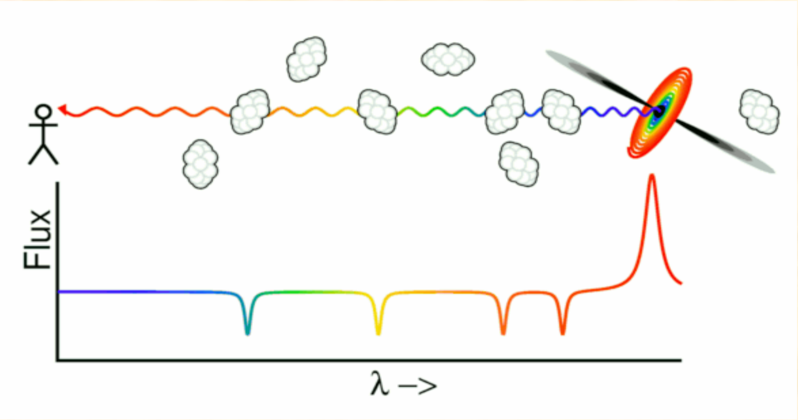
Metallicity versus *N*(HI) in DLA systems

Predictions of cosmological simulations versus observations

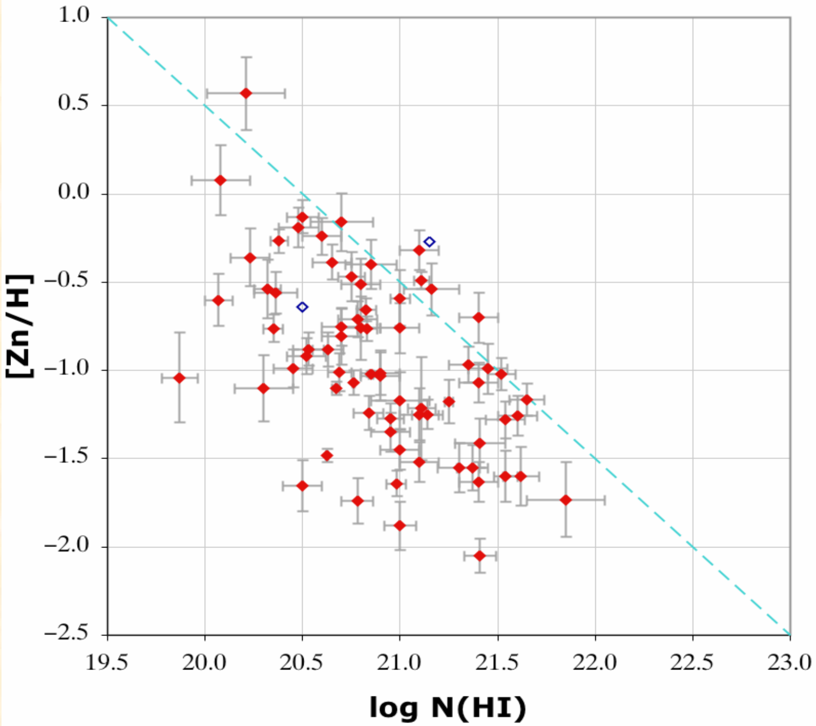
Giovanni Vladilo
Osservatorio Astronomico di Trieste - INAF



- Damped Lyman α (DLA) systems
  - Densest concentrations of HI observed as quasar absorption systems
  - Excellent probes of structure formation in the early Universe
    - Galaxy formation, star formation, and galactic/IGM interactions at early cosmic epochs

- Frequency distribution of HI column densities and metallicities in DLAs
  - Diagnostic tool of cosmological simulations
    - By considering both HI and Z we can probe the physics used to convert gas into metals

The observational HI-metallicity diagram of DLA systems



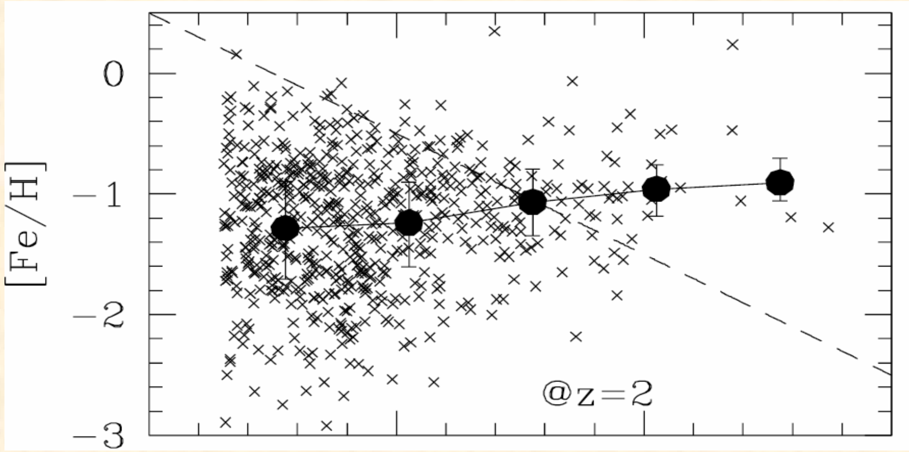
- Very few systems at [M/H] + log N(HI) > 20.5

  Intrinsic lack of DLA systems ?

  An observational limit due to dust extinction ?

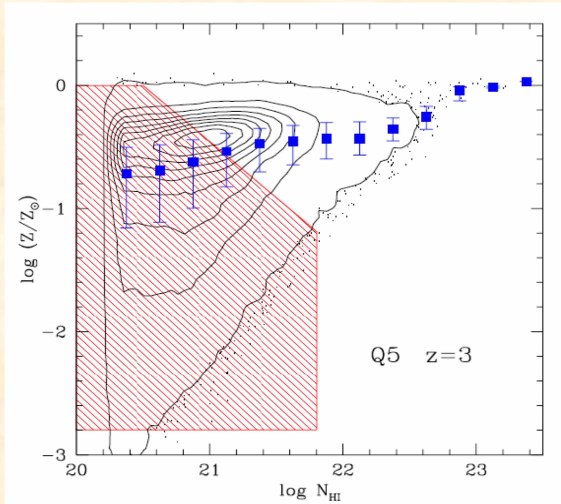
  Boissè et al. (1998)

- Cosmological simulations with
  - galaxy formation
  - sub-galactic resolution
  - detailed microphysics



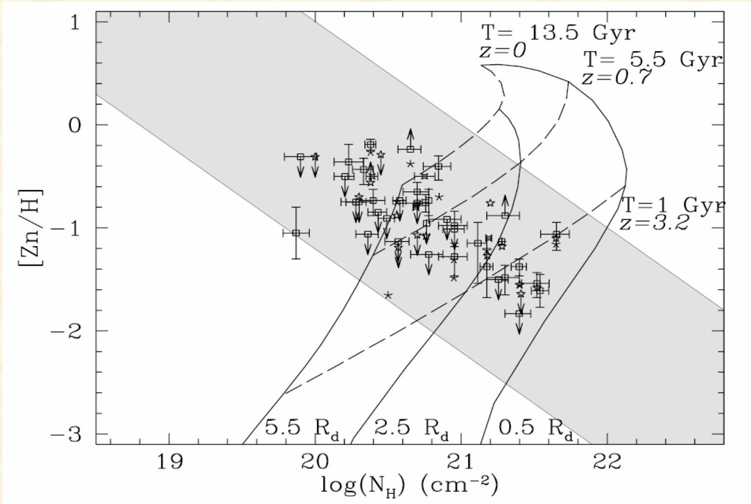
- … yield predictions on
  - the HI-Z distribution in DLA systems
    - Cen, Ostriker, Prochaska, Wolfe (2003)
    - Nagamine, Springer, Hernquist (2004)

- Cosmological simulations indicate that DLA systems should exist at log N(HI) + [M/H] > 20.5
  - A broad agreement with the observations is obtained by imposing an arbitrary cutoff



- Also models of galactic chemical evolution predict the existence of regions with
  $\log N(\mathrm{H\,I}) + [\mathrm{M/H}] > 20.5$

  Prantzos & Boissier (2000)
  Churches, Nelson & Edmunds (2004)
  Lanfranchi, Matteucci & Cescutti (2006)



Are we missing the regions of high HI column density and metallicity ?
Are we missing the regions of high SFR ?
Are we missing the regions with high molecular fraction ?

Important issues to understand ...
even in the case that the metals and gas that we don't see would not give a strong contribution to Ω_{HI} or Ω_Z

Aim of the work

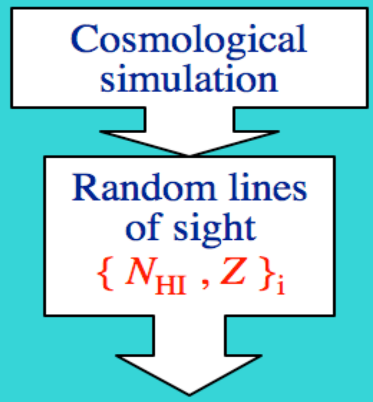
Take into account observational effects...

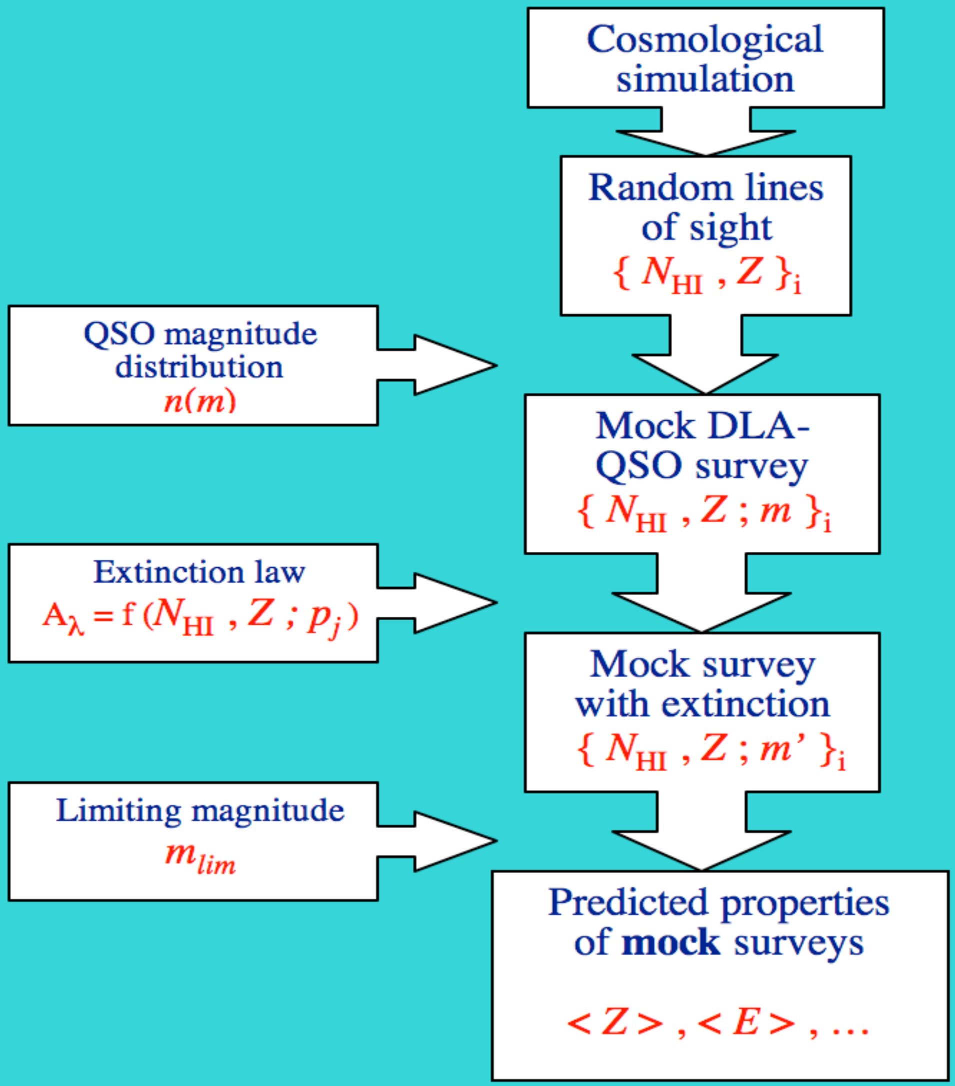
- Limited sensitivity of the instrumentation
- QSO extinction due to dust in the DLA systems

... to convert the predictions of a cosmological simulation into a distribution of metallicities and HI column densities that can be directly compared with the observations

