The properties of HI discs

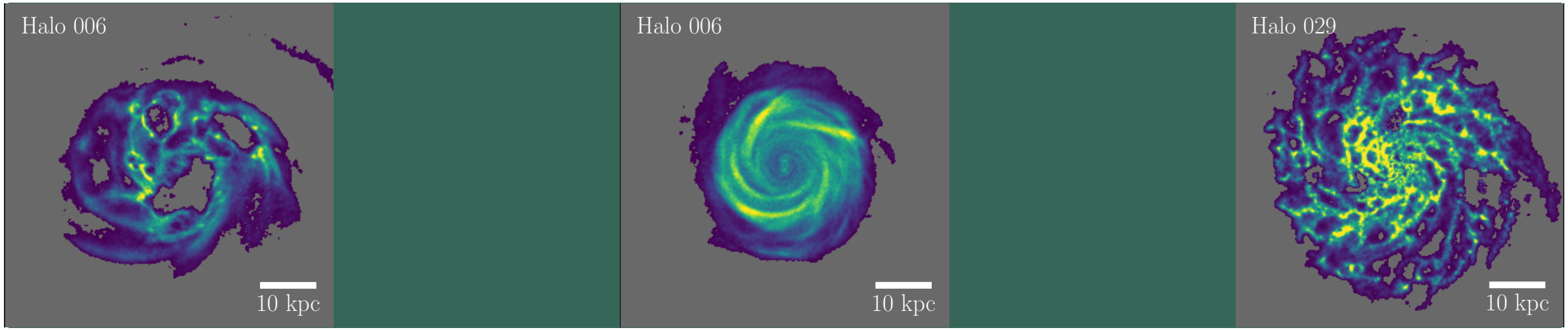
as probes of the baryonic physics of galaxy evolution

Jindra Gensior | 07.09.23

Sinergia Postdoctoral Fellow

Institute for Computational Science, University of Zurich | jindra.gensior@uzh.ch

with Lucio Mayer, Robert Feldmann & the EMP team



The properties of HI discs and their evolution across cosmic time

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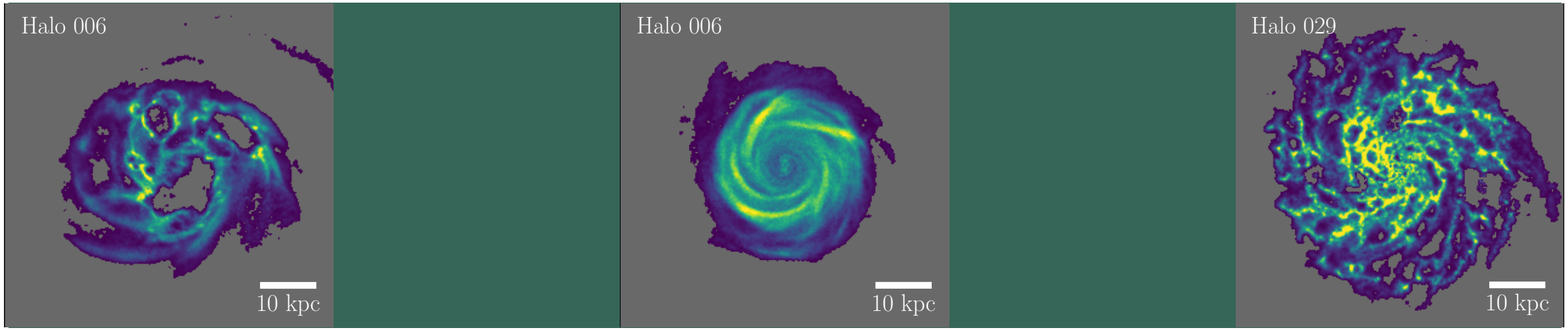
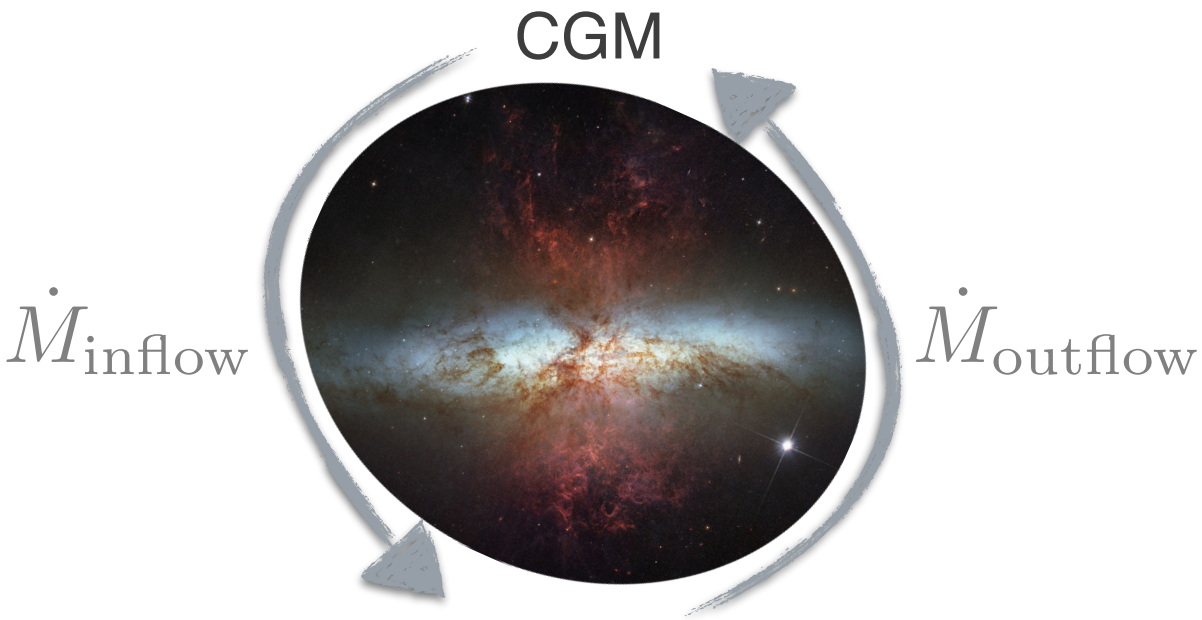


THE BARYON CYCLE OF GALAXIES



Star formation & Feedback

Gas-regulator or "bathtub model"

e.g. Finlator & Davé 2008, Bouché+ 2010, Lilly+ 2013, Dekel+ 2013, Dekel & Mandelker+ 2014, Peng & Maiolino 2014, Belfiore+ 2019, Tacchella+2020

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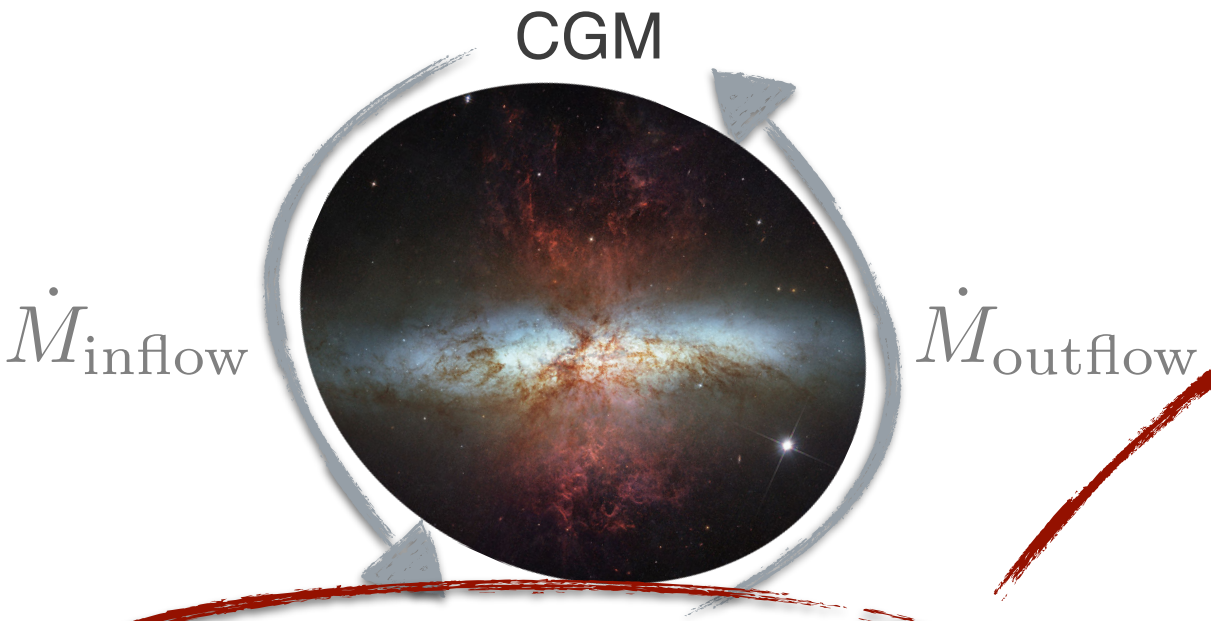

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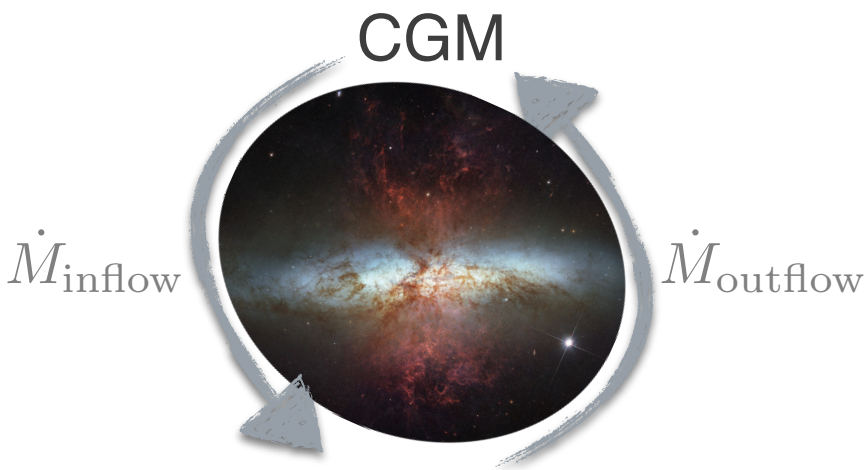
Remain uncertain

e.g. Naab & Ostriker 2017

- Star formation efficiency (SFE) varies (e.g. Utomo+2018, Sun+2023)
  - Depends on turbulent properties of gas?(e.g. Krumholz & McKee 2005, Federrath & Klessen 2012, Evans+2022)
  - Star formation could be bottleneck for baryon cycle in certain conditions (Gensior & Kruijssen 2021)
  - Relative importance of early stellar feedback vs. supernovae (e.g. Smith+2021, Keller+2022)

THE BARYON CYCLE OF GALAXIES



Star formation & Feedback

fuel

affects structure, kinematics, abundance…

HI

e.g. Saintonge & Catinella 2022

THE SAMPLE

Galaxies selected to have Milky Way halo-mass: $11.85 < \log\left(M_{\rm halo}/{\rm M}_\odot\right) < 12.48$

Cosmological zooms EMP-*Pathfinder*

Reina-Campos,…,JG+ 2022

FIREbox cosmological volume

Feldmann,…,JG+ 2023

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Constant

$\epsilon_{\rm ff} = 20\%$

21 galaxies

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Multi free-fall

$\epsilon_{\rm ff} = \frac{1}{2}\exp\left(\frac{3}{8}\sigma_{\rm s}^2\right)\left[1+{\rm erf}\left(\frac{\sigma^2 - {\rm s}_{\rm crit}}{\sqrt{2\sigma_{\rm s}^2}}\right)\right]$

=> $\epsilon_{\rm ff} = f(\alpha_{\rm vir}, \mathcal{M})$

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14 galaxies

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21 galaxies **14** galaxies **27** galaxies

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Supernovae Type Ia & II + stellar winds from AGB stars

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Supernovae Type Ia & II + stellar winds from AGB stars

+ early stellar feedback

21 galaxies	**14** galaxies	**27** galaxies

THE SAMPLE:
GALAXIES EVOLVED SELF-CONSISTENTLY ACROSS COSMIC TIME, INCLUDING A **COLD ISM**!

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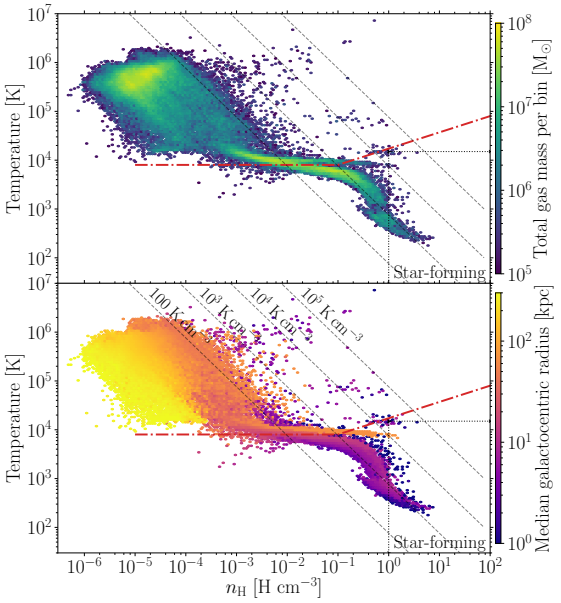

21 galaxies

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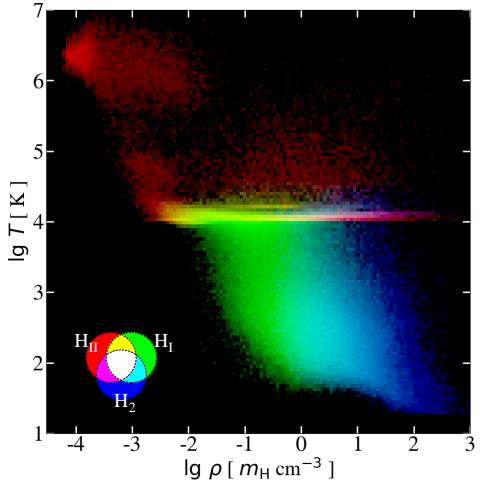

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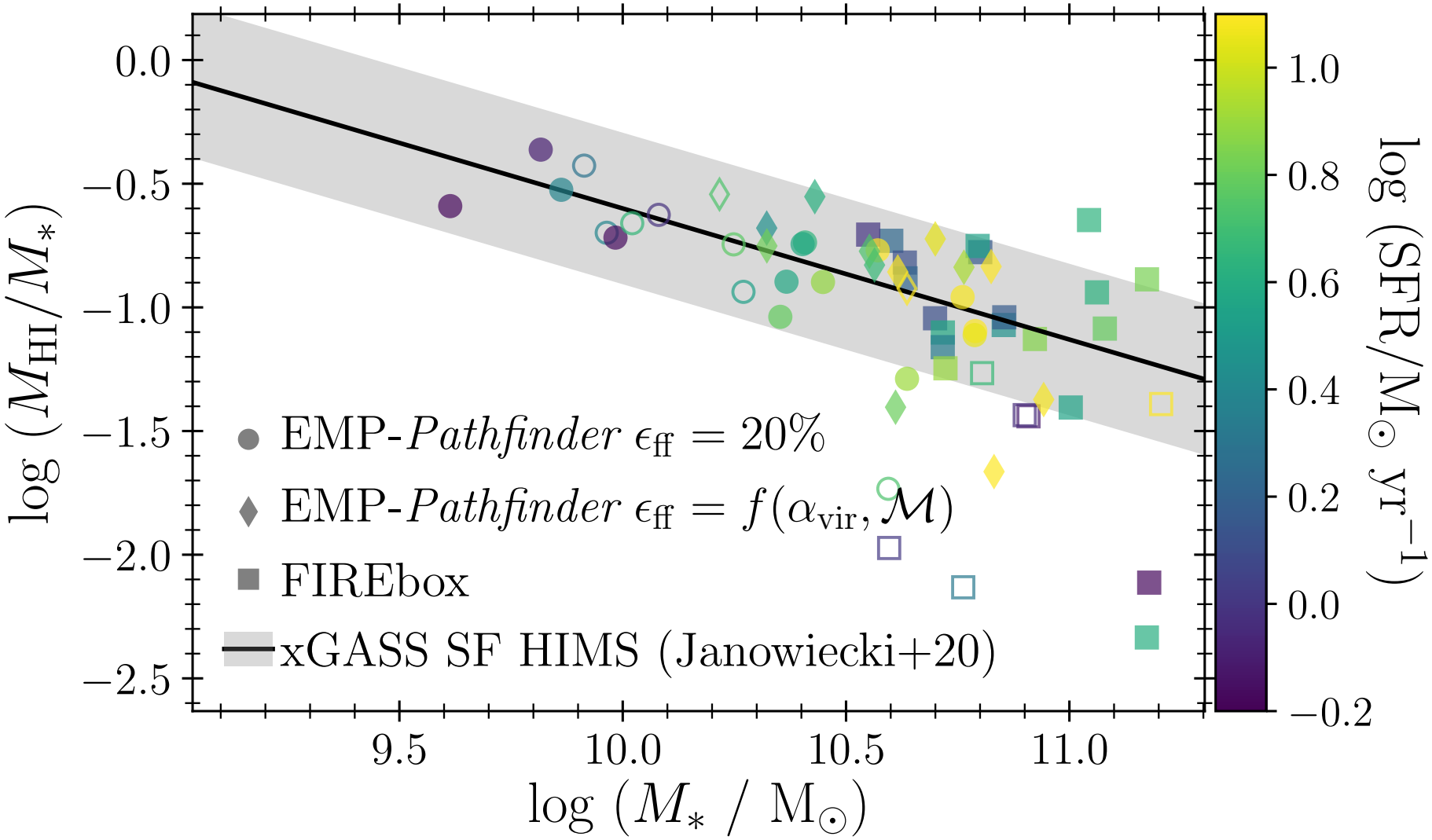
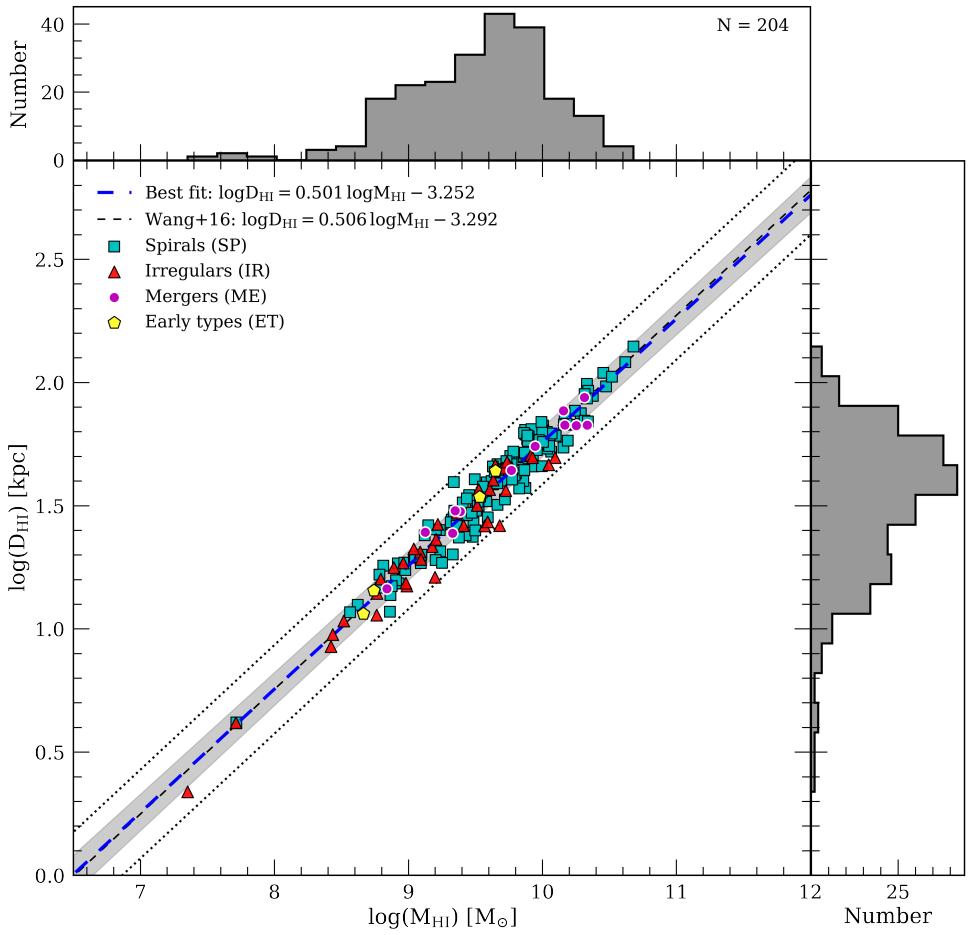


Gensior+2023 to be subm.

