Reverse Ray-Tracing in Urchin

Cosmological Radiative Transfer Comparison Project
December - 2012

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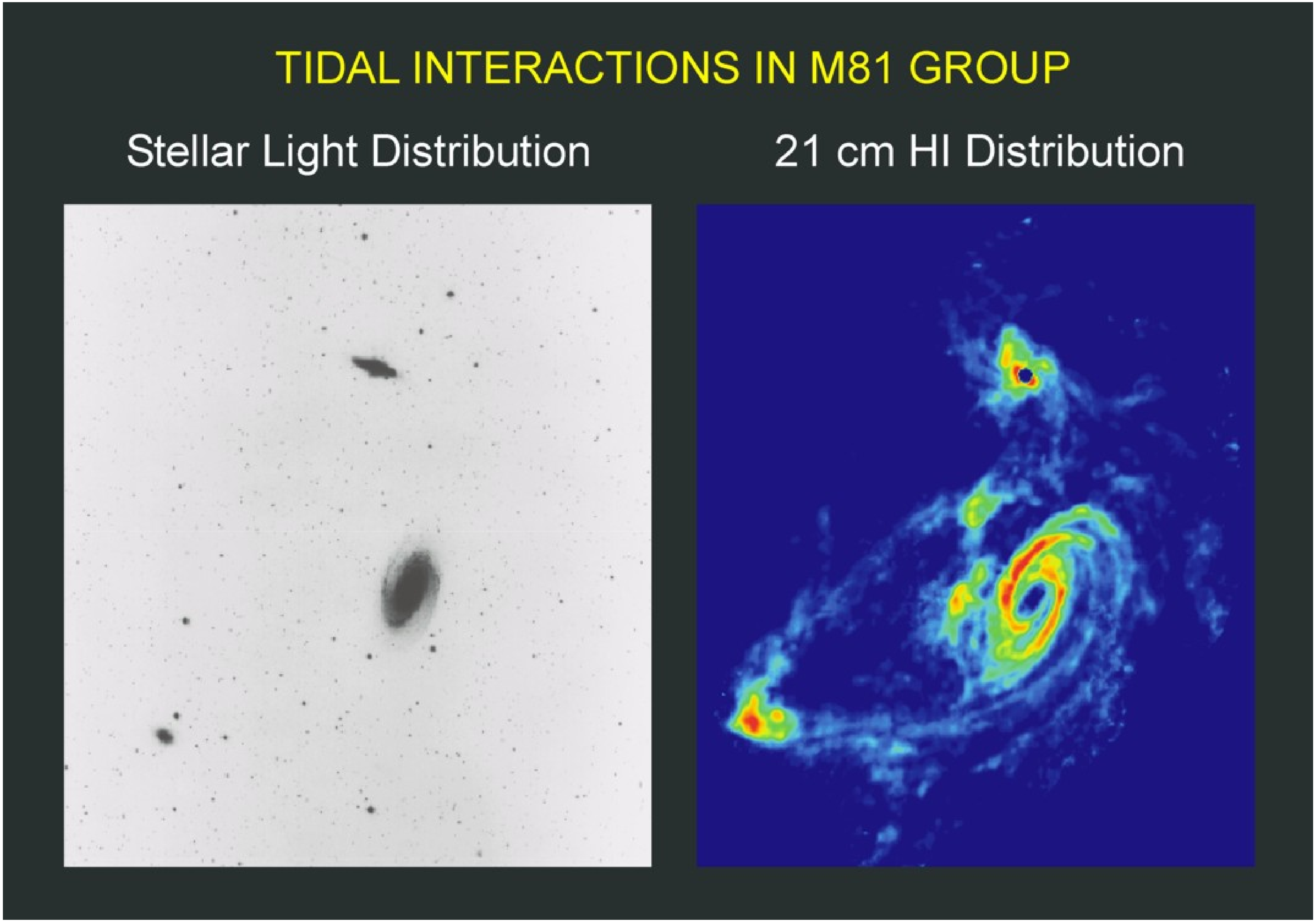
Motivation – Galaxy Formation in HI



Hydrogen Revolution - I

Westerbork Synthesis Radio Telescope
New Focal Plane Array APERTIF
Increase field of view by factor of 25 to 8 sq deg

Hydrogen Revolution - II

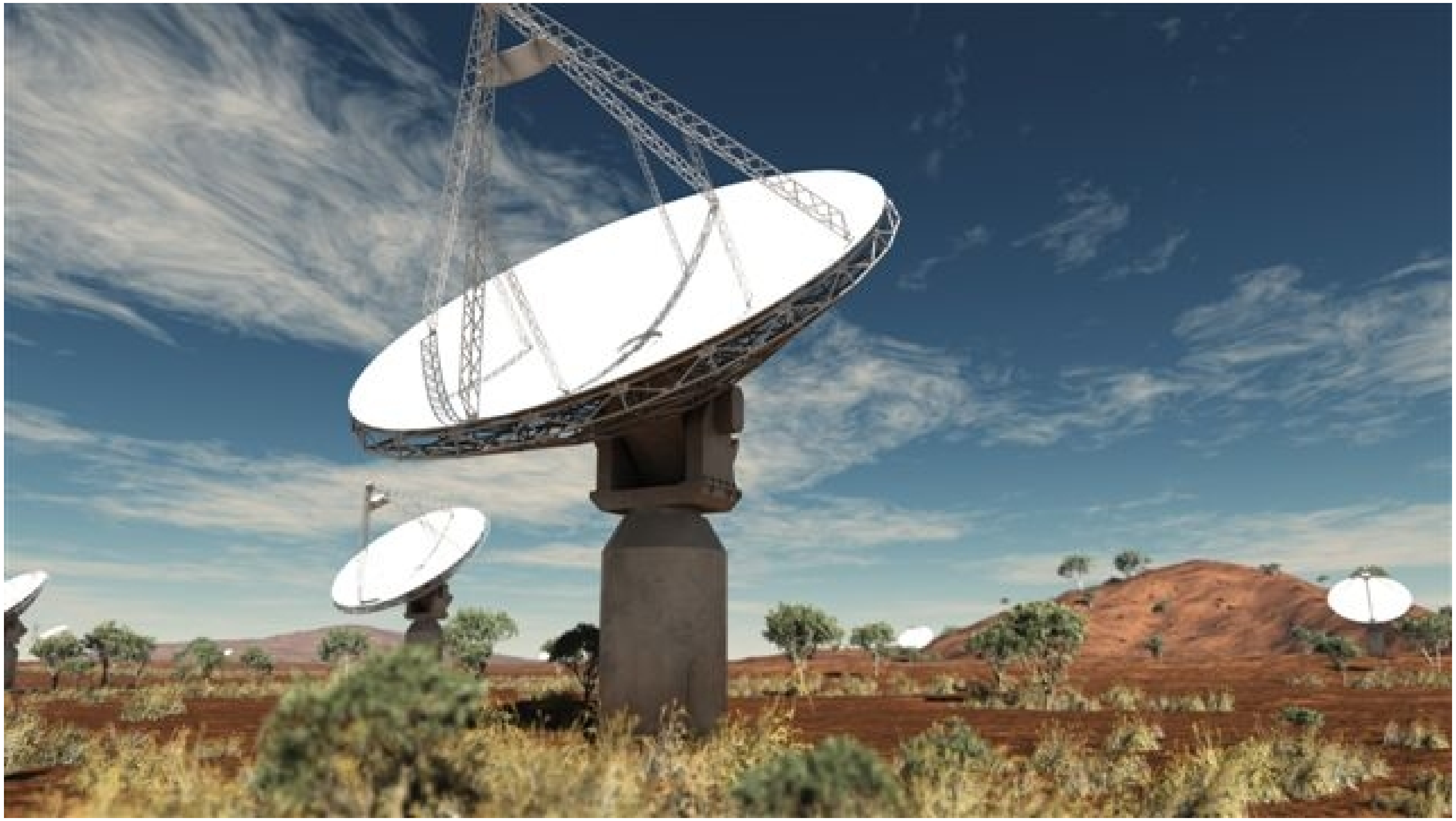
Expanded Very Large Array (EVLA)
Upgraded Electronics and Receivers
Expanded Frequency Coverage

Each pointing can cover 21cm from $0 < z < 0.53$
with resolution of a few km/s (Ott 08)

Hydrogen Revolution - III

Australian Square Kilometre Array Pathfinder (ASKAP)

WALLABY – All Sky, 500,000 galaxies to z ~ 0.26
FLASH – 21cm Absorption survey 0.5 < z < 1.0
DINGO – Deep to z ~ 0.5



Hydrogen Revolution - IV

Meer Karoo Aray Telescope (MeerKAT)

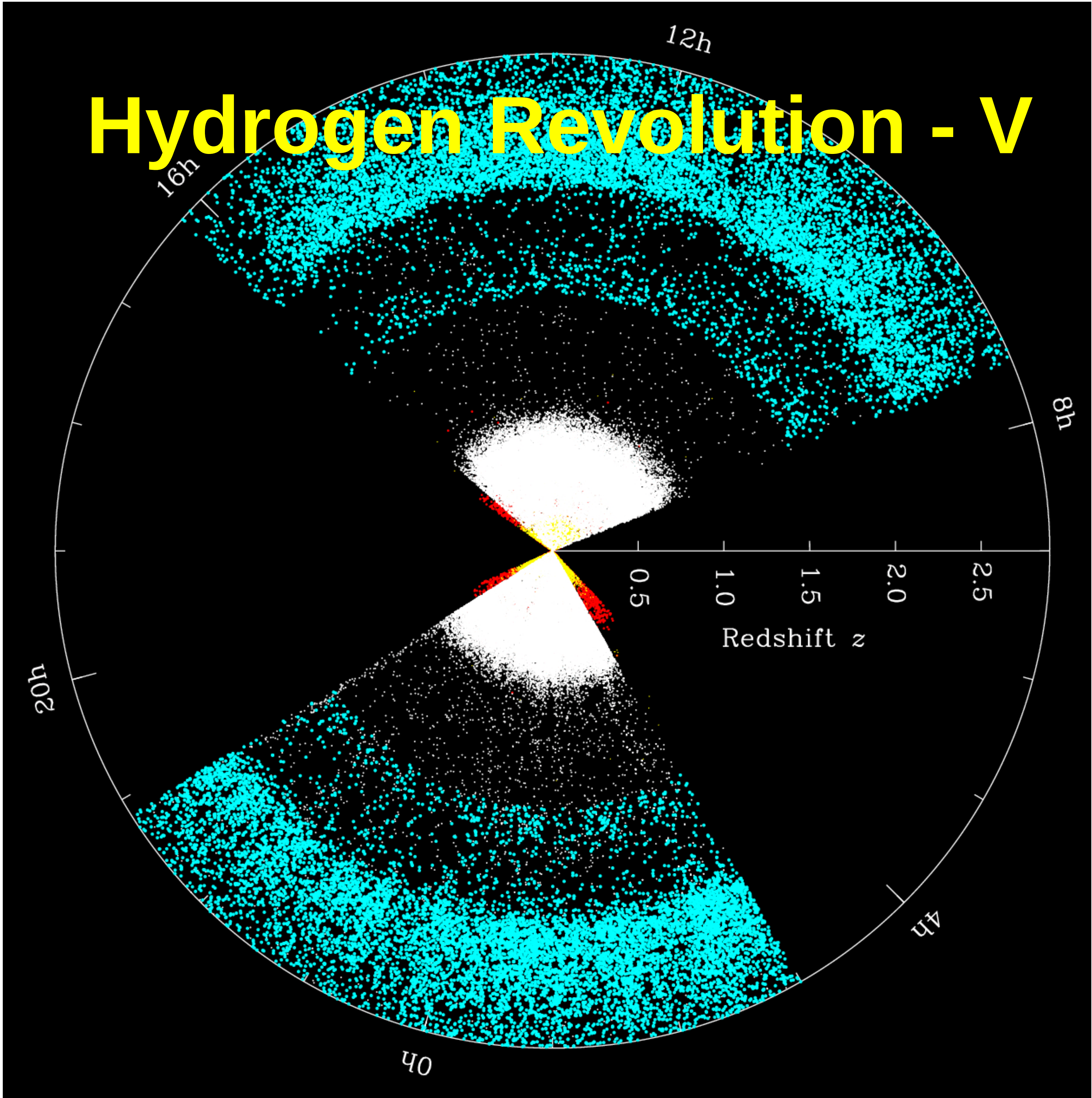
LADUMA – Single Pointing, 5000 hours, out to z > 1
MESMER – Search for CO during EoR

Hydrogen Revolution - V

BOSS

250,000 QSO
spectra by 2014

BigBOSS
600,000



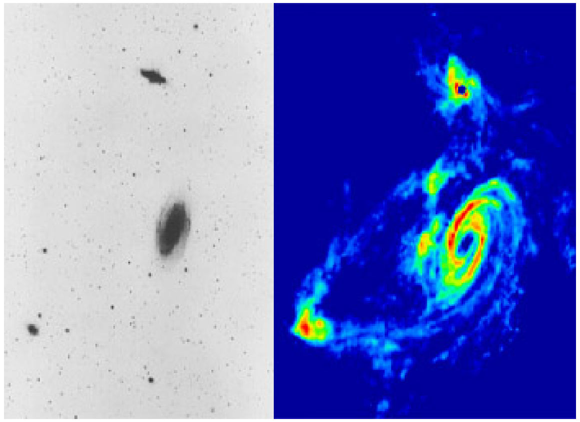
Hydrogen Revolution - VI

Hubble Space Telescope (HST)