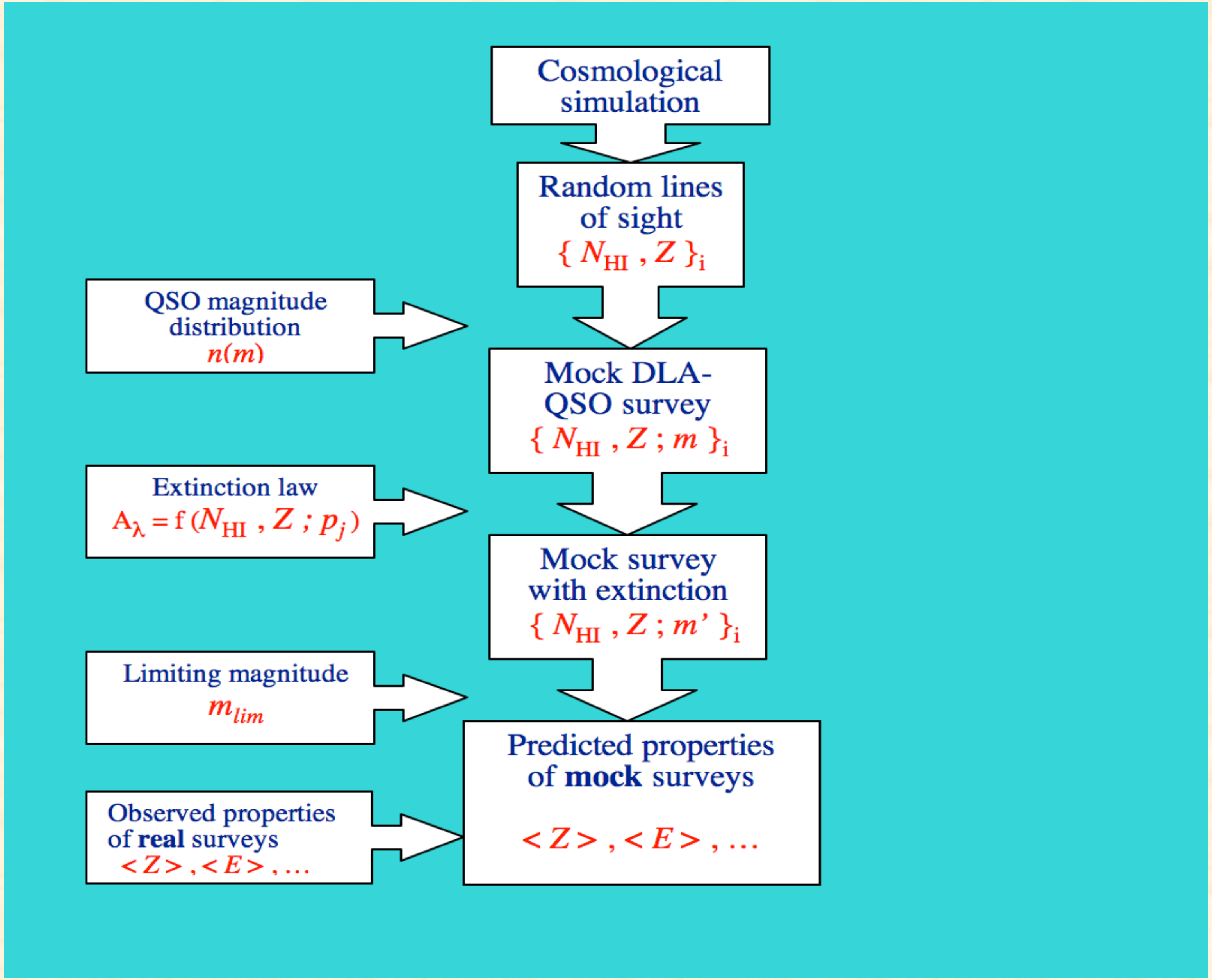
Cosmological simulation

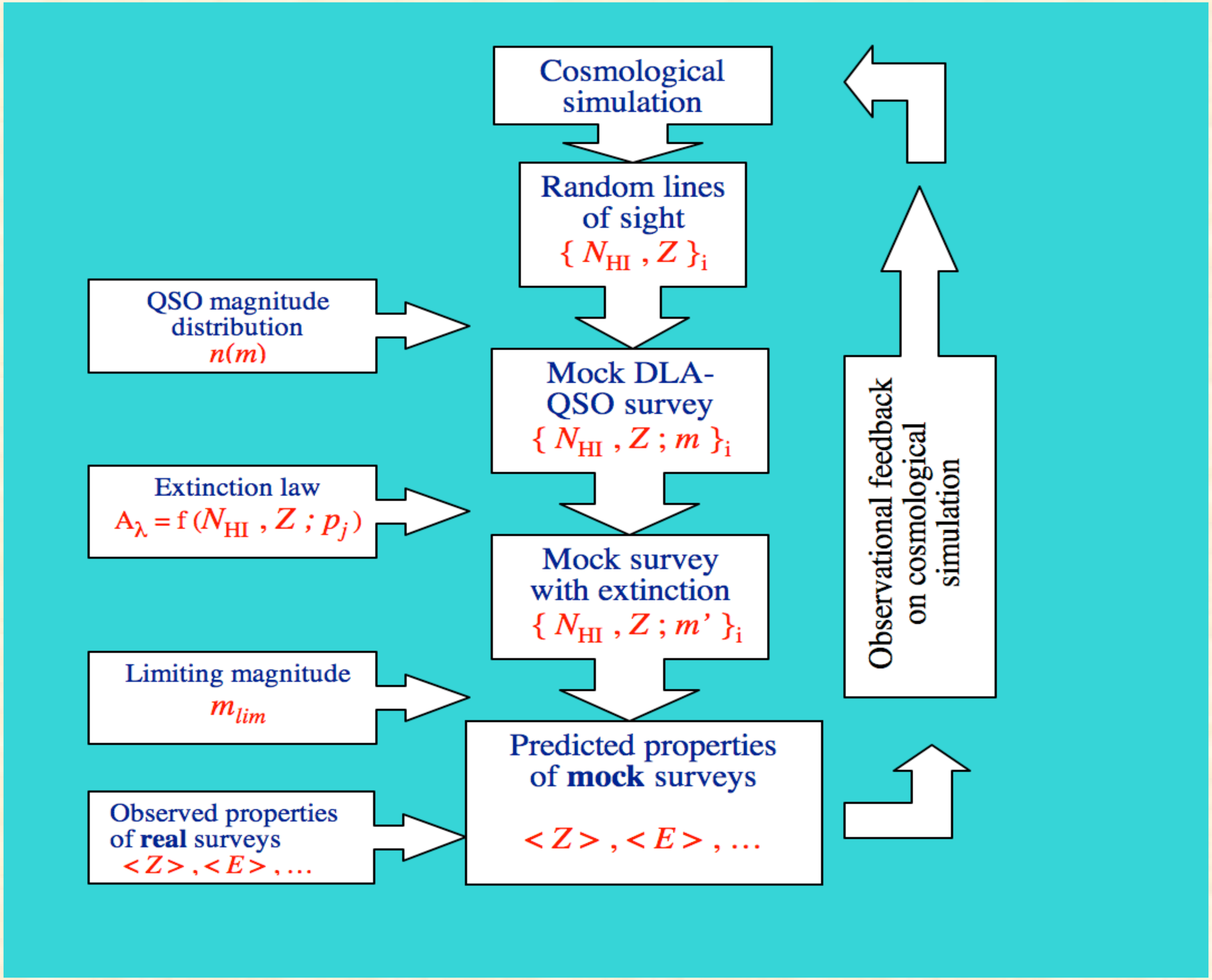
N(HI) > 2 x 10^{20} atoms cm^{-2}





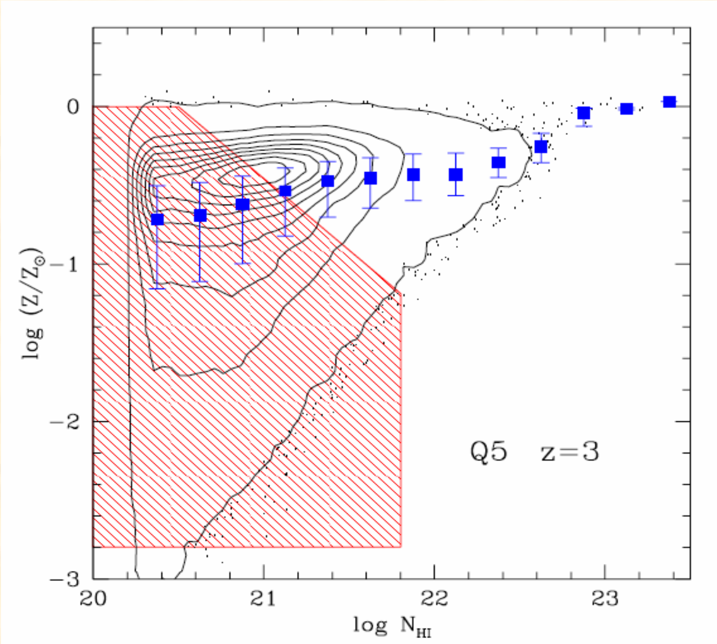
Cosmological simulation
Random lines of sight
{ N_{HI} , Z }$_i$
QSO magnitude distribution
$n(m)$
Mock DLA-QSO survey
{ N_{HI} , Z ; m }$_i$
Extinction law
$A_\lambda = f(N_{HI}, Z ; p_j)$
Mock survey with extinction
{ N_{HI} , Z ; m' }$_i$
Limiting magnitude
m_{lim}
Predicted properties of **mock** surveys
$<Z>$, $<E>$, …

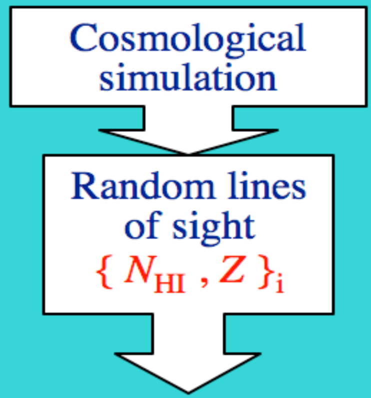

Cosmological simulation
Random lines of sight
{ N_HI , Z }_i
QSO magnitude distribution
n(m)
Mock DLA-QSO survey
{ N_HI , Z ; m }_i
Extinction law
A_λ = f (N_HI , Z ; p_j)
Mock survey with extinction
{ N_HI , Z ; m' }_i
Limiting magnitude
m_lim
Predicted properties of mock surveys
< Z > , < E > , …
Observed properties of real surveys
< Z > , < E > , …

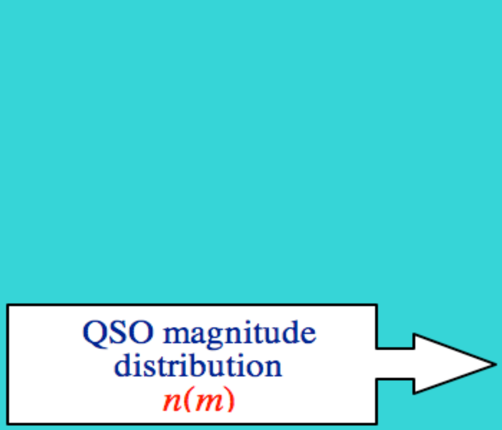

Cosmological simulation
Random lines of sight
{ N_{HI} , Z }$_i$
QSO magnitude distribution
$n(m)$
Mock DLA-QSO survey
{ N_{HI} , Z ; m }$_i$
Extinction law
$A_\lambda = f(N_{HI}, Z; p_j)$
Mock survey with extinction
{ N_{HI} , Z ; m' }$_i$
Limiting magnitude
m_{lim}
Predicted properties of **mock** surveys
< Z > , < E > , …
Observed properties of **real** surveys
< Z > , < E > , …
Observational feedback on cosmological simulation

Cosmological simulation

- Methodology tested on model Q5 by
  - Nagamine, Springer, Hernquist (2004)
    - SPH simulations, Λ-CDM model
    - boxsize: 10 h^{-1} Mpc
    - $N_p=2x324^3$
    - softening length 1.2 h^{-1} Kpc
    - feedback by galactic winds
  - ~ 9 x 10^4 random lines of sight
  - N(HI) > 2 x 10^{20} cm^{-2}
  - z=3
    - kindly provided by Ken Nagamine




Cosmological simulation
Random lines of sight
$\{ N_{HI}, Z \}_i$



To each line of sight we associate a simulated background QSO with magnitude extracted at random according to the observed distribution of QSO magnitudes

- Frequency distribution of QSOs apparent magnitudes

  SDSS Data Release 5

  $2.5 < z_{em} < 3.5$

- To simulate the observations we consider QSOs without intervening absorbers

- We then apply the effects of intervening extinction to these QSOs

$$n_m(z_e)$$

number of quasars at redshift z_e
per unit interval of apparent magnitude

$$\mathcal{C}_m(z_e) = \mathcal{C}_m(z_e; c_i)$$

instrumental completeness function

$$n'_m(z_e) = n_m(z_e) \times \mathcal{C}_m(z_e)$$

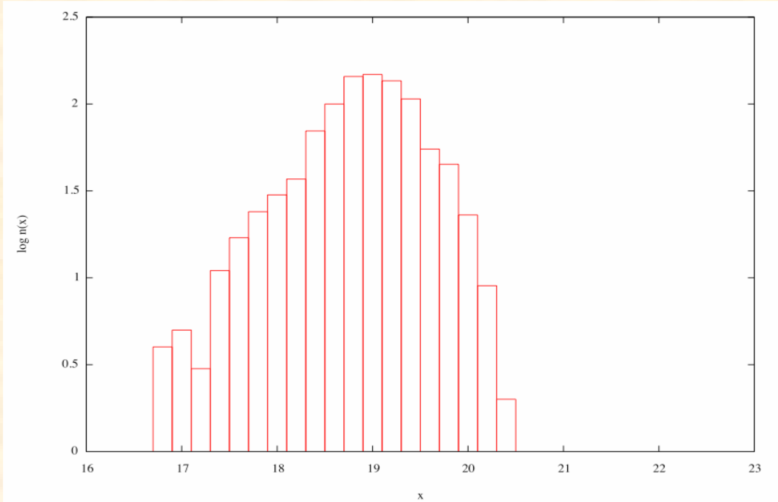
instrumentally biased magnitude distribution

