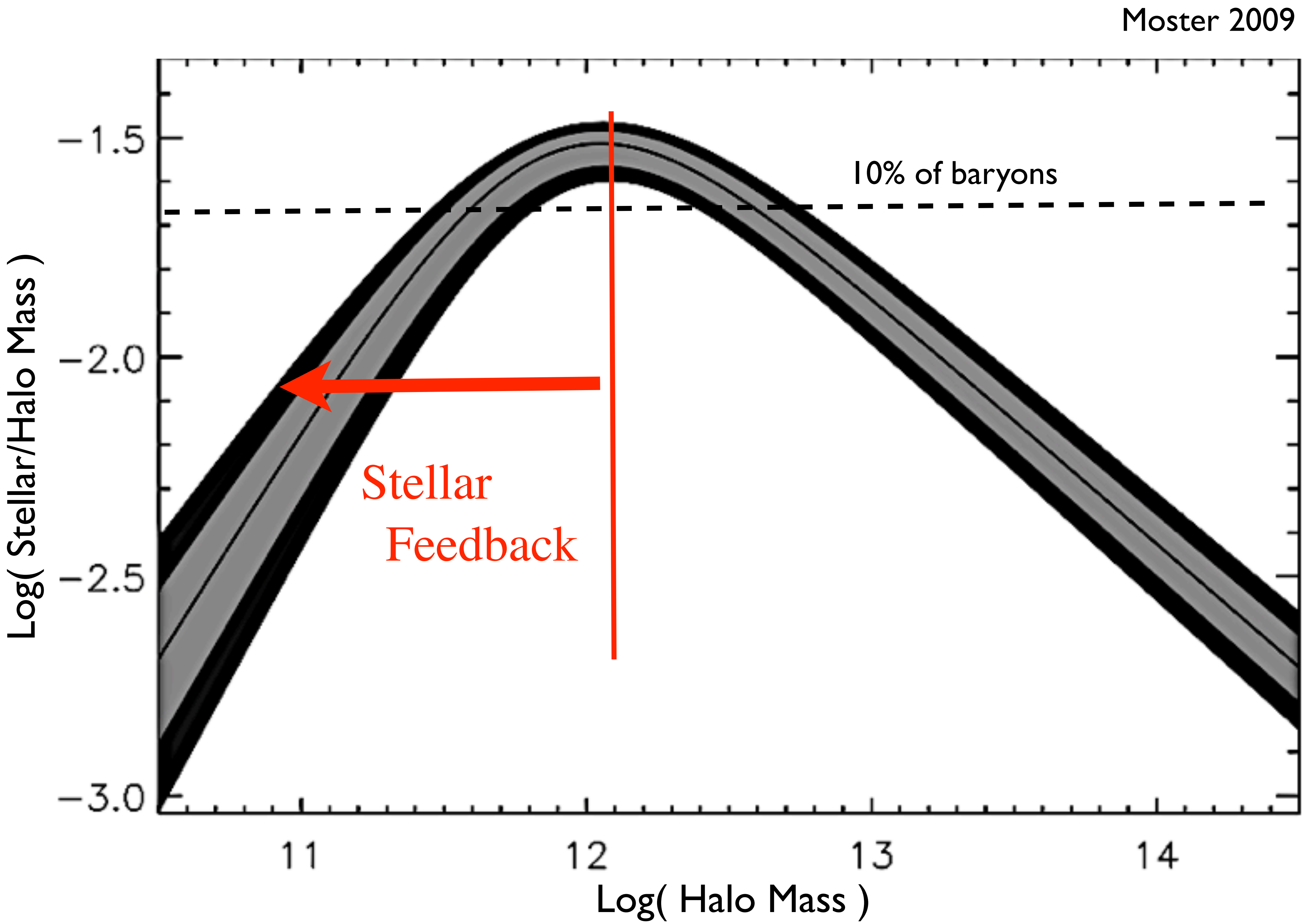
Q: WHY IS STAR FORMATION SO INEFFICIENT?

Moster 2009



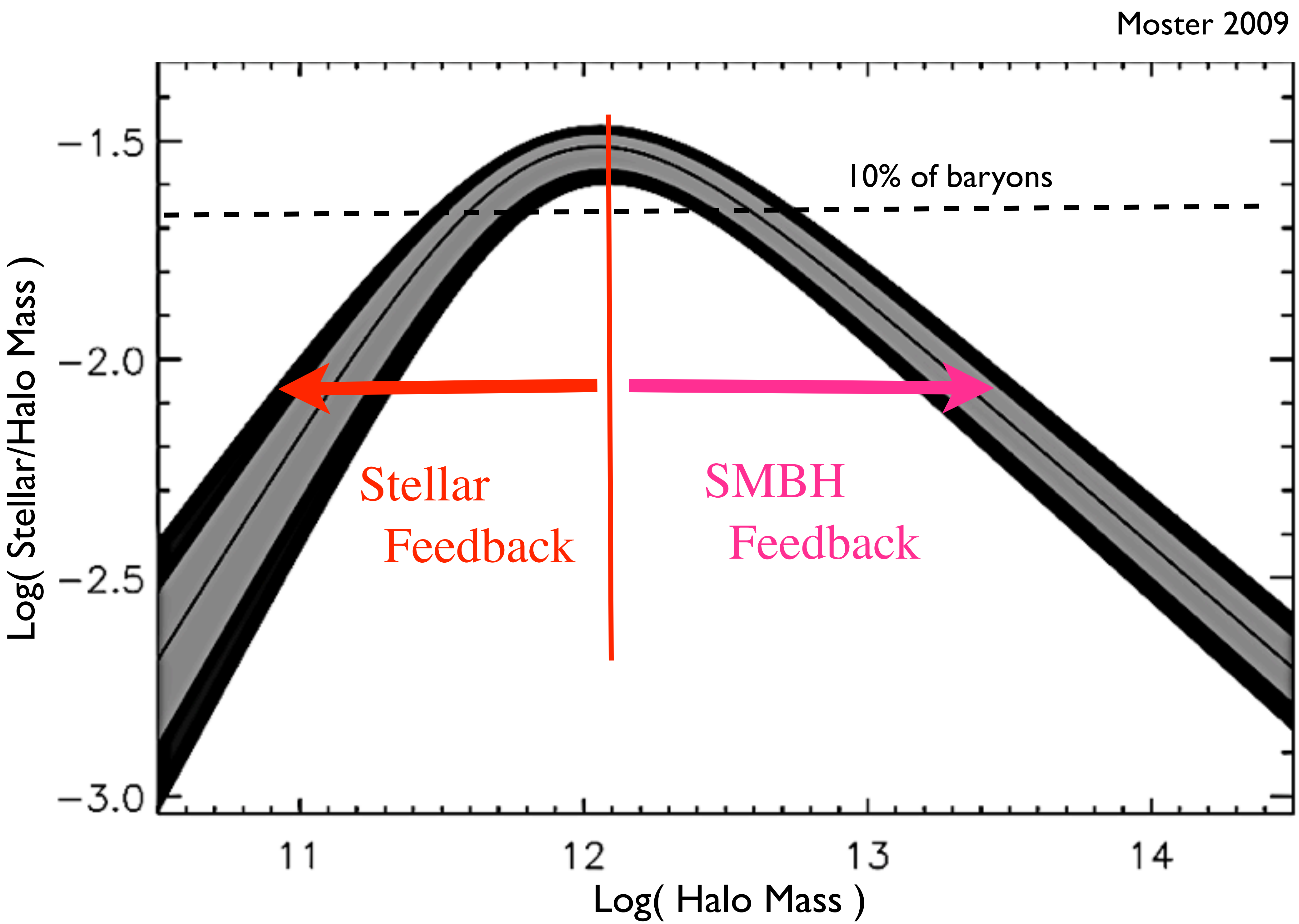
Problem:

Q: WHY IS STAR FORMATION SO INEFFICIENT?



Problem:

Q: WHY IS STAR FORMATION SO INEFFICIENT?



The predicted *swarm of small satellite galaxies* around the Milky Way

This N-body simulation of dark matter only predicts hundred of small satellite galaxies around large galaxies like the Milky Way. The actual number of galaxies is ***ten times fewer,*** suggesting that ***small dark halos have been swept clean of baryons.***

Kravtsov et al. 2004

How most simulations end up:

Galactic winds expel material from the galaxy: ***feedback*** from stars and black holes

Stellar Feedback is the Key (we think)

SO WHAT'S THE PROBLEM?

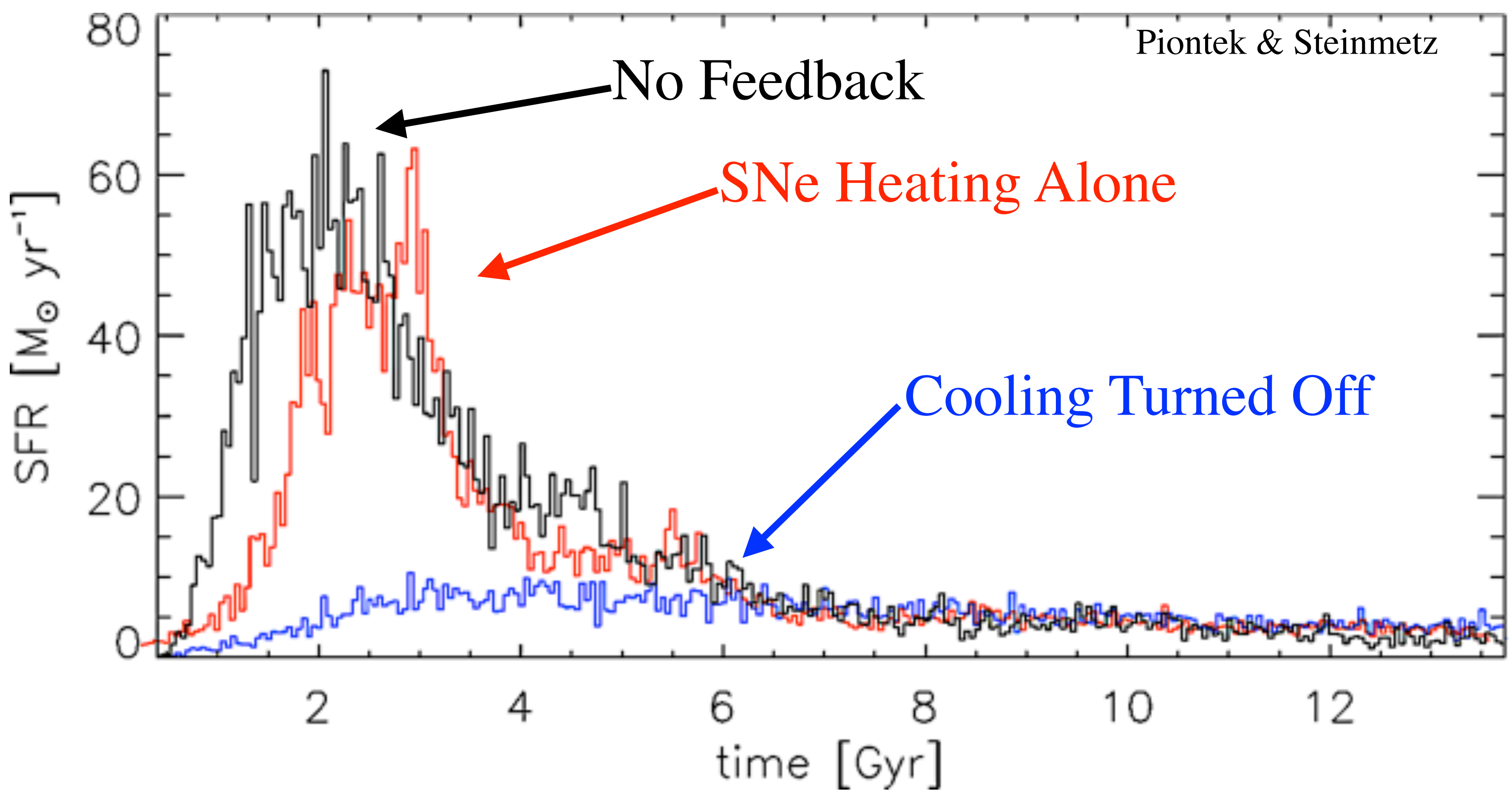
- Standard (in Galaxy Formation):
  Couple SNe (~1e51 erg/SN)
  as "heating"/thermal energy

- FAILS:

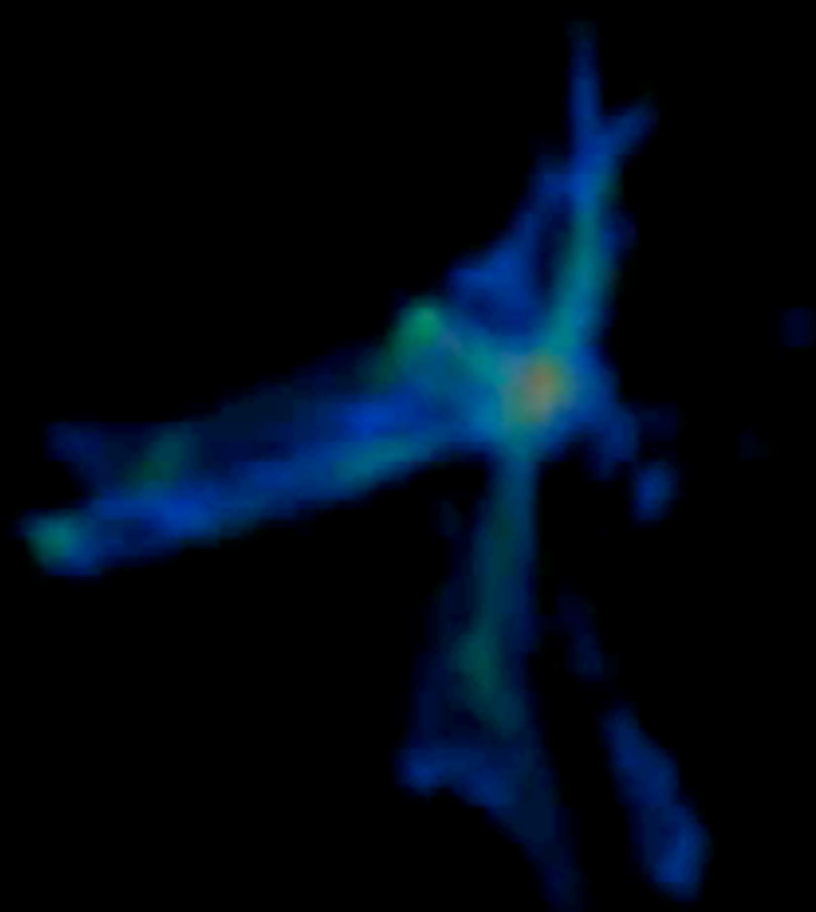
$$t_{\rm cool} \sim 4000\,{\rm yr}\left(\frac{n}{{\rm cm}^{-3}}\right)^{-1}$$

$$t_{\rm dyn} \sim 10^{8}\,{\rm yr}\left(\frac{n}{{\rm cm}^{-3}}\right)^{-1/2}$$

- "Cheat":
  - Turn off cooling
  - Force wind by hand
    ('kick' out of galaxy)



The ultimate in zoom-ins:
First Star (singular)



Stellar Feedback: How Can We Do Better?

Stellar Feedback: How Can We Do Better?

- High-resolution (~1pc), molecular cooling (<100 K), SF only at highest densities (n_H>1000 cm^{-3})

Stellar Feedback: How Can We Do Better?

- High-resolution (~1pc), molecular cooling (<100 K), SF only at highest densities (n_H>1000 cm^{-3})

- Heating:
  - SNe (II & Ia)
  - Stellar Winds
  - Photoionization (HII Regions)

Stellar Feedback: How Can We Do Better?

