Progress & Challenge in Galaxy-IGM/CGM Connection

— Insights into reionization-era galaxies and supermassive black holes —

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Galaxy-IGM workshop, virtually Tsukuba 2020

UCSB

Epoch of Cosmic Dawn & Reionization

z=1100 (CMB)

first stars z~20-30	assemble to first galaxies	emergence of first SMBHs	reionization z~6-18

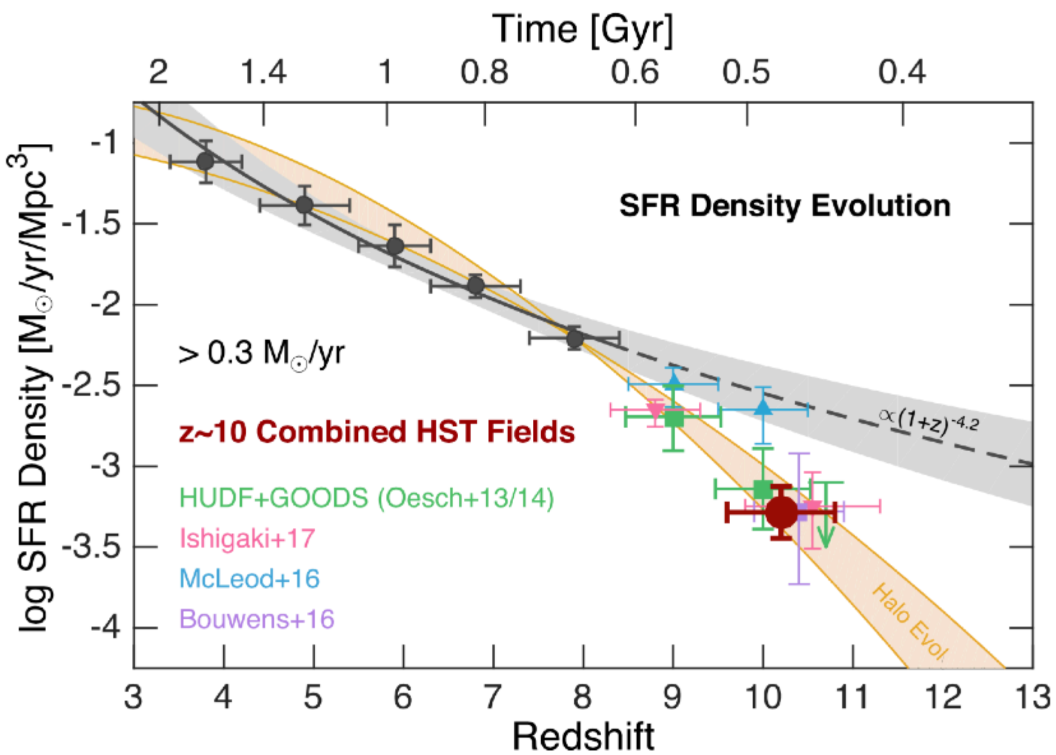
Key questions :

How did reionization happen?

What reionized the IGM? Assembly of reionization-era galaxies?

The emergence of first stars, galaxies, and black holes?

Theoretical Problem of Reionization in a Nutshell



Oesch+18

HST galaxy demographics can drive reionization & be consistent with Planck's optical depth, but "unknown ionizing capability of galaxies".

$$\dot{n}_{\rm ion} = \int f_{\rm esc}\,\xi_{\rm ion}\,{\rm SFR}\,\frac{dn_{\rm galaxy}}{dM_{\rm halo}}dM_{\rm halo} \quad \left(+ \int f_{\rm esc}\,\xi_{\rm ion}\,\dot{M}_{\rm BH}\frac{dn_{\rm SMBH}}{dM_{\rm halo}}dM_{\rm halo} \right)$$

The theoretical challenge is to understand the physics of …

Escape fraction
galactic winds, supernova feedback, stellar winds, turbulence

Ionizing production production rate
massive stellar evolution, binary, rotation, metallicity

z>6 galaxy formation
star formation history, galaxy population, massive vs. dwarf galaxy properties

z>6 SMBH formation
accretion power, variability, SMBH formation channels

Multi-wavelength Observational Windows & Tests for the Galaxy-IGM/CGM Connection

UV/optical/infrared probe:

- ***HI Lyα forest (z~0-7) (HeII Lyα forest, z~2-4)***
  Voigt profile/absorbers, flux statistics, IGM tomography
- ***Metal absorption lines (OI, CII/CIV, SiII/SiIV, MgII)***
  Absorbers, flux statistics/forest, pixel optical depth

Cross-correlate with galaxies & AGN

- ***Lyα emission***
  Haloes, line profile, LAE clustering, intensity mapping
- ***Metal emission line haloes***
  MgII 2800Å, [CII]158μm (also HeII1640, Hα)

Radio/sub-mm probe:

- ***21cm emission & absorption***
  Global signal, power spectrum, tomography, 21cm forest
- ***Other intensity mapping***
  [CII]158μm, HeII 3.46GHz …
- ***CMB***
  Thompson optical depth, Sunyaev-Zeldovich effect
- ***Fast radio bursts***
  z<1 missing baryon problem, dispersion measures

Gamma-ray probe:

- ***GeV absorption spectra along high-z blazars and gamma-ray bursts***

Gravitational wave probe (?)

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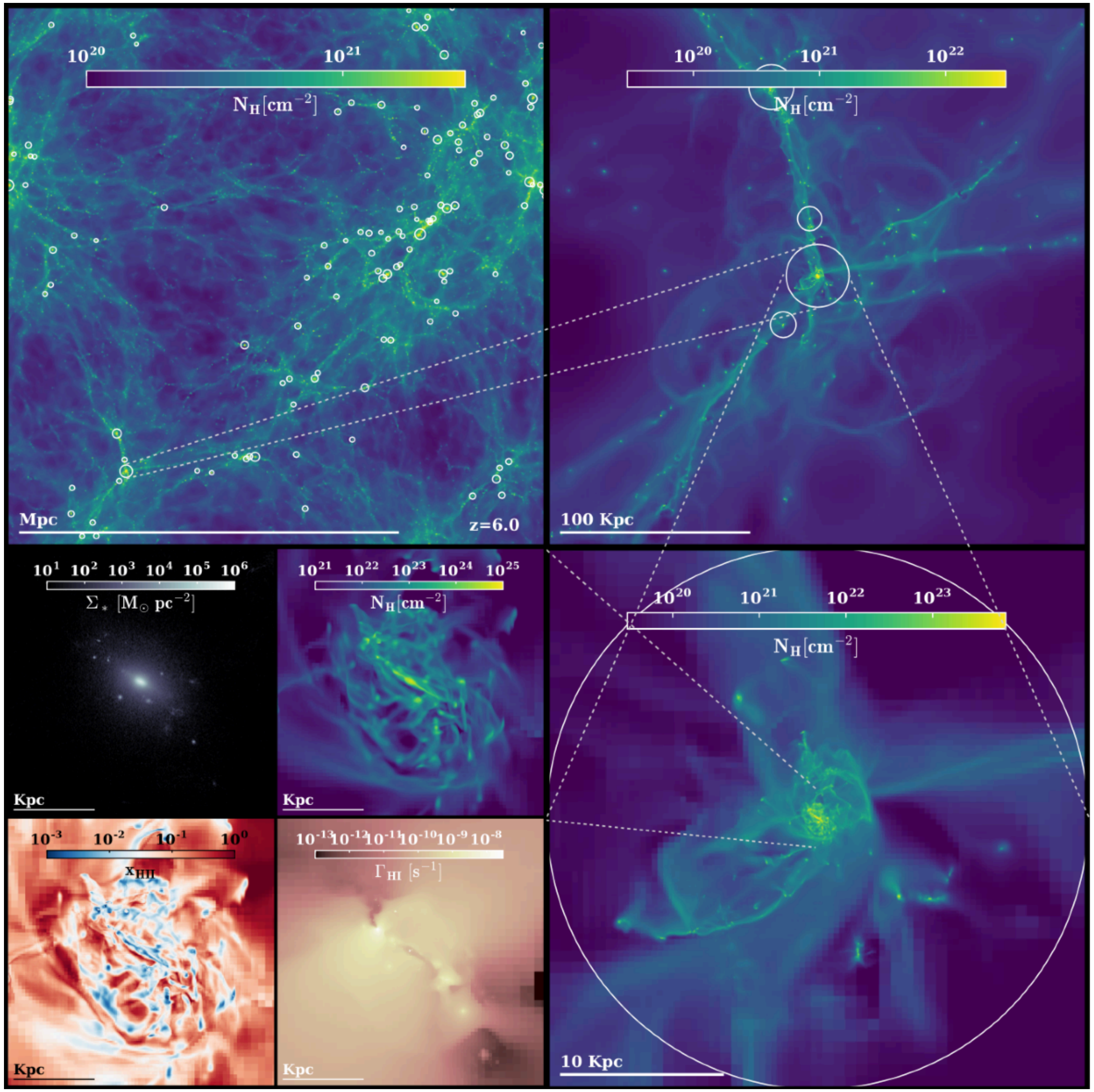
Progress in Reionization Simulations

Problem of reionization = physics of multi-scale, cosmological radiation-hydrodynamics (RHD) of galaxies and the IGM



10cMpc/h RHD RAMSES + AMR resolution ~10pc at z=6
+ Binary population synthesis model Rosdahl+18

Cosmo. RHD runs (~10cMpc/h) close to zoom-in (~10pc) resolution are now feasible

SPHINX, Rosdahl+18 on PRACE
Renaissance, O'Shea+15 on BlueWaters
Q. "Where does Fugaku (富岳) fit in?"

State-of-the-art → standard workhorse

CROC (Gnedin+14), Aurora (Pawlik+17), CoDa (Ocvirk+2018), Technicolor-DAWN (FInlator+18), RHD run in Inoue & Hasegawa+18

Processes need to be understood:

Small-scale (<10pc-1kpc):
- ***Lyman Continuum (LyC) leakage from molecular clouds and galaxies***

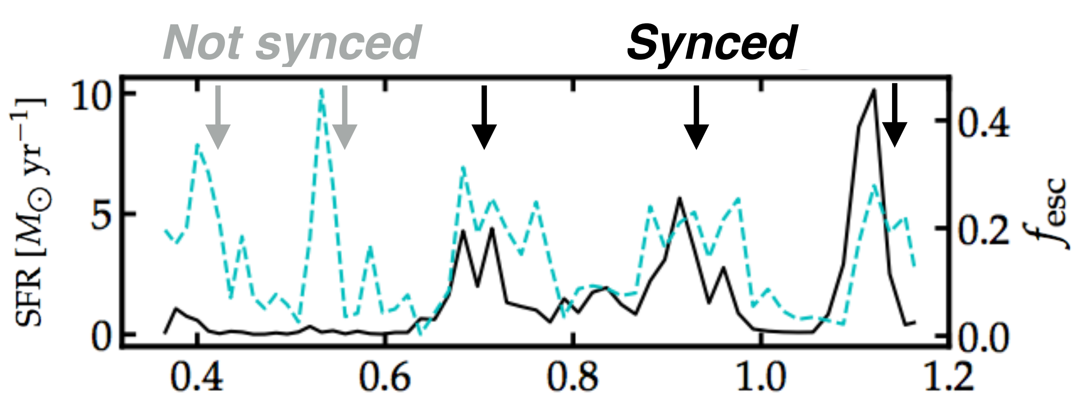
Meso-scale (~100 kpc):
- ***Galactic winds, metal enrichment, CGM***

Large-scale (~Mpc):
- ***Temperature & UV background fluctuations of the IGM***
- ***Self-shielded gas / mean free path fluctuations***
- ***Galaxy (source) clustering***

The role of small-scale process (<10-100pc)

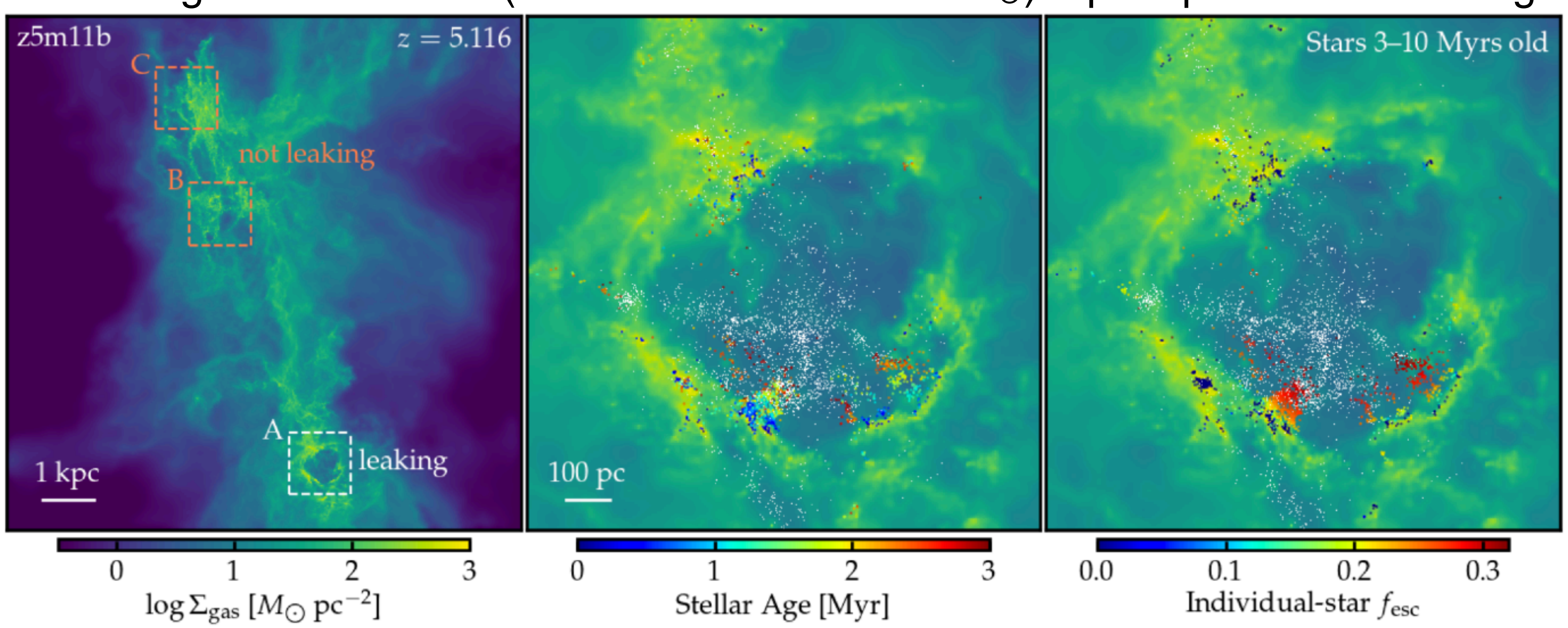
What determines LyC leakage?

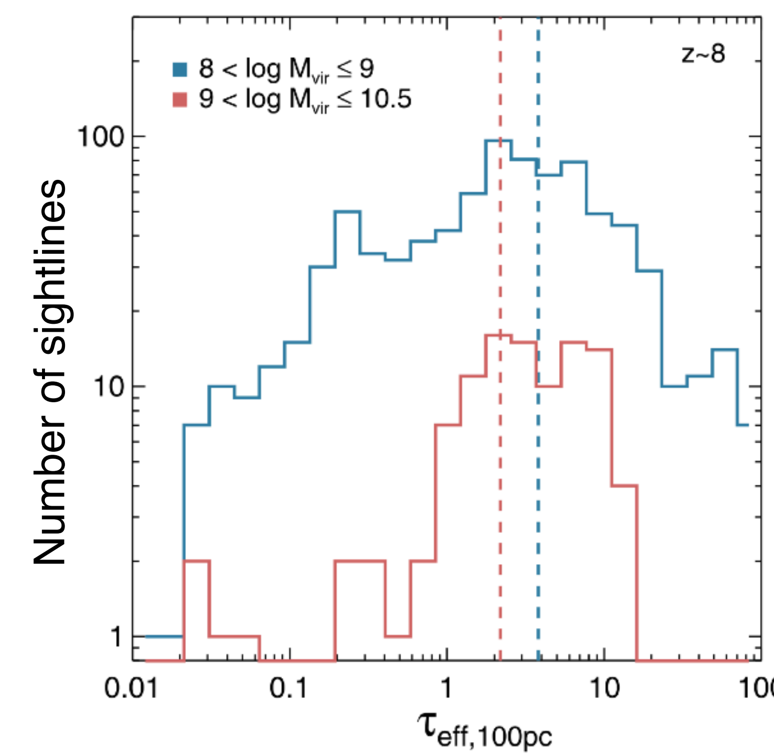
For a high ionizing capability,
a galaxy need to *synchronise* "the timing of feedback creating holes in molecular clouds & ISM, f_{esc}" with "when ionizing photon production, ξ_{ion}SFR, is available".



Insight from high-resolution (~5pc) runs:
A large fraction of LyC optical depth comes from the gas in the <100 pc region around the birth cloud of massive stars. A synced way to evacuate these gas is the key.
(Binary stellar evolution, supernova & photoionization feedback)

Zoom-in galaxies GIZMO (mass resolution ~1000 $M_\odot$) + post-processed ionizing RT





Ma+2020, 2016

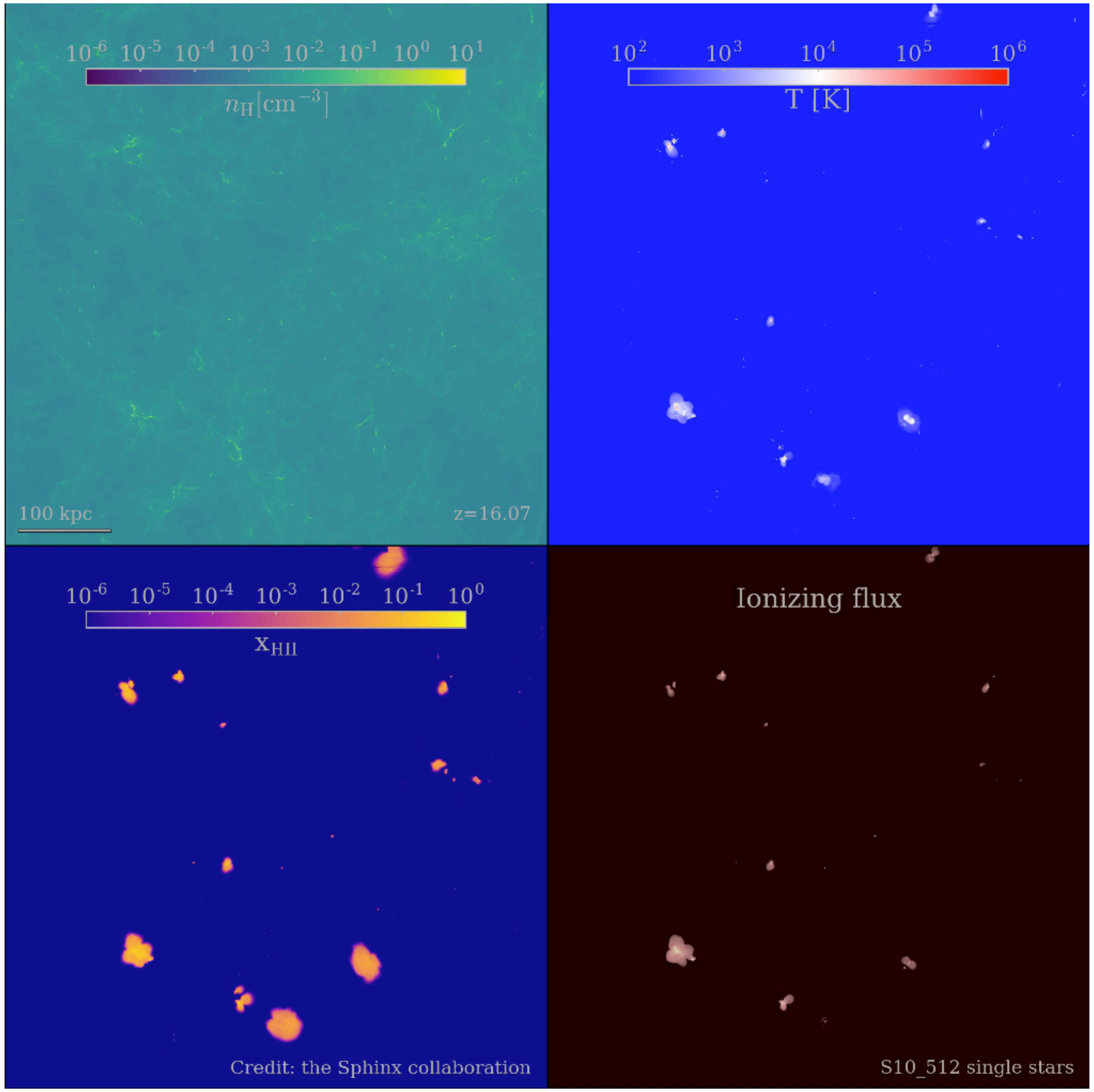
Full RHD zoom-in galaxies RAMSES-RT
~4 pc resolution (Kimm & Cen 14)

