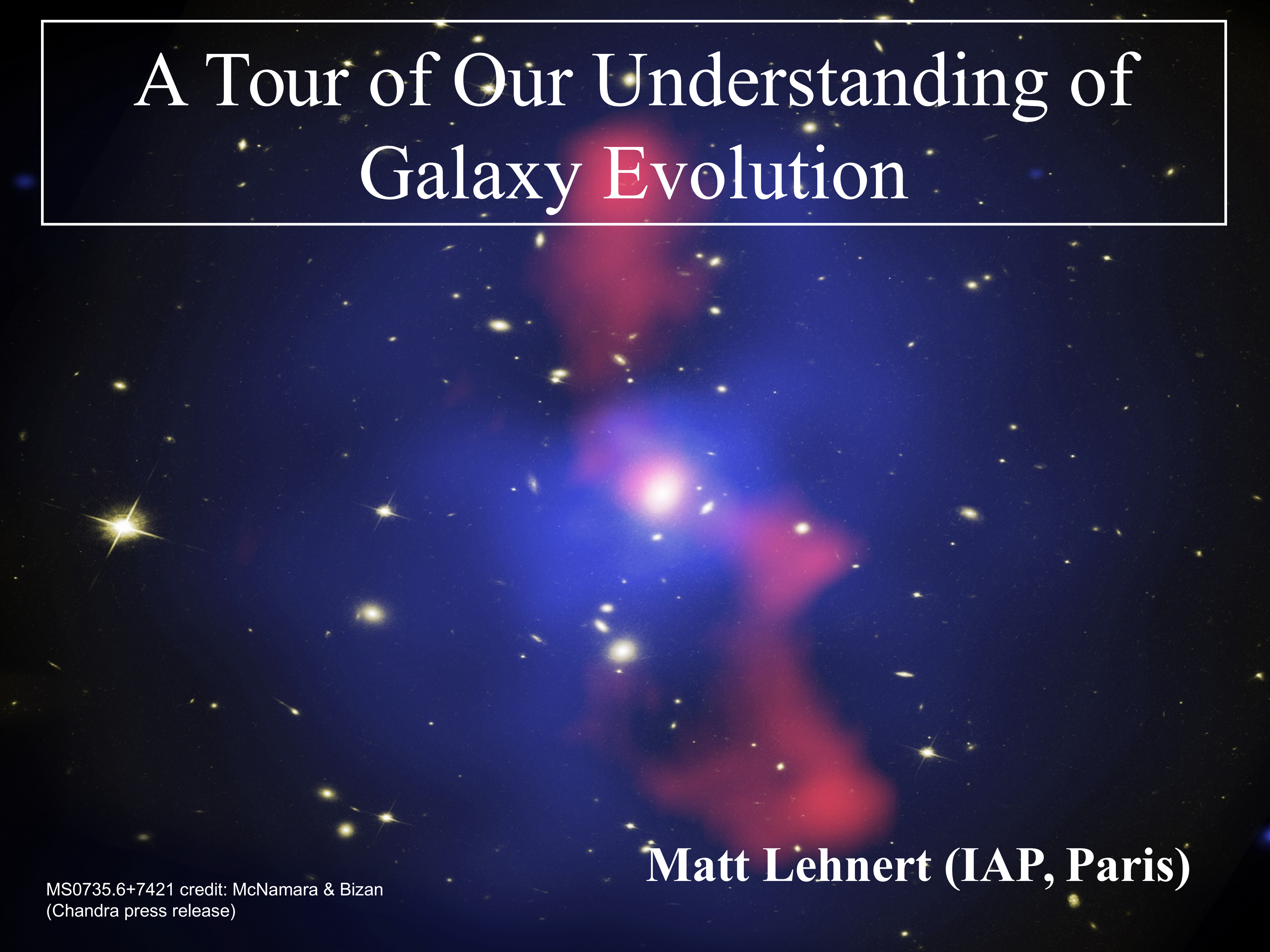
A Tour of Our Understanding of Galaxy Evolution



MS0735.6+7421 credit: McNamara & Bizan
(Chandra press release)

Matt Lehnert (IAP, Paris)

Galaxy Evolution- Cosmology, gas, stars

We now understand that galaxy growth and the develop of large scale structure of the Universe are intimately tied together, but we don't understand how. Environment is important.

Internal processes also shape galaxies, we know some of them, but do not understand all, and do not know how they interact or which are most important.

Understanding the physics of gas – heating, cooling, dissipation – is the next frontier of galaxy evolution. Over-cooling persists in models.

Without understanding how stars form, understanding galaxies is impossible.

Cosmological Perspective

Since the late 1960s, we have made substantial progress in physics.

We now have:

A standard model for particle physics

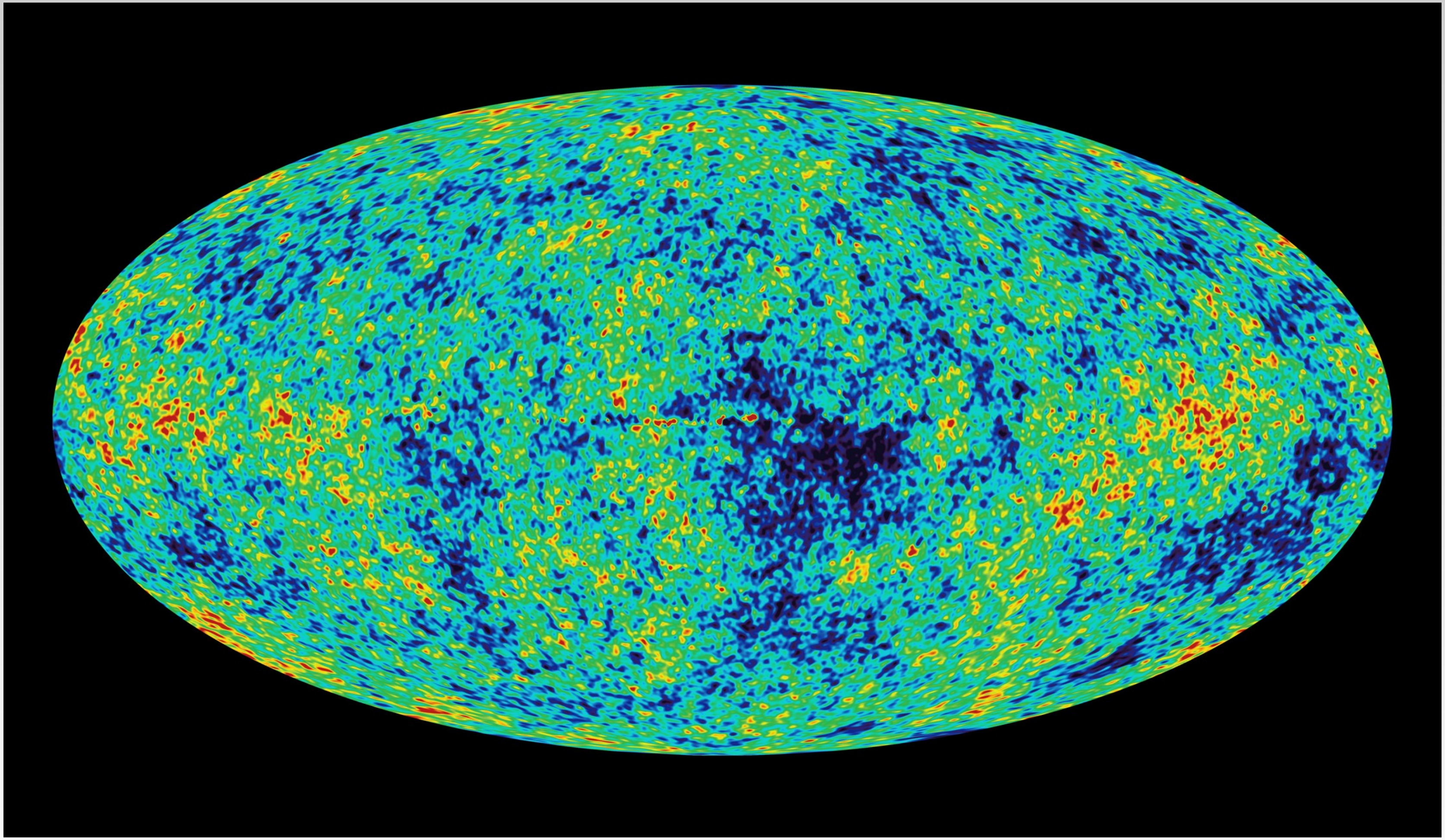
A standard model for cosmology with tightly constrained parameters

A solid frame work for understanding the growth of structure – ΛCDM

We are here to understand the non-linear growth of structure and how the baryons follow this growth.