- High-resolution (~1pc), molecular cooling (<100 K), SF only at highest densities (n_H>1000 cm^{-3})

- Heating:
  - SNe (II & Ia)
  - Stellar Winds
  - Photoionization (HII Regions)

- *Explicit* Momentum Flux:
  - Radiation Pressure

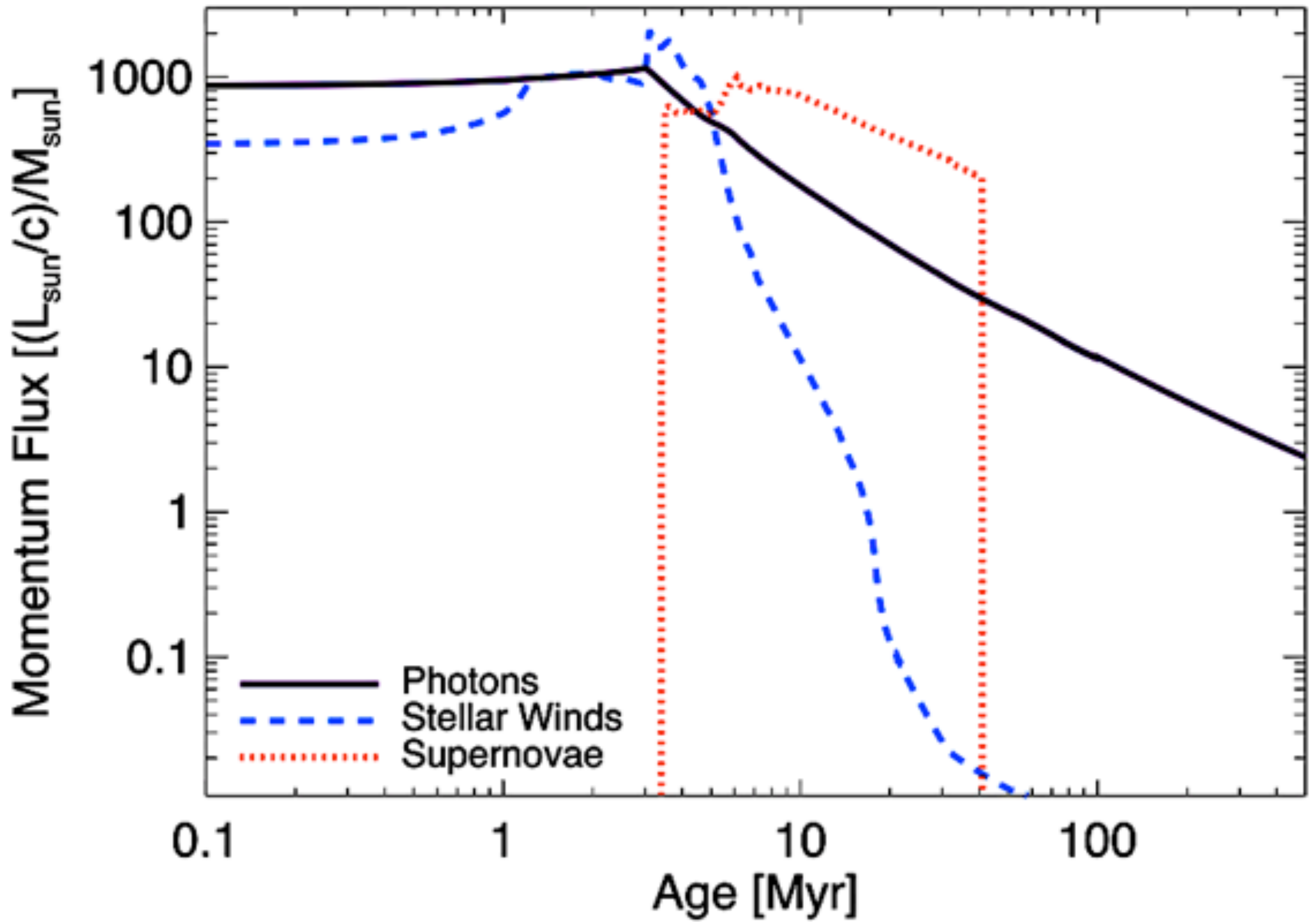
$$\dot{P}_{\rm rad} \sim \frac{L}{c}\,(1+\tau_{\rm IR})$$

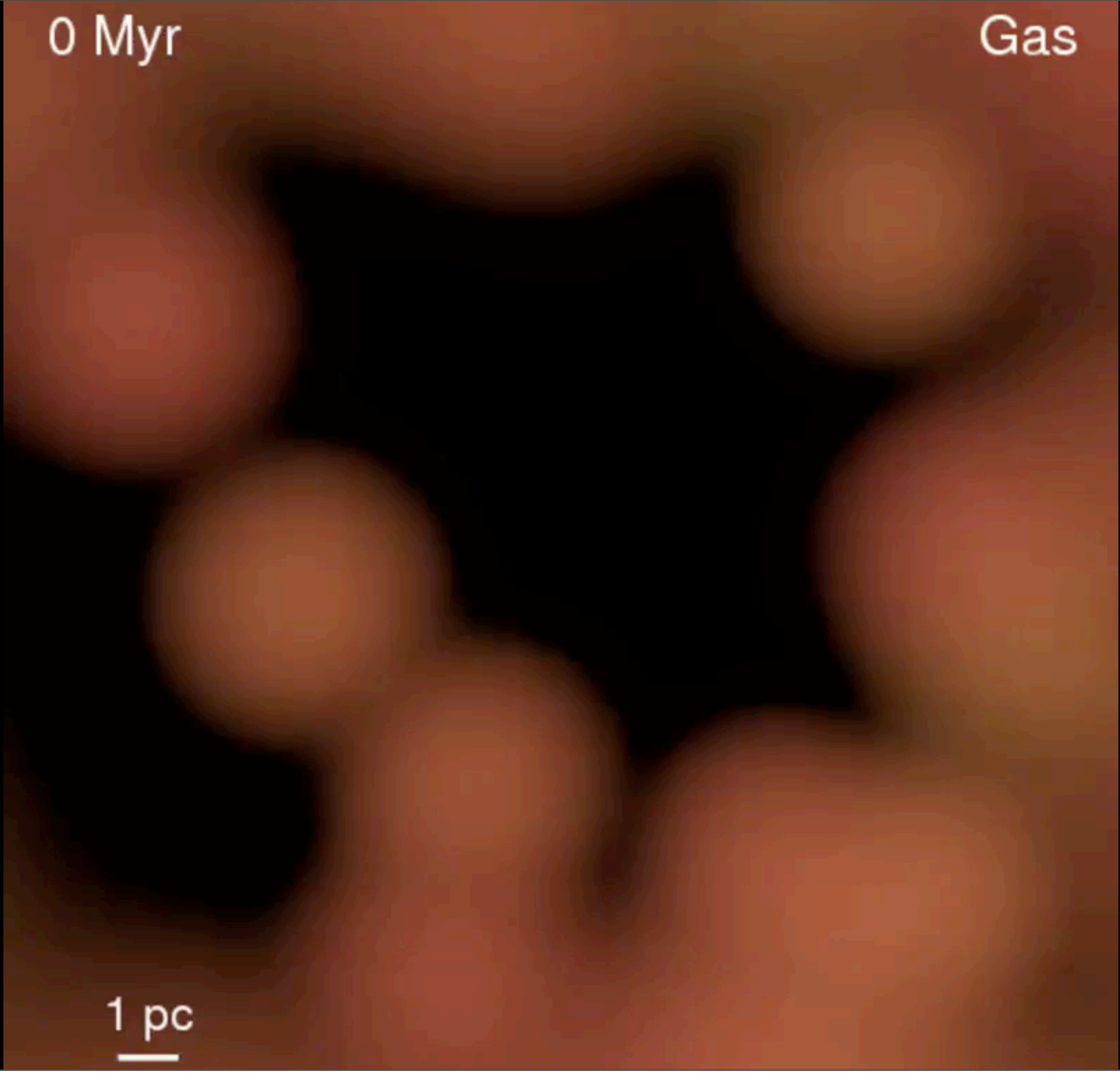
  - SNe

$$\dot{P}_{\rm SNe} \sim \dot{E}_{\rm SNe}\, v_{\rm ejecta}^{-1}$$

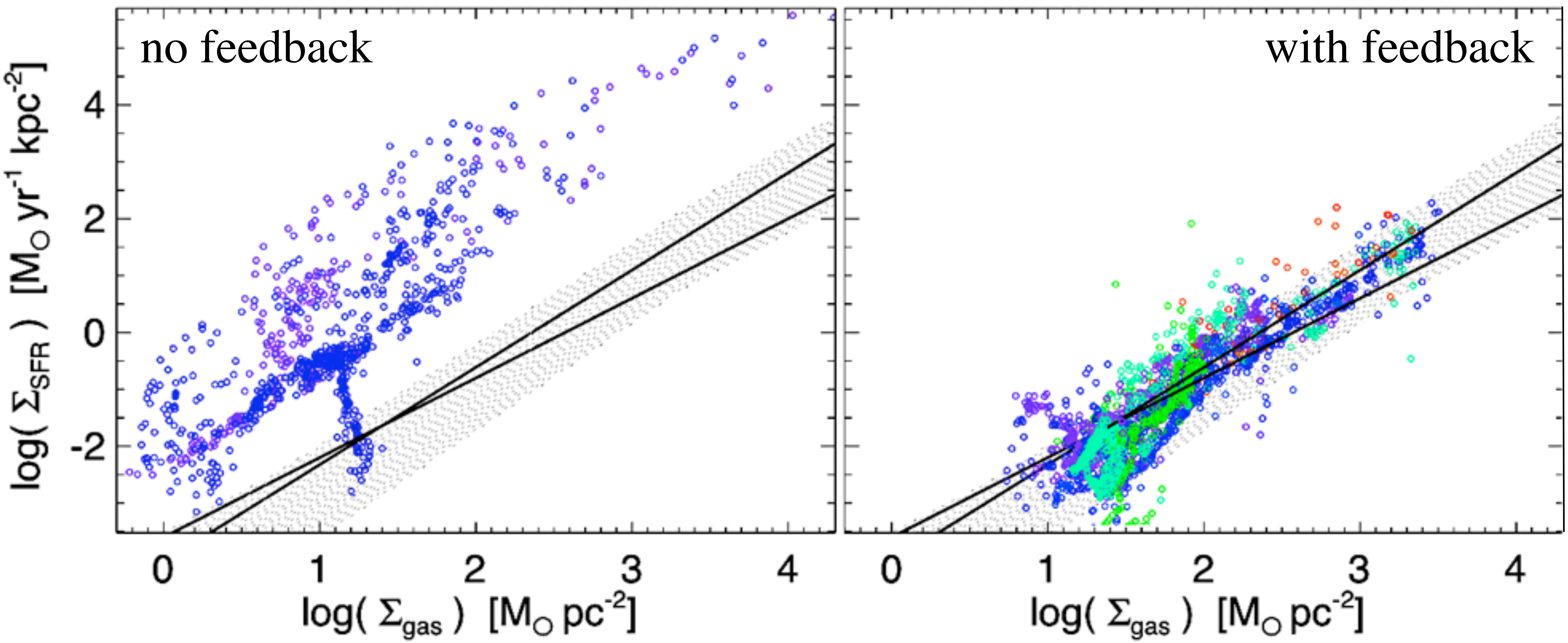
  - Stellar Winds

$$\dot{P}_{\rm W} \sim \dot{M}\, v_{\rm wind}$$




0 Myr
Gas
1 pc

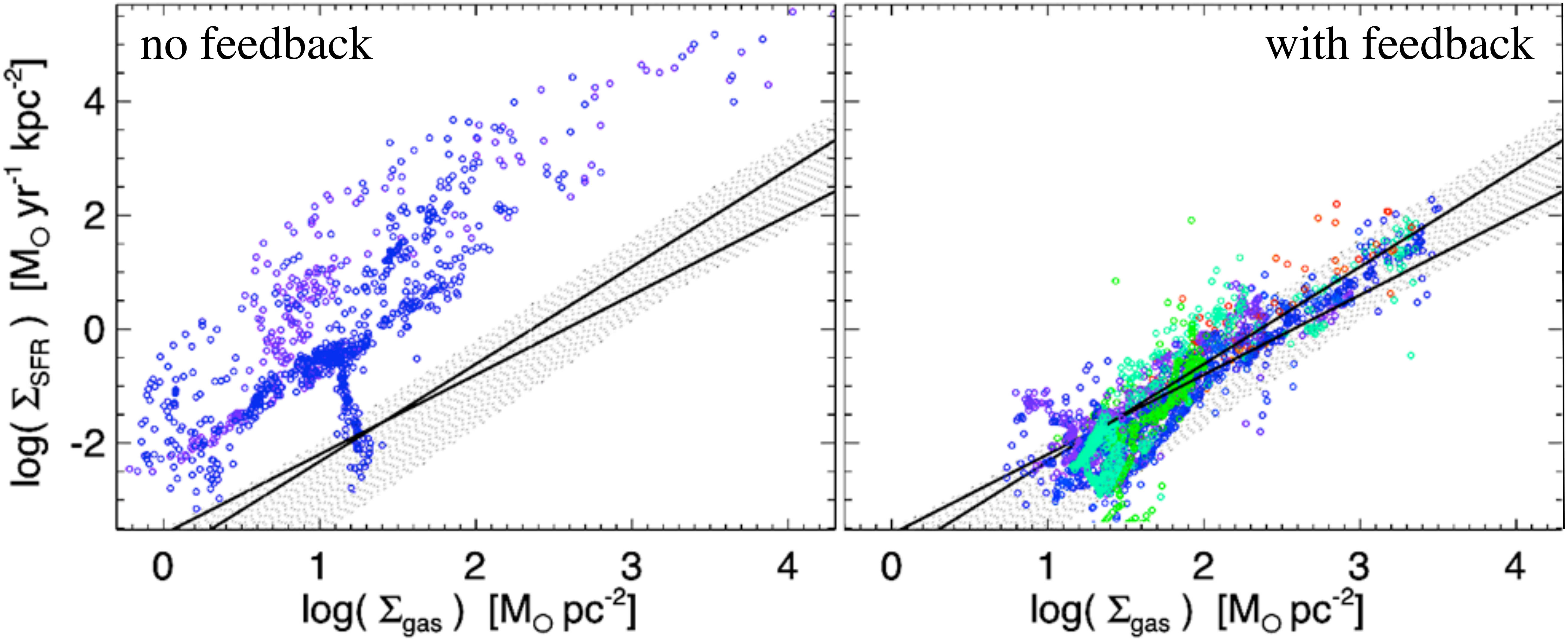
Kennicutt-Schmidt relation emerges naturally



PFH, Quataert, & Murray, 2011a

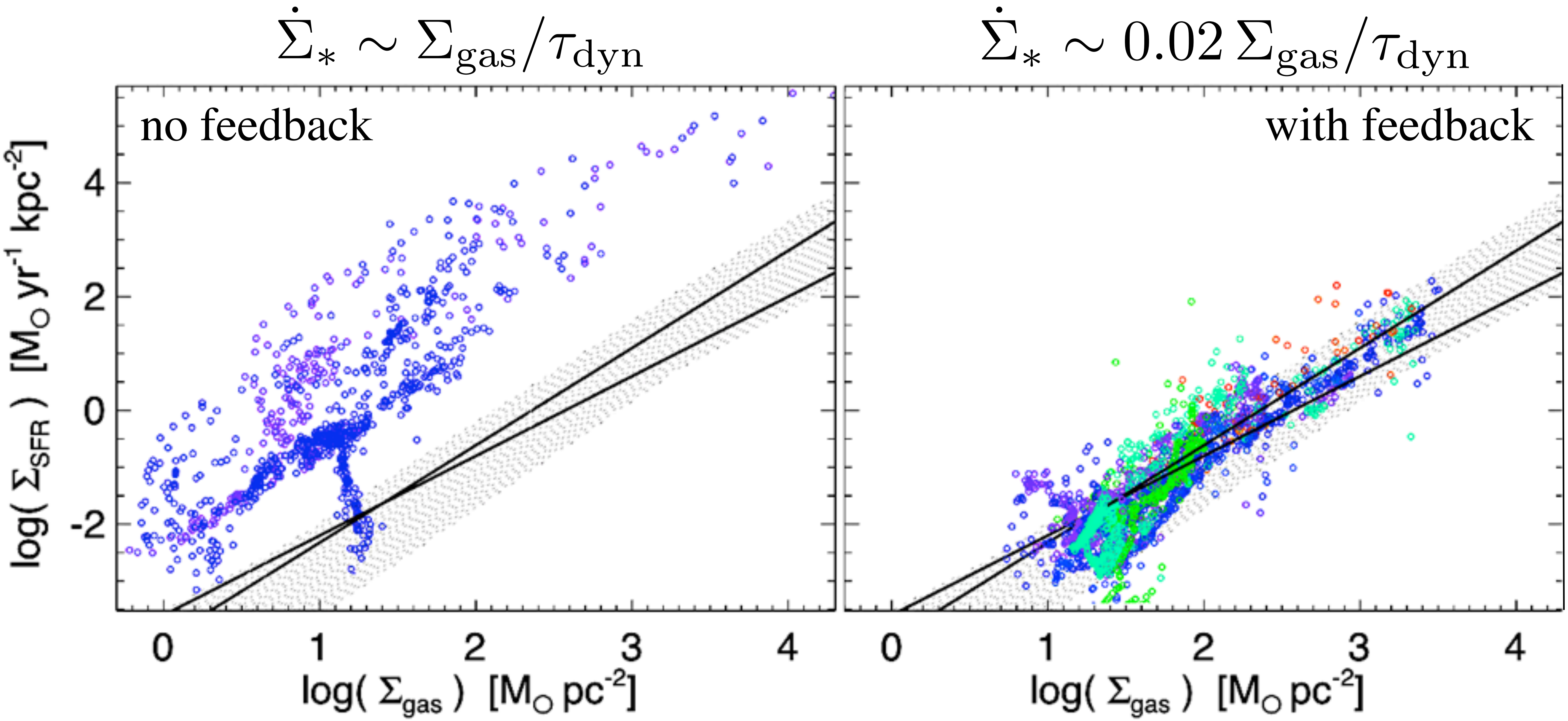
Kennicutt-Schmidt relation emerges naturally

