Simulating HI galaxies with SAMs in prep. for the SKAO late-time cosmology case

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Late-time Cosmology with SKAO

Suggested surveys in the Cosmology SWG Red Book (2018)

- SKA-MID **Wide**, (Band 1)

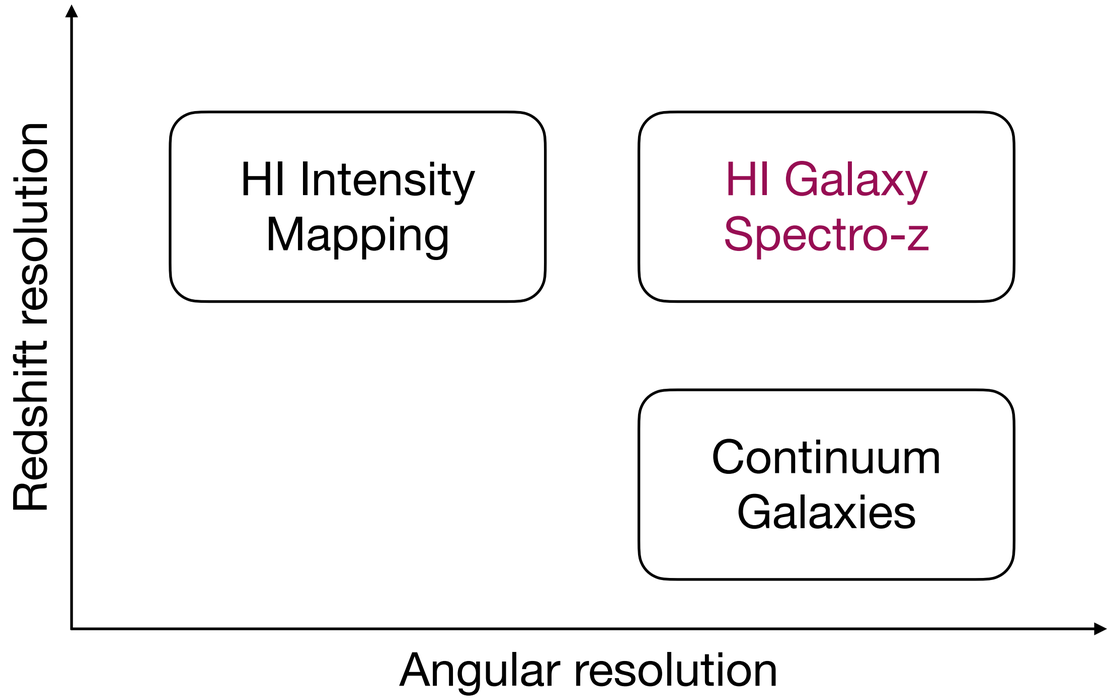
  $z \in [0.35, 3], \quad 20'000\,\mathrm{deg}^2,$

  Goals: Continuum galaxy survey
  & HI intensity mapping survey

- SKA-MID **Medium-Deep**, (Band 2)

  $z \in [0, 0.4], \quad 5000\,\mathrm{deg}^2,$

  Goals: Continuum Weak Lensing survey
  & **HI galaxy redshift survey**



Simulations of HI galaxies

Computational cost, Volume and Mass resolution

Hydro-simulations:

- Explicit gas hydrodynamics
- Follow particle distribution
- sub-grid physics
- Computationally expensive
- Relatively small volumes for cosmology

Semi-Analytical Models (SAM):

- Based on merger tree of N-body DM-only simulations
- Do not follow the particle dynamics
- Same sub-grid physics
- Faster computation
- Can be run on larger volumes

Semi-Analytical Models

GAlaxy Evolution and Assembly (GAEA)

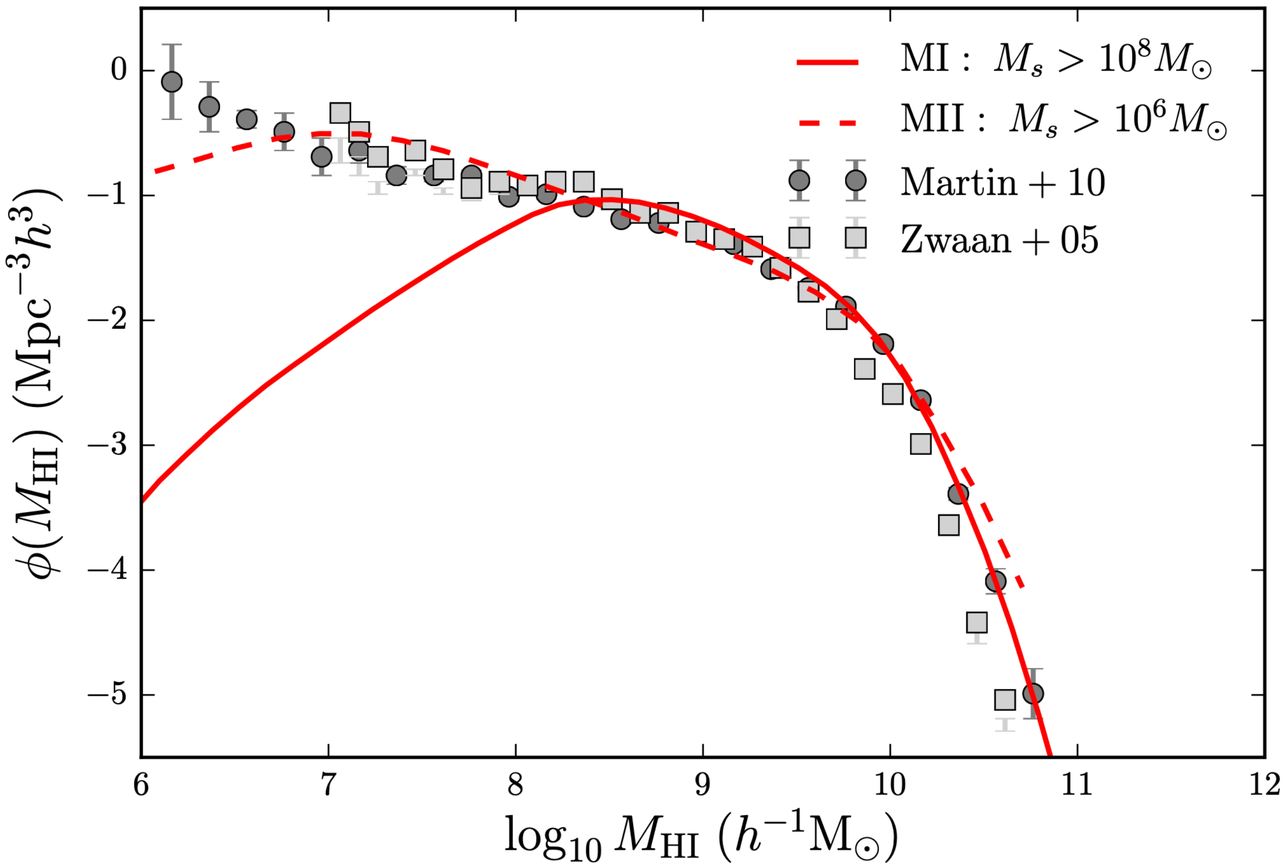
Millennium I, “cosmological size”
$V = [500\ \mathrm{Mpc}/h]^3$

