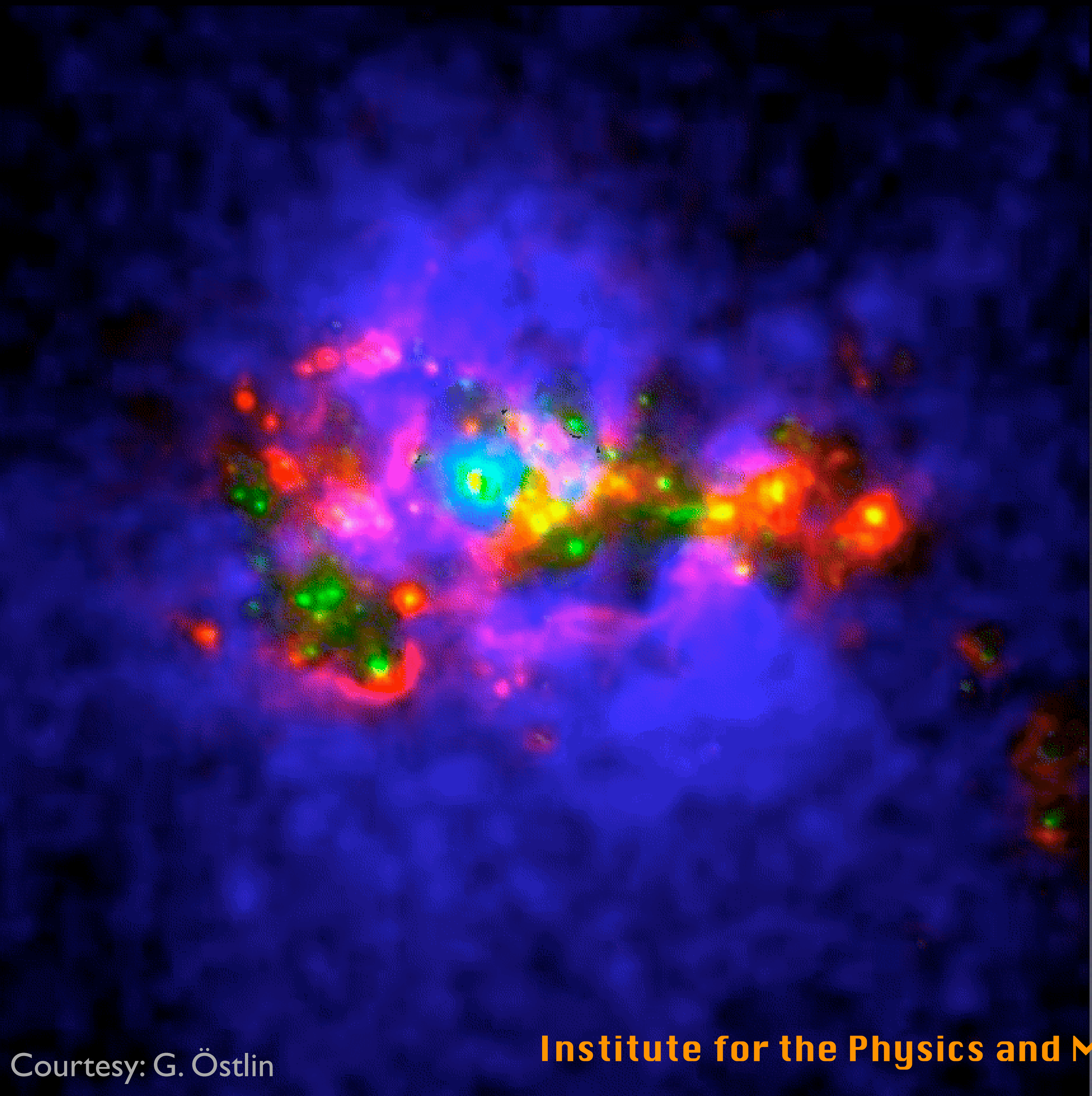
Radiative Transfer Modeling of Lyman-alpha Emitters and New Effects in Galaxy Clustering



Courtesy: G. Östlin

Zheng Zheng (郑政)

Yale Center for Astronomy and Astrophysics

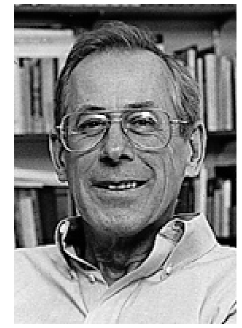
Renyue Cen (Princeton)
Hy Trac (CfA)
Jordi Miralda-Escudé (ICREA/UB)

I. Statistics of spectra & luminosity (arXiv:0910.2712)
II. Clustering properties (arXiv:1003.4990)

Institute for the Physics and Mathematics of the Universe July 27, 2010

ARE YOUNG GALAXIES VISIBLE?

R. B. Partridge and P. J. E. Peebles
Palmer Physical Laboratory, Princeton University
Received August 5, 1966; revised September 8, 1966



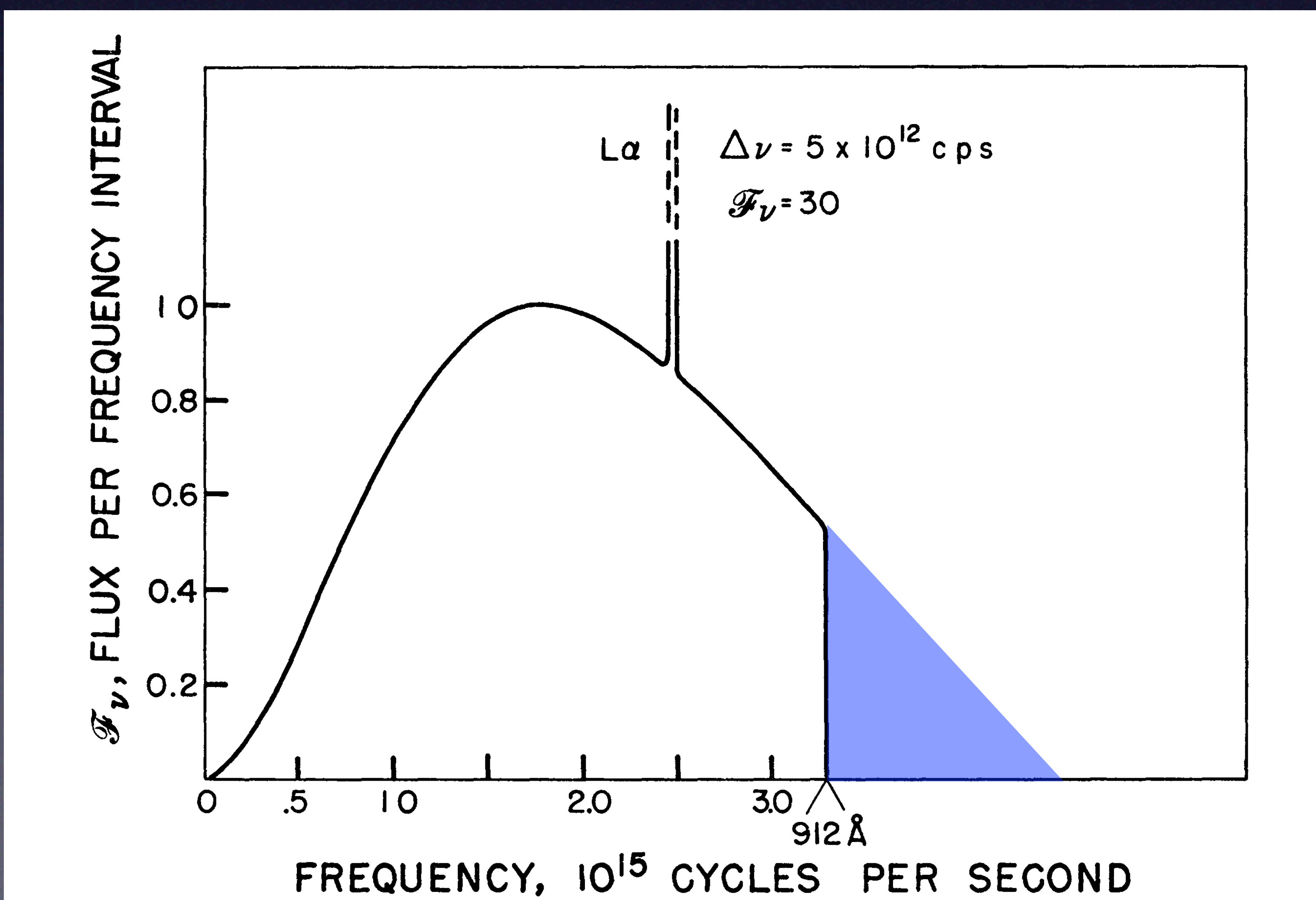
ABSTRACT

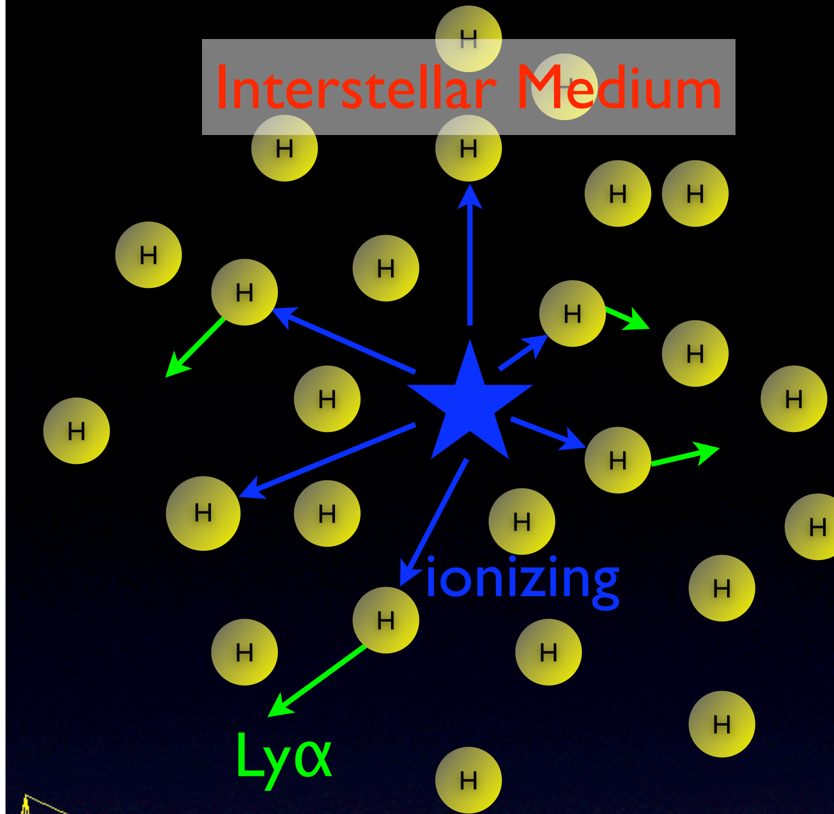
The purpose of this paper is to assess the general possibility of observing distant, newly formed galaxies. To this end a simple model of galaxy formation is introduced. According to the model galaxies should go through a phase of high luminosity in early stages of their evolution. The estimated luminosity for a galaxy resembling our own is $\sim 3 \times 10^{46}$ ergs/sec, roughly 700 times higher than the present luminosity. The bright phase would occur at an epoch of about 1.5×10^8 years, corresponding to a redshift between 10 and 30, depending on the cosmological model assumed.

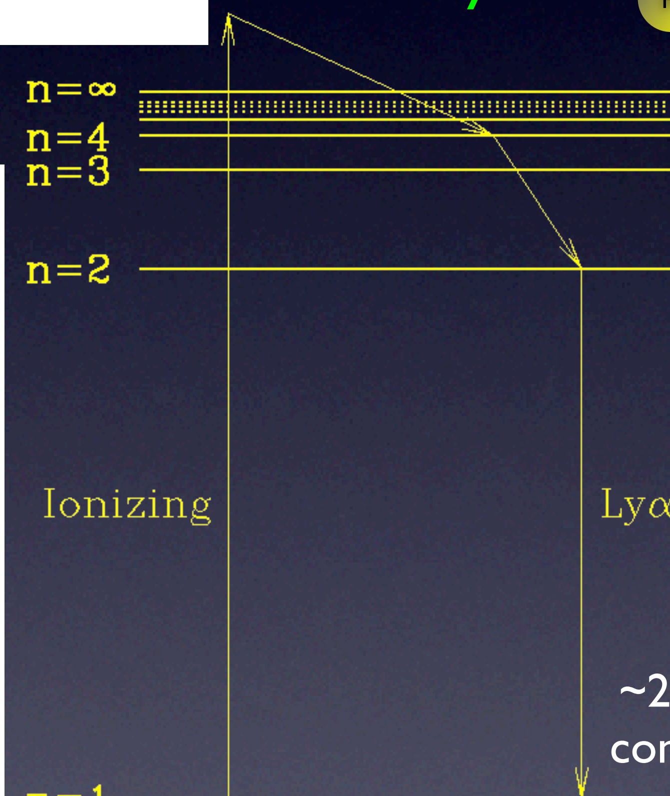
The possibility of detecting individual young galaxies against the background of the night sky is discussed. Although the young galaxies would be numerous and would have sufficiently large angular diameters to be easily resolved, most of the radiation from the young galaxies would arrive at wavelengths of 1–3 μ where detection is difficult. However, it seems possible that the Lyman-α line might be detected if it is a strong feature of the spectra of young galaxies.

It is also shown how such an experiment might help us to distinguish between various cosmological models.

Partridge & Peebles 1967







~2/3 ionizing photons are converted to Lyα photons

Lyα Luminosity ∝ Star Formation Rate

Successful detections happened ~30 years after the prediction.

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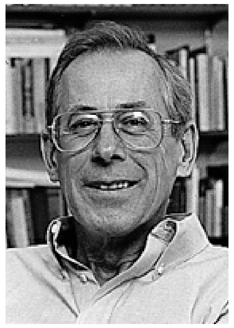

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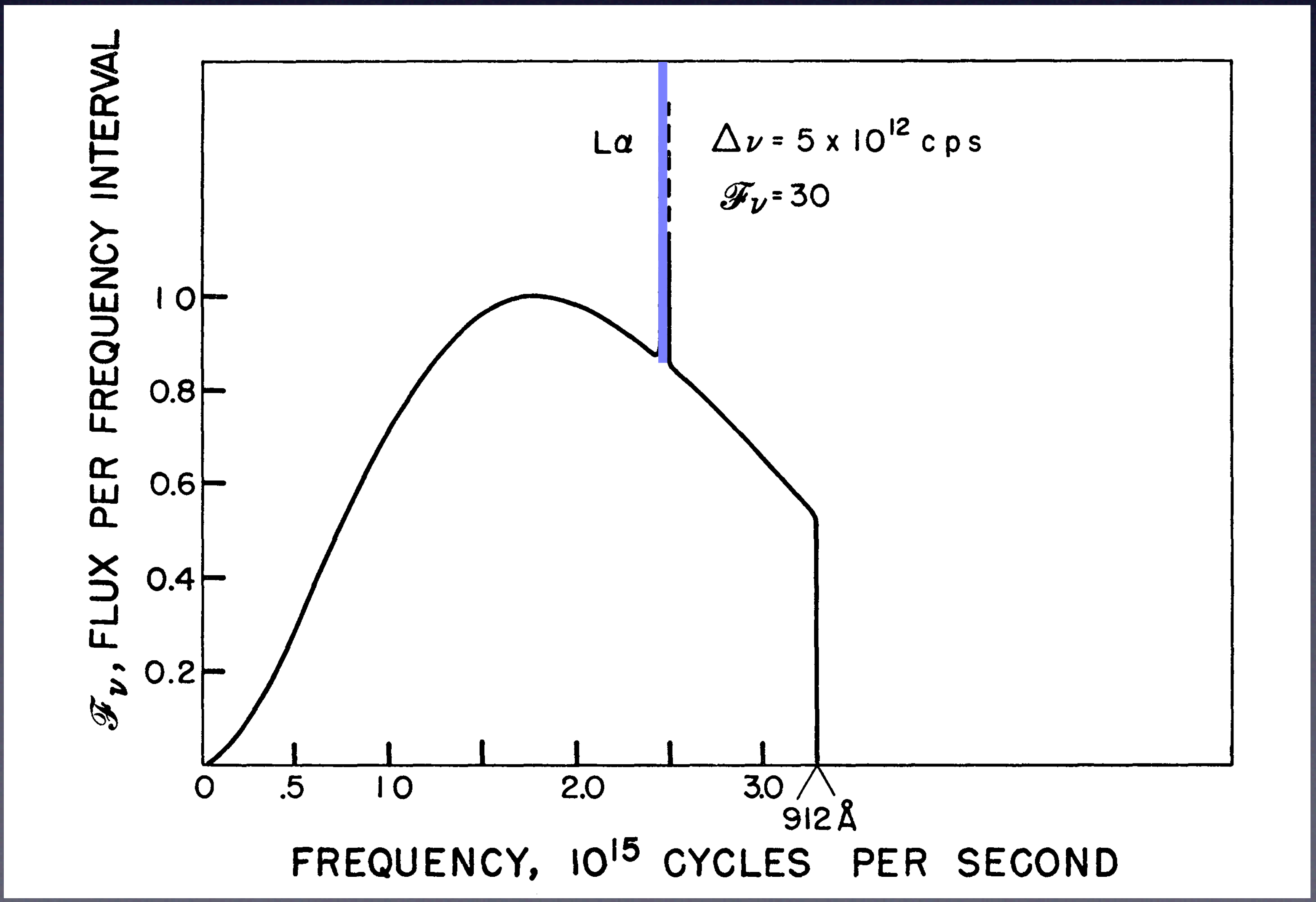

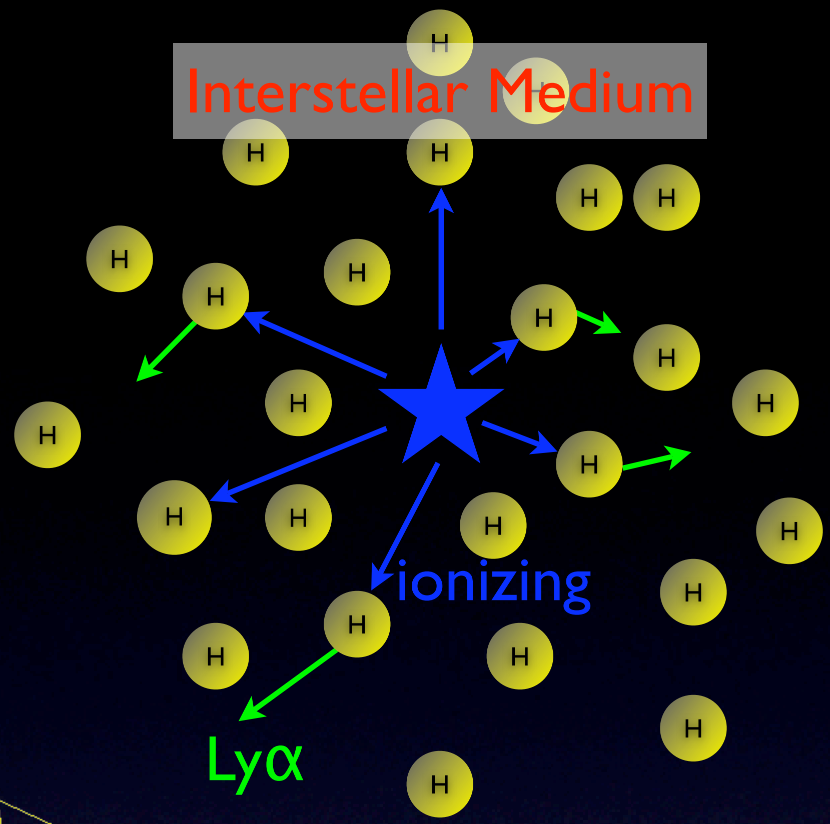

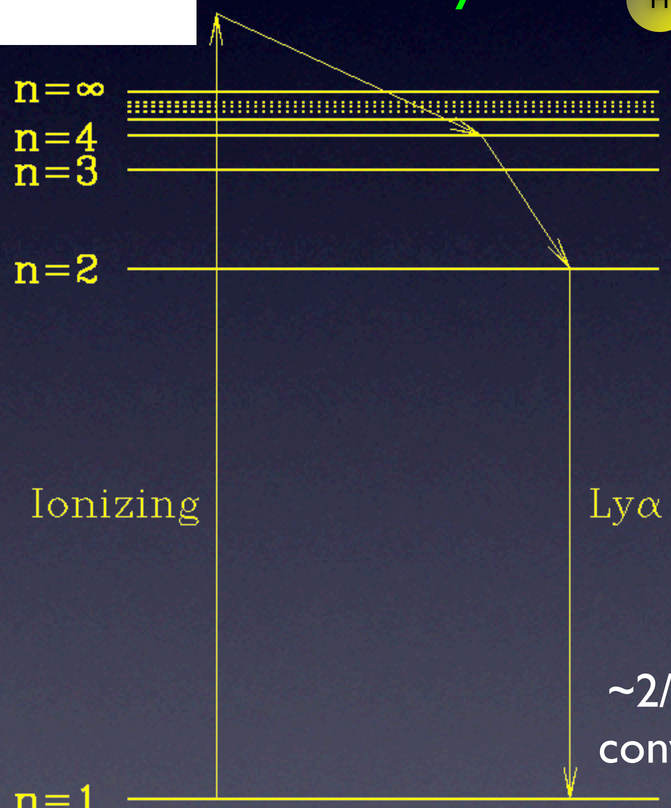

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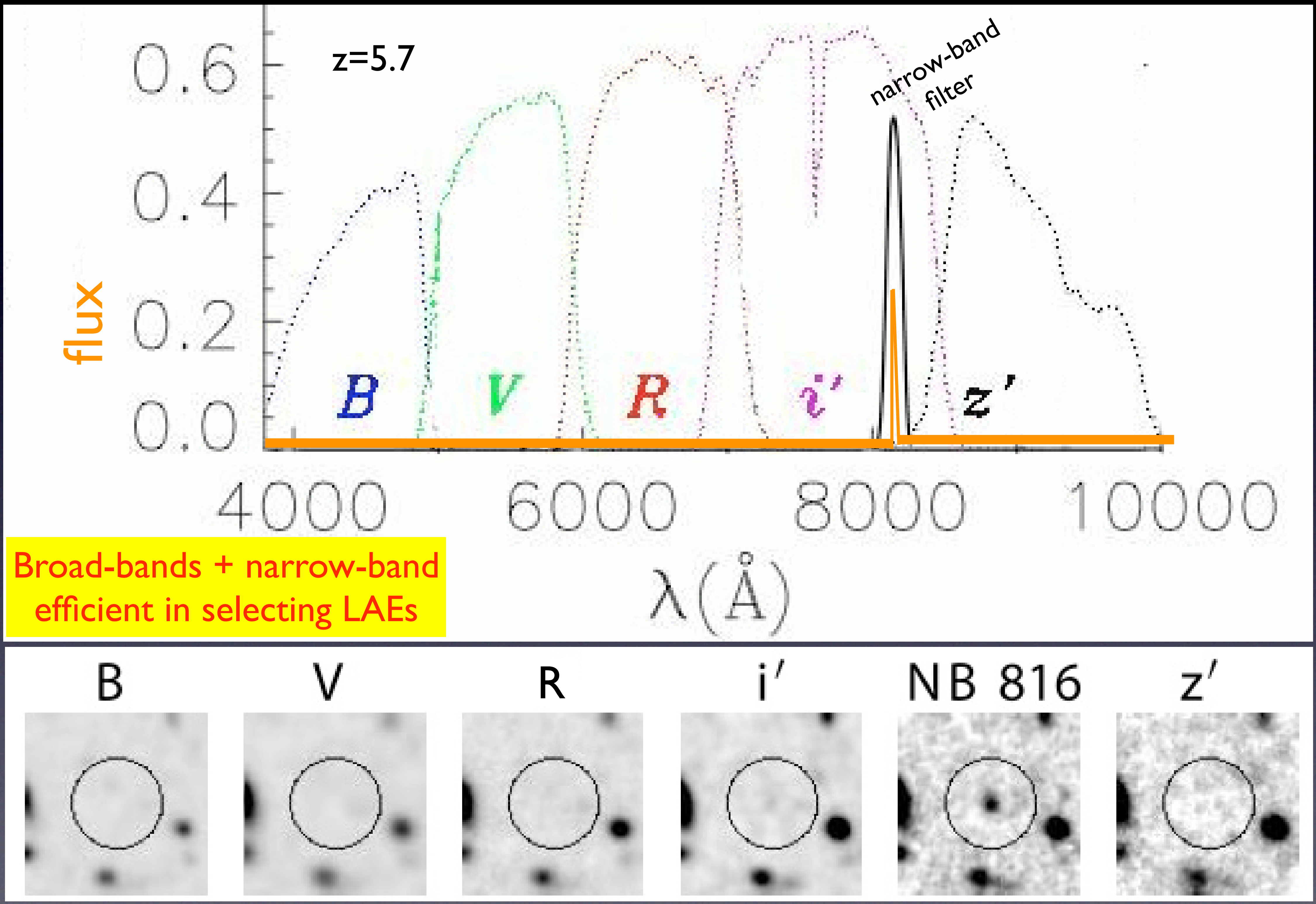
Searching for High Redshift Galaxies

Narrow-band technique: Lyman-alpha Emitters (LAEs)

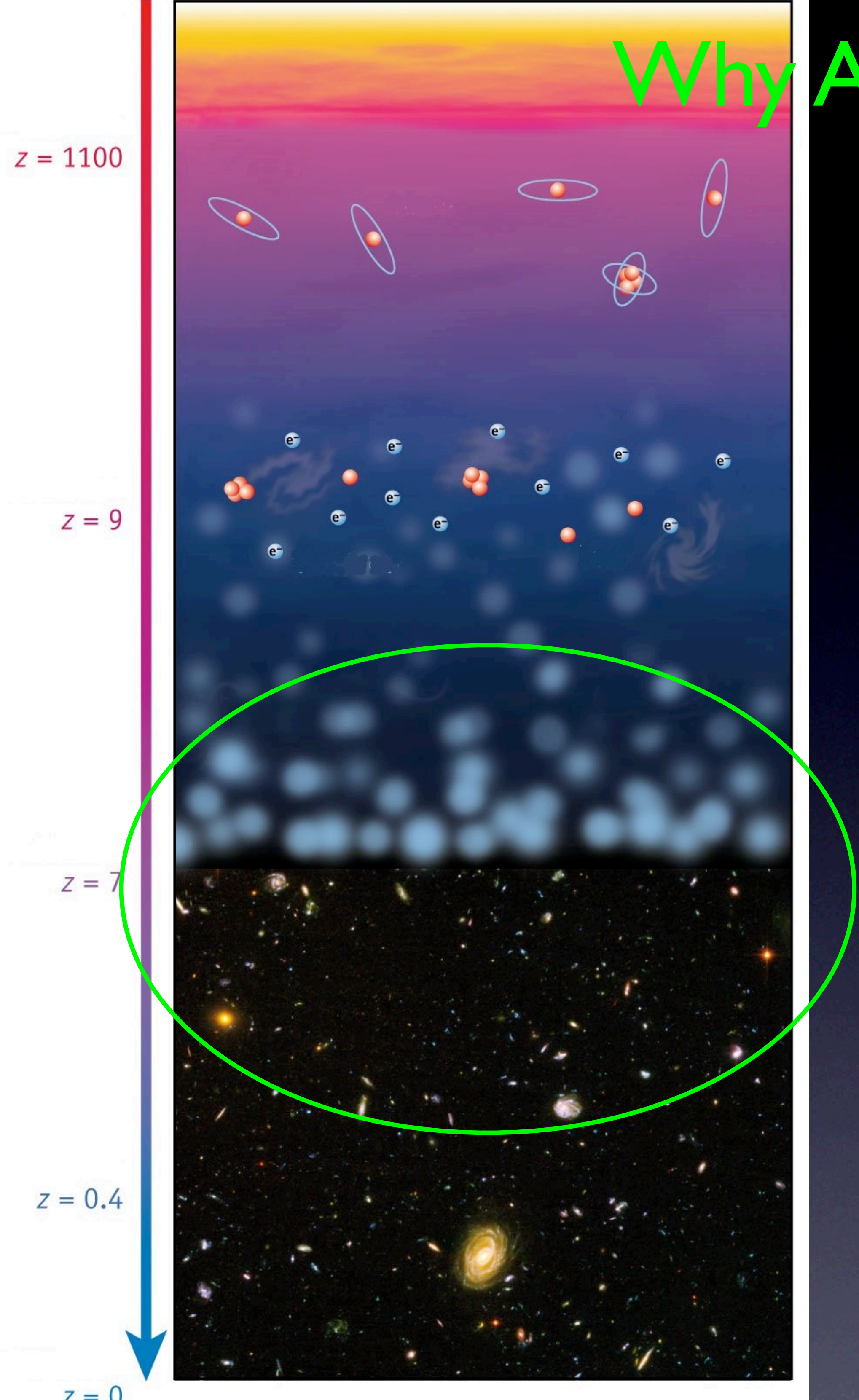


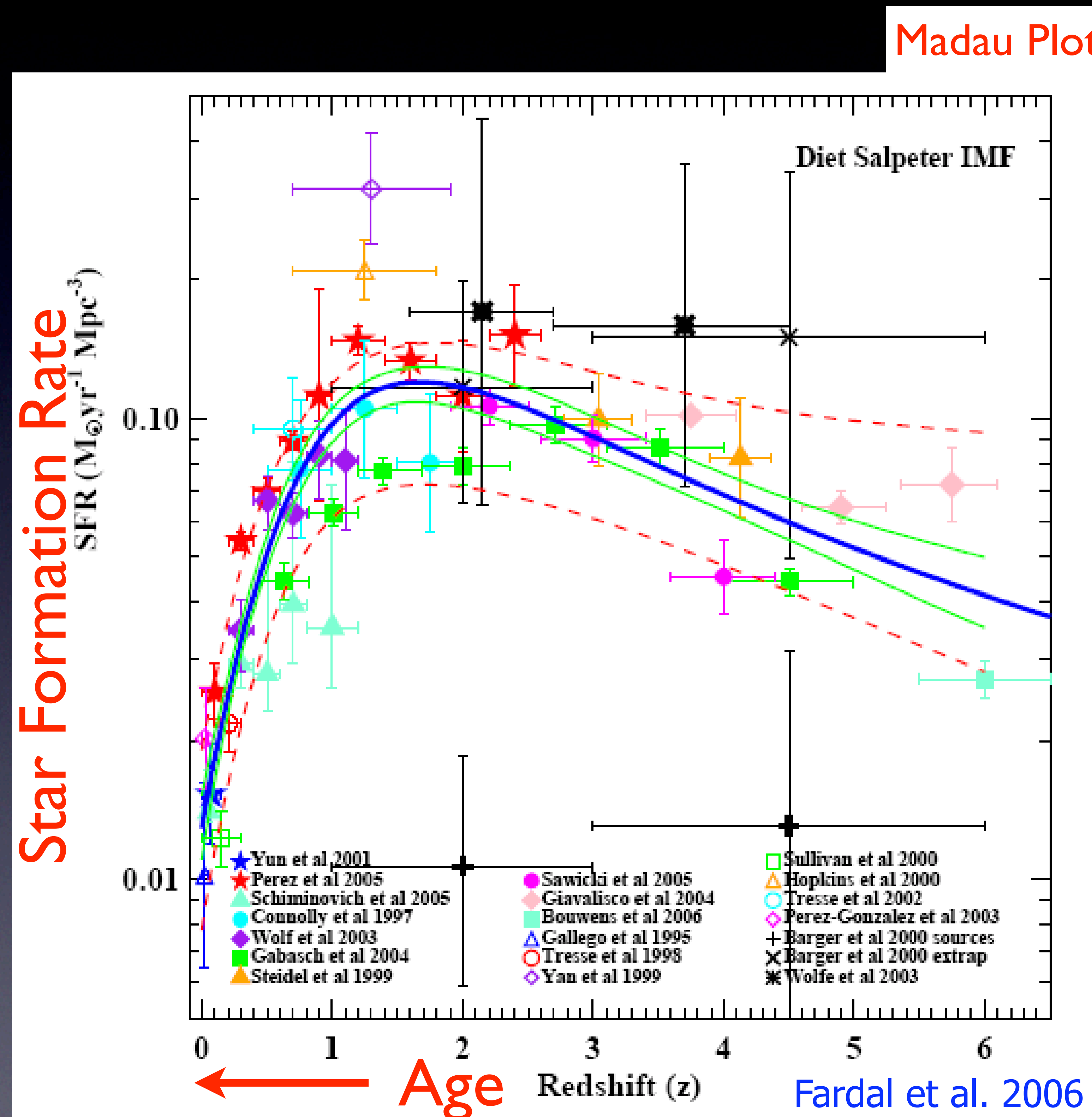
Broad-bands + narrow-band efficient in selecting LAEs

Ouchi et al. 2003, 2008

Why Are Lyman-alpha Emitters Interesting?

- study of young star-forming galaxies





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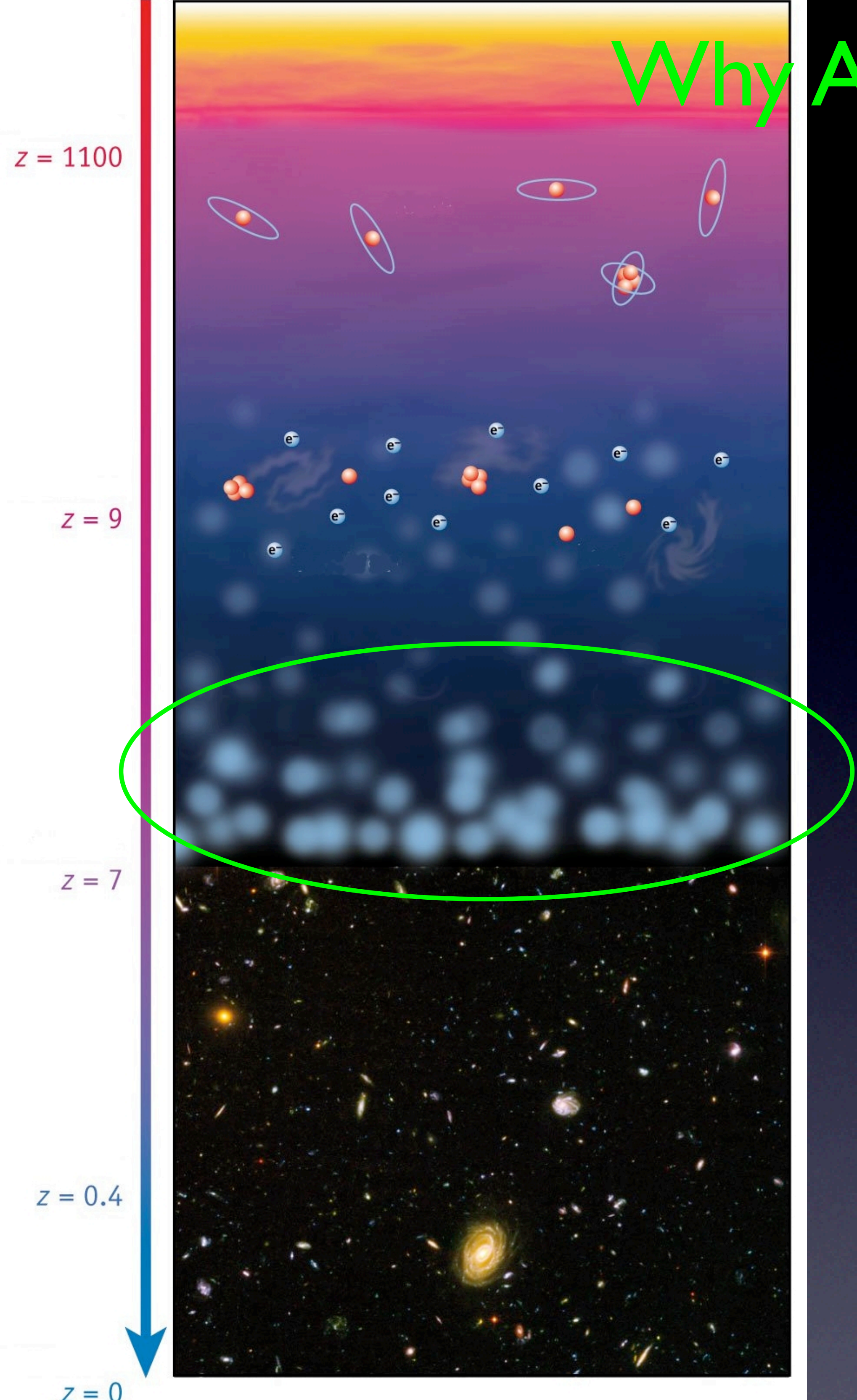

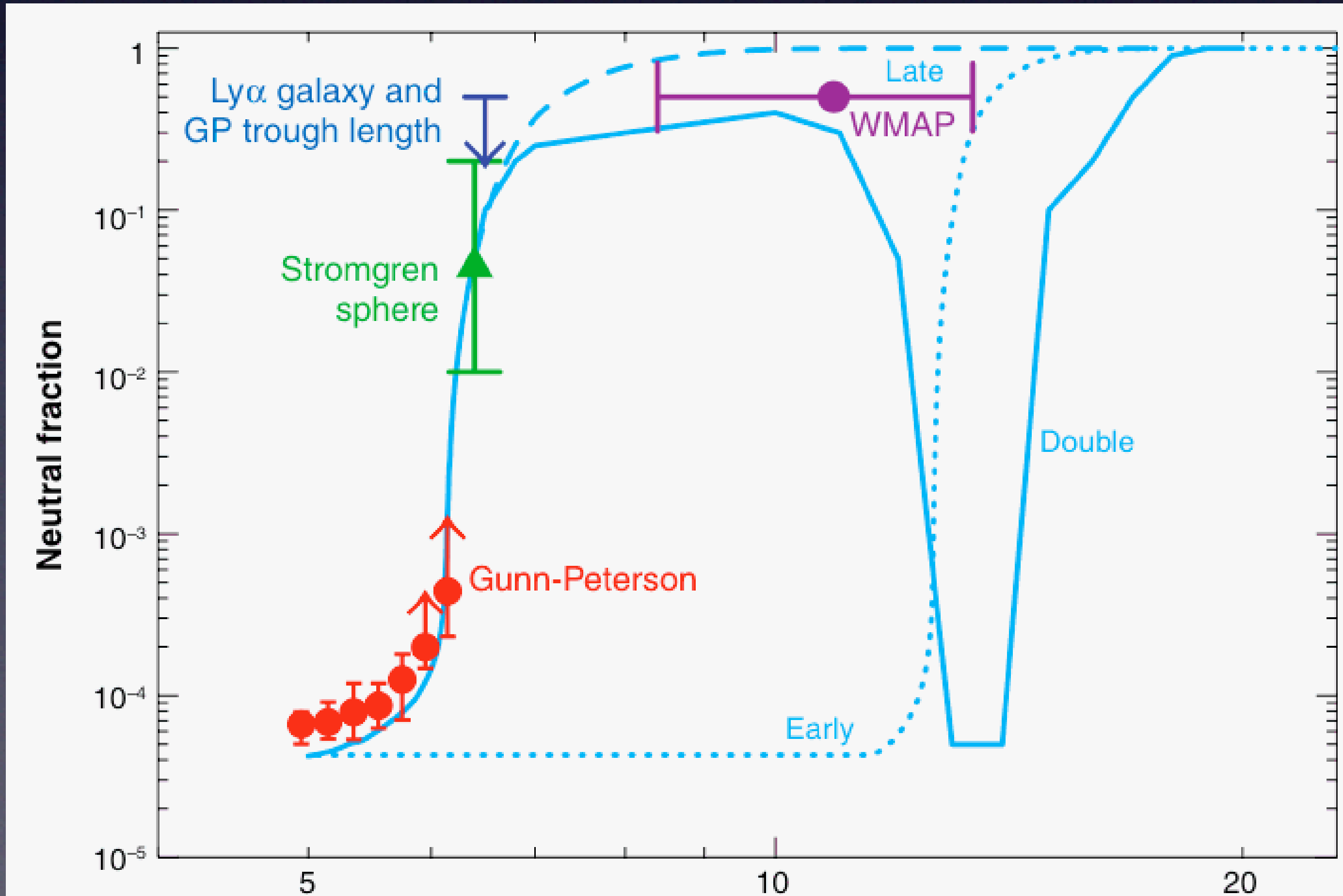

Fan, Carilli, & Keating 2006

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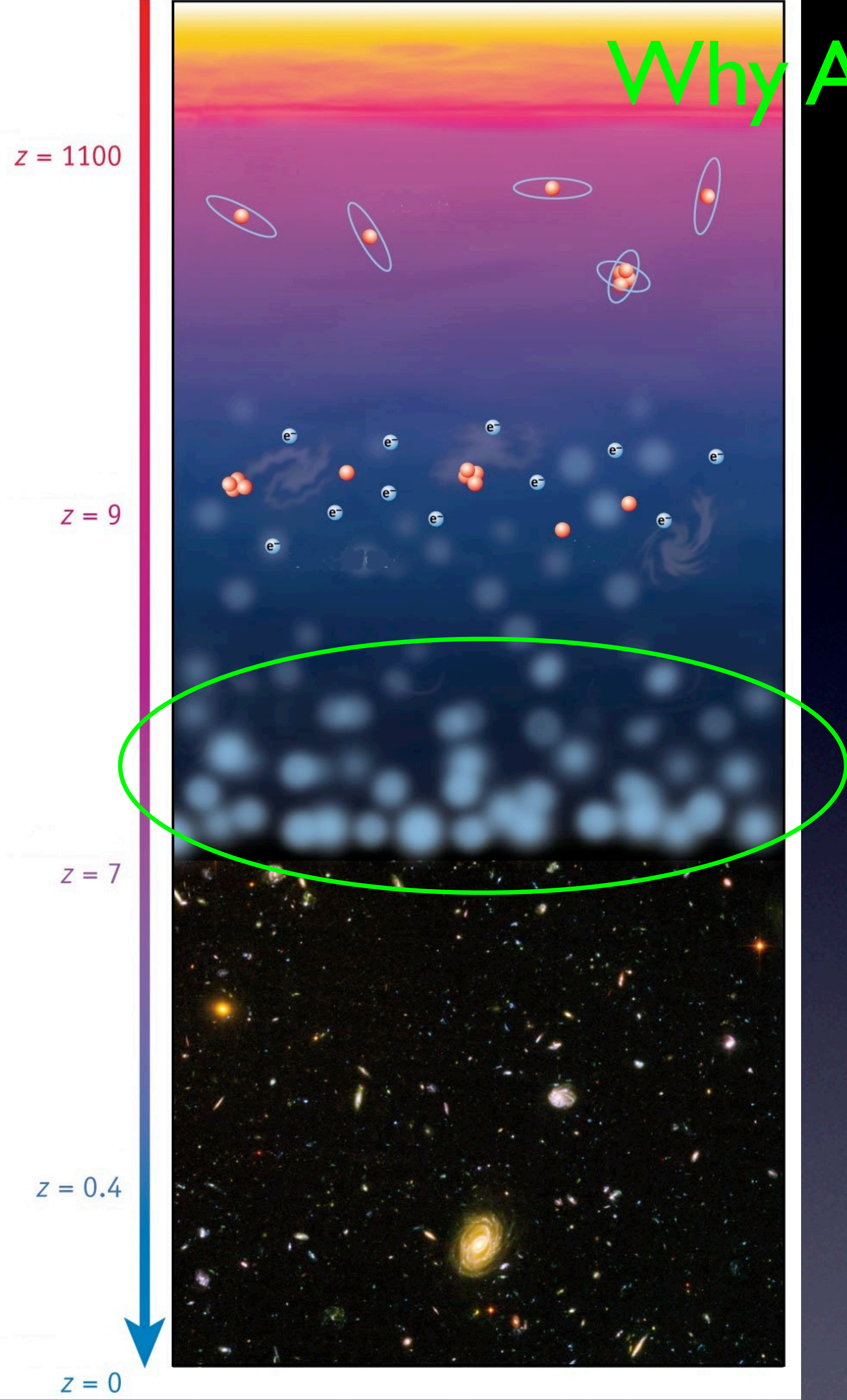

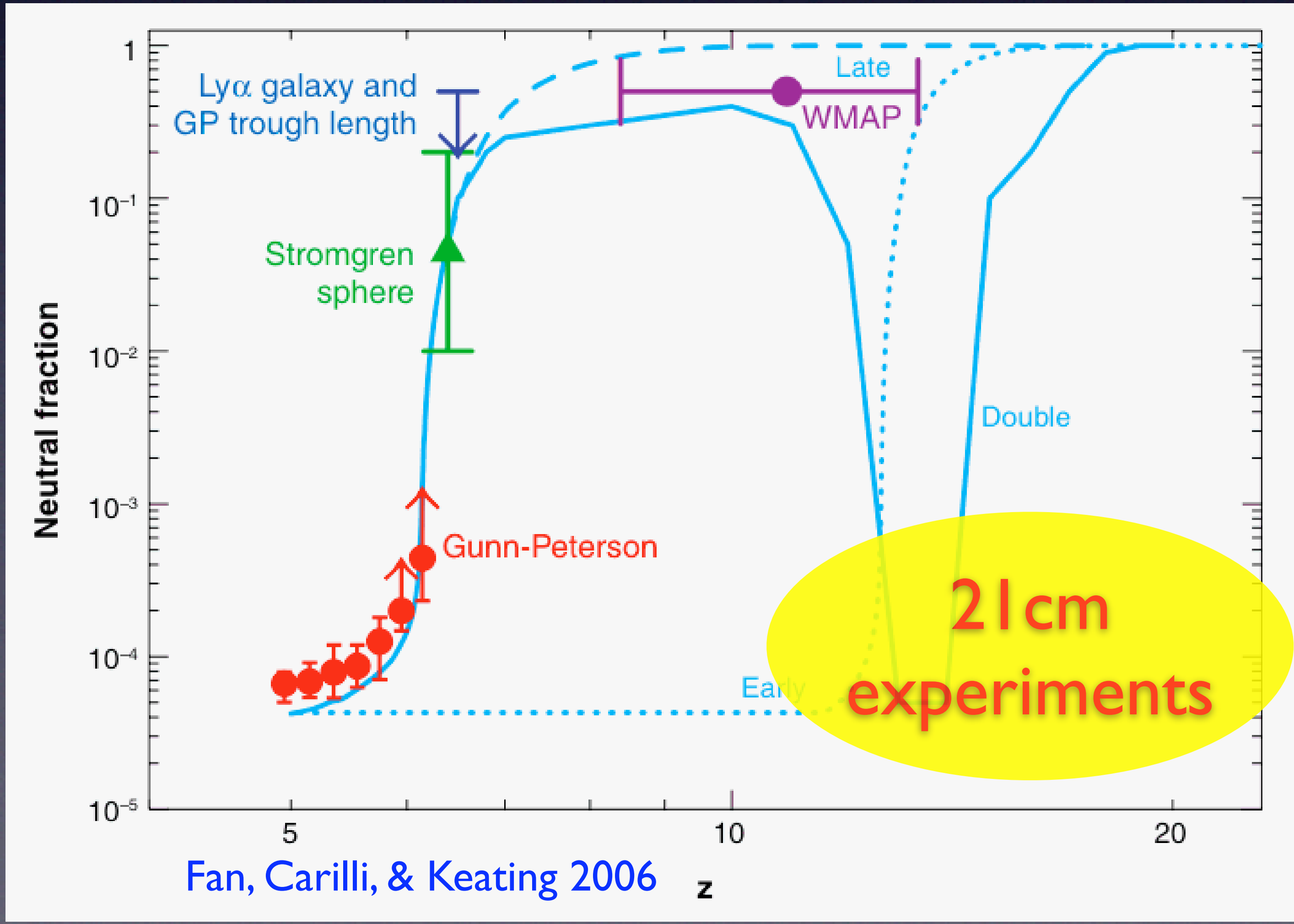

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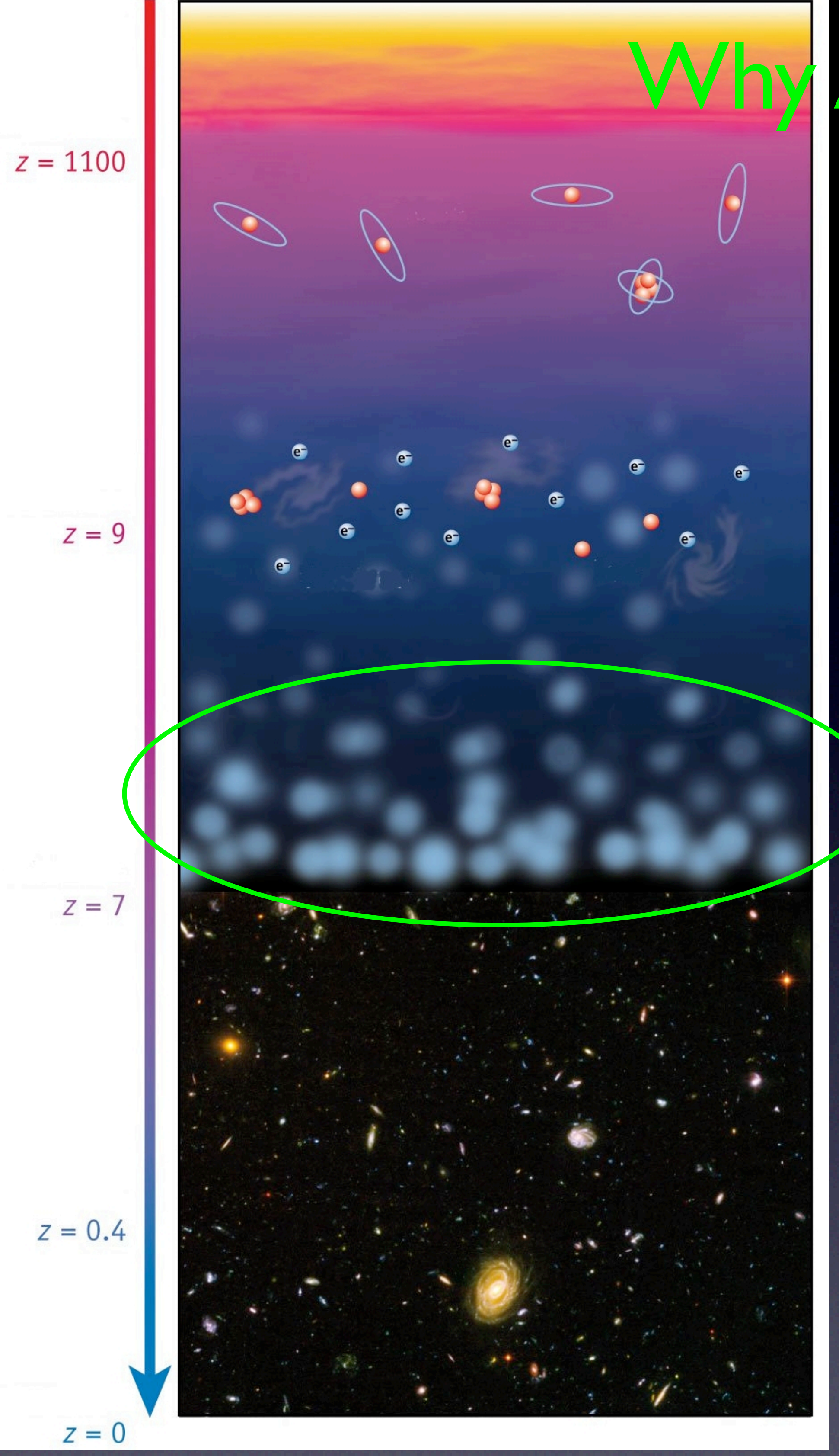