Universe when size of a grape fruit

400,000 yrs after Big Bang



Cosmological Parameters

From quark soup to nuclei and atoms to galaxies and large-scale structure

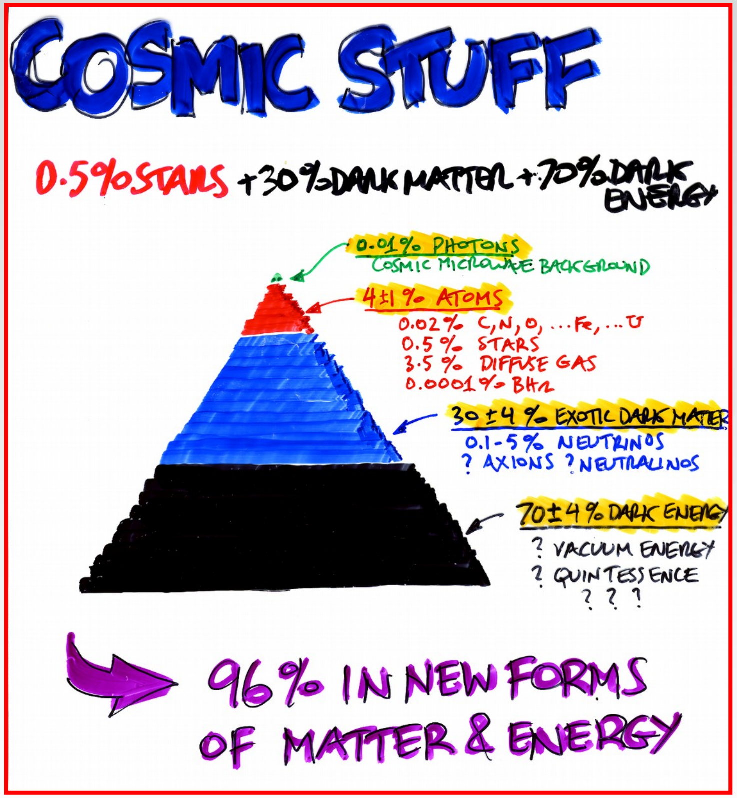
Flat, accelerating Universe

Atoms, exotic dark matter & dark energy

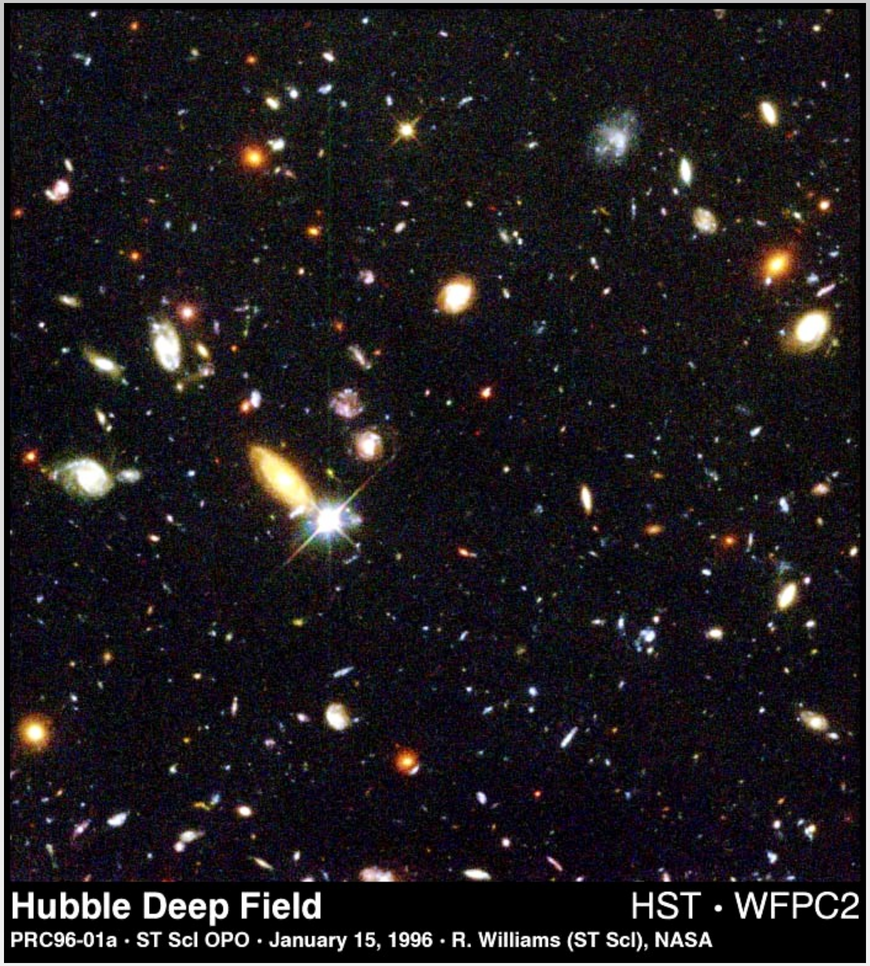
<u>Consistent with inflation</u>

Precision cosmo parameters

- $\Omega_0 = 1.005 \pm 0.006$ (uncurved)
- $\Omega_M = 0.273 \pm 0.014$
- $\Omega_B = 0.046 \pm 0.0016$
- $\Omega_{DE} = 0.73 \pm 0.015$
- $H_0 = 70.4 \pm 1.3$ km/s/Mpc
- $t_0 = 13.75 \pm 0.11$ Gyr
- $N_v = 4.34 \pm 0.9$



Universe is full of galaxies



So how to we get from inhomogeneities in the early universe to galaxies? This is the central question of galaxy formation and evolution as a branch of astrophysics.

Why is this perspective relevant?

This non-linear growth is simply driven by gravity

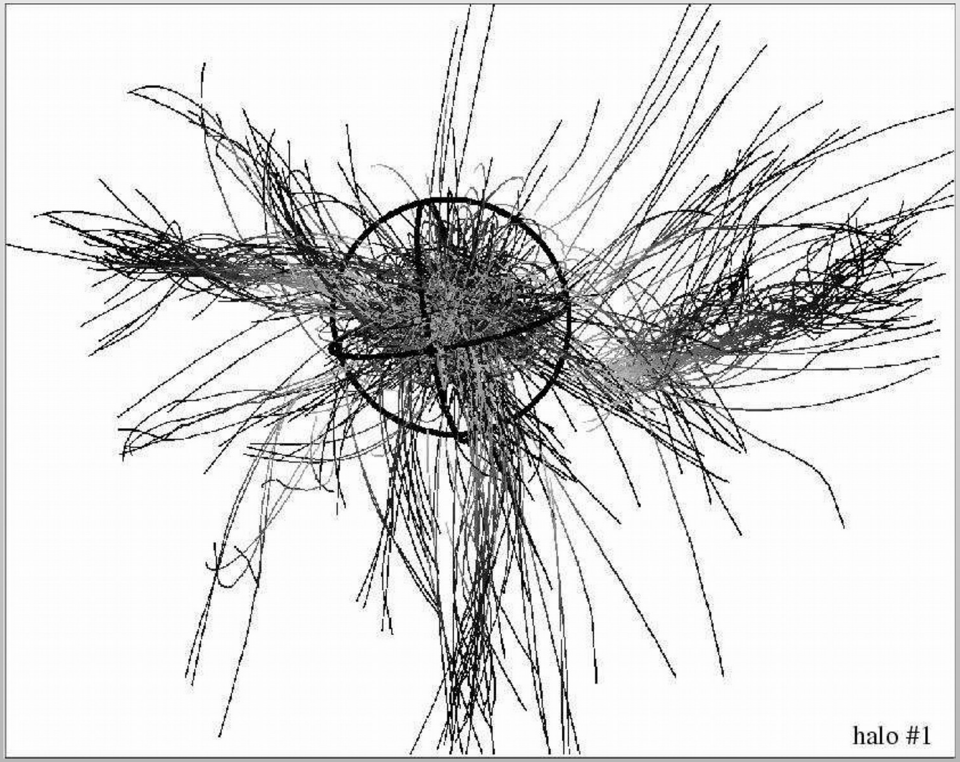
Further growth can be understood as other processes trying to regulate the collapse of structures through gravity:

- cold accretion/cooling of halo gas (instabilities important?)
- disk instabilities and clumps
- star formation
- generation of radiative and mechanical energy from AGN ….

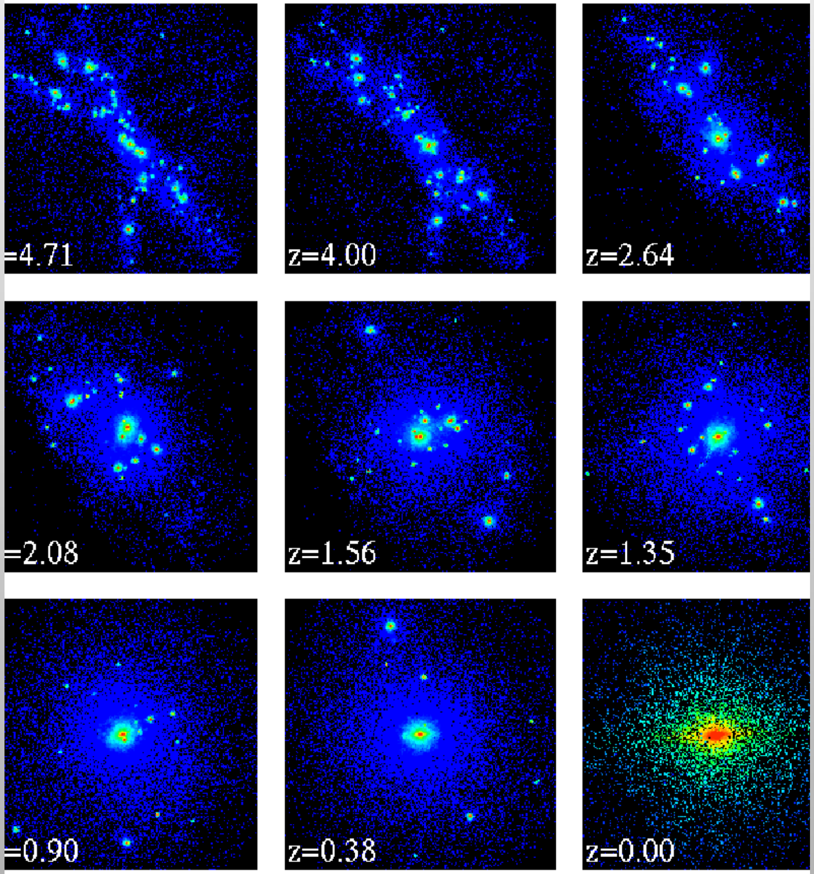
Via the virial theorem, about half, perhaps more, of this gravitational energy is feeding a turbulent cascade (random motions) …

Galaxies in Pieces – Standard Model

Dark matter distribution on 100s kpc scale.

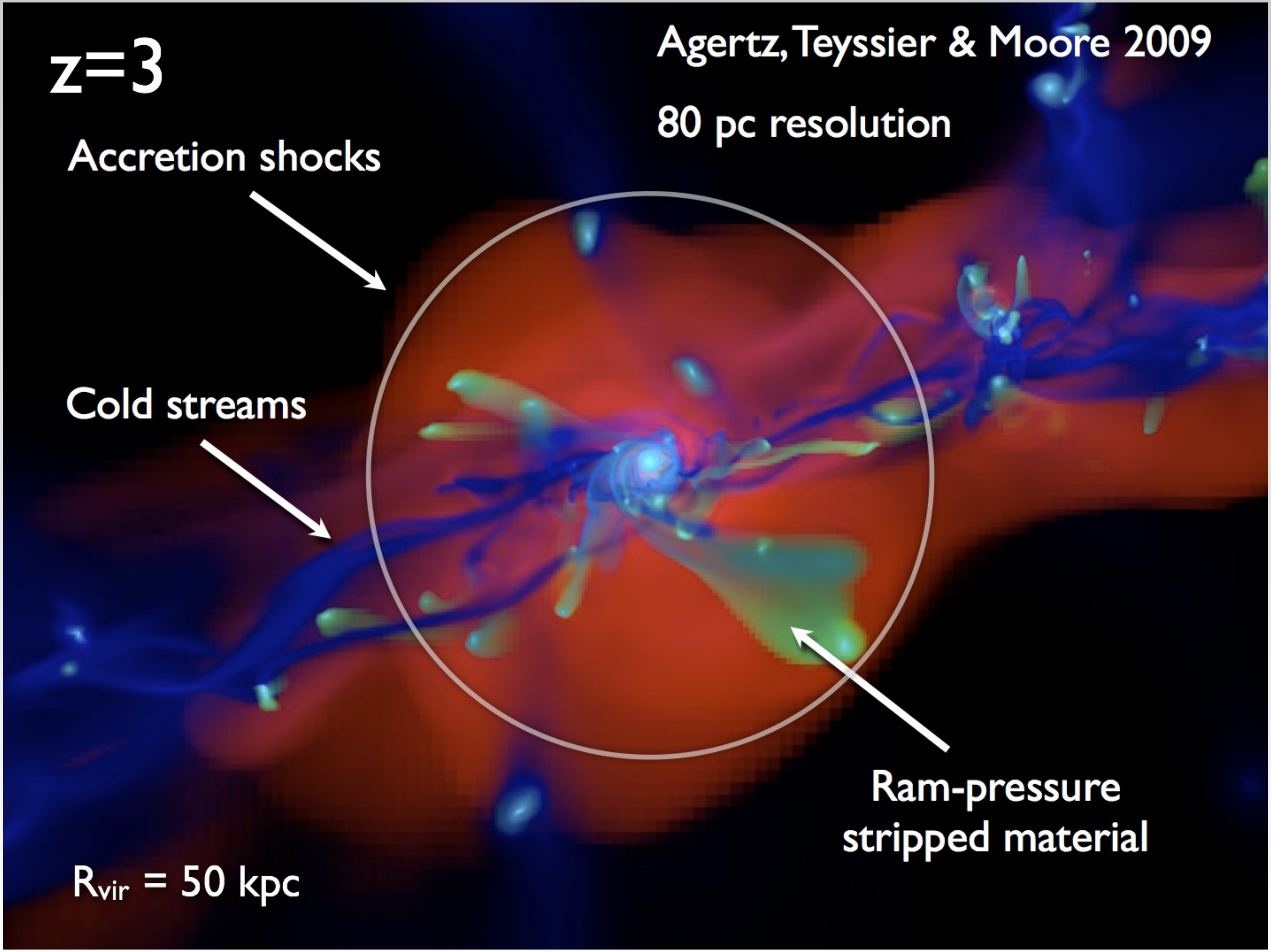


Gill et al. (2004)



Abadi et al. (2002)

