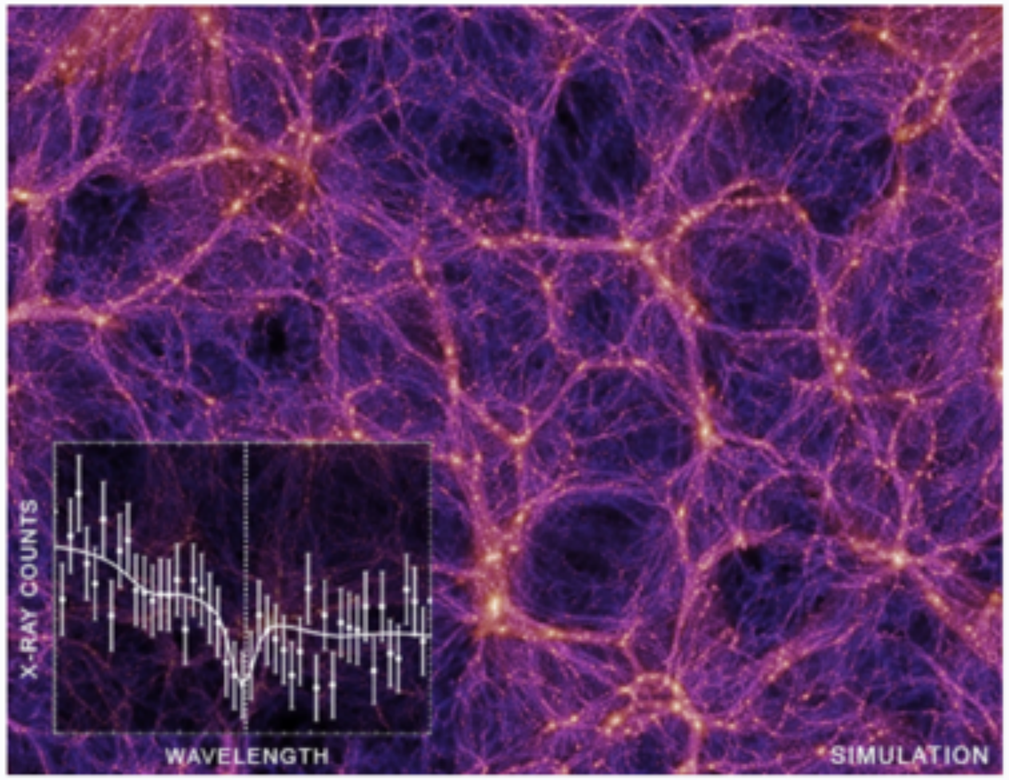
Detecting the missing baryons using X-ray absorption studies

Orsolya Kovács, Akos Bogdán, Randall Smith, Ralph Kraft, William Forman

Kovács, Bogdán, et al., ApJ, 872, 83

Where is the Universe Hiding its Missing Mass?



- **The Universe's "missing mass" may have been found, according to a new study using Chandra data.**
- **About a third of the "normal" matter (ie, hydrogen, helium, and other elements) created shortly after the Big Bang is not seen in the present-day Universe.**
- **One idea is that this missing mass is today in filaments of warm and hot gas known as the WHIM.**
- **Researchers suggest evidence for the WHIM is seen in absorption features in X-rays collected from a quasar billions of light years away.**

The Basics

What is it?
How Far Away is it?
How is it Made?
Where is it Located?

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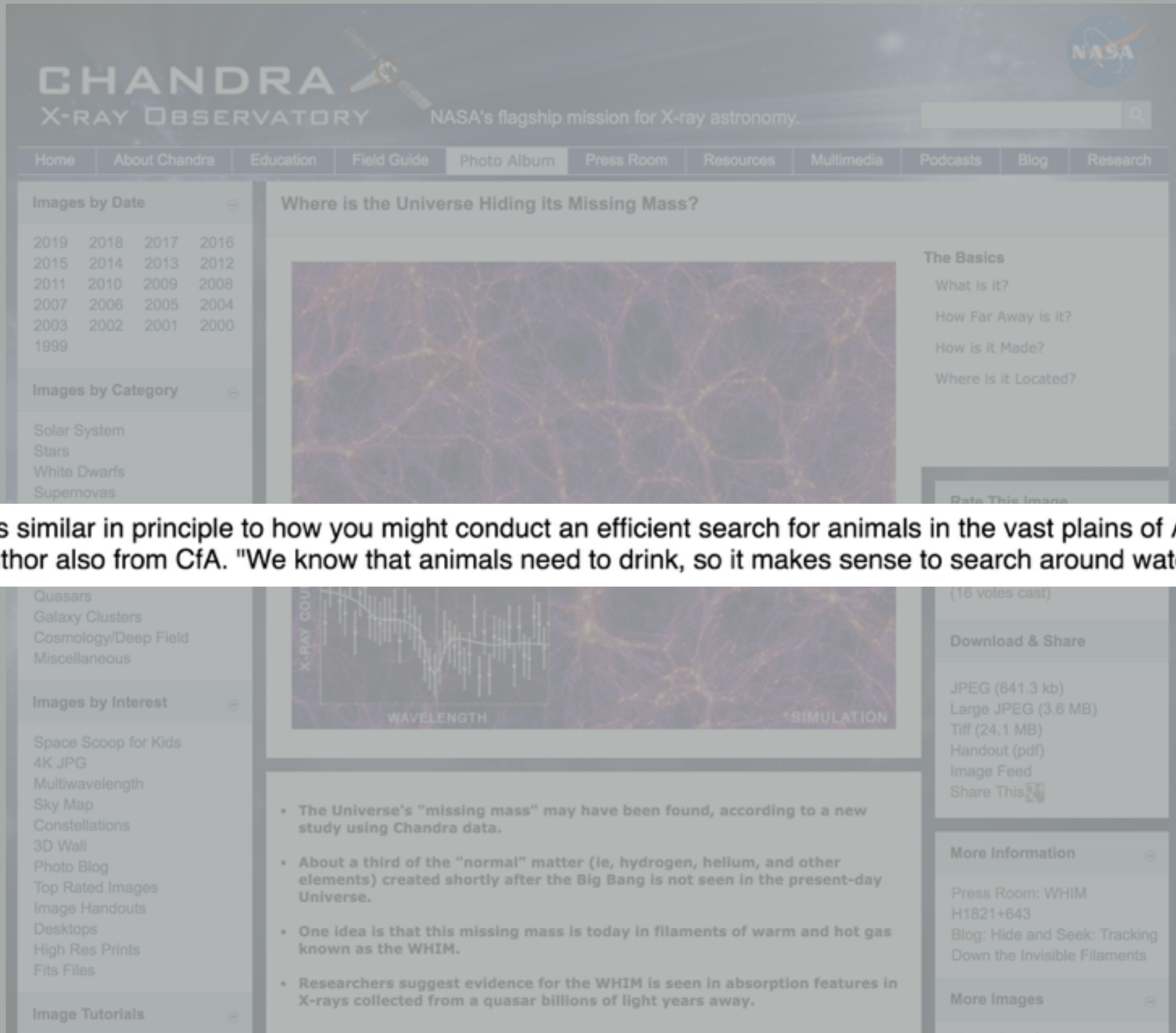

"Our technique is similar in principle to how you might conduct an efficient search for animals in the vast plains of Africa," said Akos Bogdan, a co-author also from CfA. "We know that animals need to drink, so it makes sense to search around watering holes first."

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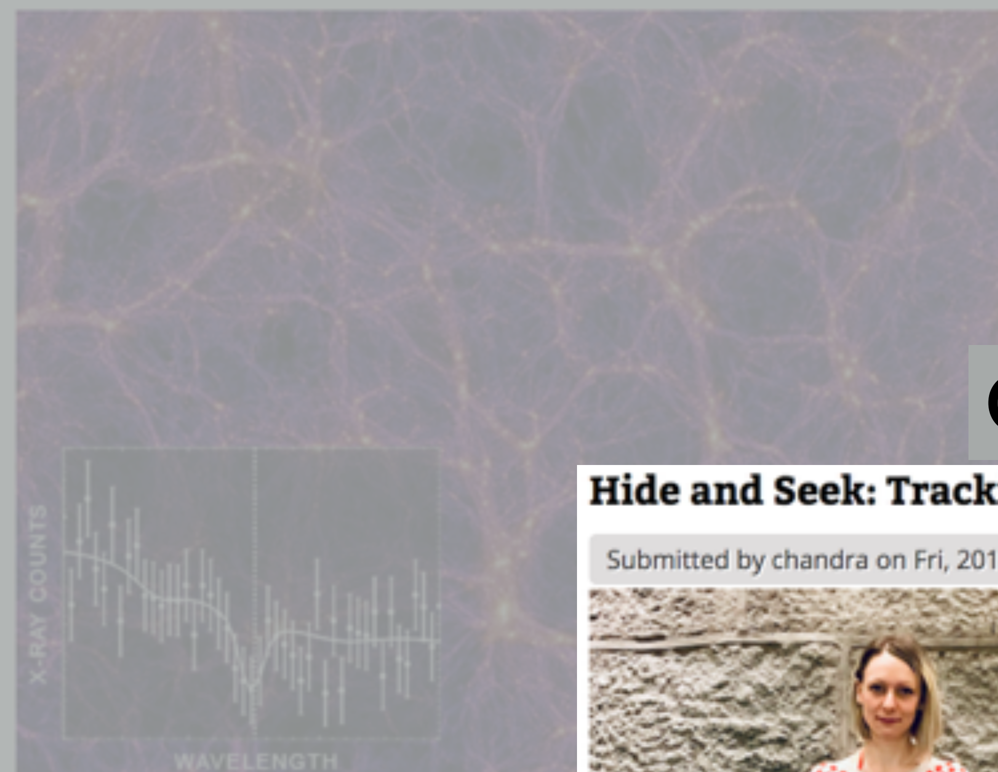

The Basics

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Orsolya Kovács

Hide and Seek: Tracking Down the Invisible Filaments

Submitted by chandra on Fri, 2019-02-15 08:40

Orsolya Kovács

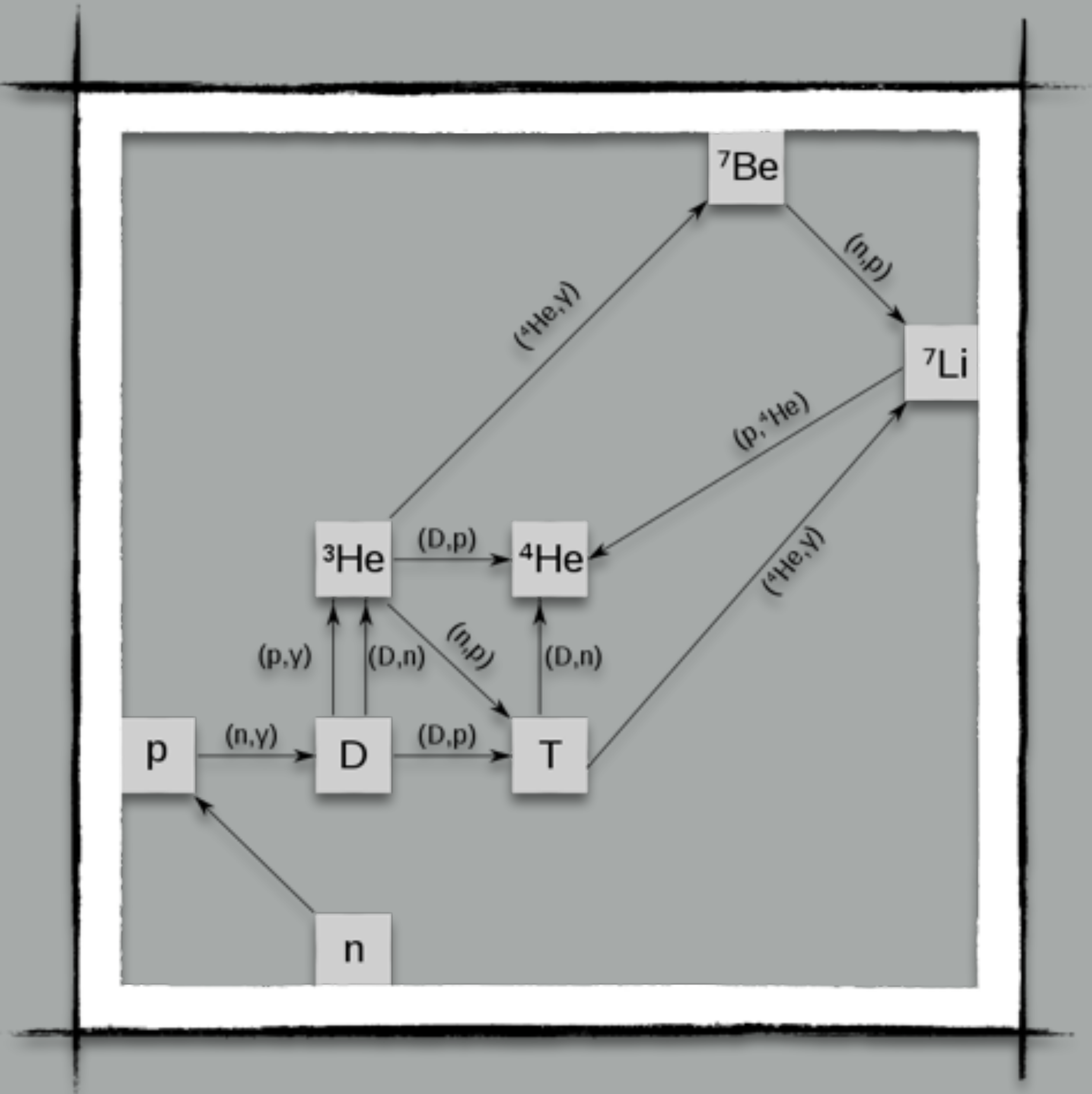
We welcome Orsolya Kovács, a third-year PhD student at the Eötvös Loránd University, Hungary where she obtained her MSc degree in astronomy, as our guest blogger. Currently, she is a pre-doctoral fellow at the Smithsonian Astrophysical Observatory, and is the first author on a recent paper on the WHIM featured in our latest press release.

