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A "universal" supernova efficiency to drive the HI turbulence in nearby star-forming galaxies

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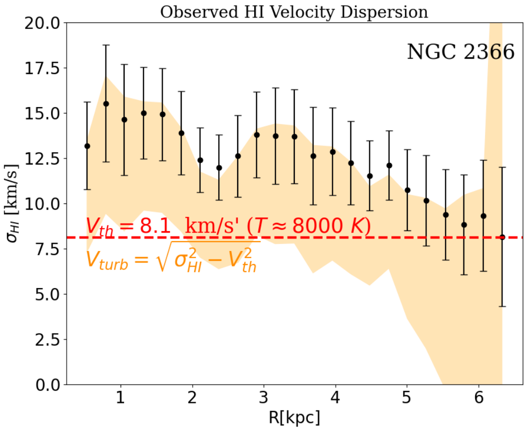
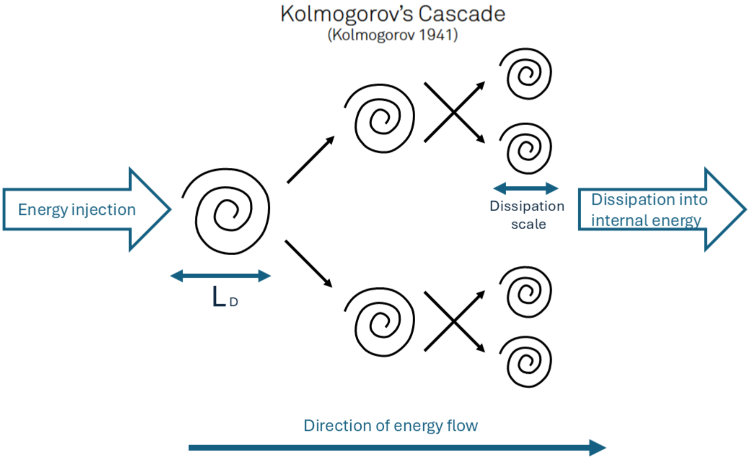
The observed turbulence in the interstellar medium

1. Broadening of emission lines gives us the velocity dispersion (σ_{HI})
2. Observed σ_{HI} is much higher than expected from thermal motions of ISM
3. Velocity excess is assigned to turbulence



Turbulence dissipation



Dissipation time:

$$\tau = \frac{L_D}{V_{\mathrm{turb}}}$$

Injection rate:

$$\dot{E}_{\mathrm{turb}} = \frac{E_{\mathrm{turb}}}{\tau}$$

Energy injection by supernovae

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

Energy injection by supernovae

1 SN = 10^{51}erg

↑

Theory

↑

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Theory

Rate of core-collapse supernovae

f ~ 1.3 x 10^{-2} per solar mass formed

Energy injection by supernovae

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Theory

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

Star formation rate density

Rate of core-collapse supernovae

f ~ 1.3 x 10^{-2} per solar mass formed

Energy injection by supernovae

1 SN = 10^{51}erg

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Theory

↑

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

- η: SN – efficiency [0,1]
- Σ_{SFR}: Star formation rate density
- f_{cc}: Rate of core-collapse supernovae
  ↓
  f ~ 1.3 x 10^{-2} per solar mass formed

Energy injection by supernovae

Combining equations of energy injection by SNe and dissipation time

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

Analytical models and numerical simulations suggest

$$\eta \lesssim 0.1$$

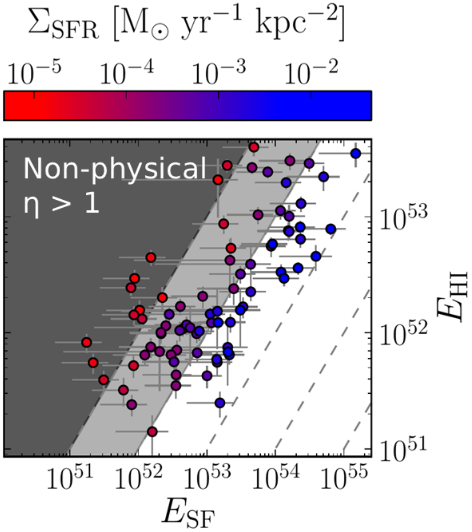
E.g. Kim & Ostriker (2015); Fierlinger et al. (2015)

