

# Unveiling the structure and dynamics of the cool CGM

**Andrea Afruni** - University of Florence

Main collaborators: Filippo Fraternali, Gabriele Pezzulli,  
Sebastian Lopez, Trystyn Berg, Francesco Urbina, Pratyush  
Anshul, Enrico di Teodoro, Lucia Armillotta

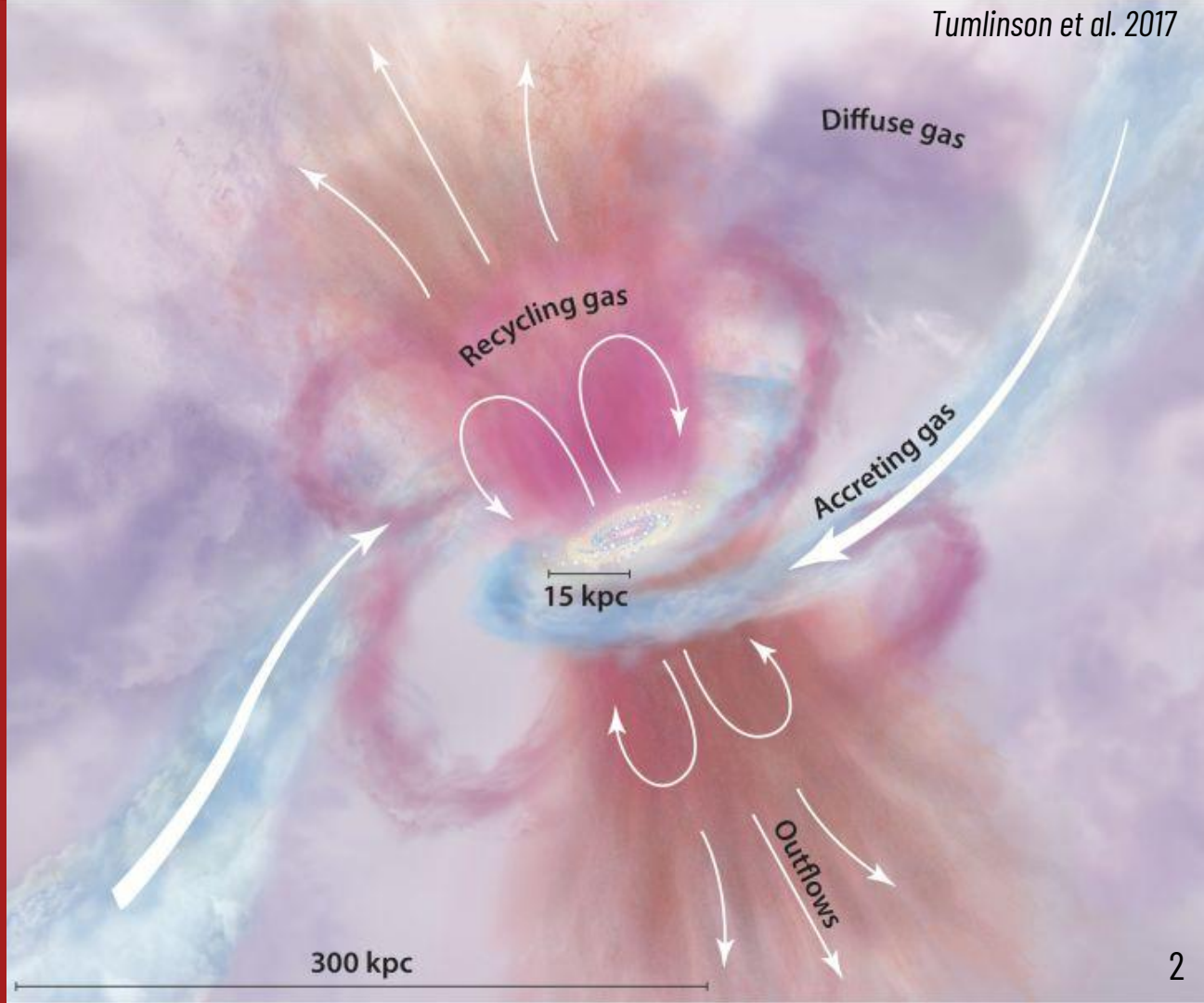


19/11/2024

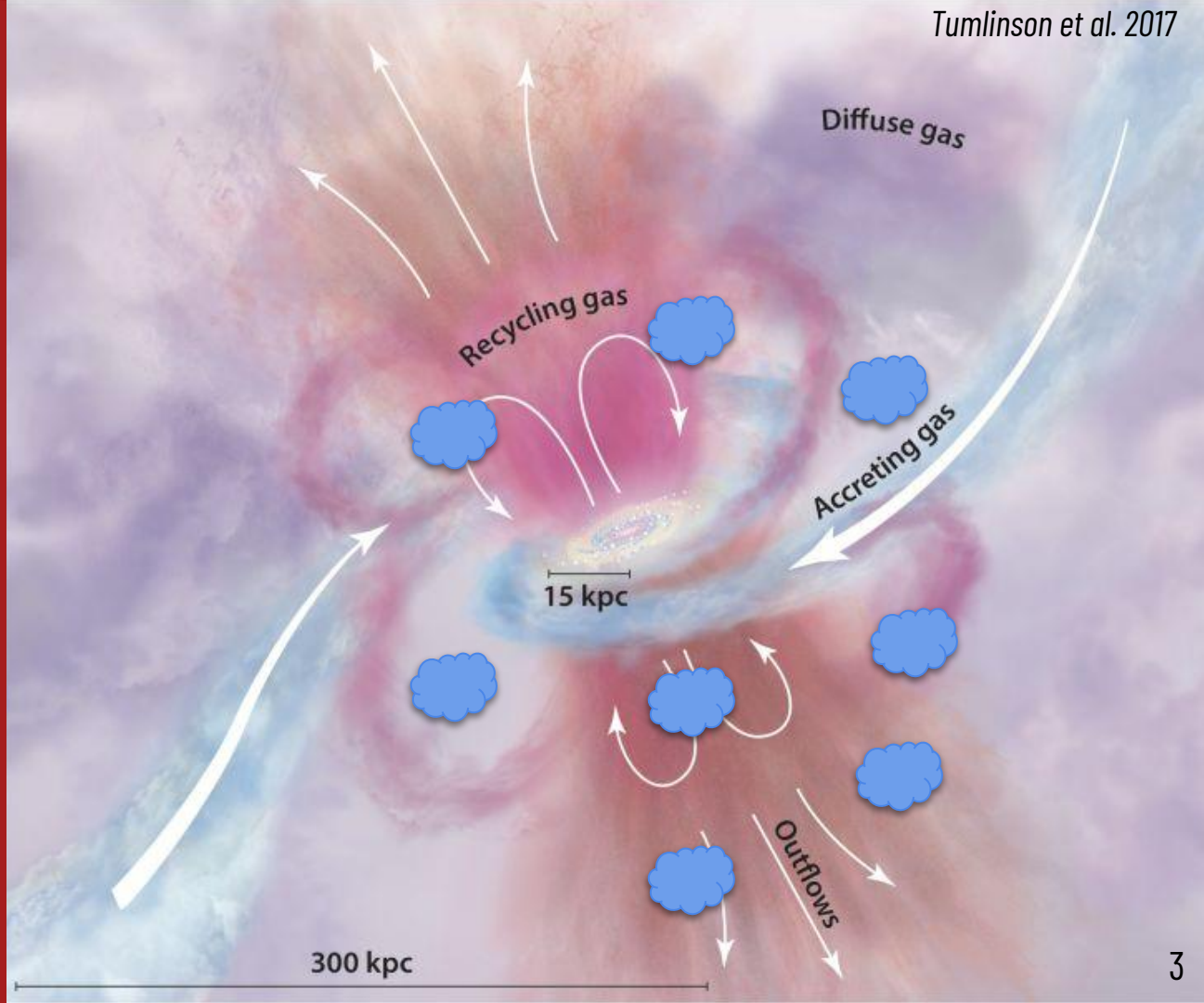
CGM-Chile 2024, Santa Cruz



# Current picture

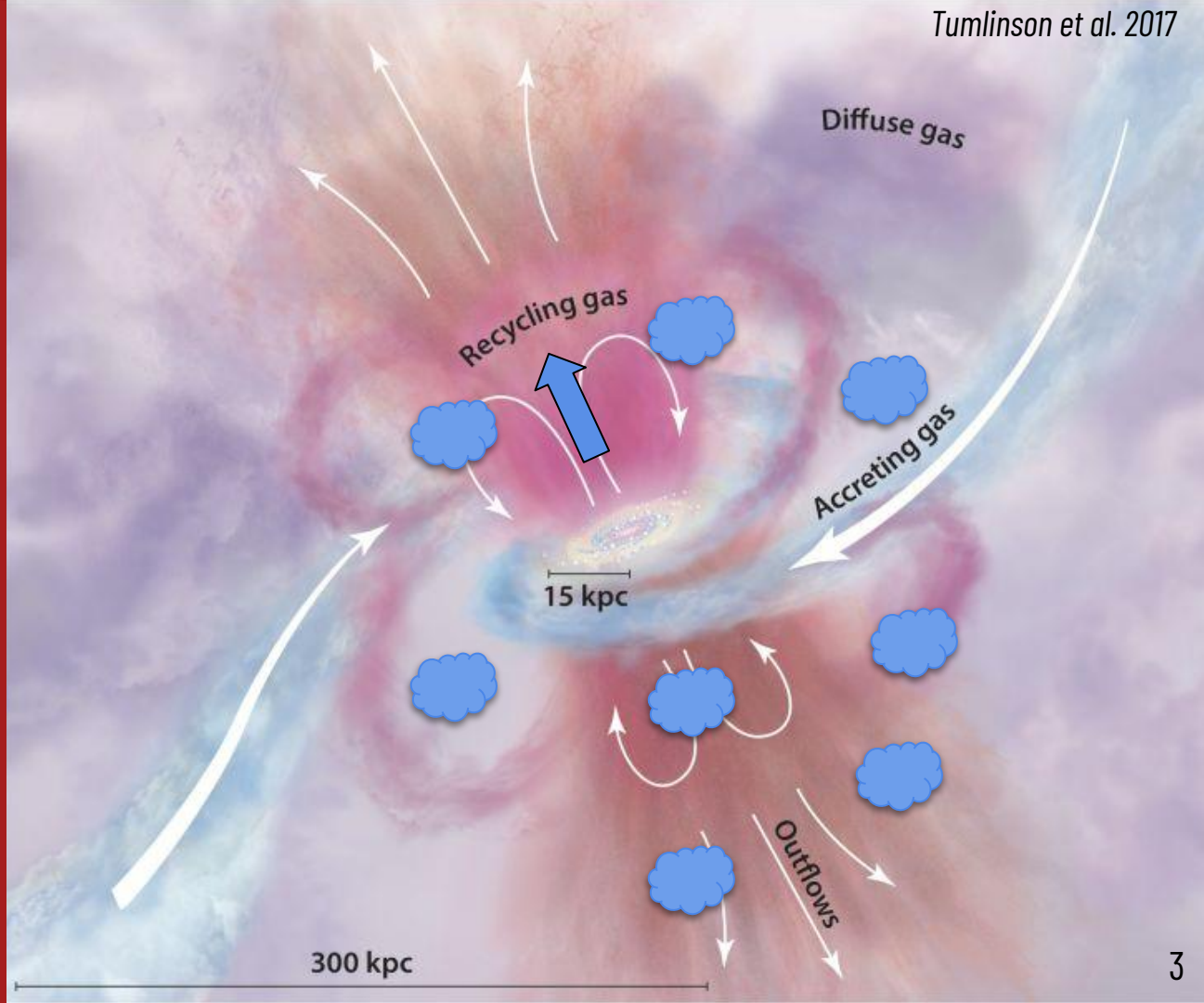


# Current picture



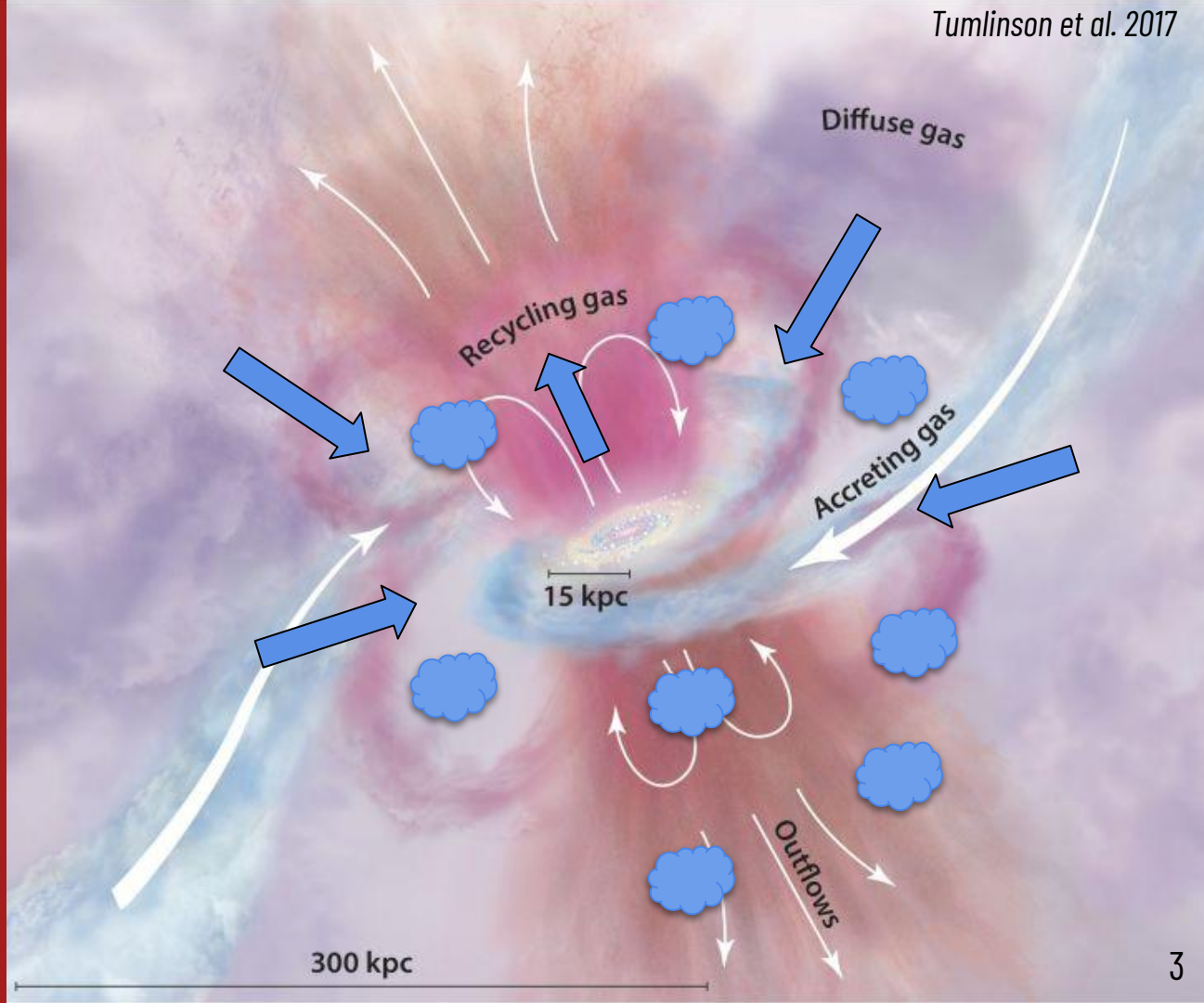


# Current picture





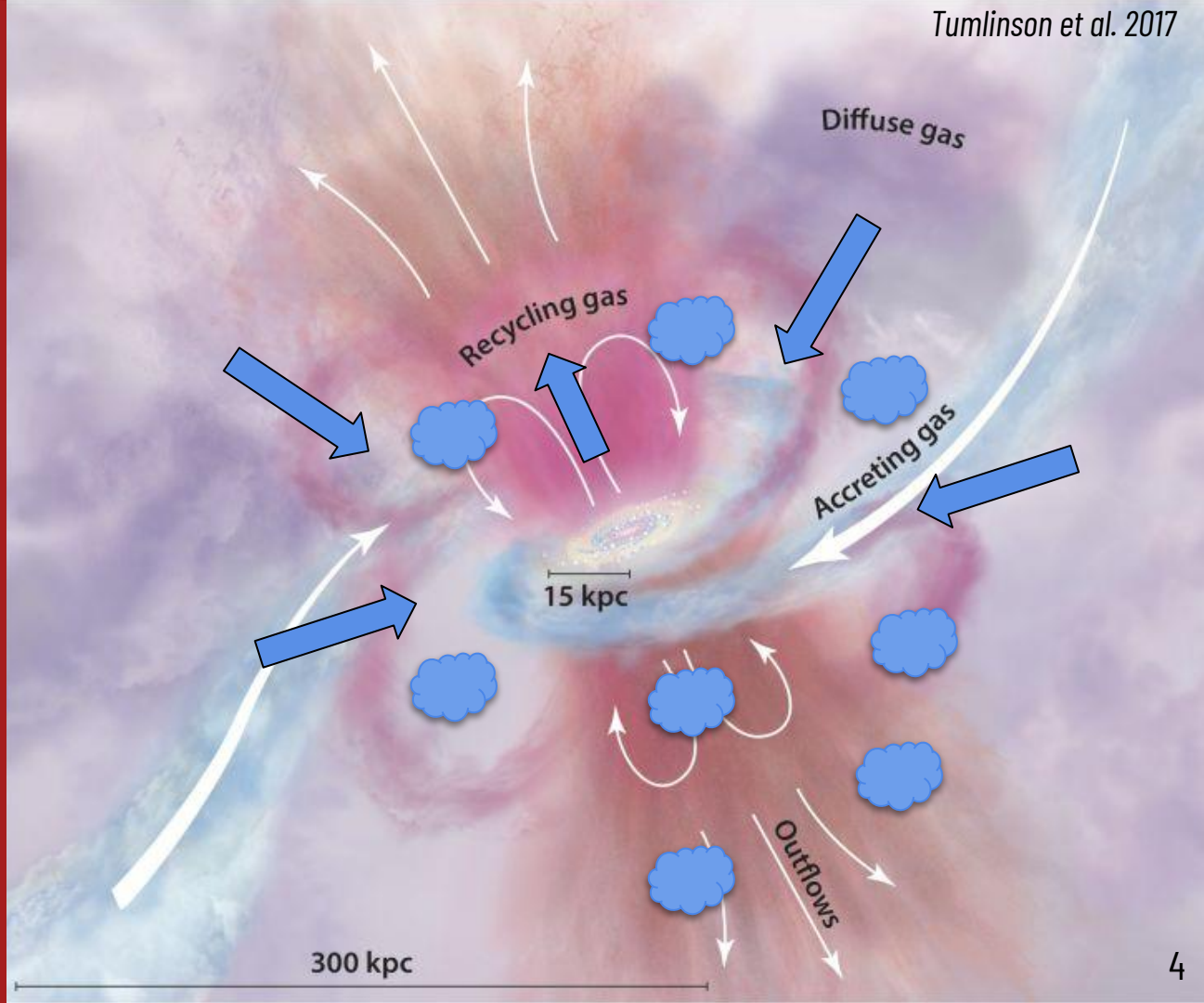
# Current picture



Spatially  
resolved  
observations

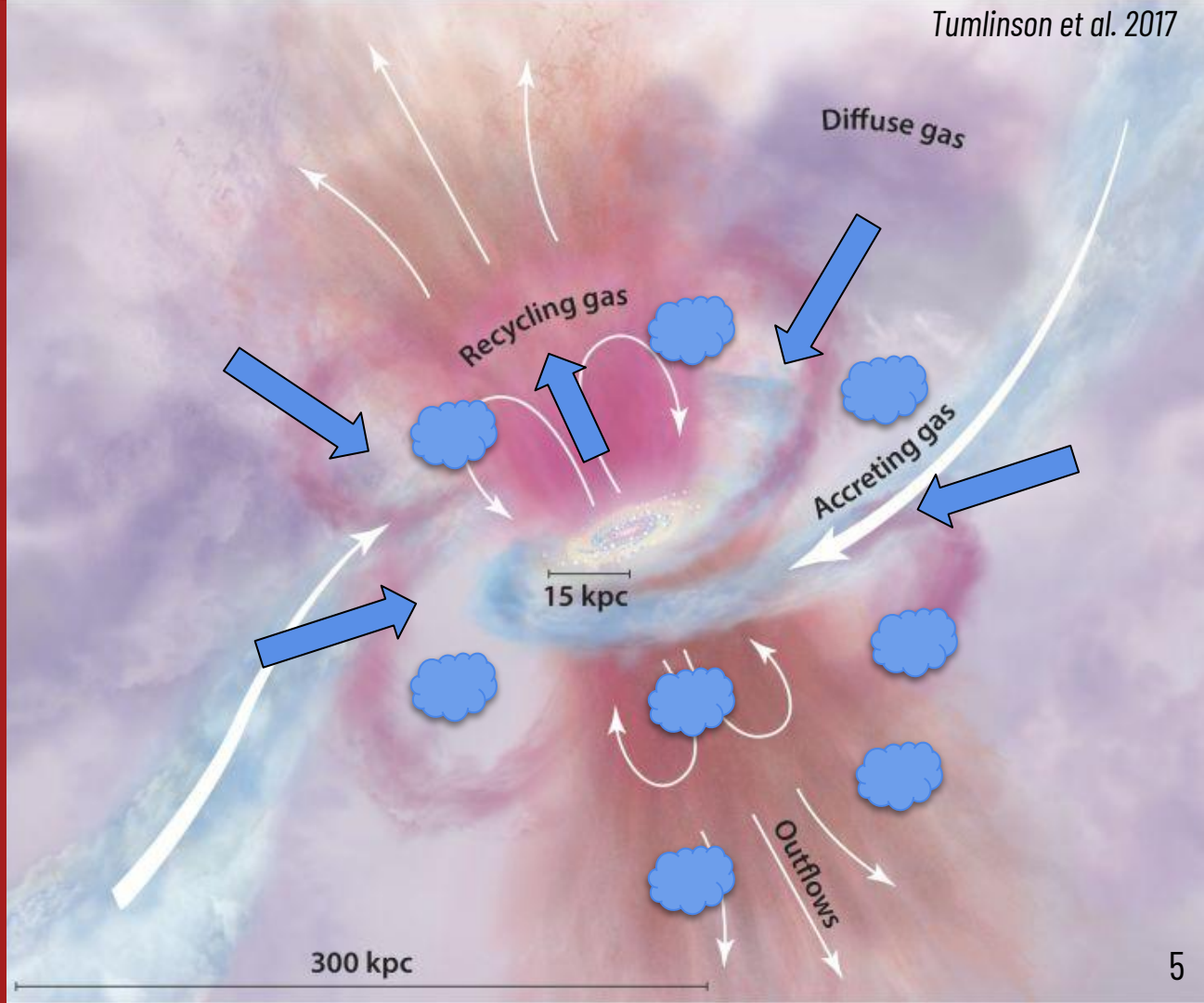


Modeling



Part I

Part II



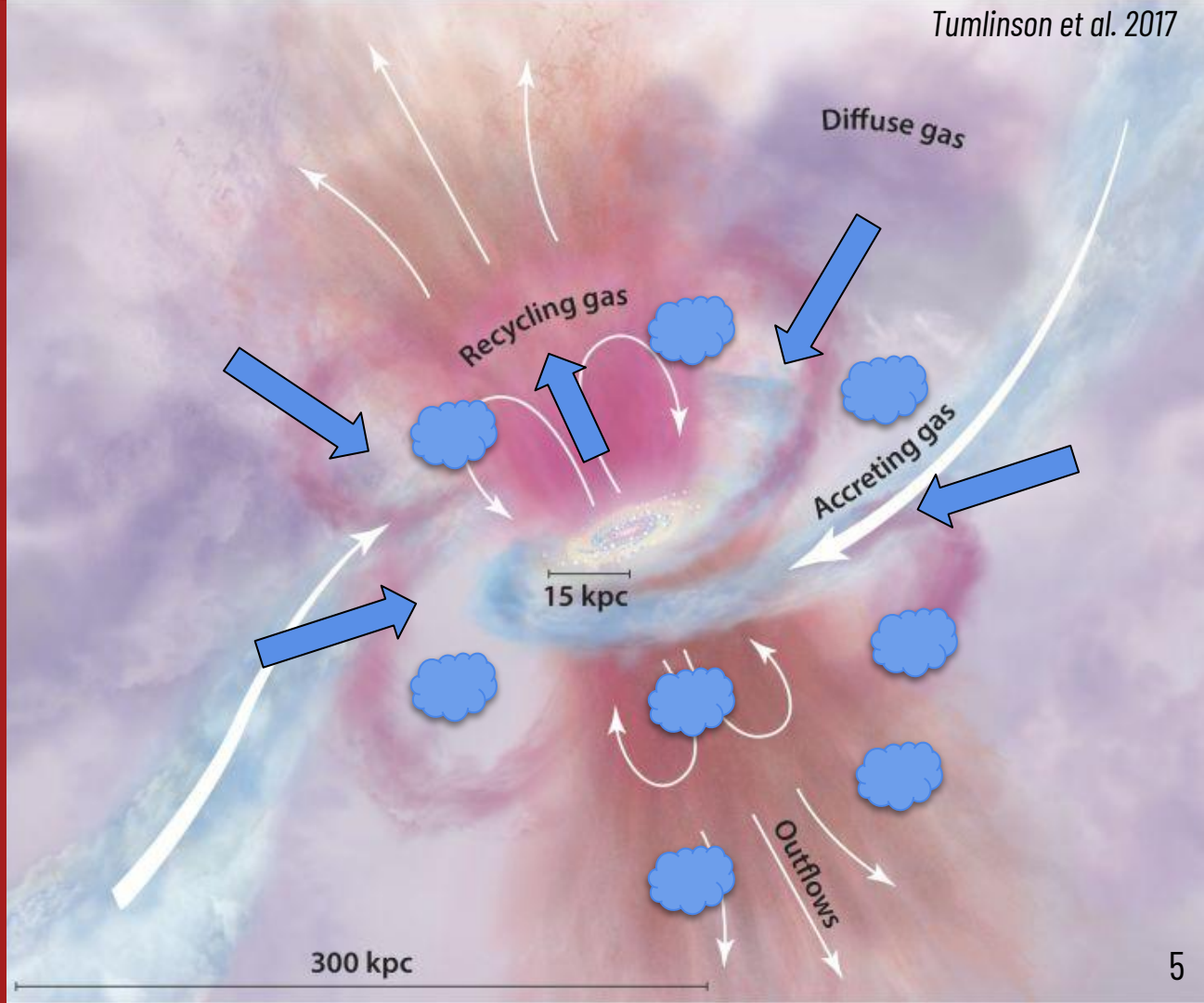


# Part I

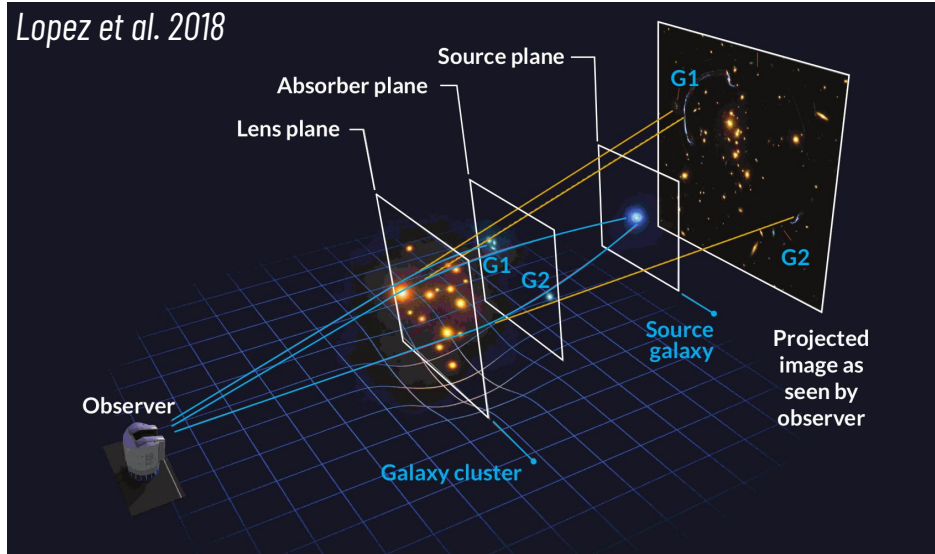
Arctomography of  
the cool CGM

# Part II

Tumlinson et al. 2017



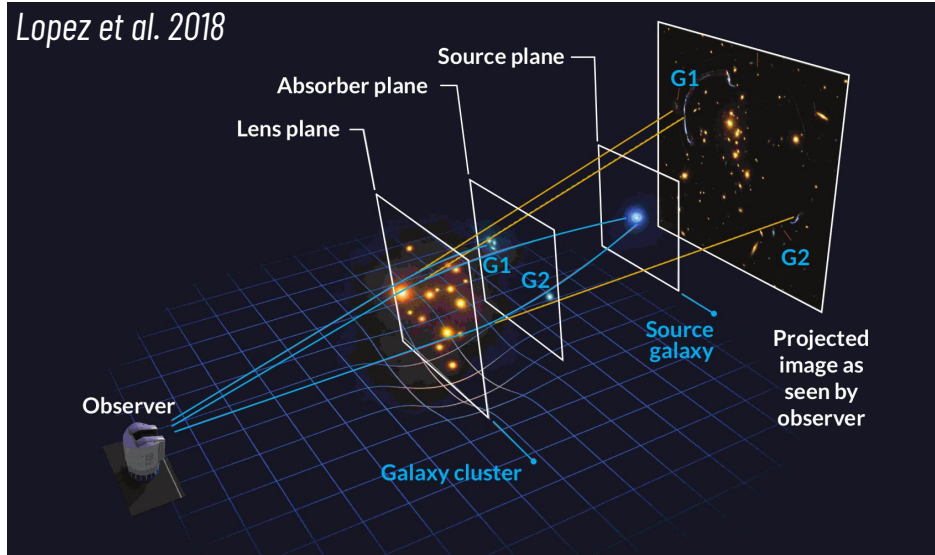
# Arc-tomographic observations



**Arctomo collaboration:** *Lopez et al. 2018, 2020;*  
*Tejos et al. 2021; Solimano et al. 2021, 2022;*  
*Fernandez-Figueroa et al. 2022, Catan et al. 2024,*  
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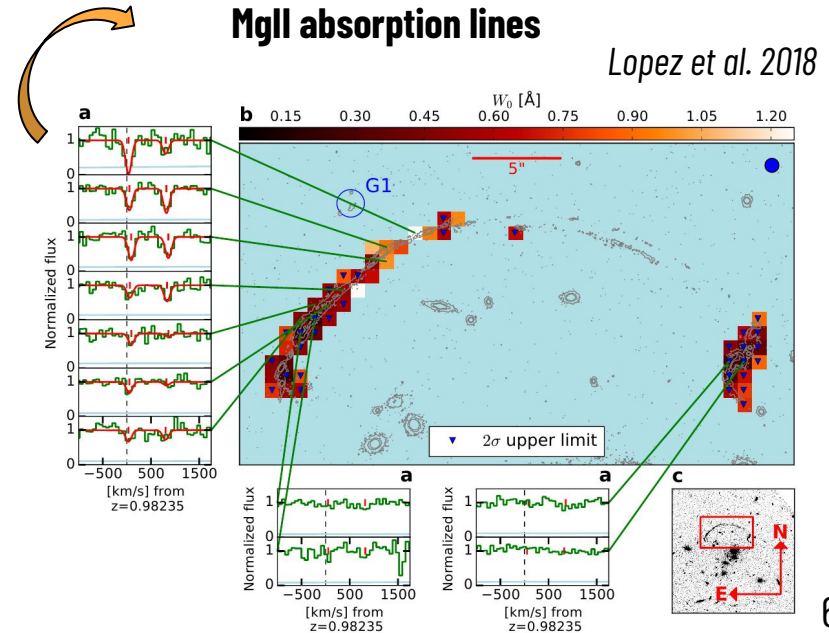
