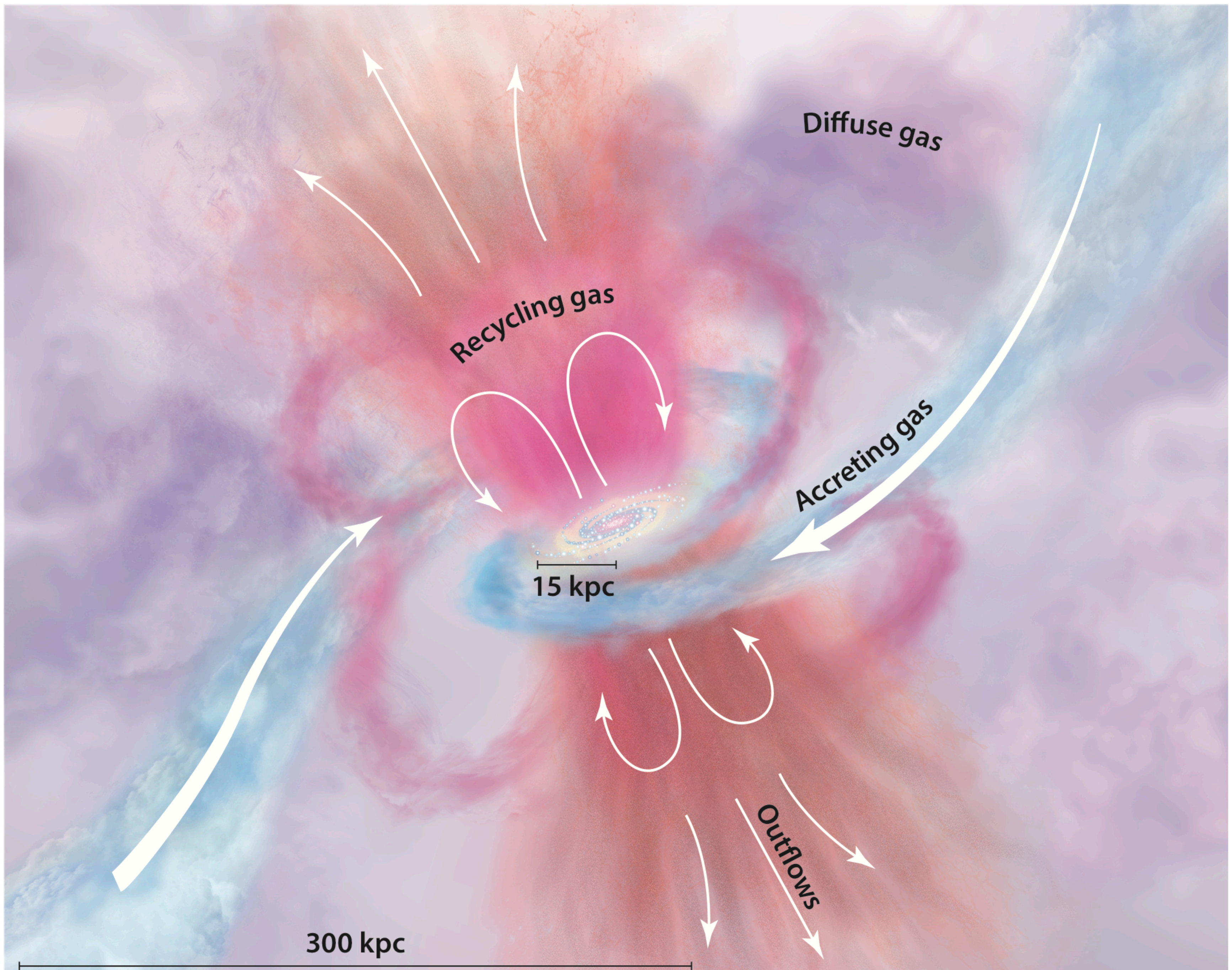
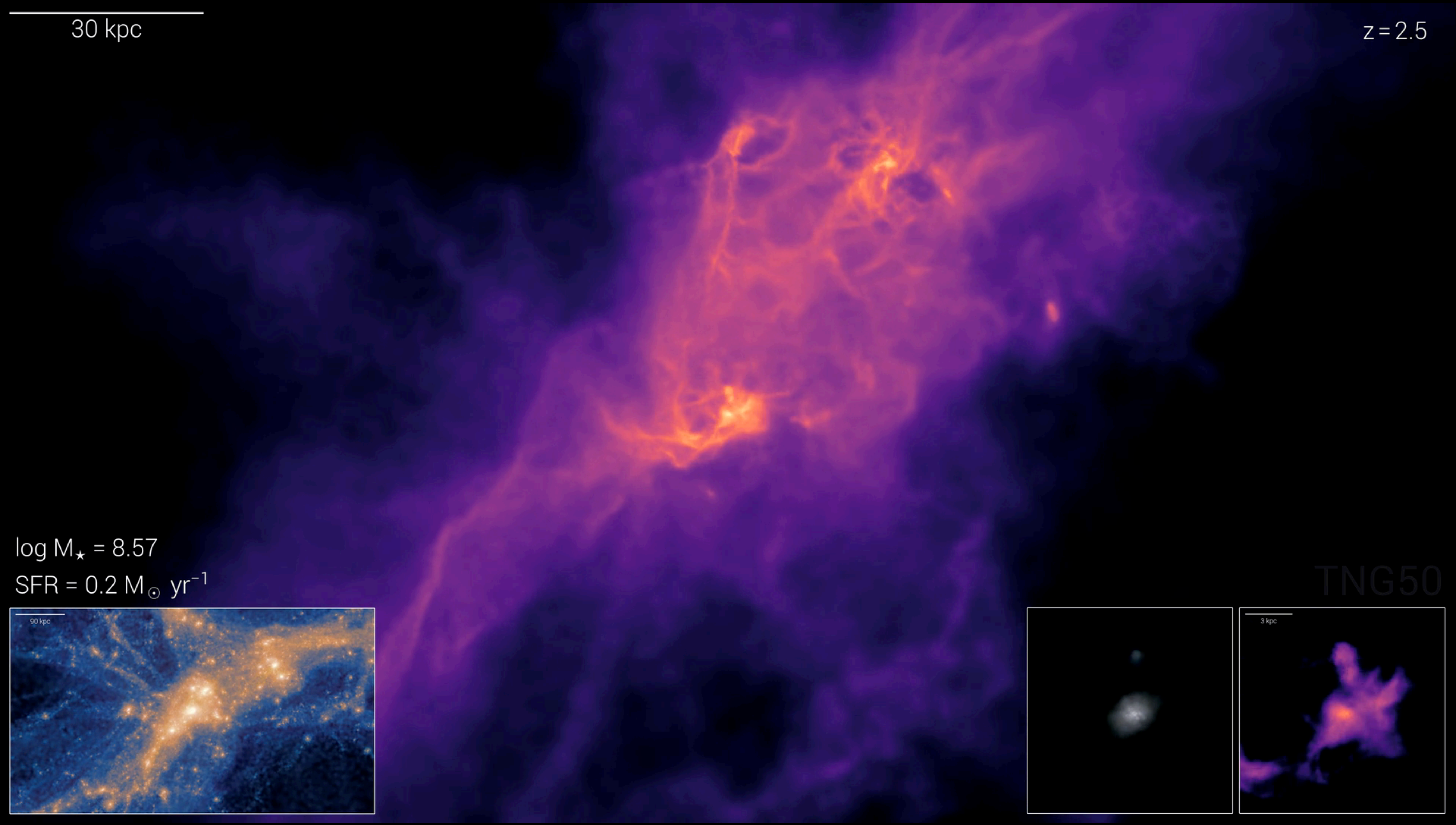
Observations of the Circum-Galactic Medium

Celine Peroux (ESO, Garching)

The CGM is



Tumlinson, Peeples&Werk 17
Faucher-Giguère&Oh23, Chen&Zahedy24


30 kpc
z = 2.5
log $M_\star$ = 8.57
SFR = 0.2 $M_\odot$ yr^{-1}
TNG50
90 kpc
3 kpc

visualization Dylan Nelson

The IllustrisTNG Team

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Federico Marinacci
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Lars Hernquist
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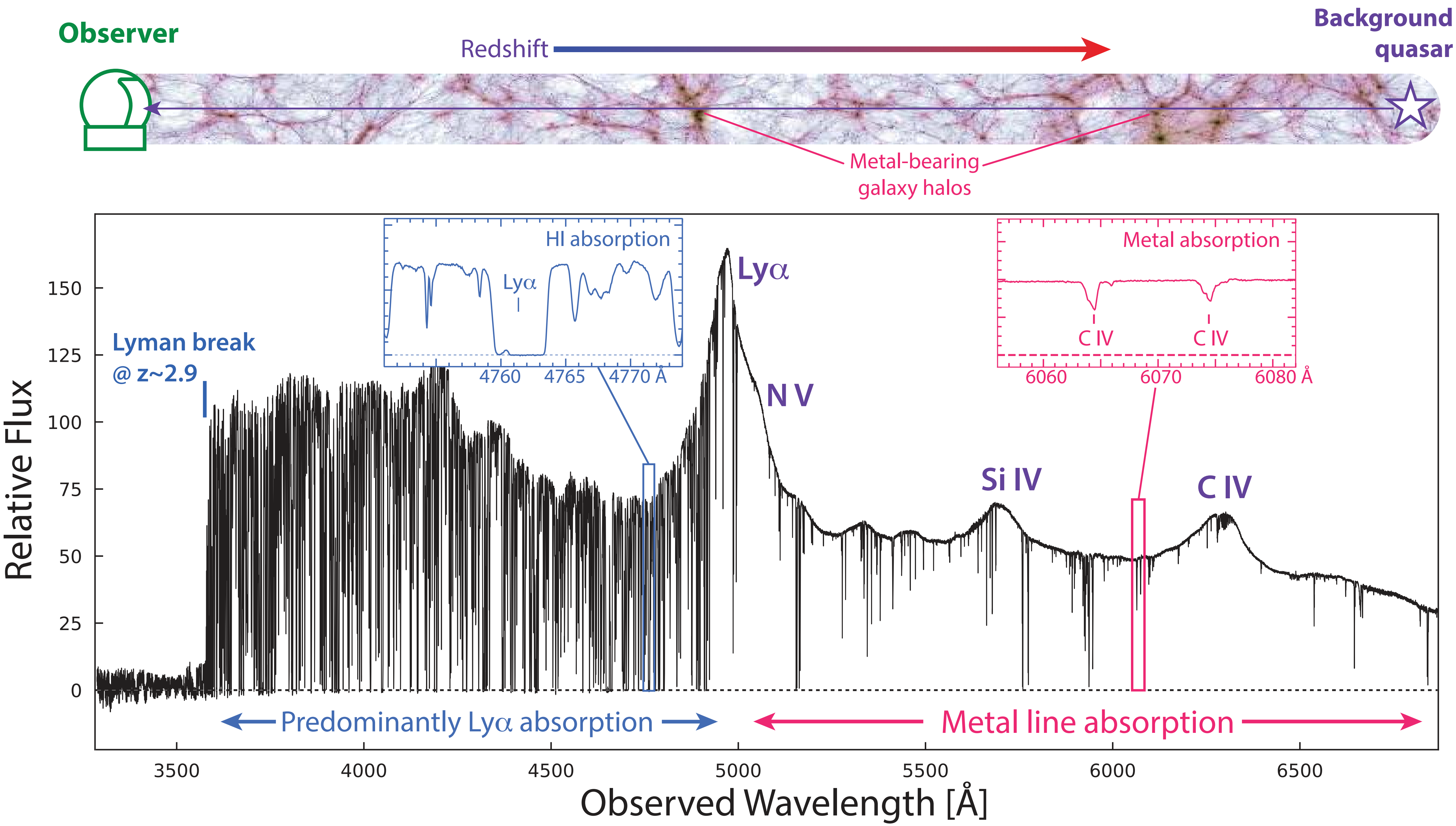
Volker Springel (PI)

(*) TNG50 Co-PIs

HITS CfA Max-Planck-Institut für Astrophysik GCS Gauss Centre for Supercomputing HLRS

TNG50

Absorption lines are powerful

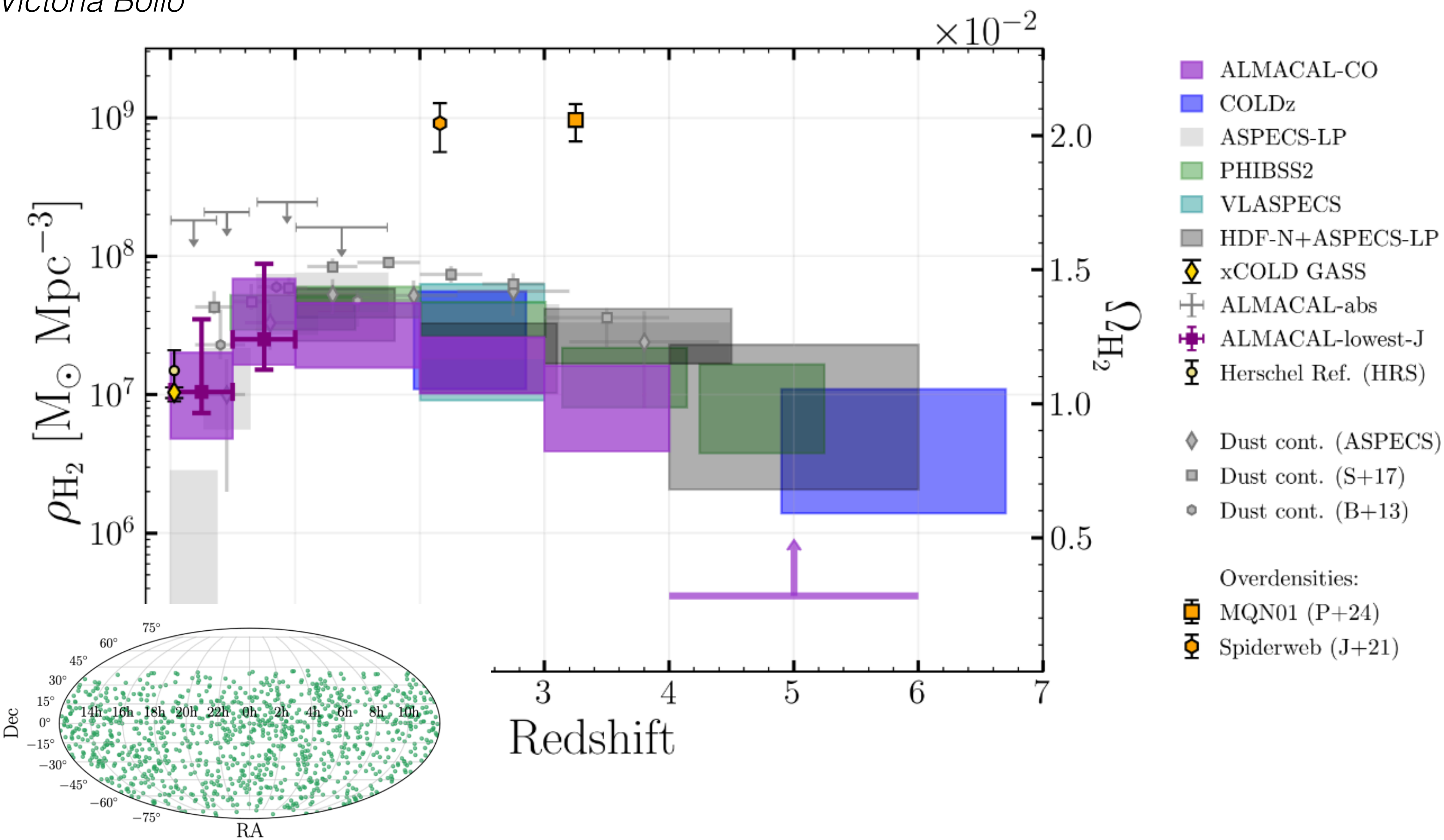


CP & Howk, ARAA, 20

1) Baryon cycle = accretion, star formation, feedback

Victoria Bollo

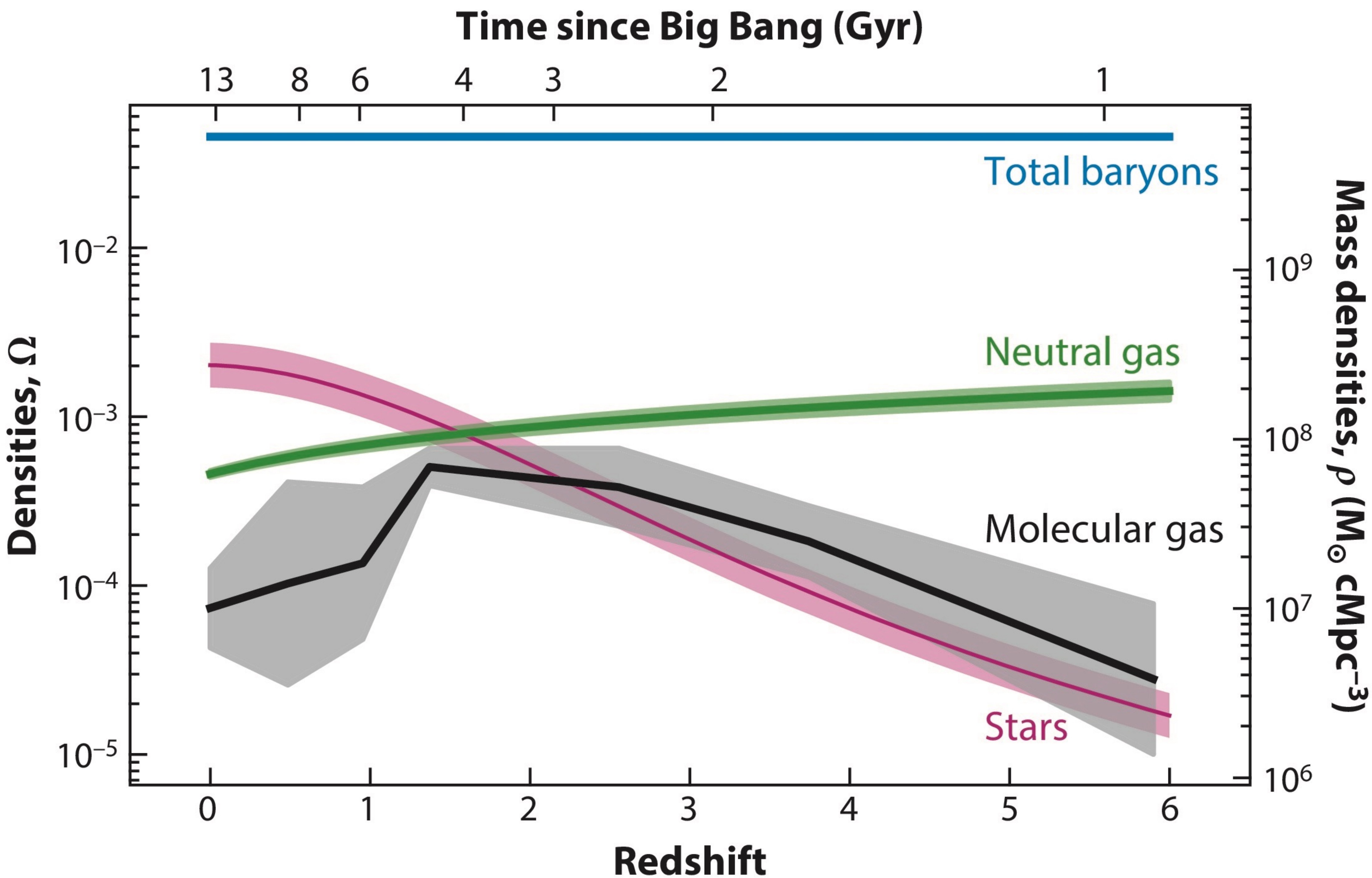
Molecular gas mirrors SFR history



Schinnerer & Leroy+24, Bollo,CP+25

Molecular gas mirrors SFR history

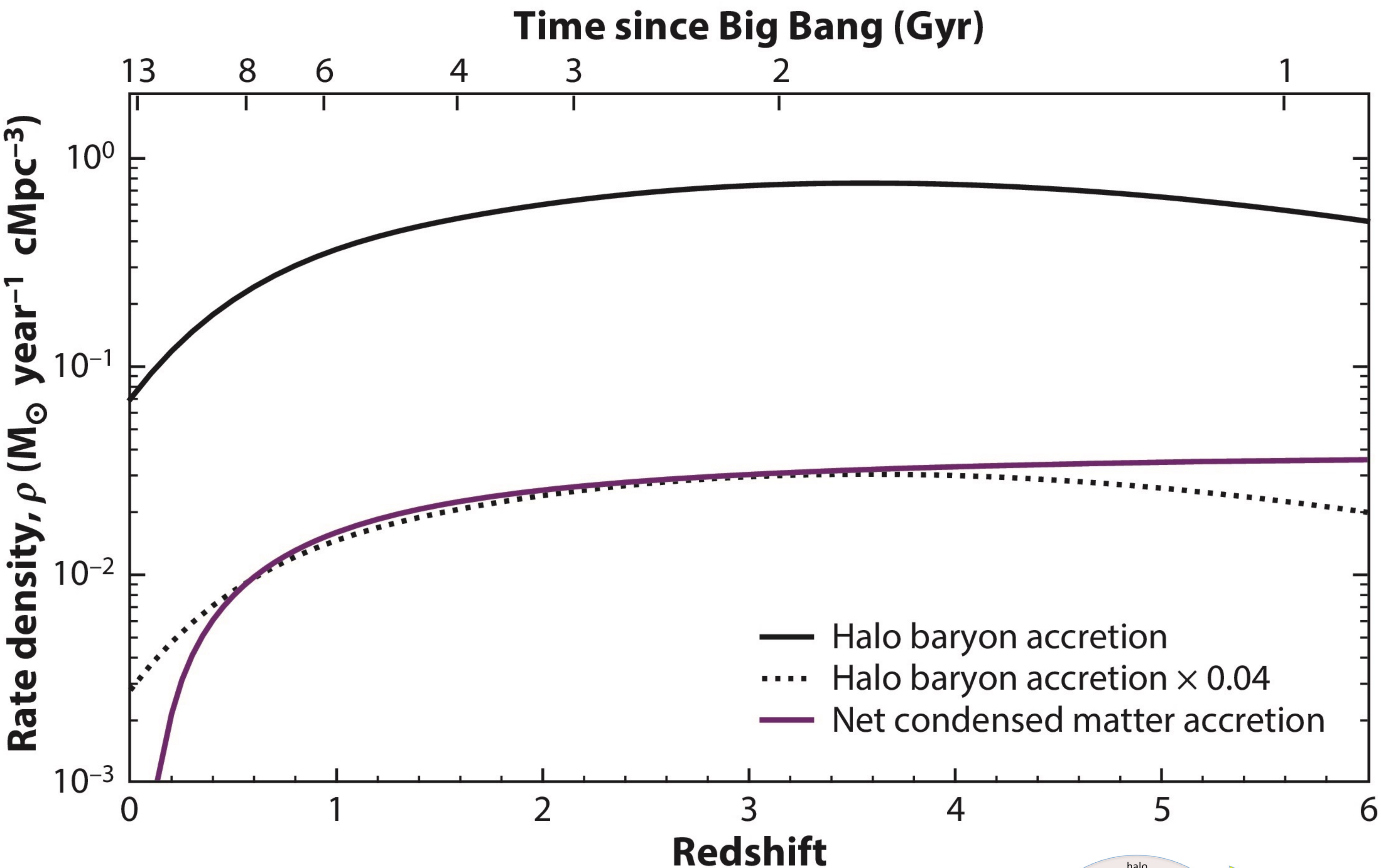
Pettini&Cooke+12, Driver+18, Walter+20, Semenov+21



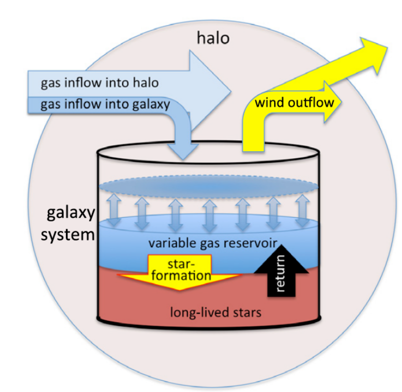
CP & Howk, ARAA, 20

Need for accretion of cold gas from IGM

Bouche+10, Lilly+13, Dekel+14,
Peng&Maiolino14, Tacconi+20, Tacchella+23

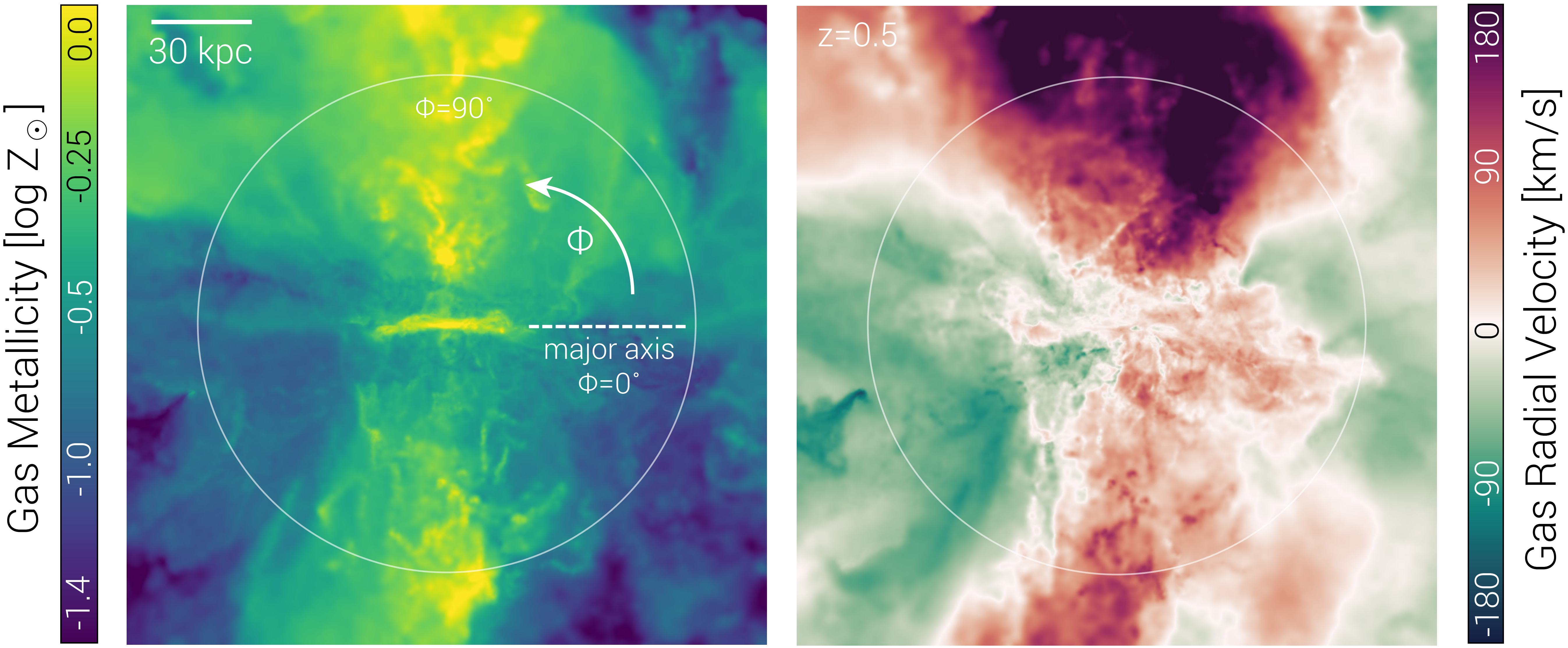


➥ *bathtub/regulator model*



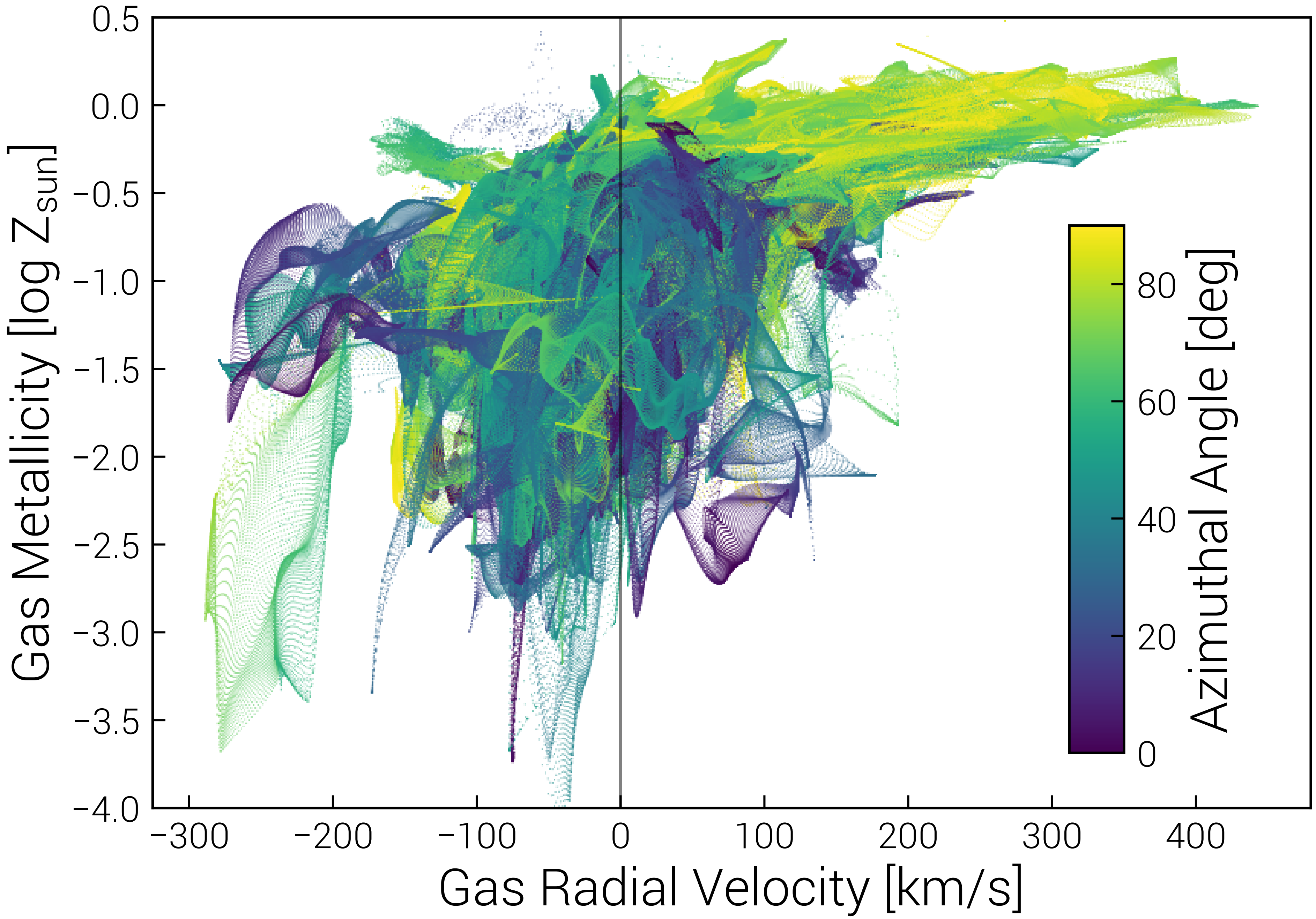
2) Observational signatures of feedback

CGM physical properties vary with angular orientation in cosmo simulations



CP, Nelson+20*, Welker+20, Galarraga-Espinosa+22, Barsanti+22*

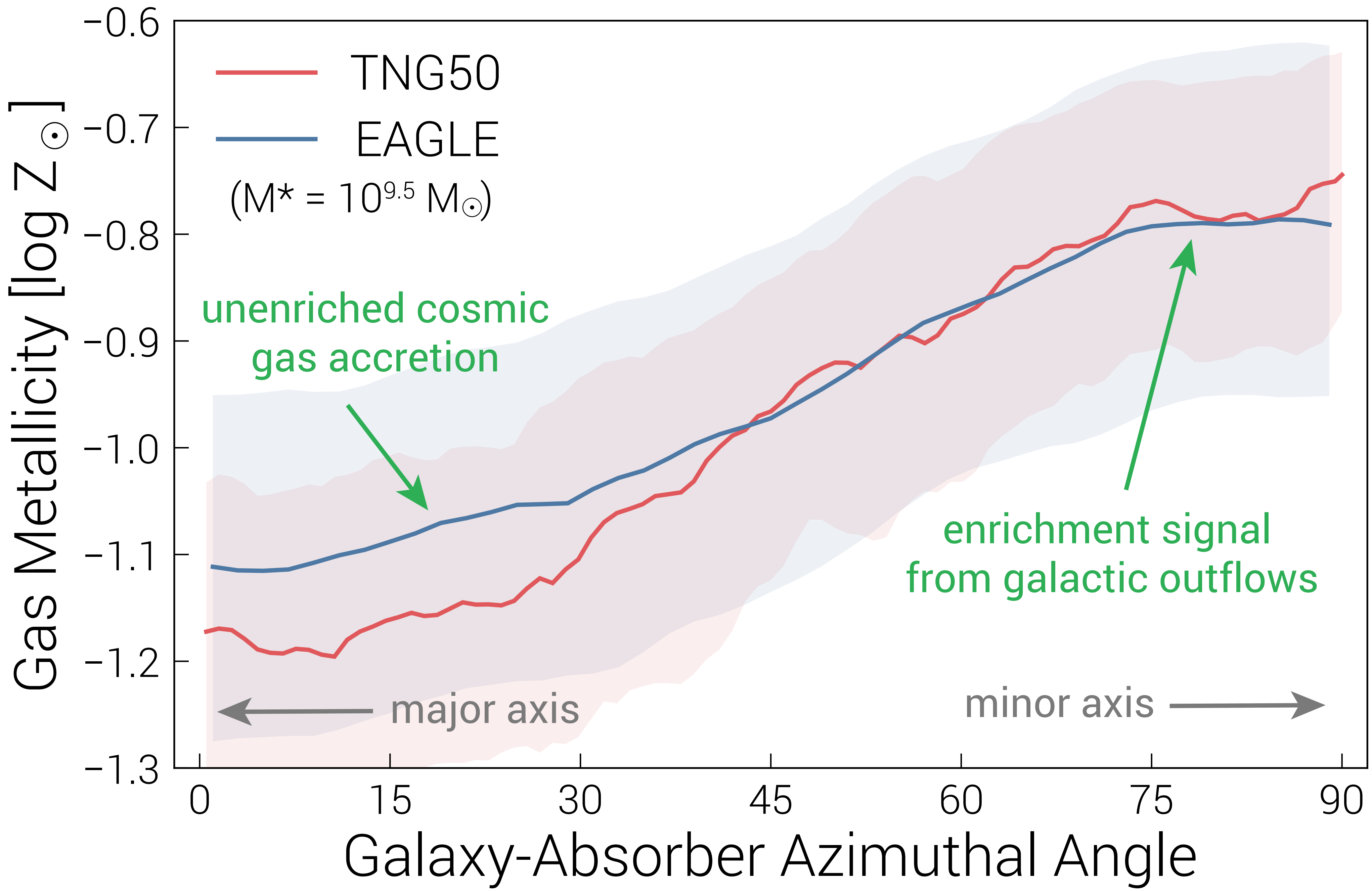
Outflows have higher metallicity than inflows



CP, Nelson+20

- https://www.tng-project.org/peroux20/

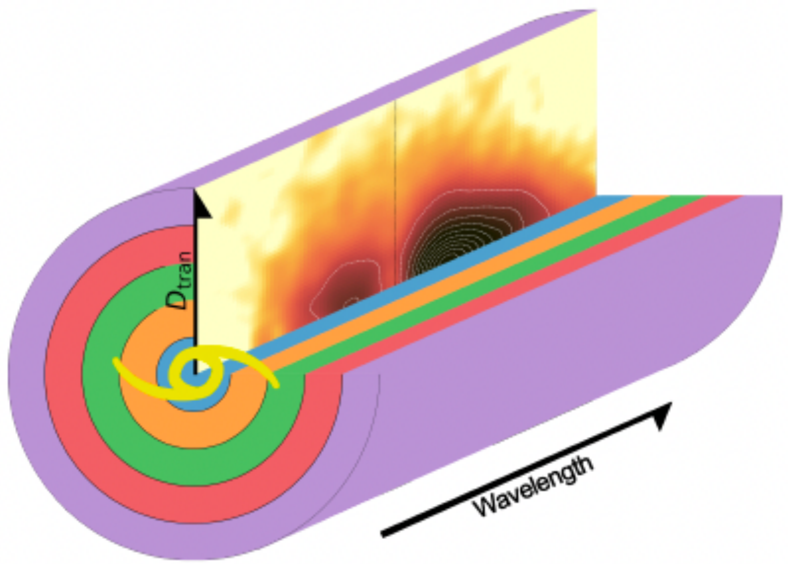
Metallicity is higher along the minor versus major axes of galaxies

