The Dark Energy Spectroscopic Instrument & Intergalactic Medium-based Cosmology

Satya Gontcho A Gontcho

University of Rochester
DESI Lead Observing Scientist

LPNHE, January 6th 2020

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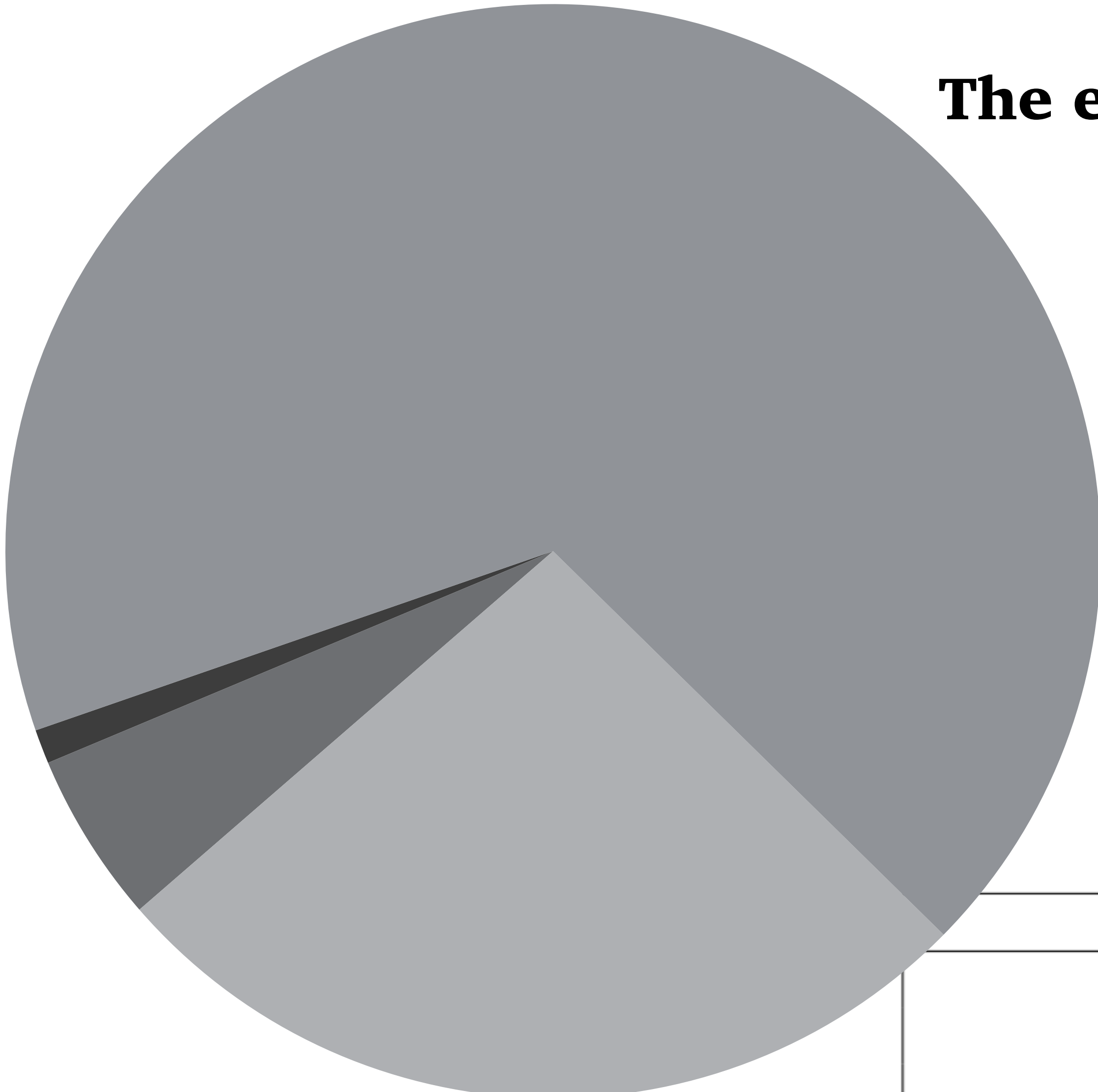
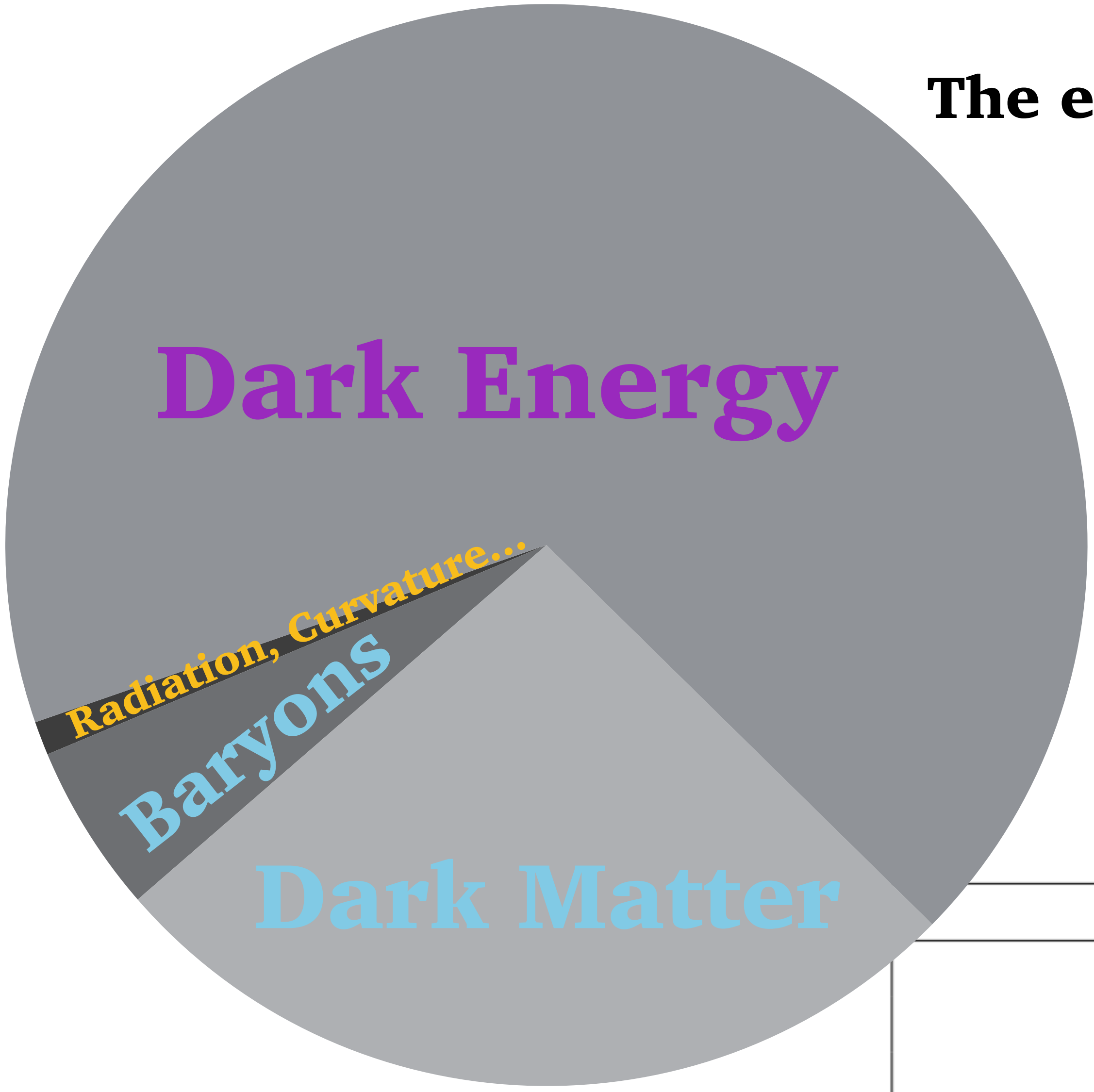
Cosmological Standard Model



The evolution of the Universe is driven by its content.

-Epoch-/Event	Time	Temp. (K)	Energy (eV)	Redshift
Hot Big Bang	-	-	-	-
Inflation	-	-	-	-
Reheating	-	0	-	$\sim 10^{28}$
-Radiation domination era-	**-**	**-**	**-**	**-**
Baryongenesis-Leptogenesis	10^{-4} s	2×10^{12}	2×10^{8}	10^{11}
Primordial Nucleosynthesis	100 s	10^{9}	10^{5}	10^{9}
-Matter domination era-	**100 kyrs**	**9000**	**0.81**	**3400**
Recombination	380 kyrs	3000	0.3	1100
reionization	320 Myrs	120	0.01	20
First galaxies formation	1.3 Gyrs	60	5×10^{-3}	10
-Dark Energy domination era-	**9.4 Gyrs**	**4.8**	$\mathbf{4 \times 10^{-4}}$	**0.75**
Today	15 Gyrs	2.7	2.35×10^{-4}	0



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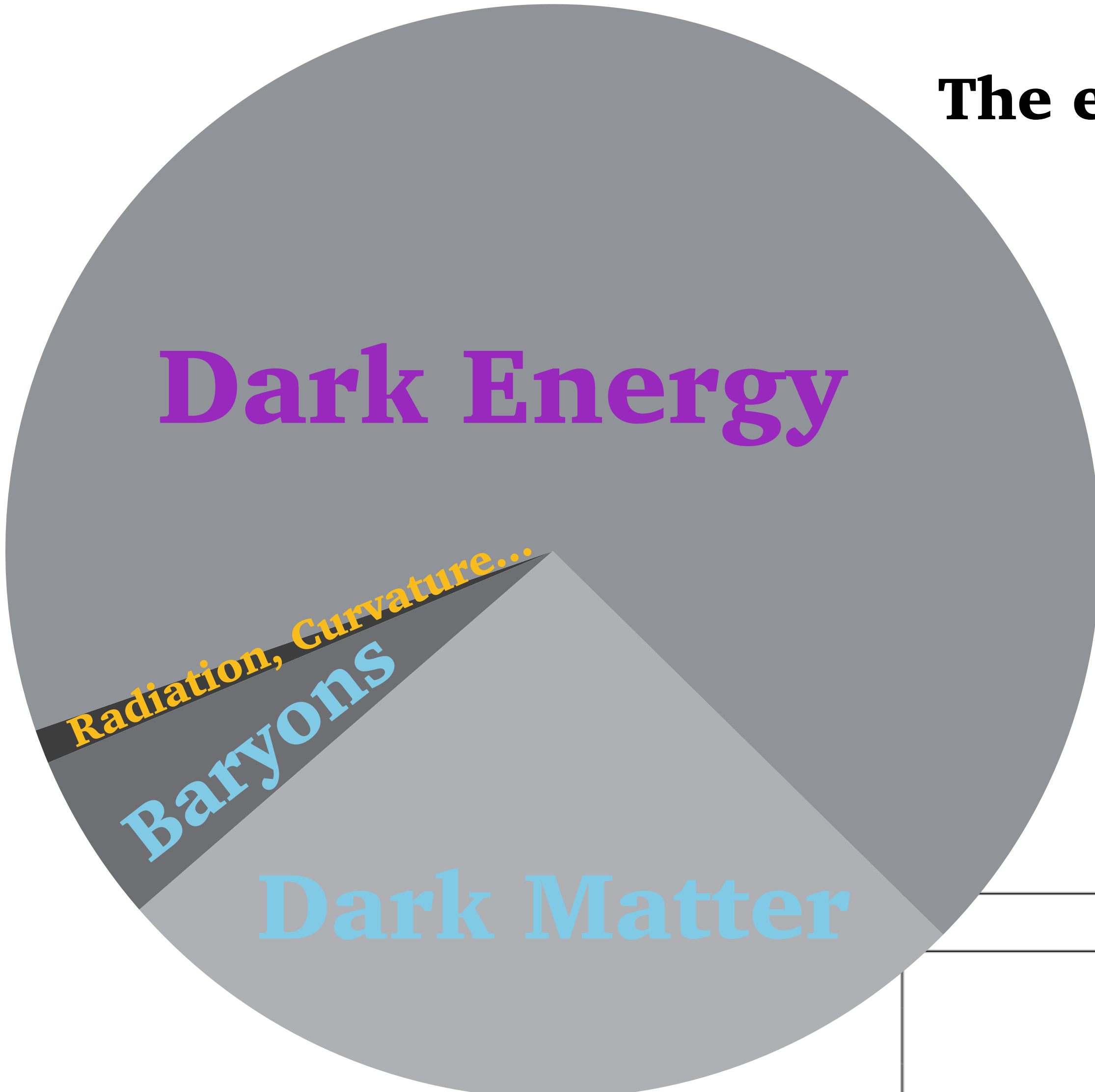

The evolution of the Universe is driven by its content.

Acceleration of the Expansion of the Universe

$\updownarrow$

Dark Energy dominated era

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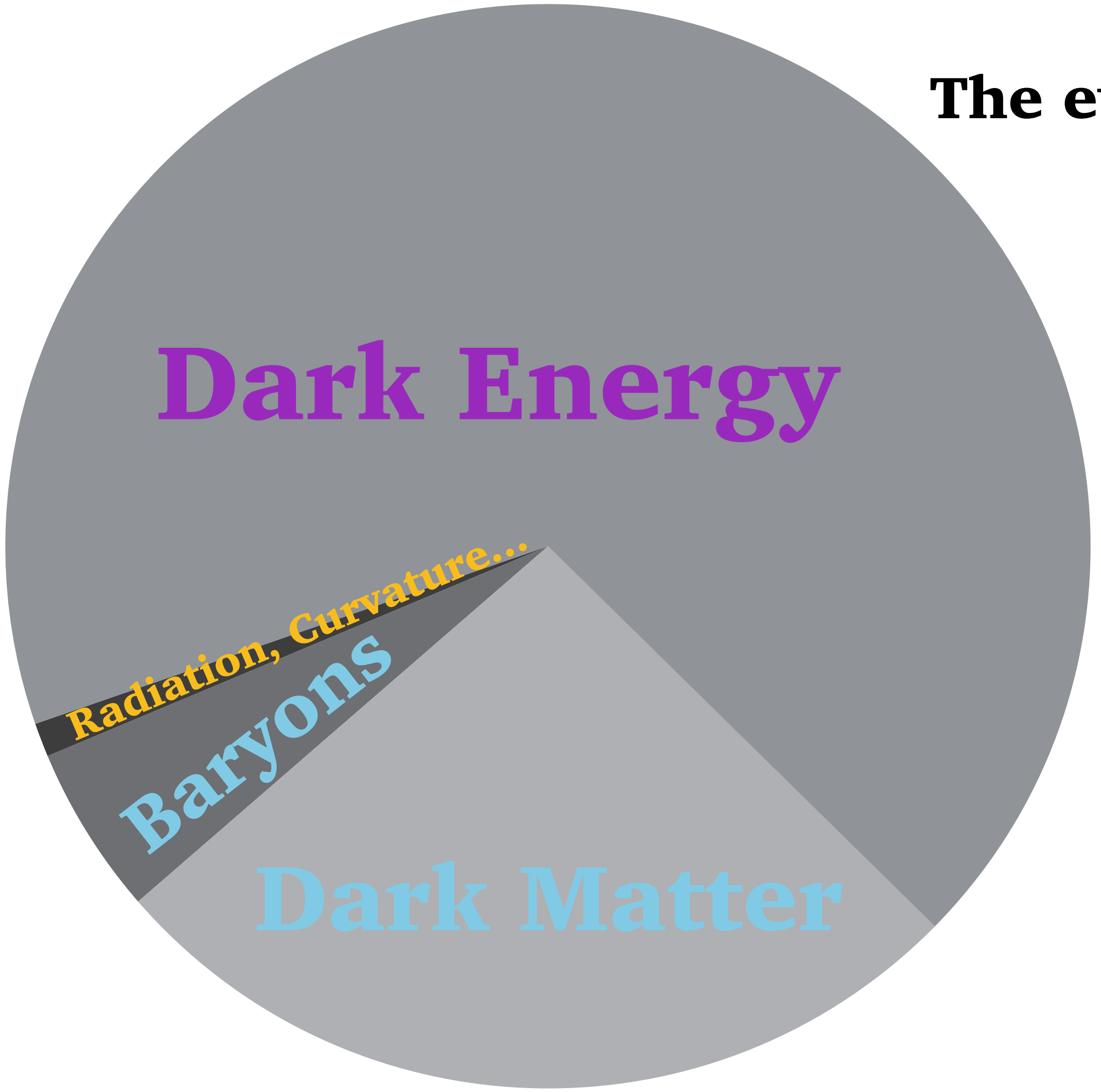
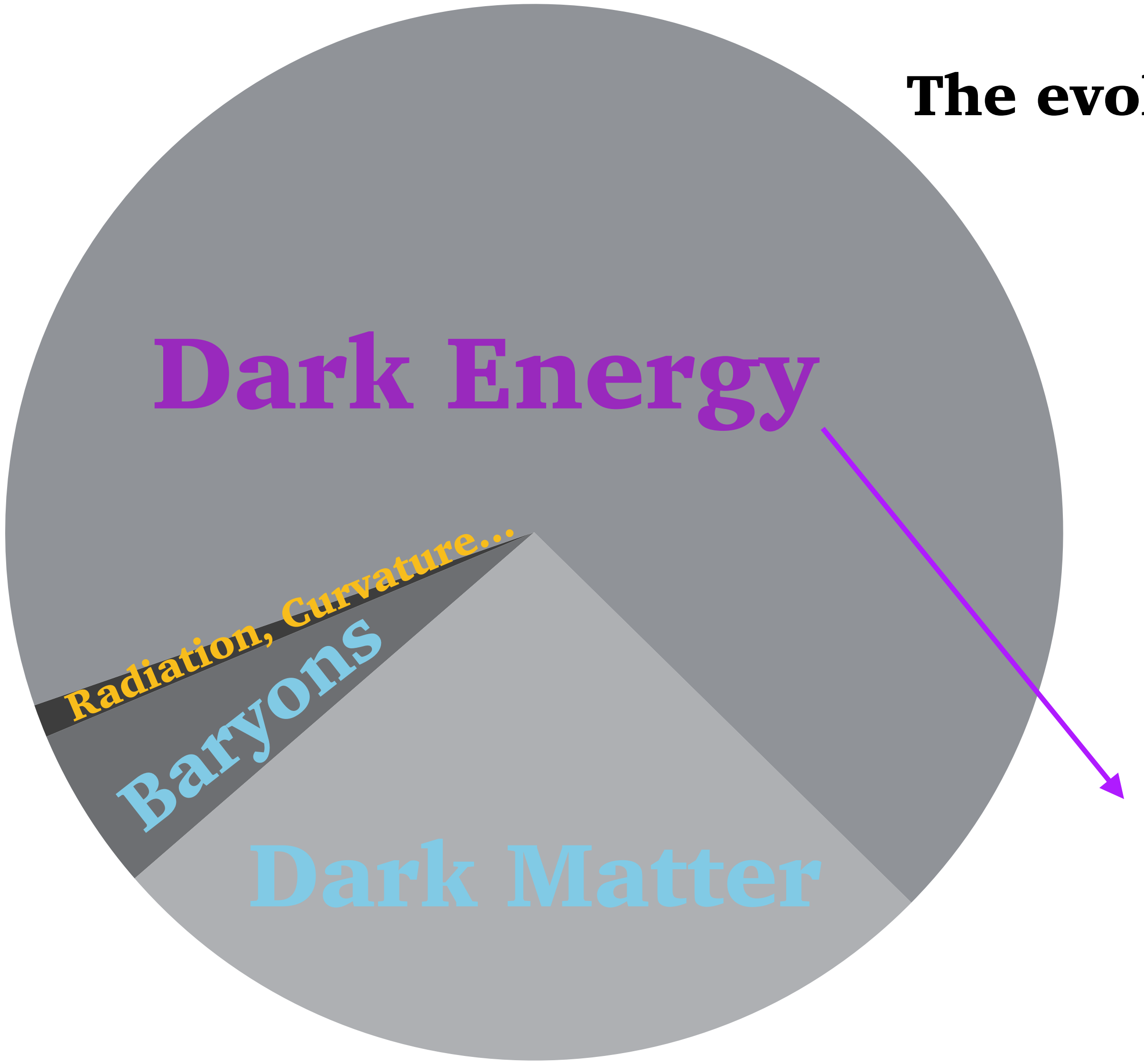


The evolution of the Universe is driven by its content.

Acceleration of the Expansion of the Universe

↕

Dark Energy dominated era



The evolution of the Universe is driven by its content.

Acceleration of the Expansion of the Universe
↕
Dark Energy dominated era

Within the context of GR Dark Energy is understood as a macroscopic manifestation of the quantum vacuum energy

$$R_{\mu\upsilon} - \frac{1}{2} R g_{\mu\upsilon} = \frac{8\pi G}{c^4} - \Lambda g_{\mu\upsilon}$$

Other alternatives include: Modified Gravity, time evolving DE,…

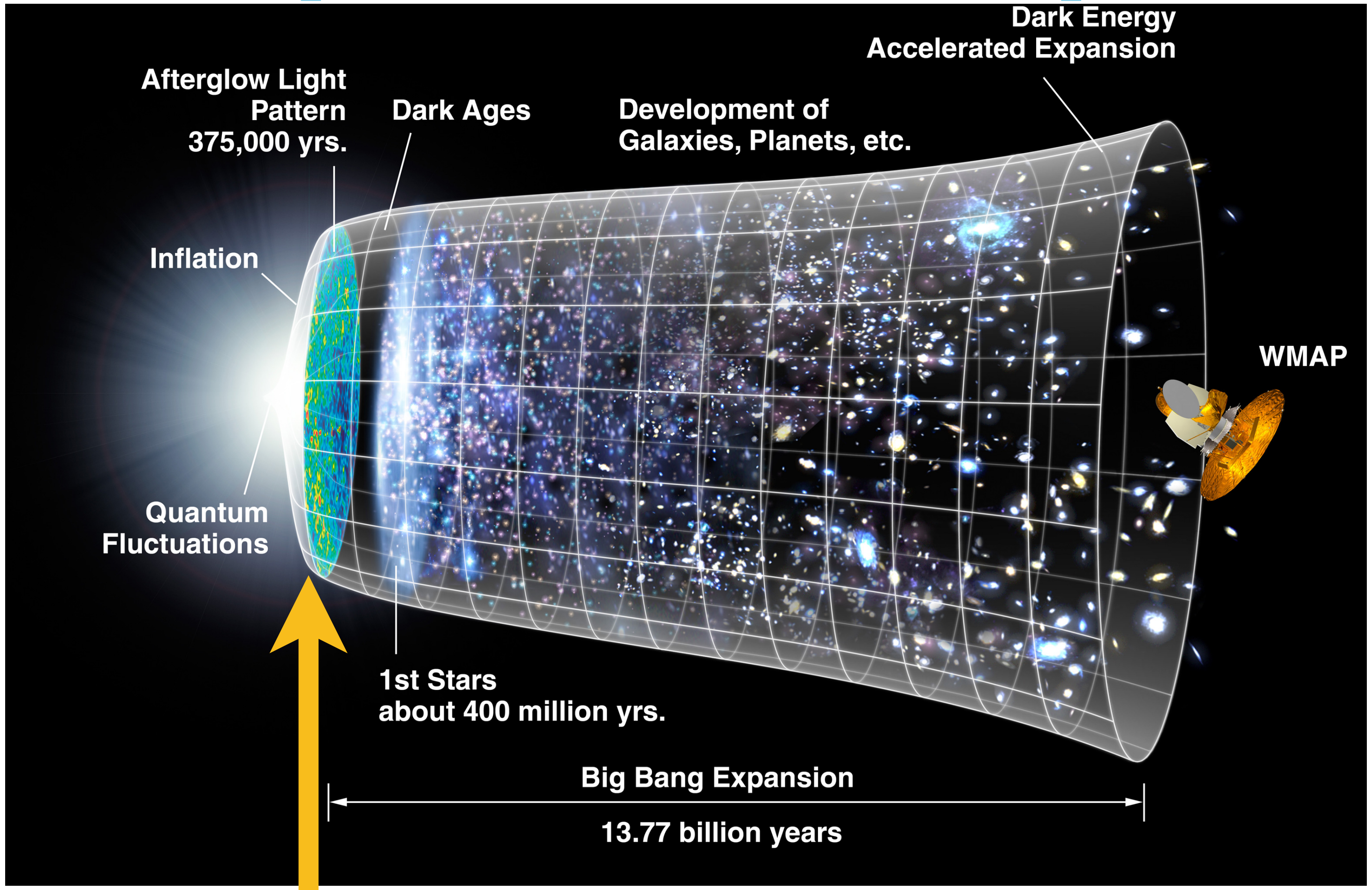
All these different DE theories —> different expansion rate H(z), and different logarithmic growth of structure factor $f(z)\sigma_8(z)$

Strong constraints on cosmology from measurements at z > 0.75 with Planck, SDSS-III/BOSS (quasars, Lyman-alpha forest)

Matter Dominated

+ SDSS-III/BOSS (galaxies) at z < 0.7

Percent level precision



Radiation Dominated

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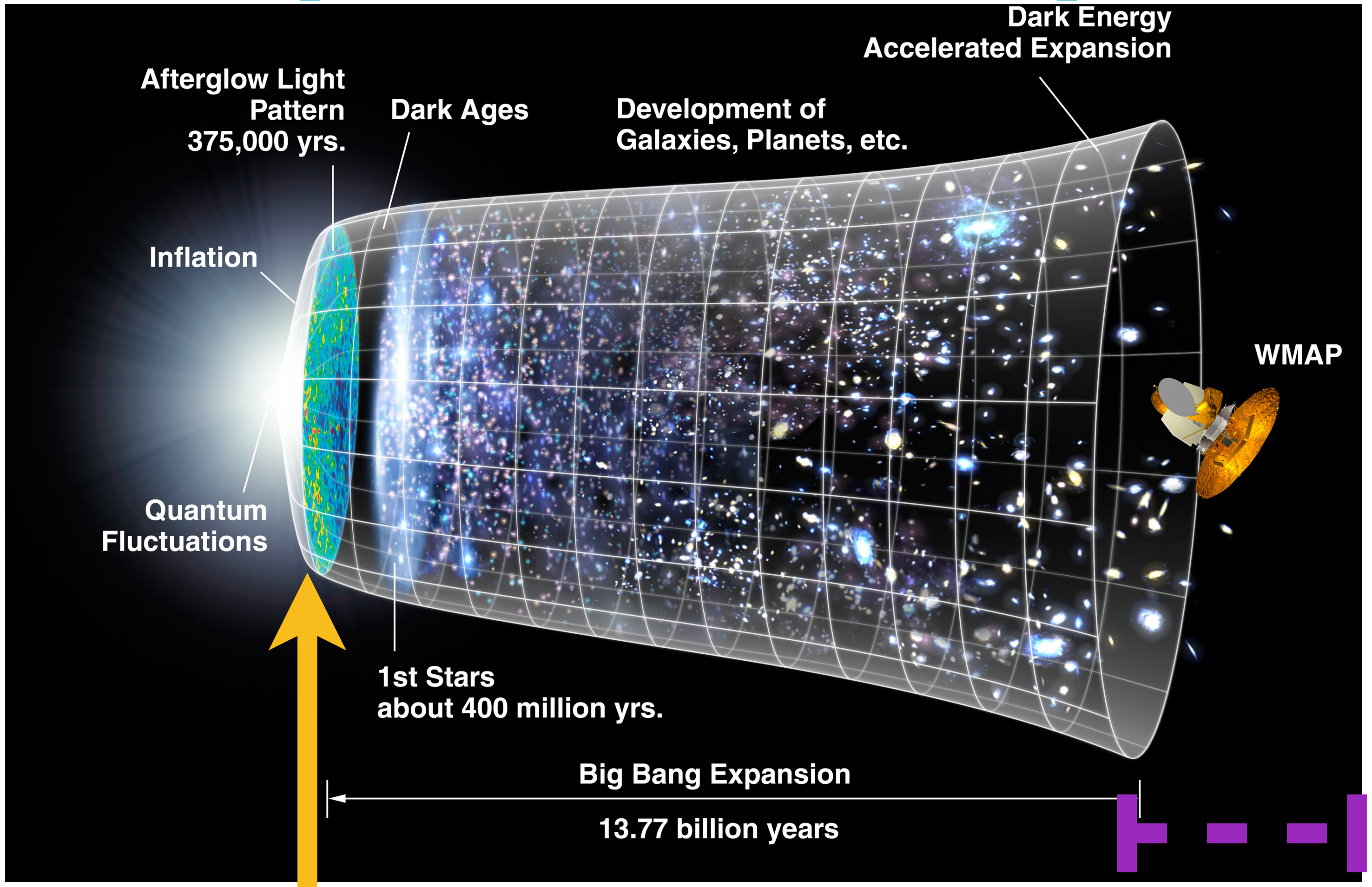


Dark Energy Dominated

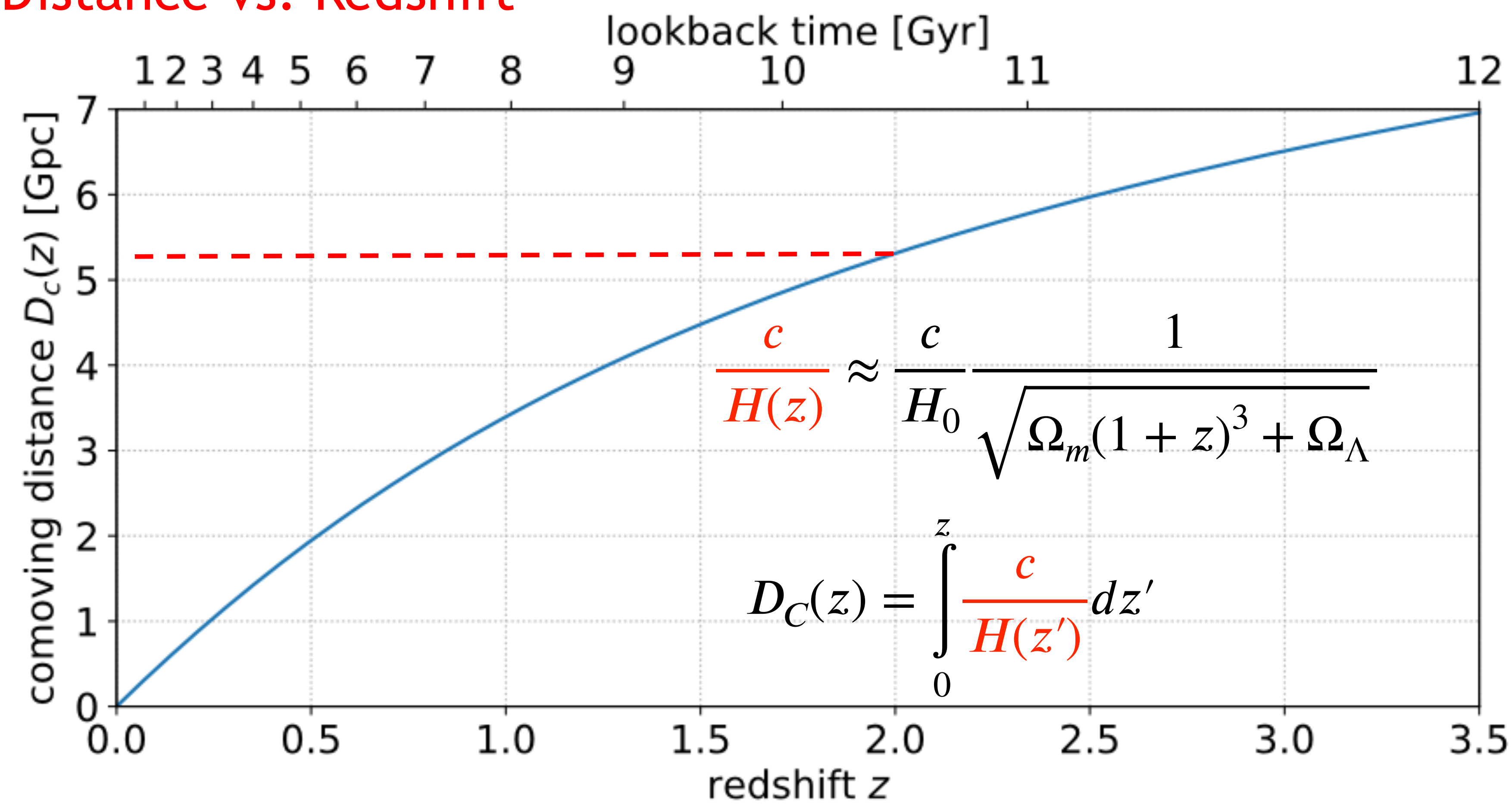
Radiation Dominated

DESI (right now!)