Millennium II, “better resolution”
$V = [100\ \mathrm{Mpc}/h]^3$

Explicit treatment of cold gas partition in atomic (HI) and molecular (H2) Hydrogen (Xie et al. 2017)

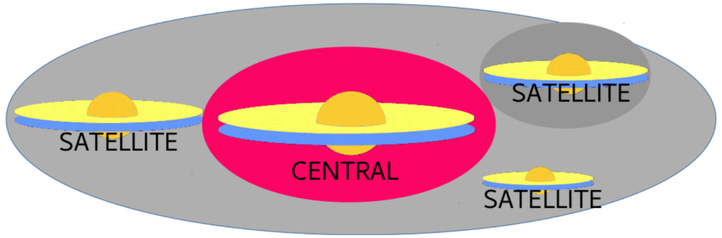
- De Lucia et al. 2014, 2023, 2024
- Hirschmann et al. 2016
- Xie et al. 2017, 2020
- Fontanot et al. 2017, 2018, 2020

Courtesy of M. Spinelli



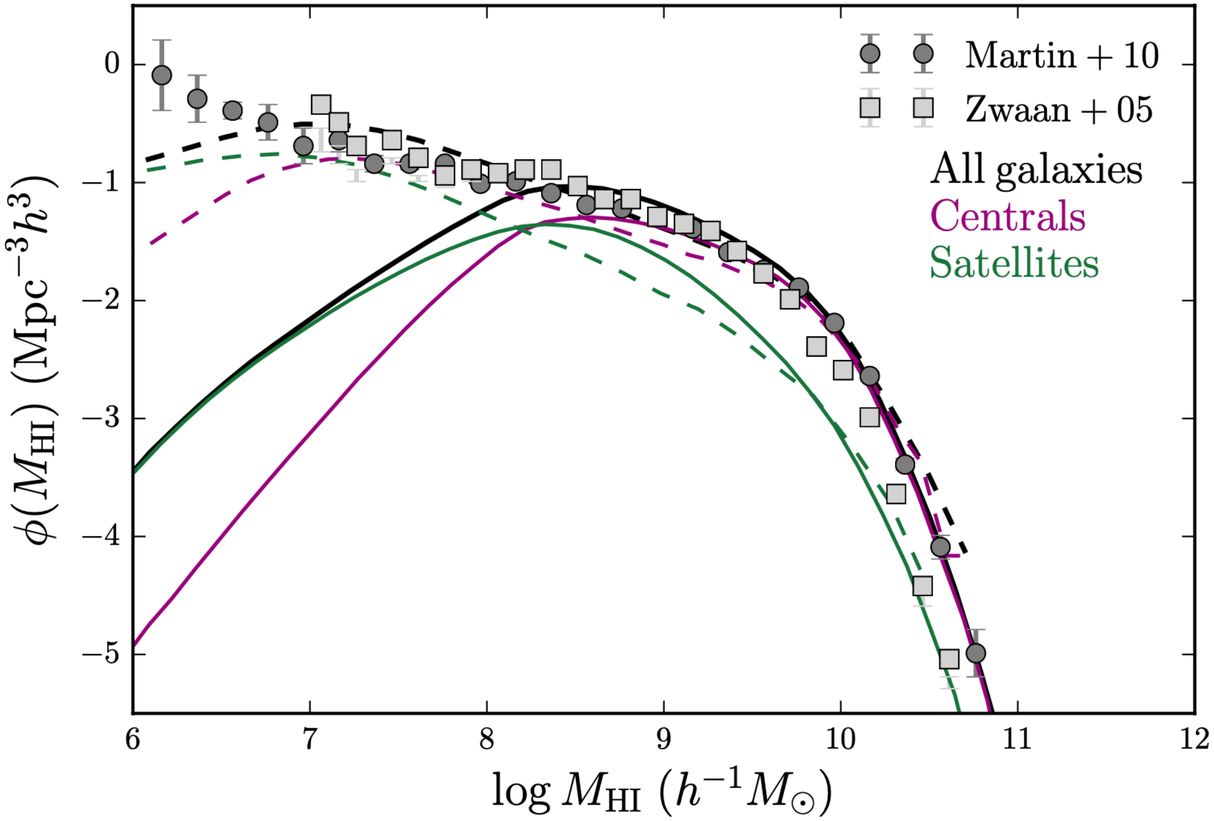
The GAEA SAM

Role of Central and Satellite galaxies



- Centrals dominate from intermediate to high HI mass
- Satellite dominate for low masses
- Orphan satellites “lost their subhalo” i.e. $M_h < 20$ MSI (resp. MSII) particles