$$\dot{\Sigma}_* \sim \Sigma_{\rm gas}/\tau_{\rm dyn}$$



PFH, Quataert, & Murray, 2011a

Kennicutt-Schmidt relation emerges naturally



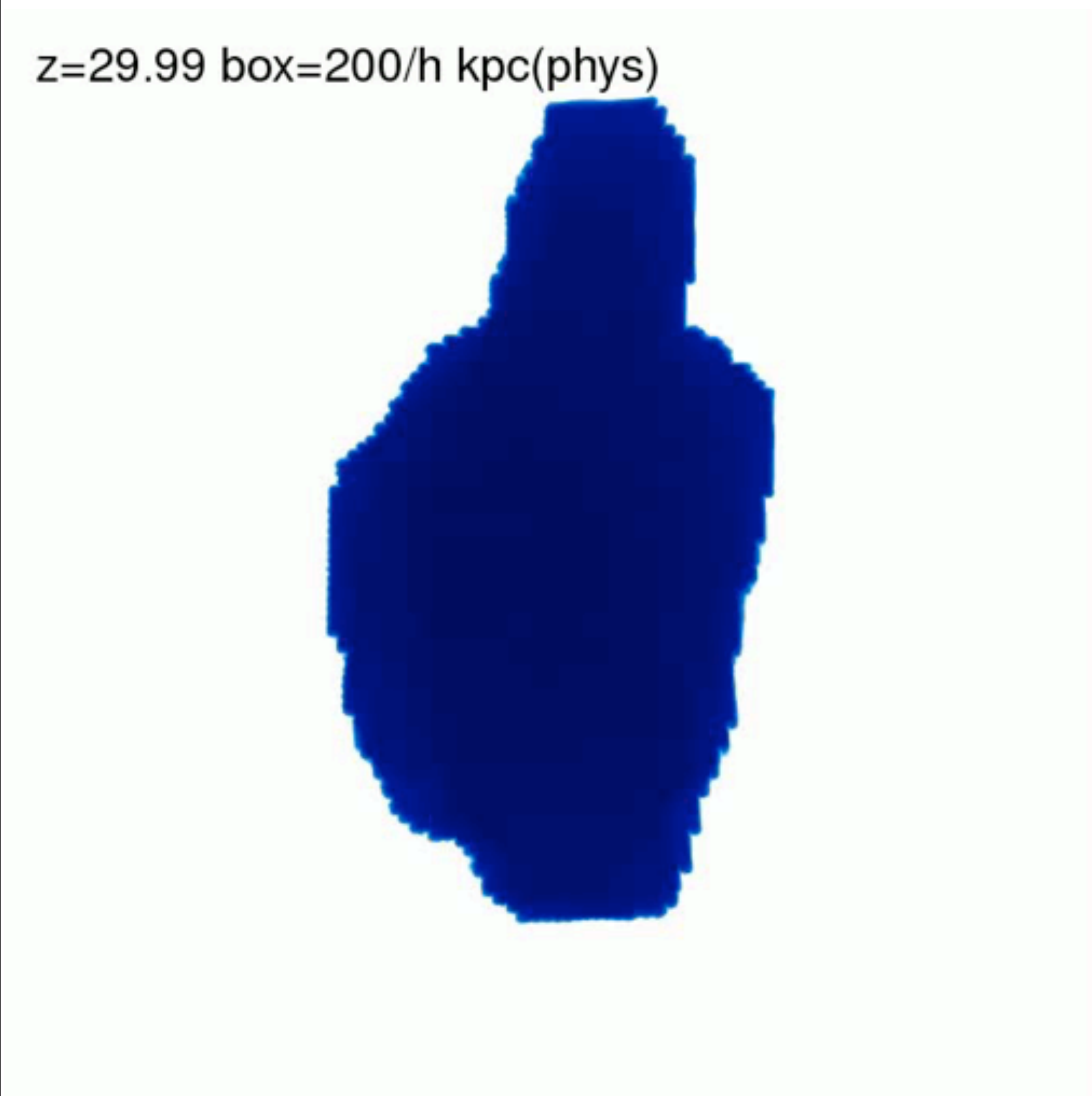
PFH, Quataert, & Murray, 2011a

Change the Outcome of (Gas-Rich) Mergers

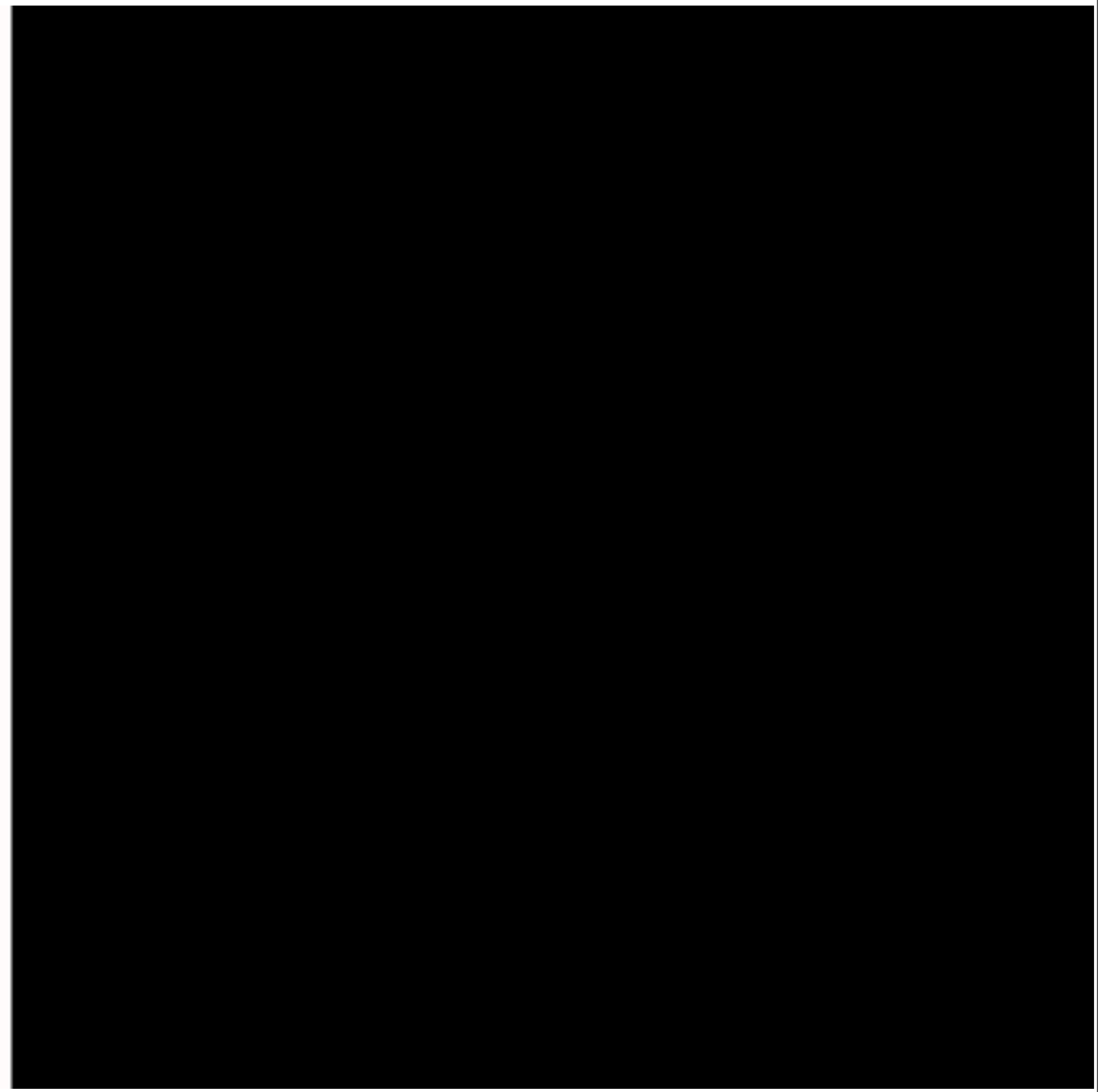
Cosmological Simulations

“ZOOM-IN” ON THE FORMATION OF A MASSIVE GALAXY

We have to compromise on resolution and/or physics!



IGM Density



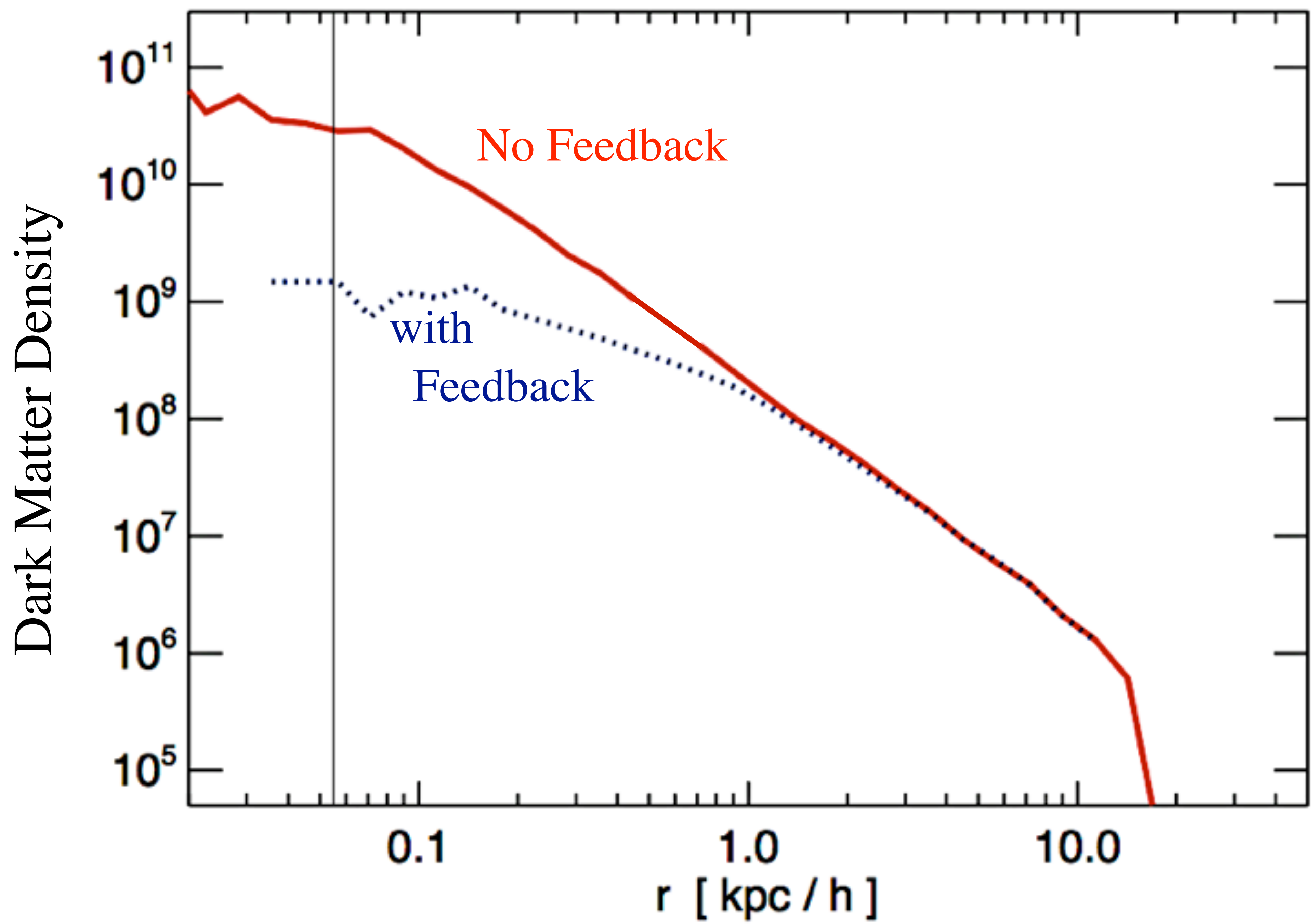
IGM Temperature

PFH & Keres et al.

Models with
"sub-grid" feedback

Dark Matter Profiles: Baryons or Cosmology?

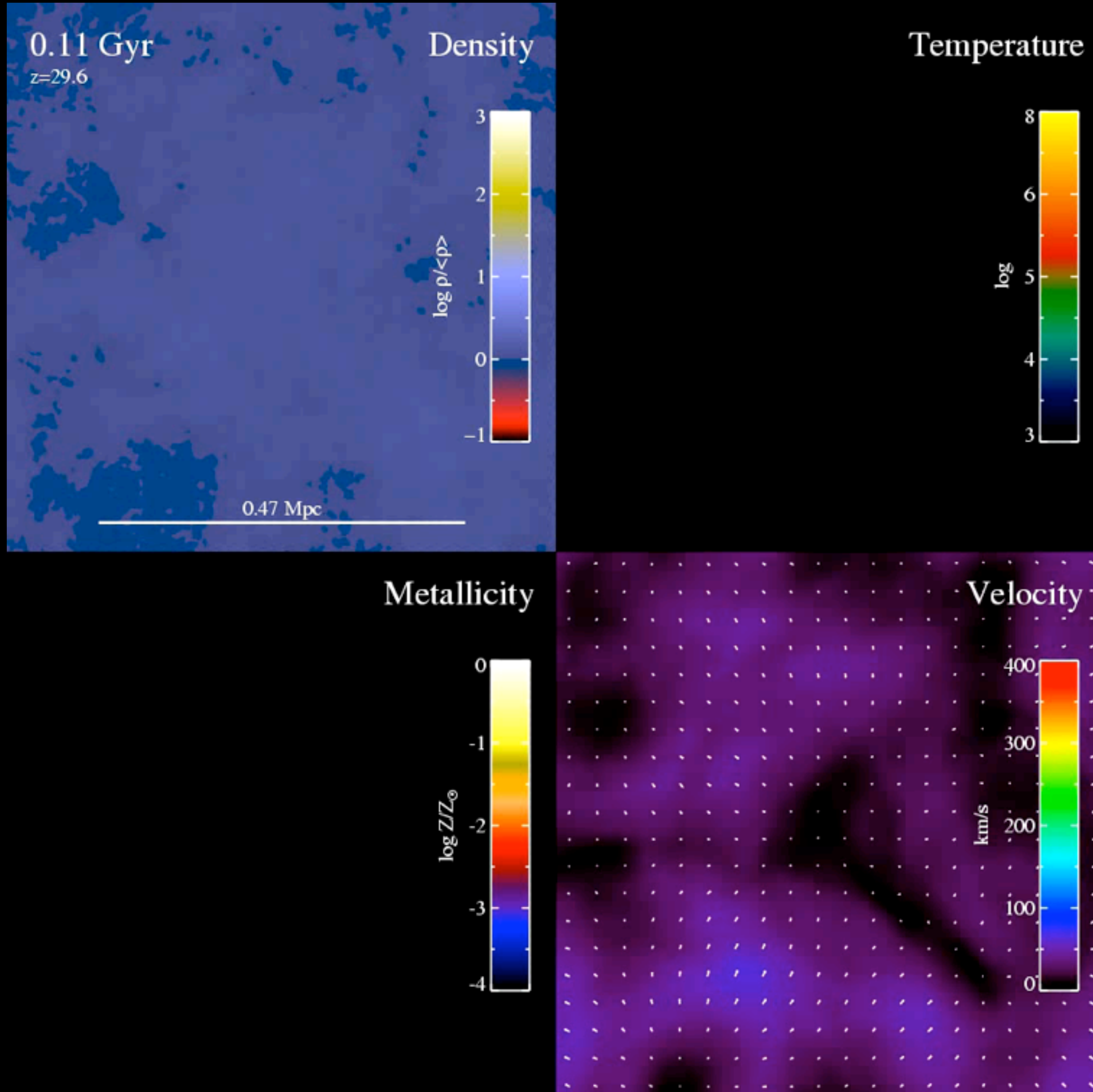
WHAT CAN WE LEARN ABOUT COSMOLOGY AND STRUCTURE FORMATION?