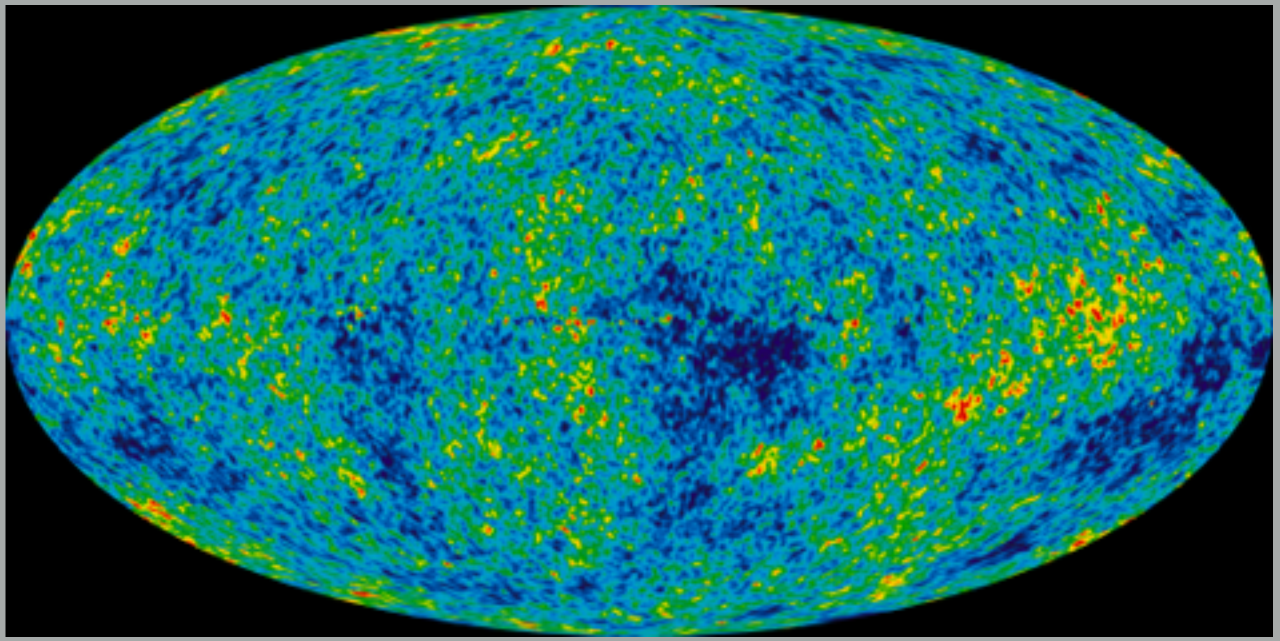
I was working on a totally different subject before I started the missing baryon project with a small group of scientists at the Smithsonian Astrophysical Observatory (SAO) about two years ago. Before I came to the United States as a Ph.D. student, I was involved in analyzing optical data of variable stars observed at the beautiful Piszkéstető Station in the Mátra Mountains, Hungary. In my master's thesis, I focused on the variable stars of an extremely old open cluster in the Milky Way, and at that time, I also got the chance to gain some observing skills from my Hungarian supervisor.

So the very beginning of my astronomy career was all about optical astronomy. But before getting really into optical astronomy and mountain life, I decided to interrupt this idyllic period, and find some new challenges: I wanted to spend part of my Ph.D. years learning X-ray astrophysics. With this in my mind, I

The missing baryon problem

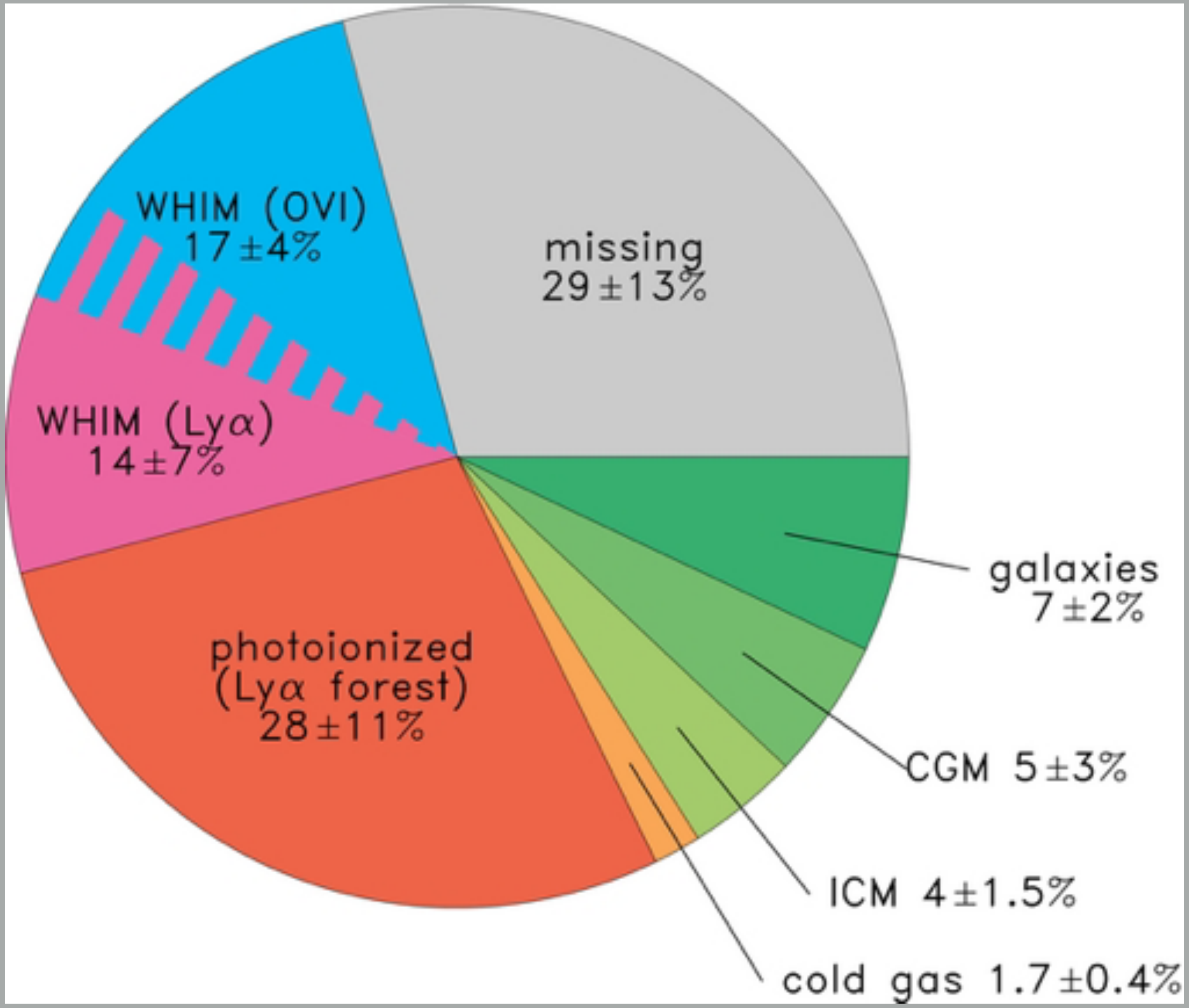
- The baryon density of the early Universe can be measured
    - Big Bang Nucleosynthesis
    - Cosmic Microwave Background
- Baryon density = 0.045





The missing baryon problem

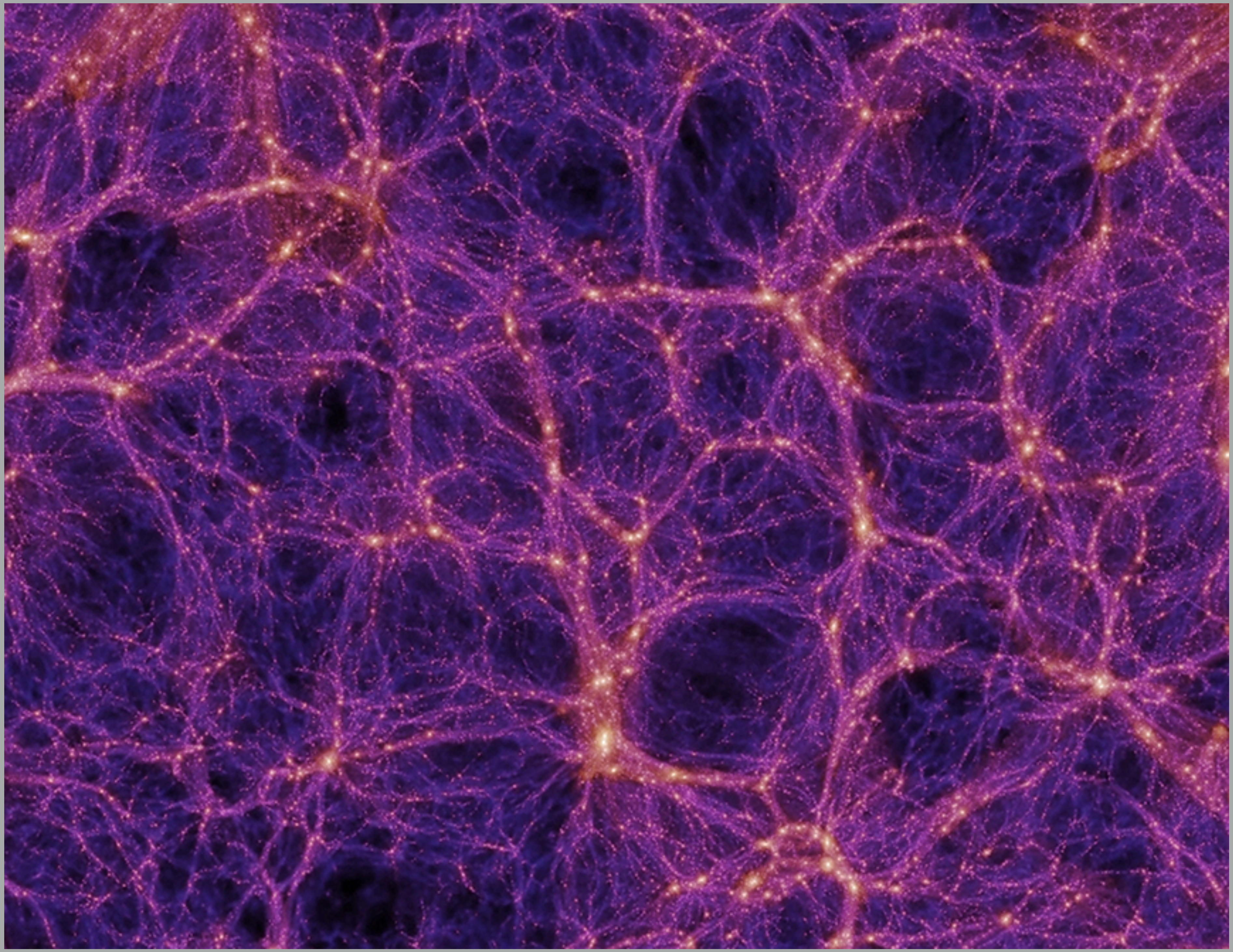
- 29±13% of the baryons are missing at z<2
- **W**arm **H**ot **I**ntergalactic **M**edium (**WHIM**)



Shull+12

Warm Hot Intergalactic Medium

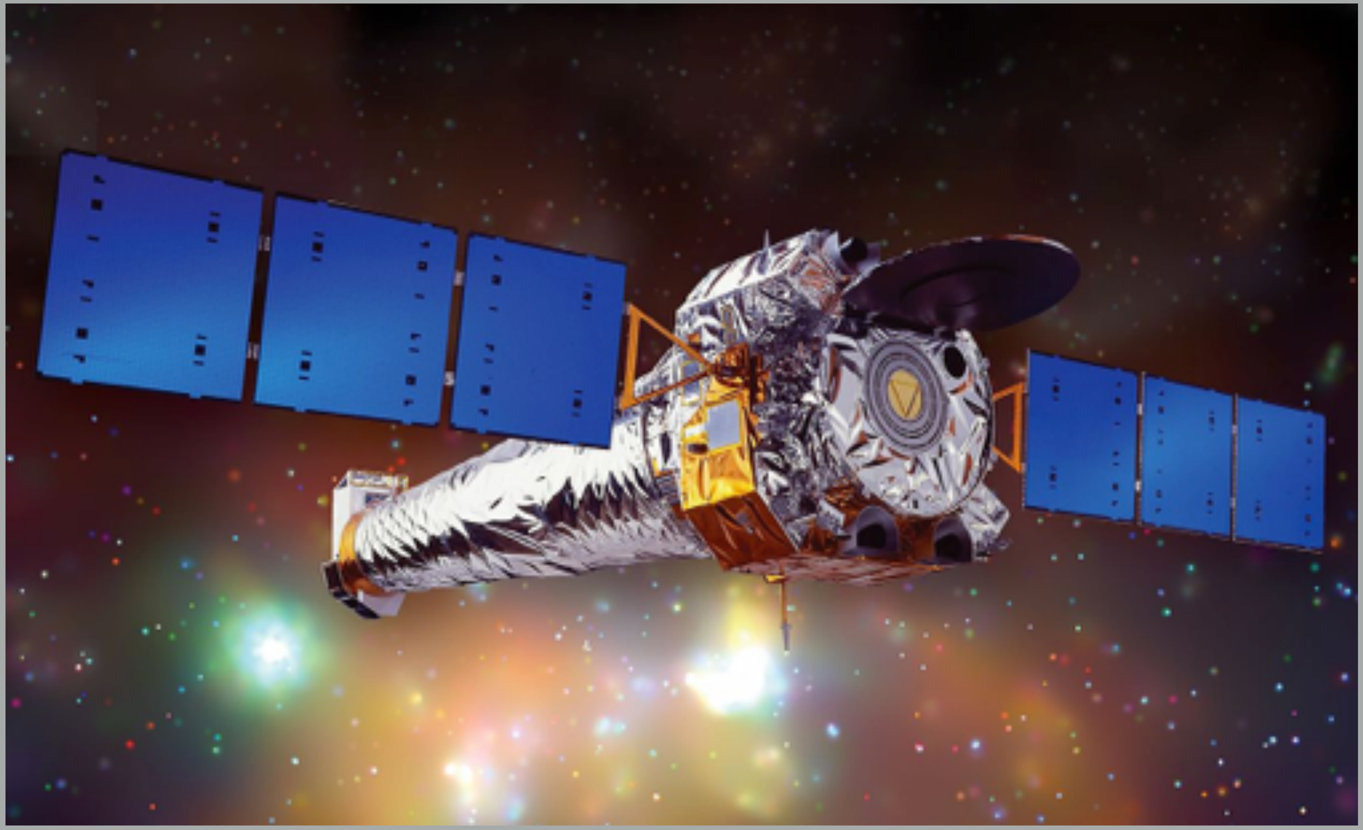
- Low density filamentary structure
- Follows the dark matter distribution
- T = 10^5-10^7 K (UV and X-ray wavelengths)



Millennium
Simulaiton

Warm Hot Intergalactic Medium

- Warm phase: UV (HST)
- Hot phase: X-ray (Chandra)
- Energy resolution and effective area of X-ray grating instruments is very low