Cosmic Origins Spectrograph (COS)
Advanced Camera for Surveys (ACS)
Wide Field Camera 3 (WFC3)

e.g. Morris, O'Meara

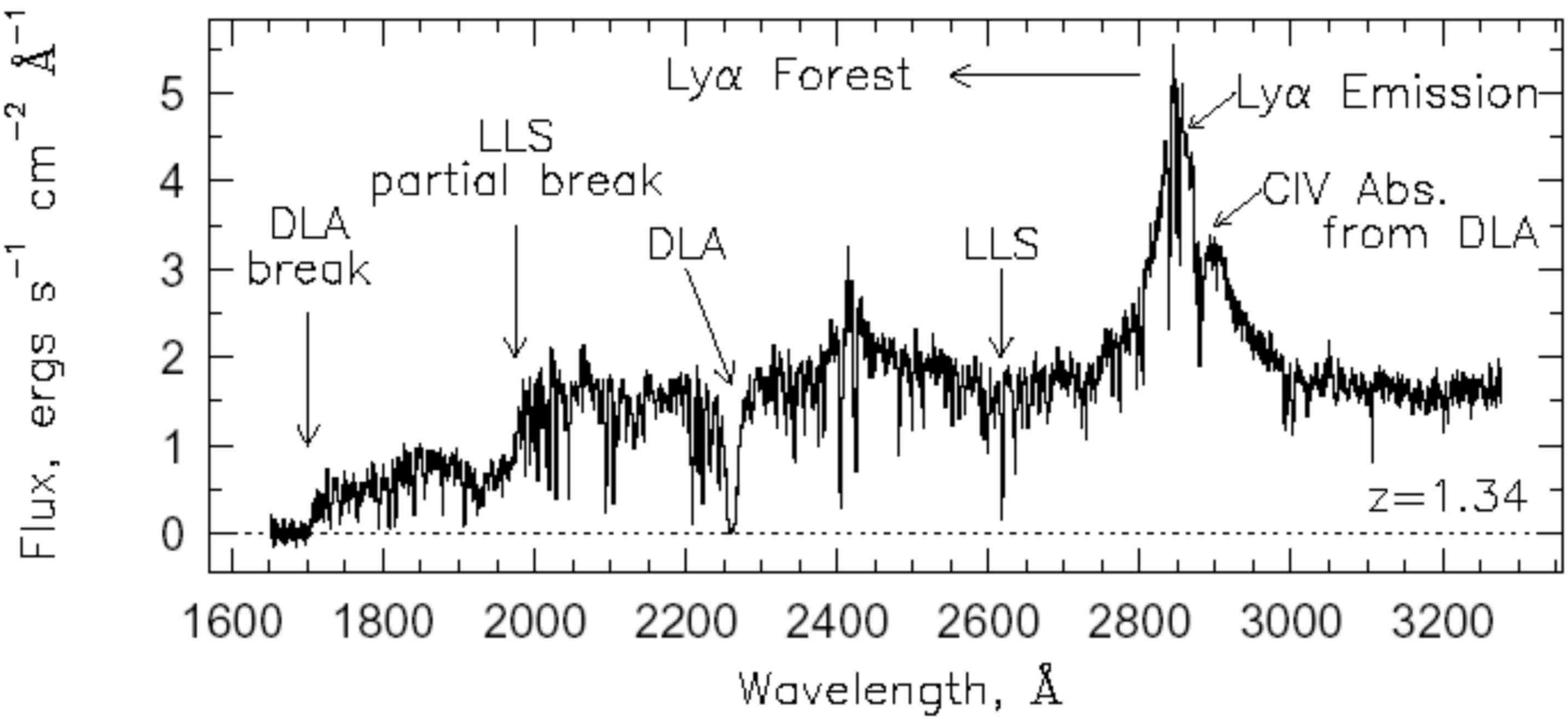
Motivation – Galaxy Formation in HI



Can see optical and HI emission at low z
Cant see either at high z (distance+quasar)

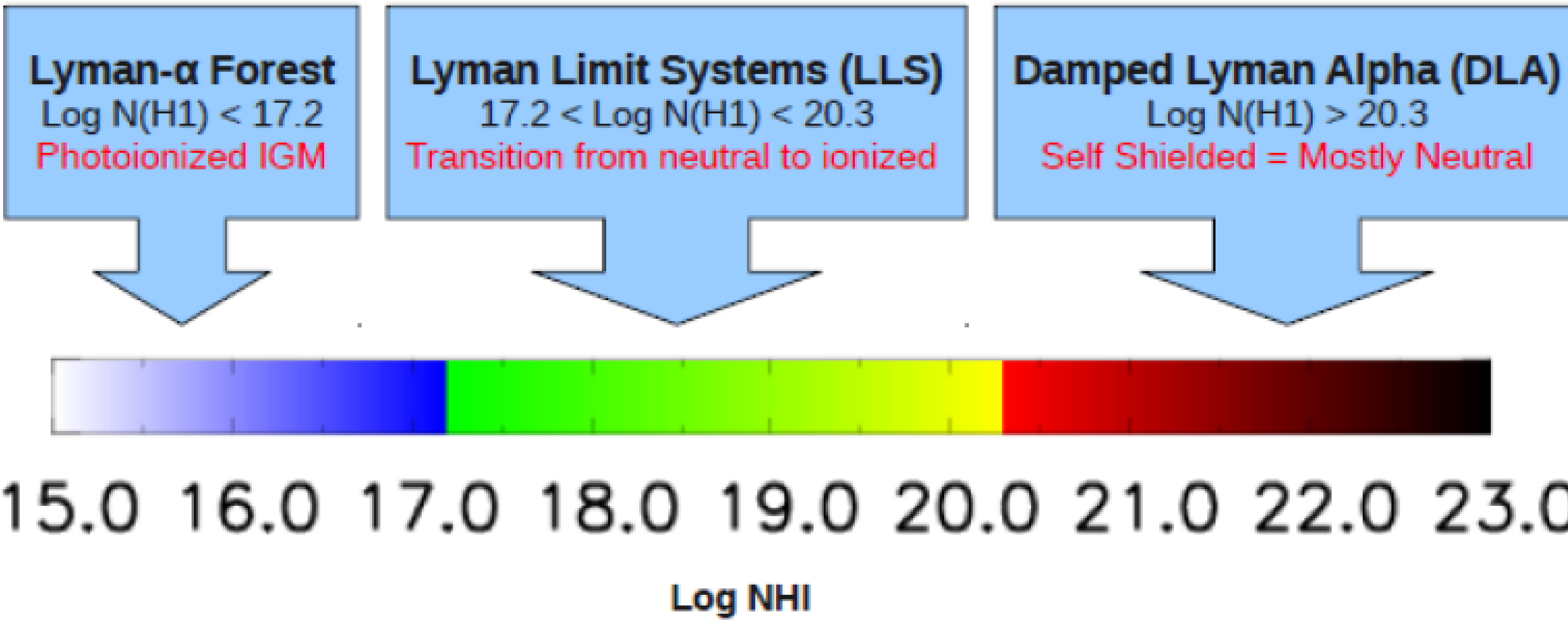
BUT

HI absorption is independent of z



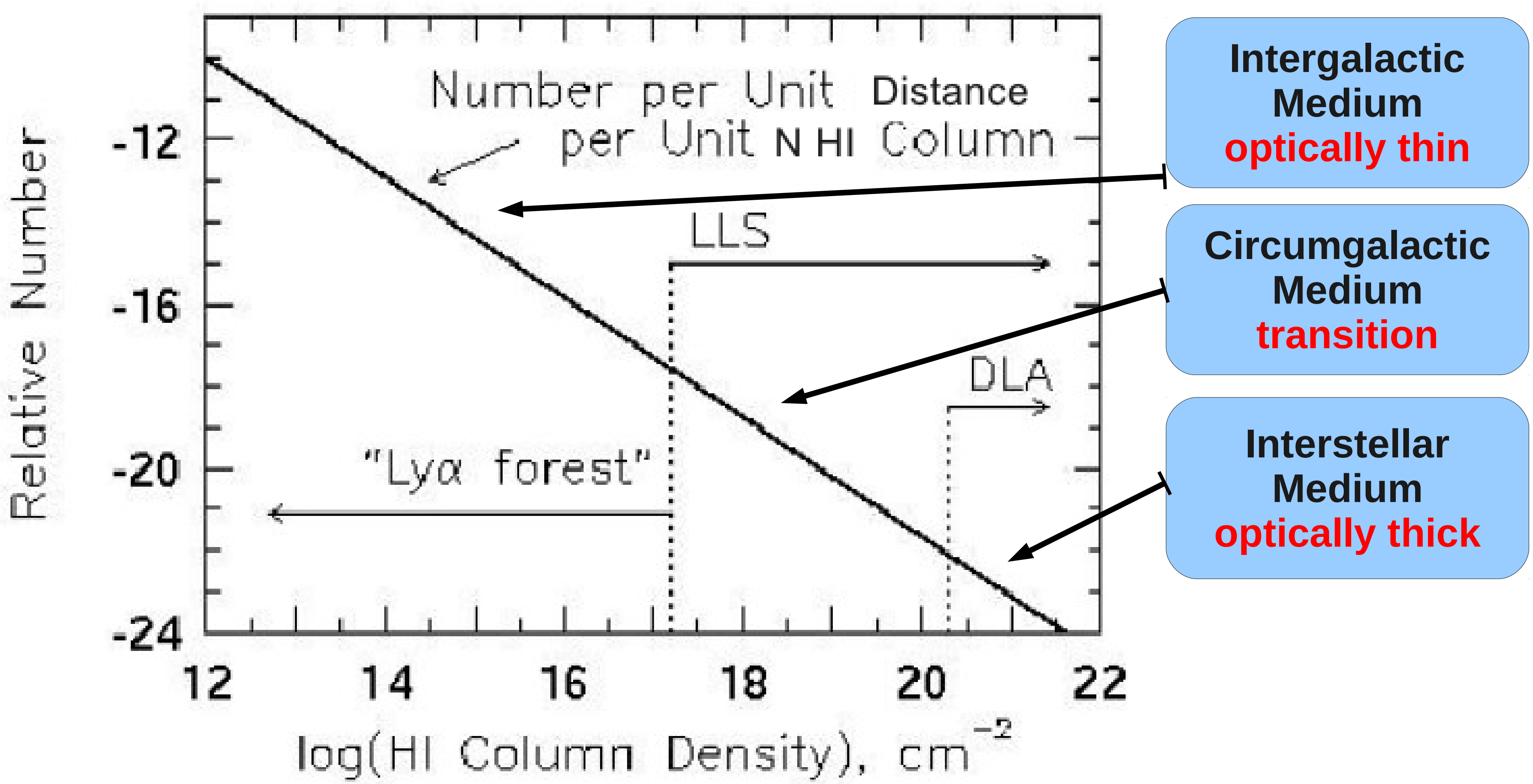
Quasar Spectrum Movie (Pontzen)

Absorption Line Taxonomy



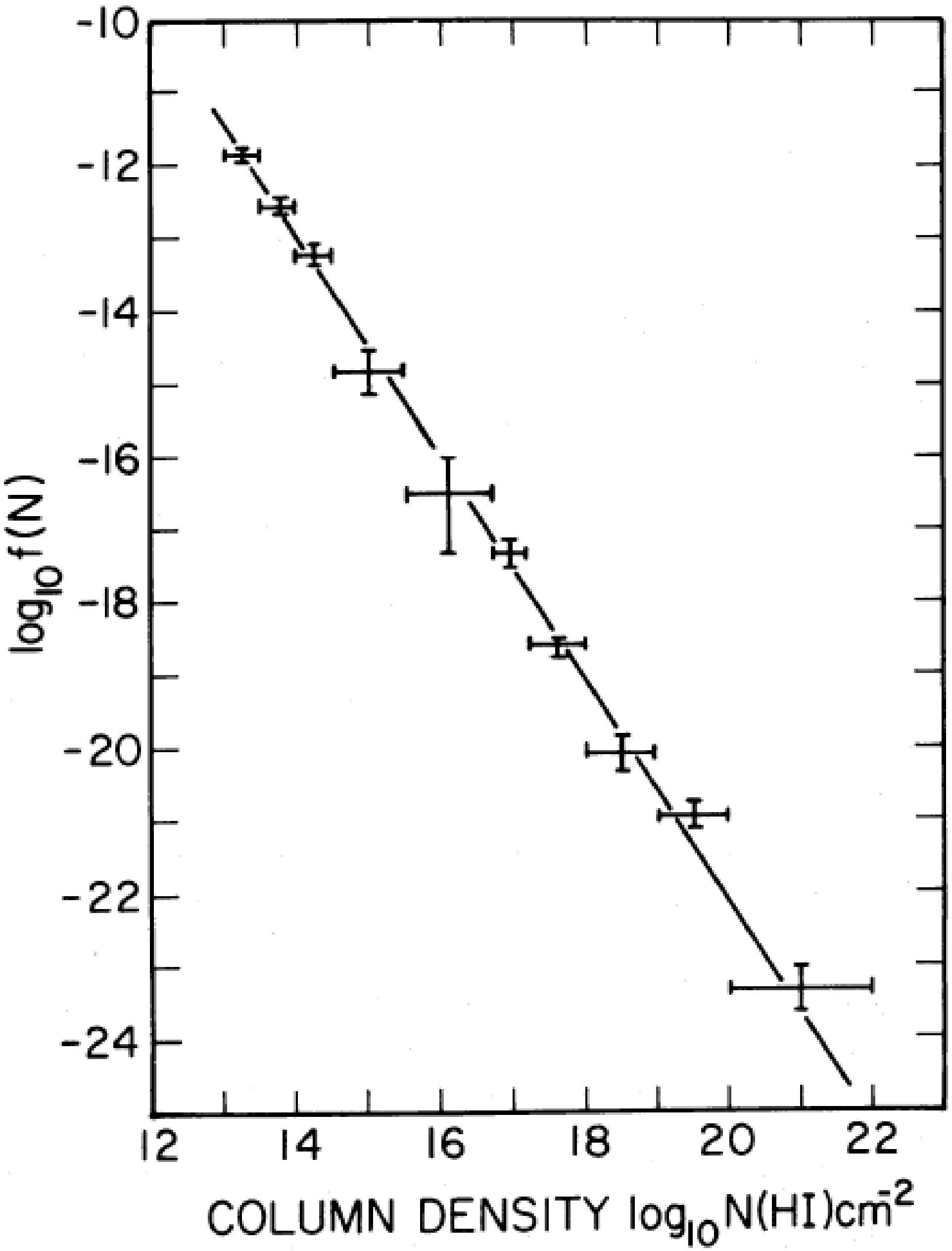
$$N_{\rm HI} = \frac{\tau}{\sigma_{\rm th}} \qquad 10^{17.2}{\rm cm}^{-2} = \frac{1}{6.3 \times 10^{-18}{\rm cm}^2}$$

