Unveiling the Role of Galactic Rotation on Star Formation

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How galaxies form stars

Motivation

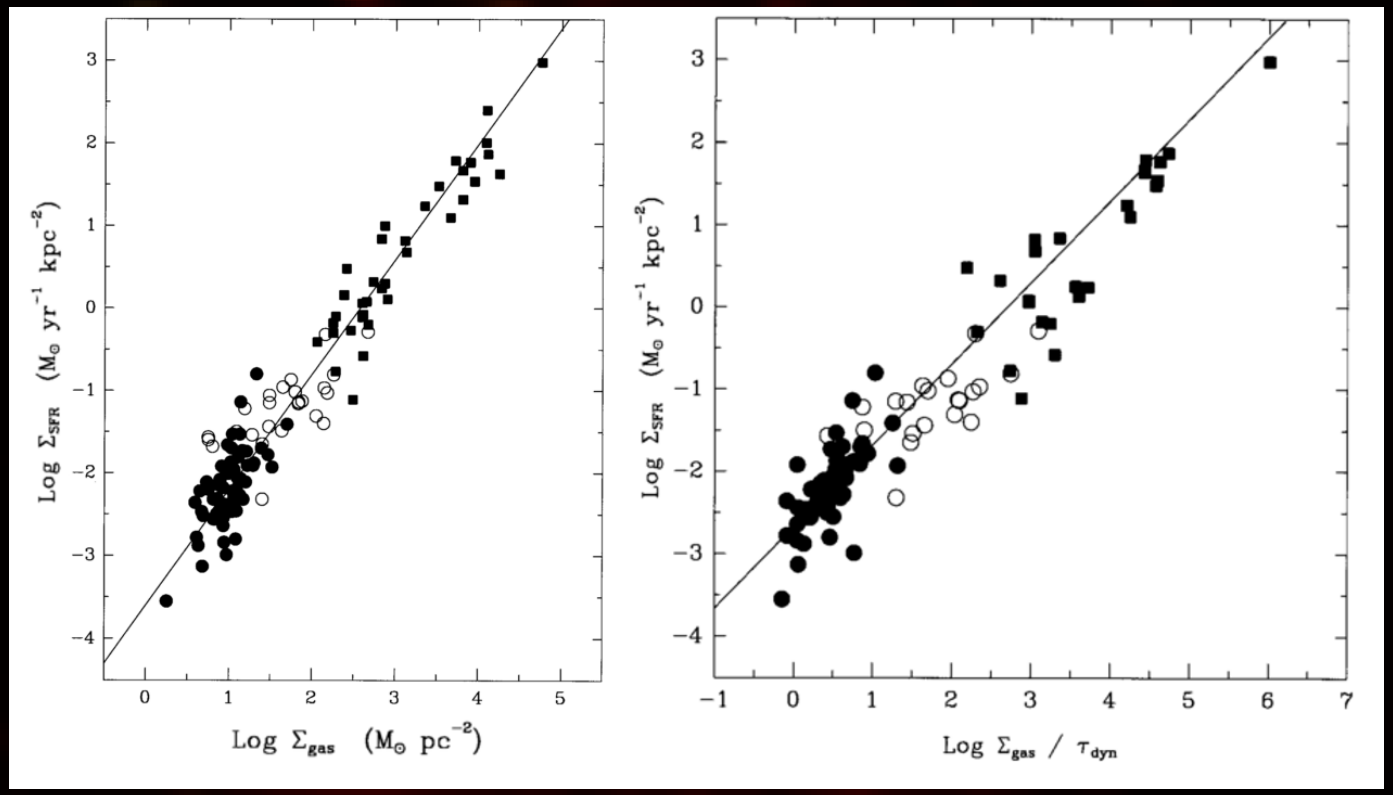
Knowing how efficiently stars are formed in galaxies is fundamental to understand the evolution of our universe.

Wide range of spatial and temporal scales combined with a large number of physical processes

$$\mathrm{SFR} = f(M_{\mathrm{gas}}, \Omega, c_s, v_{\mathrm{turb}}, ...)$$

Star Formation ~~Laws~~ Relations

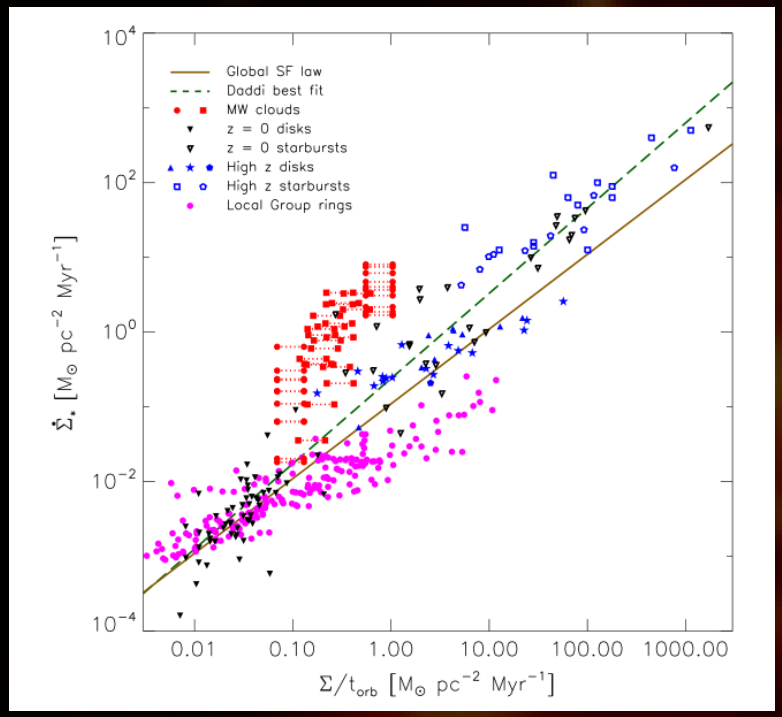
Kennicutt 1998

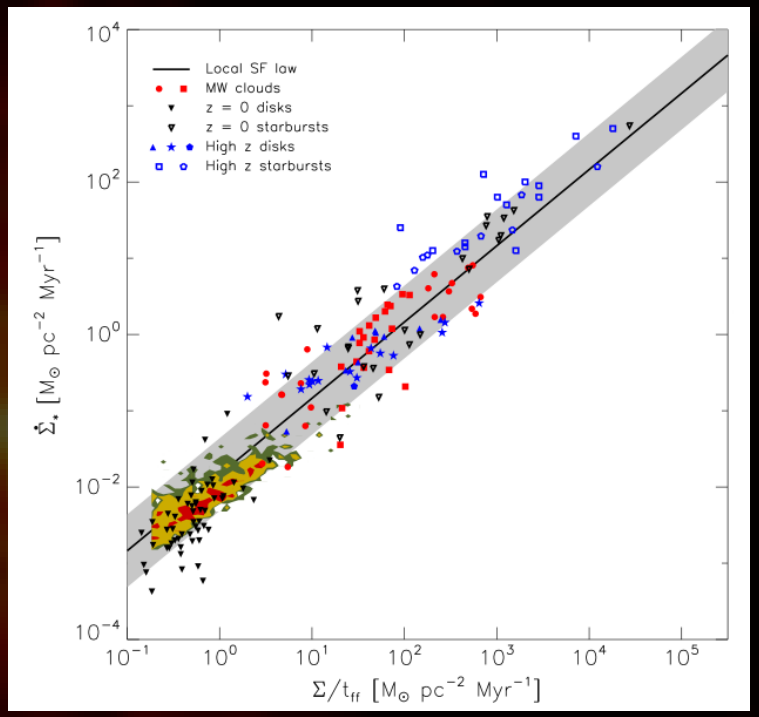


1. Kennicutt-Schmidt $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{1.4}$ ($\propto \Sigma_{\rm gas}/t_{\rm ff}$?)
2. Silk-Elmegreen $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}/t_{\rm orb}$

Universal Star Formation Relations?

