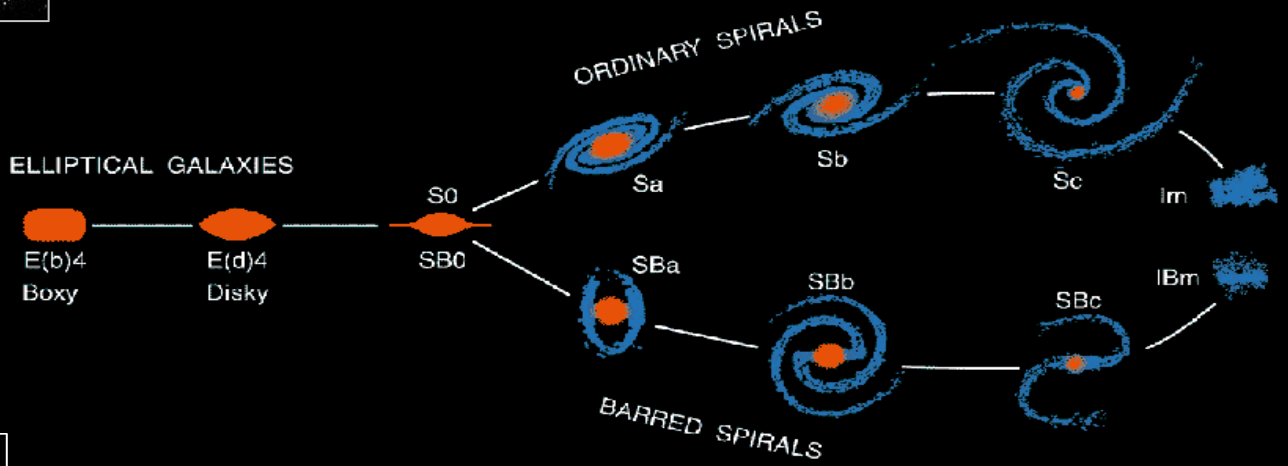
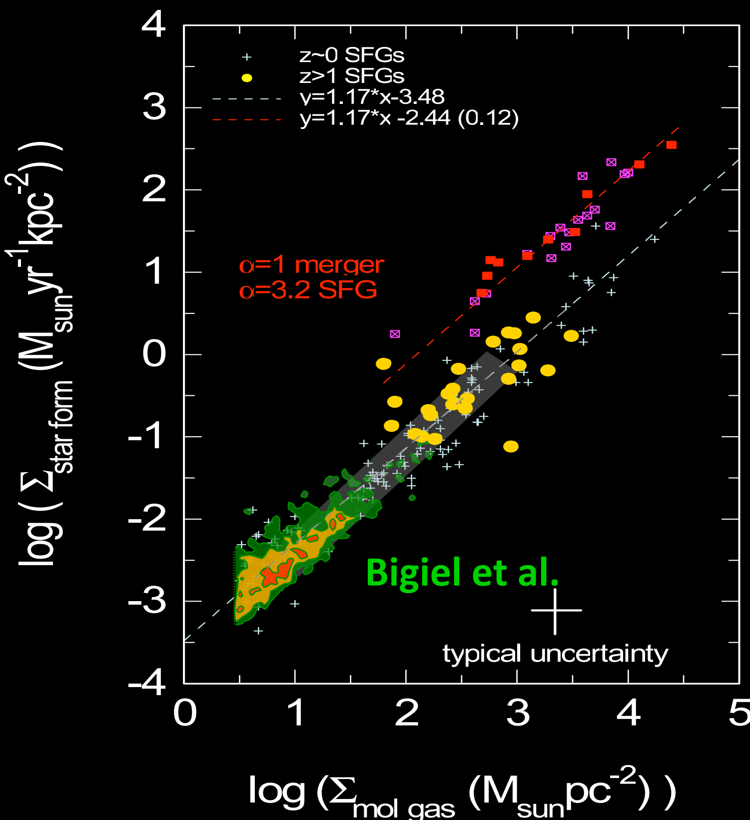
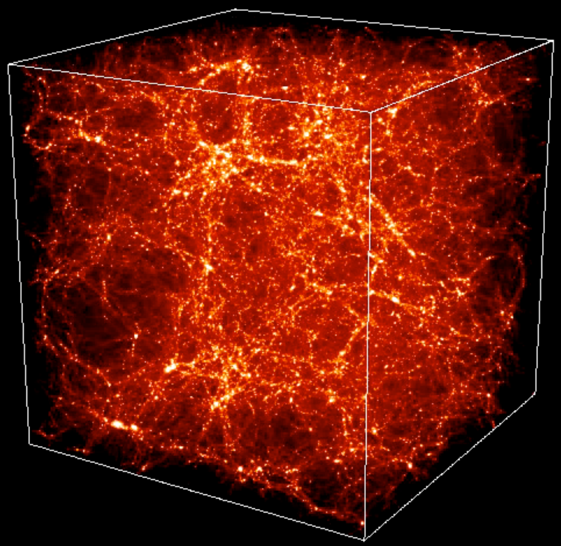
Galaxy formation modes and their relation to structure

Andreas Burkert

CAST, University of Munich







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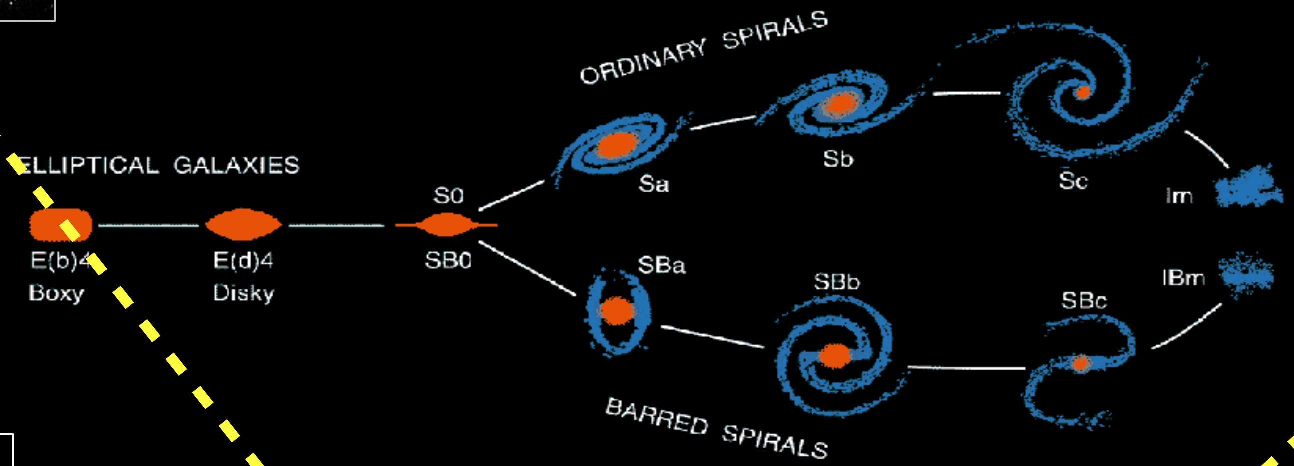
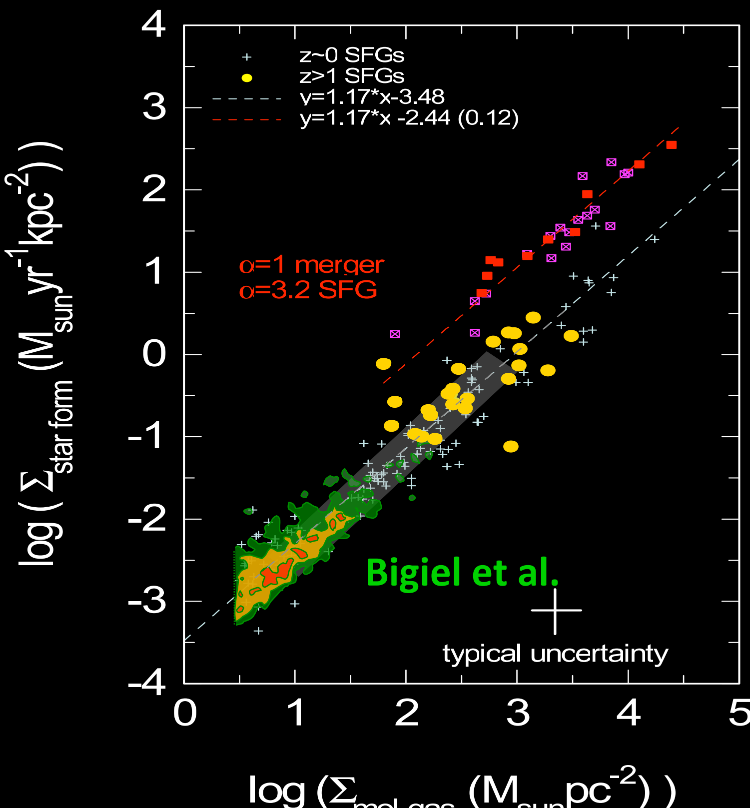
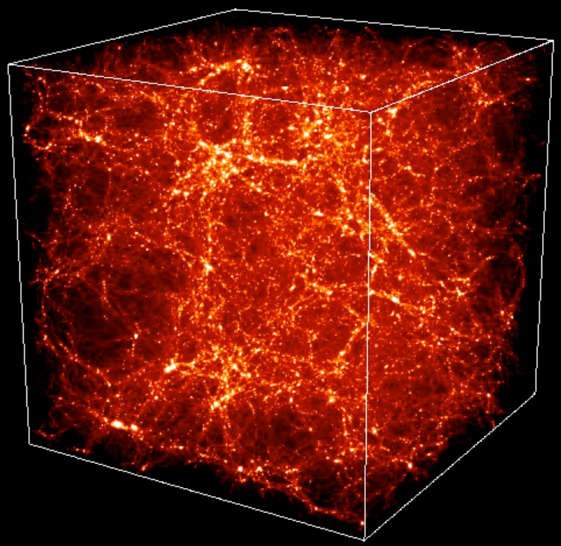
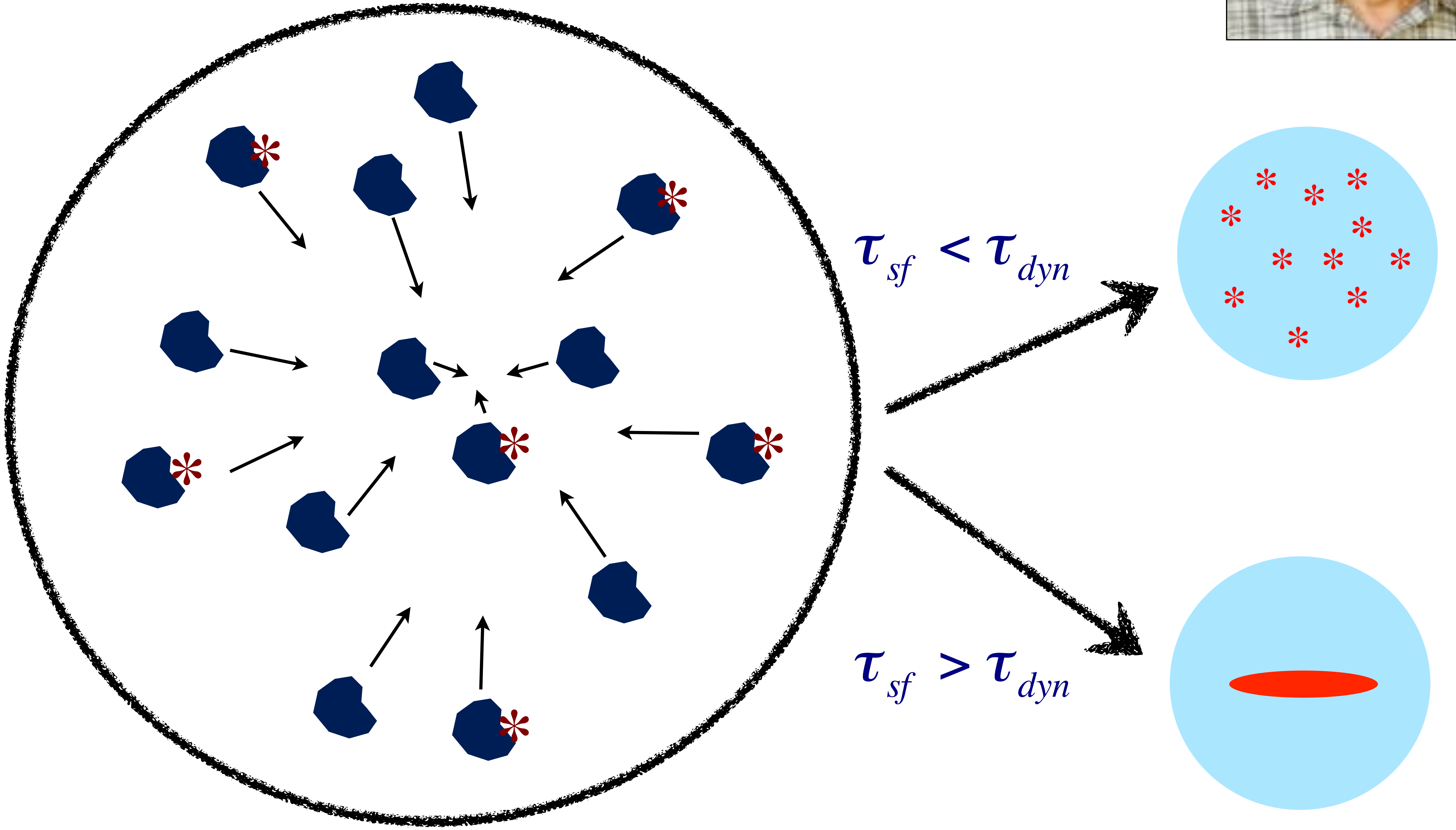






The Larson models

(Larson 69, 74, 75, 76)