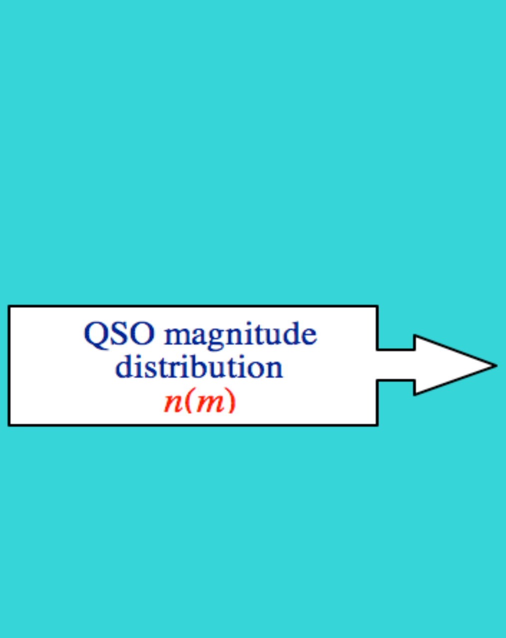
$$\mathcal{B}_m(z_e) = \mathcal{B}_m(z_e; b_j)$$

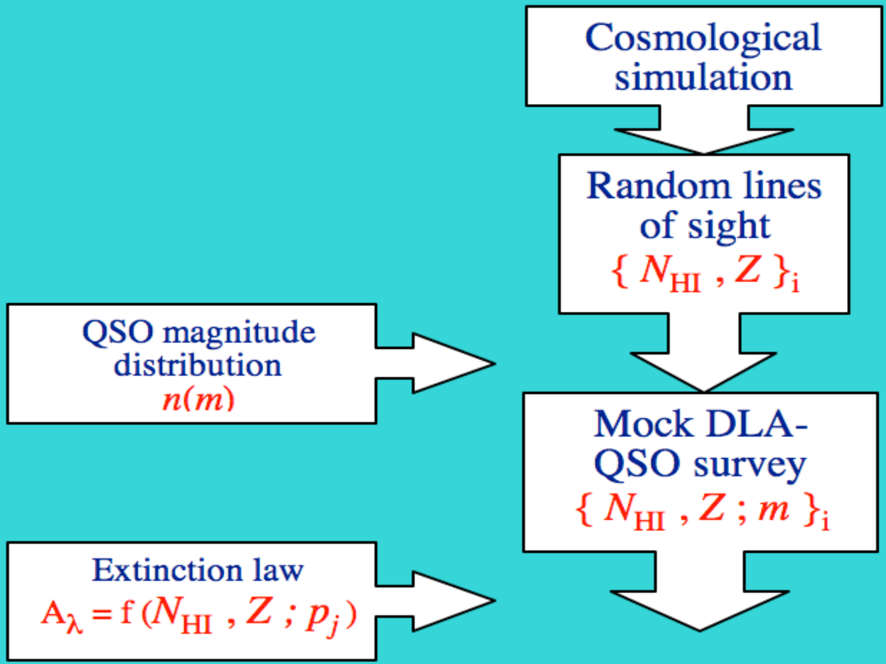
bias function inherent to the astronomical observation

$$n^{\mathrm{b}}_m(z_e) = n_m(z_e) \times \mathcal{B}_m(z_e) \times \mathcal{C}_m(z_e)$$

instrumentally and astronomically
biased magnitude distribution




Cosmological simulation
Random lines of sight
{ N_HI , Z }_i
QSO magnitude distribution
n(m)
Mock DLA-QSO survey
{ N_HI , Z ; m }_i


Cosmological simulation
Random lines of sight
$\{ N_{HI} , Z \}_i$
QSO magnitude distribution
$n(m)$
Mock DLA-QSO survey
$\{ N_{HI} , Z ; m \}_i$
Extinction law
$A_\lambda = f(N_{HI} , Z ; p_j)$

Extinction vs. metals in HI regions

The extinction increases with the dust column density and therefore

$$A_\lambda \propto \widehat{N}(\text{refractory elements})$$

$$A_V = \langle s_V^{\rm Fe} \rangle \, \widehat{N}_{\rm Fe}$$

$$\langle s_V^{\rm Fe} \rangle = 1.007 \times 10^{-22} \frac{\sum_j w_j \langle Q_{\lambda_V} \sigma_g \rangle_j}{\sum_j w_j \langle V_g \varrho X_{\rm Fe} \rangle_j} \quad \text{mag cm}^{-2}$$

Extinction per unit dust column density of iron

Q_λ Extinction efficiency factor

Relation calibrated empirically

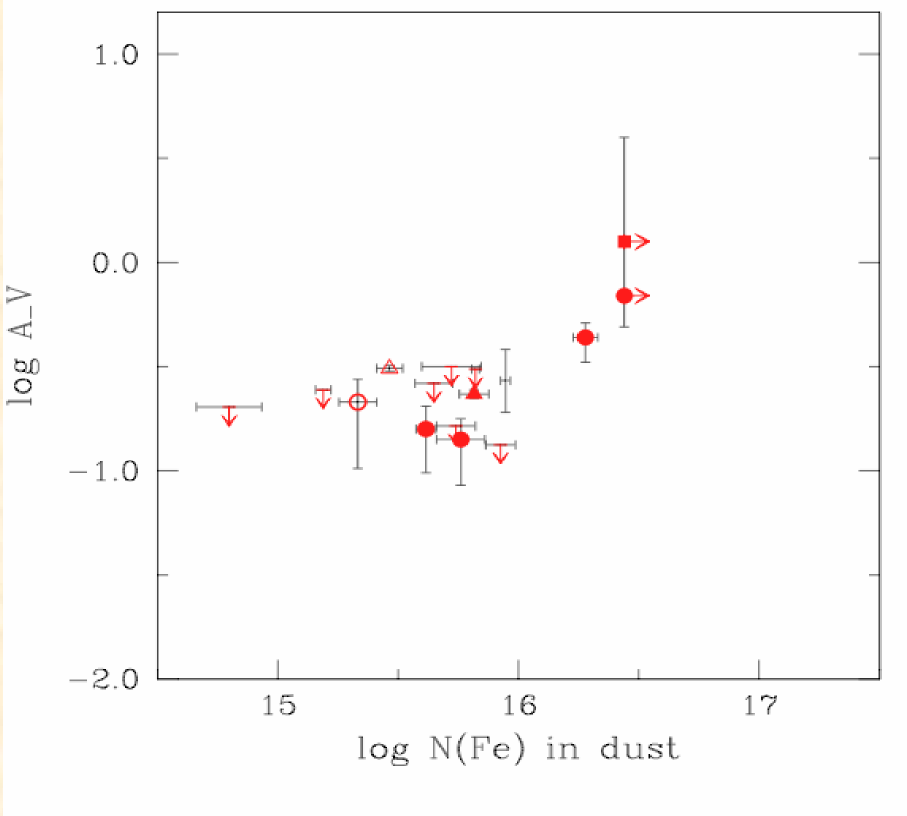
Extinction vs. metals in DLA systems

- Measurement of reddening in a selected sample of DLA-QSOs
  - Quasars in SDSS
  - Fe & Zn lines detected at high spectral resolution
- Reddening detected in different colors of the *ugriz* SDSS phot. System
  - 5 out of 13 selected cases
  - Above the dispersion of the intrinsic quasars colours
- Reddening converted to rest-frame A_V
  - SMC extinction curve
- N(Fe) & N(Zn) converted to column density of iron in dust form

$$\widehat{N}_{\mathrm{Fe}} = f_{\mathrm{Fe}} \frac{N_{\mathrm{Zn}}}{(1 - f_{\mathrm{Zn}})} \left(\frac{\mathrm{Zn}}{\mathrm{Fe}}\right)_{\mathrm{a}}^{-1}$$

Extinction and metal column density of HI regions up to redshift $z \simeq 2$

Giovanni Vladilo[1], Miriam Centurión[1], Sergei A. Levshakov[2], Celine Péroux[3], Pushpa Khare[4], Varsha P. Kulkarni[5], Donald G. York[6,7]



Comparison with other studies of absorption systems

- Surveys of metal absorption systems

  CaII systems

  Wild et al. (2006 ; open diamonds)

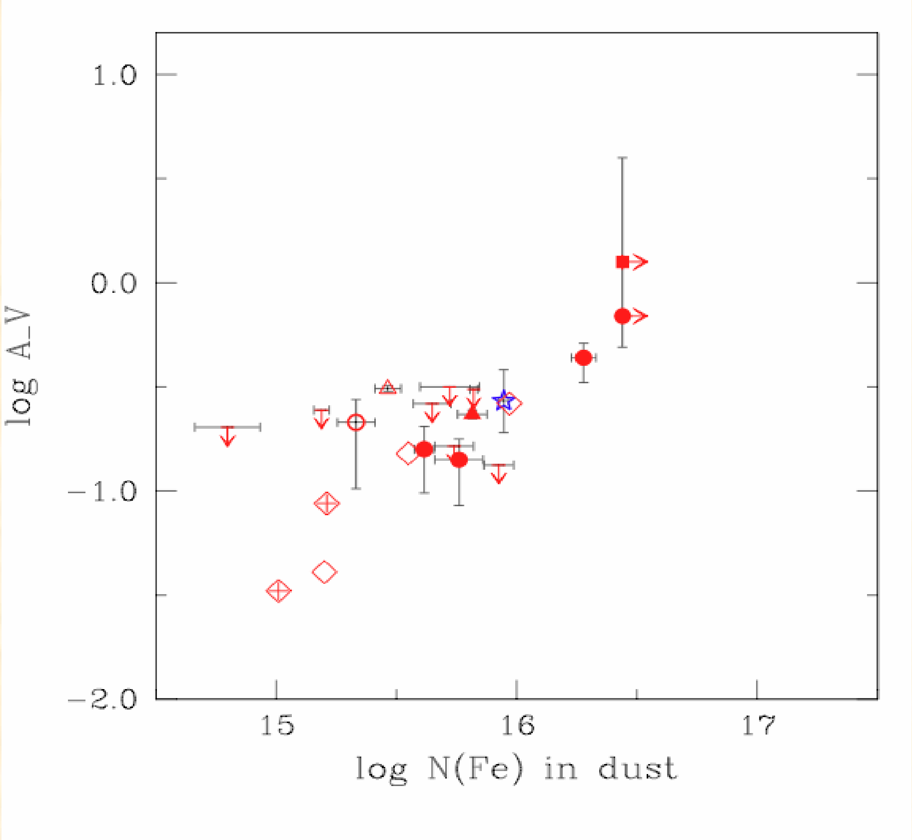
  MgII systems

  York et al. (2006 ; crossed diamonds)

- Comparison with one extragalactic measurement in the local Universe

  SMC line of sight to Sk155

  Welty et al. (2001; blue star)

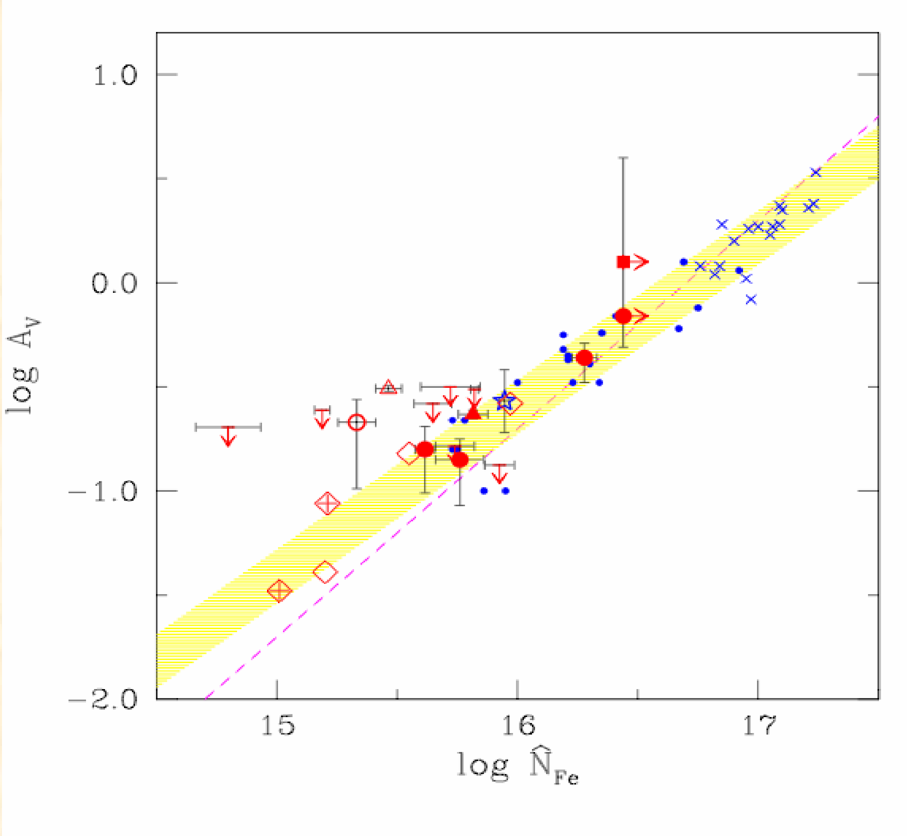


- Comparison with ISM data
  - Copernicus survey
    - Jenkins et al. (1986; blue dots)
  - FUSE survey
    - Snow et al. (2002; blue crosses)

- Data consistent with a universal relation between A_V and dust column density of iron
  - DLA sample small & limited to $z_{abs} < 2$
  - However, the data cover a wide range of physical conditions and metallicities

$$A_V = \langle s_V^{Fe} \rangle \, \widehat{N}_{Fe}$$

$$\langle s_V^{Fe} \rangle \simeq 2.4 \times 10^{-17} \text{ mag cm}^2$$



Extinction versus metals

Dust column density of iron

From the observations

$$A_V = \langle s_V^{\rm Fe} \rangle \, \widehat{N}_{\rm Fe}$$

$$\widehat{N}_{\rm Fe} = f_{\rm Fe} \times \left(\frac{\rm Fe}{\rm H}\right) \times N({\rm HI})$$

