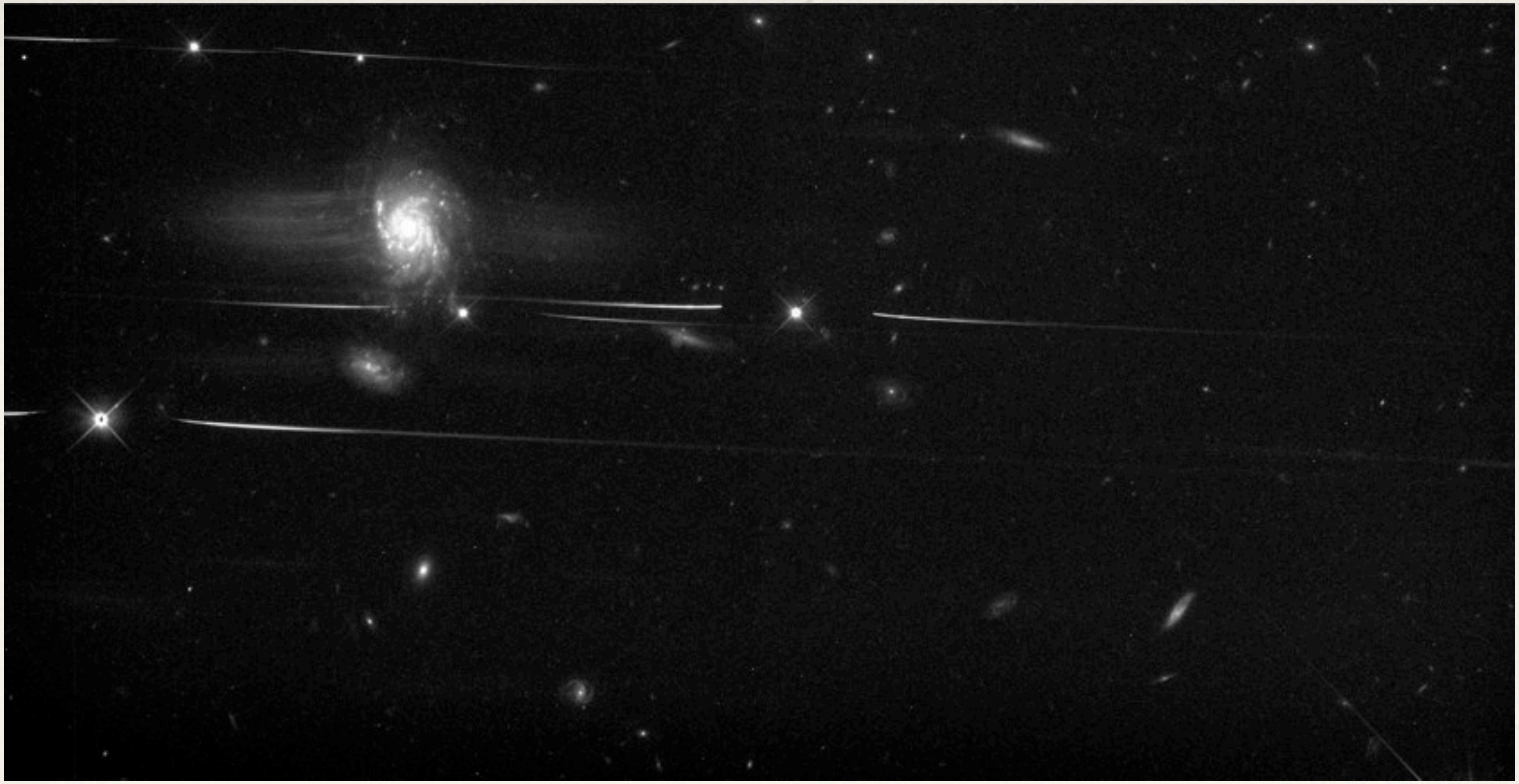

The ACS/WFC3 Survey for Lyman Limit Systems

John M. O'Meara
Saint Michael's College

J. Xavier Prochaska, Piero Madau
UCSC

Hsiao-Wen Chen
U. Chicago

October 14, 2010

THANK YOU!


ALTMAN • JOHNSON • MASSIMINO • GOOD • McARTHUR • FEUSTEL • GRUNSFELD •
125

THANK YOU!


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FUZZBOX
PIRANHA

THANK YOU!

THANK YOU!

THANK YOU!

THANK YOU!

Motivation for an LLS Survey

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- Follow the history of HI ionizing photons with cosmic time

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- Follow the history of HI ionizing photons with cosmic time
- Study the contributions of quasars and galaxies to the UVB

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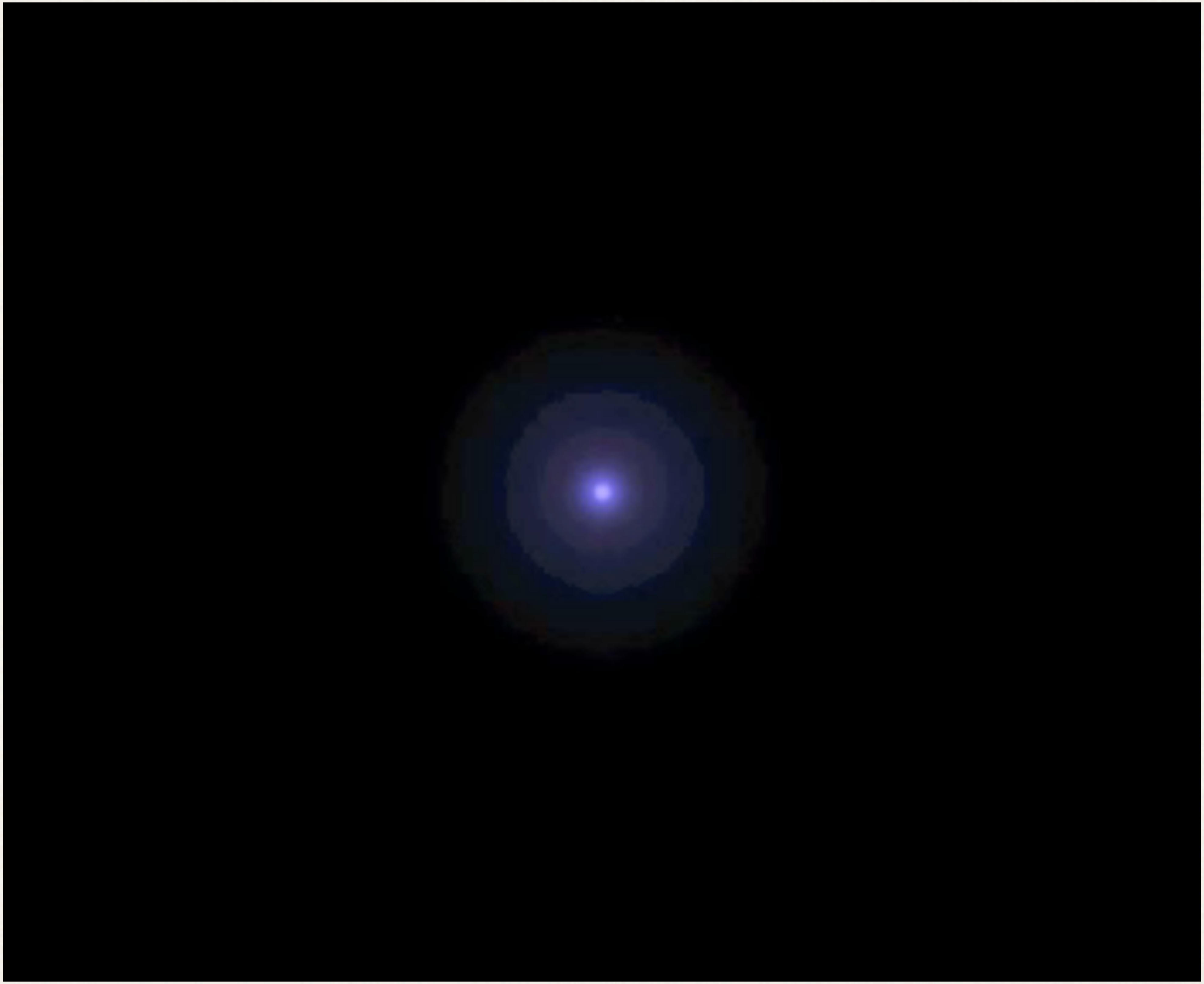
- Our answers depend on the opacity of the IGM to ionizing radiation from Lyman limit systems



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- Motivation #2: Where are the metals hiding?!?!

Motivation

- Follow the history of HI ionizing photons with cosmic time
- Study the contributions of quasars and galaxies to the UVB
- Our answers depend on the opacity of the IGM to ionizing radiation from Lyman limit systems
- Motivation #2: Where are the metals hiding?!?!
- Motivation #3: We still don't know what they are!

How to play the game

How to play the game

- Quasar surveys easily pick out Lyman limit systems with $\tau_{LL}>2$

Draft version November 30, 2009
Preprint typeset using LaTeX style emulateapj v. 08/13/06

A DEFINITIVE SURVEY FOR LYMAN LIMIT SYSTEMS AT $Z \sim 3.5$ WITH THE SLOAN DIGITAL SKY SURVEY

J. Xavier Prochaska[1], John M. O'Meara[2], Gabor Worseck[1]

Draft version November 30, 2009

ABSTRACT

We perform a semi-automated survey for $\tau_{912} \geq 2$ Lyman Limit systems (LLSs) in quasar spectra from the Sloan Digital Sky Survey, Data Release 7. From a starting sample of 2473 quasars with $z_{\rm em} = 3.6 - 4.4$, we analyze 469 spectra meeting strict seletion criteria for a total redshift path $\Delta z = 93.8$ and identify 192 intervening systems at $z_{\rm LLS} \geq 3.3$. The incidence of $\tau_{912} \geq 2$ LLSs per unit redshift, $\ell_{\tau \geq 2}(z)$, is well described by a single-power law at these redshifts: $\ell_{\tau \geq 2}(z) = C_{\rm LLS}[(1+z)/(1+z_*)]^{\gamma_{\rm LLS}}$, with $z_* \equiv 3.7$, $C_{\rm LLS} = 1.9 \pm 0.2$, and $\gamma_{\rm LLS} = 5.2 \pm 1.5$ (68% c.l.). These values are systematically lower than previous estimates (especially at $z < 4$) but are consistent with recent measurements of the mean free path to ionizing radiation. Extrapolations of this power-law to $z = 0$ are inconsistent with previous estimations of $\ell(z)$ at $z < 1$ and suggest a break at $z \approx 2$, similar to that observed for the Lyα forest. Our results also indicate that the systems giving rise to LLS absorption decrease by $\approx 50\%$ in comoving number density and/or physical size from $z = 4$ to 3.3, perhaps due to an enhanced extragalactic ultraviolet background. The observations place an integral constraint on the H I frequency distribution $f(N_{\rm HI}, X)$ and indicate that the power-law slope $\beta \equiv d \ln f(N_{\rm HI}, X)/d \ln N_{\rm HI}$ is likely shallower than $\beta = -1$ at $N_{\rm HI} \approx 10^{18}\,{\rm cm}^{-2}$. Including other constraints on $f(N_{\rm HI}, X)$ from the literature, we infer that β is steeper than $\beta = -1.7$ at $N_{\rm HI} \approx 10^{15}\,{\rm cm}^{-2}$, implying at least two inflections in $f(N_{\rm HI}, X)$. We also perform a survey for proximate LLSs (PLLSs) and find that $\ell_{\rm PLLS}(z)$ is systematically lower ($\approx 25\%$) than intervening systems. Finally, we estimate that systematic effects impose an uncertainty of $10 - 20\%$ in the $\ell(z)$ measurements; these effects may limit the precision of all future surveys.

Subject headings: absorption lines – intergalactic medium – Lyman limit systems – SDSS

1. INTRODUCTION

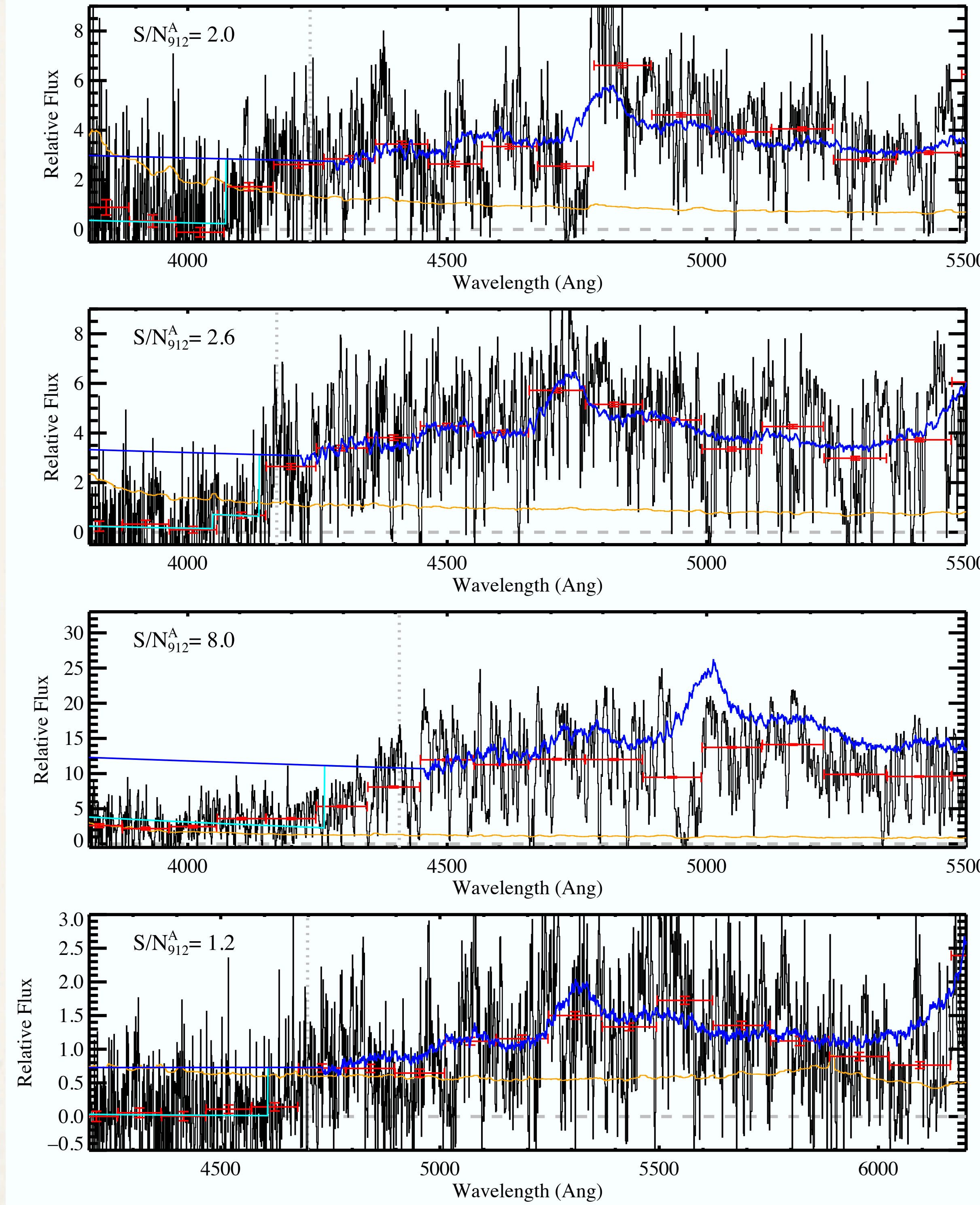
Studies of hydrogen absorption in the lines of sight towards distant quasars have served to both define, and in recent years bring precision to, our cosmological models. The low density, highly ionized Lyman–α forest lines (a.k.a. the intergalactic medium, IGM), with H I column densities $N_{\rm HI} < 10^{17.2}\,{\rm cm}^{-2}$, have through their aggregate statistical properties (e.g. their flux power spectrum, mean flux, and column density distributions) constrained cosmological parameters such as the primordial power spectrum and the baryonic mass density and astrophysical parameters like the amplitude of the ionizing background (e.g. Rauch 1998; Croft et al. 2002; McDonald et al. 2005; Tytler et al. 2004; Faucher-Giguère et al. 2008b). The high-density, predominantly neutral damped Lyα systems (DLAs), with $N_{\rm HI} \geq 10^{20.3}\,{\rm cm}^{-2}$, trace the gas which forms stars, and likely represent the progenitors of modern-day galaxies (e.g. Wolfe et al. 1995, 2005; Prochaska & Wolfe 2009).

The majority of Lyman–α forest lines and the DLAs have, through analysis of their Lyα lines, precisely measured $N_{\rm HI}$ values that permit detailed study of their physical properties (e.g. metallicity). For systems with intermediate $N_{\rm HI}$ values ($\approx 10^{18}\,{\rm cm}^{-2}$), however, Ly$\alpha$ and most of the Lyman series lines lie on the flat portion of the curve-of-growth making the $N_{\rm HI}$ value difficult to constrain. On the other hand, these systems are optically thick to ionizing radiation and impose a readily identified signature in a quasar spectrum at the Lyman limit. These so-called Lyman limit systems (LLSs), currently the least-well studied of H I absorption systems at high redshift, are the focus of this manuscript.

Historically, the LLSs were among the first class of quasar absorption line (QAL) systems to be surveyed (Tytler 1982). This is because their spectral signature is obvious in low-resolution, low S/N spectra. The principal challenge is that the Lyman limit occurs redward of the atmospheric cutoff only for systems with redshifts $z > 2.6$. For lower redshifts, one requires spectrometers on space-borne ultraviolet satellites. By the mid 1990's, samples of several tens of LLSs were generated spanning redshifts $0 < z < 4$ (Sargent et al. 1989; Lanzetta 1991; Storrie-Lombardi et al. 1994; Stengler-Larrea et al. 1995). These results were derived from heterogeneous sets of quasars discovered from a combination of color-selection, radio detection, and slitless spectroscopic surveys. The spectra, too, were acquired with a diverse set of instrumentation and therefore varying S/N and spectral resolution mitigating differing sensitivity to the precise optical depth at the Lyman limit. Although the results were not fully consistent with one another, the general picture that resulted was a rapidly evolving population of absorption systems reasonably described by a $(1+z)^{1.5}$ power-law.

Cosmologically, the LLSs contribute much if not most of the universe's opacity to ionizing radiation. And, until recently, the observed incidence of the LLS provided the only direct means of estimating the mean free path $\lambda^{912}_{\rm mfp}$

[1] Department of Astronomy and Astrophysics, UCO/Lick Observatory, University of California, 1156 High Street, Santa Cruz, CA 95064
[2] Department of Chemistry and Physics, Saint Michael's College. One Winooski Park, Colchester, VT 05439



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Preprint typeset using LaTeX style emulateapj v. 20/04/00

THE SDSS DAMPED Lyα SURVEY: DATA RELEASE 3

Jason X. Prochaska & Stéphane Herbert-Fort
Department of Astronomy and Astrophysics, UCO/Lick Observatory; University of California, 1156 High Street, Santa Cruz, CA 95064; xavier@ucolick.org, shf@ucolick.org
AND
Arthur M. Wolfe
Department of Physics, and Center for Astrophysics and Space Sciences, University of California, San Diego, Gilman Dr., La Jolla; CA 92093-0424; awolfe@ucsd.edu
Accepted to ApJ: August 15, 2005

ABSTRACT

We present the results from a damped Lyα survey of the Sloan Digital Sky Survey, Data Release 3. We have discovered over 500 new damped Lyα systems at $z > 2.2$ and the complete statistical sample for $z > 1.6$ has more than 600 damped Lyα galaxies. We measure the H I column density distribution $f_{\rm HI}(N, X)$ and its zeroth and first moments (the incidence $\ell_{\rm DLA}$ and gas mass-density $\Omega_g^{\rm DLA}$ of damped Lyα systems, respectively) as a function of redshift. The key results include: (1) the full SDSS-DR3 $f_{\rm HI}(N, X)$ distribution ($z \sim 3.06$) is well fit by a Γ-function (or double power-law) with 'break' column density $N_\gamma = 10^{21.5\pm0.1}\,{\rm cm}^{-2}$ and 'faint-end' slope $\alpha = -1.8 \pm 0.1$; (2) the shape of the $f_{\rm HI}(N, X)$ distributions in a series of redshift bins does not show evolution; (3) the incidence and gas mass density of damped systems decrease by $35 \pm 9\%$ and $50 \pm 10\%$ during $\approx 1\,$Gyr between the redshift interval $z = [3., 3.5]$ to $z = [2.2, 2.5]$; and (4) the incidence and gas mass density of damped Lyα systems in the lowest SDSS redshift bin ($z = 2.2$) are consistent with the current values. We investigate a number of systematic errors in damped Lyα analysis and identify only one important effect: we measure $40 \pm 20\%$ higher $\Omega_g^{\rm DLA}$ values toward a subset of brighter quasars than toward a faint subset. This effect is contrary to the bias associated with dust obscuration and suggests that gravitational lensing may be important. Comparing the results against several models of galaxy formation in ΛCDM, we find all of the models significantly underpredict $\ell_{\rm DLA}$ at $z = 3$ and only SPH models with significant feedback (Nagamine et al.) may reproduce $\Omega_g^{\rm DLA}$ at high redshift. Based on our results for the damped Lyα systems, we argue that the Lyman limit systems contribute $\approx 33\%$ of the universe's H I atoms at all redshifts $z = 2$ to 5. Furthermore, we infer that the $f_{\rm HI}(N, X)$ distribution for $N_{\rm HI} < 10^{20}\,{\rm cm}^{-2}$ has an inflection with slope $d \log f / d \log N > -1$. We advocate a new mass density definition – the mass density of predominantly neutral gas $\Omega_g^{\rm Neut}$ – to be contrasted with the mass density of gas associated with H I atoms. We contend the damped Lyα systems contribute $> 80\%$ of $\Omega_g^{\rm Neut}$ at all redshifts and therefore are the main reservoirs for star formation.

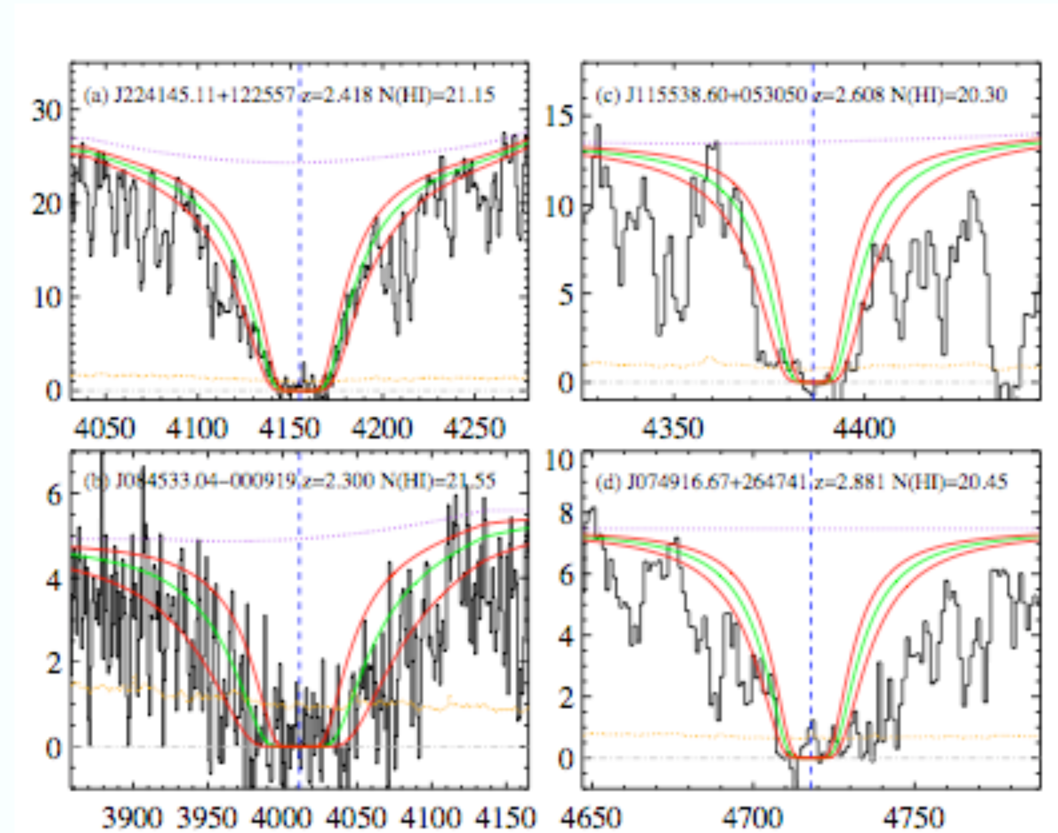
Subject headings: galaxies: evolution — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

The damped Lyα systems are the class of quasar absorption line systems with H I column density $N_{\rm HI} \geq 2 \times 10^{20}\,{\rm cm}^{-2}$ (see Wolfe, Gawiser, & Prochaska 2005, for a review). Unlike the Lyα forest, the damped Lyα systems are comprised of predominantly neutral gas and are proposed to be the progenitors of galaxies like the Milky Way (e.g. Kauffmann 1996). Wolfe et al. (1986) established the $N_{th} = 2 \times 10^{20}\,{\rm cm}^{-2}$ threshold primarily to correspond to the surface density limit of local 21 cm observations at that time. It is somewhat fortuitous that this threshold roughly corresponds to the transition from primarily ionized gas to predominantly neutral gas (e.g. Viegas 1995; Prochaska & Wolfe 1996; Prochaska 1999; Vladilo et al. 2001).

For the past two decades, several groups have surveyed high z quasars for the damped Lyα systems (Wolfe et al. 1986, 1995; Storrie-Lombardi et al. 1996a; Storrie-Lombardi & Wolfe 2000; Péroux et al. 2003). These surveys measured the H I frequency distribution function and its moments: the incidence of the damped Lyα systems $\ell_{\rm DLA}$ and the gas mass density of these galaxies $\Omega_g^{\rm DLA}$. The latter quantity has cosmological significance. Its evolution constrains the build-up of structure within hierarchical cosmology (e.g. Ma & Bertschinger 1994; Klypin et al. 1995), it serves as the important neutral gas reservoir for star formation at high redshift and describes the competition between gas accretion and star formation (e.g. Fall & Pei 1993), and it constrains models of galaxy formation in hierarchical cosmology (e.g. Somerville, Primack, & Faber 2001; Cen et al. 2003; Nagamine, Springel, & Hernquist 2004). Previous surveys have reported statistical error on $\Omega_g^{\rm DLA}$ of $\approx 30\%$ in redshift intervals $\Delta z \approx 0.5$ at high redshift. As we enter the so-called era of precision cosmology, we aspire to constrain $\Omega_g^{\rm DLA}$ to better than 10%. Although not formally a cosmological parameter, a precise determination of $\Omega_g^{\rm DLA}$ and its redshift evolution are fundamental constraints on any cosmological theory of galaxy formation.