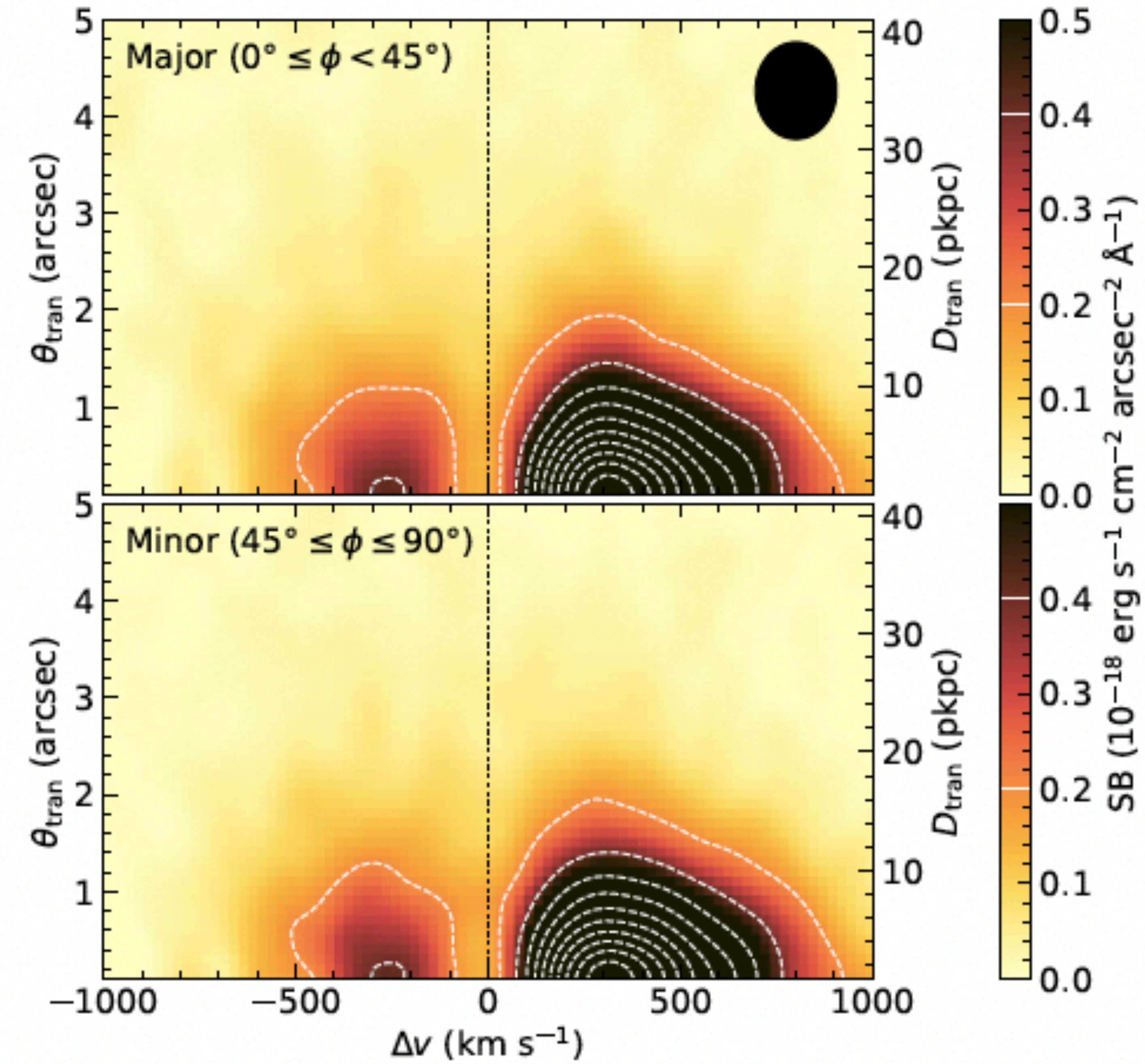


CP, Nelson+20,
van de Voort +21, Wendt+21

➥ Two readily observable quantities

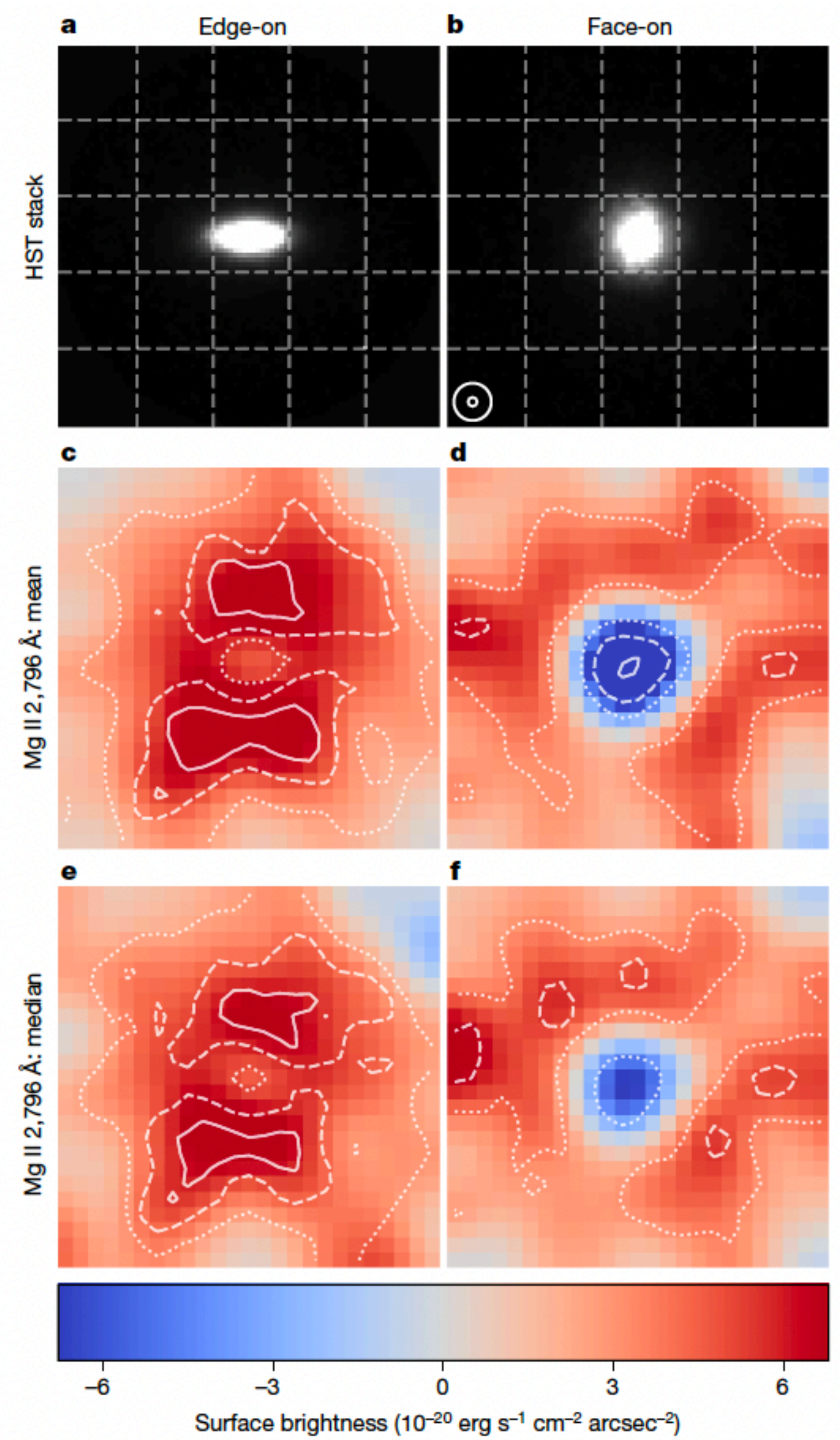
Ly-alpha stacking





Garel, Blaizot+21,
Chen, Steidel+21,
Kimm+22, Blaizot+23

MgII emission stacking

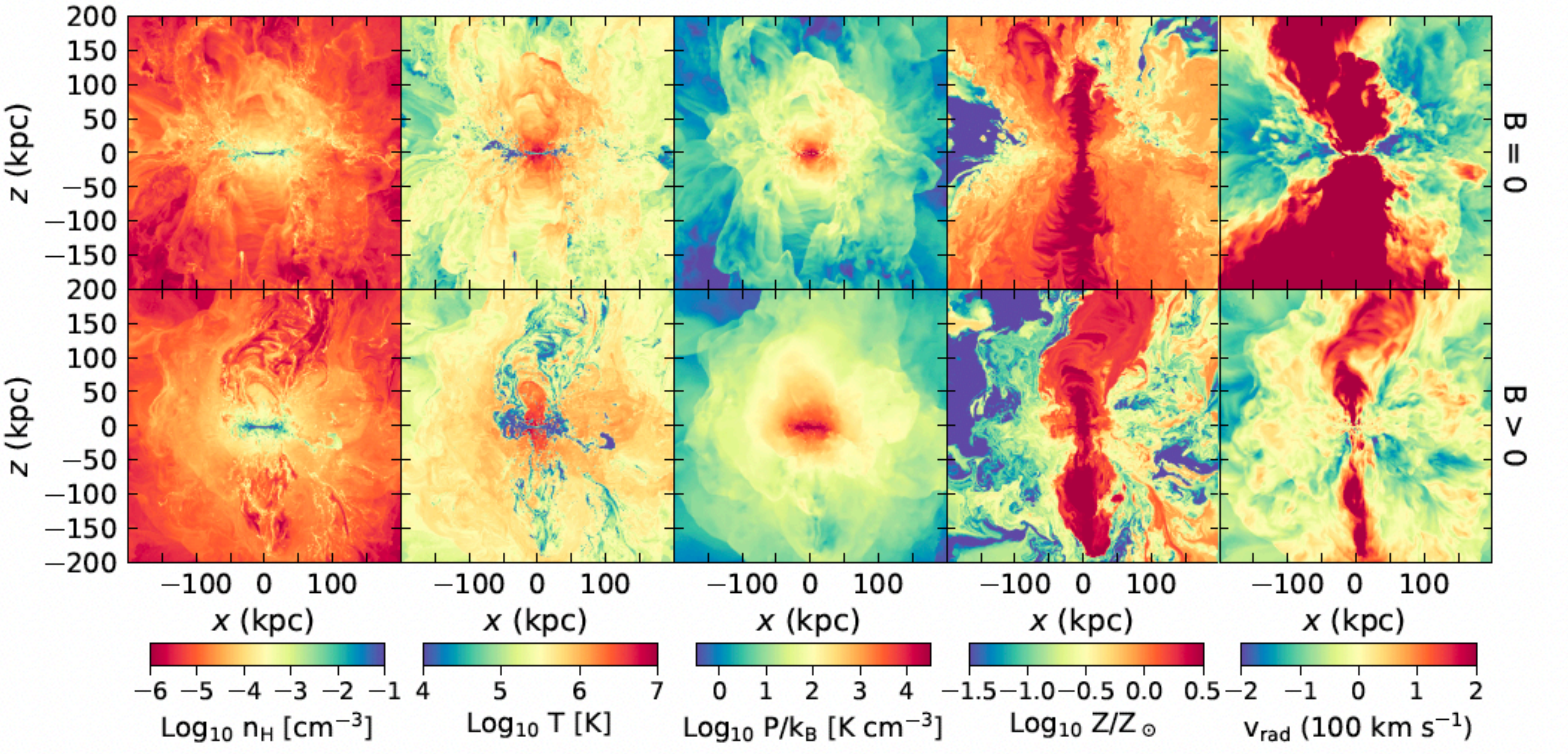


Nelson+21, Katz+22, ***Guo+, Nature, 23****, Pessa+24*

3) Multi-physics, multi-phase circumgalactic medium

Multi-physics CGM

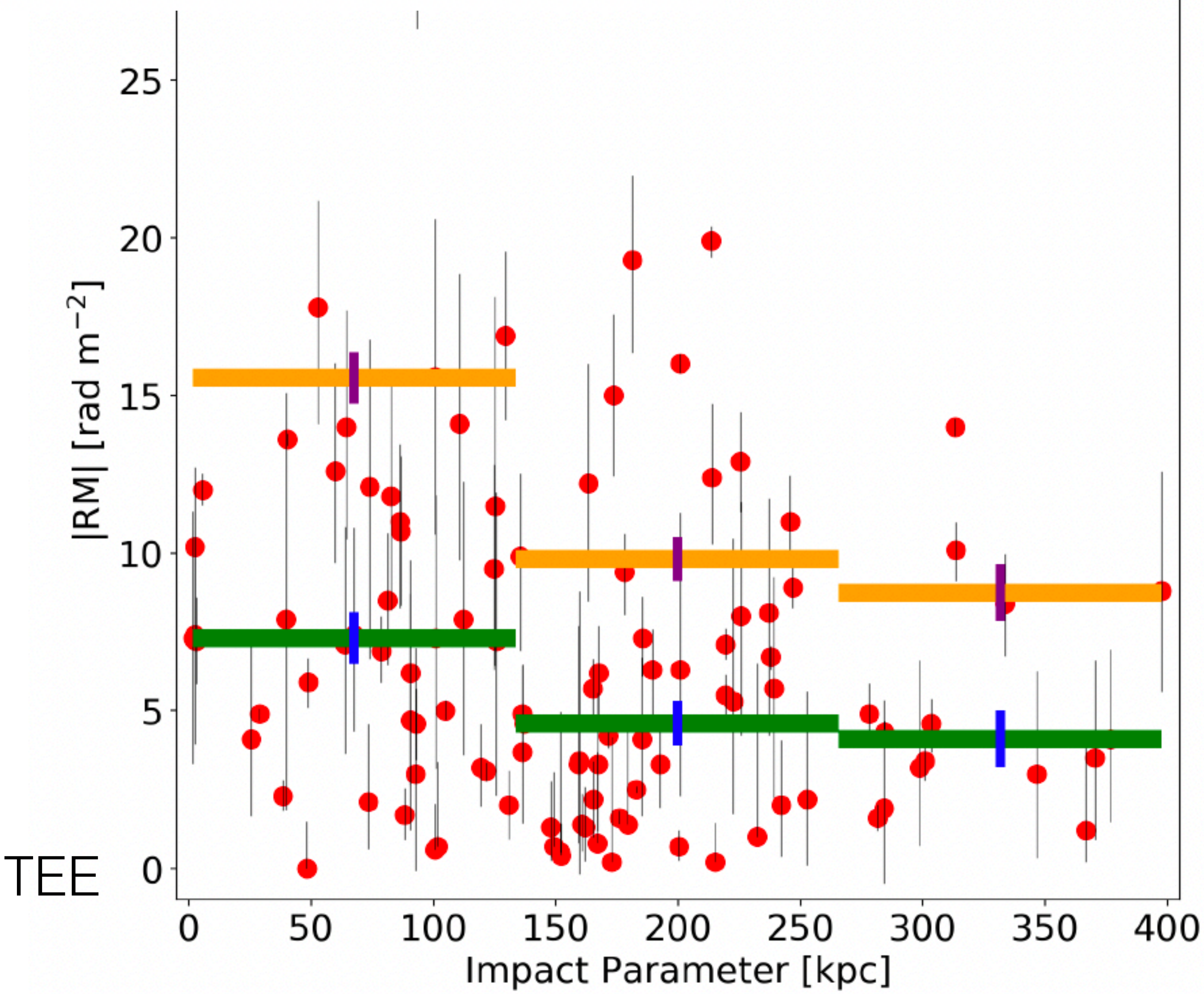
Mag Fields detected in CGM



*Pillepich+18, **van de Voort+21**, Pfrommer+22, Ramesh+23, Pakmor+22, 23*

Mag Fields detected in CGM

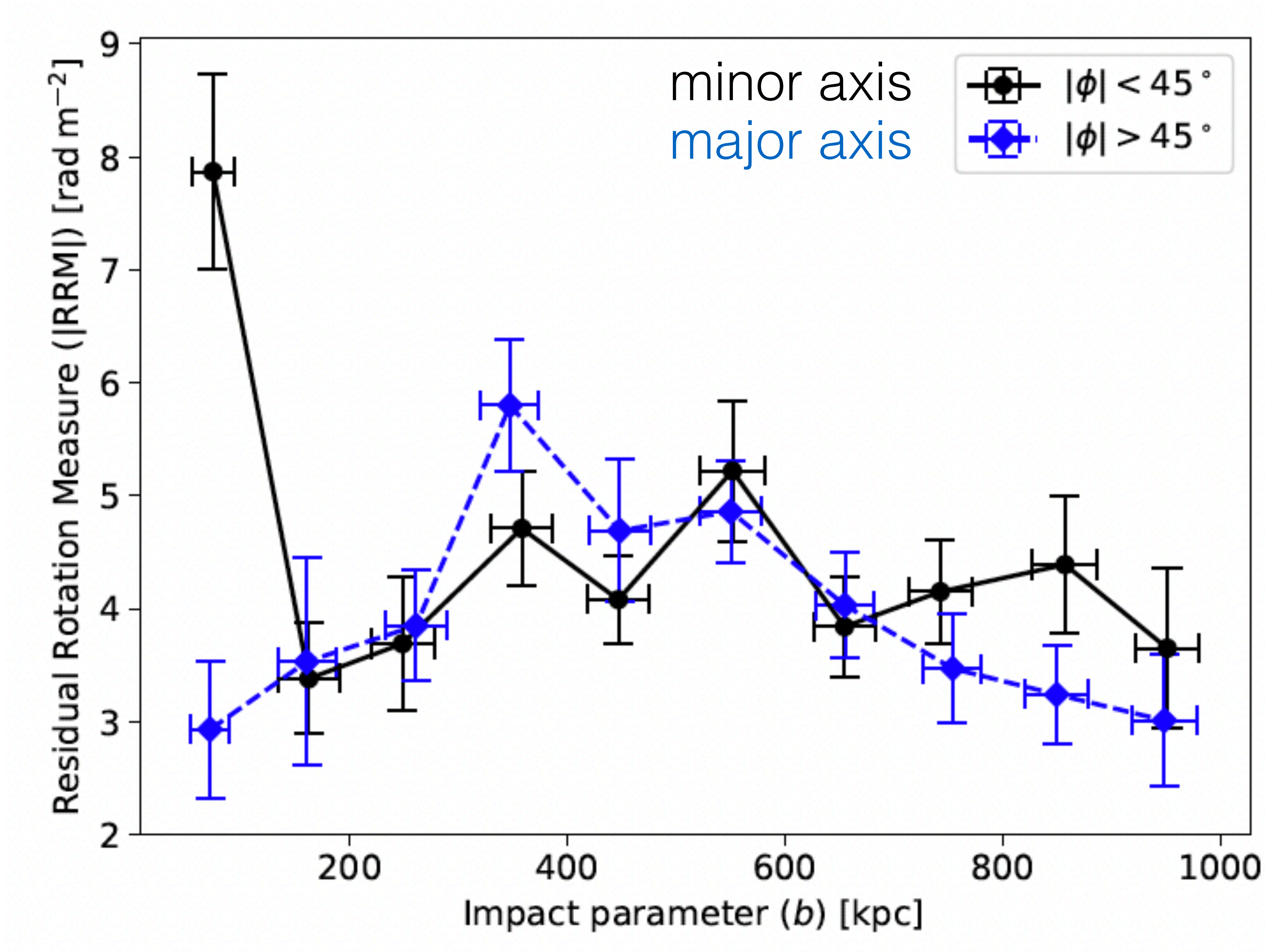
$$RM_{\rm obs} = RM_{\rm int} + RM_{\rm ex-gal} + RM_{\rm MW,CGM} + RM_{\rm MW,ISM} + RM_{\rm err}.$$



MeerKAT/MIGHTEE

Heesen+23, Bockmann+23, *Mannigns+23*
van de Voort+21, Ramesh+23, Pakmor+22, 23

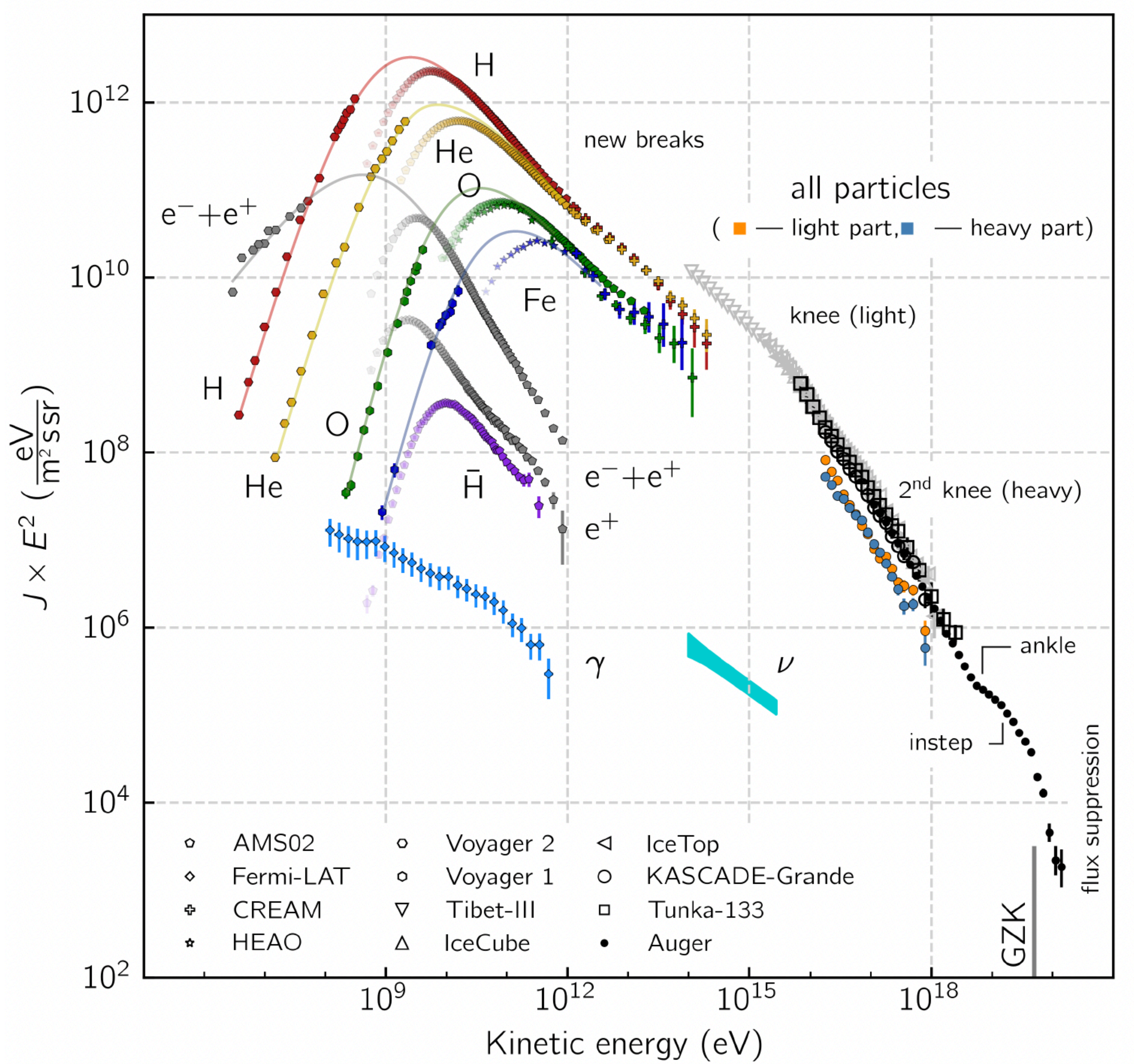
Mag field is higher along the minor versus major axes of galaxies



LOFAR

Heesen+23, *Bockmann+23, van de Voort+21, Ramesh+23,Pakmor+22, 23*

Cosmic rays



Zweibel+17, Semonov+21, Ruszkowski&Pfrommer ARAA+23, DeFelippis+24

Multi-phase CGM

The Multi-Scale Multi-Phase Circumgalactic Medium: Observed and Simulated

Lecture notes for the 52nd (March 2023) Saas-Fee Advanced School, Switzerland.

Céline Péroux & Dylan Nelson

Hands-on to analyzing cosmological galaxy formation simulations

[Hands-on #4] The baryon cycle: measuring mass flow rates

So far we have only looked at the distribution of gas in galaxies and halos, and the physical properties of that gas. What about how this gas is moving? We can consider the amount (i.e. rate) of gas inflow, and gas outflow, through the CGM.

The radial mass flux can be computed as

$$\dot{M} = \frac{\partial M}{\partial t} = \frac{1}{\Delta r} \sum_i \left(\frac{\mathbf{v}_i \cdot \mathbf{r}_i}{|r_i|} m_i \right)$$

where the subscript i enumerates gas cells with masses m_i in a particular volume of space, which we can take as a spherical shell with some thickness Δr from the center of a (central) galaxy. Each gas cell position $\mathbf{r}_i$ is **relative** to the subhalo center, and the velocity $\mathbf{v}_i$ is **relative** to the subhalo bulk motion.

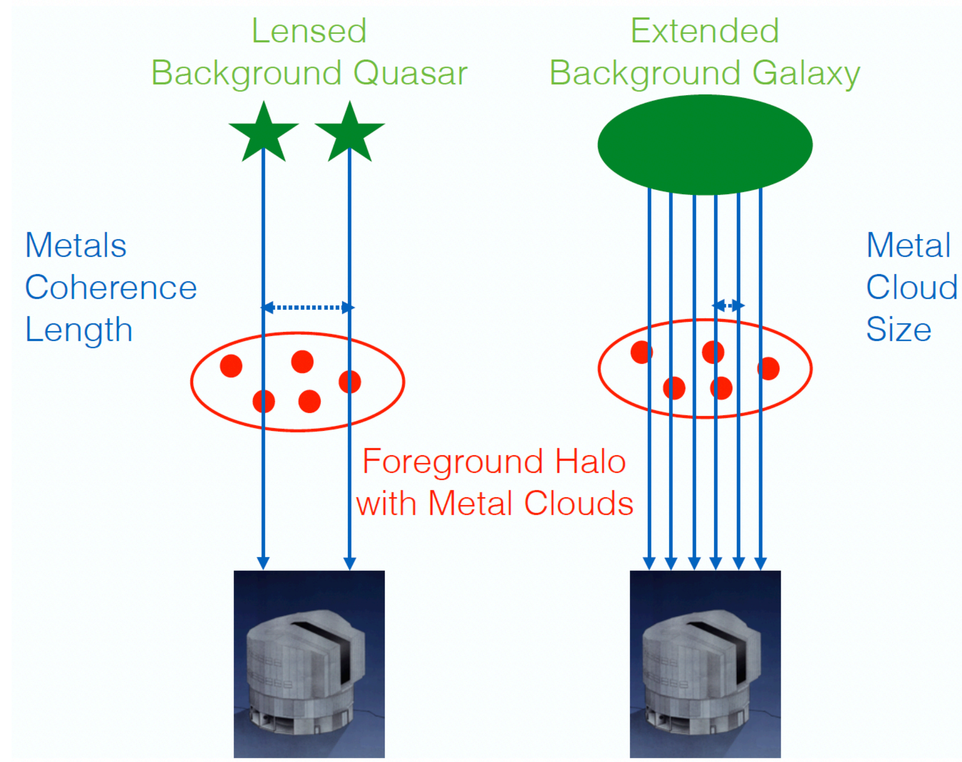
The term $\frac{\mathbf{v}_i \cdot \mathbf{r}_i}{|r_i|}$ is the radial velocity $v_{\rm rad}$, and if $v_{\rm rad} > 0$ we have outflow, while $v_{\rm rad} < 0$ denotes inflow.

Exercise

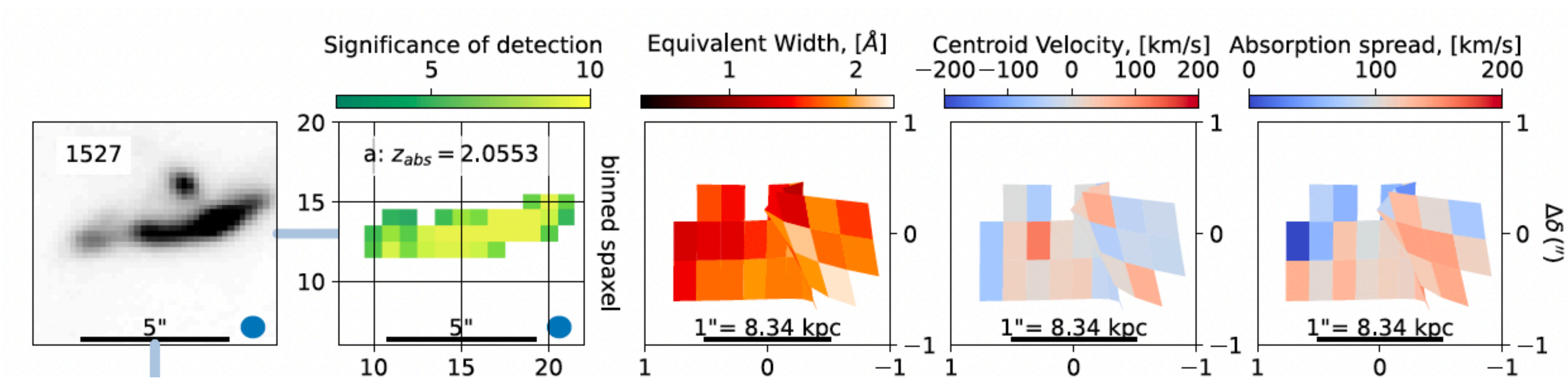
We will again focus first on a single halo.

1. Pick a simulation and redshift of interest. Pick a halo of interest. (e.g. try the 100$^{\rm th}$ most massive halo in TNG100-1 at $z = 0$).
2. Load the needed fields to compute the distance, and radial velocity, of each gas cell.
3. Use the distances to compute a radial mass density profile, i.e. in a number of bins of distance, sum up the total gas mass, and divide by the volume of that spherical shell. Plot the result in $M_\odot/{\rm kpc}^3$ as a function of distance in kpc.

Spatially extended bckgrd source

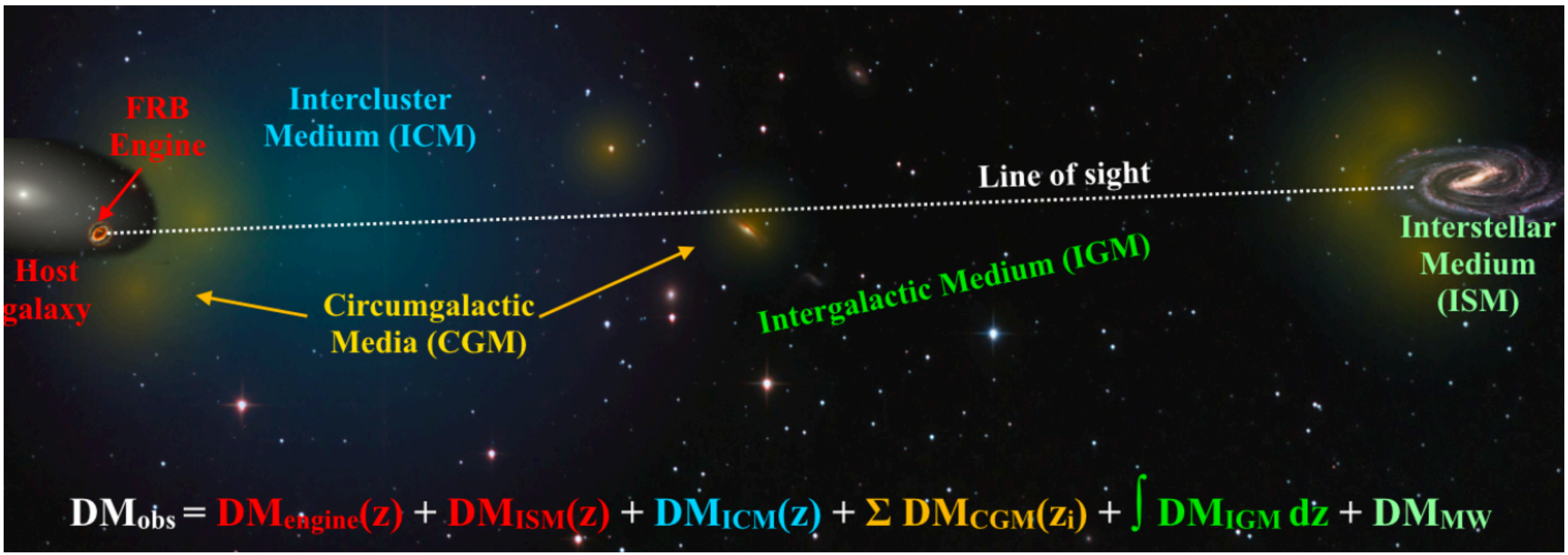


➥ JWST, ELT



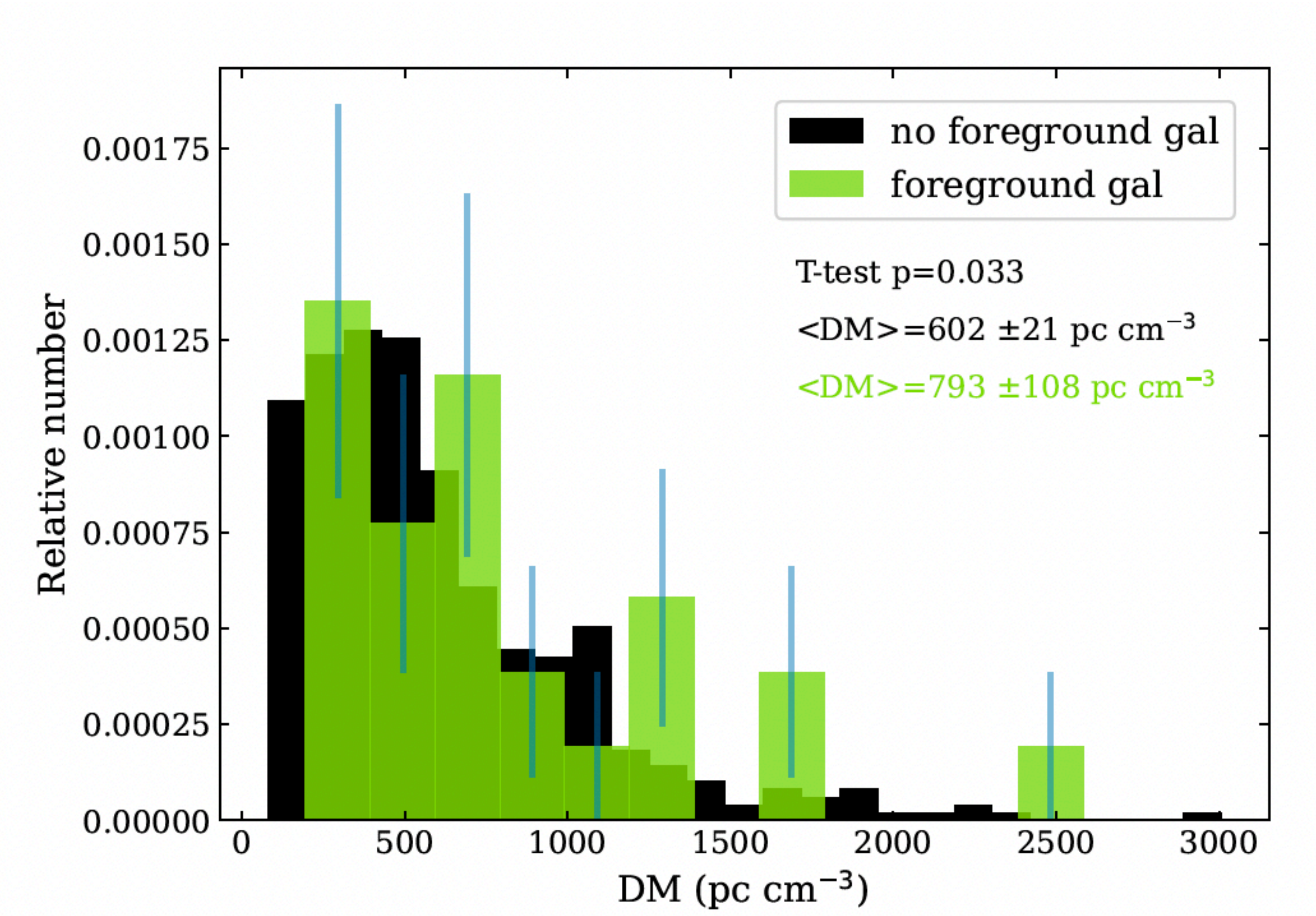
CP+18, Kreckel+20, Augustin+21, Afruni+23, *Lopez+24*