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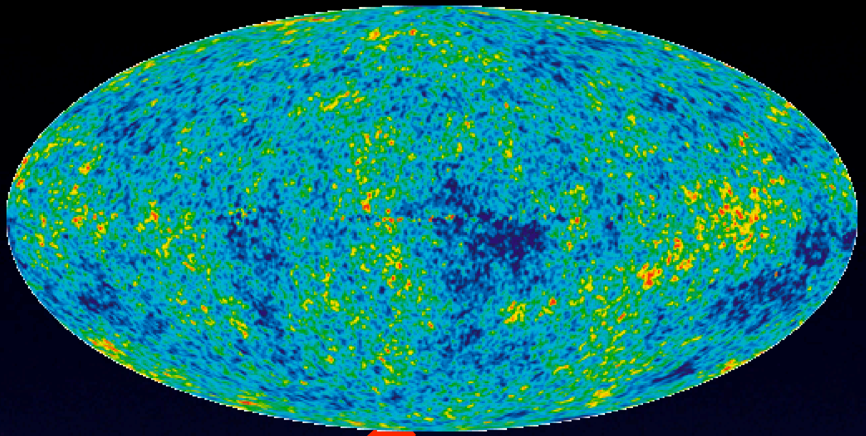

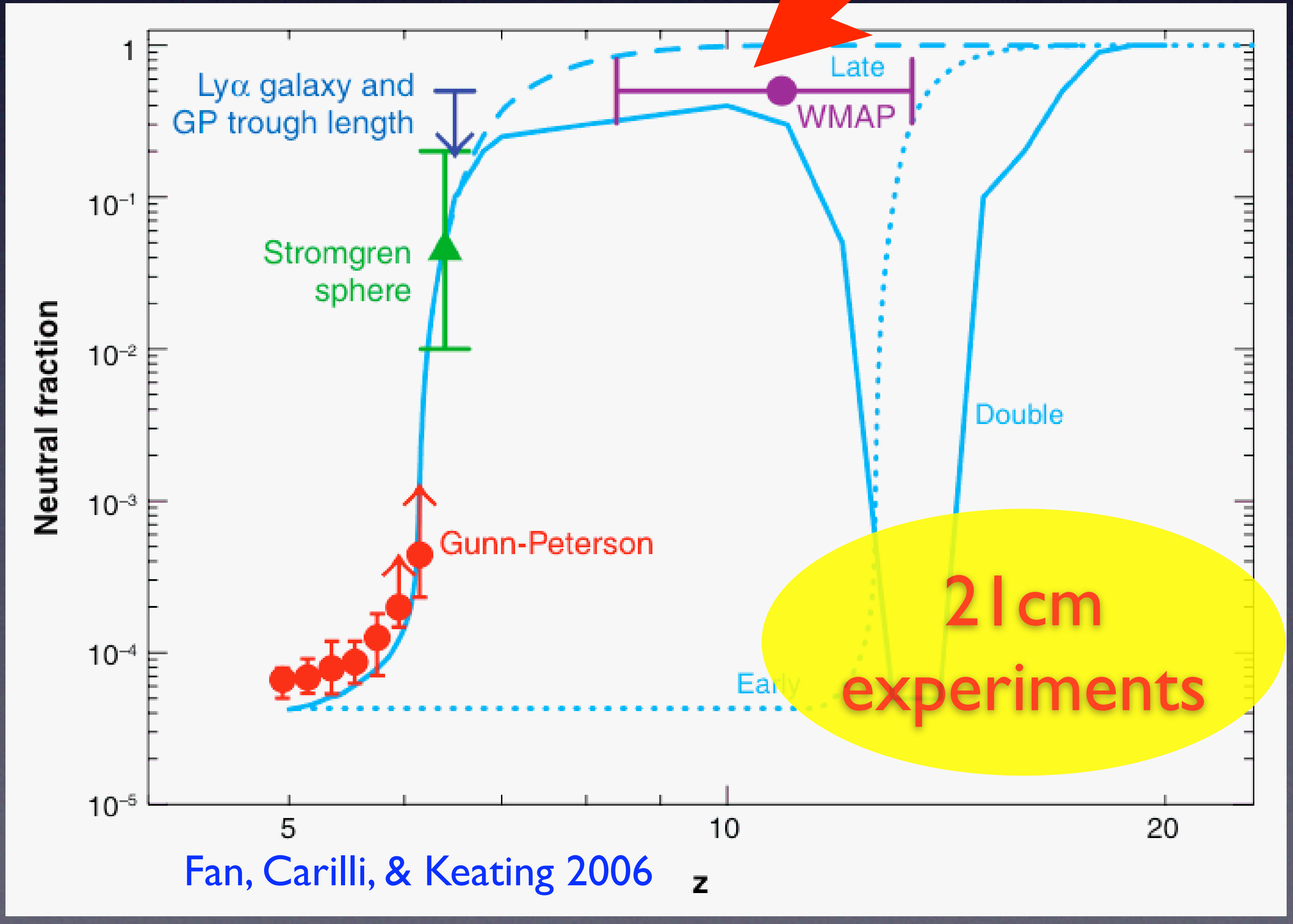

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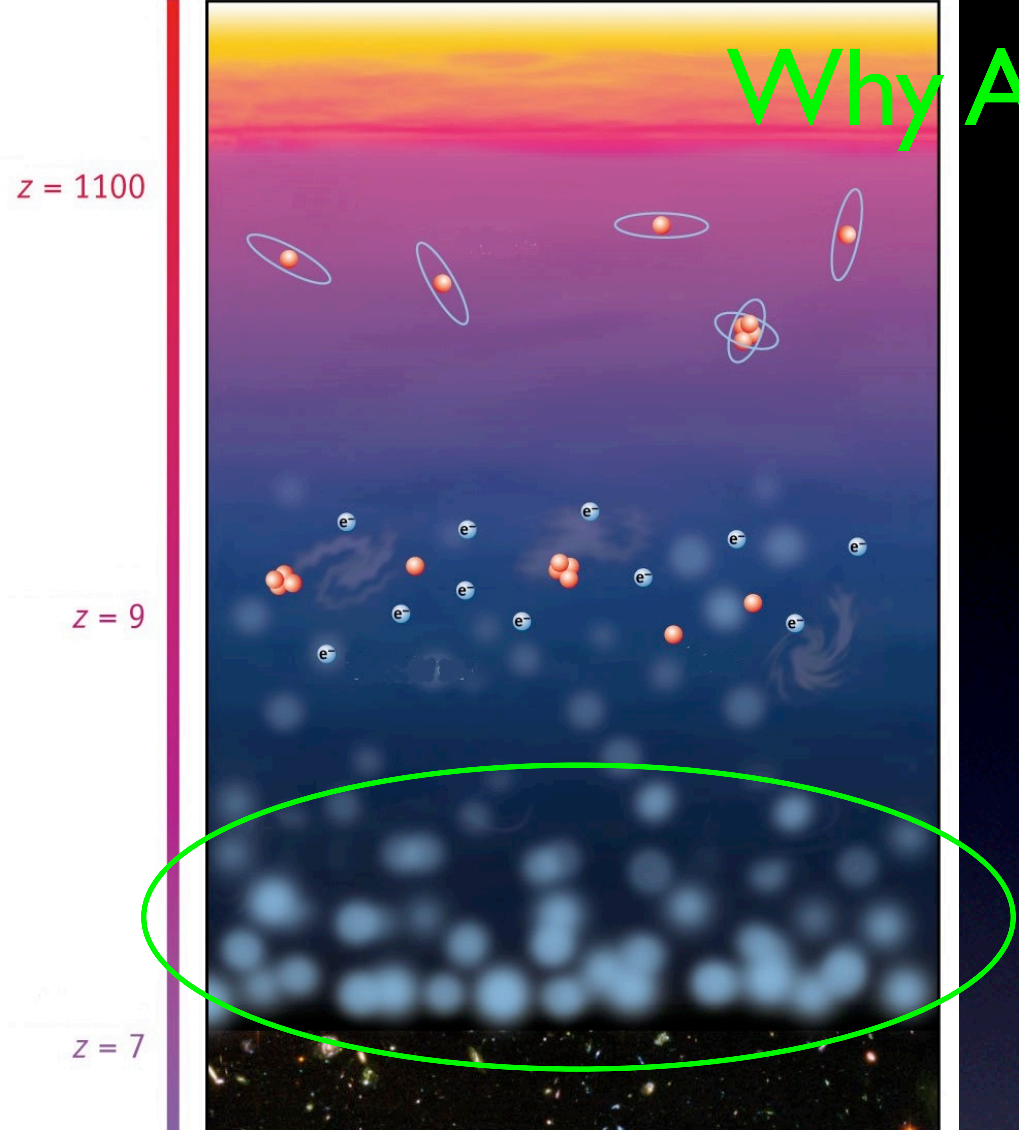

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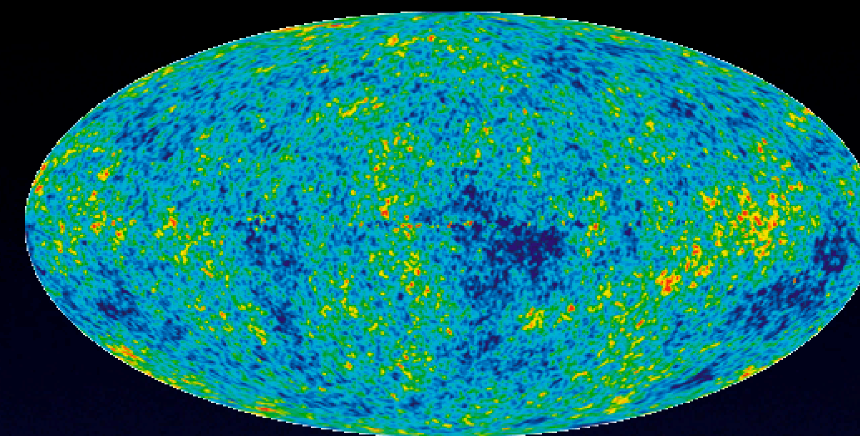

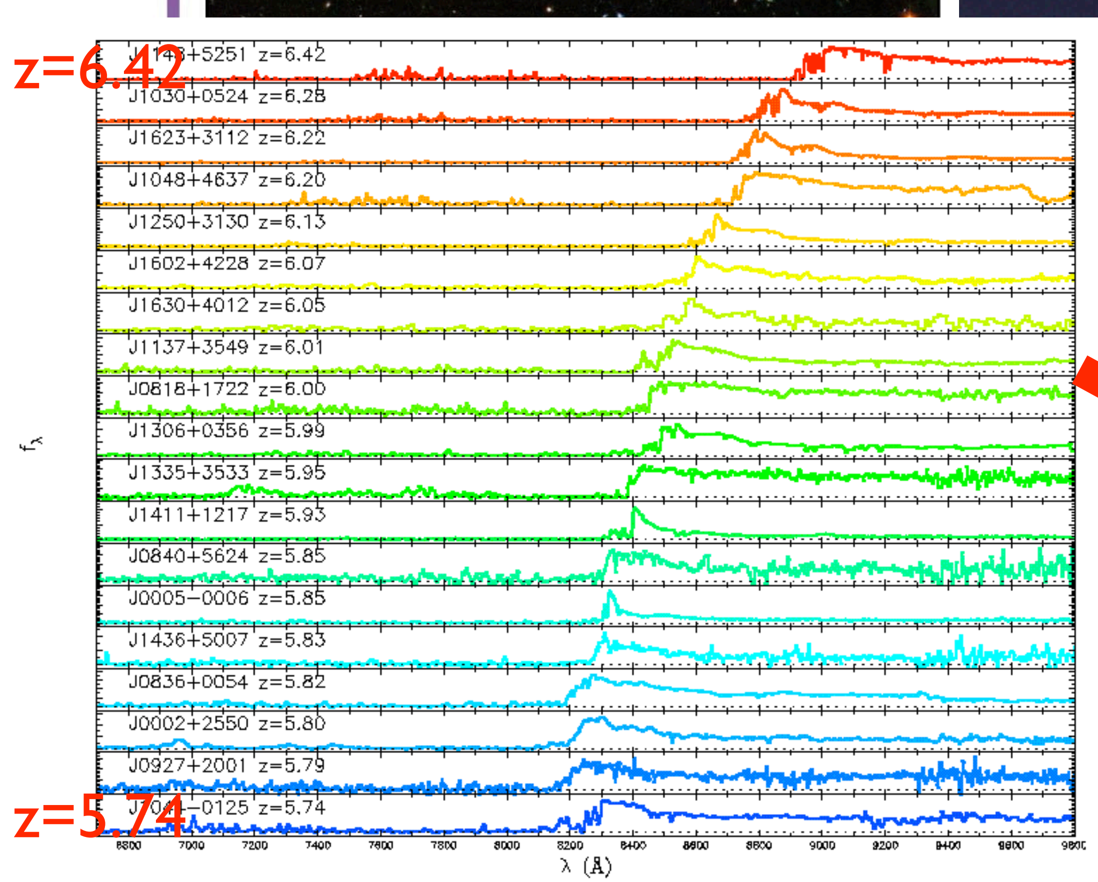

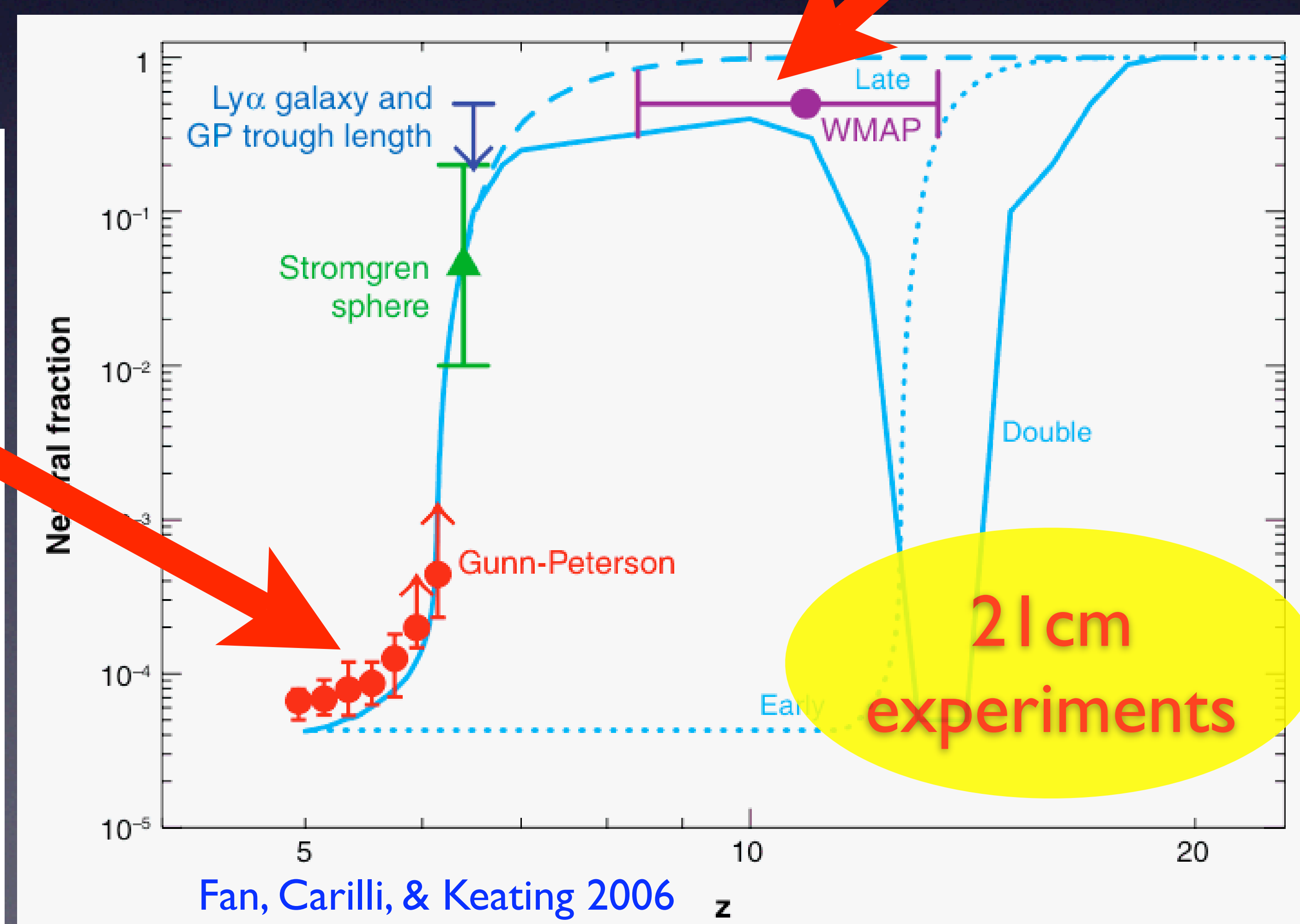

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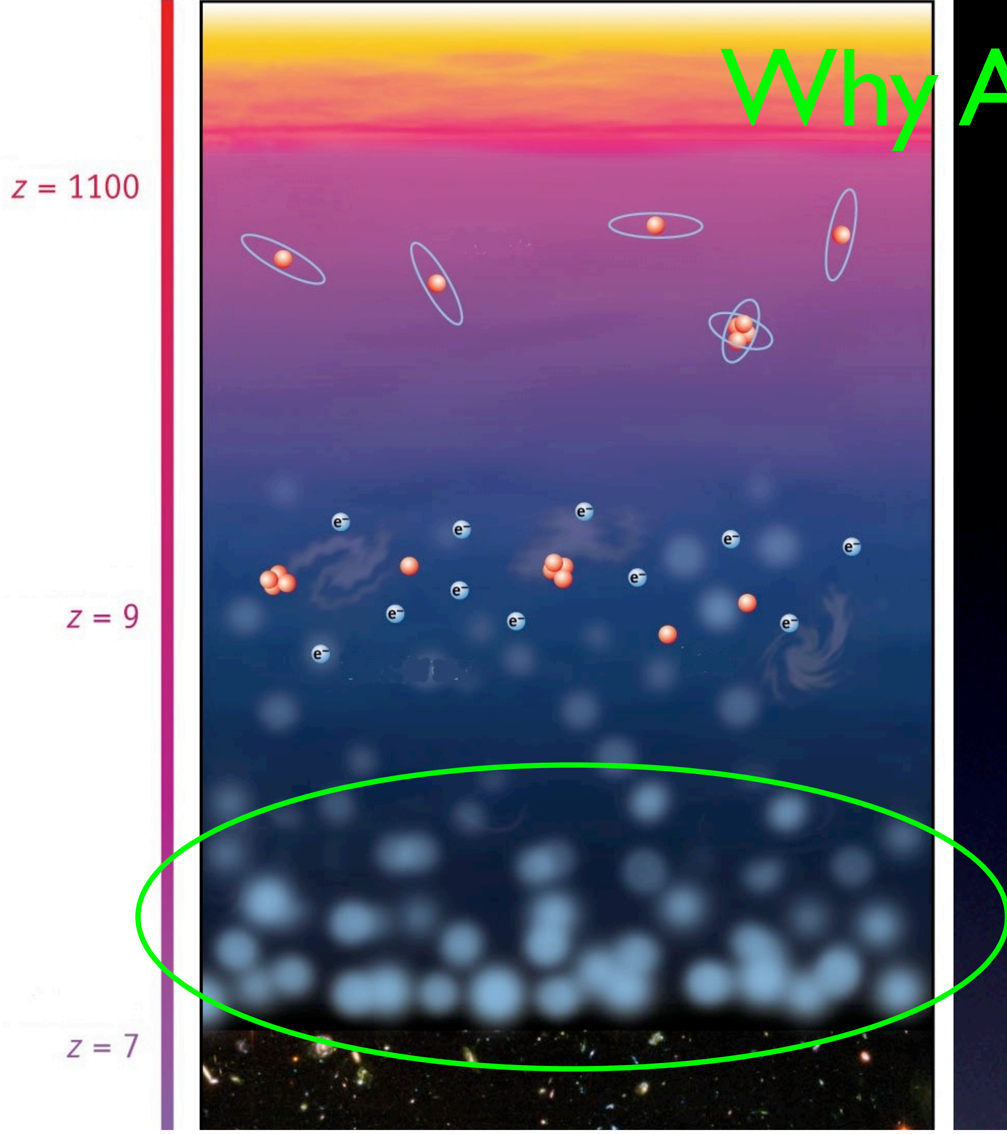
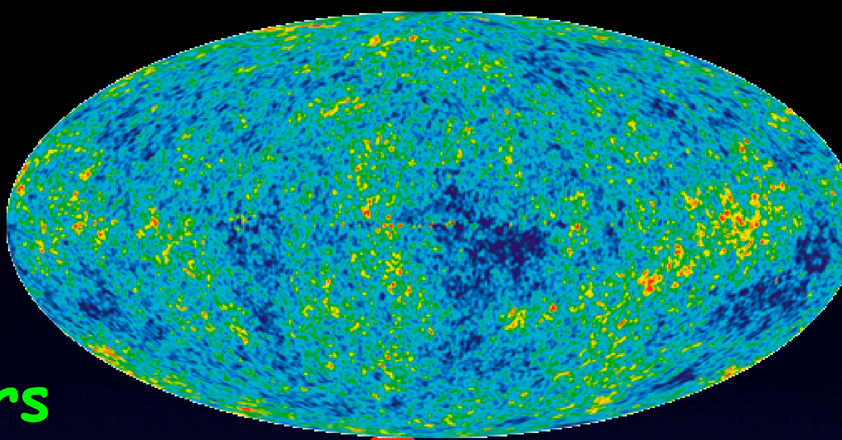
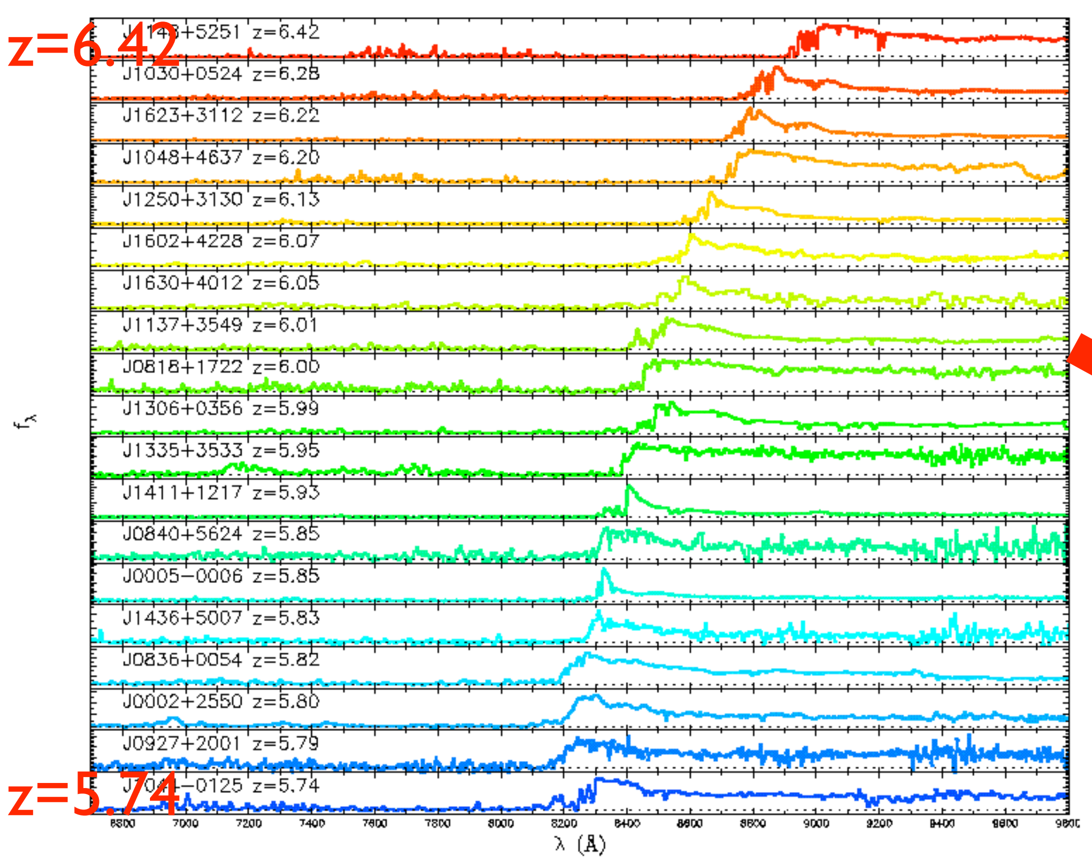
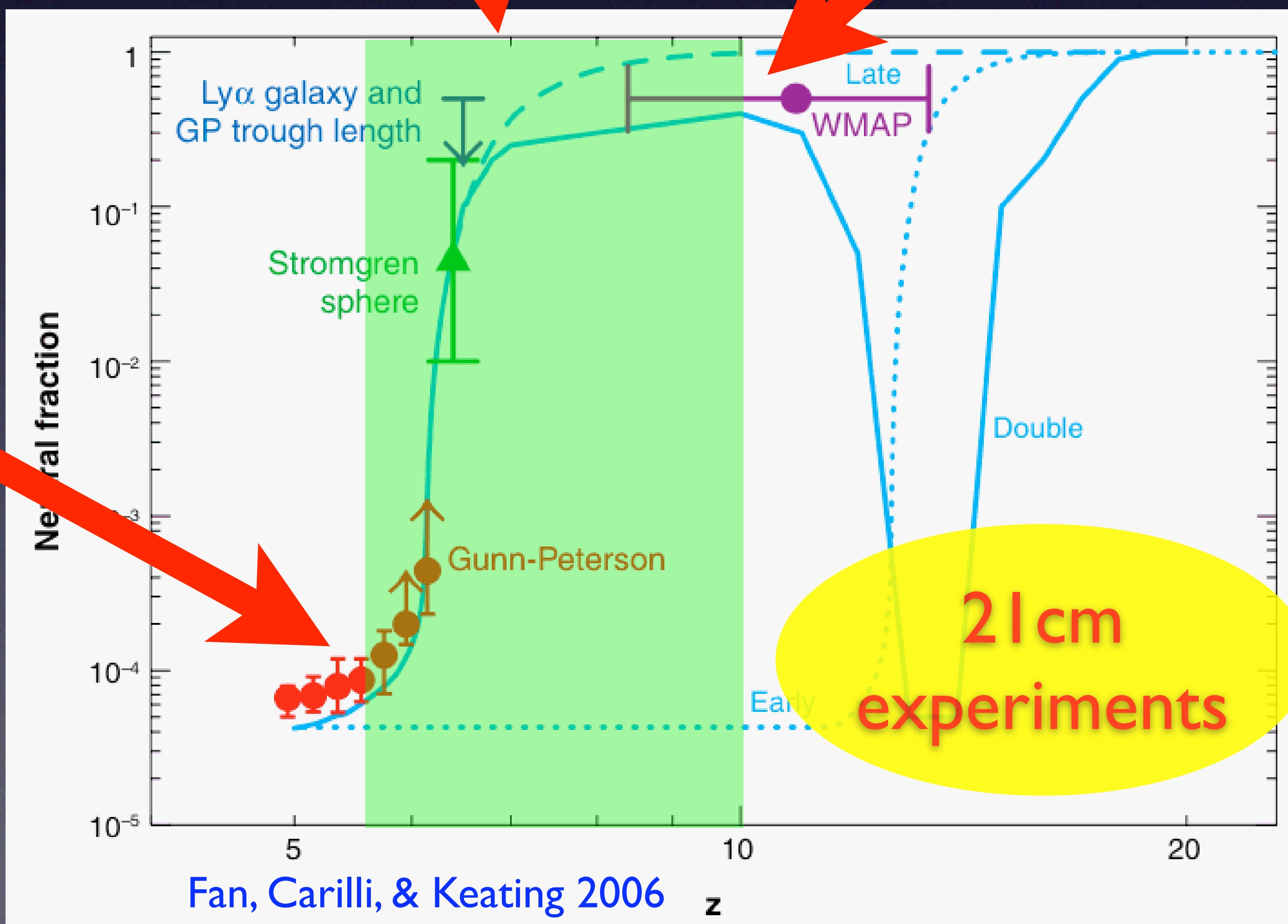




Lyman-alpha Emitters





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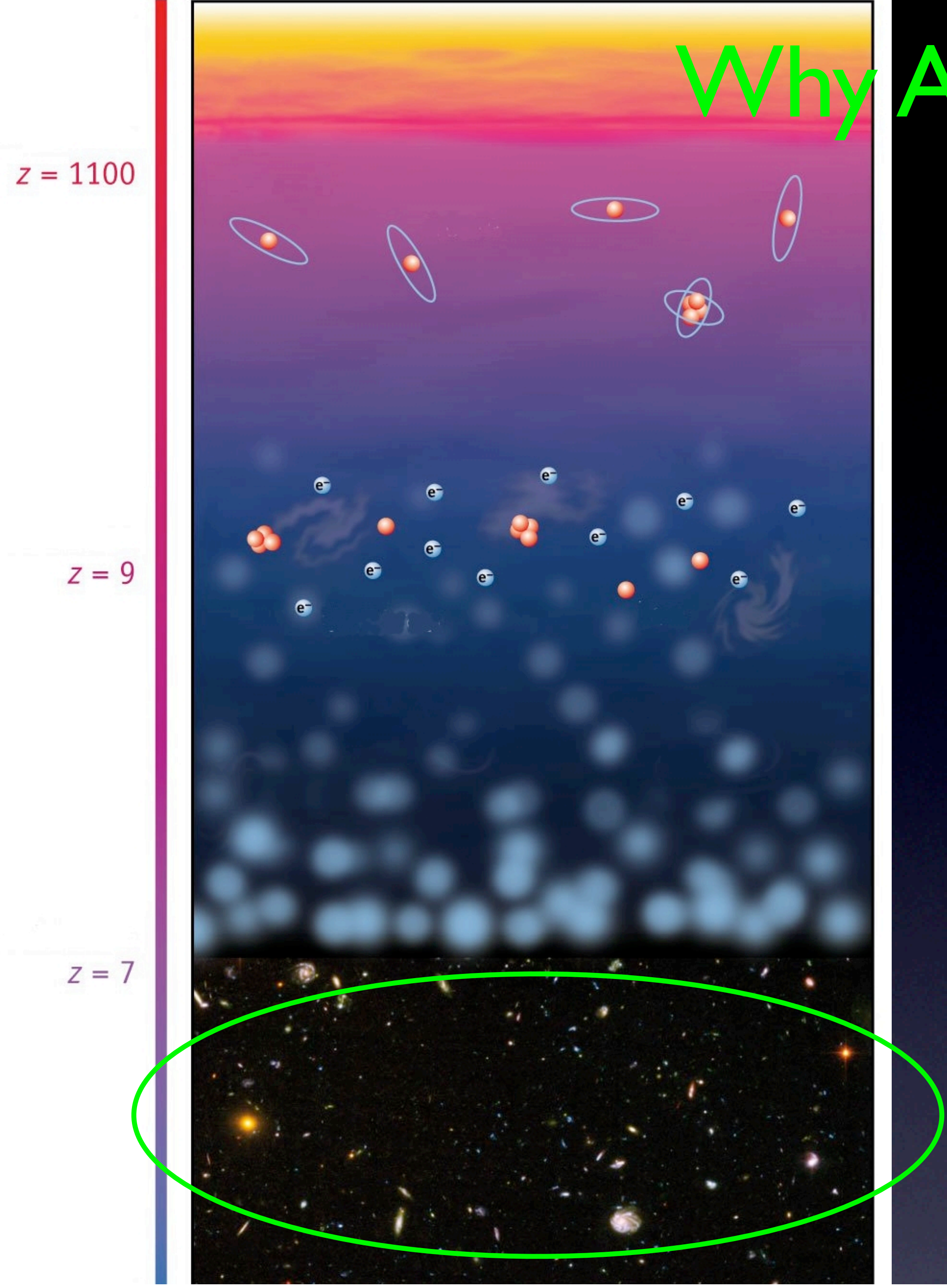
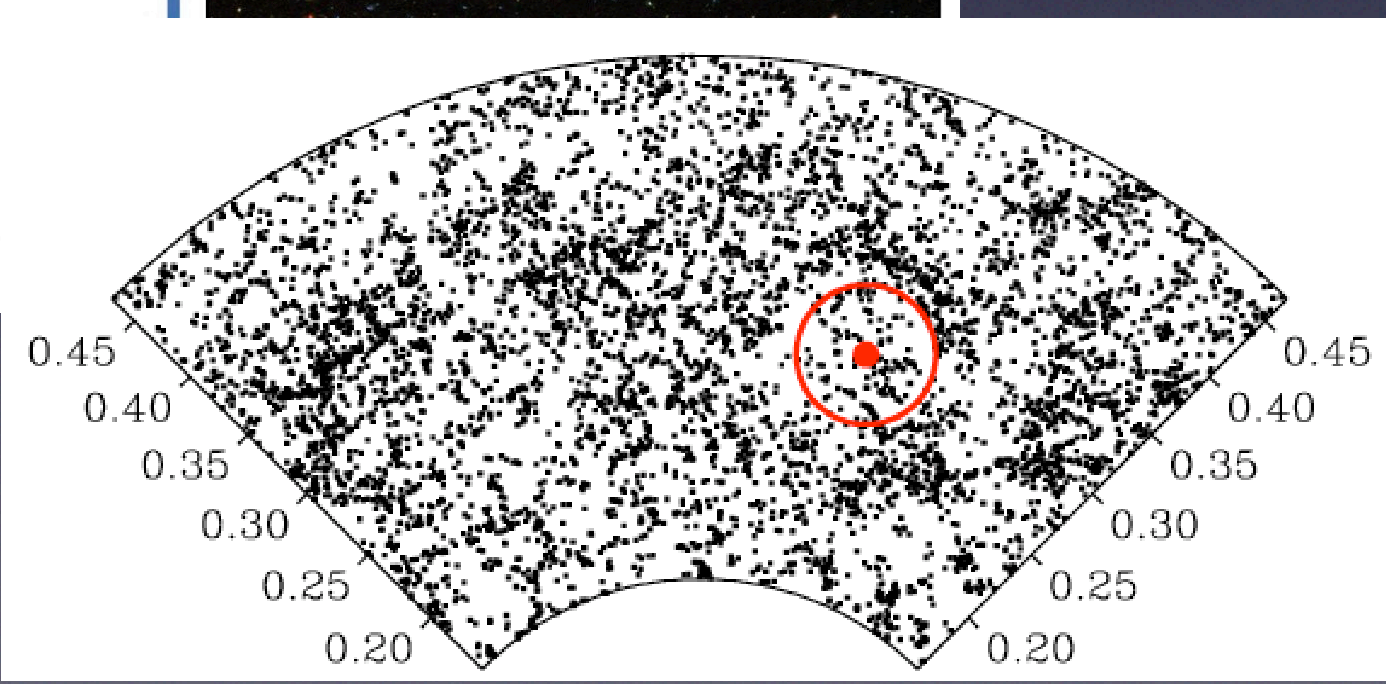
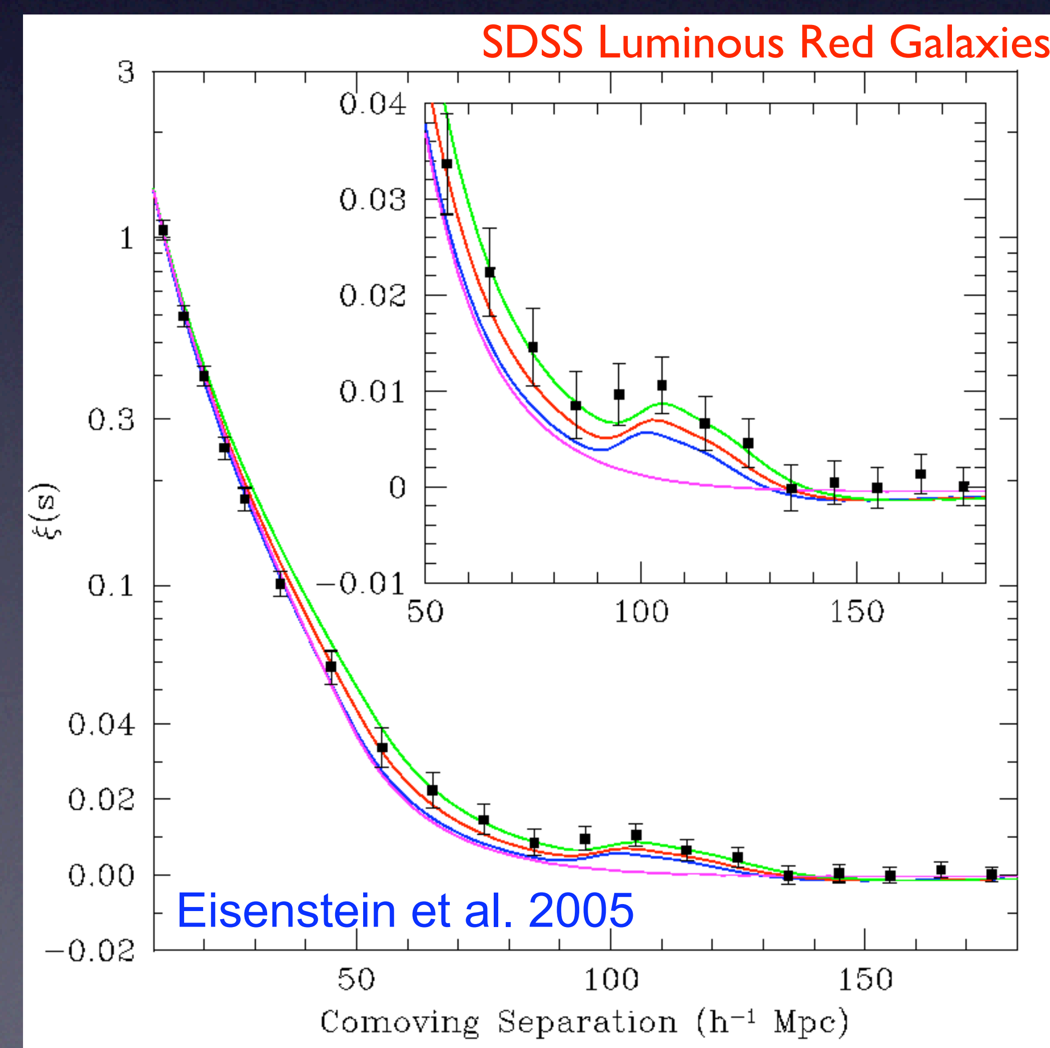
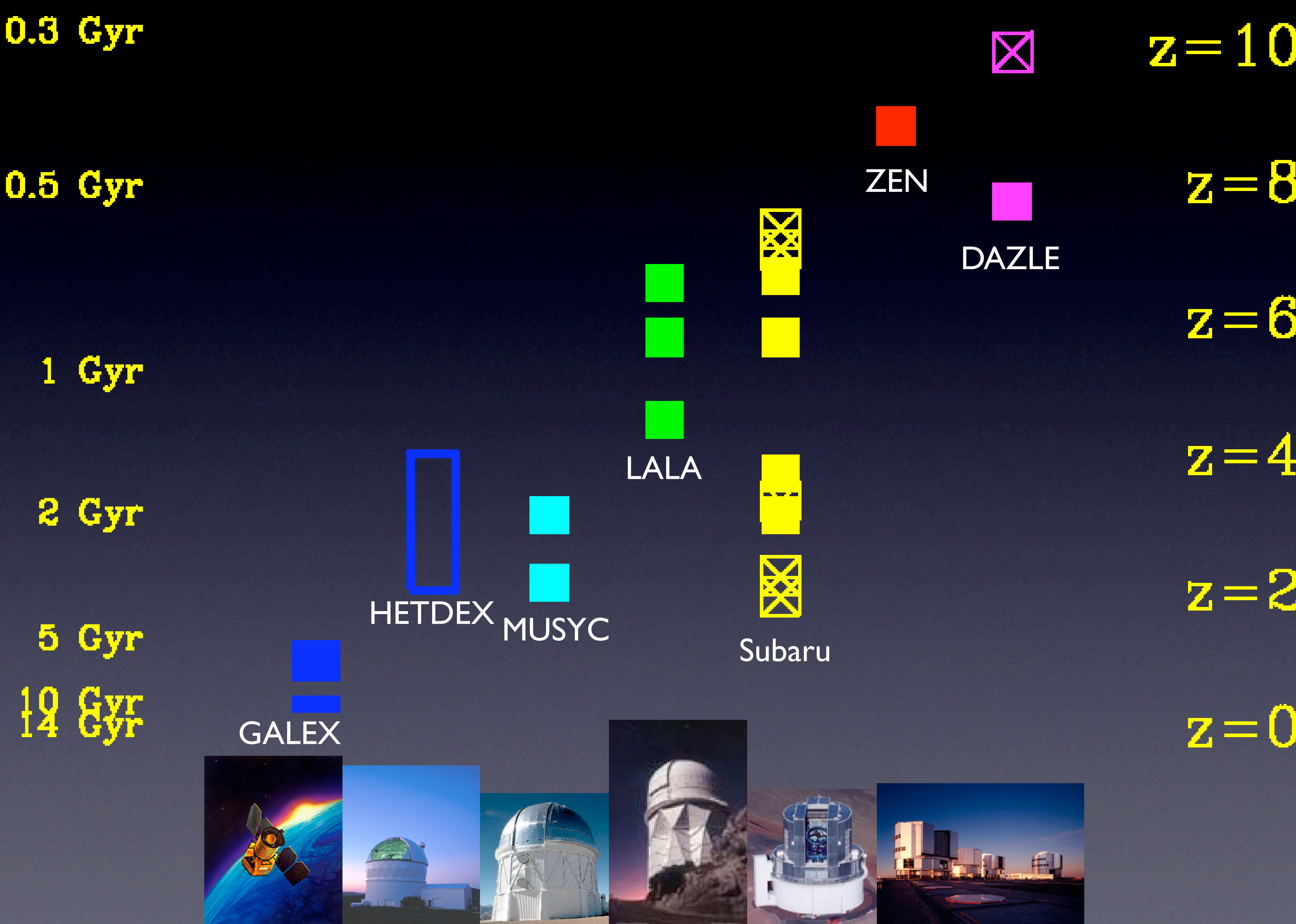


- study of young star-forming galaxies
- reionization probe
- clustering and cosmology constraints
  LAE-halo connection
  cosmology
    e.g., from Baryon Acoustic Oscillation (BAO) measurement (HETDEX, 10^6 LAEs at z~3)





Surveys for Lyman-alpha Emitters (LAEs)



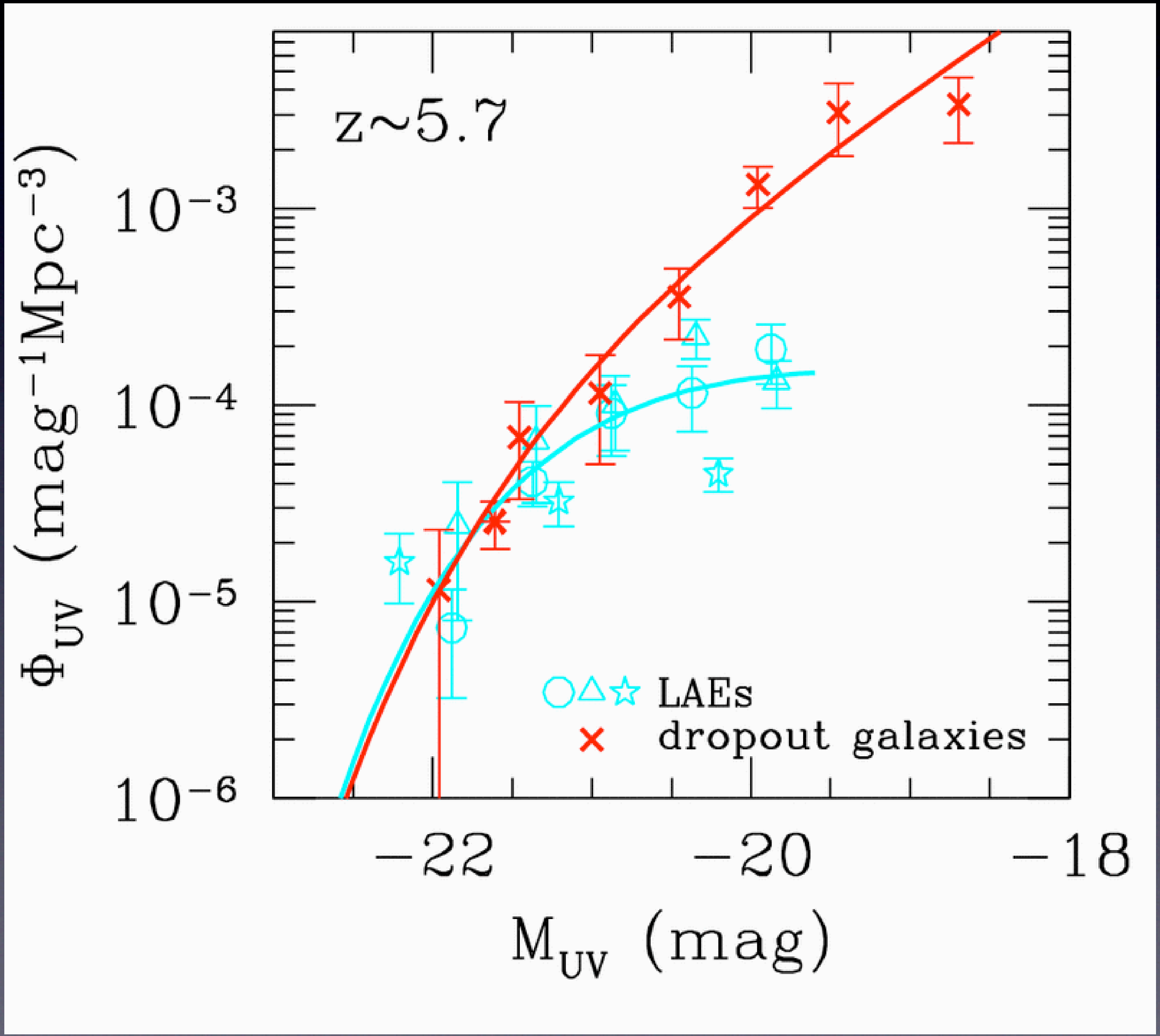
Questions about Lyman-alpha Emitters (LAEs)

- What information does the Lyα line encode?
- What determines the Lyα equivalent width?
- How to interpret the Lyα and UV continuum luminosity functions?
- What is the connection between LAEs and dark matter halos?
- How to use LAEs to probe reionization?
- What can we learn from LAE clustering?