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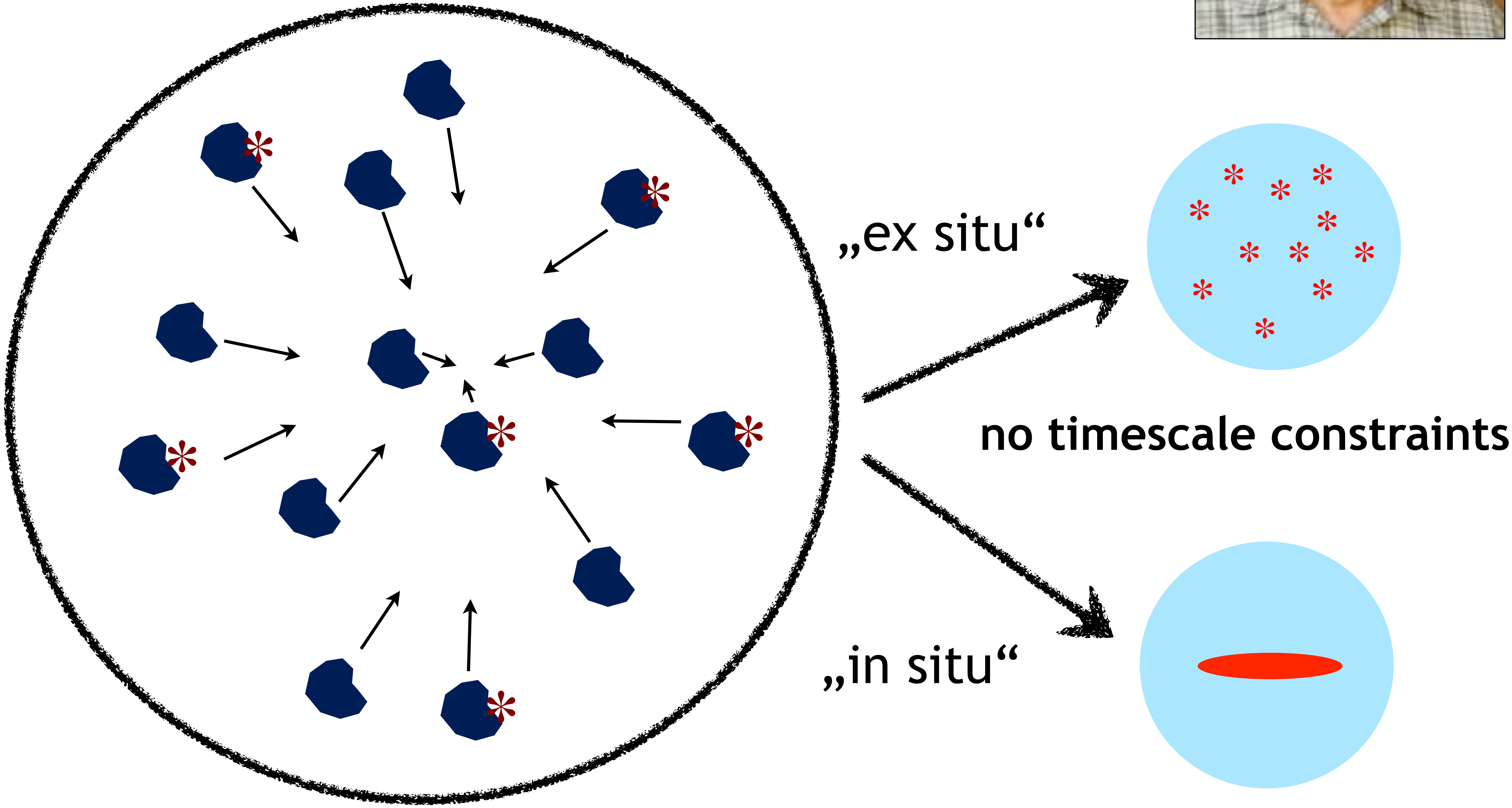
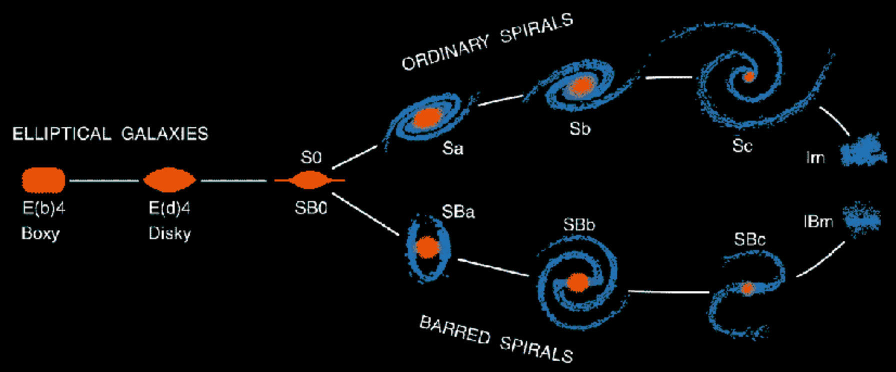
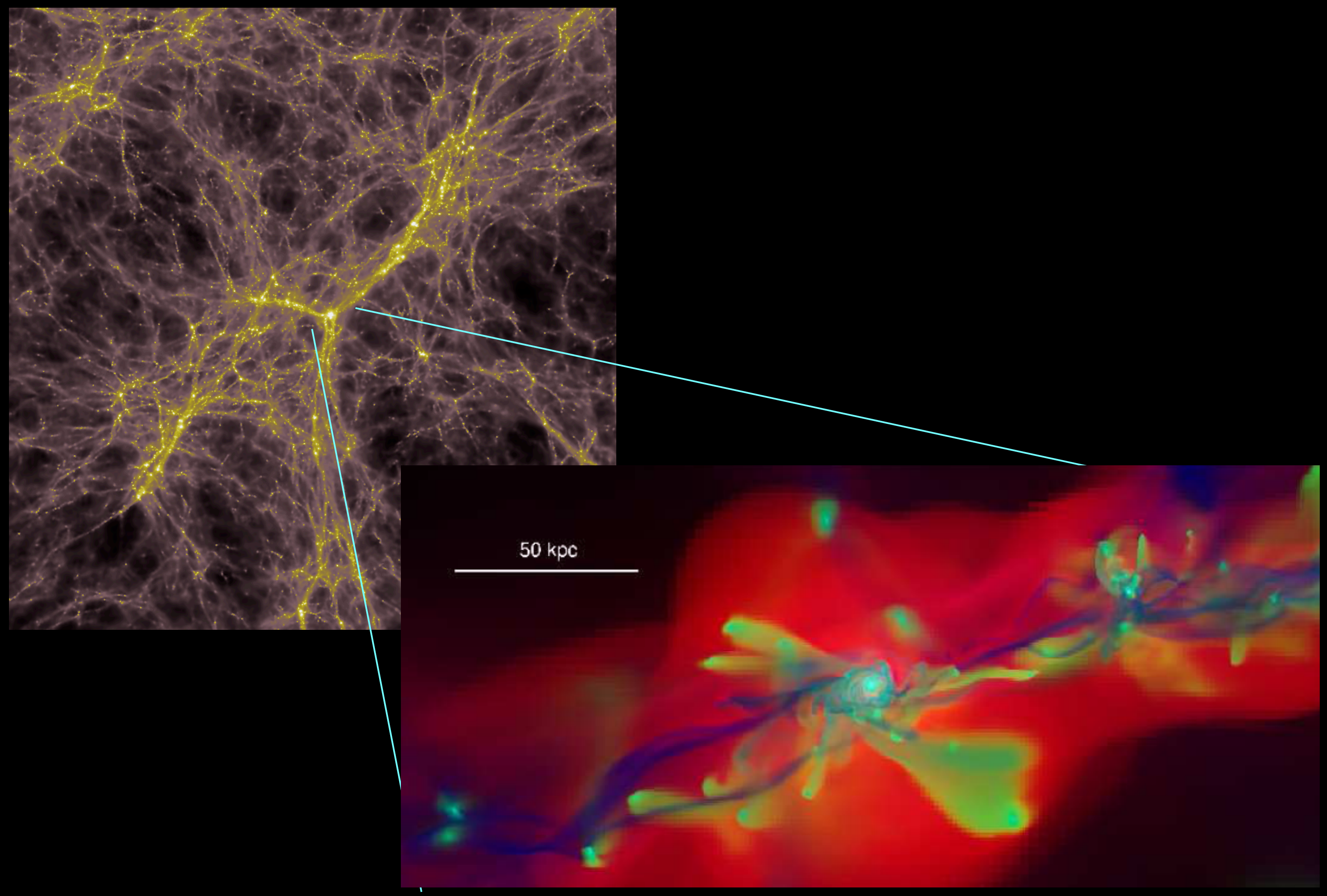


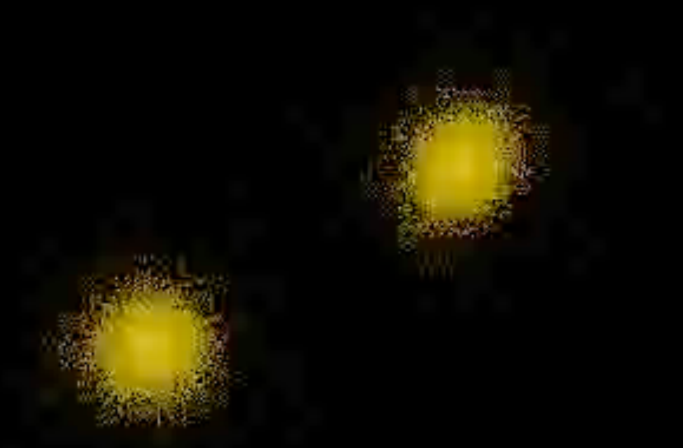
Origin of the Hubble Sequence





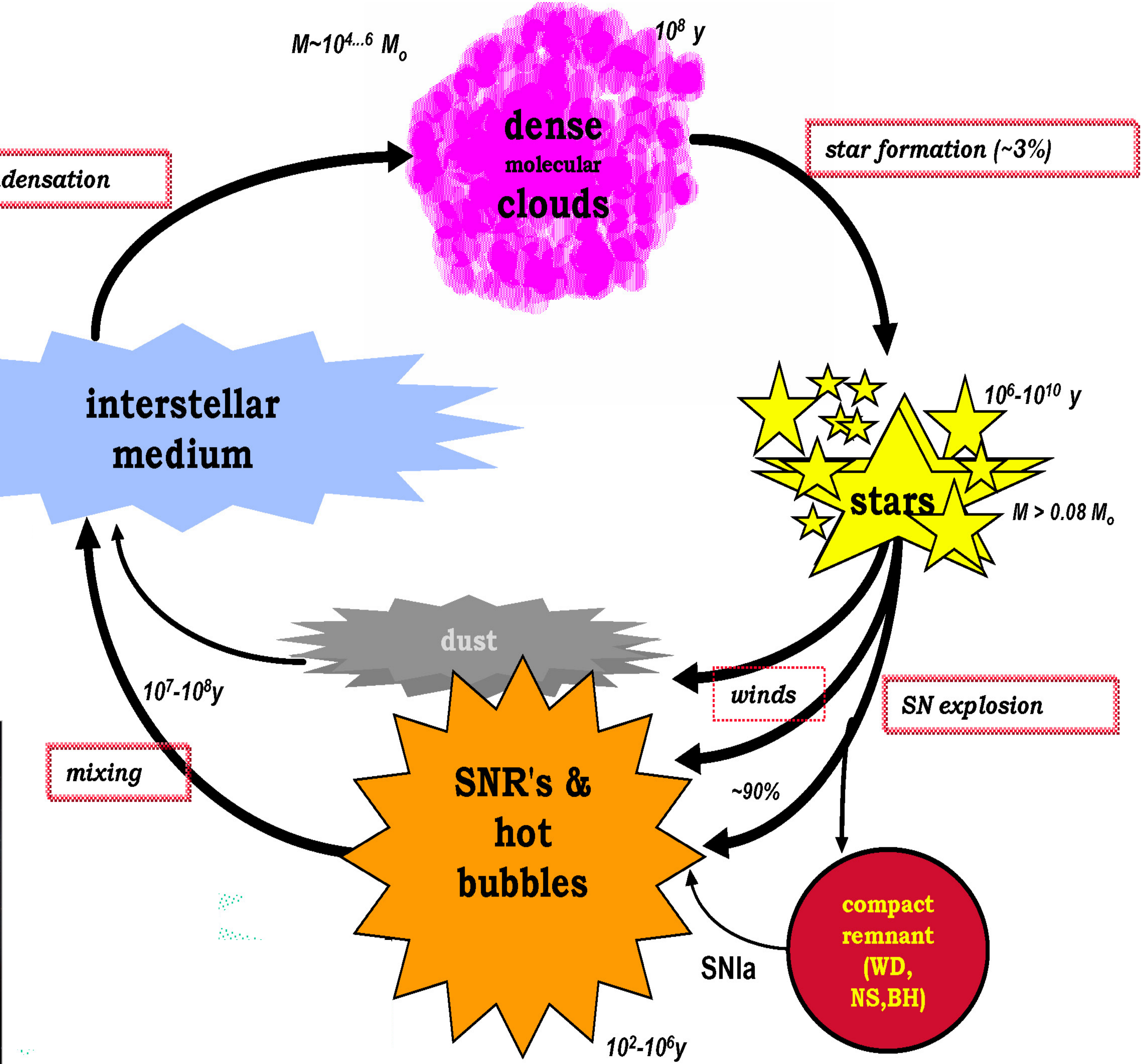
Gas infall forms disk galaxies

Dekel & Birnboim 2003,2006,2009, Keres et al. 2005, 2009, Davé 2007, Dekel et al. 2009, Agertz et al. 2009, Ceverino et al. 2010, Genel et al. 2010



Major mergers form ellipticals

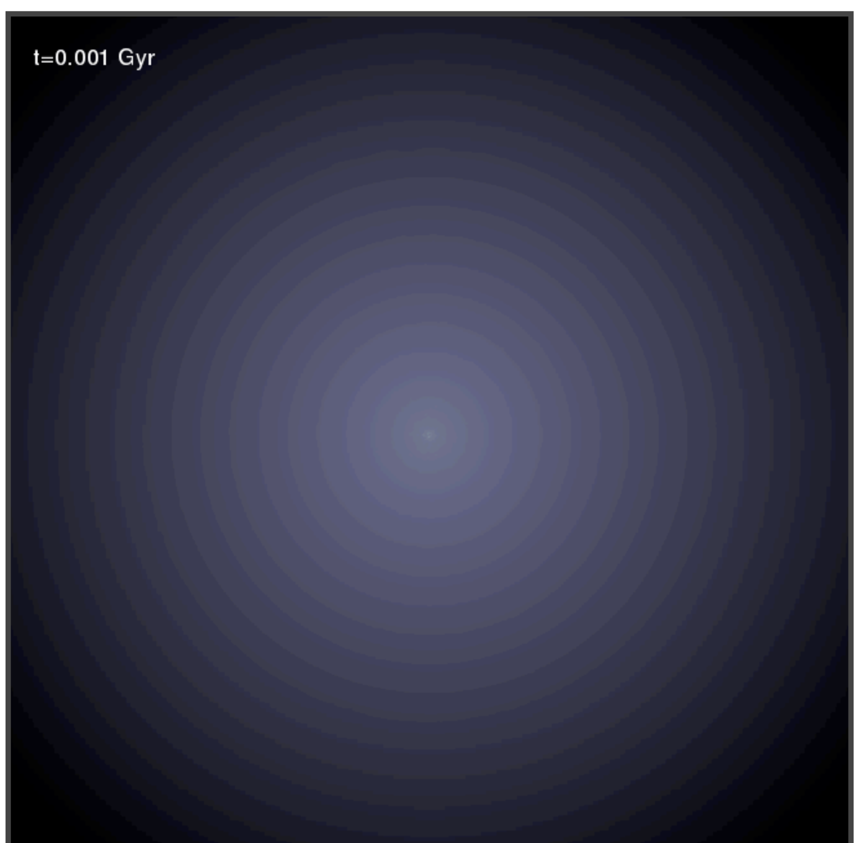
Toomre & Toomre 1972, Hernquist 1989-2011, Springel, Hopkins et al. 2003-2011, Robertson & Bullock 2008, Naab et al. 2003-2011


M~10^4...6 Mo
10^8 y
dense
molecular
clouds
condensation
star formation (~3%)
interstellar
medium
10^6-10^10 y
stars
M > 0.08 Mo
dust
winds
SN explosion
10^7-10^8y
mixing
~90%
SNR's &
hot
bubbles
compact
remnant
(WD,
NS,BH)
SNIa
10^2-10^6y

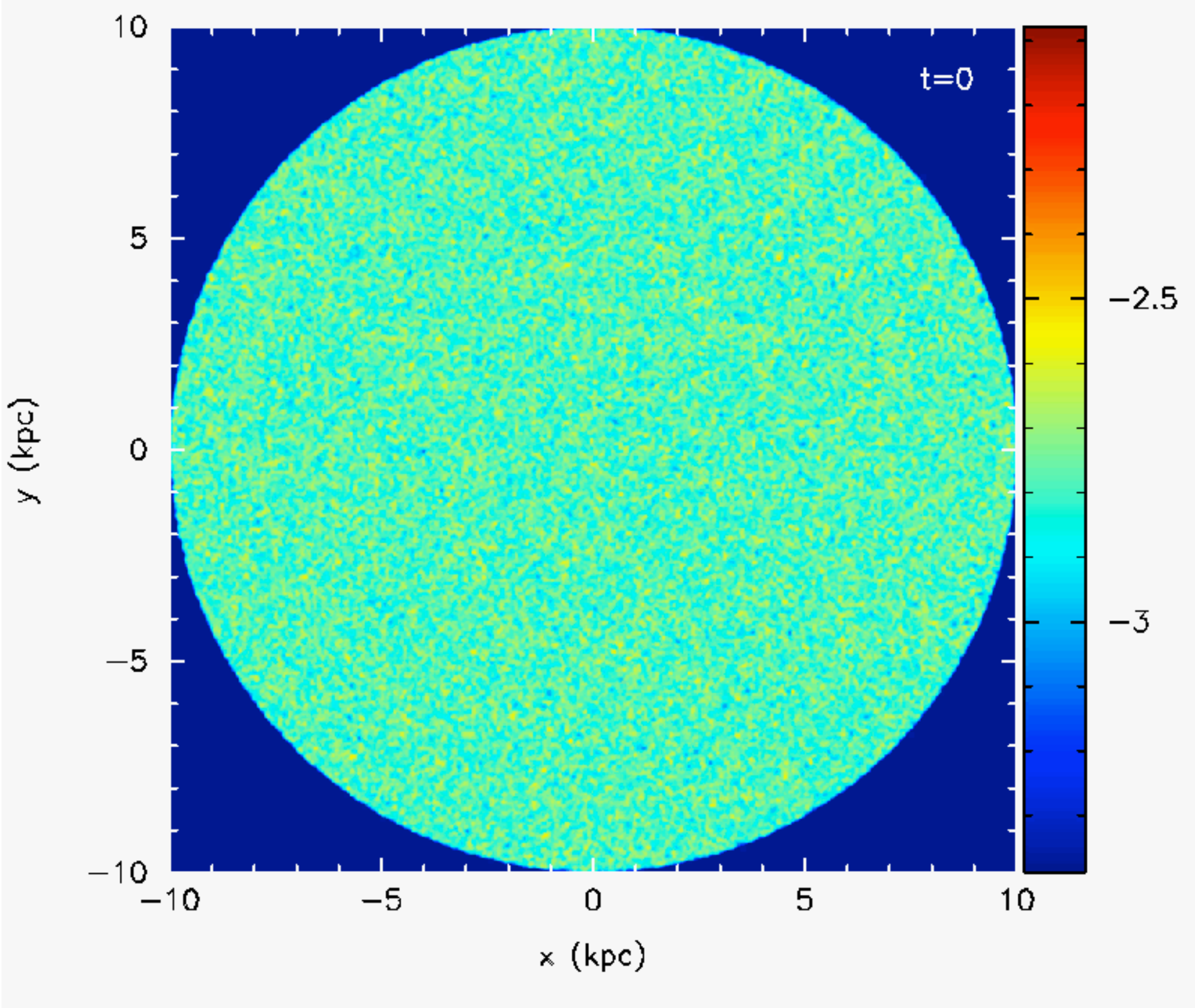
Dobbs, Burkert & Pringle 11a,b, 12a,b

Feedback puffs up disk

Filamentary interarm features (spurs)