Alternative bckgrd sources: Fast Radio Bursts



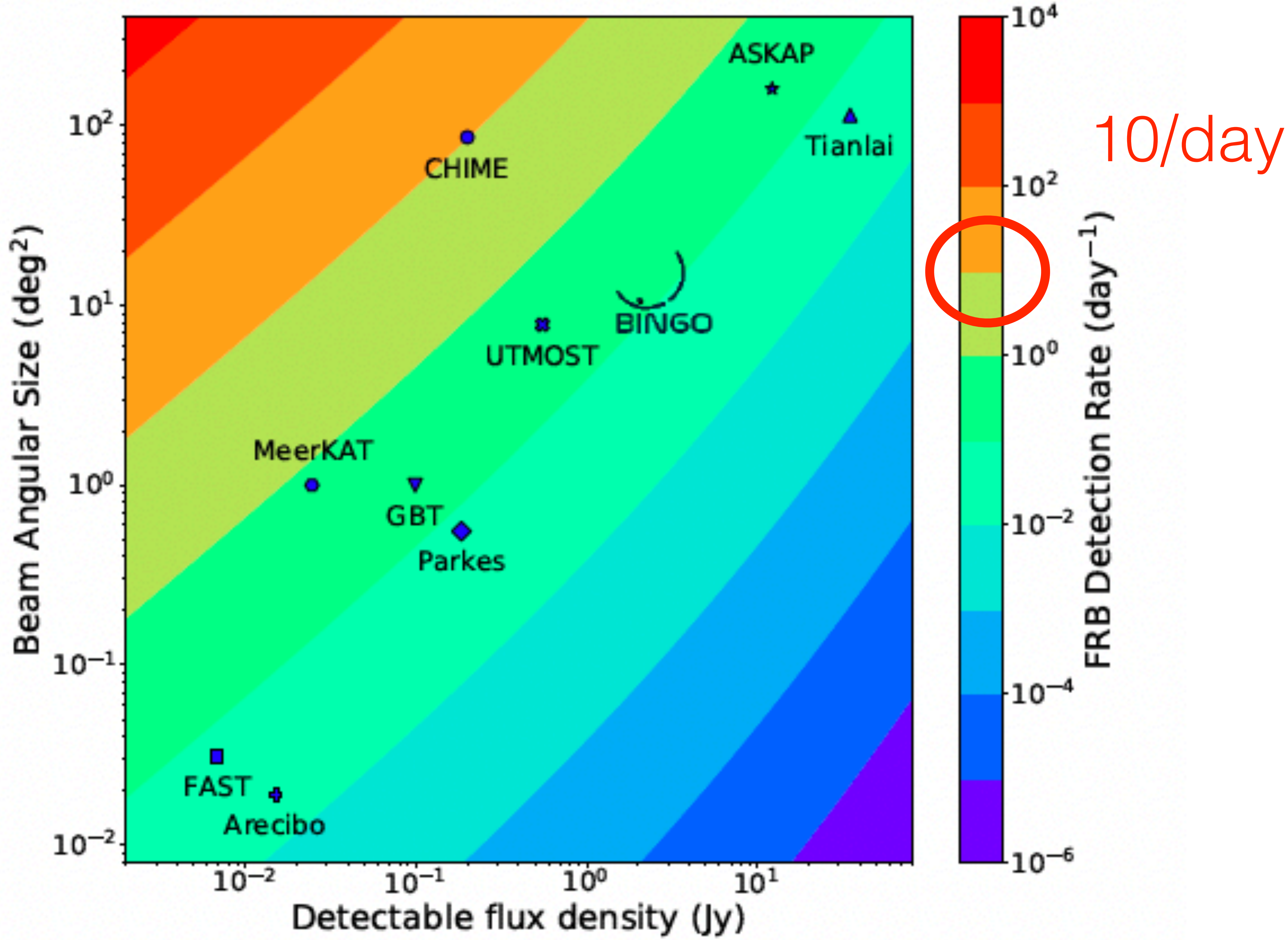
Ravi+19, Macquart+20

Fast Radio Bursts provide electron column density



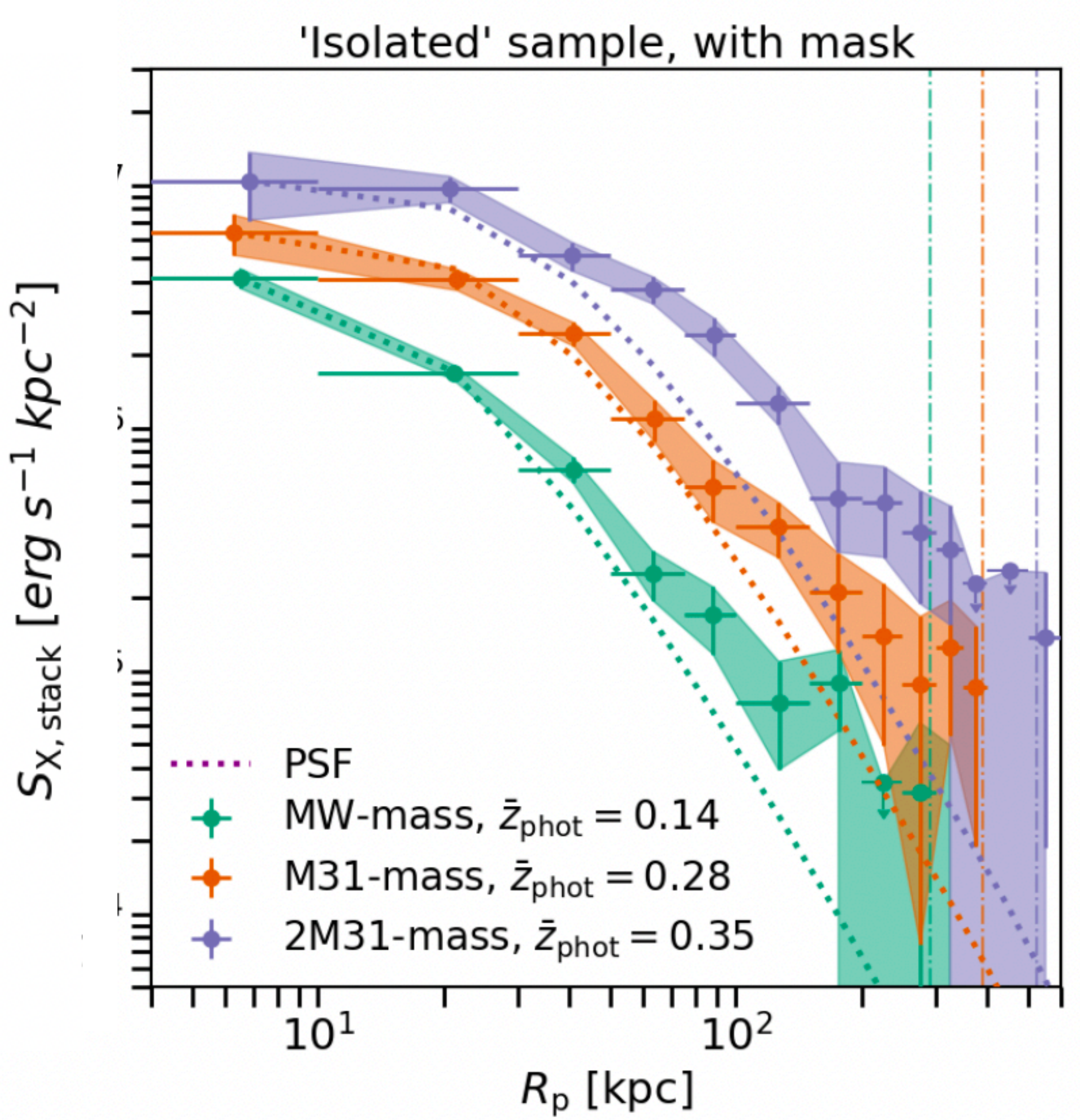
Connor+21

Large Samples of Fast Radio Bursts are coming



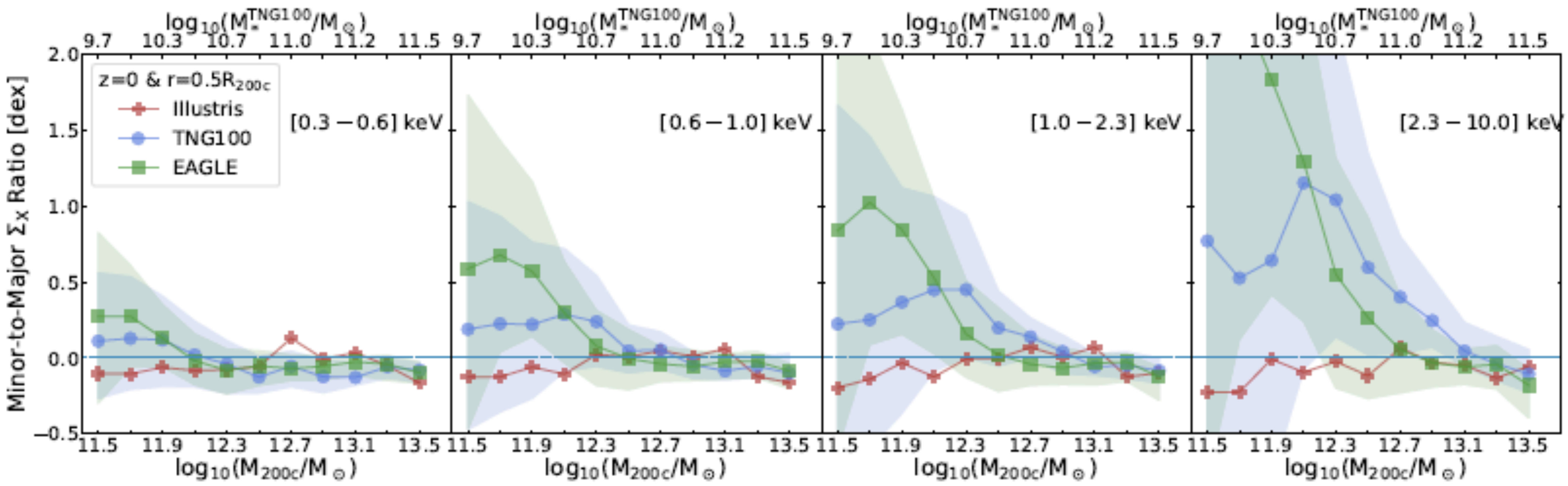
Abdalla+21

Early detection in galaxy stack



Comparat+22, Chadayammuri+22, Zhang Yi+24a, 24b, Tanimura+22

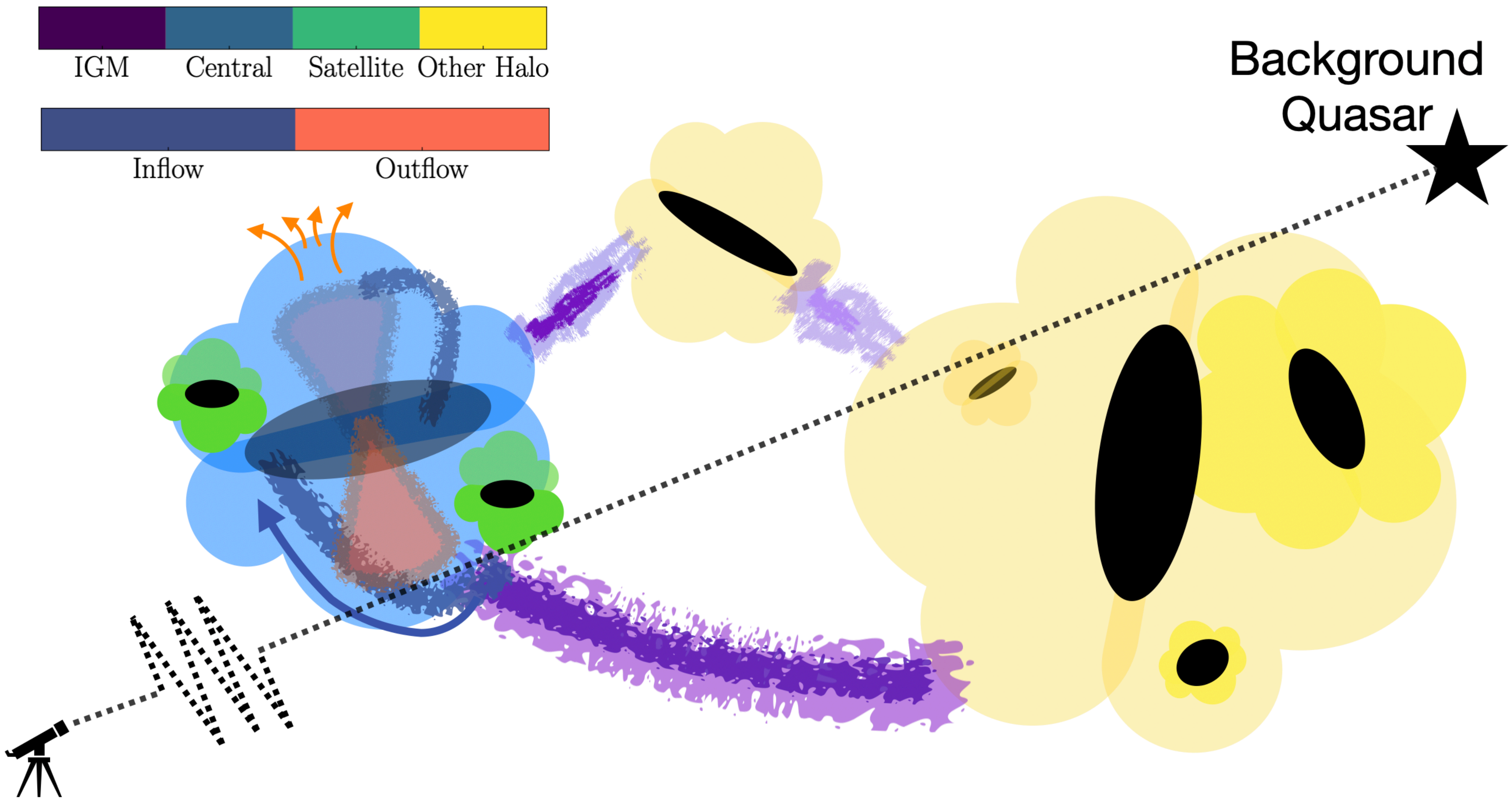
Hot gas is higher along the minor versus major axes of galaxies?



Truong+21

➥ Athena

How does the absorbing gas relates to galaxies?



Weng,CP+24, Grant+19

MUSE-ALMA Haloes: multi-wavelength dataset

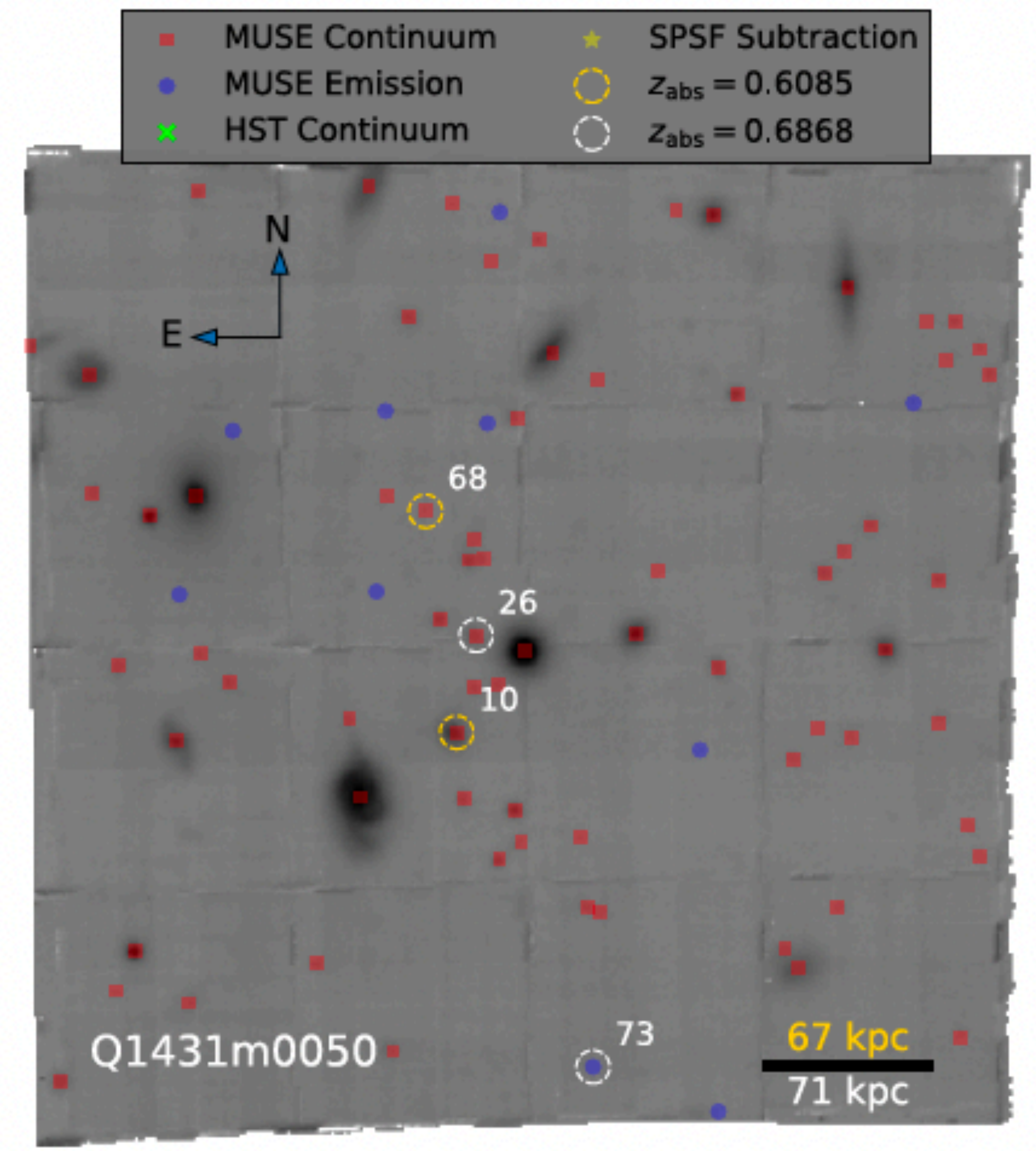
- **neutral** gas (HST UV spectro + VLT/UVES+Keck/HIRES)
- **ionised** gas (VLT/MUSE)
- **molecular** gas (ALMA)
- **stellar** content (HST)

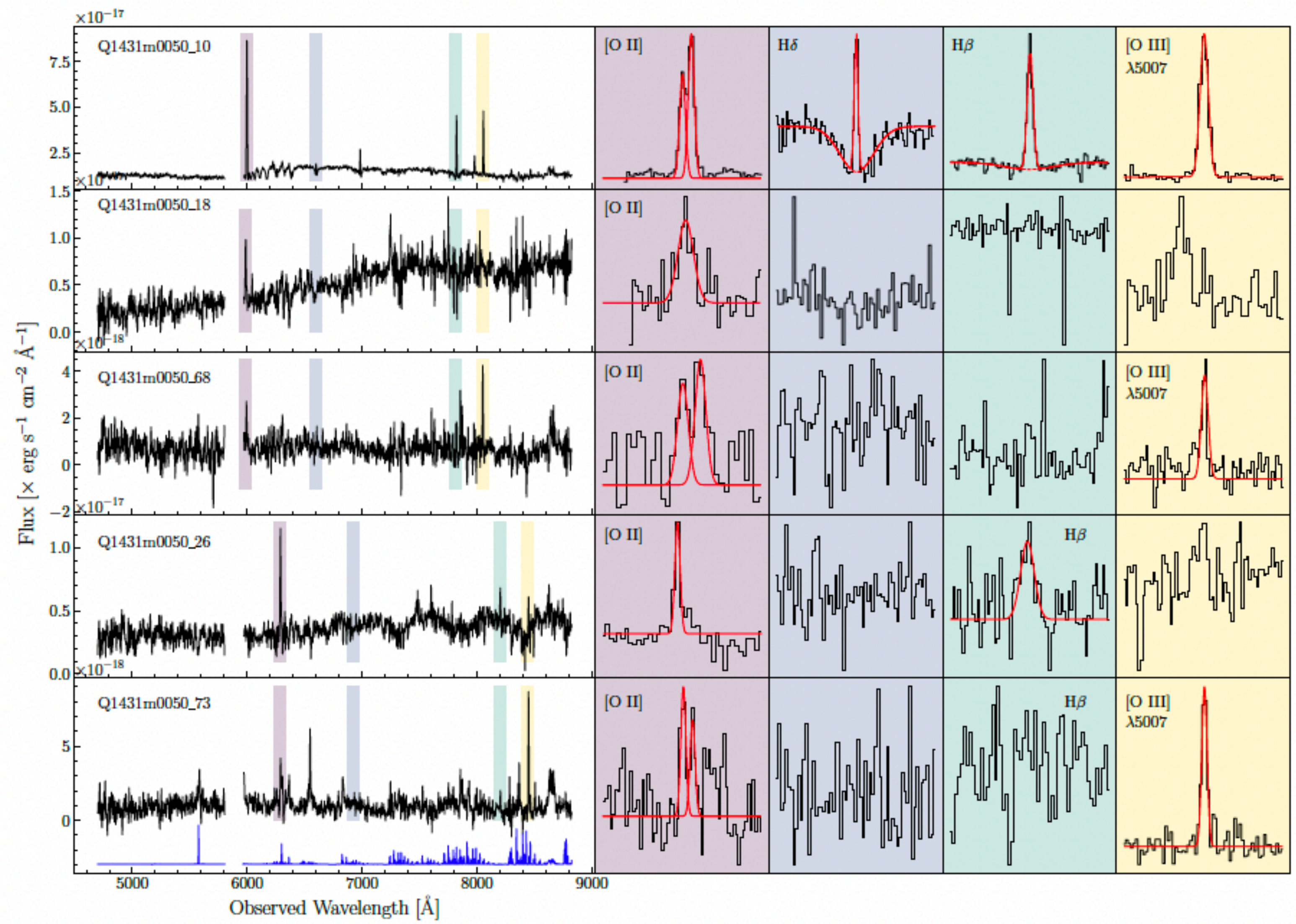
➥ eso.org/~cperoux/MUSE_ALMA_Haloes.html

Simon Weng

3D spectroscopy solved a two-decade long challenge

3000 gal

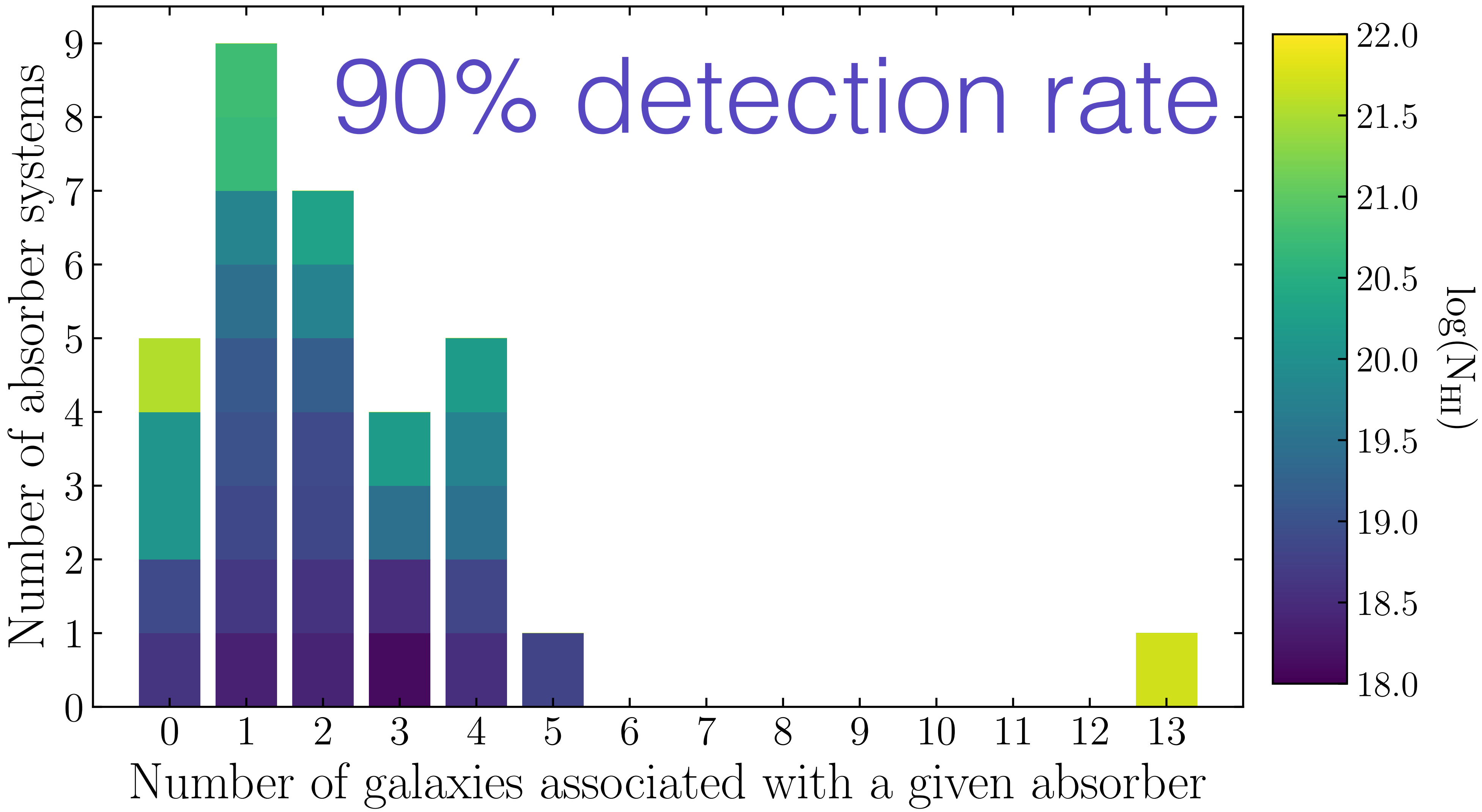




Martin+24

Simon Weng

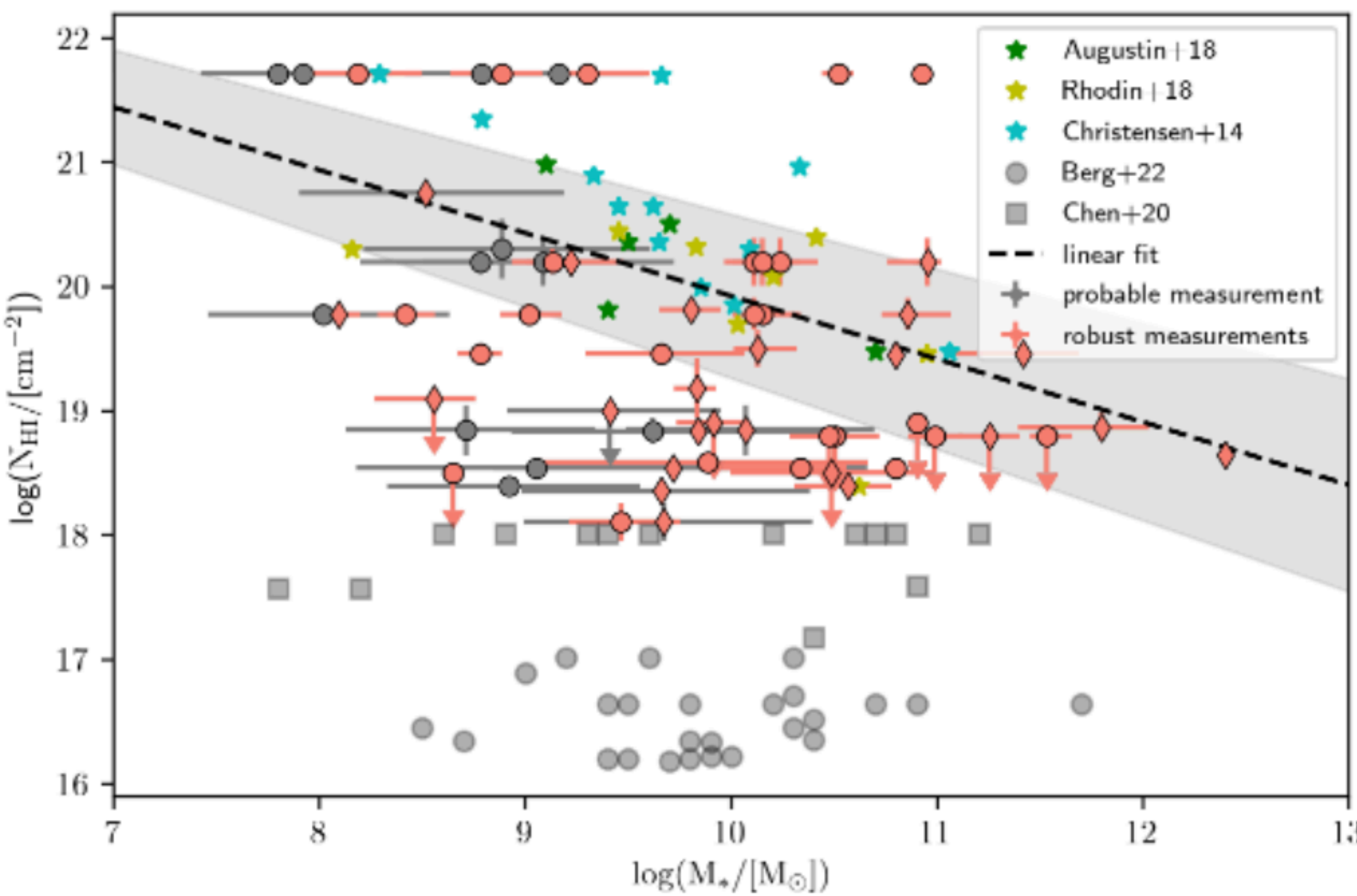
Key result I: HI-rich galaxies trace over densities



Lofthouse+20, Dutta+21,22, Weng, CP+22

Ramona Augustin

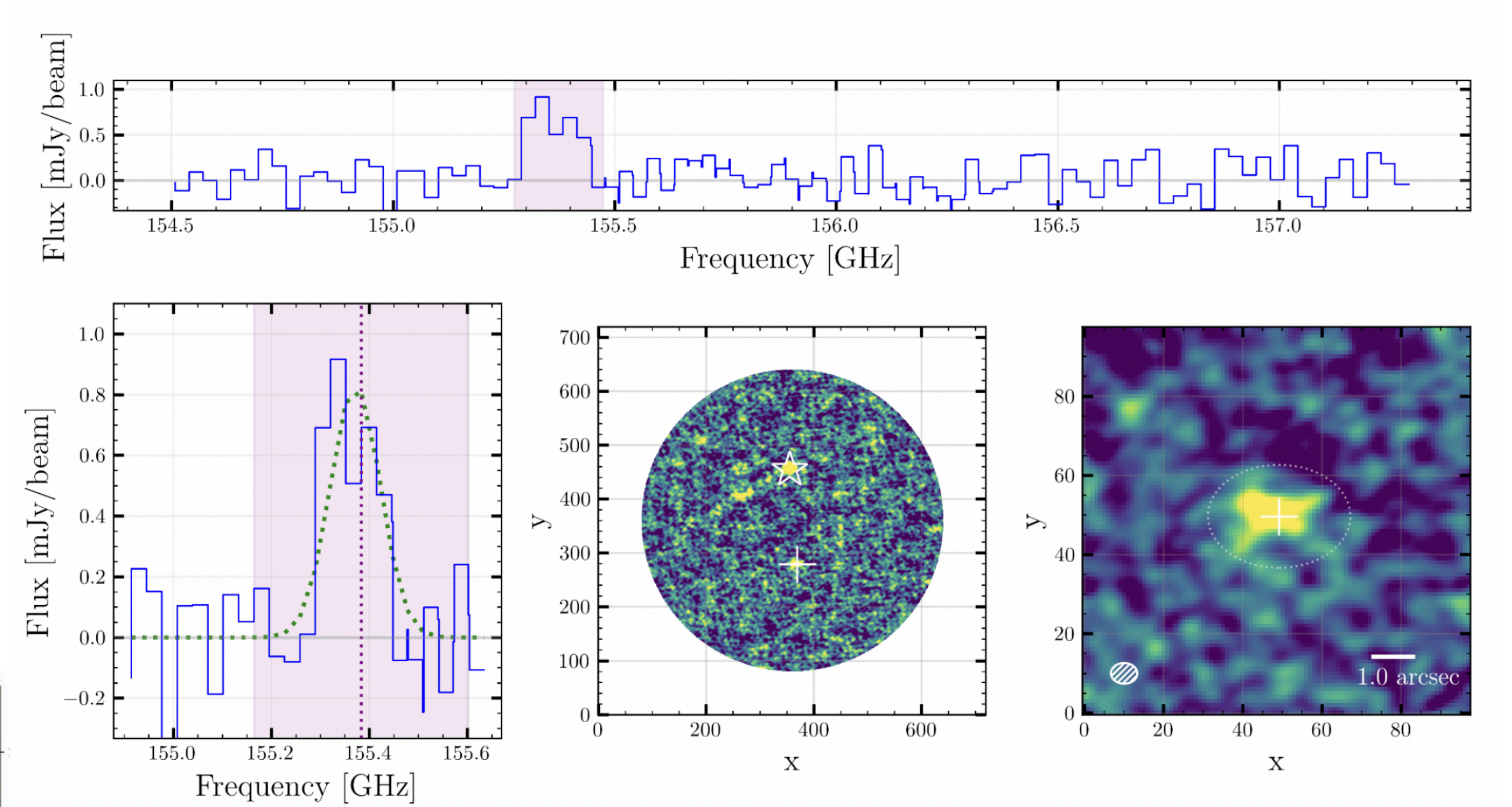
Key result II: Gas-selected galaxies probe wide M* range

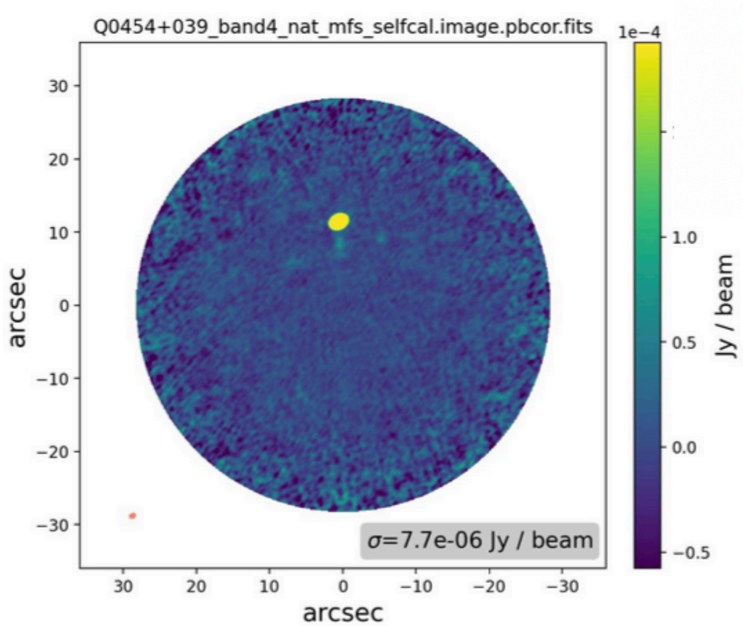


Augustin, CP+ 24

Jianhang Chen

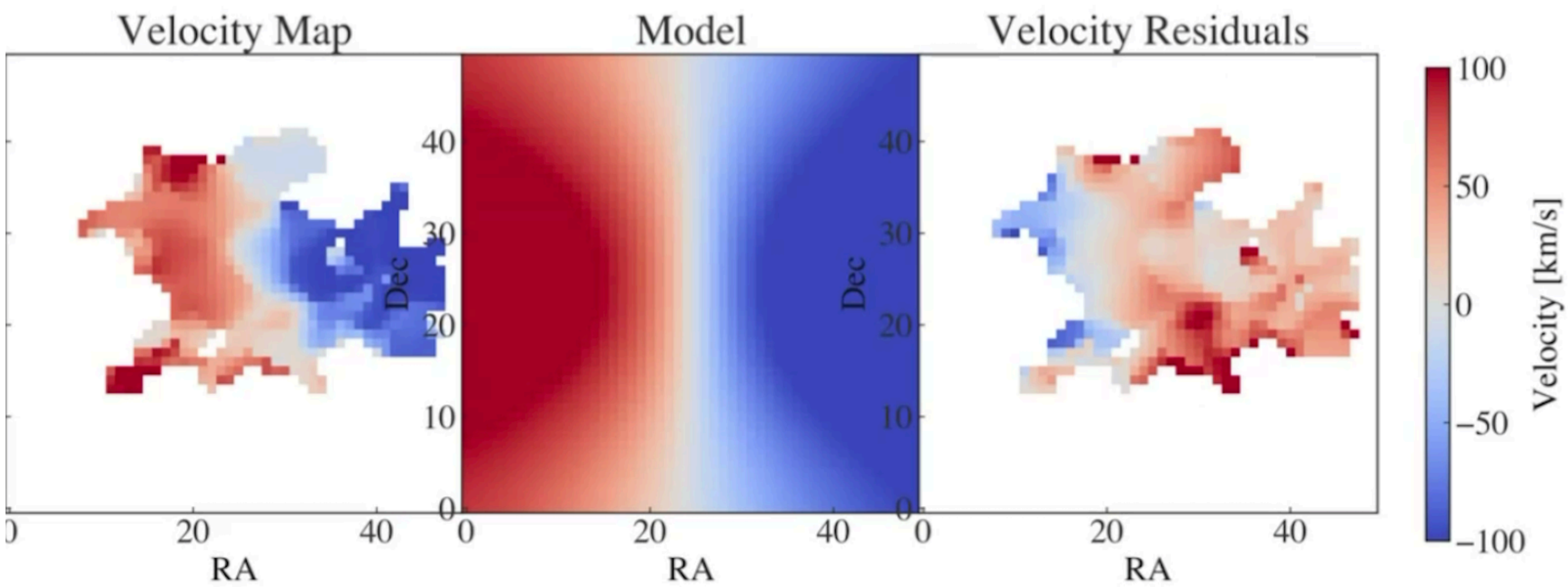
Data processing (self-calibration)