In Prochaska & Herbert-Fort (2004), hereafter PH04, we initiated a survey for the damped Lyα systems in the quasar spectra of the Sloan Digital Sky Survey (SDSS) Data Release 1 (DR1). We demonstrated that the spectral resolution, signal-to-noise ratio (SNR), and wavelength coverage of the SDSS spectra are well suited to survey the damped Lyα systems at $z > 2.2$. We reported on the number of damped Lyα systems per unit redshift and the



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How to play the game

- Quasar surveys easily pick out Lyman limit systems with $\tau_{LL}>2$
- Surveys for $\tau_{LL}>>2$ also work well
- The Lyman Alpha forest is well sampled

Difficulties

Difficulties

- Going below z~2.7 means going to space

Difficulties

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- The integrated opacity includes (and is probably dominated by) $\tau_{LL}\sim 1$

The good news

The good news

- Going below z~2.7 means going to space!

The good news

- Going below z~2.7 means going to space!
- The universe expands!

The ACS/WFC3 Survey

The ACS/WFC3 Survey

- Build a homogenous sample of QSOs from SDSS

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- Bright, $z\sim2$, no BAL

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- Cycle 15 (ACS) & Cycle 17 (WFC3) SNAP programs

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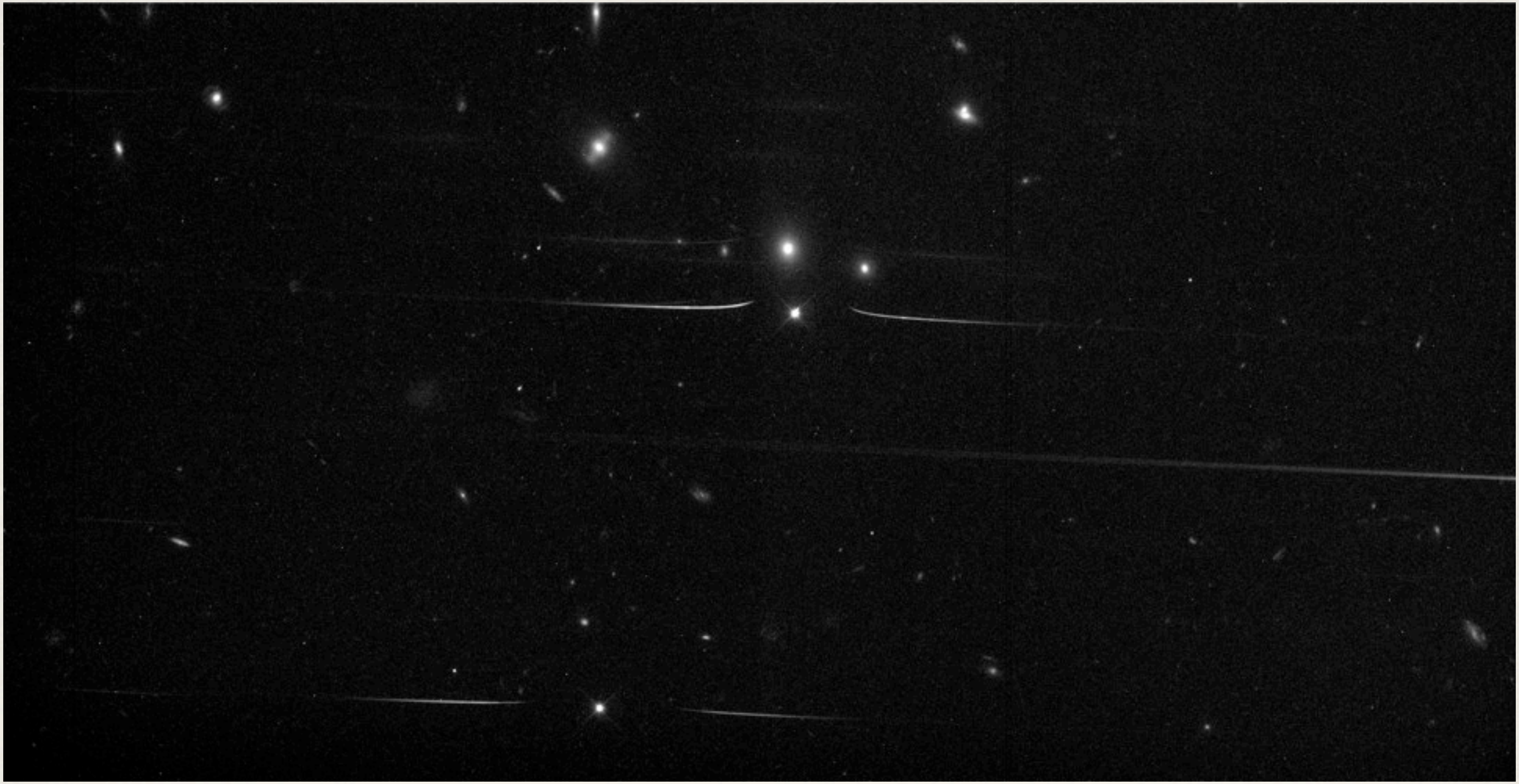
- 73 quasars to date
- Redshift path at z~2 with WFC3 **as big** as SDSS at z~4!



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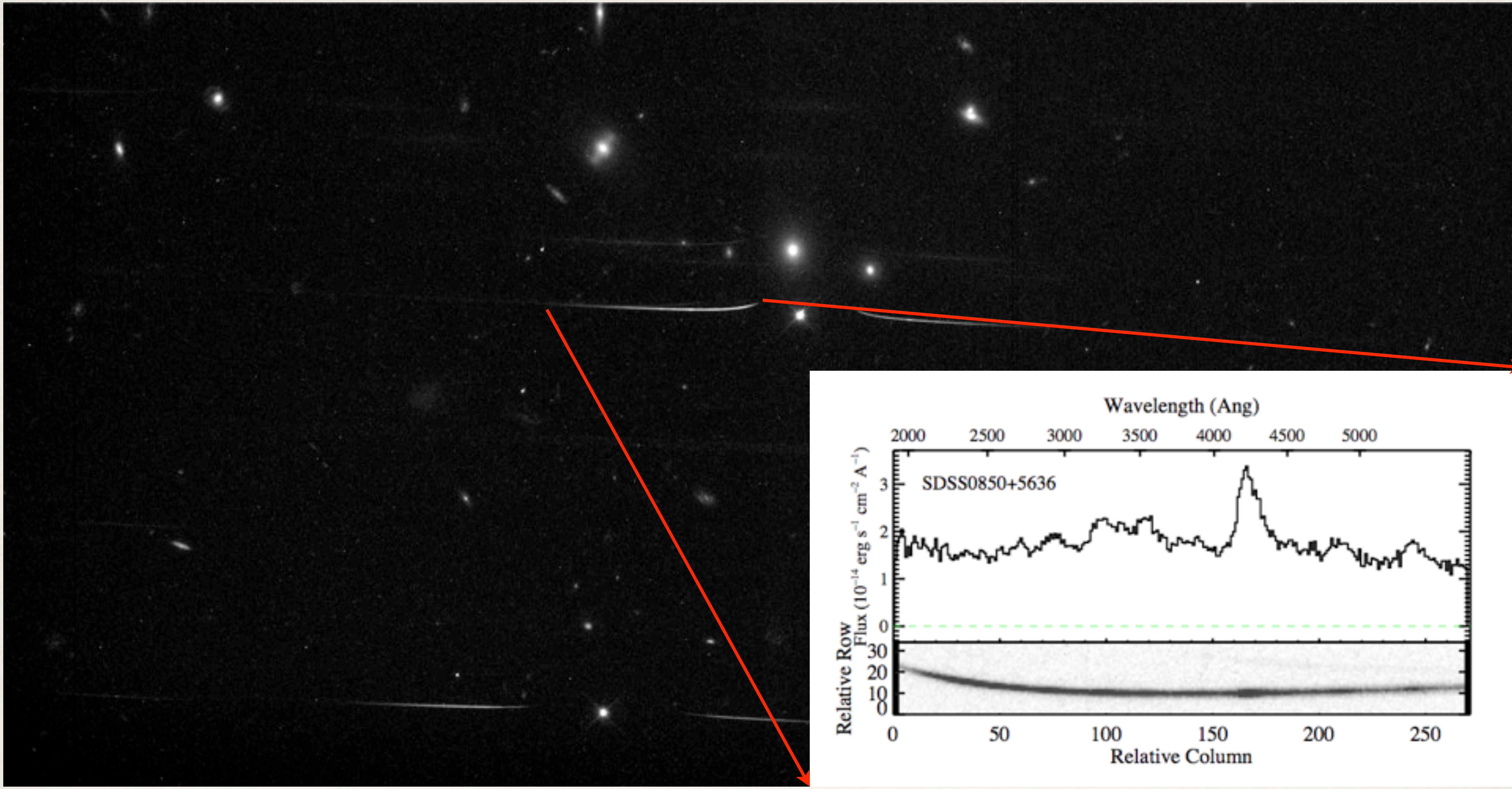

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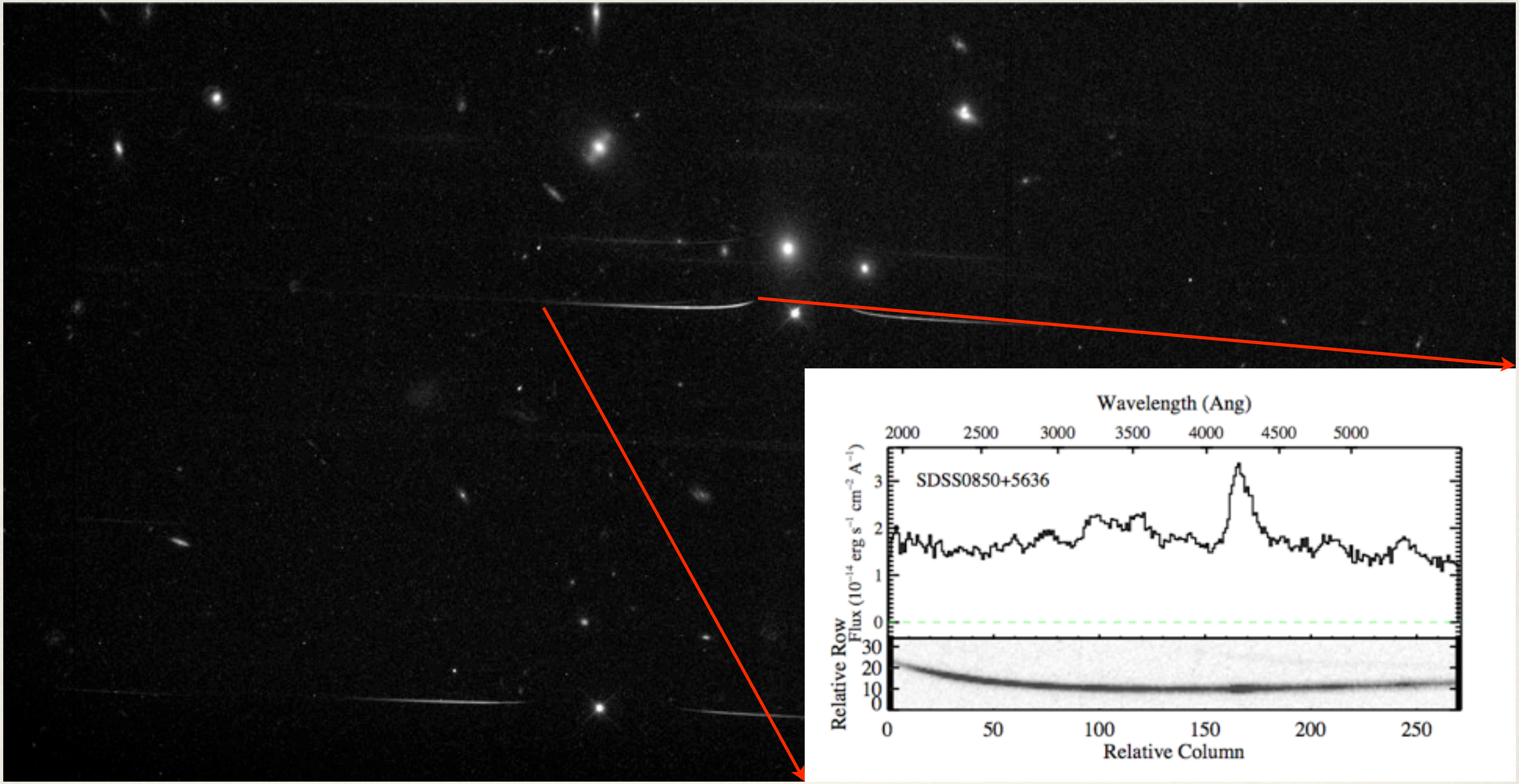

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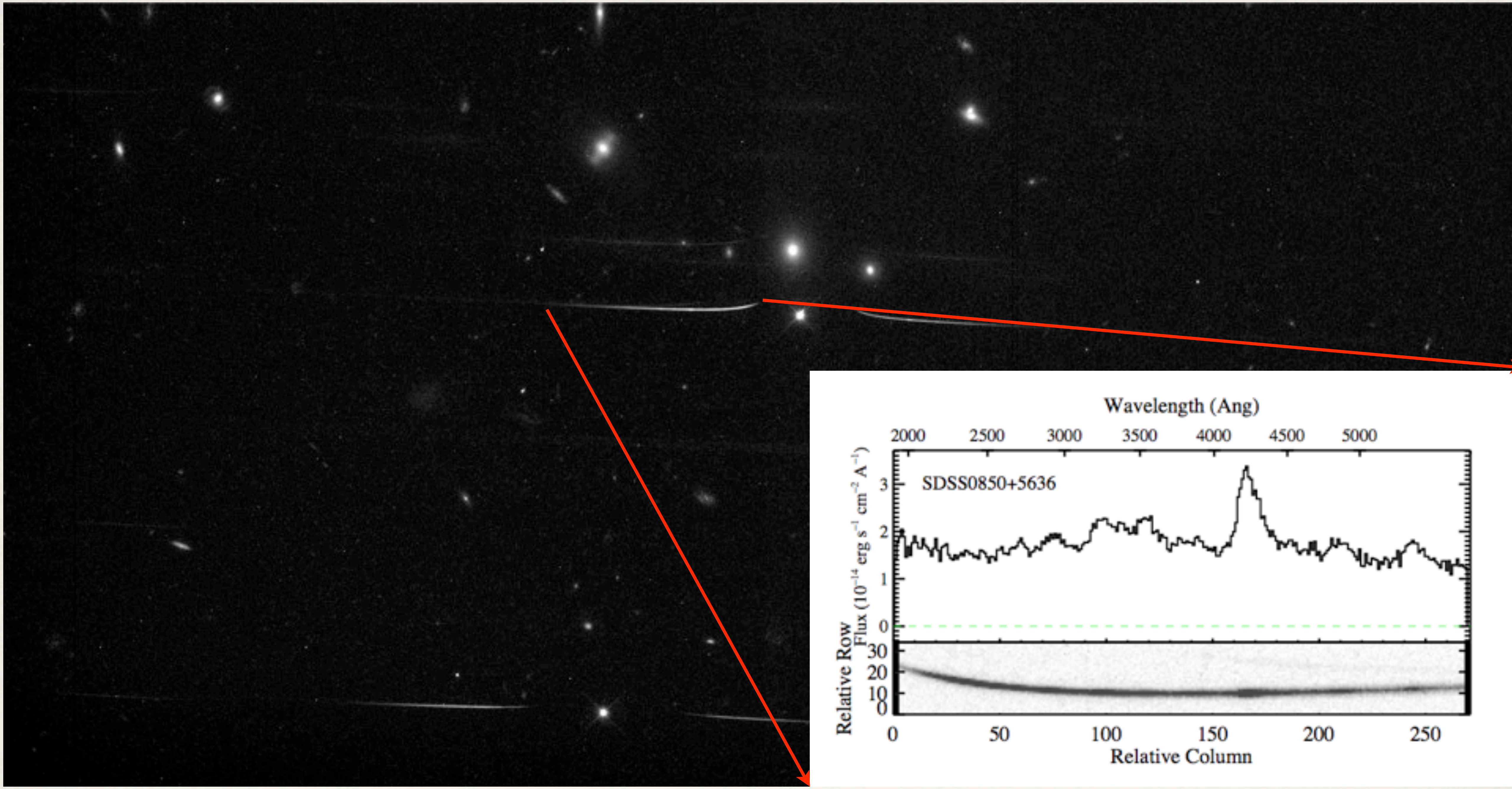
Thanks ST-ECF folks!



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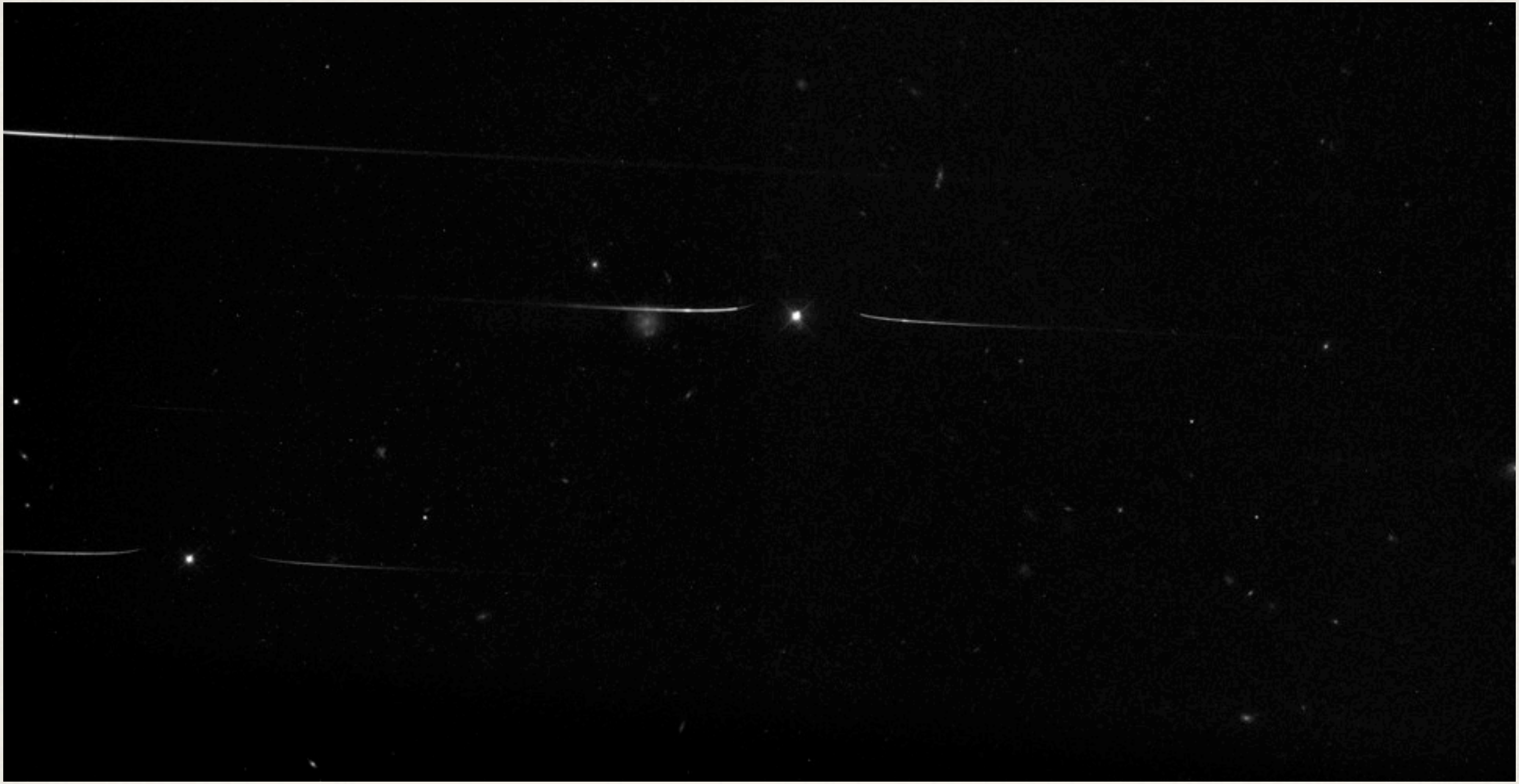
Thanks ST-ECF folks!

No LLS



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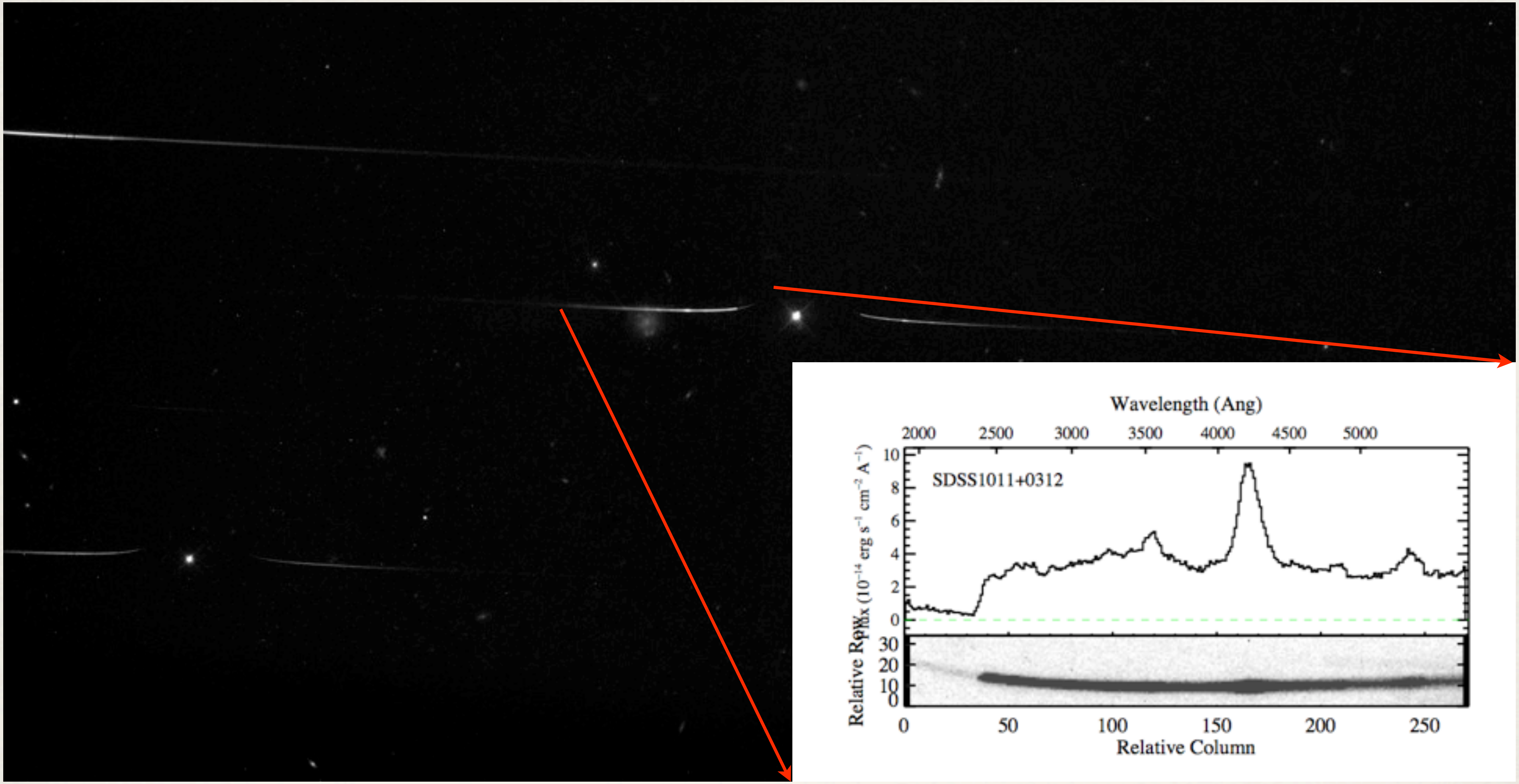

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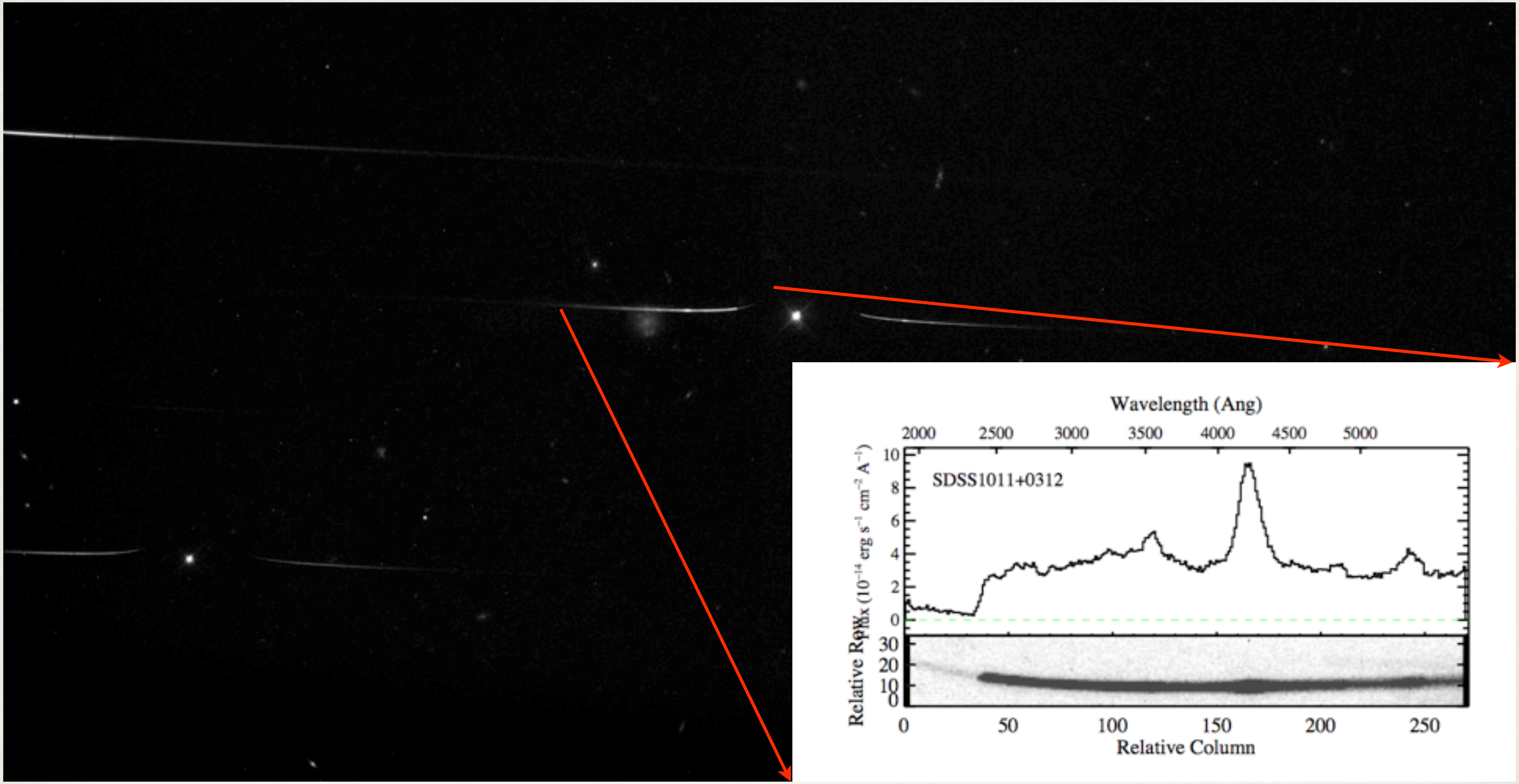