Chandra Low Energy Transmission Grating

$A = 14\ cm^2$
$R = 460$

HST Cosmic Origin Spectrograph

$A = 2000\ cm^2$
$R = 20000$

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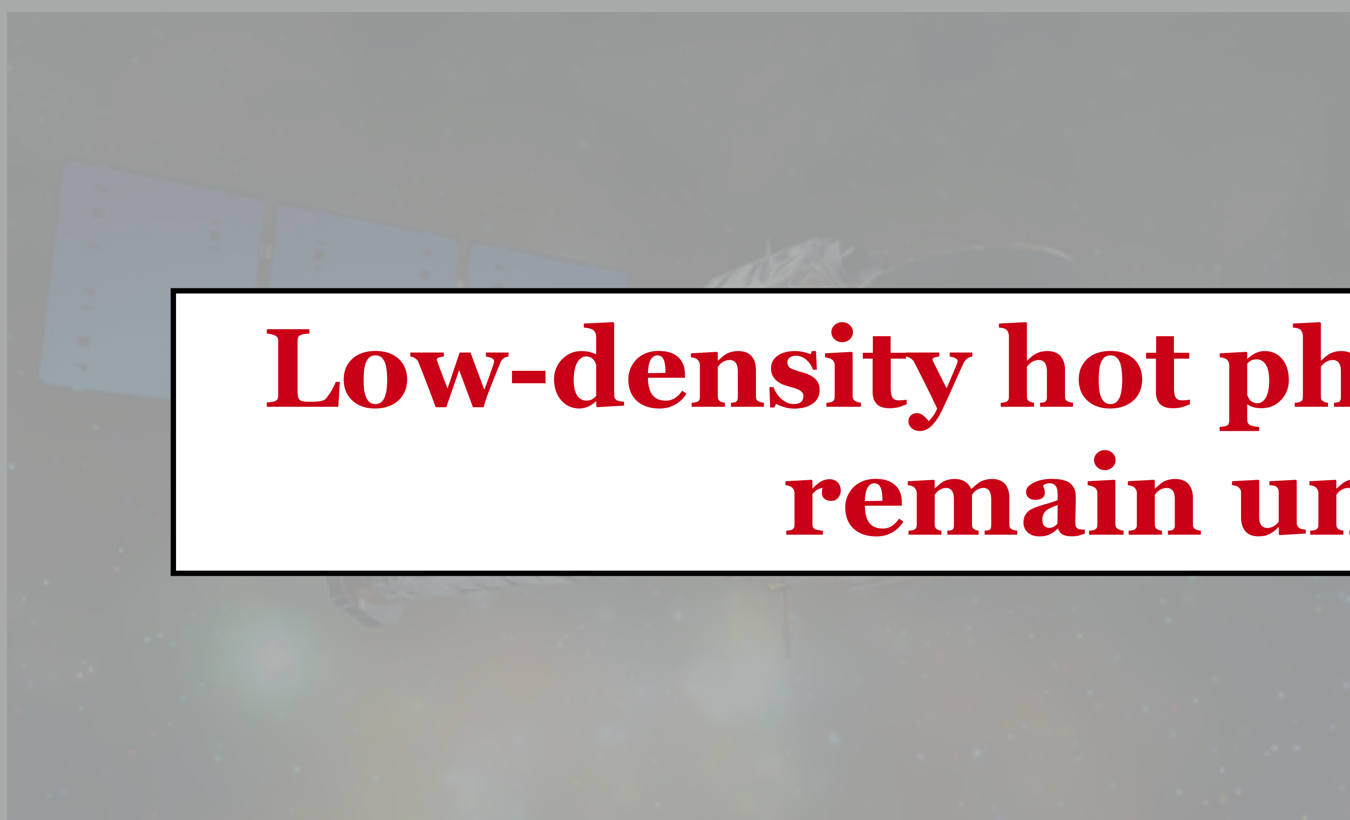
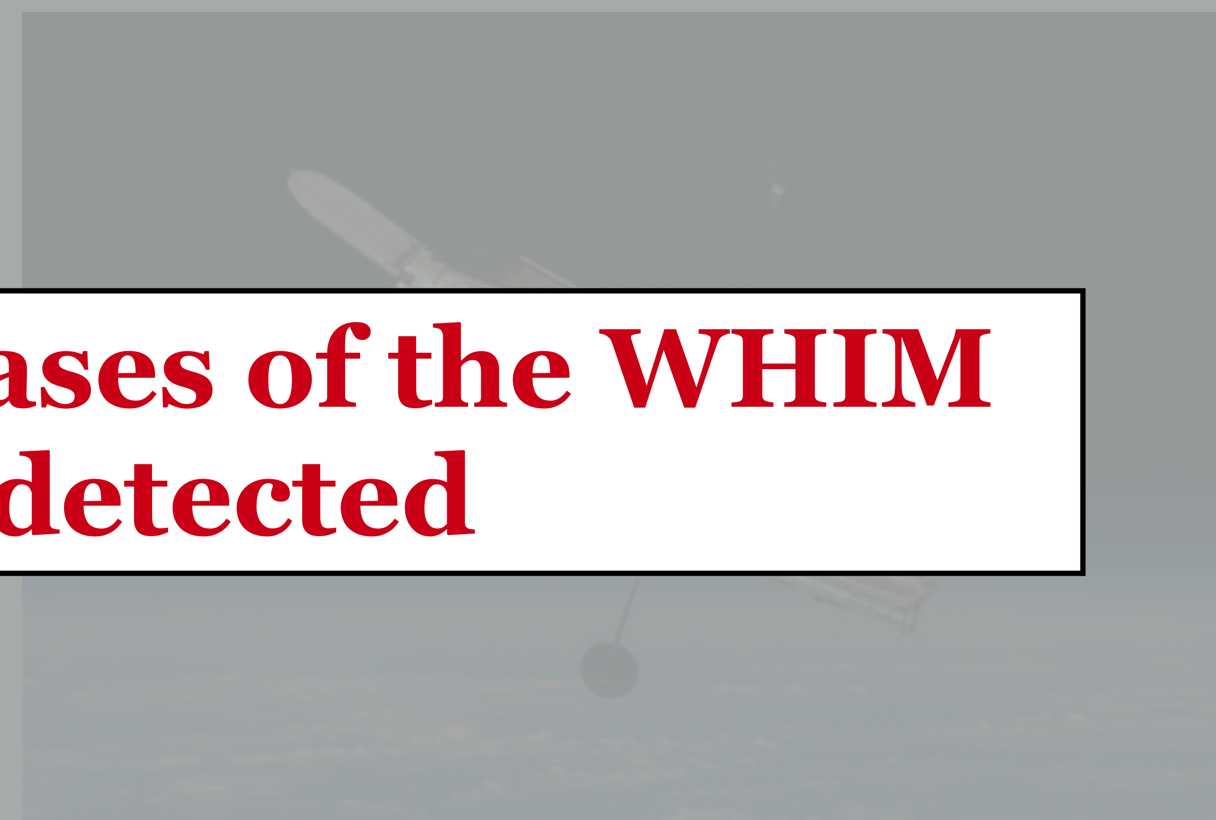




Low-density hot phases of the WHIM remain undetected

Chandra Low Energy Transmission Grating

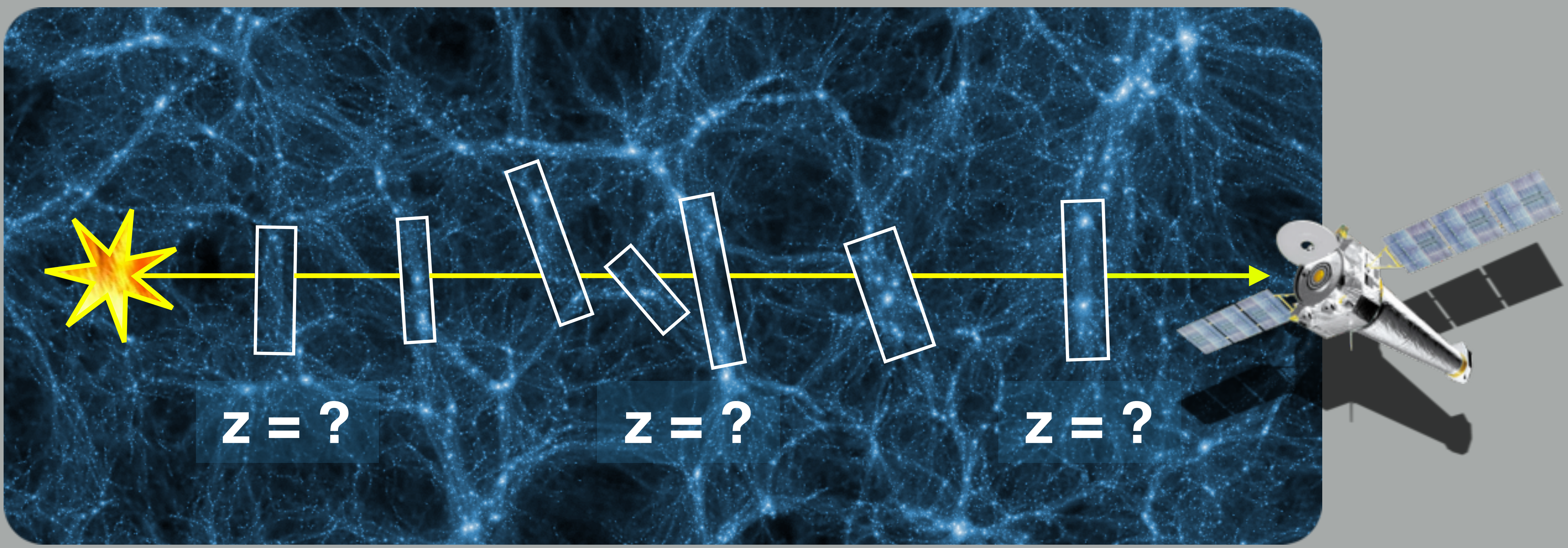
A = 14 cm
R = 460

HST Cosmic Origin Spectrograph

A = 2000 cm
R = 20000

Traditional absorption studies

- Photons from bright AGN are absorbed by halos of galaxies and WHIM filaments in the AGN sightline
- Absorption lines in the spectrum of the AGN
- “Blind” search → tentative detection



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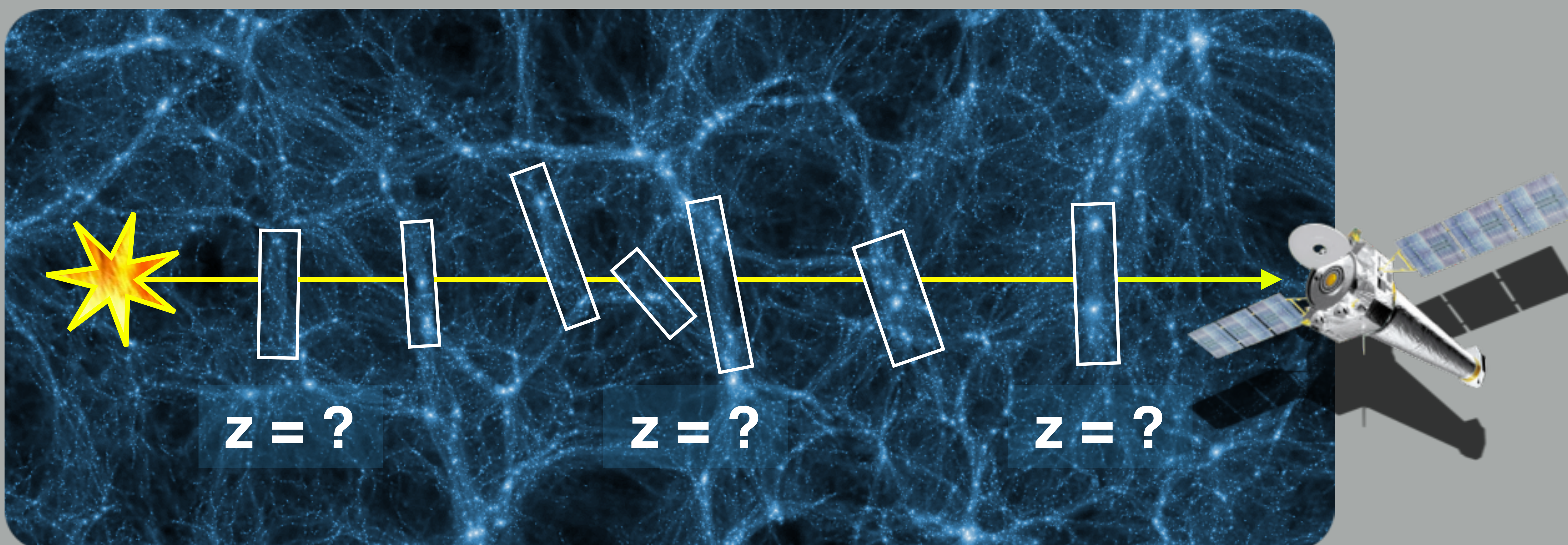
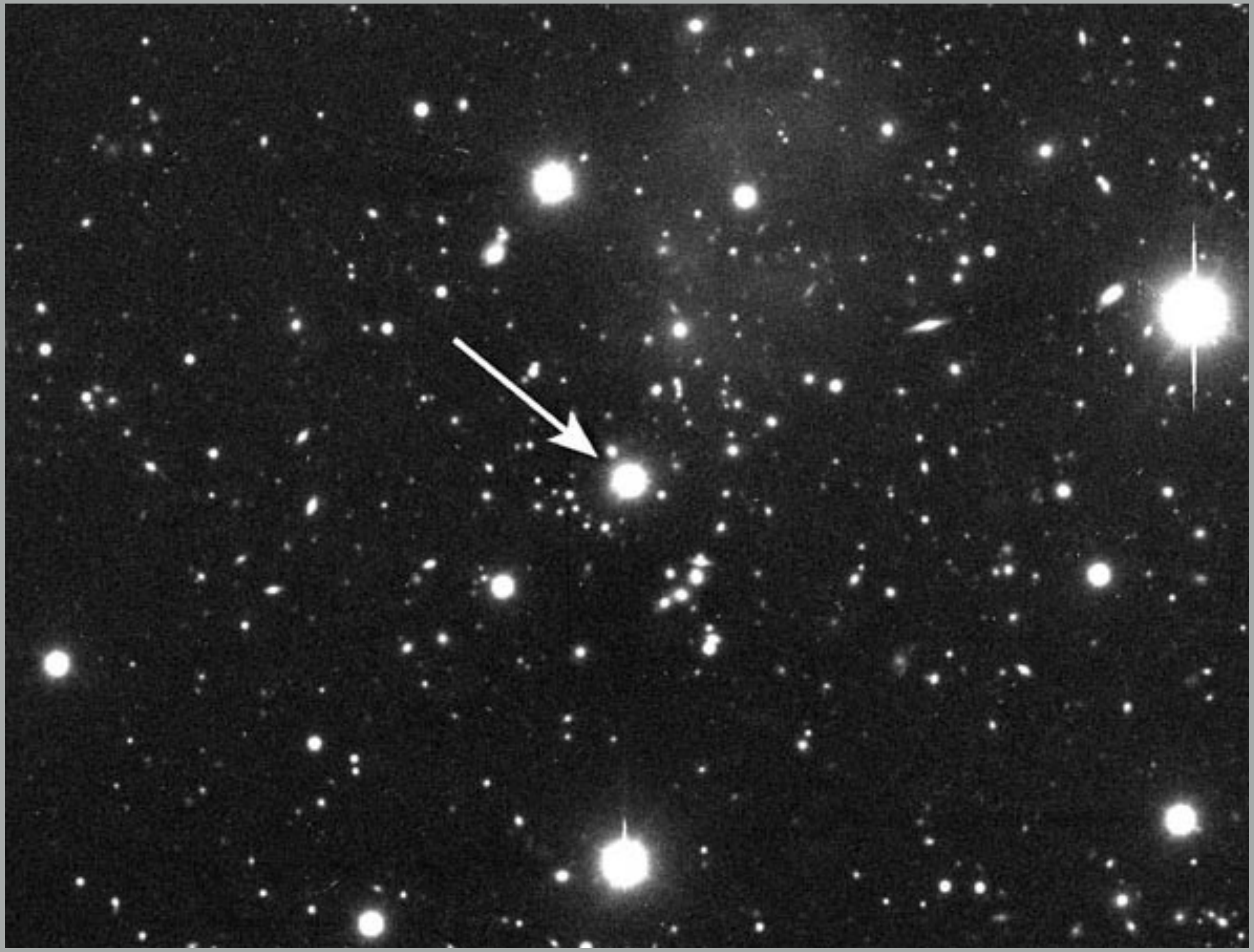