Also, Paardekooper+15, Trebitsch+17…

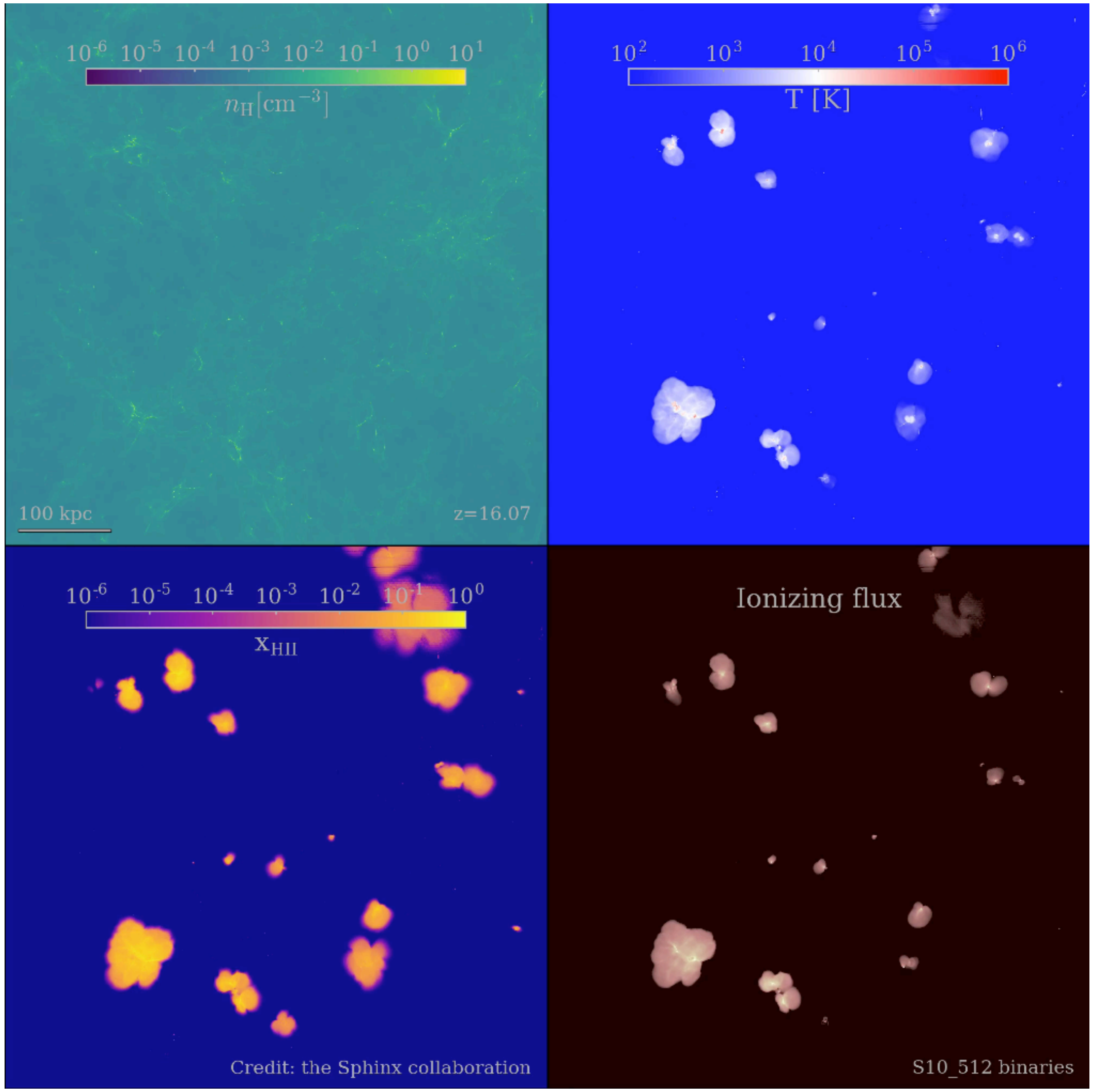
The global impact of the LyC leakage process on the large-scale reionization of the IGM

SPHINX case

Rosdahl+18



Single stars

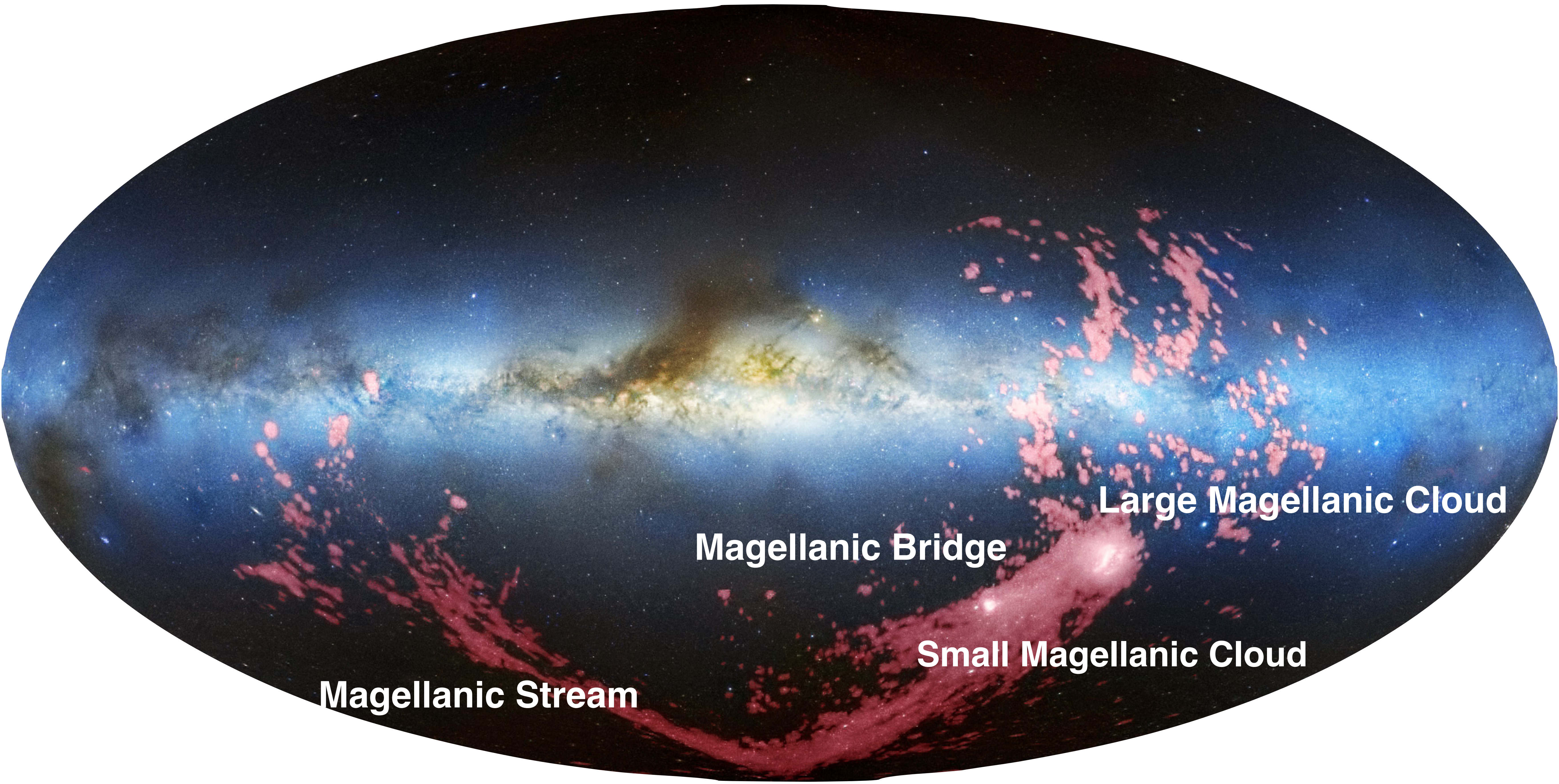


Binary stars

Binary stellar evolution is vital for (1) the elevated LyC photon production efficiency and (2) prolonged production of LyC photons synced with the episode of feedback, leading to fast and more efficient reionization by galaxies.

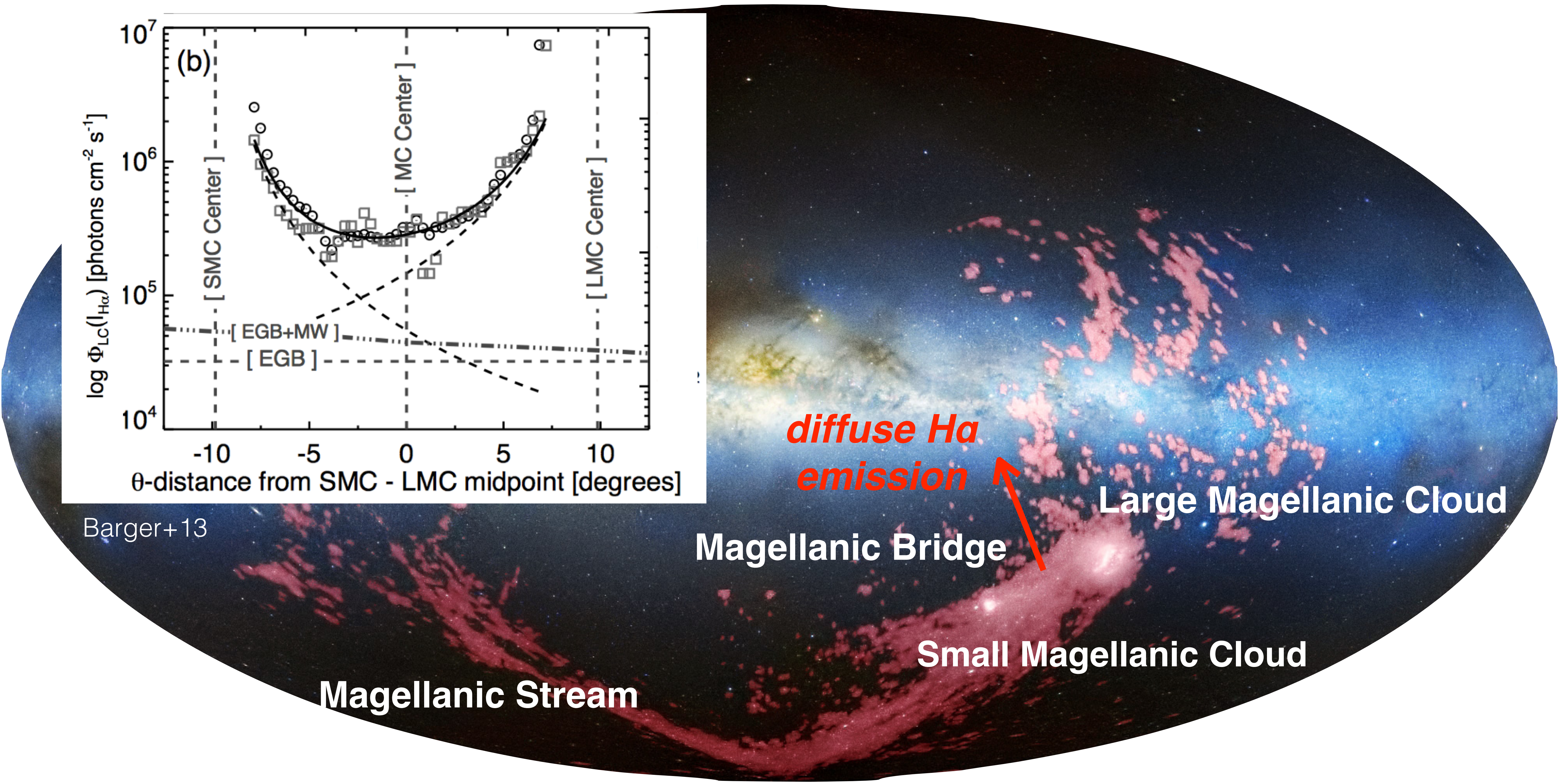
Local insight from the CGM of the Milky Way & Large Magellanic Cloud

— Scale of LyC leakage —



Local insight from the CGM of the Milky Way & Large Magellanic Cloud
— Scale of LyC leakage —

Galactic f_{esc} < 5.5 & 4.0 % for SMC & LMC



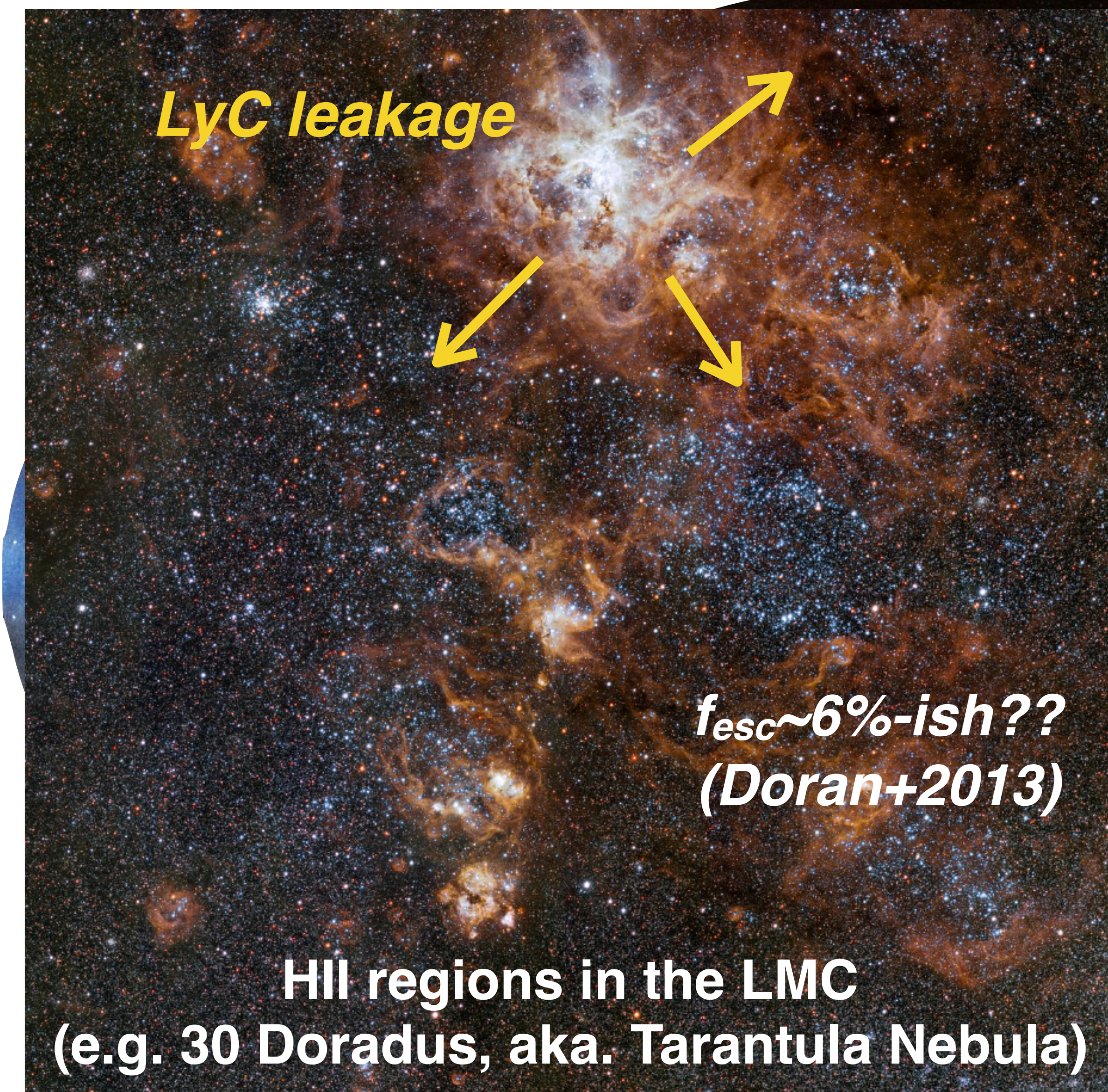
Diffuse CGM Hα emission halo as a probe of 'galactic' LyC leakage

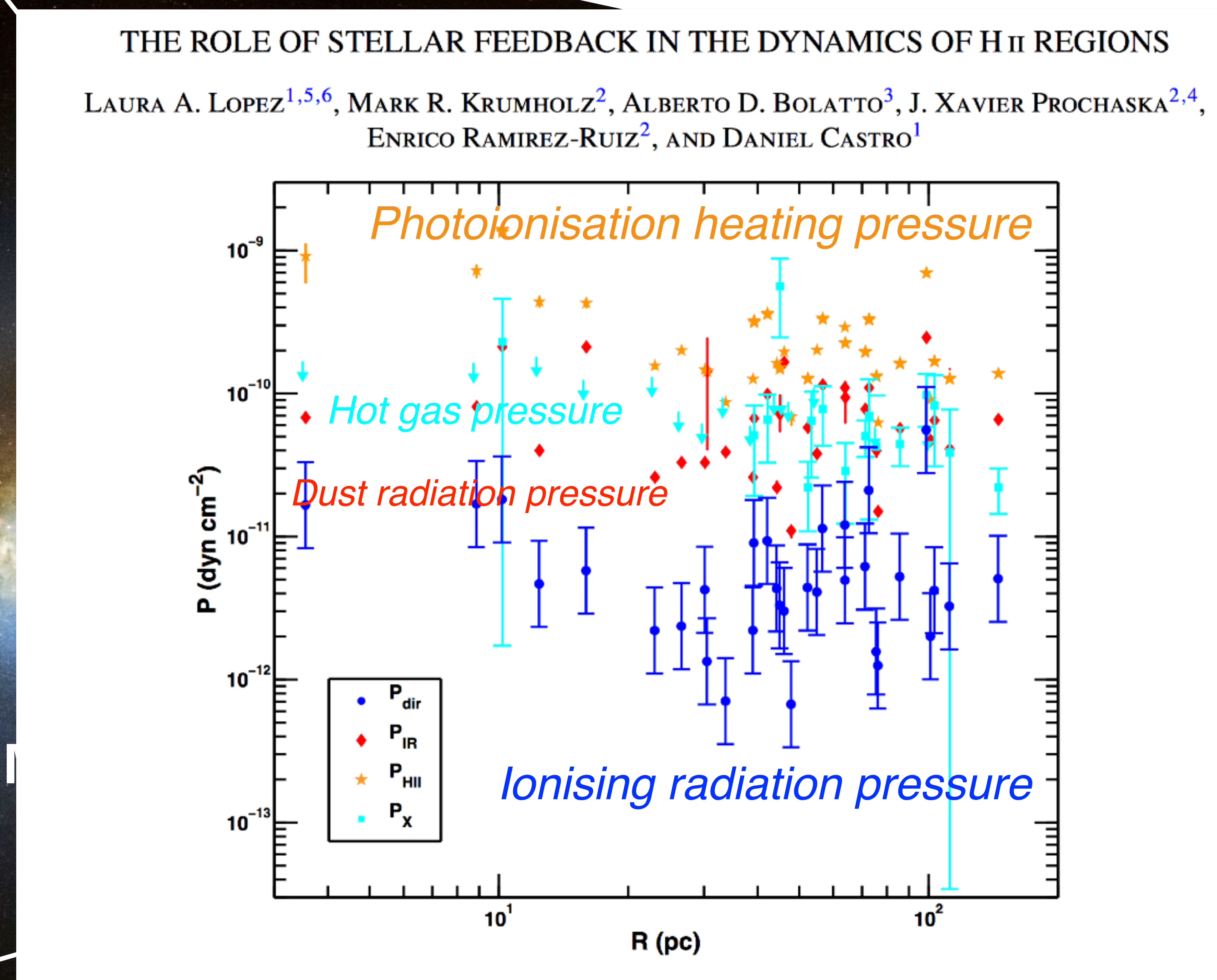
(Bland-Hawthorn & Maloney 1999,2001, Mas-Ribas+17)

Local insight from the CGM of the Milky Way & Large Magellanic Cloud

— Scale of LyC leakage —

Giant molecular cloud / HII region-scale f_{esc} ~
(Ionising photons from O stars) — (Recombination rate from Hα)





Also $f_{esc} \approx$ 40-80 % for other HII regions
MUSE (McLeod+2019)

also Pellegrini+2012

Challenge:

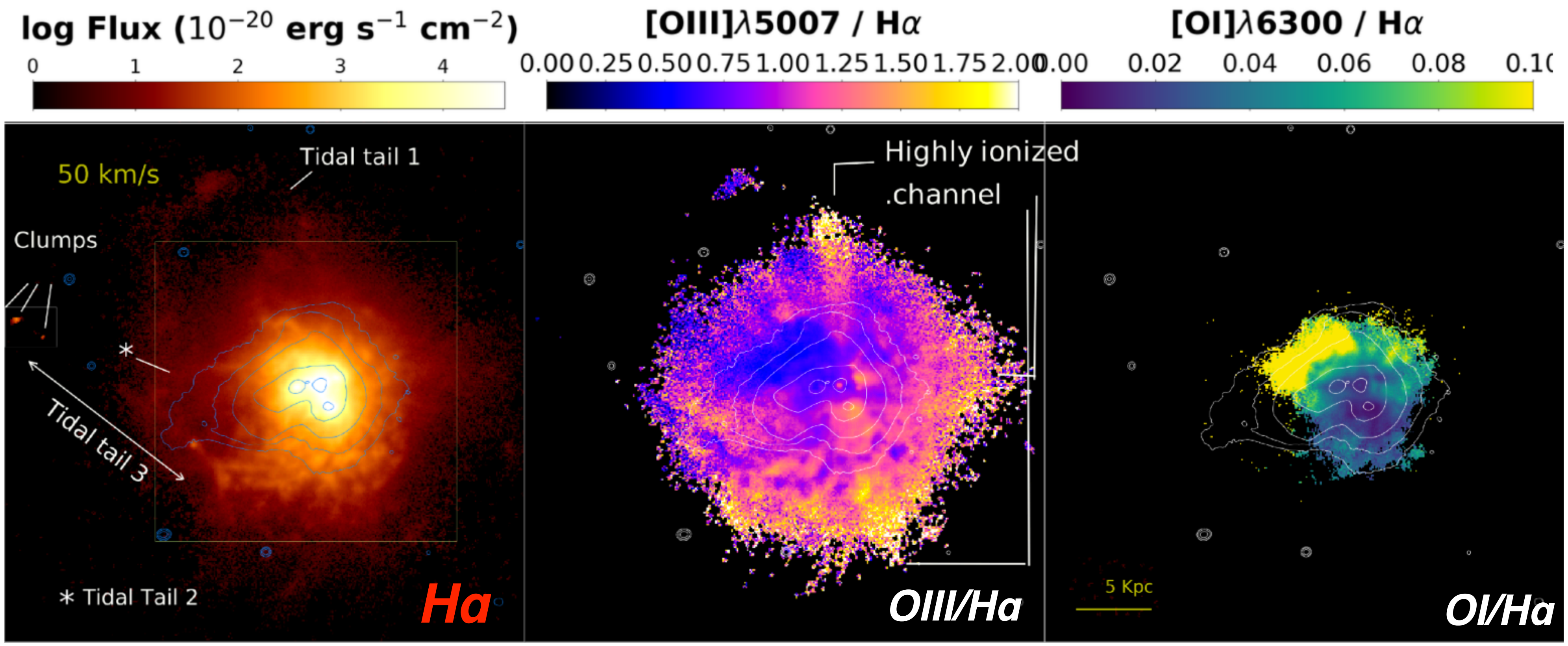
- **recently revised UVB at z~0** (Shull+15, Khaire+19)
- **reliability of LyC leakage diagnostics / ionization- vs density-bounded HII region**

(Hβ, Zackrisson+15, Lyα & [OIII], Izotov+18,19, [SII], Wang+19)

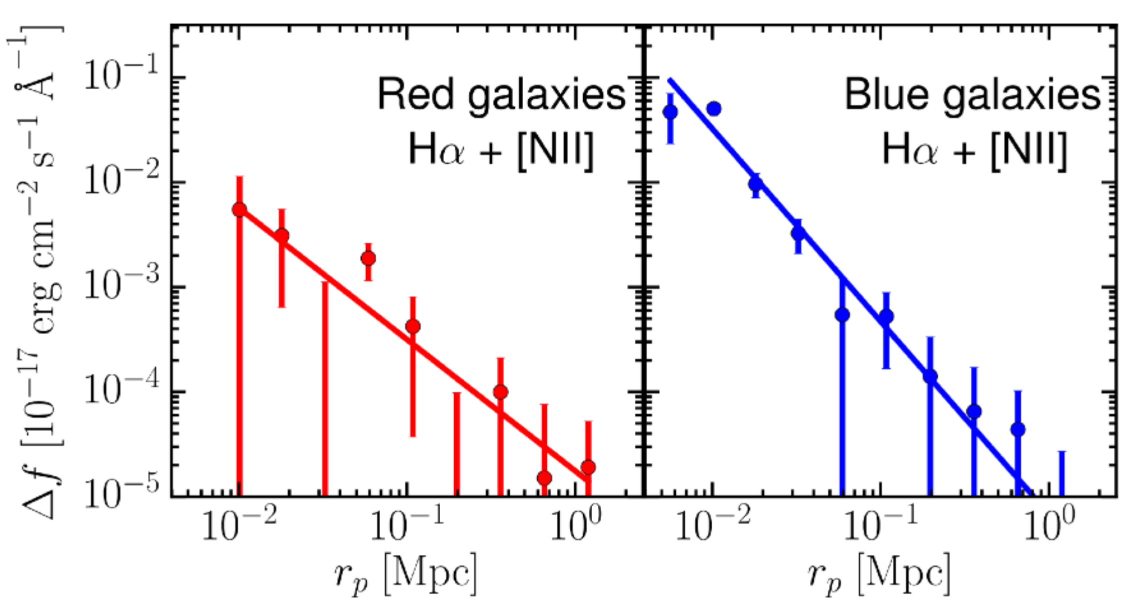
Prospect: Local insight from the CGM of Low-z Galaxies

— Scale of LyC leakage & CGM connection —

Individual: MUSE/KCWI integral-field spectroscopy of targeted high-z analogues



LARS high-z analogues with MUSE: Menacho+19, Haro 11 (Bik+15)



Extended Hα emission around 0.05<z<0.2 galaxies
(Zhang & Zarisky+16,19,20, cf. Croft+18 for Lyα z~3)

Statistical: *"SDSS spectra as extremely wide-field pseudo-integral field spectroscopy"*: galaxy-galaxy pairs in emission

→ *Ideal science case with Subaru/PFS?*

Reionization - Metal Enrichment Link:- I

What do we learn from metals?