HI SIZE-MASS RELATION



MIGHTEE (Rajohnson+2022)

See also e.g. Broils & Rhee 1997, Verheijen & Sancisi 2001, Swaters+2002, Noordermeer+2005, Begum+2008, Obreschkow+2009, Ponomareva+2016, Wang+2016 Stevens+2019

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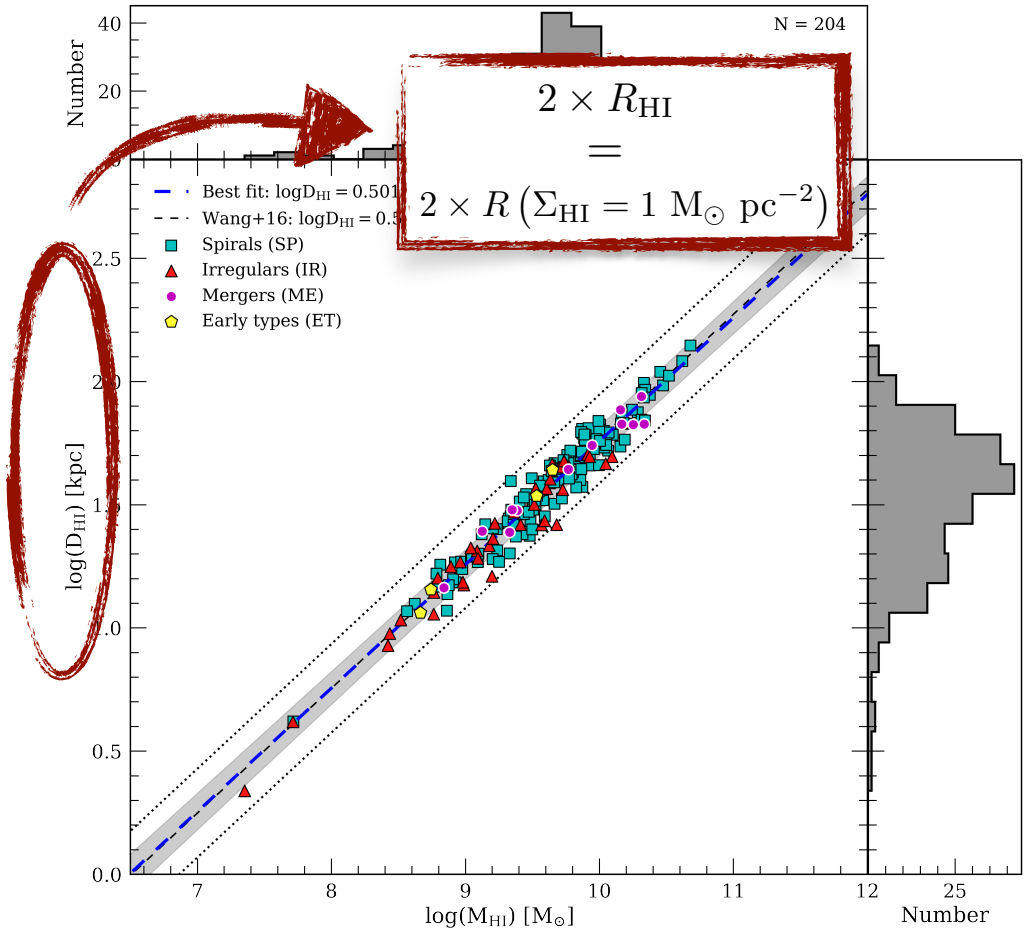

$$2 \times R_{\mathrm{HI}} = 2 \times R\left(\Sigma_{\mathrm{HI}} = 1\ \mathrm{M}_\odot\ \mathrm{pc}^{-2}\right)$$

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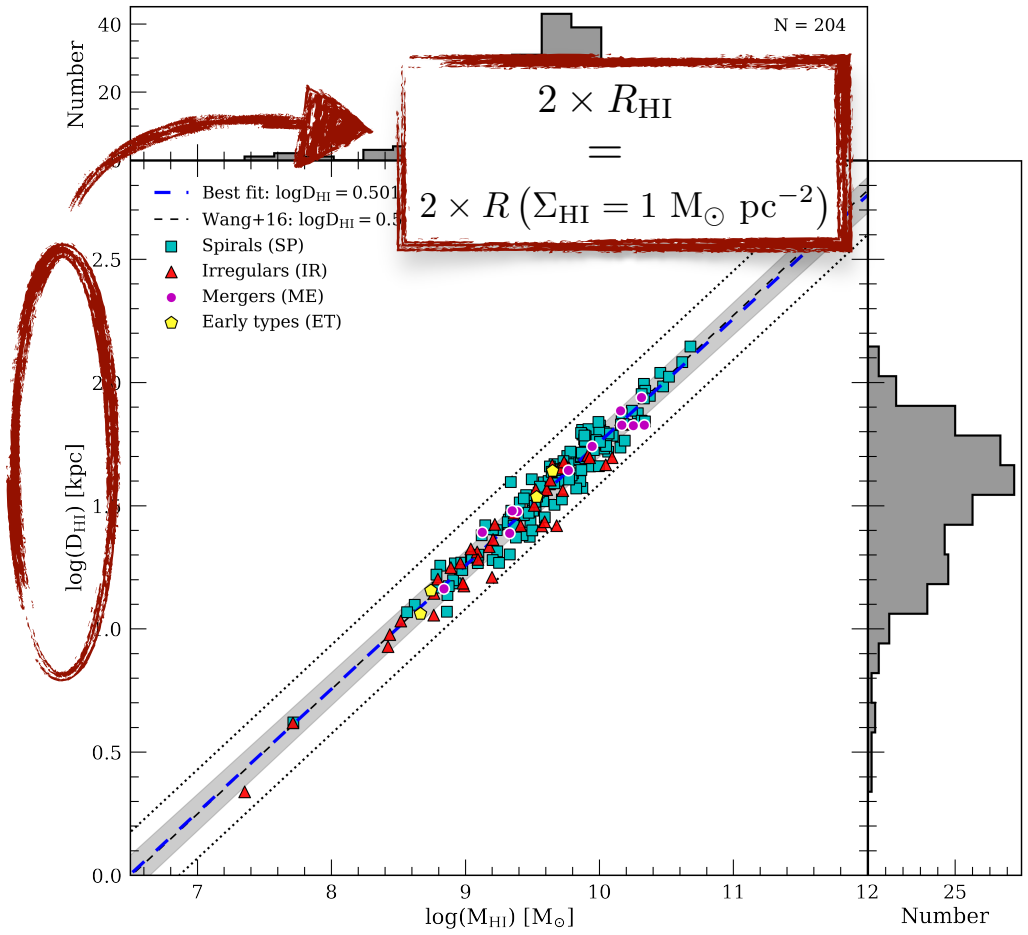

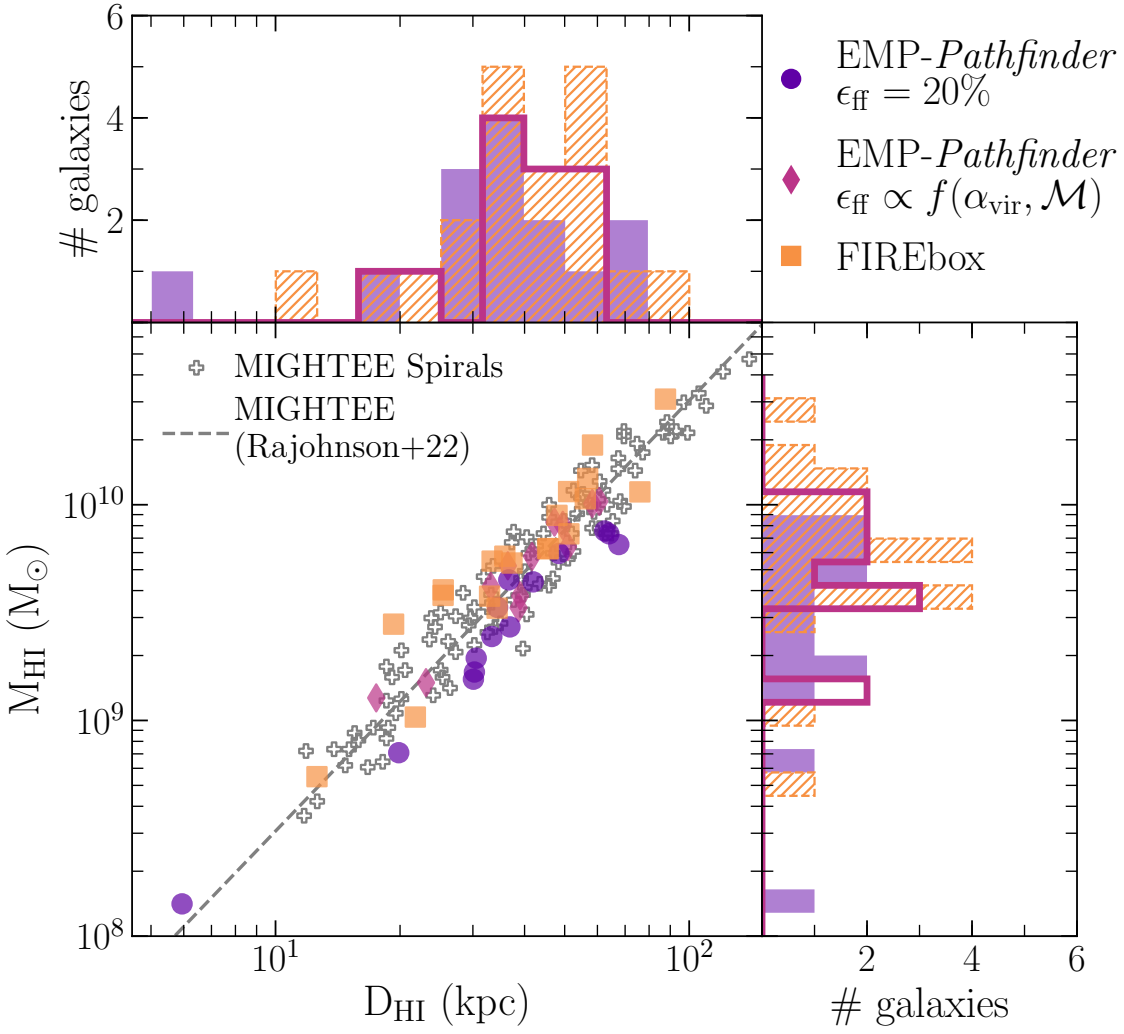

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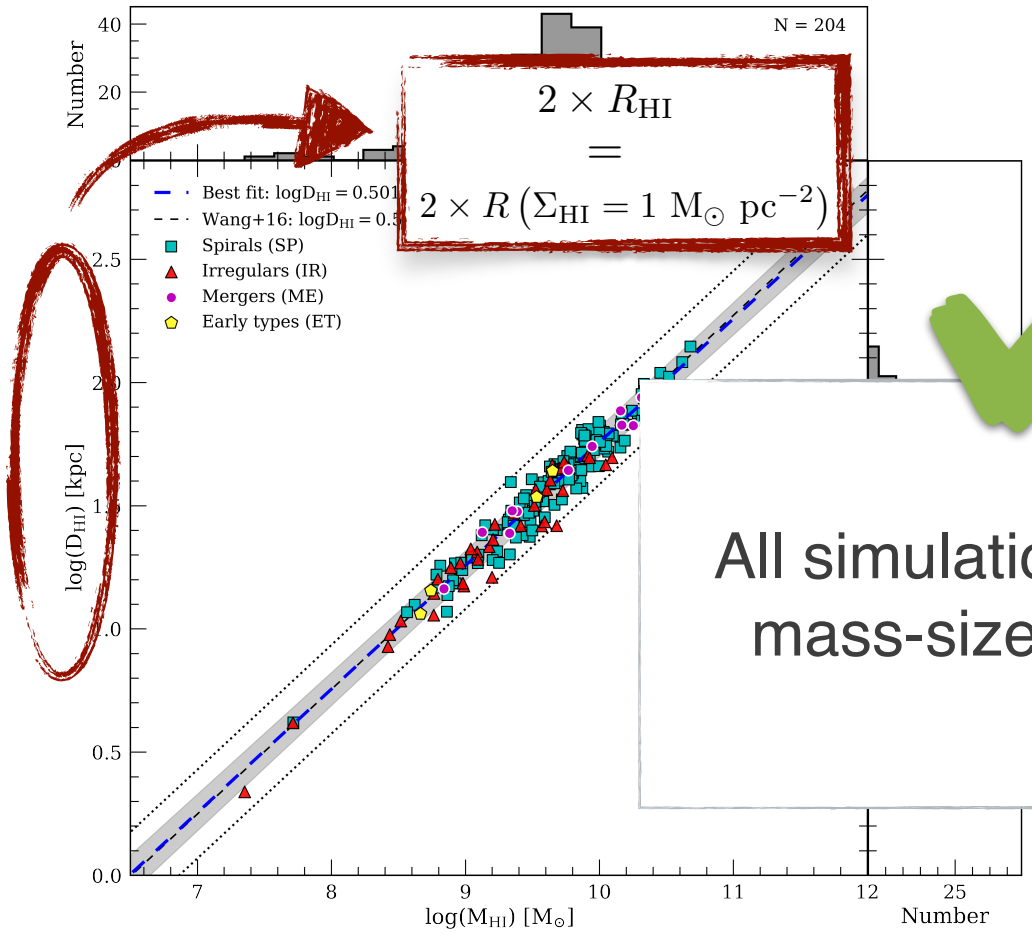
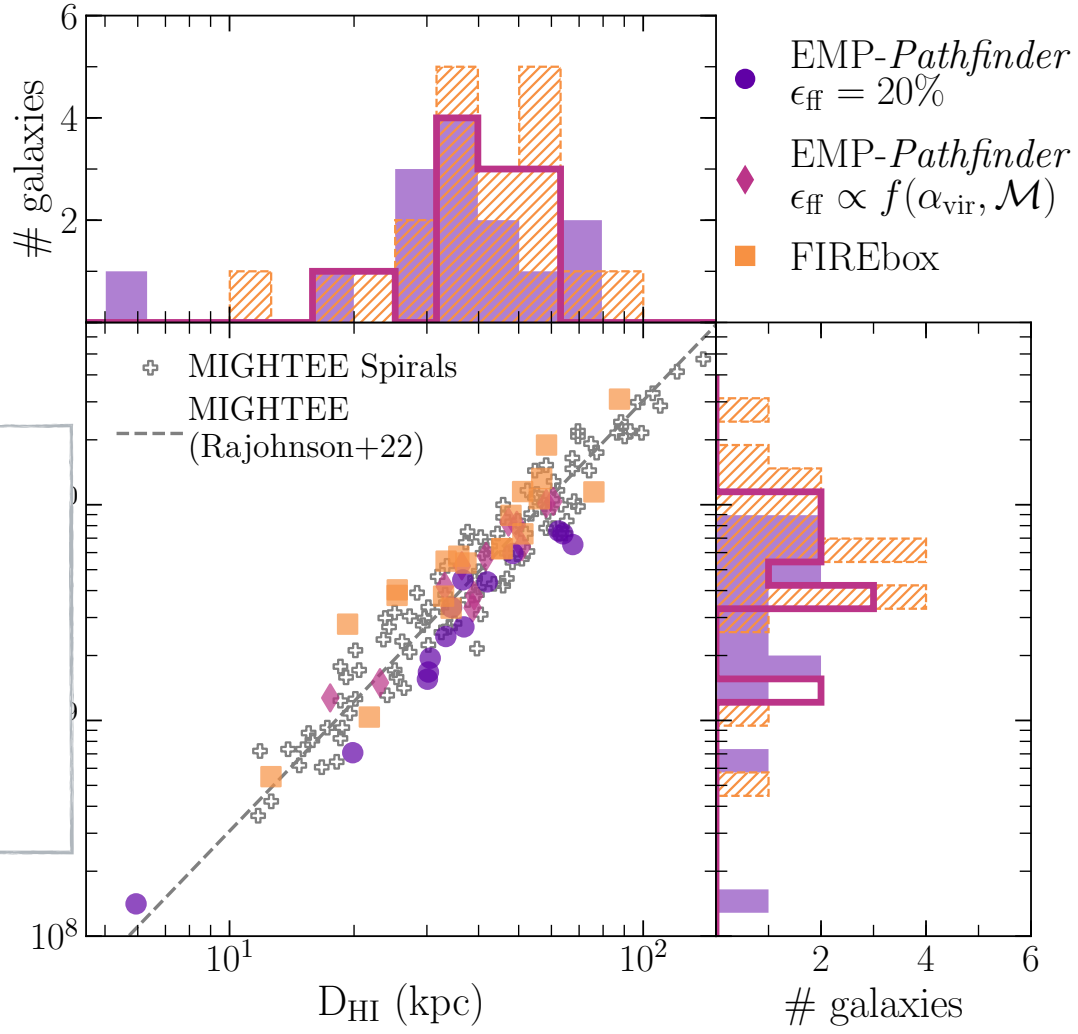


$$2 \times R_{\rm HI} = 2 \times R\left(\Sigma_{\rm HI} = 1\ {\rm M}_\odot\ {\rm pc}^{-2}\right)$$

All simulations follow mass-size relation



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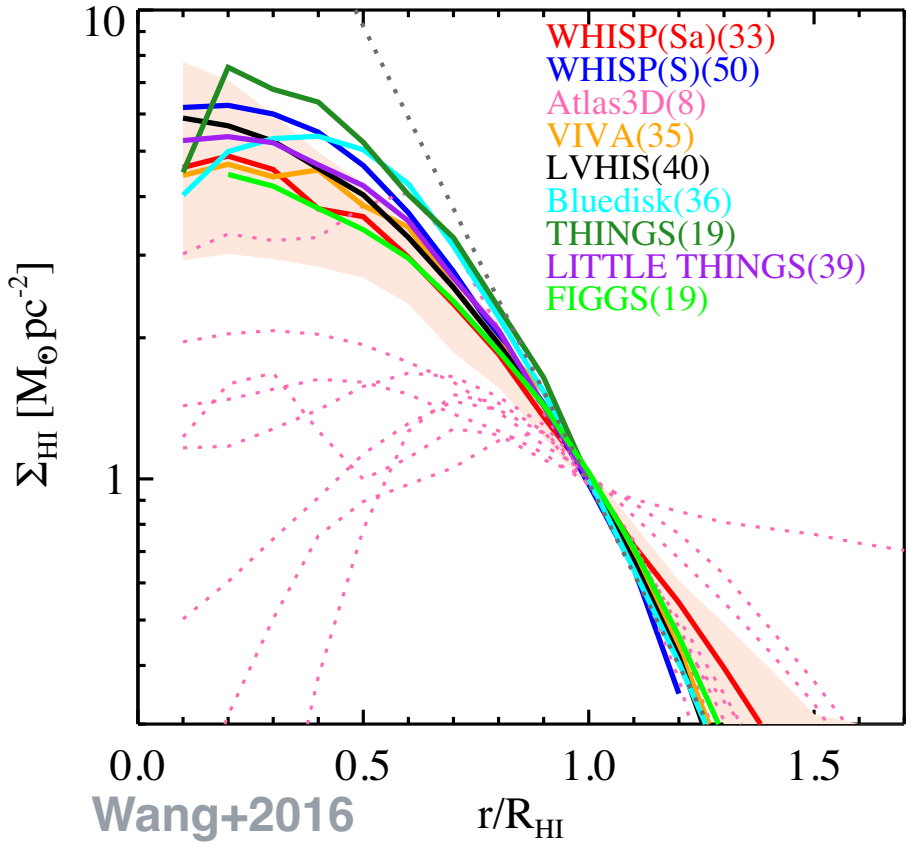
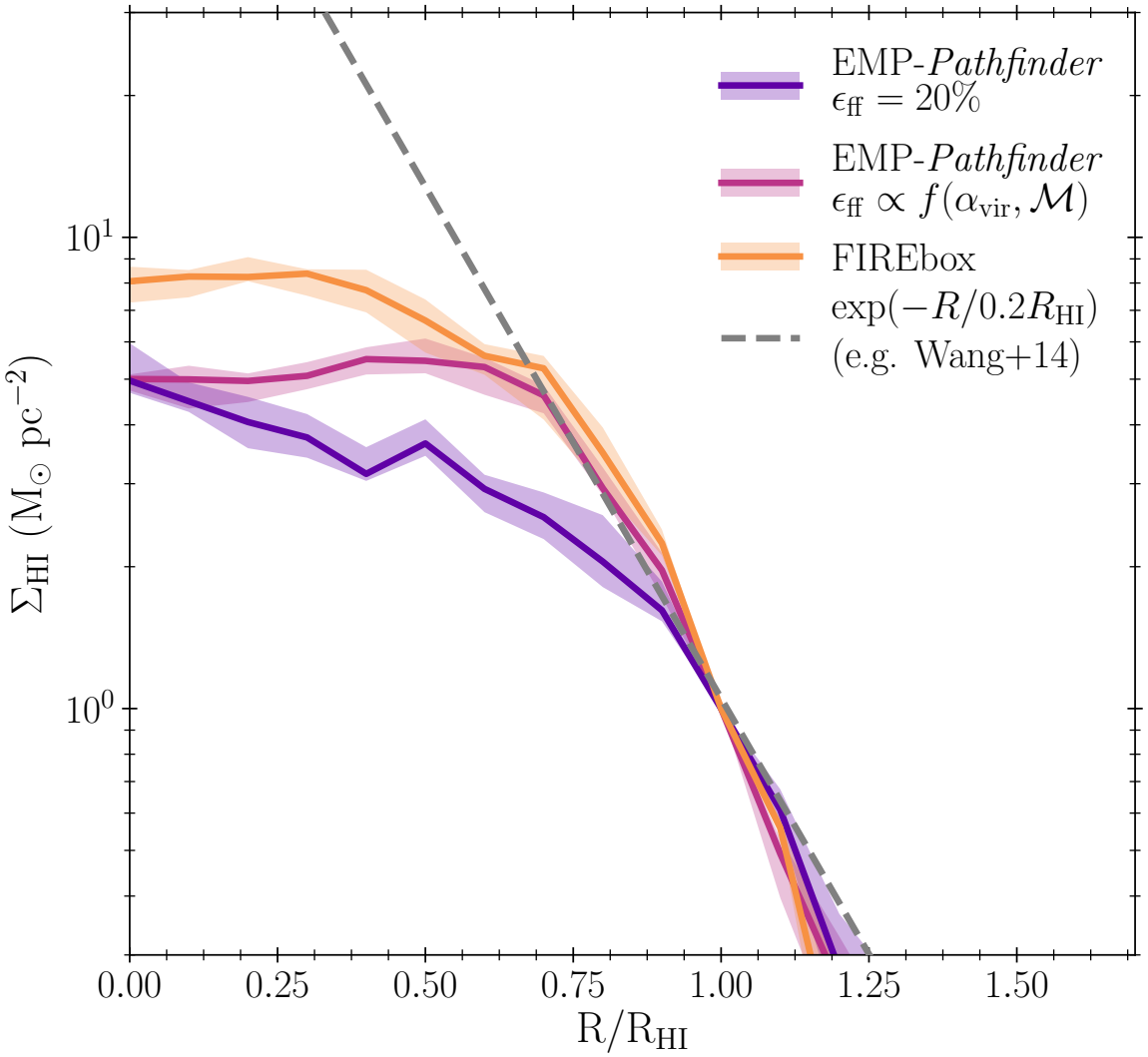
MEDIAN HI SURFACE DENSITY PROFILES