No detection using <u>individual</u> sightlines of low-density hot WHIM

A new method — H1821+643

- Bright quasar ($F_X = 9.7 \times 10^{-12}$ erg/s/cm^2)
- z=0.297
- 470 ks Chandra ACIS-LETG exposure
- Excellent target for UV and X-ray absorption line studies



Tripp+98

Stacking the X-ray line forest

I. Absorption line system selection criteria:

1. A priori detection of UV absorbers (Lyα)
2. A priori detection of galactic redshifts in the quasar field
3. Cross-correlating the Lyα and galaxy redshifts
4. Known galaxy properties

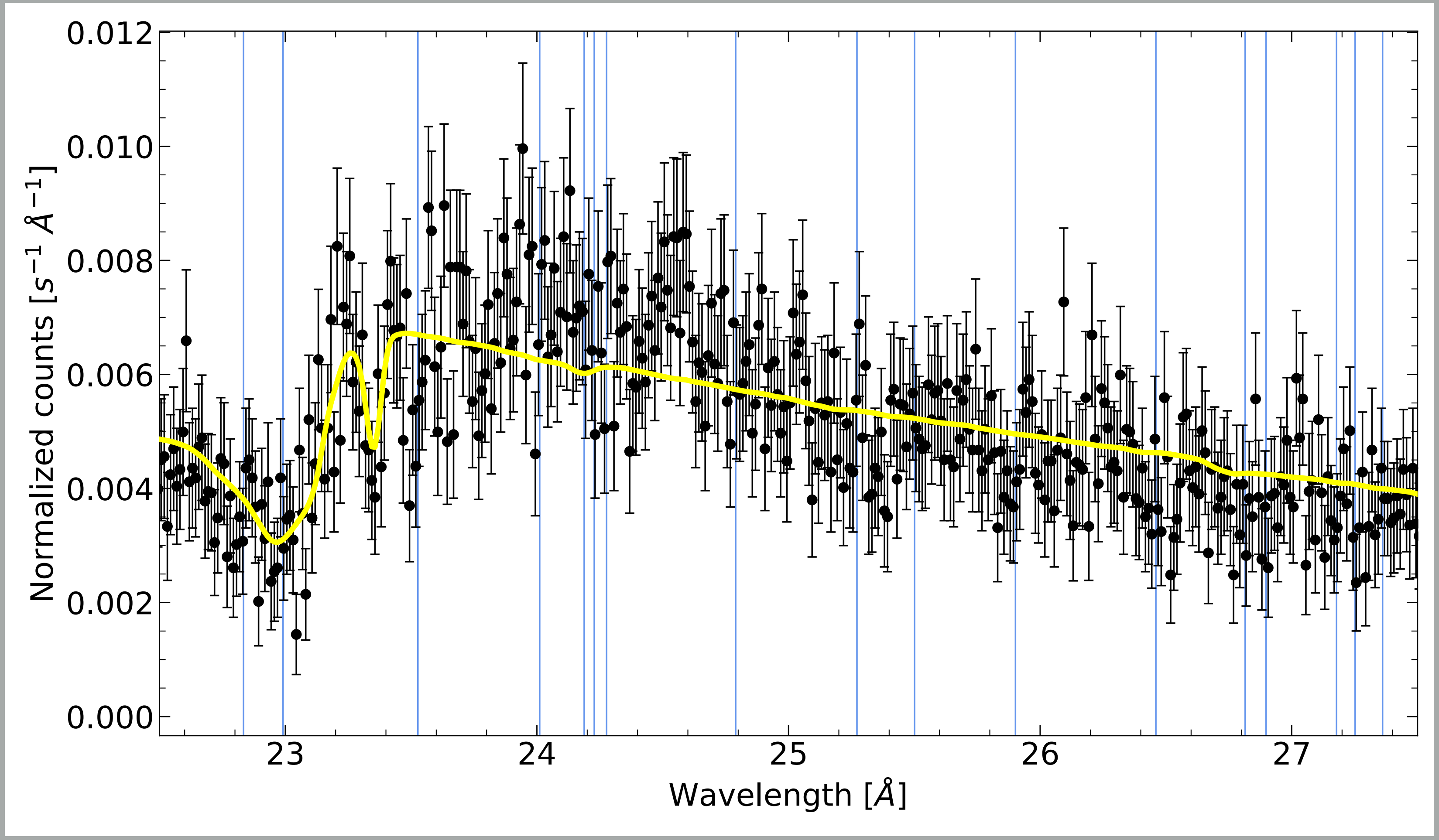
II. Stacking of the individual absorption lines

↓

- **Direct (non-tentative) detection**
- **Drastically increased S/N**
- **Detection of narrow lines becomes possible**

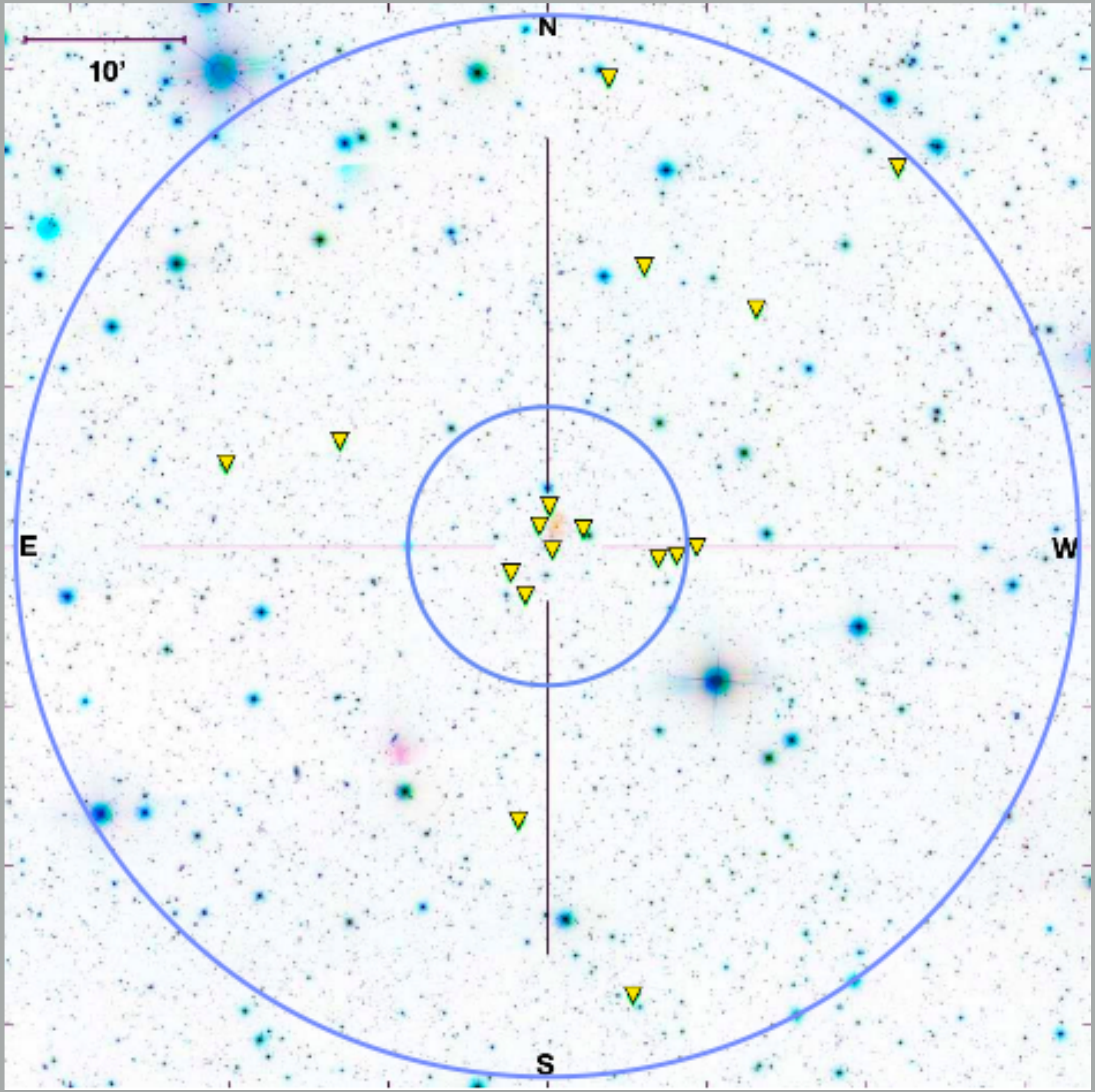
Stacking the X-ray line forest

- **A priori detection of absorbers**
  - UV Lyα absorbers detected by HST (Tripp+00)
  - Provides accurate redshifts of absorbers
  - z ≈ 0.06 - 0.27



Stacking the X-ray line forest

- **Optical survey of galaxies in the quasar field**
  - Spectroscopic redshift of 154 galaxies (Tripp+00)
  - 1 deg^2 area surveyed with WIYN telescope
  - Galaxy properties can be measured

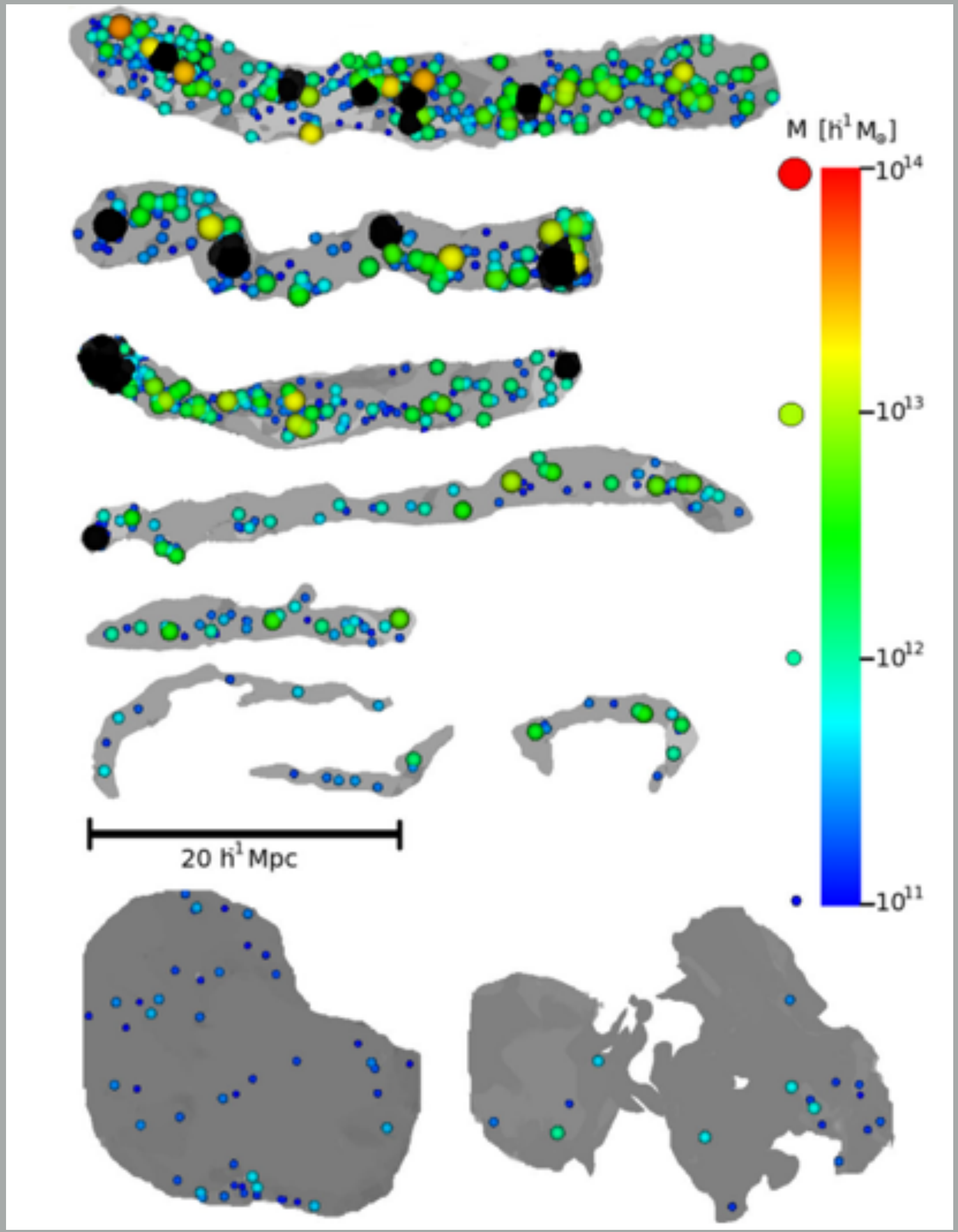


Stacking the X-ray line forest

- **Cross correlating the Lyα and galaxy redshifts**
  - 24 Lyα absorption lines and galaxy redshifts are matching
  - Galaxy mass determination using FAST code (SED fitting)
  - 17 Lyα systems belong to $M_{halo} > 3 \times 10^{11}\ M_{\odot}$ galaxies