Galaxy evolution directly tied to cosmology & DM



Galactic and Extra-Galactic Cycles

Big bang cooling to nucleosynthesis

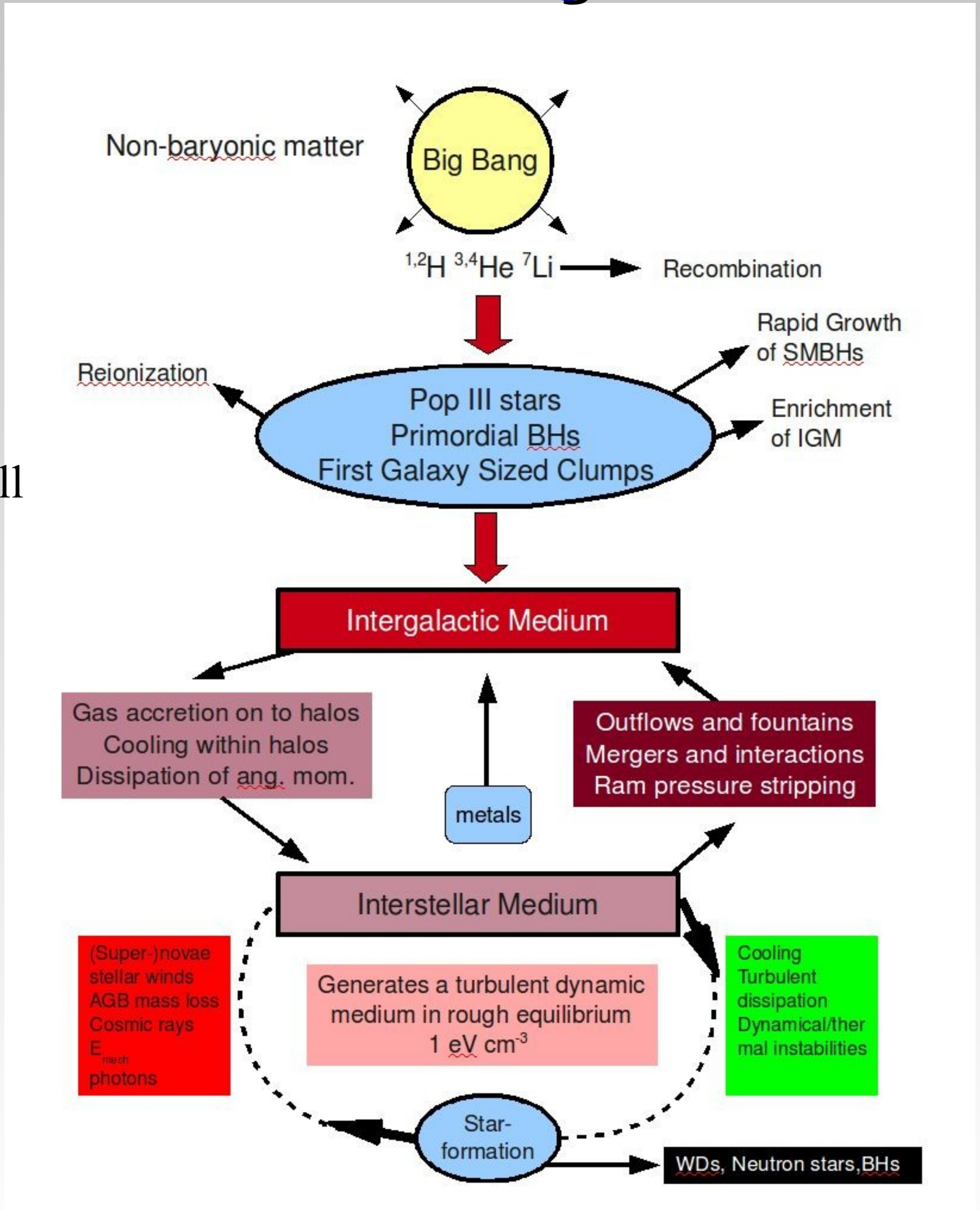
First objects and galaxies form
Reionization

Cosmic web forms through gravitational infall

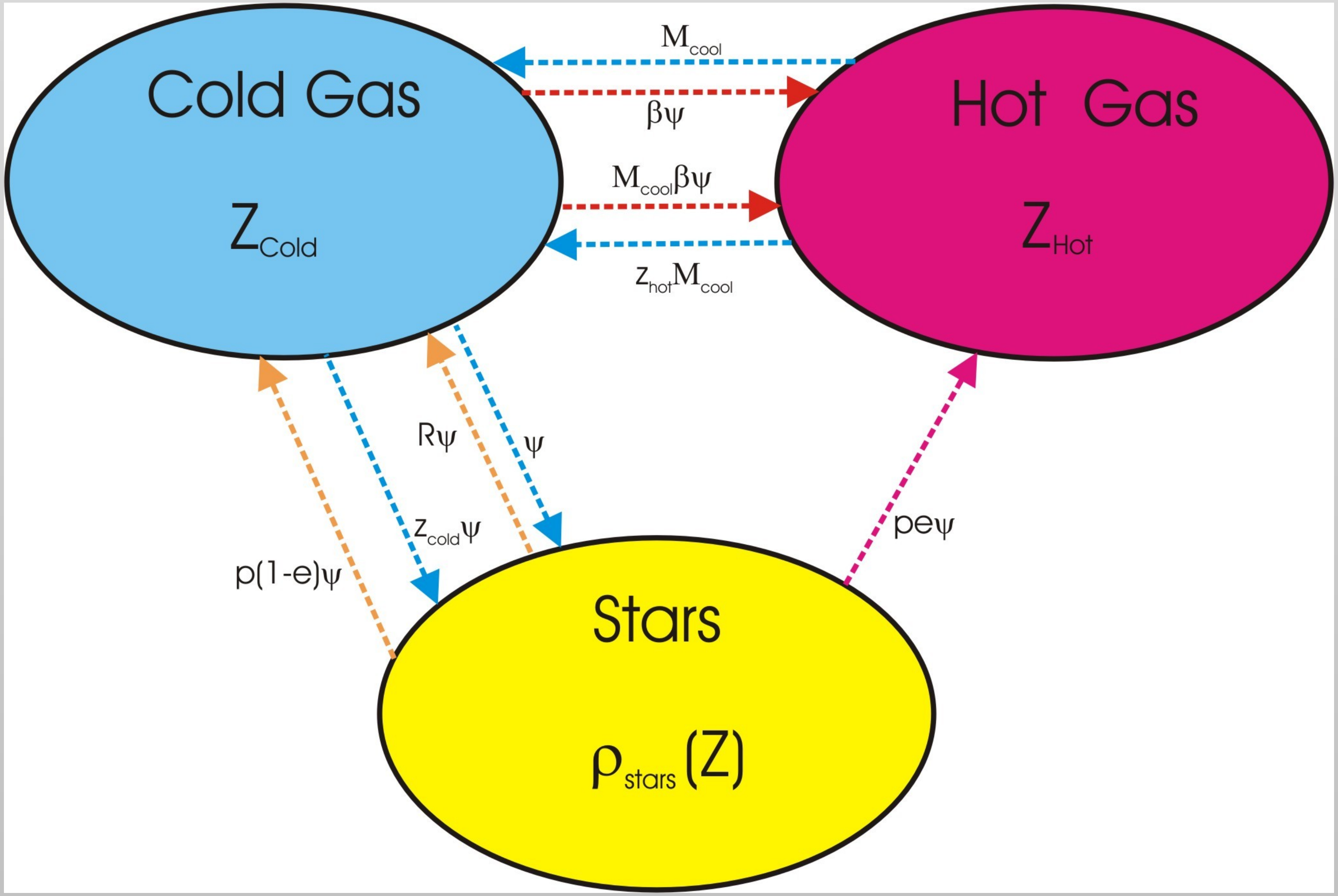
Infall and outflow into and out of halos