Courtesy of M. Spinelli



Model of the 21cm emission line profile of HI galaxies

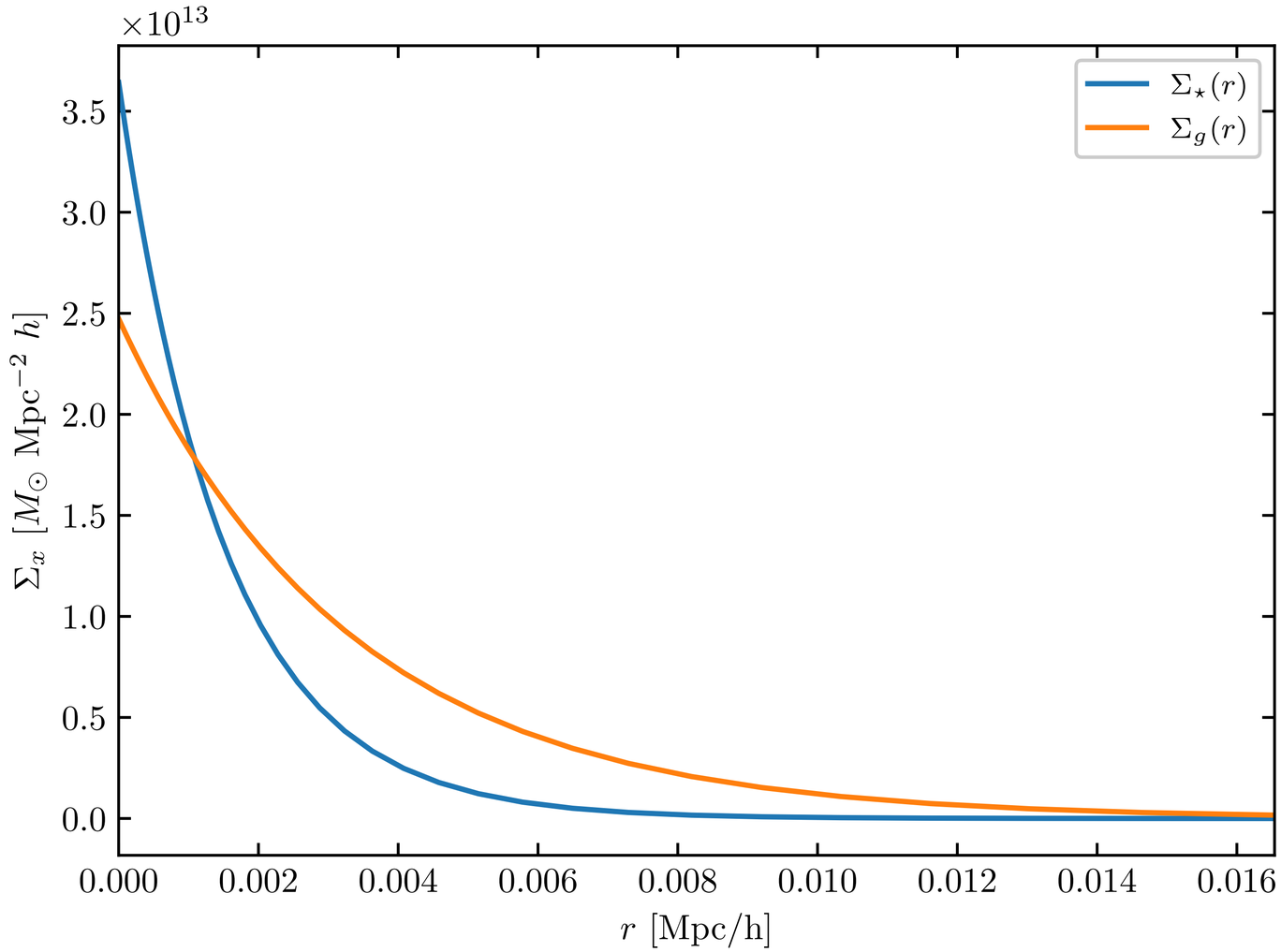
Surface Density Profiles

Stellar disk & Cold Gas disk

- Rotationally supported flat disks
- Axially symmetric surface density profiles
- Exponential surface density profiles

$$\Sigma_\star(r) = \frac{M_\star}{2\pi r_\star} \exp\left[-\frac{r}{r_\star}\right]$$

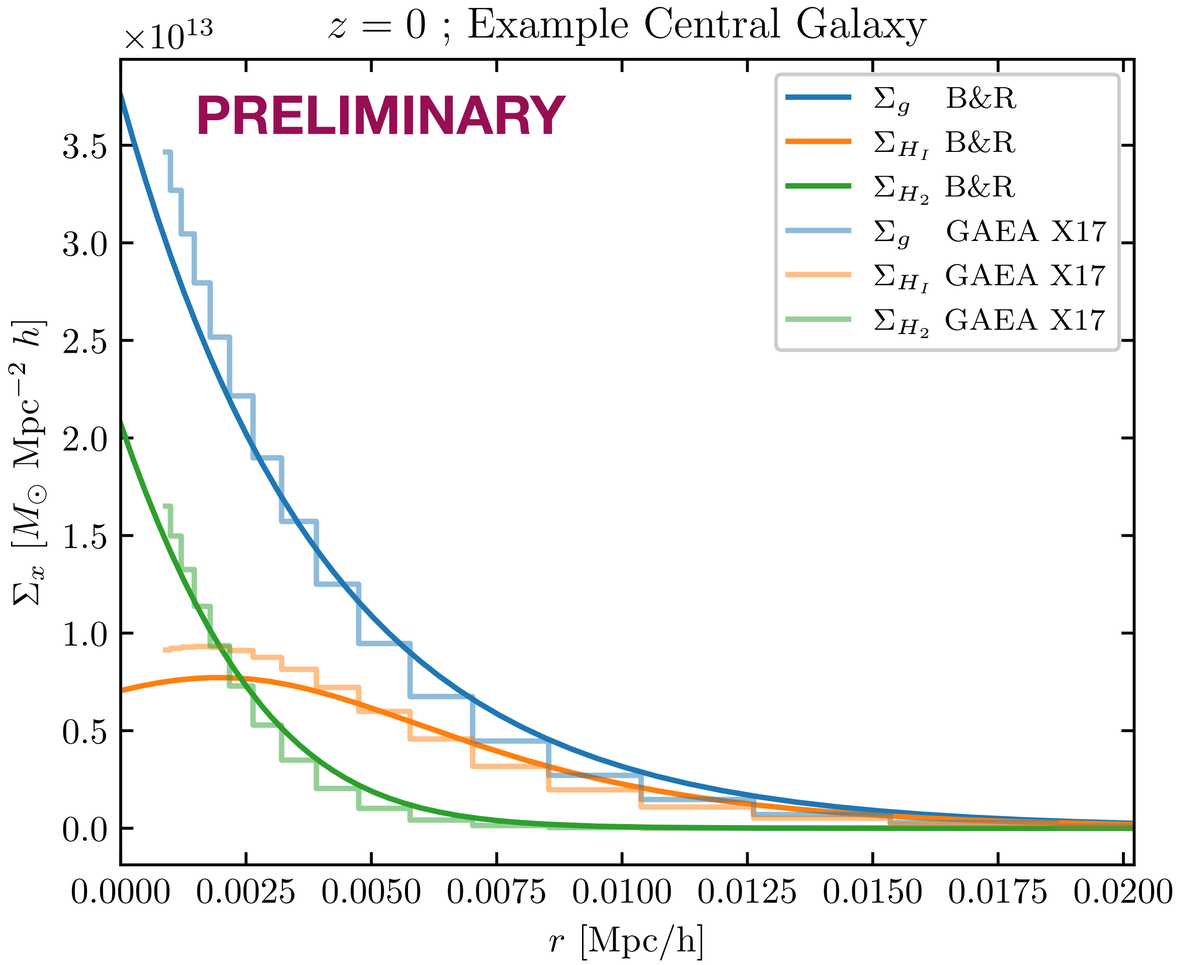
$$\Sigma_g(r) = \frac{M_g}{2\pi r_g} \exp\left[-\frac{r}{r_g}\right]$$



Surface Density Profiles

Partition of the cold gas

$$\Sigma_{H_2}(r) = f_{\mathrm{mol}}(r) \cdot \Sigma_H(r)$$
$$\Sigma_{HI}(r) = (1 - f_{\mathrm{mol}}(r)) \cdot \Sigma_H(r)$$



- Blitz & Rosolowsky 2006:

  Empirical relation between ratio of atomic gas and hydrostatic pressure

- GAEA: Xie et al. 2017:

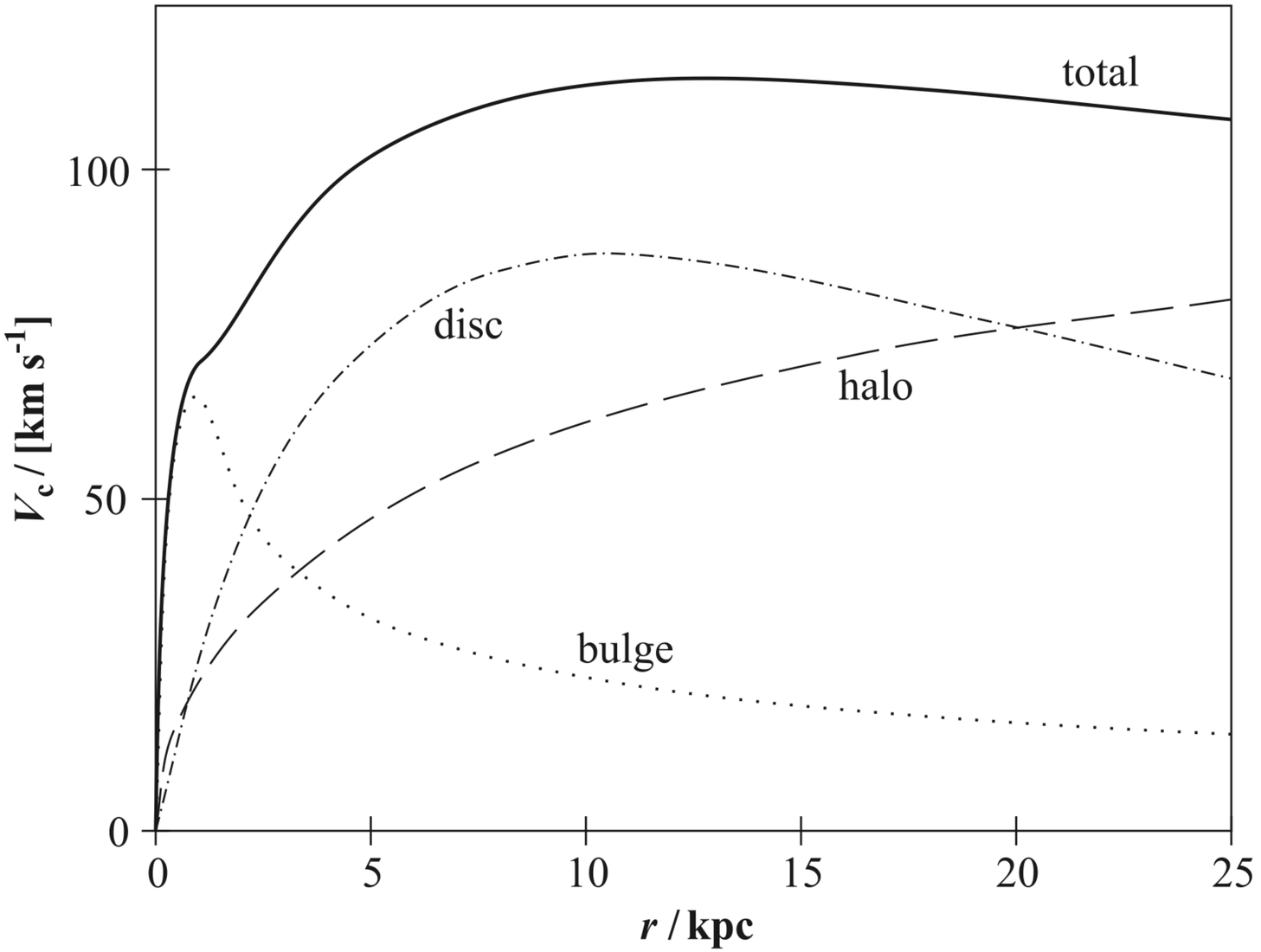
  Tracking the B&R partition at each timestep of the SAM evolution

- Krumholz et al. 2008:

  Empirical relation between ratio of atomic gas and gas phase metallicity

Circular velocity profiles

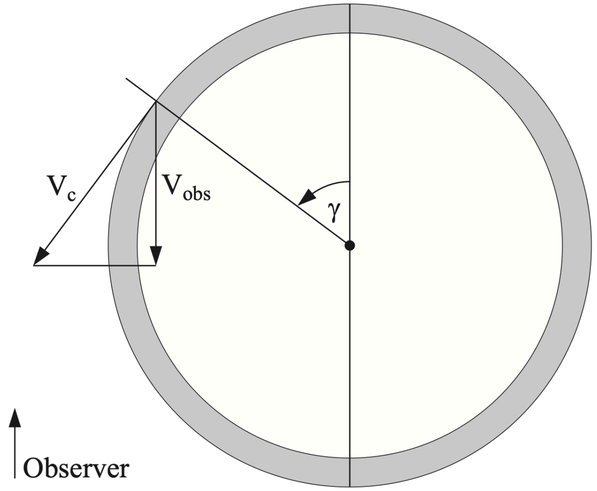
Obreschkow et al. 2009



HI 21cm emission line profiles

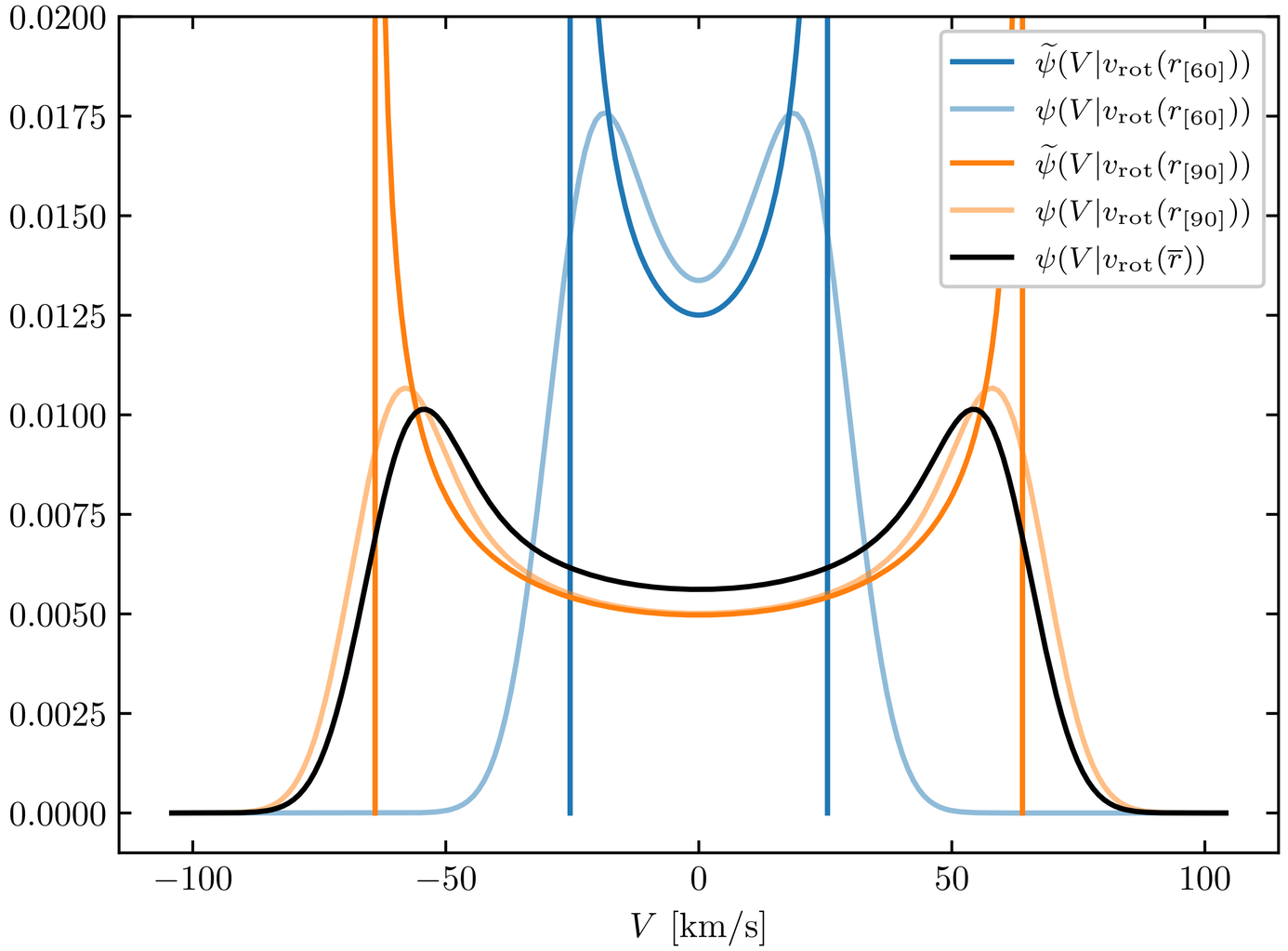
Contributions from each ring, projected on the L.o.S.