- *Metal absorbers as a tracer of faint unseen population $\times$ Lyα forest (Meyer+19)*
- *Metal statistics as a means to constrain feedback in early galaxies (Keating+16)*
- *Metal ionisation states as a signature of UV background shape and evolution (Finlator+18)*
- *Metal abundance pattern as a signature of the source of early enrichment, e.g. first stars*
- *Metal abundance as an integral count of ionizing photons emitted (Madau+01)*

…

Massive stars in early galaxies → **During main-sequence lifetime, they ionize the IGM/CGM**

Massive stars in early galaxies → **After core-collapse supernova, they pollute the IGM/CGM**

⇒ **Average metallicity at the end of reionization at redshift z_r**

$$\langle Z \rangle = 5.5 \times 10^{-4} \left(\frac{1 + z_r}{7} \right)^{3/2} Z_{\odot}$$

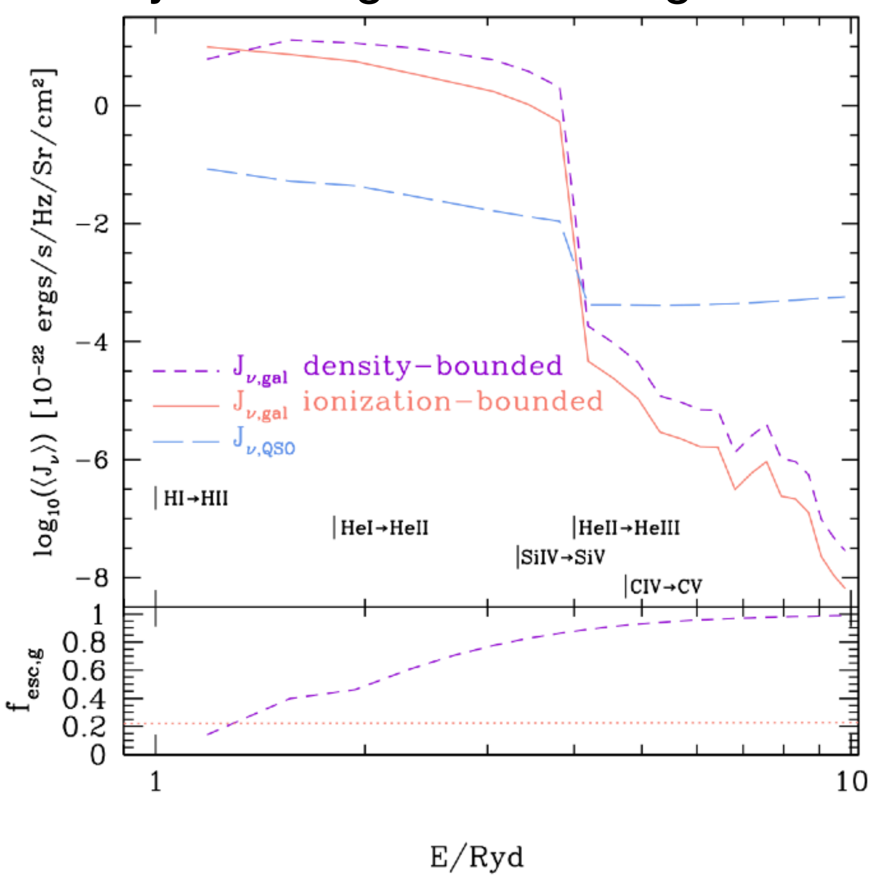
Ferrara 14 for review

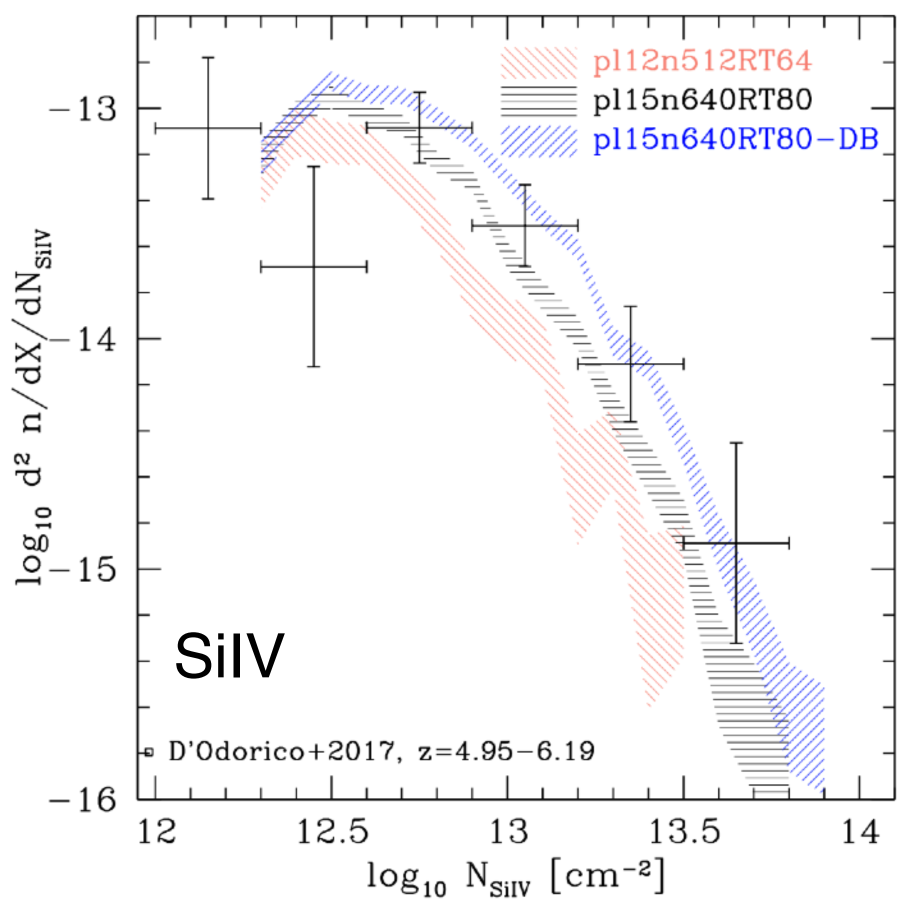
Reionization - Metal Enrichment Link:- II

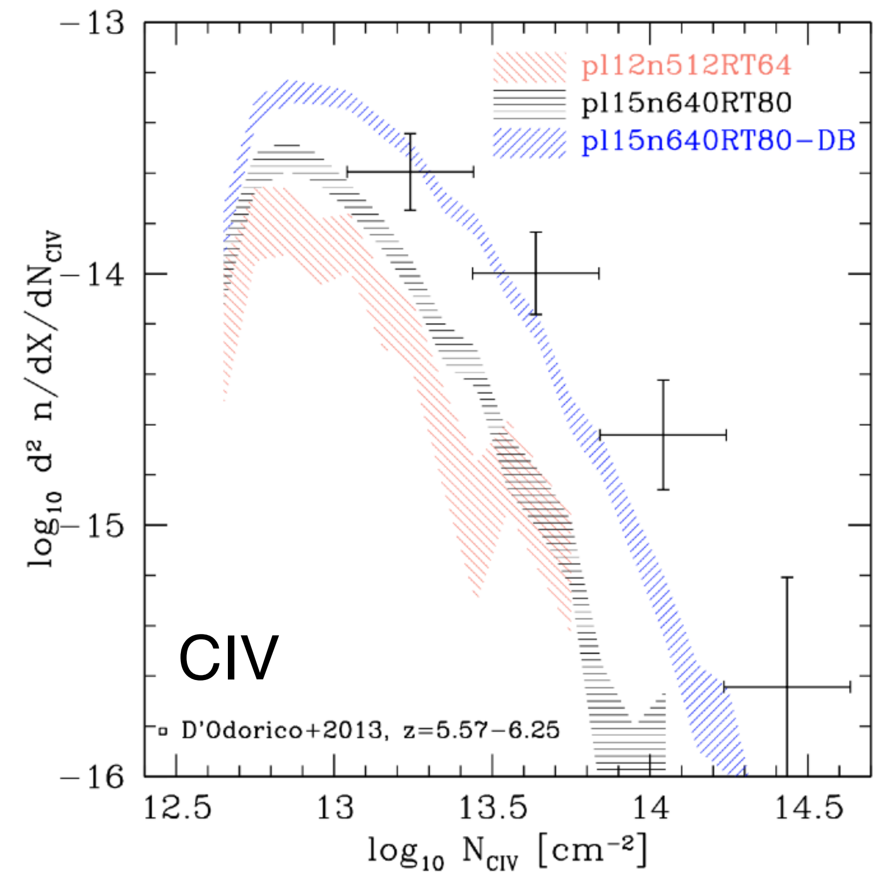
Ionizing capability - CGM/IGM metal abundance connection?

Multi-frequency full RHD simulations, Technicolor-DAWN (Finlator+18)

LyC leakage - UV background







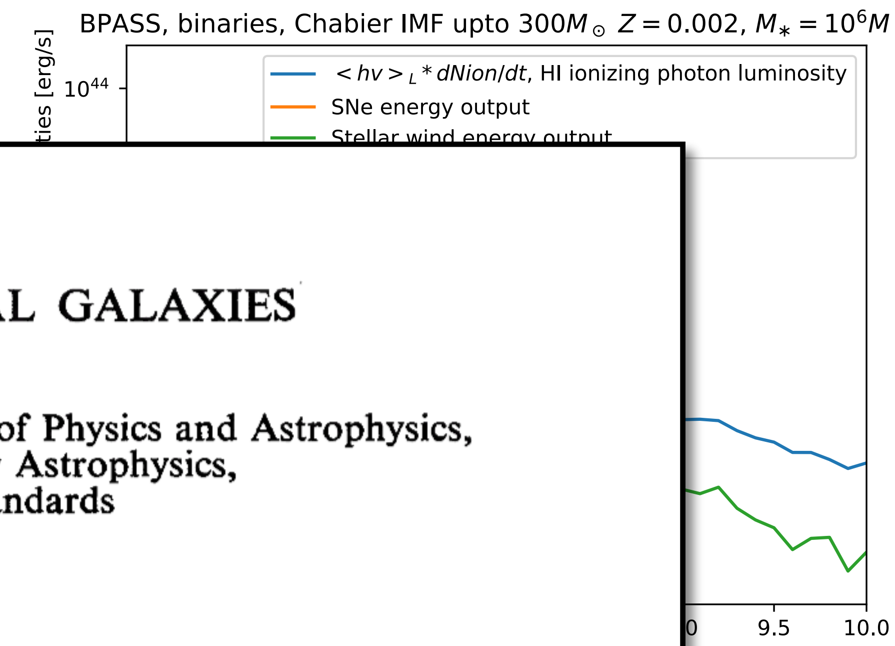
Spectral hardening by density-bounded LyC leakage makes the z~6 UV background steeper, preferentially boosting the ionization state of carbon to CIV.
(vs. elevated C abundance, CII & CIV ↗)

Galaxy environment of CIV absorbers reflects the density-bounded LyC escape?
A possible resolution for z=6 CIV discrepancy (Finlator+20)

Speculation: Reionization - Metal Enrichment Link:- II

Ionizing capability - CGM/IGM metal abundance connection?

Escape to CGM/IGM
Reionization of



MODEL EMISSION SPECTRA FROM PRIMEVAL GALAXIES

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Berkeley Astronomy Department, University of California

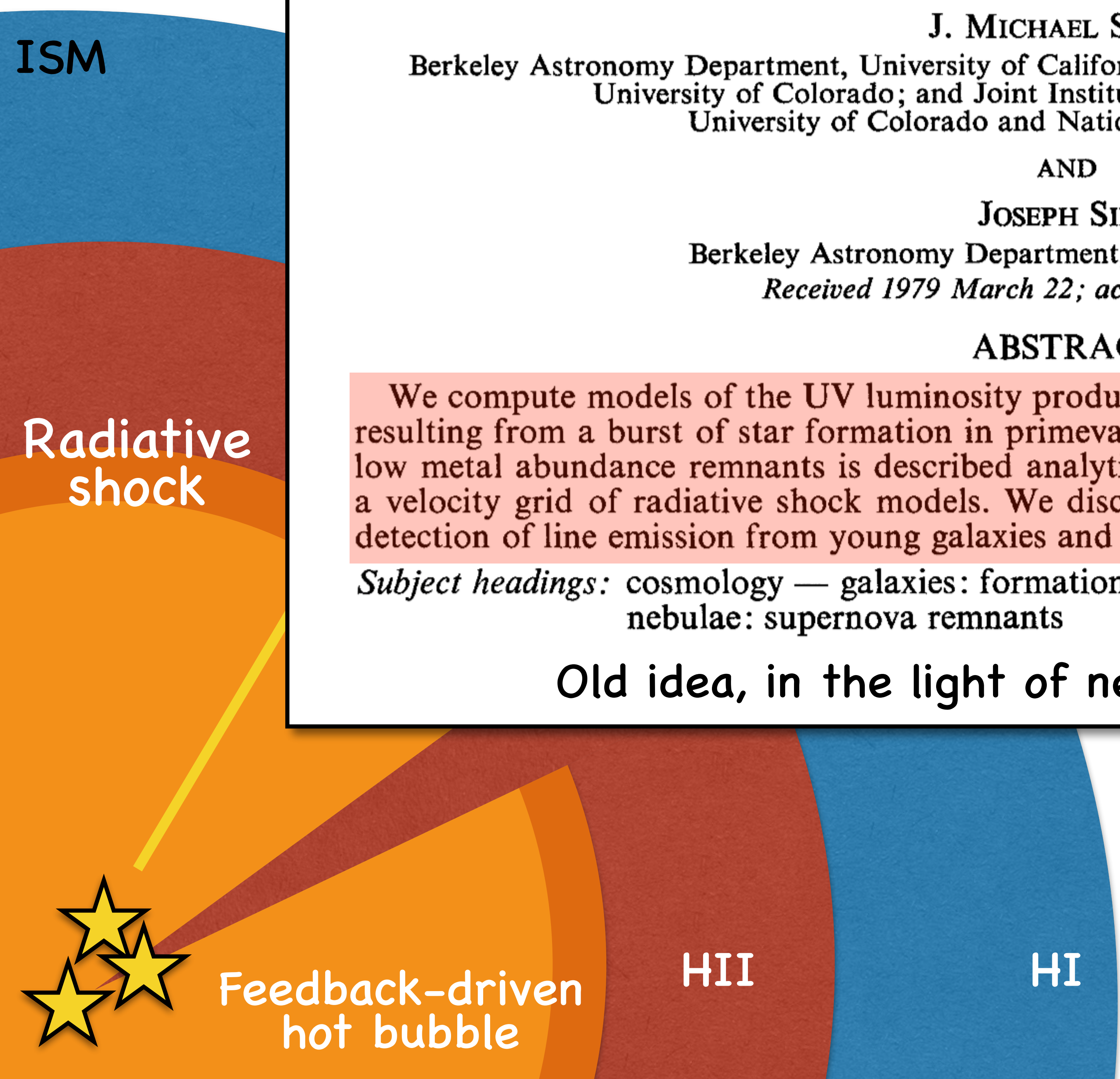
Received 1979 March 22; accepted 1979 June 11

ABSTRACT

We compute models of the UV luminosity produced by a distribution of supernova remnants resulting from a burst of star formation in primeval galaxies at large redshift. The evolution of low metal abundance remnants is described analytically, and their UV emission is found from a velocity grid of radiative shock models. We discuss the implications of these results for the detection of line emission from young galaxies and for the diffuse background radiation.

Subject headings: cosmology — galaxies: formation — galaxies: stellar content — nebulae: supernova remnants

Old idea, in the light of new data and simulations?



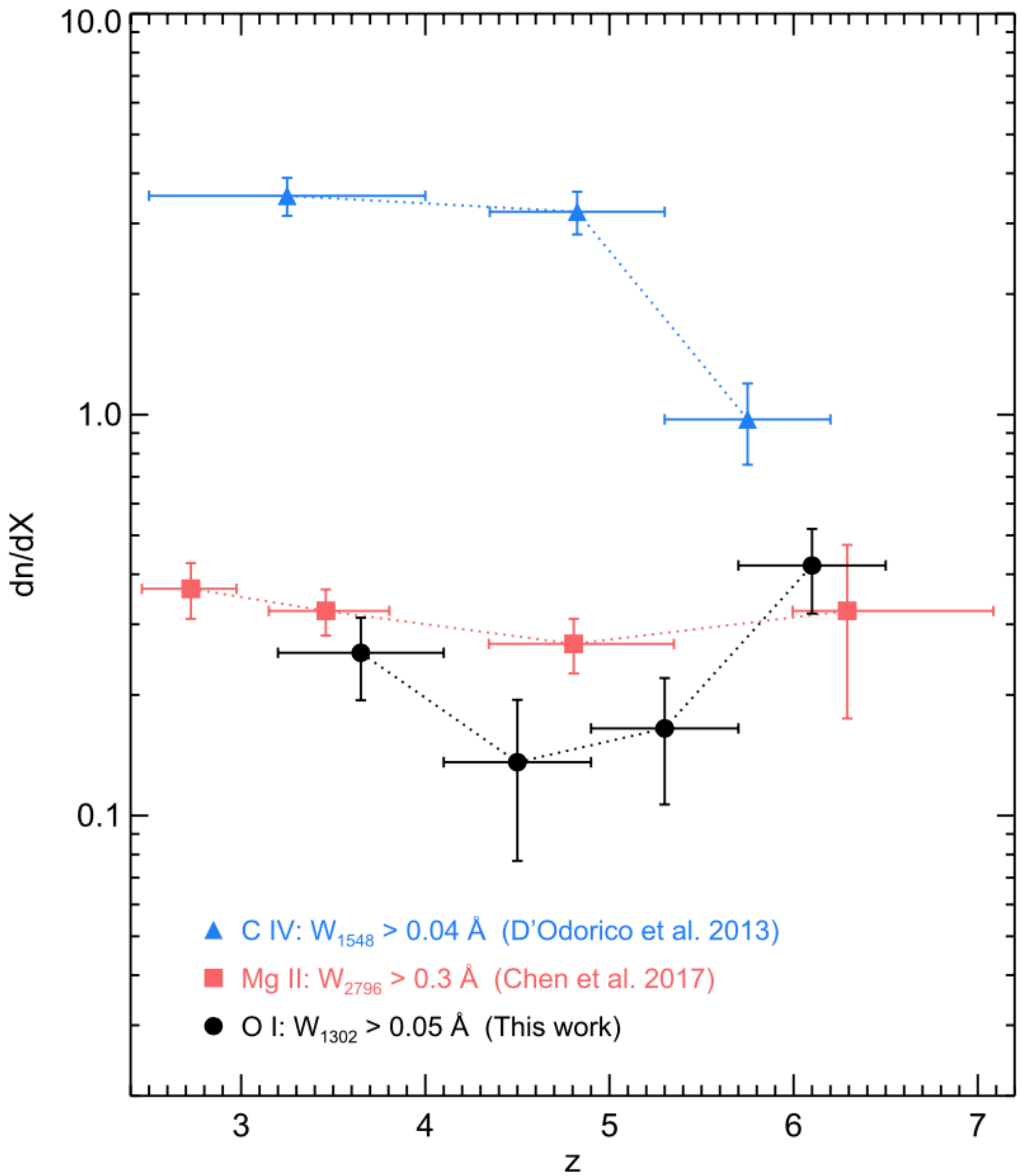
Elevated LyC production efficiency per SFR…