Agertz



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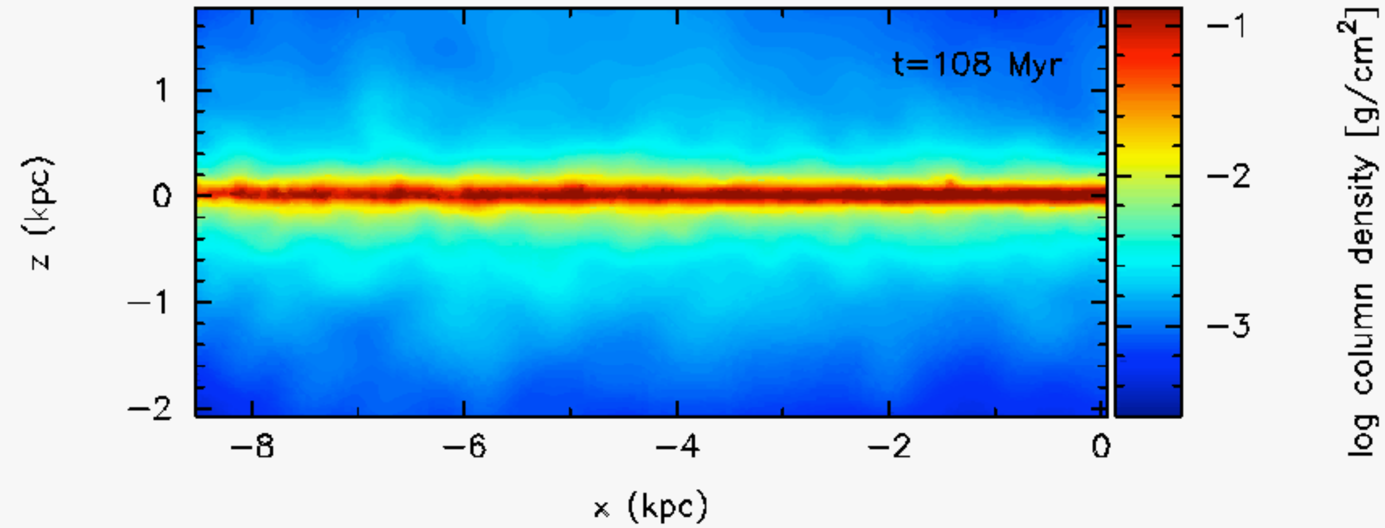

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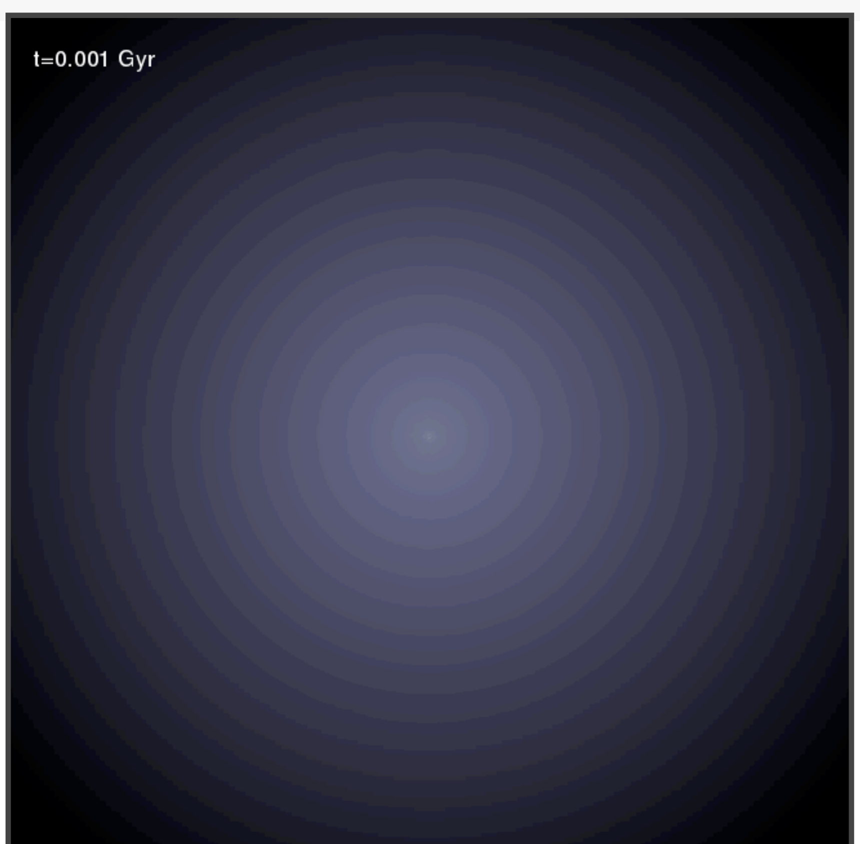
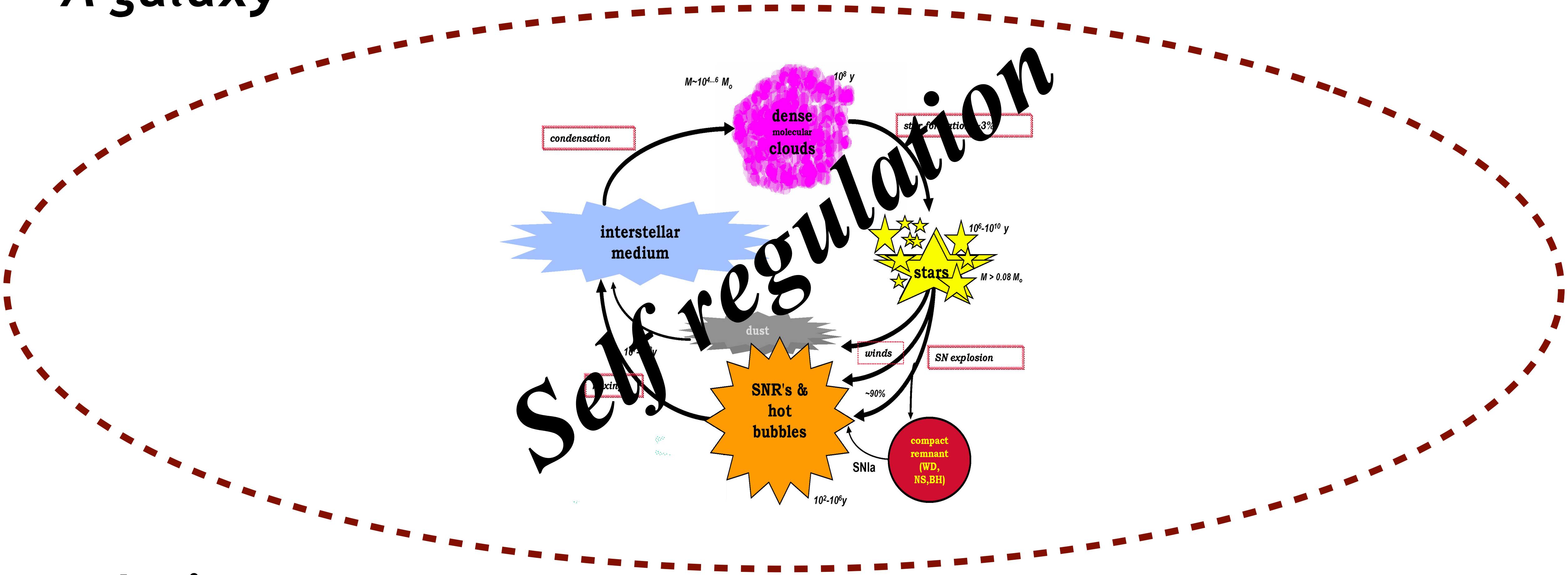


Agertz

The closed box model of self-regulated disk galaxy formation

(Wada+04; Dobbs+11a,b,12a,b; Bonnell+13; Brunner+13)

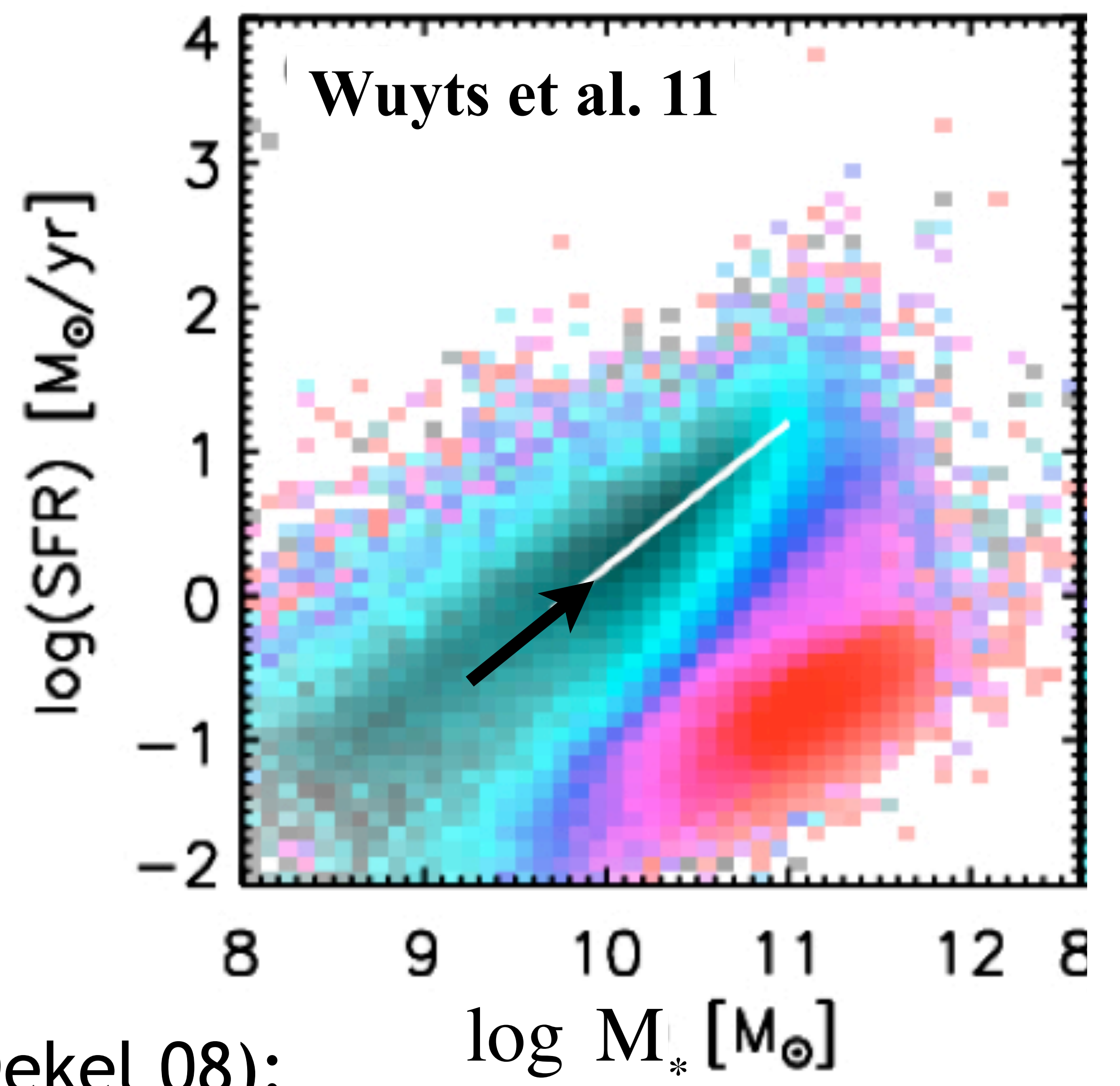
A galaxy



Evolution:

$$SFR(t) \downarrow \quad \text{and} \quad M_* \uparrow$$

The galaxy main sequence



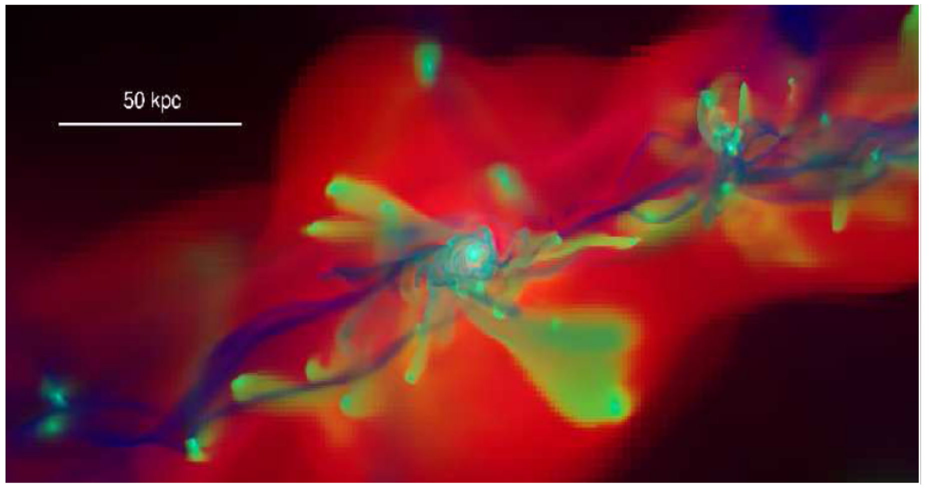
Galaxy main sequence (Noeske et al. 07; Daddi et al. 07, Peng et al. 10, Bouche et al. 10, Wuyts et al. 11):