Sub-percent level precision

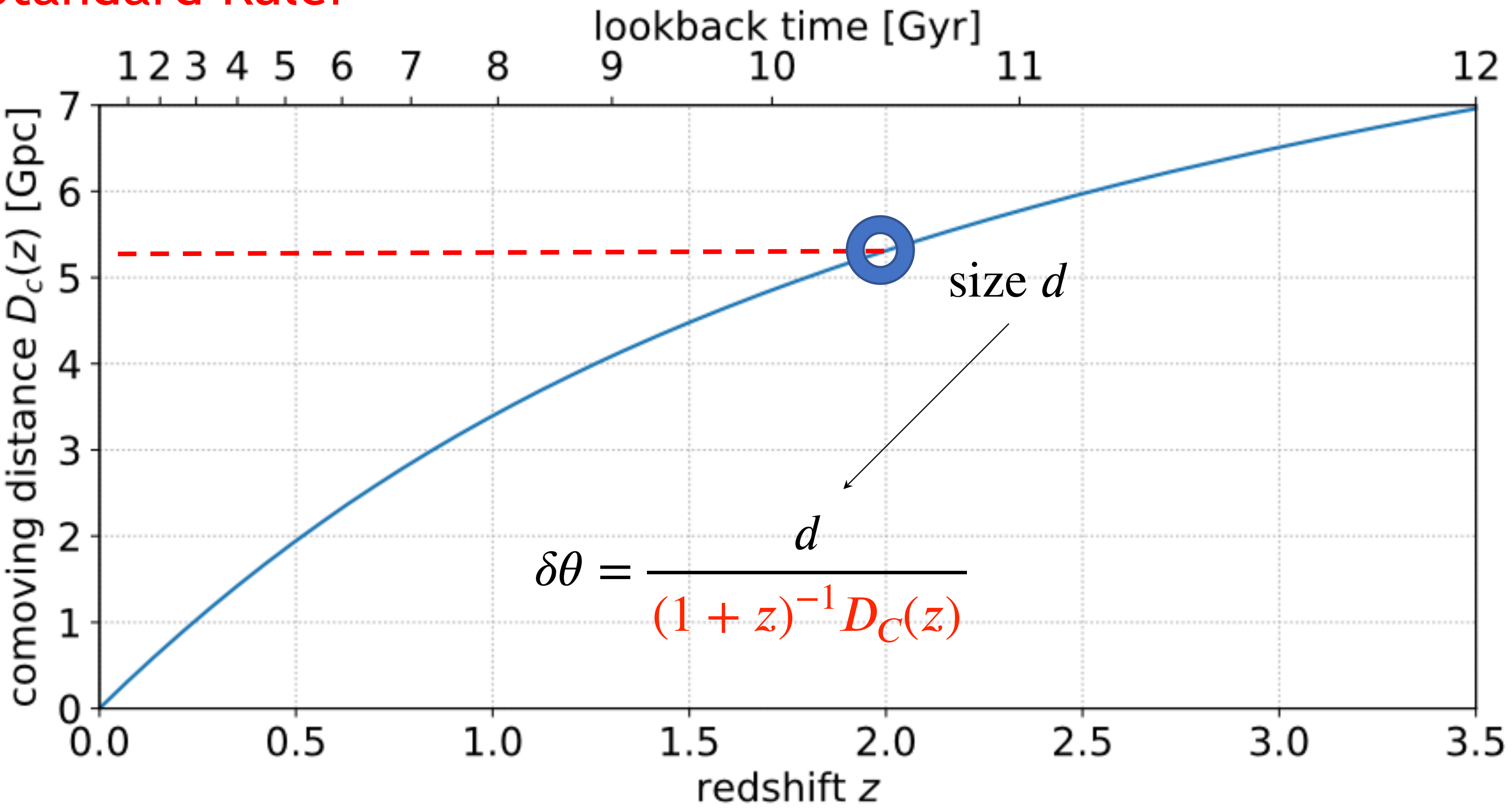
Measuring the Hubble Expansion

Distance vs. Redshift



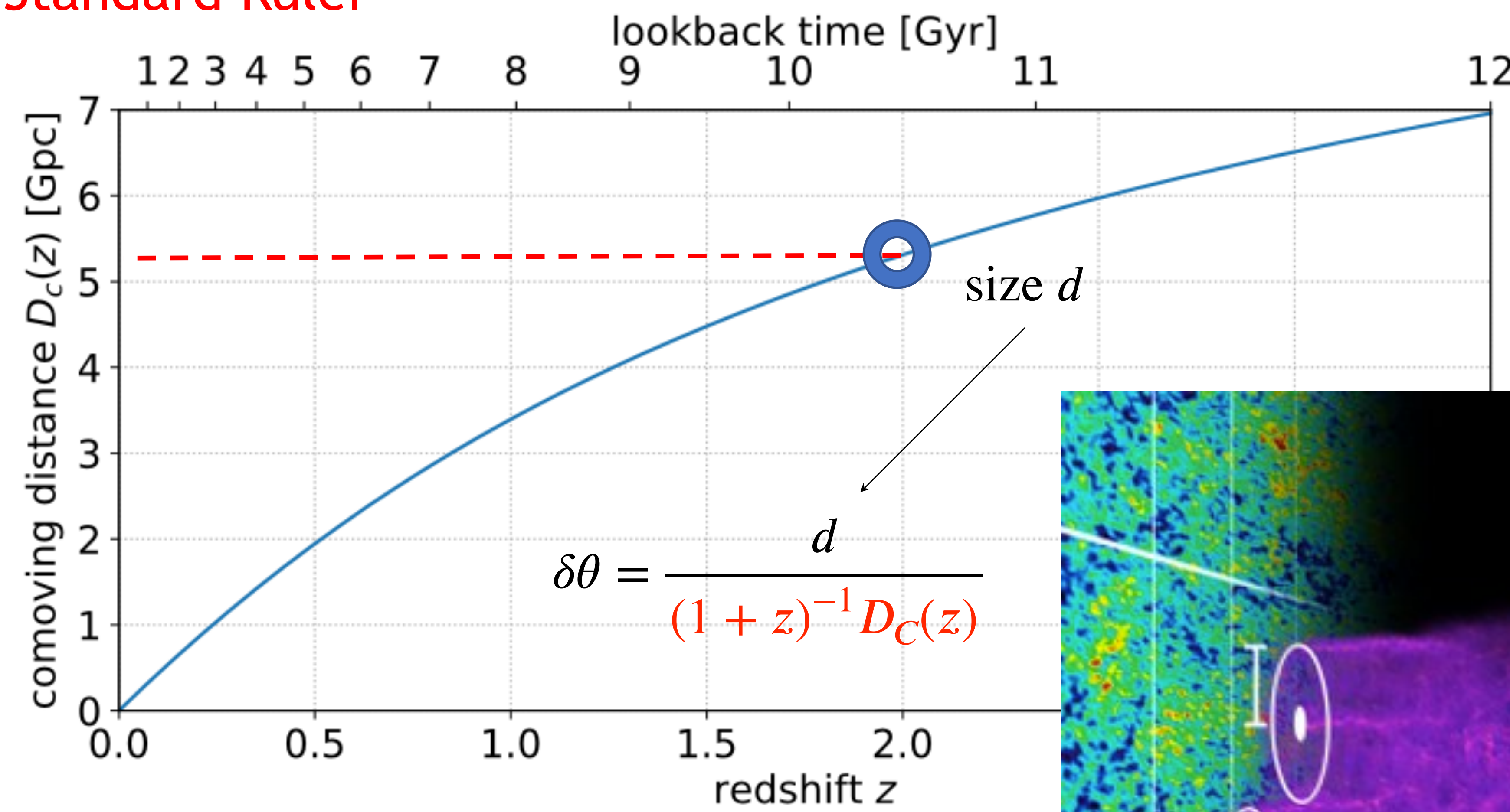
Credit: D. Kirkby

Standard Ruler

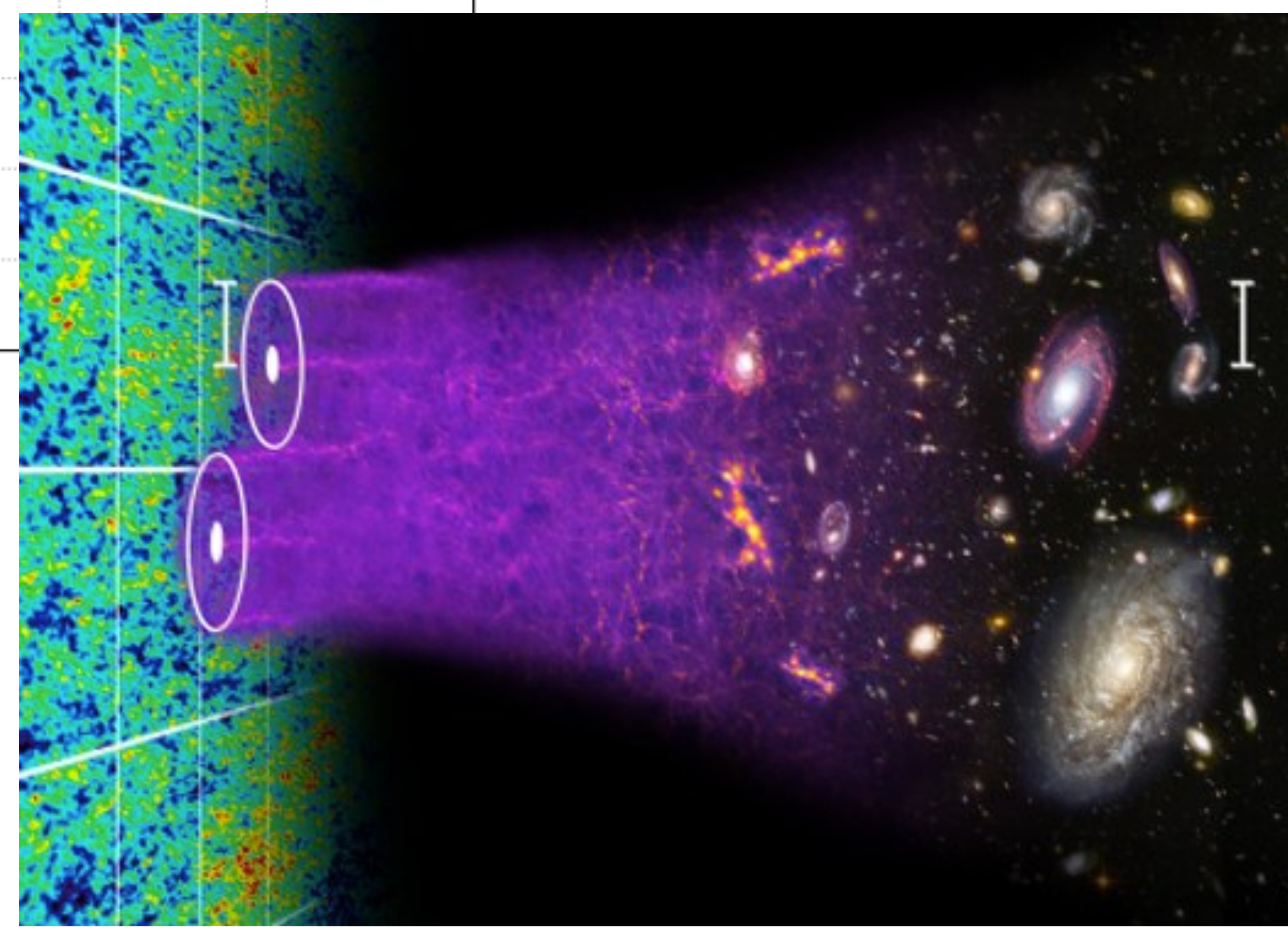


Credit: D. Kirkby

Standard Ruler

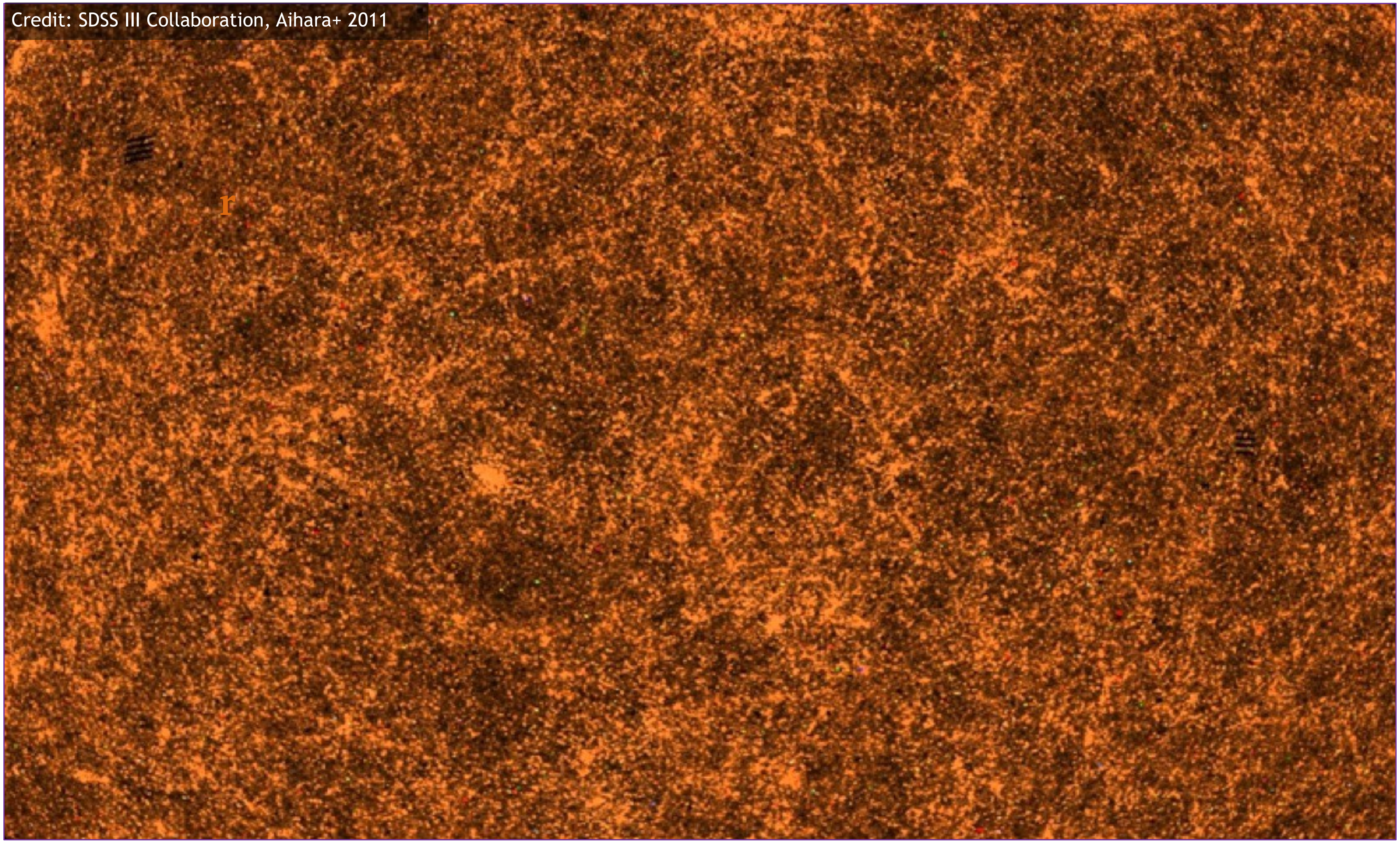


$$\delta\theta = \frac{d}{(1+z)^{-1} D_C(z)}$$

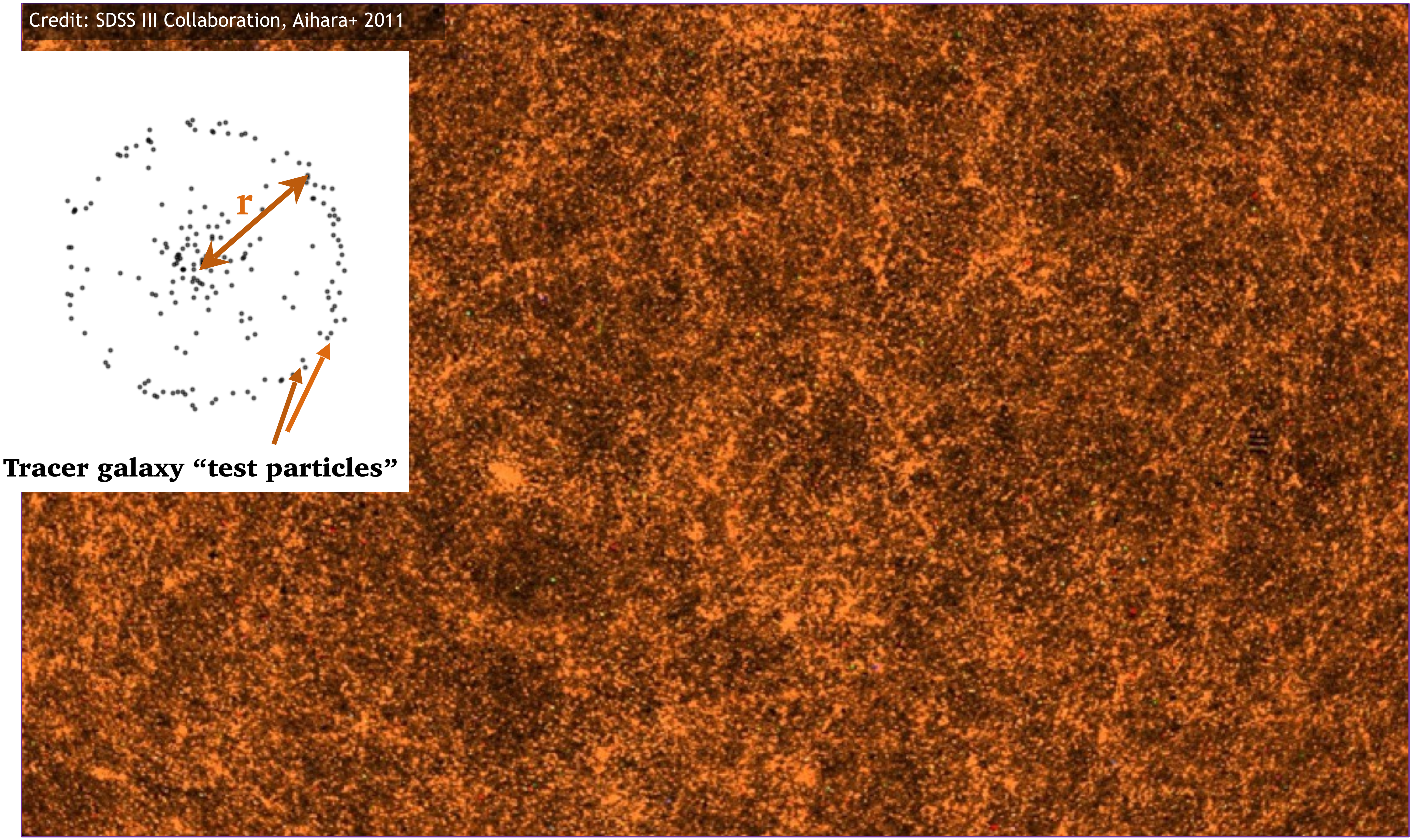


Credit: D. Kirkby, SDSS-III

Mapping the density field



Mapping the density field



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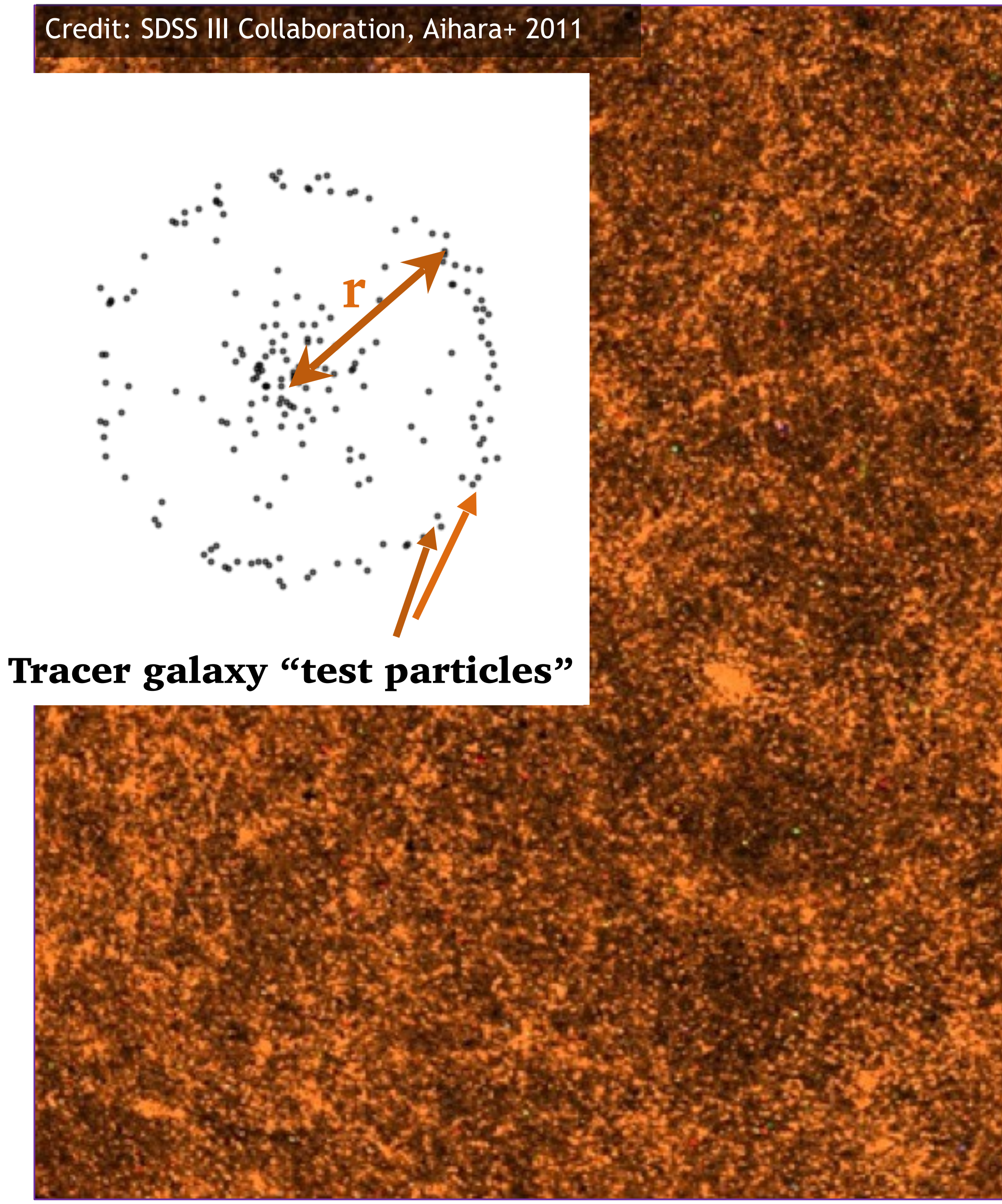
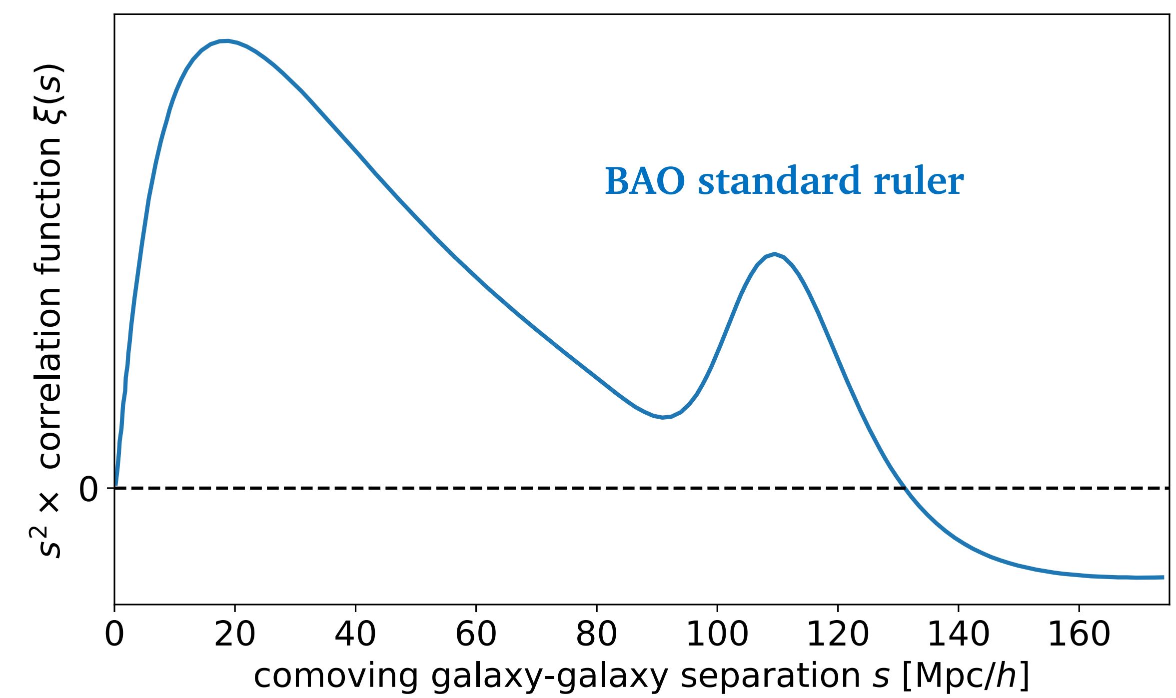


$$\xi(s) = \frac{\mathrm{DD}(s) - 2\mathrm{DR}(s) + \mathrm{RR}(s)}{\mathrm{RR}(s)} =$$

Excess galaxy pair counts in data w.r.t. random background pair counts in survey volume.



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Mayall, a 4-meter at Kitt Peak, Arizona, USA

its twin at CTIO (DESI imaging)

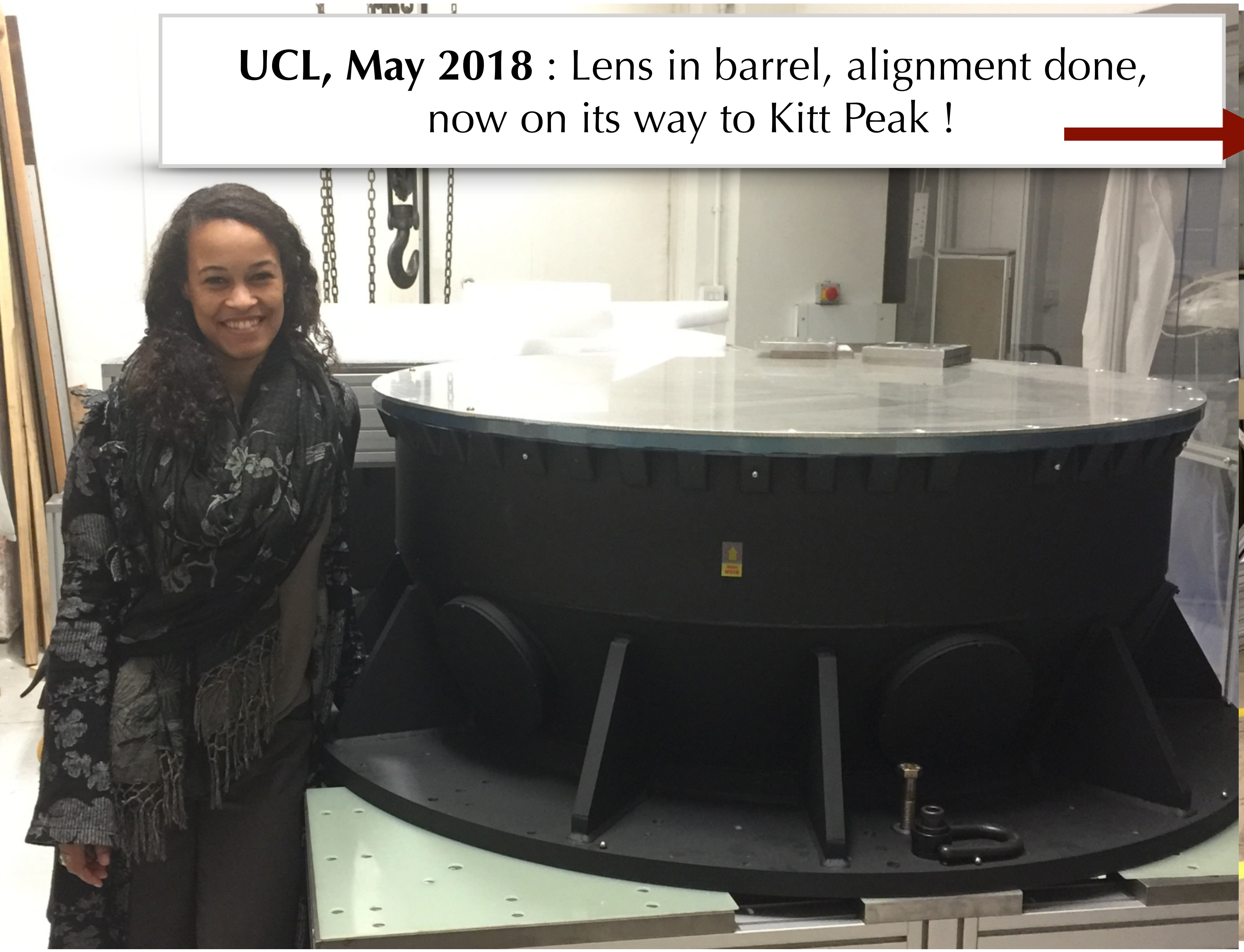
DESI

- 6 lenses, largest ∼1m in diameter

DESI

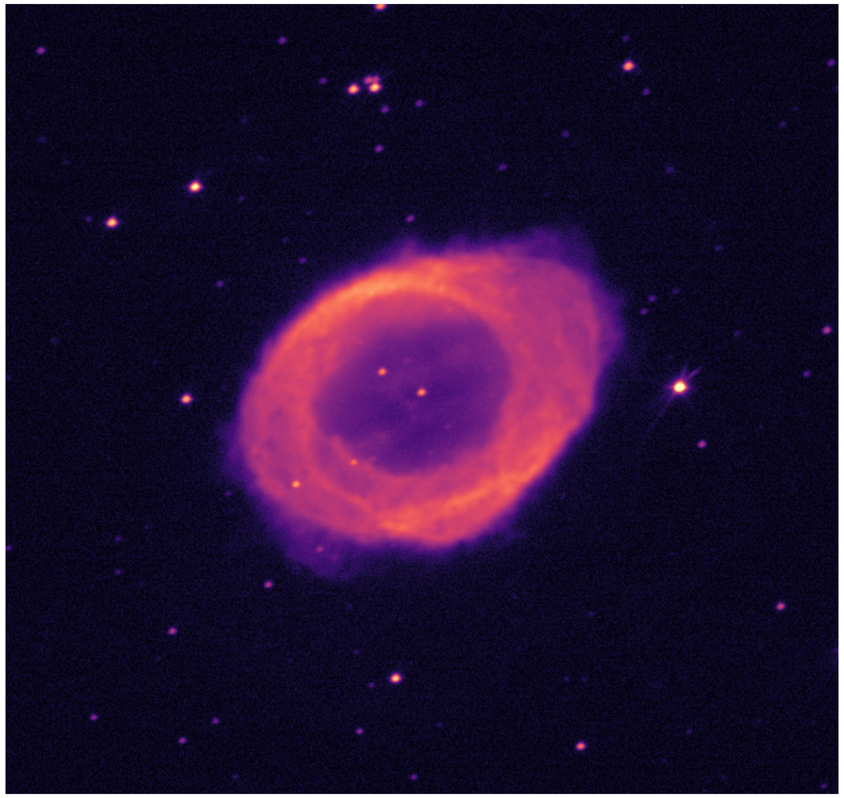
- 6 lenses, largest ~1m in diameter
- assembled in a corrector barrel

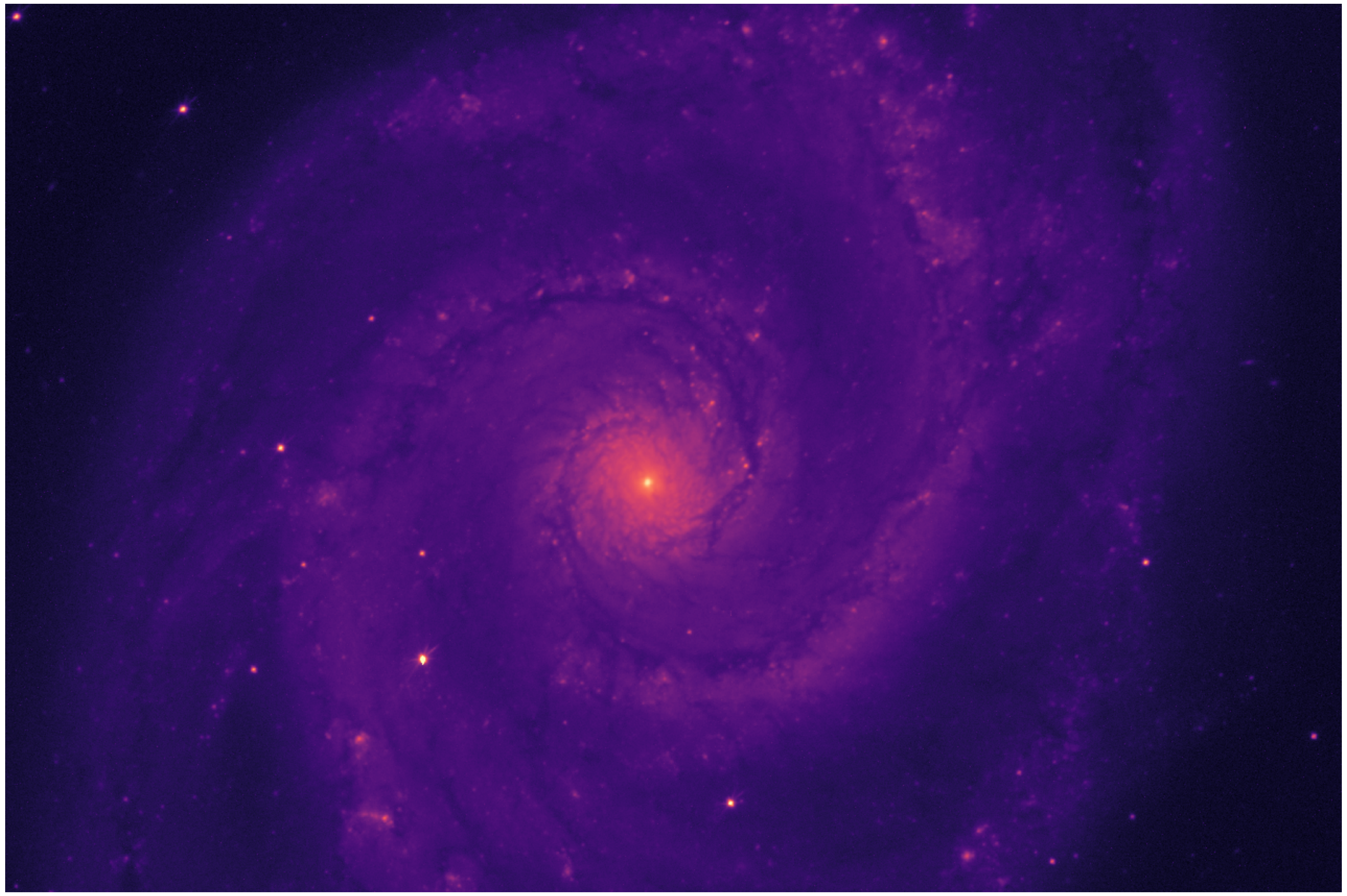
UCL, May 2018 : Lens in barrel, alignment done, now on its way to Kitt Peak !