- Obreschkow et al. 2009:



$$\tilde{\psi}\left(V\,|\,v_{\rm rot}(r)\right) = \begin{cases} \dfrac{1}{\pi\sqrt{v_{\rm rot}(r)^2 - V^2}} & \text{if } |V| < v_{\rm rot}(r) \\ 0 & \text{if } |V| \geq v_{\rm rot}(r) \end{cases}$$

$$\psi\left(V\,|\,v_{\rm rot}(r)\right) = \frac{\sigma_g^{-1}}{\sqrt{2\pi}} \int dV' \exp\left[\frac{(V-V')^2}{-2\sigma_g^2}\right] \tilde{\psi}\left(V'\,|\,v_{\rm rot}(r)\right)$$

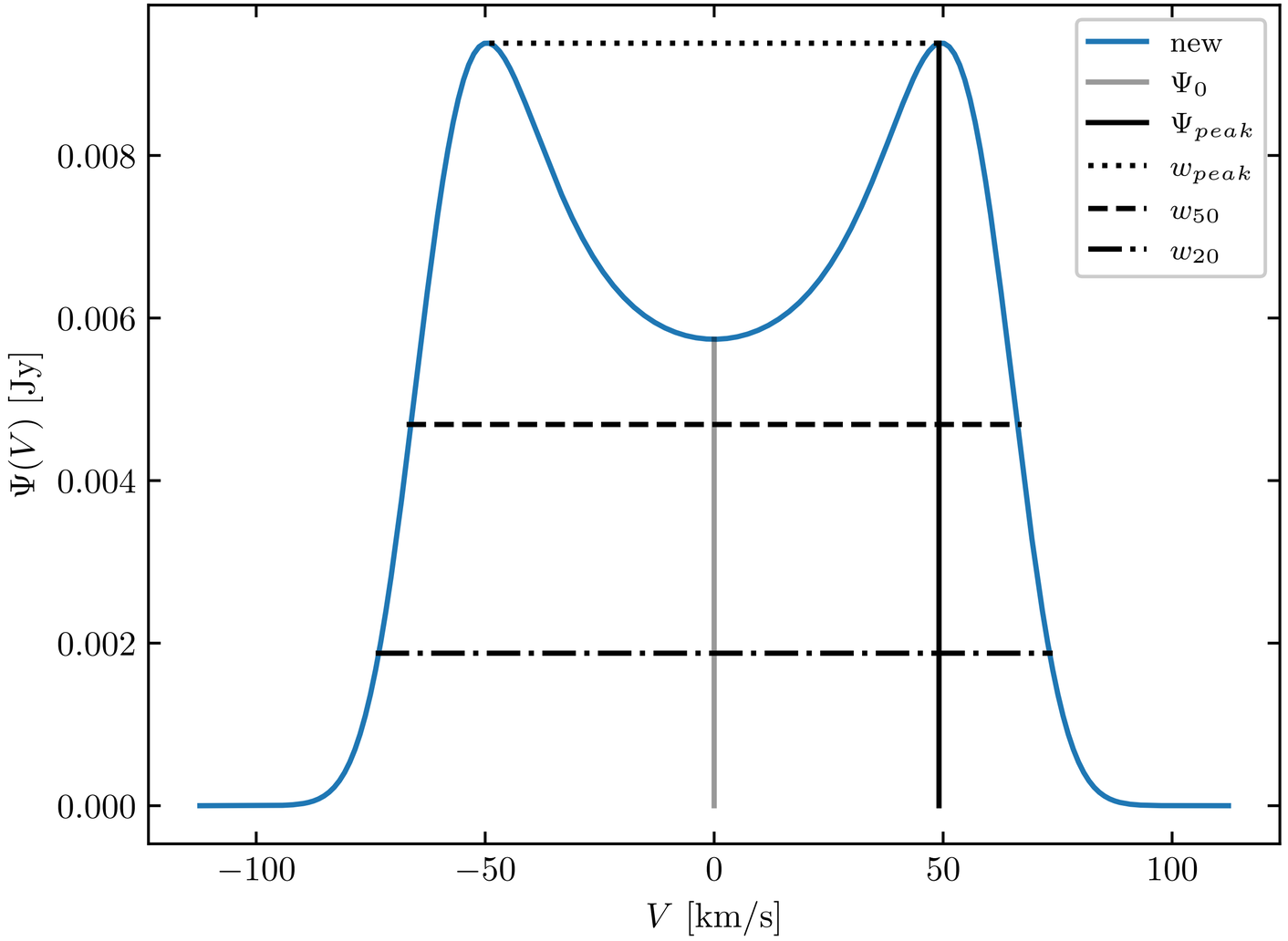


HI 21cm emission line profiles

Integrating the emission profile

- Obreschkow et al. 2009:

$$\Psi_{H_I}(V) = \frac{2\pi}{M_{H_I}} \int dr\ r\ \Sigma_{H_I}(r)\ \psi\left(V \,|\, v_{\rm rot}(r)\right)$$