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

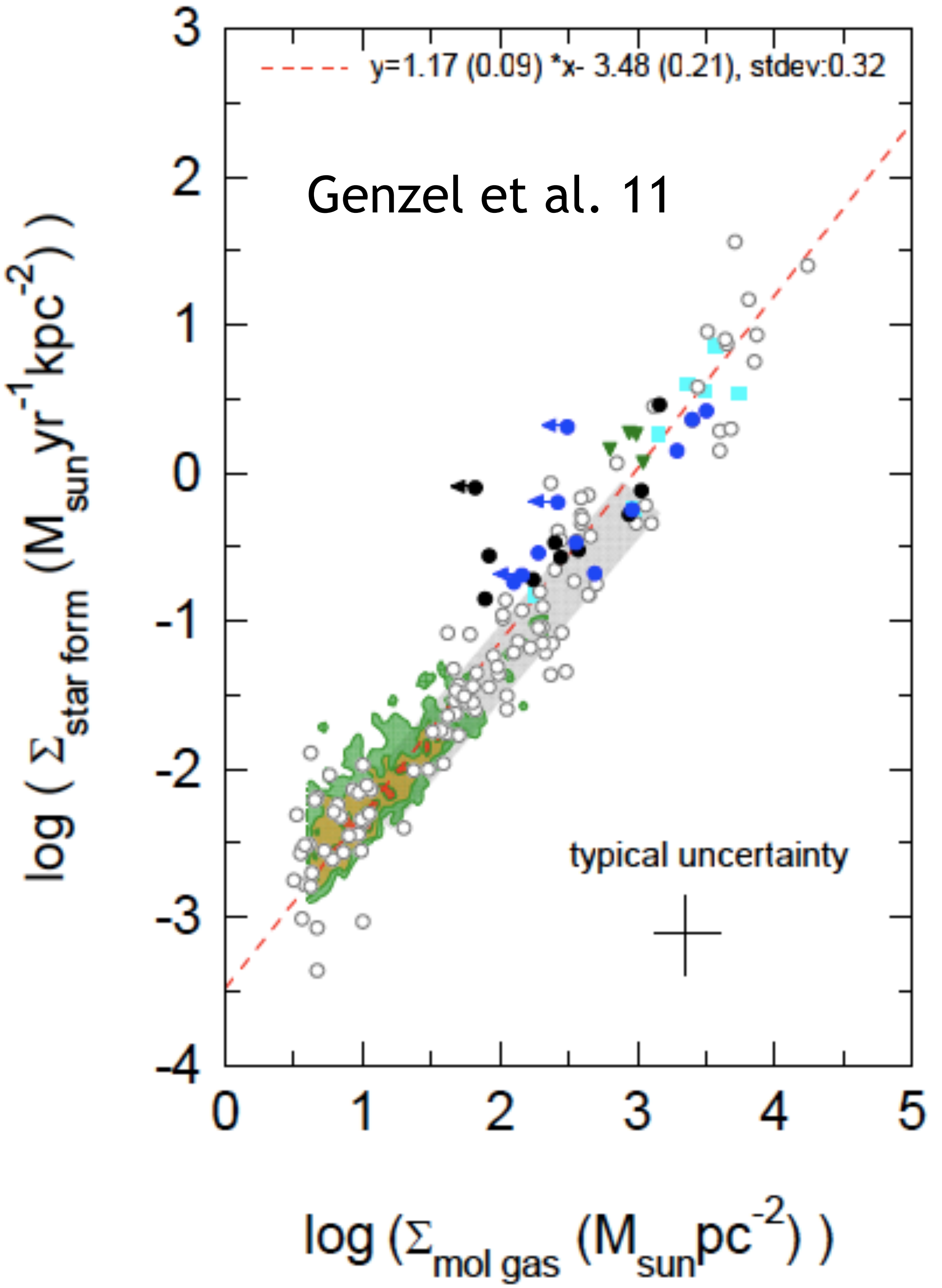
Cosmic baryonic **accretion rate** (Neistein & Dekel 08):

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

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



The universal gas depletion timescale



$$SFR = \frac{M_{H_2}}{\tau_{sf}} \text{ with } \tau_{sf} \approx 1 - 2 \cdot 10^9\, yrs$$

- Central limit theorem
- τ_{sf} is almost independent of redshift
- Gas depletion timescale **50 times** greater than local free-fall timescale.

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

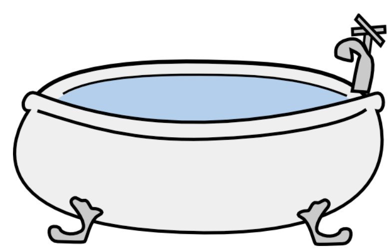
→ continuous replenishment

(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)

What determines SFR?

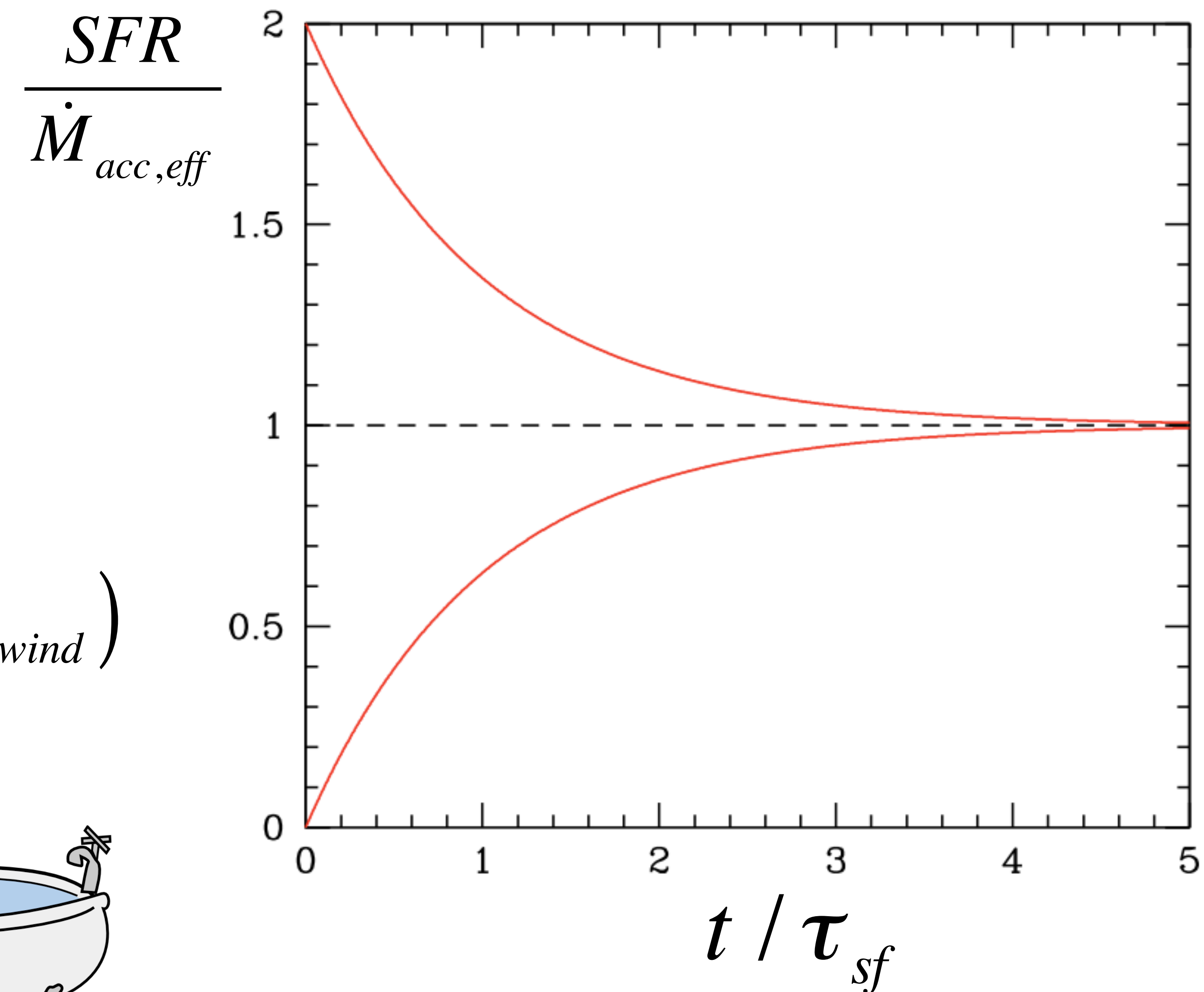
(Bouche et al. 10; Davé et al. 11a,b; Forbes et al. 13)

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



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

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



→ $SFR = \dot{M}_{acc,eff}$

- τ_{sf} **does not determine SFR**

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)

What's about the (molecular) gas mass?

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

Implications of the bathtub model

(Forbes+, astro-ph/1311.1509; Burkert+14)

$$M_g = SFR \cdot \tau_{sf} \sim M_* \cdot \tau_{sf} \longrightarrow$$

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$$\tau_{sf} \sim \frac{M_g}{M_*}$$

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$$\boxed{\tau_{sf} \approx 3Gyr(1+z)^{-1}\left(\frac{M_{vir}}{10^{12}M_\odot}\right)^{-0.5}}$$

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?

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$$Z_g = y \frac{R}{\alpha_{wind} + R} \longrightarrow \alpha_{wind} = \left(\frac{M_{vir}}{10^{12} M_\odot} \right)^{-2/3}$$

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?

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

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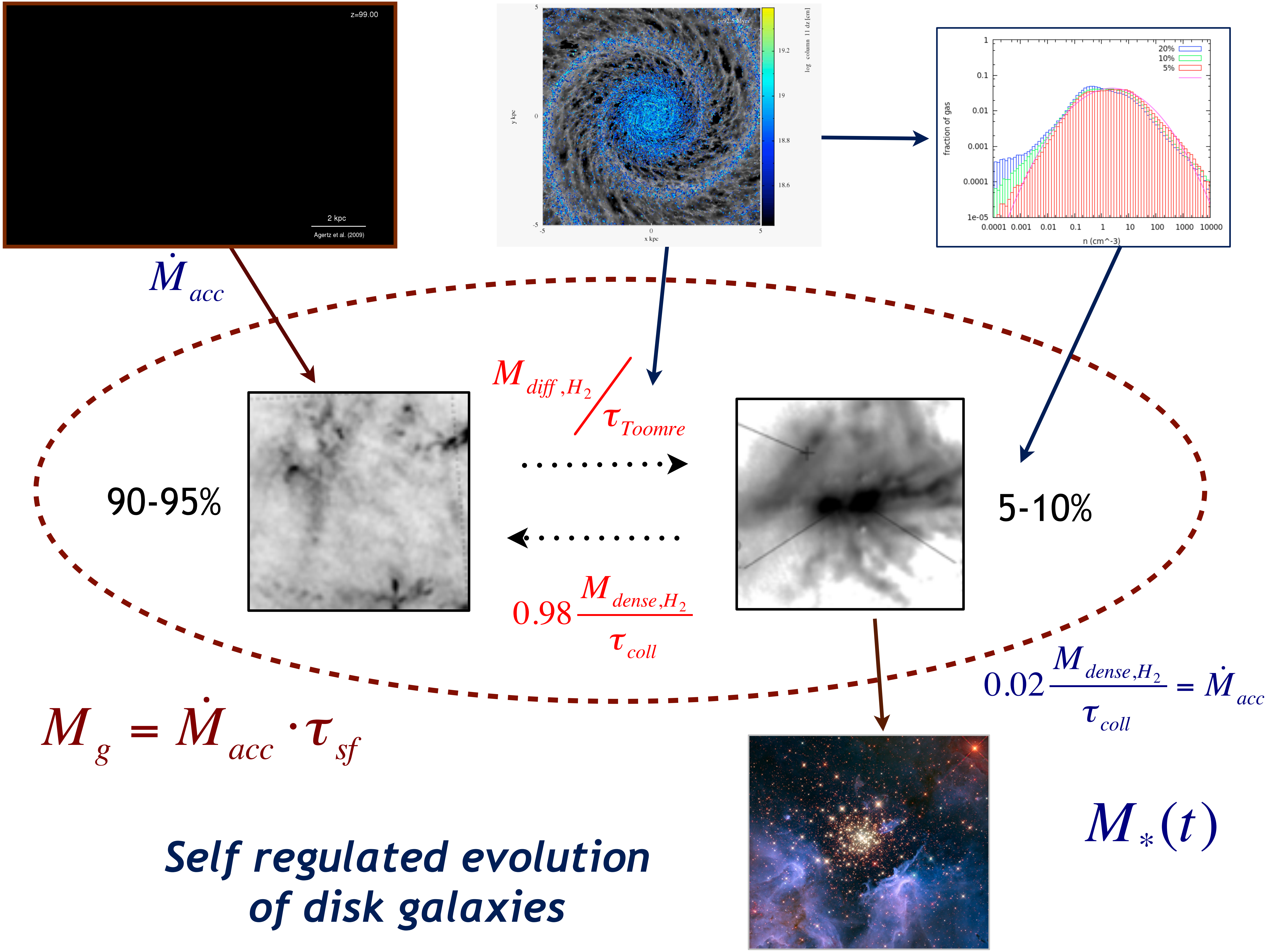
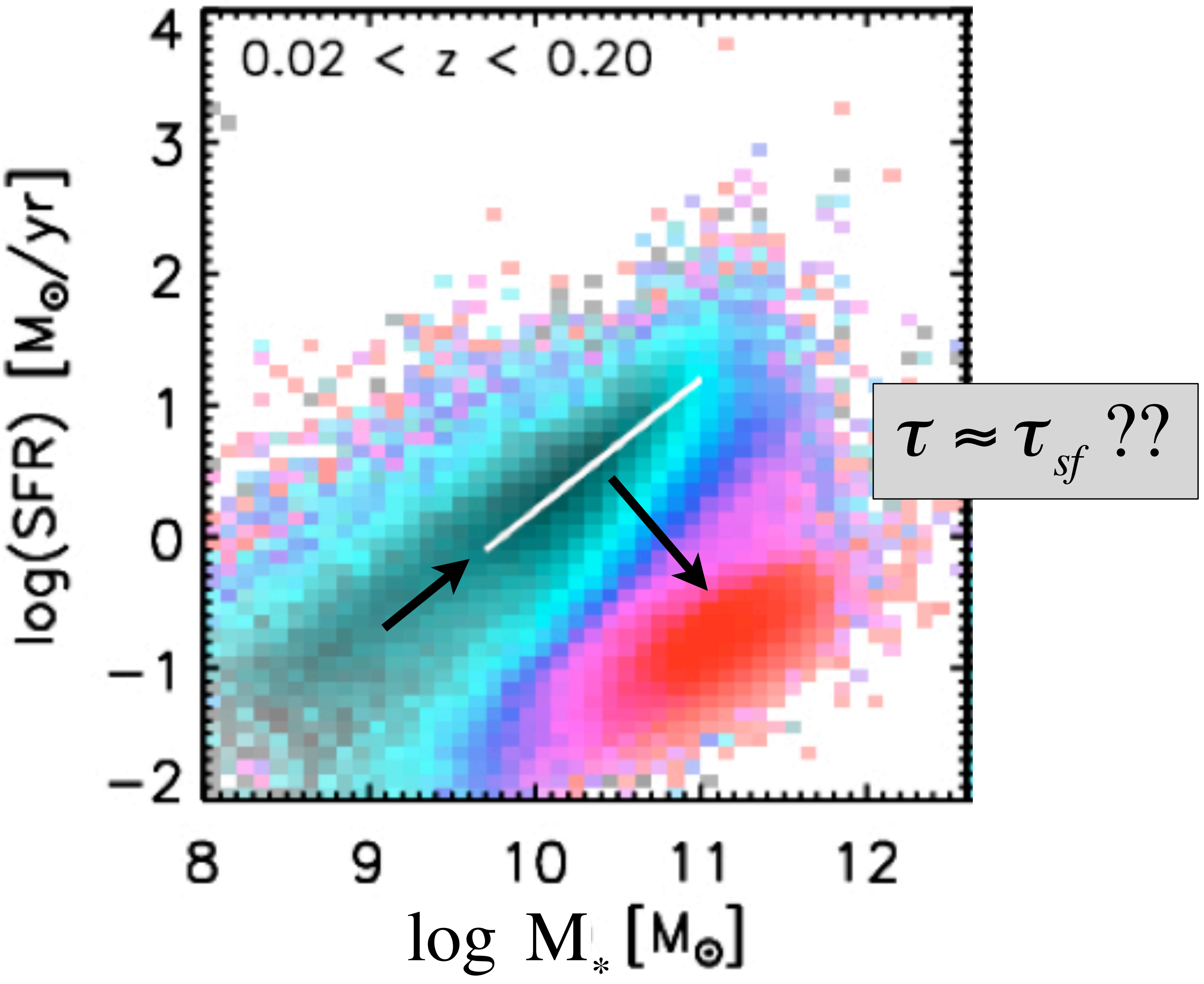
This is consistent with recent models of **cosmic-ray driven** galactic winds (Wadepuhl&Springel 11; Salem&Bryan 13, Booth+13)



