The Volumetric Star Formation laws

Fundamental correlations between gas and SFR

Bacchini et al. to be submitted soon

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In collaboration with: Filippo Fraternali, Giuliano Iorio, Gabriele Pezzulli

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Why volume densities?

1) **More physically meaningful**

$$\Sigma \rightarrow \rho$$

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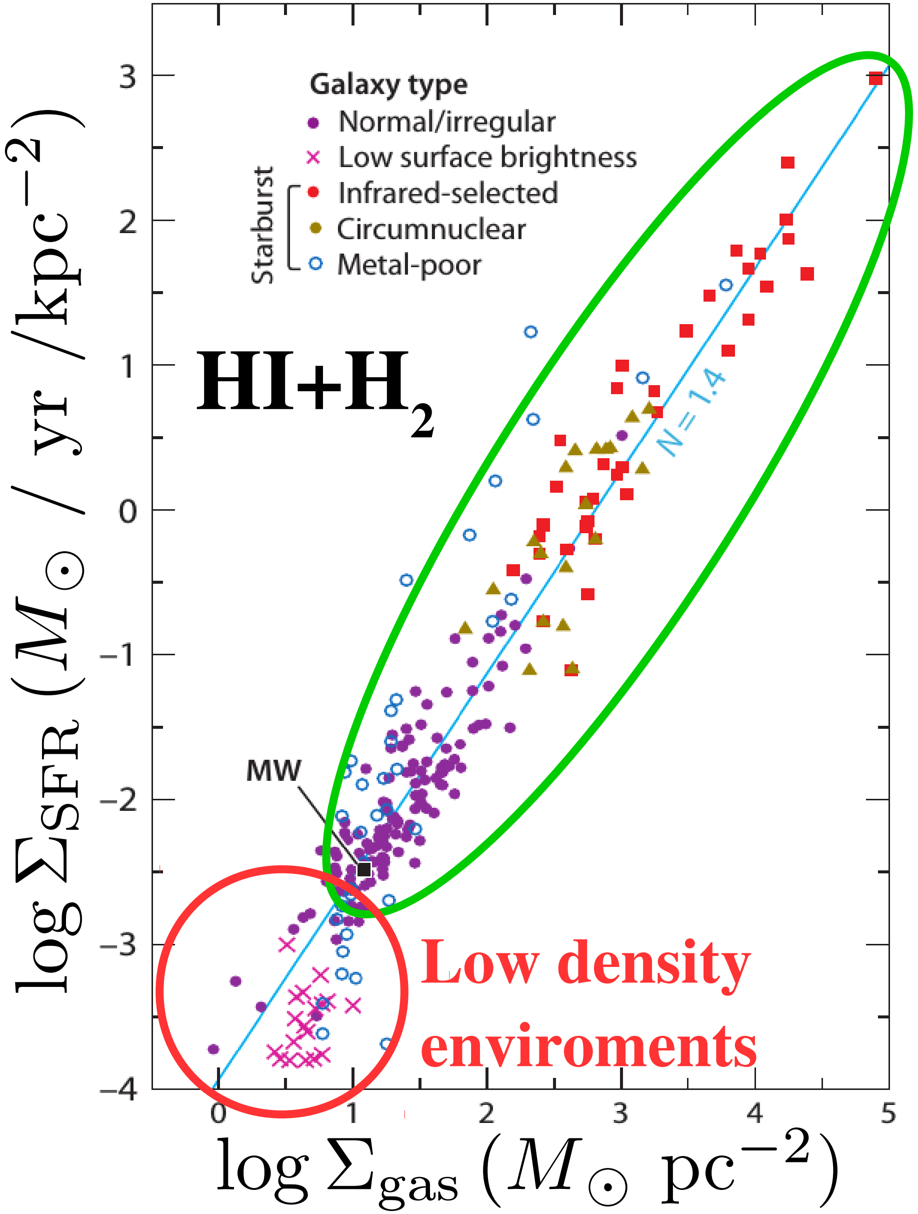
2) Does the Kennicutt law (1989) have a **slope break?**

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

Kennicutt & Evans 2012



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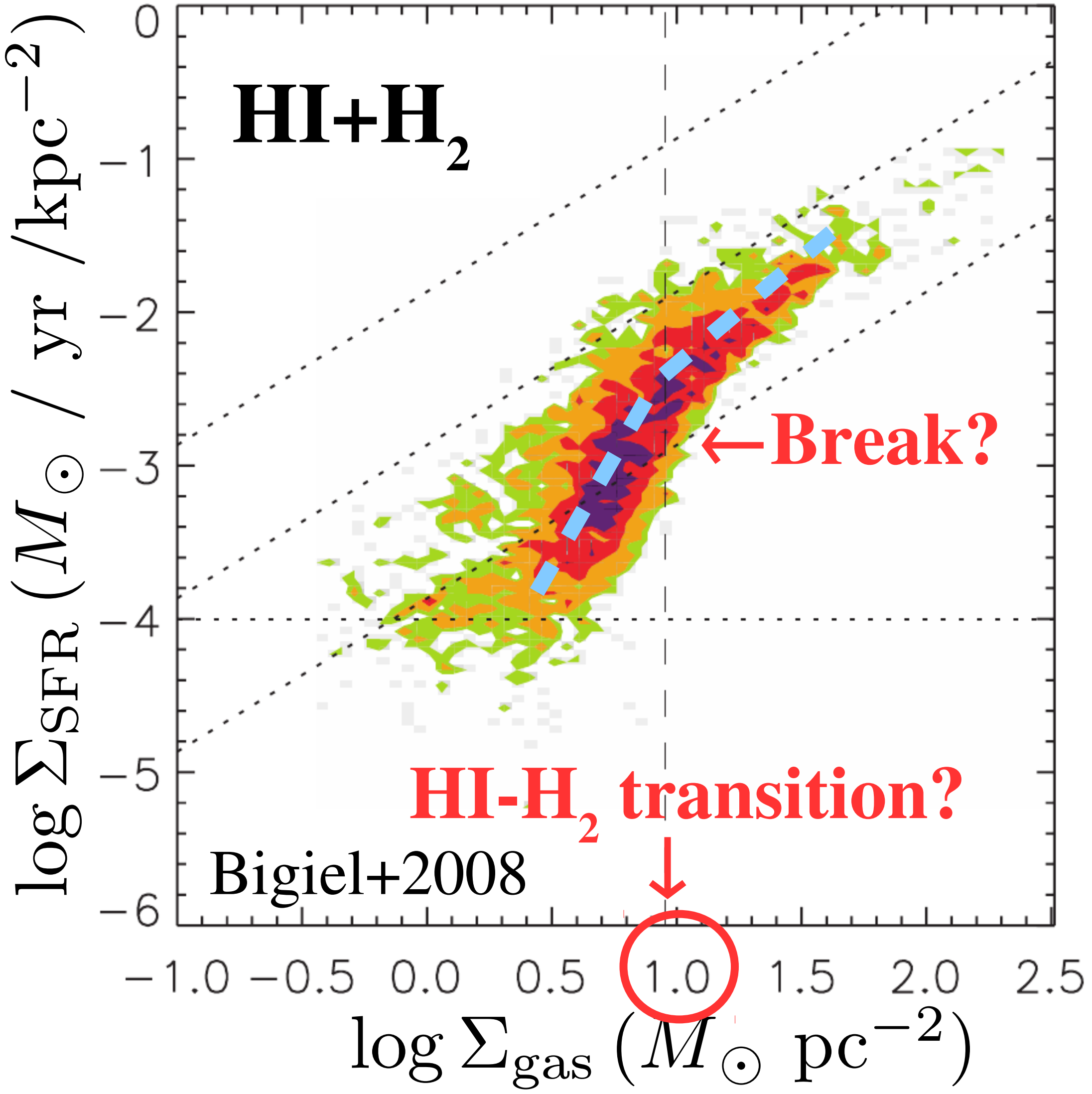

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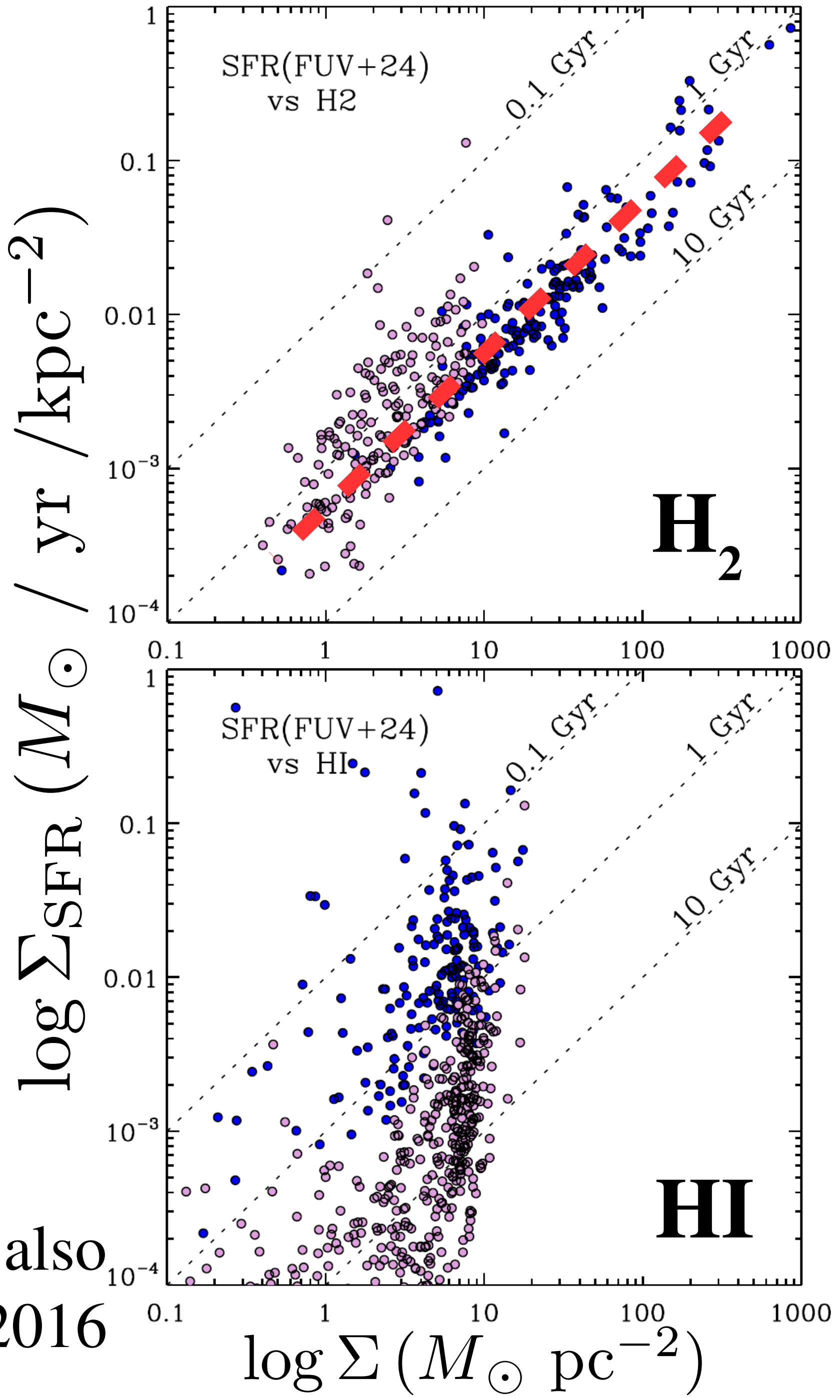
2) Does the Kennicutt law (1989) have a **slope break?**

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

3) Which **gas phase** is fundamental for star formation?