- **Implication to observed ξ_{ion} of EELGs?**
- **Reionization of metals?**

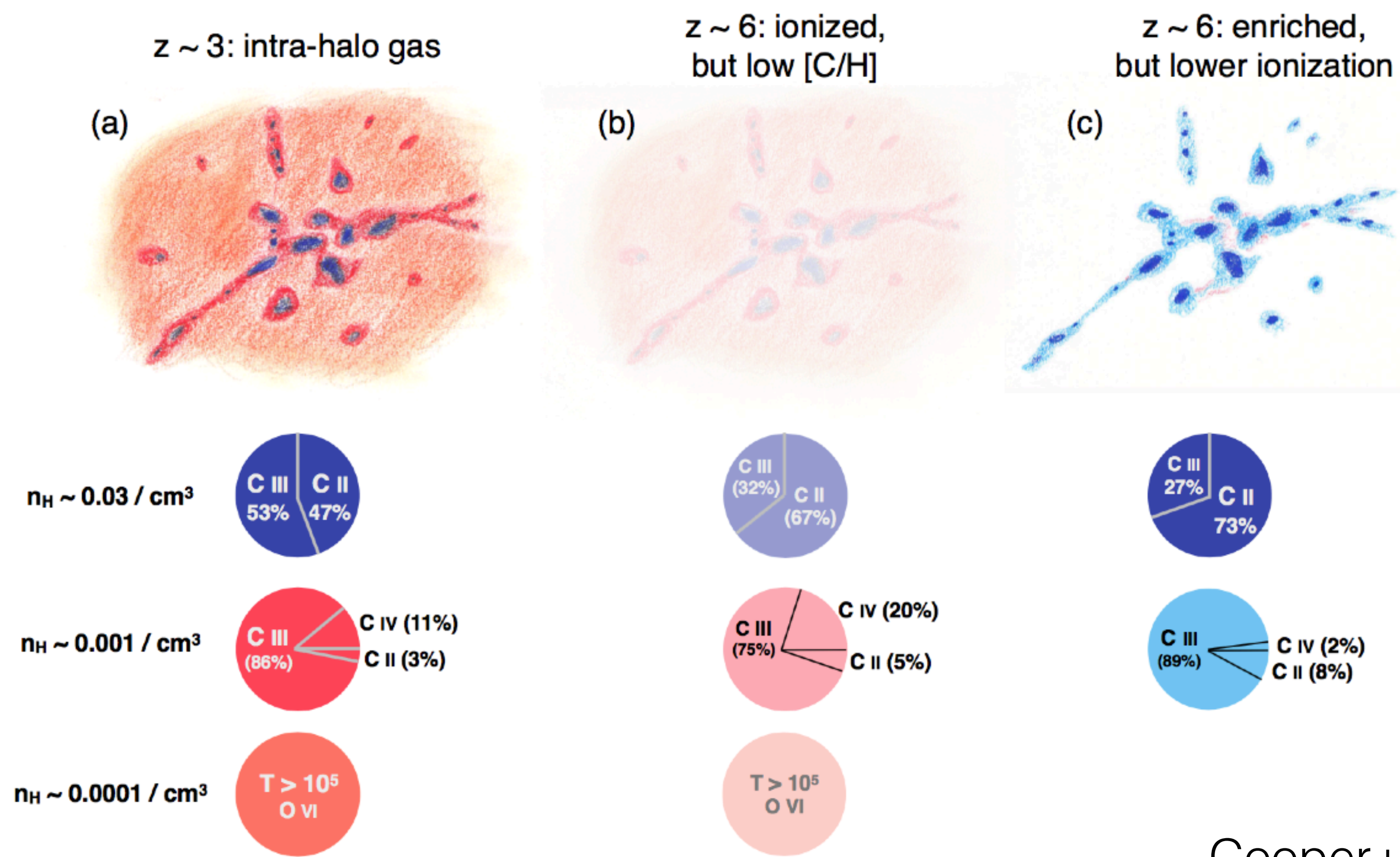
Shull & Silk 79, Oh 02, Johnson & Khohfar 11, Wyithe et al 11

Reionization - Metal Enrichment Link:- III

Redshift evolution of metals



Becker+19
(also Codoreanu+17,18, Meyer+19)



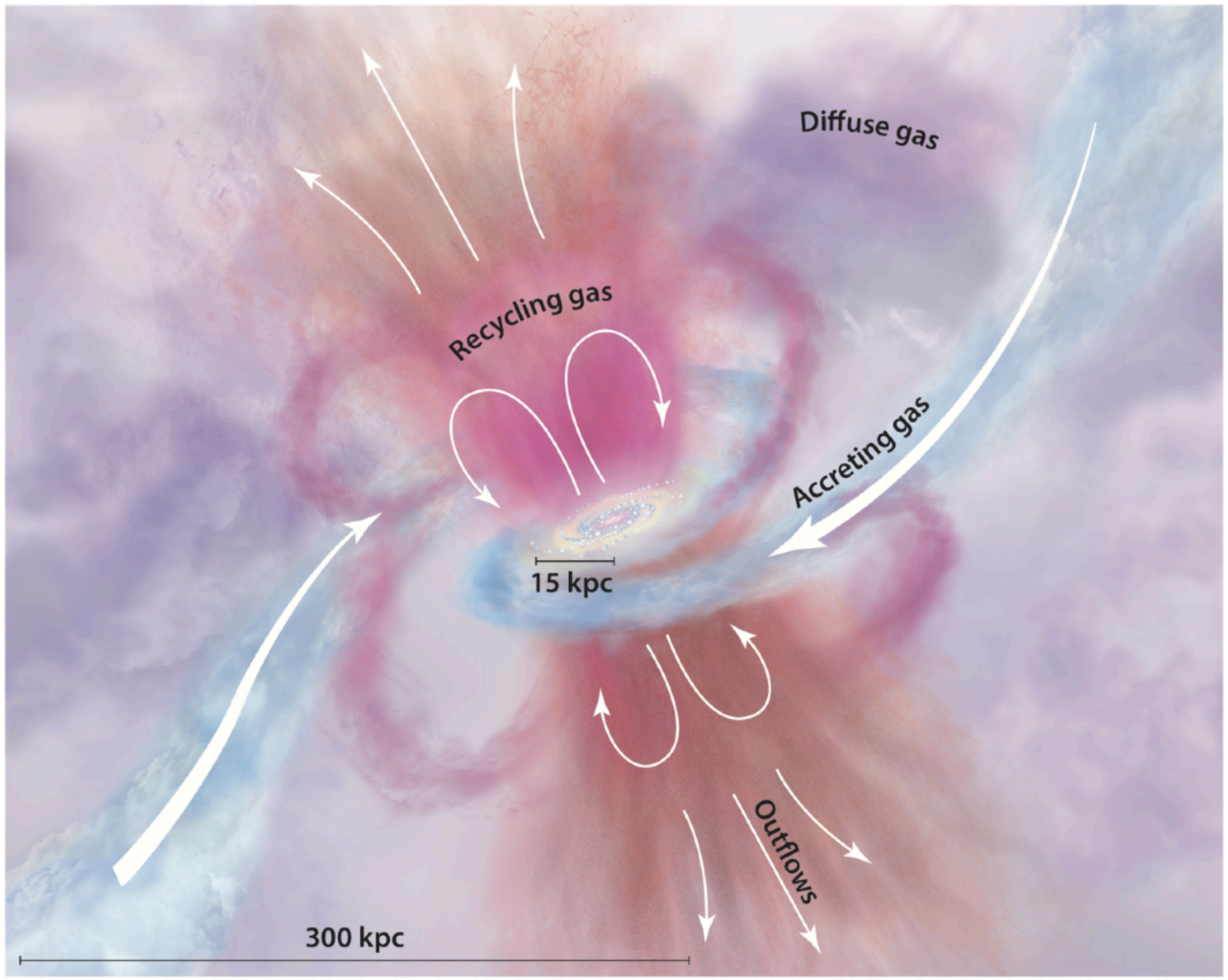
Cooper+19

1. The evolution of O I absorbers implies that metal-enriched CGM at z~6 is undergoing an ionization transition driven by a strengthening UV background.
2. This in turn suggests that the reionization of the diffuse IGM may still be ongoing at or only recently ended by this epoch.

Progress in CGM theory

Where does cold gas ($T \sim 10^4$K) come from?

Tumlinson+17



<u>Multiphase CGM</u>

Hot gaseous halo

$$T_{\rm vir} \sim 2 \times 10^6 \left(\frac{M_{\rm halo}}{10^{11}\,{\rm M}_\odot} \right)^{2/3} \left(\frac{1+z}{4} \right) {\rm K}$$

Cold gas in the CGM

$T \sim 10^4\,{\rm K}$ (H I, O I, Mg II)

Origin of cold gas:

- cold gas entrained in hot galactic winds
- cold accretion streams from the IGM
- thermal instability, cosmic-ray driven winds, stripped gas from satellite galaxies

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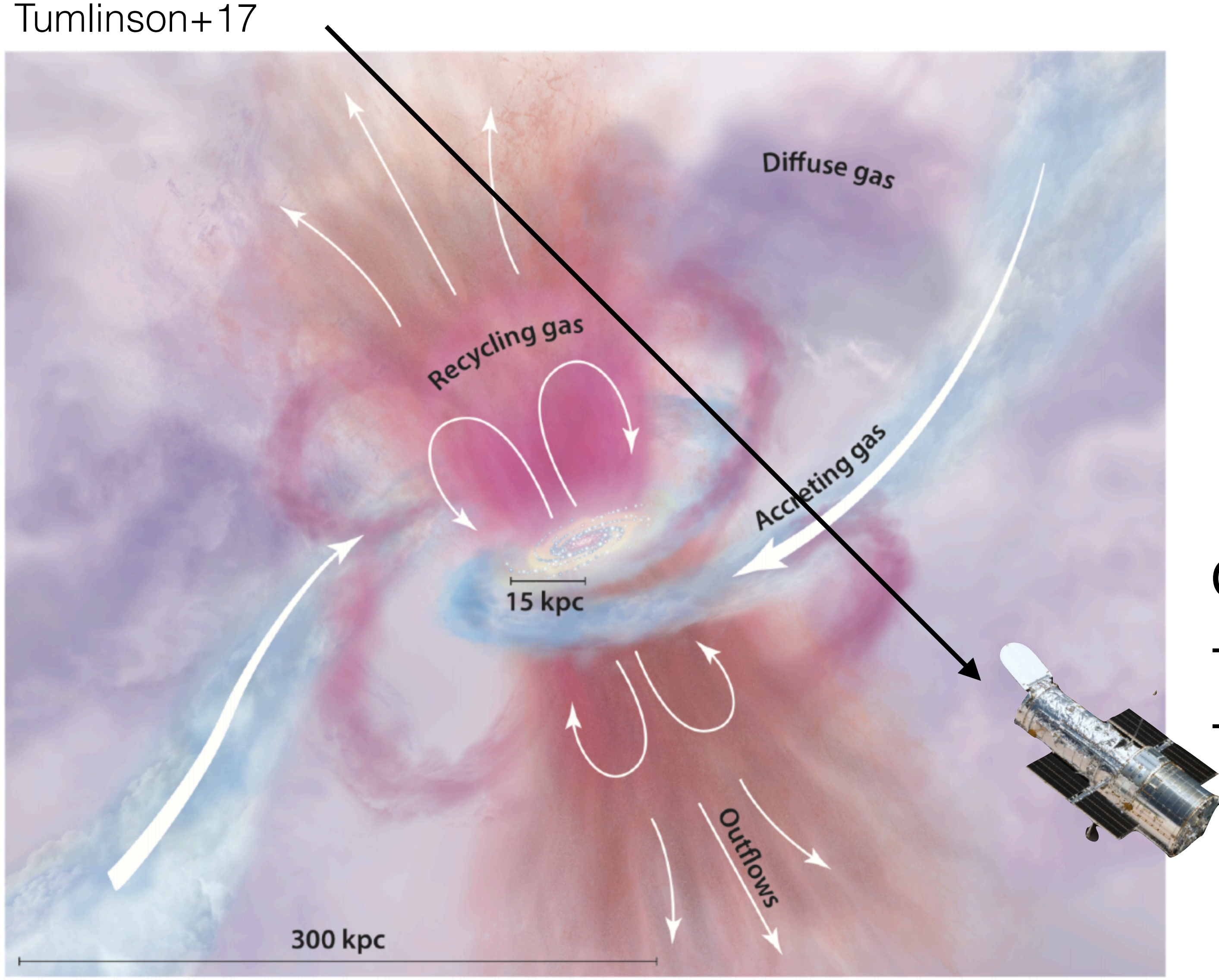

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Scale of CGM cold gas cloud (McCourt+18)

Absorption line study

$$r_{\rm cl}\sim\frac{N_{\rm HI}}{n_{\rm HI}}\sim 30\,{\rm pc}$$

Photoionization modelling

CGM cold gas come as tiny droplets?

cf. IGM Lyα forest scale ~ Jeans length 150 kpc at z=3

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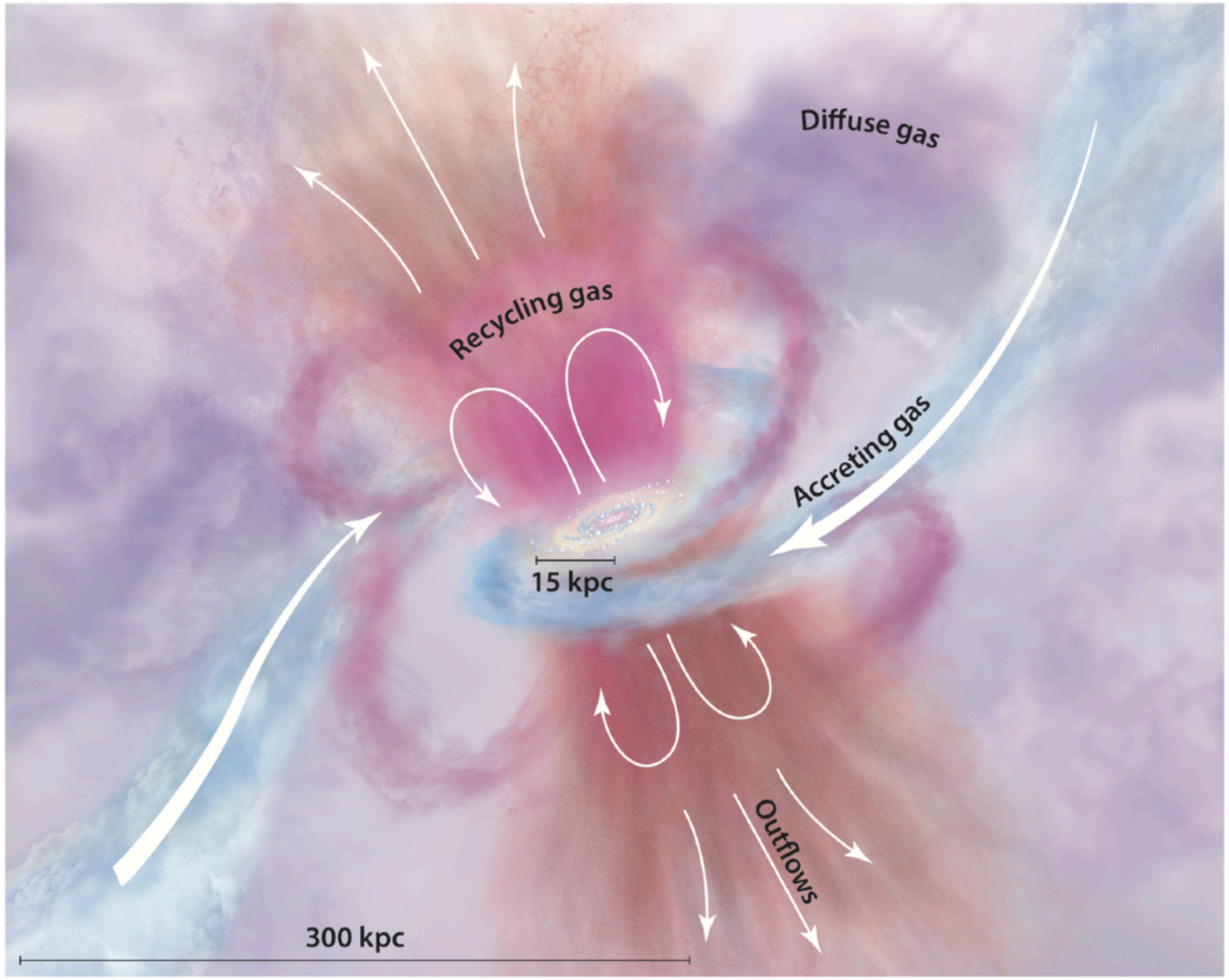
Tumlinson+17



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Destruction timescale of cold cloud

(~Kelvin-Helmholtz instability timescale)

$$t_{\rm dest} \sim \left(\frac{\rho_{\rm cl}}{\rho_{\rm wind}}\right)^{1/2} \frac{r_{\rm cl}}{v_{\rm wind}} \sim 2\,{\rm Myr} \left(\frac{r_{\rm cl}}{30\,{\rm pc}}\right) \left(\frac{v_{\rm wind}}{250\,{\rm km\,s^{-1}}}\right)^{-1}$$

Acceleration timescale of cold cloud in a hot wind

$$\frac{t_{\rm acc}}{t_{\rm dest}} \sim \left(\frac{\rho_{\rm cl}}{\rho_{\rm wind}}\right)^{1/2} \sim 10-30 \quad \rightarrow \quad t_{\rm acc} \ll t_{\rm dest}$$

“Entrainment in trouble”

Cold gas clouds are destroyed before being accelerated in hot winds !

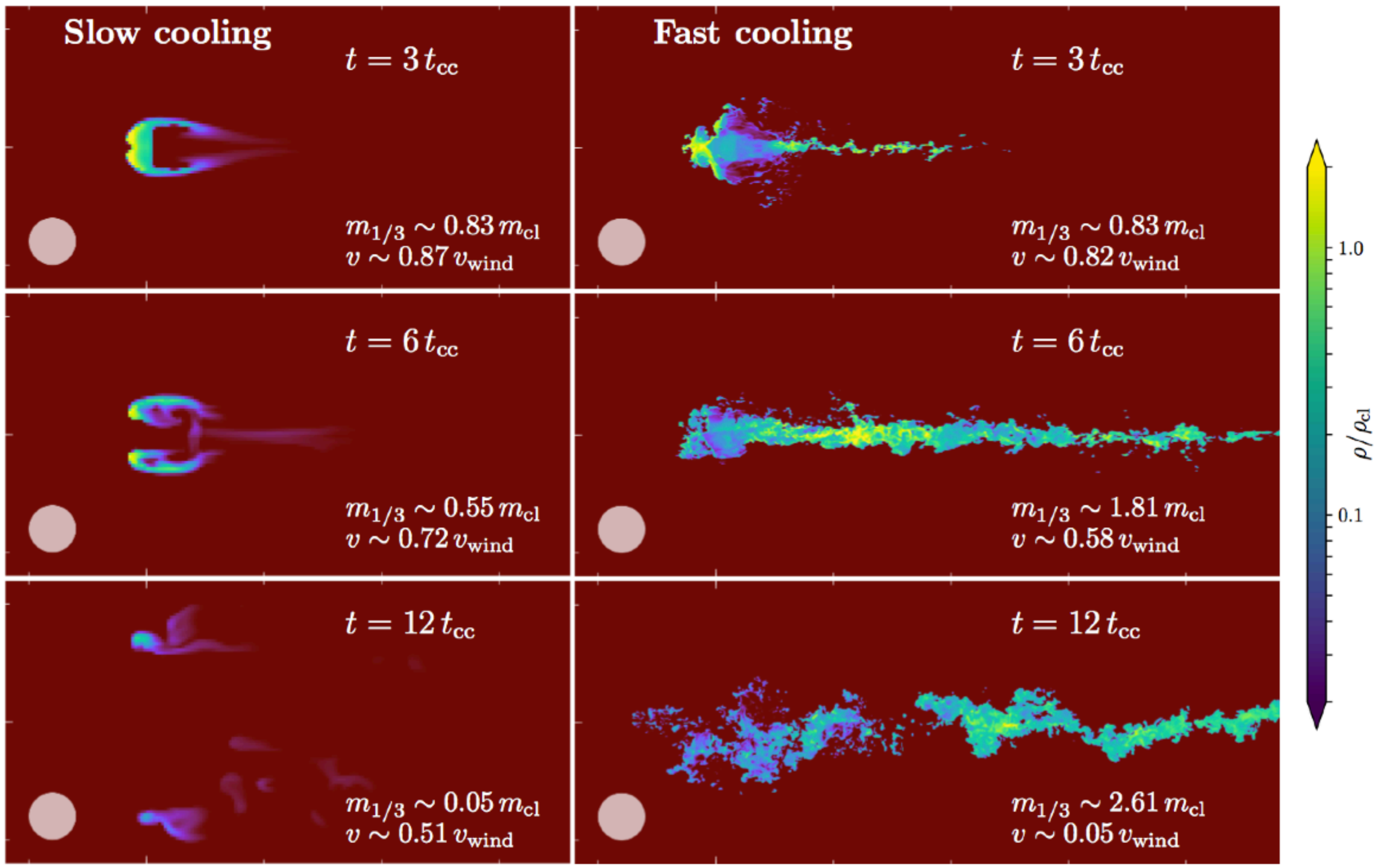
Zhang & Thompson+17, Klein+94

CGM theory - I: Insight from small-scale numerical experiments

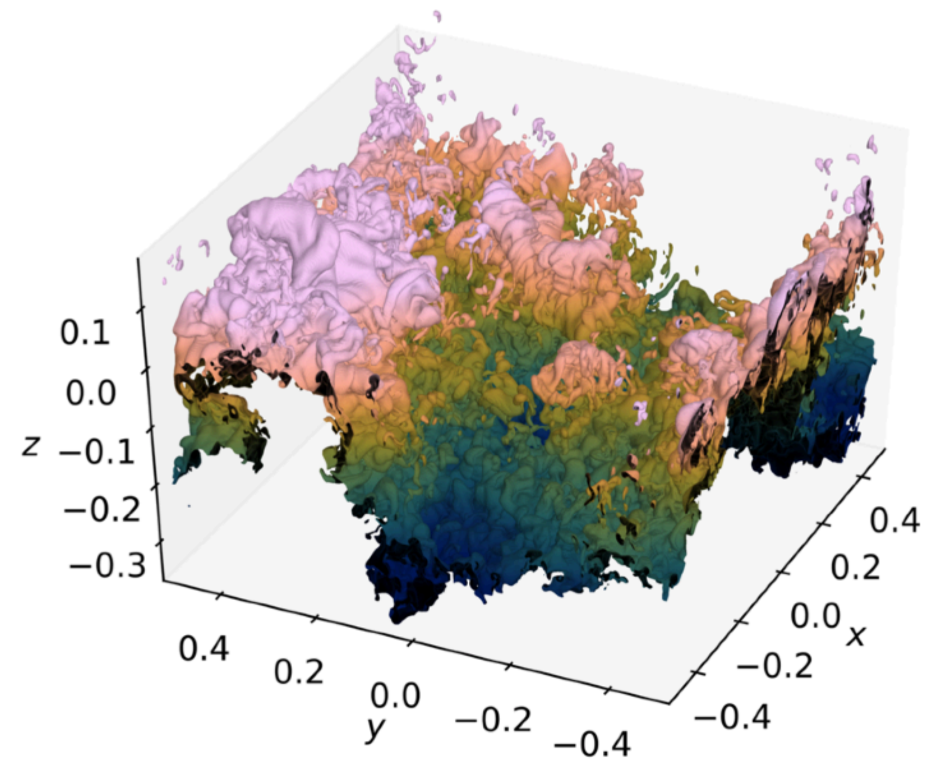
Where does cold gas ($T \sim 10^4$K) come from?

Entrainment and growth of cold gas in hot winds

$t_{cool} > t_{dest}$ $t_{cool} < t_{dest}$



Gronke & Oh 18,19 (with Athena++, Stone 2018 w/ & w/o magnetic fields)



Fractal nature of the turbulent mixing layer
Cooling surface of the cold-hot interface

Fielding+20, Ji+19

Cooling timescale t_{cool} in the radiative turbulent mixing layer mediated by Kelvin-Helmholtz instability. Cold gas cloud can be entrained, and even grow in mass, with a hot wind when the gas cools faster than being destroyed.

