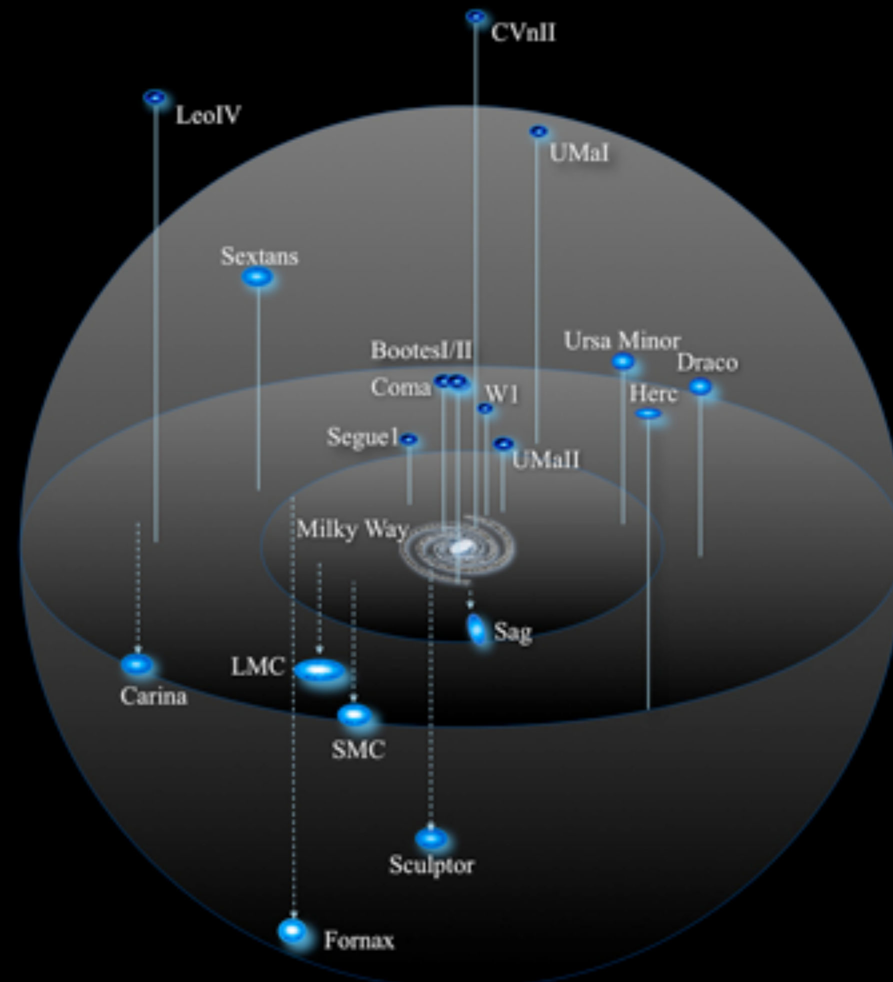
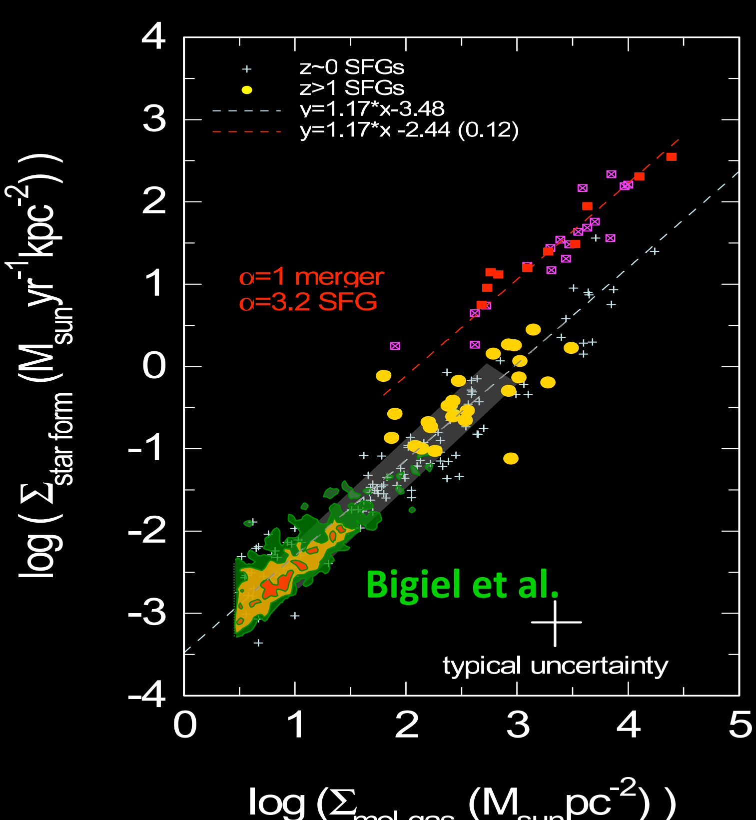
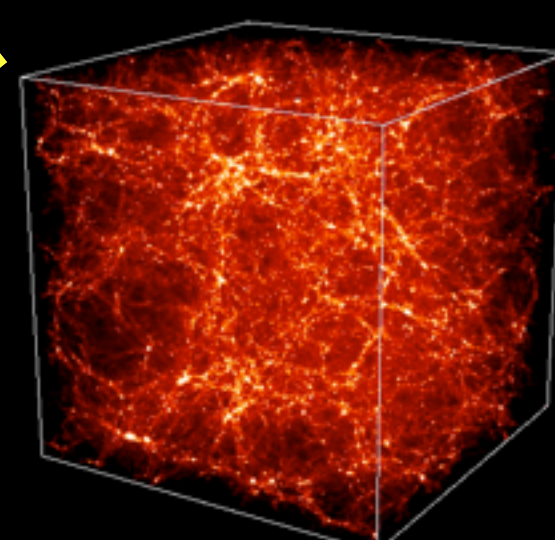
Connecting Galaxy Formation to the Cosmic Web

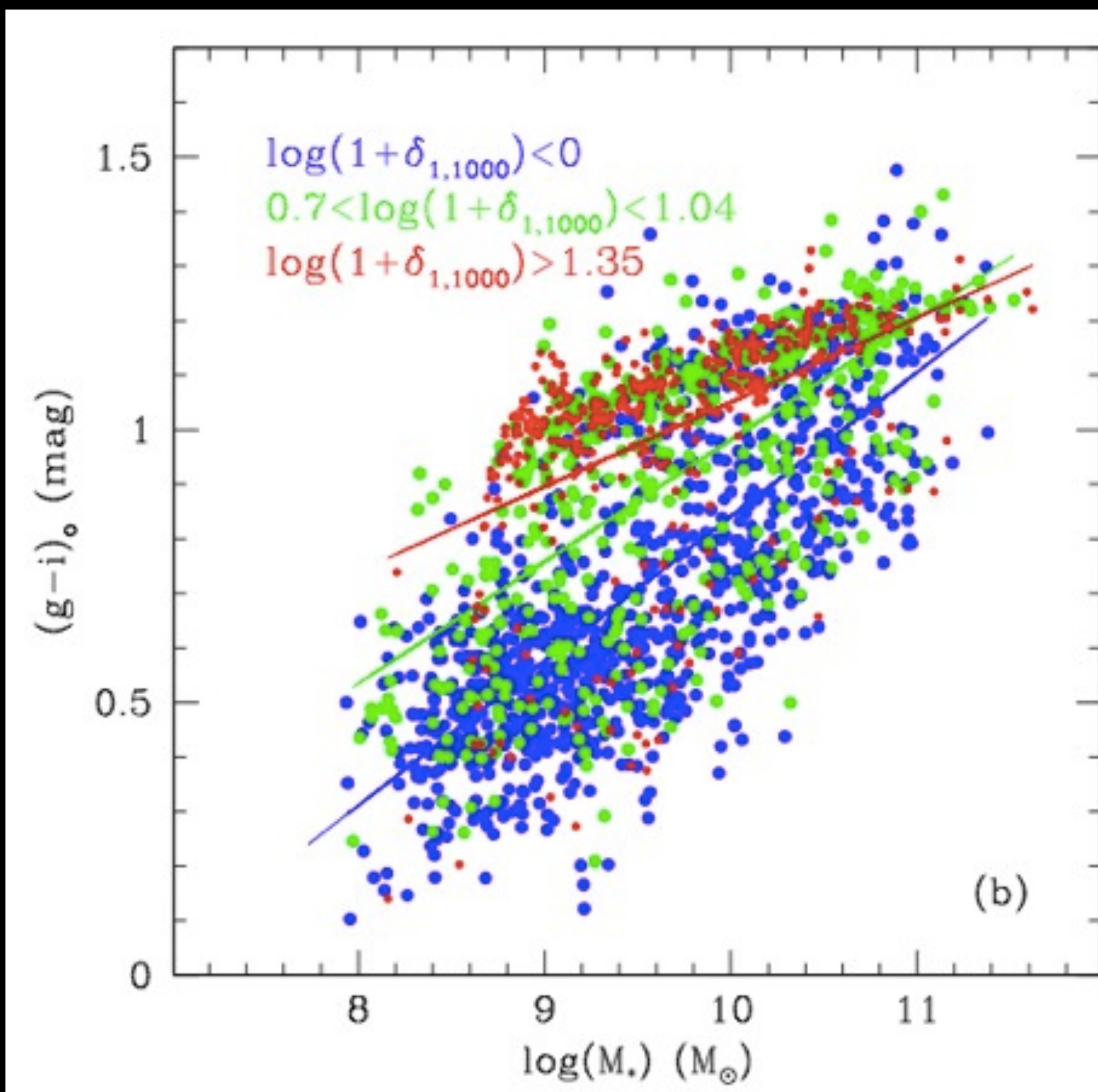


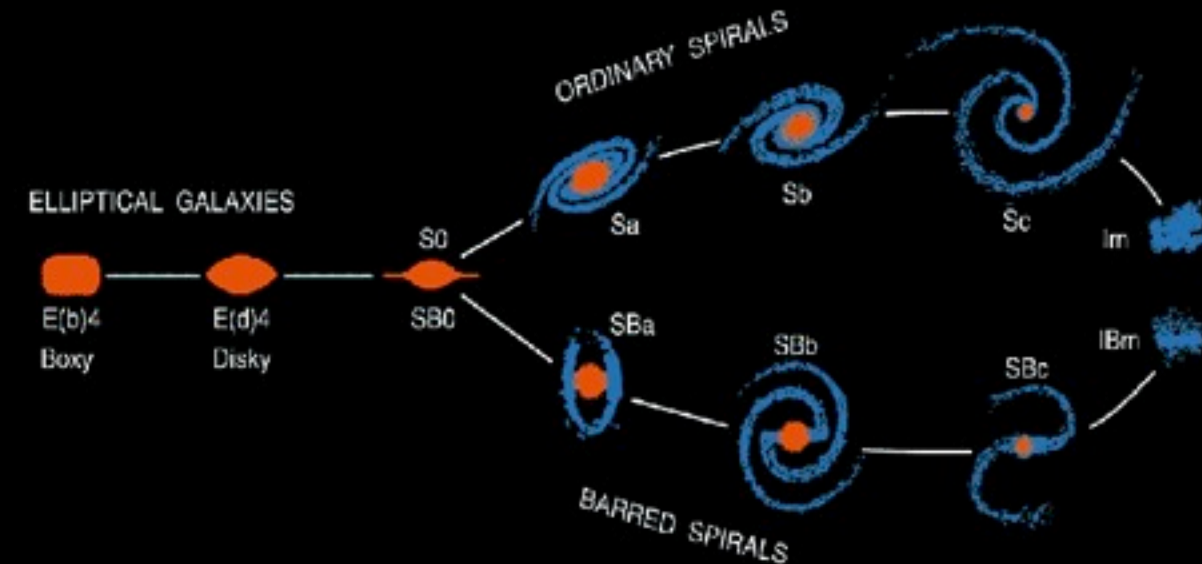




Properties of the Hubble Sequence

Halpha imaging surveys
(galaxy assembly in the great wall)

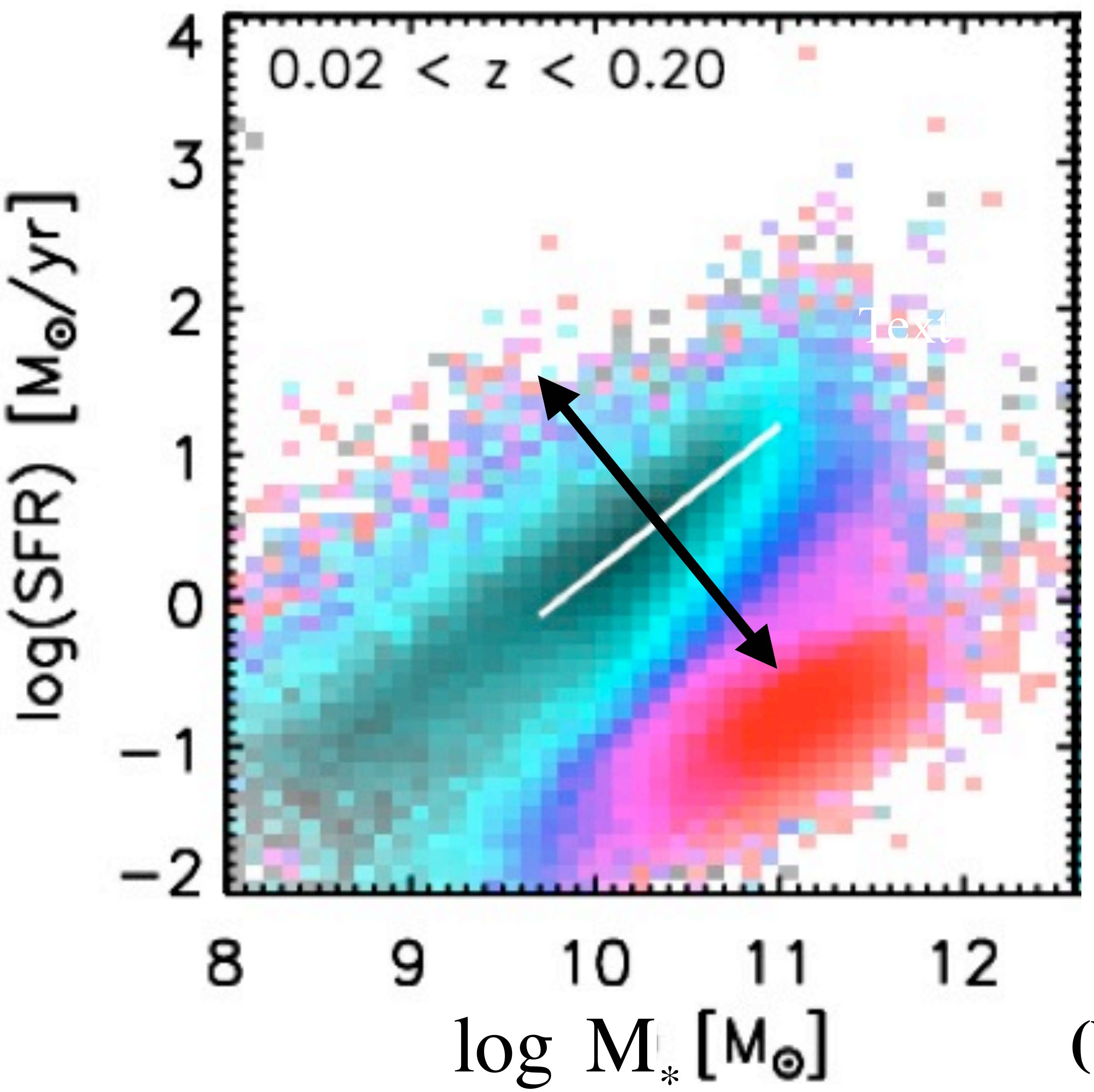




(Gavazzi+ 13, 15)

The galaxy main sequence

Systematic changes of galaxy properties with distance from the main sequence mid line (Genzel+ 15; Burkert+ 15)



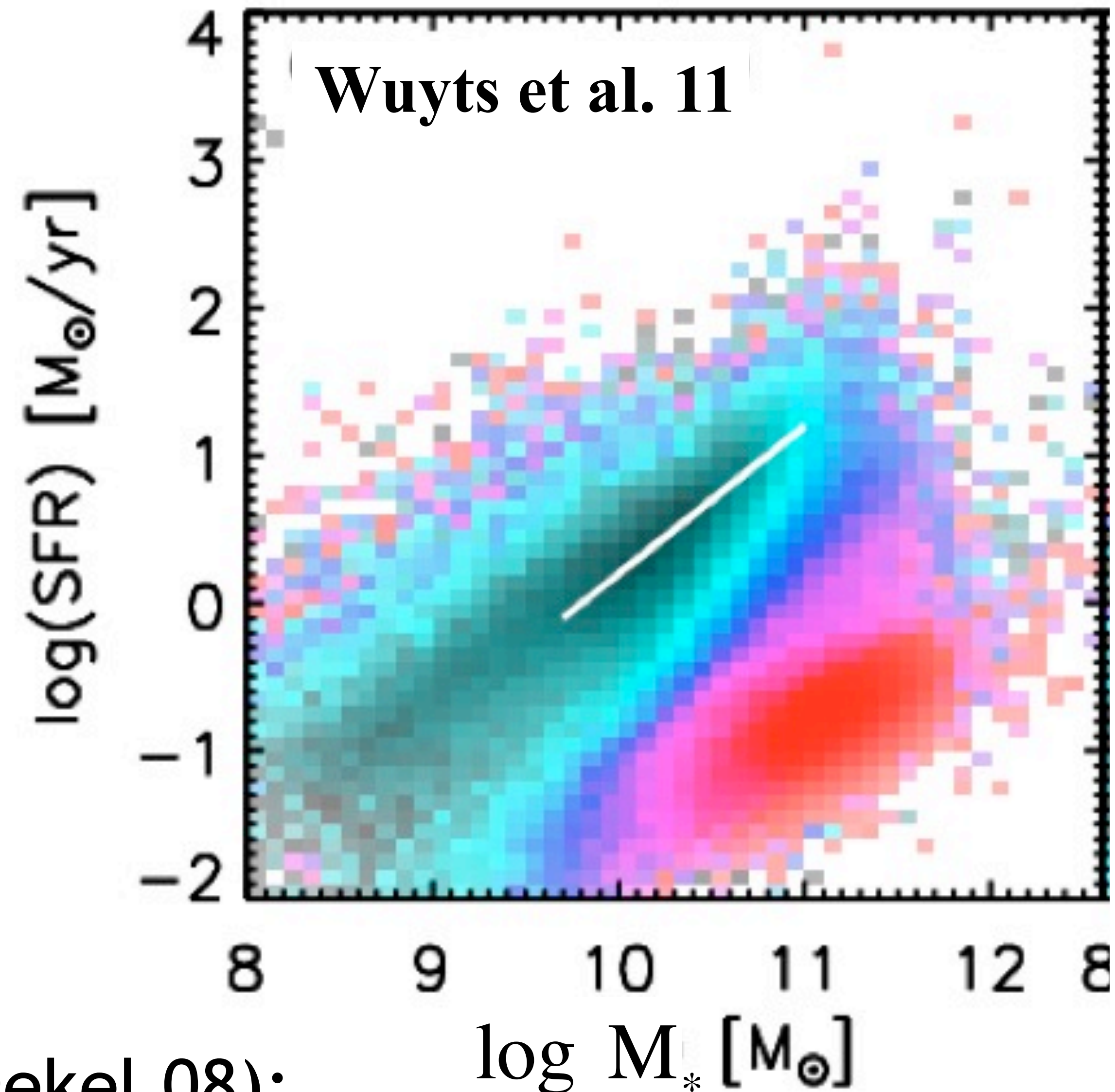
- Color
- Geometry
- Structure (Sersic-n)
- Age
- Gas Content

(Wuyts+11)

