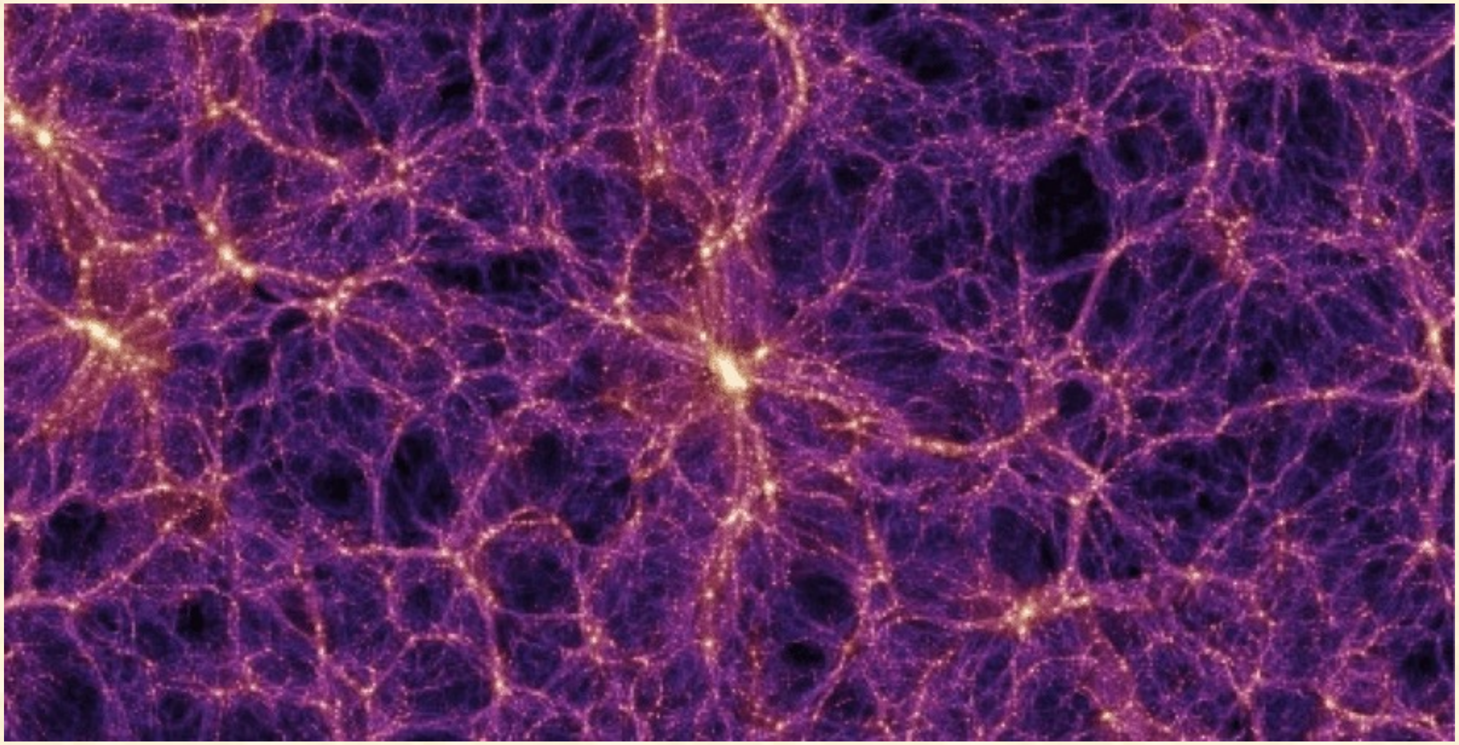
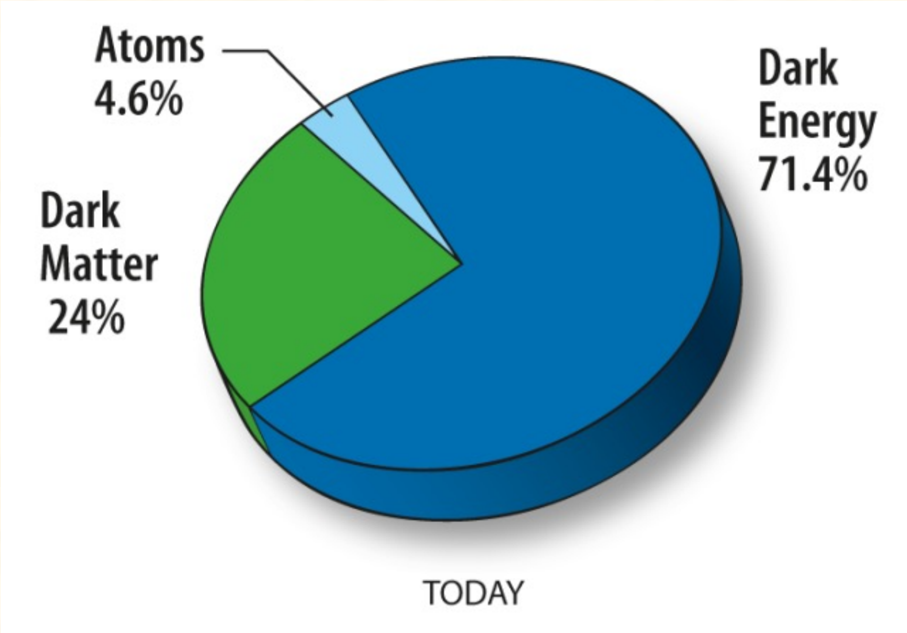
The Intergalactic Medium (IGM)

- Constituents – WHIM, CGM, ICM, etc.
- Baryon budget
- Why is most of the IGM so hot?



(Millenium Simulation, Springel et al. 2005, Nature, 435, 629)

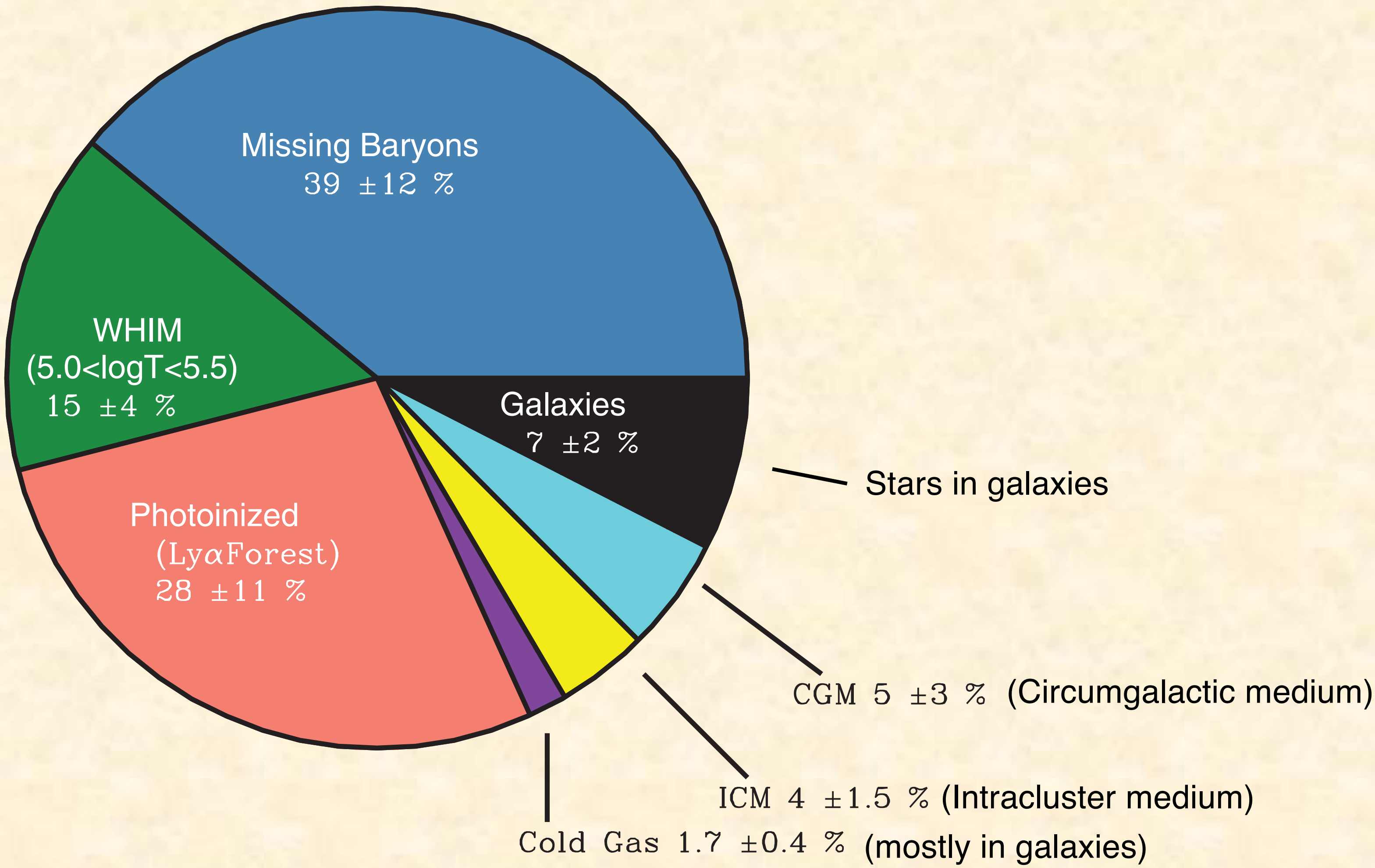
We live in a ΛCDM (accelerating) Universe.



