DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

清華大學天文系

Department of Astronomy, Tsinghua University

$(\lambda_{\rm mfp}^{912})$

Measuring the Mean Free Path of HI Ionizing Photons with DESI Y1

Anning Gao

Department of Astronomy, Tsinghua University

Advisors: J. Xavier Prochaska, Zheng Cai, Siwei Zou, Cheng Zhao

OUTLINE

- Scientific Motivation
- Methodology
- Results & Validations

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

清華大學天文系
Department of Astronomy, Tsinghua University

Motivation

"Mean Free Path" ? → IGM opacity caused by photoelectric absorption

Evolution of extragalactic UV background J_ν:

Emissivity from QSOs, galaxies, …

$$\left(\frac{\partial}{\partial t} - \nu H \frac{\partial}{\partial \nu}\right) J_\nu + 3HJ_\nu = -c\kappa_\nu J_\nu + \frac{c}{4\pi}\epsilon_\nu$$

Haardt & Madau 2012

Lyα absorber distribution $f(N_{\rm HI}, z)$: $\tau_{\rm LL} = \int f(N_{\rm HI}, z)\,(1 - e^{-N_{\rm HI}\sigma})\,{\rm d}N_{\rm HI}\,{\rm d}z$

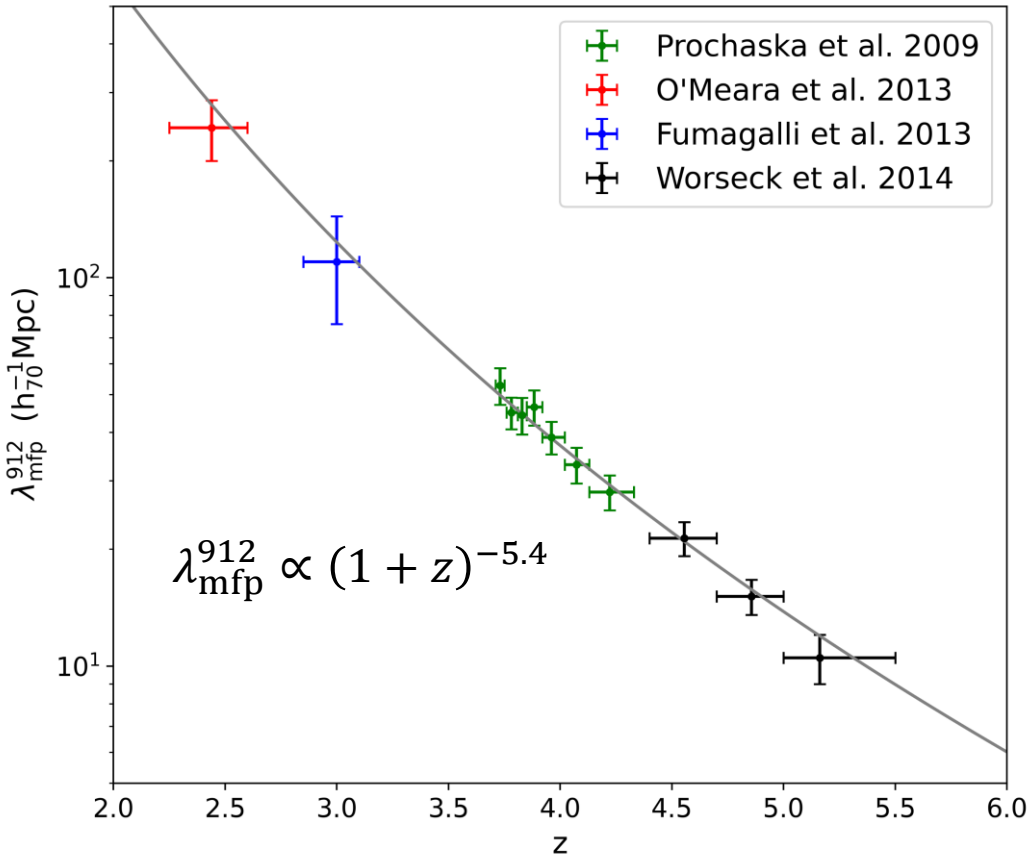
Useful in Lyα mocks!