The galaxy main sequence

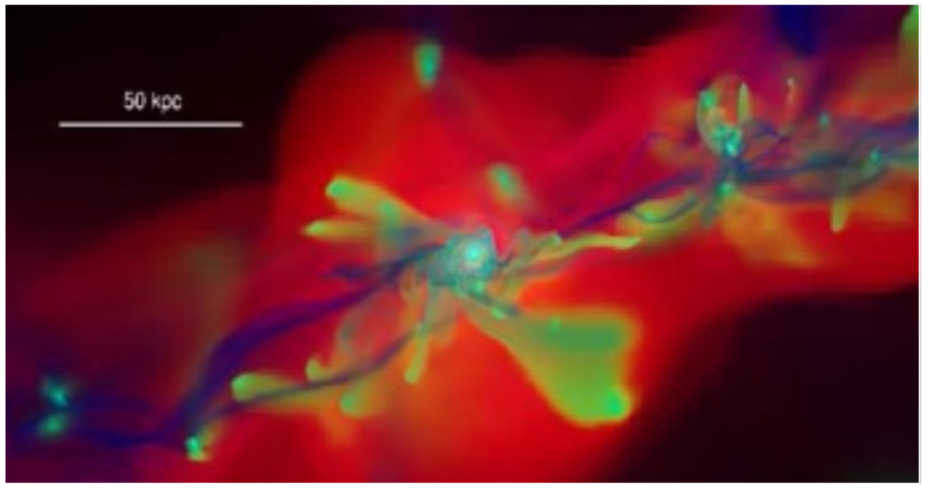
Galaxy main sequence (Noeske et al. 07; Daddi et al. 07, Peng et al. 10, Bouche et al. 10, Wuyts et al. 11,...):

$$SFR \approx 6\left(\frac{M_*}{10^{11}M_\odot}\right)(1+z)^{2.5}\frac{M_\odot}{yr}$$



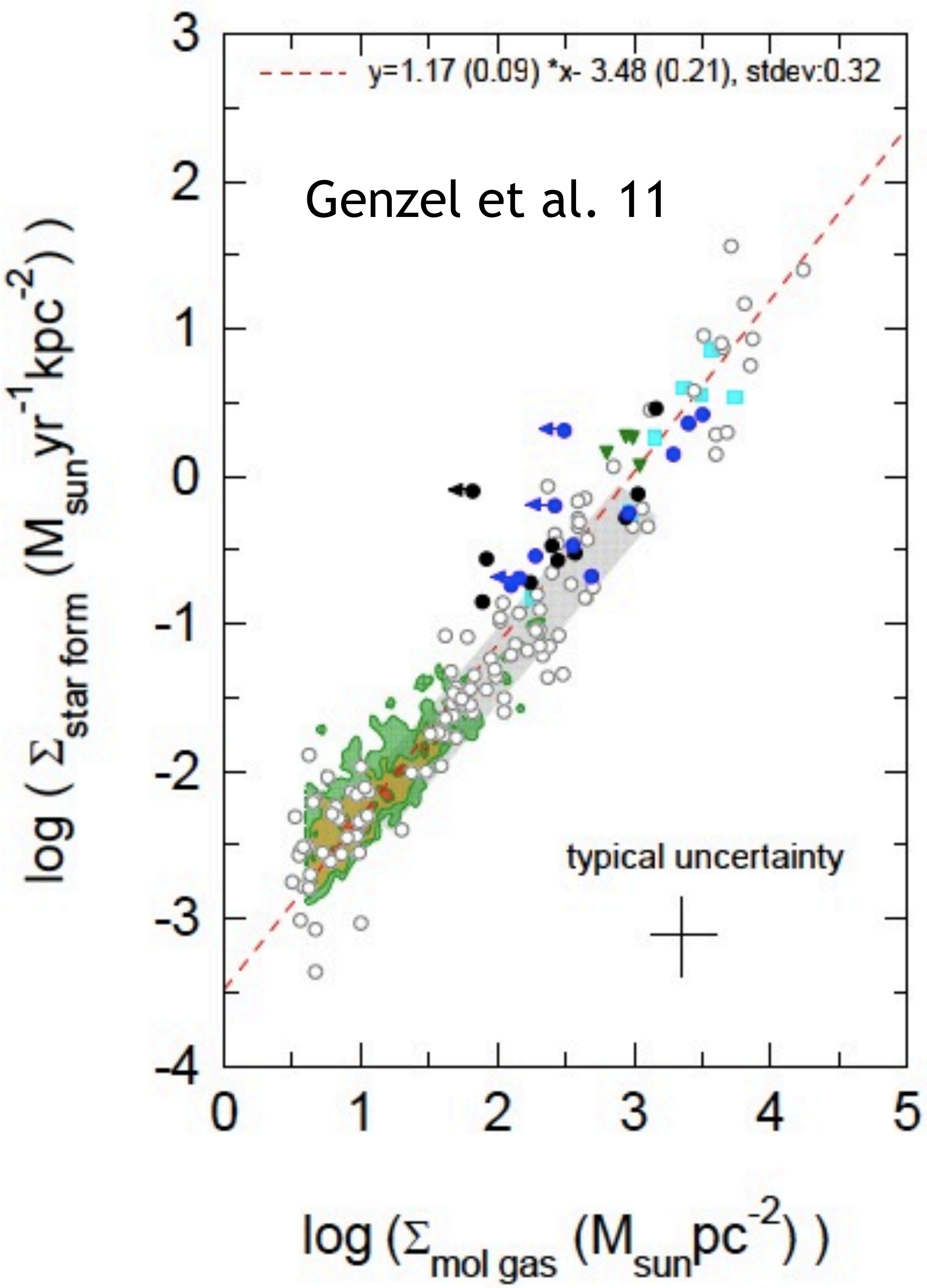
Cosmic baryonic **accretion rate** (Neistein & Dekel 08):

$$\left(\frac{dM_g}{dt}\right)_{acc} \approx 7\cdot\varepsilon_g\left(\frac{M_{DM}}{10^{12}M_\odot}\right)^{1.1}(1+z)^{2.2}\frac{M_\odot}{yr}$$



(Birnboim & Dekel 03; Dekel & Birnboim 06; Ceverino et al. 10, 12)

The universal gas depletion timescale



$$SFR = \frac{M_{H_2}}{\tau_{sf}} \text{ with } \tau_{sf} \approx 10^9 \, yrs$$

- Gas depletion timescale **50 times** longer than local free-fall timescale.

$$\tau_{ff} \ll \tau_{sf} < \tau_{\text{Hubble}}$$

→ continuous replenishment

(Bouché et al. 07, McKee & Ostriker 08, Genzel et al. 10,11, Daddi et al. 10, Dave 11,12, Krumholz+ 12, Lilly et al. 13, Forbes et al. 13,14)

What determines SFR?

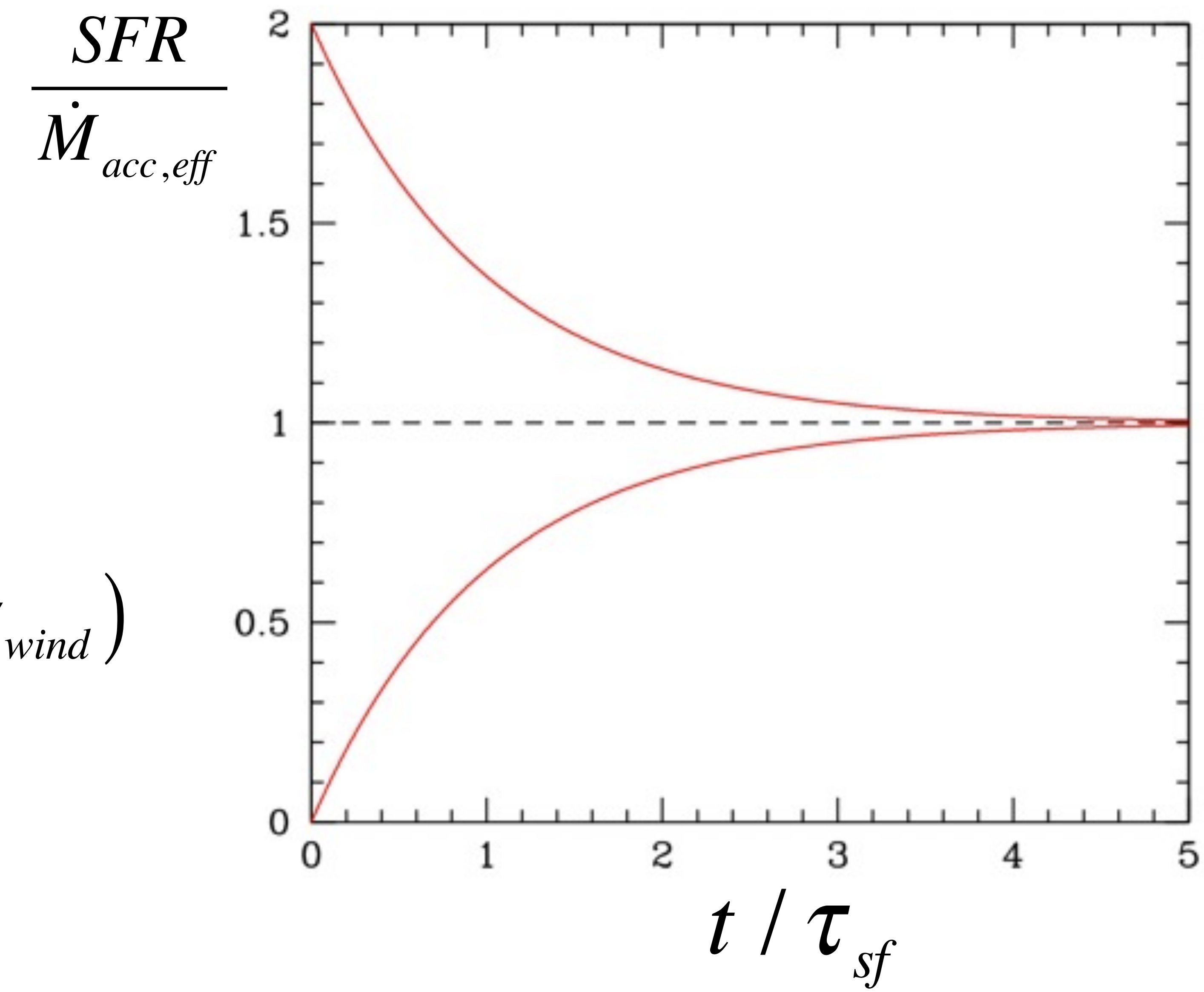
(Bouche+10; Davé+11a,b; Forbes+13, Lilly+13)

$$\frac{dM_g}{dt} = \left(\frac{dM_g}{dt}\right)_{acc} - \frac{M_g}{\tau_{sf}}\left(1 - R + \alpha_{wind}\right)$$

$\dot{M}_{acc,eff}$

$$SFR = \frac{M_g}{\tau_{sf}} = \frac{1}{1 - R + \alpha_{wind}}\left(\frac{dM_g}{dt}\right)_{acc}$$

→ $SFR = \dot{M}_{acc,eff}$ → τ_{sf} **does not determine SFR**



What's about the (molecular) gas mass?

$$M_{H_2} = SFR \cdot \tau_{sf} = \dot{M}_{acc,eff} \cdot \tau_{sf}$$

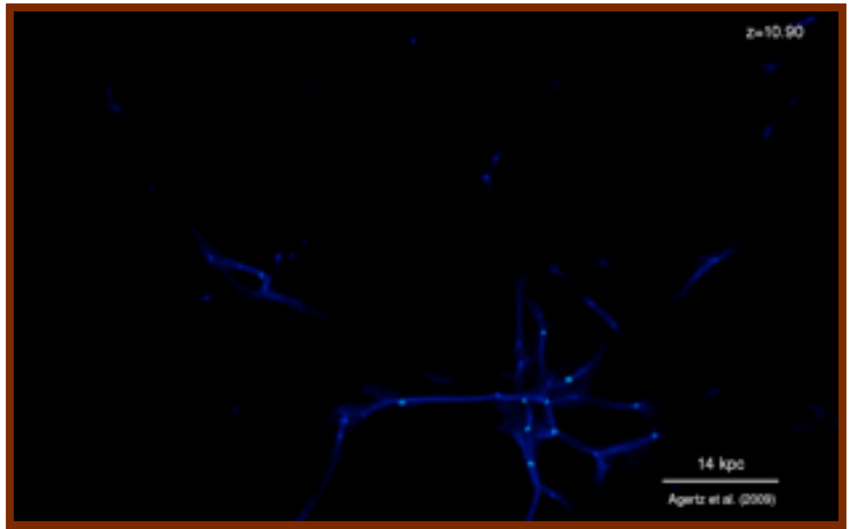
A measure of the effective infall rate, averaged over the past Gyr.

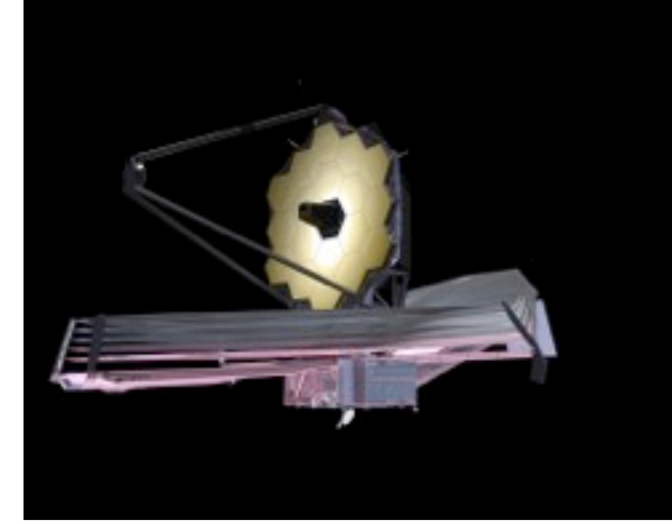
What's about metallicity?

$$Z_g = Z_{IGM} + y \frac{R}{\alpha_{wind} + R}$$

(Everett+ 8,10, Brook+ 11, Hopkins+ 12, Dalla Vecchia+ 12, Bolatto+ 13, Hirschmann+13, von Glasow+ 13, Hanasz+ 13, Agertz+ 13)

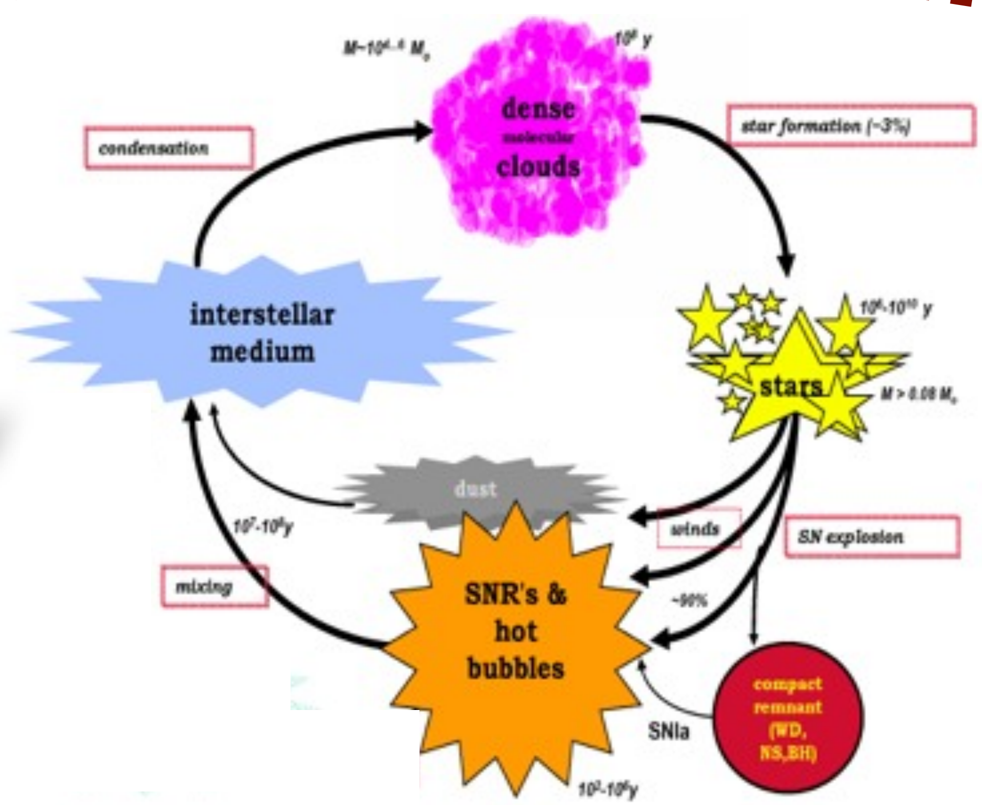
The cosmic gas flow





$\dot{M}_{acc}$

$$M_g = \dot{M}_{acc,eff} \cdot \tau_{sf}$$



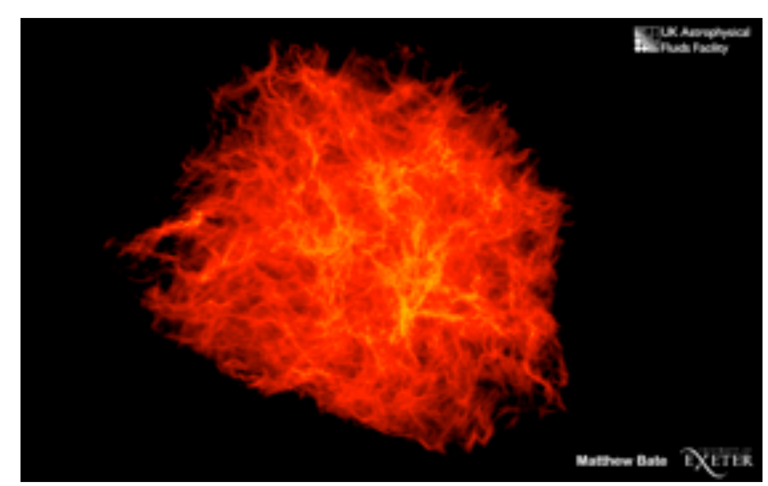
$$M_*(t)$$

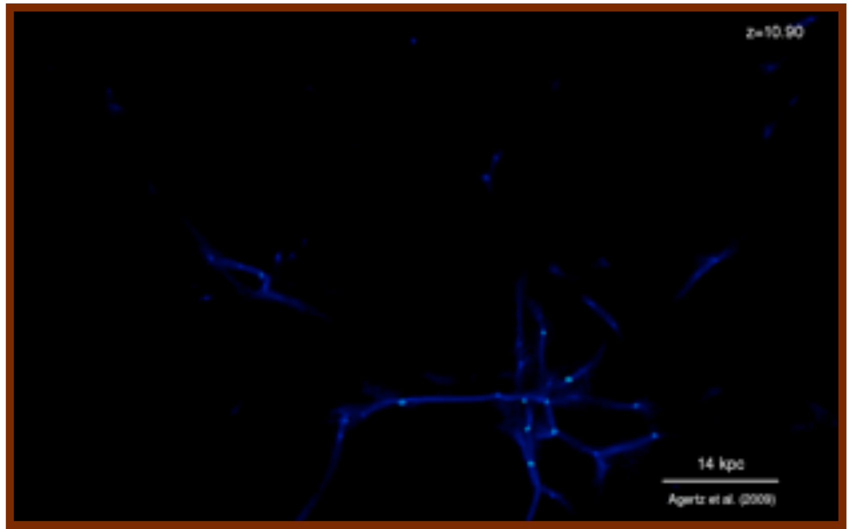
$\dot{M}_{wind} = \alpha \cdot SFR$

$$SFR = \frac{M_g}{\tau_{sf}}$$

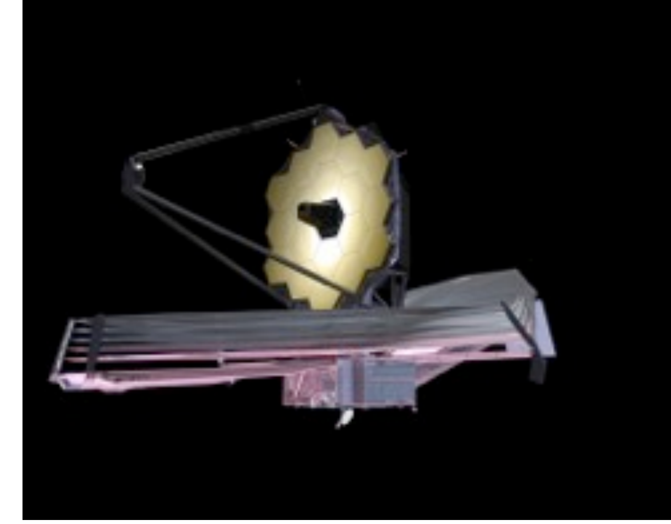
$$SFR = \dot{M}_{acc,eff}$$

see e.g. Somerville+ 15



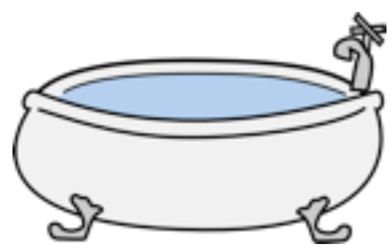


The cosmic gas flow



$\dot{M}_{acc}$

Are nearby star-forming galaxies



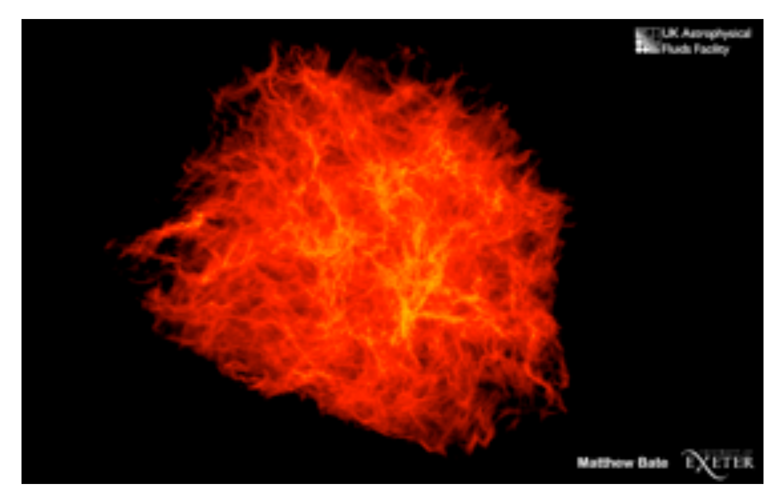
s?

