X-Ray Opacity Towards High-z GRBs and an IGM Connection

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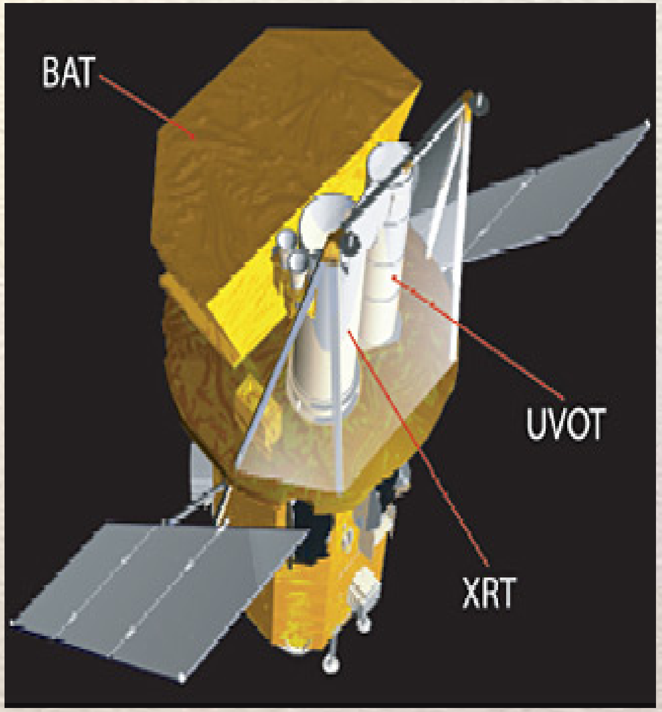
Outline

- How one measures X-ray absorption of GRB afterglows (or quasars for that matter)
  - what we can't measure
- GRB opacity results at high-z
- Diffuse Intergalactic Medium (IGM) paradigm
- Connection to Lyα
- Confront with Illustris cosmological simulations
- Discussion

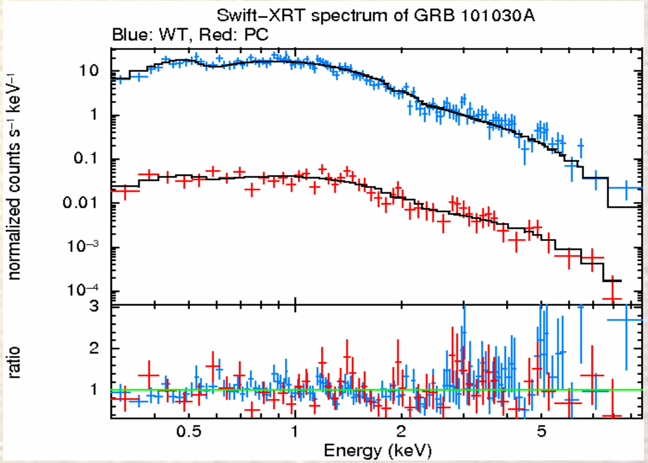
Swift / XRT & UVOT

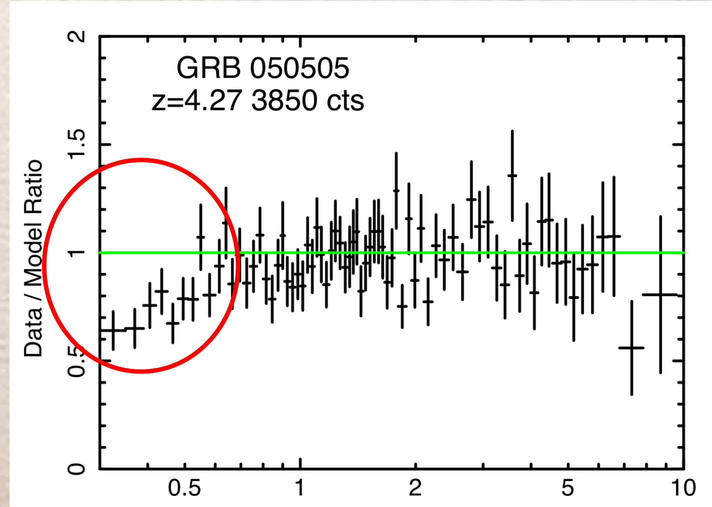
- Swift/XRT observes the GRB afterglow ~1 minute from detection (3″ localization)
  - 0.3 - 10 keV spectra
- UVOT after ~3 minutes (1″ localization)
  - Two grisms covering 170 - 520 nm
  - Highest red-shifted absorption system determines GRB redshift (or from the ground)



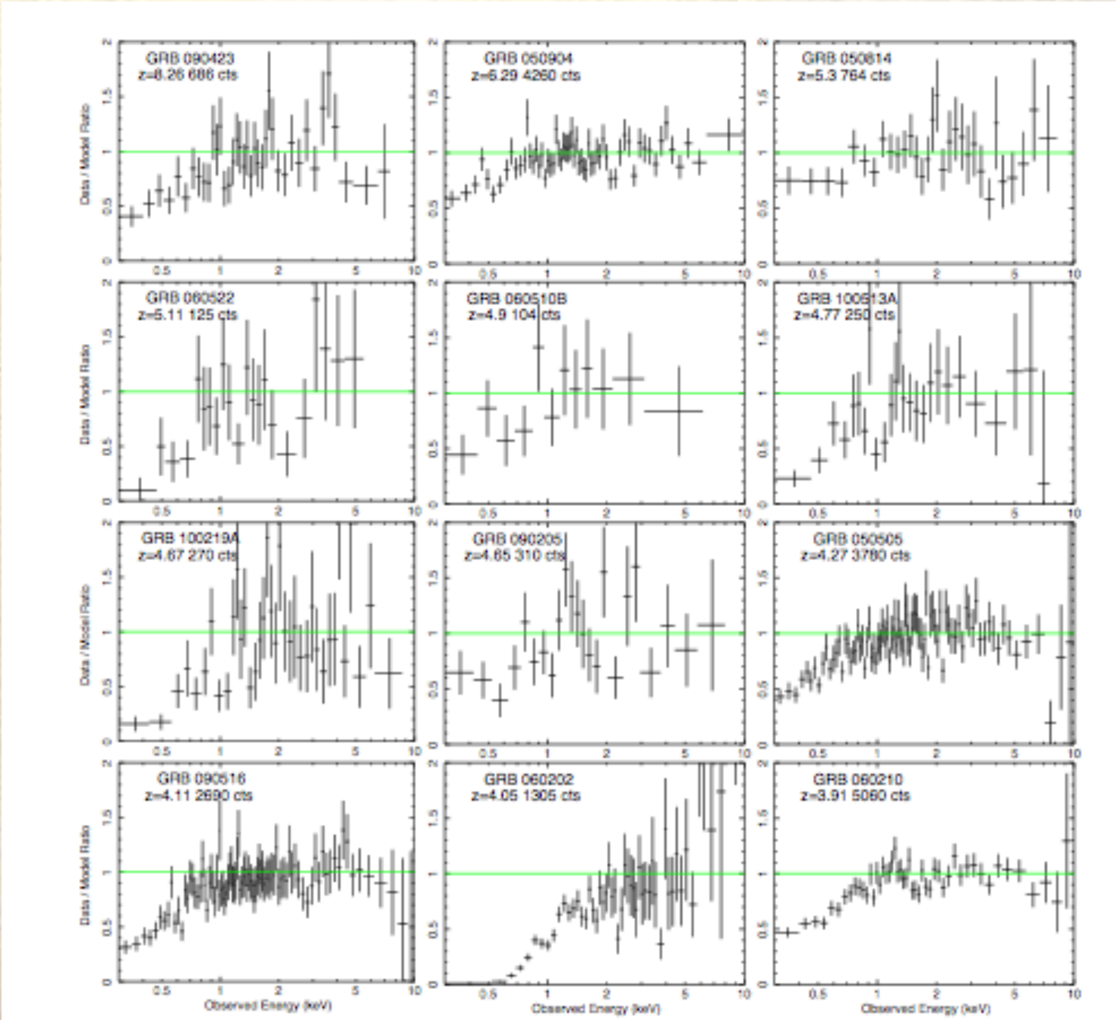
X-Ray Absorption Observations

- <u>Soft X-ray turnover</u>, compared to the hard power-law fit
- Interpreted as photo-electric effect comprising known Galactic and <u>unknown</u> <u>extra-galactic</u>
- <u>No distinct spectral features - edges or lines - can be discerned</u>





Soft X-Ray Absorption is Common

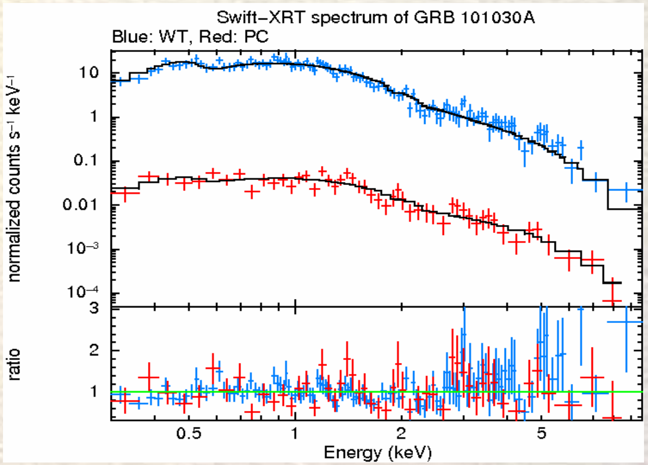


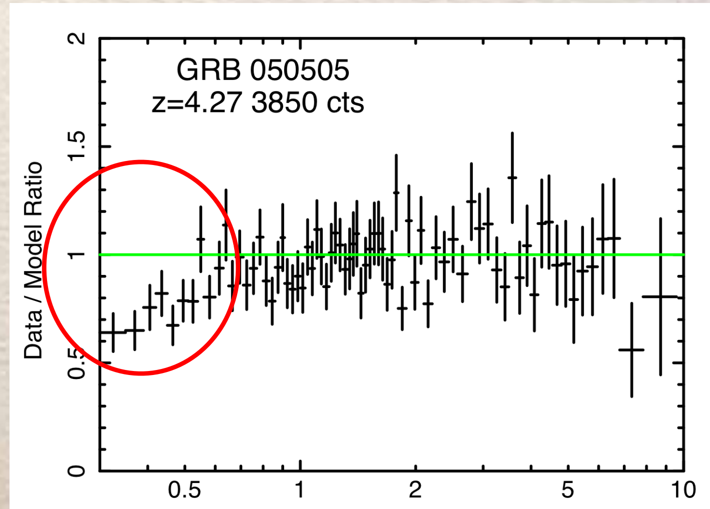
X-Ray Absorption Measurements

- No distinct edges or lines can be discerned means one CANNOT measure
    - Redshift (z)
    - Elemental abundances (Z)
    - Ionization
- These need to be assumed in fit
- On one hand, models provide excellent fits to the data <u>regardless of these assumptions</u>
- On the other, equivalent H column density