*See also Mortensen et al. 2021, Bordoloi et al. 2022*

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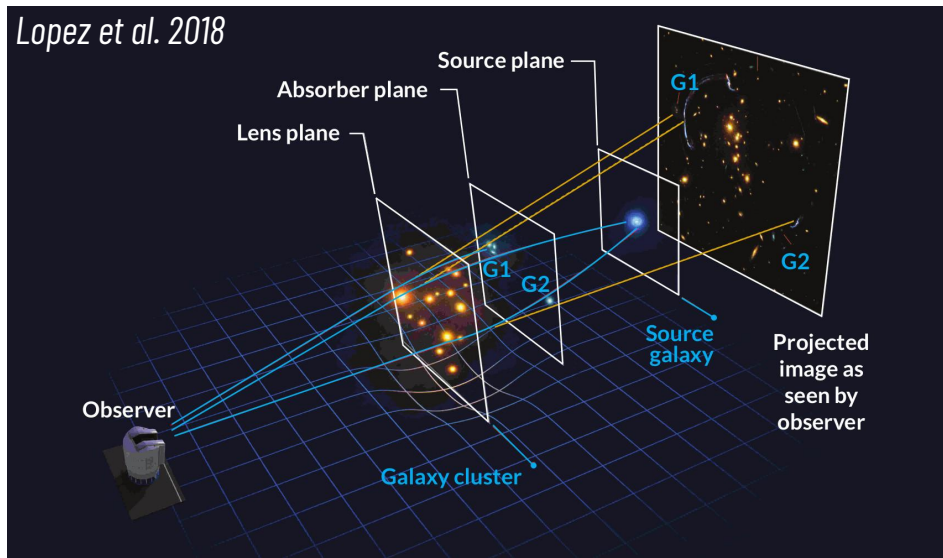
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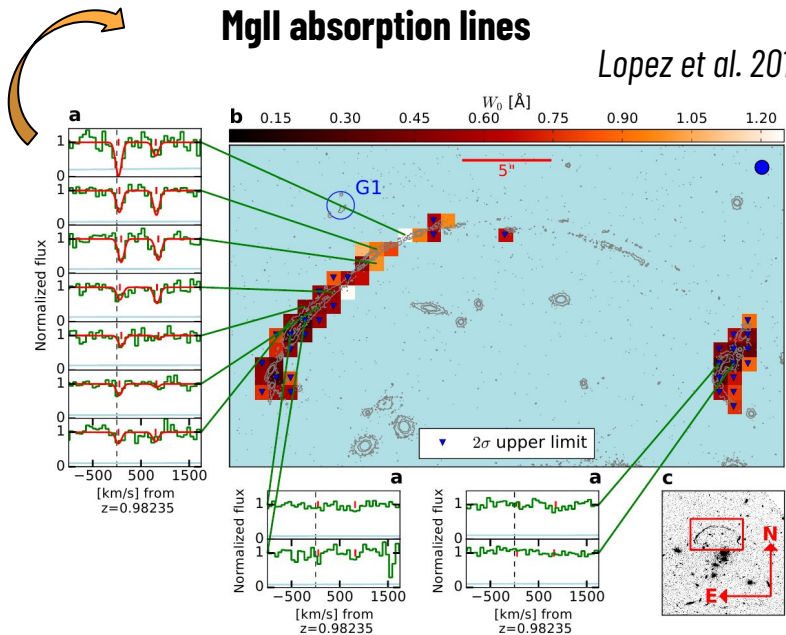
# Arc-tomographic observations



**Multiple and extended sources  
(MUSE spaxels) around single  
galaxies!**

**MgII absorption lines**

*Lopez et al. 2018*

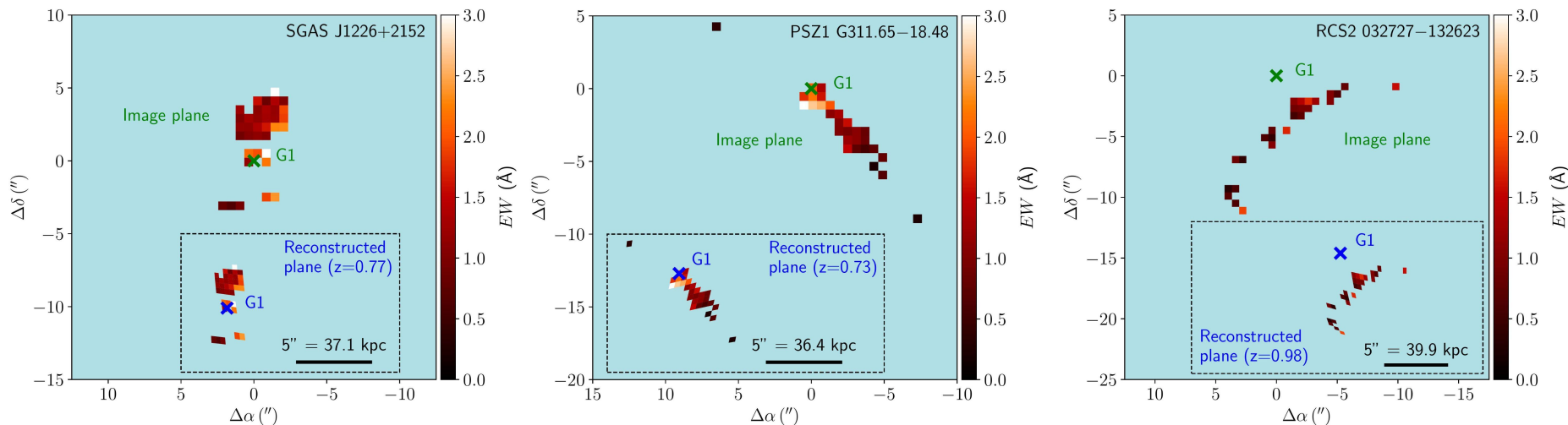


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# Data - MUSE fields

Afruni et al. 2023b

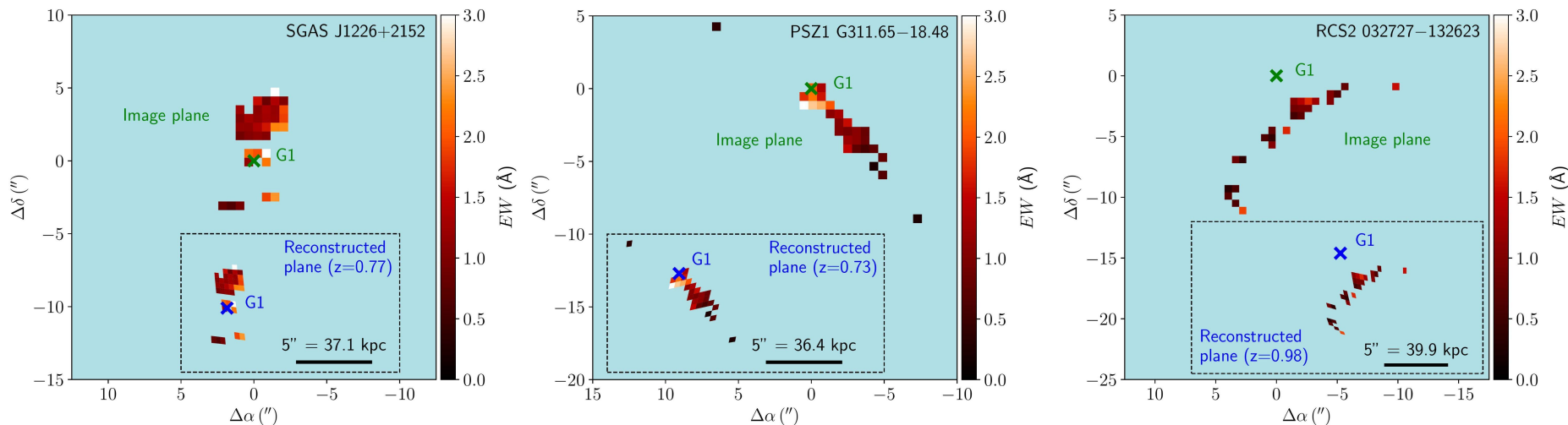


Sample of 3 galaxies (G1) at  $z \lesssim 1$ , with  $M_* \sim 10^{10} M_\odot$  and  $\text{SFR} \sim 1 M_\odot \text{ yr}^{-1}$

**Extended structure of the  
cool CGM**

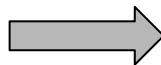
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**Extended structure of the cool CGM**



**Coherence scale**  $\equiv$  scale of variation MgII EW  
(e.g. Rubin et al. 2018)

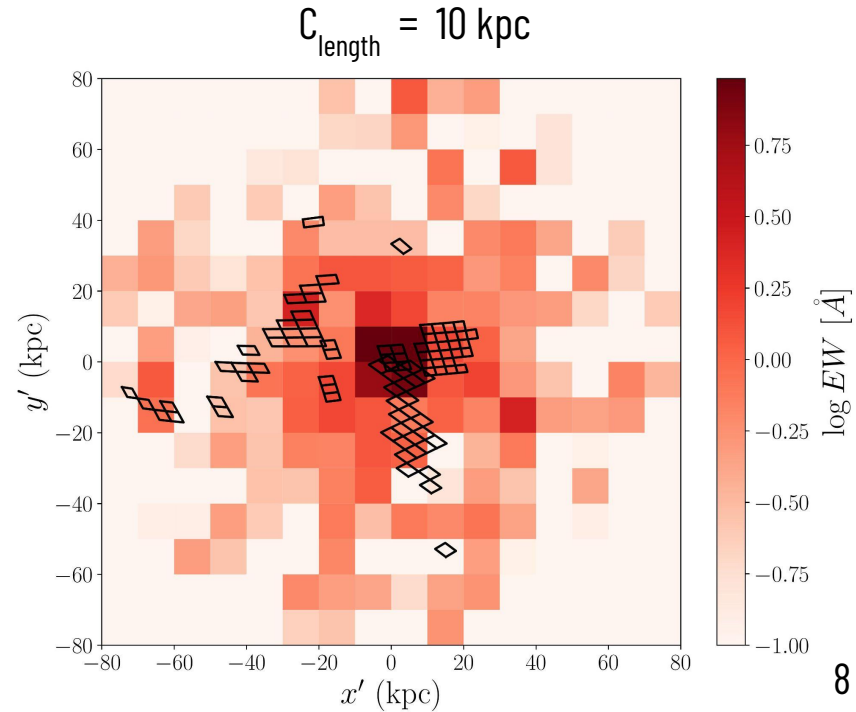
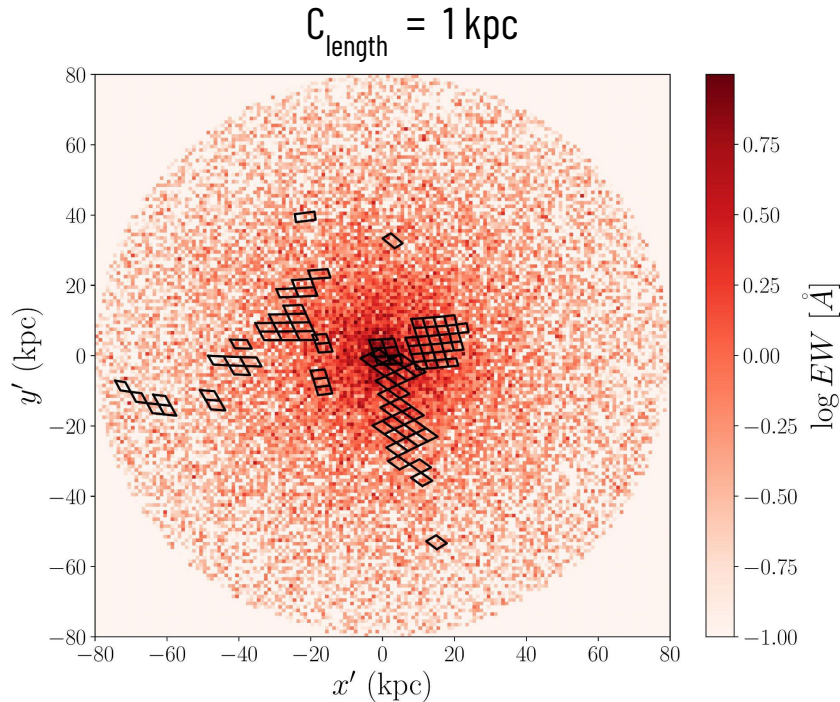


# Coherence scale of the cool CGM

Afruni et al. 2023b

## Empirical models of the cool CGM

(based on Huang et al. 2021)