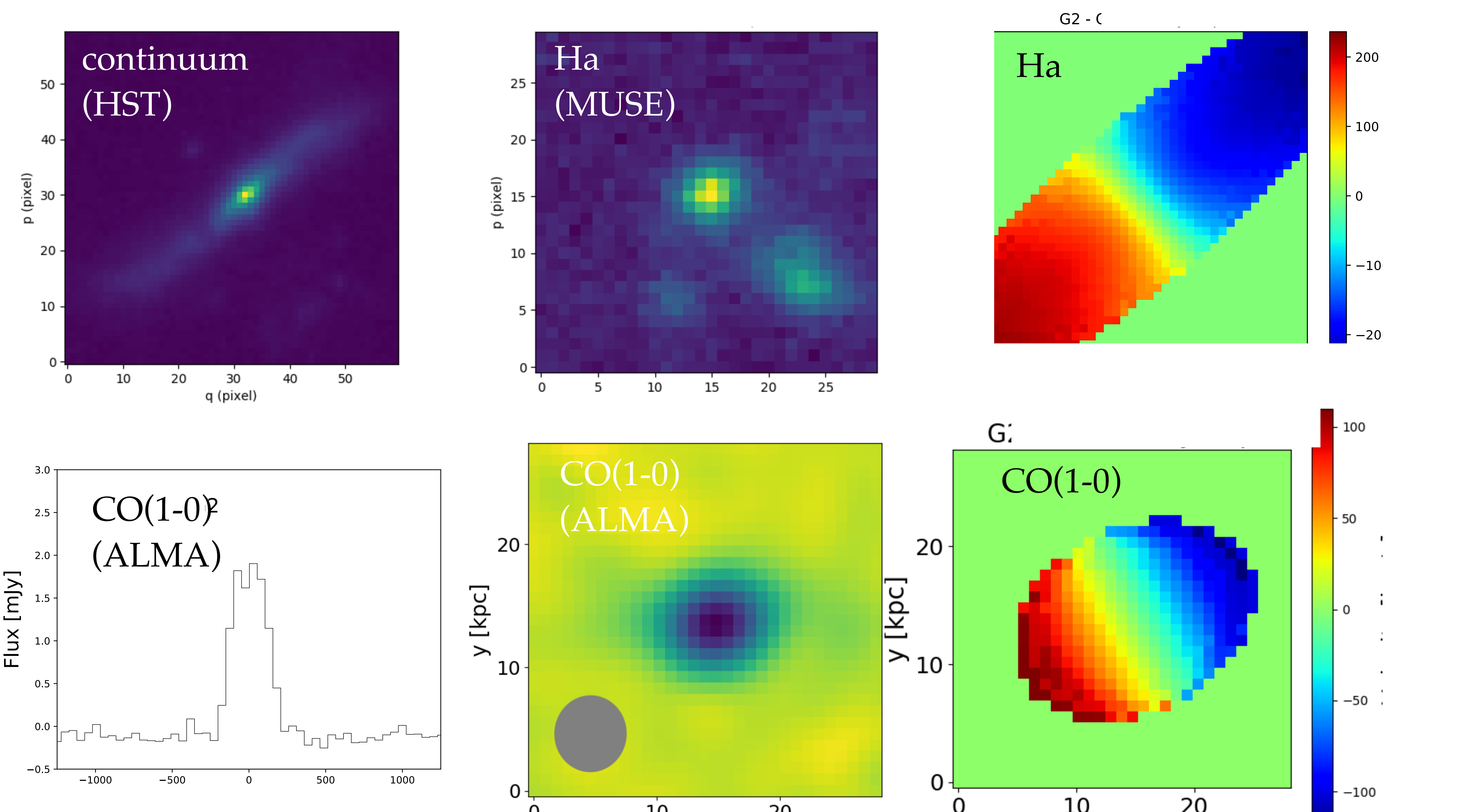
Capucine Bartefy

Molecular gas kinematics

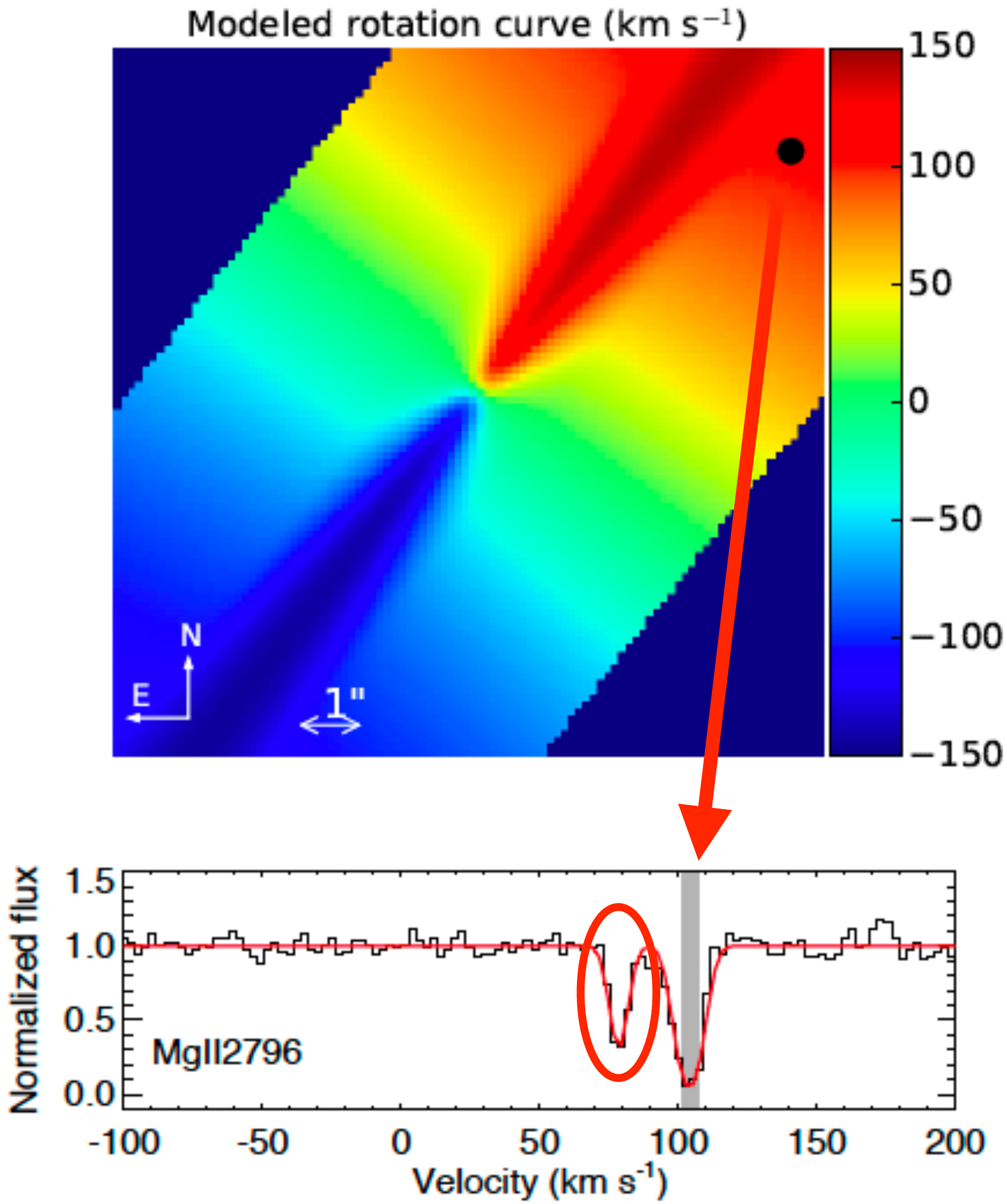


Bartefy+in prep

Key Result III: coupling of multiphase gas kinematics



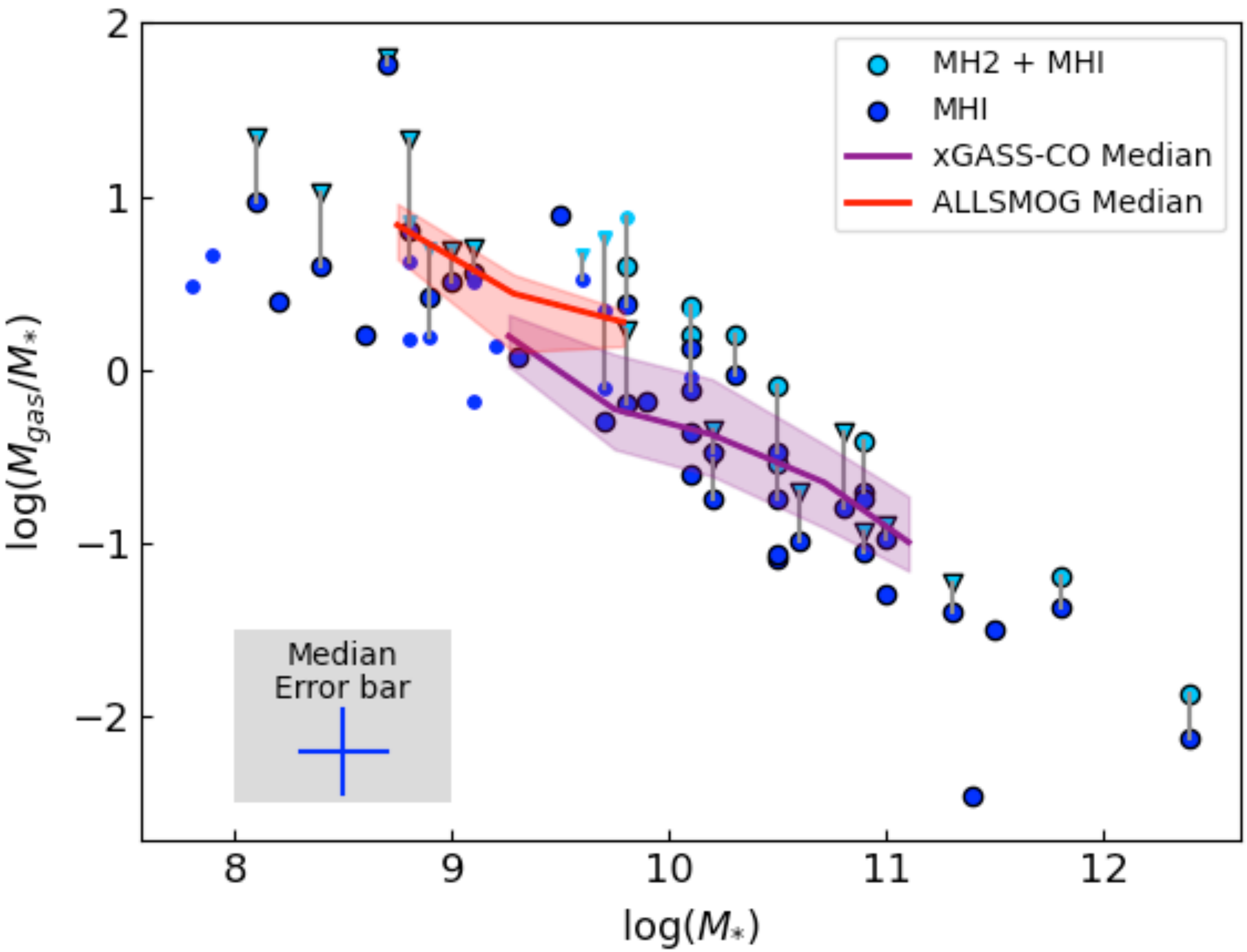
Cold flow accretion



Rahmani, CP+18

Tamsyn O'Beirne

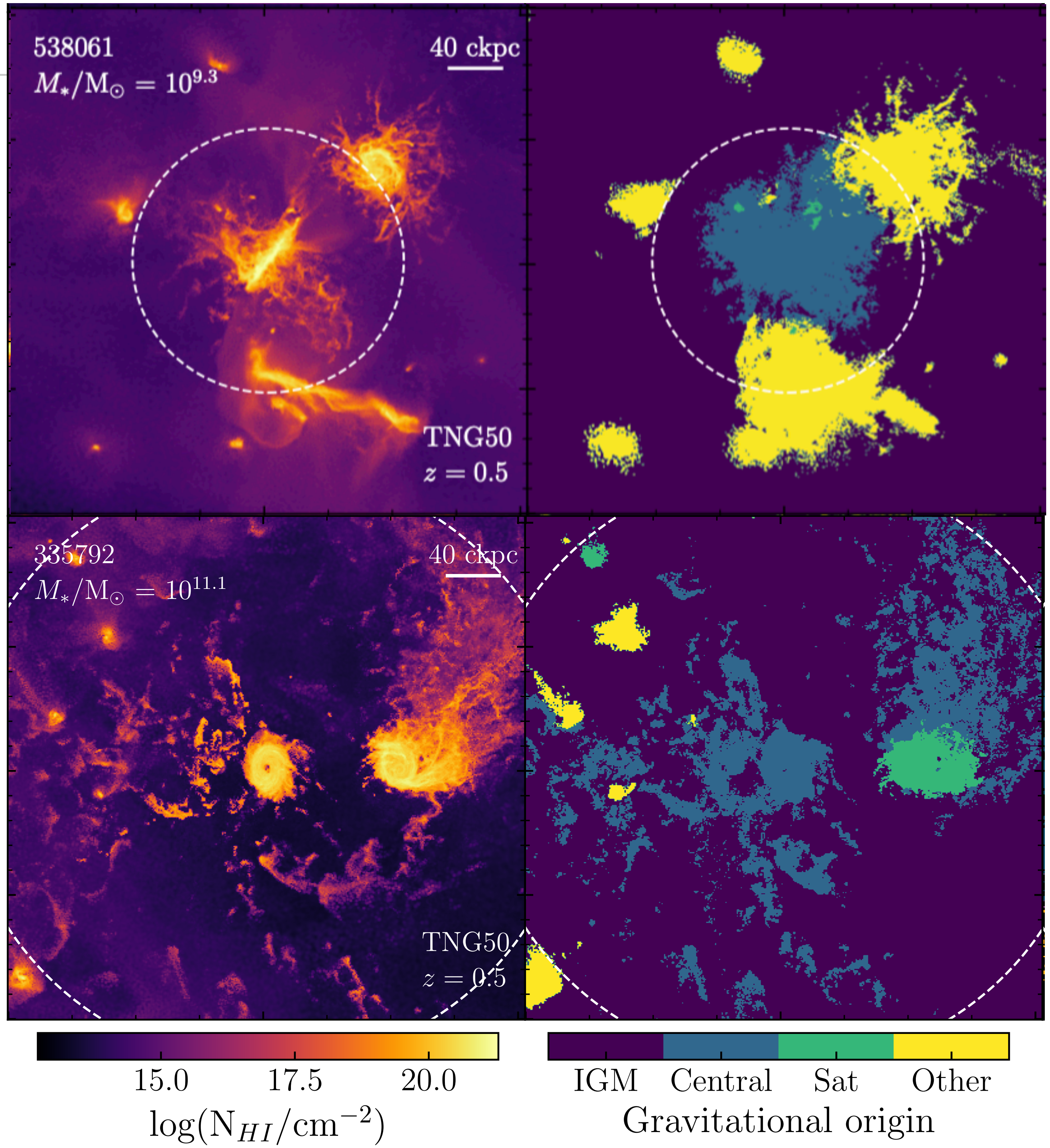
Key Goal IV: condensed baryons census



Kriek+24, O'Beirne, CP+in prep

MUSE-ALMA Haloes Digital Twin

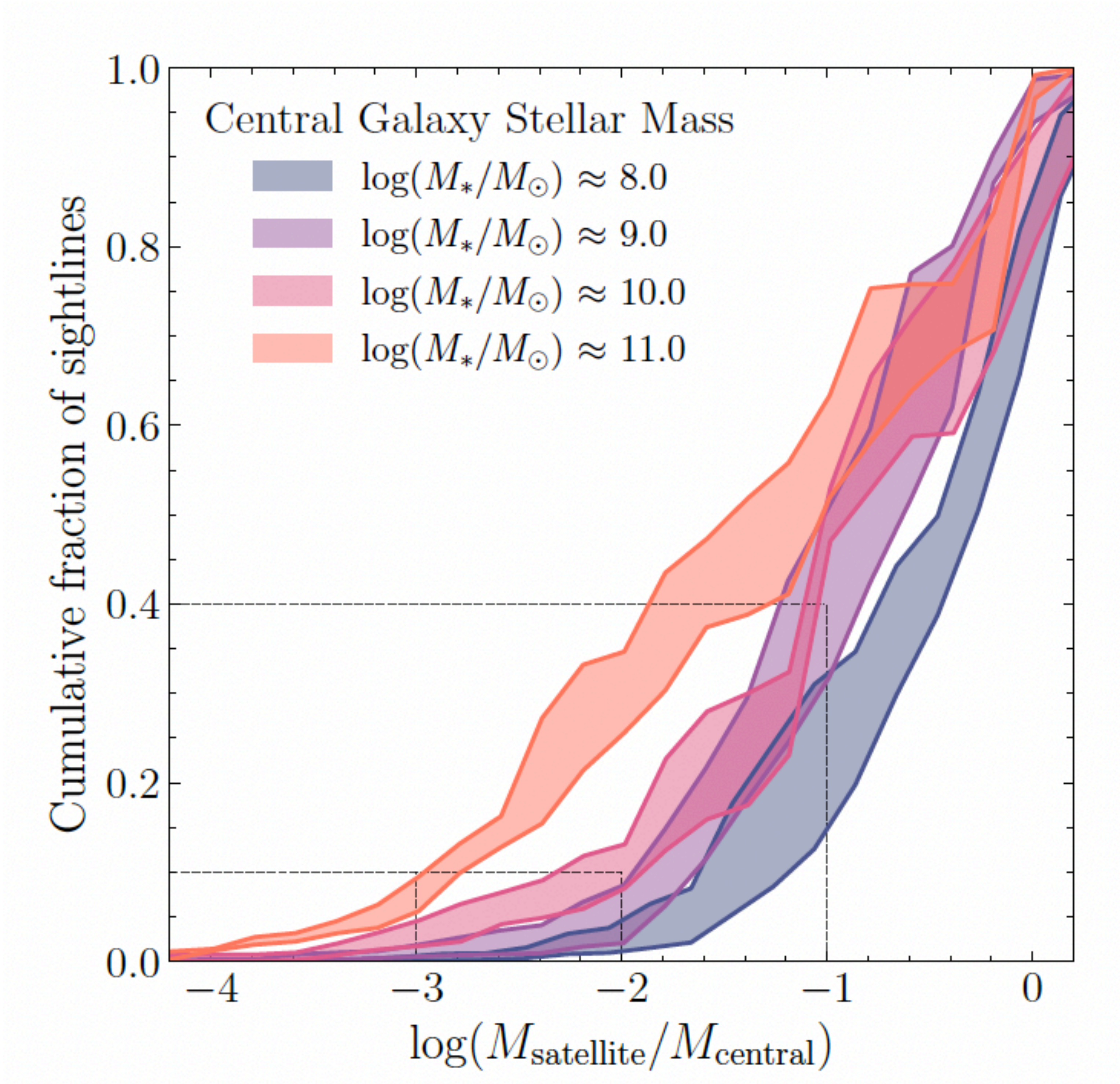
TGN50



Ramesh, Nelsone+23c,
Weng,CP, Ramesh, Nelson+24

Simon Weng

Contribution of satellites



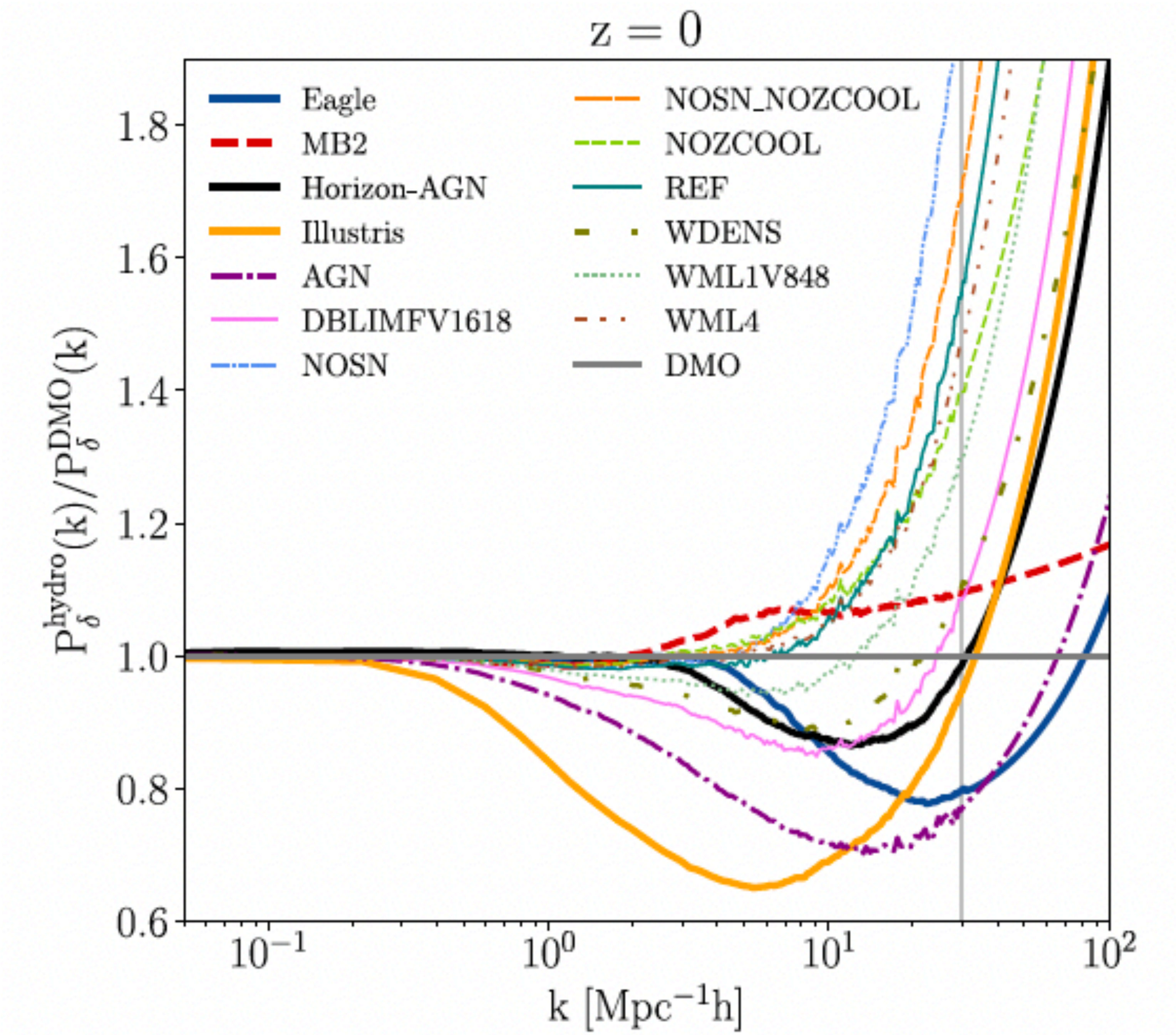
Weng, CP, Ramesh, Nelson+24

TGN50

4) Future:

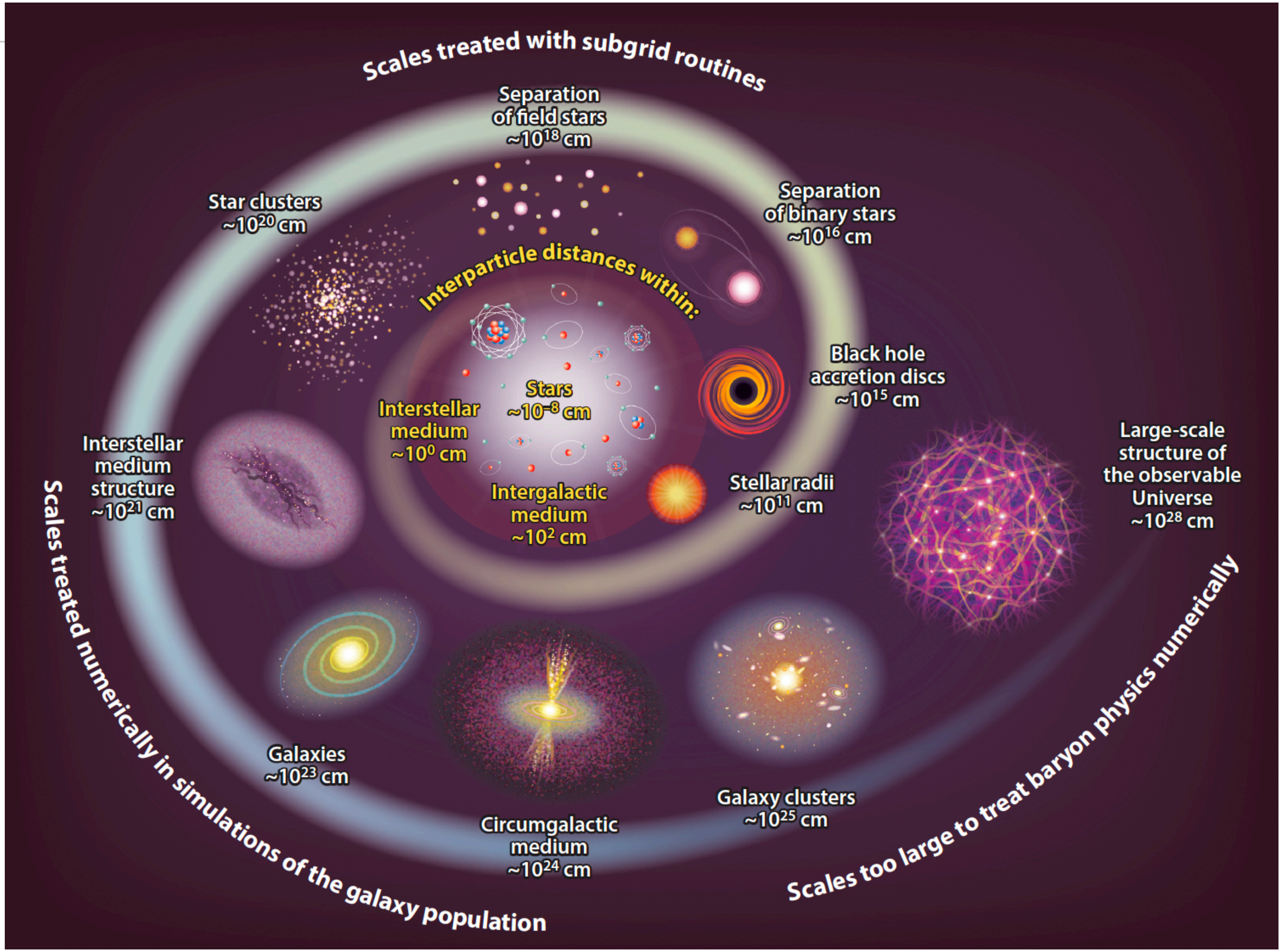
connect with simulations, statistics

Dark Matter Power Spectrum



Chisari+18, Schneider+19, Huang+19, Correa+22, Amon & Efstathiou22, Ferlito+23

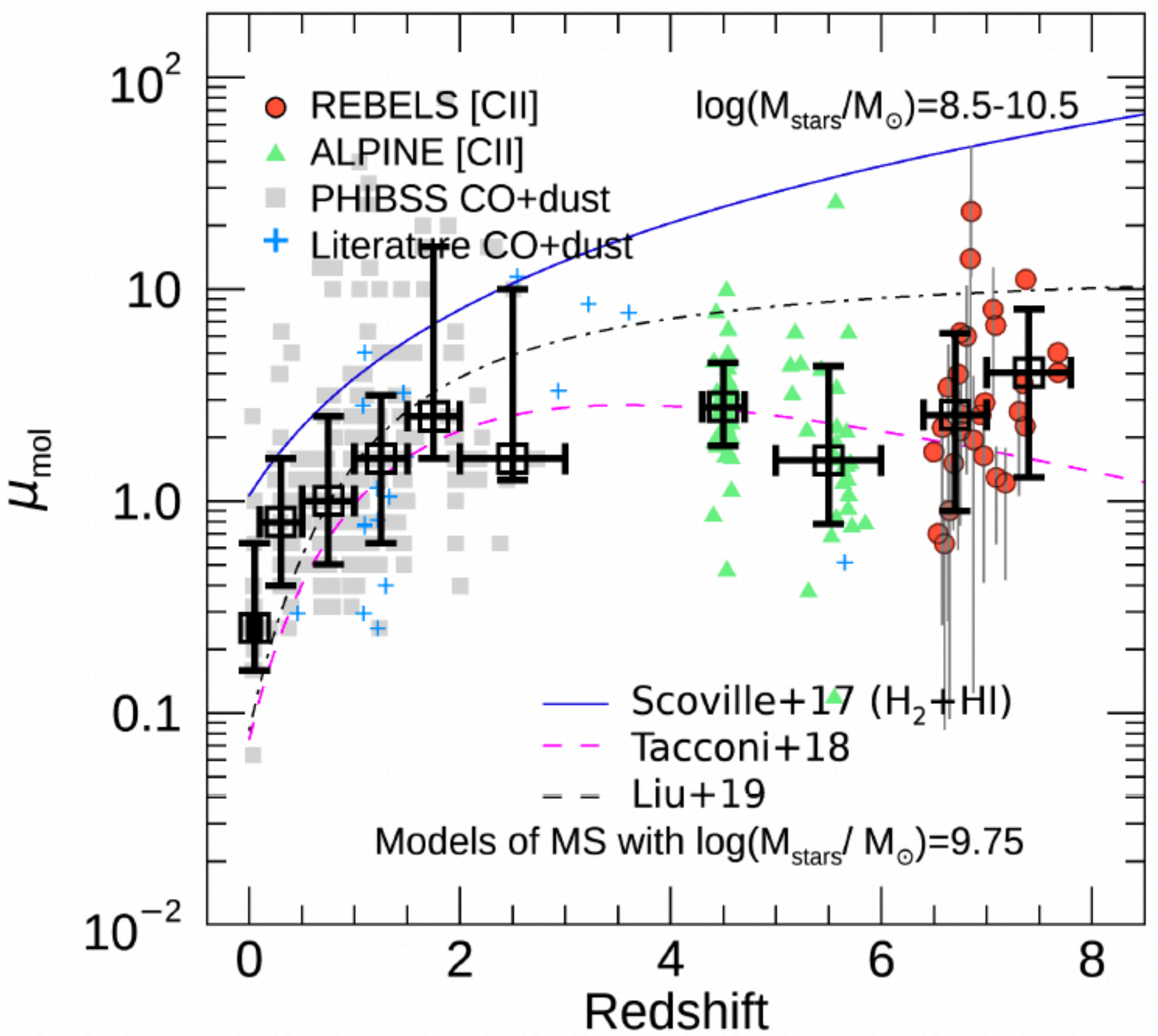
Dynamical range challenge



Crain & van de Voort, ARAA, 23

Naab+17, Faucher-Giguere & Oh, ARAA, 23, Pakmor+23, MRNG, Weinberger&Hernquist23

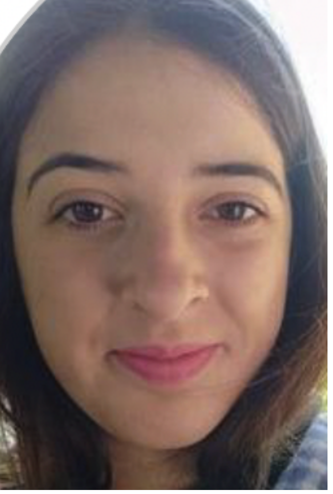
[CII] routinely used as a molecular tracer at high-z