  $N_H = \int n_H dl = (Z_\odot)^{-1} \int n(Z,z) dl$

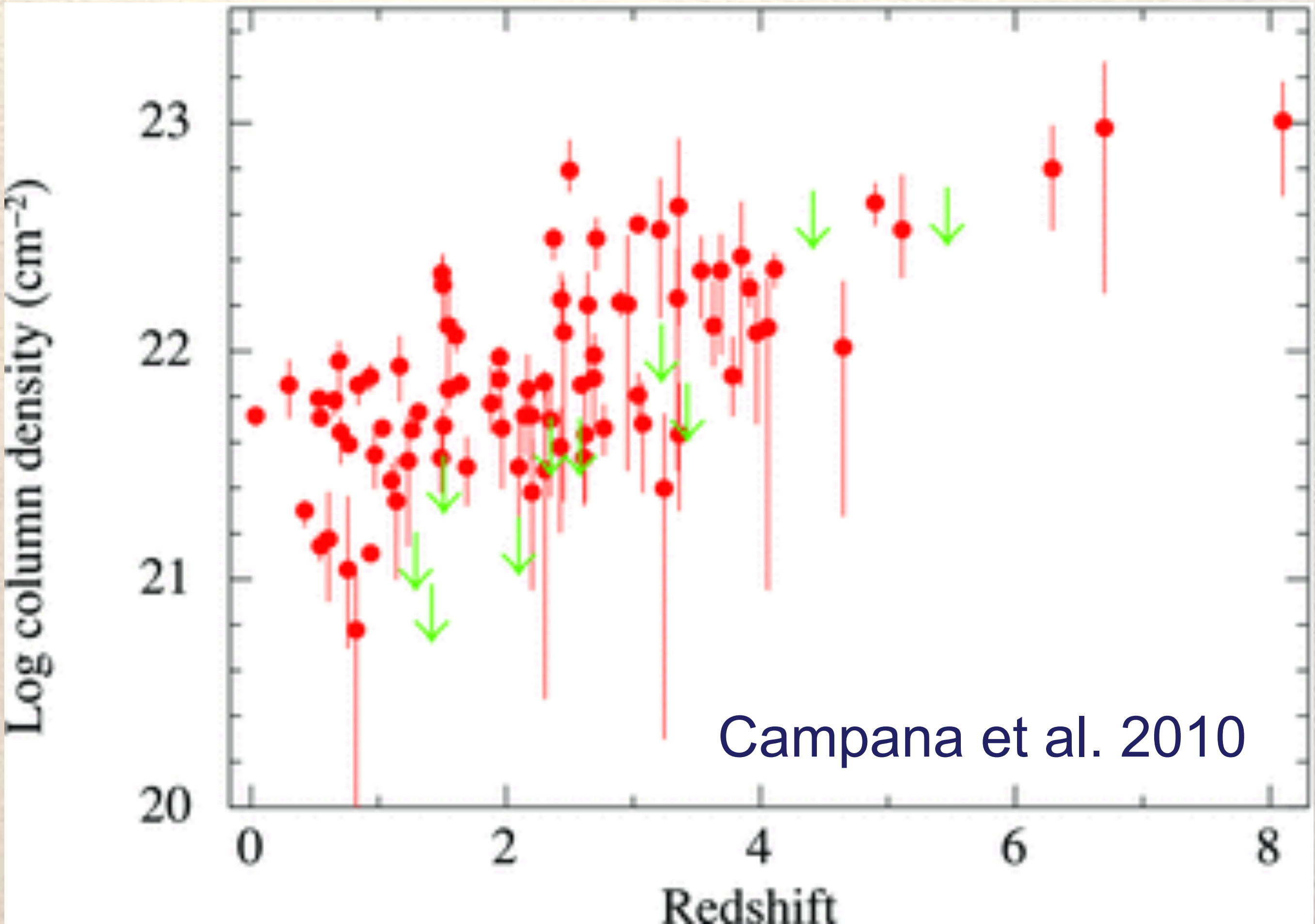
  STRONGLY depends on these assumptions





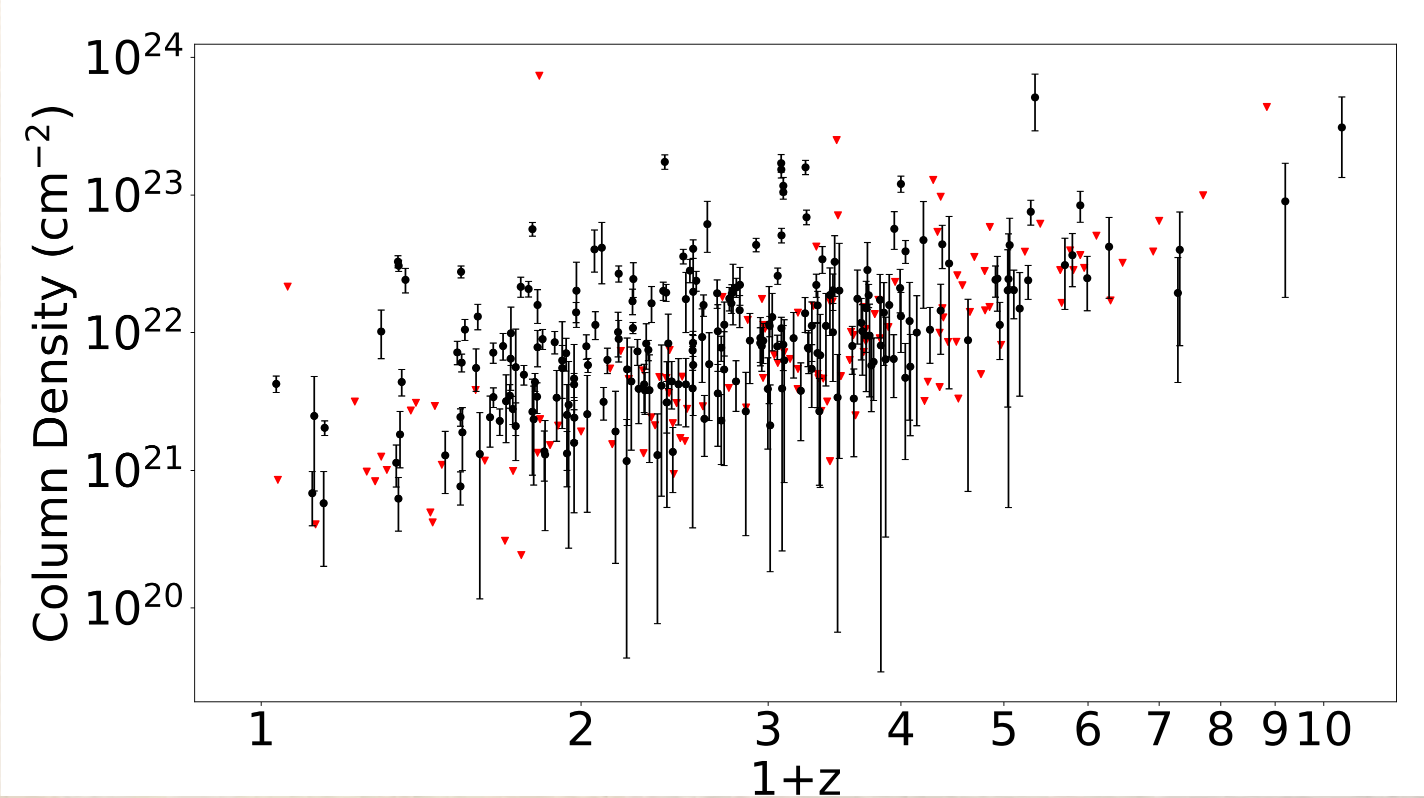
Assuming Host Neutral Absorber (z) and Solar Abundances ($Z_\odot$)