DESI

- 6 lenses, largest ~1m in diameter
- assembled in a corrector barrel
- First light of corrector images were measured to be 0.7 arcsec
- Ring nebula and whirlpool galaxy:

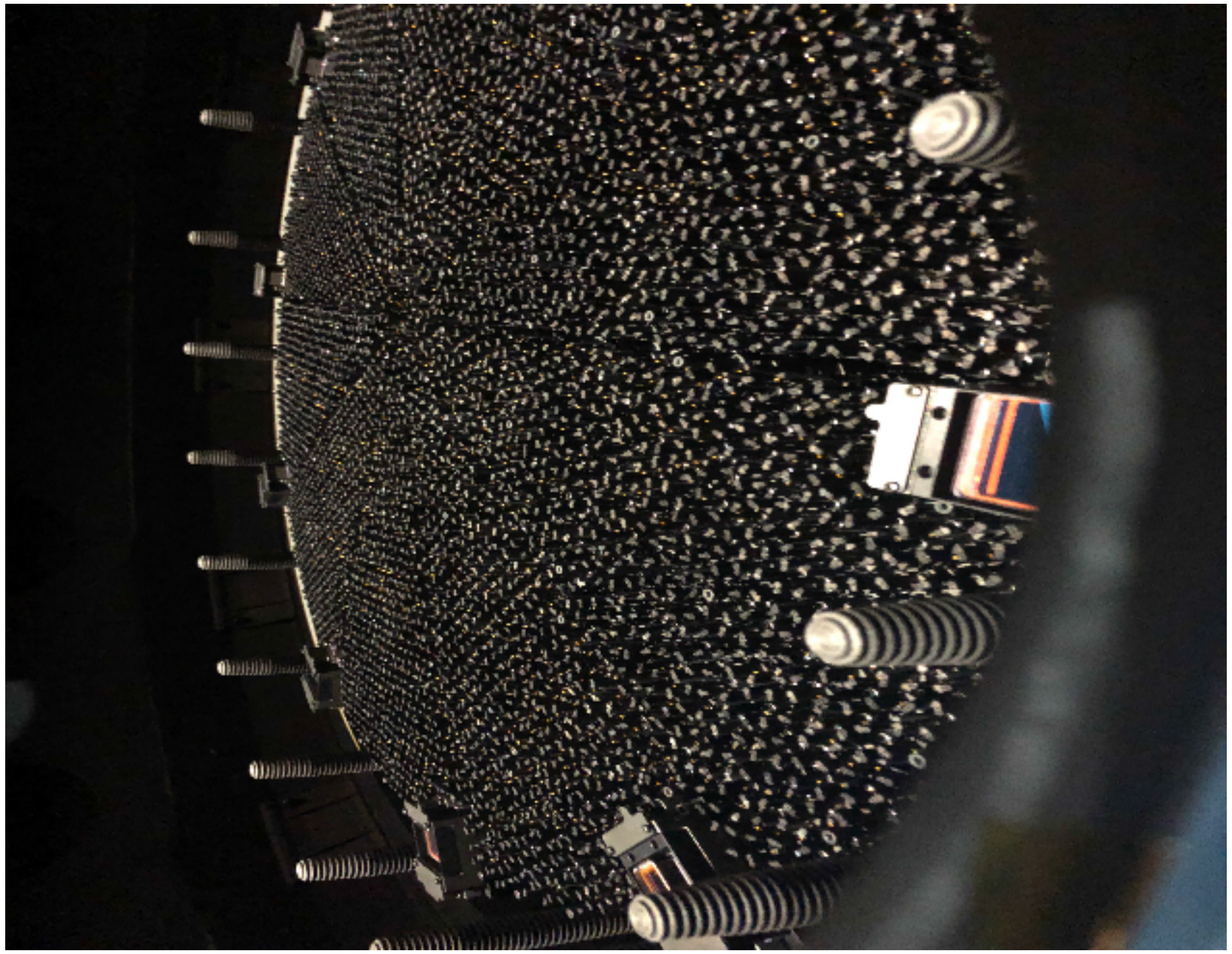


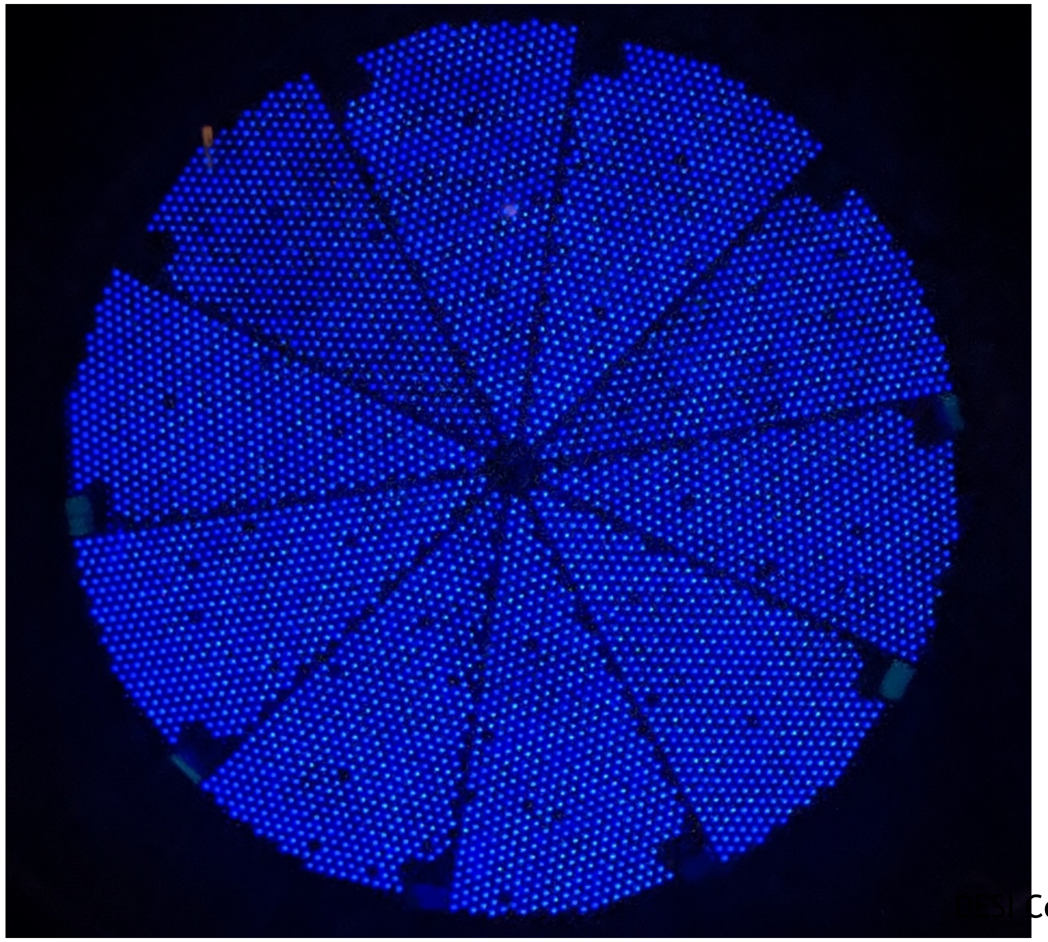


DESI

Installation of the focal plane instrument was completed in August, 2019.

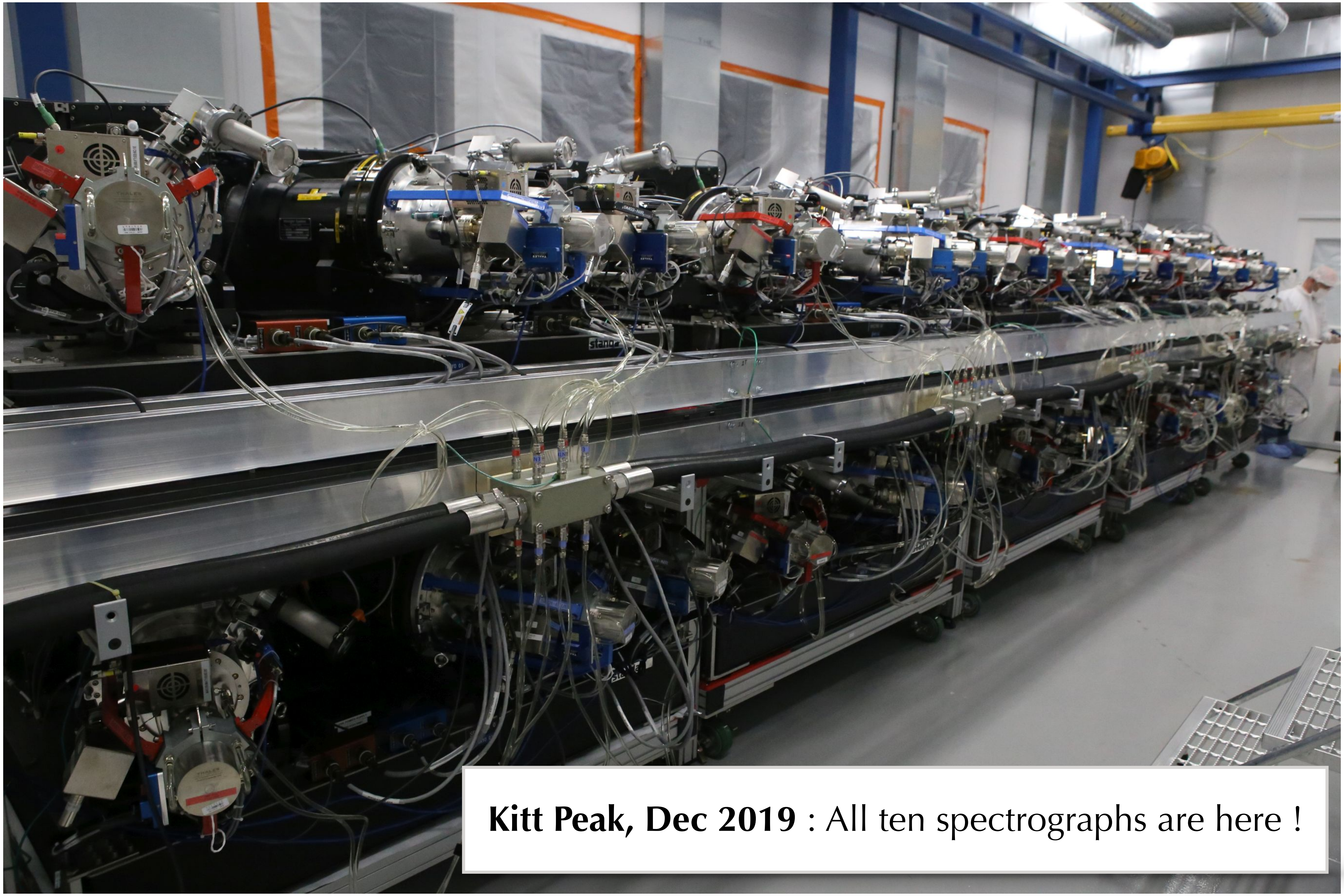
The picture shows the fiber ends of the 5,000 robotic positioners on the focal plane, and back-illuminated.





Collaboration

DESI



DESI Collaboration

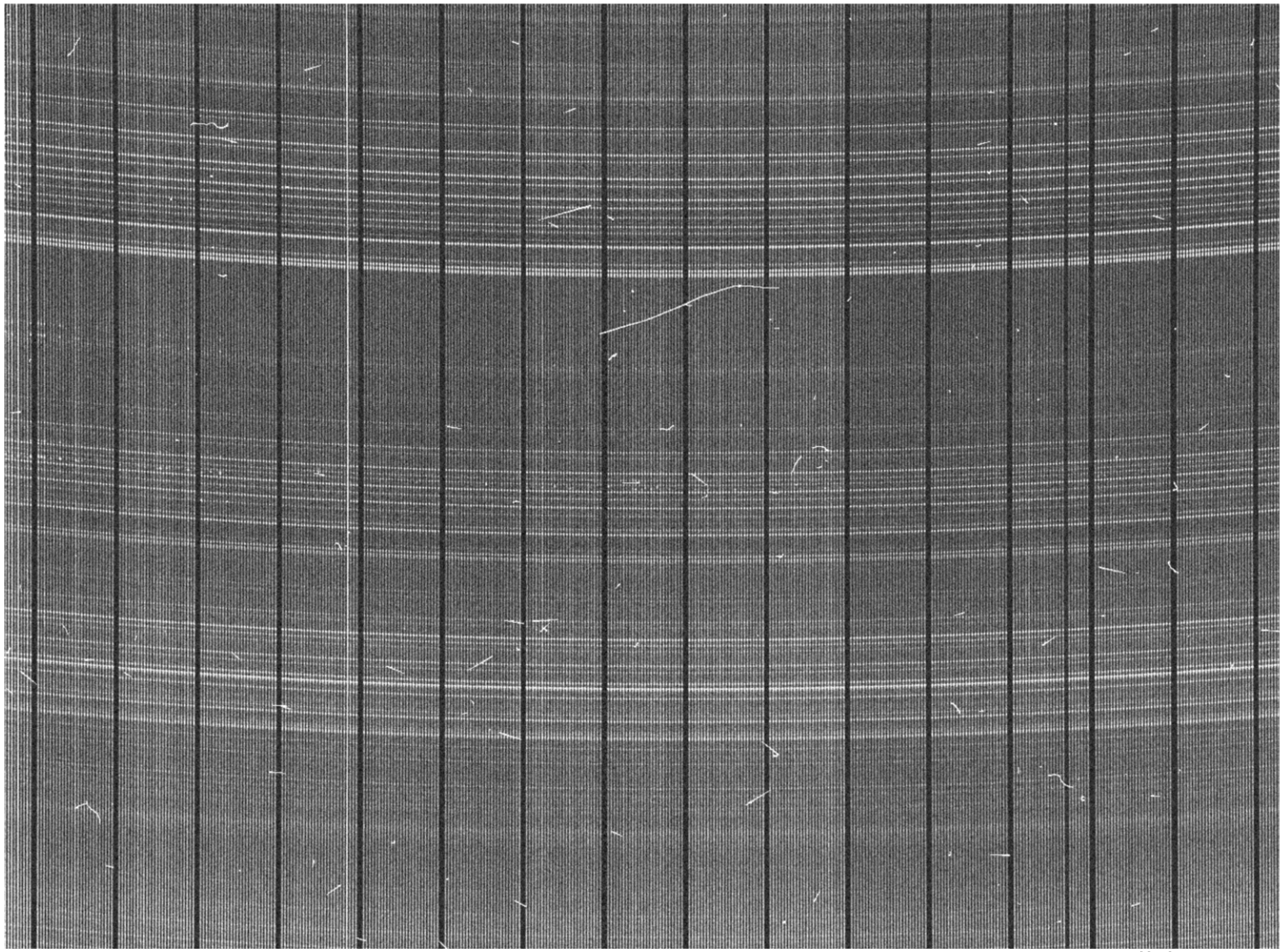
DESI

DESI Collaboration

DESI

- We have 500M pixels within the ten 3-arm spectrographs (30 cryostats)
- Spectroscopic pipeline is working well, and the sky background subtraction is working near statistical limit

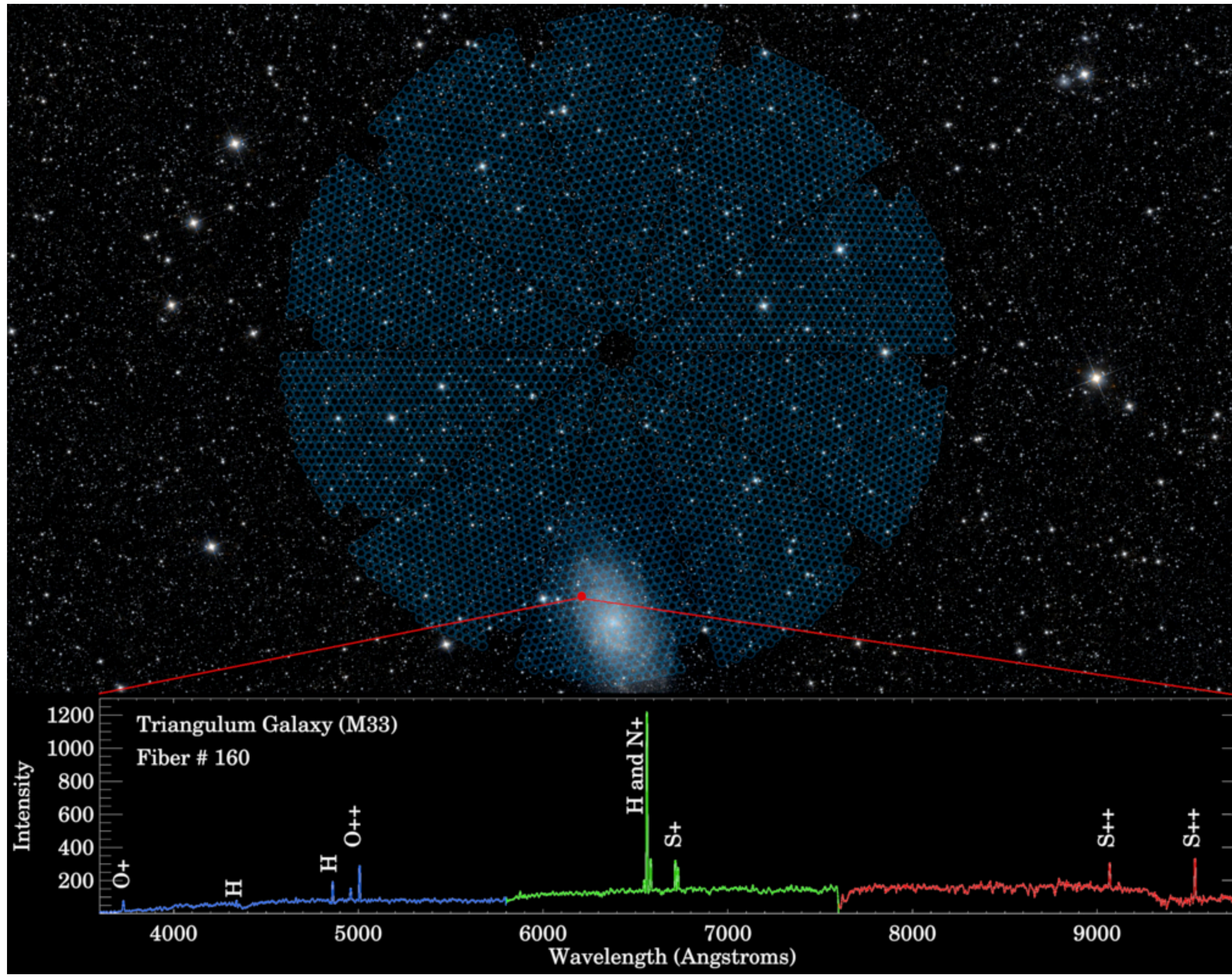
Raw Data of one chip (of 30):



DESI Collaboration

DESI : 1st light

- First Light achieved on Oct 22, 2019, on the first day of the start of commissioning. The spectrum shown was collected by one fiber from a small section of the Triangulum Galaxy. The blue circles represent the sky footprint of the 5000 fiber positioners on the DESI focal plane.



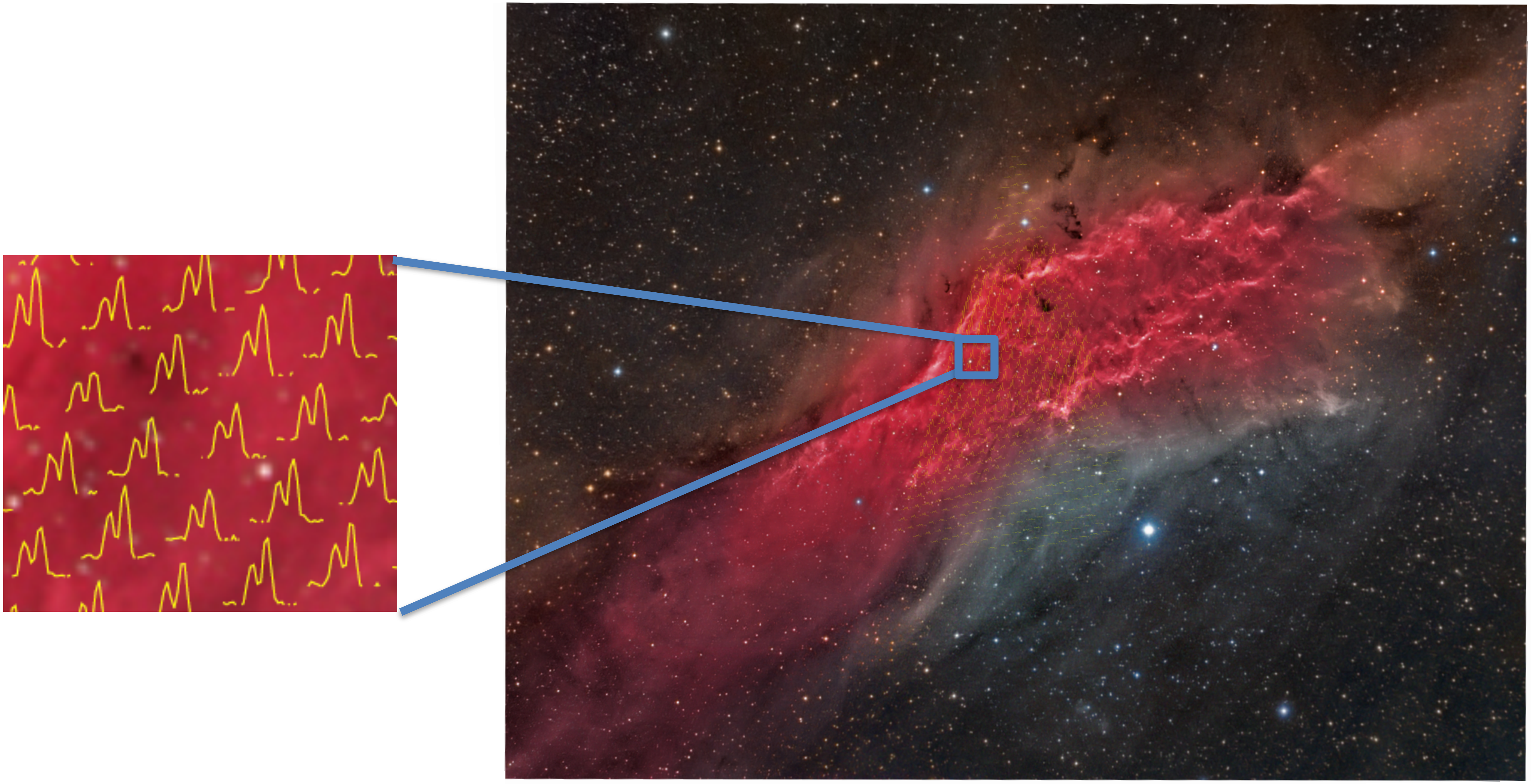
- Commissioning started Oct. 22. Expected to last for 5 months, ending in March 2020

- Measured instrument performance so far surpasses requirements and expectations!

Background: Legacy Surveys image viewer

DESI : 1st light

The OII emission-line doublet is a “signature” line that we will be using for most of our DESI redshift mapping



Background: Antonis Farmakopoulos

DESI : 1st light

DESI : 1st light

BOSS v. DESI

The Dark Energy Spectroscopic Instrument : Mayall (4 m) at Kitt Peak, AZ

- Mirror area **x 2.4**
- Number of fibers **x 5**
- Telescope throughput **x 1.6**

- Resolution **x 2.3** at 7000 Å (for ELGs OII doublet detection, but higher S/N for all lines)

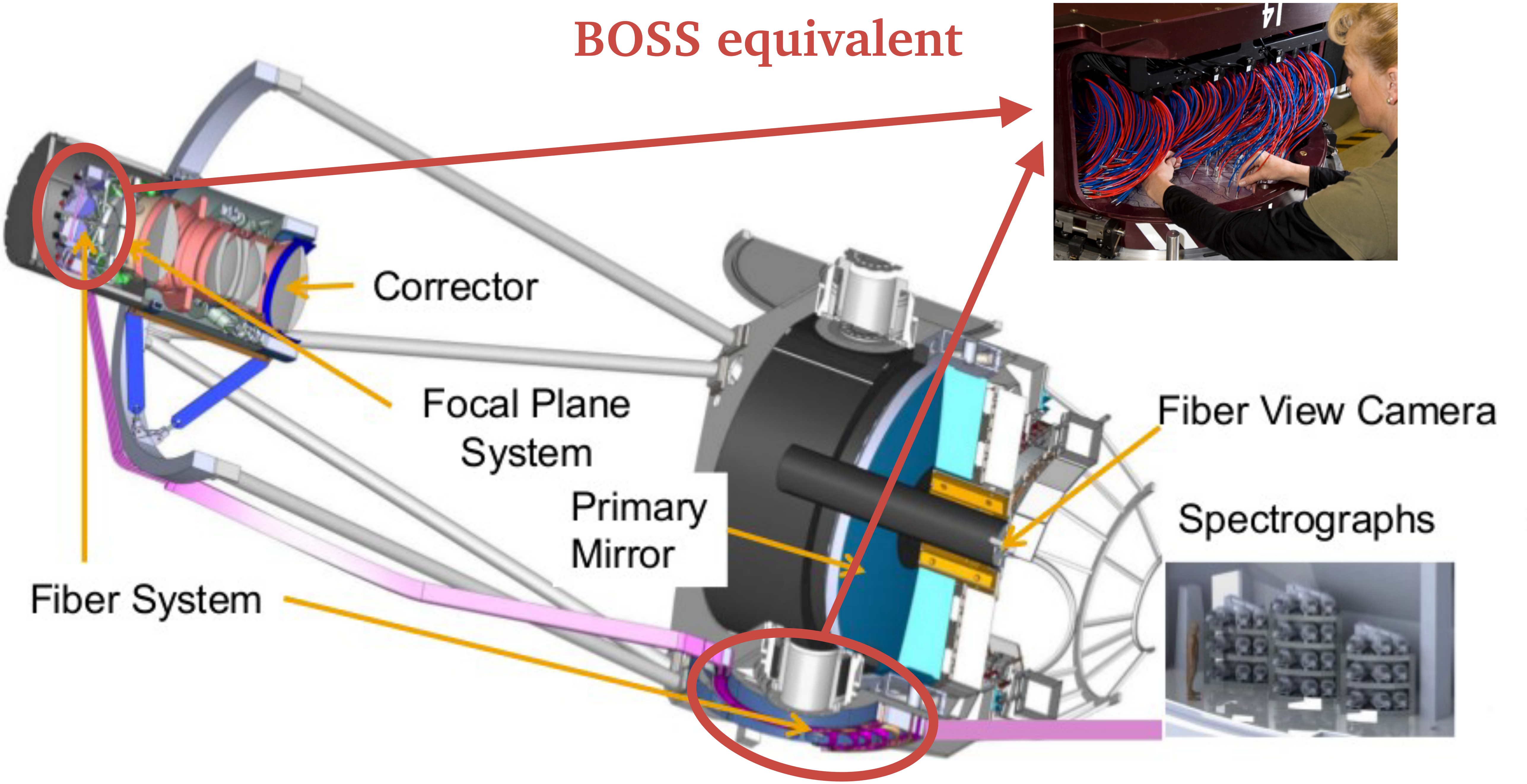
- Fiber positioners instead of drilled plates : more flexibility/science
- Stable spectrographs : smaller sky systematic residuals
- Atmospheric Dispersion Compensator : smaller fiber aperture losses

- DESI can an detect an emission line **3 times fainter** than BOSS in the same exposure time
- …or detect the same galaxy **9 times faster**

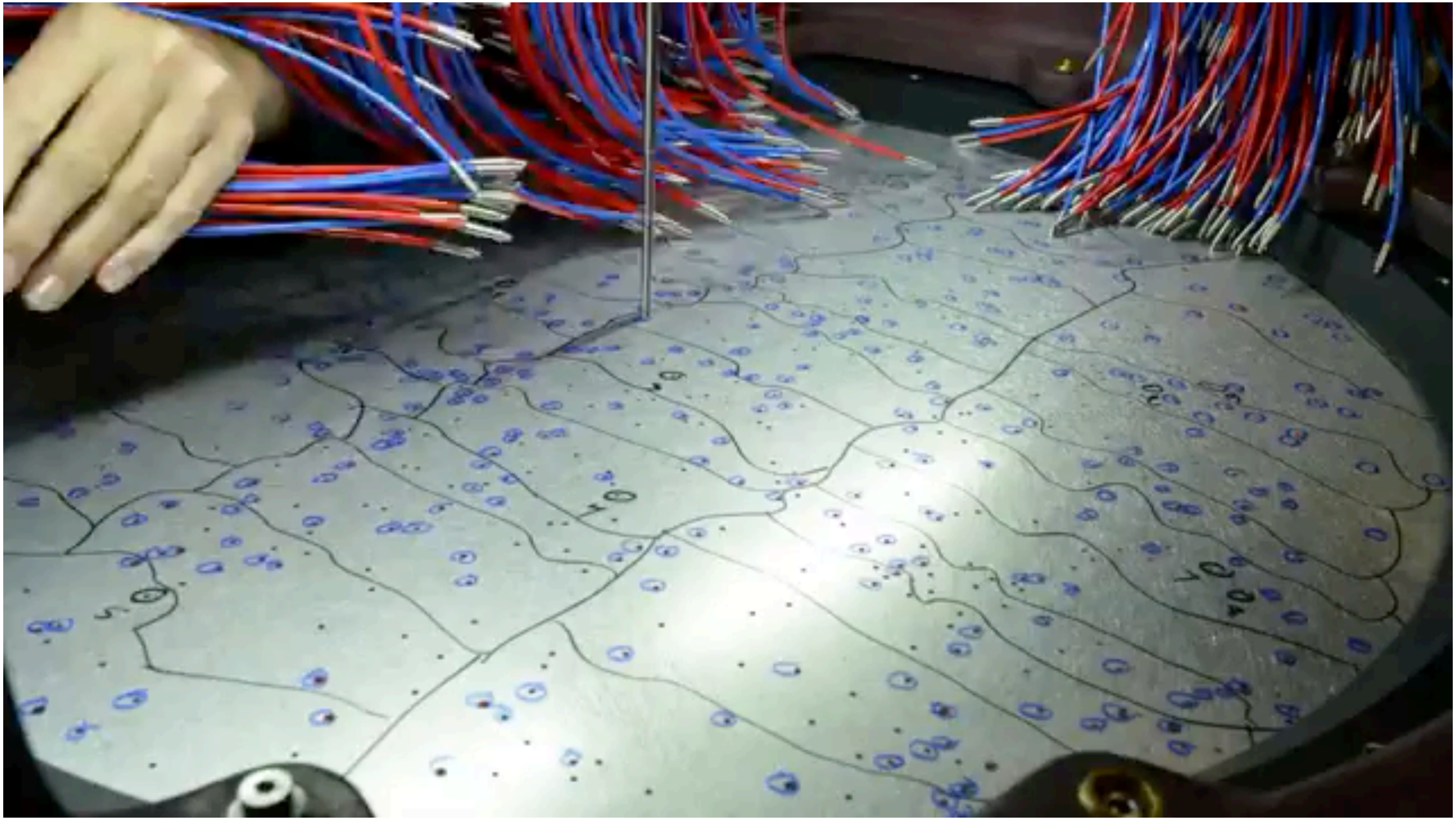
- and so **DESI can measure redshifts 45 times faster than BOSS for ELGs and 20 times faster for QSOs** (no resolution gain)

Thank you Julien Guy for this on point comparison !

Stage III — BOSS v. Stage IV — DESI



BOSS/eBOSS Plate: 1000 optical fibers (2009-2018)



Credit: SDSS-III / Apache Point Observatory

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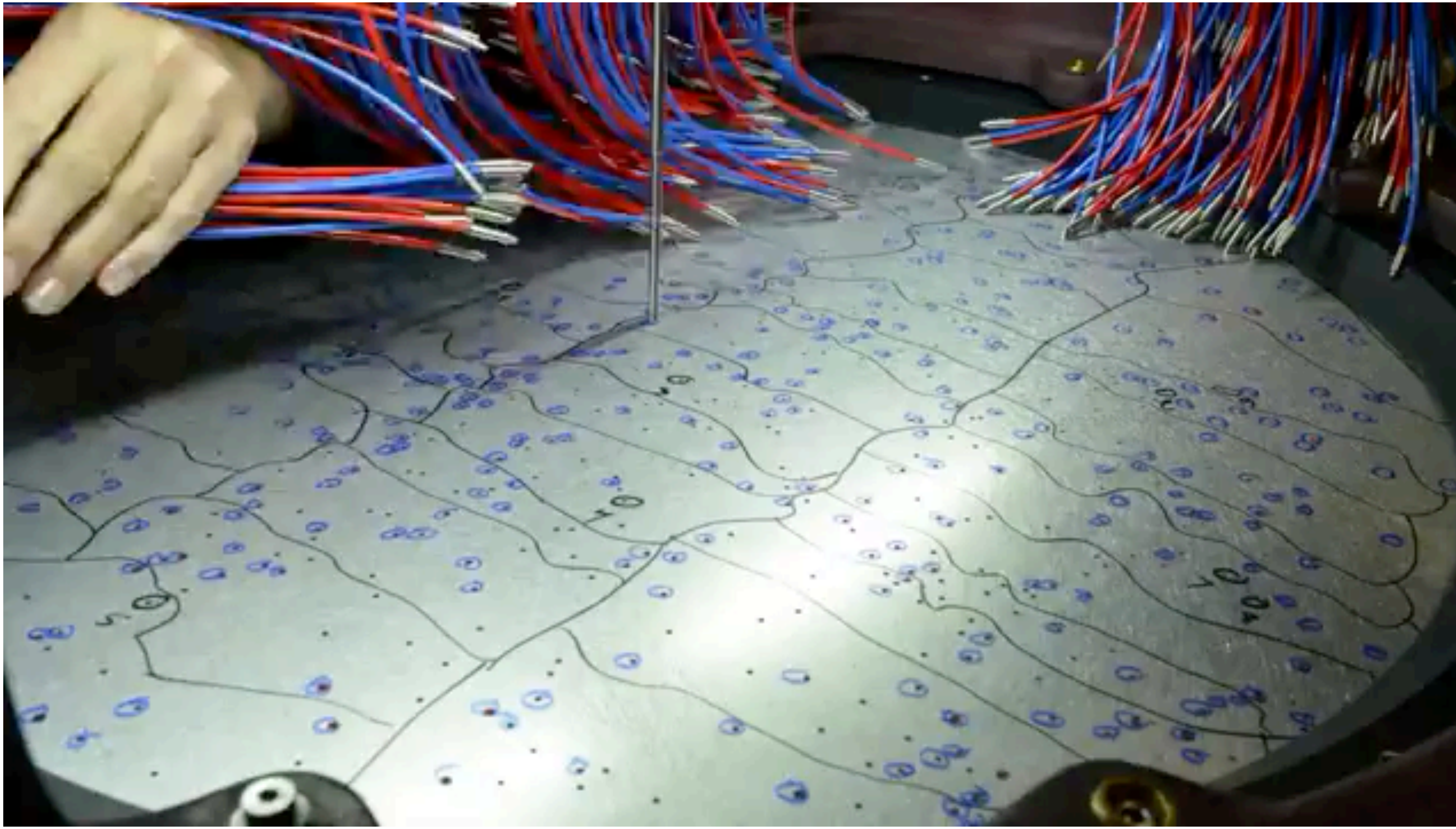
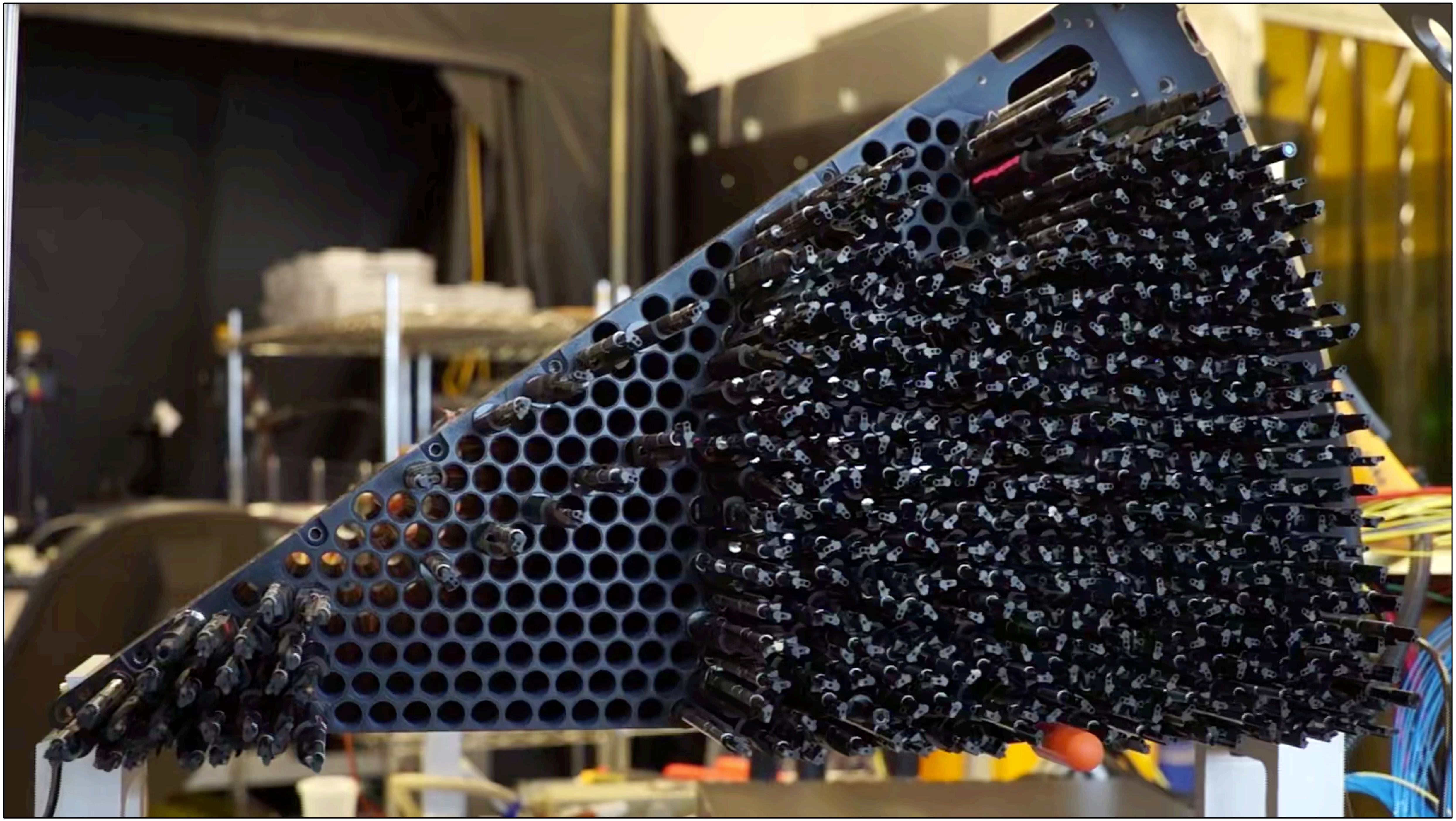


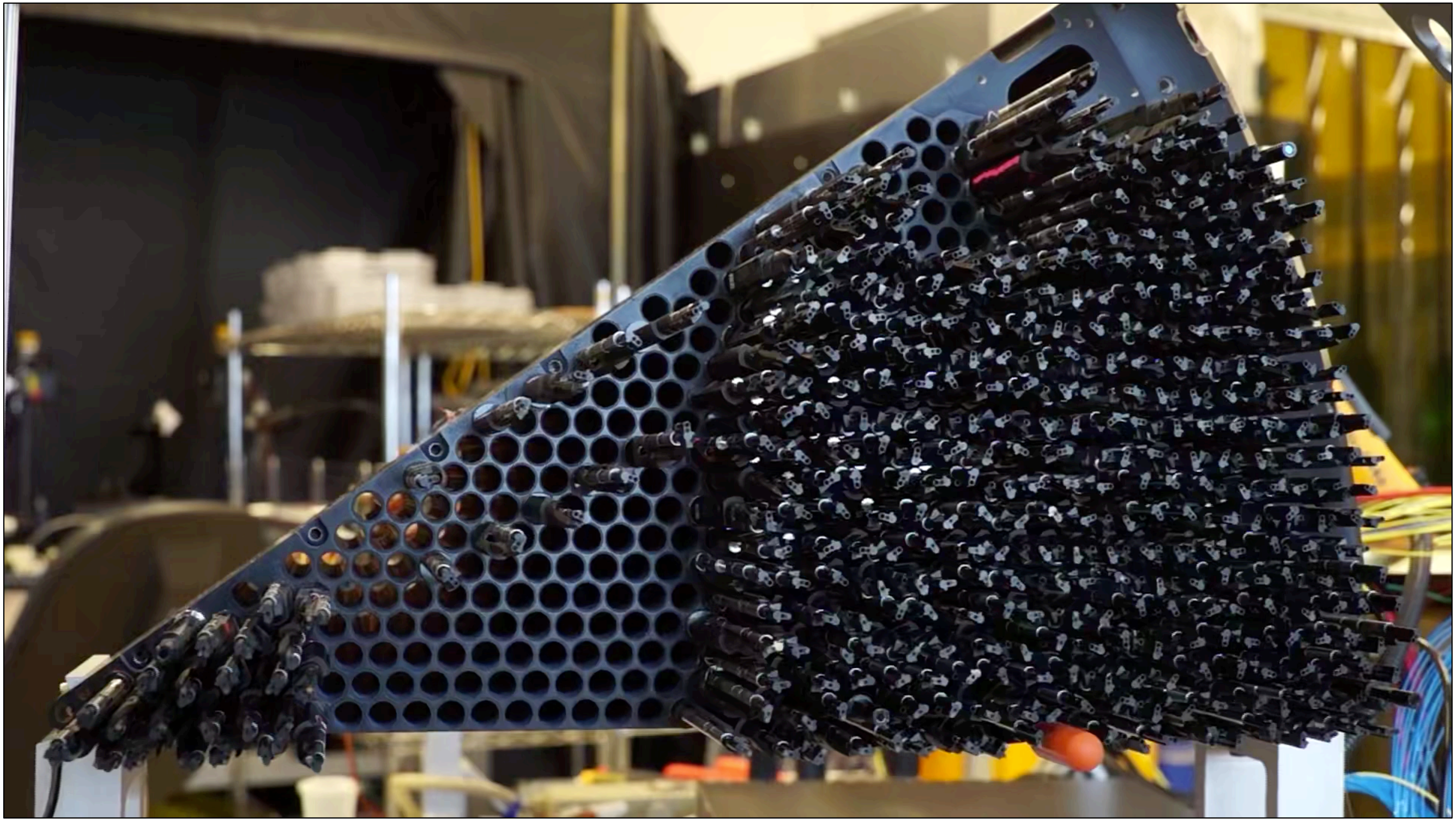
Credit: SDSS-III / Apache Point Observatory

DESI Petal with Fiber Positioners: 500 fibers x 10 petals (now !)



