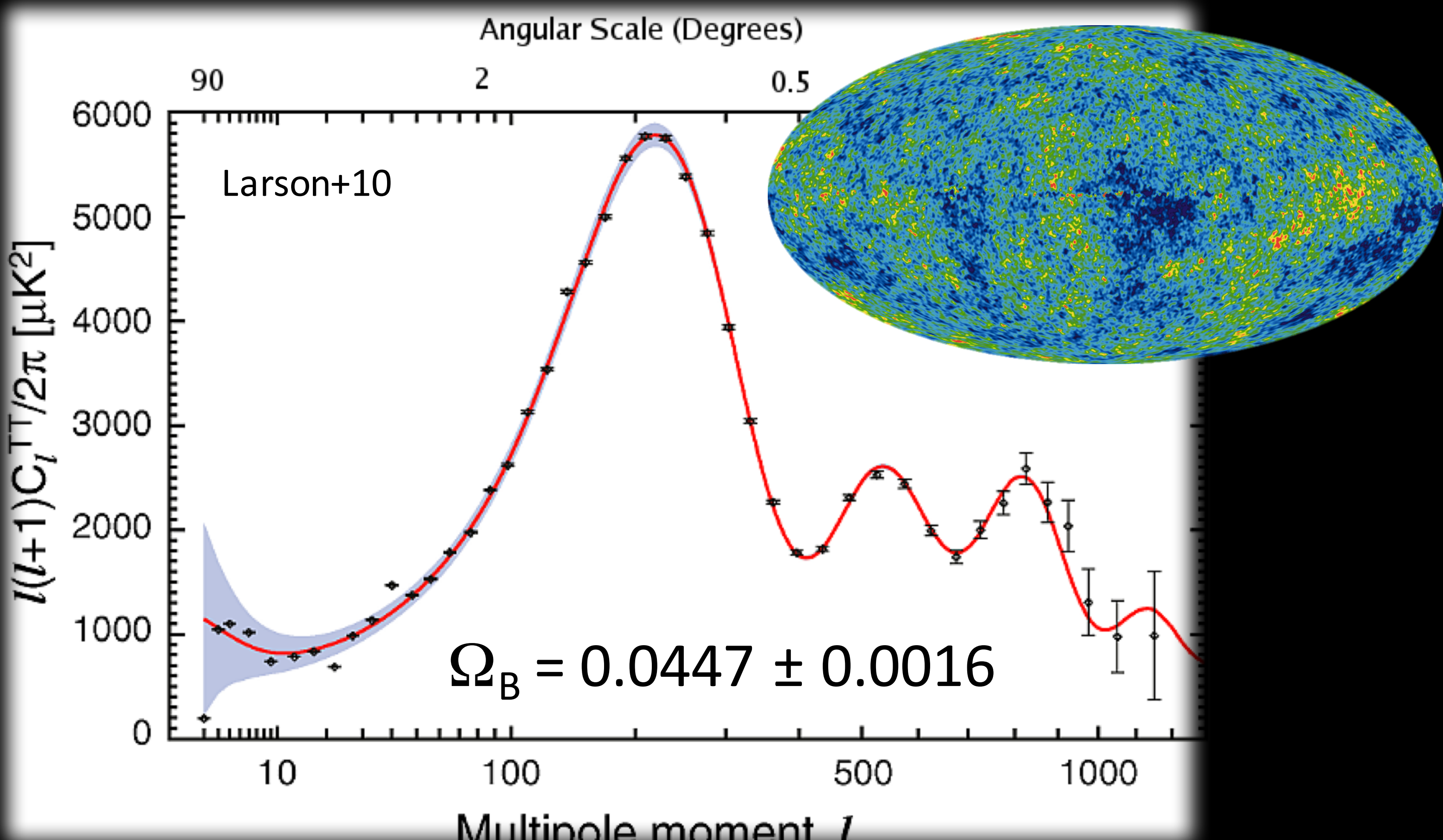
Metal Absorption in the IGM
or
Where the Universe Really is…

The Cosmic Baryon Fraction: CMB



Estimating Ω_B: CMB (WMAP7)

WMAP Cosmological Parameters

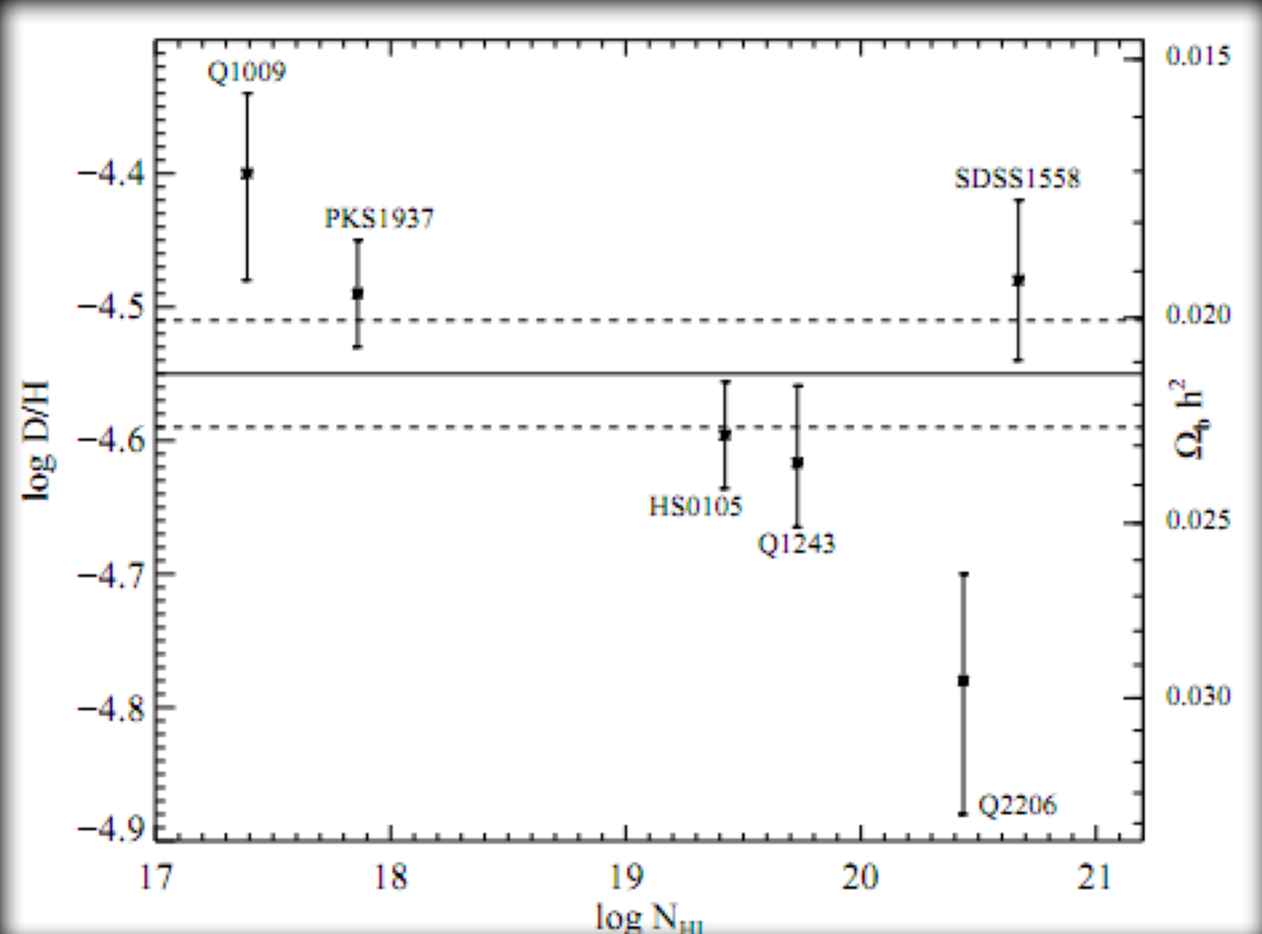
Model: lcdm+sz+lens+iso1

Data: wmap7+bao+h0

$10^2\Omega_b h^2$	$2.269^{+0.053}_{-0.054}$	$1-n_s$	0.028 ± 0.013
$1-n_s$	$0.0017 < 1-n_s < 0.0526$ (95% CL)	$A_{\rm BAO}(z=0.35)$	0.463 ± 0.011
α_{-1}	< 0.0047 (95% CL)	C_{220}	5762^{+36}_{-37}
$d_A(z_{\rm eq})$	14219^{+129}_{-128} Mpc	$d_A(z_*)$	14054^{+130}_{-129} Mpc
$\Delta^2_{\mathcal{R}}$	$(2.358^{+0.100}_{-0.098}) \times 10^{-9}$	h	0.713 ± 0.014
H_0	71.3 ± 1.4 km/s/Mpc	$k_{\rm eq}$	0.00983 ± 0.00026
$\ell_{\rm eq}$	$138.1^{+2.5}_{-2.6}$	ℓ_*	$301.90^{+0.84}_{-0.82}$
n_s	0.972 ± 0.013	Ω_b	0.0447 ± 0.0016
$\Omega_b h^2$	$0.02269^{+0.00053}_{-0.00054}$	Ω_c	0.221 ± 0.014
$\Omega_c h^2$	$0.1119^{+0.0034}_{-0.0035}$	Ω_Λ	0.734 ± 0.015
Ω_m	0.266 ± 0.015	$\Omega_m h^2$	$0.1346^{+0.0035}_{-0.0036}$
$r_{\rm hor}(z_{\rm dec})$	284.8 ± 1.9 Mpc	$r_s(z_d)$	152.7 ± 1.3 Mpc
$r_s(z_d)/D_v(z=0.2)$	$0.1923^{+0.0038}_{-0.0039}$	$r_s(z_d)/D_v(z=0.35)$	$0.1153^{+0.0020}_{-0.0021}$
$r_s(z_*)$	146.2 ± 1.1 Mpc	R	1.719 ± 0.010
σ_8	0.811 ± 0.024	A_{SZ}	$0.95^{+0.68}_{-0.95}$
t_0	$13.69^{+0.12}_{-0.11}$ Gyr	τ	$0.085^{+0.014}_{-0.013}$
θ_*	$0.010406^{+0.000028}_{-0.000029}$	θ_*	$0.5962^{+0.0016}_{-0.0017}$ °
t_*	378115^{+3204}_{-3124} yr	$z_{\rm dec}$	1088.1 ± 1.1
z_d	1020.6 ± 1.3	$z_{\rm eq}$	3224^{+85}_{-87}
$z_{\rm reion}$	$10.2^{+1.2}_{-1.1}$	z_*	$1090.73^{+0.68}_{-0.69}$

The Cosmic Baryon Fraction: BBN

$\Omega_B = 0.043 \pm 0.003$

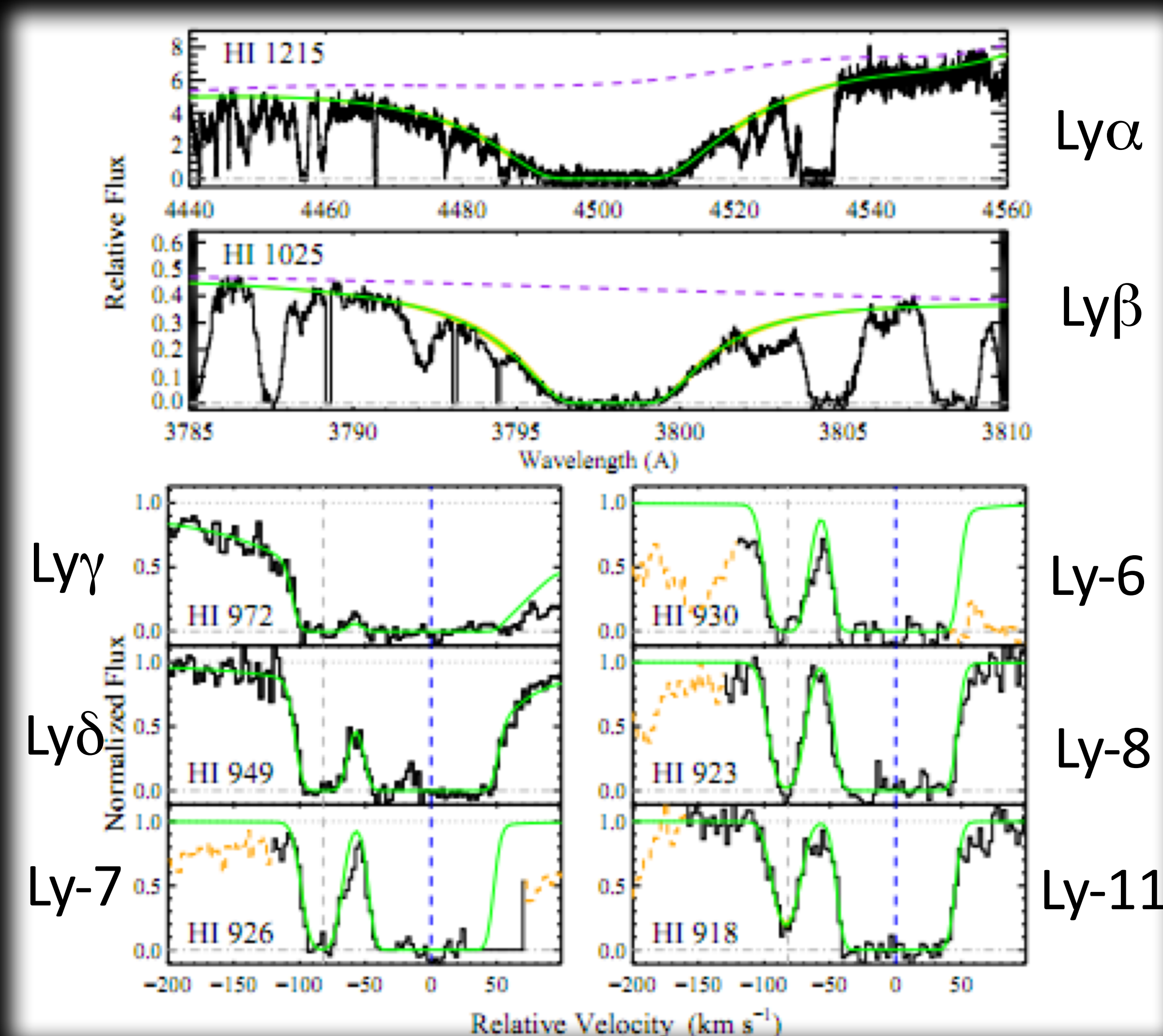


O`Meara+06

Estimating Ω_B: D/H ratio

- Compare light elements abundances (H, D, ^3He, ^4He, Li) against BBN.
- Sensitive to photon-to-baryon ratio @ BBN
- D only created during BBN, later astrated
- N(D I) / N(H I) ~ D/H

Estimating Ω_B: D/H ratio



O`Meara+06

The local shining baryons

- $\rho_B = \Omega_B \, \rho_{crit} = 4 \times 10^{-31}$ g cm^{-3}

- $M_* \sim 10^{11} M_\odot$
- $n(L_*) \sim 0.01$ Mpc^{-3}
- $\rho_* \sim 4 \times 10^{-32}$ g cm^{-3}

Most of the baryonic mass in diffuse gas!

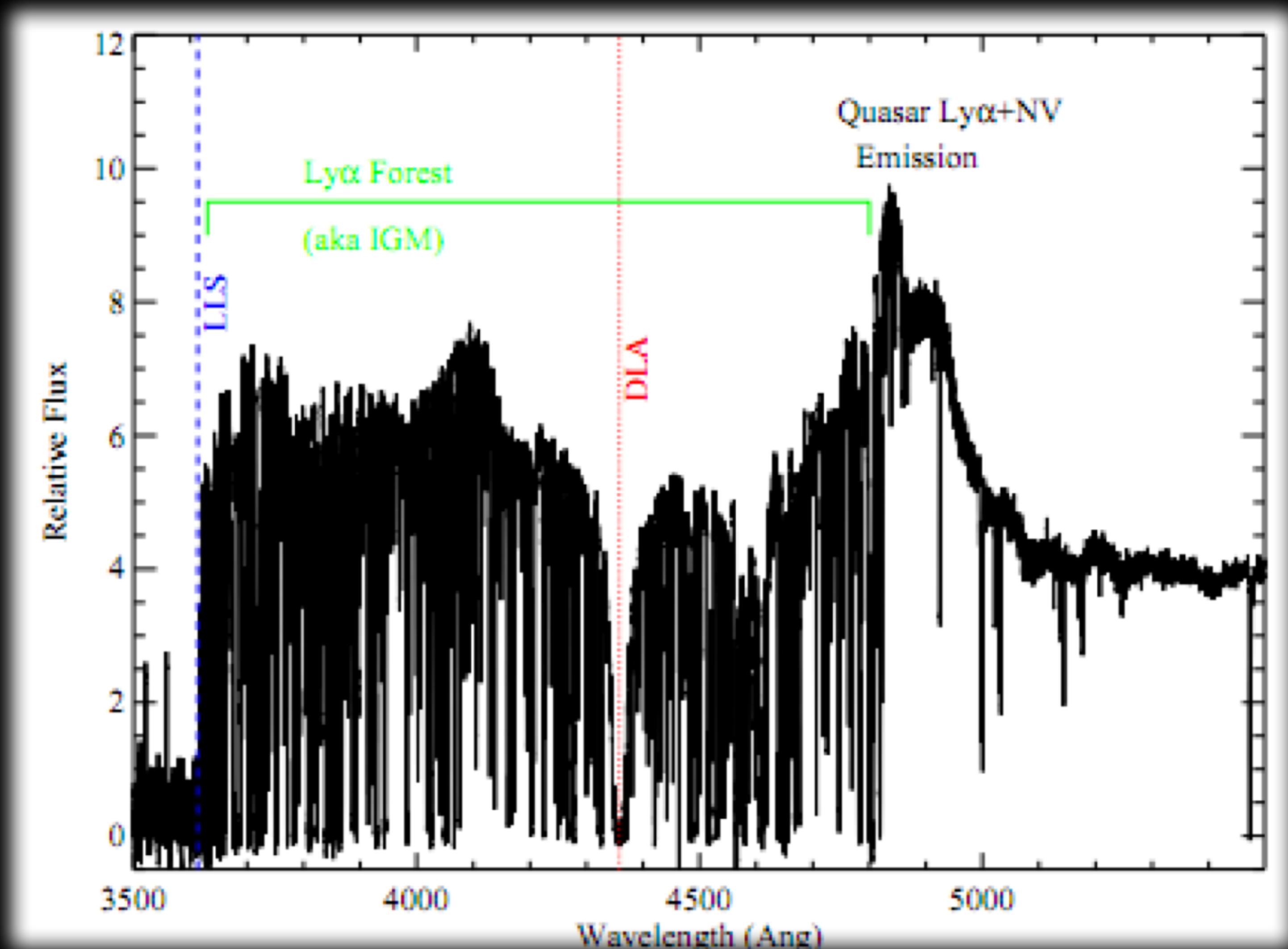
Baryons in the Universe

- > 90% of baryons in diffuse ionized gas
- Crucial component in galaxy and star formation
- Unfortunately – difficult to observe
- …and theoretical interpretations challenging