$N_H(z) \sim (1+z)^{2.5}$



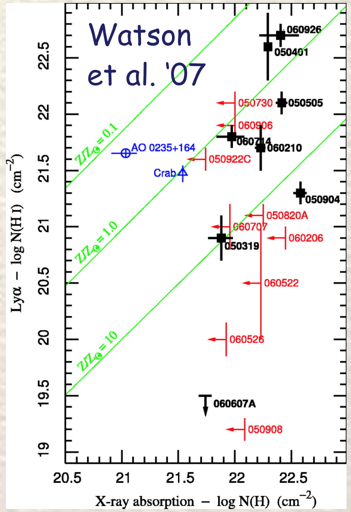
More (recently 2019) GRBs

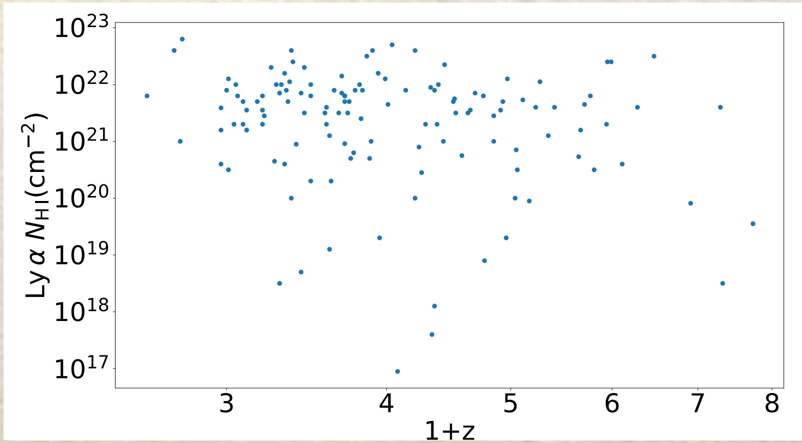
Roi Rahin



Issues with $N_H(z) \sim (1+z)^{2-3}$

- No evidence for GRBs evolving cosmologically
  - see many previous talks this week
- Host galaxy environments could be denser at high z, but …
- N_H (X-ray) >> N_H (Lyα)
  - ionization?
  - sub-solar metallicity makes problem worse
  - and no correlation
- Importantly, no sign of Lyα column evolving with z at all