Credit: DESI / LBL

DESI Petal with Fiber Positioners: 500 fibers x 10 petals (now !)

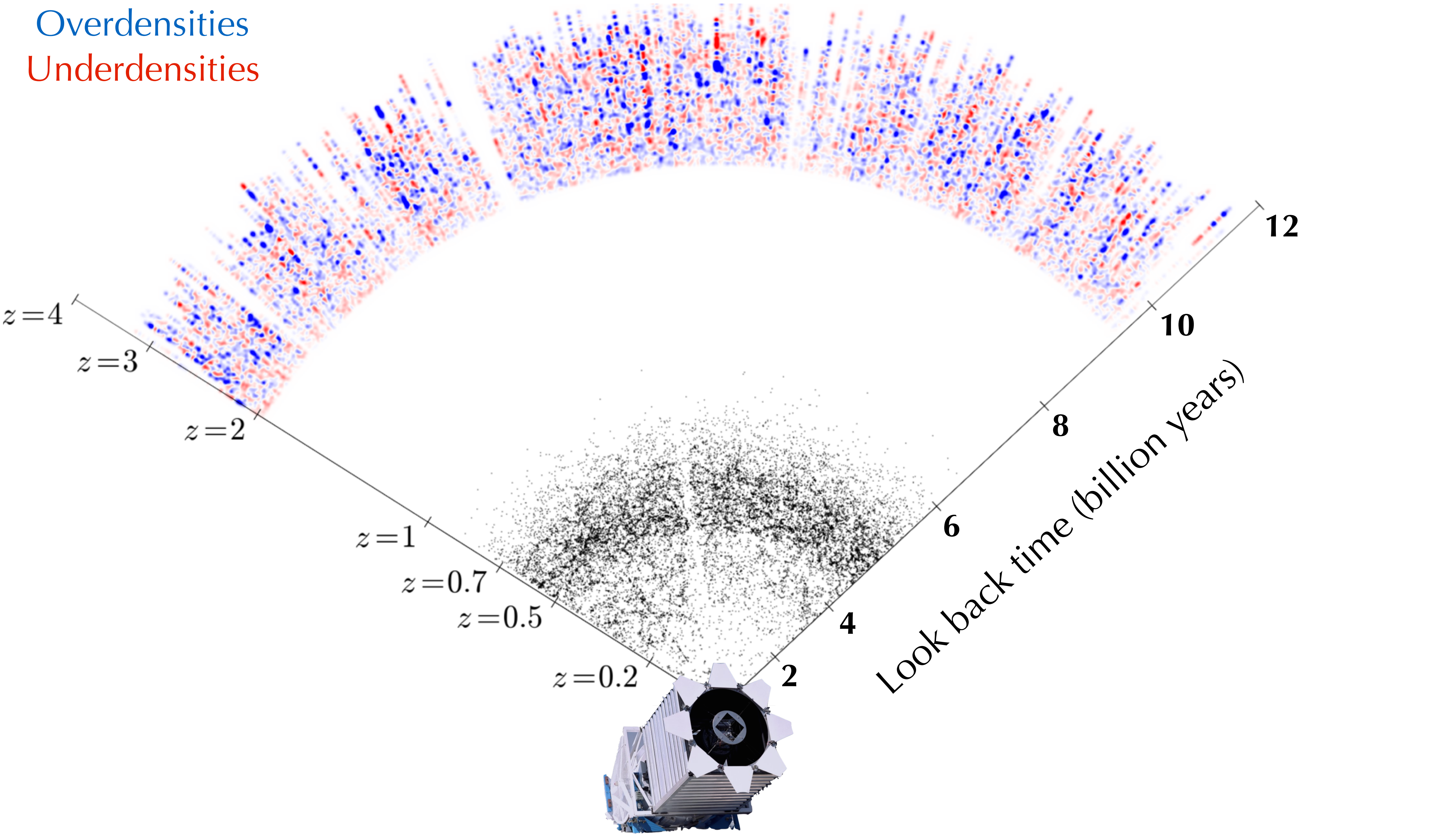


Credit: DESI / LBL

Mapping the Universe with SDSS-III

Early 2010s

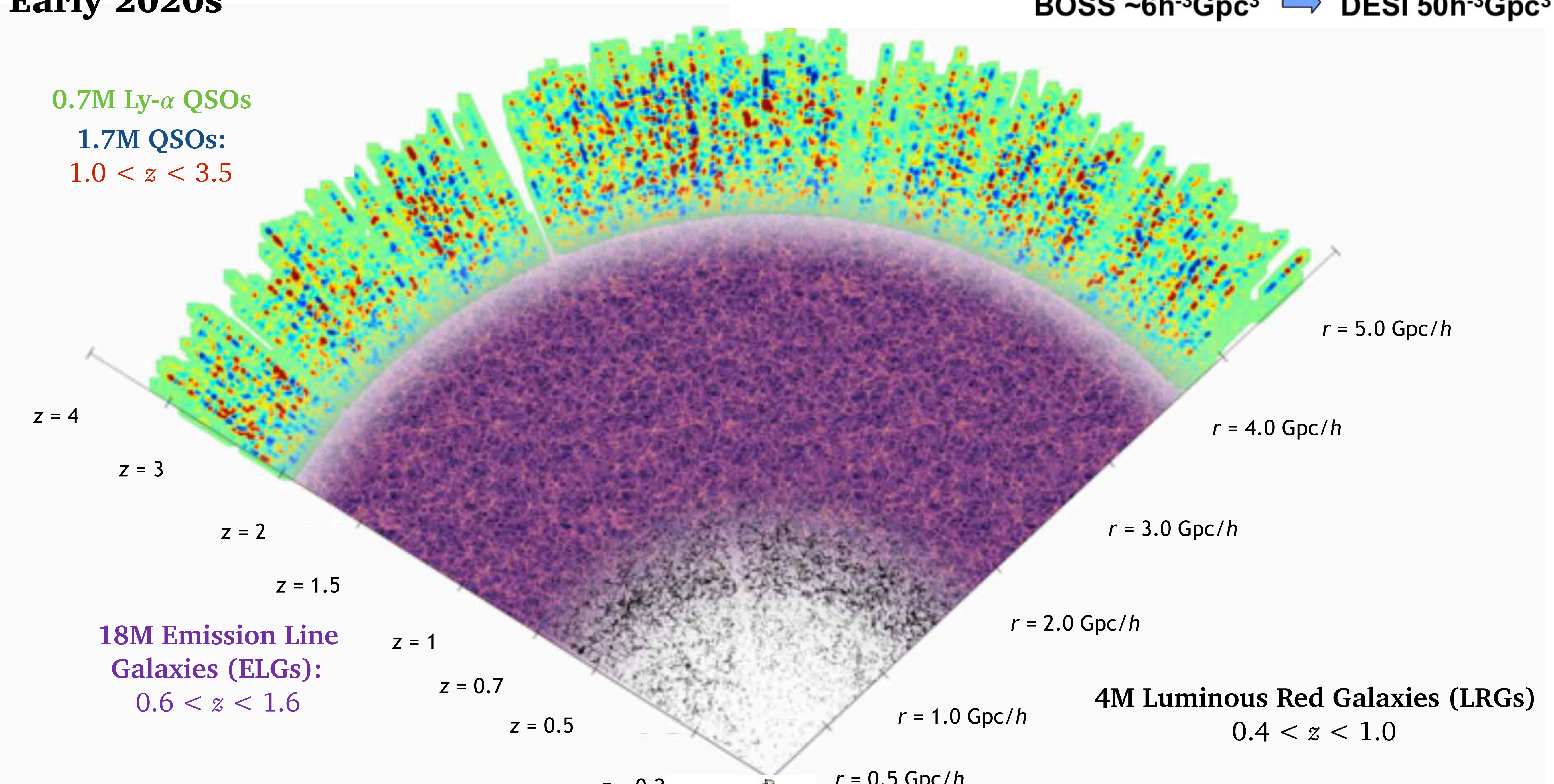
SDSS ~2h^{-3}Gpc^3 ➡ BOSS ~6h^{-3}Gpc^3

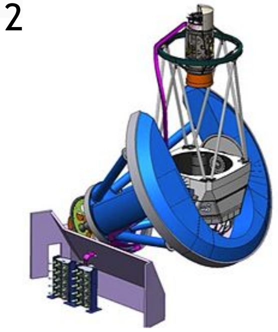


DESI Survey: 35M redshifts in 5 years

Early 2020s

BOSS ~6h^{-3}Gpc^3 ➡ DESI 50h^{-3}Gpc^3





Milky Way Survey: ~10M stars

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Outline

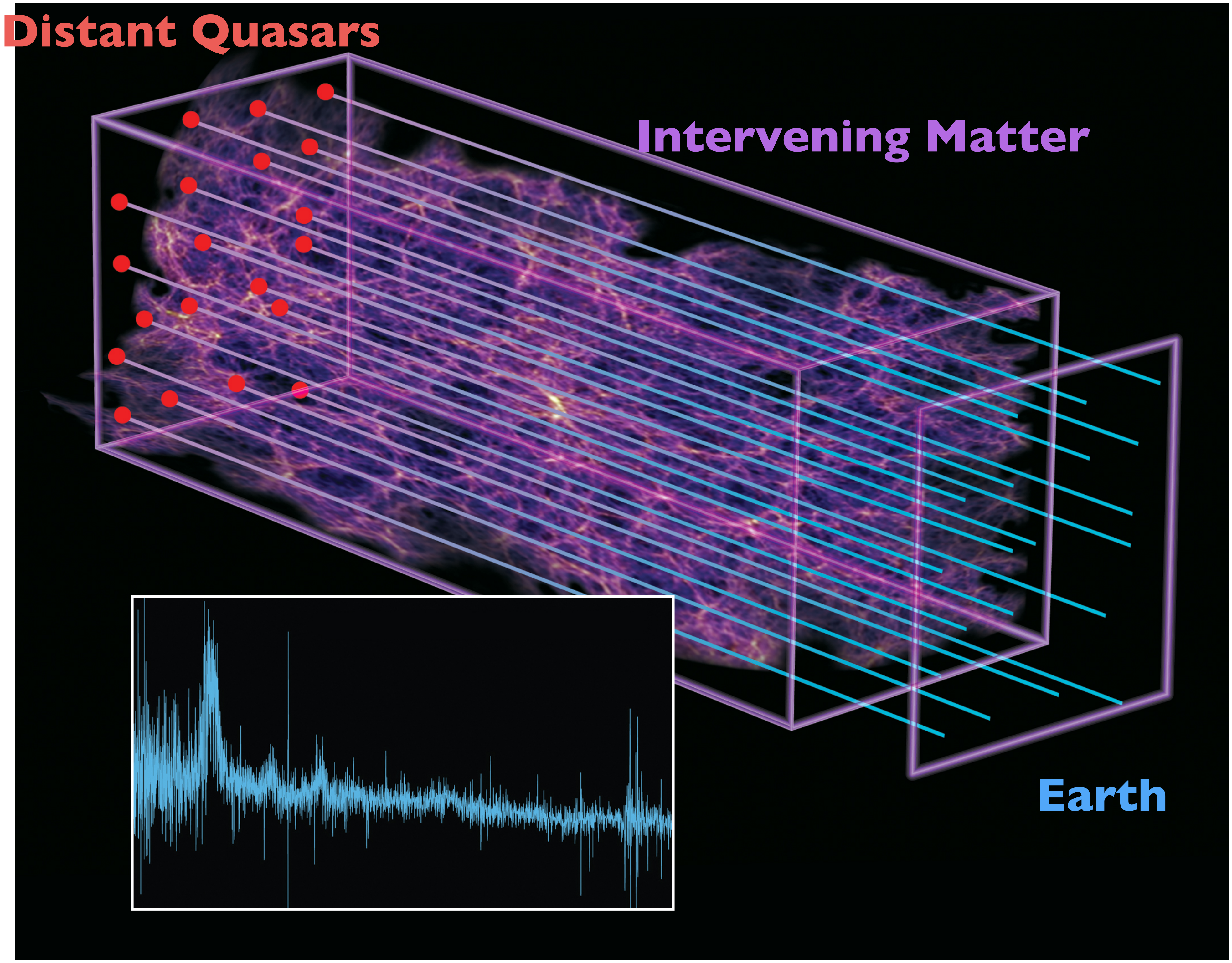
- **Intergalactic Medium - based Cosmology :**
    - **What is it ?**
- The SDSS-III Baryon Oscillation Spectroscopic Survey
    - Main cosmological results
    - Corrections
    - Adjacent science
- The Dark Energy Spectroscopic Instrument
    - Forecasts for DESI Lyα
    - Opportunities & Challenges

Quasars

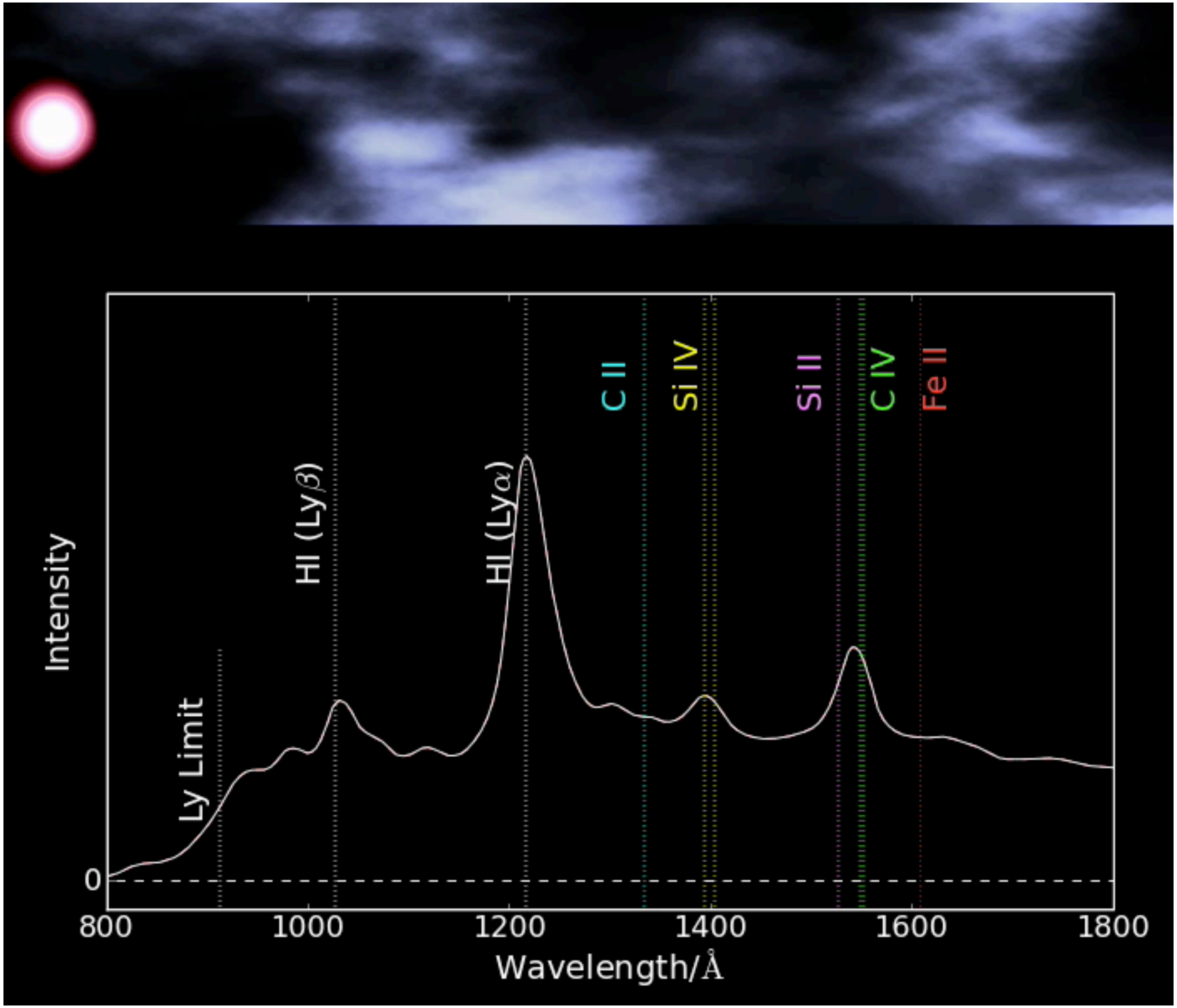
- Brightest objects in the Universe powered by accretion disk of a SMBH
- Emit across the EM spectrum and can be observed in radio, IR, visible, UV and X-ray
- Reach maximum luminosity in UV at 1216 Å (the Lyα e- transition of HI)
- Can be found on a broad range of distances: $0.1 < z < 7$
- More abundant in the earlier Universe than today ; higher density of quasars at redshift $z = 2 — 3$
- Provide an uncalibrated broadband backlight

… what does that mean ?

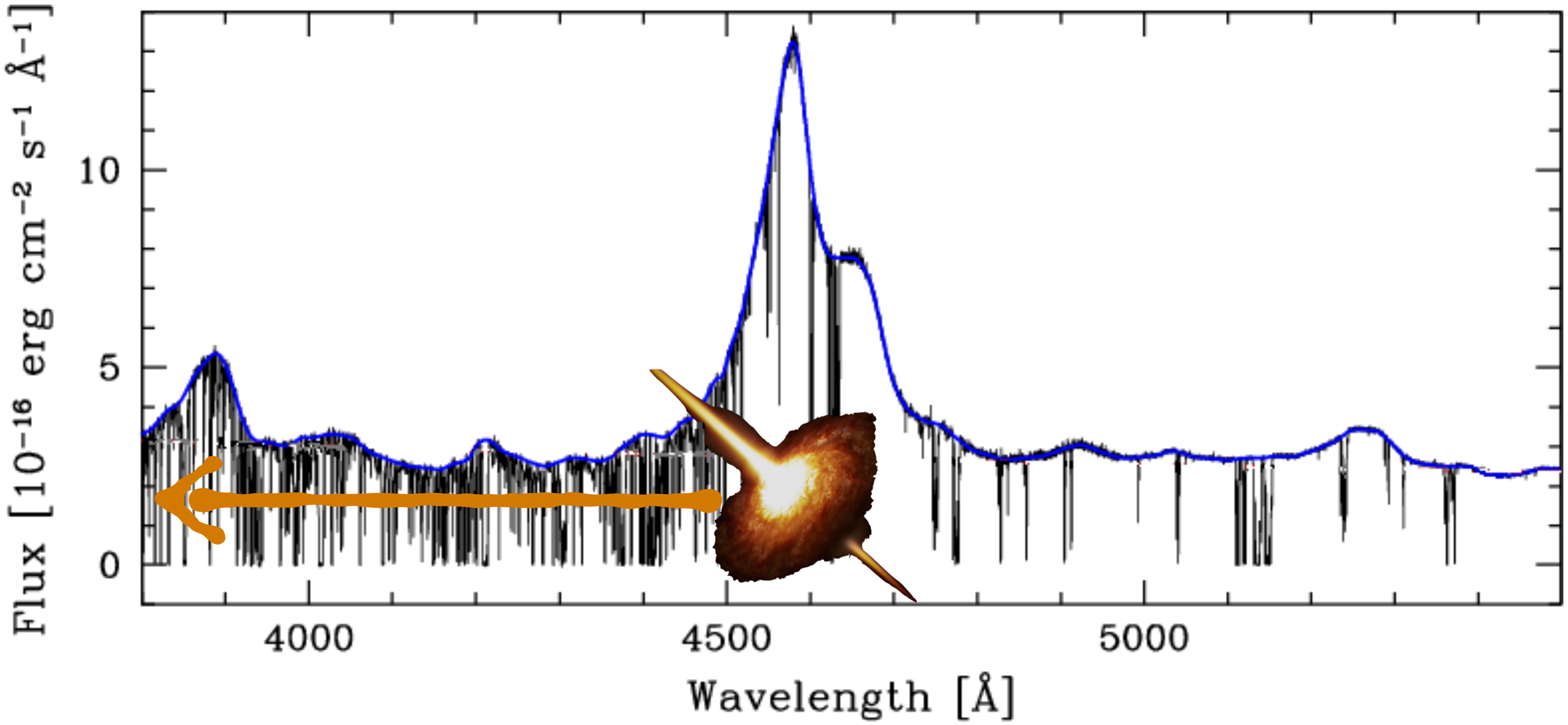
Quasars as a backlight



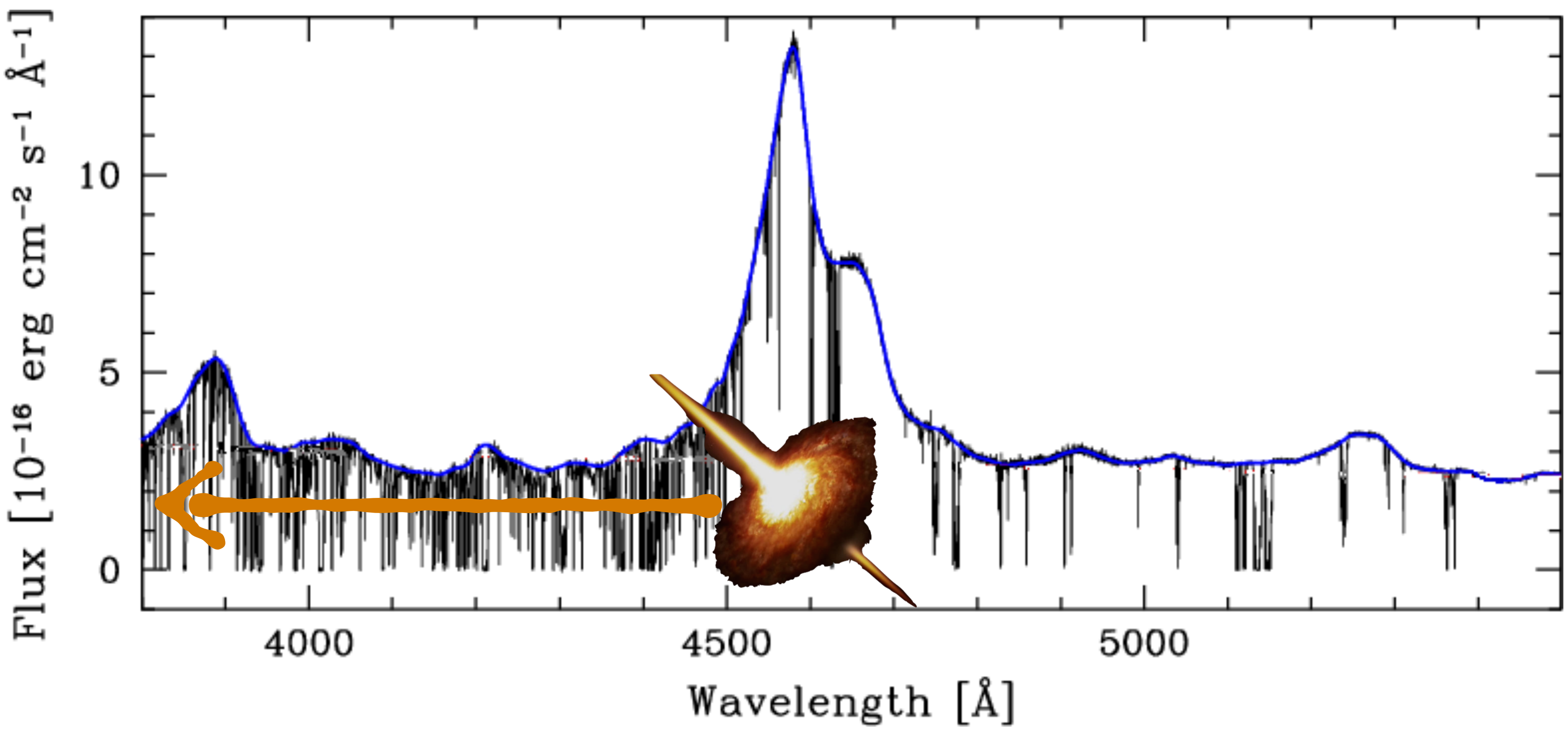
Quasars as a backlight



Observed Flux to Cosmological Fluctuations



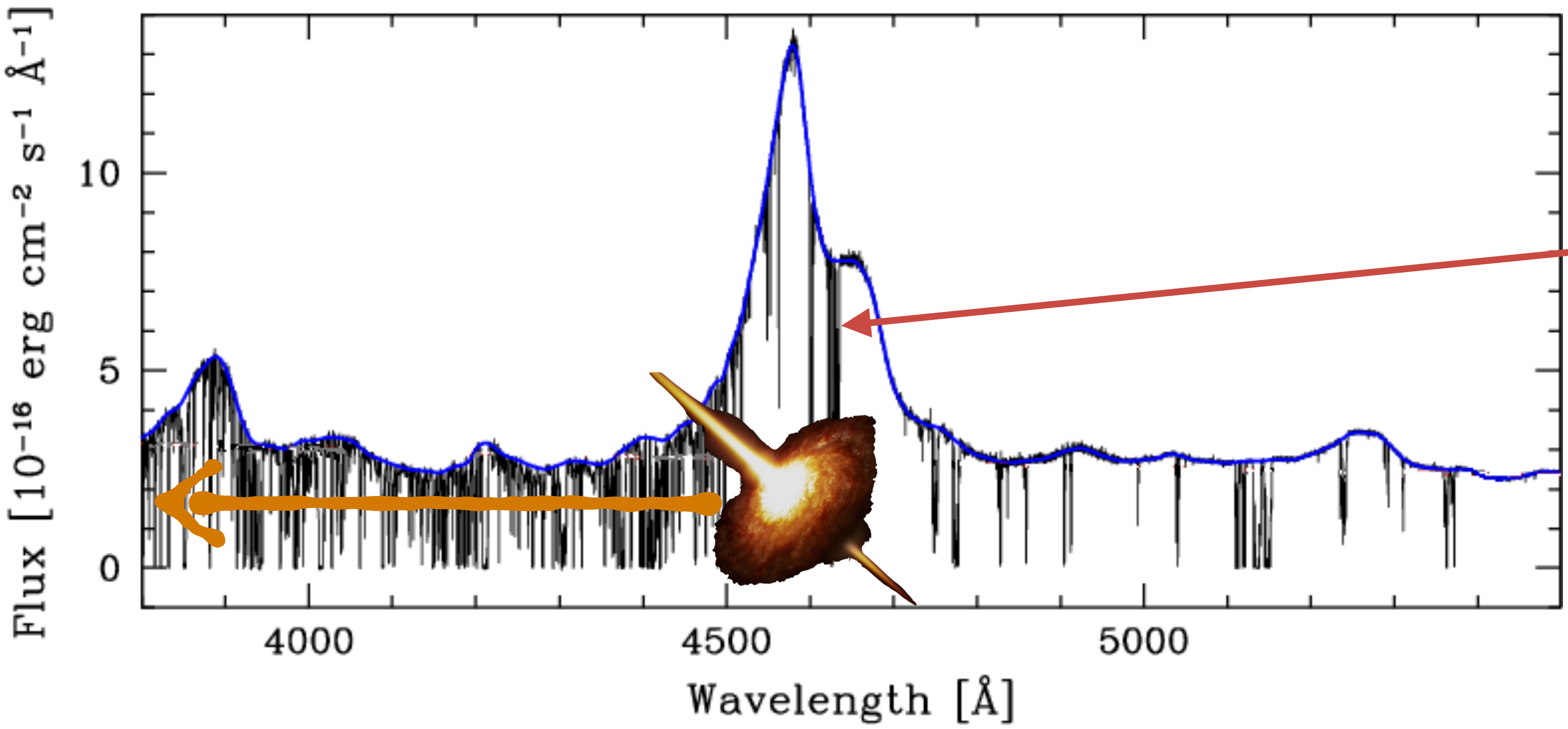
Observed Flux to Cosmological Fluctuations



Transmitted flux fraction

$$F(\lambda) = \frac{f(\lambda)}{C(\lambda)}$$

Observed Flux to Cosmological Fluctuations



Transmitted flux fraction

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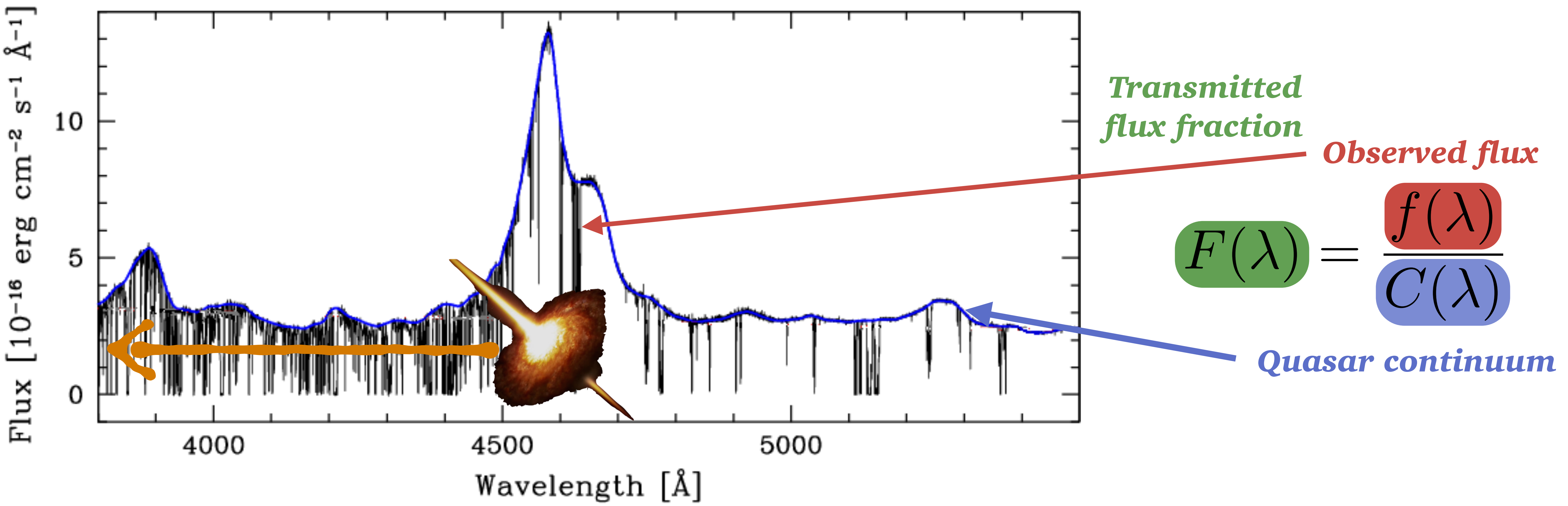
Observed Flux to Cosmological Fluctuations