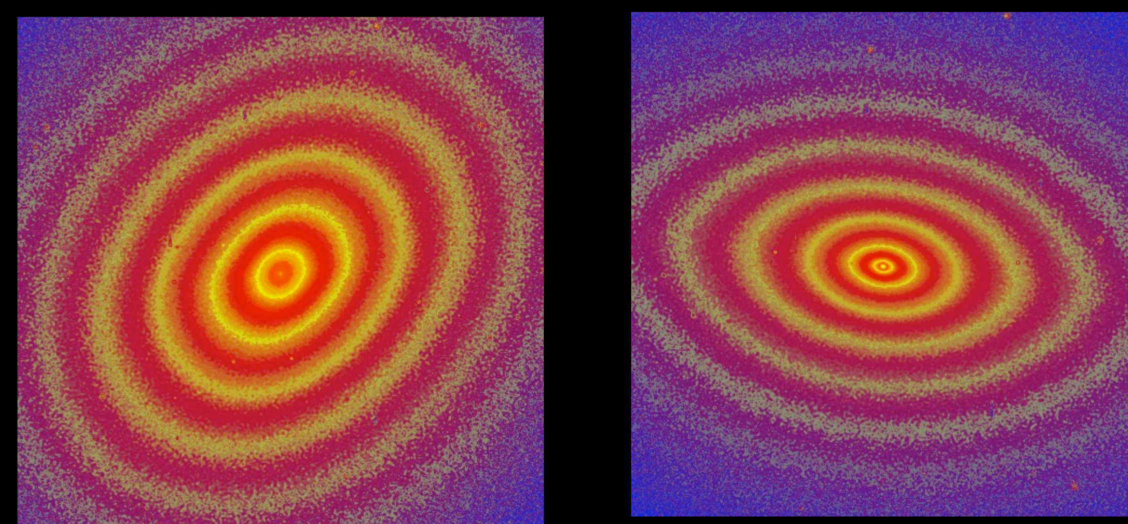
z=99.00
2 kpc
Agertz et al. (2009)
x kpc
y kpc
fraction of gas
n (cm^-3)
20%
10%
5%
$\dot{M}_{acc}$
$M_{diff,H_2} / \tau_{Toomre}$
90-95%
5-10%
$0.98 \frac{M_{dense,H_2}}{\tau_{coll}}$
$0.02 \frac{M_{dense,H_2}}{\tau_{coll}} = \dot{M}_{acc}$
$M_g = \dot{M}_{acc} \cdot \tau_{sf}$
$M_*(t)$
Self regulated evolution
of disk galaxies

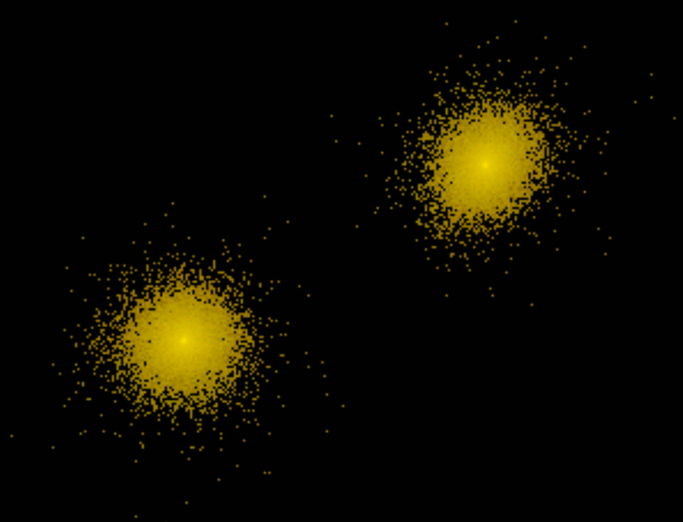
Evolution off the galaxy main sequence and the formation of red and dead galaxies



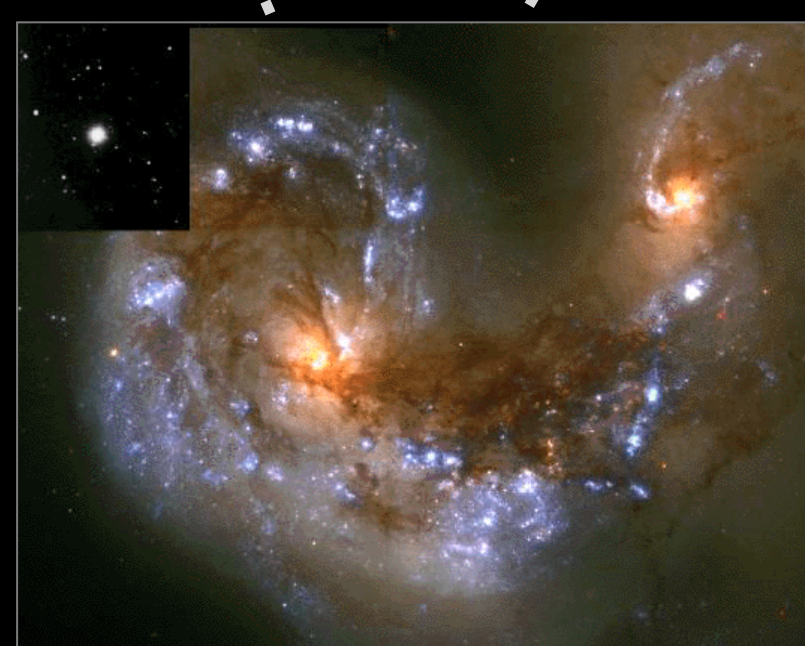
Major mergers clearly happen

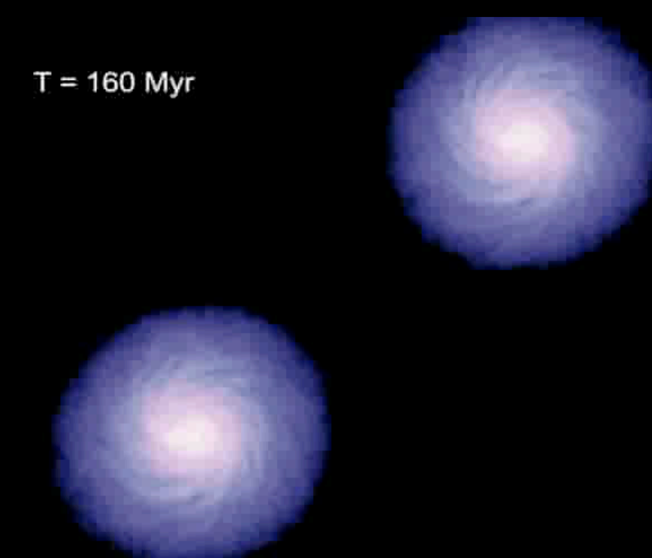
(e.g. Hopkins+ 03-11; Naab+ 03-11, Johansson+09-11; Remus+12, see poster by Schauer+13)





(Naab)





(Springel)

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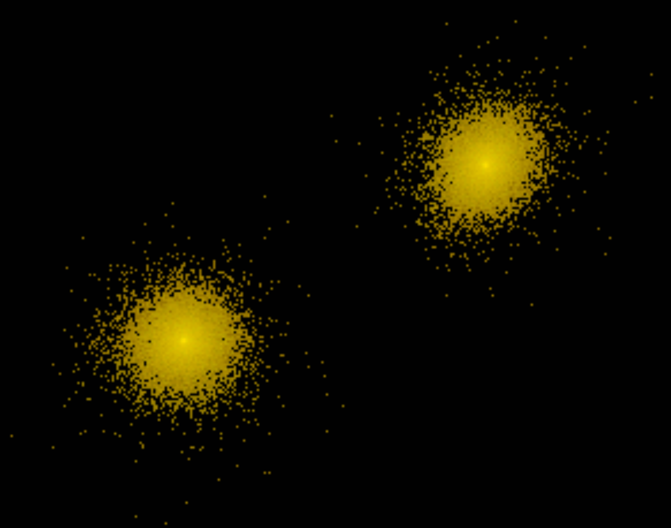
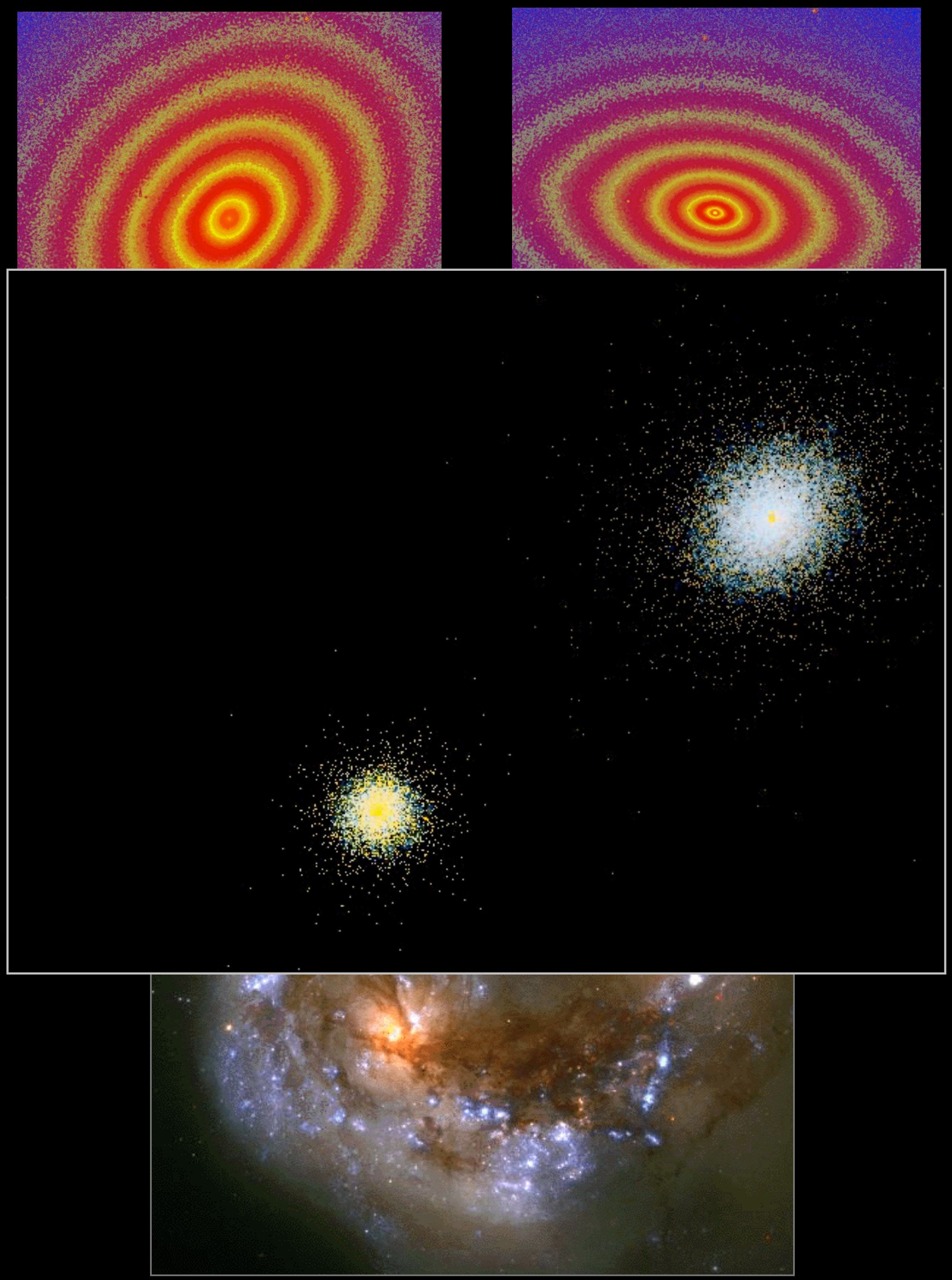


(Naab)



T = 160 Myr

(Springel)

Disks can sometimes be quite robust

Teyssier 08

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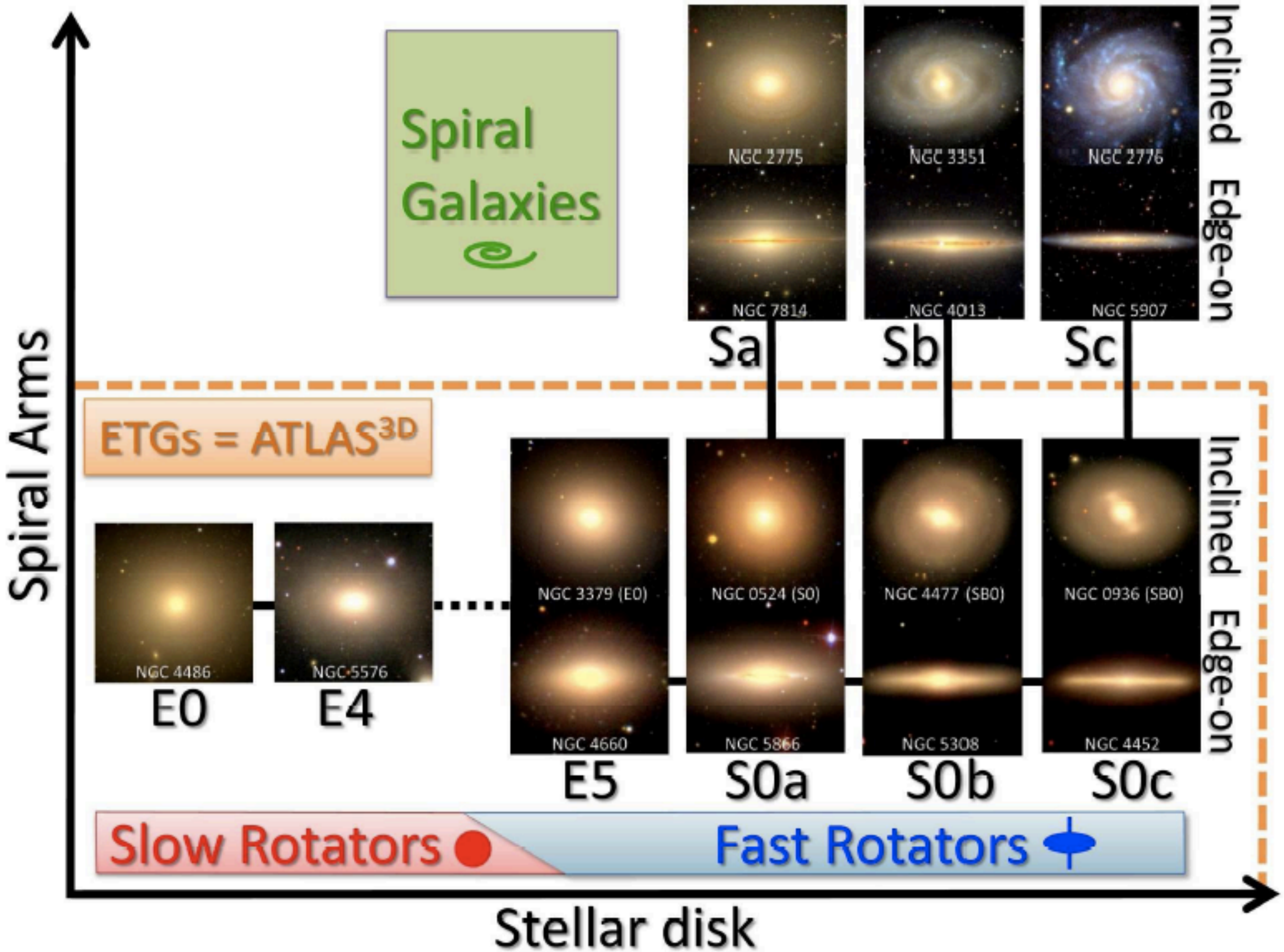
Teyssier 08

