The low-redshift (z=1) CGM with

muse
multi unit spectroscopic explorer

Nicolas F. Bouché

CRAL
CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

CNRS, Univ. Lyon, Center Research Astrophysics of Lyon

I. Schroetter J. Zabl M. Cherrey I. Langan M. Wendt Y. Guo

& S. Muzahid, T. Contini, J. Schaye, R. Bacon, & MUSE team...

A couple of disclaimers

muse
multi unit spectroscopic explorer

1) I only care about star-forming galaxies [OII]
2) The most interesting mass range is log M* = 9 – 10.5
3) The most interesting redshift range is 0.5 < z < 1.5
4)

A couple of disclaimers

1) I only care about star-forming galaxies [OII]
2) The most interesting mass range is log M* = 9 – 10.5
3) The most interesting redshift range is 0.5 < z < 1.5
4) I only care about cool CGM [Mg+]
5)

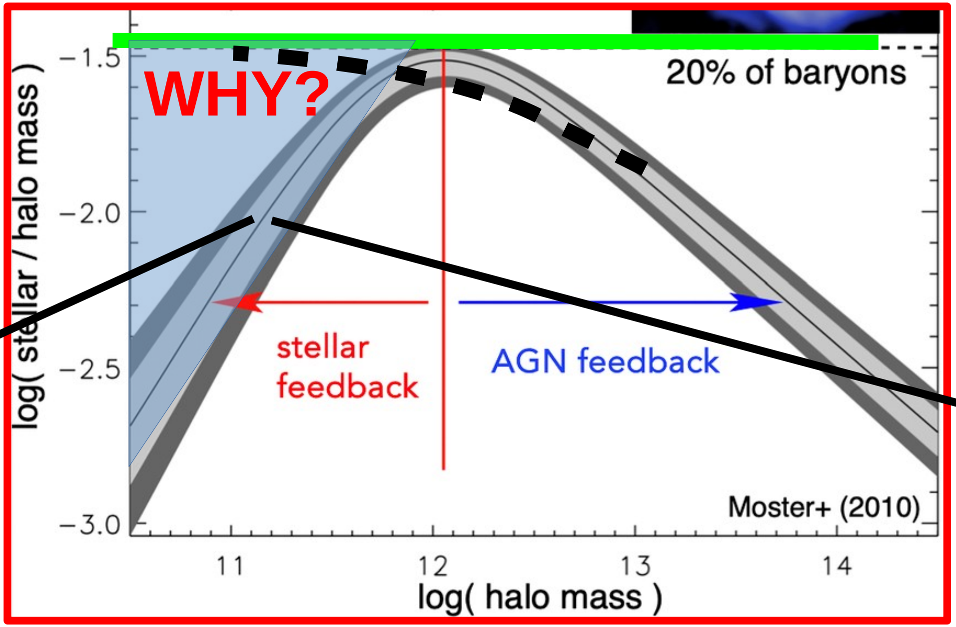
A couple of disclaimers

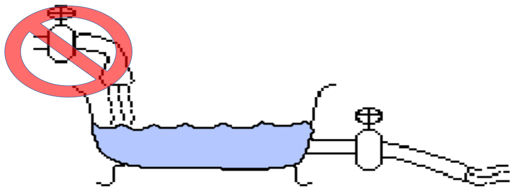
muse
multi unit spectroscopic explorer

1) I only care about star-forming galaxies [OII]
2) The most interesting mass range is $\log M^* = 9 - 10.5$
3) The most interesting redshift range is $0.5 < z < 1.5$
4) I only care about cool CGM [Mg+]
5) I do care about B-fields !

Problem #1

Efficiency = $M_* / (f_B M_h)$





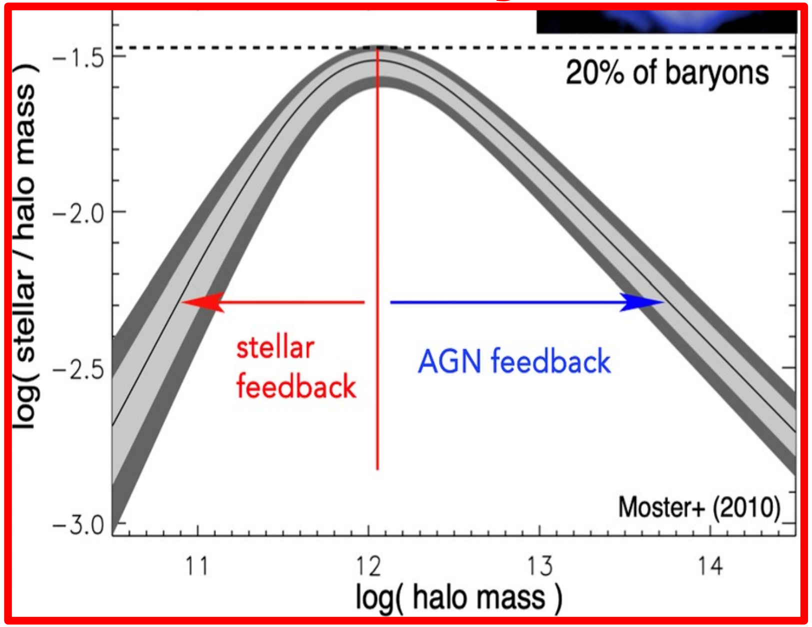
Ruszkowski & Pfrommer 2025
Moster et al. 2013
Behroozi et al. 2013, 2016

Bouché2010

Bennett, Smith+24

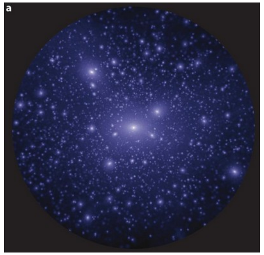
Problem #1

Efficiency

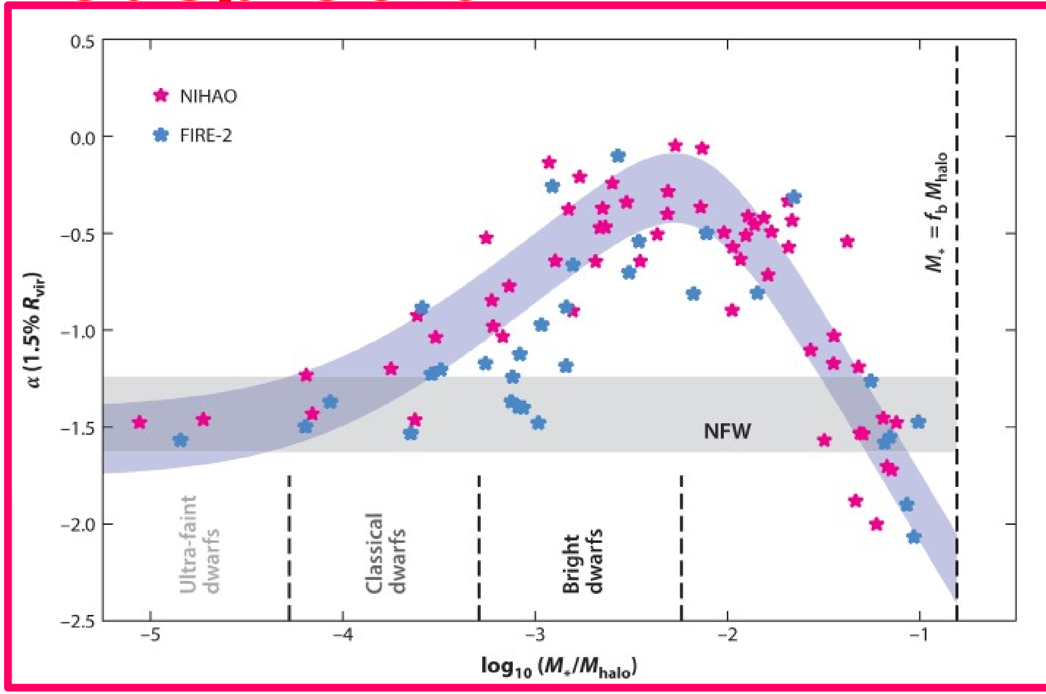


Ruszkowski & Pfrommer 2025 (Review)
Moster et al. 2013
Behroozi et al. 2013, 2016

Problem #2



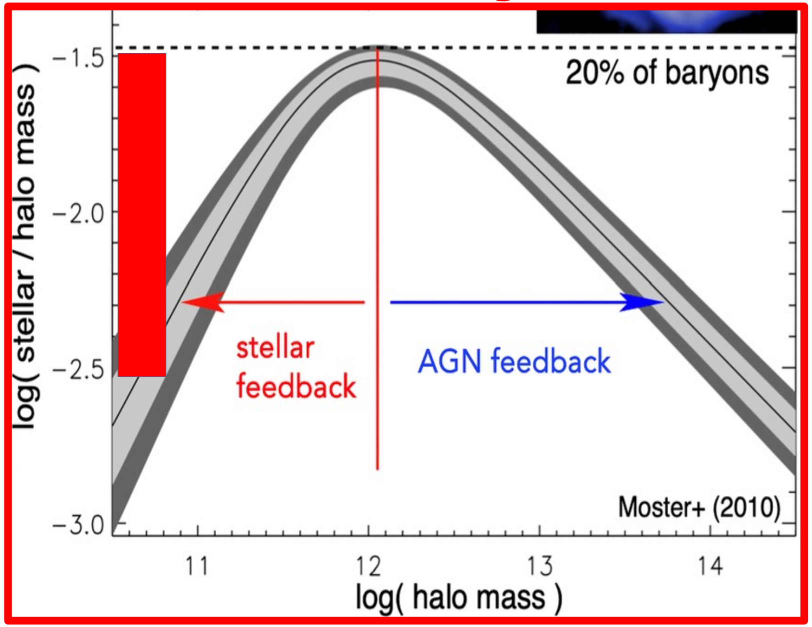
Cusp-Core



Bullock et al. 2017 (Review)
Lazar et al. 2020; Di Cintio 2014,
NFW 96; Governato 2007; Pontzen 12,14

Problem #1

Efficiency

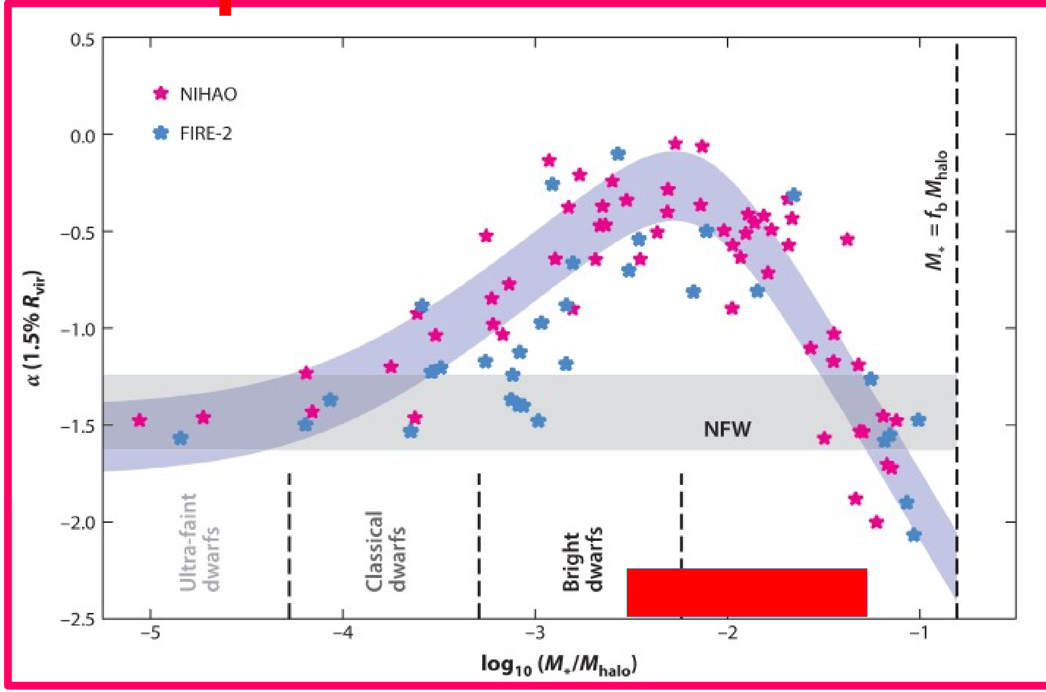


MUSE Gas Flow and Wind (MEGAFLOW)