Complex cycle of cooling and heating controls the ISM

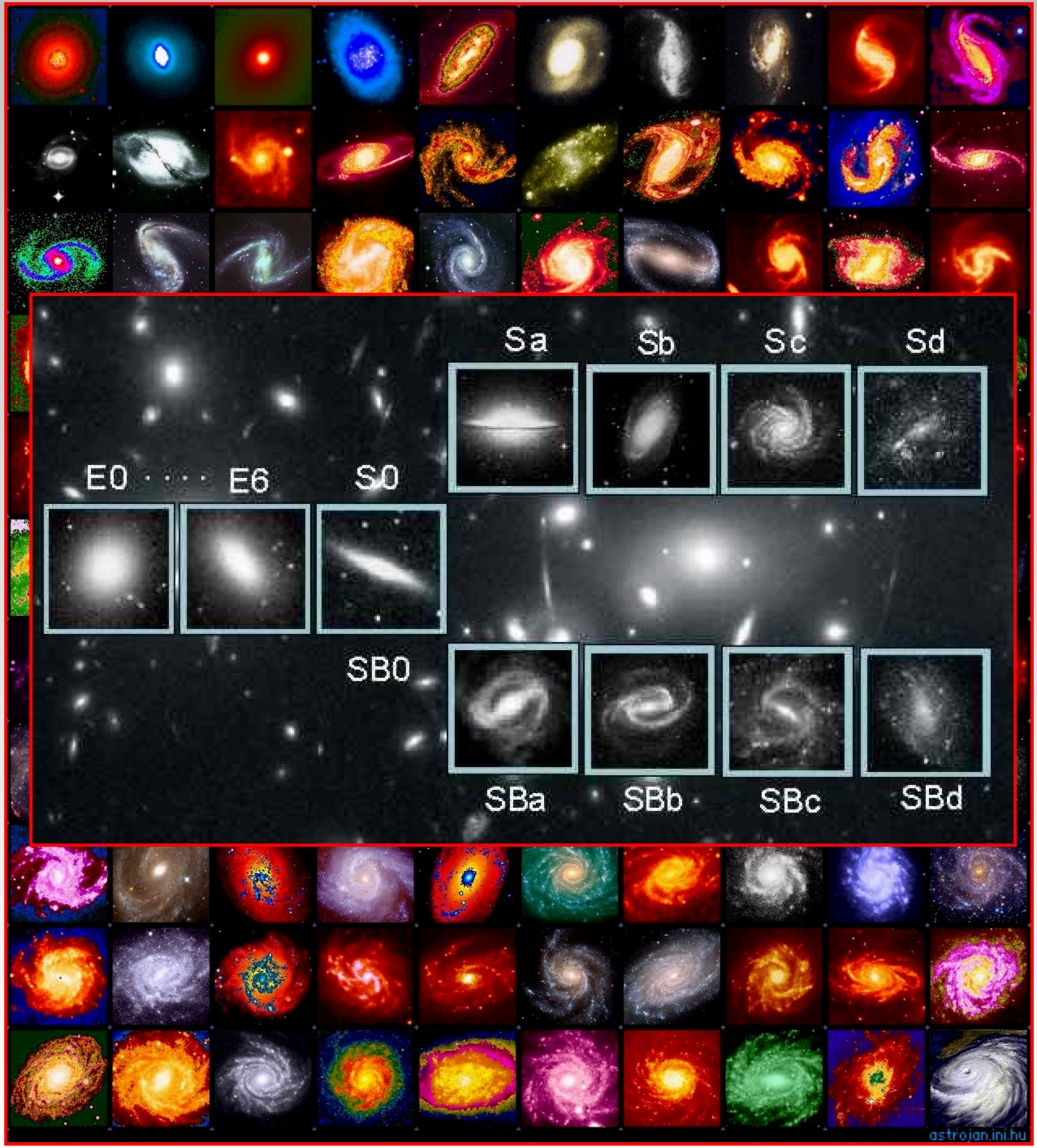
Galaxies become stellar dominated



Complex physics



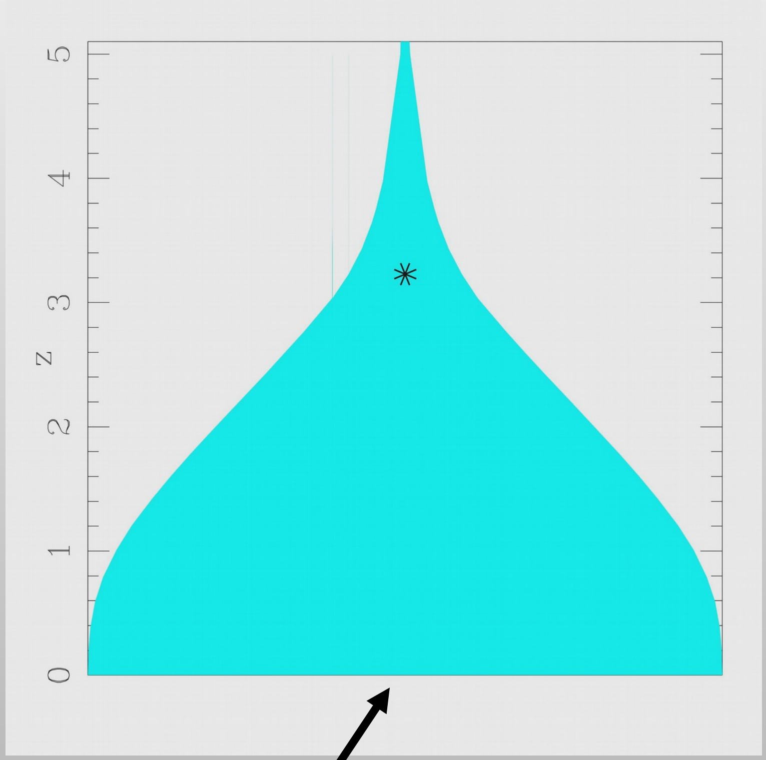
Carlos Frenk & Cole et al.


Sa
Sb
Sc
Sd
E0
E6
S0
SB0
SBa
SBb
SBc
SBd
astrojan.ini.hu

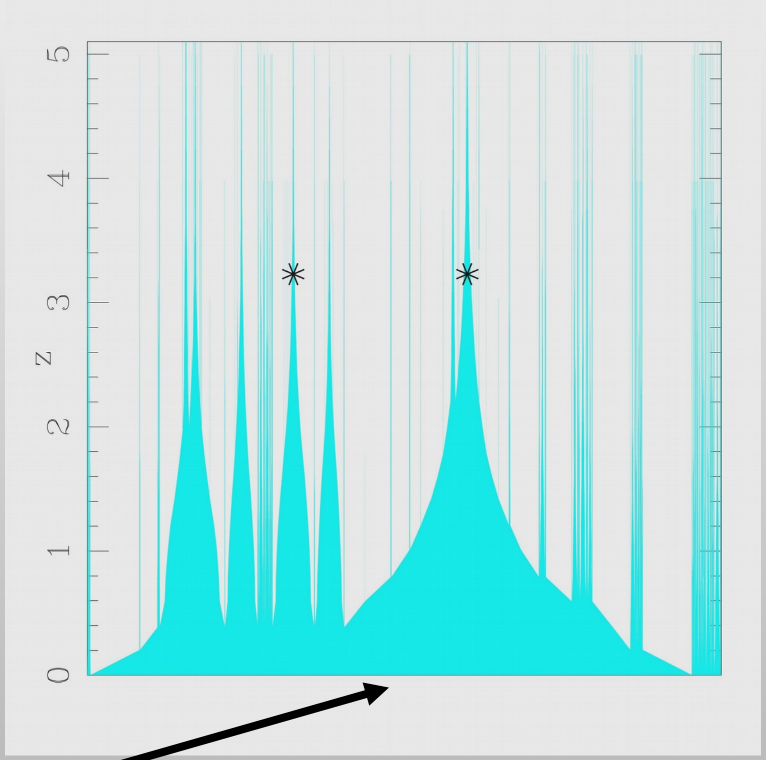
Merger Tree

Ultimately:

Spiral



Elliptical



Frenk, Baugh, & Cole (1996)

smooth vs complex … angular momentum …
dissipative vs. non-dissipative collapse

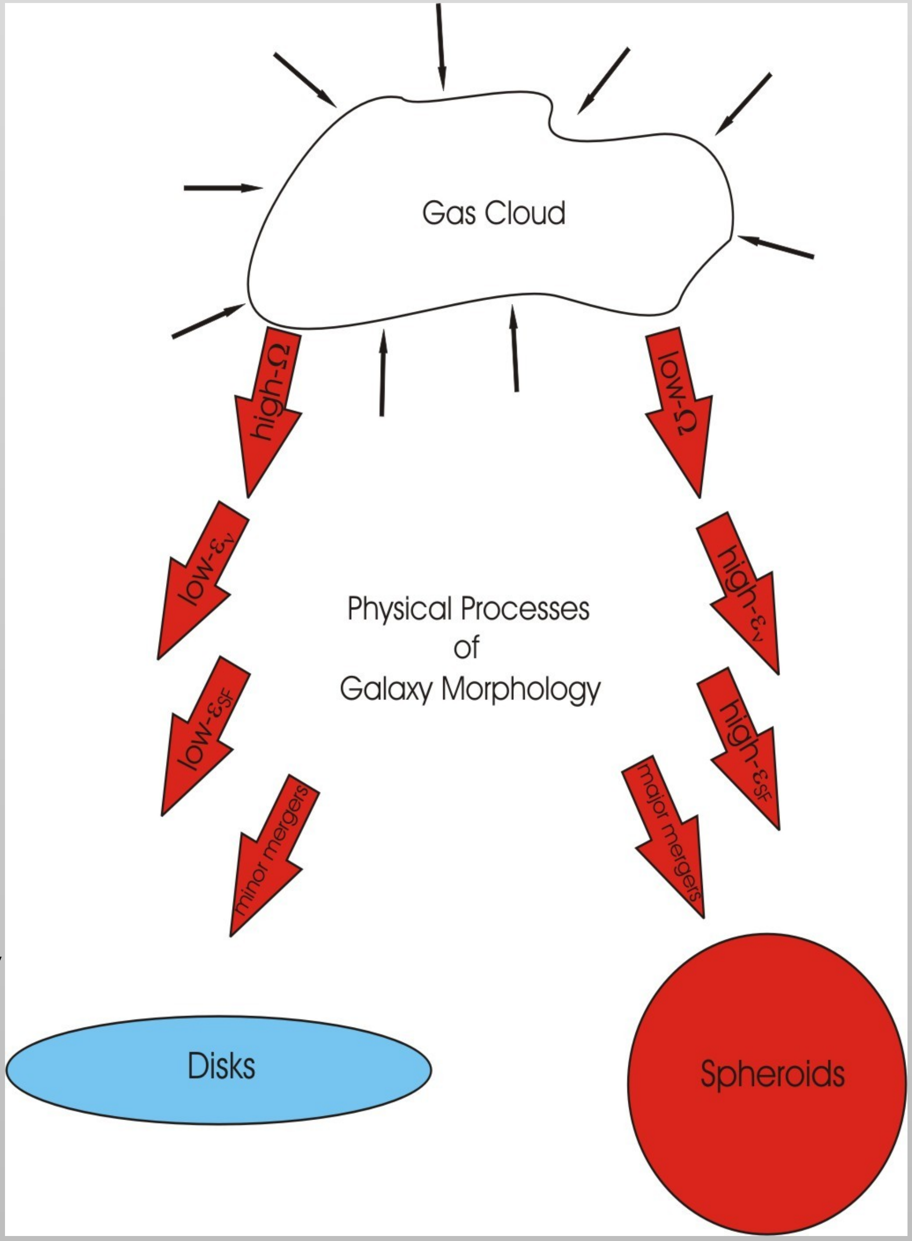
The Path to Morphology

Disks:

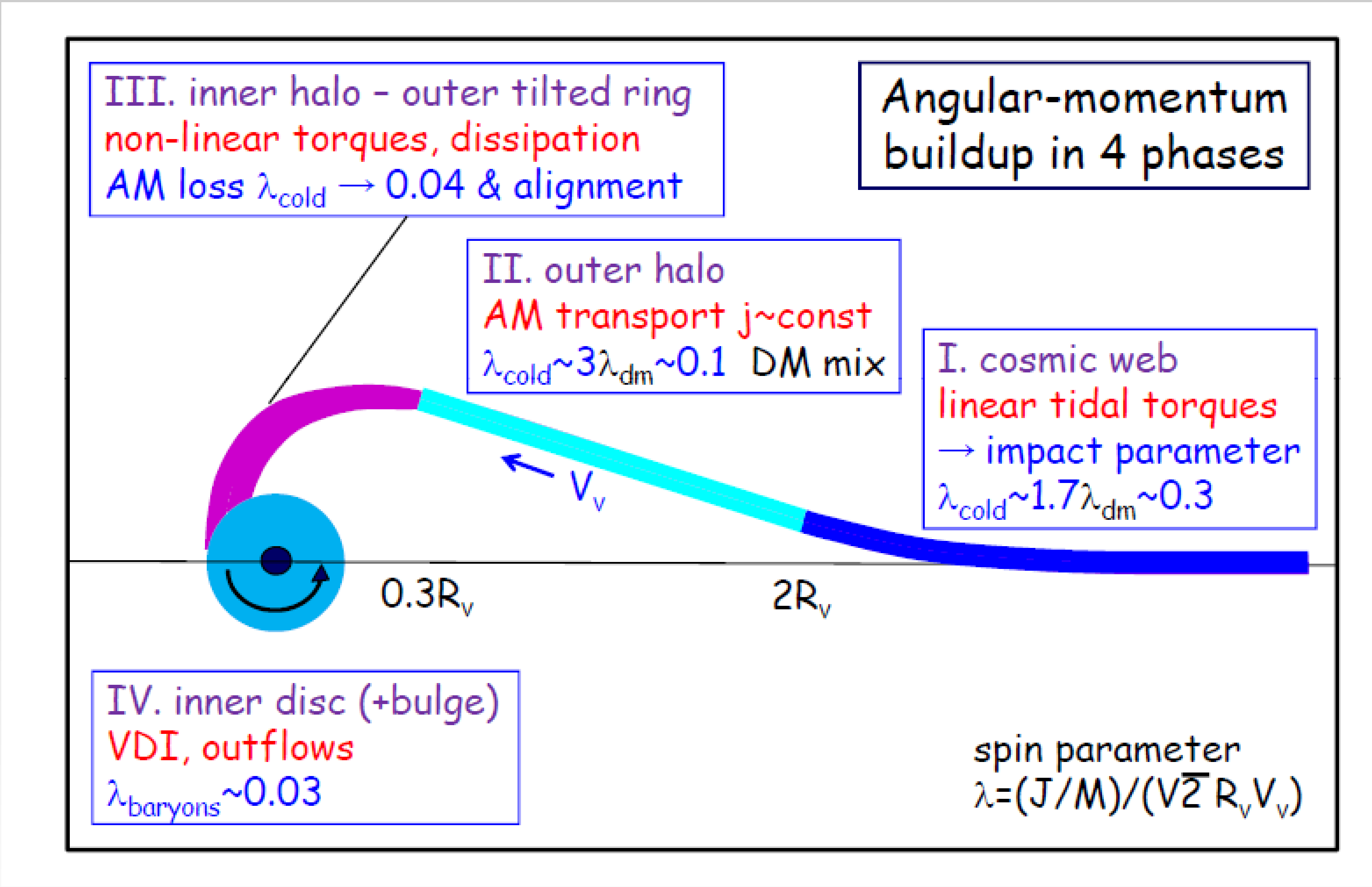
High angular momentum
weak feedback
low star-formation efficiency
formed relatively recently
gas accretion/minor mergers