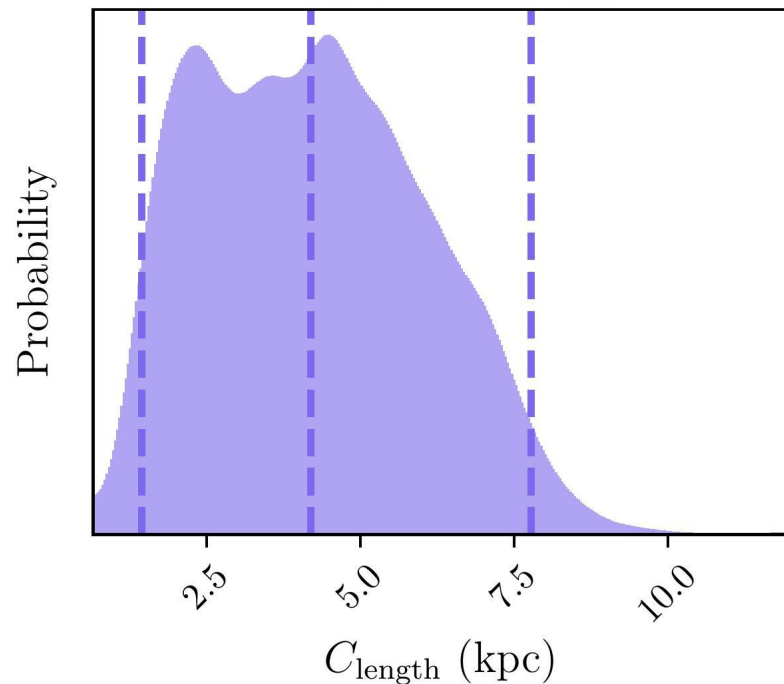


# Coherence scale of the cool CGM

Afruni et al. 2023b

Posterior distribution of  $C_{\text{length}}$

$$C_{\text{length}}/\text{kpc} = 4.2^{+3.6}_{-2.8}$$



**$1.5 \text{ kpc} \leq \text{Coherence scale} \leq 8 \text{ kpc}$**

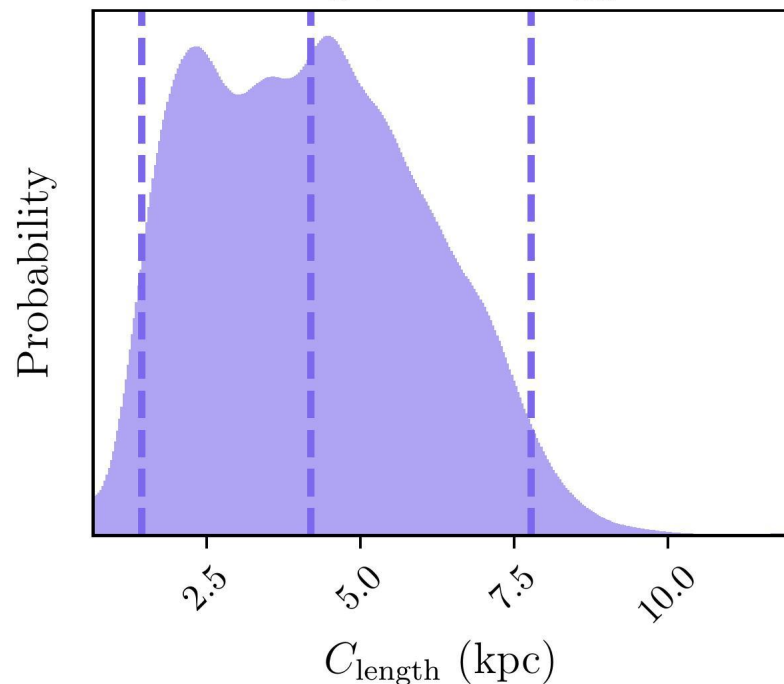
Consistent with previous results (e.g. Rauch et al. 2002, Chen et al. 2014, Rubin et al 2018, Okoshi et al. 2021), but  
**unprecedented accuracy!**

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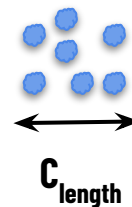


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We do not resolve **single** clouds

**Size of cool CGM  
'complexes'**



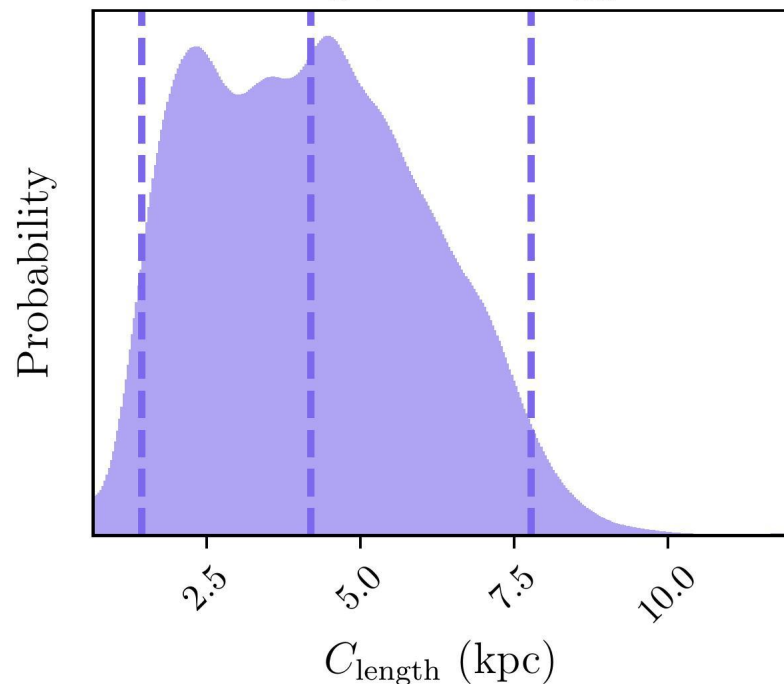


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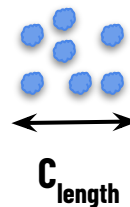


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Constraint for CGM dynamical  
models and simulations

**See Francisco Urbina's  
talk on Thursday!**

# Arc-tomography of DLAs

*Berg, Afruni et al. 2024,  
accepted for publication  
on A&A*

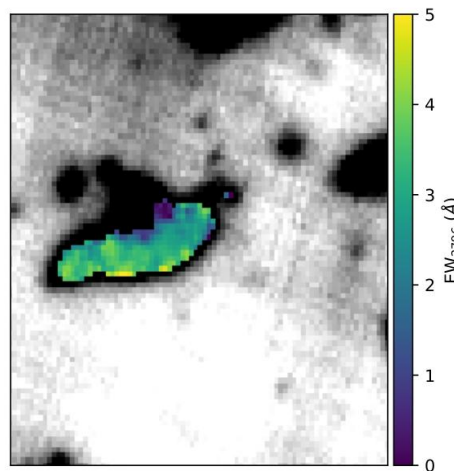
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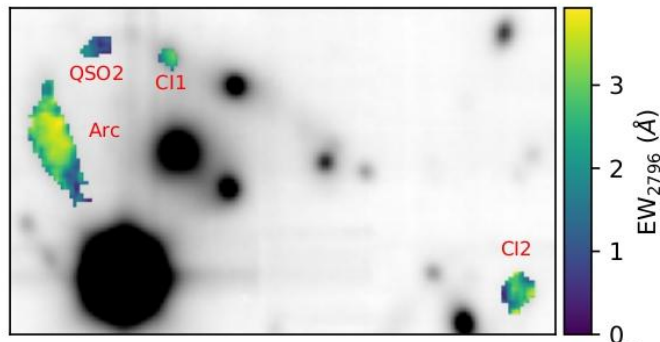
Strong MgII absorption  
( $EW \gtrsim 2 \text{ \AA}$ ) at  $z \sim 1-2$



Signature of **extended** Damped Ly $\alpha$   
systems (DLAs,  $N_{\text{H I}} > 2 \times 10^{20} \text{ cm}^{-2}$ )?



J1527 field  $z = 2.056$



J0033 field  $z = 1.167$

# Arc-tomography of DLAs

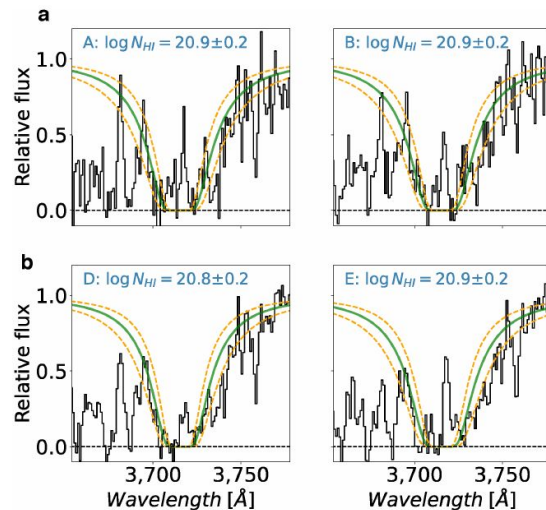
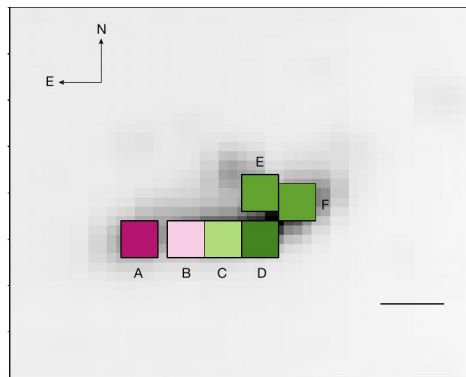
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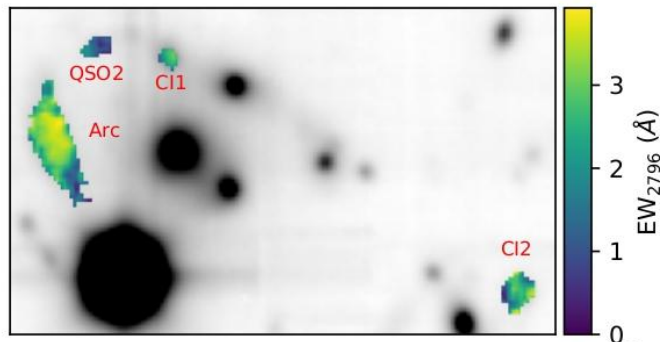


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Bordoloi et al. 2022



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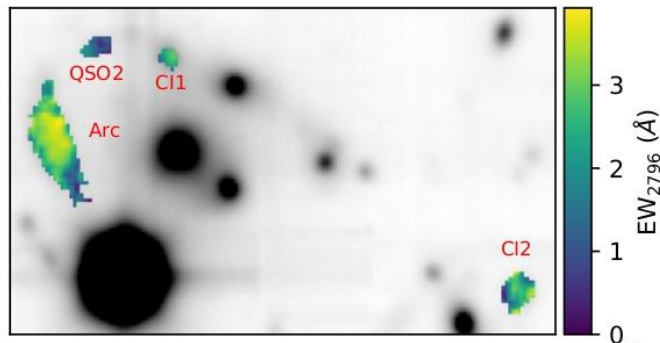
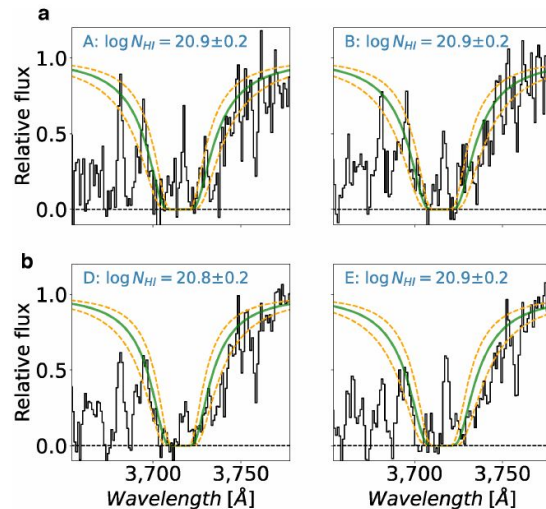
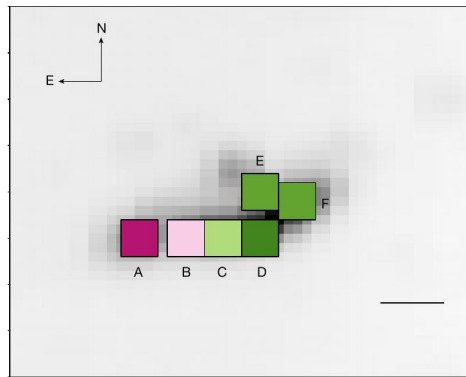
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Bordoloi et al. 2022



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**Also likely a DLA!**

$\log N_{\text{HI}} \sim 20.6 [\text{cm}^{-2}]$

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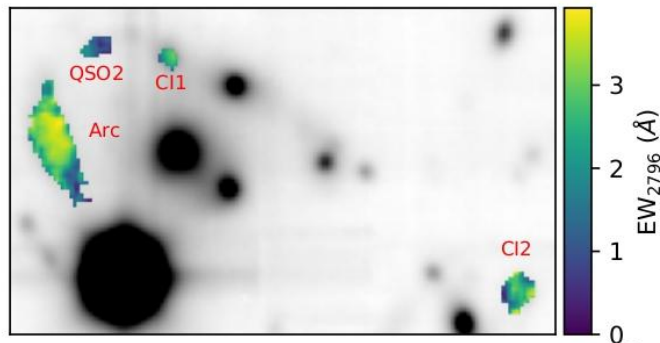
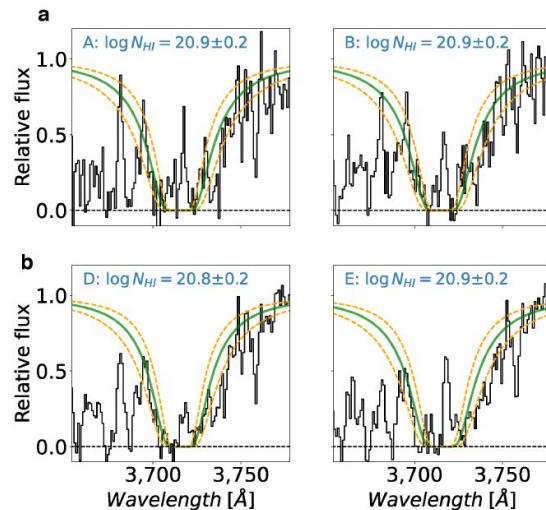
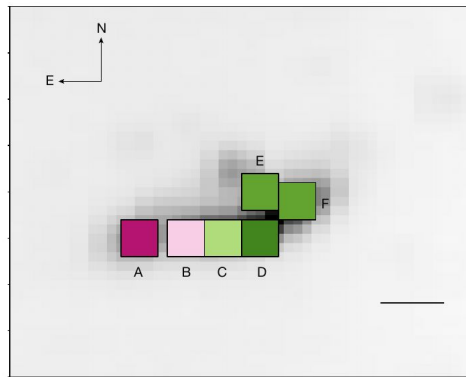
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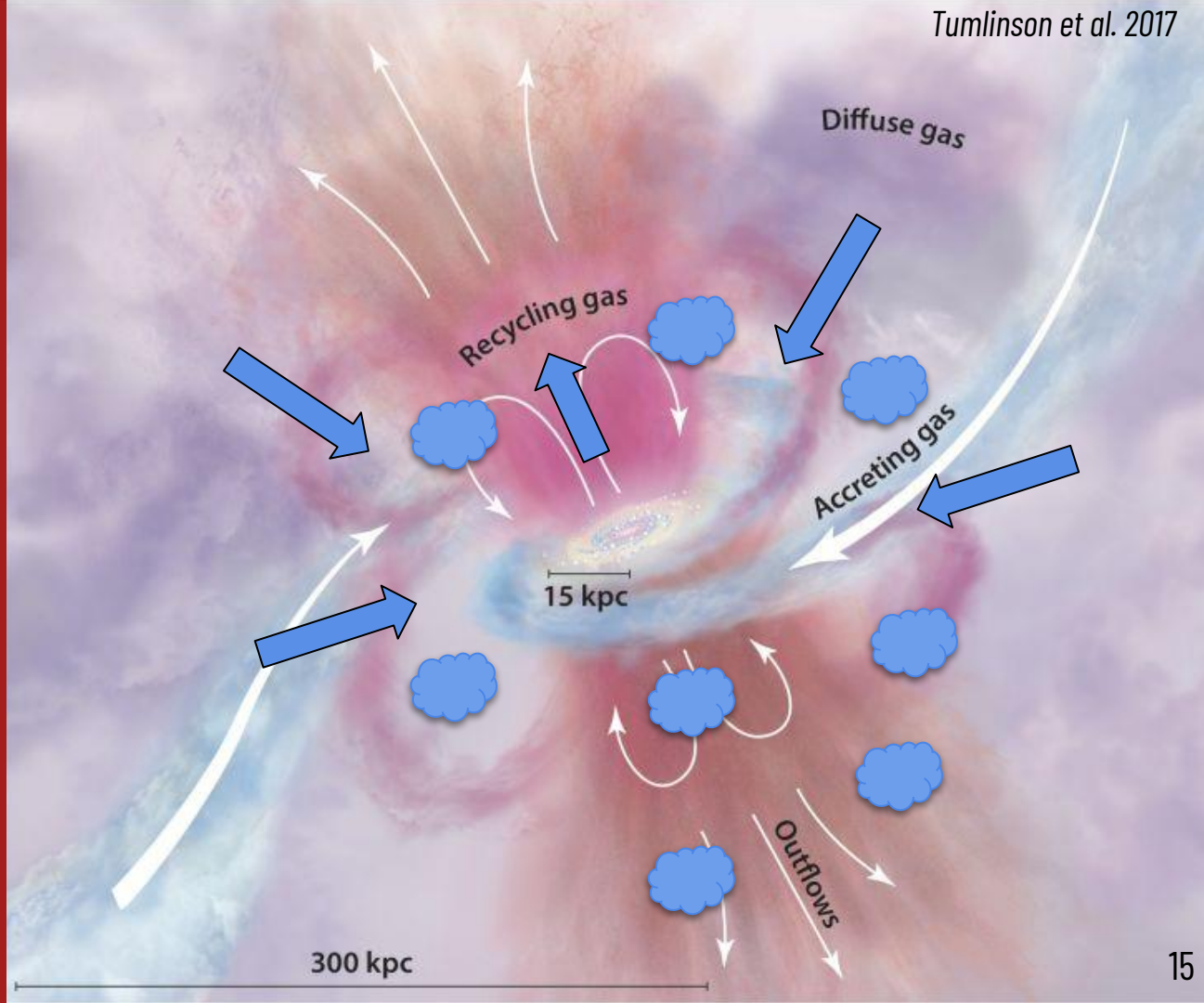
**Both DLAs are clumpy**  
covering fractions  $\sim 0.6-0.8$

J0033 field  $z = 1.167$

# Part I

## Part II

Cool gas around  
M31 and the MW



# Cool CGM around M31

*Afruni et al. 2022*

Observations from the **AMIGA Project** (*Lehner et al. 2020*)



Kinematics and column densities (Si absorption lines)  
from **tens of QSO sightlines across the halo**