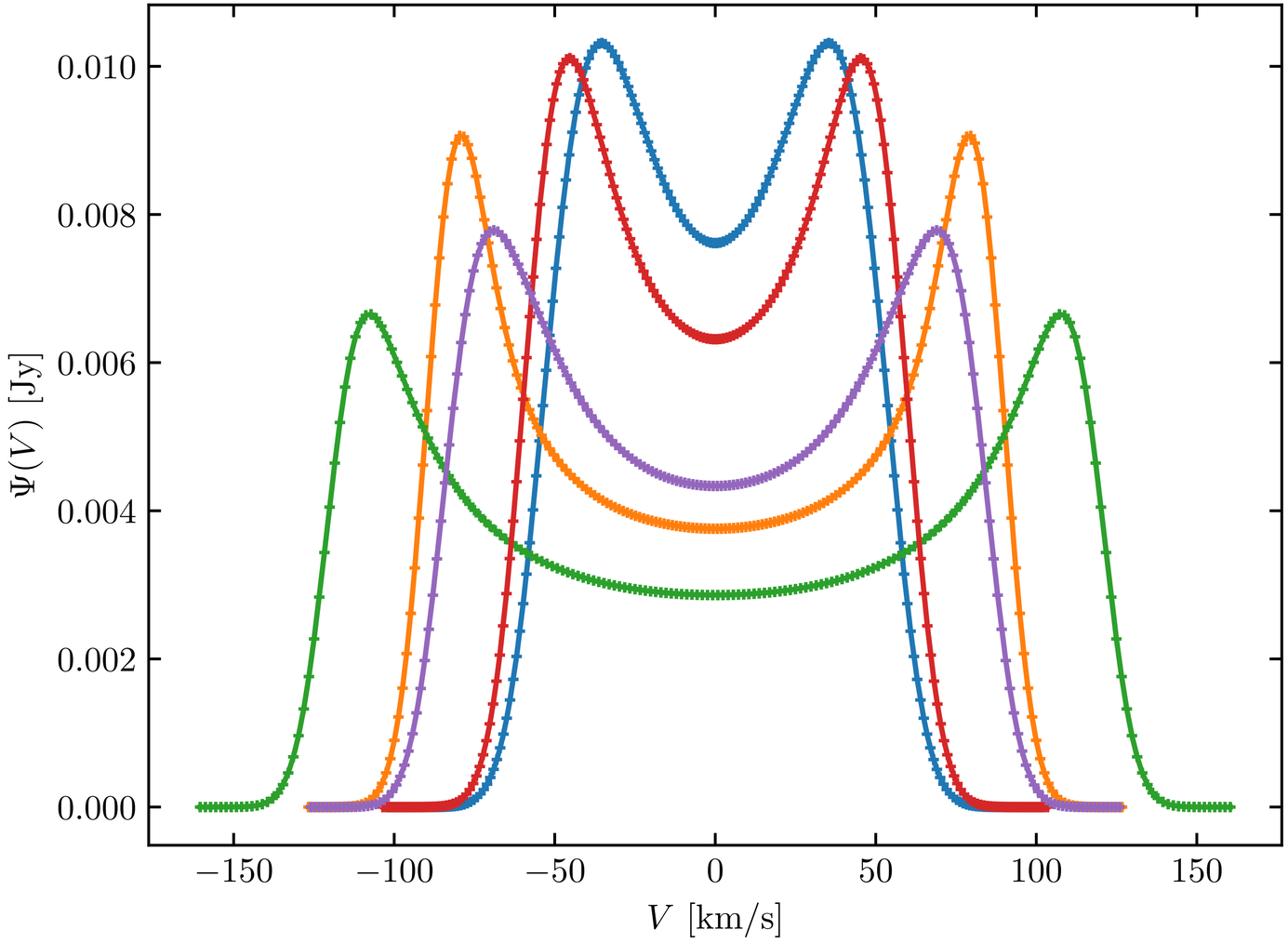


New modular python package

Vectorized & Parallelized

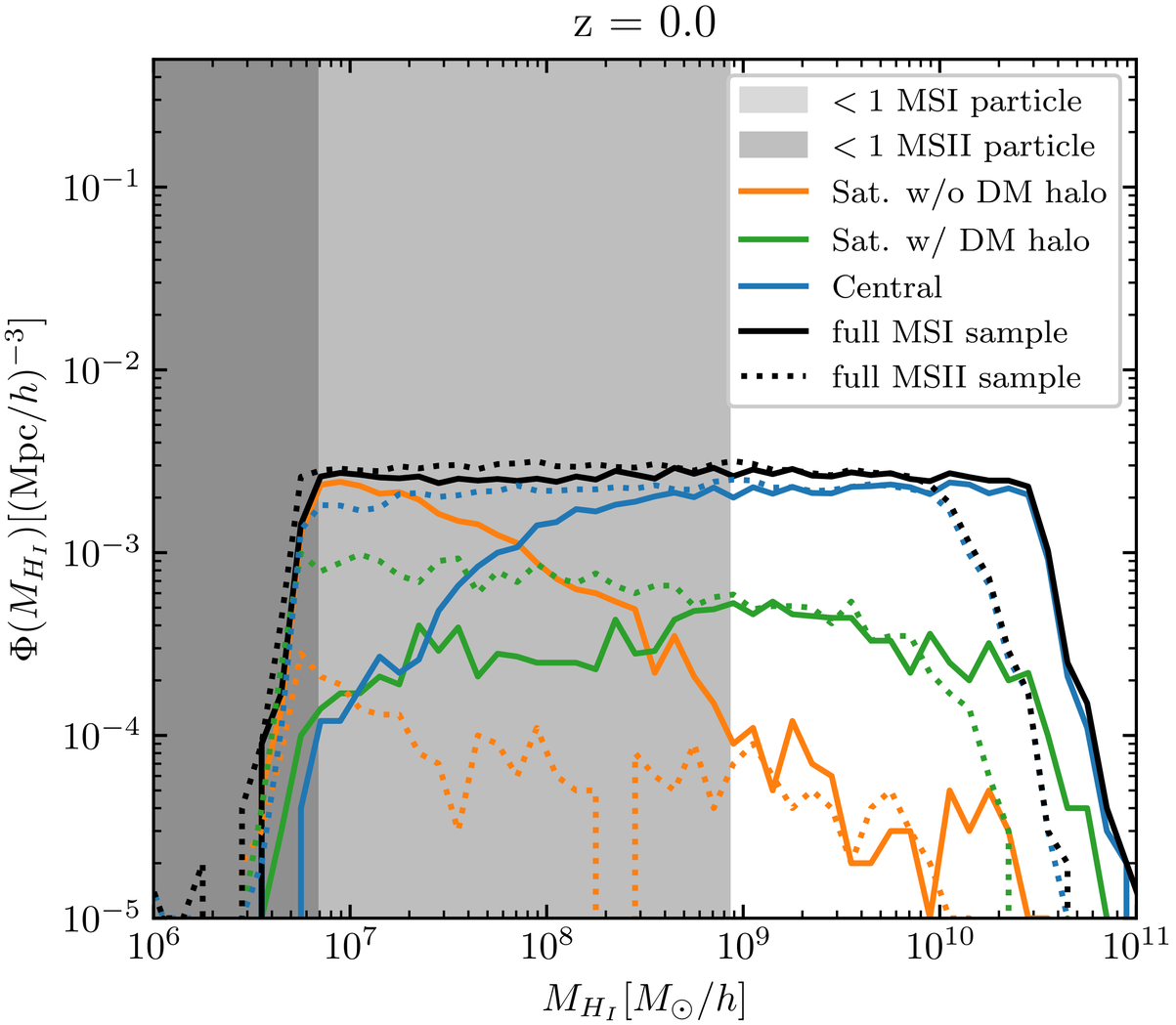
- Galaxy parameters module
- Galaxy profiles module
- Line profile module
- Line parameters module