Spheroids:

low angular momentum
strong AGN/SB feedback
high star-formation efficiency
formed many Gyrs ago
major mergers

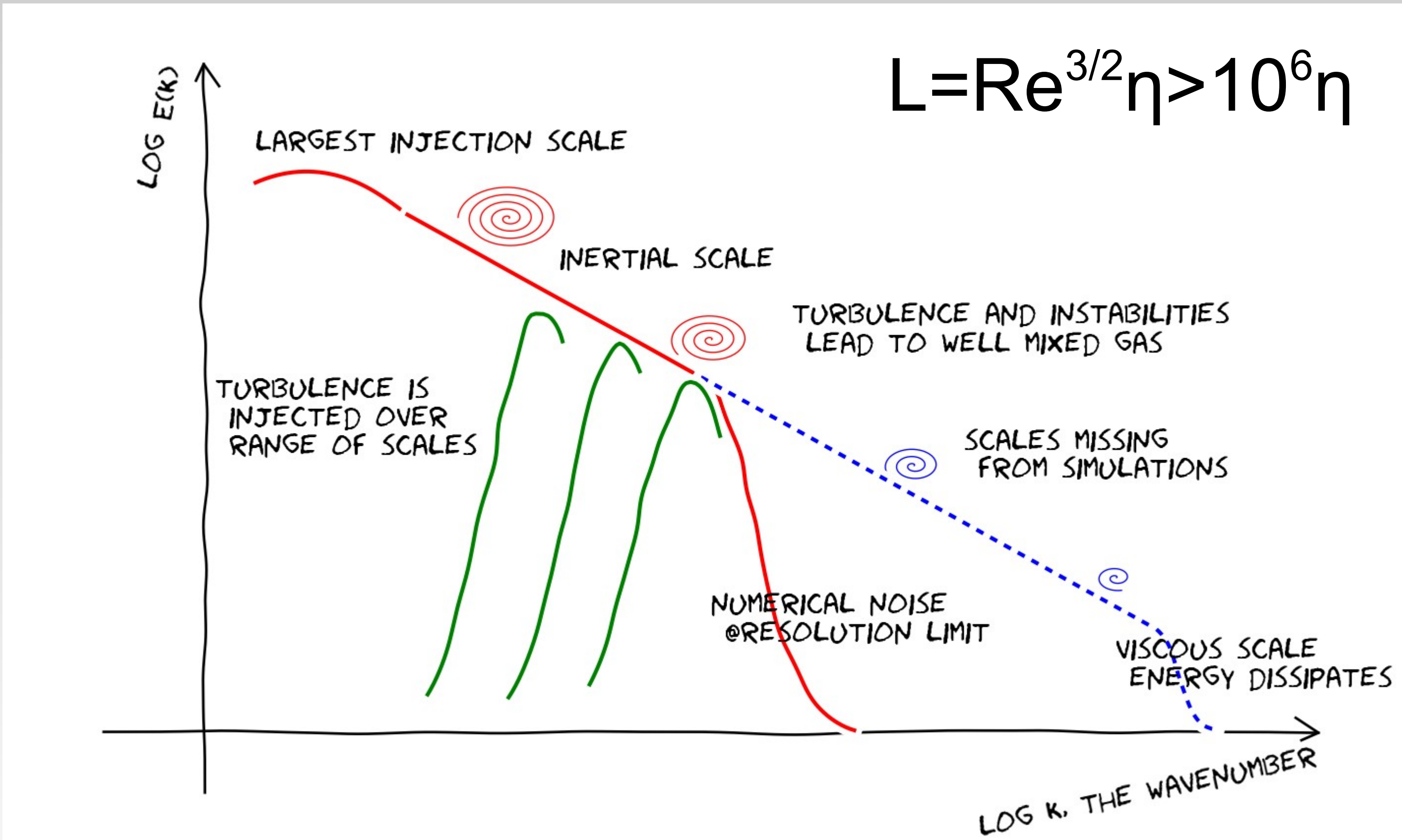


Galaxy evolution directly tied to cosmology & DM



Why do model galaxies overcool?

$E_{turb} > E_{thermal}$ in astrophysical plasmas, while in models, $E_{thermal}$ is generally dominate unless there is a lot of large scale forcing ...



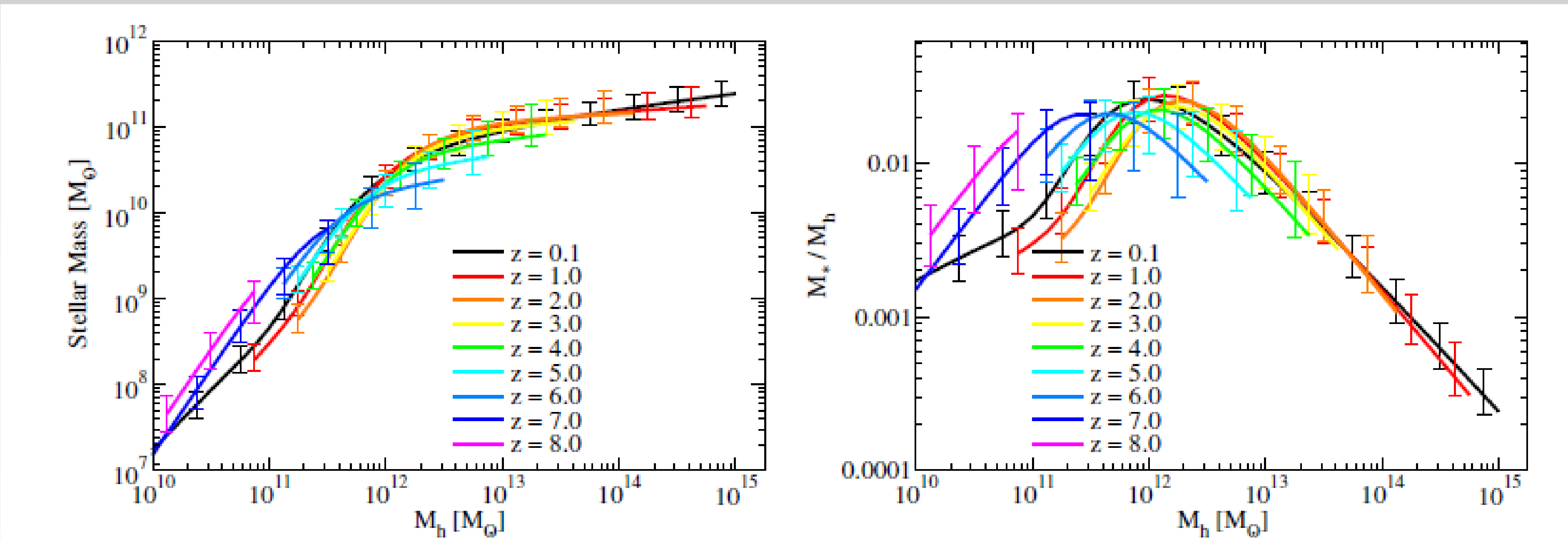
Turbulent compression, rarefaction, and mixing is what makes the ISM multiphase … dynamics and phases are inextricably coupled.

Constituent	Observable	Diagnostic
Relativistic Plasma	Radio continuum X-ray continuum	Magnetic field, aging of electrons, relativistic or thermal pressure, jet collimation star-formation rate, number of X-ray binaries
Hot ionized gas $T \sim 10^7$ to 10^8 K $\log n_e \sim -3$ to -1 cm^{-3}	X-ray continuum, emission and absorption lines Radio depolarization	Thermal pressures, metal abundances, density, mass, cooling rate, viscosity, turbulence, outflow rate
Warm ionized gas $T \sim 10^4$ to 10^6 K $\log n_e \sim -1$ to 3 cm^{-3}	UV absorption lines Optical emission lines Radio recombination lines Far-IR emission lines	Temperature, shock heating or photoionization rate, density, mass, turbulence, dynamics, metallicity, filling factor, pressure, outflow rate, cooling rate
Warm neutral gas $T \sim 4\text{-}8 \times 10^3$ K $\log n_e \sim 0$ to 2 cm^{-3}	Optical em/abs lines HI emission and absorption Mid-IR H-H lines Far-IR lines of neutral species	Filling factor, temperature, column densities, cooling rate, pressures,masses, etc.
Cold neutral gas $T \sim 10^2$ K $\log n_e \sim -1$ to 0 cm^{-3}	HI emission and absorption	Filling factor, temperatures, column densities, cooling rate, pressure, masses, etc.
Warm molecular gas $T \sim 0.5\text{-}2 \times 10^3$ K $\log n_e \sim 1$ to 4 cm^{-3}	Mid-IR H-H lines High order molecular lines of neutral and ionized species	Filling factor, temperatures, column densities, cooling rate, pressure, masses, etc.
Cold molecular gas/dust $T < 10^2$ K $\log n_e > 4$ cm^{-3}	Molecular lines Infrared dust continuum Mid-infrared features	Heating and cooling rates, dynamics, turbulence, masses, densities, temperature, pressure, cosmic ray heating rate, interstellar chemistry, etc
Stars	UV/optical/near-infrared continuum	Mass, dynamics, star-formation history, metallicity, energy injection rate, mass return rate, etc.

Galaxy growth is inefficient

AGN + SF + accretion:

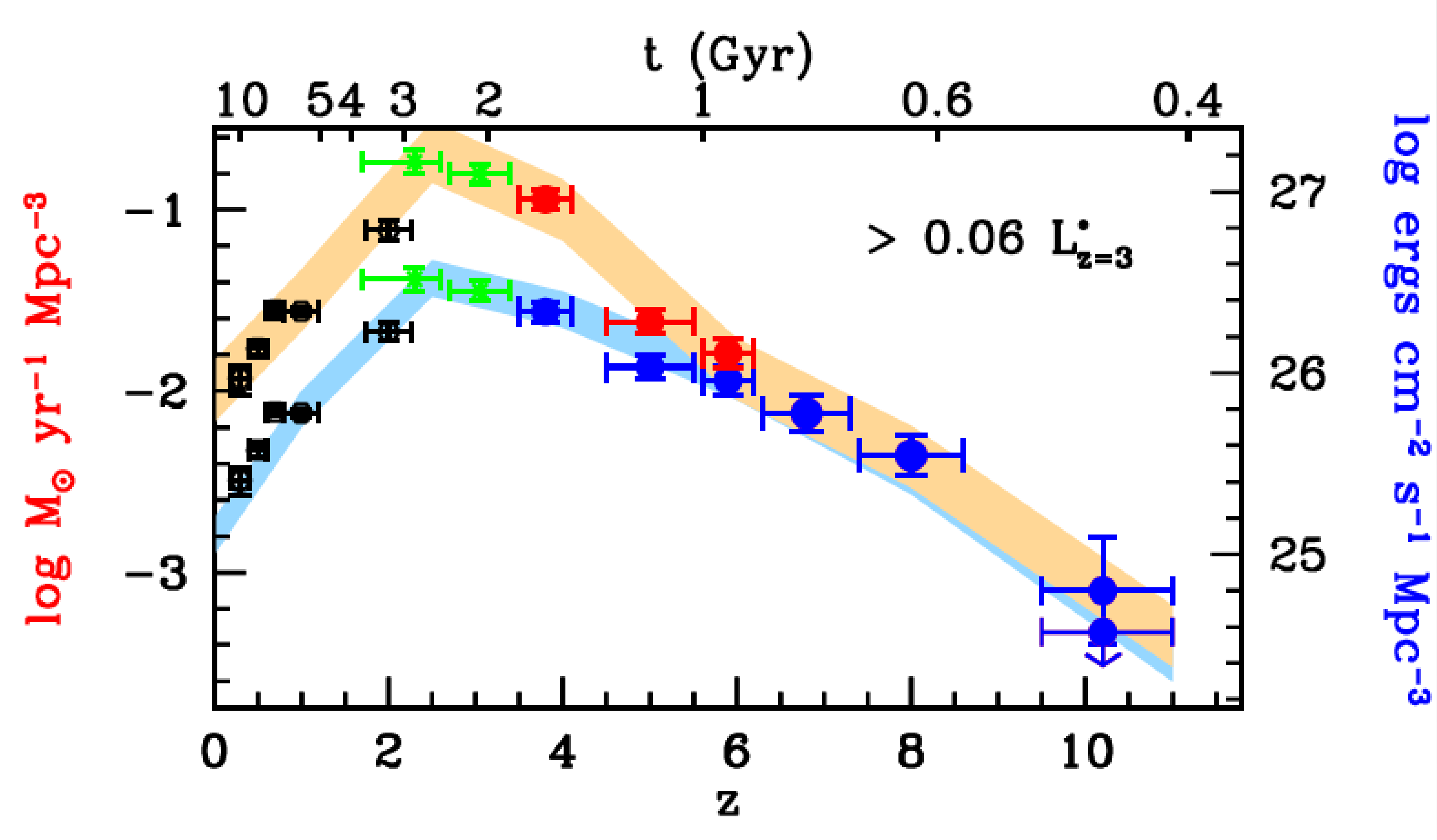
Turbulent pressure, cosmic ray pressure, B-field pressure, radiation pressure, ionization, shocks, gravitational instabilities ….