PFH & Keres et al

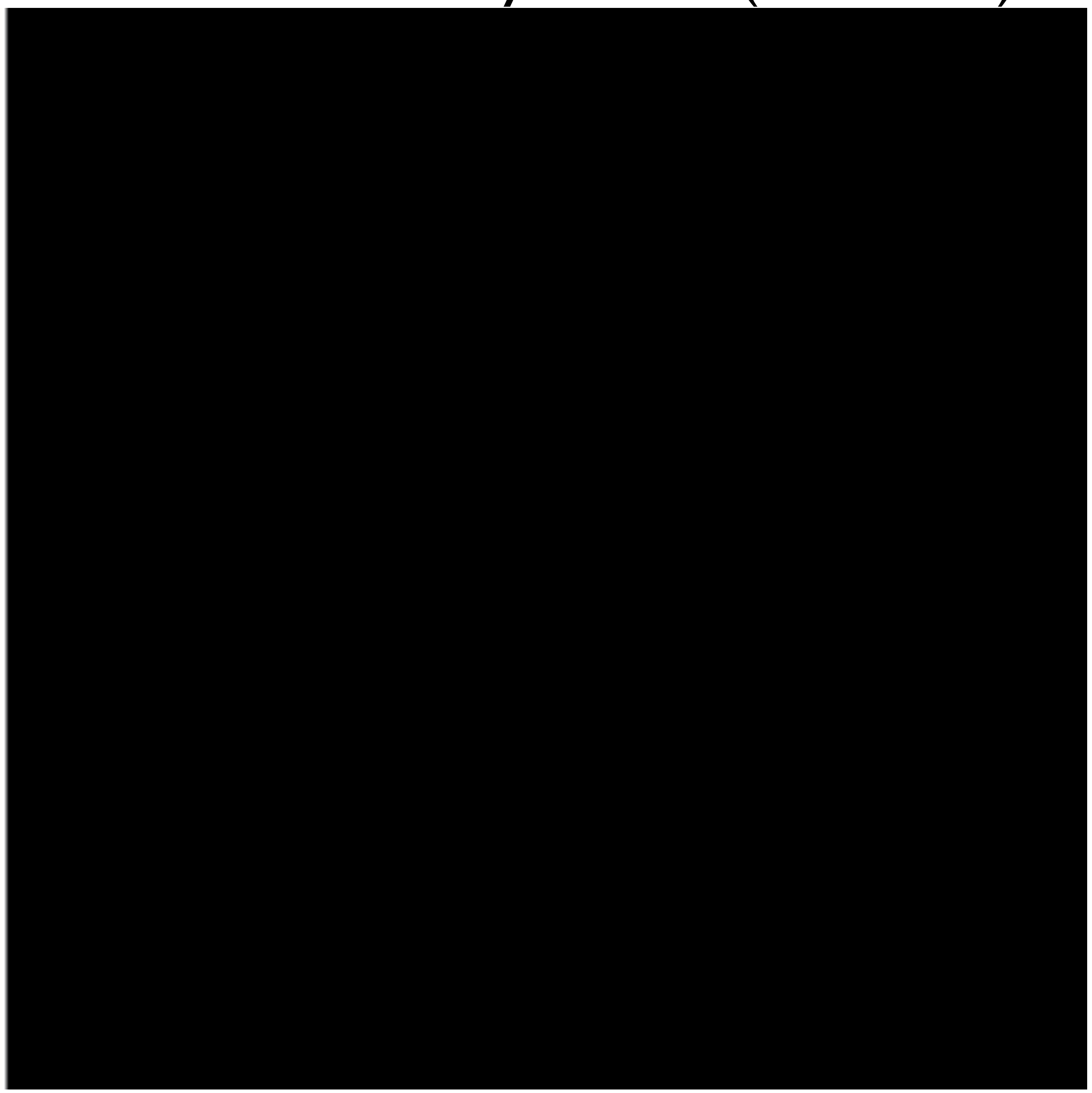
PFH, Bullock, & Onorbe et al.

- Photo-Heat the IGM (H & He Ionization)
- Eject Metals
- Directly shock "nearby" systems

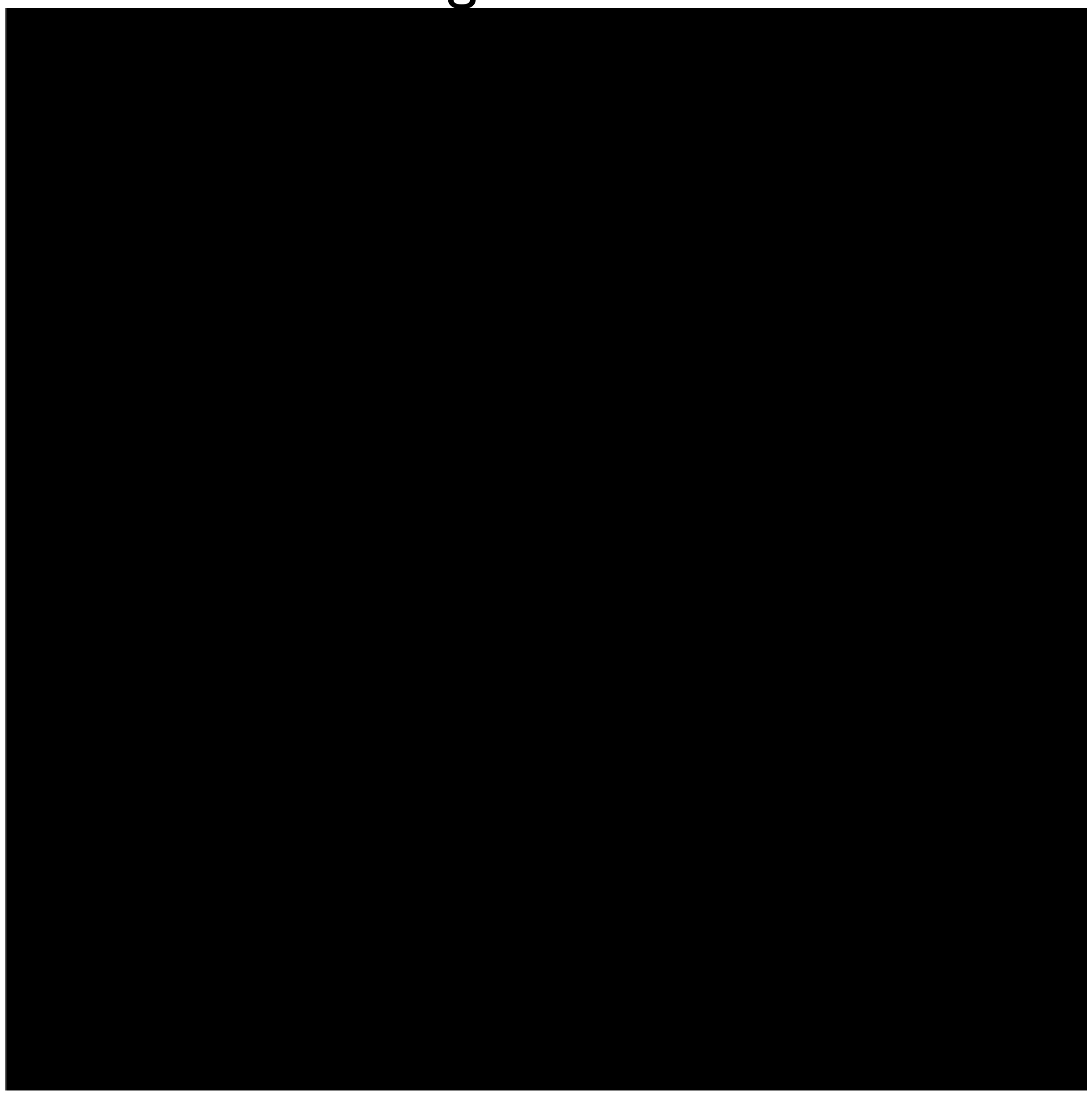


Proto-MW: Gas Temperature:

Insert Winds “By Hand” (Sub-Grid)

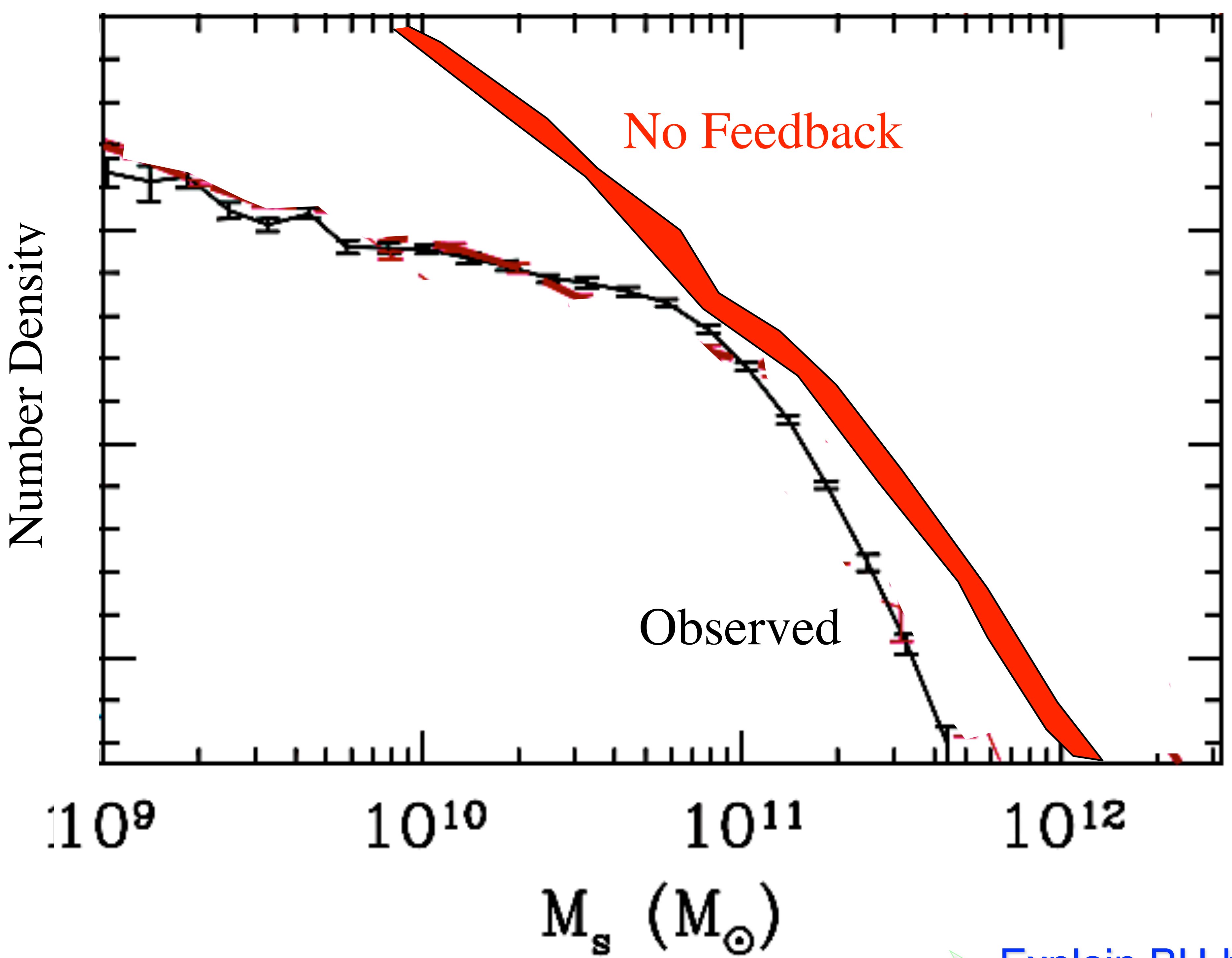


Following Full Feedback



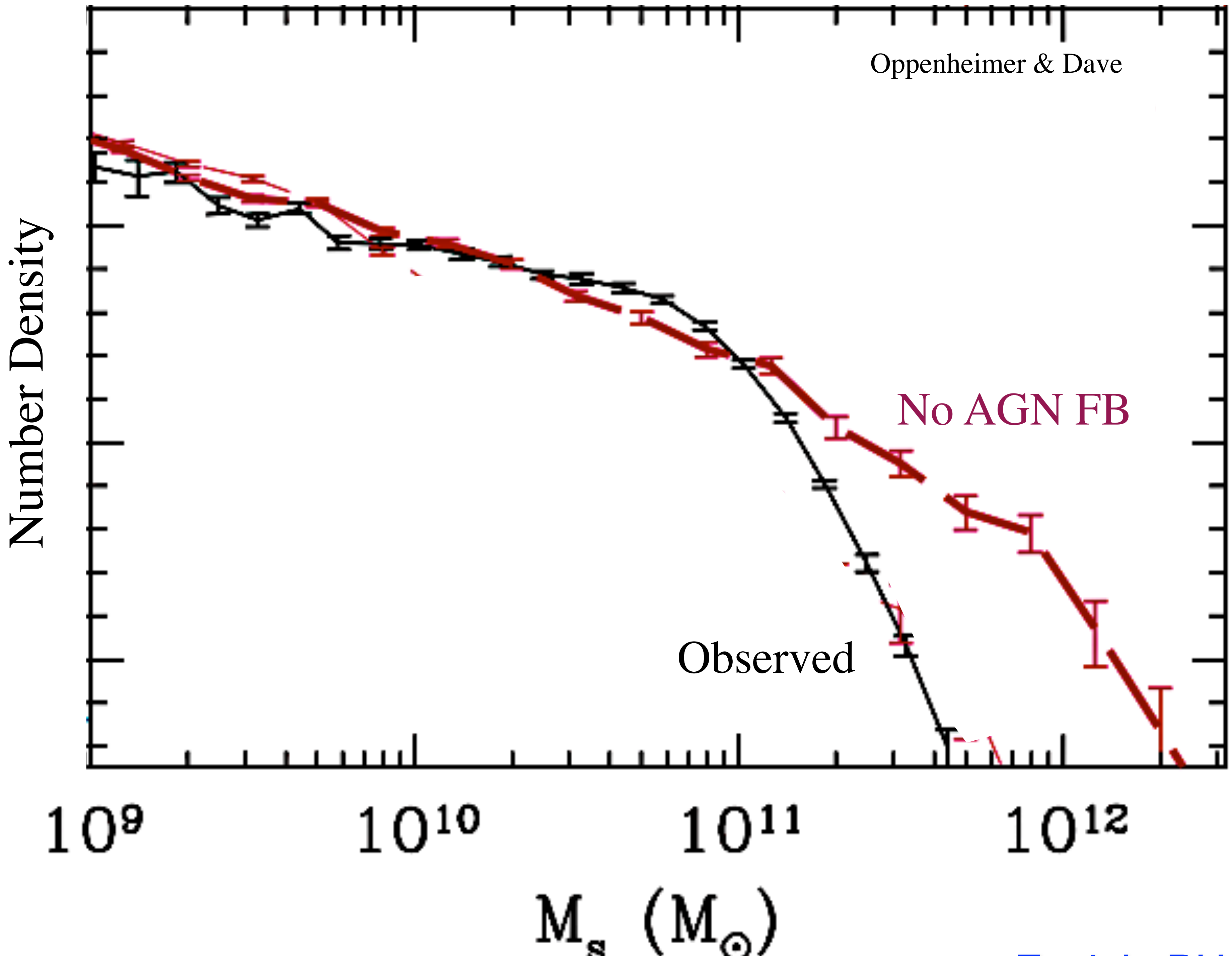
PFH & Keres et al.

Why Do We Need AGN Feedback?



- Explain BH-host correlations
- Sharp color bimodality
- Removing/heating gas in groups

Why Do We Need AGN Feedback?



- Explain BH-host correlations
- Sharp color bimodality
- Removing/heating gas in groups

Feedback Energy:

SILK & REES '98

$$L = \epsilon_r \, \dot{M}_{\rm BH} \, c^2 \qquad (\epsilon_r \sim 0.1)$$

$$\rightarrow E_{\rm rad} \sim 0.1 \, M_{\rm BH} \, c^2 \sim 10^{61} \, {\rm erg}$$

$$(M_{\rm BH} \sim 10^8 \, M_\odot)$$

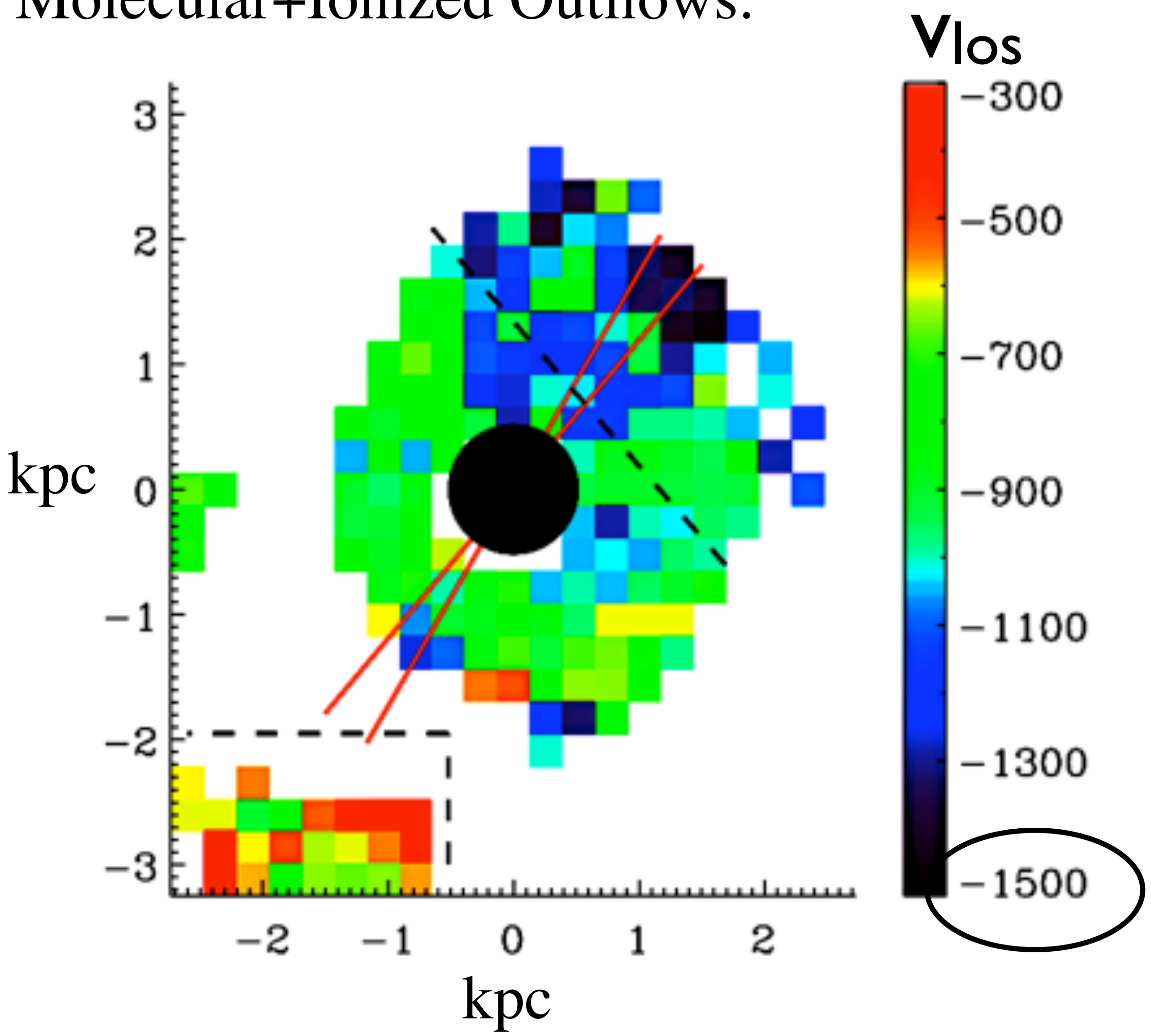
$$E_{\rm gal} \sim M_{\rm gal} \, \sigma^2 \sim (10^{11} \, M_\odot) \, (200 \, {\rm km/s})^2 \sim 10^{59} \, {\rm erg}$$