$\dot{M}_{wind} = \alpha \cdot SFR$

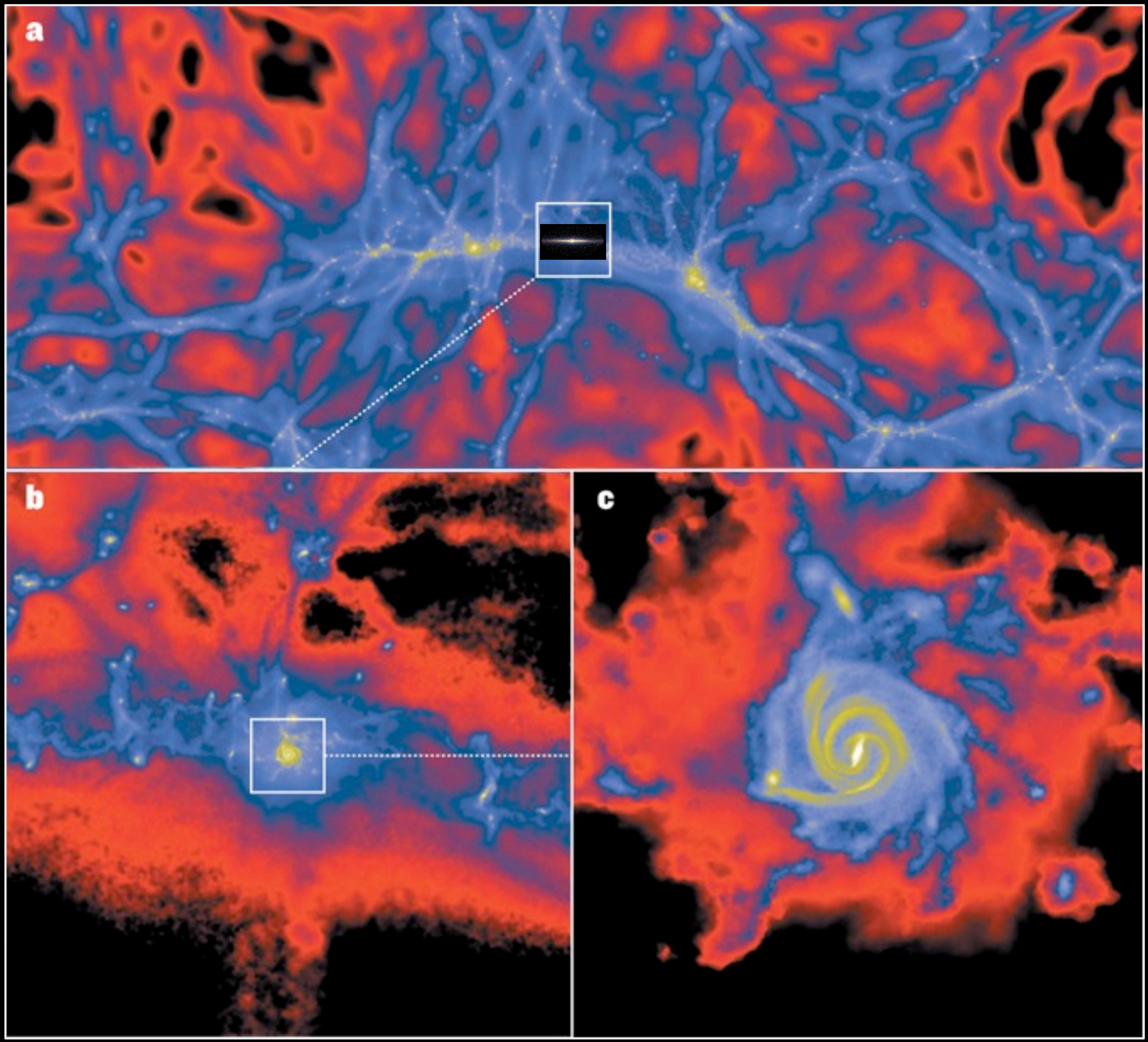
$SFR = \frac{M_g}{\tau_{sf}}$

$$SFR = \dot{M}_{acc,eff}$$

see e.g. Somerville+ 15

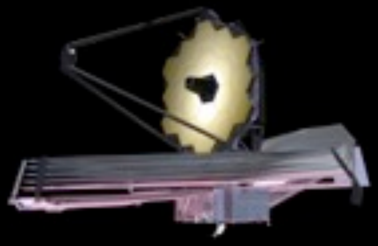


The Milky Way

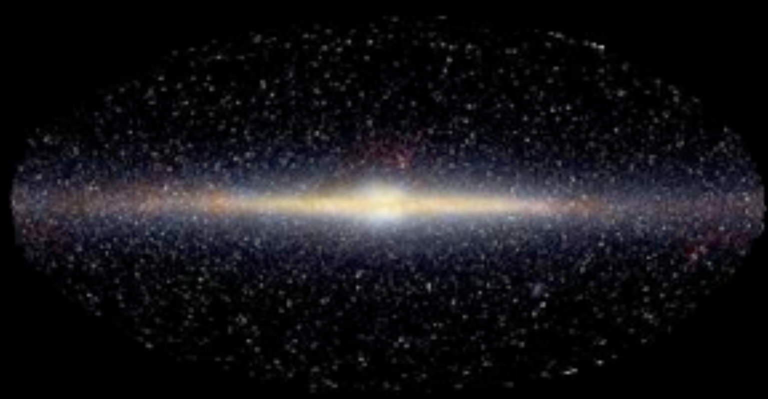


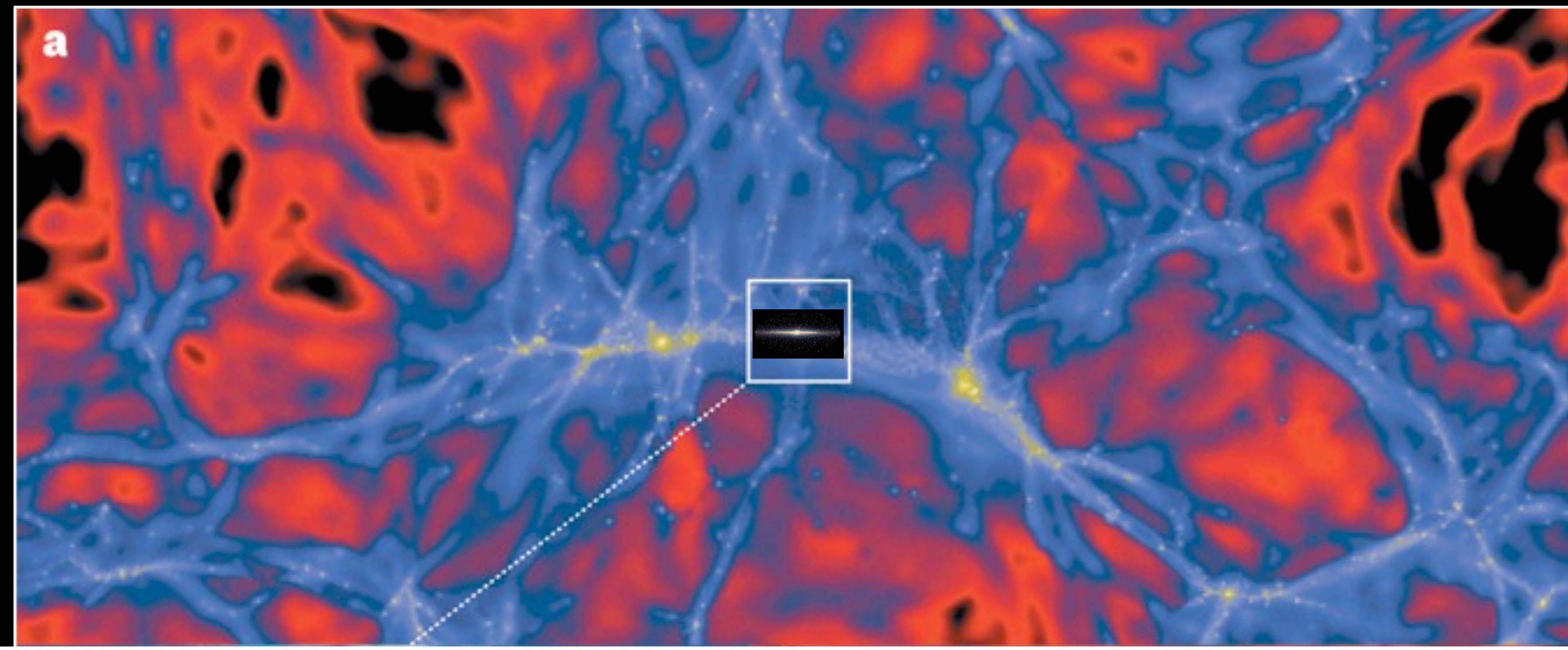
$$SFR = 1\ M_\odot / yr$$

$$M_{H_2} \approx 3 \cdot 10^9\ M_\odot$$

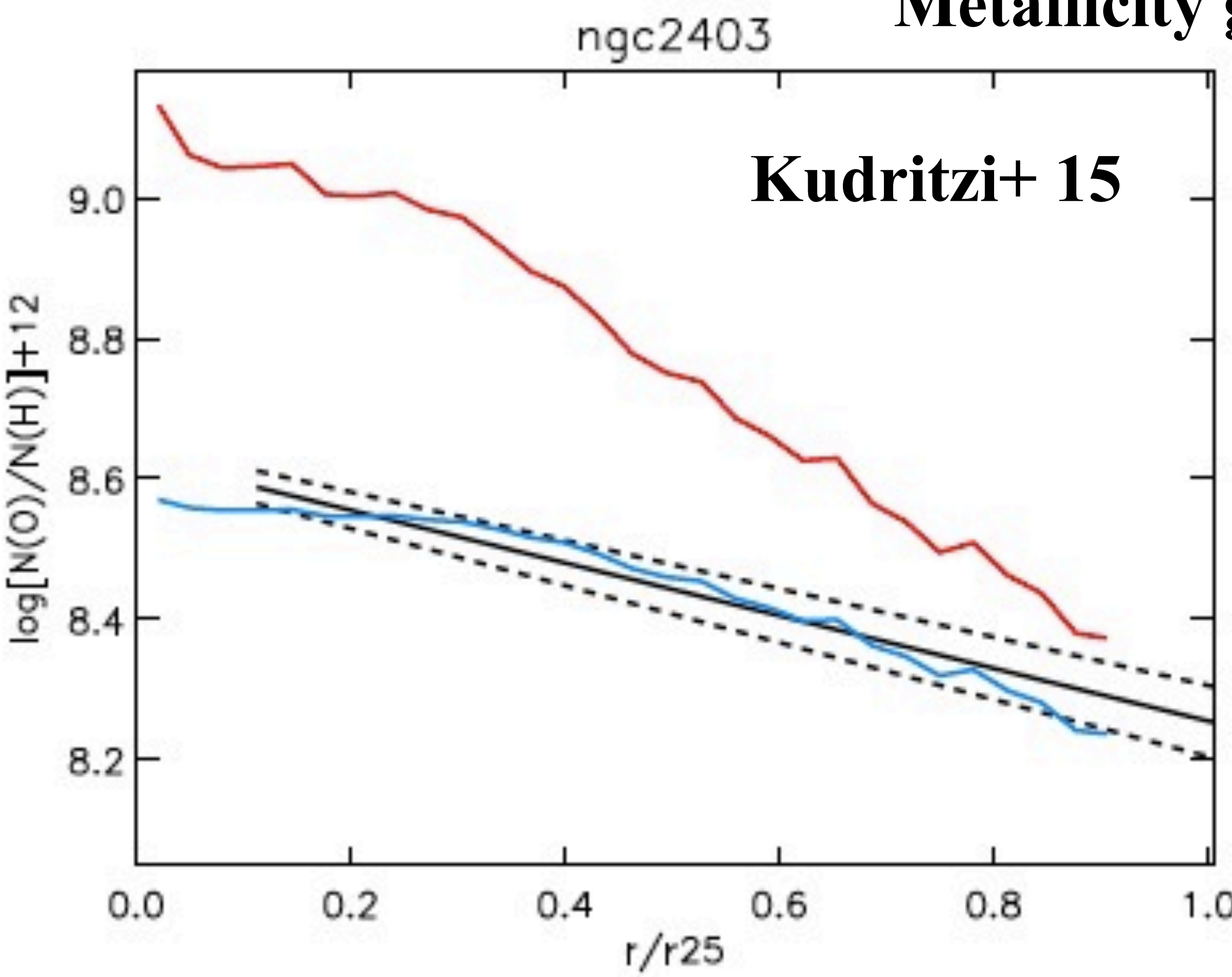


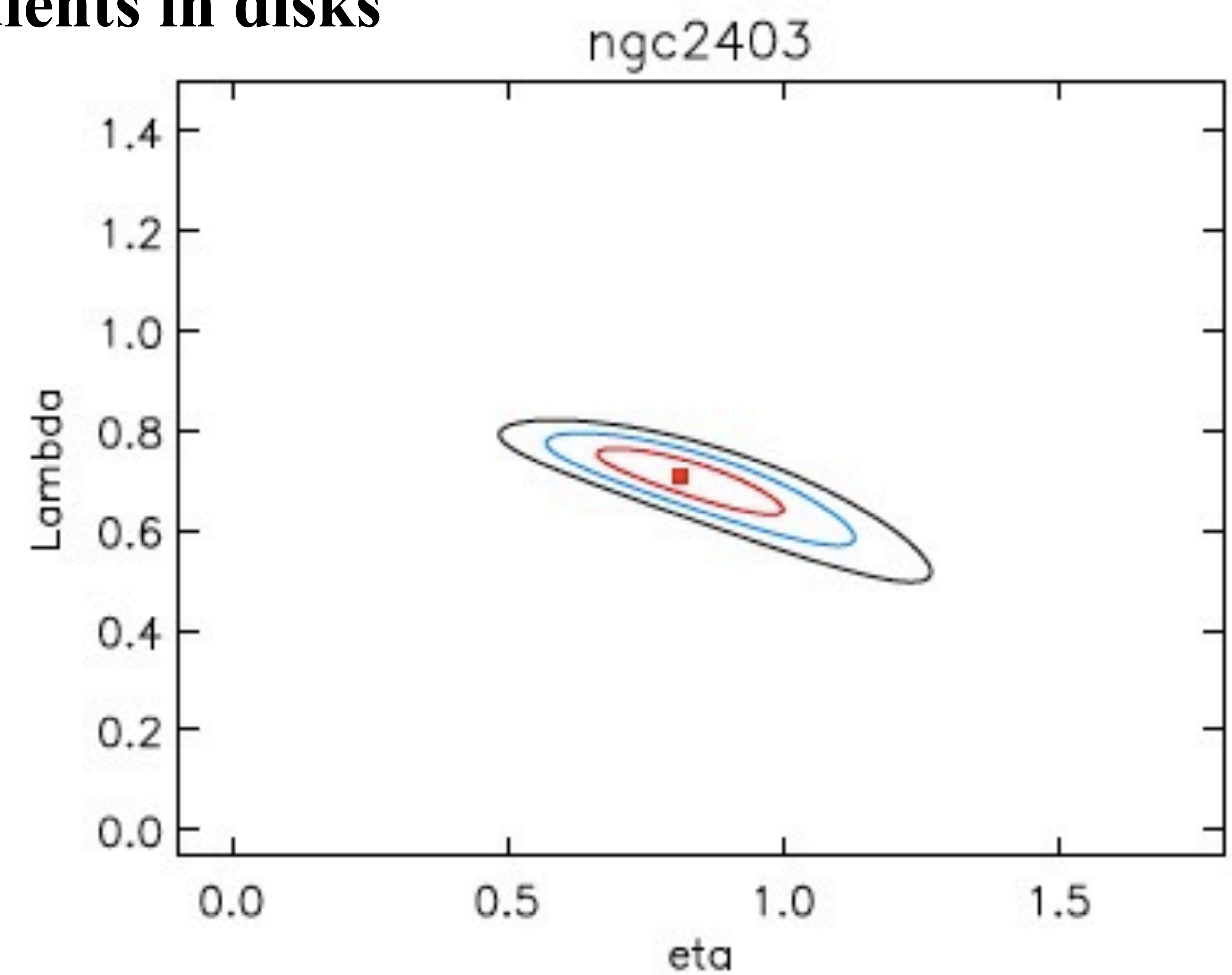
The Milky Way





Metallicity gradients in disks

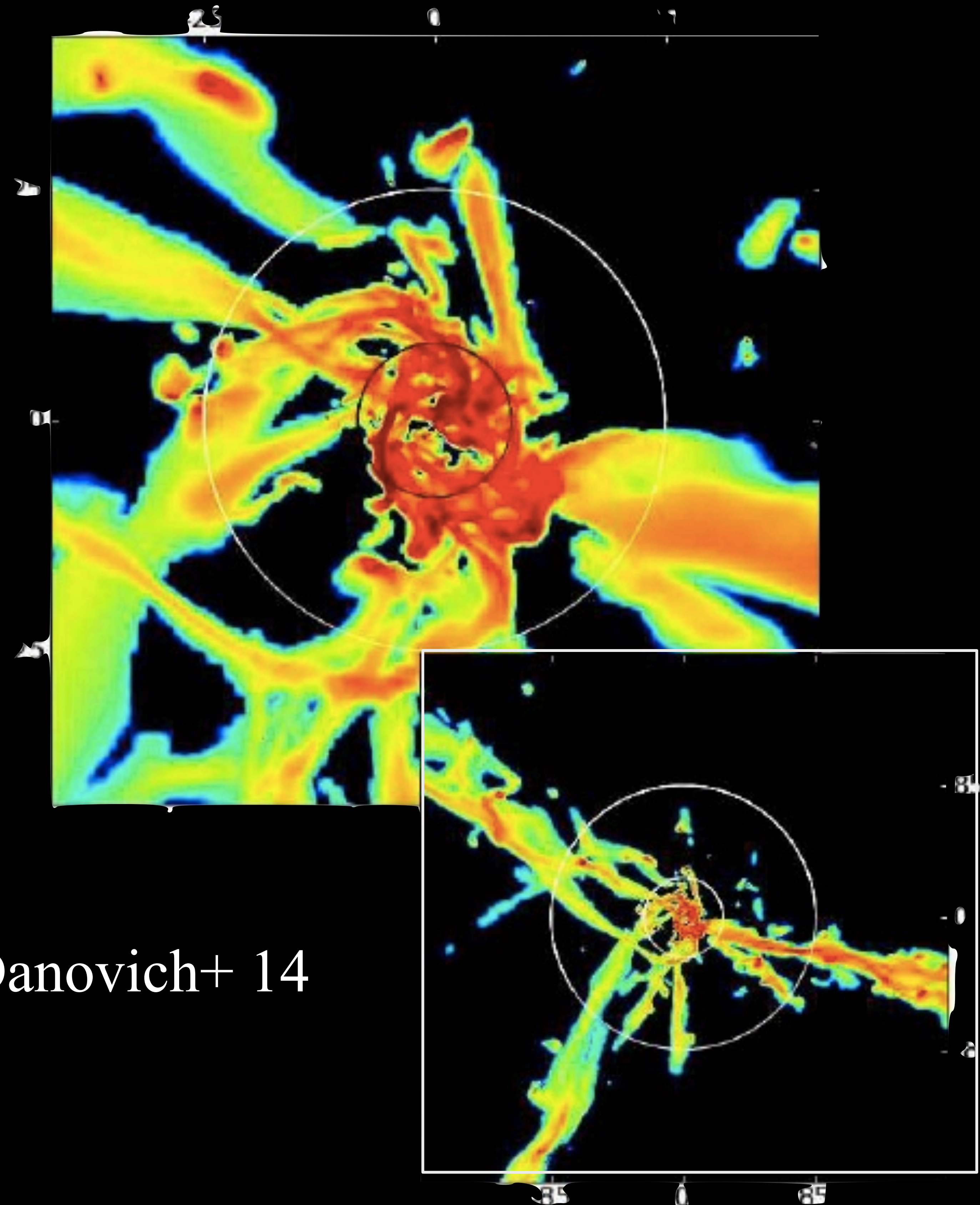




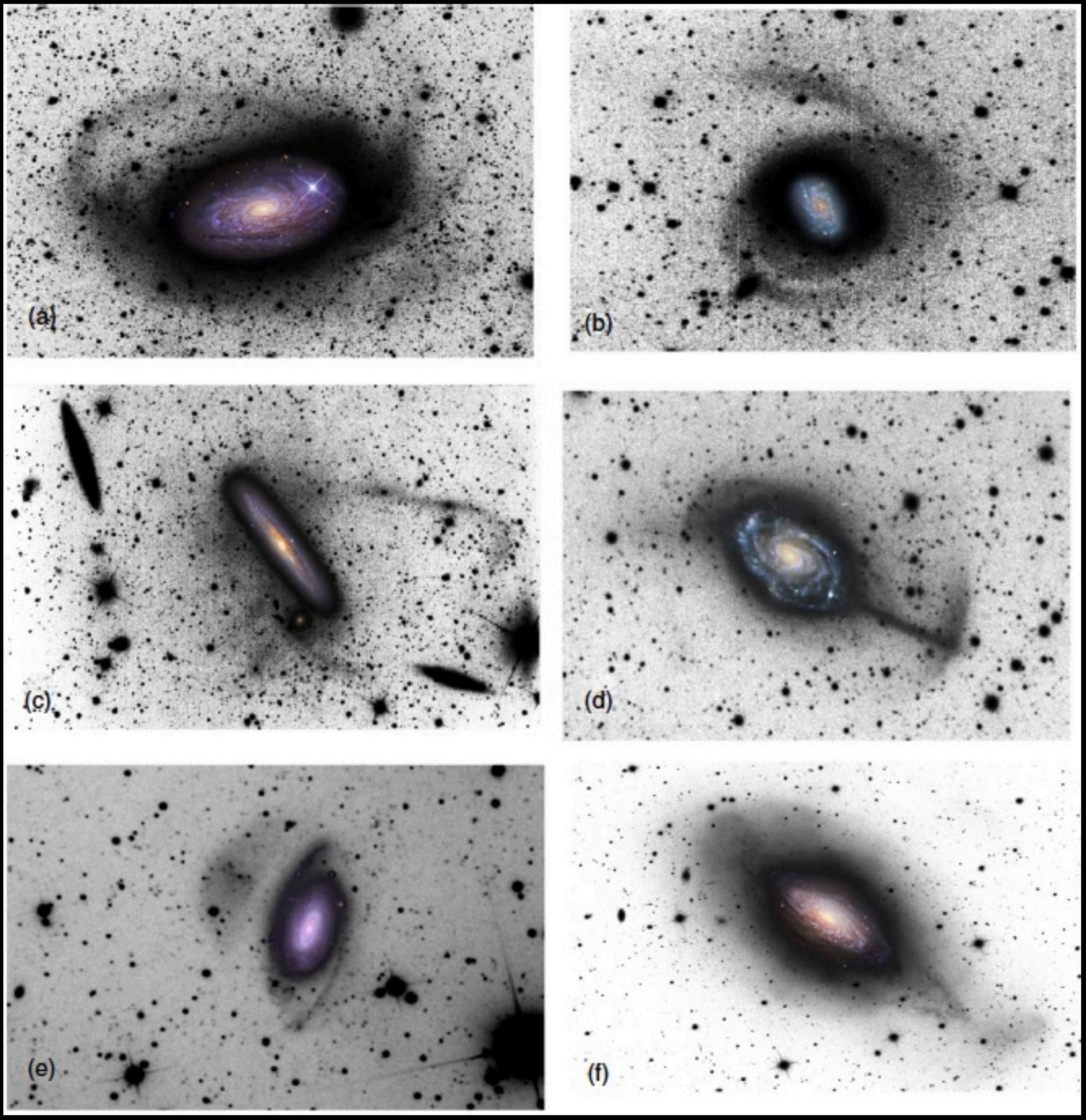
The Milky Way

$$SFR = 1\, M_{\odot} / yr$$

$$M_{H_2} \approx 3 \cdot 10^{9}\, M_{\odot}$$

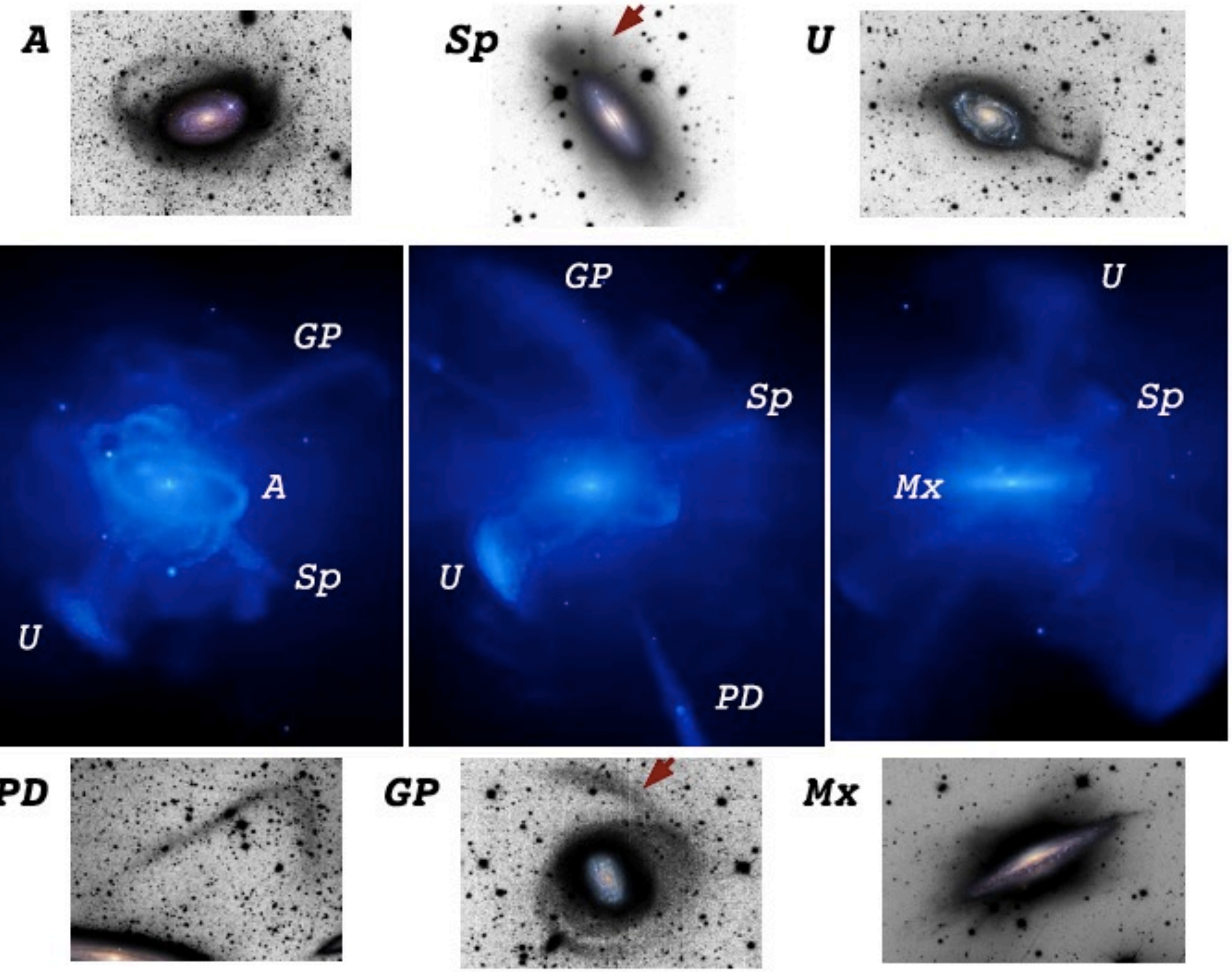


Danovich+ 14



(Martinez-Delgado + 10)

Comparison with numerical simulations

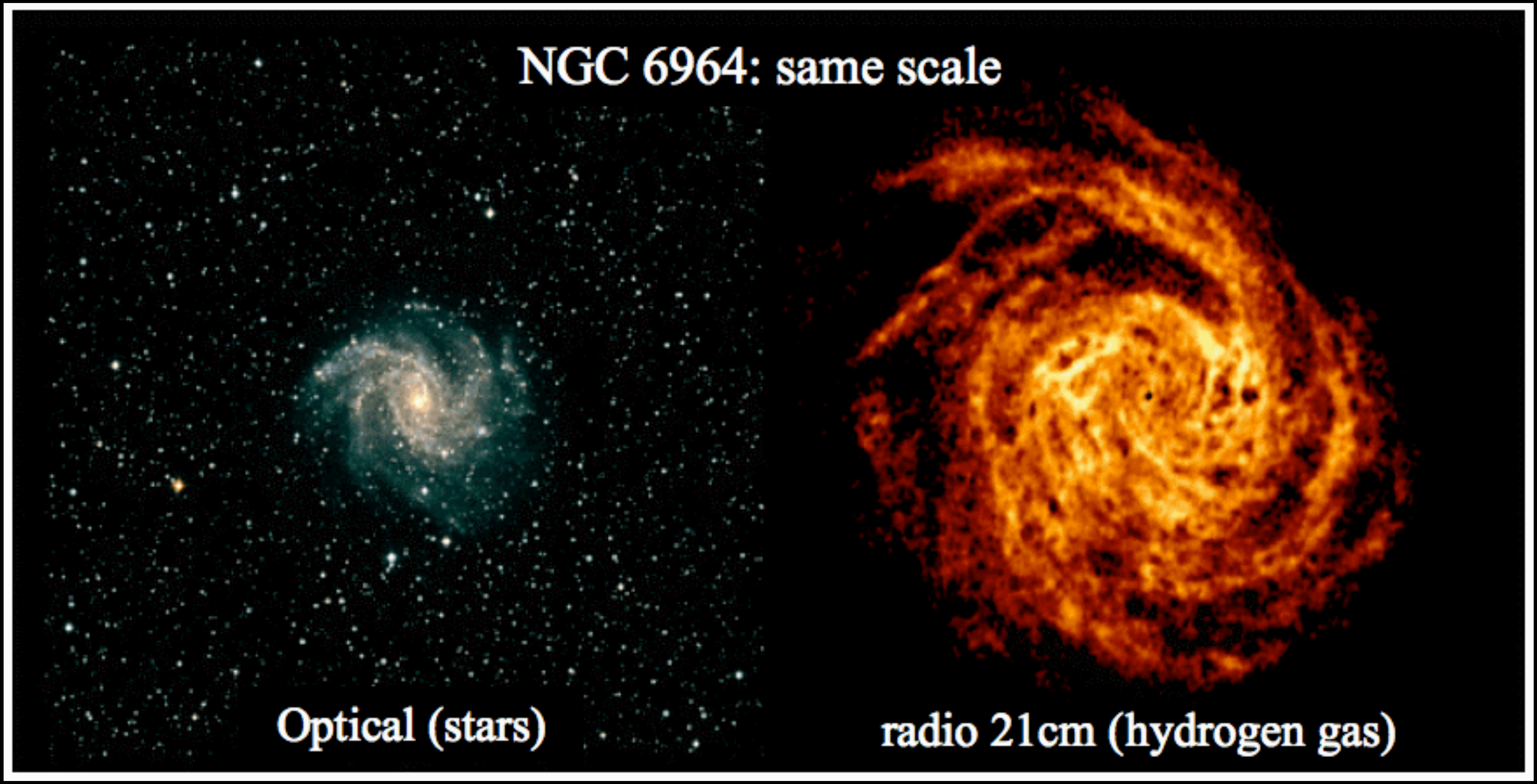