(e.g., Wyithe & Cen 2005; Dijkstra, Lidz, & Wyithe 2007; McQuinn et al. 2007; Mesinger & Furlanetto 2008; Iliev et al. 2008; Dayal et al. 2008,2010; Kobayashi et al. 2008; Nagamine et al. 2008; Dijkstra & Wyithe 2010; Shimizu & Umemura 2010; ...)

UV Continuum Luminosity Function

Lyman Break Galaxies (LBGs) vs Lyman-alpha Emitters (LAEs)



from Ouchi et al. (2008)

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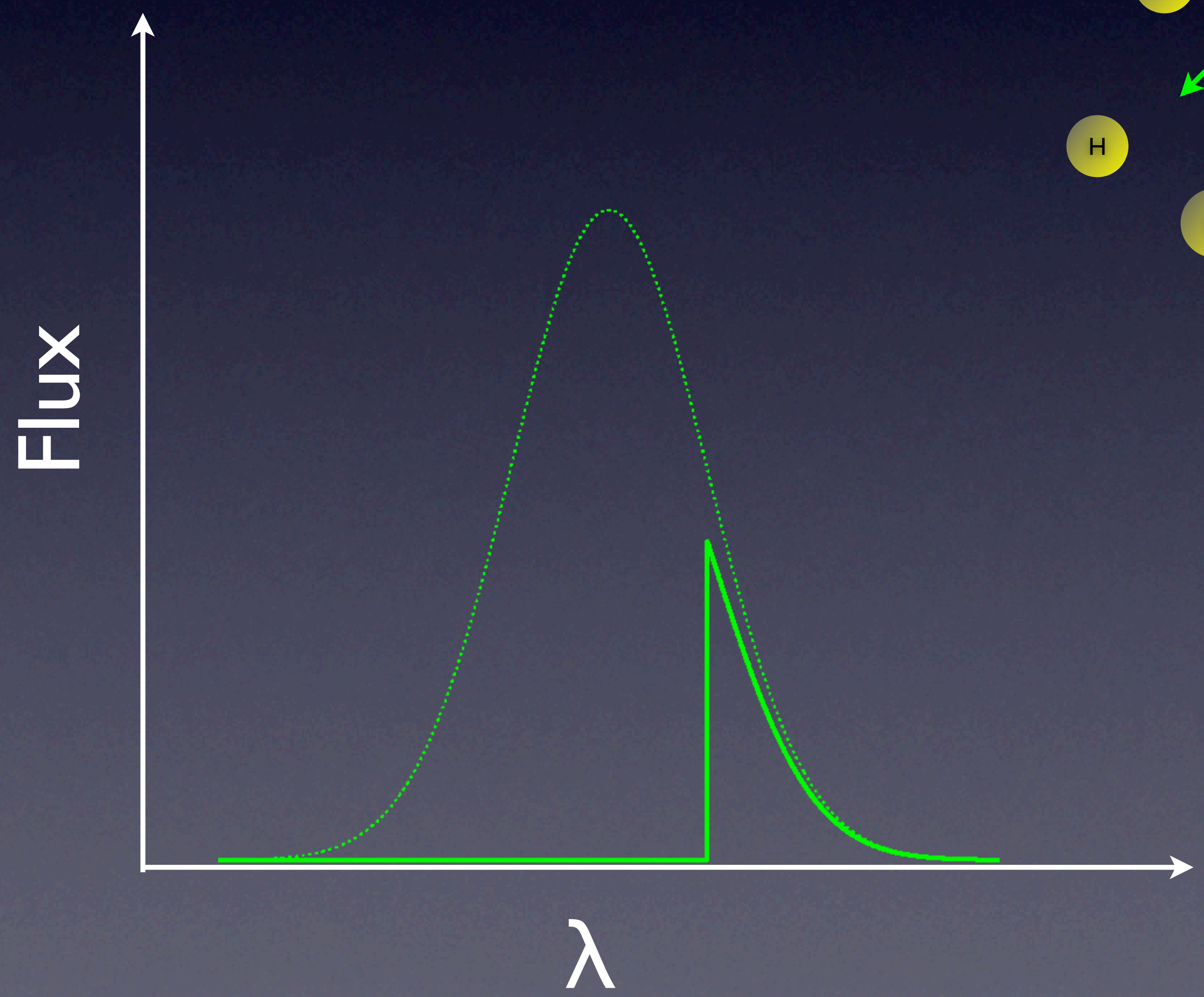
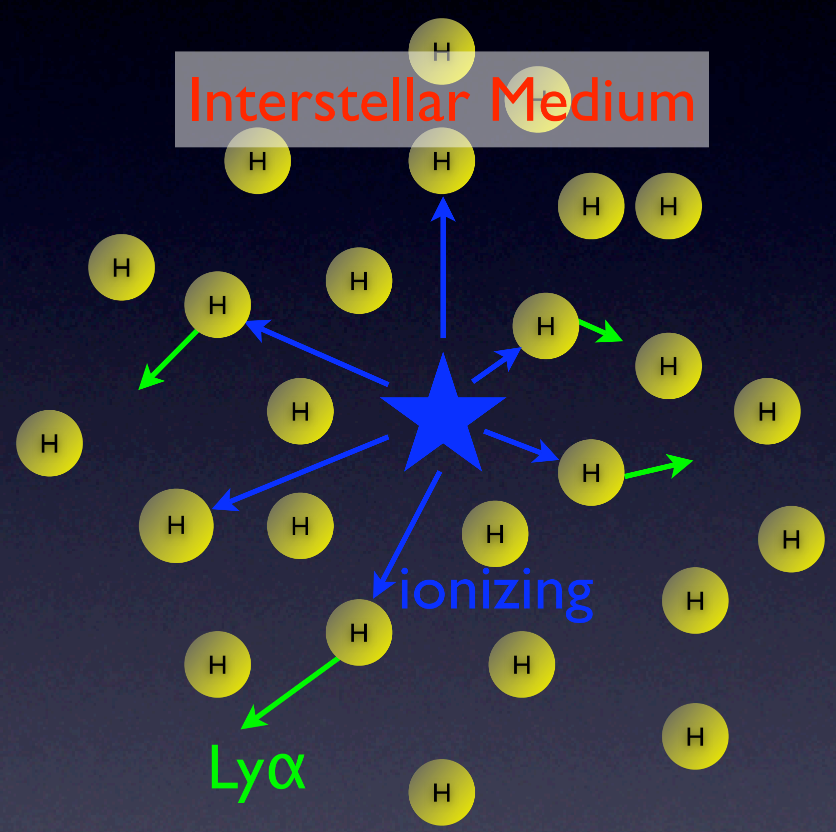
Lyα Radiative Transfer

Simplified "Radiative Transfer" Calculations

$\exp(-\tau_\nu)$ model

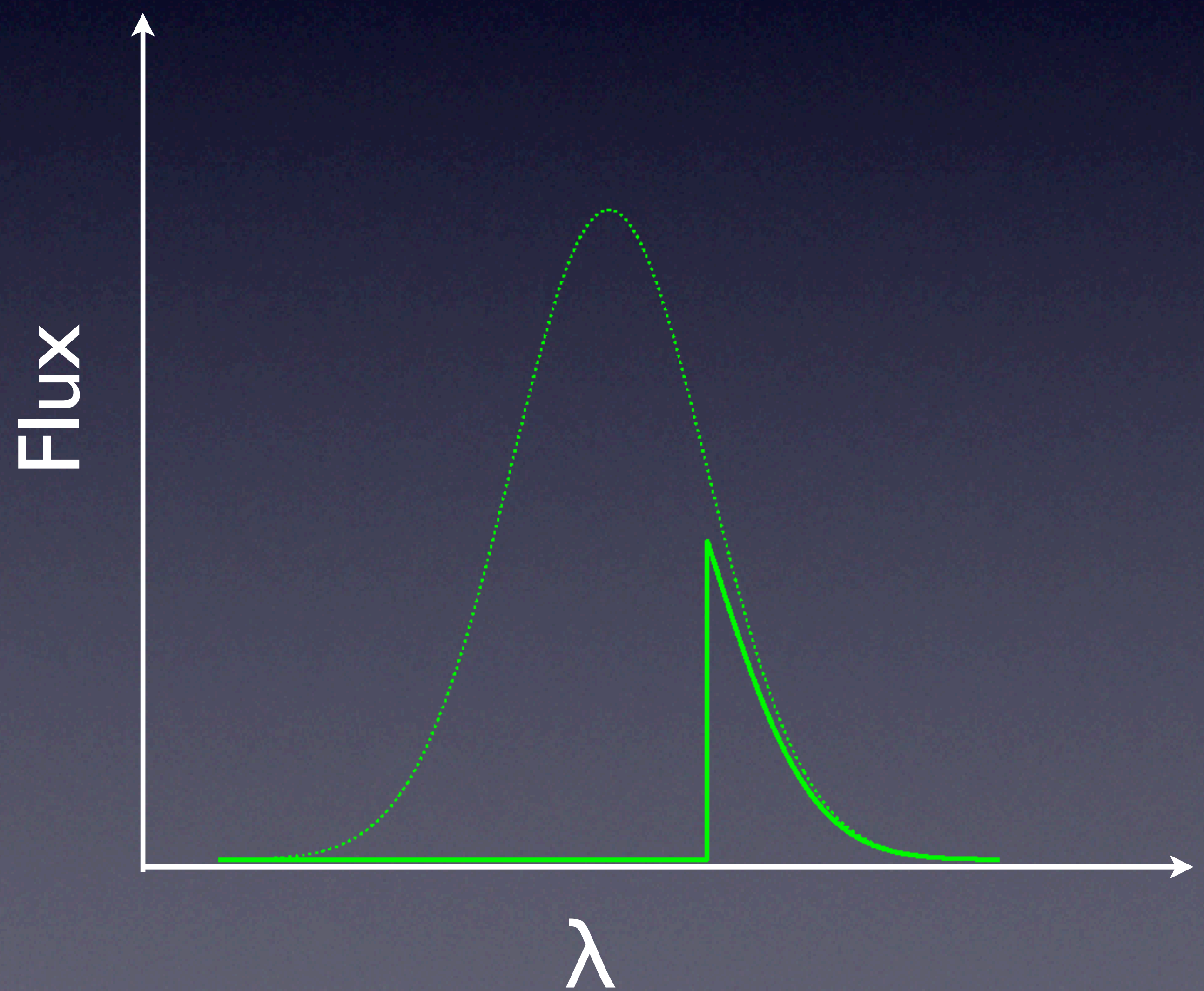


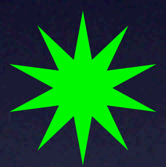


Lyα Radiative Transfer

Simplified "Radiative Transfer" Calculations

exp(- τ_ν) model





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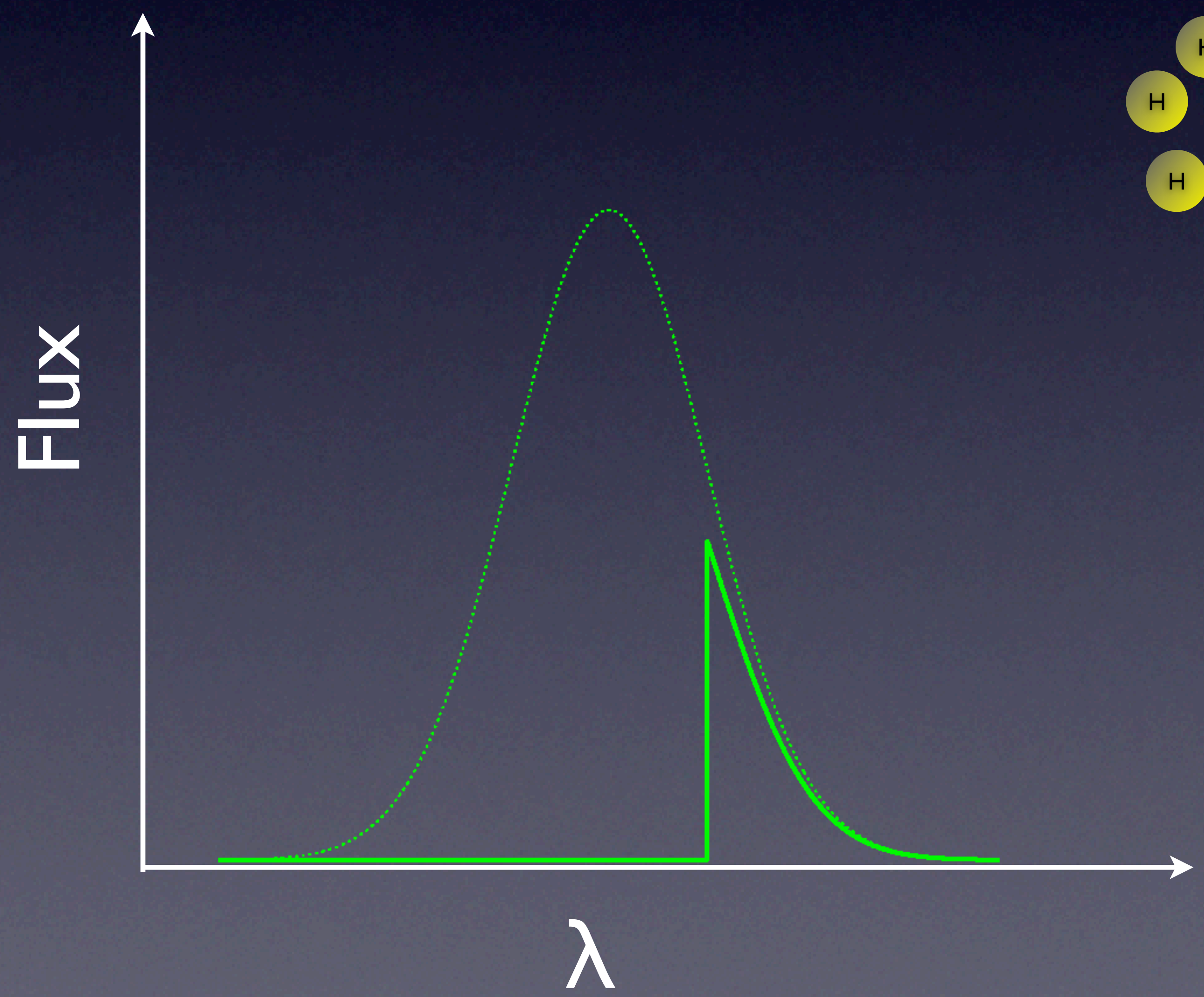

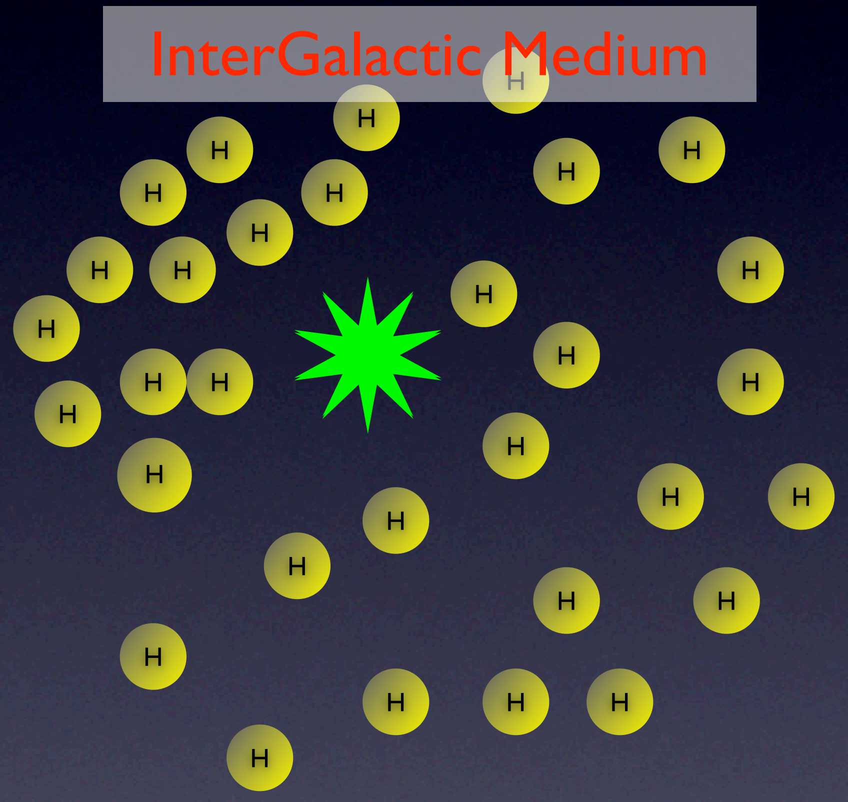

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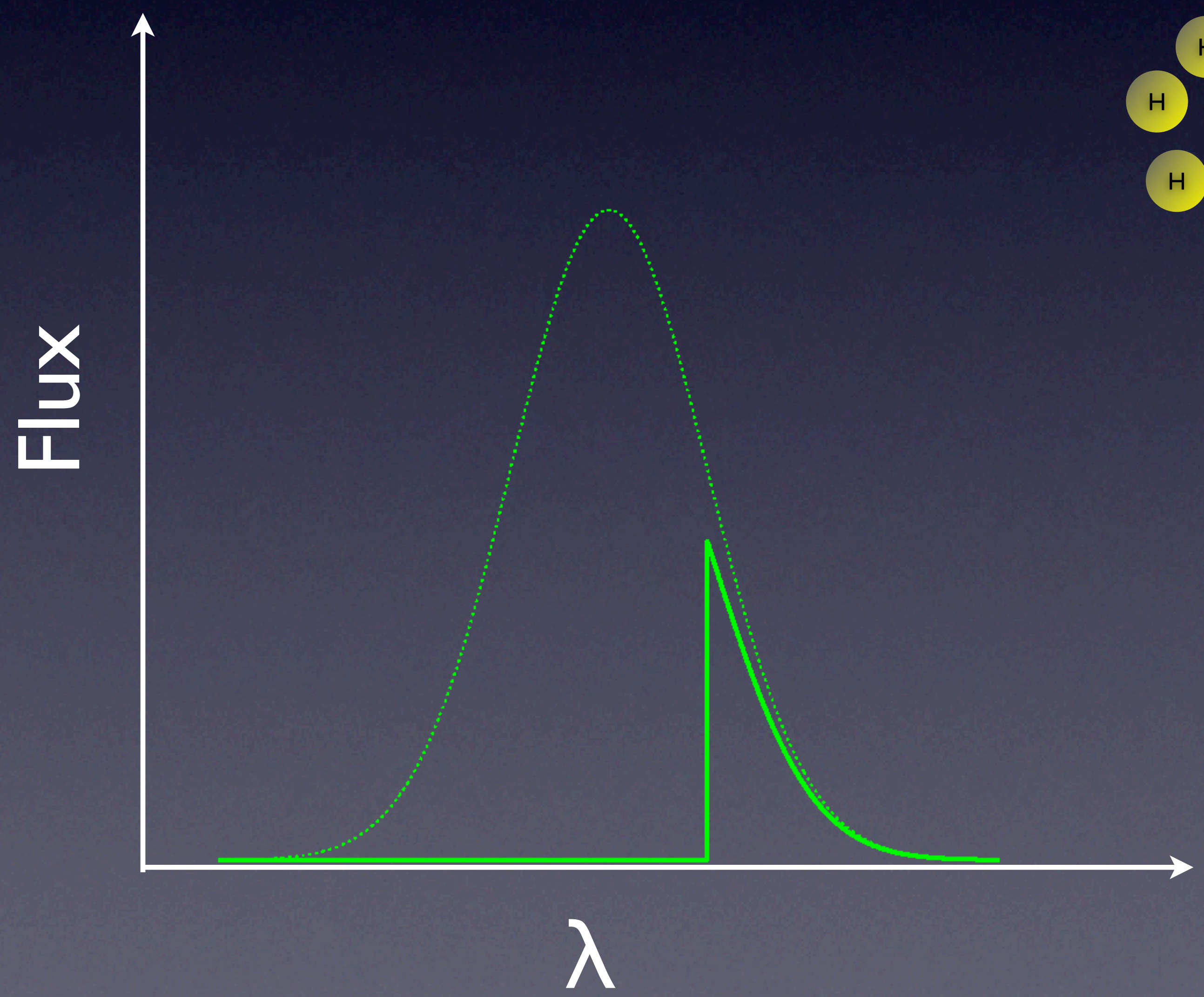
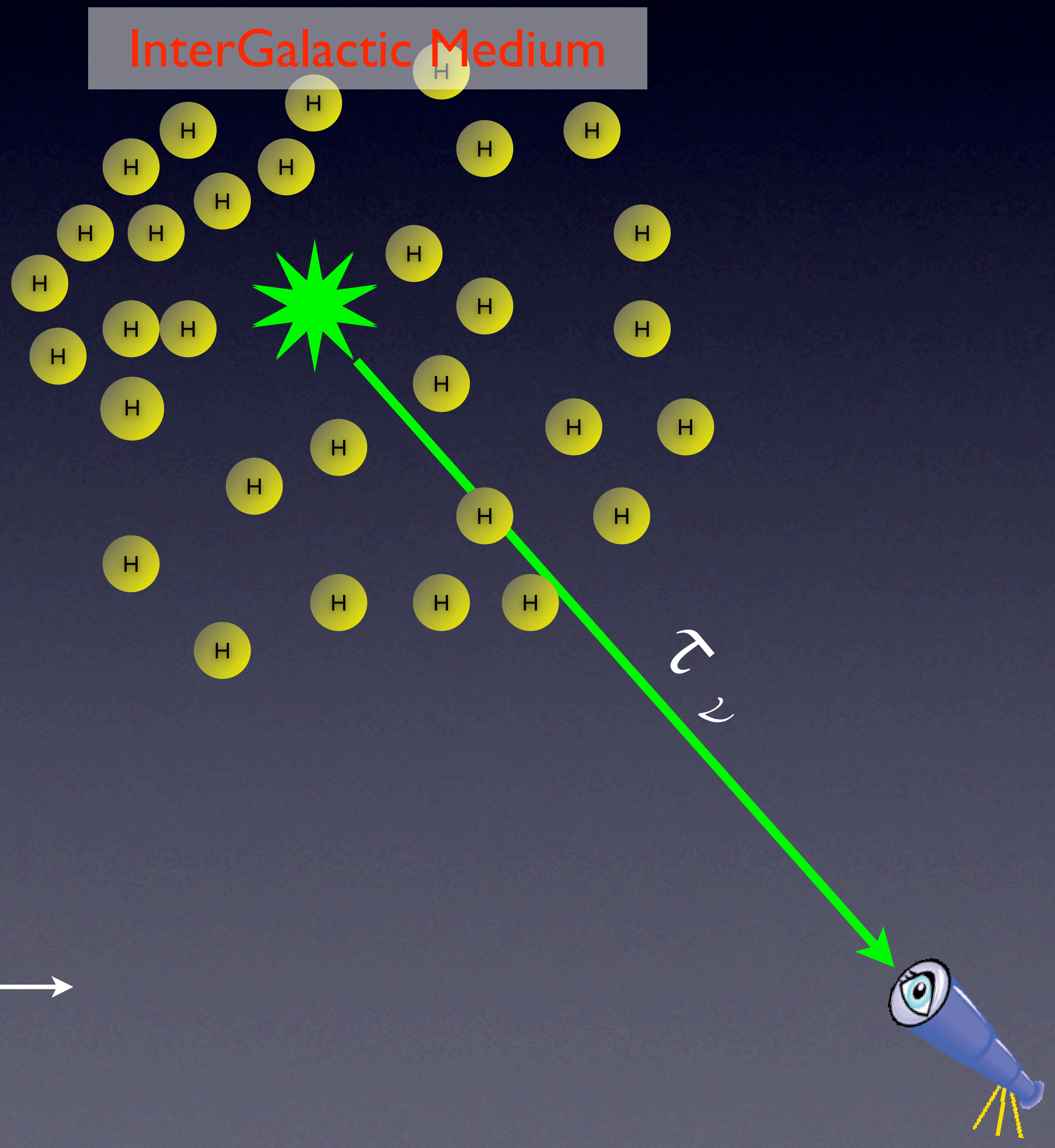




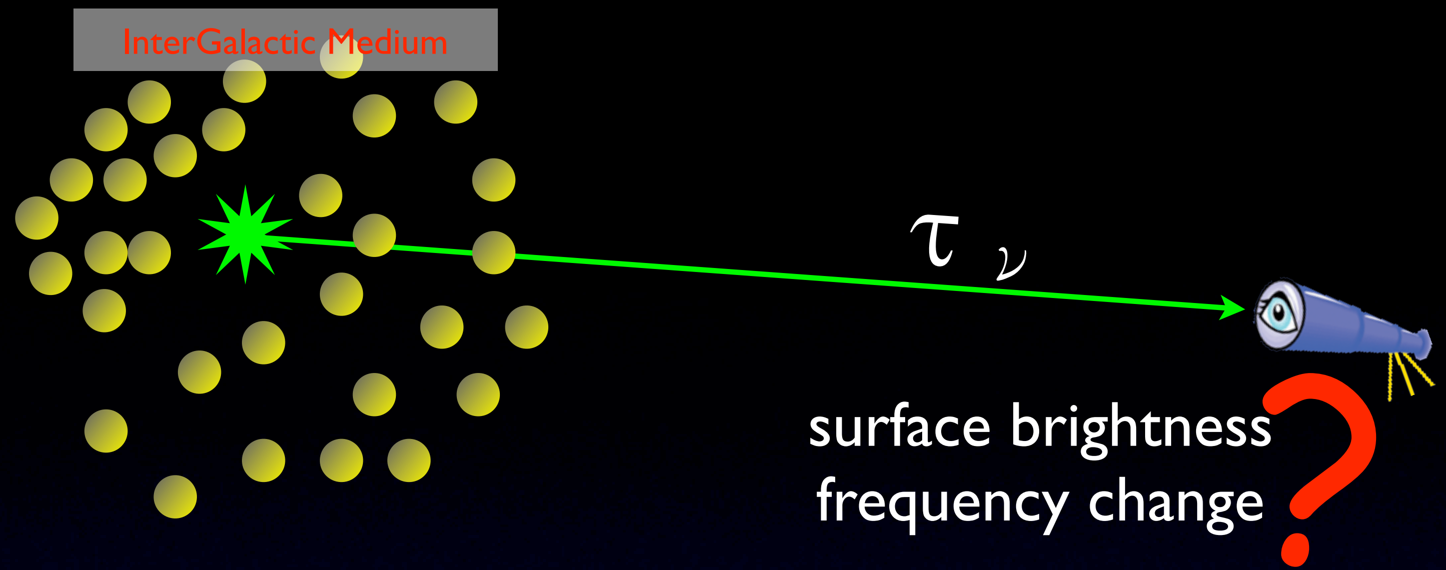
Lyα Radiative Transfer

Lyα line

$1s - 2p$ transition

$\lambda_0 = 1216\AA$

lifetime $\sim 10^{-8}$sec



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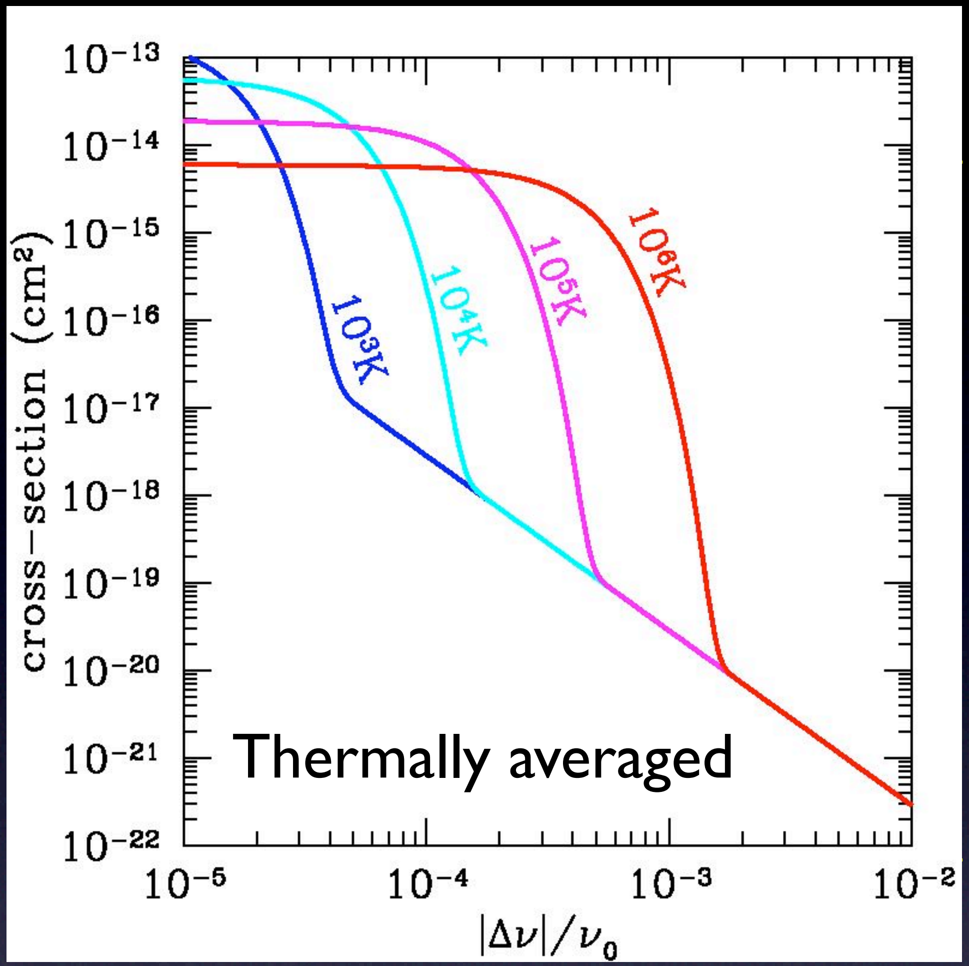
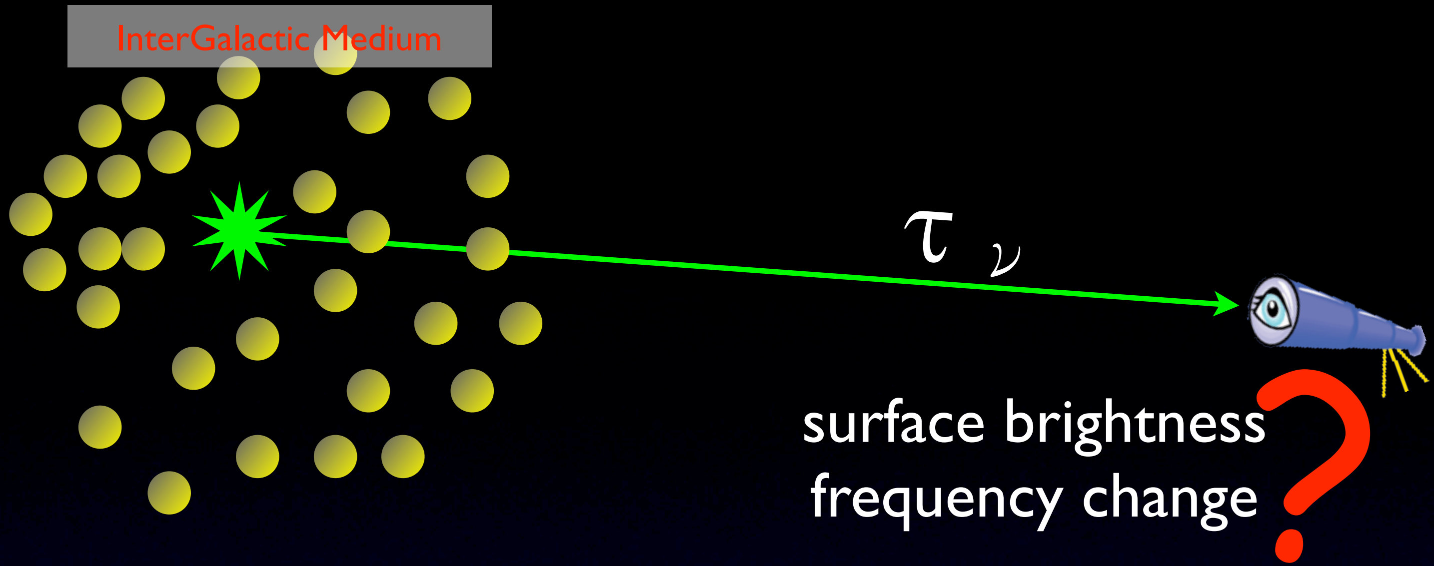


scattering cross-section: large at line center
small at line wings



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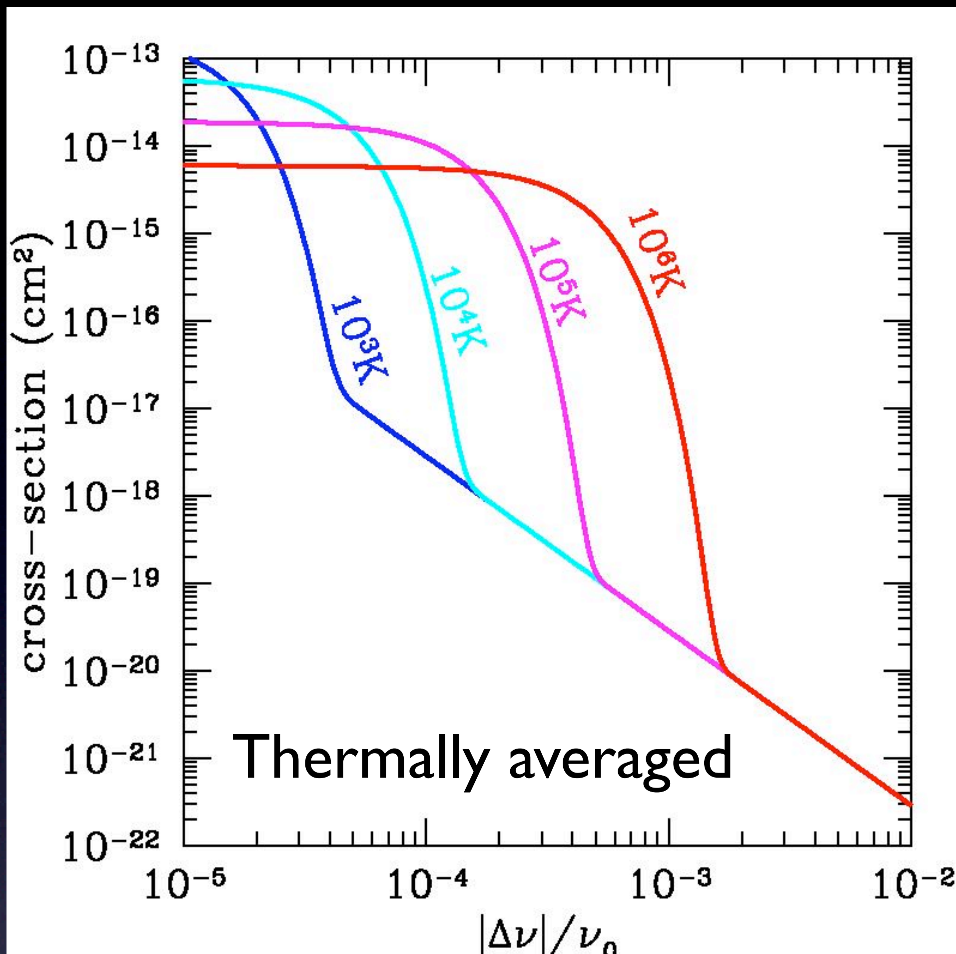

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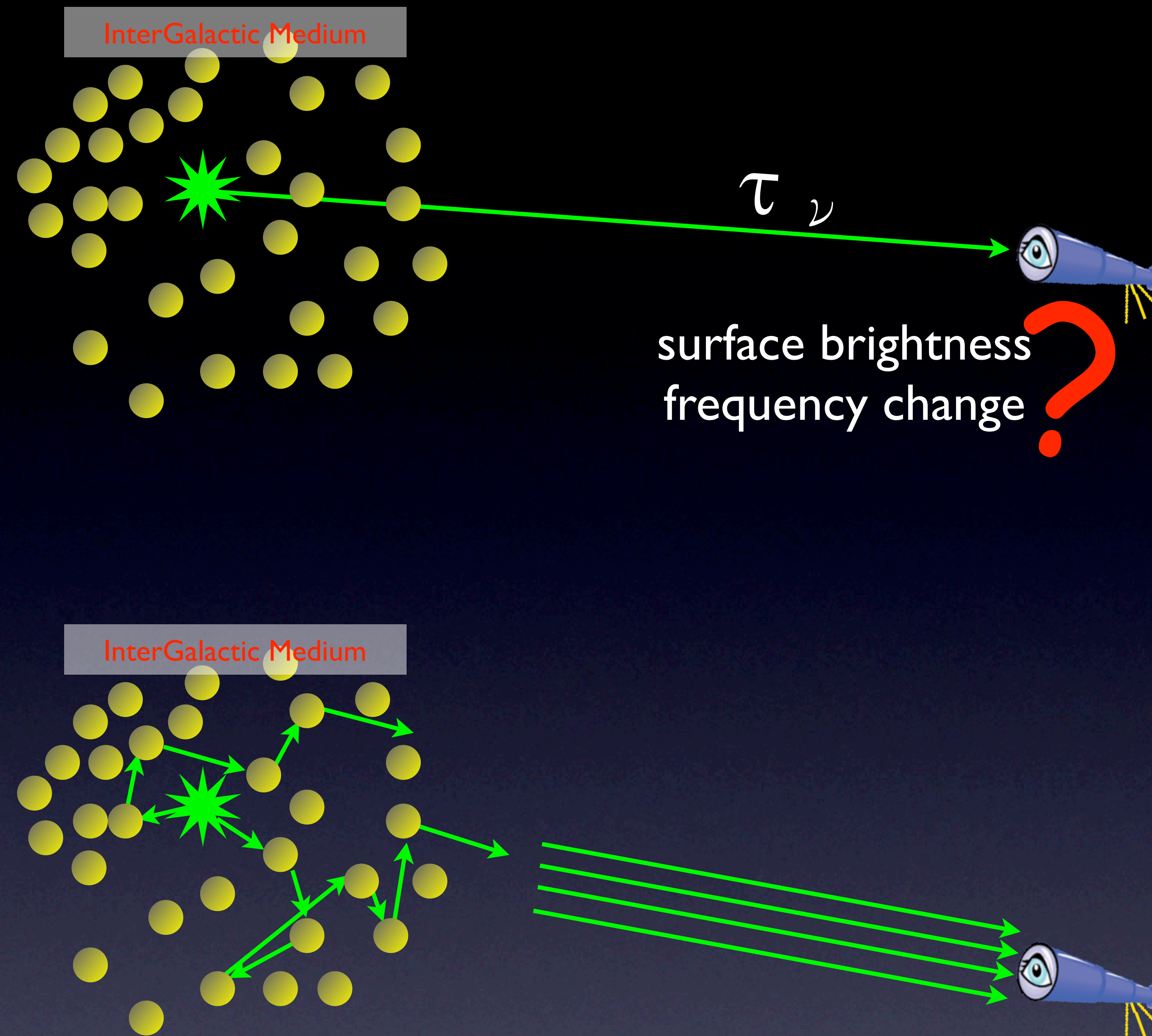

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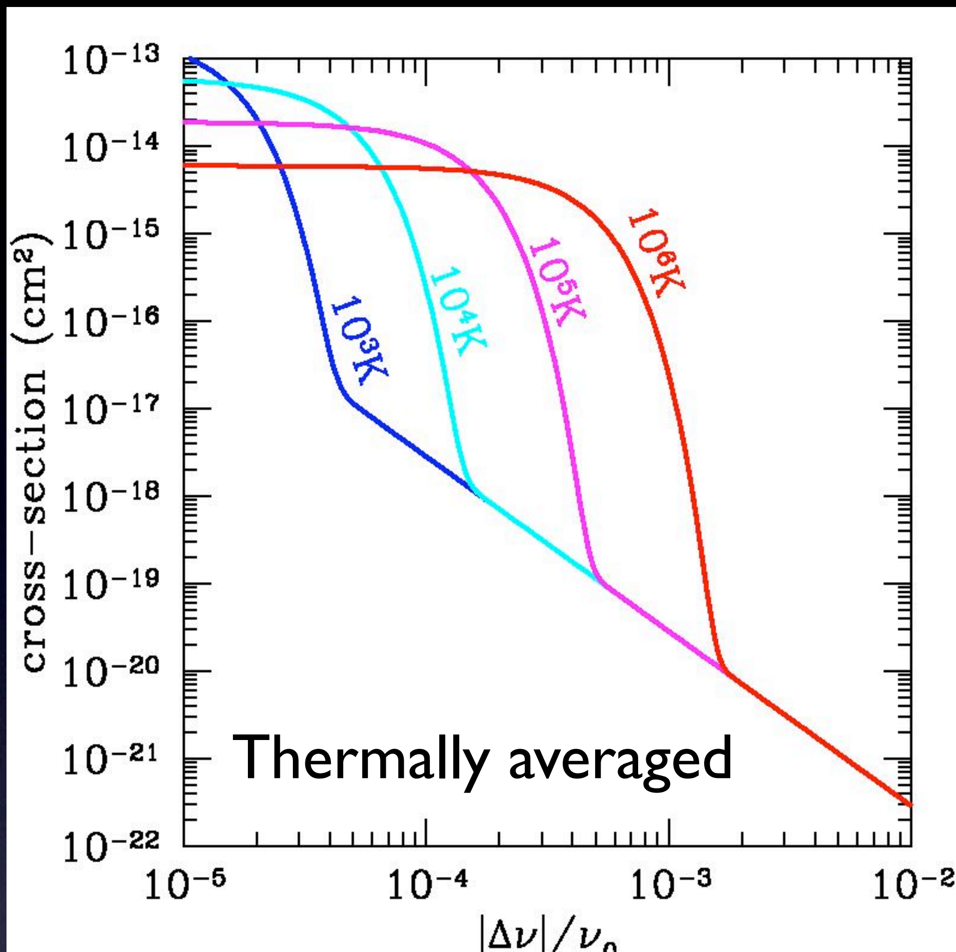

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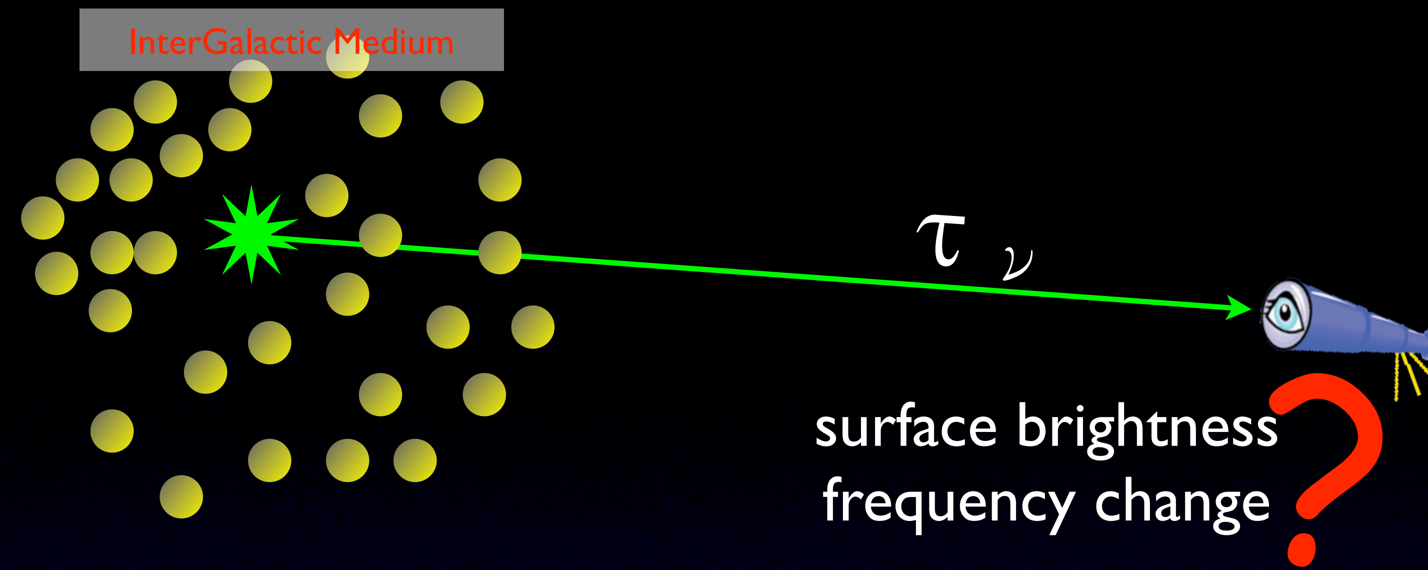
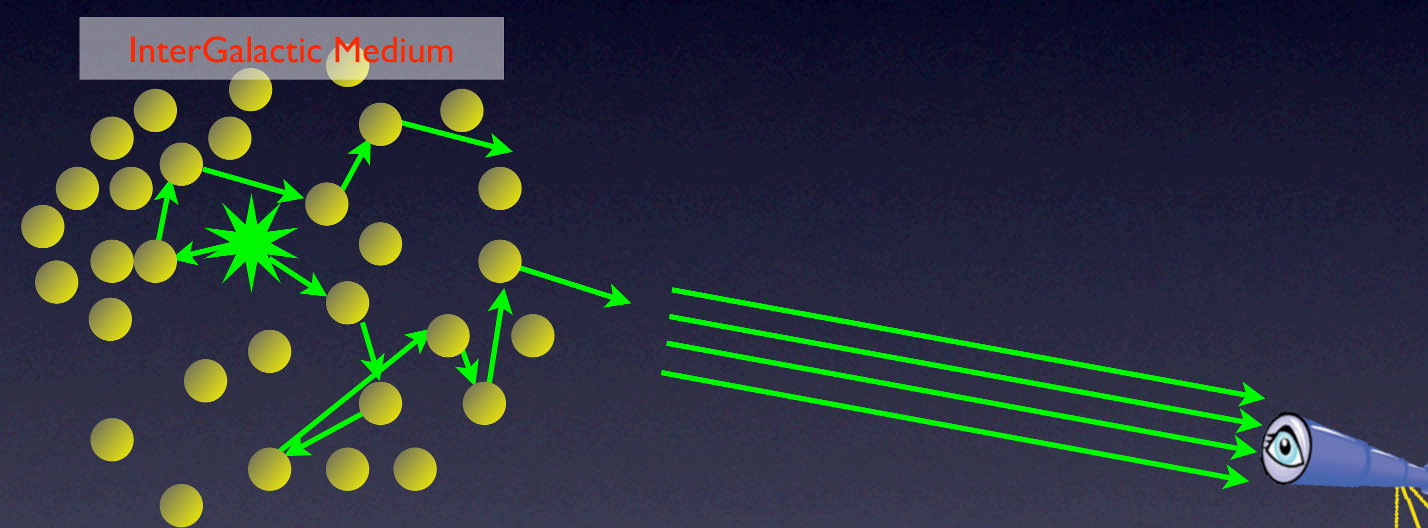
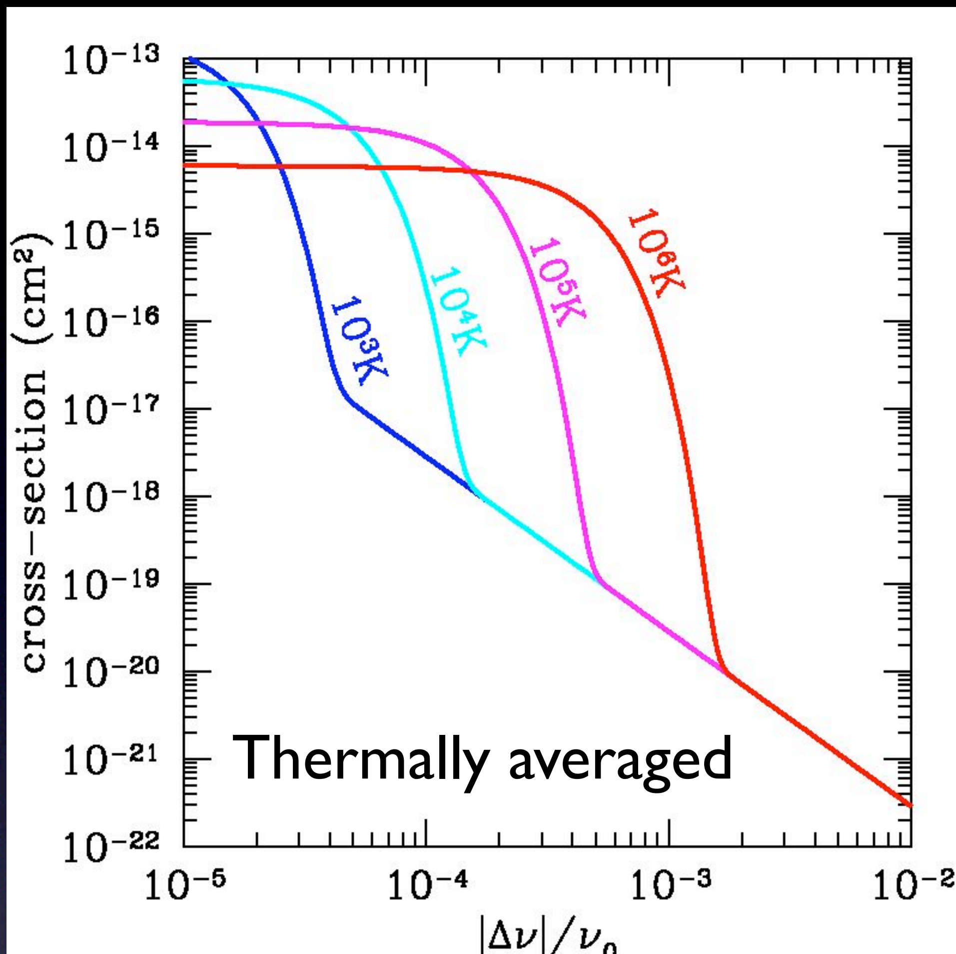




atom rest frame

Lyα Radiative Transfer



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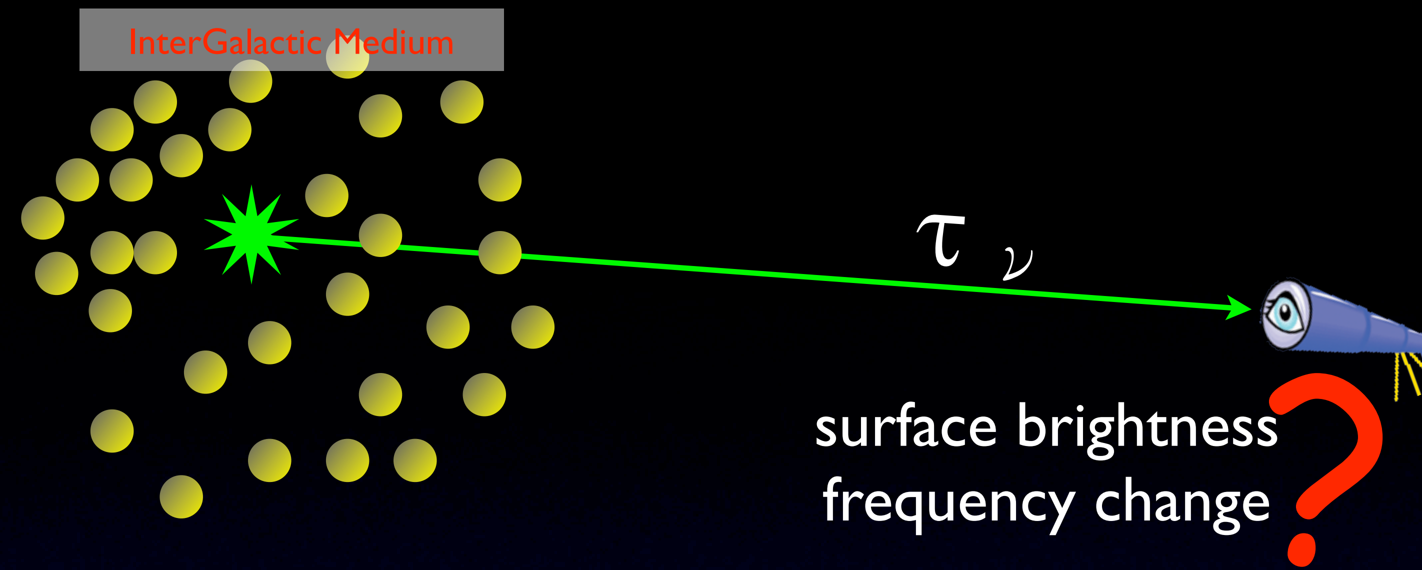