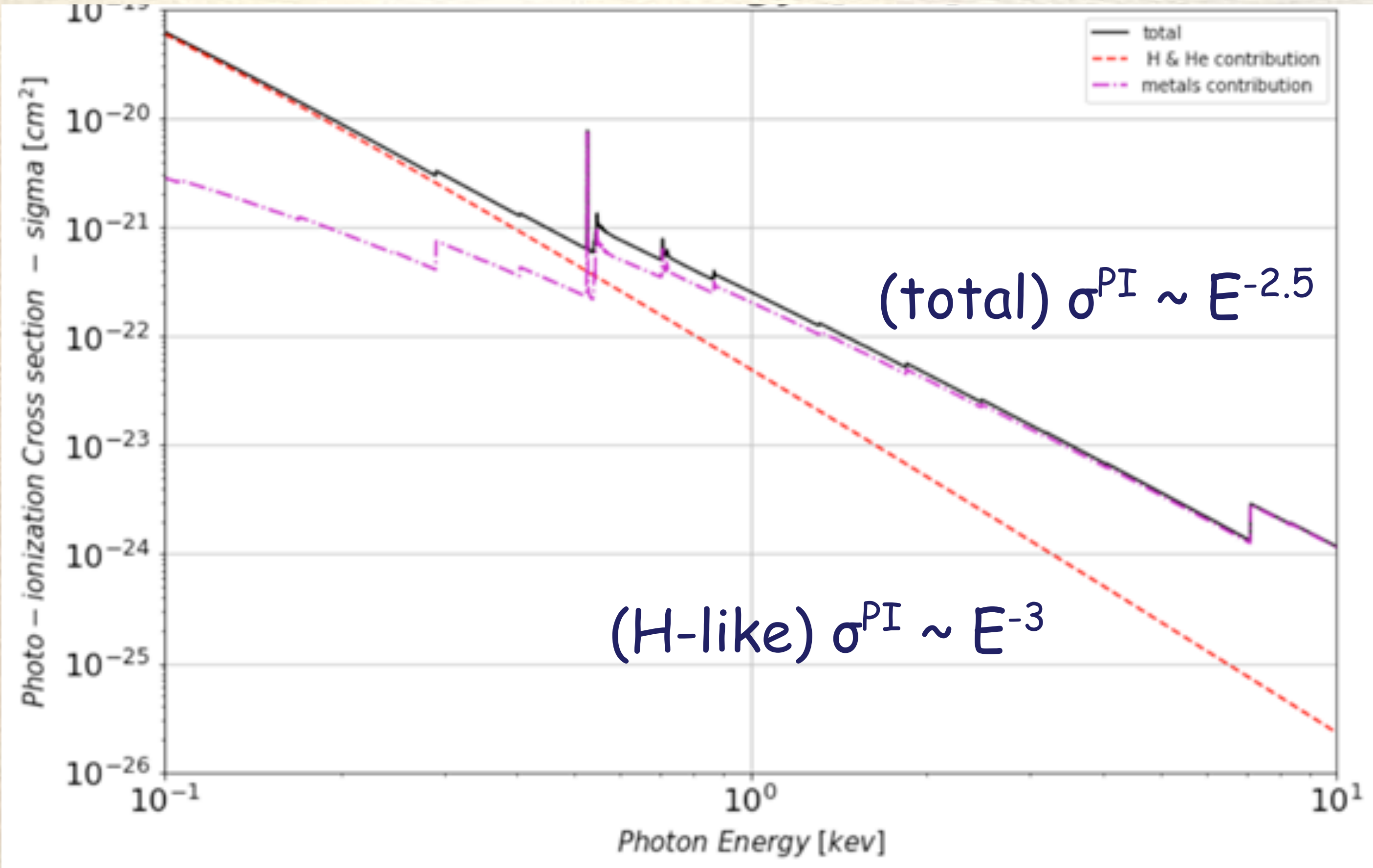




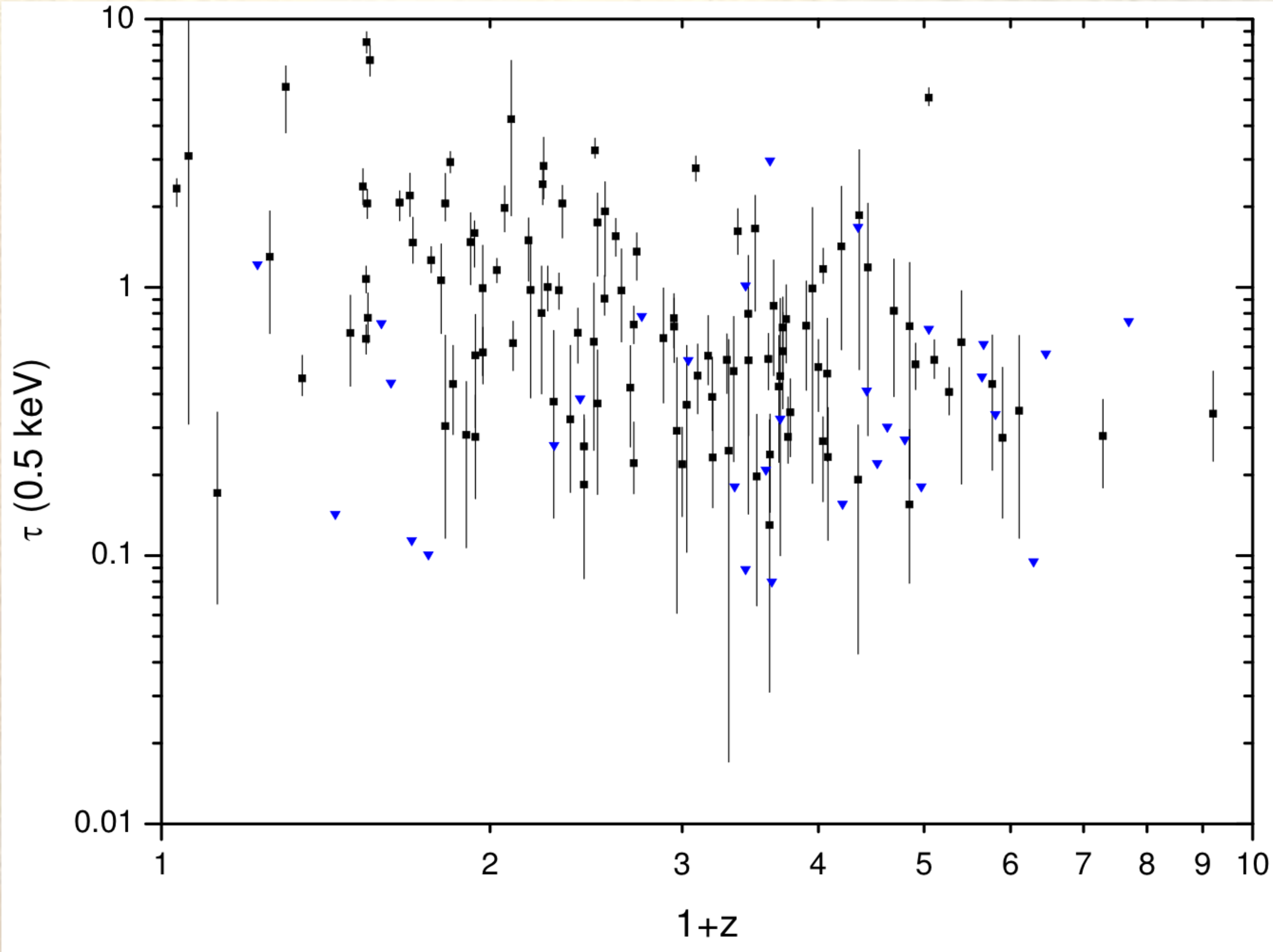
Rahin & EB '19, Lyα N_H from Tanvir+'19

Suspiciously $\sigma^{PI}(E)$ per H-atom ~ $E^{-2.5}$

High-z absorber $E_{abs} = (1+z)\, E_{obs}$ => low σ => High N_H

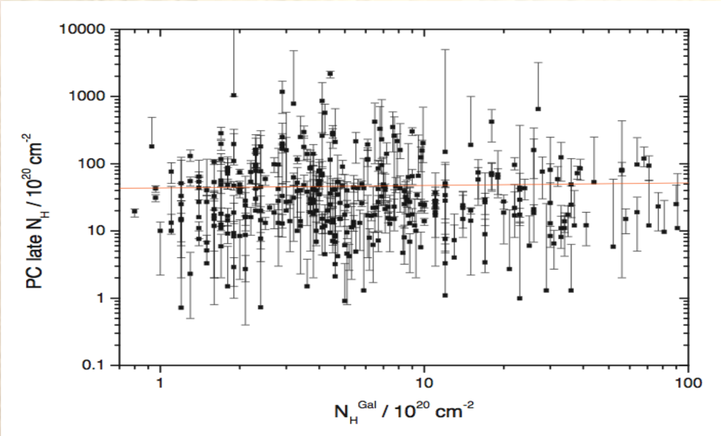


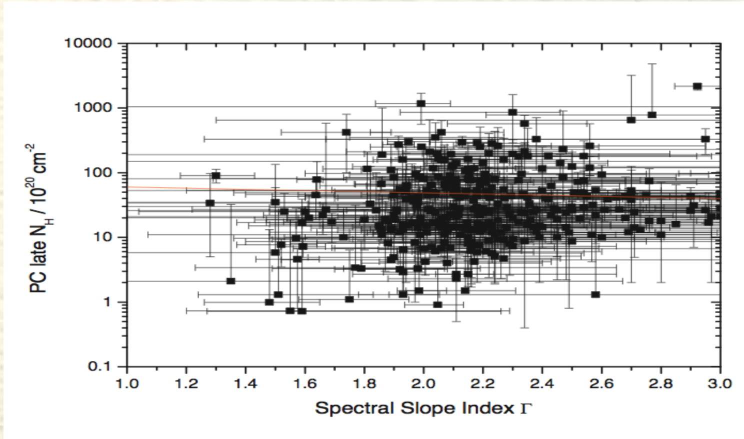
Optical Depth τ (0.5 keV)

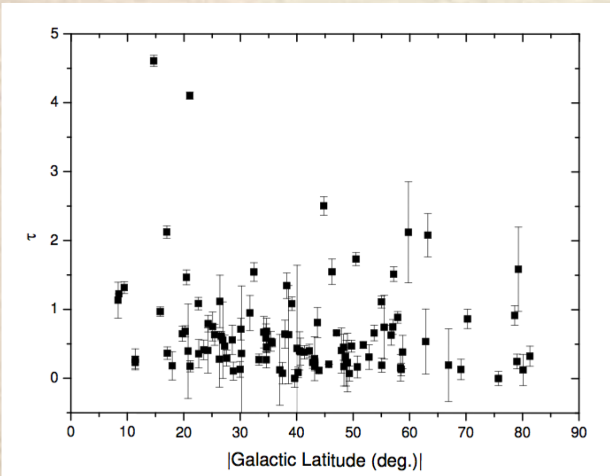


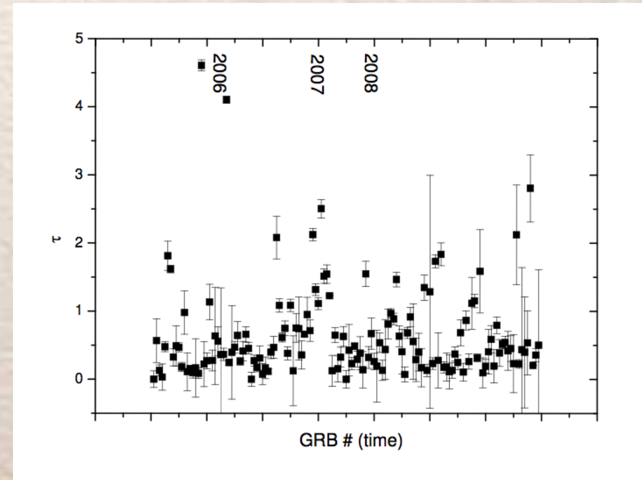
tends to 0.4
at z > 2
~constant

Systematics?







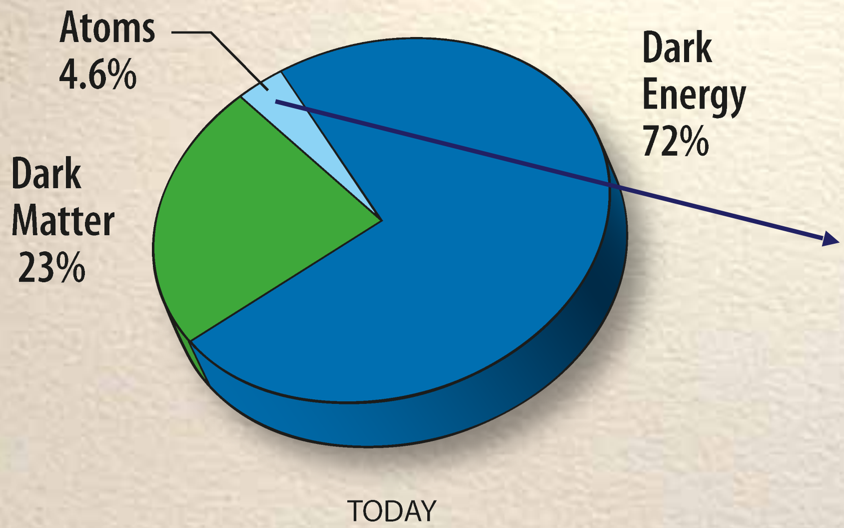


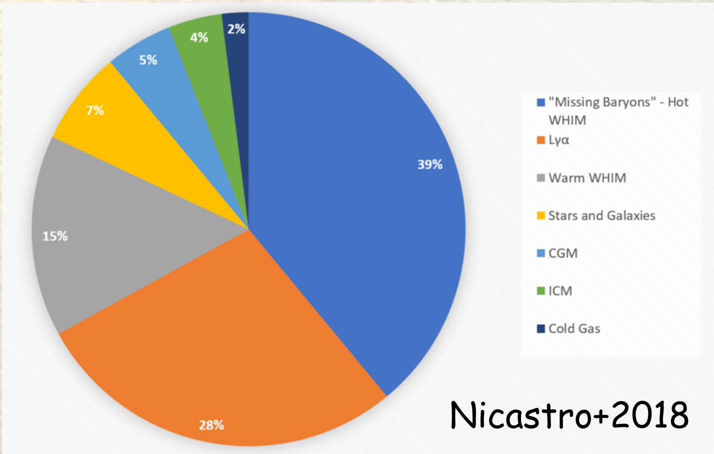
The Proposed Paradigm

- Intrinsic GRB columns, which scale $N_H \sim (1+z)^{2.5}$ could explain approximately fixed τ

- An attractive alternative explanation is the diffuse IGM; the "missing baryons"

Cosmic Inventory and The Missing Baryons





Naive, Mean Cosmological X-ray Opacity

- standard cosmology
- baryon (H) density $n_H = n_0(1+z')^3$
- PI cross section $\sigma(E,z',Z) = \sigma(E,0,Z_\odot)(1+z')^{-2.5}$
- metallicity evolution, $Z(z') = Z_0\eta(z') = Z_0(1+z')^{-k}$
- Still neutral

$$\tau_{IGM}(E,z,Z_\Theta) = \int_0^z n_H(z')\sigma(E,z',Z_\Theta)c\left(\frac{dt'}{dz'}\right)dz' \cong$$

$$\frac{n_0 c Z_0}{H_0}\sigma(E,0)\int_0^z \frac{(1+z')^3\eta(z')dz'}{(1+z')^{5/2}(1+z')\sqrt{(1+z')^3\Omega_M+\Omega_\Lambda}}$$

$\propto (1+z')^{-2}\eta(z')$

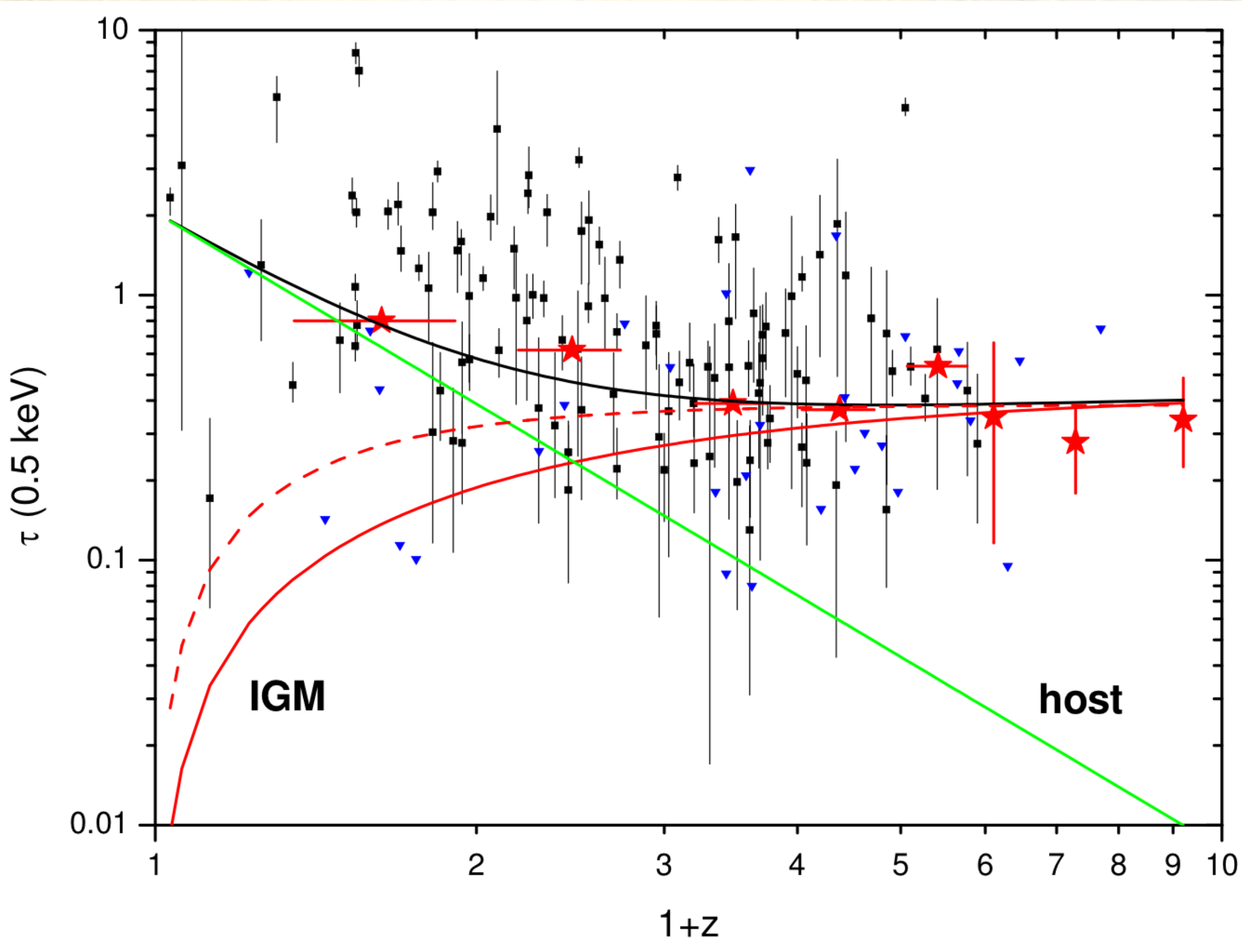
Only Metallicity Determines the IGM Optical Depth