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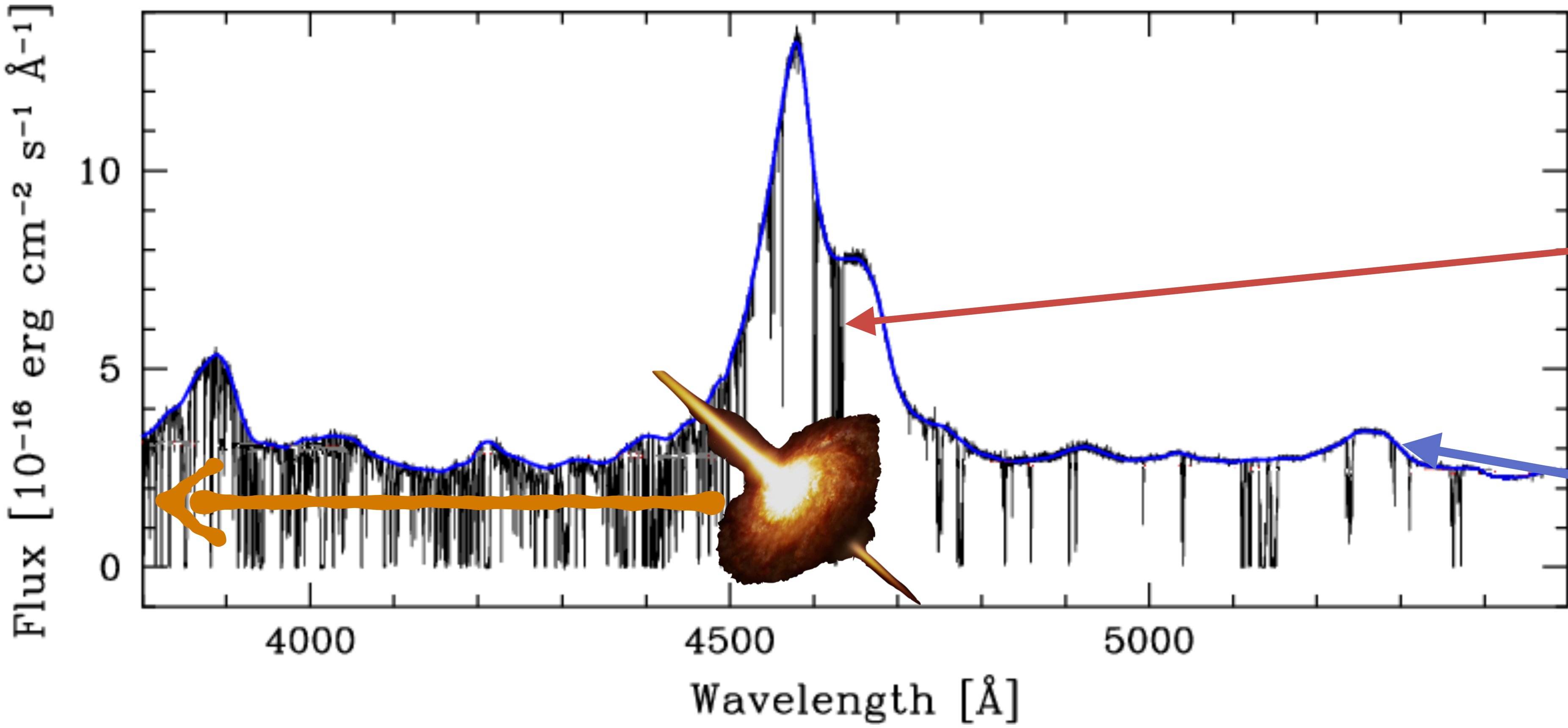
Observed Flux to Cosmological Fluctuations



Transmitted flux fraction

Observed flux

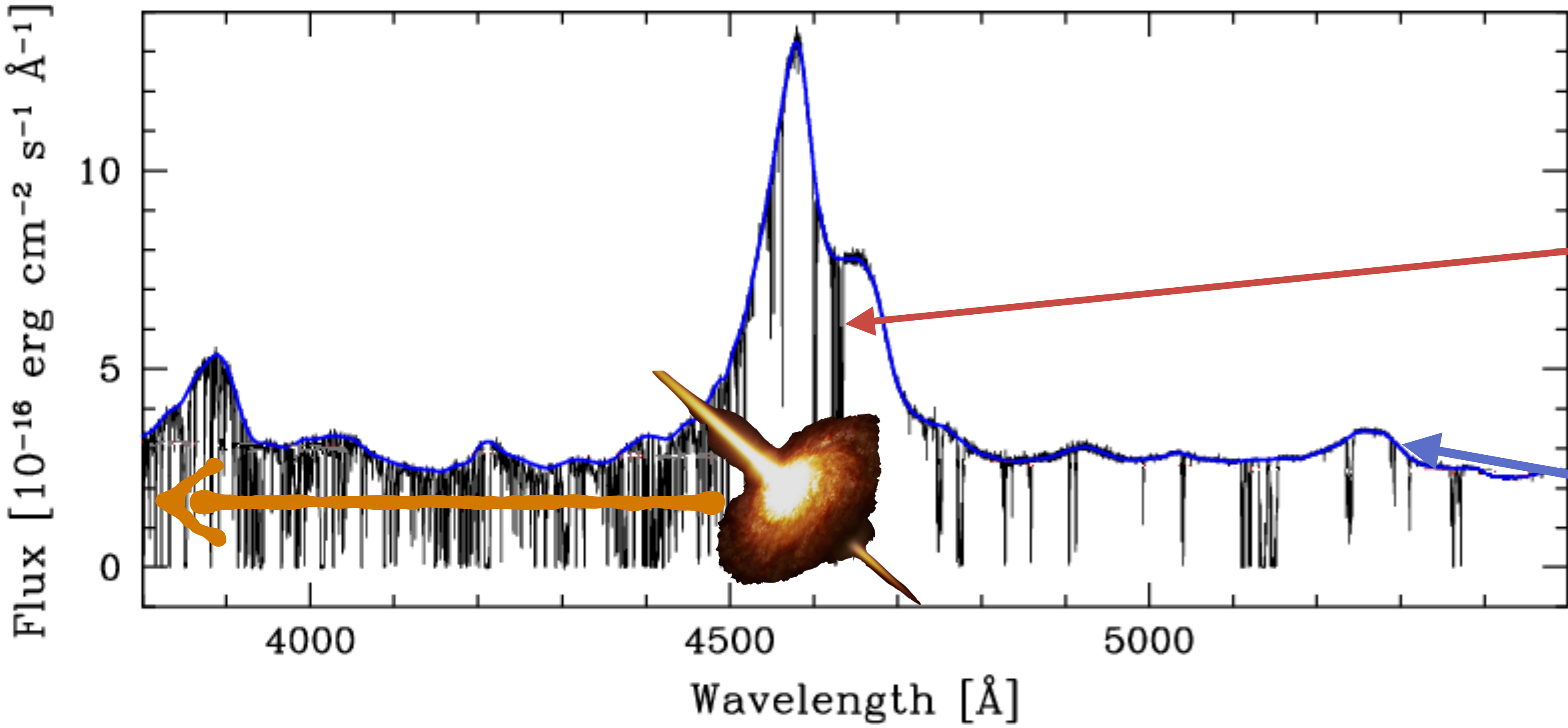
$$F(\lambda) = \frac{f(\lambda)}{C(\lambda)}$$

Quasar continuum

Observed Wavelength

$$\lambda = \lambda_{\alpha,c}(1 + z_{\alpha,c})$$

Observed Flux to Cosmological Fluctuations



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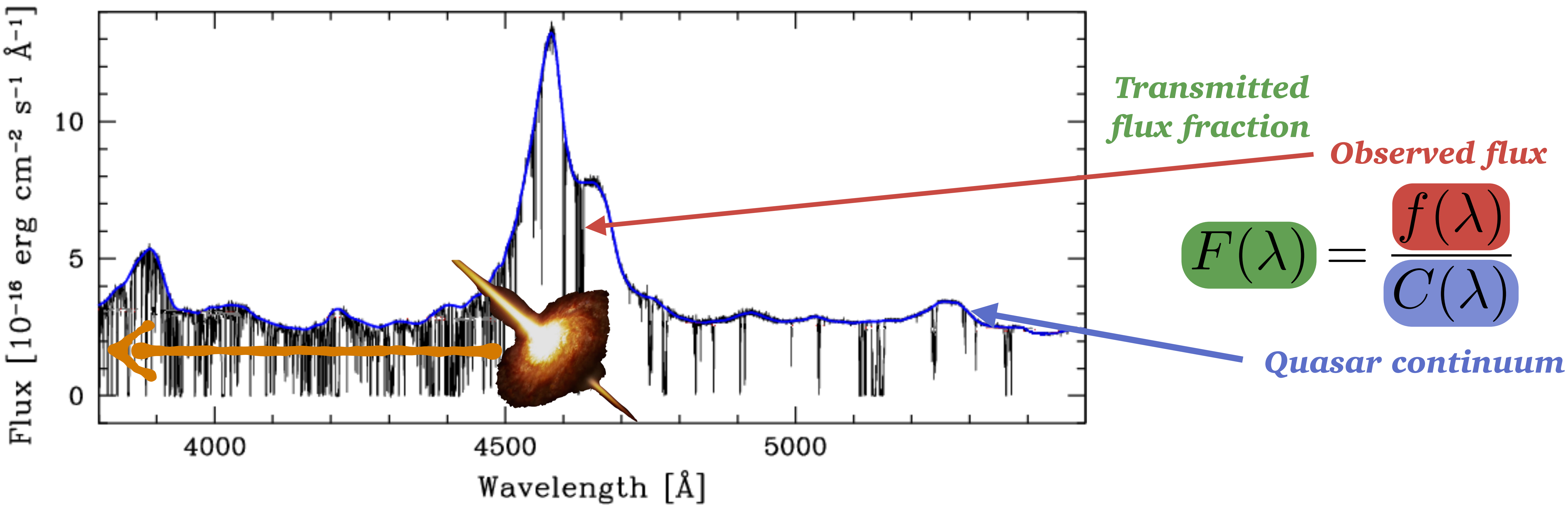
$$\lambda = \lambda_{\alpha,c}(1 + z_{\alpha,c})$$

Lyman Alpha wavelength : 1216 Å

Triply ionized Carbon wavelength : 1550 Å

Observed Flux to Cosmological Fluctuations



$$F(\lambda) = \frac{f(\lambda)}{C(\lambda)}$$

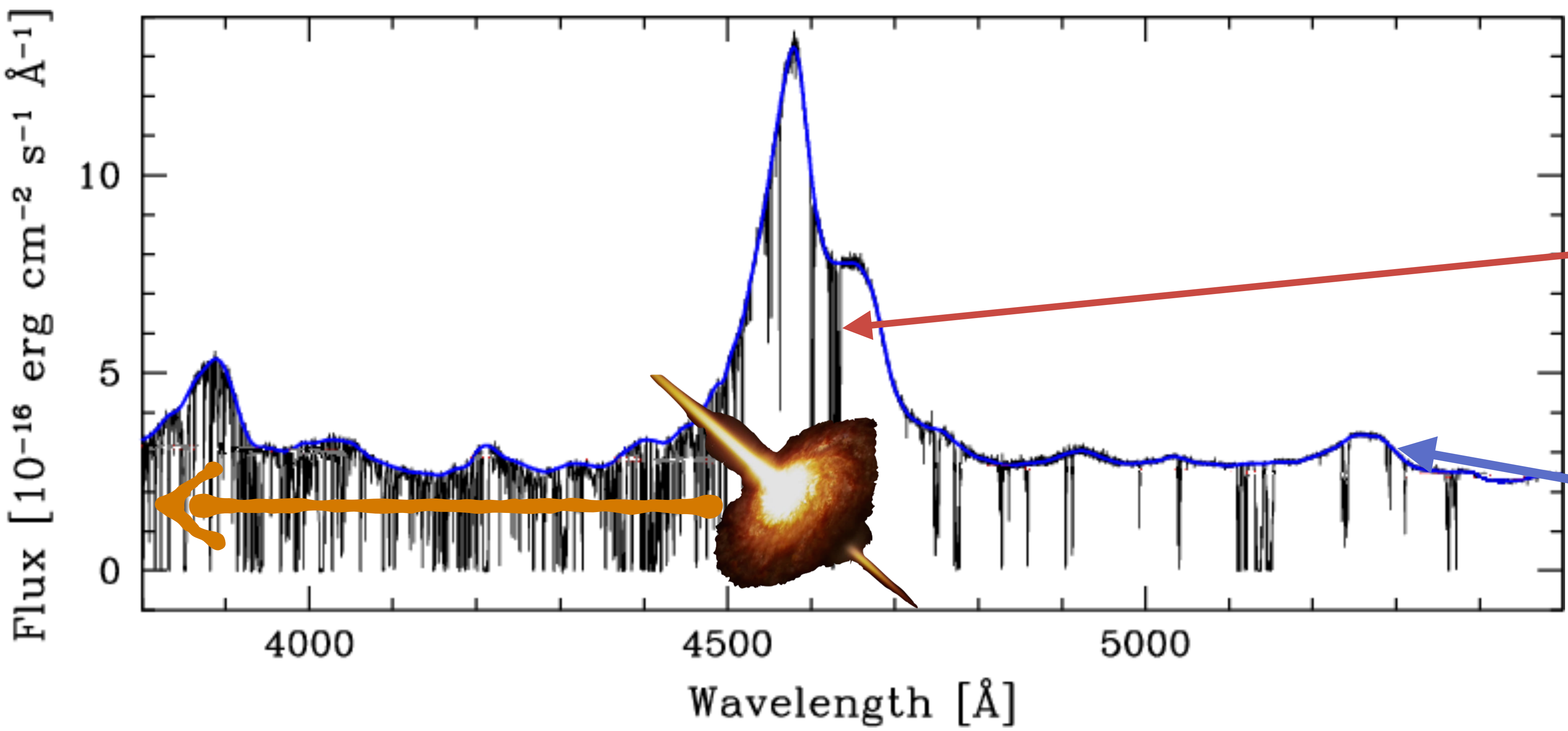
Observed Wavelength Absorption Redshift

$$\lambda = \lambda_{\alpha,c}(1 + z_{\alpha,c})$$

Lyman Alpha wavelength : 1216 Å

Triply ionized Carbon wavelength : 1550 Å

Observed Flux to Cosmological Fluctuations



Transmitted flux fraction

Observed flux

$$F(\lambda) = \frac{f(\lambda)}{C(\lambda)}$$

Quasar continuum

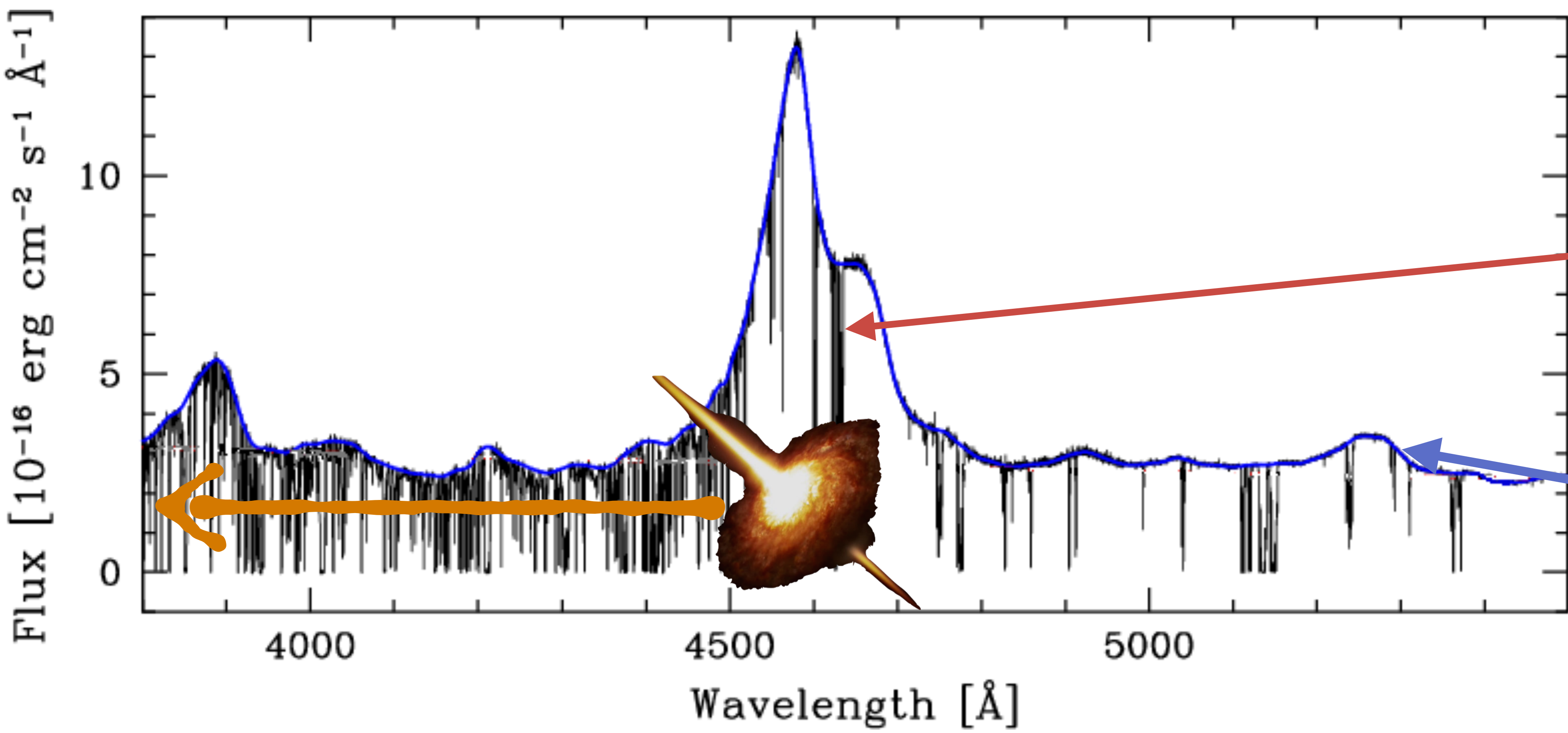
Observed Wavelength **Absorption Redshift**

$$\lambda = \lambda_{\alpha,c}(1 + z_{\alpha,c})$$

Lyman Alpha wavelength : 1216 Å
Triply ionized Carbon wavelength : 1550 Å

As a result, for an observed wavelength of 4000 Å :

Observed Flux to Cosmological Fluctuations



$$F(\lambda) = \frac{f(\lambda)}{C(\lambda)}$$

Observed Wavelength   Absorption Redshift

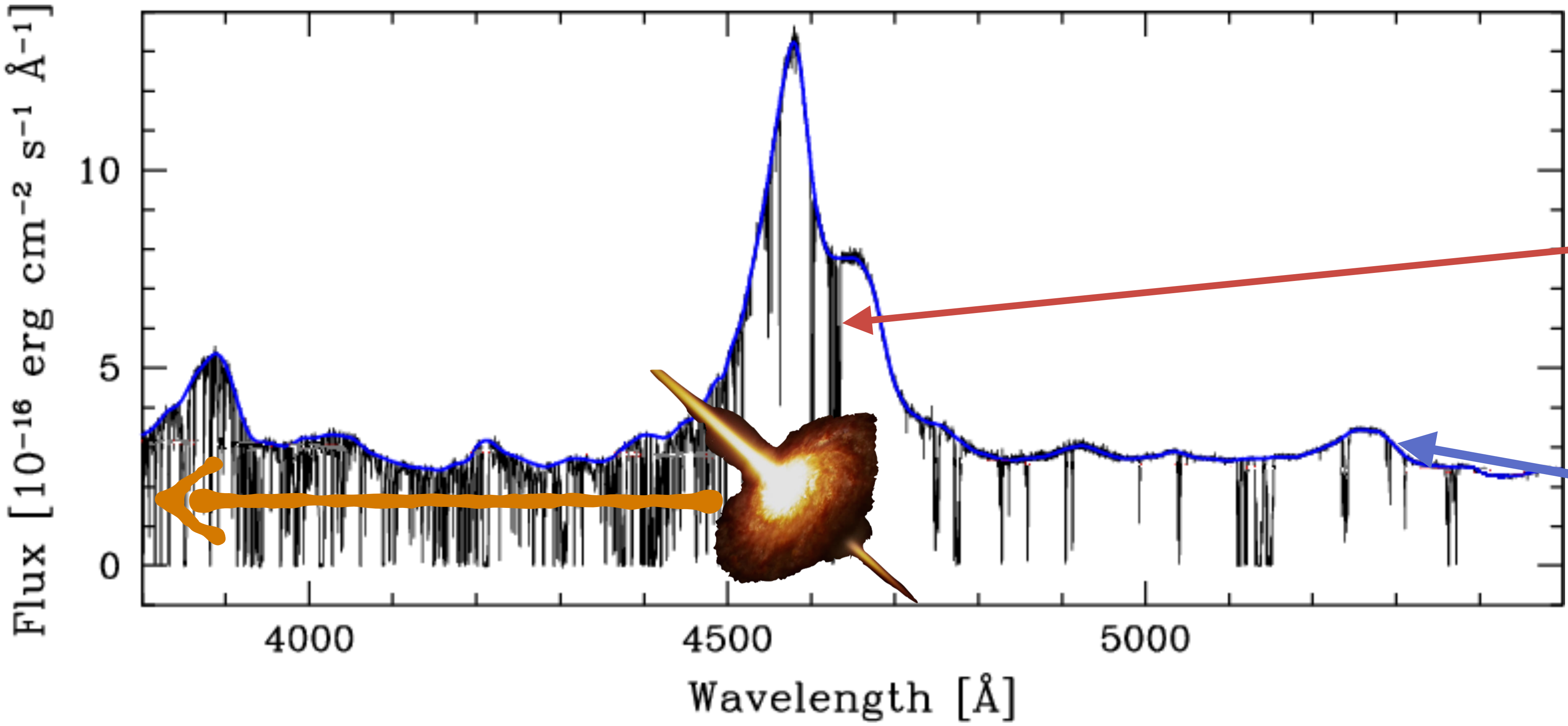
$$\lambda = \lambda_{\alpha,c}(1 + z_{\alpha,c})$$

Lyman Alpha wavelength : 1216 Å
Triply ionized Carbon wavelength : 1550 Å

As a result, for an observed wavelength of 4000 Å :

$z_\alpha = 2.29$ while $z_c = 1.58$

Observed Flux to Cosmological Fluctuations

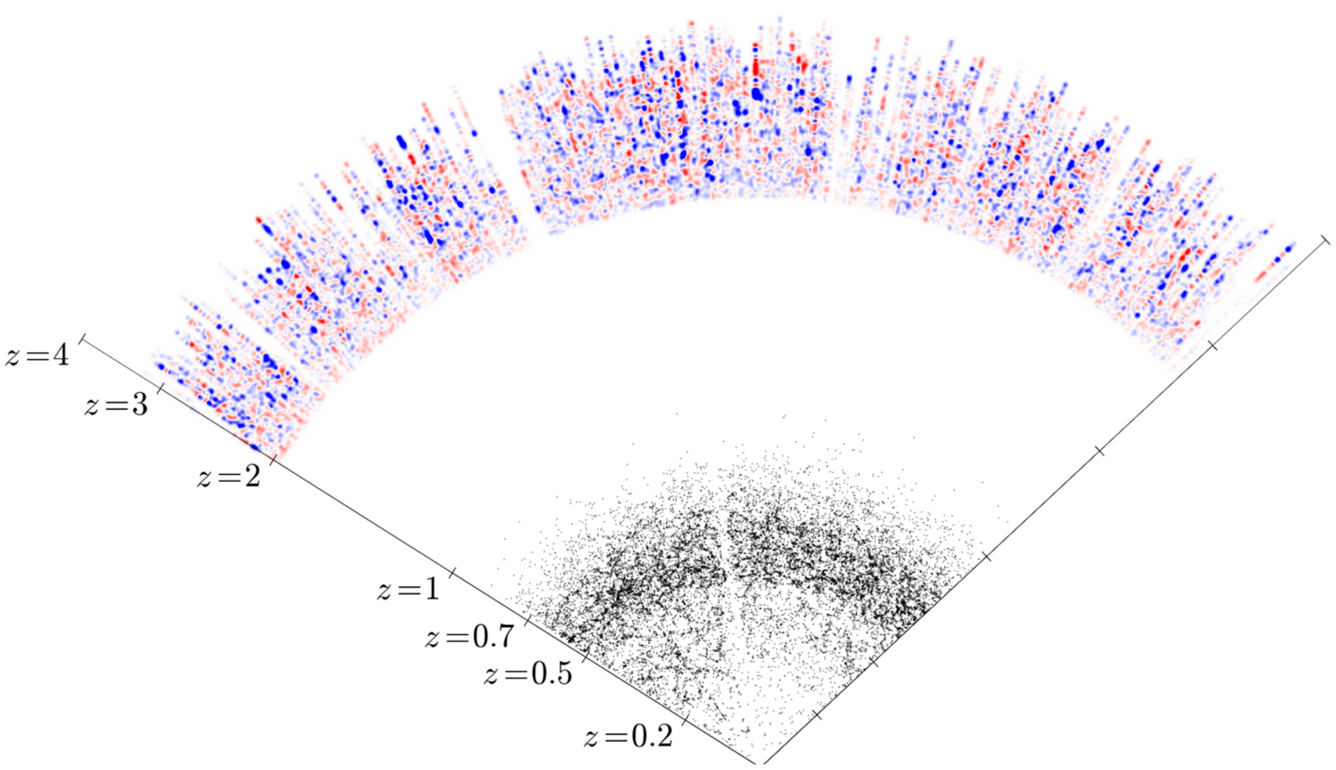


Transmitted flux fraction

Observed flux

$$F(\lambda) = \frac{f(\lambda)}{C(\lambda)}$$

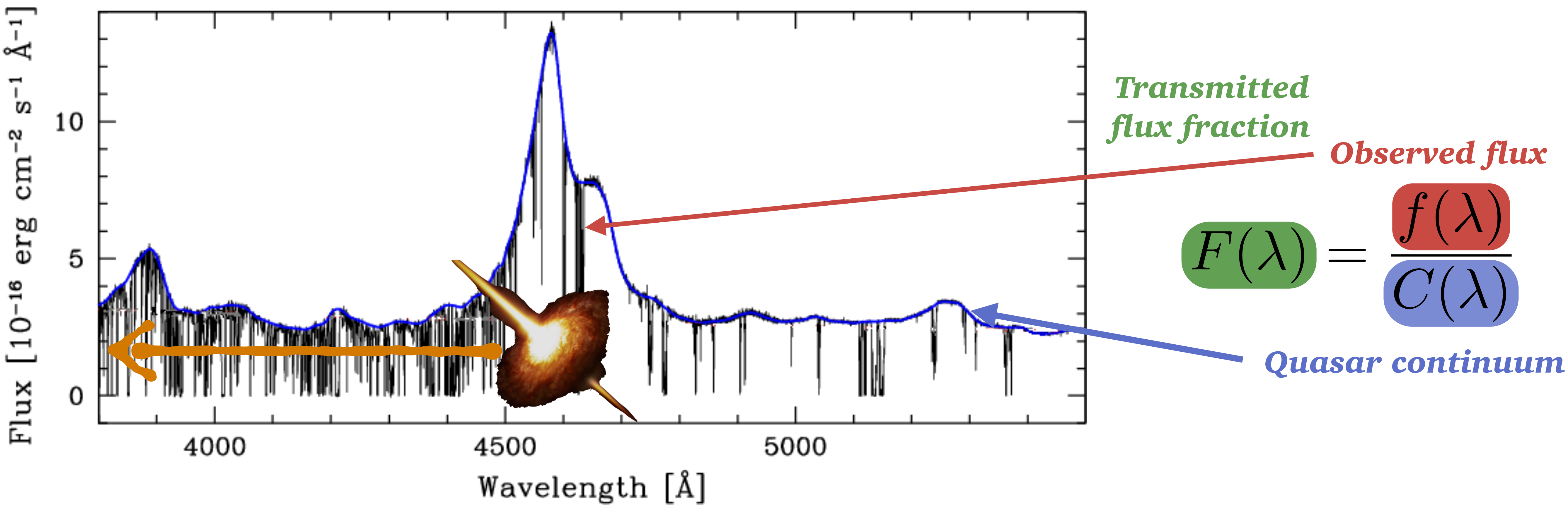
Quasar continuum



As a result, for an observed wavelength of 4000 Å :

$z_\alpha = 2.29$ while $z_c = 1.58$

Observed Flux to Cosmological Fluctuations



$$F(\lambda) = \frac{f(\lambda)}{C(\lambda)}$$

$$\delta_F(x) = \frac{F(x) - \bar{F}}{\bar{F}}$$

Flux fluctuations in pixels trace the **density** along the line of sight to the quasar

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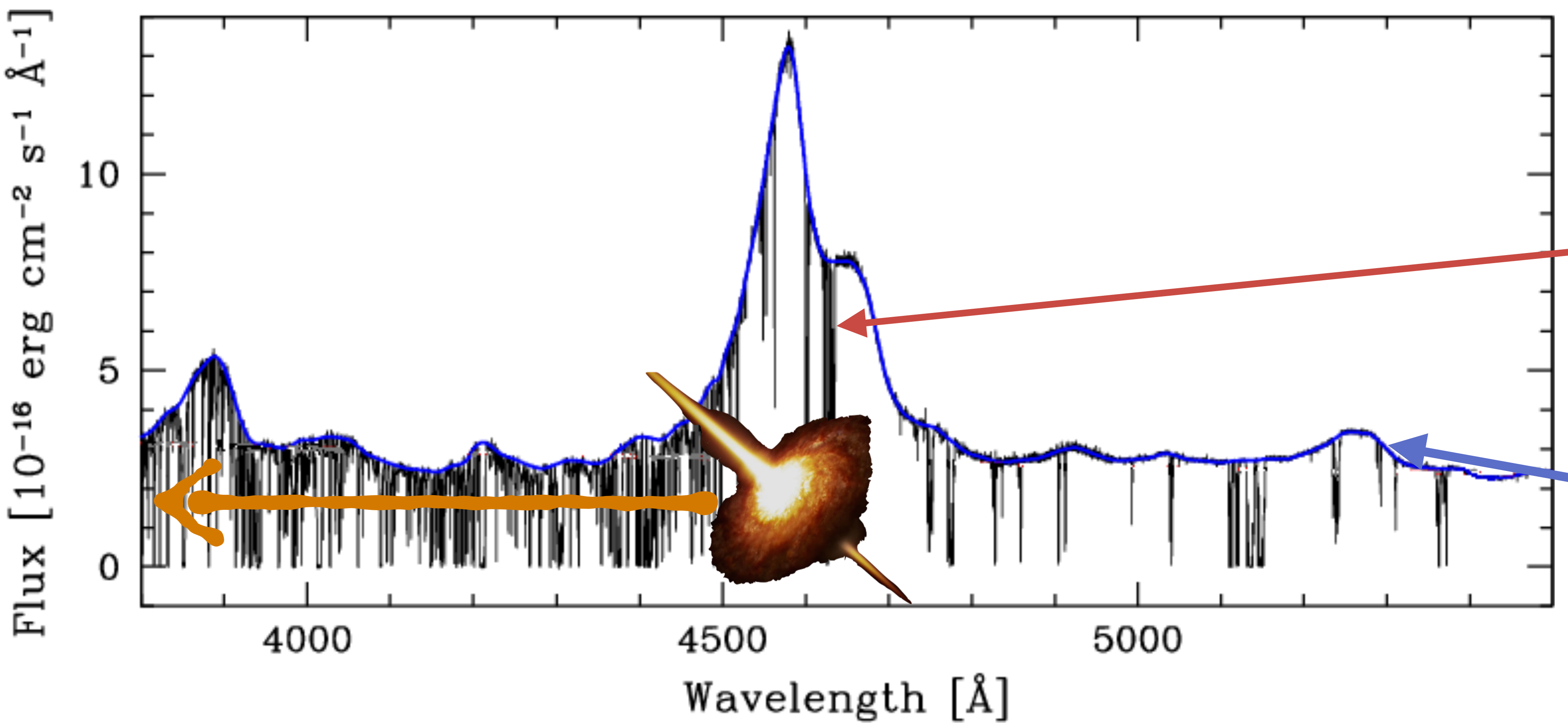

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Flux fluctuations in pixels trace the **density** along the line of sight to the quasar

$$\delta_F = b_F \delta$$

bias

Observed Flux to Cosmological Fluctuations

Measurement of the two-point correlation function of Hydrogen clouds, assuming a linear bias, **gives us access to the dark matter distribution** :

$$\xi_F(r) = b_F^2 \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle = b_F^2 \xi(r)$$

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$$\xi_F(r) = b_F^2 \langle \delta(\vec{x}) \delta(\vec{x} + \vec{r}) \rangle = b_F^2 \xi(r)$$

The two-point correlation function is the Fourier transform of the power spectrum :

$$\xi_F(r) = \frac{1}{(2\pi)^3} \int \mathcal{P}_F(k) e^{-i\vec{k} \times \vec{r}} d^3 k$$

Measured from observation

Flux 3D power spectrum

Observed Flux to Cosmological Fluctuations

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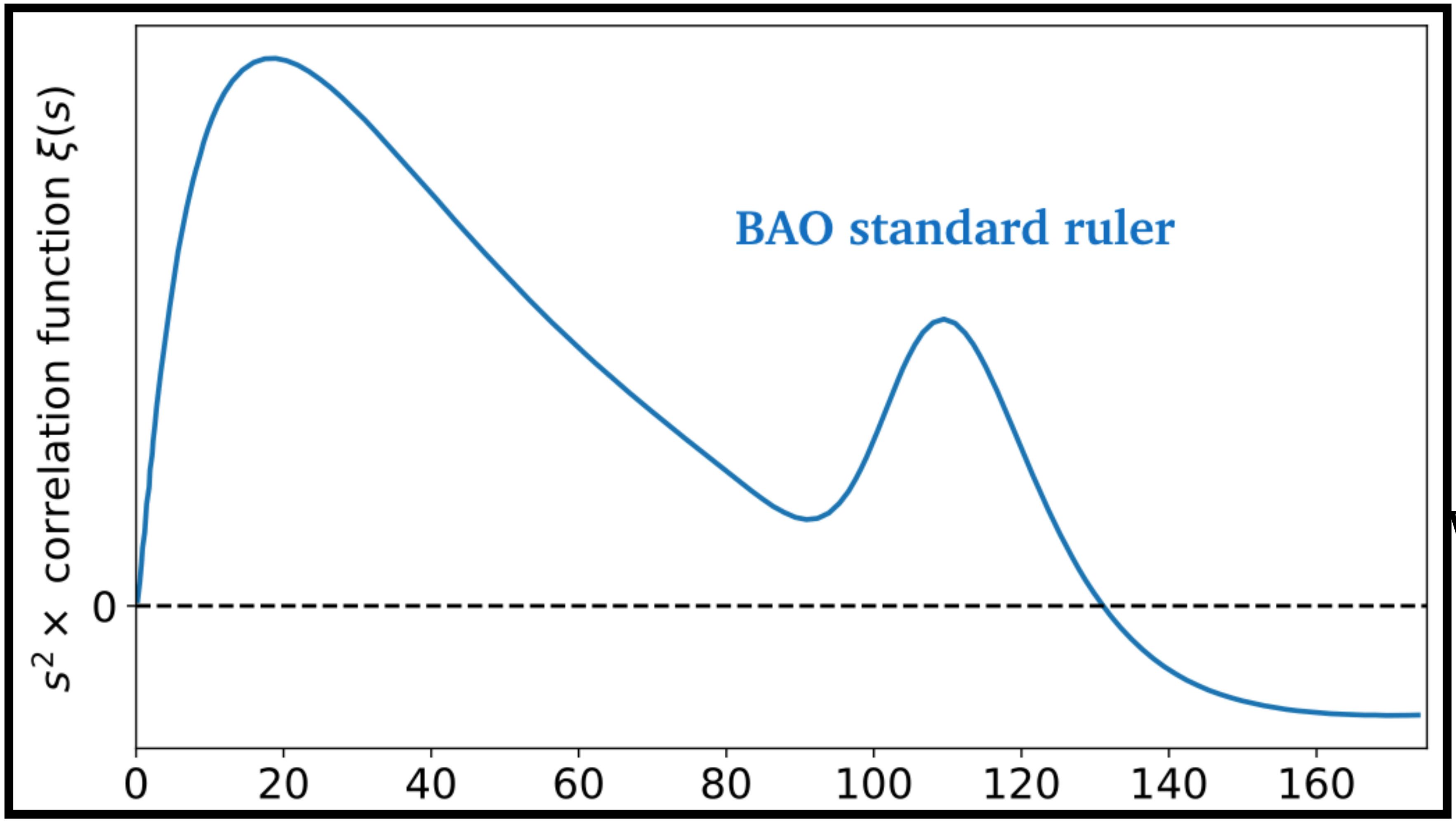
The two-point 

wer spectrum :