ALMA

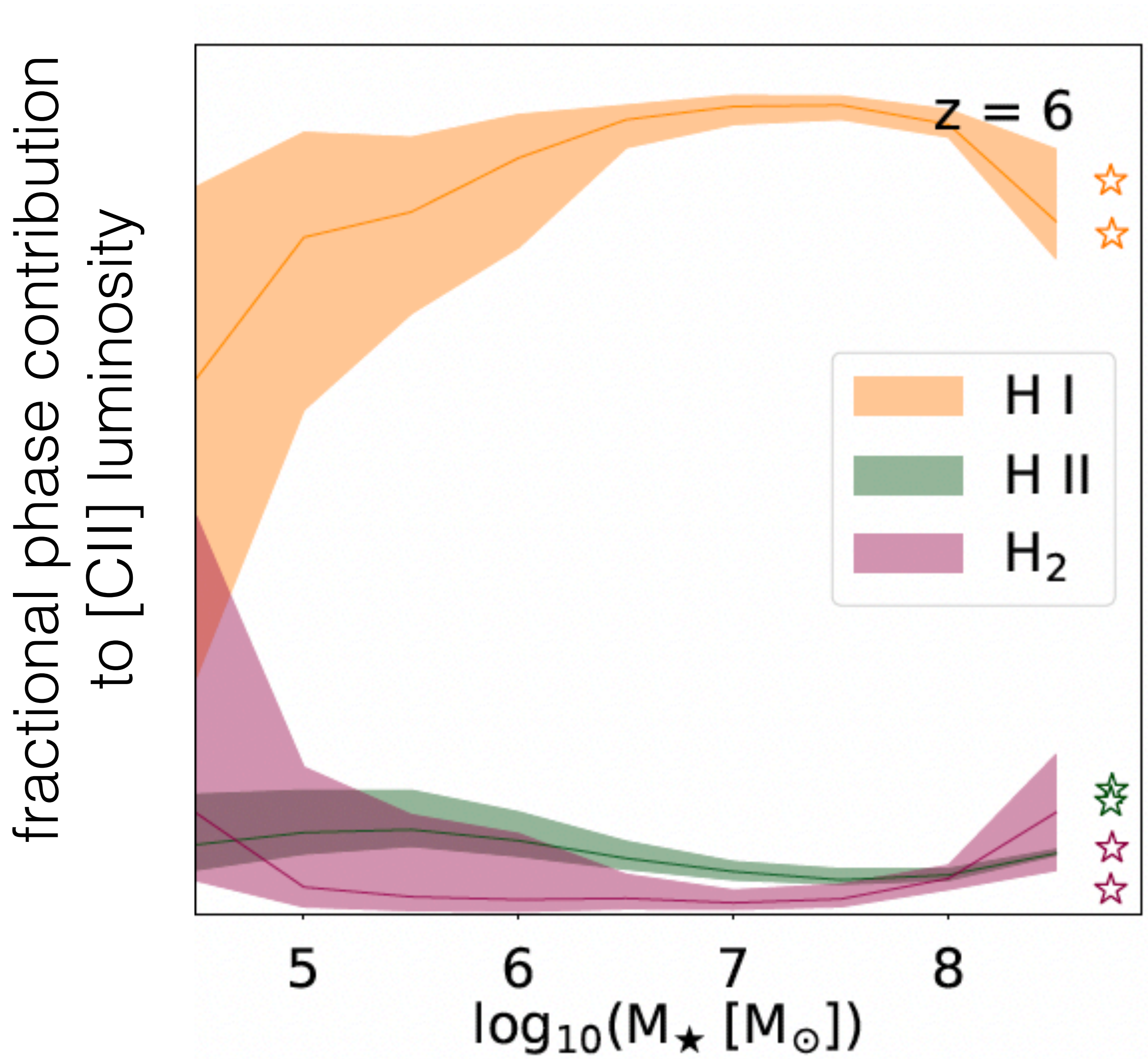
Pallottini+22, Peng+23, Aravena+23

Time-dependent non-equilibrium chemistry



Benedetta Casavecchia

See poster



ColdSIM

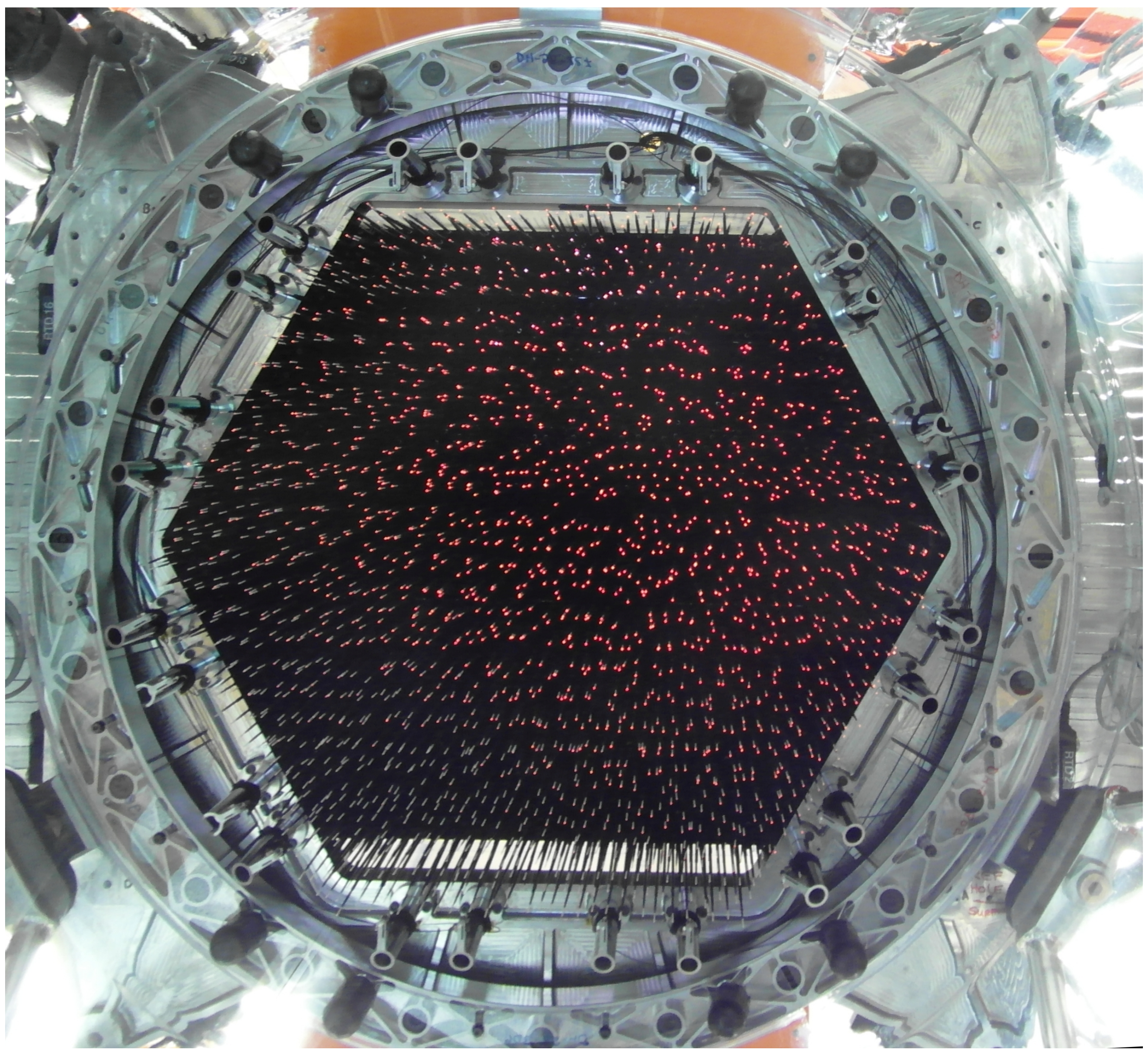
Diemer+19, Girichidis+21, Katz+22, Werhahn+23, Polzin+24, Casavecchia, Maio, CP+25

Statistics

4MOST project

Built at AIP

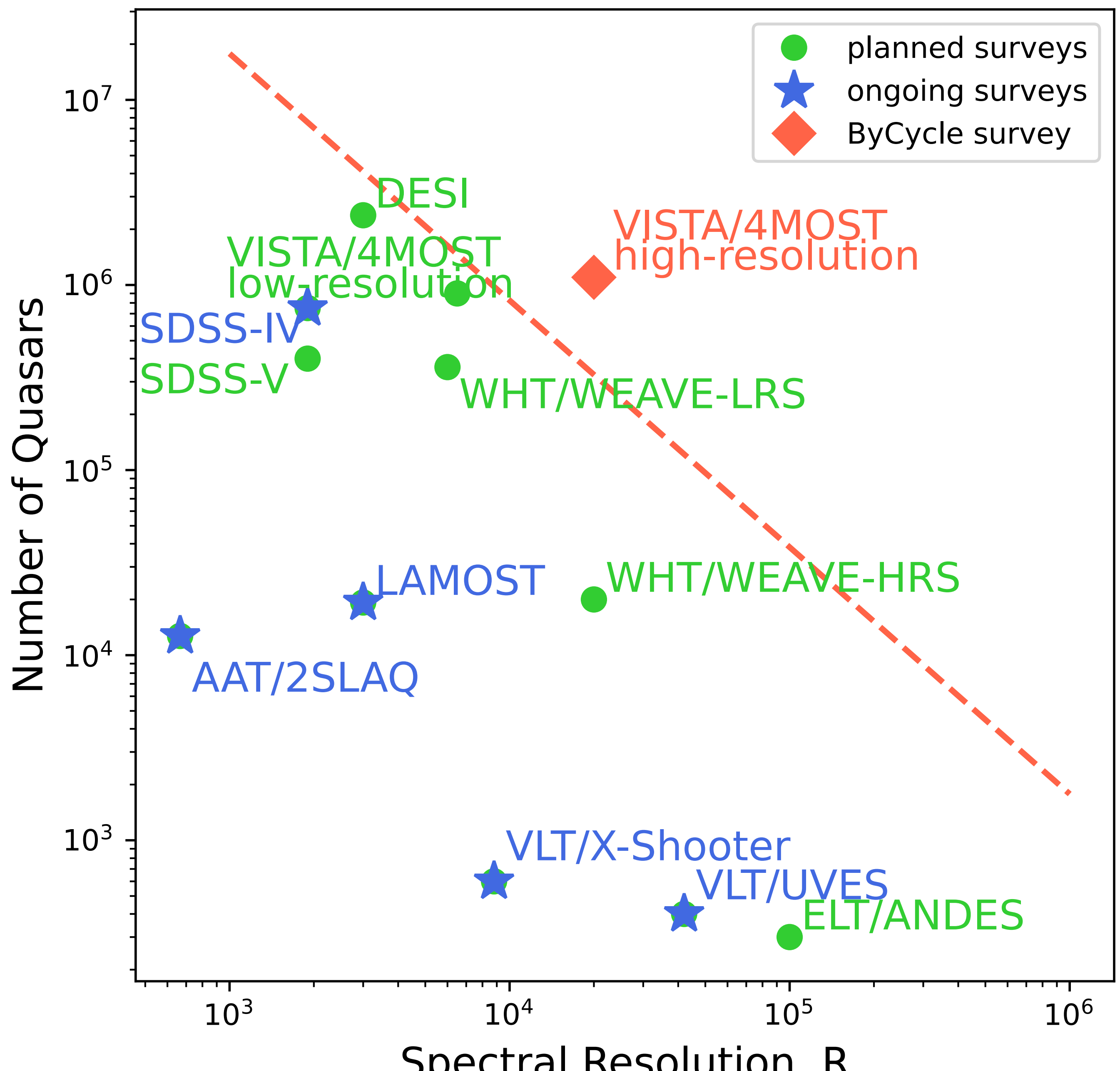
de Jong+19



- 2500 fibres
- shared focal plane
- 5-yr project,
  start of operation 2026
- 2 spectral resolution
  R=6,000
  R=20,000

2.8 million fibre-hours

10x Res



1000x #

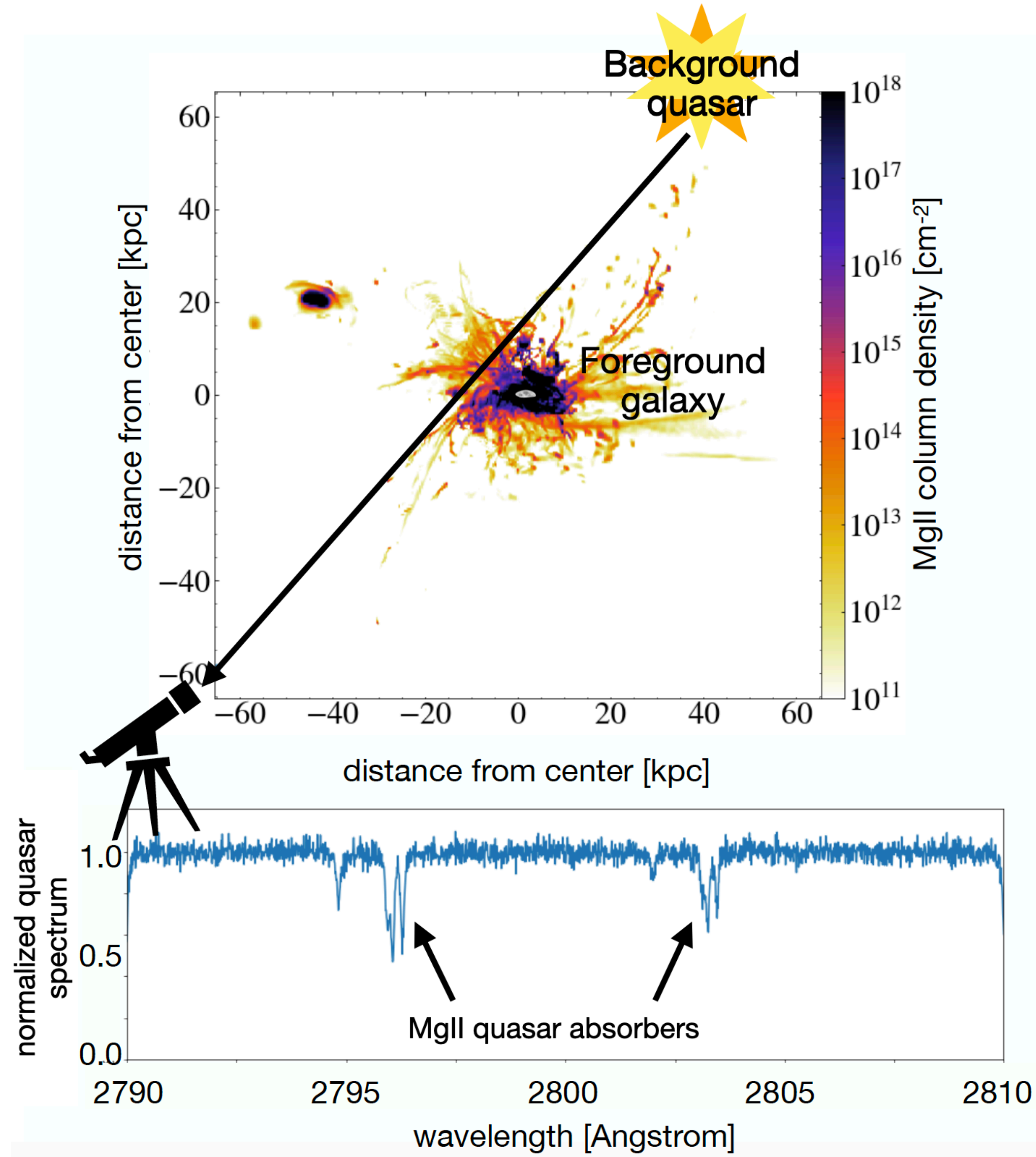
Bouche+04, Pieri+16, Lehner+22, Welsh+24

Kauffmann+19, CP+23, ESO Messenger

Ramona Augustin

The *ByCycle* experiment

- ✦ 1 million background quasars
- ✦ **1.5 million** foreground objects: low-z gal, AGN, clusters, groups, Magellanic Clouds



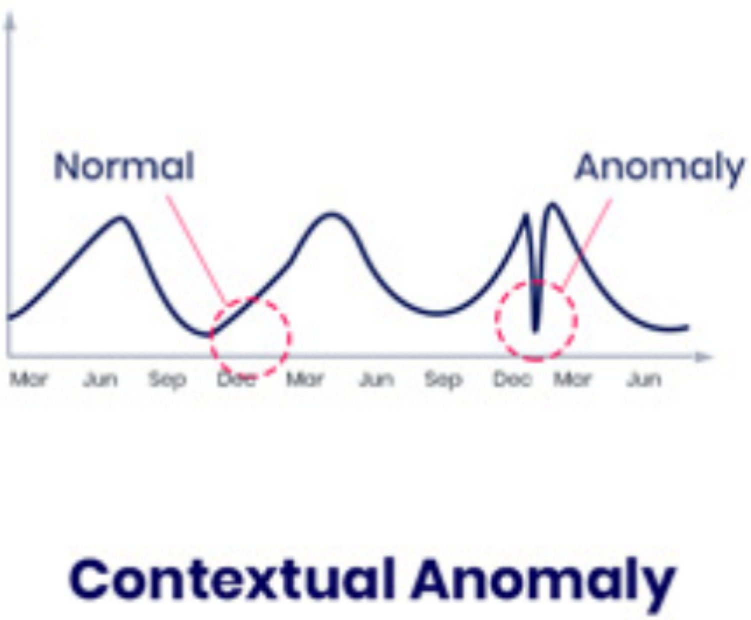
Peeples+19, Locchhaas+23

➥ www.eso.org/~cperoux/ByCycle.html

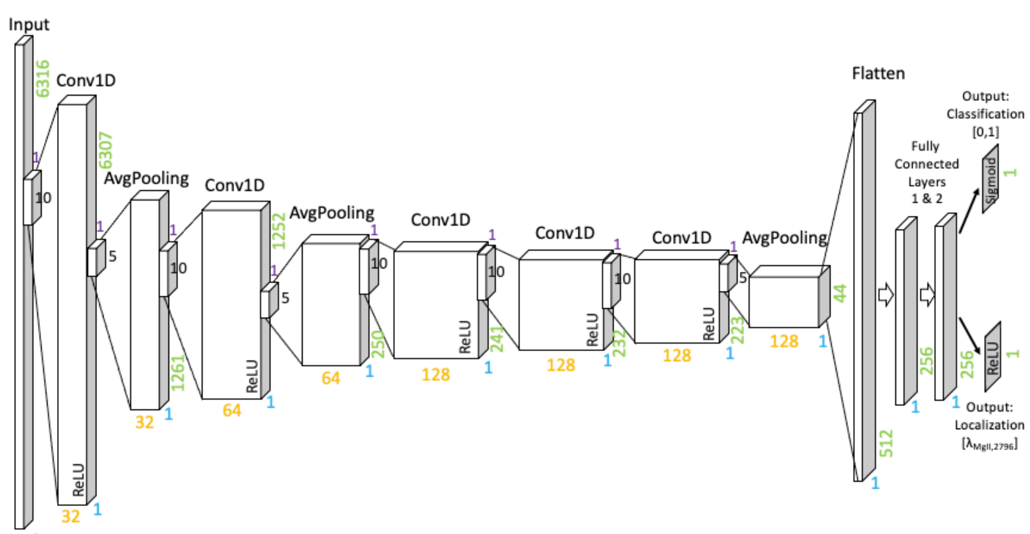
Nicolas Guerra Varas

Characterising abs with Machine Learning

See poster



GPU

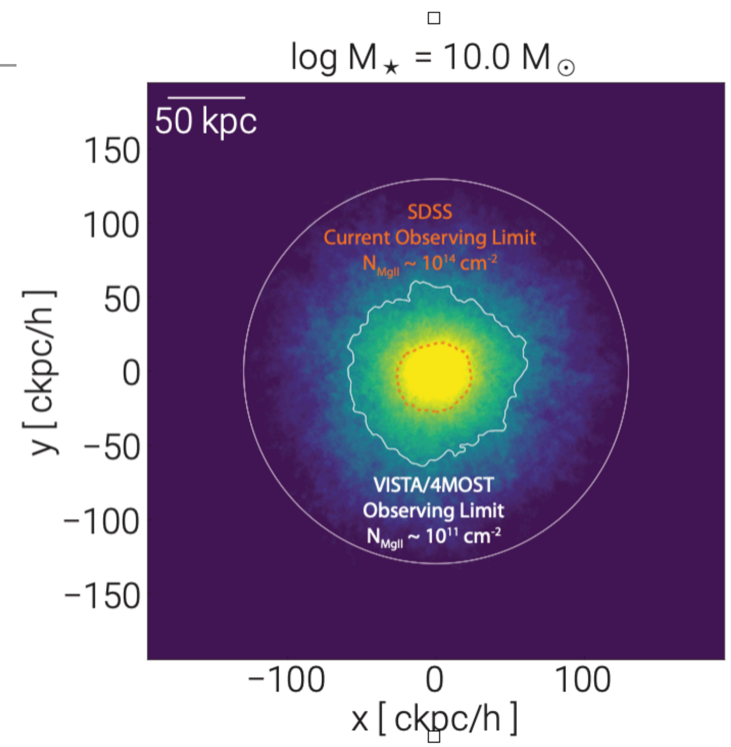


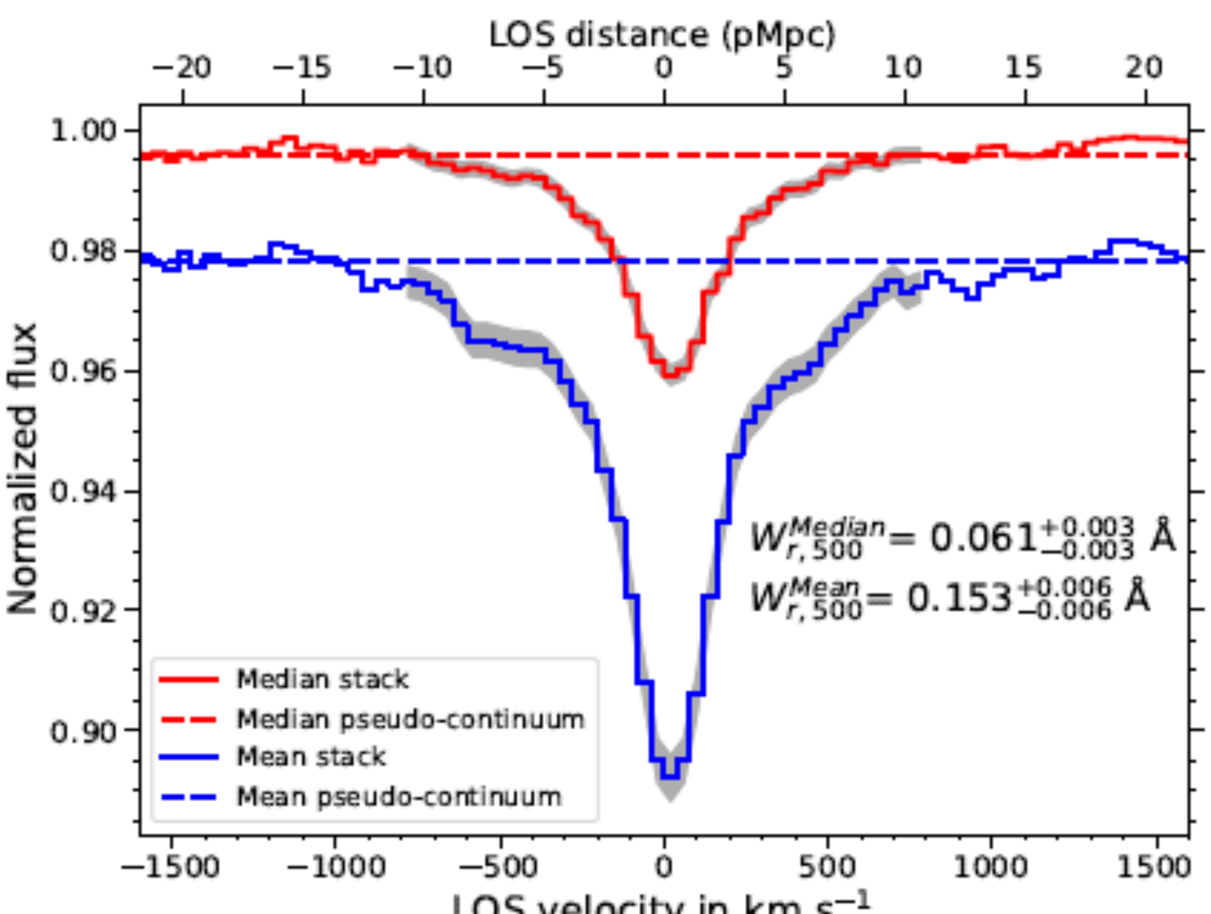
- **Anomaly detection** = find abs
- **Dense/Convolutional auto encoders** = derive physical prop (z, EW)

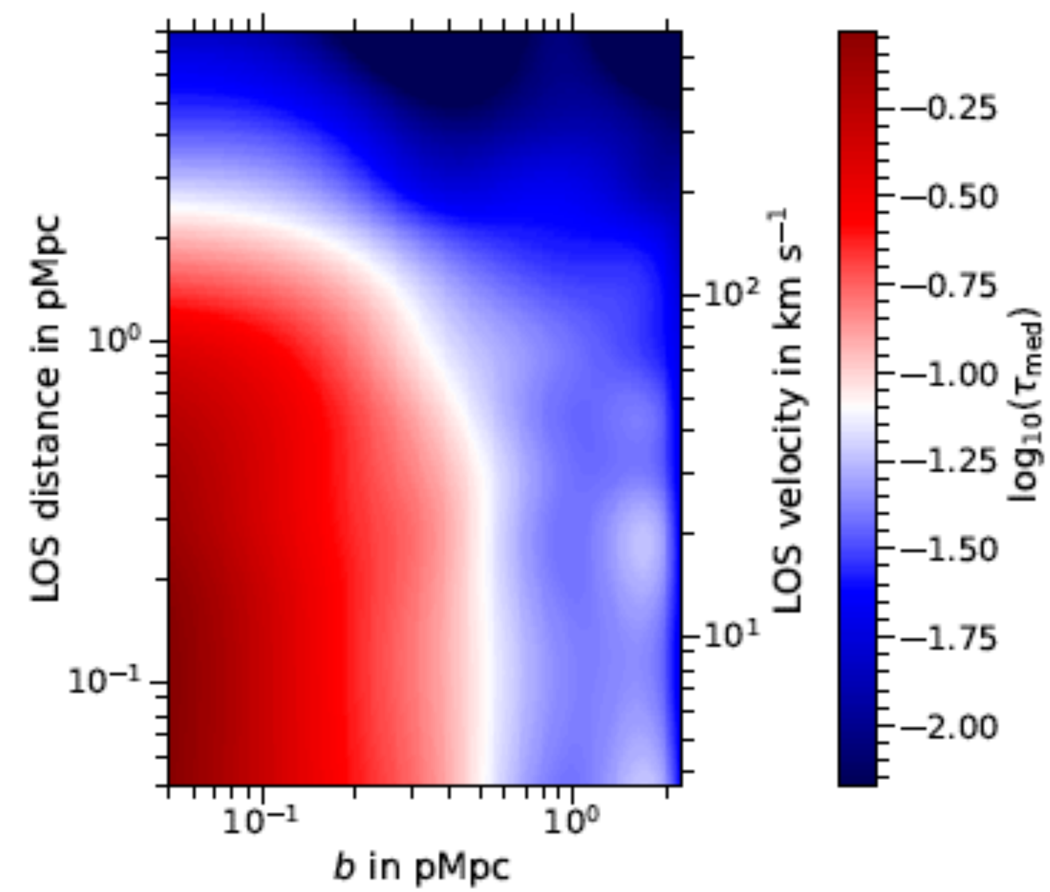
Cheng+23, Szakacs, CP+ 23

Statistical approach to CGM map

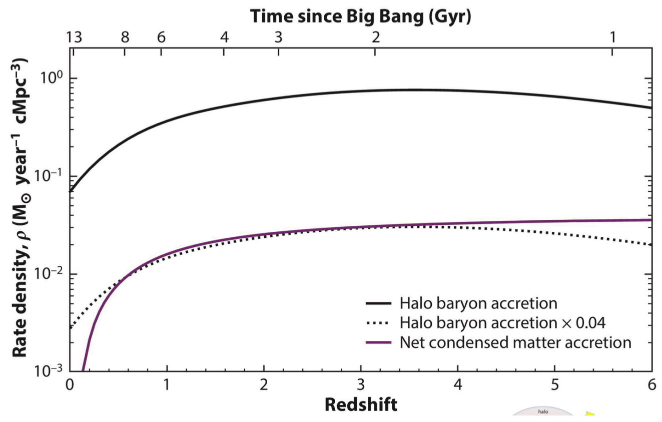
Turner, Schaye+14, 17, Kauffmann+16
Chen, Steidel+21, Lujan Niemeyer+22,
Dutta+23



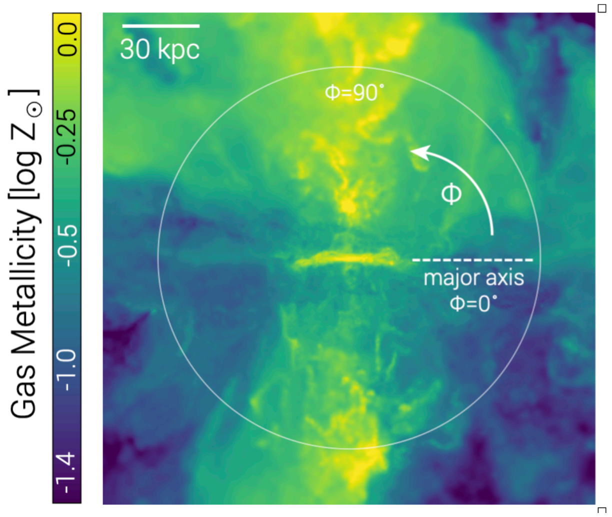




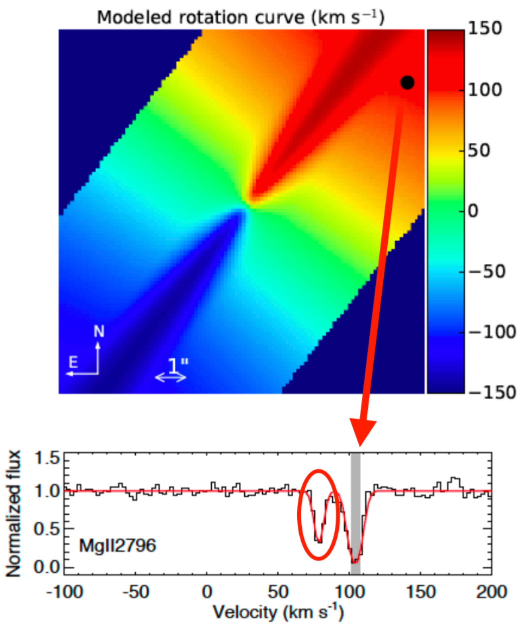
Take home Messages



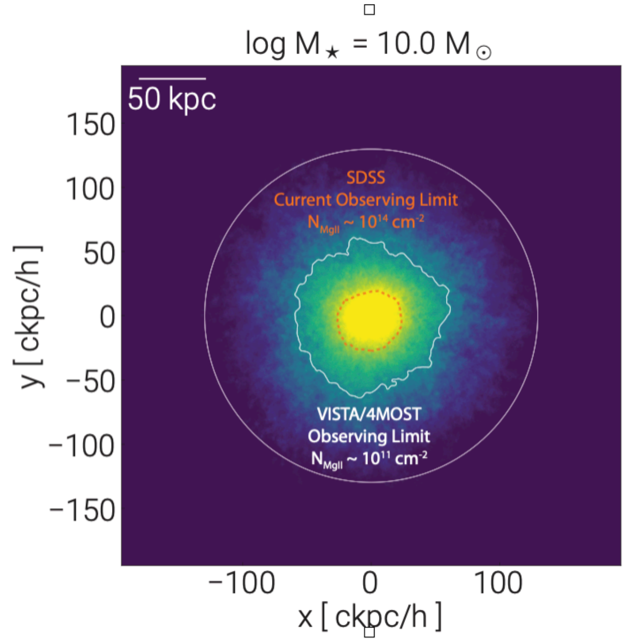
✦ Baryon cycle: accretion, SF, feedback



✦ Statistical obs feedback signatures



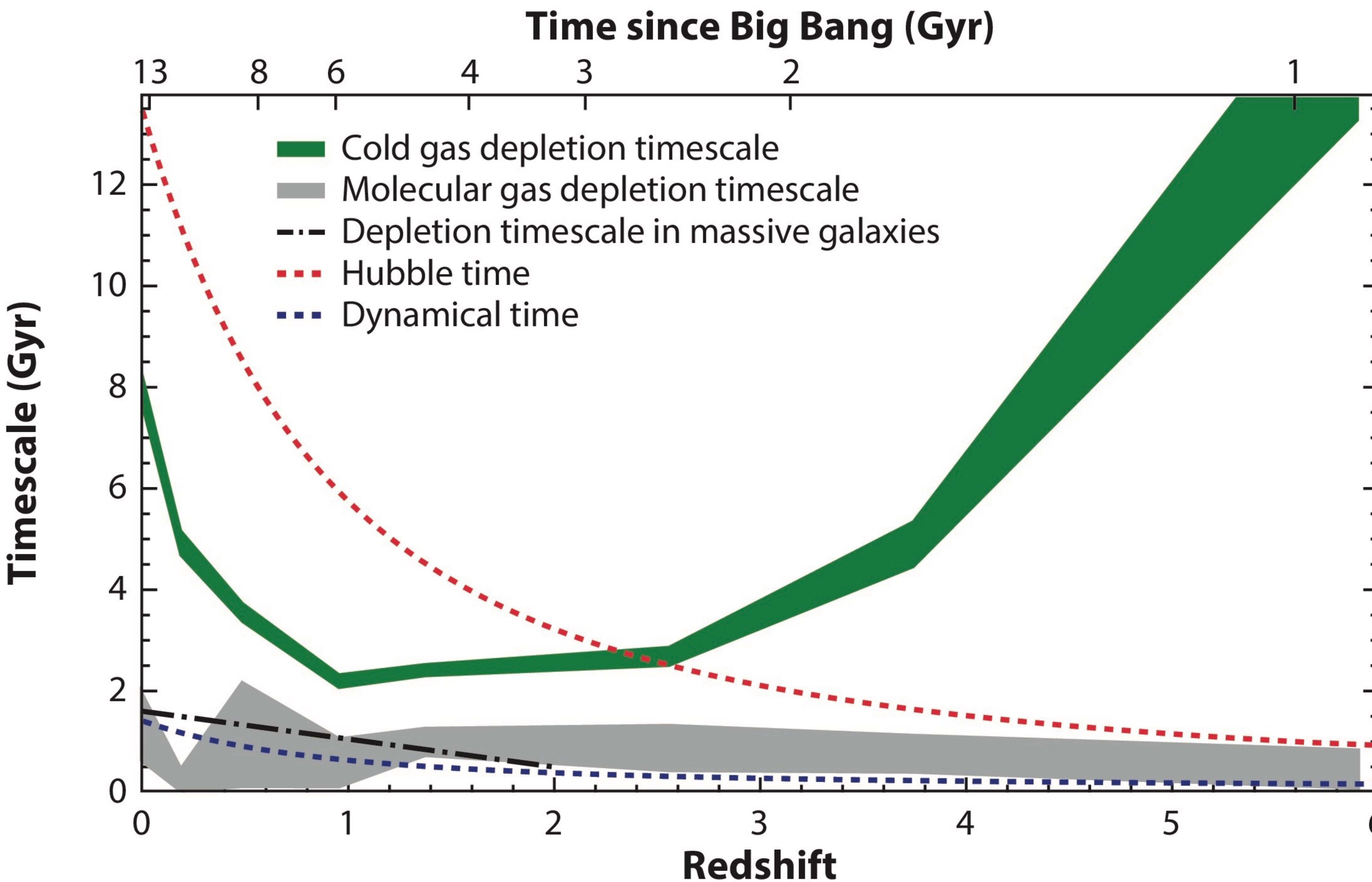
✦ Obs accretion is essential



✦ Next generation survey increases x1000

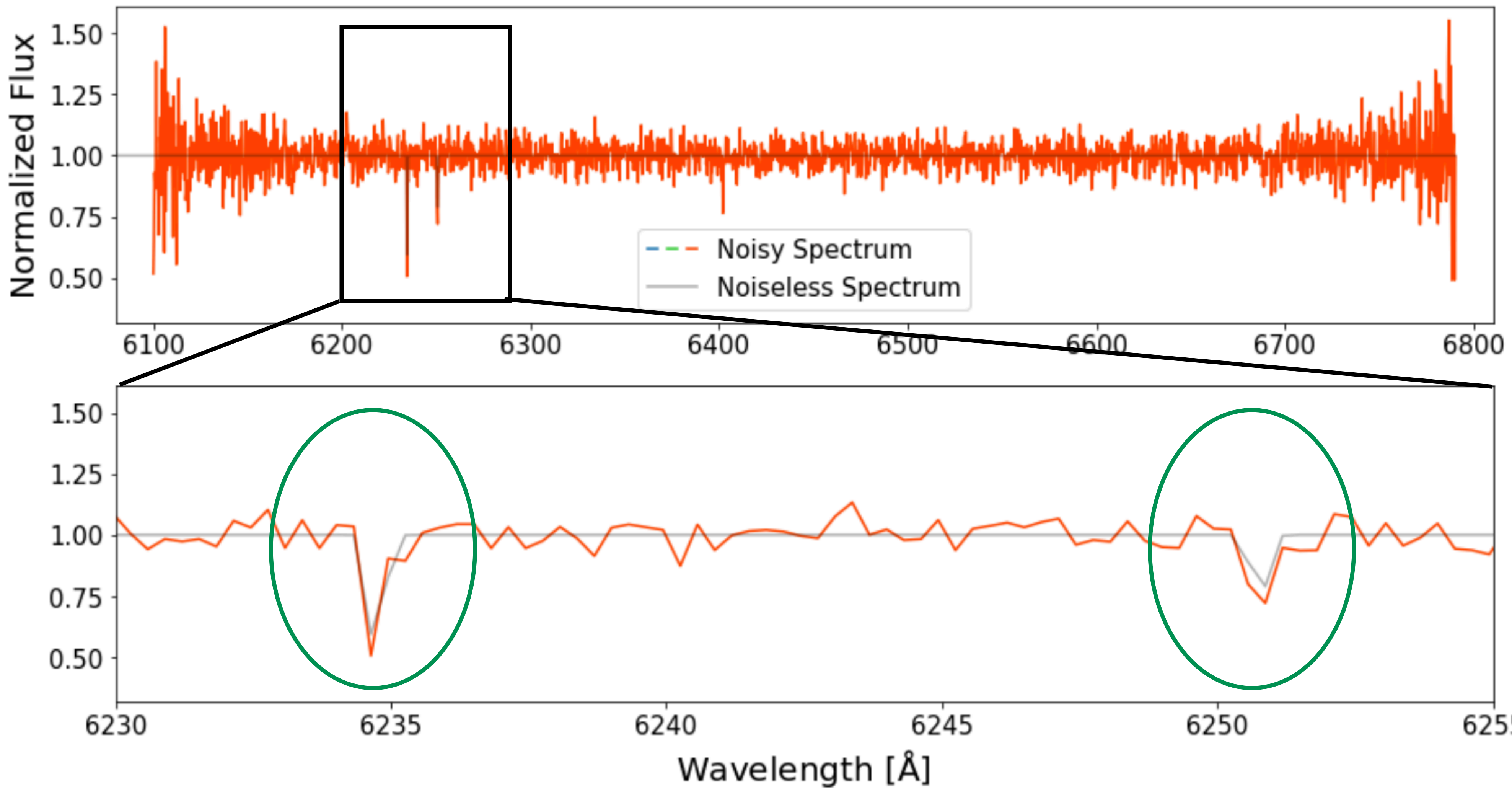
Gas depletion timescale universal

$$\tau_{\rm dep} = \rho_{\rm gas}/\dot{\rho}_{\star},$$



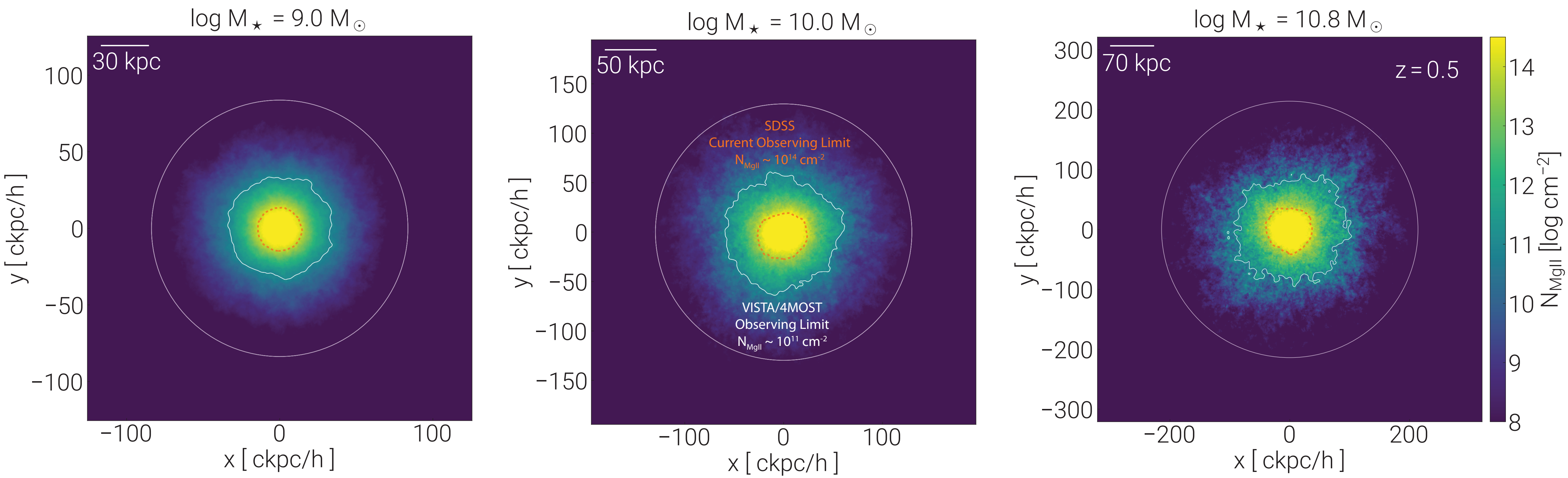
Genzel+15, Tacconi+20, Ellison+21

TNG50 Mock *ByCycle* Spectra



Nelson+ in prep.