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

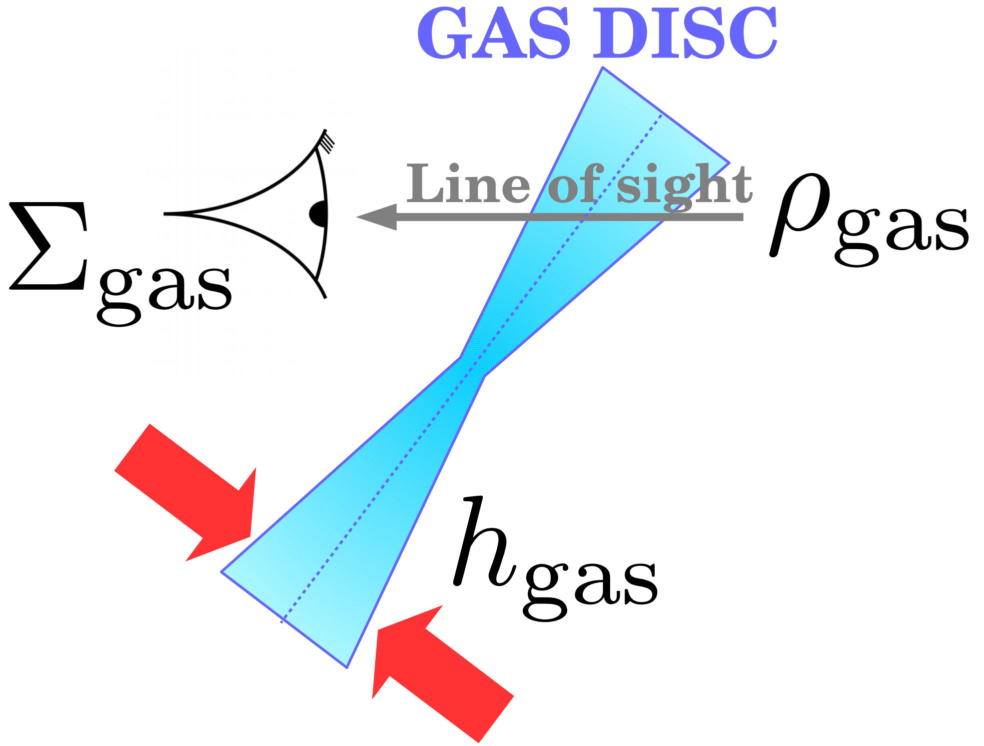
Schruba+2011, see also
Yim & van der Hulst 2016

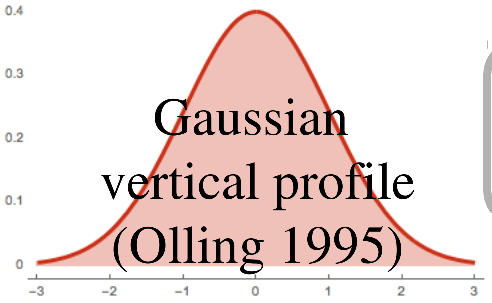


The main idea: including the gas disc flaring

Standard
2D method
surface densities

Kennicutt law





Gaussian
vertical profile
(Olling 1995)

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

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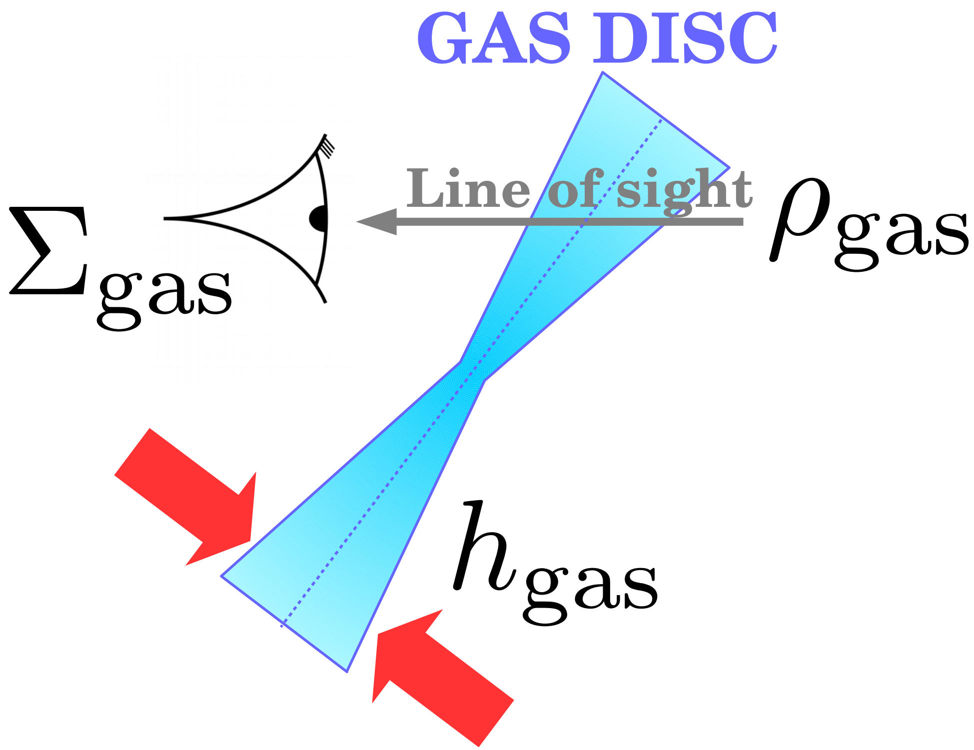
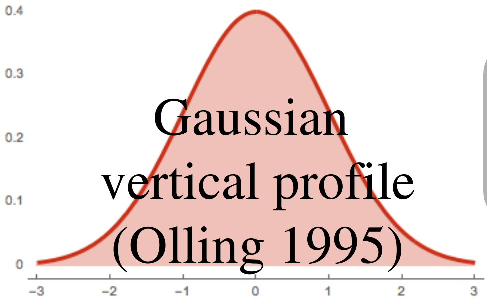


New 3D method:
volume densities

Volumetric
Schmidt-type law



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

$$\rho(R,0) = \frac{\Sigma(R)}{2.5\,h(R)}$$

From surface to volume densities

- **Atomic gas**

Observed

$$\rho_{\mathrm{HI}}(R,0) = \frac{\Sigma_{\mathrm{HI}}(R)}{2.5\, h_{\mathrm{HI}}(R)}$$

- **Molecular gas**

$$\rho_{\mathrm{H_2}}(R,0) = \frac{\Sigma_{\mathrm{H_2}}(R)}{2.5\, h_{\mathrm{H_2}}(R)}$$

- **Star formation rate**

$$\rho_{\mathrm{SFR}}(R,0) = \frac{\Sigma_{\mathrm{SFR}}(R)}{2.5\, h_{\mathrm{SFR}}(R)}$$

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$$\rho_{\rm SFR}(R,0) = \frac{\Sigma_{\rm SFR}(R)}{2.5\, h_{\rm SFR}(R)}$$

Hydrostatic Equilibrium

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

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

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

Sample selection

THINGS: 34 galaxies
Walter+2008

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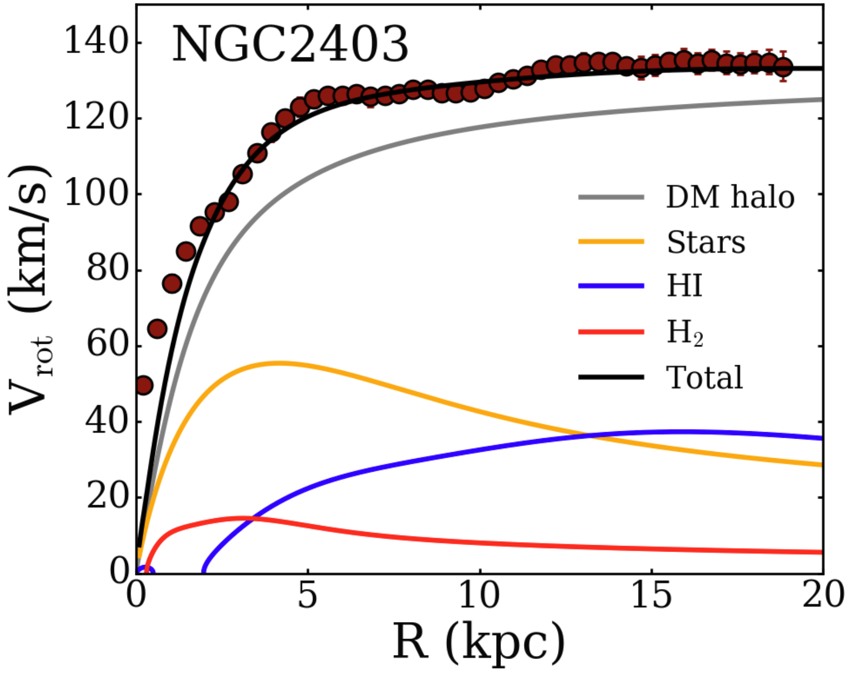
1) Mass models: → Φ_{tot}
- de Blok+2008
- Frank+2016