Krumholz et al. (2012)



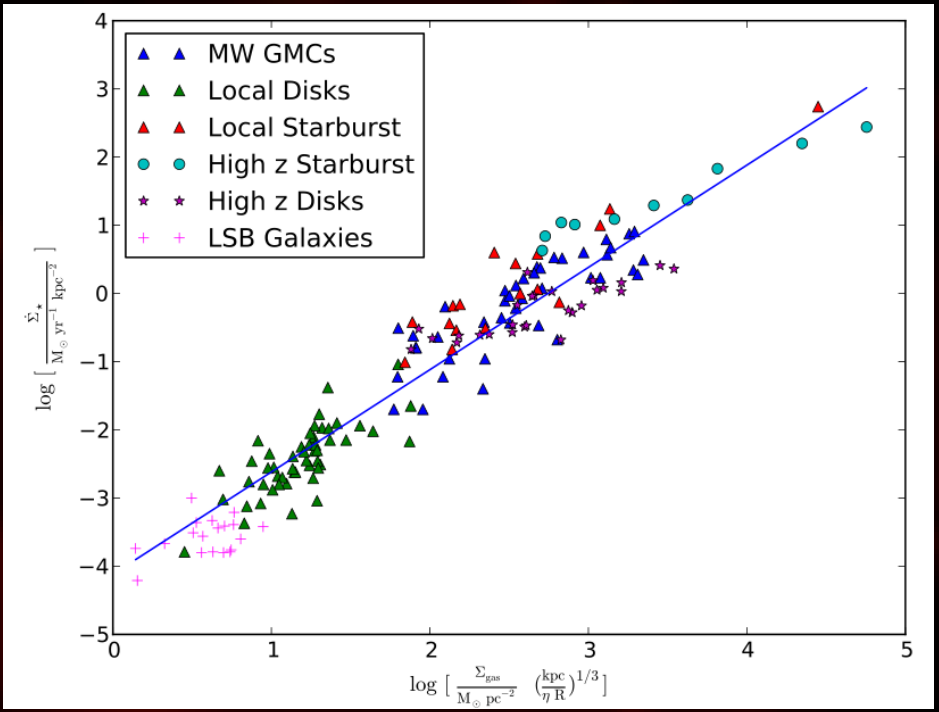


Two different regimes:

- Giant molecular cloud regime
- Toomre regime

Universal Star Formation Relations?

Escala (2015)



$$\Sigma_{\rm SFR} = \epsilon \left[\frac{v_{\rm turb}}{\sqrt{G\Sigma L}}, \mathcal{M}_s, \mathcal{M}_a, Q \right] \sqrt{\frac{G}{L}} \Sigma_{\rm gas}^{3/2}$$

Dimensional Homogeneity

Comparing quantities with the same units.

How to find such relations: Buckingham Π theorem

For a physically meaningful relation involving N physical variables and K dimensions, the original equation can be rewritten in terms of a set of P=N-K dimensionless parameters

Confounding variables

- Several physical processes usually dynamically coupled
- Difficult study of their independent effects

Eg.

$$\Omega = \Omega(M_{\rm gas}, ...)$$

$$t_{\rm ff} = t_{\rm ff}(M_{\rm gas}, ...)$$

- In numerical simulations is easier to separate their effects.

Simulations of Spiral & Starburst Galaxies

Simulations

- Hydrodynamic AMR code Enzo (Bryan et al. 2014)

Spiral Galaxies

- Exponential gaseous disk ($R_{\rm g}$ =3.5 kpc)
- Stellar potential: Miyamoto-Nagai profile (disk+bulge)
- Dark matter: NFW profile

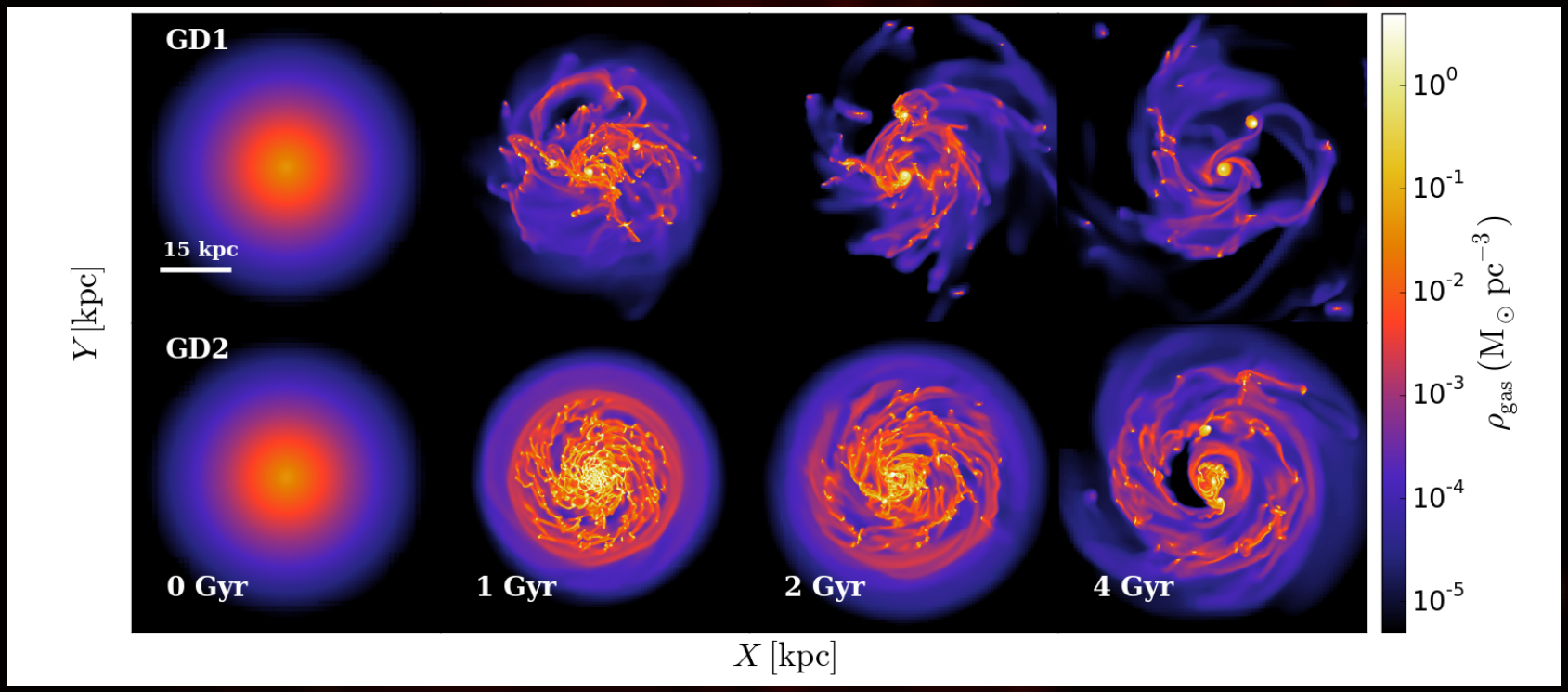
Starburst Galaxies

- Gaseous Disk (Mestel-Disk)
- Stellar potential: Isothermal sphere

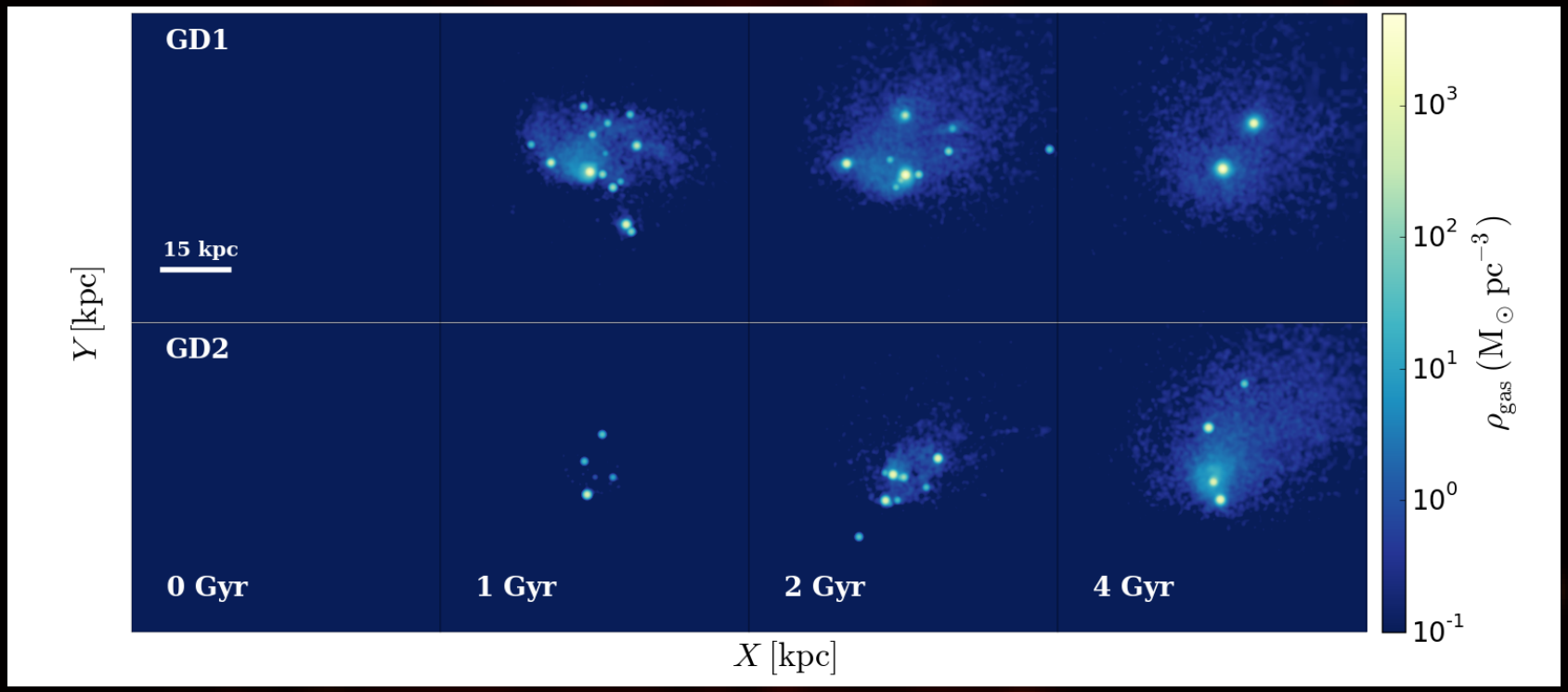
- The initial gas distribution is the same
- We change Ω by changing the external potentials.