14 papers; NB+2025 (Survey)

Problem #2

Cusp-Core

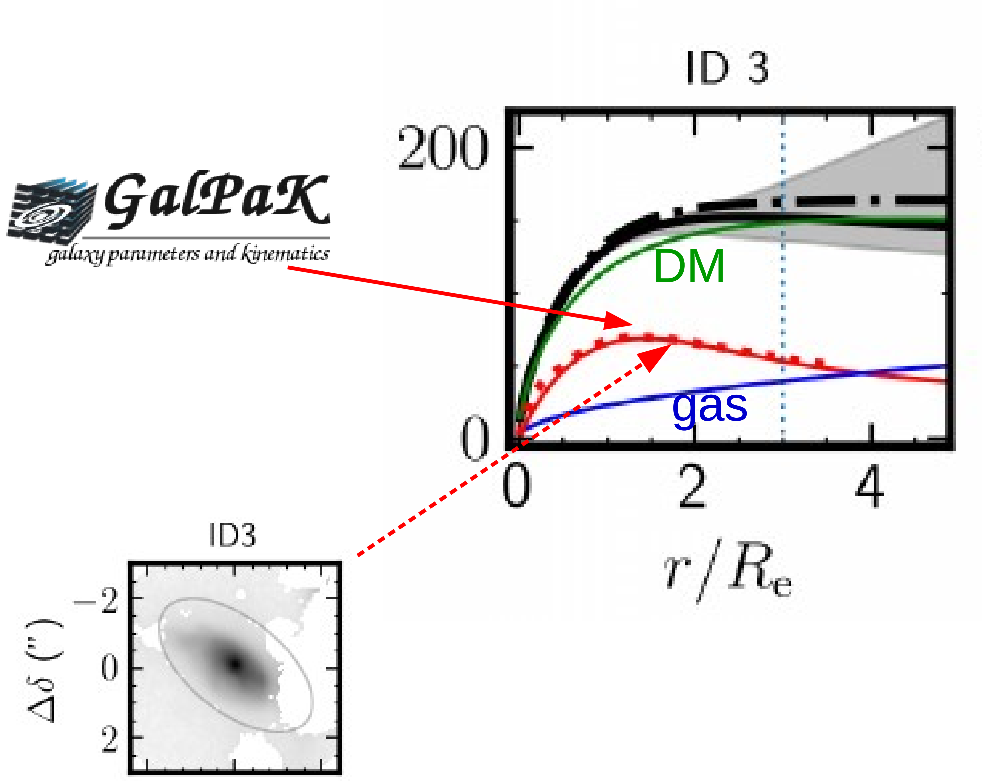


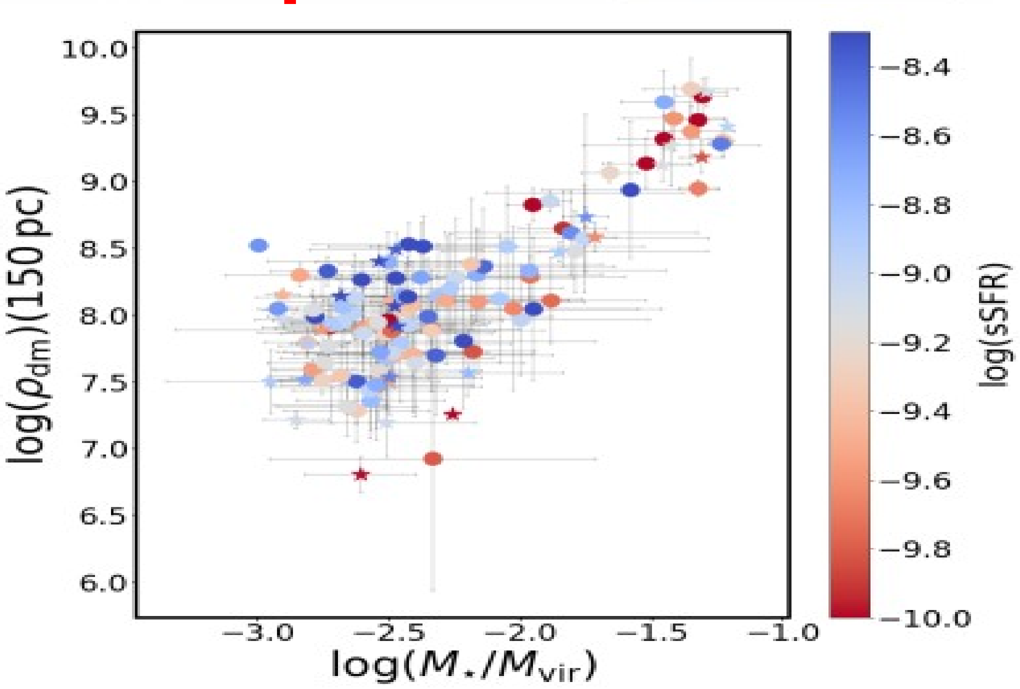
MUSE DARK Survey (130 SFGs z=1)

Ciocan, NB 2025 arXiv 250619721

Problem #2

Cusp-Core

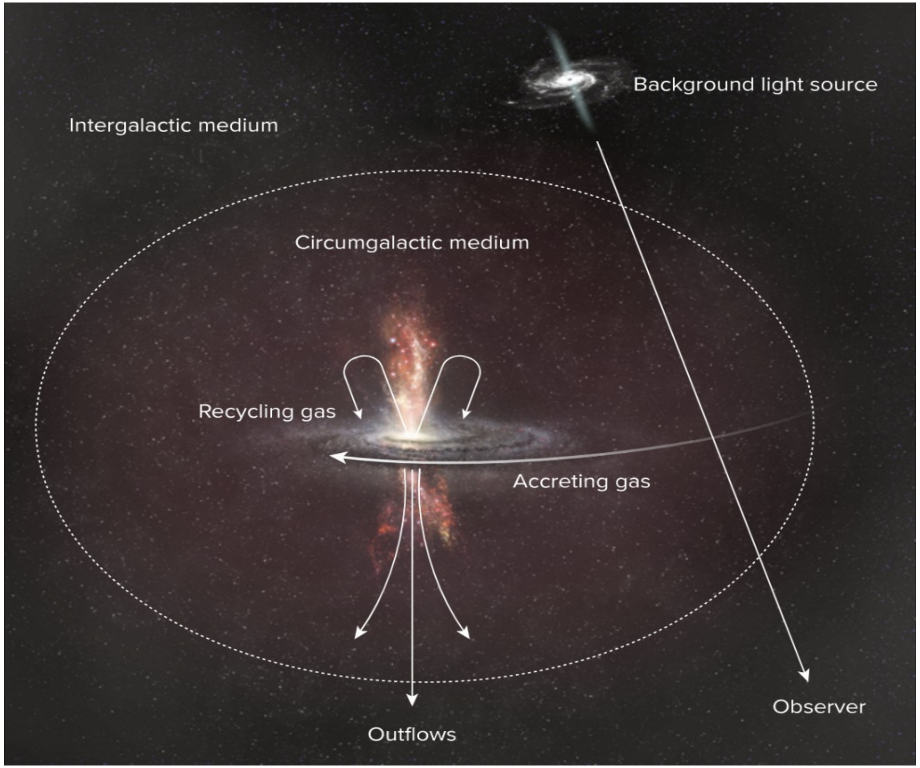




MUSE DARK-I (130 SFGs z=1)

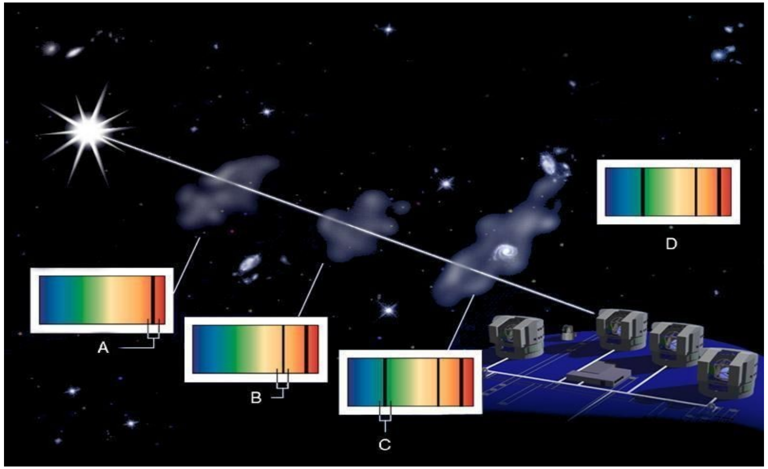
Ciocan, NB 2025 arXiv 250619721

Can be best studied with QSO abs. lines



$$\dot{M}_{\rm out}(b) = 0.41 {\rm M}_\odot\,{\rm yr}^{-1}\,\frac{\mu}{1.5}\,\frac{\Omega_w}{2}\,\frac{N_H(b)}{10^{19}{\rm cm}^2}\,\frac{V_{\rm out}}{200{\rm km\,s}^{-1}}\,\frac{b}{25\,{\rm kpc}}$$

https://megaflow.univ-lyon1.fr/



QSO with Multiple (N=3,4,5) Mg+

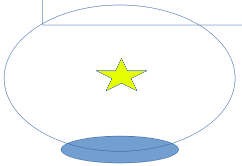
Data: Catalogs & Cubes

https://amused.univ-lyon1.fr

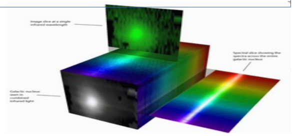
MusE GAs Flow and Wind Survey

A) Absorption-centric
For an absorption,
what is the galaxy doing ?

Schroetter et al. 2016, 2019, [Outflows]
Zabl et al. 2019 [Inflows]
Zabl et al. 2020 [Tomography]
Zabl et al. 2021 [Mg+ emission]
Wendt et al. 2021 [CGM dust]
Freundlich et al. 2021 [gas content]
Langan et al. 2022 [M-Z relation]

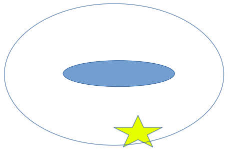


EASY!



B) Galaxy-Centric ("blind")
For a galaxy,
what is the absorption doing ?

Schroetter et al. 2021 [f-covering]
Cherrey et al. 2024 [groups]
Cherrey et al. 2025 [isolated gals]
...



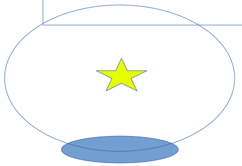
Bouché et al. 2025 [Survey]

HARD! (Need to be complete)

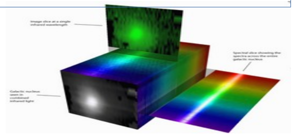
MusE GAs Flow and Wind Survey

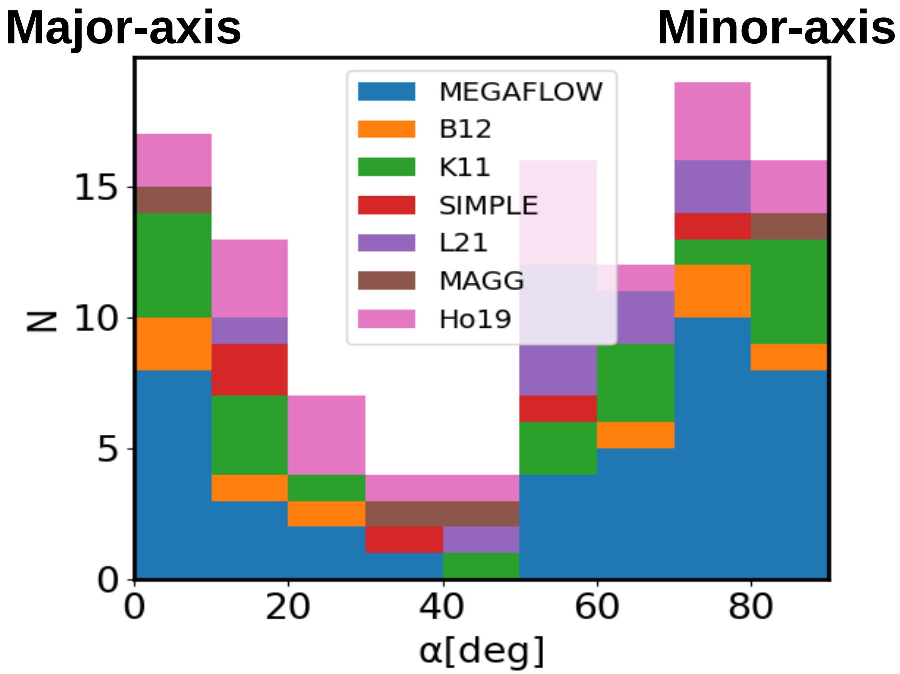
A) Absorption-centric
For an absorption,
what is the galaxy doing ?