Previous studies (the motivation)

Previous studies:

- Supernovae are only enough in the inner regions of galactic discs ($\Sigma_{\rm SFR} > 5 \times 10^{-4}\, M_\odot\, {\rm yr}^{-1}\, {\rm kpc}^{-2}$)
- Too inefficient in the regions of low $\Sigma_{\rm SFR}$

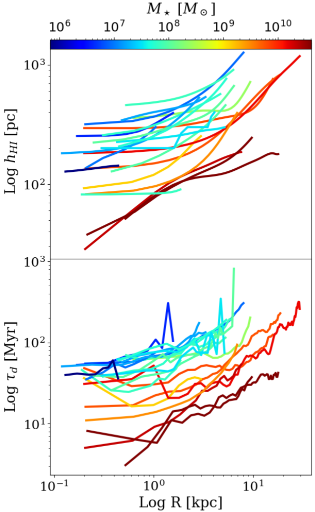
See also Tamburro+2009, Hunter+2021, Elmegreen+2022



Stilp et al. 2013

Previous studies (motivation)

Flaring of the galactic disc was not taken into account!



$$\tau = \frac{L_D}{V_{\rm turb}} \approx \frac{2h}{V_{\rm turb}}$$

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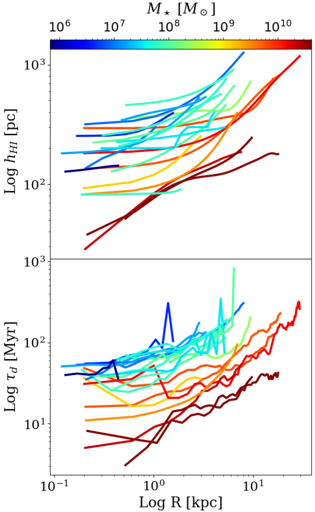

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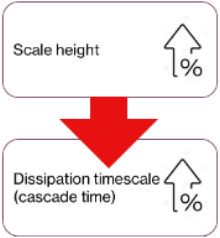

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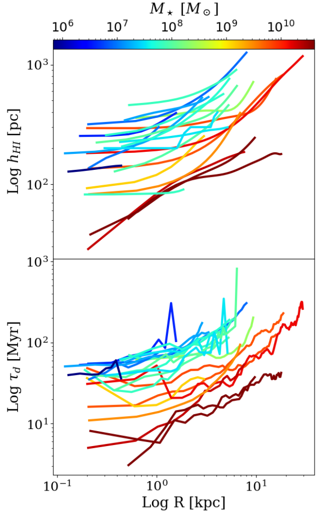

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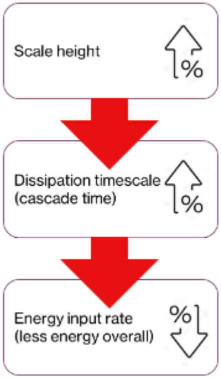

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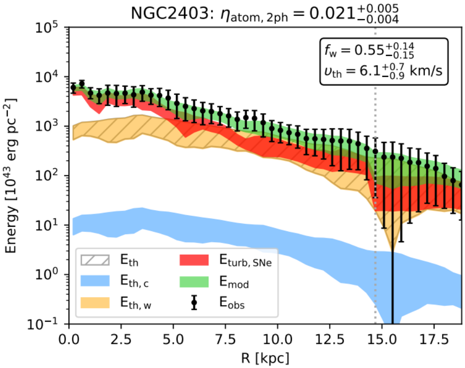
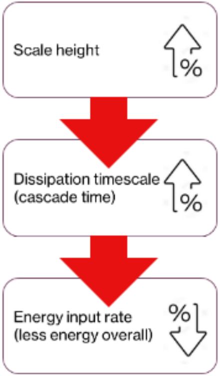