Spiral Galaxies				
Run	$M_{gas}[M_\odot]$	$M_\star[M_\odot]$	$M_{DM}[M_\odot]$	t_{orb} [Myr] 10 kpc
GD1	1×10^{10}	1×10^{10}	1×10^{10}	640
GD2	1×10^{10}	1×10^{11}	1×10^{11}	275
Starburst Galaxies (Nuclear Disks)				
Run	$M_{gas}[M_\odot]$	$M_\star[M_\odot]$	σ [km/s]	t_{orb} [Myr] 300 pc
SD1	4×10^8	1.24×10^9	100	11.51
SD2	4×10^8	2.10×10^9	130	9.308
SD3	4×10^8	4.49×10^9	190	6.600
SD4	4×10^8	6.02×10^9	220	5.802

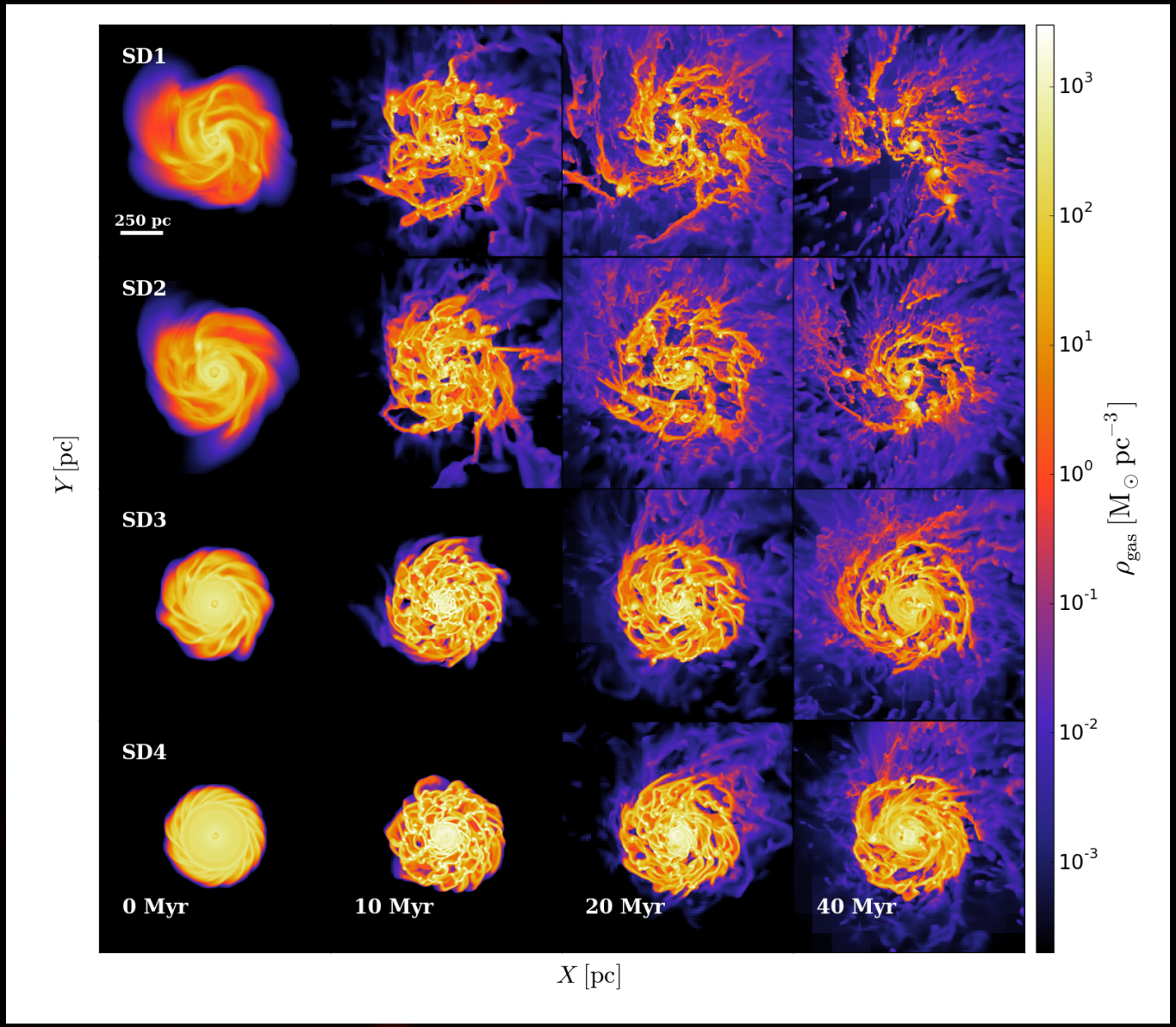
Spiral galaxies



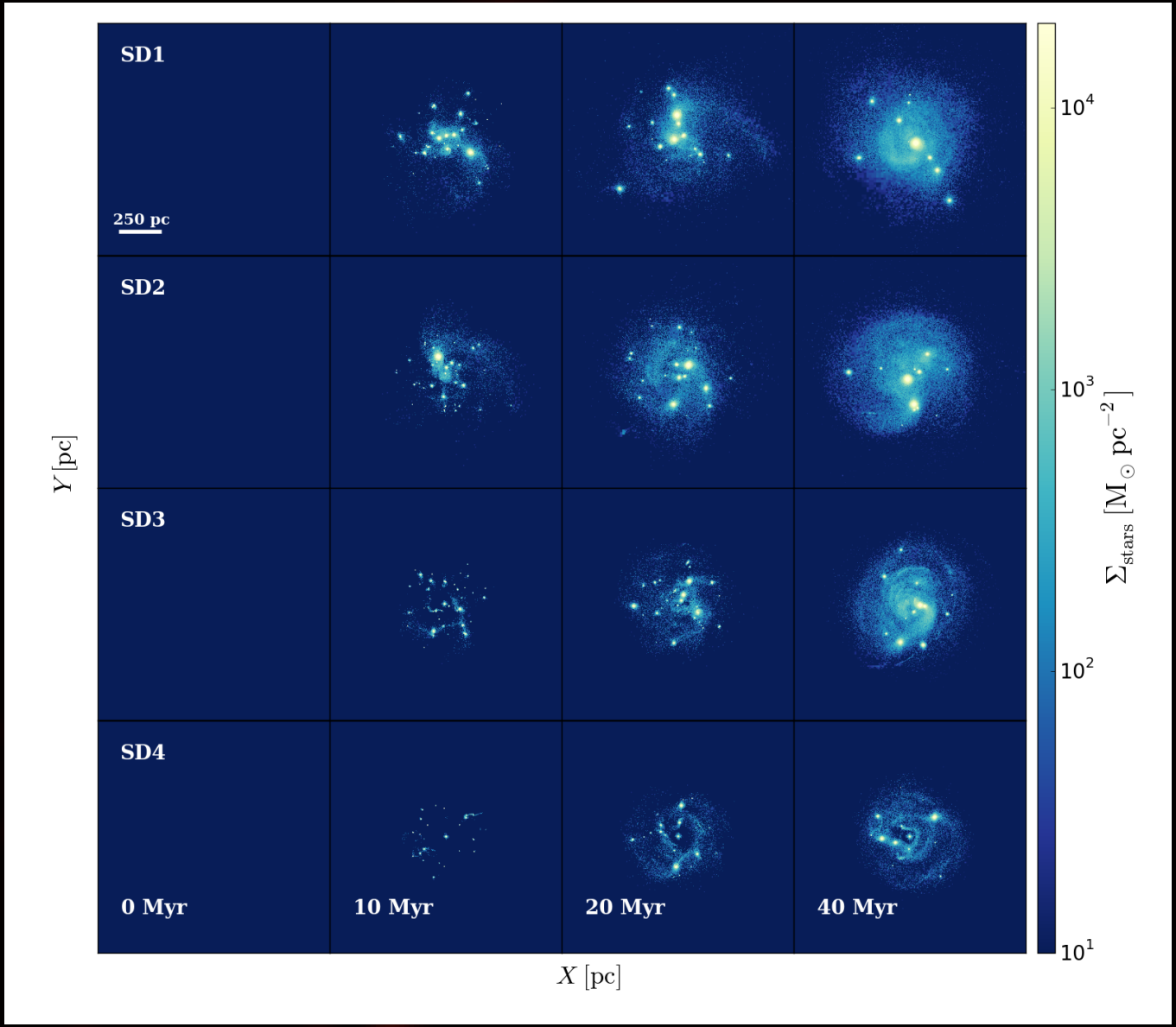
Spiral galaxies



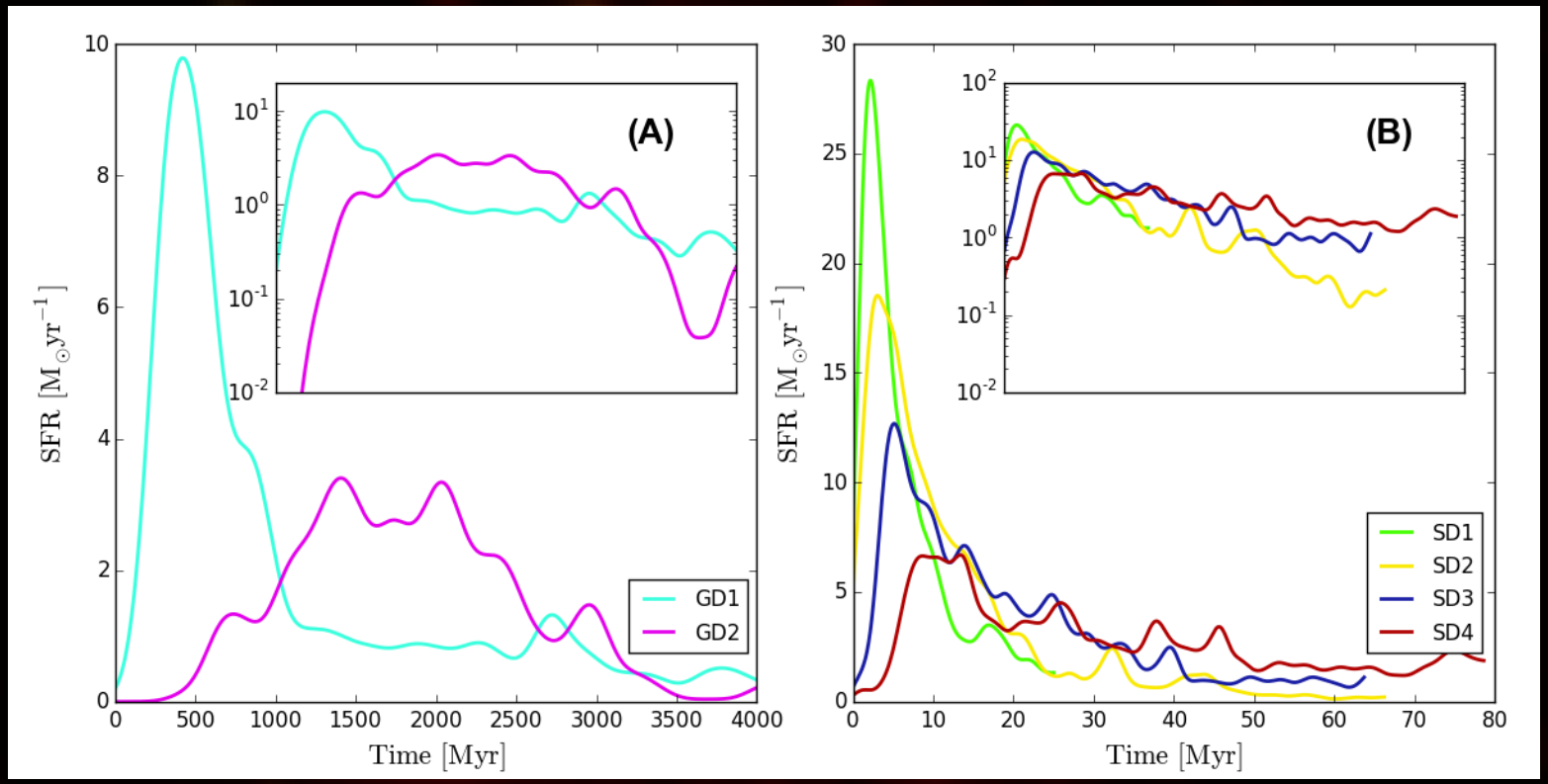
Starburst galaxies



Starburst galaxies



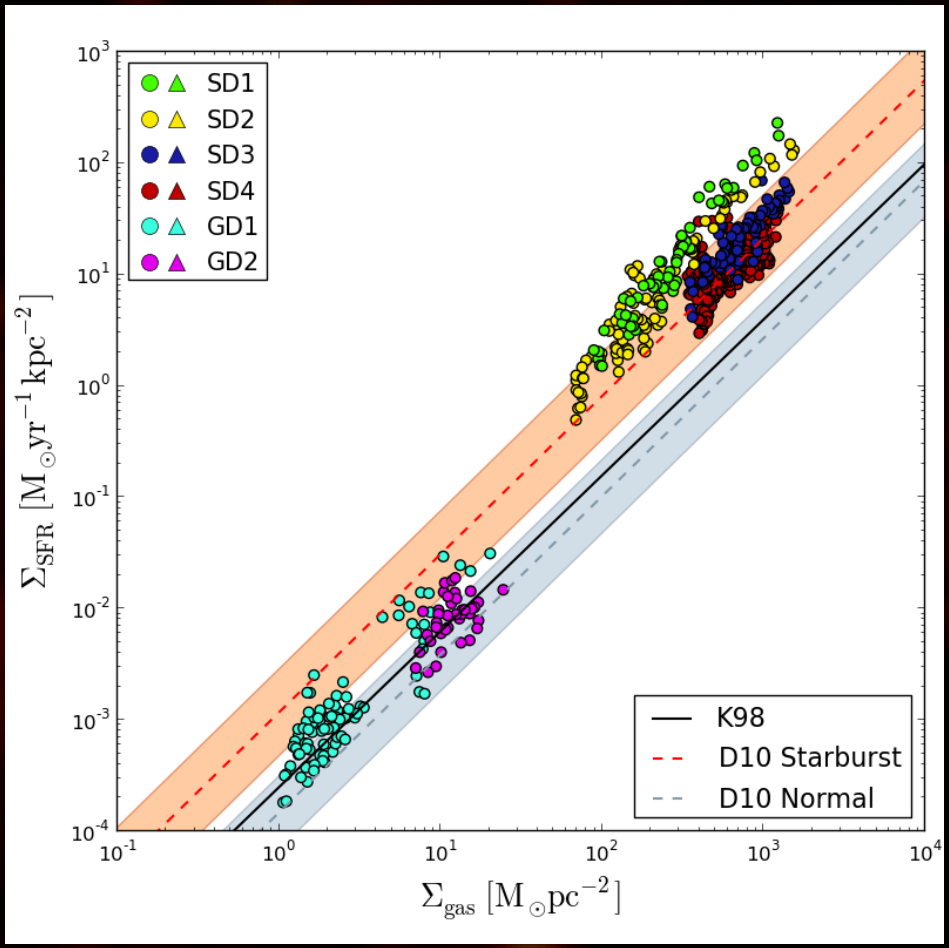
Star Formation through time



- Low $\Omega \rightarrow$ fast formation of stars

Kennicutt-Schmidt Relation