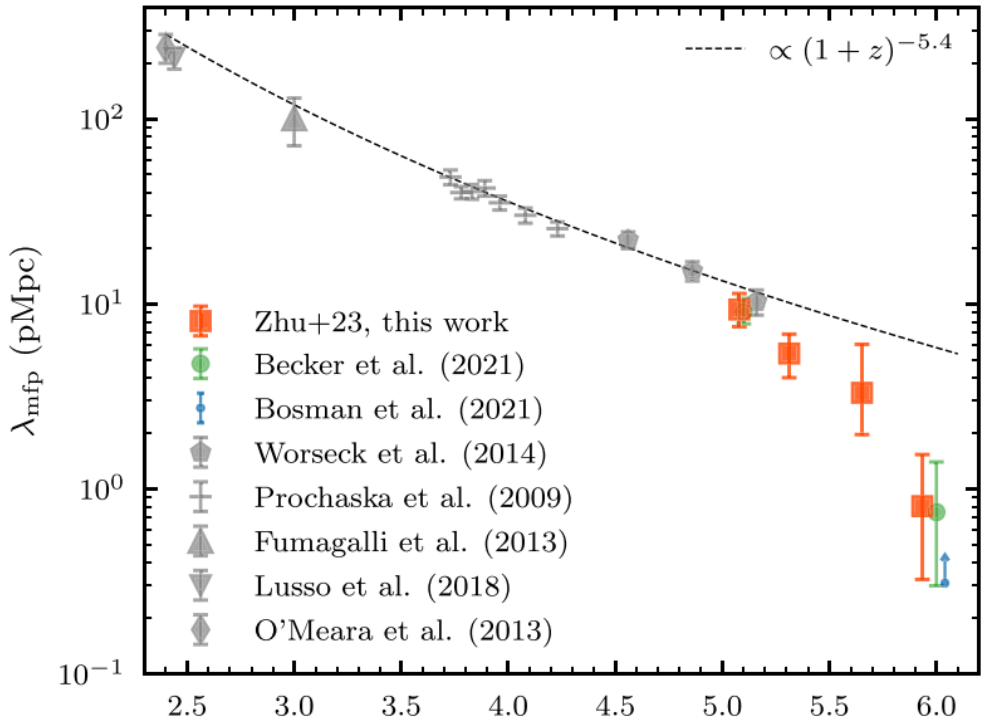
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

清華大學天文系
Department of Astronomy, Tsinghua University

Motivation

Worseck et al. 2014





Zhu et al. 2023

Spectra from:
LRIS
GMOS
Keck/ESI
VLT/X-Shooter

Constrain the reionization model

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

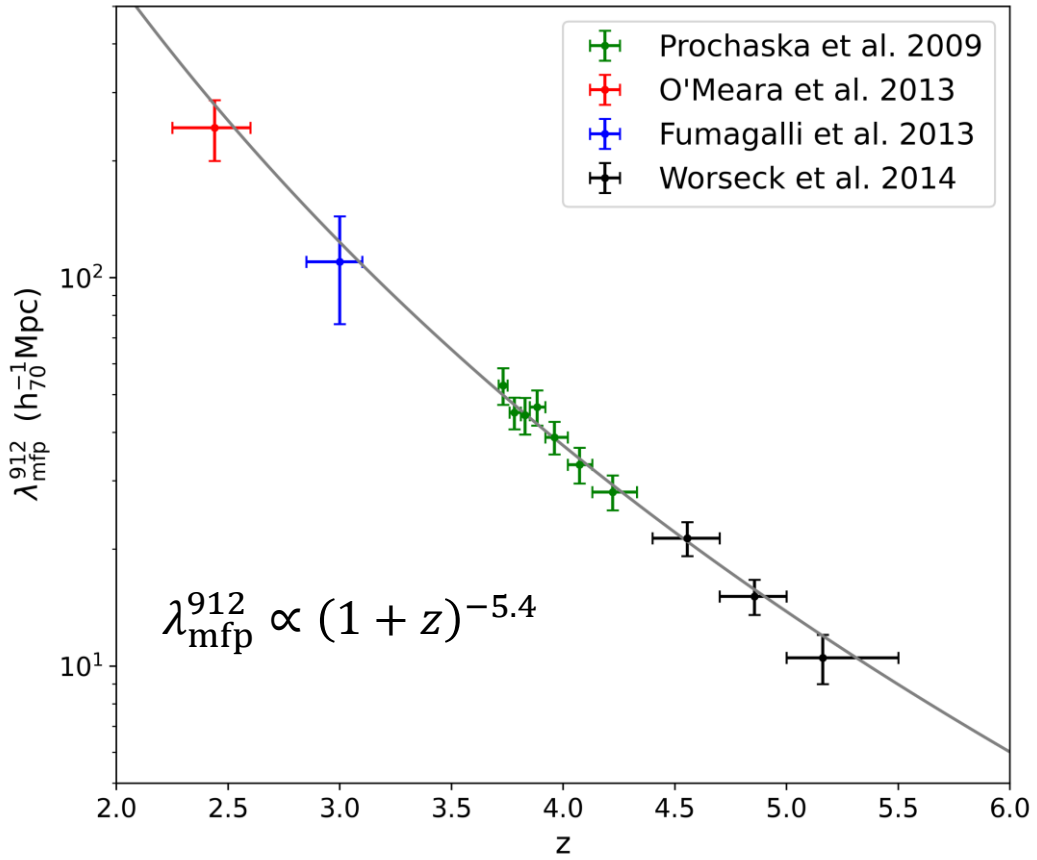
清華大學天文系
Department of Astronomy, Tsinghua University