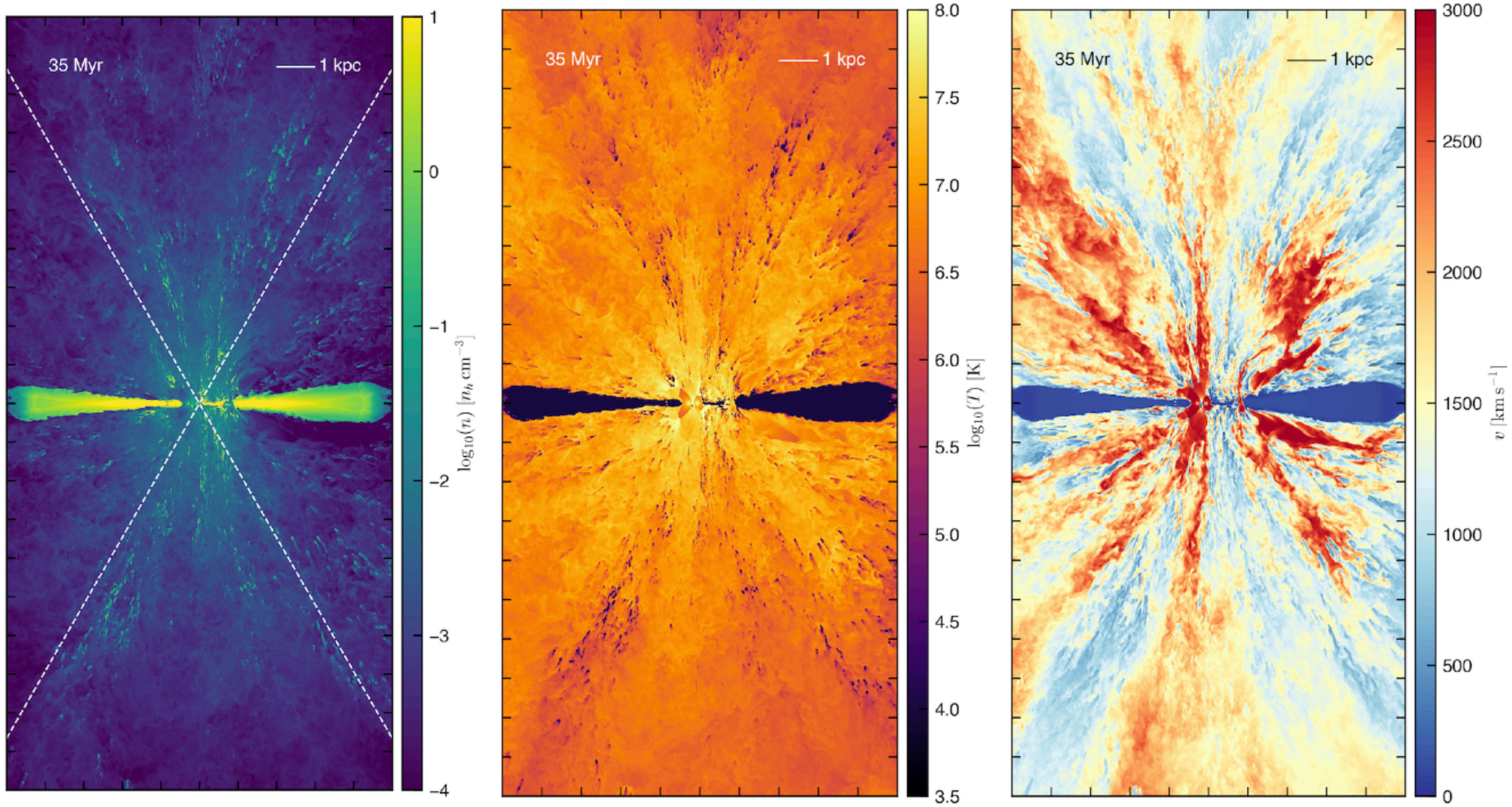
→ origin of CGM cold gas in winds?

Survival criterion of a cloud in size: $R_{cloud} > \frac{v_{wind}\, t_{cool,mix}}{\chi^{1/2}} \simeq 2\mathrm{pc}\, \frac{T_{cloud,4}^{5/2}\, \mathcal{M}_{wind}}{P_3\, \Lambda_{mix,-21.4}}\, \frac{\chi}{100}.$

CGM theory - II: large-scale galaxy simulations

Entrainment and convergence properties

Entrainment of cold gas in SNe-driven galactic winds



GPU hydro galaxy simulation

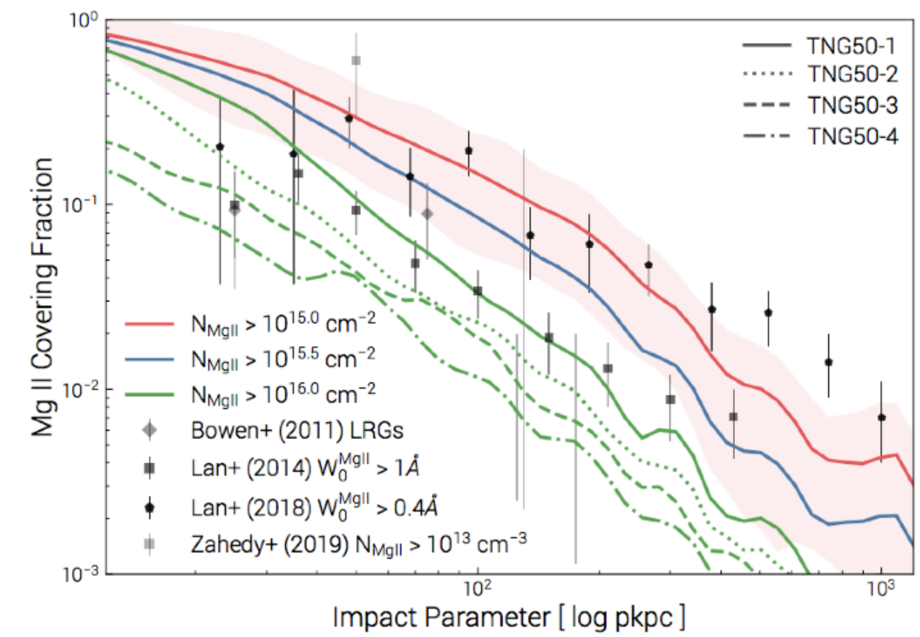
Schneider+20

2048×2048×4096, 5 pc resol. in 10×20 kpc box

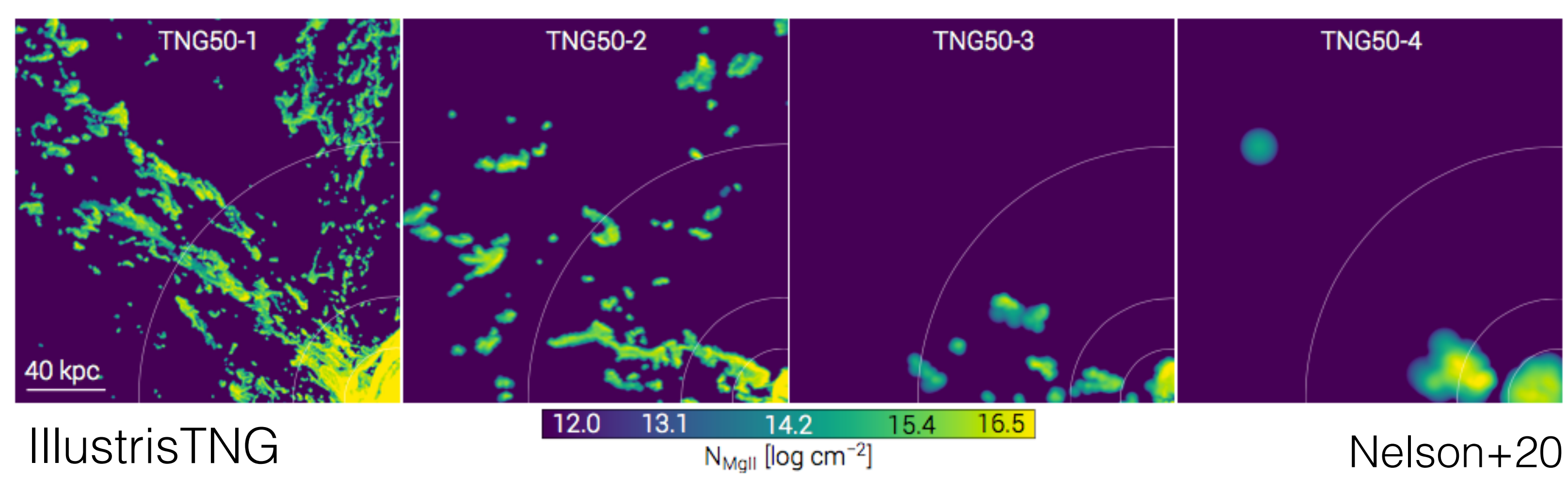
Entrainment of cold clouds (~500km/s) occurs in a more realistic turbulent kinematics of the CGM, but growth?

(Also, Hummel+19, van de Voort+19)

Convergence:
Cold gas morphology & covering fraction are NOT converging…
but the total mass is?



Higher resolution (max. ~100 pc)



IllustrisTNG

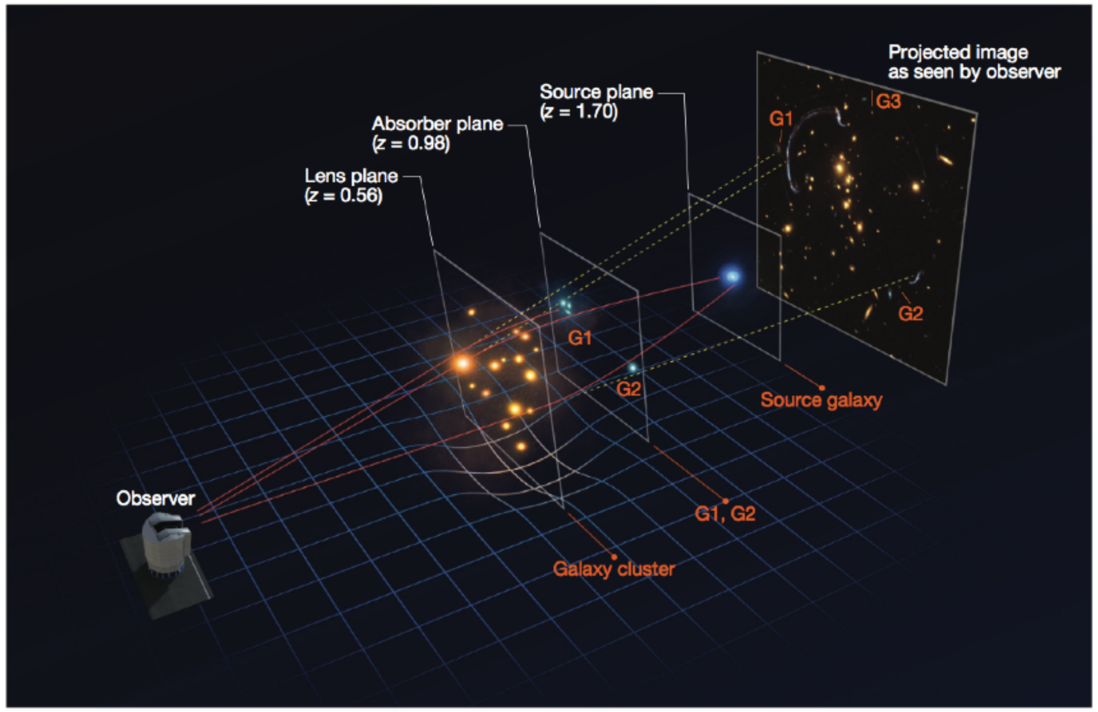
Nelson+20

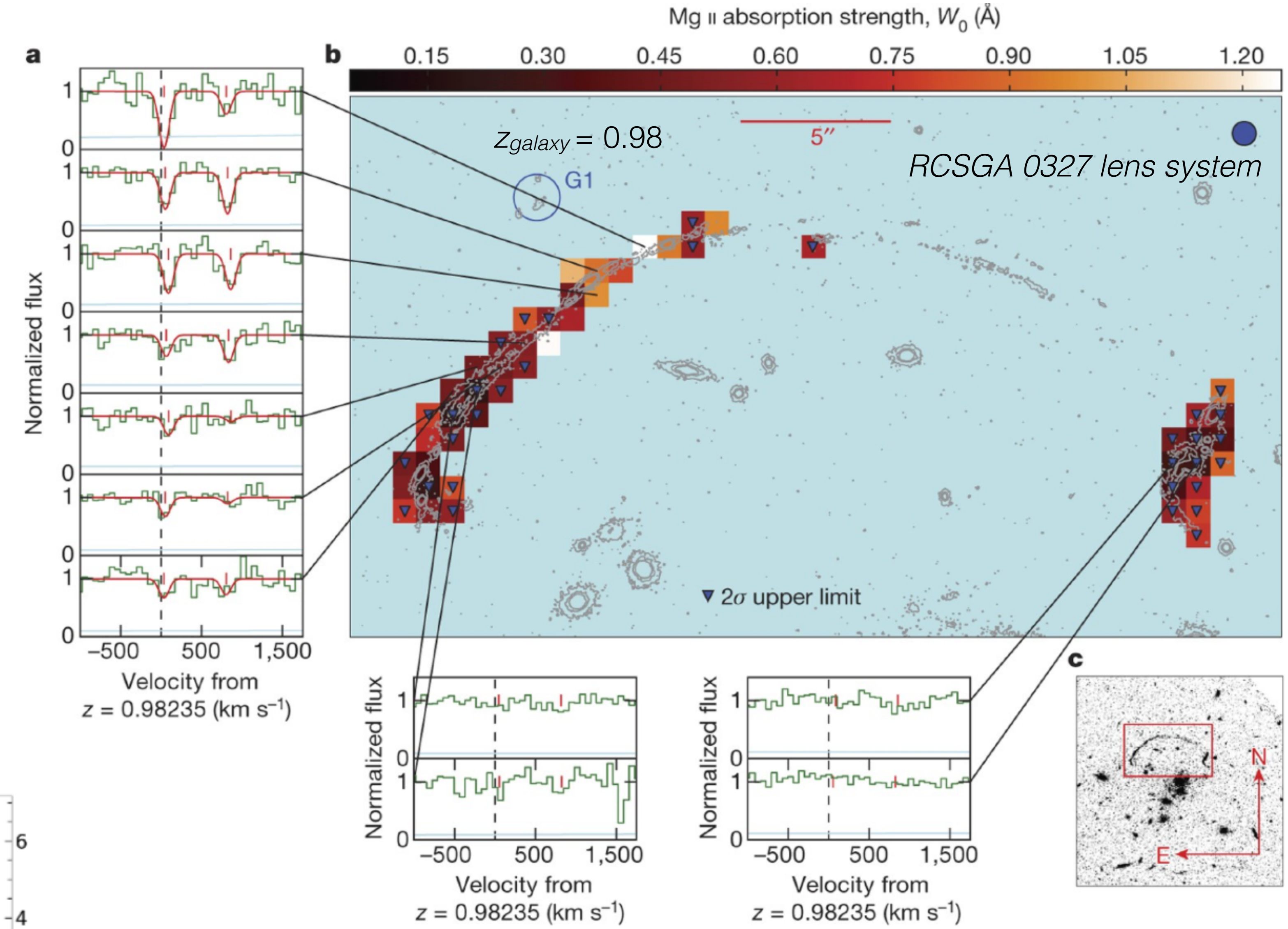
Micro-scale cloudlet structure & fragmentation may exist even down to $c_s\, t_{cool} \sim 0.1$ pc..

McCourt+18

Probing Spatial fluctuations of the CGM by lensing tomography

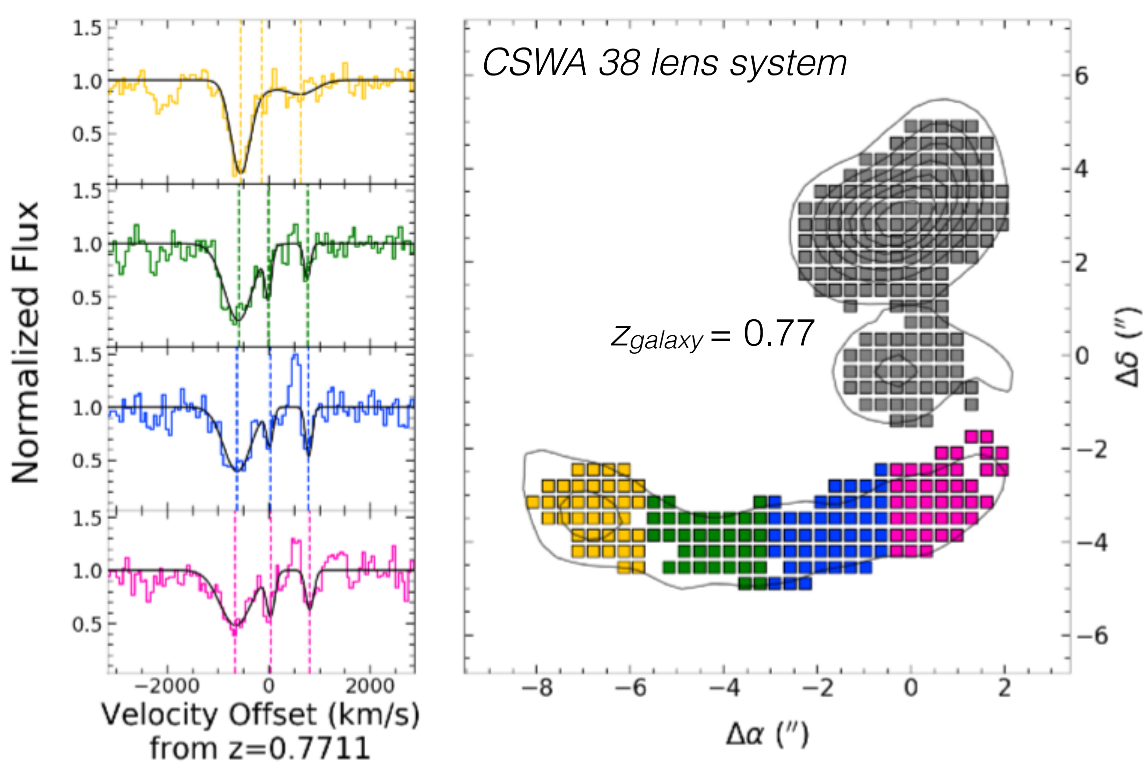
Absorption line tomography using gravitational arcs as backlight





MUSE, Lopez+18,20

MgII tomography



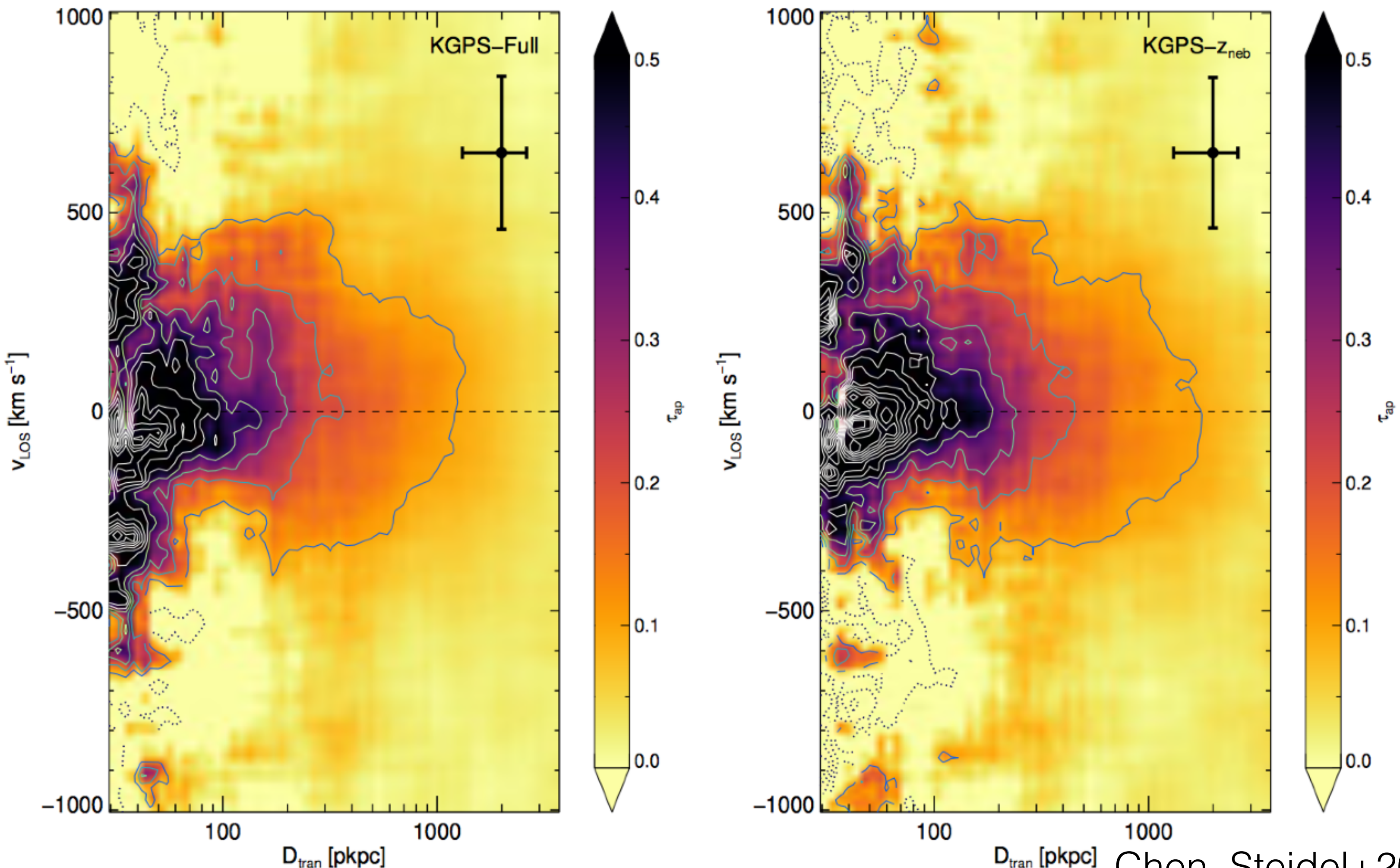
KCWI, Mortensen+20

Spatial variation (~4 kpc resolution) of the MgII absorption line strength and kinematics by the CGM cold gas at impact parameters ~10-40 kpc around a galaxy. Clues to recycling cold gas / galactic winds / in-situ thermal instability?