Kennicutt-Schmidt Relation



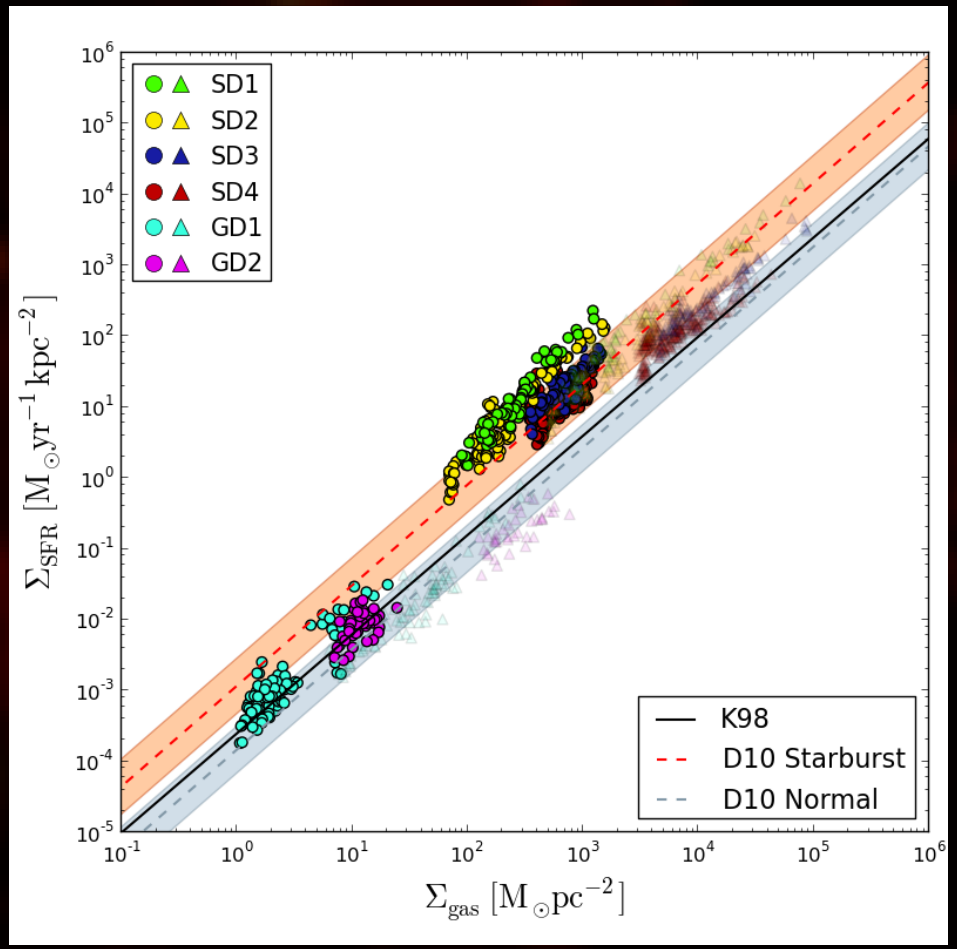
Integration problem

What about the inclination of the object?

Just an numerical experiment!

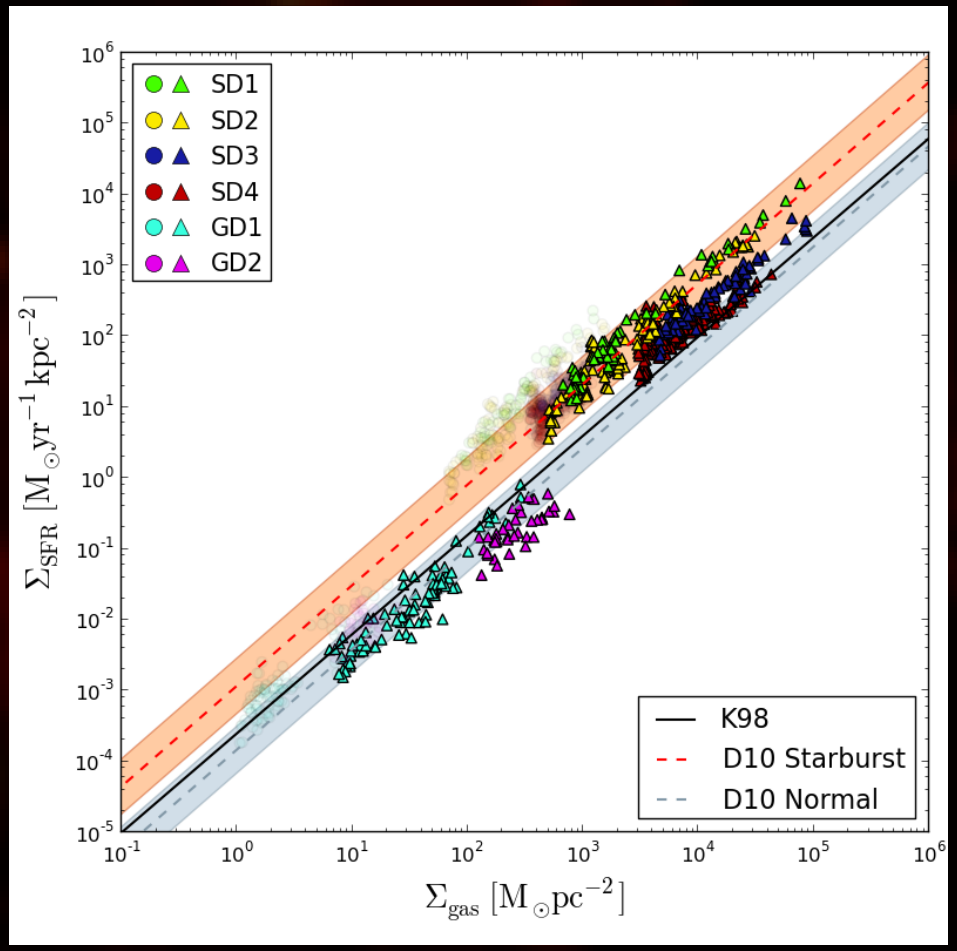
Kennicutt-Schmidt Relation

Integration along z-axis (face-on)



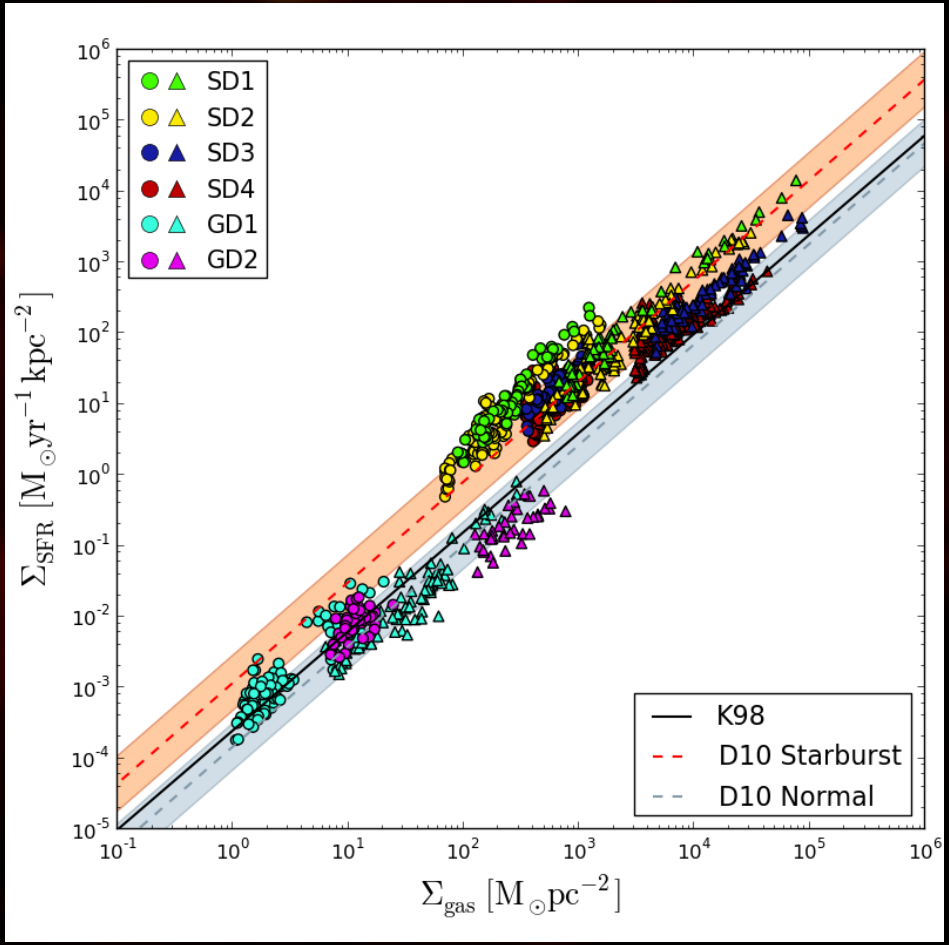
Kennicutt-Schmidt Relation

Integration along x-axis (edge-on)