Molecular Outflows in AGN & ULIRGs

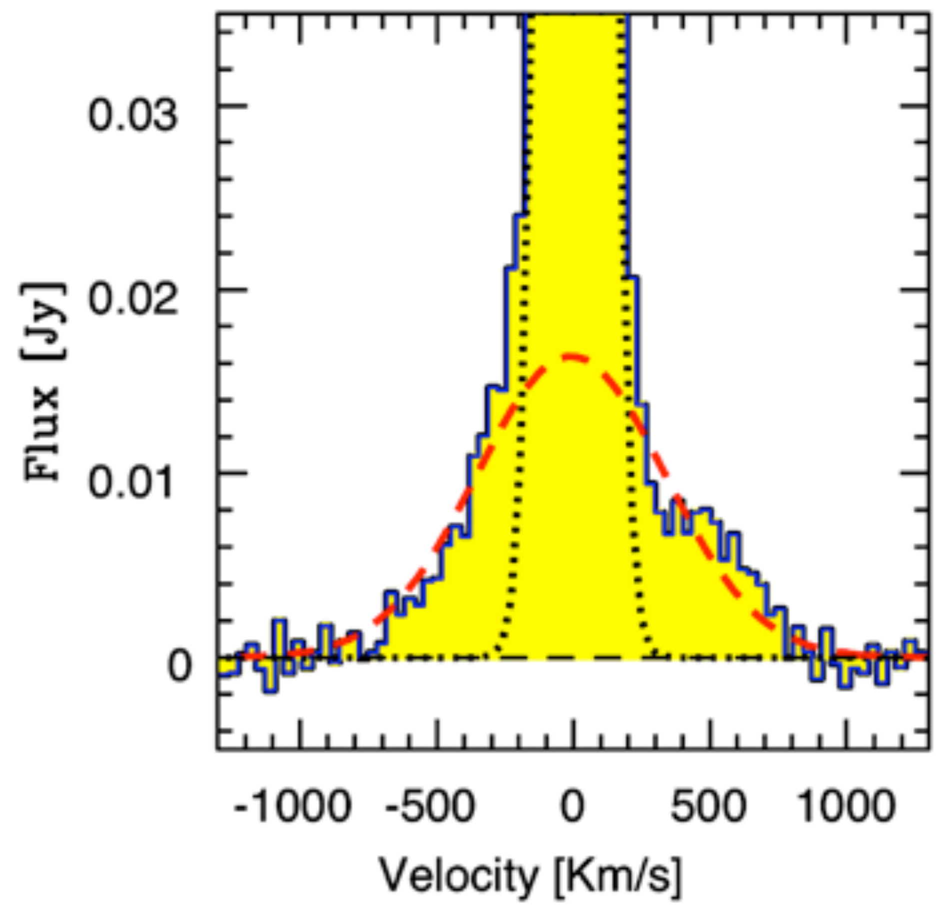
OBSERVED WINDS at >1000 km/s

Rupke & Veilleux 2005,2011
Fischer et al. 2010 (Mrk 231)
Feruglio et al. 2010 (Mrk 231)
Alatalo et al. 2011 (NGC 1266)

Molecular+Ionized Outflows:



CO:



$$R_{\rm wind} \sim 1 - 4\,{\rm kpc}$$

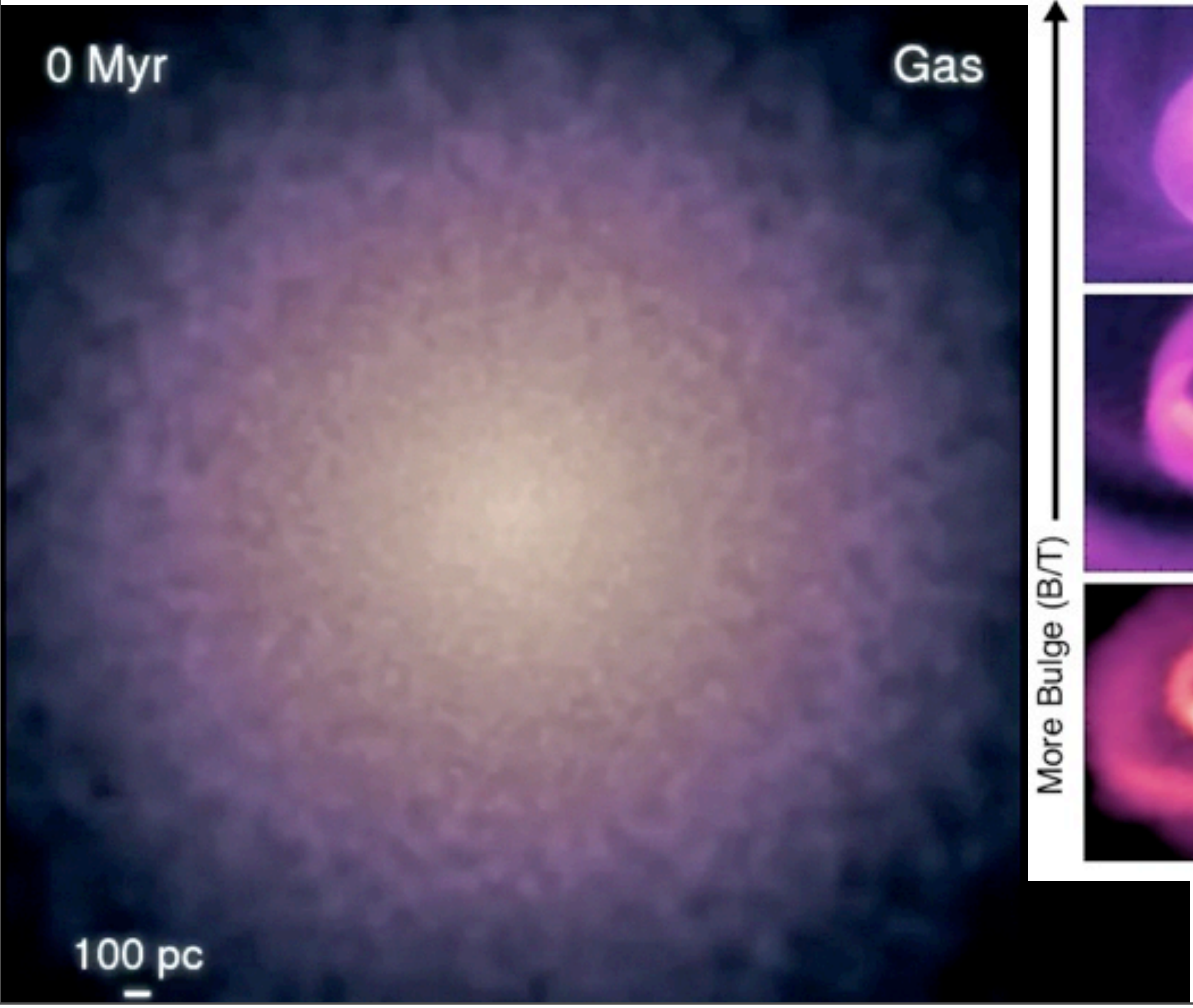
$$v > 500\,{\rm km\,s^{-1}}$$

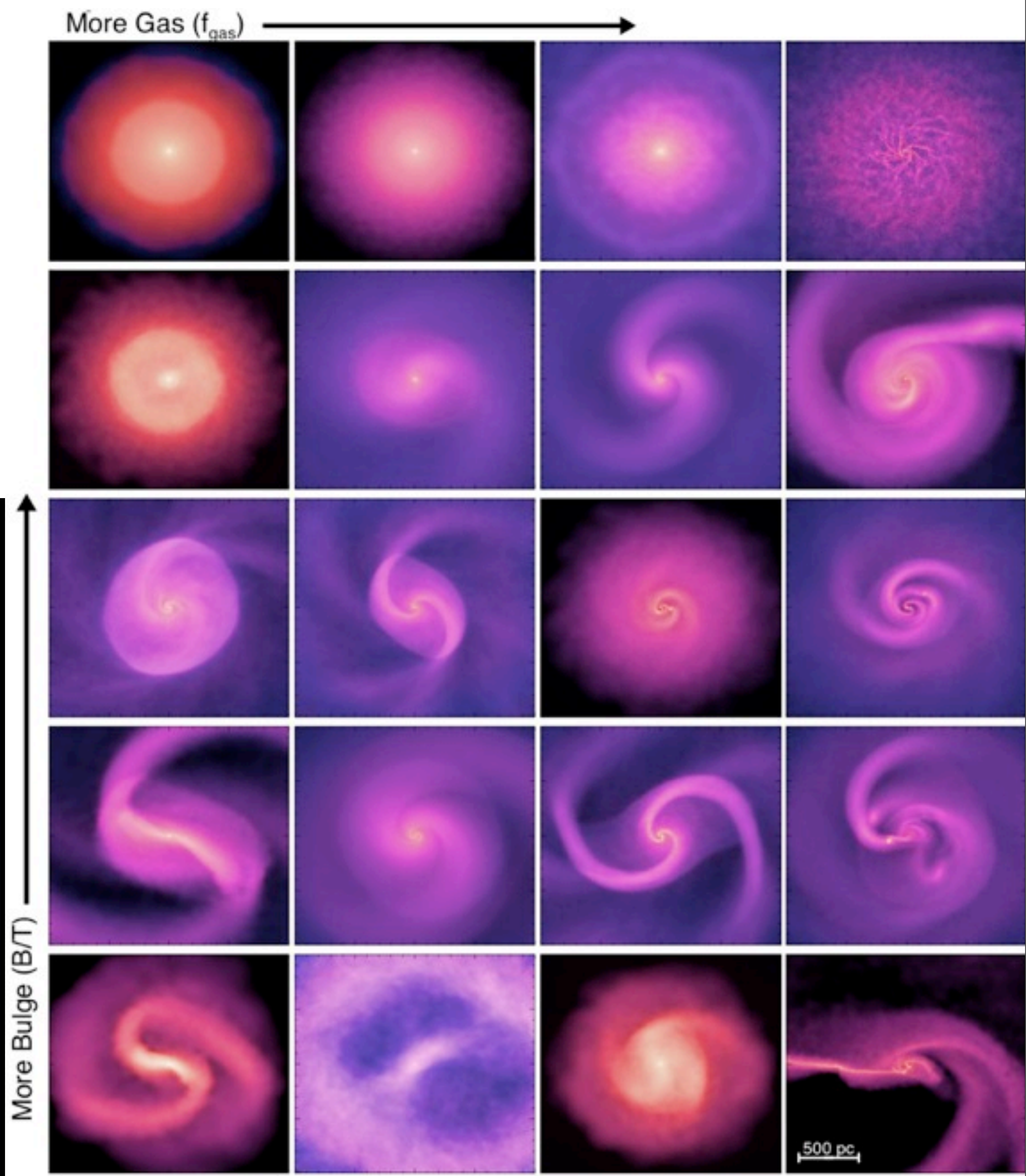
$$\dot{M}_{\rm wind} \gtrsim 1000\,M_\odot\,{\rm yr^{-1}}$$

Inflow?