Schroetter et al. 2016, 2019, [Outflows]
Zabl et al. 2019 [Inflows]
Zabl et al. 2020 [Tomography]
Zabl et al. 2021 [Mg+ emission]
Wendt et al. 2021 [CGM dust]
Freundlich et al. 2021 [gas content]
Langan et al. 2022 [M-Z relation]



EASY!

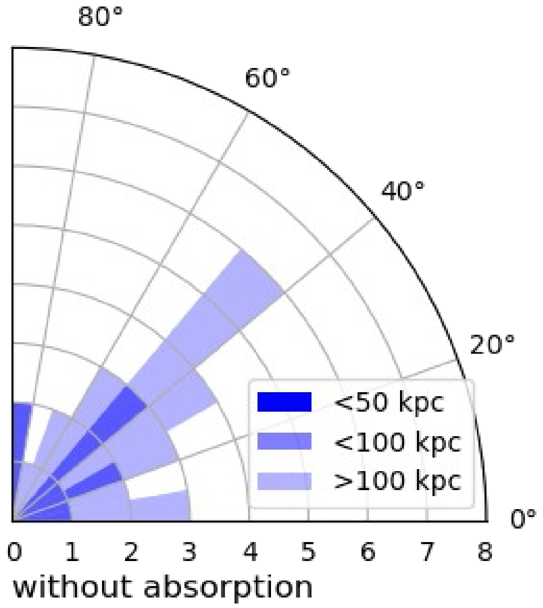




When matching
REW>0.5; incl>30; b<100 kpc

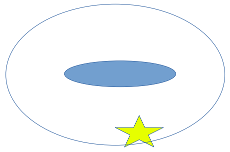
MusE GAs Flow and Wind Survey

Cherrey, NB 2025



B) Galaxy-Centric ("blind")
For a galaxy,
what is the absorption doing ?

Schroetter et al. 2021 [f-covering]
Cherrey et al. 2024 [groups]
Cherrey et al. 2025 [isolated gals]
...



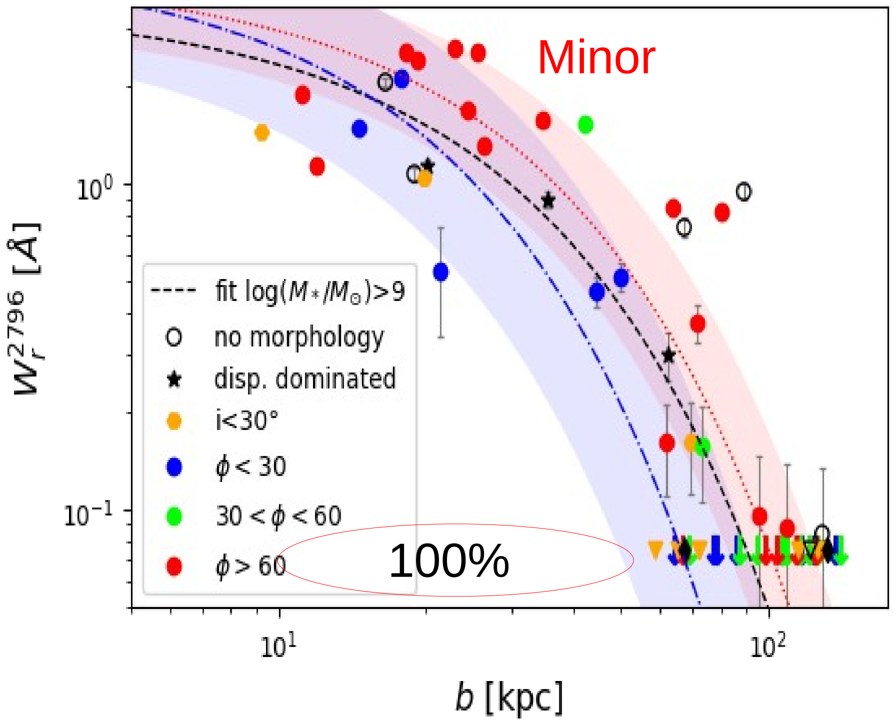
Bouché et al. 2025 [Survey]

HARD! (Need to be complete)

Also, Lundgren+21, Chen+, Huang+21; Dutta+20

MusE GAs Flow and Wind Survey

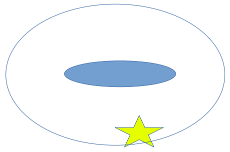
Cherrey, NB 2025



<u>B) Galaxy-Centric (“blind”)</u>

For a galaxy,
what is the absorption doing ?

Schroetter et al. 2021 [f-covering]
Cherrey et al. 2024 [groups]
Cherrey et al. 2025 [isolated gals]
...



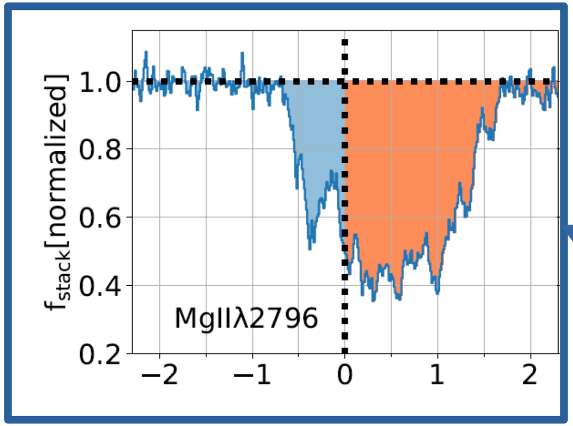
Bouché et al. 2025 [Survey]

HARD! (Need to be complete)

Also, Lundgren+21, Chen+, Huang+21; Dutta+20

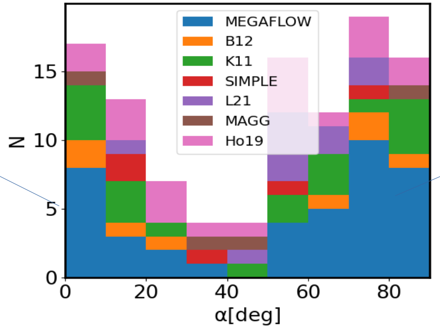
Consequences

disky" gaseous disks to 60 kpc

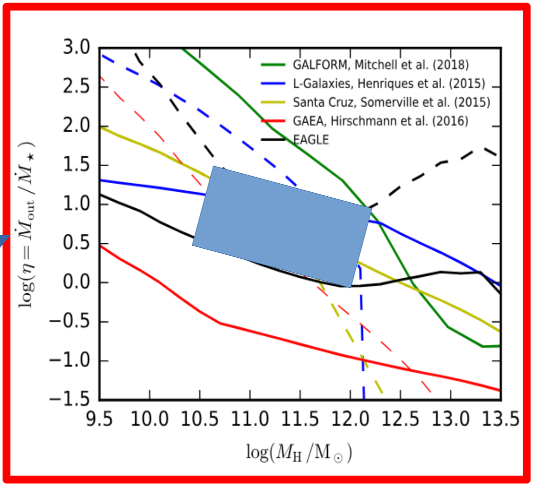


Inflows

Outflows



Outflows to 100 kpc



- **Co rotating to 60kpc &**
- **dMin ~ SFR**

For M>1e9: Vout< Vesc

→ gas does not escape

Loading ~ V^-1

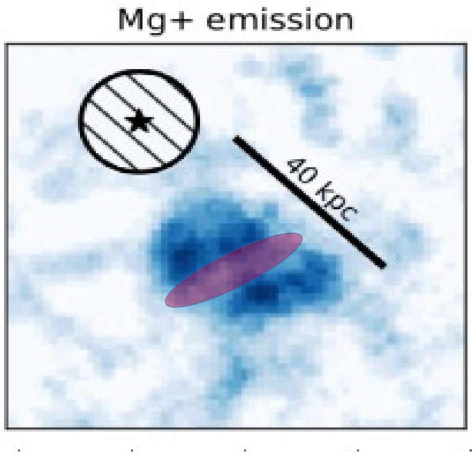
Zabl et al. 2019,
Also Ho et al. 2019, Martin 19, Kacprzak et al.
Rahmani+21
OK in simulations (DeFelippis+2021; Stewart+11,13)

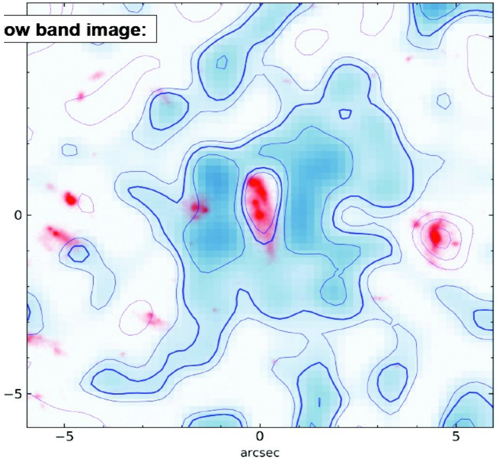
Schroetter+21, 24

Cool CGM anisotropy

Seeing is believing

Mg+ in Emission





Zabl et al. 2021
(Megaflow)

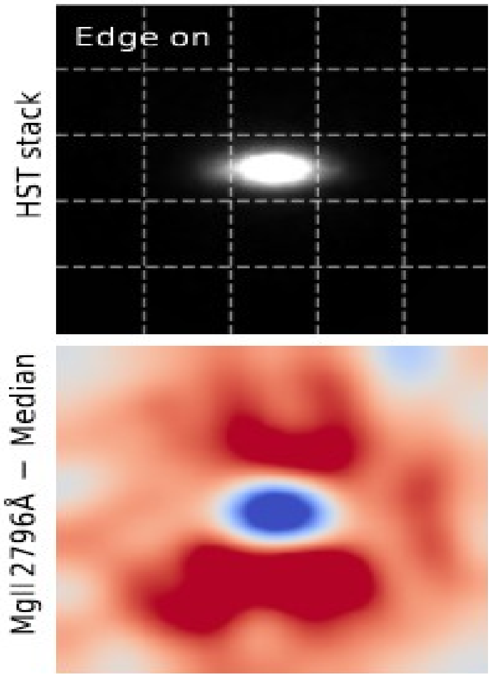
Pessa in prep.
Pessa 2024

See also Burchett+ 2020 (Kcwi); Leclercq in prep.