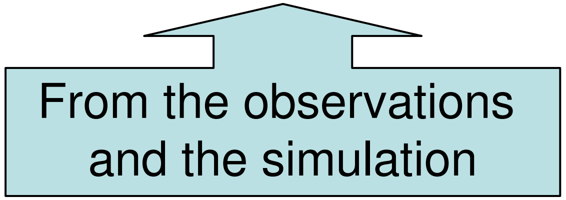
From the simulation

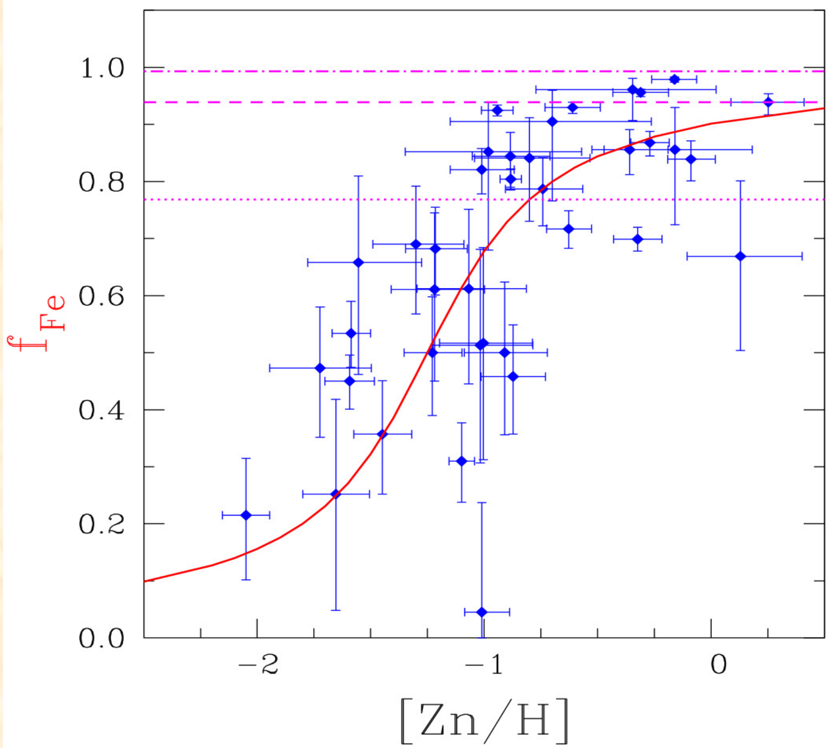
Extinction versus metals

Dust fraction

$$A_V = \langle s_V^{\rm Fe} \rangle \, \widehat{N}_{\rm Fe}$$

$$\widehat{N}_{\rm Fe} = f_{\rm Fe} \times \left(\frac{\rm Fe}{\rm H}\right) \times N({\rm HI})$$





Vladilo (2004)

Extinction versus metals

Conversion from rest-frame to observer's-frame extinction

$$A_V = \langle s_V^{\mathrm{Fe}} \rangle \, \widehat{N}_{\mathrm{Fe}}$$

$$\widehat{N}_{\mathrm{Fe}} = f_{\mathrm{Fe}} \times \left(\frac{\mathrm{Fe}}{\mathrm{H}}\right) \times N(\mathrm{HI})$$

$$A_\lambda^{\mathrm{obs}} = A_V \times \xi\left(\frac{\lambda}{1+z_a}\right)$$

$$A_\lambda^{\mathrm{obs}} = \langle s_V^{\mathrm{Fe}} \rangle \times \xi\left(\frac{\lambda}{1+z_a}\right) \times f_{\mathrm{Fe}} \times \left(\frac{\mathrm{Fe}}{\mathrm{H}}\right) \times N(\mathrm{HI})$$

Extinction versus metals

The extinction curve

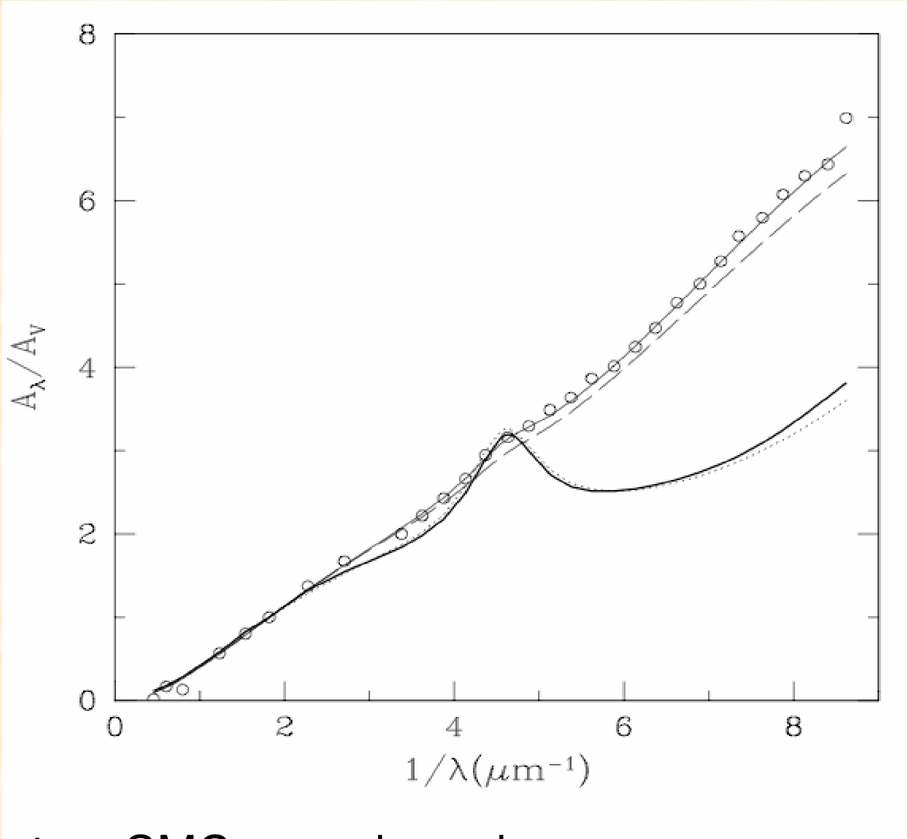
$$A_V = \langle s_V^{\rm Fe} \rangle \, \widehat{N}_{\rm Fe}$$

$$\widehat{N}_{\rm Fe} = f_{\rm Fe} \times \left(\frac{\rm Fe}{\rm H}\right) \times N({\rm HI})$$

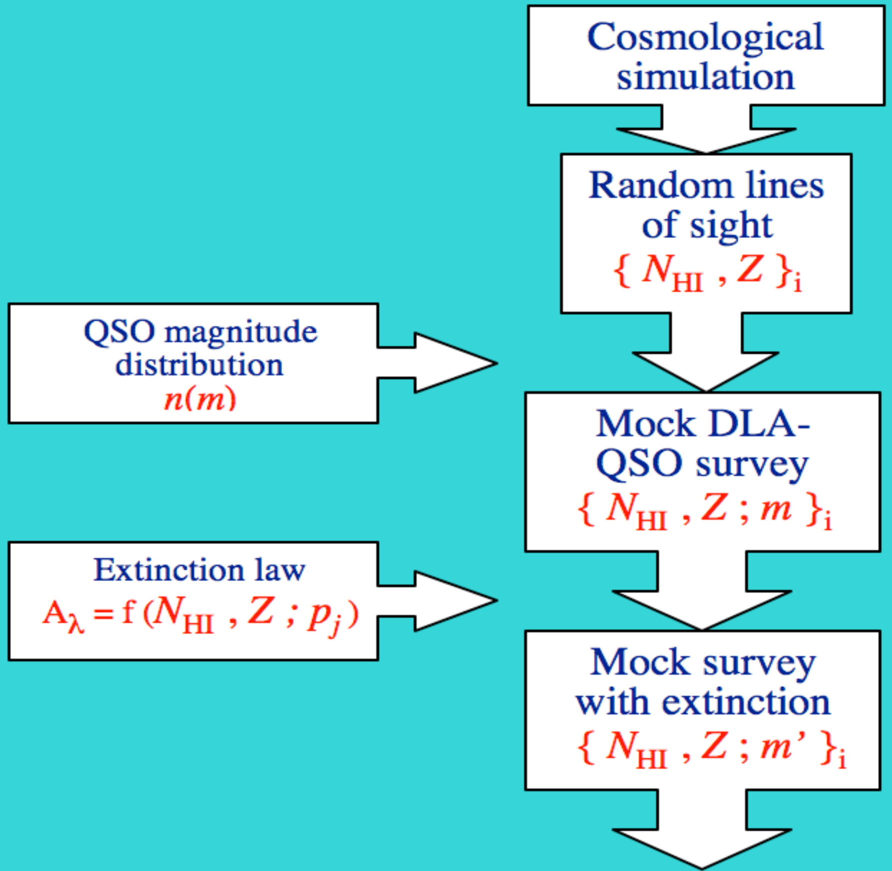
$$A_\lambda^{\rm obs} = A_V \times \xi\left(\frac{\lambda}{1+z_a}\right)$$

$$A_\lambda^{\rm obs} = \langle s_V^{\rm Fe} \rangle \times \xi\left(\frac{\lambda}{1+z_a}\right) \times f_{\rm Fe} \times \left(\frac{\rm Fe}{\rm H}\right) \times N({\rm HI})$$

