Joint Astrophysical Colloquium – OAS Bologna

Star formation laws and gas turbulence in nearby galaxies

Cecilia Bacchini

INAF-Padova

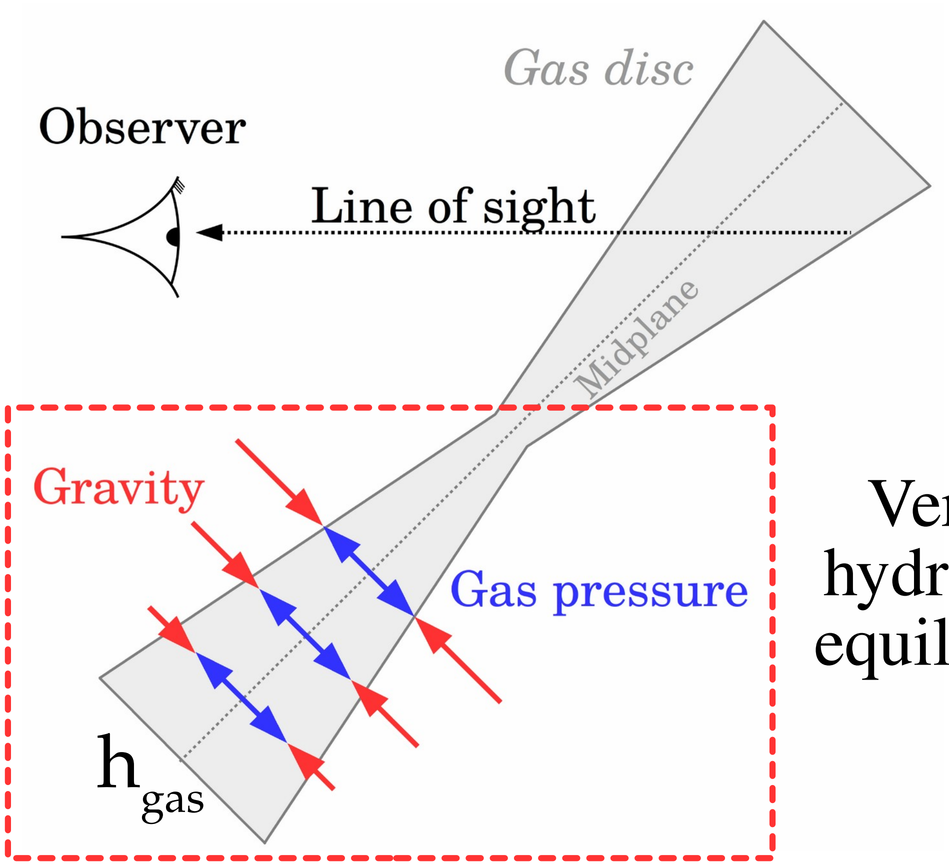
This talk is based on my PhD thesis

supervised by Filippo Fraternali (Kapteyn Institute, University of Groningen) & Carlo Nipoti (DIFA, University of Bologna),

in collaboration with Gabriele Pezzulli (Kapteyn), Giuliano Iorio (University of Padova) & Antonino Marasco (INAF-Arcetri)

The ‘fil rouge’

Gas discs have the flaring!

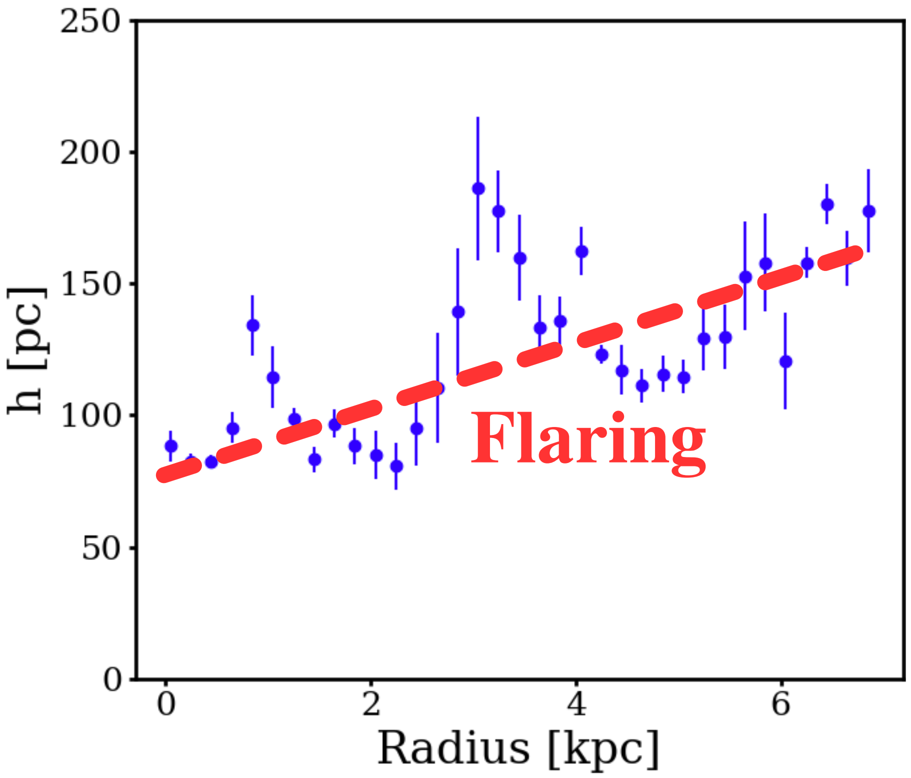


Vertical hydrostatic equilibrium

Flaring from observations

Milky Way

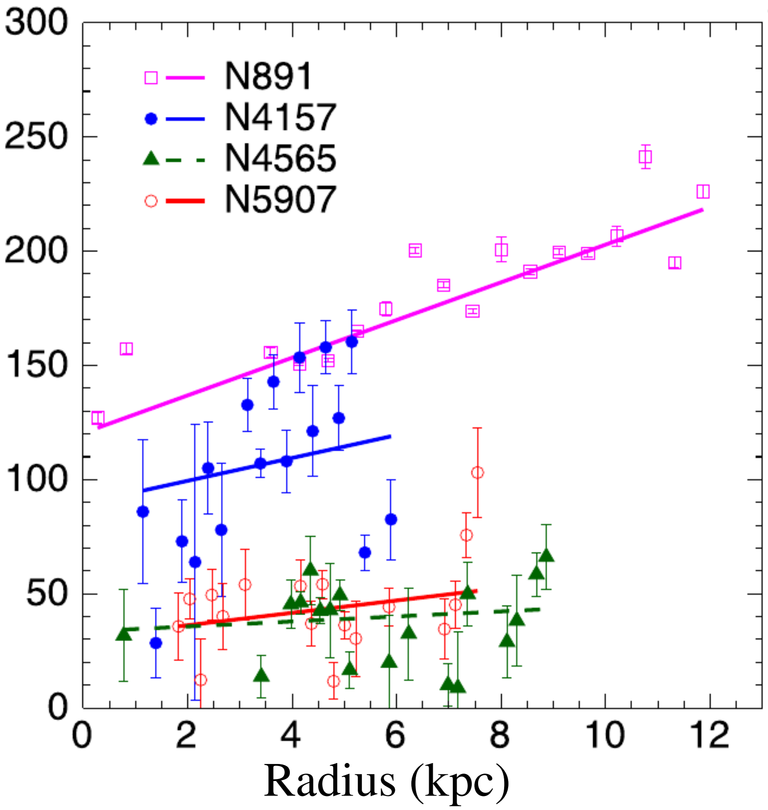
HI scale height



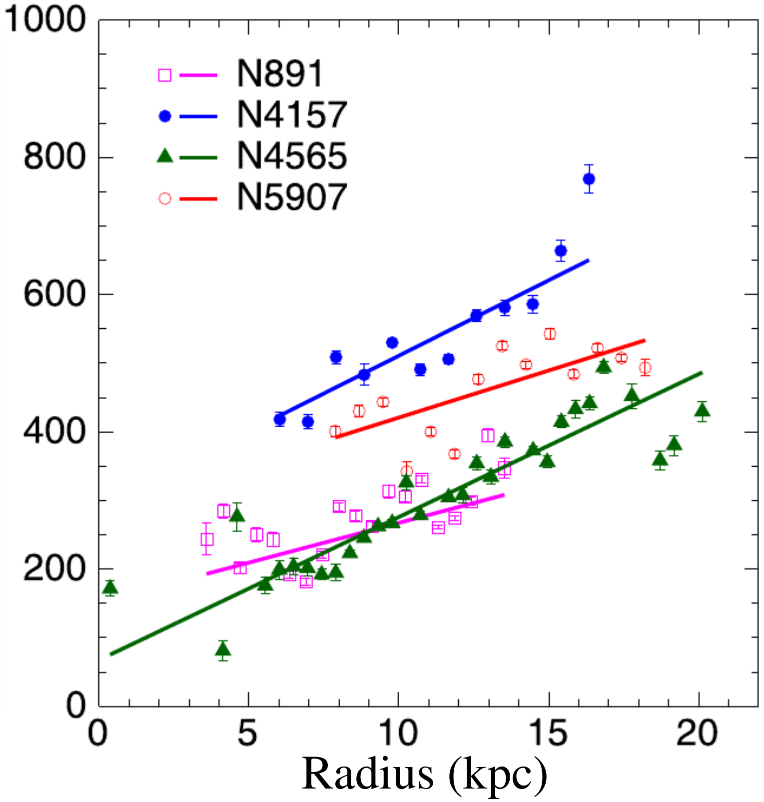
Marasco+2017

Highly-inclined galaxies

H_2 scale height



HI scale height



Yim+2014

Credit: NASA, ESA, STScI/AURA-Hubble/Europe Collaboration

Part I

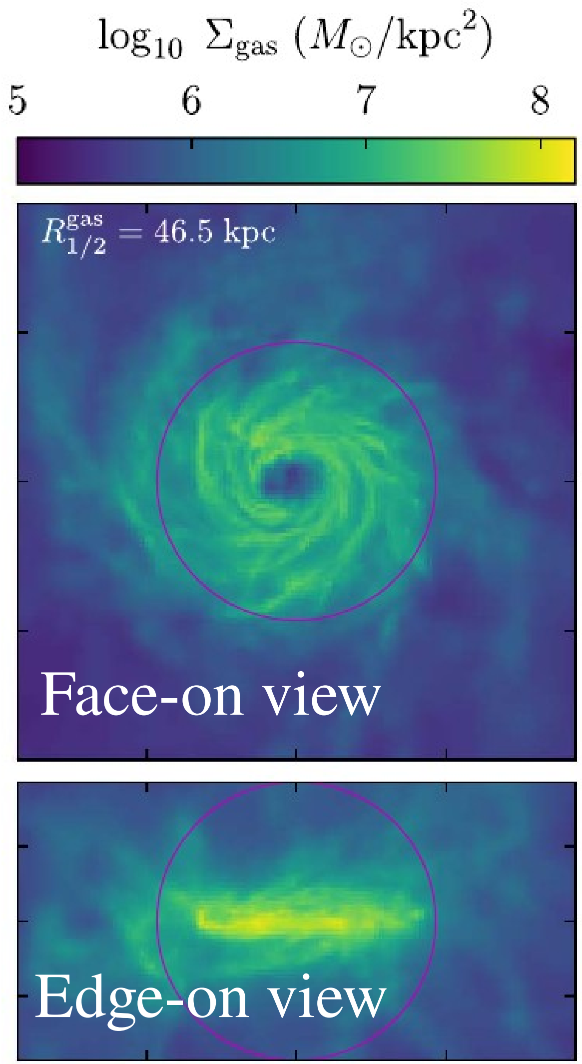
The volumetric star formation law in nearby galaxies

1) Volumetric star formation laws of disc galaxies
Bacchini, Fraternali, Iorio & Pezzulli, 2019a, A&A, 622, A64.

2) The volumetric star formation law in the Milky Way
Bacchini, Fraternali, Pezzulli, Marasco, Iorio & Nipoti, 2019b, A&A, 632, A127.

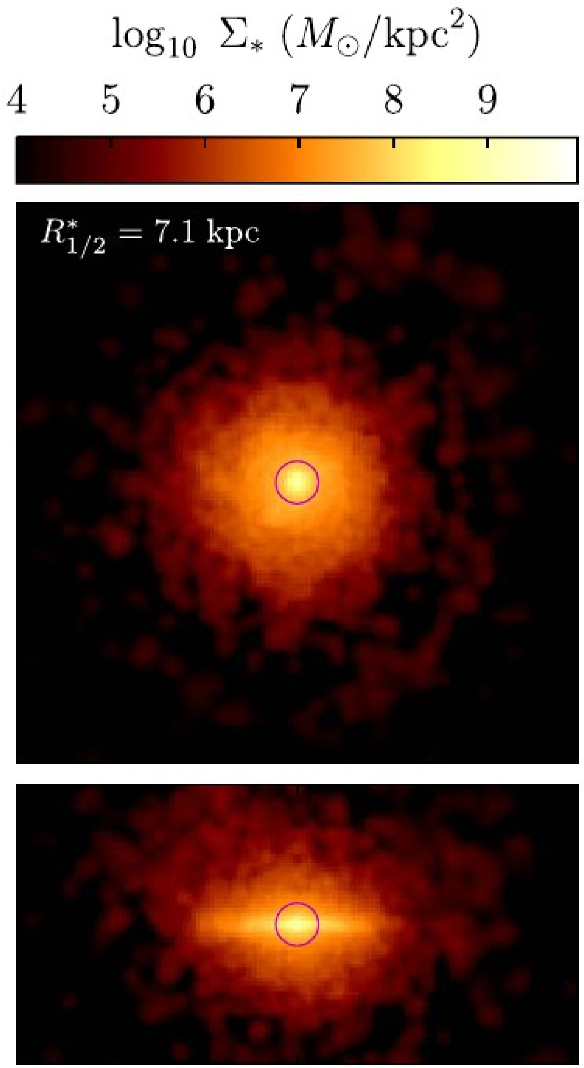
3) The volumetric star formation law for nearby dwarf galaxies
Bacchini, Fraternali, Pezzulli & Marasco, 2020b, A&A, 644, A125.

Why star formation laws are fundamental?

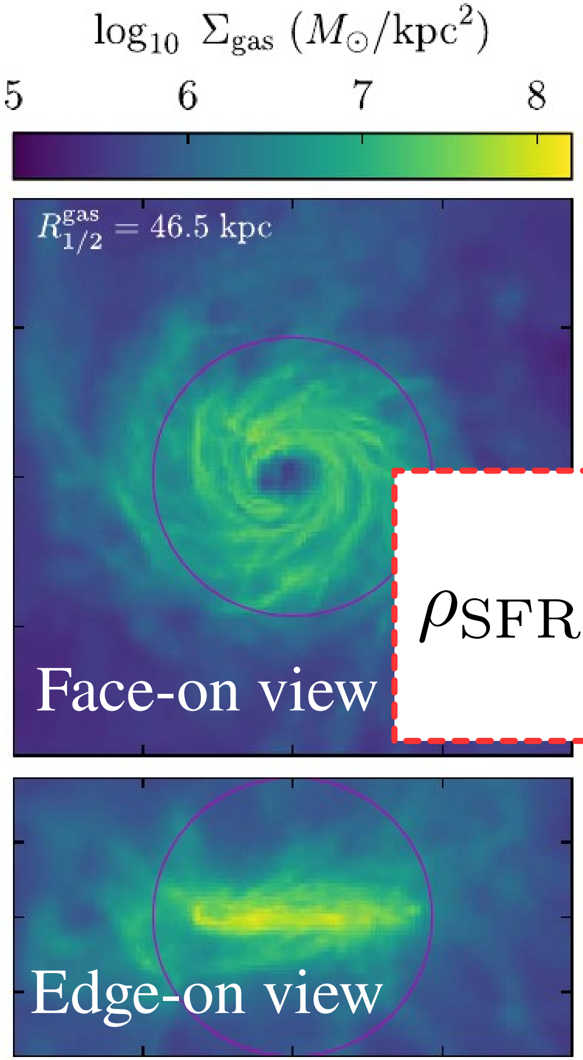


How do stars form?

Diemer+2018
(IllustrisTNG)

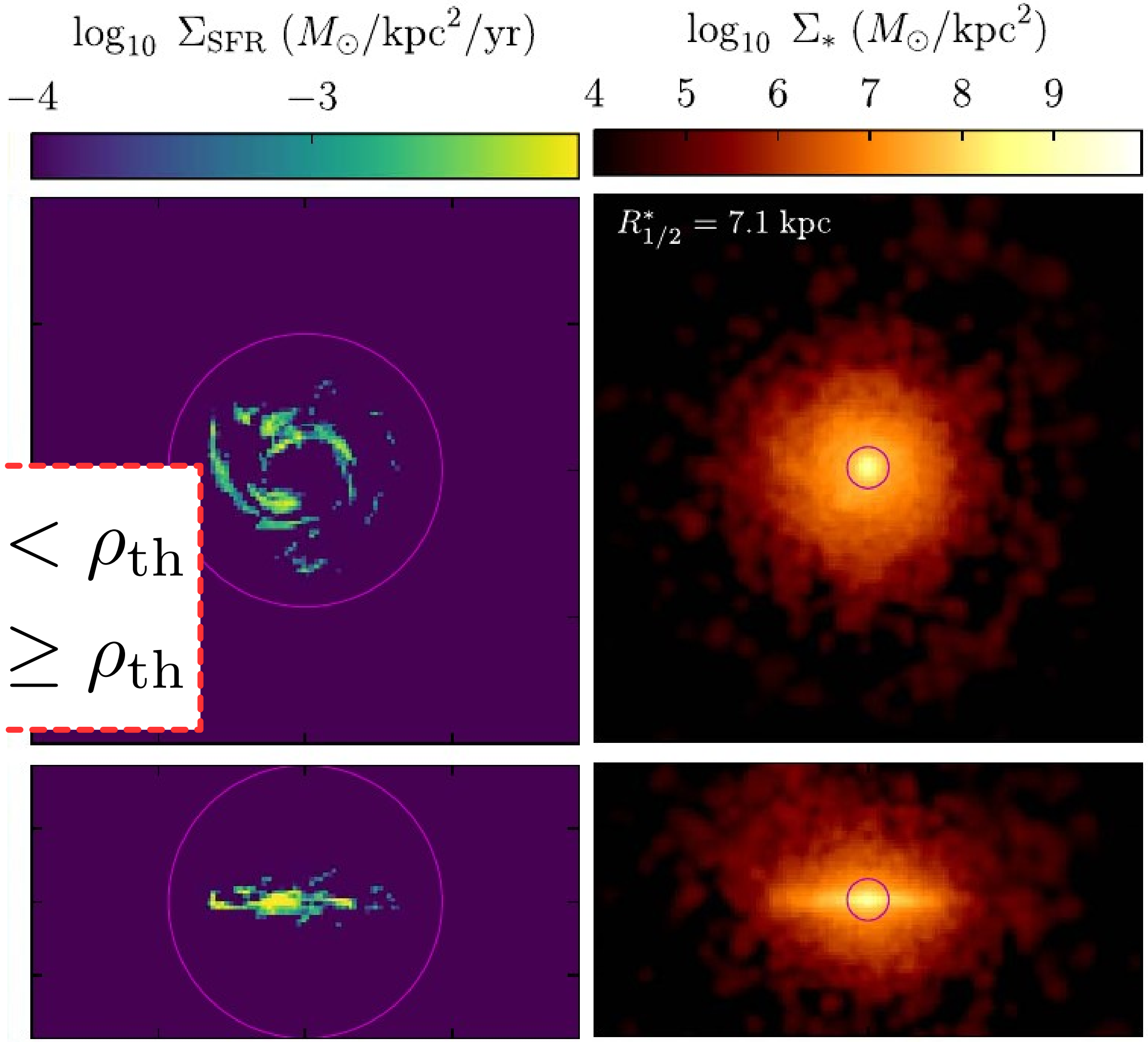


Why star formation laws are fundamental?