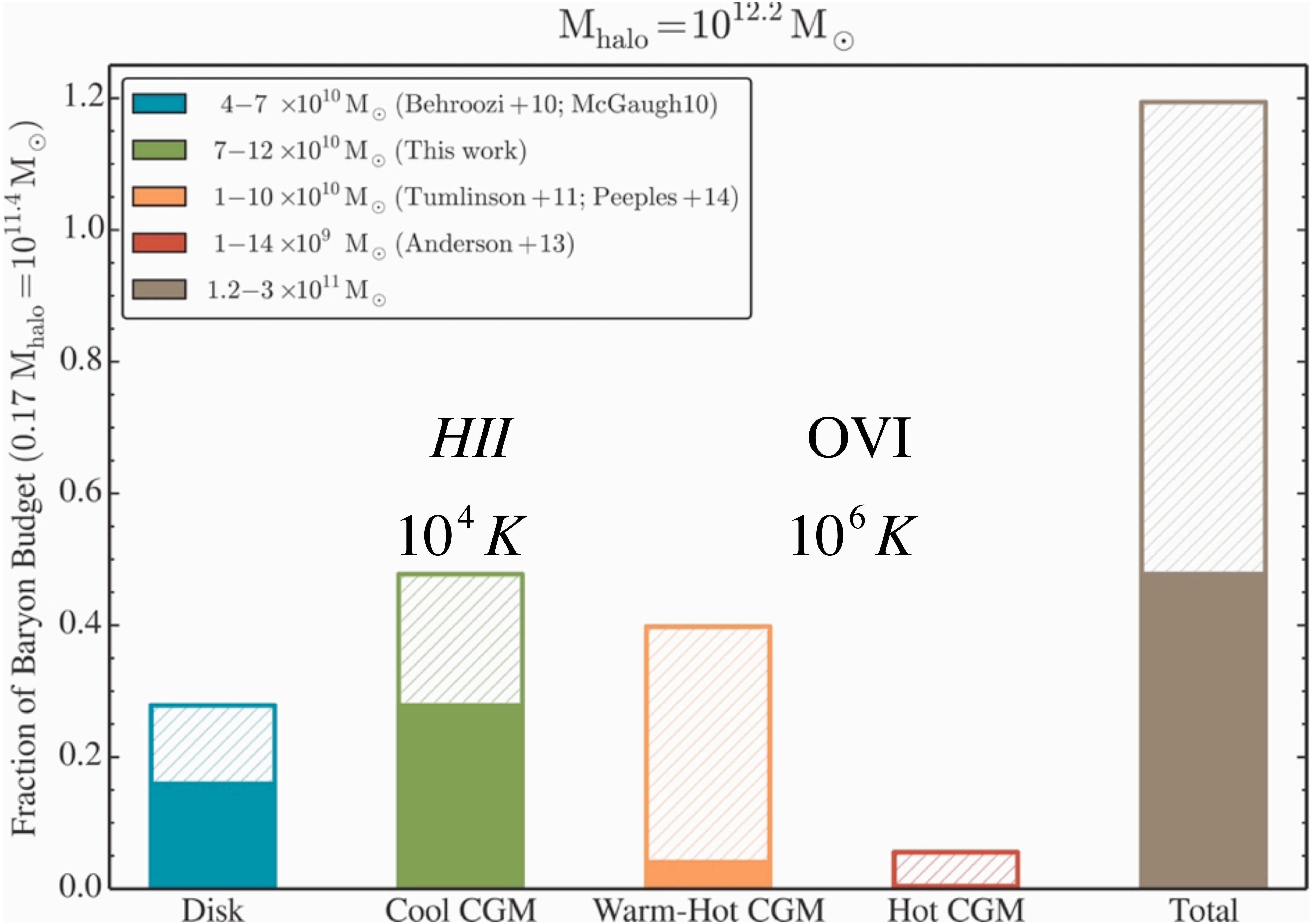
(Johnston+ 08)

Important questions

- frequency
- structure
- mass
- metallicities
- correlation with galaxy properties
- correlation with environment
- infall rate of gas and stars
- relation to satellite system

Bound gas reservoirs: extended HI disks

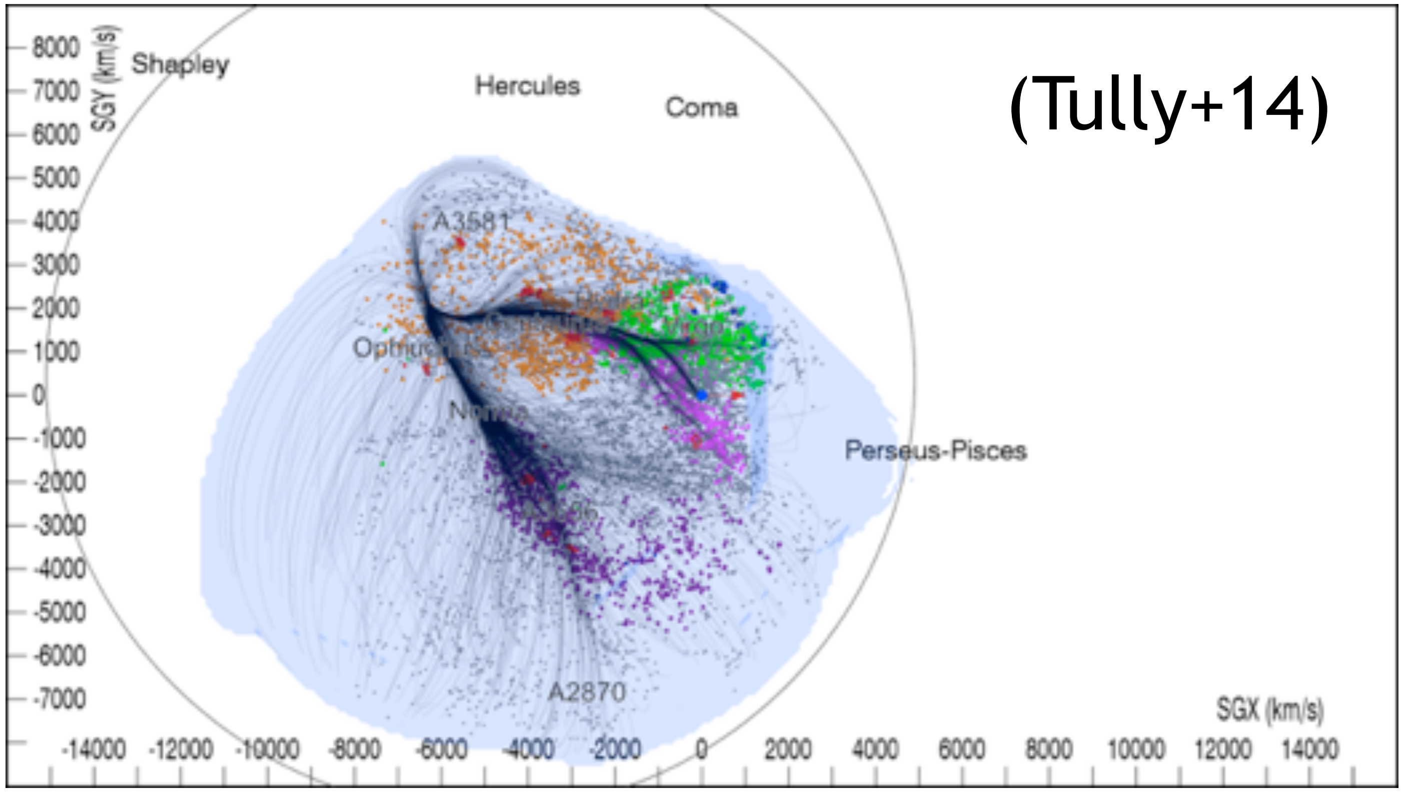




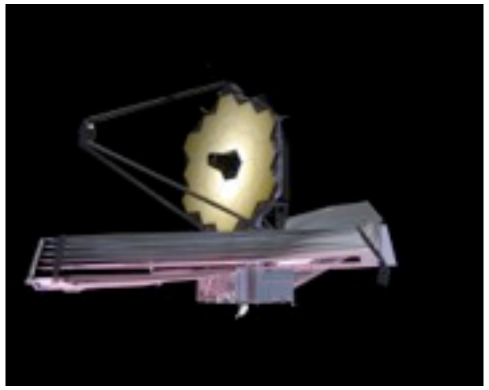
$M_{halo} = 10^{12.2} M_\odot$
4–7 $\times 10^{10} M_\odot$ (Behroozi+10; McGaugh10)
7–12 $\times 10^{10} M_\odot$ (This work)
1–10 $\times 10^{10} M_\odot$ (Tumlinson+11; Peeples+14)
1–14 $\times 10^{9} M_\odot$ (Anderson+13)
1.2–3 $\times 10^{11} M_\odot$
Fraction of Baryon Budget (0.17 $M_{halo} = 10^{11.4} M_\odot$)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
HII
$10^4 K$
OVI
$10^6 K$
Disk
Cool CGM
Warm-Hot CGM
Hot CGM
Total