Principle Absorption Features

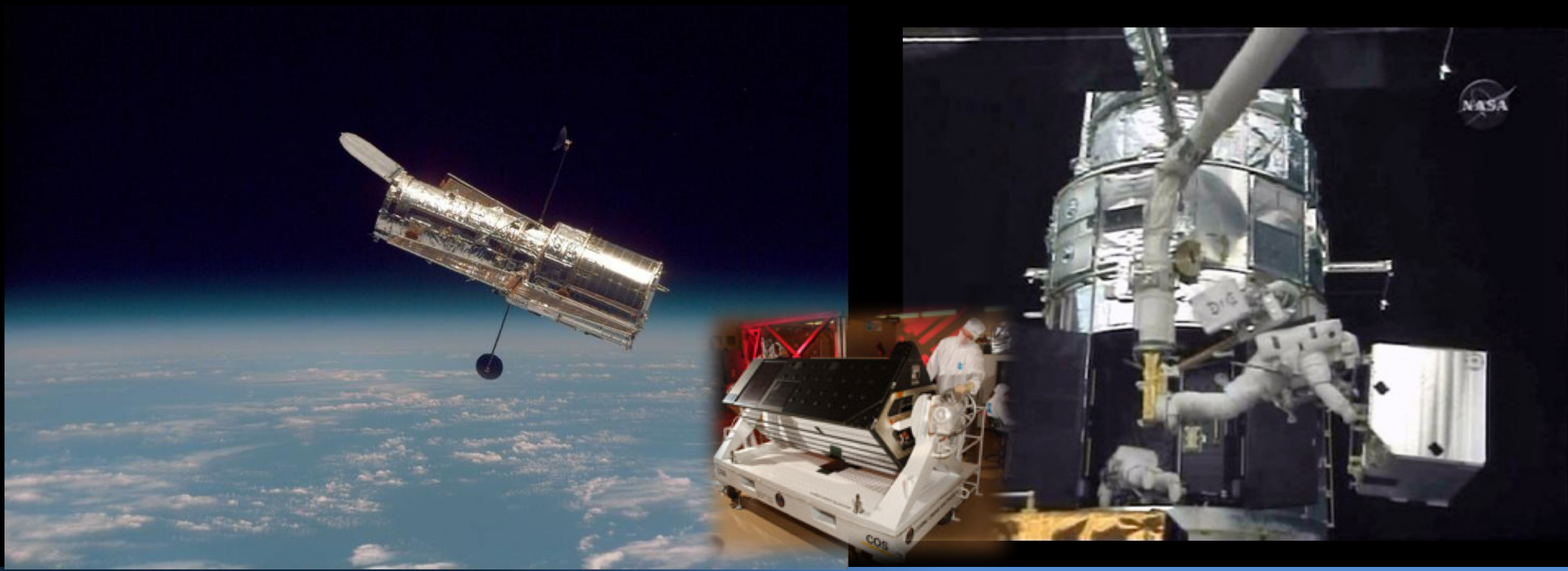
Line	Phase	T (K)	λ (A)
21cm	Atomic gas	100-1,000	21cm
Lyα	Atomic+Ionized	100-40,000	1216
Hα	Ionized gas	10,000-40,000	6560
Lyman limit	Ionized gas	10,000-40,000	912
He II	Ionized gas	10,000-40,000	304
C IV	Ionized gas	20,000-40,000	1550
O VI	Warm/hot gas	20,000-10^6	1030
OVII, OVIII	Hot gas	10^6-10^8	21.6, 18.9
Ne VIII	Hot gas	10^7	775

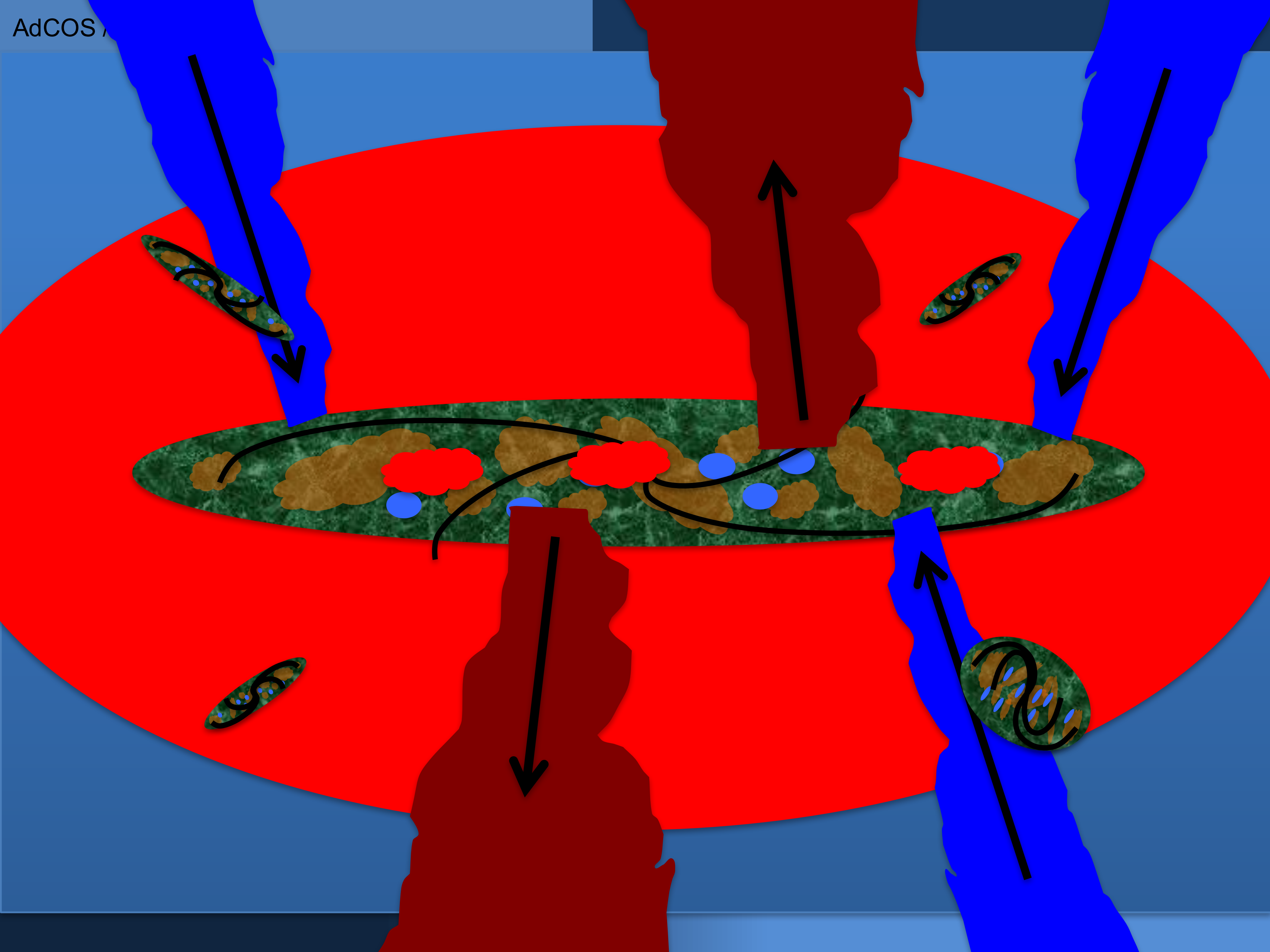
Absorption lines galore



Theoretical and Numerical studies of Plasma

- Understanding Astrophysical Plasma is challenging
  - Its whereabouts are uncertain
  - Departures from equilibrium impede interpretation



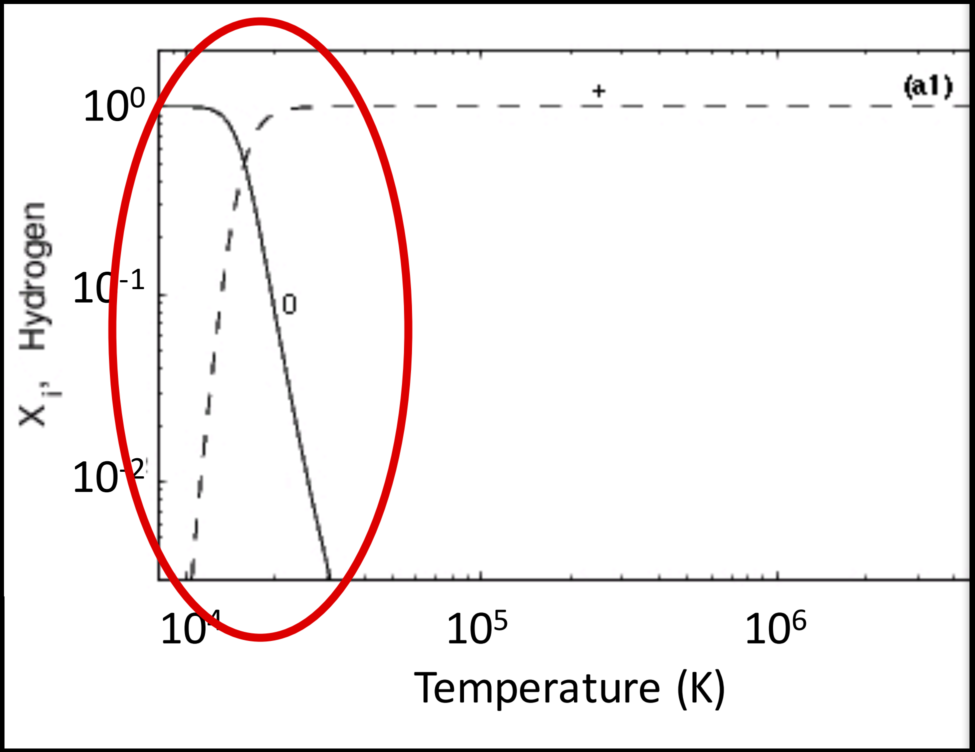


As a Result of these interactions

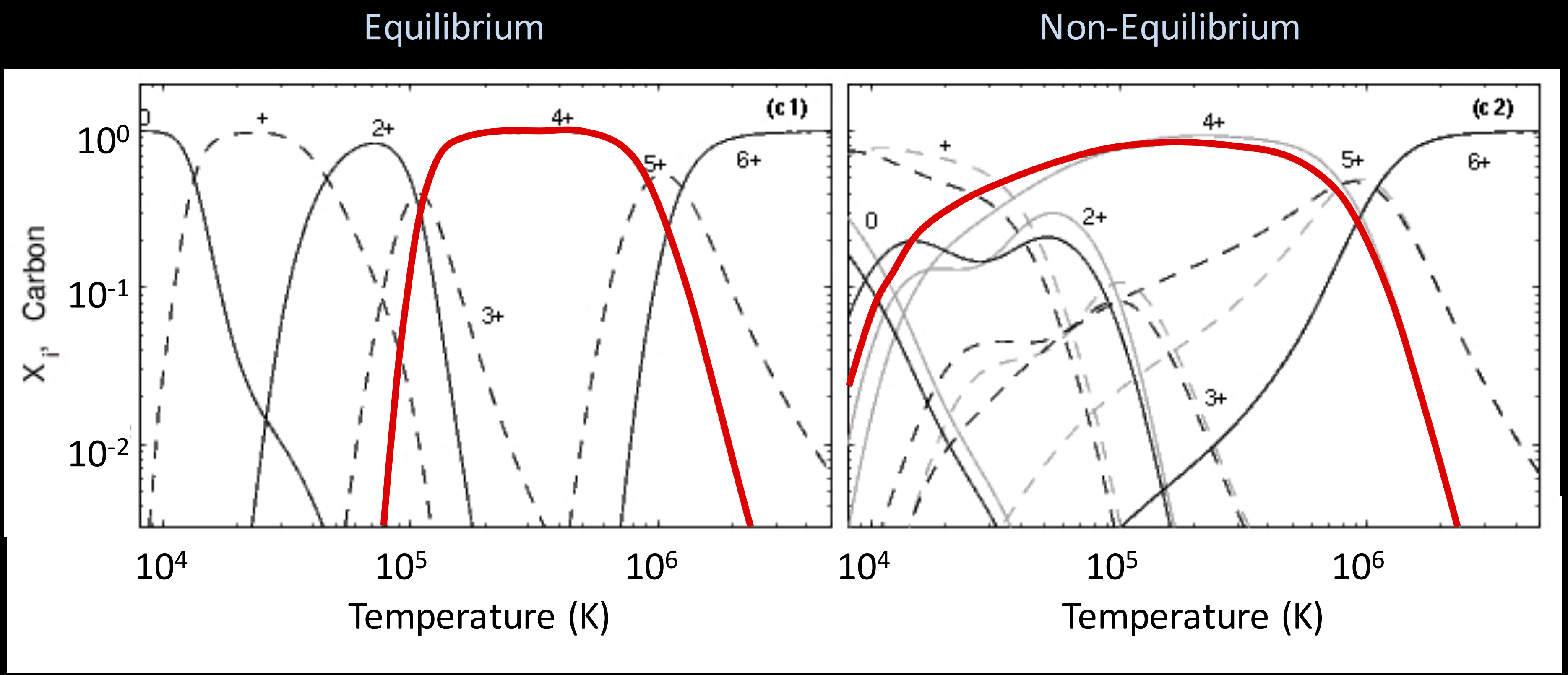
- UV Absorption Signatures!
- Departures from Equilibrium Ionization:
  - Shock Waves (e.g. virial shocks)
  - Cooling / Flash Heating
  - Condensation / Evaporation
  - Shearing & Mixing