Star formation law

$$\rho_{\rm SFR} = \begin{cases} 0, & \rho_{\rm gas} < \rho_{\rm th} \\ \epsilon\rho_{\rm gas}^{1.5} & \rho_{\rm gas} \geq \rho_{\rm th} \end{cases}$$



Diemer+2018 (IllustrisTNG)

Empirical relations

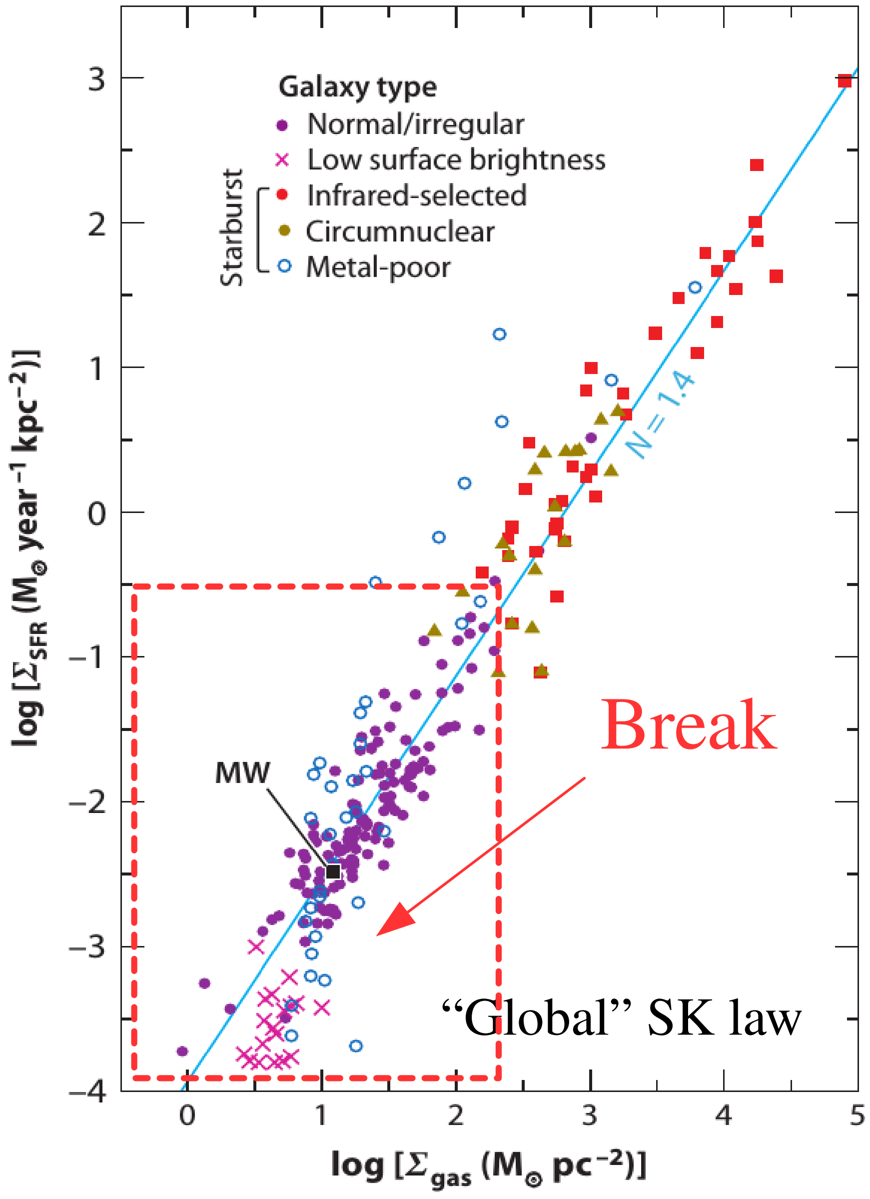
Schmidt-Kennicutt (SK) law

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{N}$$

$\text{gas} = \text{HI} + \text{H}_2$

$$N \approx \begin{cases} 1.4 & \Sigma_{\rm gas} \gtrsim 10\ \text{M}_\odot \text{pc}^{-2} \\ ??? & \Sigma_{\rm gas} < 10\ \text{M}_\odot \text{pc}^{-2} \end{cases}$$

Kennicutt & Evans 2012



Empirical relations

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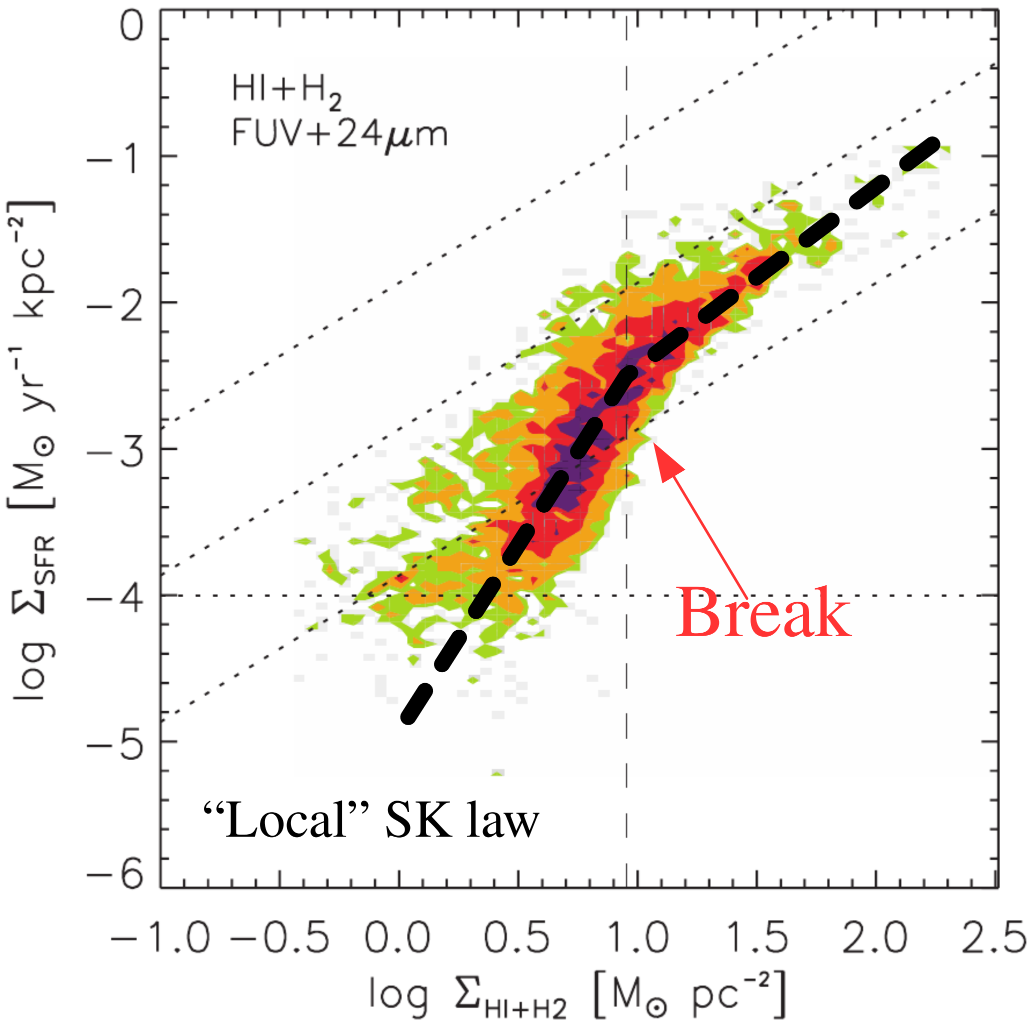
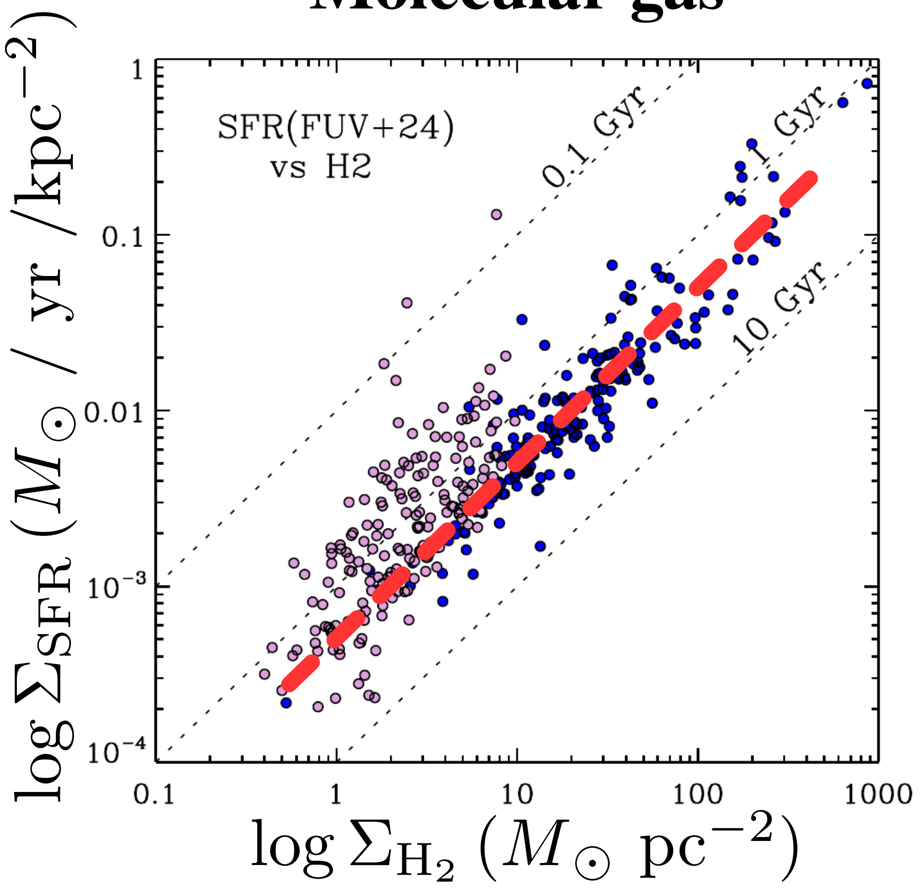
Bigiel+2008



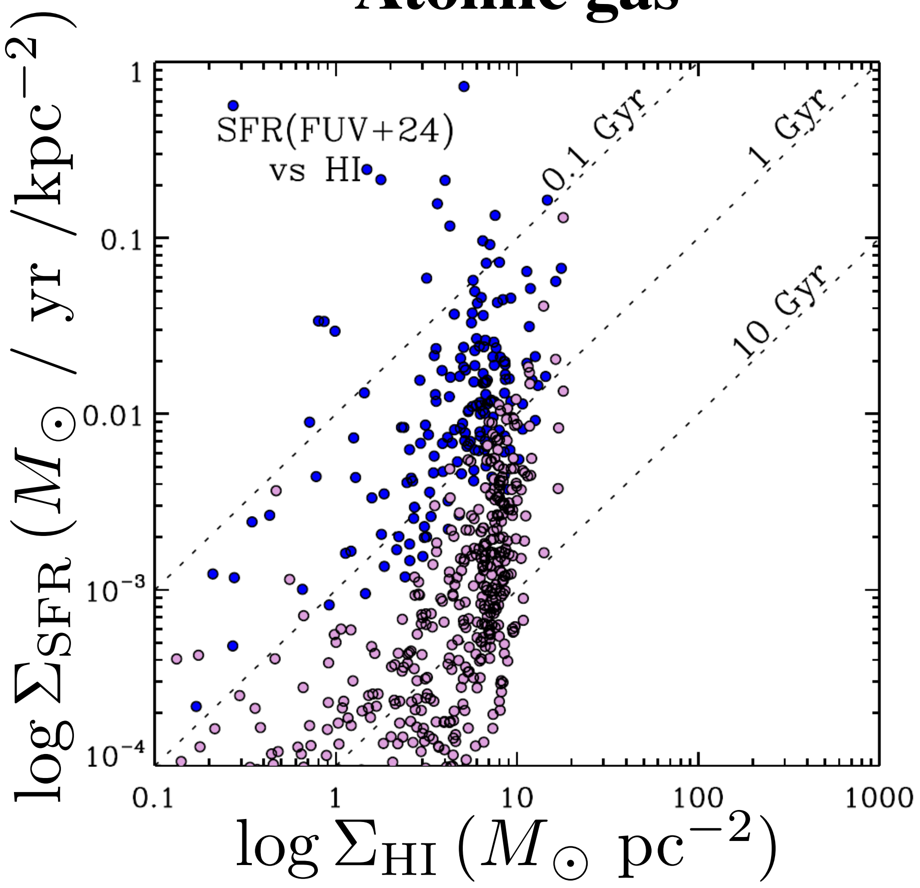
Empirical relations

Molecular gas



$\Sigma_{\rm SFR} \propto \Sigma_{\rm H_2}$

Atomic gas

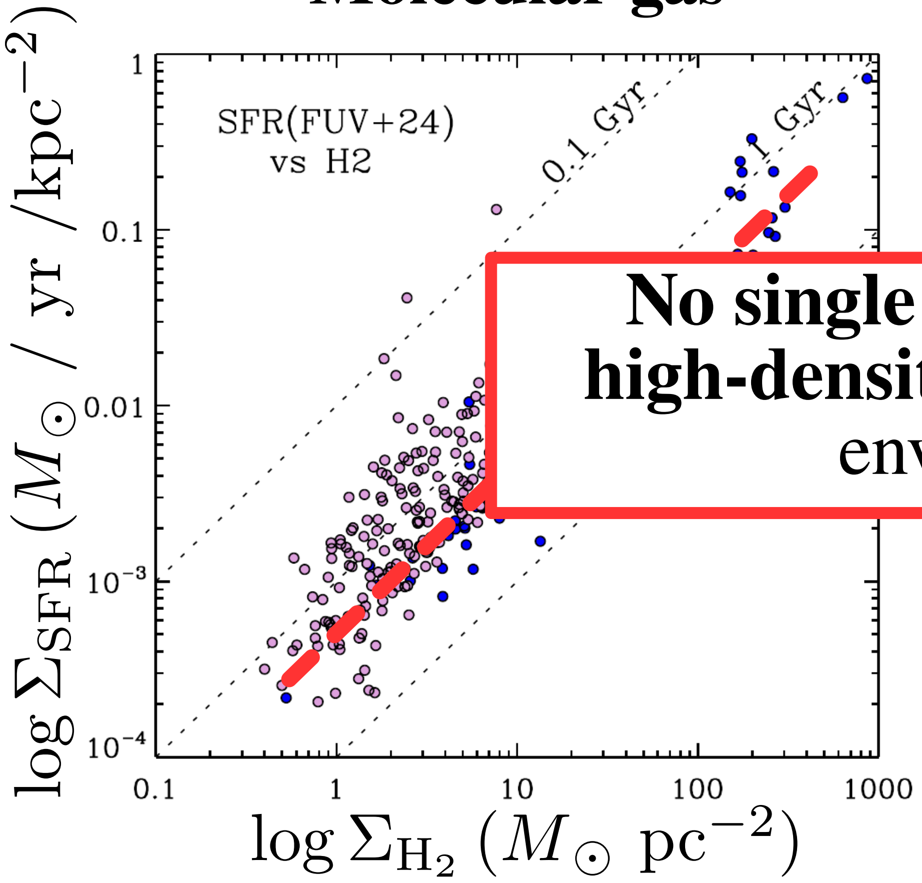


No correlation

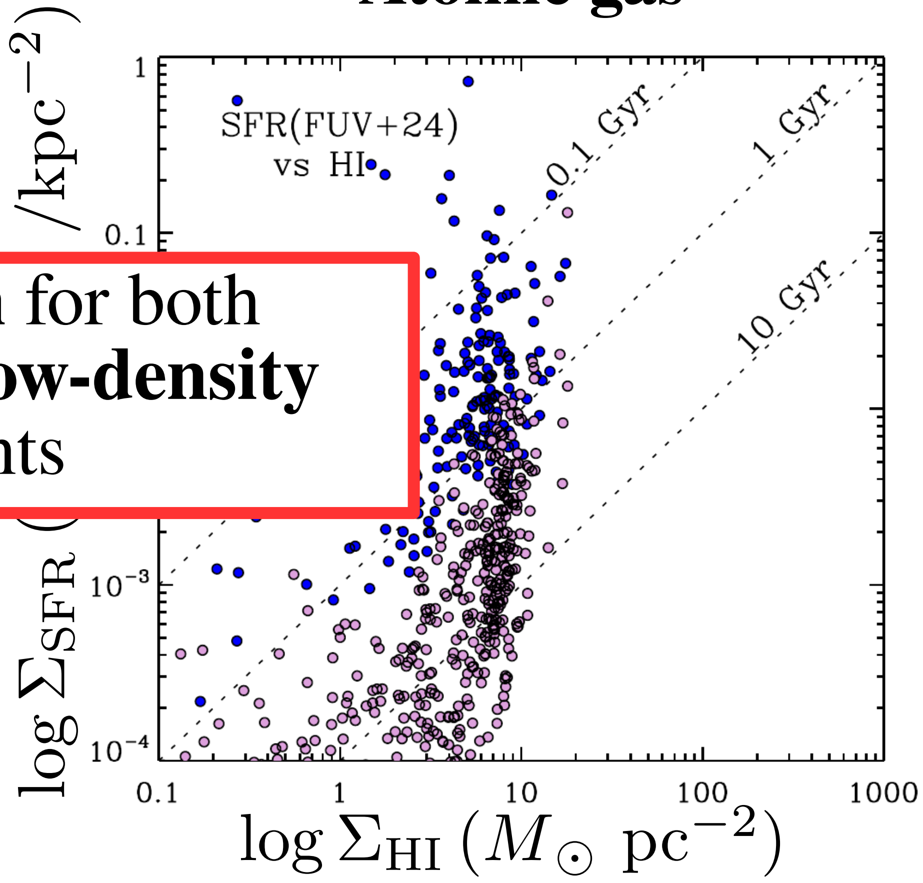
Schruba+2011

Empirical relations

Molecular gas



Atomic gas



No single relation for both **high-density and low-density** environments

$\Sigma_{SFR} \propto \Sigma_{H_2}$

Schruba+2011

No correlation

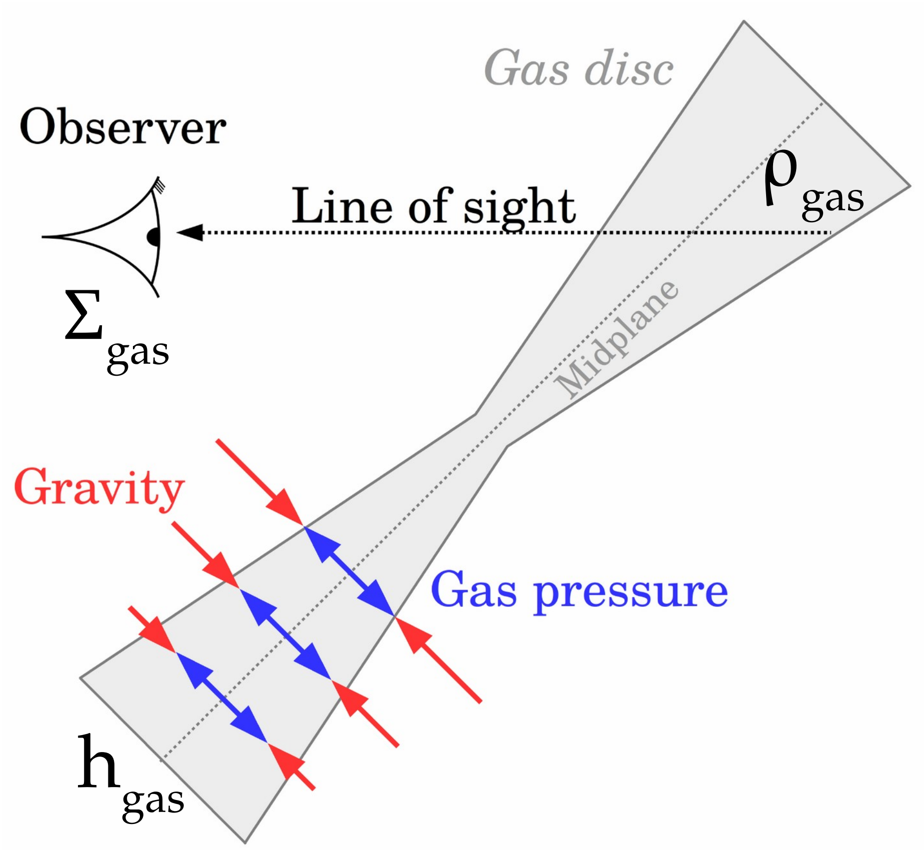
From surface densities to volume densities

Gas discs have the flaring!

Observed
surface densities

↓

SK law



$$\Sigma(R) = \int_{-\infty}^{+\infty} \rho(R, z) dz$$

↓

Volume densities

$$\rho(R, 0) = \frac{\Sigma(R)}{\sqrt{2\pi} h(R)}$$

↓

Volumetric star formation (VSF) law

How to derive the volume densities?

- Atomic gas

Observed

$$\rho_{\mathrm{HI}}(R,0) = \frac{\Sigma_{\mathrm{HI}}(R)}{\sqrt{2\pi}h_{\mathrm{HI}}(R)}$$

- Molecular gas

$$\rho_{\mathrm{H_2}}(R,0) = \frac{\Sigma_{\mathrm{H_2}}(R)}{\sqrt{2\pi}h_{\mathrm{H_2}}(R)}$$

- Star formation rate

$$\rho_{\mathrm{SFR}}(R,0) = \frac{\Sigma_{\mathrm{SFR}}(R)}{\sqrt{2\pi}h_{\mathrm{SFR}}(R)}$$

How to derive the volume densities?

- Atomic gas

Observed

$$\rho_{\rm HI}(R,0) = \frac{\Sigma_{\rm HI}(R)}{\sqrt{2\pi}h_{\rm HI}(R)}$$

- Molecular gas

$$\rho_{\rm H_2}(R,0) = \frac{\Sigma_{\rm H_2}(R)}{\sqrt{2\pi}h_{\rm H_2}(R)}$$

- Star formation rate

$$\rho_{\rm SFR}(R,0) = \frac{\Sigma_{\rm SFR}(R)}{\sqrt{2\pi}h_{\rm SFR}(R)}$$

Hydrostatic equilibrium

$$\sigma = \sigma(R)$$

$$h(R) \propto \frac{\sigma}{\sqrt{G\rho_{\rm tot}}}$$

$$\Phi_{\rm tot}(R,z) = \Phi_\star + \Phi_{\rm DM} + \Phi_{\rm gas}$$

Gas self-gravity

Sample selection

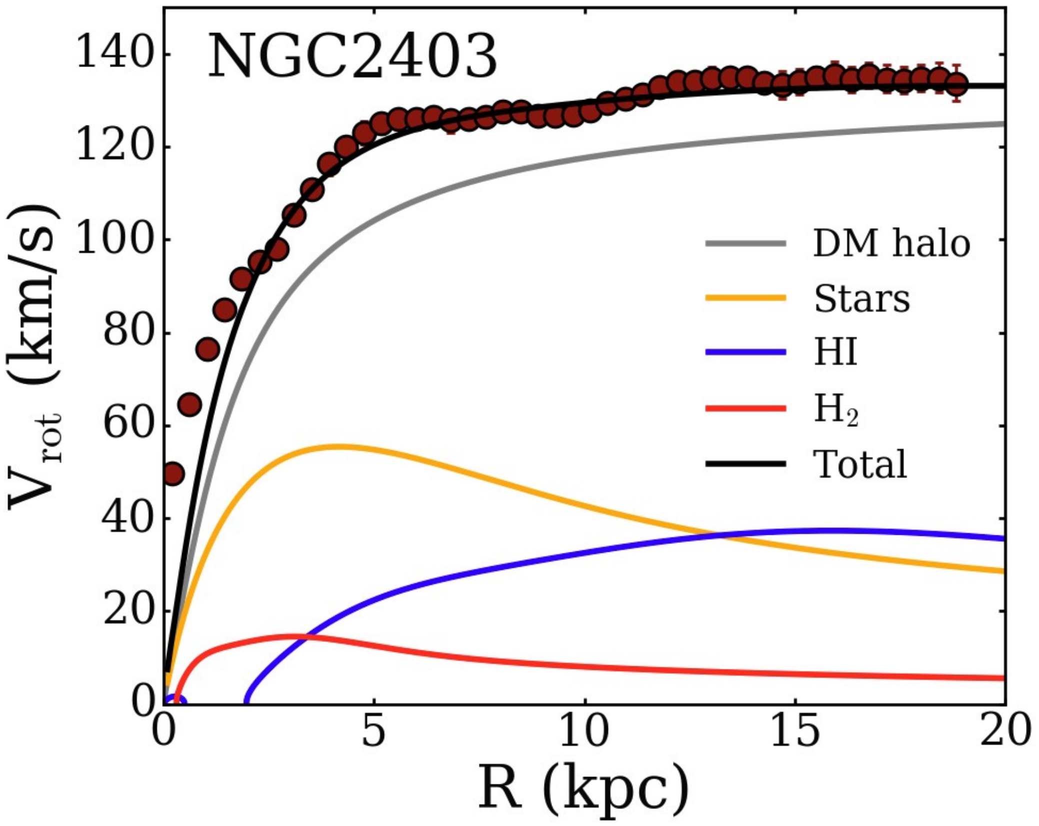
- 10 **spiral** galaxies (THINGS; *Walter+2008)*
- 2 **dwarf** galaxies (THINGS; *Walter+2008*)

From the literature:

1) Rotation curve decomposition → **gravitational potential**

2) HI, H_2 and SFR (FUV+24μm) **surface densities**

(de Blok+2008; Leroy+2008; Frank+2016)