Extinction curve

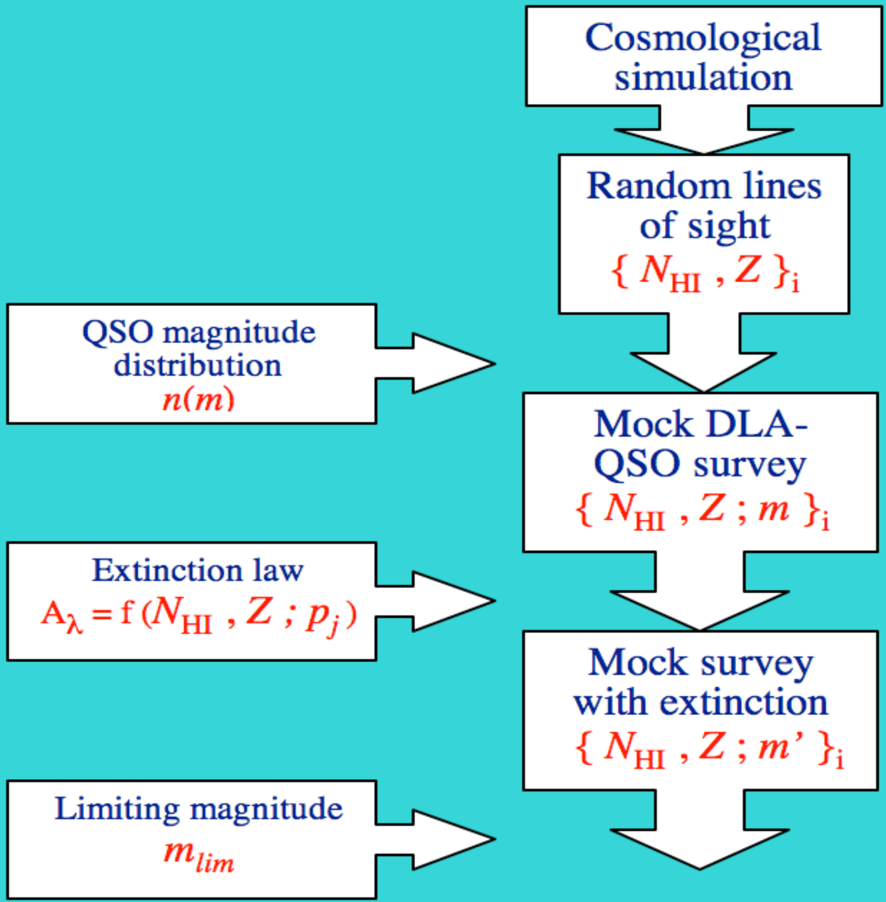


We adopt an SMC curve based on previous work on QSO absorbers



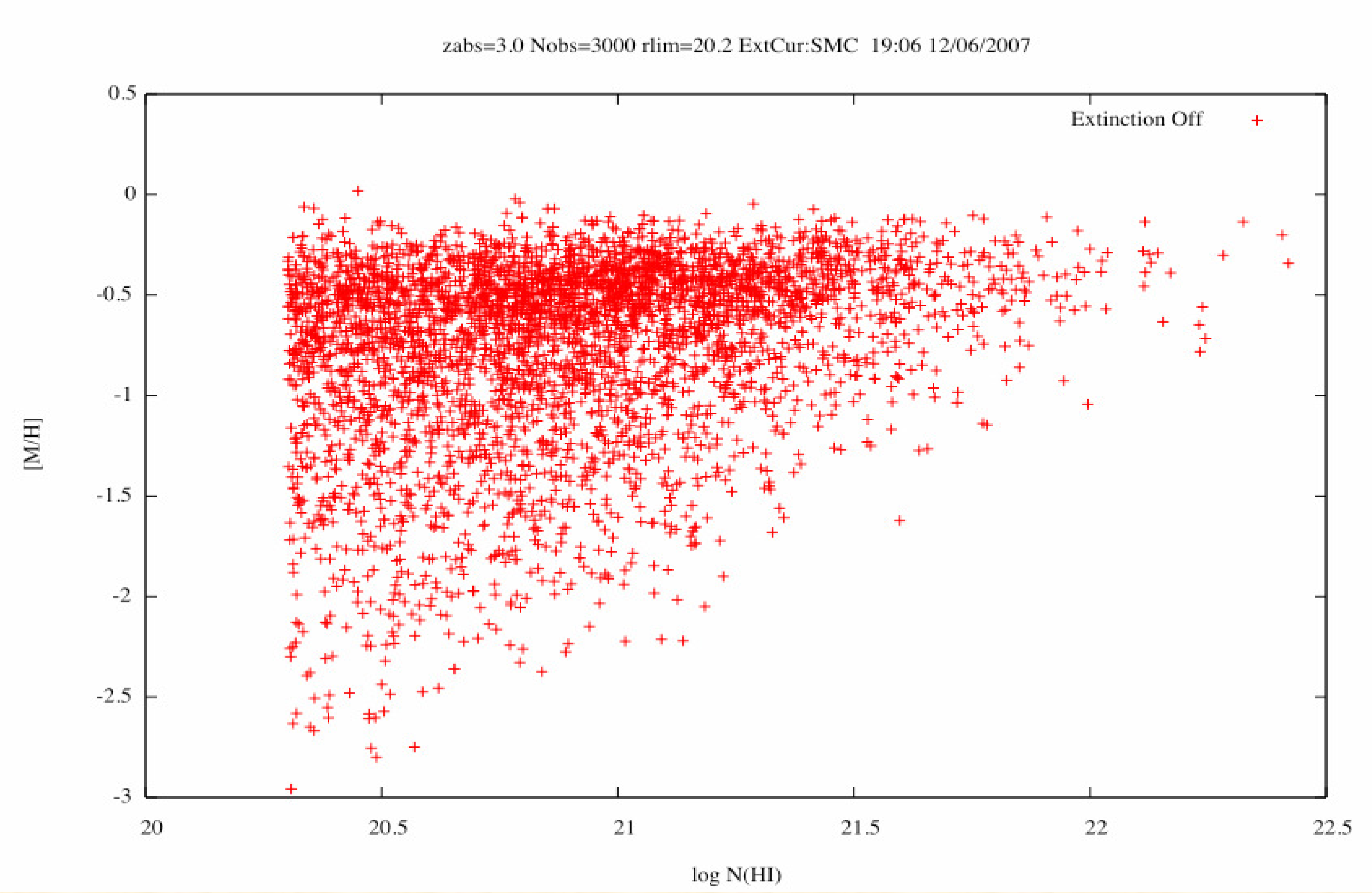
Cosmological simulation
Random lines of sight
{ N_{HI} , Z }$_i$
QSO magnitude distribution
$n(m)$
Mock DLA-QSO survey
{ N_{HI} , Z ; m }$_i$
Extinction law
$A_\lambda = f(N_{HI}, Z; p_j)$
Mock survey with extinction
{ N_{HI} , Z ; m' }$_i$

$m' = m + A_\lambda$



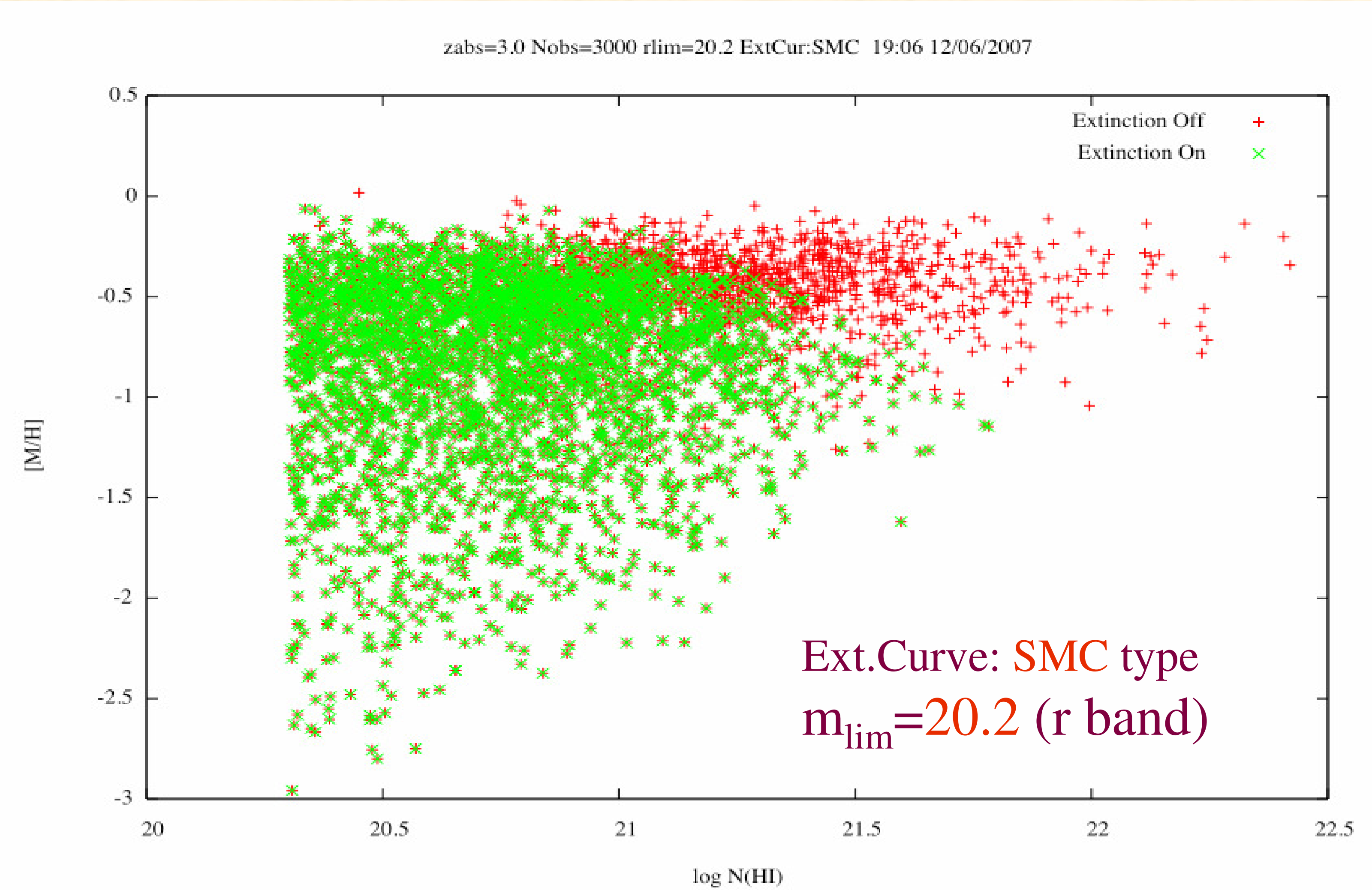
Cosmological simulation
Random lines of sight
$\{ N_{HI} , Z \}_i$
QSO magnitude distribution
$n(m)$
Mock DLA-QSO survey
$\{ N_{HI} , Z ; m \}_i$
Extinction law
$A_\lambda = f(N_{HI} , Z ; p_j)$
Mock survey with extinction
$\{ N_{HI} , Z ; m' \}_i$
Limiting magnitude
m_{lim}

... without extinction ...

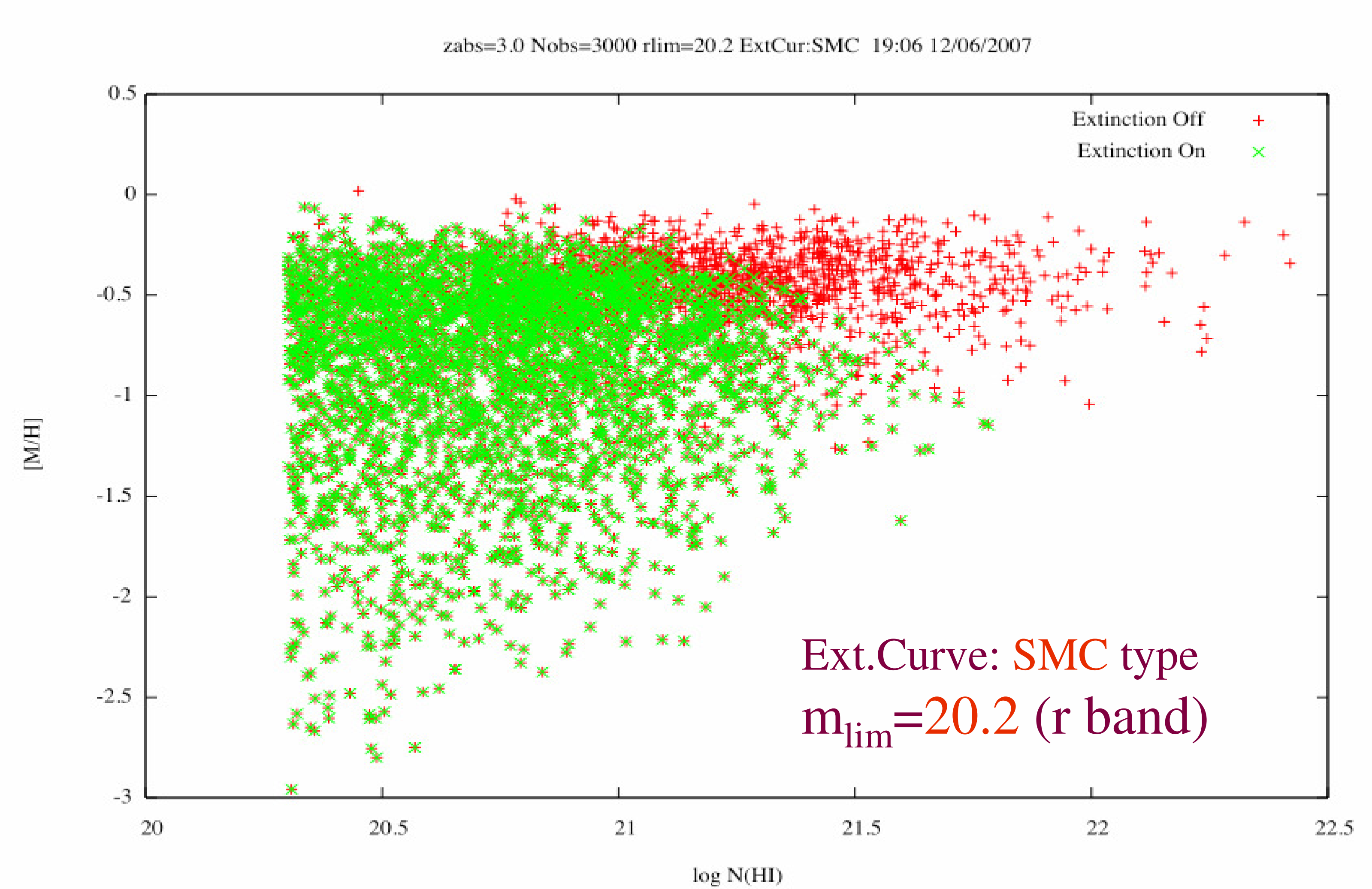


... with extinction...

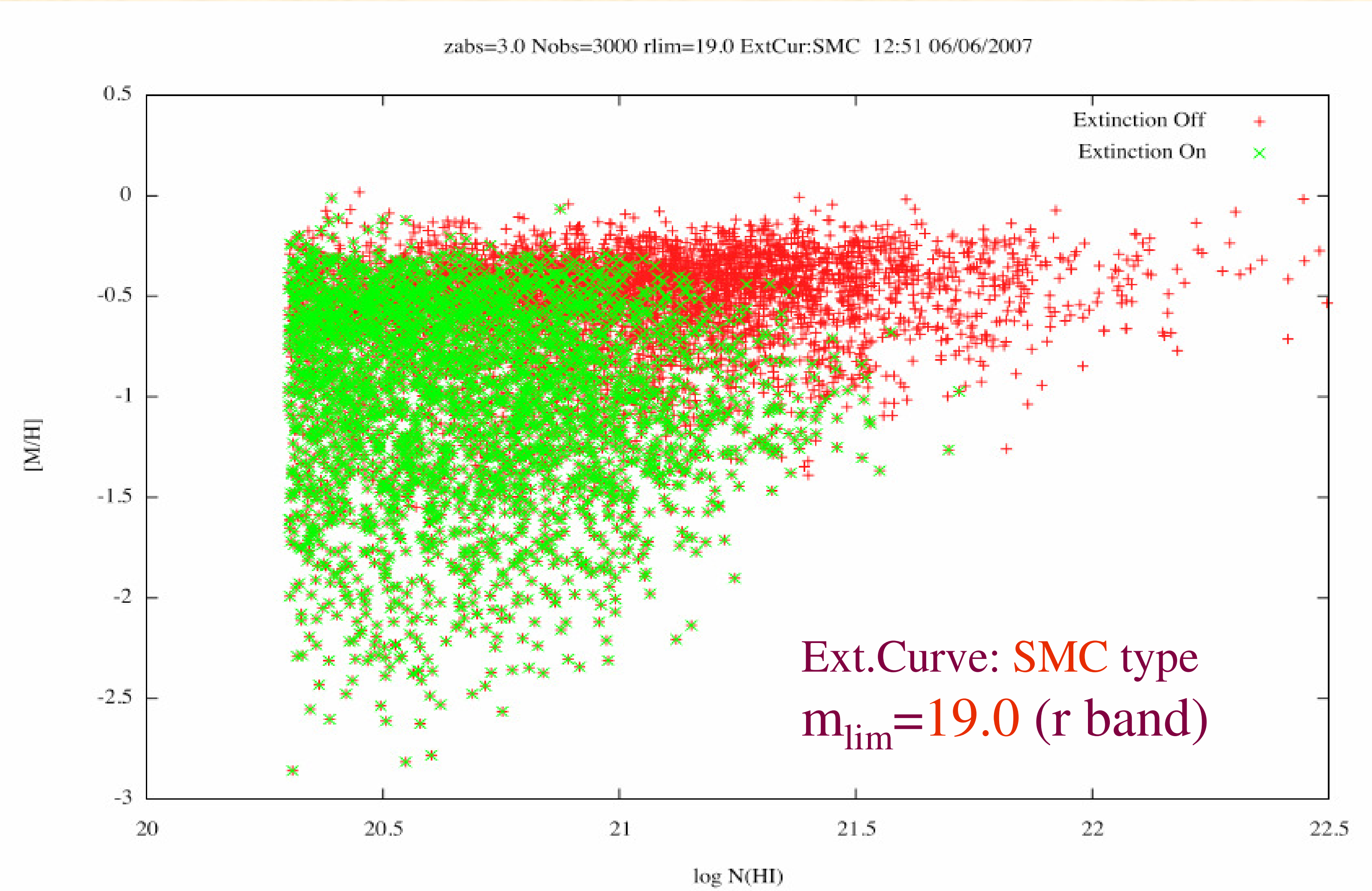
DLA systems with highest metal column density are lost