Evidence:

- Accelerating expansion of the Universe (Type Ia SN).
- Abundances of H, Deuterium, He, and Li.
- Structure of Cosmic Microwave Background (CMB).
- Agreement between models and observations (e.g., SDSS survey) of large-scale structure.

Baryon Budget at z ≈ 0

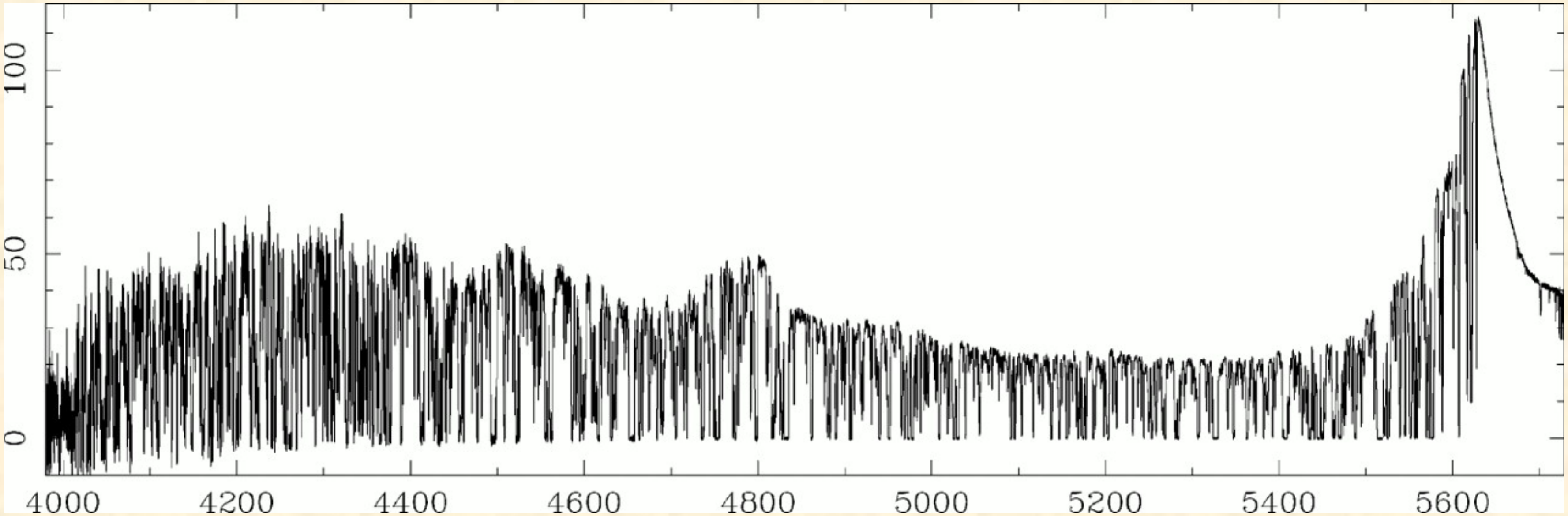


(Nicastro+, 2016, Astronomische Nachrichten, 338, 281)

- Up to ~1/2 of the baryons seen in the CMB are missing in today's Universe
  → likely hiding in Warm/Hot IGM (WHIM) and or CGM.

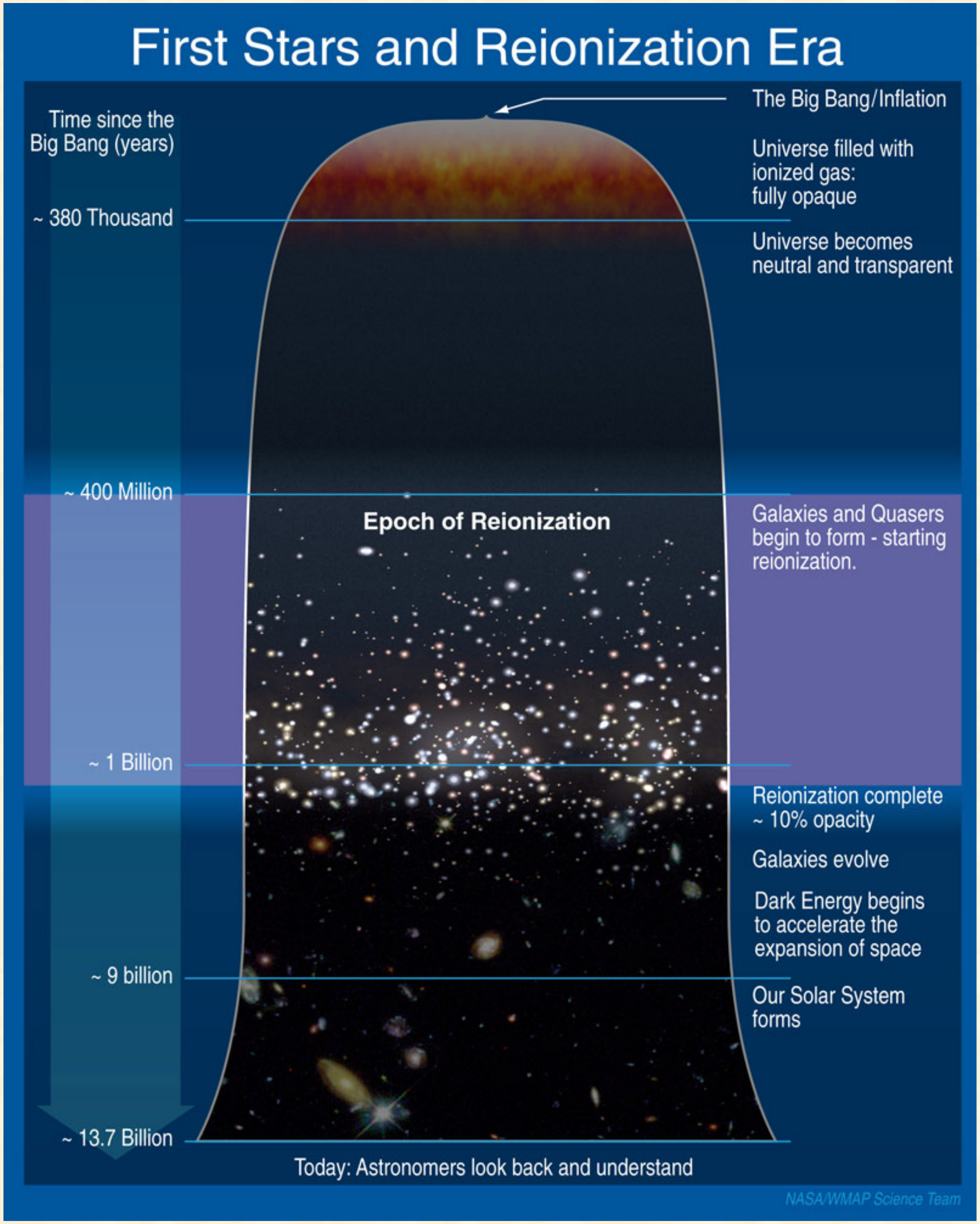
1) Lyα Forest (Diffuse IGM)