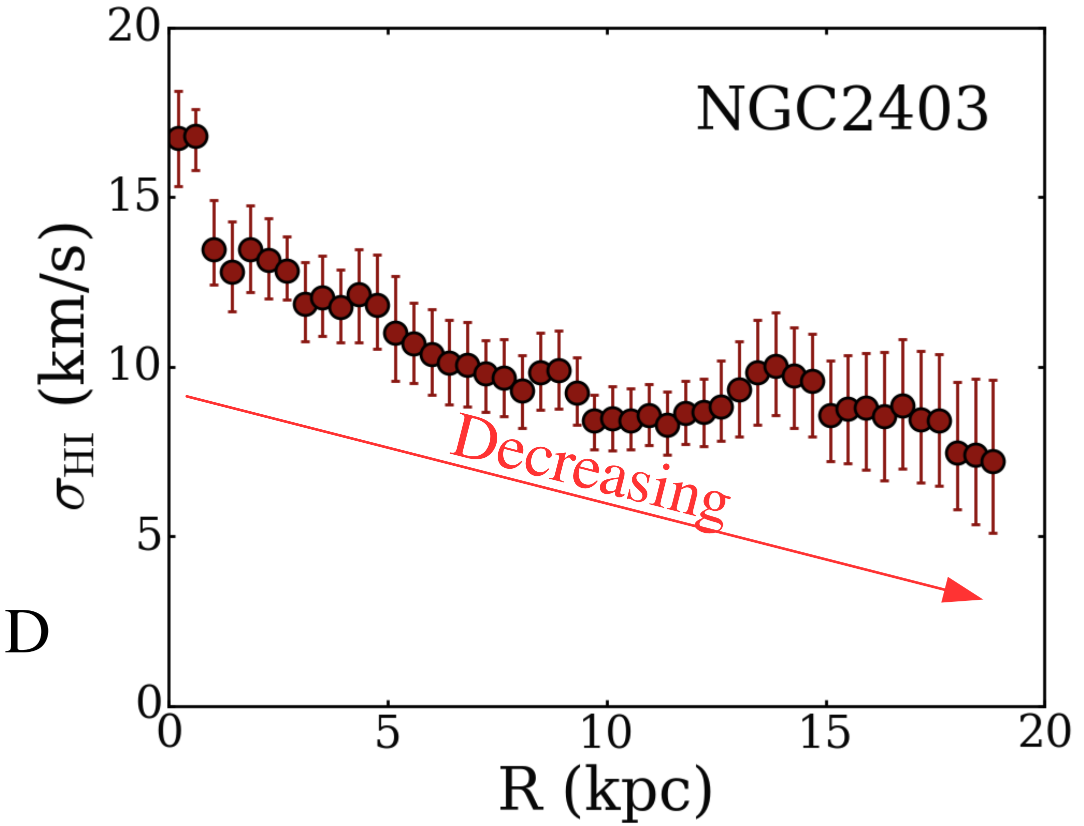


Gas velocity dispersion

Di Teodoro & Fraternali 2015

3D Based Analysis of Rotating Objects via Line Observations

- Emission-line data cubes
- Tilted-ring modelling of rotating discs in 3D
- Beam smearing correction



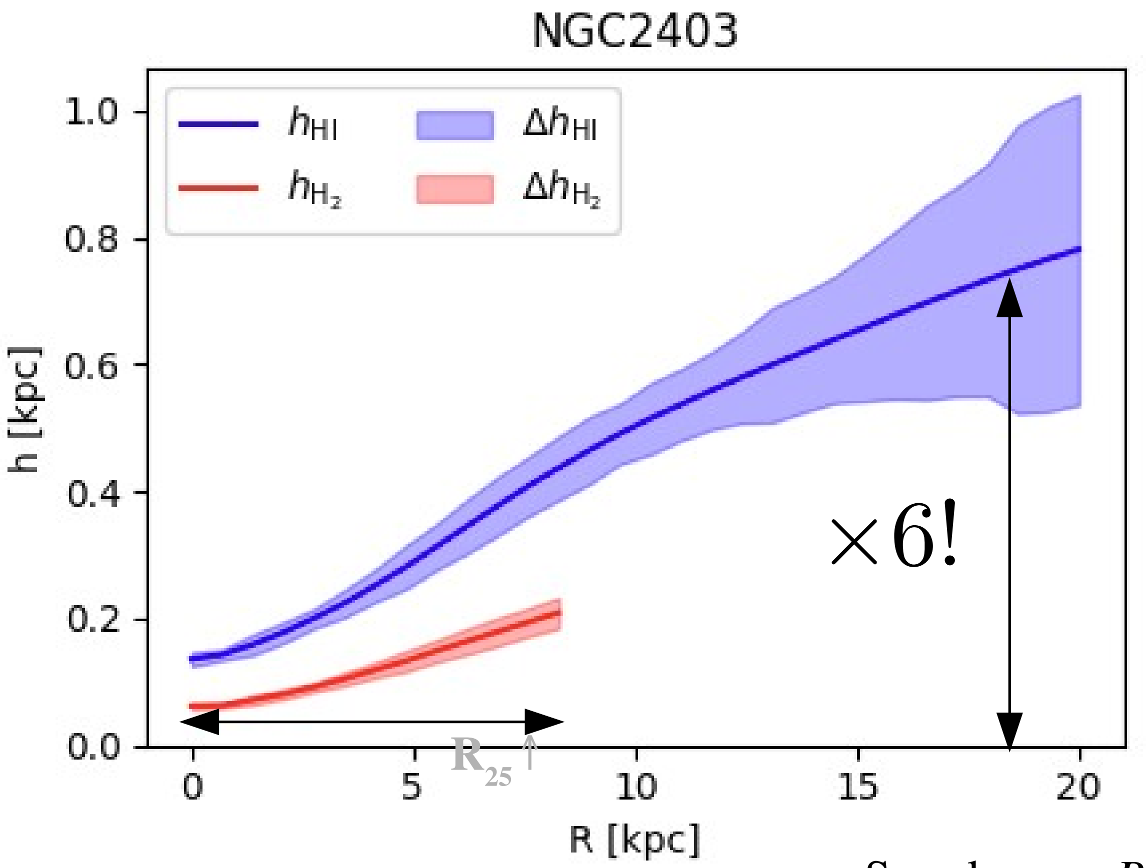
The gas scale height

Python module ***Galpynamics*** (Iorio, PhD thesis):

- Assumes vertical hydrostatic equilibrium
- Iteratively derives the scale height

The gas scale height

Gas discs have the flaring! → Constant thickness **not** a good approximation



See also e.g. *Banerjee+2011 Patra 2019, 2020a*

How to derive the volume densities?

- Atomic gas

$$\rho_{\mathrm{HI}}(R,0) = \frac{\Sigma_{\mathrm{HI}}(R)}{\sqrt{2\pi}h_{\mathrm{HI}}(R)}$$

- Molecular gas

$$\rho_{\mathrm{H_2}}(R,0) = \frac{\Sigma_{\mathrm{H_2}}(R)}{\sqrt{2\pi}h_{\mathrm{H_2}}(R)}$$

- Star formation rate

$$\rho_{\mathrm{SFR}}(R,0) = \frac{\Sigma_{\mathrm{SFR}}(R)}{\sqrt{2\pi}h_{\mathrm{SFR}}(R)}$$

???

How to derive the volume densities?

- Atomic gas

$$\rho_{\mathrm{HI}}(R,0) = \frac{\Sigma_{\mathrm{HI}}(R)}{\sqrt{2\pi}h_{\mathrm{HI}}(R)}$$

- Molecular gas

$$\rho_{\mathrm{H_2}}(R,0) = \frac{\Sigma_{\mathrm{H_2}}(R)}{\sqrt{2\pi}h_{\mathrm{H_2}}(R)}$$

- Star formation rate

$$\rho_{\mathrm{SFR}}(R,0) = \frac{\Sigma_{\mathrm{SFR}}(R)}{\sqrt{2\pi}h_{\mathrm{SFR}}(R)}$$

$$h_{\mathrm{SFR}} = \begin{cases} \mathrm{const} \\ h_{\mathrm{gas}} \end{cases}$$

e.g. Van der Kruit & Searle 1981

e.g. Mackereth+2017

$$h_{\mathrm{gas}} = f_{\mathrm{HI}} h_{\mathrm{HI}} + f_{\mathrm{H_2}} h_{\mathrm{H_2}}$$

Gas fractions

How to derive the volume densities?

- Atomic gas

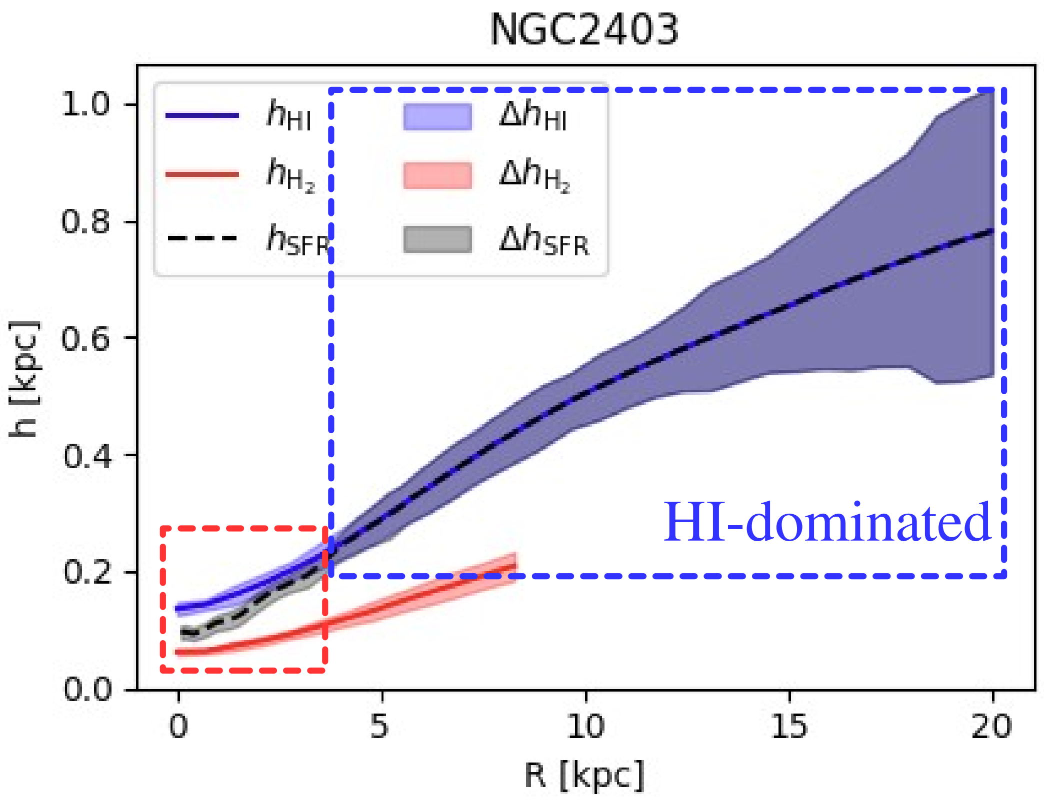
$$\rho_{\mathrm{HI}}(R,0) = \frac{\Sigma_{\mathrm{HI}}(R)}{\sqrt{2\pi}h_{\mathrm{HI}}(R)}$$

- Molecular gas

$$\rho_{\mathrm{H_2}}(R,0) = \frac{\Sigma_{\mathrm{H_2}}(R)}{\sqrt{2\pi}h_{\mathrm{H_2}}(R)}$$

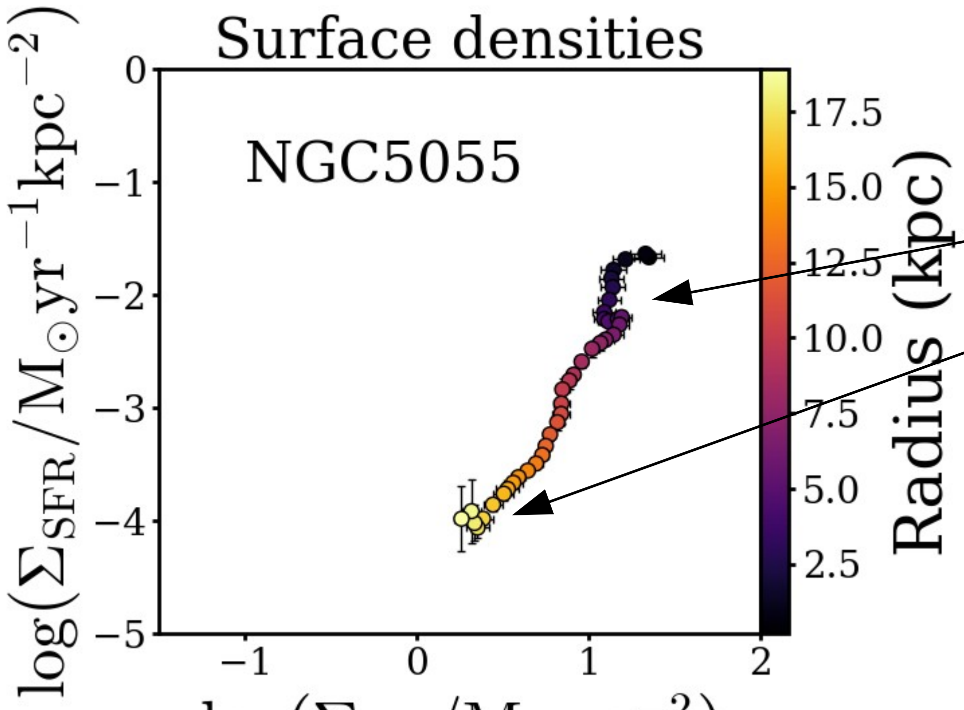
- Star formation rate

$$\rho_{\mathrm{SFR}}(R,0) = \frac{\Sigma_{\mathrm{SFR}}(R)}{\sqrt{2\pi}h_{\mathrm{SFR}}(R)}$$

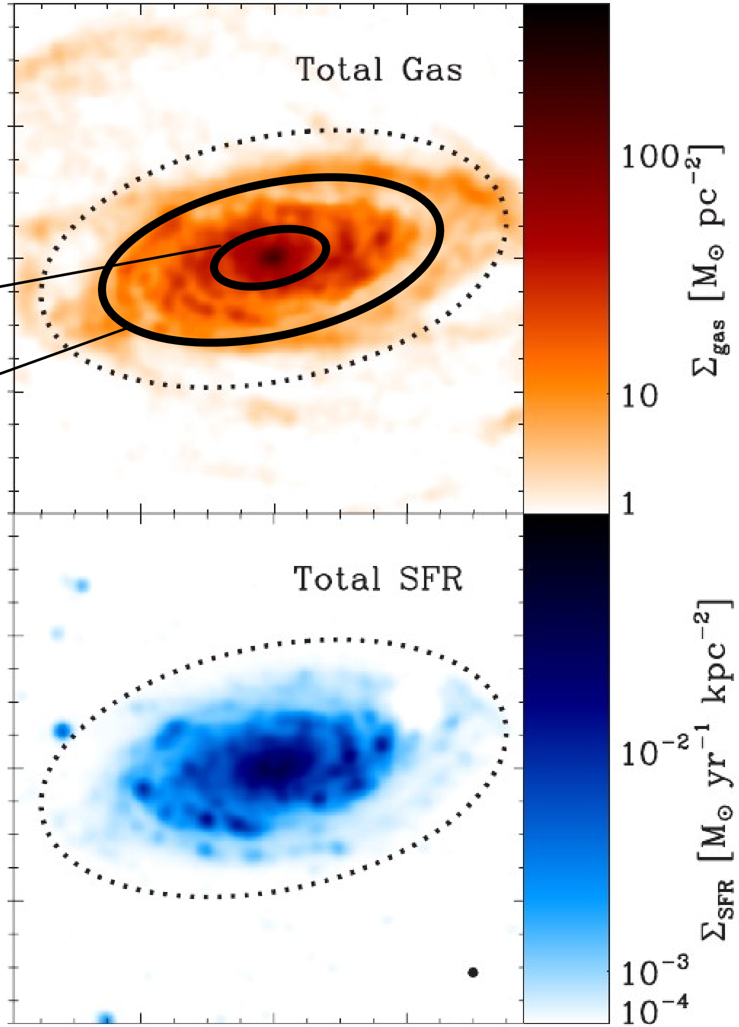


Flaring h_{SFR}

Effect of the conversion to volume densities



Azimuthally averaged radial profiles



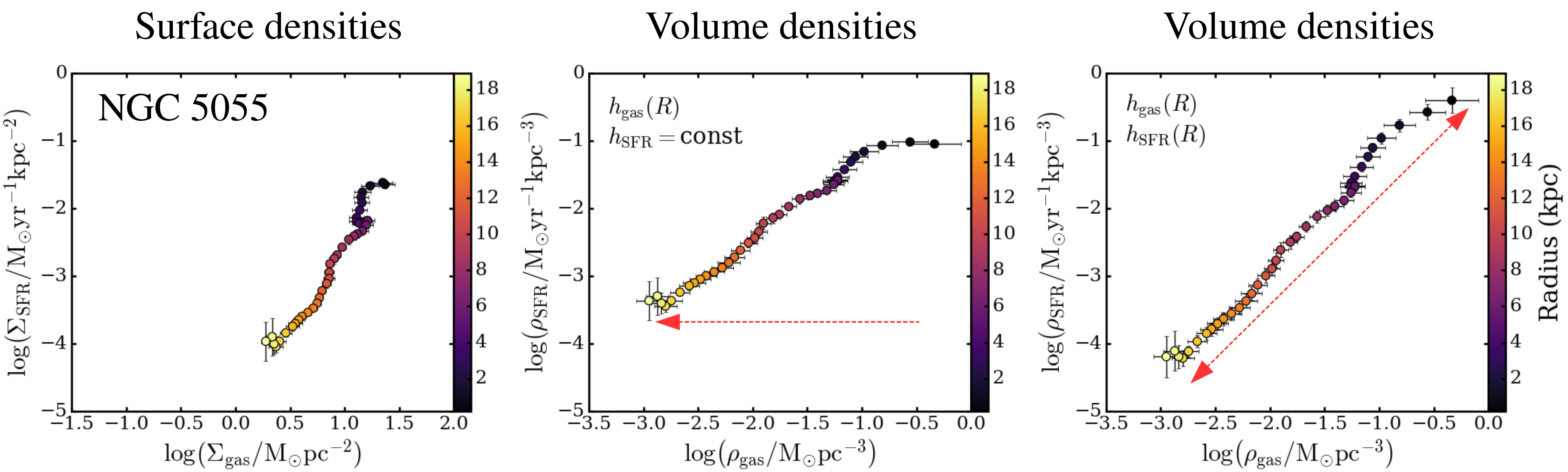
Leroy+2008

$\Sigma_{\rm gas}$

$R \leq R_{25}$

$\Sigma_{\rm SFR}$

Effect of the conversion to volume densities

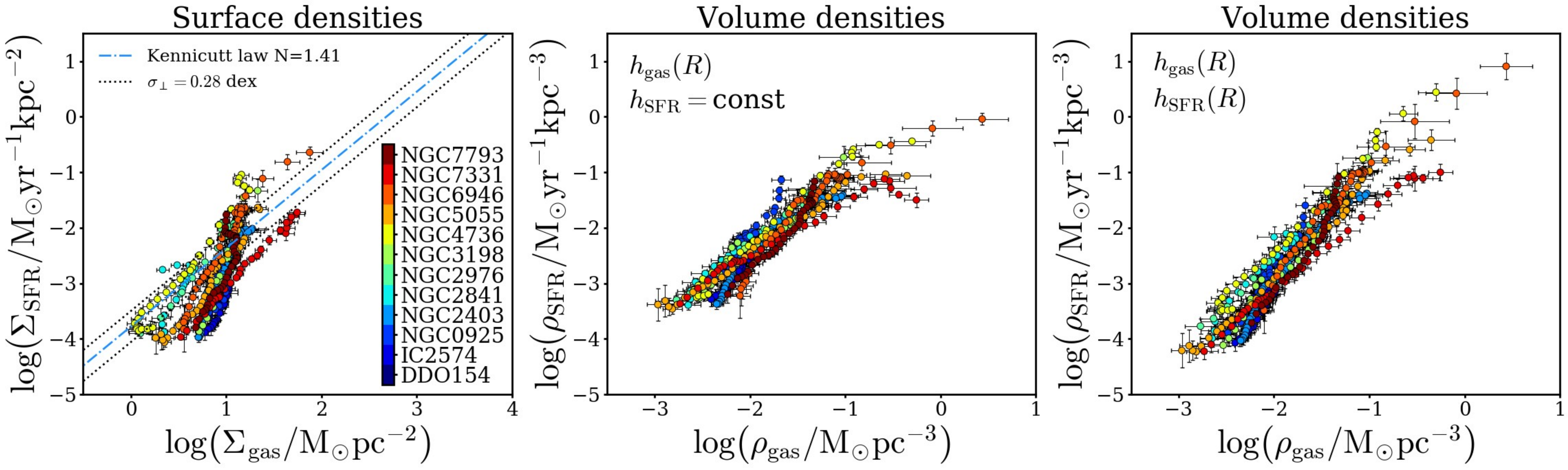


$$R \leq R_{25}$$

VSF law with total gas

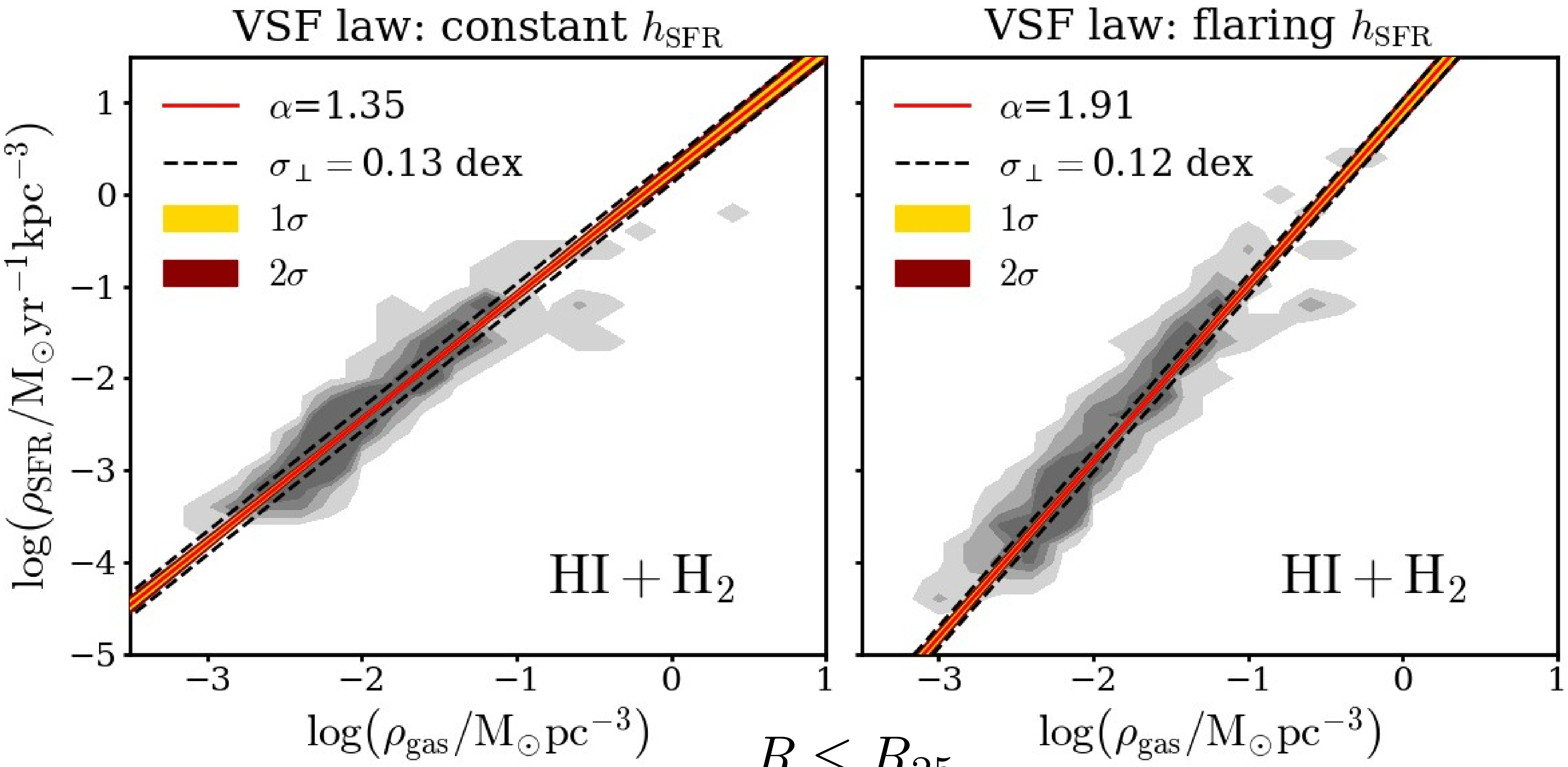
Break
Density threshold?