HI Column Density Distribution Function



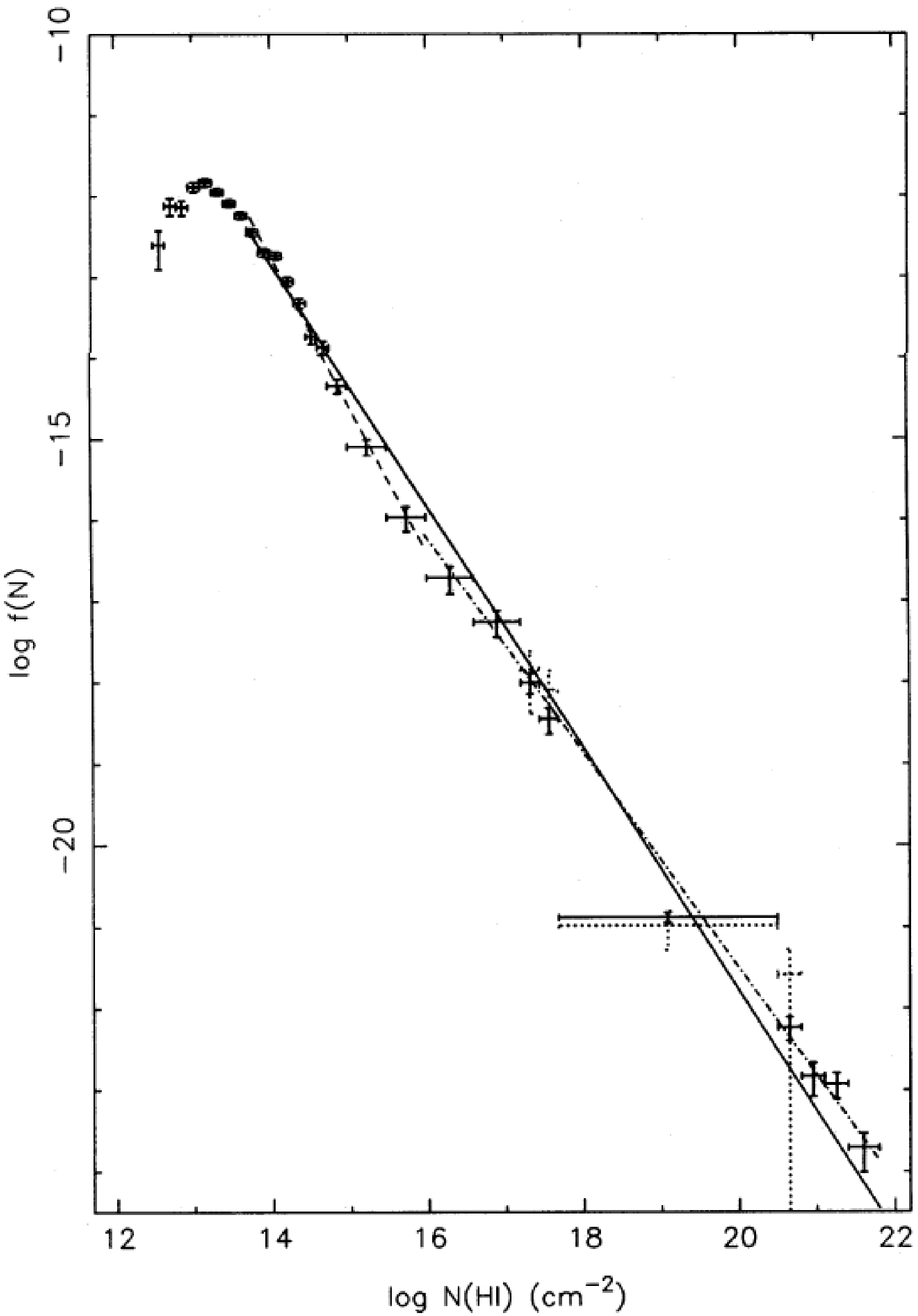
$$f(N_{\rm HI}, z) = \frac{d^2\mathcal{N}}{dN_{\rm HI}dX} = \frac{d^2\mathcal{N}}{dN_{\rm HI}dz}\frac{dz}{dX}$$

HI Column CDDF, z ≈ 3, Tytler 1987



- 3 systems above log NHI = 20
- 26 Lyman Limit Systems
- 54 Lyman-α Forest systems
- In 1987, single power law, $f = A\ NHI^{-B}$ with B ≈ 1.5 works over whole range

HI Column CDDF, z ≈ 3, Petitjean 1993

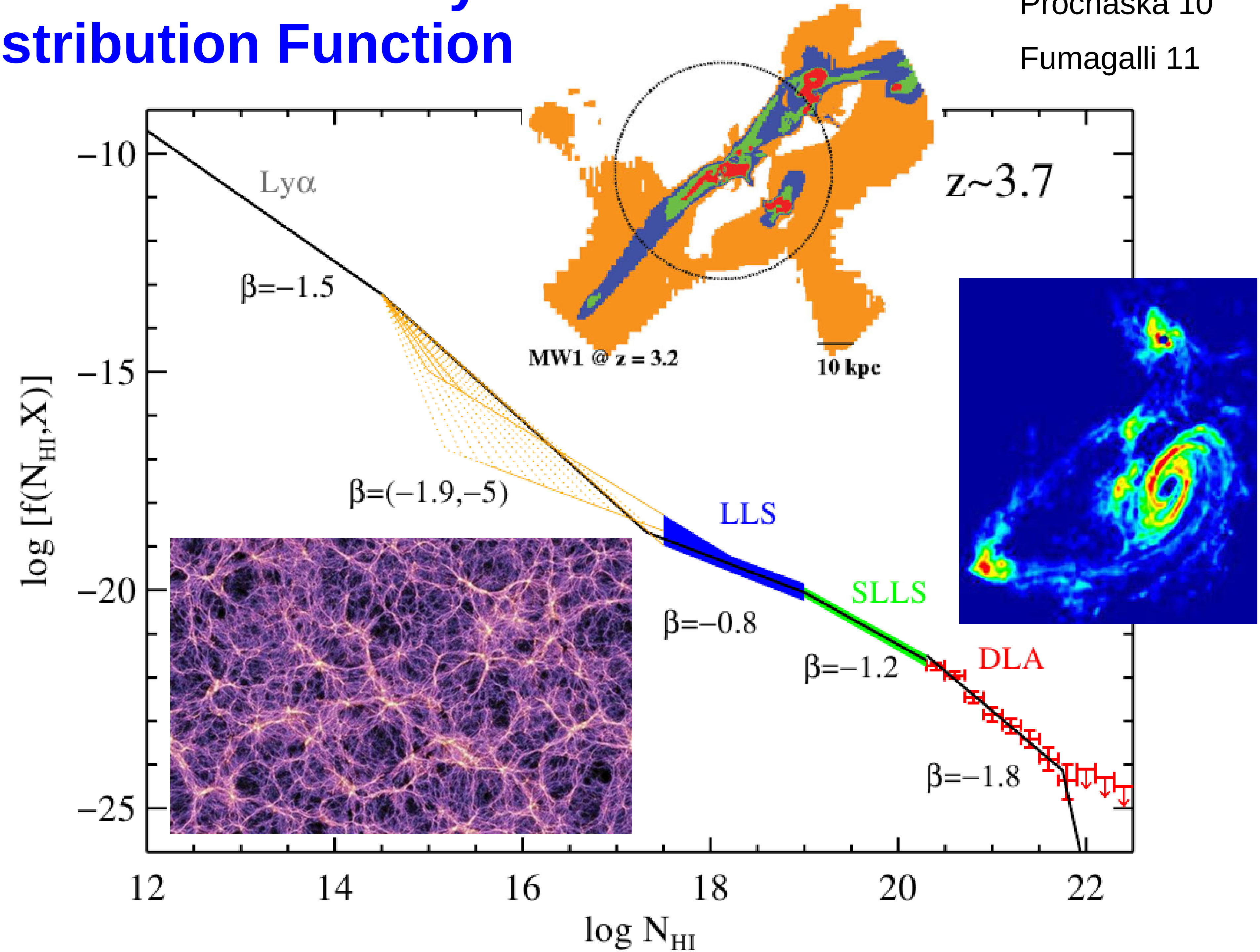


- 27 systems above log NHI = 20.5
- 73 Lyman Limit Systems
- 489 Lyman-α Forest systems
- In 1993, best fit single power law still has B ≈ 1.5, but evidence of structure emerges.

HI Column Density Distribution Function

Prochaska 10

Fumagalli 11



HI Column Density Distribution Function

Prochaska 10

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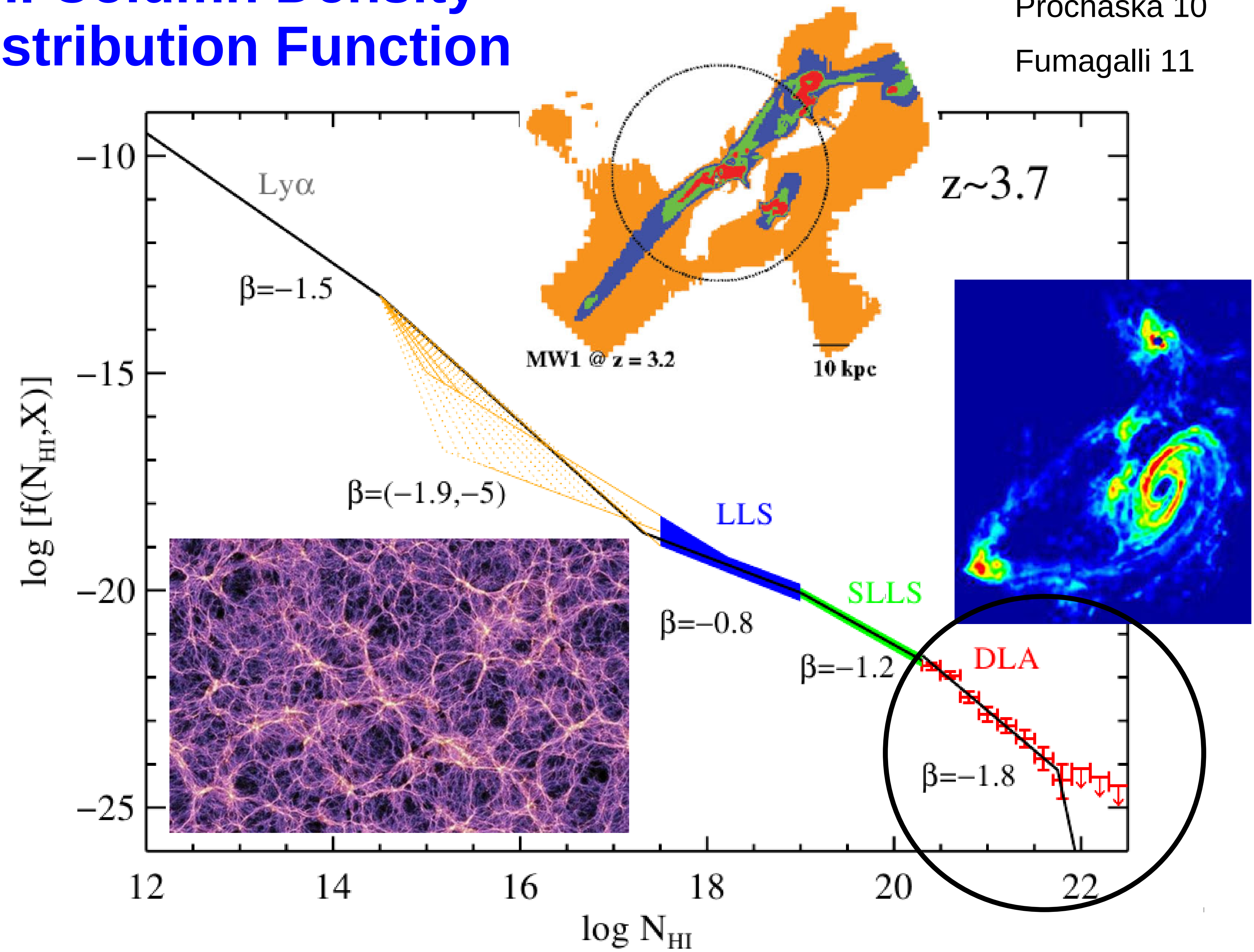
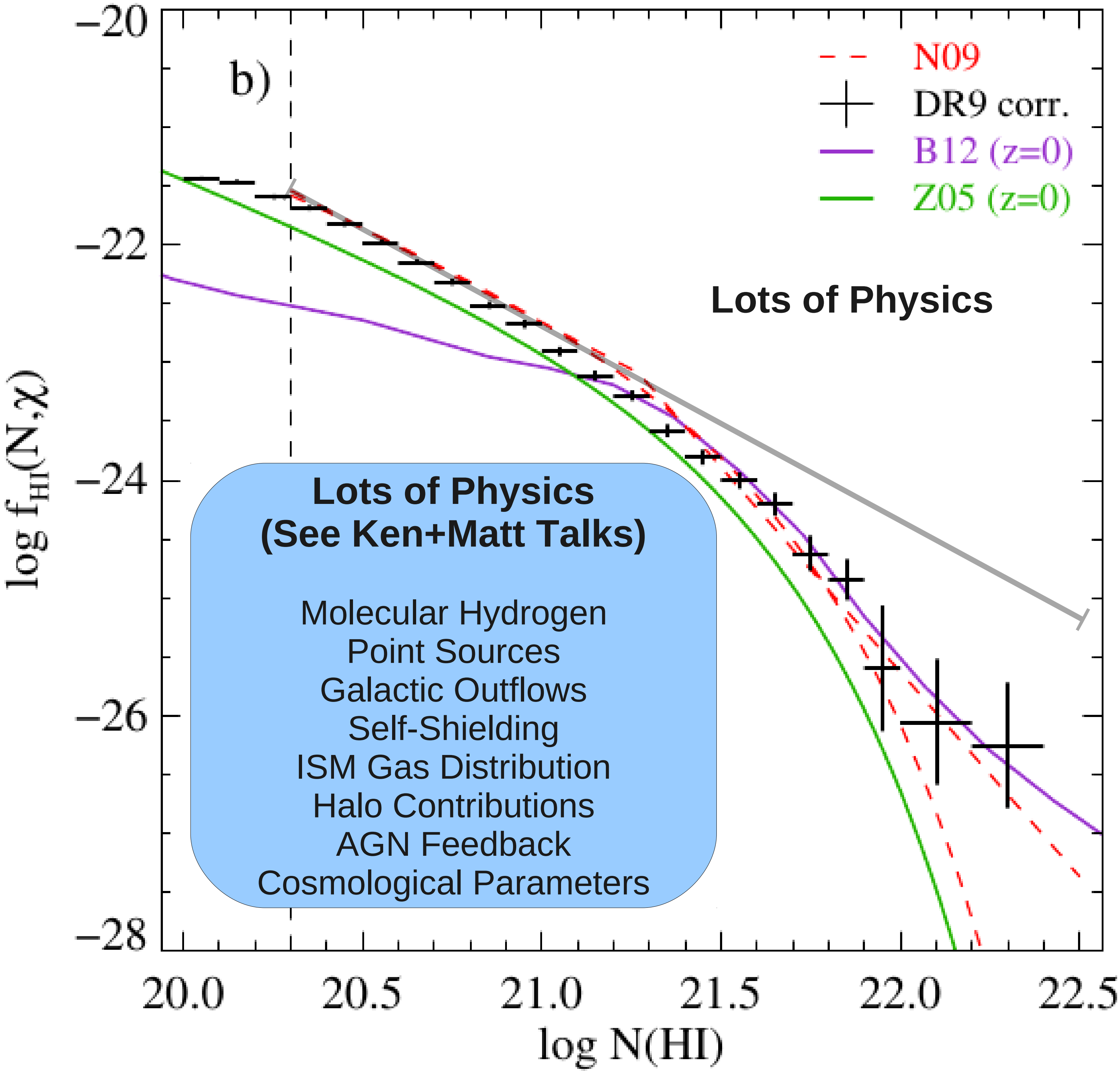
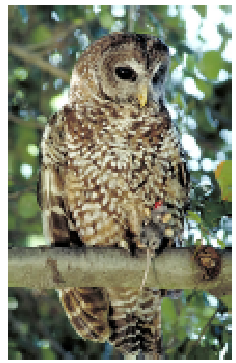
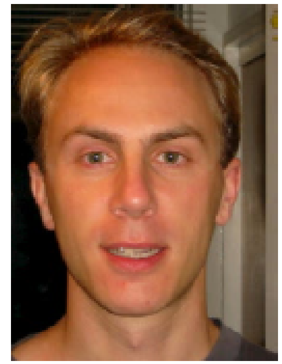