Hydrogen Ionization in Collisional Plasma

Equilibrium



Results: Metal Ionization

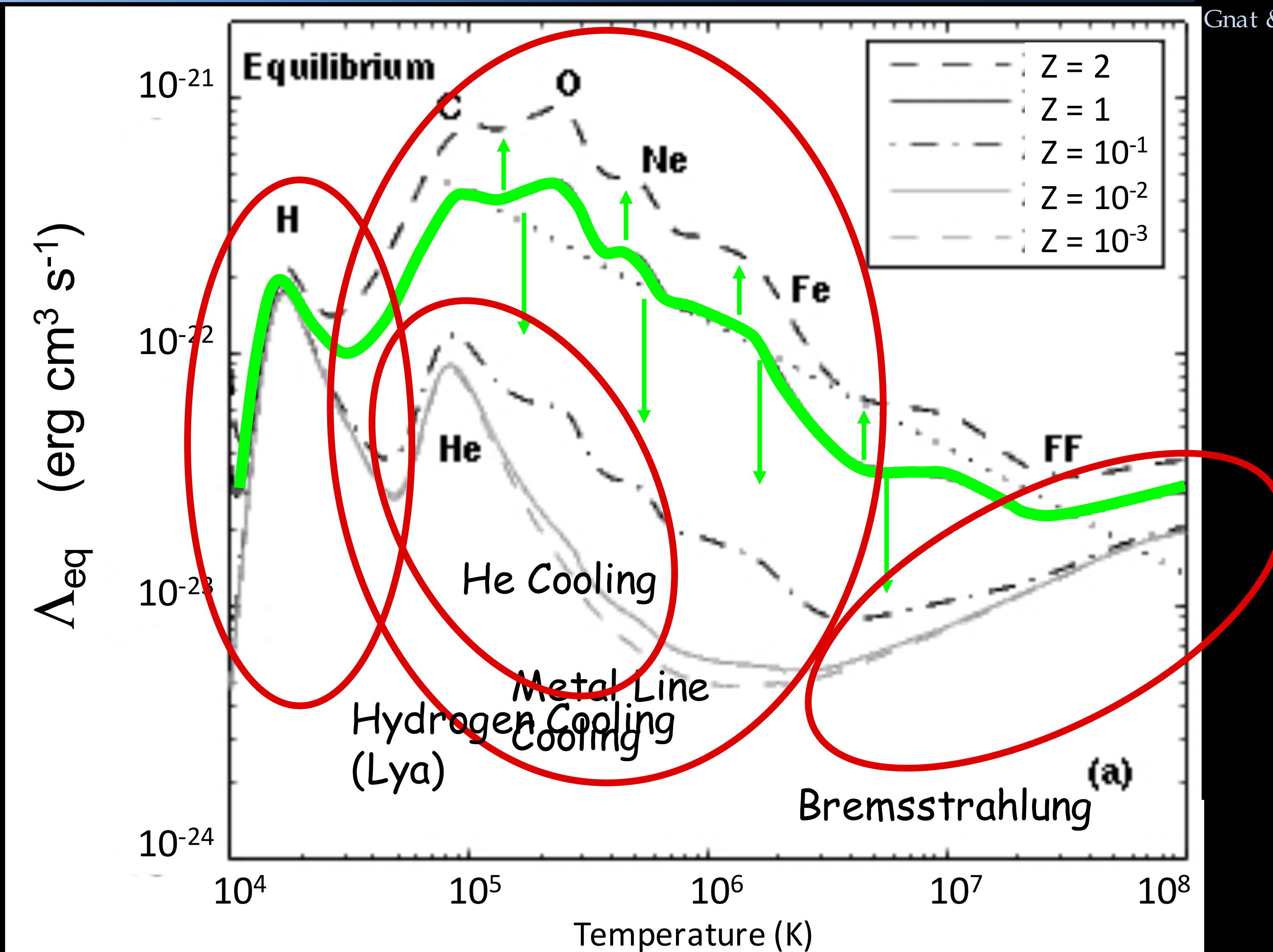


Gnat & Sternberg 2007
ApJS, 168, 213

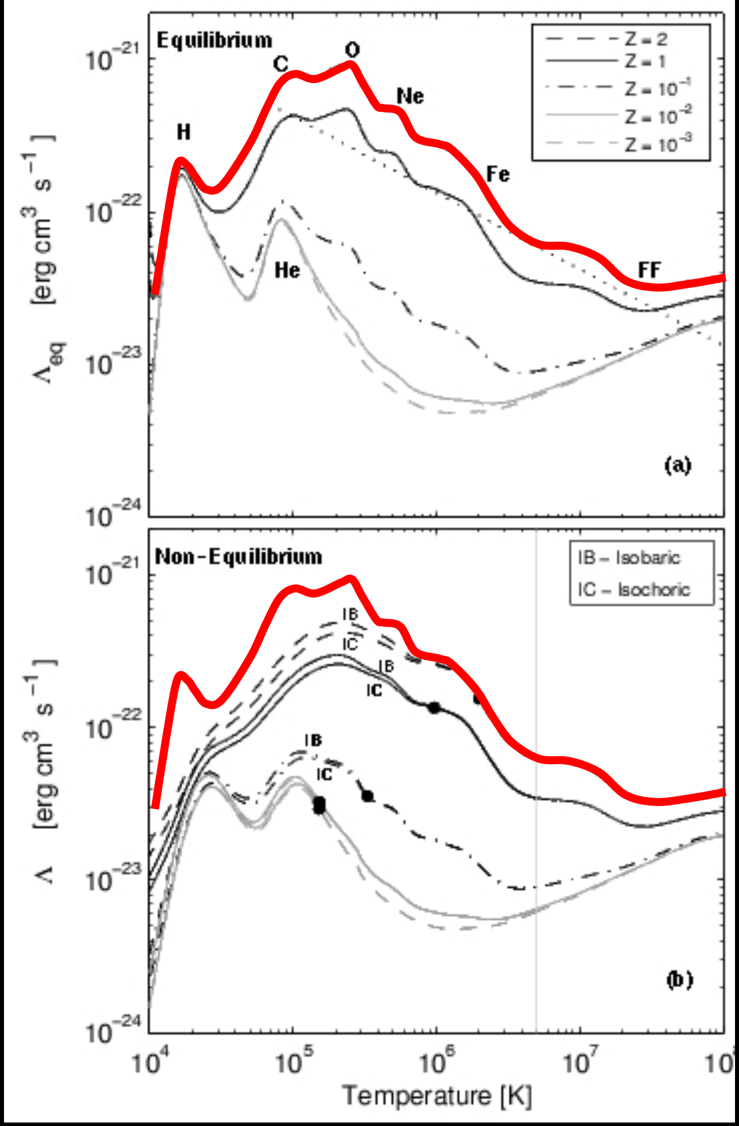
CIE Cooling

Gnat & Sternberg 2007
ApJS, 168, 213

cooling efficiency



Collisional Non-Equilibrium Cooling



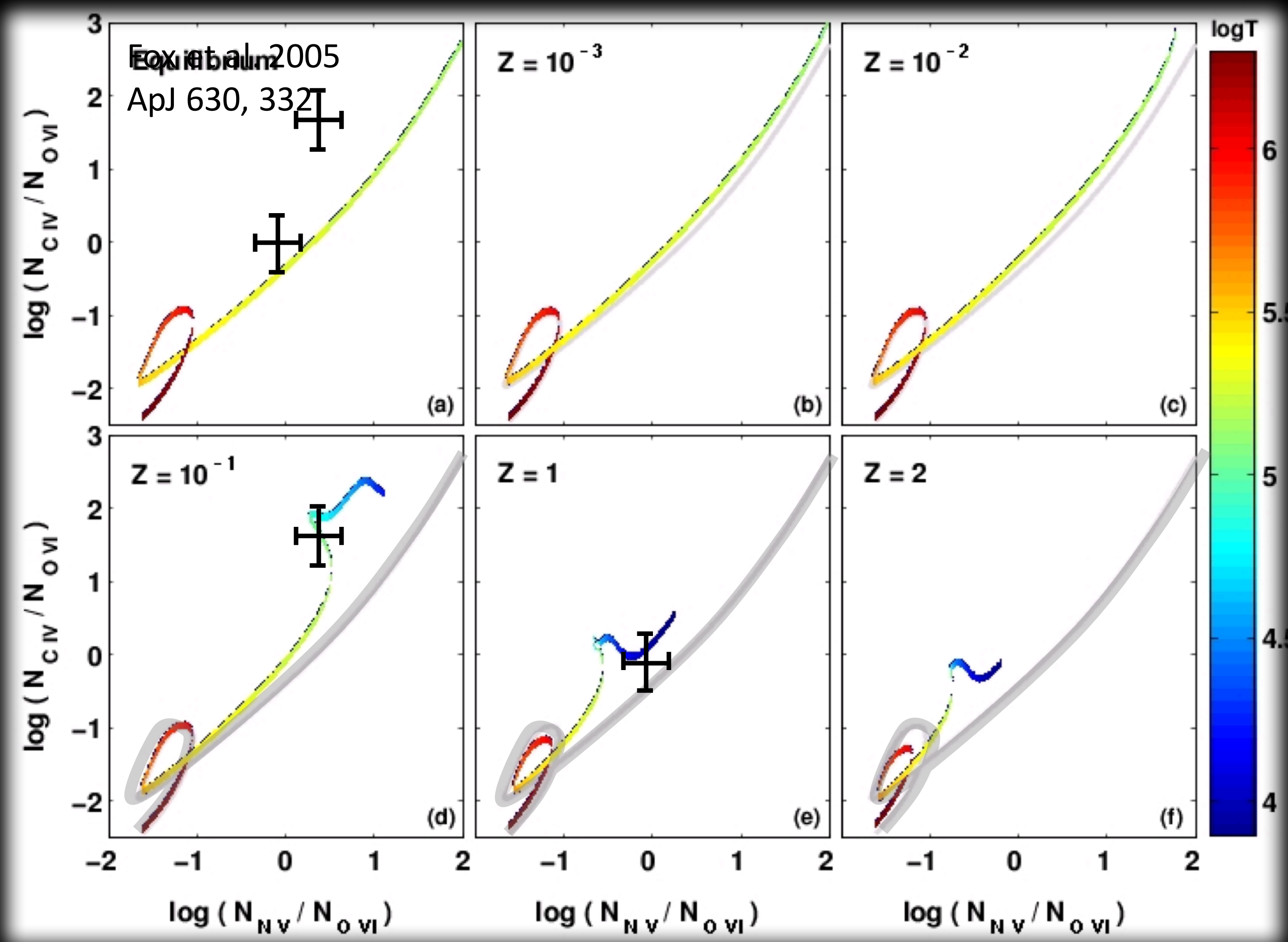
Gnat & Sternberg 2007
ApJS, 168, 213

Departures from Equilibrium...

- ...Modify Ion Fractions
- => Modified Cooling Efficiencies (thermal evolution)
- => Modified Diagnostics

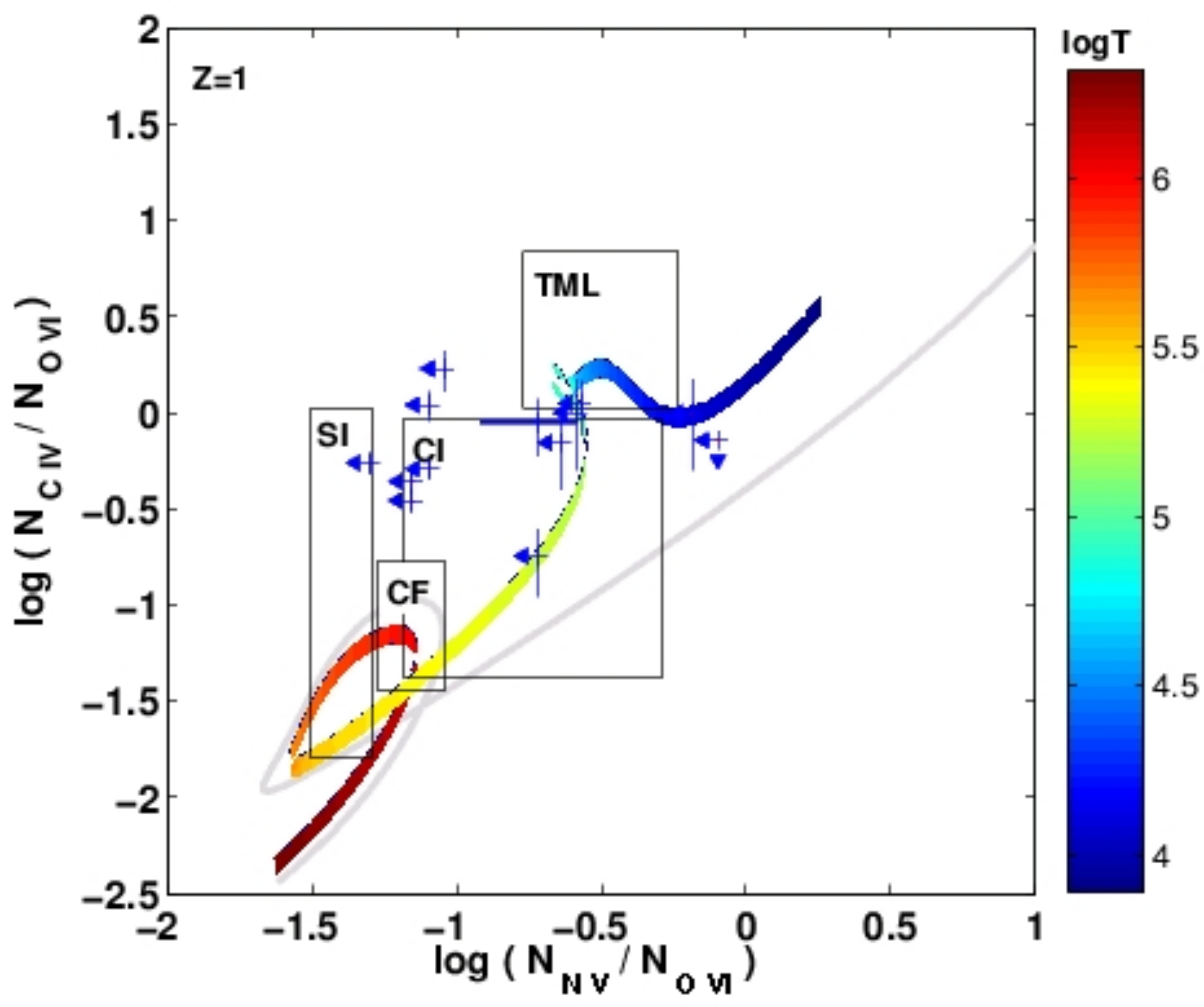
Not including Departures from Equilibrium
when interpreting observations
results in false interpretation
of the physical parameters!