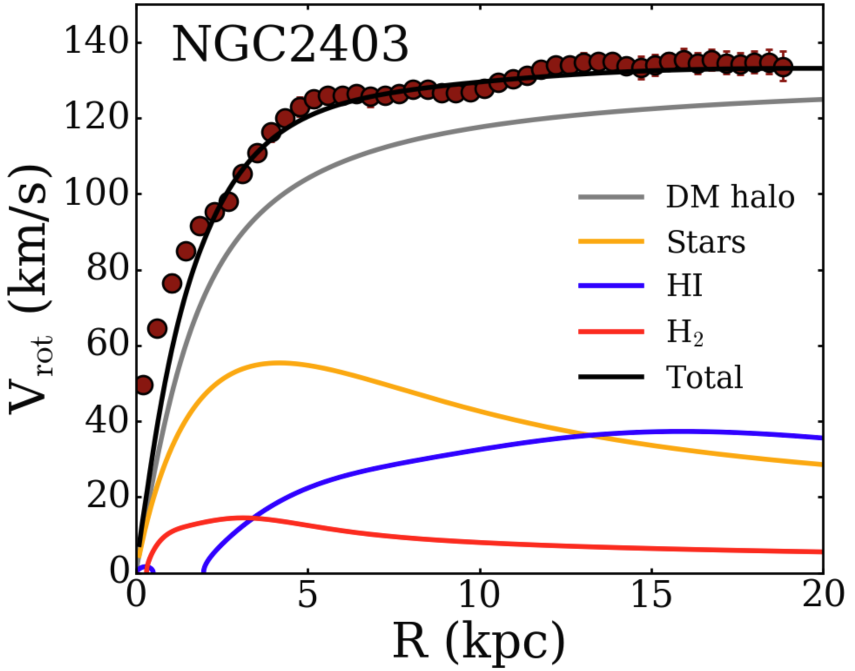


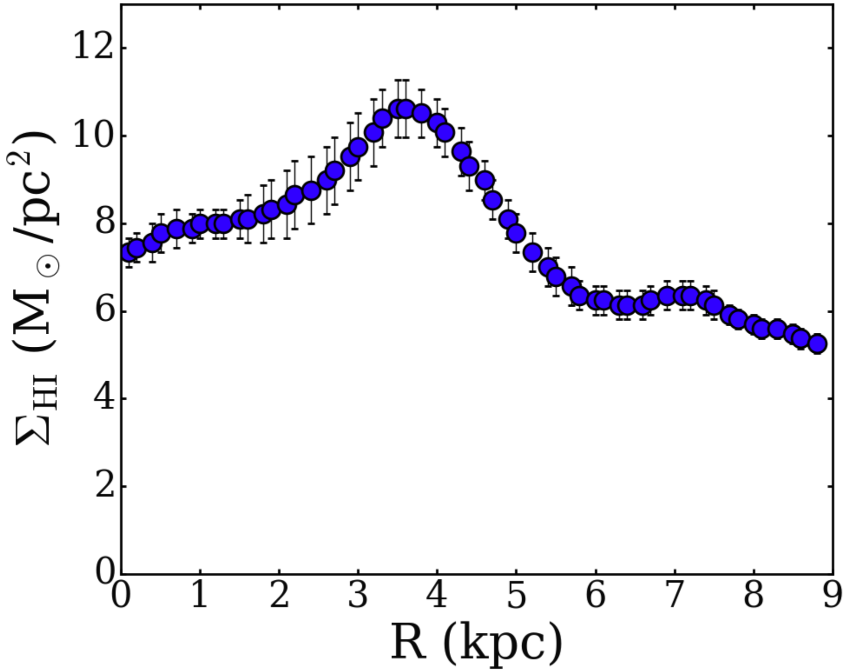
Sample selection

THINGS: **34** galaxies
Walter+2008

1) Mass models: → Φ_{tot}
- de Blok+2008
- Frank+2016

2) Surface densities:
- Leroy+2008 → HI, SFR
- Frank+2016 → H_2

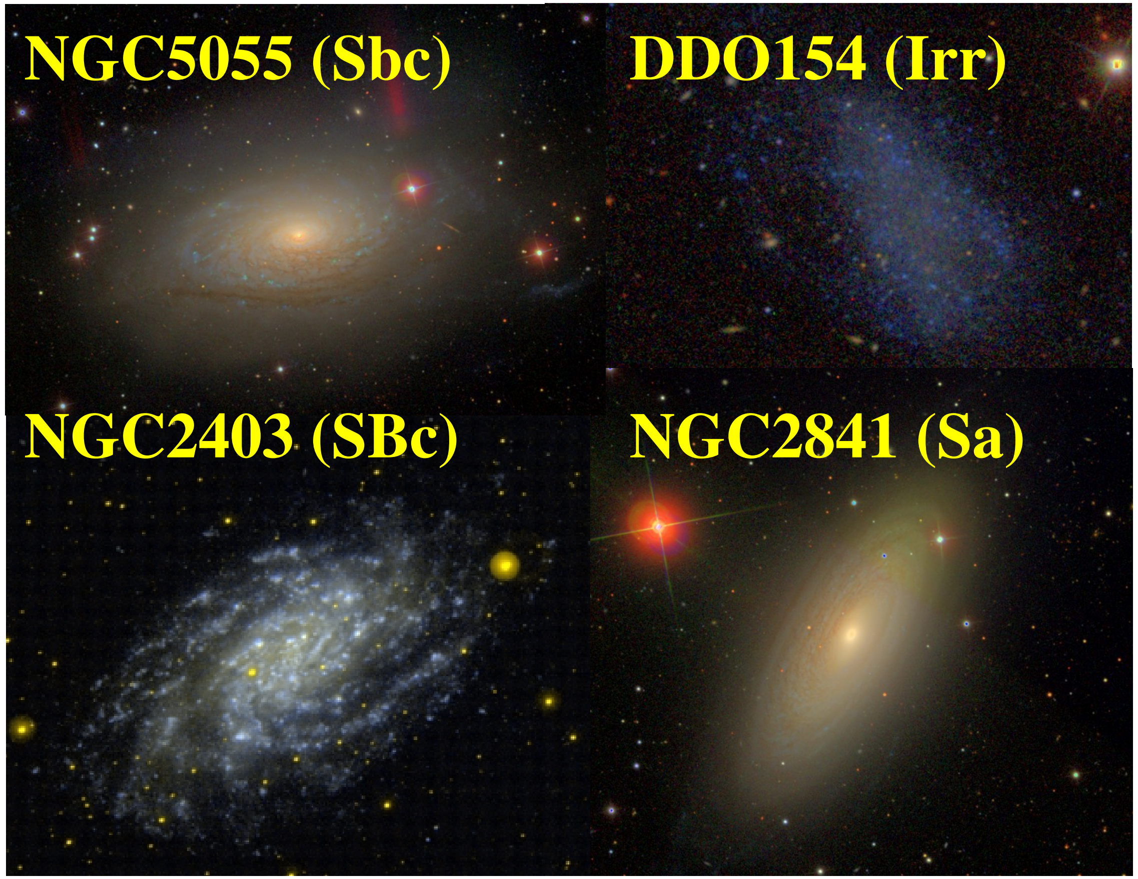




Sample selection

12 star forming galaxies

6 normal spirals + 6 “dwarfs”



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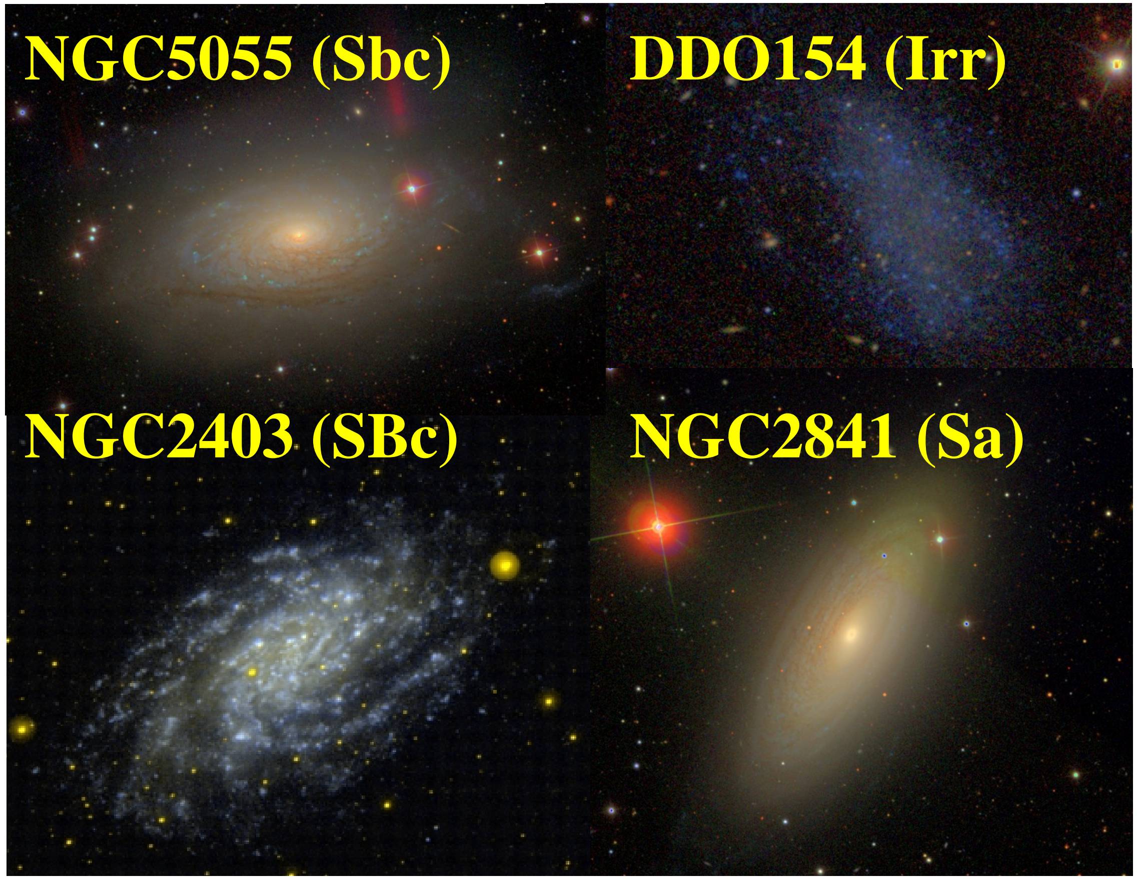
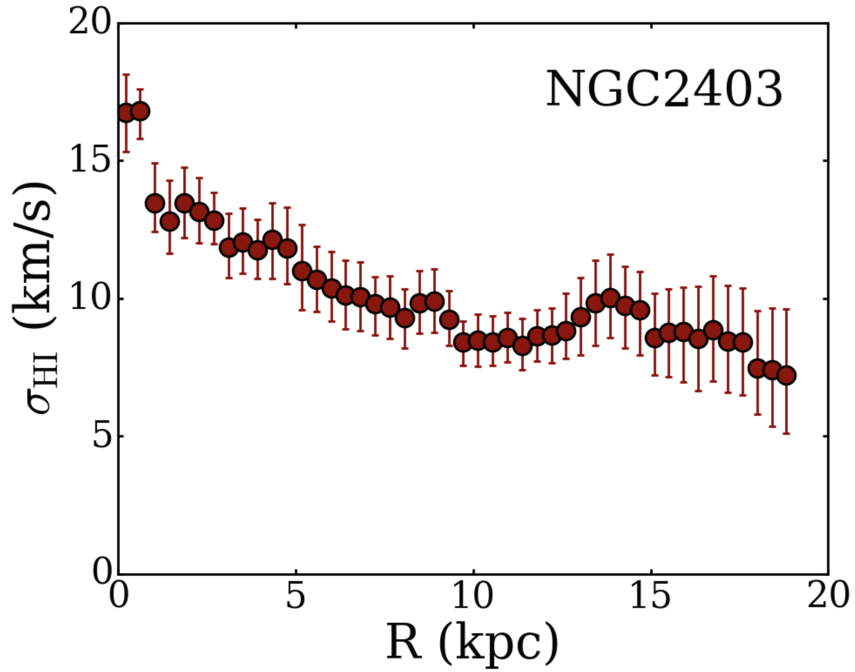


3) Velocity dispersion

Di Teodoro & Fraternali 2015

BBAROLO

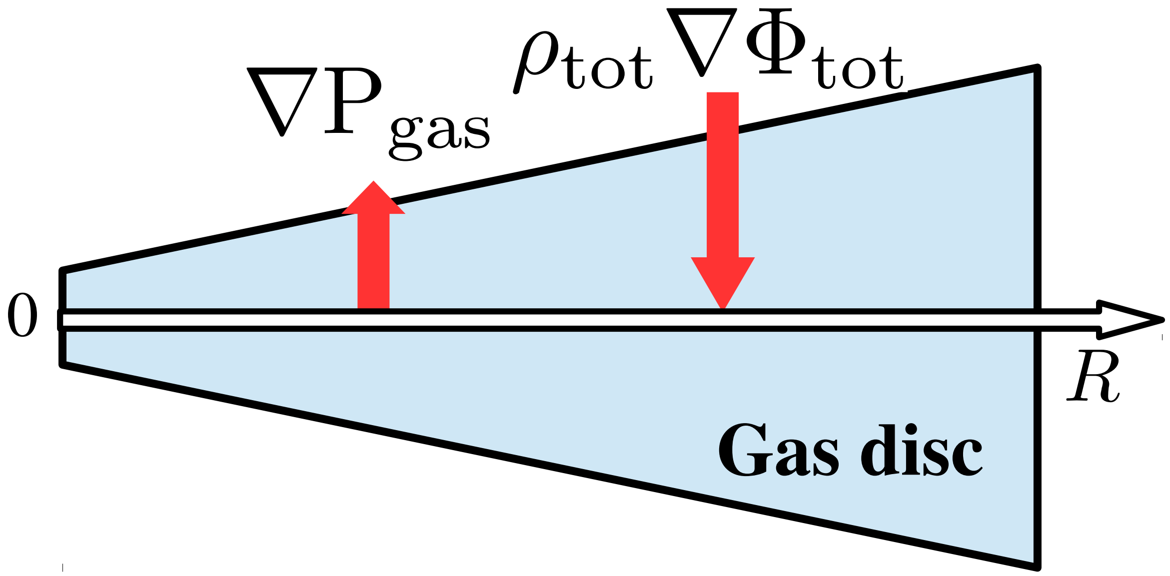
3D Based Analysis of Rotating Objects via Line Observations



Determining the thickness: not so easy!