- Indeed, at high-z τ tends to constant that depends on Z(z) and Z_0 the metallicity

$$\tau_{IGM}(0.5\mathrm{keV}, z) \xrightarrow{z>>1} 2Z_0 \int_0^{z>>1} \frac{dz'}{(1+z')^{2+k}} \cong \frac{2Z_0}{1+k}$$

- Counterintuitive (c.f., lines, Thomson scat.)
- For observed τ_{GRB}(0.5keV) = 0.4,
  - $Z_0 \sim 0.2$, k = 0 (lower Z_0 => k < 0)
  - $Z_0 \sim 0.4$ k = 1

Asymptotic IGM Behavior



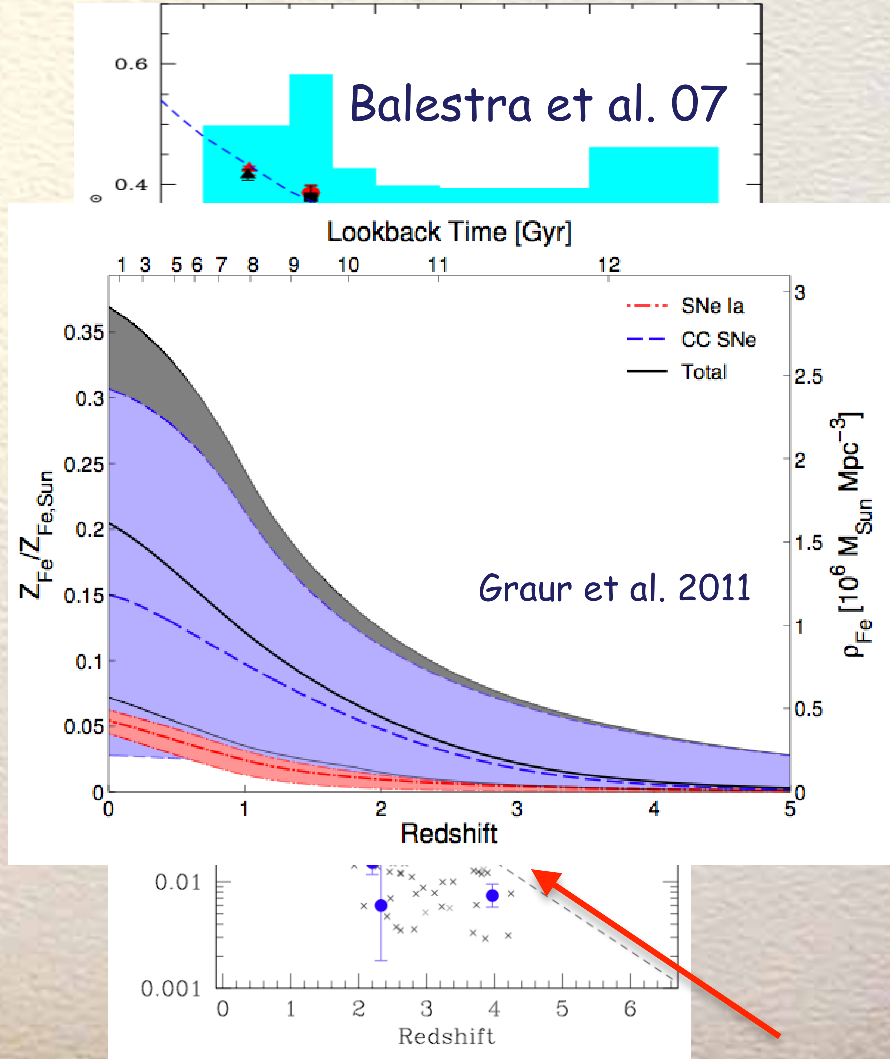
$2Z_0/(1+k)$

Is the Derived z=0 Metallicity of 0.2 - 0.4 Solar Reasonable?

- In hot galaxy cluster gas
  - no baryons are missing
  - $Z_\odot(\mathrm{Fe}) = 0.5\,(1+z)^{-1.25}$

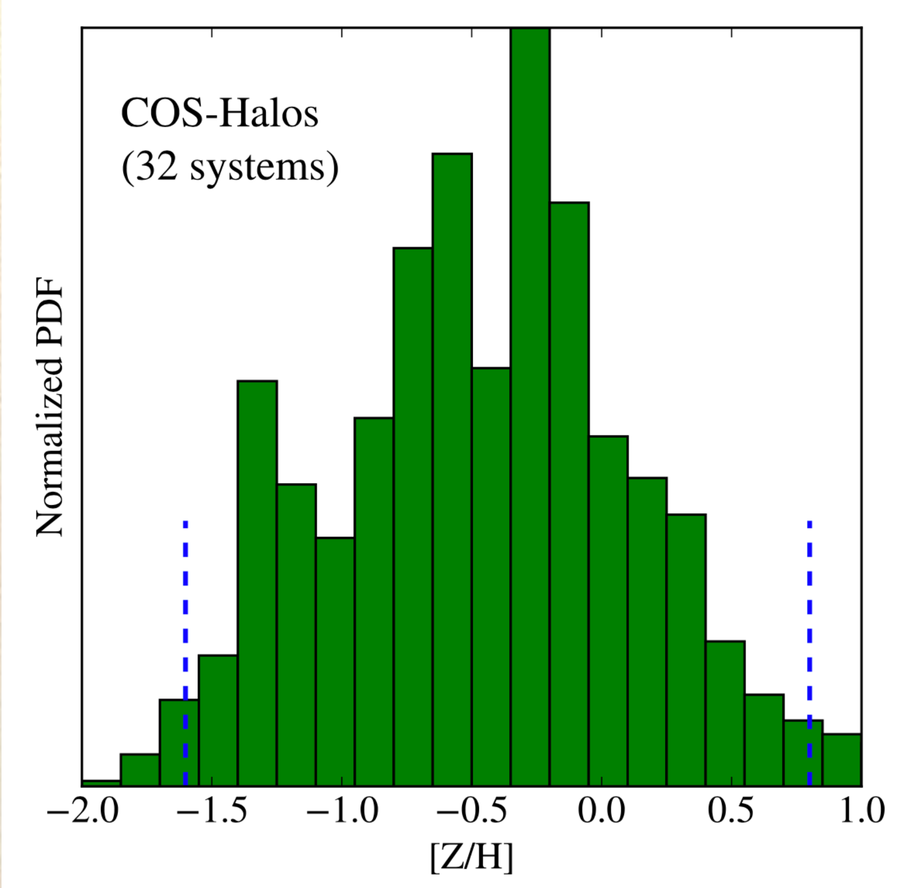
    $\tau(0.5\mathrm{keV}) = 0.45 \pm 0.15$
- In damped Lyα QSO sys.
  - $Z_\odot = 0.85(1+z)^{-3.25}$

    $\tau(0.5\mathrm{keV}) = 0.4$
- In z < 0.4 Lyα systems
  - $Z_\odot \cong 0.1$ (Danforth & Shull '08)
- And huge scatter in all
- Supernovae history
  - $Z_\odot(\mathrm{Fe}) = 0.2\,(1+z)^{-1}$



More Recently ~0.3 solar
but CGM lines of sight

Prochaska et al. 2017



Idea Gaining Traction

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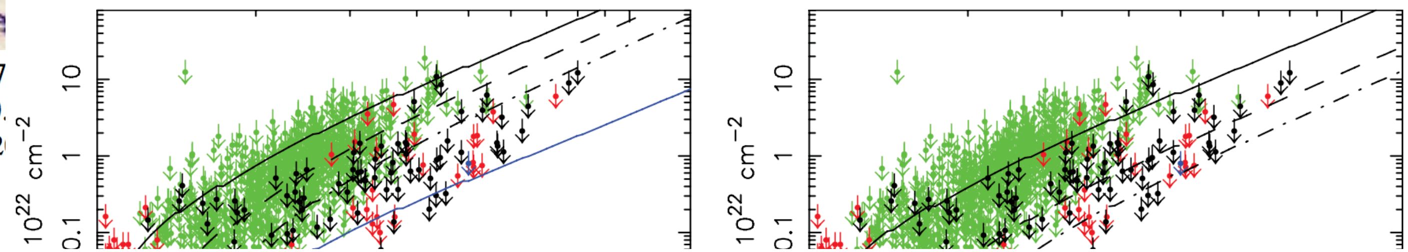