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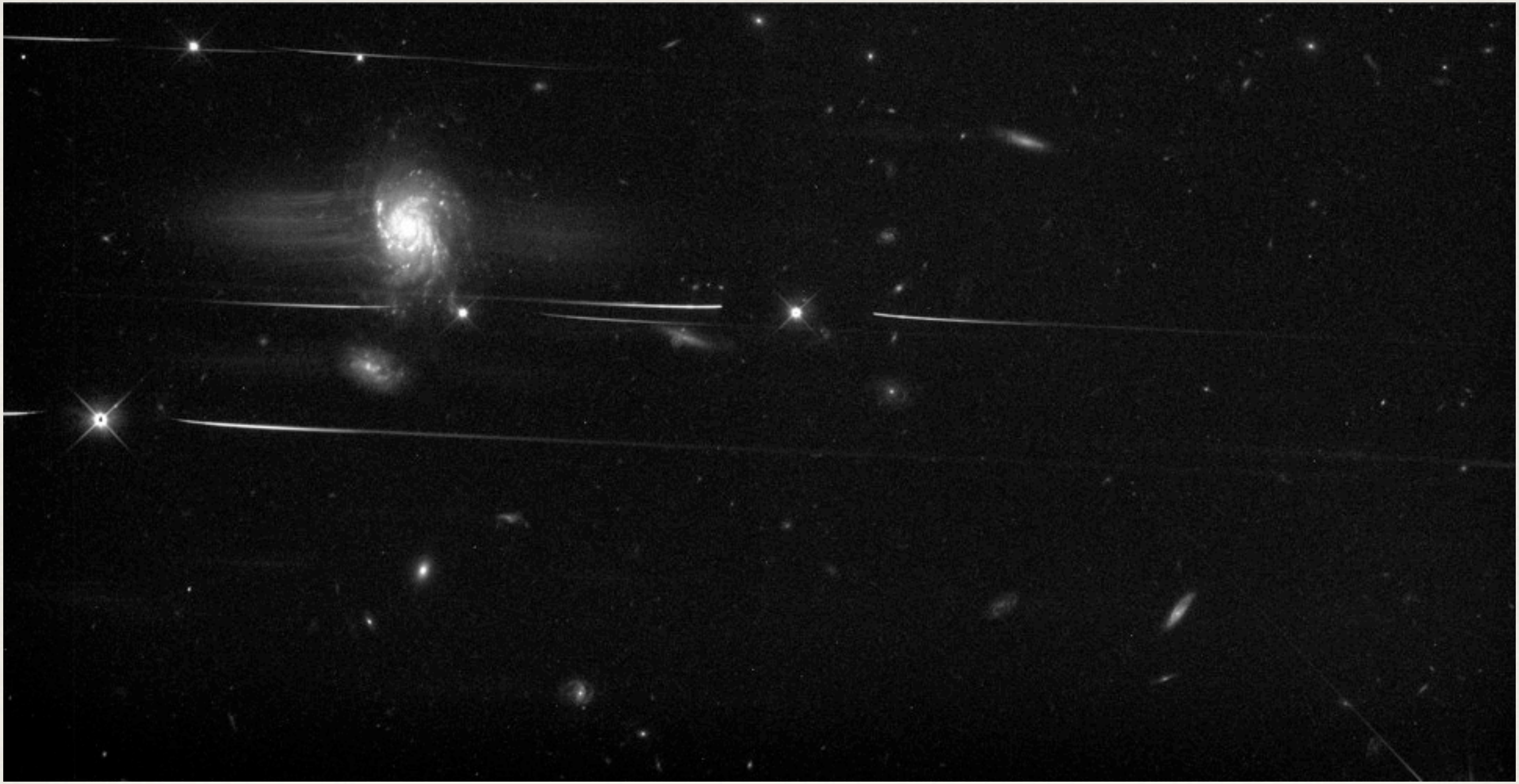
Partial LLS



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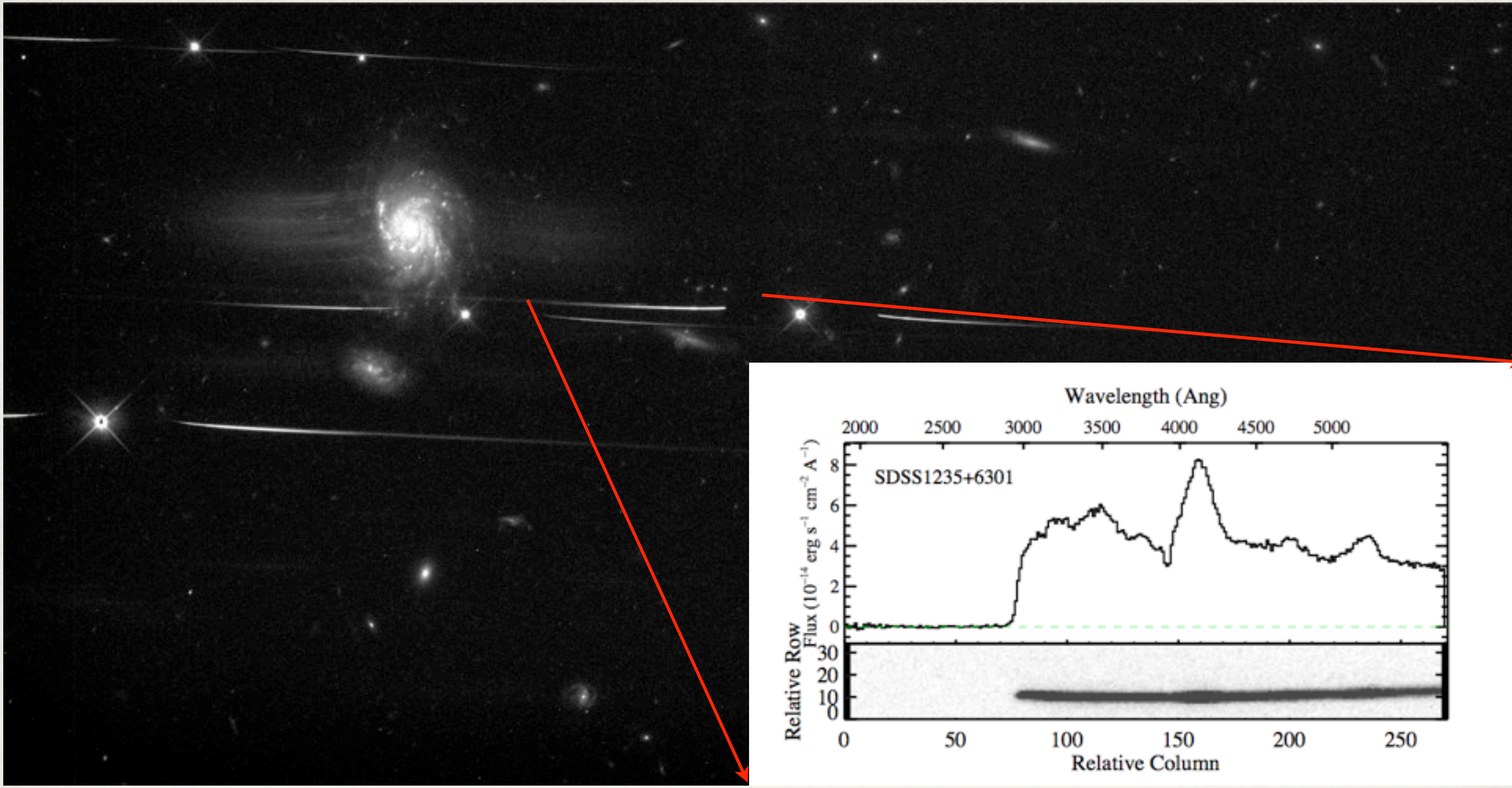

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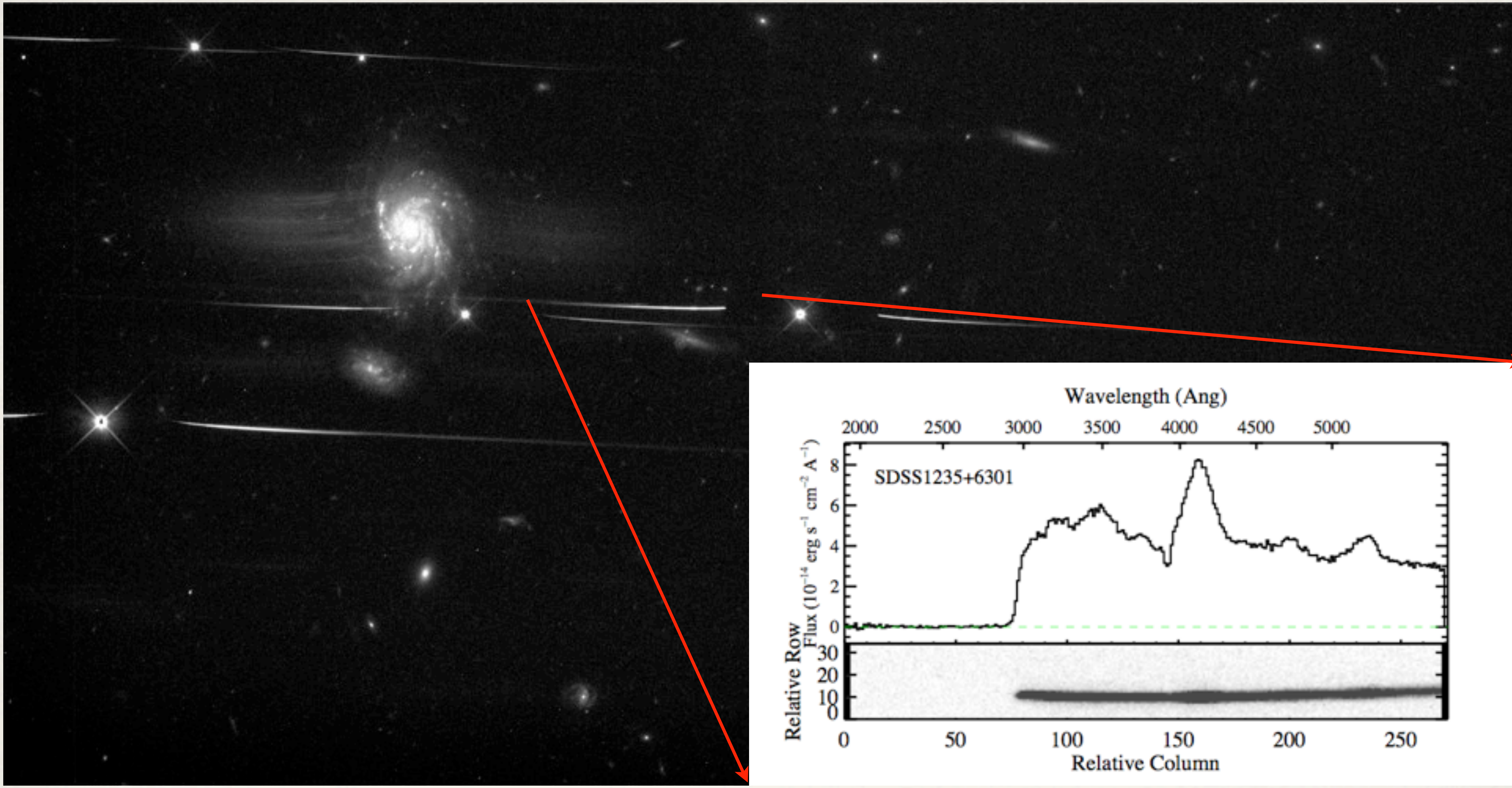
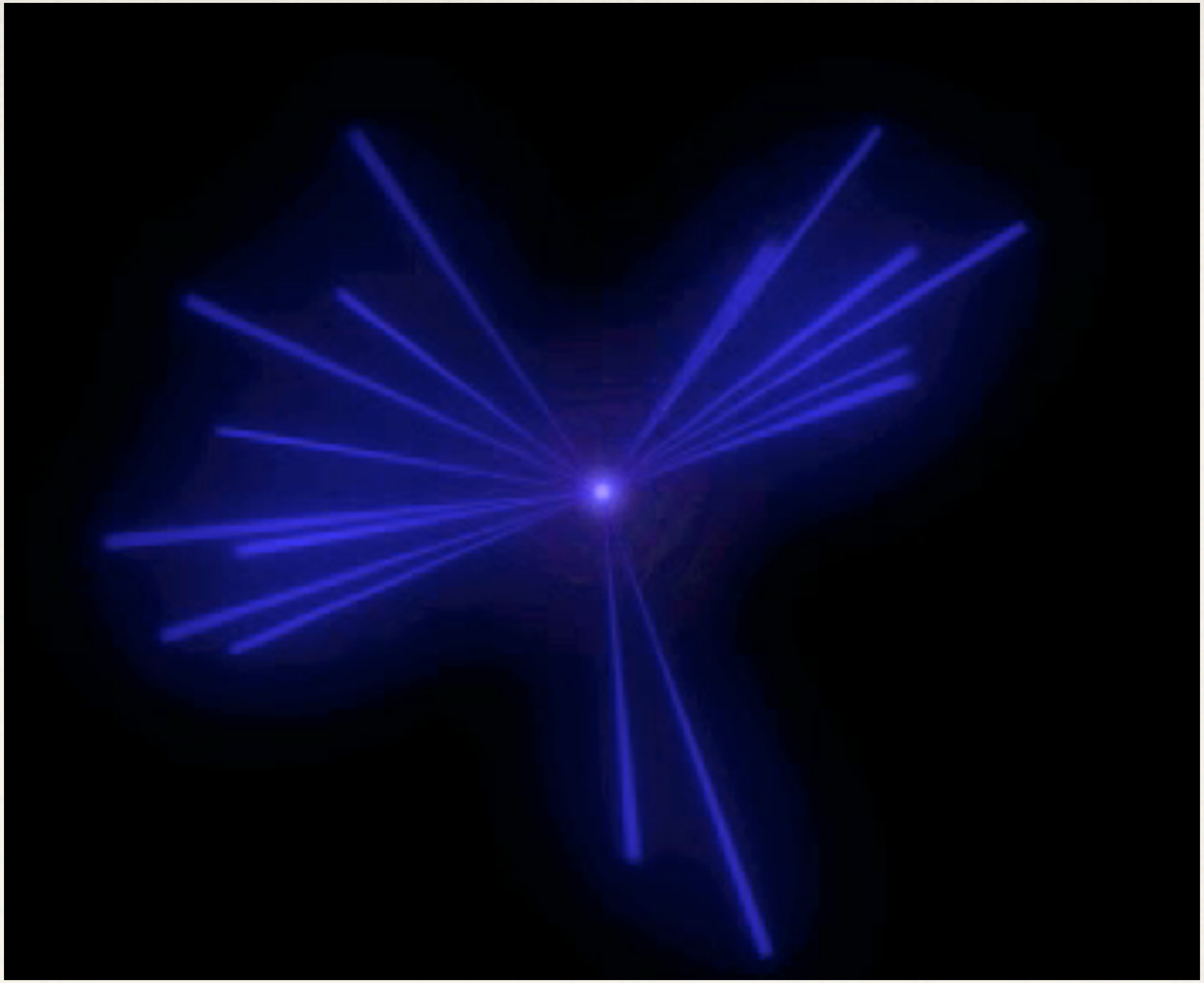


SDSS1235+6301

Full LLS

IGM Opacity-->The Mean Free Path



IGM Opacity-->The Mean Free Path

Old School

Old School

- Begin with counting the LLS

Old School

- Begin with counting the LLS
- Determine the N(HI) frequency distribution

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- Integrate them up!

Old School

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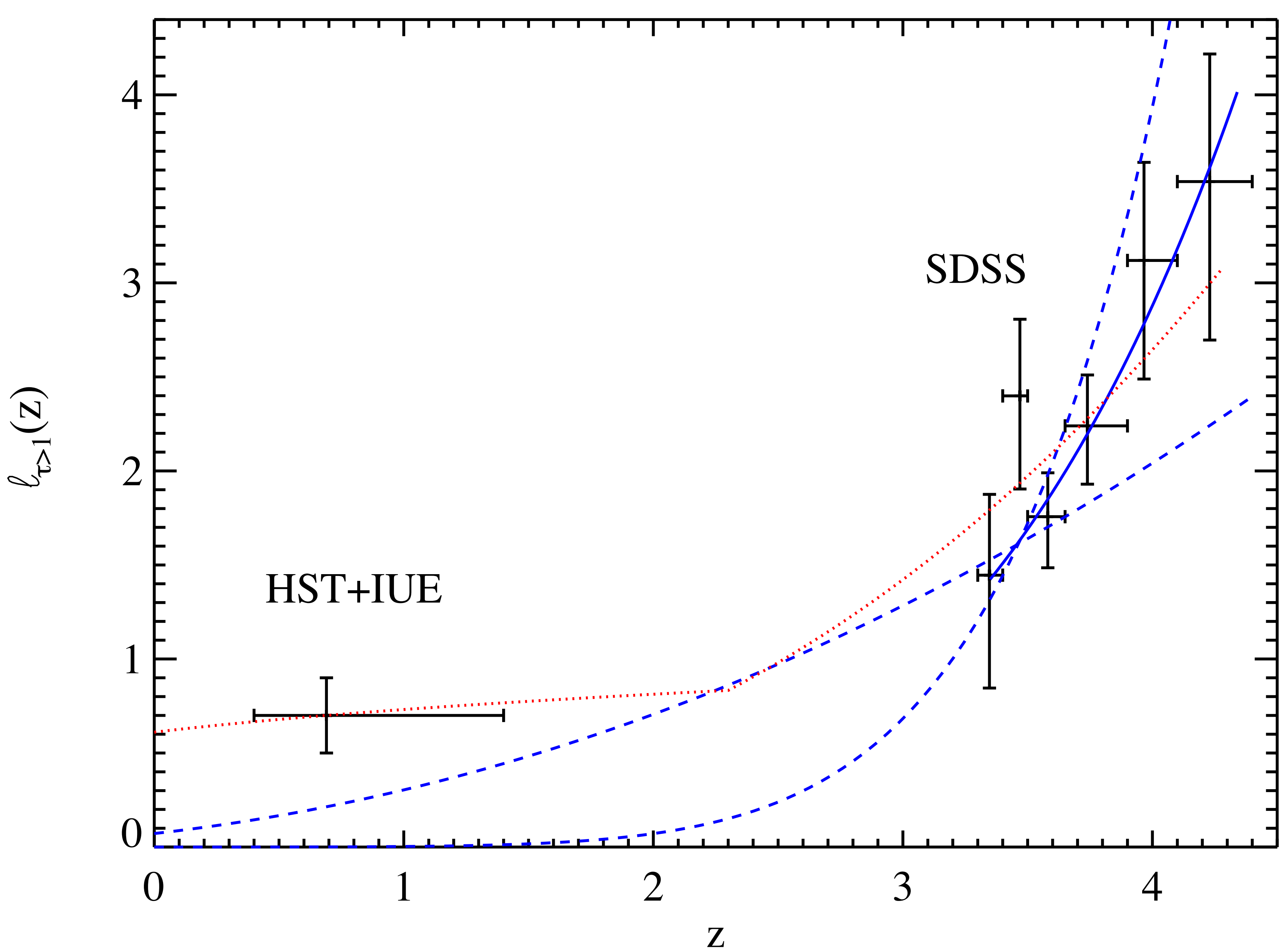
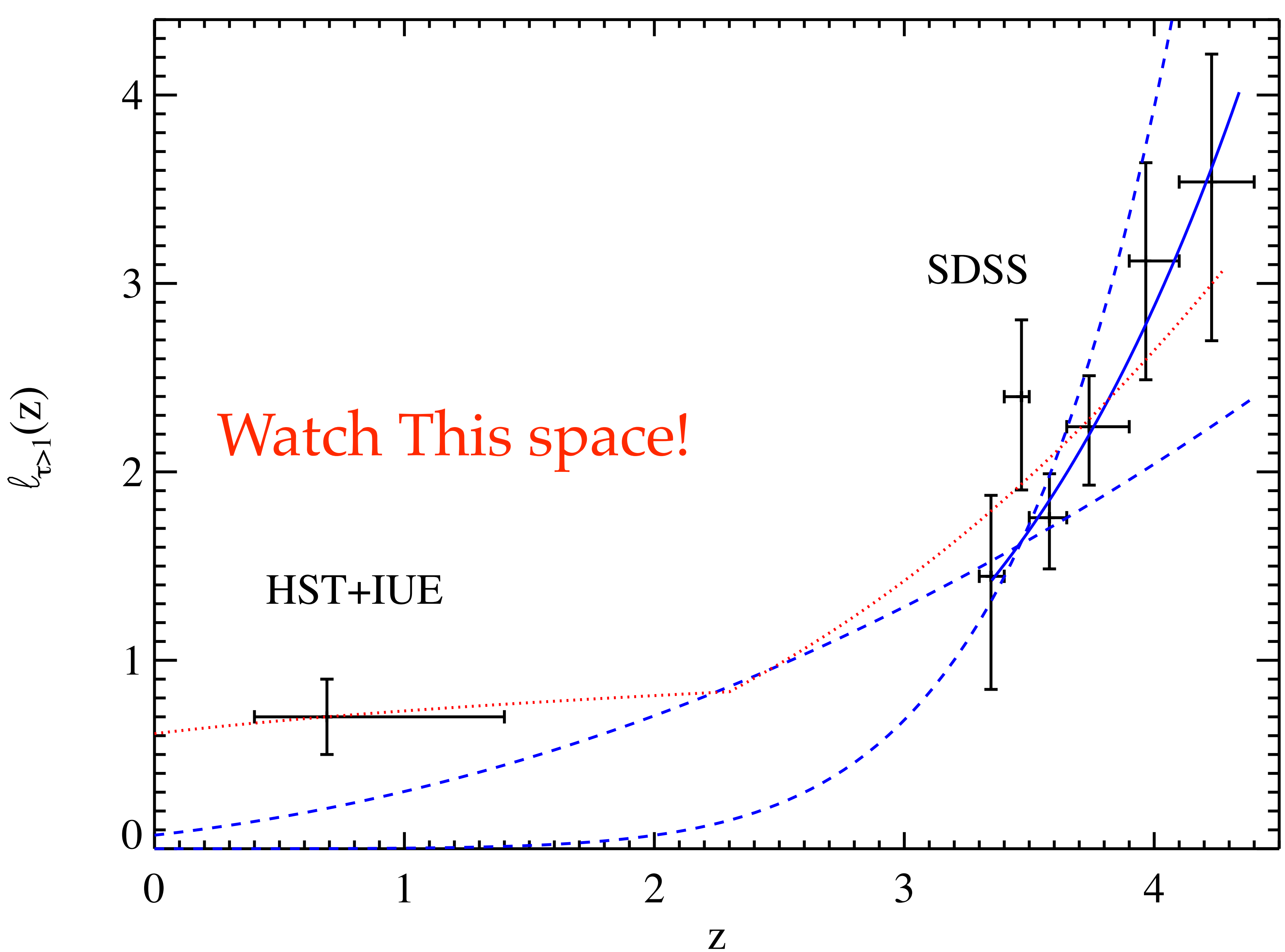
- Determine the N(HI) frequency distribution
- Integrate them up!

$$\tau_{\mathrm{eff,LL}}(z_{912}, z_q) = \int\limits_{z_{912}}^{z_q} \int\limits_0^{\infty} f(N_{\mathrm{HI}}, z')\{1 - \exp\left[-N_{\mathrm{HI}}\sigma_{\mathrm{ph}}(z')\right]\} dN_{\mathrm{HI}} dz'$$