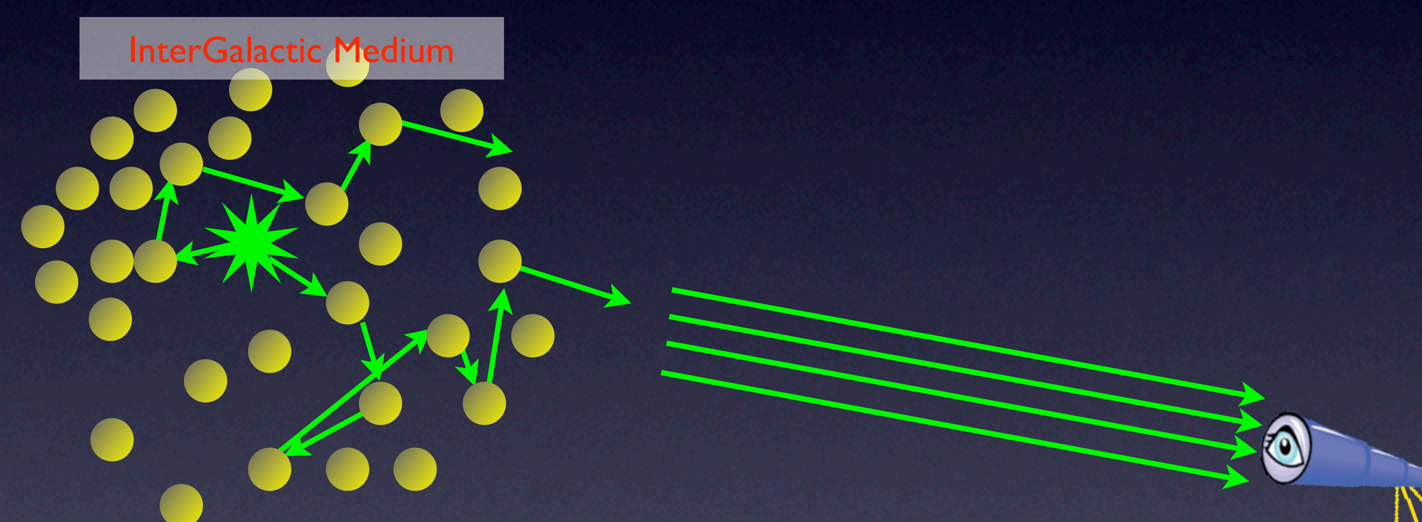

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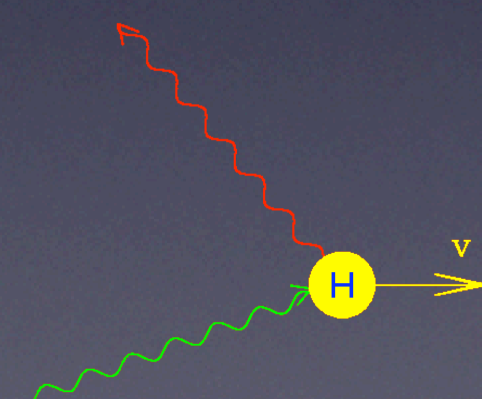
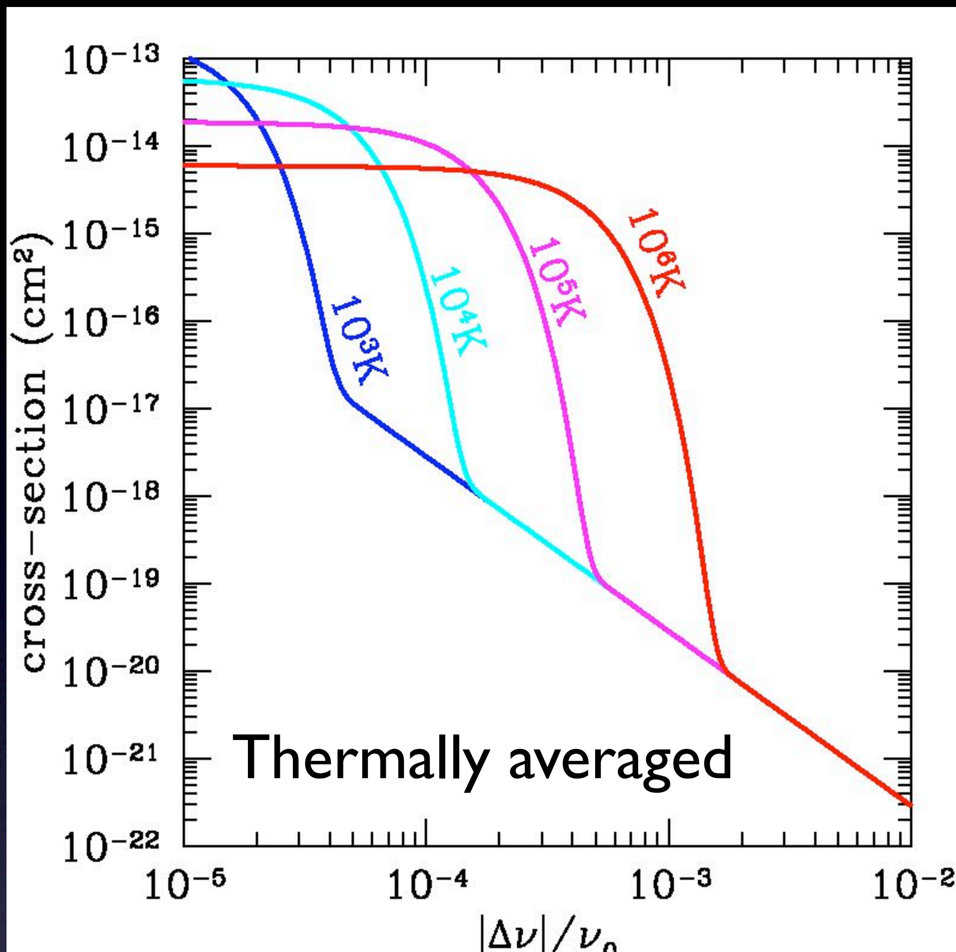


laboratory frame

Lyα Radiative Transfer



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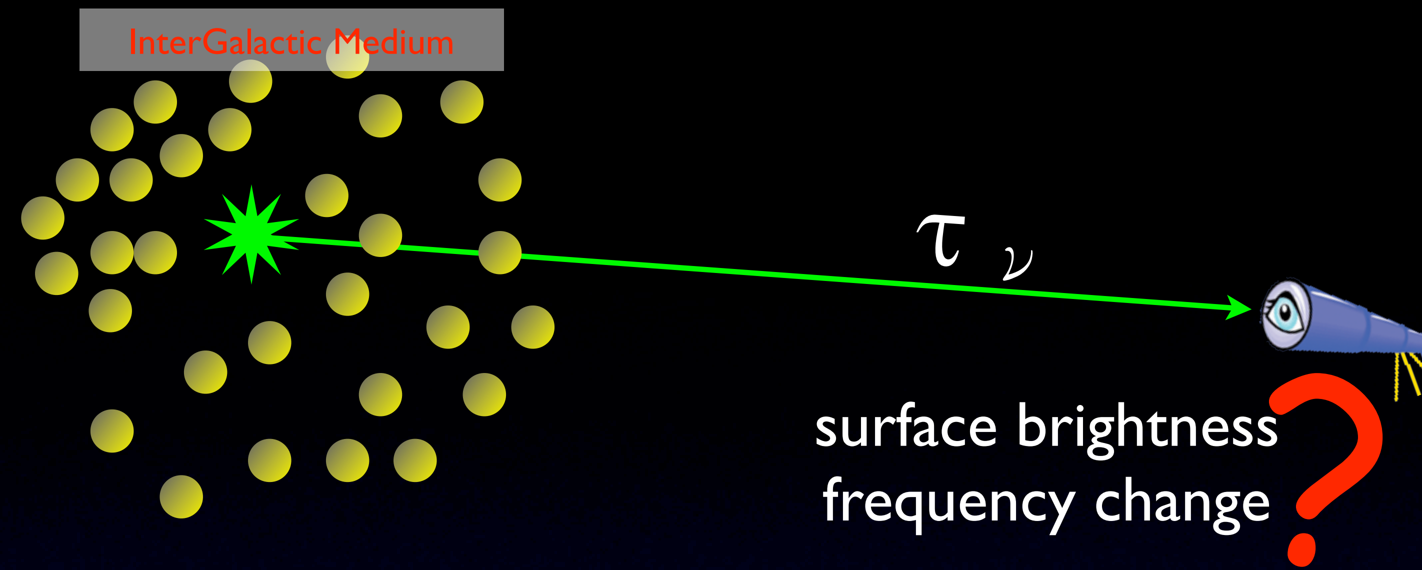

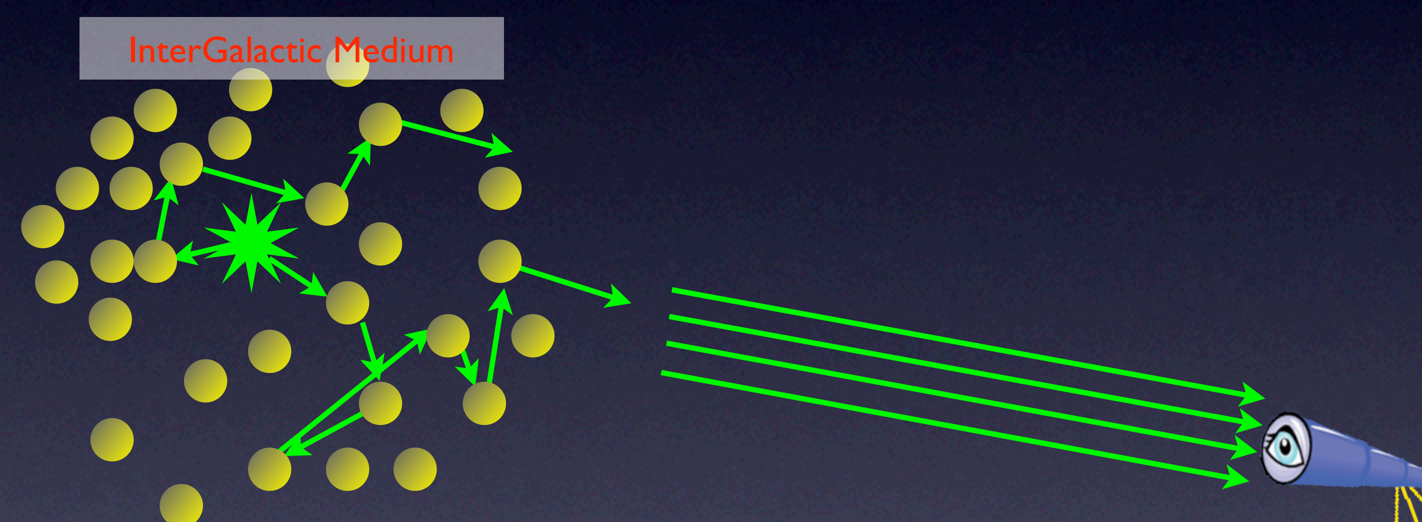

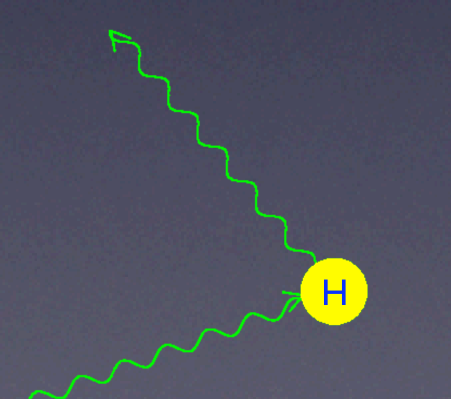

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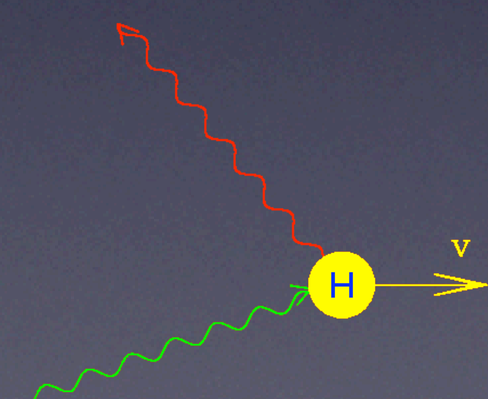


laboratory frame

- a large number of scatterings
- position change from scattering
- frequency change after each scattering

Monte Carlo Code for Lyα Radiative Transfer

(Zheng & Miralda-Escudé 2002)

can be applied to systems with *arbitrary*

- gas geometry
- gas emissivity distribution
- gas density distribution
- gas temperature distribution
- gas velocity distribution

well suited for applying to cosmological simulation outputs

generates an IFU-like data cube, which can be used to obtain Lyα image and spectra

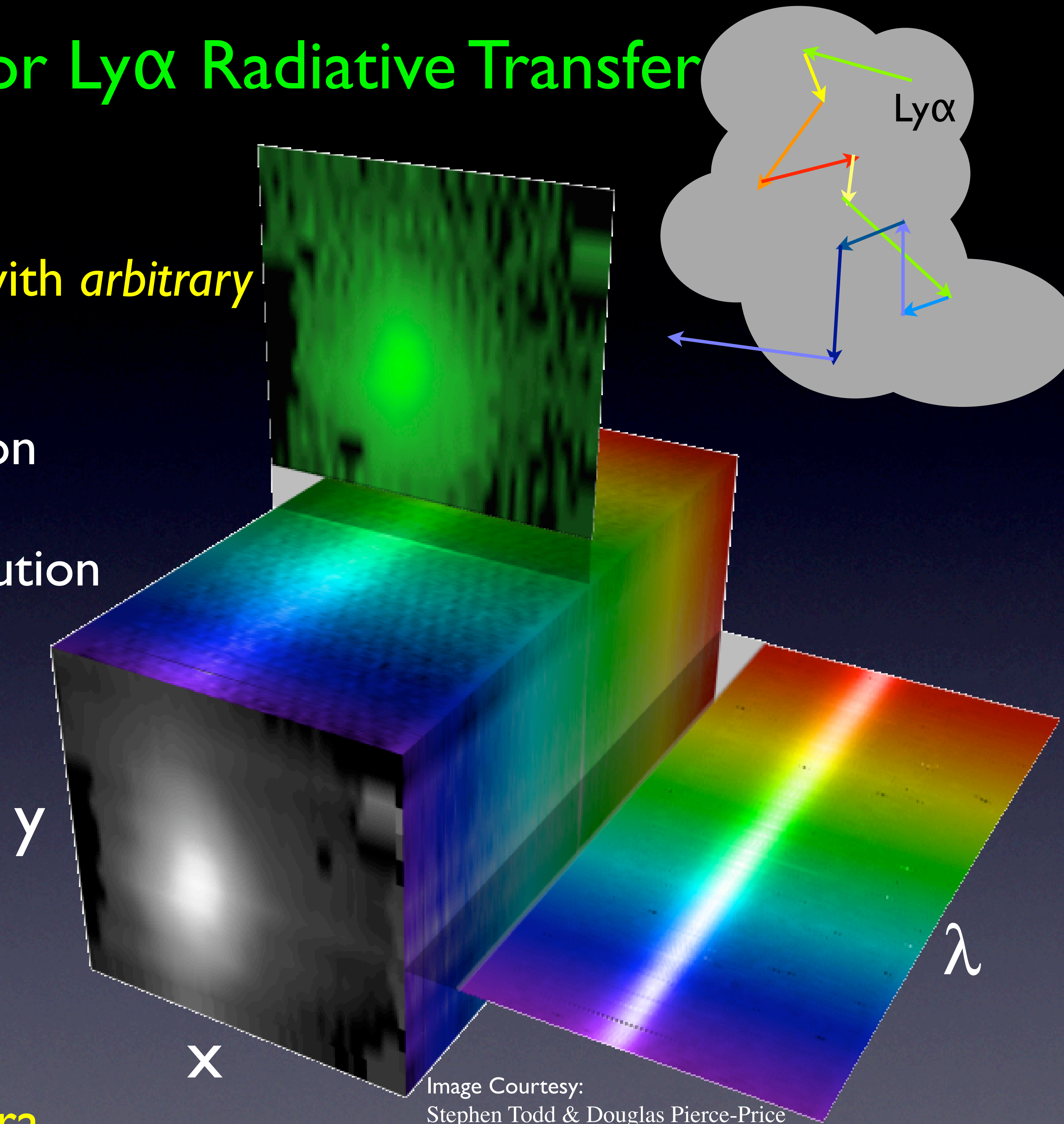
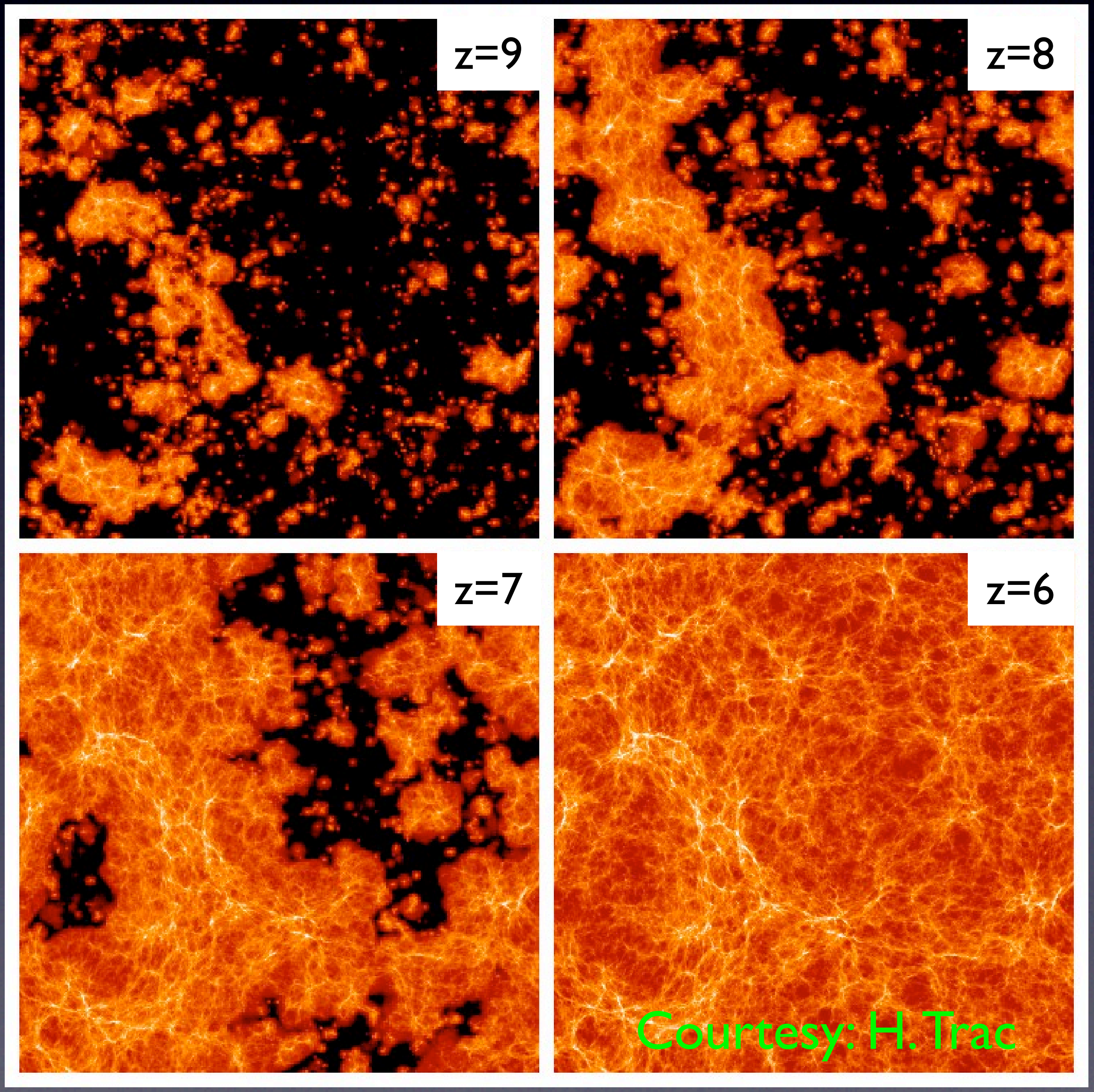


Image Courtesy:
Stephen Todd & Douglas Pierce-Price

Radiative Transfer Modeling of LAEs

Input:

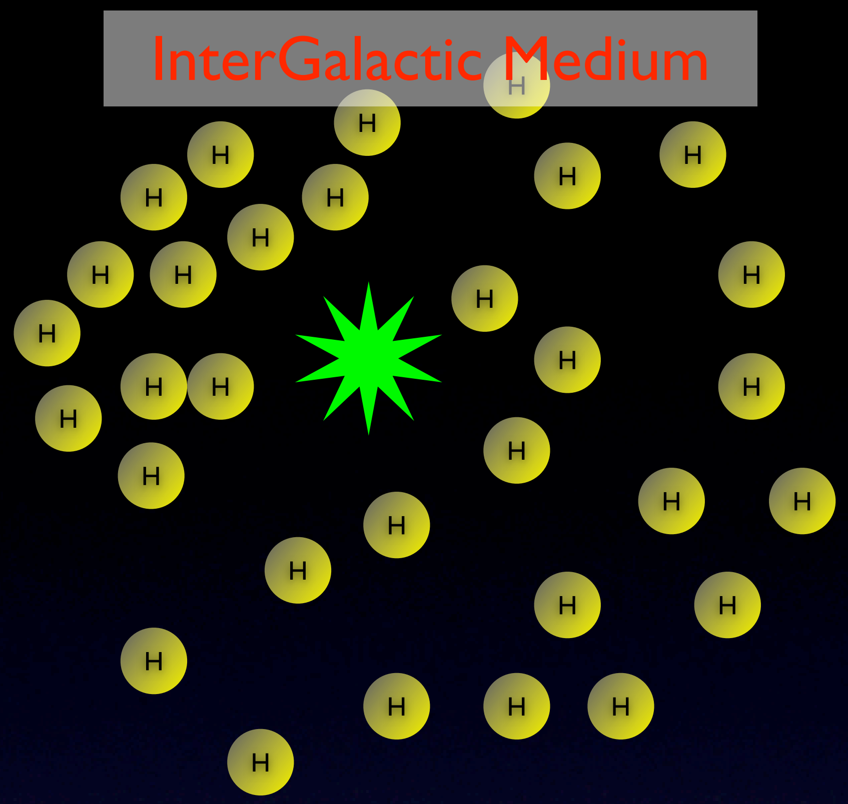
Radiation Hydrodynamic Simulation of Cosmological Reionization



Trac & Cen 2007
Trac, Cen, & Loeb 2008

- (100 Mpc/h)^3 box
- reionization completed at z~6
- use the z~5.7 output
  halos, SFR, gas distribution, ...
- 3X the volume of the Subaru/XMM-Newton Deep Survey (SXDS) at z~5.7 (~1 sq. deg.)

Model of Lyman-alpha Emitters



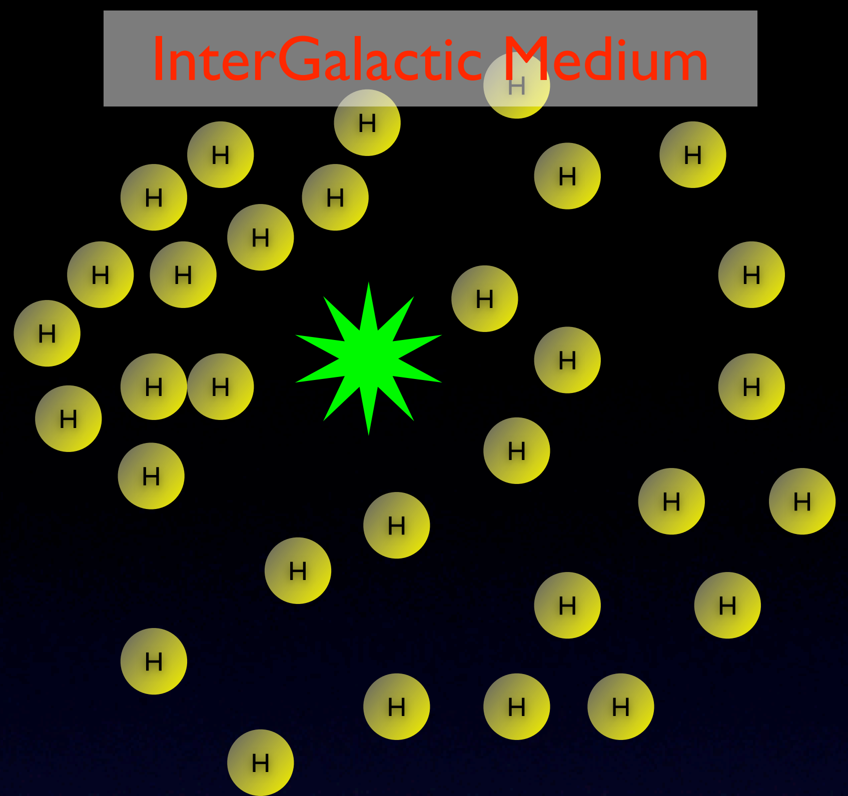
intrinsic Lyα emission

(after escaping from ISM)

- point source at halo center
- intrinsic Lyα luminosity from star formation rate
- Gaussian initial line profile
- line width from halo virial temperature

apparent (observed) Lyα emission

Model of Lyman-alpha Emitters



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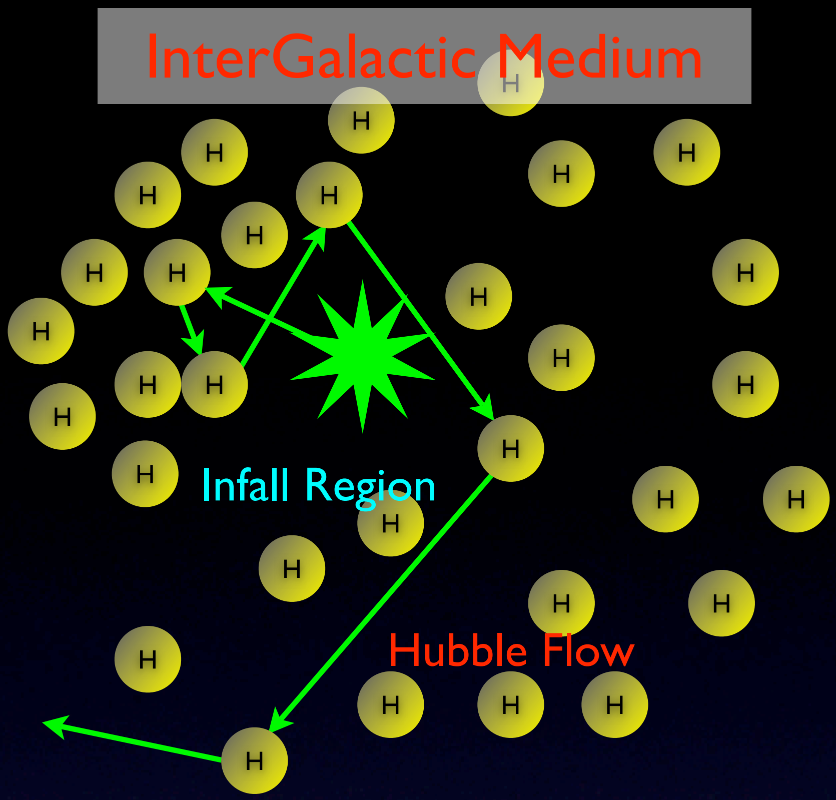
Lyα Radiative Transfer

(in the circumgalactic and intergalactic media)

apparent (observed) Lyα emission

Model of Lyman-alpha Emitters



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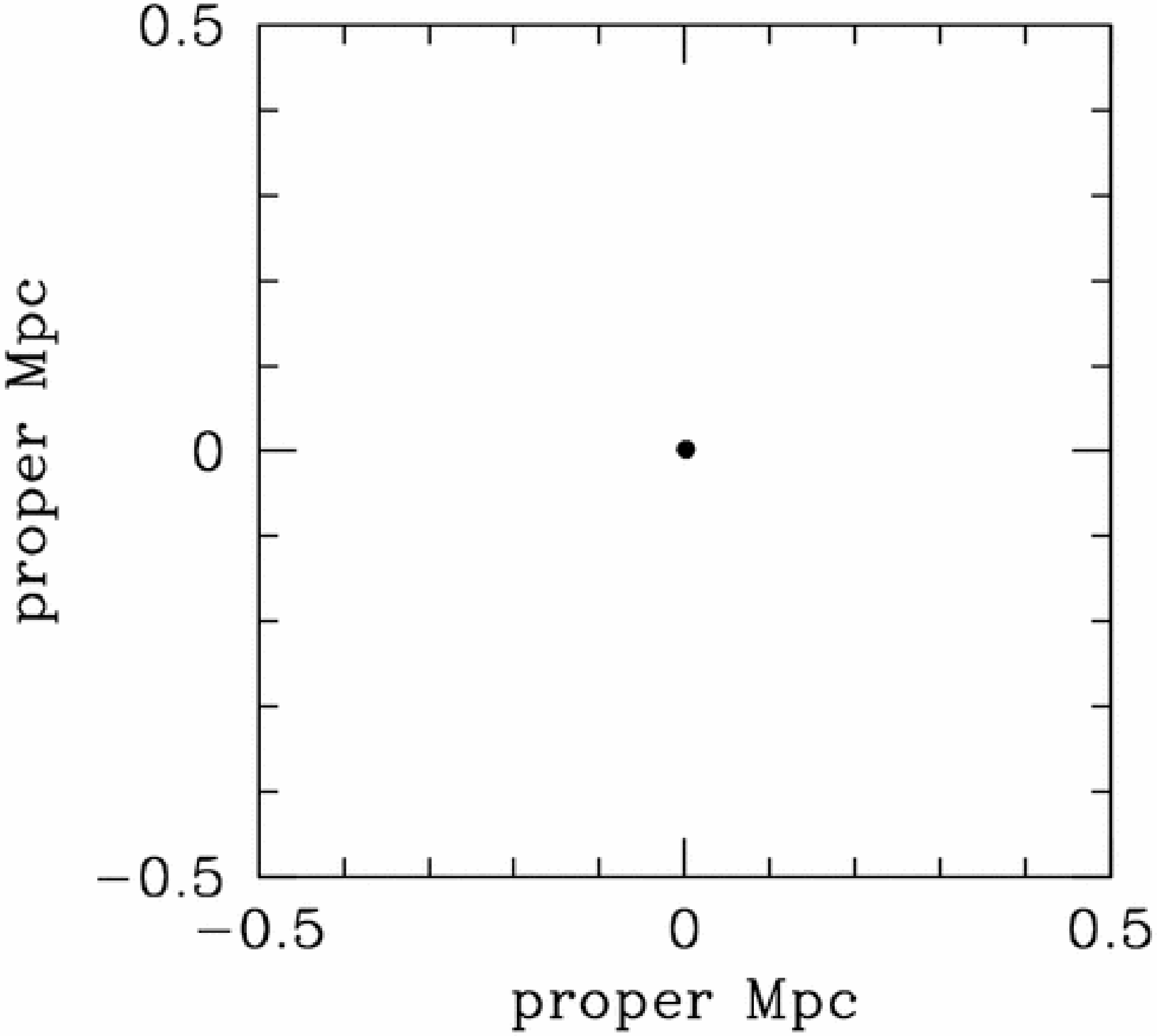
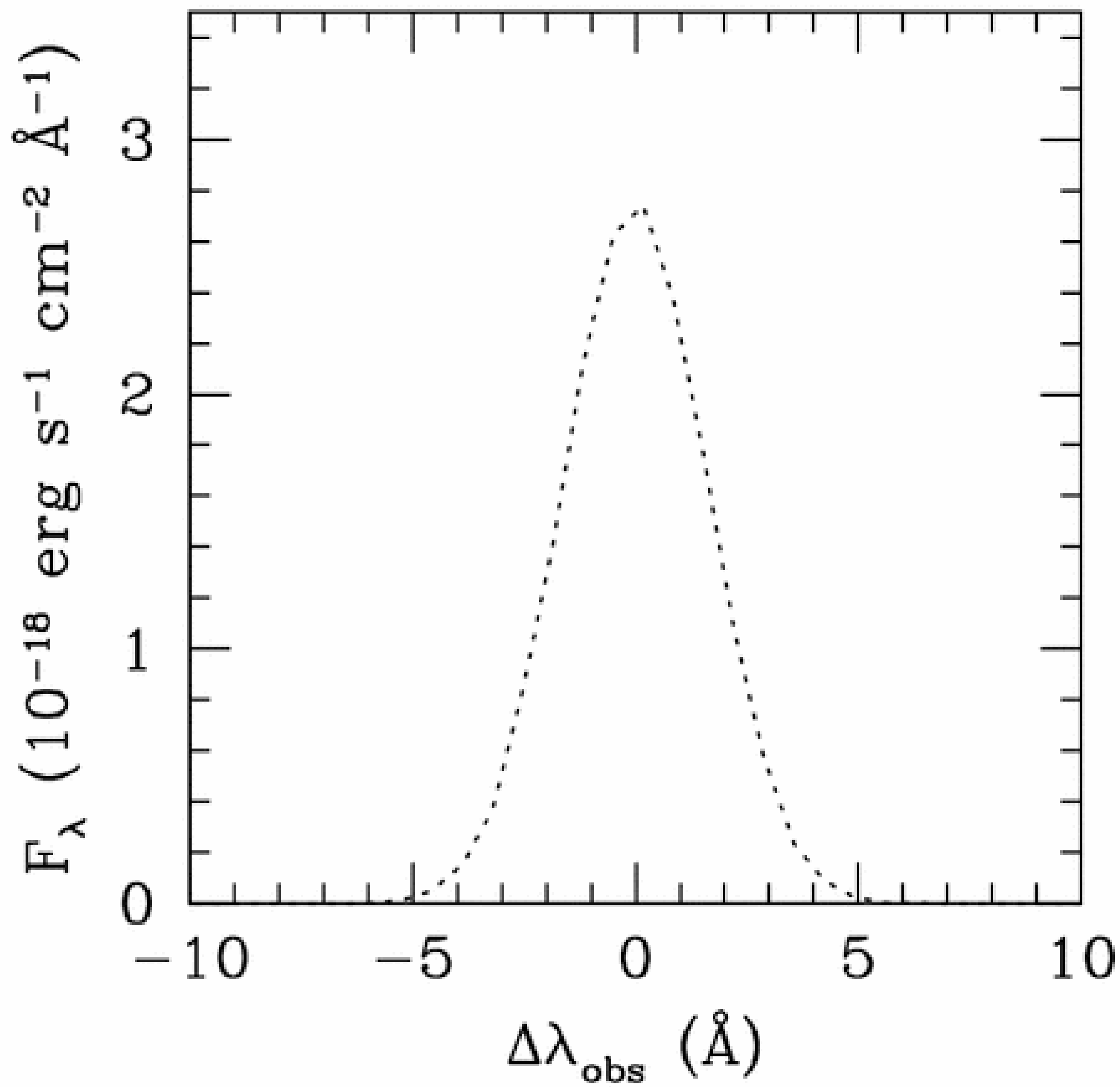
Lyα Radiative Transfer Modeling of LAEs

An Individual LAE

Lyα photons: spatial diffusion
frequency diffusion





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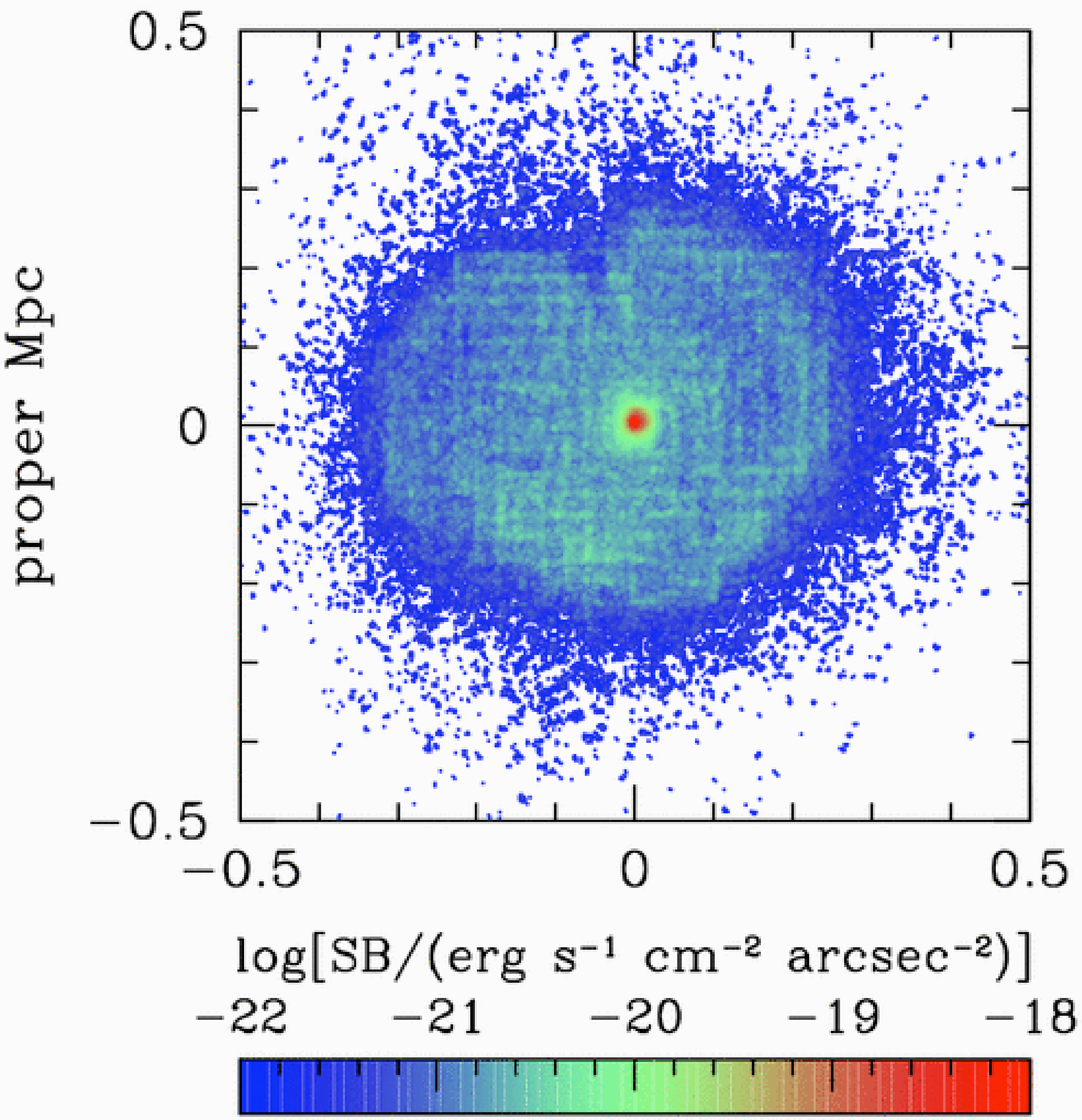

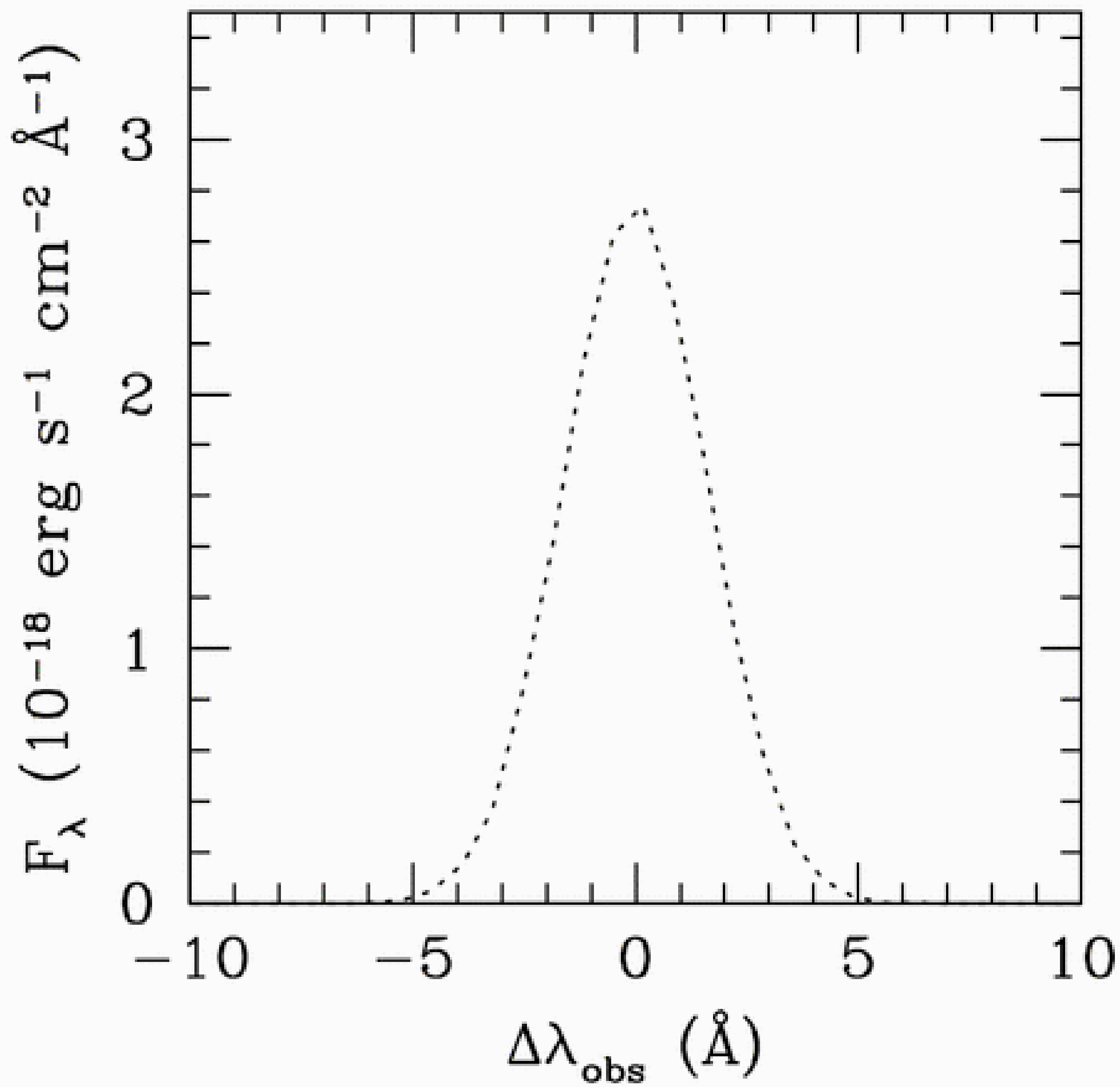

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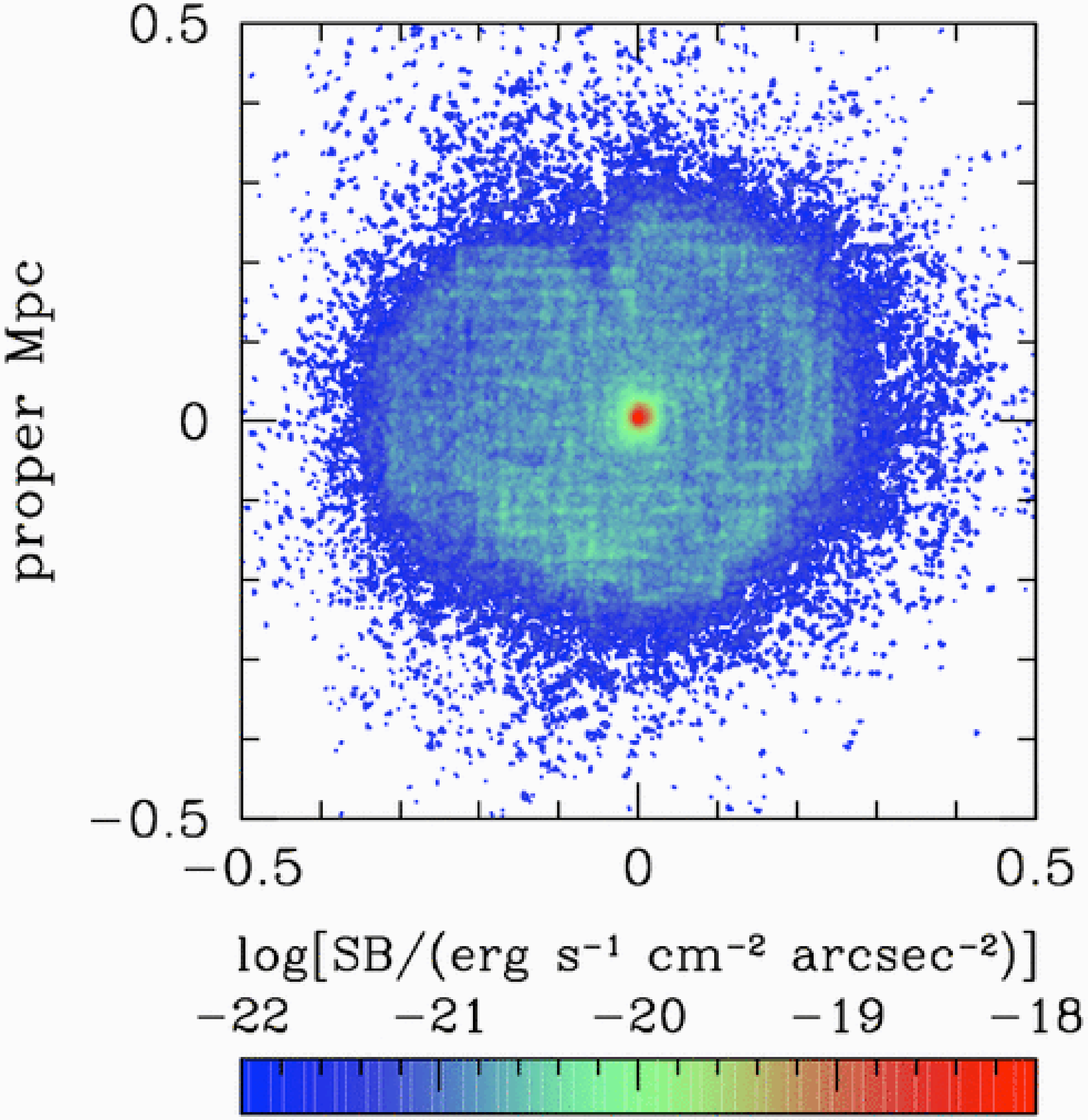