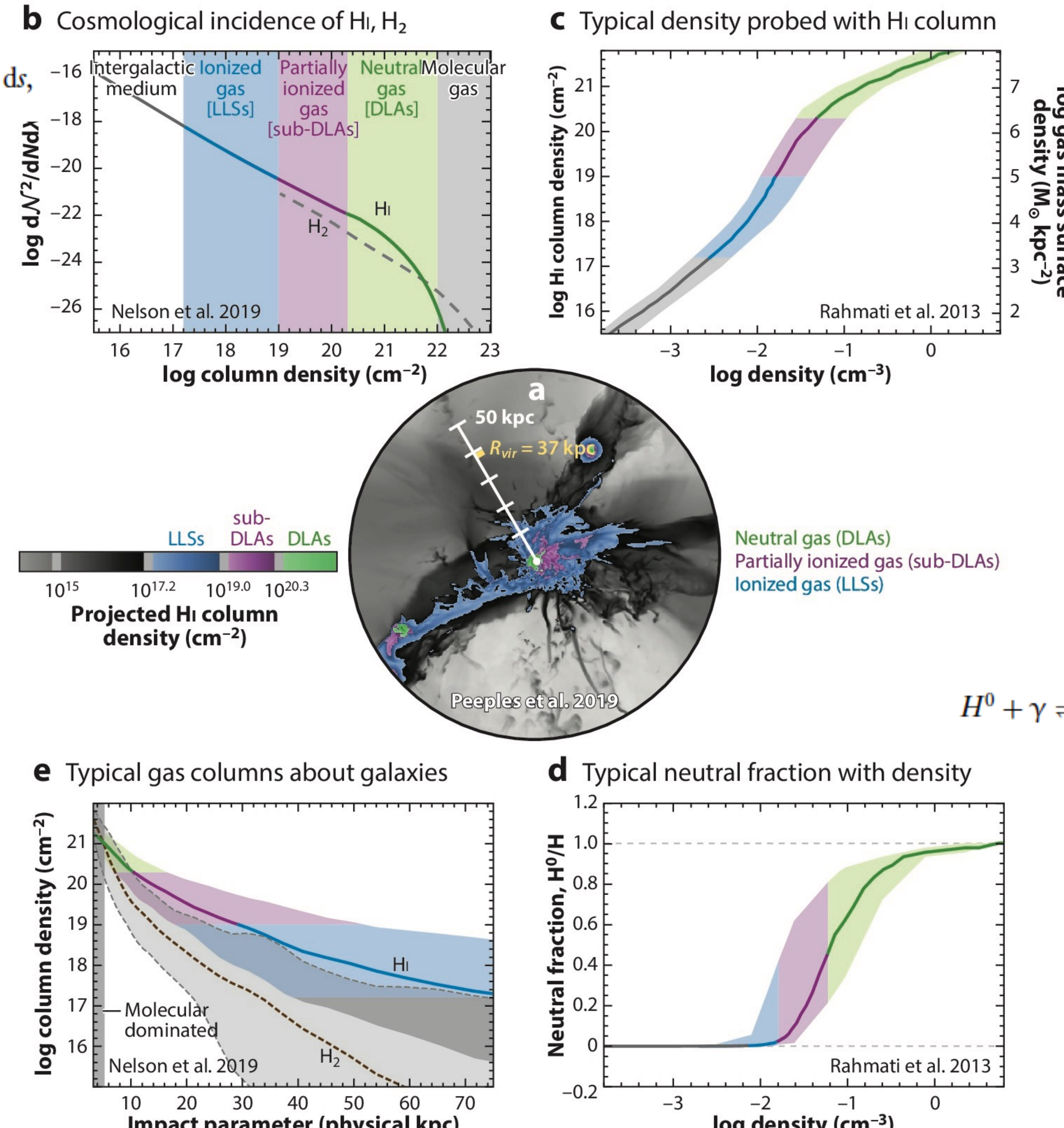
Map the Circumgalactic Medium



✦ 1000-fold increase
wrt what is available now

*Cantalupo+19,
Bordoloi+24,
Khaire+24,
Szakacs, CP+23*

$$N(\mathrm{H\,I}) \equiv \int n_{\mathrm{HI}}\, ds,$$



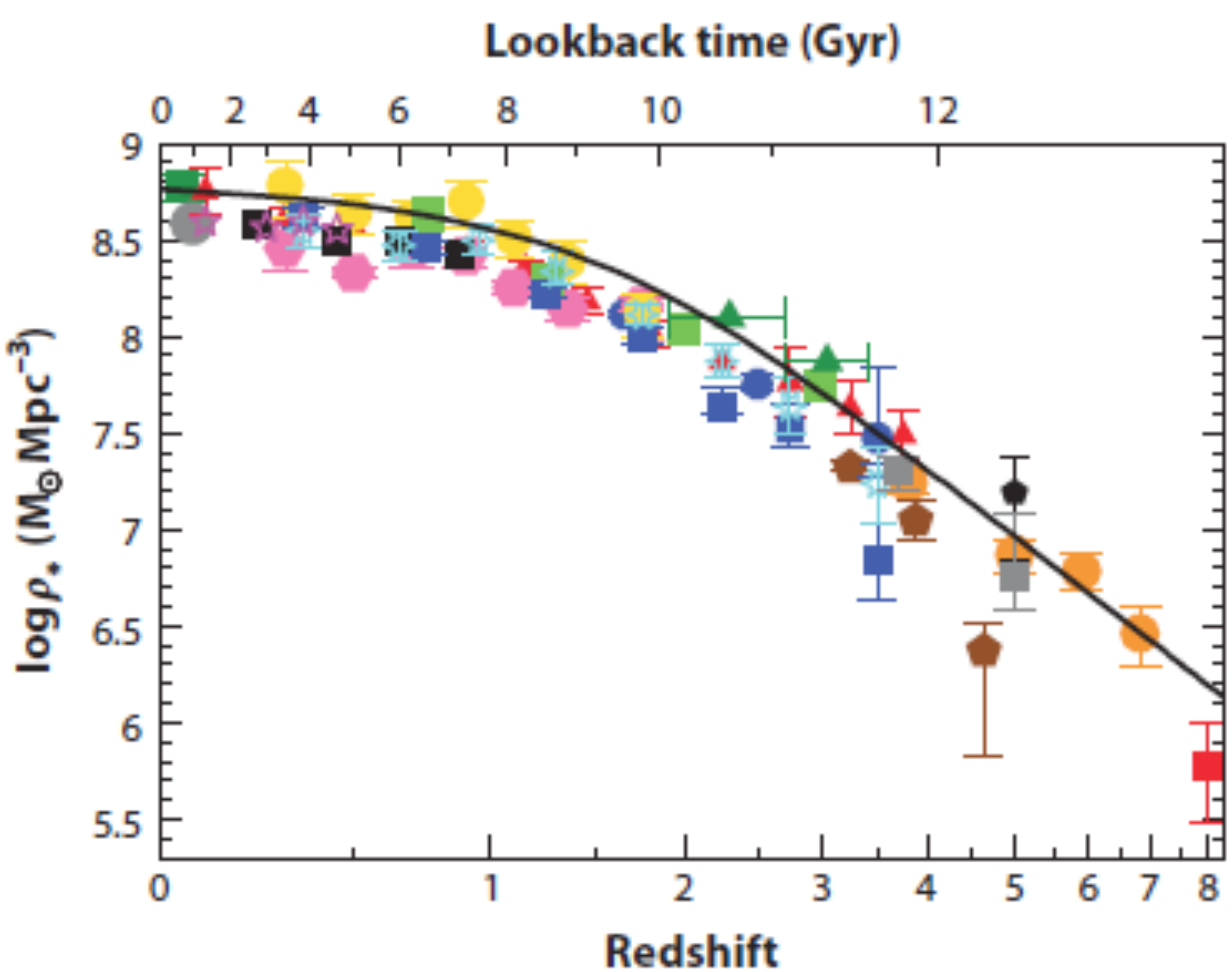
$$H^0 + \gamma \rightleftharpoons H^+ + e^-.$$

CP & Howk, ARAA, 20

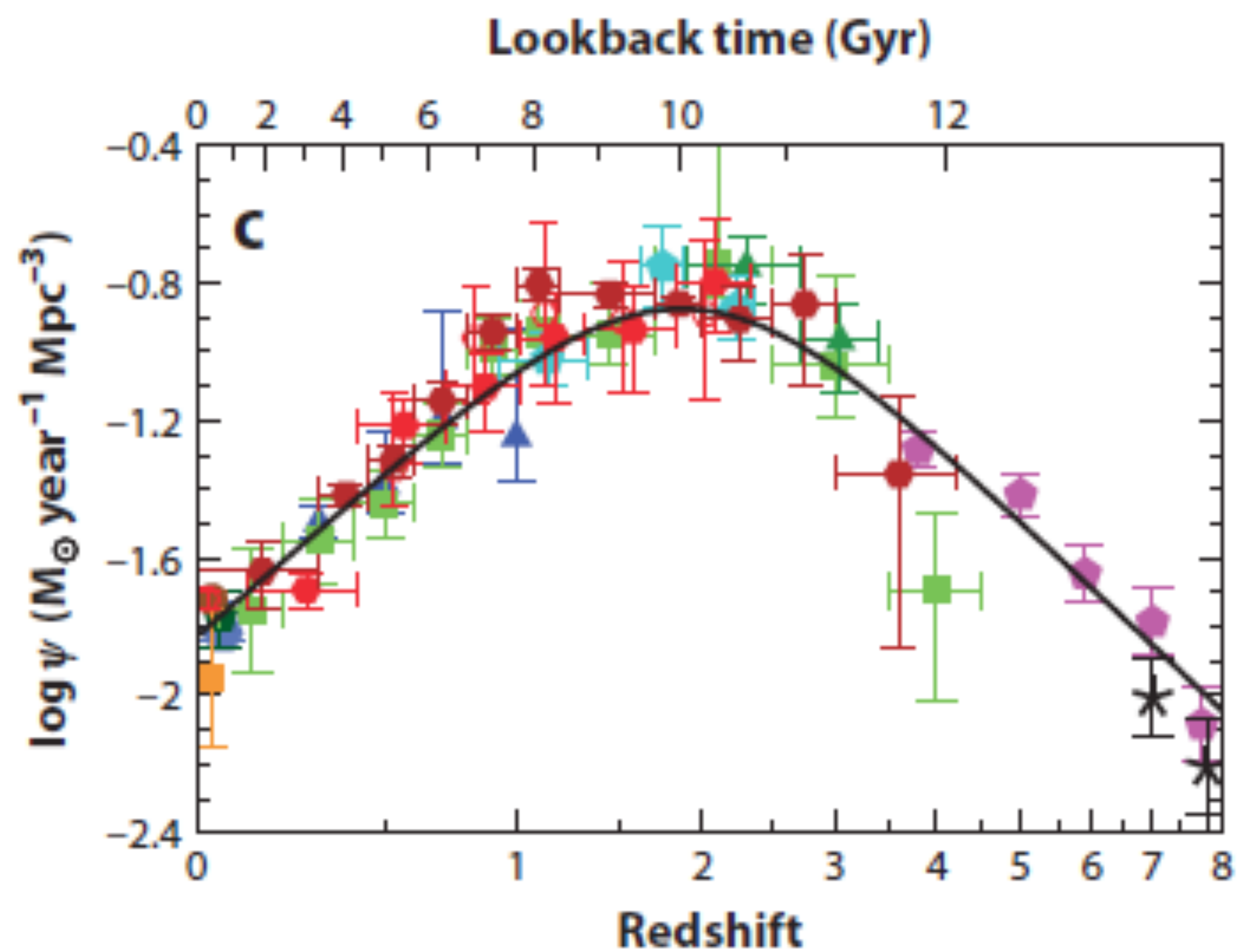
Which physical process drives the decrease in SFR history?

Bromm+11, Madau & Dickinson14

Stellar Mass Density



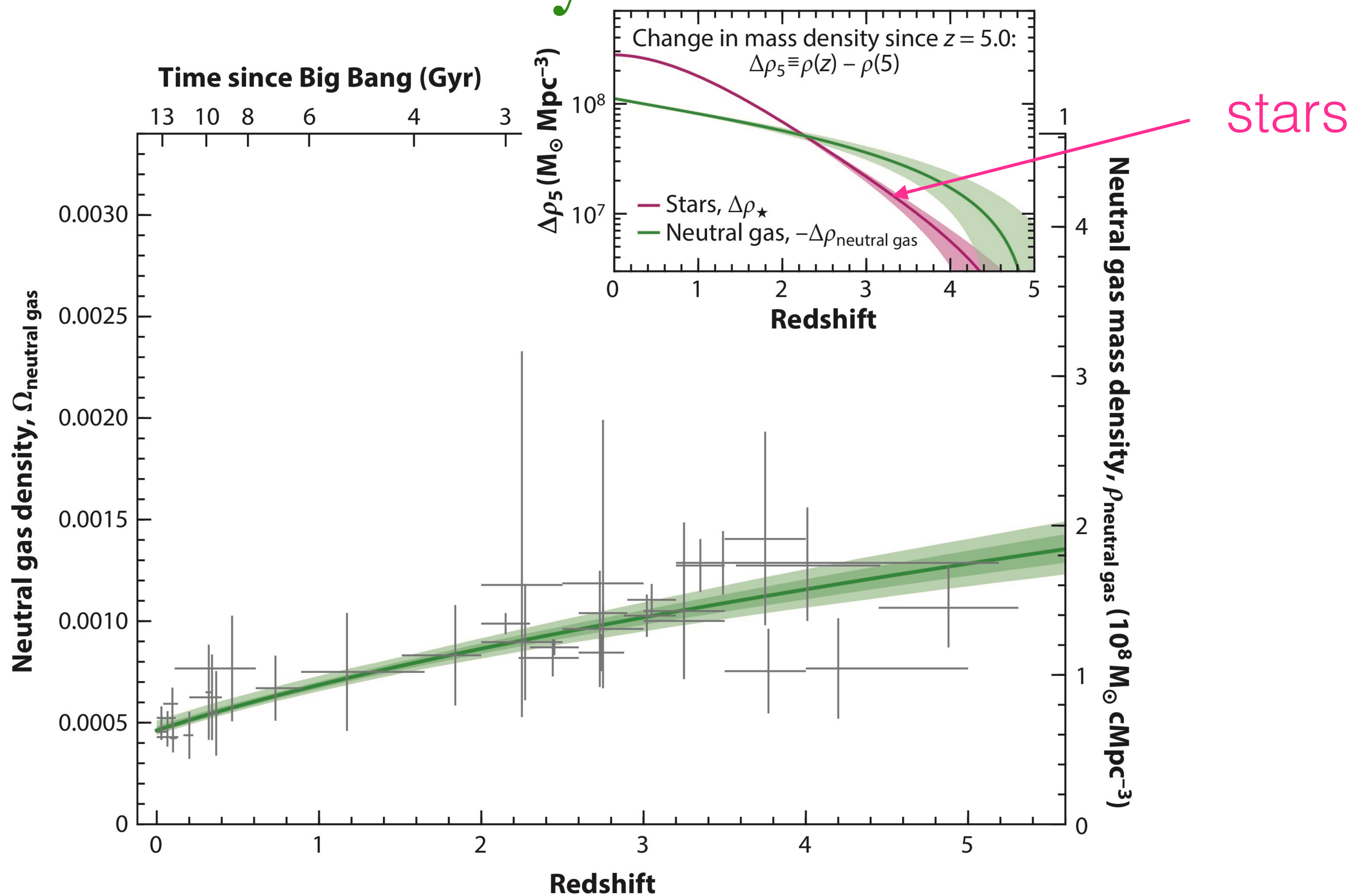
SFRH



$$\rho_\star(z) = (1-R)\int_0^{t(z)} \psi(z)\frac{dz}{dt}dt.$$

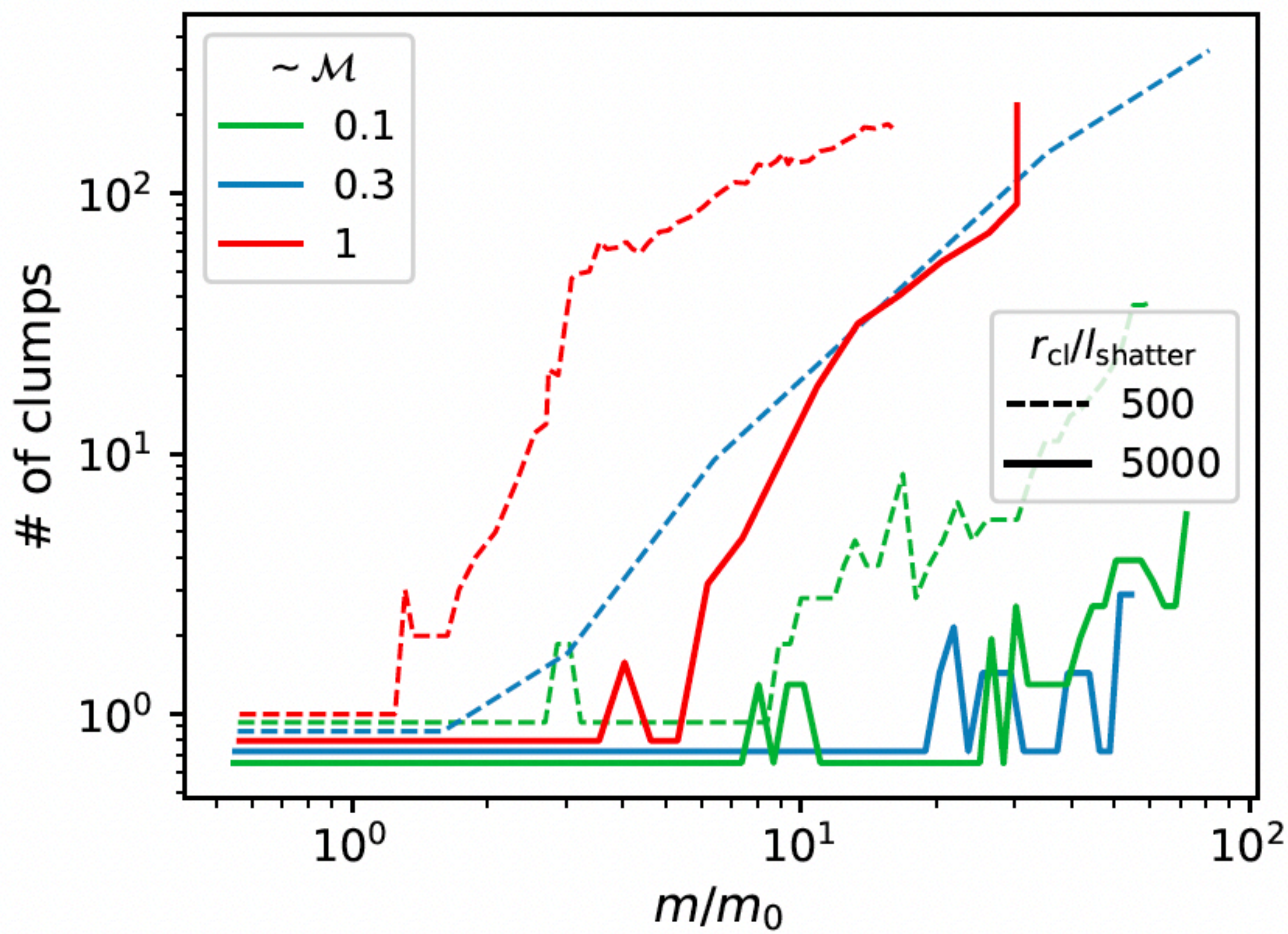
Evolution neutral gas mass shallower than stellar density

CP & Howk, ARAA, 20



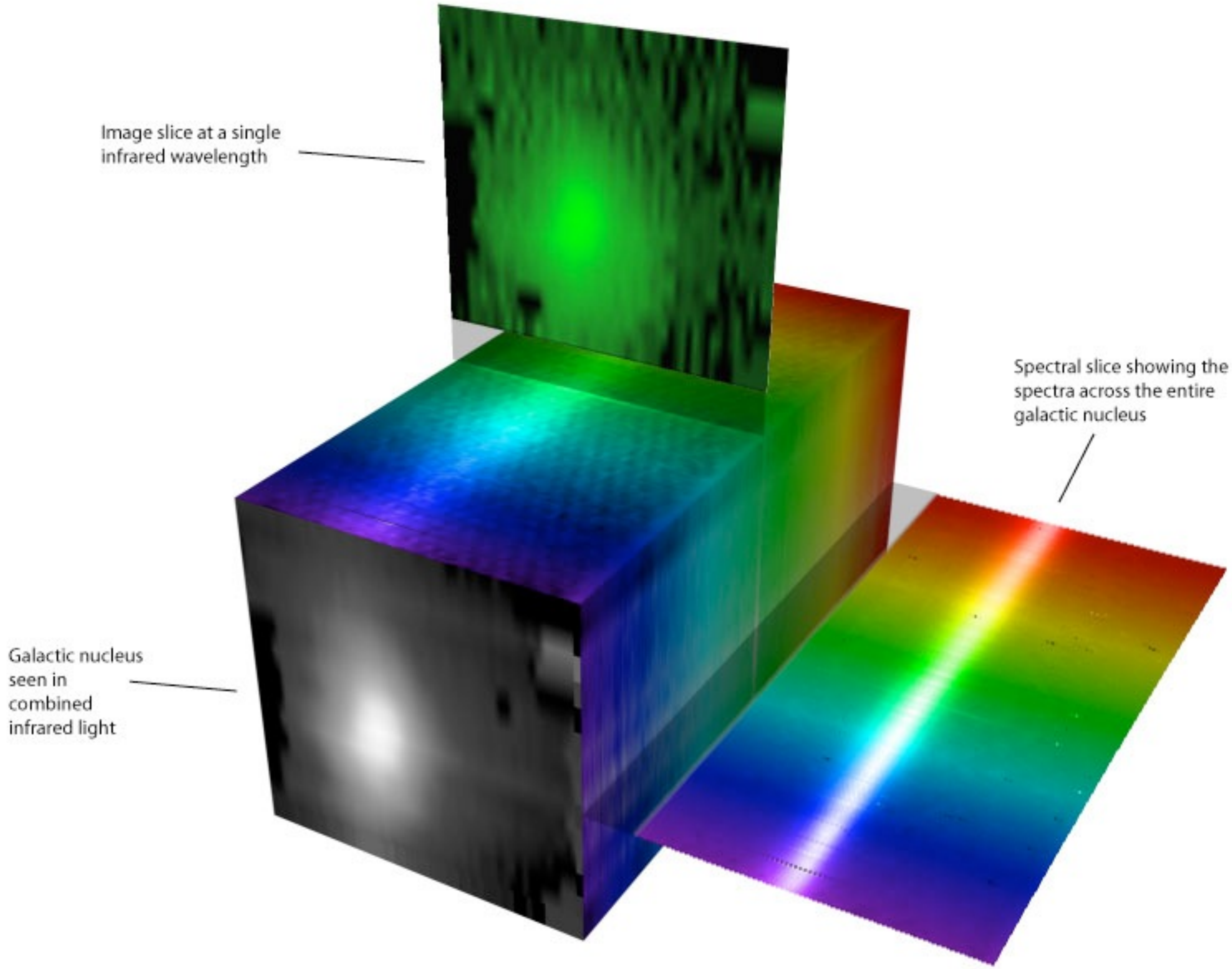
$$\Omega_{\rm neutral\ gas}(z) = [(4.6 \pm 0.2) \times 10^{-4}](1+z)^{0.58 \pm 0.04}$$

Small scales matter

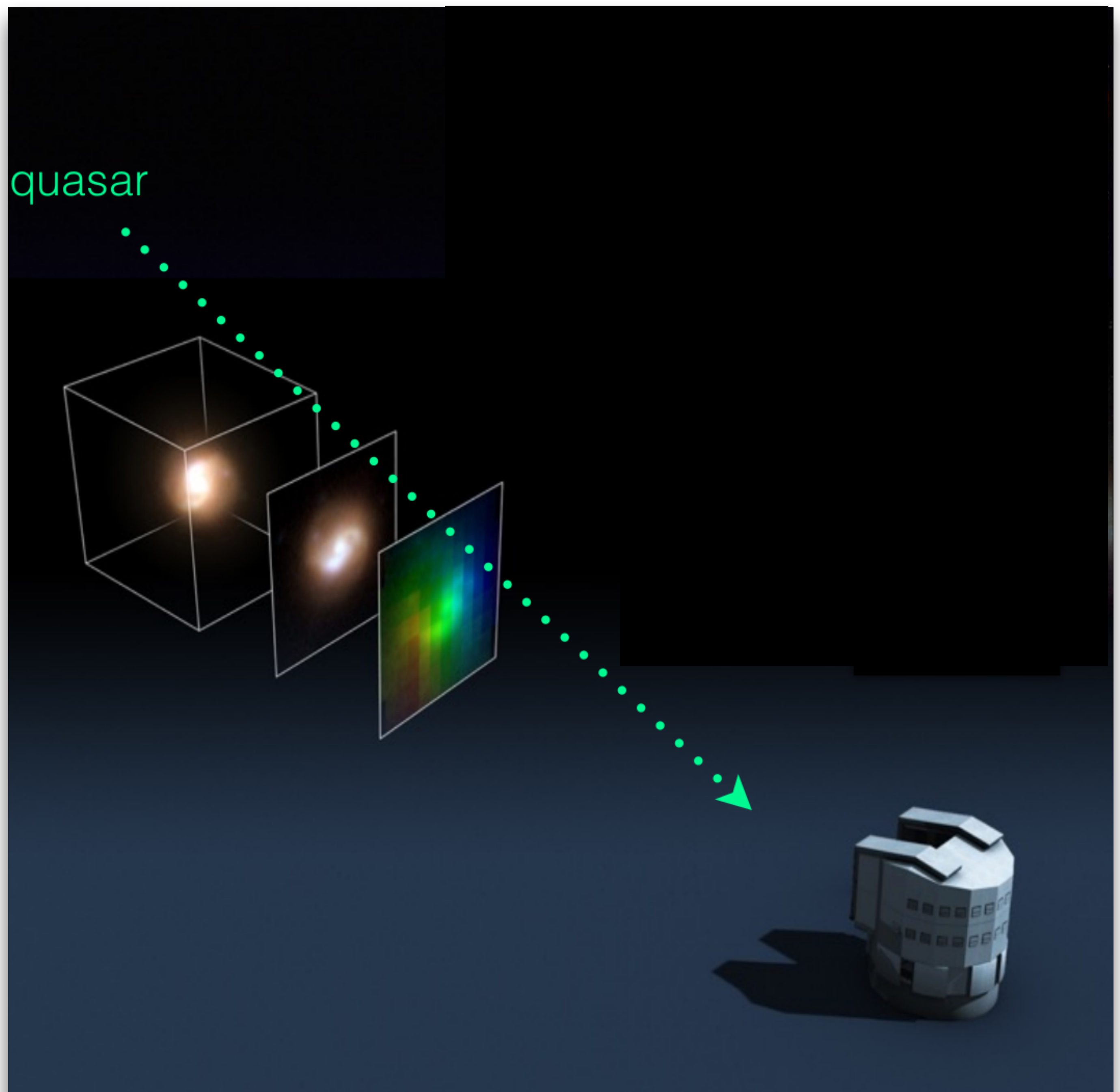


Fensch+23, Kraljic+23, Ramesh+23a, 23b, Gronke+23, Fielding+23, Stern+23, Das+24, Chen+23

3D spectroscopy



3D spectroscopy solved a two-decade long challenge



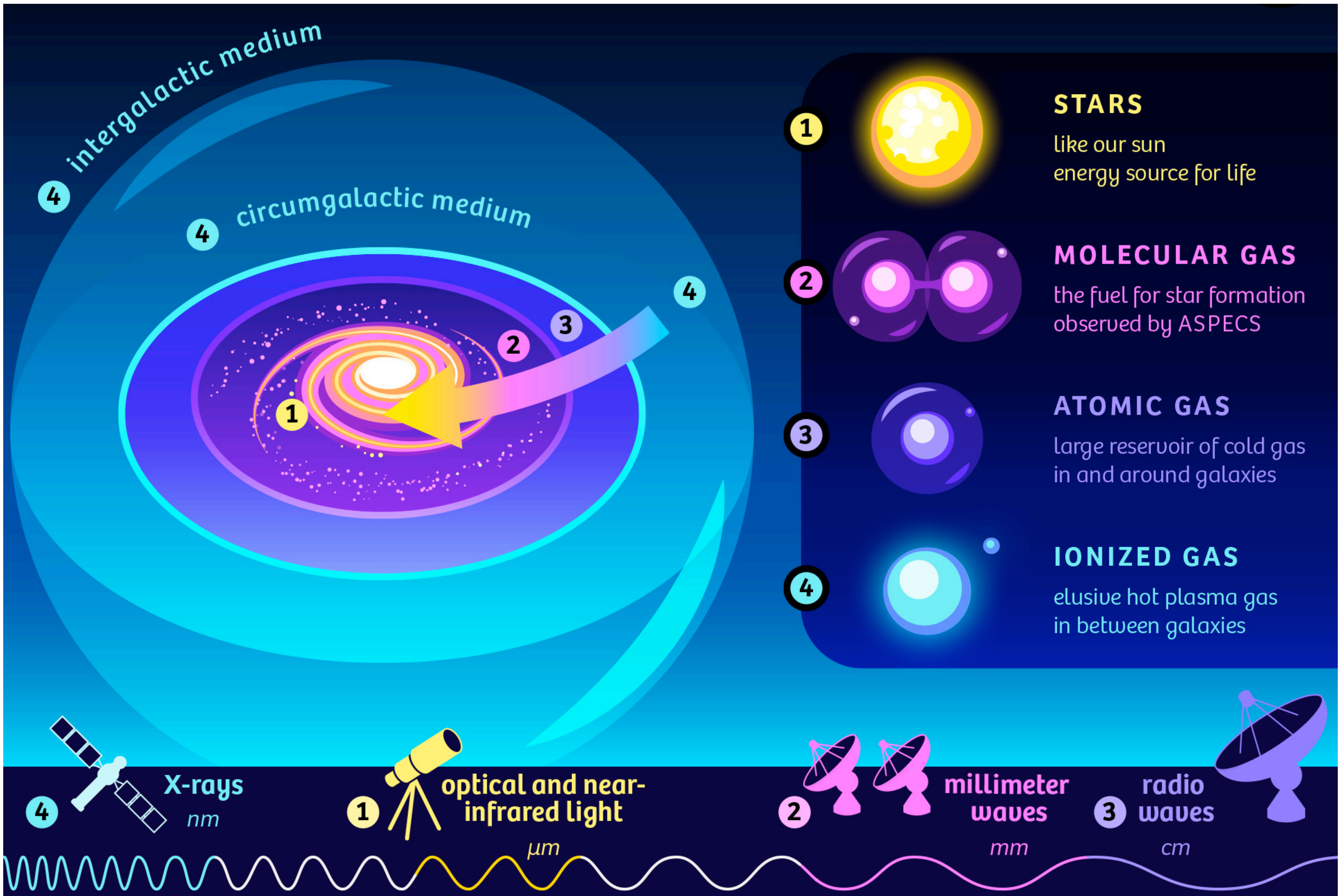
- ➡ geometry
- ➡ physical prop
- ➡ metallicity
- ➡ kinematics