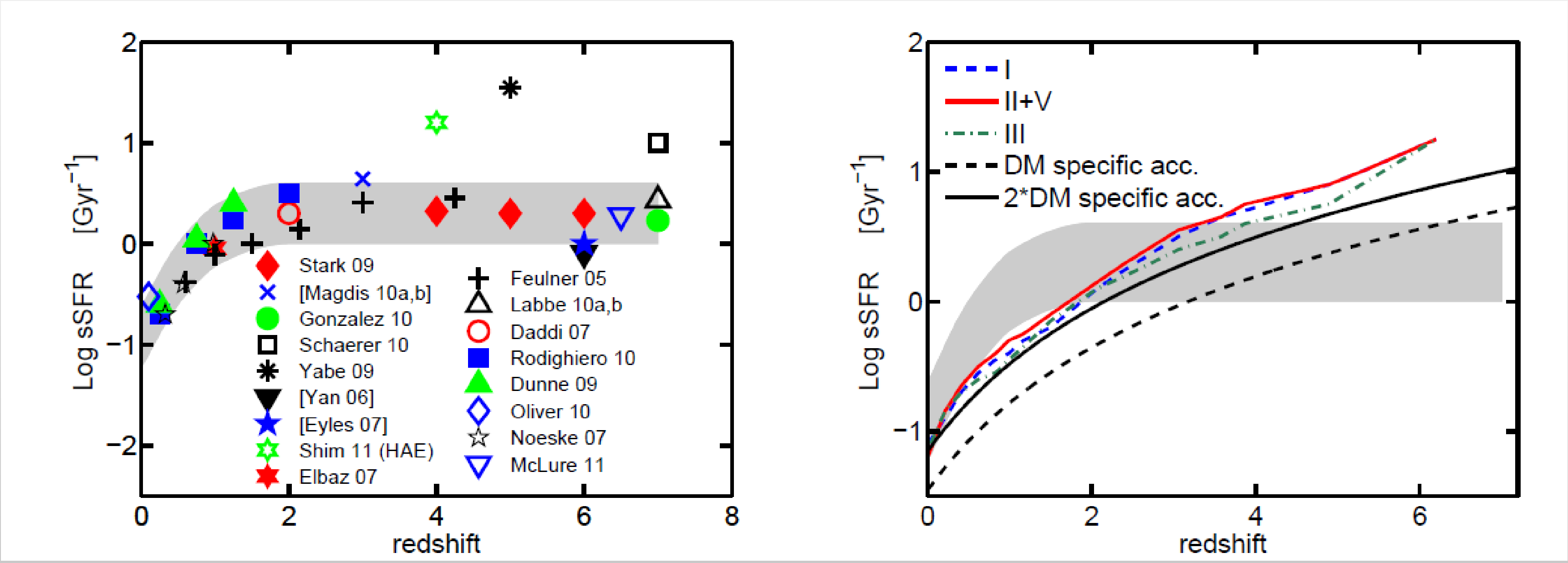
Galaxy formation is inefficient … most baryons not in galaxy proper … are most of the baryons in the halos? This is often called the missing baryons problem.

Behroozi et al. (2012)

"star formation history"



What drives the time evolution of the mass growth?



Weinmann et al. (2011)

Why doesn't the specific growth rate follow the specific accretion rate of the gas? Too simple as growth rates are mass dependent.

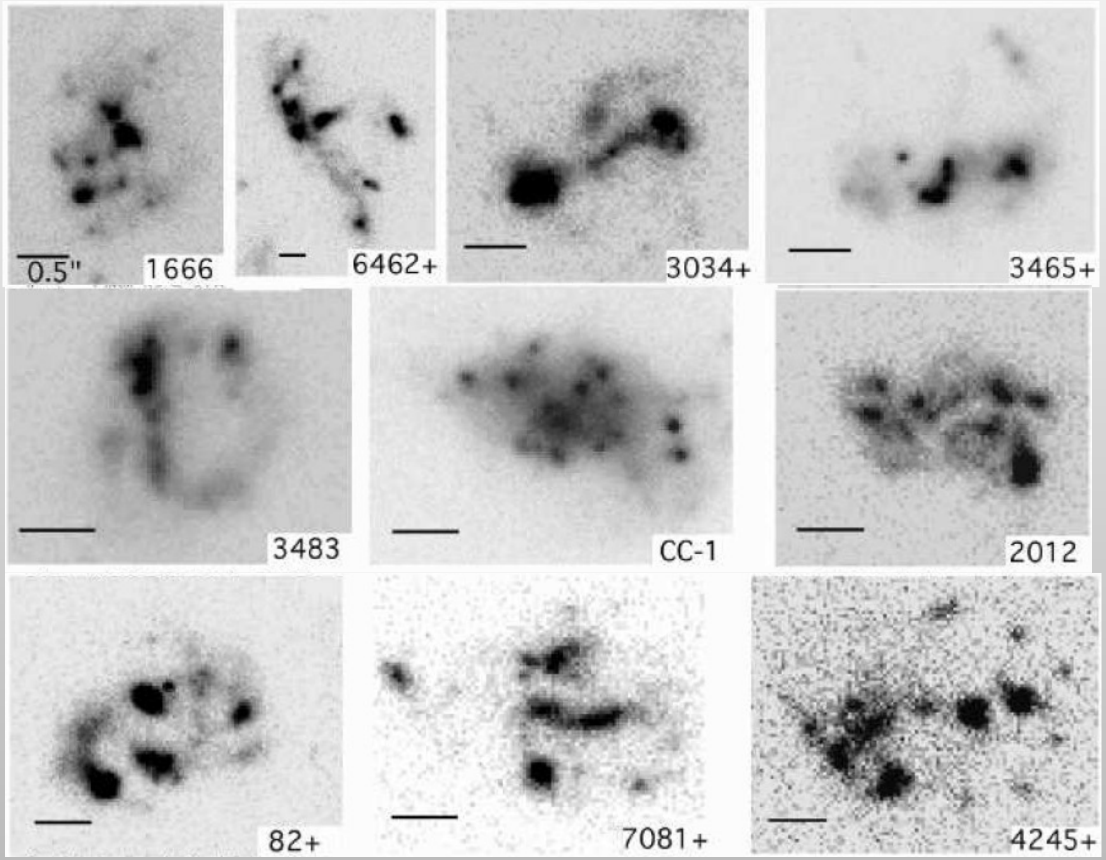
Outflows and feedback?

Angular momentum?

Accretion rate over-estimated (over-cooling)?

Disk formation – clumpy disks at high redshift

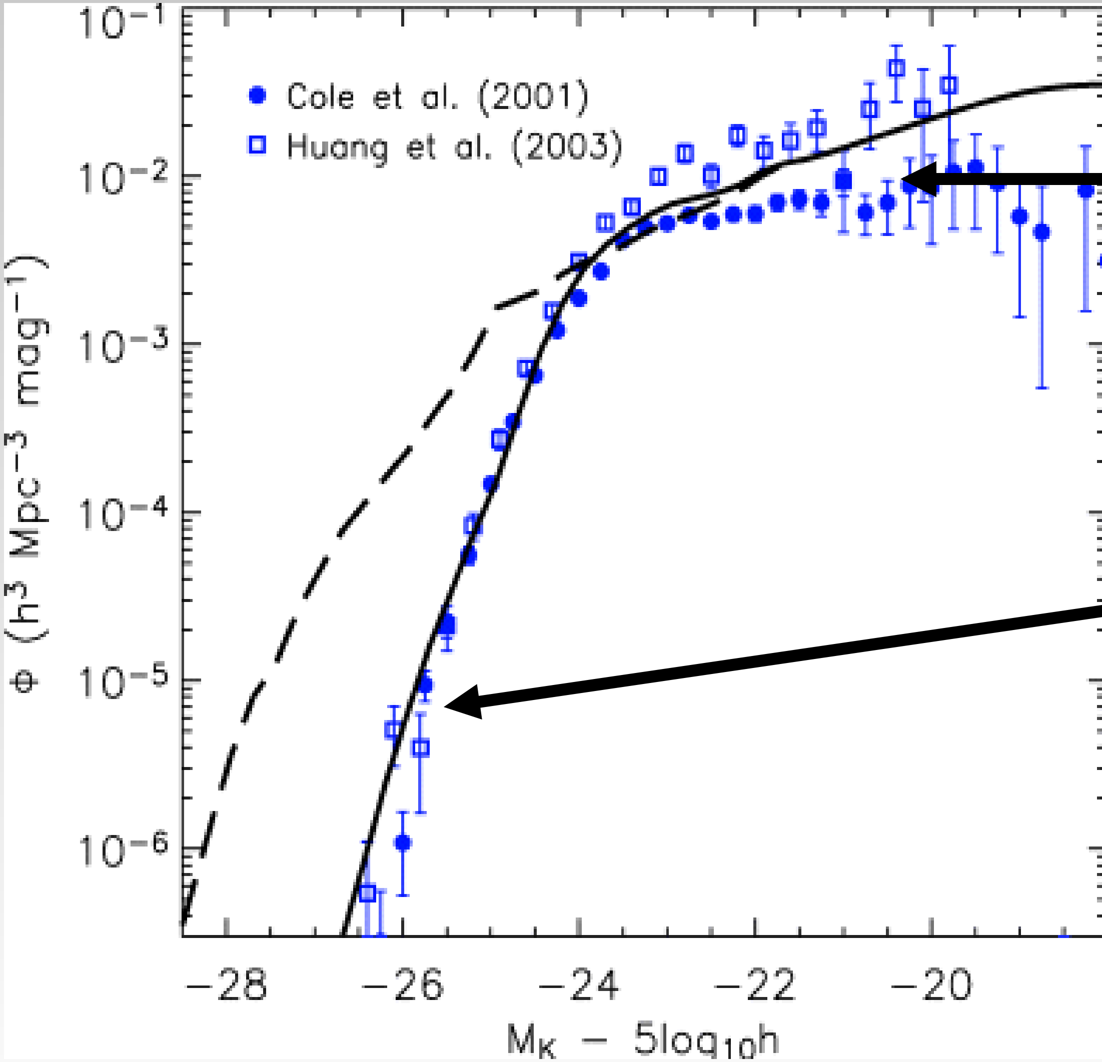
Clumpy galaxies in the UDF …



Elmegreen & Elmegreen (2005)

Galaxies at high redshift are increasingly dominated by their gas.
Locally, 10%, about 10 Gyrs ago, 50% of galaxy mass is molecular.