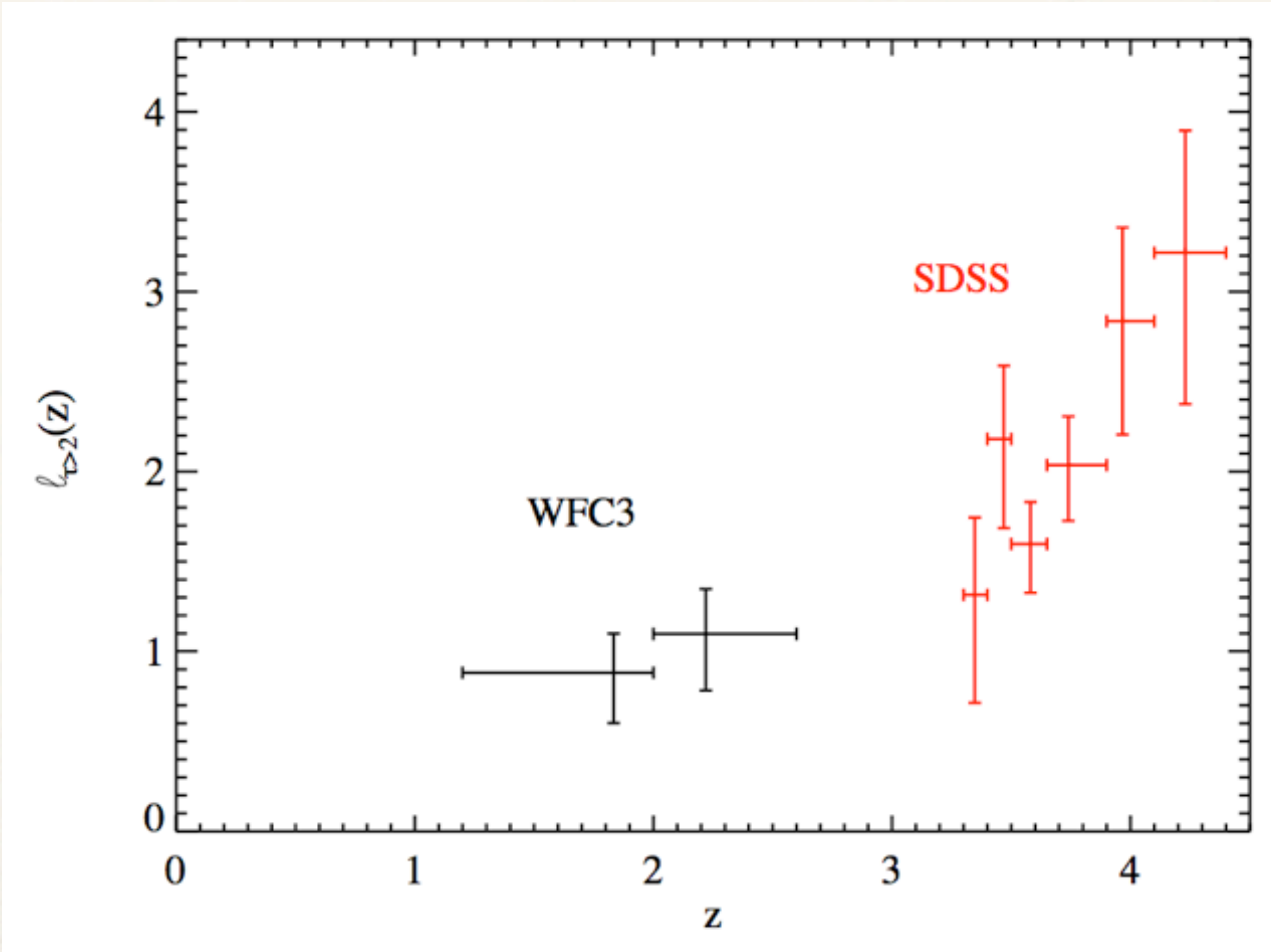
LLS Incidence Frequency



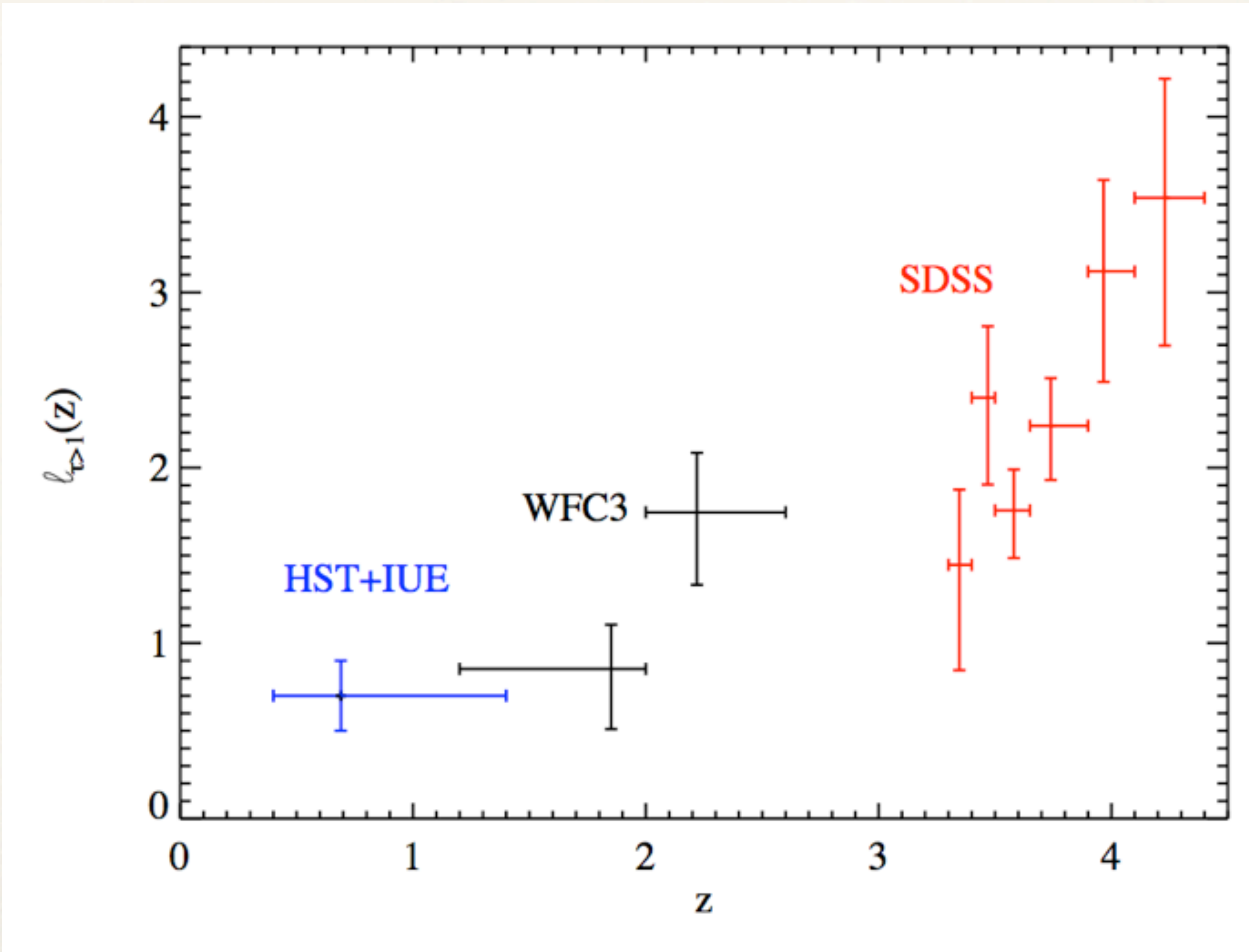
LLS Incidence Frequency



LLS Incidence Frequency

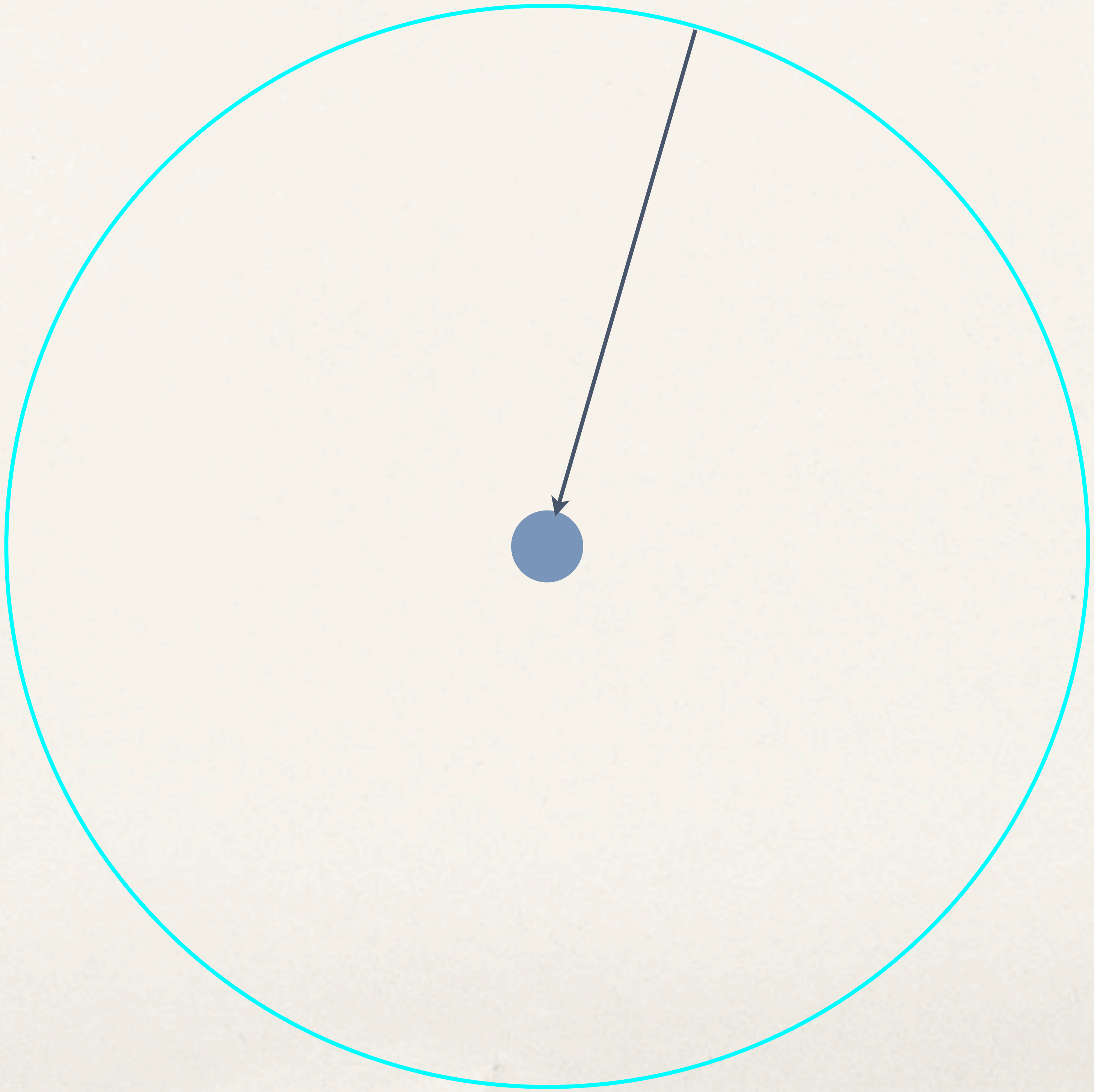


LLS Incidence Frequency



New School

New School



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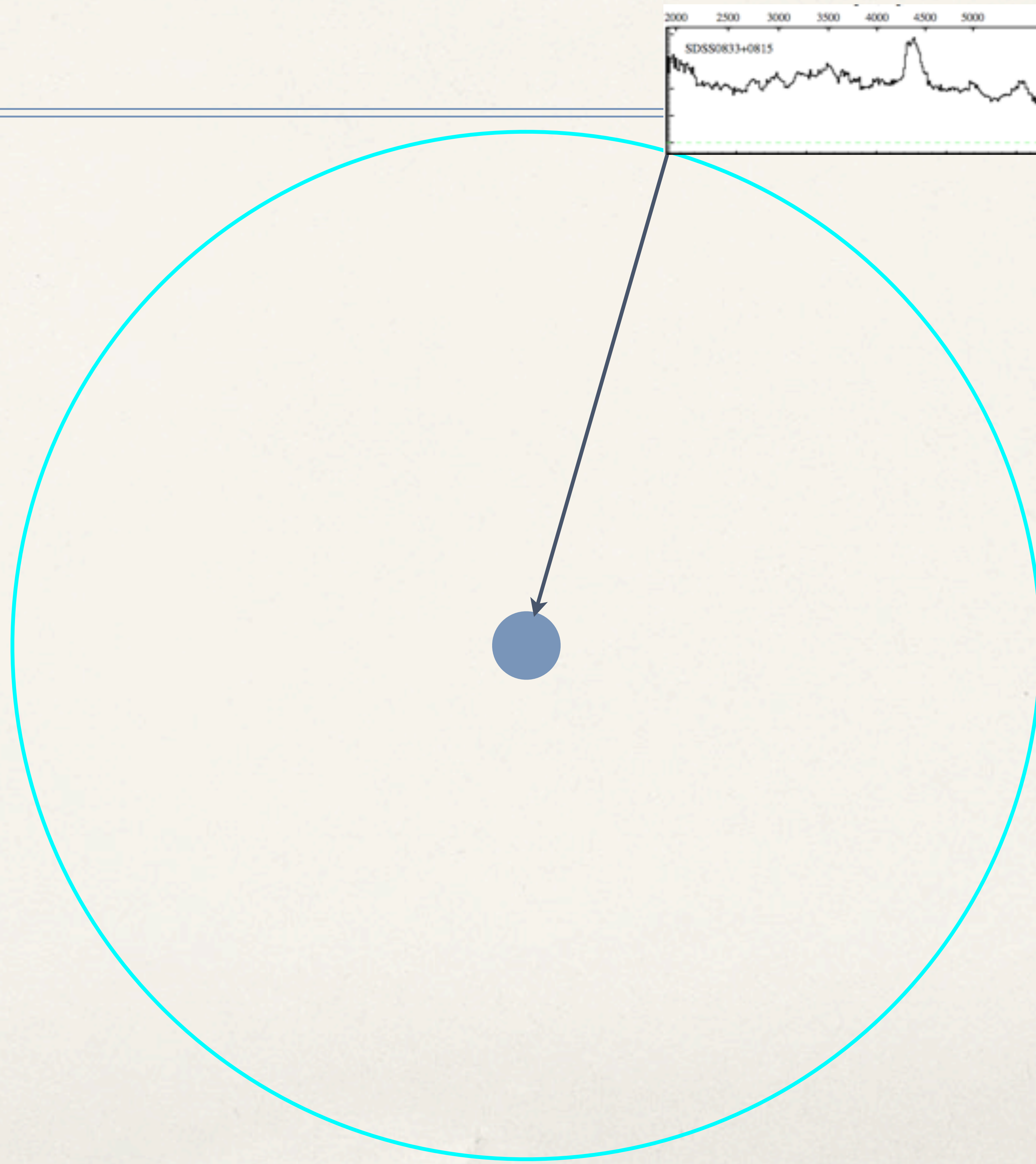

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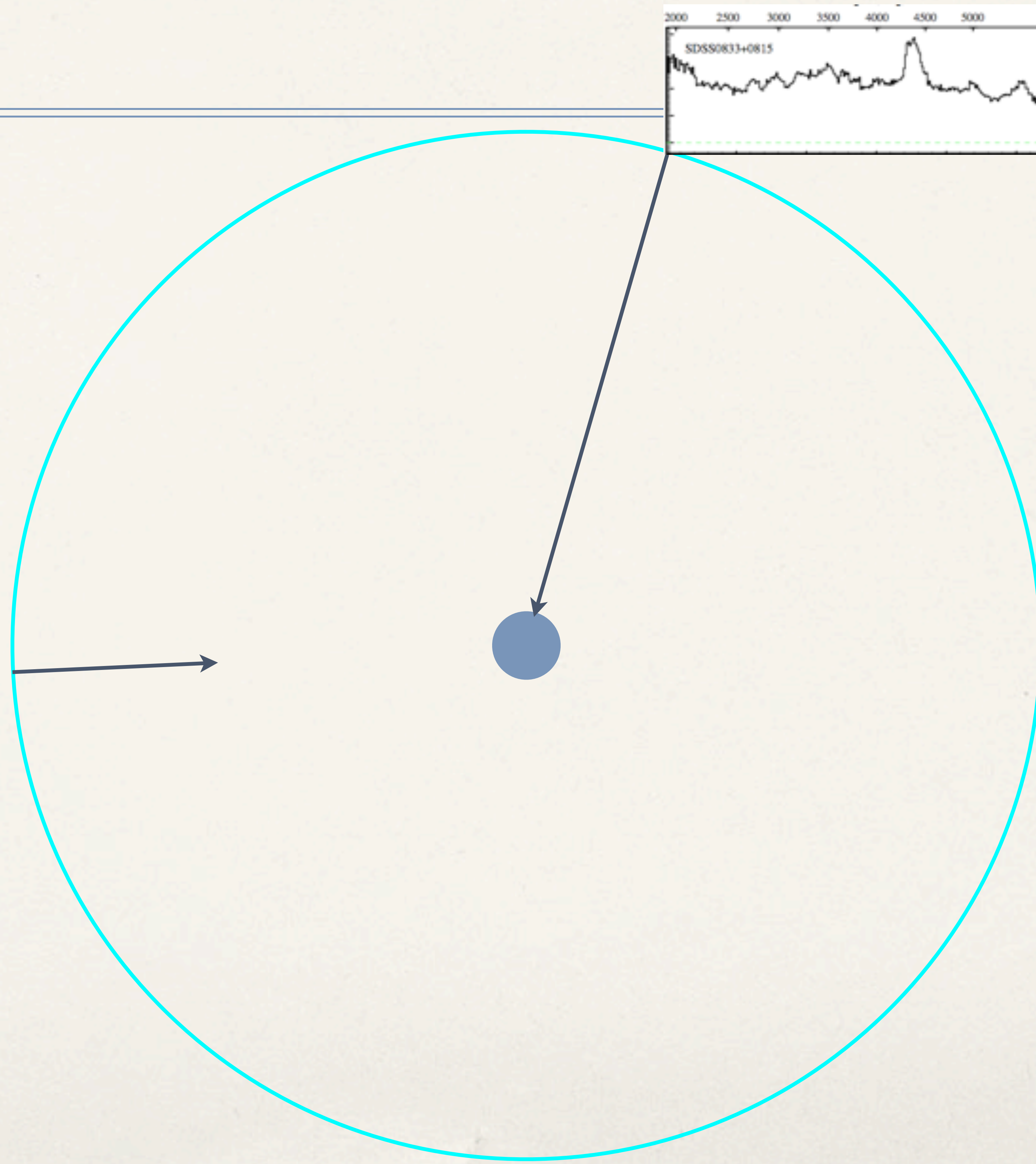

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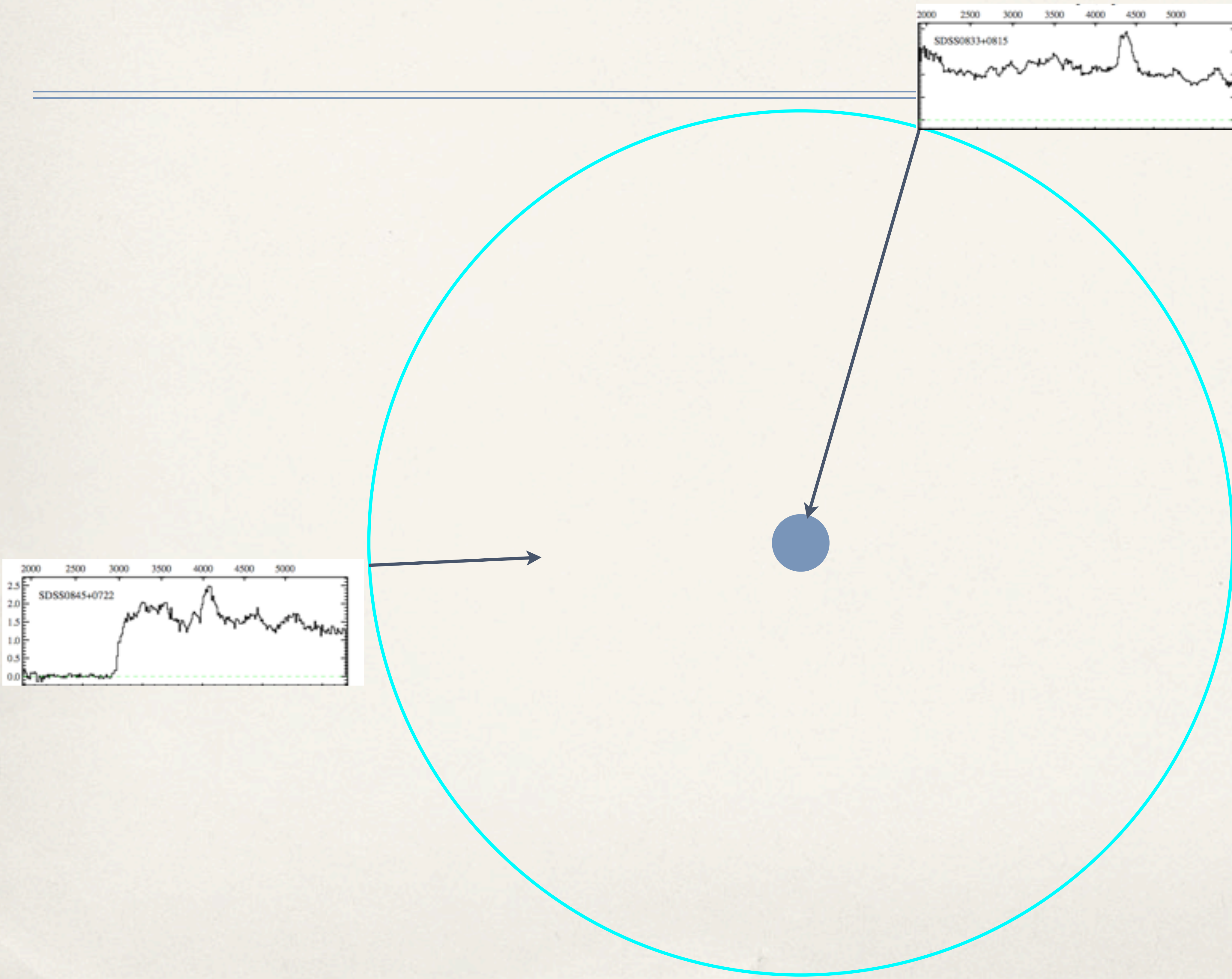
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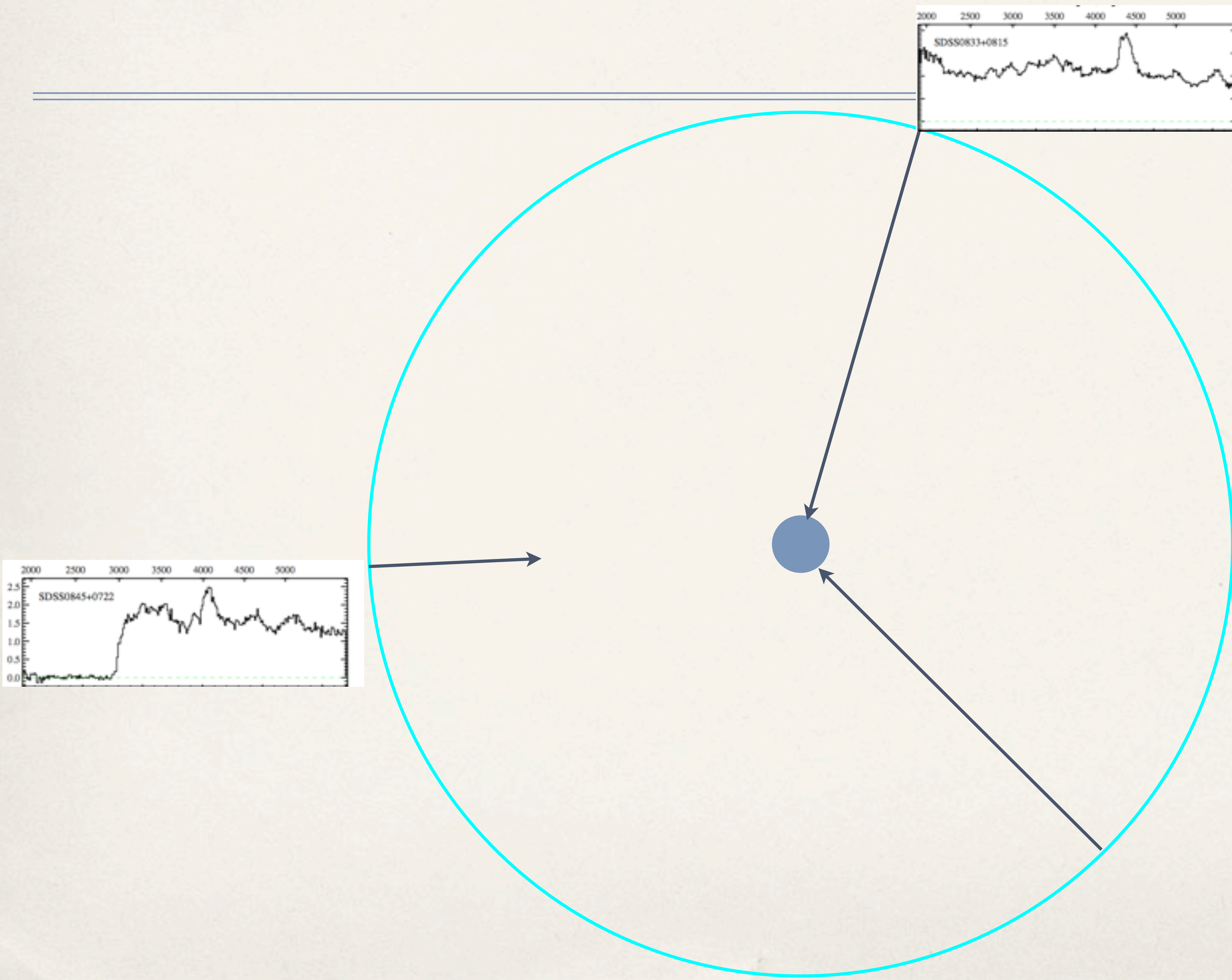
SDSS0845+0722
2000 2500 3000 3500 4000 4500 5000
2.5 2.0 1.5 1.0 0.5 0.0

New School


SDSS0833+0815
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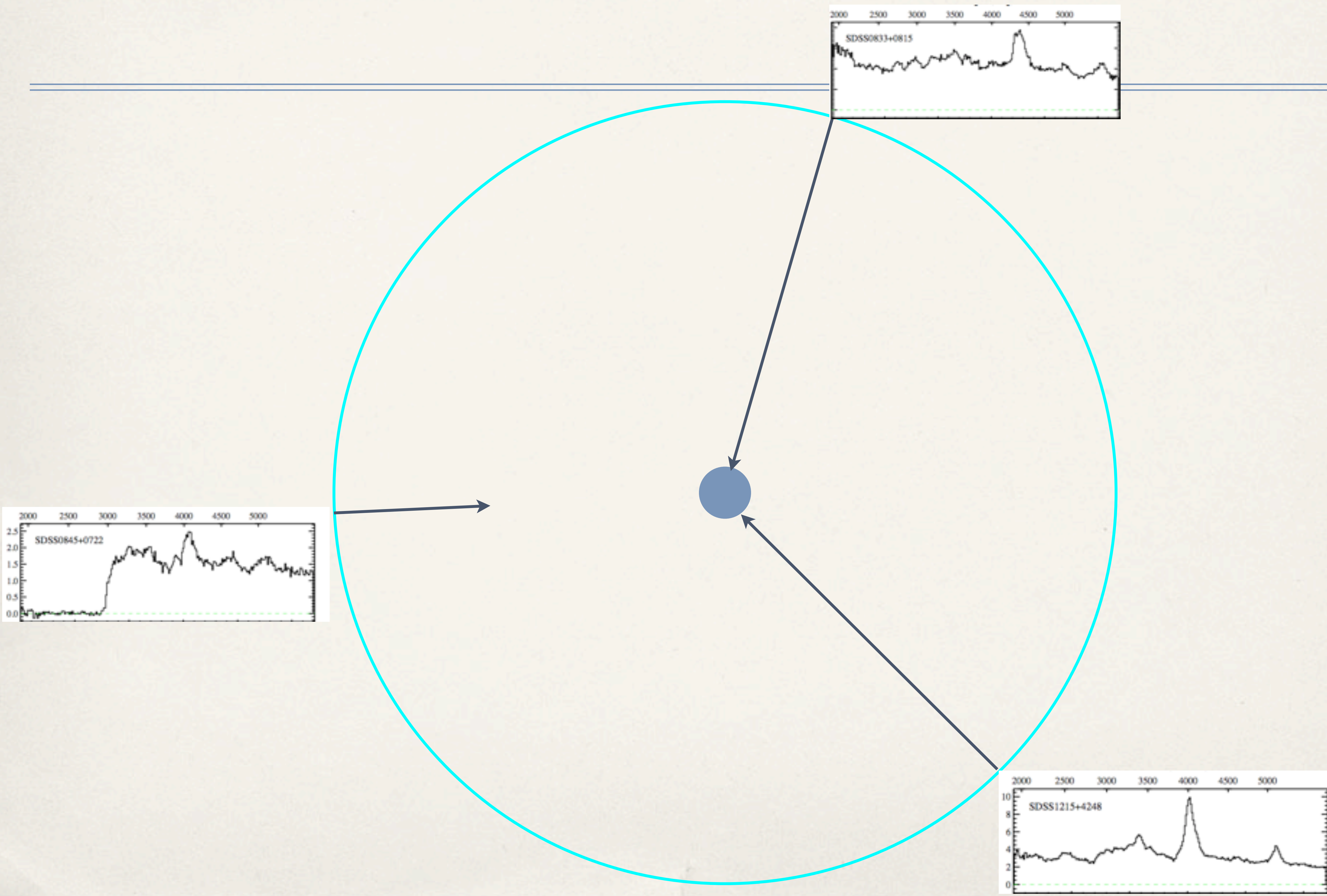
SDSS0845+0722
2000 2500 3000 3500 4000 4500 5000
2.5 2.0 1.5 1.0 0.5 0.0