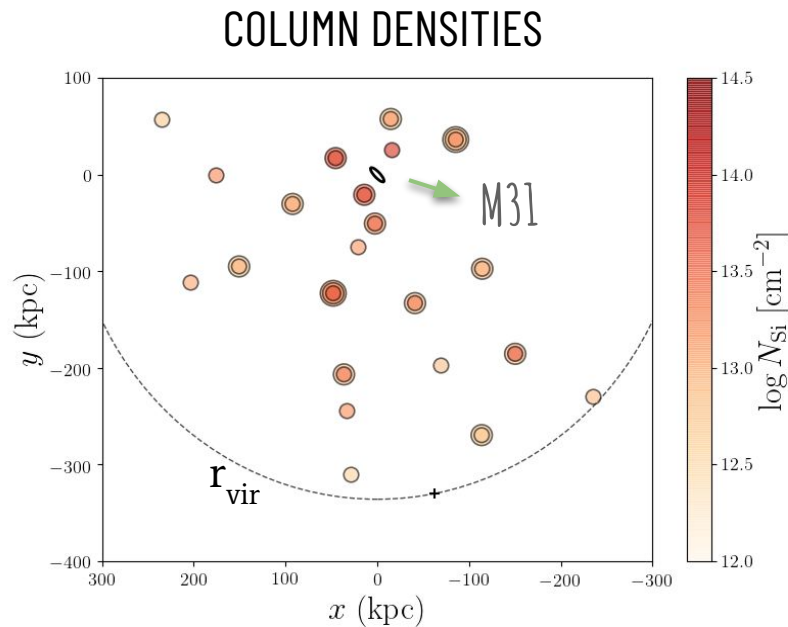
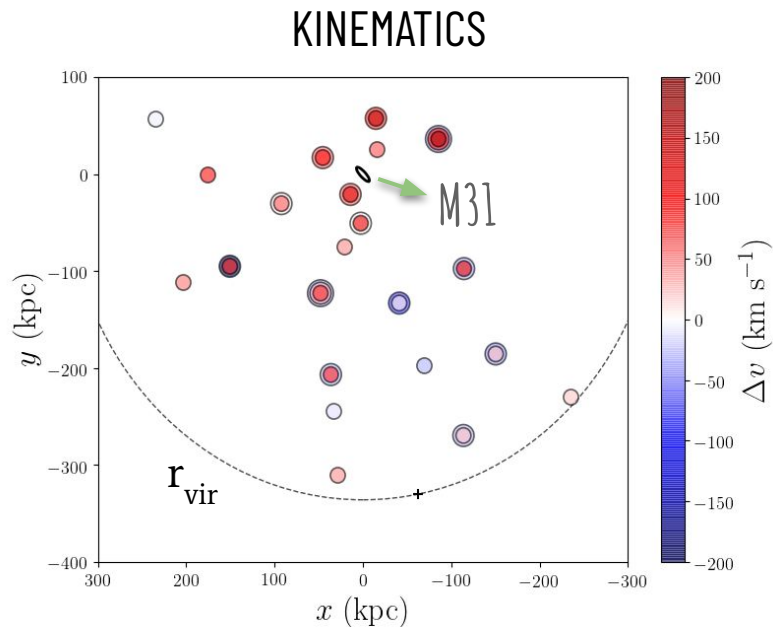
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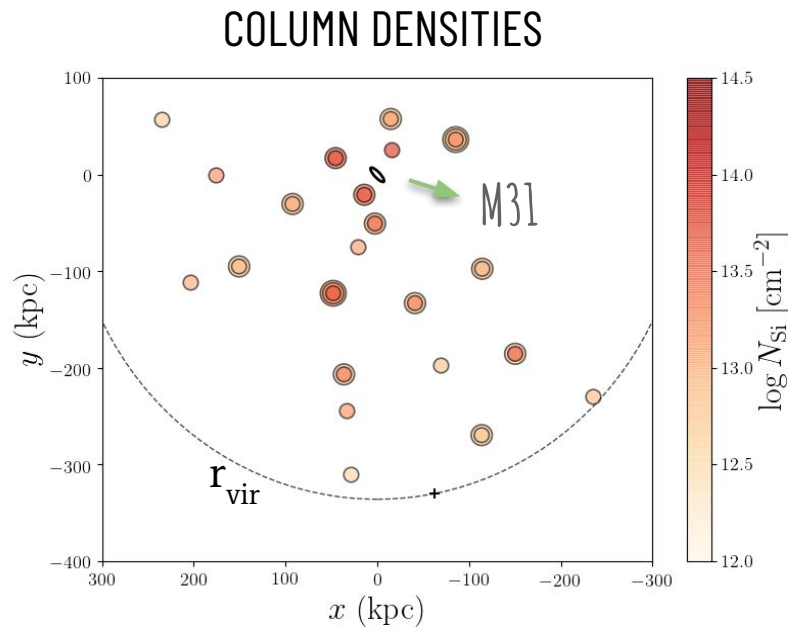
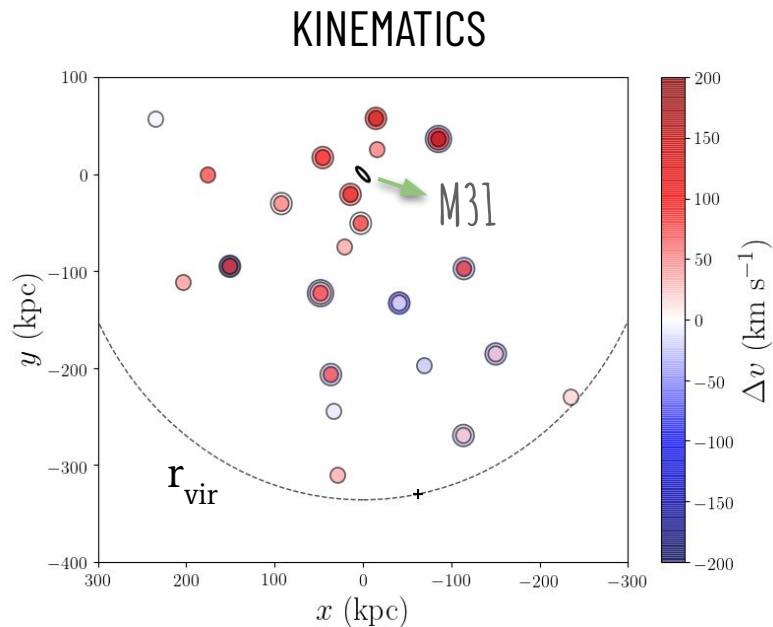
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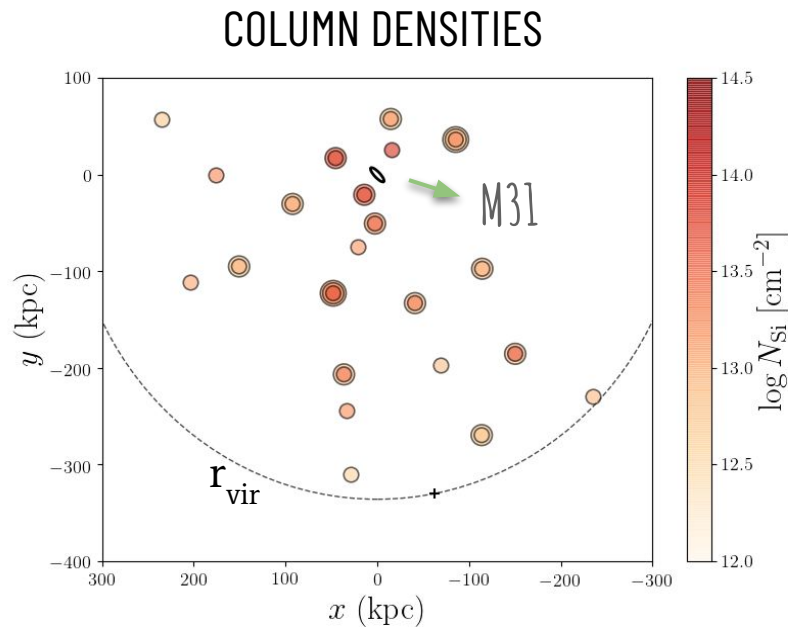
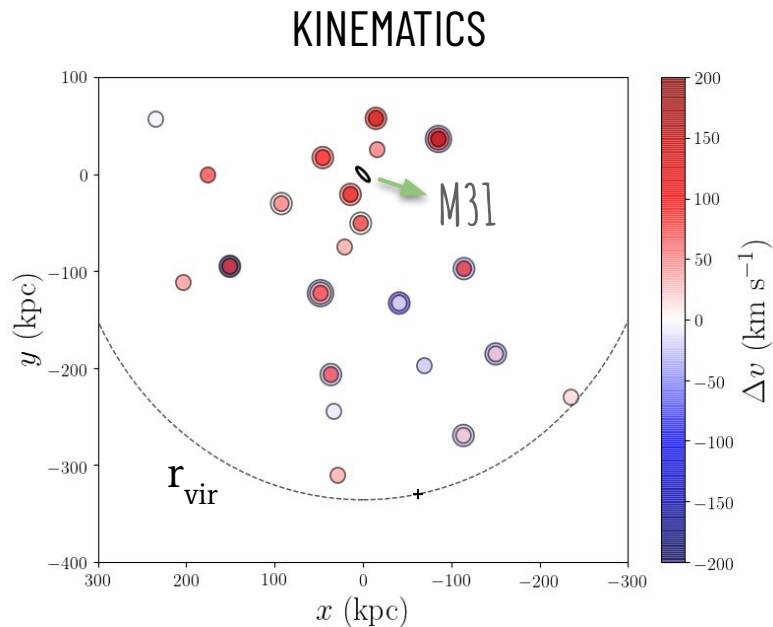
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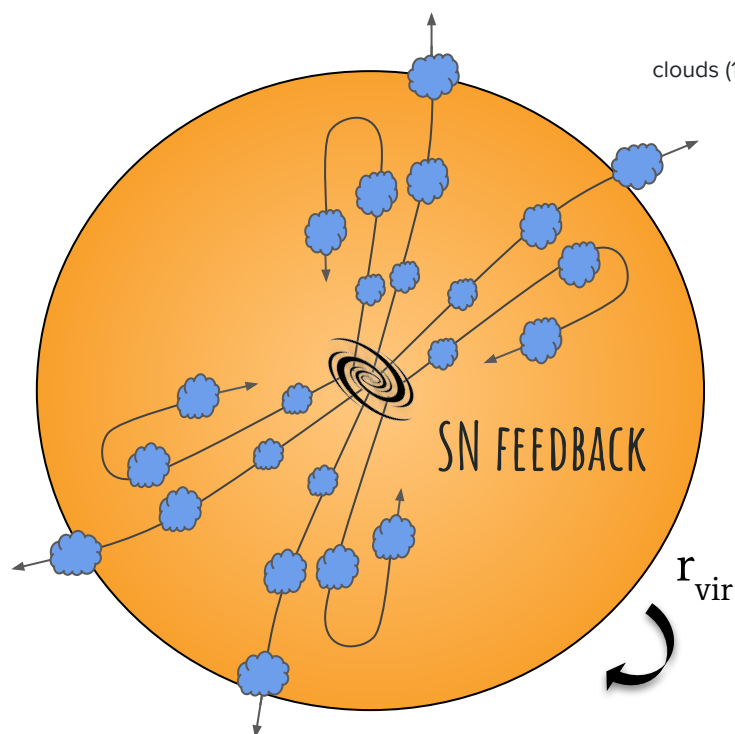


**Metallicity** estimate



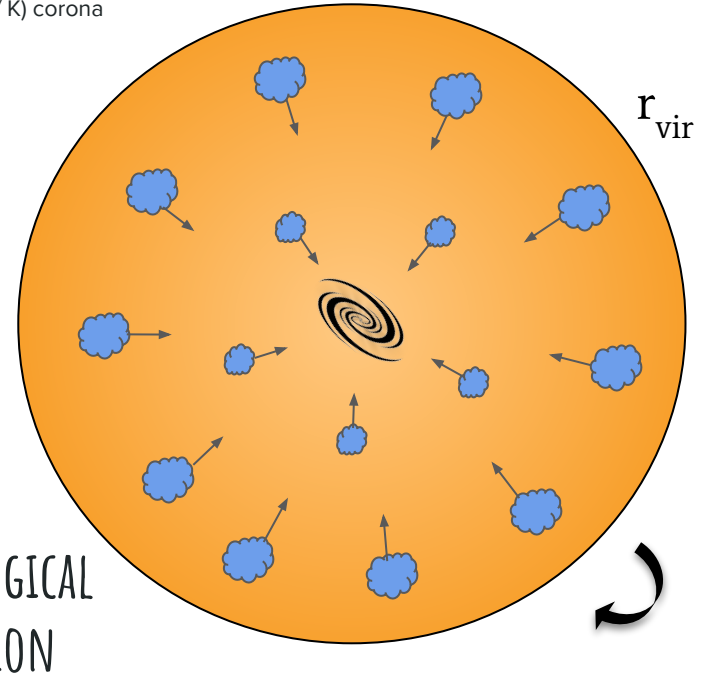
$$N_{\text{Si}} = \left( \frac{Z}{Z_{\odot}} \right) \left( \frac{\text{Si}}{\text{H}} \right)_{\odot} N_{\text{H}}$$

## Semi-analytical models of the CGM

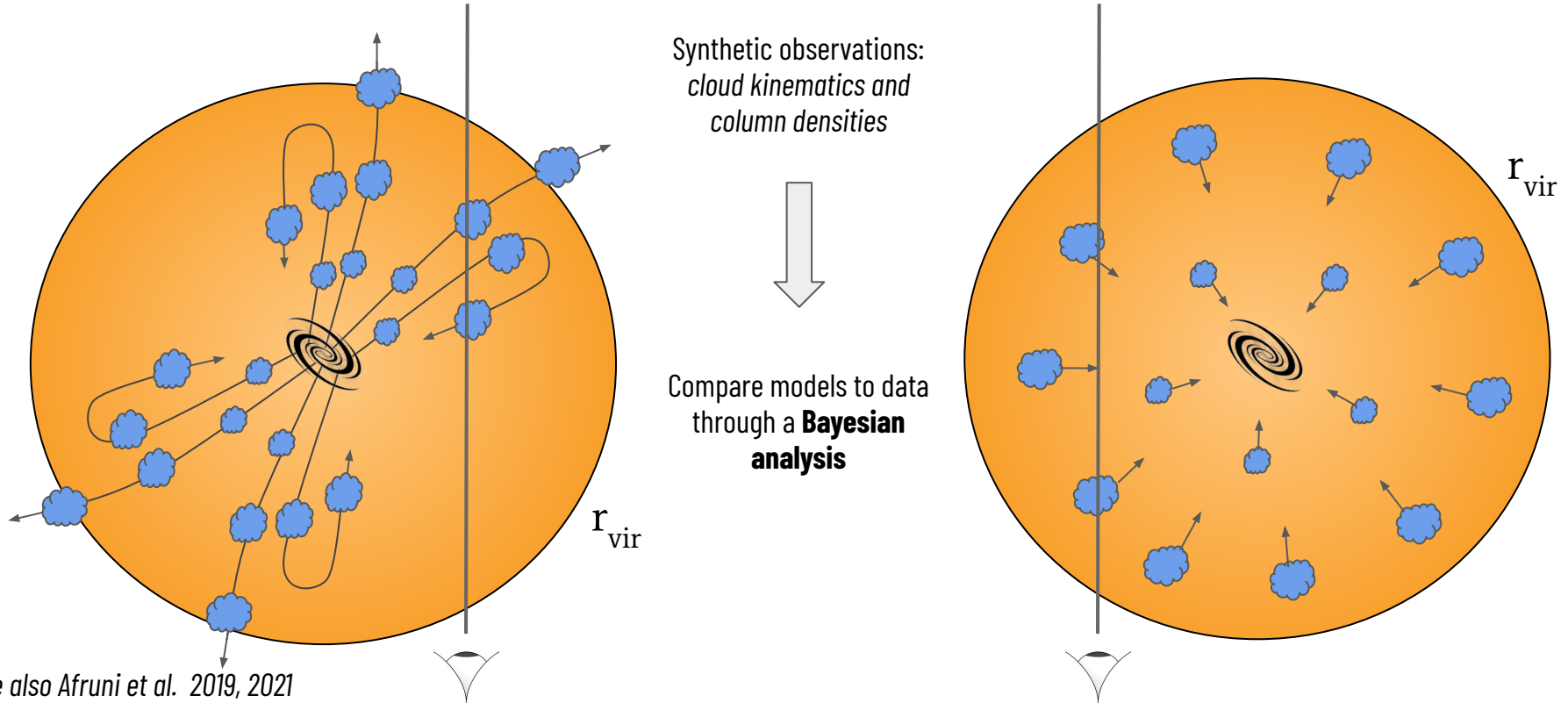


2 - PHASE MEDIUM  
clouds ( $10^4$  K) in pressure eq. with hot ( $10^{6-7}$  K) corona

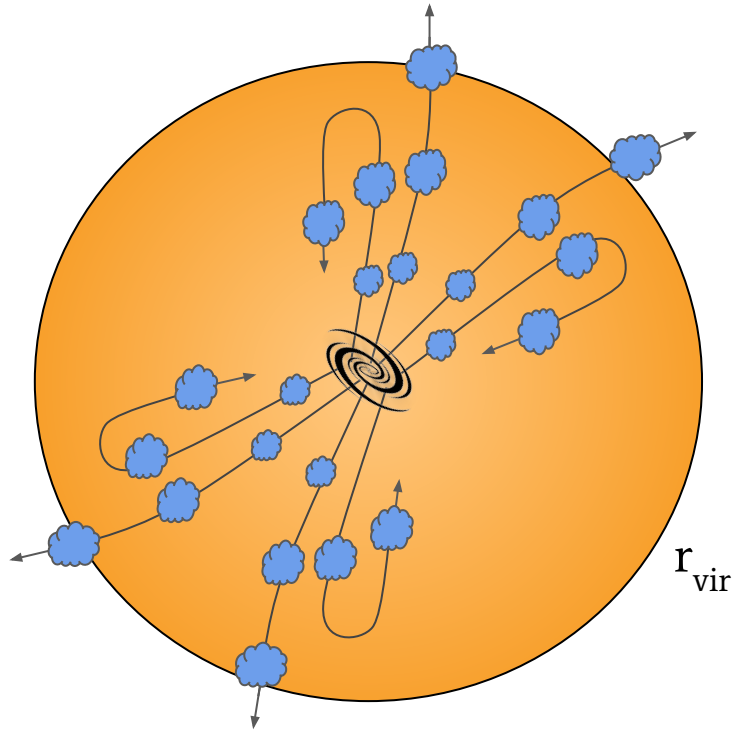
GRAVITY  
DRAG FORCE  
ROTATION



## Semi-analytical models of the CGM



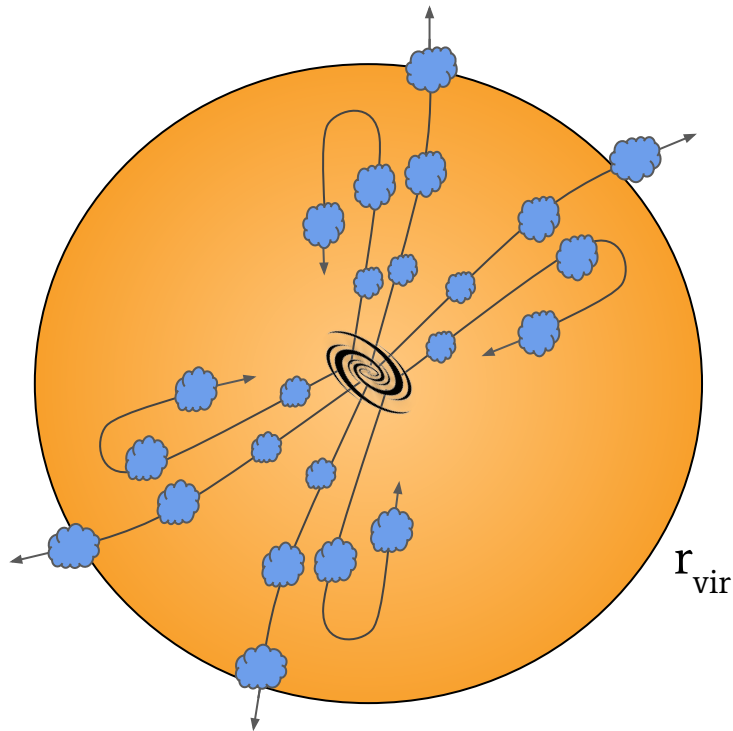
## Outflow scenario



$$\dot{K}_{\text{out}} = \frac{1}{2} \dot{M}_{\text{out}} v_{\text{kick}}^2$$

$$\dot{K} \approx 3 \times 10^{41} f_{\text{SN}} \left( \frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right) \left( \frac{\text{SFR}}{M_{\odot} \text{ yr}^{-1}} \right) \text{ erg s}^{-1}$$

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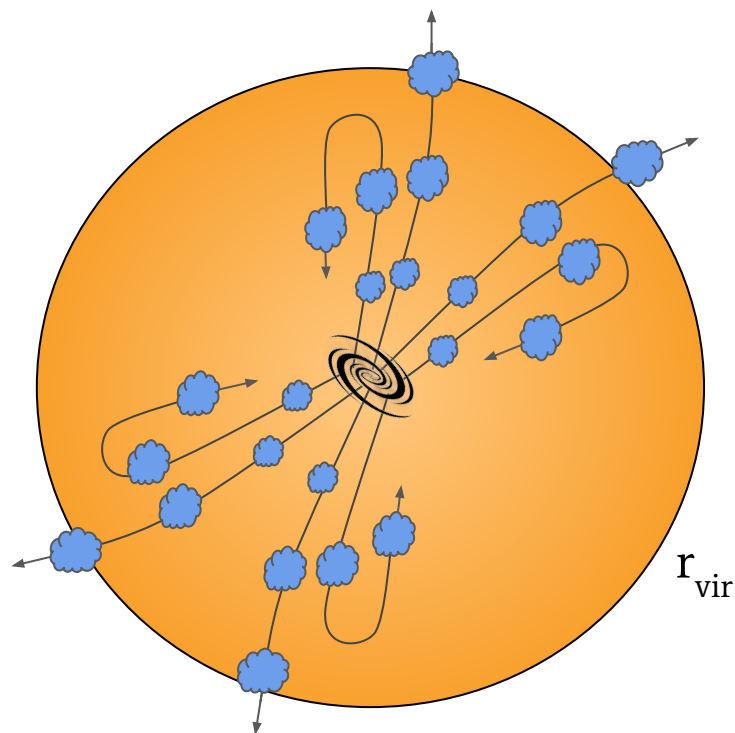
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Supernova efficiencies  $\sim 700\%$  - **Unphysical!**



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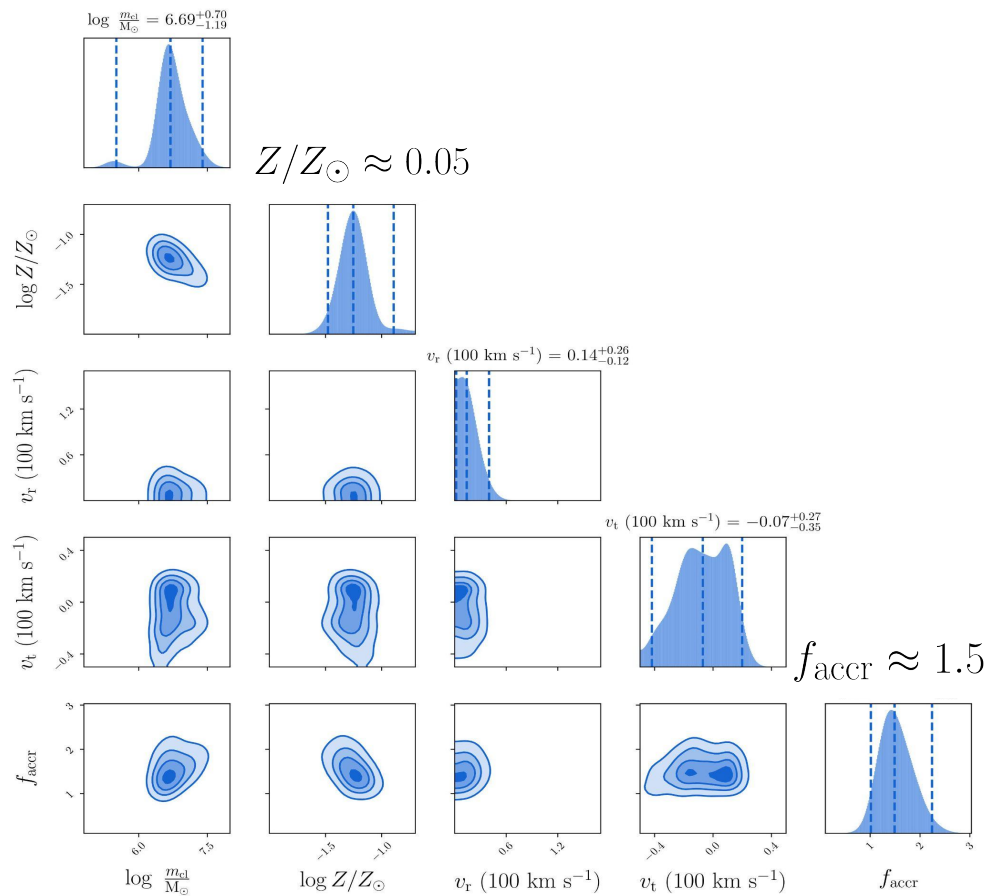
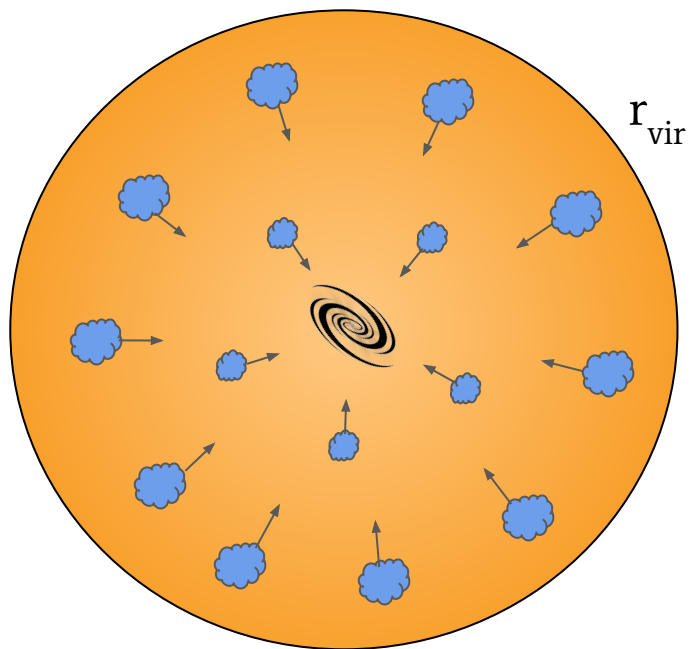
Not a viable way to reproduce the cool CGM,  
especially at  $R \gtrsim 100 \text{ kpc}$