Results: Diagnostics



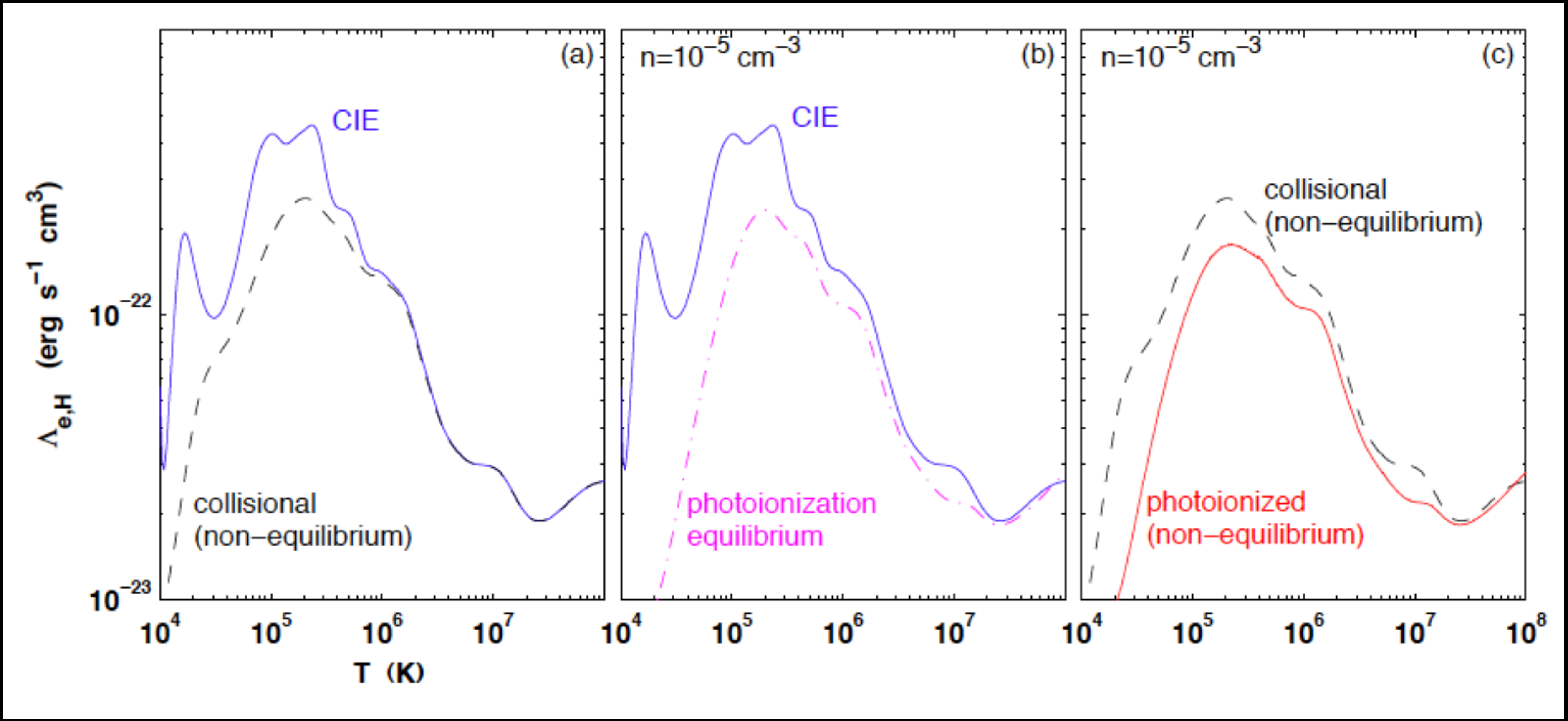
Gnat & Sternberg 2007 ApJS, 168, 213

Results: High-Velocity Metal-Absorbers

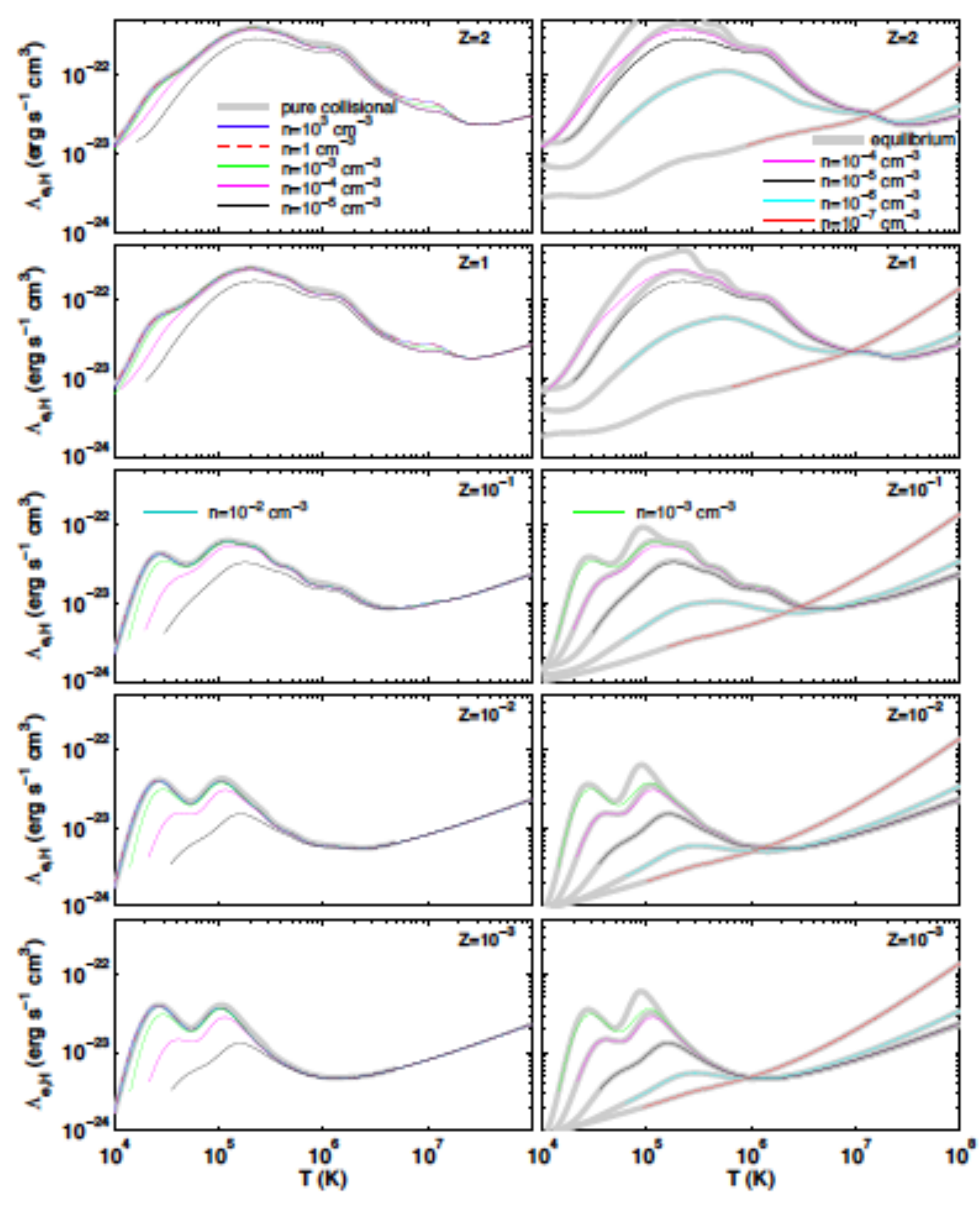


Gnat & Sternberg 2007
ApJS, 168, 213

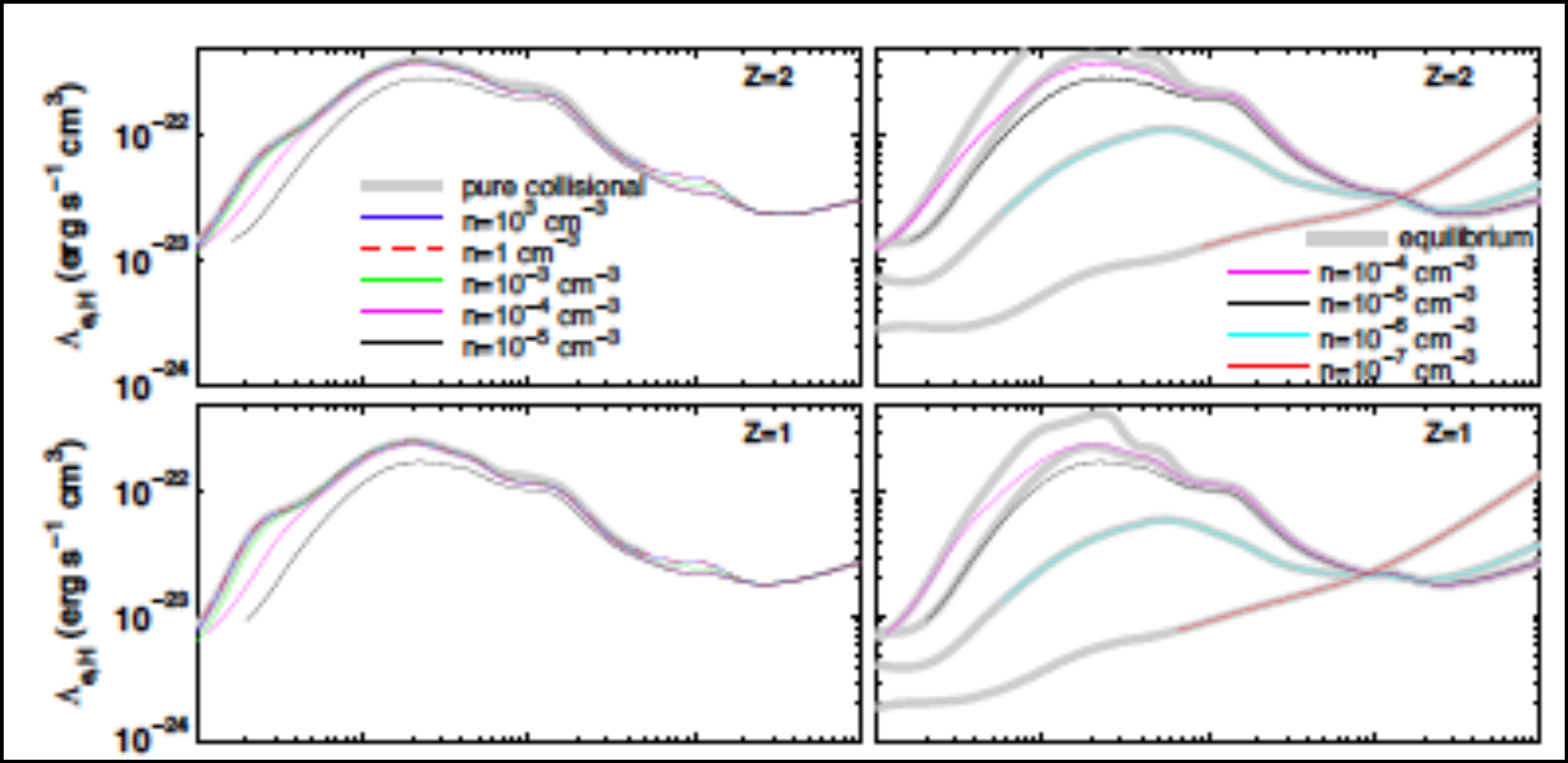
Cooling with Radiation



Cooling w/ Radiation



Cooling w/ Radiation



Cooling w/ Radiation

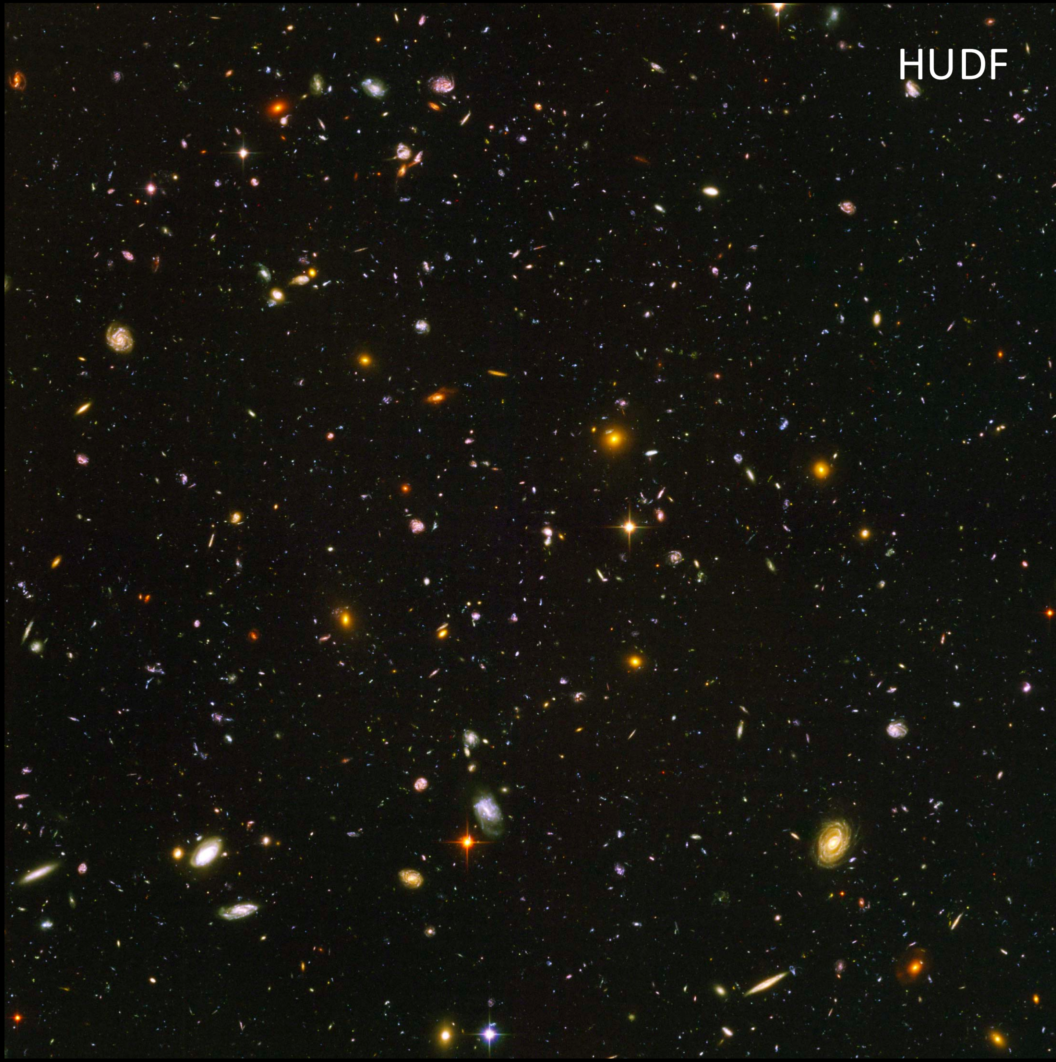
- For every Z there exists a threshold density = ionization parameter:
  - Lower-n : in photoionization equilibrium (departures from equilibrium negligible)
  - Higher-n: time-dependent collisional (impact of radiation negligible)

Metallicity ($Z_\odot$)	$n_{\rm th}(z=0)$ ($\rm cm^{-3}$)	$U_{\rm th}$
$1-2$	10^{-5}	3.3×10^{-2}
$10^{-1}-10^{-3}$	10^{-3}	3.3×10^{-4}

Are the baryons Really in the IGM?

Baryon census at z=3

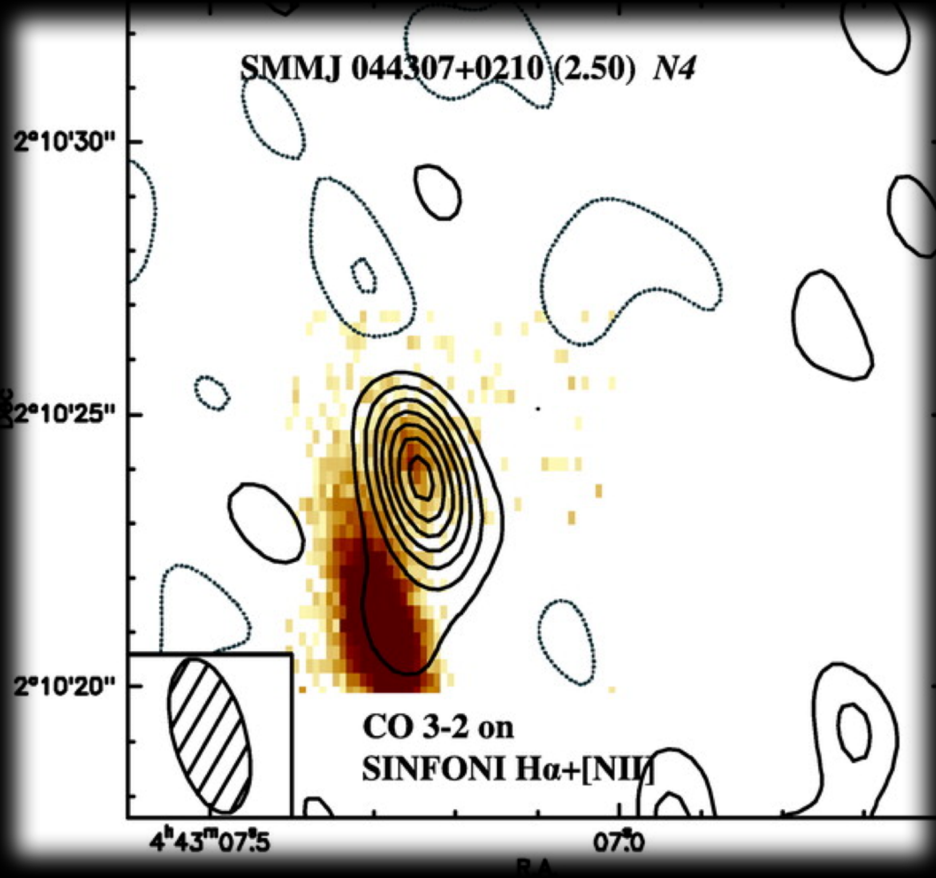
- Stellar component
  – galaxy surveys



$\Omega/\Omega_B = 0.005 \pm 0.002$

Baryon census at z=3

- Stellar component – galaxy surveys
- Molecular gas – CO emission, H_2 absorption



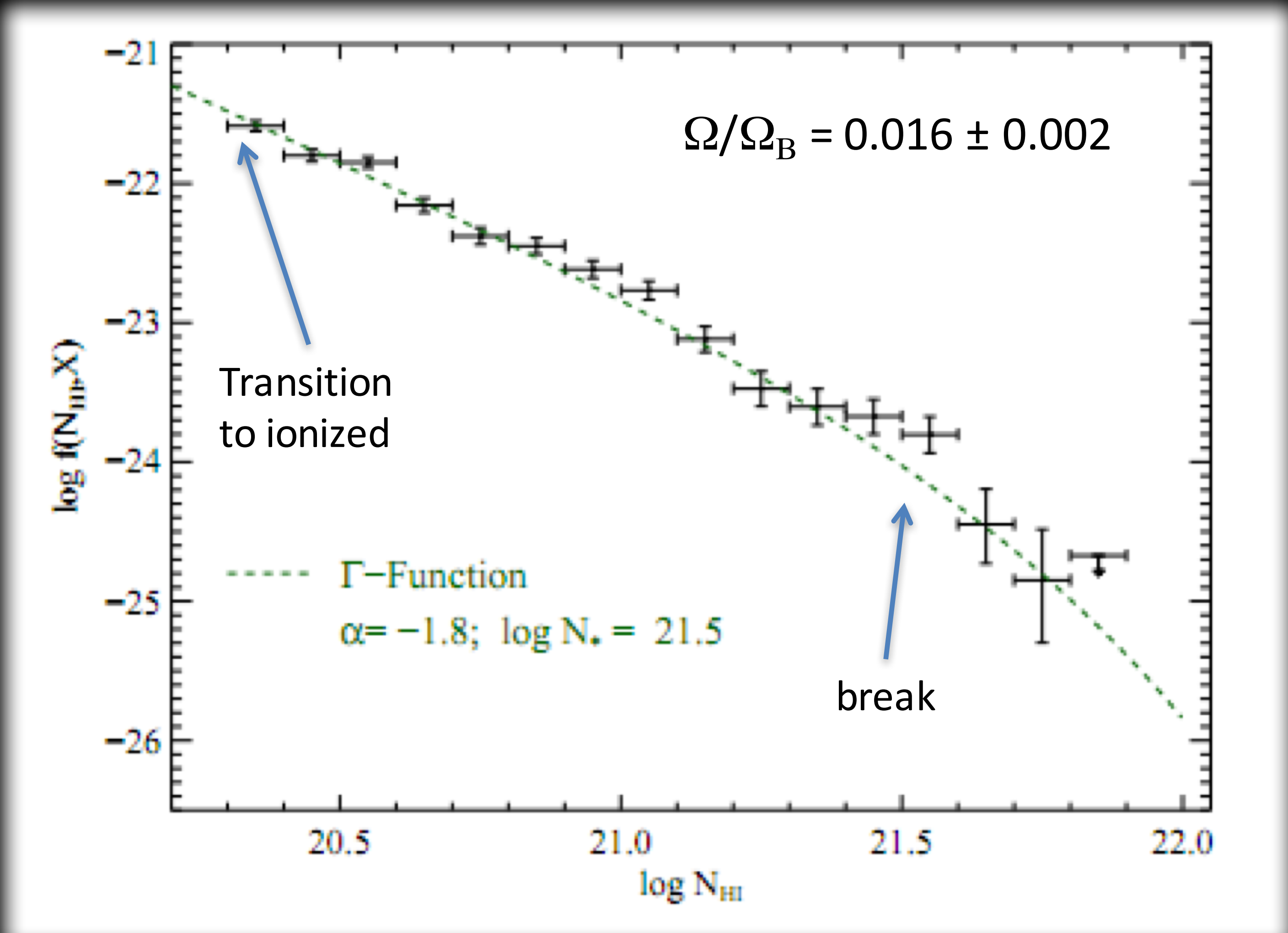
Ω/Ω_B = 0.001 – 0.1

Tacconi+06

Baryon census at z=3

- Stellar component – galaxy surveys
- Molecular gas – CO emission, H_2 absorption
- Neutral gas

Baryon census at z=3

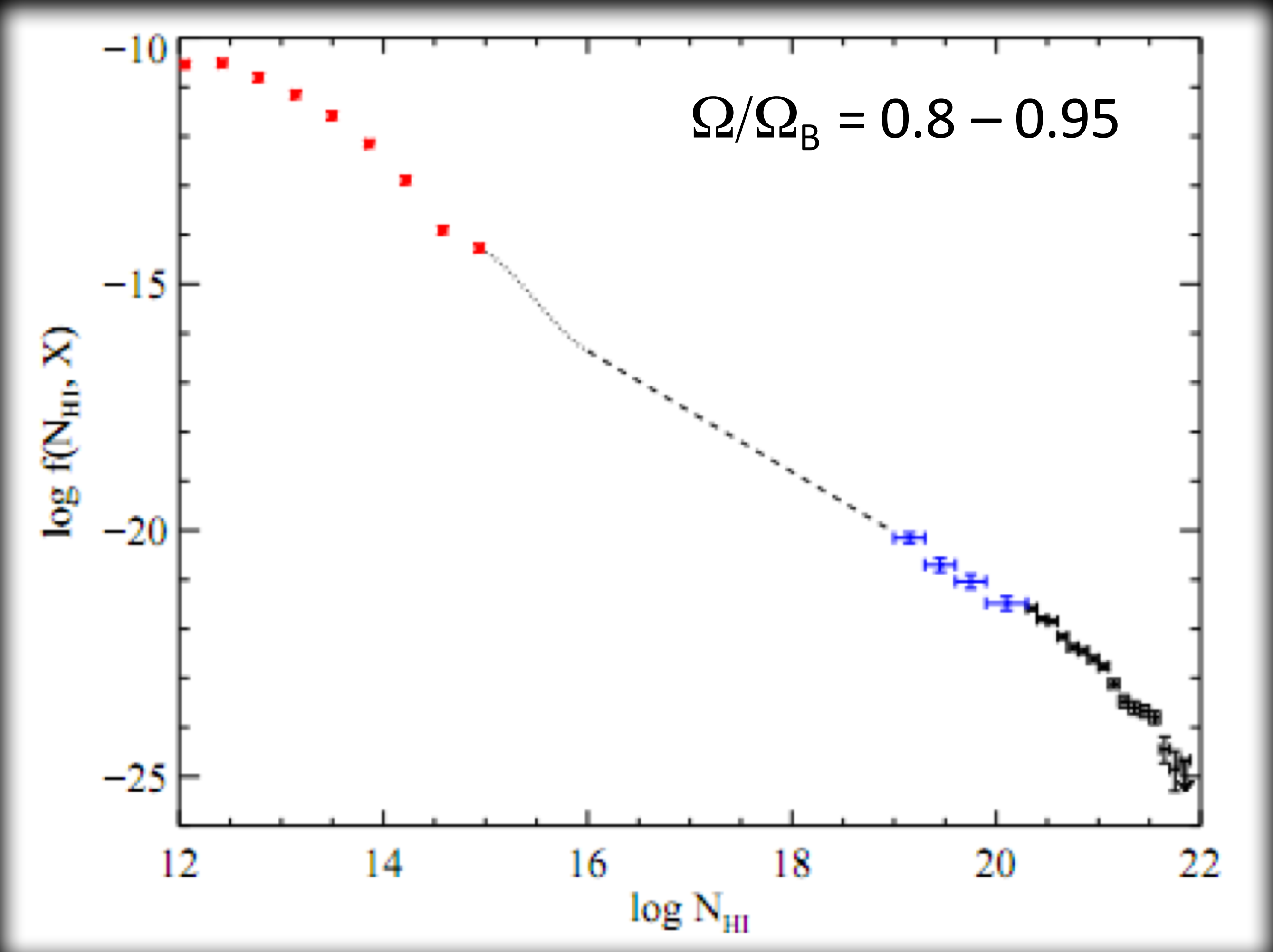


(SDSS)
Prochaska+05

Baryon census at z=3

- Stellar component – galaxy surveys
- Molecular gas – CO emission, H_2 absorption
- Neutral gas
- Warm ionized gas