MUSEQuBES,
MEGAFLOW,
MAGG,
CUBS,
BASIC,
+

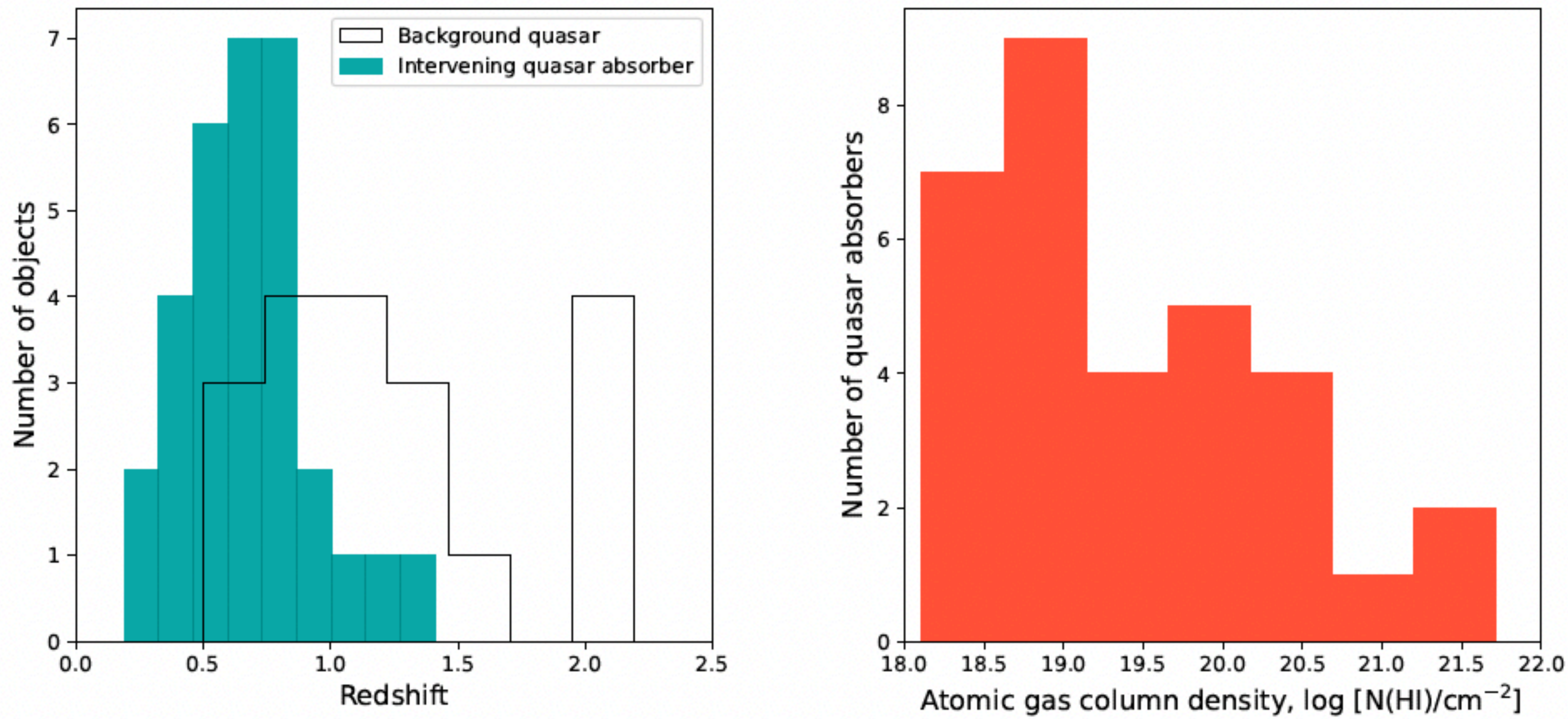
Bouche+16, Dutta+23, Galbiati+23

Multi-phase gas requires multi-wavelength observations

courtesy of ASPECS

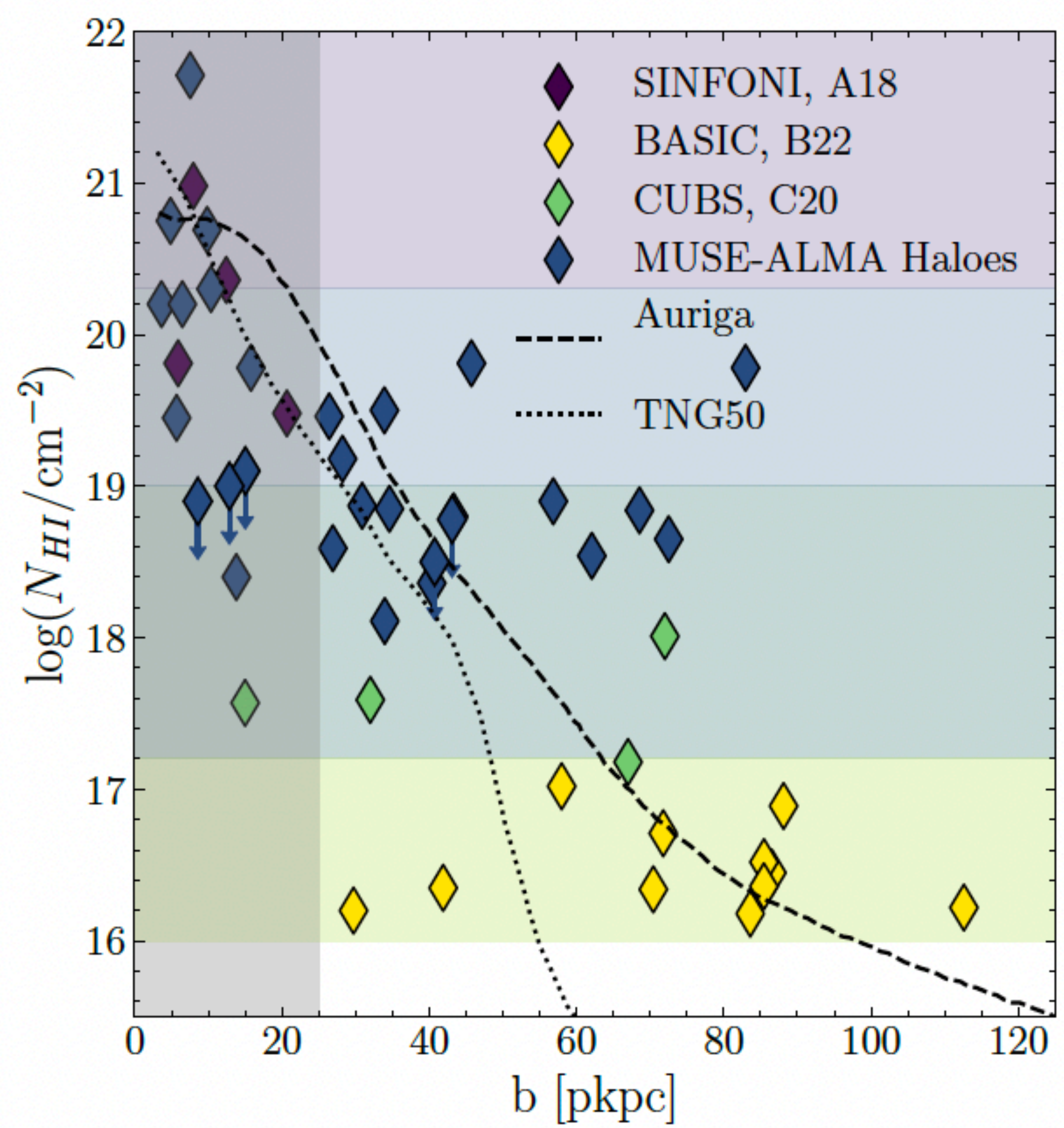


Known atomic hydrogen column density



CP, Weng+22

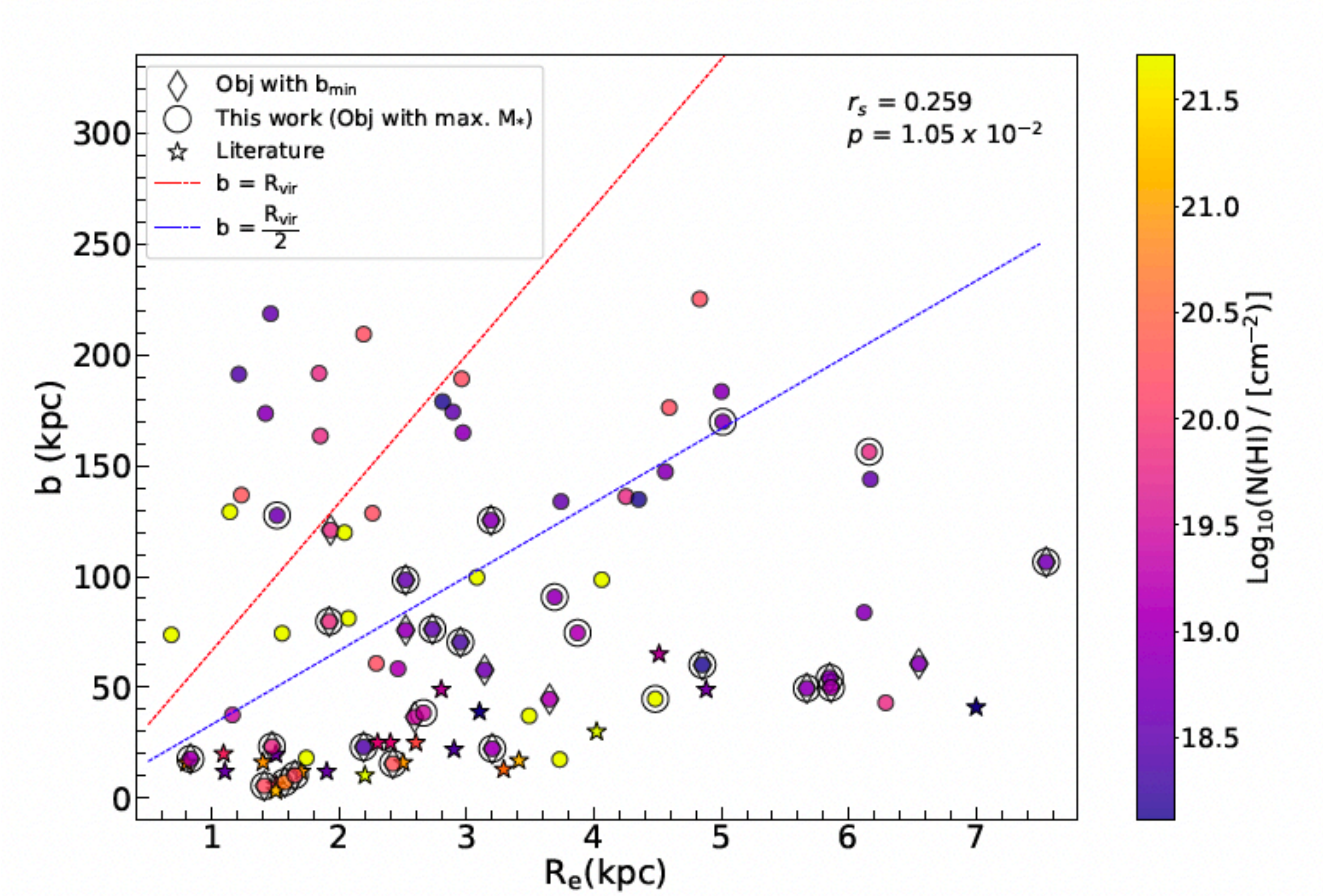
HI gas column decreases with radius



Weng,CP+23a

Arjun Karki

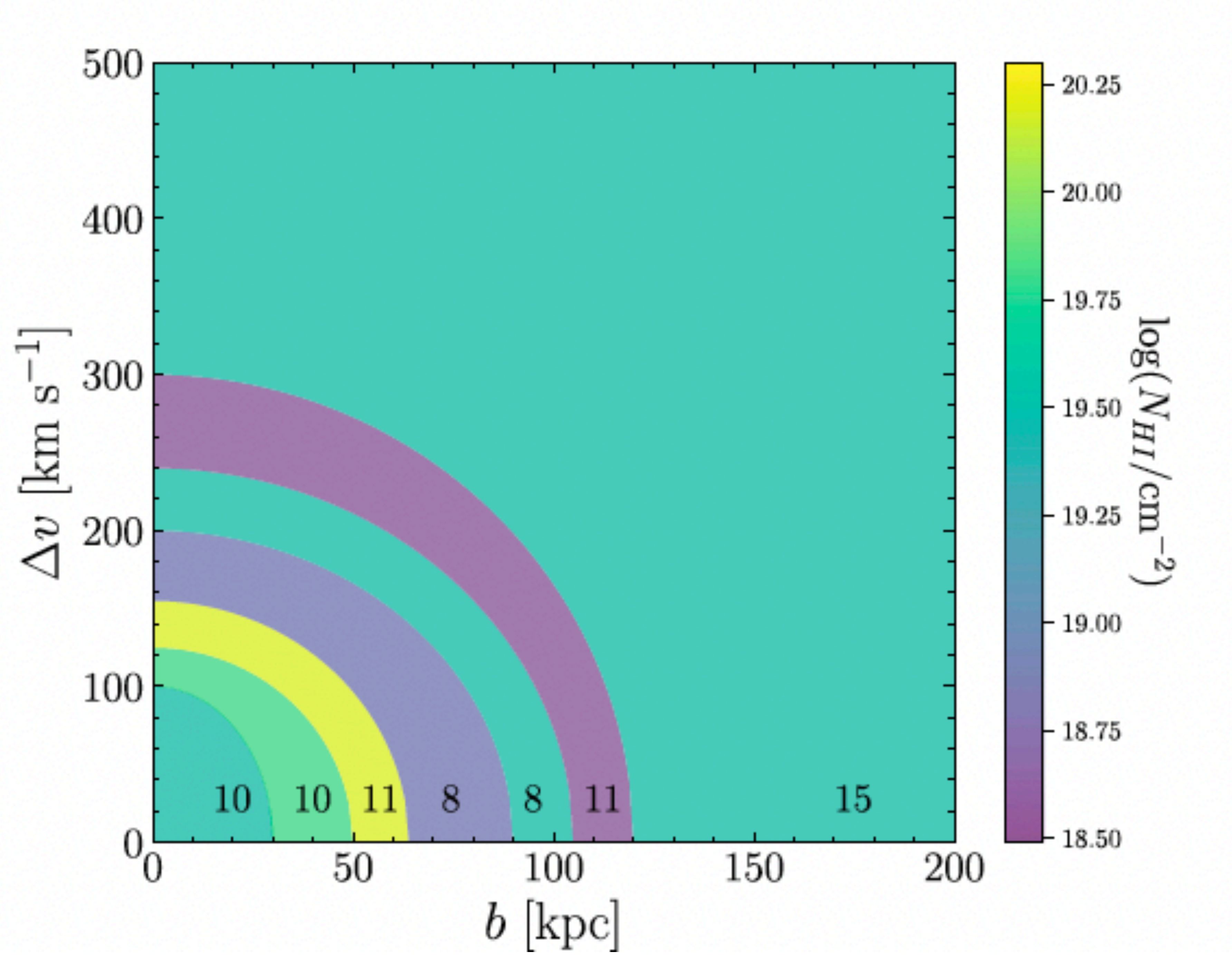
Absorbers within $R_{vir}/2$



Karki+inc CP+23

Simon Weng

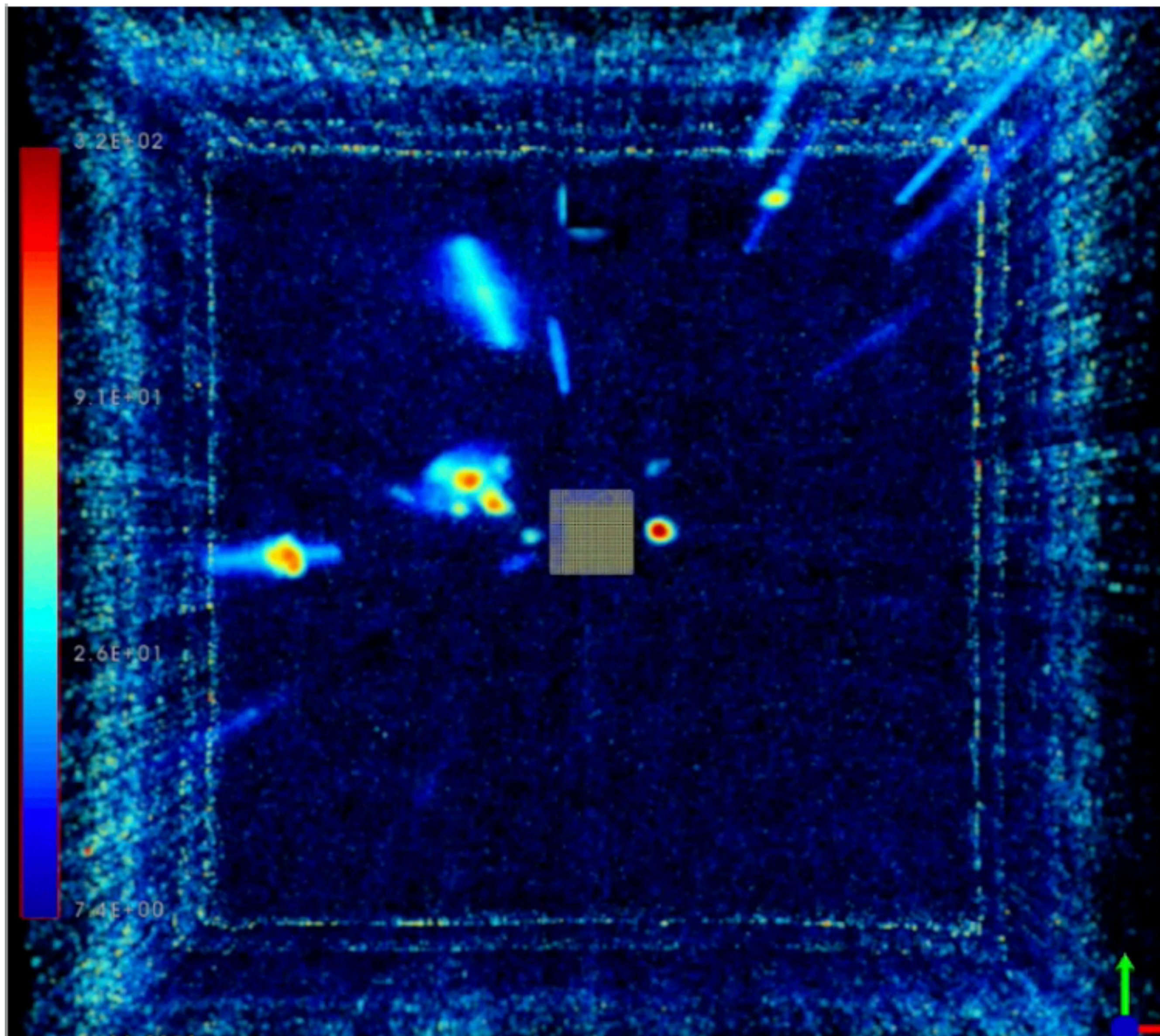
Towards mapping gas around galaxies



Weng,CP+23a

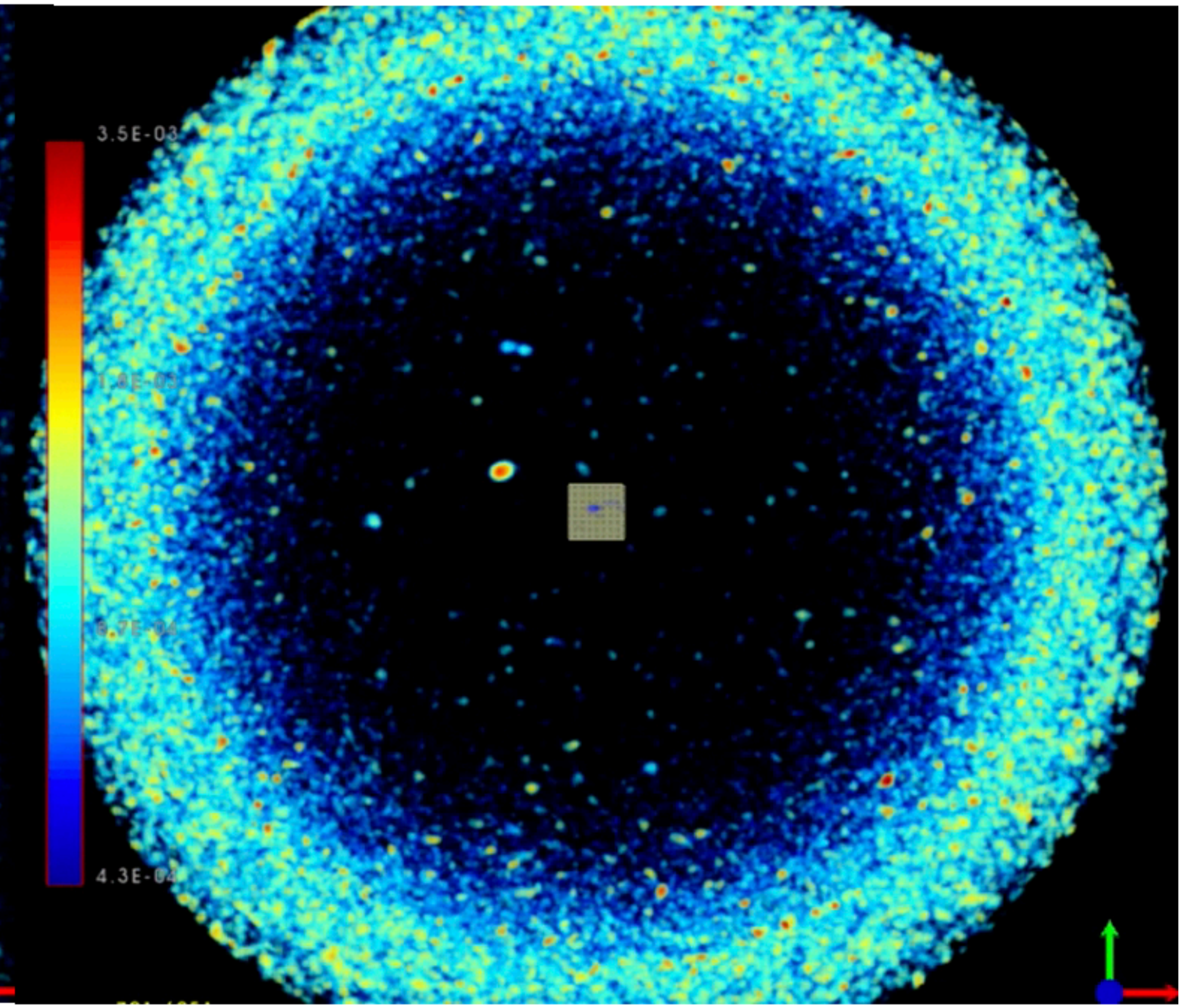
CP+19

Ionised Gas



[OIII] VLT/MUSE

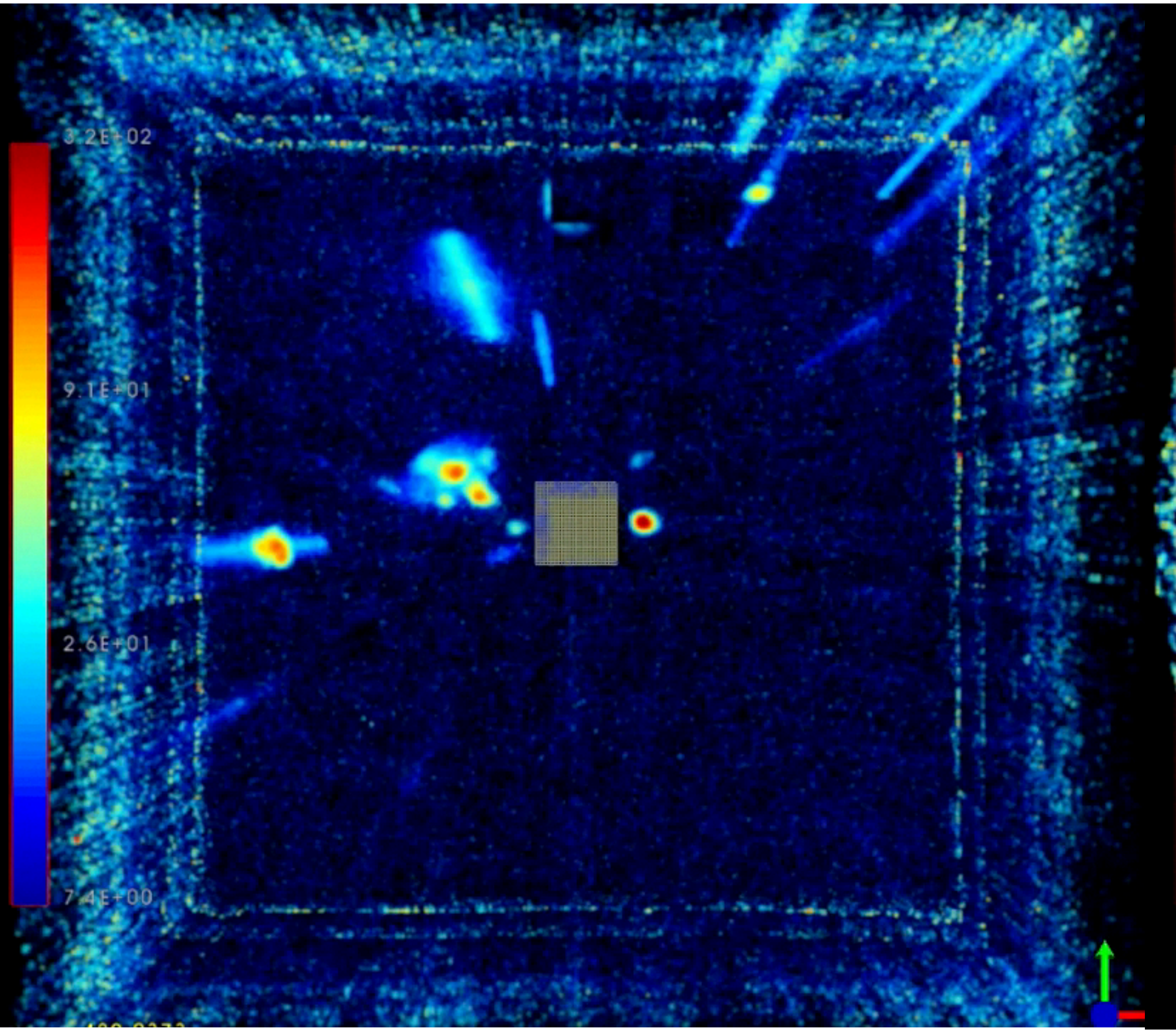
Molecular Gas



CO(1-0) ALMA

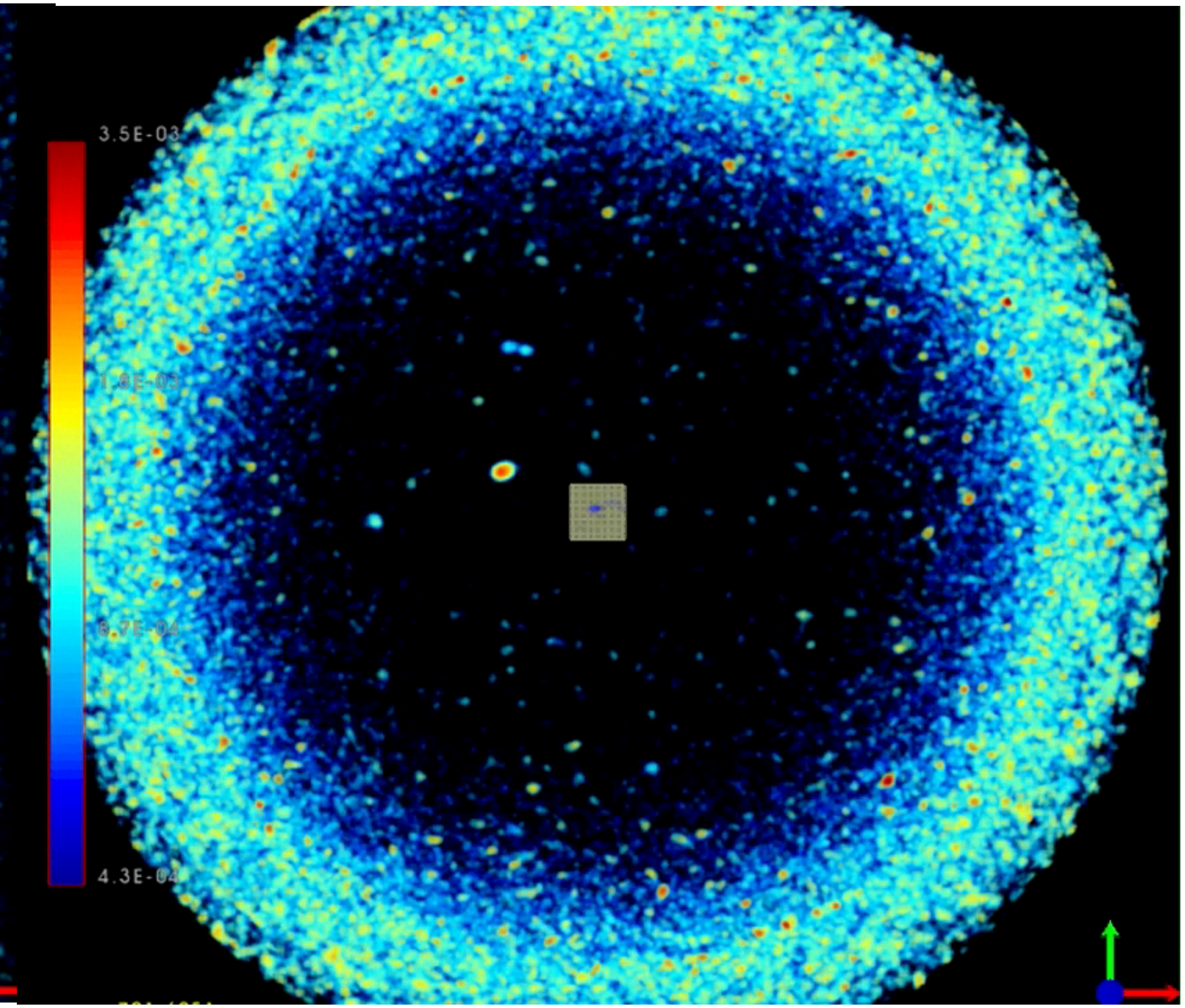
CP+19

Ionised Gas



[OIII] VLT/MUSE

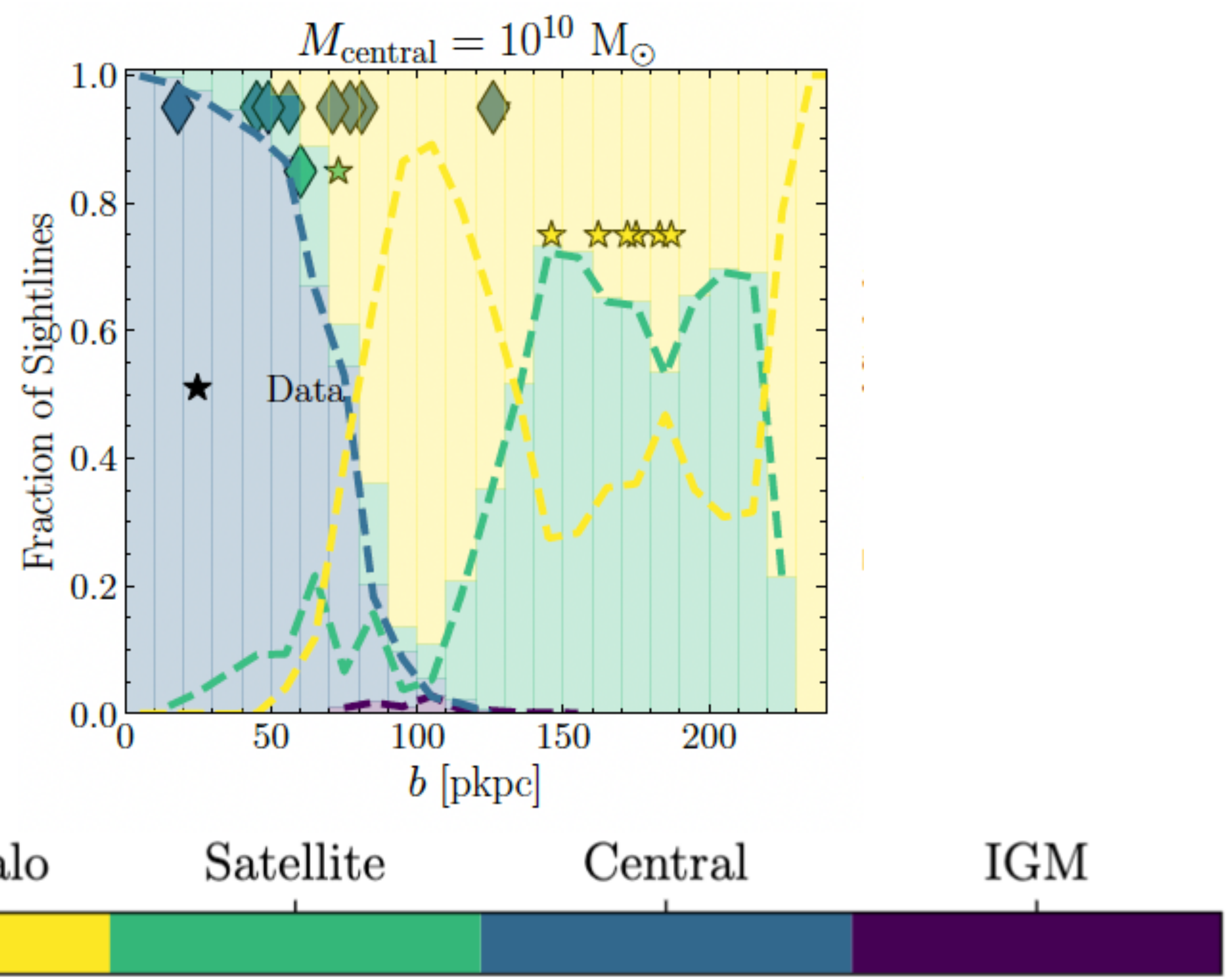
Molecular Gas



CO(1-0) ALMA

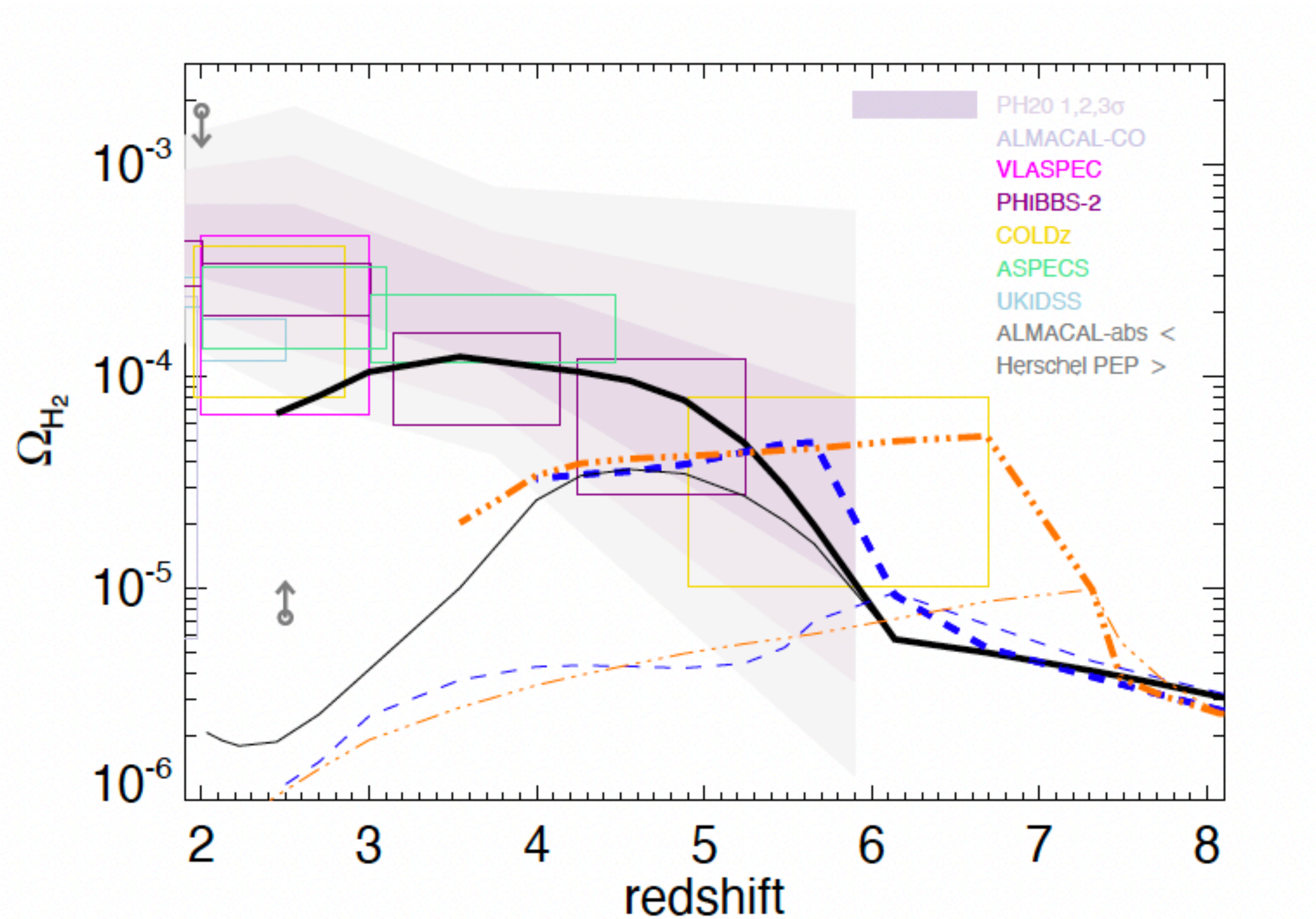
Broad agreement with observations

Simon Weng



Weng, CP, Ramesh, Nelson+24

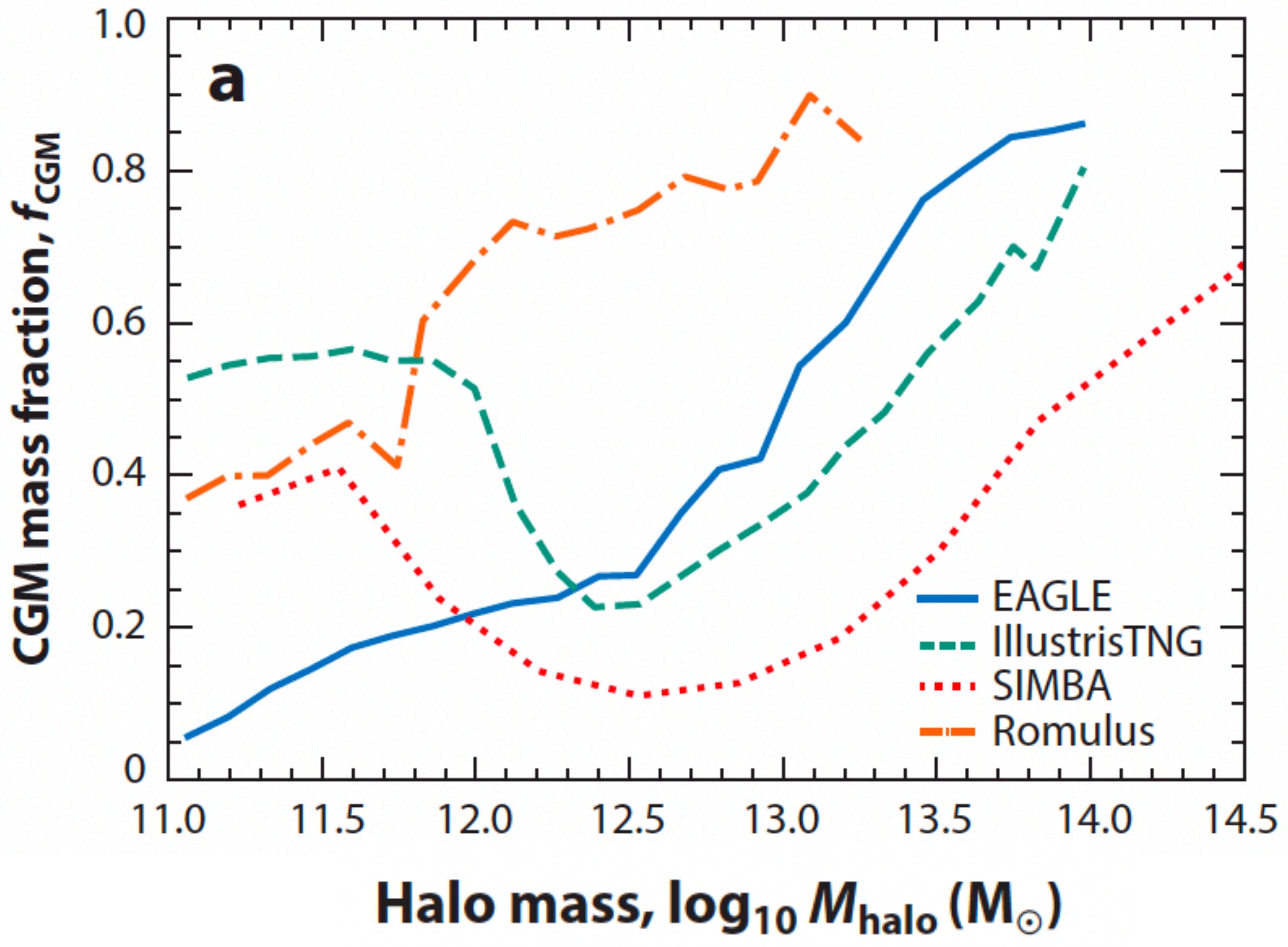
Time-dependent non-equilibrium chemistry