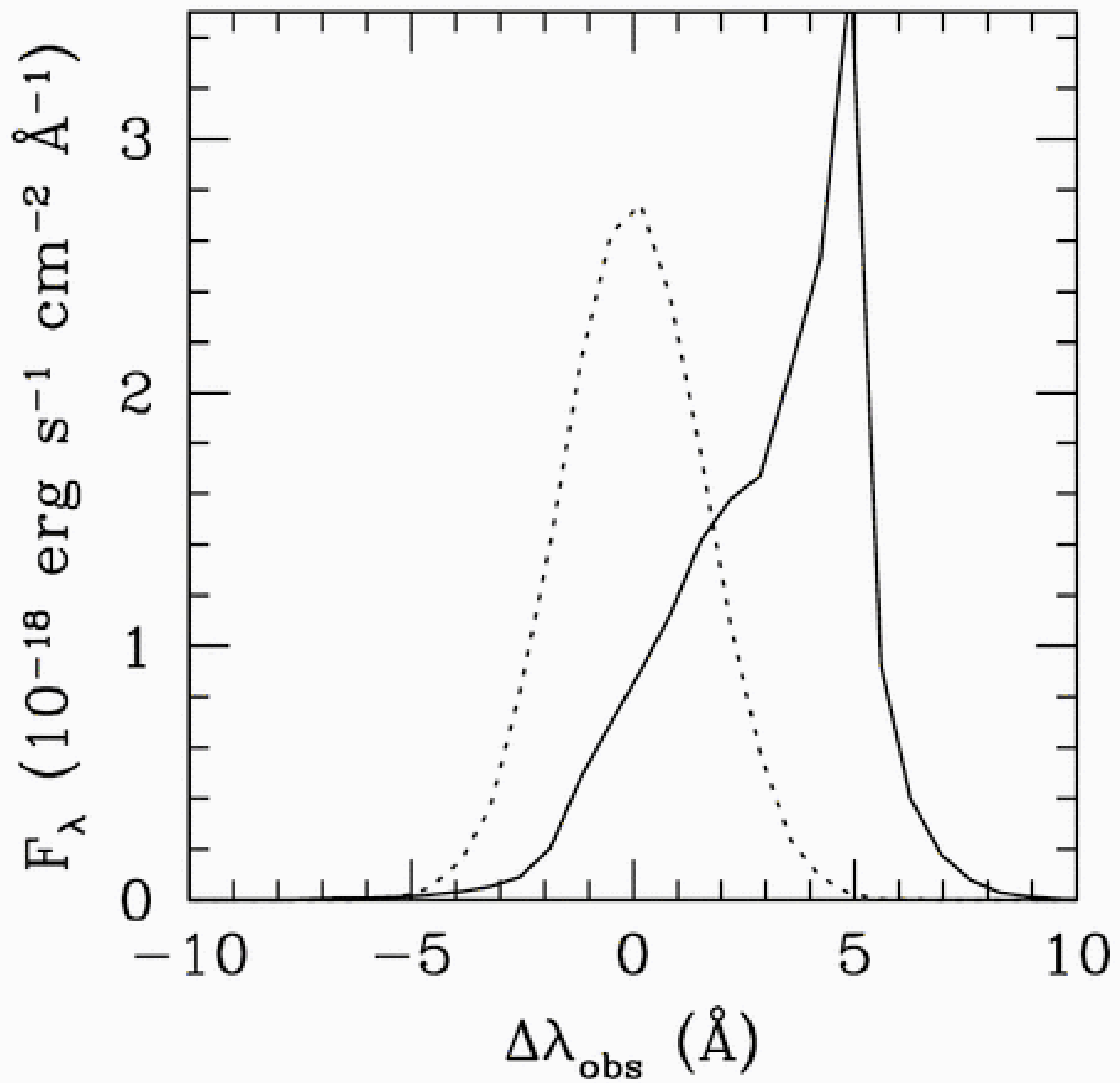

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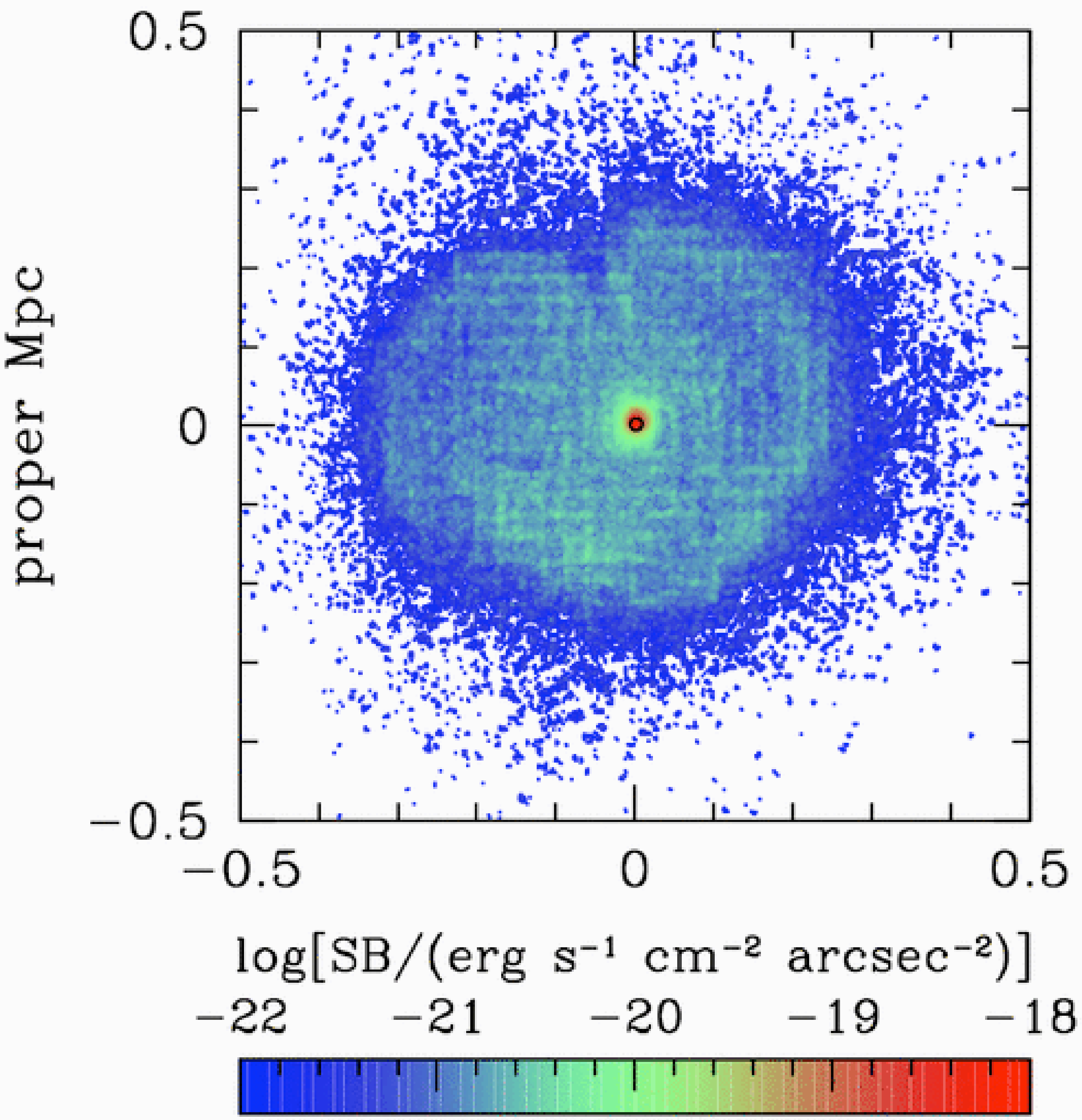

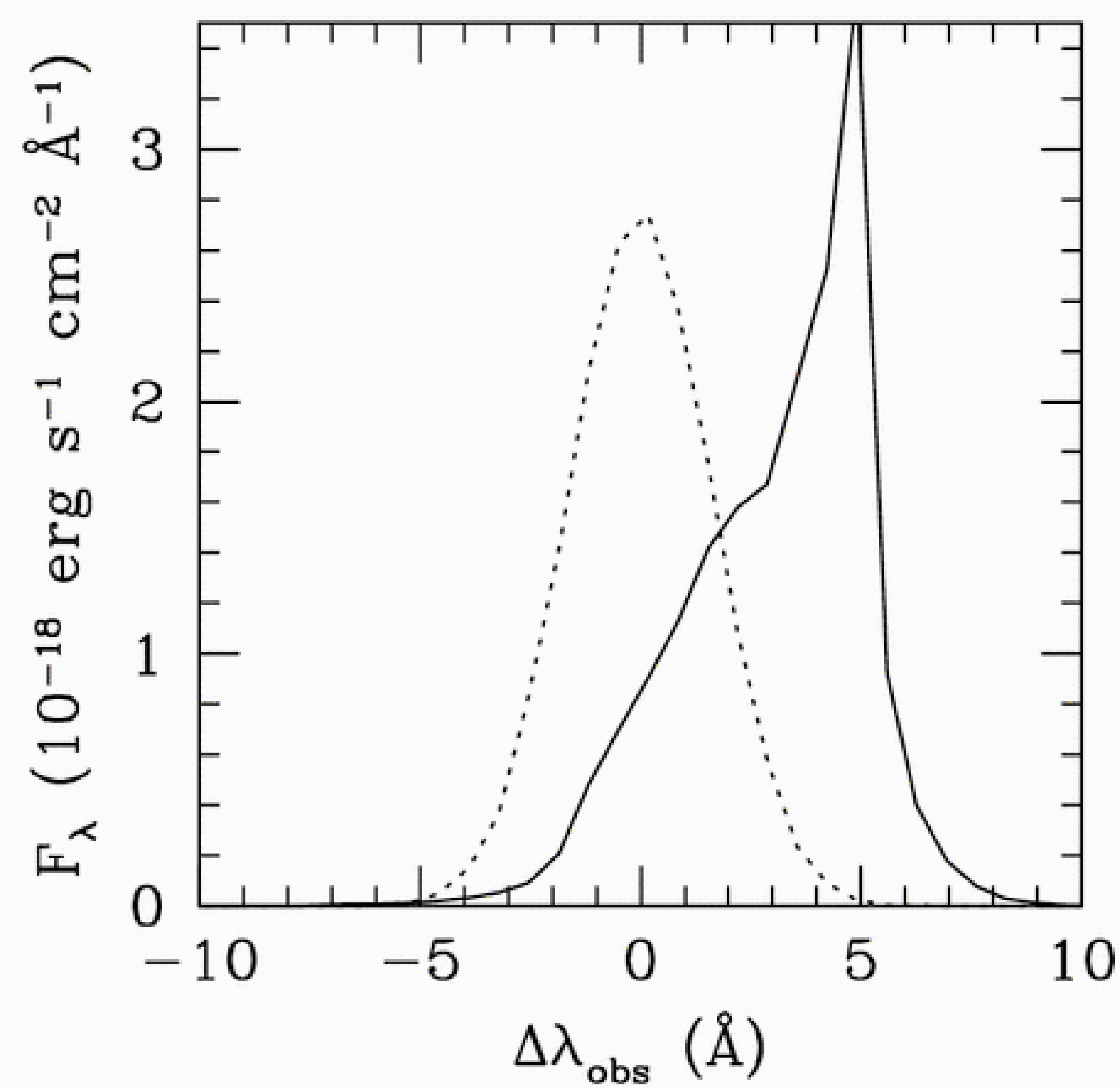

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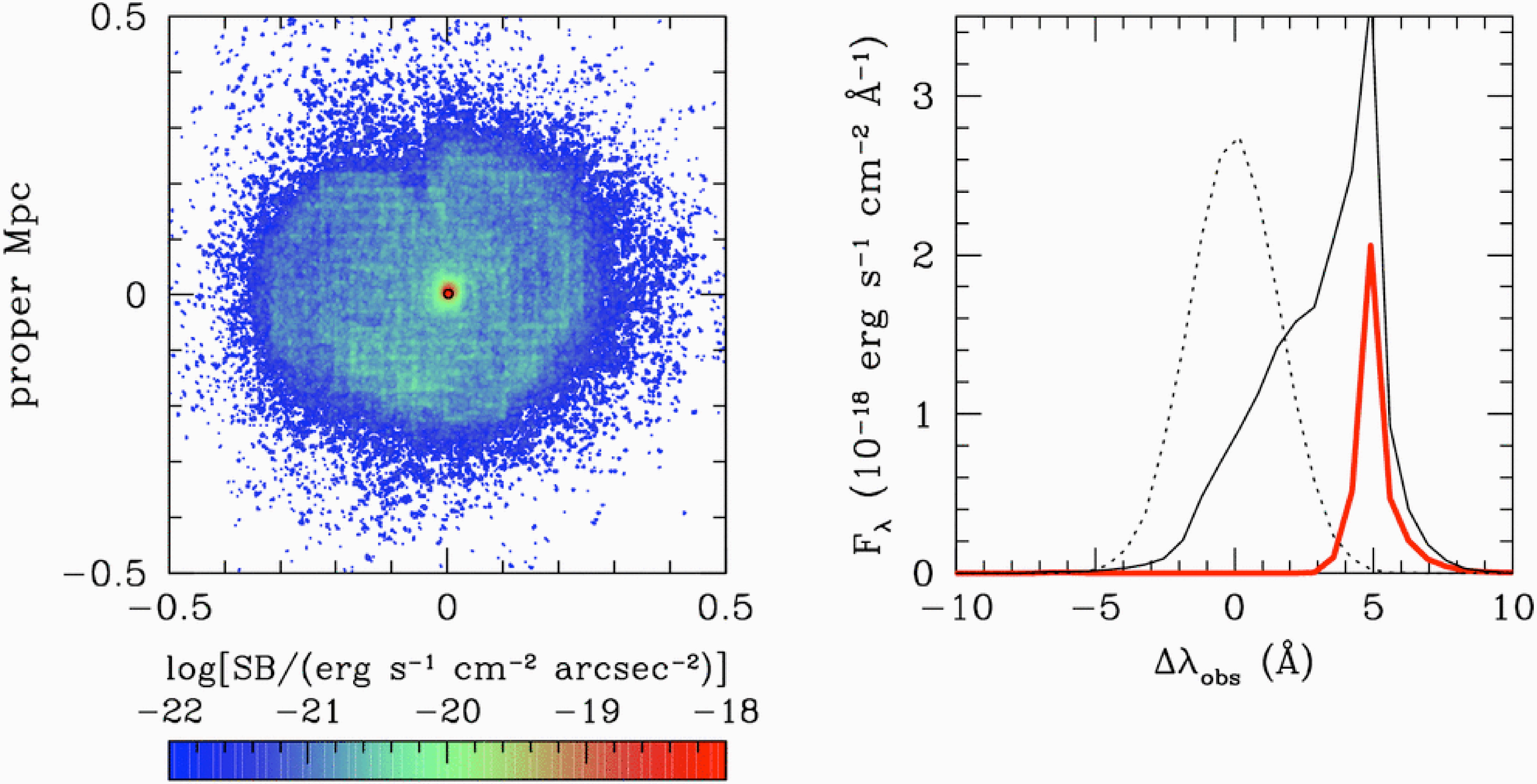

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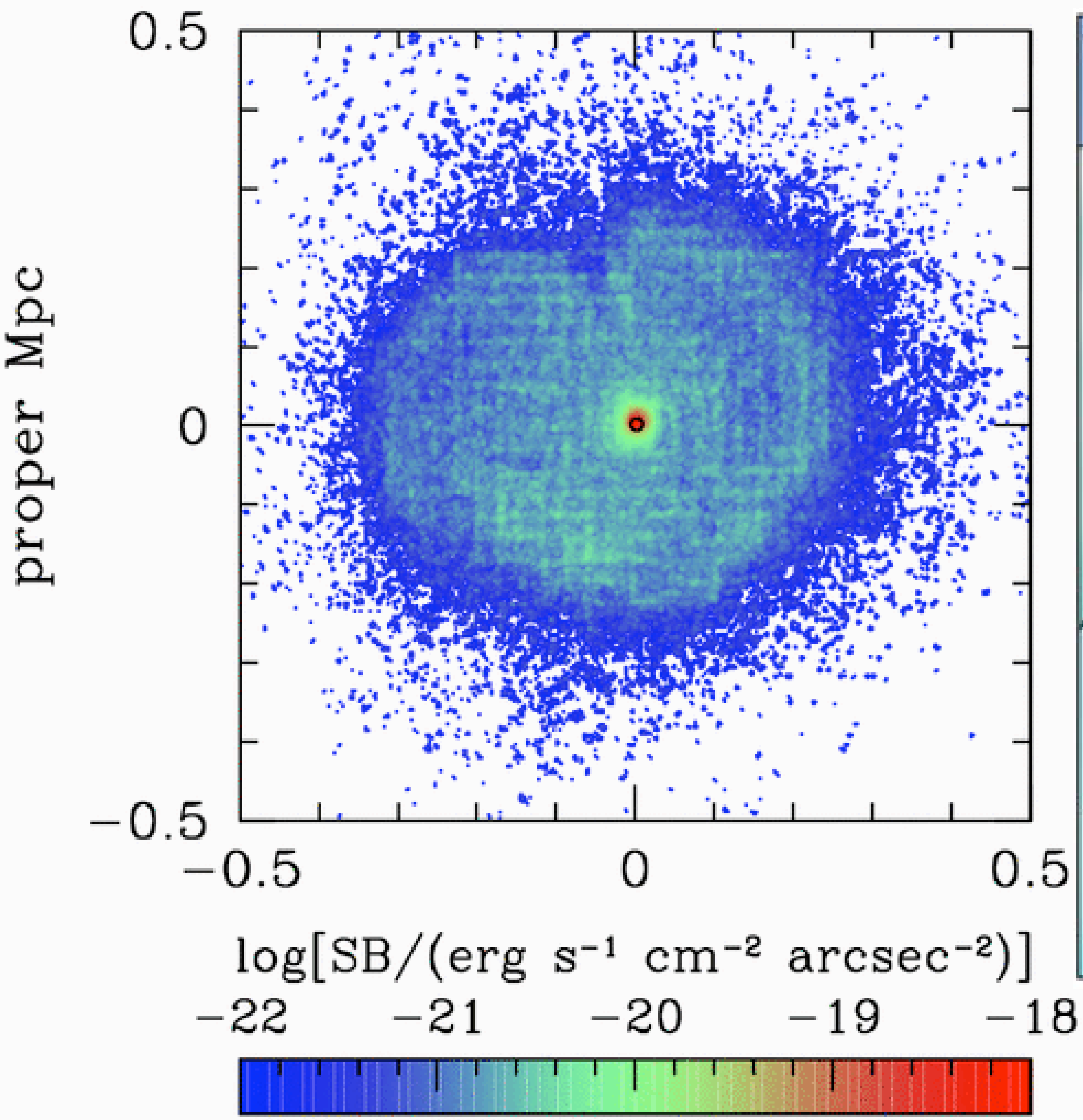
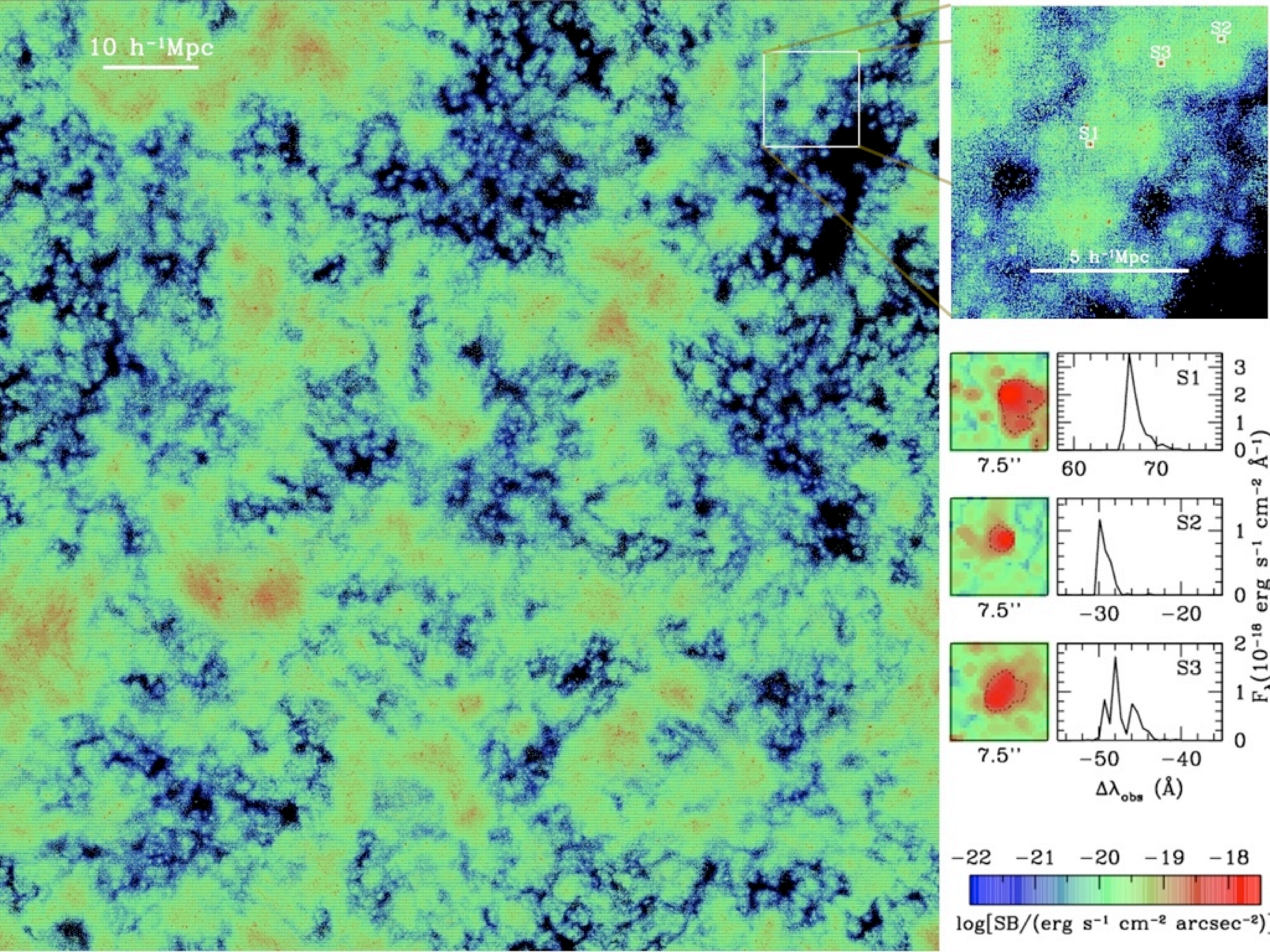
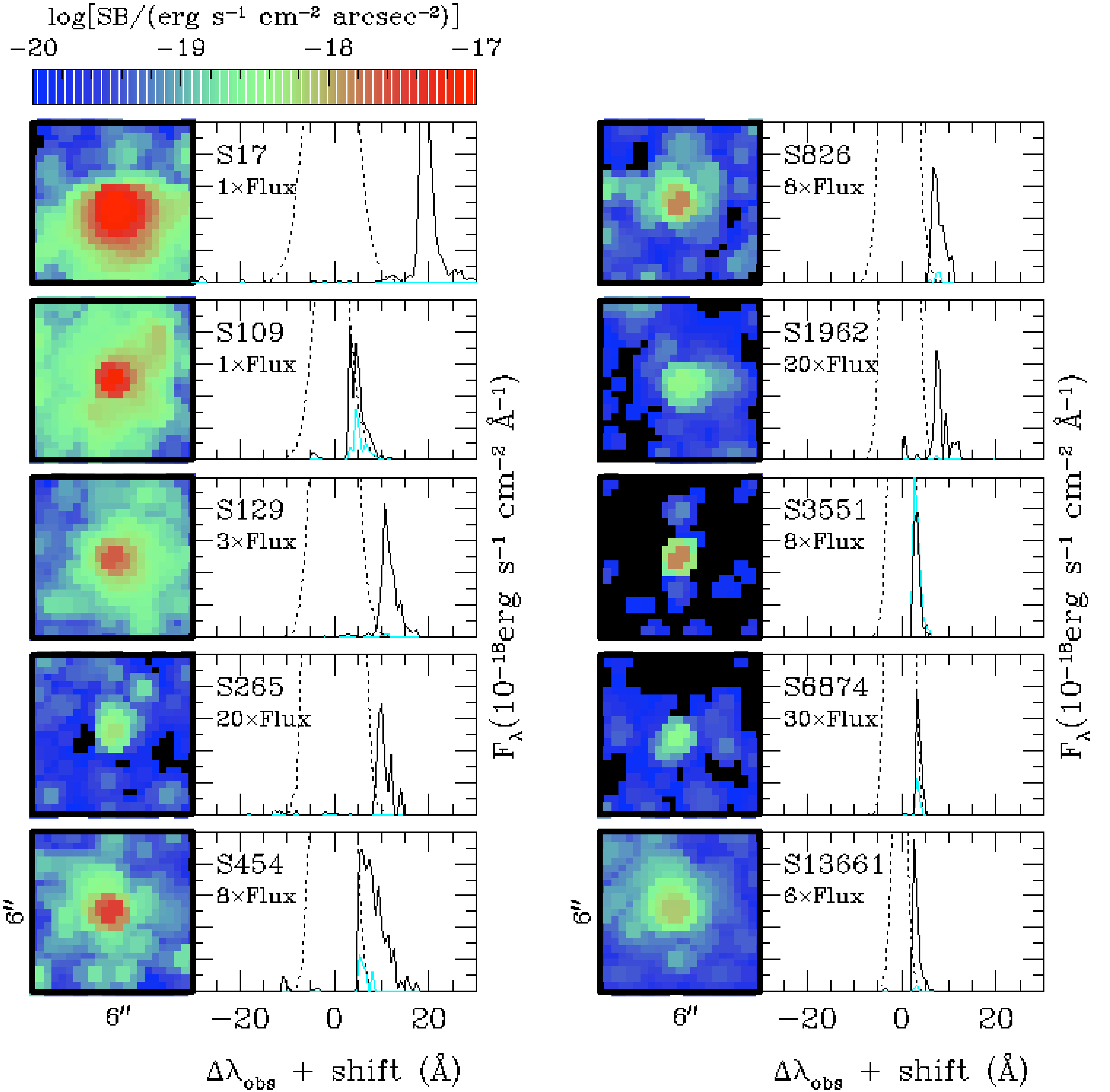
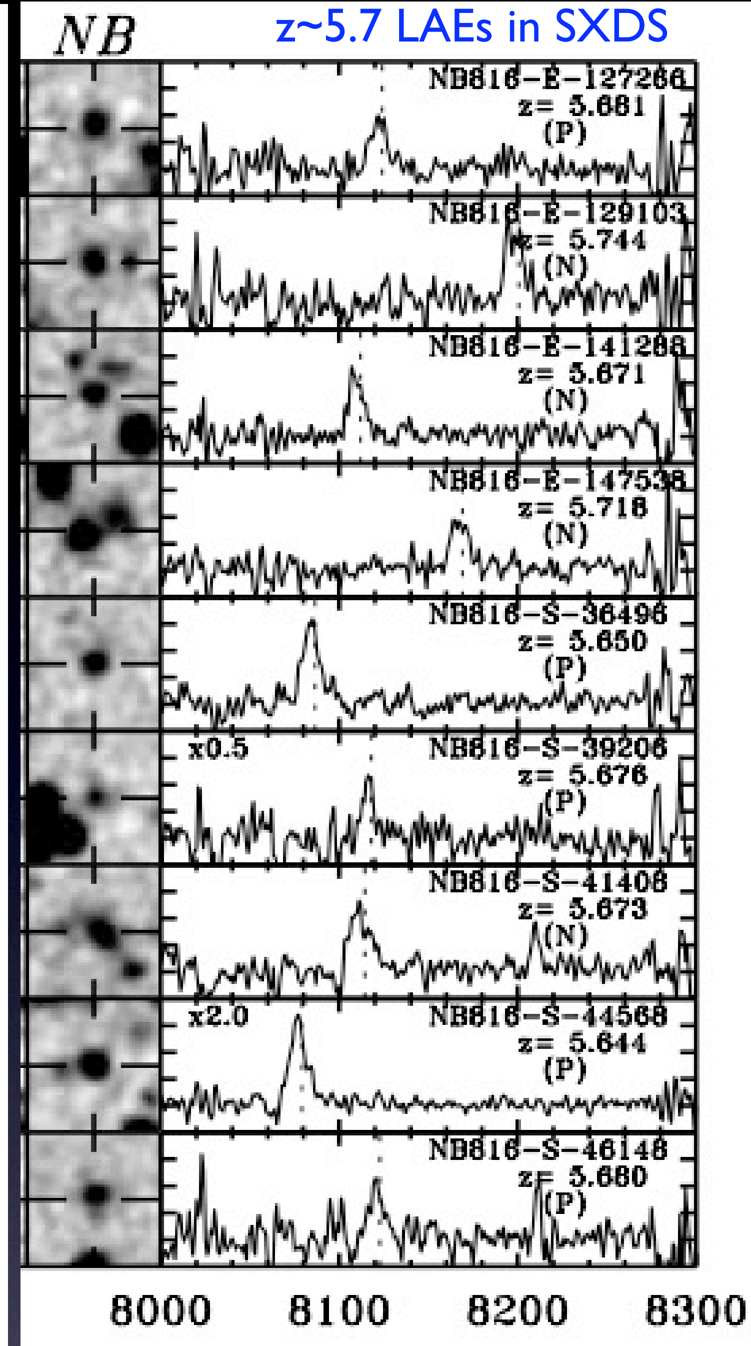




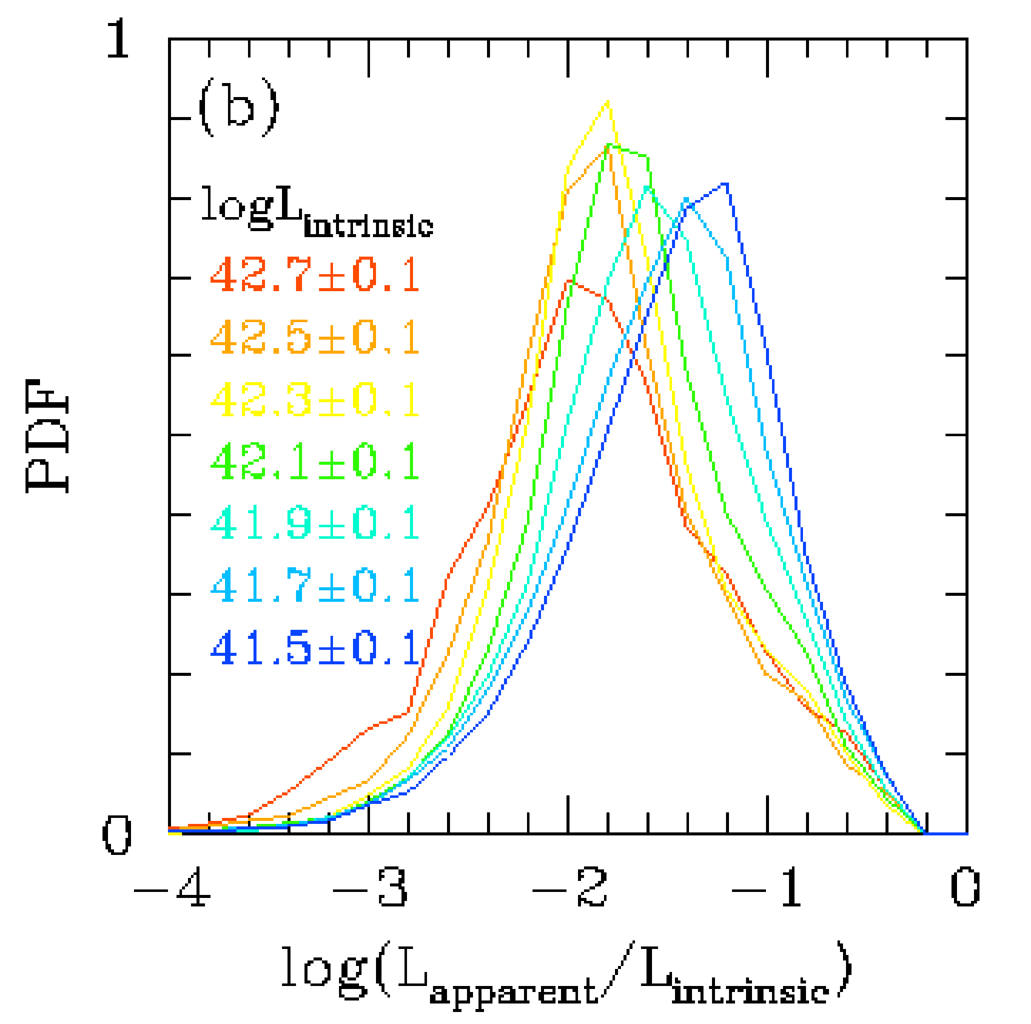
10 h⁻¹Mpc
S1
S2
S3
5 h⁻¹Mpc
7.5''
7.5''
7.5''
60
70
−30
−20
−50
−40
0
1
2
3
$\Delta\lambda_{obs}$ (Å)
$F_\lambda(10^{-18}$ erg s^{-1} cm^{-2} Å$^{-1})$
−22 −21 −20 −19 −18
log[SB/(erg s^{-1} cm^{-2} arcsec^{-2})]

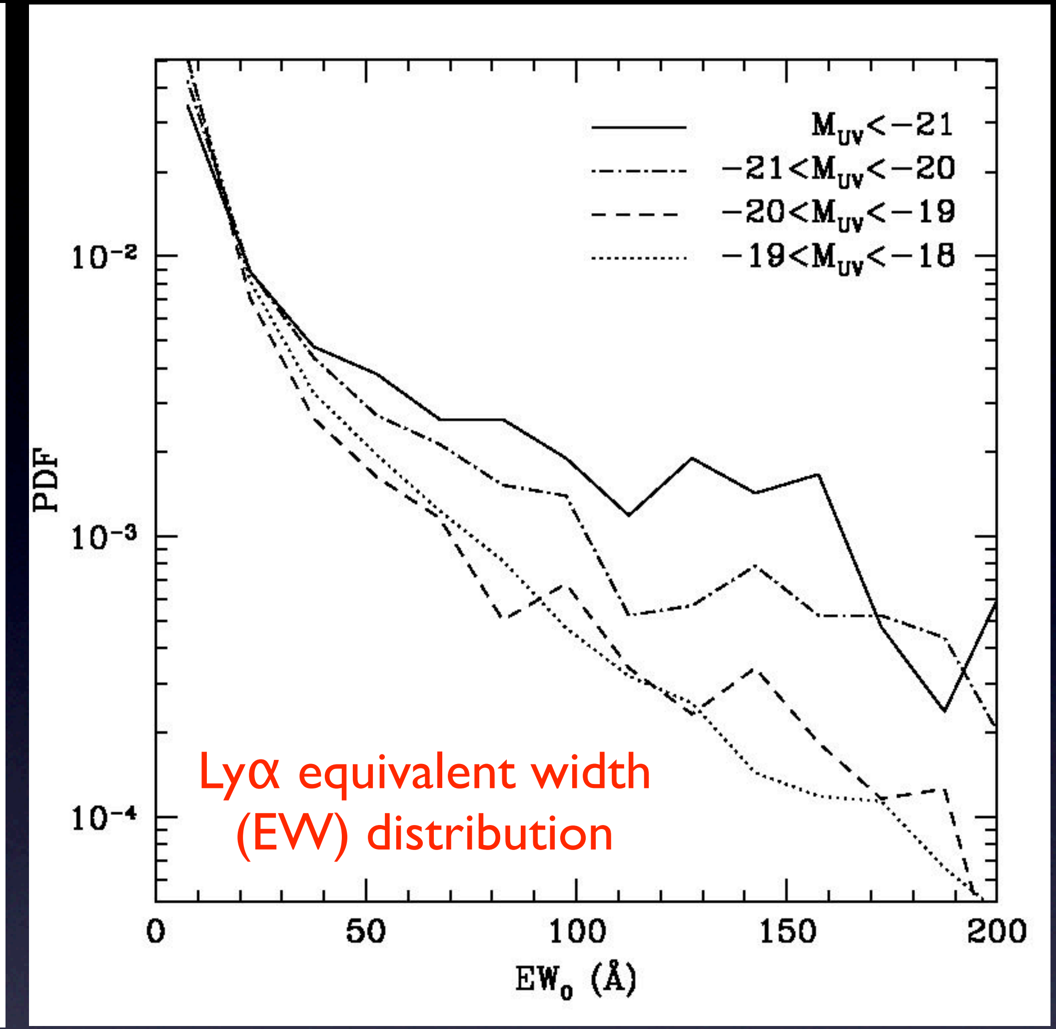




Ouchi et al. 2008

Intrinsic and Apparent Lyα Luminosity





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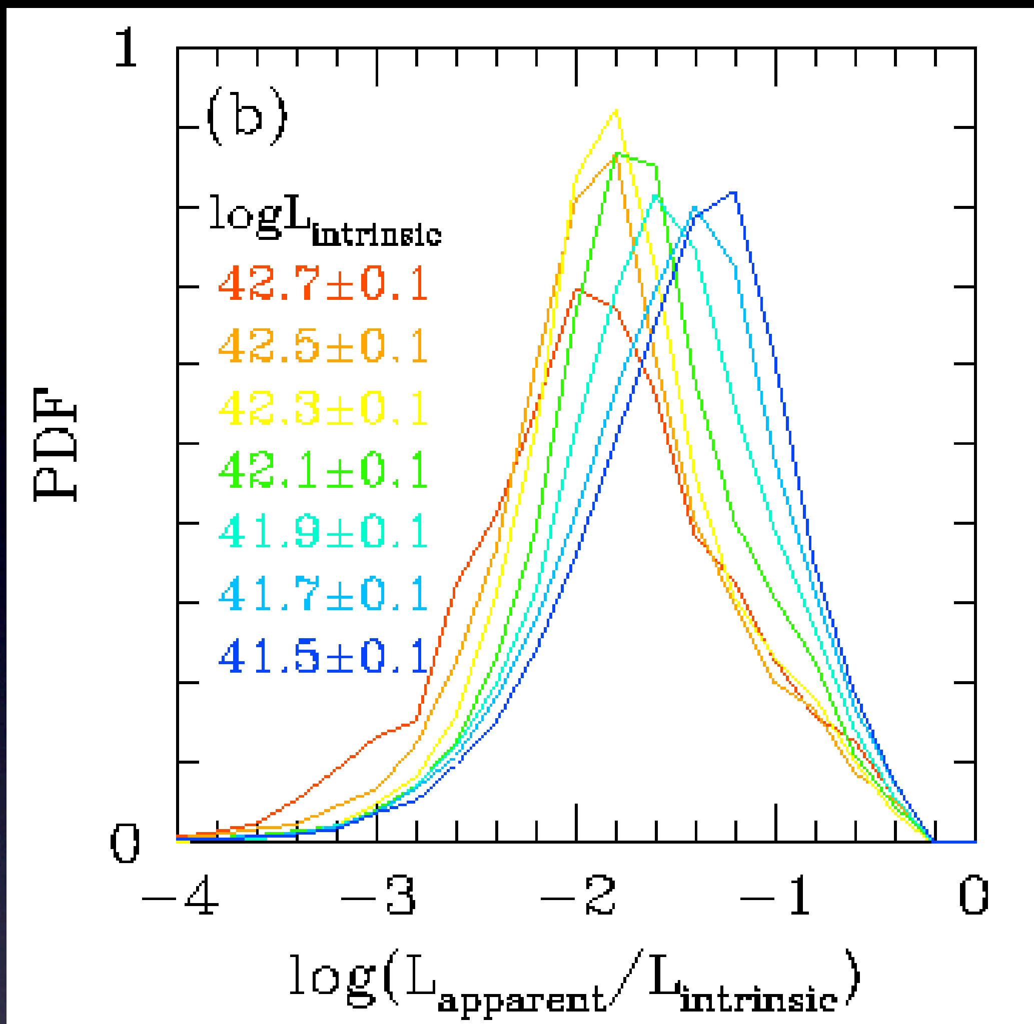
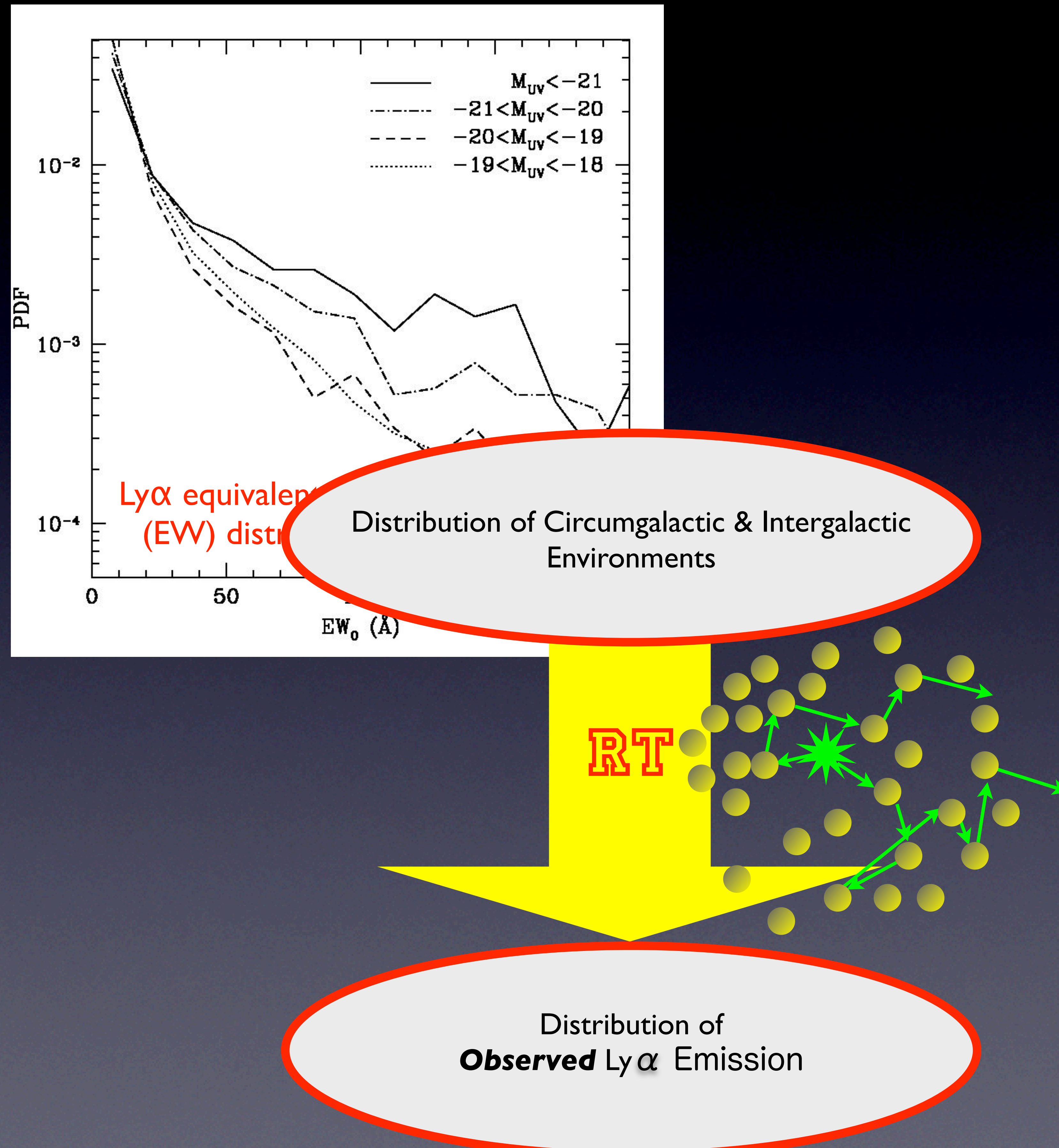
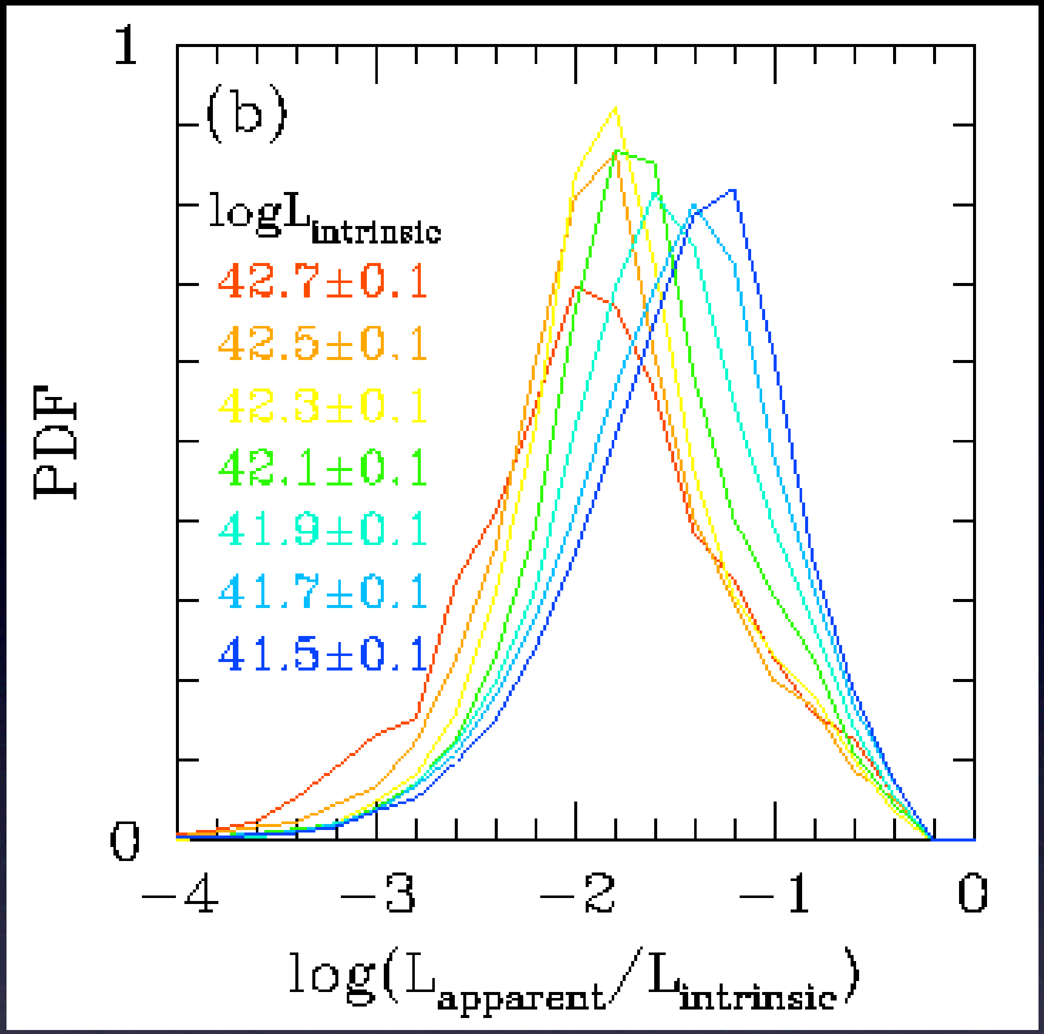
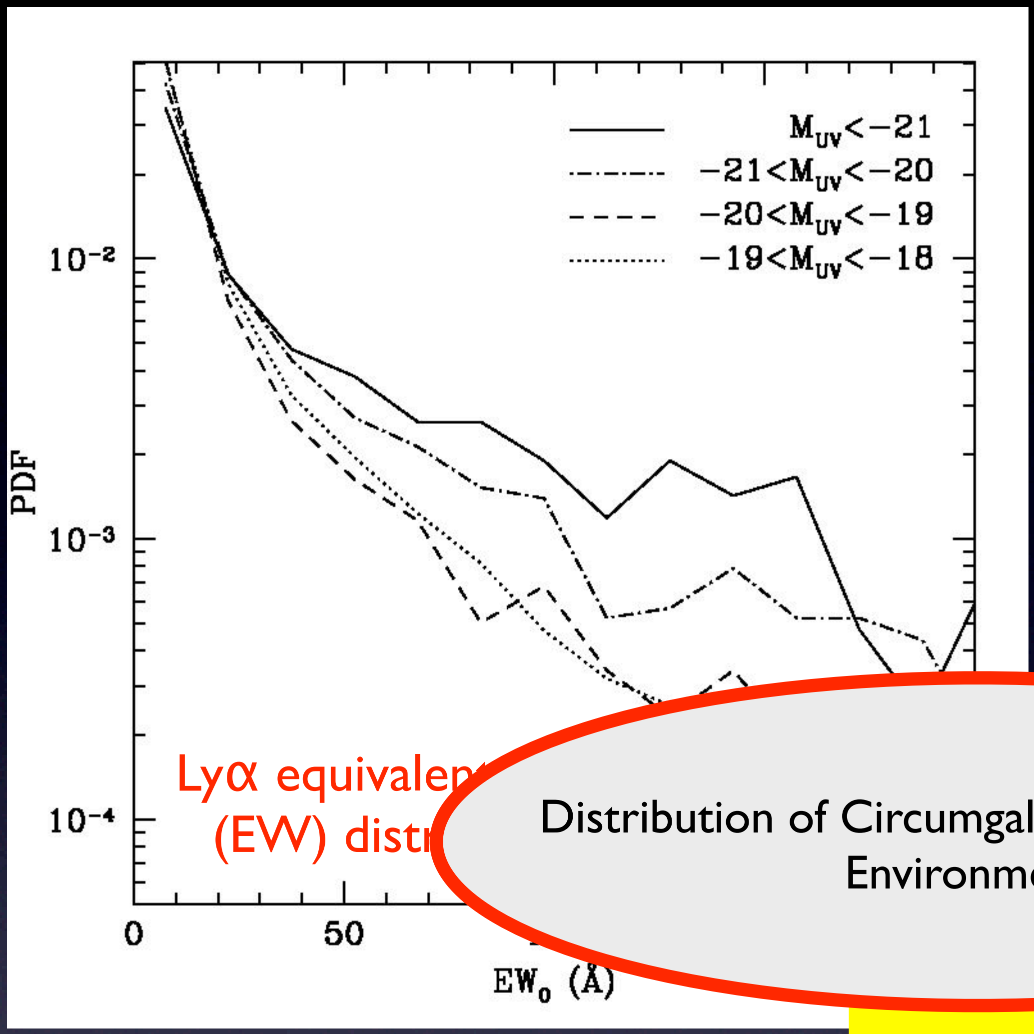
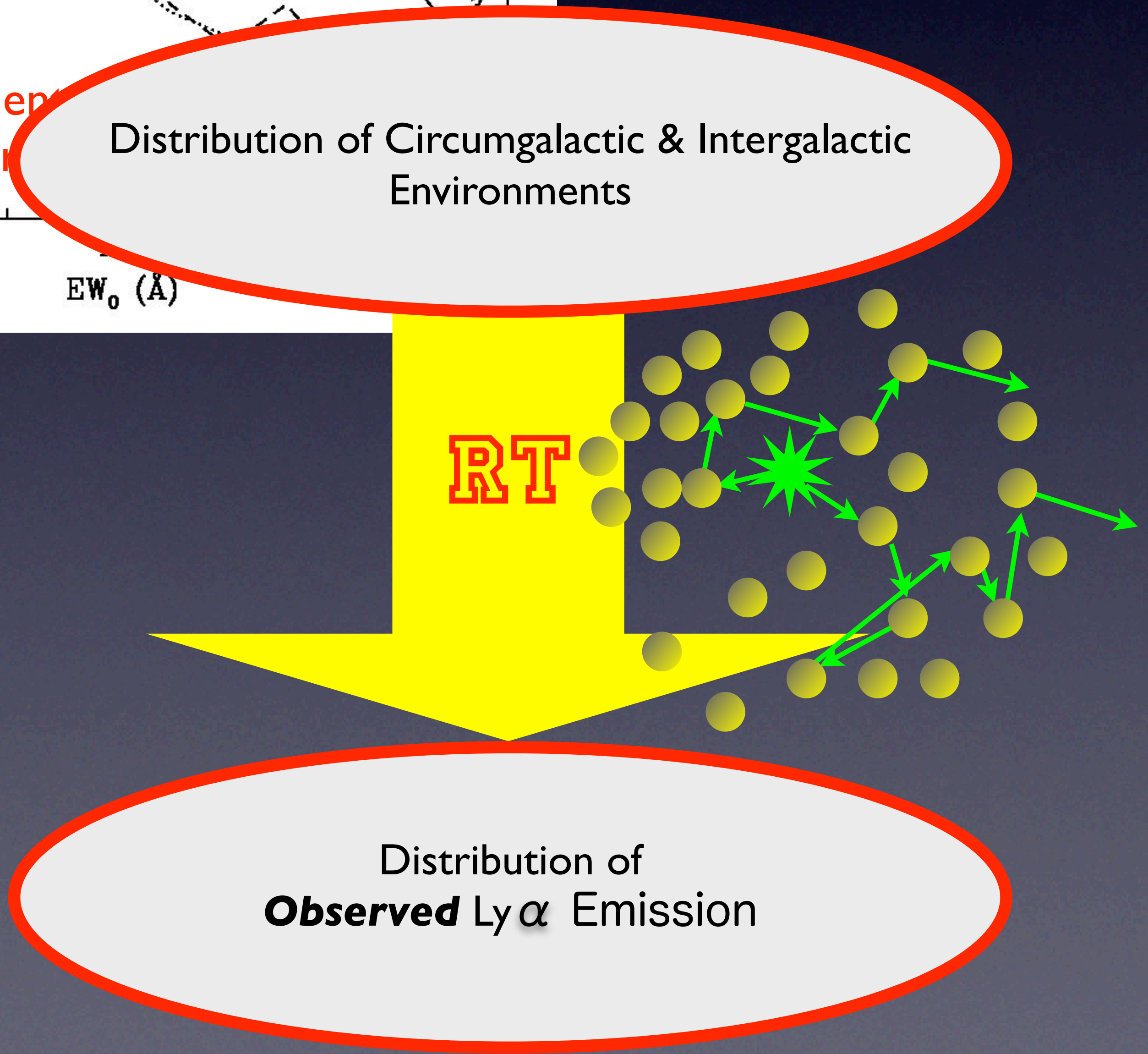