Dense filaments

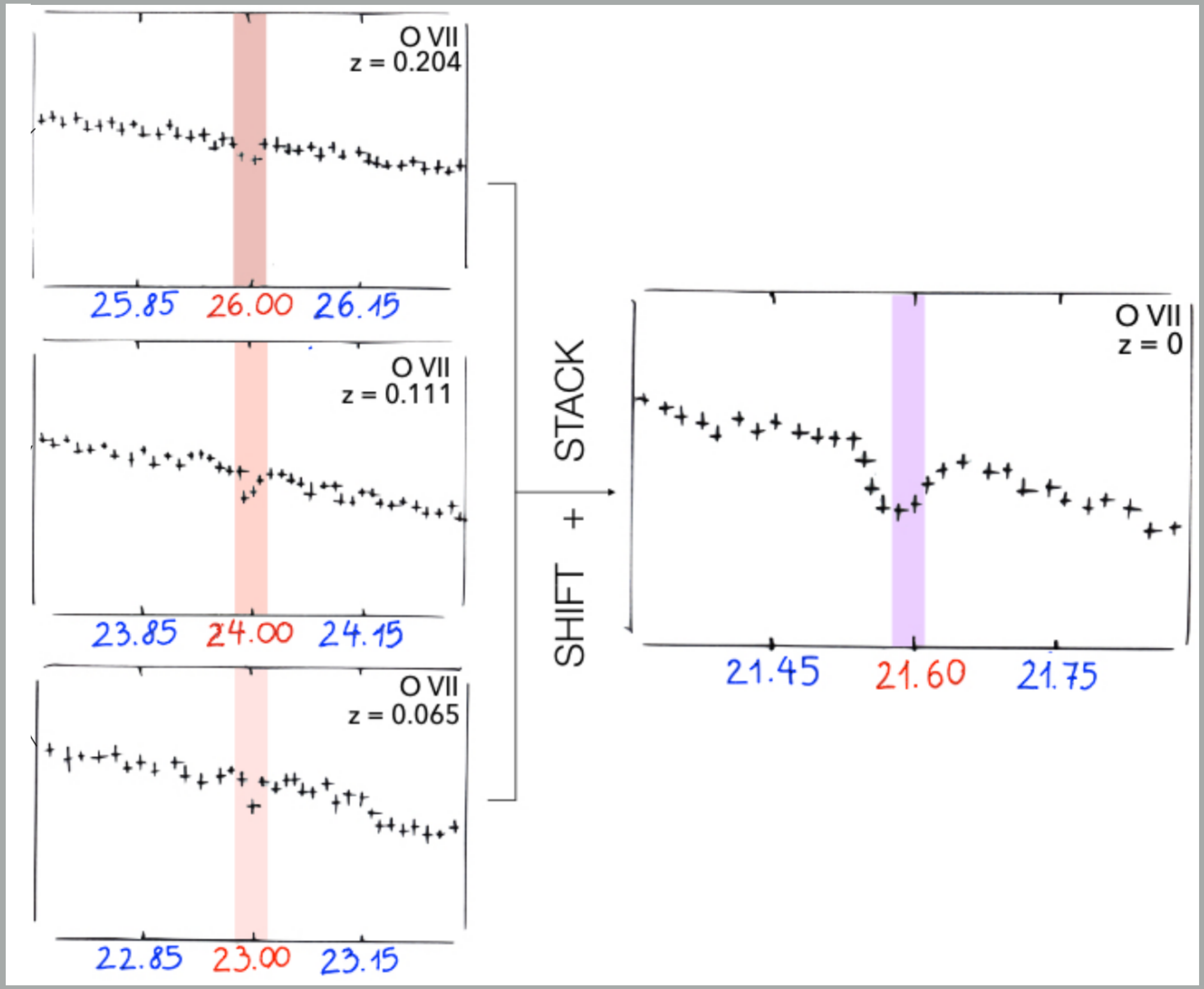
Low density walls



Cautun+14

Stacking the X-ray line forest

- Chandra LETG-ACIS data of H1821+643
- t_{exp} = 470 ks
- 17 redshifted OVII absorption lines in the spectrum to stack
- Stacked exposure time: $t_{exp} = 17 \times 470$ ks = 8.0 Ms



Stacking method

1. Eliminating overlapping redshifts
2. Blueshifting the spectra toward the rest-frame wavelength
3. Blueshifting the RMF and ARF files
4. Re-binning the spectra and response files on the same wavelength grid
5. Cropping the spectra and response files
6. Stacking the spectra 17 times

Stacking method

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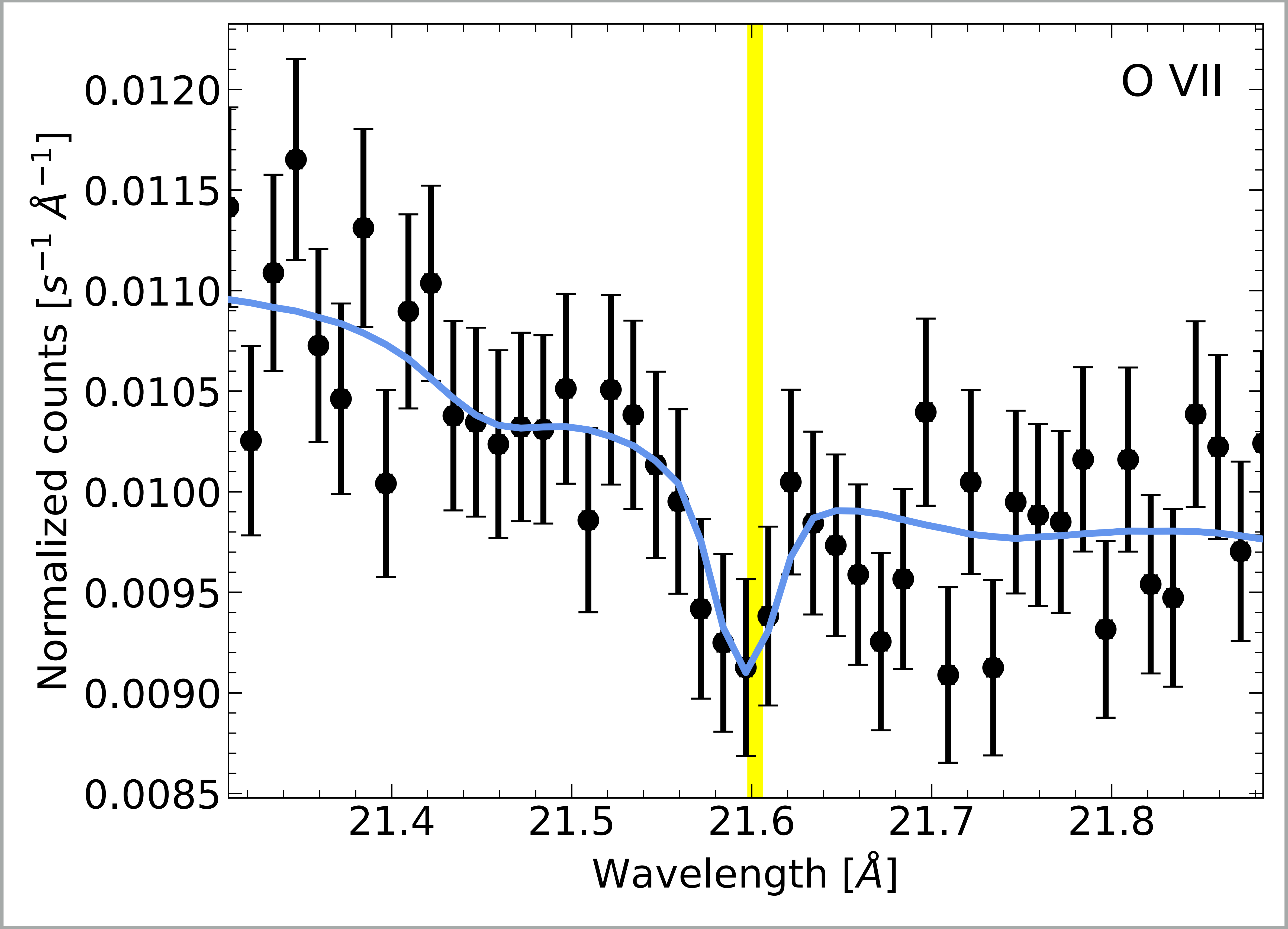
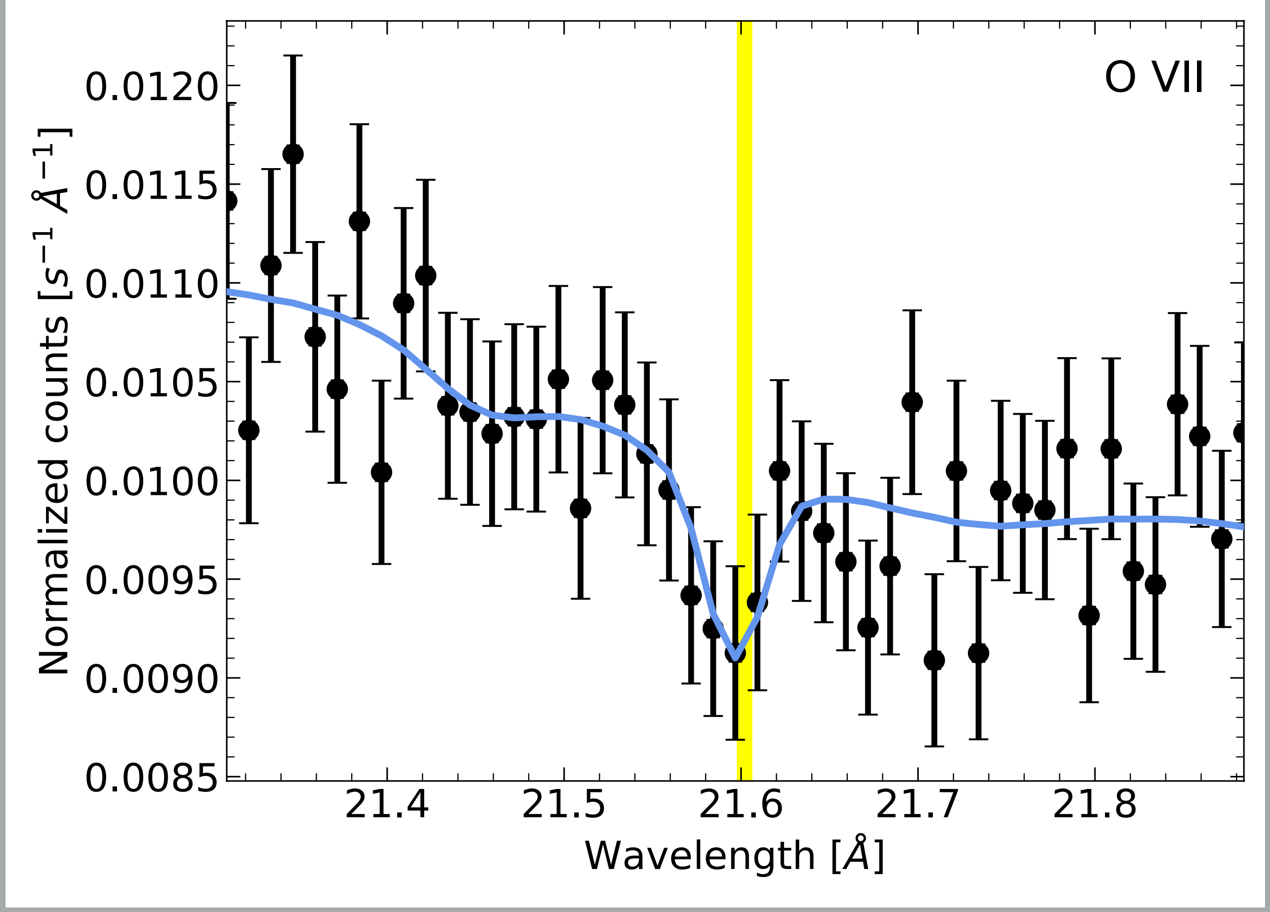
8.0 Msec total exposure time

Result: OVII absorption line



Result: OVII absorption line

- Gaussian line profile
- Detection significance from Xspec fitting = 3.3σ
- Equivalent width = 4.1 mÅ
- Column density = 1.4×10^{15} cm^{-2}

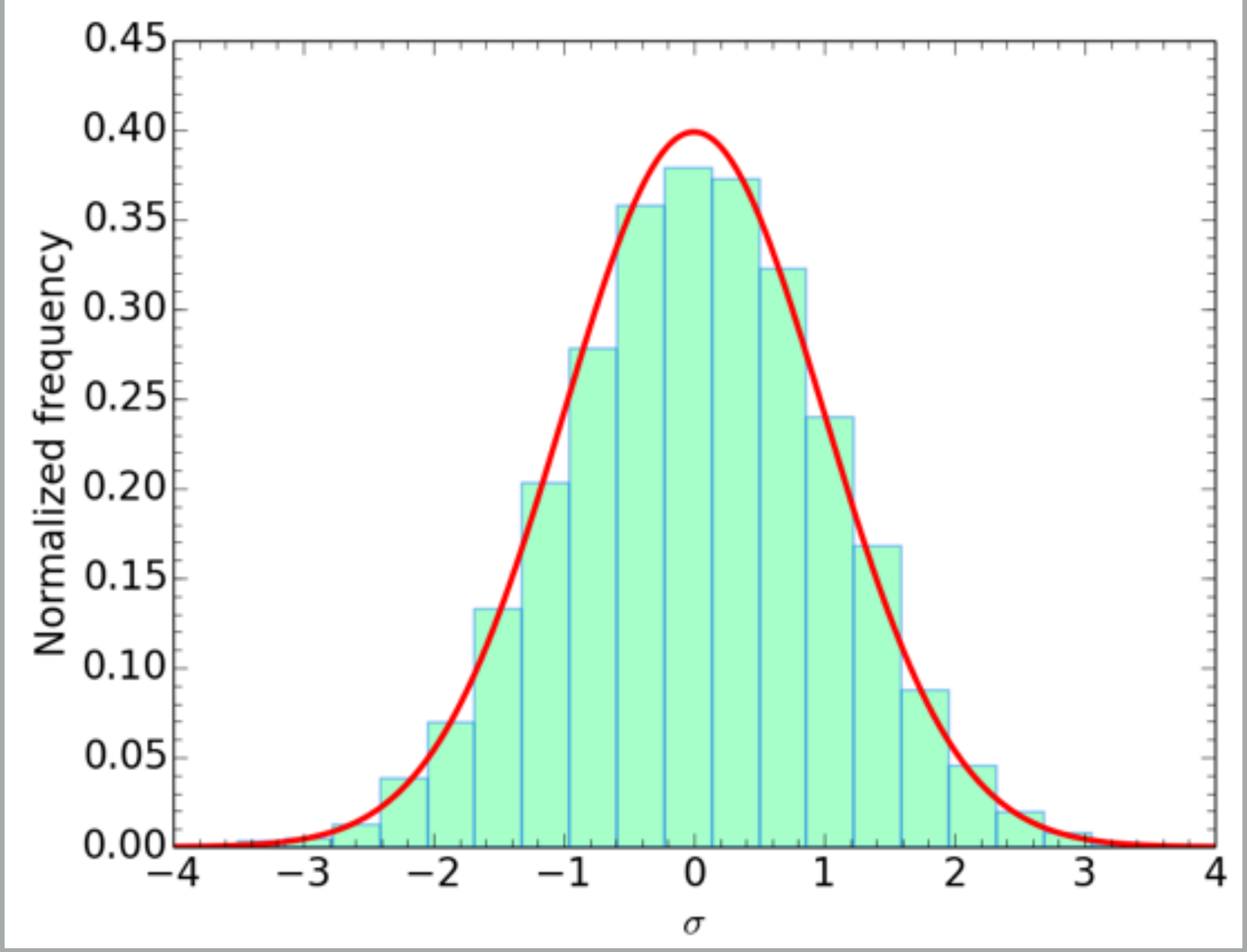


First statistically significant <u>non-tentative</u> detection of an X-ray absorption line

Monte Carlo simulations

What is the chance coincidence of a similar detection?