See also Afruni et al. 2021 for other star-forming galaxies

# Cool CGM around M31

Afruni et al. 2022

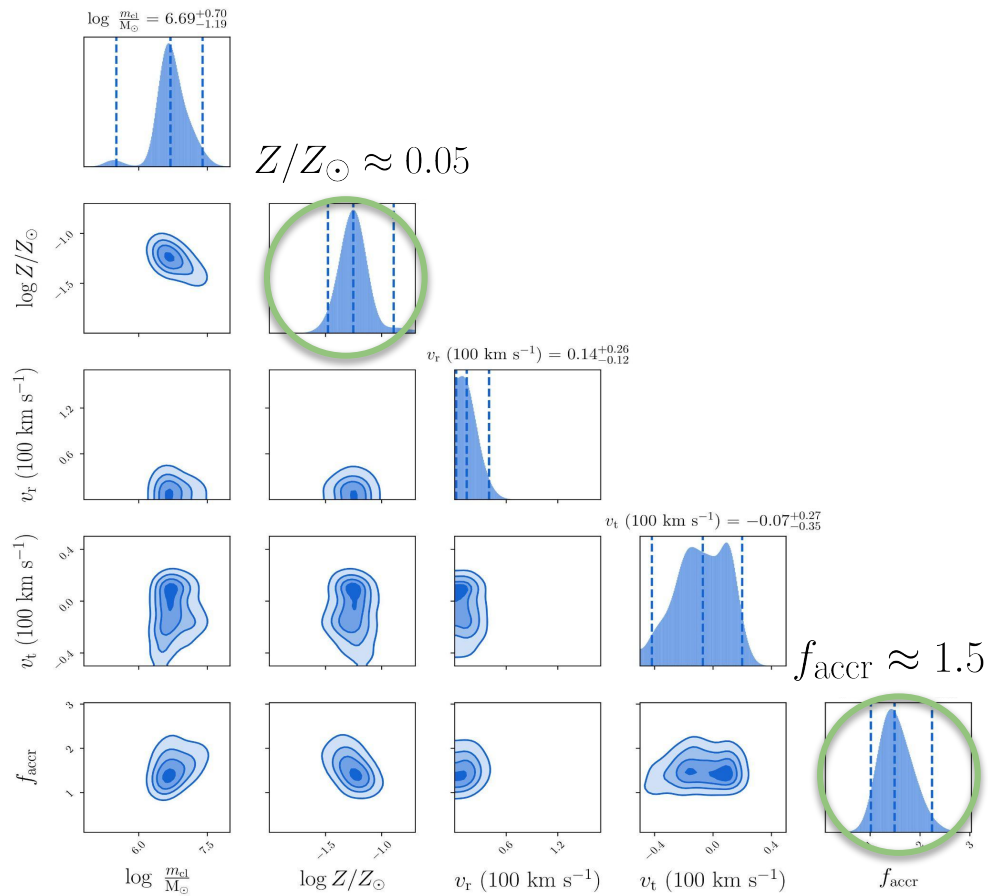
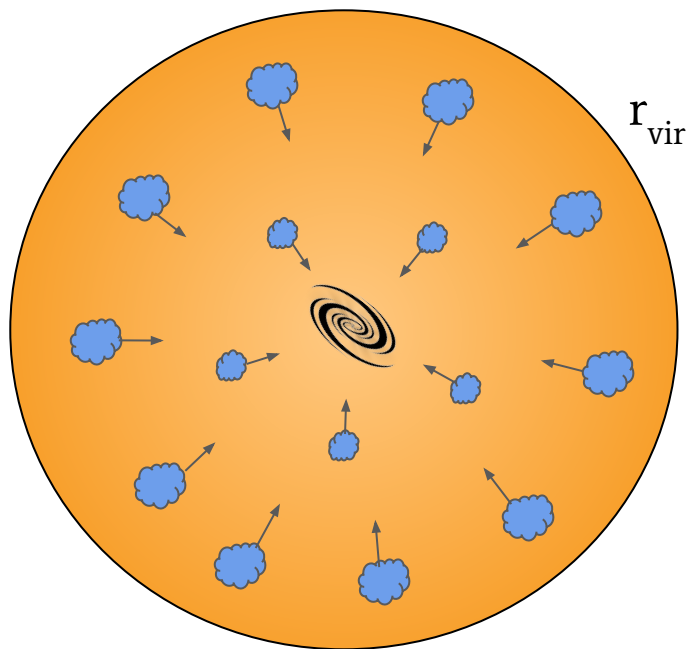
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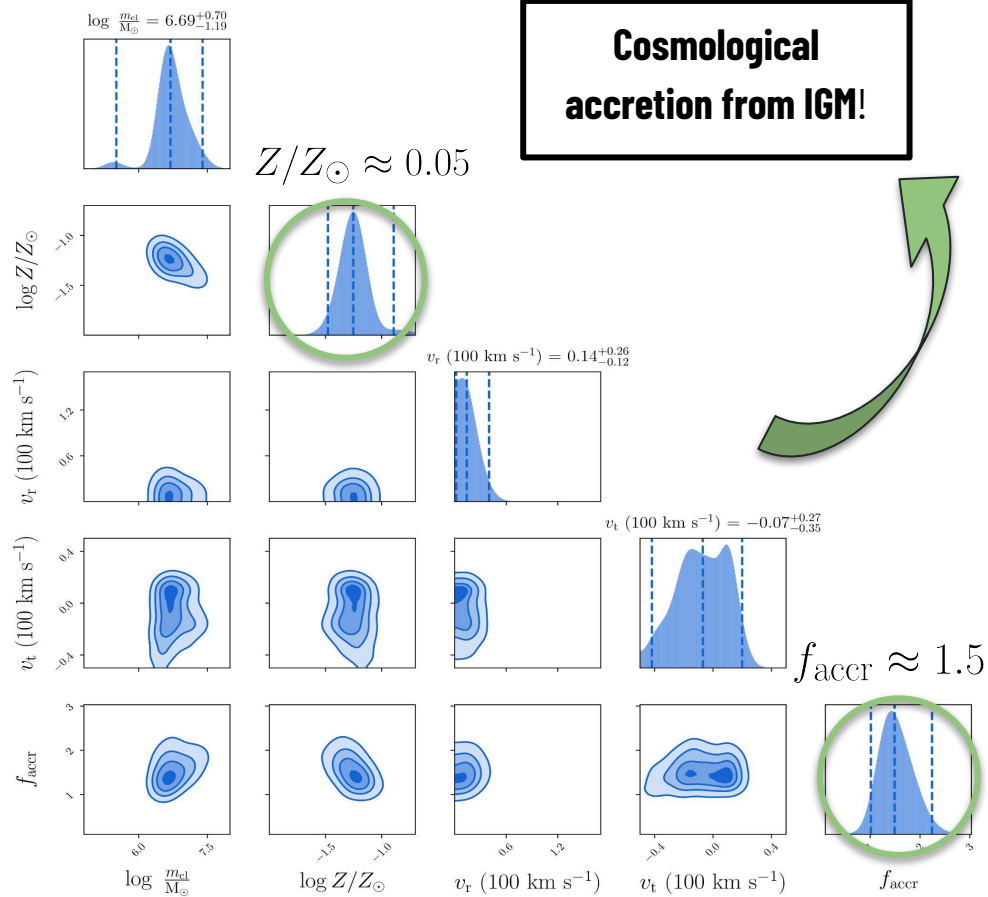
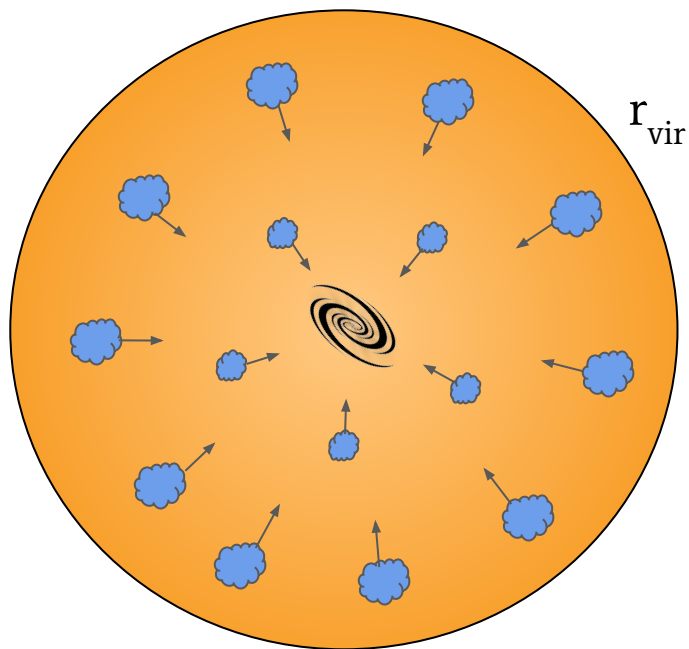
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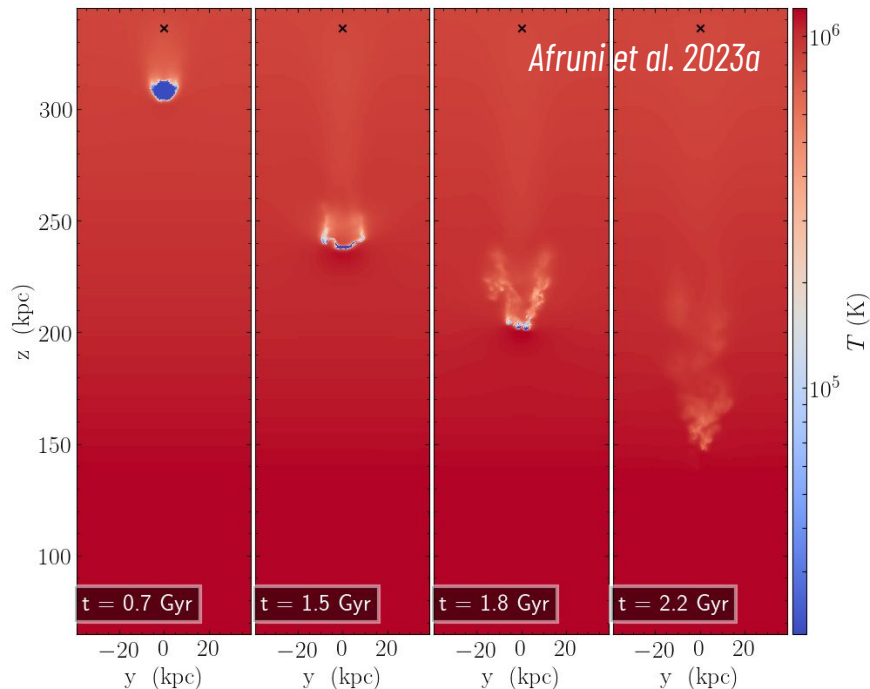
Afruni et al. 2022

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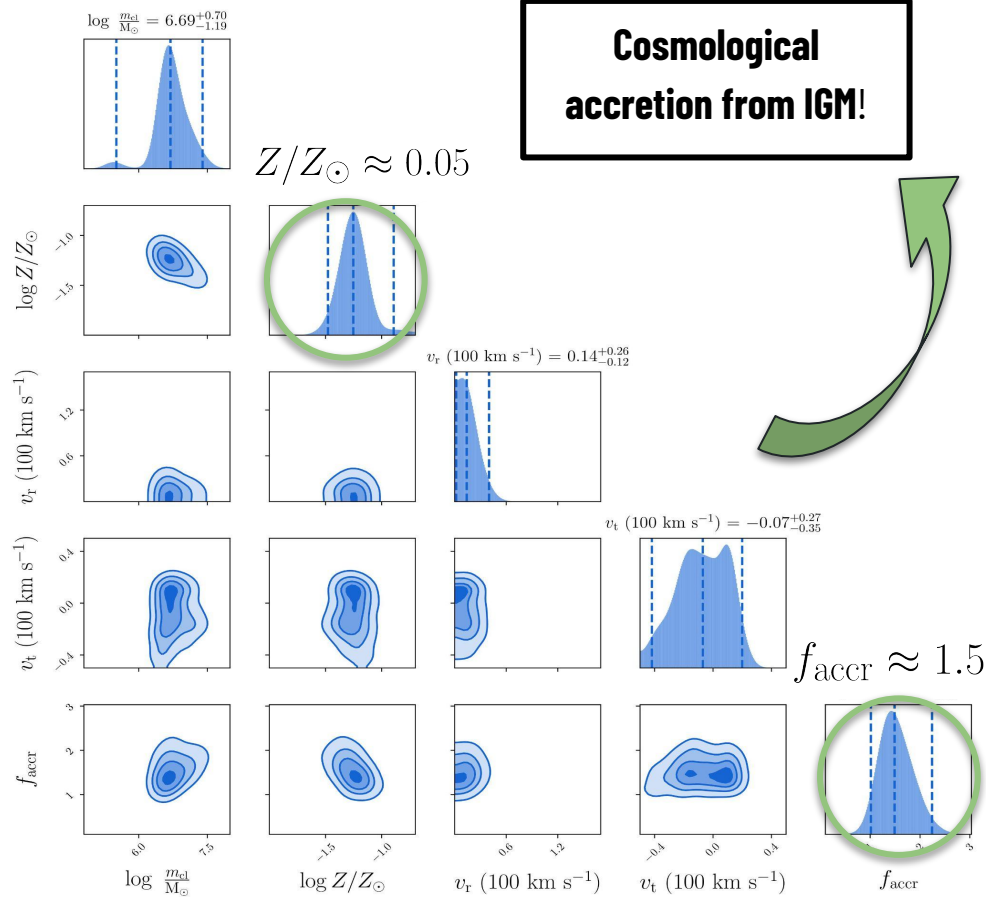


# Cool CGM around M31

Afruni et al. 2022



The cloud is **destroyed** by the interactions with the hot gas



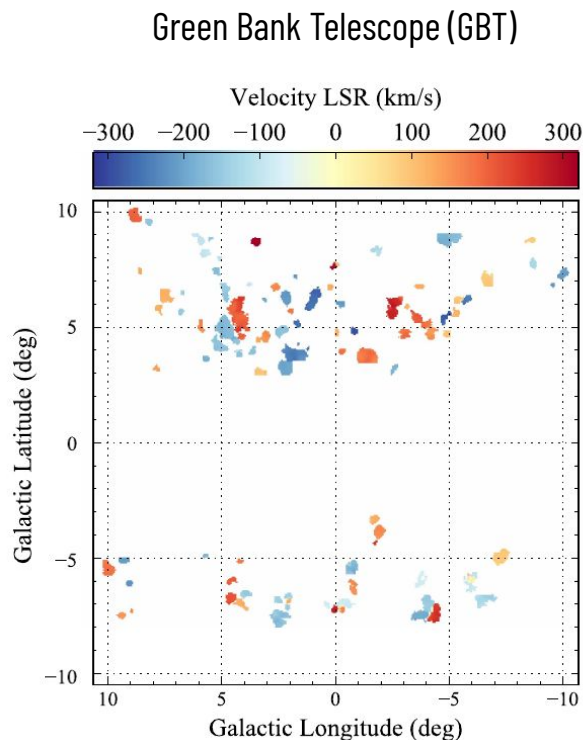


# HI clouds near the MW center

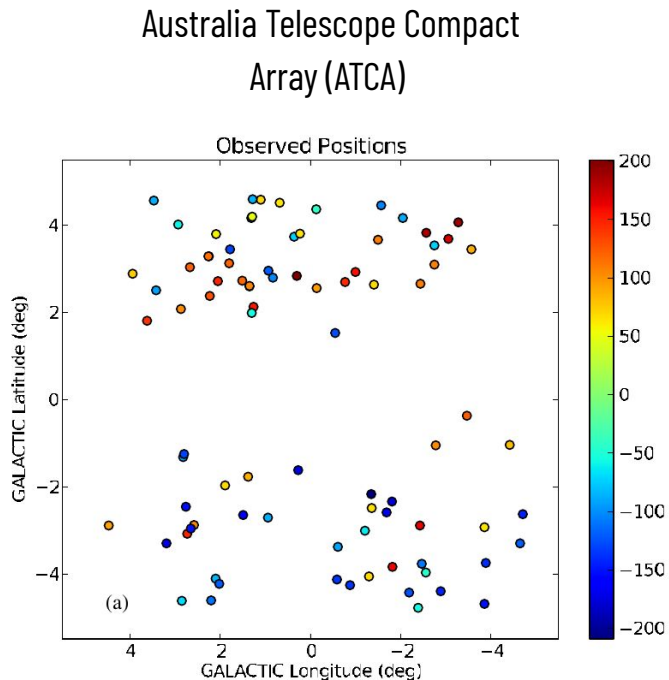
Population of anomalous  
high-velocity clouds near galactic  
center

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Population of anomalous  
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center



*Di Teodoro et al. 2018*



*McClure-Griffiths et al. 2013*

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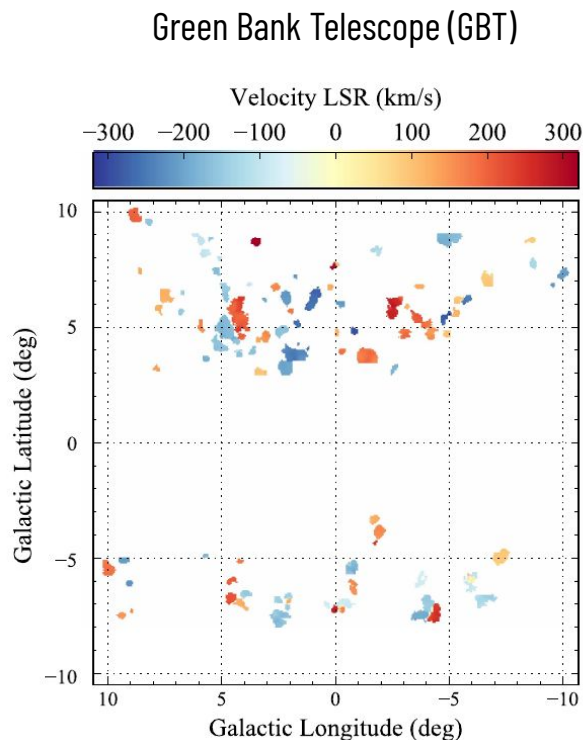
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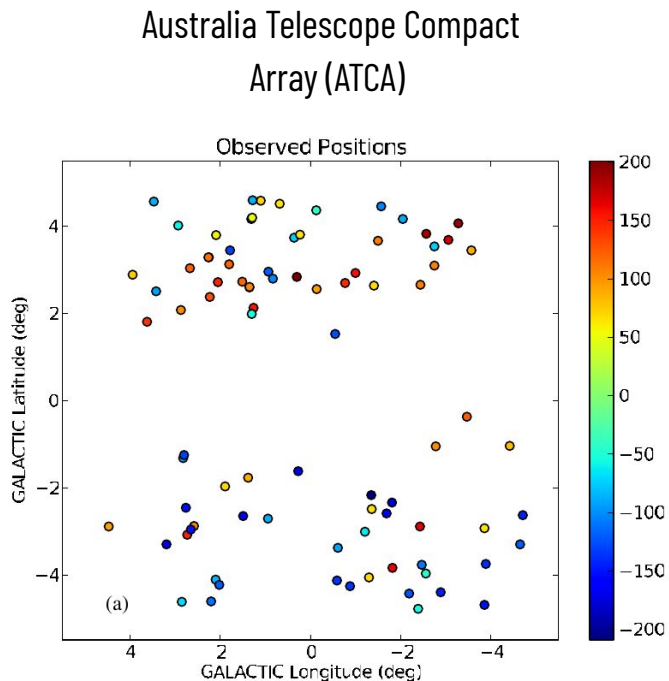
Kinematics consistent with  
**acceleration** from wind

$$V_{\text{out}}(d) = \begin{cases} V_0 + (V_{\text{max}} - V_0) \frac{d}{d_{\text{acc}}} & \text{for } d < d_{\text{acc}} \\ V_{\text{max}} & \text{for } d \geq d_{\text{acc}} \end{cases}$$

*Lockman et al. 2020*



*Di Teodoro et al. 2018*



*McClure-Griffiths et al. 2013*

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high-velocity clouds near galactic  
center