- Beginning to directly follow inflow to sub-pc scales

PFH & Quataert 2009,10,11
Levine, Gnedin, Kravtsov 09,10
Mayer, Callegari, 09,10

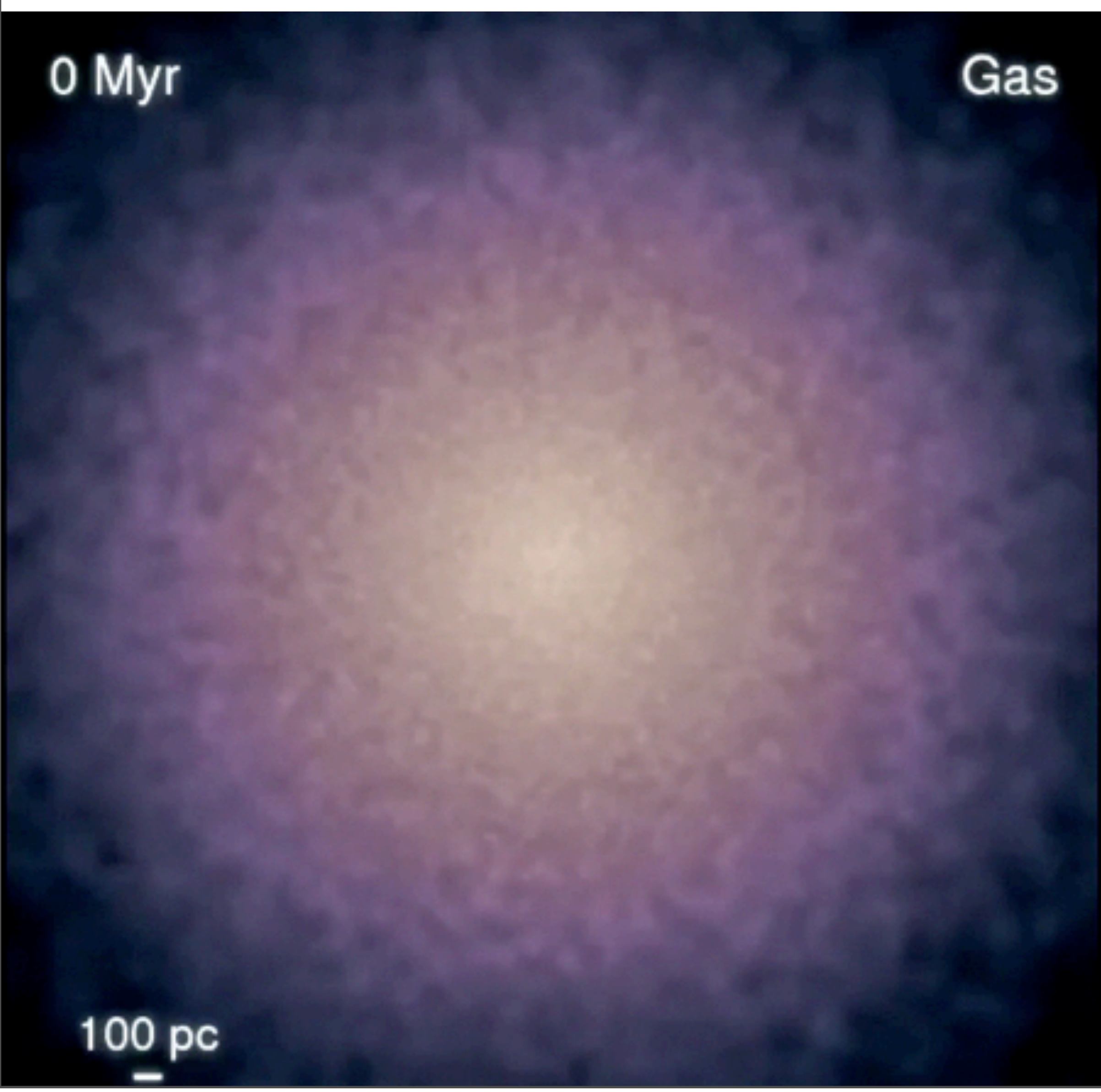


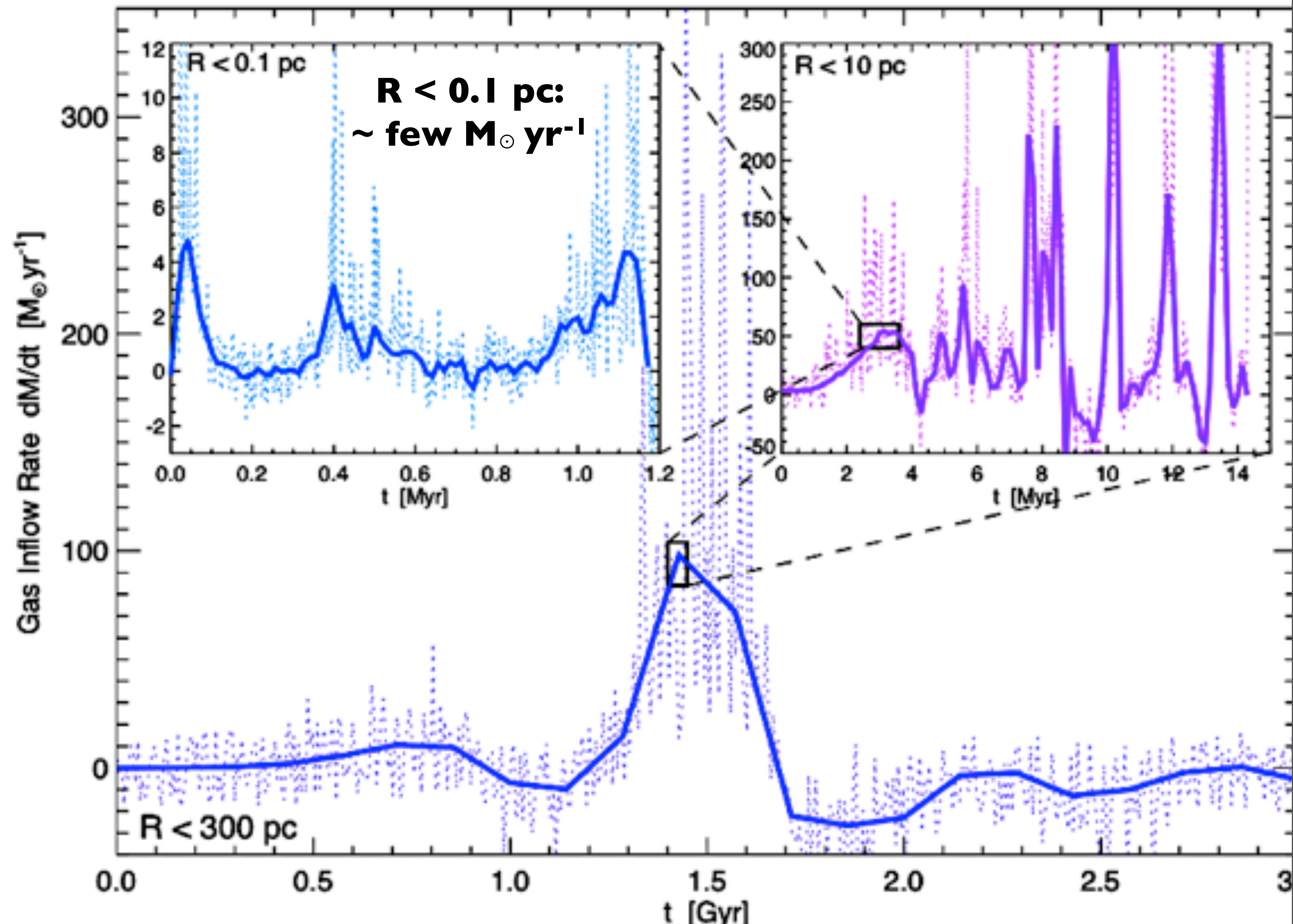


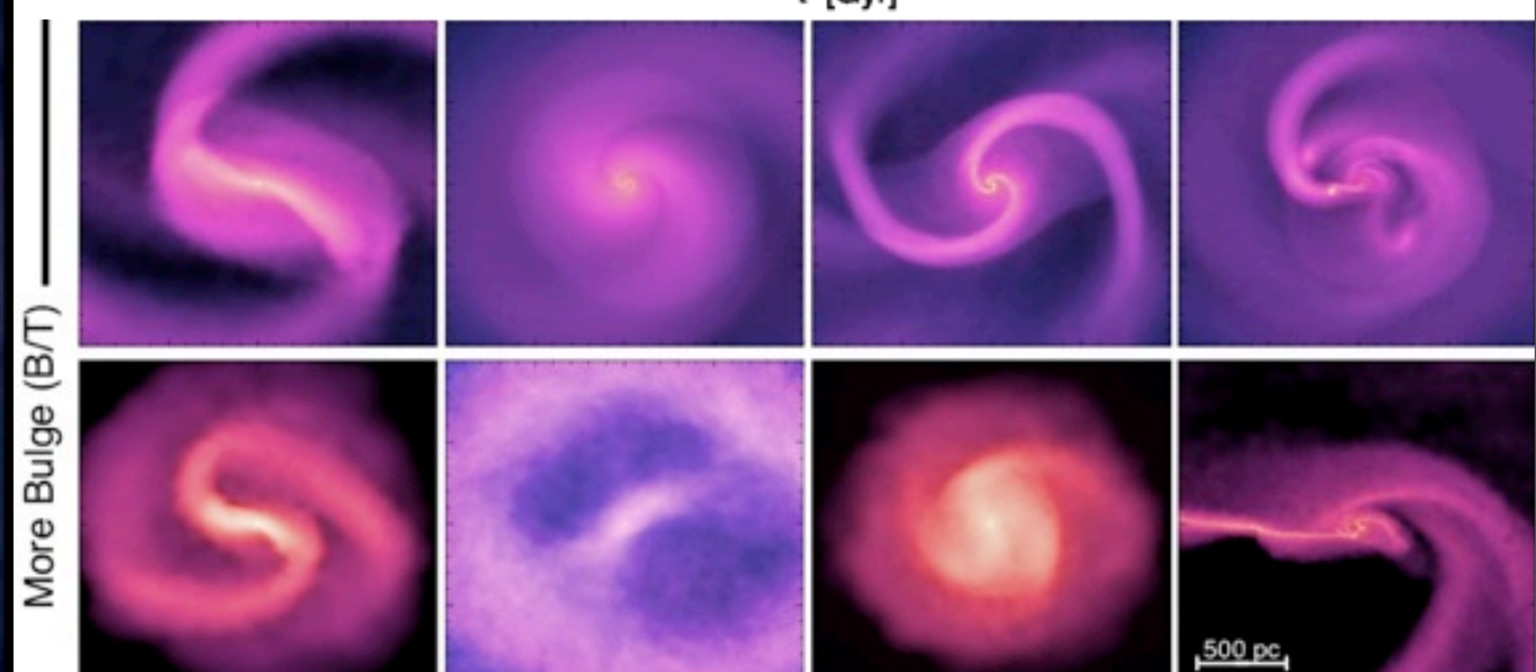
Inflow?

- Beginning to directly follow inflow to sub-pc scales

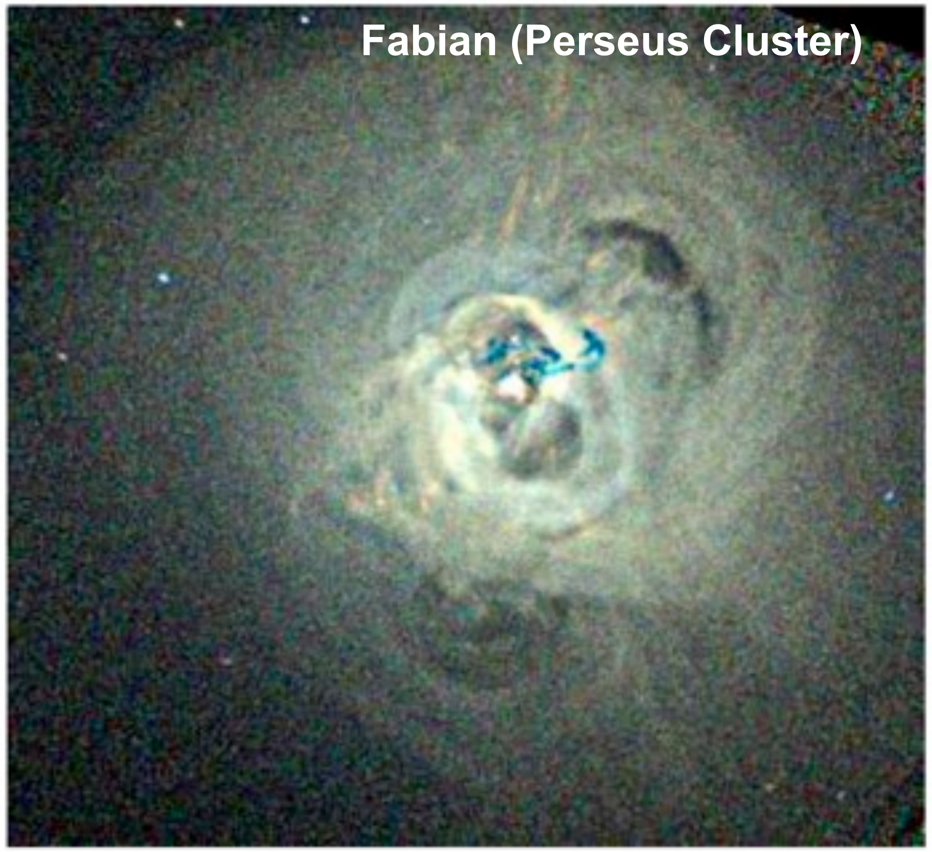
PFH & Quataert 2009,10,11
Levine, Gnedin, Kravtsov 09,10
Mayer, Callegari, 09,10







Observed Sources of AGN Feedback

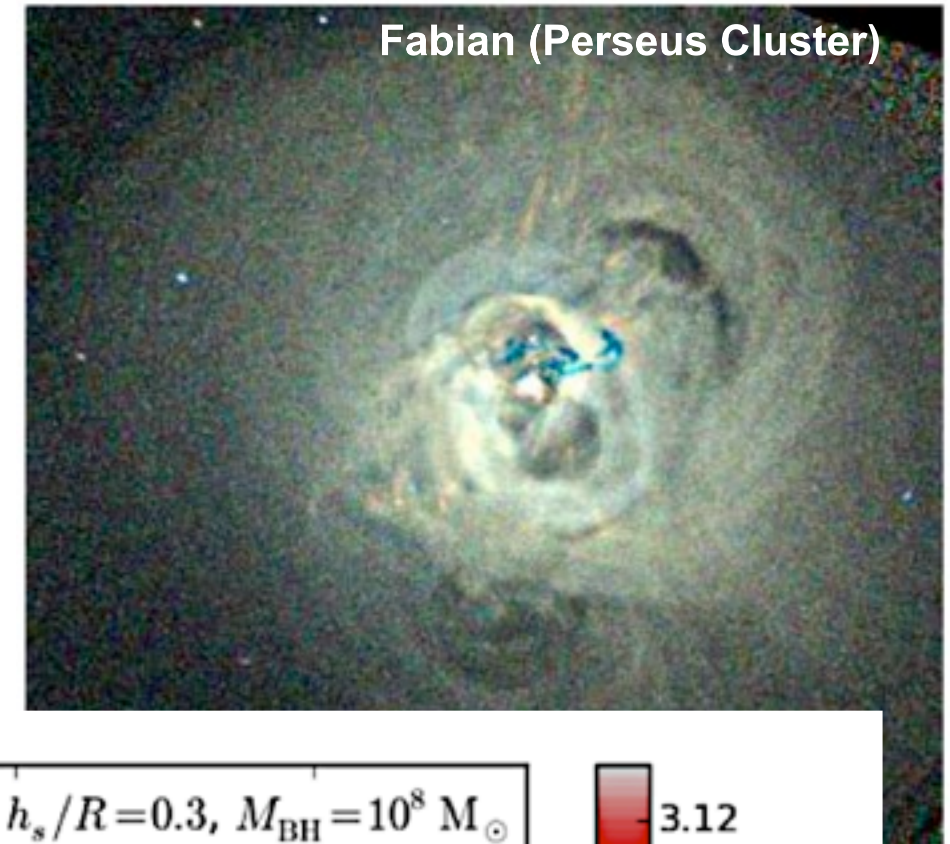


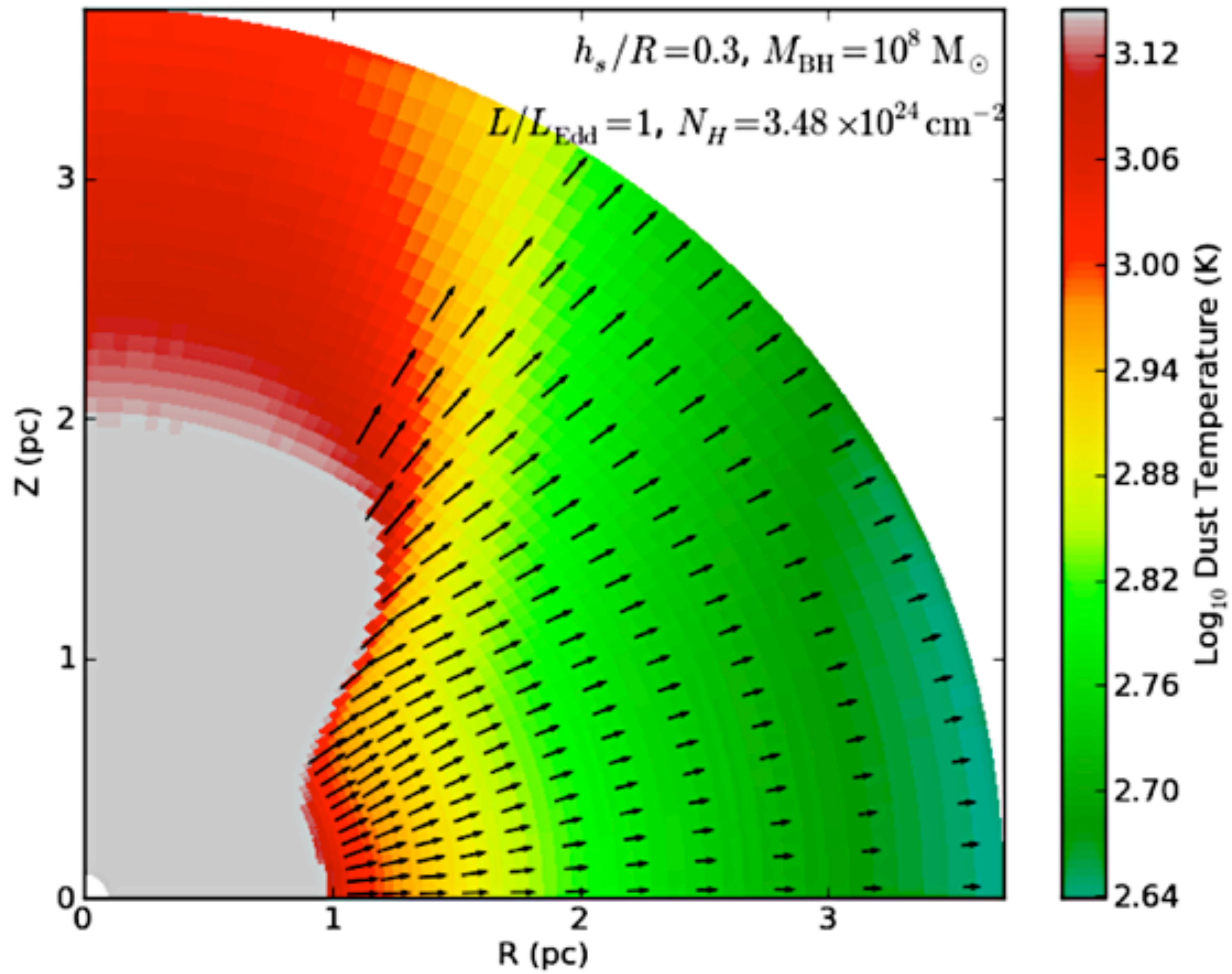
- Jets
  - heat IGM/ICM (low-density), but not dense ISM

Observed Sources of AGN Feedback

- Jets
  - heat IGM/ICM (low-density), but not dense ISM

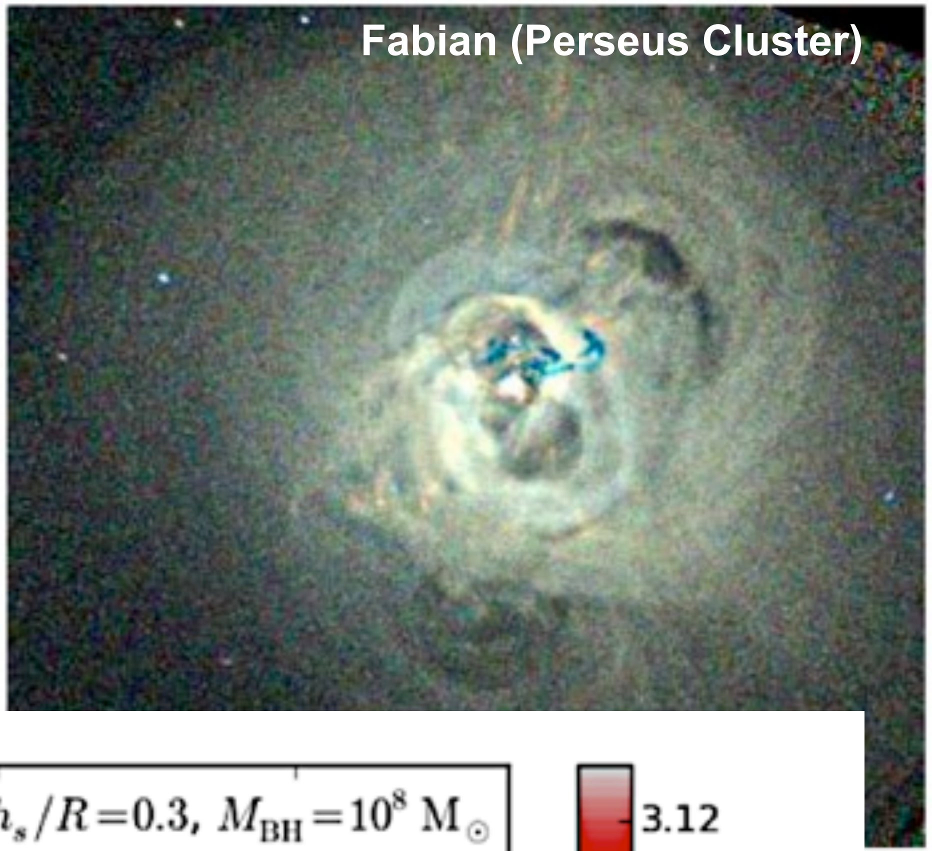
- Radiation Pressure
  - $L_{AGN} >> L_{stars}$