New School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SDSS0845+0722
SDSS1215+4248
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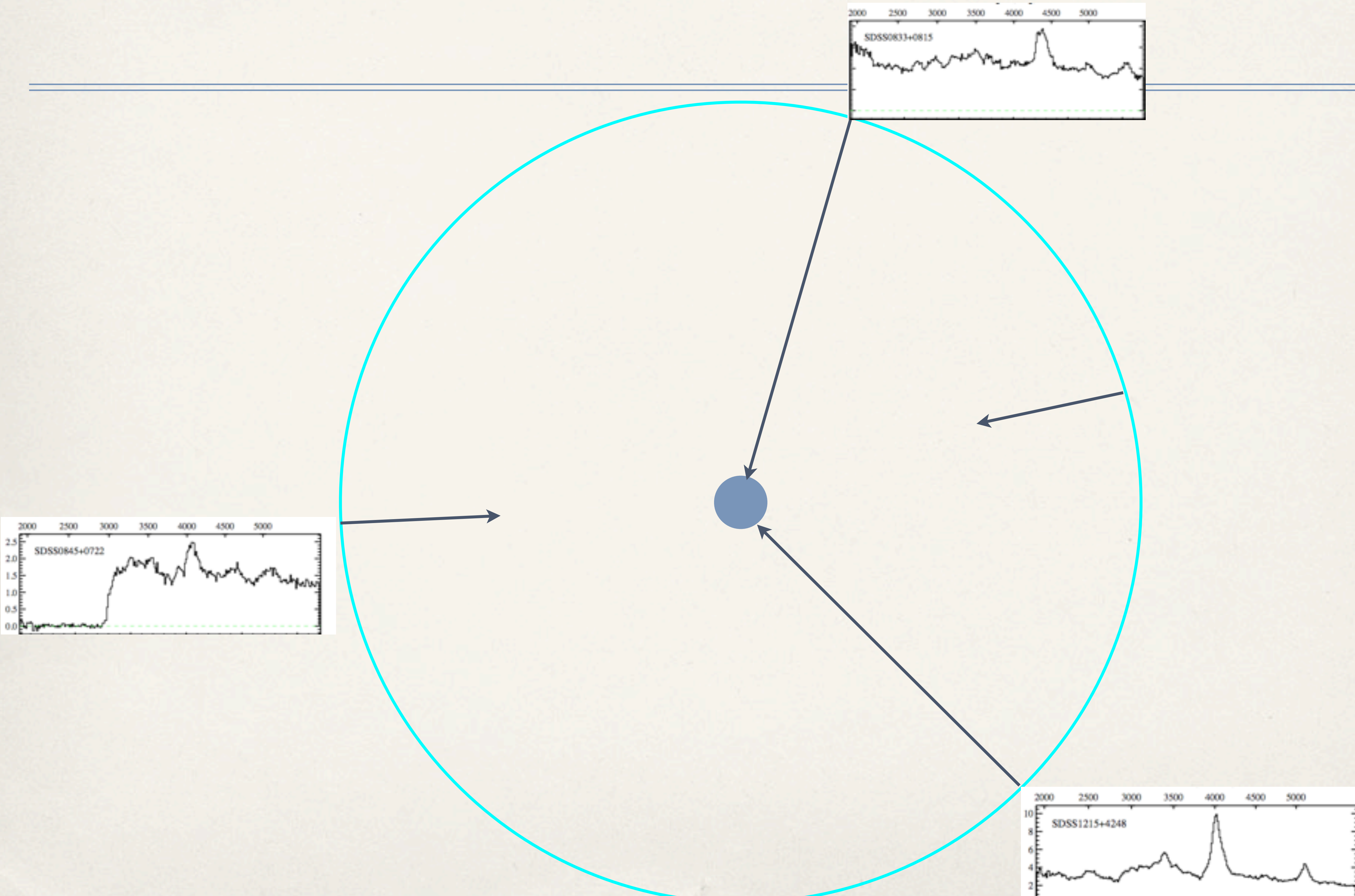

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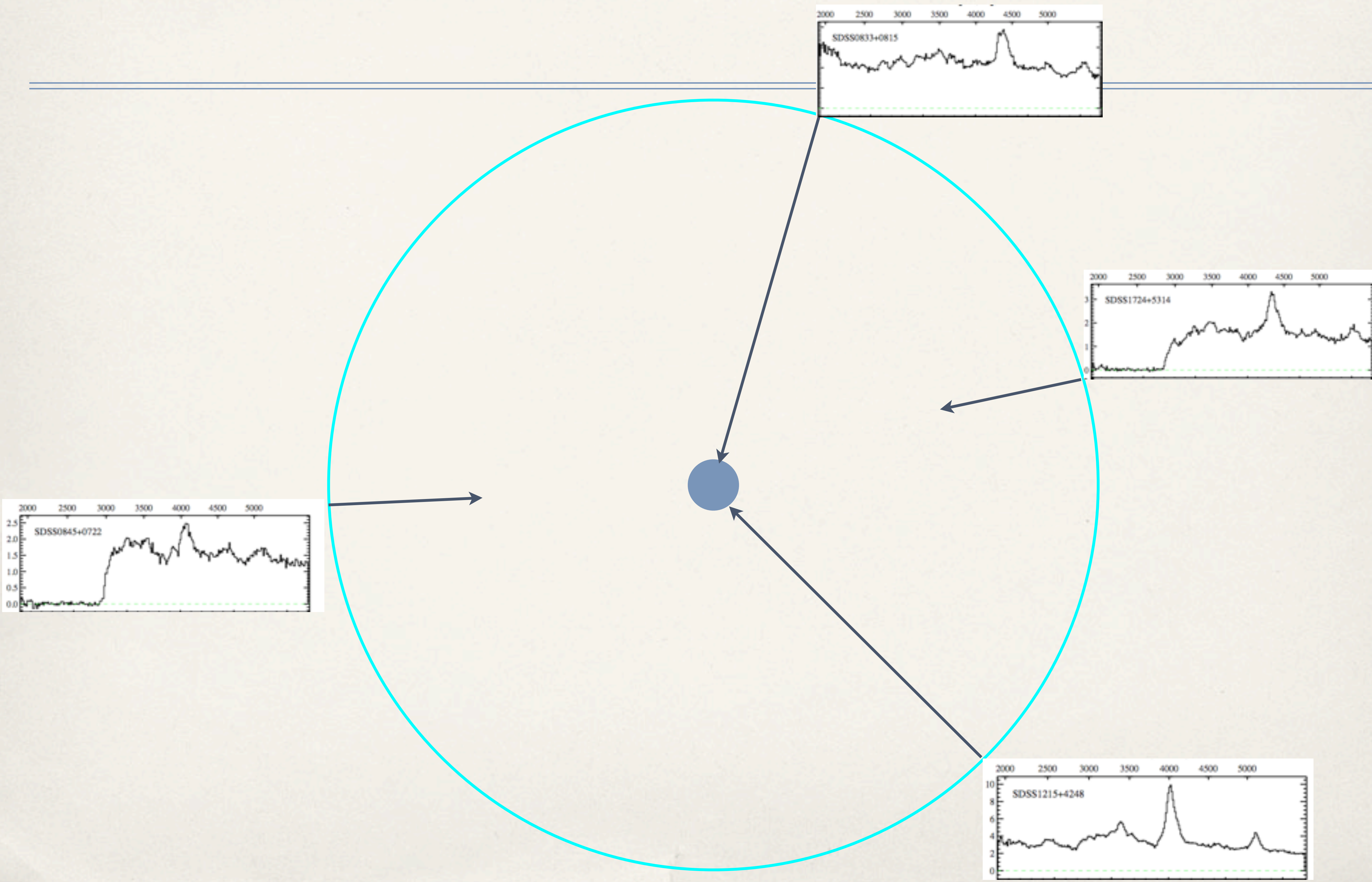

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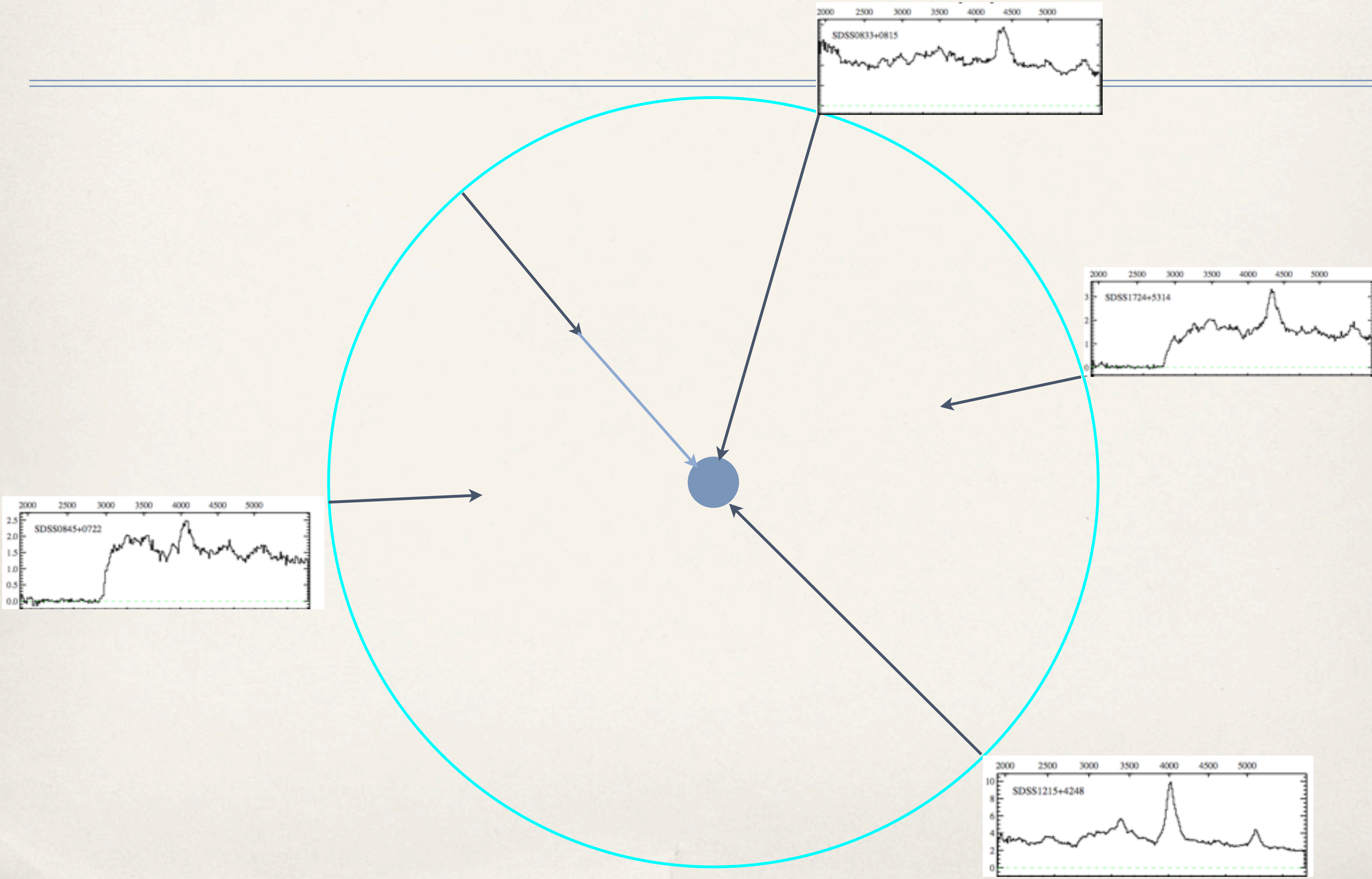

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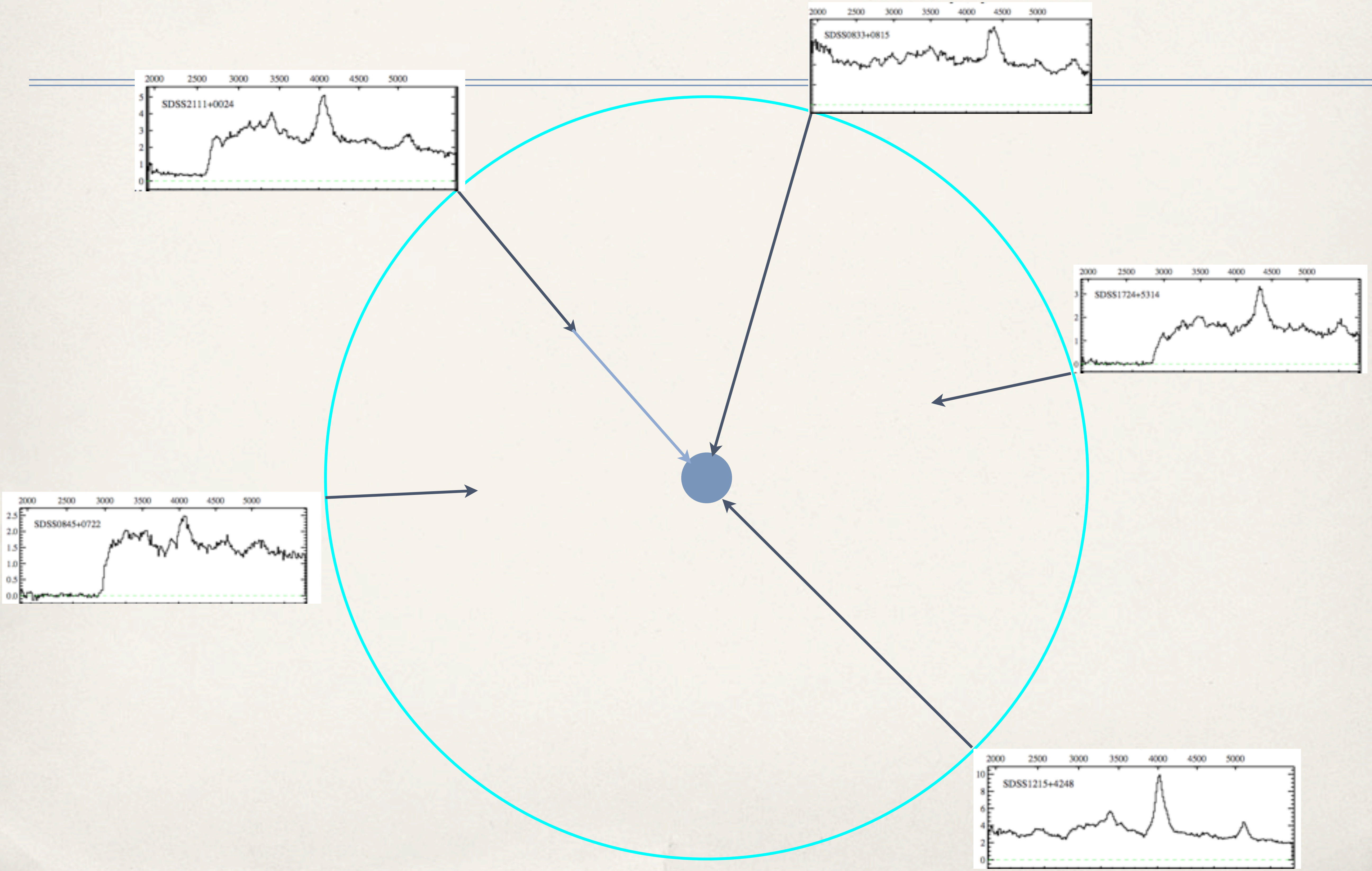
SDSS2111+0024
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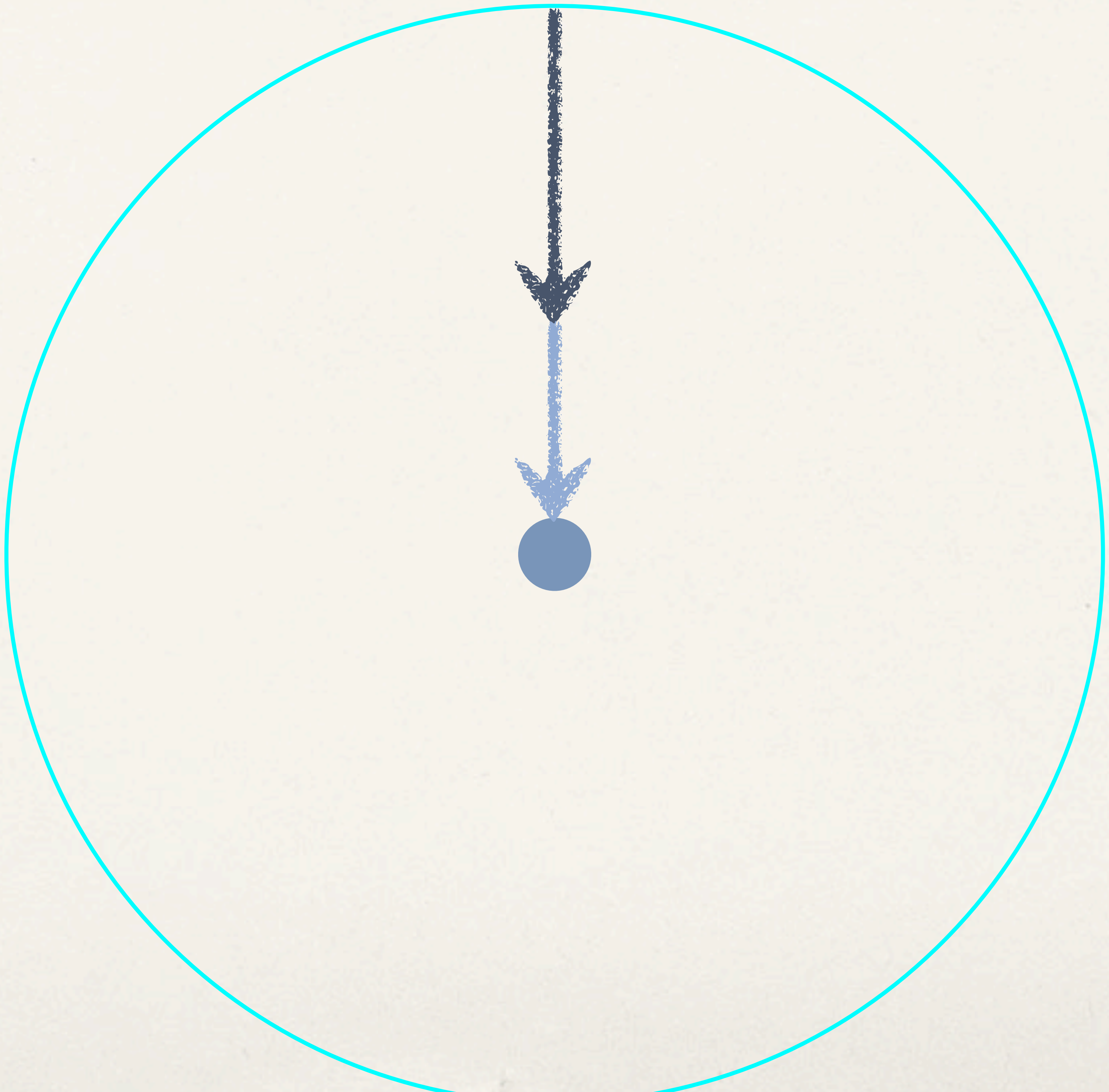
SDSS1215+4248

New School



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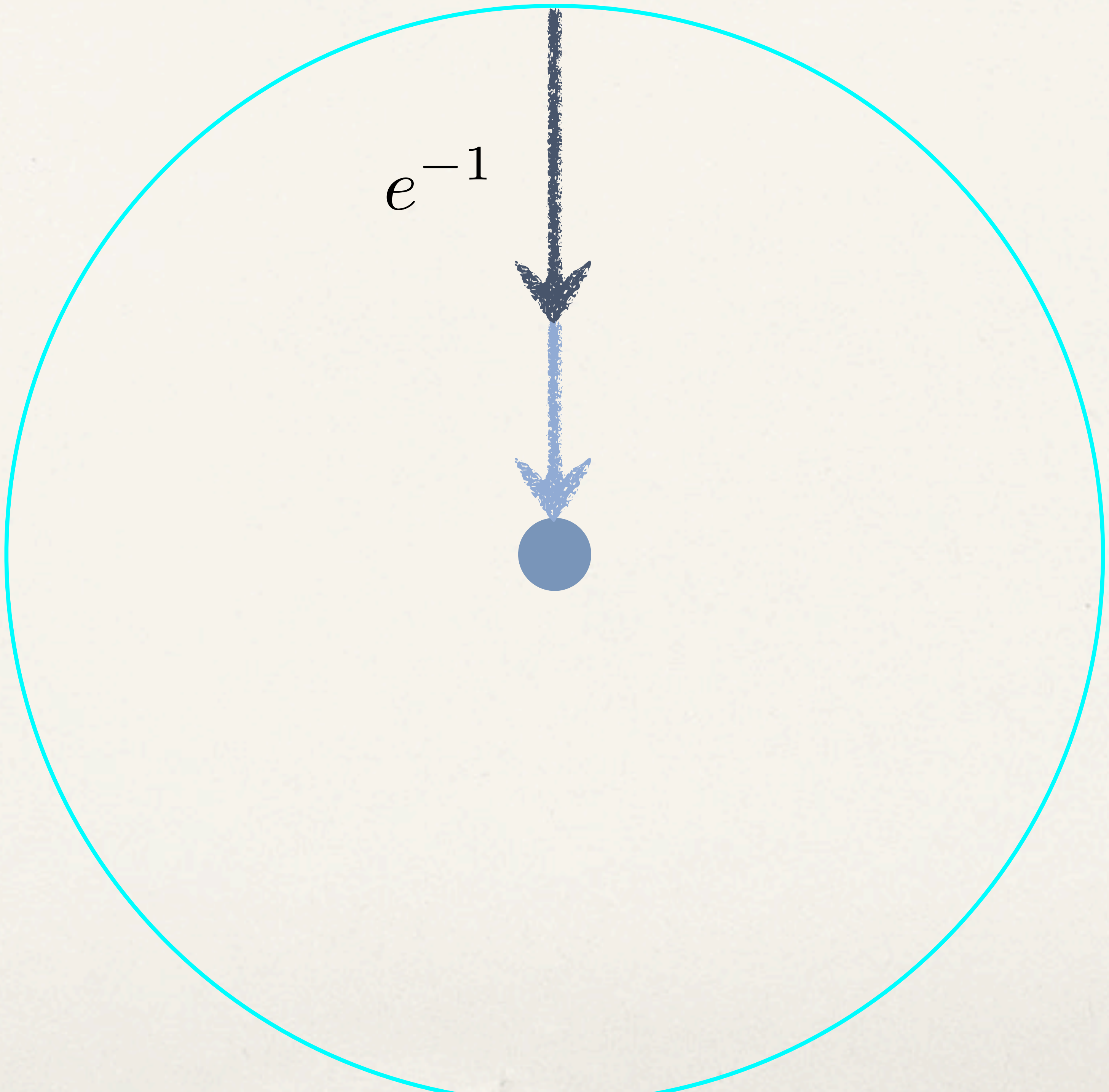