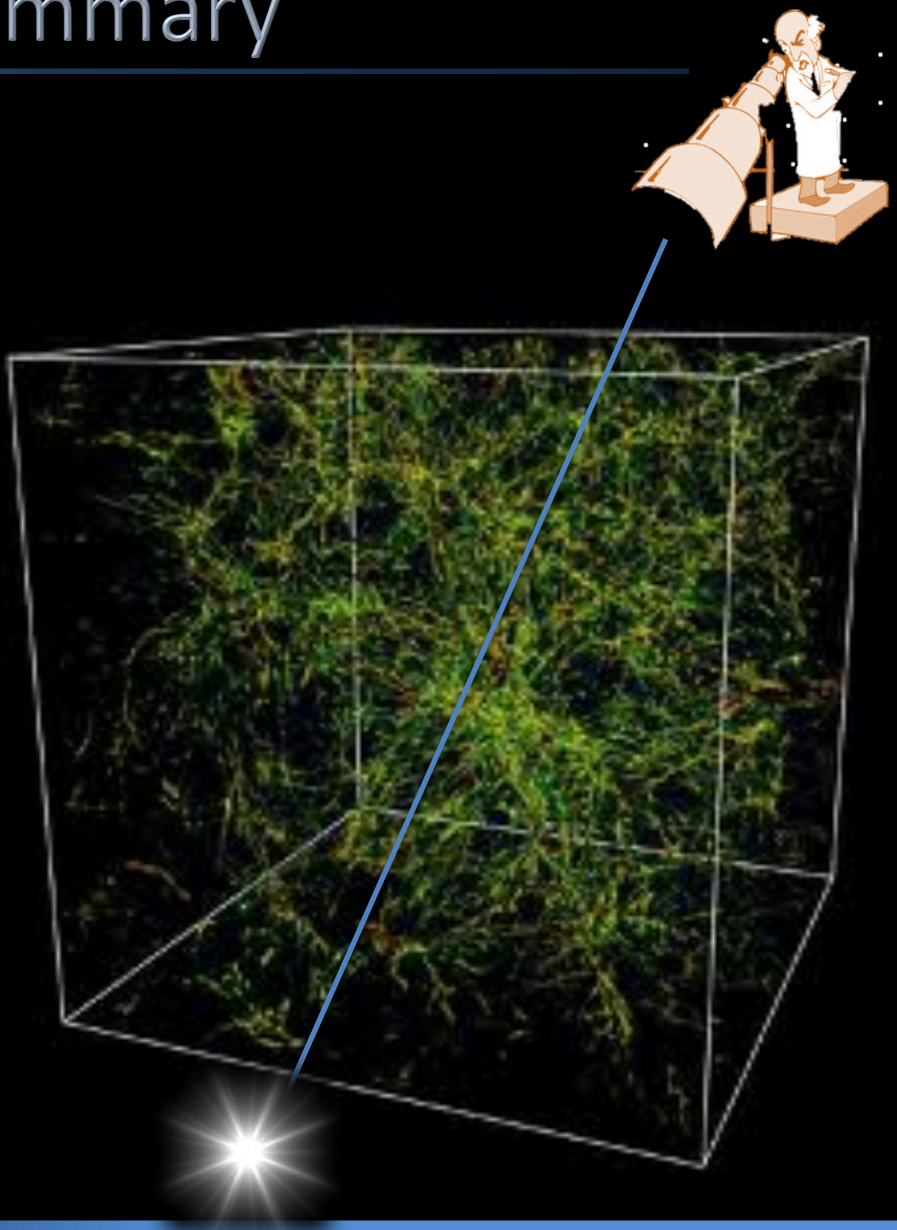
Baryon census at z=3



(SDSS)
Prochaska+05

Baryon census at z=3: Summary

Phase	fraction
Stars	0.005±0.002
Molecular gas	0.001-0.1
Neutral gas	0.016±0.002
Warm Ionized gas	0.8-0.95
Hot gas	?

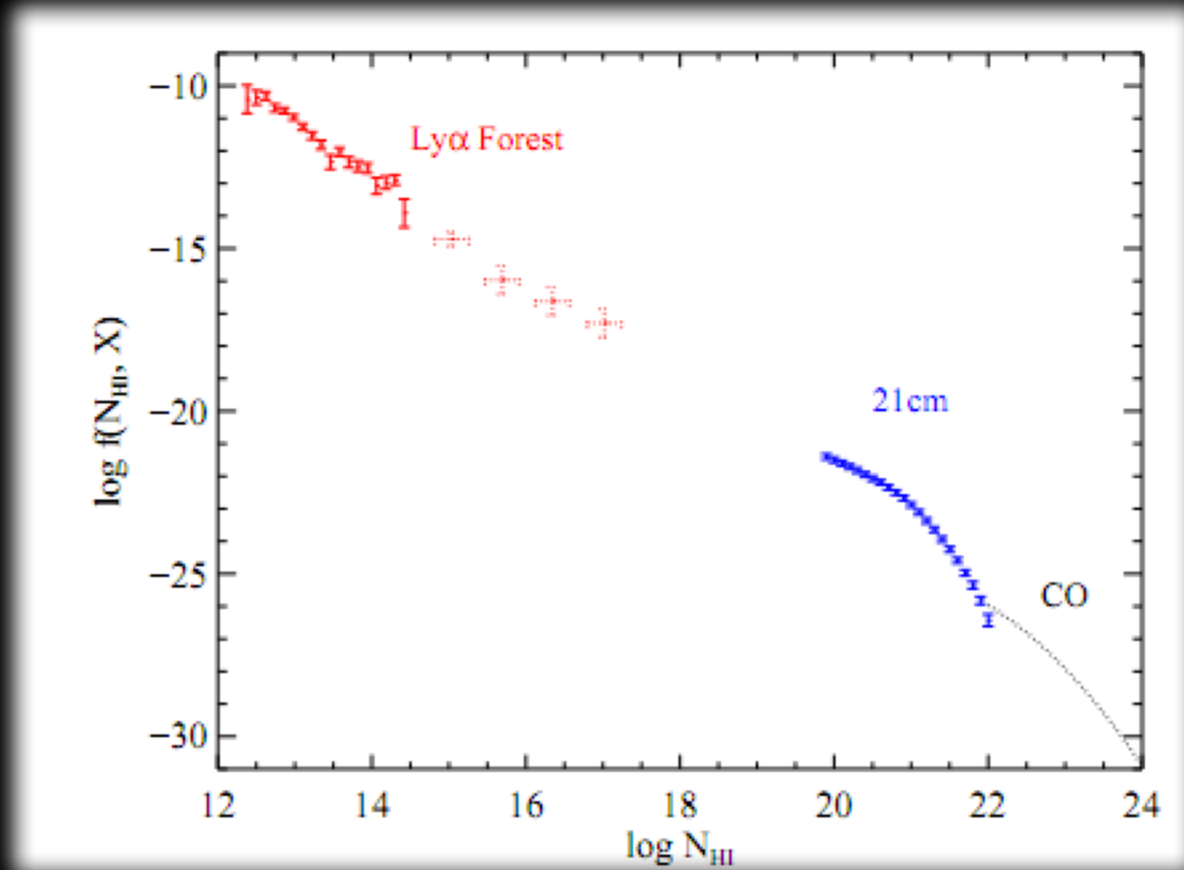


Baryon census at z=0

What about the local universe?

- Stars
- Molecular gas
- Neutral gas
- Warm ionized gas

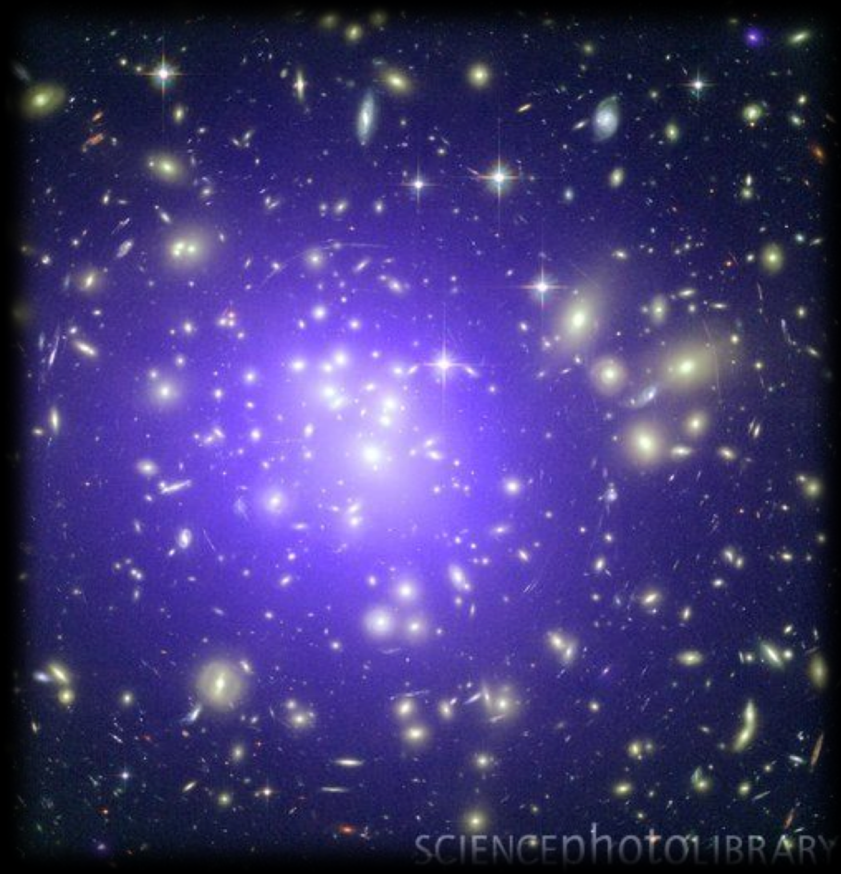
Danforth+08



Prochaska+08

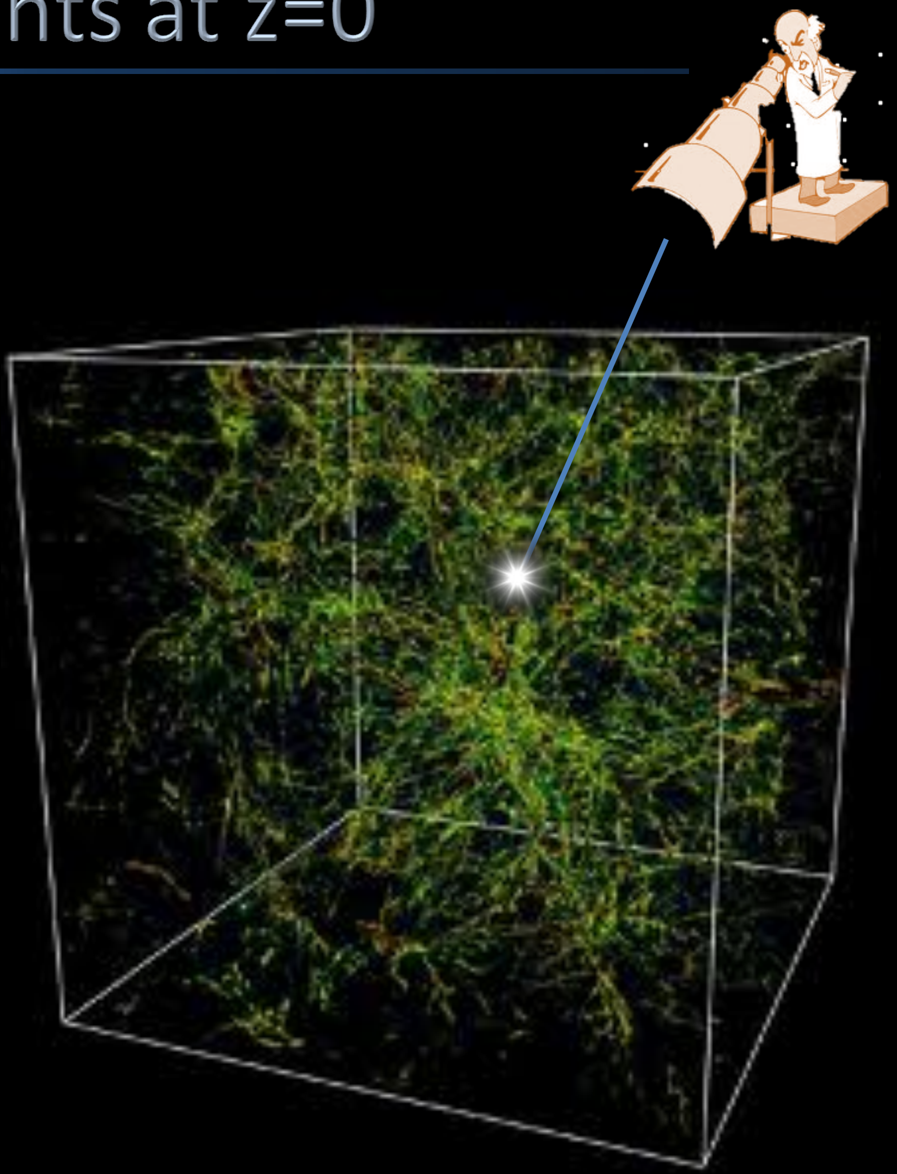
What about the local universe?

- Stars
- Molecular gas
- Neutral gas
- Warm ionized gas
- Hot gas
  (Intracluster medium)



Same baryonic components at z=0

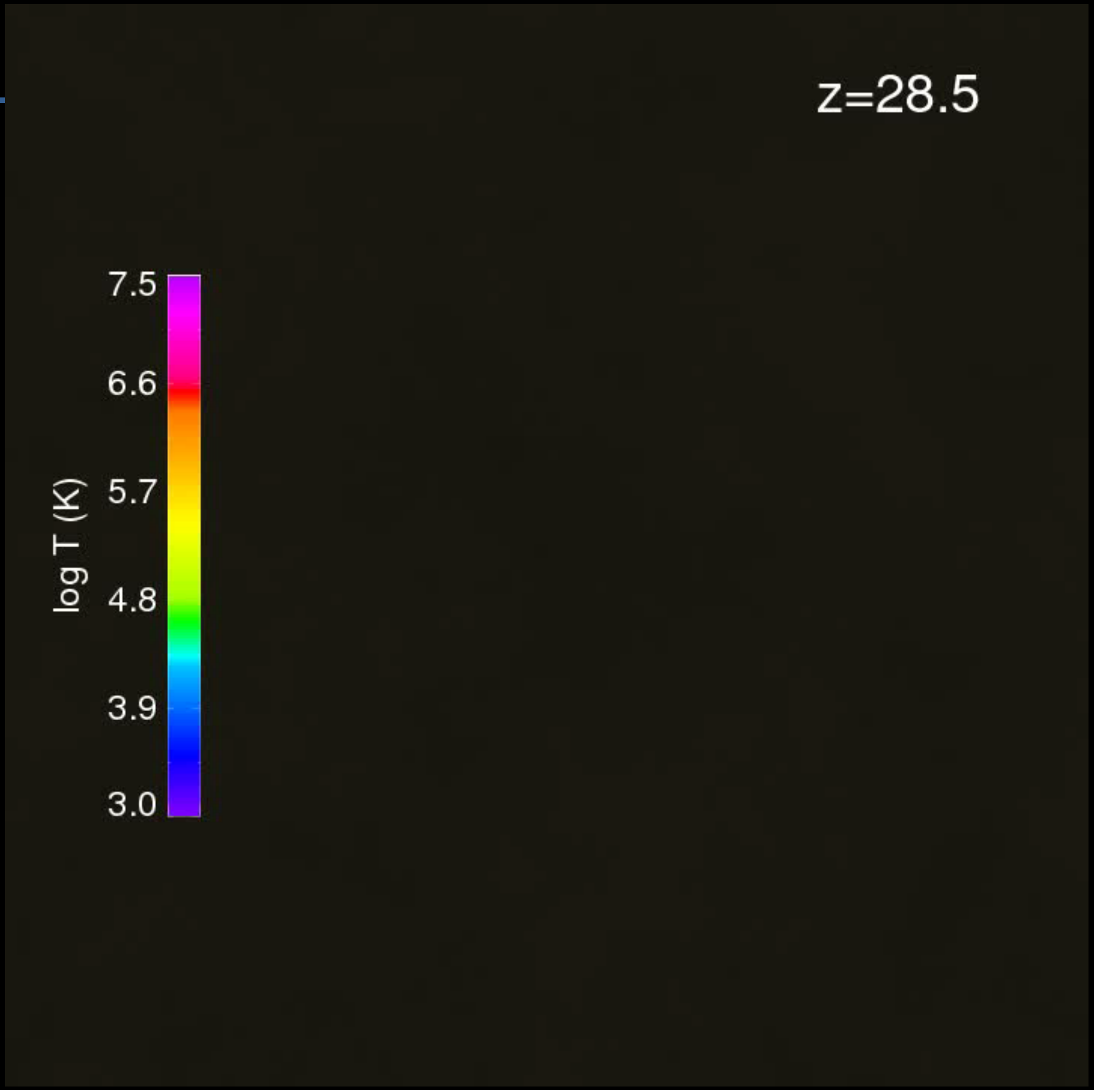
Phase	fraction
Stars	0.07±0.02
Molecular gas	0.0029±0.0015
Neutral gas	0.017±0.004
Ionized gas	0.28±0.11
Hot gas	0.04±0.015



Total ~ 0.4 ??!!

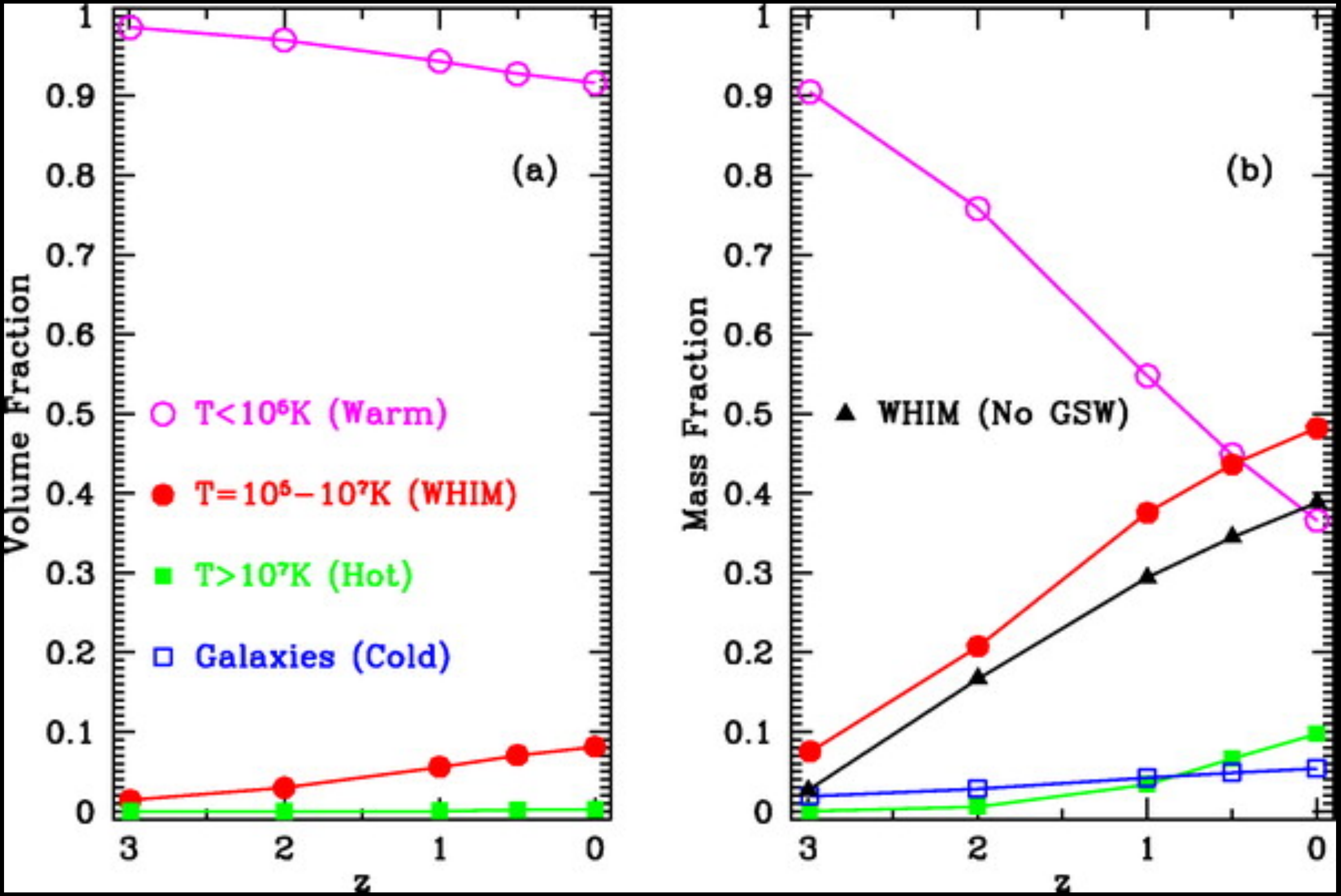
So where are they?