QSO1422+23, z(emis) = 3.62

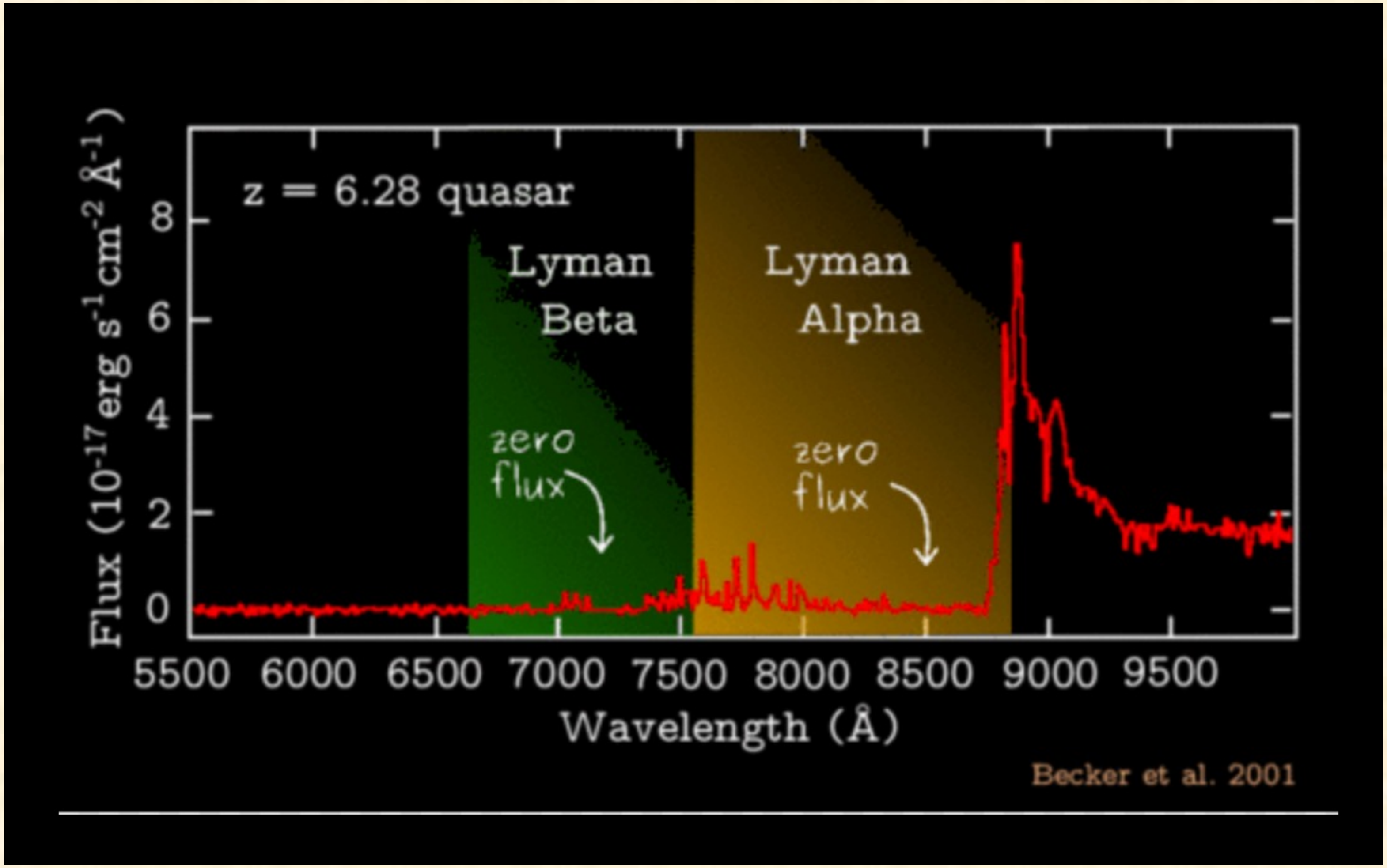


(Rauch, 1998, ARAA, 36, 267)

- Seen as narrow Lyα absorption lines in quasars at $z_{abs} < z_{emis}$.
- Intervening low-column clouds in the IGM ($N_H \approx 10^{14} - 10^{15}$ cm^{-2})
- $T \approx 10^4$ K, Z (metallicity) ≈ 0.1
- Discrete IGM clouds photoionized at the epoch of reionization at $6 < z < 20$ (150 million to one billion years after the Big Bang).

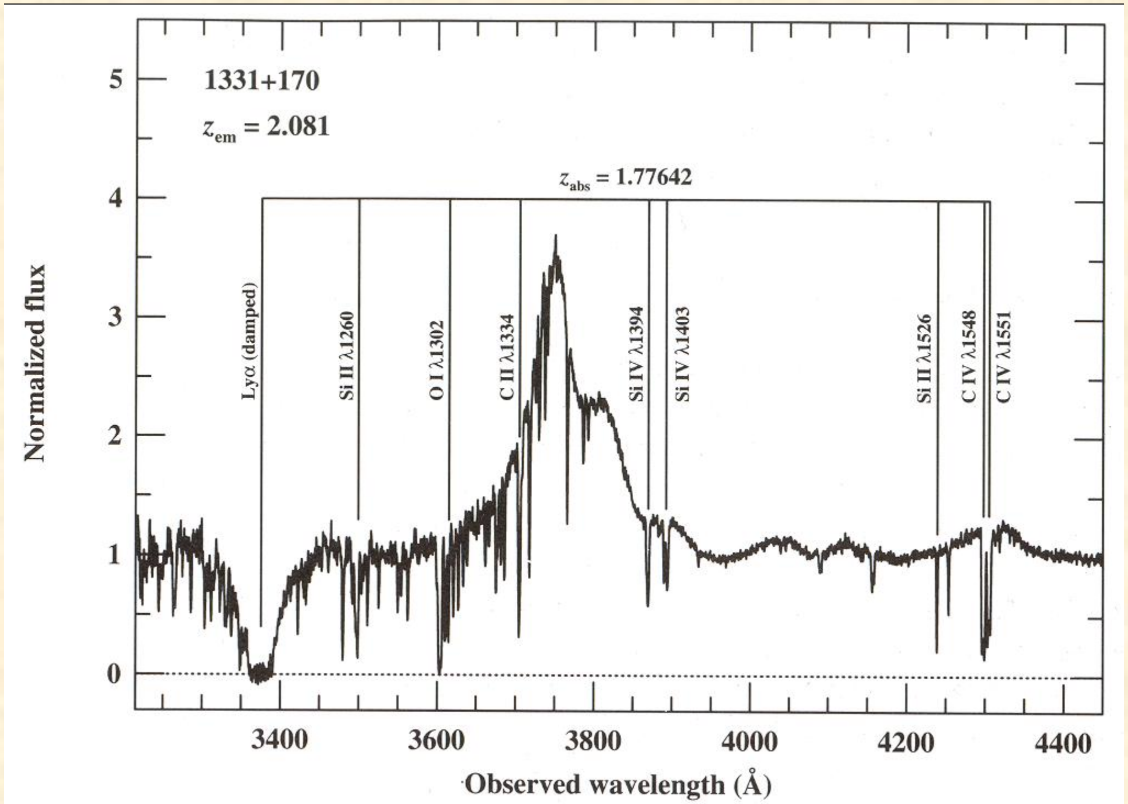

First Stars and Reionization Era
Time since the Big Bang (years)
~ 380 Thousand
~ 400 Million
~ 1 Billion
~ 9 billion
~ 13.7 Billion
The Big Bang/Inflation
Universe filled with ionized gas: fully opaque
Universe becomes neutral and transparent
Epoch of Reionization
Galaxies and Quasars begin to form - starting reionization.
Reionization complete ~ 10% opacity
Galaxies evolve
Dark Energy begins to accelerate the expansion of space
Our Solar System forms
Today: Astronomers look back and understand
NASA/WMAP Science Team

Gunn-Peterson Effect (Trough)



- Total absorption of Lyman absorption at z = 6.2 (and lack of trough at z = 5.8) indicates end of reionization epoch at z ≈ 6.