10^3 Lines: ~4s on 10 cores



Consistency checks

Scaling relations for an equi-representative random sample

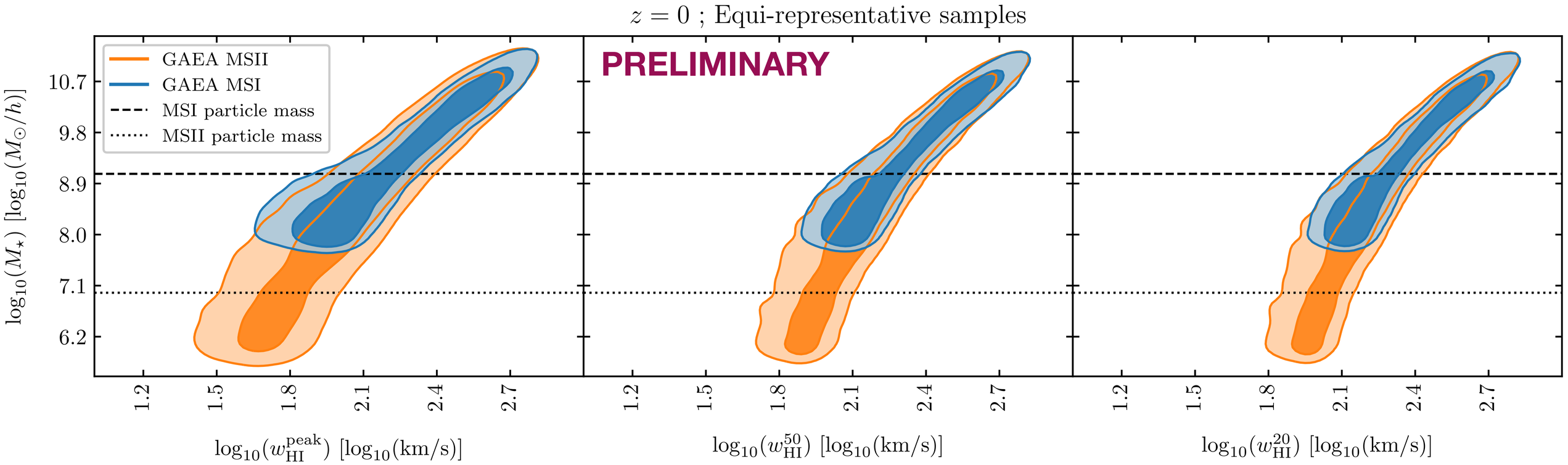


$$N = 10^4$$

- Effect of Resolution (MSI vs MSII)
- Role of Central / Satellite galaxies
- Choice of Semi-Analytical Model (GAEA vs L-Galaxies)
- Effect of Inclination
- Comparison with available observational data

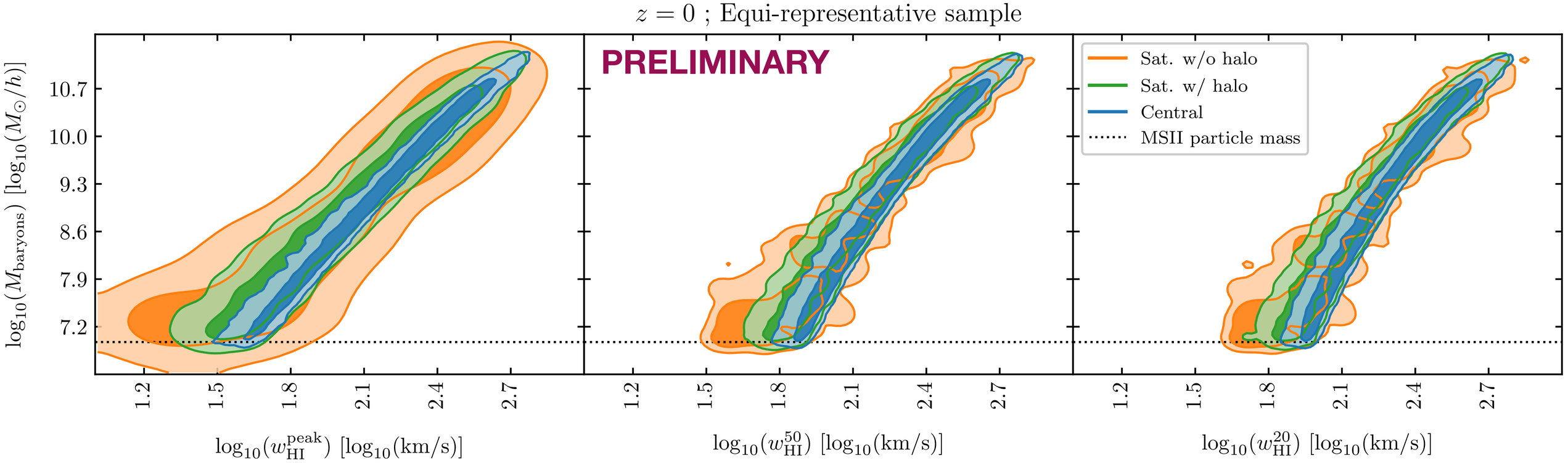
Scaling relations

Tully-Fisher (TF) relation: Stellar Mass <—> HI line widths



Scaling relations

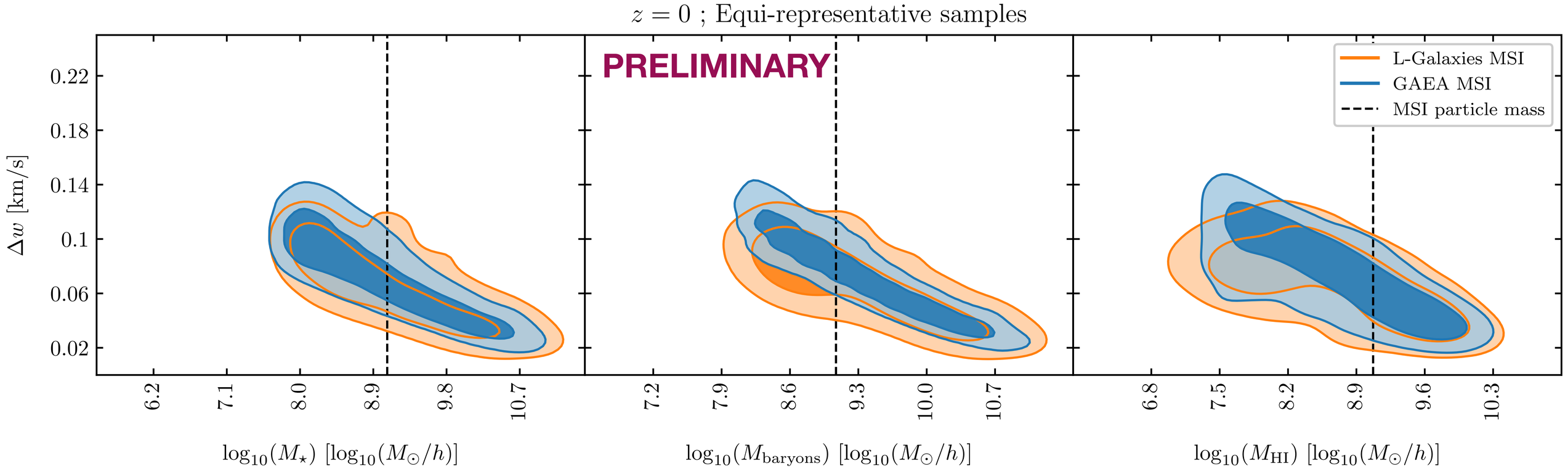
Baryonic Tully-Fisher (BTF) relation: Baryonic Mass <—> HI line widths