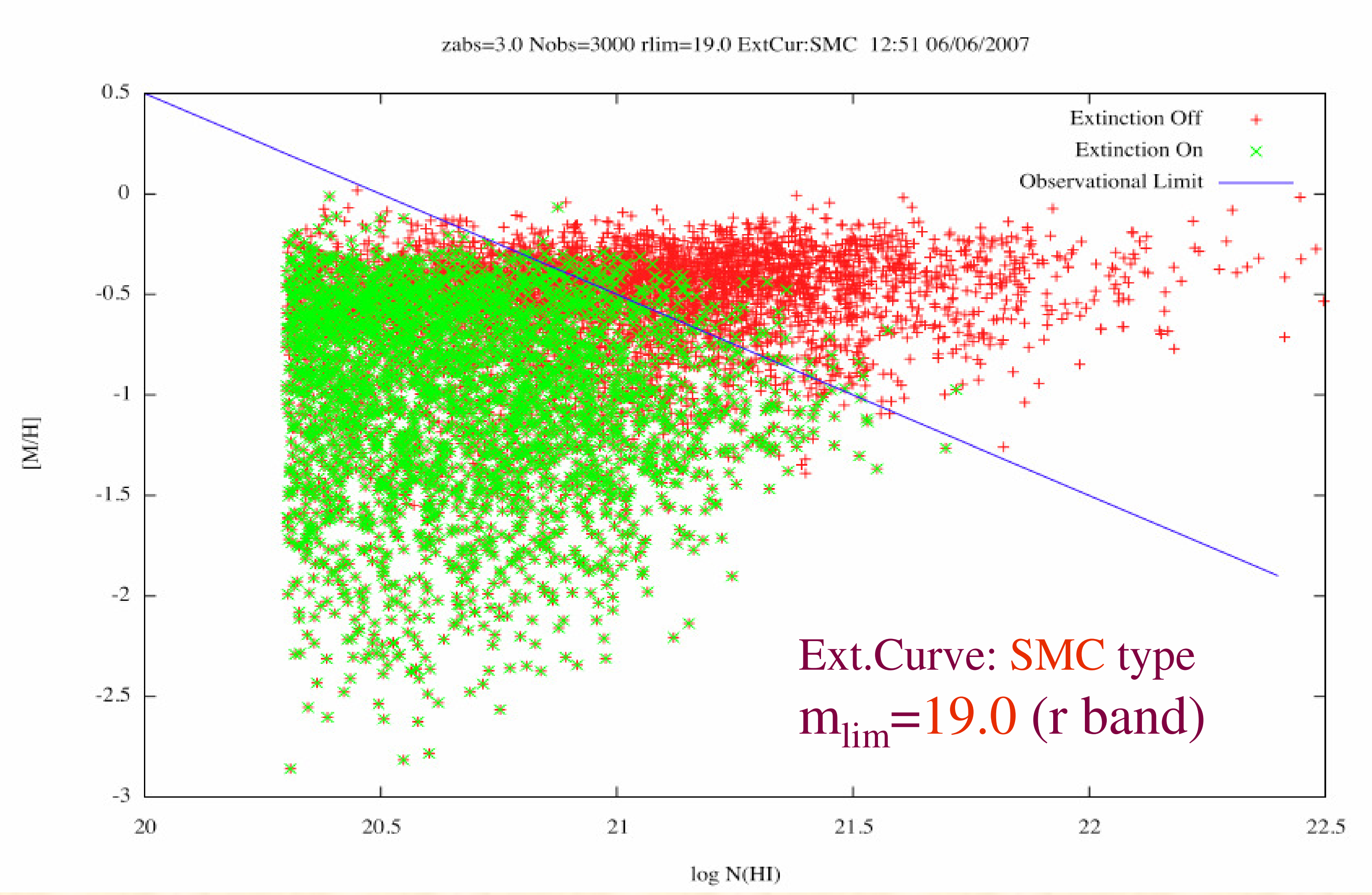
The extinction effect depends on the limiting magnitude of the survey



The extinction effect depends on the limiting magnitude of the survey



m_{lim} ~ 19 appropriate for metallicity surveys
we obtain a deficiency of DLA systems at [M/H] + log N(HI) > 20.5

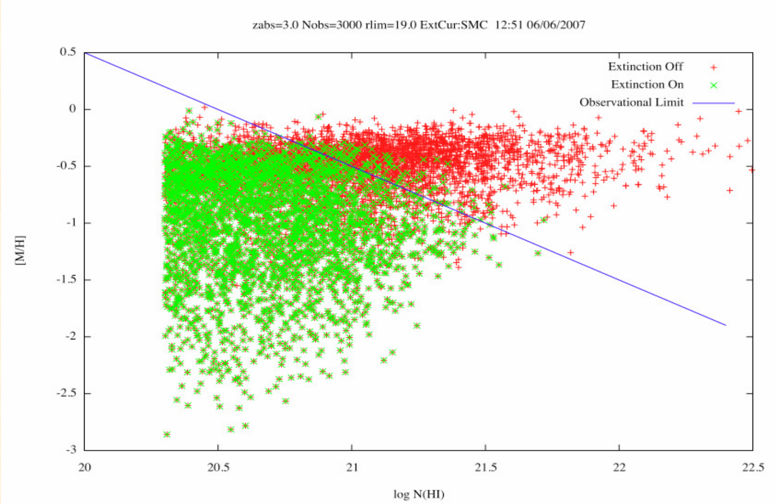


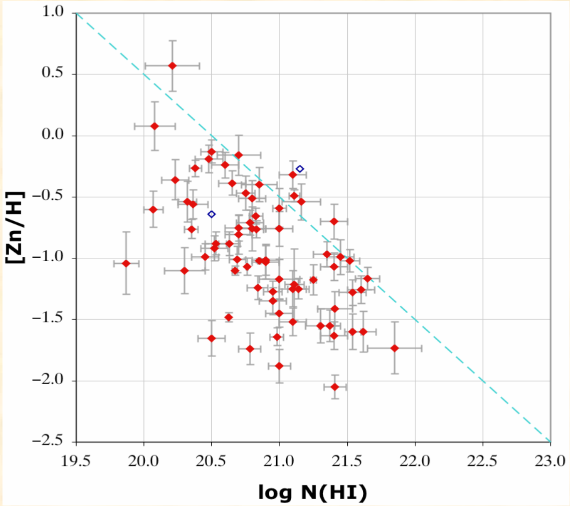
- The deficiency of systems at
  $[M/H] + \log N(HI) > 20.5$
  is naturally explained by the extinction effect

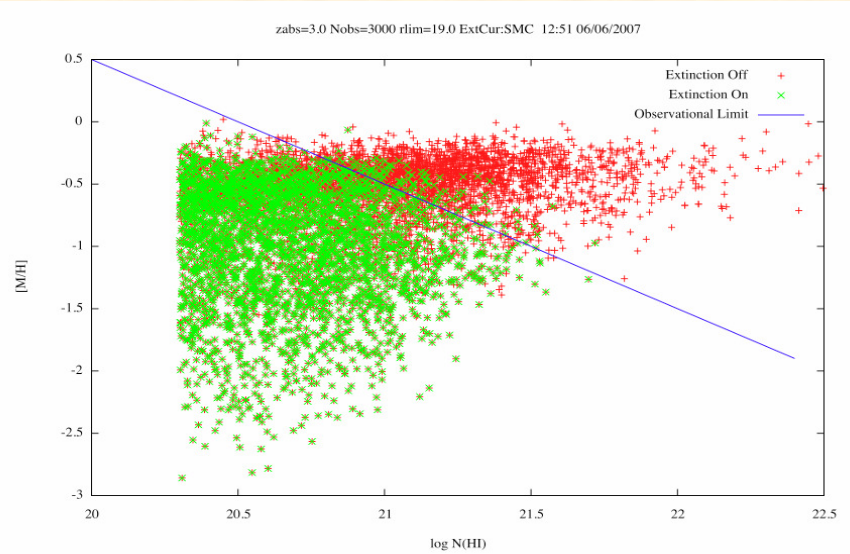
- At m_{lim}=19 the fraction of outliers in agreement with observations
  ~ 4%

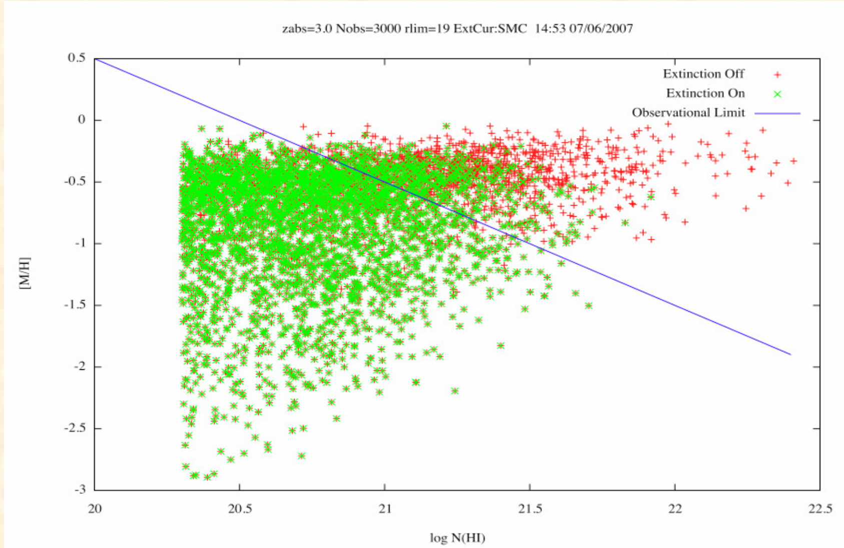
- Result obtained without tuning the dust extinction parameters