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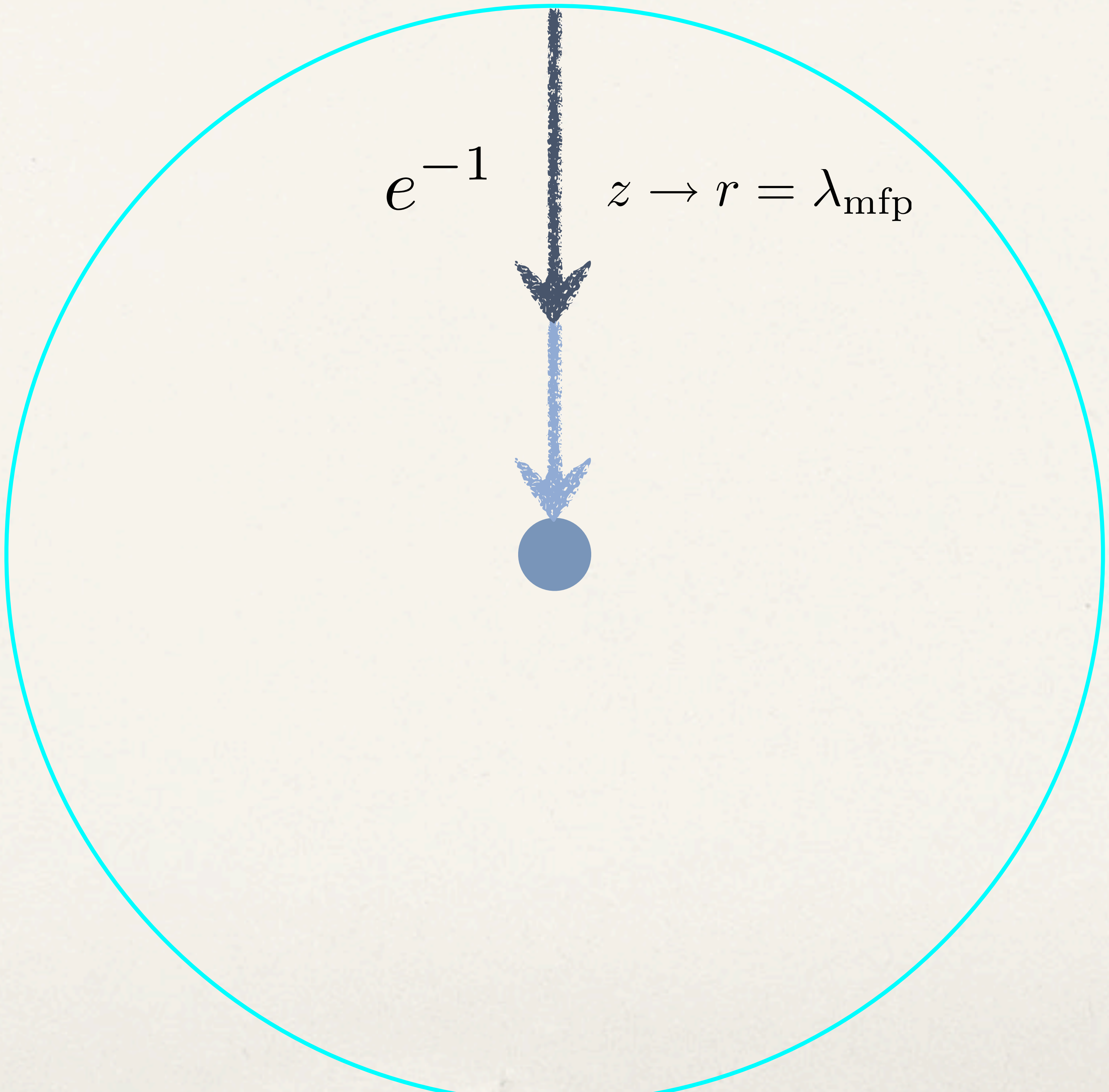
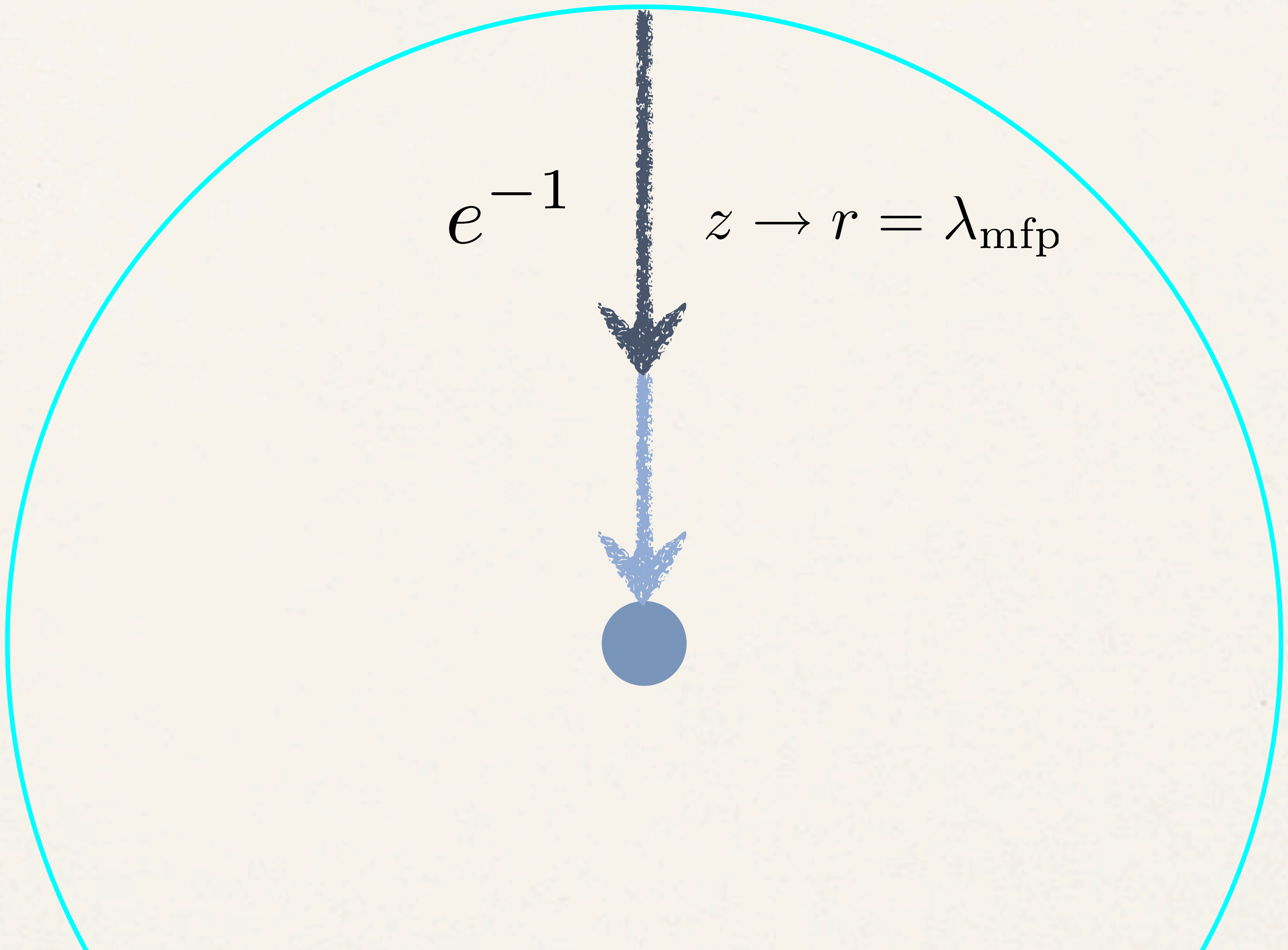
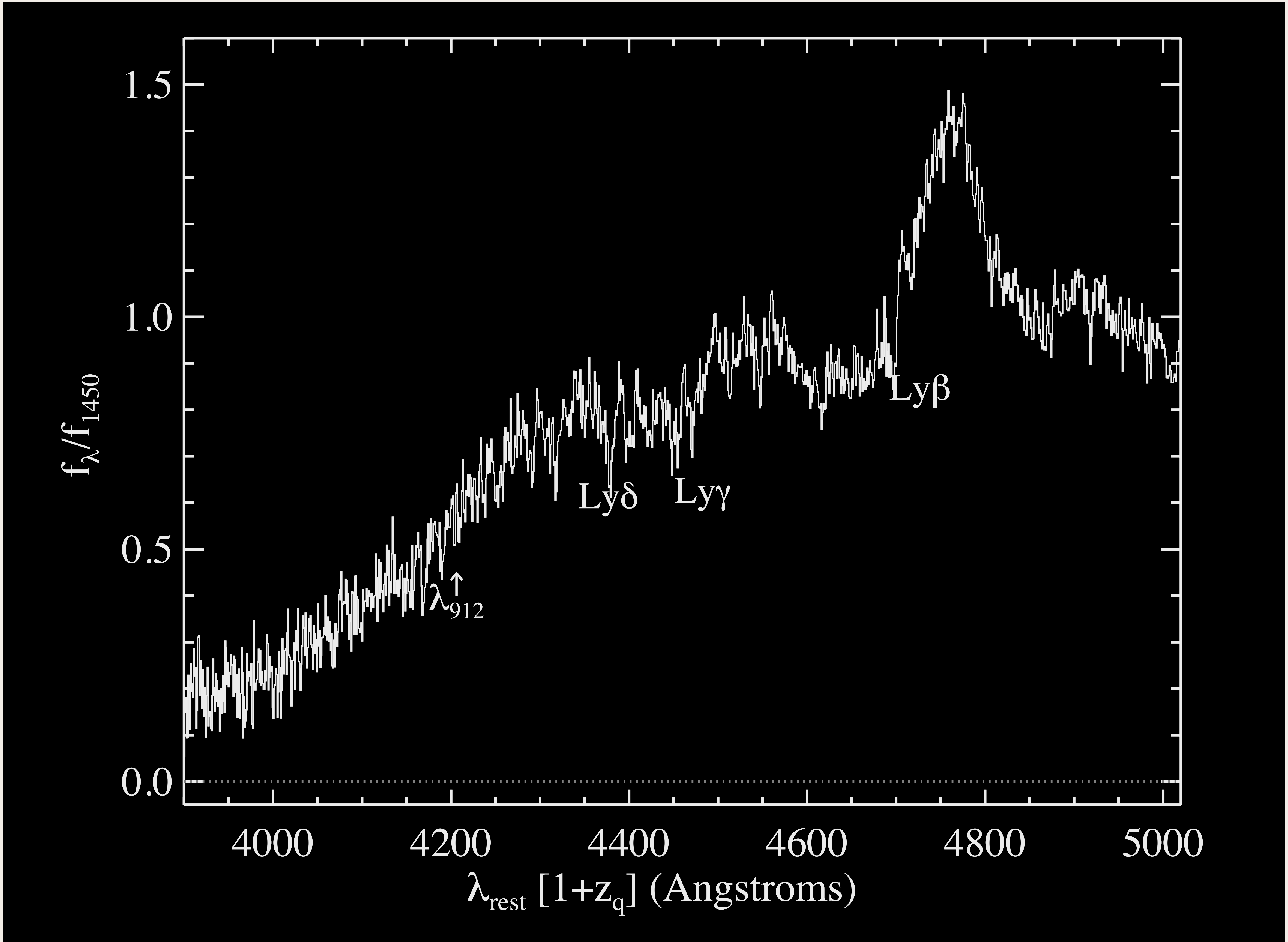


New School

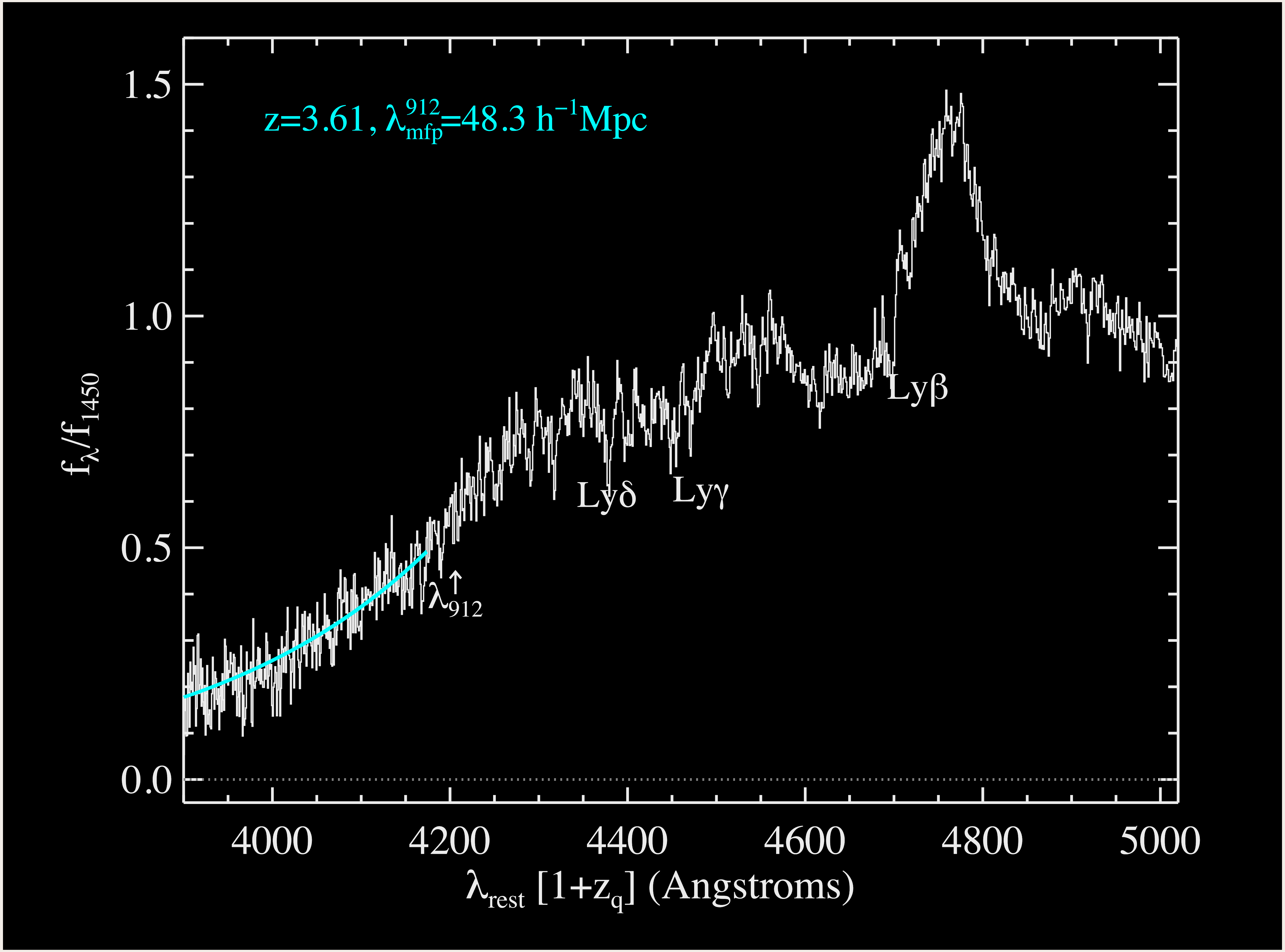


$$\tau_{\mathrm{eff,LL}}\left(z_{912}, z_q\right) = \frac{c}{H_0 \Omega_m^{1/2}} \left(1 + z_{912}\right)^3 \int_{z_{912}}^{z_q} \kappa_{912}(z')(1 + z')^{-11/2} dz'$$

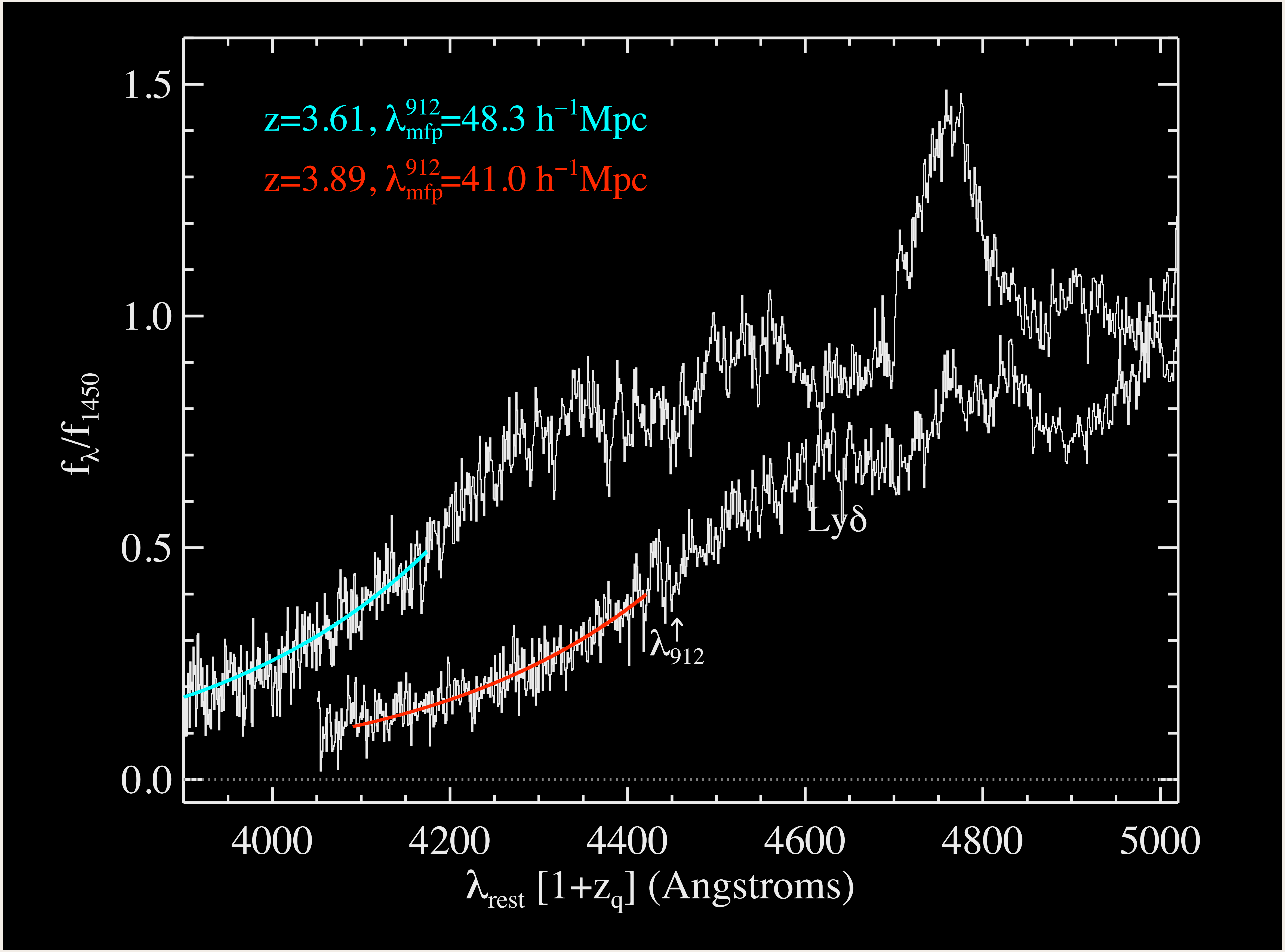
SDSS Stacked Spectra



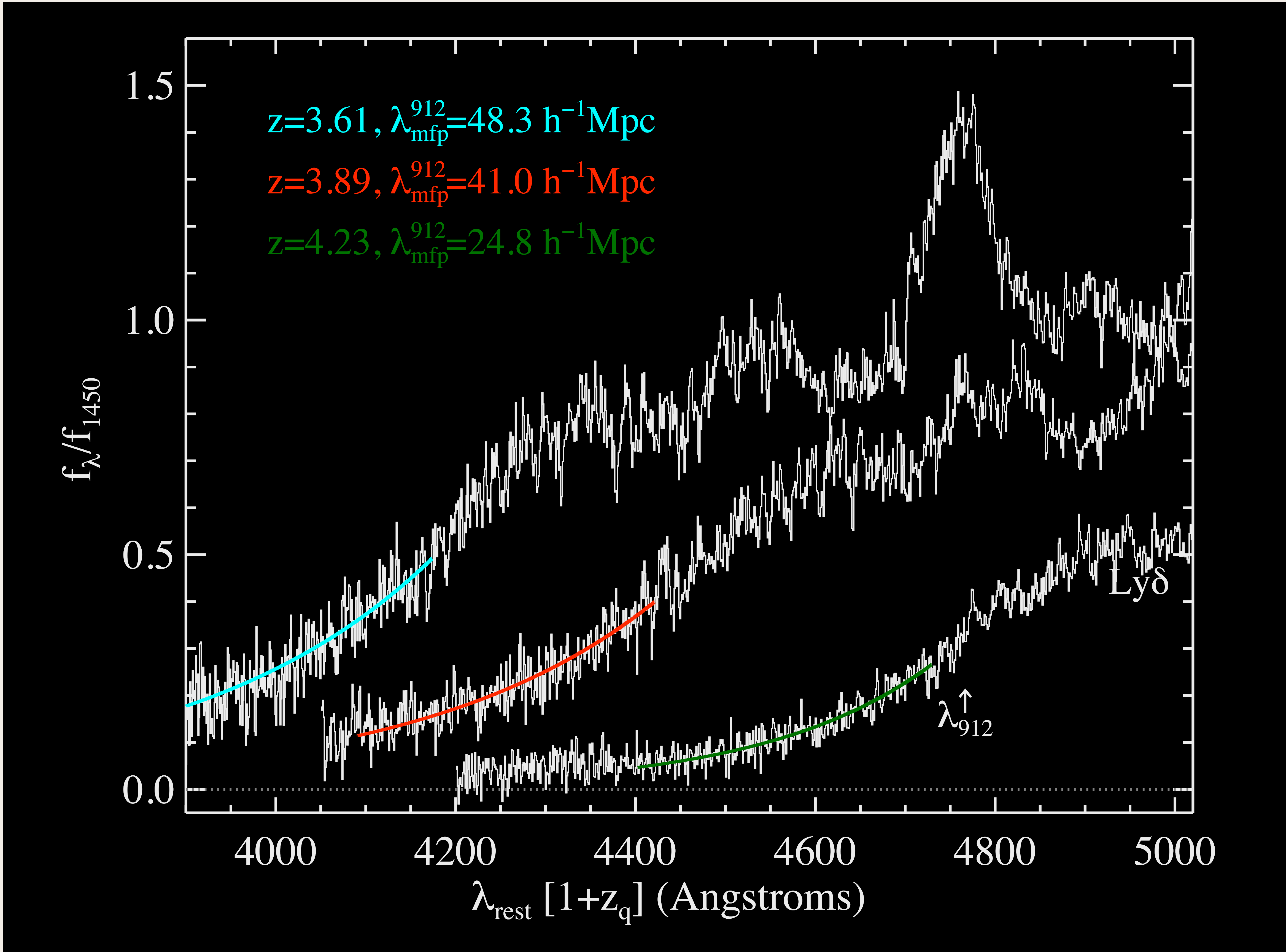
SDSS Stacked Spectra



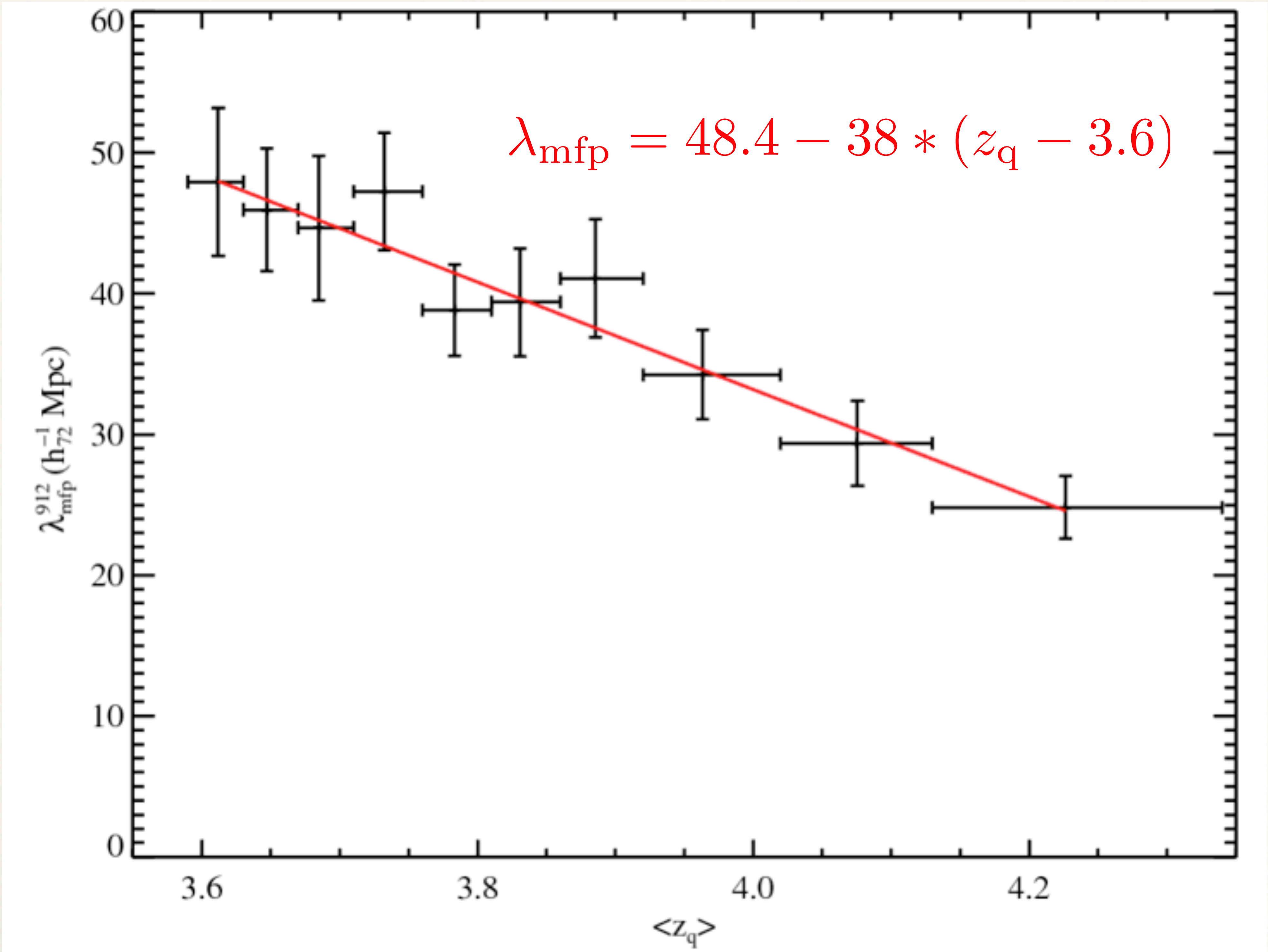
SDSS Stacked Spectra



SDSS Stacked Spectra



SDSS MFP

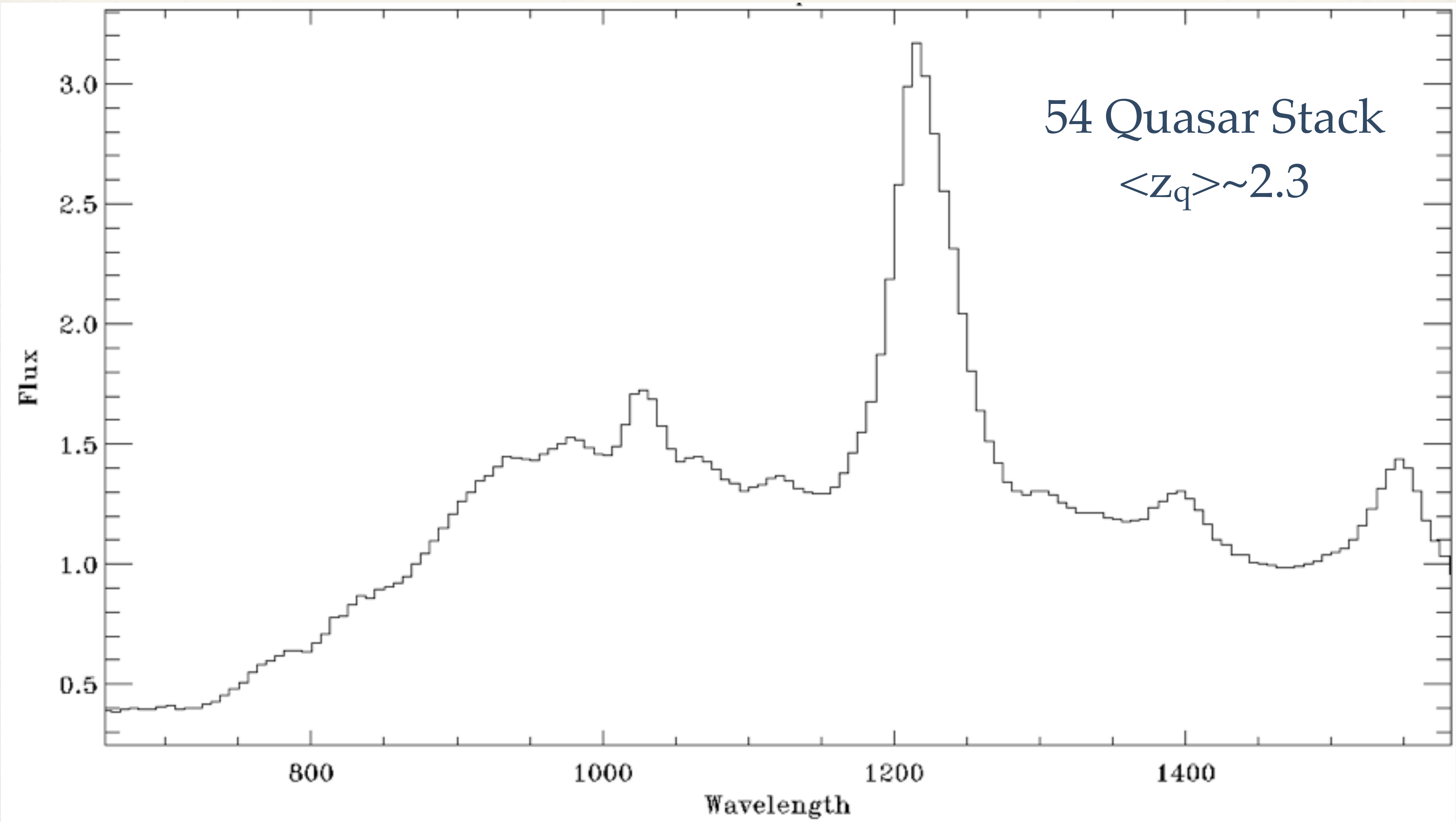


$\lambda_{\rm mfp} = 48.4 - 38 * (z_{\rm q} - 3.6)$
$\lambda^{912}_{\rm mfp}$ (h^{-1}_{72} Mpc)
<z_q>
60
50
40
30
20
10
0
3.6
3.8
4.0
4.2

WFC3 Stack

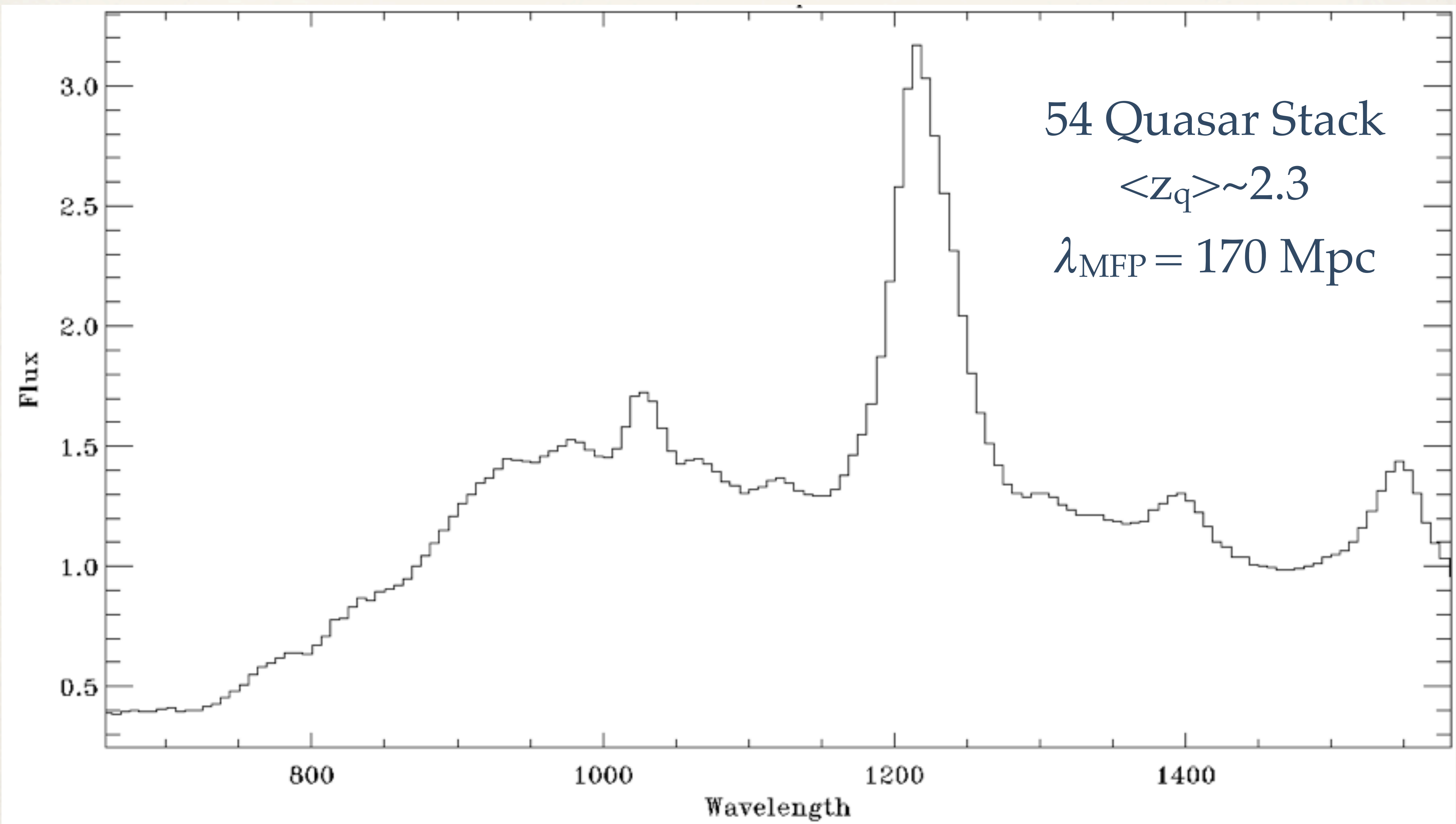
- Can we play the same game at lower z?