Guo et al. 2023

M* > 1e9

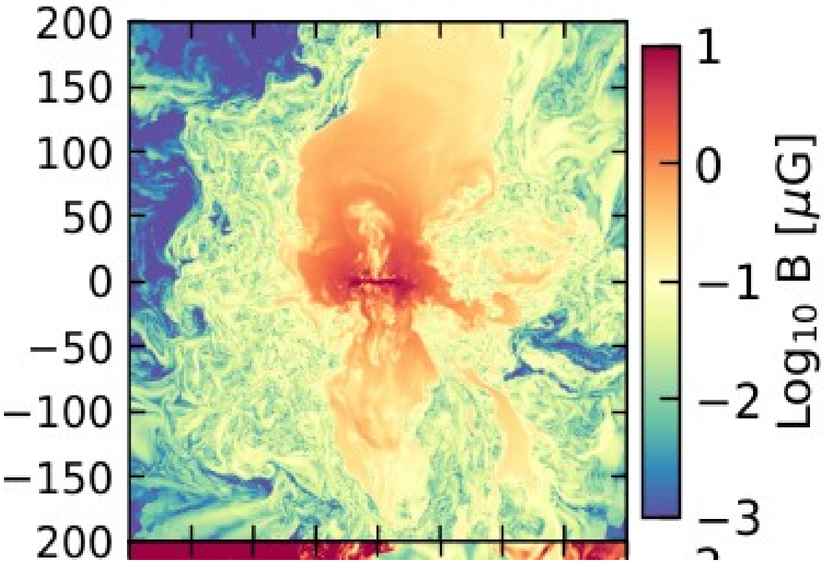
Stacking in UDF



B-field anisotropy @z=0

Simulations :

Van de Voort+20 (B>0)

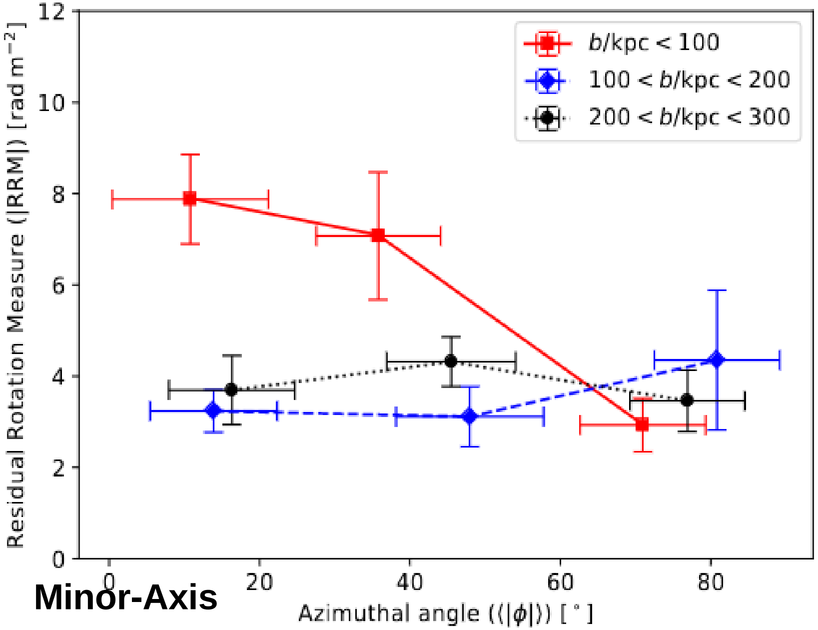


Also
Jacob, Pakmor+ 2018
Whittingman 2023

Observations:

Heesen+23 (SF, i>55deg)

Excess Rotation Measure (LOFAR)

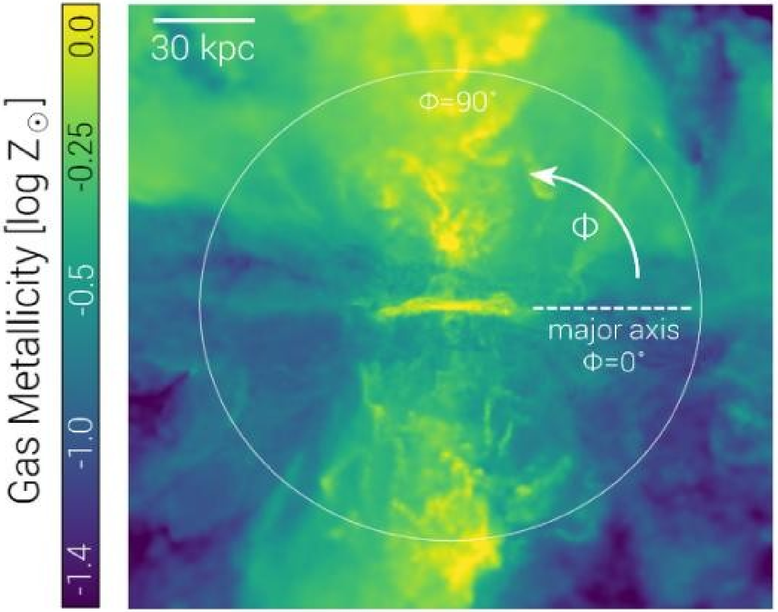


Minor-Axis

Also Bockmann+23

Metallicity/Dust anisotropy

Simulations :

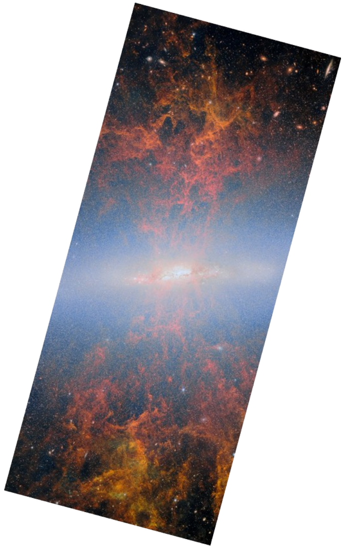


Peroux 2021 (TNG50)

Also van de Voort+21

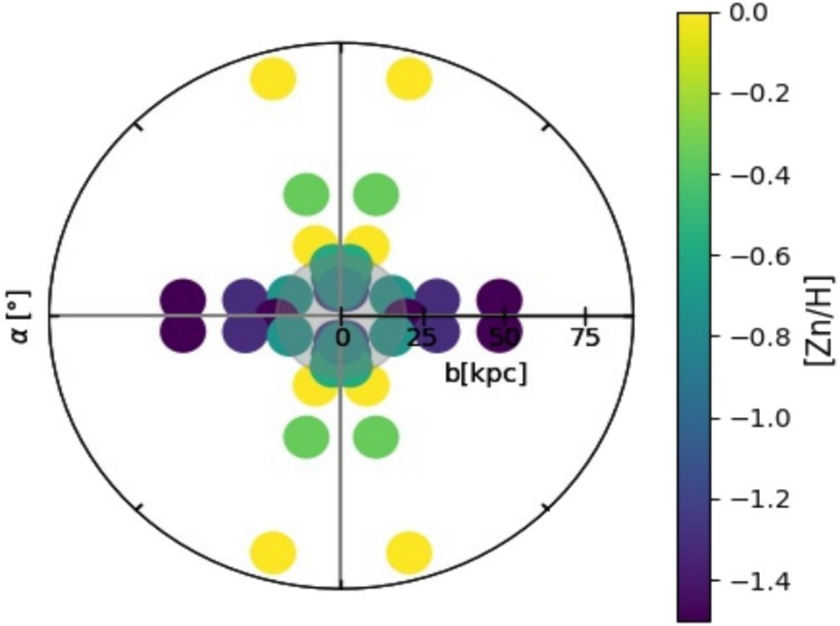
PAH M82
JWST

Bolatto+



Observations:

Wendt, NB 2021 (Megaflow)



Using depletion pattern over multiple elements (Zn,Mn, Fe, Ti,..)

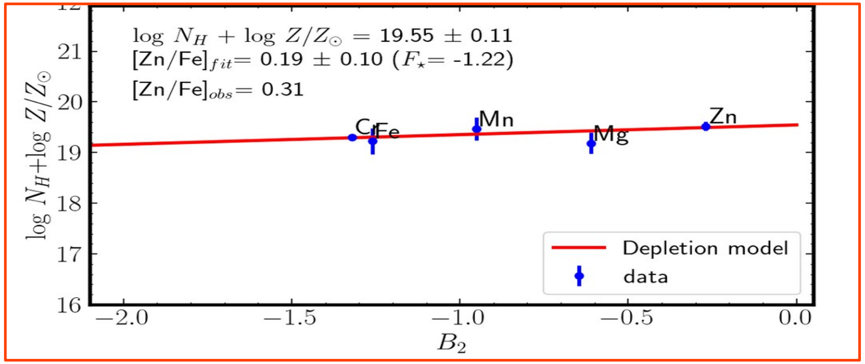
Dust depletion

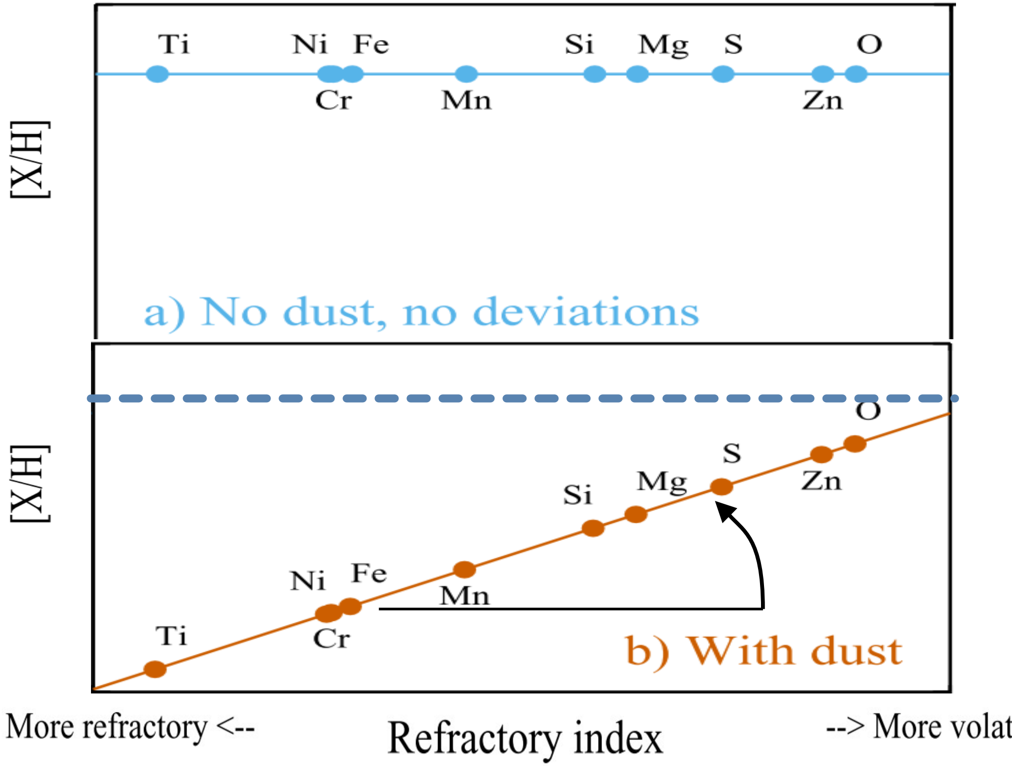
Jenkins 2009 (ISM, MW)

DeCia +16

2 parameters:

1) $[Zn/Fe]_{fit}$ depletion
2) Log N_{HI} + log Z / [M/H]





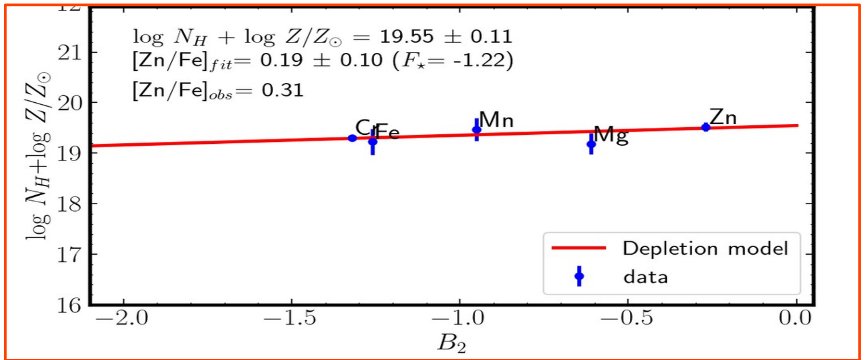
Dust depletion

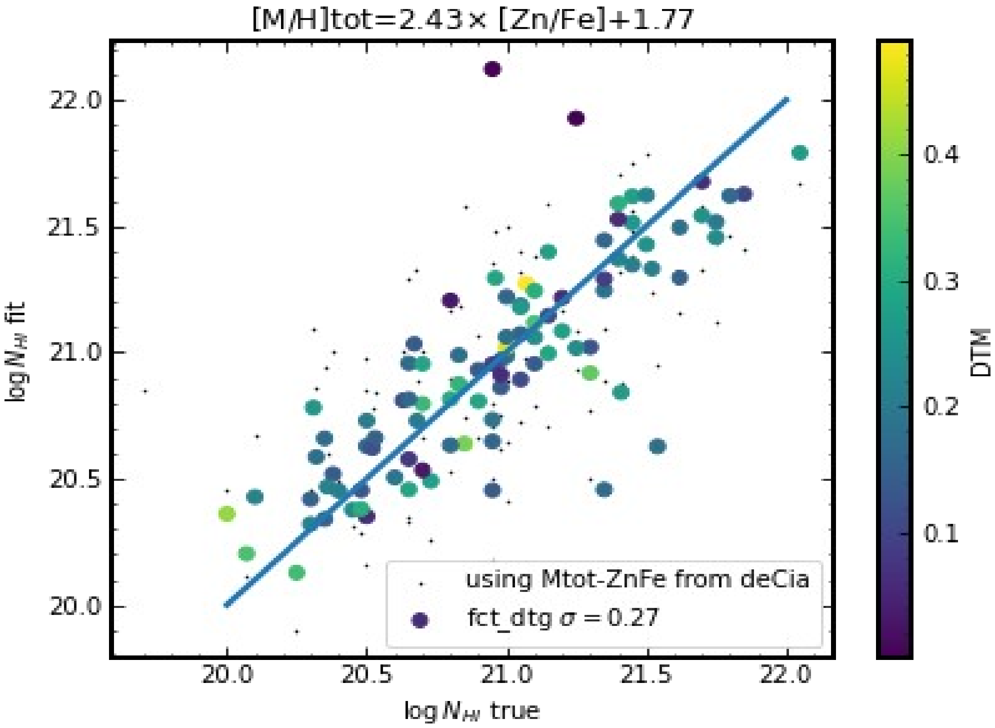
Jenkins 2009 (ISM, MW)
DeCia +16

Wendt, NB in prep.