Intrinsic and Apparent Lyα Luminosity

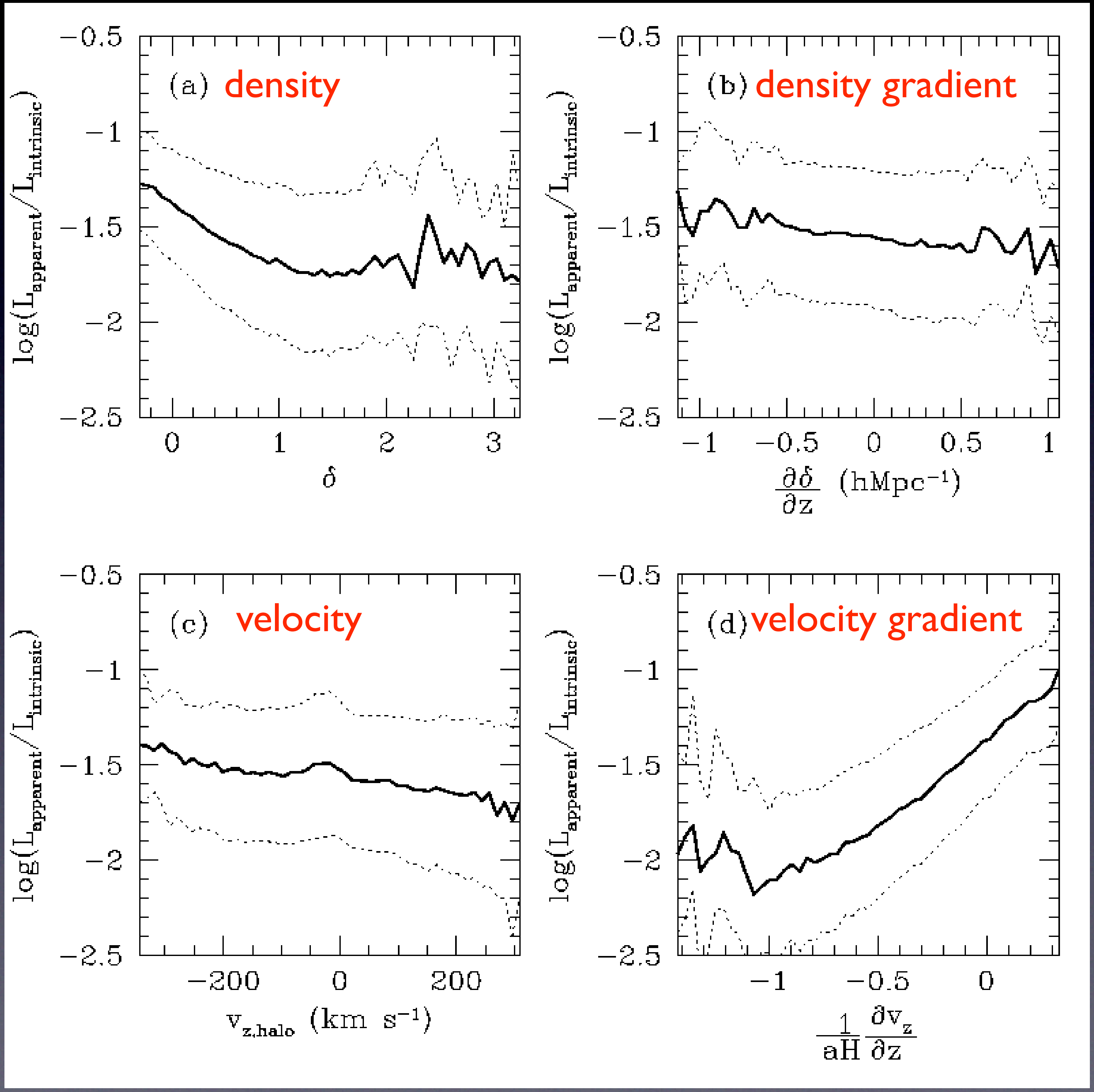


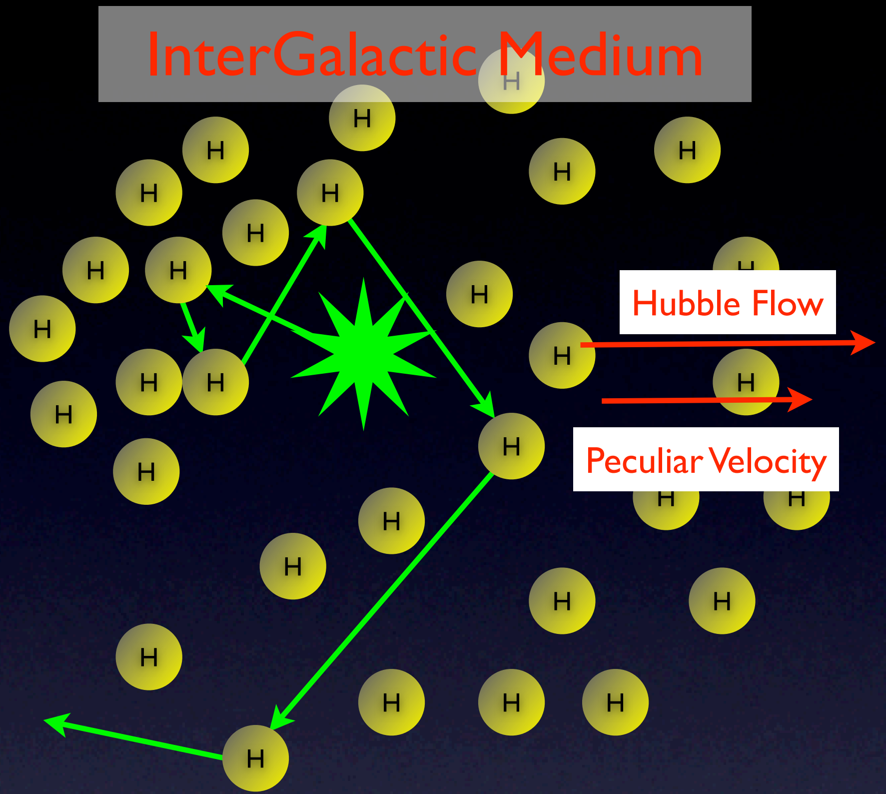


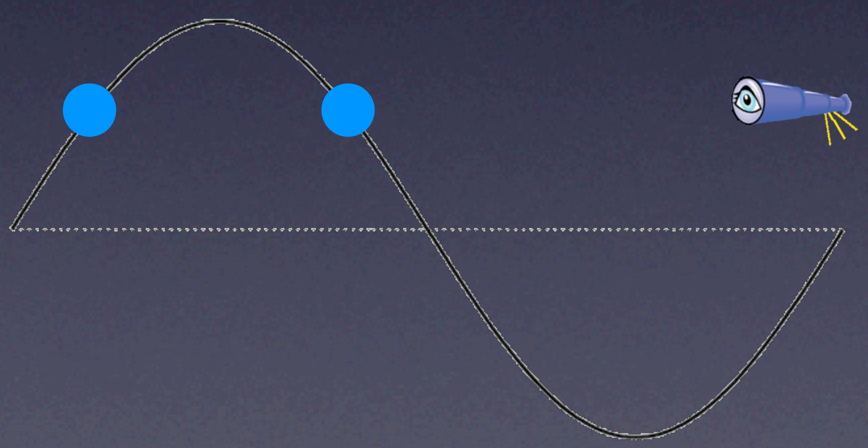


- Mechanism for Lyα EW distribution
- Effective Lyα escape fraction
- Effective duty cycle of LAEs

Various Environment Factors Determining the Apparent to Intrinsic Luminosity Ratio



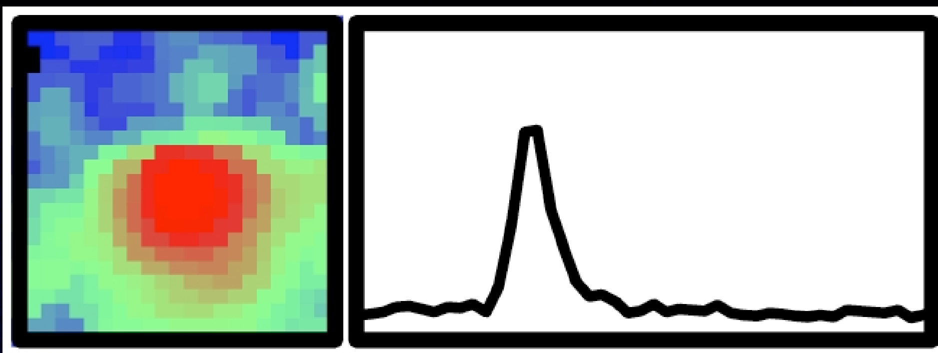




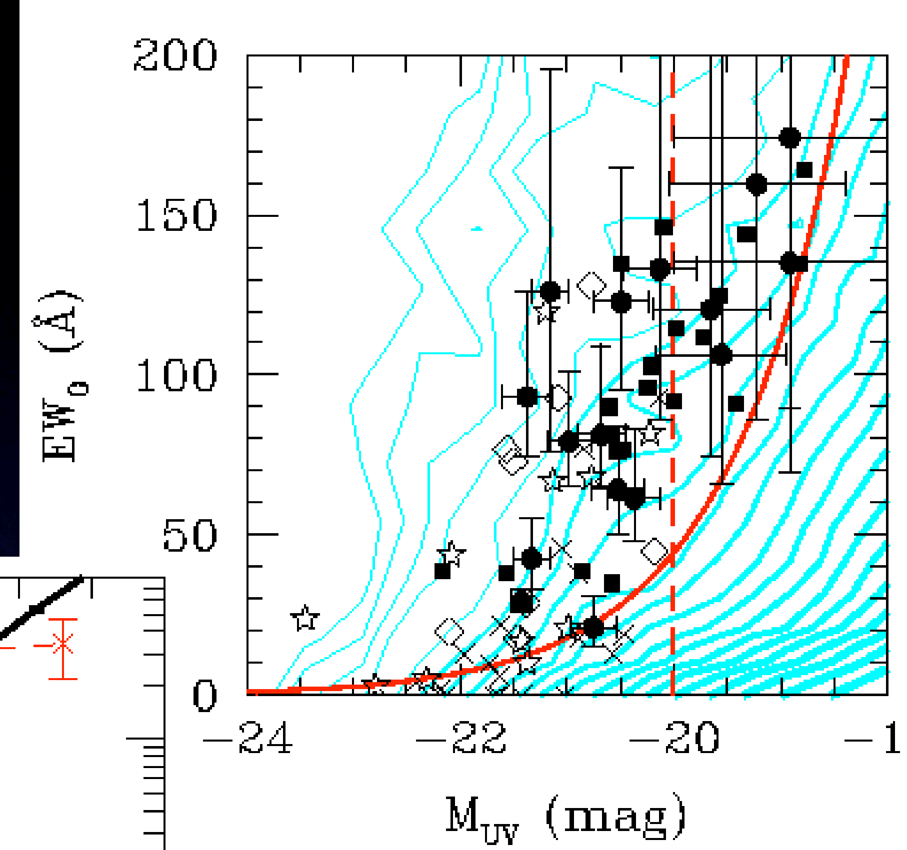
Comparison with Observation

Morphology

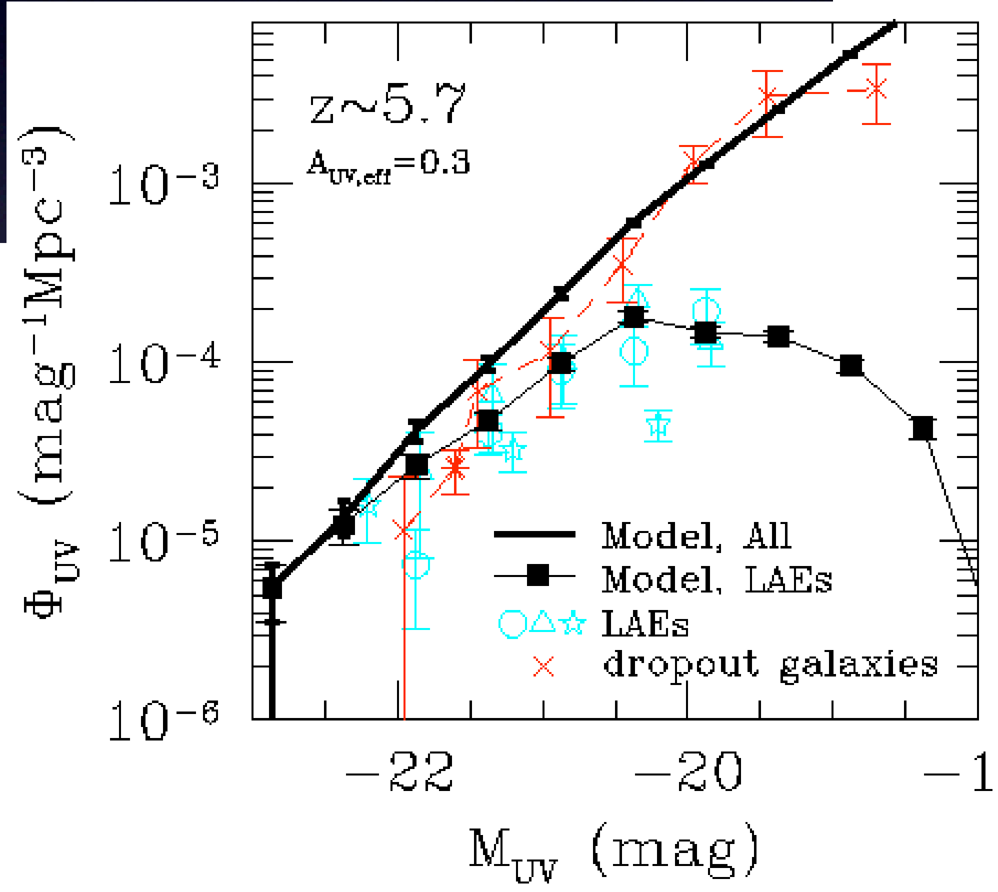
Spectra



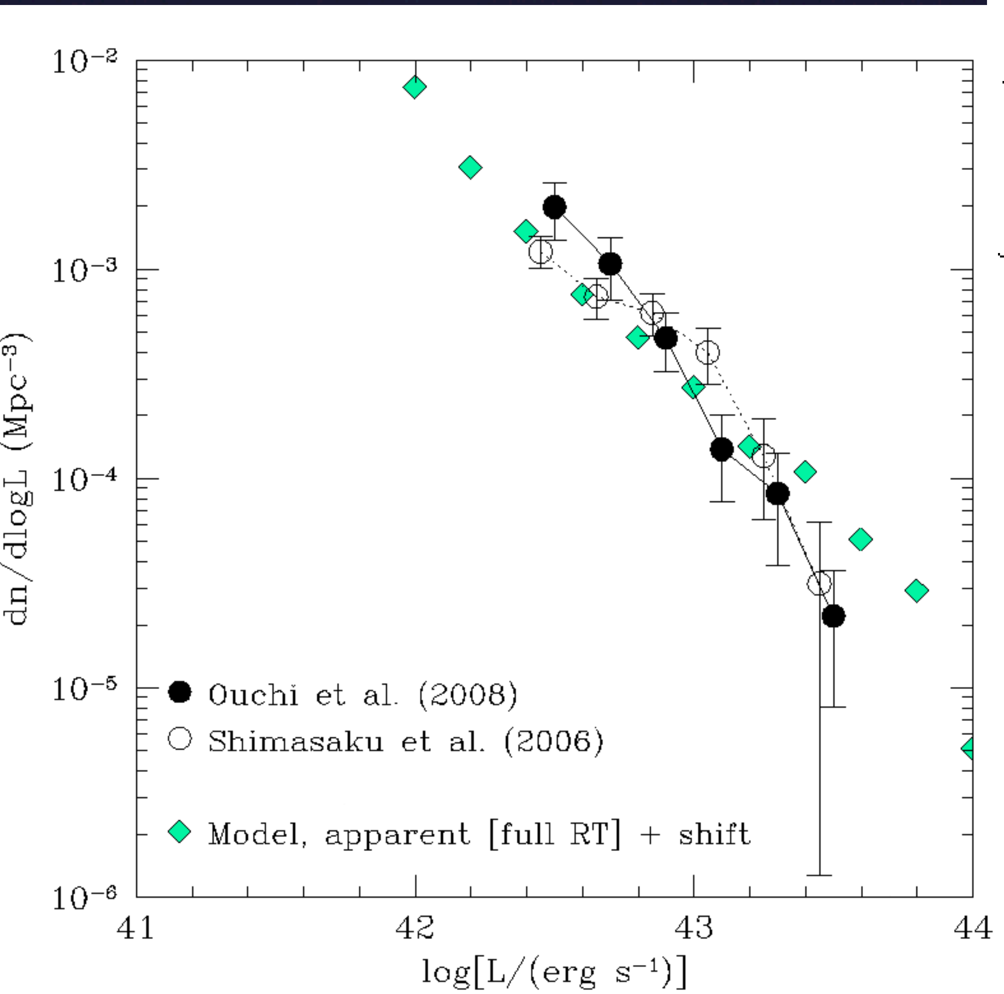
Lyα Equivalent Width Distribution



UV Luminosity Function

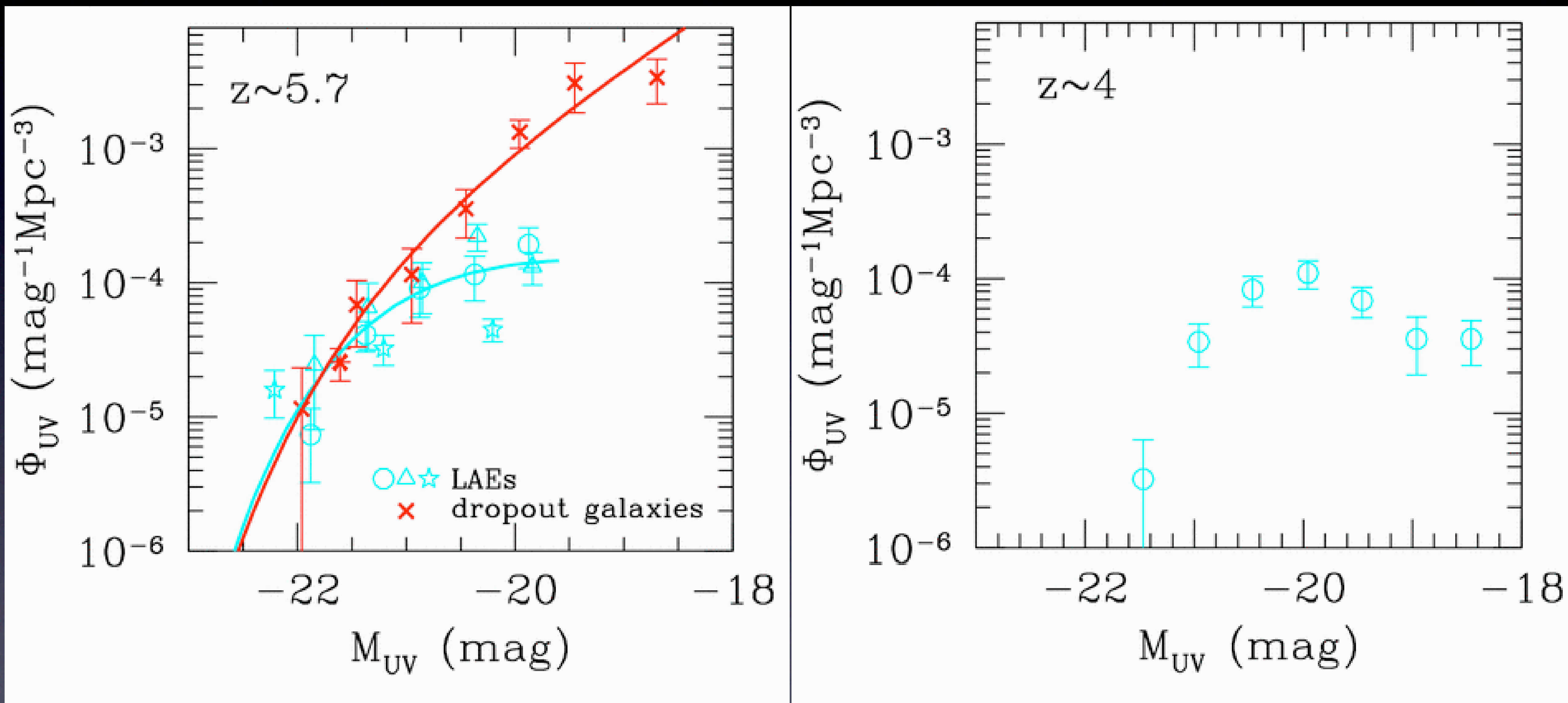


Lyα Luminosity Function



Comparison with Observation

UV Luminosity Function

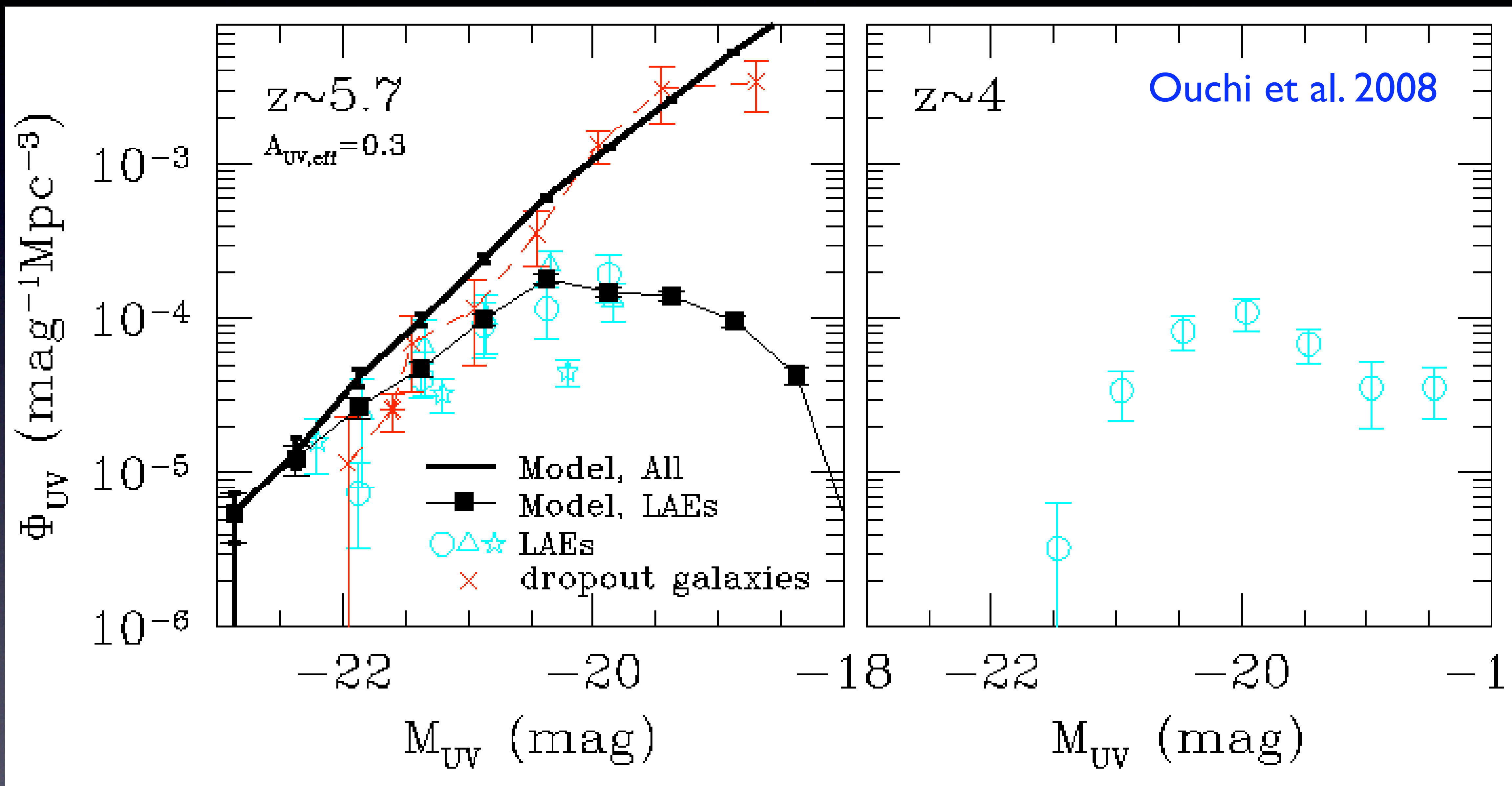


Ouchi et al. 2008

Puzzle: turnover and drop toward low luminosity

Comparison with Observation

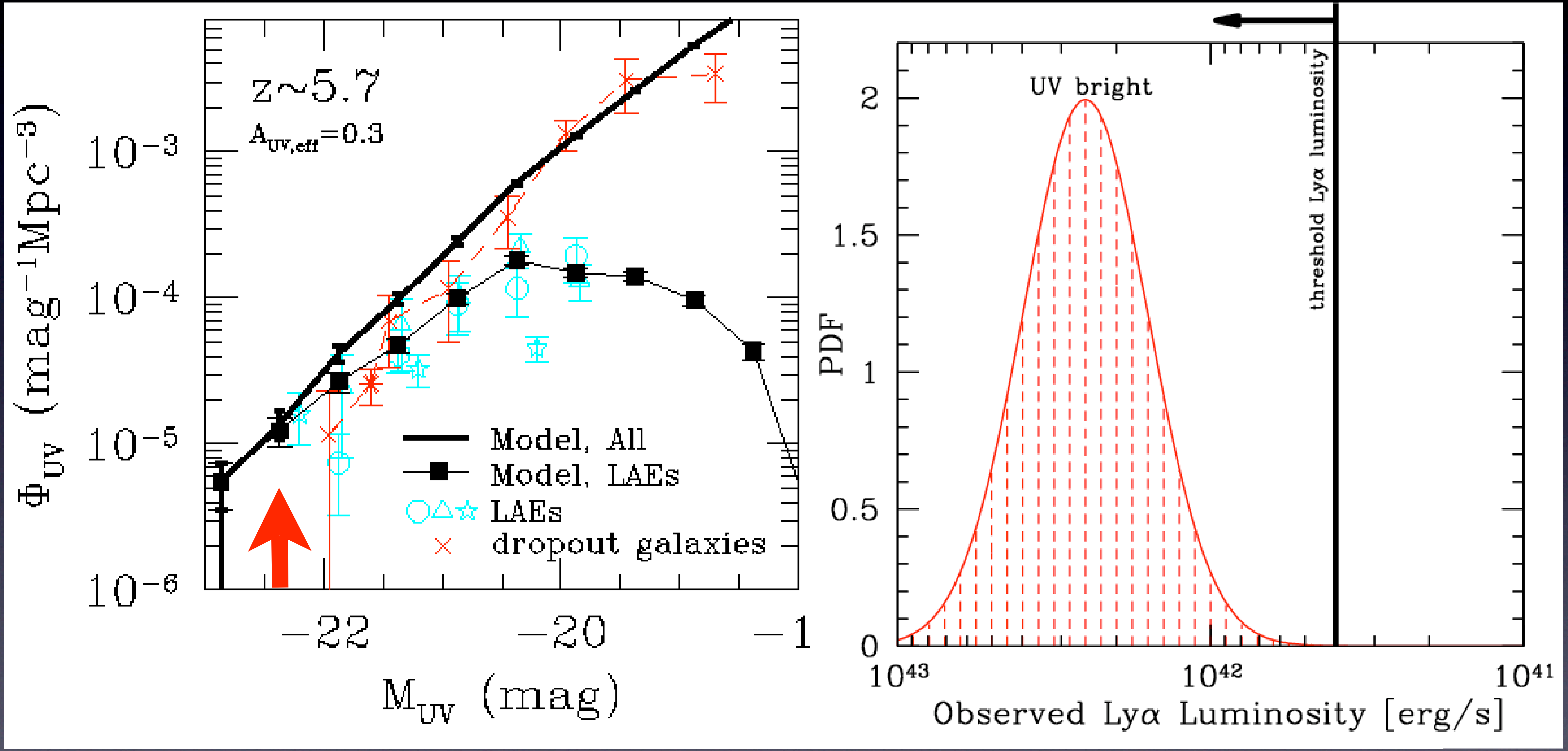
UV Luminosity Function



Puzzle Solved: broad distribution of apparent Lyα luminosity at fixed intrinsic (UV) luminosity

Comparison with Observation

UV Luminosity Function



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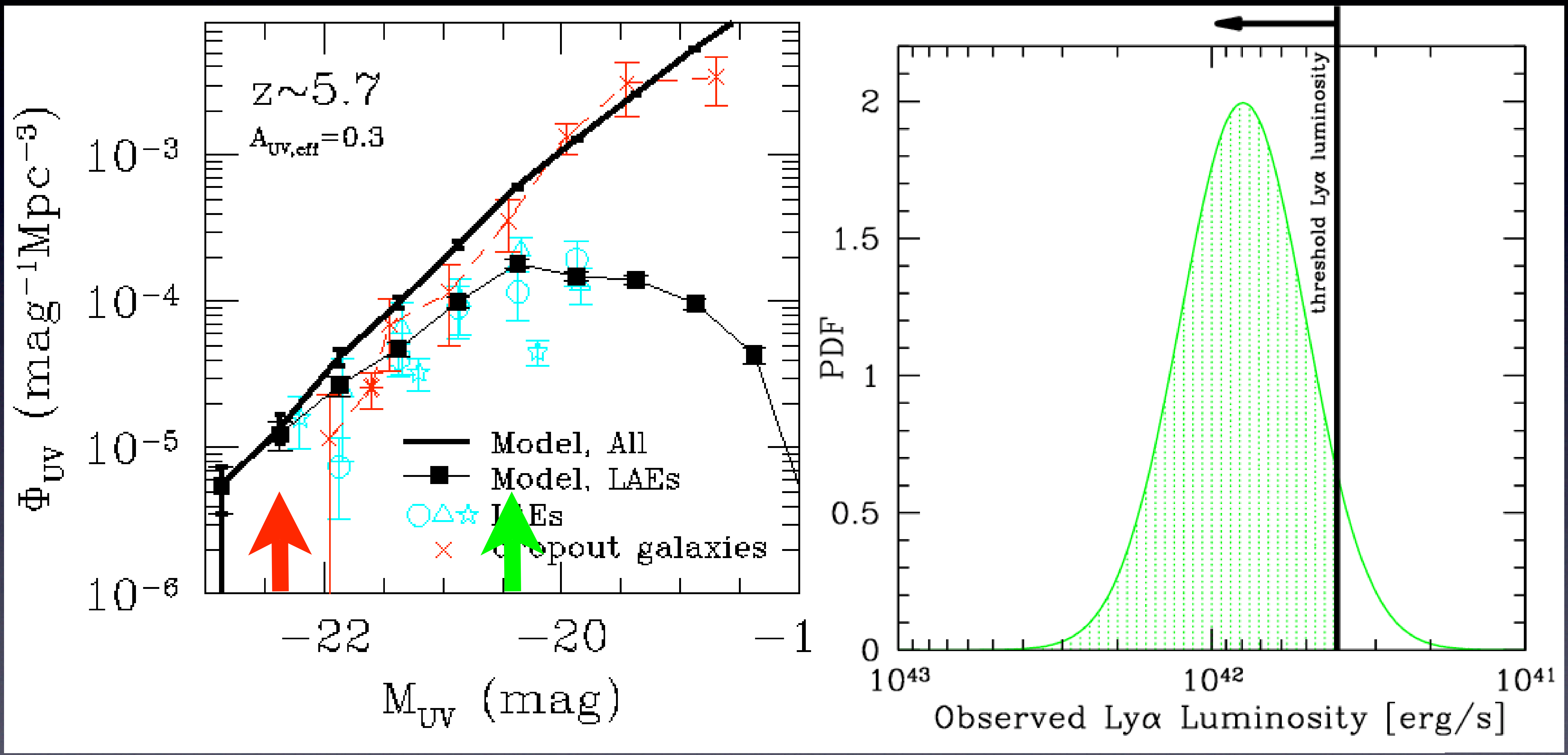
Comparison with Observation
UV Luminosity Function



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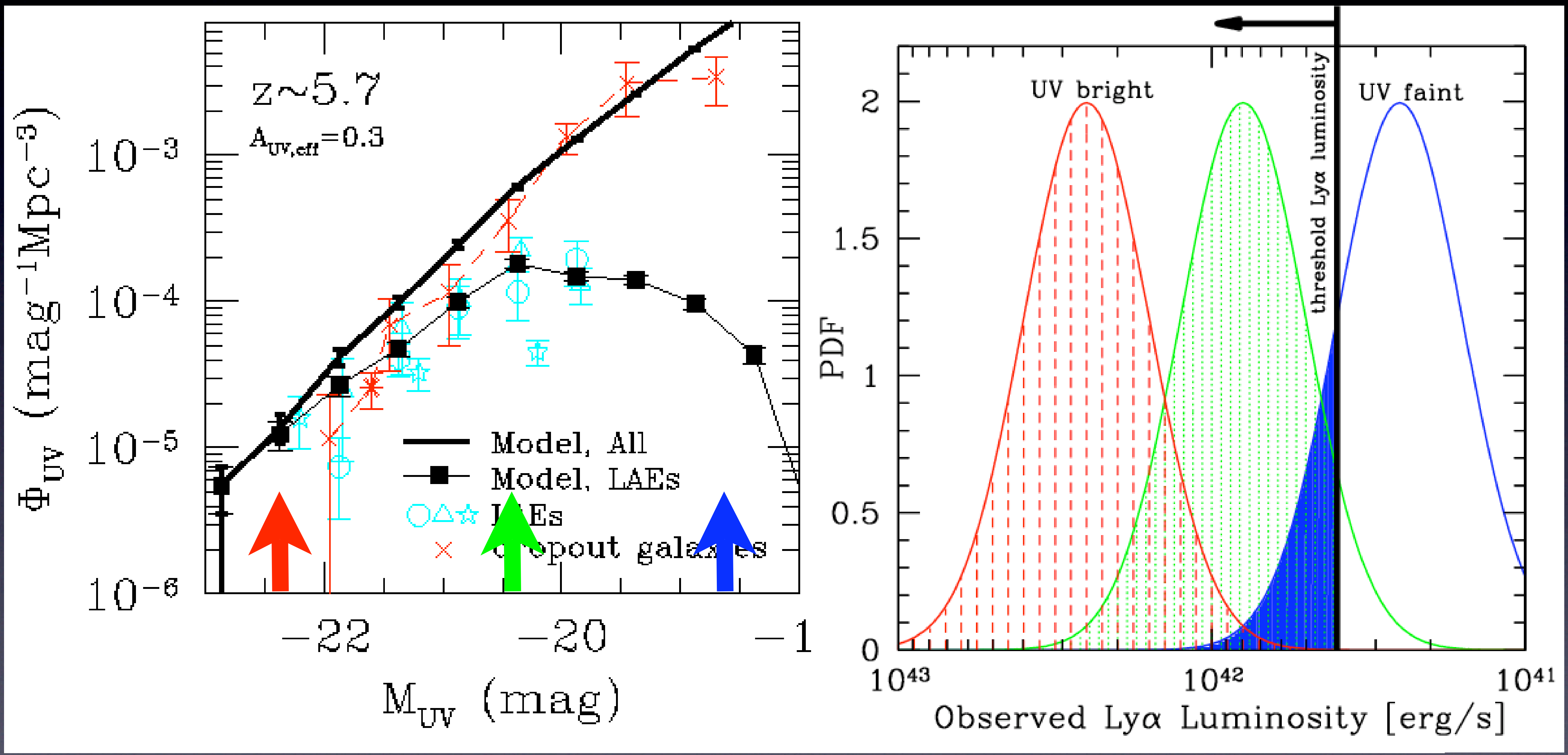
UV Luminosity Function



Puzzle Solved: broad distribution of apparent Lyα luminosity at fixed intrinsic (UV) luminosity

Summary:

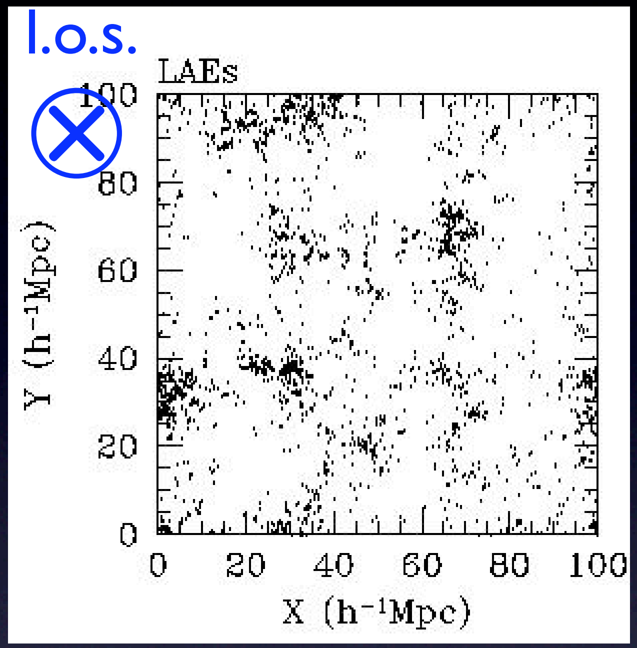
Spectra and Luminosity of Lyman-alpha Emitters

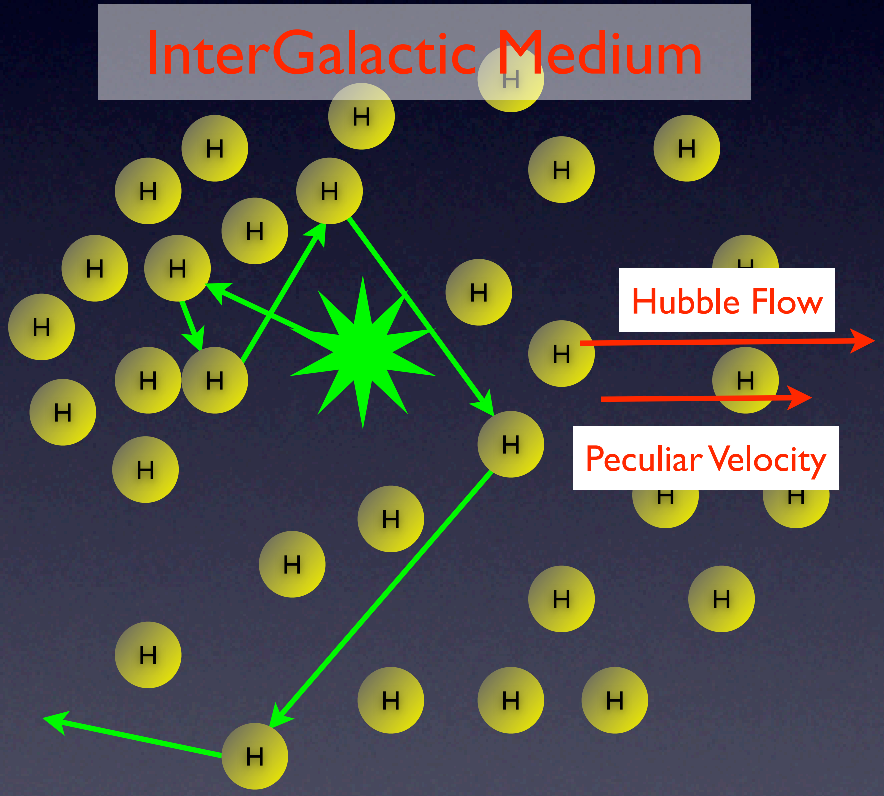
- Radiative transfer leads to extended Lyα emission and only the central part with high surface brightness can be detected.
- The observed Lyα emission shows asymmetric line profile with the peak shifted redward.
- Environment dependent radiative transfer effect causes a broad distribution in the observed Lyα luminosity at a fixed intrinsic luminosity.
- The model provides natural explanations to the observed LAE morphology, Lyα line profile, Lyα luminosity function, UV luminosity function, and Lyα equivalent line width distribution.