OMG w00t!



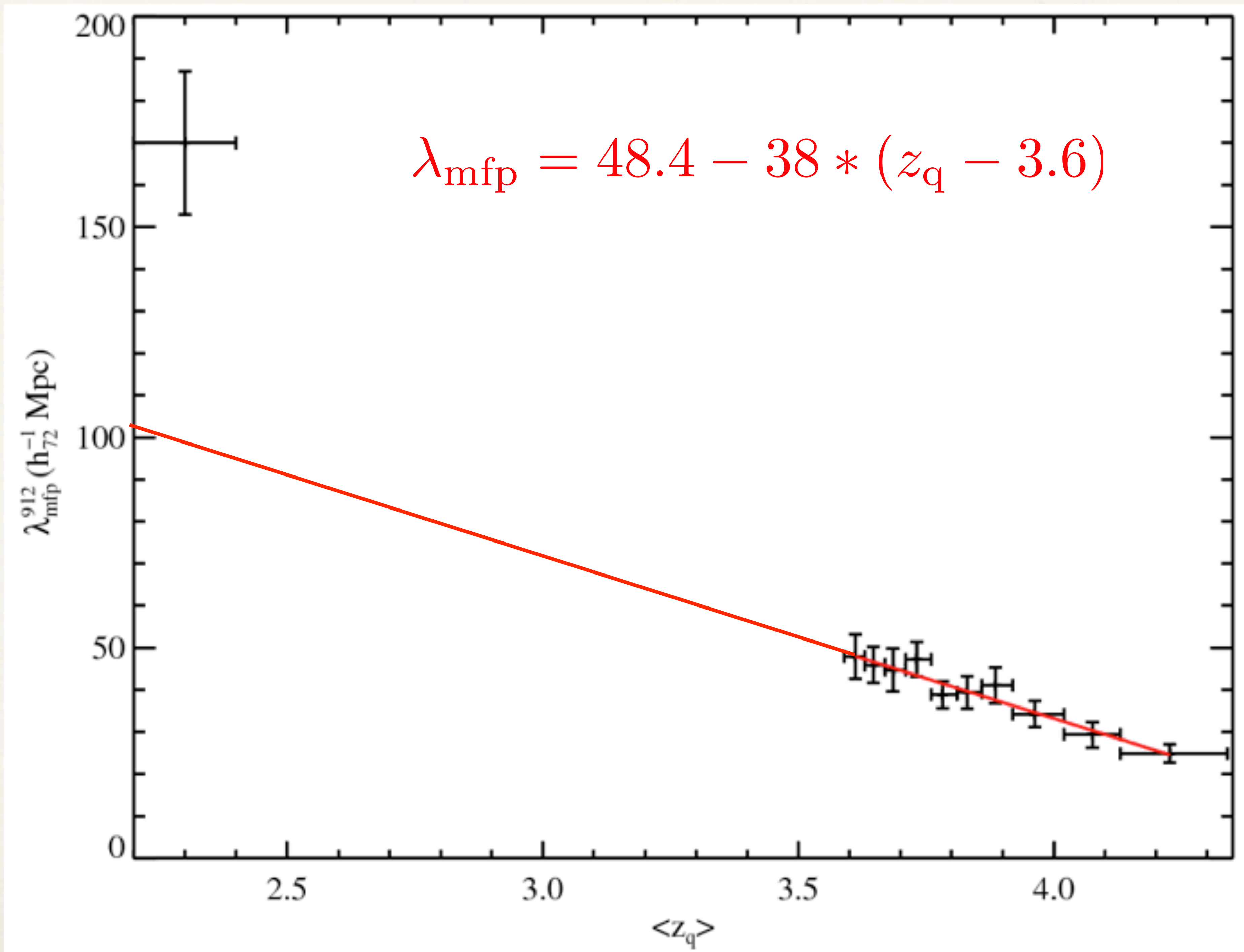
54 Quasar Stack
<z_q>~2.3
Flux
Wavelength
3.0
2.5
2.0
1.5
1.0
0.5
800
1000
1200
1400

OMG w00t!

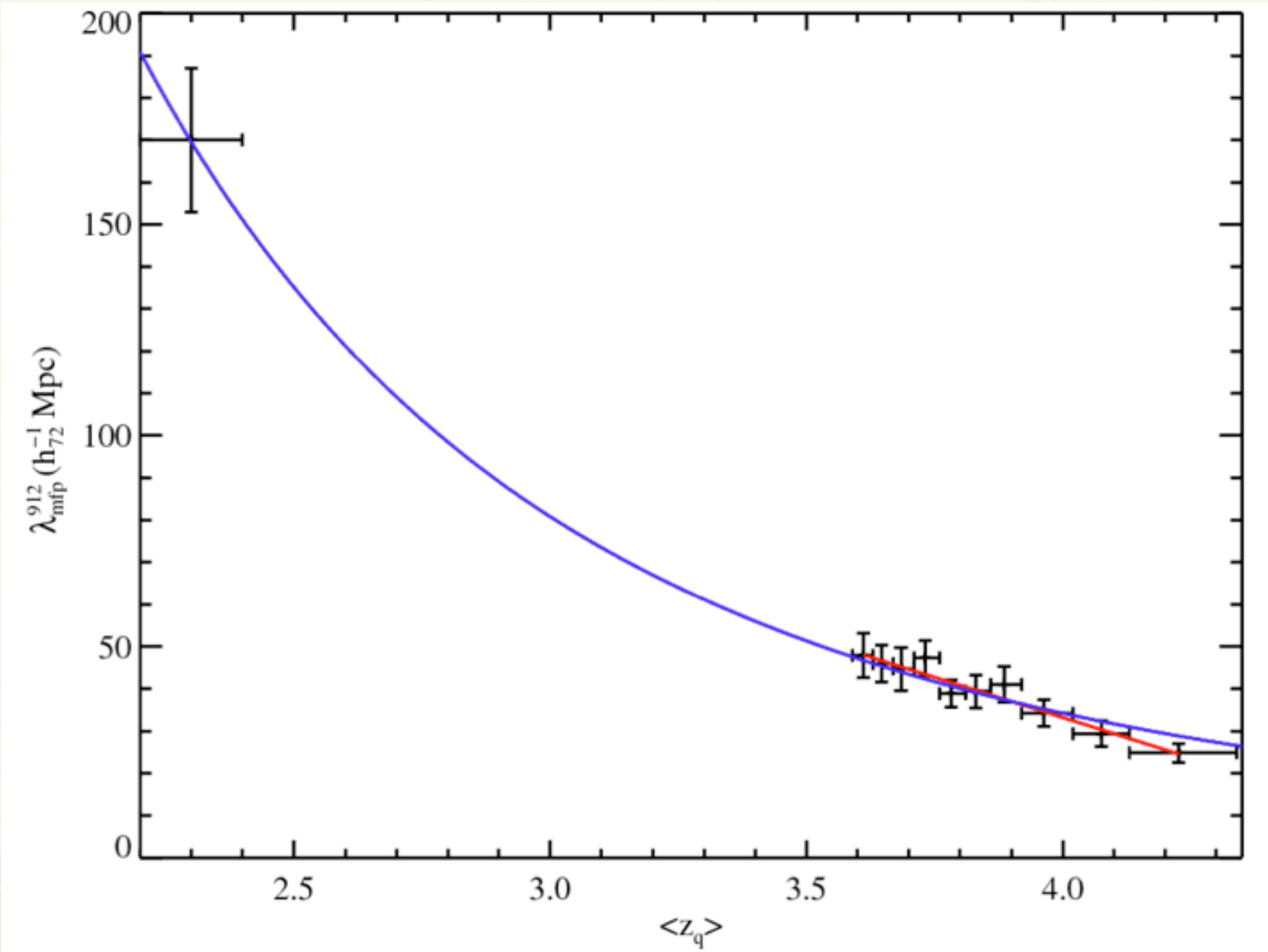


54 Quasar Stack
$\langle z_q \rangle \sim 2.3$
$\lambda_{MFP} = 170$ Mpc
Flux
Wavelength
3.0
2.5
2.0
1.5
1.0
0.5
800
1000
1200
1400

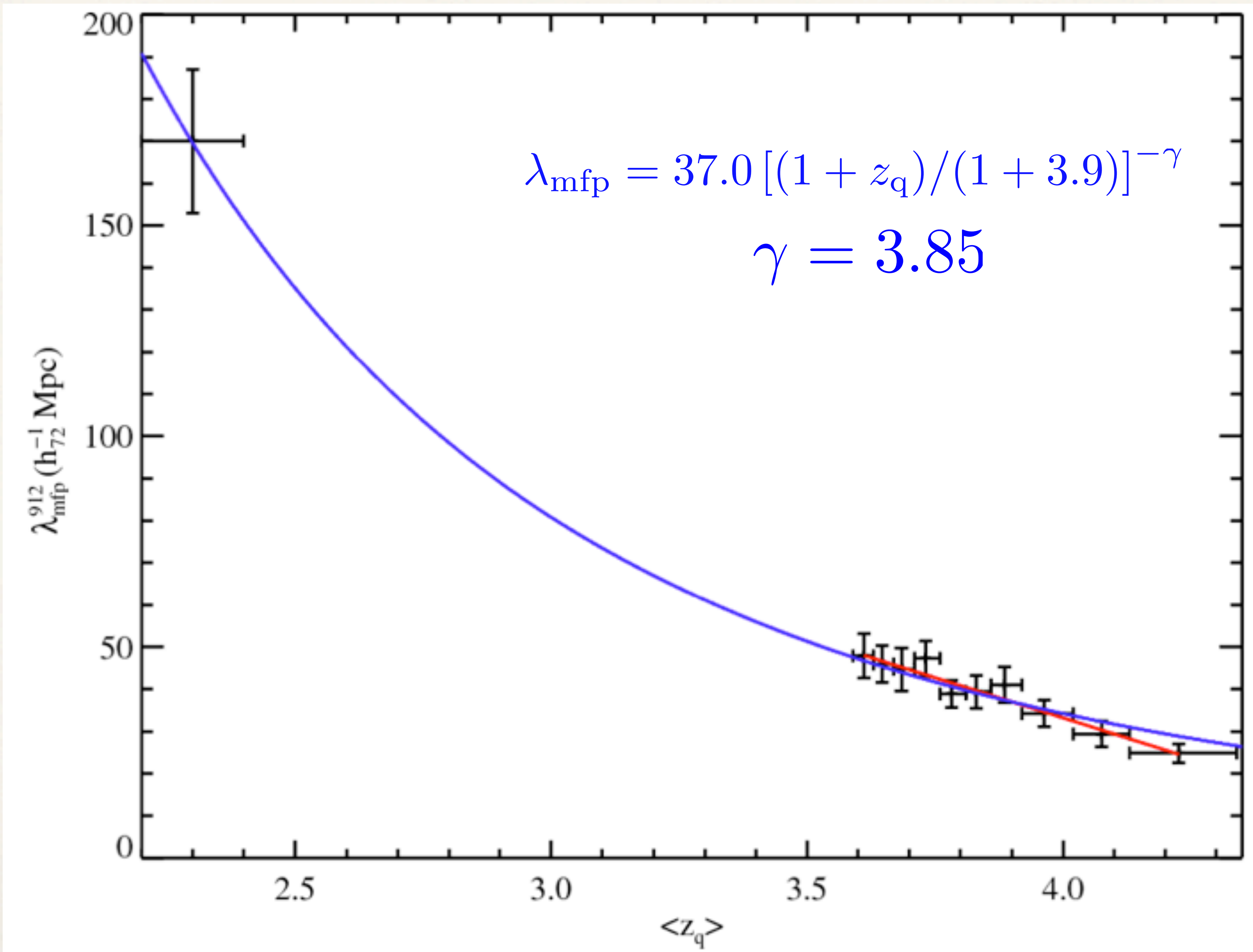
Mean Free Path



Mean Free Path



Mean Free Path



Much left to do!

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- Refine the l(z) analysis, incorporating ACS data

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- f(N,z) for the partial LLS

Much left to do!

- Refine the l(z) analysis, incorporating ACS data
- f(N,z) for the partial LLS
- Do the stack right!

Questions

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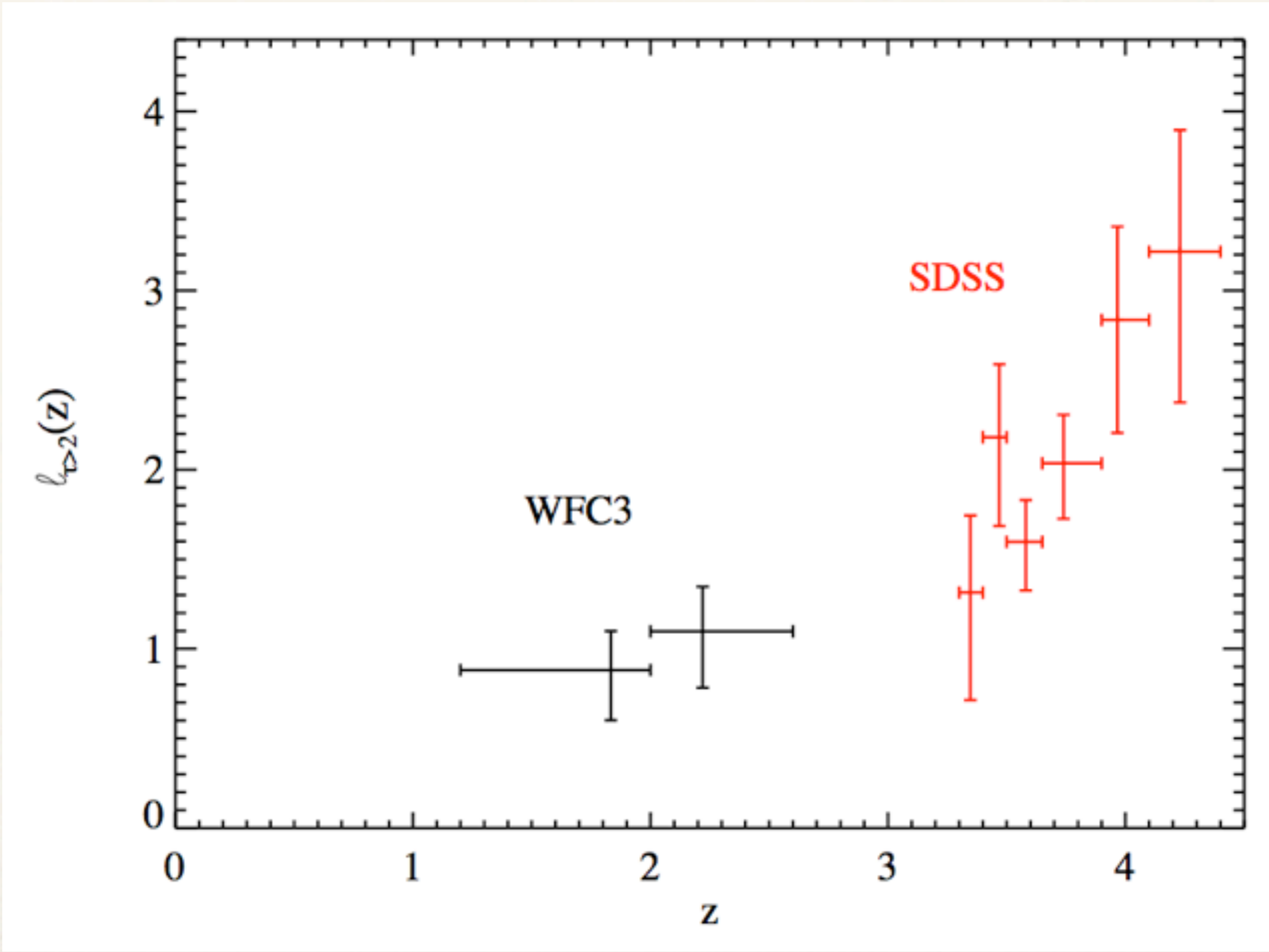
- How does the MFP evolve in z?

Questions

- How does the MFP evolve in z?
- How do l(z) and f(N,z) evolve in z?

LLS Incidence Frequency



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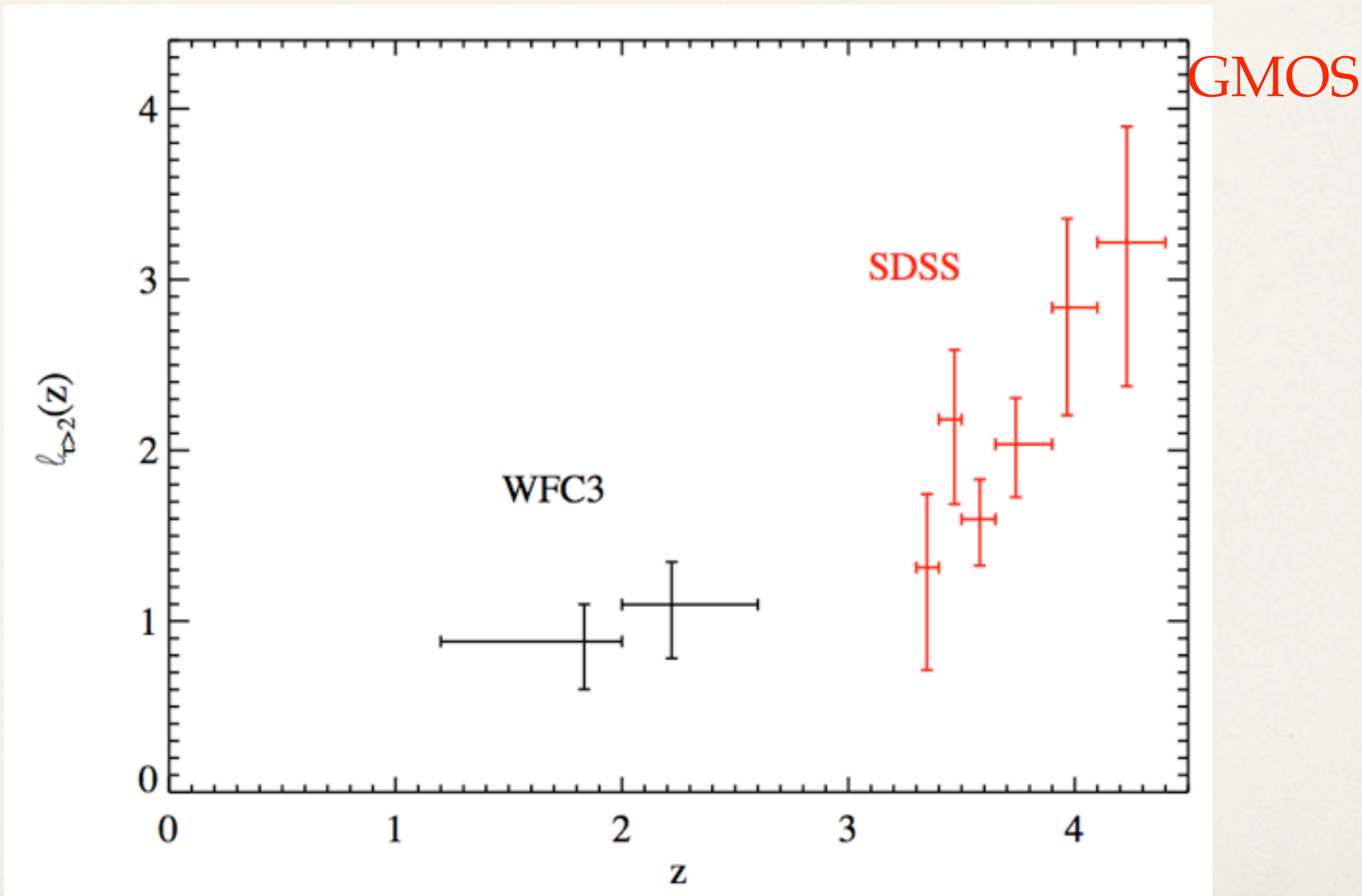

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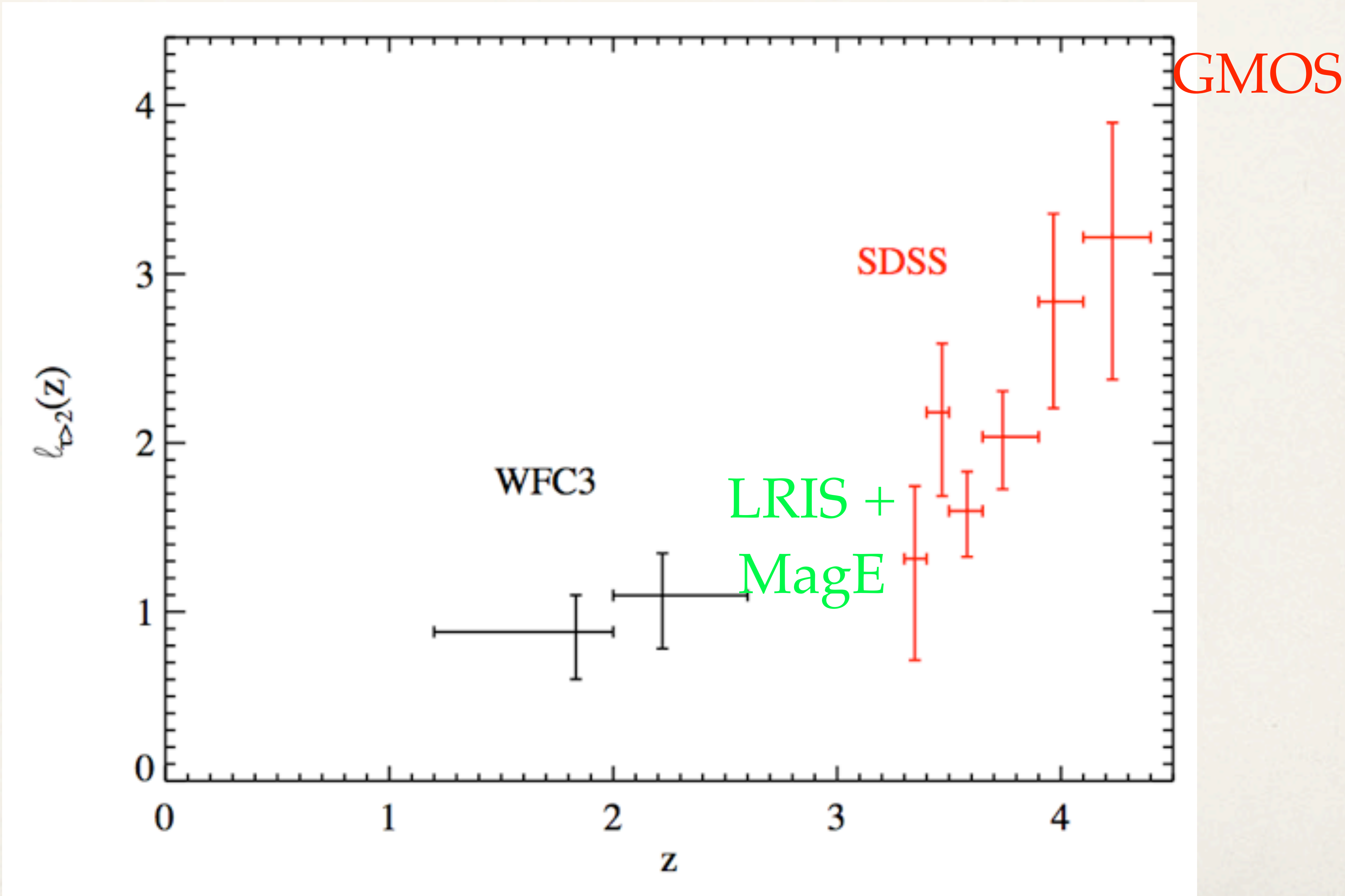