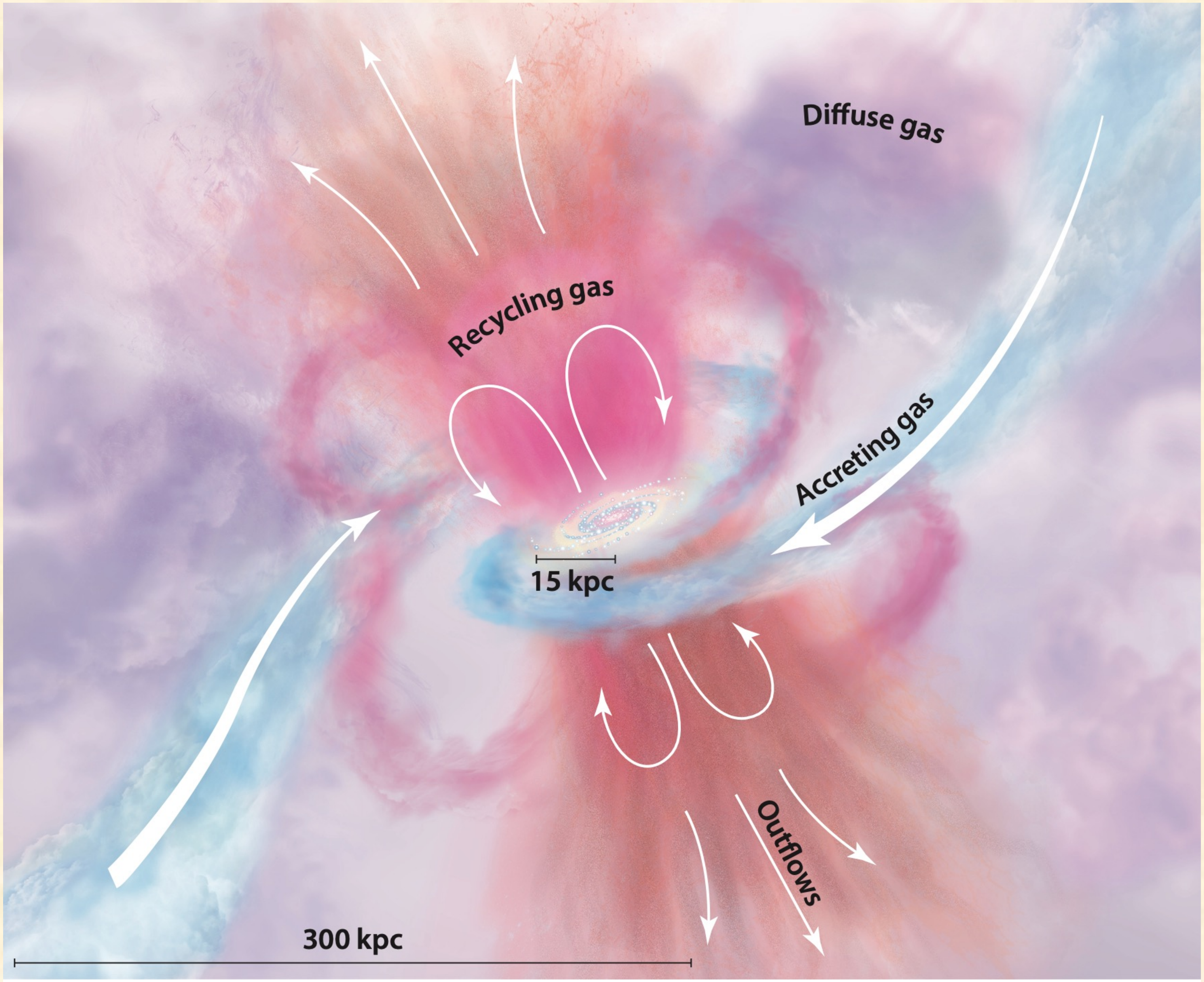
2) Circumgalactic Medium (CGM)



(Peterson, 1997, An Introduction to AGN, p. 201)

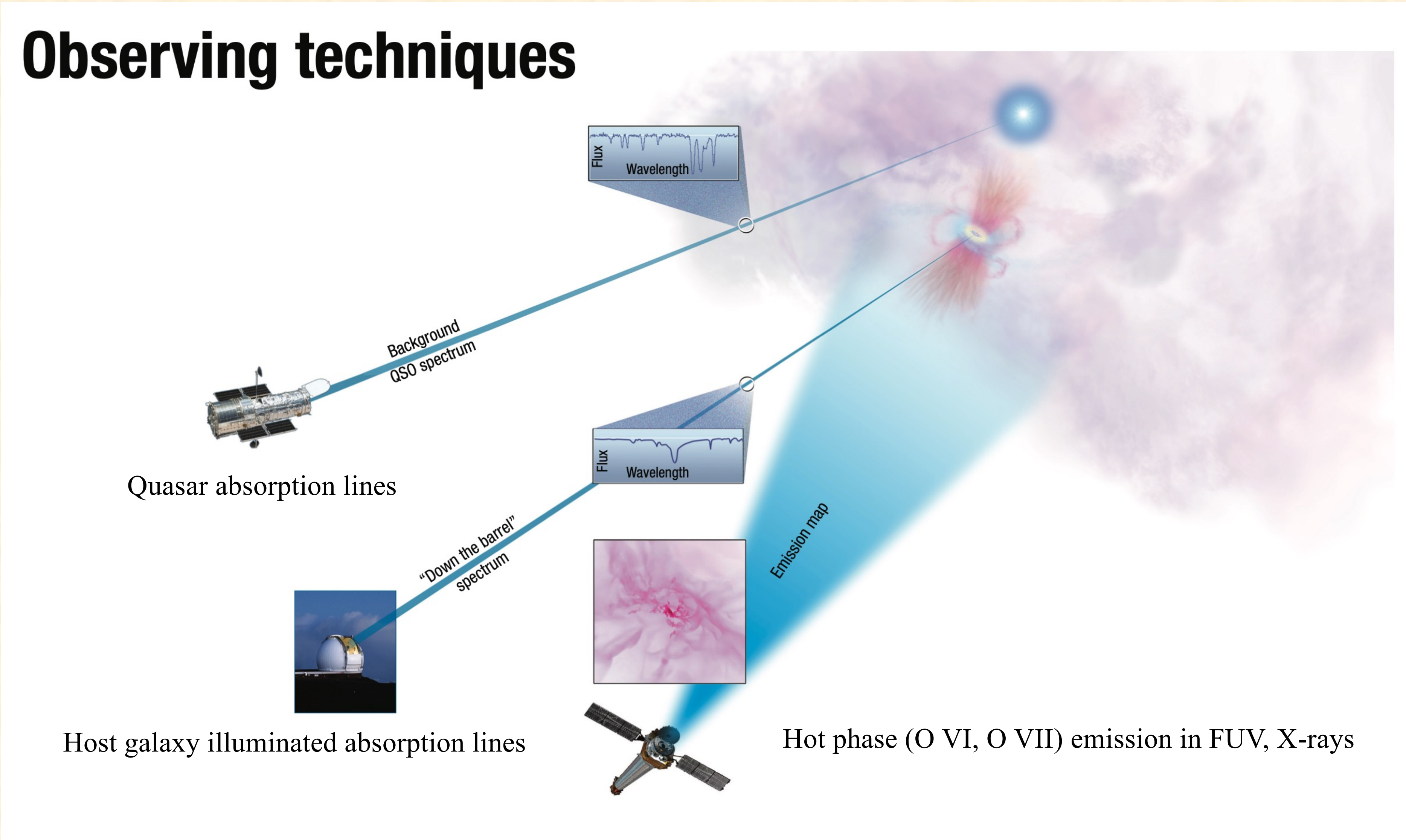
- ”Metal” lines seen in quasars at $z_{abs} < z_{emis}$ from intervening galaxies.
- Also known as “damped Lyα” systems due to their higher columns
- Low-ionization (C II, Si II, etc.) lines from galactic disks.
- High-ionization lines (C IV, N V, O VI, etc.) from galactic halos (CGM)
- CGM is photo- & collisionally ionized: $T \approx 10^{4.5-6}$ K, $n_H \approx 10^{-4 \text{ to } -6}$ cm^{-3}