Wang+2016



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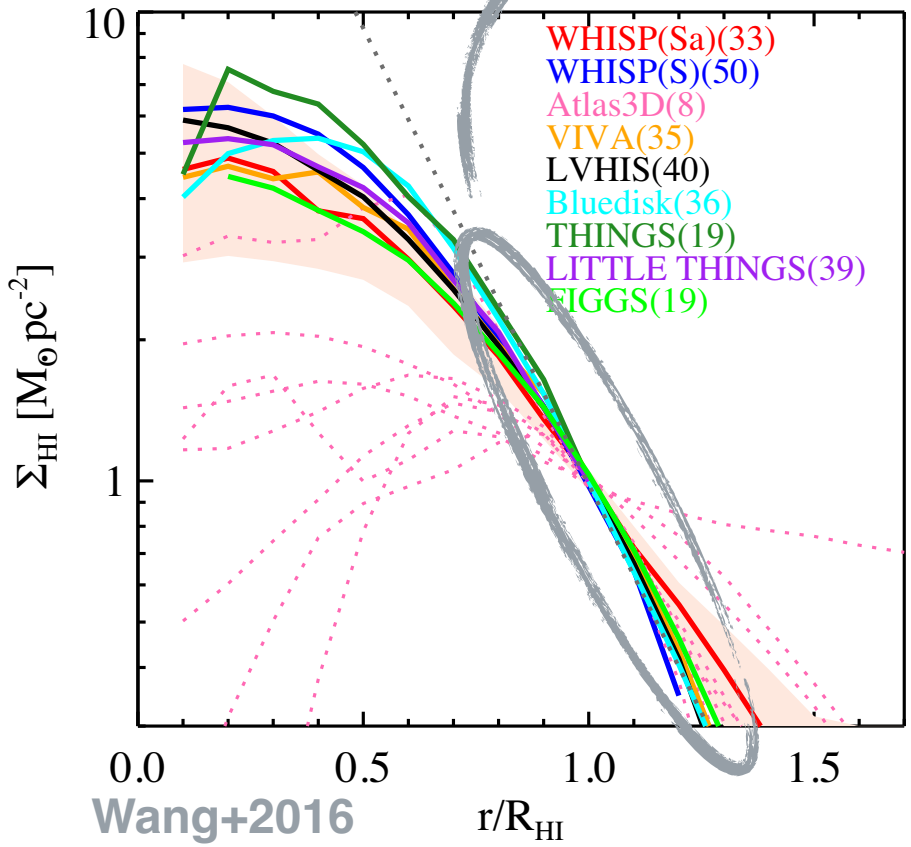
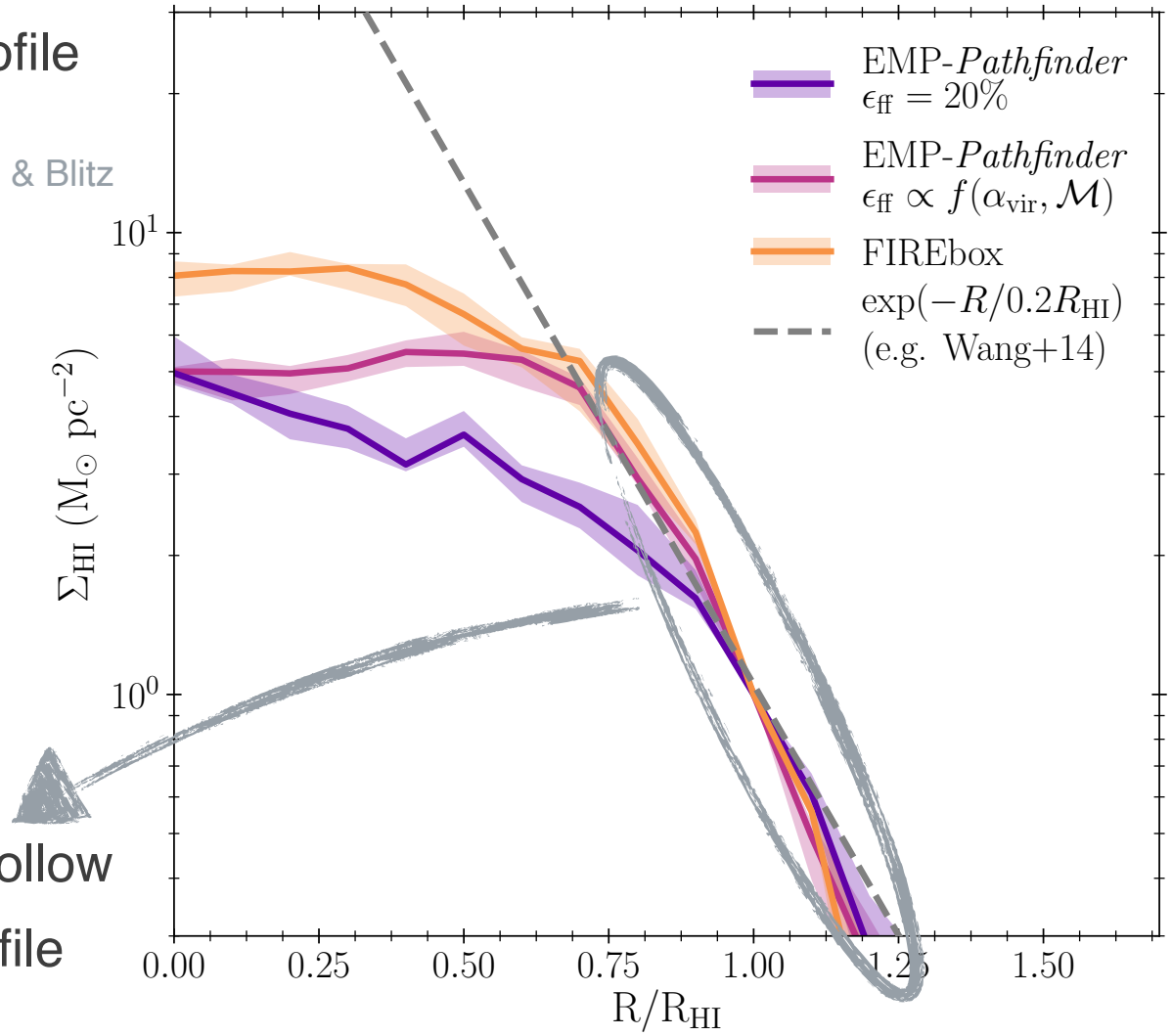


Wang+2016

exponential profile

R > 0.8 R_{HI} (e.g Swaters+2002, Bigiel & Blitz 2012, Wang+2014, Wang+2016)

approximately follow exponential profile

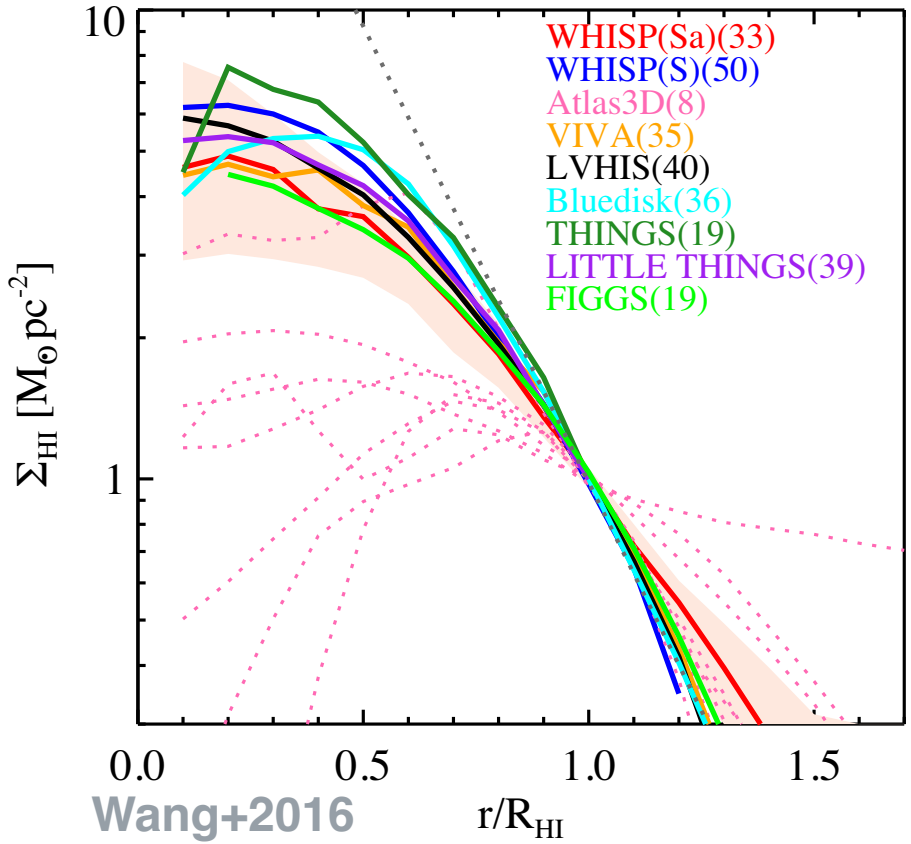


Gensior+2023 to be subm.

MEDIAN HI SURFACE DENSITY PROFILES

Very different central profiles

(normalisation & shape)



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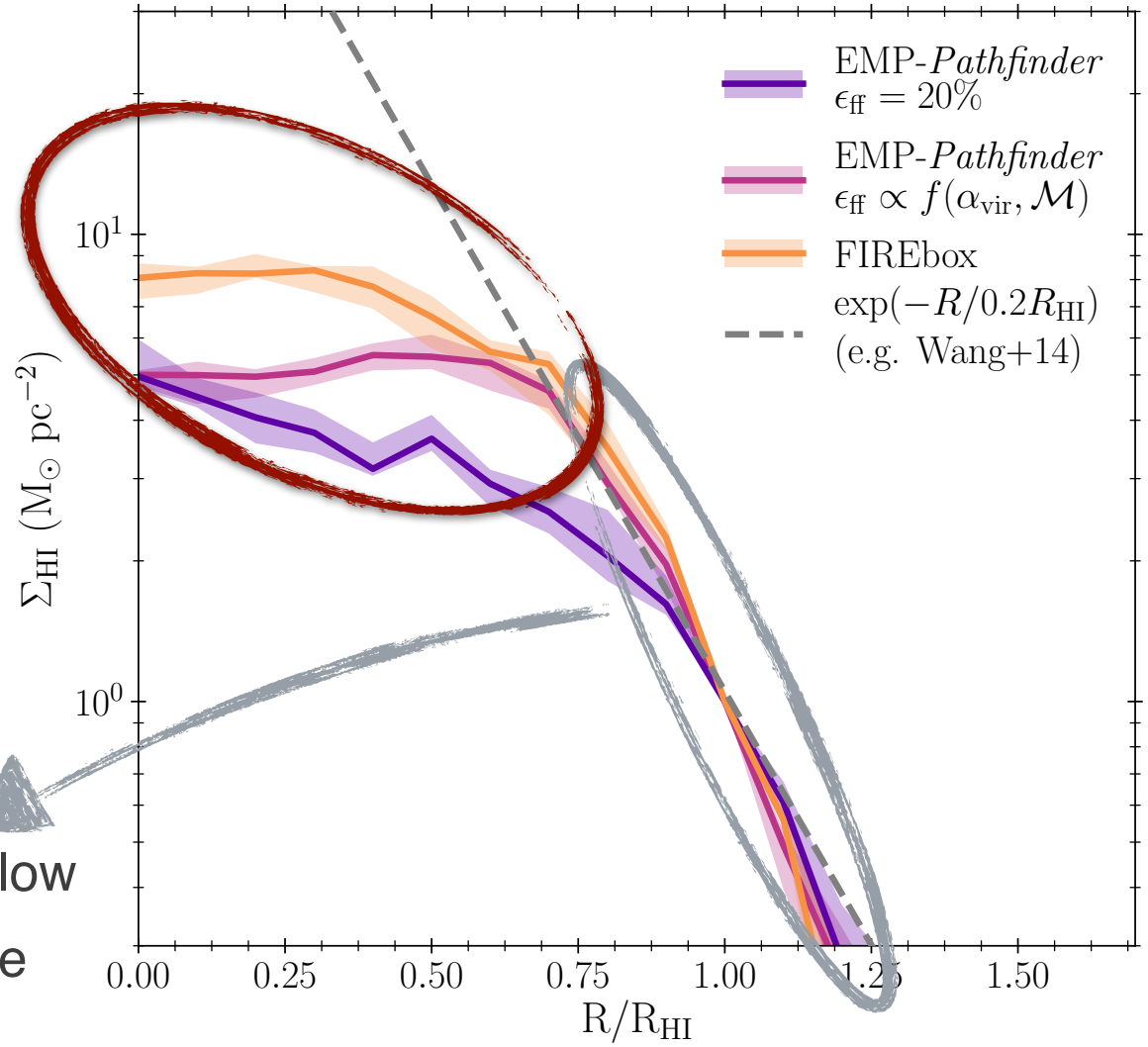
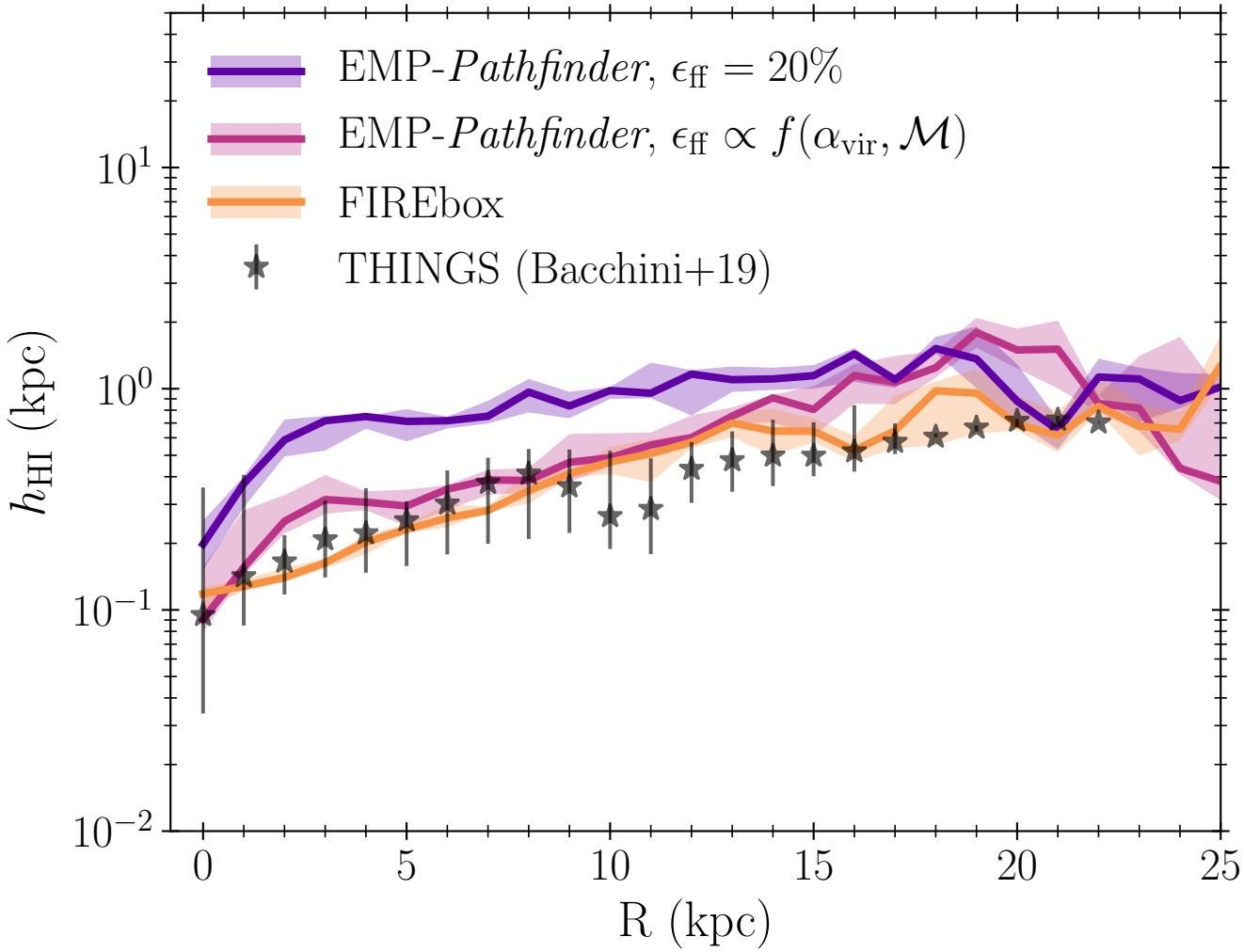


Gensior+2023 to be subm.