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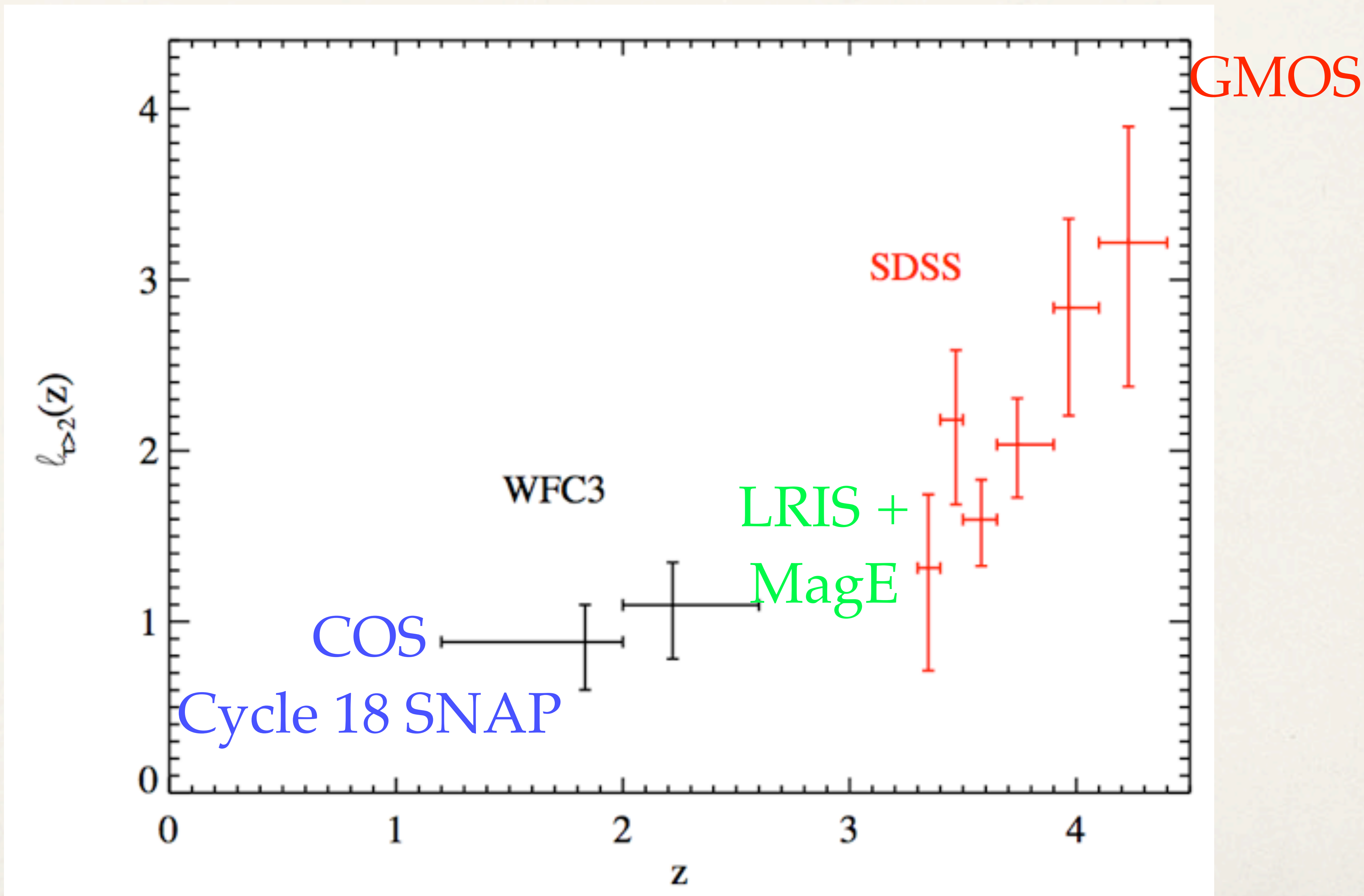
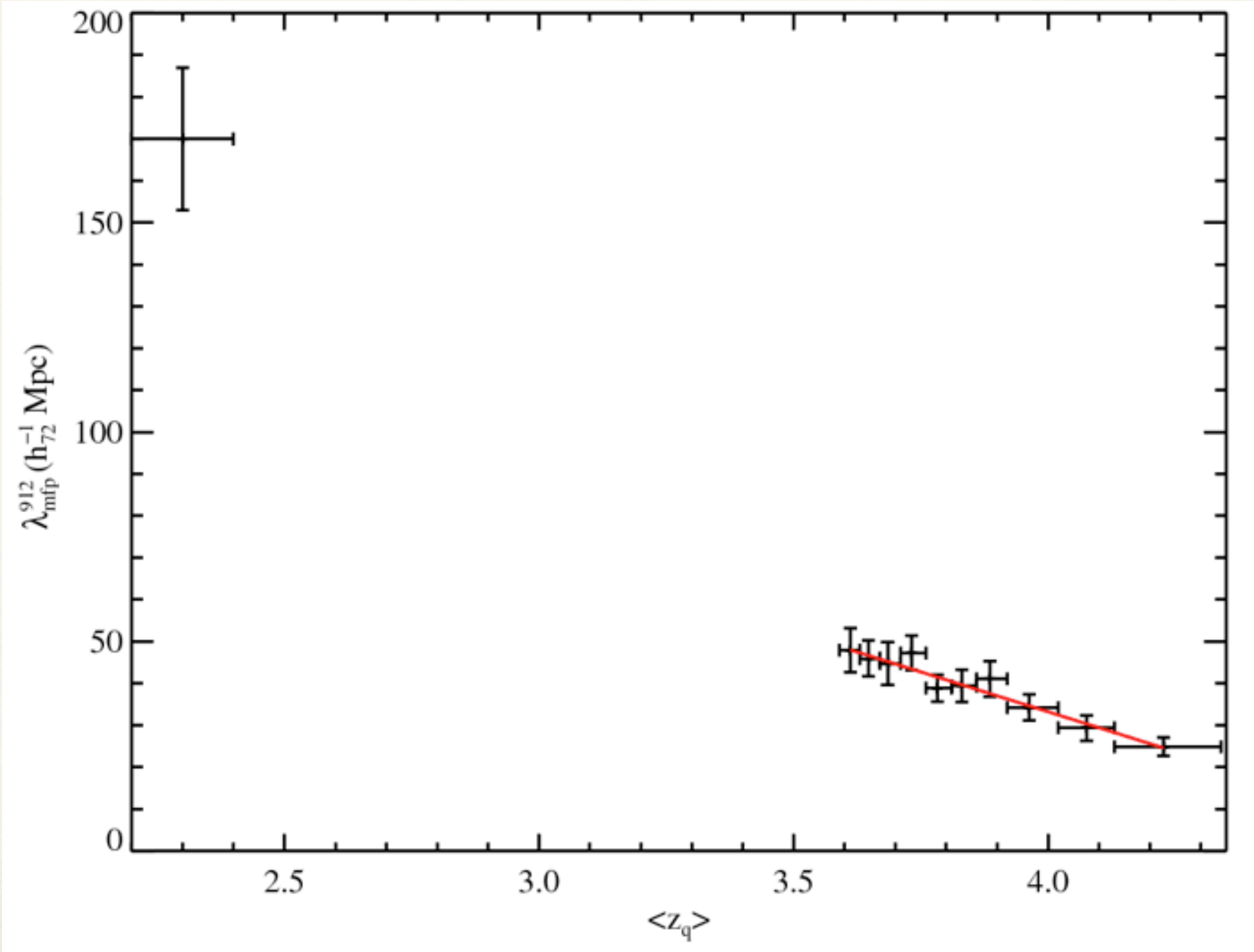
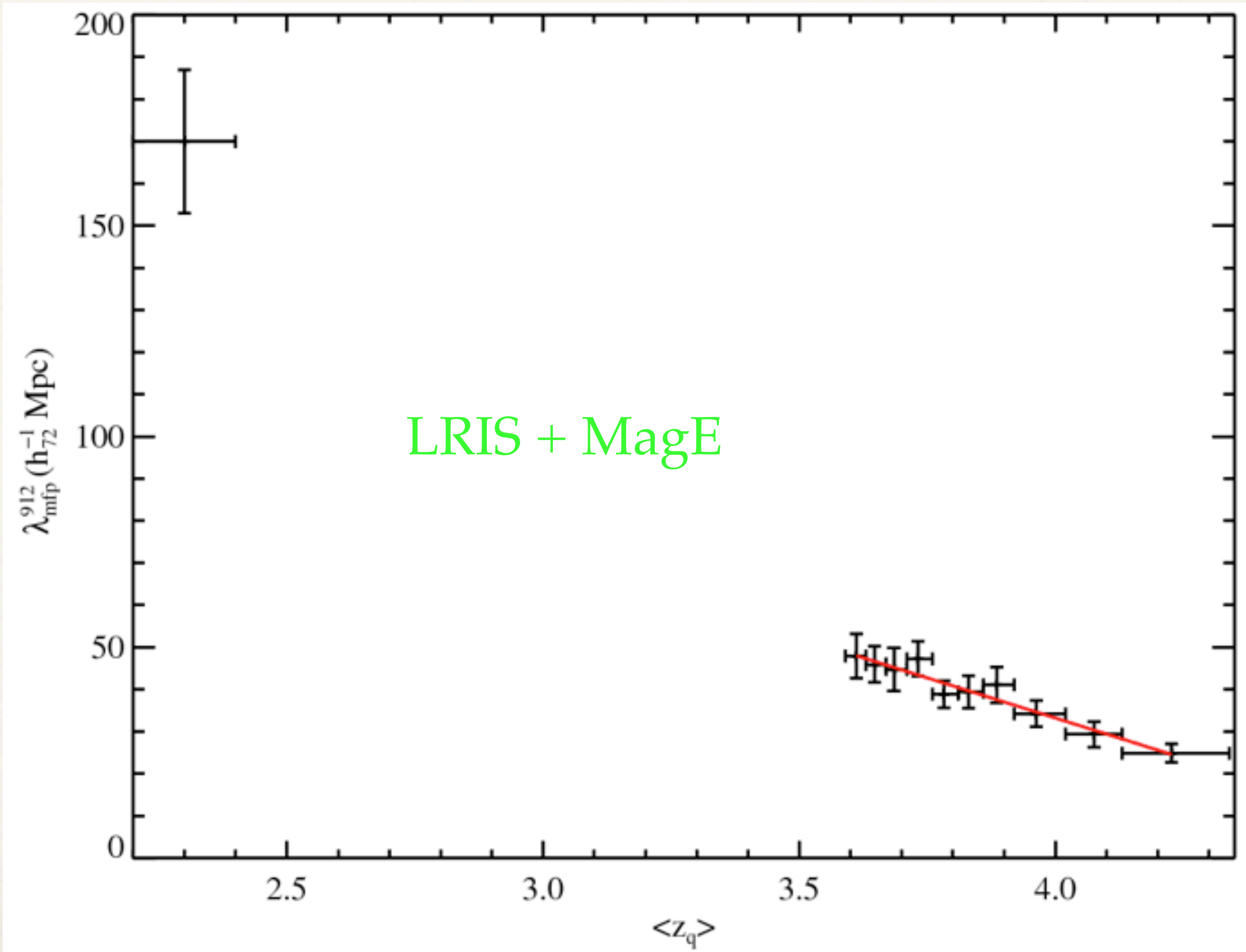


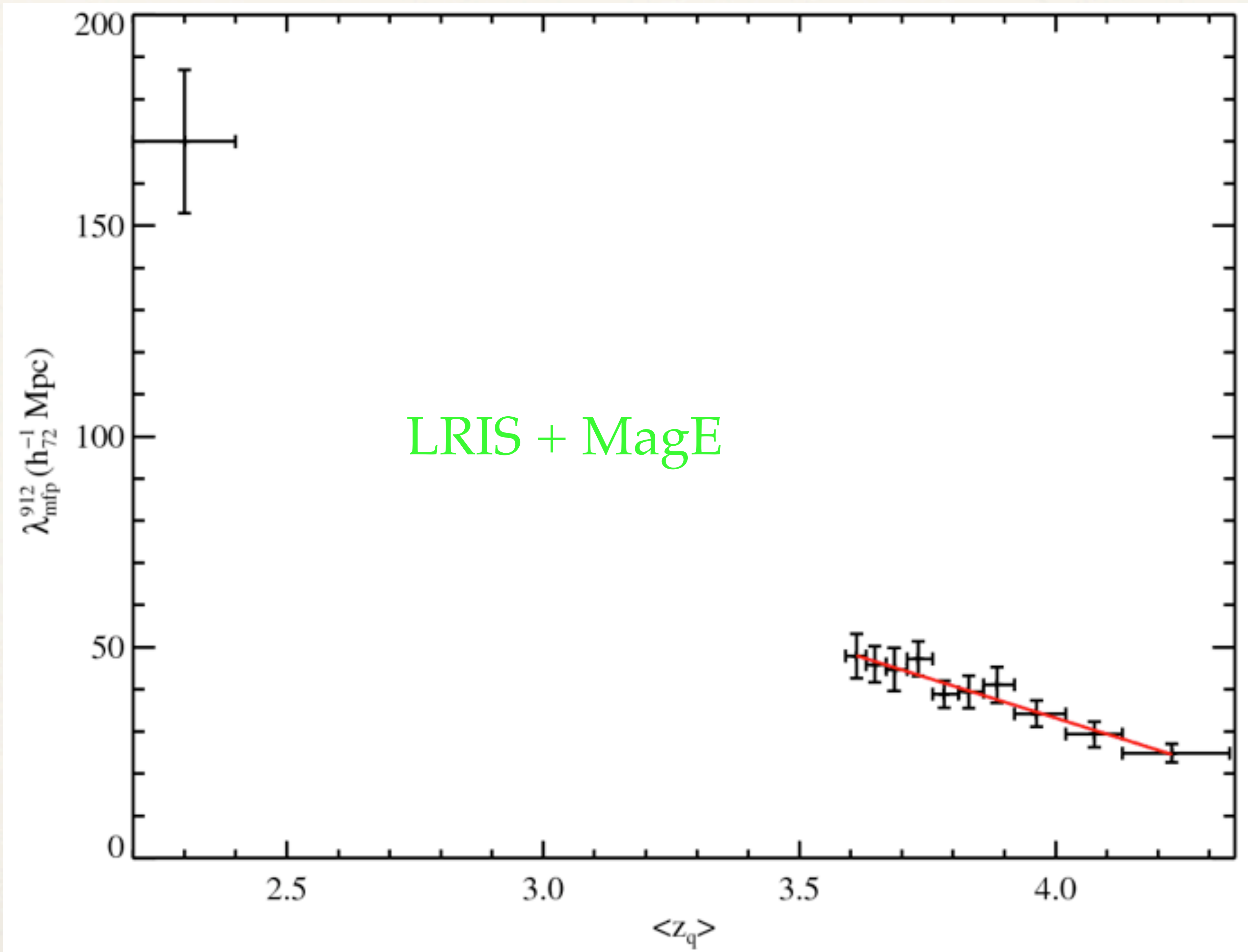
Mean Free Path



Mean Free Path

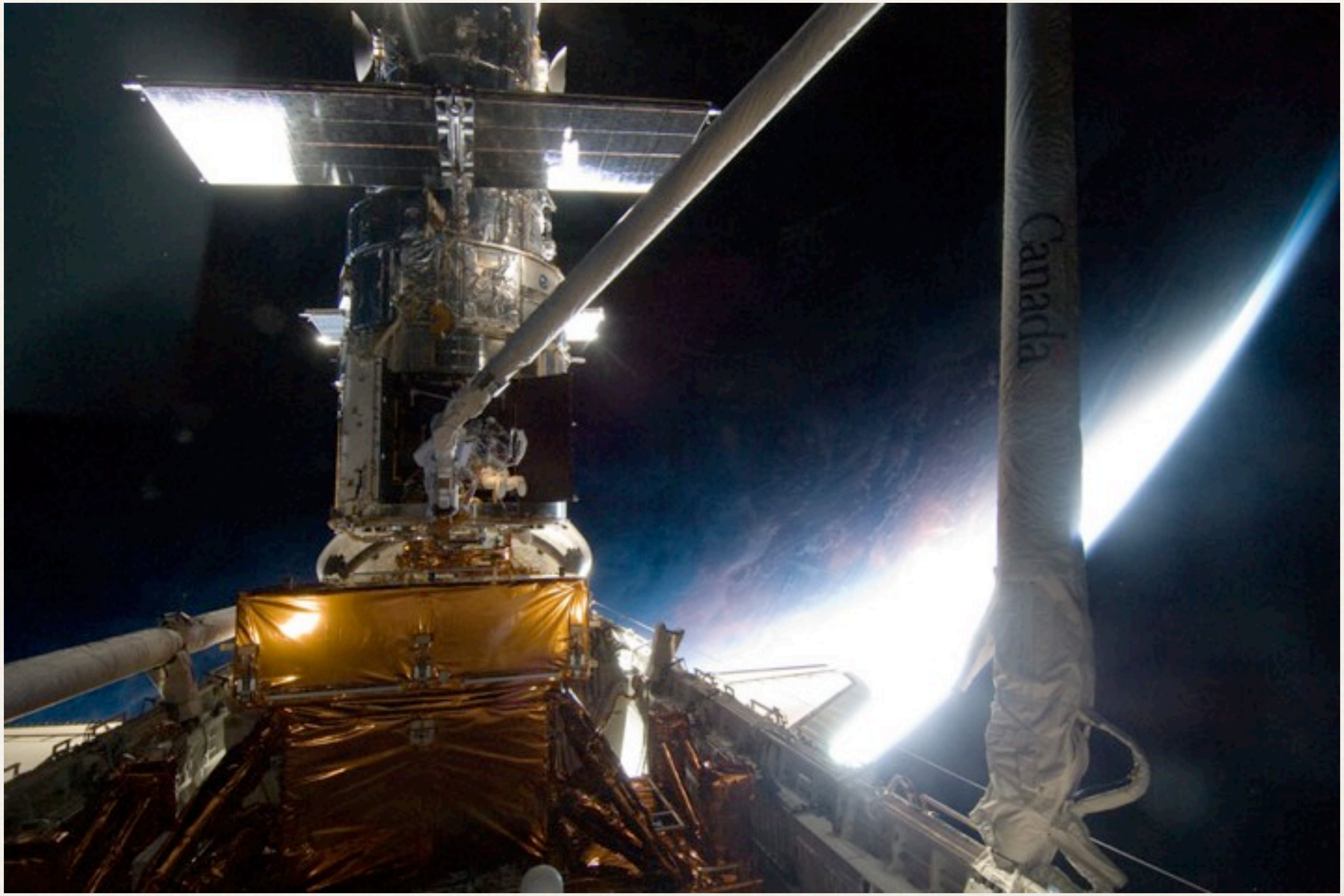


Mean Free Path

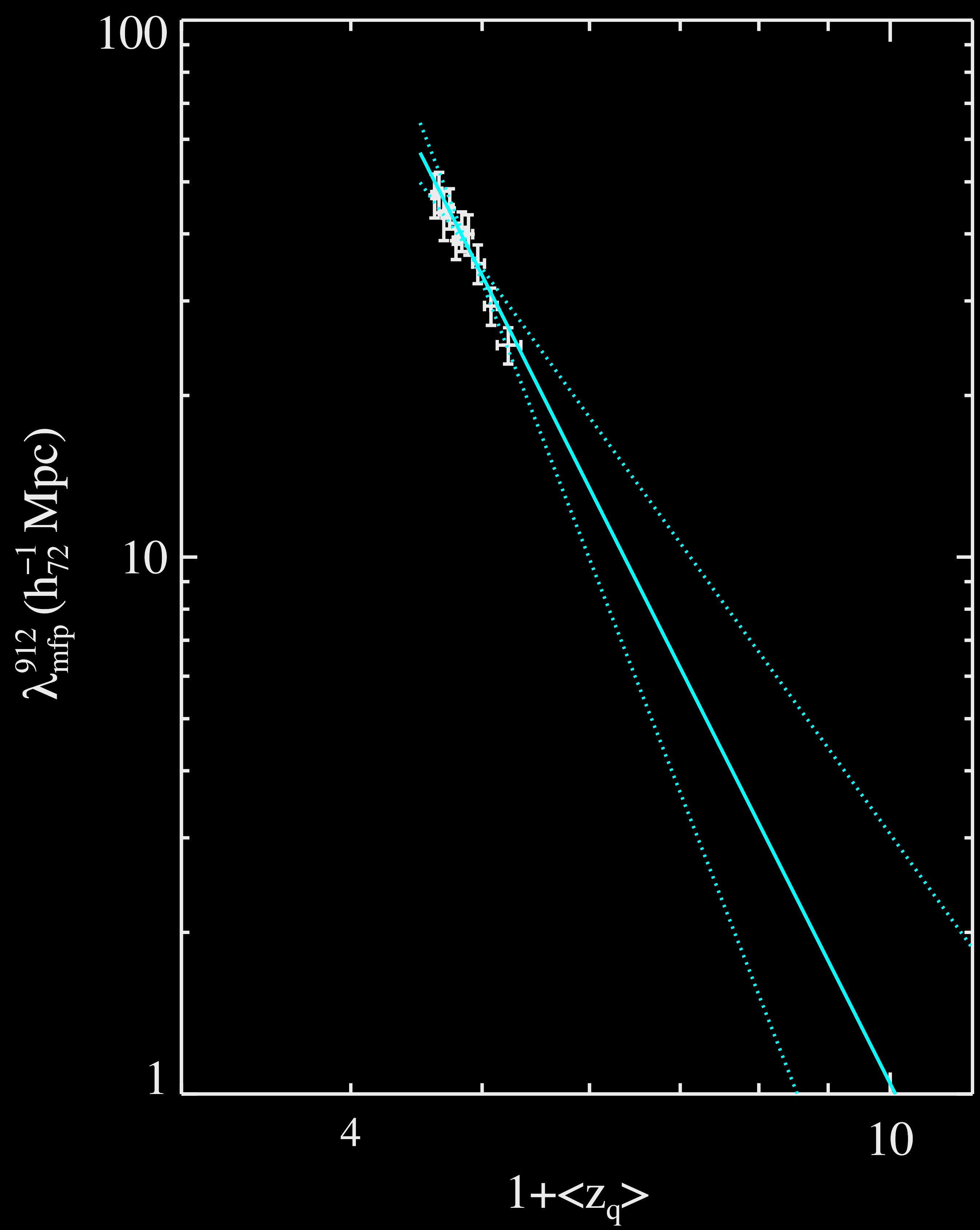


GMOS

Thanks!

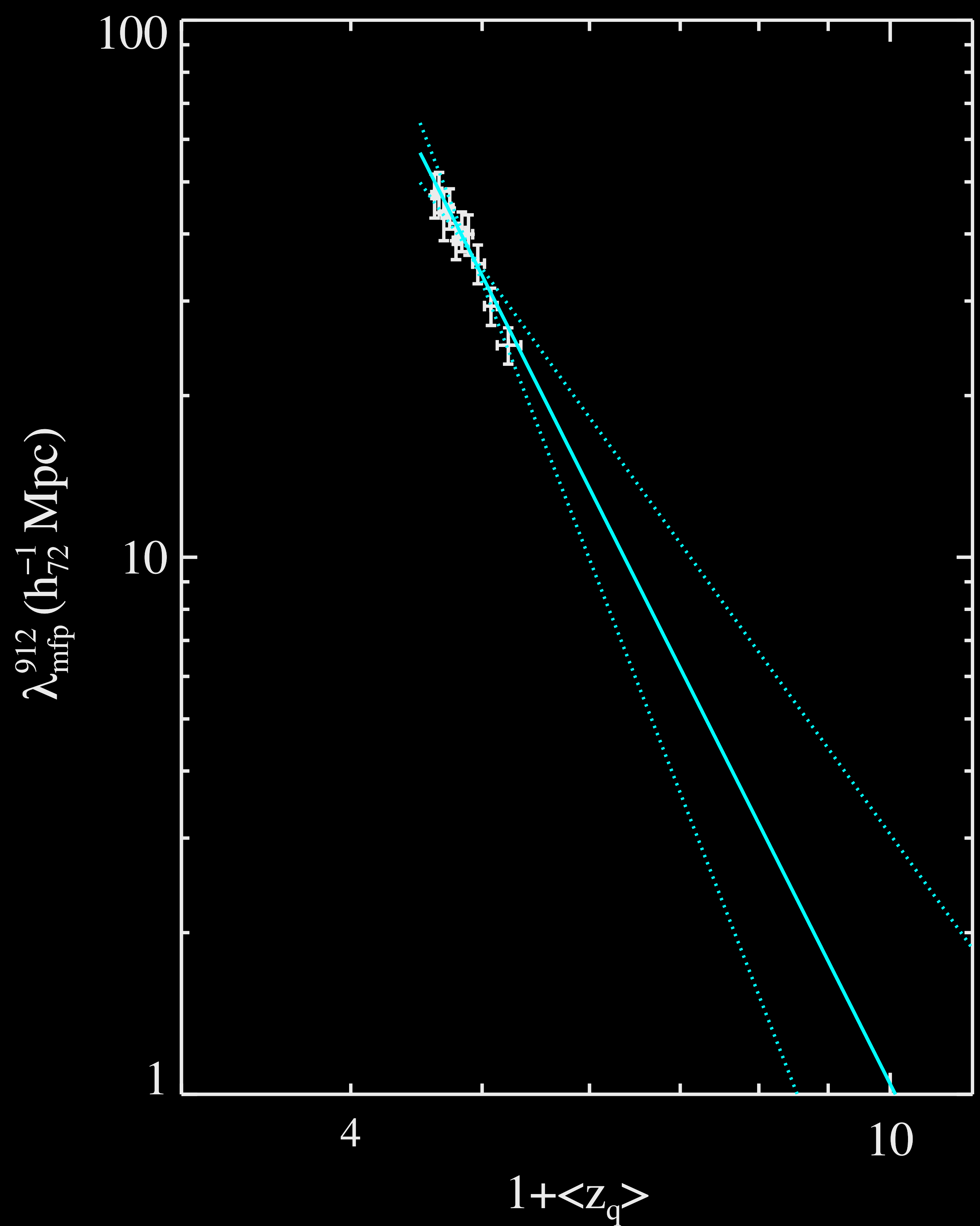


λ_{mfp} Implications: Reionization



λ_{mfp} Implications: Reionization

- Ansatz
  - Demand $\lambda_{mfp} \sim (1+z)^{\gamma}$
    - Physically motivated
- Extrapolate to z>4
  - $z_{reion} > 7.5$
  - $z_{reion} < 20$



λ_{mfp} Implications: Reionization

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  - $z_{reion} > 7.5$
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- Comparisons
  - Guesstimates from Lyα
  - Theory 'predictions'