Mon. Not. R. Astron. Soc. **421,** 1697–1702 (2012) doi:10.1111/j.1365-2966.2012.20428.x

The X-ray absorbing column density of a complete sample of bright *Swift* gamma-ray bursts

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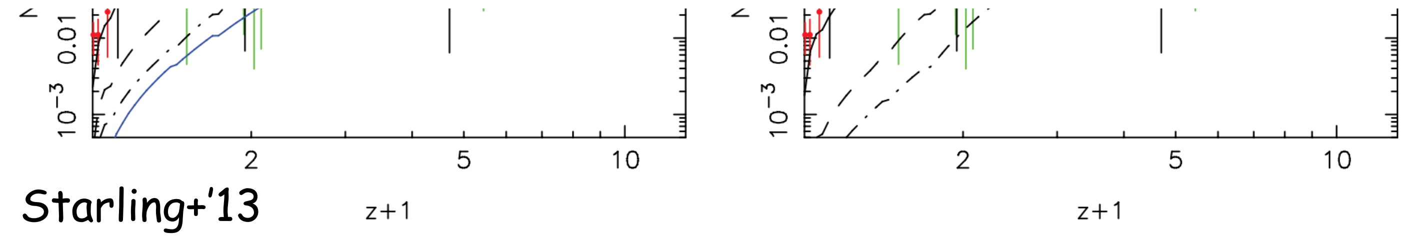
537X/776/2/96



Starling+'13

Dipartime

Figure 13. Measured intrinsic column density at solar metallicity for the GRBs (black points), AGN (green), quasars (red) and stacked spectrum of high-redshift quasars (blue) as described in Sections 2, 5 and 4.2, with constrained non-zero values in the lower panels and upper limits in the upper panels. Overlaid are the models for a cold IGM (solid line), 10^4 K warm IGM (dashed line) and 10^6 K warm IGM (dot–dashed line). Here, we compare IGM models which use a metallicity of $Z = Z_\odot$ on the left and $Z = 0.2\,Z_\odot$ on the right. The blue curves in the left-hand panels indicate the contribution expected from absorption by Lyman α clouds, assuming a prescription for their declining metallicity with redshift as described in Section 6.2.

n of both the diffuse

But maybe not?

- wrong MW dust-to-metal ratios (Watson'11)
- dust extinction, but only up to z<4 (Watson & Jakobsson '12)
- pure natal HeI absorption with no metals (Watson+'13)
- Dense massive $10^6 M_\odot$ clouds (Krongold & Prochaska '13)
- Highly turbulent ISM (Tanga+'16)
- Highly ionized (NV) gas (Heintz, Watson et al. '18)
- None of these gives truly convincing evidence for z-dependence

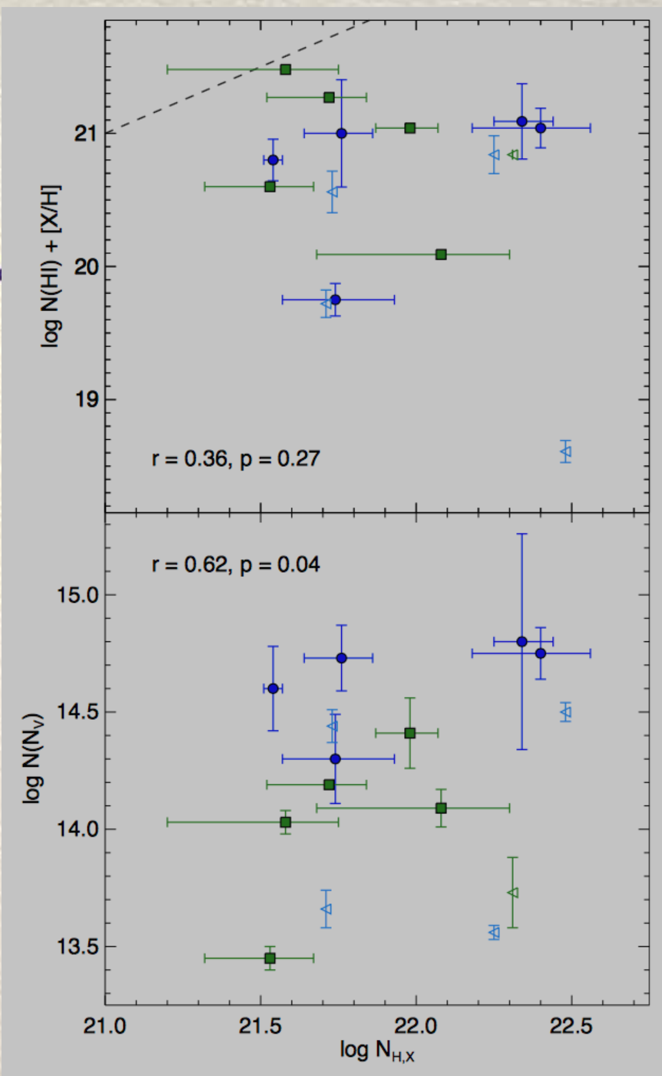
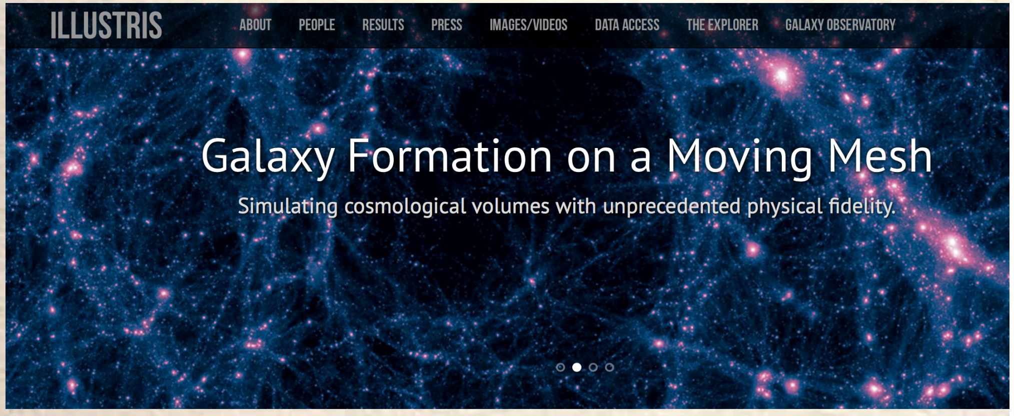
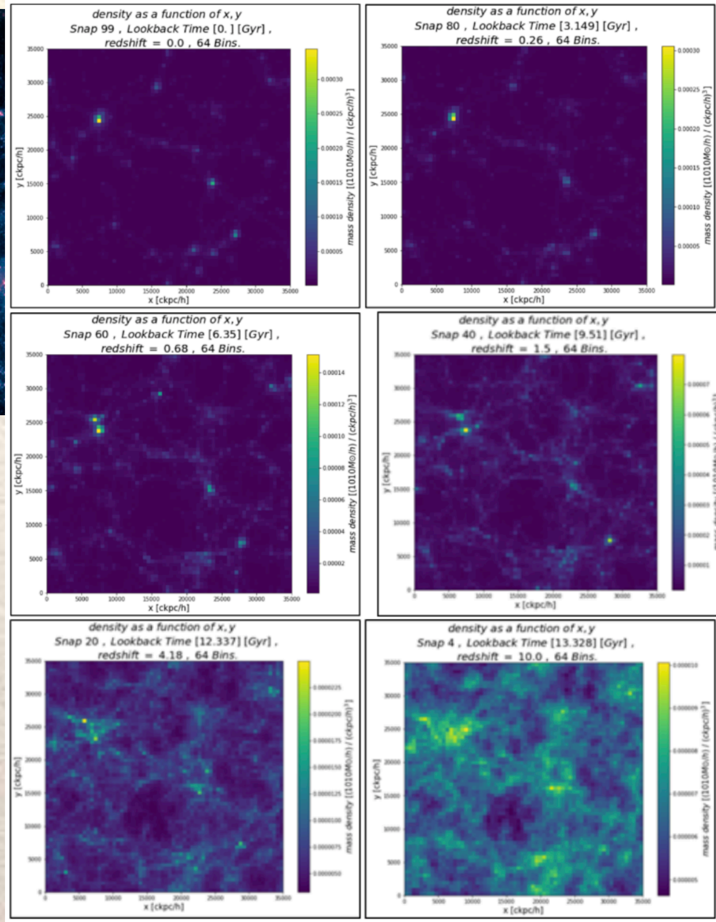


Figure 8. The *Swift*/XRT soft X-ray derived metal column density, $N_{H,X}$, as a function of the UV/optical metal column density, log N(H I) + [X/H], (upper panel), and the Nv column density (bottom panel). In both panels the computed r and p values are shown. In the upper panel the 1:1 ratio between the two distinct metal column densities is represented as the dashed line. Only the GRBs from our sample and the two previous samples with N v detections are plotted in both panels. Open triangles denote GRBs with upper limits on $N_{H,X}$.