Scaling relations

HI line widths differences <—> Masses

$$\Delta w = \frac{w_{20} - w_{50}}{w_{20}}$$

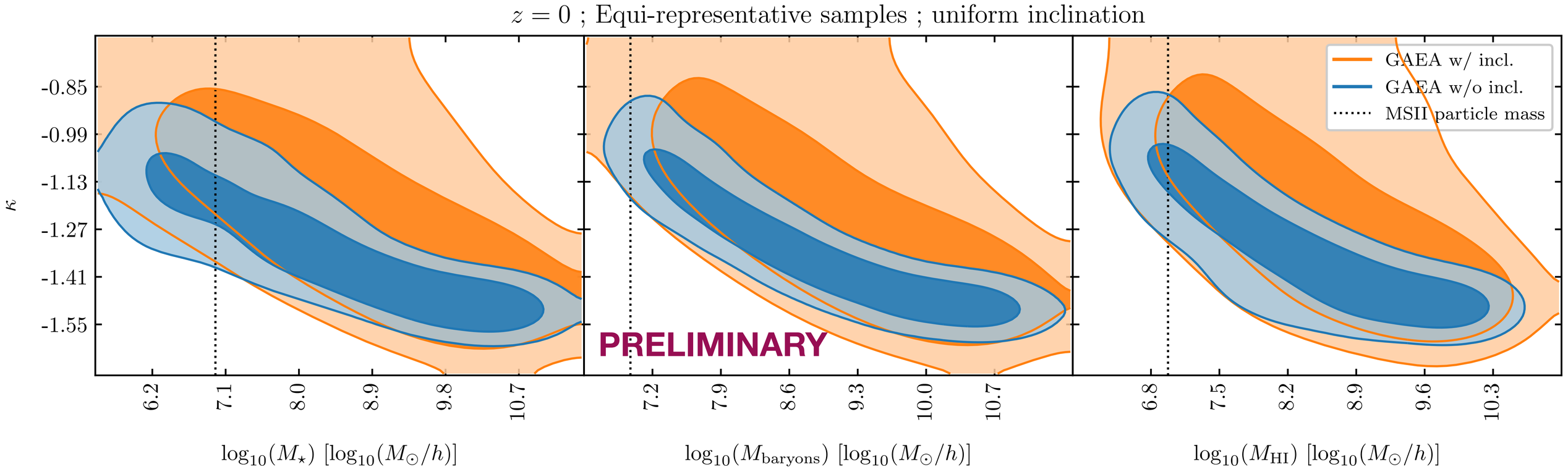


Scaling relations

HI line kurtosis <—> Masses

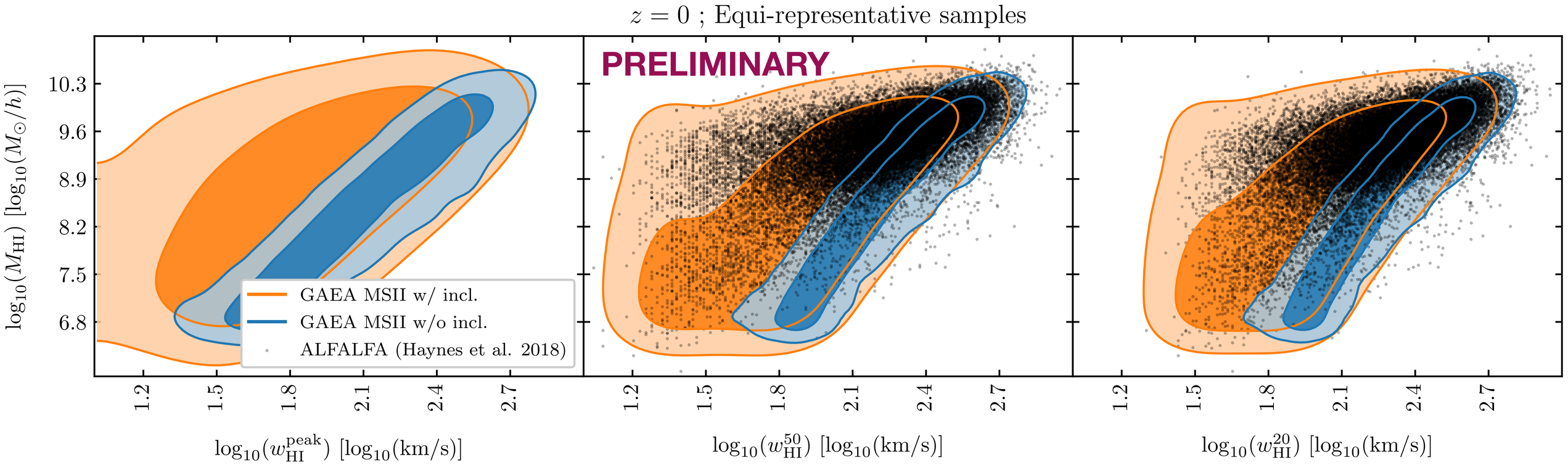
$$\kappa = \frac{\mu_4}{\mu_2^2} - 3$$

$$\mu_n = \frac{\int_{-\infty}^{\infty} \Psi_{HI}(V)(V - \bar{V})^n dV}{\int_{-\infty}^{\infty} \Psi_{HI}(V) dV}$$



Scaling relations

Neutral Hydrogen Mass - HI line widths



Realistic mock catalogues

For potential SKAO HI galaxy redshift survey

- Forecasts for dN/dz
- Forecasts for HI galaxy clustering

But also of interest:

- Forecast TF/BTF Peculiar Velocities

Building a mock PV catalog

Outlook on the steps

- Building a lightcone
- Mock observing a simulated sky: including surveys systematics
  - HI galaxy redshift survey —> 21cm lines parameters (w_{50}, w_{20}, etc.)
  - Counterpart Opt./IR photometric survey —> apparent magnitudes & inclinations
- Mock calibrating the TF/BTF relation
- Constructing a TF/BTF distances catalog
- Deducing a TF/BTF peculiar velocities catalog

Conclusion

- SAMs = ready tools to simulate cosmology sized volumes
- New (fast) code to compute HI galaxy 21cm emission line profiles
- Carefully checked output: simulated scaling relations

Ongoing efforts to produce **realistic mock catalogues** for potential SKAO HI galaxy redshift surveys:

SKAO *“Cosmology - HI Galaxy”* Focus Group (synergy between the two eponymous SWG) led by G. De Lucia and A. Ponomareva

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