2 parameters:

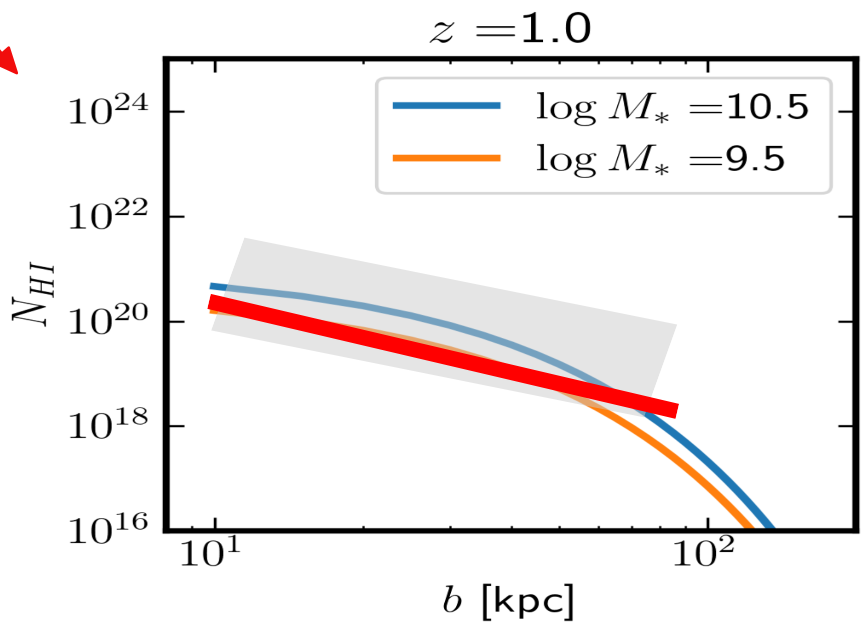
1) $[Zn/Fe]_{fit}$ depletion
2) Log N_{HI} + log Z / [M/H]

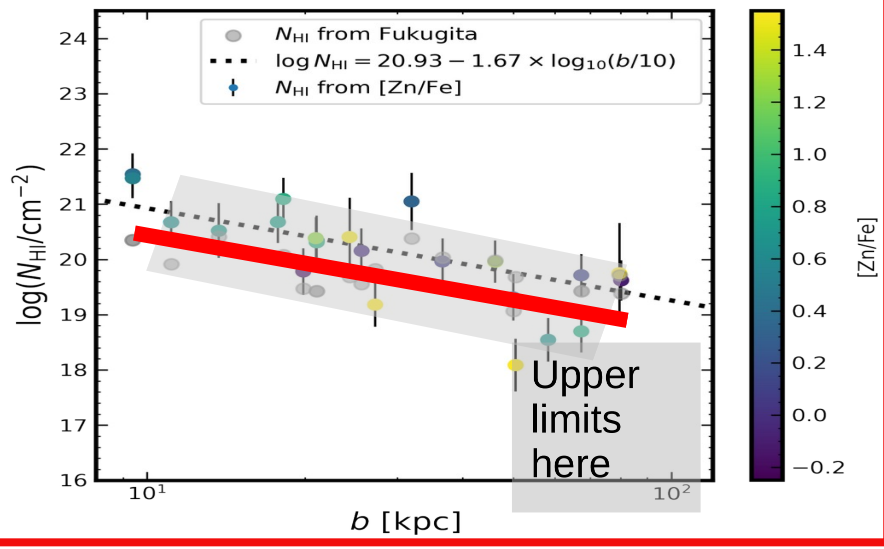




Converting MgII to HI

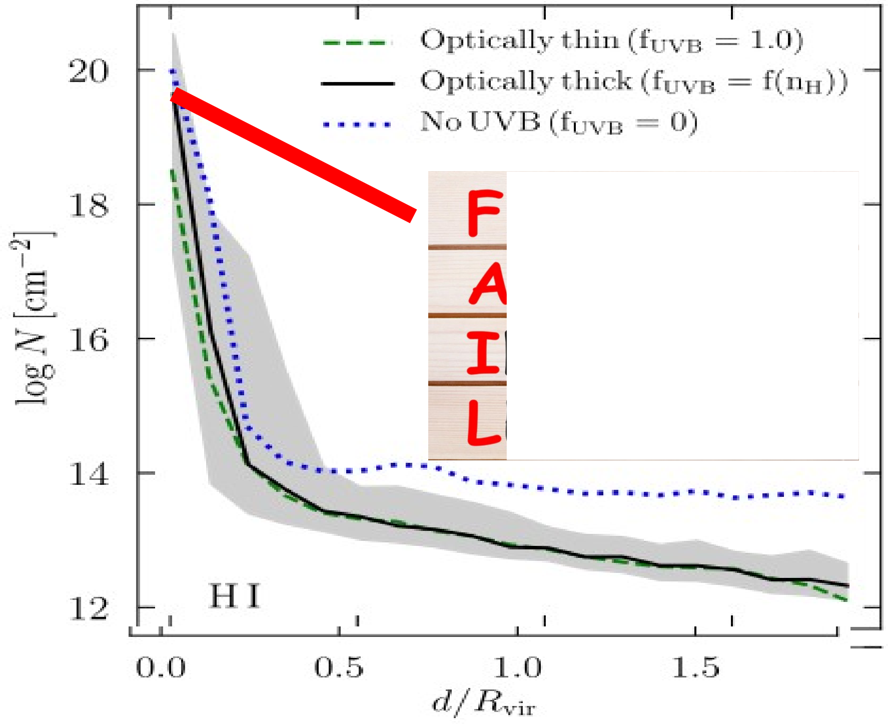
1) Use REW(MgII)--HI relation Lan, Fukugita 17
2) Use N_MgII and fixed metallicity Moretti+25
3) Use depletion pattern Jenkins 2009 / De Cia 2016



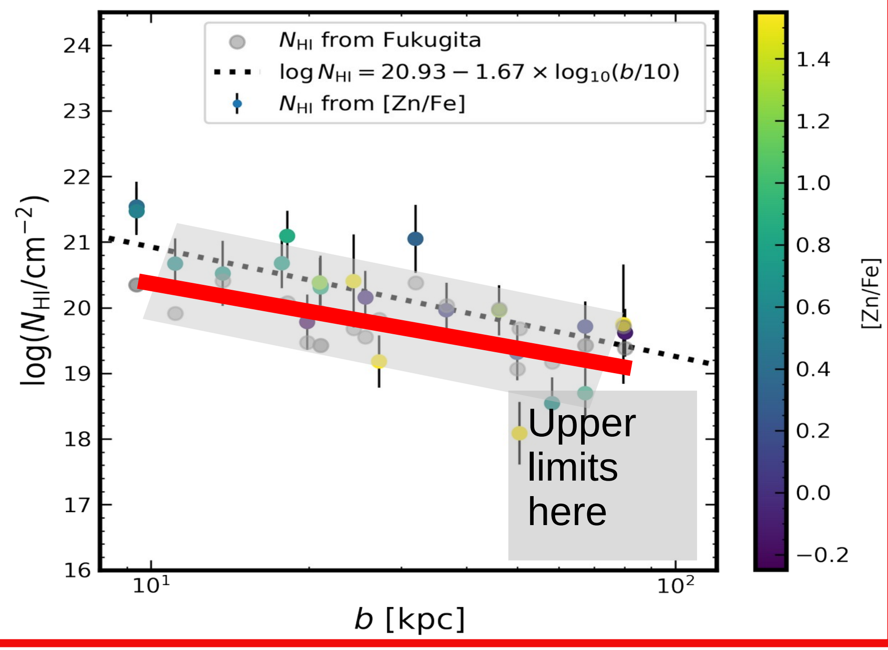


Neutral Gas density profile

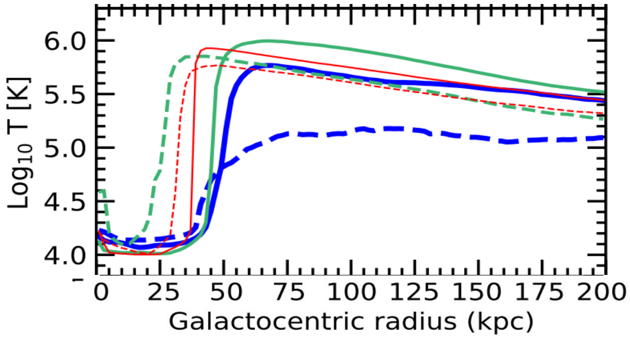
Simulations :



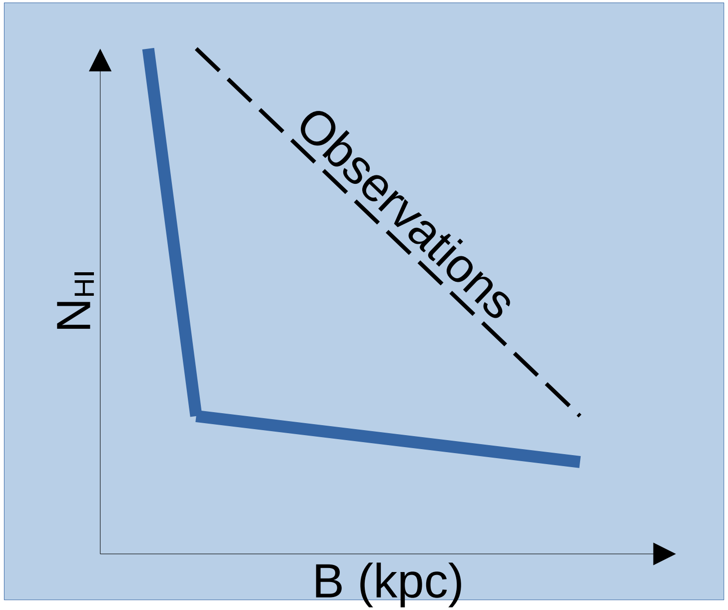
Observations:



A generic problem!