- Gives confidence on the adopted extinction relation



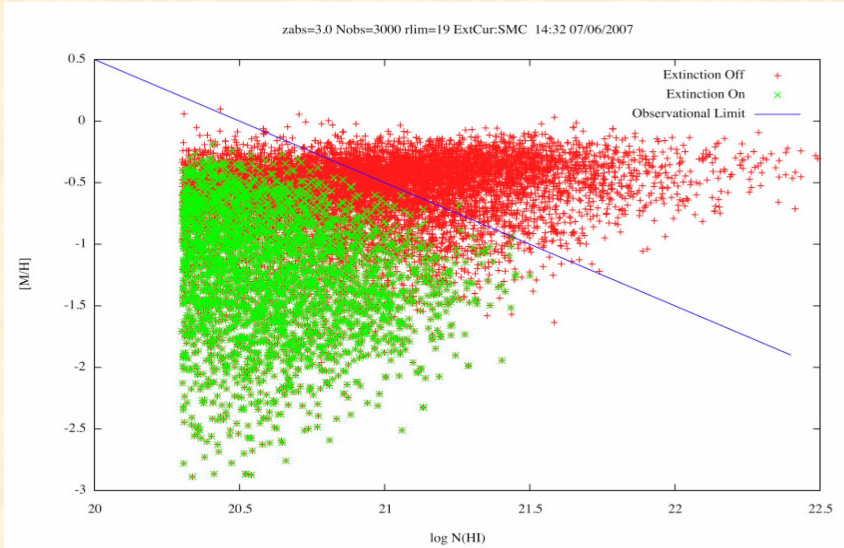


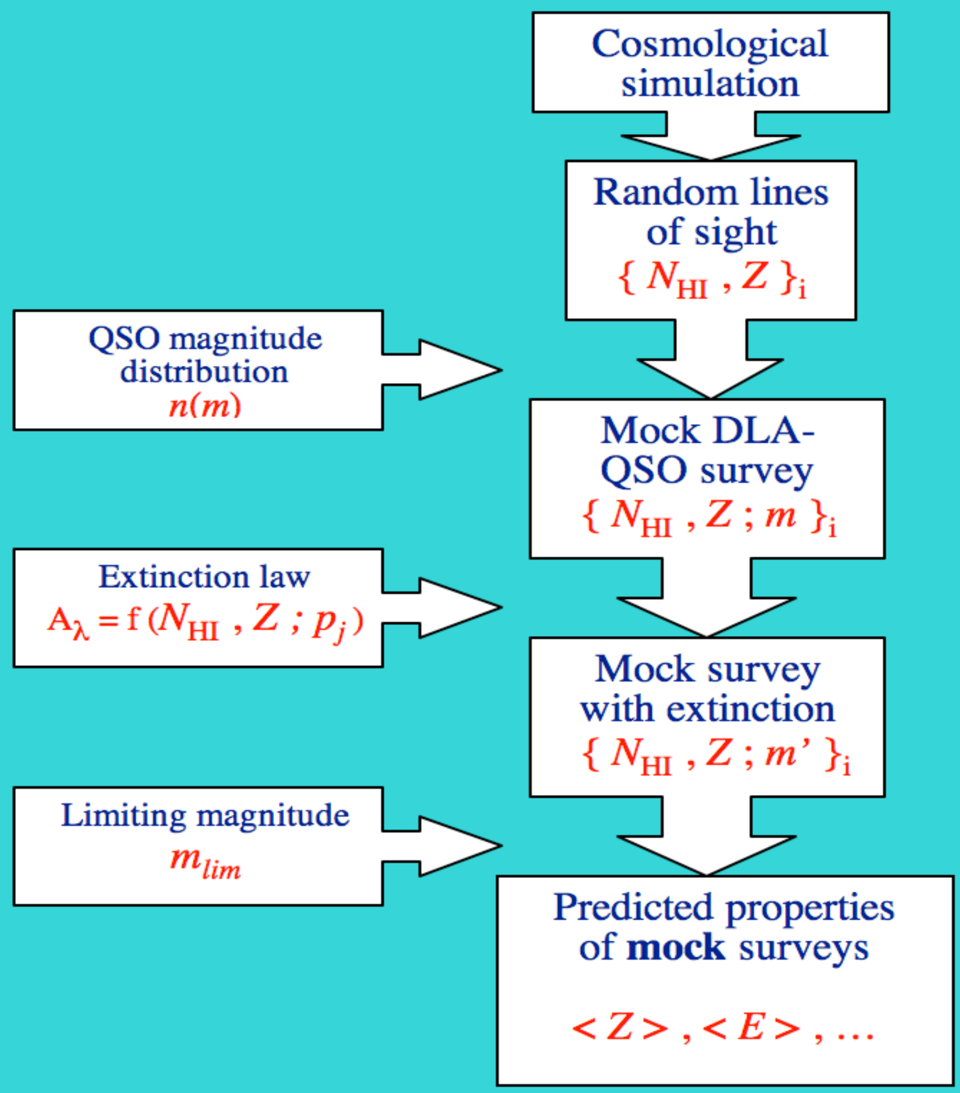


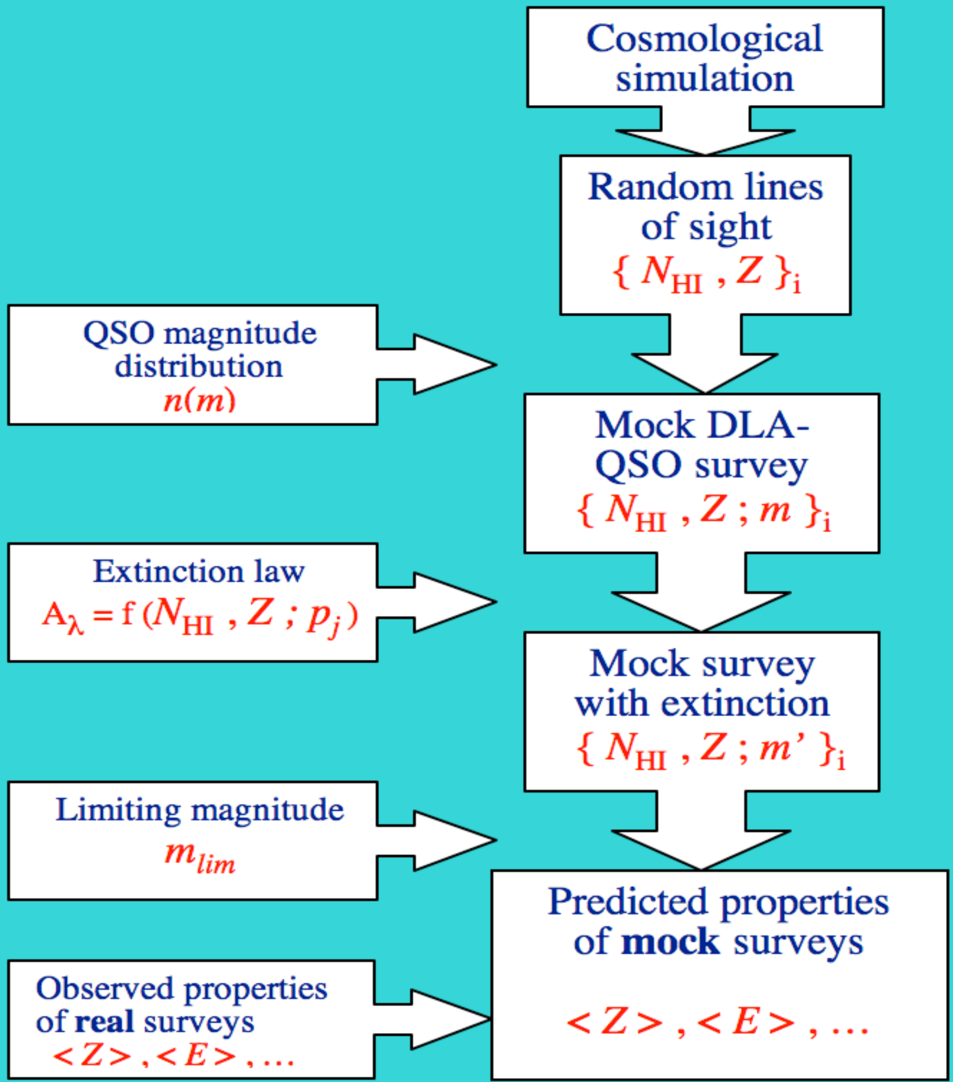


- Arbitrary tuning of the dust parameters yield results inconsistent with the observations

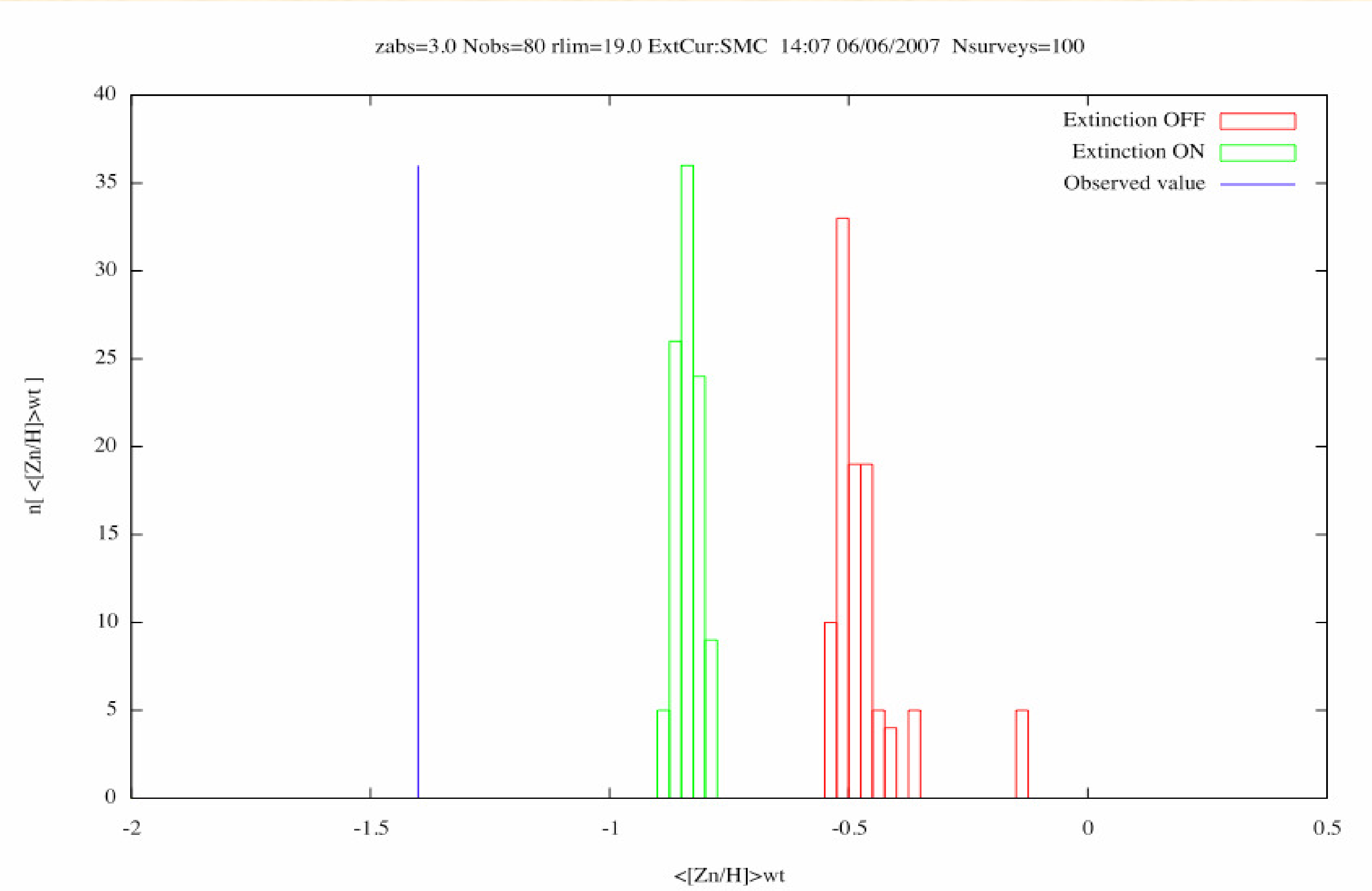
- The adopted extinction relation is likely to be accurate within a factor of 2




Cosmological simulation
Random lines of sight
$\{ N_{HI}, Z \}_i$
QSO magnitude distribution
$n(m)$
Mock DLA-QSO survey
$\{ N_{HI}, Z ; m \}_i$
Extinction law
$A_\lambda = f(N_{HI}, Z ; p_j)$
Mock survey with extinction
$\{ N_{HI}, Z ; m' \}_i$
Limiting magnitude
m_{lim}
Predicted properties of **mock** surveys
$<Z>, <E>, \ldots$


Cosmological simulation
Random lines of sight
{ N_{HI} , Z }$_i$
QSO magnitude distribution
$n(m)$
Mock DLA-QSO survey
{ N_{HI} , Z ; m }$_i$
Extinction law
$A_\lambda = f(N_{HI}, Z; p_j)$
Mock survey with extinction
{ N_{HI} , Z ; m' }$_i$
Limiting magnitude
m_{lim}
Predicted properties of **mock** surveys
$< Z >$, $< E >$, ...
Observed properties of **real** surveys
$< Z >$, $< E >$, ...

Predicted mean HI-Weighted Metallicity $<[Zn/H]_w>_{sim} \sim -0.8$ dex
too high compared to the observed one $<[Zn/H]_w>_{obs} \sim -1.4$ dex



The extinction effect is not sufficient to reconcile
the high values of metallicity predicted by the simulation
with the lower values observed in DLA surveys

Possible reasons for the discrepancy

Limited resolution of the simulation ?

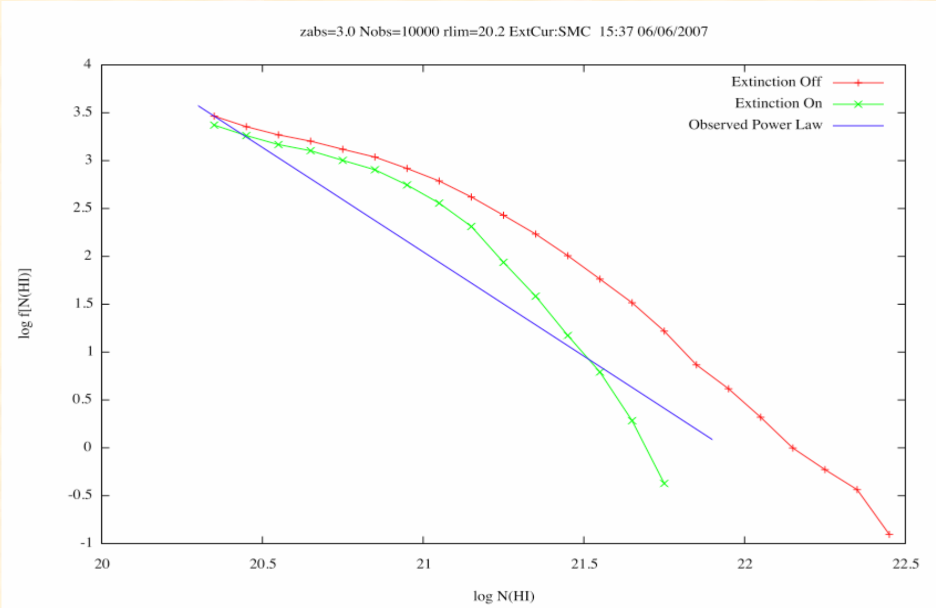
Physical ingredients of the simulation ?

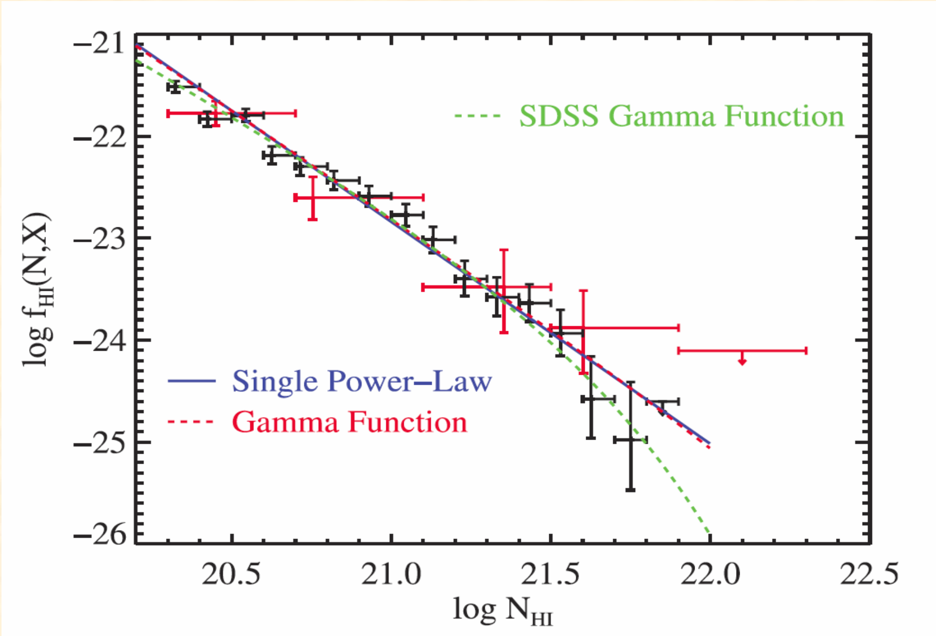
Method used for extracting the random lines of sight ?