(Werk+ 14)

Cosmic web imaging

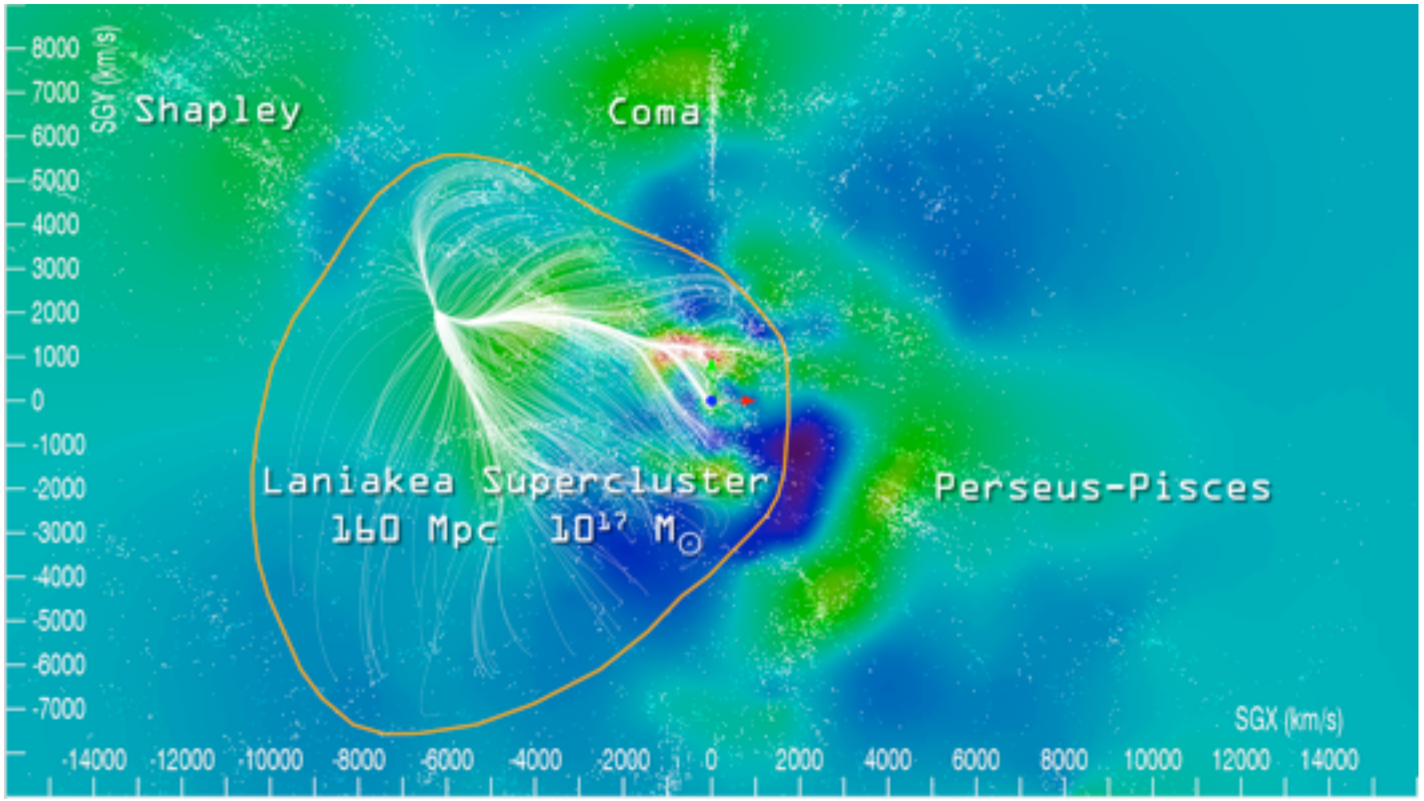


Most of the **gas reservoir** lies not in galaxies but in the extended filamentary surroundings.



Photometry in K-Band

JWST will measure precise, extinction free Cepheid distances out to 270 Mpc



Cosmic web structure in a giant volume

Why is $\tau_{sf} \approx 1 - 2 \cdot 10^9\ yrs$?

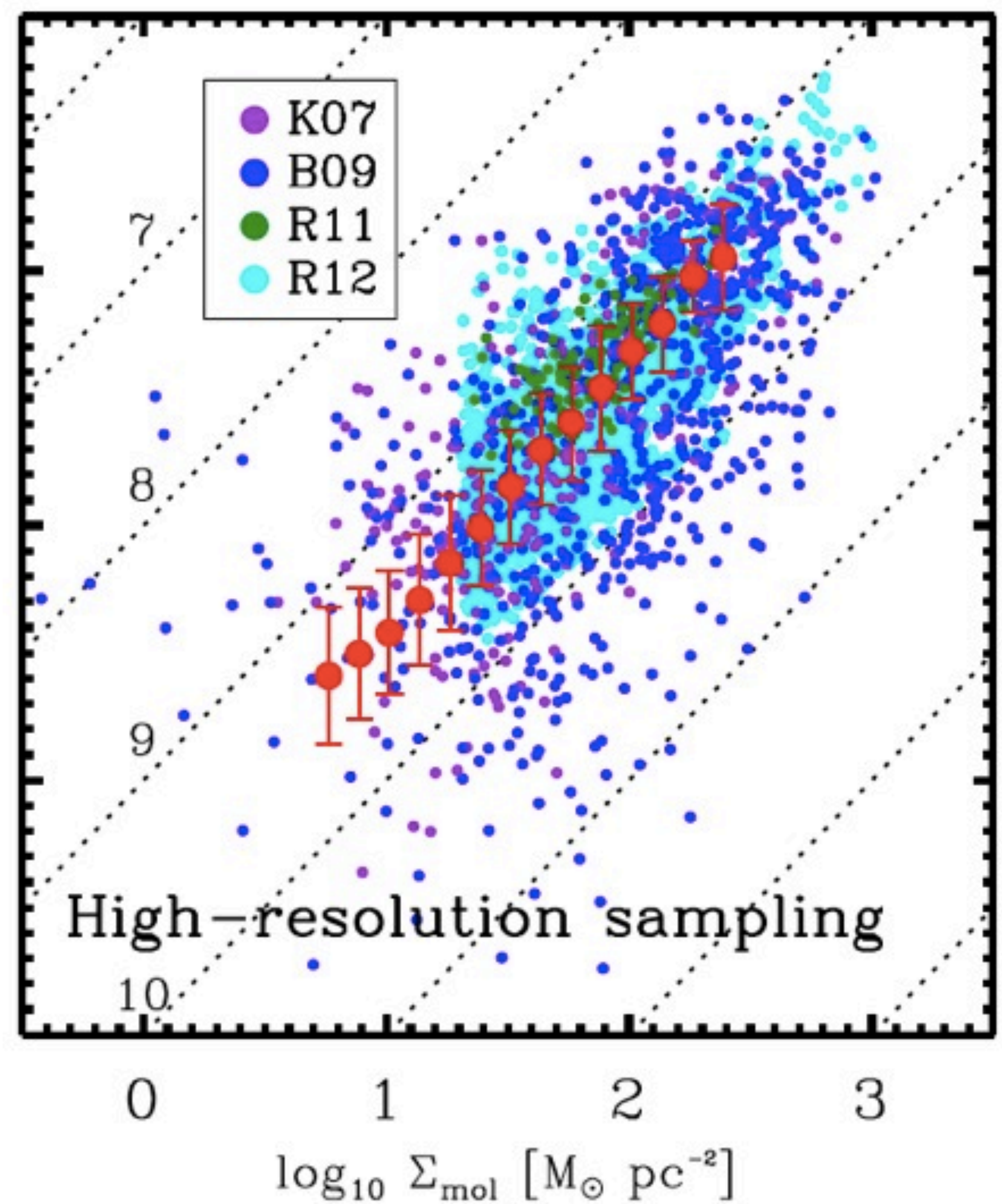
Observations of spatially resolved SF show **increased scatter** (Bigiel+08, Schruba+10, Leroy+13 ...)

$$SFR = \frac{M_{H_2}}{\tau_{sf}}$$

$\log \Sigma_{SFR}$

$[M_\odot / yr / pc^2]$

Leroy+ 13



Central limit theorem

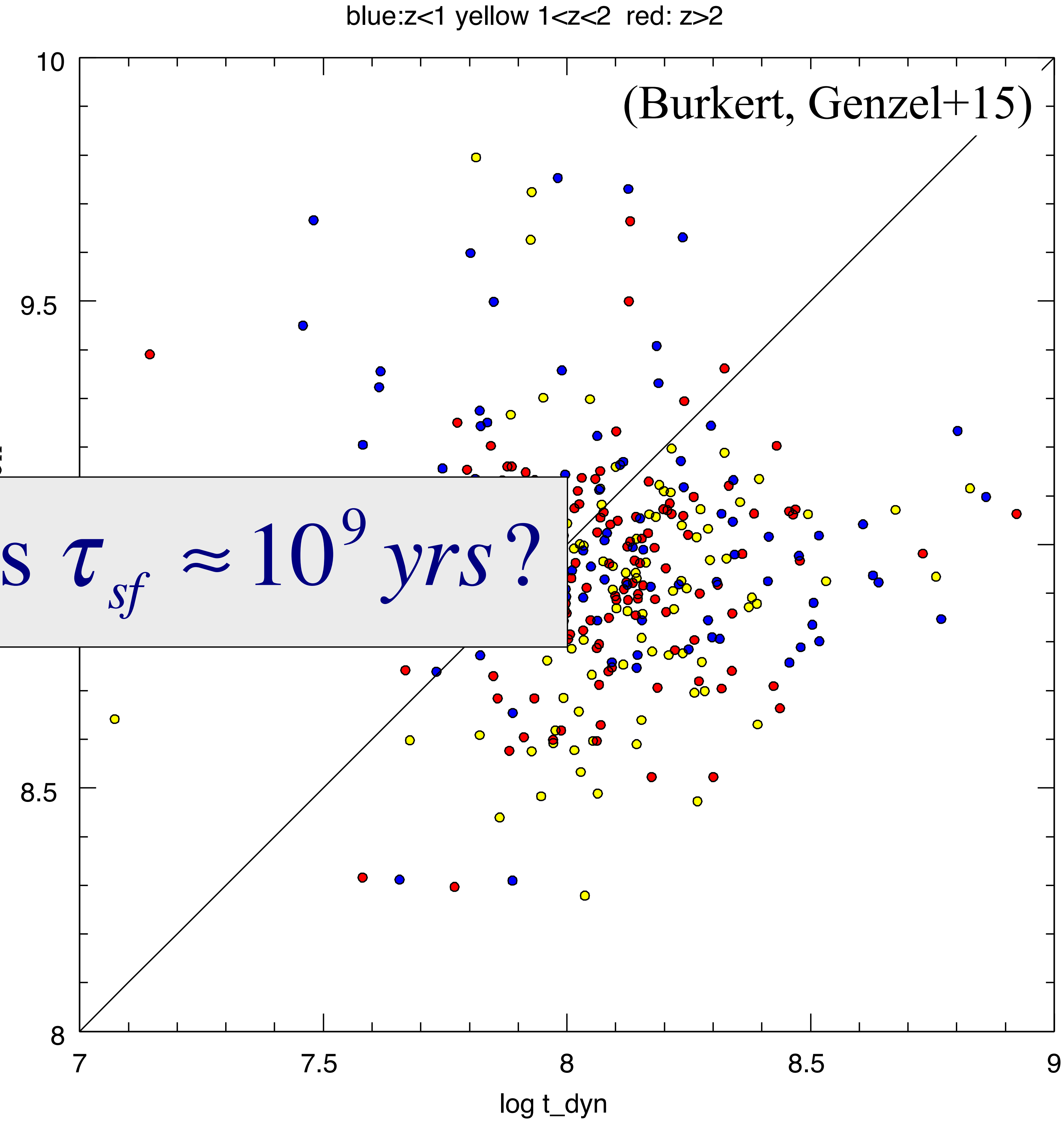
$$\tau_{sf} = \frac{\tau_{dyn}}{\varepsilon_{sf}} \; ???$$