HI DISC SCALE HEIGHTS



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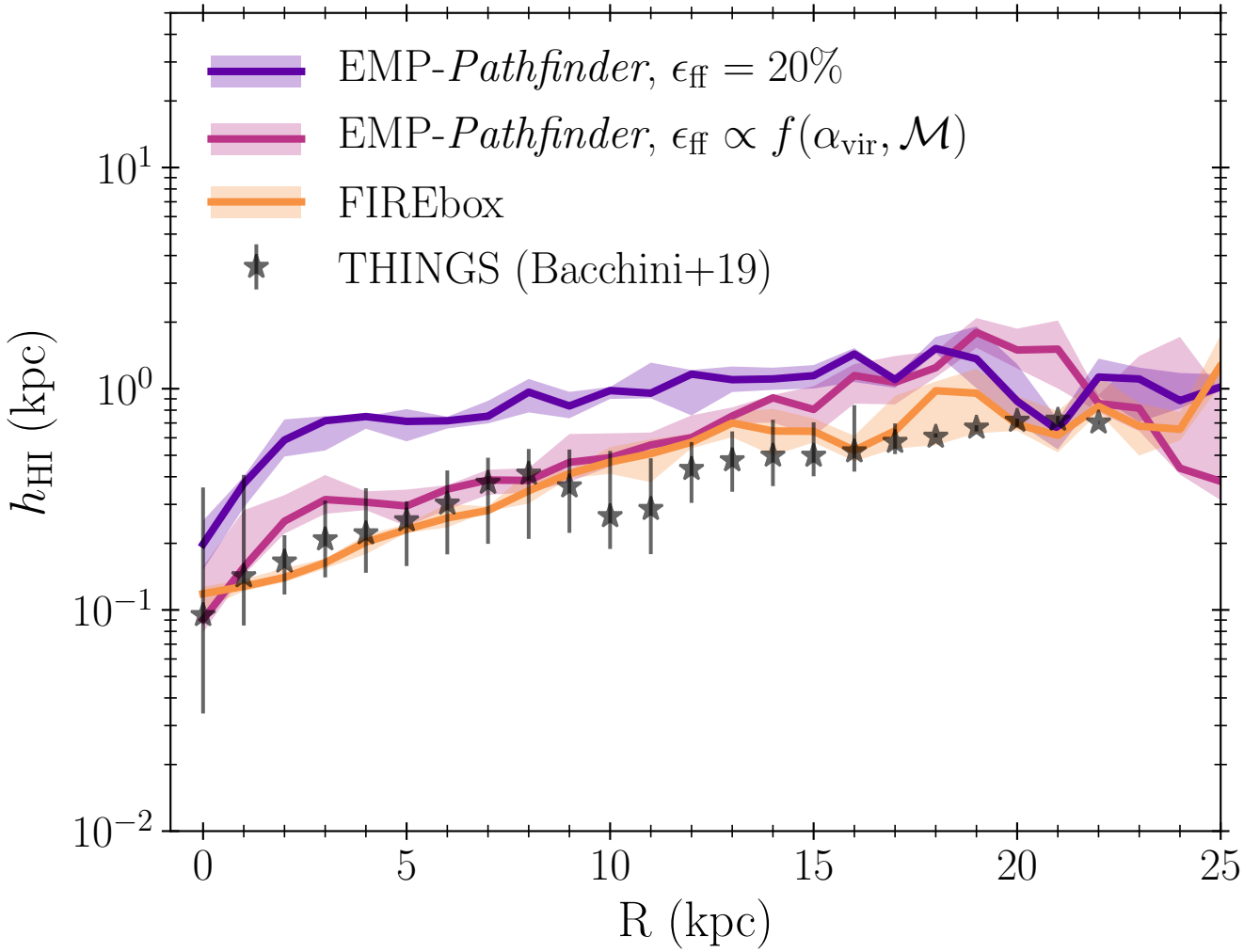
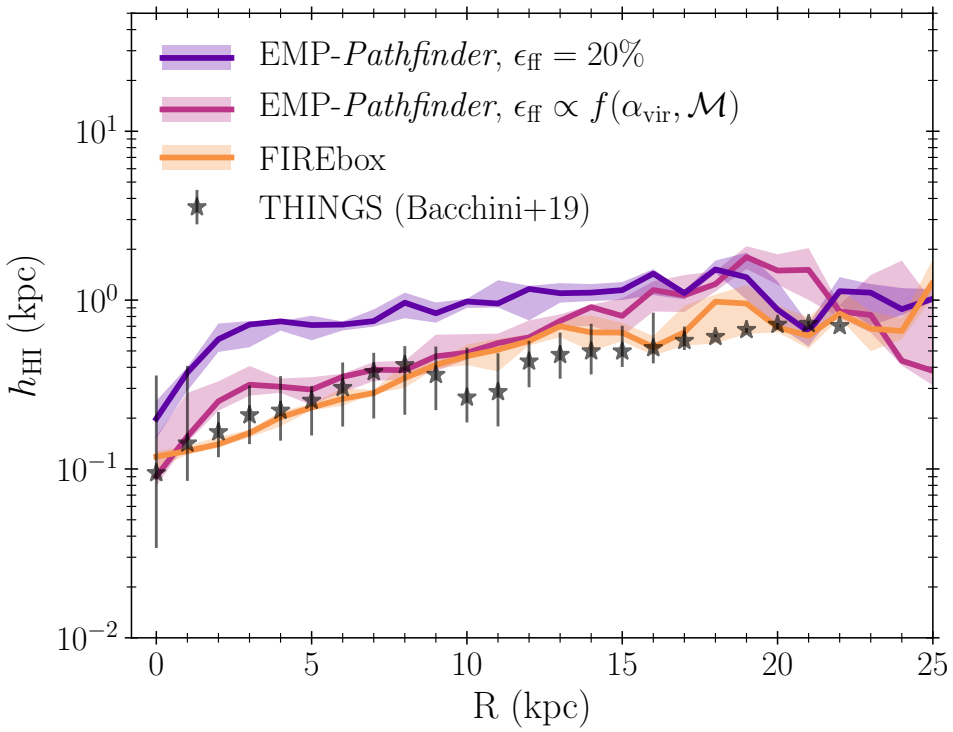


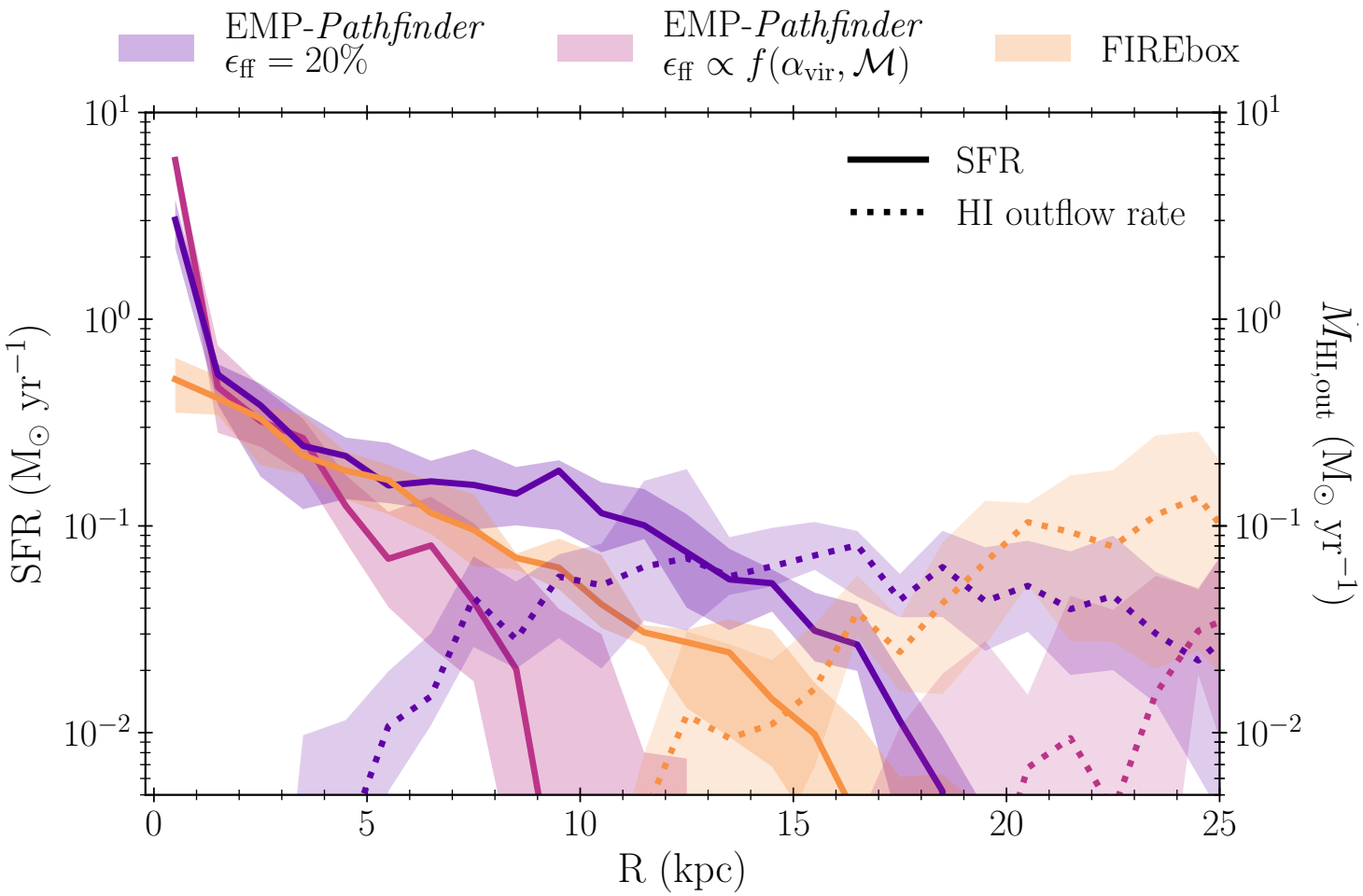
Constant SFE EMP-*Pathfinder* is too thick

Gensior+2023 to be subm.

HI DISC SCALE HEIGHTS



Sensitive to outflows



Gensior+2023 to be subm.

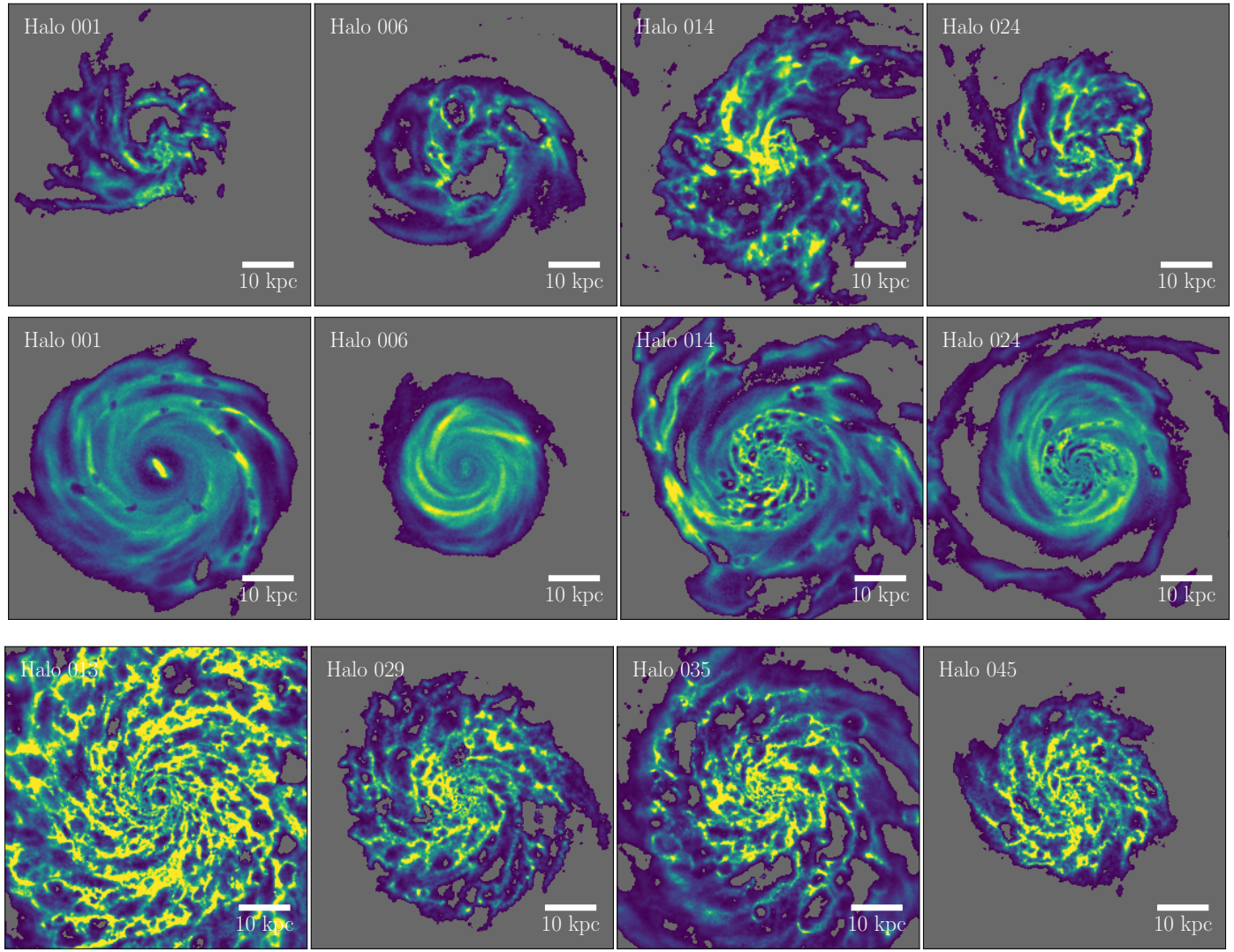
HI DISC MORPHOLOGY

EMP-*Pathfinder*

$$\epsilon_{\rm ff} = 20\%$$

EMP-*Pathfinder*

$$\epsilon_{\rm ff} = f(\alpha_{\rm vir}, \mathcal{M})$$

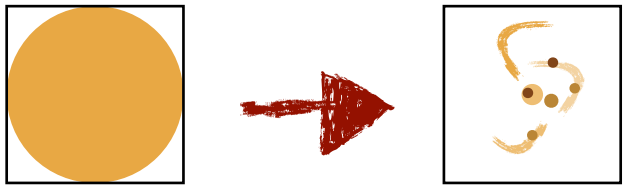


Gensior+2023 to be subm.

QUANTIFYING DISC MORPHOLOGY WITH NON-PARAMETRIC MORPHOLOGICAL INDICATORS

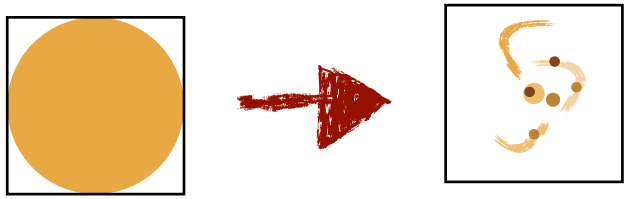
Asymmetry

$$A \equiv \frac{\sum_{i,j} |I_{ij} - I_{ij}^{180}|}{\sum_{i,j} |I_{ij}|}$$



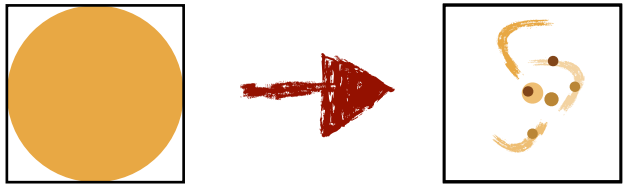
Gini

$$G \equiv \frac{1}{\bar{X} n(n-1)} \sum_{i=1}^{n} (2i - n - 1) X_i$$



Smoothness

$$S \equiv \frac{\sum_{i,j} I_{ij} - I_{ij}^{S}}{\sum_{i,j} I_{ij}}$$

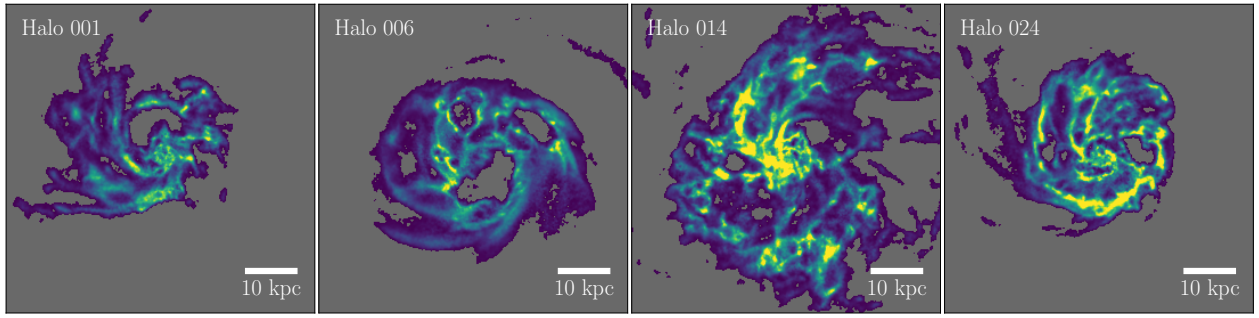


Low High

HI DISC MORPHOLOGY

STRONGLY AFFECTED BY BARYONIC PHYSICS

EMP-*Pathfinder* $\epsilon_{\rm ff} = 20\%$



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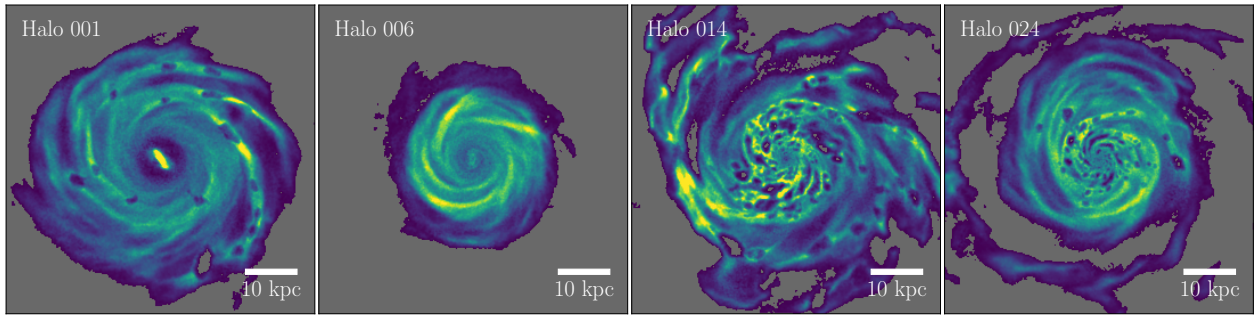

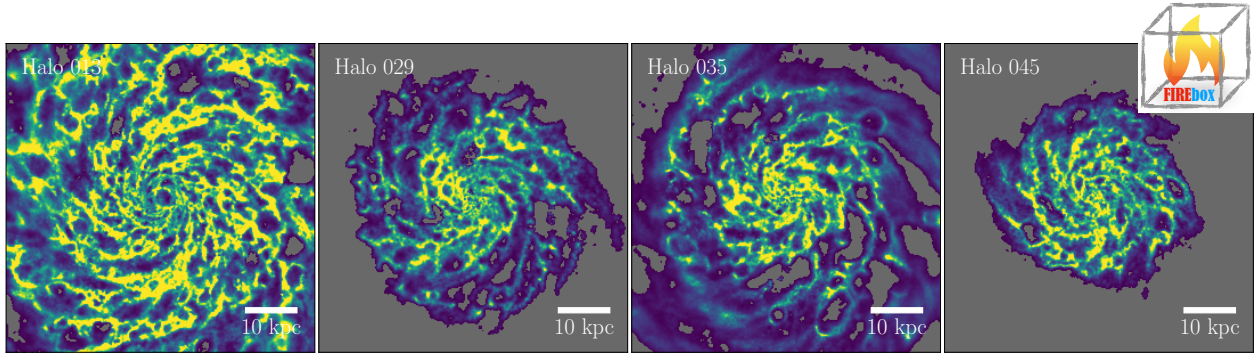

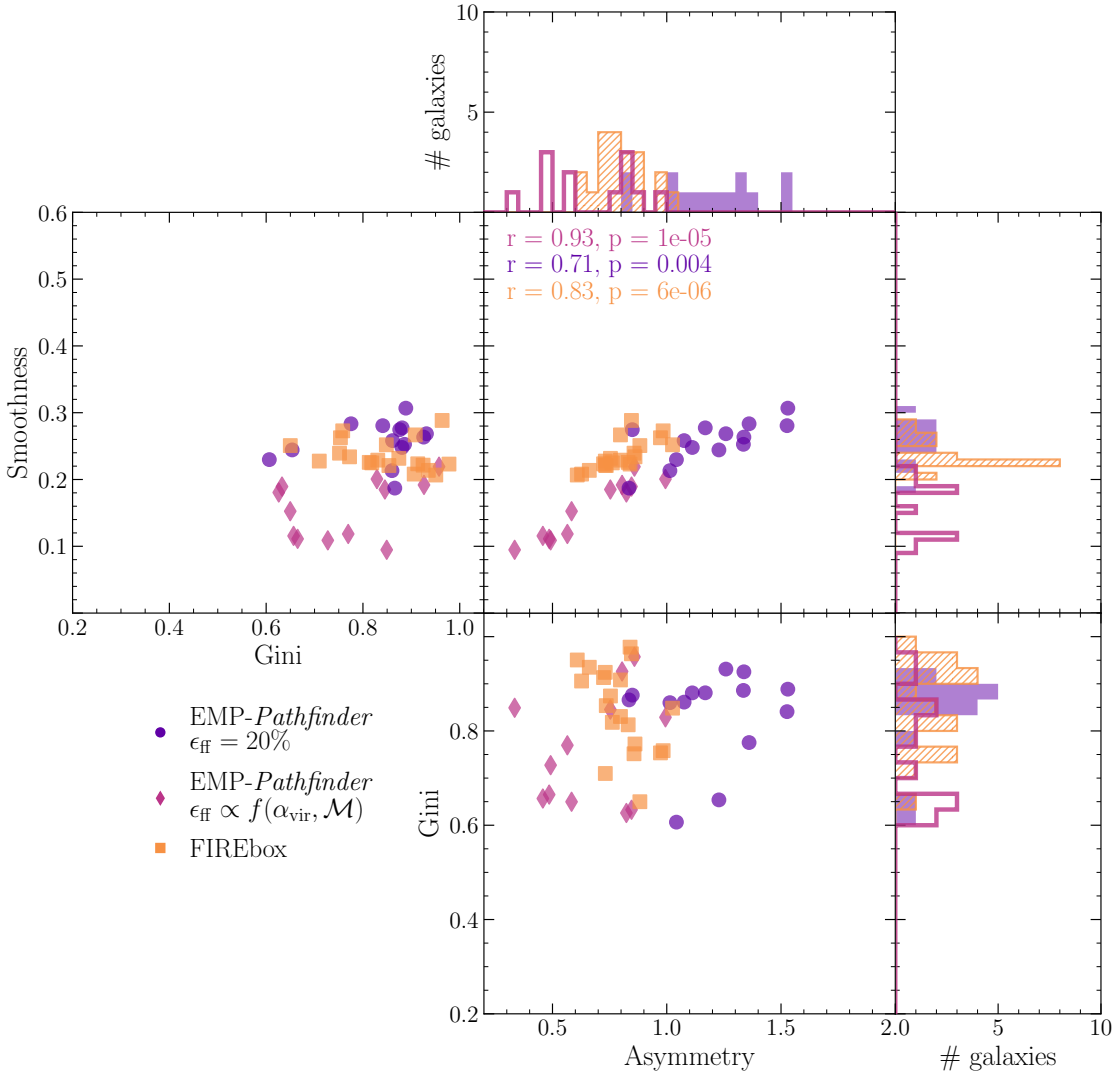

Gensior+2023 to be subm.