What Do Cosmic Simulations Say?
(work in progress)

Matan Grauer

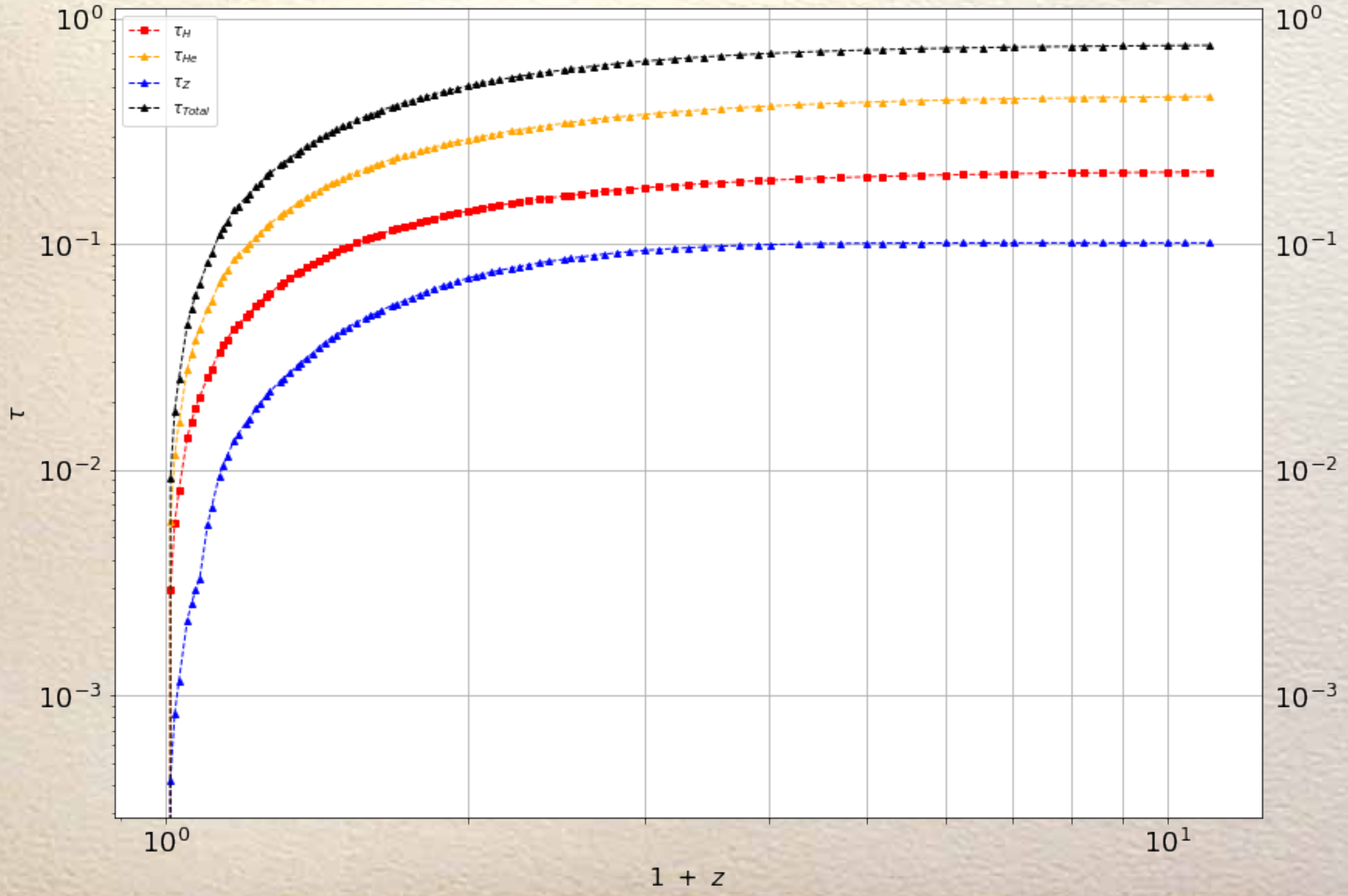




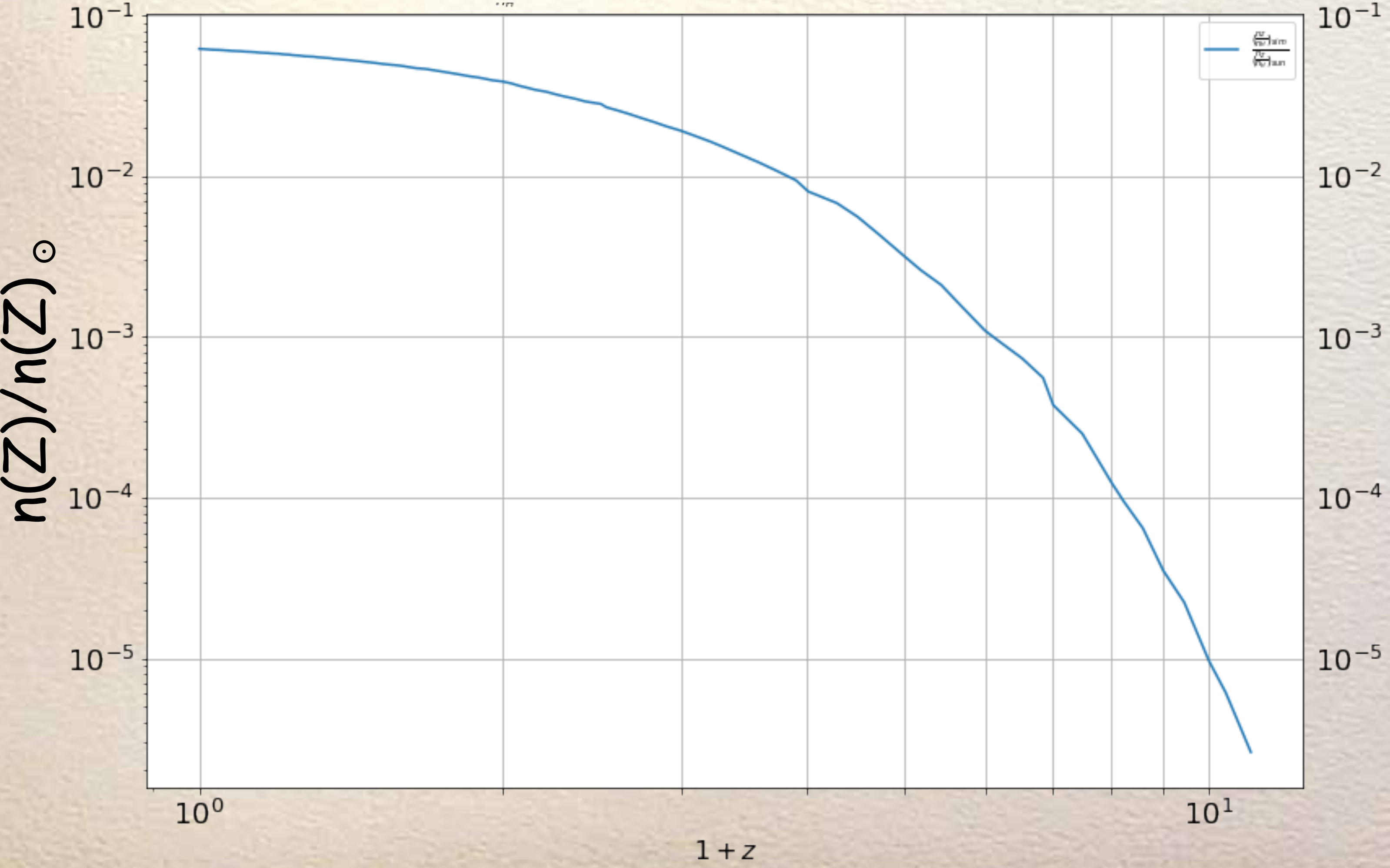
Simulations give (theoretical) handle on

- redshift
- metallicity
- ionization (of H)

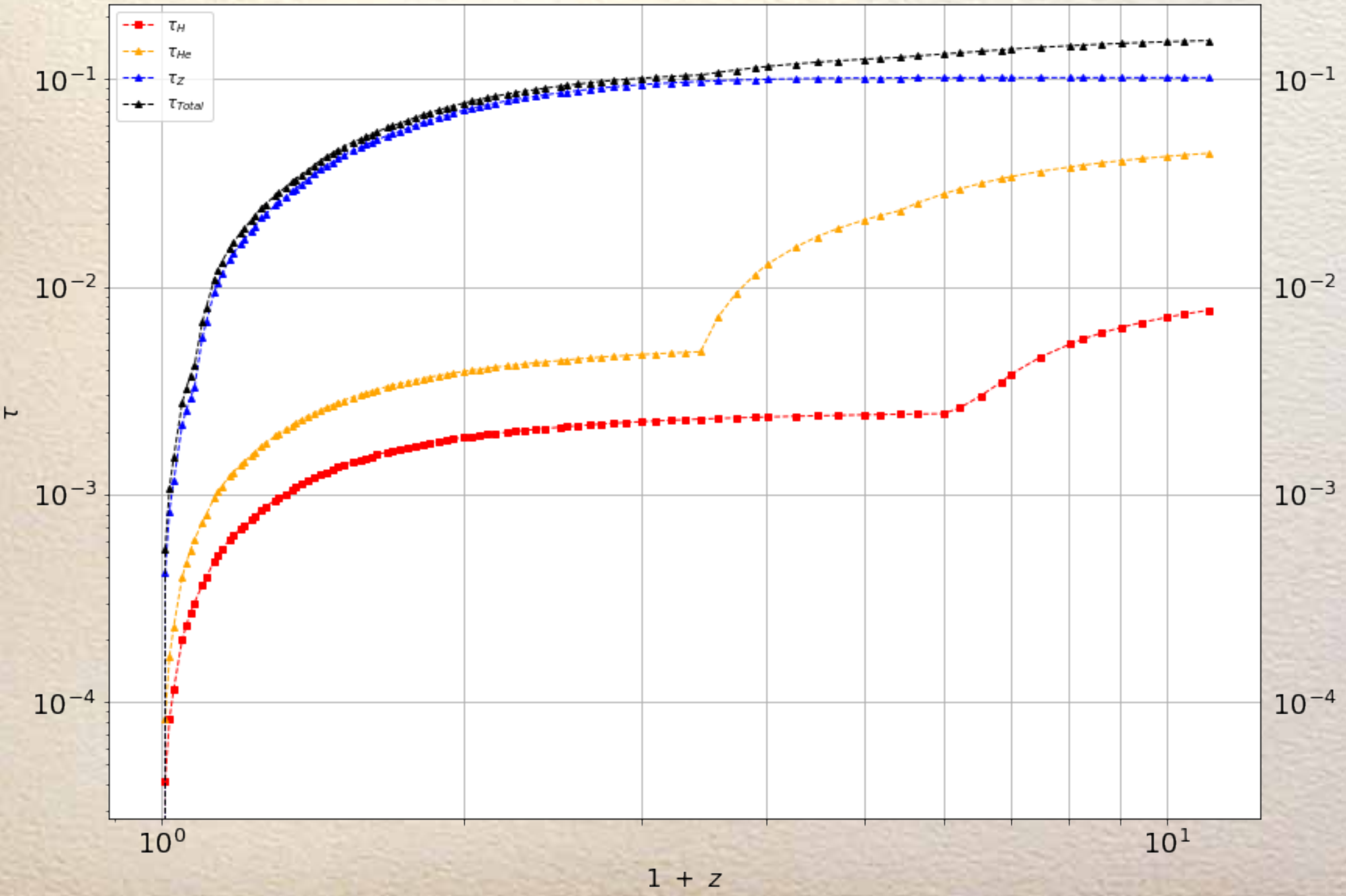
Total Optical Depth τ ~ 1
Dominated by H & He at low-z