No break
No density threshold



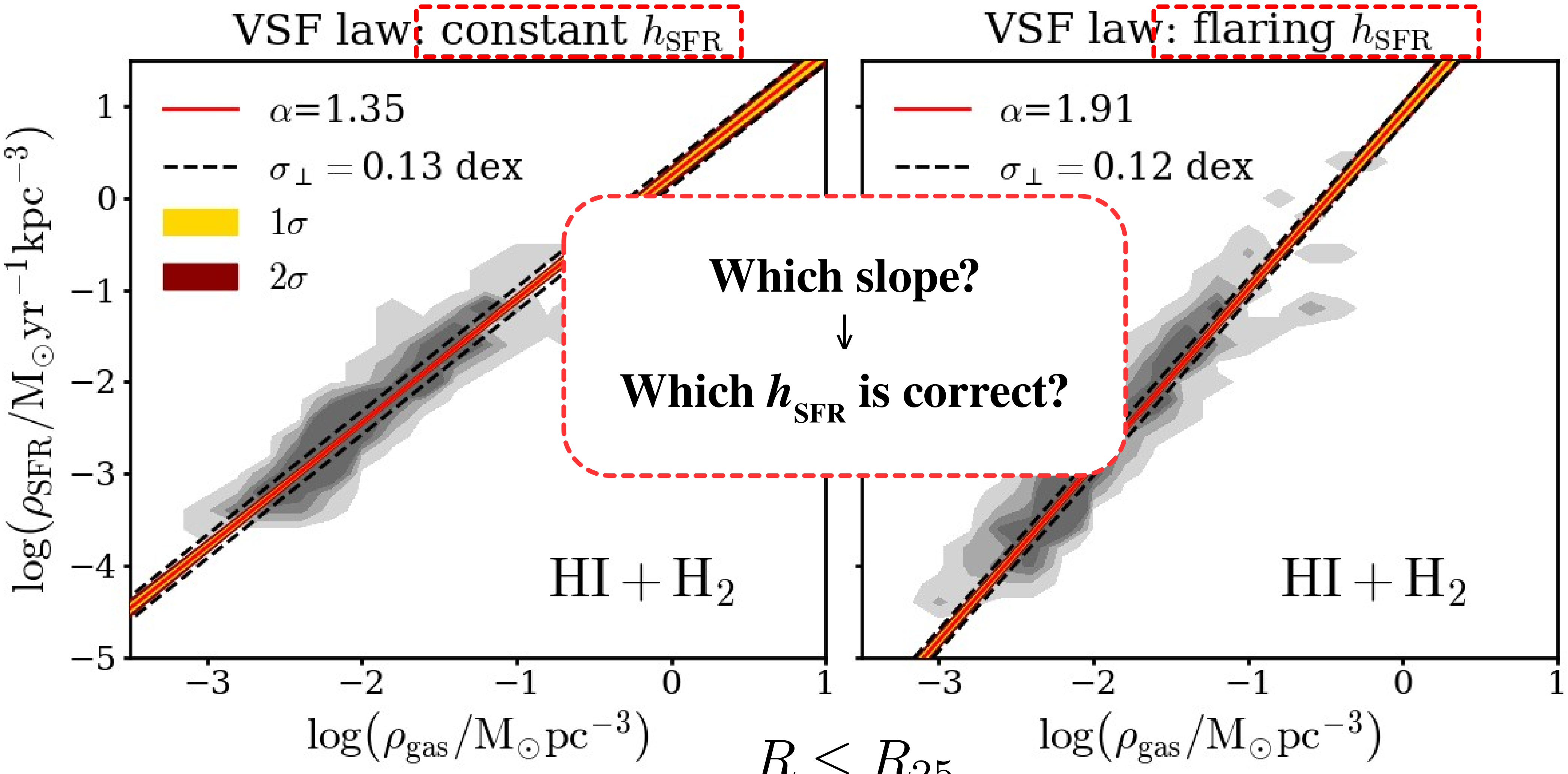
$$R \leq R_{25}$$

VSF law with total gas



$R \leq R_{25}$

VSF law with total gas



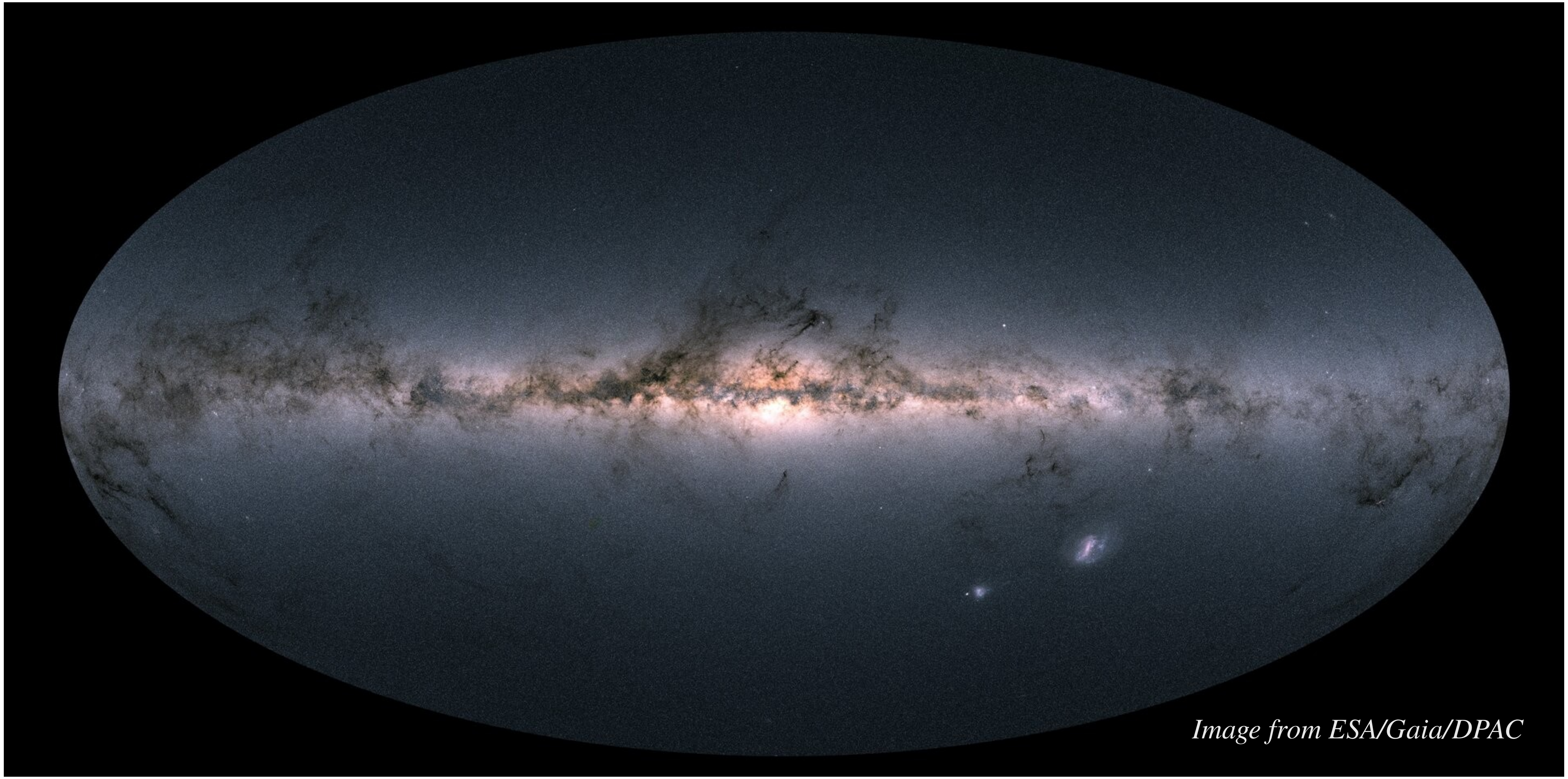
Which slope?

↓

Which h_{SFR} is correct?

$R \leq R_{25}$

The volumetric star formation law in the Milky Way
Bacchini, Fraternali, Pezzulli, Marasco, Iorio, & Nipoti, 2019b, A&A, 632, A127.



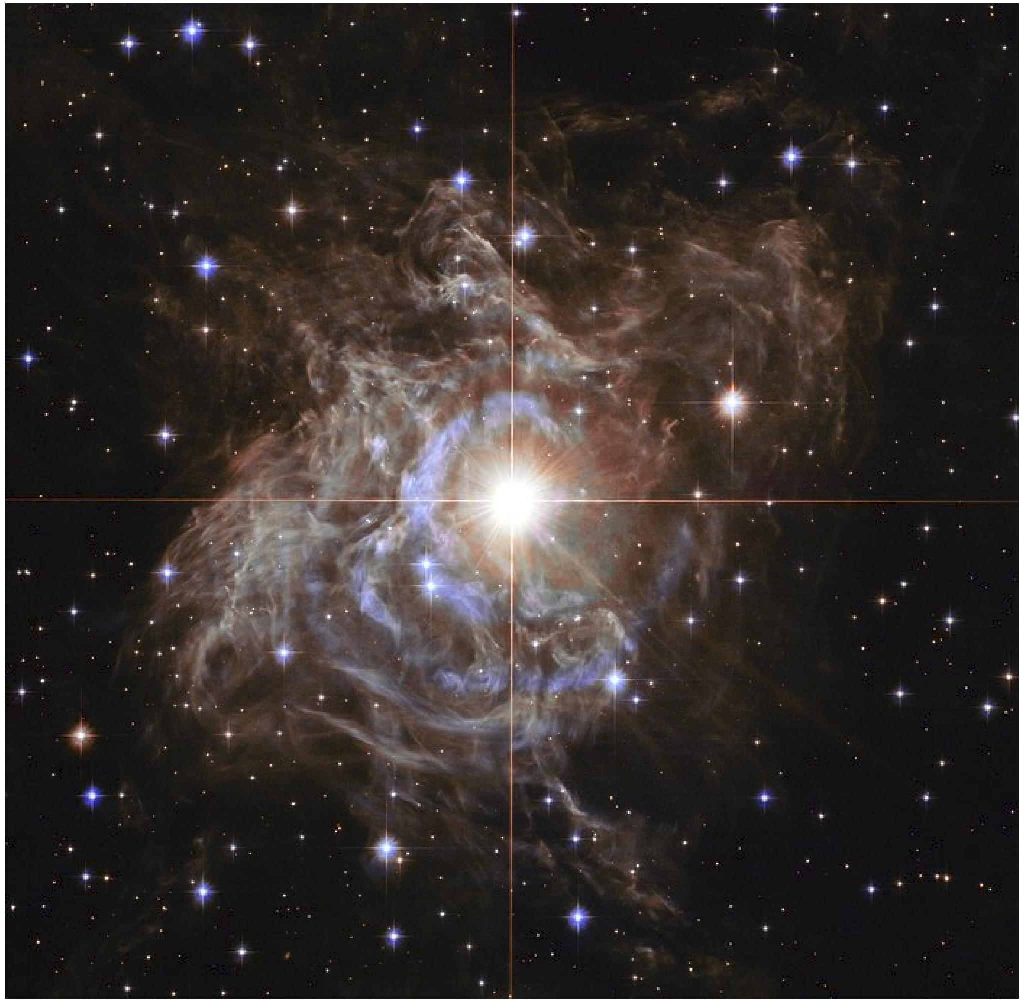
The SFR scale height in the Milky Way

Observed
SFR scale height

↓

Classical Cepheids
(age $\lesssim$ 200 Myr)

Credit: NASA, ESA, STScI/AURA-Hubble/Europe Collaboration



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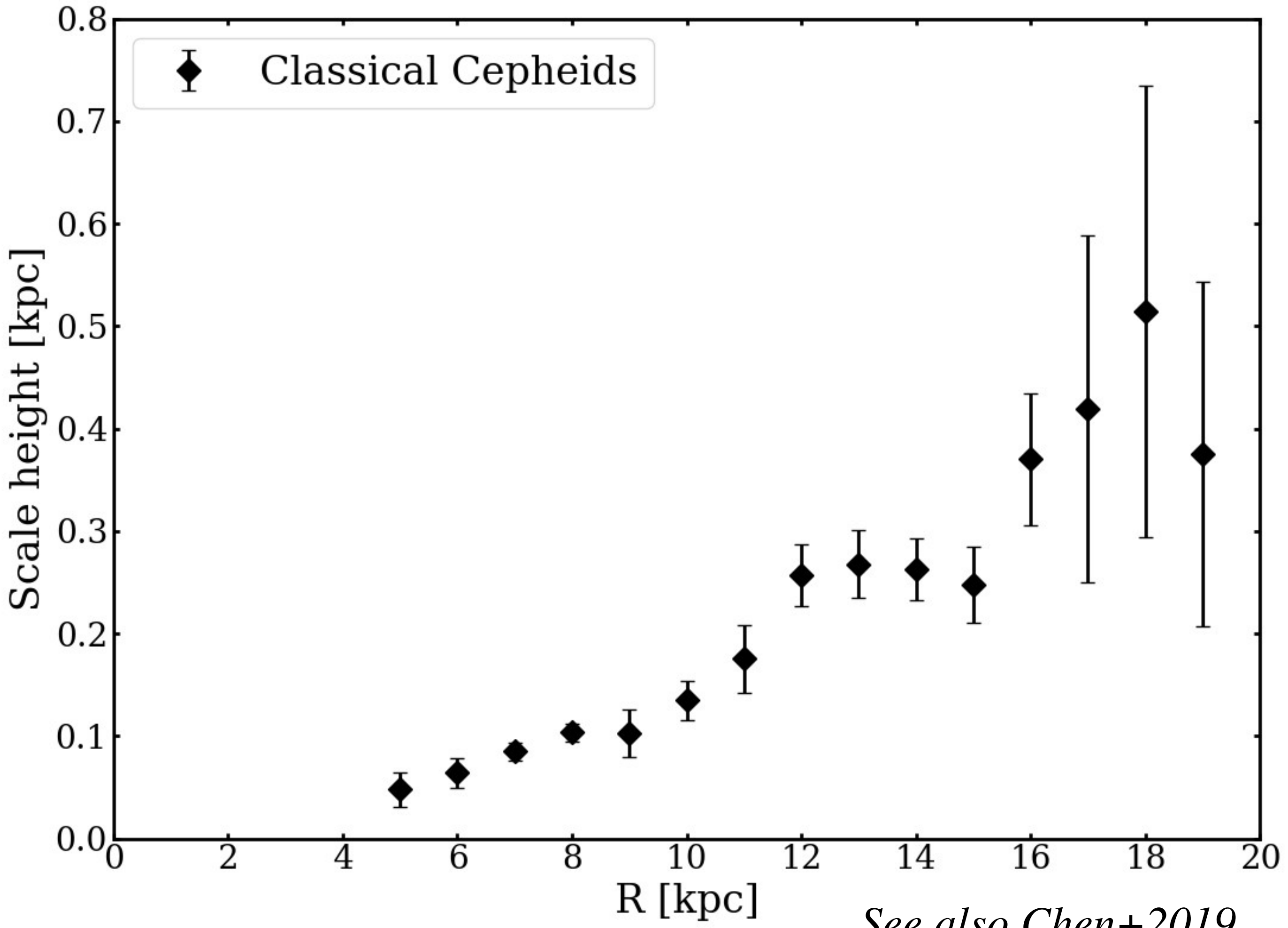


See also Chen+2019

The SFR scale height in the Milky Way

Observed
SFR scale height

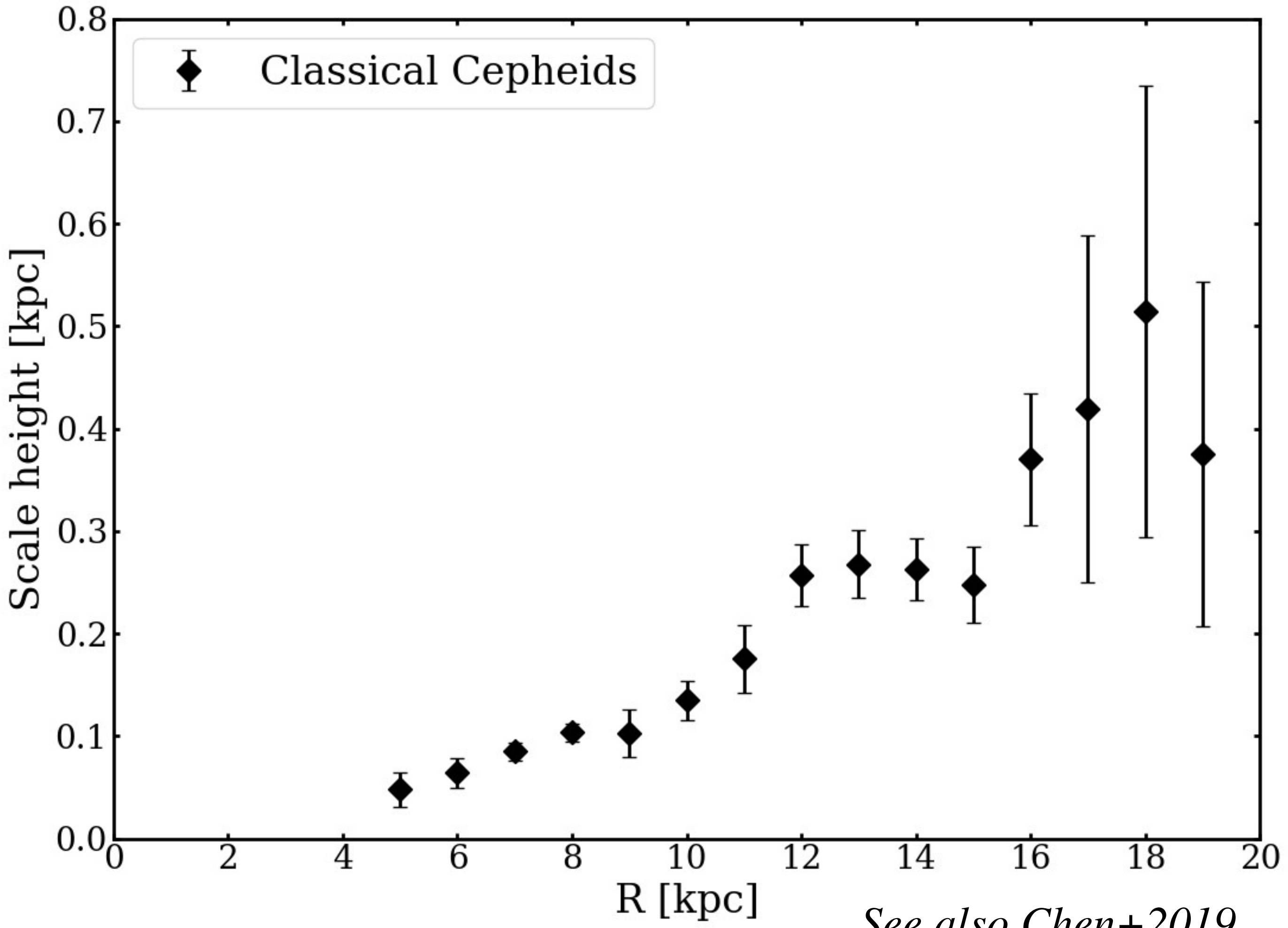
↓

Classical Cepheids
(age $\lesssim$ 200 Myr)