Hydro simulations



Oppenheimer & Dave

Cosmological Simulations: WHIM



Cen & Ostriker 98

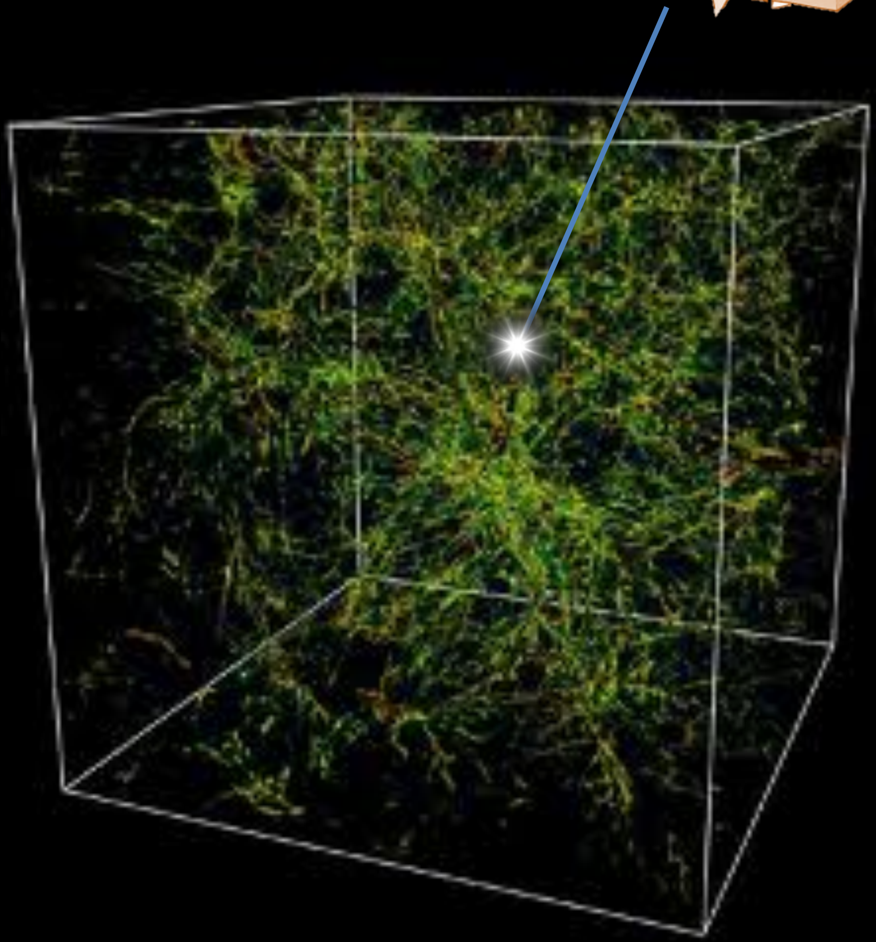
Gravitational Heating

- Shocks heating of gas accreting onto large scale structure
- Robust result of hydrodynamic simulations
- Verified by analytic approximations
- Some (~30-40%) in large virialized halos
- Much outside, but nearby R_{vir}, some filamentary

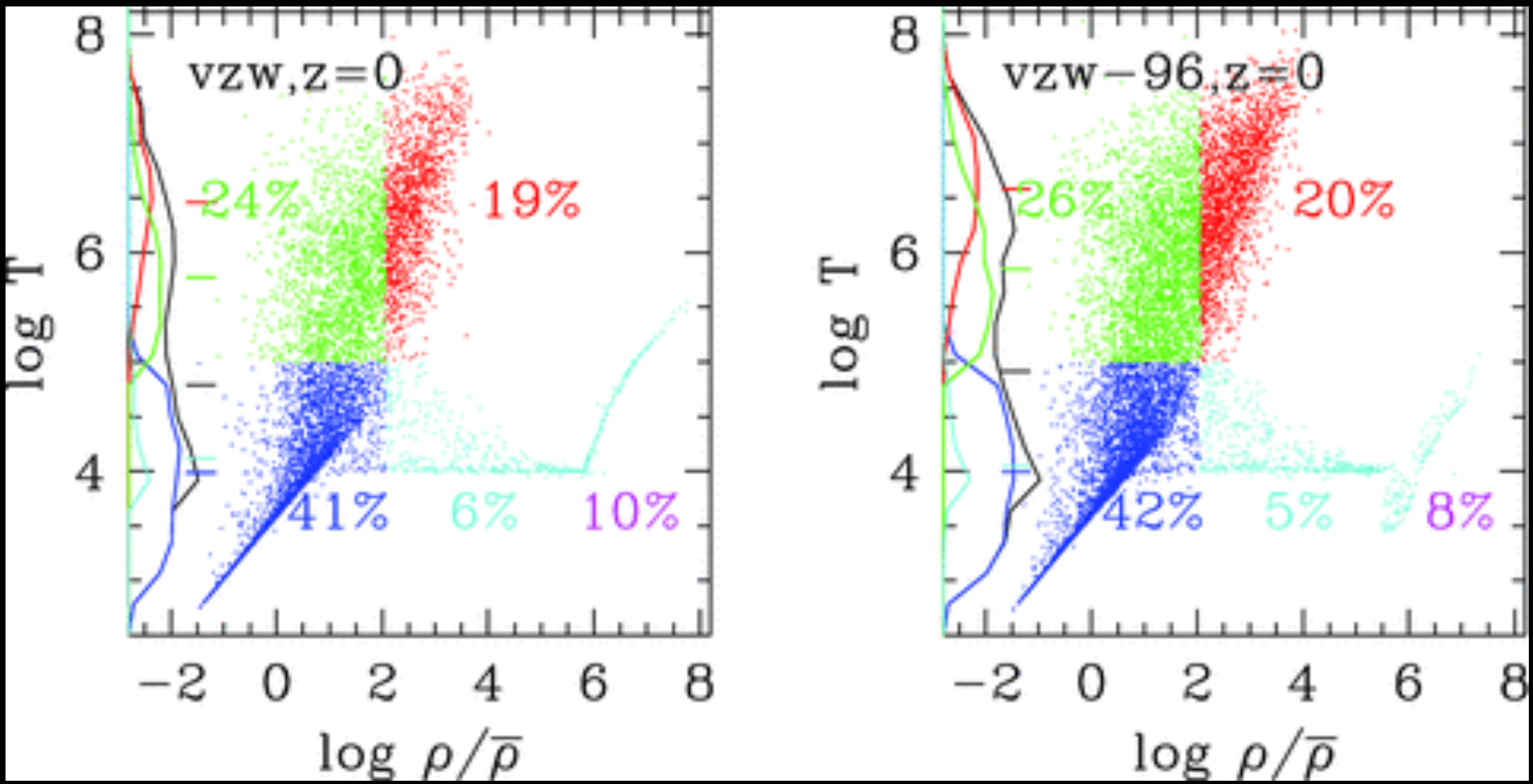
(e.g. Sunyaev & Zeldivich 72; Cen & Ostriker 98; Dave+01; Furlanetto & Loeb 05; Bertone+08; Cen+12…)

So…

Phase	fraction
Stars	0.07±0.02
Molecular gas	0.0029±0.0015
Neutral gas	0.017±0.004
Ionized gas	0.28±0.11
WHIM	**up to 0.6 ?**
Hot gas	0.04±0.015



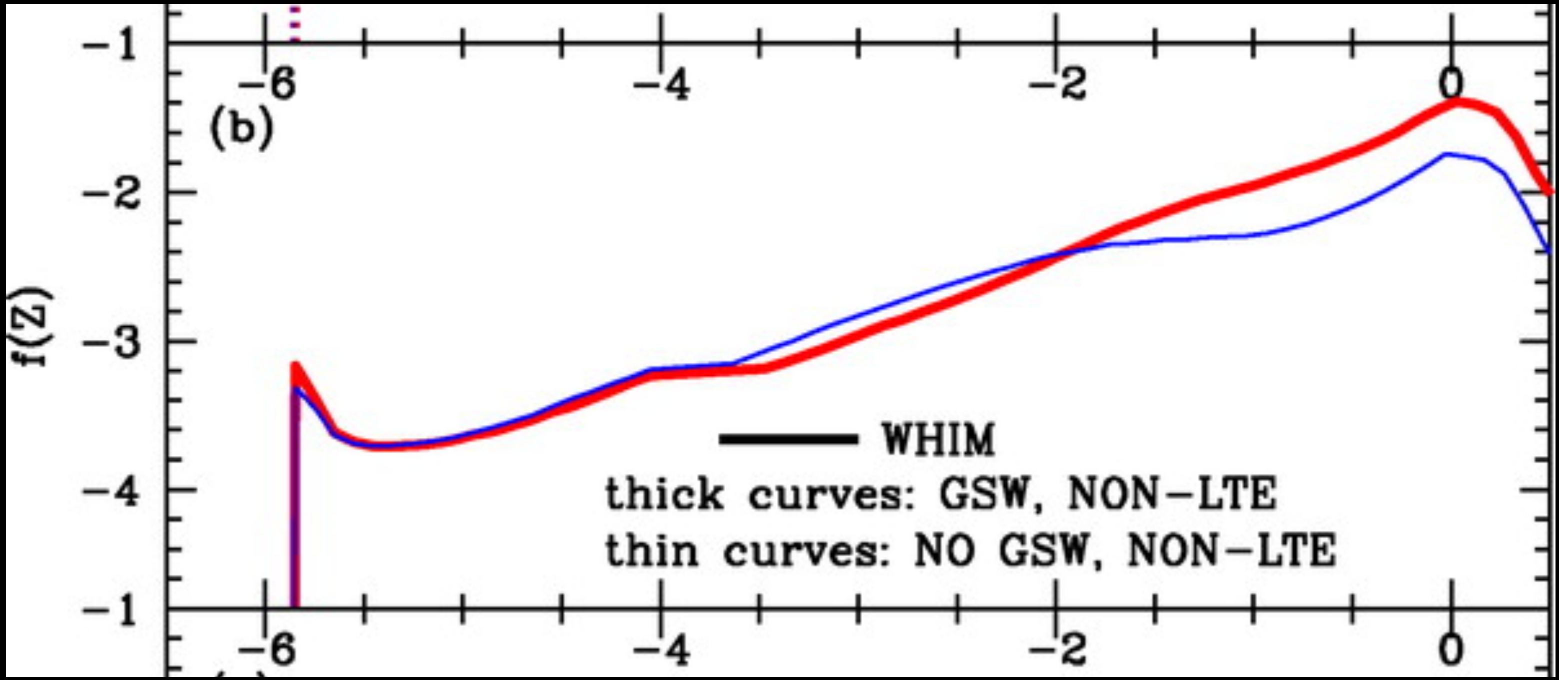
WHIM properties :over-density



Dave+10

WHIM properties: Metallicity

- Mean Z=0.18

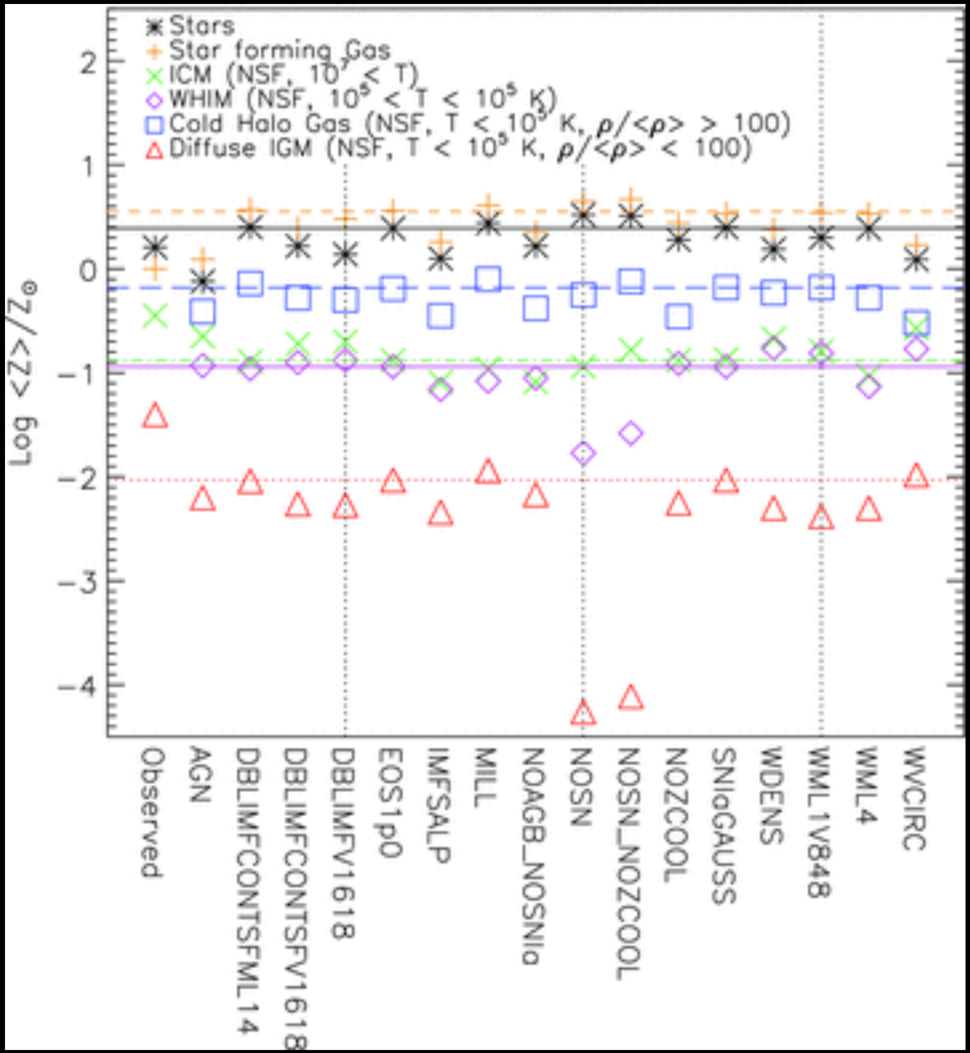


Cen & Ostriker 2006

WHIM properties: Metallicity

- Z_{WHIM}~0.1

Wiersma+11



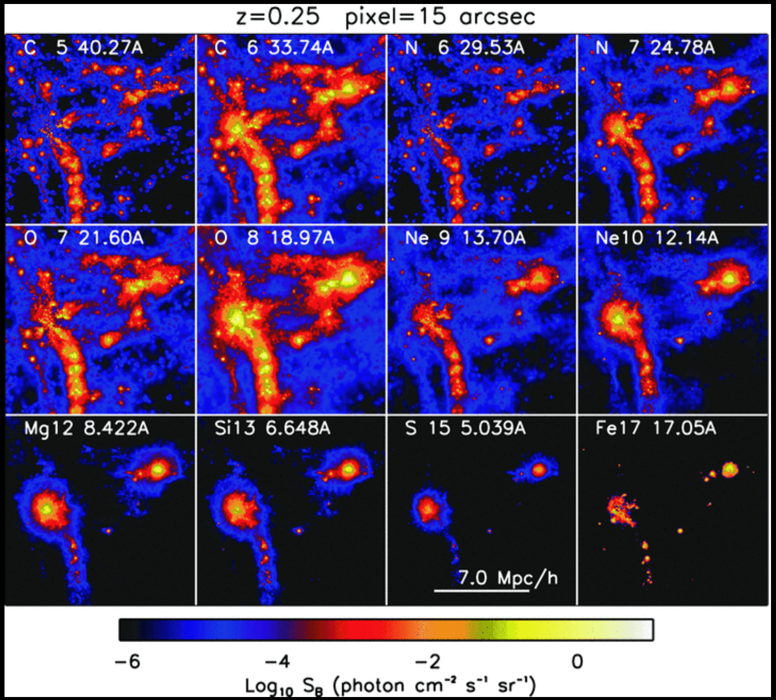
Searching for the WHIM

- Emission or absorption ?