- 17 random redshift in the z=0-0.297 range
- Spectra are stacked just like the real data
- Repeat the stacking for 10,000 random redshift sets



3 spectra with >3.3σ detection

Chance coincidence = 3 x 10^{-4}

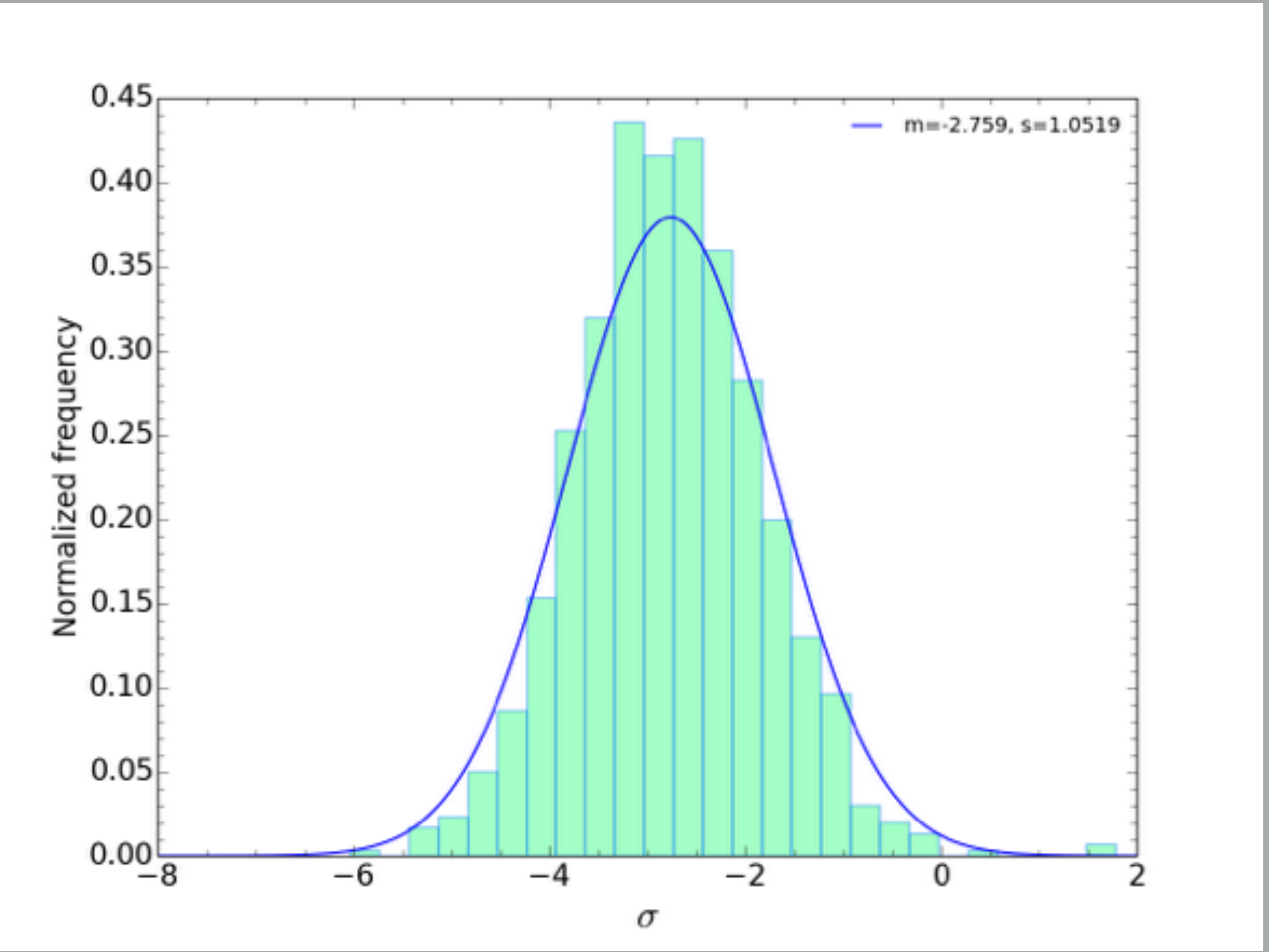
Random detections do not have Gaussian line profiles!

Verifying the stacking method

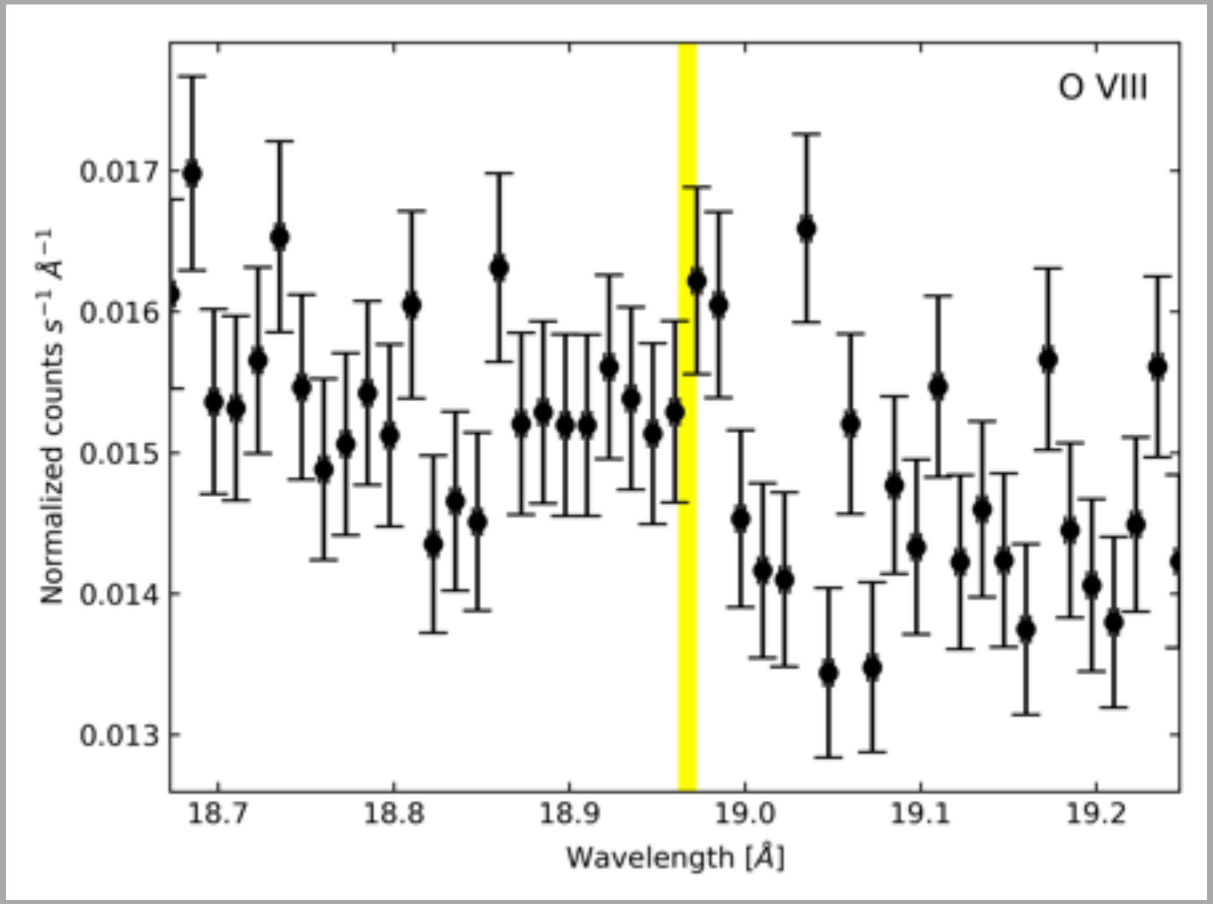
Can many small-significance signal result in a statistically significant detection?

- 17 weak absorption lines stacked
- Repeat stacking for 10,0000 sets
- Statistically significant detection in the stacks

