Title: Imaging the Cosmic Web

Speakers: Chris Martin

Collection/Series: Cosmic Ecosystems

Subject: Cosmology

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Abstract:

The intergalactic medium (IGM) represents the dominant reservoir of baryons at high red- shift, traces the architecture of the cosmic web dominated by dark matter, and fuels on-going galaxy evolution. Using a purpose-built instrument, with nod-and-shuffle and dual-field subtraction, we have detected, for the first time, an emission Lyman α forest (ELAF). The emission forest is highly extended, shows filamentary morphology with filaments connecting galaxies, exhibits statistics like the absorption Lyman α forest, displays spectra resembling the absorption forest, and is correlated with galaxy-traced overdensities consistent with bias like dark matter. We conclude that the ELAF may provide a new tool for tracing a significant fraction of the cosmic web of baryons and dark matter. Finally, I will present status of the STABLE Cosmic Web Imager (SCWI) program, a Brinson Exploration Hub balloon experiment, focused on emission from the Circum-QSO, the Circum-Galactic Medium, and the cosmic web. SCWI offers the opportunity to image the cosmic web in the local universe for the first time, and compare its properties to those at high redshift.

The Cosmic Web in Emission

Chris Martin (Caltech)+++

+++
Matt Matuszewki
Patrick Morrissey
Zeren Lin
Donal O'Sullivan
Keri Hoadley
Bruno Milliard
David Schiminovich
Erika Hamden
Daphne Chang
Anna Moore
Behnam Darvish
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Chuck Steidel
Zheng Cai
Sarah Tuttle
Nicole Melso
Vincent Picouet
Avishai Dekel
Renyue Cen
and more

I. Program
II. IGM emission
III. Low z CGM
IV. Future missions

R. Cen Lyα Sim

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I. IGM Project: Motivation

- *Global Quantities*
  - Luminosity $\mathcal{L}$
  - Mass M
  - Velocity dispersion σ_v
  - Size L = θ D
  - Mass flux in/out $\dot{M}_{in}, \dot{M}_{out}$
  - Angular Momentum $\vec{L} = \vec{r} \times \vec{v}$
  - Minimize astrophysical "noise"
- Density $n_i = N_i/L$
  - Overdensity δ
  - Ionization Γ/n
  - Total density $n = f(\Gamma, n_i)$
  - Pressure p=nkT
  - Filling Factor f
- Temperature T
  - Heating/cooling balance
  - Non-thermal support
- Timescales
  - Cooling $t_{cool} \sim T/n\Lambda$
  - Collapse time $t \sim \delta^{-1/2}$
- Morphology
  - outflows/inflows
  - shocks, filaments
- Gas Kinematics
  - Divergence $\nabla \cdot \vec{v}$
  - Rotation $\nabla \times \vec{v}$
  - Kinematic morphology
  - Mass flux in/out $\dot{M}_{in}, \dot{M}_{out}$
- Large Scale Structure Mapping
  - large scale structure statistics, P(k)
  - Correlation of IGM with CGM and galaxies, AGN

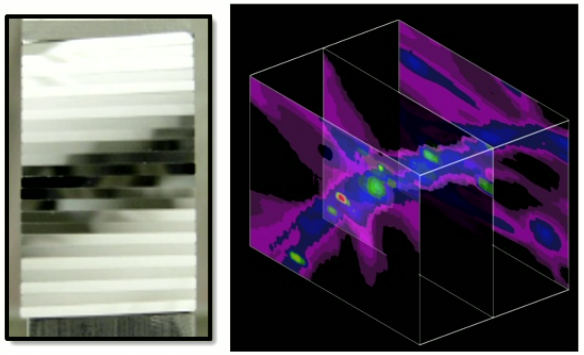
Ideally combine UV/O+X-ray emission and absorption+SZ+mm+...

2 Big Questions:

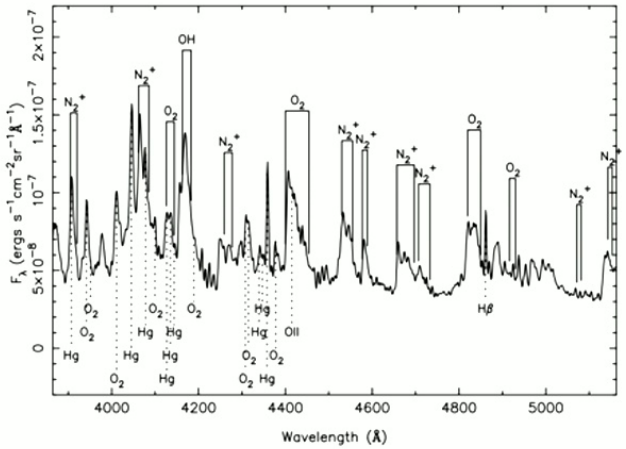
1. *Can we detect it?* ✓✓
2. *Can we extract physical parameters?* ✓

I. IGM Project: Methods

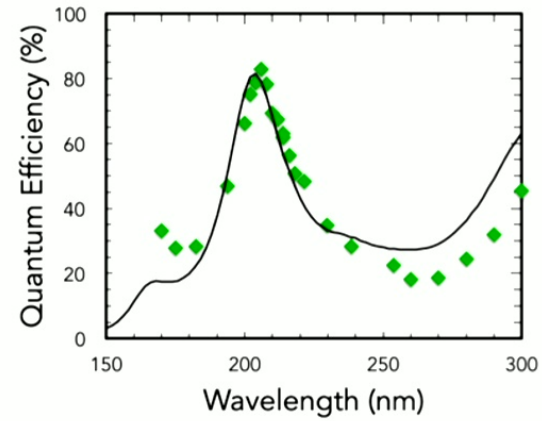
A. Imaging/Multiplexed UV Emission Line Spectroscopy



B. Precision Skv Subtraction



C. High Efficiency, Low Noise, Photon-Counting Detectors

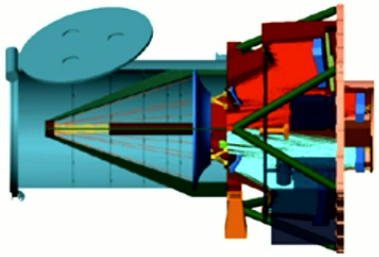


D. Extracting Physical Parameters

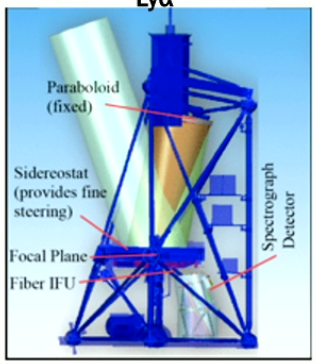
- Mass M
- Velocity dispersion σ_v
- Size L = θ D
- Mass flux in/out $\dot{M}_{in}$, $\dot{M}_{out}$
- Angular Momentum $\vec{L} = \vec{r} \times \vec{v}$

I. IGM Project: Program

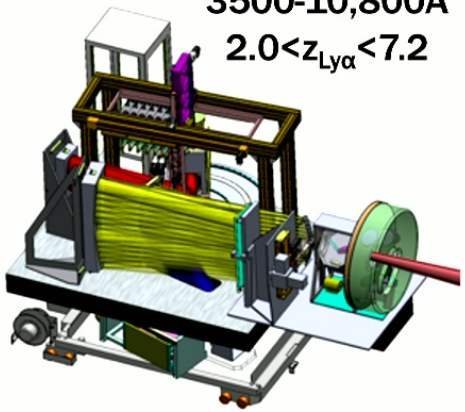
XCWI
Explorer
1230-2500Å
$0.05<z_{Ly\alpha}<1.2$



FIREBALL/SCWI
Balloon
2050-2250Å
$0.7<z_{Ly\alpha}<0.85$



KCWI
Keck
3500-10,800Å
$2.0<z_{Ly\alpha}<7.2$



Time since Big Bang	12	10	7	5.7	3	2	1.5	0.9	0.75	Billion yrs
Redshift	0.1	0.3	0.7	1	2	3	4	6	8	

ISTOS F | KCWI-B | KCWI-R

Cosmic Epoch: WHIM Grows, SF dies | Star Formation Epoch | SF Grows | Reionization

Wavelength (μm)	0.13	0.2	0.3	0.5	0.7	1.0	1.2

II. IGM/Cosmic Web Emission

Hogan & Weymann 87

Lyman-alpha emission from the Lyman-alpha forest

Summary. It is suggested that high-dispersion long-slit spectra or very narrow-band etalon images of 'blank' sky could reveal patches of Ly-α line emission from the population of clouds whose absorption produces the 'Ly-α forest' in QSO spectra. A non-observation can put limits on the ionizing background at high redshift which are better than those obtainable by direct measurements of background light.

Cantalupo+05

FLUORESCENT Lyα EMISSION FROM THE HIGH-REDSHIFT INTERGALACTIC MEDIUM

SEBASTIANO CANTALUPO, CRISTIANO PORCIANI, SIMON J. LILLY, AND FRANCESCO MINIATI
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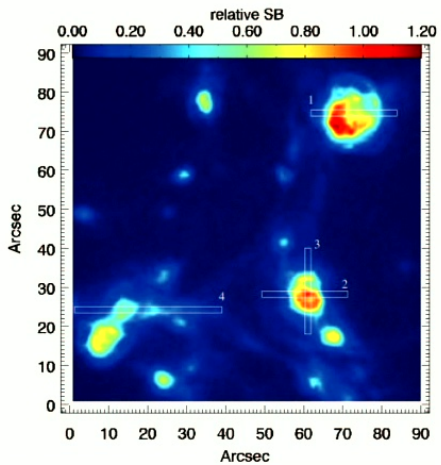
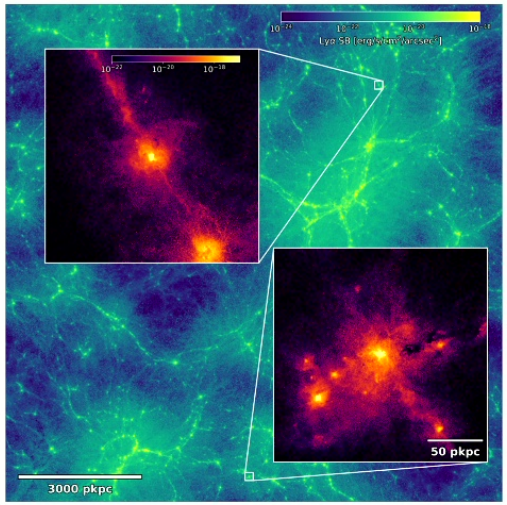
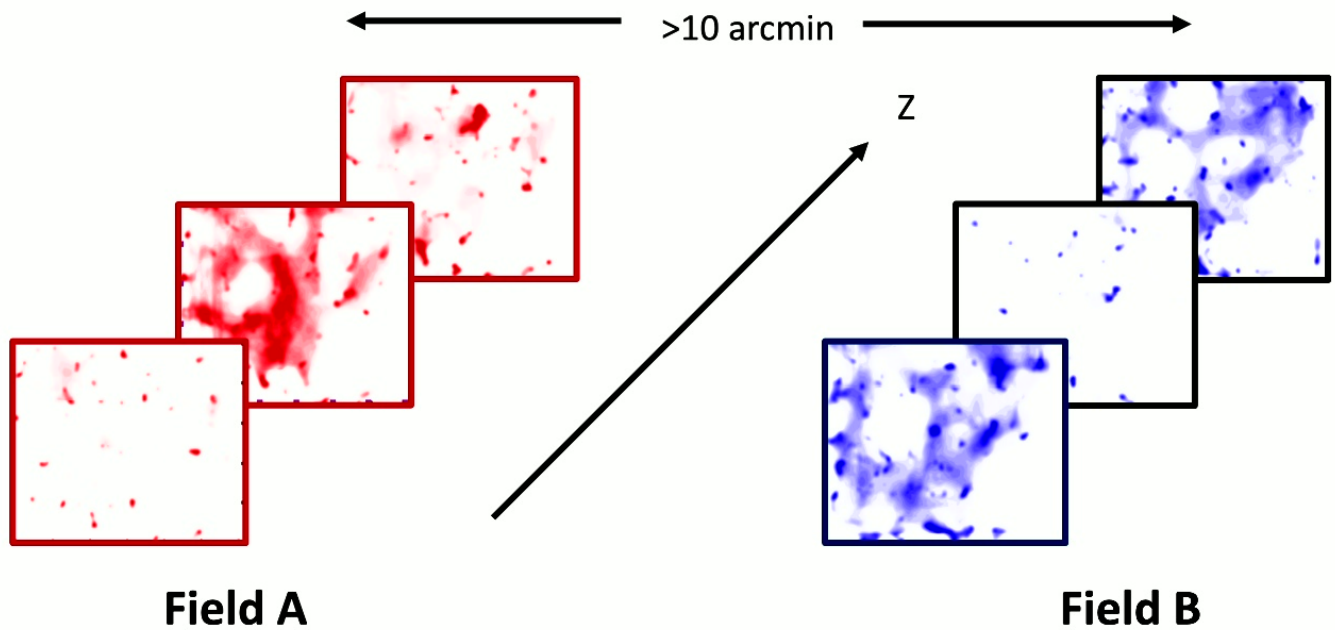