- Hydrostatic equilibrium

$$\nabla \mathrm{P}_{\mathrm{gas}} = -\rho_{\mathrm{tot}} \nabla \Phi_{\mathrm{tot}}$$



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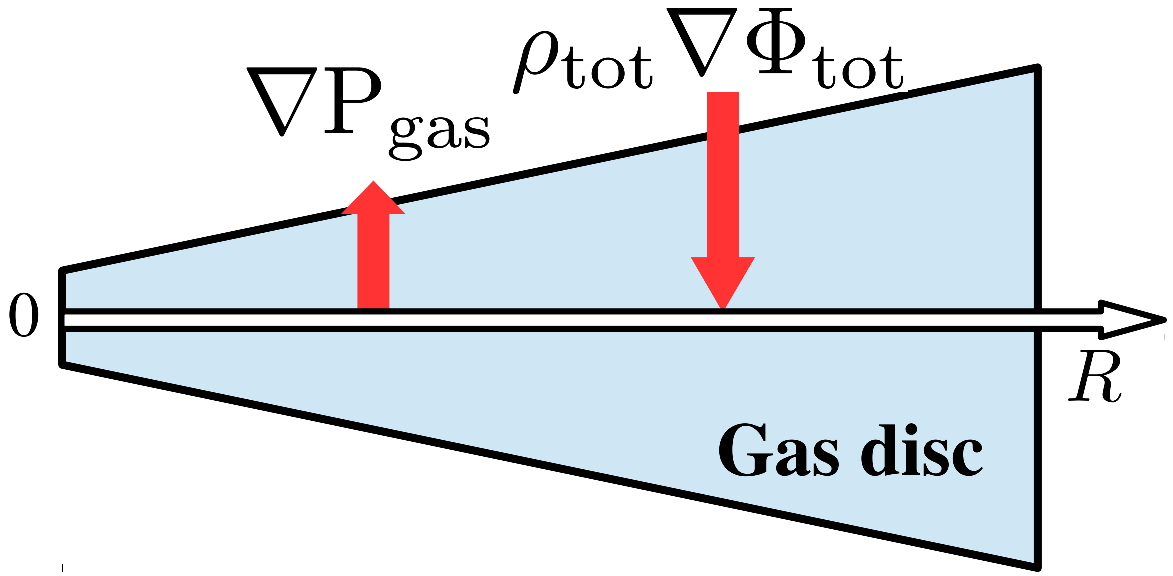
- **Gas self-gravity** $\rightarrow$ iterative method



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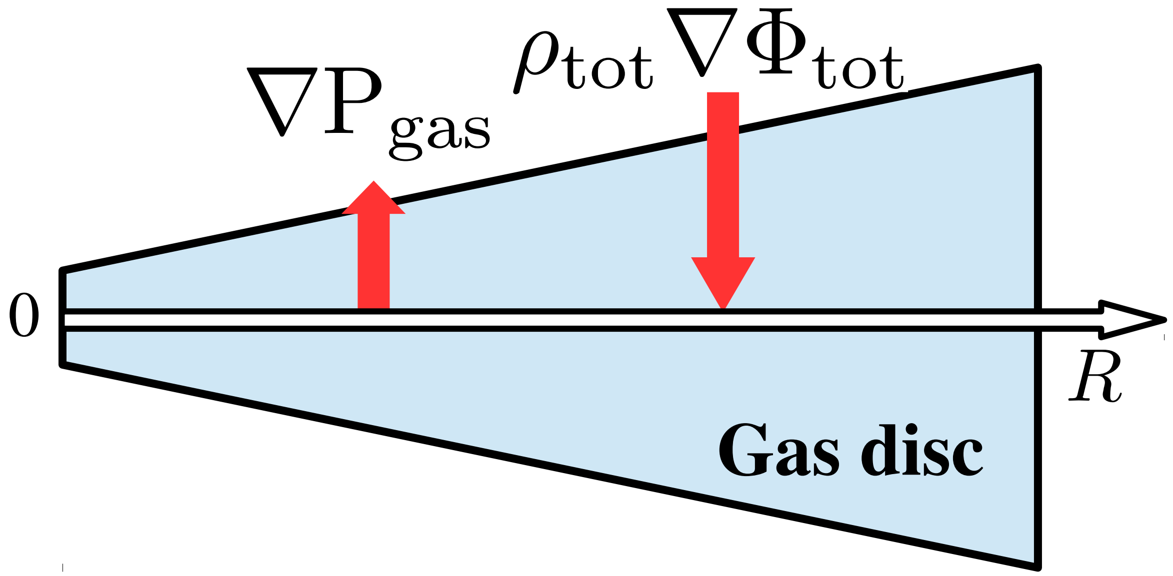
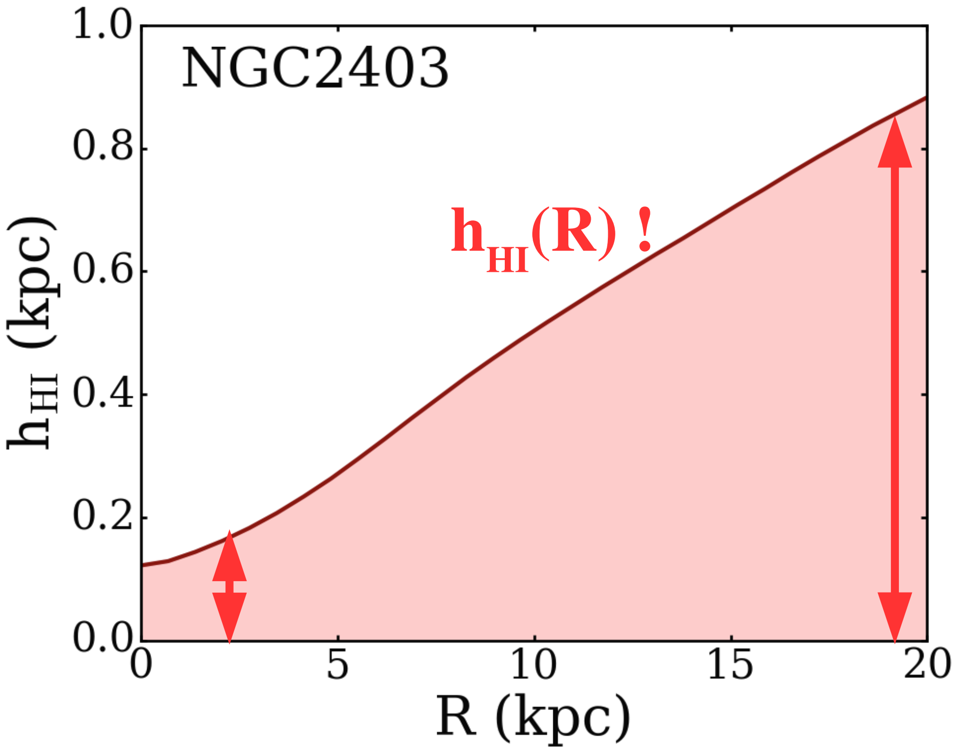
Galpynamics
Iorio PhD thesis (2018)





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$$\boxed{\sigma_{\rm H_2} \approx 0.5 \times \sigma_{\rm HI}}$$

$$\boxed{\rm h_{H_2} \approx 0.5 \times h_{HI}}$$

Marasco+2017

(Mogotsi+2015)

$$\frac{\sigma_{\rm H_2}}{\sigma_{\rm HI}} \approx 0.7$$

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$$\rm h_{H_2} \approx 0.5 \times h_{HI}$$

Marasco+2017
(Mogotsi+2015)

$$\frac{\sigma_{\rm H_2}}{\sigma_{\rm HI}} \approx 0.7$$

Two extreme choices

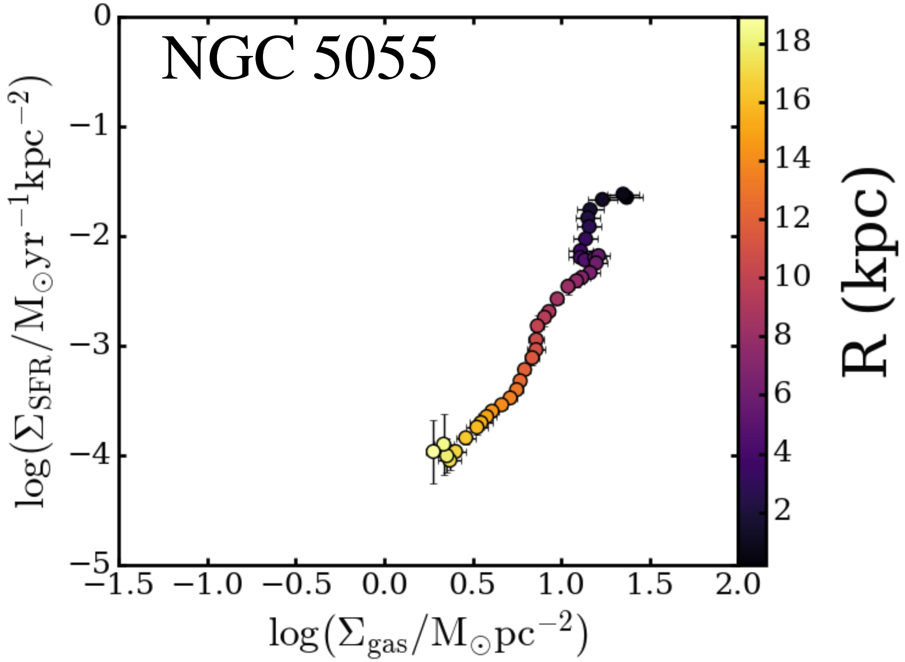
$$h_{\rm SFR} = \begin{cases} \text{const} \\ h_{\rm gas} \end{cases}$$