Cappellari+11,13



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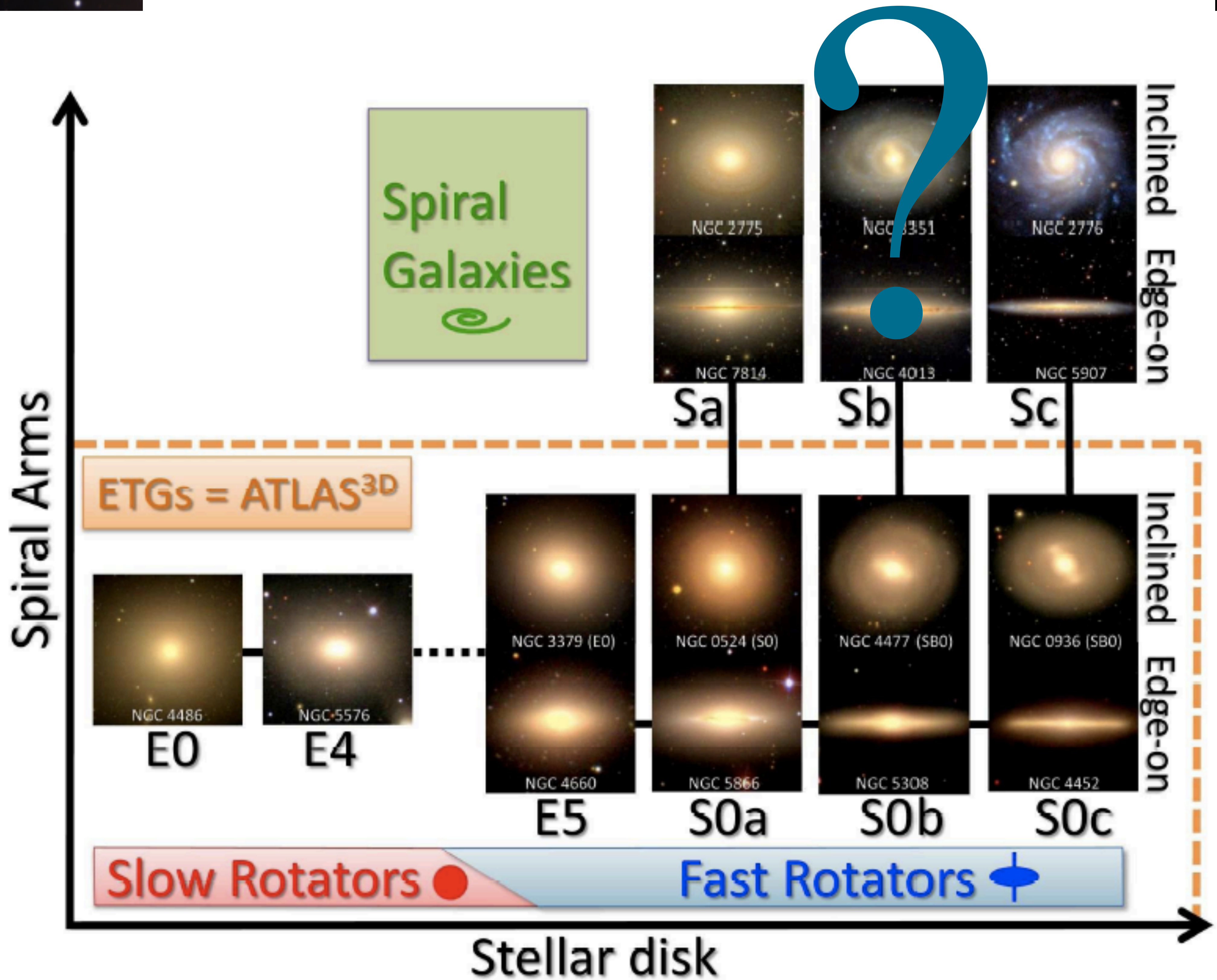

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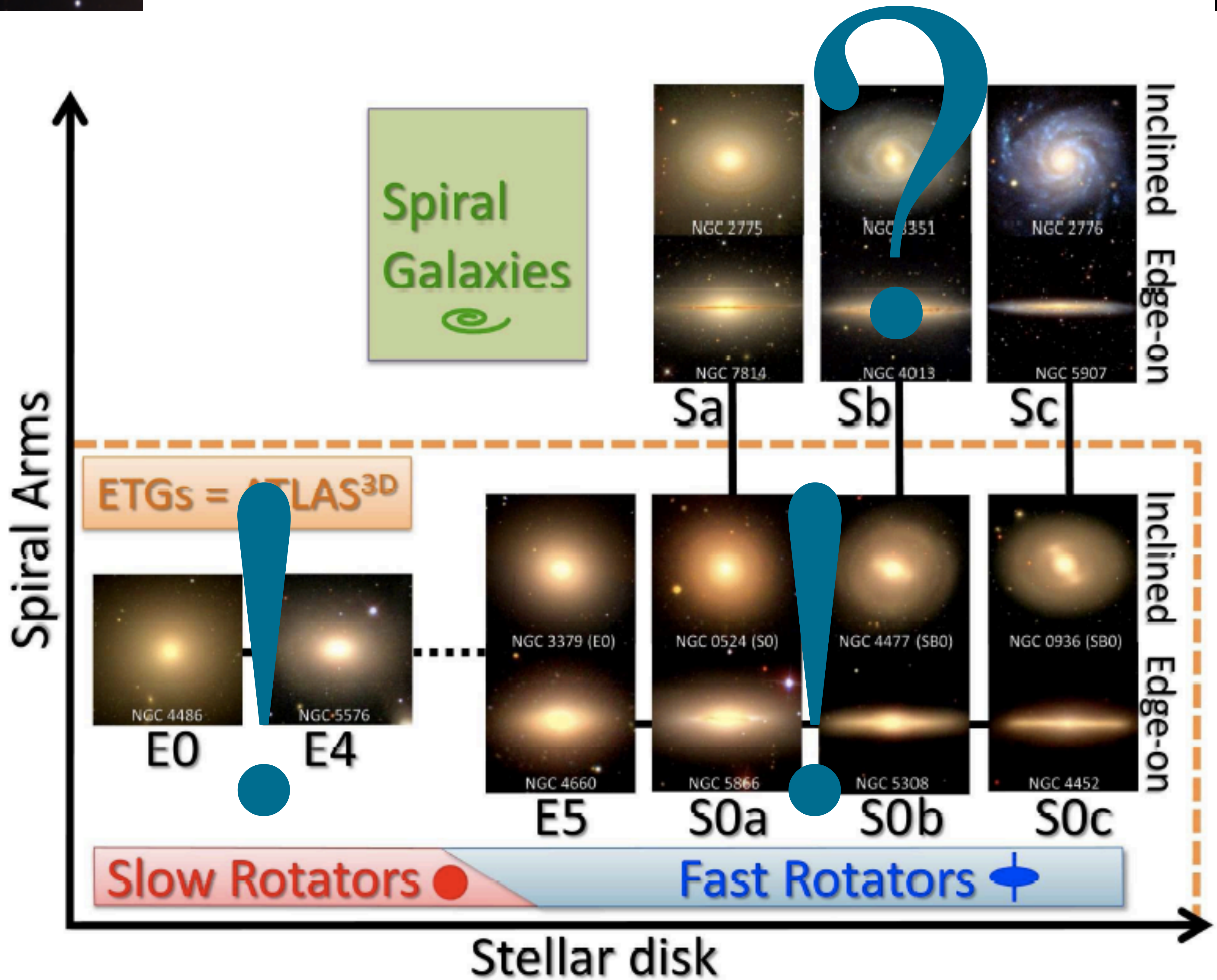
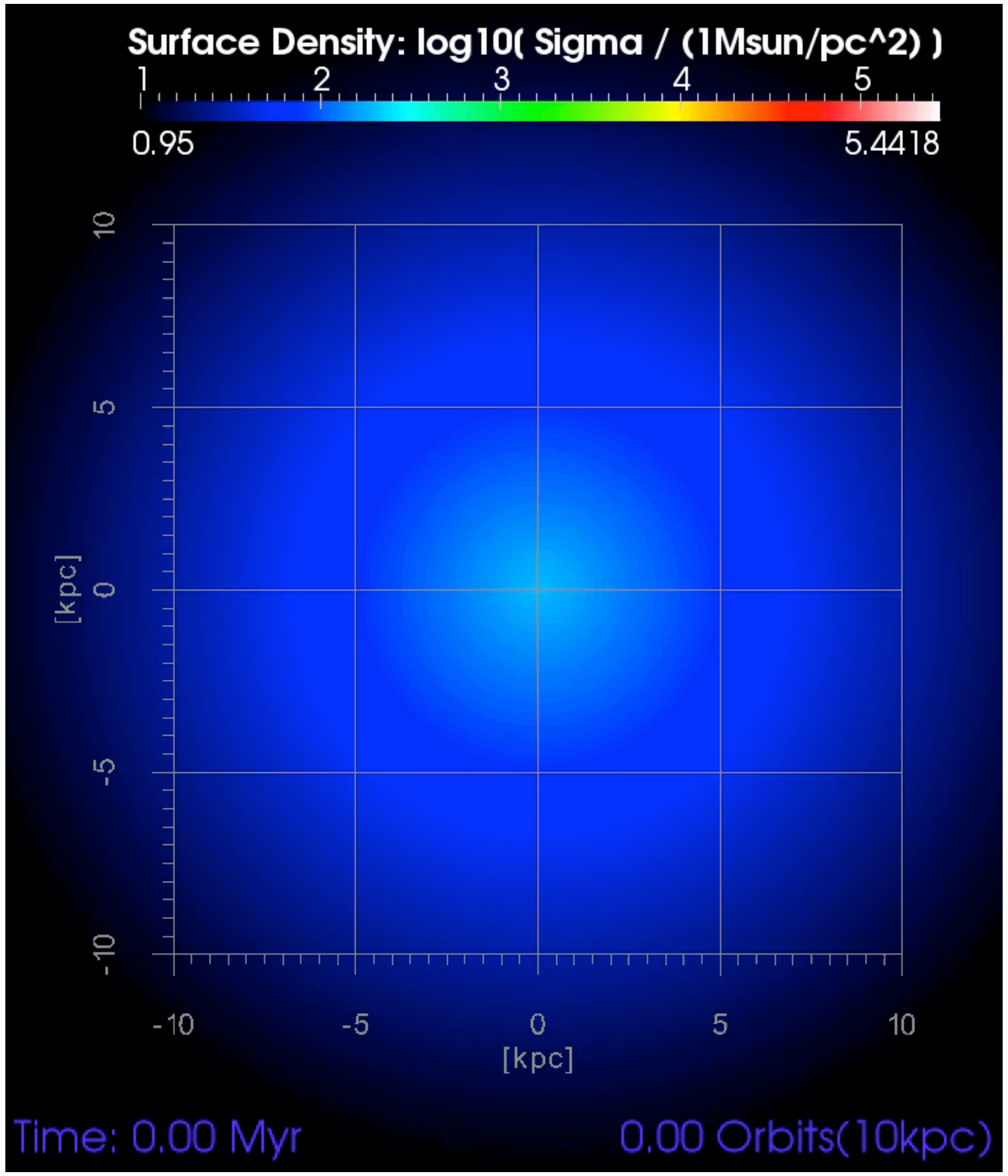


Connecting high-z and low-z

- High-z **compact ellipticals** are **flattened** and **disky** (Bezanson+09,van der Wel+11, 13; Chang+ 13)
- They might have formed from extended high-z massive gas disks, going through **violent disk instability** (Dekel & Burkert, astro-ph/1310.1074)

Behrendt+13



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$$Q = 1 \rightarrow \sigma = \delta_g \cdot v_{rot}$$

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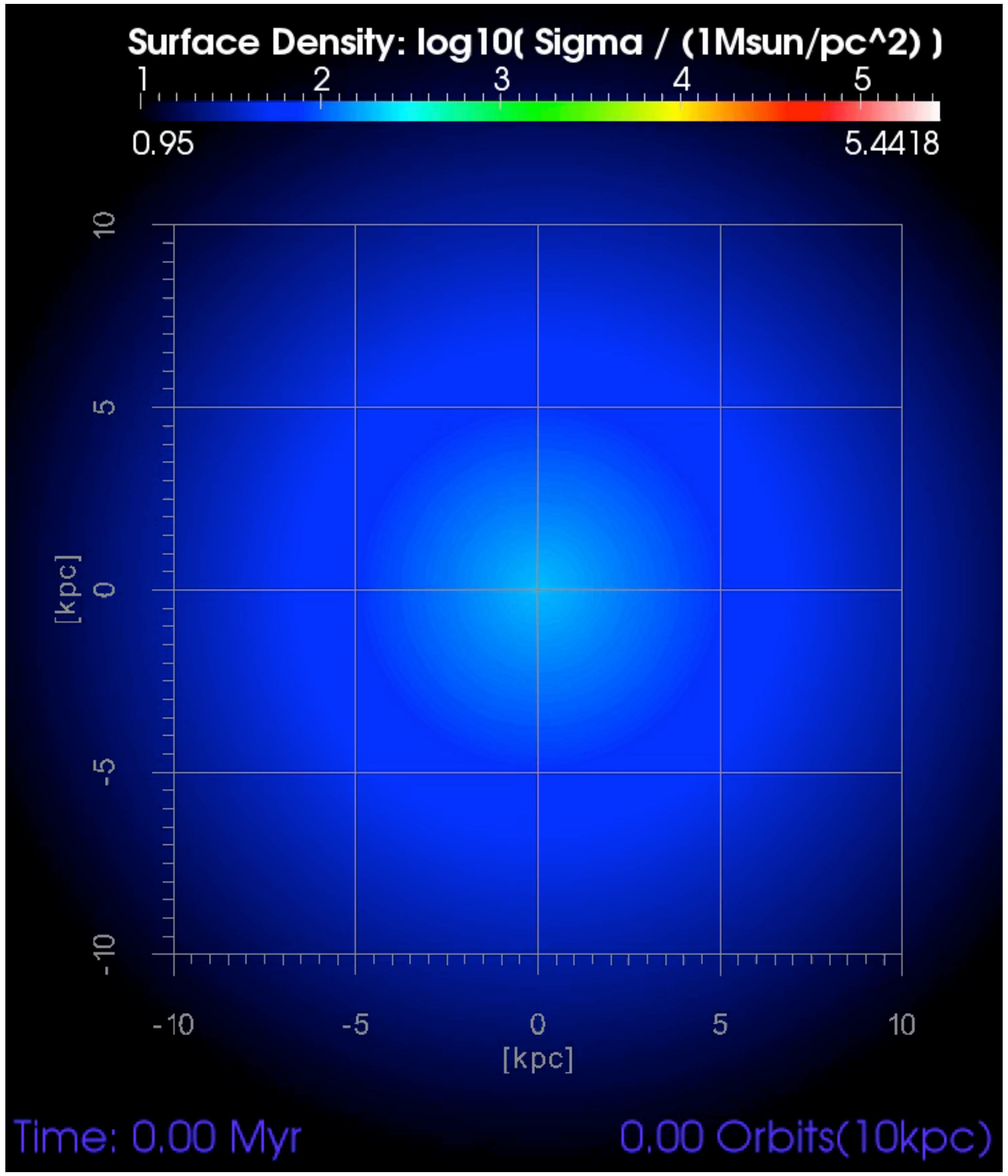