CGM Dynamics



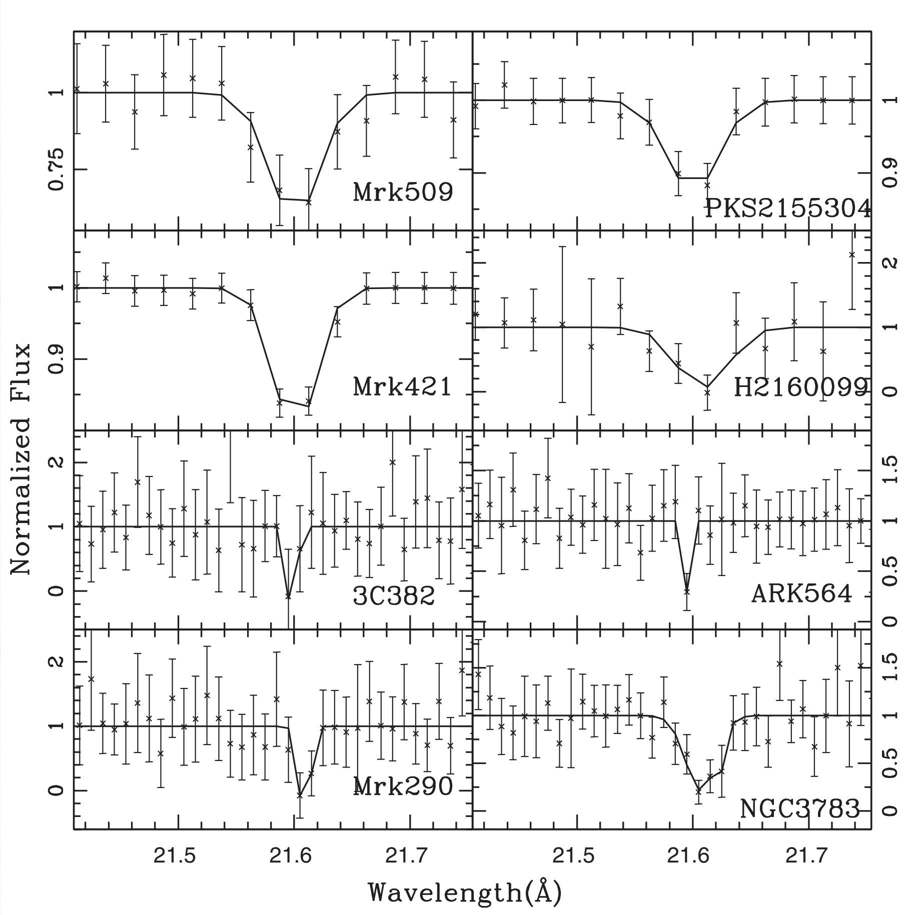
Tumlinson+, 2017, ARAA, 55, 389

CGM Observations



Tumlinson+, 2017, ARAA, 55, 389

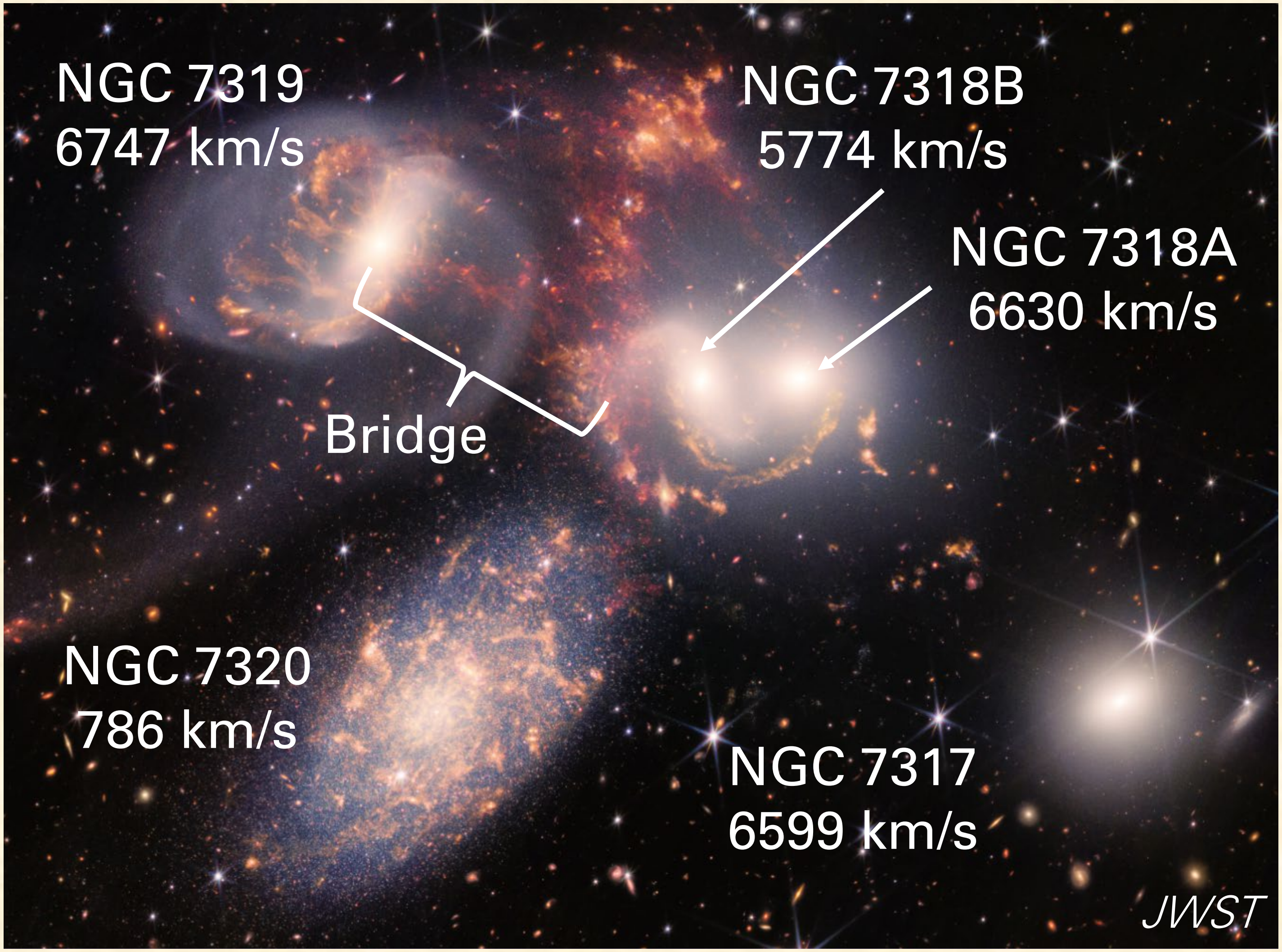
Hot CGM – Milky Way



(Gupta, 2012, ApJ, 756, L8.)

- Chandra X-ray spectra of AGN show O VII absorption at z ~ 0.
- $T \approx 10^6$ K, $n(H) \approx 10^{-4}$ cm^{-3} → hot gas around MW up to ~100 kpc.
- Most other galaxies in groups likely have hot halos.
- Is there a substantial intragroup medium? (hiding some of the missing mass)

Stephan's Quintet – Compact Group

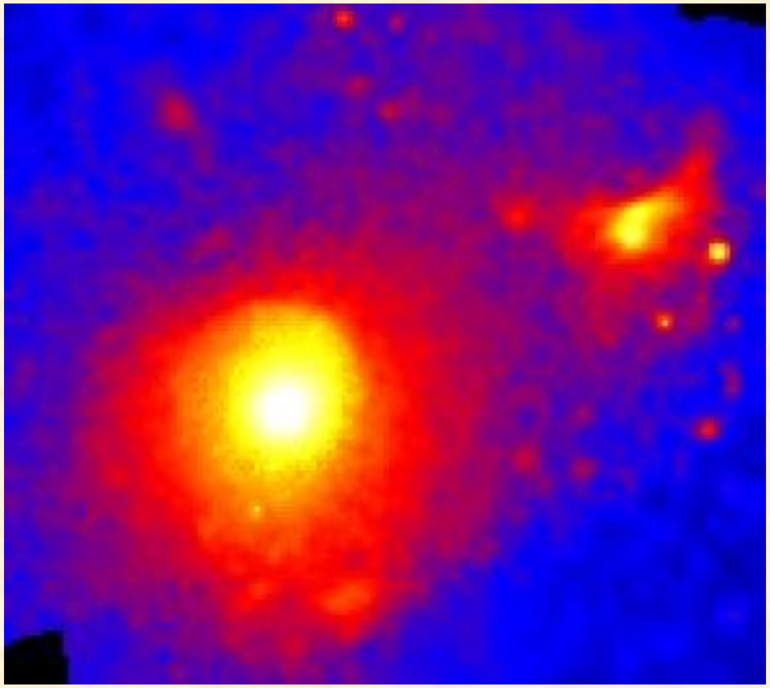


- NGC 7318B creates shock front in intragroup medium (https://chandra.harvard.edu/photo/2009/stephq/)
- Unclear how much gas there is outside of shock.

3) Intracluster Medium (ICM)

- Virgo: nearest rich cluster at ~ 16 Mpc
- Home of cD galaxy (and AGN) M87 in core
- Relatively loose and irregular in shape
- Kinematics: infalling galaxies at edges – still growing