Motivation

Use SDSS DR7 QSOs

Works	Redshift Range	Total Sample Size
Prochaska et al. 2009	3.71~4.34	1260
O'Meara et al. 2013	2.3~2.6	53
Fumagalli et al. 2013	2.8~3.2	105
Worseck et al. 2014	4.4~5.5	145
This Work	**3.2~4.6**	**12595**

DESI significantly enlarges the sample size!



Worseck et al. 2014

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

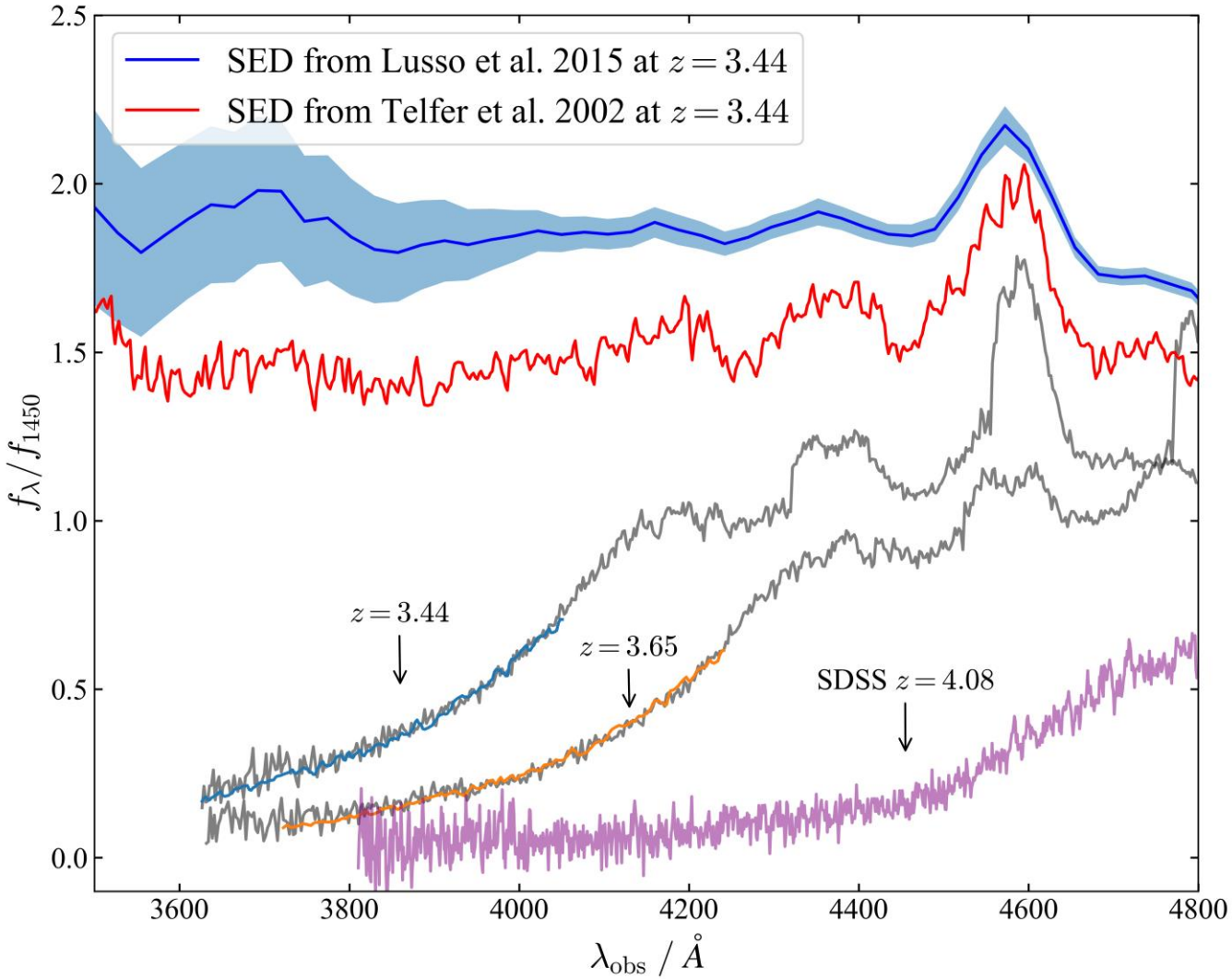
清華大學天文系
Department of Astronomy, Tsinghua University