TNG -- Byrohl+21

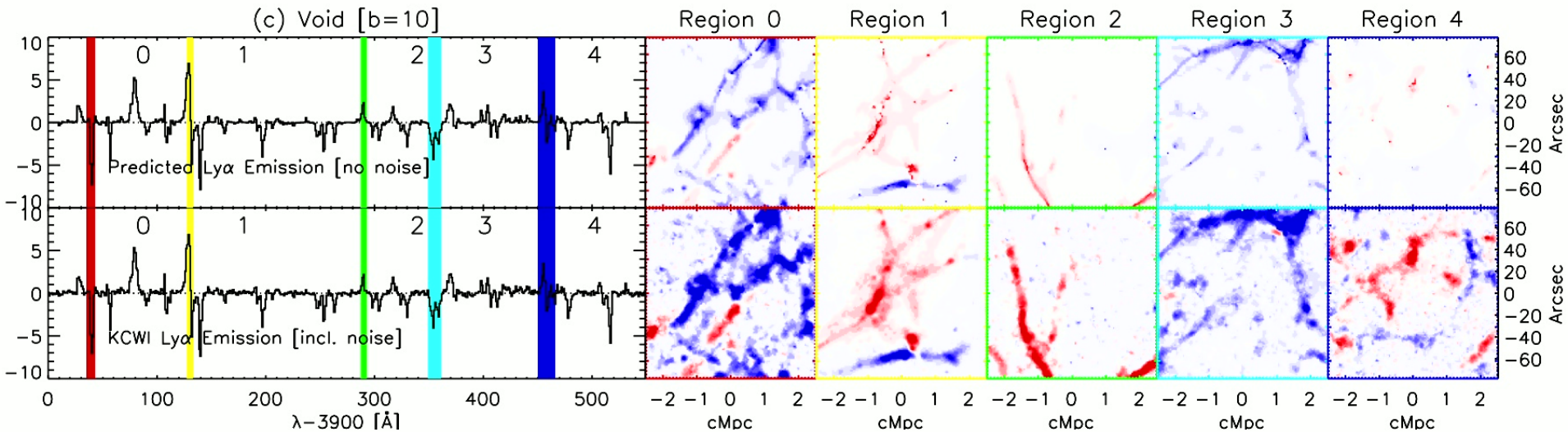


Early observational hints: Bacon+21 MUSE XDF

Dual Field Subtraction + Nod-and-Shuffle

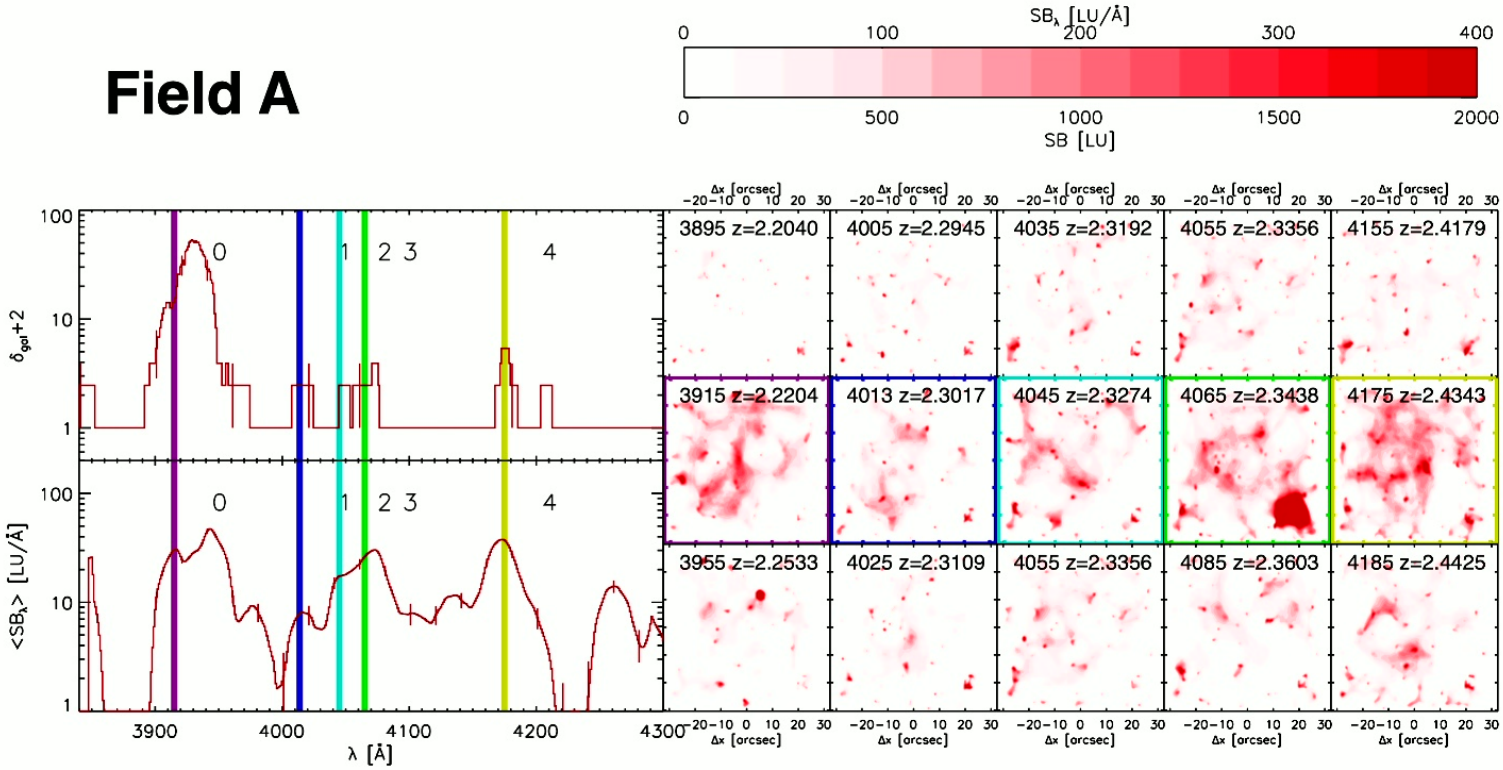


Dual Field Subtraction + Nod-and-Shuffle Simulation



a) Emission correlated with galaxy-traced structure

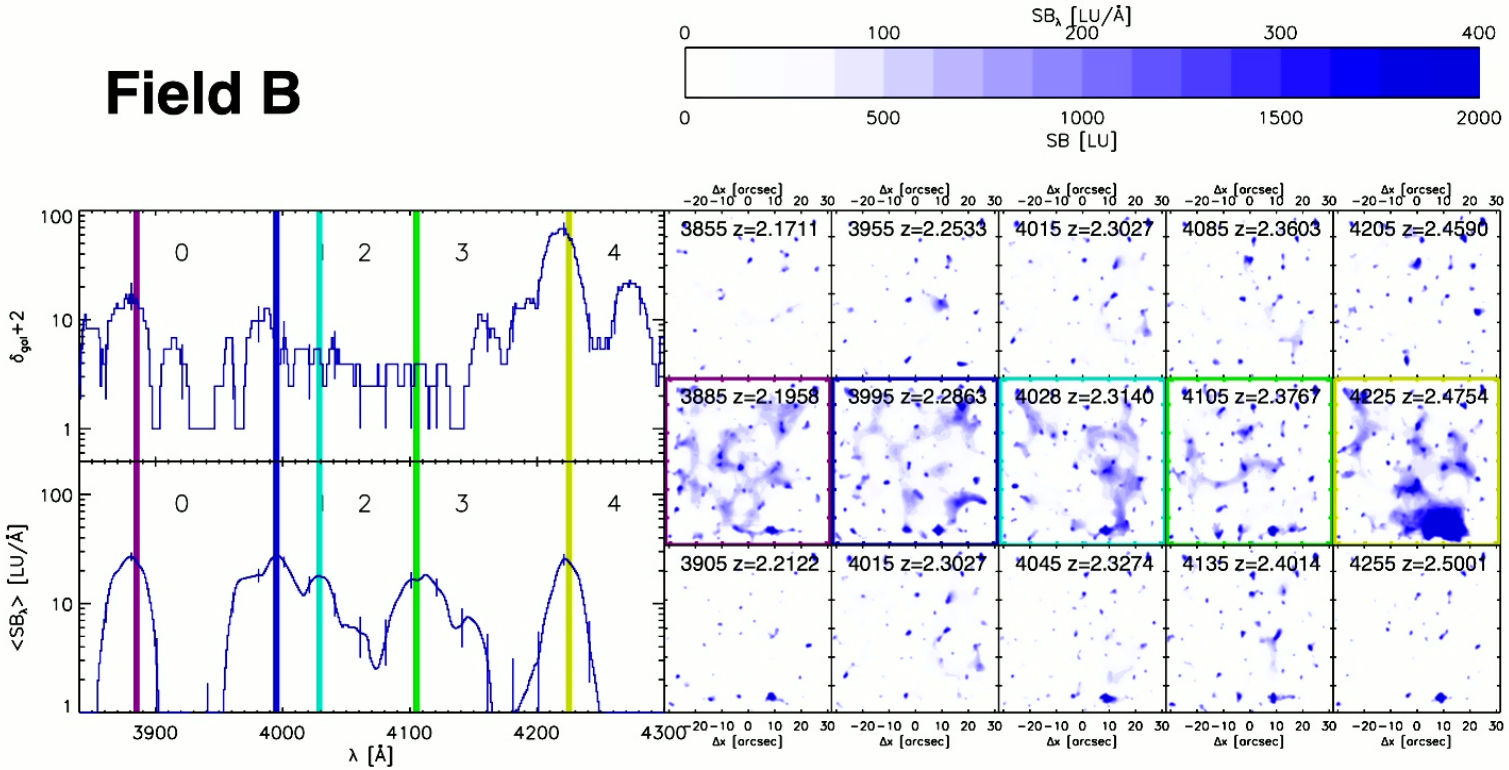
Field A



Martin, Darvish, Lin+2023 Nature Astronomy

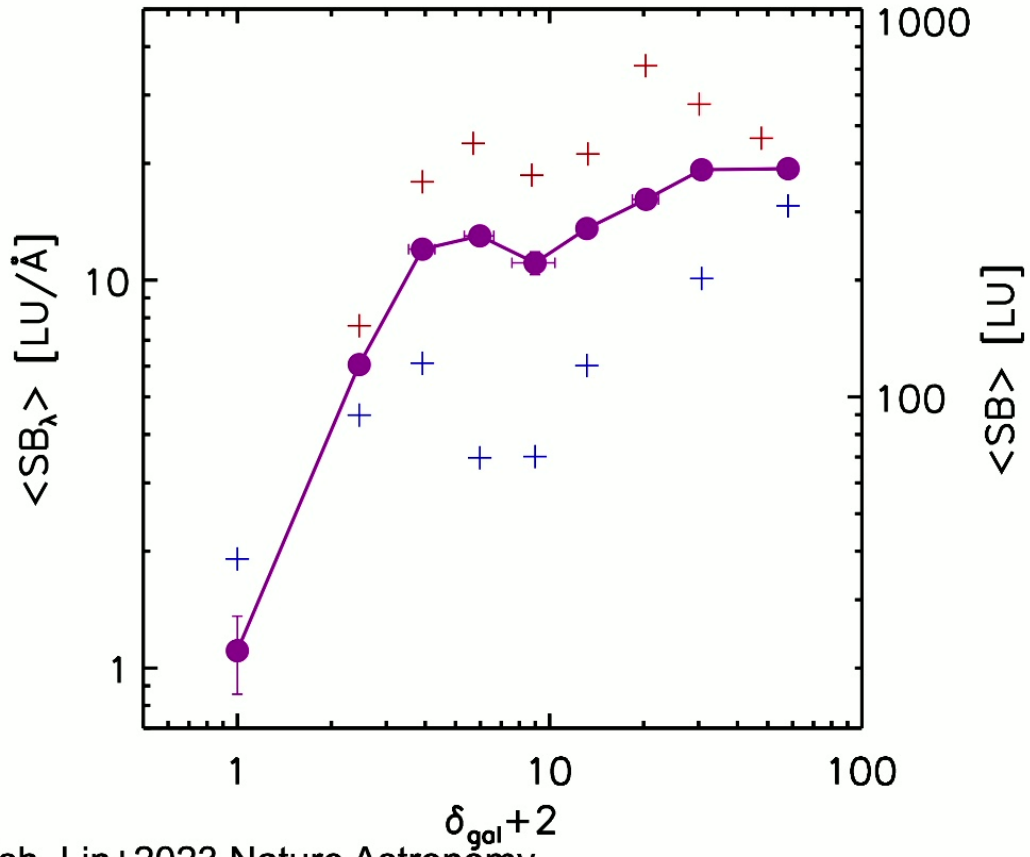
a) Emission correlated with galaxy-traced structure