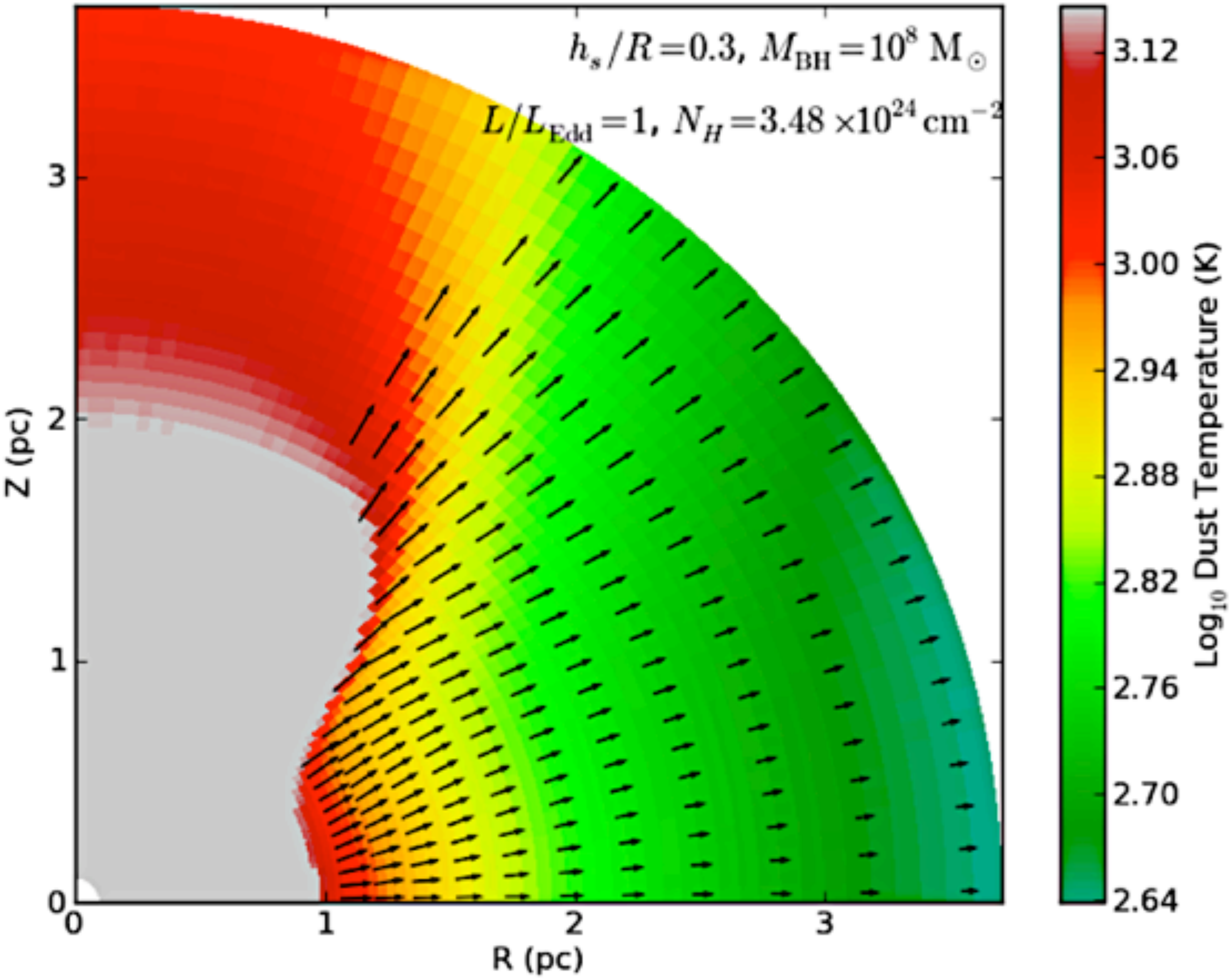


Roth, Kasen, Quataert, PFH

Observed Sources of AGN Feedback



- Jets
  - heat IGM/ICM (low-density), but not dense ISM
- Radiation Pressure
  - $L_{AGN} >> L_{stars}$
- Accretion Disk Winds
  - Broad Absorption Line Winds

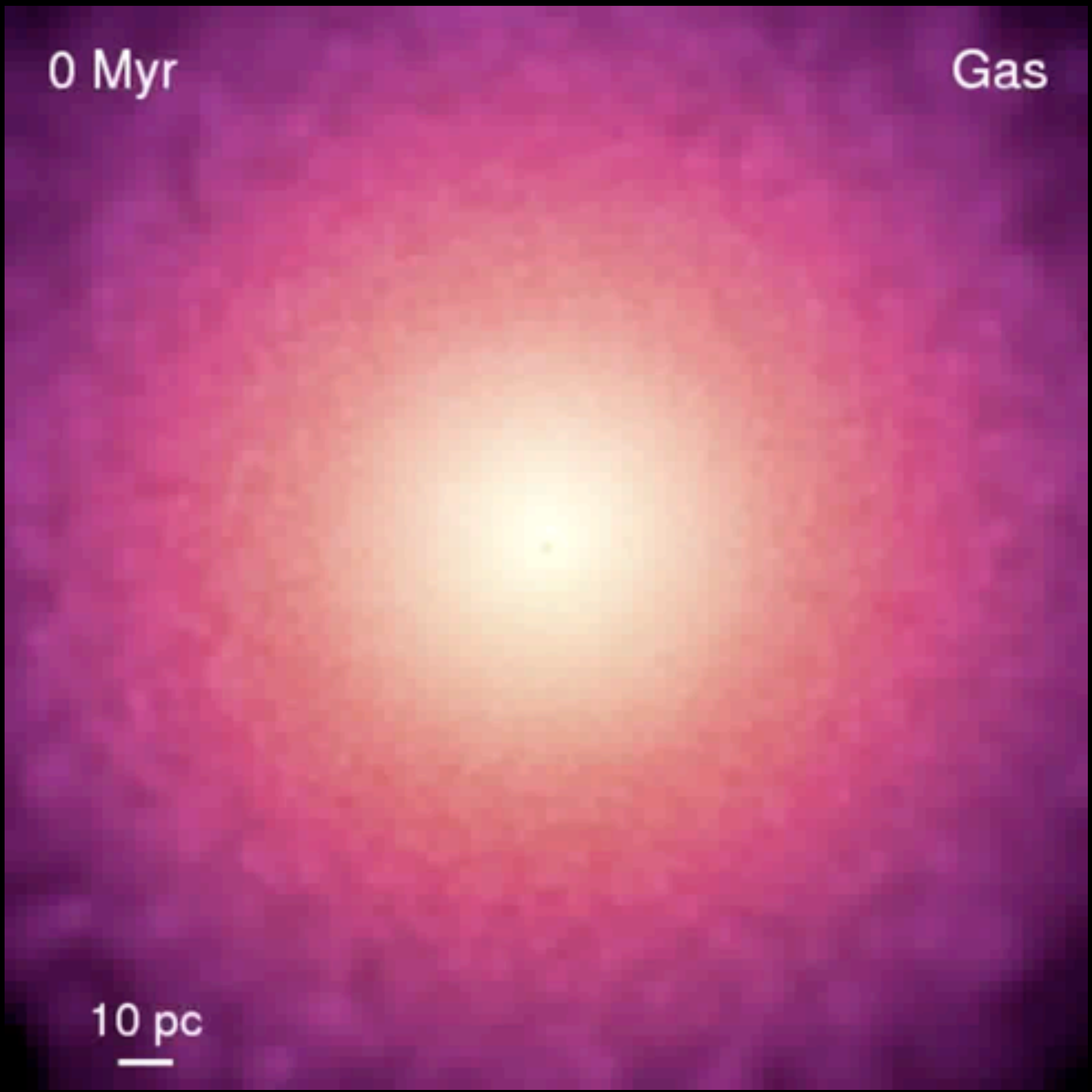


Roth, Kasen, Quataert, PFH in prep

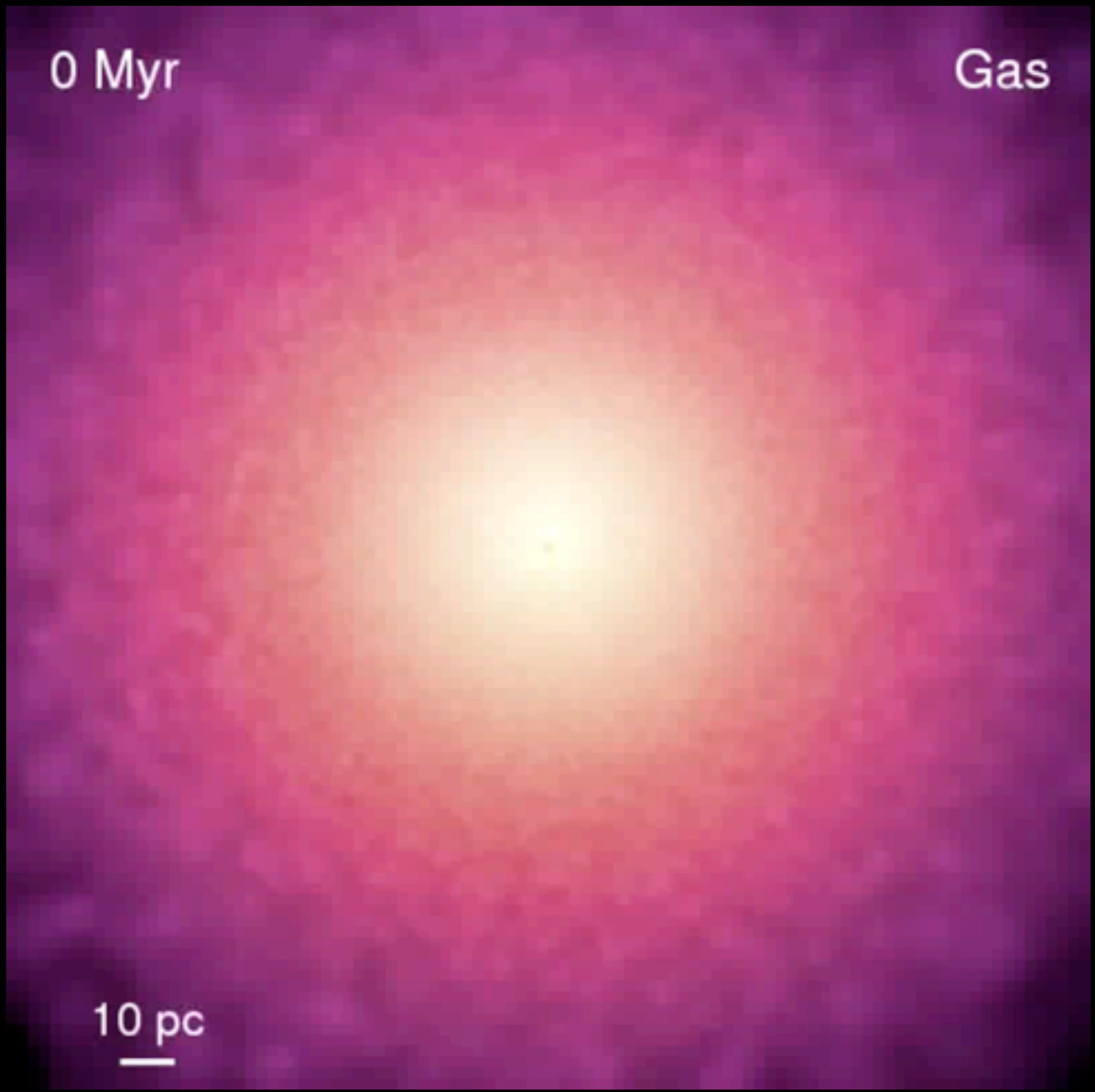
BAL Winds on ~1pc - 1kpc scales:

PFH in prep
Wada et al.

No BAL Winds



With BAL Winds

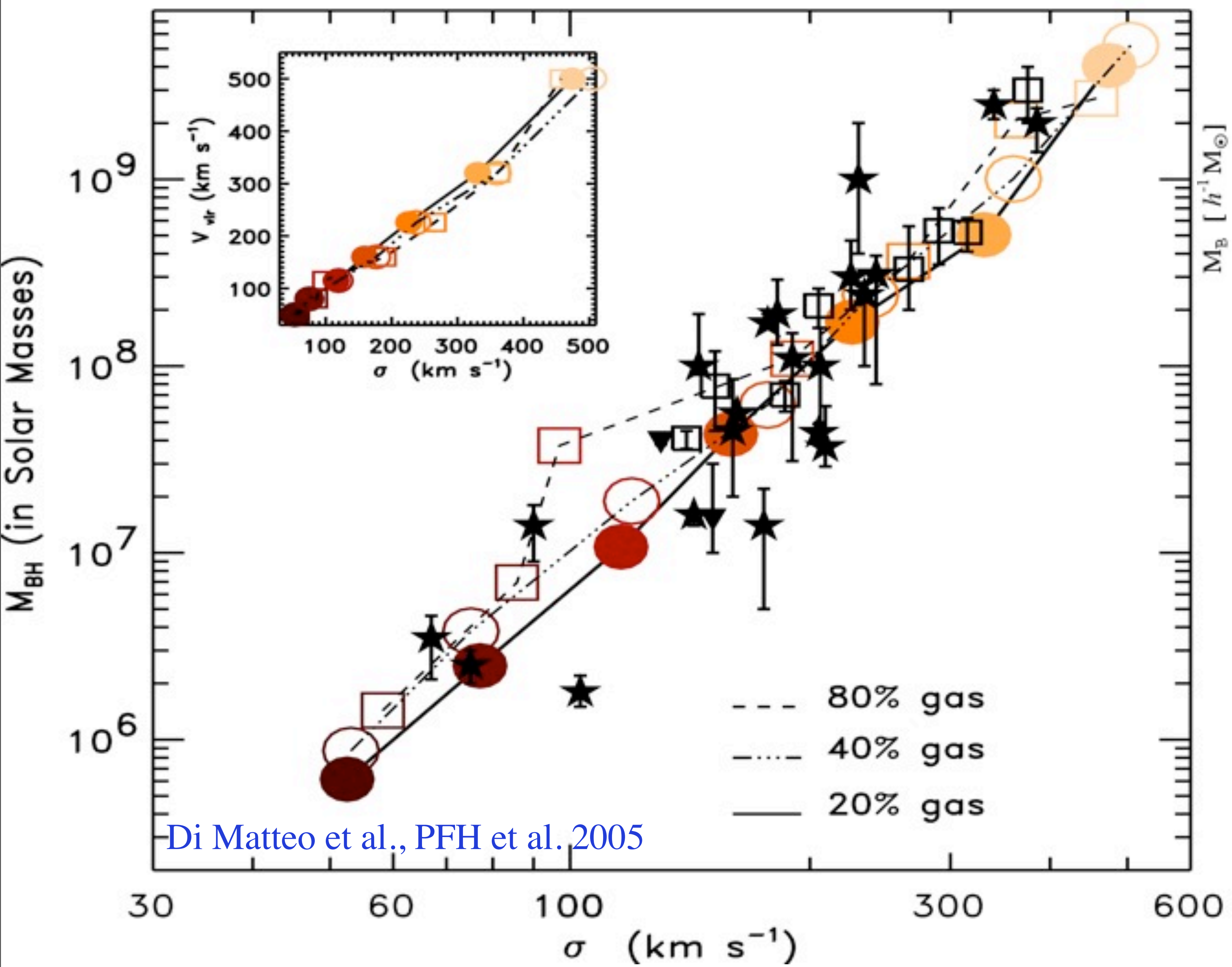


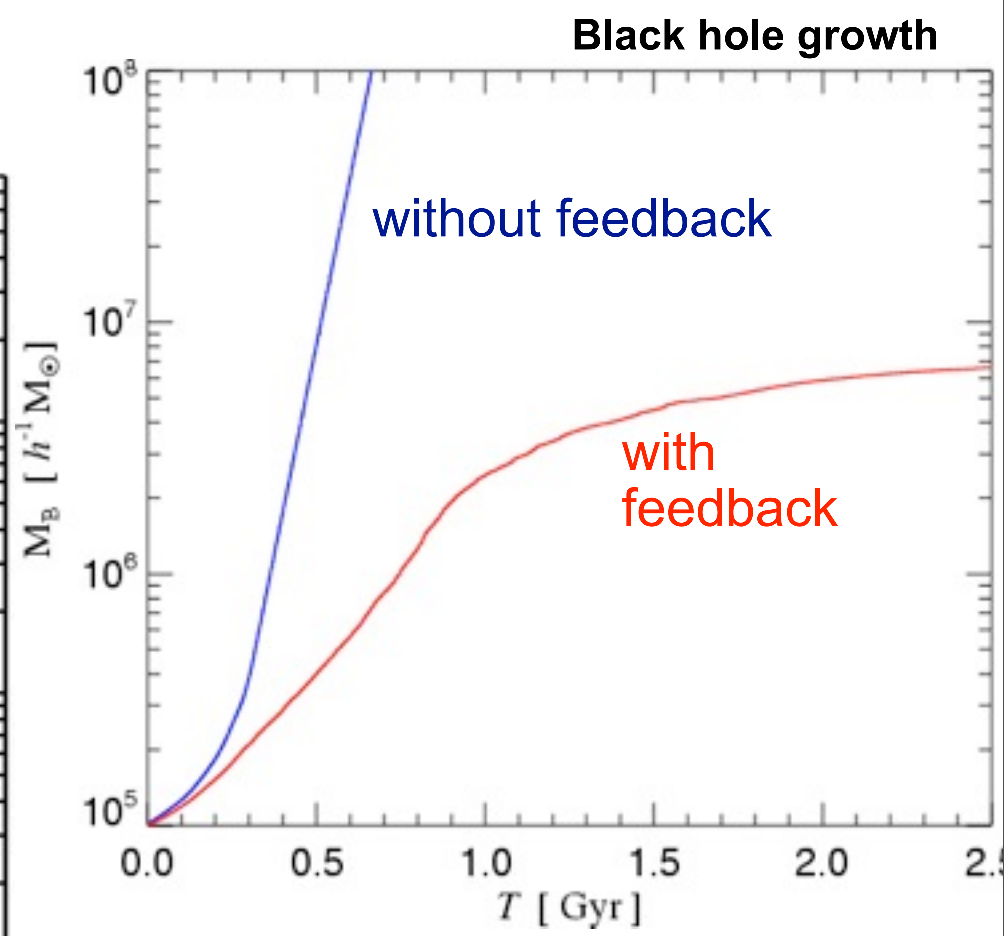
$$\dot{M}_{\rm launch}(0.1\,{\rm pc}) = 0.5\,\dot{M}_{\rm BH}$$