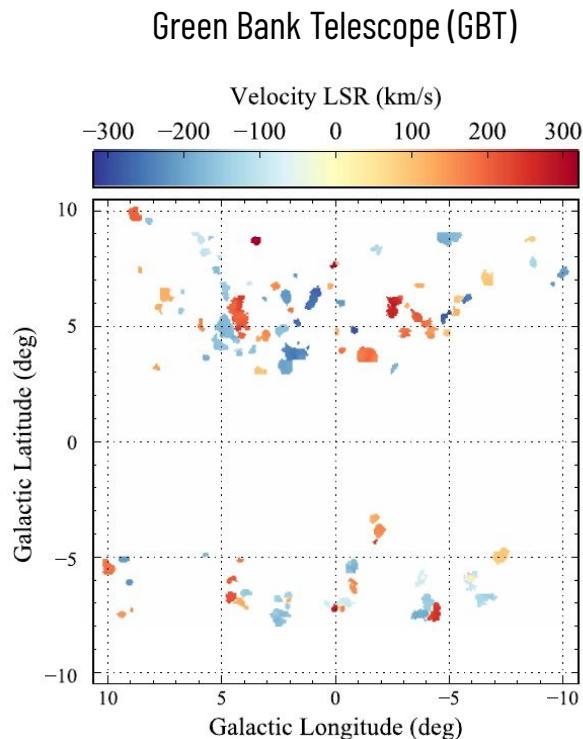


Kinematics consistent with  
**acceleration** from wind

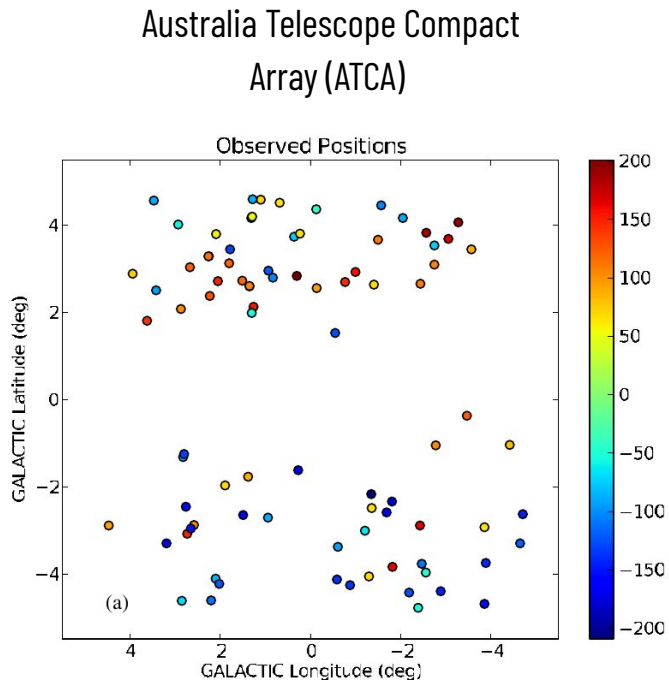
$$V_{\text{out}}(d) = \begin{cases} V_0 + (V_{\text{max}} - V_0) \frac{d}{d_{\text{acc}}} & \text{for } d < d_{\text{acc}} \\ V_{\text{max}} & \text{for } d \geq d_{\text{acc}} \end{cases}$$

*Lockman et al. 2020*

**Dynamical models?**



*Di Teodoro et al. 2018*



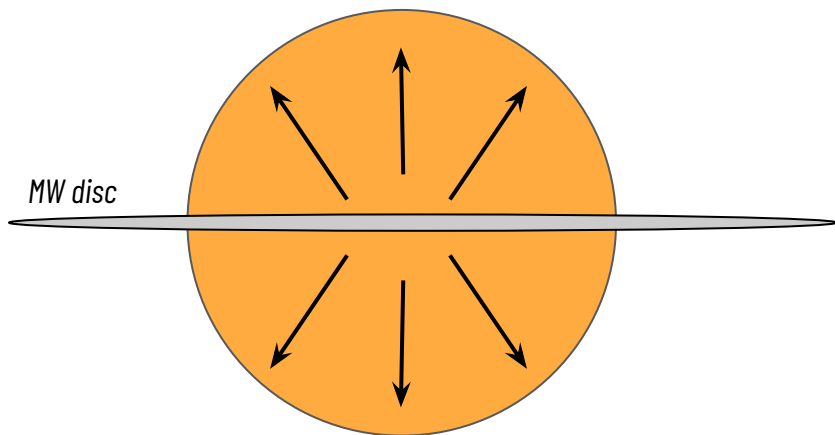
*McClure-Griffiths et al. 2013*

# HI clouds near the MW center

Hot entraining wind model  
(Chevalier & Clegg 1985)

$$\dot{\epsilon} = \eta_E (E_{\text{SN}}/m_*) \dot{M}_* / (4\pi r_*^3/3)$$

$$\dot{\rho} = \eta_{\text{M,hot}} \dot{M}_* / (4\pi r_*^3/3)$$



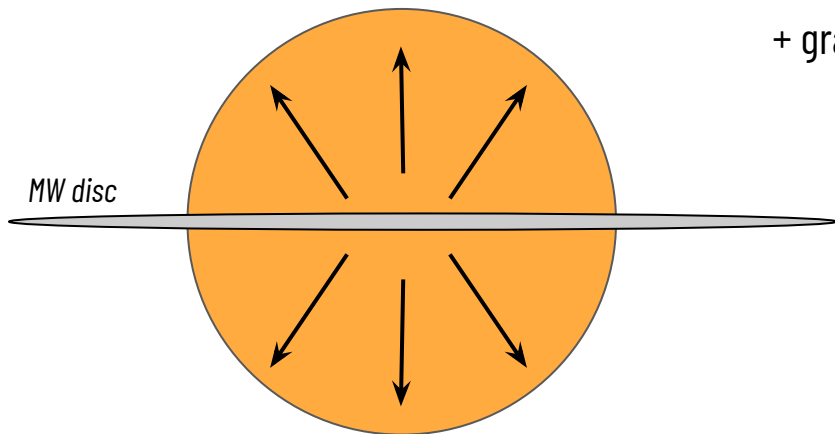
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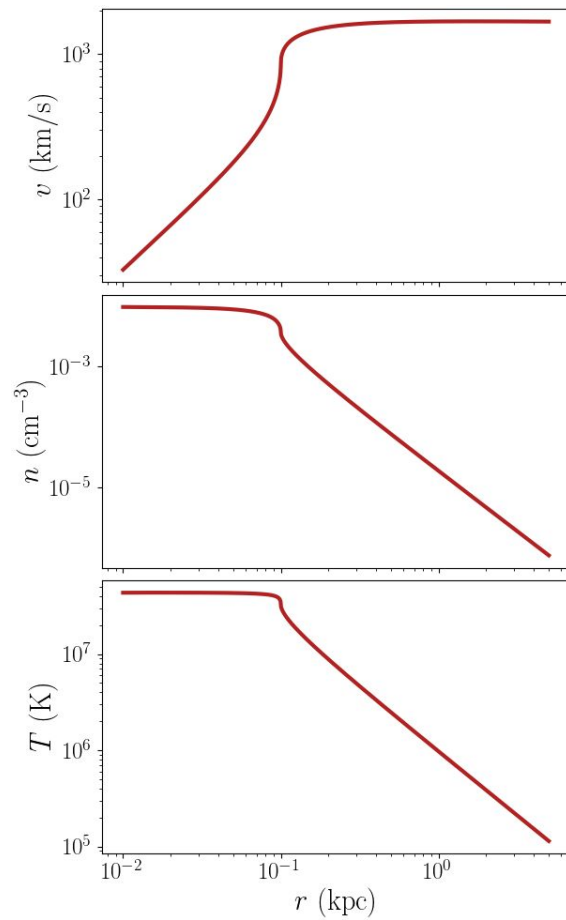
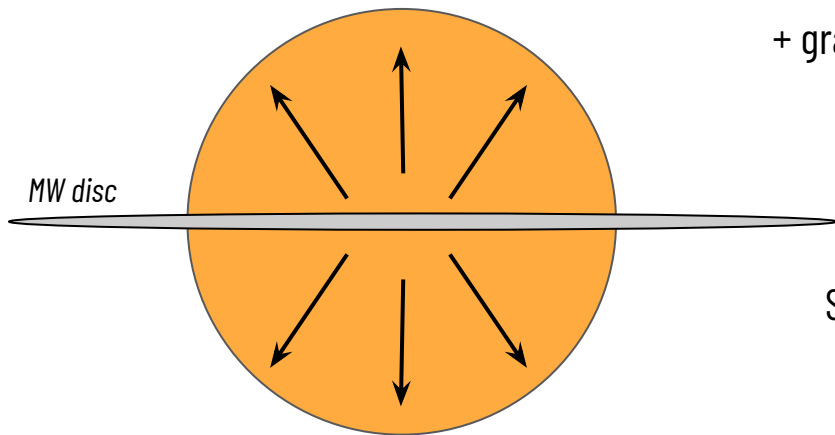
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SFR =  $0.1 M_{\odot} \text{ yr}^{-1}$  in the CMZ  
(e.g. Longmore et al. 2013)

$\eta_E \approx 0.3$ ,  $\eta_M \approx 0.1$  from high-res  
hydro simulations, e.g. TIGRESS  
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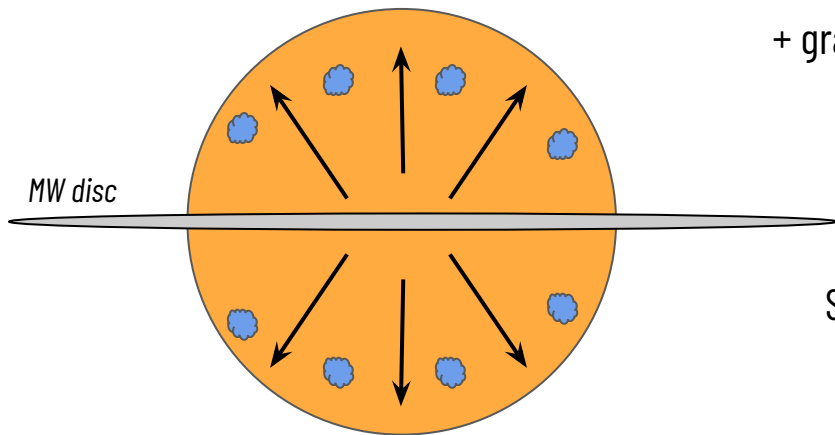
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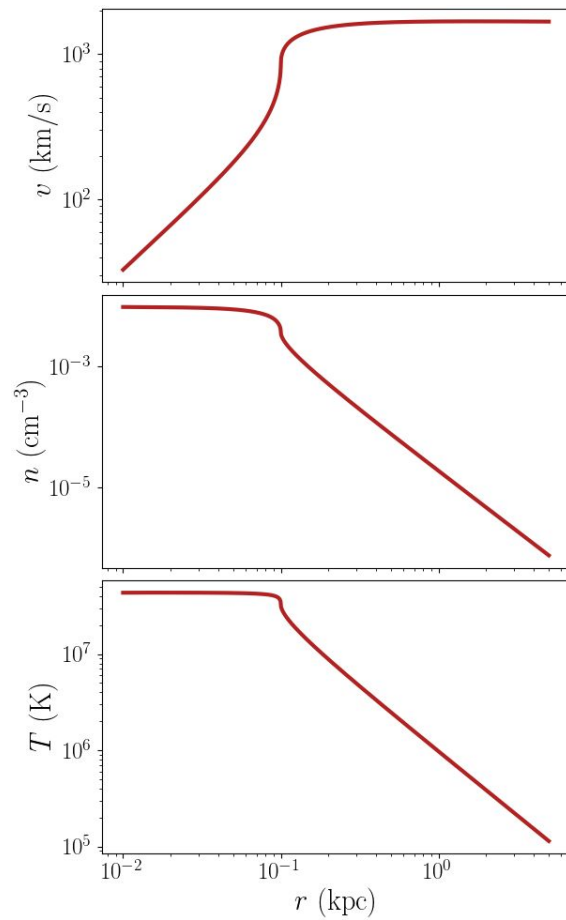
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**Cold clouds ( $T \sim 5000$  K) in pressure  
equilibrium** with the hot wind

Model orbits for 10 Myr

(typical lifetime, Di Teodoro et al. 2018)



# HI clouds near the MW center

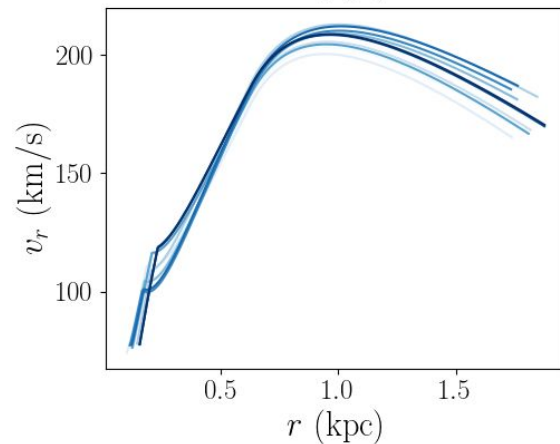
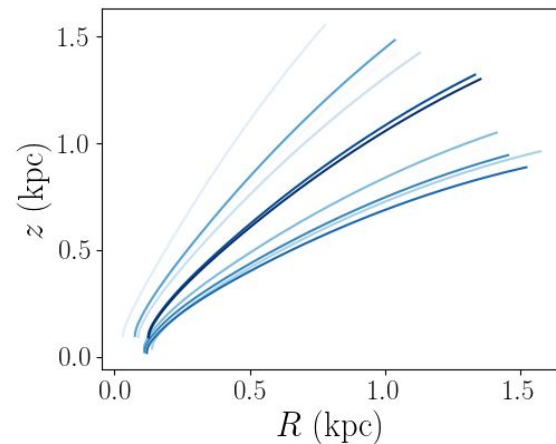
Bayesian comparison between the  
kinematics of modeled and observed clouds

# HI clouds near the MW center

Bayesian comparison between the  
kinematics of modeled and observed clouds



**Best-fit models**

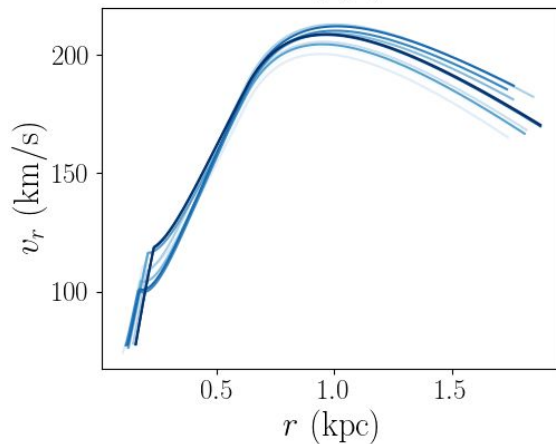
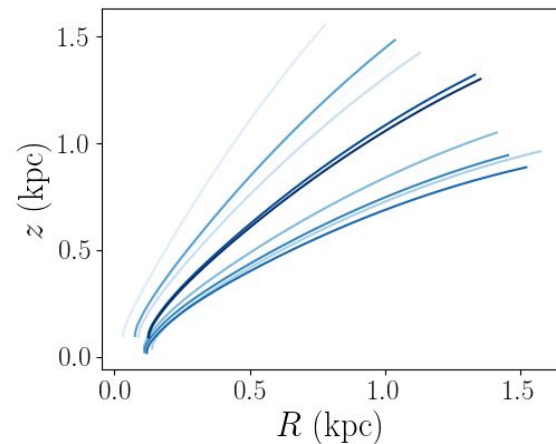
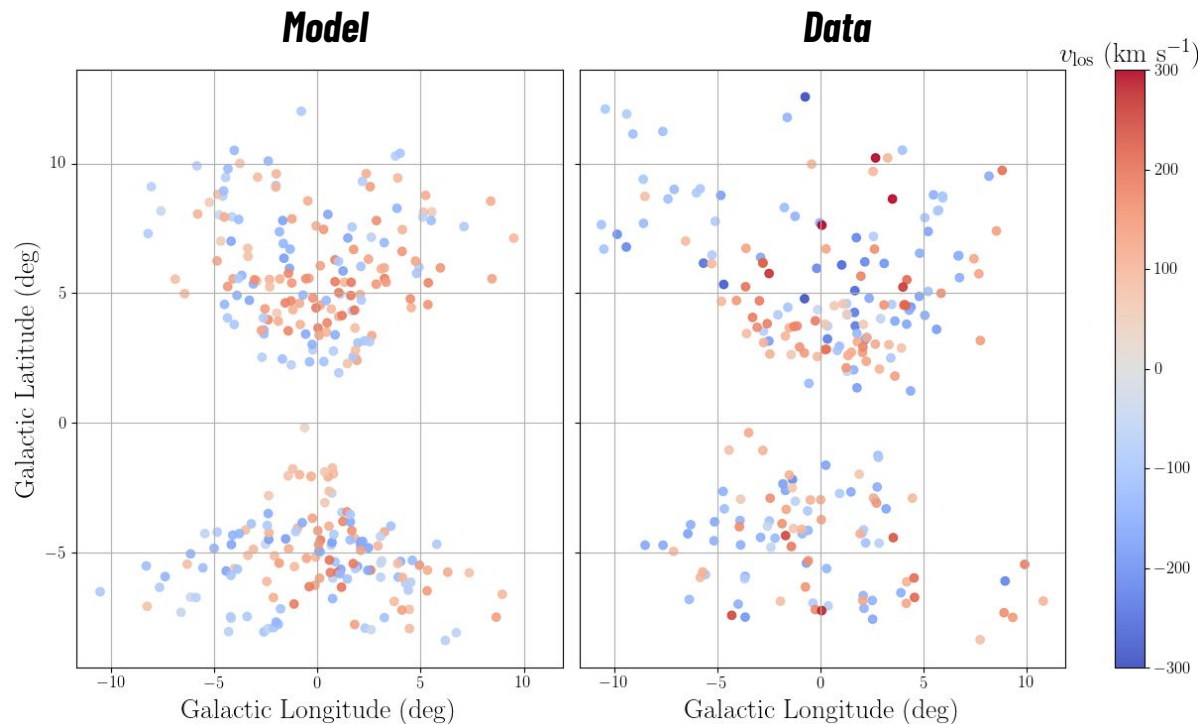


# HI clouds near the MW center

Bayesian comparison between the kinematics of modeled and observed clouds



**Best-fit models**



## Conclusions

### Part I:

- **Arctomographic data** can be used to infer the **extended structure** of the CGM
- We infer a cool CGM **coherence length between 2 and 8 kpc**
- We detect two **extended (tens of kpc)** DLAs that appear **clumpy**, with covering fractions lower than 1

### Part II:

- **Semi-analytical models** are a great tool to infer origin and dynamics of cool CGM
- **Cool gas in M31** consistent with **cosmological accretion**, with **no feeding** of the central star formation
- **HI clouds up to ~1.5 kpc from the MW** disk are dynamically consistent with **acceleration from hot SN wind**

## Future directions

- Apply dynamical models to arctomographic data
- Improve models with interactions between hot and cool phase

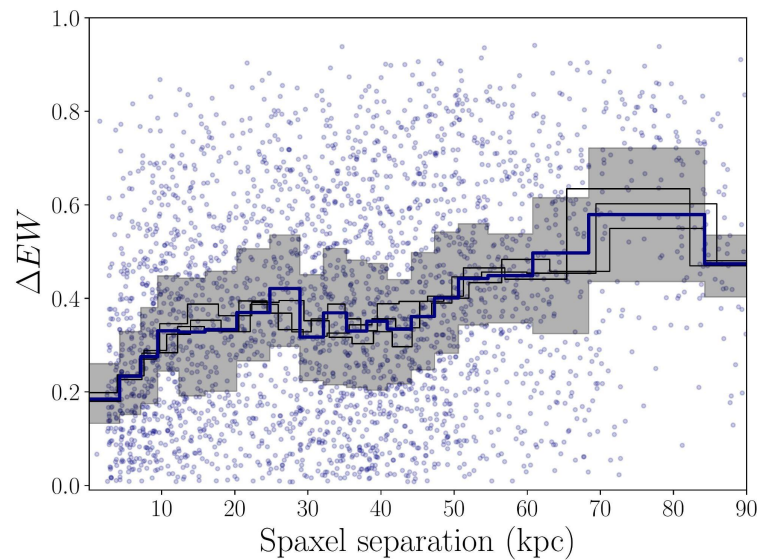
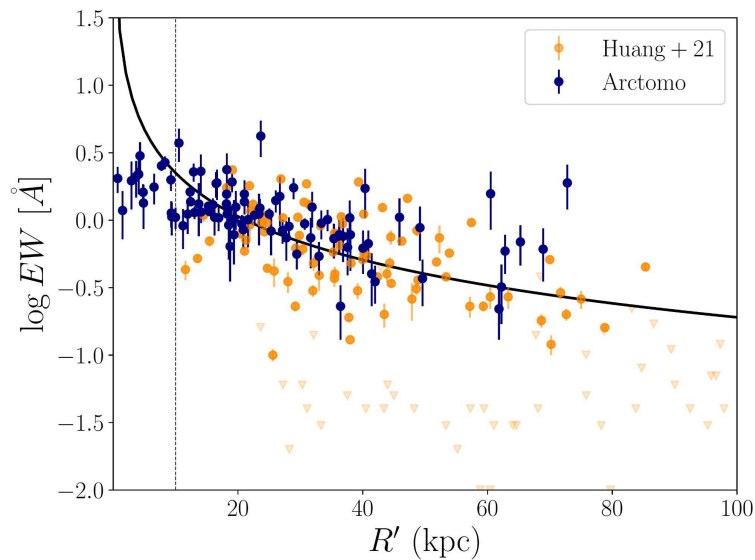




# Coherence scale of the cool CGM

Afruni et al. 2023b

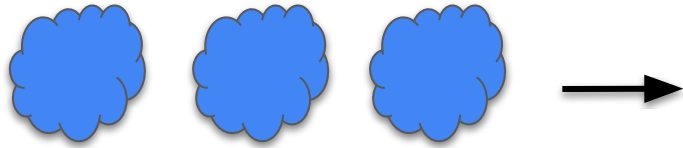
$$\Delta EW = \frac{|EW_1 - EW_2|}{\max(EW_1, EW_2)}$$



# Arc-tomography of DLAs

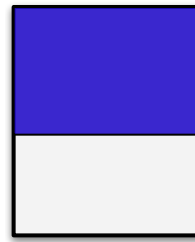
Berg, Afruni et al. 2024,  
accepted for publication  
A&A

## Kinematic model of the cool gas



Population of cool gas clouds, defined by a  
metallicity, HI column density (MgII column  
densities from CLOUDY) and velocity  
dispersion

Spaxel



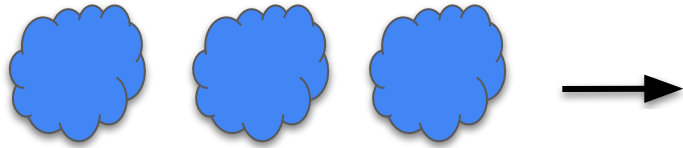
$C_{\text{frac}}$ ,  $N\text{H I}_{\text{spaxel}}$

$$F_{\text{spaxel}} = F_{\text{los}} * C_{\text{frac}} + F_{\text{bg}} * (1 - C_{\text{frac}})$$