Need for (Self-)regulation



Flatness of mass function
Wide range of ages
Wide range of stellar densities
Φ(gal) < Φ(halo) at low mass

Steepness of mass function
Old, red, & dead
Φ(gal) < Φ(halo) at high mass
M_{BH} M_{Sph} relation

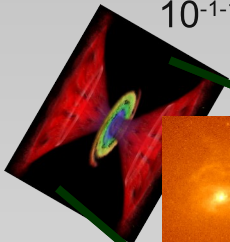
Hypothesize:
1) quenching (high-z)
2) maintenance (low-z)

Nonetheless, need some self-regulation of BHs for exponential cut-off

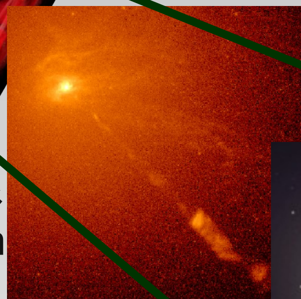
Benson et al. (2003)

Influence of AGN

$10^{-1\text{-}1}$ pc



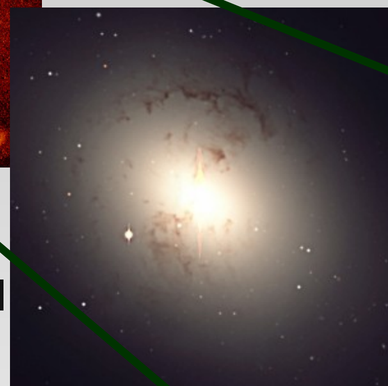
$10^{1\text{-}3}$ pc



$10^{3\text{-}4}$ pc

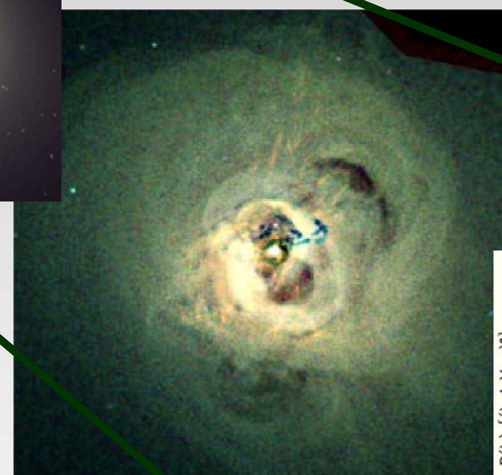
[M/H] and $\vec{B}$

Self-reg & Eddington limiting



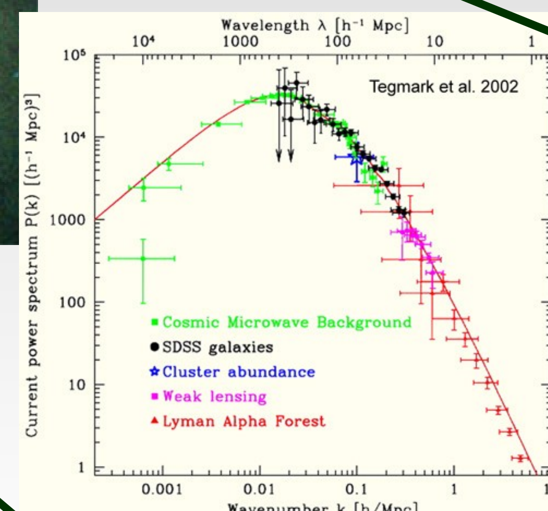
$10^{4\text{-}6}$ pc

M_{BH}-σ & mass disposal



$10^{6\text{-}8}$ pc

Regulate ISM Galaxy formation

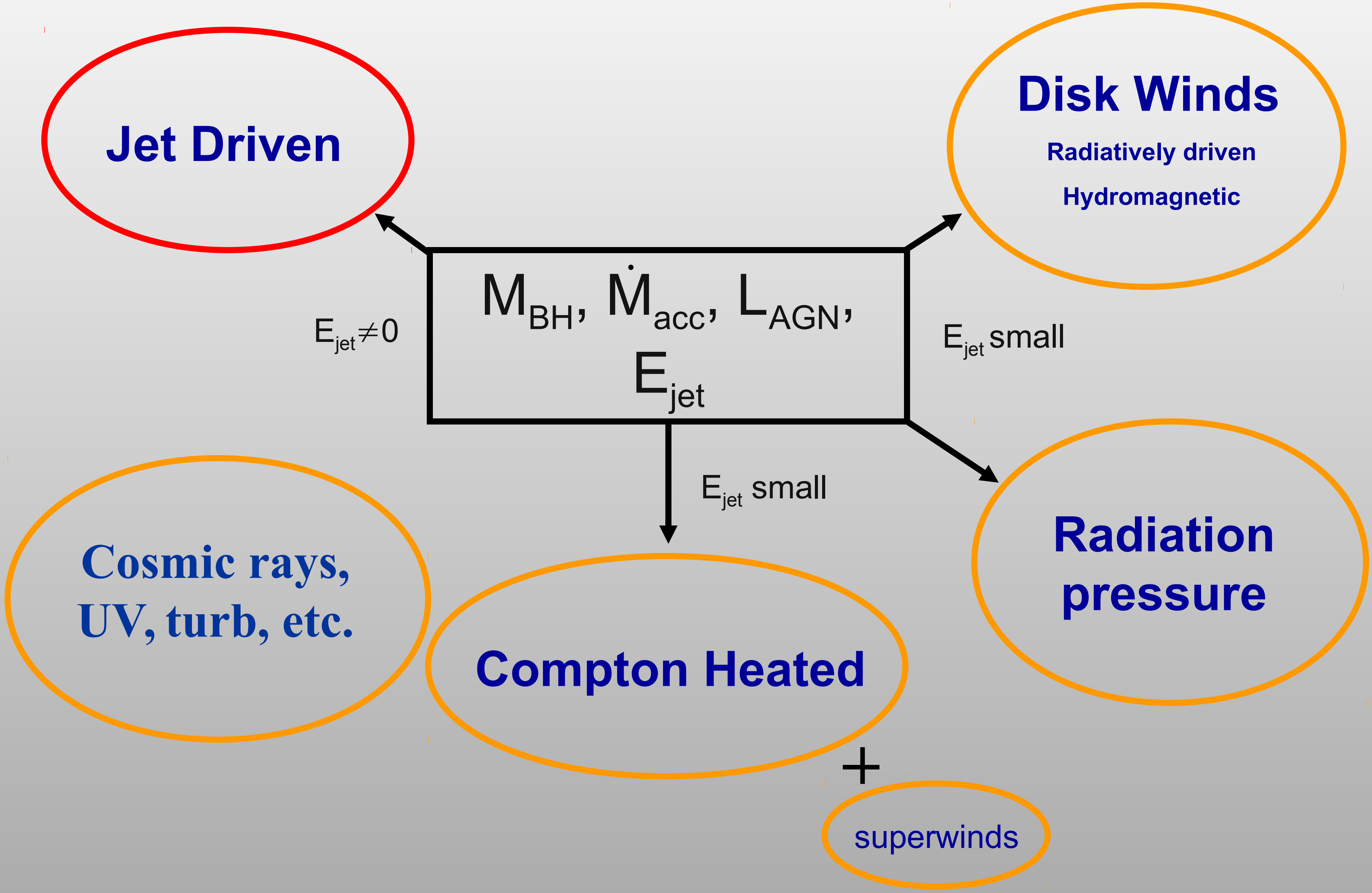


Dynamical evolution of galaxy centers & star-clusters

Heat halo & cluster gas

LSS

Underlying Mechanisms for AGN Feedback



Physics of Winds

Outflows driven by the collective thermalization of stellar winds and supernova

Thermalization of SNe: $$T_{postshock} = \frac{3}{16} v_{ejecta}^2 m_H / k = 9.1 x 10^7 v_{ejecta,2000}^2 K$$

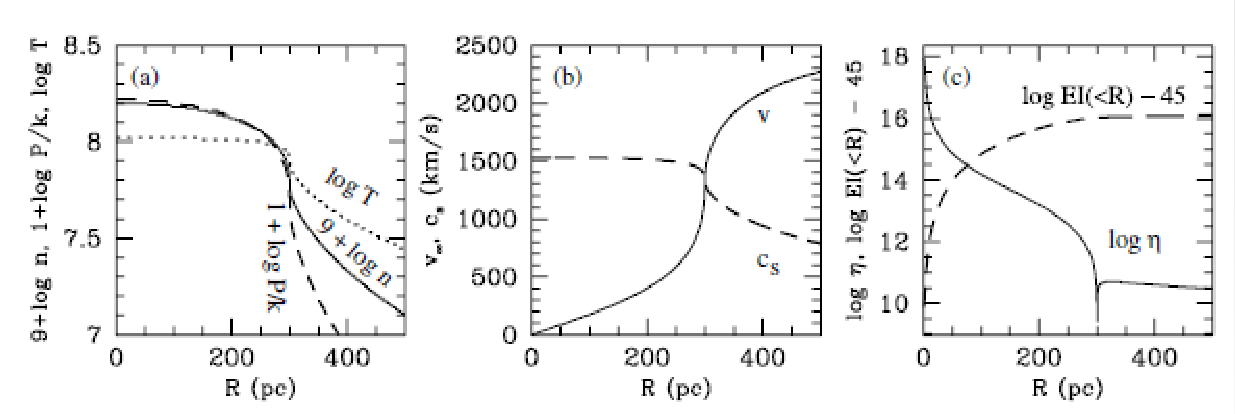
Injection region: $$T_c = 0.4 \mu m_H \dot{E}_{total} / k \dot{M}_{total}$$