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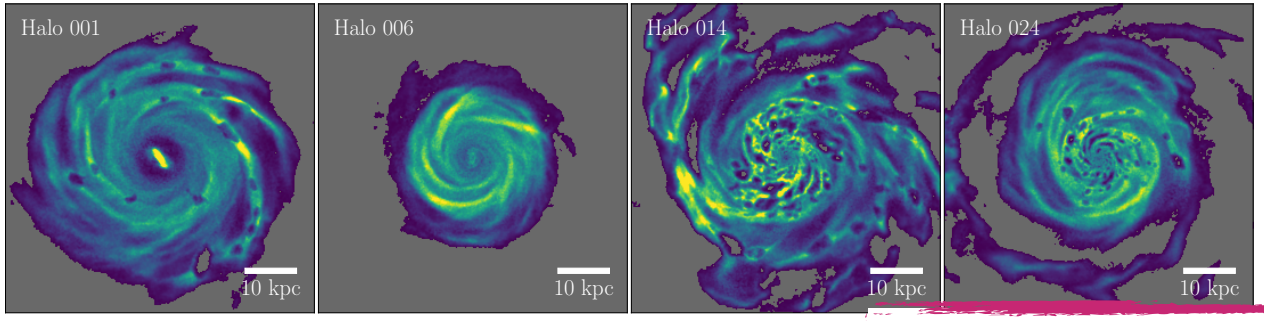

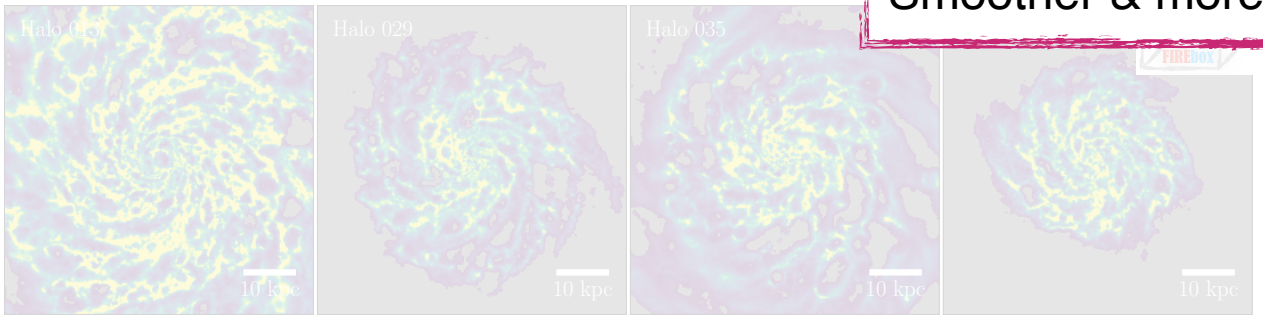

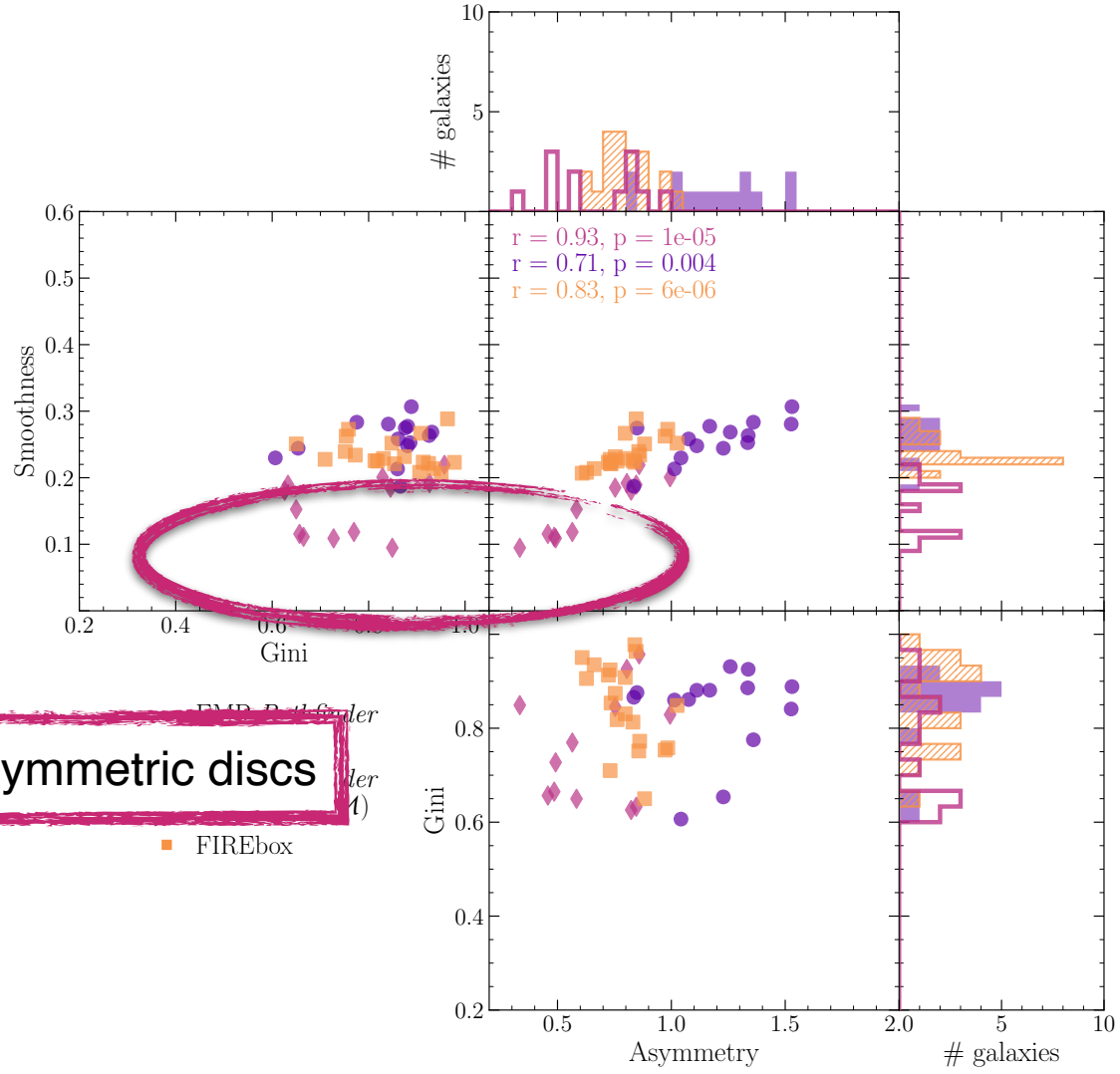

Smoother & more symmetric discs

Gensior+2023 to be subm.

HI DISC MORPHOLOGY

STRONGLY AFFECTED BY BARYONIC PHYSICS

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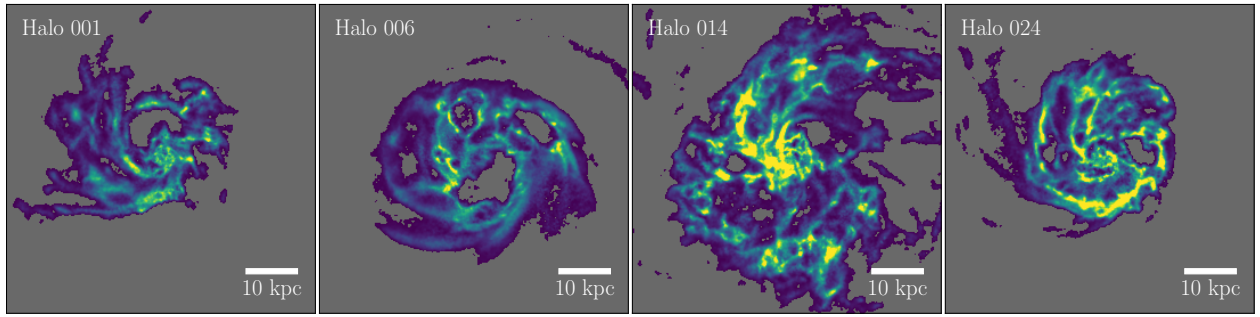

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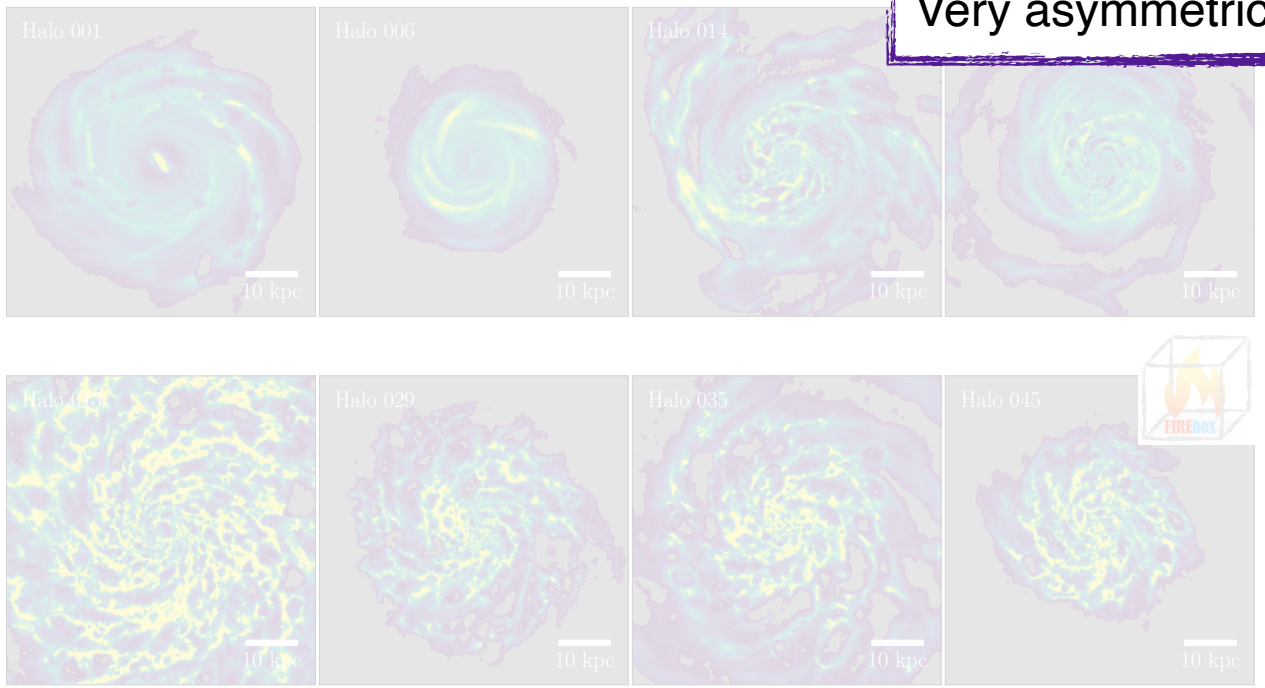
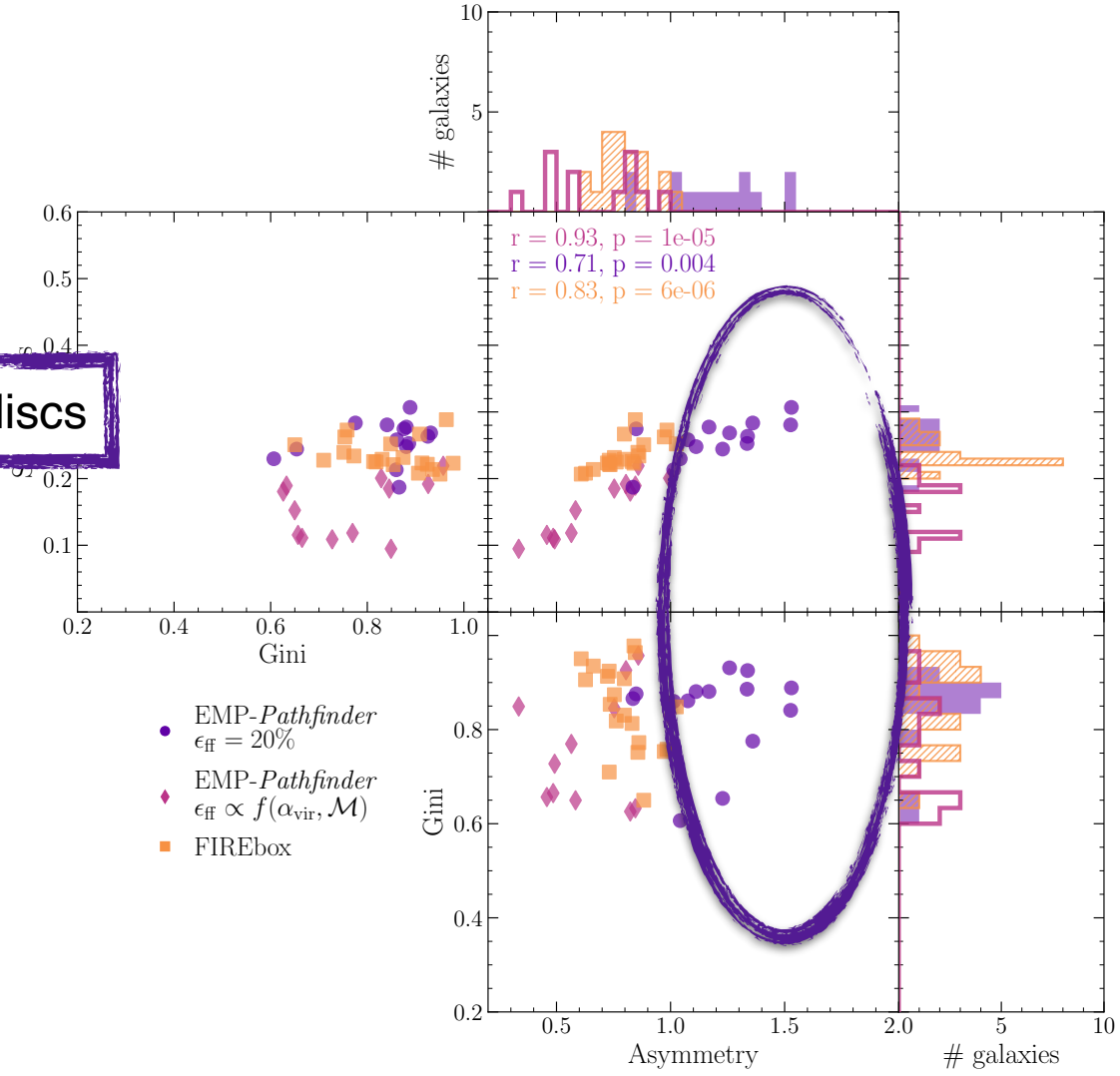


Very asymmetric discs



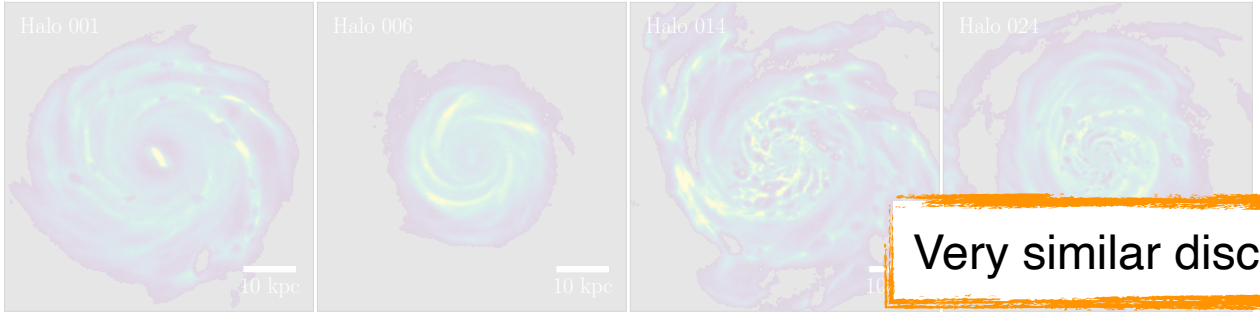
Gensior+2023 to be subm.

HI DISC MORPHOLOGY

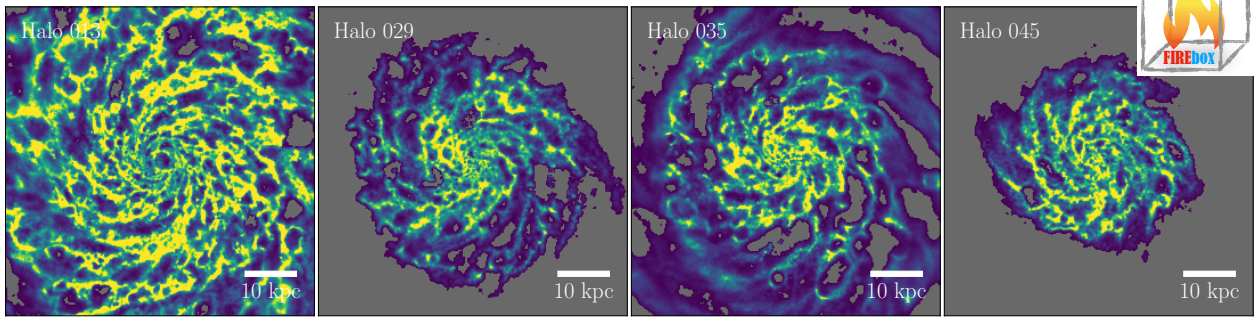
STRONGLY AFFECTED BY BARYONIC PHYSICS

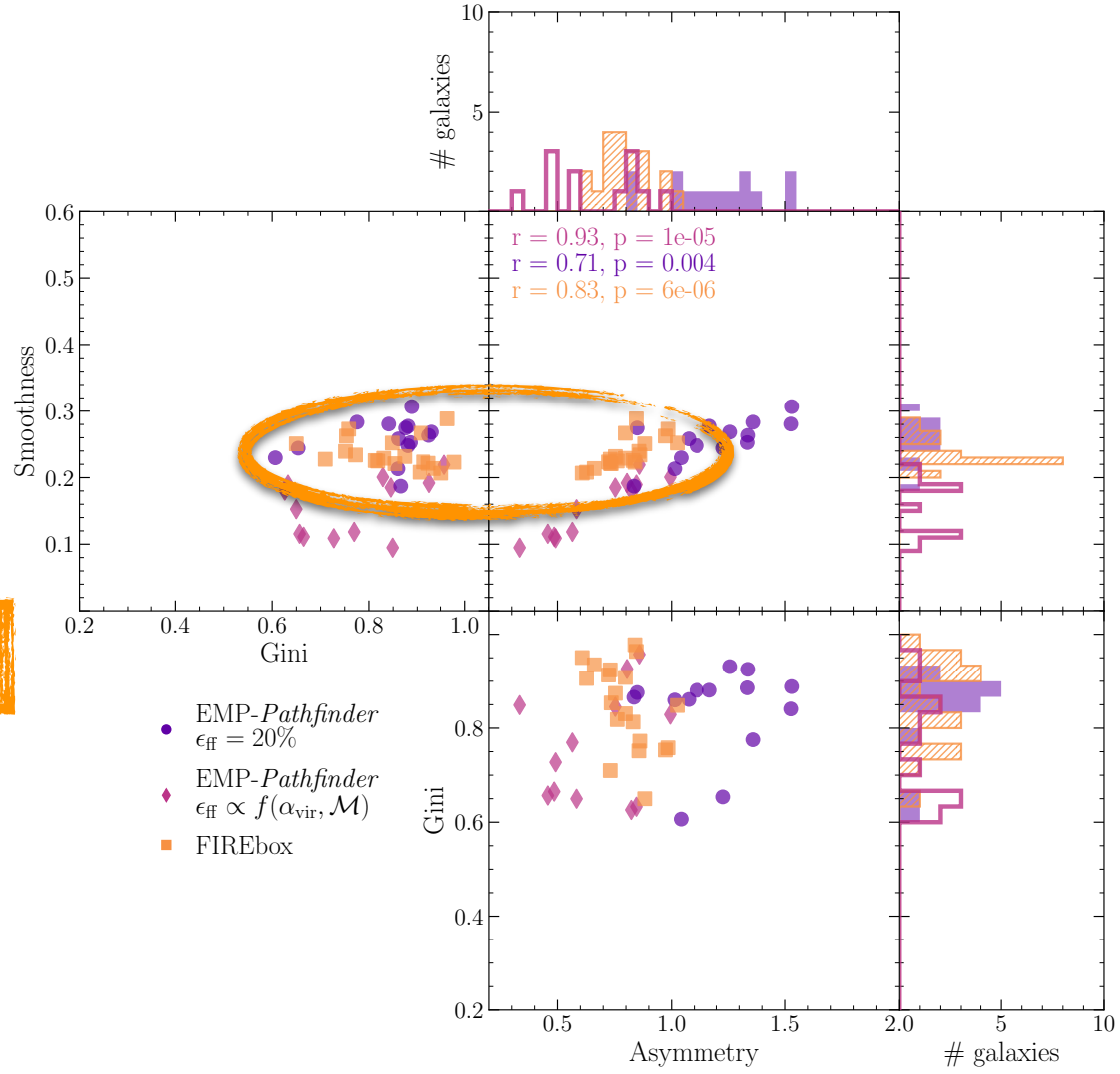
EMP-*Pathfinder* $\epsilon_{\rm ff} = 20\%$