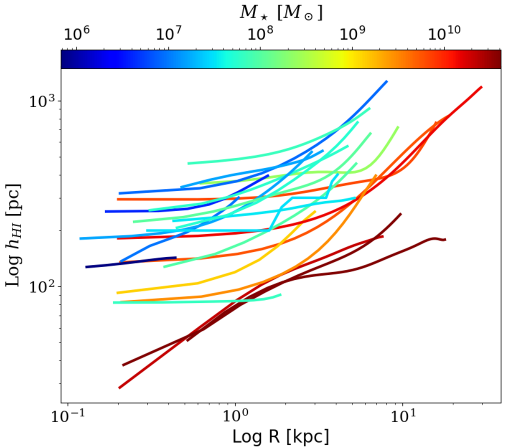
Bacchini et al. 2020

$$\tau = \frac{L_D}{V_{\rm turb}} \approx \frac{2h}{V_{\rm turb}}$$



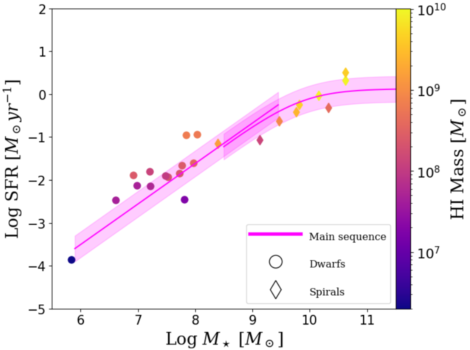
Sample & Method

Radial scale height $h_{\rm HI}(R)$ profiles were derived by Bacchini+2020 assuming vertical hydrostatic equilibrium



Our sample covers a broad range of galaxies

- 14 Dwarf galaxies
- 9 Spirals



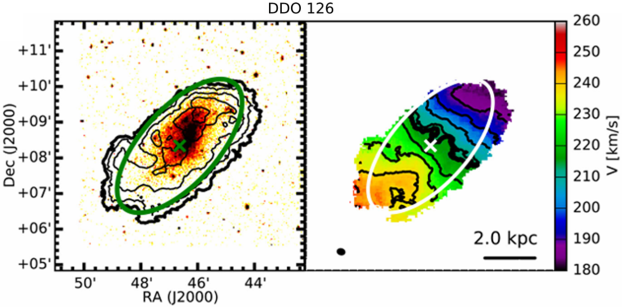
Sample & Method

We leverage archival HI data of LITTLE THINGS 2012

From the photometric (UV) data can one derive the **star formation rate density**

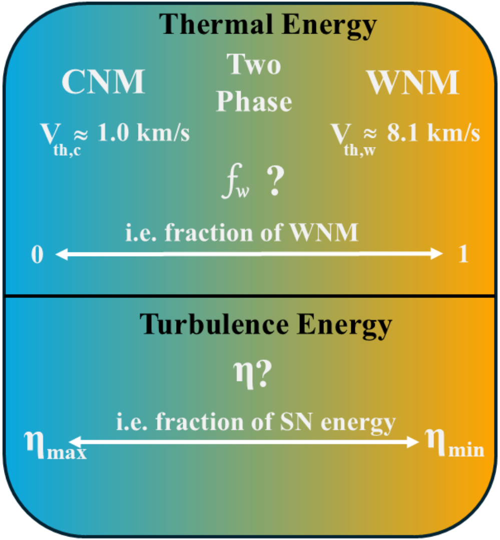
$$\Sigma_{\mathrm{SFR}} = \cos(i)\times 10^{-0.4\left(\frac{\mu_{\mathrm{FUV}}}{\mathrm{mag\ arcsec}^{-2}}\right)}$$