Hummels,Bryan 2013;
Liang, Kratsov+ 2016;
VandeVoort2024 (AURIGA)
Cook 24 (AURIGA)
DeFelippis21,24 (TNG50);
Oren 24 (EAGLE),
Jin 20 (FIRE2)
Lu, Keres 25 (FIRES2 & CR)
Rey+25 (Architect)



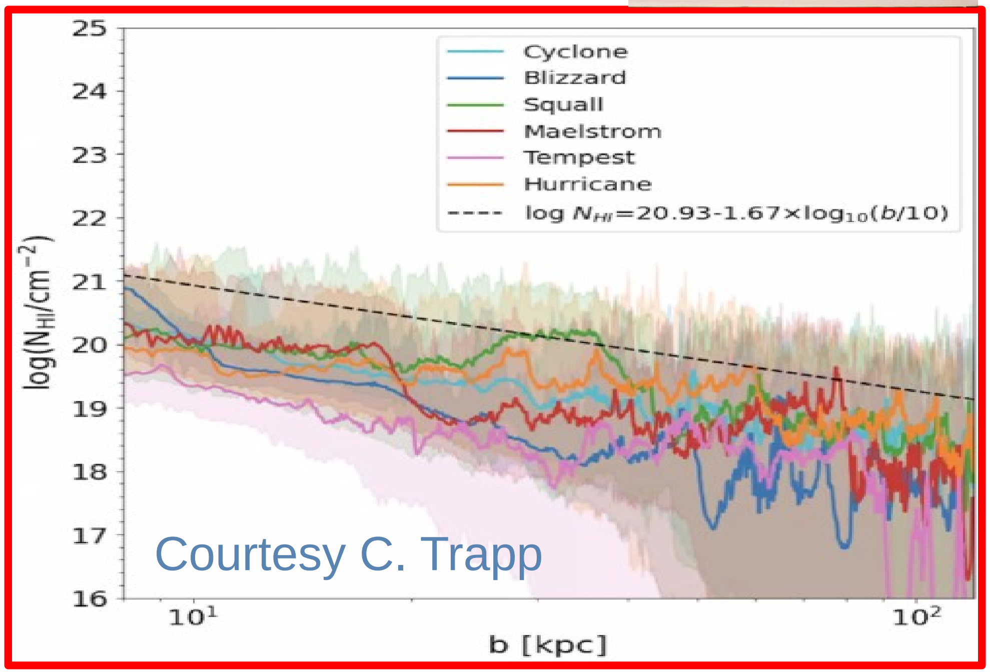
Promising simulations?

Cadiou, Katz H. (MEGATRON) - tbd
Huang, Katz N. +22 (PhEW) - tbd
Smith, Fielding+24 (Arkenstone) -tbd

Neutral Gas density profile

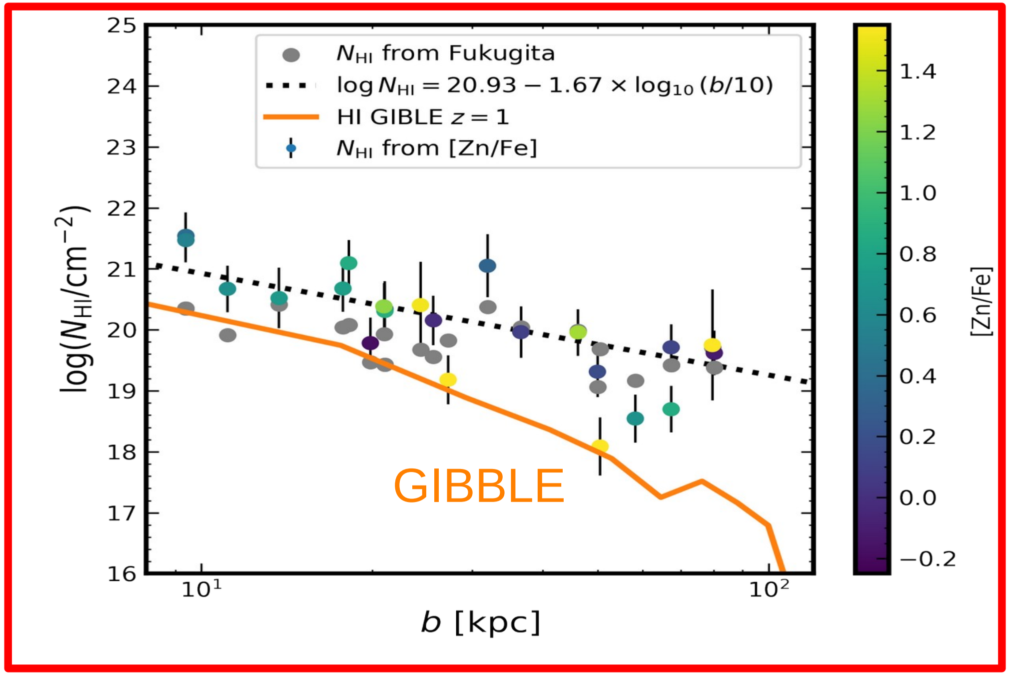
Simulations :

- FOGGIE ok



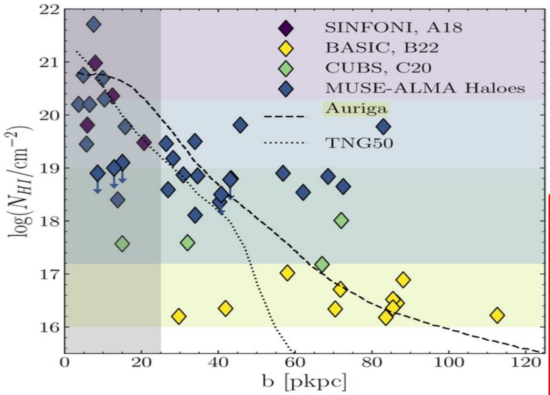
Observations:

Wendt, NB in prep.

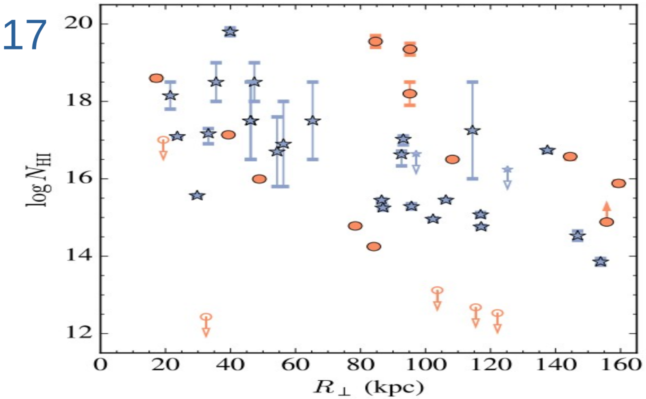


But: Not all surveys agree

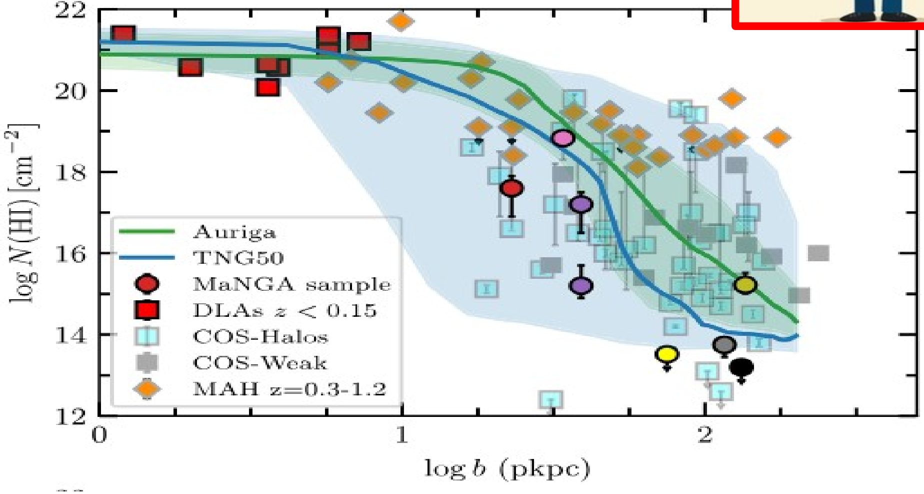
Weng+23

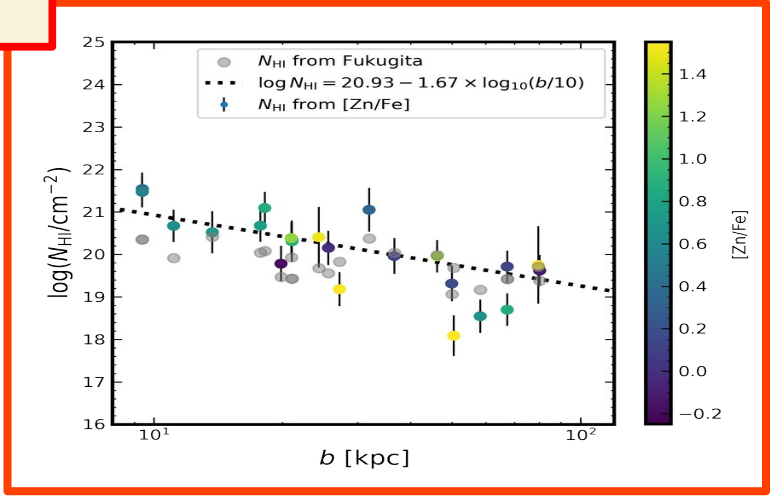


Prochaska+17



Klimenko, Kulkarni+23





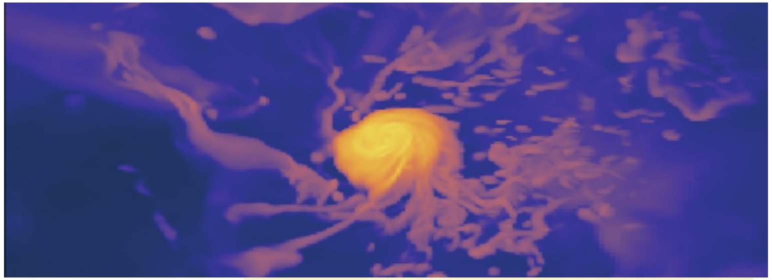
Why such disparity ?

1) The CGM is inherently messy

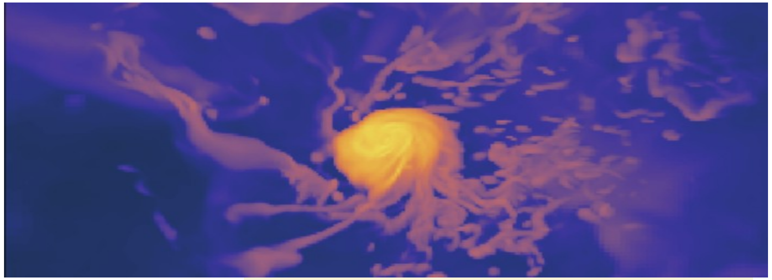
2) The data is inhomogenous/incomplete

3) There is some underlying scaling

f(M,z,alpha)



Why such disparity ?



1) The CGM is inherently messy

2) The data is inhomogenous/incomplete

Selection effects ..

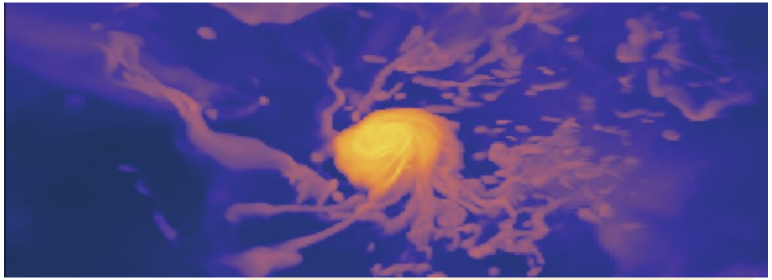
WARNING: Having MUSE data is not sufficient

3) There is some underlying scaling

f(M,z,alpha)

Why such disparity ?