Noterdaeme 12



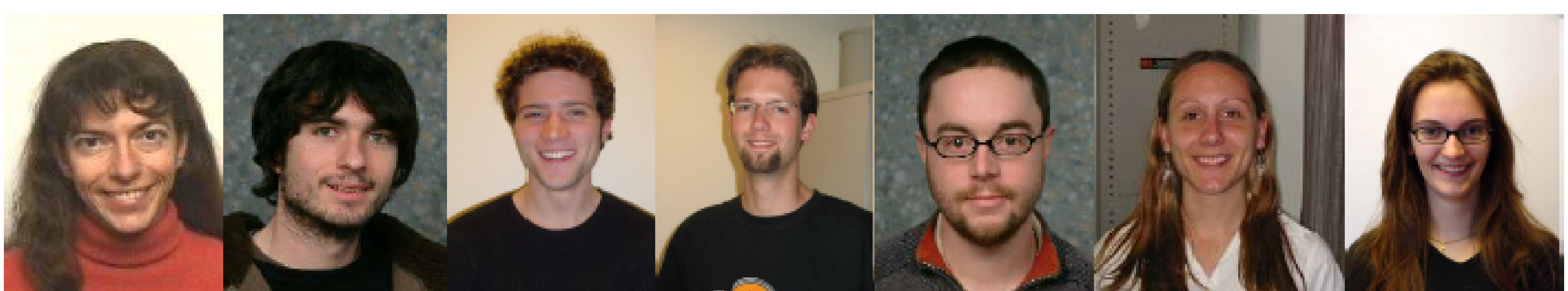
Cosmological Galaxy Formation Simulations
OverWhelmingly Large Simulations Project





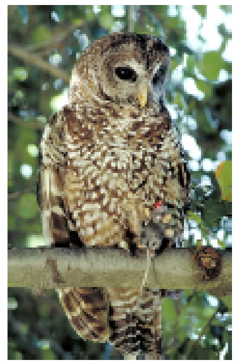
Joop Schaye

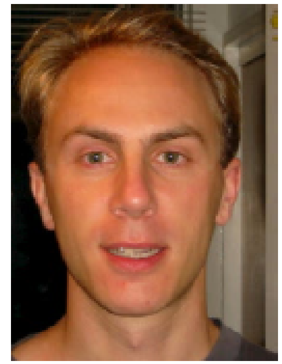
Booth Dalla Vecchia Springel Theuns Tornatore Wiersma



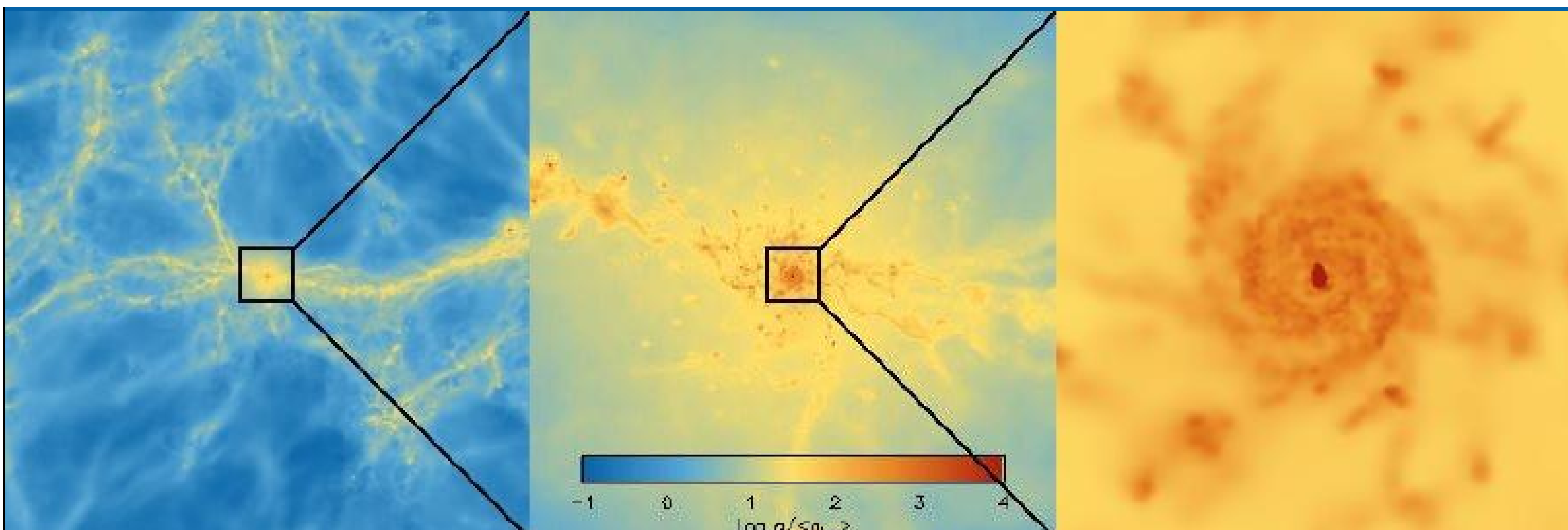
Bertone Crain Duffy Haas McCarthy Sales Van de Voort

Cosmological Galaxy Formation Simulations
OverWhelmingly Large Simulations Project





Joop Schaye



Numerical Post Reionization UV Background

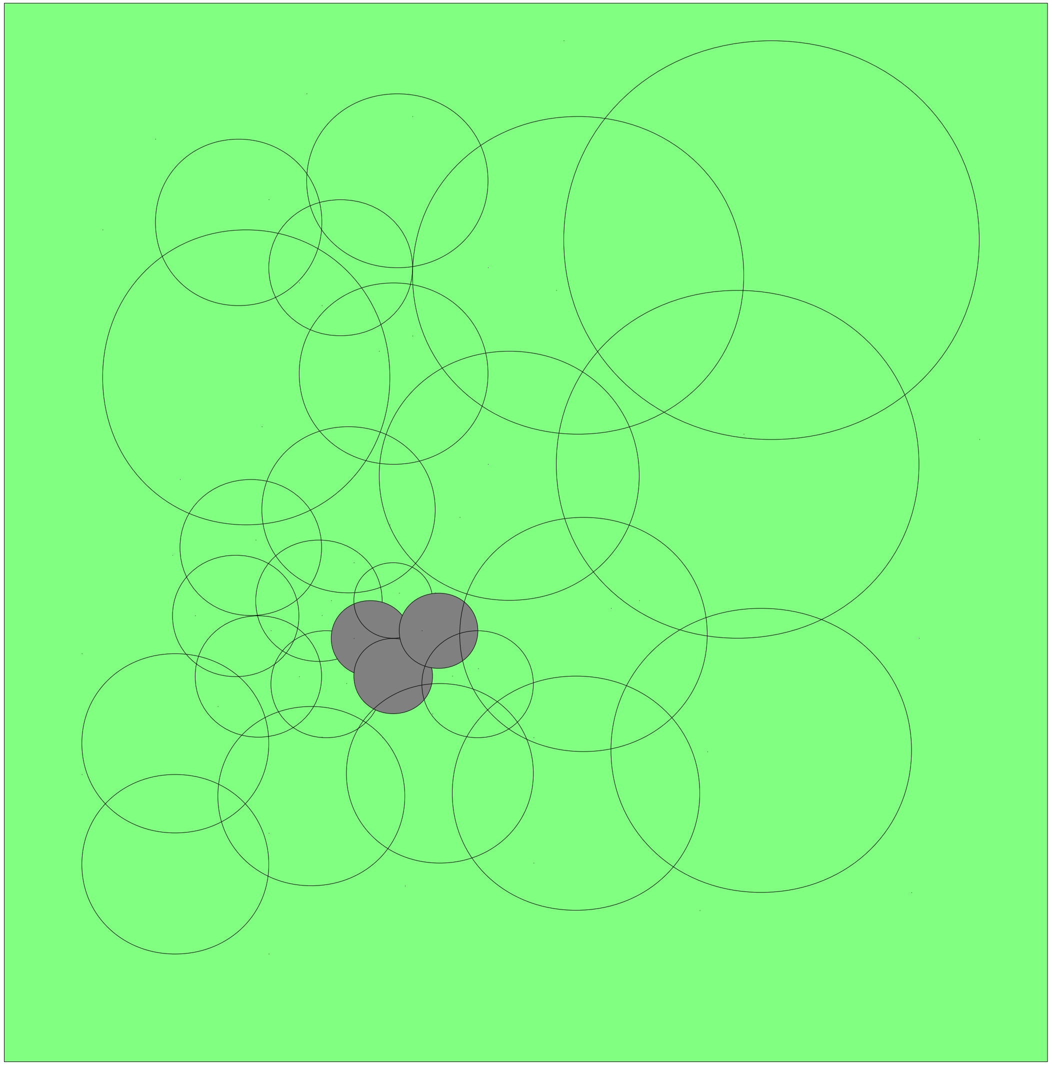
"Standard" Approach

Assume the Following

1) Optically Thin Gas
2) Spatially Uniform Radiation
3) Photo/Collisional Equilibrium

For HI Absorbers

Works for Low NHI Forest
Breaks Badly for Most HI



Post-Reionization Requirements

To go beyond standard approach we need radiative transfer

This almost always involves using the walls of the simulation volume as sources

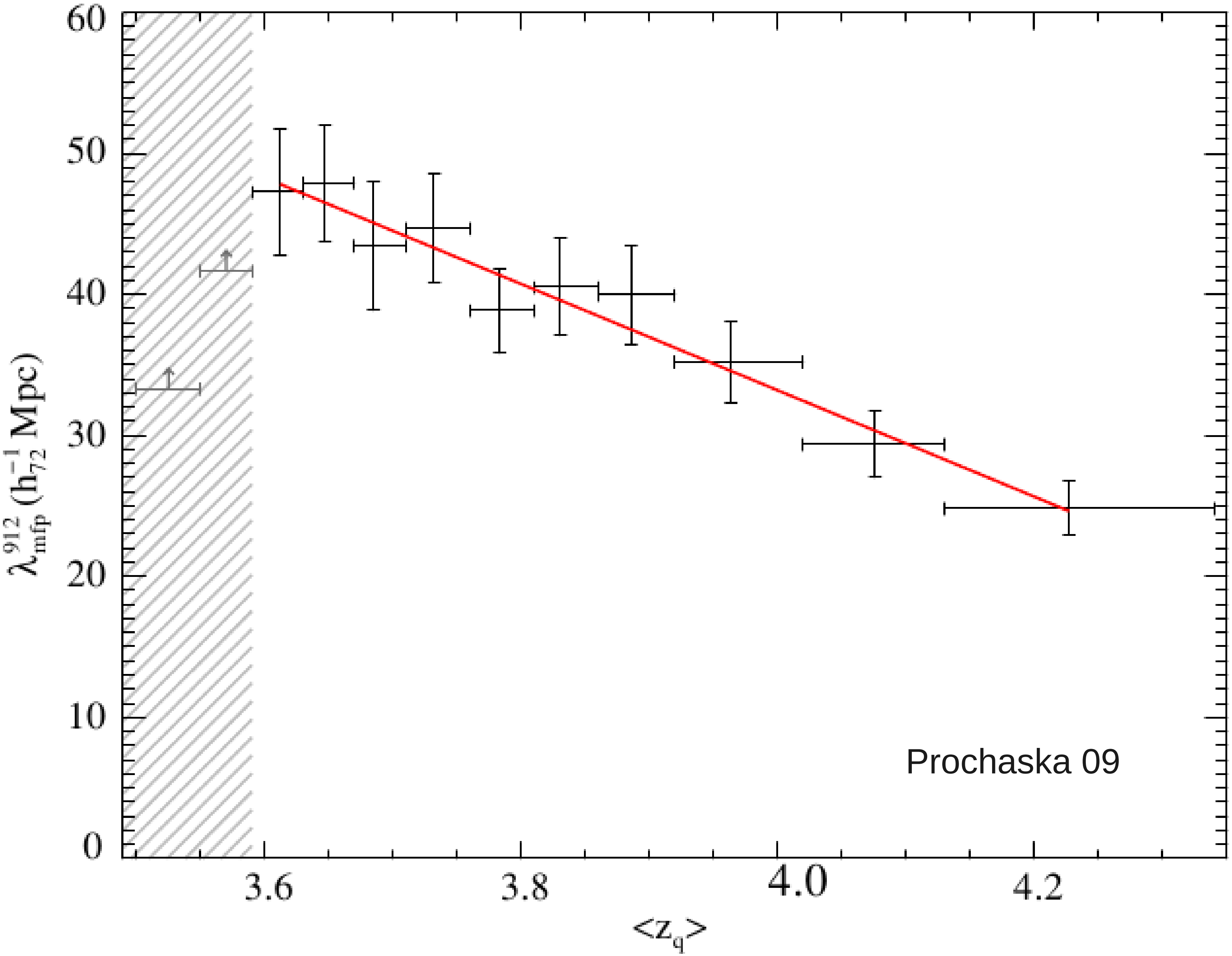
WHY?