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In redshift space, the **Kaiser effect** describes the **redshift space distortions** resulting from peculiar velocities :

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Flux 3D power spectrum

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$$\mathcal{P}_F(k) = b_F^2 (1 + \beta\mu_k^2)^2 \mathcal{P}_L(k)$$

bias

redshift distortion parameter

Predicted by cosmological models

Observed Flux to Cosmological Fluctuations

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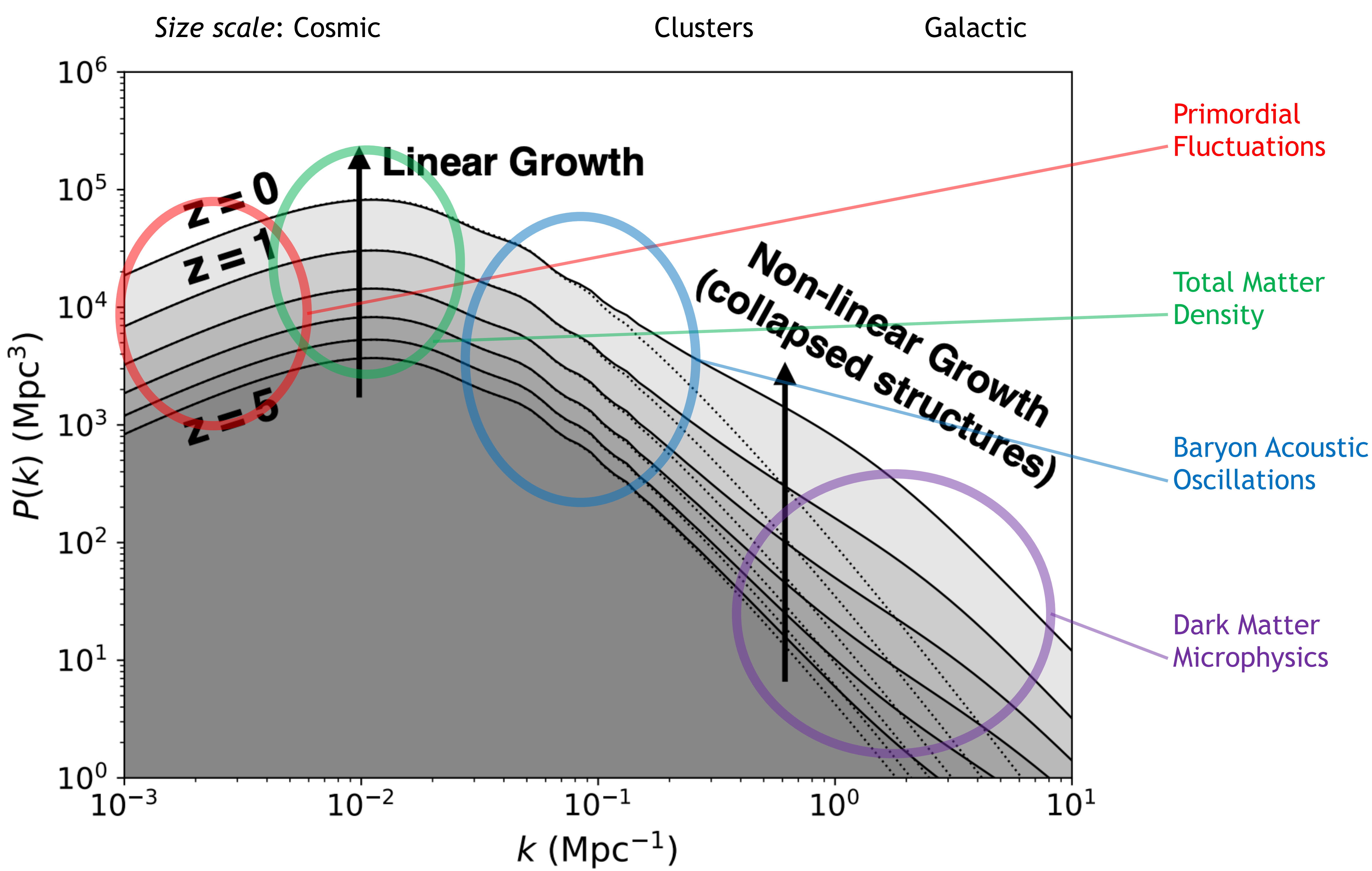
x Correction Terms

bias

redshift distortion parameter

Predicted by cosmological models

Information encoded in the Power Spectrum



Credit: K. Bechtol/LSST-DESC

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BAO from BOSS Lyα

Two independent ways of measuring the BAO scale :

Lyα auto-correlation
Bautista et al. (2017)

Lyα x Quasars cross-correlation
du Mas des Bourboux et al. (2017)

SDSS-III/BOSS DR12

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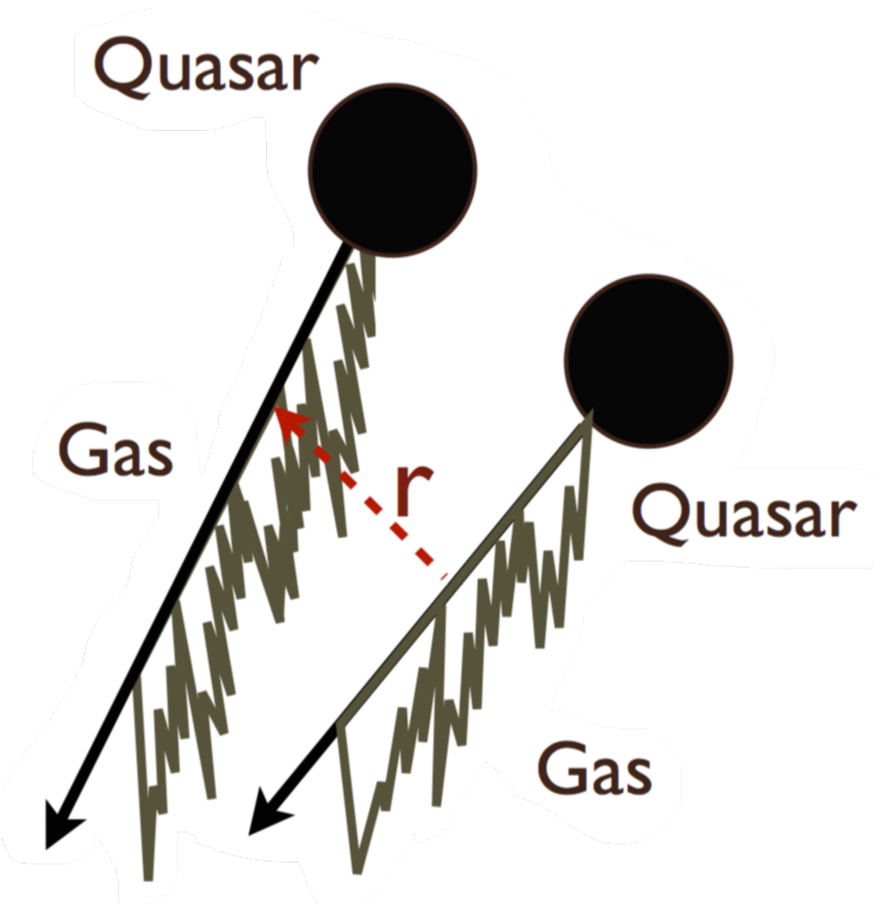

Lyα auto-correlation
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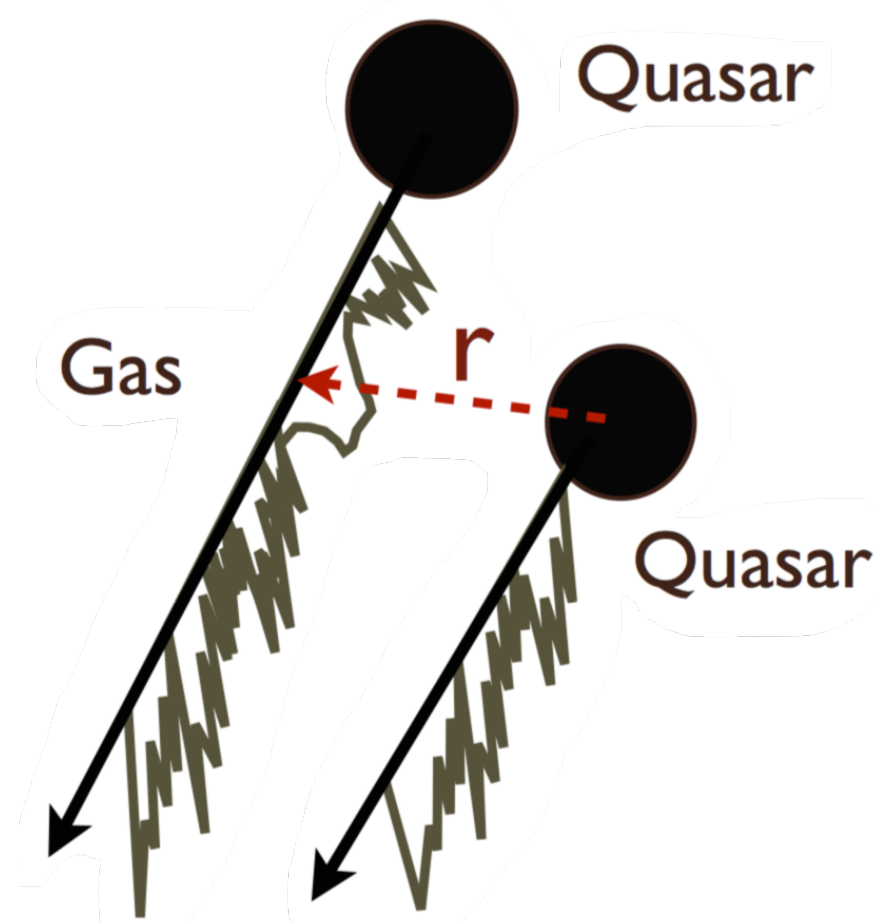

Lyα x Quasars cross-correlation
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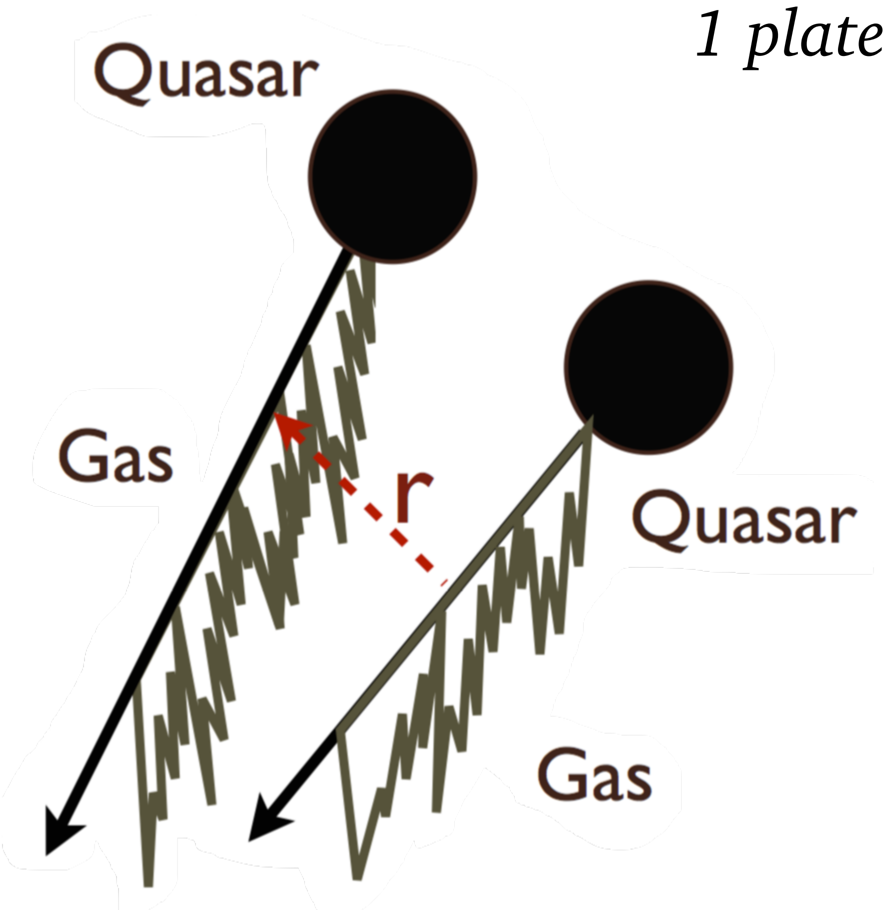
SDSS-III/BOSS DR12

BAO from BOSS Lyα

Two independent ways of measuring the BAO scale :

1 analysis pixel : $1\text{Å} \sim 70\text{kms}^{-1} \sim 0.7h^{-1}\text{Mpc}$

1 plate : $3 \text{ deg} \sim 210\, h^{-1}\text{Mpc}$



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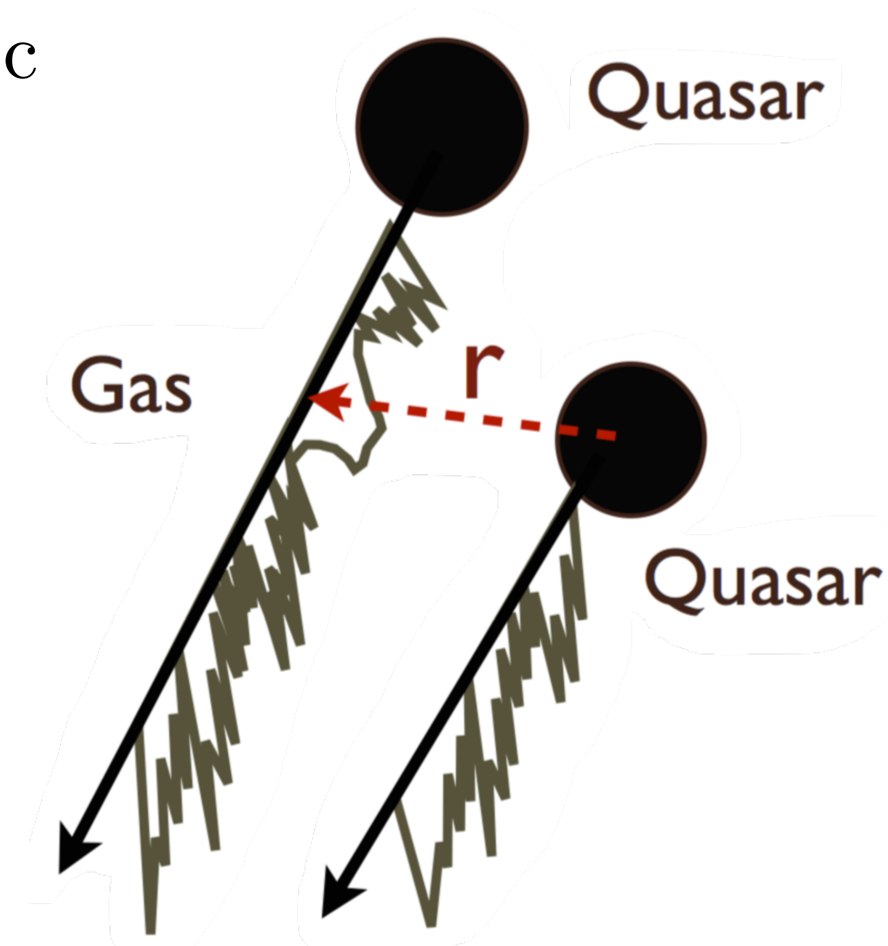

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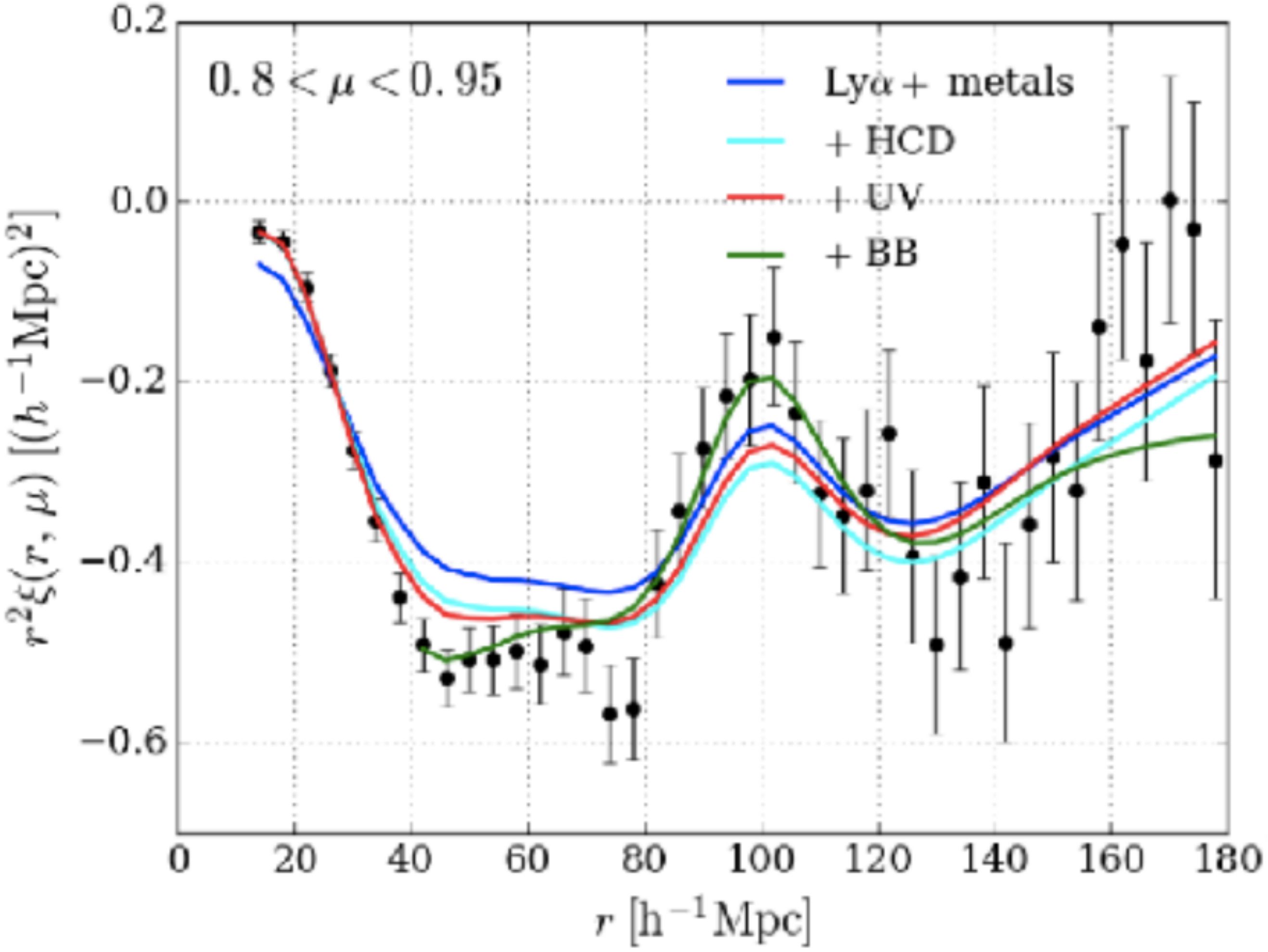

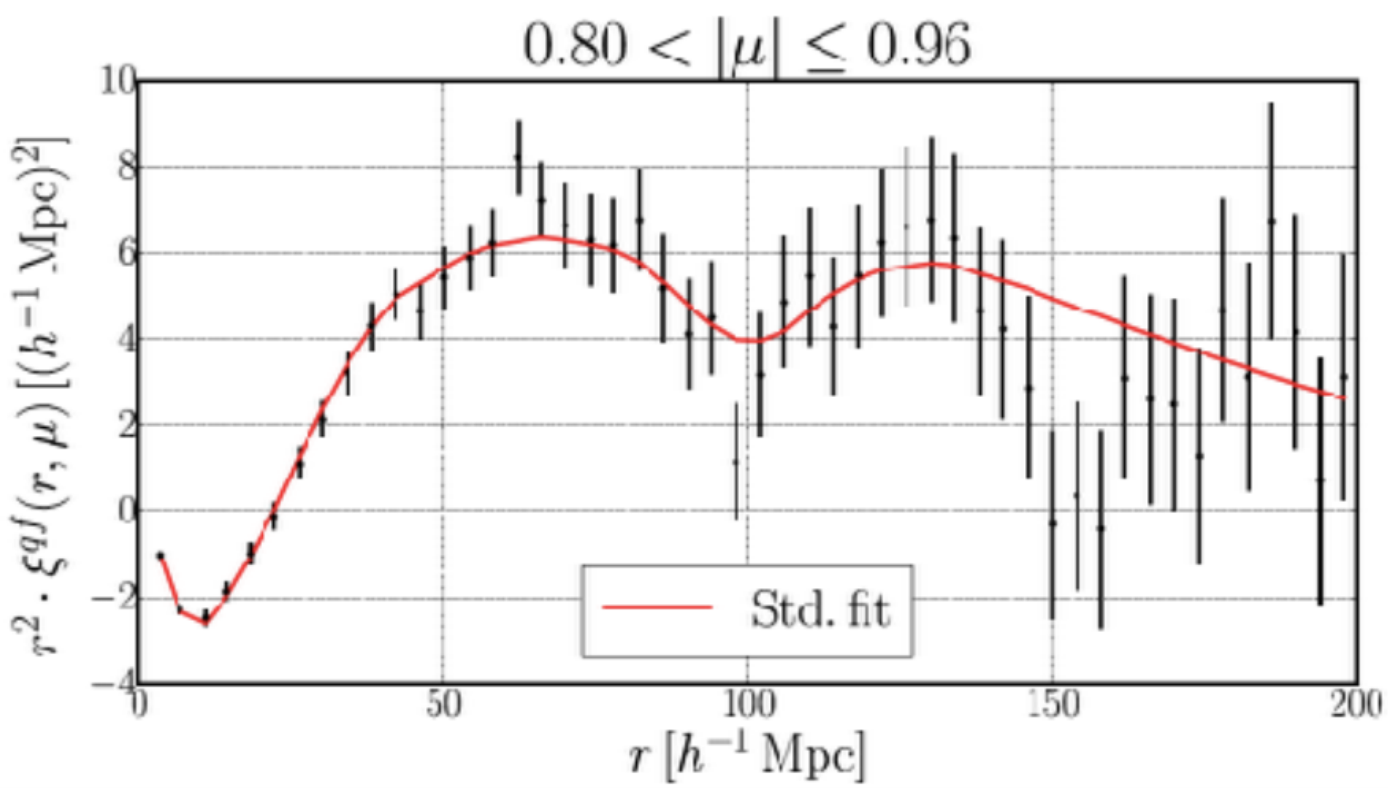

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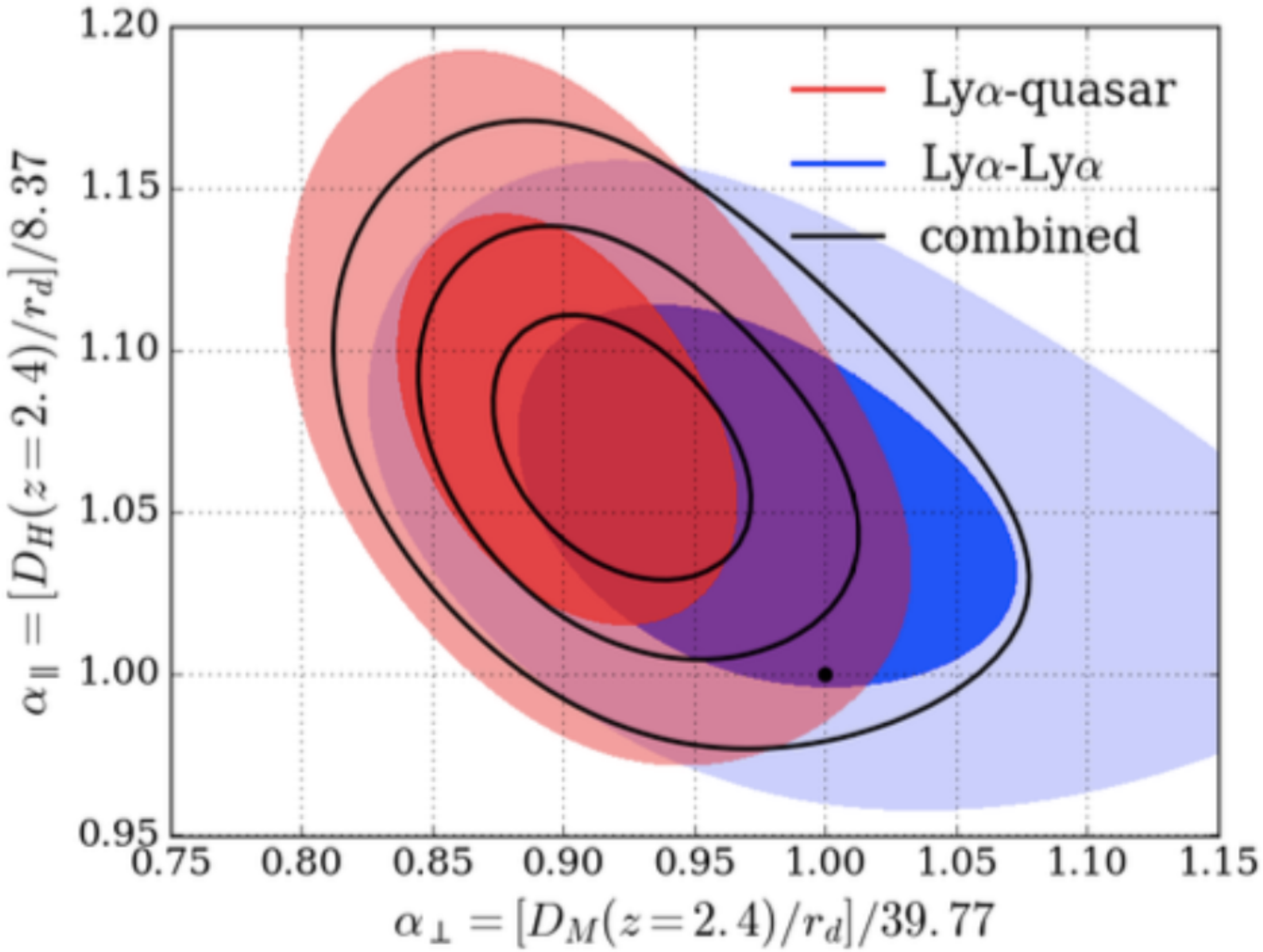
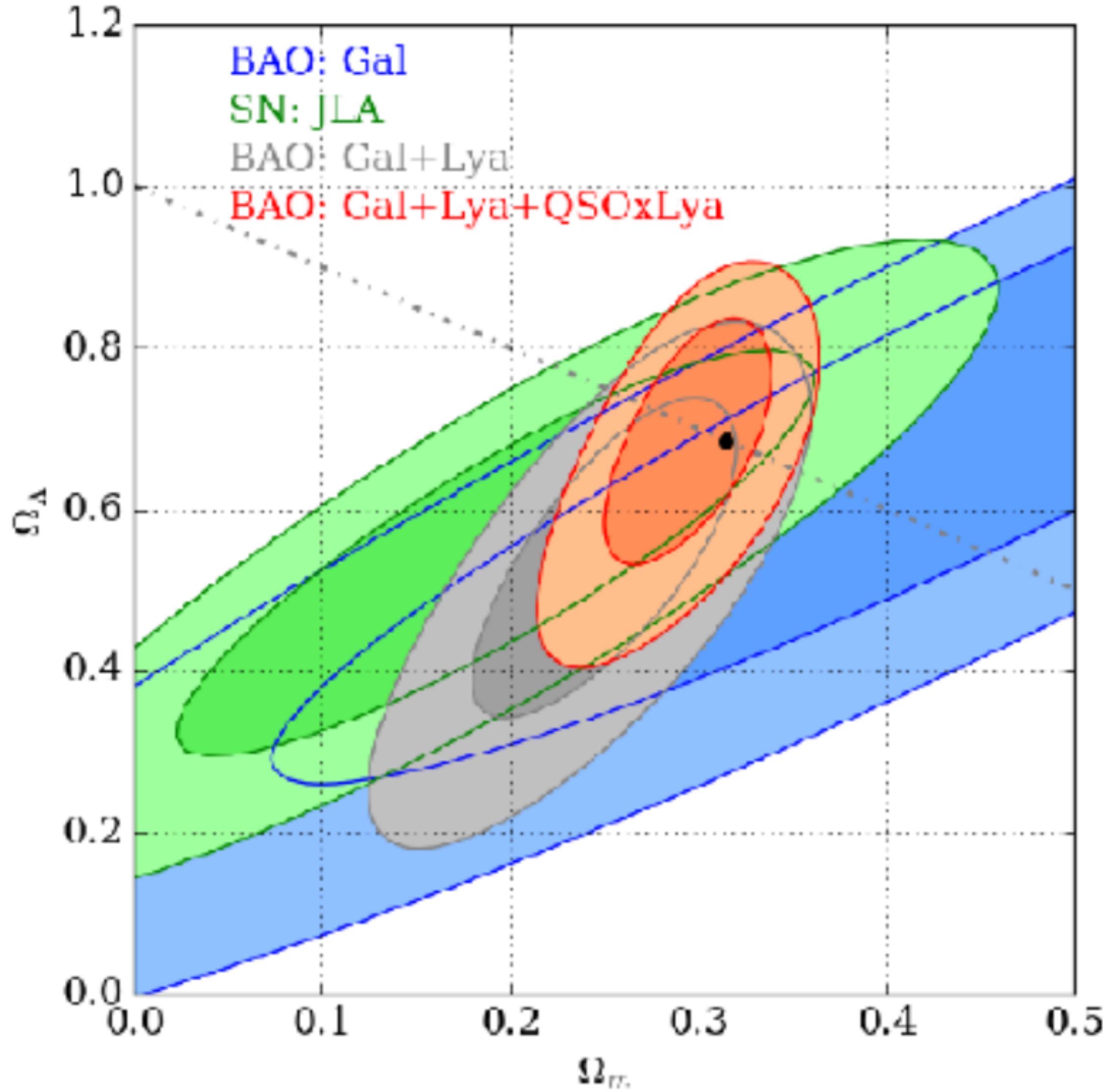
BAO from BOSS Lyα



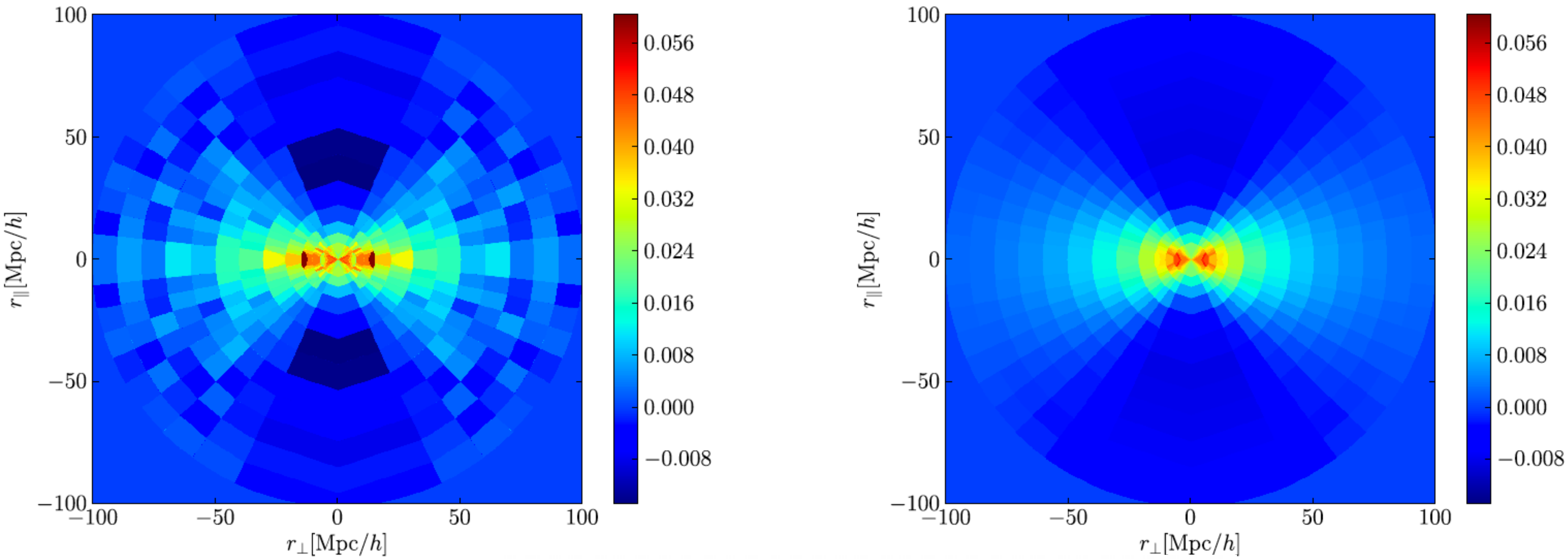


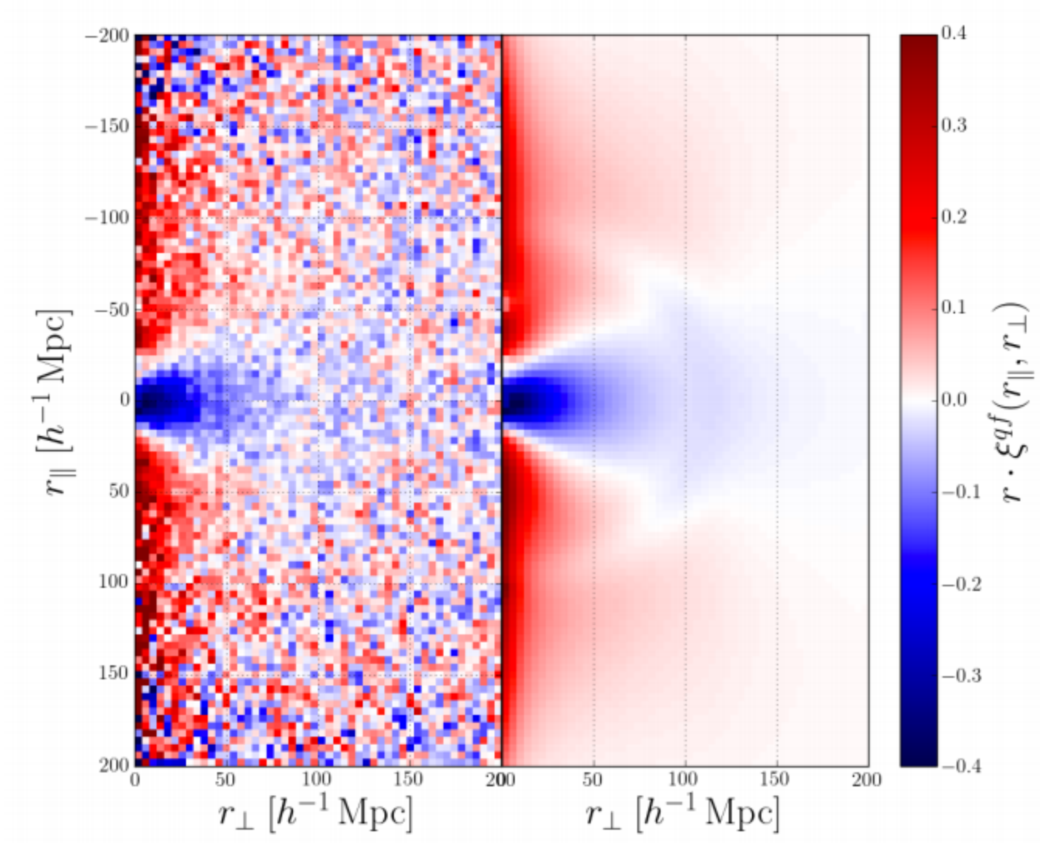
In a flat ΛCDM model :