1) The CGM is inherently messy



2) The data is inhomogenous/incomplete

3) There is some underlying scaling

f(M,z,alpha)

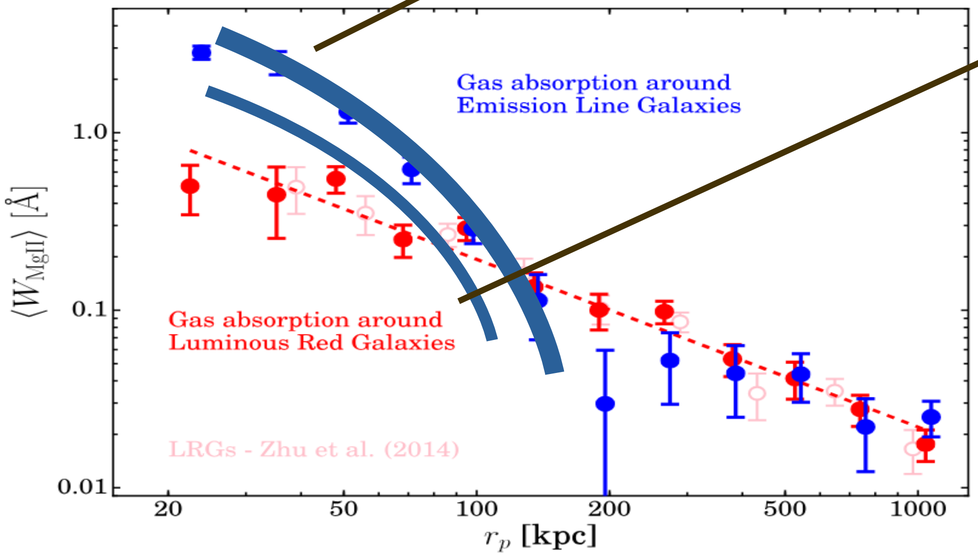
Cherrey, NB 2024 Groups
Cherrey, NB 2025 Isolated

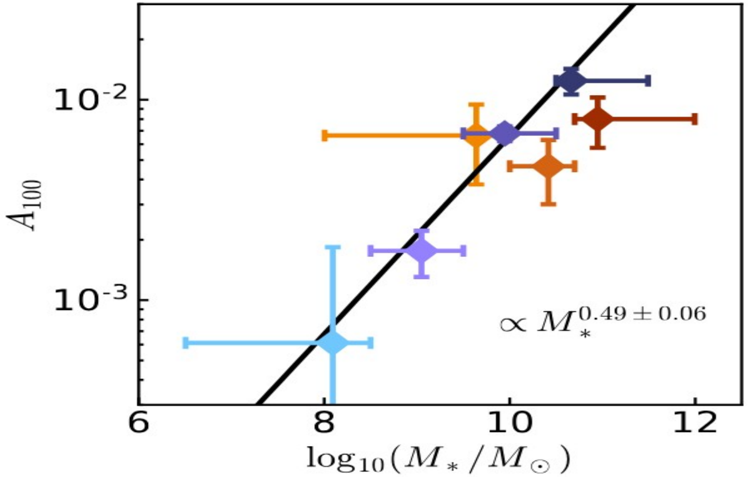
The CGM scale up w/ M*

(weak) as $M^{0.5}$ [9-10.5]

Lan, Mo 2018 **M>1e10 (15,000 eBOSS)**

Cherrey, NB 2025 **(M>1e9)**



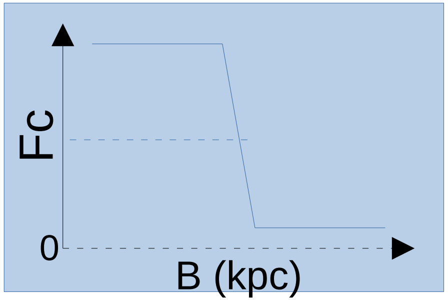


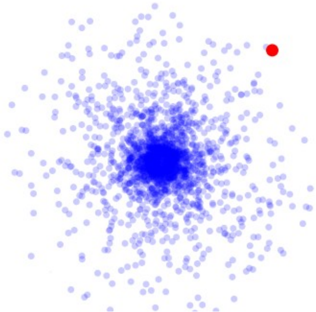
Ng, Lan TW 2025 (DESI) 900,000 CaII pairs;

Also,

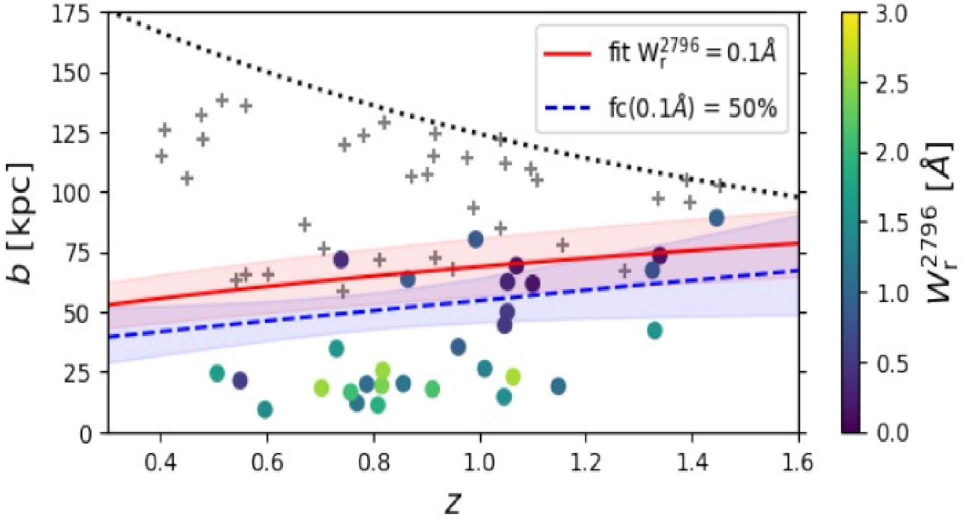
Steidel 2010; HW Chen 2010; Prochaska+2017 (COS-Halo)

The CGM size scales as $(1+z)^{1\text{--}2}$ [9-10.5]





Radius at fc=50%



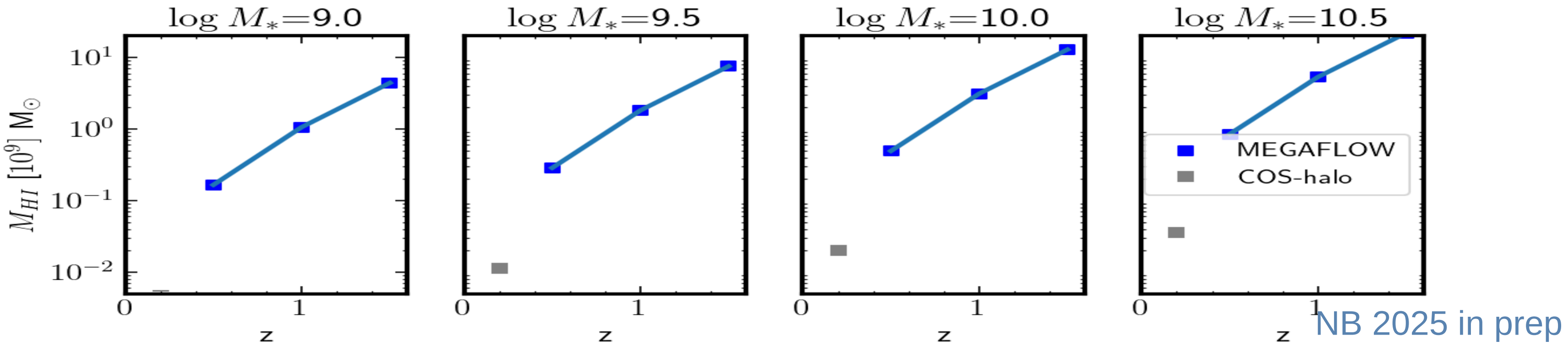
Cherrey, NB 2025 **(M>1e9) [70]**
Schroetter, NB+ 2021

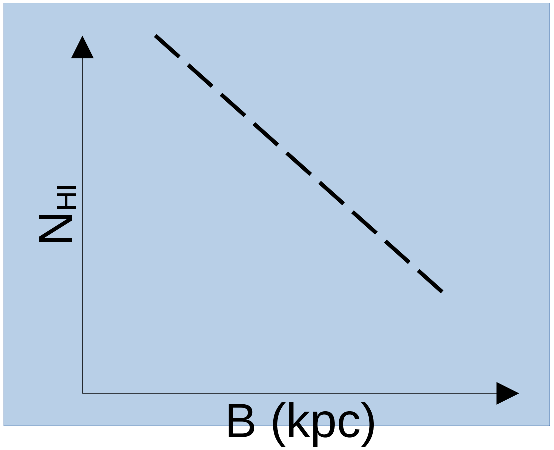
→ CGM shrinks as halos grow !

Why ?? Stern, Sternberg+2021

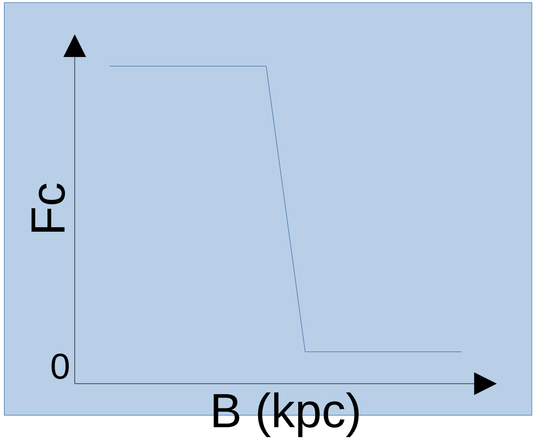
Also,
Huang+21; Dutta+20
Lan+ 2020 (SDSS eBOSS 15,000)

Putting it all together: M_{cgm}(HI)

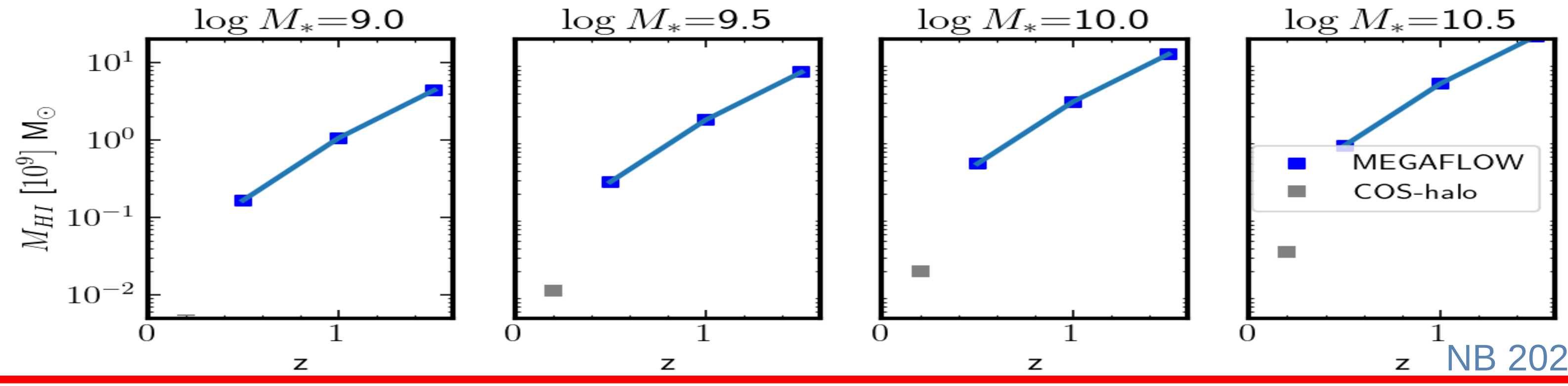


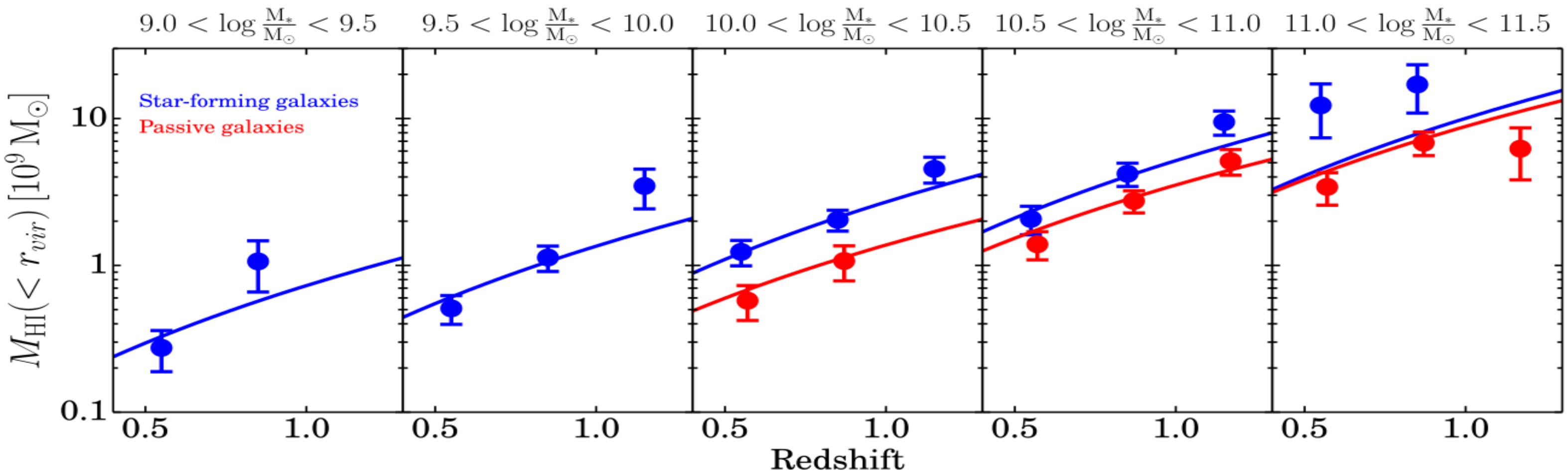


$$M_{\rm H\,I}(r_p < r_{p,\rm max}) \sim 2\pi\; m_{\rm H} \int_{20\,\rm kpc}^{r_{p,\rm max}} \hat{N}_{\rm H\,I}\, f_c\,(r_p) r_p\; dr_p,$$