Clustering of Lyman-alpha Emitters

Clustering of LAEs: Model Prediction

selection effect caused by environment dependent Lya RT





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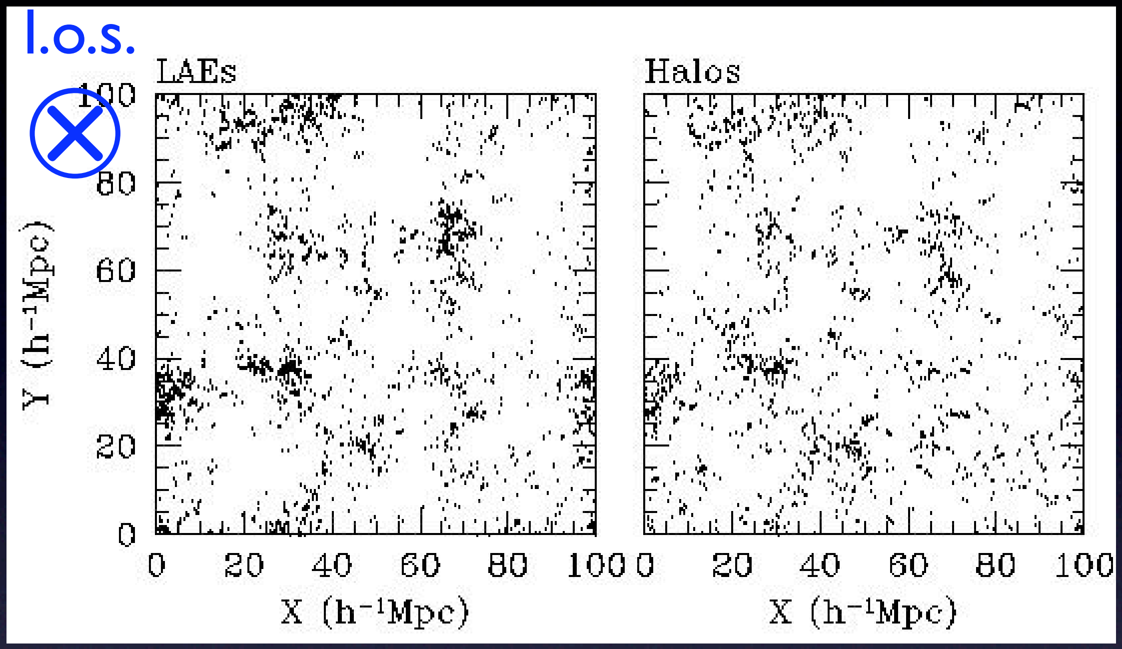

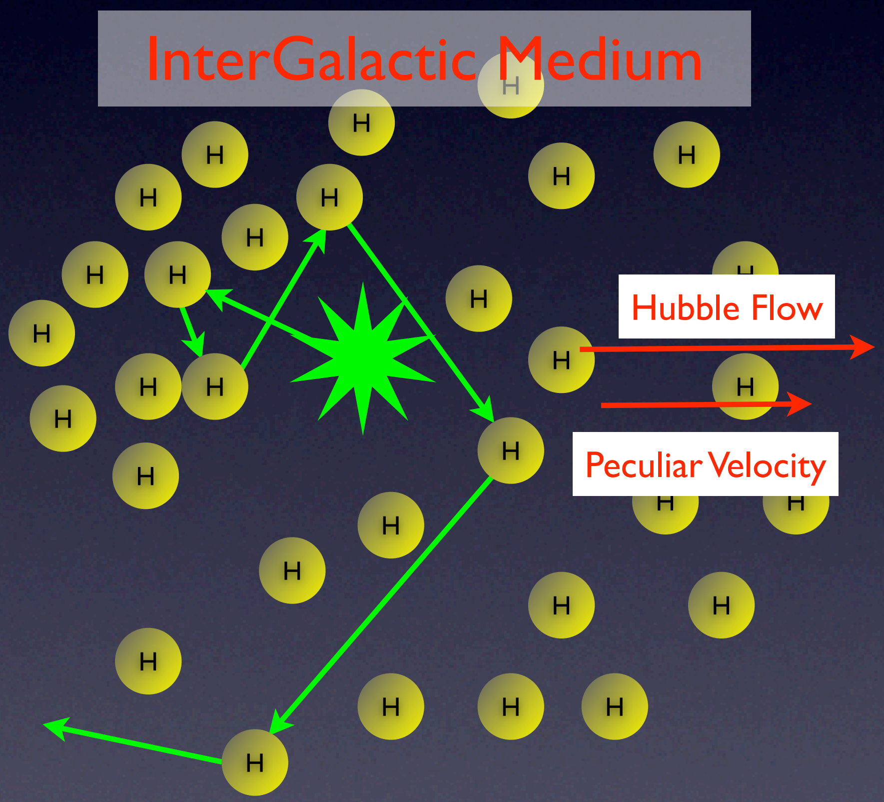

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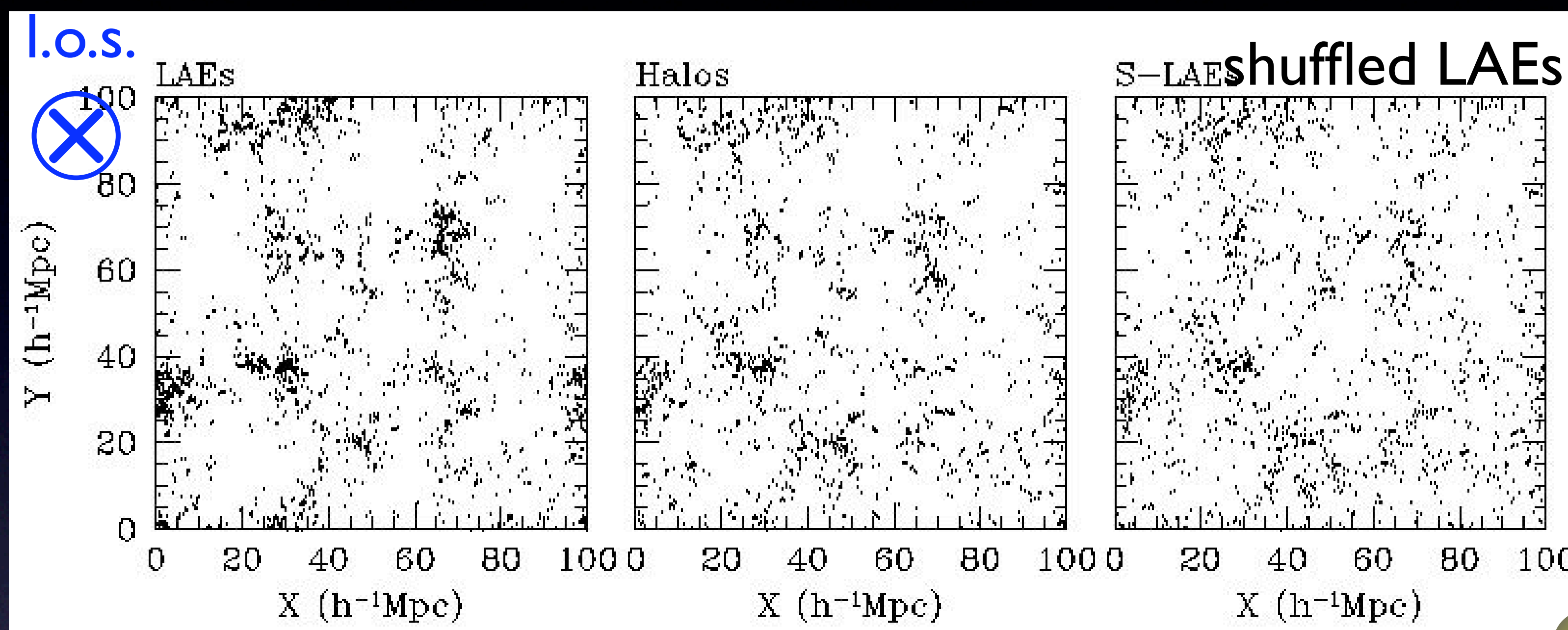

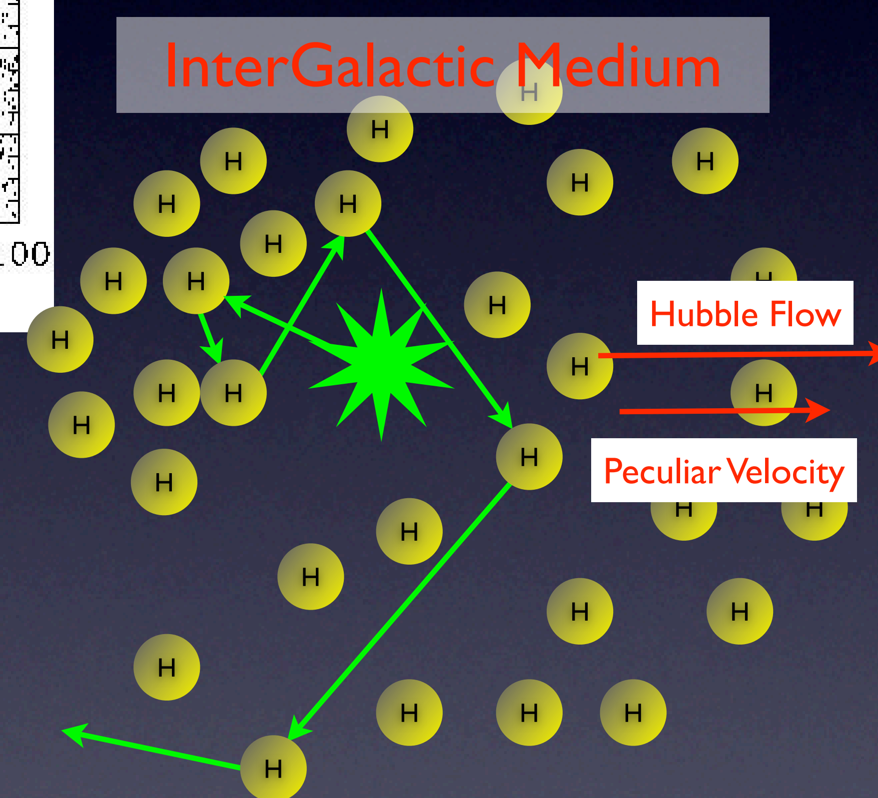

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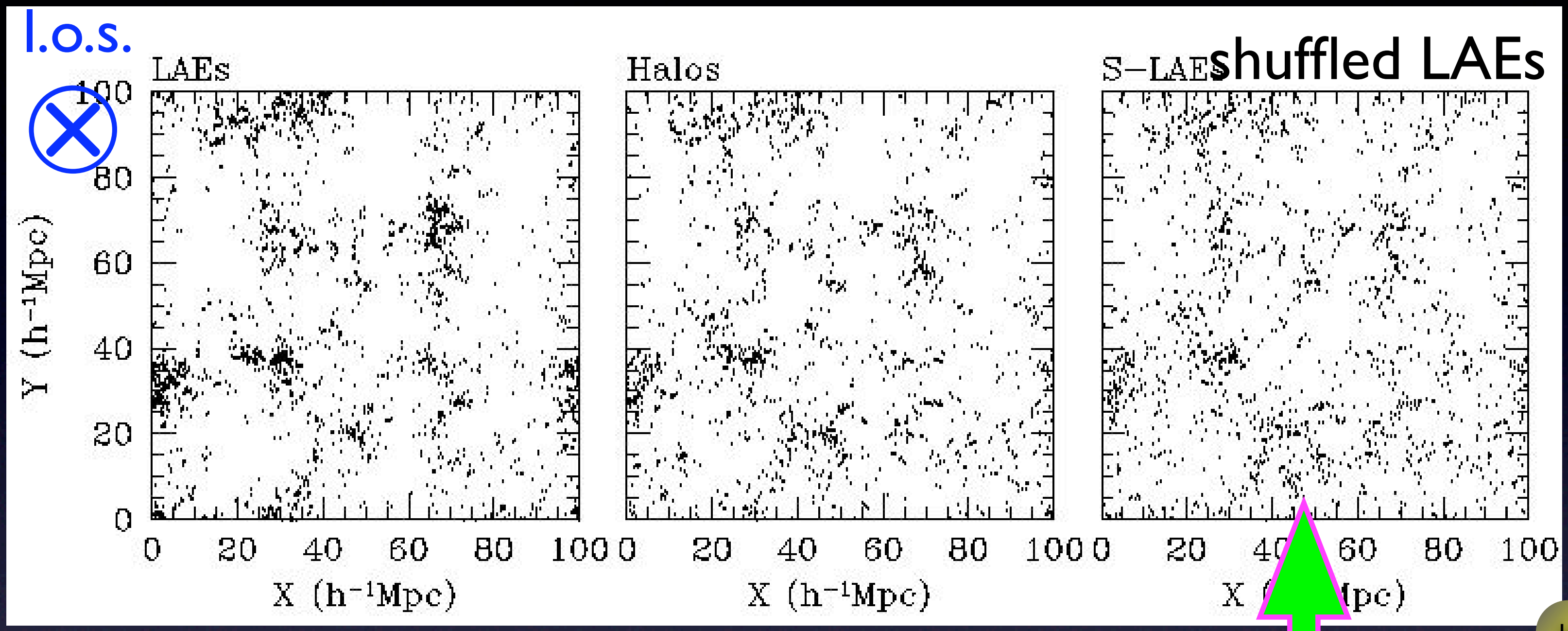
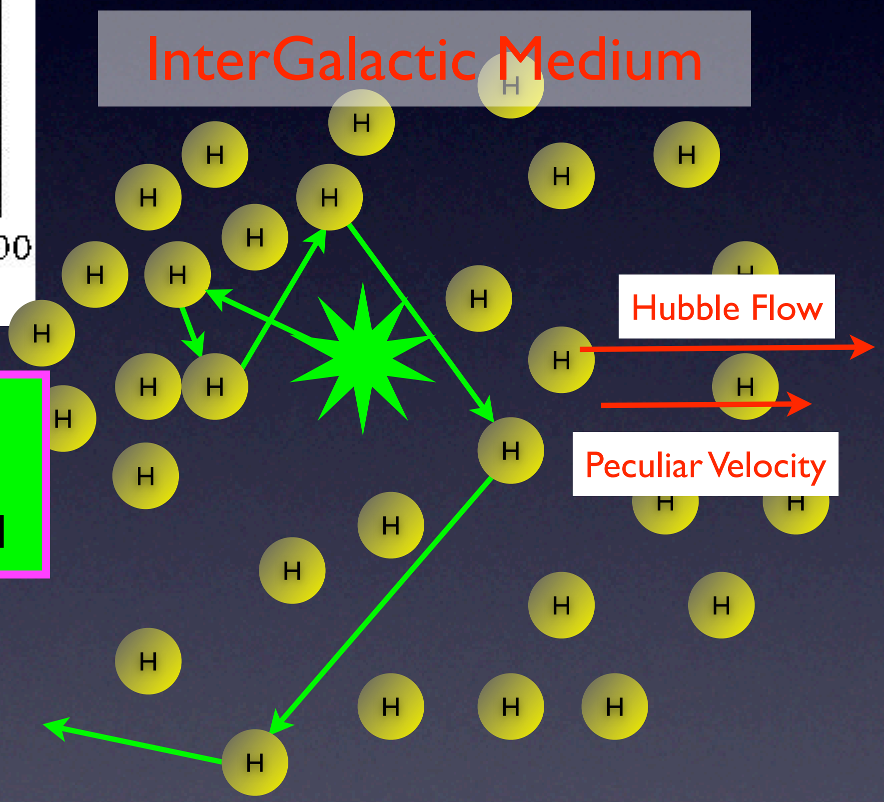


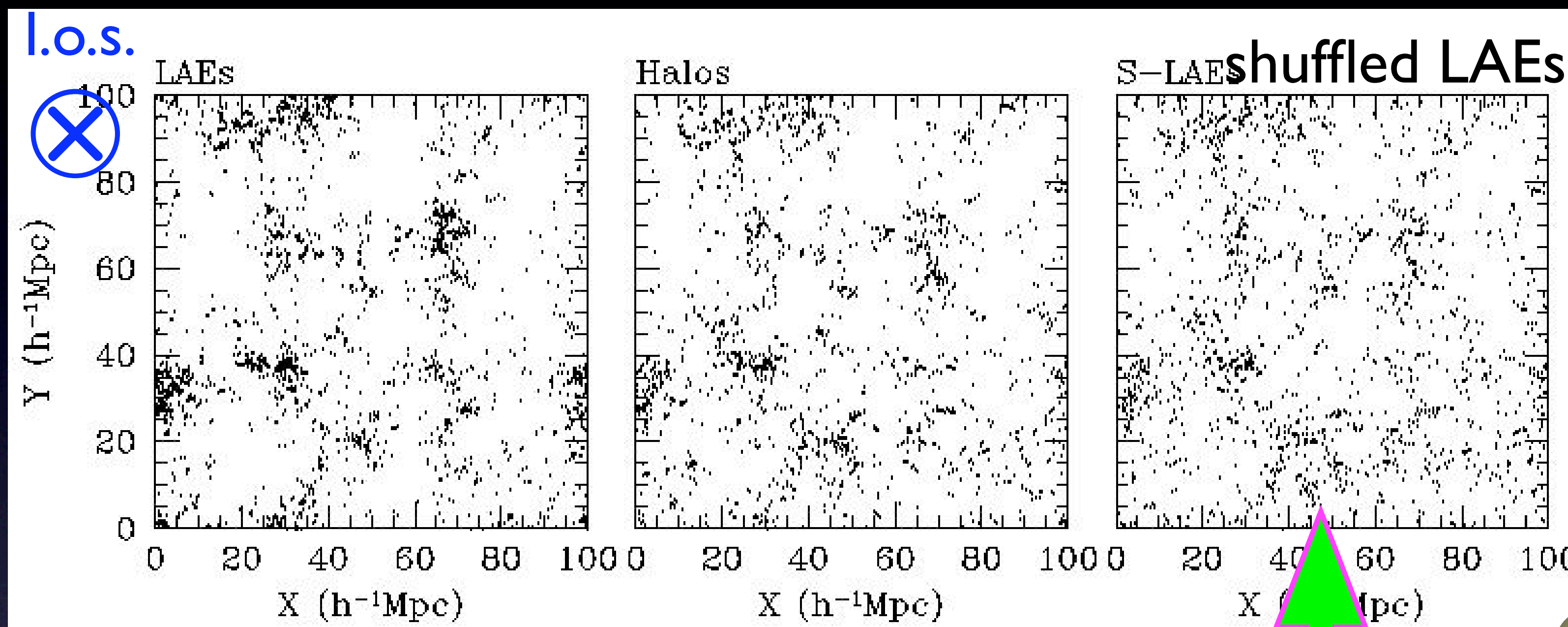
if the environment dependence of radiative transfer were eliminated



Clustering of LAEs: Model Prediction

enhancement in the transverse fluctuation

selection effect caused by environment dependent Lya RT



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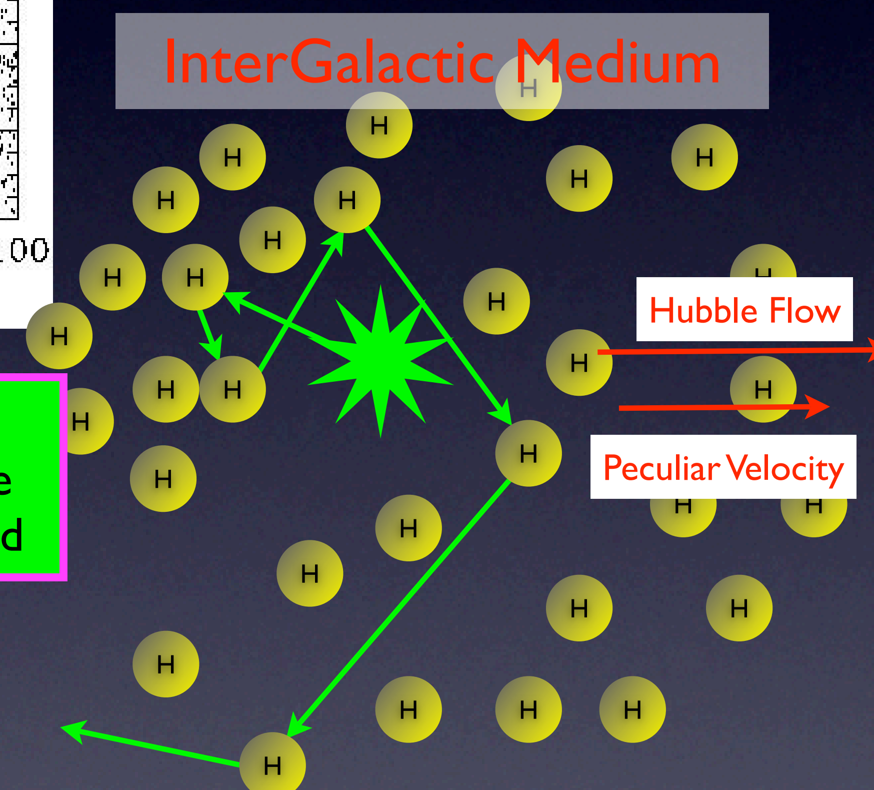

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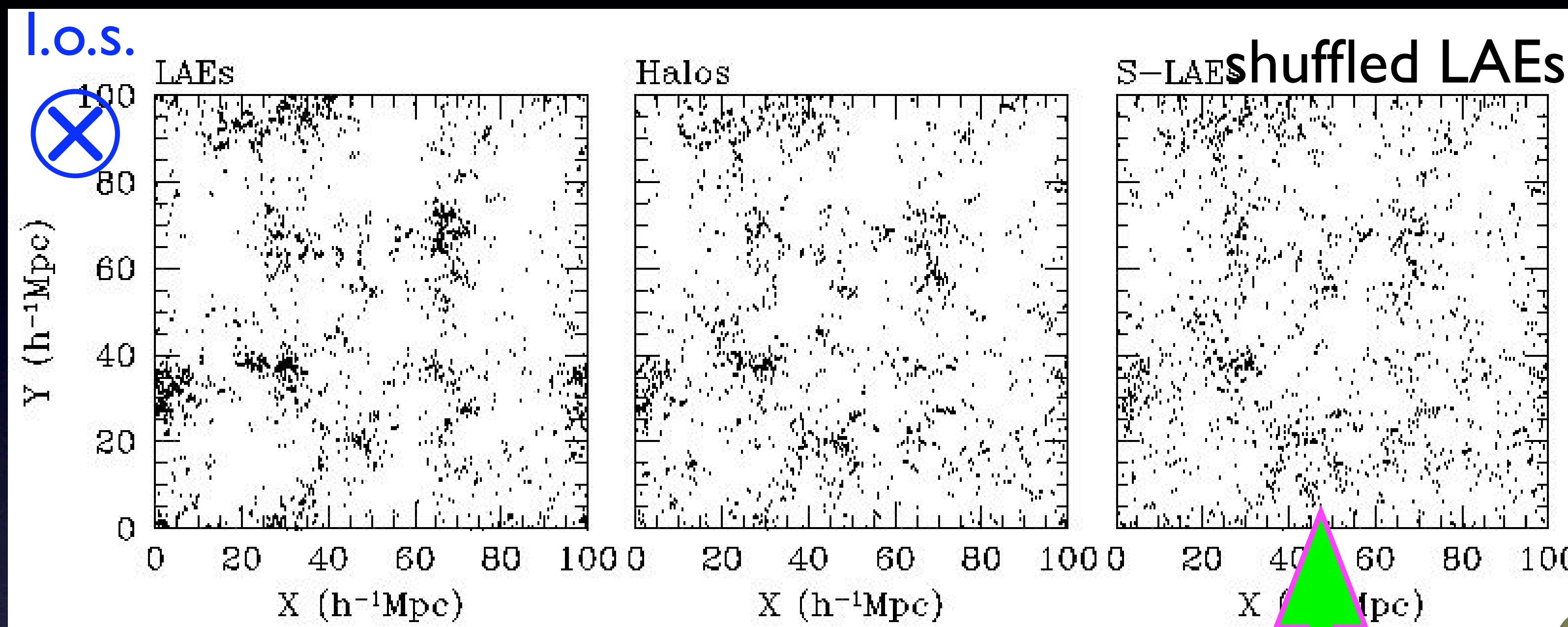

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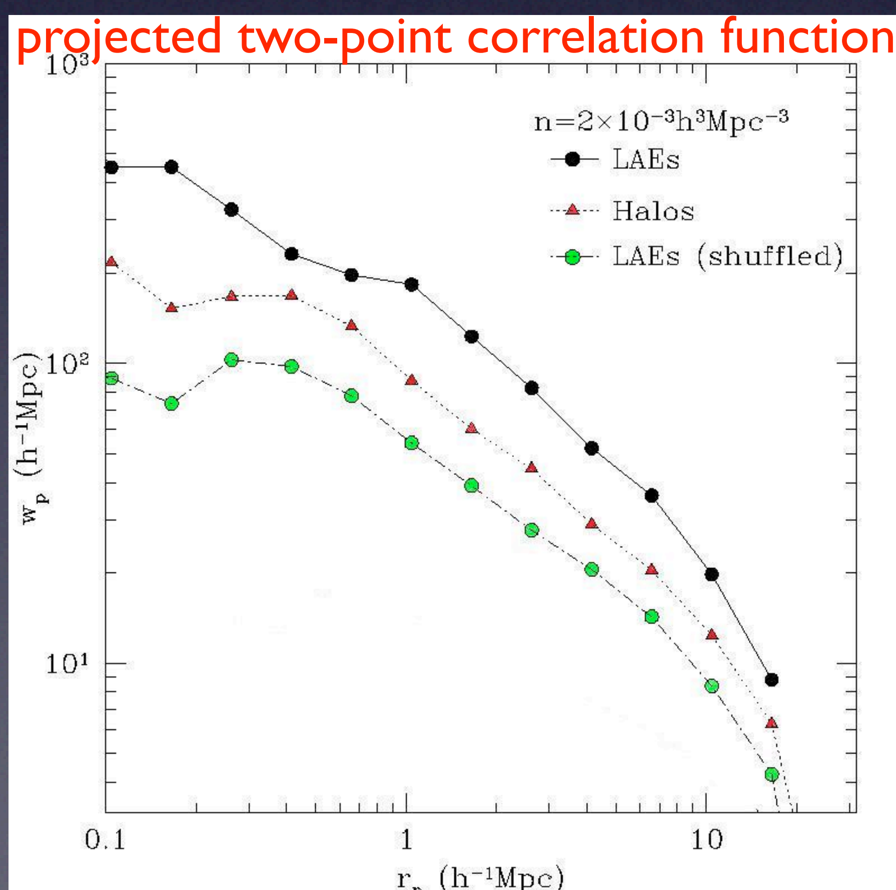

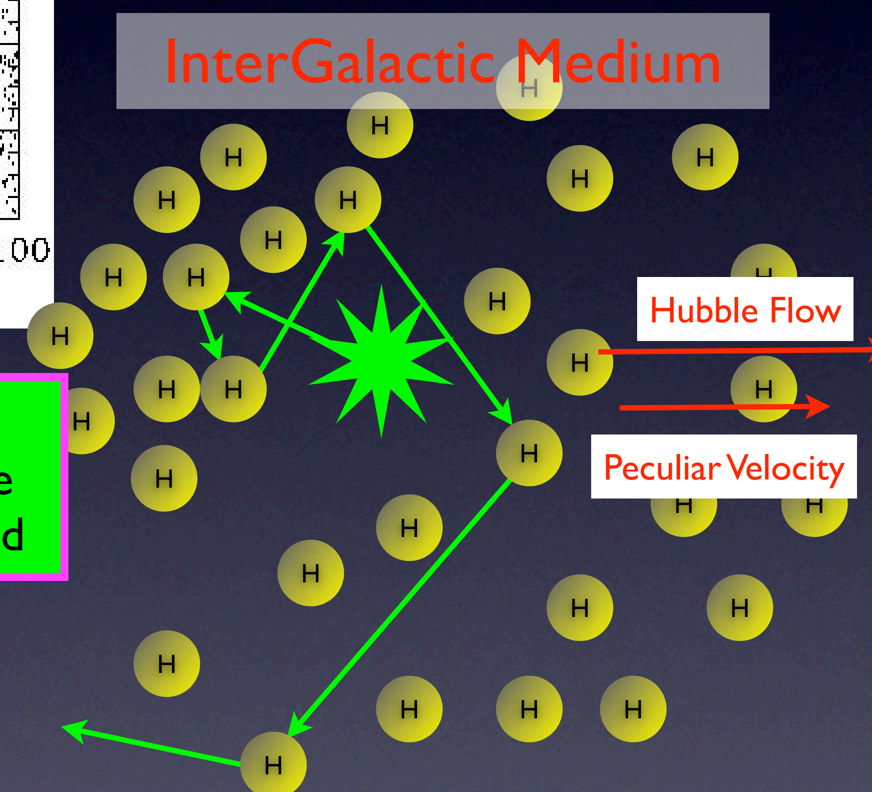

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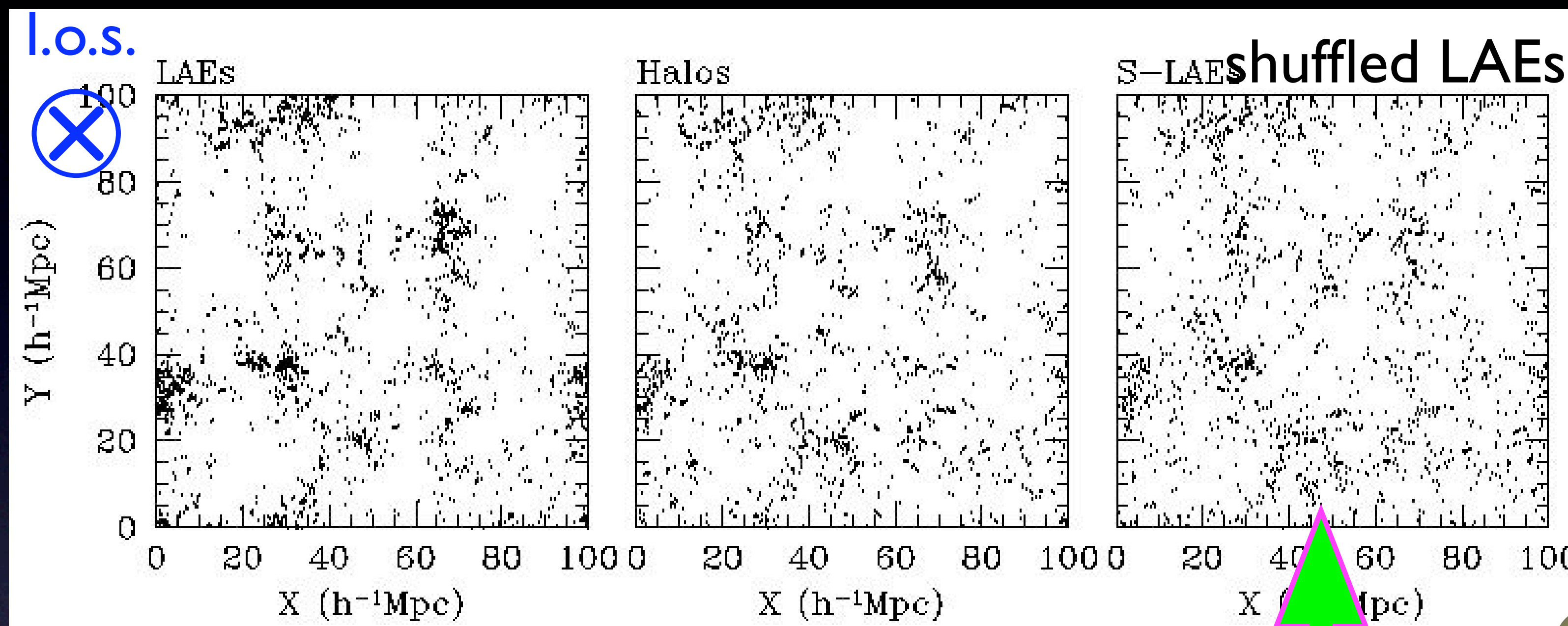
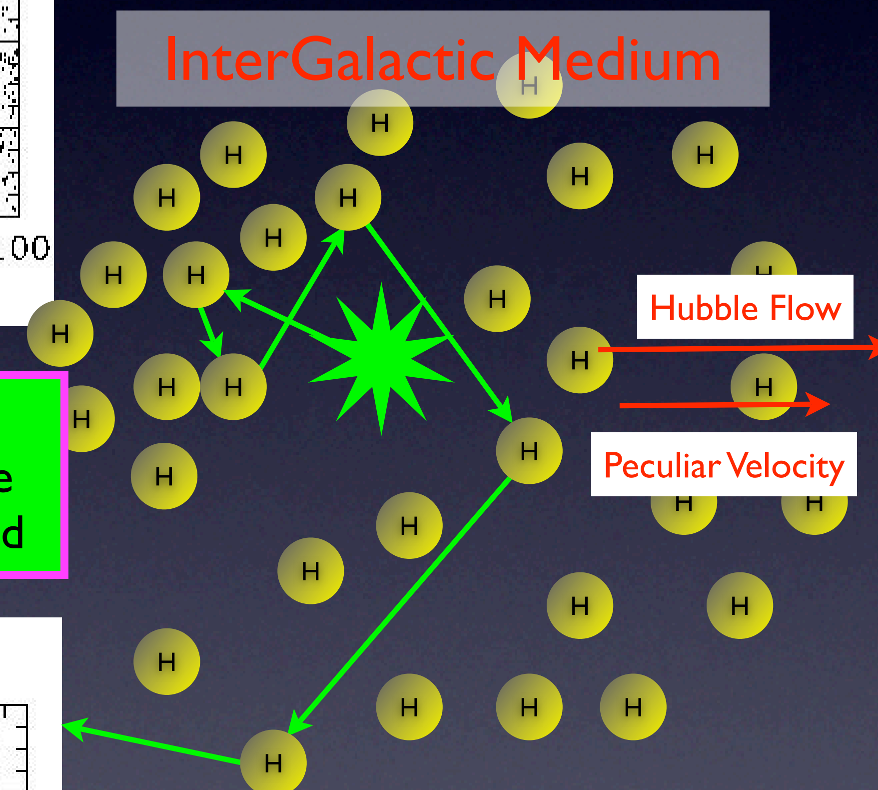
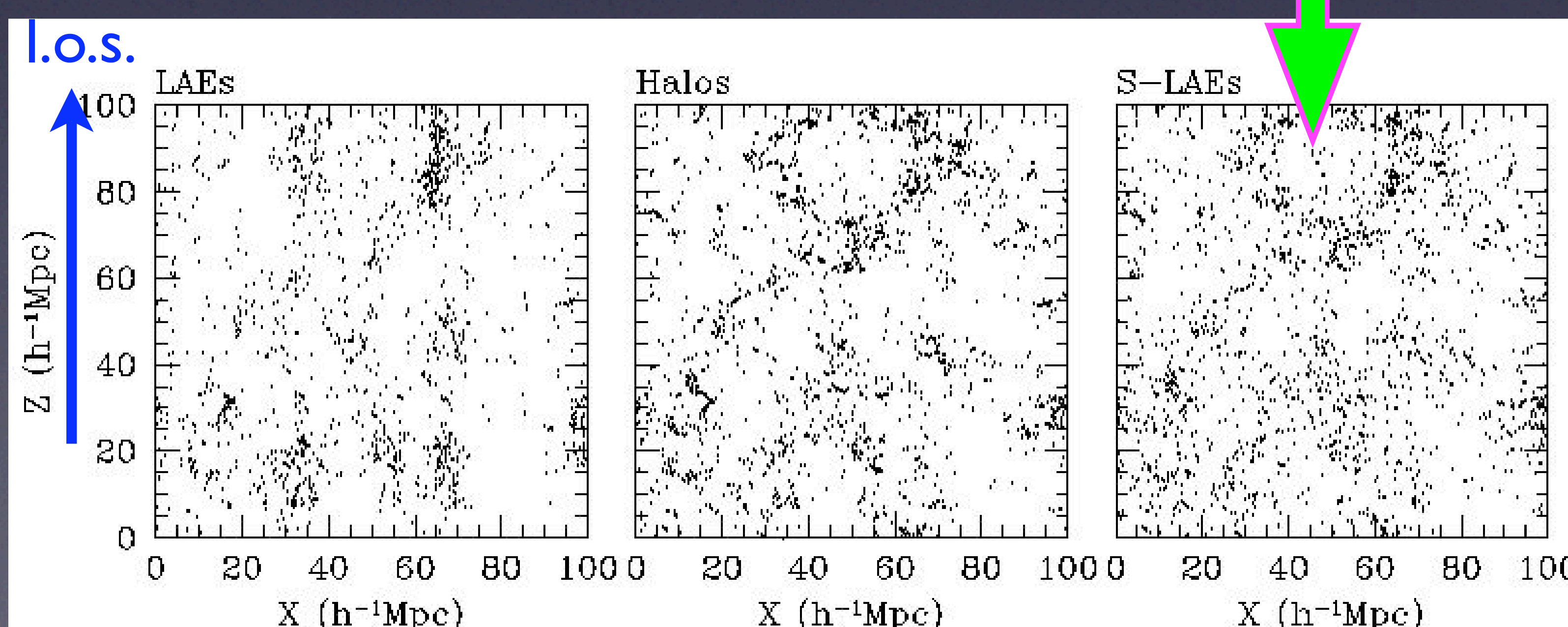


if the environment dependence of radiative transfer were eliminated

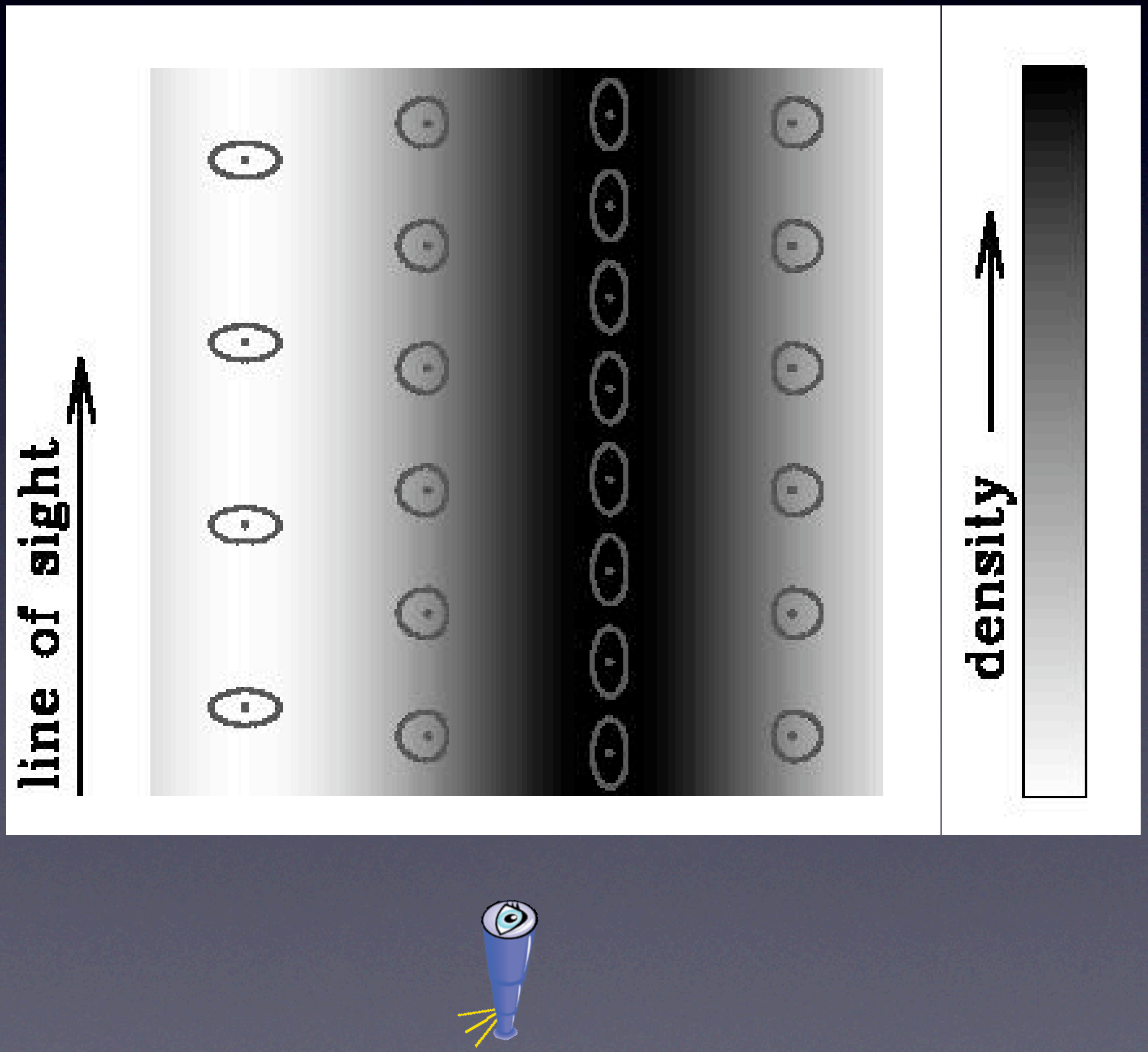


suppression in the line-of-sight fluctuation



Clustering of LAEs: Model Prediction

An intuitive picture



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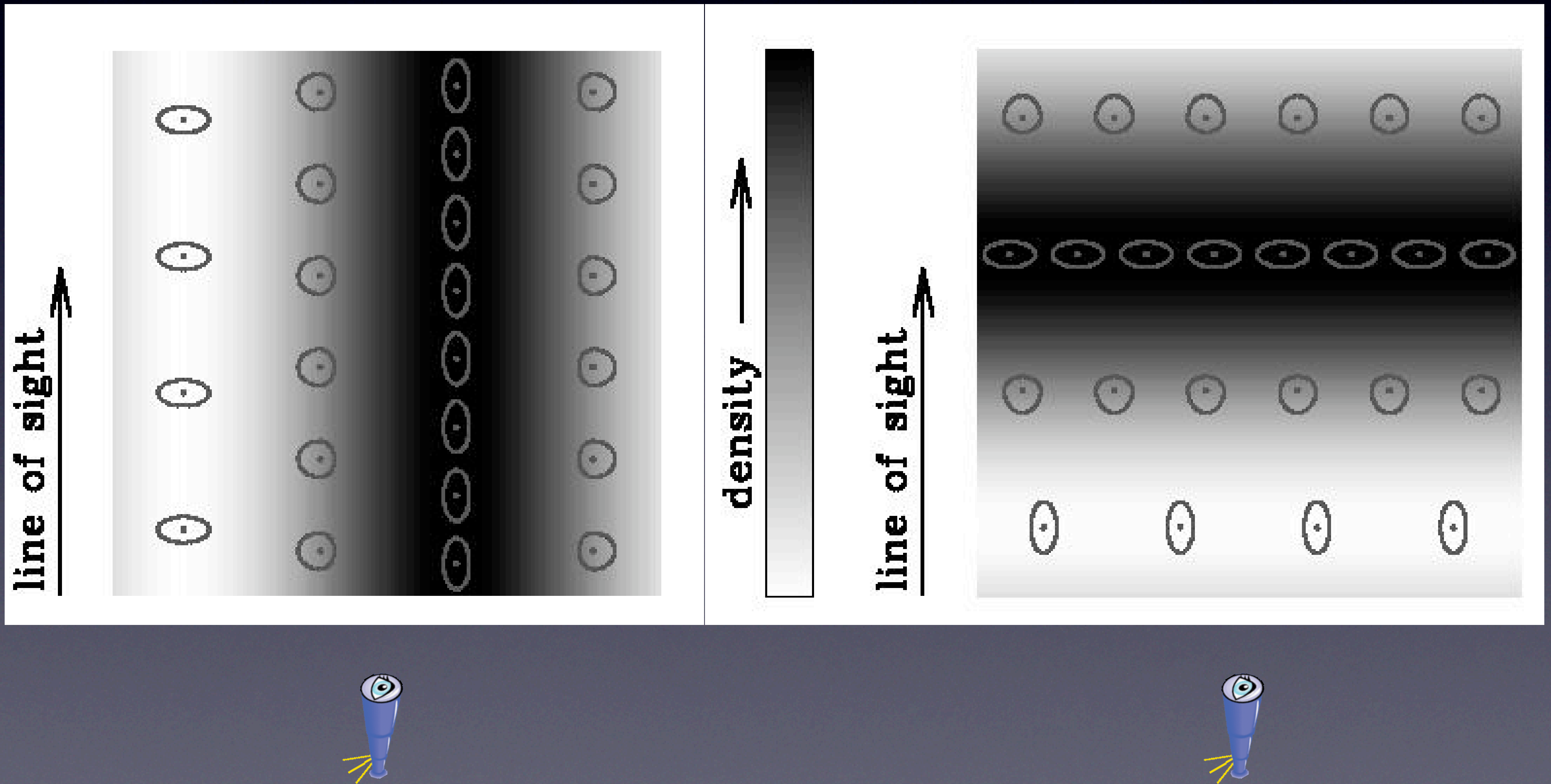
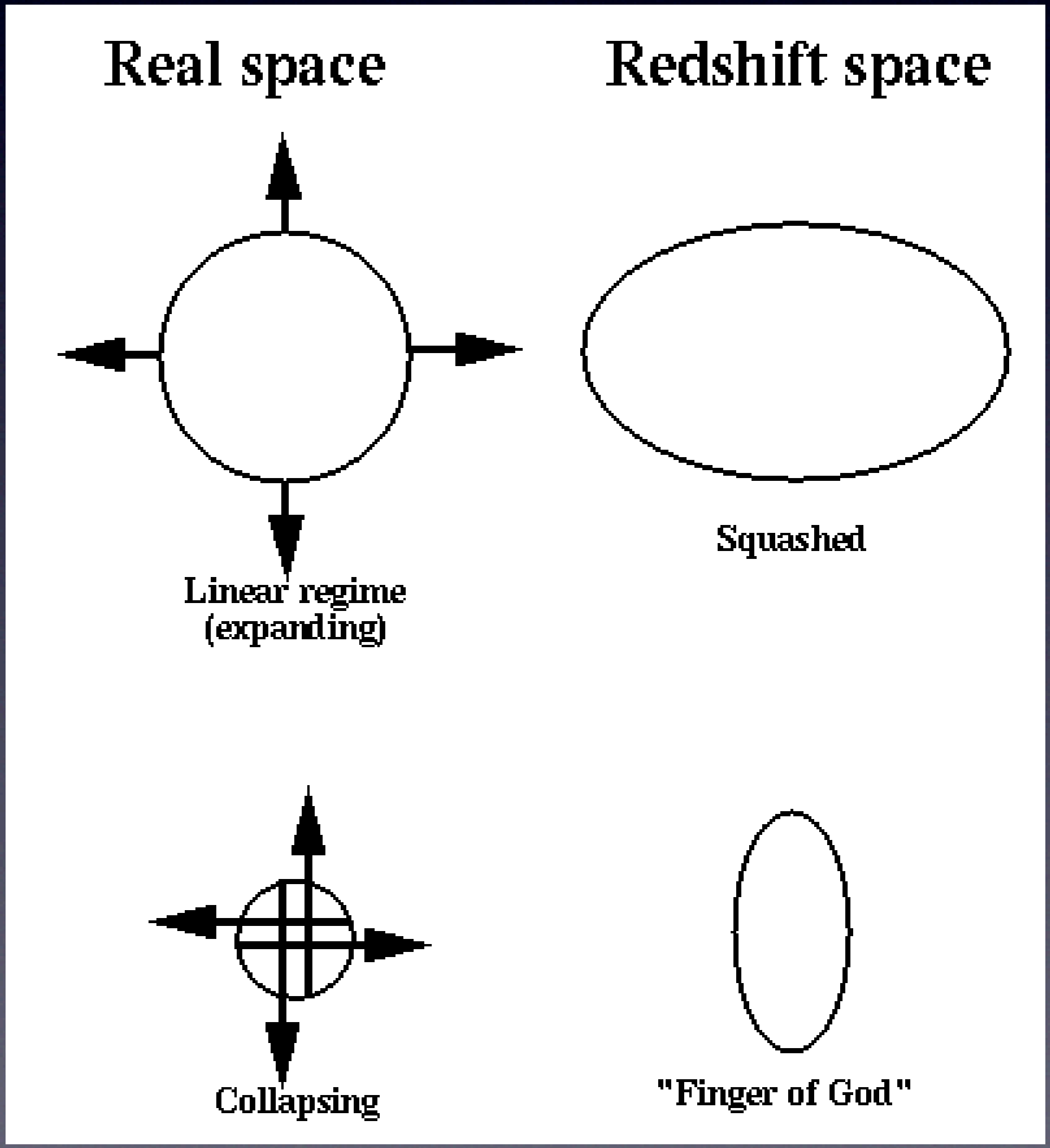
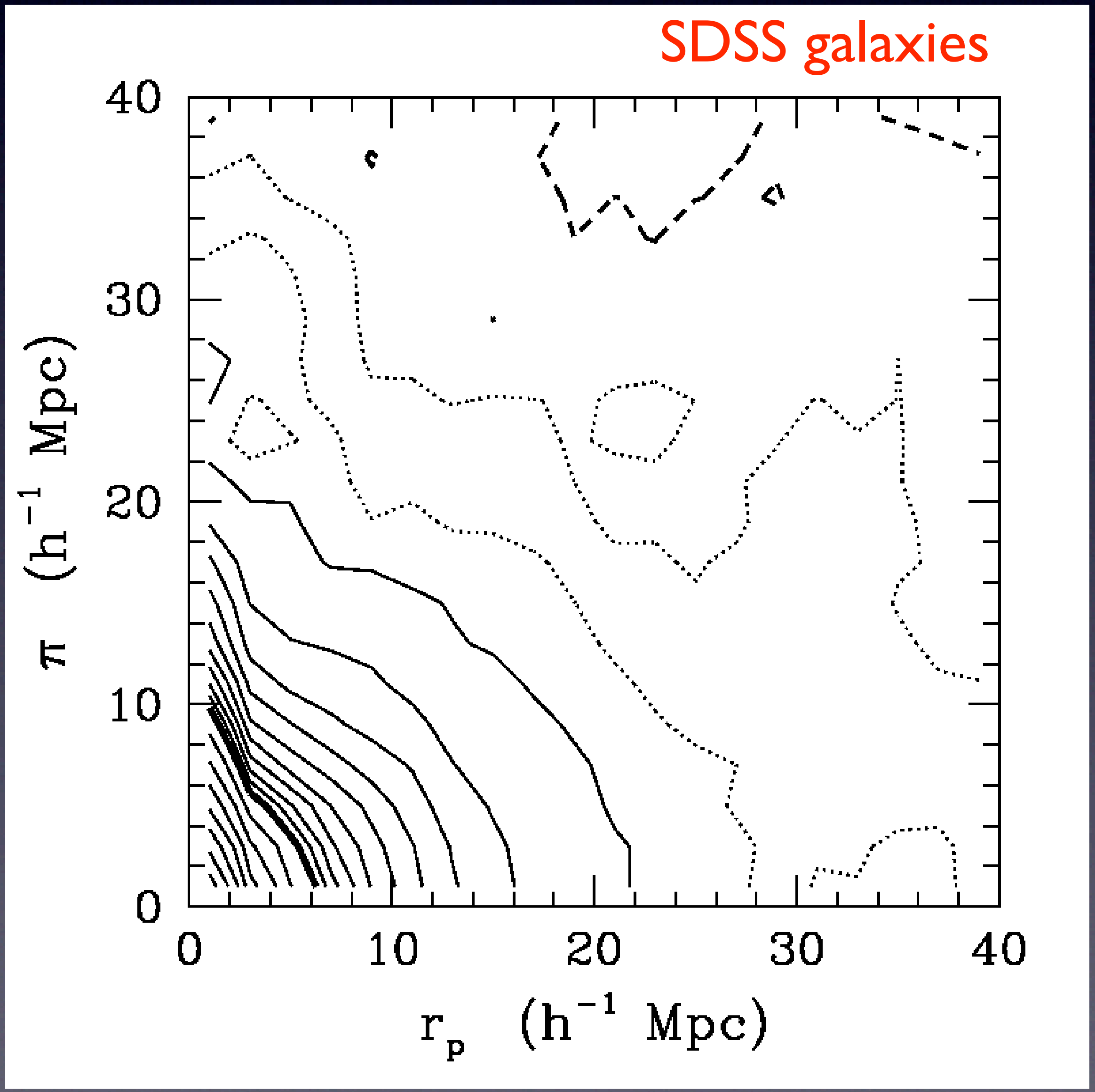