EMP-*Pathfinder* $\epsilon_{\rm ff} = f(\alpha_{\rm vir}, \mathcal{M})$



Very similar discs

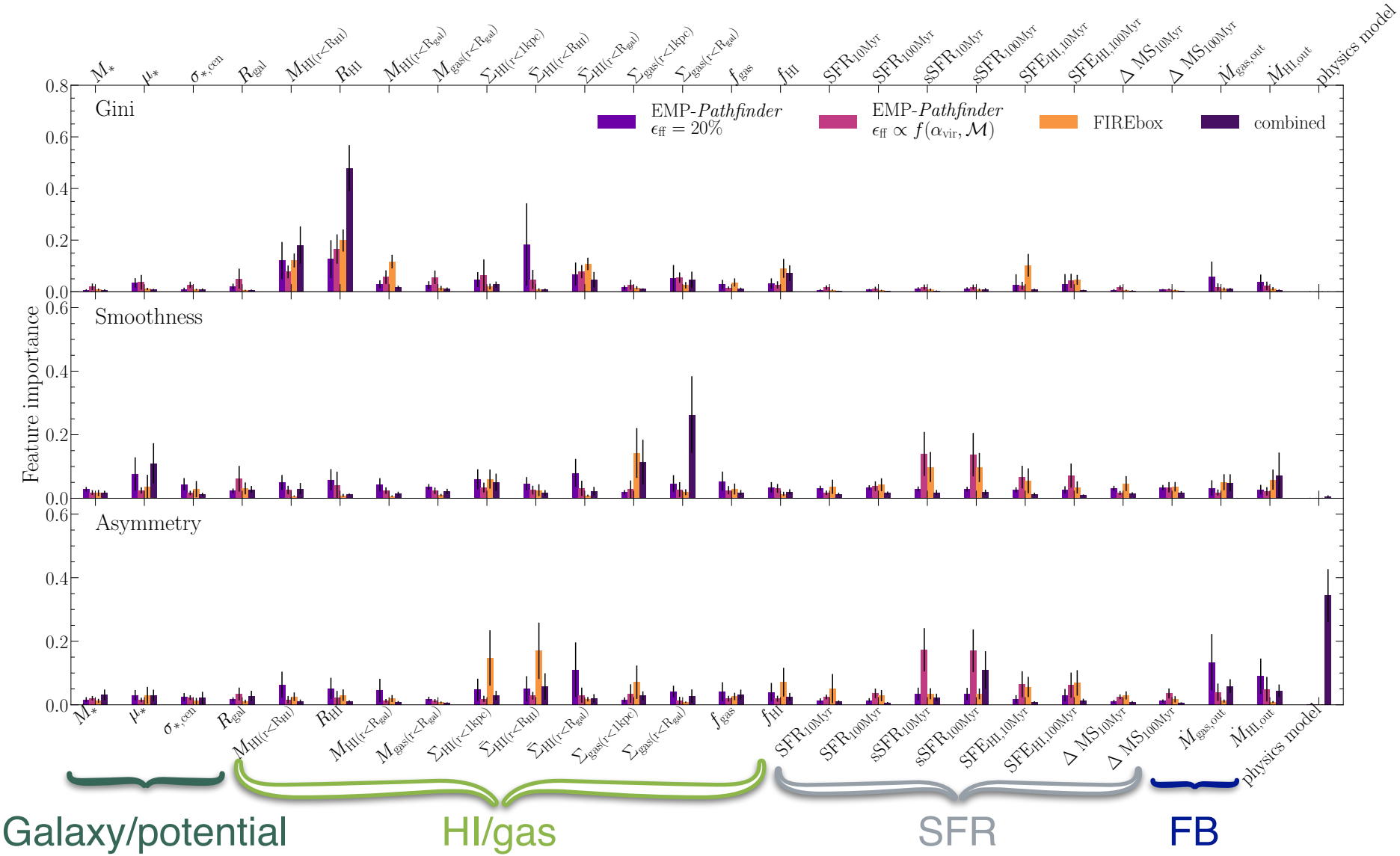




Gensior+2023 to be subm.

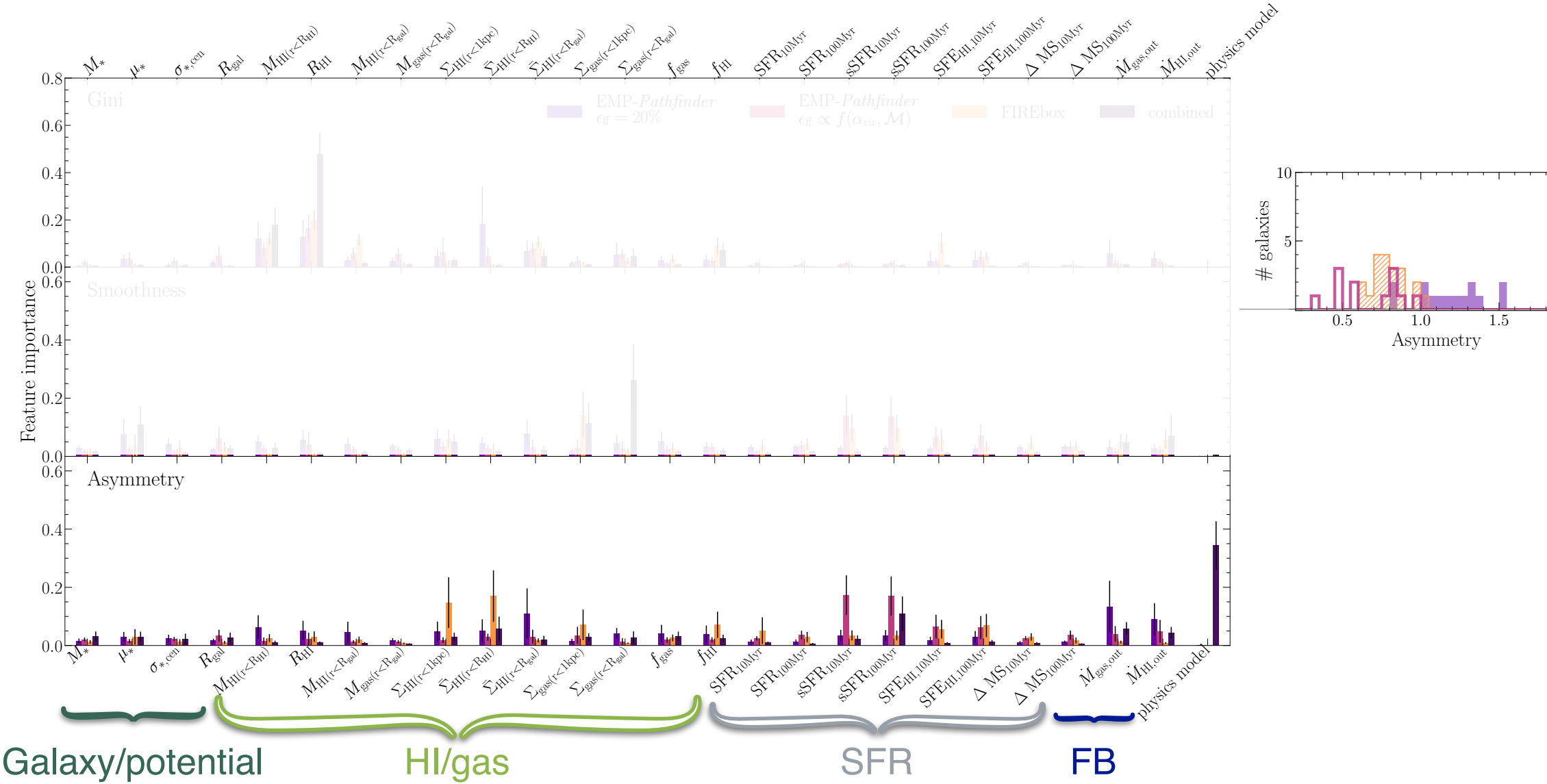
Can we infer what drives these differences in HI disc morphology?

BEST PREDICTOR FOR HI DISC MORPHOLOGY



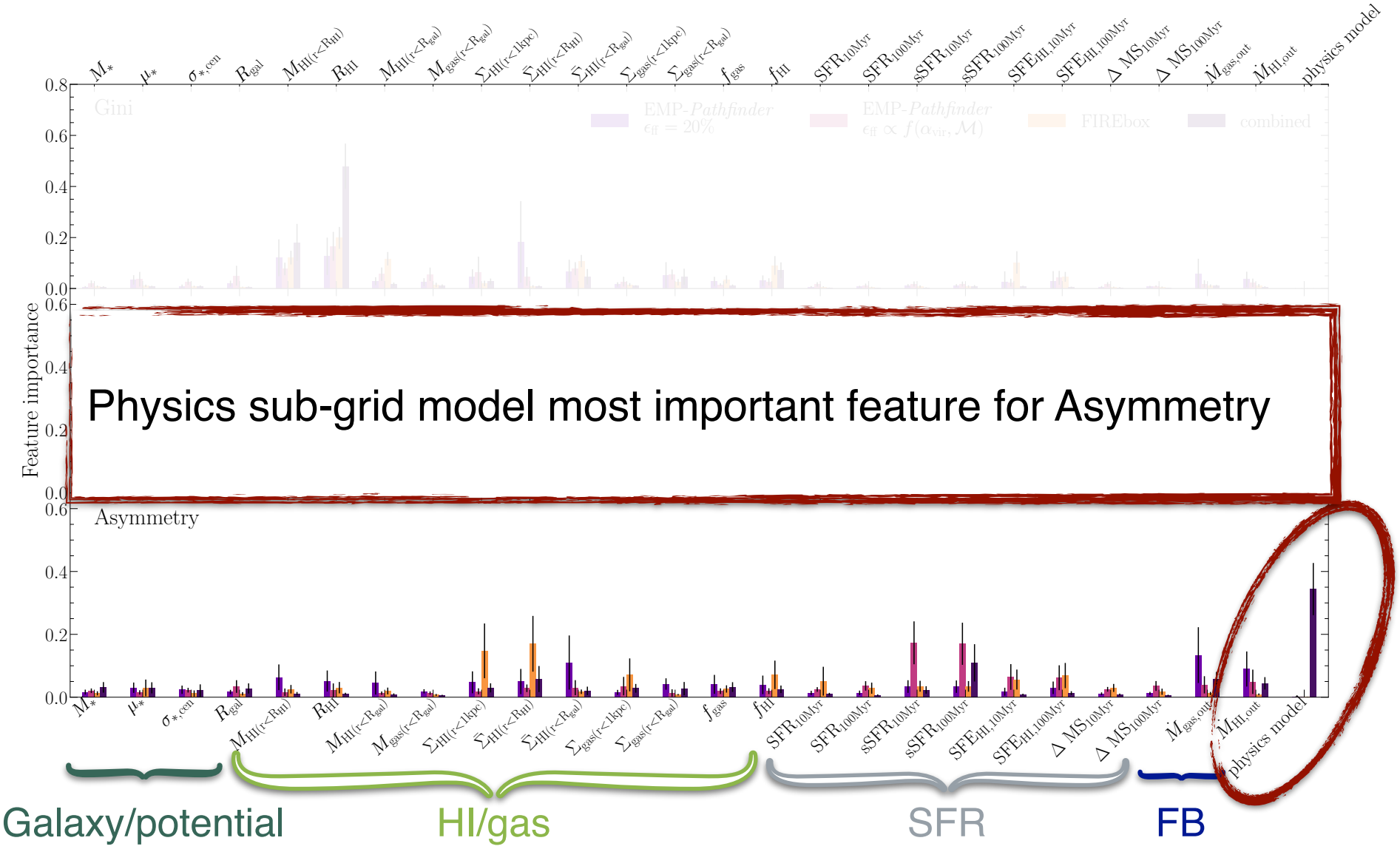
Gensior+2023 to be subm.

BEST PREDICTOR FOR HI DISC MORPHOLOGY



Gensior+2023 to be subm.

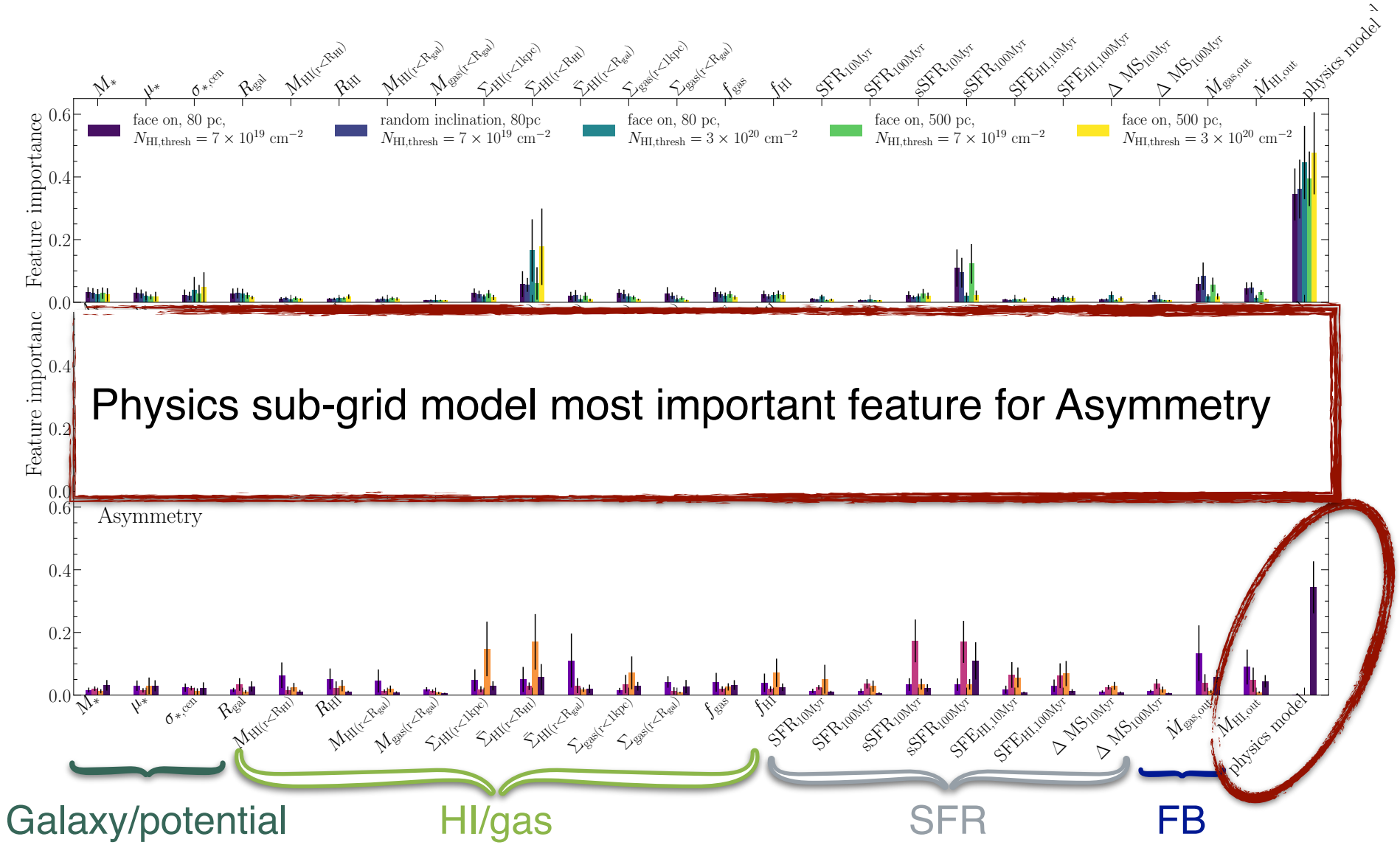
BEST PREDICTOR FOR HI DISC MORPHOLOGY



Physics sub-grid model most important feature for Asymmetry

Gensior+2023 to be subm.

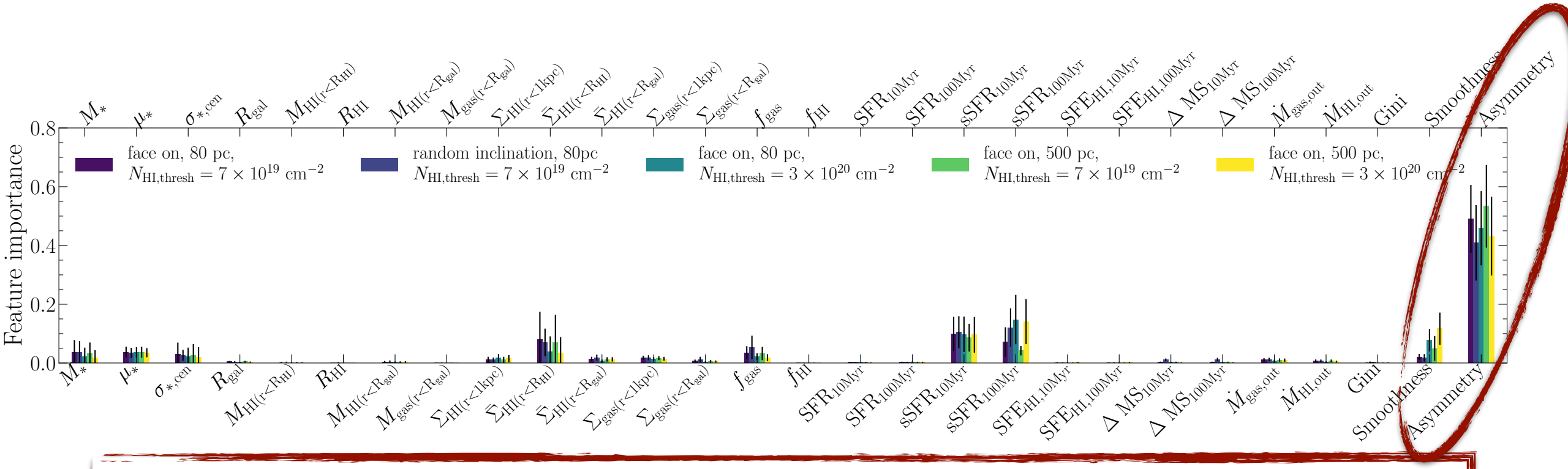
BEST PREDICTOR FOR HI DISC MORPHOLOGY



Physics sub-grid model most important feature for Asymmetry

Gensior+2023 to be subm.

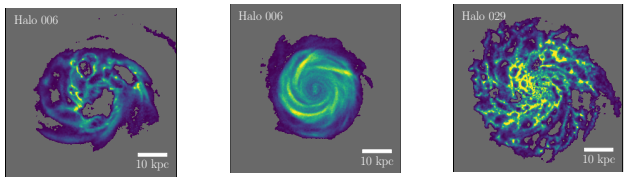
BEST PREDICTOR FOR SUB-GRID PHYSICS

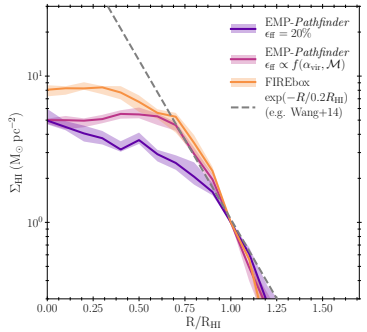


Reverse also holds: Asymmetry most important feature to predict physics model

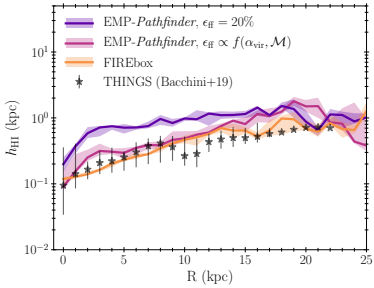
Gensior+2023 to be subm.