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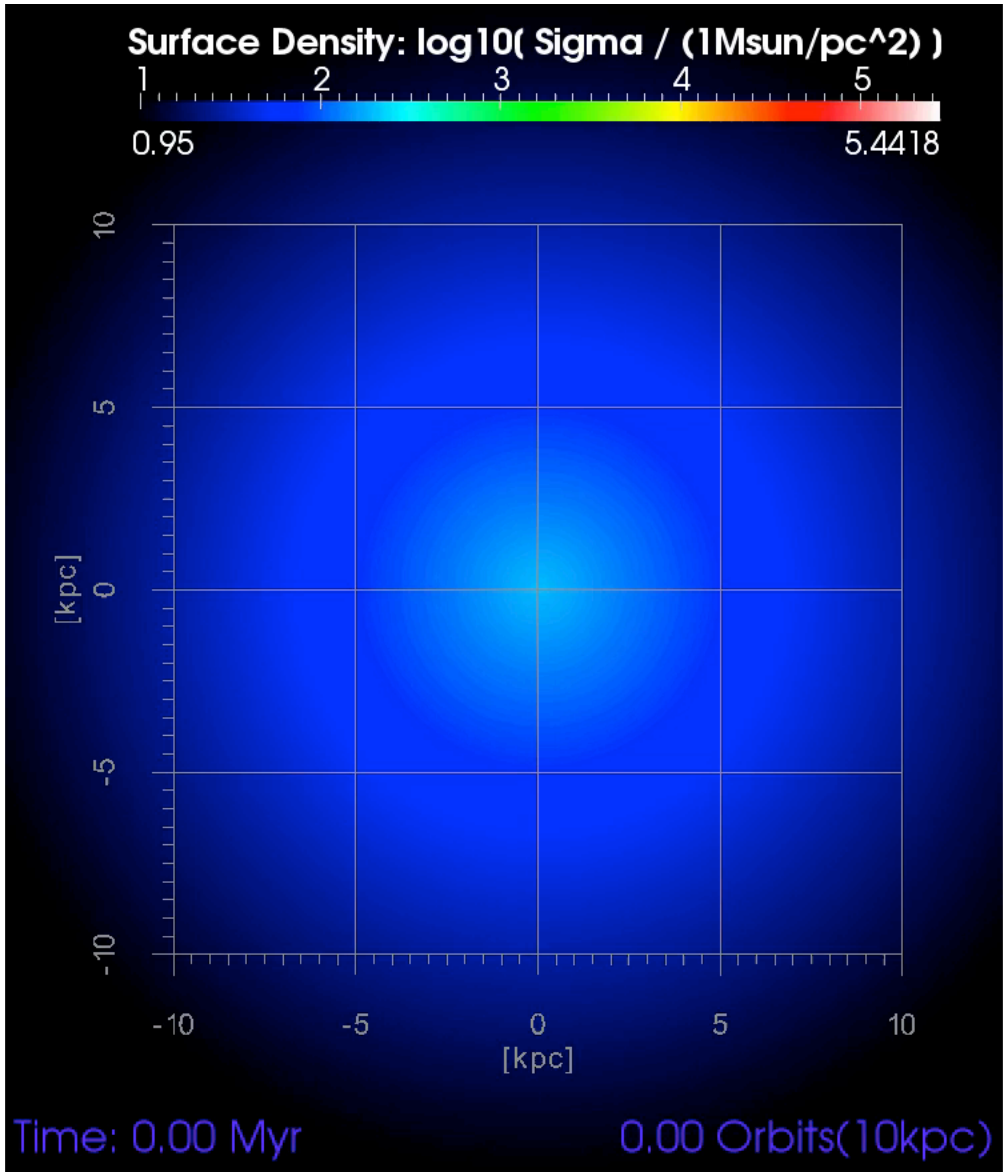

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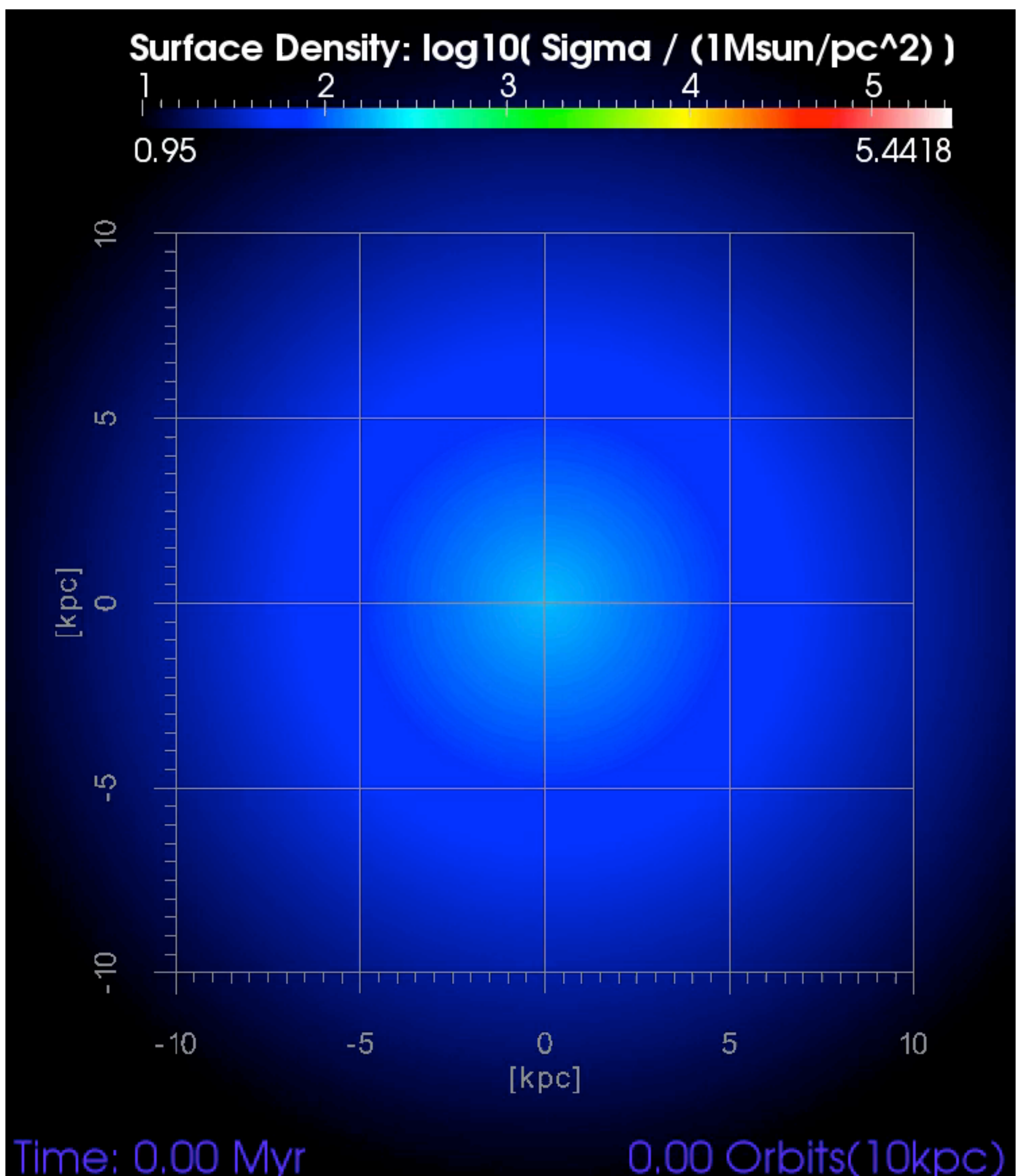

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VDI: (Dekel&Burkert 13)

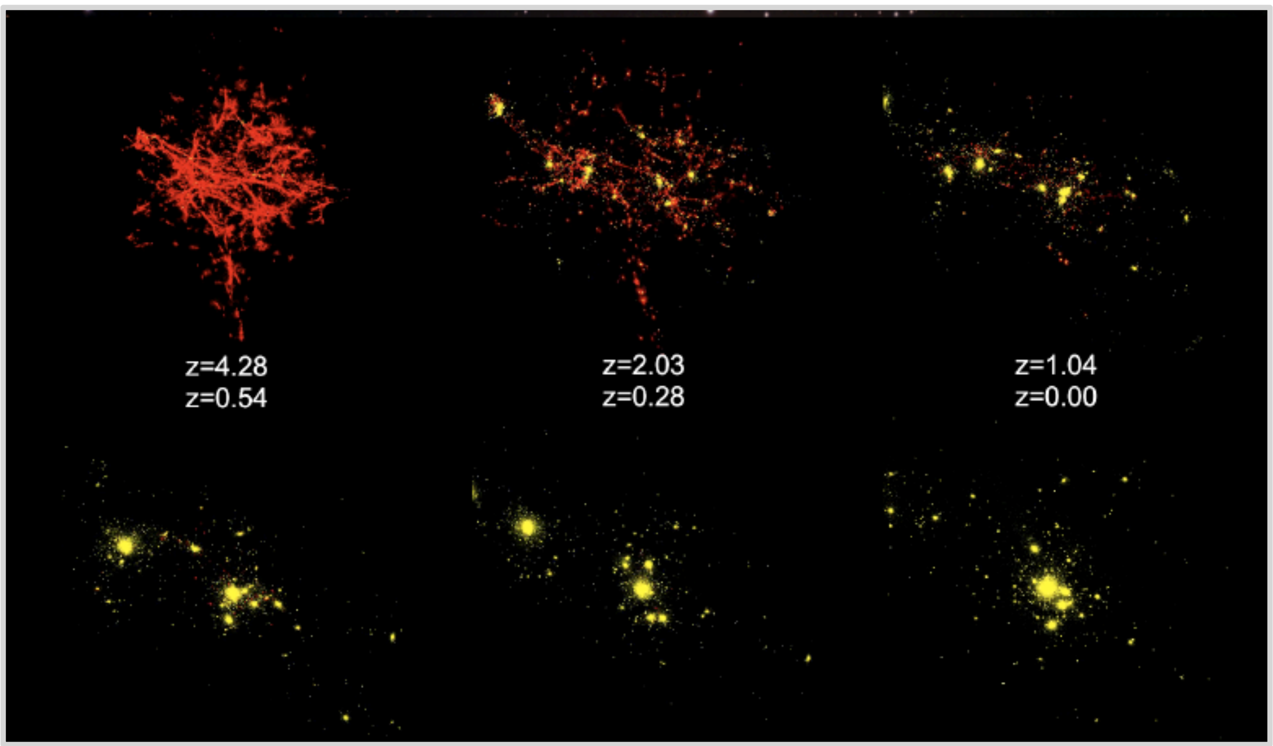
$$\tau_{sf} < \tau_{\text{inflow}} \rightarrow \lambda_{disk} \leq 0.05$$

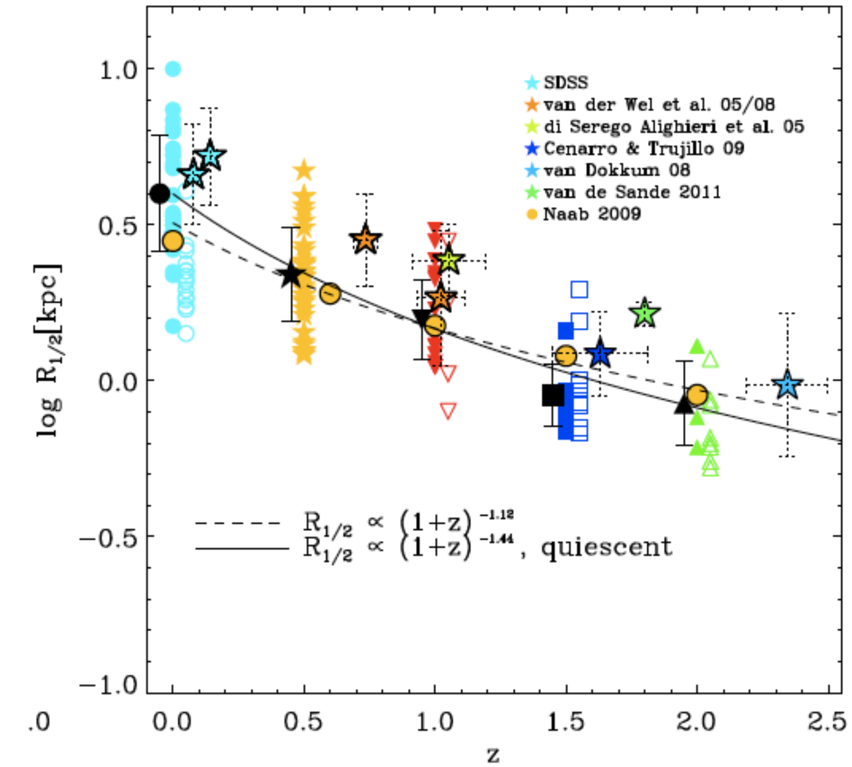
Oser 10,12

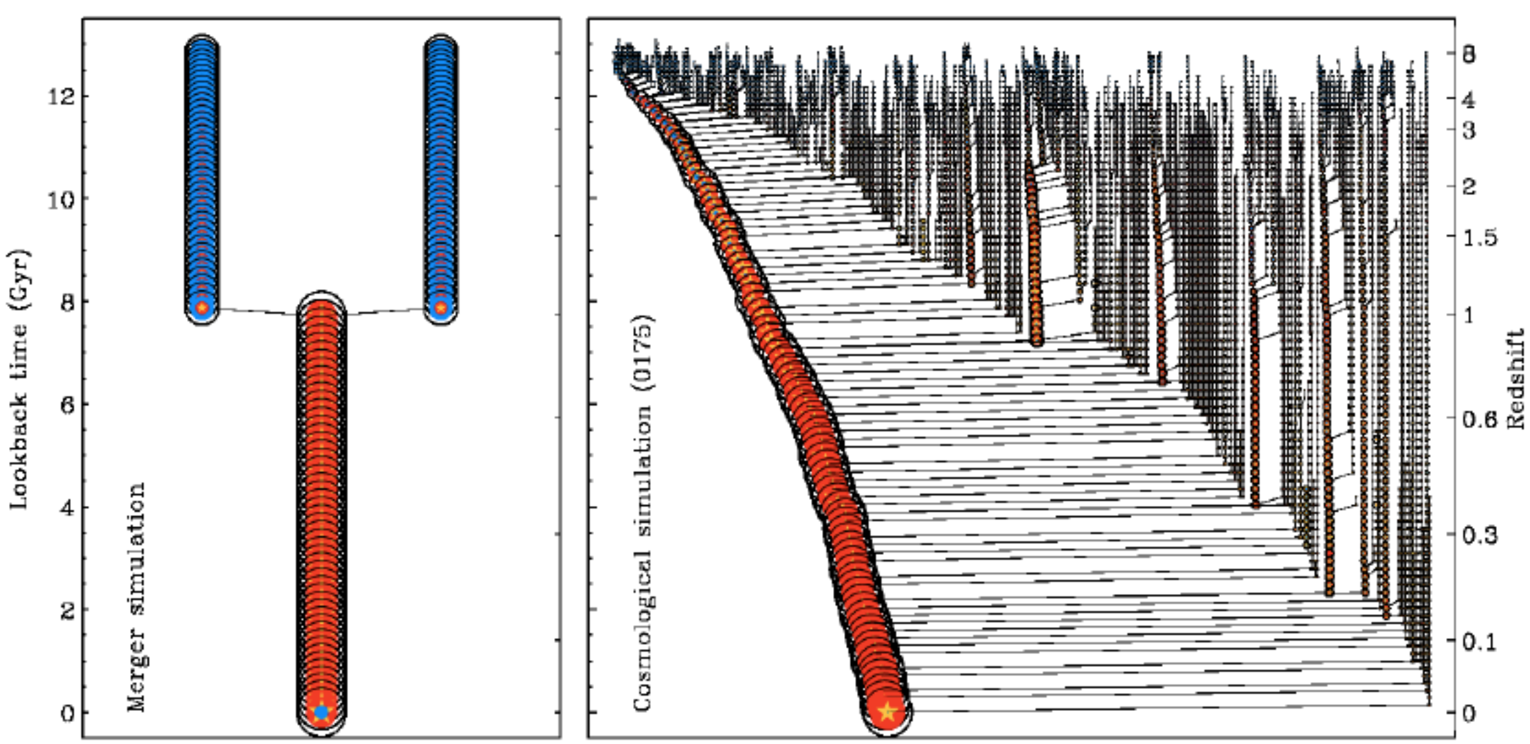
Oser 10,12

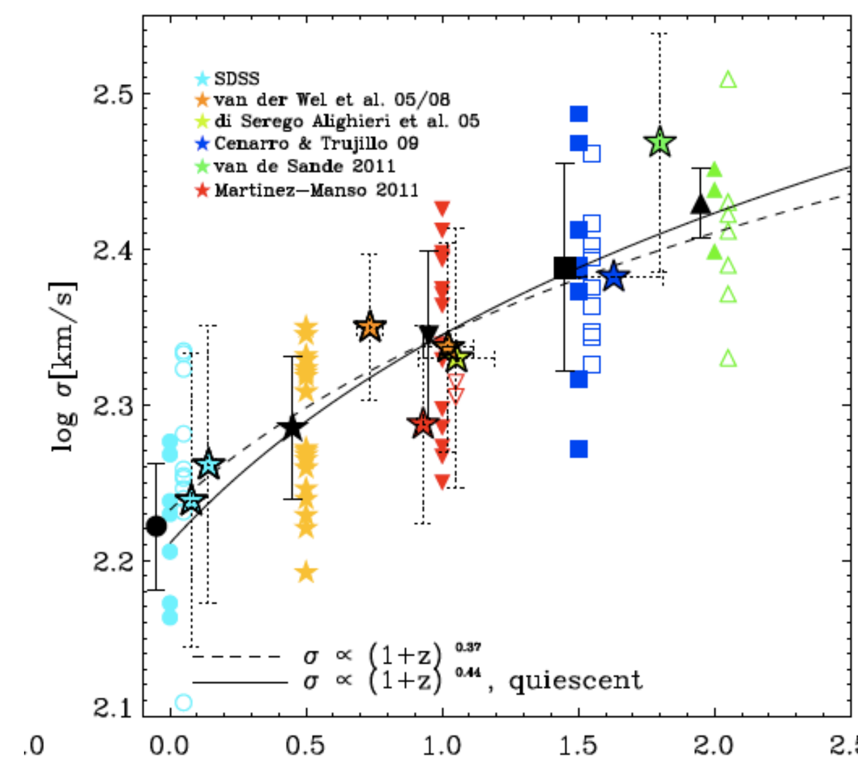
The evolution of massive ellipticals

(de Lucia+06; Oser+10,12; Johansson+09,12; Hirschmann+12; Hilz+12.13; Naab+07, 09,13; see however e.g. Gallego+12; Posti+13)