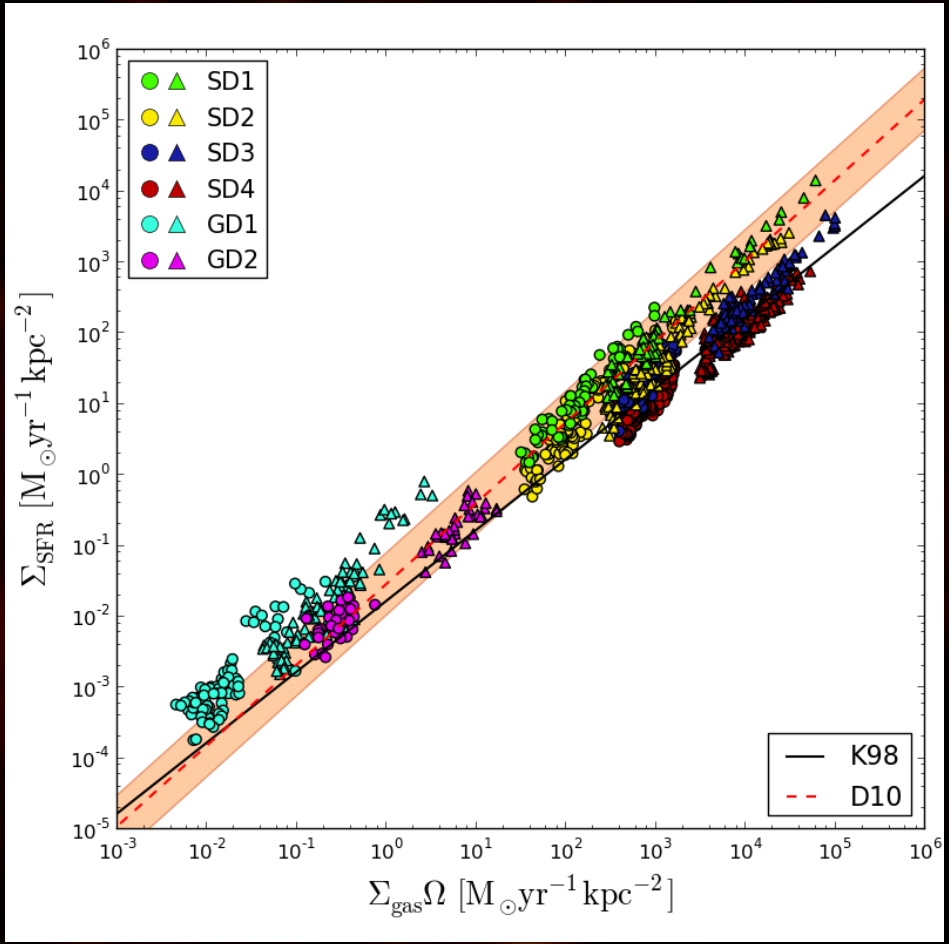


Kennicutt-Schmidt Relation

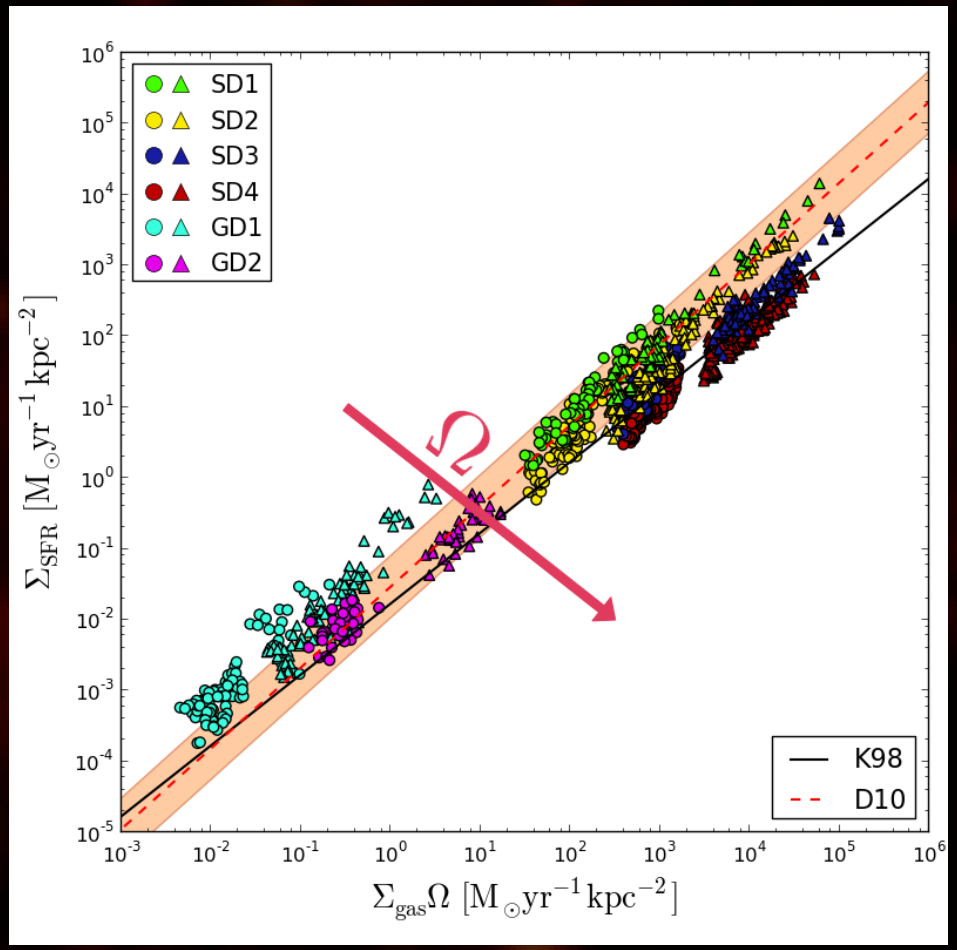
Both integrations



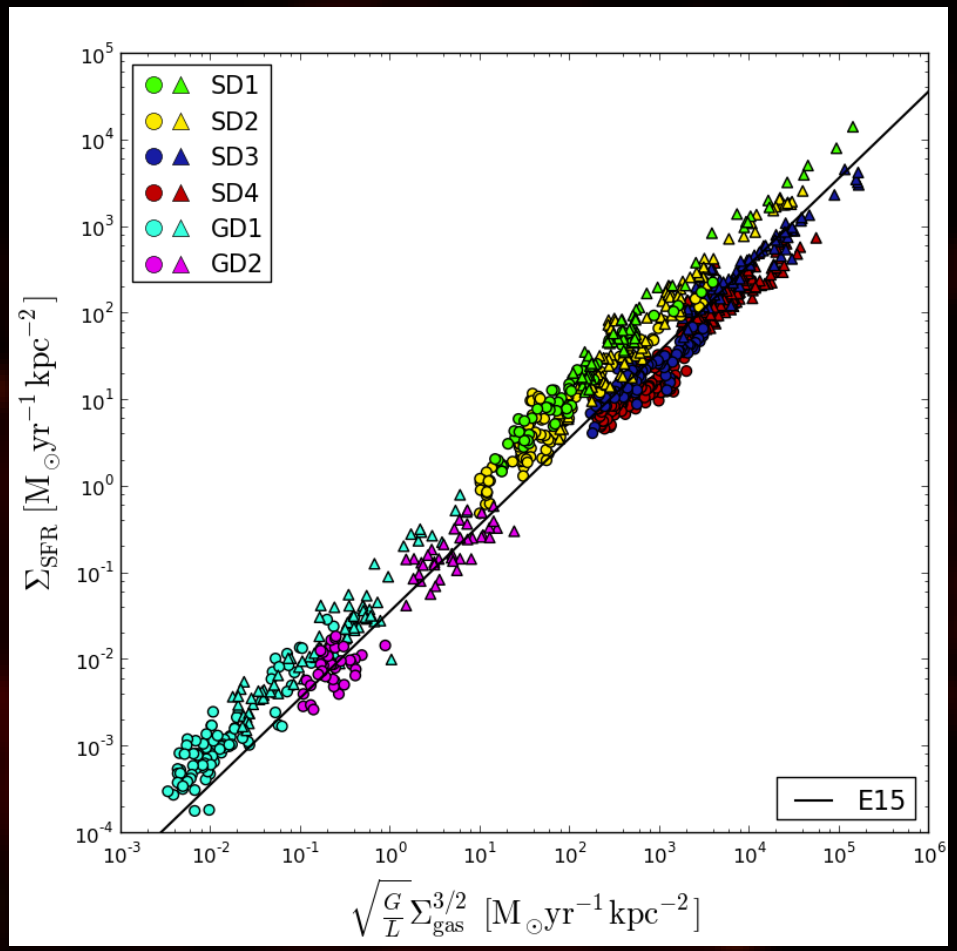
Silk-Elmegreen Relation



Silk-Elmegreen Relation



Escala Relation (2015)