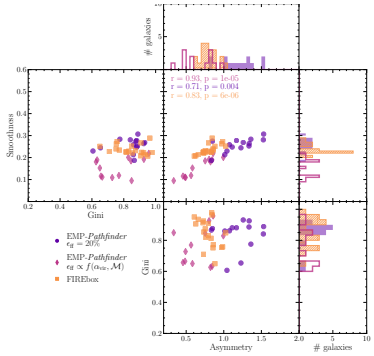
SUMMARY: HI DISC PROPERTIES @z=0



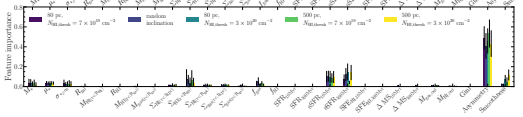


- HI discs are extremely sensitive to the physics of star formation and stellar feedback:
  - Central HI surface density profile differs depending on physics model
  - Only FIREbox & multi free-fall SFE EMP-*Pathfinder* produce thin HI discs
  - Very different HI morphologies:
    - ➡ multi free-fall SFE EMP-*Pathfinder* galaxies have very smooth & symmetric HI discs
    - ➡ FIREbox: porous & sub-structured (very similar amount of structure in all discs)
    - ➡ constant SFE EMP-*Pathfinder*: very asymmetric





➡ Baryonic physics model selected as best predictor for Asymmetry & vice versa



FAQ:

But what about z=2 or z=3?

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Let’s take a look with EMP-*Pathfinder*

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Let's take a look with EMP-*Pathfinder*

Galaxies selected to have Milky Way halo-mass: $11.85 < \log\left(M_{\rm halo}/{\rm M}_\odot\right) < 12.48$ at z=0

Cosmological zooms EMP-*Pathfinder*

Reina-Campos,…,JG+ 2022

2 different star formation models!

Constant

$\epsilon_{\rm ff} = 20\%$

Multi free-fall

$\epsilon_{\rm ff} = \frac{1}{2}\exp\left(\frac{3}{8}\sigma_s^2\right)\left[1+\mathrm{erf}\left(\frac{\sigma^2 - s_{\rm crit}}{\sqrt{2\sigma_s^2}}\right)\right]$

=> $\epsilon_{\rm ff} = f(\alpha_{\rm vir}, \mathcal{M})$

Supernovae Type Ia & II + stellar winds from AGB stars

21 galaxies

14 galaxies

FAQ:

But what about z=2 or z=3?

Let's take a look with EMP-*Pathfinder*

Galaxies selected to have Milky Way halo-mass: $11.85 < \log\left(M_{\rm halo}/{\rm M}_\odot\right) < 12.48$ at z=0

=> lower mass galaxies at higher-z

Cosmological zooms EMP-*Pathfinder*

Reina-Campos,…,JG+ 2022

2 different star formation models!

Constant

$\epsilon_{\rm ff} = 20\%$

Multi free-fall

$\epsilon_{\rm ff} = \frac{1}{2}\exp\left(\frac{3}{8}\sigma_s^2\right)\left[1+\mathrm{erf}\left(\frac{\sigma^2 - s_{\rm crit}}{\sqrt{2\sigma_s^2}}\right)\right]$

=> $\epsilon_{\rm ff} = f(\alpha_{\rm vir}, \mathcal{M})$

Supernovae Type Ia & II + stellar winds from AGB stars

21 galaxies

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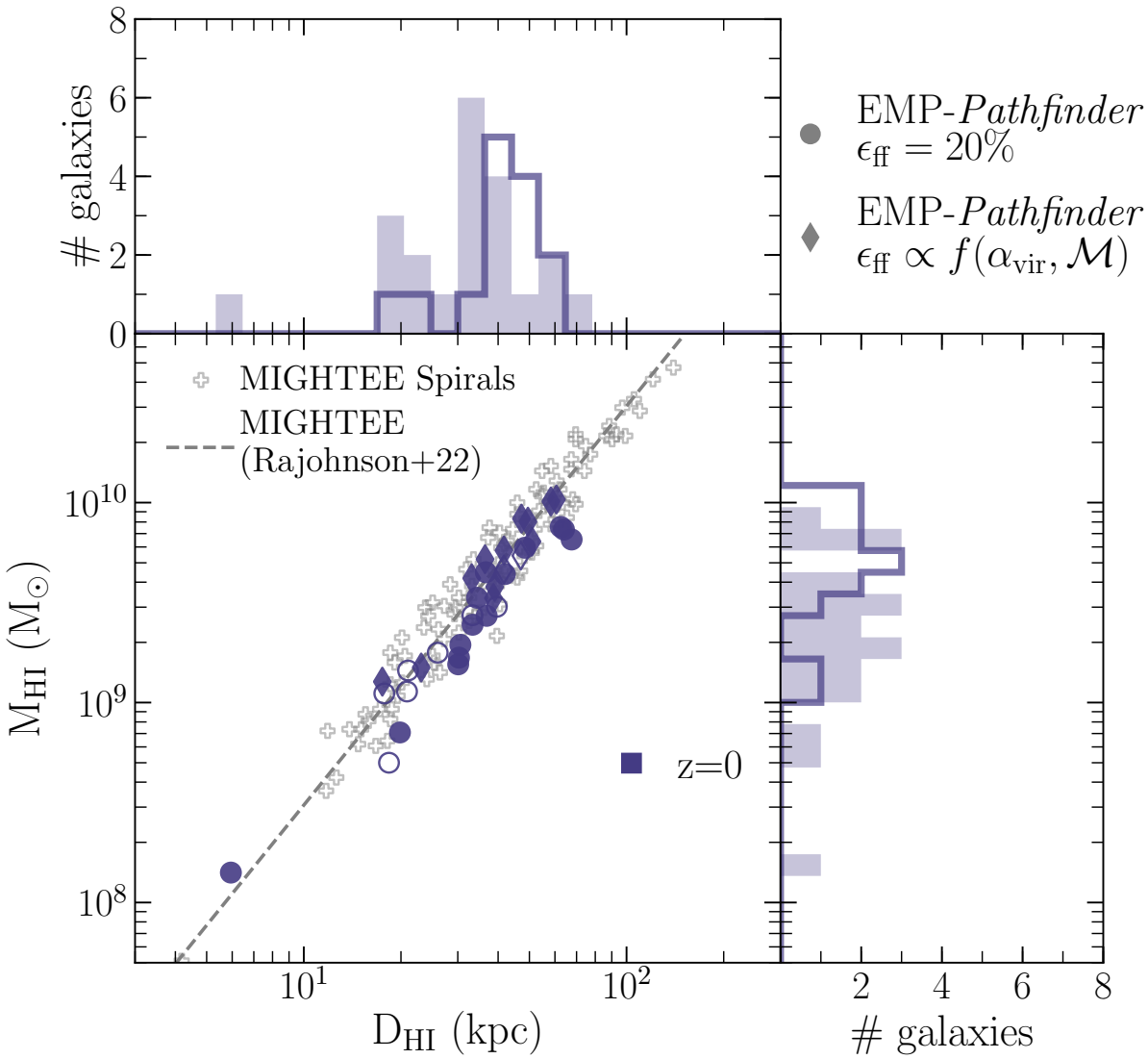
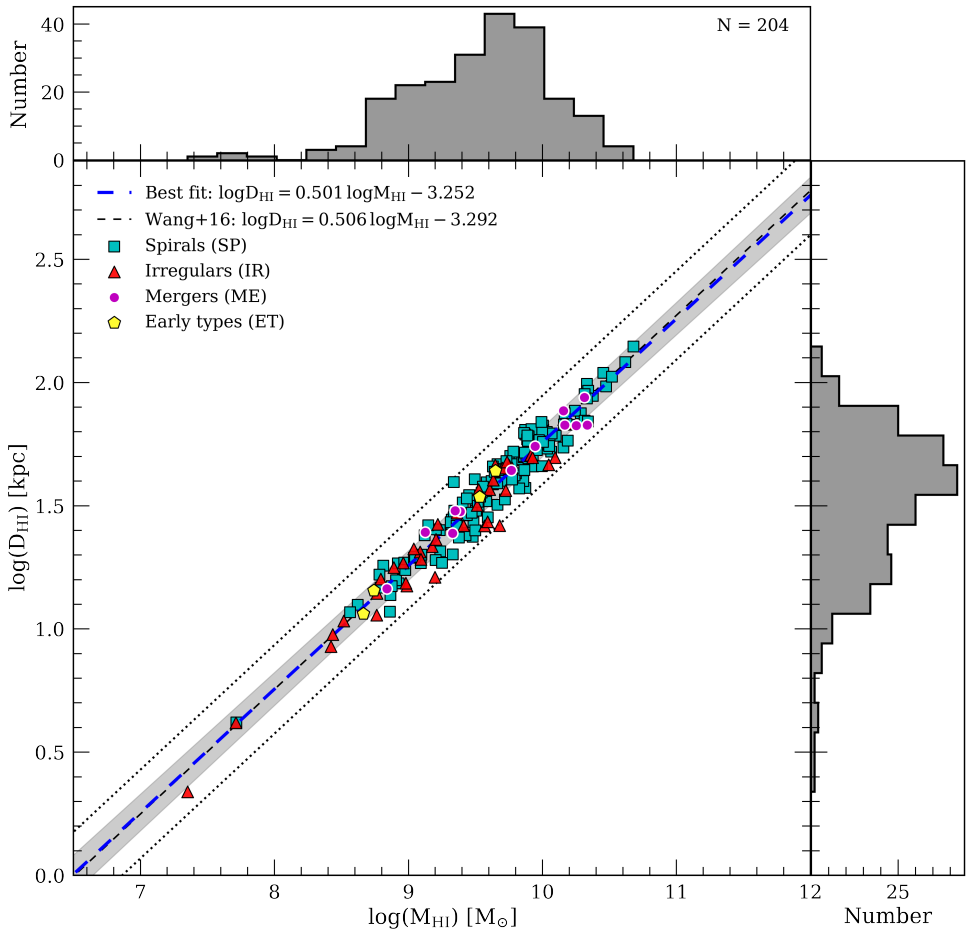
DOES THE HI MASS-SIZE RELATION EVOLVE WITH REDSHIFT?

EMP-*PATHFINDER* HI MASS-SIZE RELATION @ z=0



HI SIZE-MASS RELATION

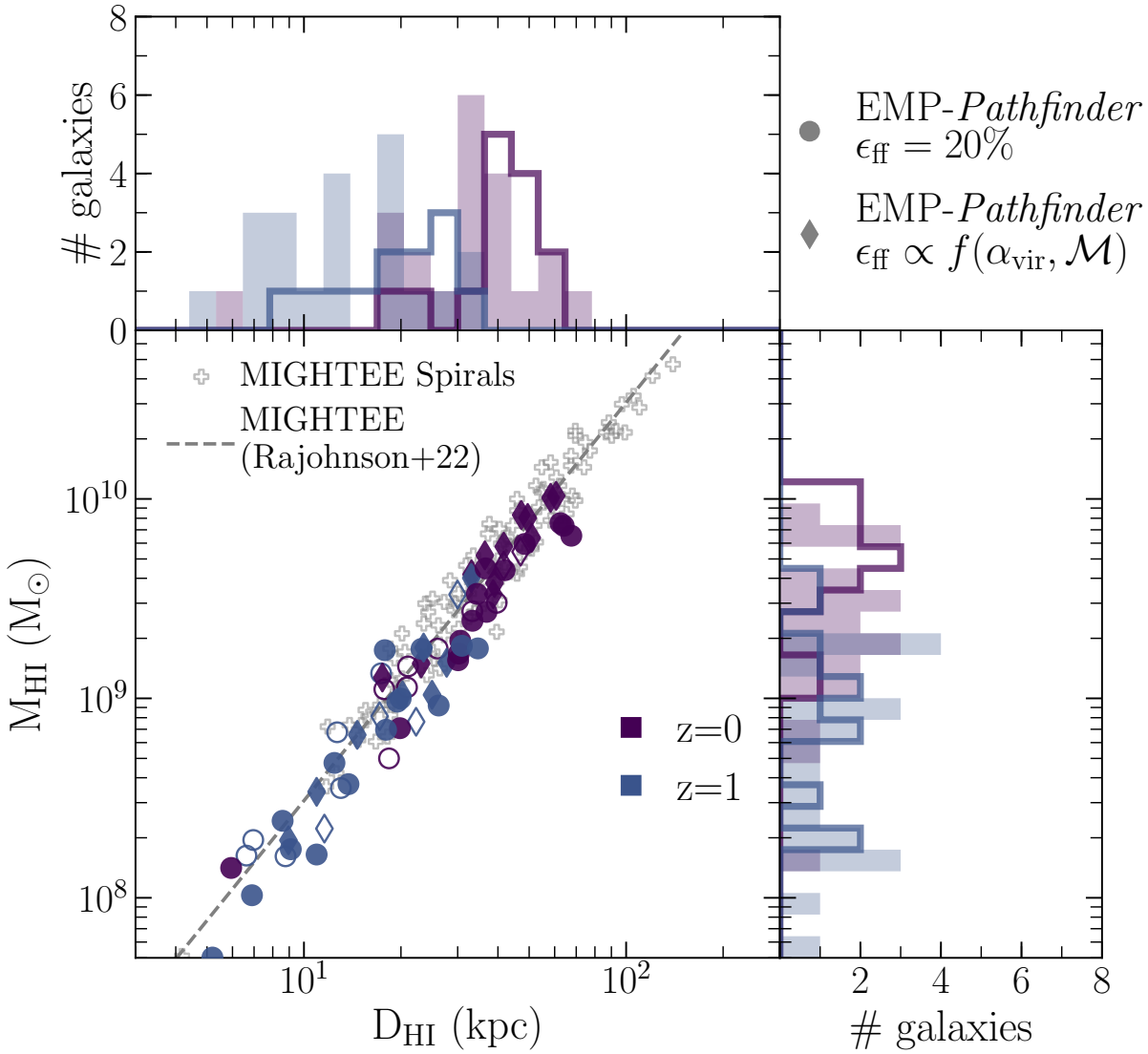


MIGHTEE (Rajohnson+2022)

See also e.g. Broils & Rhee 1997, Verheijen & Sancisi 2001, Swaters+2002, Noordermeer+2005, Begum+2008, Obreschkow+2009, Ponomareva+2016, Wang+2016 Stevens+2019

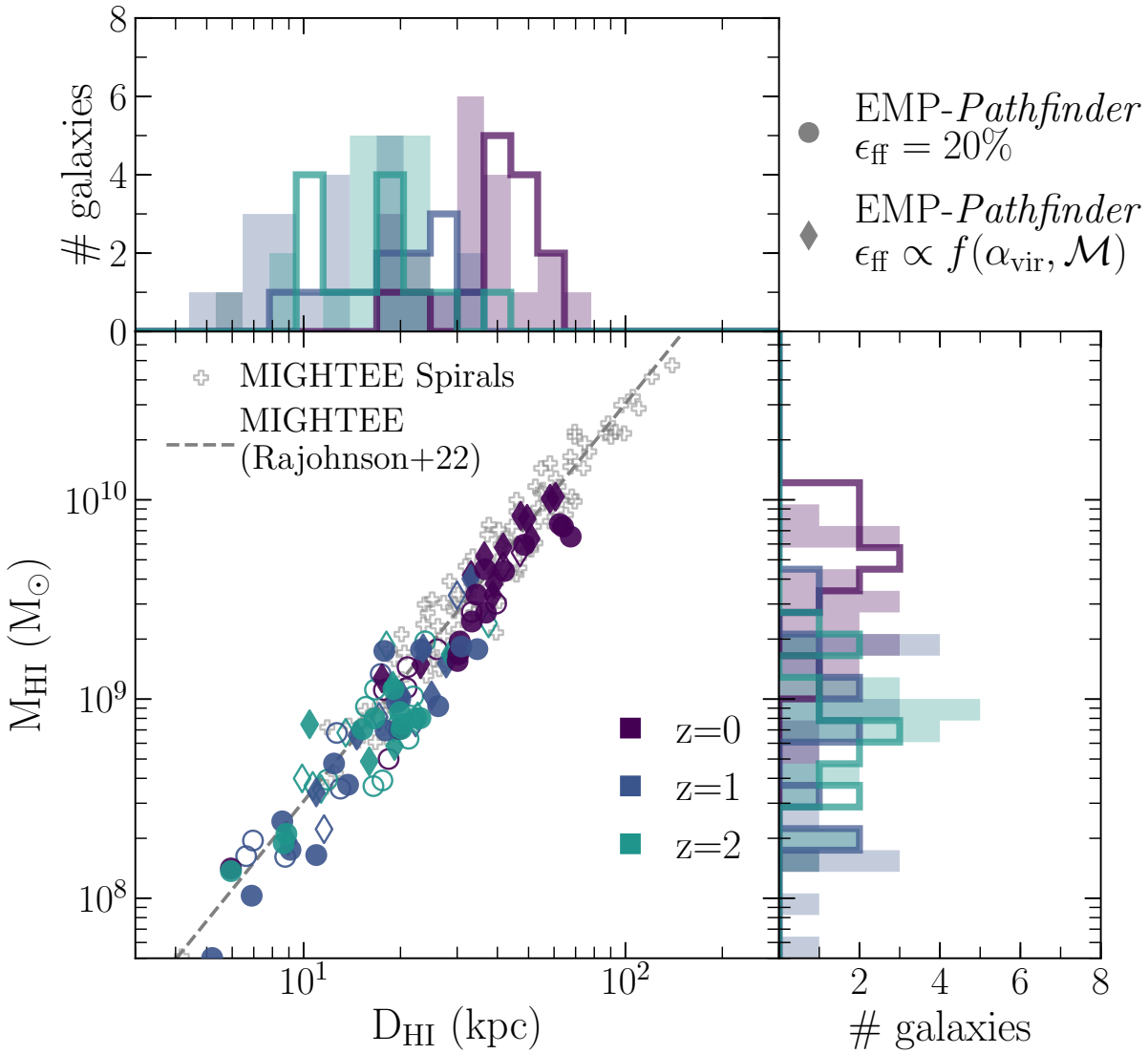
DOES THE HI MASS-SIZE RELATION EVOLVE WITH REDSHIFT?

EMP-*PATHFINDER* HI MASS-SIZE RELATION @ z=0,1



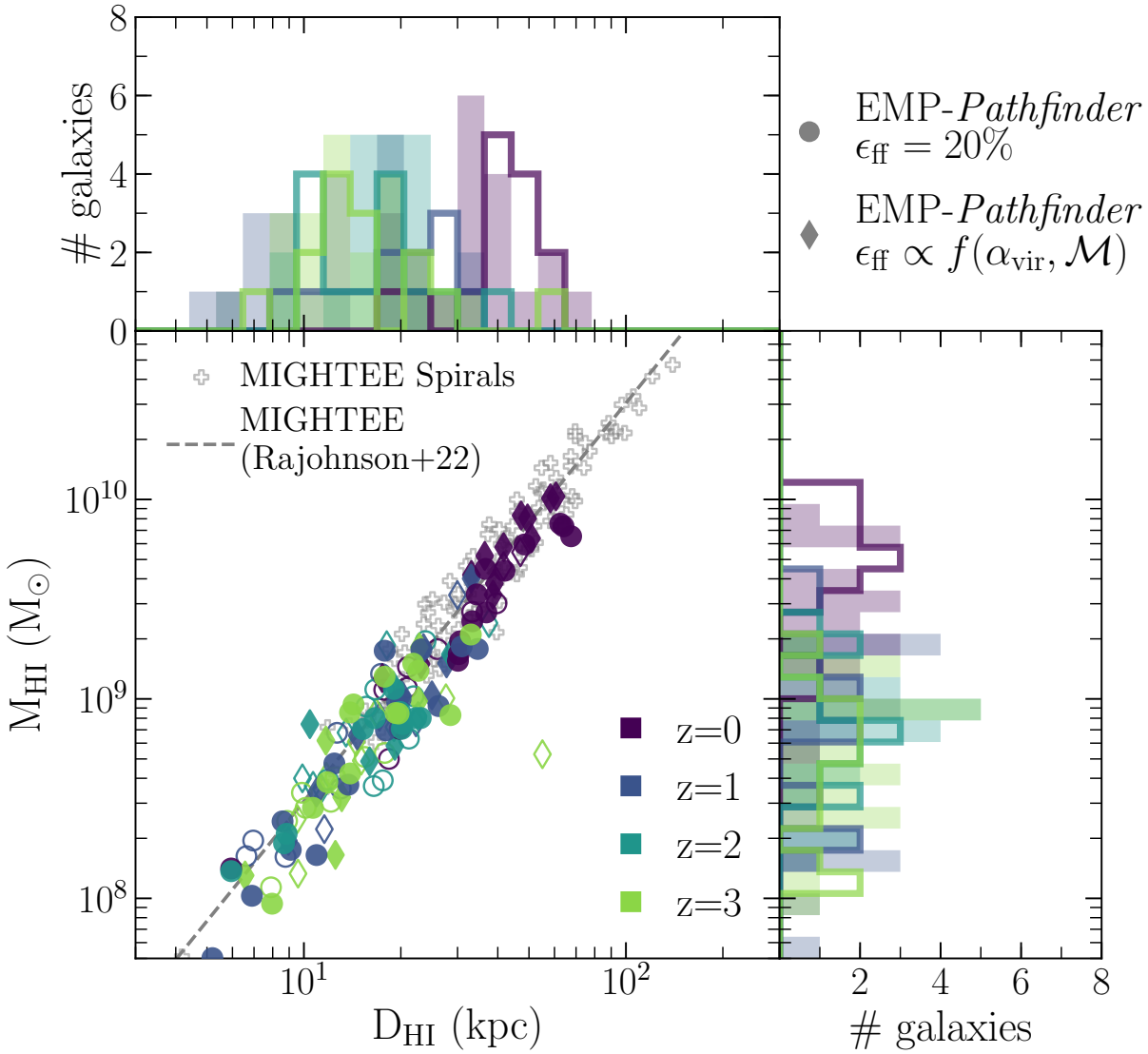
DOES THE HI MASS-SIZE RELATION EVOLVE WITH REDSHIFT?