Field B



Martin, Darvish, Lin+2023 Nature Astronomy

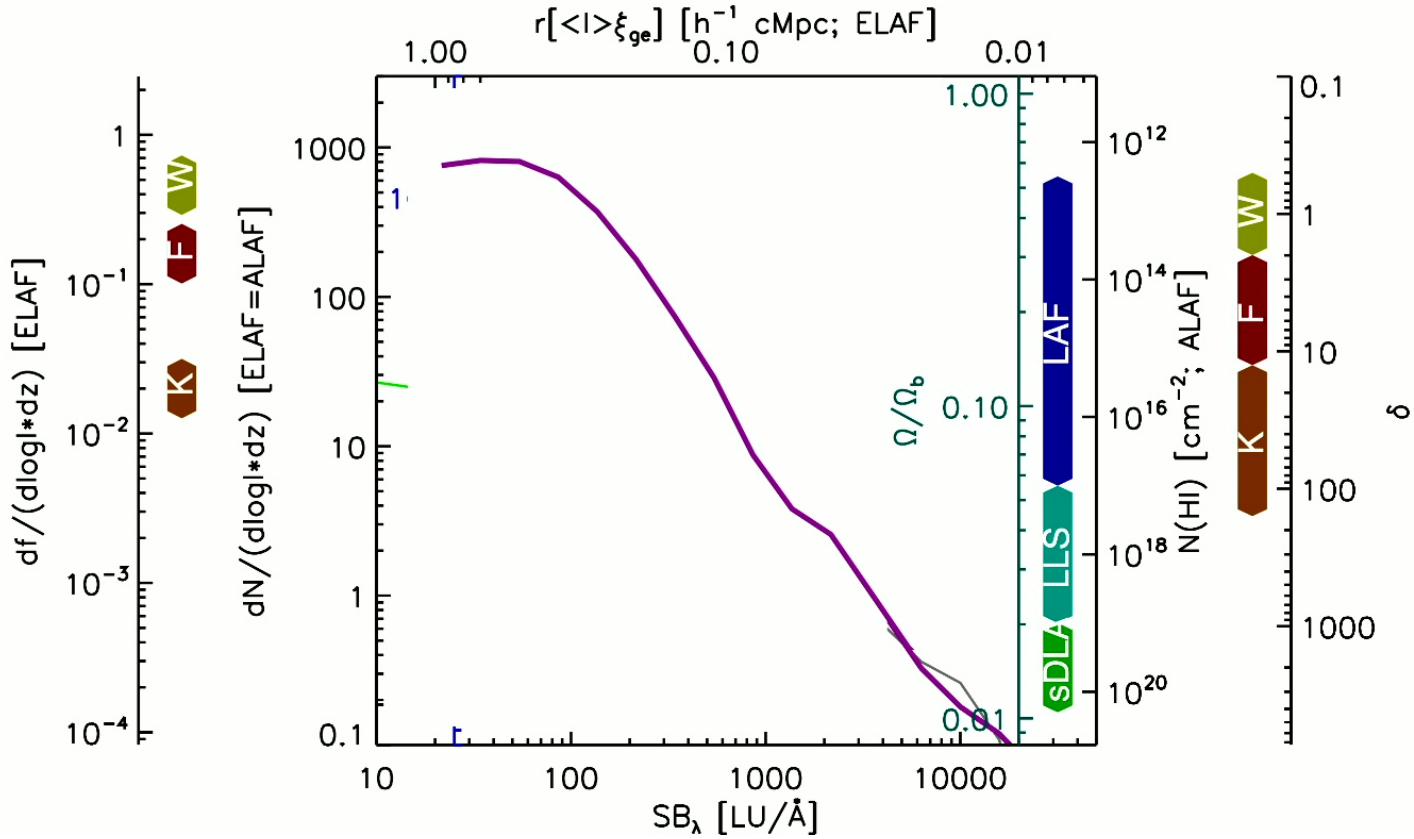
a) Emission correlated with galaxy-traced structure



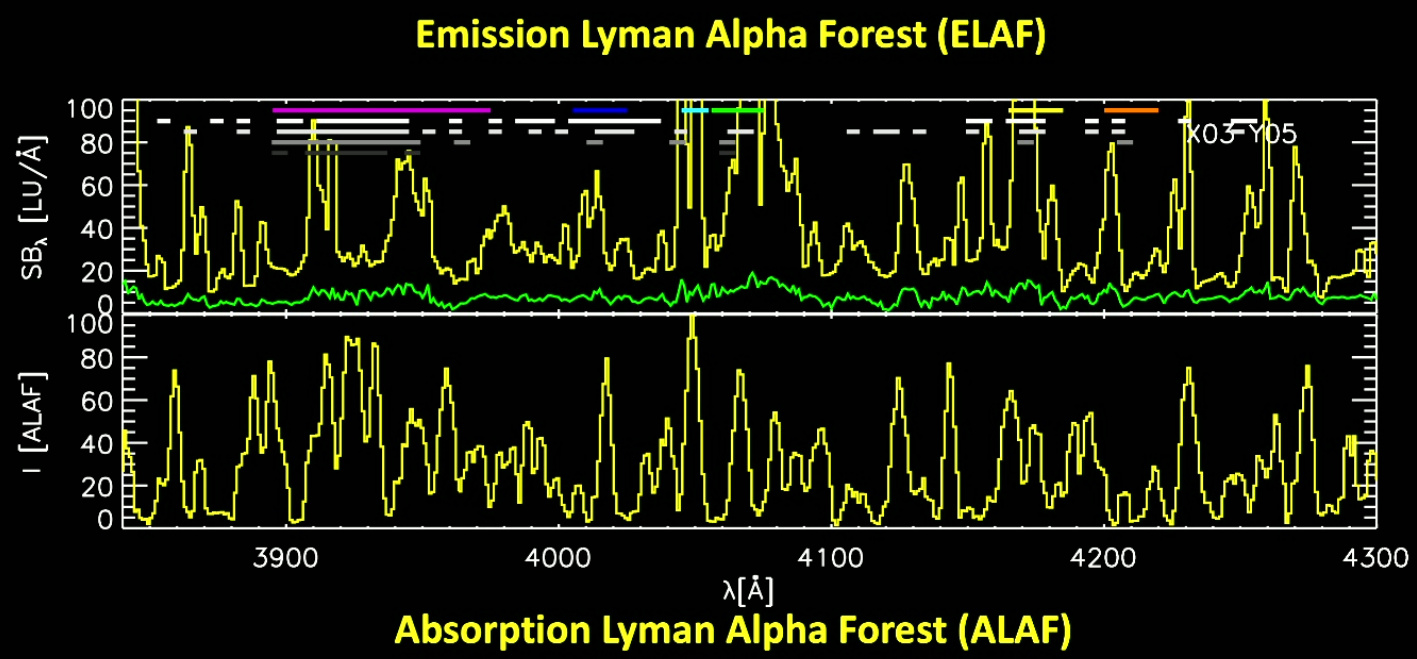
Martin, Darvish, Lin+2023 Nature Astronomy

b) Emission is pervasive: large covering factor Emission LAF ≈ Absorption LAF

Assume: $$\left(\frac{dN}{dlogI*dz}\right)_{ELAF} = \left(\frac{dN}{dlogN_{HI}*dz}\right)_{ALAF}$$

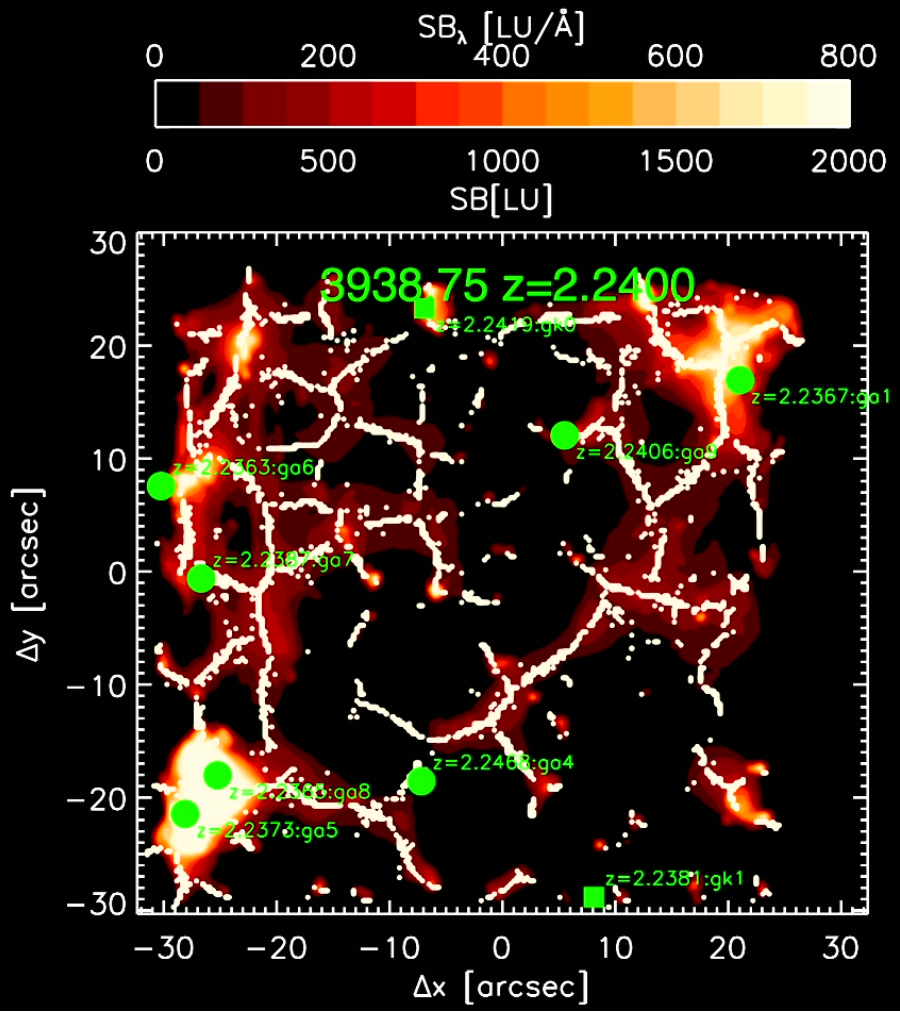


c) Spectra: Absorption LAF ≈ Emission LAF



Martin, Darvish, Lin+2023 Nature Astronomy

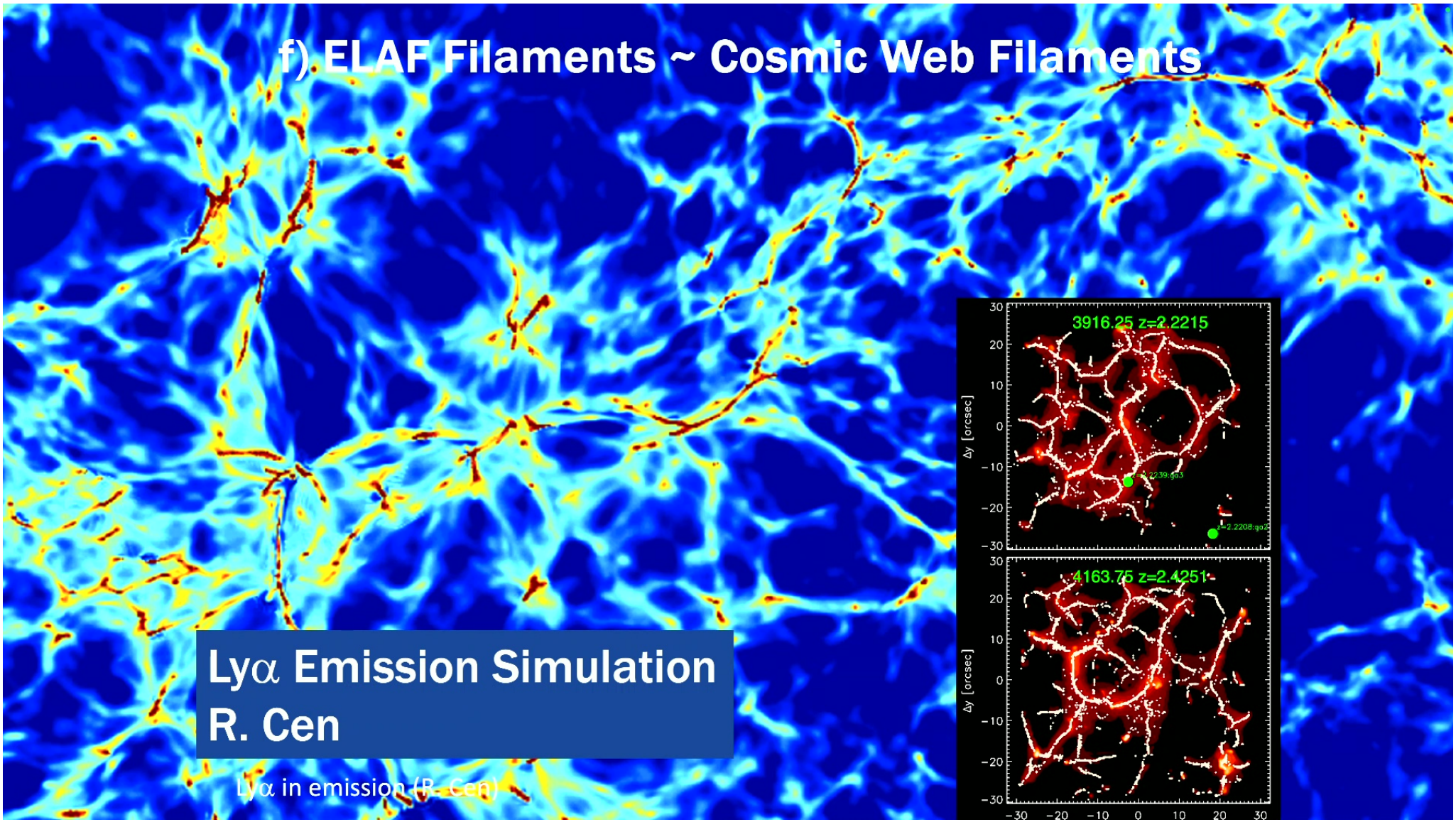
e) Percolation SB ↔ ALAF N(HI) ~ Filaments