Method

1. Stack the spectrum

$$f_\lambda^{\mathrm{SED}} = f_\lambda^{\mathrm{template}} \left(\frac{\lambda}{1450\text{Å}} \right)^{\gamma_t}$$

Our Choice: $\gamma_t = 0$



DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

清華大學天文系
Department of Astronomy, Tsinghua University

Method

2. Model the spectrum

$$f_\lambda^{\rm obs} = C\, f_\lambda^{\rm SED} \exp\left(-\tau_{\rm eff}^{\rm Lyman}\right) \exp\left(-\tau_{\rm eff}^{\rm LL}\right)$$

Definition:

$$z_{912} \equiv \frac{\lambda_r}{\lambda_{\rm LL}}\left(1+z_{\rm qso}\right) - 1$$

$$(\lambda_{\rm LL} = 911.76\text{Å})$$

The redshift at which a photon of λ_r emitted at $z_{\rm qso}$ is redshifted to $\lambda_{\rm LL}$ (i.e. **absorption stops at this redshift**).

$$\tau_{\rm eff}^{\rm Lyman} = \tau_{\rm eff,912}^{\rm Lyman}\left(\frac{1+z_{912}}{1+z_{\rm qso}}\right)^{\gamma_\tau} \quad (\text{Our choice: } \gamma_\tau = 3.0)$$

Prochaska et al. 2014

$$\tau_{\rm eff}^{\rm LL} = \kappa \frac{c}{H_0}(1+z_{912})^{2.75} \int_{z_{912}}^{z_{\rm qso}} (1+z')^{-5.25}\, {\rm d}z'$$

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

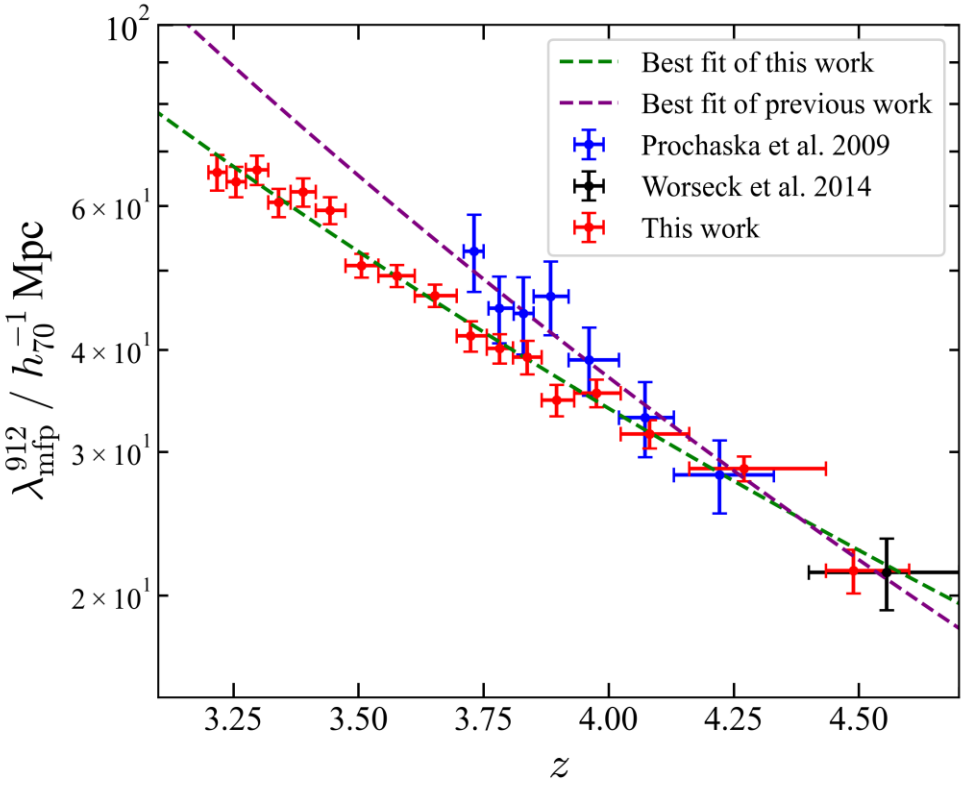
清華大學天文系
Department of Astronomy, Tsinghua University