HI kinematics (σ_{HI}, V_{rot}) are derived by Iorio+2017 utilising 3D-Barolo tilted ring modeling software

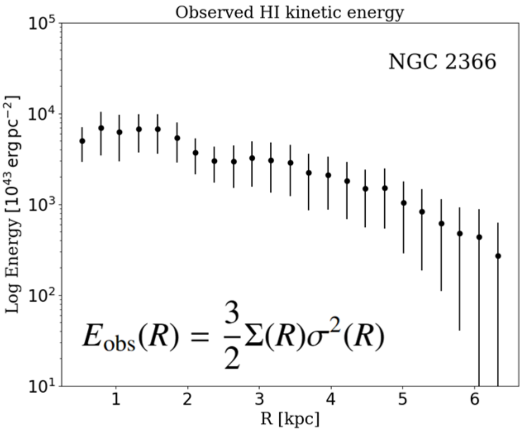


https://editeodoro.github.io/Bbarolo/

Model



Thermal Energy
CNM
Two Phase
WNM
$V_{th,c} \approx 1.0$ km/s
$V_{th,w} \approx 8.1$ km/s
f_w ?
i.e. fraction of WNM
0
1
Turbulence Energy
η?
i.e. fraction of SN energy
η_{max}
η_{min}



Observed HI kinetic energy
NGC 2366
Log Energy [10^{43} erg pc^{-2}]
R [kpc]
$E_{obs}(R) = \frac{3}{2}\Sigma(R)\sigma^2(R)$

Goal

Research Question 1:

How big of a fraction of SN energy do we need to maintain turbulence in dwarf galaxies?

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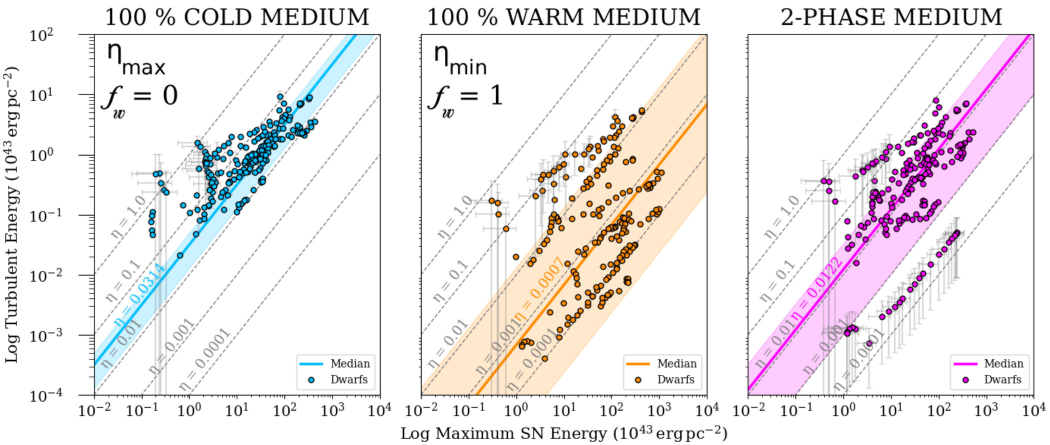
How big of a fraction of SN energy do we need to maintain turbulence in dwarf galaxies?

Approach:

Each dwarf galaxy is fit with a own set of η and f_{w} parameters.

Characteristic SN efficiencies



Goal

Research Question 1:

How big of a fraction of SN energy do we need to maintain turbulence in dwarf galaxies?

Approach:

Each dwarf galaxy is fit with a own set of η and f_{w} parameters.

Result:

SN-efficiencies required to maintain turbulence range between $\eta \approx 0.02 - 7\,\%$ in the two-phase medium

(Never exceeding 9% even in the 100% CNM).