Searching for the WHIM: Emission

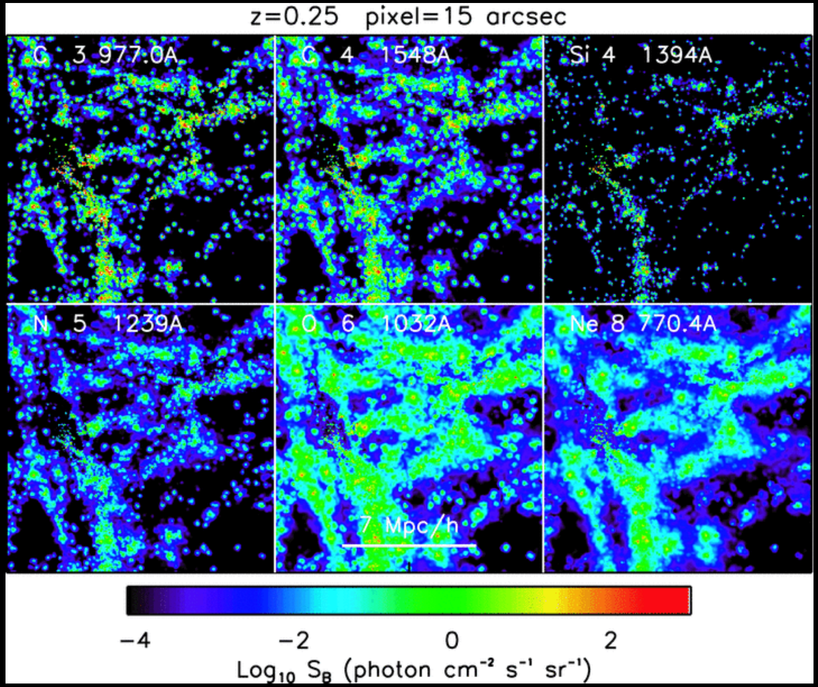
- Can provide a "map" of the WHIM
- but ~n^2

X-rays



Bertone+10a

UV



Bertone+10b

e.g. Anderson, Bertone, Cappelluti, Ettori, Fang, Finoguenov, Galeazzi, Giodini, Molendi, Simionescu, Takei, Ursino, Zappacosta….

Searching for the WHIM: Emission

- Can provide a "map"
- but ~n^2
- Currently below detection limits (e.g.Bertone+10; Soltan 06)

  Too faint to close the baryon budget with current instruments

(But see, for example, Xray emission reported in Zappacosta+05, from the Sculptor wall, Werner+08, from a filament connecting Abell 222 & 223)

Searching for the WHIM

- Tracers:
  - H I
  - O VI
  - Ne VIII
  - O VII, O VIII

H I, O VI: 10^5-10^6K

Ne VIII, O VII, O VIII: 10^6-10^7K

H I, O VI, Ne VIII: UV

O VII, O VIII: Xray

Danforth+10,11; Savage+11

Danforth & Shull 05, 08; Tripp+08; Thom & Chen 08

Savage+05; Narayanan+09, 11; Meiring+12

Nicastro+05; Boute+09; Fang+02,07,10; Zappacosta+10; c.f. Kaastra+06; Williams+06; Rasmussen+07; Danforth+11; Yao+12; Gupta+12

- Key question: observed -> total mass?

What is the total mass?

- In a population (e.g. O VI survey)
  - "simple" correction
  - Use "standard" cosmological simulations
  - Improved simulations for specific observations (Oppenheimer & Dave 10; Shull+11; Gnat & Ferland 12)
- For individual absorbers
  - Assuming equilibrium conditions
  - Including non-equilibrium physics (e.g. Gnat & Sternberg 07; Gnat+10)

What is the baryon fraction?

- In individual absorbers

Table 3
Equivalent widths and AOD column densities for transitions observed in the z_{abs}=0.6838 system.

Transition	W_0 mÅ	N_a (AOD) cm^{-2}
H I 1025	276±17	14.77±0.02
H I 972	246±18[a]	<15.12
H I 949	54±15	14.74±0.11
H I 937	37±9	14.82±0.09
C III 977	188±12	13.65±0.02
O III 832	148±7[a]	< 14.47
N IV 765	80±8	13.47±0.04
O IV 787	153±8	14.60±0.02
O VI 1031	234±19	14.47±0.03
O VI 1037	149±23	14.50±0.06
Ne VIII 770	51±12	13.98±0.09
Ne VIII 780	59±11[a]	< 14.39

[a] Blended

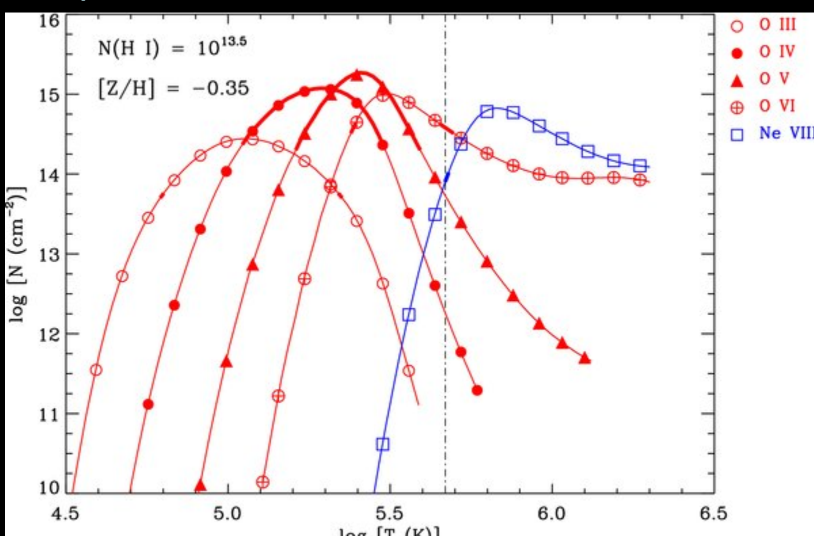
Meiring+12

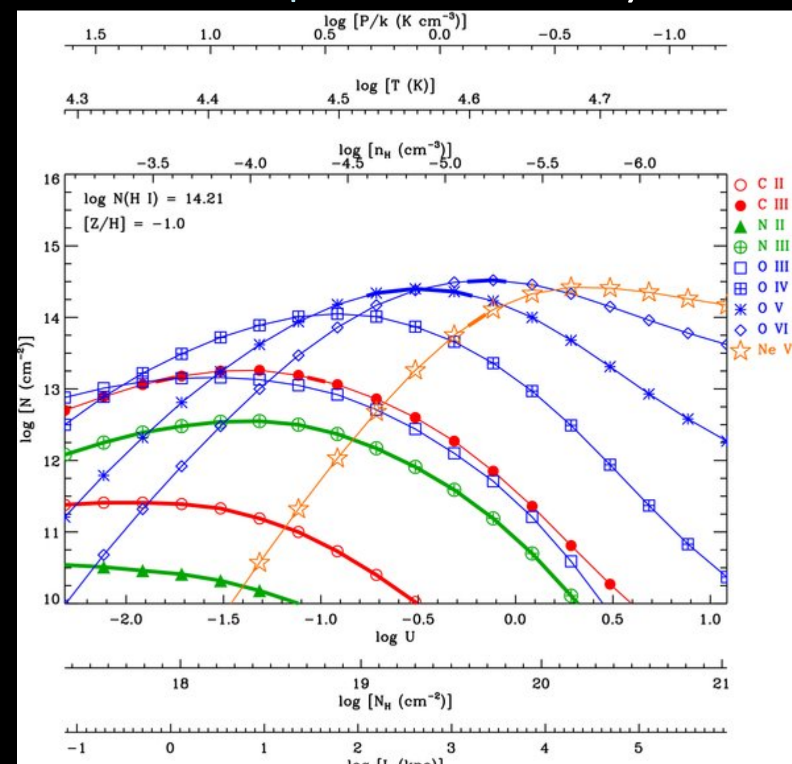
What is the baryon fraction?

- In individual absorbers
  - Assuming equilibrium conditions

Photoionized phase Narayanan+11

CIE phase



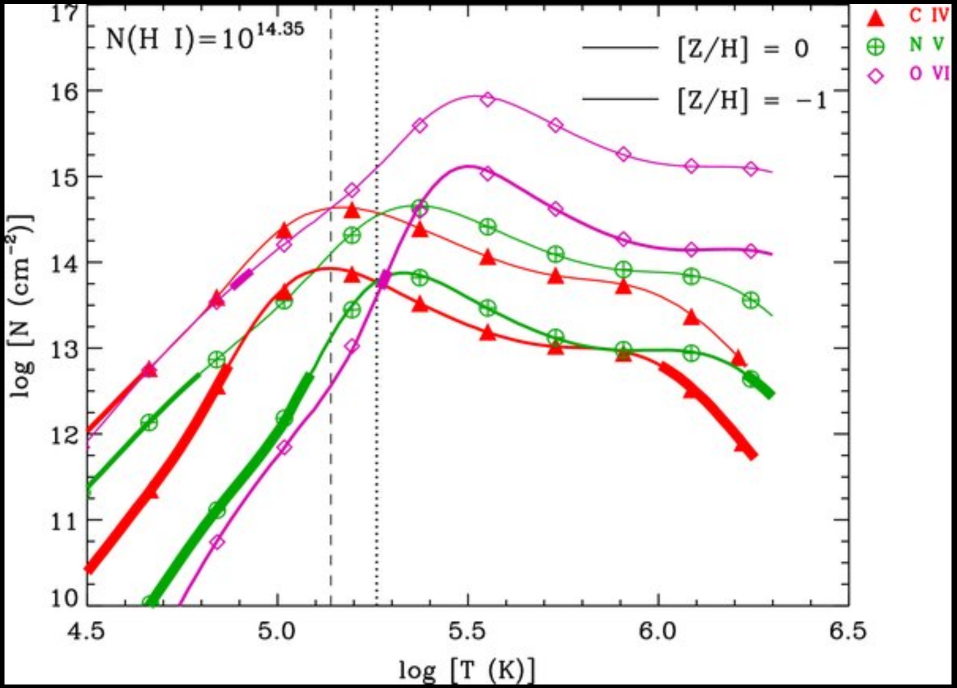


What is the baryon fraction?

- In individual absorbers
  - Assuming equilibrium conditions
  - Including non-equilibrium physics

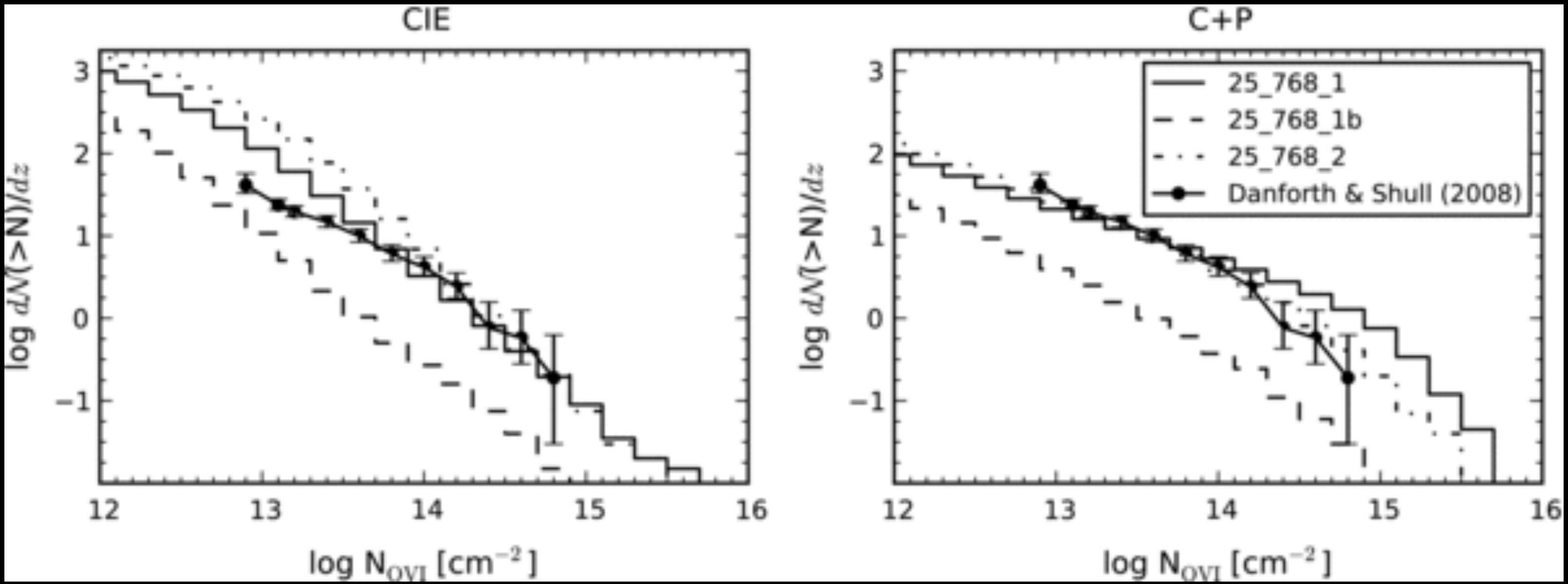
    (e.g. Yoshikawa & sasaki 06; Gnat & Sternberg 07; Gnat+10; Kwak & Shelton 10; Gnat & Ferland 2012)

Narayanan+10



What is the total mass?

- In a population (e.g. O VI survey)
  - Cosmological simulations predict the abundance and properties of absorbers



Smith+11

Cen+01; Yoshikawa+03; Furlanetto+05; C
& Dave 09; Smith+11;
Tepper-Garcia+11; Yao+12;

What is Ω_B?

- in a population

  e.g. OVI survey:

  - Correct O VI to total oxygen: $f_{O\ VI}$
  - Correct O to total gas: O/H
  - Derive baryon fraction in WHIM:

$$\Omega_b^{(\mathrm{OVI})} = \left[\frac{\mu_b H_0}{c\rho_{\mathrm{cr}}(\mathrm{O/H})_\odot}\right] \int_{N_{\min}}^{N_{\max}} \frac{d\mathcal{N}(N)}{dz} \frac{N\, dN}{Z_{\mathrm{O}}(N)\, f_{\mathrm{OVI}}(N)}$$

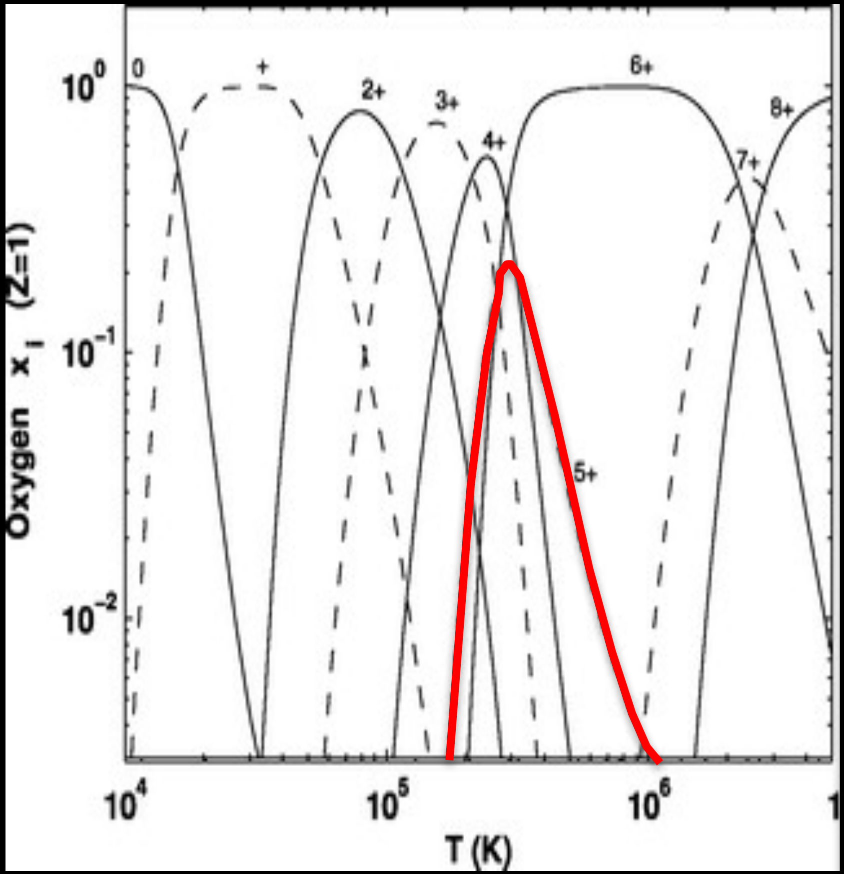
e.g. Shull+11

What is the total mass?

- In a population (e.g. O VI survey)
  - "simple" correction

    f=0.2

    Z=0.1

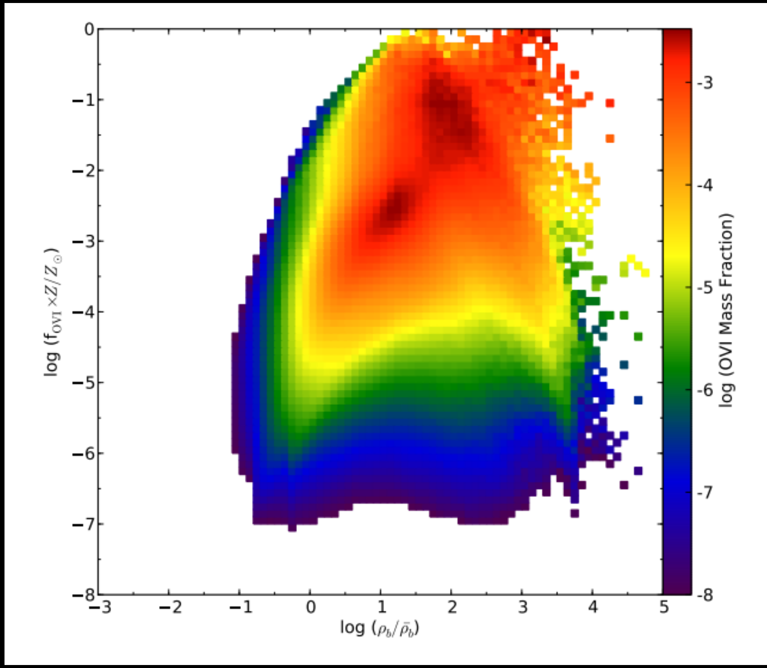


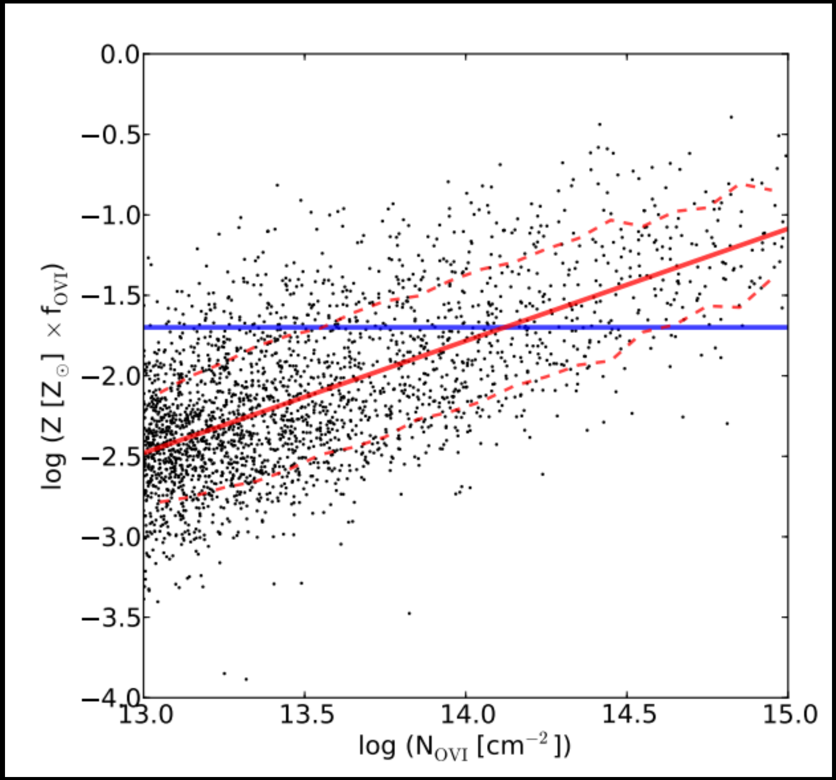
Gnat & Sternberg 07

What is the total mass?