Mean detection significance is 2.8σ

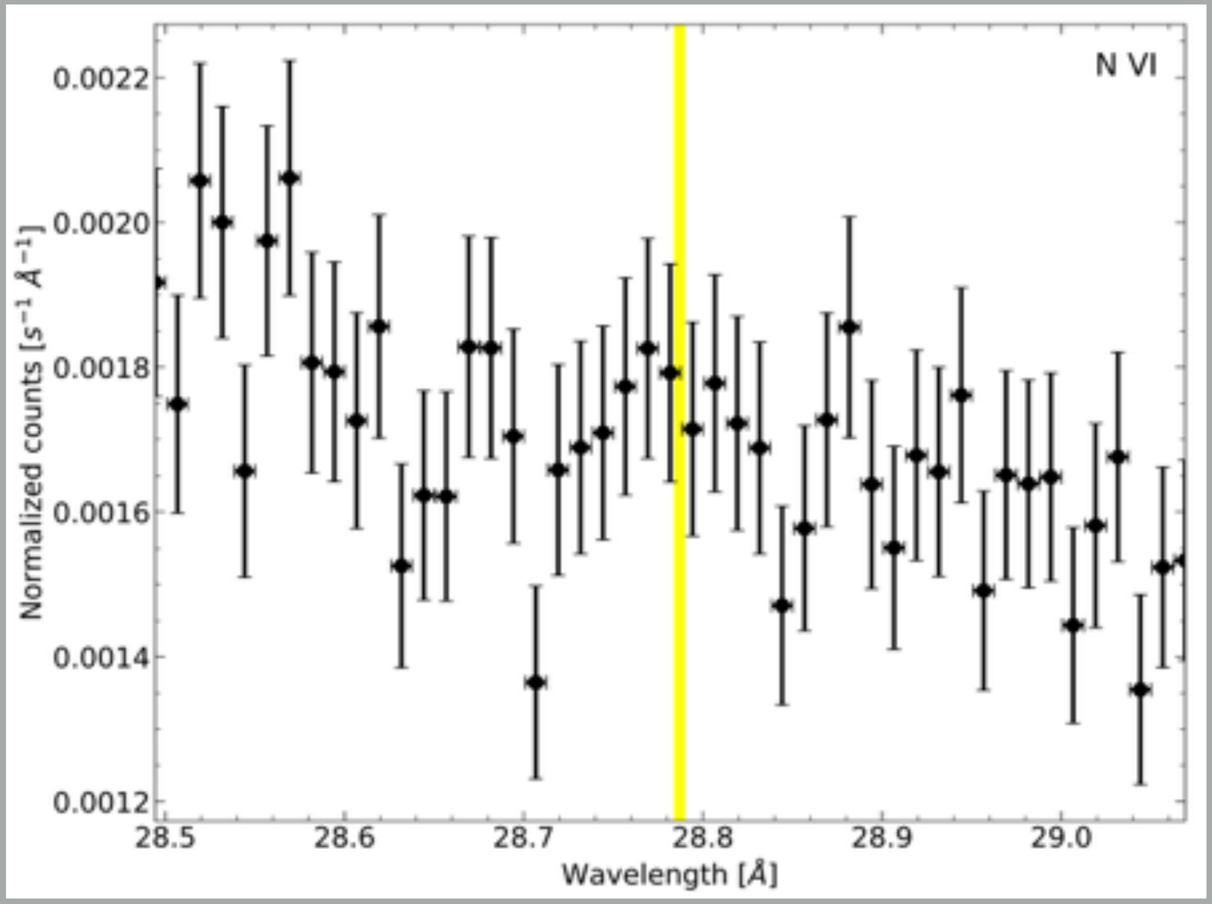


Other non-detected metal lines

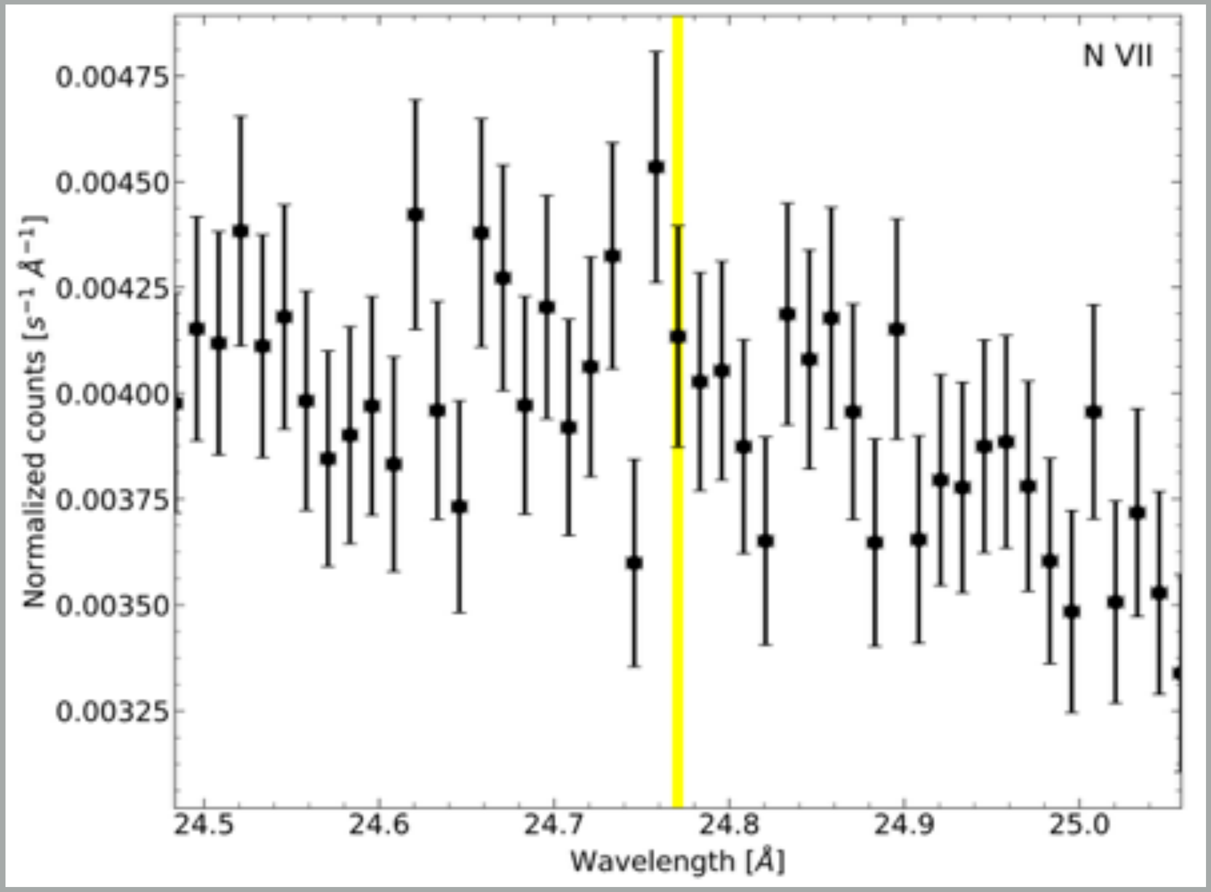


EW <0.7 mÅ

EW <0.6 mÅ



EW <0.8 mÅ



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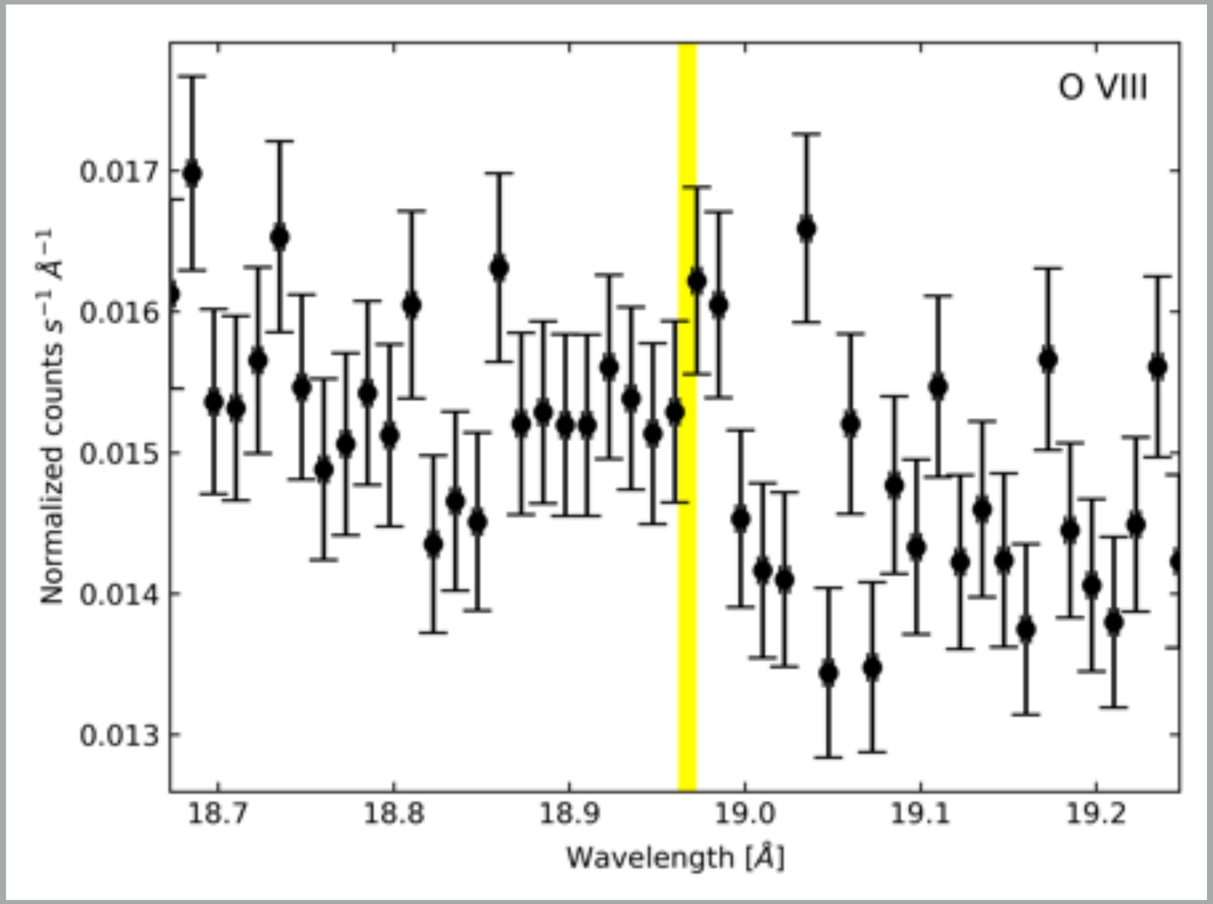

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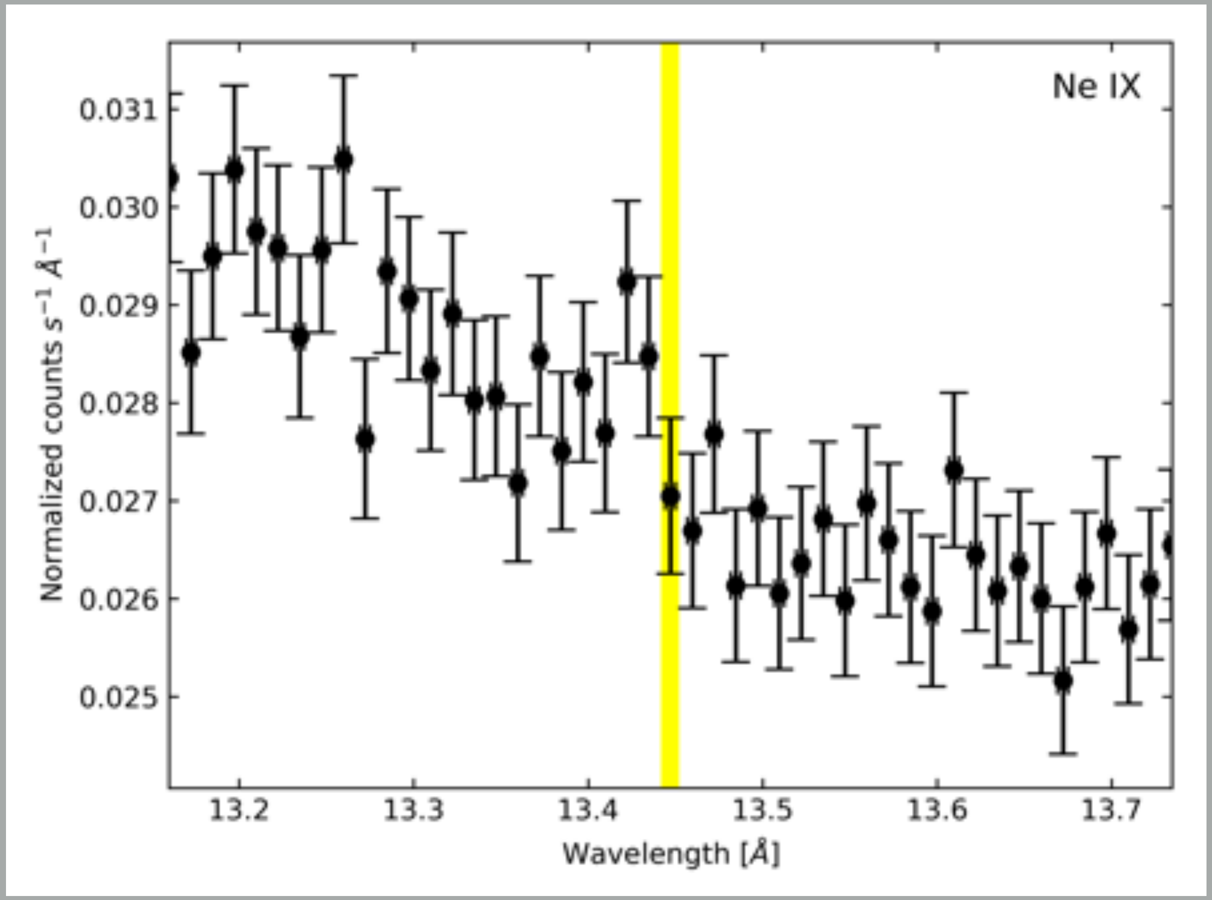
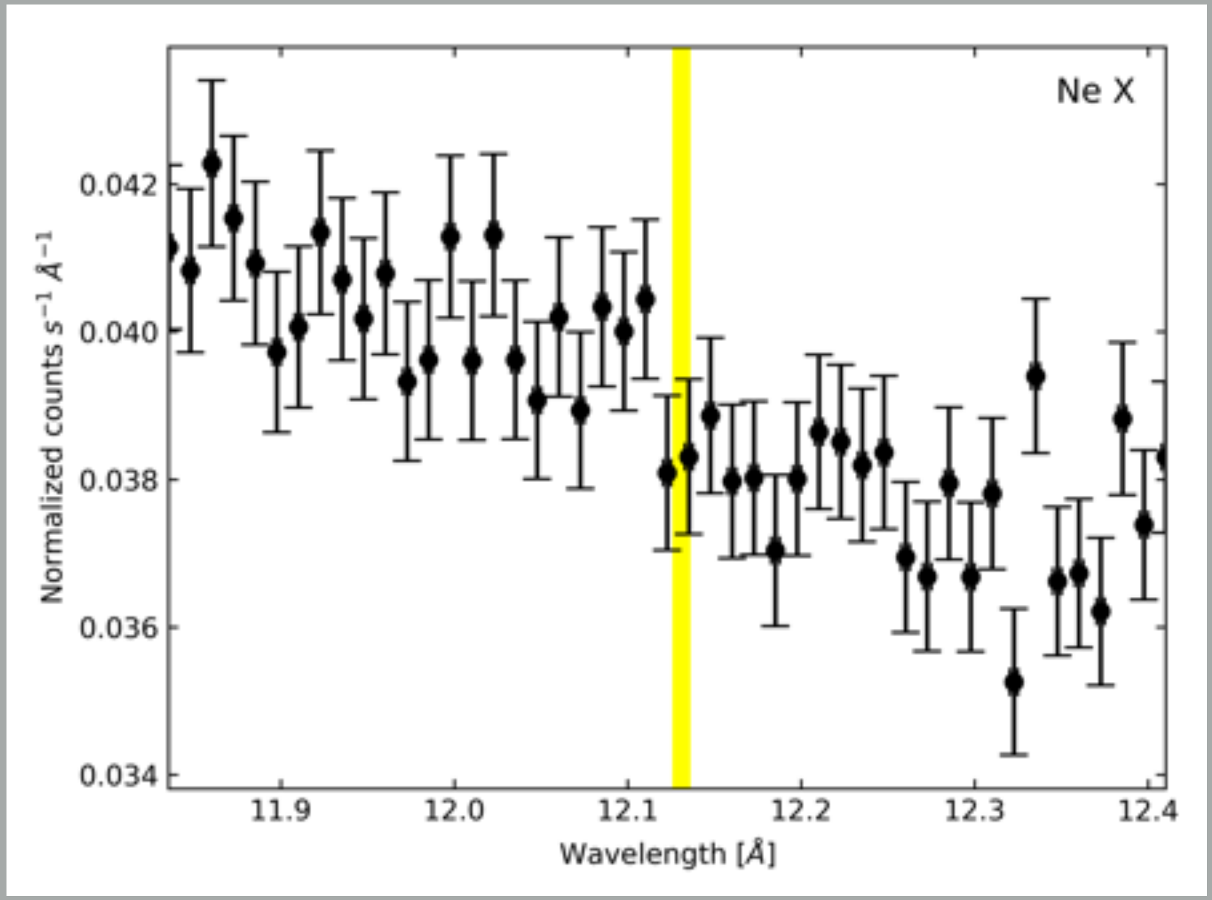