Goal

Research Question 2:

Can a single ”universal” SN efficiency maintain the turbulence in all star forming galaxies from dwarfs to spirals

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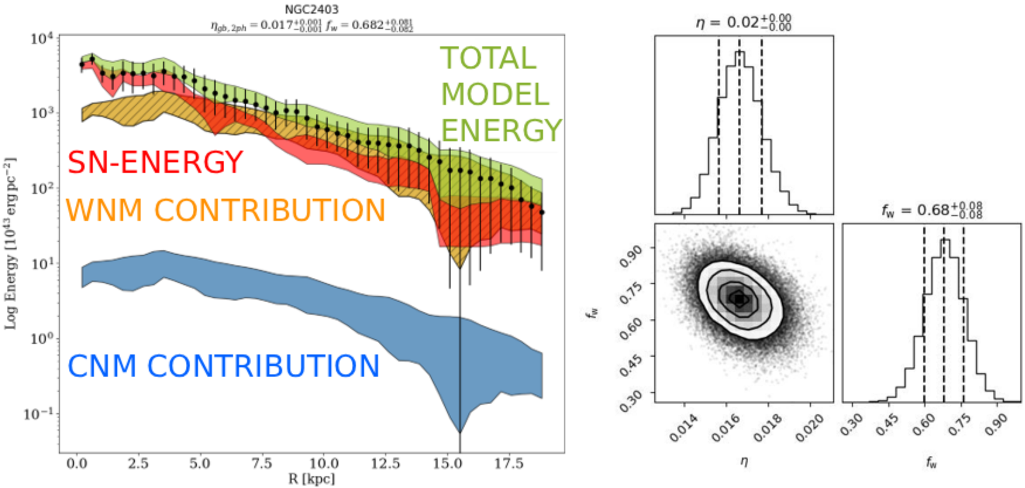
Can a single ”universal” SN efficiency maintain the turbulence in all star forming galaxies from dwarfs to spirals

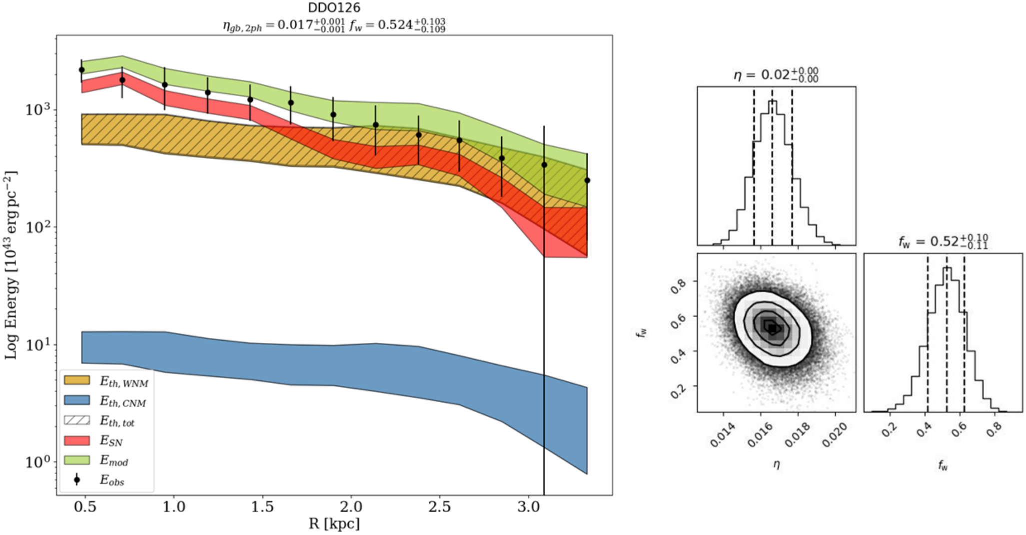
Approach:

The η parameter is fitted simultaneously across all galaxies, together with the corresponding f_{w} value for each individual galaxy.