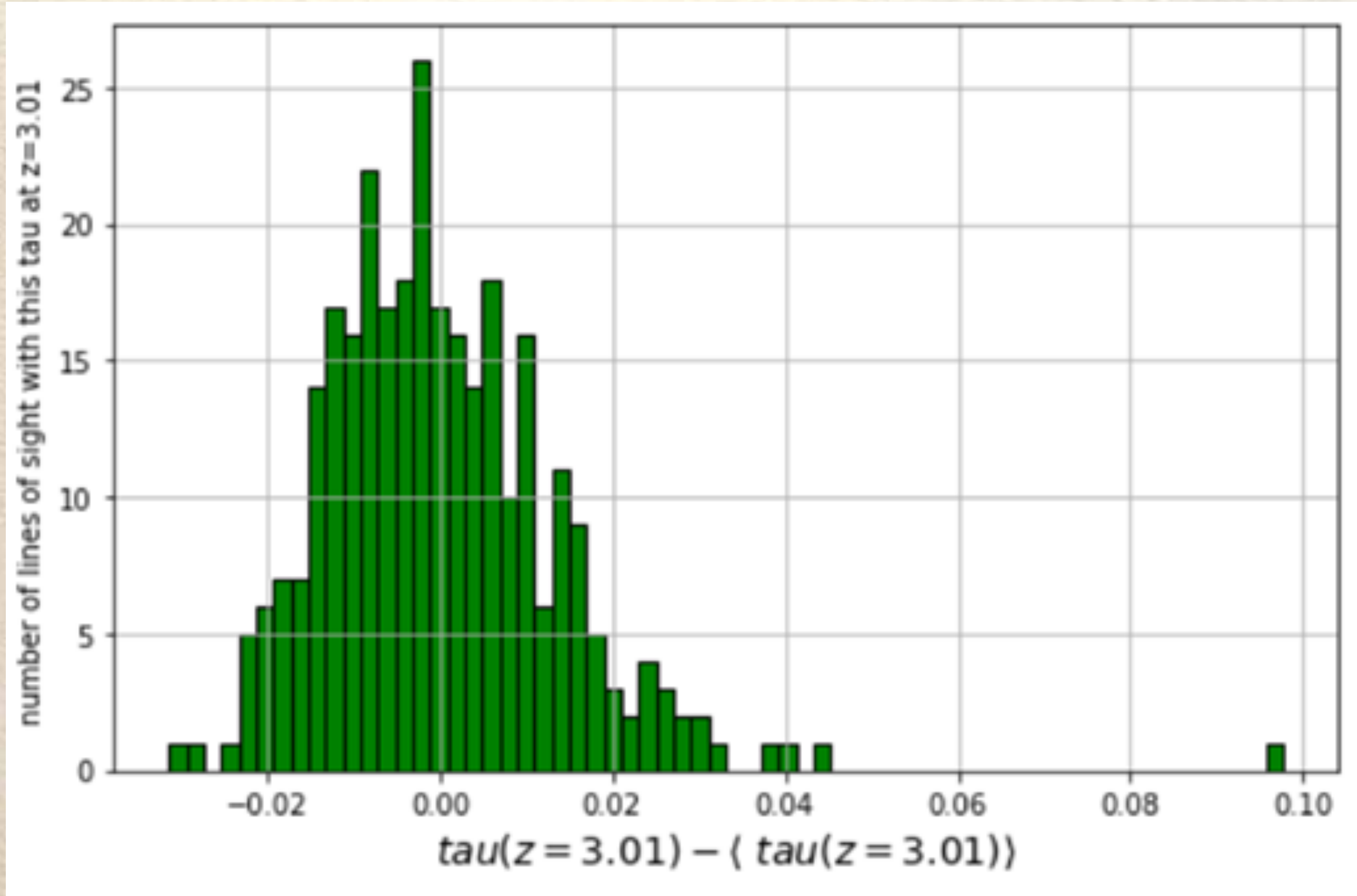
Mean Cosmological Metallicity (Z_0 < 1)



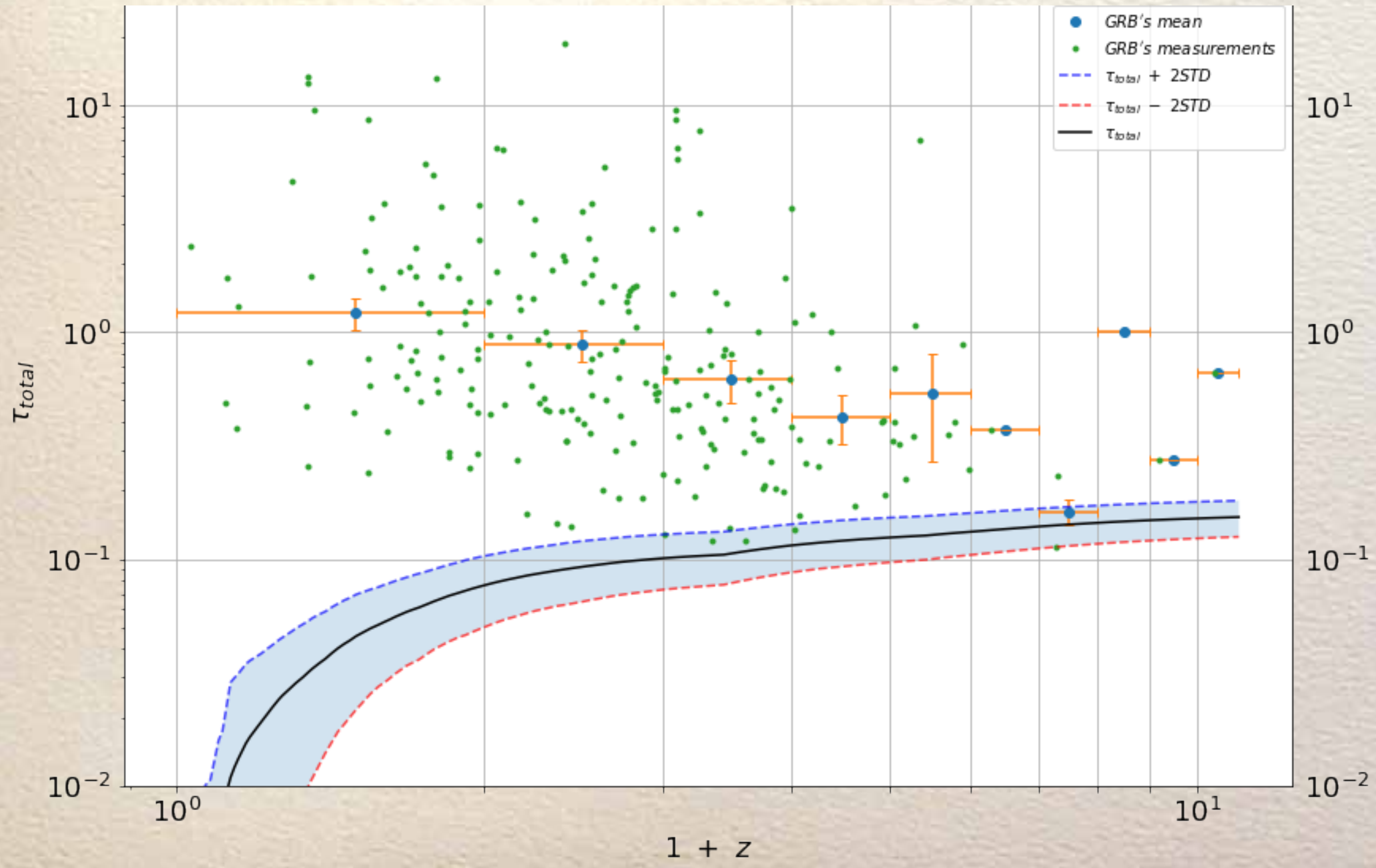
Considering Ionization of H & He => τ <~ 0.2 now dominated by the metals



(too) Narrow Distribution of IGM $\Delta\tau \sim 0.02$



Comparison with Measurements



Points for Discussion

- Current X-ray measurements of GRB afterglows are limited in detecting absorber redshift, abundances, and ionization
- A crude analytical approximation of the diffuse (or not) IGM could explain the τ_X-> 0.4 tendency at high-z
- Any other explanation must explain z-dependence (not only discrepancy with Lyα column, which has many explanations)
- If true, bad news for GRB physics, but good news for using GRBs as cosmology probes - will we see lines?
- Cosmological simulations allow us to consider ionization and metallicity effects, predicting
  - τ(high-z) tends to 0.1 - 0.2 due to metals (H, He ionized)
  - Very low dispersion $\Delta\tau = 0.02$ (probably due to resolution)
  - Low metallicity (agree with observations?)

THANK YOU
FOR YOUR ATTENTION