EW <1.1 mÅ



The missing baryons

- Typical metallicity of filaments: Z = 0.18
- OVII ionization fraction = 0.75

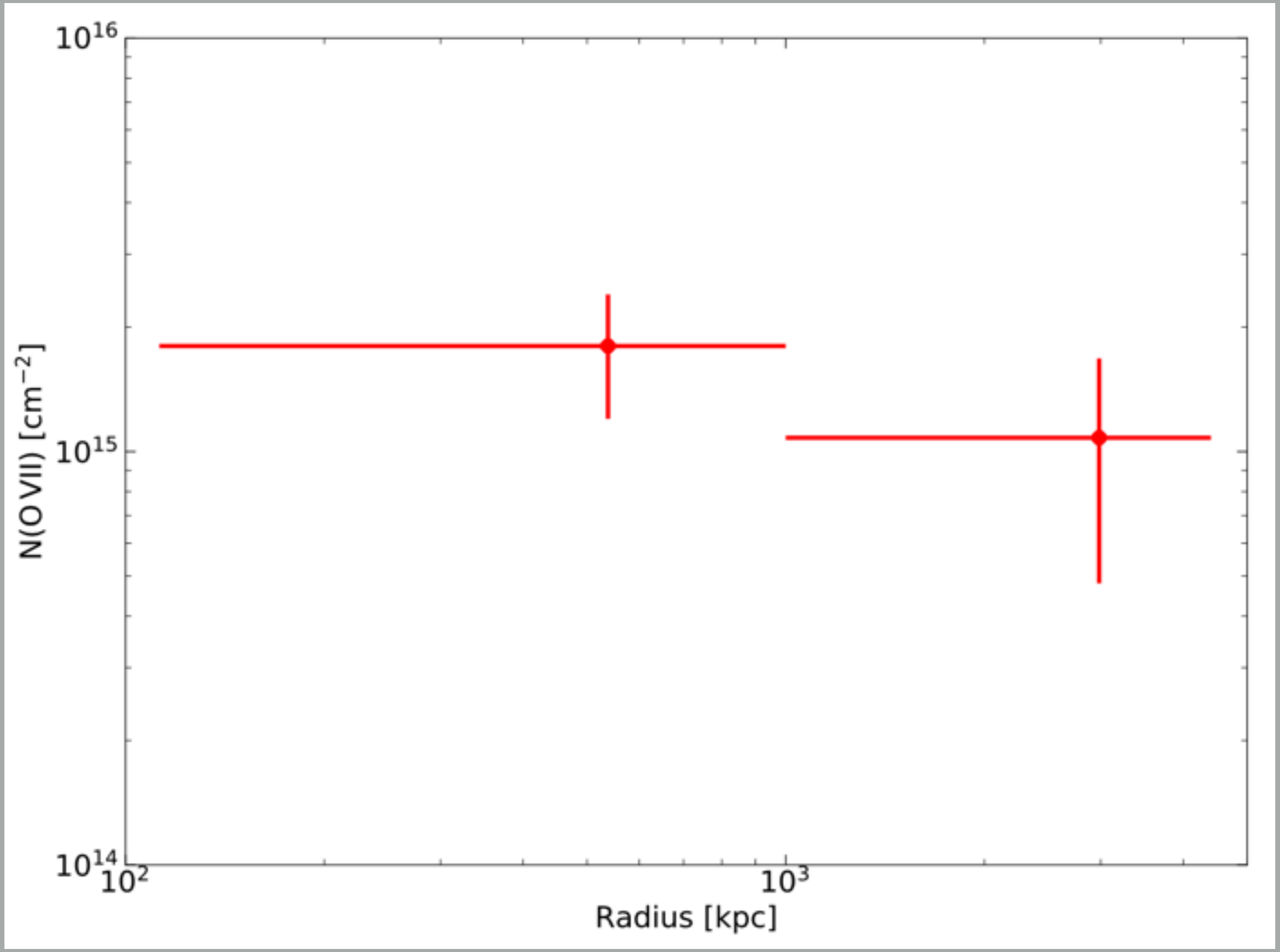
- Cosmological mass density of OVII absorbers

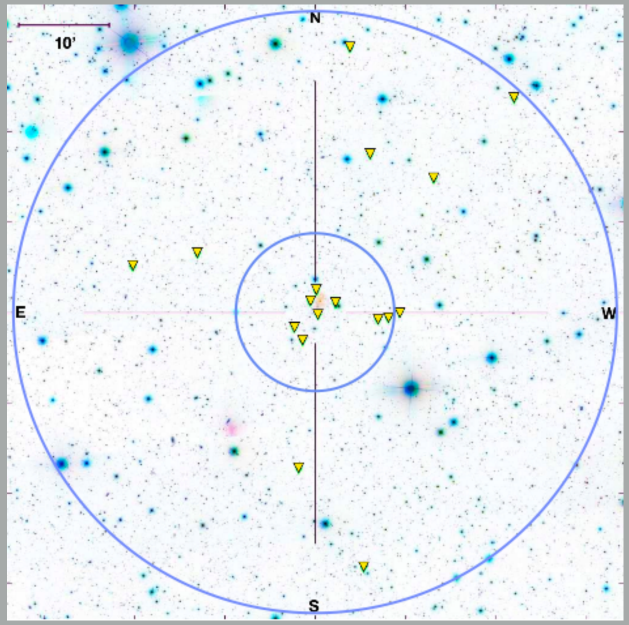
$$\Omega_b(\mathrm{O\ VII}) = 0.017 \pm 0.005$$

- **~38 % of the baryons are in the hot phase of the WHIM (OVII)**
- Comparable with simulations

Binning the absorbers as a function of radius

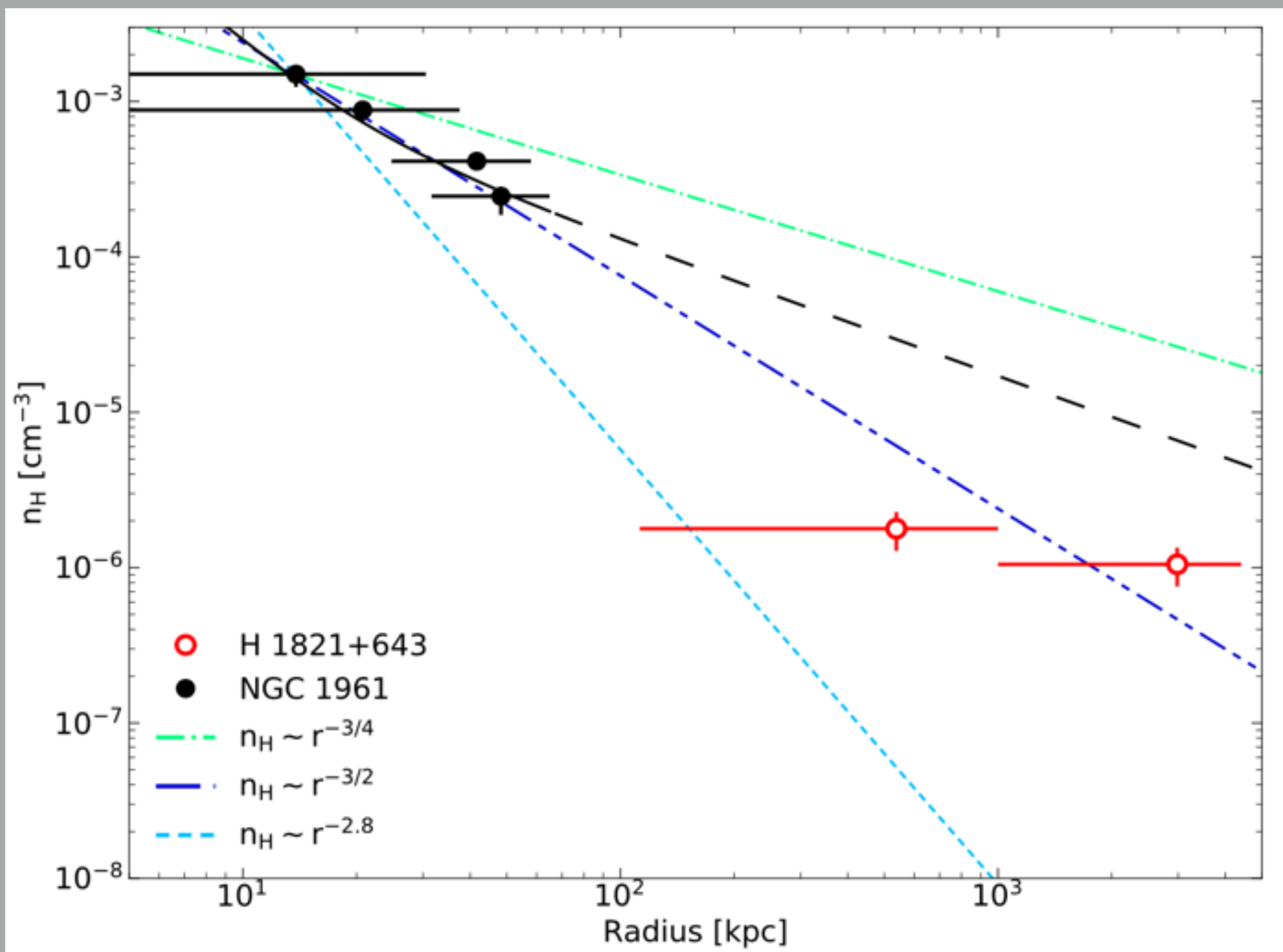
- Bin the 17 absorbers as a function of the host galaxy's impact parameter
- Stack the absorbers in each bin

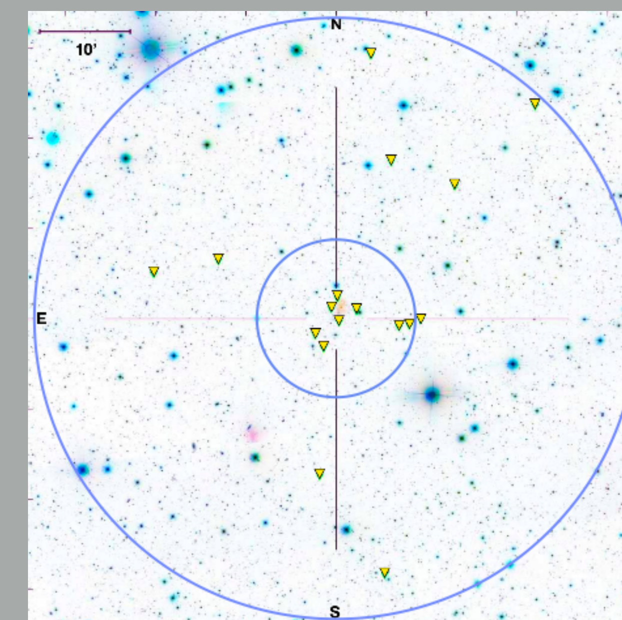




Density profile of the WHIM

- Hot gas profile in NGC 1961 (massive spiral galaxy)
- Path length in WHIM ~ 5 Mpc
- Density in **individual WHIM** filaments is shown





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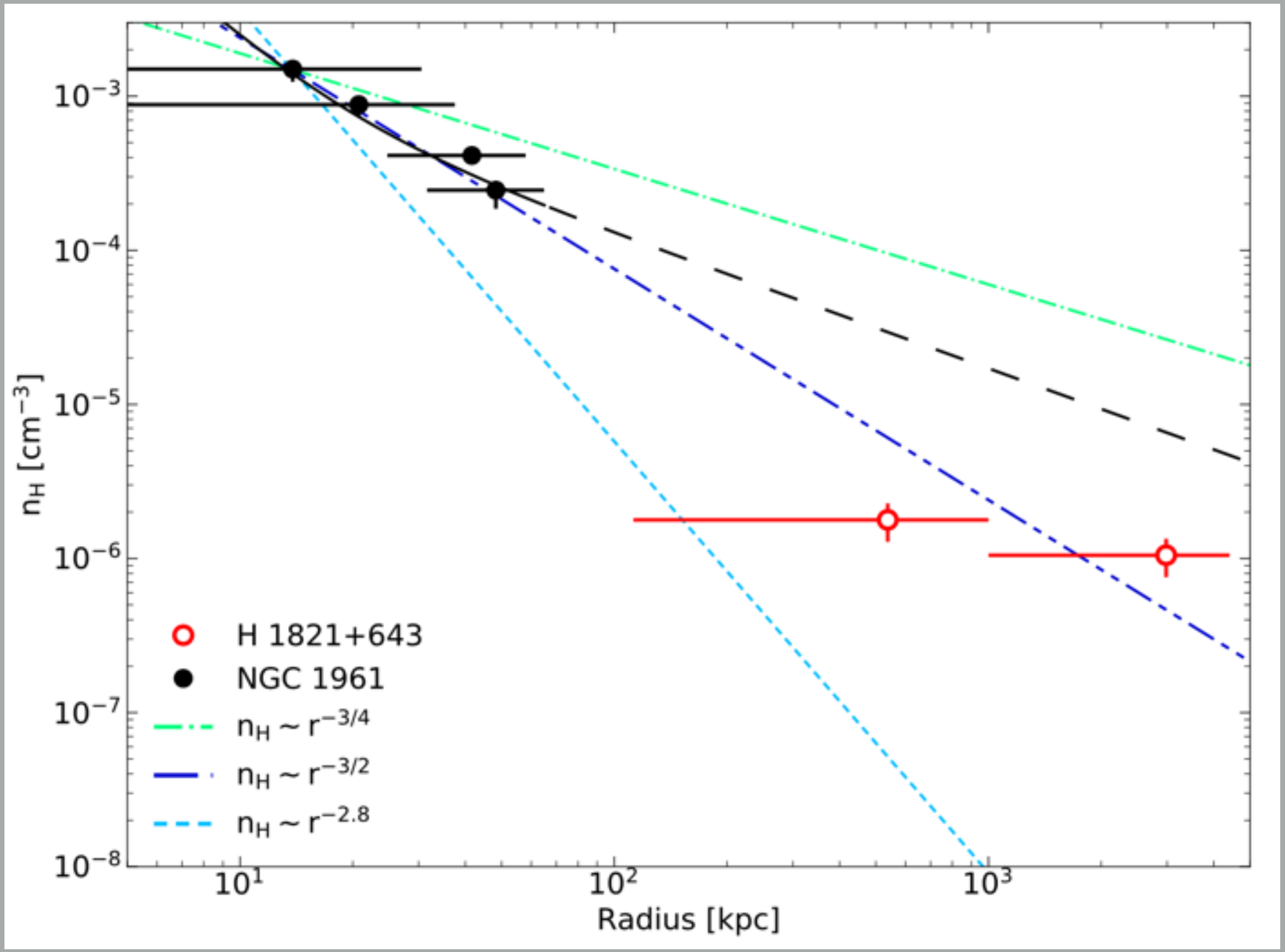

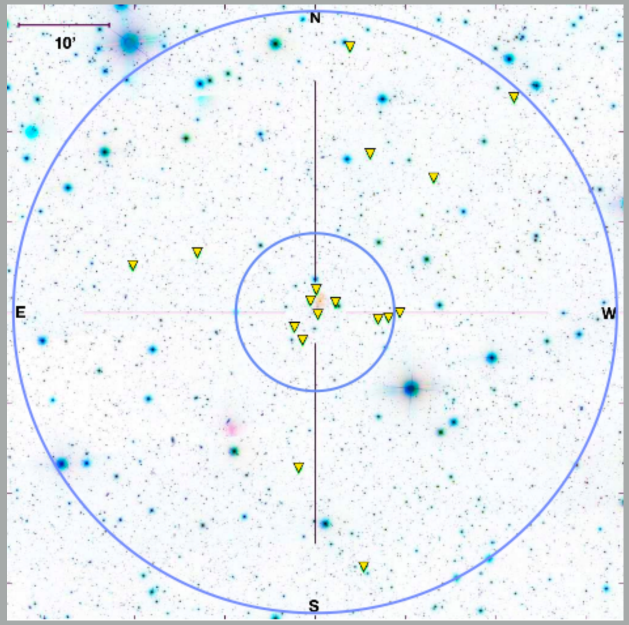

δ ≈ 5-9

Typical overdensity in WHIM filaments

Thank you!