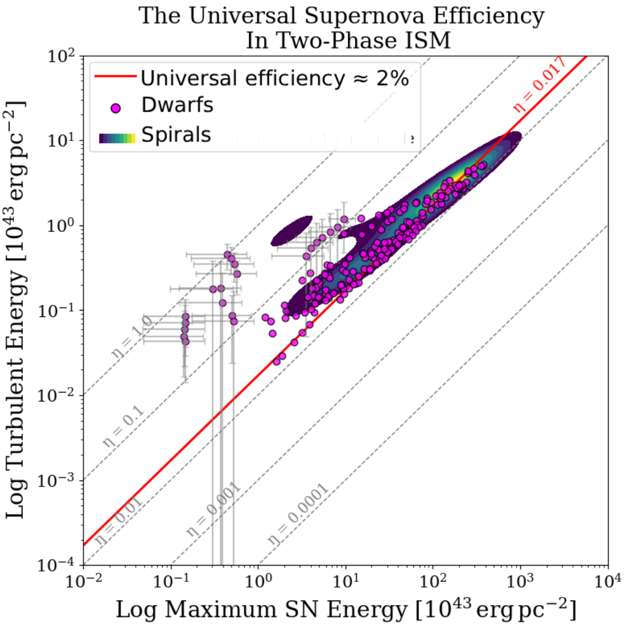
Universal efficiency?



Universal efficiency?



Universal efficiency?



Goal

Research Question 2:

Can a single ”universal” SN efficiency maintain the turbulence in all star forming galaxies from dwarfs to spirals

Approach:

The η parameter is fitted simultaneously across all galaxies, together with the corresponding f_{w} value for each individual galaxy.

Result:

YES!

Only a fraction of SN energy, $(\eta \approx 2\,\%)$ is needed to explain the observed turbulence both in spirals and dwarfs.

Key takeaway

A single ”universal” SN efficiency of $\boldsymbol{\eta \approx 2\,\%}$ can sustain the HI turbulence in present-day galaxies on the main sequence.

Hire me! Looking for a PhD position:

CV

Extra slides

Model

$$E_{\mathrm{mod}} = E_{\mathrm{th}} + E_{\mathrm{turb,SNe}}$$

Model

$$E_{\mathrm{mod}} = \underbrace{E_{\mathrm{th}}}_{\frac{3}{2}\Sigma\left[(1-f_{\mathrm{w}})v_{\mathrm{th,c}}^2 + f_{\mathrm{w}}v_{\mathrm{th,w}}^2\right]} + E_{\mathrm{turb,SNe}}$$

Model

$$E_{\mathrm{mod}} = \underbrace{E_{\mathrm{th}}}_{\frac{3}{2}\Sigma\left[(1-f_{\mathrm{w}})v_{\mathrm{th,c}}^2 + f_{\mathrm{w}}v_{\mathrm{th,w}}^2\right]} + \overbrace{E_{\mathrm{turb,SNe}}}^{\eta\Sigma_{\mathrm{SFR}}f_{\mathrm{cc}}E_{\mathrm{SN}}\frac{2h}{v_{\mathrm{turb}}}}$$

Model

$$\overbrace{\eta \Sigma_{\rm SFR} f_{\rm cc} E_{\rm SN} \frac{2h}{v_{\rm turb}}}$$

$$E_{\rm mod} = \underbrace{E_{\rm th}}_{\frac{3}{2}\Sigma \left[(1 - f_{\rm w}) v_{\rm th,c}^2 + f_{\rm w} v_{\rm th,w}^2\right]} + \overbrace{E_{\rm turb,SNe}}^{\eta \Sigma_{\rm SFR} f_{\rm cc} E_{\rm SN} \frac{2h}{v_{\rm turb}}}$$

$$\frac{3}{2}\Sigma \left[(1 - f_{\rm w}) v_{\rm th,c}^2 + f_{\rm w} v_{\rm th,w}^2\right]$$

Through Bayesian hierachical modeling we fit observed energies $E_{\rm obs} = \frac{3}{2}\Sigma(R)\sigma_{\rm obs}^2$ against the model energies to infer $\boldsymbol{\eta}$ and $\mathbf{f_w}$