"Cosmic variance" ?

N(HI) frequency distribution

- Distribution predicted by the simulations deviates from the observed power law
- After correction for extinction the deviation from the power law are even stronger
  - The excess of metal-rich systems predicted by the simulations yield strong deviations from the power law
- The high end of the HI distribution may be affected by extinction
  - The effect would be milder if the cosmological simulation would predict less metallicity





Summary

- Method for converting the results of a cosmological simulation into a HI-metallicity survey of DLA systems

  Accounts for extinction effects and limited sensitivity of the instrumentation

- The deficiency of DLA systems with high metal column density is quantitatively reproduced by the extinction effect

  $[M/H] + \log N(\mathrm{HI}) > 20.5$ at $m_{\mathrm{lim}} = 19$

- The extinction may steepen the high end of the HI frequency distribution

  at $\log N(\mathrm{HI}) > 21.5$

- Powerful tool for testing predictions of cosmological simulations

  Application to model Q5 by Nagamine et al. (2004)

- Current simulations overpredict the mean metallicity of DLA systems

  Extinction insufficient to reconcile the simulations with the observations

- Future work

  Application to new cosmological simulations

  Trieste group M. Viel, L. Tornatore, S. Borgani, A. Ferrara

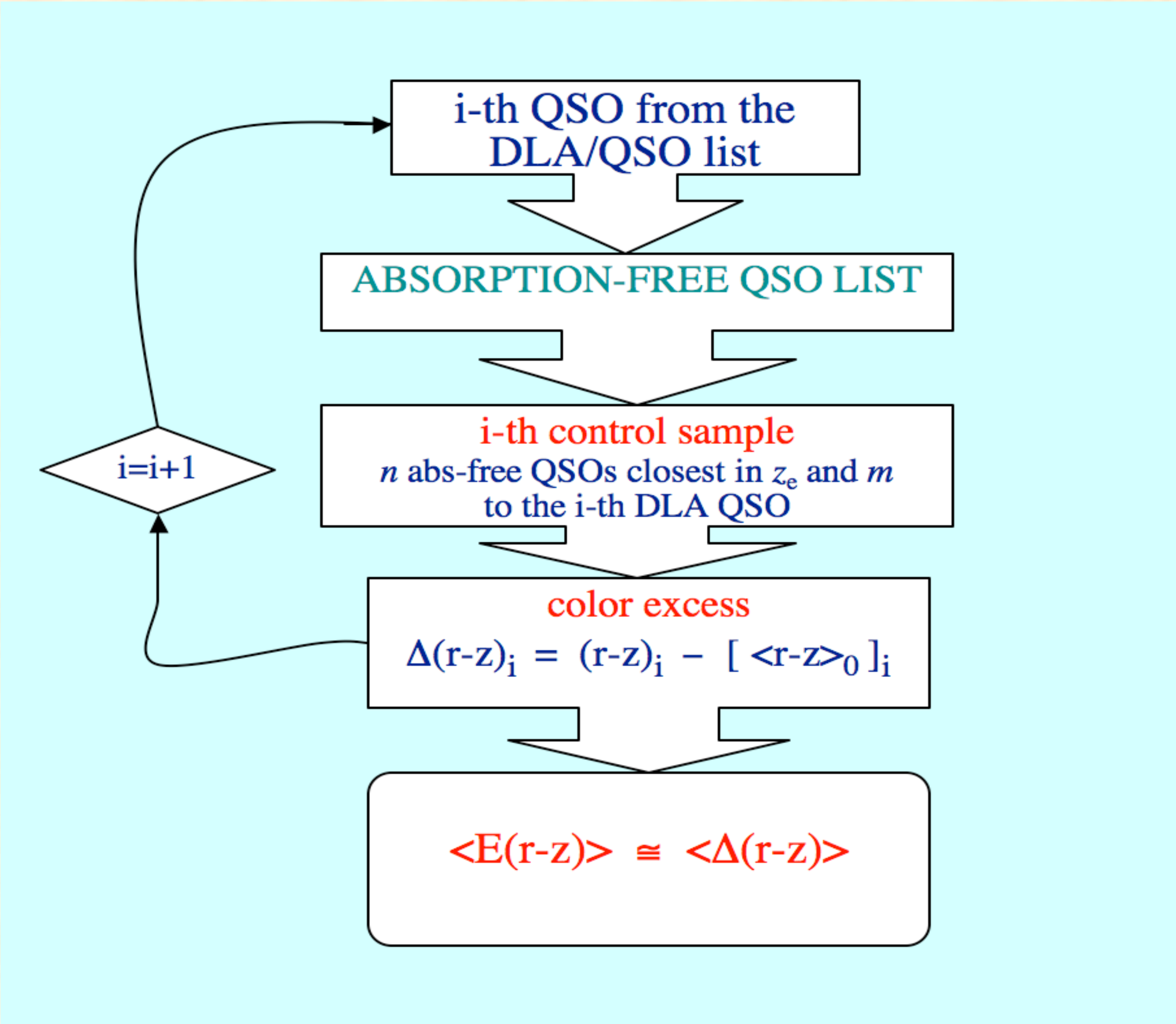
The mean reddening of QSOs with intervening DLA systems

Work in progress...

in collaboration with J. Prochaska & A. Wolfe

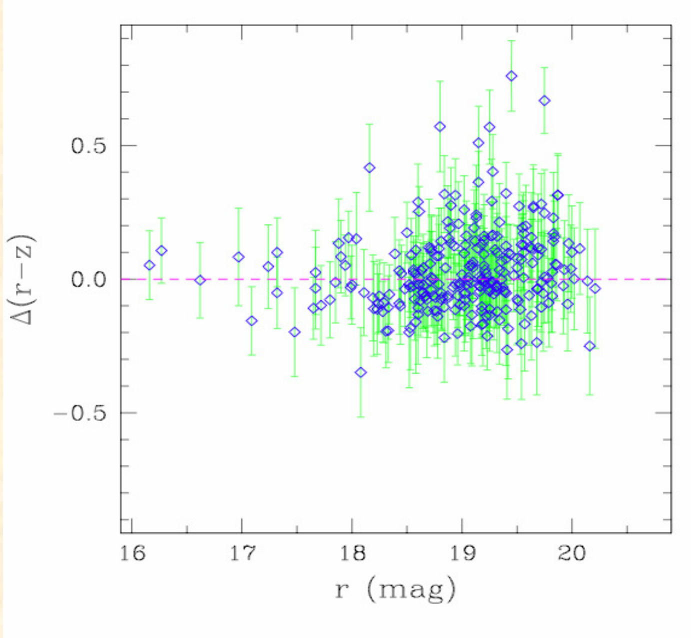
- Spectroscopic and photometric database of SDSS DR5
  - Generation of a QSO/DLA list
    - Updated DR5 list provided by J.Prochaska
  - Generation of a control list of absorption-free QSOs
    - Rejected QSOs with spectral signatures of intervening absorption systems
      - In part, automatic process
        - Updated DR5 strong MgII list by G. Prochter
      - In part, visual inspection
        - Very time-consuming, but necessary
  - Estimate of the mean reddening
    - SDSS photometry
      - (r-z) colour
        - Not contaminated by Ly α forest up to zabs=3.5

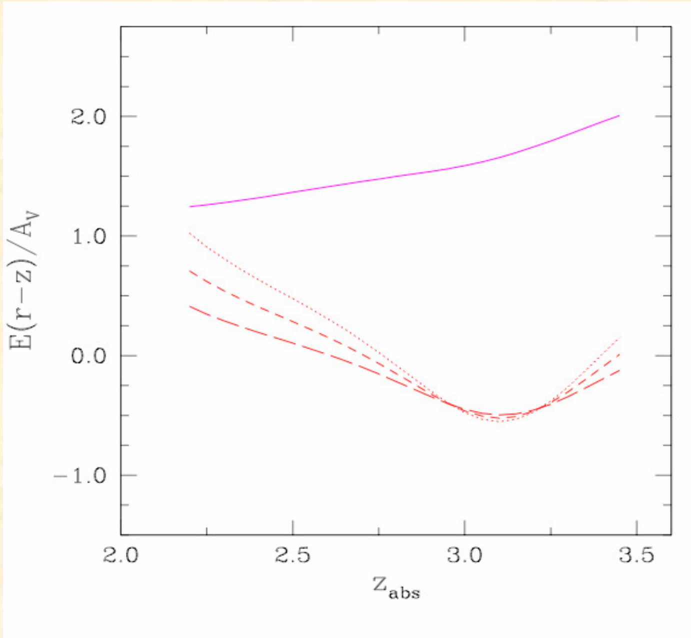
Estimate of the mean reddening



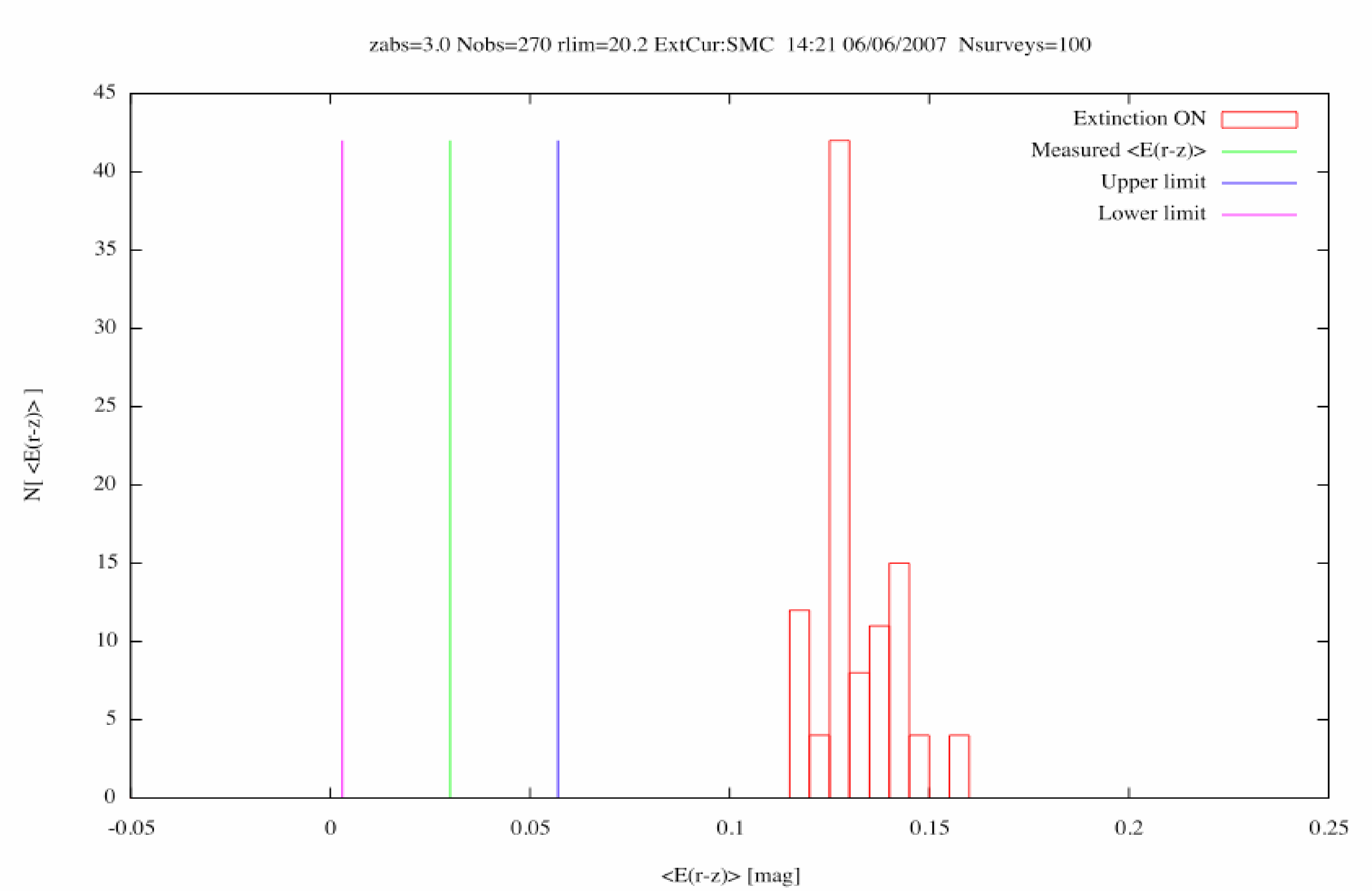
Preliminary results

- < E(r-z)> ~ 0.03 ± 0.009
  at <z_{abs}> = 2.75 r_{lim}~20.2
  Reddening in the observer frame
- <E(B-V)> ~ 0.007
  In the rest frame
  For an SMC-type extinction curve
- Dust-to-gas ratio one order of magnitude lower than in the MW
- Fraction of DLAs with A_r > 1 mag (observer's frame) ~3%
- The detection implies a predominance of SMC-type extinction curve





Predicted mean color excess r_{lim}=20.2 <E(r-z)>$_{sim}$ ~ 0.13 mag
also too high compared to the observed one <E(r-z)>$_{obs}$ ~ 0.03 mag



- Adopting a mix of SMC- and MW-type extinction curves

  25% MW

  75% SMC

  Mean reddening

  Disagreement reduced

  Mean metallicity

  Strong disagreement