$$\rho_c = 0.3 \dot{M}_{total}^{3/2} \dot{E}_{total}^{-1/2} R_{SB}^{-2}$$

$$v_\infty = \sqrt{2} \dot{E}_{total}^{1/2} \dot{M}_{total}^{-1/2}$$

$$\frac{\dot{M}_{wind}}{SFR} \neq \eta$$

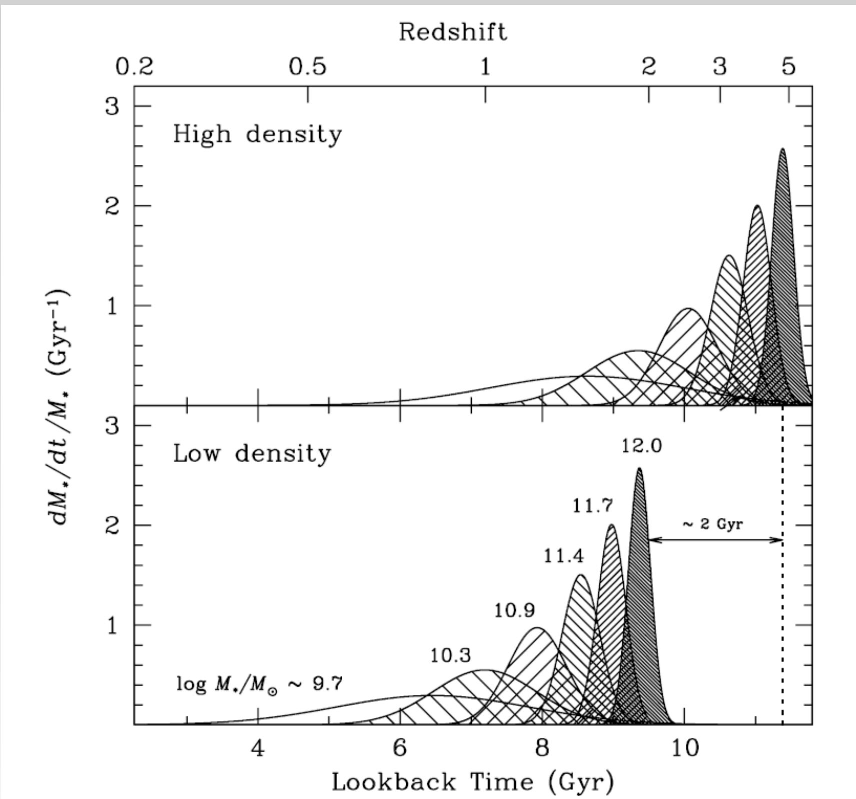
SNe/SW are efficiently thermalized

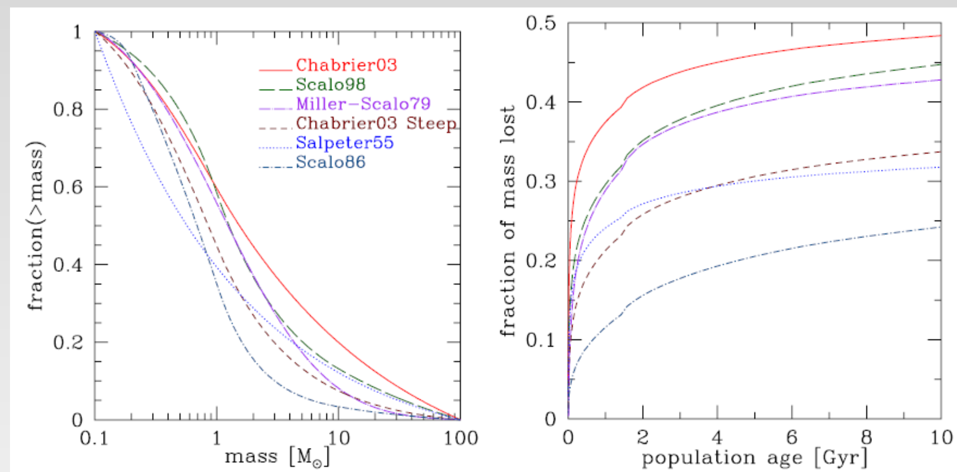


Chevalier & Clegg (1985), Strickland & Heckman (2009)

Mass dependent

We have discussed the efficiency of outflows, but the need for a catastrophic phase of outflow or inhibition depends of mass.





But mass return is ~20-40% for old populations … and cooling time is $<t_{H0}$ ….
internal velocity dispersions are not extreme … 10s km s^{-1}

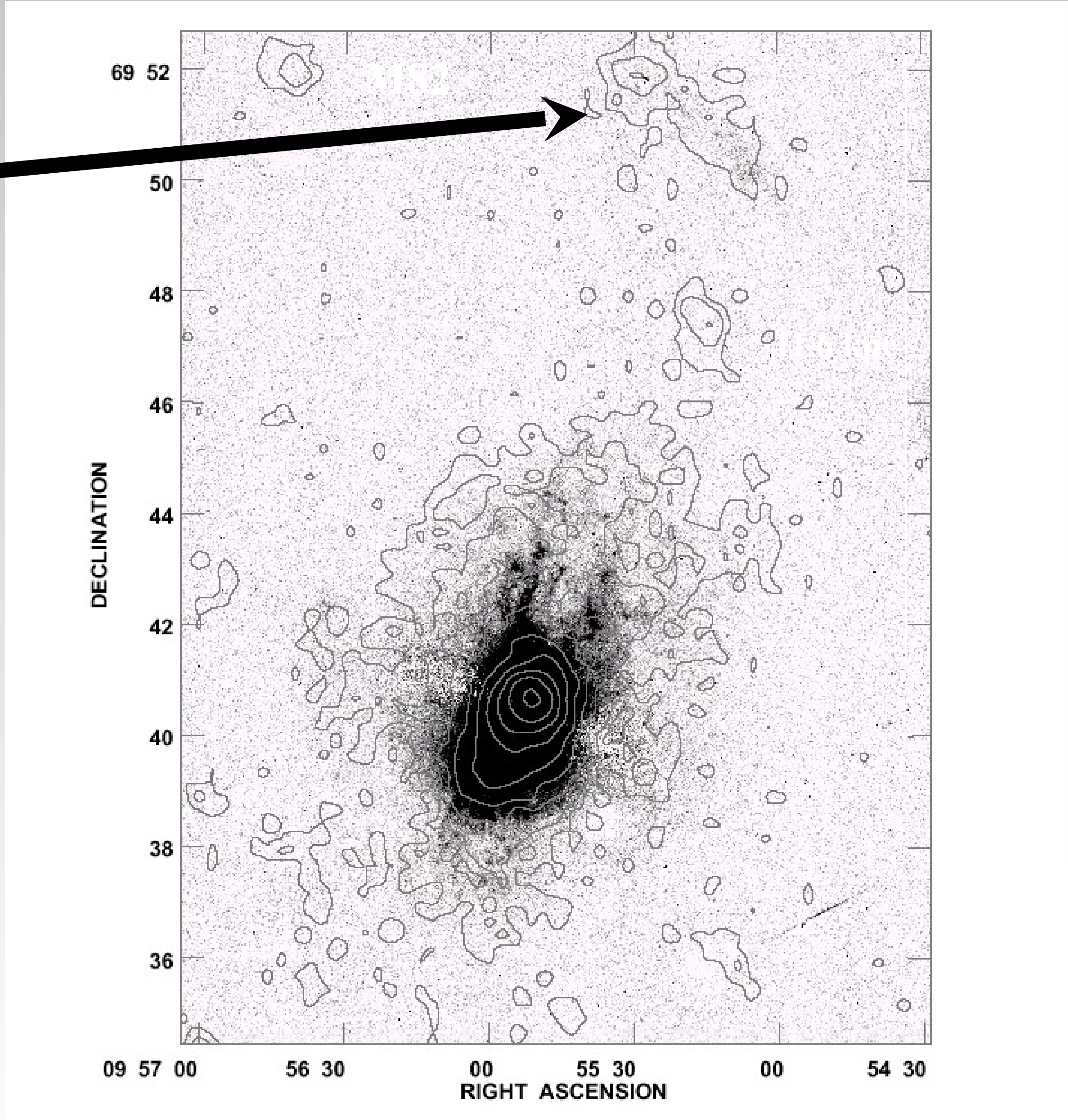
Thomas et al. (2005); Leitner & Kravtsov (2011)

Escaping Wind in M82

Region of spatially coincident X-ray and H-alpha emission

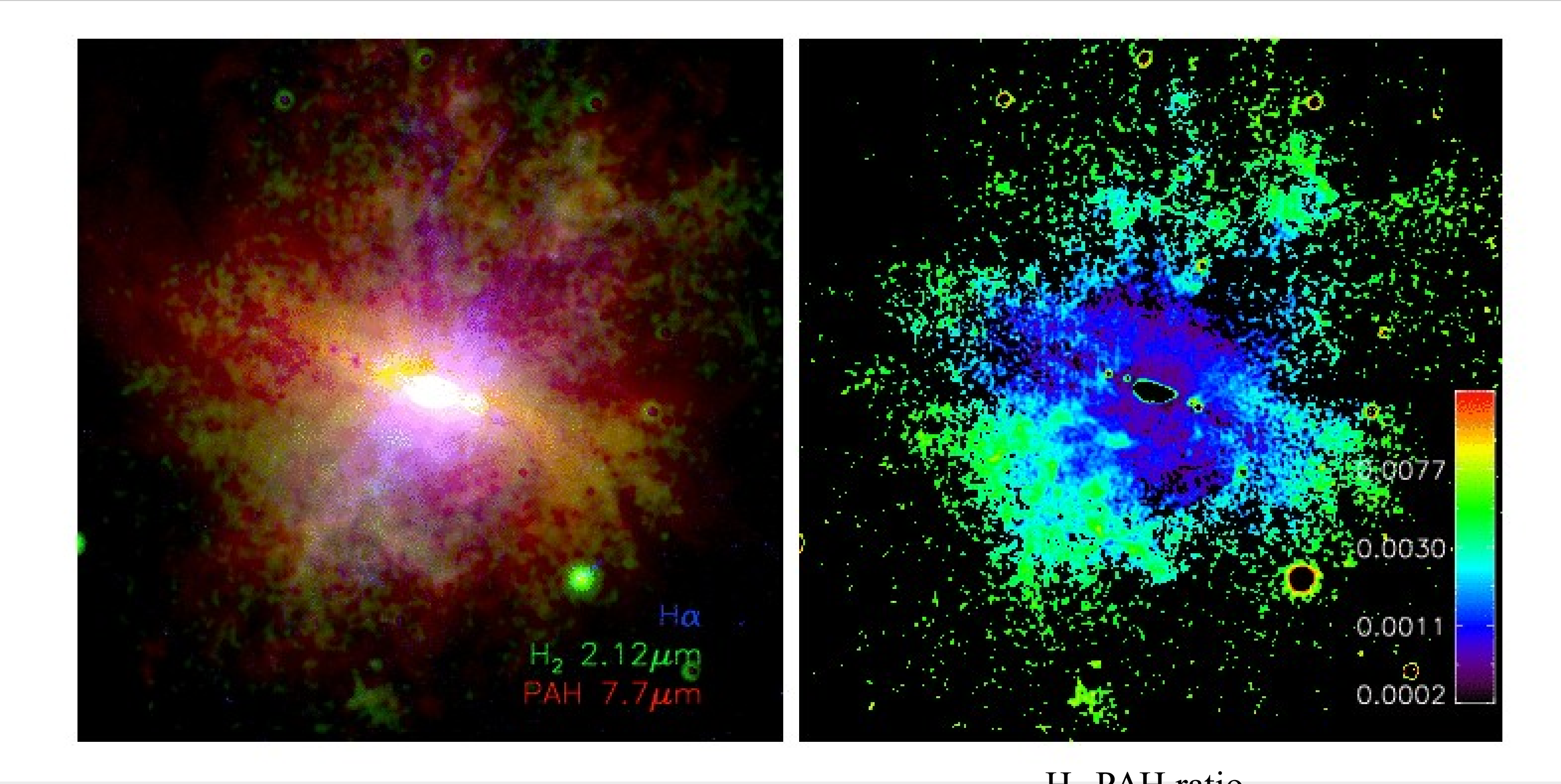
Characteristics suggest fast shock of 800 km s^{-1} being driven in an ambient halo cloud. $V_{shock} > V_{escape}$

Escaping



Lehnert, Heckman, & Weaver (1999)

Near-IR and Mid-IR Molecular emission



H_2-PAH ratio

Warm H_2, PAHs, and H-alpha trace the same gas

-extends about 3 kpc above the plane

-likely to be shock heated – similar to the optical emission line gas

-authors favor entrainment and not significant energetically

Veilleux et al. (2009)

Outstanding Questions

Why is galaxy formation and evolution so inefficient? Where are most of the baryons? They are not in galaxies … that we know. Are they in the halos?

What regulates gas accretion, the star-formation rate and distribution, the outflow rate of mass, energy, and momentum?

What is the relative rate of growth due to mergers, accretion of gas from the cosmic web, and cooling of gas in the halo itself? How does this depend on halo mass?

What is the relation between the growth of structure and the growth of galaxies? How does the relative location of galaxies – in nodes, walls, streams, voids – affect their growth rates, morphologies, star formation histories, etc?

How do AGN regulate the growth of galaxies, especially massive galaxies?

How important are outflows generally in regulating the galactic gas cycle? What are the energy sources regulating star formation and outflows? Cosmic rays, radiation pressure, mechanical energy, photo-ionization/photo-dissociations?

What creates and destroys angular momentum in galaxies?