3D-Barolo

3D-Based Analysis of Rotating Object via Line Observations

- Fits tilted ring models directly on the emission line data cubes, without extracting the velocity fields first (minimizes the beam smearing).
- In practice, the model iteratively adjusts a set of tilted ring models to best match the observed data by minimizing residuals.
- Can fit up to 8 parameters (central coordinates, $V_{\rm sys}$, i, PA, $\Sigma_{\rm HI}$, HI thickness, $V_{\rm rot}$, σ).
- In some of the dwarfs, the velocity dispersions found by the 3DB were not well constrained, seen in the profiles as inconsistent behaviour from the general trend such as very small errors, sudden drop or rise in the profile. All of the sample galaxies were manually checked for abrupt changes and irregularities (Removed points account for $\approx 5\%$ of data points).

GALPYNAMICS

The scale heights very numerically calculated using the `GALPYNAMICS` python module (`https://gitlab.com/iogiul/galpynamics`)

- Calculates the vertical distribution and scale height of gas discs inside the gravitational potential assuming the vertical hydrostatic equilibrium.
- **Inputs:** gas velocity dispersion and the gravitational potential (Φ) from both gaseous ($\Phi_{\rm HI}$) and non-gaseous components ($\Phi_{\rm ext}$).
- $\Phi_{\rm ext}$ includes both the dark matter halo modeled by cored Navarro-Frenk-White (NFW) profile and the stellar disc.
- Scale height is calculated as the σ of Gaussian profiles fitted to the vertical distribution of gas at each radius. After this, the self-gravity is recalculated using the updated scale-height and process repeats...

SuperBubble blowouts

Superbubble = The blowout effect of multiple SNe and stellar wind.
diameter $\sim$ disc thickness (Mac Low & McCray 1999)

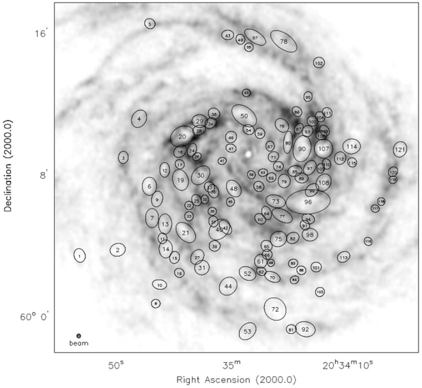


Figure: HI disc of NGC 6946 (Boomsma+2008)

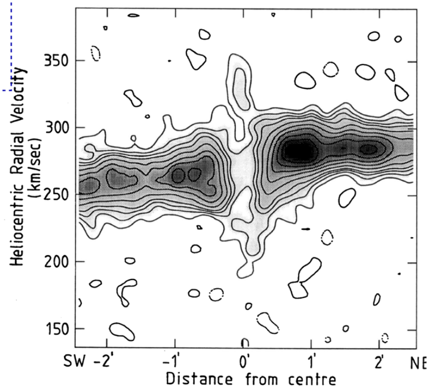
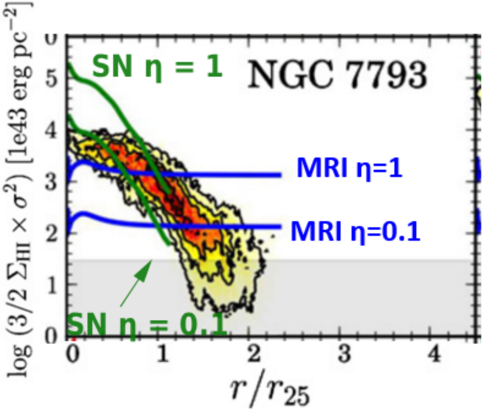


Figure: HI disc of M101 (Kamphuis+1991)

Previous studies (the motivation)

Similar conclusion by Tamburro et al. 2009



Tamburro et al. 2009