The large mean free path @ 912 Angstroms

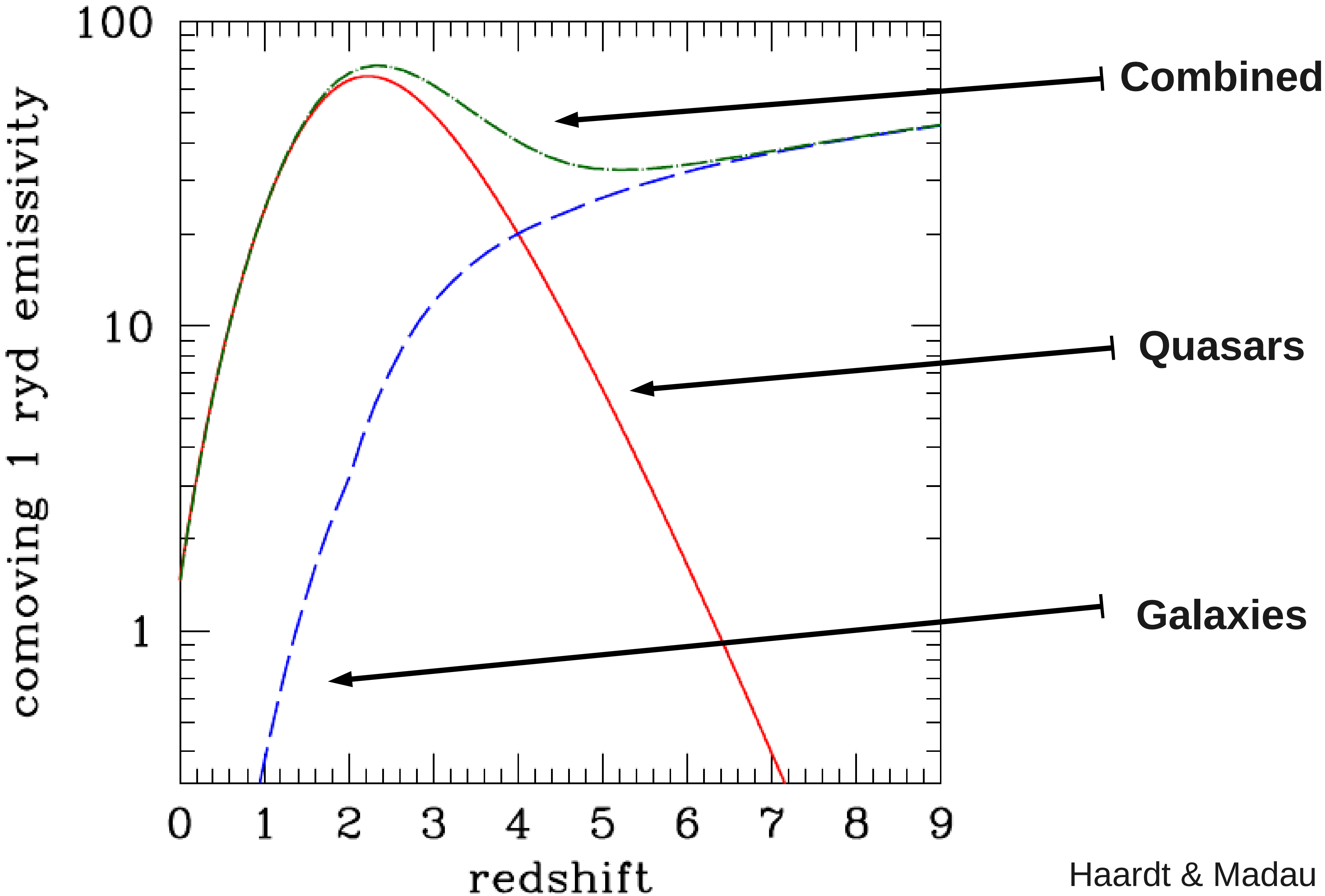
The rarity of bright quasars

Need large box to self-consistently produce UV background
BUT cant resolve HI absorbers in large boxes
Therefore most UV background comes from outside the box

Mean Free Path at 912 Angstroms

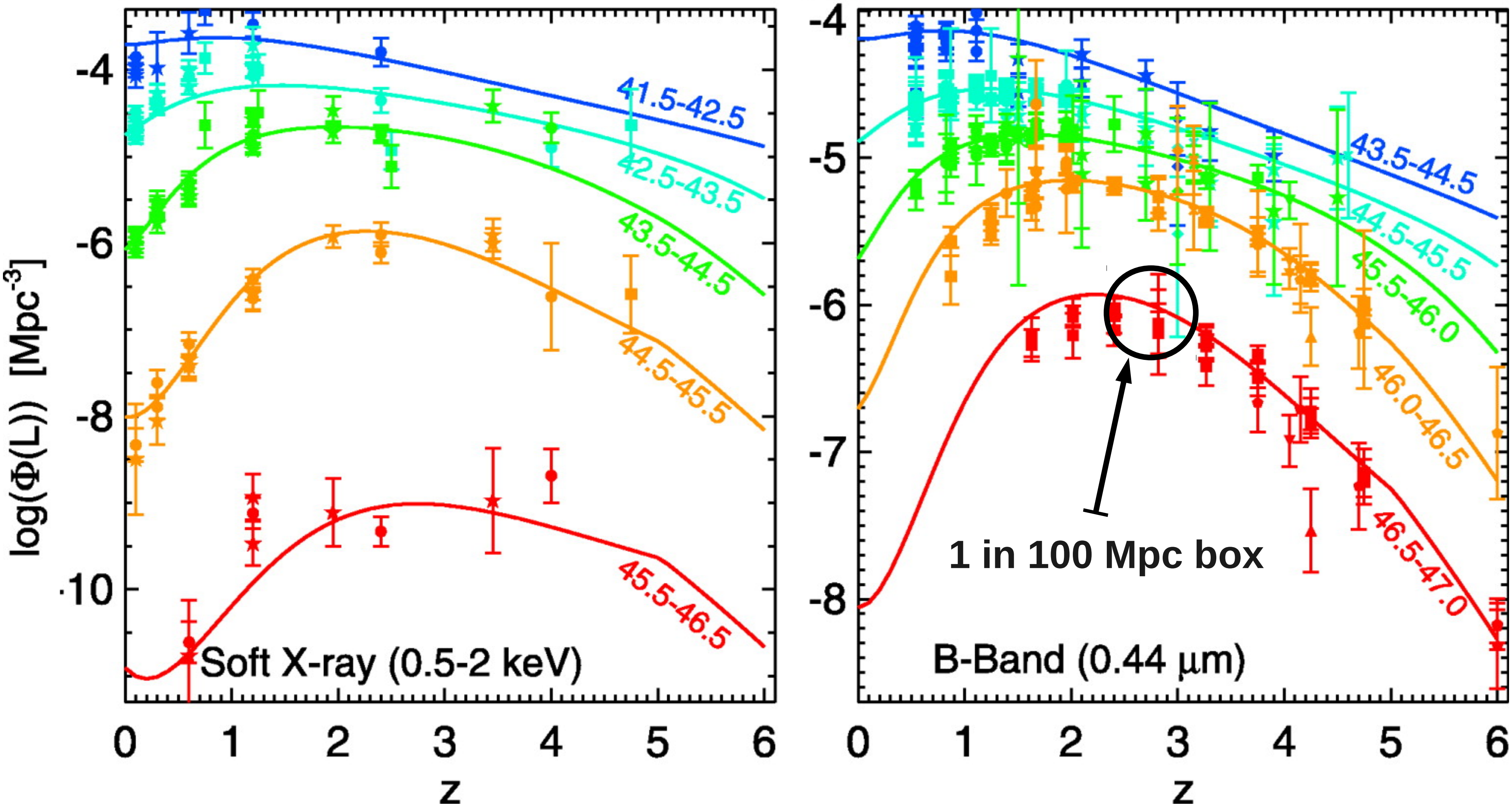


Galaxy + Quasar Emissivity @ 1 Ryd



Haardt & Madau 12

Bright Quasar Number Density



Hopkins 07

Numerical Post Reionization UV Background
Optically Thin Approximation

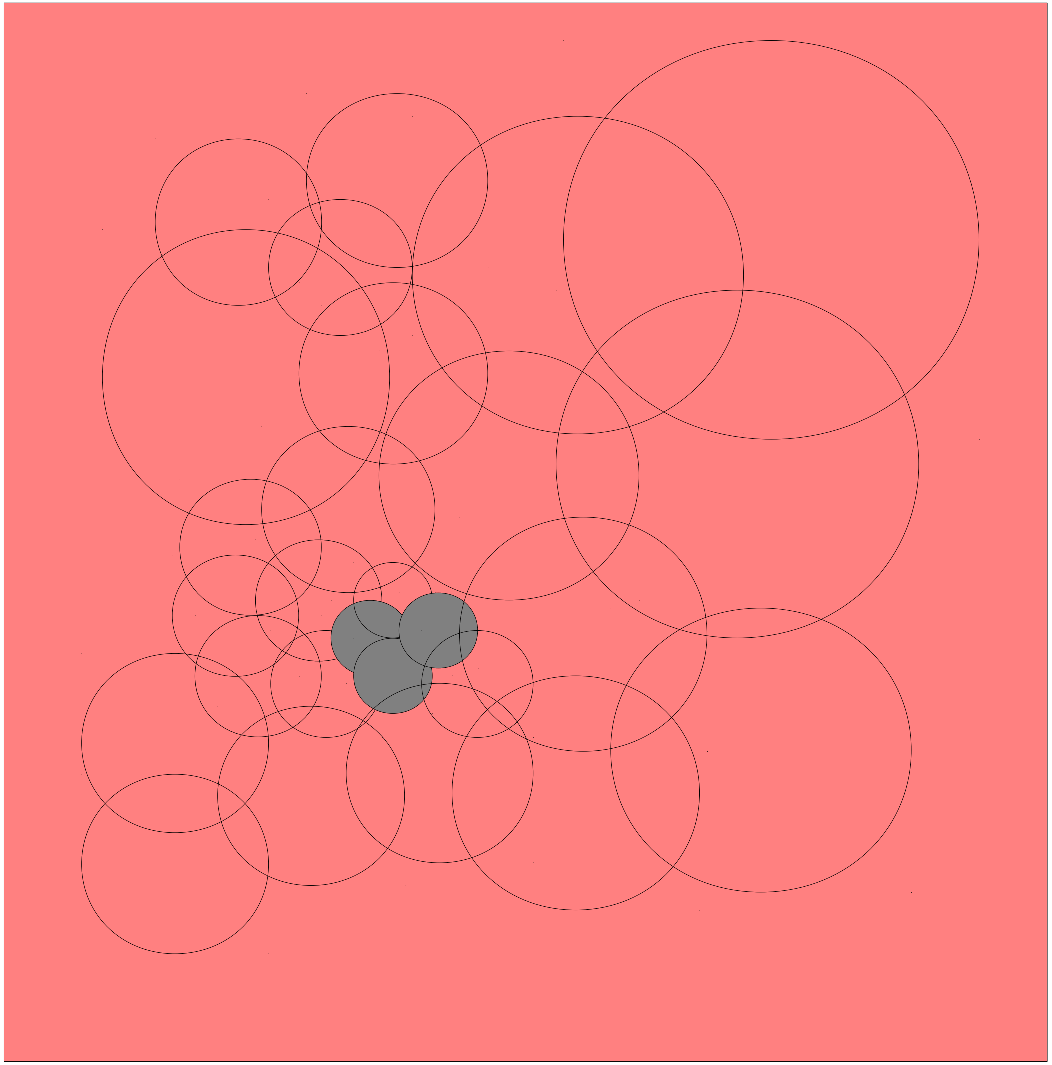
”Standard” Approach

Assume the Following

1) Optically Thin Gas
2) Spatially Uniform Radiation
3) Photo/Collisional Equilibrium

For HI Absorbers

Works for Low NHI Forest
Breaks Badly for Most HI



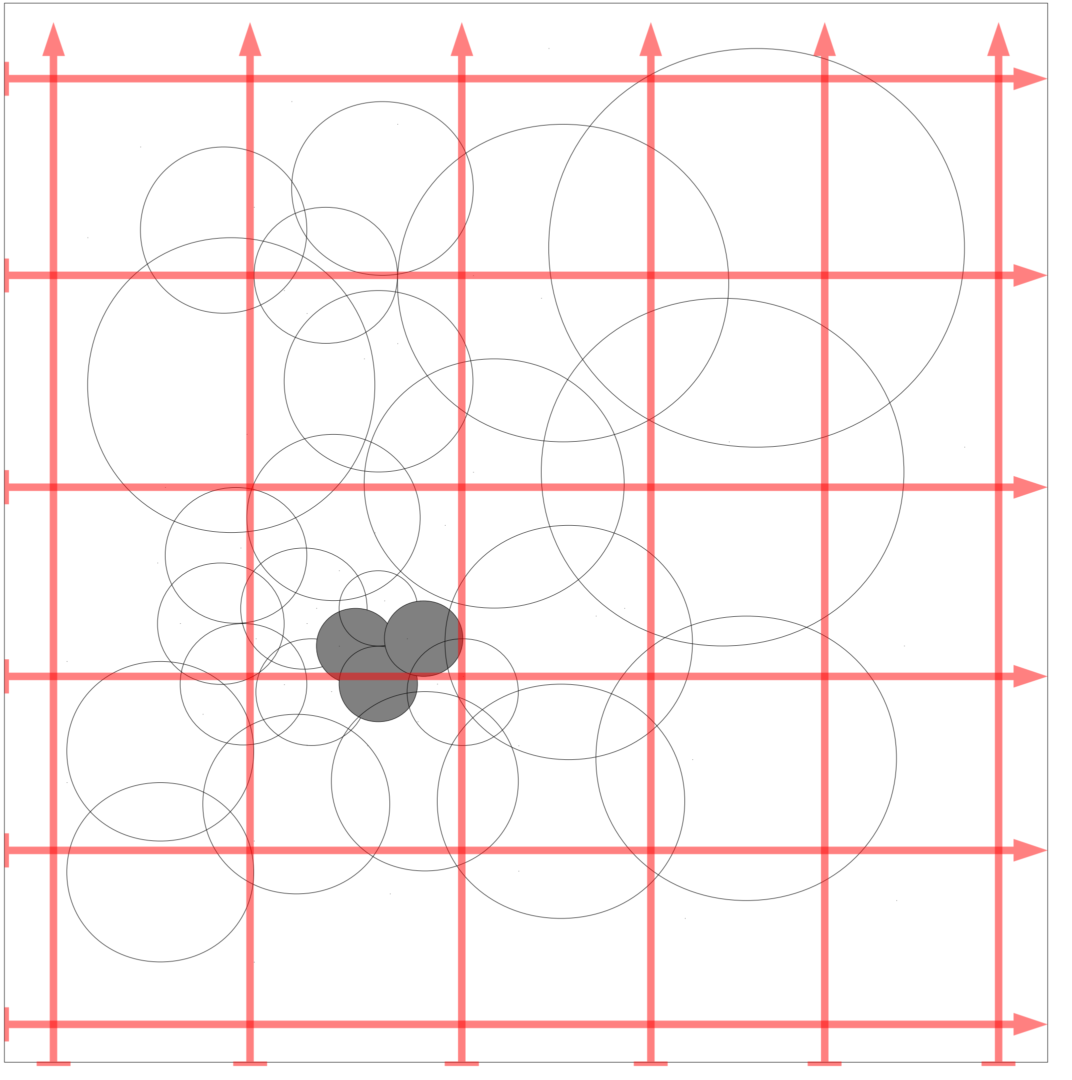
Numerical Post Reionization UV Background Forward Ray Tracing

Trace rays from sources.
Large mean free path means can't model UV background with internal sources i.e. walls must be sources.