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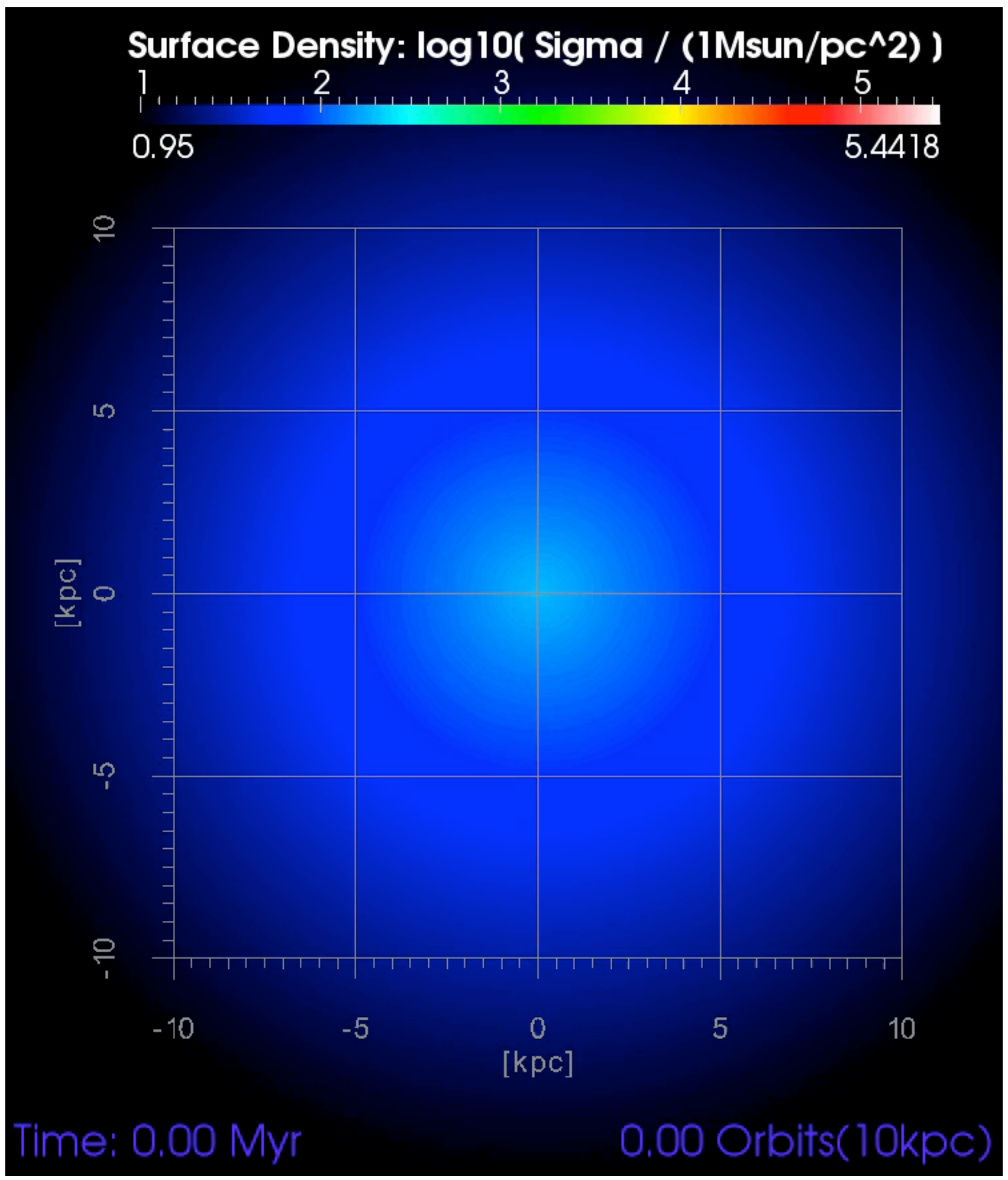
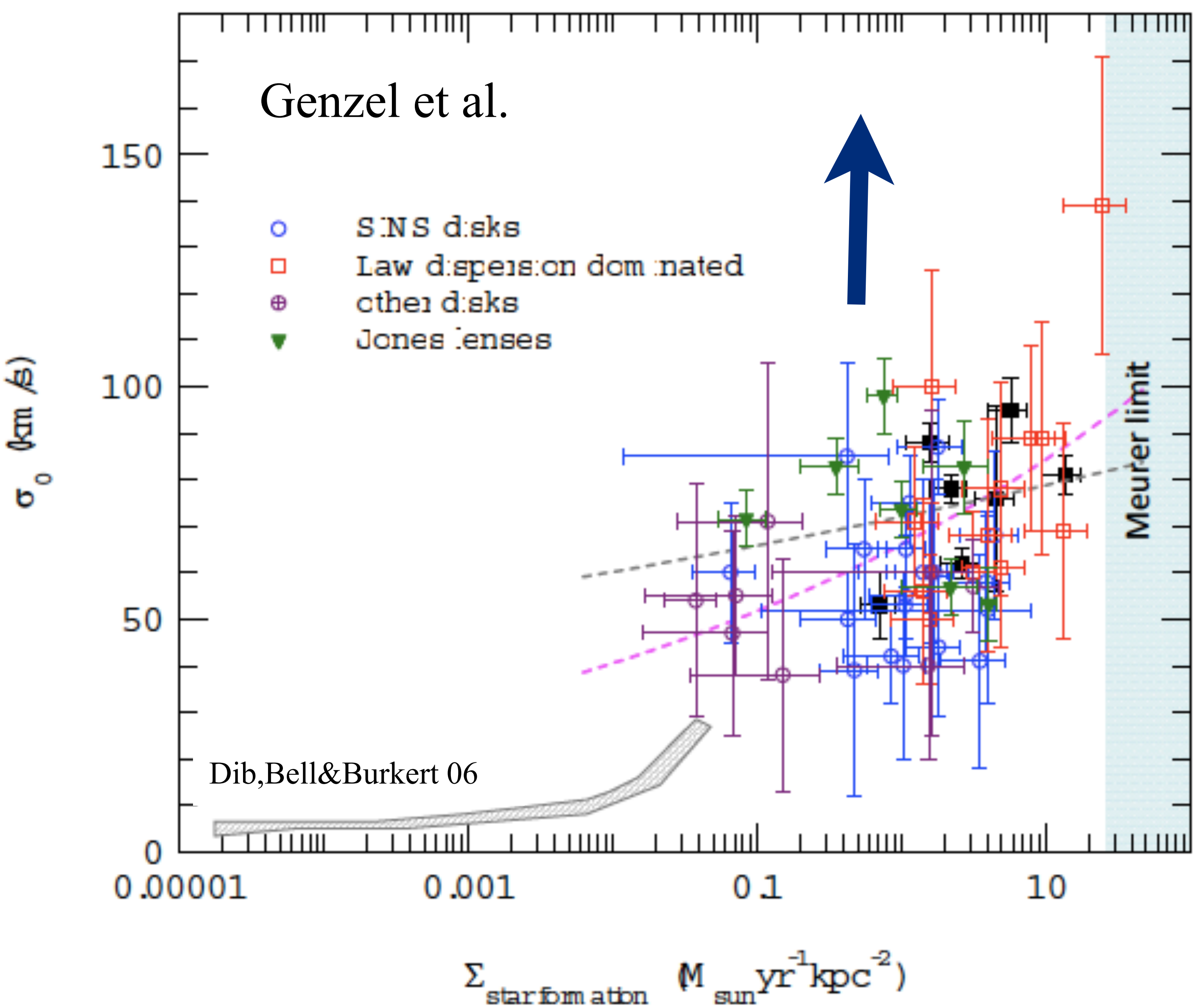
- High-z disks that did not experience VDI form **fast rotating Es.**

Behrendt+13





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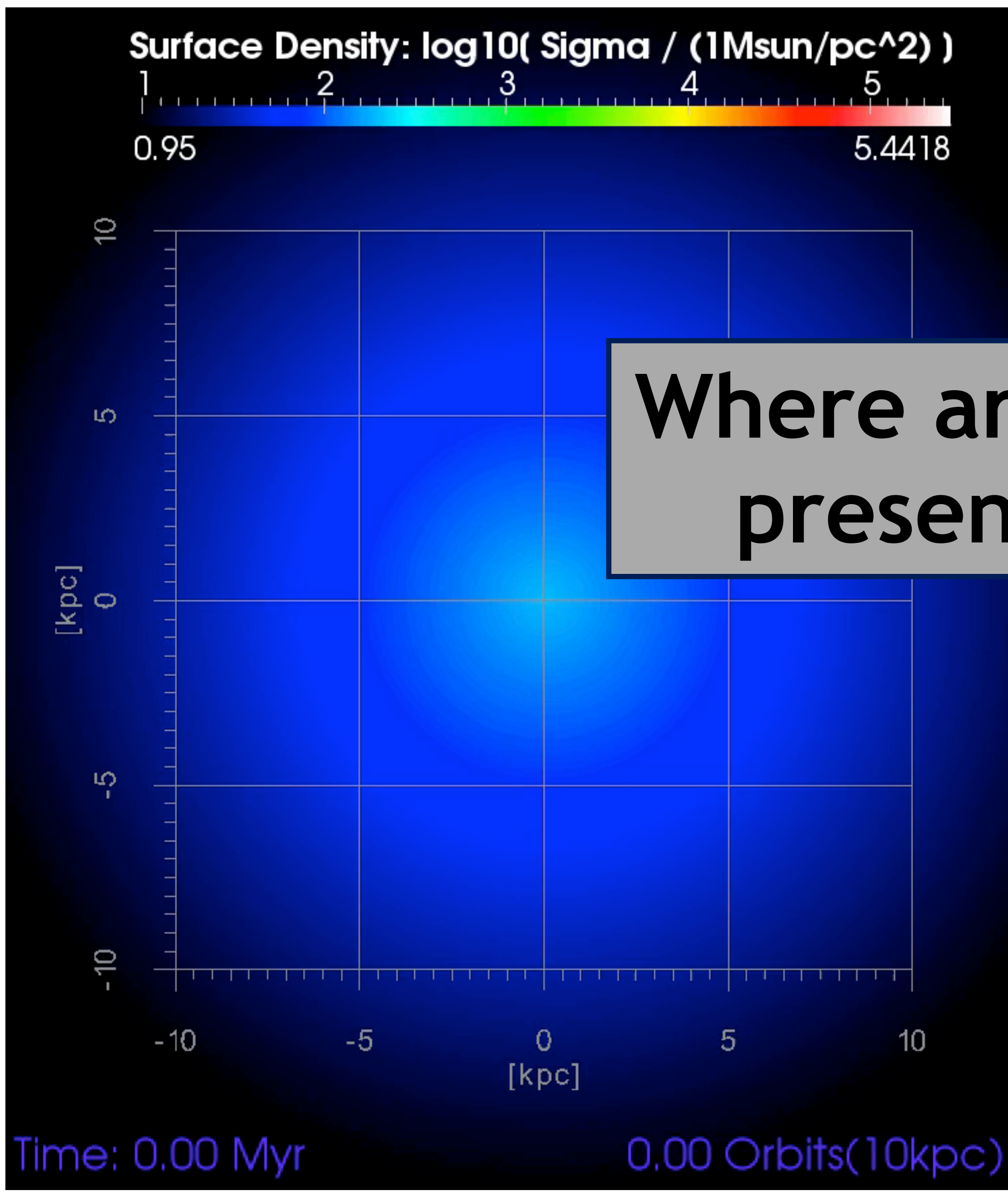

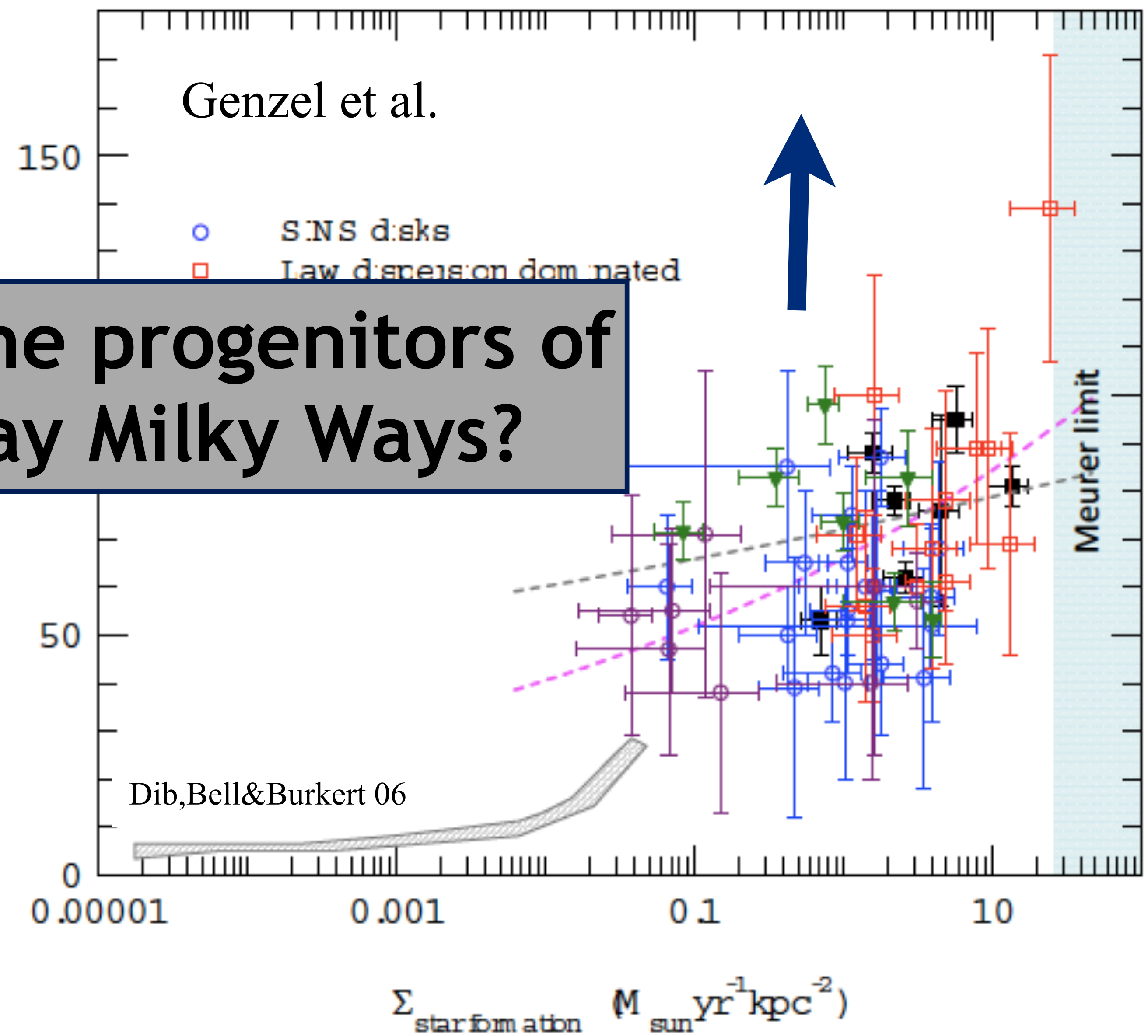

Where are the progenitors of present-day Milky Ways?

Galaxy formation is a boundary condition problem

- *Self-regulated disk evolution versus VDIs*
- *Depletion versus accretion timescale*
- *In situ versus ex-situ star formation*
- *Major versus minor mergers*