→ *More lens-absorber pair systems for tomography with Subaru/HSC?*

Distribution and Kinematics of the HI gas around z~2 Galaxies

200,000 galaxy-galaxy pairs from Keck Baryonic Structure Survey



Chen, Steidel+20

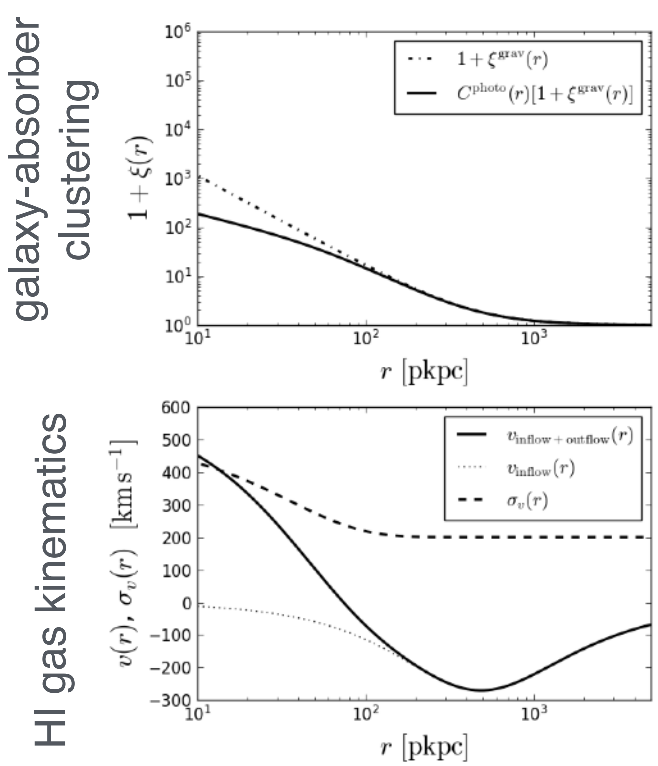
1. Evidence of outflow / inflow around galaxies?

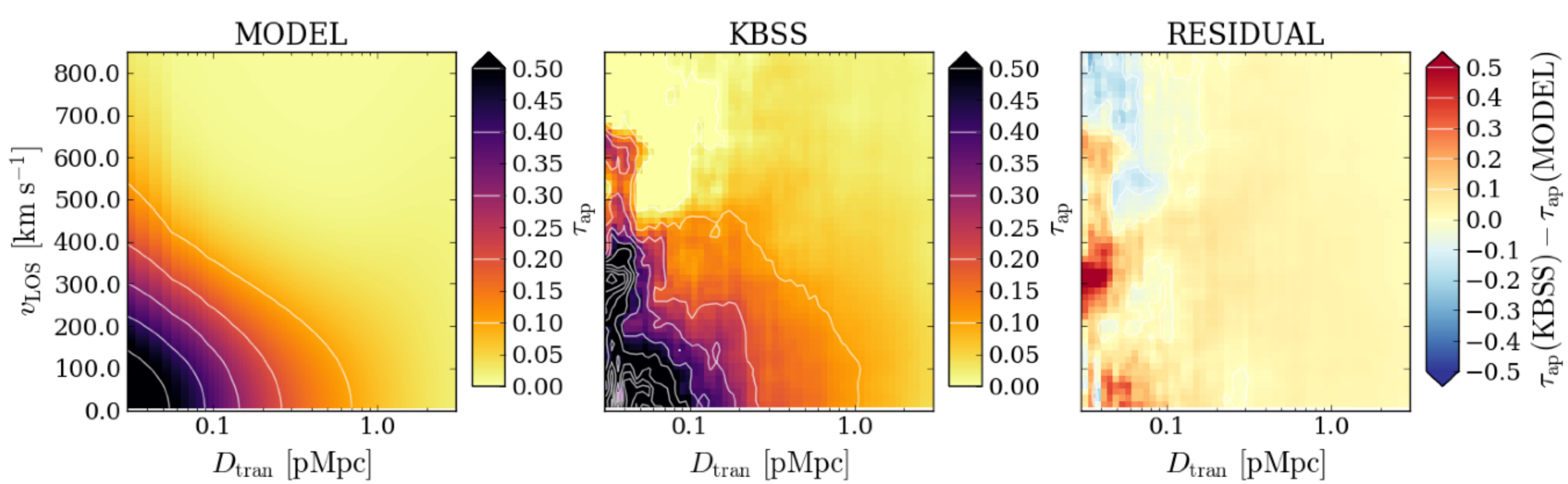
Finger-of-god effect & redshift-space distortion (RSD)

2. Large-scale line-of-sight “asymmetry” in the RSD??

Real? observational bias? physical effect?

Substantial potential with Subaru/PFS

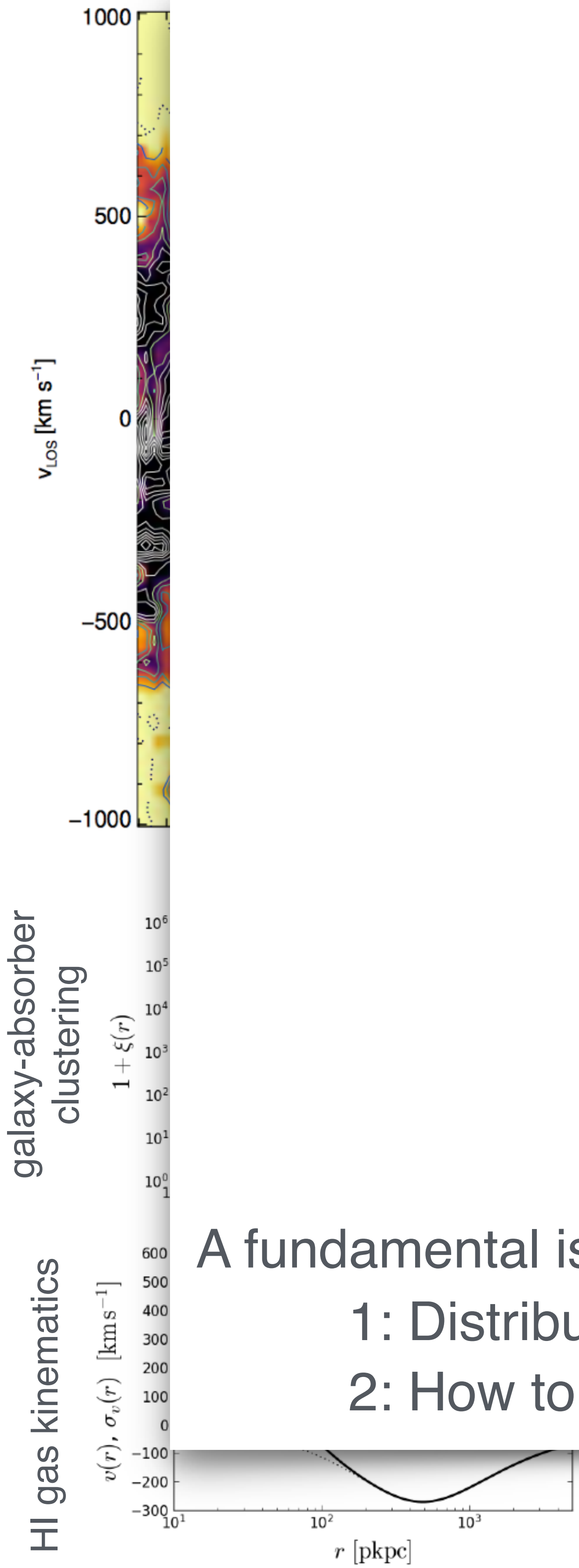




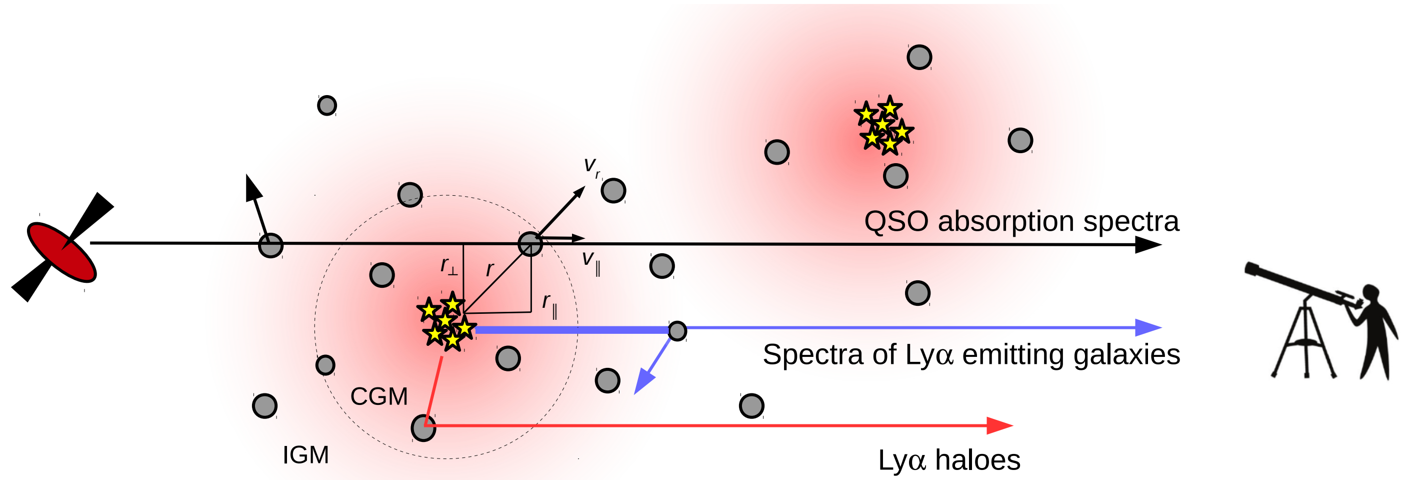
w/ Kakiichi & Dijkstra 2019 model

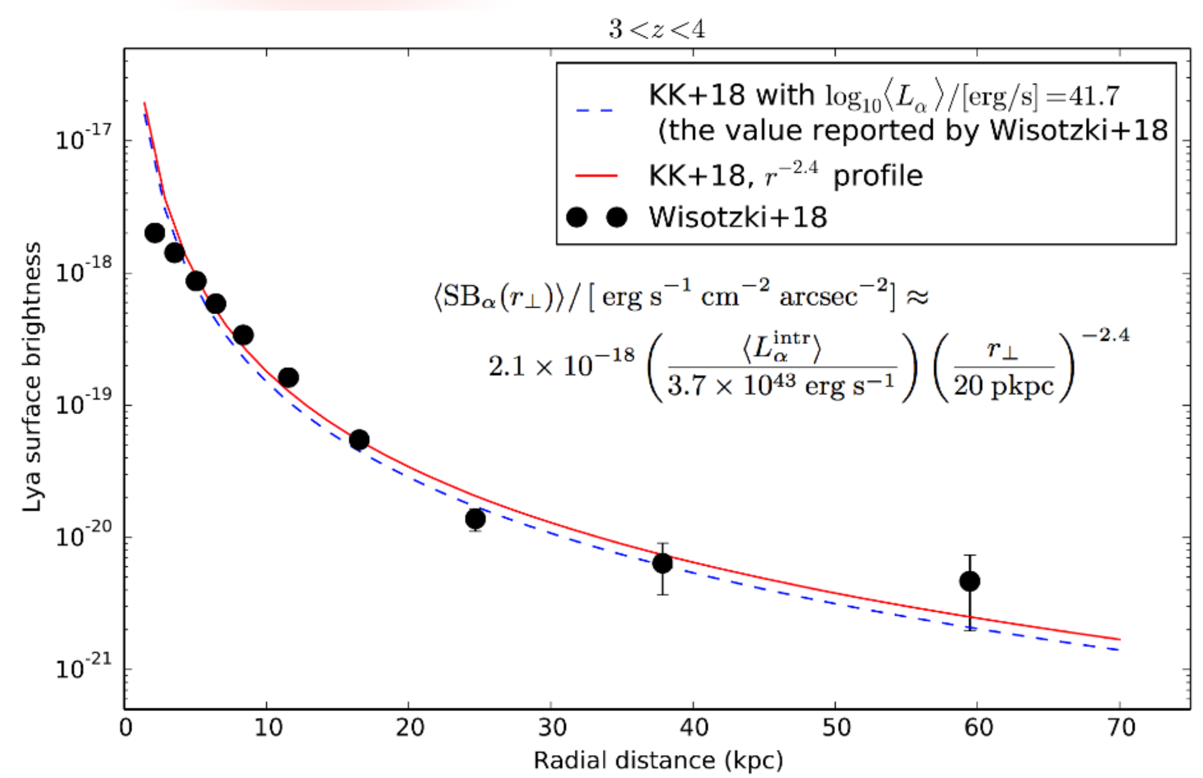
Distribution and Kinematics of the HI gas around z~2 Galaxies

200,000 galaxy-galaxy pairs from Keck Baryonic Structure Survey



Lyα absorption - emission connection





A fundamental issue when understanding the origin of Lyα haloes. We don't know:

1: Distribution/kinematics of cold gas

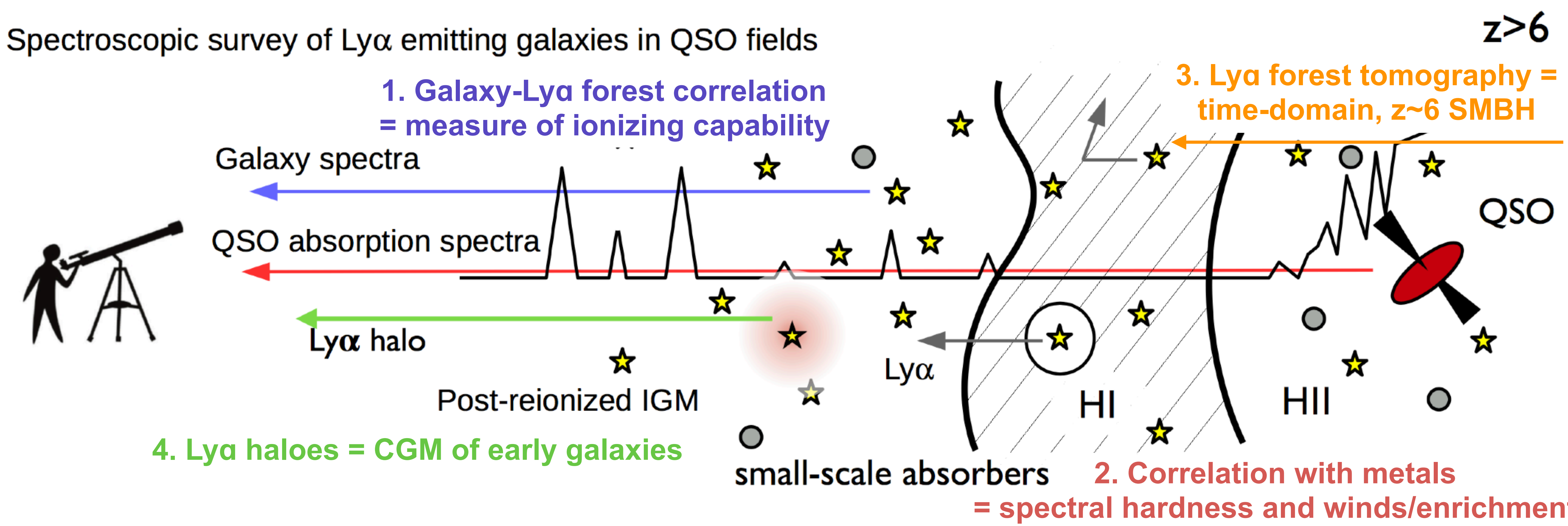
2: How to illuminate the cold gas

⇨ Two unknowns, two constraints needed.

w/ Kakiichi & Dijkstra 2018 model

Galaxy-IGM Connection at the Reionization-Era z>6

Probing what reionized the Universe?

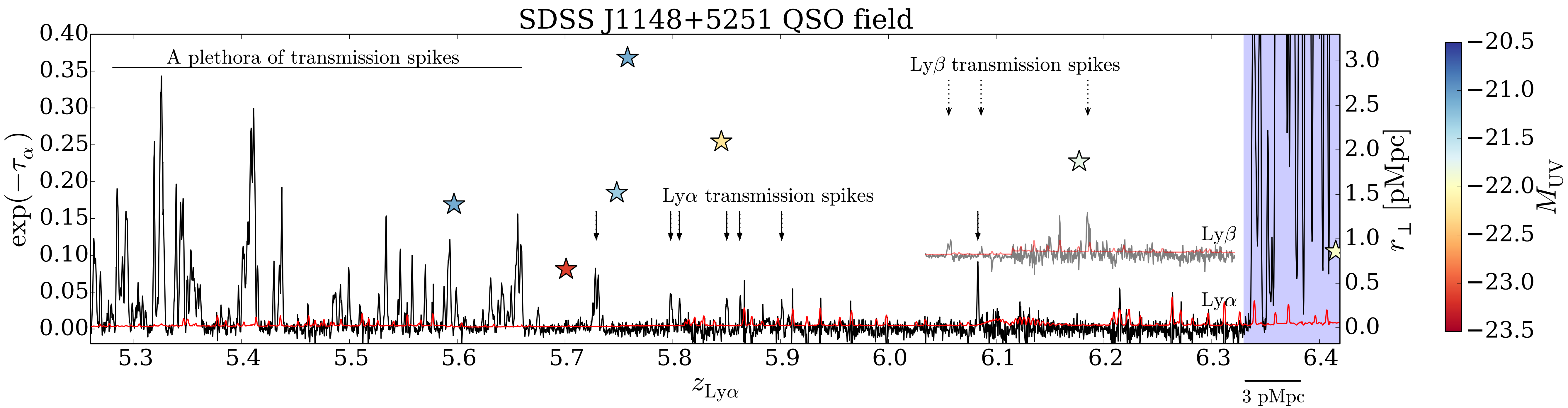


"Lyα probing Lyα"

A reionisation-era extension of idea in
COS-halo Survey, CASBaH survey (e.g. Tumlinson et al 2013, Burchett+2019)
Keck Baryonic Structure Survey (Steidel et al, e.g. Rudie+12, Turner+14)
and Quasar Probing Quasar Survey (Hennawi & Prochaska et al) e.g. Prochaska+13, Schmidt+17

Probing the Ionizing Capability of Galaxies from Galaxy-Lyα Forest Cross-Correlation at z~6 -: I

Galaxy-IGM map in the Keck/DEIMOS J1148+5251 quasar field



Ionising UV radiation from galaxies →

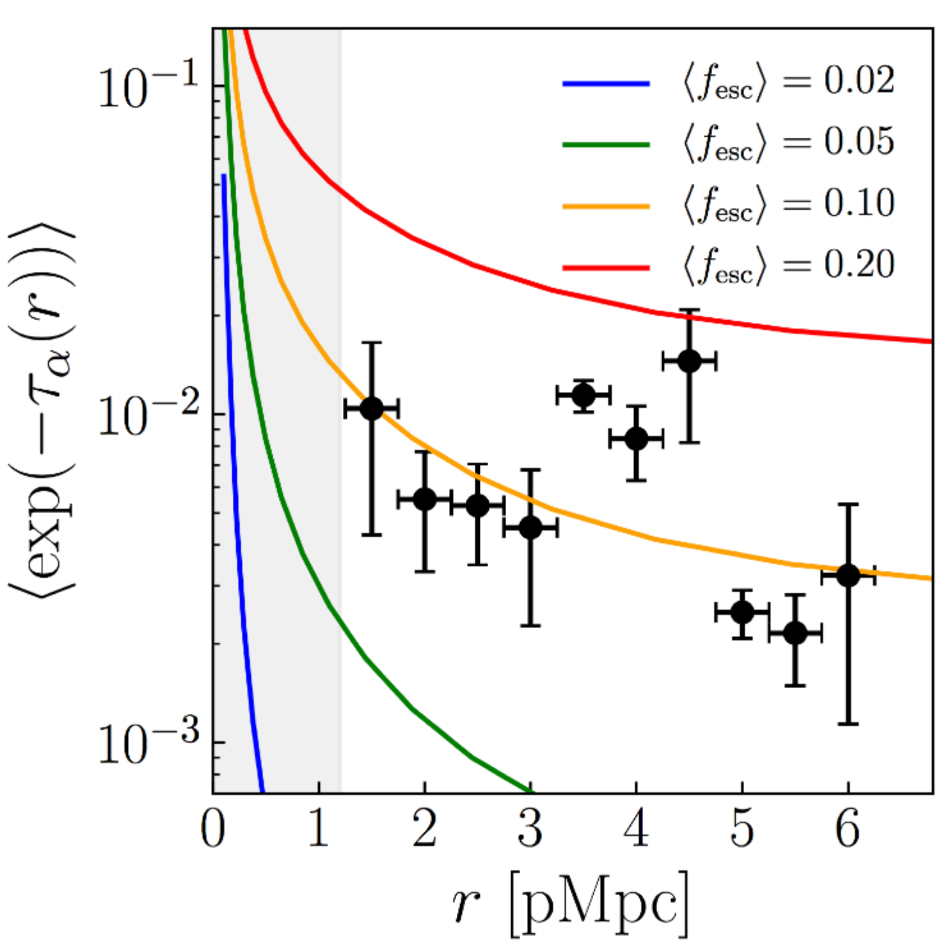
more Lyα transmission spikes around galaxies

but the individual associations are "*stochastic*"

Lyα optical depth

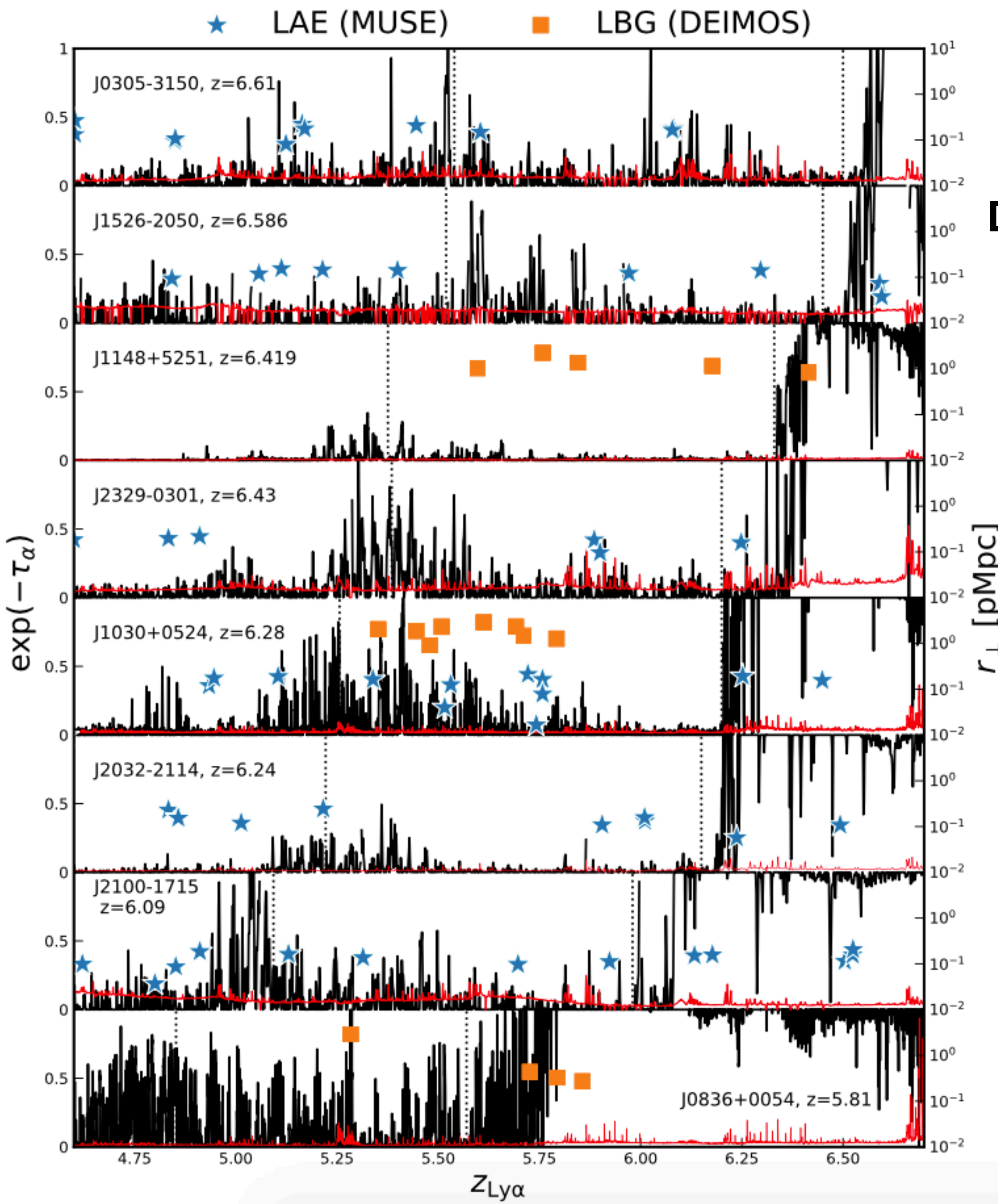
$$\tau_\alpha \simeq 11(1+\delta_m)^2 \left(\frac{\Gamma_{\mathrm{HI}}}{10^{-12}\ \mathrm{s}^{-1}}\right)^{-1} \left(\frac{T}{10^4\ \mathrm{K}}\right)^{-0.72} \left(\frac{1+z}{7}\right)^{9/2}$$

Gas density UV background Temperature



The statistical HI proximity effect requires " *faint unseen galaxies clustering around the detected galaxies with f_{esc}~10%* ".