Clustering of LAEs: 3D Clustering

Known anisotropy in 3D two-point correlation function for continuum selected galaxies: redshift space distortion

- linear regime - Kaiser effect
- nonlinear regime - Finger-of-God effect



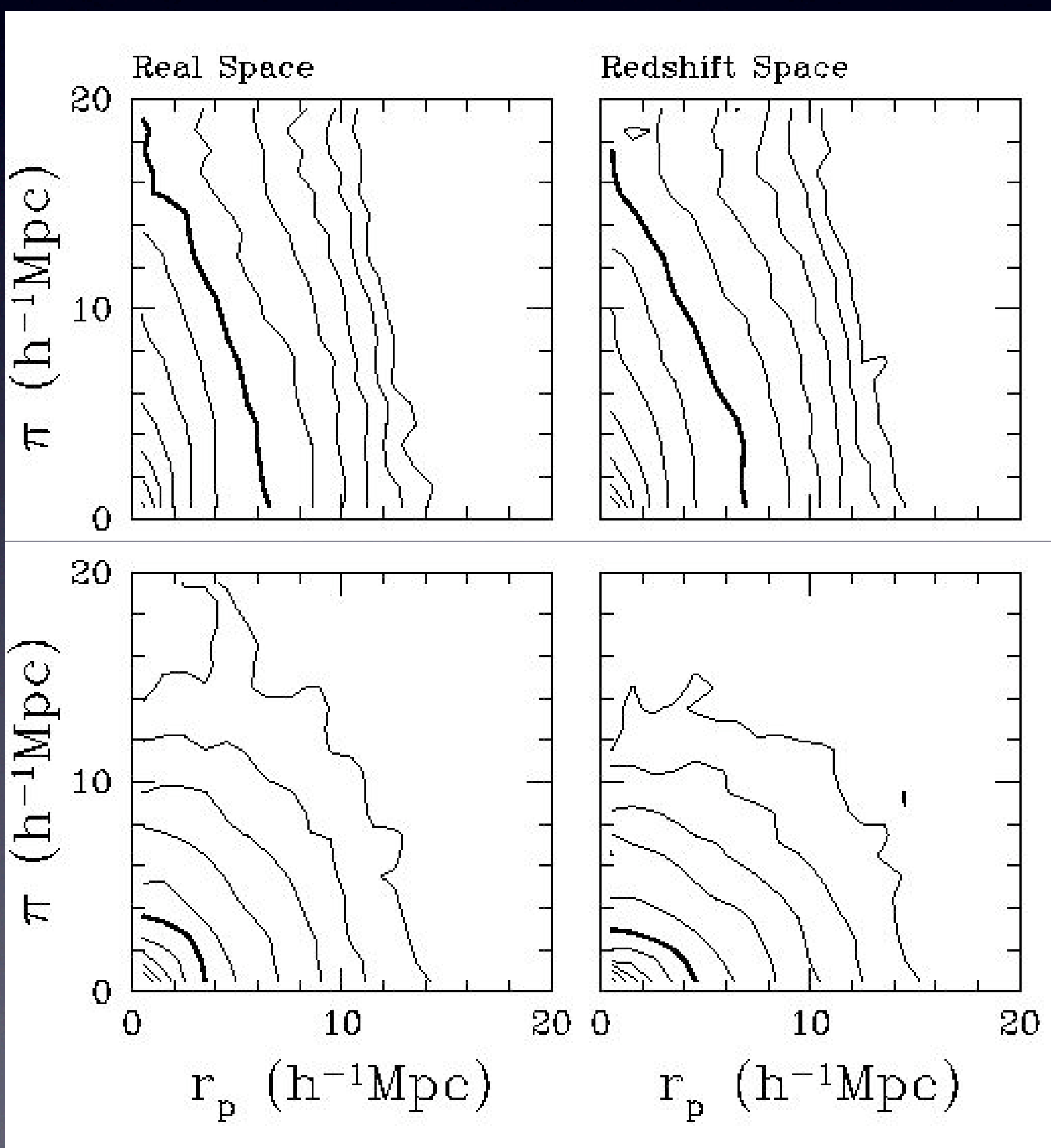


Zehavi, Zheng, et al. (2010)

Clustering of LAEs: 3D Clustering

Anisotropic 3D two-point correlation function of LAEs

- prominent line-of-sight elongation on large scales
- opposite to and stronger than linear redshift distortion effect
- different from nonlinear redshift distortion (Finger-of-God) effect
- a real space effect
- scale dependent bias

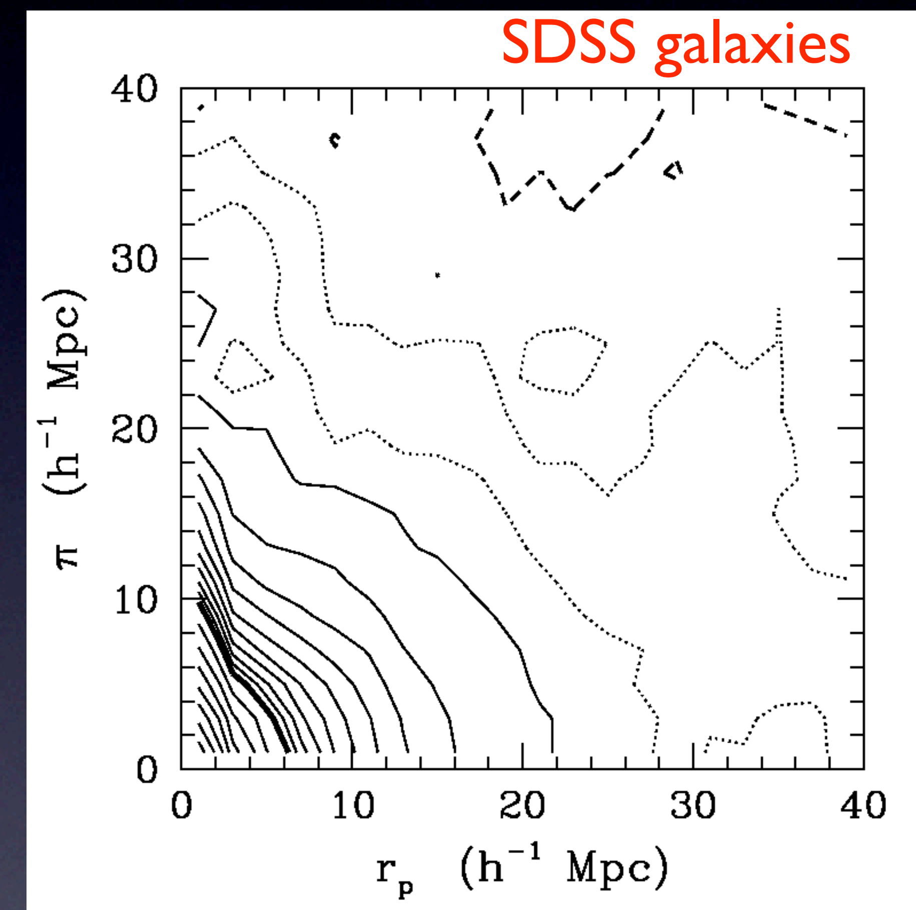


LAEs

Shuffled LAEs

environment dependence
of radiative transfer

Eliminated



Zehavi, Zheng, et al. (2010)

Summary: Clustering of Lyman-alpha Emitters

- new effects in galaxy clustering caused by environment dependent Lyman-alpha radiative transfer
- enhancement in the transverse fluctuation
- suppression in the line-of-sight fluctuation
- anisotropic 3D two-point correlation function
  - real space effect
  - different from linear and nonlinear redshift distortions
- scale-dependent bias

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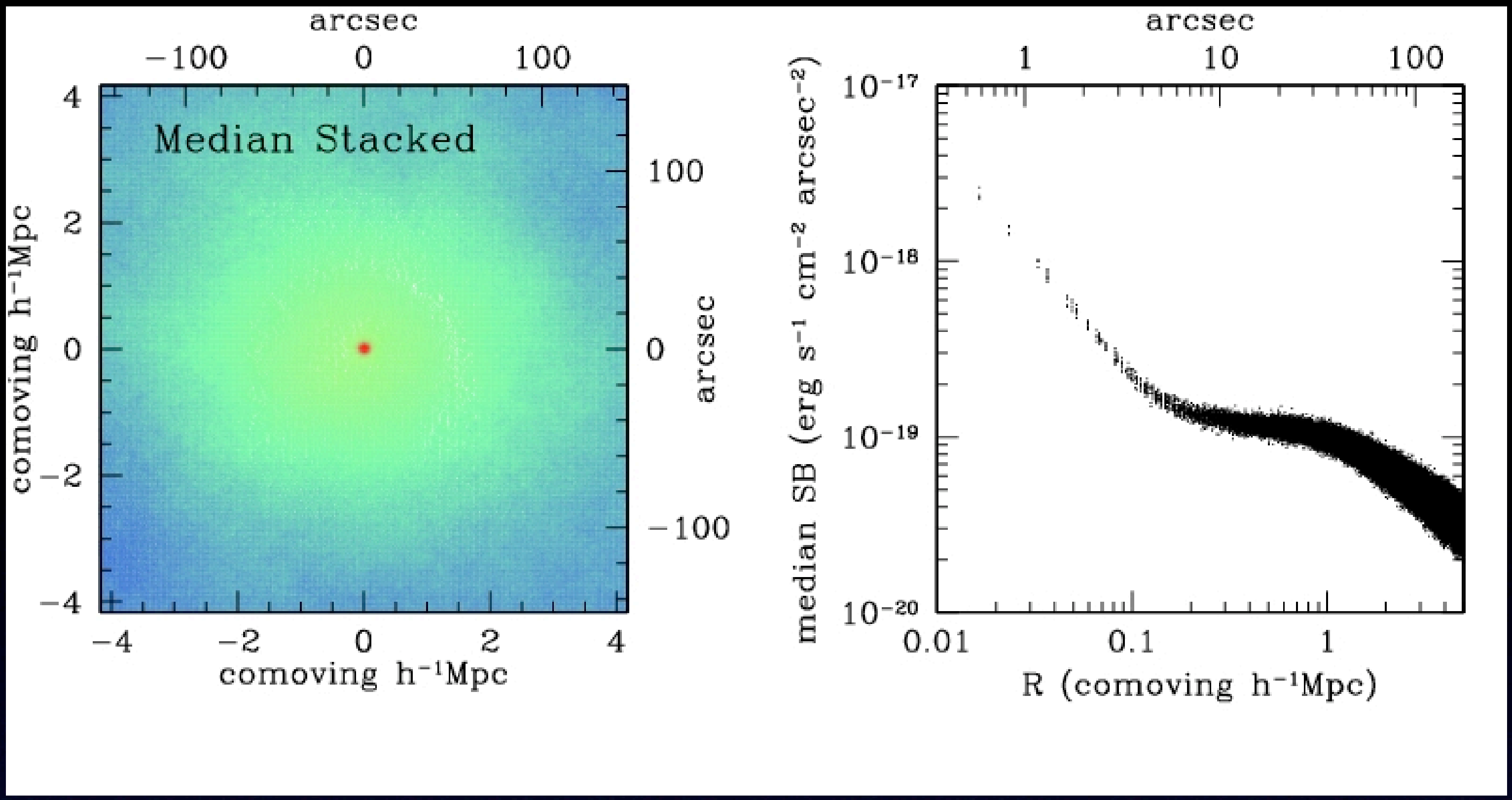
density
transverse velocity gradient
redshift distortion
l.o.s. velocity gradient
transverse velocity gradient
velocity
density gradient

$$P_g^s(\mathbf{k}) = \left\{ \left[\left(1 + \frac{\alpha_1 - \alpha_3 f}{b} \right) + (1 - \alpha_2 + \alpha_3)\beta\mu^2 \right]^2 + \left(\alpha_4 \beta \frac{1}{k r_H} + \frac{\alpha_5}{b} k r_H \right)^2 \mu^2 \right\} b^2 P_m(\mathbf{k})$$

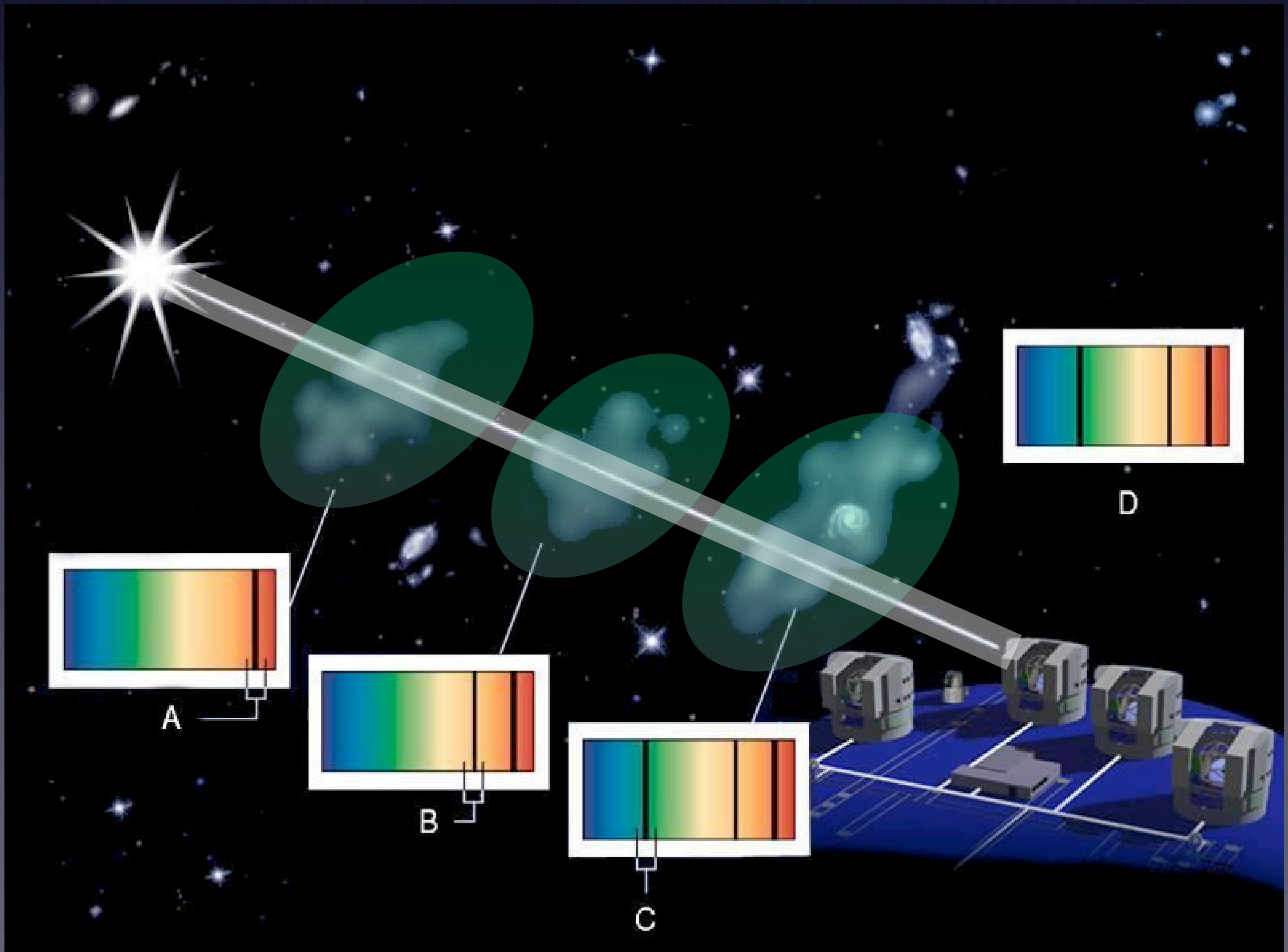
Future Work

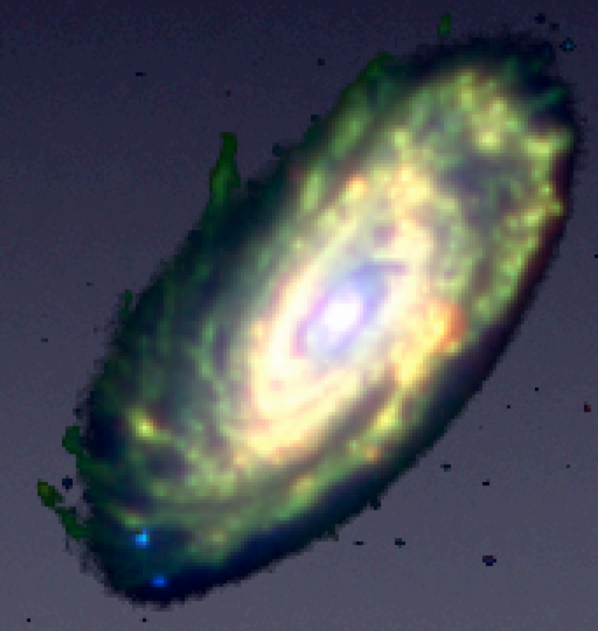
Extended Lyα Emission

Completing the Lyα inventory from Lyman-alpha emitters and Lyman break galaxies



Stacking narrowband images (Zheng et al., in prep.)





Stacking spectra of quasar absorption systems (w/ Brice Menard, in prep.)

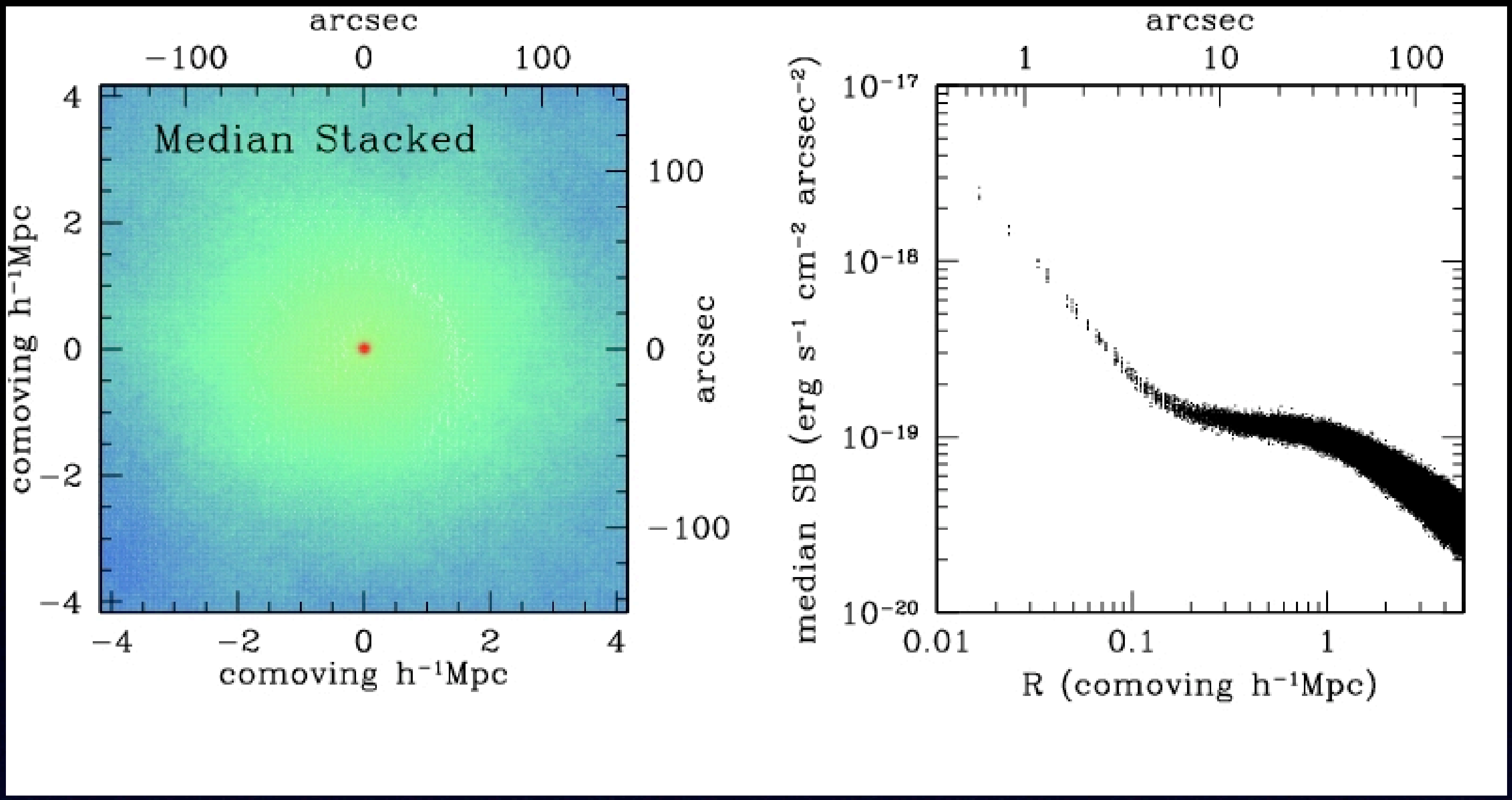
currently with SDSS quasar spectra

future project with SDSS III data

Future Work

Extended Lyα Emission

Completing the Lyα inventory from Lyman-alpha emitters and Lyman break galaxies



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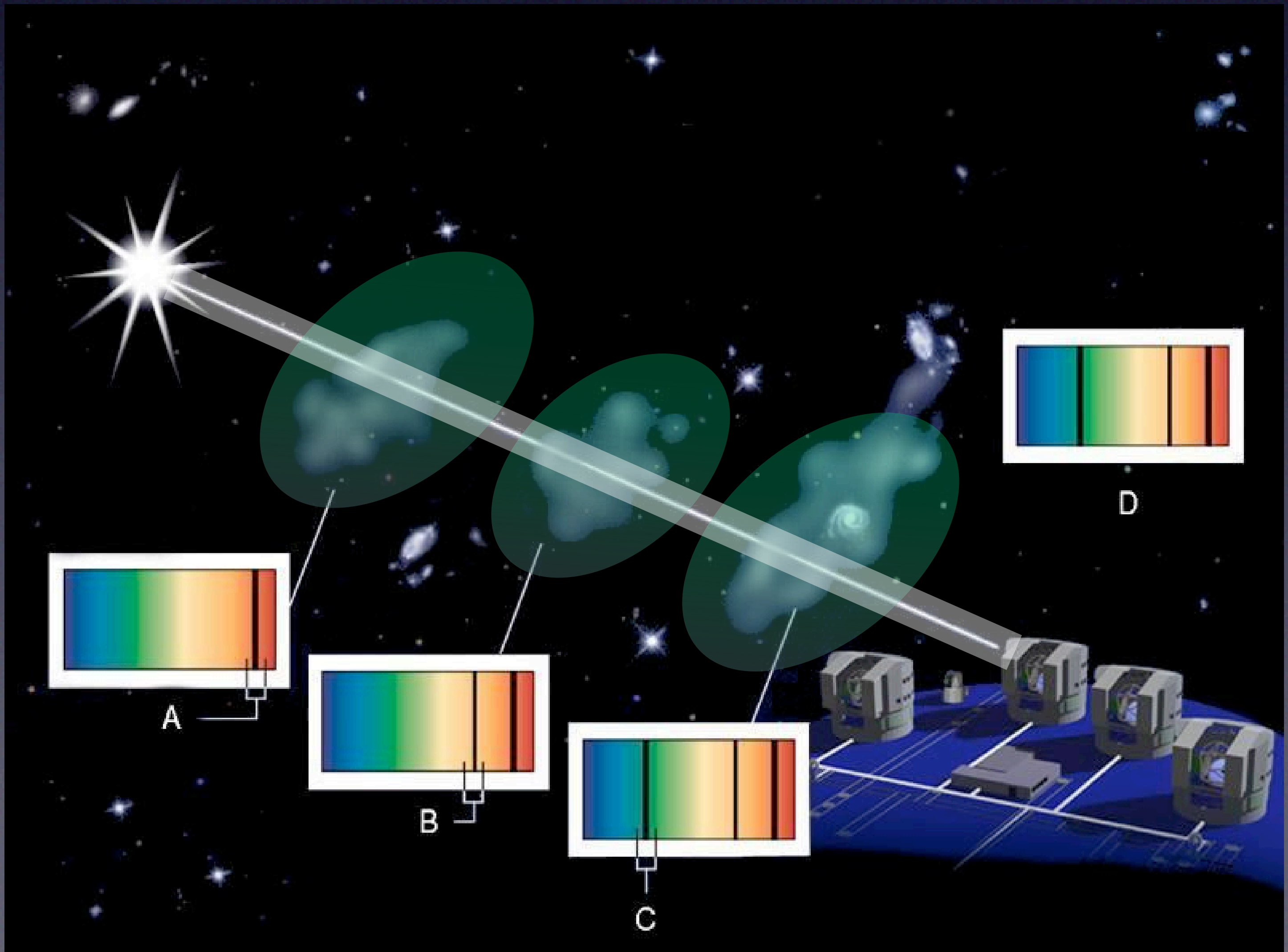

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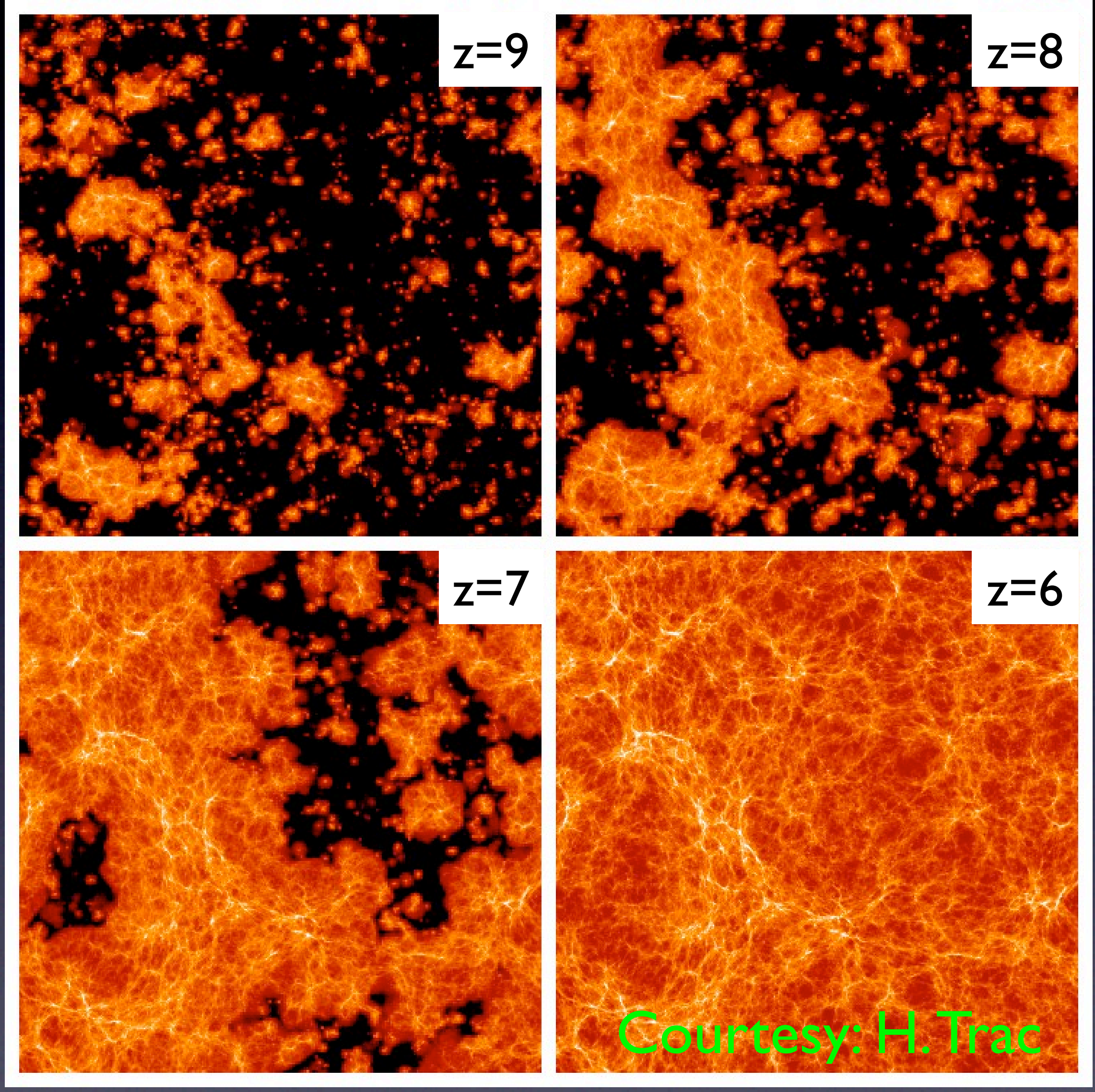
Future Work

Probing the Late Stage of Reionization with LAEs



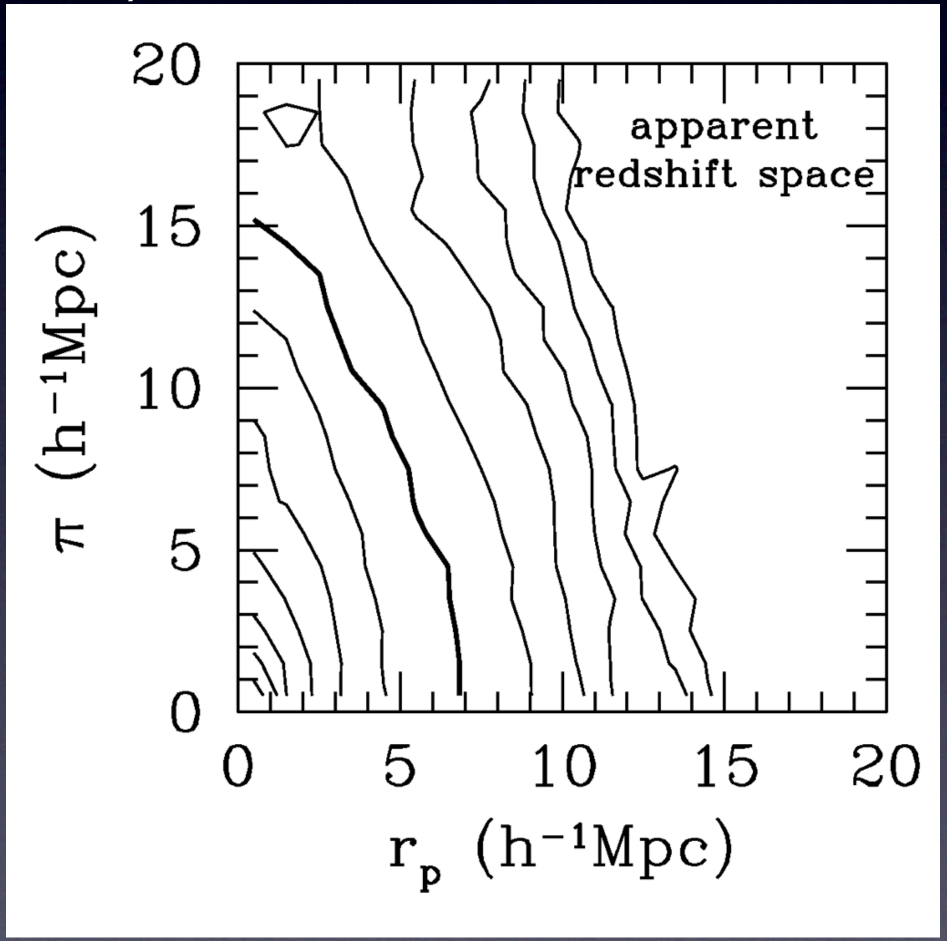
- ✳ Gemini NIRI z~8.2
- ✳ DAzLE (VLT+DAzLE) z~7.7, 9.9
- ✳ ZEN (VLT+ISAAC) z~8.8
- ✳ Subaru HyperSuprimeCam Survey z~5.7, 6.6, 7.0 (40 deg^2 wide survey, 4 deg^2 deep survey)
- ✳ ...

- Line profile and equivalent width
- Evolution of Lyα and UV luminosity functions
- Anisotropic clustering of LAEs
  distribution of HII bubbles
  (additional fluctuation from f_{HI},T)

Future Work

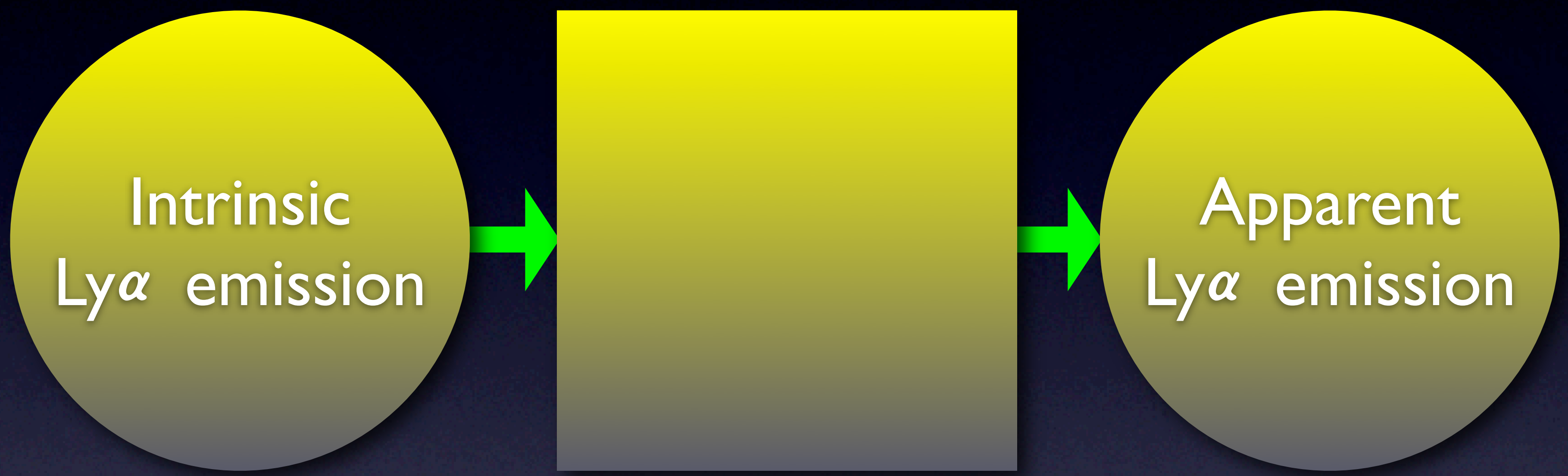
LAEs at Lower Redshifts

* Subaru HyperSuprimeCam Survey z~5.7 (40 deg^2)
* LAEs from samples of Lyman Break Galaxies (LBGs z~3-5)
* HETDEX (10^6 LAEs at z~2-4, BAO measurement)



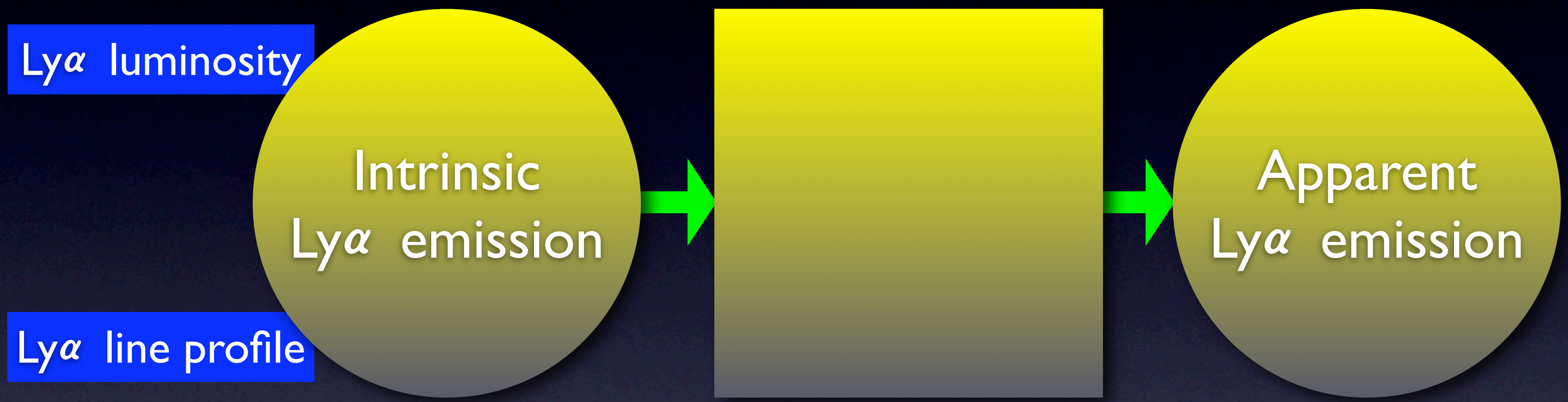
- Connection between LAEs and LBGs
- Role of Lyman-alpha radiative transfer
- Interpreting the clustering of LAEs
  - redshift distortion
  - nonlinear evolution
  - scale-dependent bias
  - Lyman-alpha selection induced distortion
- Effects on baryon acoustic oscillation (BAO) measurements

A Simple Model of LAEs



- radiative transfer as the single factor in transforming the intrinsic properties of Lyα emission to observed ones
- natural interpretations to observations
- high predictive power

A Simple Model of LAEs



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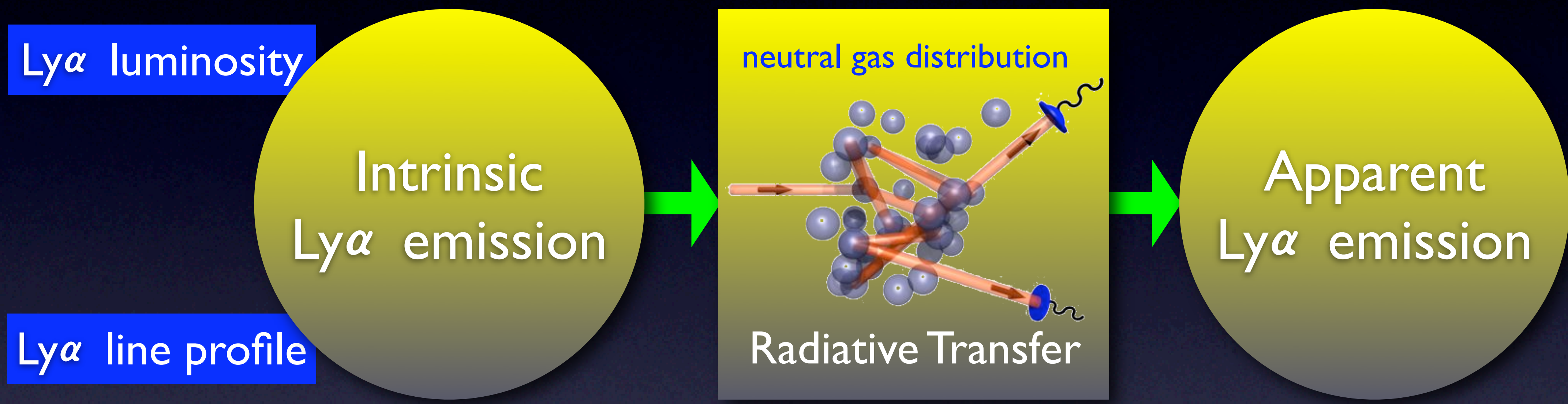

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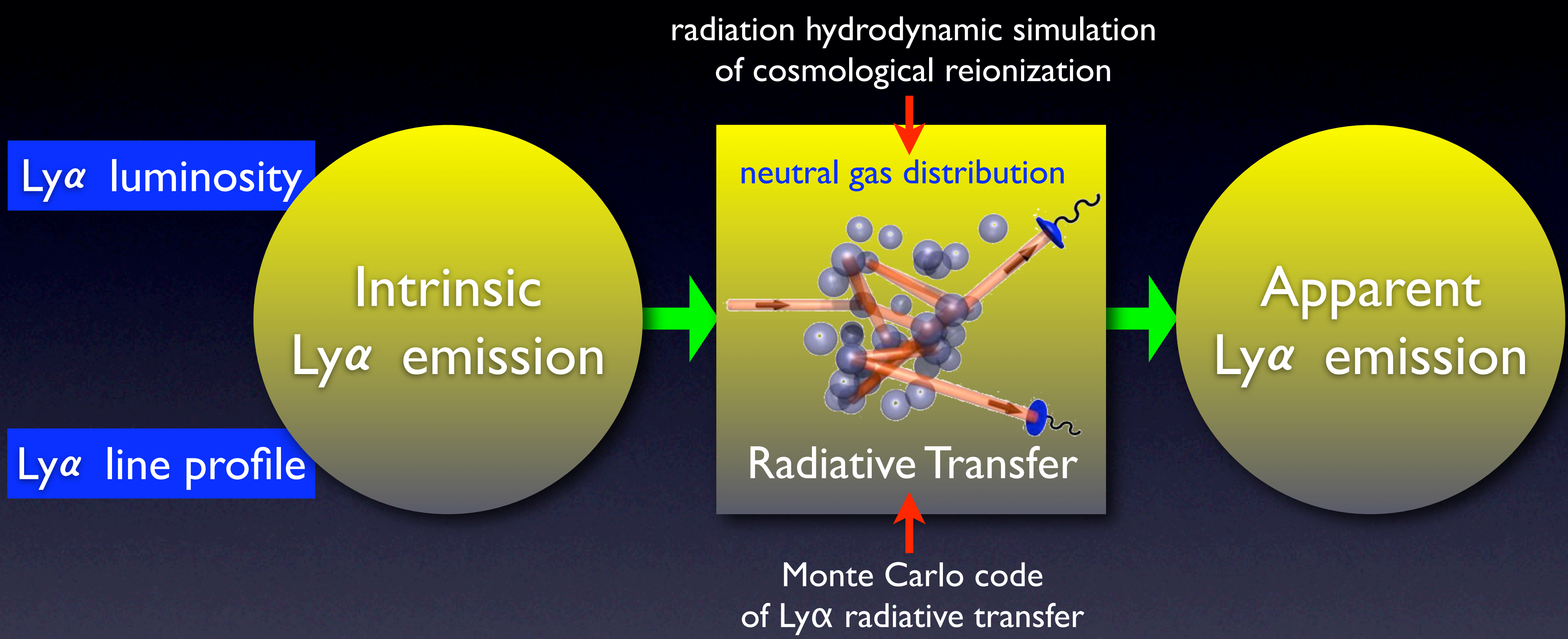

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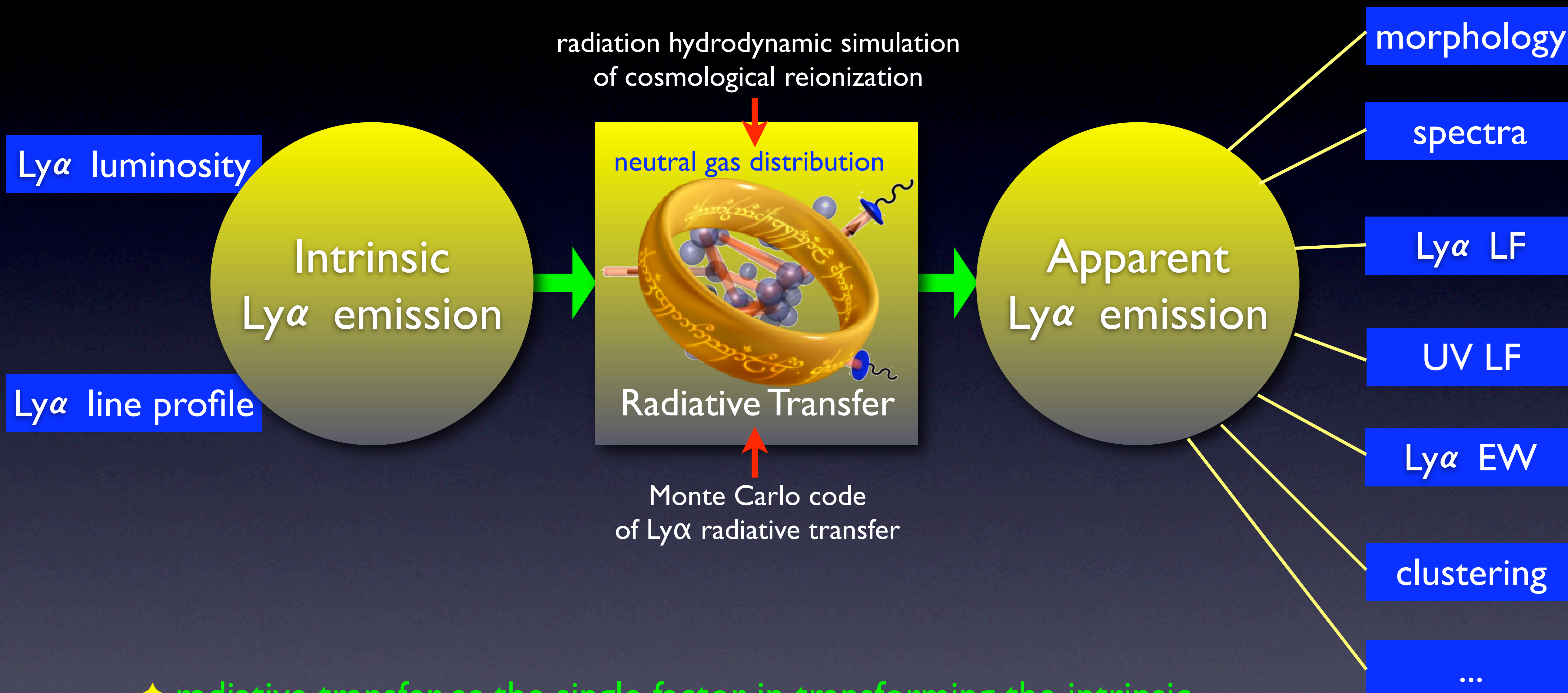

- ✦ radiative transfer as the single factor in transforming the intrinsic properties of Lyα emission to observed ones
- ✦ natural interpretations to observations
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Summary

- For the first time, a realistic Lyα radiative transfer (RT) calculation is performed in a cosmological volume to study Lyman-alpha emitters (LAEs).
- RT leads to coupling between the observed Lyα emission and circumgalactic and intergalactic environments (density and velocity structures).
- The simple model is able to provide natural explanations for an array of observed properties of LAEs.
  - asymmetric line profile with peak shifted redward
  - broad distribution of observed Lyα luminosity at fixed intrinsic luminosity
  - morphology, spectra, and Lyα and UV luminosity distributions reproduced
- The model predicts new effects in the clustering of LAEs caused by environment dependent Lyα radiative transfer.
  - enhancement (suppression) in the transverse (line-of-sight) fluctuation
  - anisotropic 3D clustering (prominent elongation along the line of sight)
  - scale-dependent bias
- Future work:
  - extended Lyα emission
  - high redshifts: How to use LAEs to probe the late stage of reionization?
  - low redshifts: What is the connection between LBGs and LAEs?
How to model the clustering of LAEs?
How strong is the radiative transfer effect on the clustering at BAO scales?
  - model uncertainties: galactic wind, dust, ...