↓

$$h_{\rm SFR} \simeq h_{\rm gas}?$$

$$h_{\rm gas} = f_{\rm HI} h_{\rm HI} + f_{\rm H_2} h_{\rm H_2}$$



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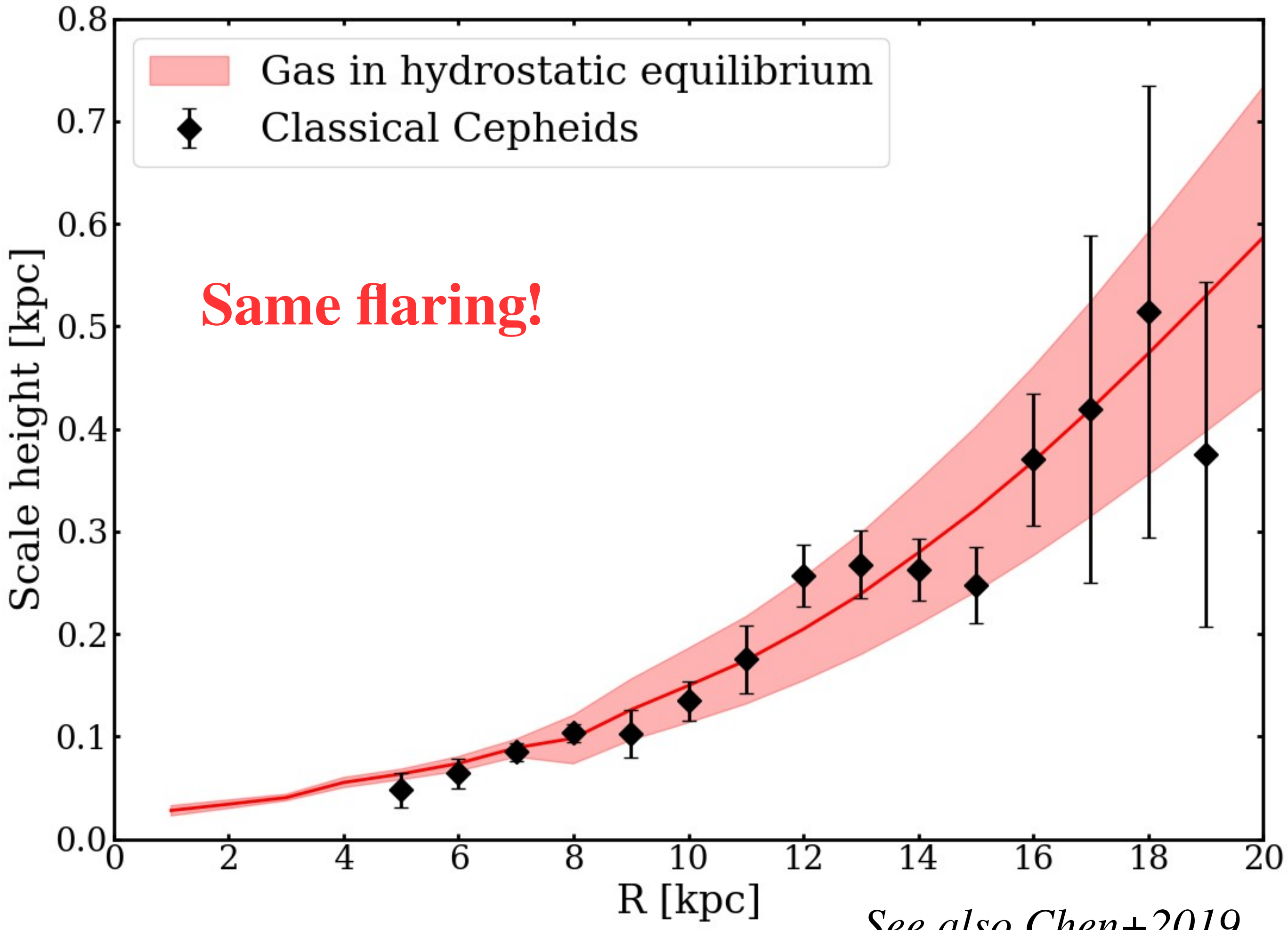
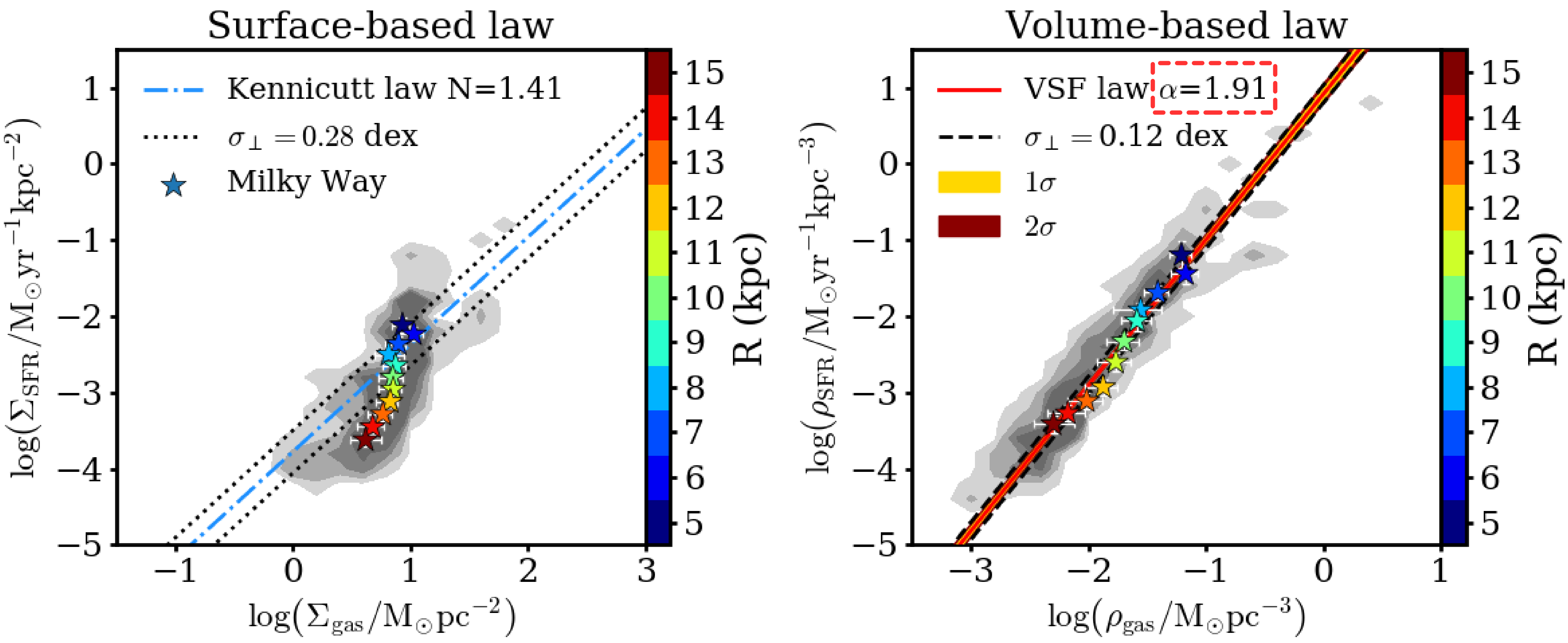
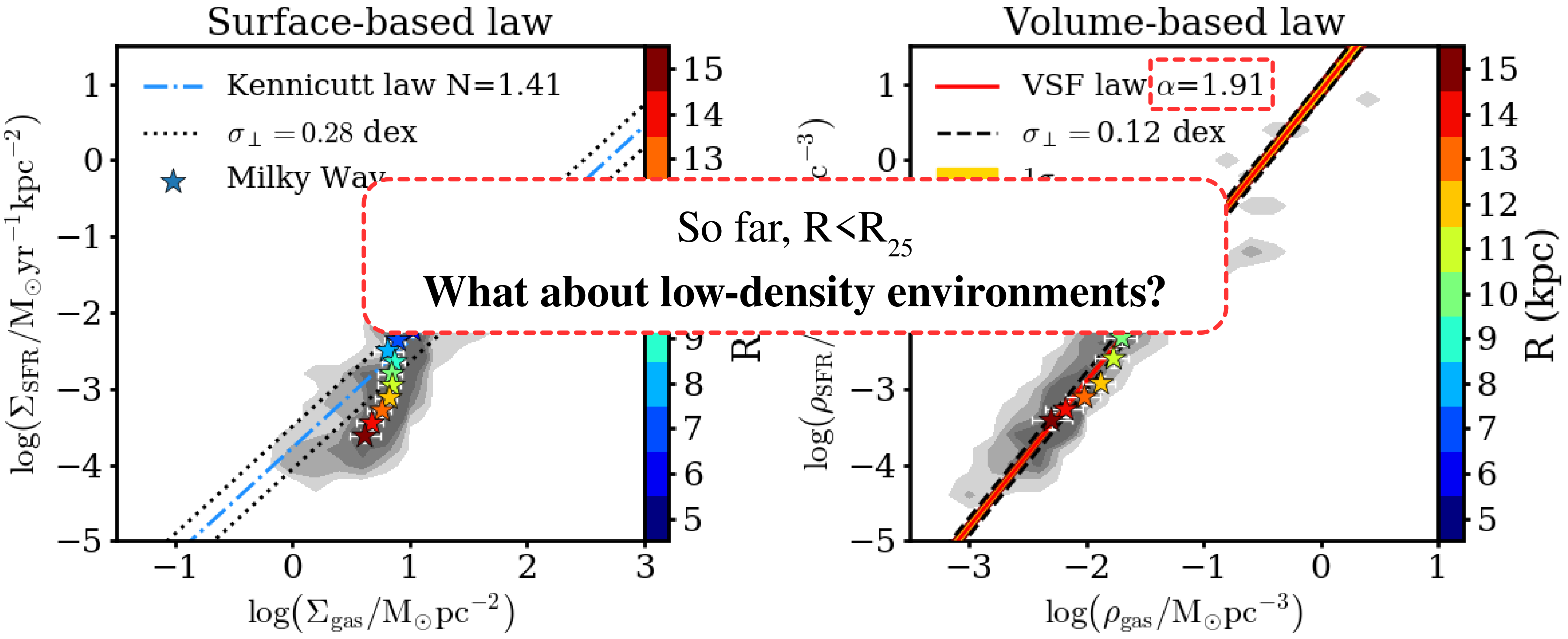


See also Chen+2019

VSF law vs SK law in the Milky Way



VSF law vs SK law in the Milky Way



So far, $R<R_{25}$

What about low-density environments?

The volumetric star formation law for nearby dwarf galaxies

Bacchini, Fraternali, Pezzulli & Marasco, 2020b, A&A, 644, A125.

Credit: NASA, ESA, STScI/AURA-Hubble/Europe Collaboration

Sample selection

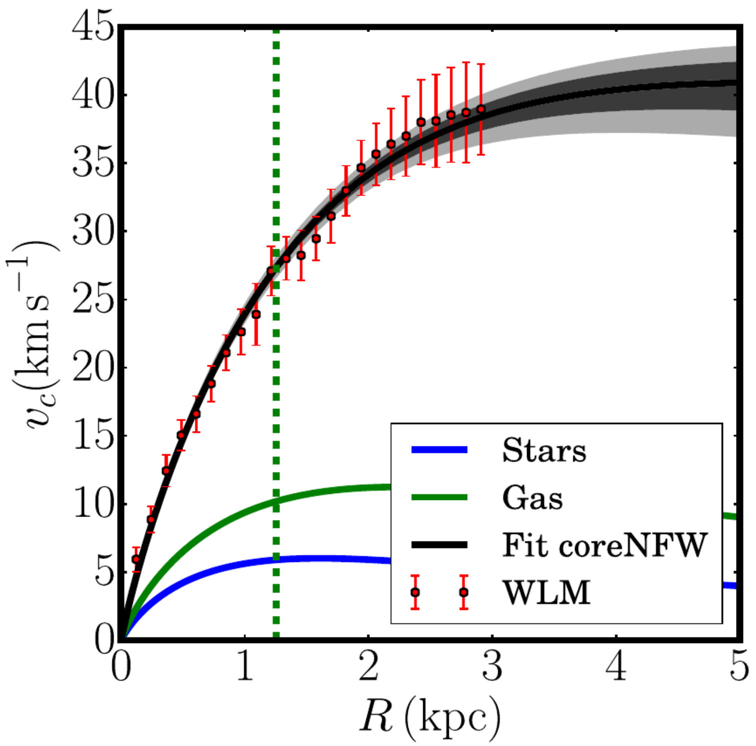
- 10 **dwarf** galaxies (LITTLE THINGS; *Hunter+2012*);
- Extend analysis of 5 spiral and 2 dwarf galaxies beyond R_{25}.

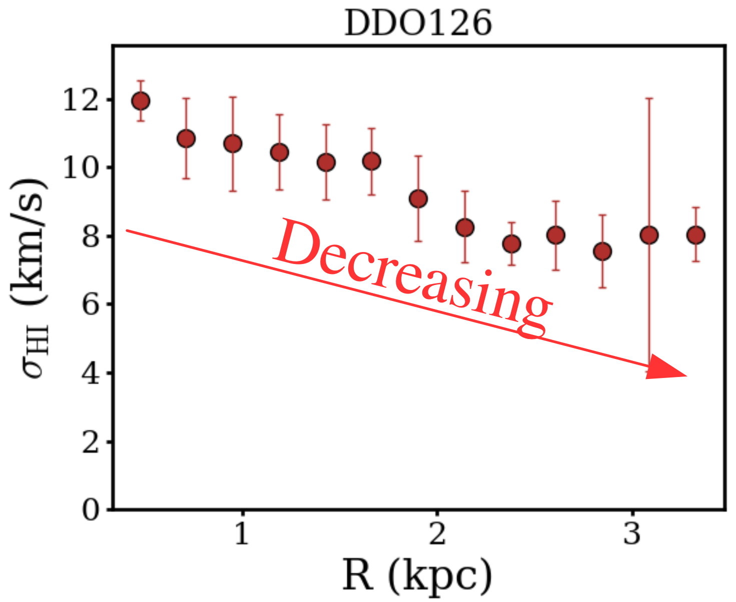
From the literature:

1) Rotation curve decomposition *(Read+2017)*
→ **gravitational potential**

2) HI and SFR (FUV) **surface densities**
(Bigiel+2008; McQuinn+2015)

3) HI velocity dispersion *(Iorio+2017)*



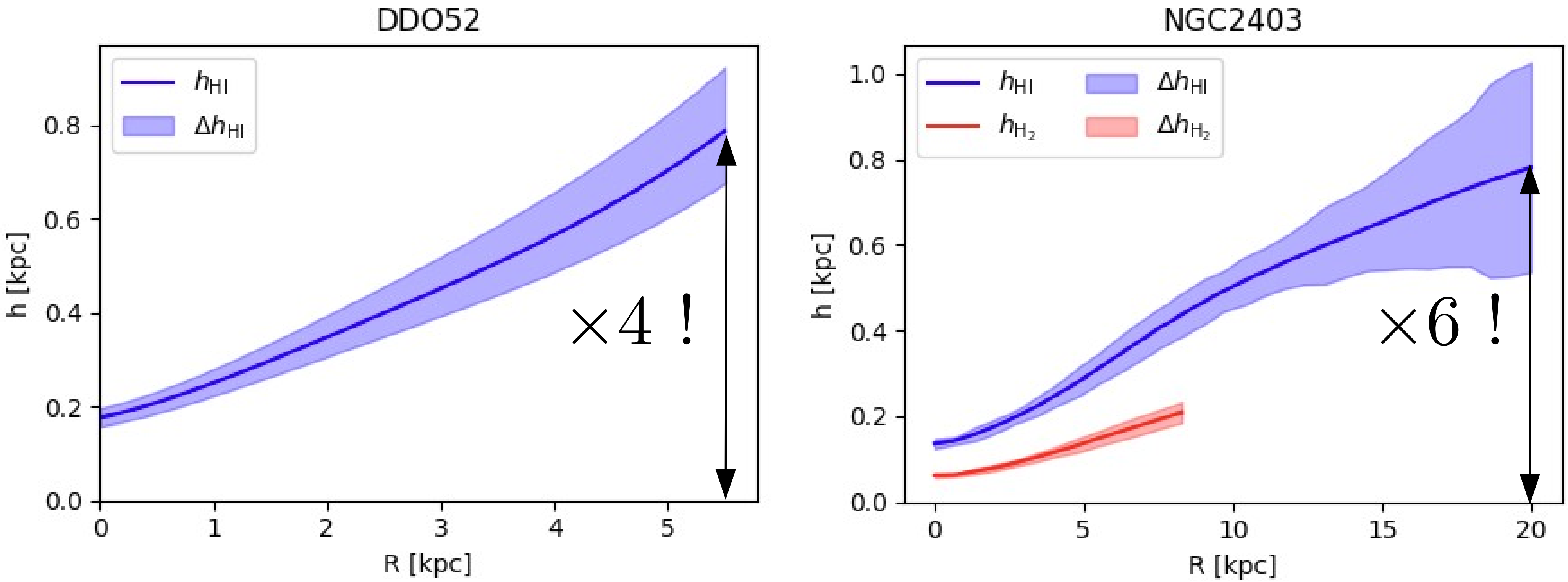


The gas scale height

Gas discs have the flaring! → Constant thickness **not** a good approximation

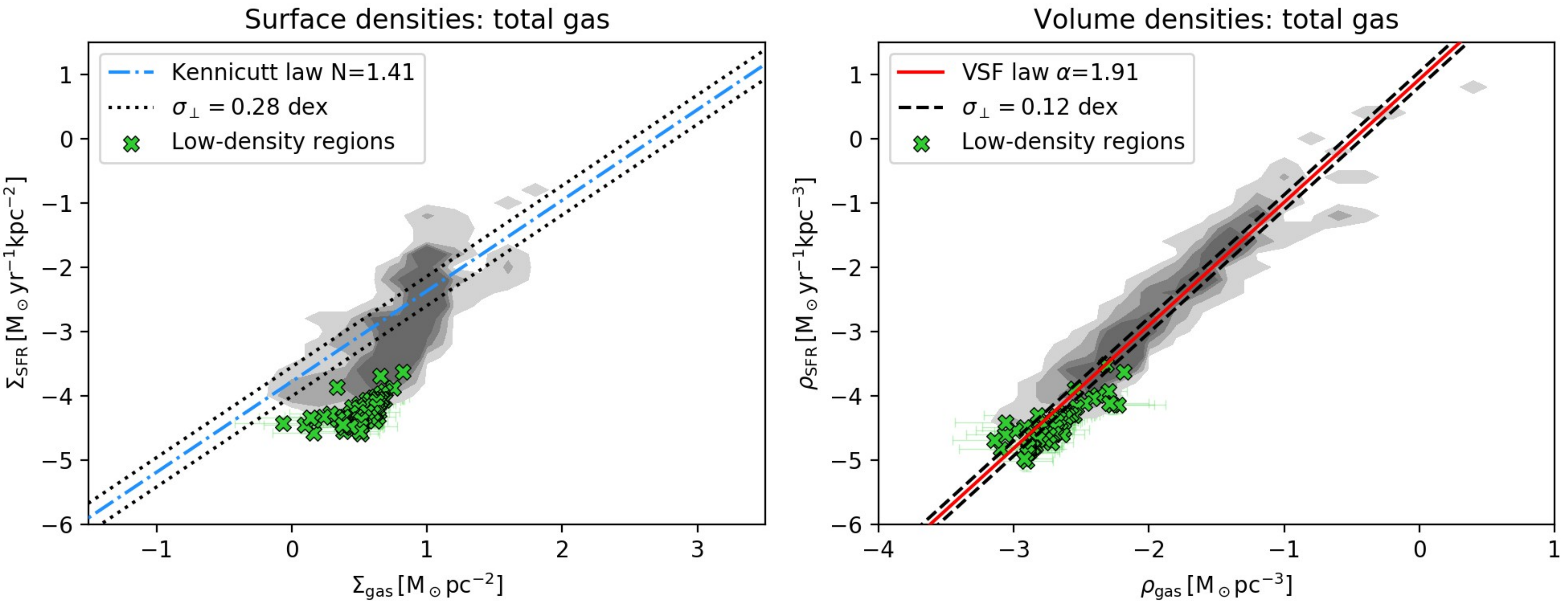
Dwarf galaxy

Spiral galaxy



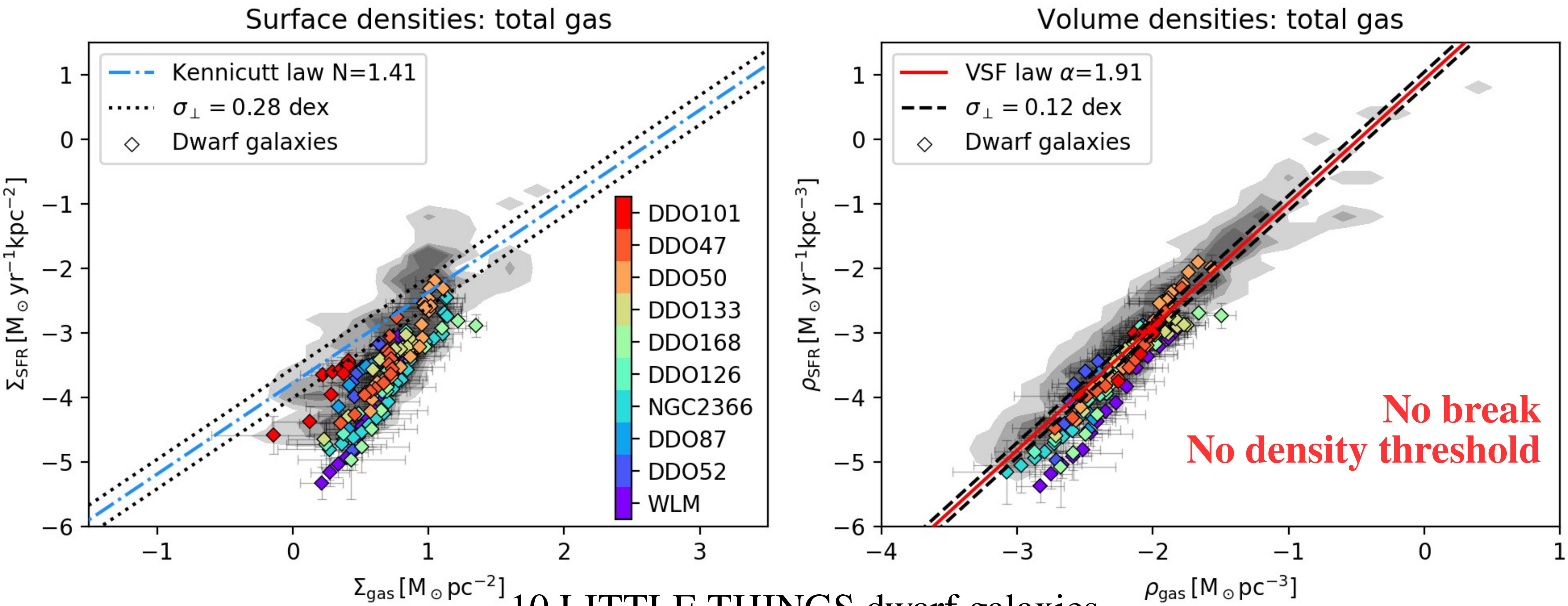
See also e.g. *Banerjee+2011 Patra 2019, 2020a*