~1%

$\log(\tau_{sf}\,/\,yr)$

BUT

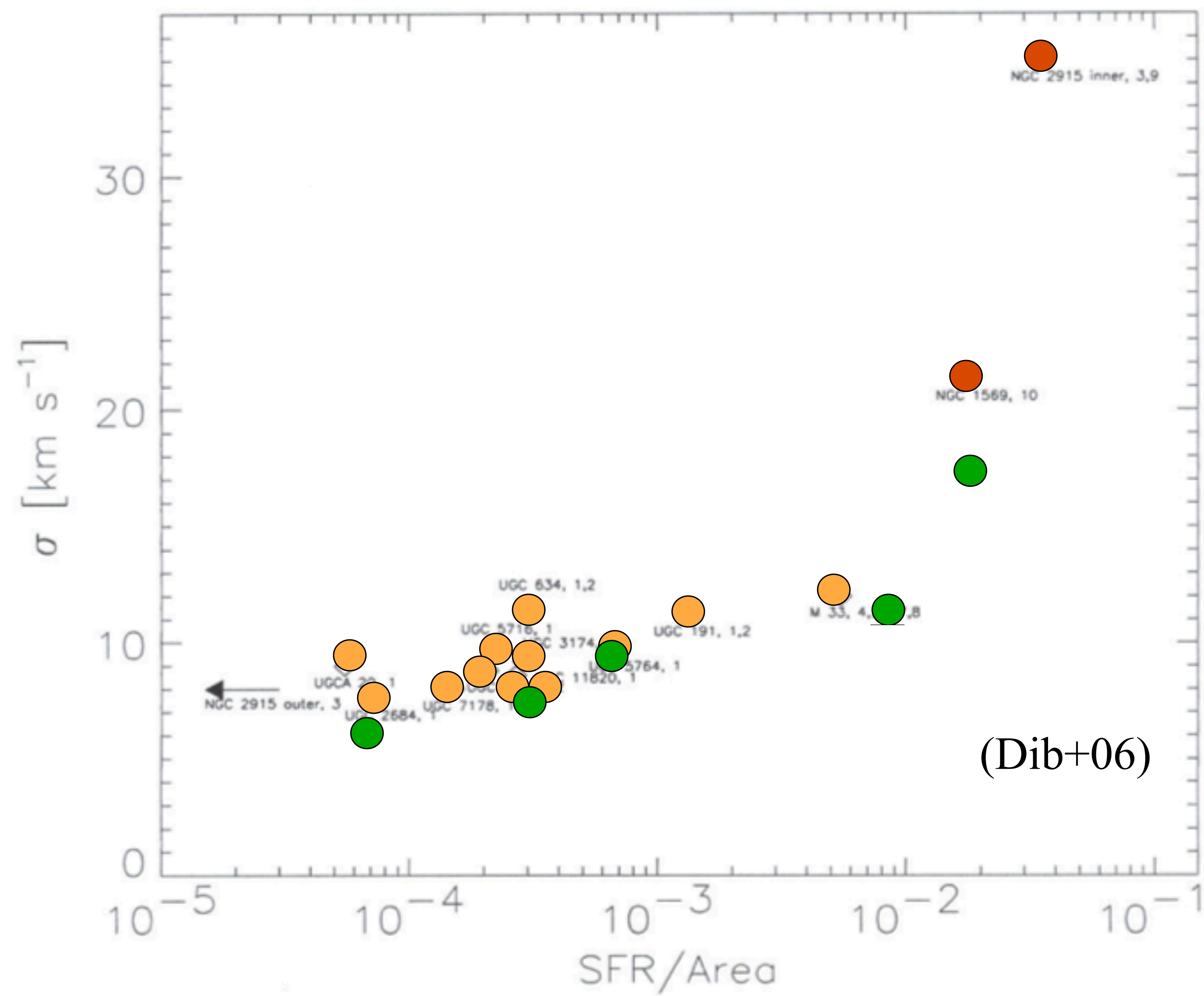
No correlation

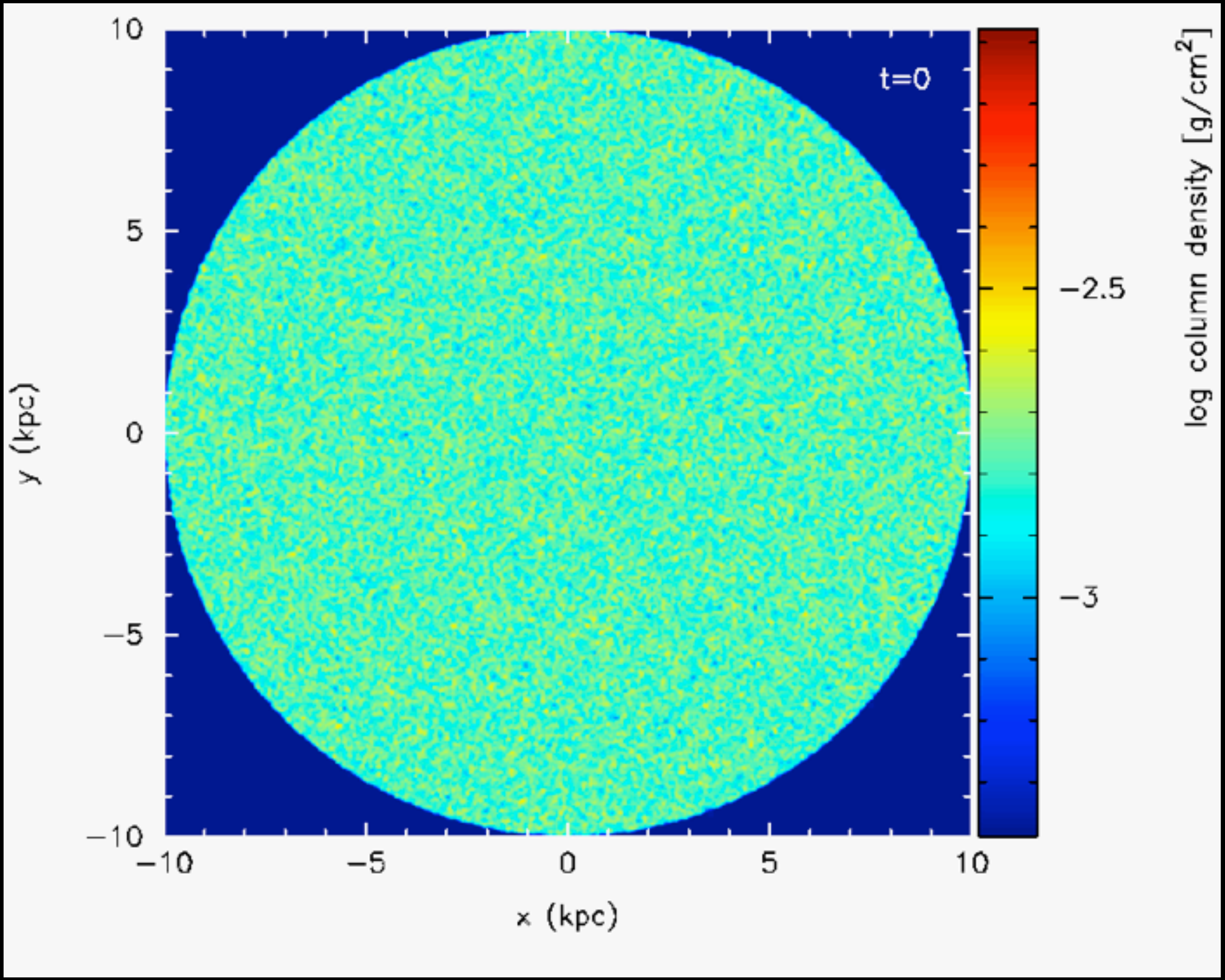


$$\text{Why is } \tau_{sf} \approx 10^9\, yrs\,?$$

$\log(\tau_{dyn}\,/\,yr)$

Stellar feedback regulated turbulence and star formation

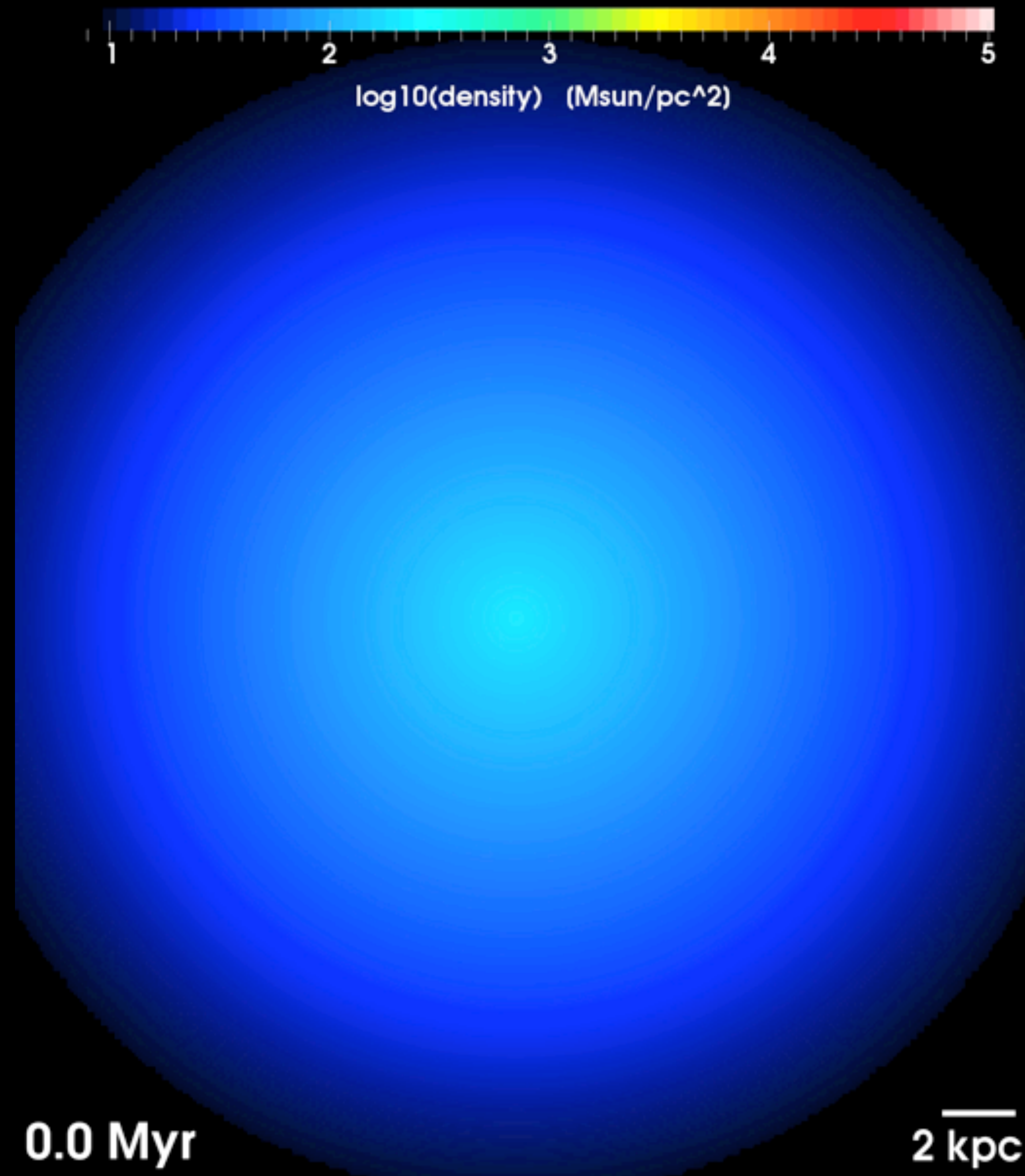


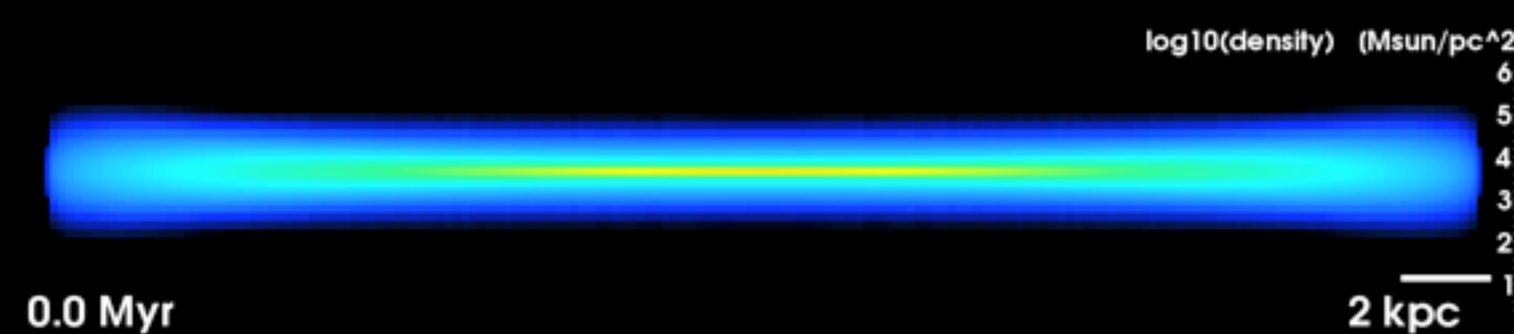


Dobbs, Burkert & Pringle 11a,b, 12a,b

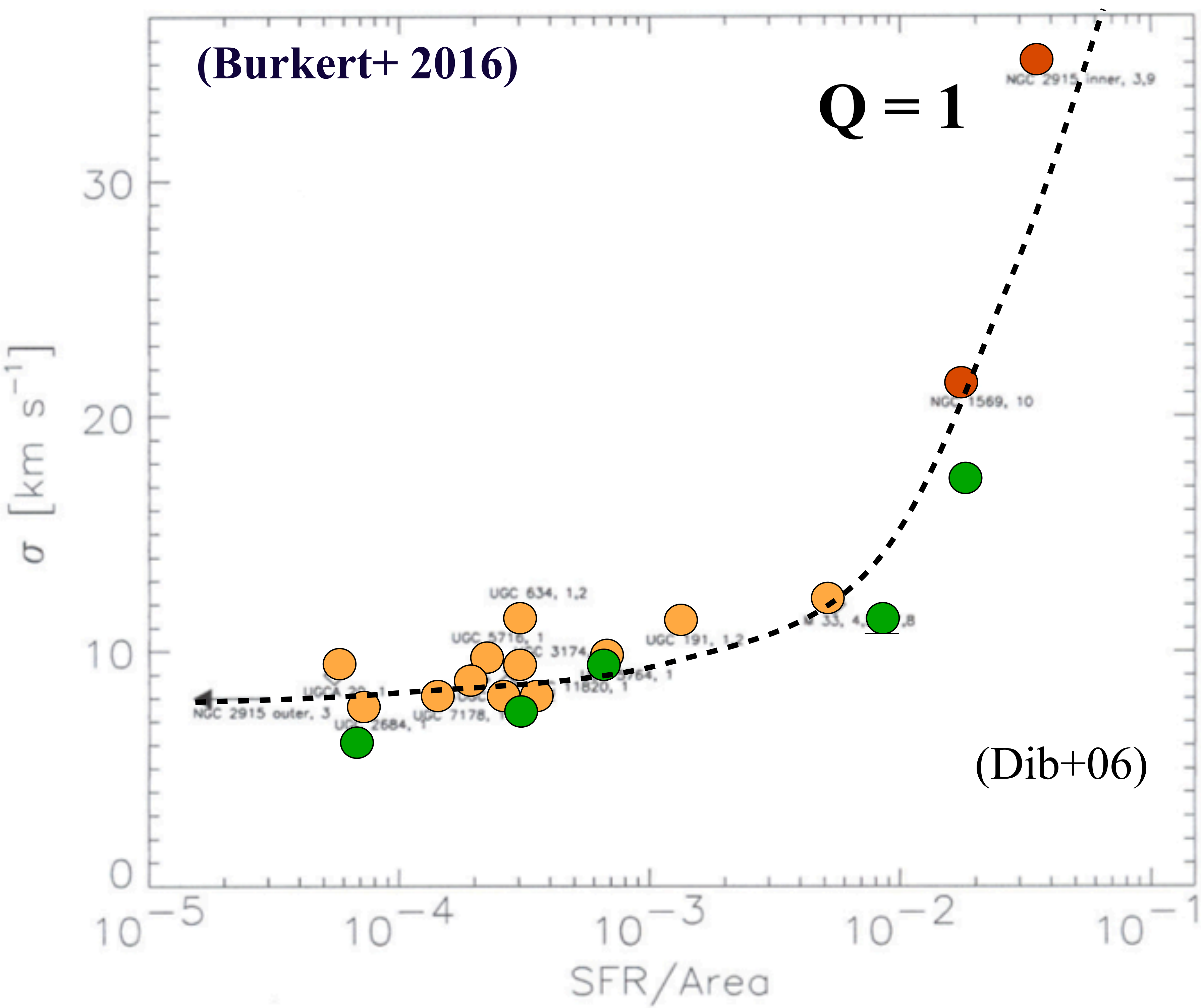
Stellar feedback versus disk instability

(Krumholz&Burkert 10; Forbes +12,14; Behrendt+ 15)





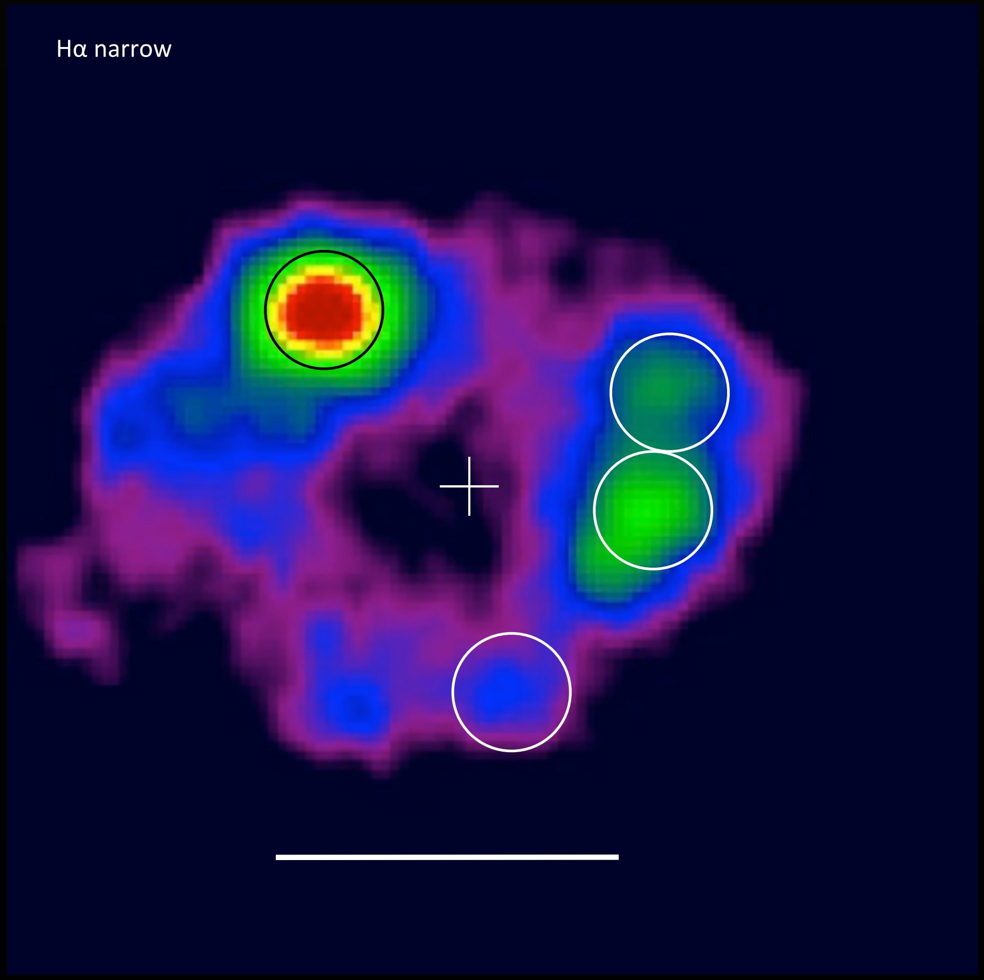
Stellar feedback versus disk instabilities



$$Q \equiv \frac{\kappa\sigma}{\pi G \Sigma} \approx 1-2$$

A Nearby, Normal
Star Forming Disk Galaxy

A Normal
Star Forming Disk Galaxy
Far, Far Away



Nearby star forming galaxies

$$M_{gas} / M_{dyn} \approx 0.05 - 0.1$$

$$\sigma \approx 10 - 20 \; km/s$$

$$\mathrm{M}_{clumps} \approx 10^4 - 10^6 M_\odot$$

High-z star forming galaxies

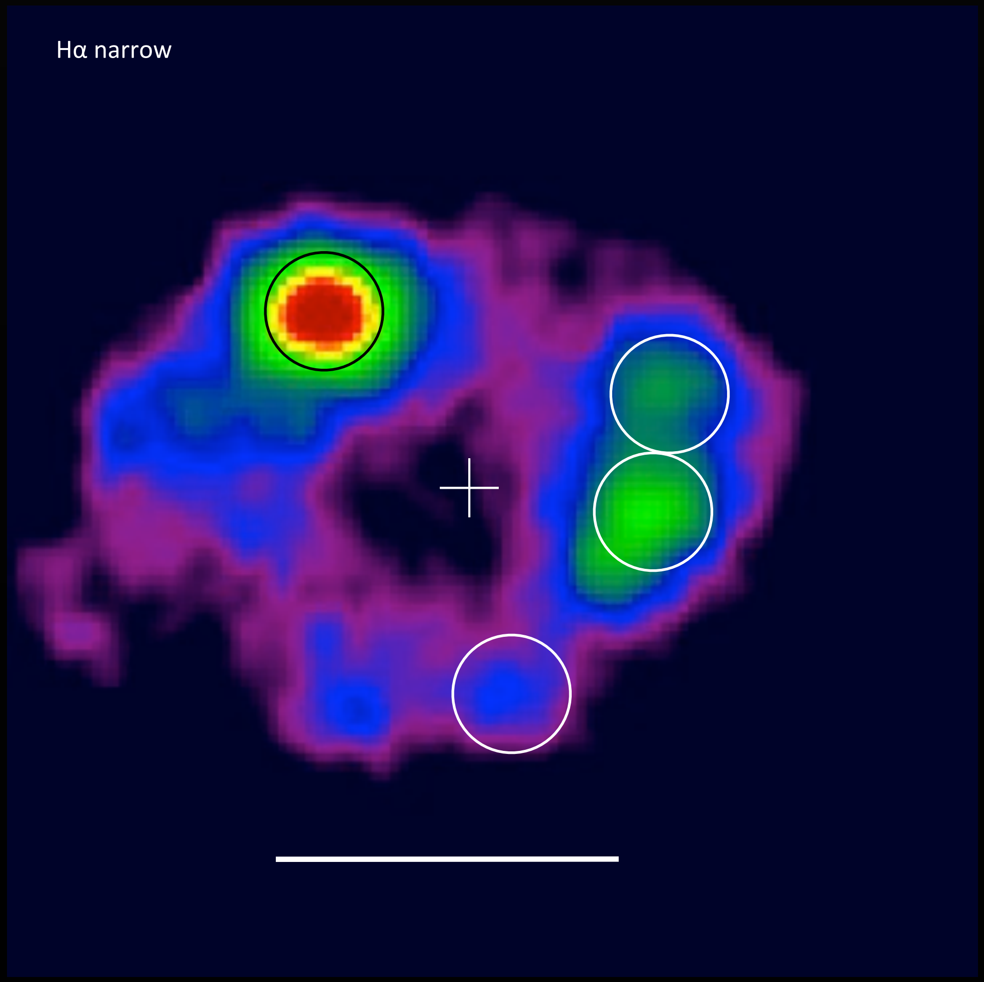
$$M_{gas} / M_{dyn} \approx 0.3 - 0.6$$

$$\sigma \approx 40 - 60 \; km/s$$

$$\mathrm{M}_{clumps} \approx 10^8 - 10^9 M_\odot$$

A Nearby, Normal
Star Forming Disk Galaxy

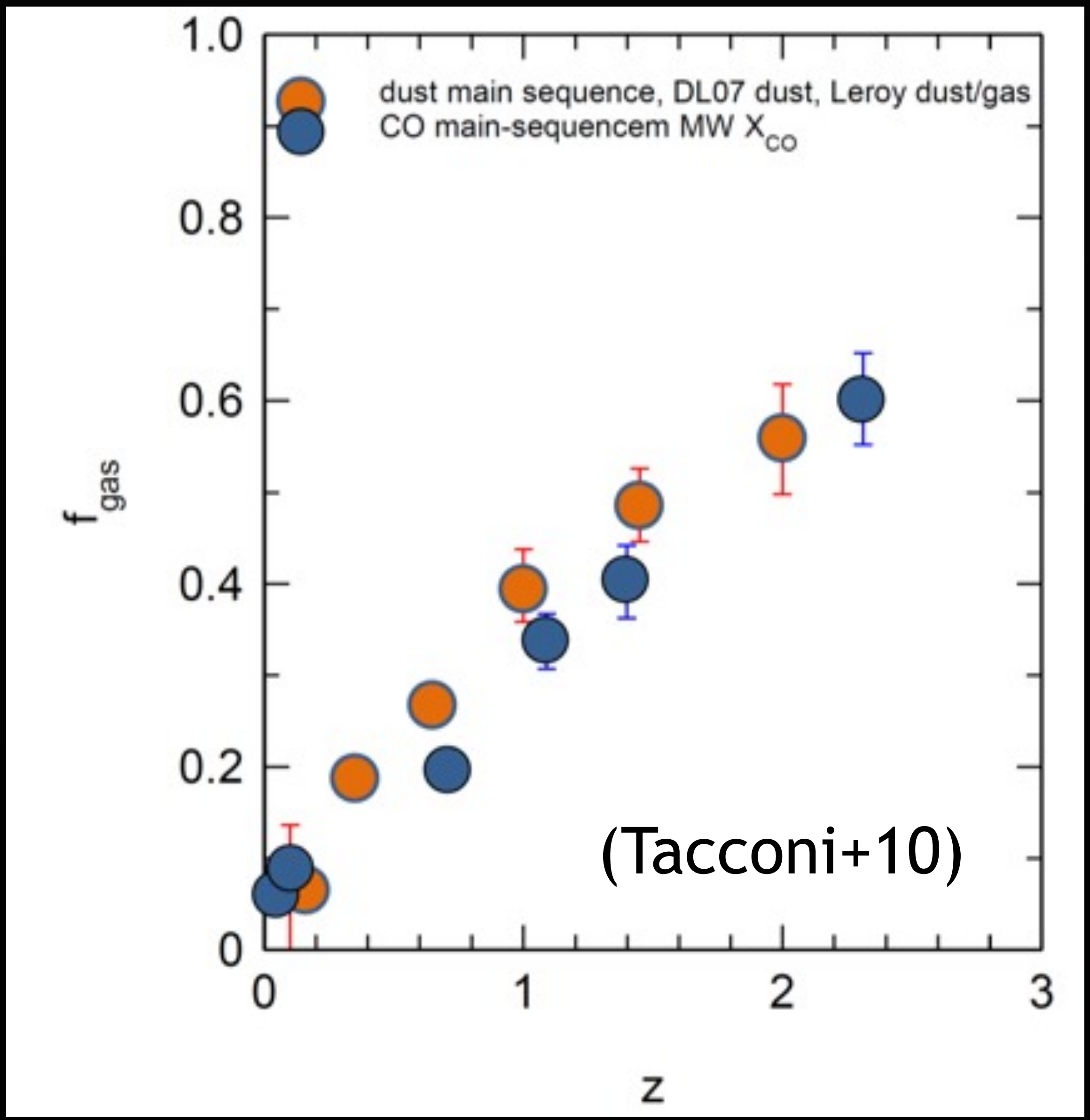
A Normal
Star Forming Disk Galaxy
Far, Far Away



Is there a fundamental difference?