Kakiichi+18



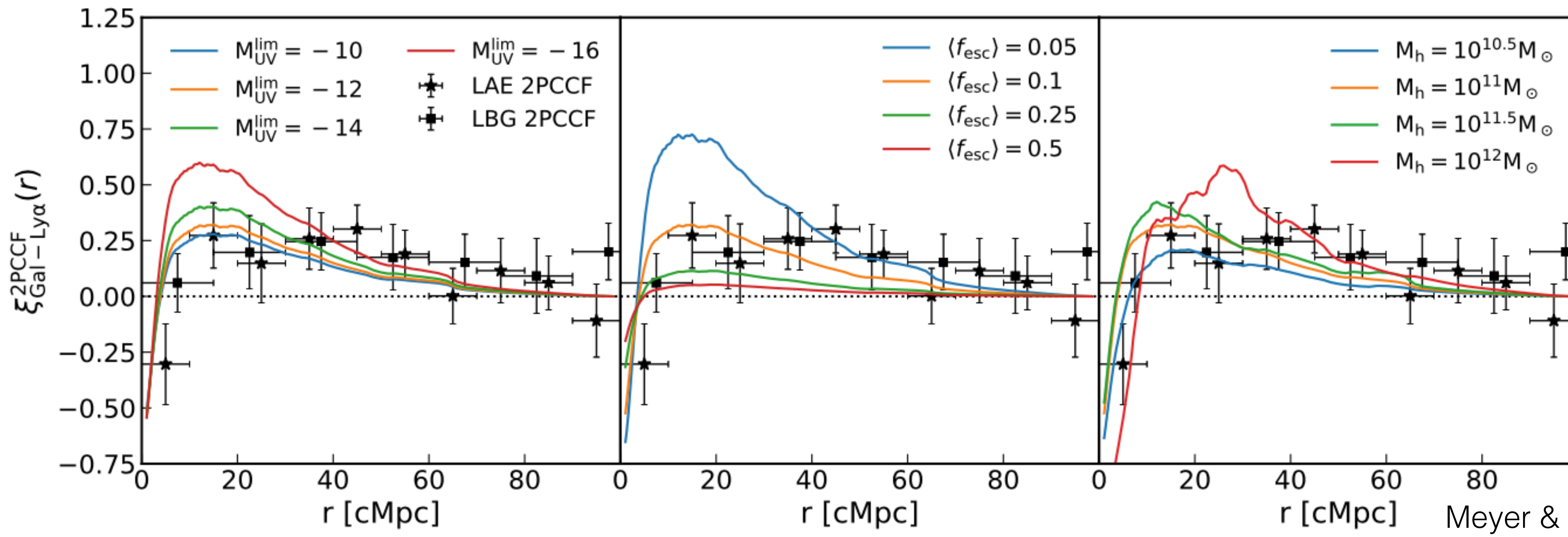
DEIMOS+MUSE galaxy survey in multiple quasar fields

- *Some Lyα transmission spikes seem to visually correlate with galaxies' location.*
- *Diversity in the mean Lyα transmitted flux around galaxies "large field-to-field variation*
  e.g. 5.25<z<75 patch of J1030+0524 vs. J2032-2114

Meyer & Kakiichi+20

Probing the Ionizing Capability of Galaxies from Galaxy-Lyα Forest Cross-Correlation -: II

Multiple multi-object & integral field spectroscopic survey of 8 quasar fields



Meyer & Kakiichi+20

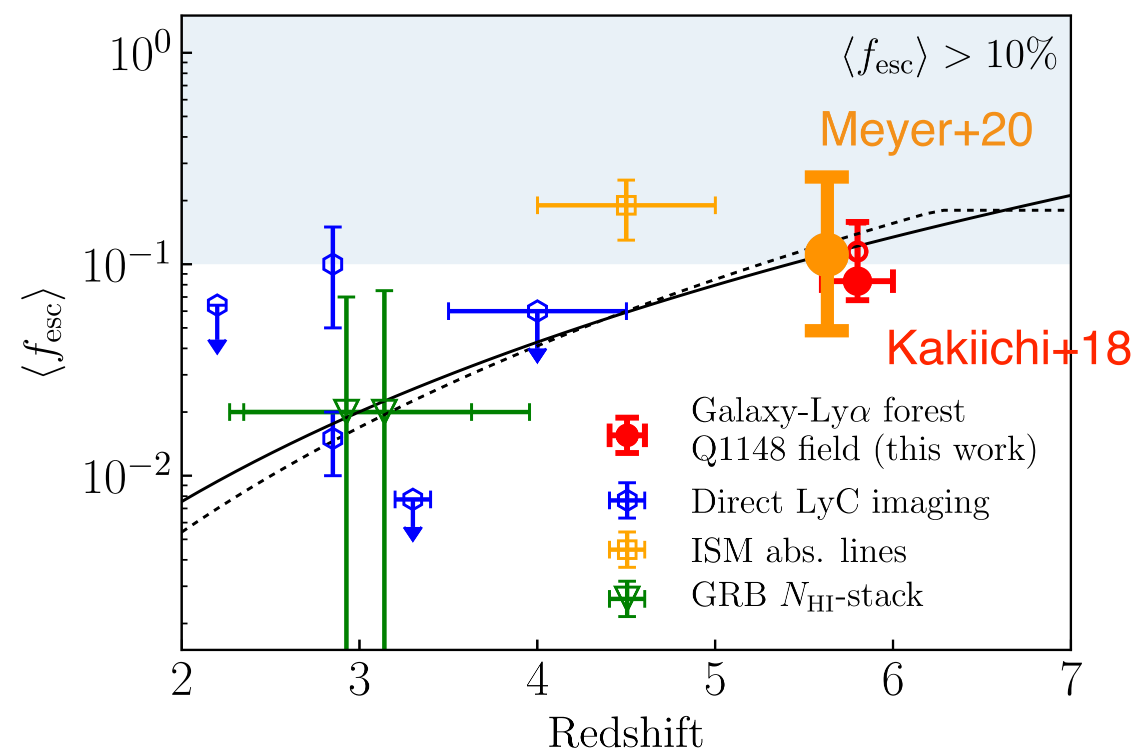
Improved galaxy-IGM model includes:

- enhanced UV background around galaxies
- gas overdensity fluctuations around galaxies
- varying mean free path of ionizing photons
- redshift error/random peculiar velocities of galaxies

Challenge:

- *Cosmic variance*
- *Ab initio theoretical framework*

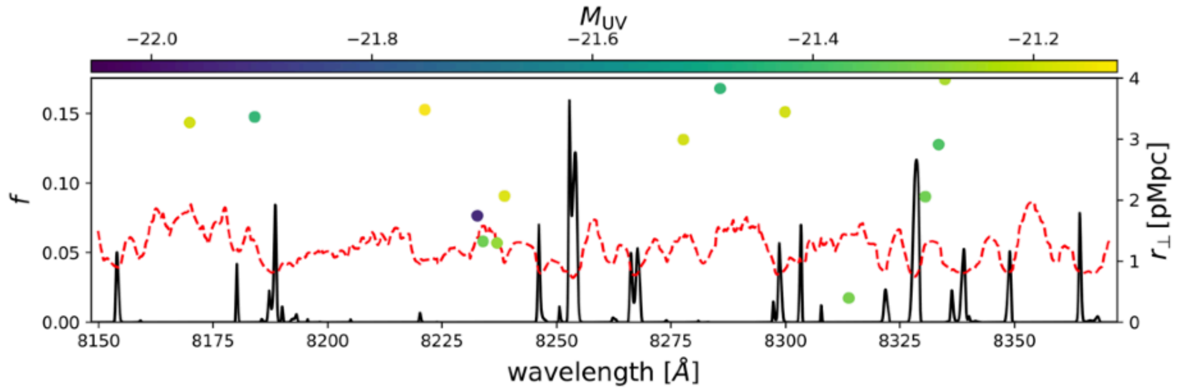
→ *Must be solved prior to the JWST, otherwise we will face the same challenge.*

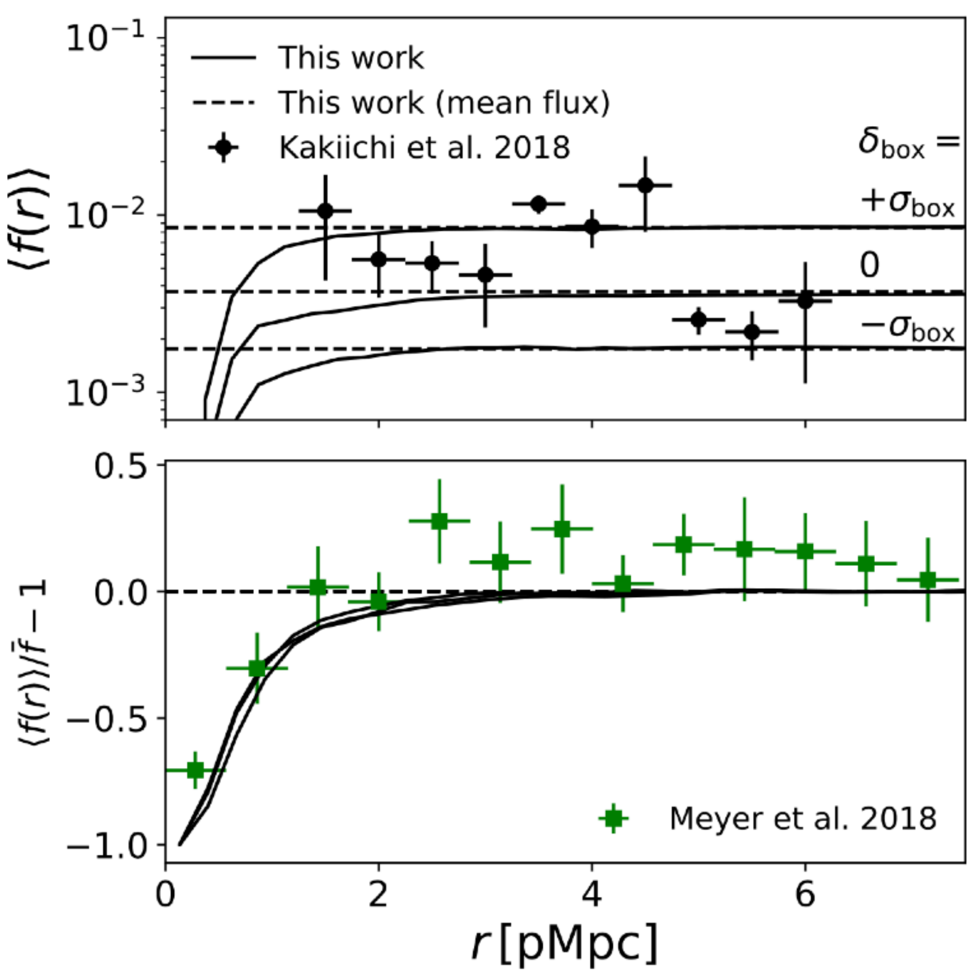


Physical Origin of the Galaxy-IGM HI Lyα Forest Cross-Correlation-: III

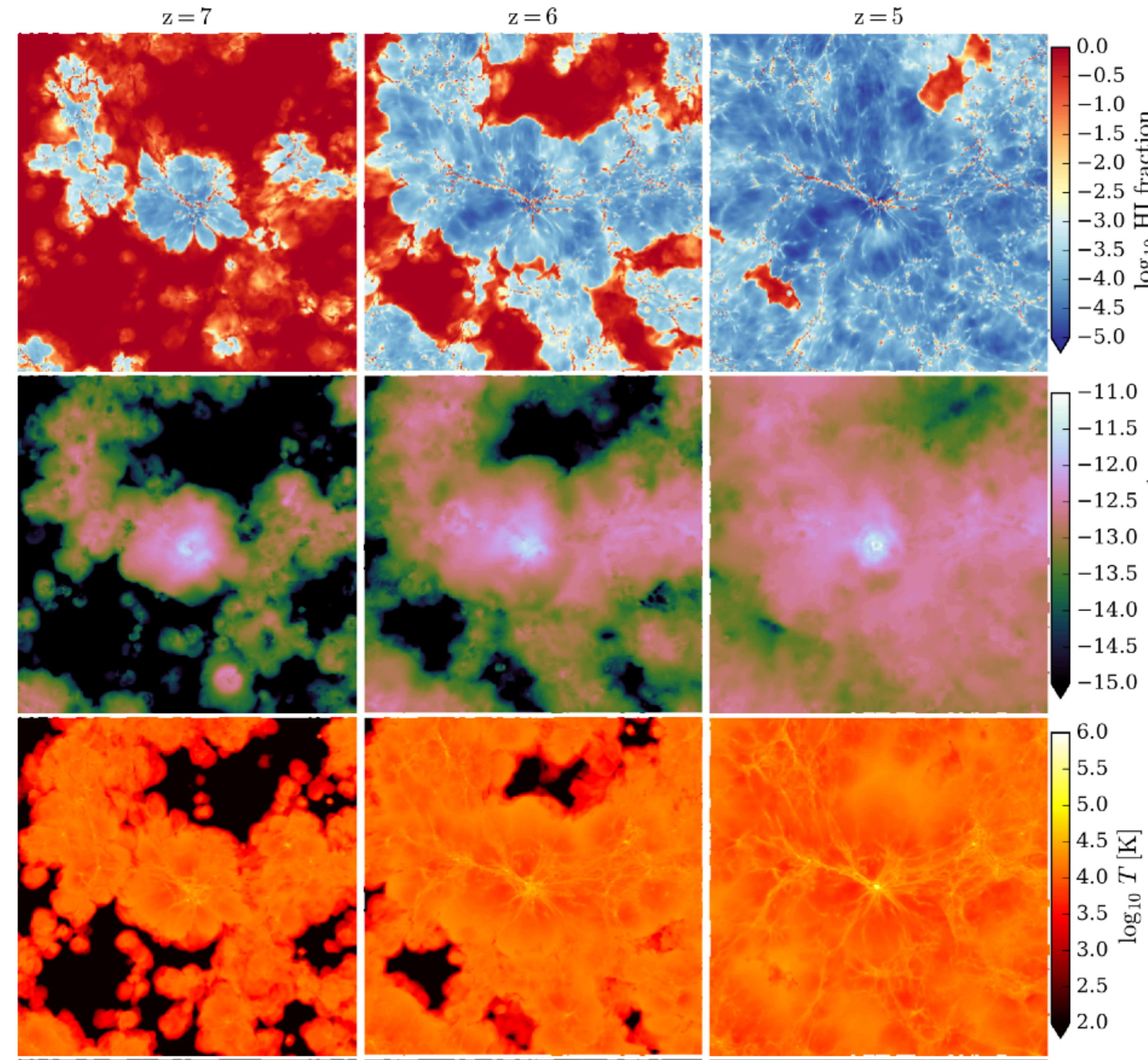
Does the cross-correlation naturally emerge in radiation-hydro. simulations?

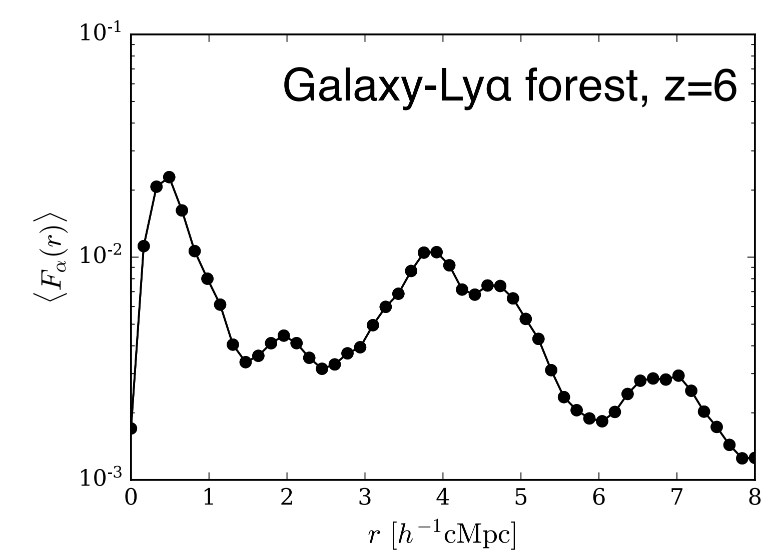
Cosmo. RHD simulation 80 h^{-1}cMpc box, CROC (Garaldi+19)





Cosmo. 'zoom-in' RHD simulation, 20 h^{-1}cMpc region around a massive galaxy in 100 h^{-1}cMpc box (Kakiichi+)





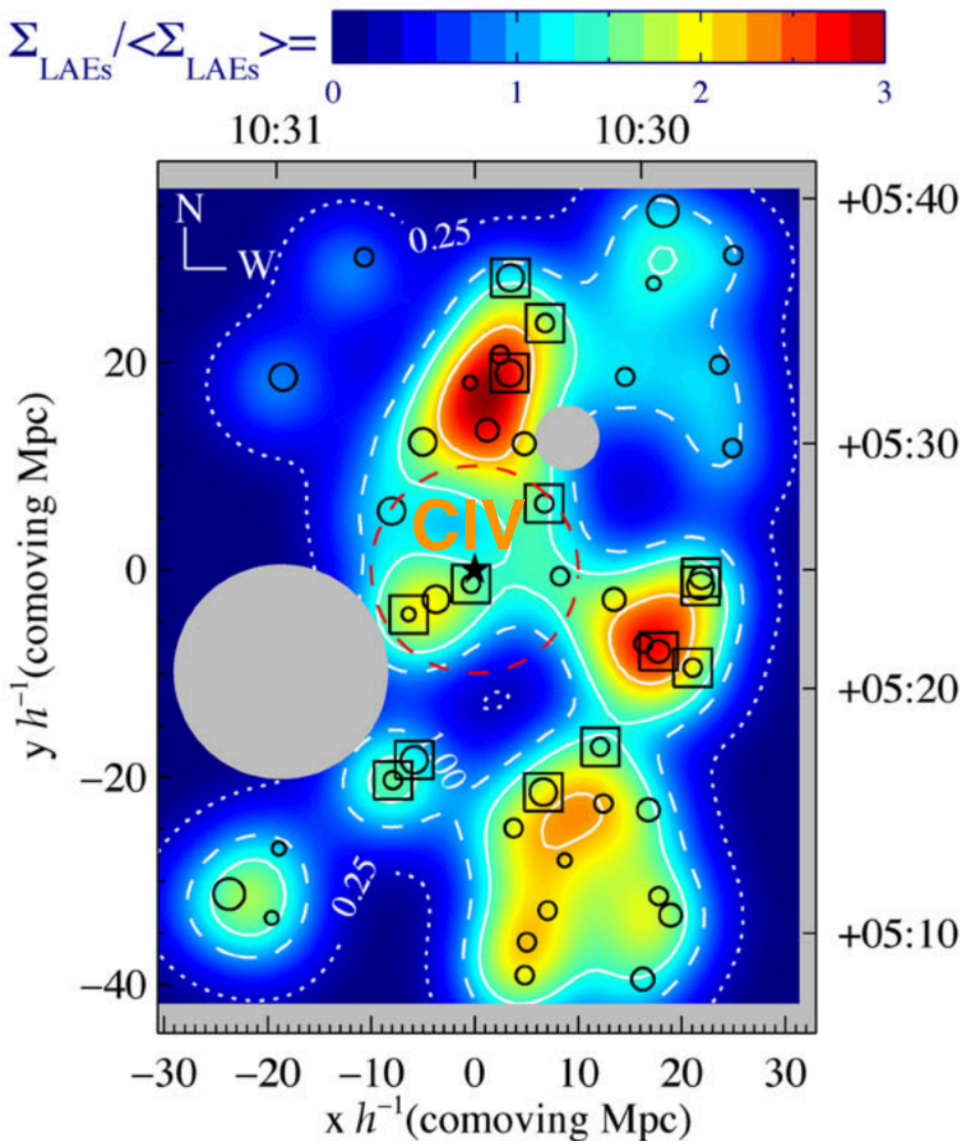
Whether the cross-correlation naturally arises in the full RHD sim. is still uncertain. Many processes could contribute to the signal:

- Numerical issue: large-scale mode / repeating LyC photons in a box
- UV background & thermal fluctuations act together: opposing effect
- Late reionization? remnant of ionized bubbles at the tail end, z~5.8??