Van der Kruit & Searle 1981
Mackereth+2017

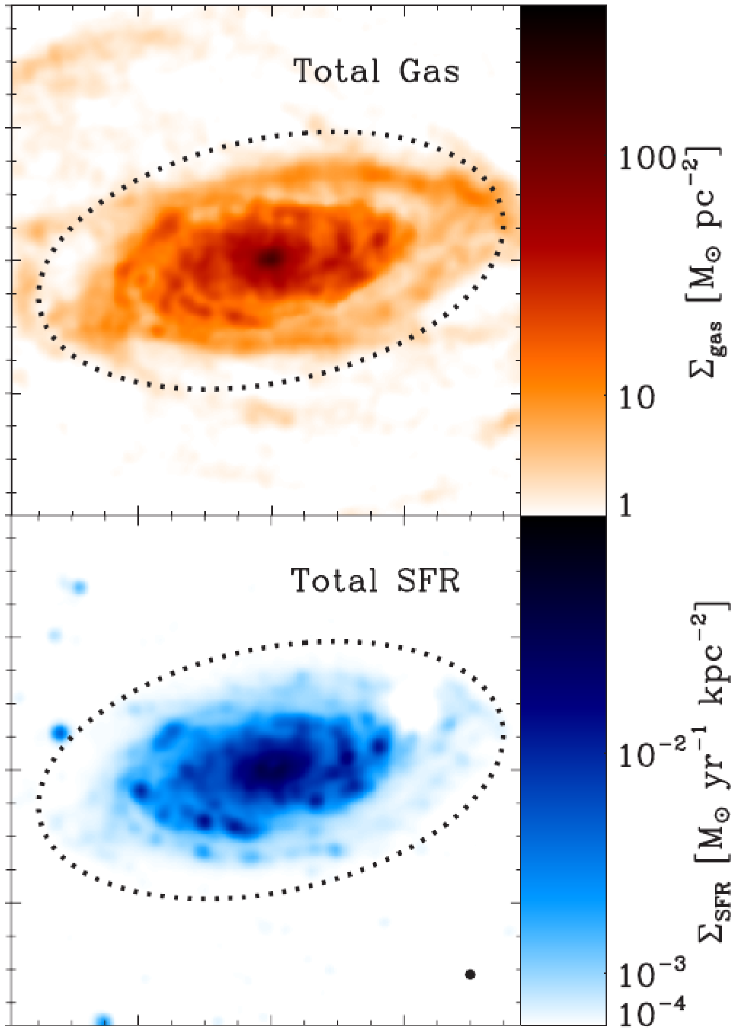
$$h_{\rm gas} = f_{\rm HI} h_{\rm HI} + f_{\rm H_2} h_{\rm H_2}$$

VSF law: example for a single galaxy

Surface densities



Azimuthally averaged radial profiles



Leroy+2008

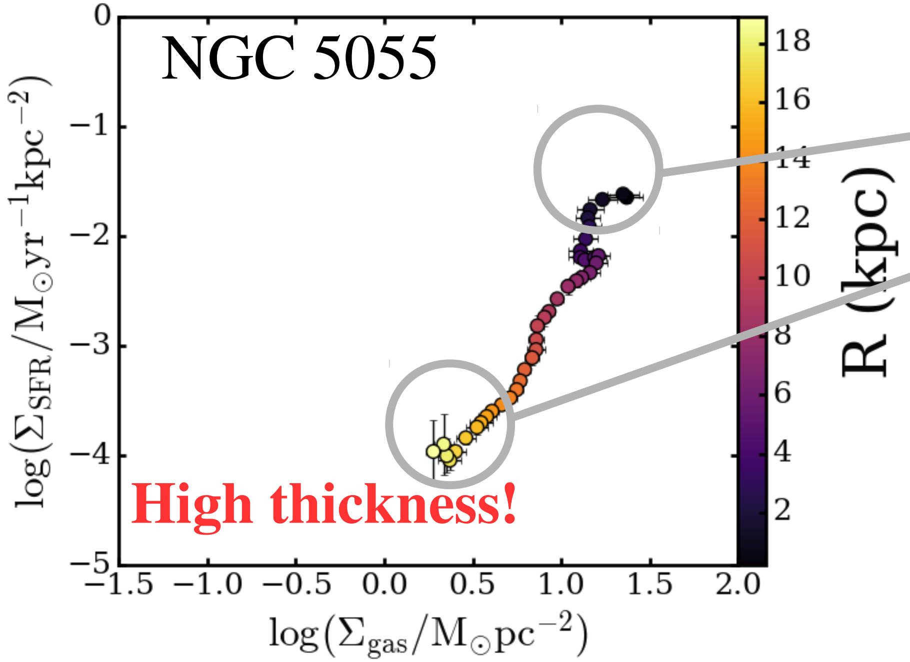
Σ_{gas}

Σ_{SFR}

VSF law: example for a single galaxy

Leroy+2008

Surface densities



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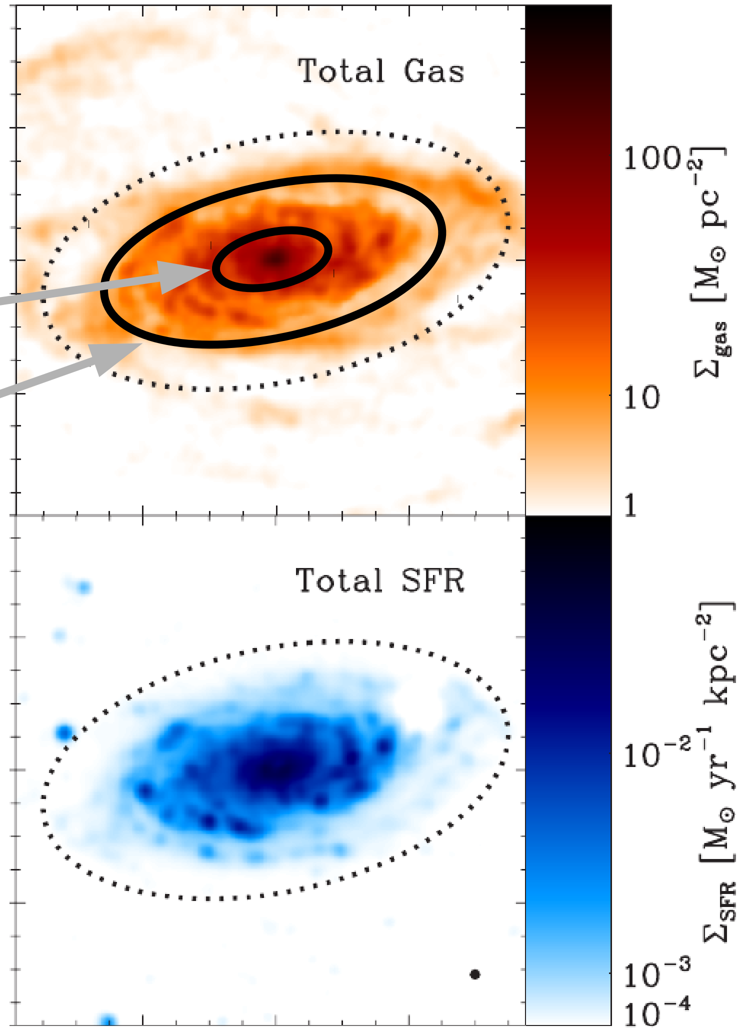
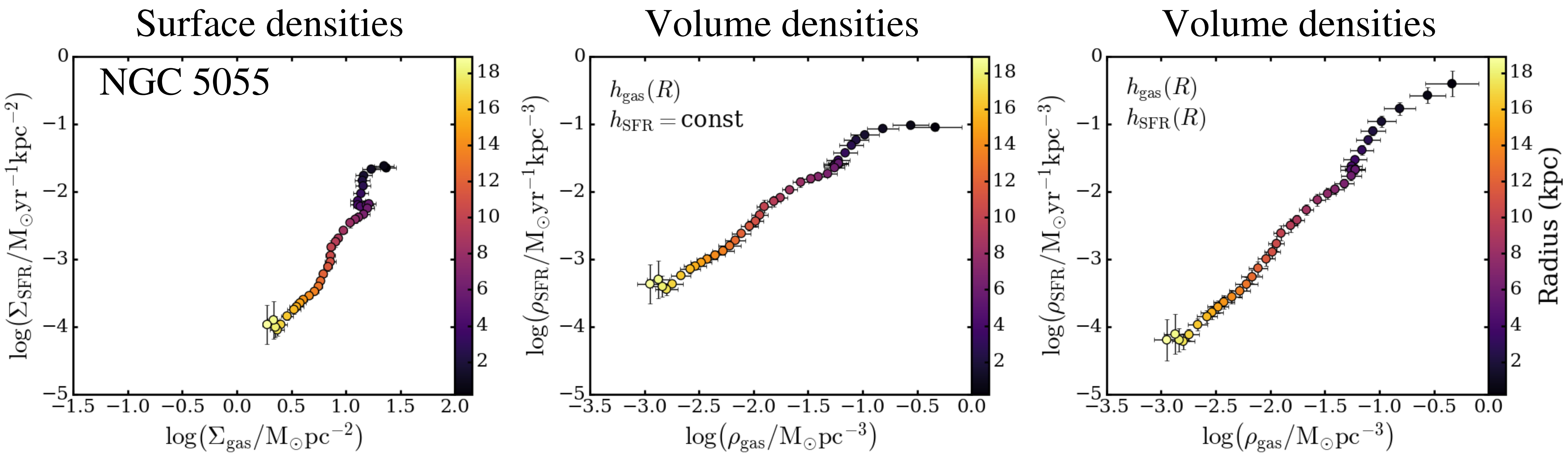


Σ_{gas}

Σ_{SFR}

VSF law: example for a single galaxy



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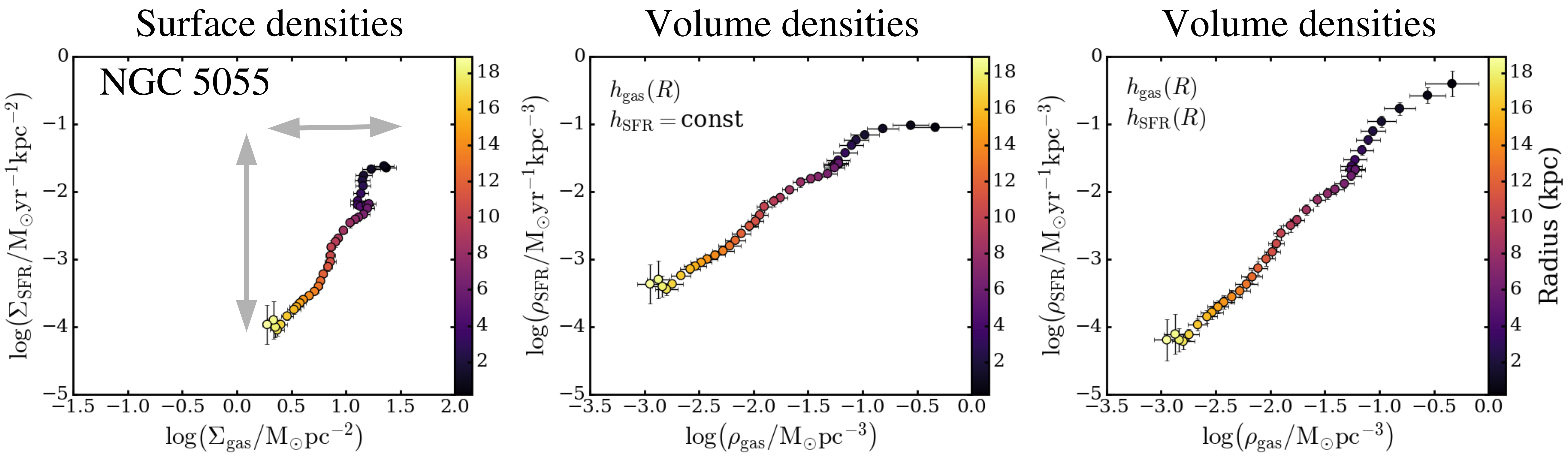