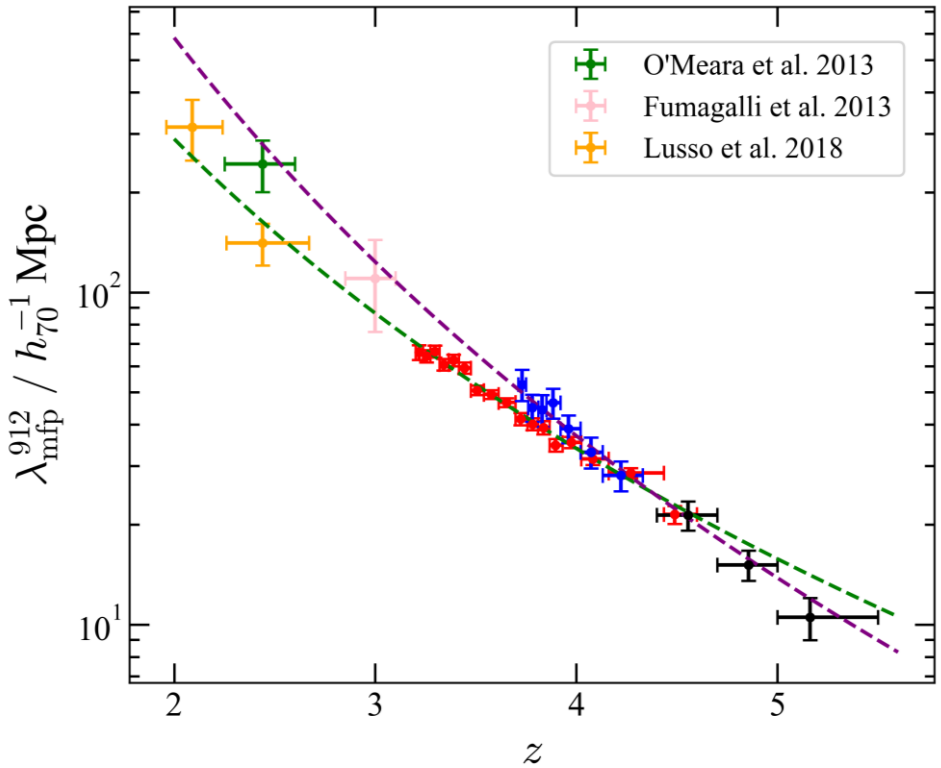
Result

$$\lambda_{\rm mfp}^{912} \propto (1+z)^{-\eta}$$

Worseck et al. 2014: $\eta = -5.4 \pm 0.4$

This work: $\eta = -4.20 \pm 0.14$ (with Telfer SED)





DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

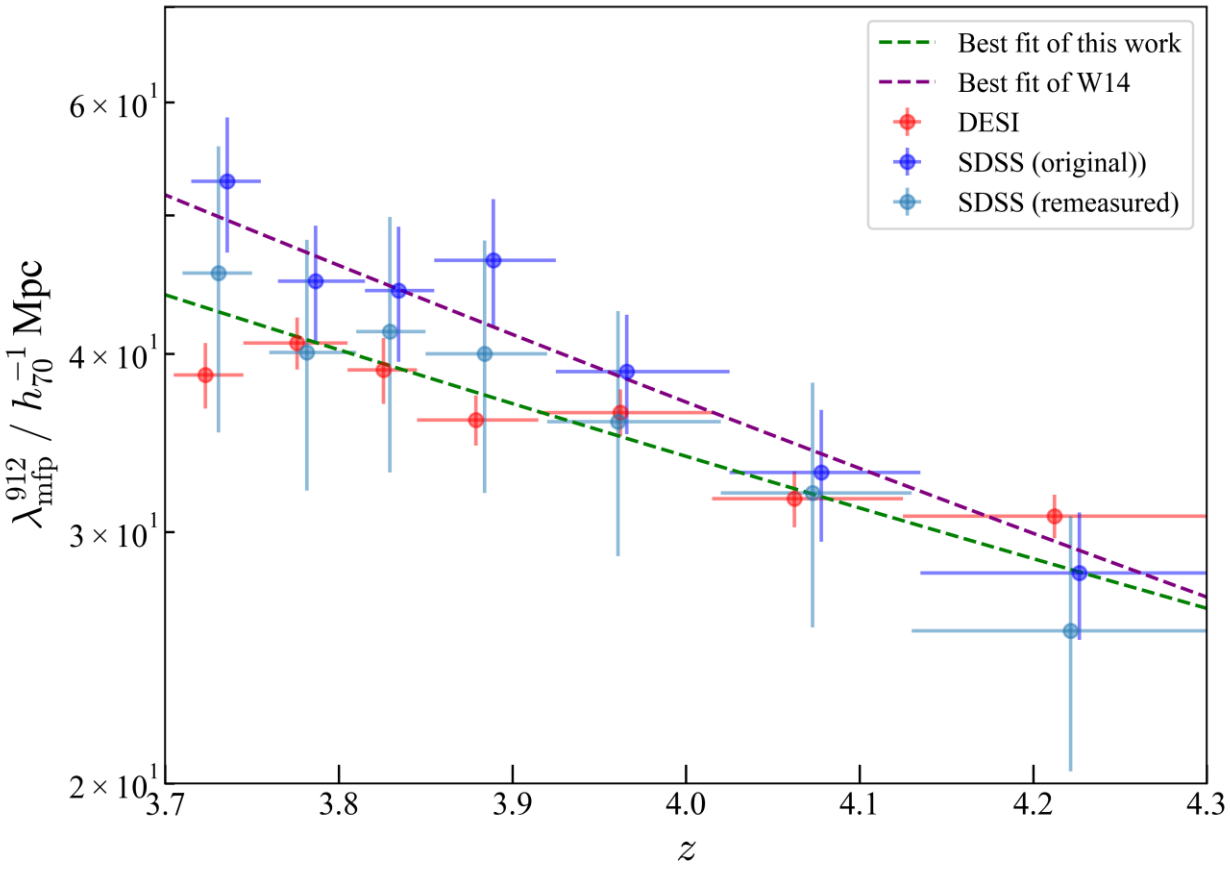
清華大學天文系
Department of Astronomy, Tsinghua University

Validation

Remeasure using their data and our fitting pipeline:

- **DESI**: MFPs measured with DESI quasar stacks at the same redshift range
- **SDSS (original):** MFPs measured in *Prochaska et al. 2009*
- **SDSS (remeasured):** MFPs remeasured using our fitting pipeline.

After correcting for the Lyman series opacity, the MFPs from the SDSS becomes closer to **our** power law!



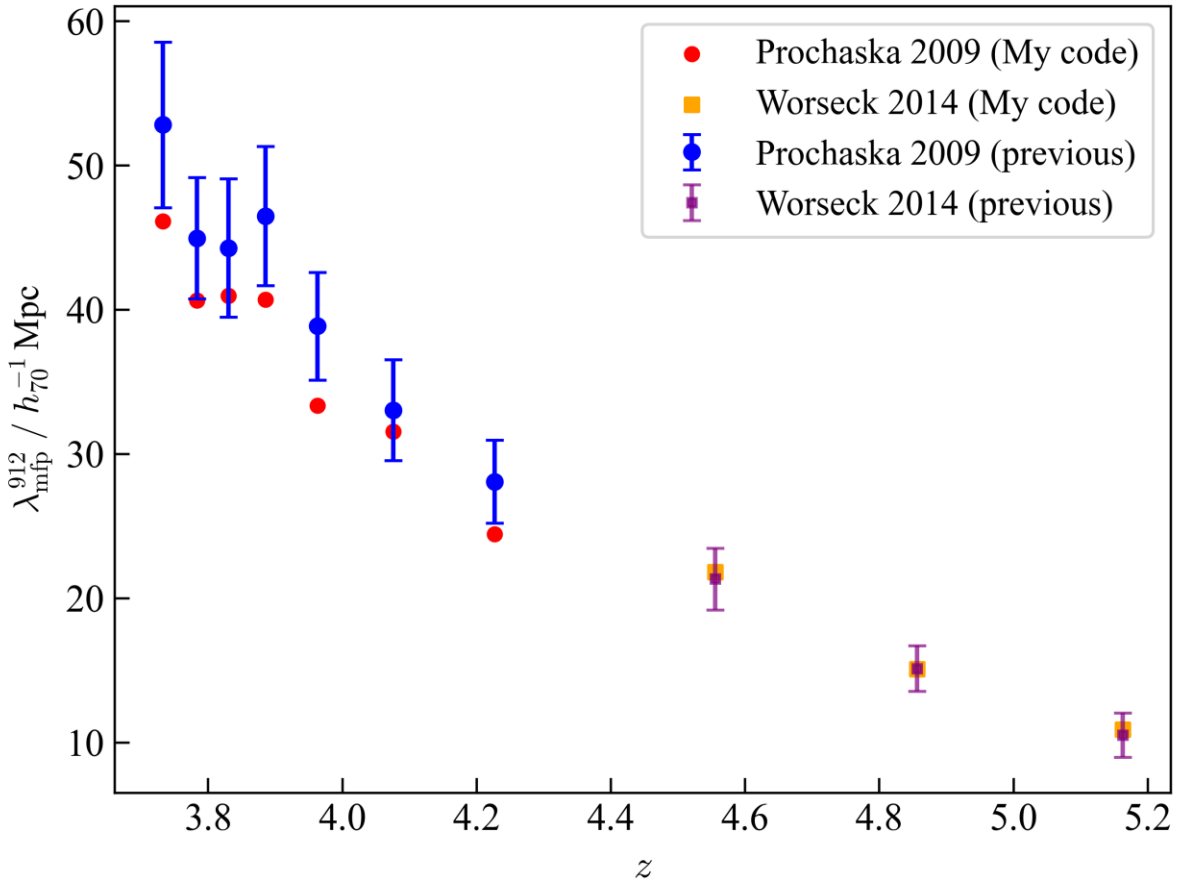
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