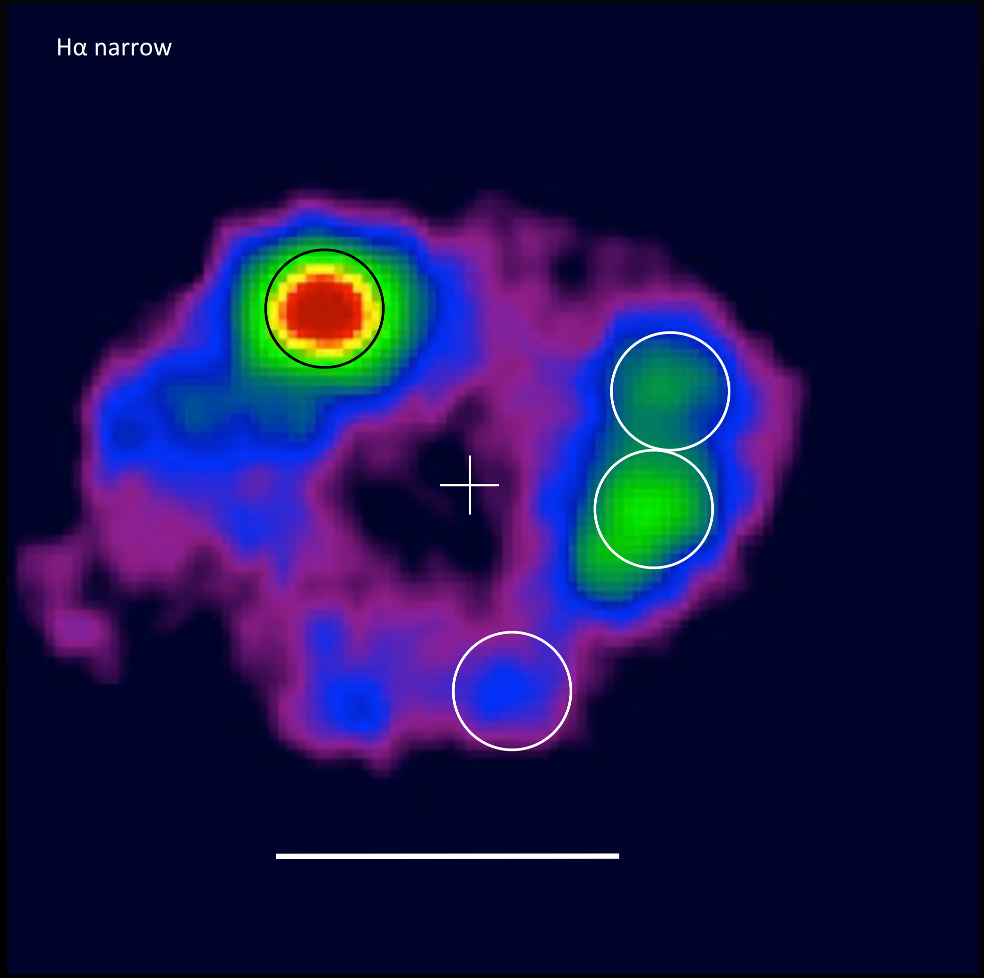
NO

Gas fraction as function of redshift

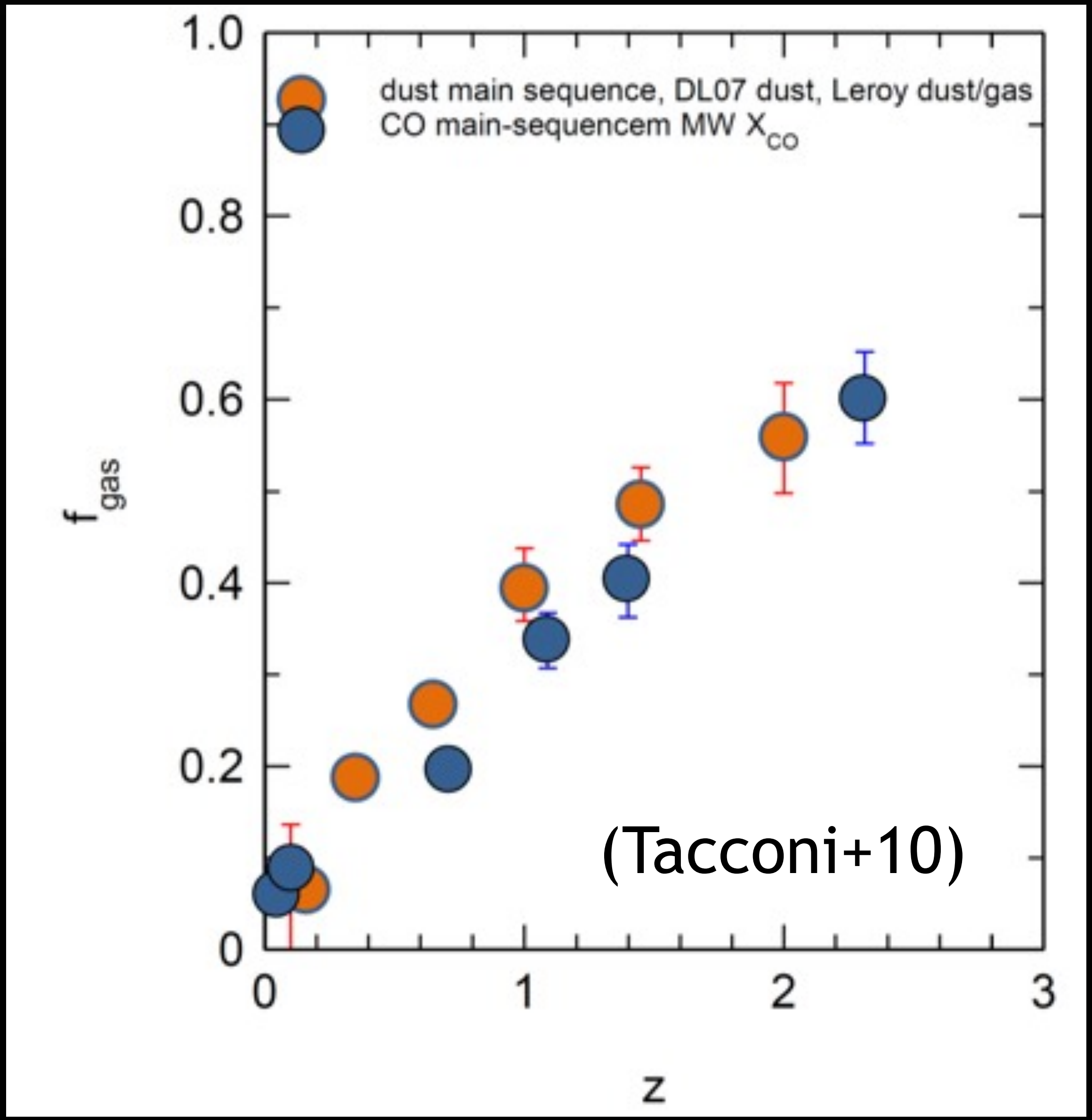


$$M_g = \dot{M}_{acc} \cdot 10^9\, yrs$$

A Normal
Star Forming Disk Galaxy
Far, Far Away



Gas fraction as function of redshift



$$M_g = \dot{M}_{acc} \cdot 10^9\, yrs$$

Fundamental disk galaxy properties

Violent disk instability

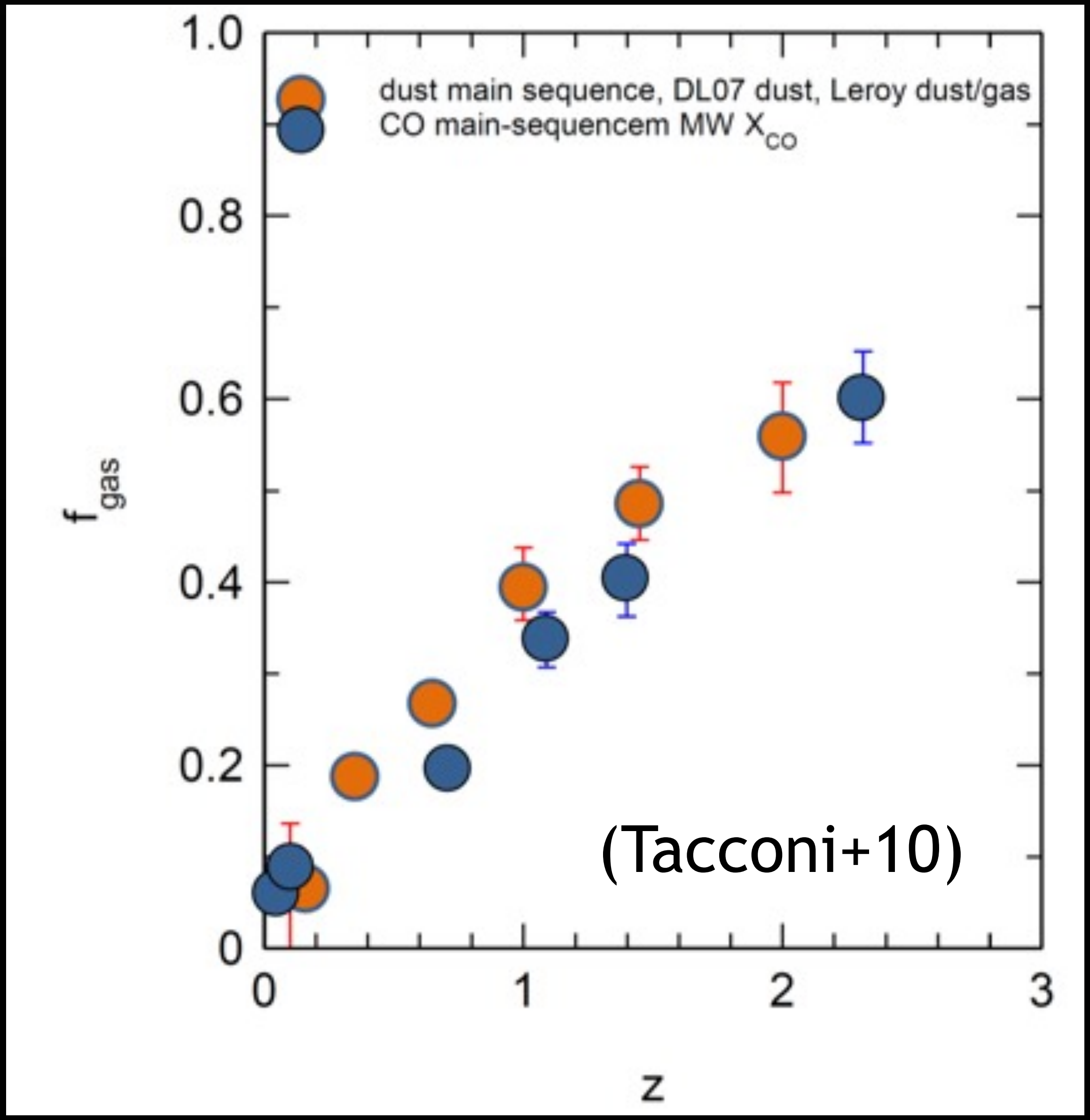
$$\delta \equiv M_{gas} / M_{dyn}$$

$$Q = \frac{\sqrt{2}}{\delta}\left(\frac{\sigma}{v_{rot}}\right) \approx 1 \quad \downarrow$$

$$\frac{\sigma}{v_{rot}} = \frac{\delta}{\sqrt{2}} \qquad \frac{\lambda}{R} = \delta$$

$$\frac{M_{clump}}{M_{disk}} \approx \delta^2$$

Gas fraction as function of redshift



Fundamental disk galaxy properties

Violent disk instability

$$\delta \equiv M_{gas} / M_{dyn}$$

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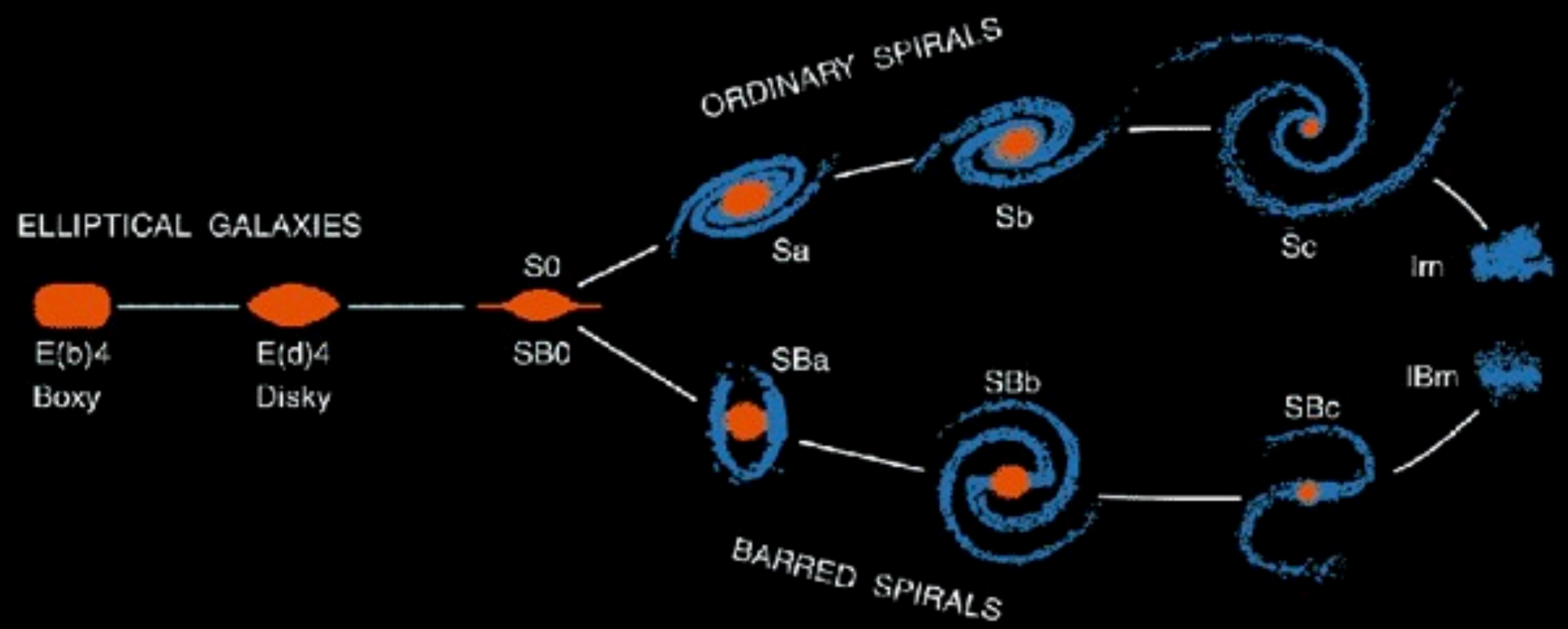
↓

$$\frac{\sigma}{v_{rot}} = \frac{\delta}{\sqrt{2}} \qquad \frac{\lambda}{R} = \delta$$

$$\frac{M_{clump}}{M_{disk}} \approx \delta^2$$

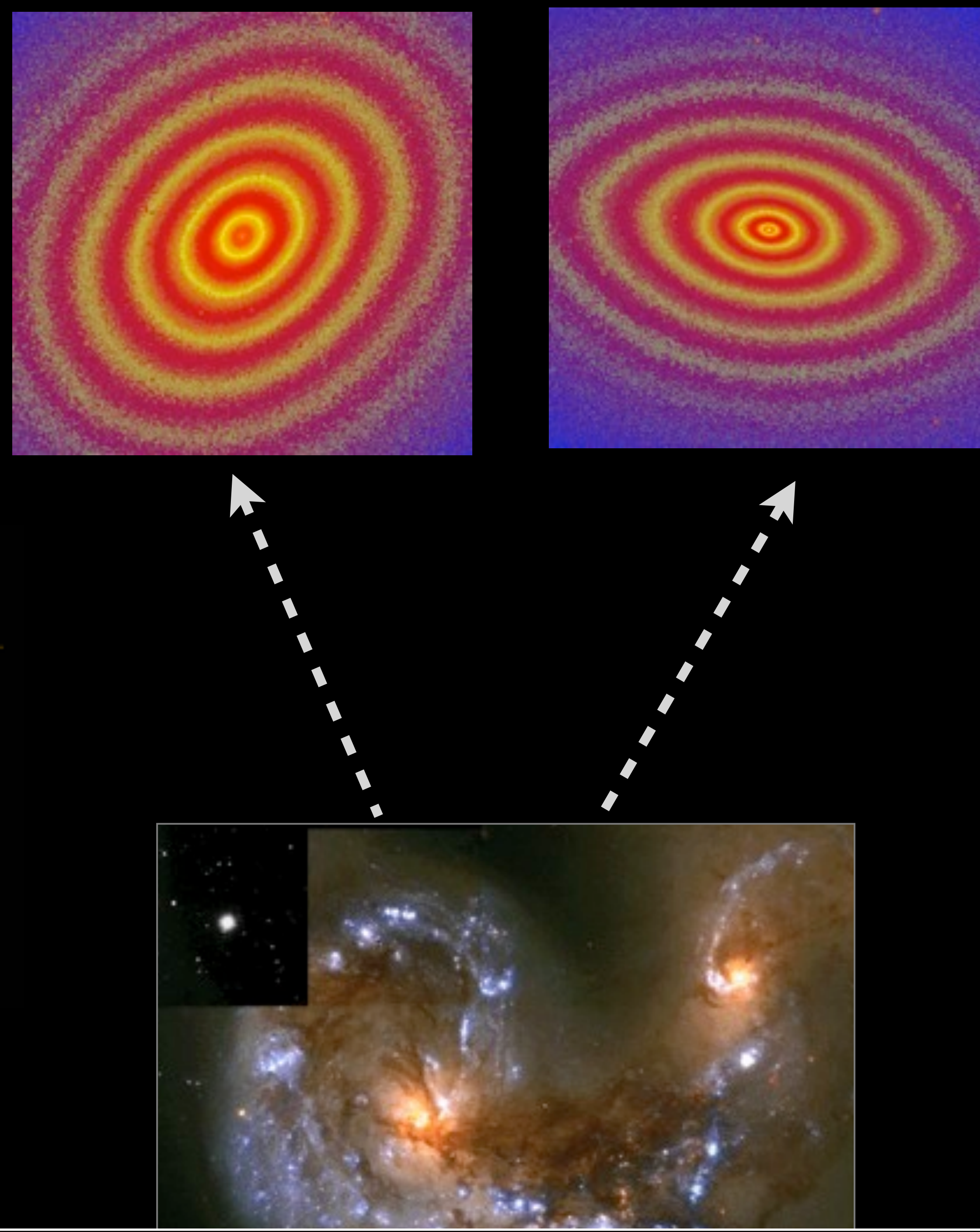
Gravitational disk instability dominates the disk structure

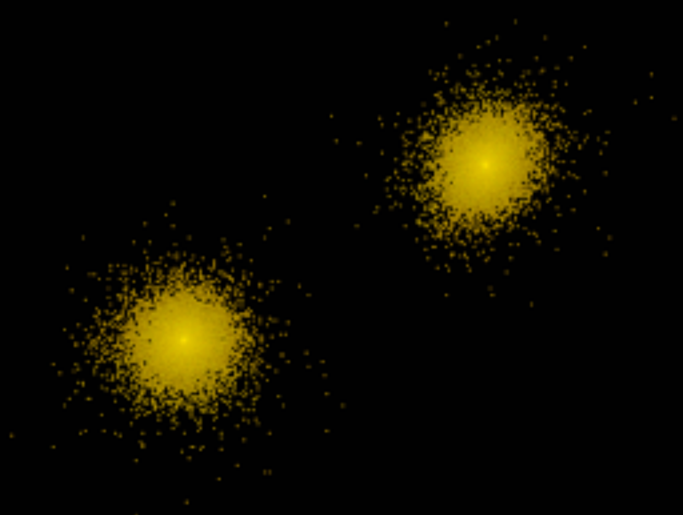
The emergence of quiescent, red ellipticals



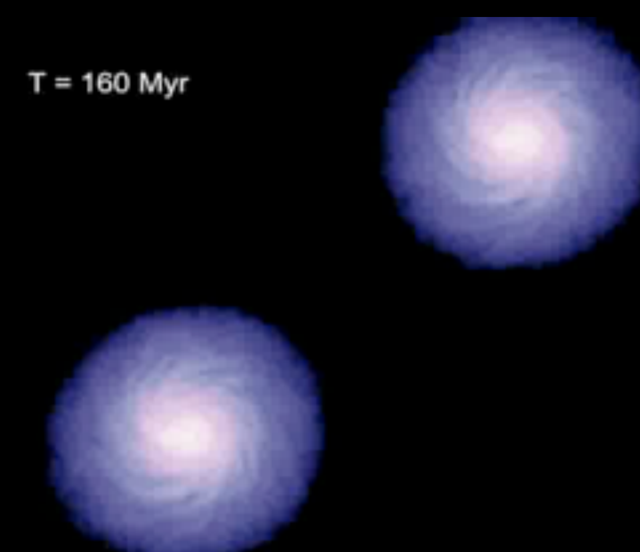
Major mergers clearly happen

(e.g. Hopkins+ 03-11; Naab+ 03-11, Johansson+09-11; Remus+12, however Robertson+ 06)





(Naab)