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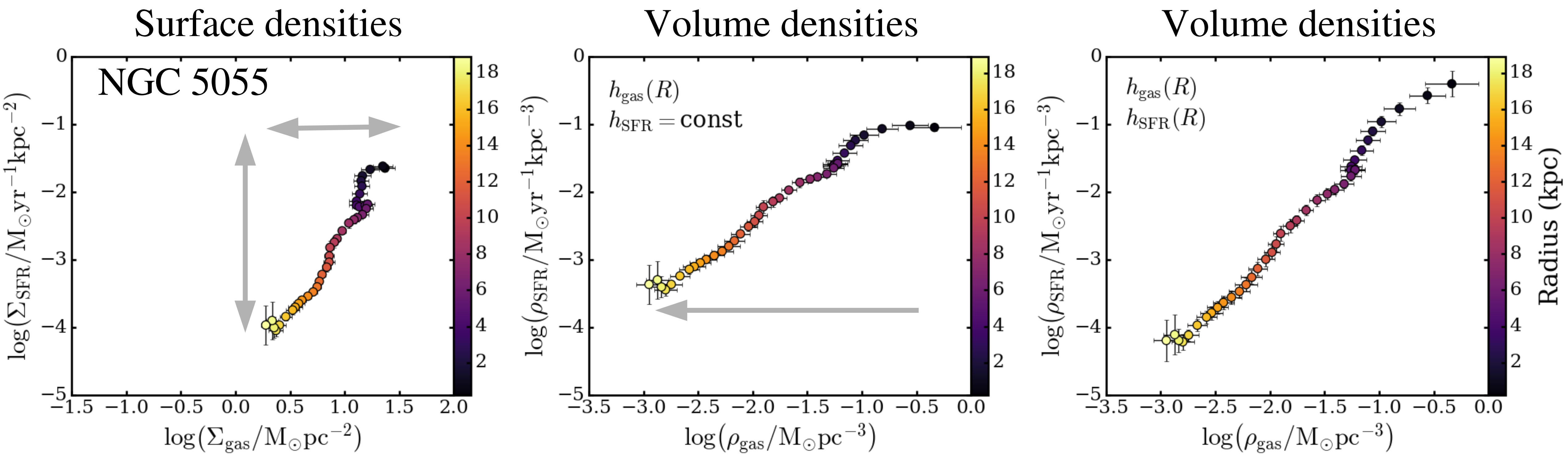

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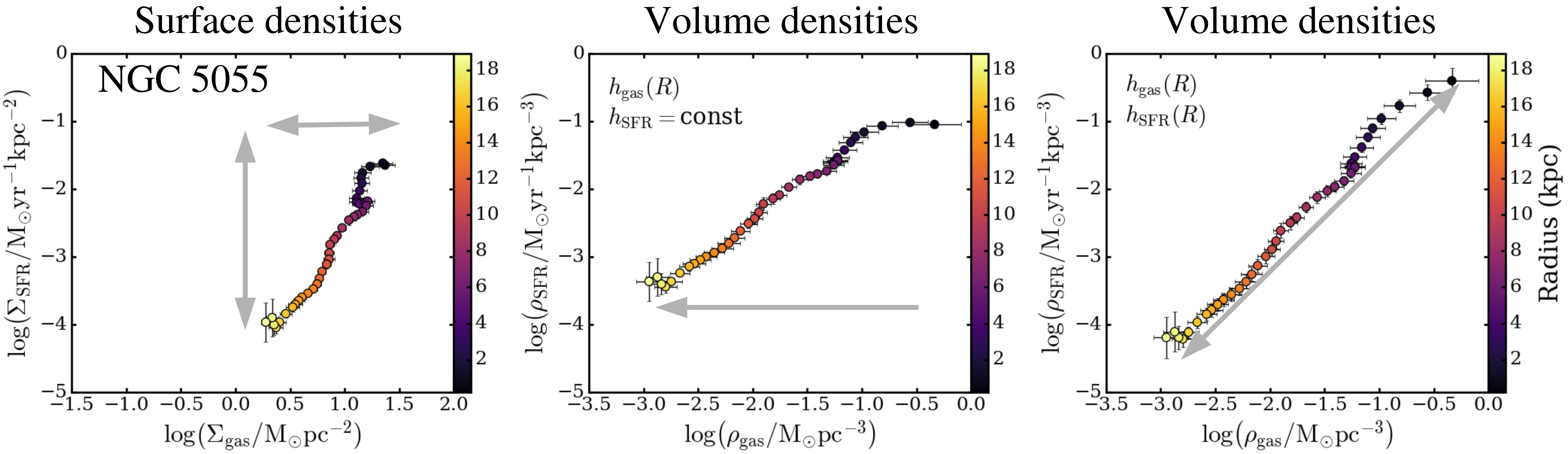
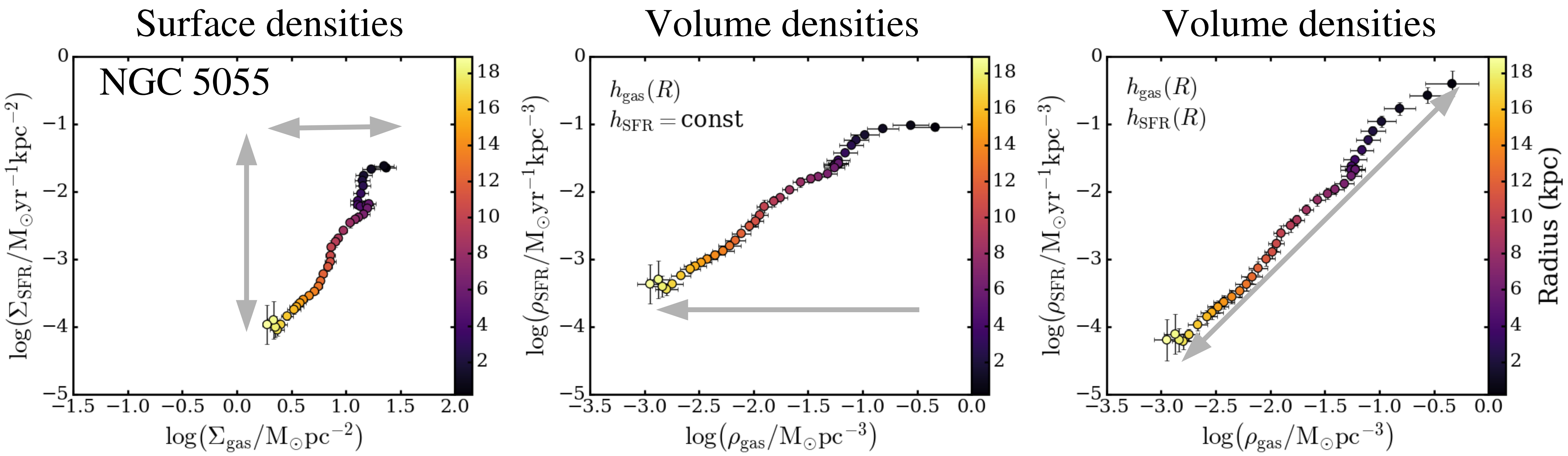