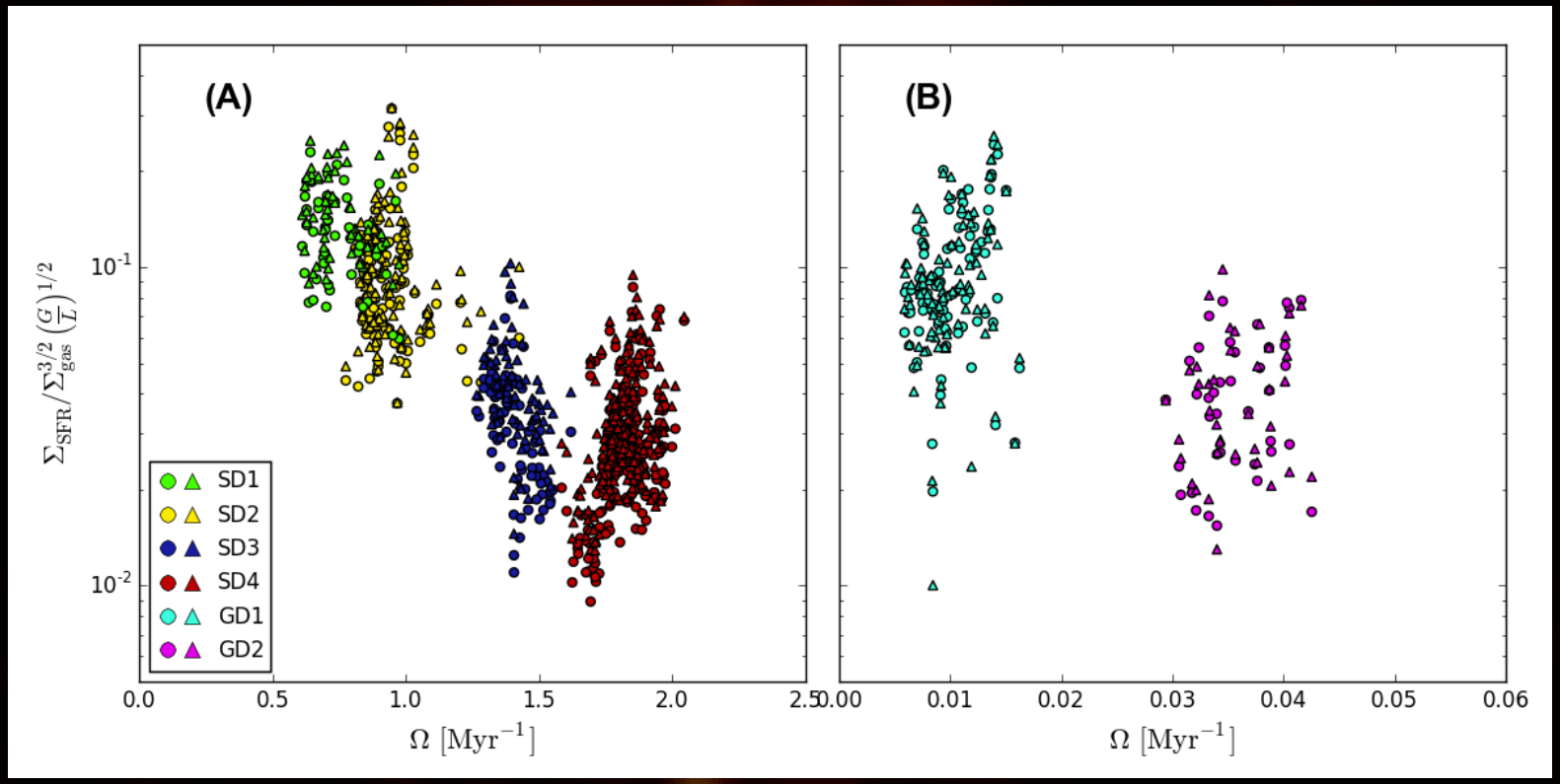


$$L_{x_i} = \sqrt{\langle x_i^2 \rangle - \langle x_i \rangle^2} \; ; \langle x_i \rangle = \frac{\int_V \rho(\vec{x}) x_i dx^3}{\int_V \rho(\vec{x}) dx^3}$$

Star formation efficiency

Star formation efficiency vs Ω

Utreras et al. 2016 (*submitted to ApJ.*)



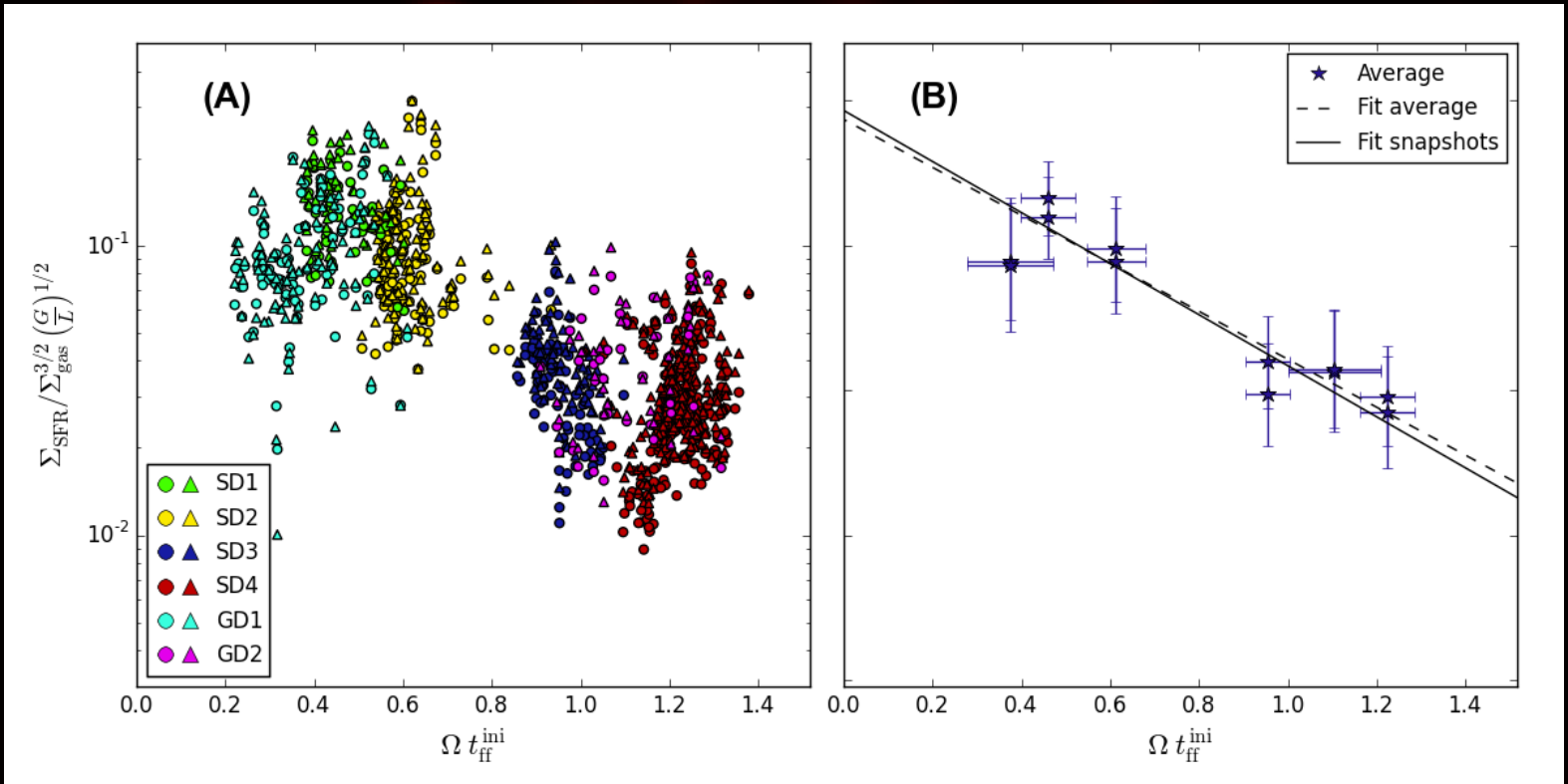
The role of rotation

- Star formation efficiency decreases with increasing rotation.
If $\Sigma_{\rm SFR} = \epsilon \Sigma_{\rm gas}/t_{\rm ff}$ the simplest explanation is that the collapse is slowed down by Ω.