30 LU/Å

f_{MAX}=0.53

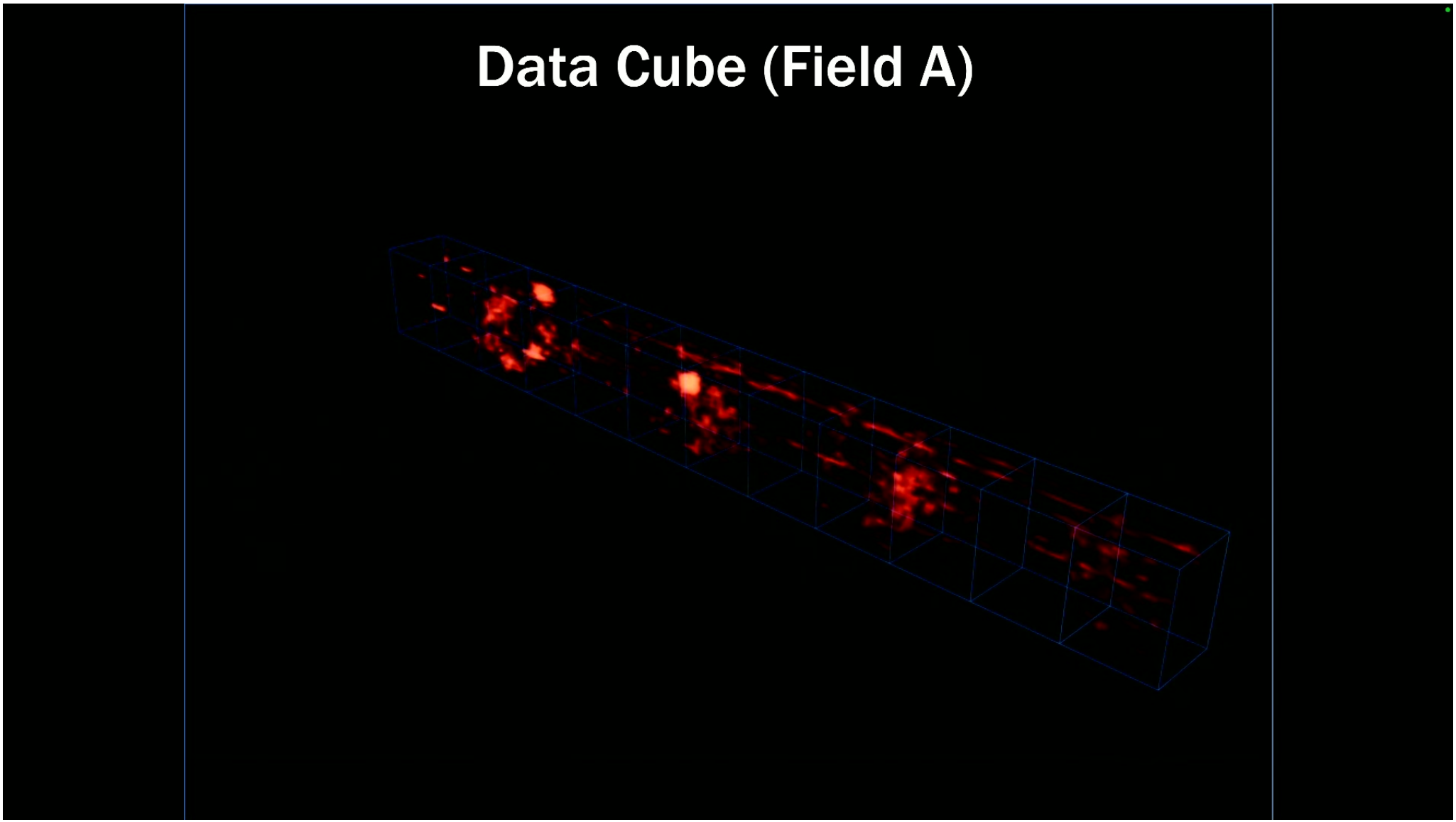
f) ELAF Filaments ~ Cosmic Web Filaments



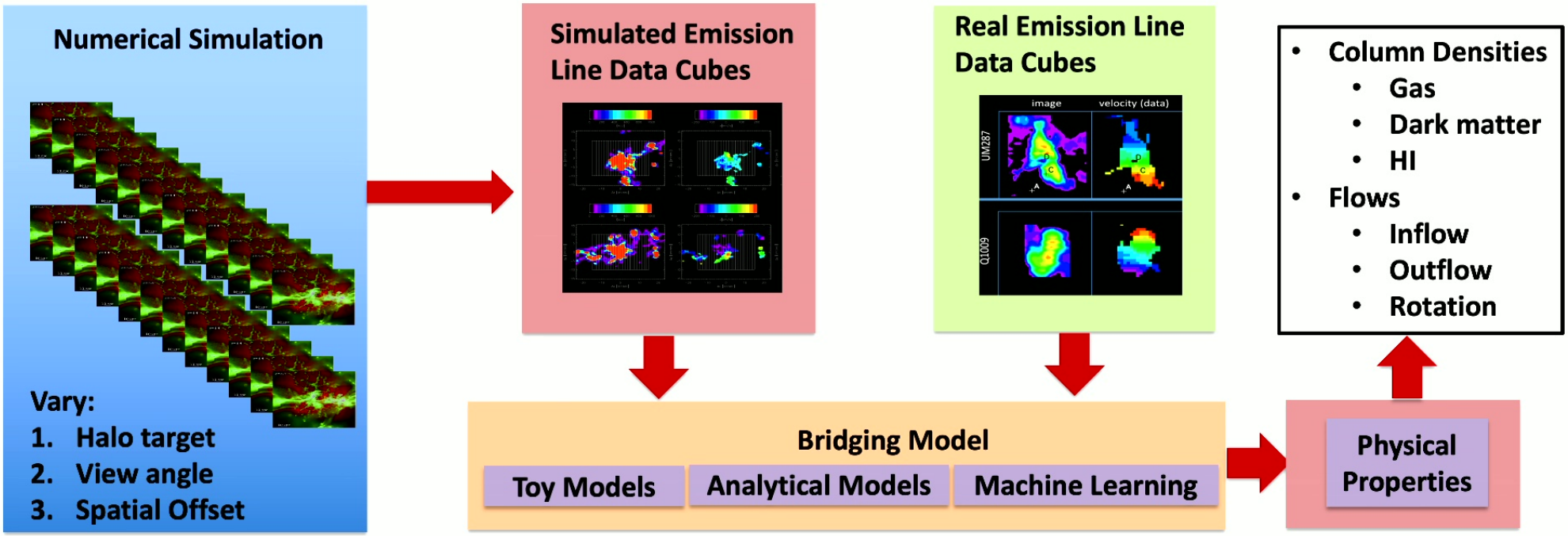
Lyα Emission Simulation
R. Cen

Lyα in emission (R. Cen)

Data Cube (Field A)



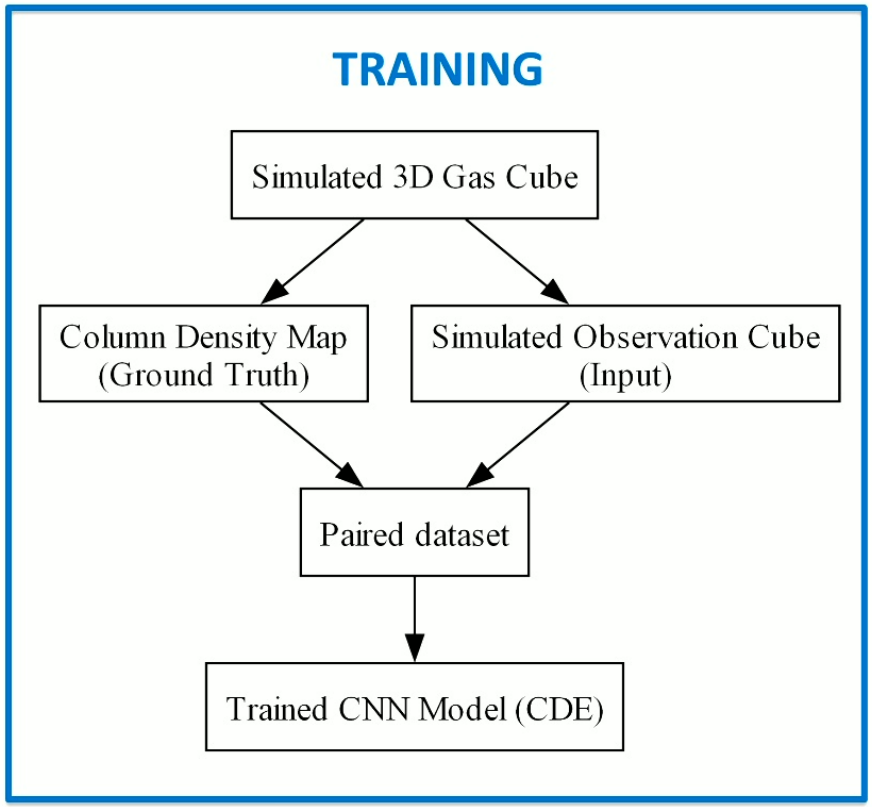
Machine Learning Approach to Derivation of Physical Parameters



Deng+25

h) Machine Learning: Lyα emission → N(H) column density

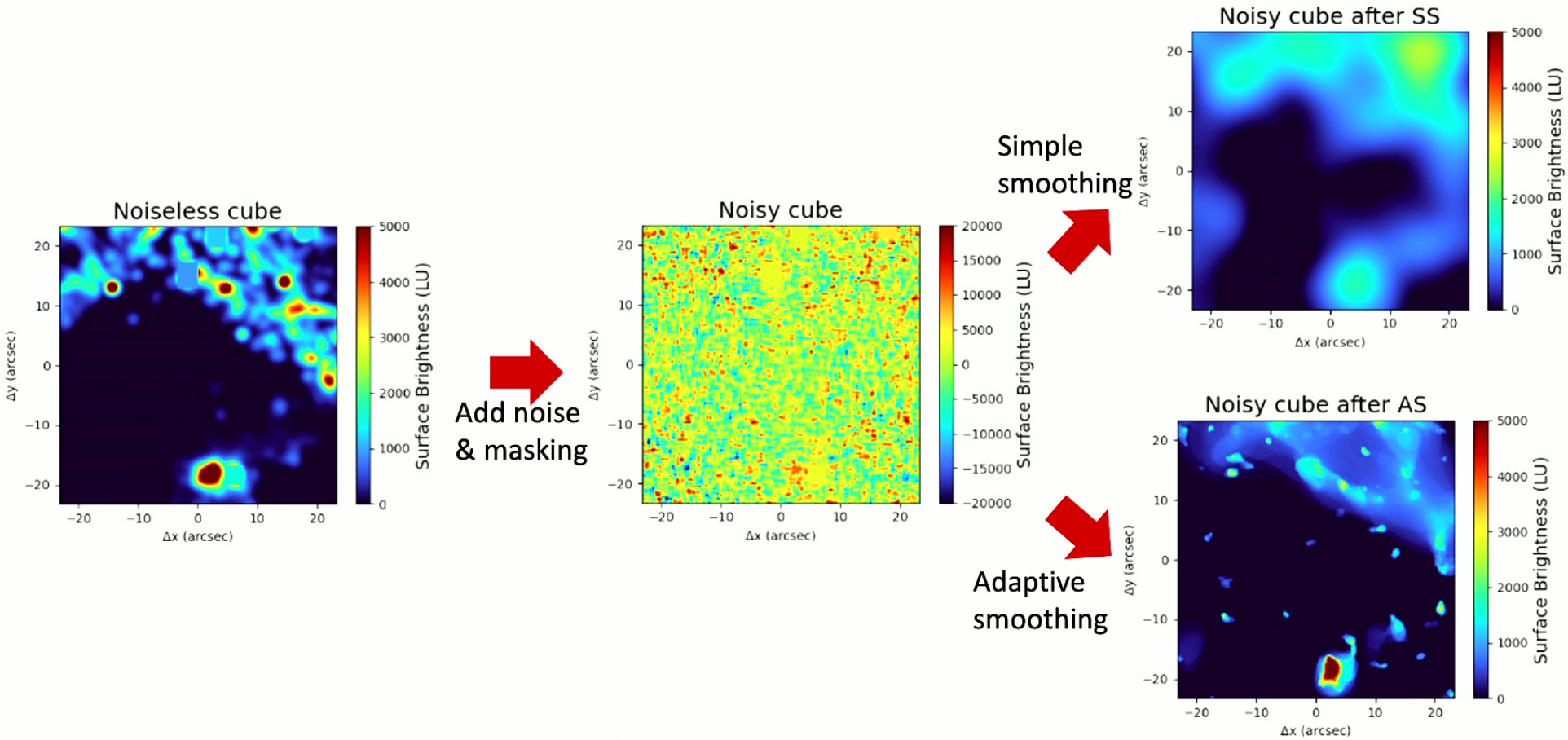
COLUMN DENSITY ESTIMATOR: CDE



Deng+25

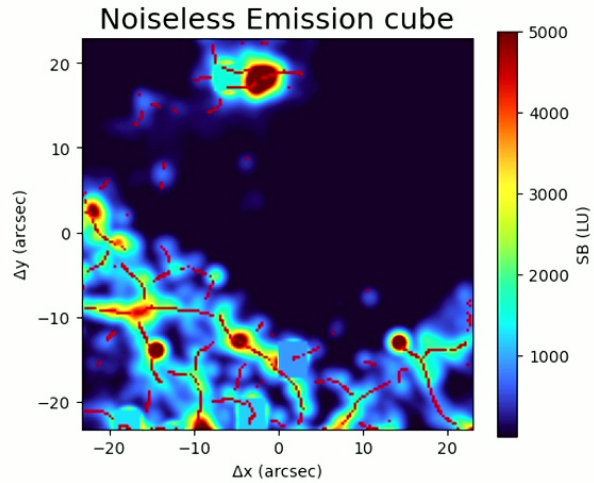
Deng+25

h) Machine Learning: Forward model including analysis

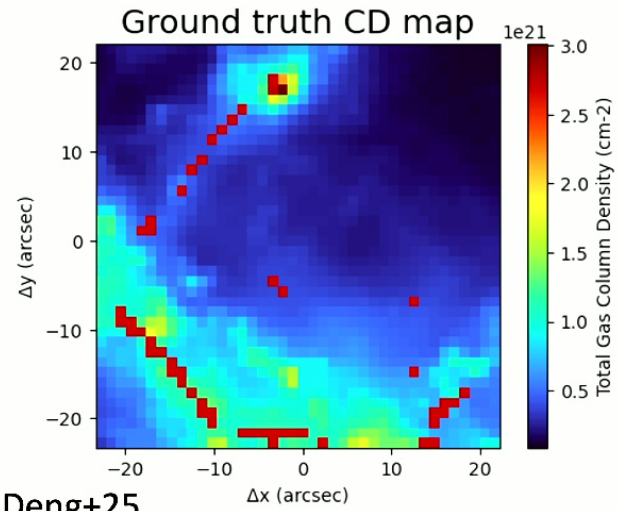


An example of noisy cube smoothing. SS (Simple Smoothing) smooths the noisy cube with a fixed spatial Gaussian kernel of FWHM ≈ 9″, while AS (Adaptive Smoothing) adjusts the smoothing scale based on local SNR.