$$v_{\rm launch}(0.1\,{\rm pc}) = 10,000\,{\rm km/s}$$

M-sigma Suggests *Self-Regulated* BH Growth

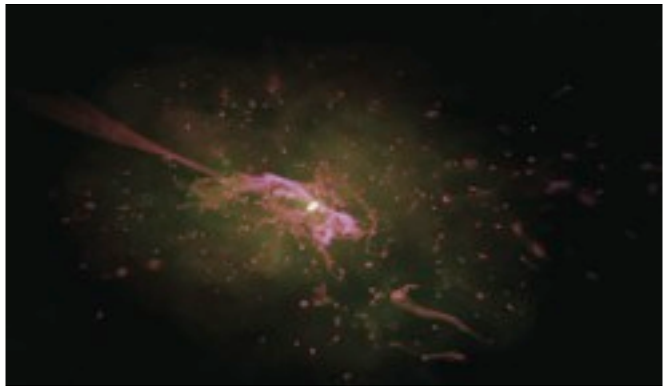
FEEDBACK PREVENTS RUNAWAY BLACK HOLE GROWTH





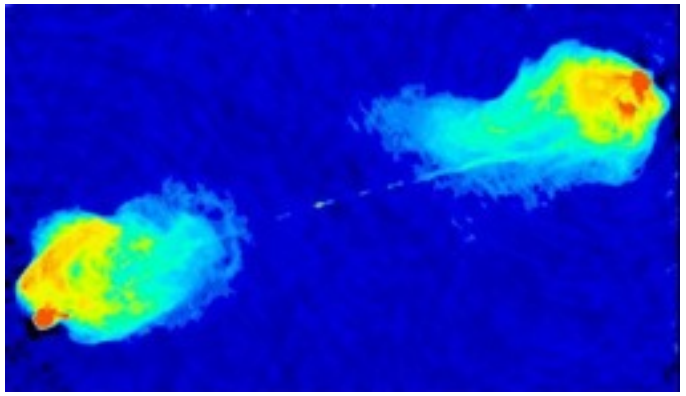
"Transition" vs. "Maintenance"

- **"Quasar"** mode (high mdot)
- Move mass from Blue to Red?
- Rapid (~10^7 yr)
- Small(er) scales (~pc-kpc)
- Morphological Transformation
- Gas-rich/Dissipational Mergers?

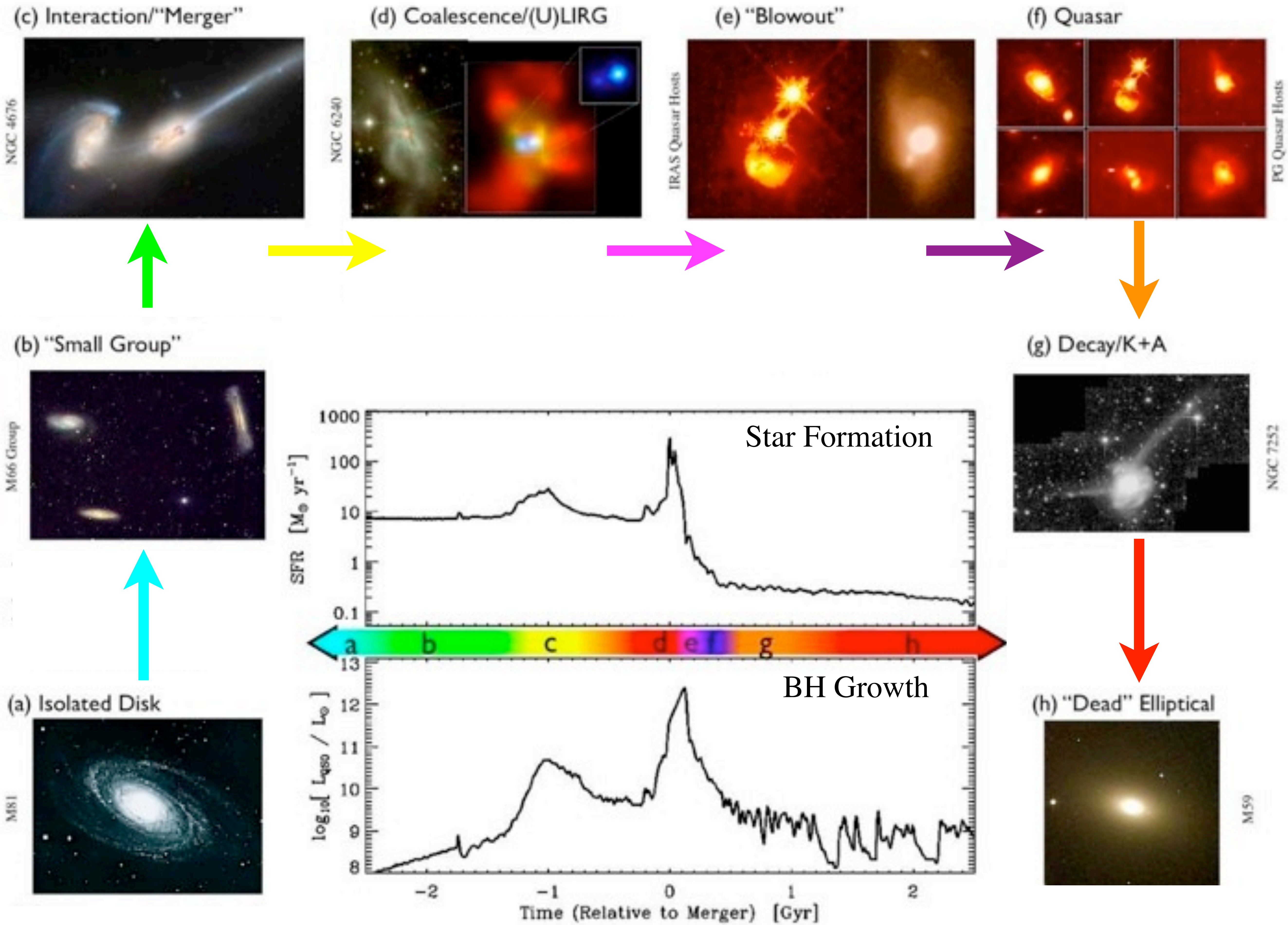


- Regulates *Black Hole* Mass

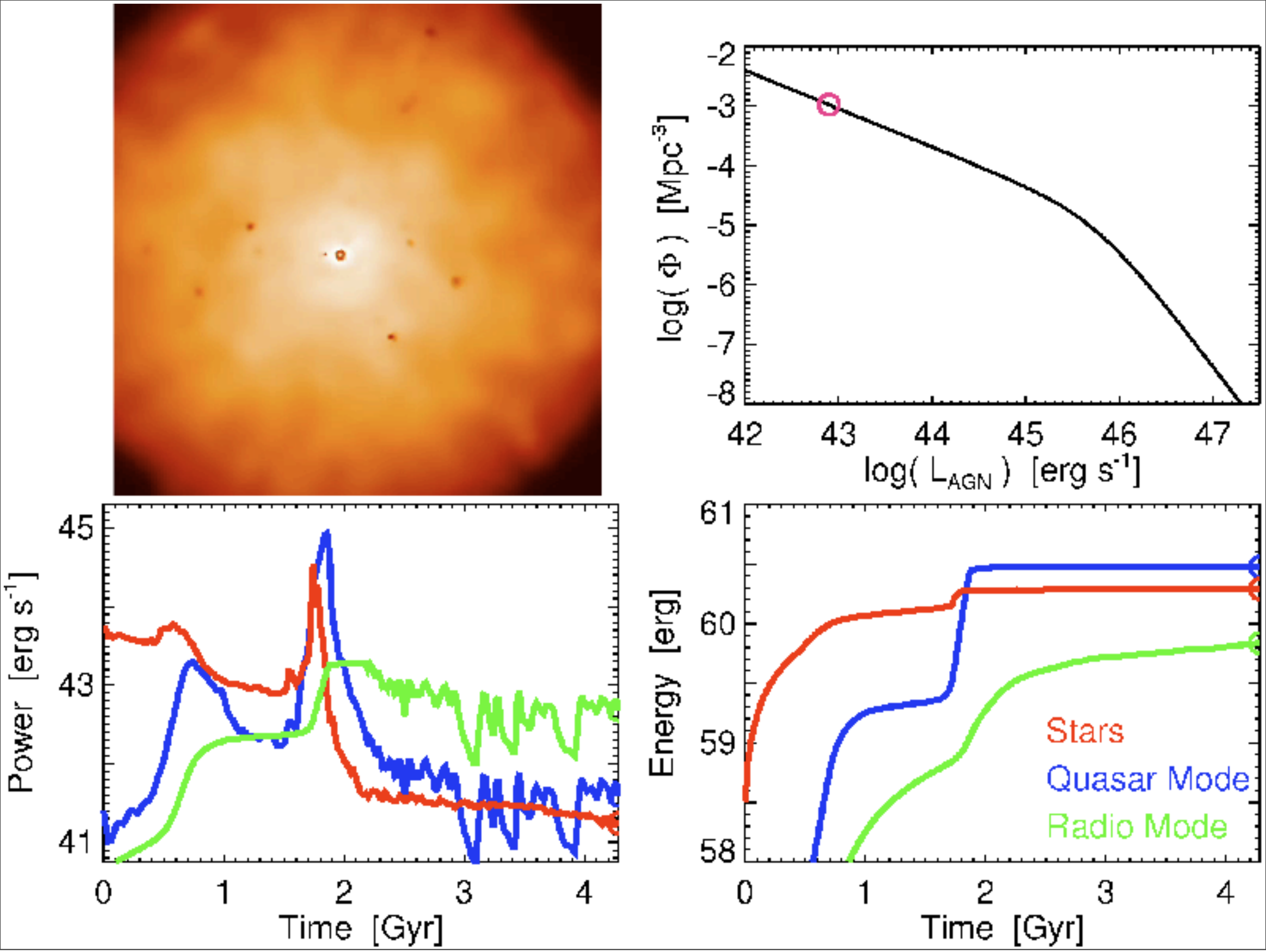
- **"Radio"** mode (low mdot)
- Keep it Red
- Long-lived (~Hubble time)
- Large (~halo) scales
- Subtle morphological change
- Hot Halos & Dry Mergers



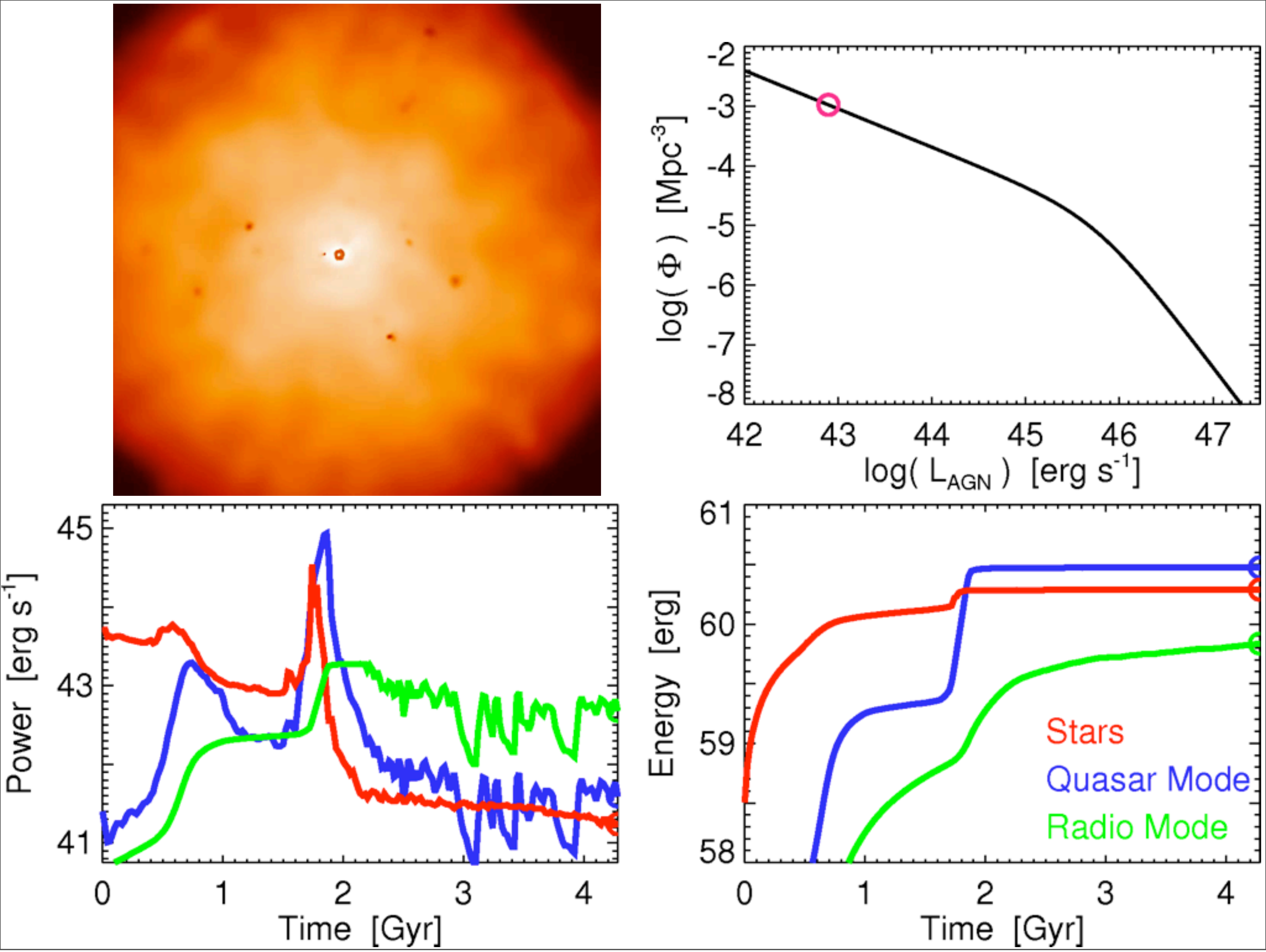
- Regulates *Galaxy* Mass



Sanders, Scoville, many subsequent



-2
-3
-4
-5
-6
-7
-8
log(Φ) [Mpc^{-3}]
42
43
44
45
46
47
log(L_{AGN}) [erg s^{-1}]
45
43
41
Power [erg s^{-1}]
0
1
2
3
4
Time [Gyr]
61
60
59
58
Energy [erg]
Stars
Quasar Mode
Radio Mode
0
1
2
3
4
Time [Gyr]


-2
-3
-4
-5
-6
-7
-8
log(Φ) [Mpc^-3]
42
43
44
45
46
47
log(L_AGN) [erg s^-1]
45
43
41
Power [erg s^-1]
0
1
2
3
4
Time [Gyr]
61
60
59
58
Energy [erg]
Stars
Quasar Mode
Radio Mode
0
1
2
3
4
Time [Gyr]