Chandra X-ray Image



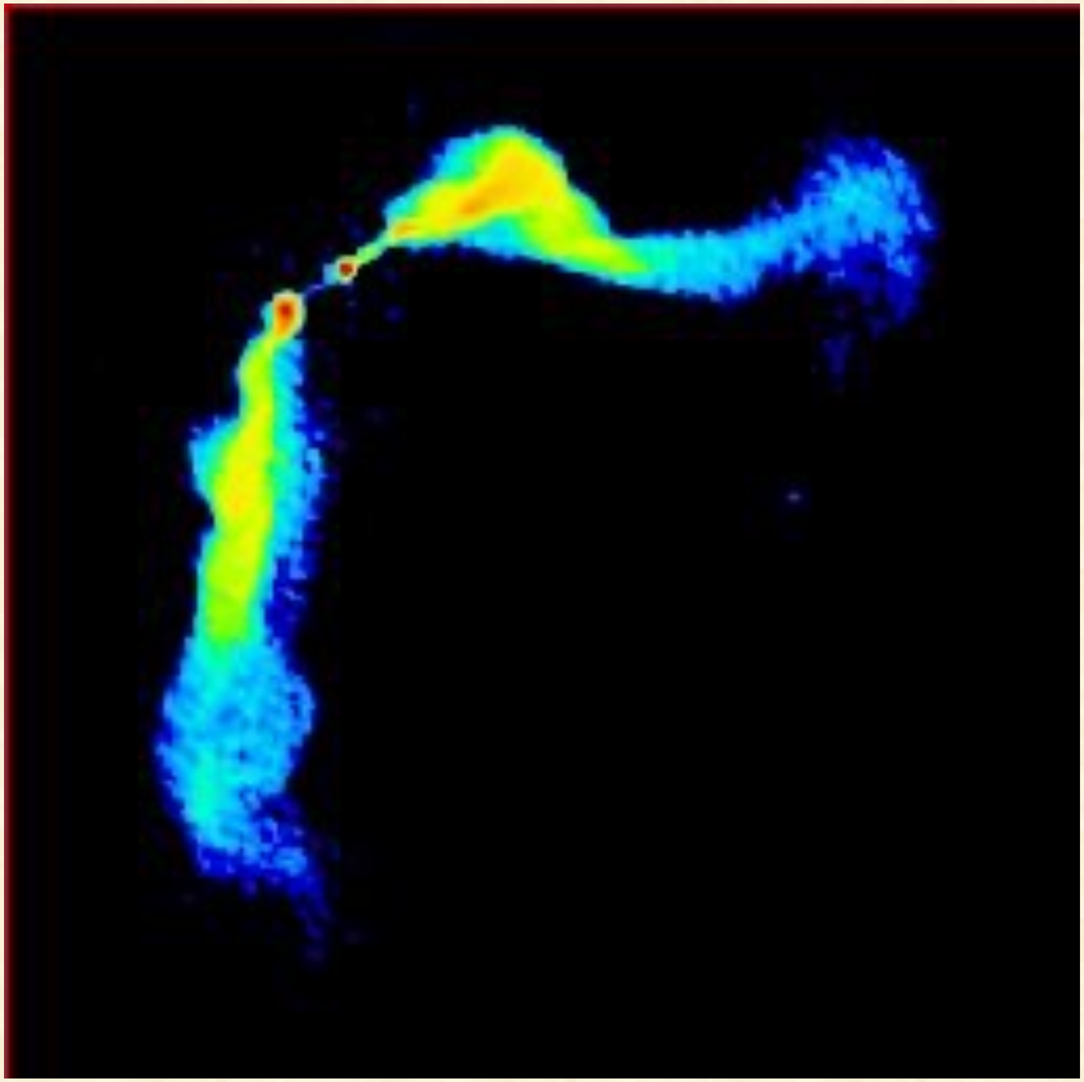
HST Visible Image

Intracluster Medium (ICM)

- X-ray observations: hot ($T = 10^7$ to 10^8 K) intracluster gas
  - 3 to 6 times the stellar mass.
  - Cooling is primarily due to bremsstrahlung radiation.
  - Likely comes from WHIM (cosmic web).

  → ongoing collapse of large-scale structure on these scales
- $Z \approx 1/3\ Z_{\odot}$ → enrichment from galactic outflows
- Ram pressure as galaxies move through cluster gas
  - Strips neutral gas in spirals, hot gas in E's; pushes back radio lobes

3C 465 in Abell 2634

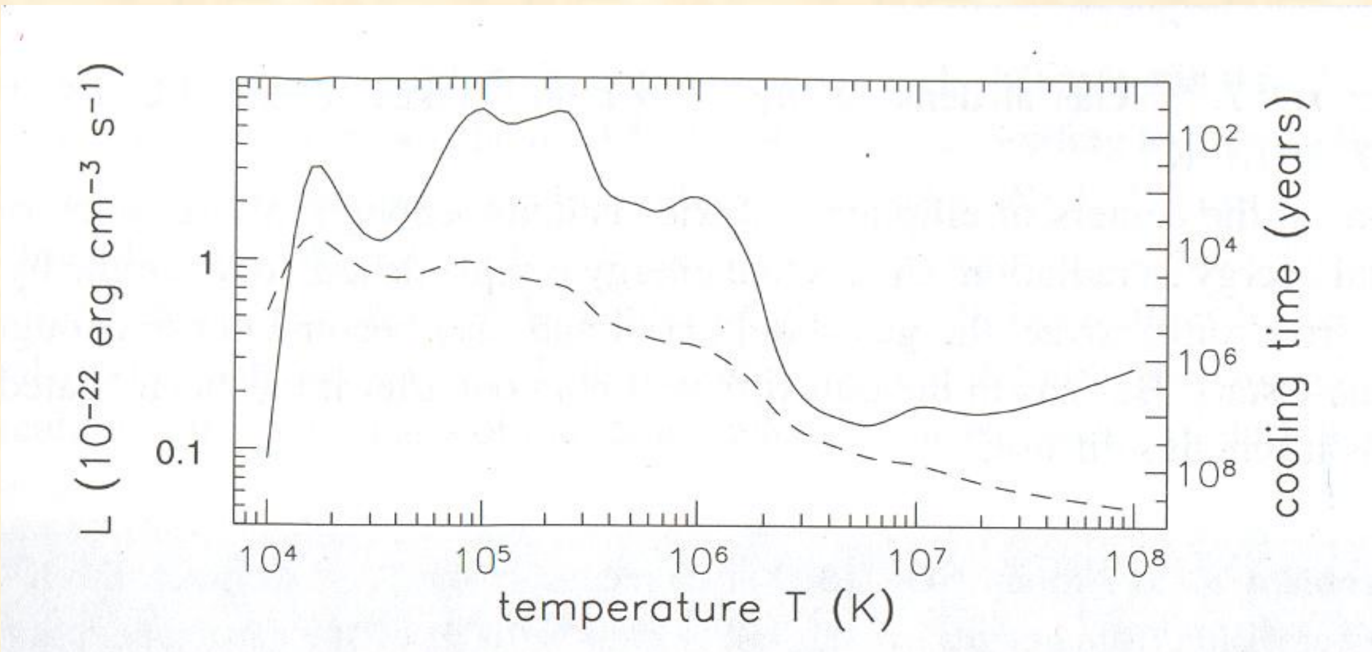


VLA 4.9 GHz image

Hot Gas in Giant Ellipticals (and cD Galaxies)

- X-ray missions (Einstein, ROSAT) discovered hot ($T \approx 10^7$ K) gas in nearby giant Es (now studied with Chandra and XMM).
- Gas is almost completely ionized – cooled by bremsstrahlung, H- and He-like emission lines from recombination.
- Fueled by ICM.

Cooling curve for gas with solar composition and $n_H = 1\ cm^{-3}$



solid – luminosity density, dashed – cooling time

Why is the gas so hot?

- Gas clouds are on random orbits like their progenitor stars
- Collisions between gas clouds:

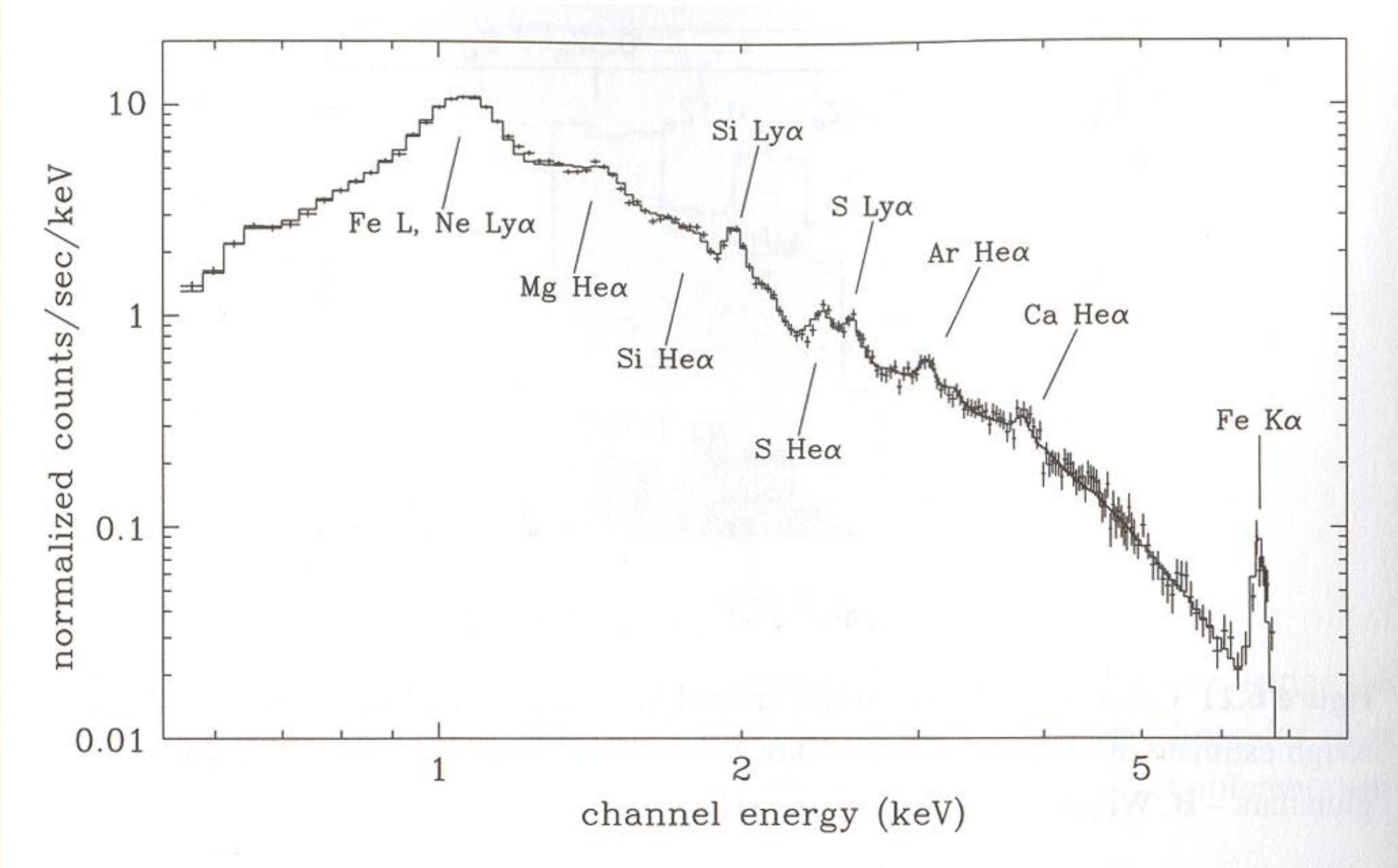
$$kT = m_p\sigma^2 \;\; \rightarrow T = 6 \text{ x } 10^6 \left(\frac{\sigma}{300 \text{ km s}^{-1}}\right)^2 \text{ K}$$