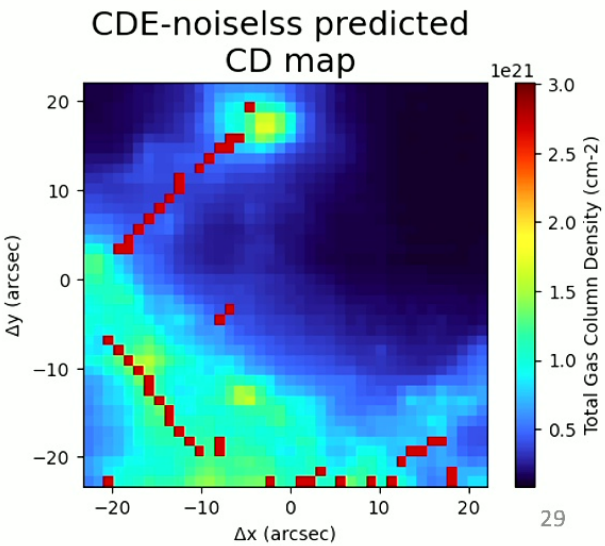
CDE Proof of Concept



Predict by CDE-noiseless



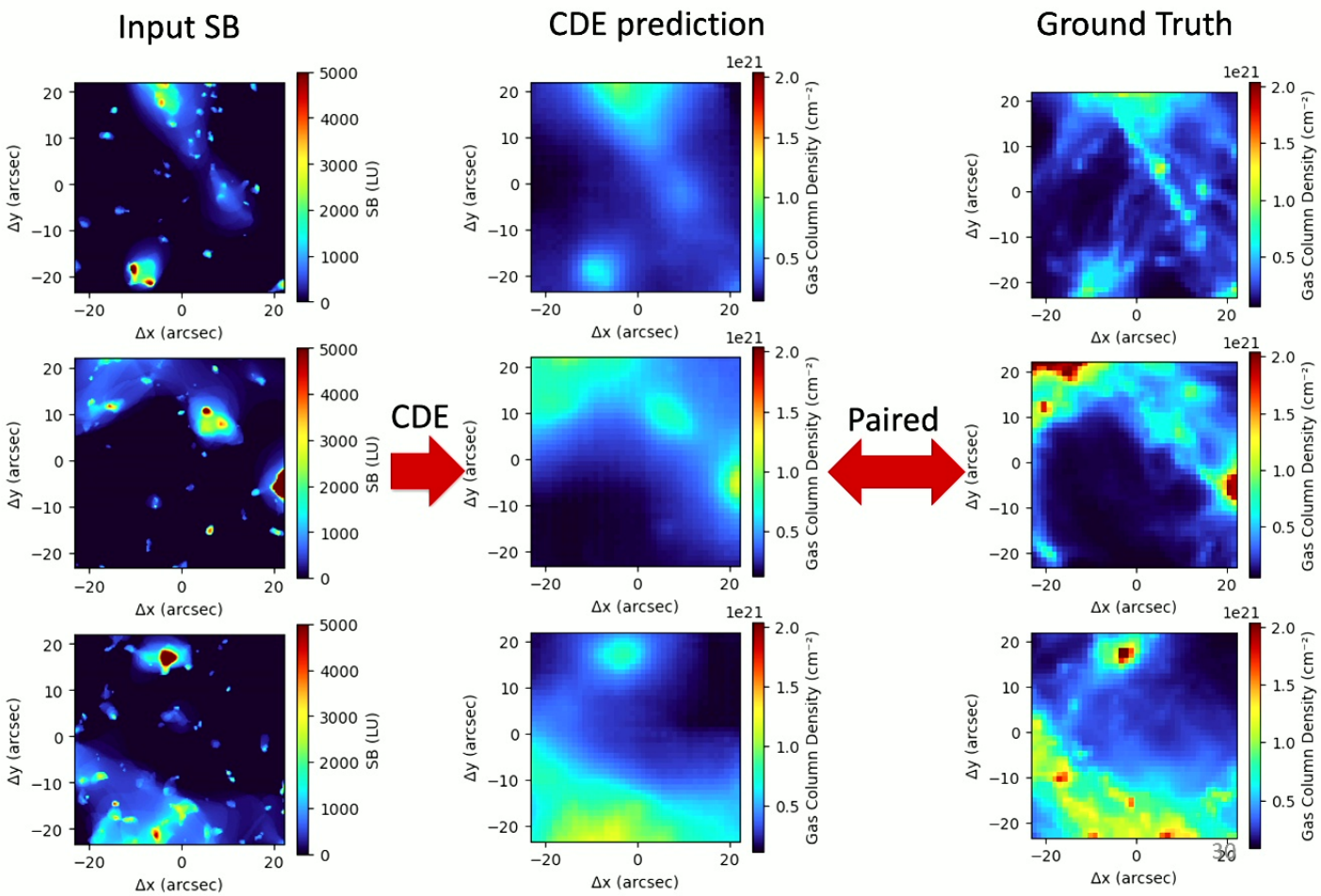
Prediction very similar to ground truth



Deng+25

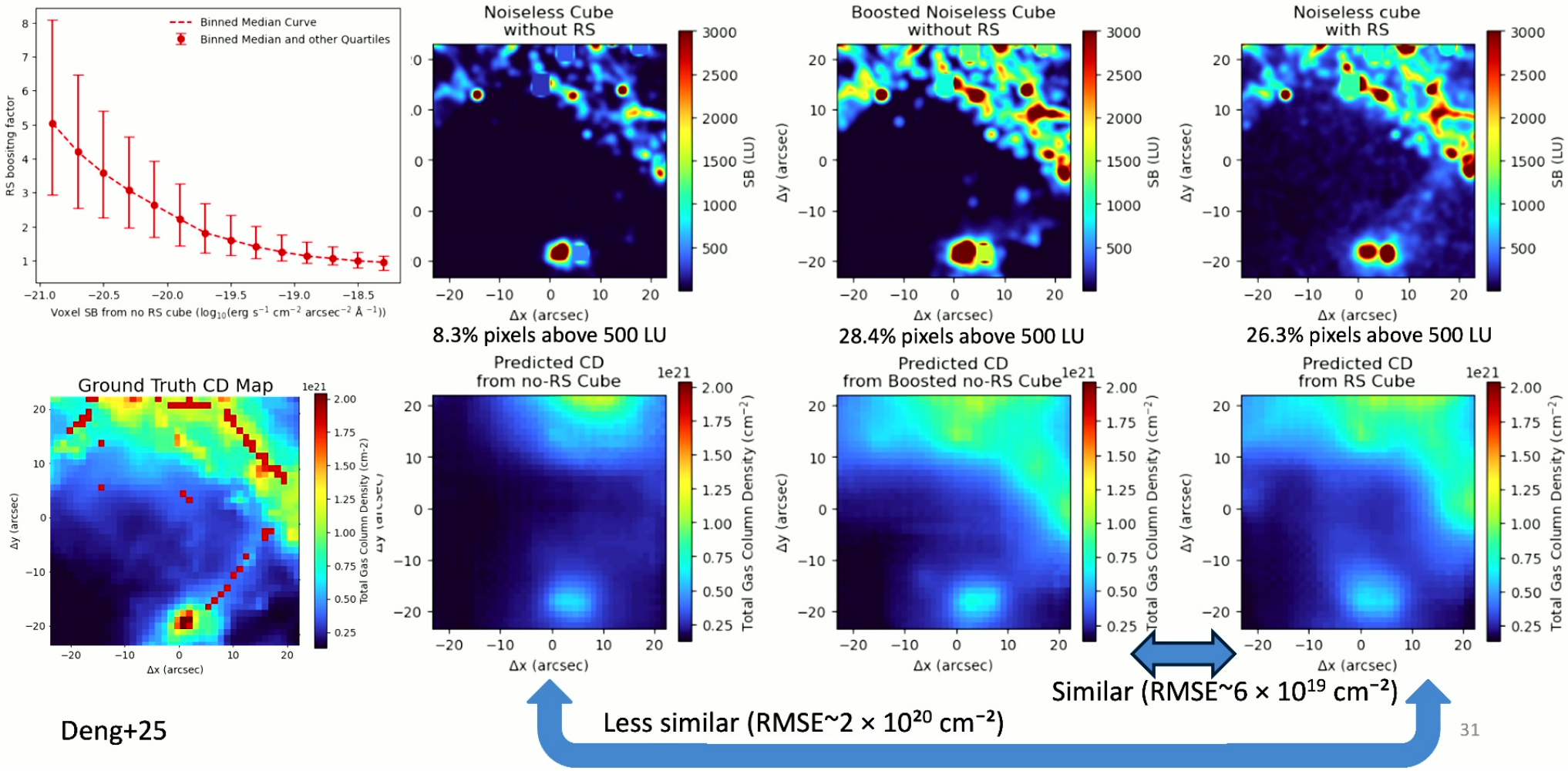
29

Column Density Estimator (CDE)