$\Omega_m = 0.292 \pm 0.019$ BAO (BOSS)

$\Omega_m = 0.315 \pm 0.017$ CMB (PLANCK)

RSD from Lyα autocorrelation





Credit : Slosar et al. (2011)

Credit : Bautista et al. (2017)

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Corrections

- Fluctuations of the ionizing background — **Gontcho A Gontcho et al. (2014)**

Corrections

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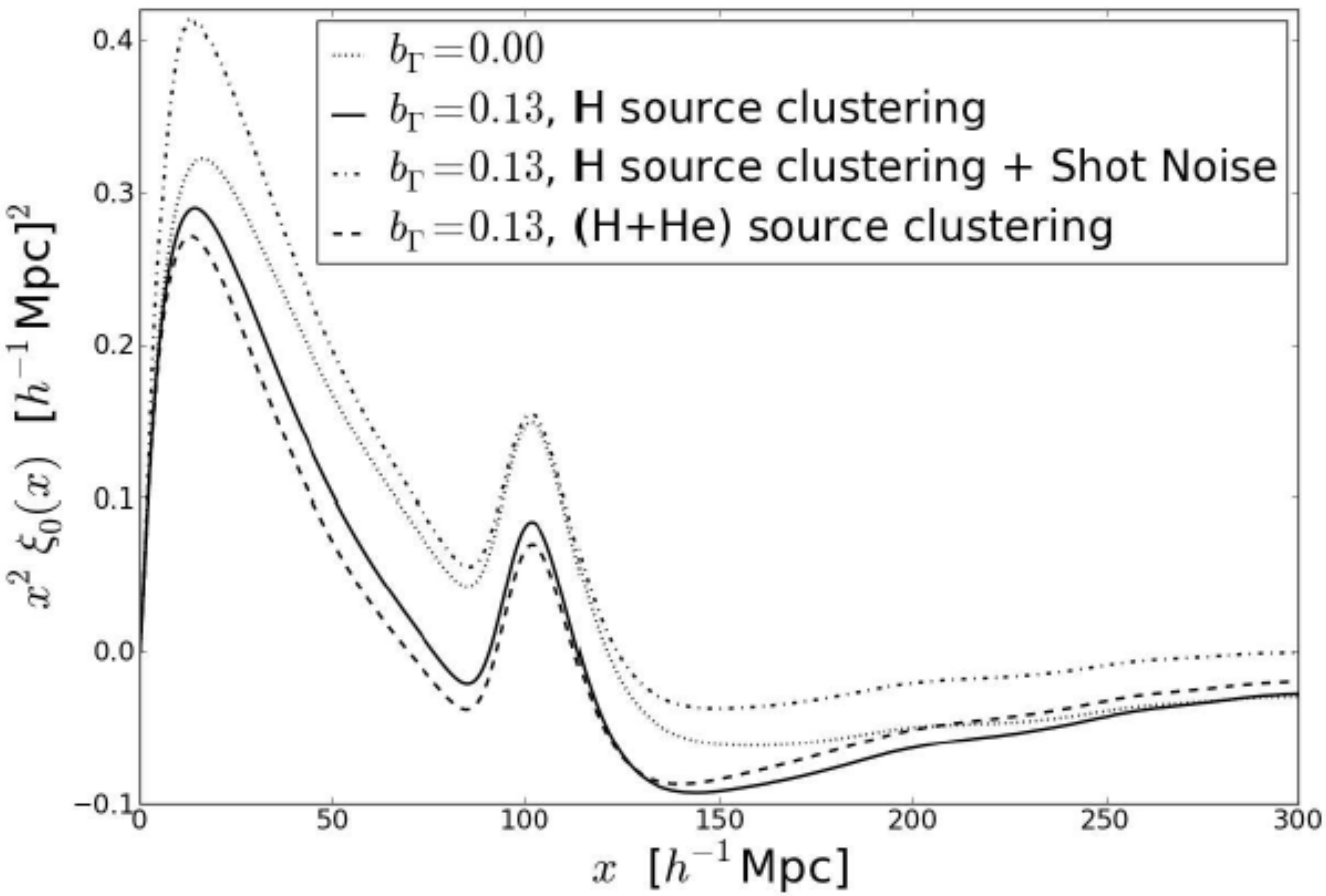

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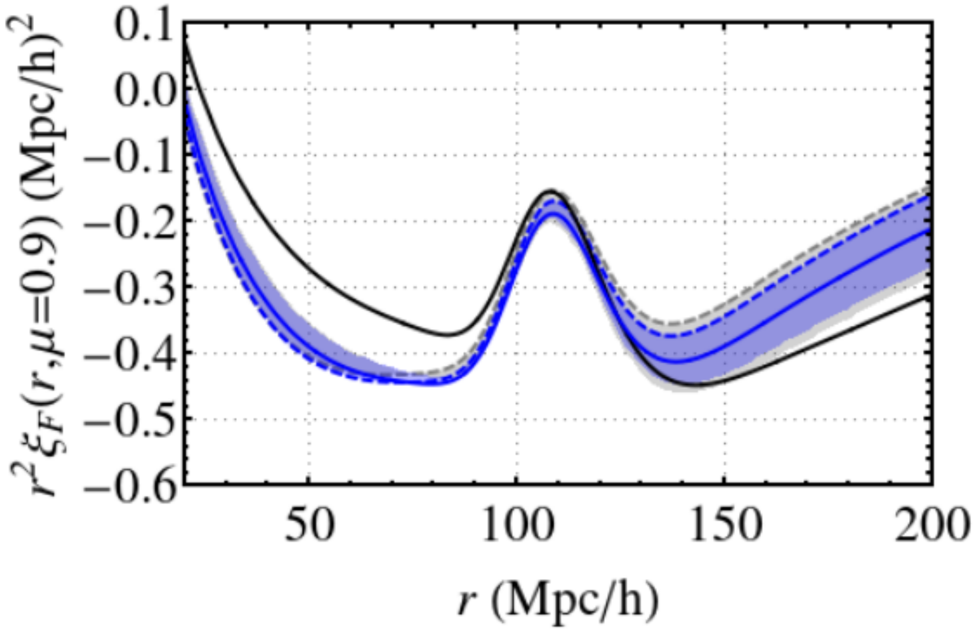
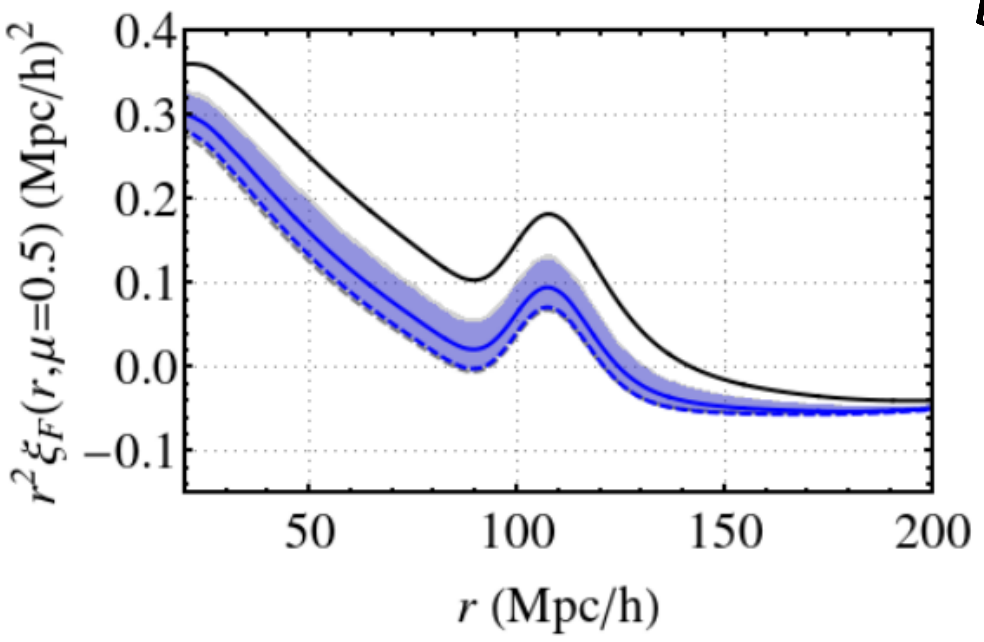
Corrections

- Fluctuations of the ionizing background — **Gontcho A Gontcho et al. (2014)**
- Broadband distortions — **Blomqvist et al. (2015)**



solid black *: undistorted*
solid blue *: distorted*
bands : different nlc considerations



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Adjacent Science

- P1D from Lyα forest — **Palanque-Delabrouille et al. (2013)**

Adjacent Science

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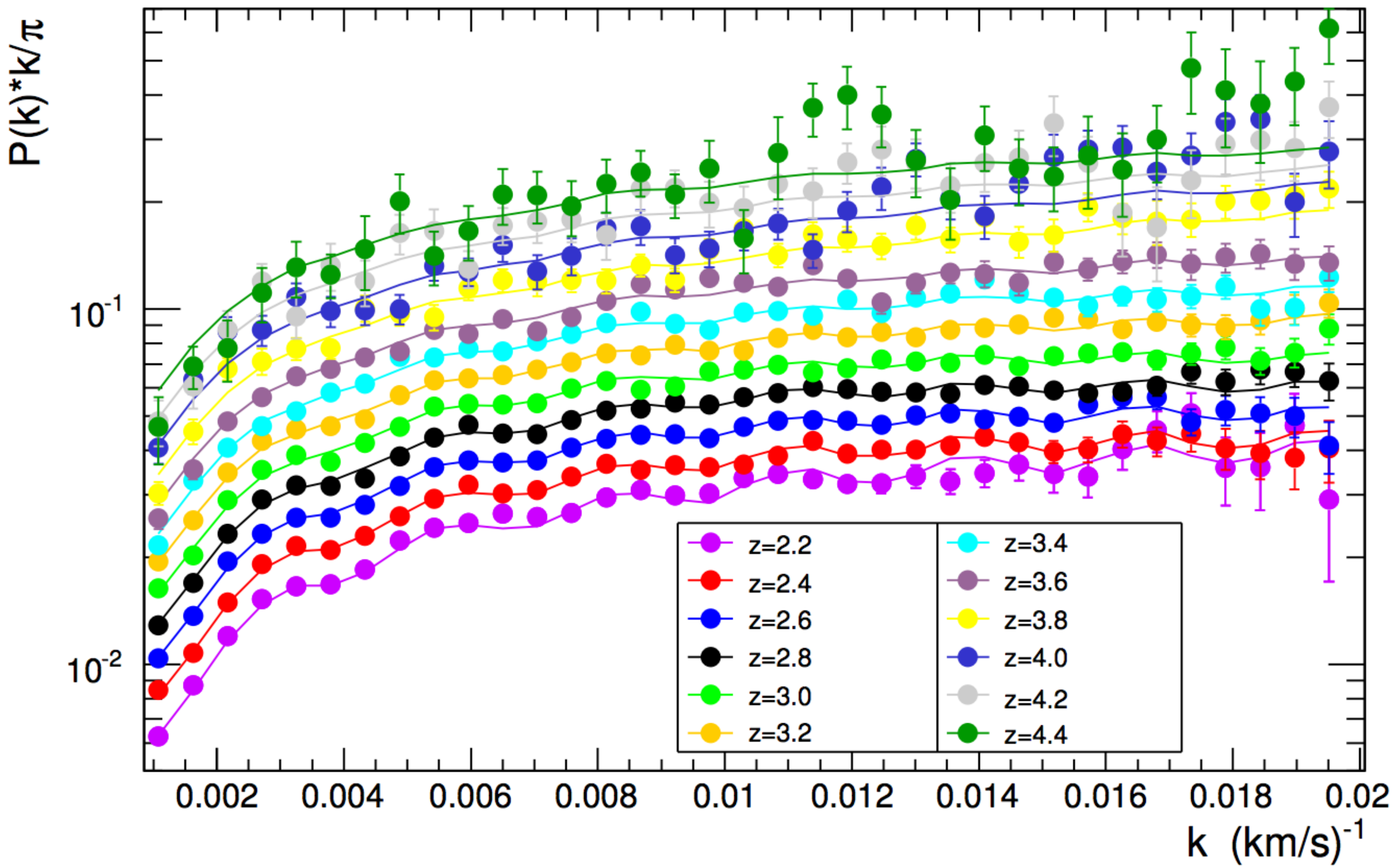
1D correlations, one skewer at the time



~ 0.1 h/Mpc — Line of sight (1D) wavenumber — ~ 2 h/Mpc

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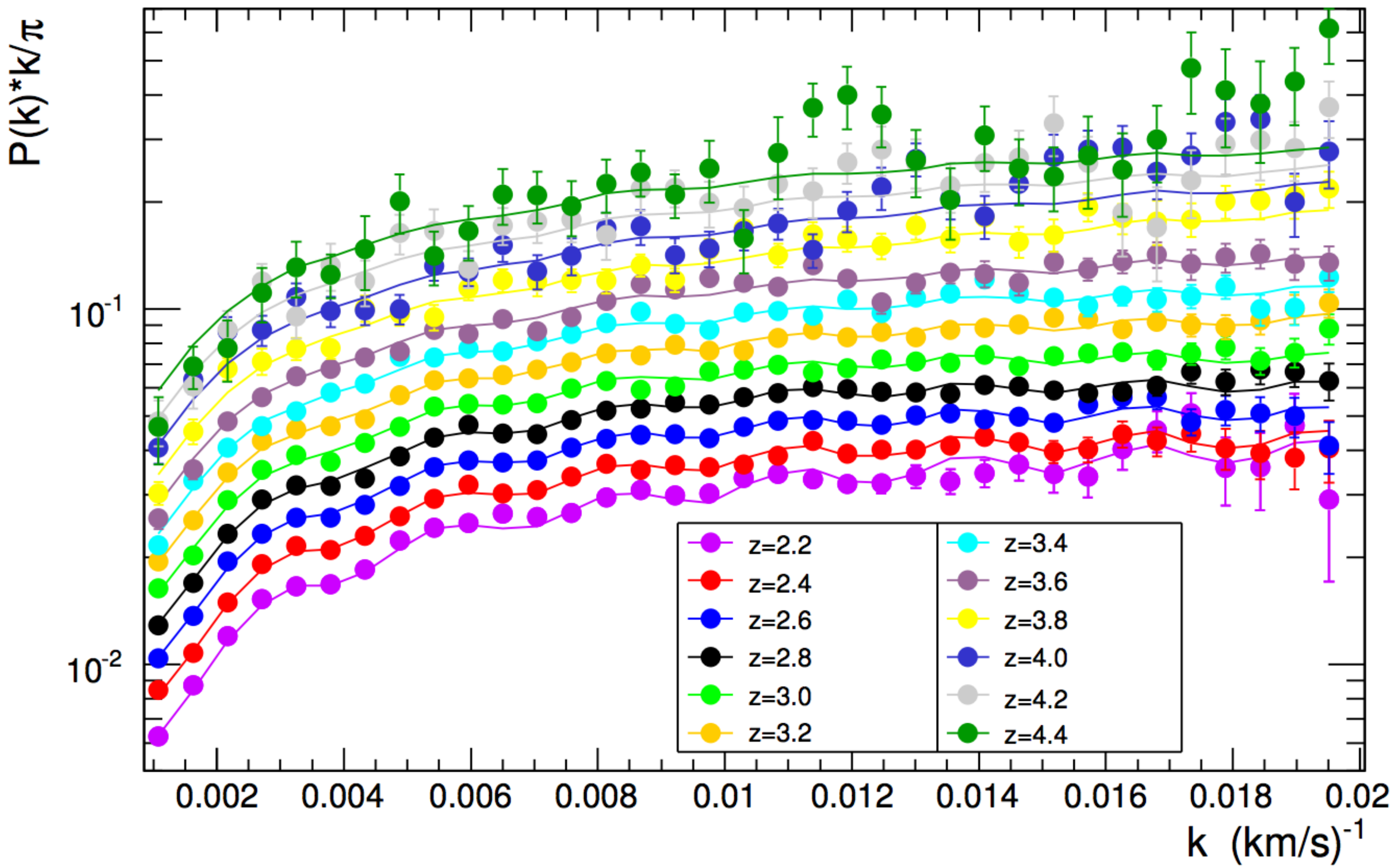

~ 0.1 h/Mpc Line of sight (1D) wavenumber ~ 2 h/Mpc

state of the art. opportunity for precision cosmology

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- Constrains on Σmν from Lyα P1D — **Palanque-Delabrouille et al. (2015)**

$\sum m_\nu < 0.12$ eV (95% C.L.)   SDSS-III/BOSS DR9 + Planck 2013

Adjacent Science

- P1D from Lyα forest — **Palanque-Delabrouille et al. (2013)**
- Constrains on Σmν from Lyα P1D — **Palanque-Delabrouille et al. (2015)**
- Non Linearities — **Arinyo-i-Prats et al. (2015)**

$$P_{3D,\alpha}(k,\mu) = P_L(k) b_\alpha^2 \left(1 + \beta_\alpha \mu^2\right)^2 D_{NL}(k,\mu)$$

Parametrization of non linearities from Hydrodynamical Simulations

Redshift Space Distortions
Kirkby et al. (2013)
Kaiser (1987)

Adjacent Science

- P1D from Lyα forest — **Palanque-Delabrouille et al. (2013)**
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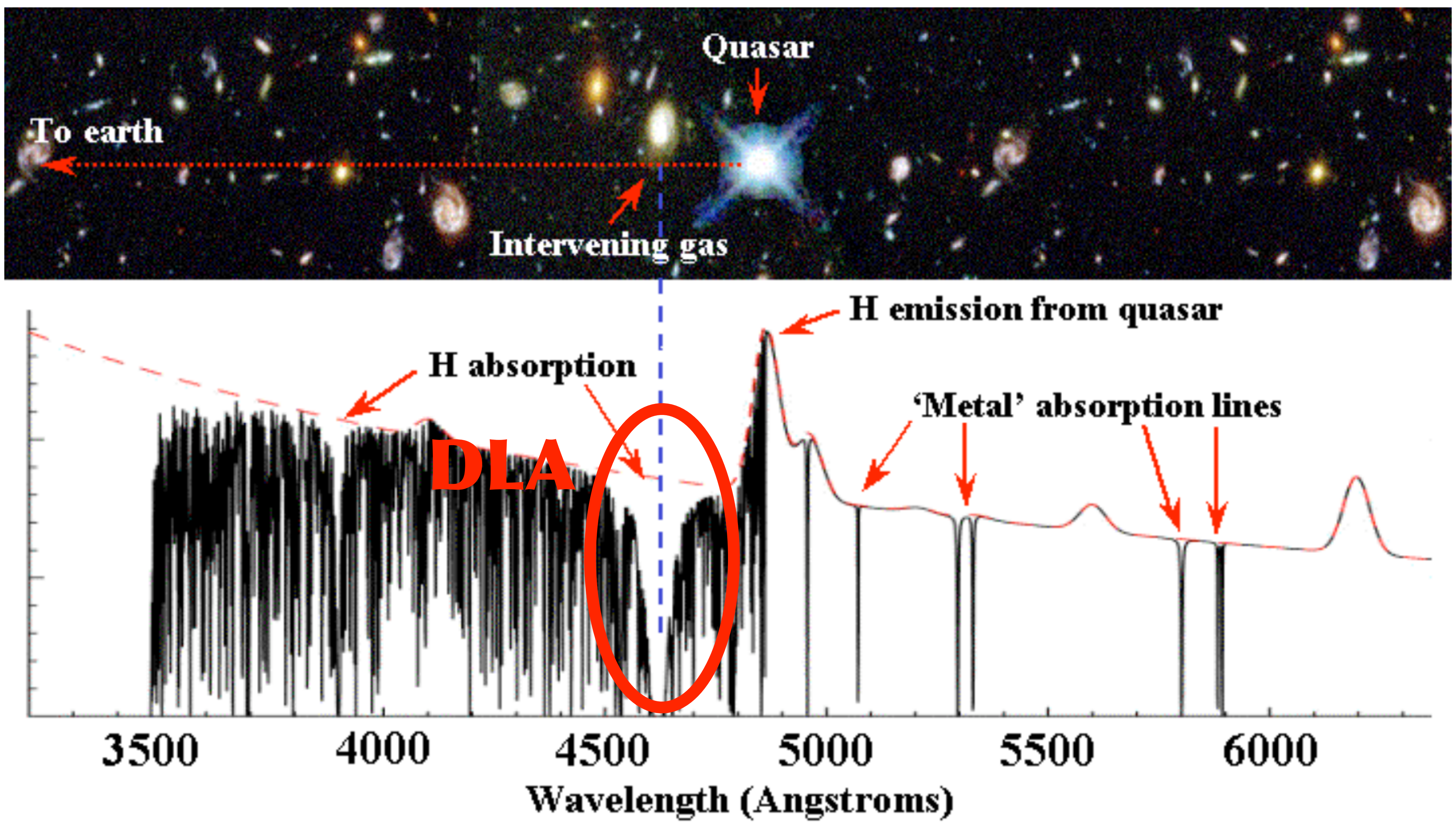
- DLA x Lyα forest — **Pérez-Ràfols et al. (2017)** → b_{DLA}



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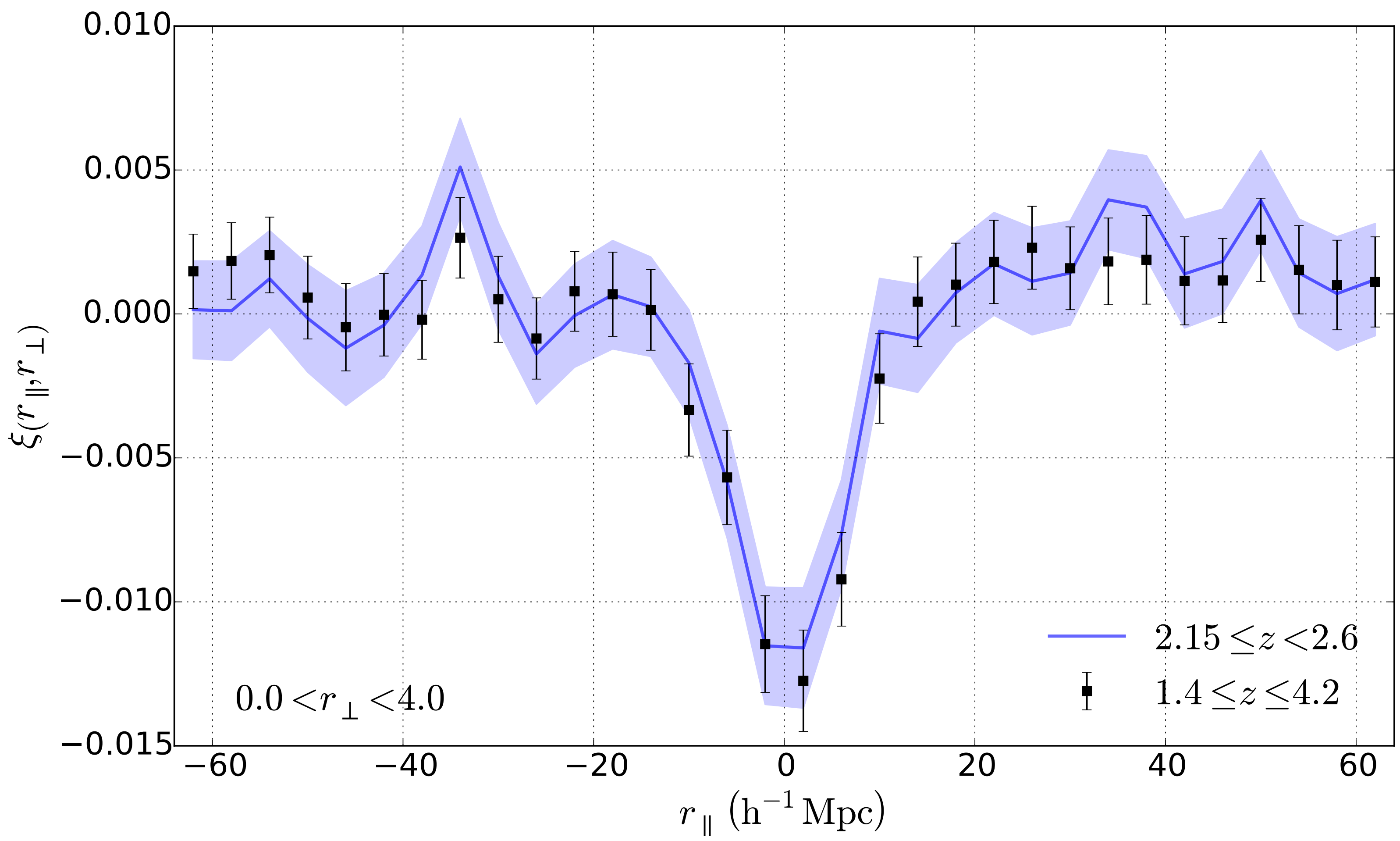

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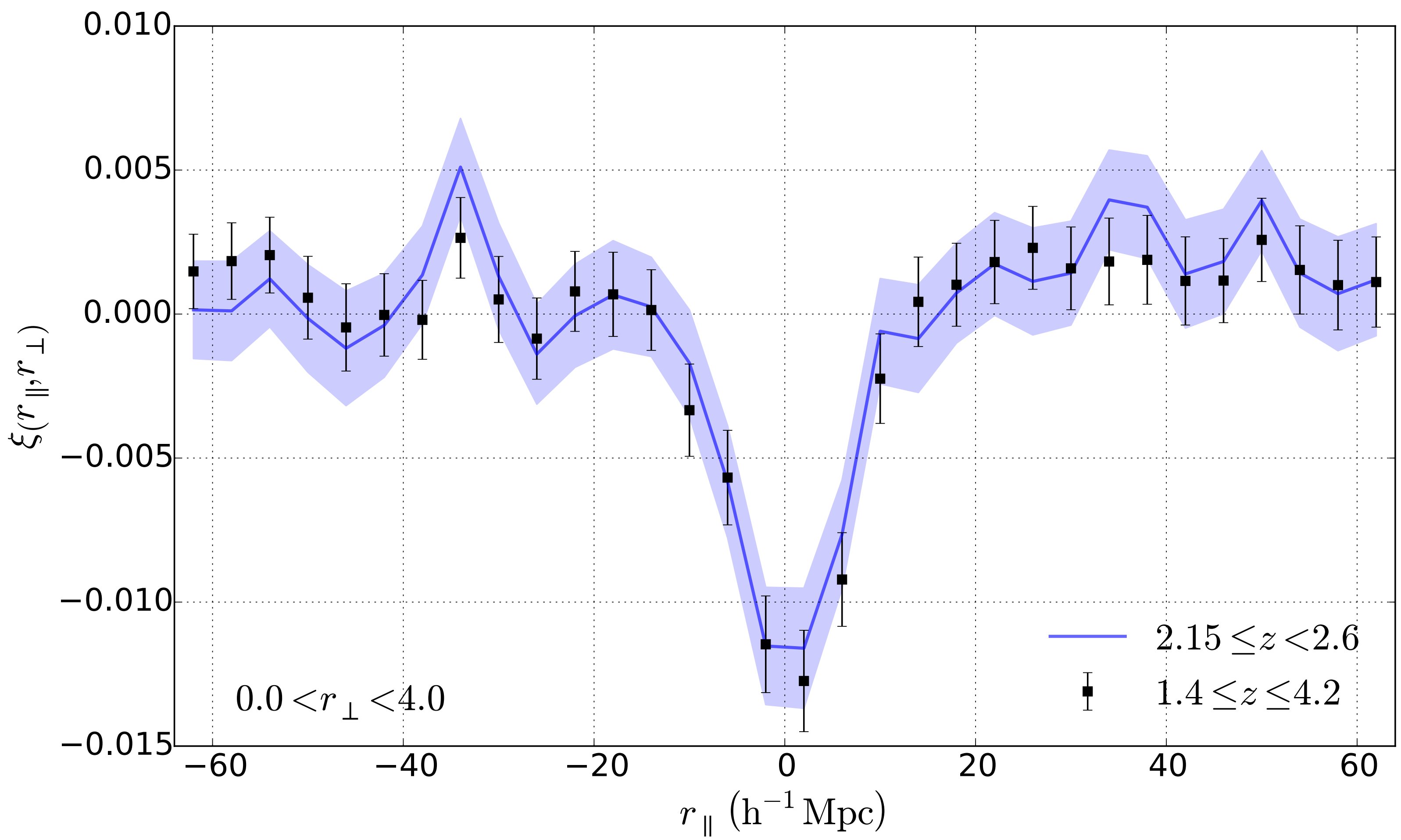
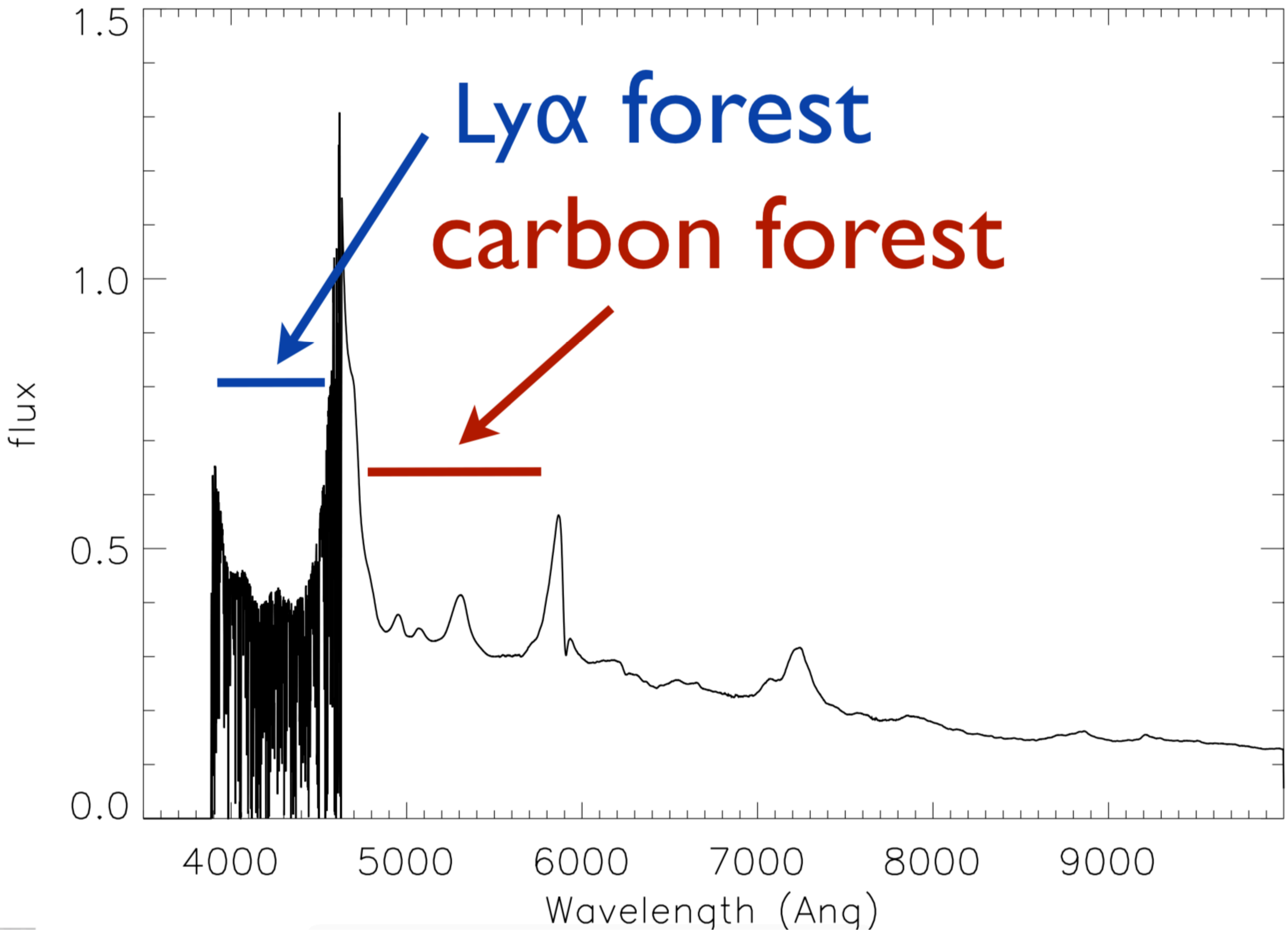