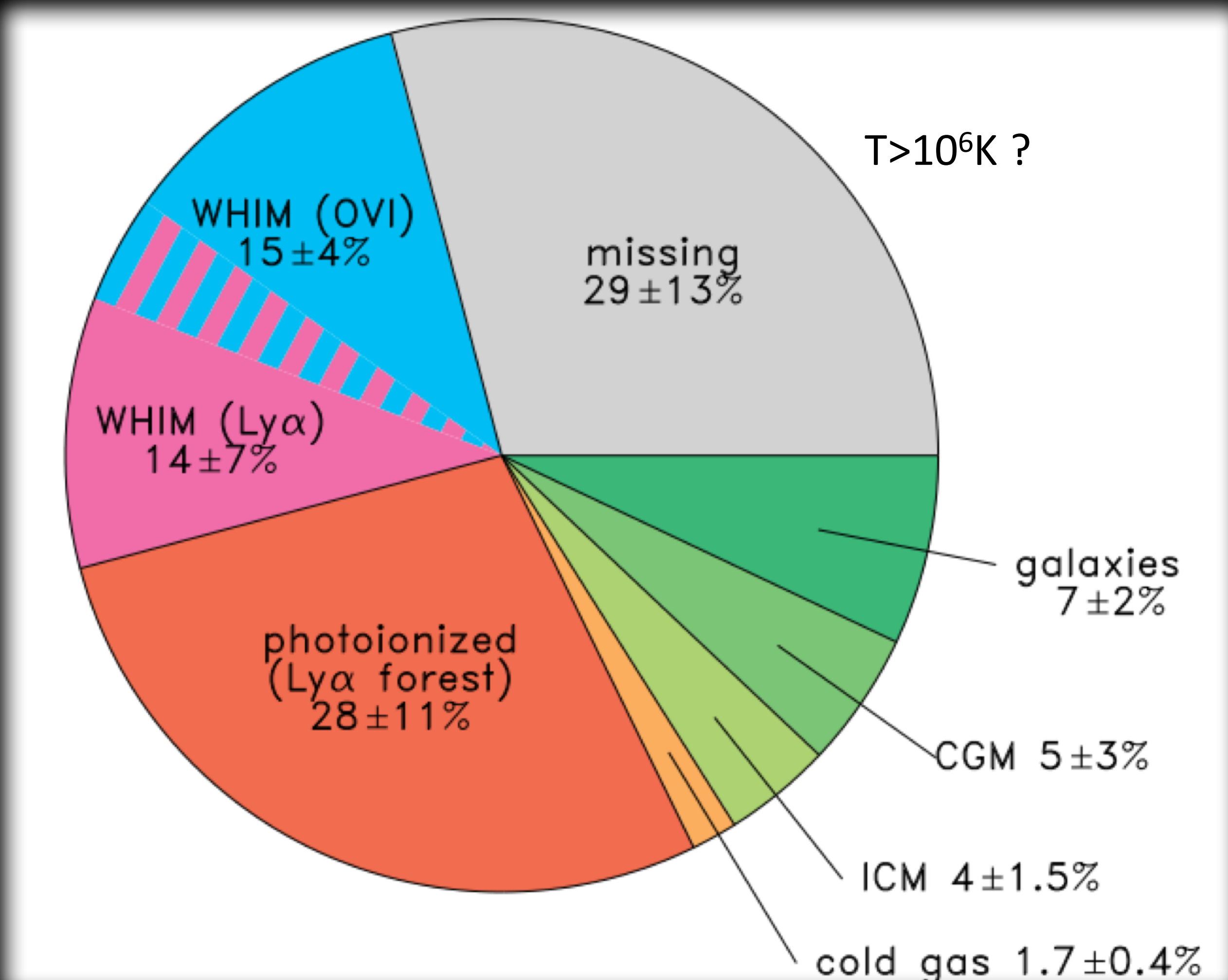
- In a population (e.g. O VI survey)
  - "simple" correction
  - Improved corrections

Shull+11





Baryon census at z=0

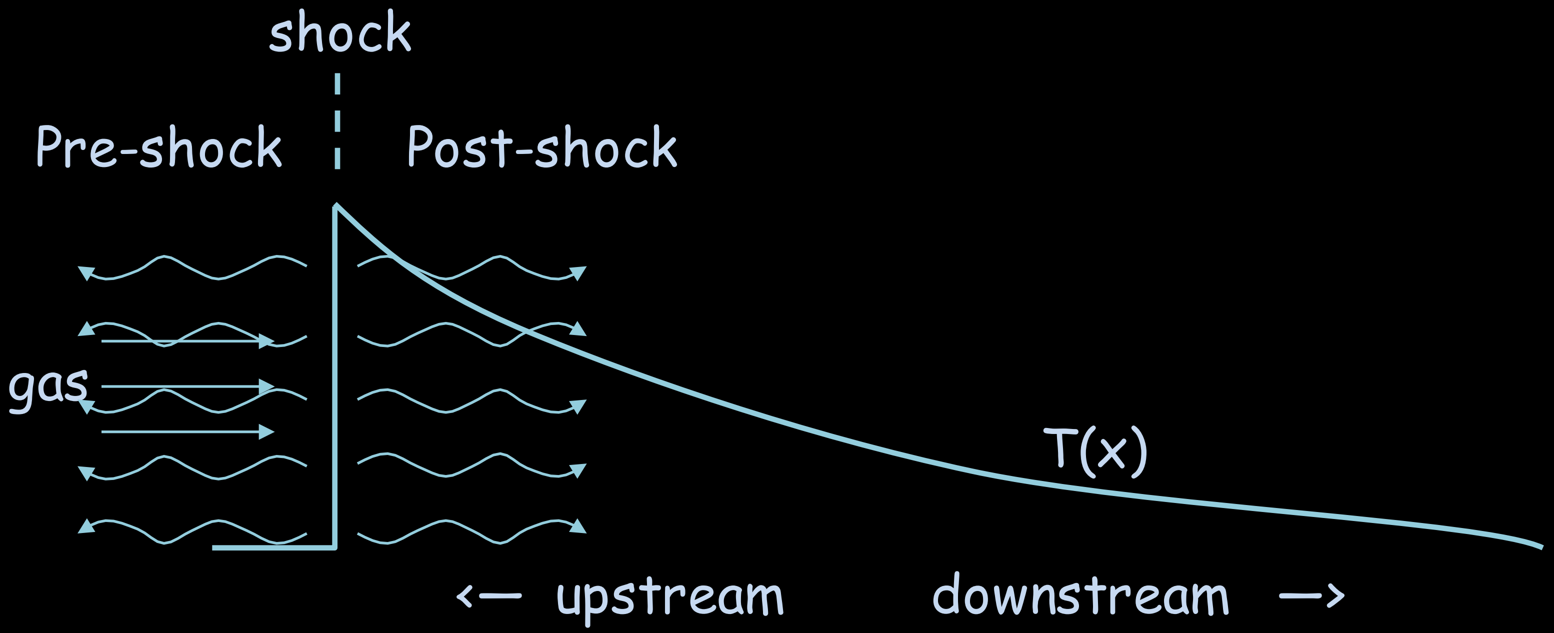


summery

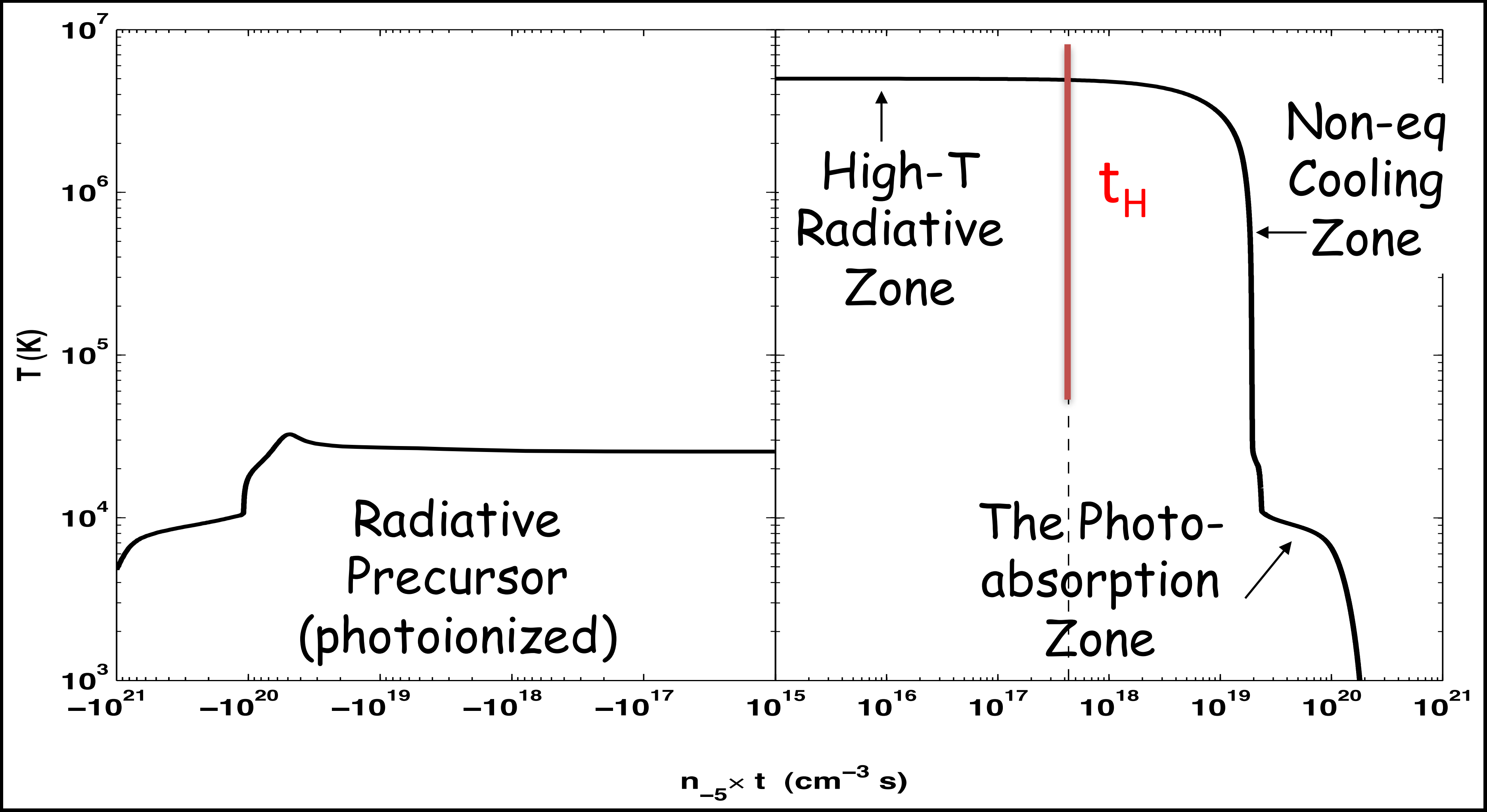
- WHIM is a robust consequence of gravitational structure formation in LCDM cosmology
- WHIM over-density: few x 10; Metallicity < 0.2
- Currently, emission too faint to close the baryon budget
- Absorption revealed the lower-T part of the WHIM ($10^5<T<10^6$ K), with ~30%Ω_B
- Still missing: ~30% of mass, in >10^6 K shocks

WANTED!

- Intergalactic gas
- Shocked to $T>10^6$K
- $Z\lesssim 0.2$

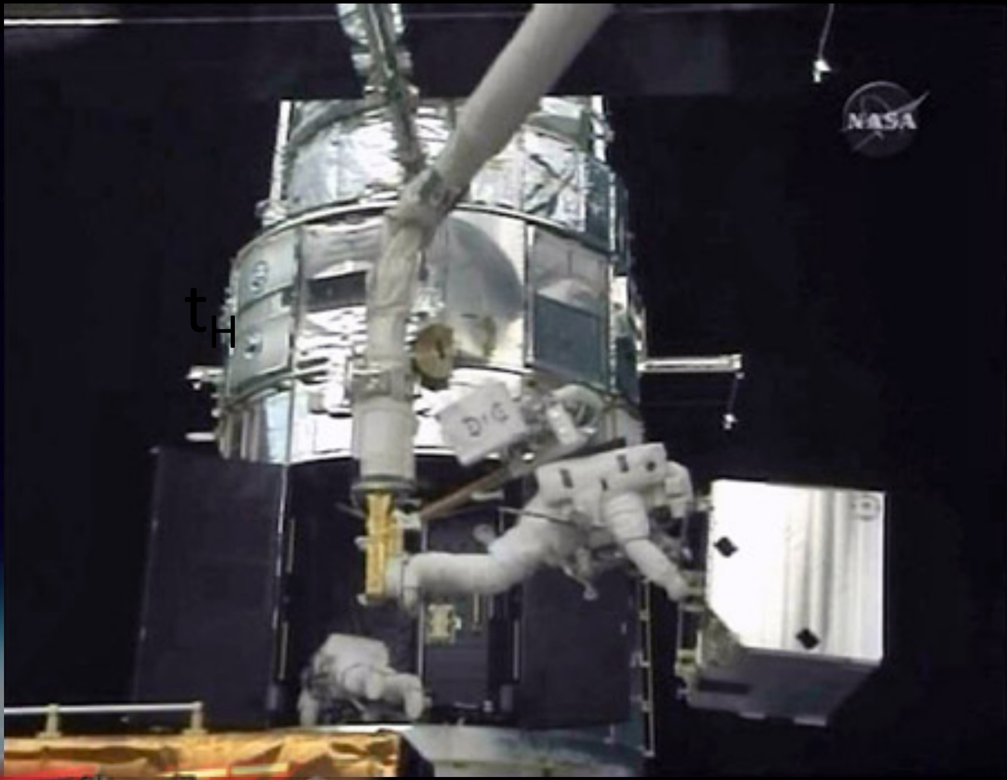


Steady-State Shock Structure



Gnat & Sternberg 2009
ApJ, 693, 1514

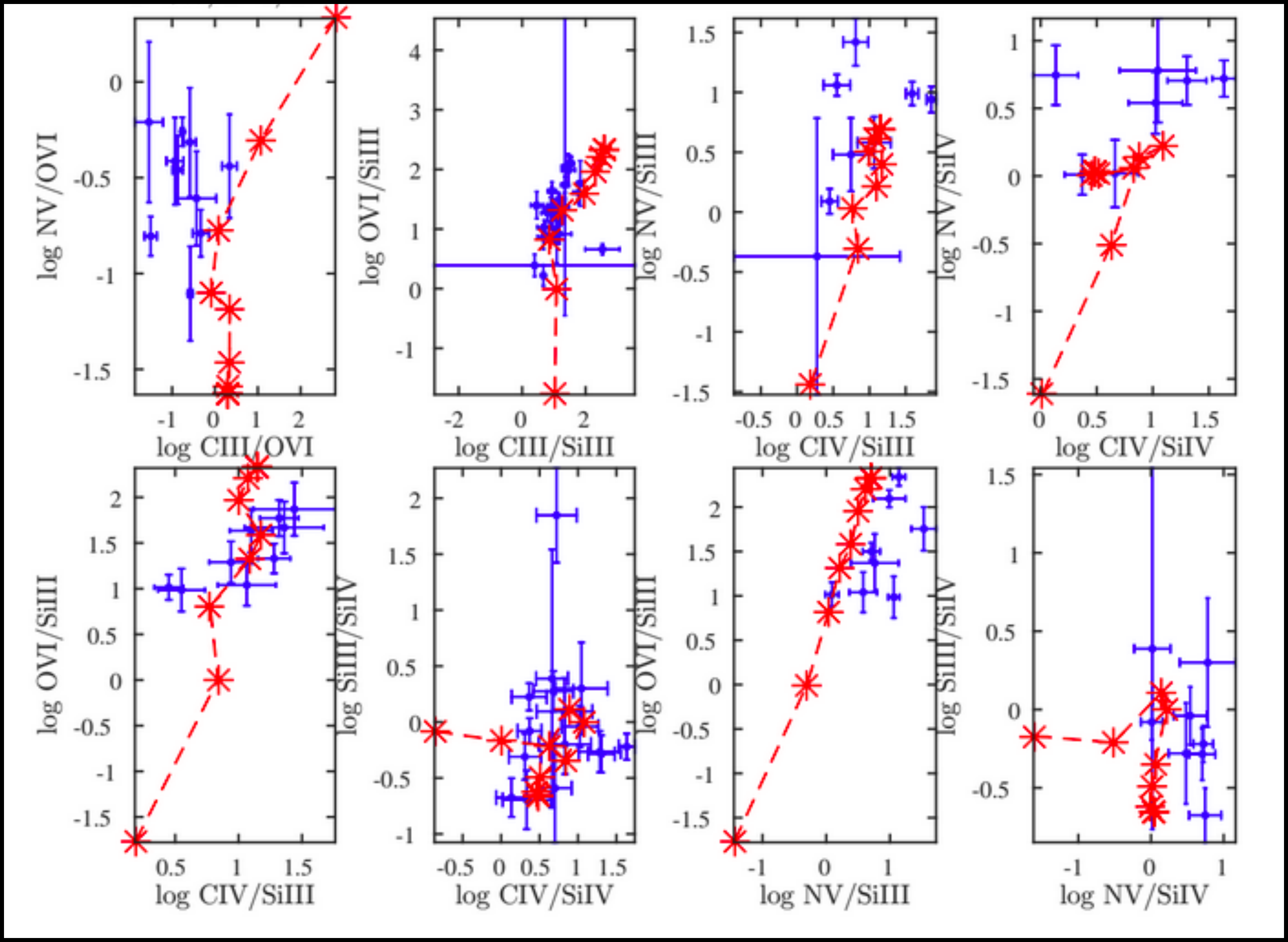
COS



Fitting COS Observations of WHIM Absorbers

T=10^7K, Z=1

dataset: Danforth+14



preliminary