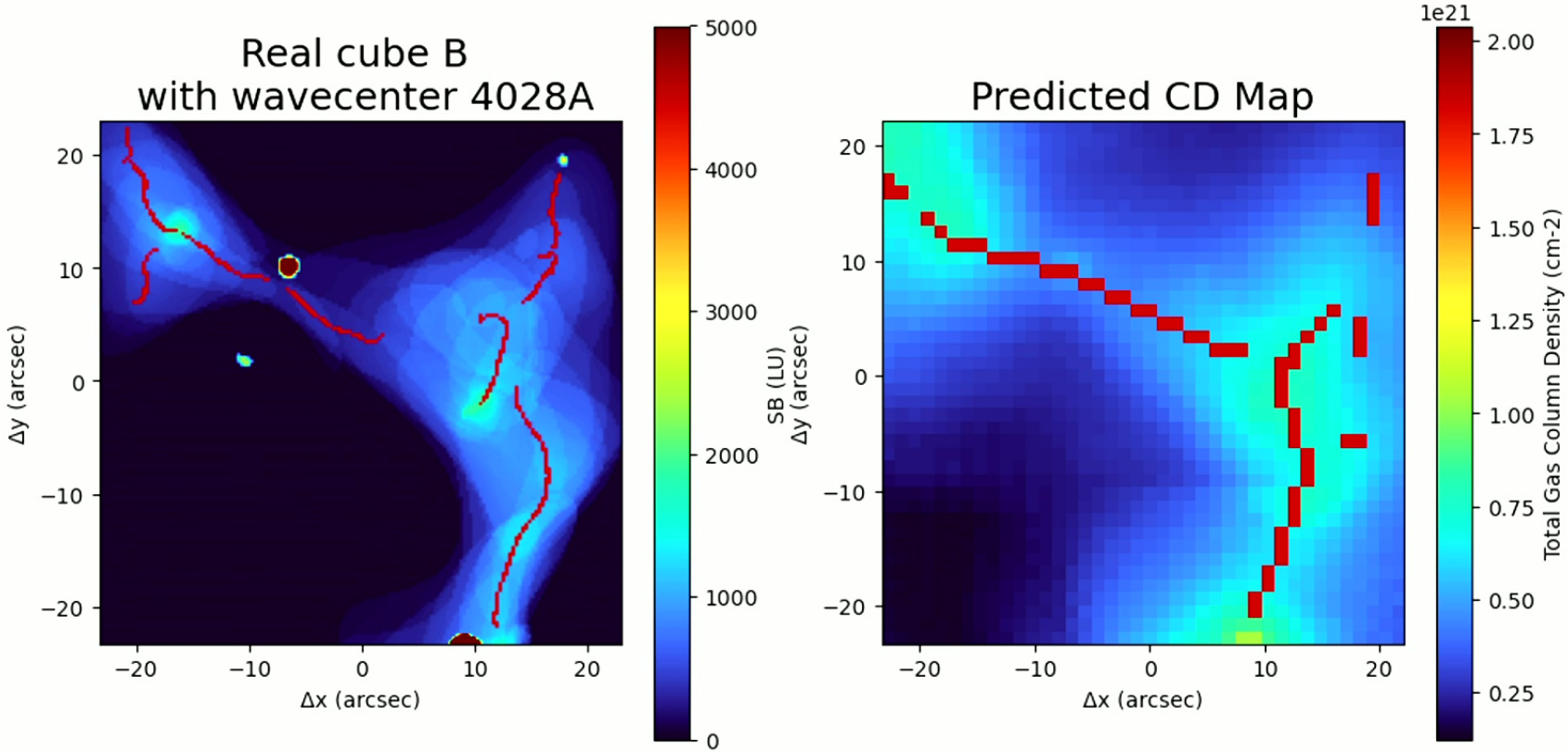
Deng+25

CDE: Impact of Lyα Resonant Scattering



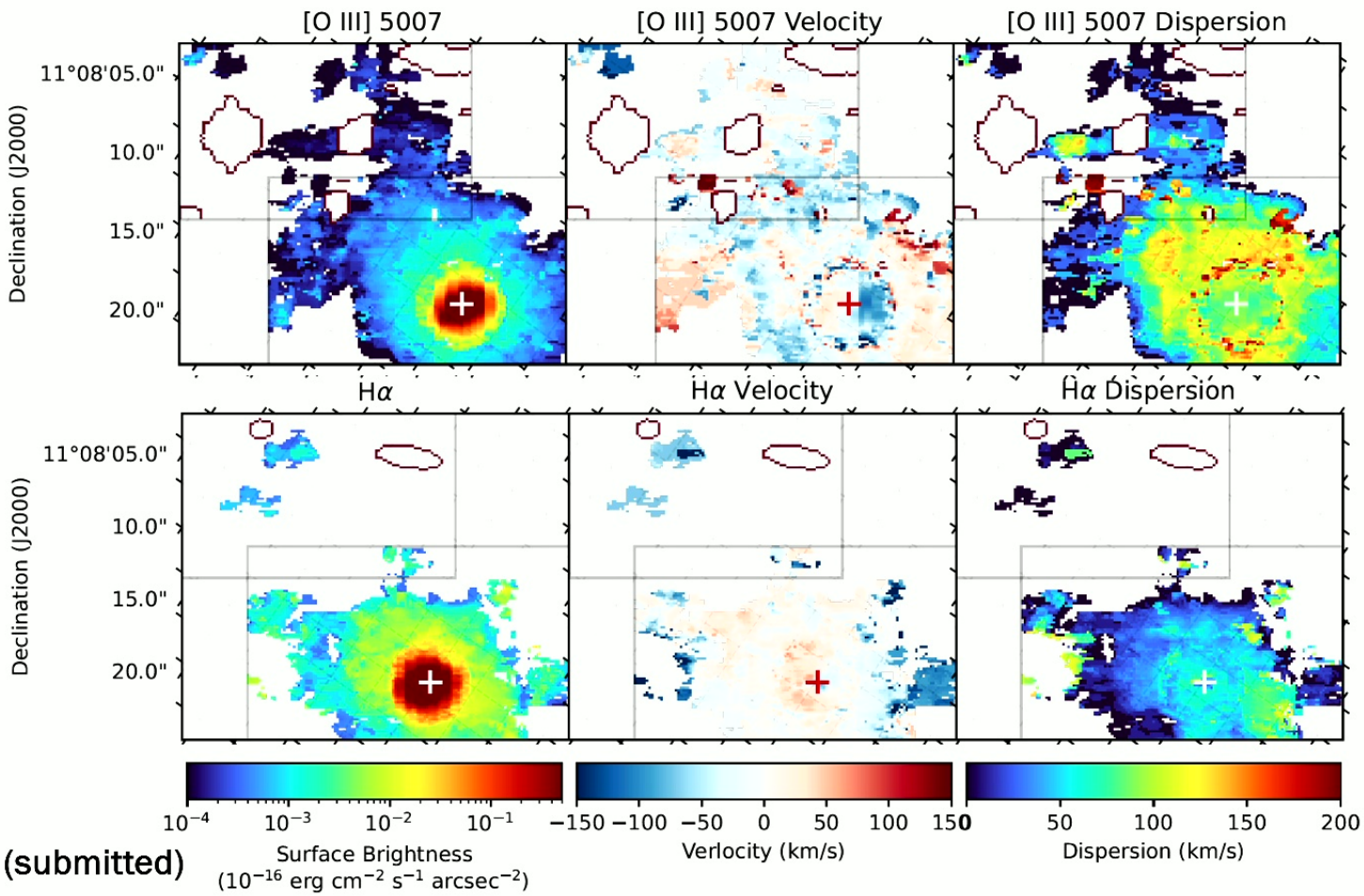
Deng+25

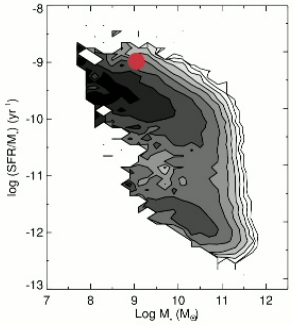
h) Machine Learning: Lyα emission → N(H) column density



Deng+25

III. Low Redshift CGM: J0359b





Lin+2025 (submitted)

III. Low Redshift CGM: J0359b
Derived Parameters

Schematic: Baryon Cycle in J0910b

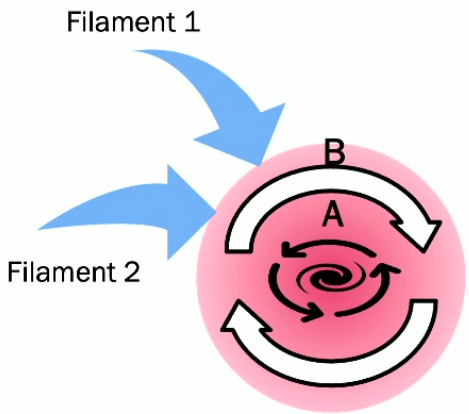


Table 4. CLOUDY-Derived Parameters for CGM Components in J0910b

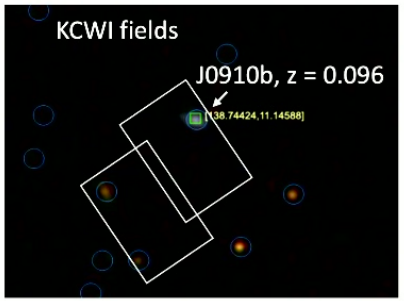
Region	$\log n_{\rm H}$ [cm^{-3}]	UV Boost[a]	$Z/Z_\odot$	$\log N(\rm H)$ [cm^{-2}]
Counter-Rotating CGM				
Point A	-1.16 ± 0.08	46^{+7}_{-6}	$0.20^{+0.05}_{-0.04}$	20.3 ± 0.5
Point B	-2.34 ± 0.07	$5.0^{+0.7}_{-0.6}$	$0.7^{+0.2}_{-0.3}$	20.3 ± 0.5
Filamentary Inflow				
Filament 1	$-3.80^{+0.07}_{-0.09}$	$0.52^{+0.08}_{-0.07}$	0.07 ± 0.01	$21.6^{+0.6}_{-0.7}$
Filament 2	$-2.87^{+0.07}_{-0.08}$	1.0 ± 0.1	0.26 ± 0.06	20.8 ± 0.8

[a]UV Boost is the ionizing photon field strength relative to the MUVB.

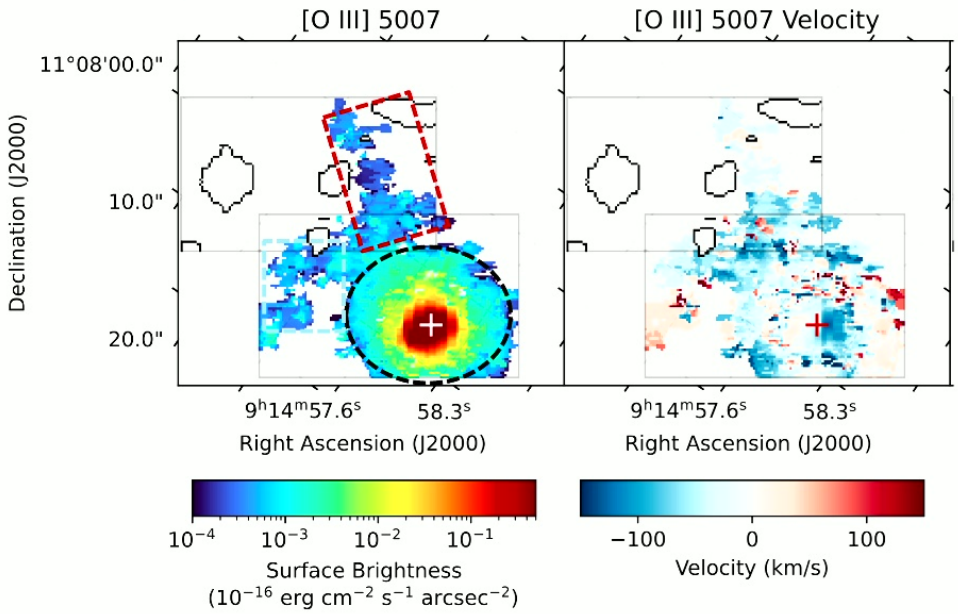
NOTE—Uncertainties reflect 68% confidence intervals from MCMC posterior distributions.

Lin+2025 (submitted)

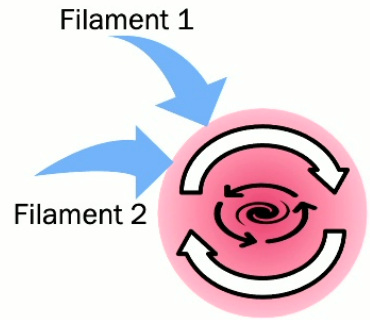
III. Low Redshift CGM: J0359b Interpretation



Counter-Rotating CGM
Filament 1
Filament 2



Schematic: Baryon Cycle in J0910b



Filament 1

- Temperature ~ 10^4 K
- Mass ~ 1 x 10^7 $M_\odot$ (~ 0.008 $M_\star$)
- Specific angular momentum 3.7 x 10^3 kpc km/s
- Metallicity 0.07 $Z_\odot$
- Accretion rate 0.05 $M_\odot$/yr

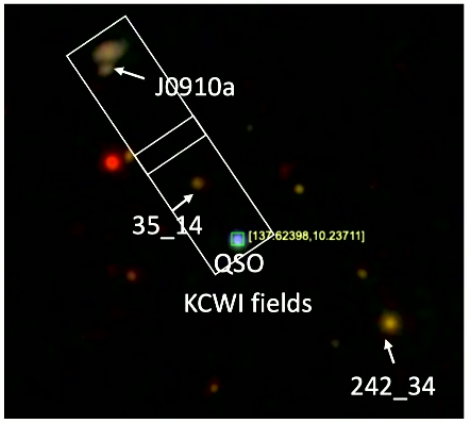
Counter-Rotating CGM

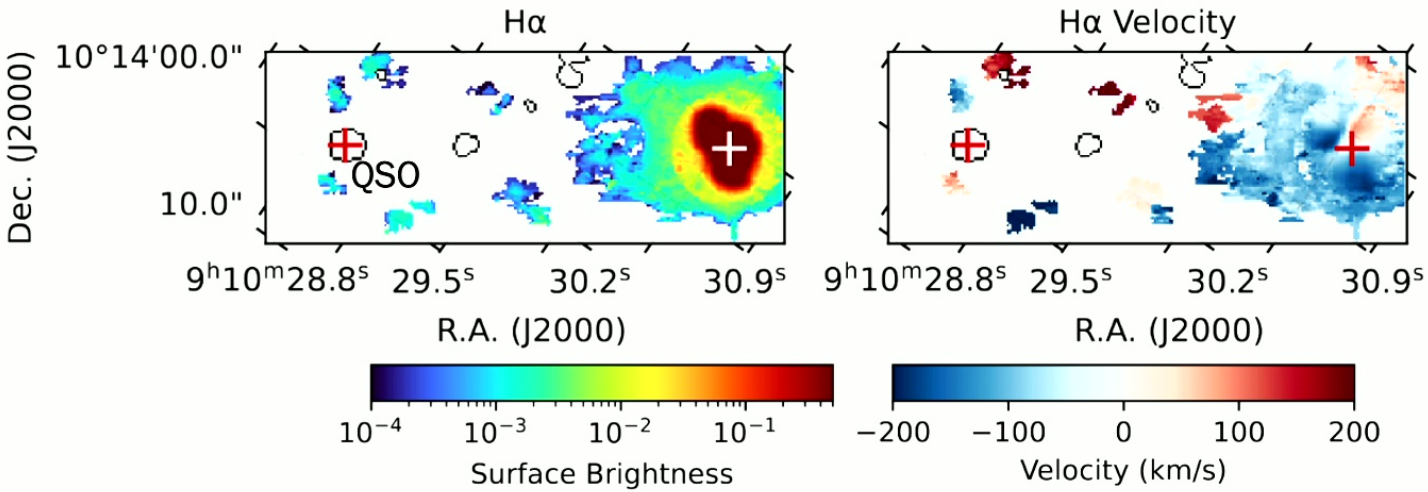
- Temperature ~ 10^4 K
- Mass ~ 7 x 10^9 $M_\odot$ (~ 5 $M_\star$)
- ~33 % of the total baryons expected from the halo mass (~ 10^{11} $M_\odot$)
- Metallicity 0.2 $Z_\odot$ at 9 kpc to 0.65 $Z_\odot$ at 16 kpc
- Cooling time 0.3-2 Myr

Lin+2025 (submitted)

Part 2

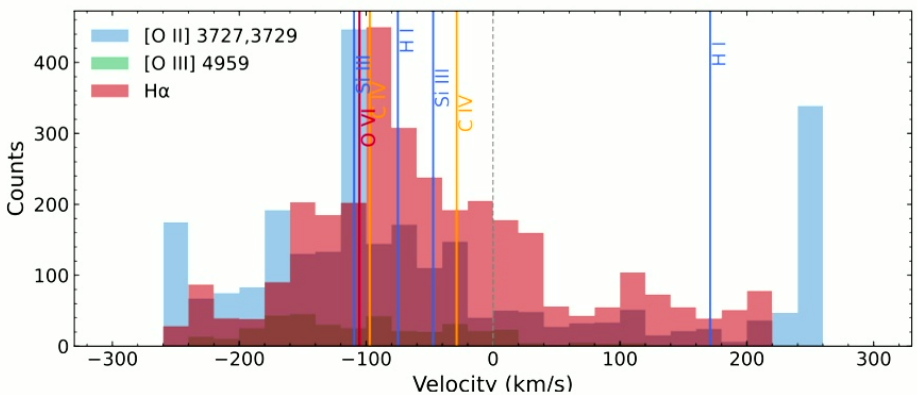
III. Low Redshift CGM: COS-Halos Galaxy





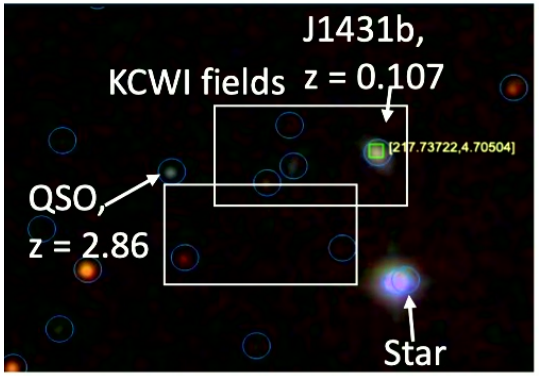
Lin+2025 (in prep)