- The cooling time is: $t_{cool} \approx n_H^{-1}\, T^{1/2}$ at these high temperatures.
- At centers of giant E's, the gas may be dense ($n_H = 0.1$ cm^{-3}) enough to cool in ~ 1 Gyr → new star formation in core
- However, cooling flows are rarely observed.

  → gas likely heated by AGN feedback.
- Above equation applies to gas and galaxies moving in ICM of rich clusters at ~1000 km s^{-1}.

  → Gas Temperatures up to ~10^8 K

ASCA X-ray Spectrum of Hot Gas around M87

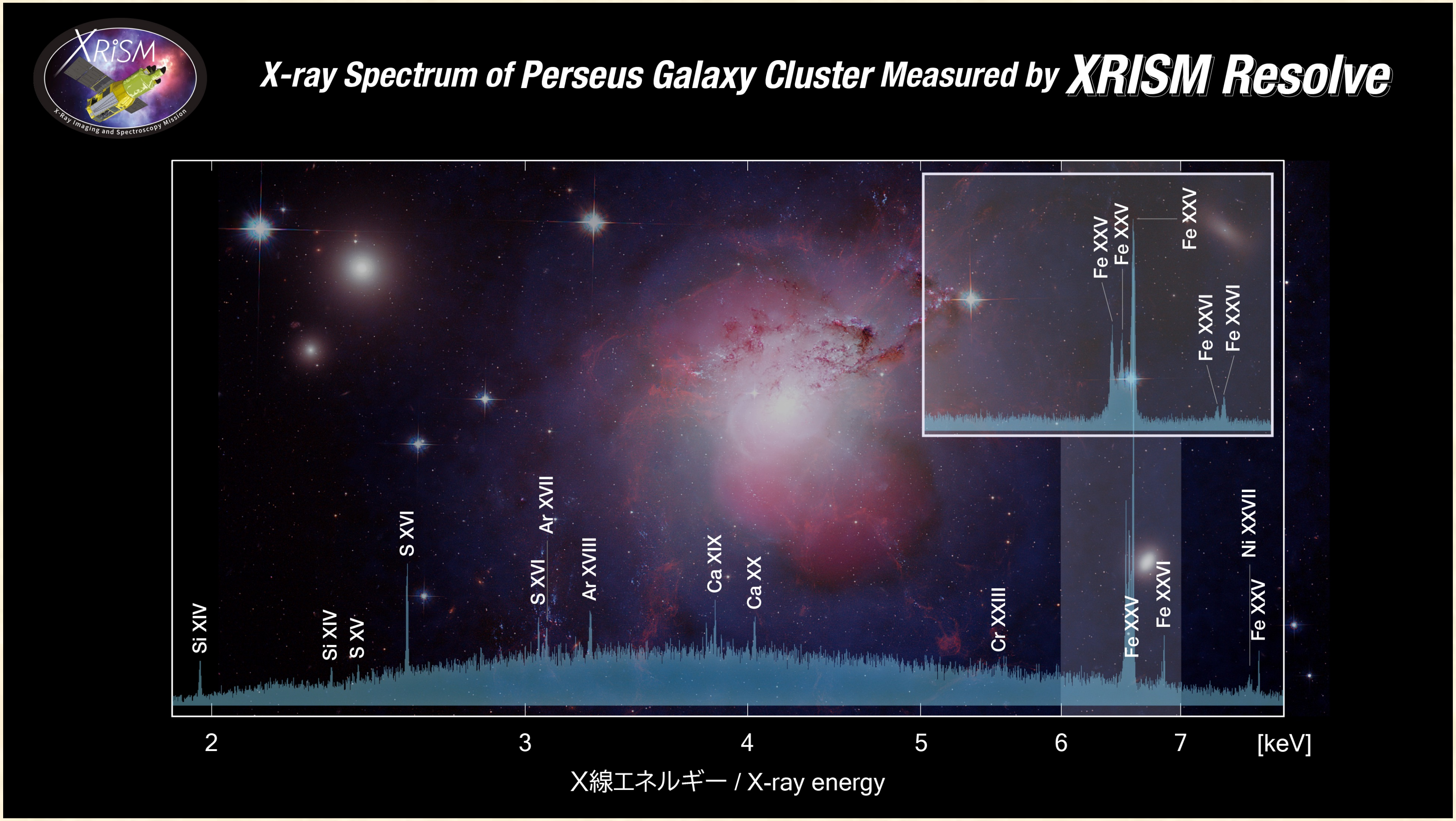


(Sparke & Gallagher, p. 272)

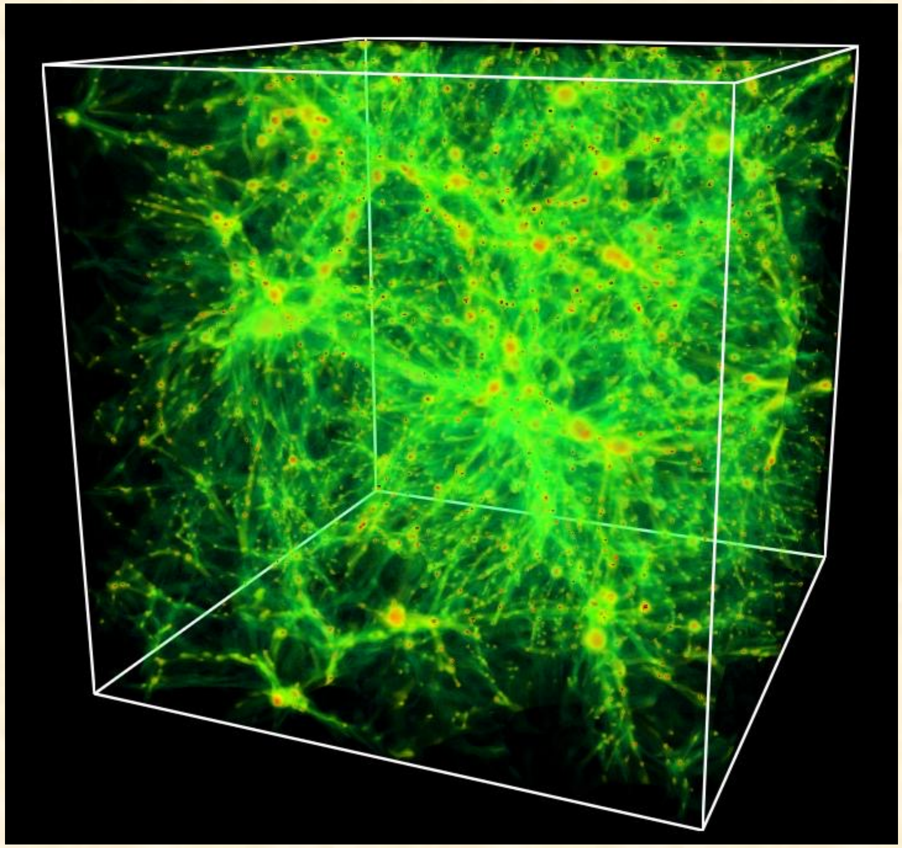
- H and He-like emission lines in addition to bremmstrahlung
- $Z = 0.5\ Z_\odot$ → material ejected by RG and AGB stars