Putting it all together: M_{cgm}(HI)

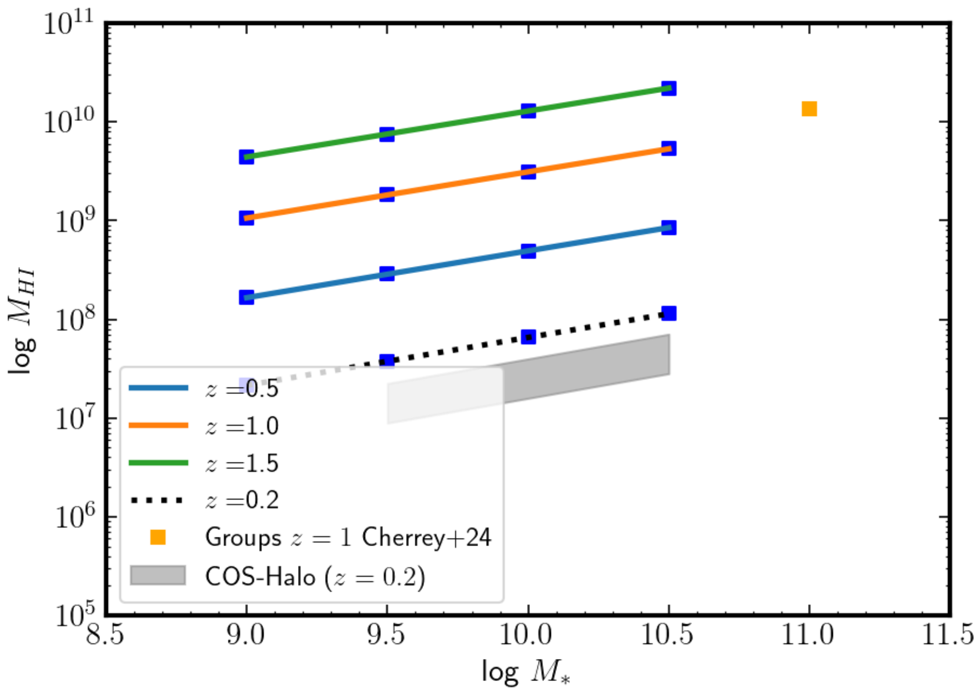


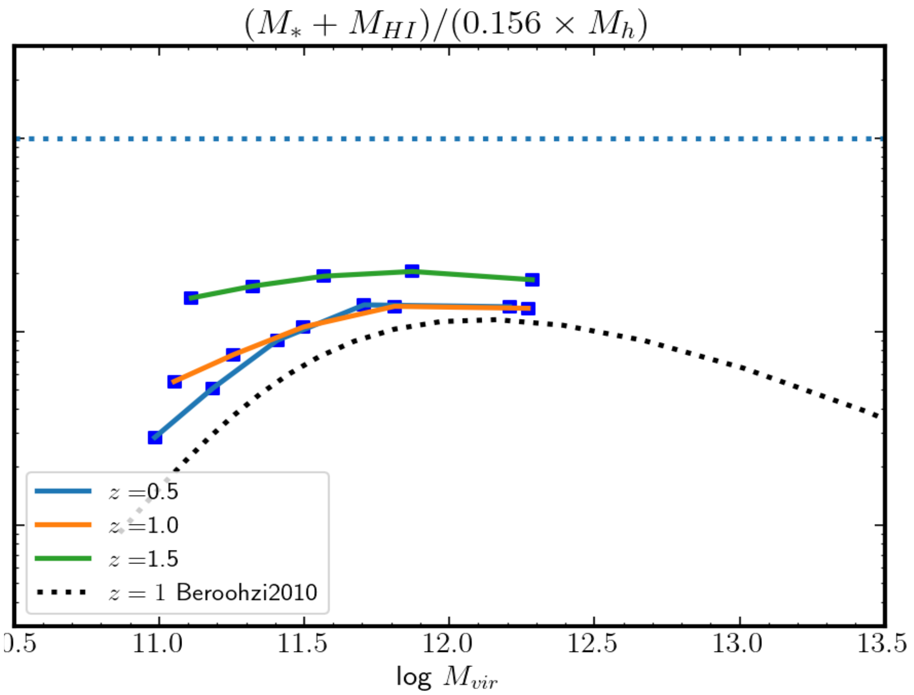


Lan 2020

Putting it all together

NB 2025 in prep.



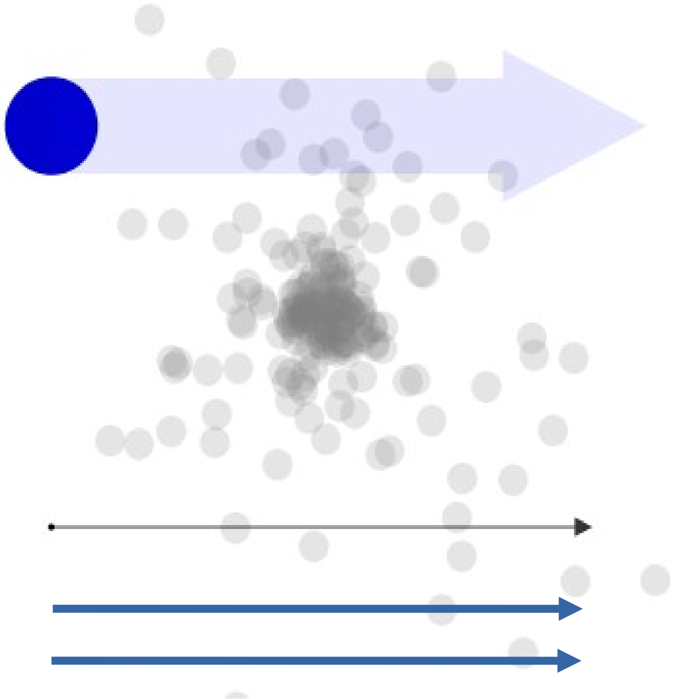


What's next: Size of CGM Clouds

Guo, Wendt in prep.

- With stacking spectra

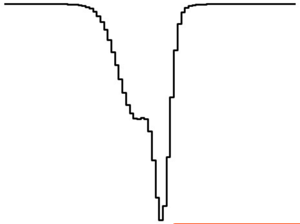
Background galaxy



Background quasar

Low f-covering

Mean ~ Median



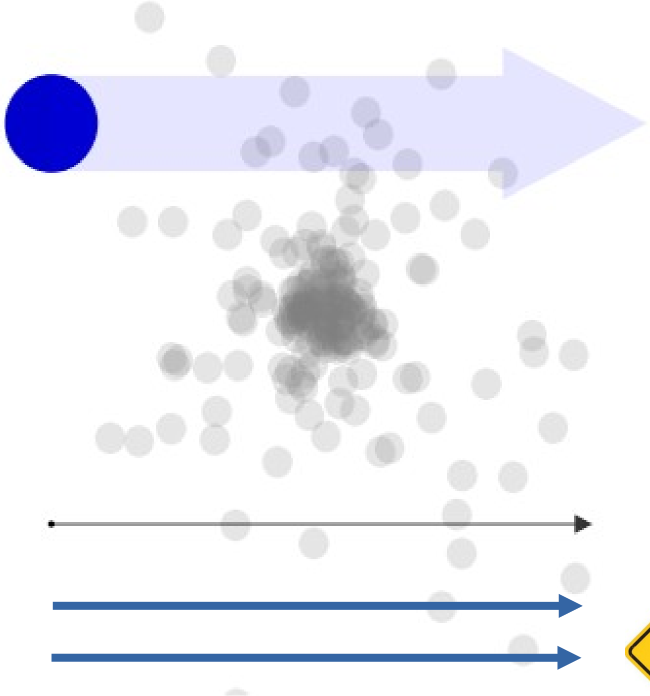
Mean != Median

What's next: Size of CGM Clouds

Guo, Wendt in prep.

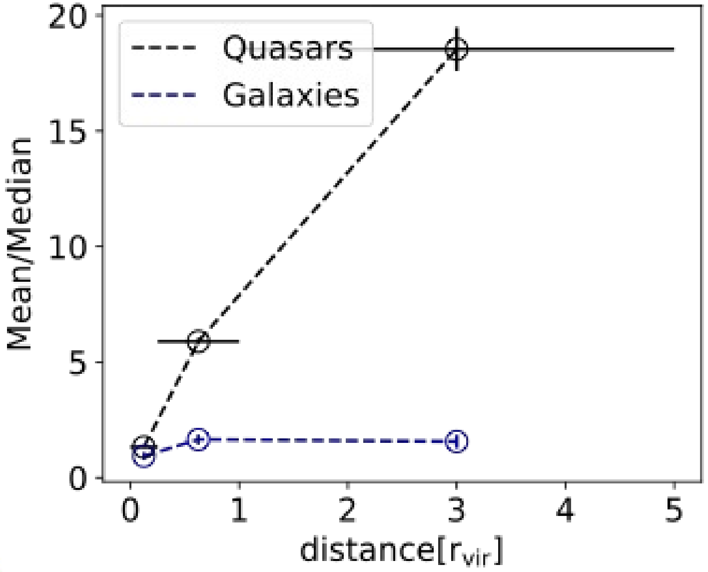
- With stacking spectra

Background galaxy

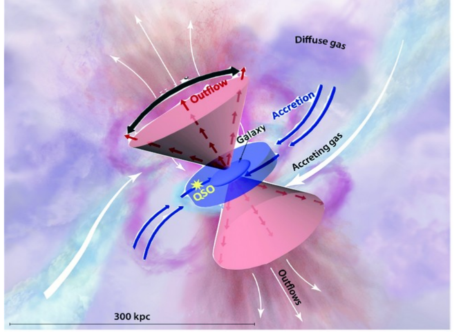


Background quasar

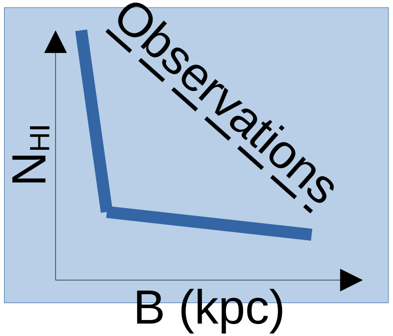
Low f-covering



Conclusions



- For SFGs 1e9<M*<3e10
  - Cool CGM is anisotropic (Metals, dust, B-field)
  - CGM uniform (~100% f-c) within 60 kpc



- Neutral CGM
  - M(HI)~1e9 **f(z,M):** ~ $(1+z)^{1-2}$ (strong) ~ $M^{0.5}$ (weak)
  - N(HI) and f-covering: challenge for simulations
- Next:
  - Size of clouds with bckg galaxies
  - Link between DM, SFH and CGM profiles ?