Leads to BAD things,

1) Gradient in UV bgnd.
(Loss of Galilean Invariance)
2) Non-uniform sampling

Hard to produce uniform UV where you would like one



Post-Reionization UV Background

During Reionization

Large Fluctuations in Radiation Field

Ionization State far from Equilibrium

Majority of Gas not Optically Thin

After Reionization

Gentle Fluctuations in Radiation Field

Ionization State close to Equilibrium

Majority of Gas is Optically Thin

Numerical Post Reionization UV Background
Reverse Ray Tracing

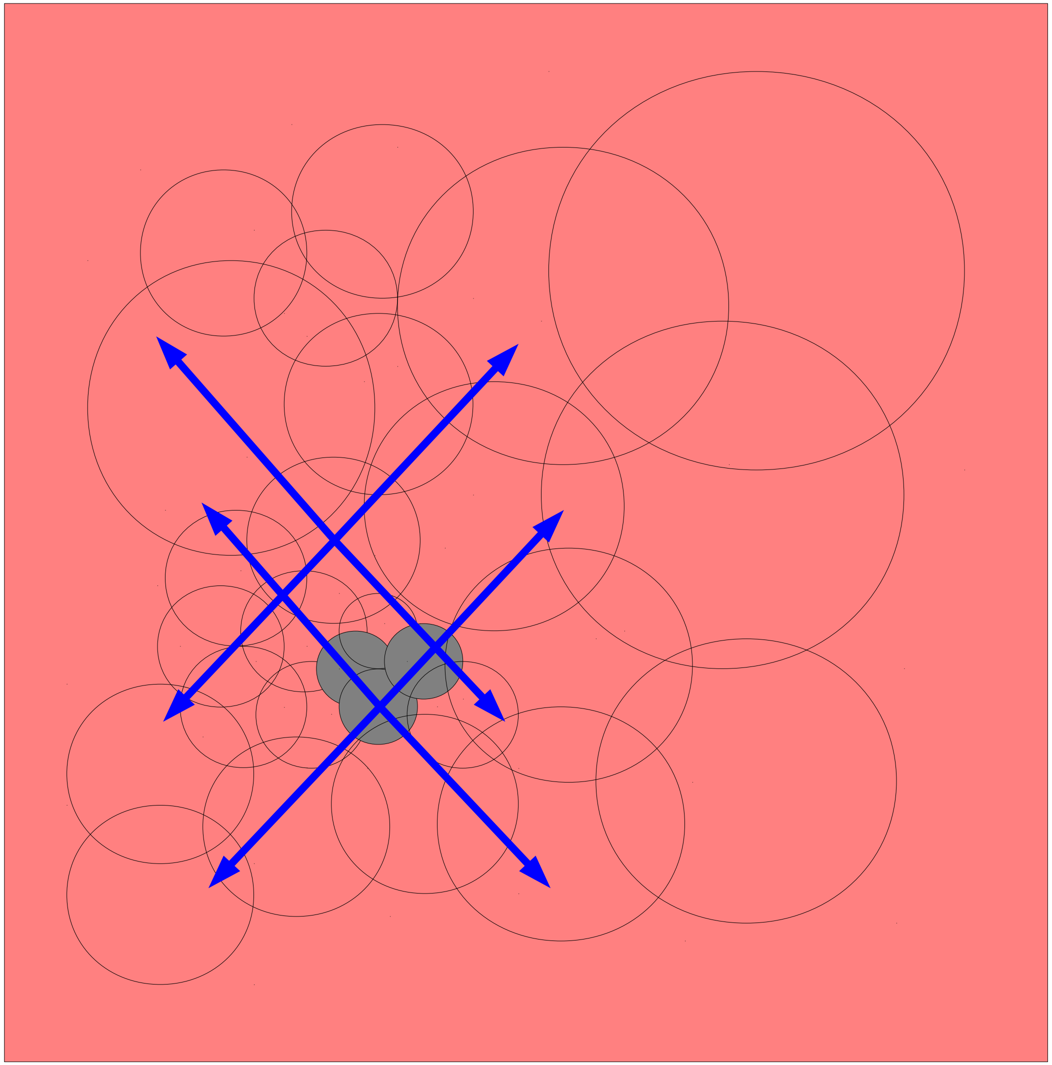
Start with standard approach.
Trace rays from gas.
Boxsize doesn't matter.

Removes BAD things,

1) ~~Gradient in UV bgnd.~~
2) ~~Non-uniform sampling~~

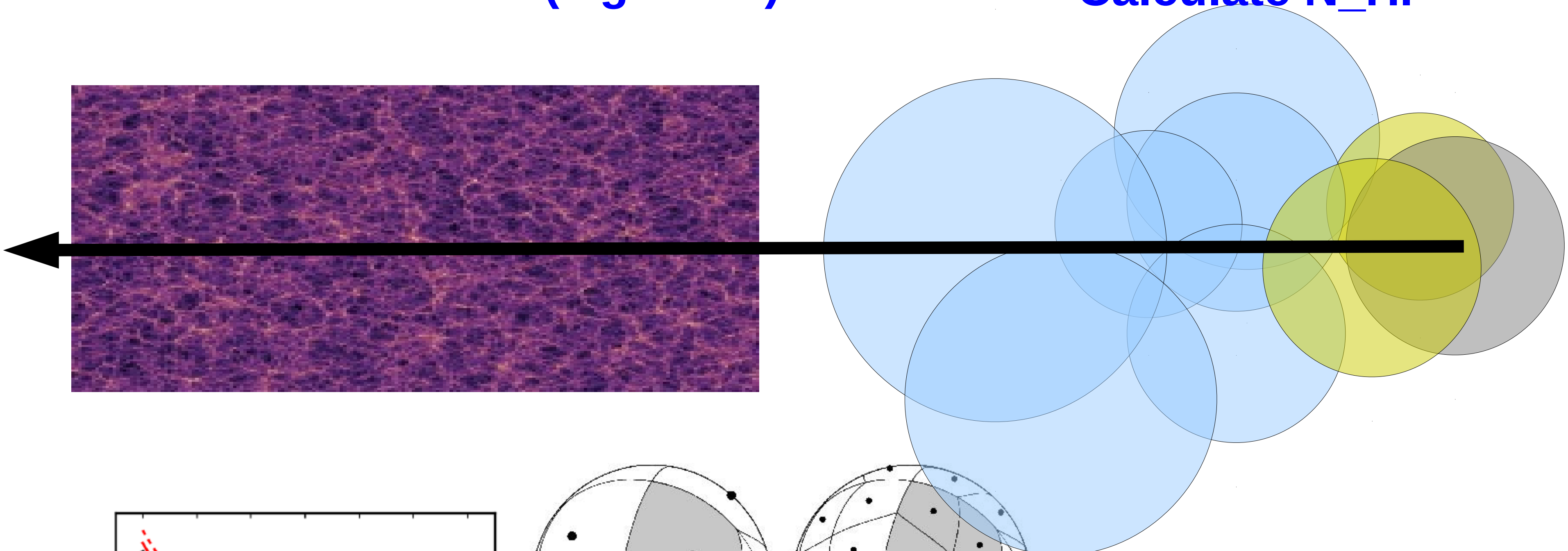
Adds GOOD things,
1) Each ray is independent
2) Sub-volumes independent
(modulo ray length)
3) Allows for optimizations
Skip ionized, case A/B

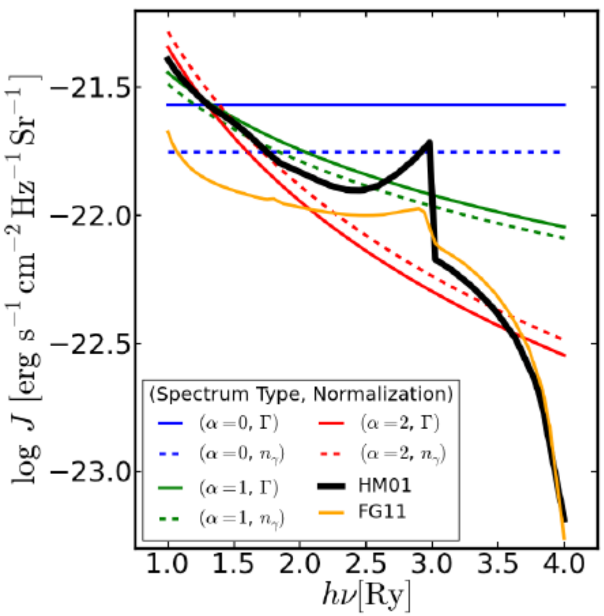
Converged with lray = 100 pkpc

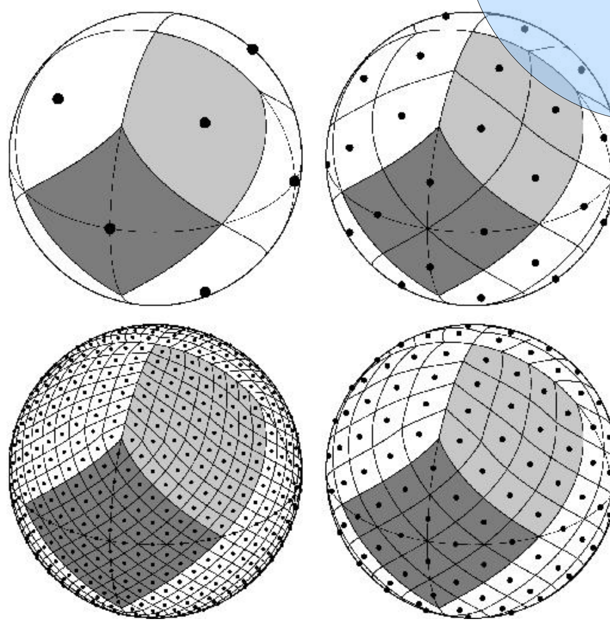


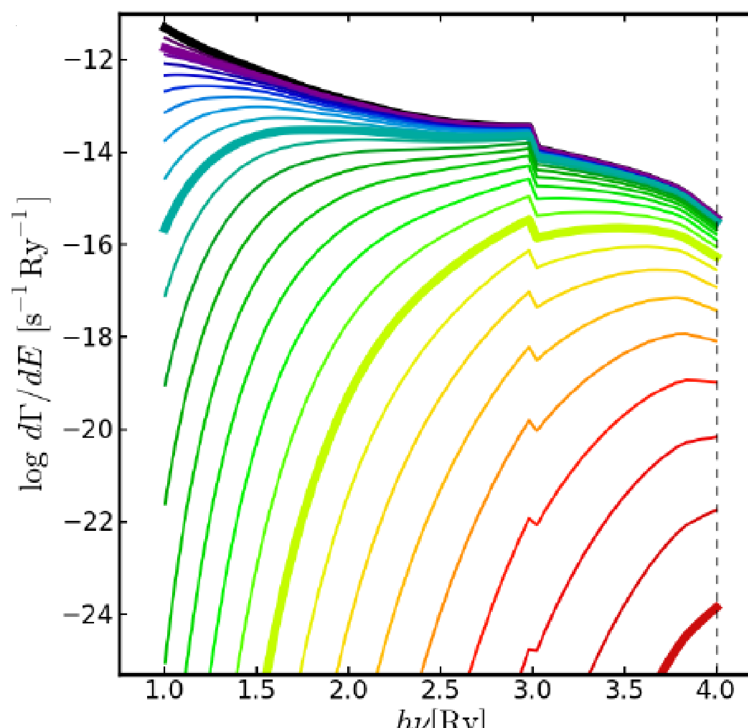
Standard UVB Model (e.g. H&M)

Calculate N_HI



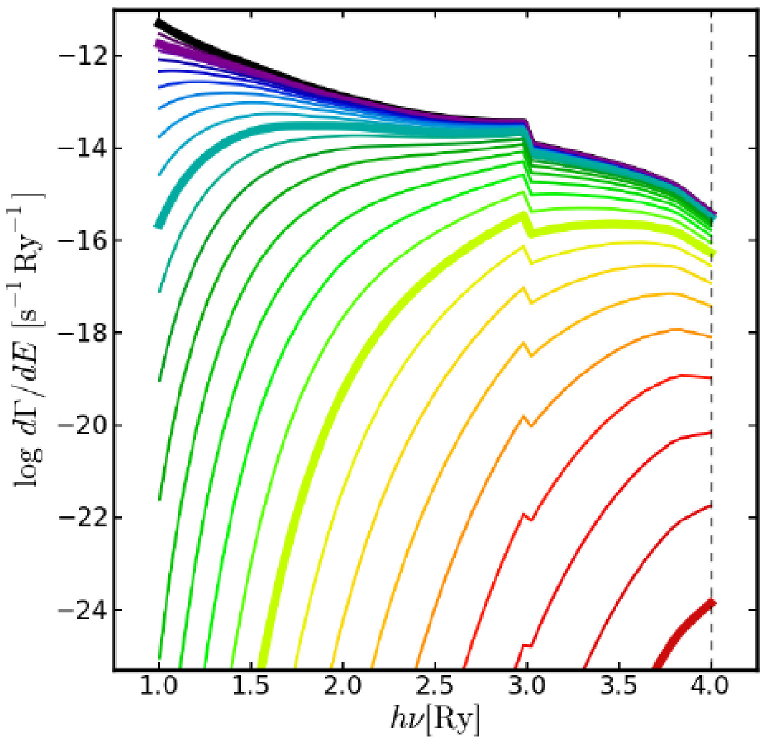


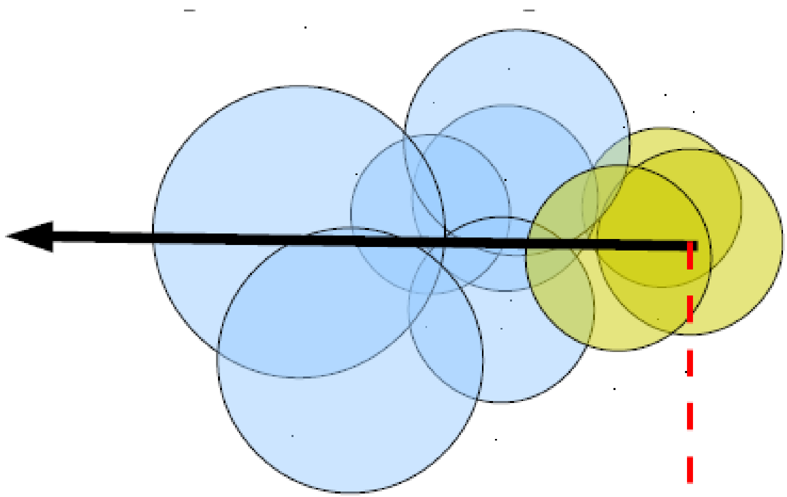




$$\Gamma^{\rm shld} = \frac{4\pi}{N_{\rm ray}} \sum_{k=1}^{\rm N_{ray}} \int_{\nu_{\rm th}}^{q\nu_{\rm th}} \frac{I_\nu \sigma}{h\nu} \exp(-\tau_k) d\nu$$