First measurement of the transmission bias of CIV forest

→ b_c

Adjacent Science

- P1D f
- Const
- Non I
- DLA x



eBOSS, extending range of useful data

- Detection of BAO with CIV forest — **Blomqvist et al. (2018)**

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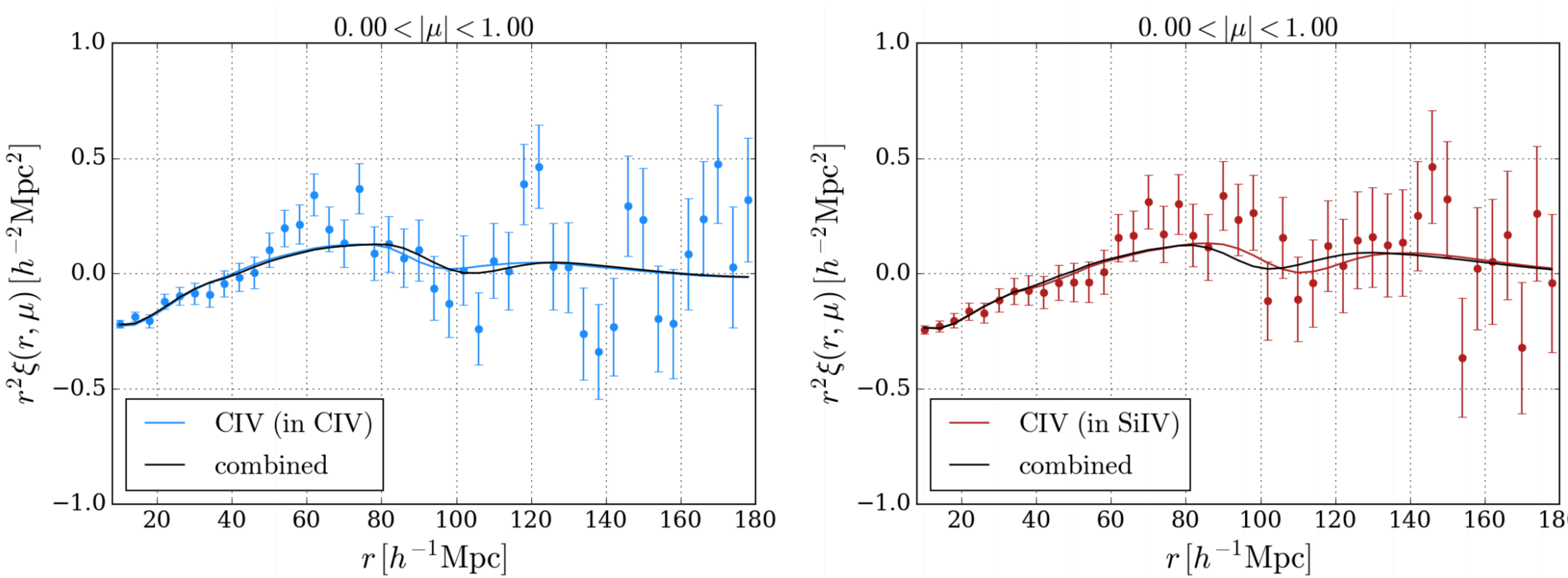

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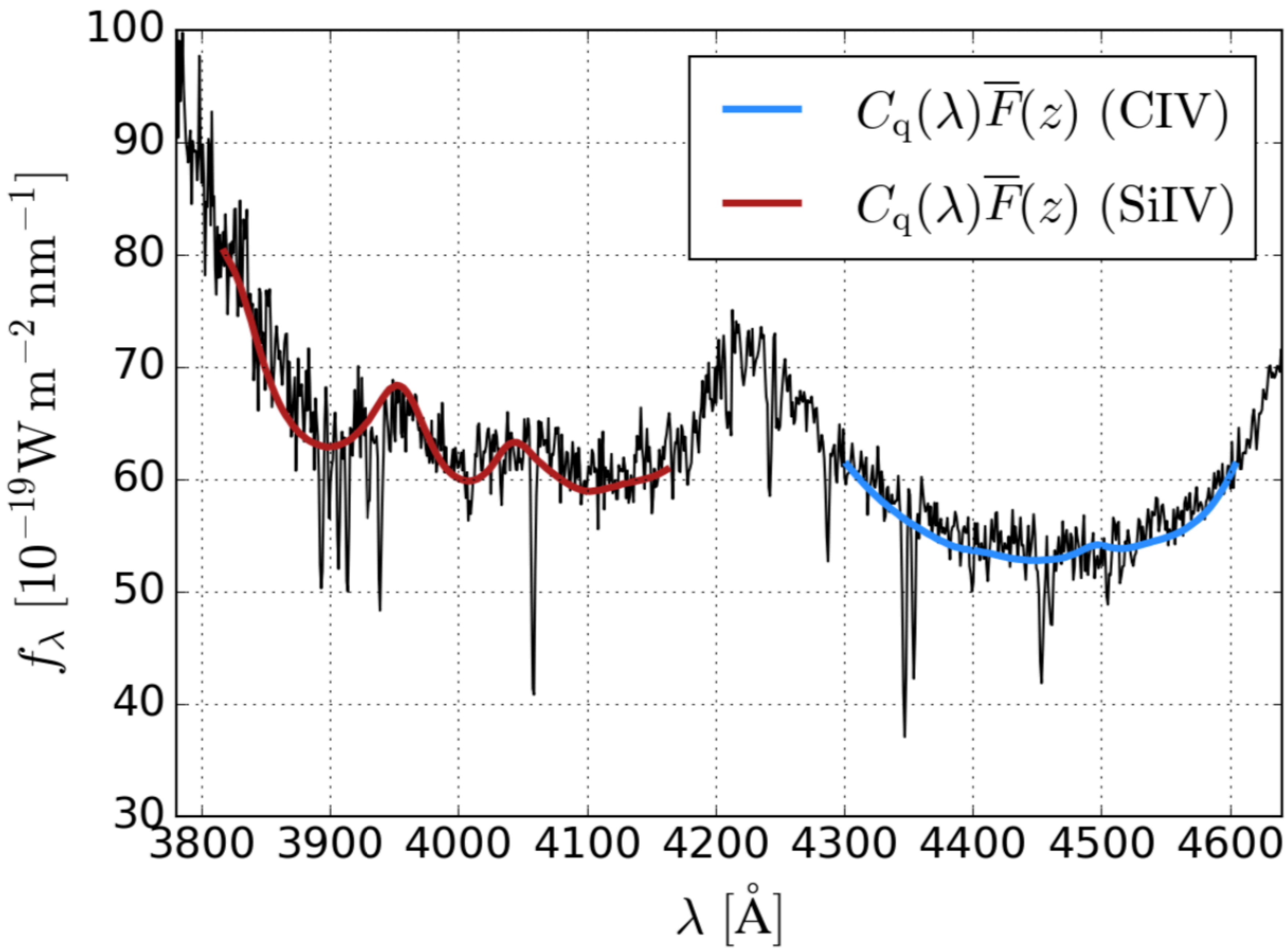

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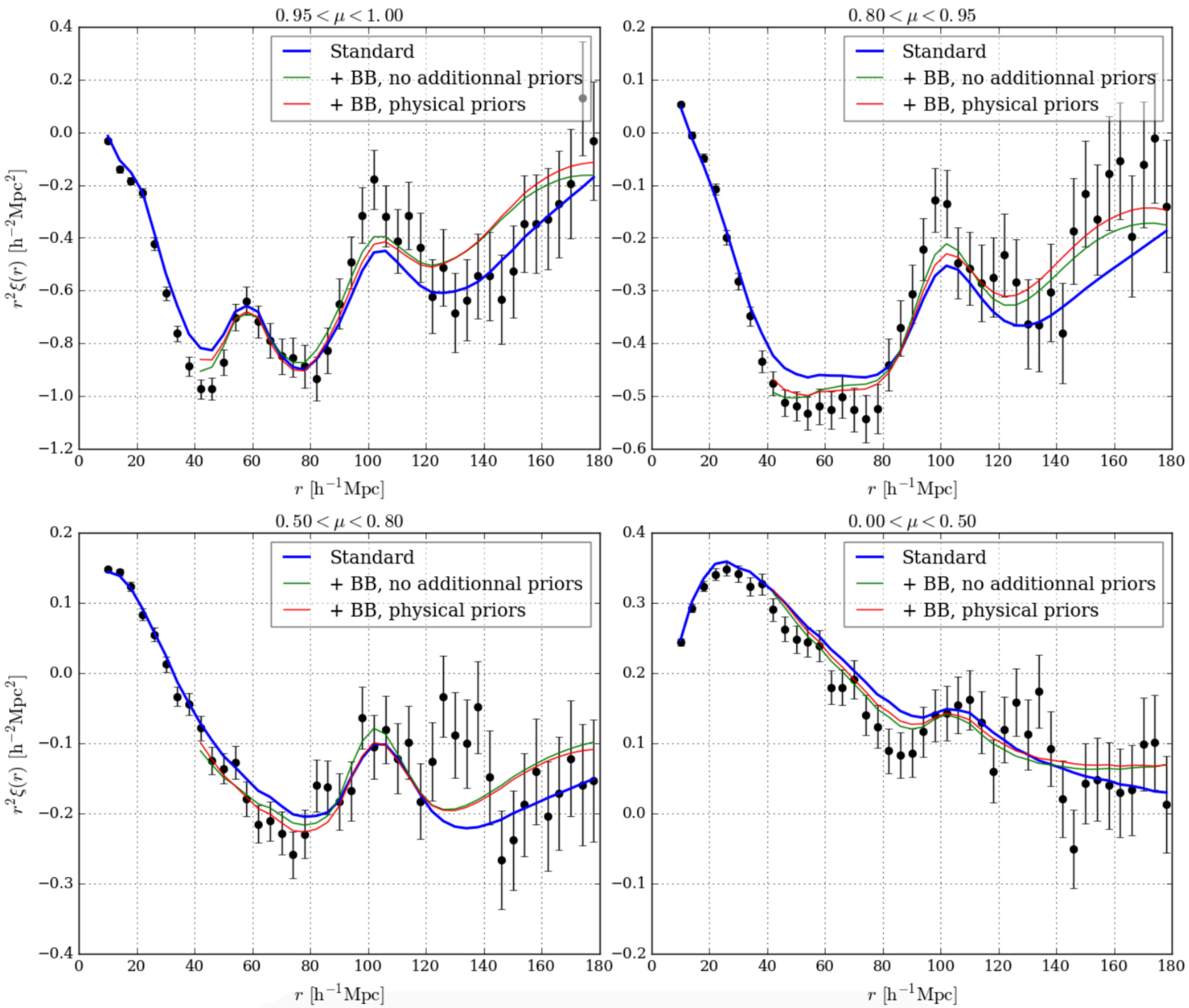

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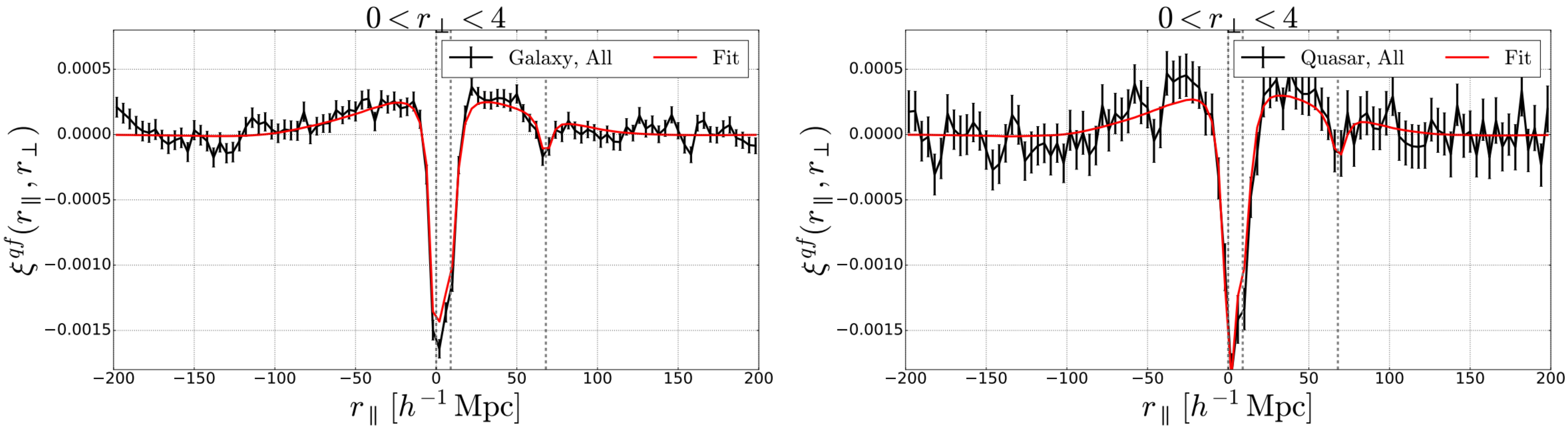
- MgII x Quasars and Galaxies — **du Mas des Bourboux et al. (2019)**



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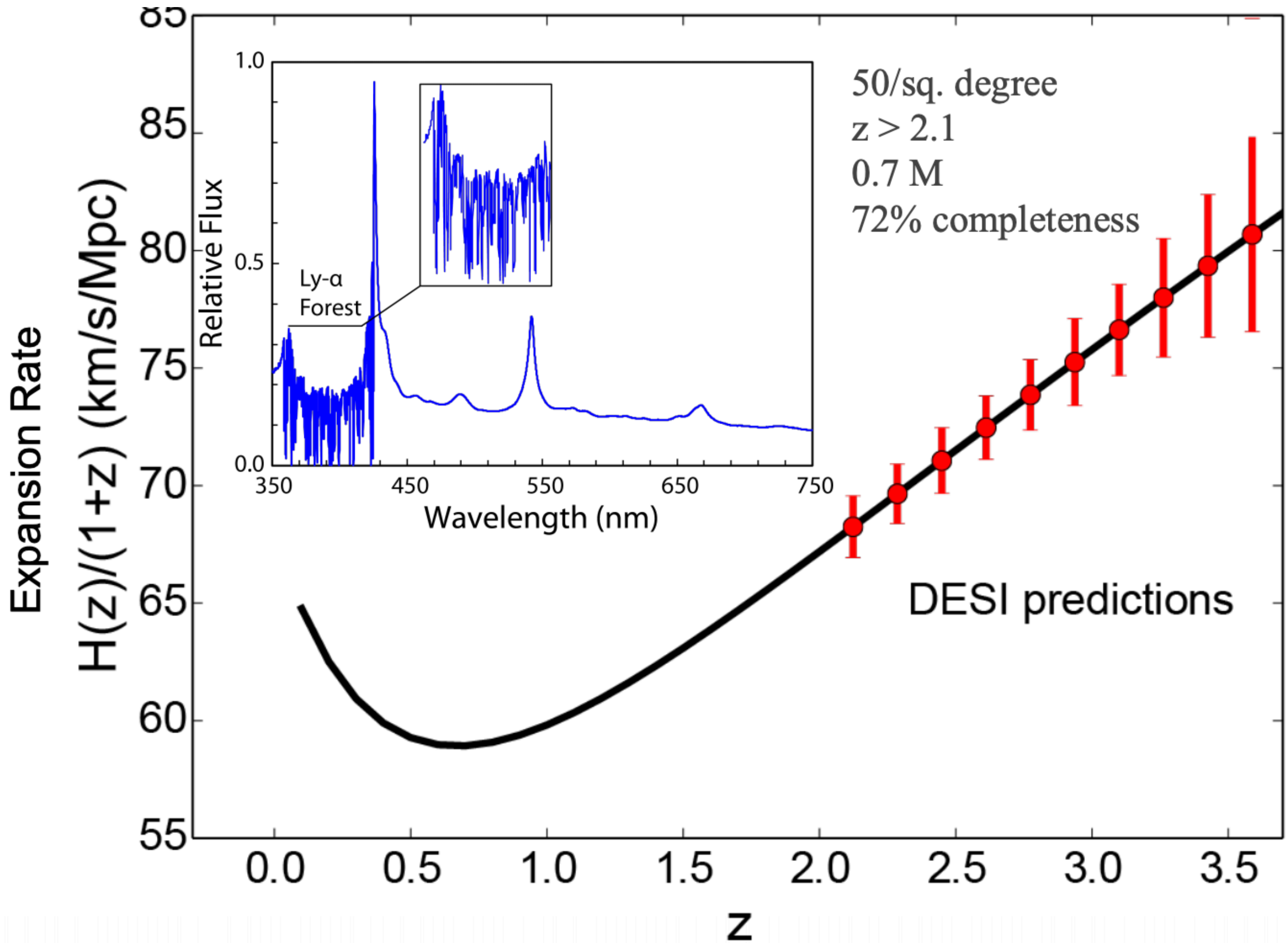
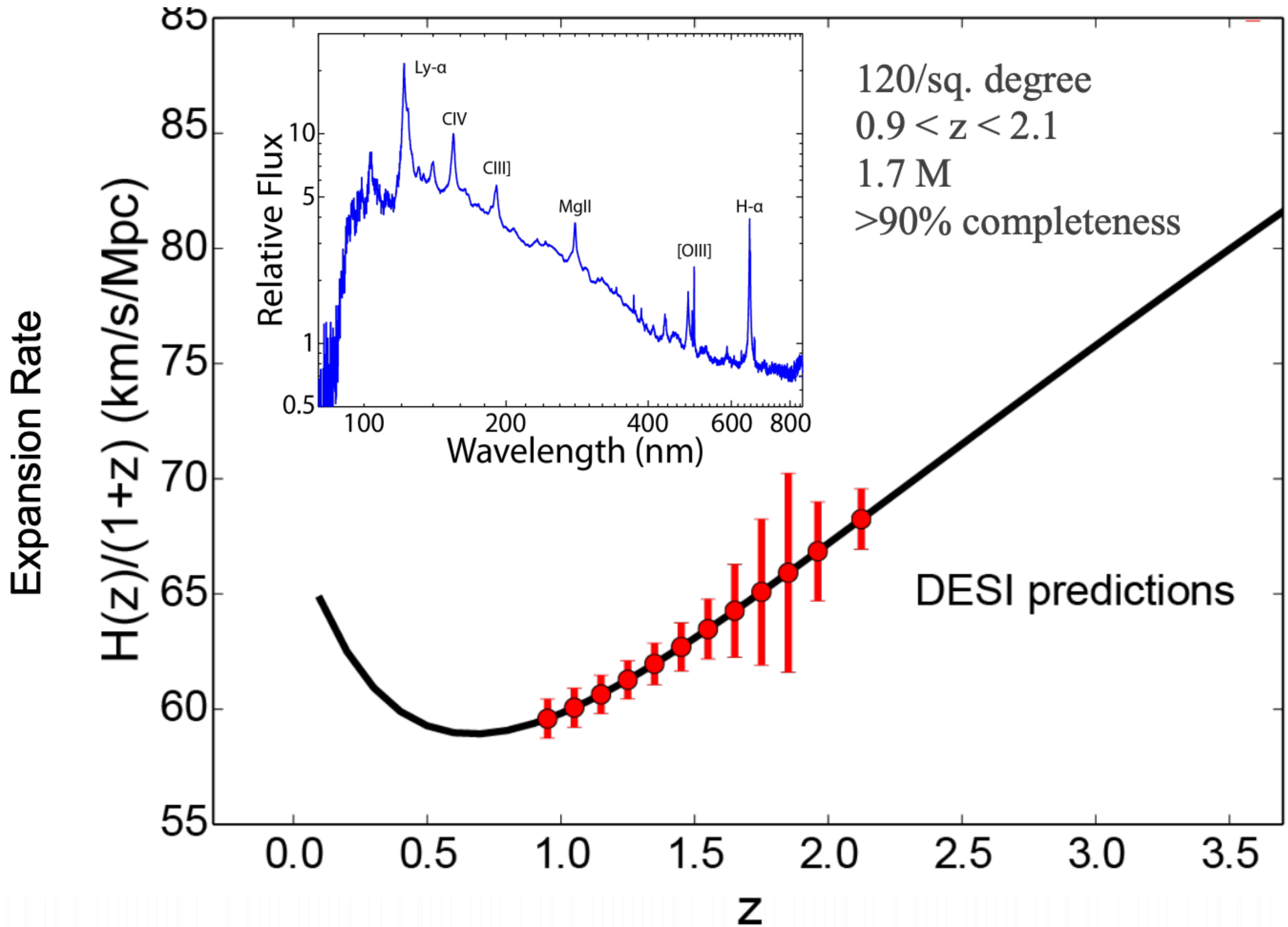
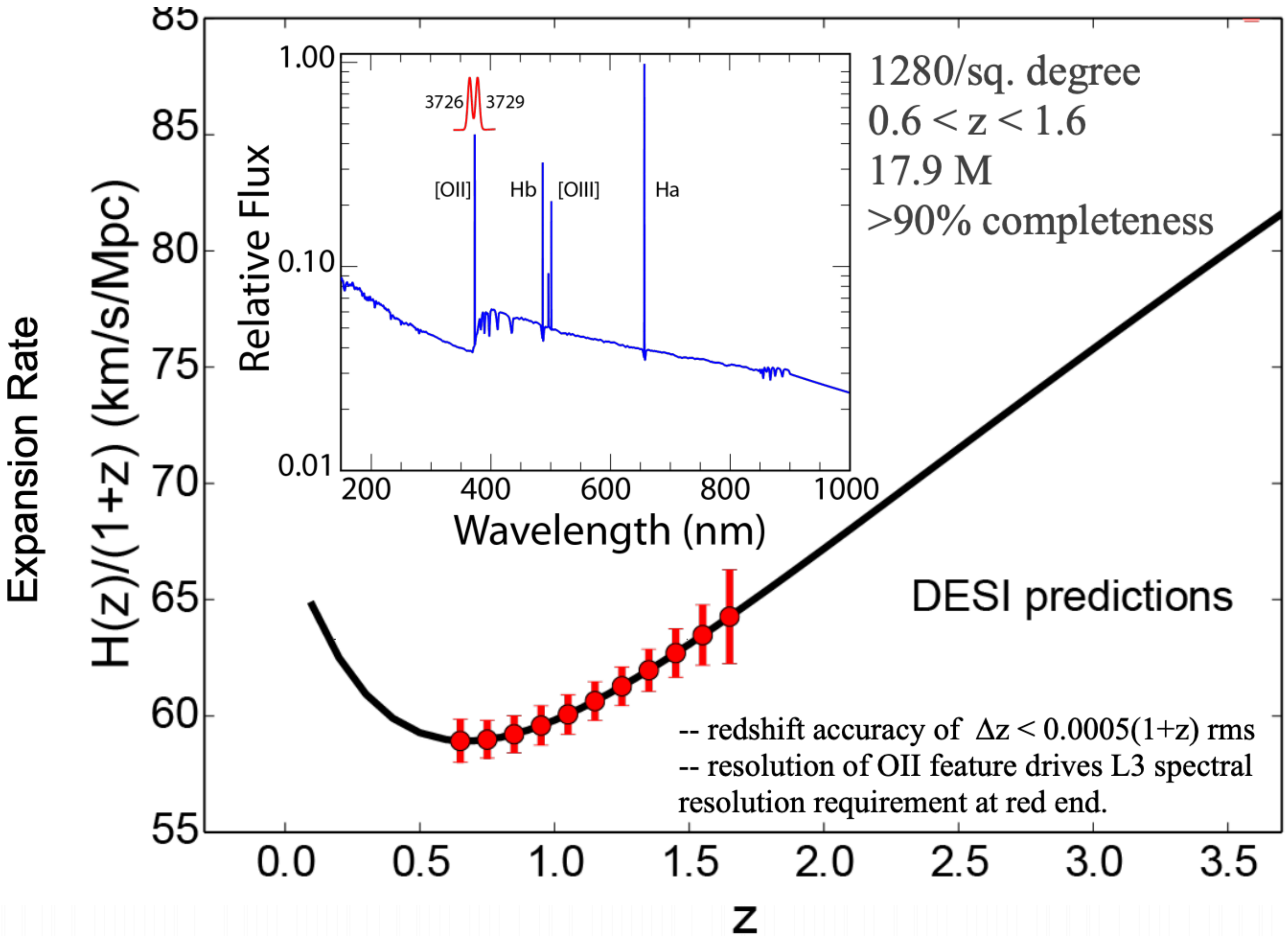
DESI Lyman-Alpha Forest Quasars



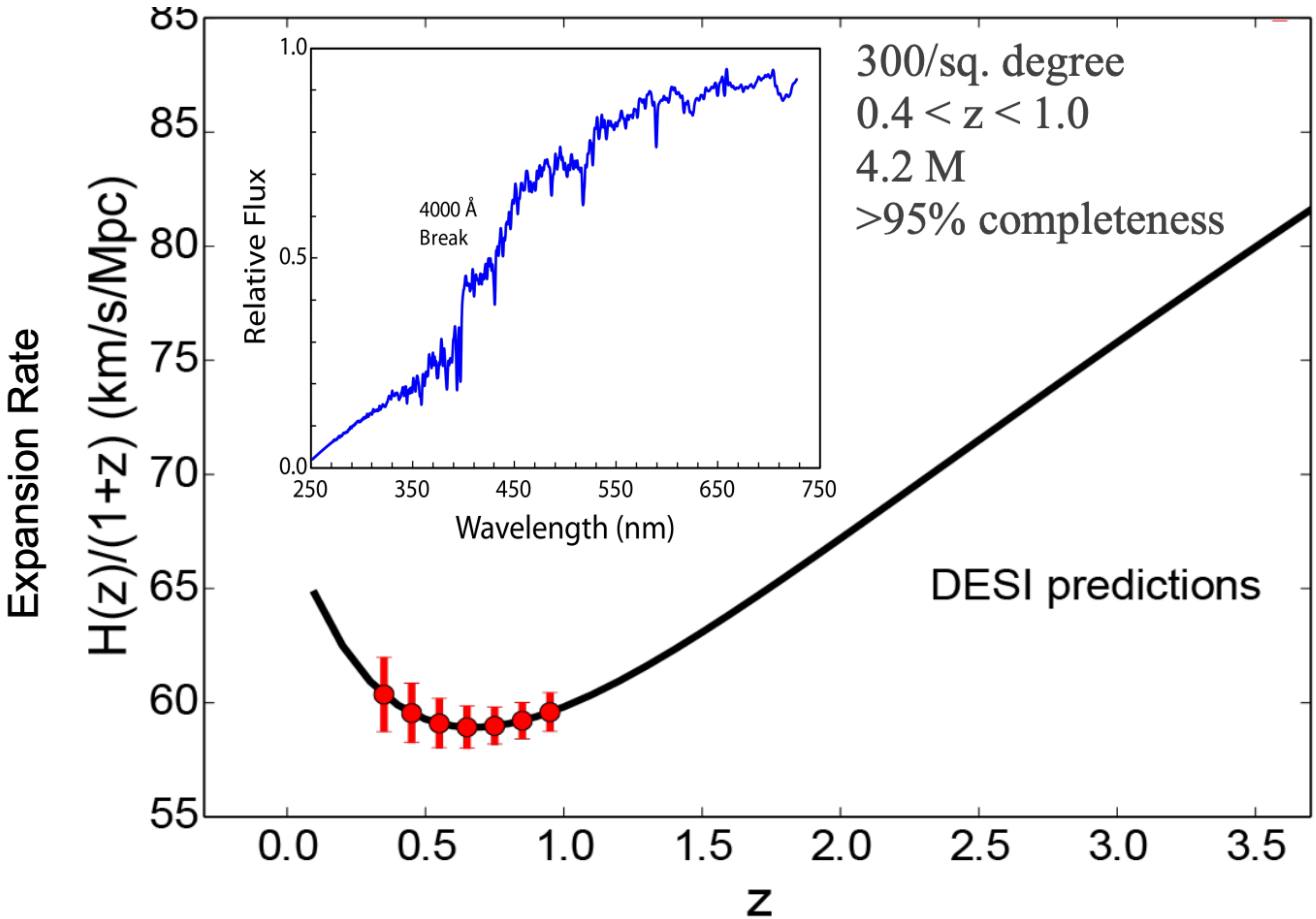
DESI Quasars (QSOs)



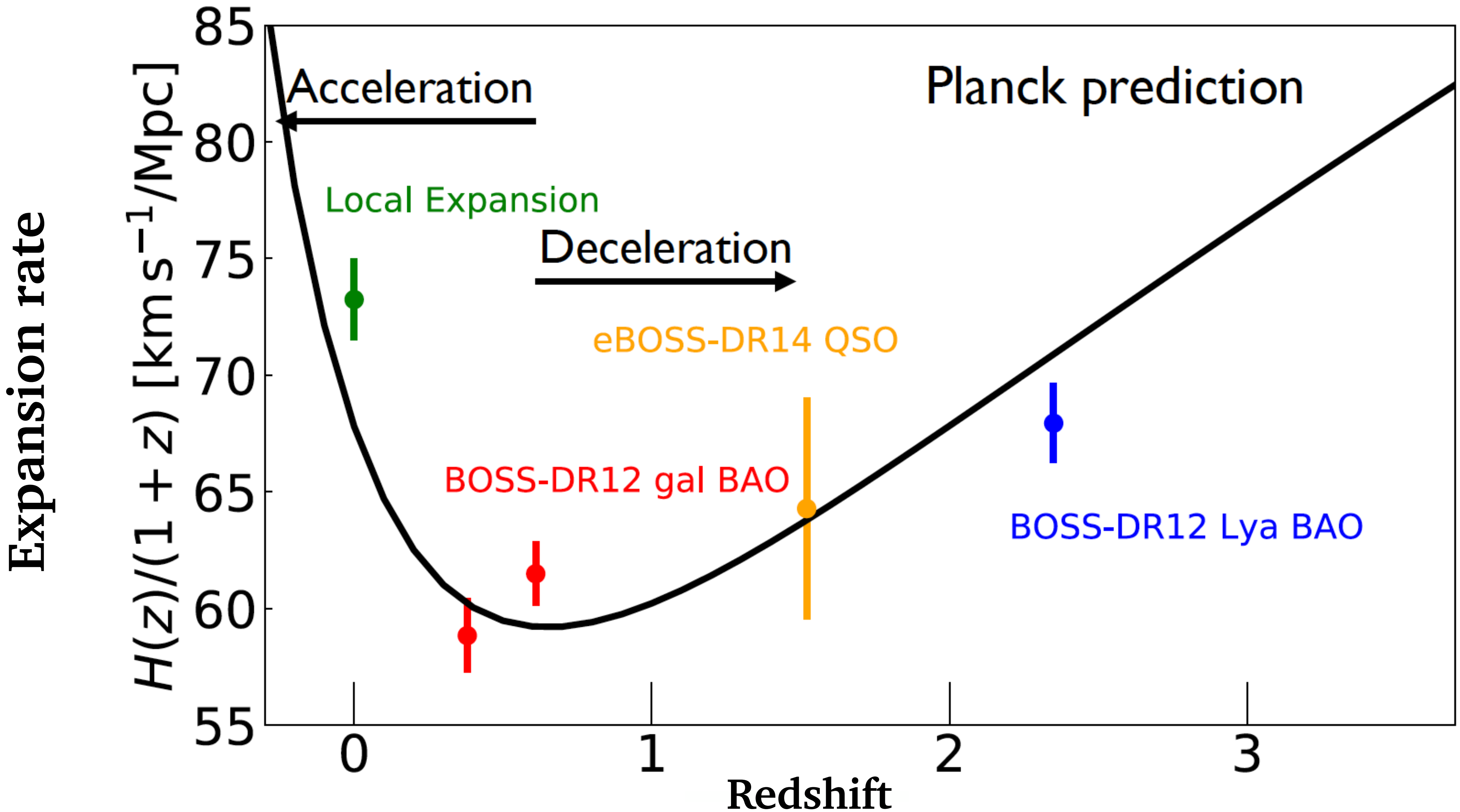
DESI Emission Line Galaxies (ELGs)



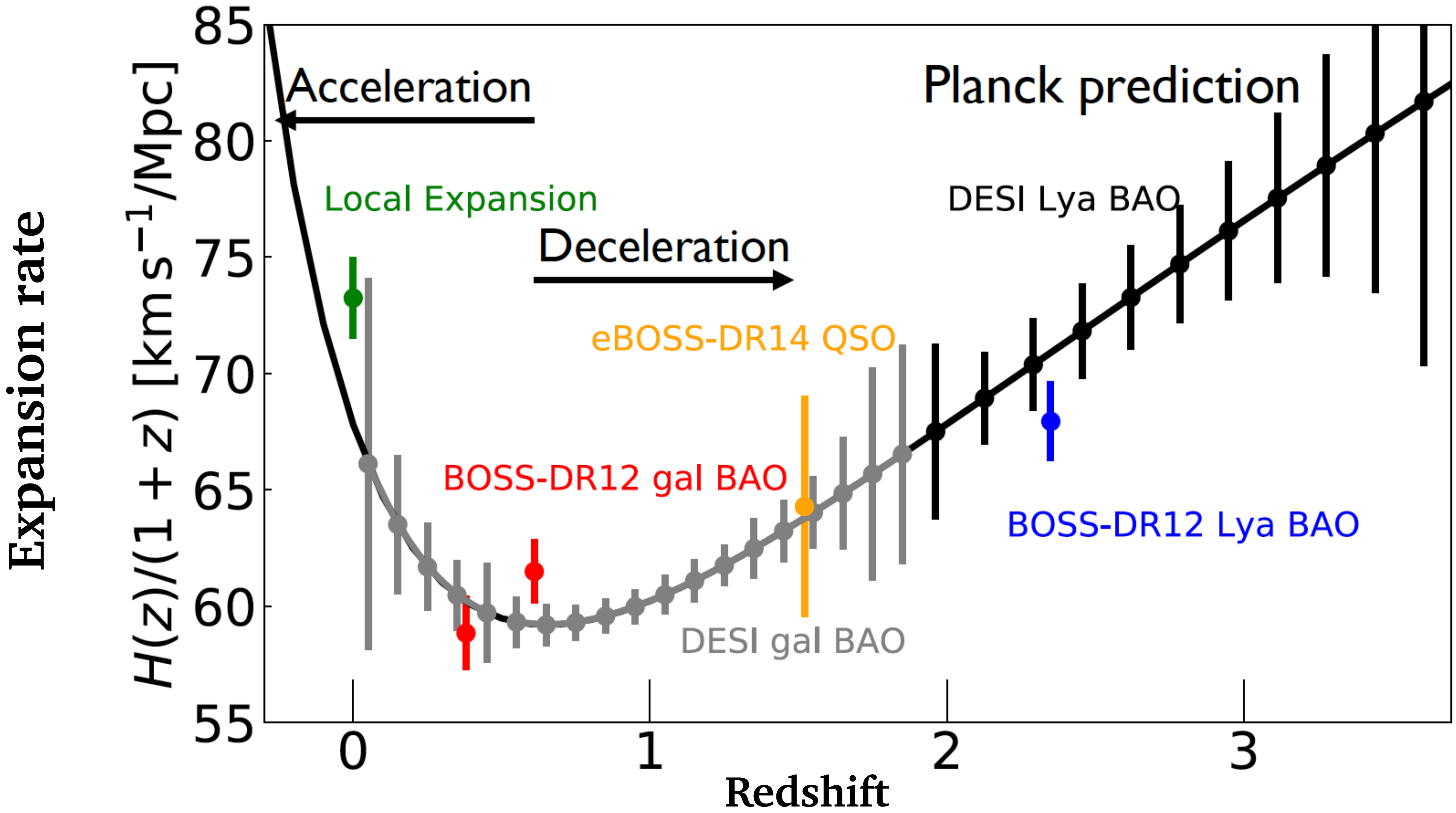
DESI Luminous Red Galaxies (LRGs)



DESI overall after 5 years



DESI projections, **Font-Ribera et al. (2014b)**



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Main Science Cases

One step further from Stage III surveys

- Significantly update BAO and H(z) measurements : Lyα and CIV forests
- Make use of new range of data to measure BAO : MgII forest
- Window open to wide range of cross-checks between different populations

New challenges

- Estimator of the Lyα 3D power spectrum : statistical challenge
- Use the unprecedented statistics to better control systematics

Summary

The SDSS-III Baryon Oscillation Spectroscopic Survey

- 2% measurement at z$\sim$2.3 (quasars and the Lyman-α forest)
- BOSS Lyα showed the forest is ready for precision cosmology

The Dark Energy Spectroscopic Instrument

- DESI will represent an order of magnitude jump in precision
- IGM cosmology a unique, continuous window into different scales
- Statistical and computational challenges…

Exciting times ahead !

Conclusion

"For the past 13 years, we've had a simple model of how dark energy works. But the truth is, we only have a little bit of data, and we're just beginning to explore the times when dark energy turned on. If there are surprises lurking out there, we expect to find them."

–DAVID SCHLEGEL*

*co-PI of the DECals, Project Scientist of DESI