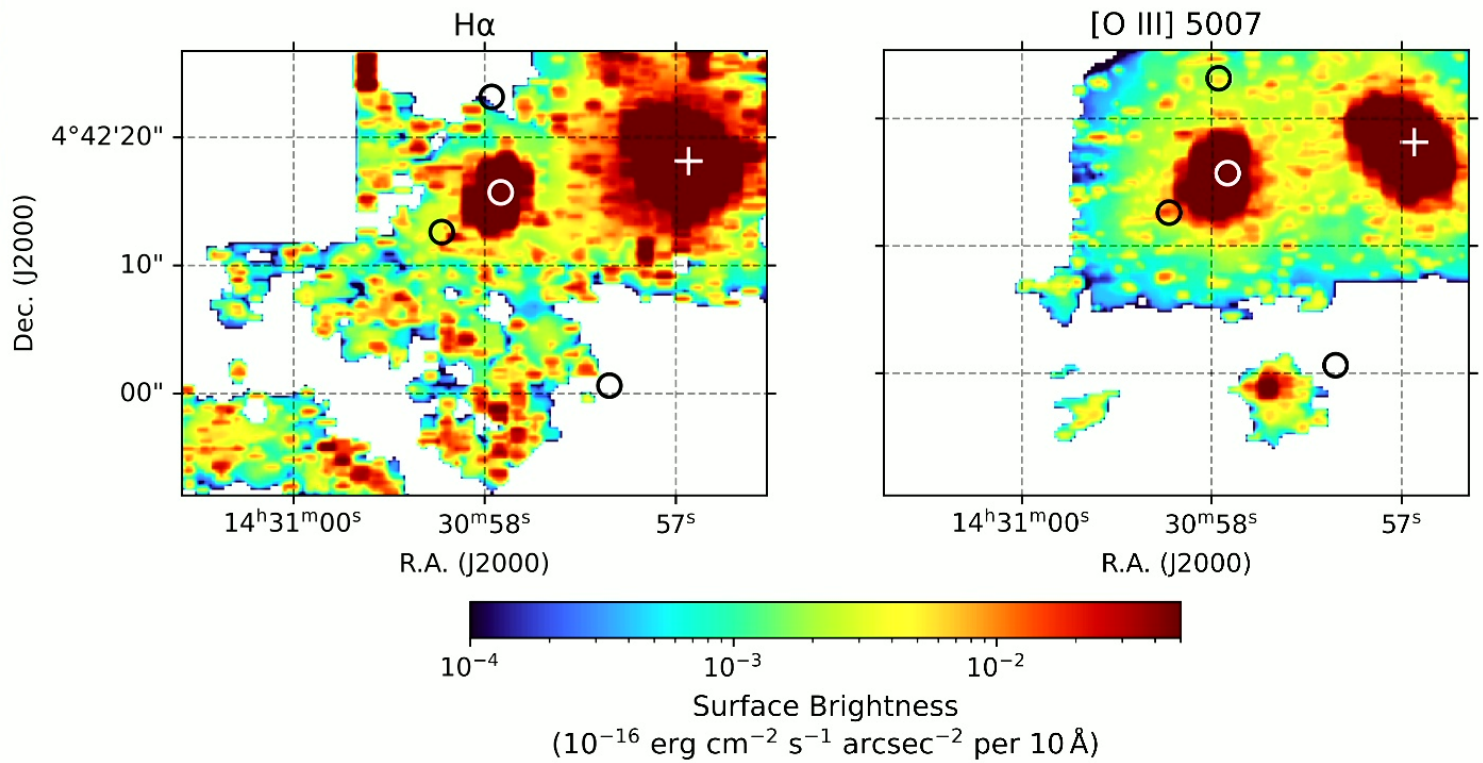
Velocity distribution (ISM-excluded) aligns with COS-Halos absorption



Lin+25b

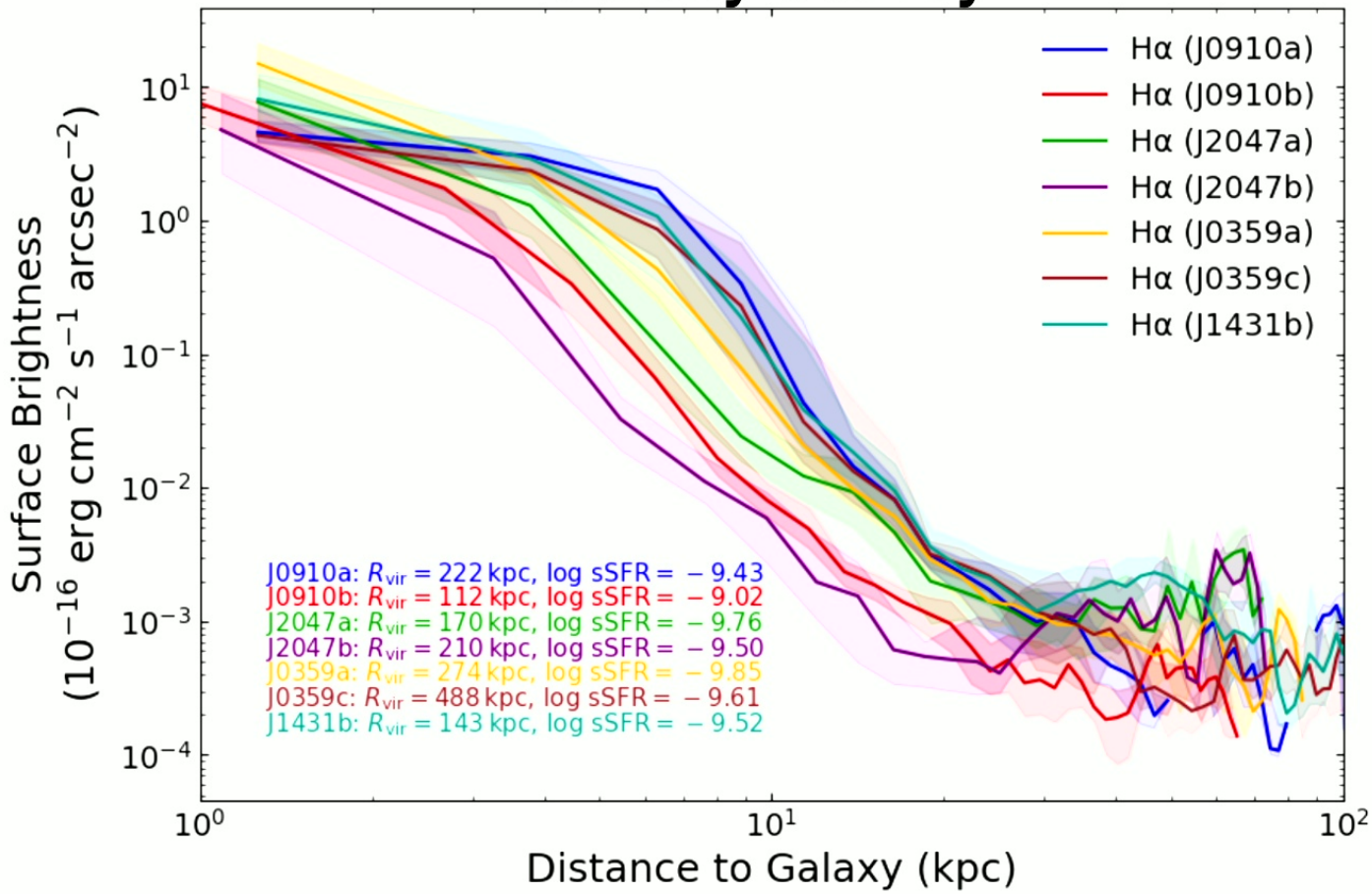
III. Low Redshift CGM
High Mass Galaxy with Satellites