Urchin - Overview

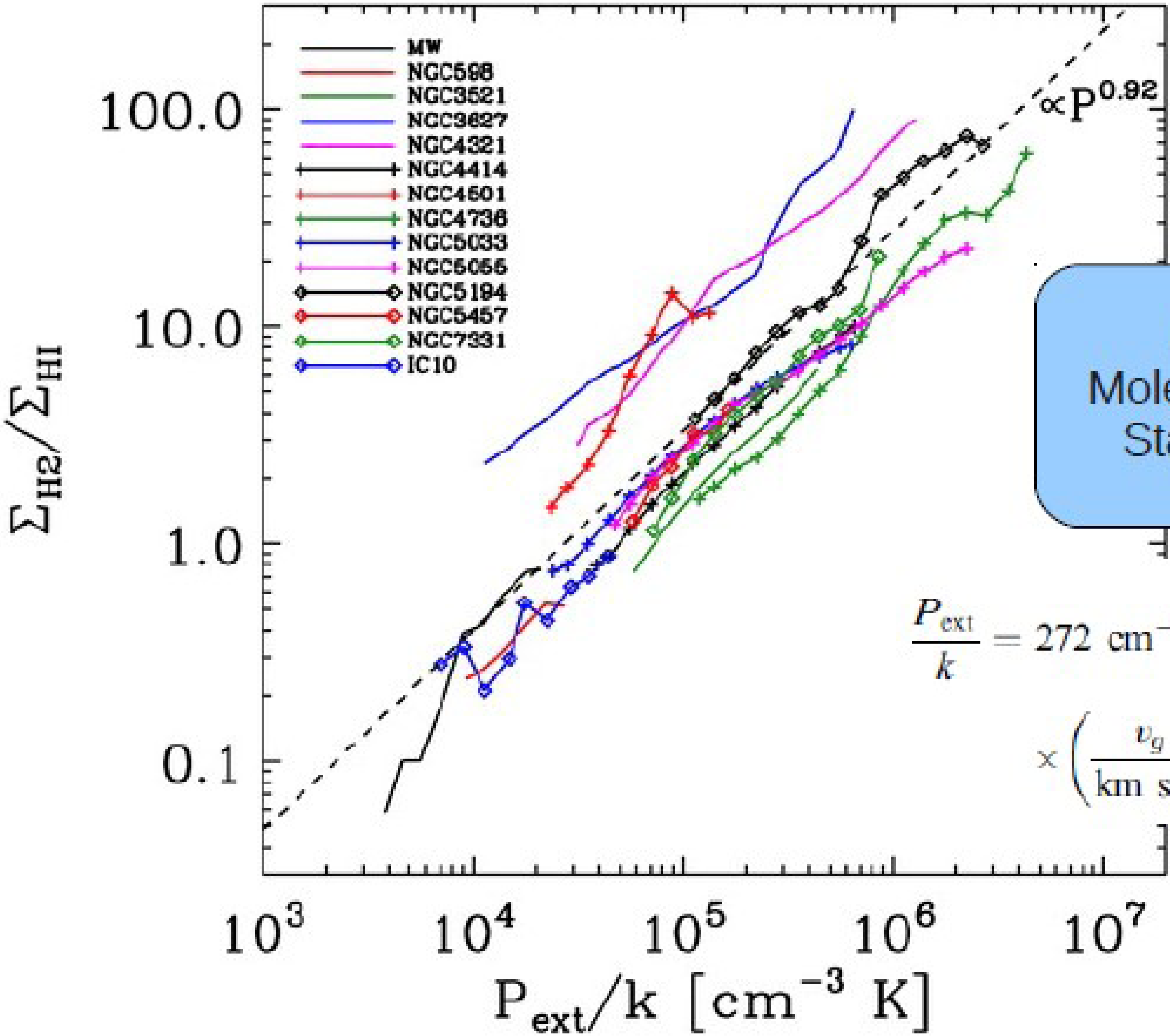




$$\Gamma^{\mathrm{shld}} = \frac{4\pi}{N_{\mathrm{ray}}} \sum_{k=1}^{\mathrm{N_{ray}}} \int_{\nu_{\mathrm{th}}}^{q\nu_{\mathrm{th}}} \frac{I_\nu \sigma}{h\nu} \exp(-\tau_k) d\nu$$

- **Loop over all particles.**
- **Skip highly ionized (99% of) particles**
- **Calc. HI optical depth out to fixed distance along Healpix directions.**
- **Calculate new $\Gamma < \Gamma_{\mathrm{thin}}$**
- **Calculate new eq. $x_{\mathrm{HI}}(n_H, T, \Gamma, y_e)$**
- **Iterate until convergence**
- **No Poisson Noise**
- **Full Spectral Information**
- **Takes Full advantage of Post Reionization Opportunities**

Blitz & Rosolowsky 06 – H2 vs Pressure



Atomic Gas - 21 cm
Molecular Gas - CO (J= 1-0)
Stars – K_s band emission

$$\frac{P_{\rm ext}}{k} = 272\ {\rm cm^{-3}\ K}\left(\frac{\Sigma_g}{M_\odot\ {\rm pc^{-2}}}\right)\left(\frac{\Sigma_\star}{M_\odot\ {\rm pc^{-2}}}\right)^{0.5} \times \left(\frac{v_g}{\rm km\ s^{-1}}\right)\left(\frac{h_\star}{\rm pc}\right)^{-0.5}.$$

Urchin Summary

Fully Coupled to Hydro = Hard

Progress: ENZO, OTVET, HART, Petkova 09

Jumping into the deep end

Needs to be done, but will always be expensive

Accomplished Goals of Urchin

1) Incremental improvement of standard approach

2) Preserve adaptive resolution of hydro run

3) Eliminate Noise in Samping Radiation Field

4) Preserve full spectral information

Upcoming Goals

1) Include point sources + non equilibrium ionization state

2) Further parallelization

3) Further Optimization

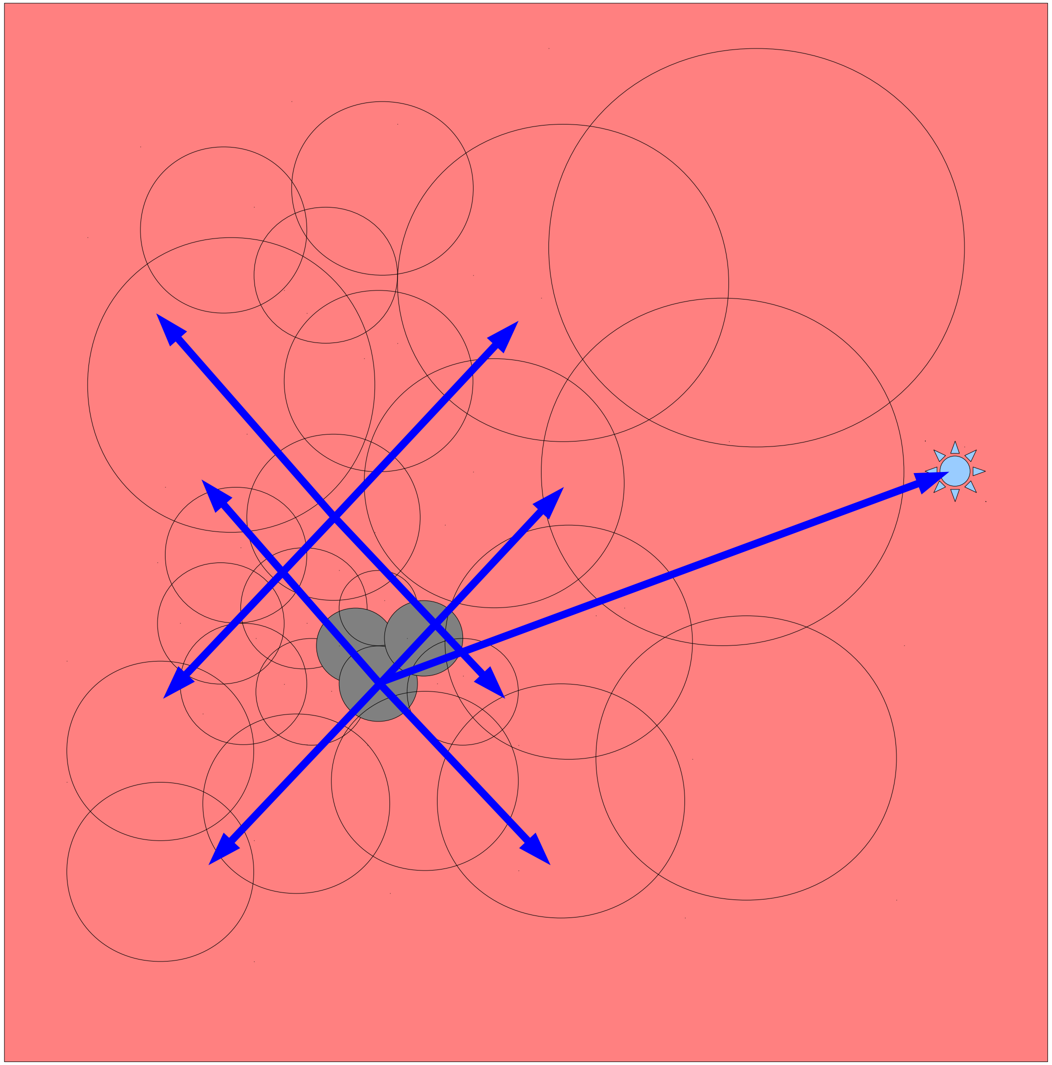
Plan for Point Sources

To add point sources proceed as before plus trace a ray to each Source.

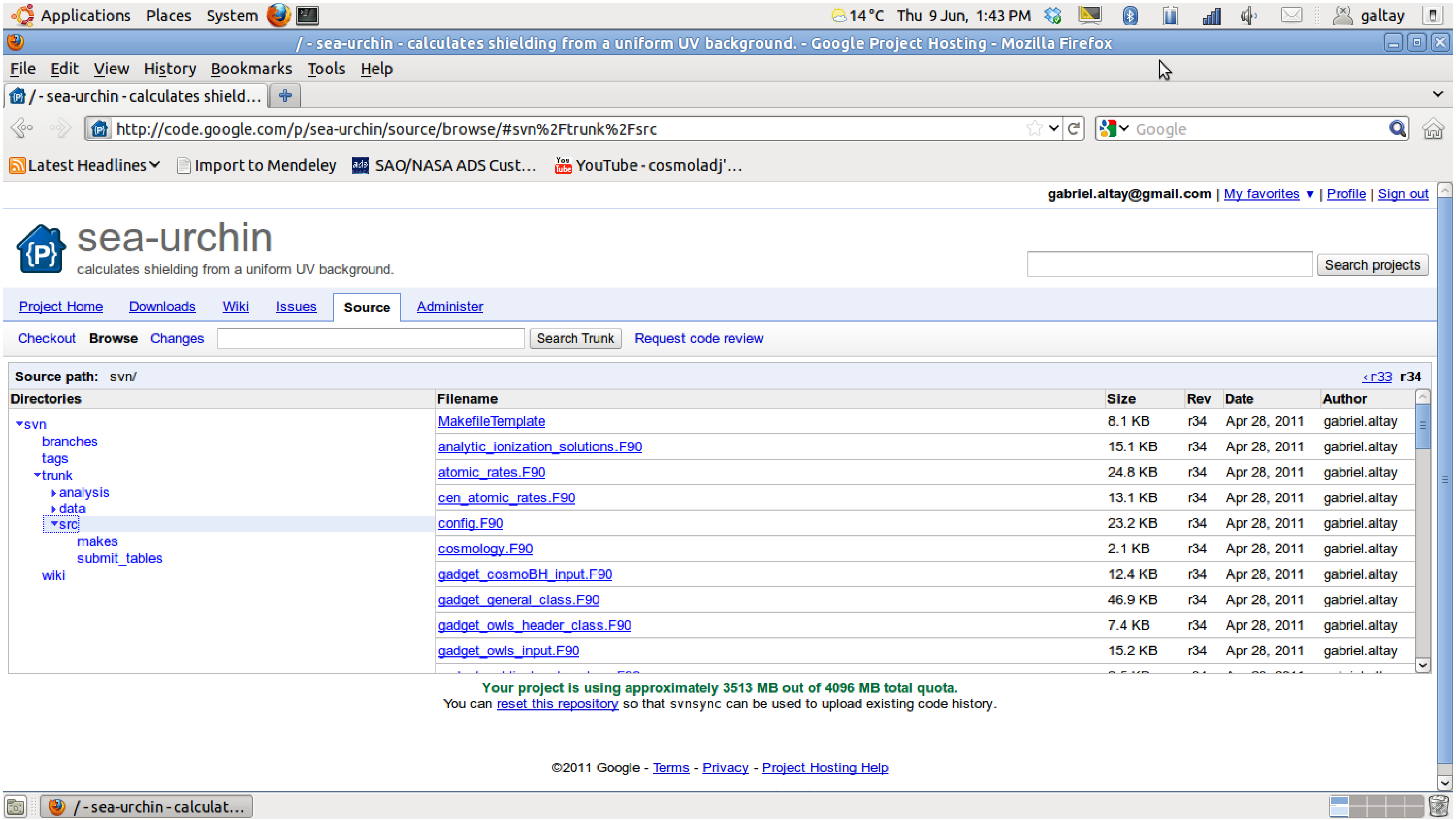
Rays still independent

Can skip distant and dim sources

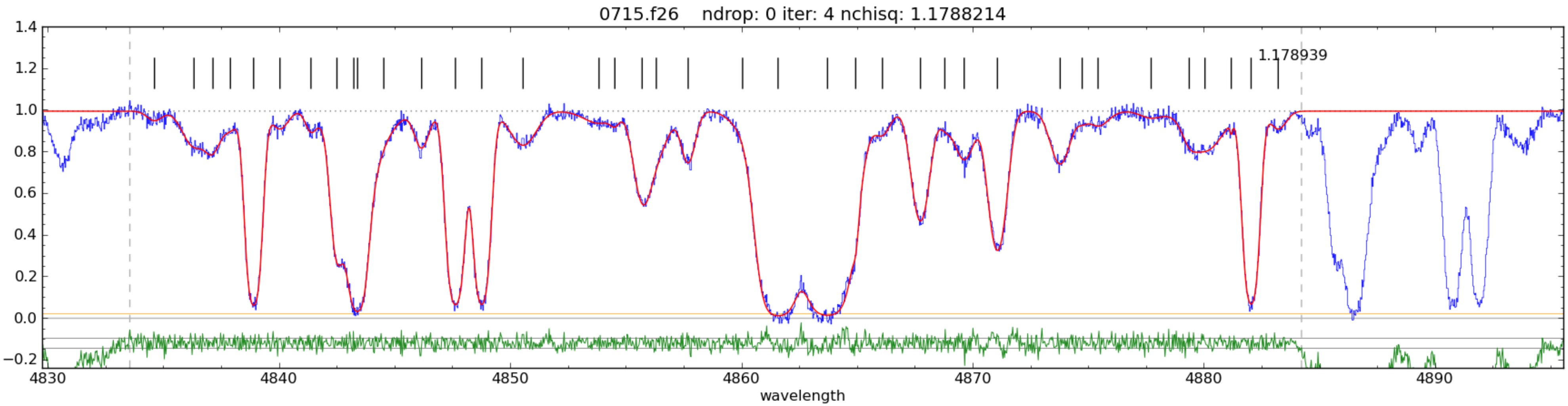
Tree can serve double duty for locating good point sources and finding ray intersections.