SF laws in the outermost star-forming regions



Beyond R_{25}

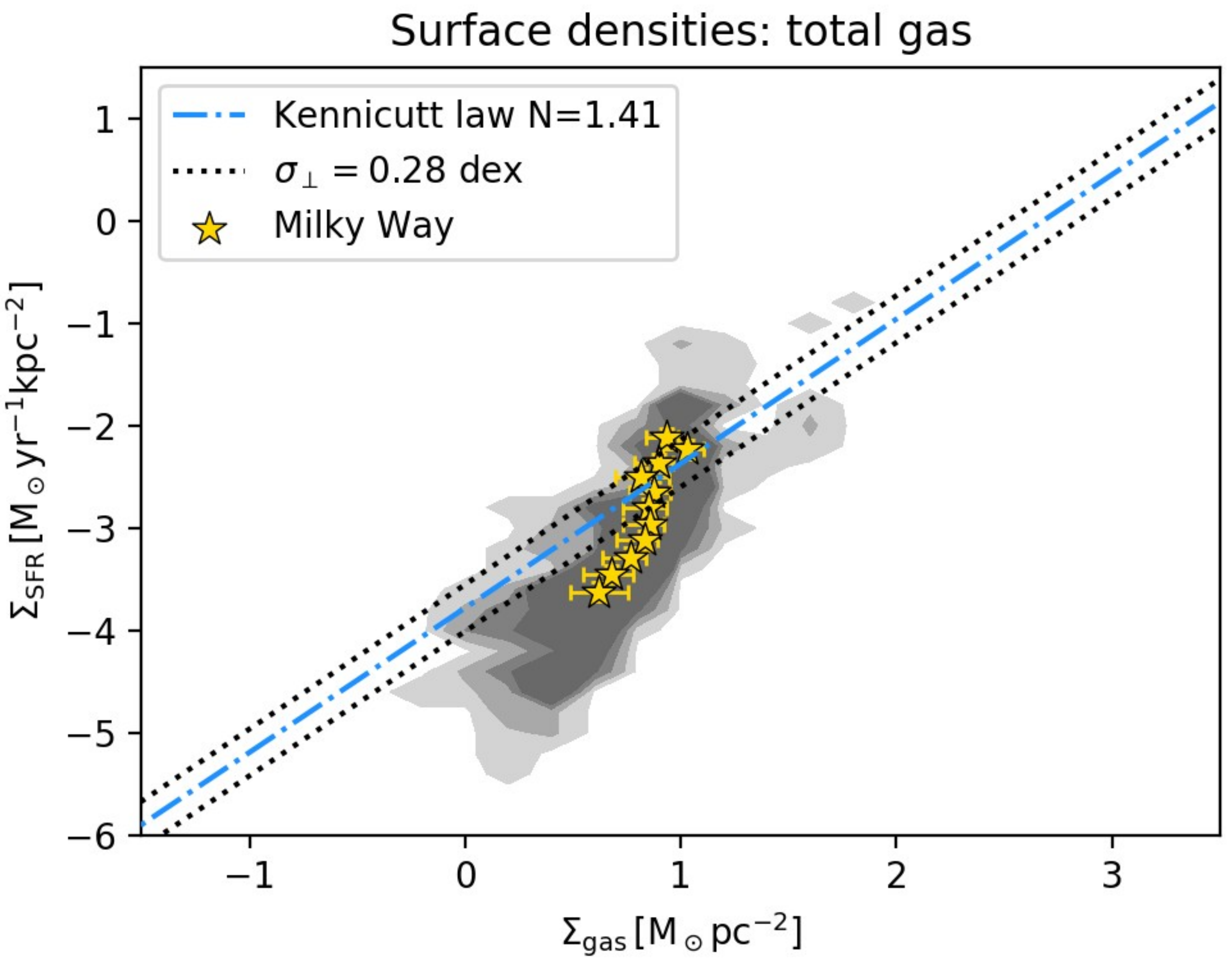
SF laws in dwarf irregular galaxies

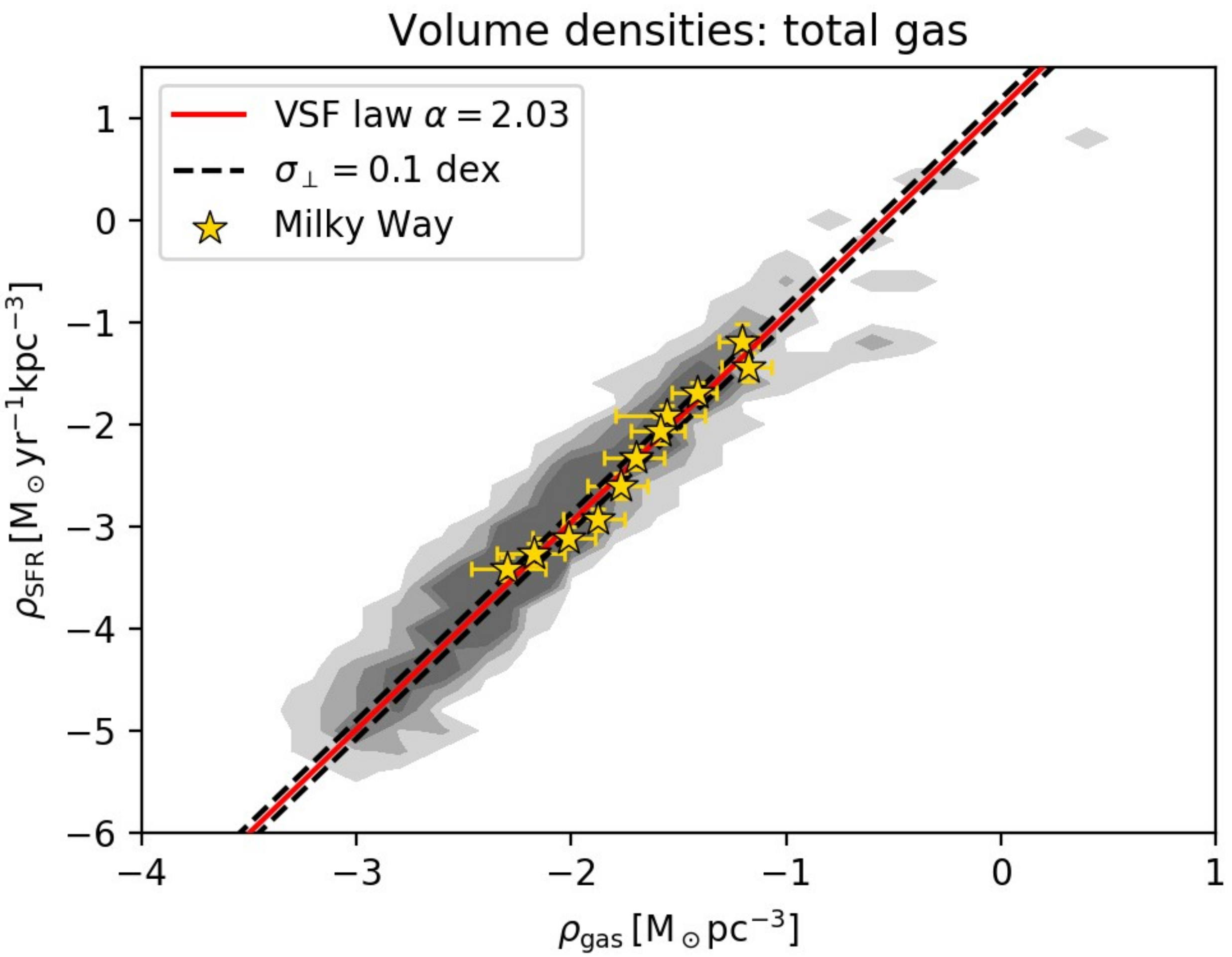


No break
No density threshold

10 LITTLE THINGS dwarf galaxies

New best-fit VSF law



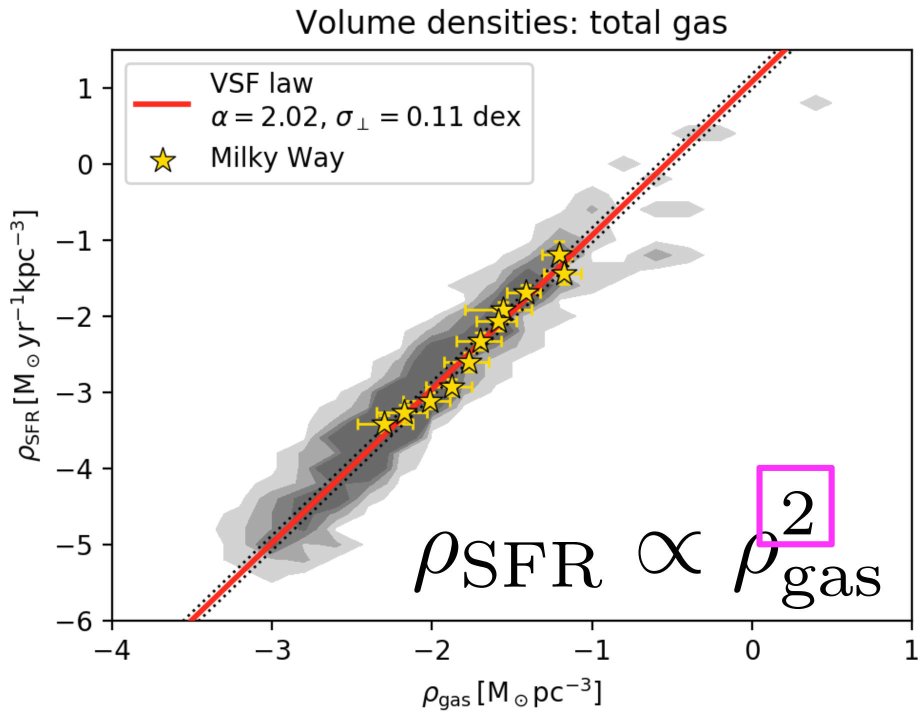


Physical interpretation

$$\rho_{\rm SFR} = \epsilon \frac{\rho_{\rm gas}}{\tau_{\rm sf}} \qquad \begin{aligned} \epsilon &= \text{ efficiency} = \text{ constant} \\ \tau_{\rm sf} &= \text{ star formation timescale} \end{aligned}$$

Gravitational instability

$$\tau_{\rm ff} \propto (G\rho_{\rm gas})^{-\frac{1}{2}} \Rightarrow \rho_{\rm SFR} \propto \rho_{\rm gas}^{1.5}$$



$$\rho_{\rm SFR} \propto \rho_{\rm gas}^{2}$$

Physical interpretation

$$\rho_{\mathrm{SFR}} = \epsilon \frac{\rho_{\mathrm{gas}}}{\tau_{\mathrm{sf}}}$$

$\epsilon =$ efficiency $=$ constant

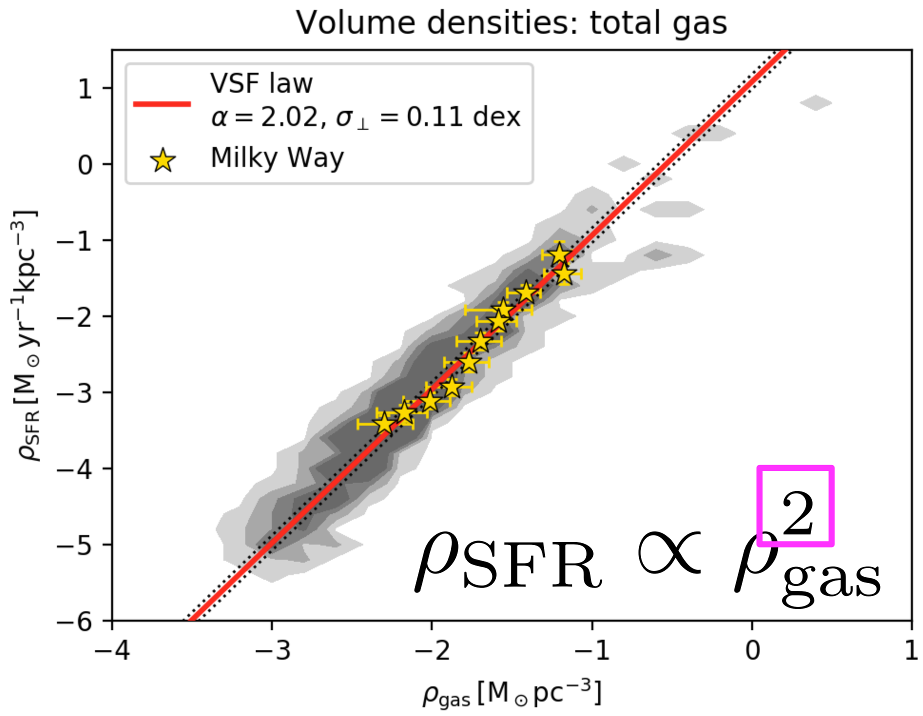
$\tau_{\mathrm{sf}} =$ star formation timescale

~~Gravitational instability~~

$$\tau_{\mathrm{ff}} \propto (G\rho_{\mathrm{gas}})^{-\frac{1}{2}} \Rightarrow \rho_{\mathrm{SFR}} \propto \rho_{\mathrm{gas}}^{1.5}$$

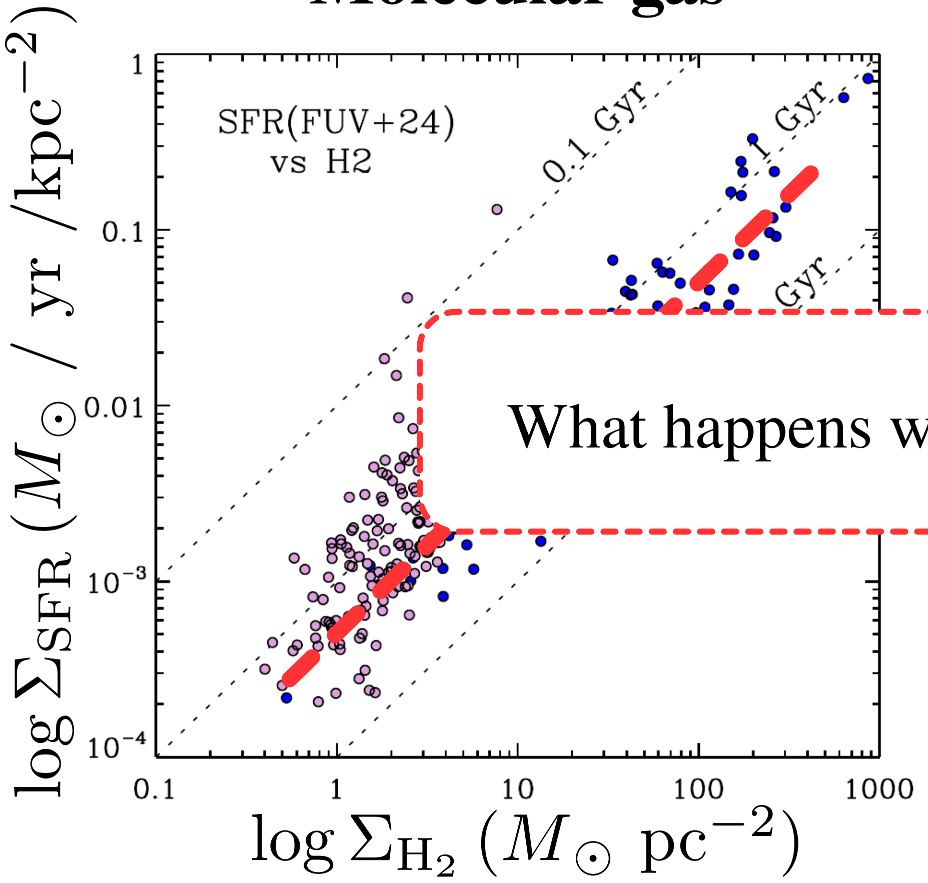
$$\tau_{\mathrm{sf}} \propto \rho_{\mathrm{gas}}^{-1} \Rightarrow \rho_{\mathrm{SFR}} \propto \rho_{\mathrm{gas}}^{2}$$

- Cooling?
- H_2 formation?

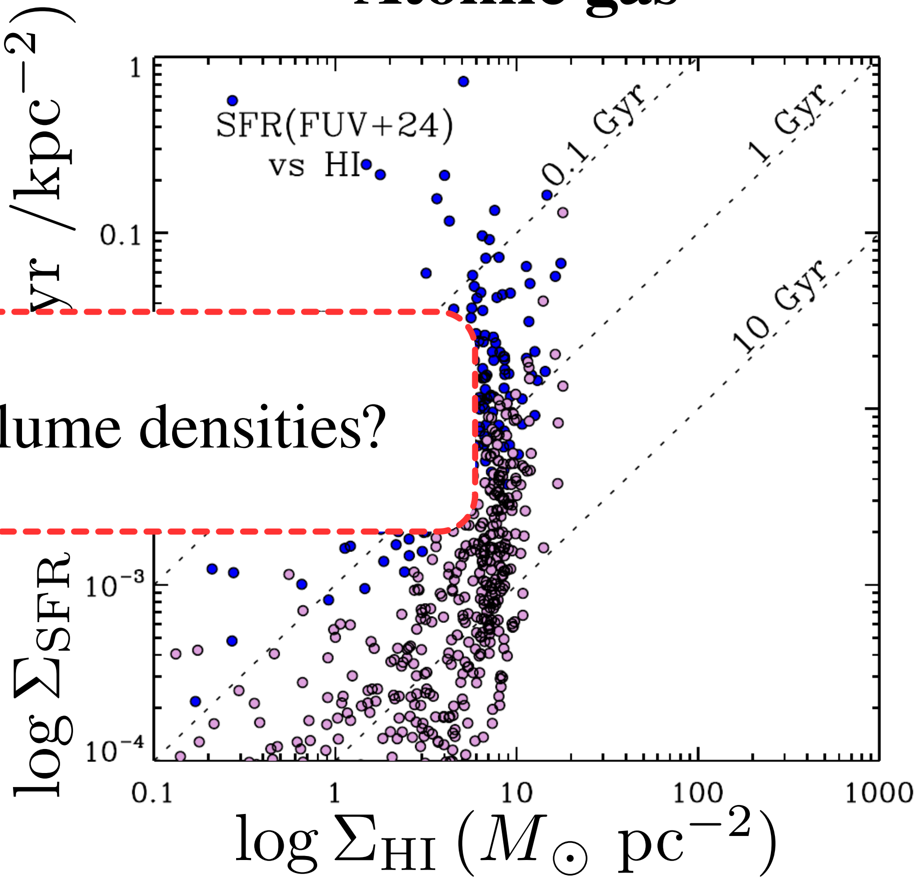


Empirical relations

Molecular gas



Atomic gas



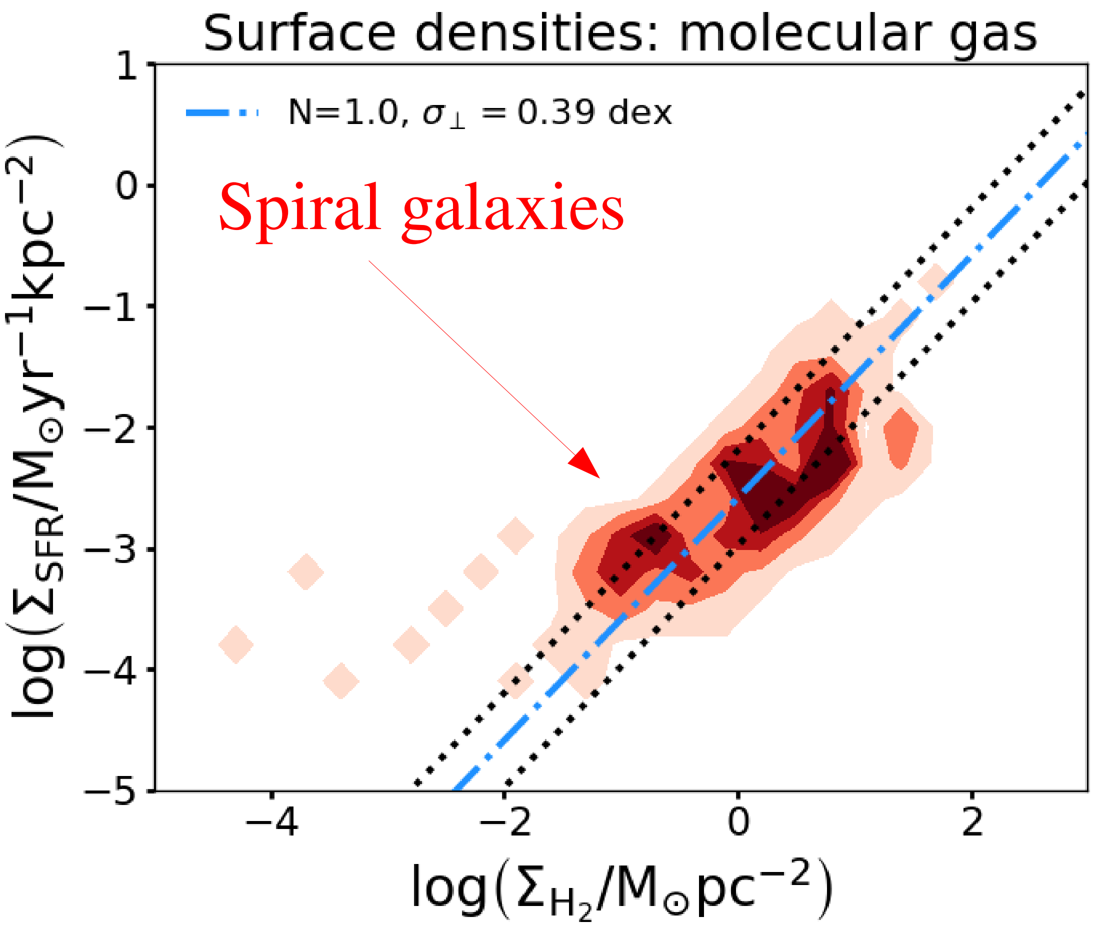
What happens with the volume densities?