Lahen+20, Katz+22, Farber+22,
Gronke+22, 23, Maio, CP, Ciardi+22

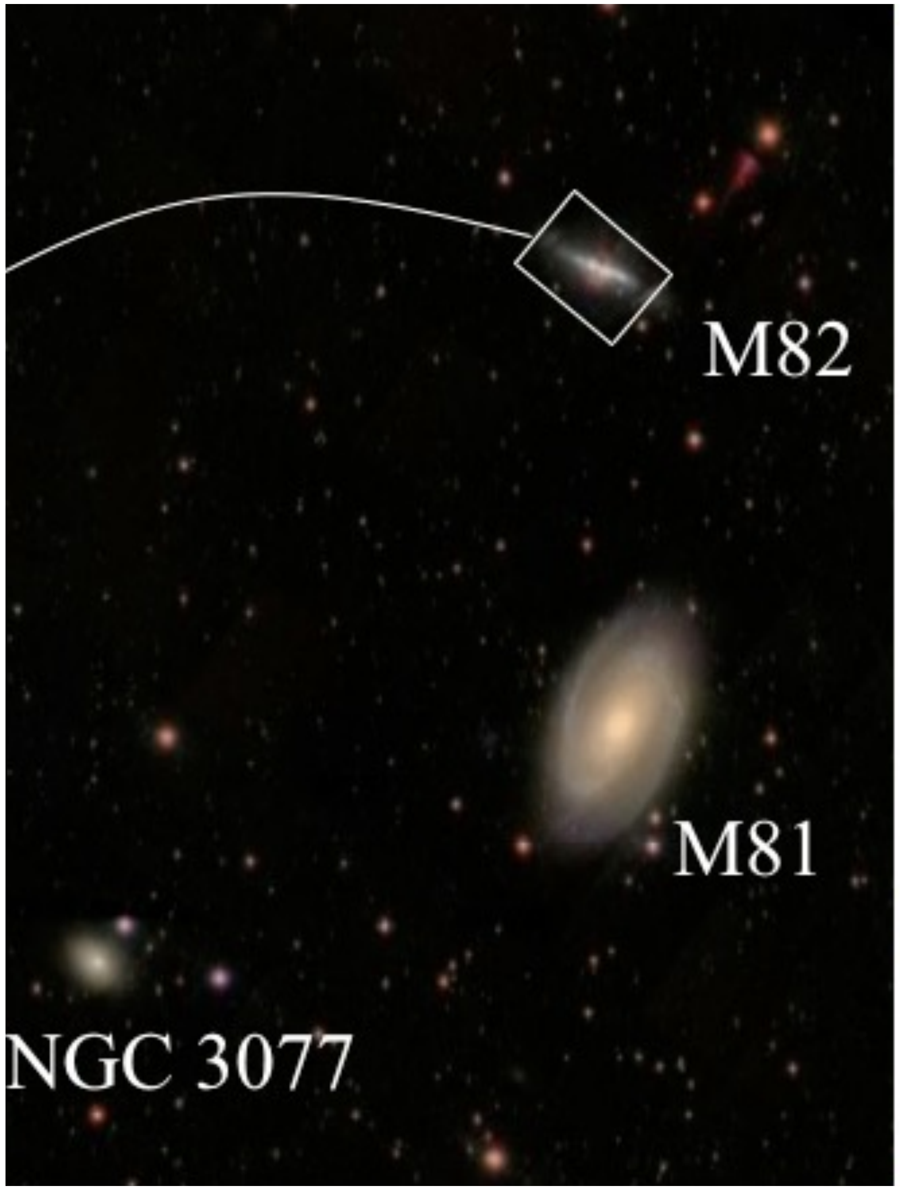
ColdSIM

Not yet a consensus on feedback



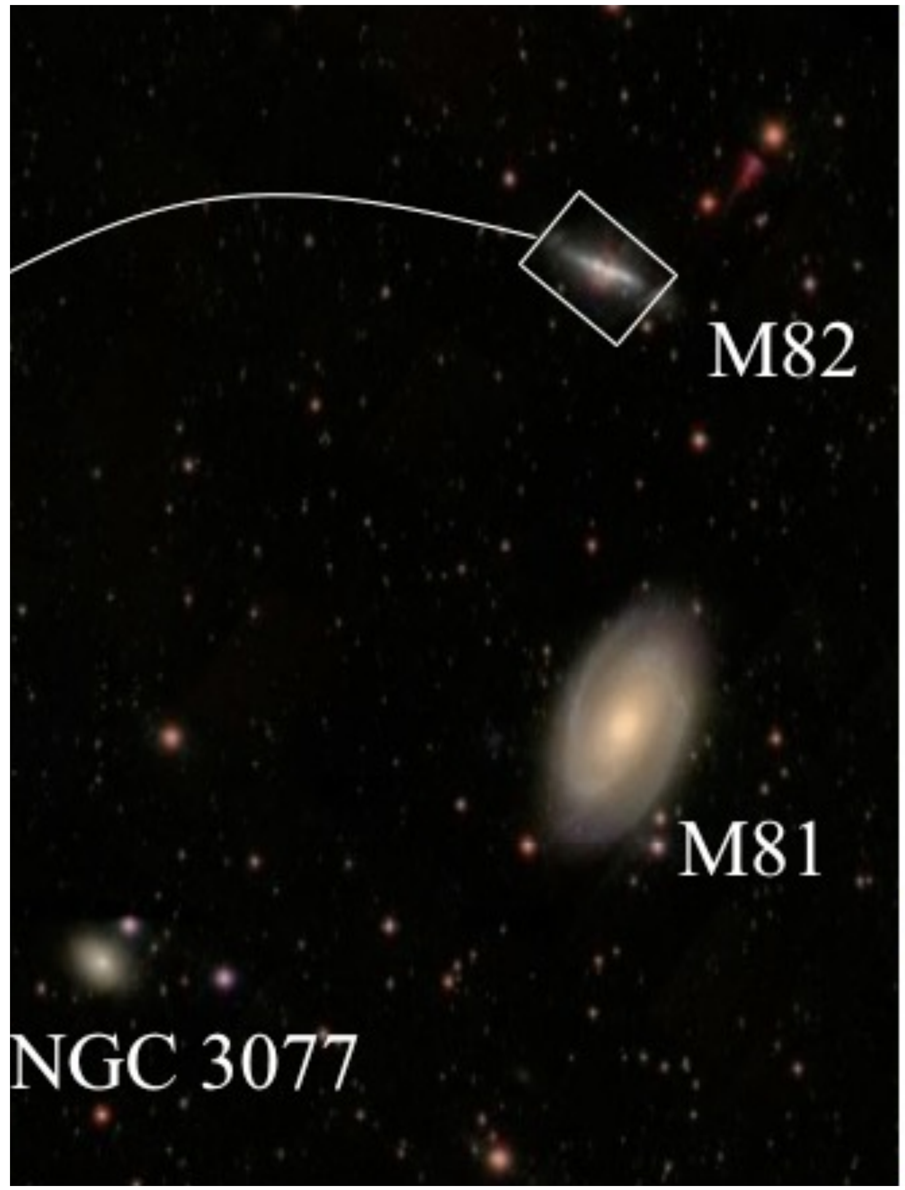
Costa+22, Ward+22, Crain&van de Voort, ARAA, 23,

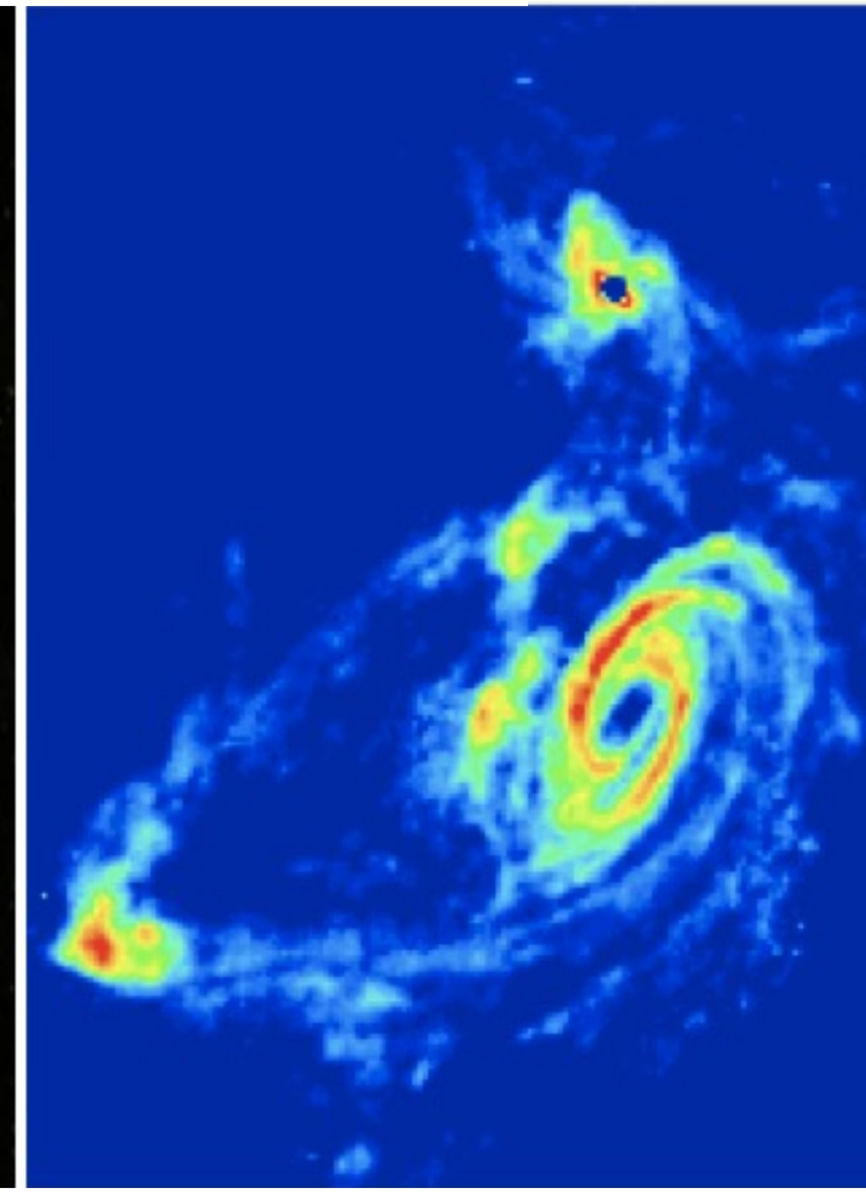
Low-redshift Analog



Starlight
(optical)

Low-redshift Analog

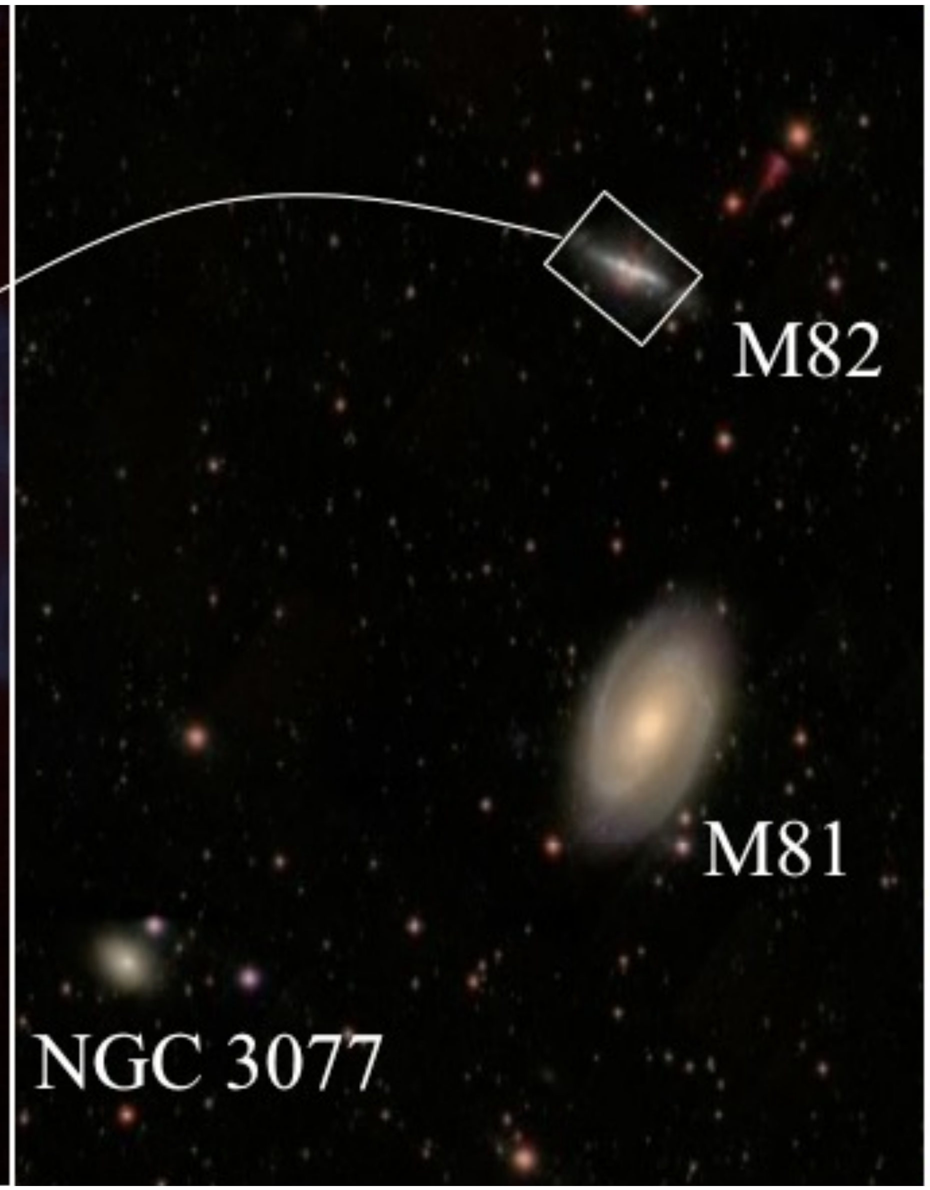


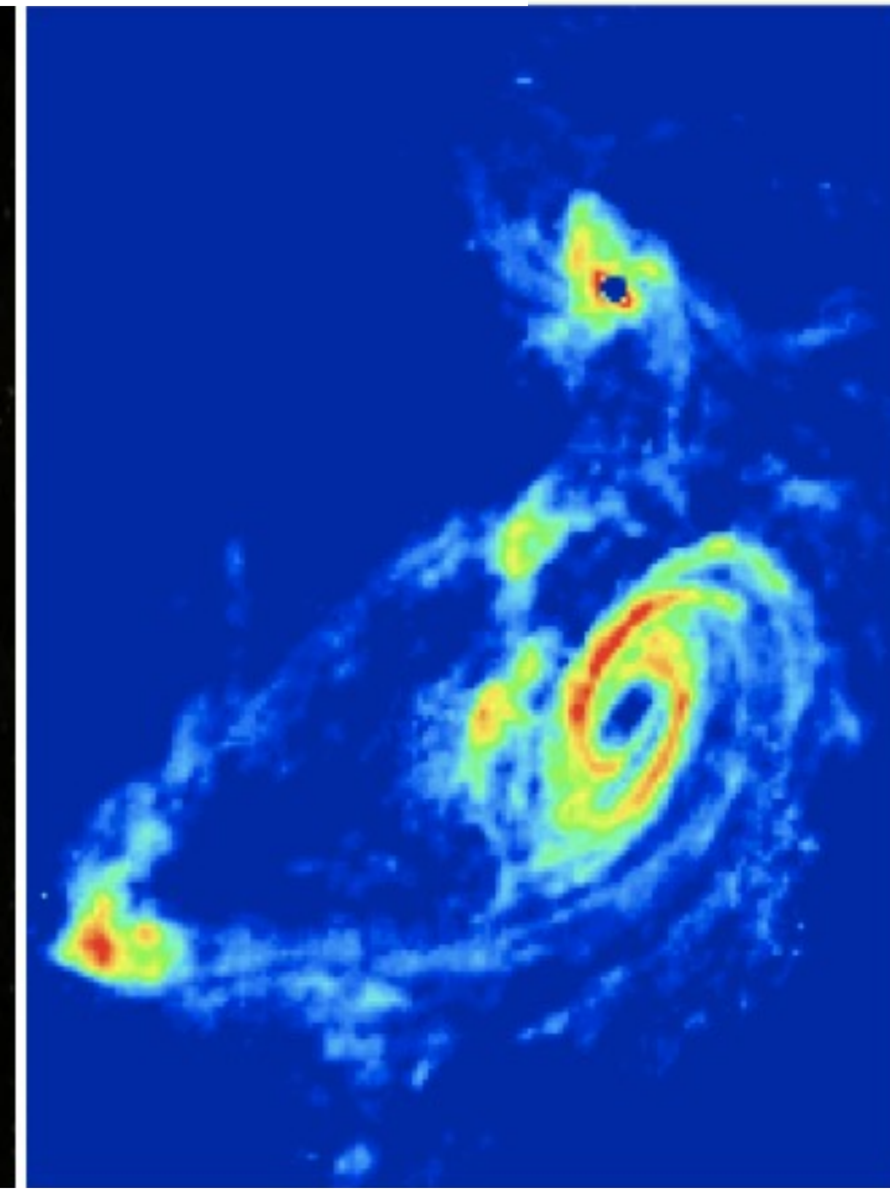


Starlight
(optical)

HI Gas
(radio)

Low-redshift Analog



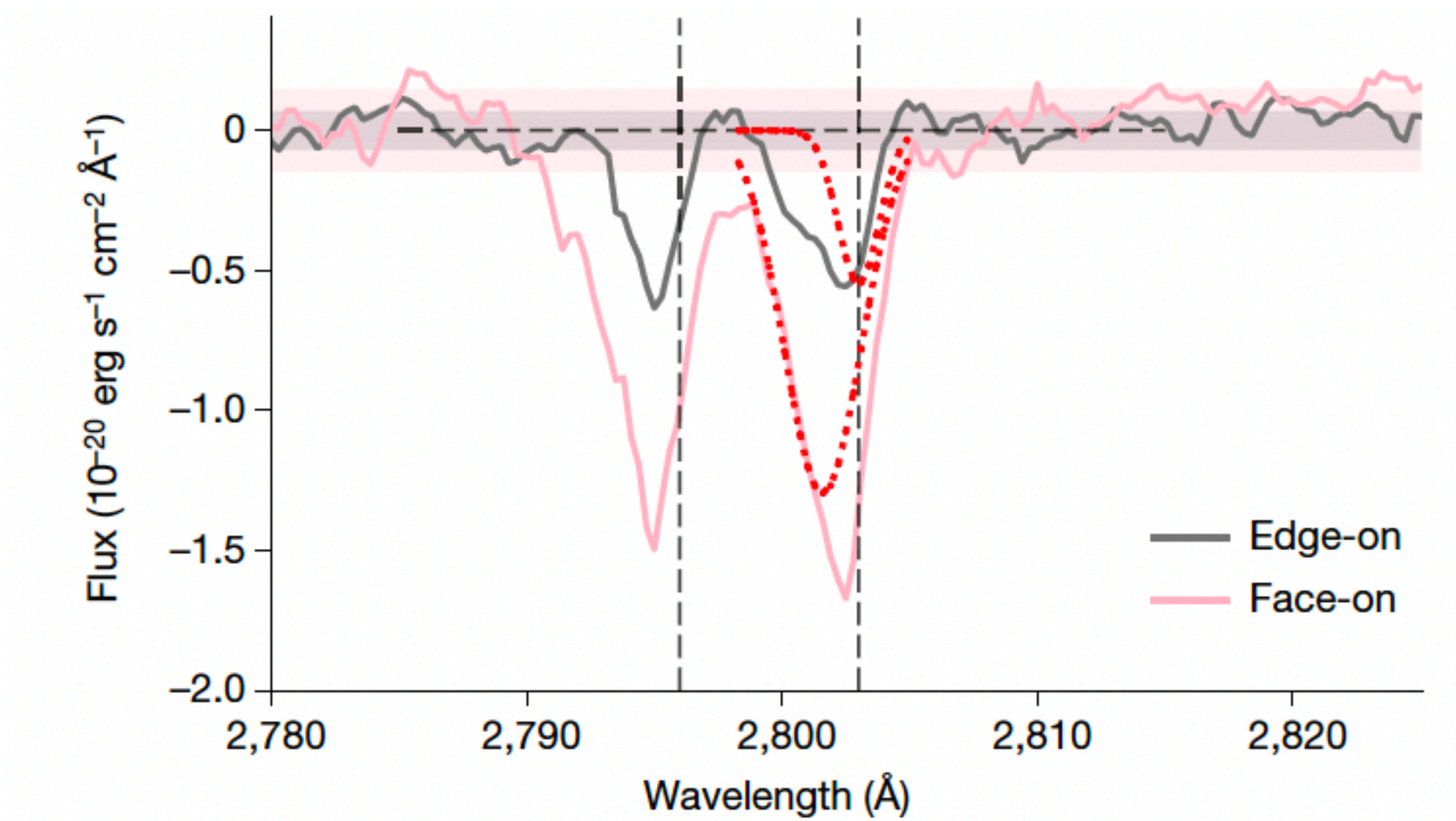


Galactic Wind (M82)

Starlight (optical)

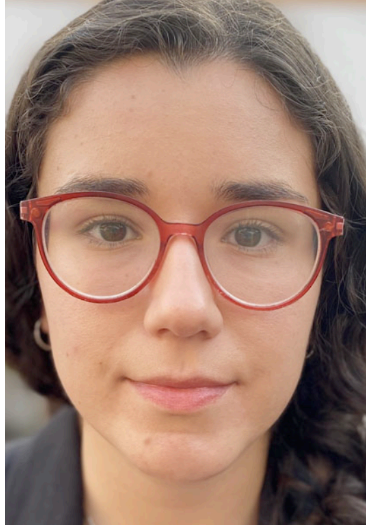
HI Gas (radio)

MgII emission stacking

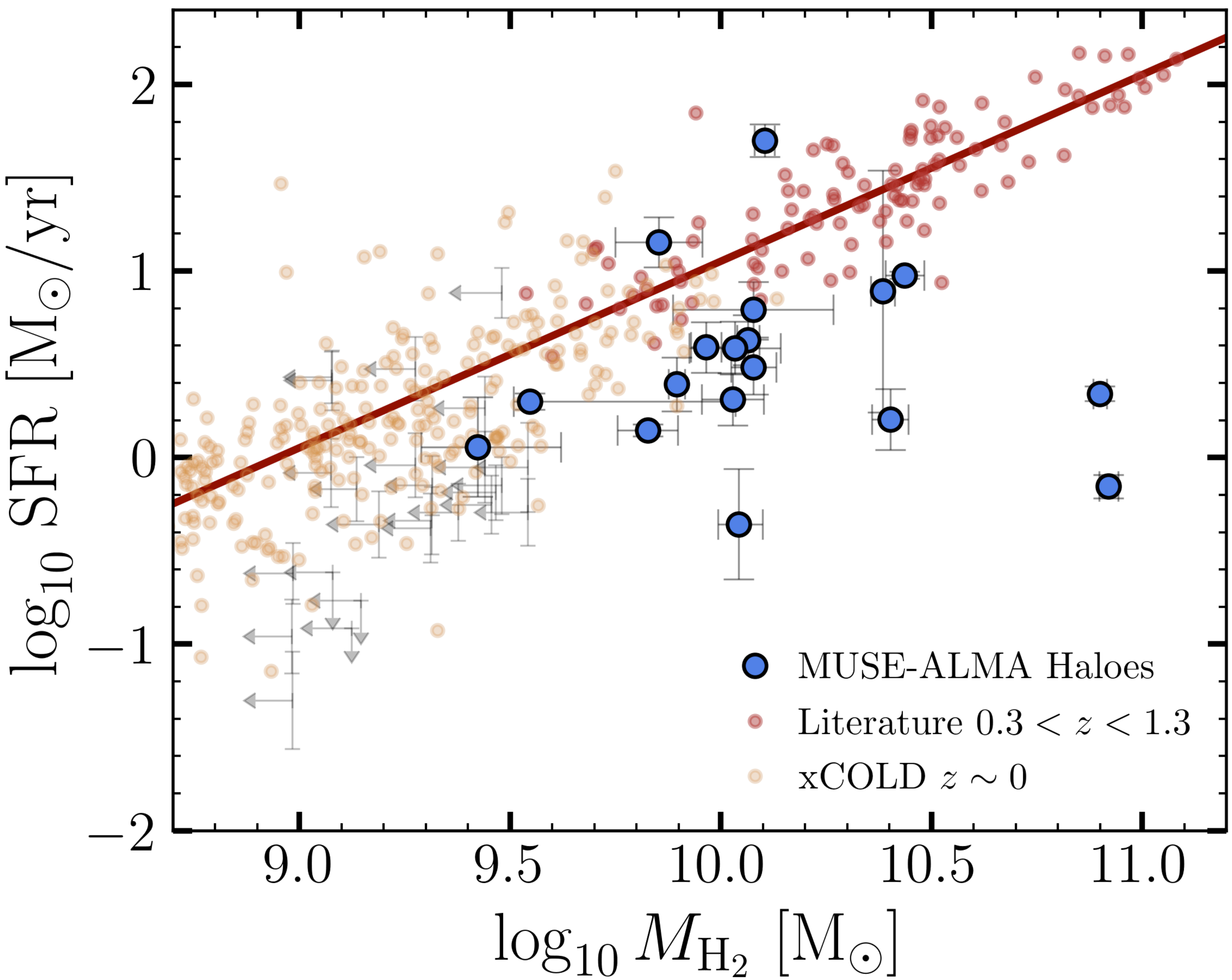


Guo+, Nature, 23

Key Goal I: role of H2 gas in HI-selected galaxies

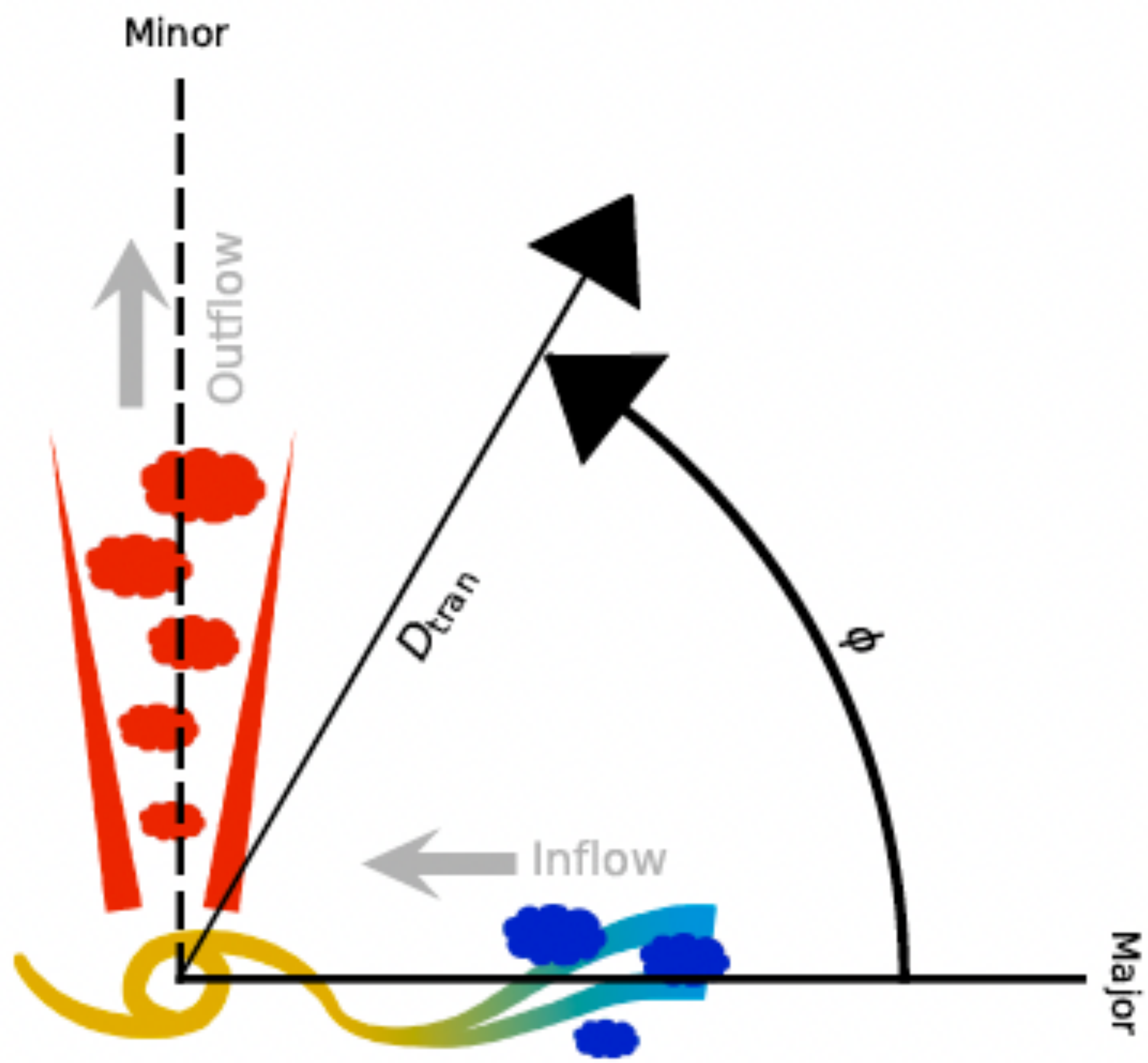


Victoria Bollo



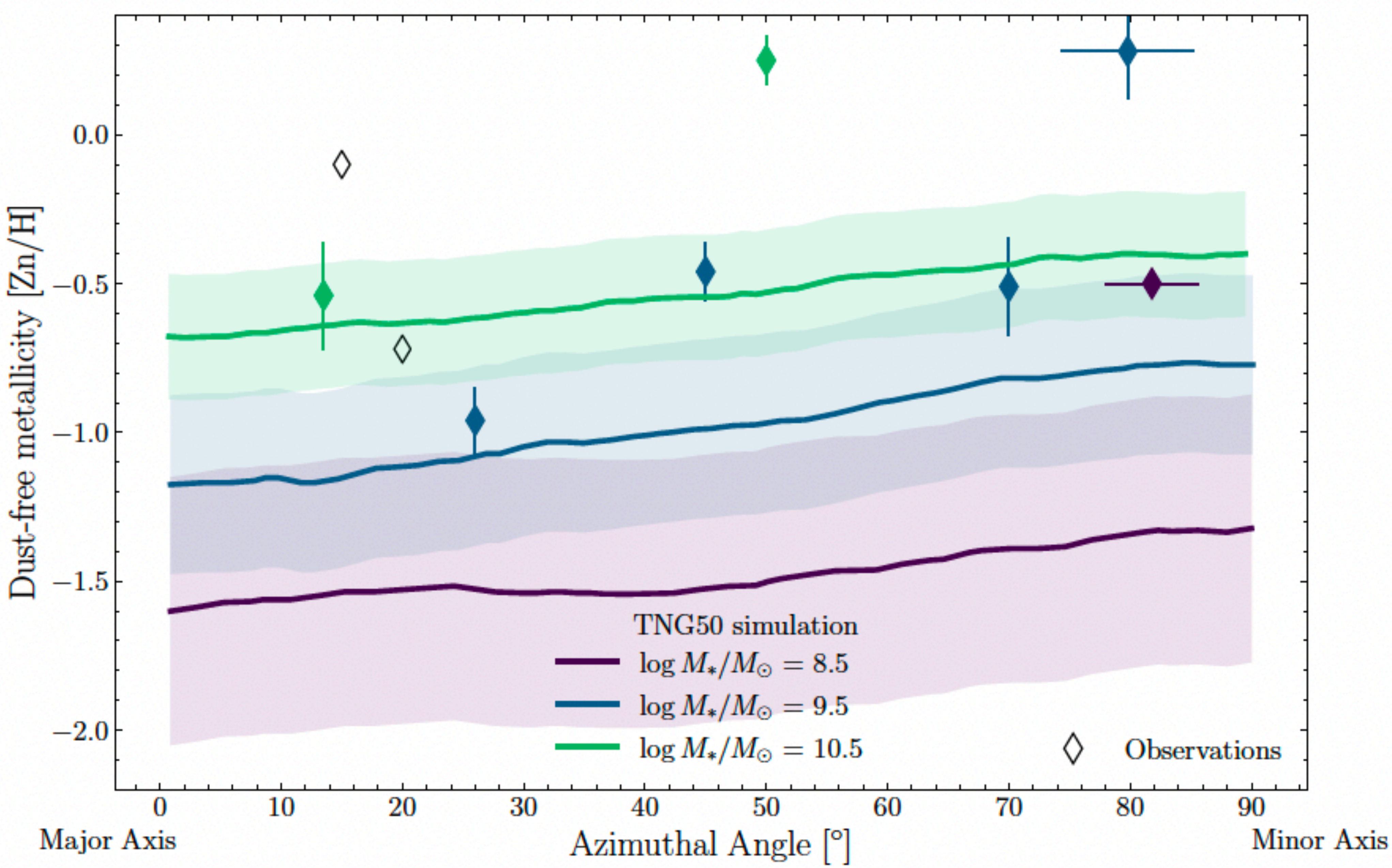
Bollo+in prep

Do CGM physical properties vary with angular orientation?



Chen, Steidel+21

Current state of metallicity along the minor versus major axes of galaxies



Weng, CP+23b