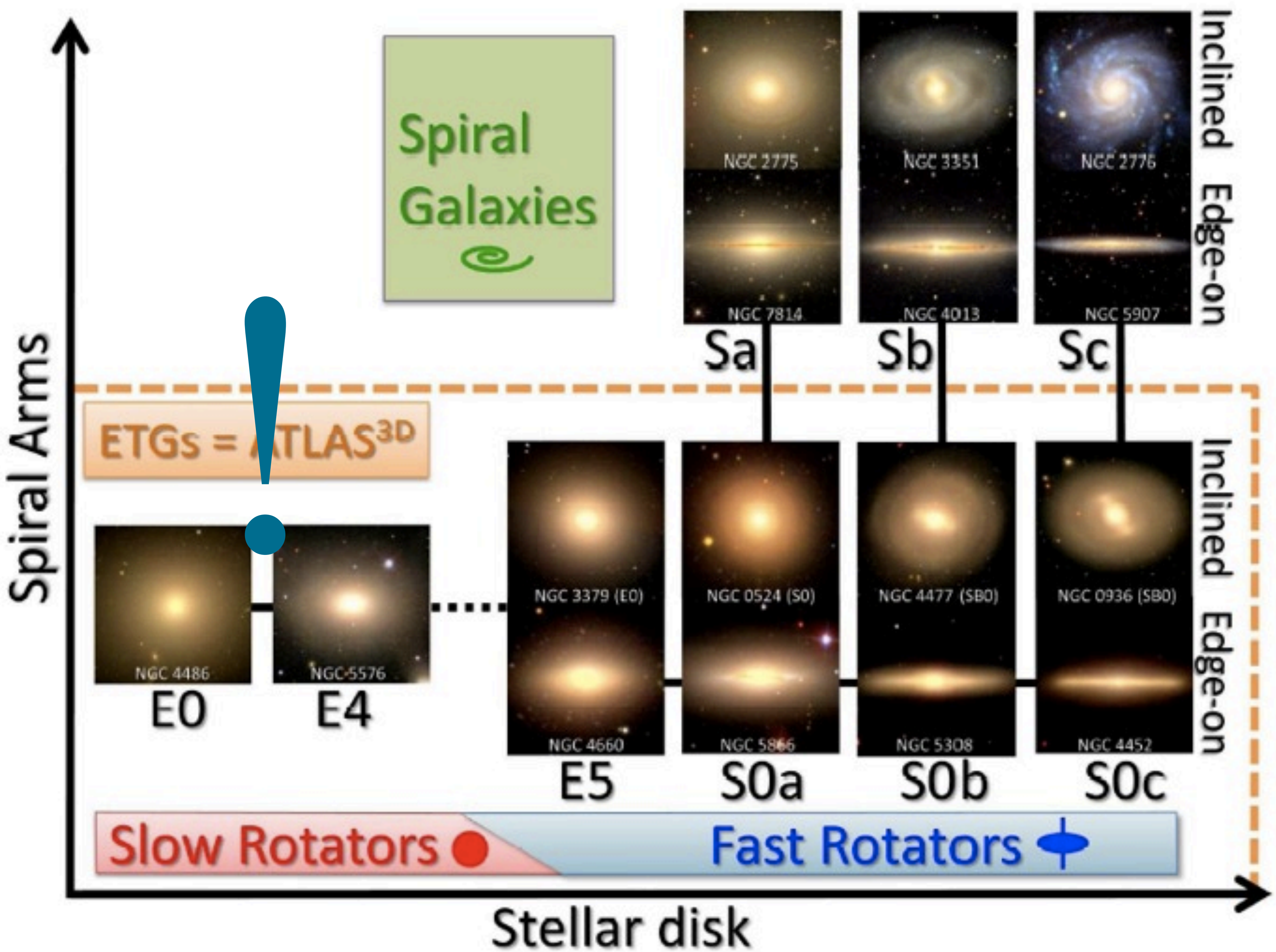


(Springel)

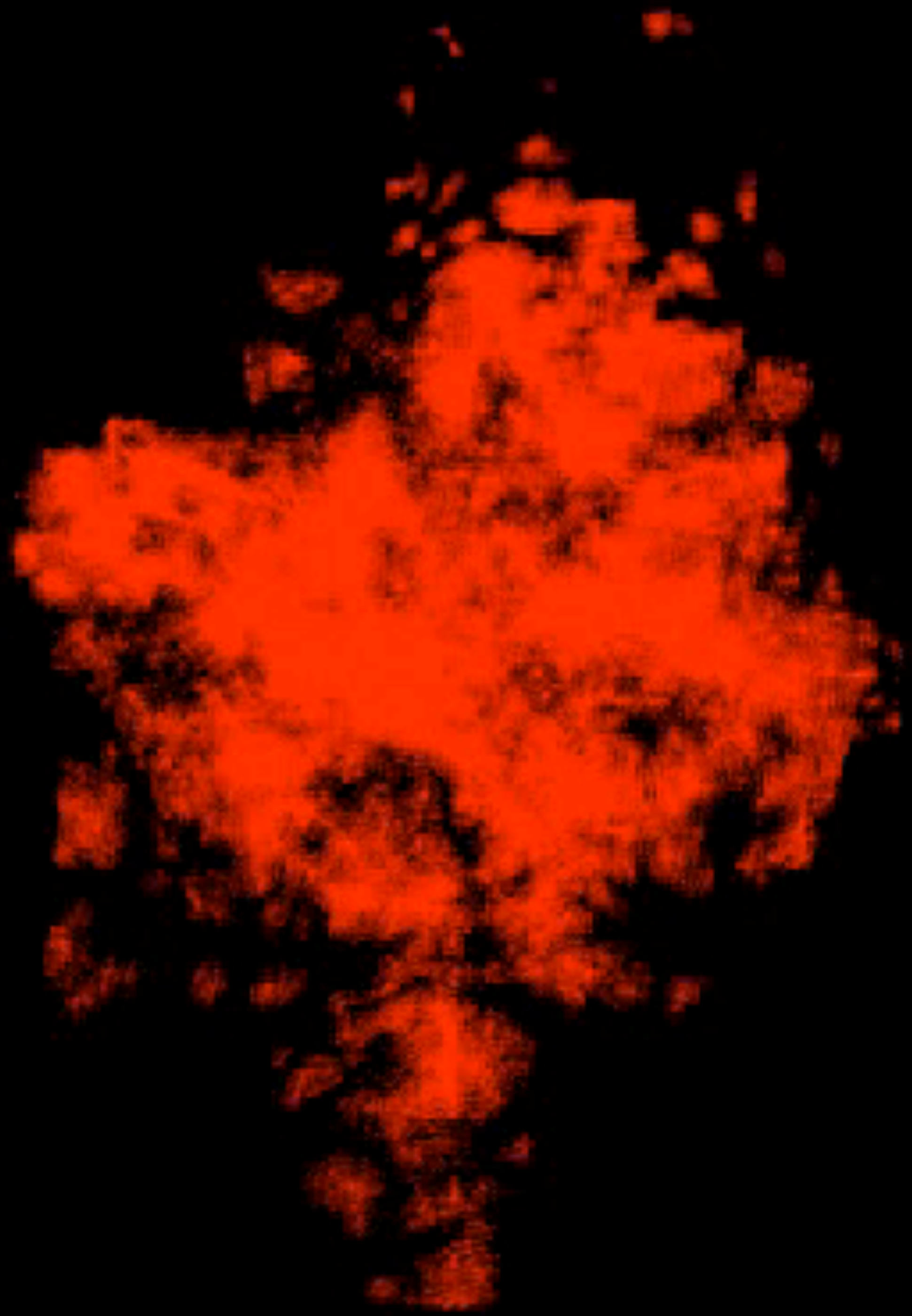
Major mergers are too rare in order to explain the population of ellipticals

The violent transition onto the red sequence

Strangulation, stripping, quenching, harrassment, blowout



Cappellari+11,13

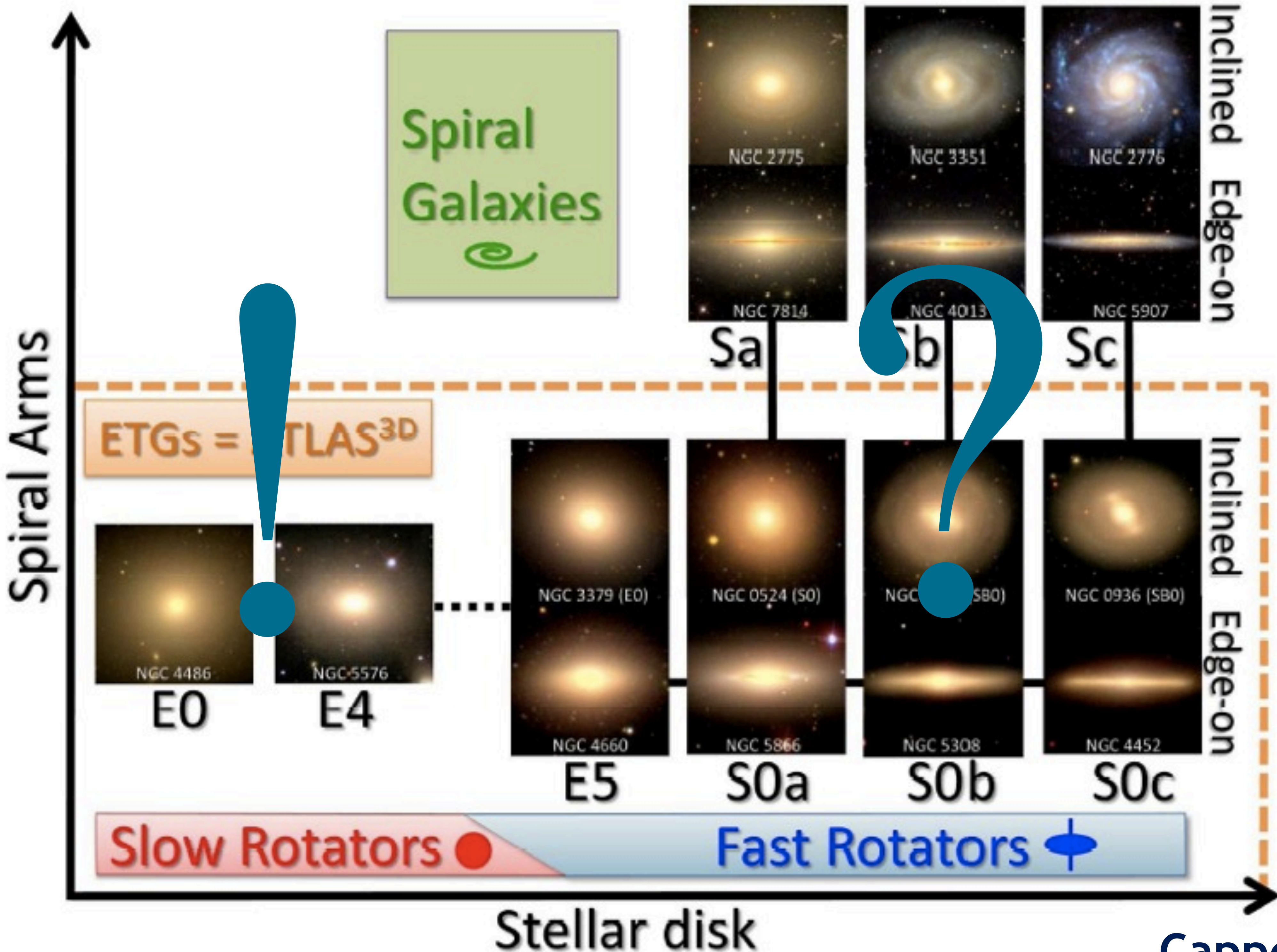


Oser 10,12


NGC 474

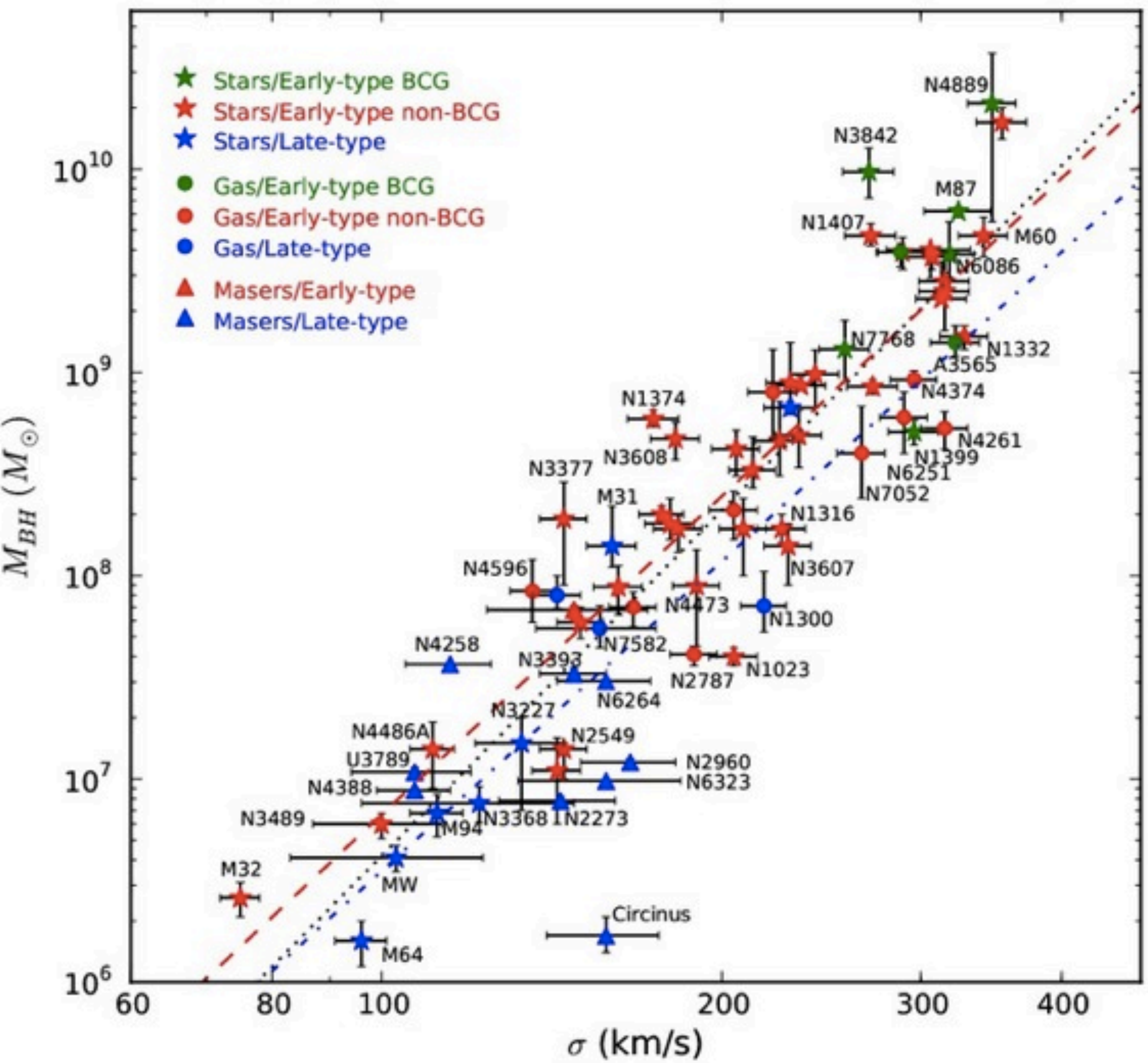
The violent transition onto the red sequence

(strangulation, stripping, quenching, harrassment, blowout)



Cappellari+11,13

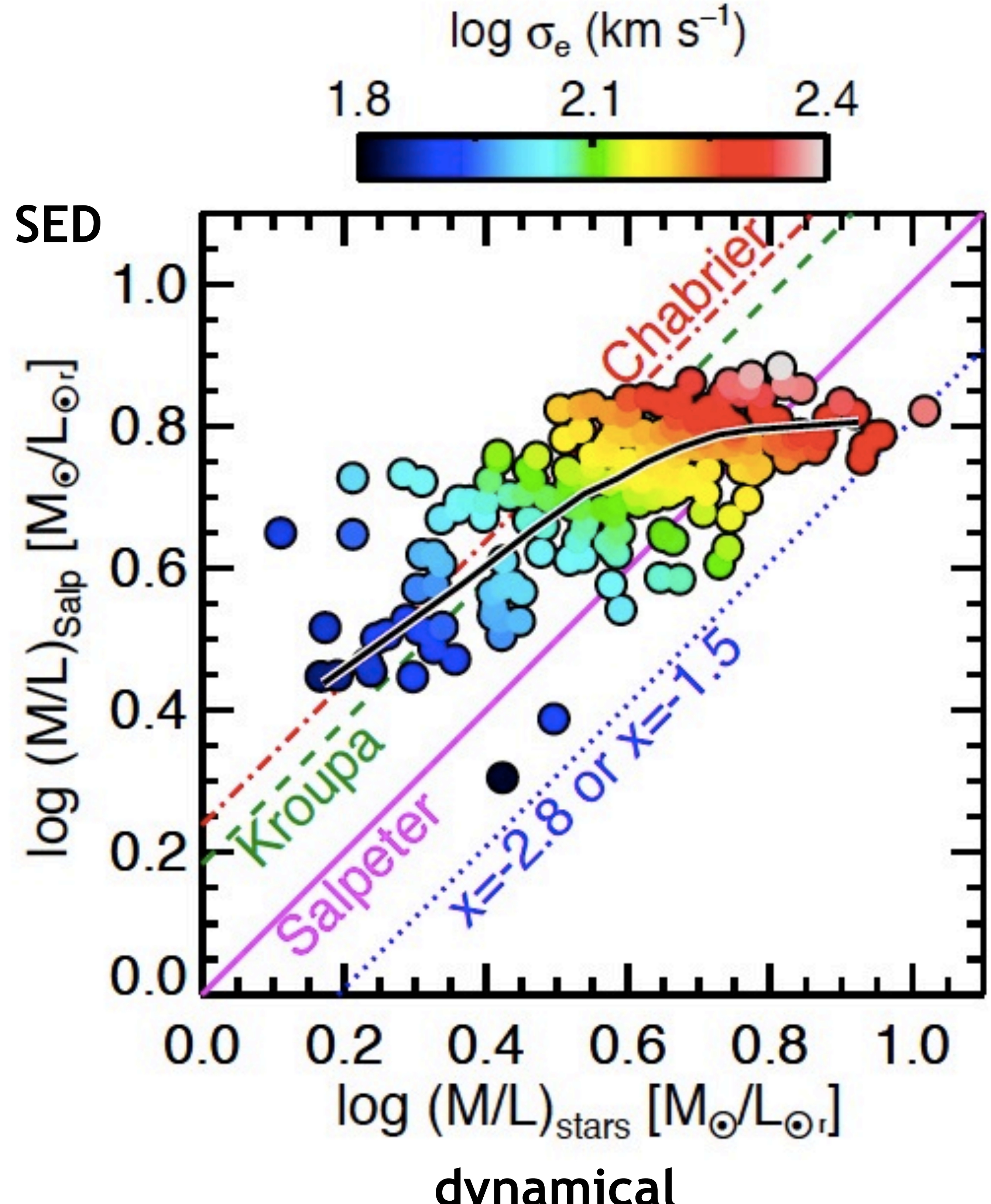
Nearly all galaxy properties scale mainly with velocity dispersion, rather than other global parameters (Cappellari+ 13,15).



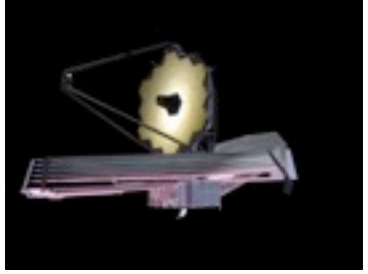
(McConnel&Ma 13)

- BH mass
- Number of globular clusters
- Total mass
- Size
- Surface brightness
- Density distribution
- Colour
- Stellar population
- Molecular gas fraction
- IMF Variation

Nearly all galaxy properties scale mainly with velocity dispersion, rather than other global parameters (Cappellari+ 13,15).



- BH mass
- Number of globular clusters
- Total mass
- Size
- Surface brightness
- Density distribution
- Colour
- Stellar population
- Molecular gas fraction
- **IMF Variation**



Summary

Galaxy formation is a **boundary condition** problem (inflow and outflow).

Low-redshift galaxies still contain **important information** about their **cosmic merger and assembly history**.

Understanding the **assembly history** of galaxies requires a detailed investigation of their **interaction with the cosmic web** (**cosmic web imaging**).

High- and low redshift star forming galaxies appear to be driven by **similar self-regulated internal feedback processes and disk instabilities.**

The universal **gas depletion timescale** is a key ingredient in order to understand galaxy evolution. Its origin is not clear.

The **stellar IMF** changes with **galactic environment**, linking large-scale cosmic web galaxy formation to **subpc-scale star formation.**