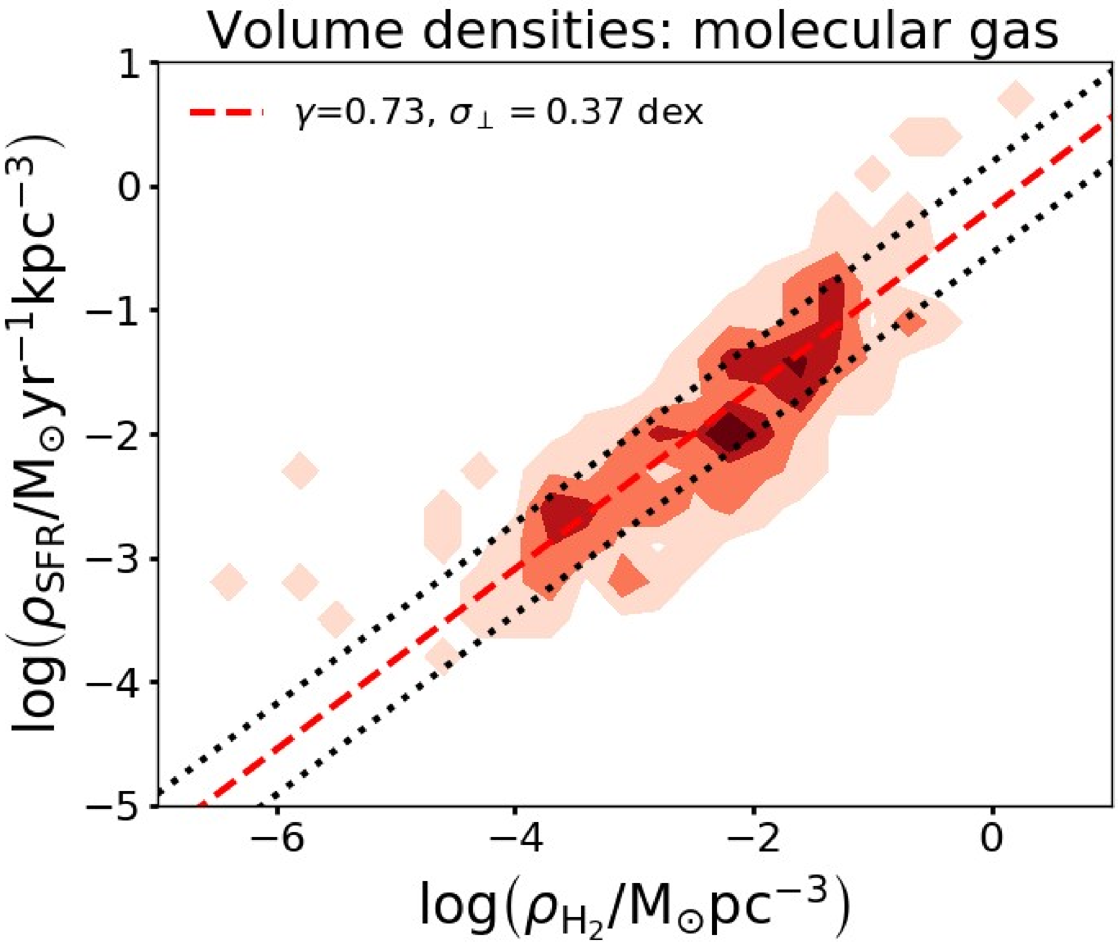
$\Sigma_{SFR} \propto \Sigma_{H_2}$

Schruba+2011

No correlation

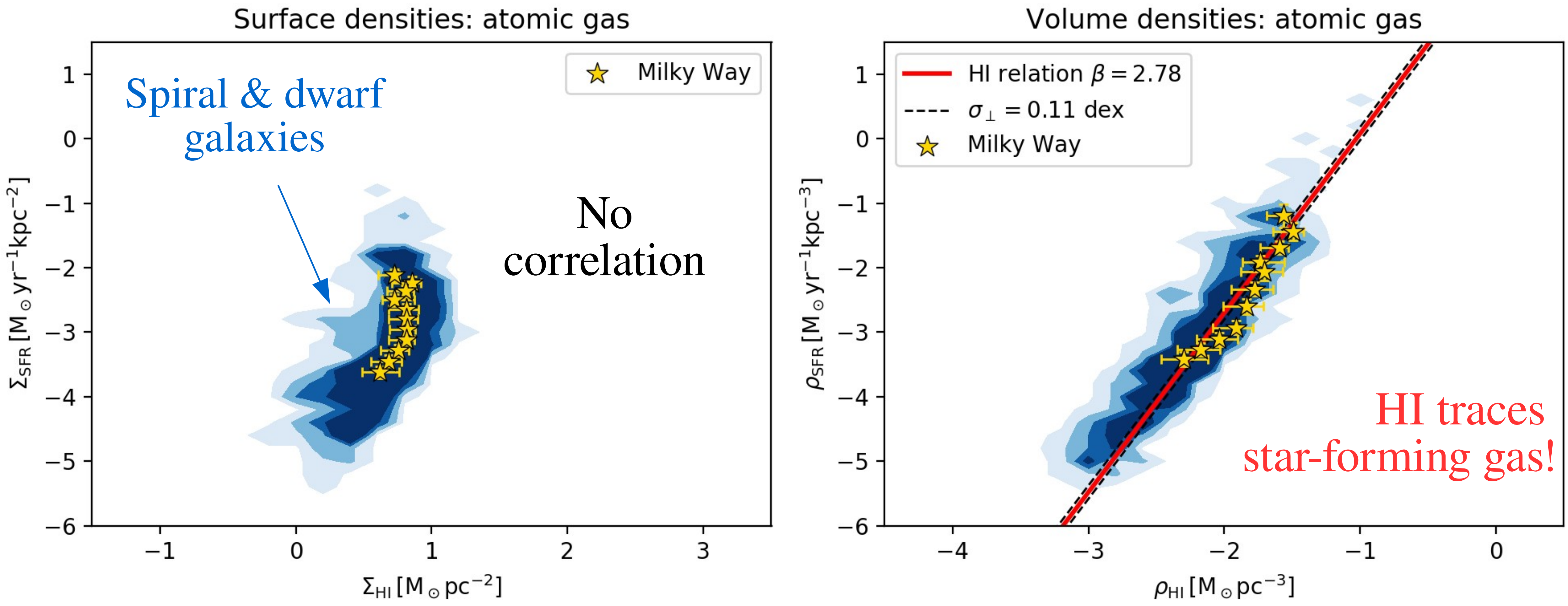
Molecular gas vs SFR





No significant improvement → small variation of H_2 scale height

Atomic gas vs SFR



Conclusions – part I

1. **Flaring** significant → no constant thickness!
2. **VSF law** (HI+H_2) for **high- & low-density** regimes, from dwarf to spiral galaxies:
    - volume densities → more fundamental;
    - no break → no density threshold;
    - $\rho_{\rm SFR} \propto \rho^2_{\rm gas}$ → not only gravity.
3. Volumetric relation **SFR-HI** → HI traces star-forming gas.

Open questions

- Is the VSF law valid for starbursts?
- … and for early-type galaxies hosting a star-forming disc?
- How to measure the scale height from observations?

Part II

Gas turbulence in nearby galaxies

Evidence for supernova feedback sustaining gas turbulence in nearby star-forming galaxies

Bacchini, Fraternali, Iorio, Pezzulli, Marasco, and Nipoti, 2020a, A&A, 641, A70.

Image from Gaensler+2011

How is the ISM turbulence measured?

Velocity dispersion (σ)

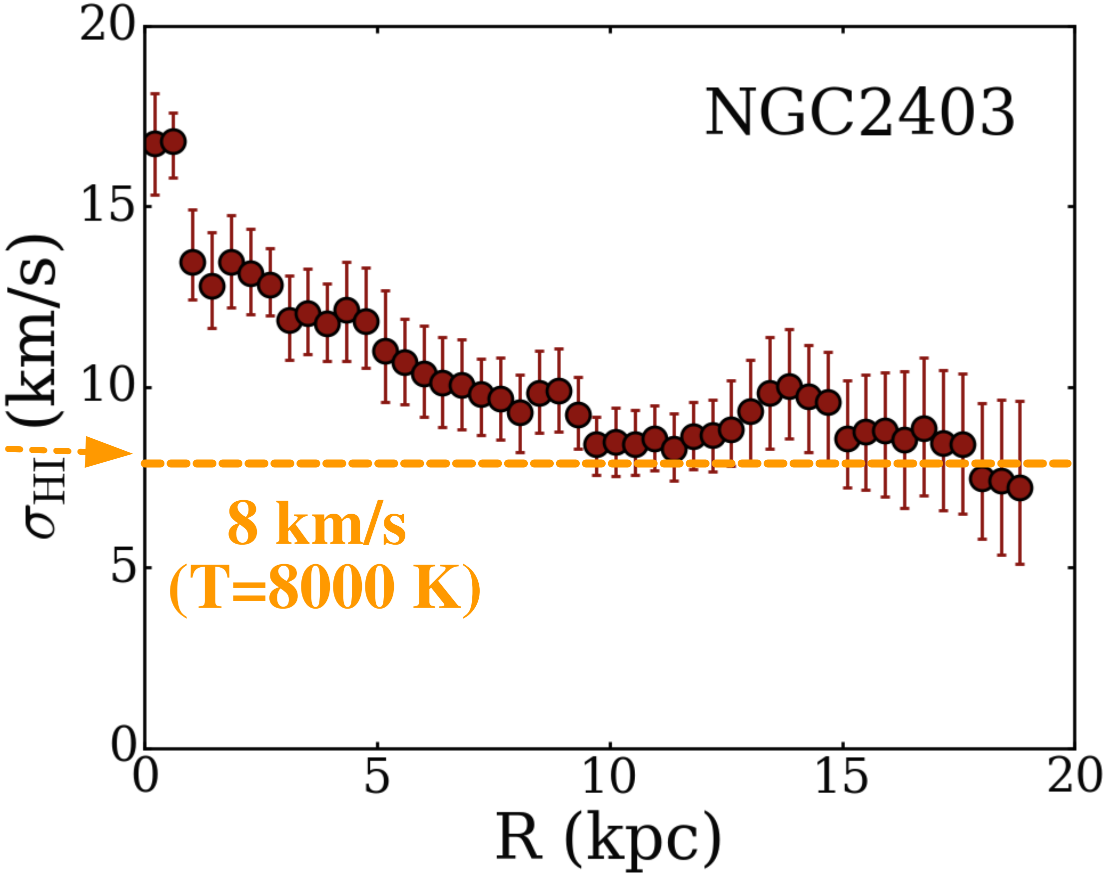
↓

σ >> thermal speed (v_{th})

↓

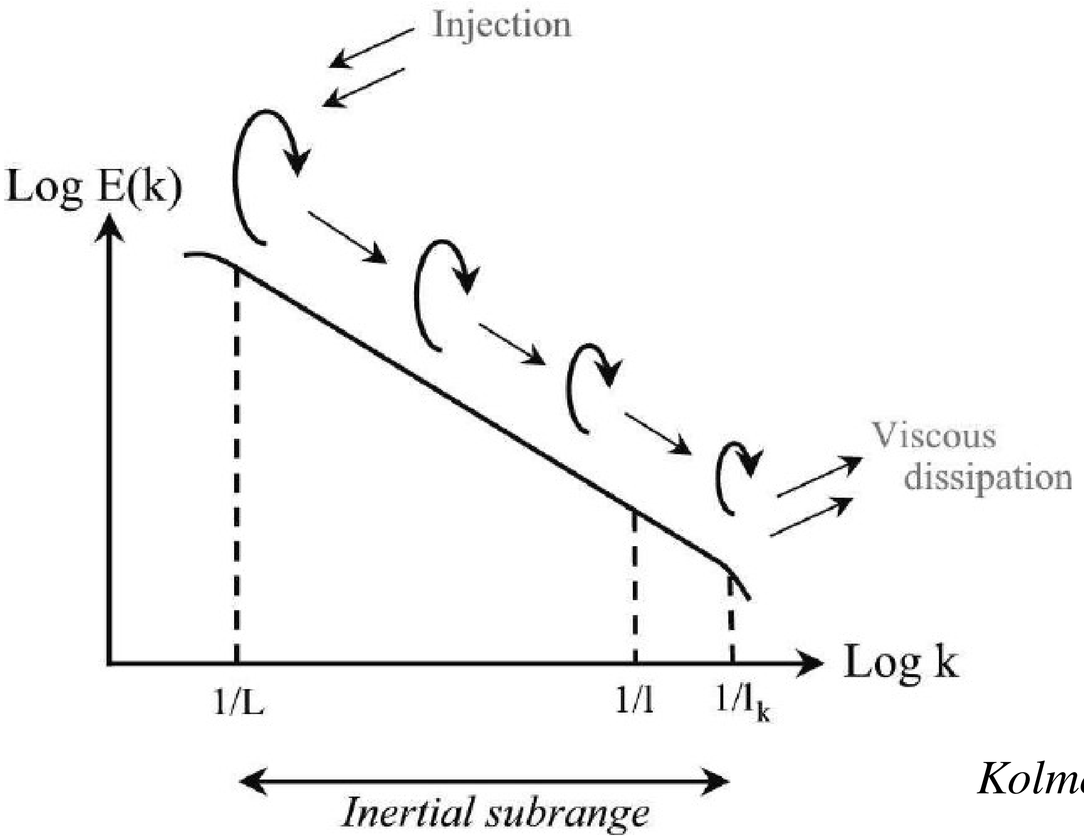
Turbulence

HI velocity dispersion



Turbulence dissipation

Kolmogorov's cascade



Stationary state:

injection rate = dissipation rate

↓

Turbulence maintained by **energy source**

Injection rate $$\dot{E}_{\rm turb} = \frac{E_{\rm turb}}{\tau}$$

Dissipation timescale $$\tau = \frac{L}{v_{\rm turb}}$$

Kolmogorov 1941

Supernova feedback

$$\dot{E}_{\mathrm{turb,SNe}} = \eta \, \Sigma_{\mathrm{SFR}} \, f_{\mathrm{cc}} \, E_{\mathrm{SN}}$$

1 SN = 10^{51} erg

SN efficiency

Star formation rate

Fraction of core-collapse SNe

Analytic models and numerical simulation

(Chevalier 1974; Thornton+1998; Fierlinger+2016; Ohlin+2019)

Only **a few percent** of the SN energy available to feed turbulence

$$\eta \lesssim 0.1$$

Comparison with observations

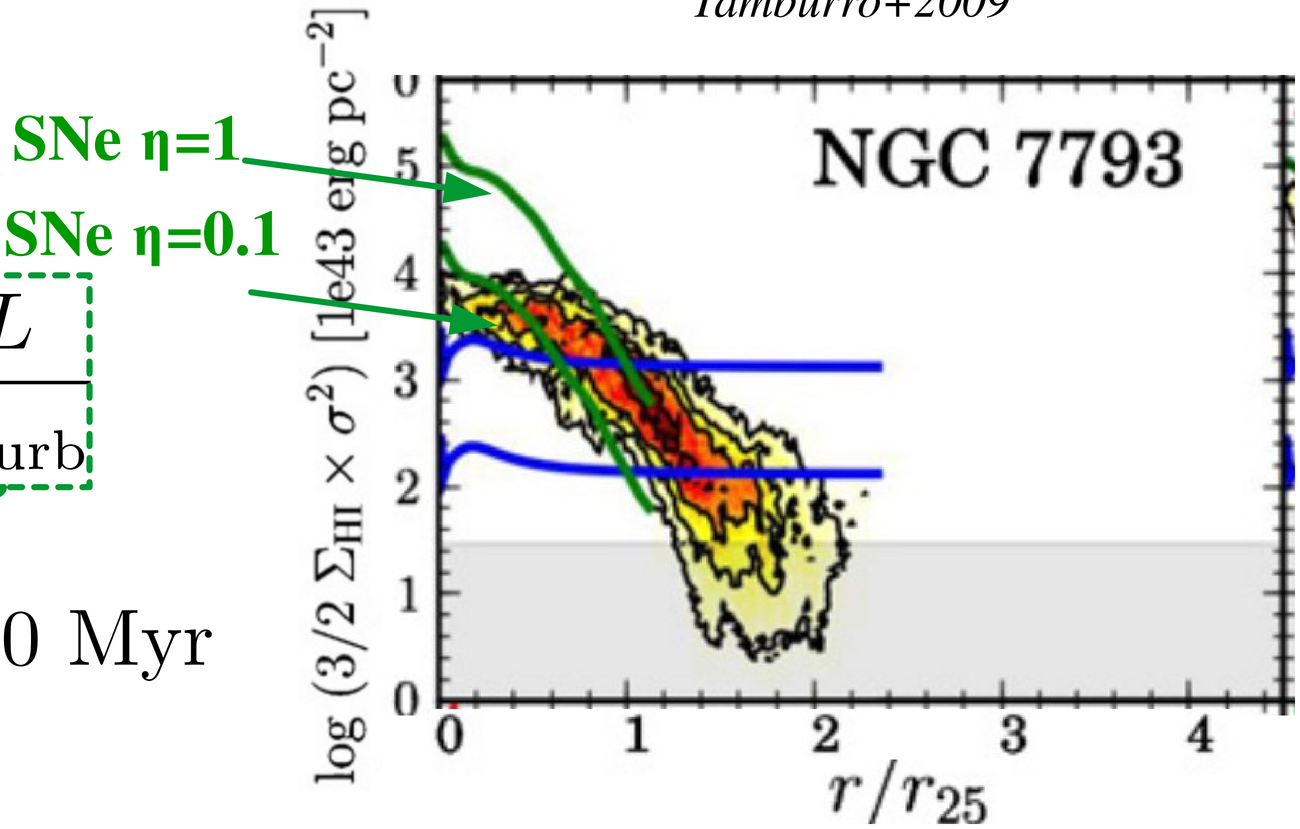
$$E_{\rm obs,HI} = \frac{3}{2}\Sigma_{\rm obs,HI}\sigma^2_{\rm obs,HI}$$

vs

$$E_{\rm turb,SNe} = \eta\Sigma_{\rm SFR} f_{\rm cc} E_{\rm SN}\frac{L}{v_{\rm turb}}$$

$$\left.\begin{aligned} L &= 100\ \text{pc} \\ v_{\rm turb} &= 10\ \text{km/s} \end{aligned}\right\} \Rightarrow \tau = 10\ \text{Myr}$$

Tamburro+2009



Comparison with observations

$$E_{\mathrm{obs,HI}} = \frac{3}{2}\Sigma_{\mathrm{obs,HI}}\sigma^2_{\mathrm{obs,HI}}$$

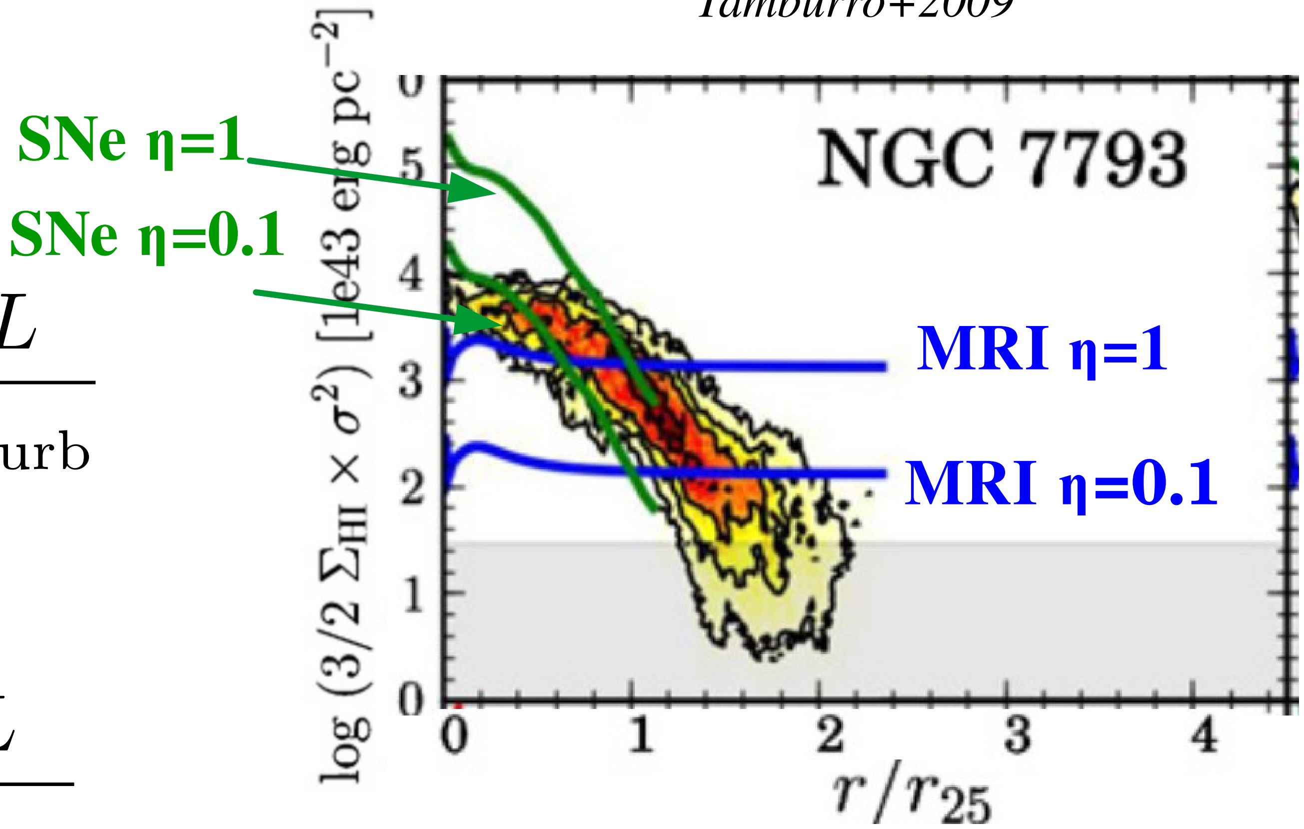
vs

$$E_{\mathrm{turb,SNe}} = \eta\Sigma_{\mathrm{SFR}} f_{\mathrm{cc}} E_{\mathrm{SN}} \frac{L}{v_{\mathrm{turb}}}$$

Magneto-rotational instability

$$E_{\mathrm{MRI}} = 0.6\frac{B^2}{8\pi}\frac{d\Omega}{d\ln R}h\frac{L}{v_{\mathrm{turb}}}$$

Tamburro+2009



See also Utomo+2019

Comparison with observations

Tamburro+2009

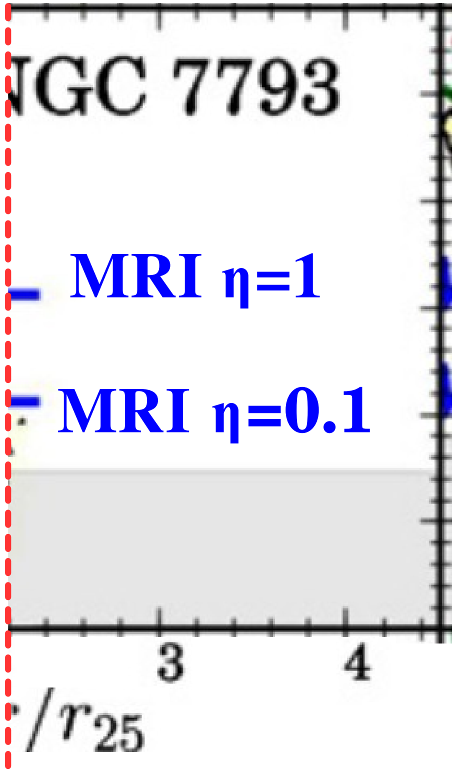
$$E_{\mathrm{obs,HI}} = \frac{3}{2}$$

$$E_{\mathrm{turb,SNe}} = \eta\Sigma$$

Magneto-rotatio

$$E_{\mathrm{MRI}} = 0.6$$

- Magneto-rotational instability *(Velikhov 1959; Chandrasekhar1960; Balbus & Hawley1991; Sellwood & Balbus 1999)*
- Rotational shear *(e.g. Wada 2002)*
- Gas infall (e.g. *Klessen & Hennebelle 2010; Elmegreen & Burkert 2010; Utomo+2019*)
- Disc instability (e.g. *Bournaud et al. 2010; Krumholz & Burkhart 2016*)



See also Utomo+2019

Comparison with observations

$$E_{\rm obs,HI} = \frac{3}{2}\Sigma_{\rm obs,HI}\sigma^2_{\rm obs,HI}$$

vs

$$E_{\rm turb,SNe} = \eta\Sigma_{\rm S}$$

What is sustaining turbulence?