Association to Metals and Galaxy-Metal Absorption Clustering

Information content & prospects

1: z~5.7 galaxy-CIV absorber association



z~5.7 LAEs (CIV environment)

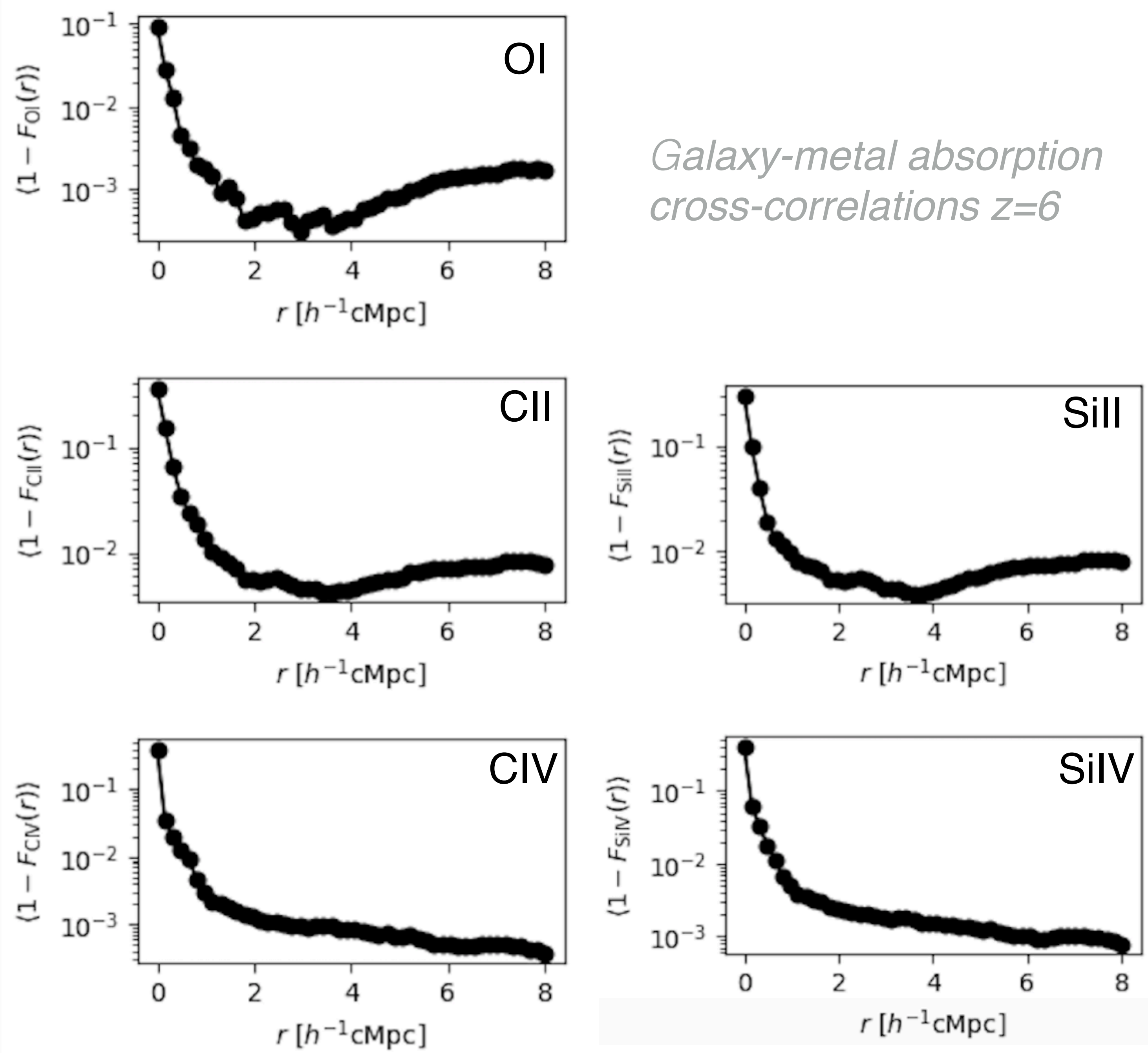
Diaz+2015, 20

2: z=6.18 galaxy-OI absorber overdensity association in the J1148 QSO field

Kakiichi+18, Becker+05

RAMSES-RT RHD simulation + CLOUDY
Zoom-in 20 h^{-1}cMpc region around
a massive galaxy in 100 h^{-1}cMpc box

Galaxy-metal absorption cross-correlations z=6

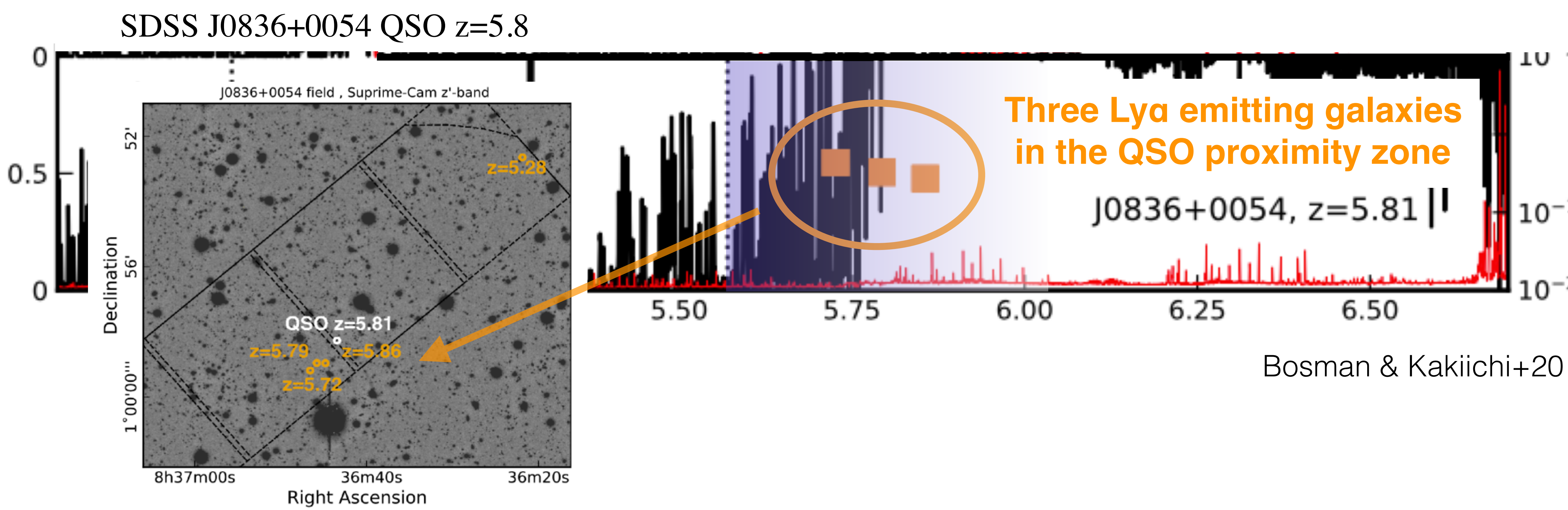


What do we learn from galaxy-metal clustering?

e.g. Keating+16, Finlator+18 …

Lyα Forest Tomography of a z~6 Quasar IGM Environment

“Time-domain” view to a SMBH activity



Bosman & Kakiichi+20

Deep spectroscopy of foreground and background galaxies around a QSO, “Lyα forest tomography of QSO proximity zone” provides a window to the “time-variable ionizing property of a SMBH”.

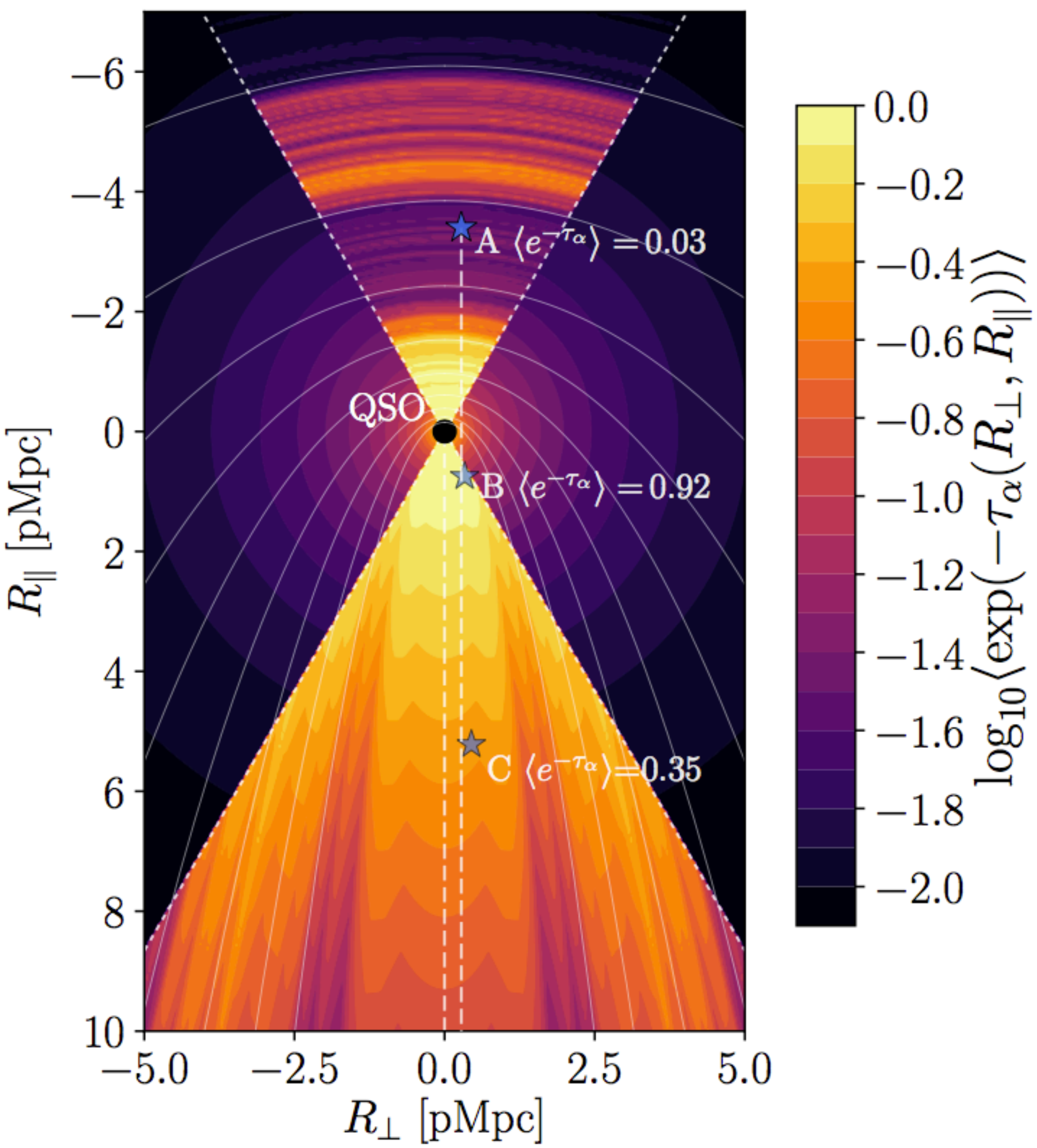
Idea introduced by Adelberger+2004

Lyα Forest Tomography of a z~6 Quasar IGM Environment :- I

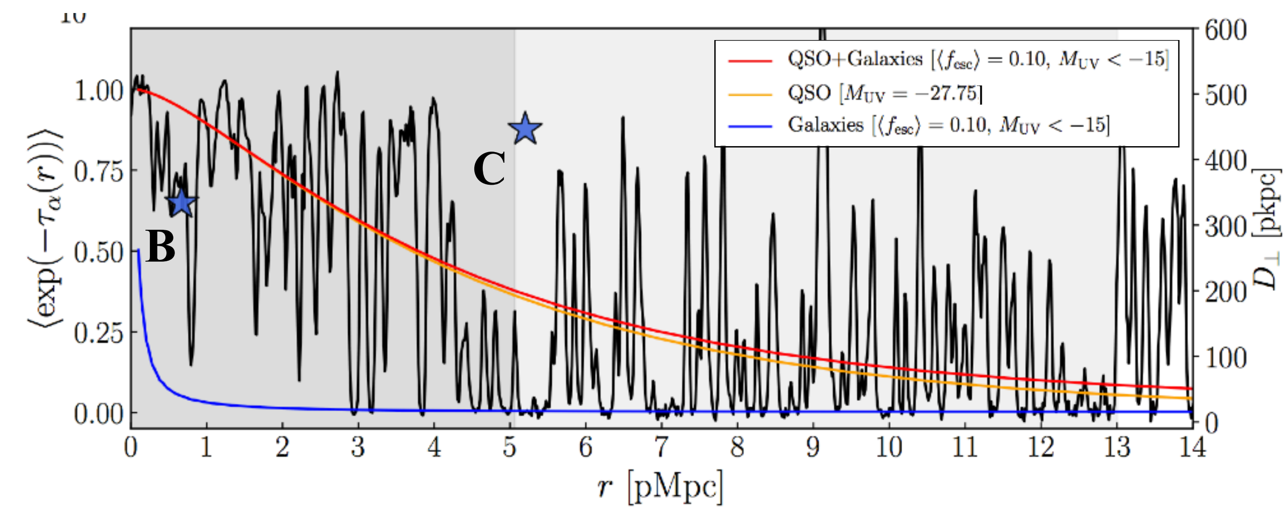
"Time-domain" approach to a SMBH activity

Bosman & Kakiichi+20

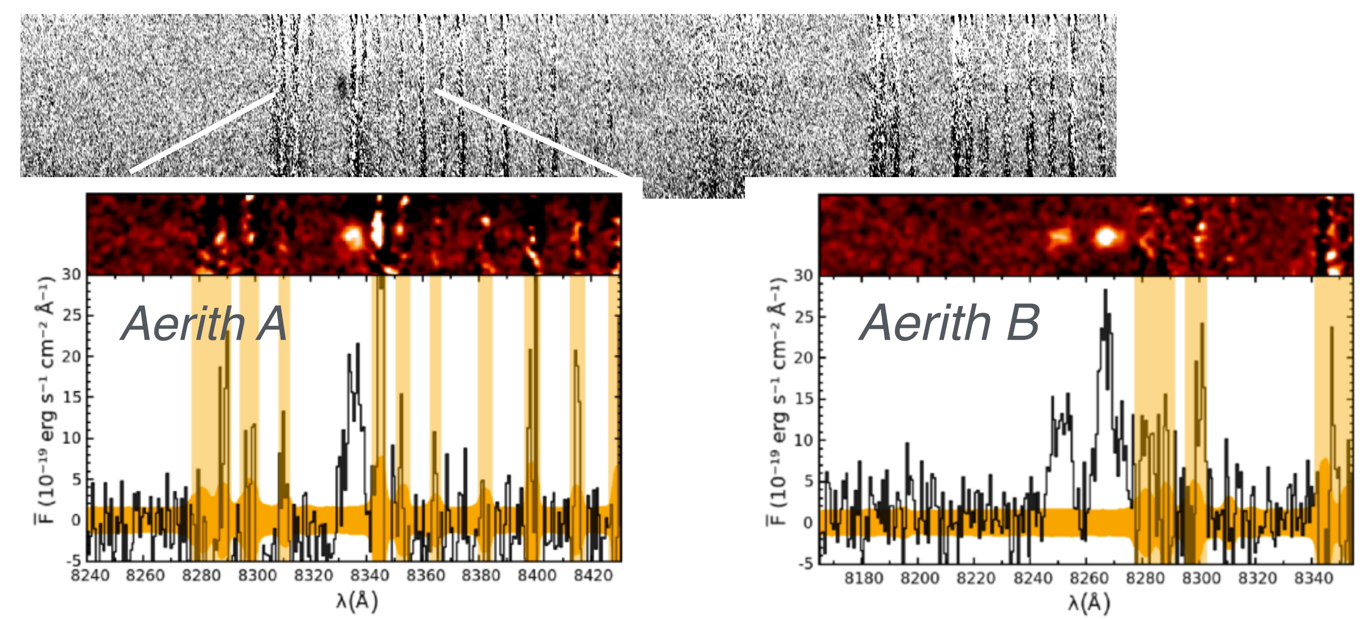
3D+time domain map



- 1D line of sight proximity zone along a QSO



- Background (A) & foreground LAEs (B)



<u>A Proof-of-concept study: Ionizing activity of a z=5.8 QSO</u>

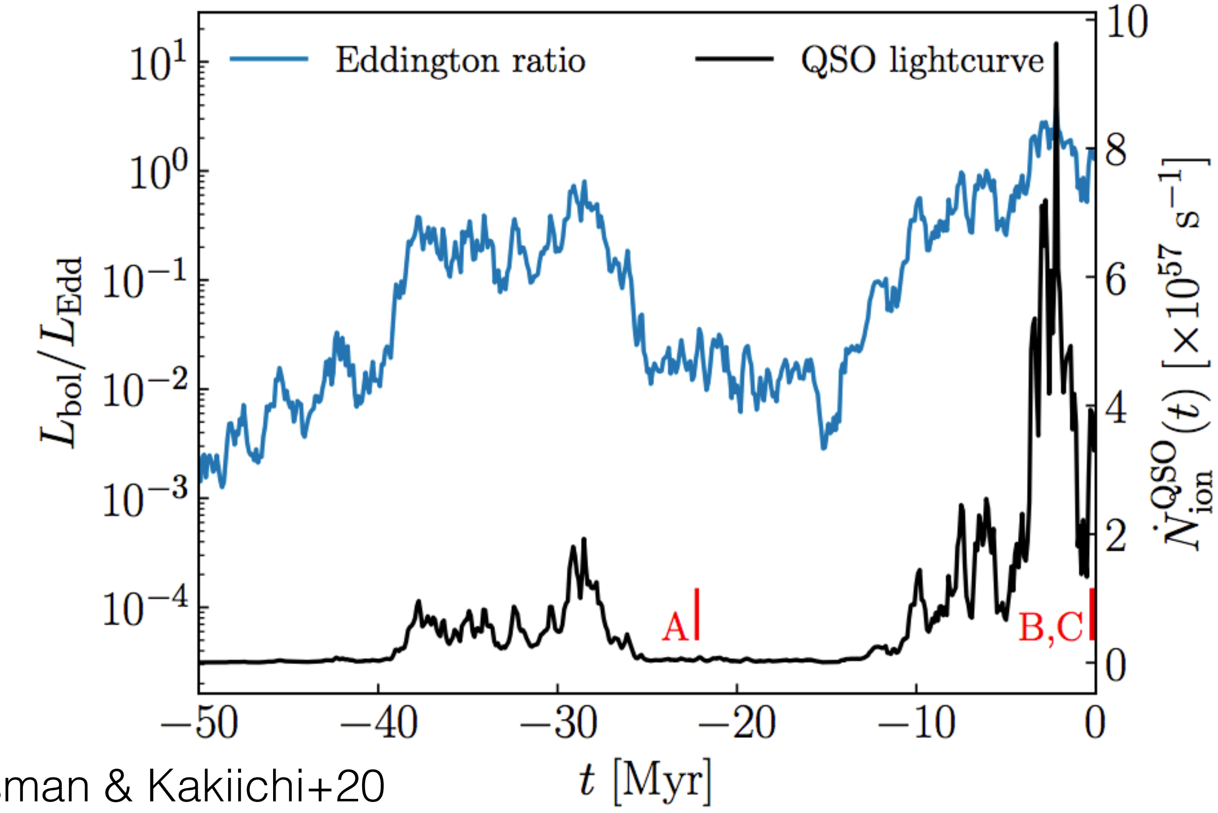
QSO time variability 2.3×10^5 yr < t_{age} < 2.2×10^7 yr & radiative opening angle >24°

see also Schmidt+2019

Lyα Forest Tomography of a z~6 Quasar IGM Environment :- II

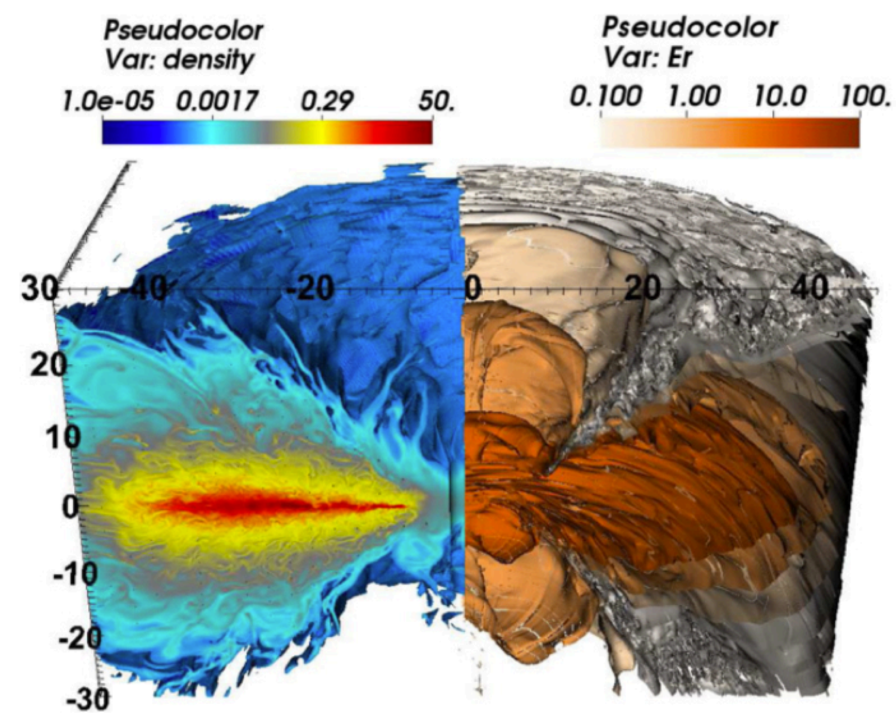
Implication to z>6 SMBH growth

Episodic ionising activity of SMBHs?



Bosman & Kakiichi+20

Super-Eddington slim disk of a SMBH



RMHD, Jiang+14,17
(McKinney+14,17)

1. Variable accretion rate/feeding onto SMBH?
2. Episodic QSO obscuration in the host-galaxy?

Cf. Short QSO lifetimes at z~6

Eilers+20

Growth & formation channels of z>6 SMBHs

- **Eddington-limited accretion on massive seeds, e.g. direct collapse black hole/supermassive stars** **(e.g. Woods+18)**
- **Super-Eddington accretion on stellar-mass seeds** **(e.g. Madau+14)**

Summary: Galaxy-IGM/CGM Connection

Progress & Challenge

1. ***Progress in Cosmological Radiation-Hydrodynamic Simulations***
   - ***Small-scale LyC leakage × large-scale IGM***
   - ***Low-redshift universe as a laboratory for reionization physics***

2. ***Reionization-Metal Links: Reionization of Metals***
   - ***Connection to the ionizing sources & high-z feedback***

3. ***CGM Theory: Origin of Cold Gas***
   - ***Observations: Lensing tomography & 2D galaxy-HI forest cross-correlation***
   - ***Lyα emission - absorption connection***

4. ***Galaxy-IGM Connection at the Reionization Era***
   - ***Ionizing capability of galaxies from galaxy-Lyα forest cross-correlation***
   - ***Association with metal absorption lines & galaxy-metal clustering***
   - ***Lyα forest tomography as a time-domain window to z>6 SMBH growth***