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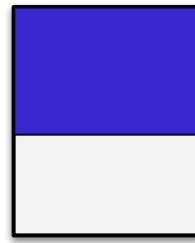
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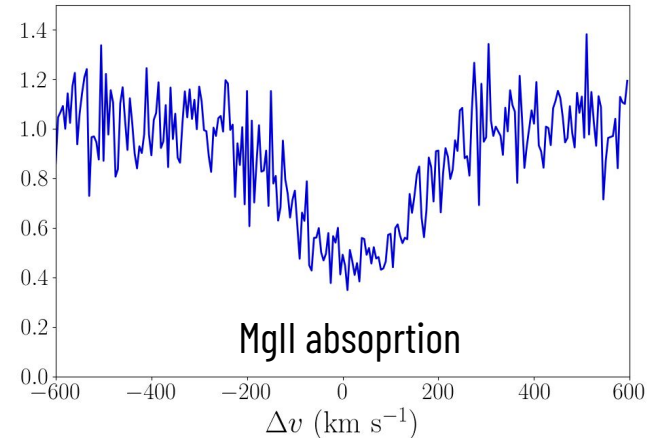
Spaxel



$C_{\text{frac}}$ ,  $N_{\text{HI}}^{\text{spaxel}}$

$$F_{\text{spaxel}} = F_{\text{los}} * C_{\text{frac}} + F_{\text{bg}} * (1 - C_{\text{frac}})$$

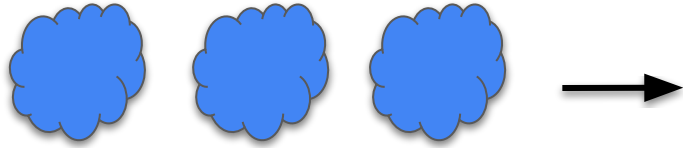
+ MUSE PSF and noise



# Arc-tomography of DLAs

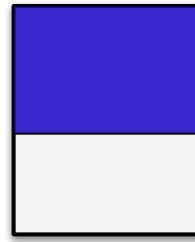
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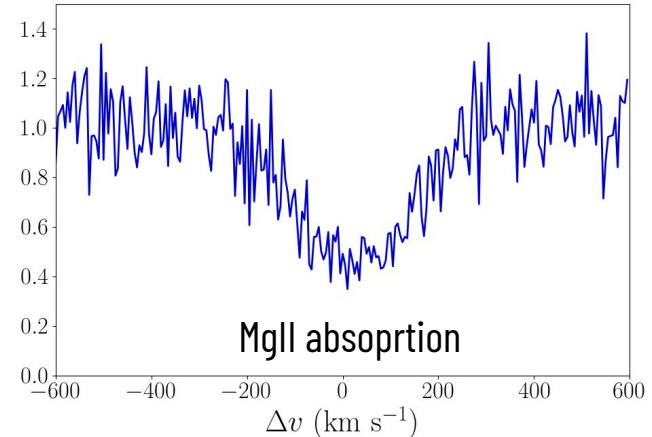
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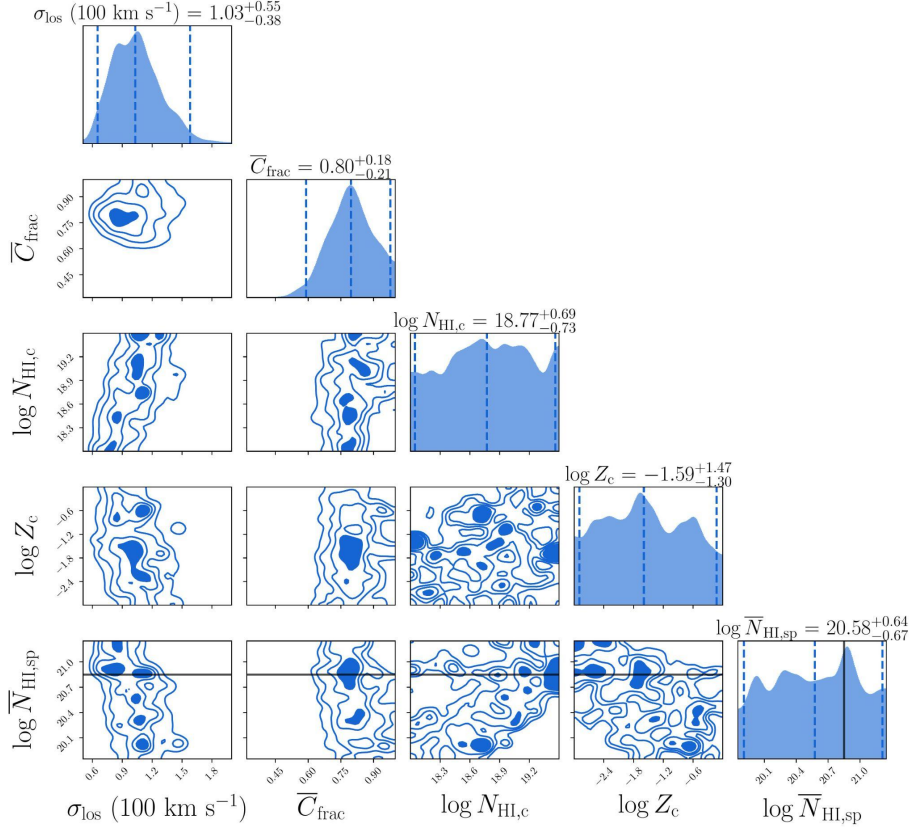
Comparison with the observed  
distributions



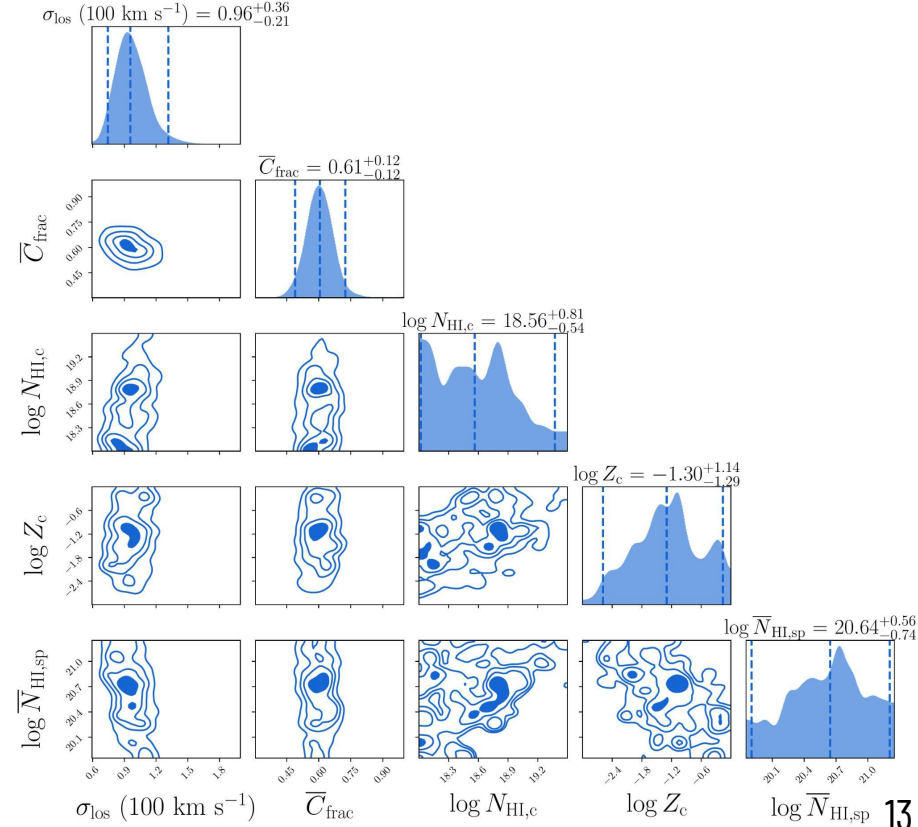
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Berg, Afruni et al. 2024,  
accepted for publication  
A&A

J1527



J0033

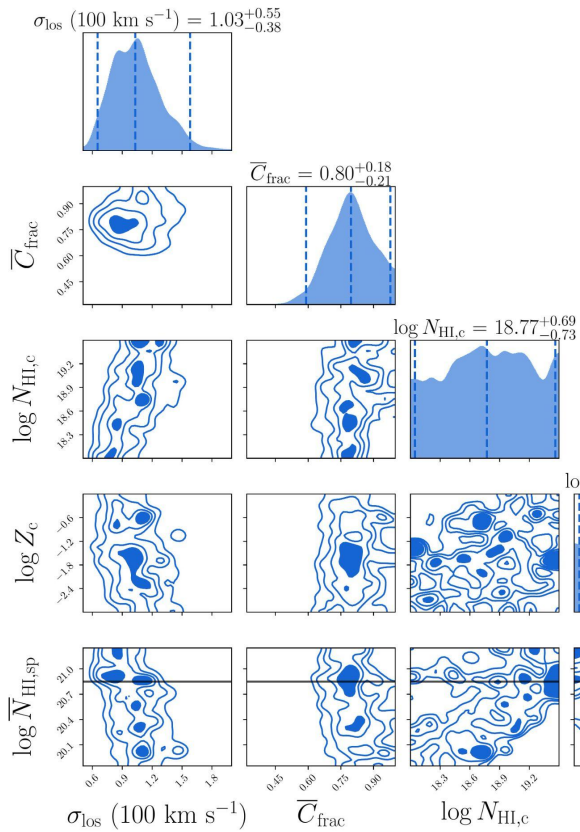




# Arc-tomography of DLAs

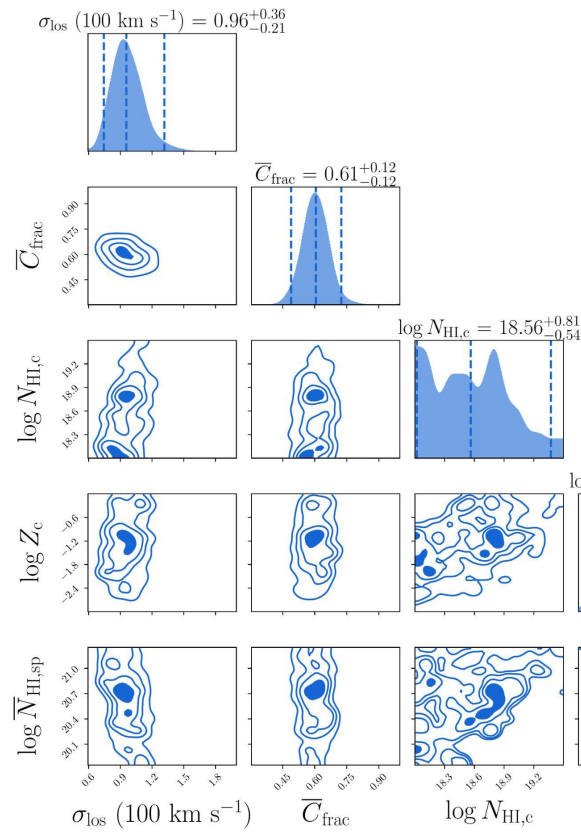
Berg, Afruni et al. 2024,  
accepted for publication  
A&A

J1527



**$N_{\text{HI}}$  is uncertain, but  
consistent with B22**

J0033

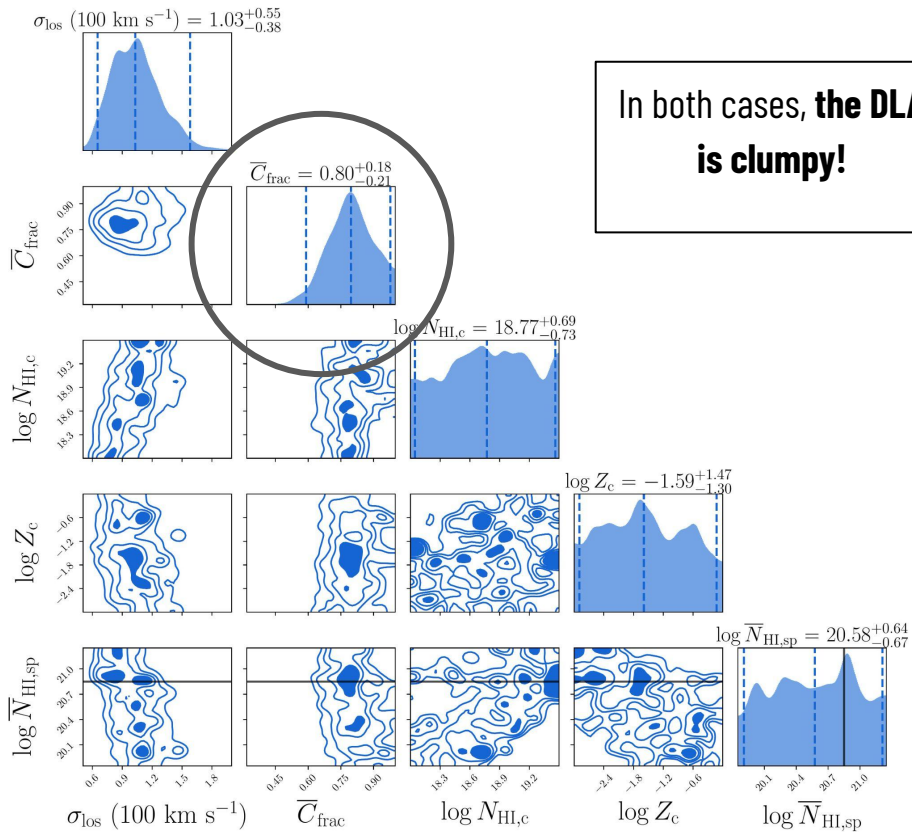


**$N_{\text{HI}}$  is uncertain, but  
likely a DLA!**

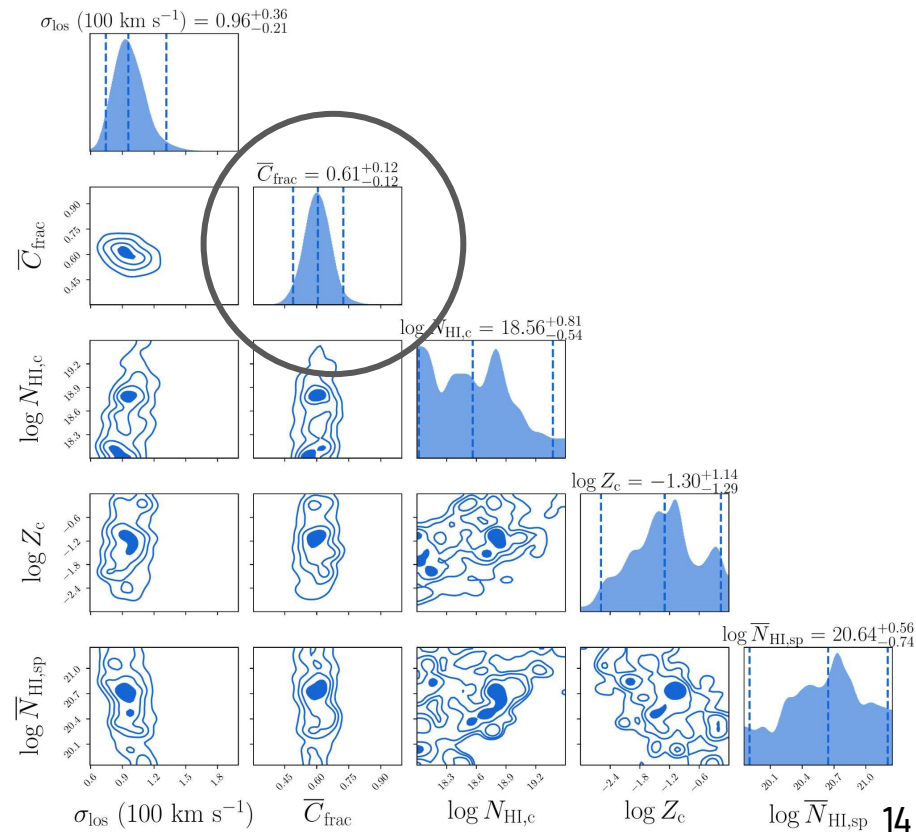
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Berg, Afruni et al. 2024,  
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A&A

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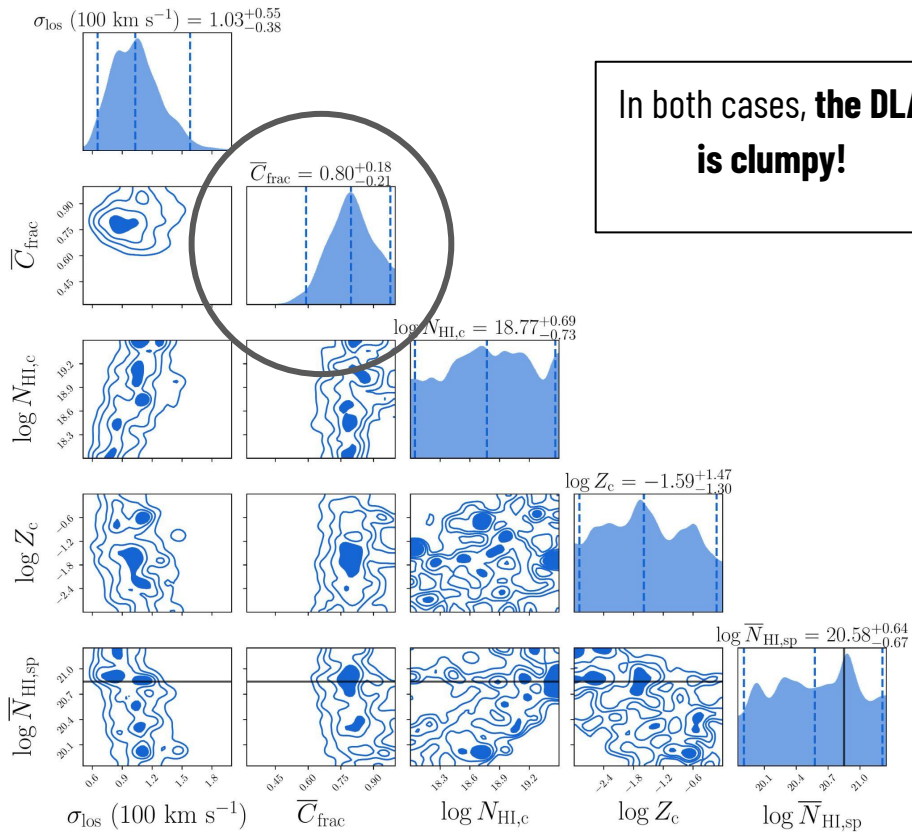
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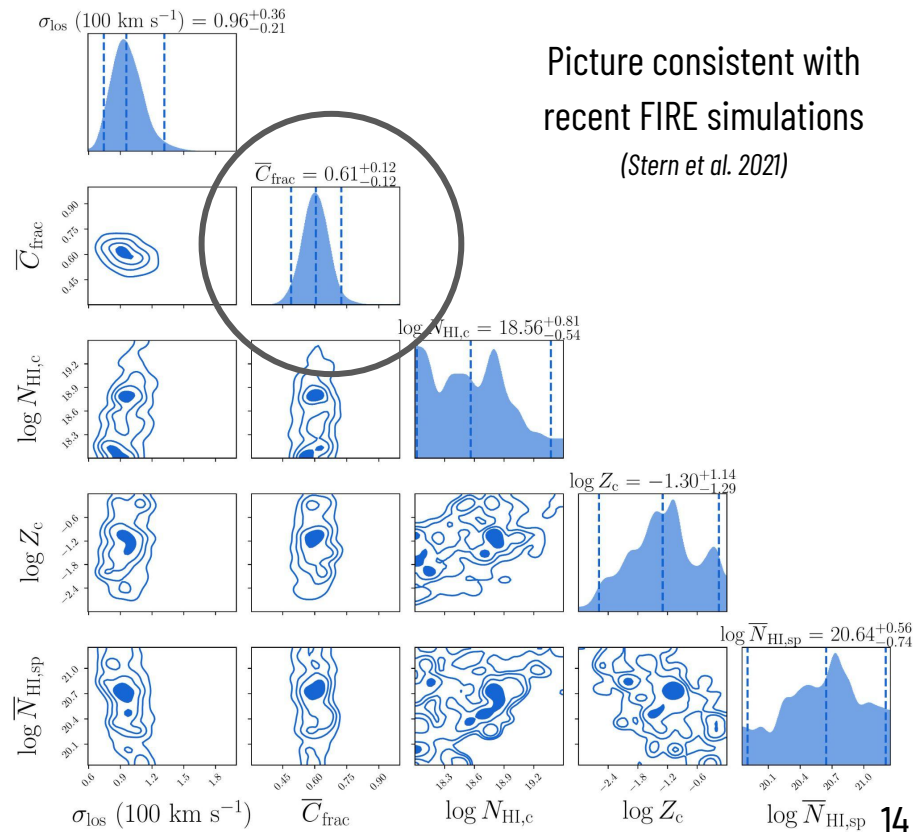
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A&A