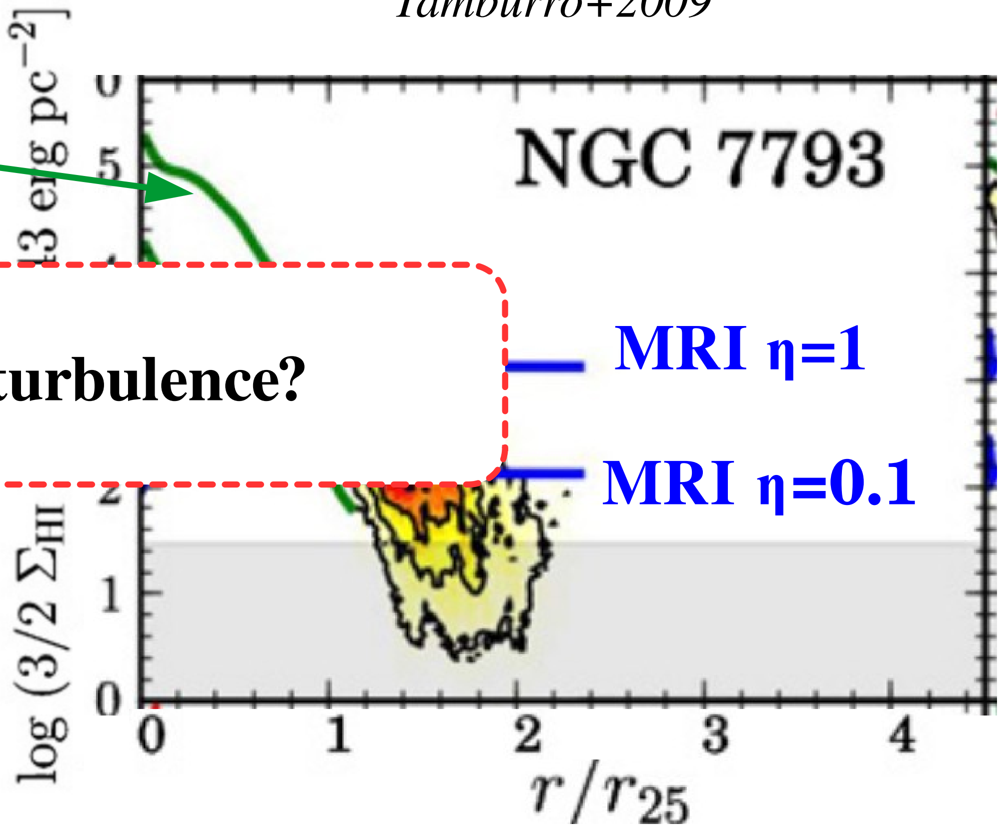
Magneto-rotational instability

$$E_{\rm MRI} = 0.6\frac{B^2}{8\pi}\frac{d\Omega}{d\ln R}h\frac{L}{v_{\rm turb}}$$

SNe η=1

SNe η=0.1

Tamburro+2009

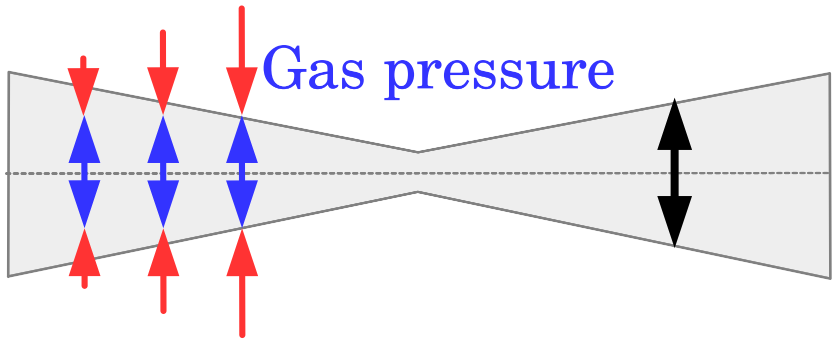


MRI η=1

MRI η=0.1

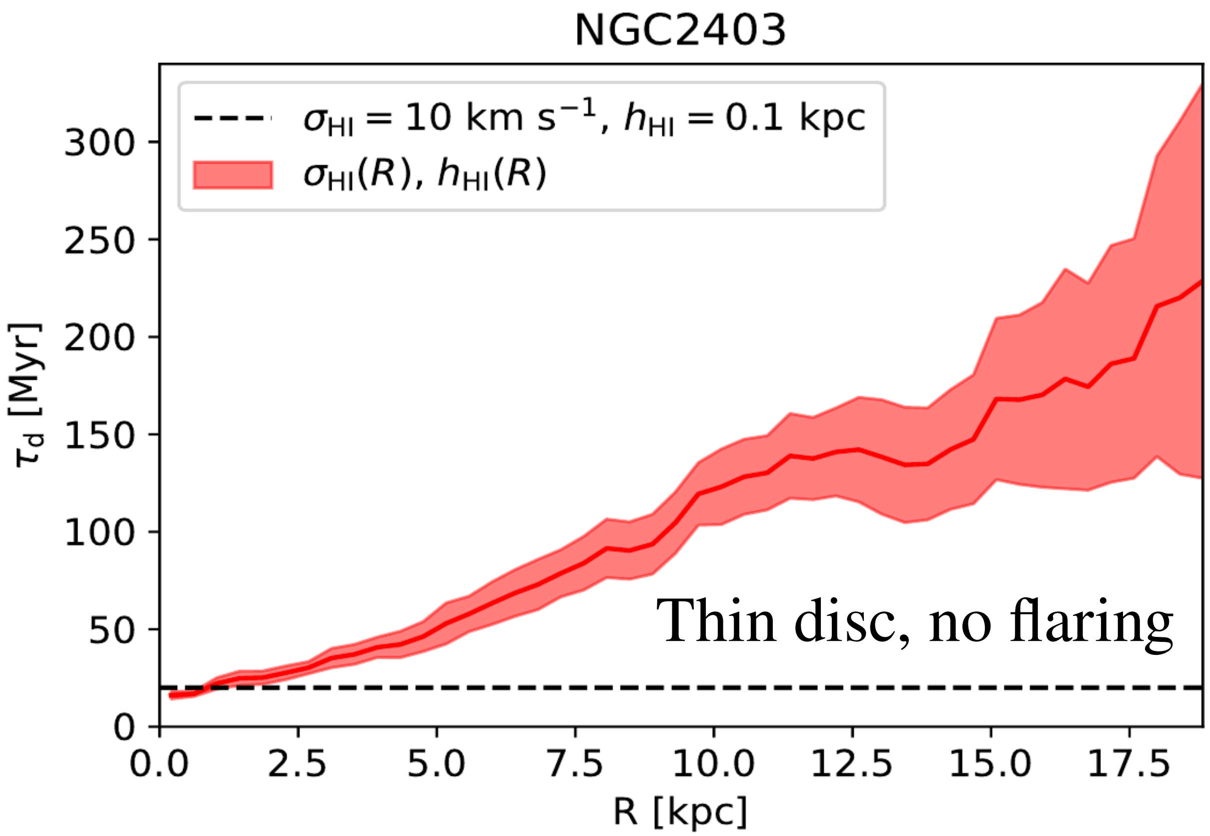
See also Utomo+2019

Slow dissipation in flaring discs



$$L(R) = 2h(R)$$

$$\tau(R) = \frac{L(R)}{v_{\rm turb}} = \frac{2h(R)}{v_{\rm turb}}$$



Sample and method

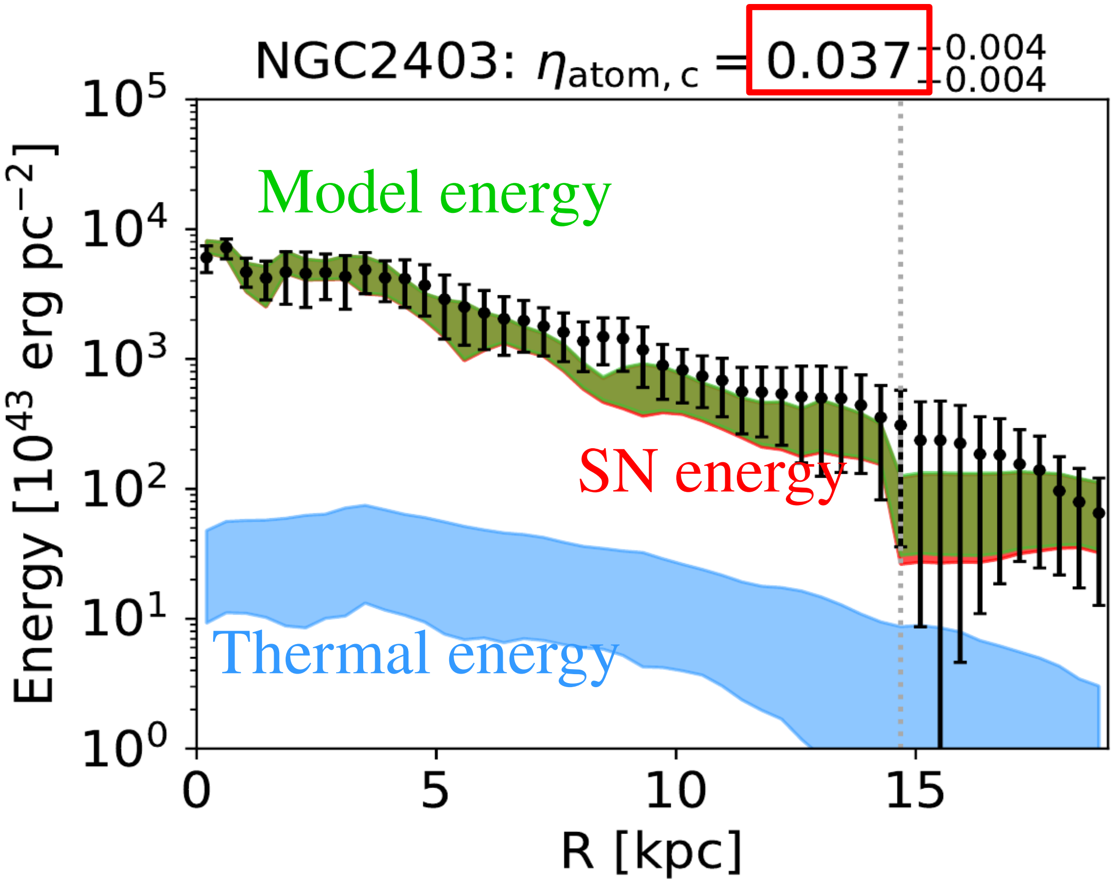
- Sample of 10 galaxies: **2 dwarfs** and **8 spirals**.

2/10 galaxies

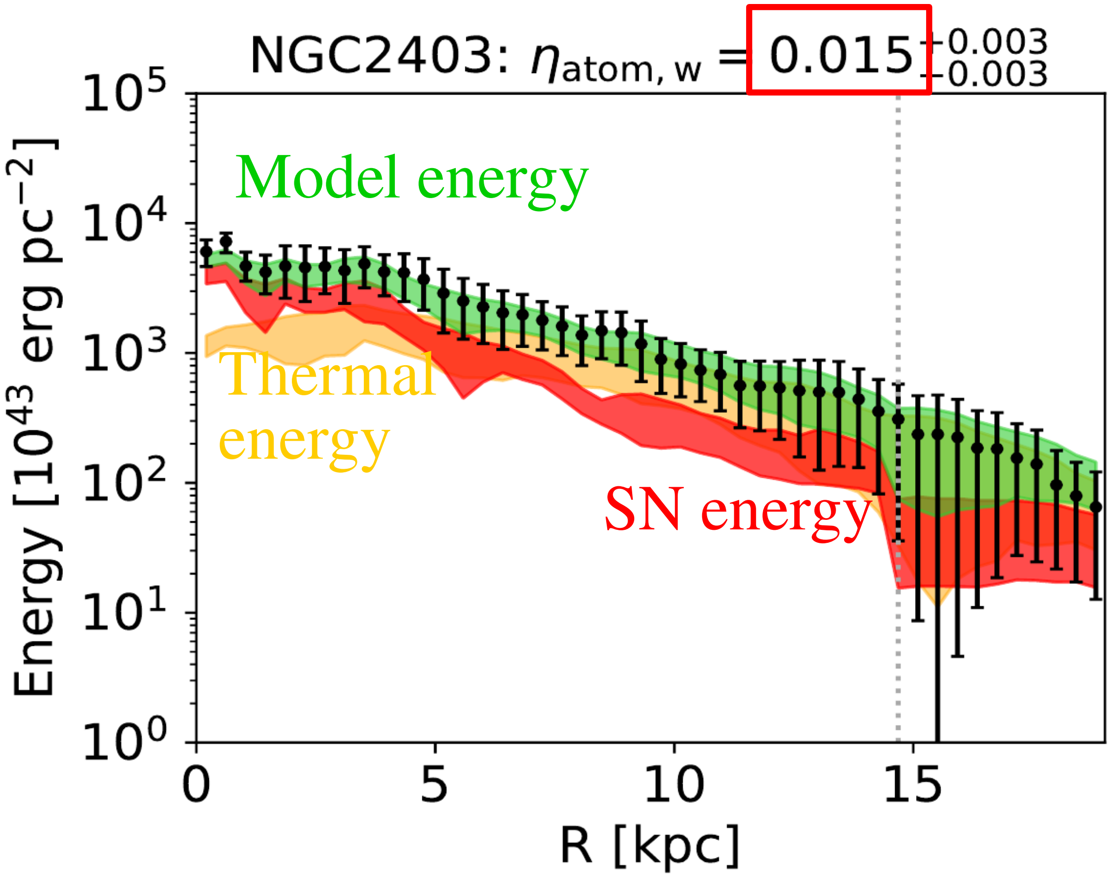
- Hierarchical Bayesian inference *(e.g. Delgado+2019; Lamperti+2019; Cannarozzo+2020)*.
- Atomic gas:
  - CNM with T = 40 – 190 K;
  - WNM with T = 7000 – 8330 K;
  - 2-phase case (CNM & WNM) → WNM fraction.
- Molecular gas with T = 10 -15 K.

Atomic gas – extreme cases

All CNM

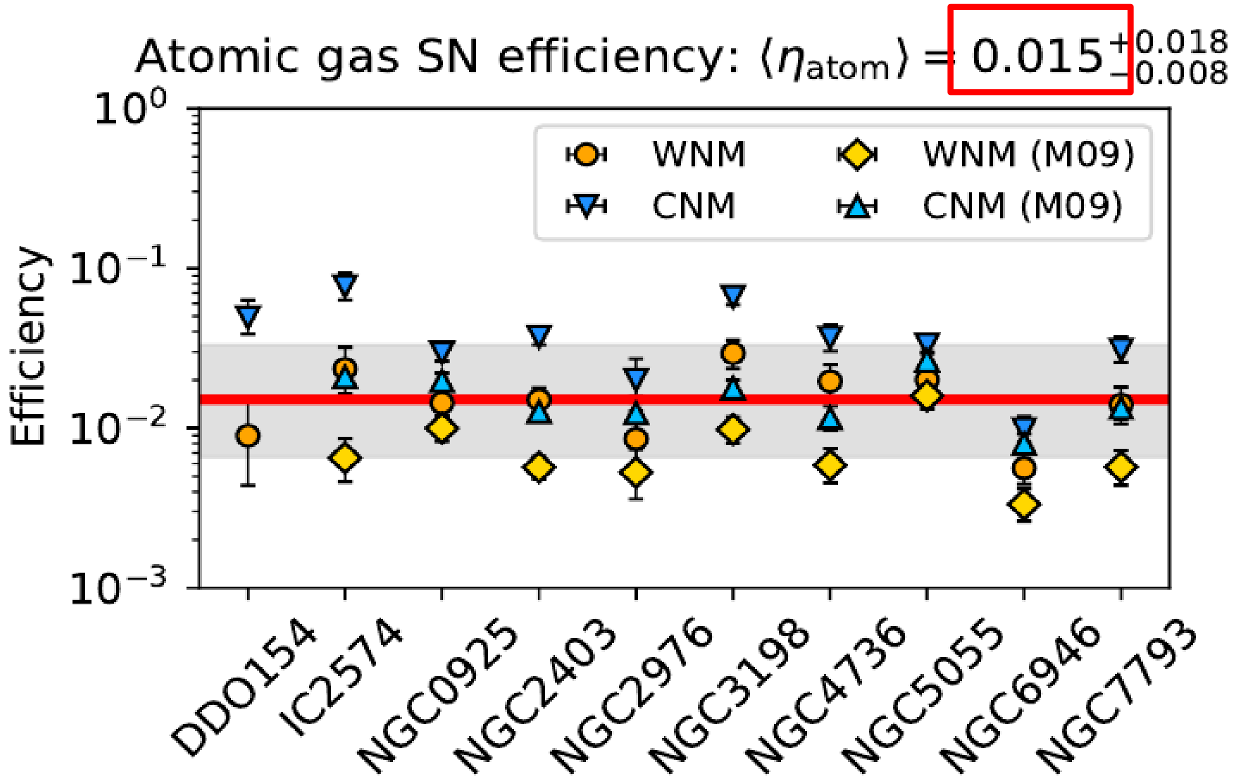


All WNM

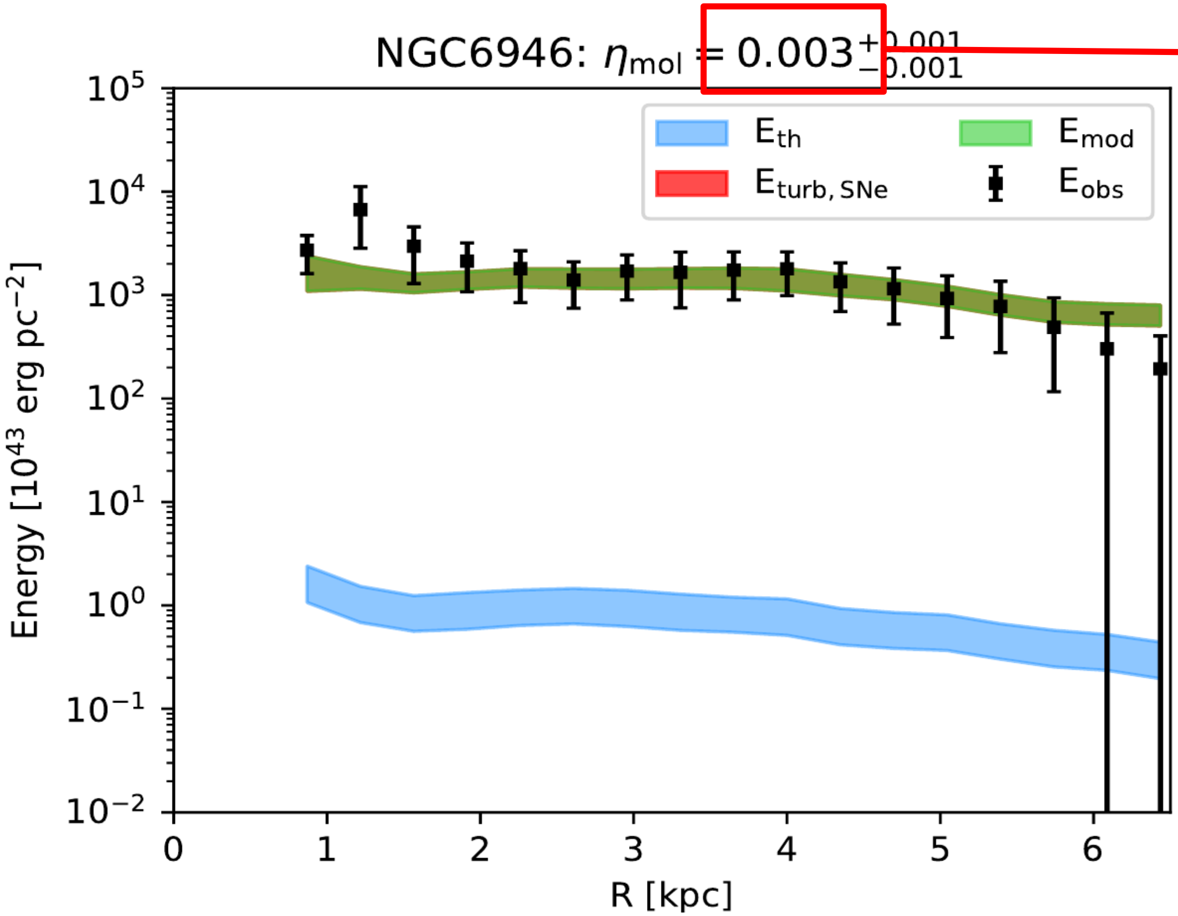


Atomic gas – “global” SN efficiency

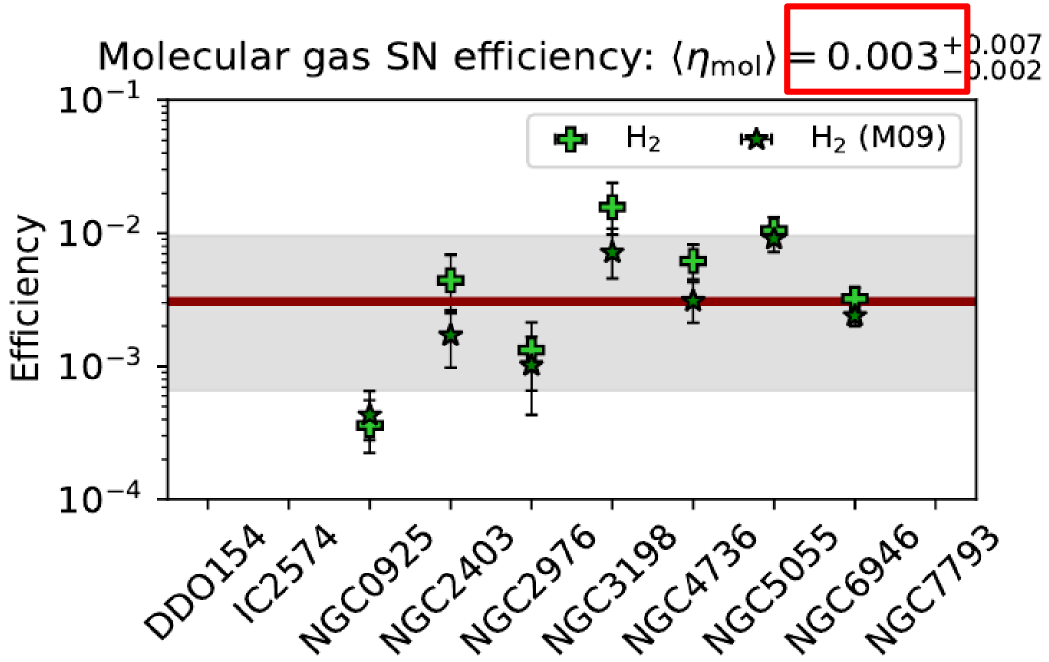
- Average for each galaxy in the CNM and WNM cases → average “global” value
- Test using different Σ_{SFR}



Molecular gas



<1% of the total SN energy



Conclusions – part II

1) Only **a few % of the total SN energy** is needed to maintain turbulence

→ No additional source of energy;

2) Thermal energy contribution significant in outer and low-SFR regions.

Summary of conclusions

- **Flaring significant** → no constant thickness!

→ Part I – *The volumetric star formation law in nearby galaxies*

- **VSF law ($HI+H_2$)** for high- & low-density regimes, **from dwarf to spiral galaxies**:
    - Volume densities → more fundamental;
    - No break → no density threshold;
    - $\rho_{SFR}=A\rho_{gas}^{2}$ → not only gravity.
- Volumetric relation SFR-HI → HI traces star-forming gas.

→ Part II – *Gas turbulence in nearby galaxies*

- Only **a few % of the total SN energy needed to maintain turbulence** → No additional source;
- Thermal energy contribution significant in outer and low-SFR regions.