($1 - 2\ M_\odot\ yr^{-1}$ per $10^{10}\ L_\odot$)

XRISM Observations of ICM



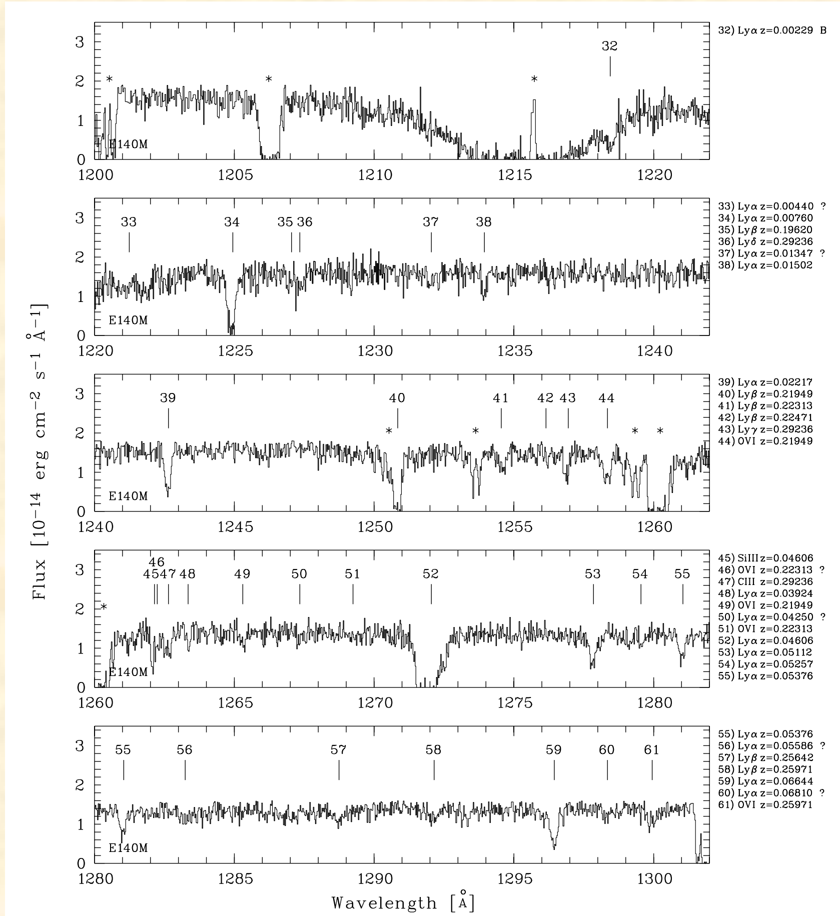
4) Warm/Hot Intergalactic Medium (WHIM)

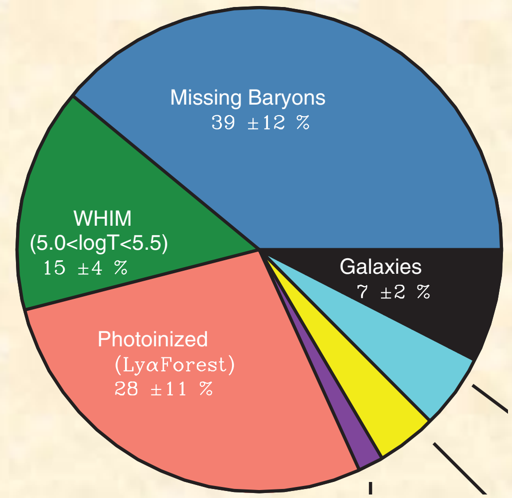


- Predicted by cosmological simulations to have web-like structure at $T = 10^{5-7}$ K.
- Still streaming into galaxy clusters and groups at $z \approx 0$.
- Likely contains ~1/2 of the baryons in the Universe.

Warm WHIM – Detected

FUSE + HST/STIS observations of quasar PG 1259+593



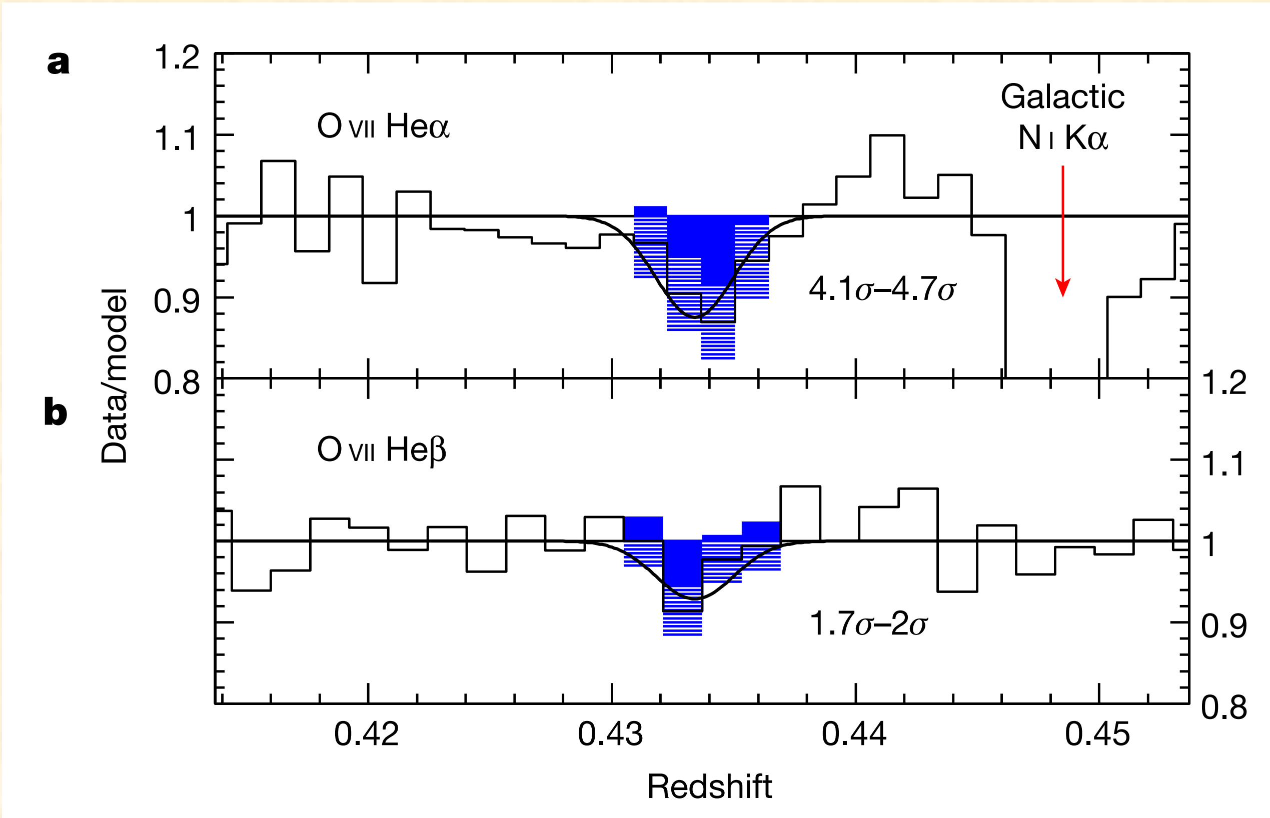


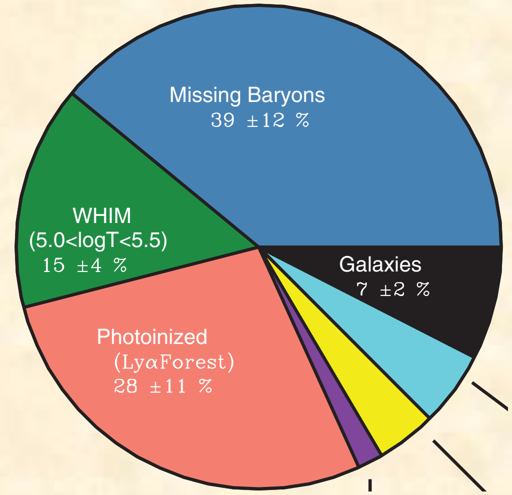
(Richter+ 2004, ApJS, 153, 165

- WHIM warm phase: T ≈ $10^{5-5.5}$ K, detected in O VI absorption
- 15% of baryons in Universe
- Above: 6 intervening (IGM) detections of O VI

Hot WHIM – Detected?

XMM-Newton spectrum of blazar 1ES 1553+113





(Nicastro+ 2018, Nature, 558, 406.)

- WHIM hot phase: T ≈ 10^6 K, detected in O VII absorption
- 9% – 40% of baryons in Universe (could be part or all of missing mass)
- WHIM in very hot phase (T ≈ 10^7 K) uncertain.
- Large area X-ray telescopes needed for O VII, O VIII absorption, emission