Urchin - Online

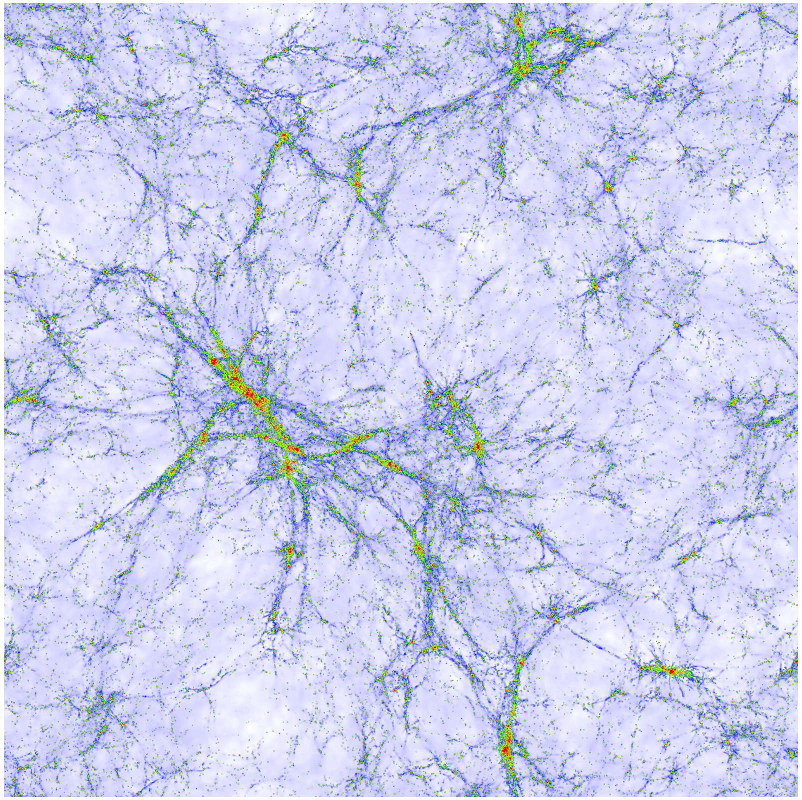


Low NHI - VP Fit Mock Spectra

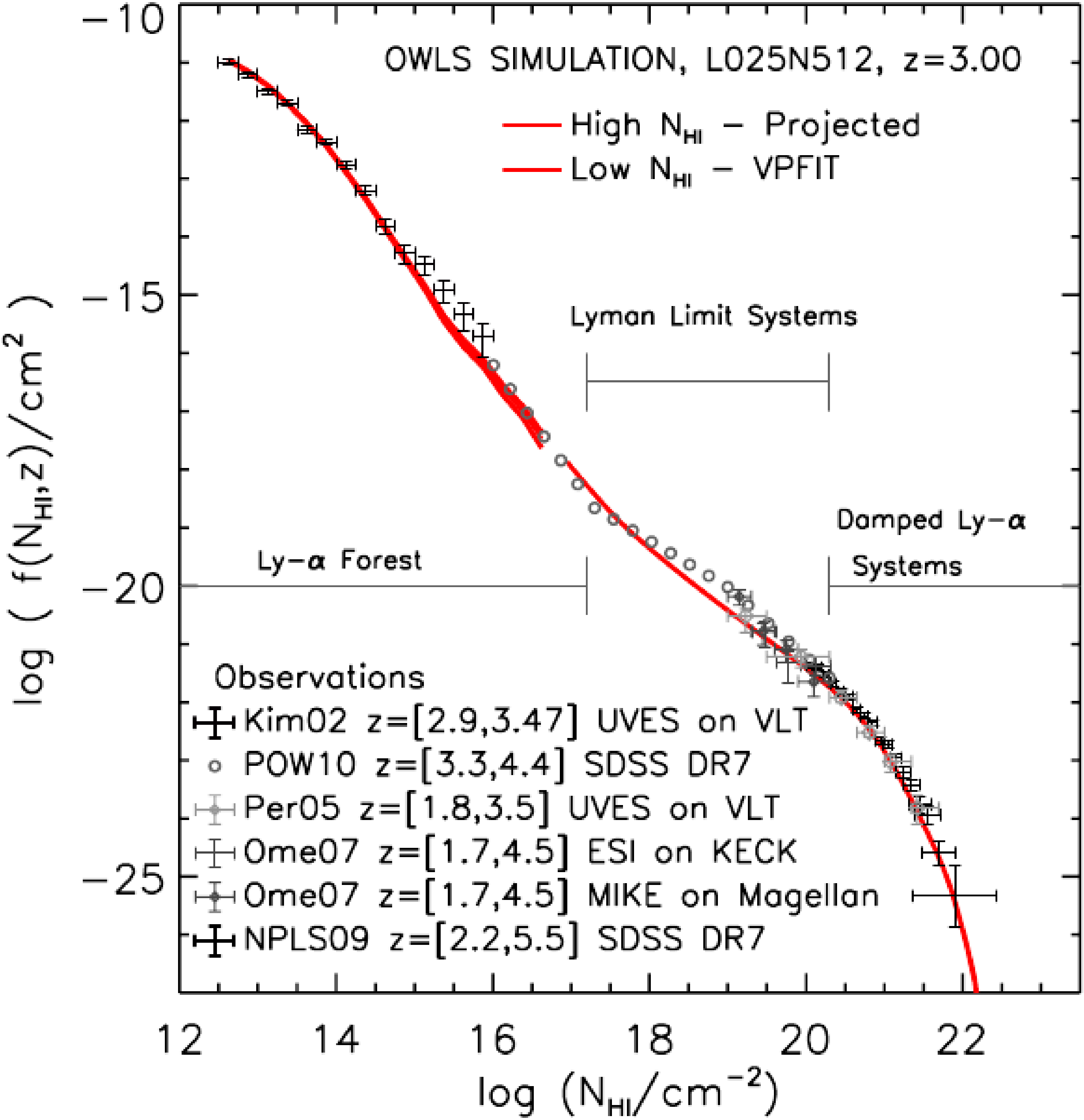


- Generate 1000 mock spectra
- Apply instrumental broadening w/ FWHM 6.6 km/s
- Add gaussian noise such that S/N = 50 in continuum
- Fit mock spectra w/ VPFIT (Carswell 87)

High NHI – Project Whole Box

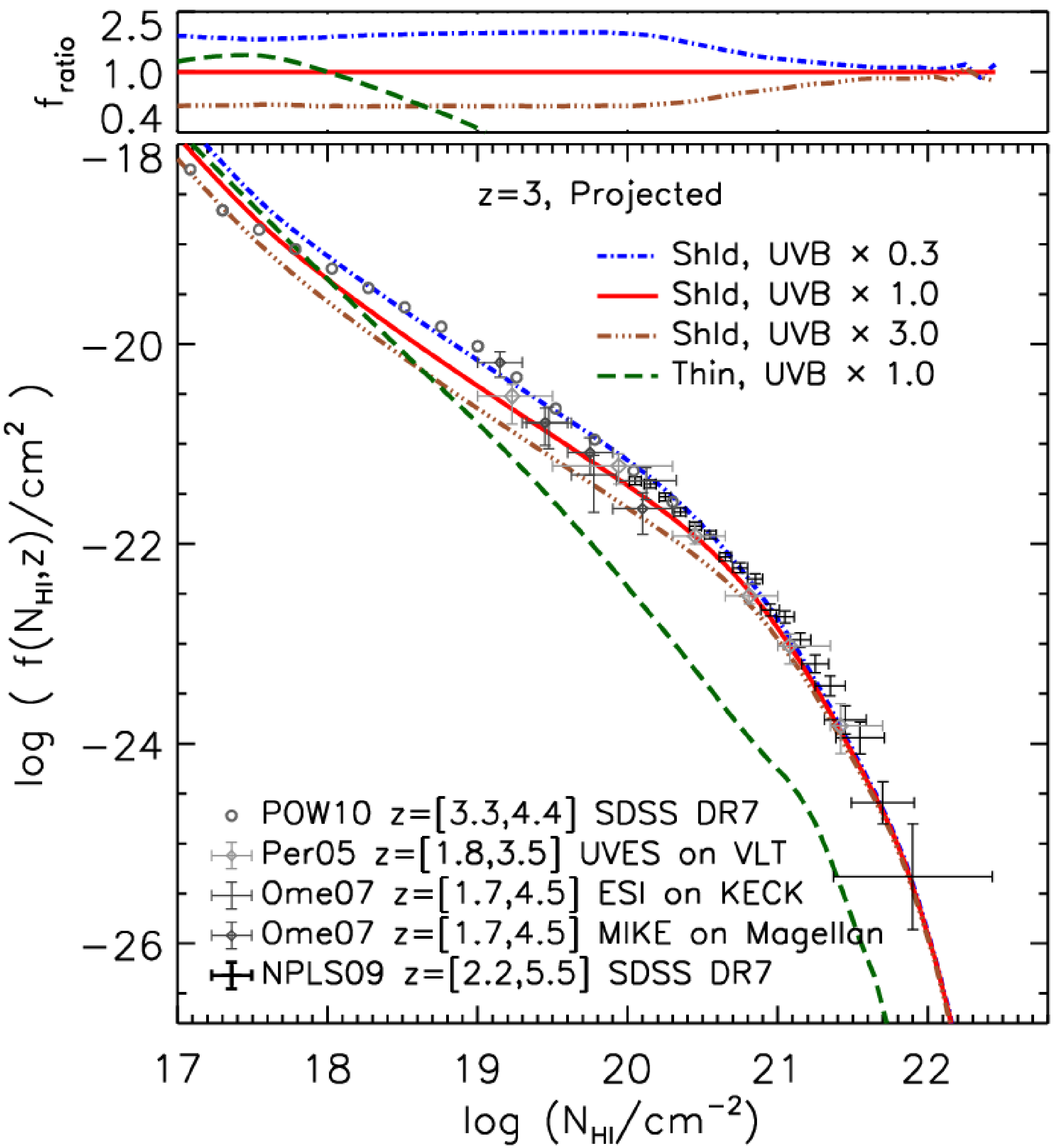


- 16,384 * 16,384 pixels.
- Use the fact that the typical sight line has much less than one absorber with log NHI >= 17.0
- Accounts for gas not in halos.
- Side benefit = very high resolution images of the simulation



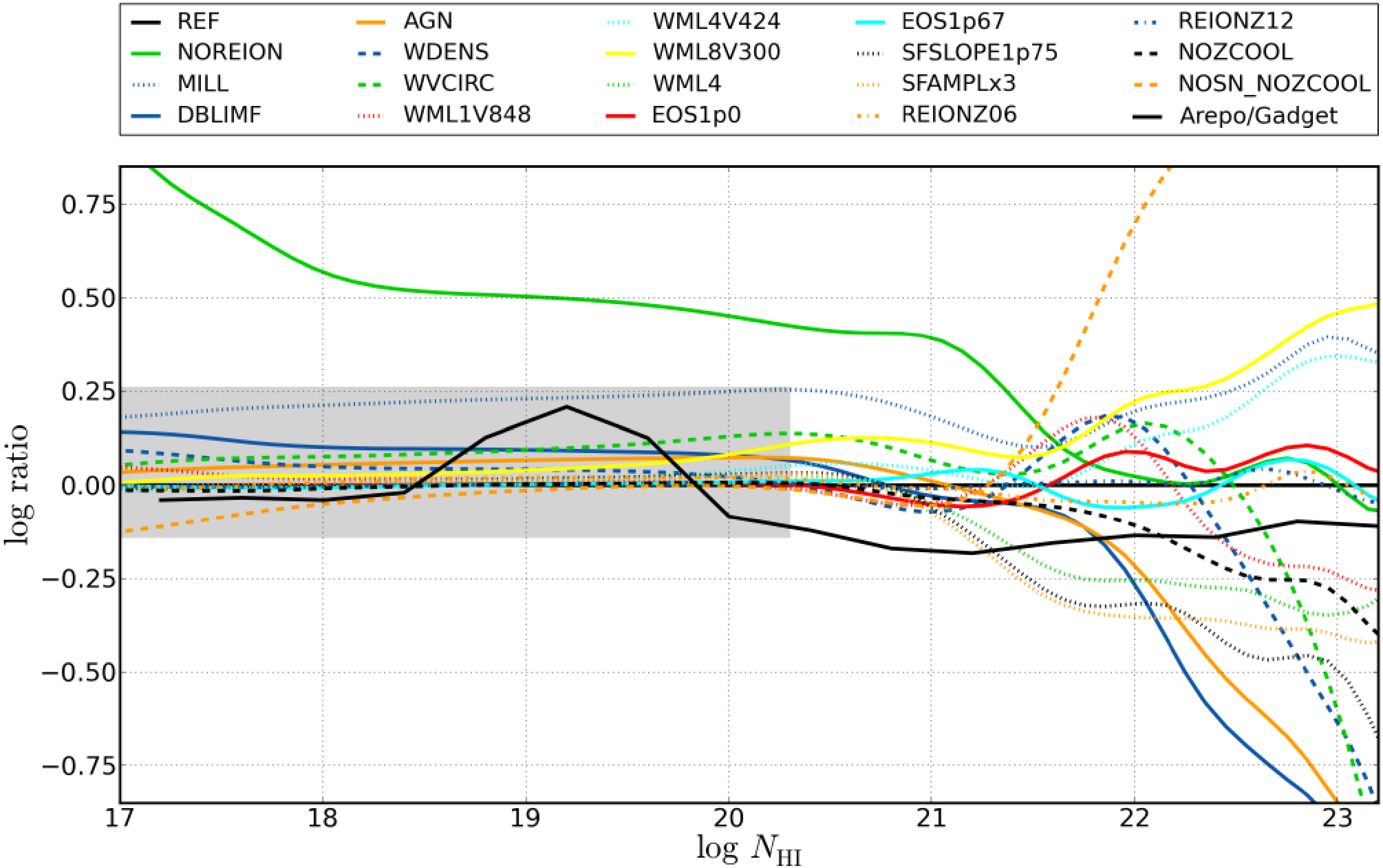
OWLS SIMULATION, L025N512, z=3.00
High N_{HI} – Projected
Low N_{HI} – VPFIT
Lyman Limit Systems
Damped Ly-α Systems
Ly-α Forest
Observations
Kim02 z=[2.9,3.47] UVES on VLT
POW10 z=[3.3,4.4] SDSS DR7
Per05 z=[1.8,3.5] UVES on VLT
Ome07 z=[1.7,4.5] ESI on KECK
Ome07 z=[1.7,4.5] MIKE on Magellan
NPLS09 z=[2.2,5.5] SDSS DR7
log (f(N_{HI},z)/cm^2)
log (N_{HI}/cm^{-2})
−10
−15
−20
−25
12
14
16
18
20
22

Large Improvement over Thin UVB



- UV Normalization has linear effect below log NHI ~ 20
- Γ_{12} = 1.2 */ 3
- Optically thin approx. breaks down around log N_HI = 18.0

Performed on Many OWLS Models



Conclusions

Lots of HI data coming
Need better modeling of UV Background
Urchin is one answer
(go backwards to go forwards)
OWLS + Urchin can match f(N,X) over 10 dex
LLS robust to subgrid physics
DLA sensitive to subgrid physics