EMP-*PATHFINDER* HI MASS-SIZE RELATION @ z=0,1,2



DOES THE HI MASS-SIZE RELATION EVOLVE WITH REDSHIFT?

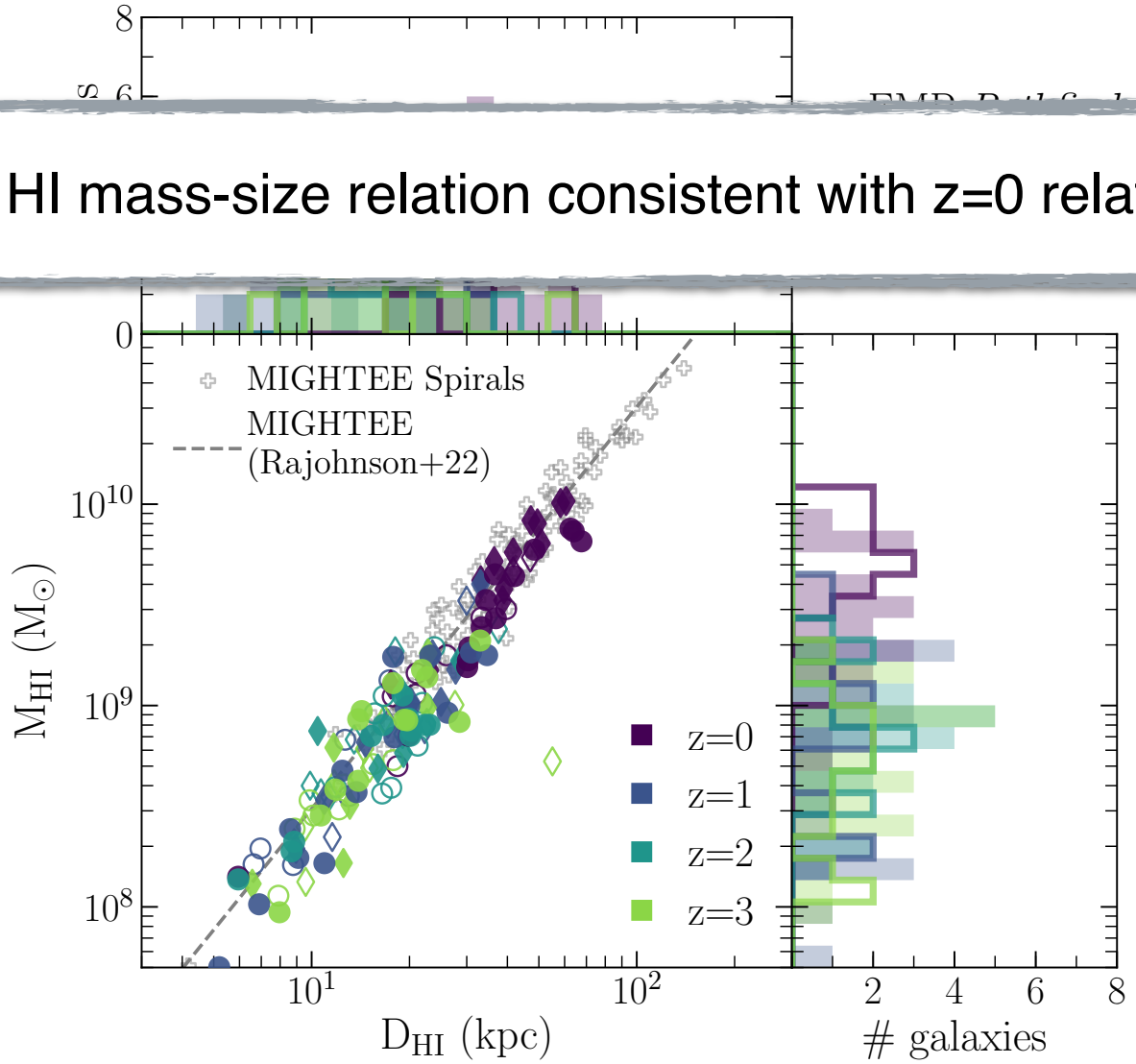
EMP-*PATHFINDER* HI MASS-SIZE RELATION @ z=0,1,2,3



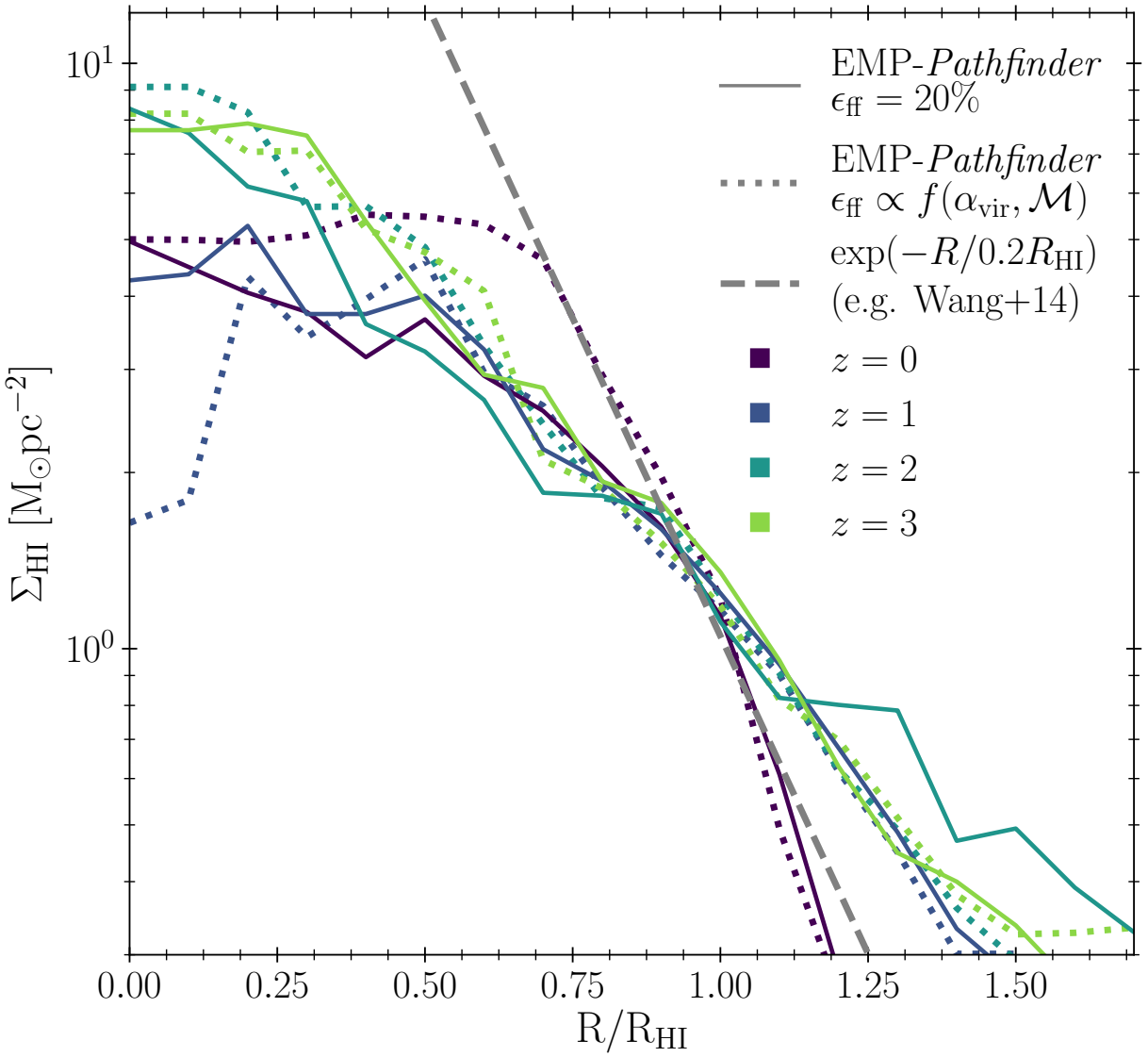
DOES THE HI MASS-SIZE RELATION EVOLVE WITH REDSHIFT?

EMP-*PATHFINDER* HI MASS-SIZE RELATION @ z=0,1,2,3

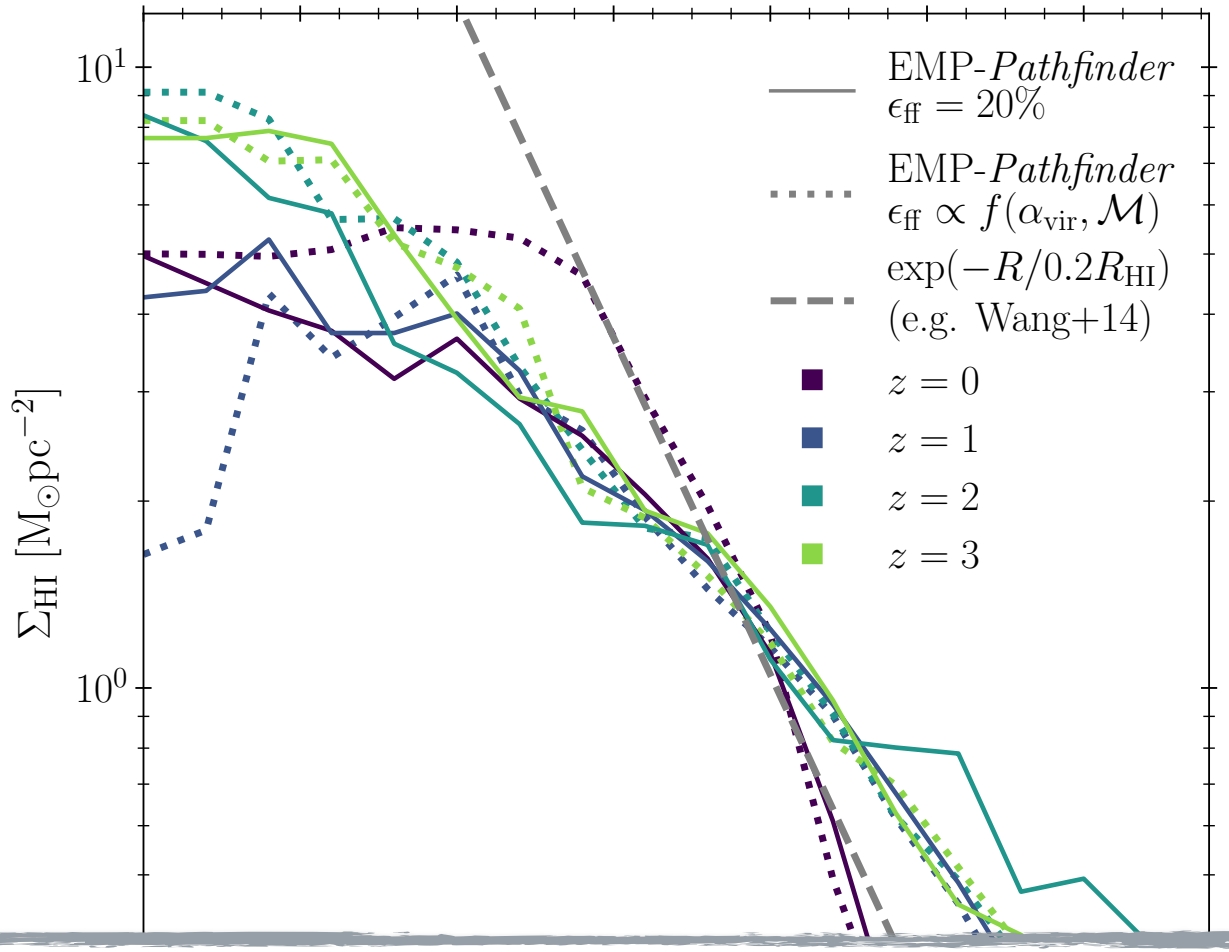
High-z HI mass-size relation consistent with z=0 relation



HI MASS SURFACE DENSITY PROFILES: SHALLOWER DECLINE AT z>0

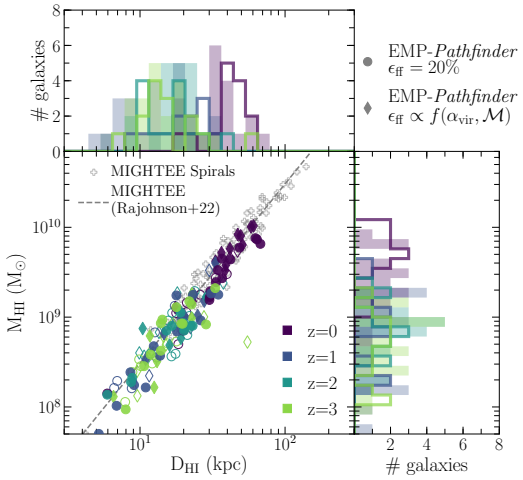


HI MASS SURFACE DENSITY PROFILES: SHALLOWER DECLINE AT z>0



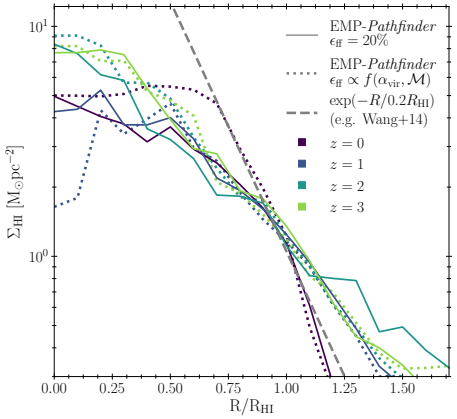
High-z HI surface density profiles not consistent with z=0 relation

SUMMARY: HI DISC PROPERTIES @higher-z



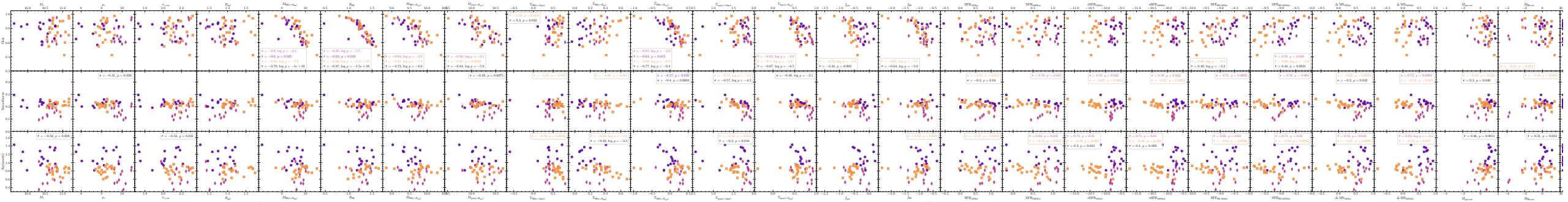
- HI mass-size relation at z=1,2,3 consistent with z=0 relation
- Radial HI surface density profiles decline more shallowly at $R>R_{HI}$ cf. z=0

➡ Stay tuned for further analysis



CORRELATIONS WITH NON-PARAMETRIC MORPHOLOGICAL INDICATORS

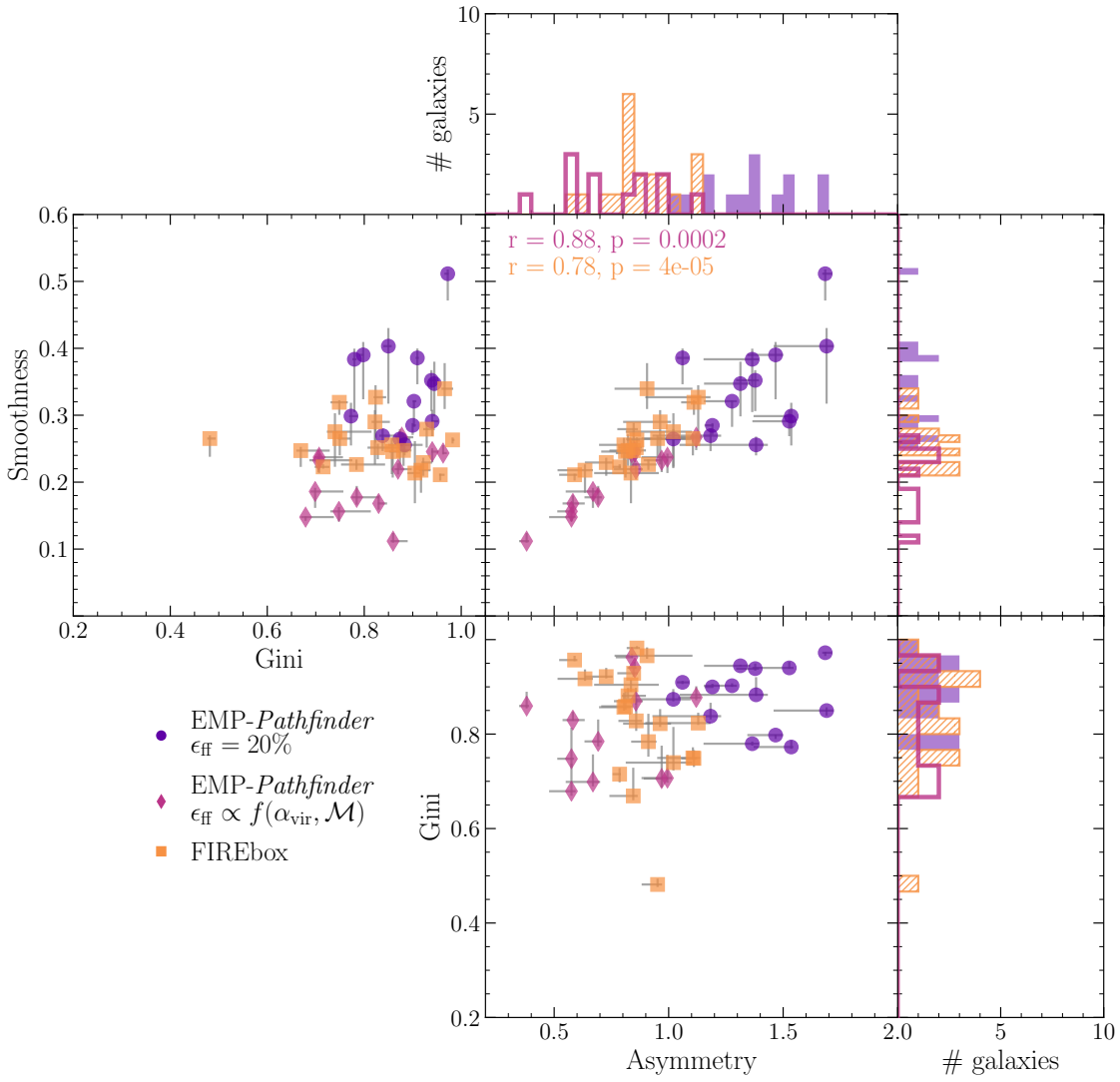
EMP-*Pathfinder* $\epsilon_{\rm ff} = 20\%$ | EMP-*Pathfinder* $\epsilon_{\rm ff} \propto \alpha_{\rm vir}, \mathcal{M}$ | FIREbox | combined



Galaxy/potential | HI/gas | SFR | FB

Gensior+2023 to be subm.

INCLINATION EFFECT ON NON-PARAMETRIC INDICATORS



Gensior+2023 to be subm.