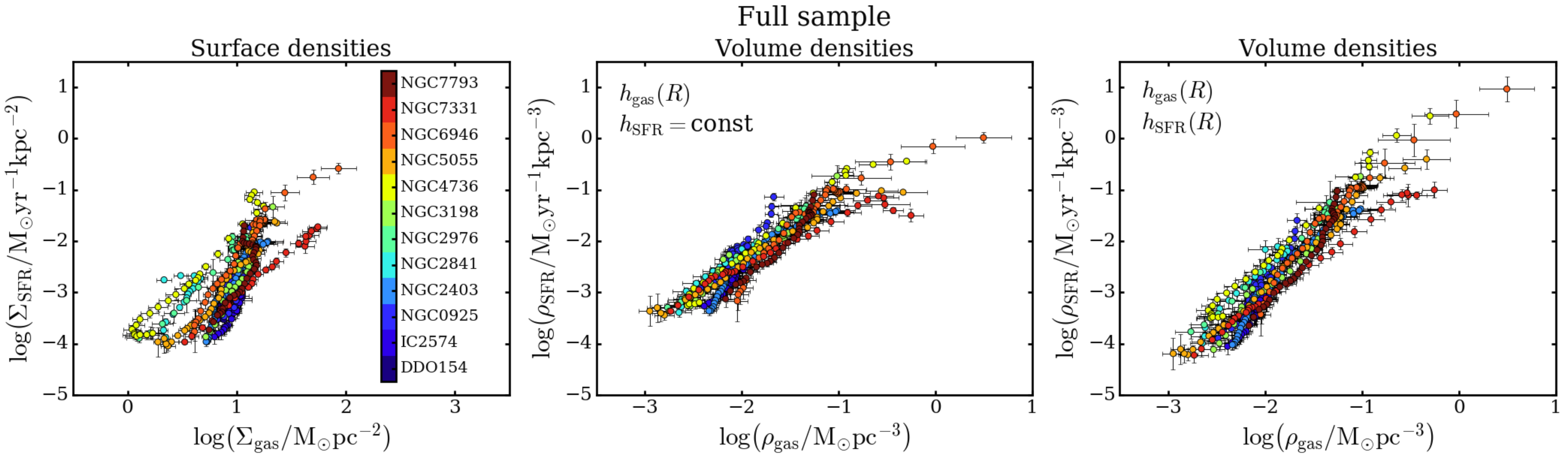
VSF law: example for a single galaxy



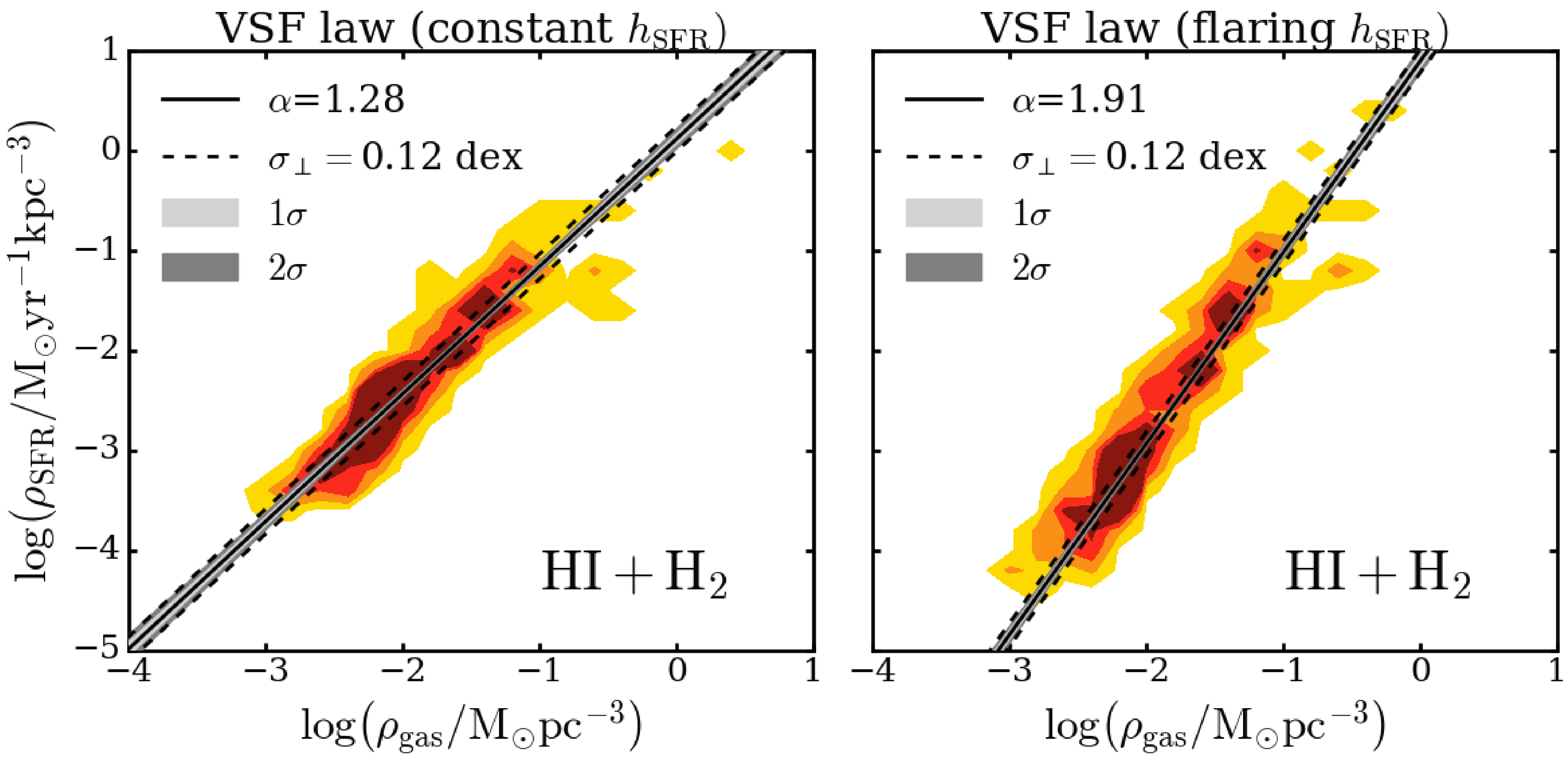
What about the full sample?

VSF law: the whole sample

Atomic + molecular gas



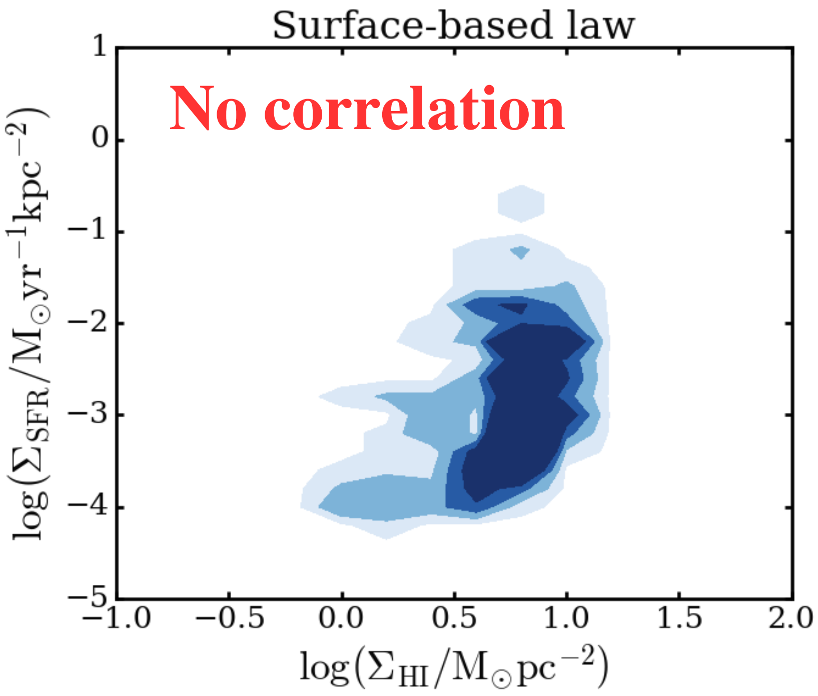
VSF law with total gas: slope and scatter



$$1.3 < \alpha < 1.9 \Rightarrow \rho_{SFR} \propto \rho_{gas}^{1.5}$$

Small intrinsic scatter!

VSF law: HI vs SFR



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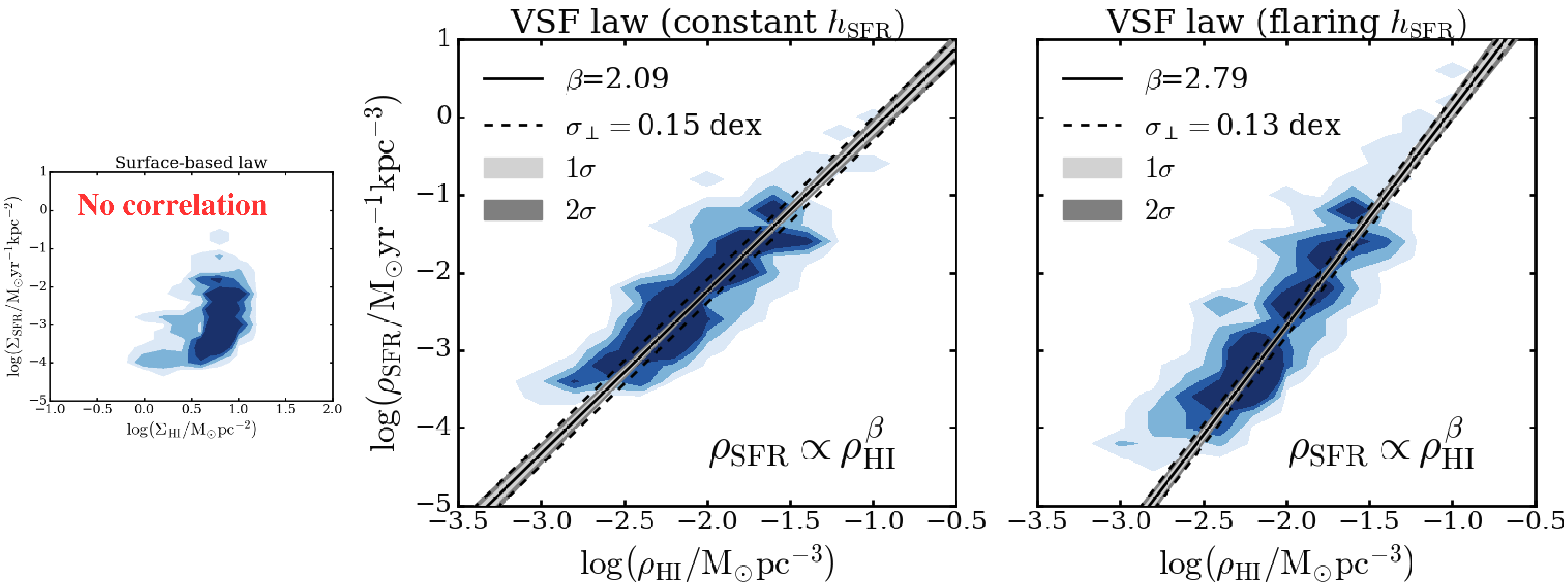


Schmidt law (1959): $\rho_{SFR} \propto \rho_{HI}^{n} \quad 2 < n < 3$

Small intrinsic scatter!

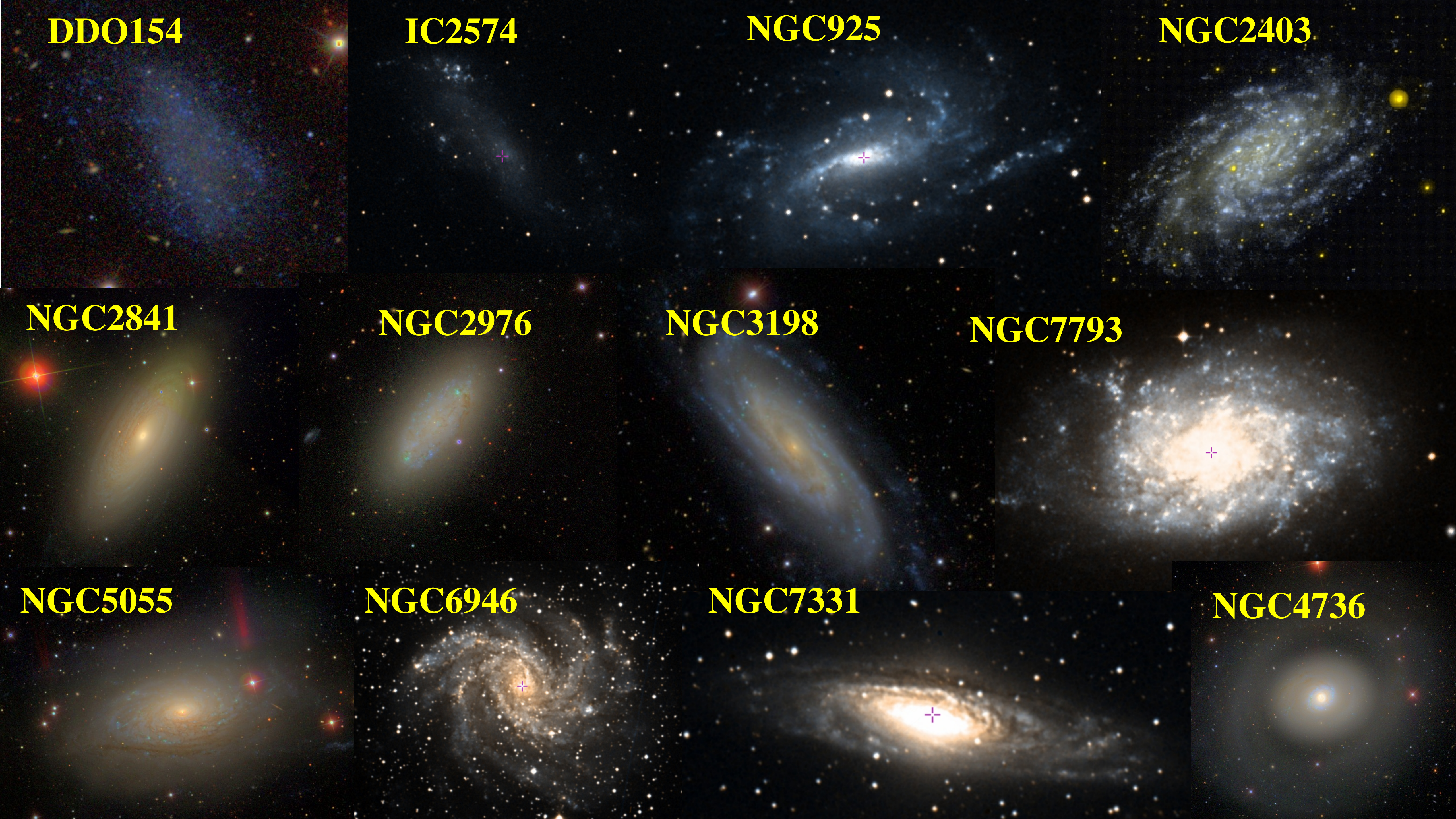
Conclusions

1. **Thickness flare** is significant for any galaxy;
2. Volumetric SF law between **SFR and HI+H$_2$**

   → slope bracketed between 1.3 and 1.9;
3. Tight correlation between **SFR and HI** volume densities.