$$t_{\rm ff} \propto (G\rho)^{-1/2} f(\Omega/\sqrt{G\rho})$$

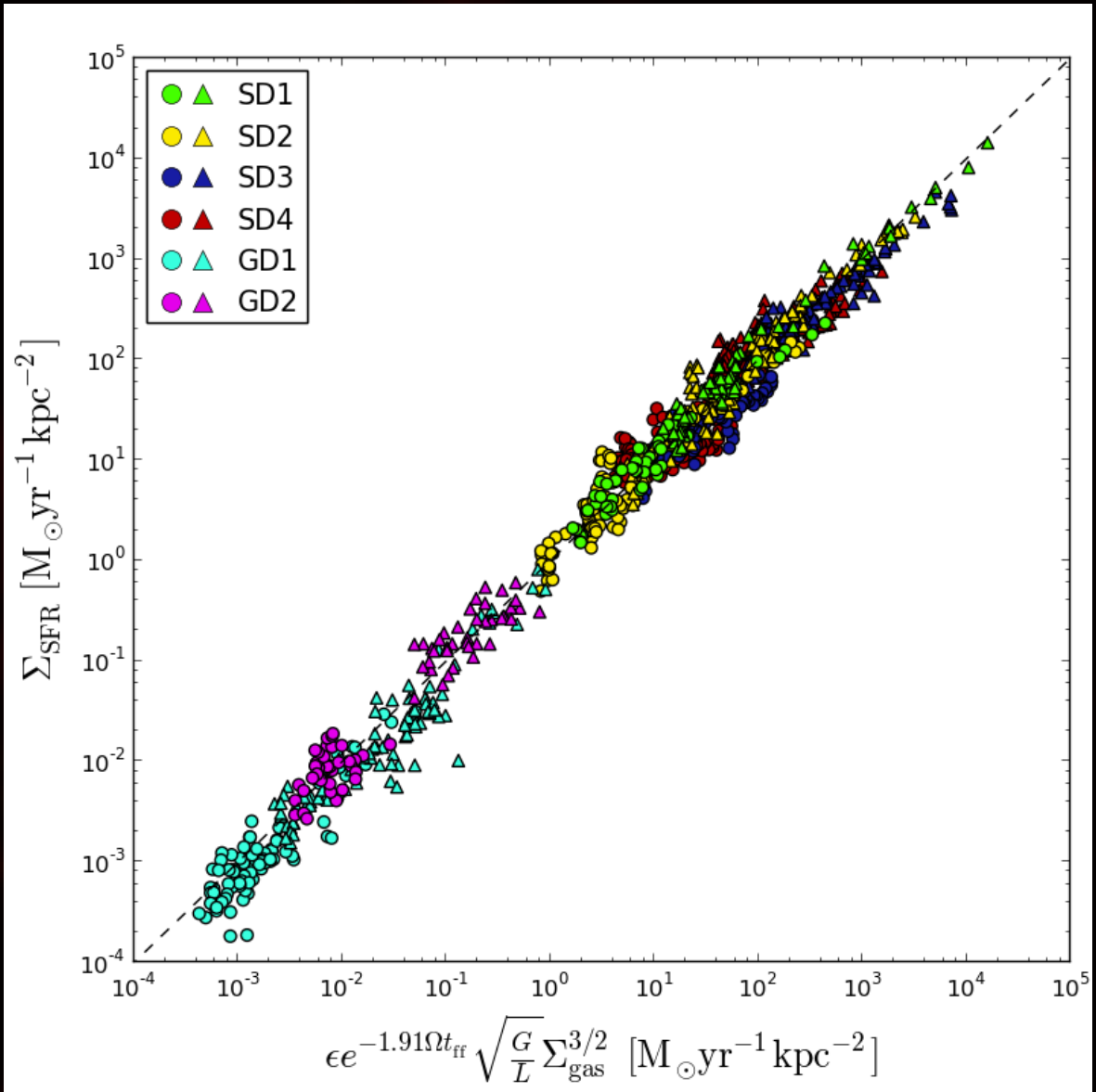
We choose the "initial" free-fall time (measured after first vertical collapse). Similiar to Padoan et al. 2012.

Star formation efficiency vs Ω



- Additional time-scale normalizes relation
- $t_{\rm ff}^{\rm ini}$ is the initial free-fall time

Star formation efficiency



Comparing different relations

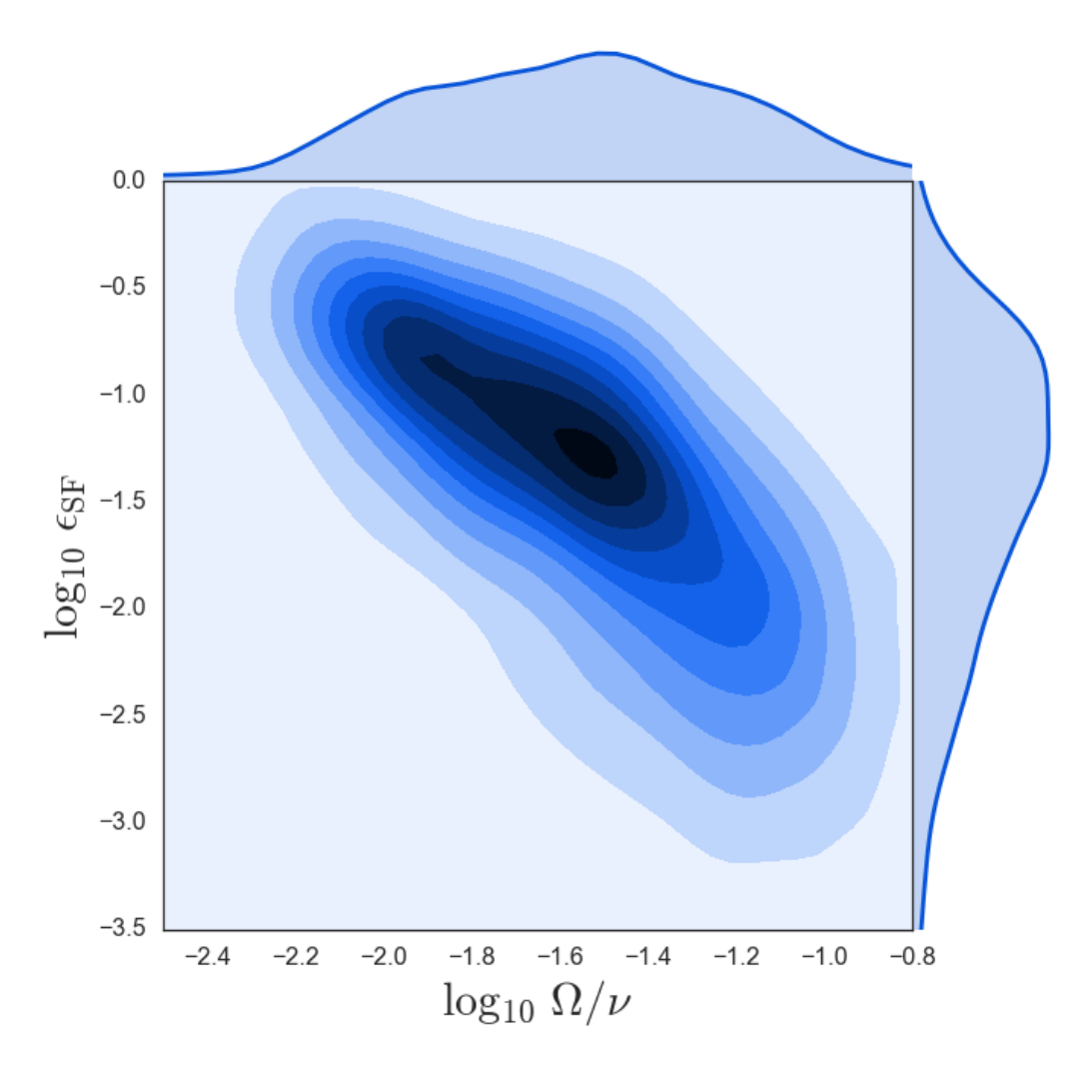
Star formation Relation	Scatter [dex]
KS	0.490
Bi-modal KS	0.360
SE	0.362
E15	0.316
This work	0.206

Dividing the disks in rings

What do we measure?
Orbital and vertical frequencies

$$\Omega/\nu$$

Dividing galaxies into rings



Summary

- Coupled variables may lead to spurious relations
- A meaningful star formation relation must be dimensionally homogeneous
- Galactic rotation suppresses the formation of stars (maybe in a specific regime)
- Dimensional homogeneity requires a normalizing time-scale
- Must be considered when prescriptions of SF are used
- Need to consider shear
- There is a freedom in the normalizing time-scale ($t_{\rm ff}$,ν)

Thanks!