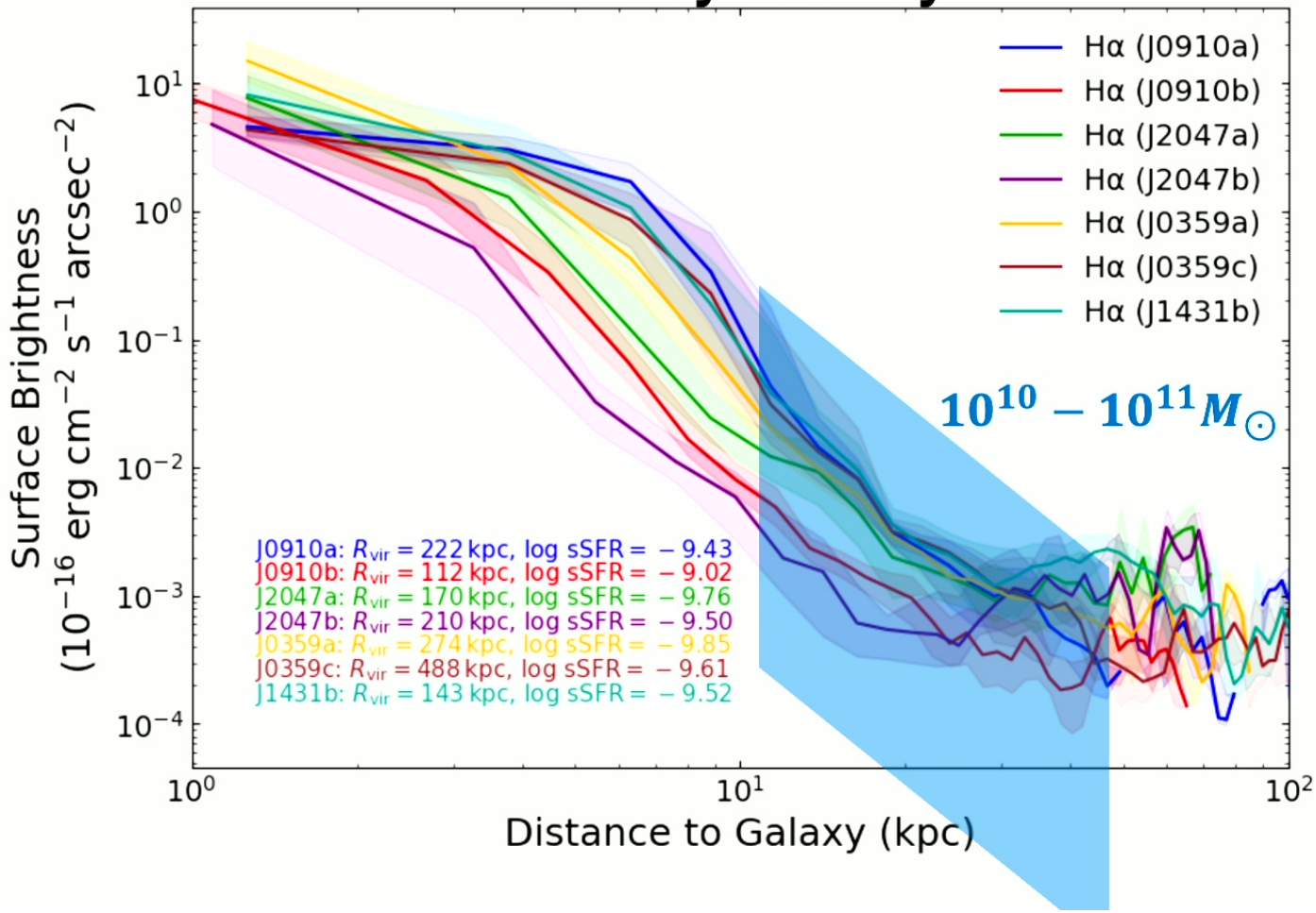
Lin+25b

III. Low Redshift CGM Galaxy Survey



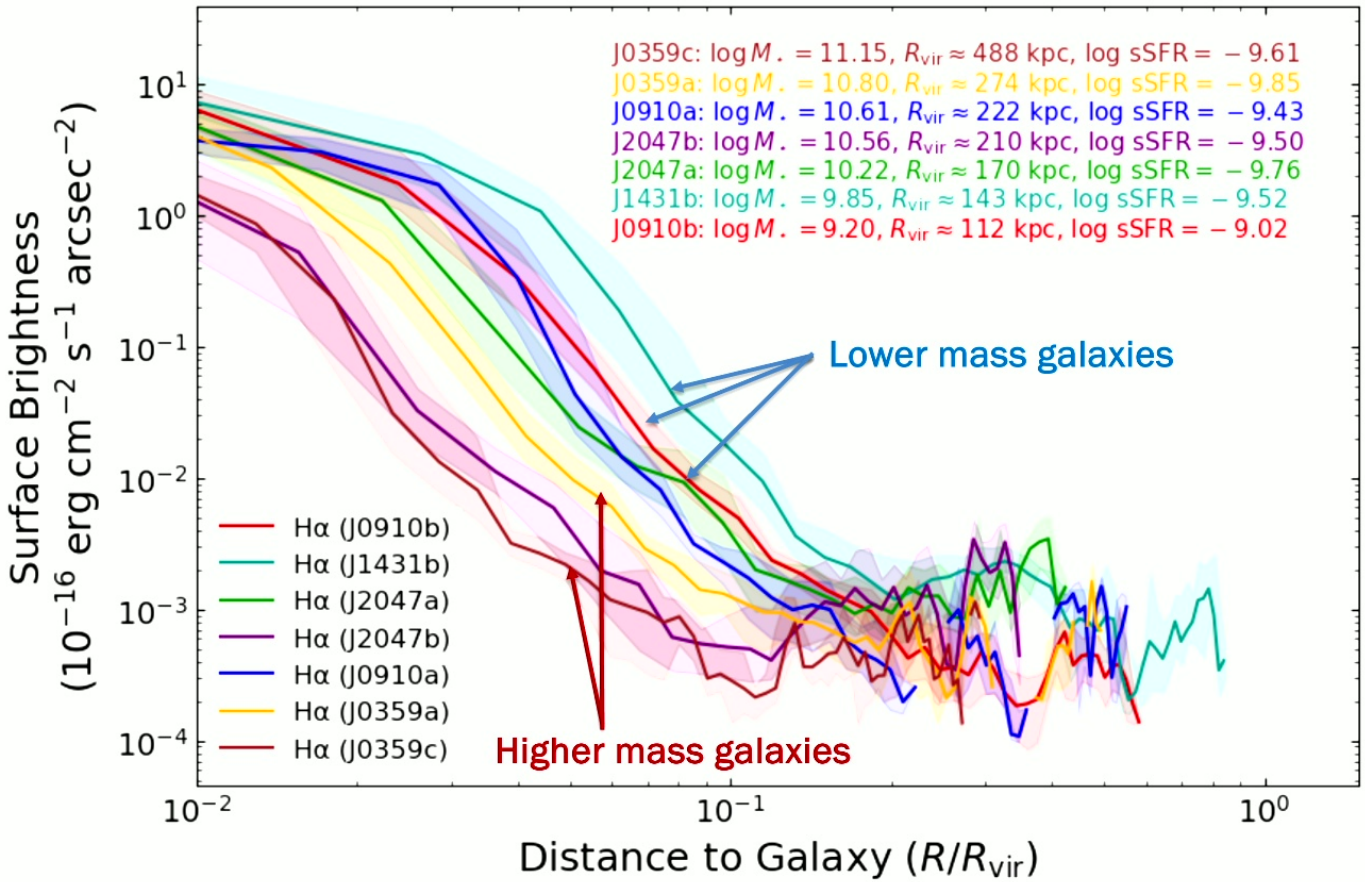
Lin+25b

III. Low Redshift CGM Galaxy Survey



Lin+25b

III. Low Redshift CGM Galaxy Survey



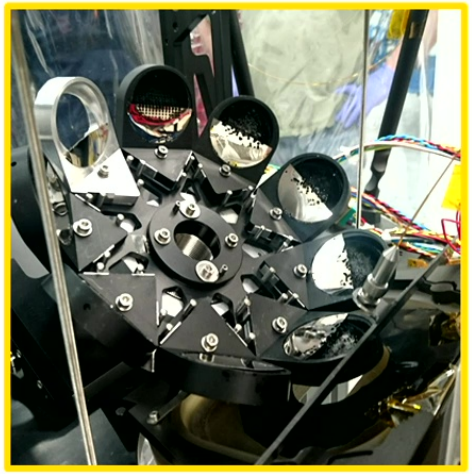
Lin+25b

III. Low Redshift CGM: Lyα
FIREBall-2 Spectrograph

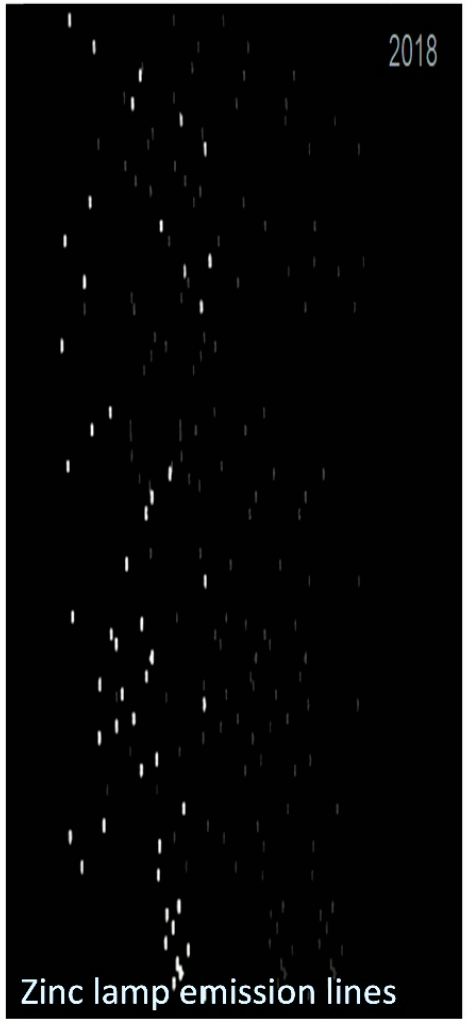
UV Multi-Object Spectrograph

- Multi-Object slit mask- Up to 50 targets per field
- Field Corrector- FOV = 35 arcmin diameter
- 4 arcsec resolution
- R=2150, 2000-2010 Å, $\Delta\lambda$=1Å
- Electron Multiplying CCD detector
- >5 % overall system throughput

Multislit Mask Carousel



Multislit Mask Spectra



Zinc lamp emission lines (Picouet+ 2020)

Picouet+ 2020

III. Low Redshift CGM/IGM: Lyα

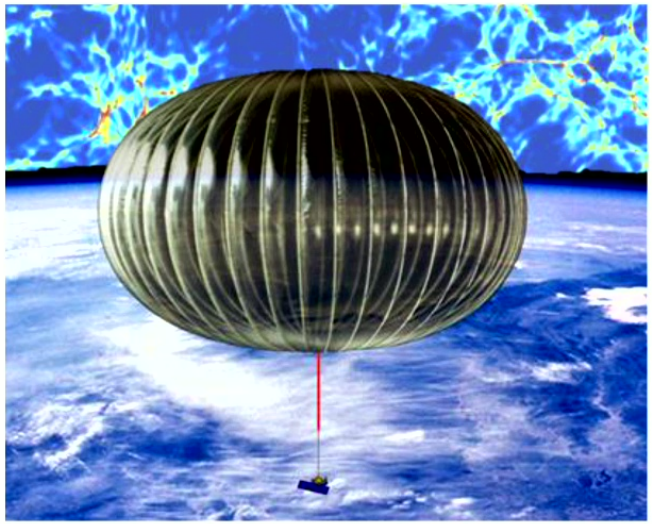
Super-pressure Cosmic Web Imager (SCWI)

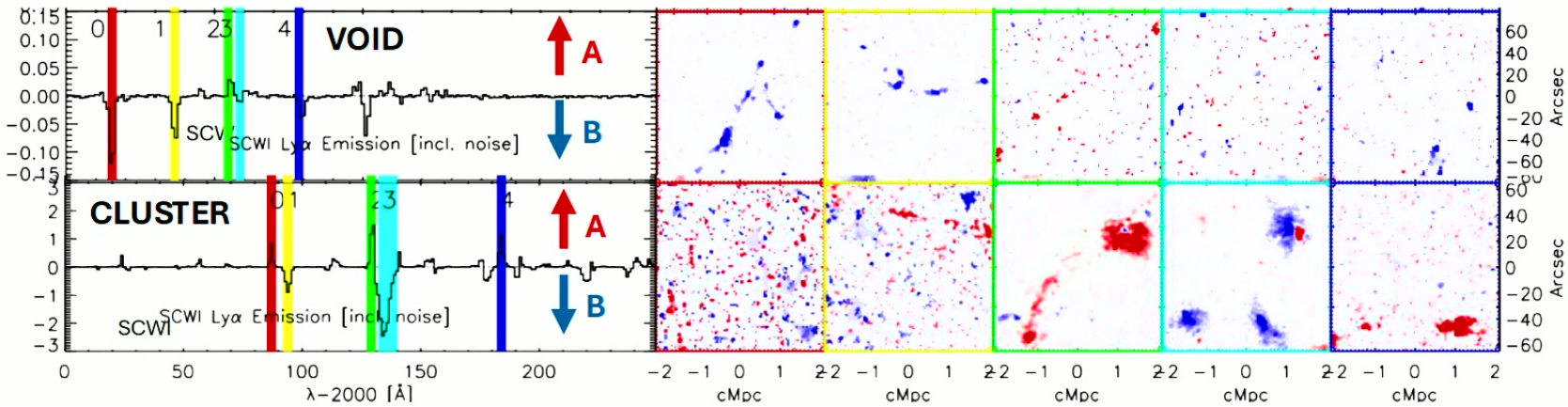
- Telescope 50 cm
- Integral Field Spectrograph (reflective image slicer): 120” x 120”, 5” slice
- Bandpass: 2000-2200Å, z(Lyα)~0.7
- Detector: EMCCD or qCCD
- ***Mission length: 50-100 days!***
- Funding sources: Various
- ***Science goal: Detecting Cosmic Web in emission at z=0.7; CGM/CQM halo survey***

III. Low Redshift CGM: Lyα — SCWI

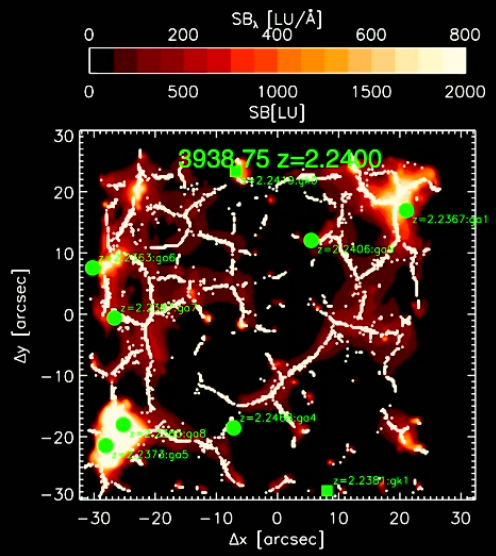
b. SCWI Science Program

Science Goal	Observation Plan (min [goal])
O1a. CQM survey z~0.7	3 [5] CQM-Lyα targets
O1b. CGM survey z~0.7	10 [18] CGM-Lyα targets
O1c. CQM/CGM metal lines (CIII, CIV, OVI, H_2)	2 [4] galaxy/galaxy group targets
O2/O3. Deep cosmic web in two 4 arcmin x 4 arcmin fields	15 [20] nights targets A & B, mosaic 4 x 2 arcmin x 2 arcmin = 32 arcmin^2
Margin	2 [3] nights Calibration/inefficiency



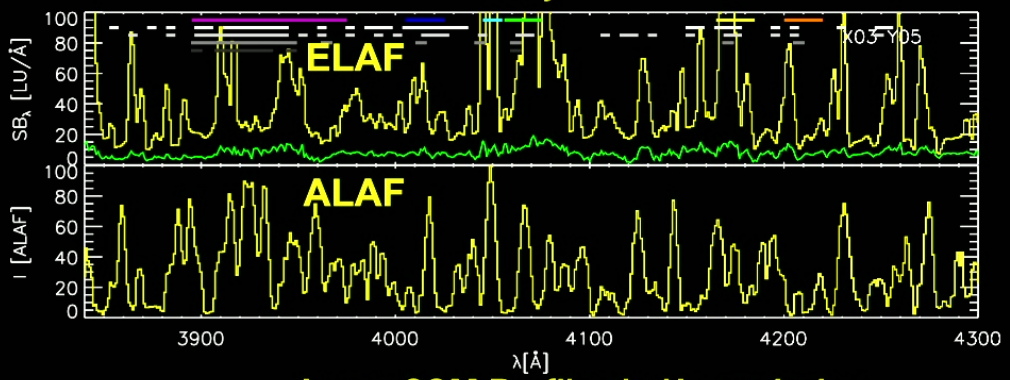
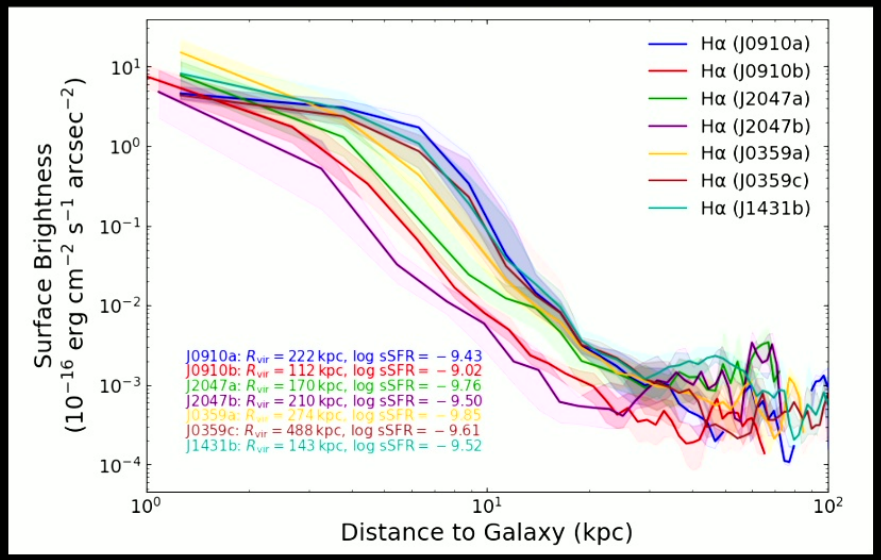


Summary



Super-pressure Cosmic web Imager (SCWI)

Emission Lyα forest



Low z CGM Profiles in Hα emission