J1527



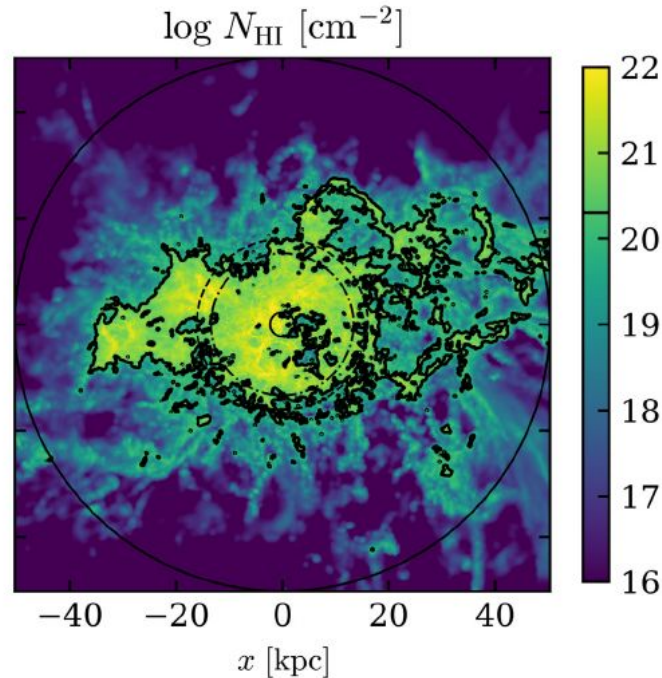
J0033



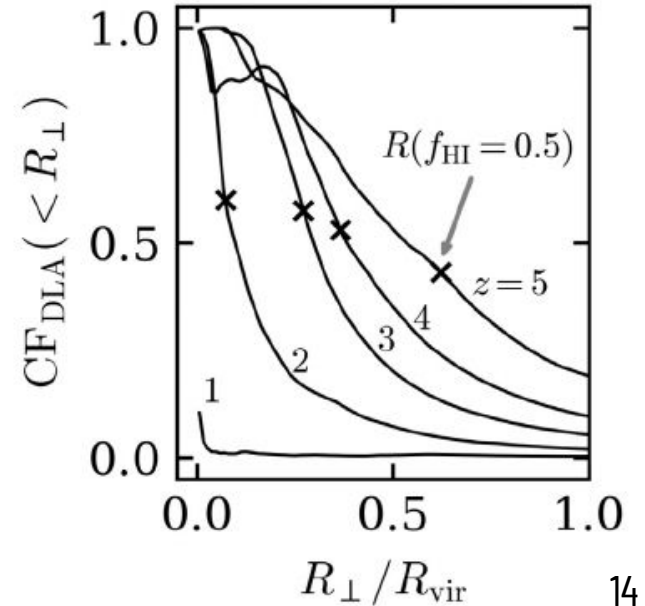
# Arc-tomography of DLAs

Berg, Afruni et al. 2024,  
accepted for publication  
A&A

**Picture consistent with FIRE simulations** (Stern et al. 2021)



Large covering fractions up to several  
tens of kpc from the galaxy





# Arc-tomography of DLAs

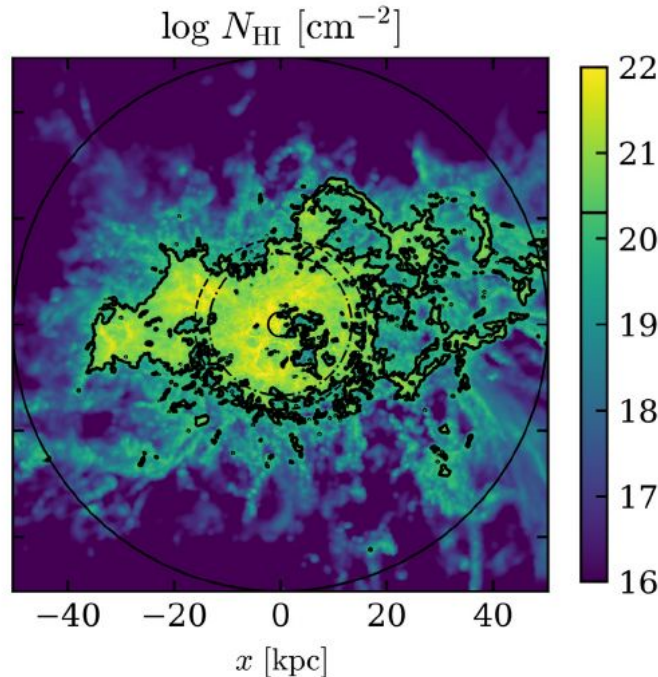
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A&A

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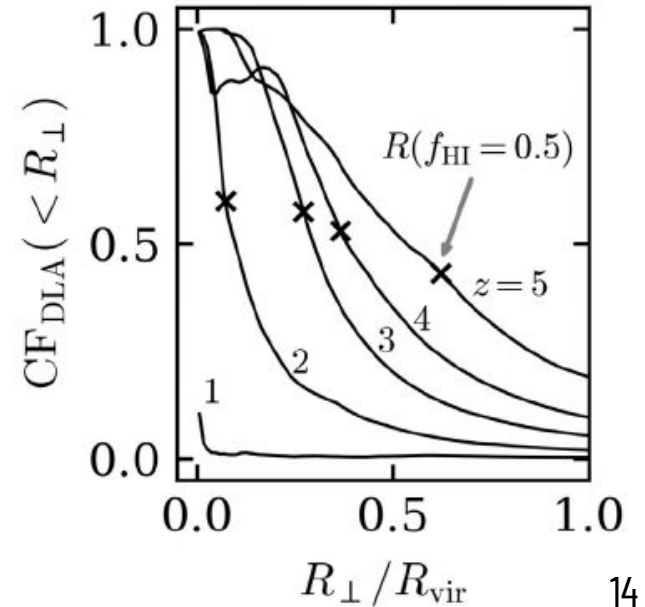
We estimate **HI masses**  $\gtrsim 10^9 M_{\odot}$



If inflowing, large amount  
of **fuel for future star  
formation!**



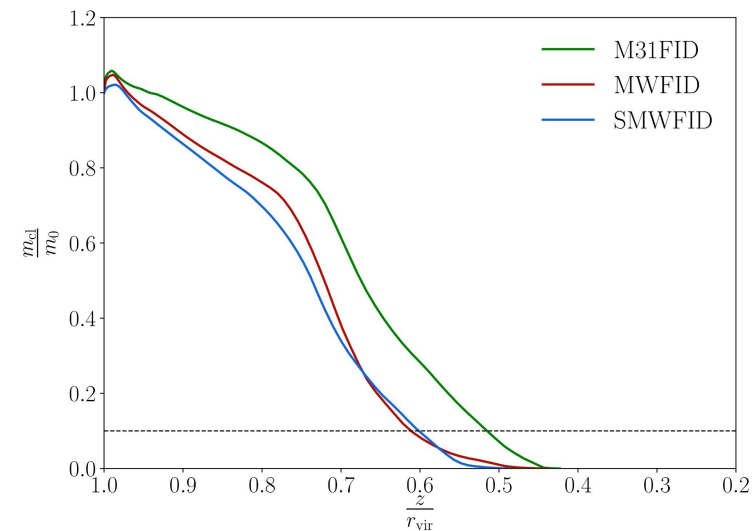
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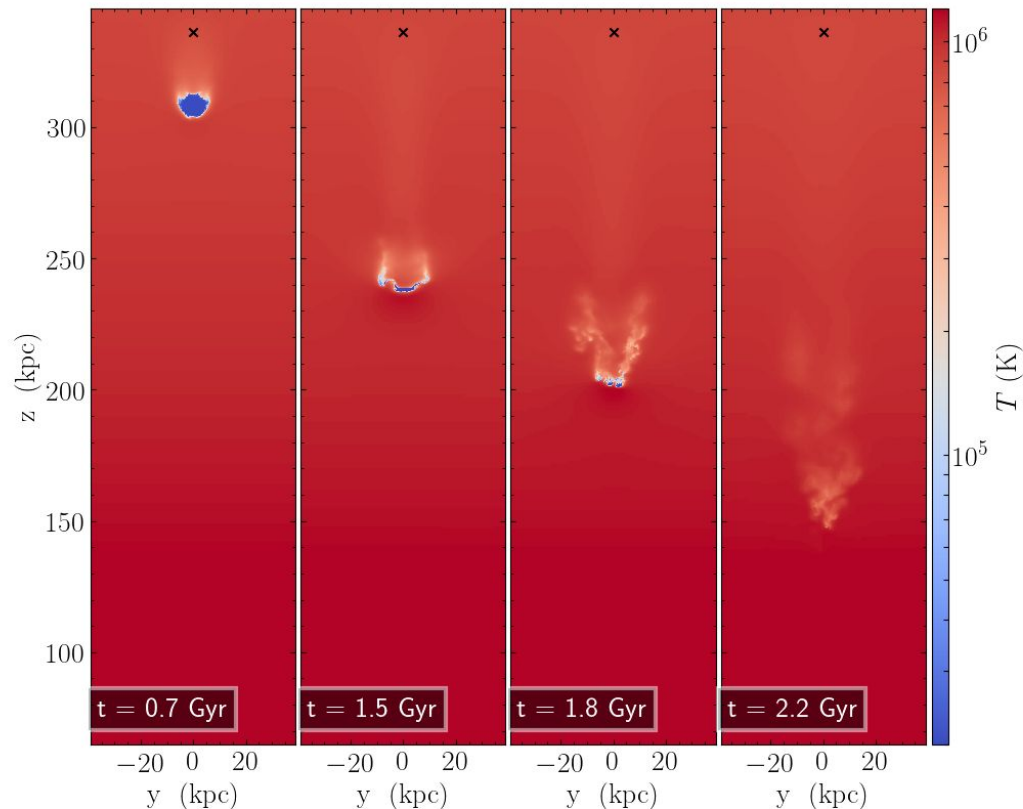
# Accretion of clouds from the IGM

*Afruni et al. 2023*

High-resolution (few tens of pc)



The cloud is **destroyed** by the interactions with the hot gas

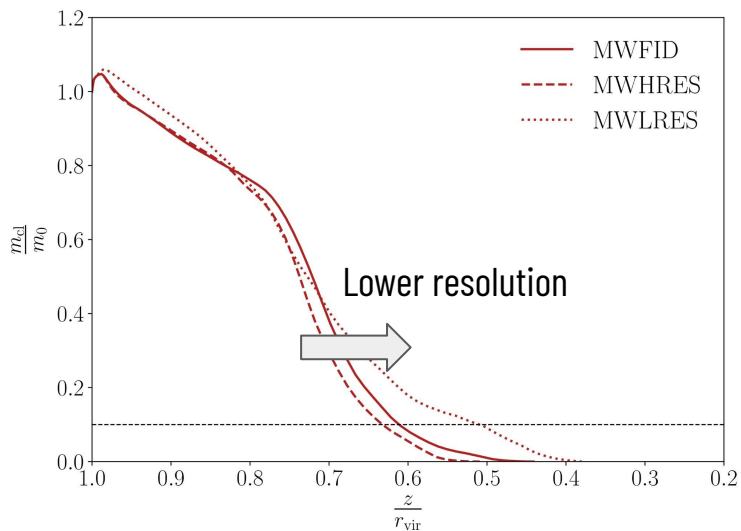




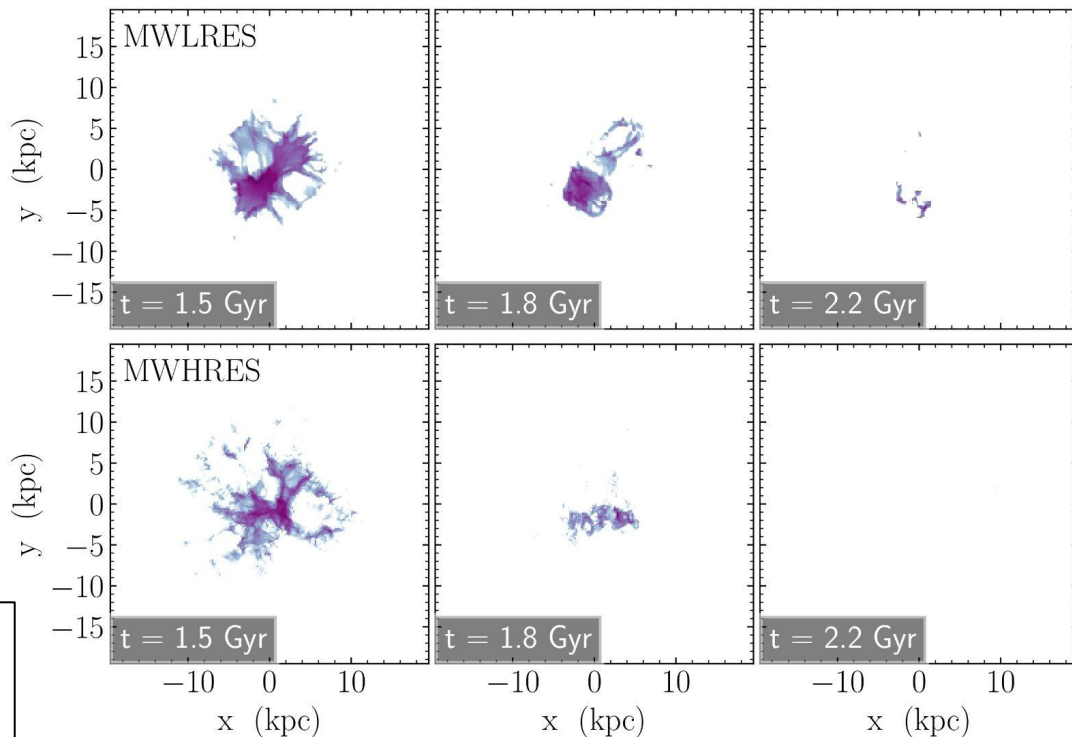
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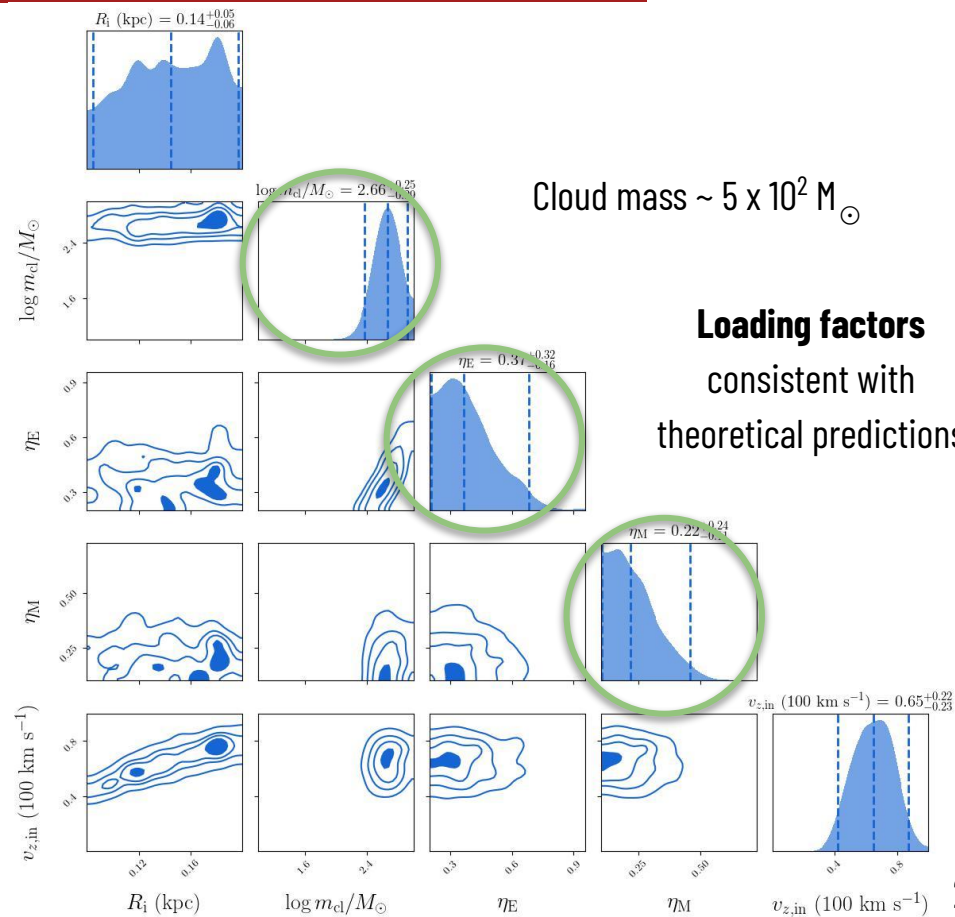


**High resolution** is crucial to capture **cloud fragmentation** → Shorter survival time!



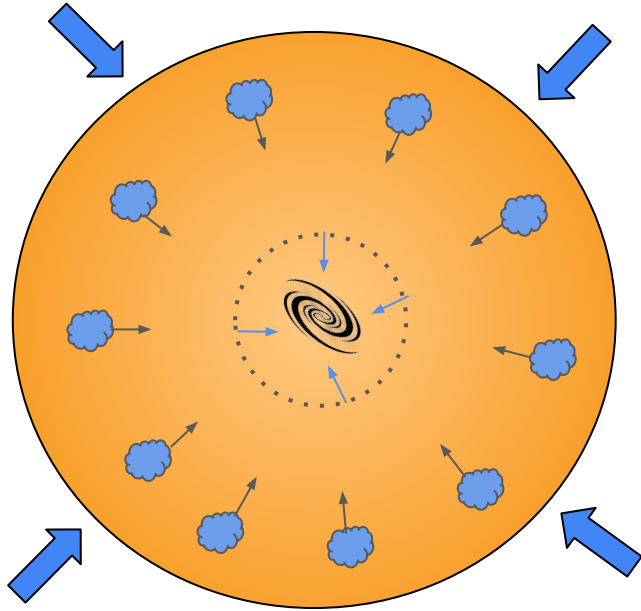
# HI clouds near the MW center

**Bayesian comparison between the kinematics of modeled and observed clouds**



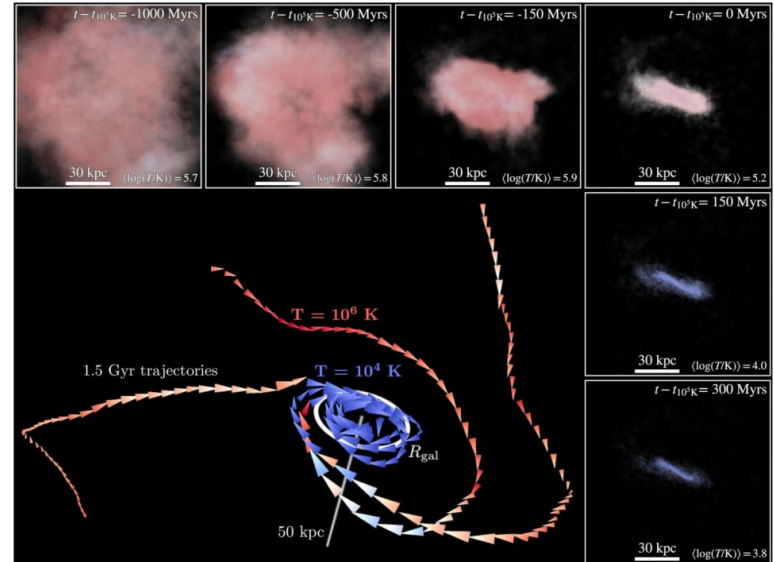
# The CGM of a MW-like galaxy

- Some of the cool gas accretes directly from the IGM
- Spontaneous cooling of hot gas (see also Stern et al. 2019, 2021)

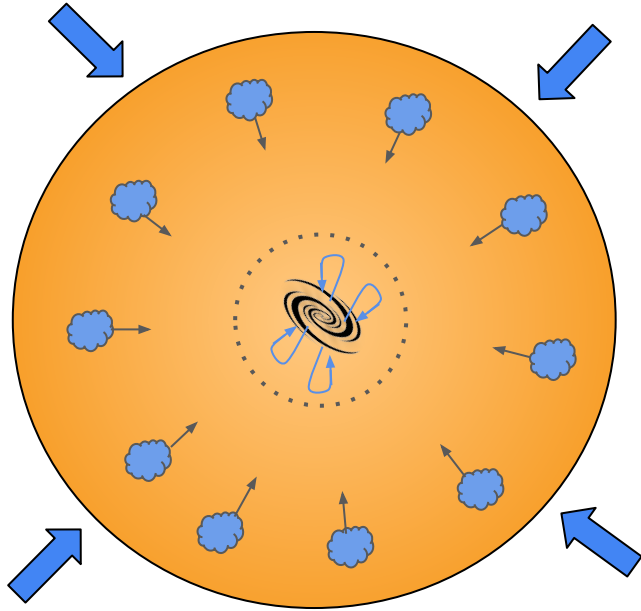


How does the CGM accrete onto the galaxy?

Hafen et al.  
2022



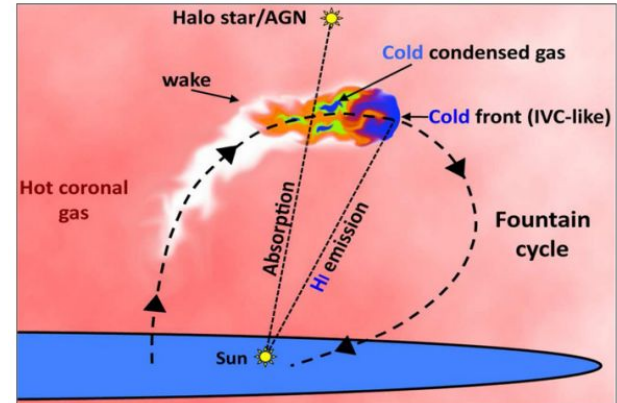
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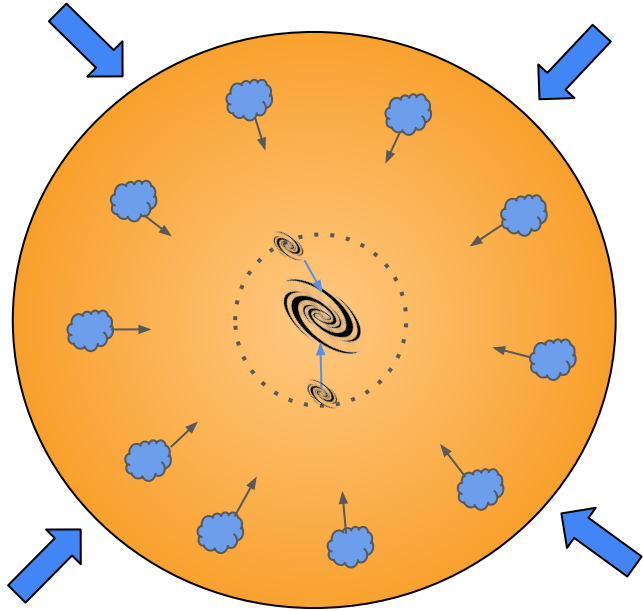
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- Induced accretion by galactic fountain (see also Marinacci et al. 2010, Armillotta et al. 2016, Marasco et al. 2012, Fraternali 2017, Li et al. 2023, Barbani et al. 2023)

*Fraternali et al. 2013*



# The CGM of a MW-like galaxy



- Some of the cool gas accretes directly from the IGM
- Spontaneous cooling of hot gas (*see also Stern et al. 2019, 2021*)
- Induced accretion by galactic fountain (*see also Marinacci et al. 2010, Armillotta et al. 2016, Marasco et al. 2012, Fraternali 2017, Li et al. 2023, Barbani et al. 2023*)
- Stripping from satellite galaxies (*see e.g. Johnson et al. 2018, Poggianti et al. 2017, 2019, Putman et al. 2021, Moretti et al. 2023*)

How does the CGM accrete onto the galaxy?