清華大學天文系
Department of Astronomy, Tsinghua University

Validation

A further confirmation:

Add *Worseck et al. 2014* remeasurements



DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

清華大學天文系
Department of Astronomy, Tsinghua University

Result

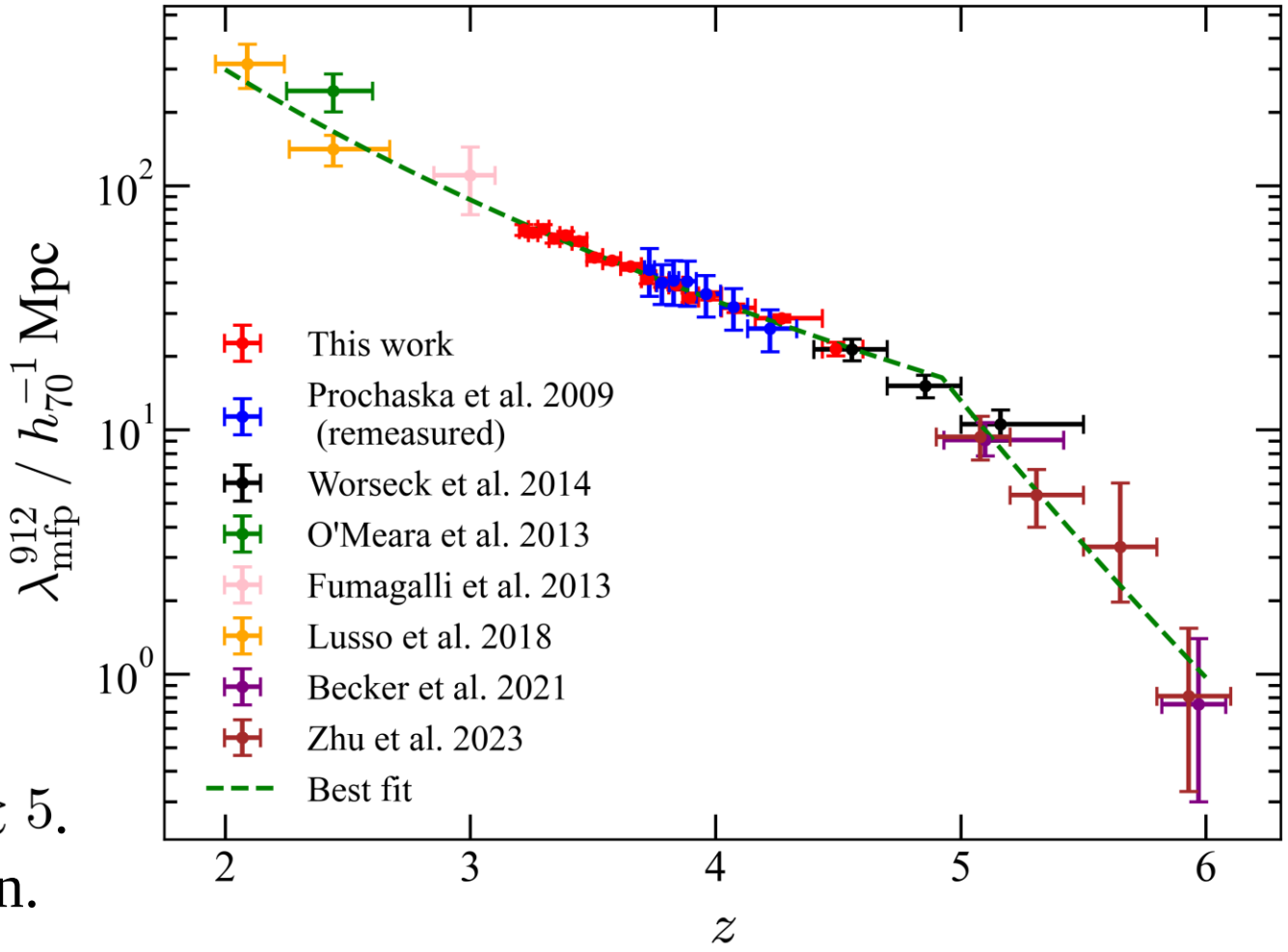
Broken power-law:

$$\lambda_{\rm mfp}^{912} \propto \begin{cases} (1+z)^{-\eta_1}, & z < z_0 \\ (1+z)^{-\eta_2}, & z \geq z_0 \end{cases}$$

$$z_0 = 4.90^{+0.08}_{-0.11}$$

$$\eta_1 = 4.26^{+0.12}_{-0.12} \qquad \eta_2 = 16.28^{+2.57}_{-3.41}$$

- Reionization may still be ongoing at $z \gtrsim 5$.
- $f(N_{\rm HI}, z)$ may need further consideration.



MUST MUltiplexed Survey Telescope

https://must.astro.tsinghua.edu.cn/en

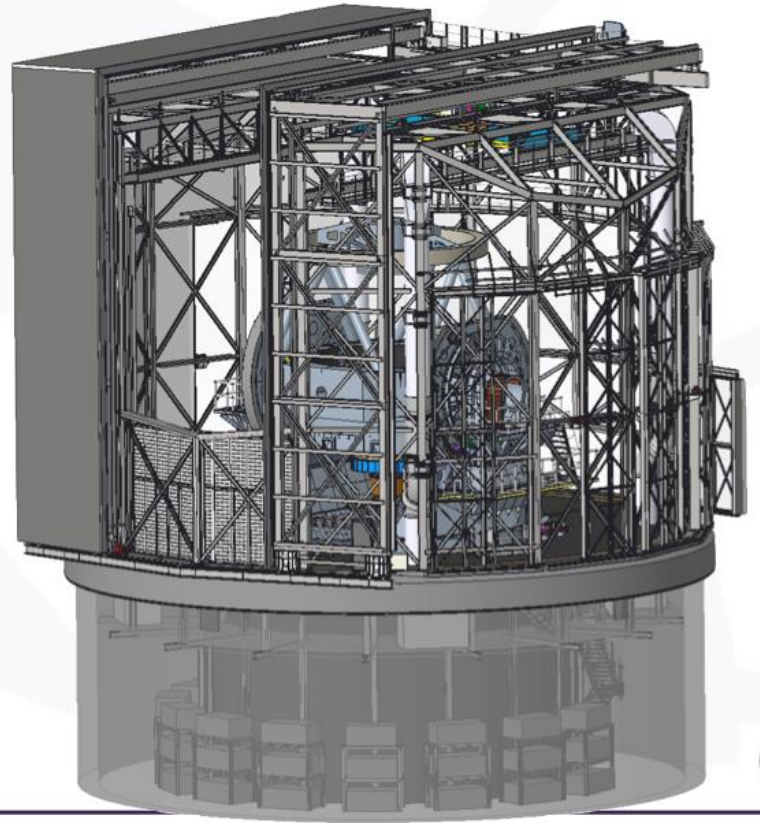
- MUST aims to carry out the world's First Stage-V spectroscopic survey for Cosmology and create the Largest 3-D Map of the Universe.
- MUST will constrain cosmological models with unprecedented precision and strive for breakthroughs in Fundamental Physical Problems, such as the primordial condition of the Universe, the origin and evolution of Dark Energy, and the nature of Dark Matter.

6.5m Primary

2.4m Secondary

1.6m Lens for WFC

7deg² FoV



20,000 Fiber Positioners

MODULAR Focal Plane

40 Spectrographs

0.37–0.98 micron

R~2000–4000

Credit: MUST Team

DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

清華大學天文系
Department of Astronomy, Tsinghua University

Summary

We remeasured the Mean Free Path of HI ionizing photons at $3.2 \leq z \leq 4.6$.

$$\lambda_{\rm mfp}^{912} \propto \begin{cases} (1+z)^{-4.26}, & z < 4.90 \\ (1+z)^{-16.28}, & z \geq 4.90 \end{cases}$$

Public Code (under construction):
https://github.com/AnningGao/MeanFreePath