Take home message

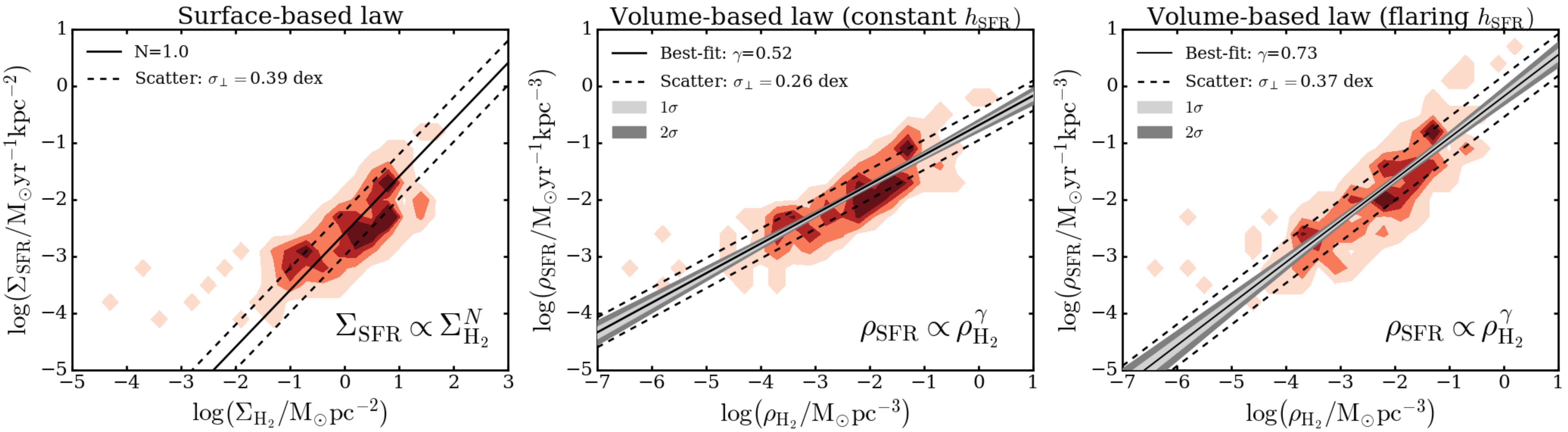
Fundamental SF laws with volume densities



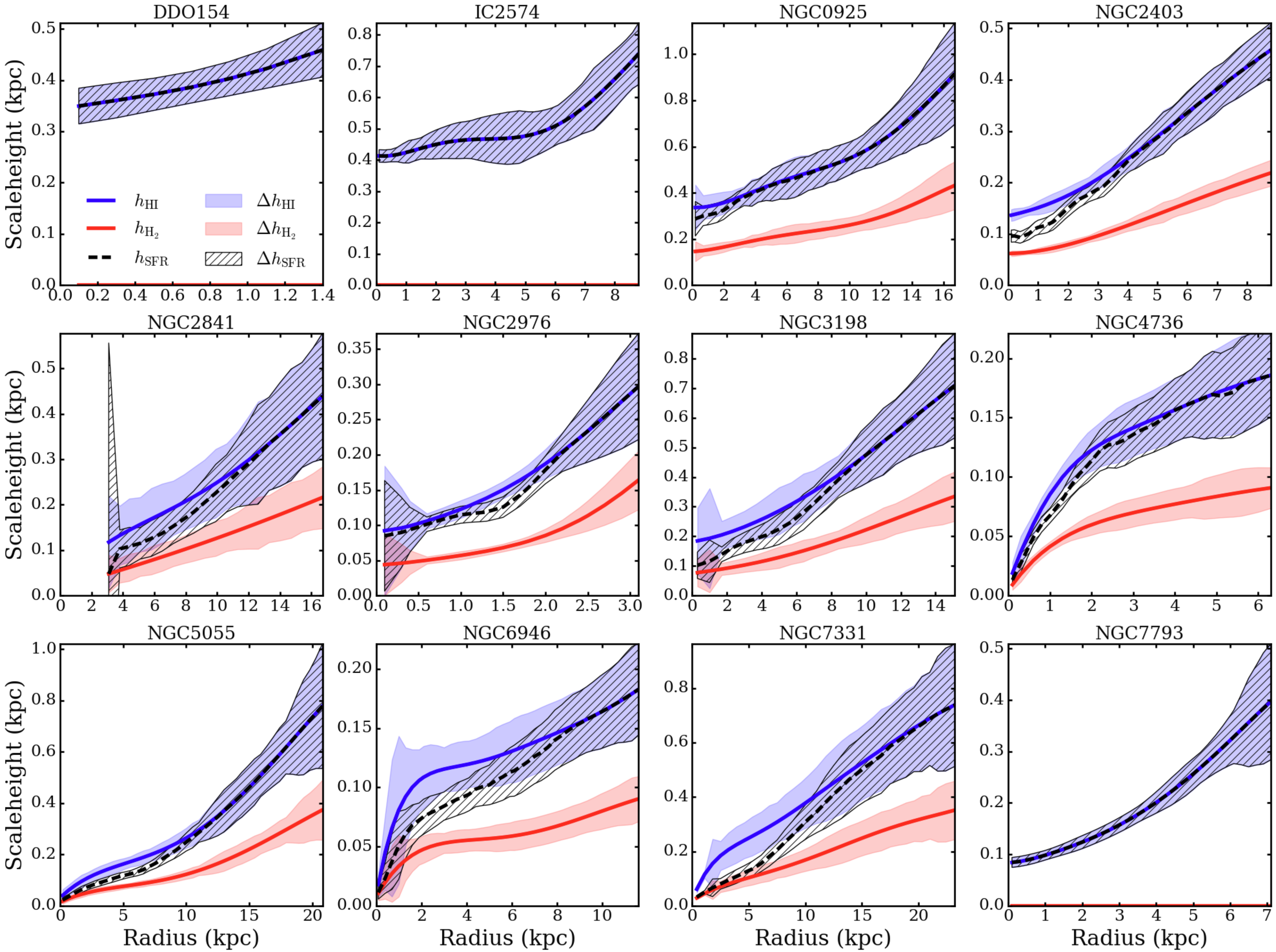
DDO154
IC2574
NGC925
NGC2403
NGC2841
NGC2976
NGC3198
NGC7793
NGC5055
NGC6946
NGC7331
NGC4736

VSF law: molecular gas vs SFR

Only molecular gas

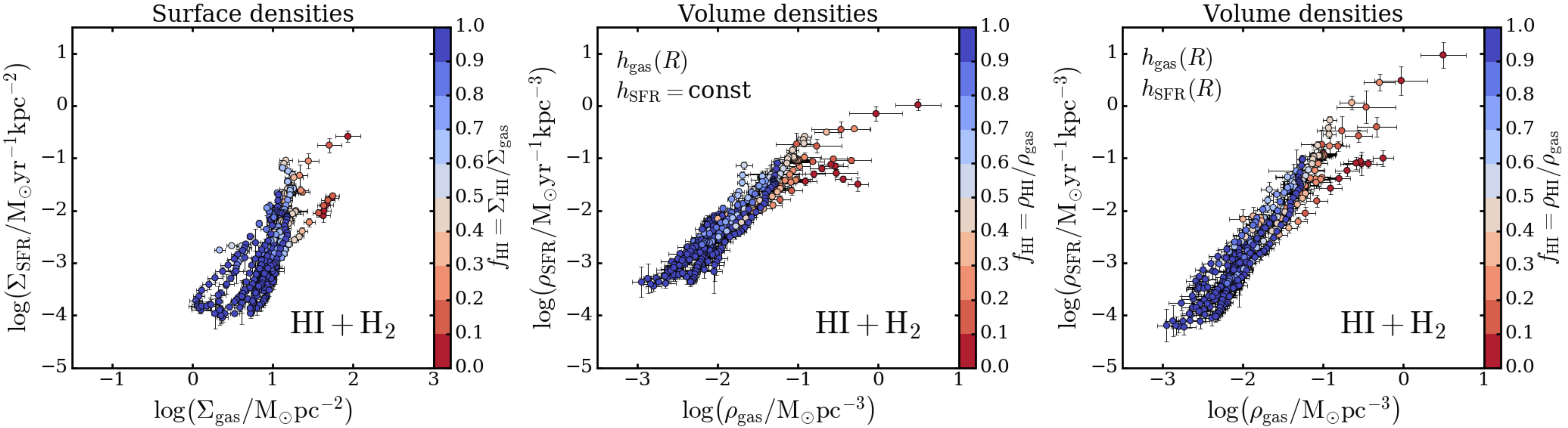


No significant improvement → **small variation of H_2 scaleheight**

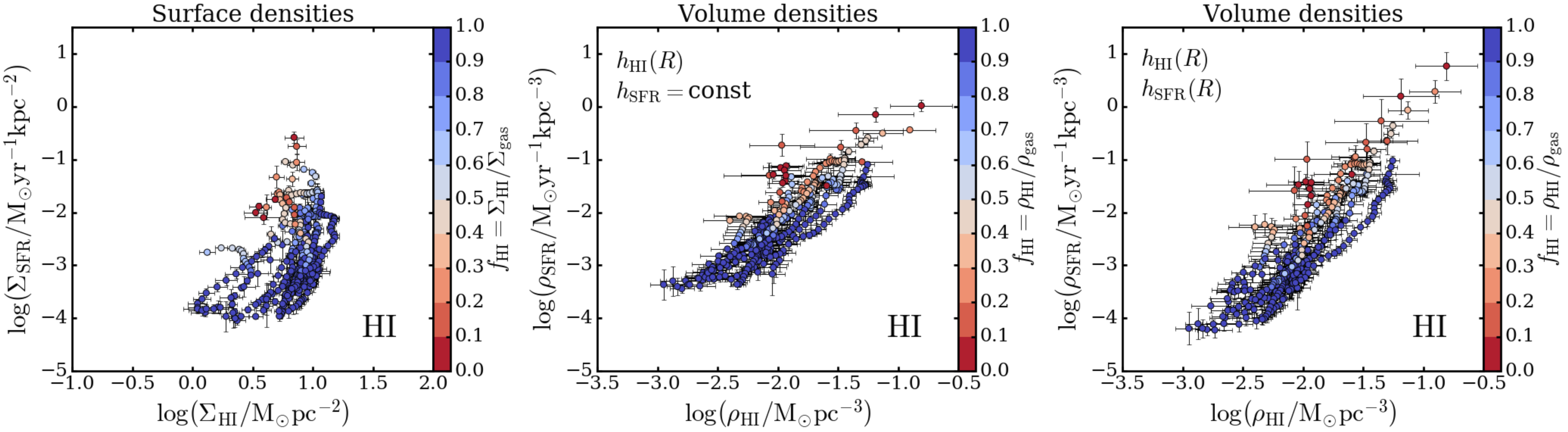


DDO154
IC2574
NGC0925
NGC2403
NGC2841
NGC2976
NGC3198
NGC4736
NGC5055
NGC6946
NGC7331
NGC7793
Scaleheight (kpc)
Radius (kpc)
$h_{\rm HI}$
$h_{\rm H_2}$
$h_{\rm SFR}$
$\Delta h_{\rm HI}$
$\Delta h_{\rm H_2}$
$\Delta h_{\rm SFR}$

VSF law: total gas vs SFR



VSF law: atomic gas vs SFR



VSF law: molecular gas vs SFR