Measuring the Universe with the Dark Energy Spectroscopic Instrument

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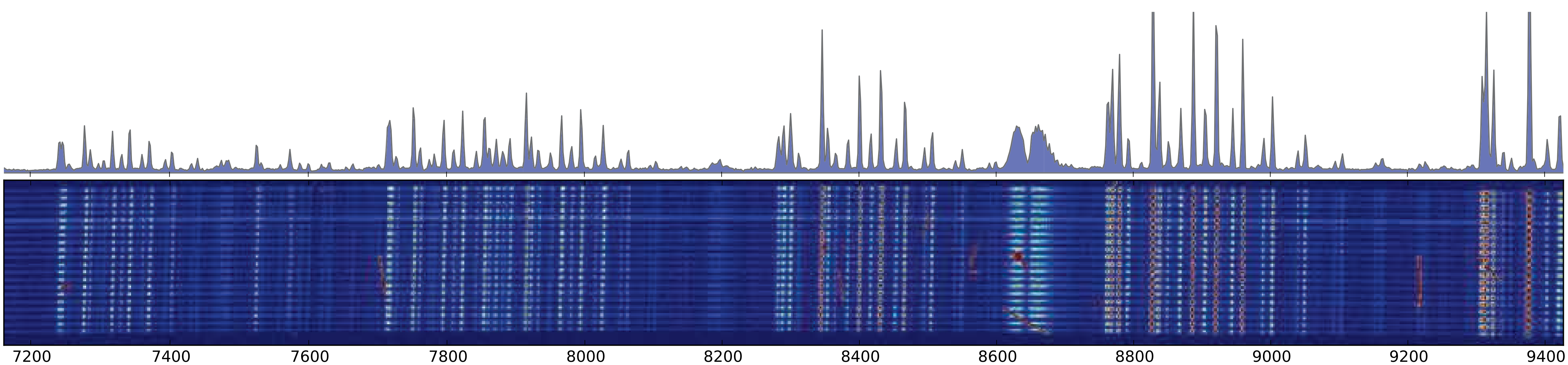
IPMU



Outline

Context

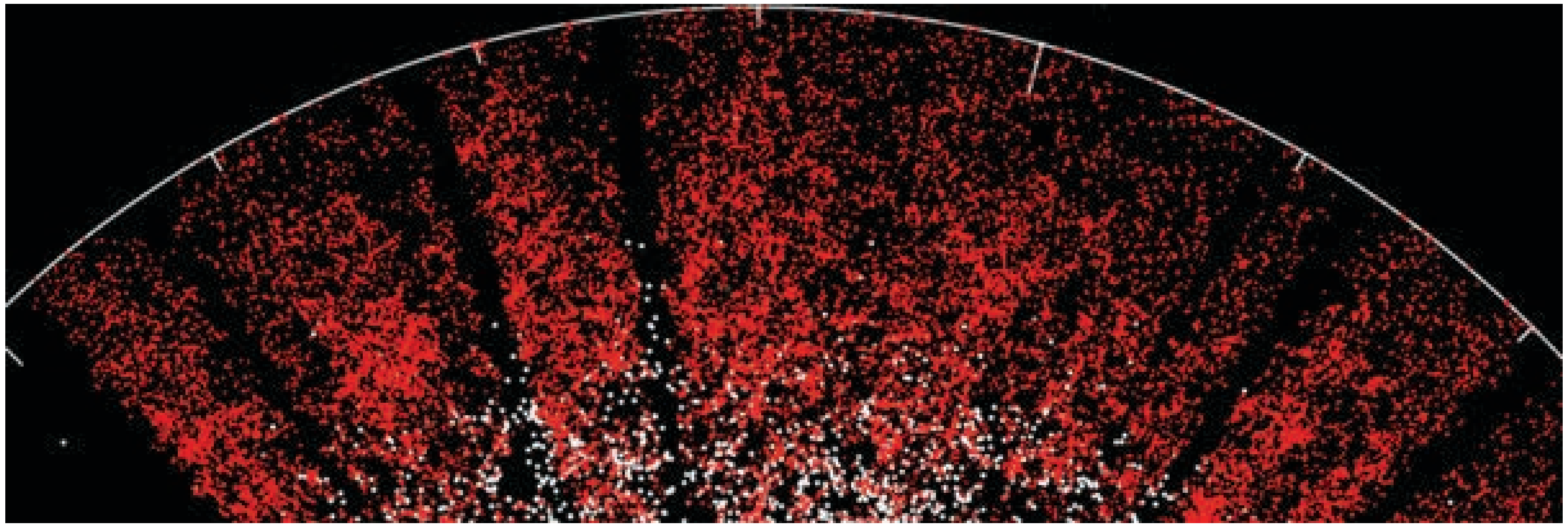
- Galaxy redshift surveys
- Baryon Acoustic Oscillations (BAO) & related probes

Current generation surveys

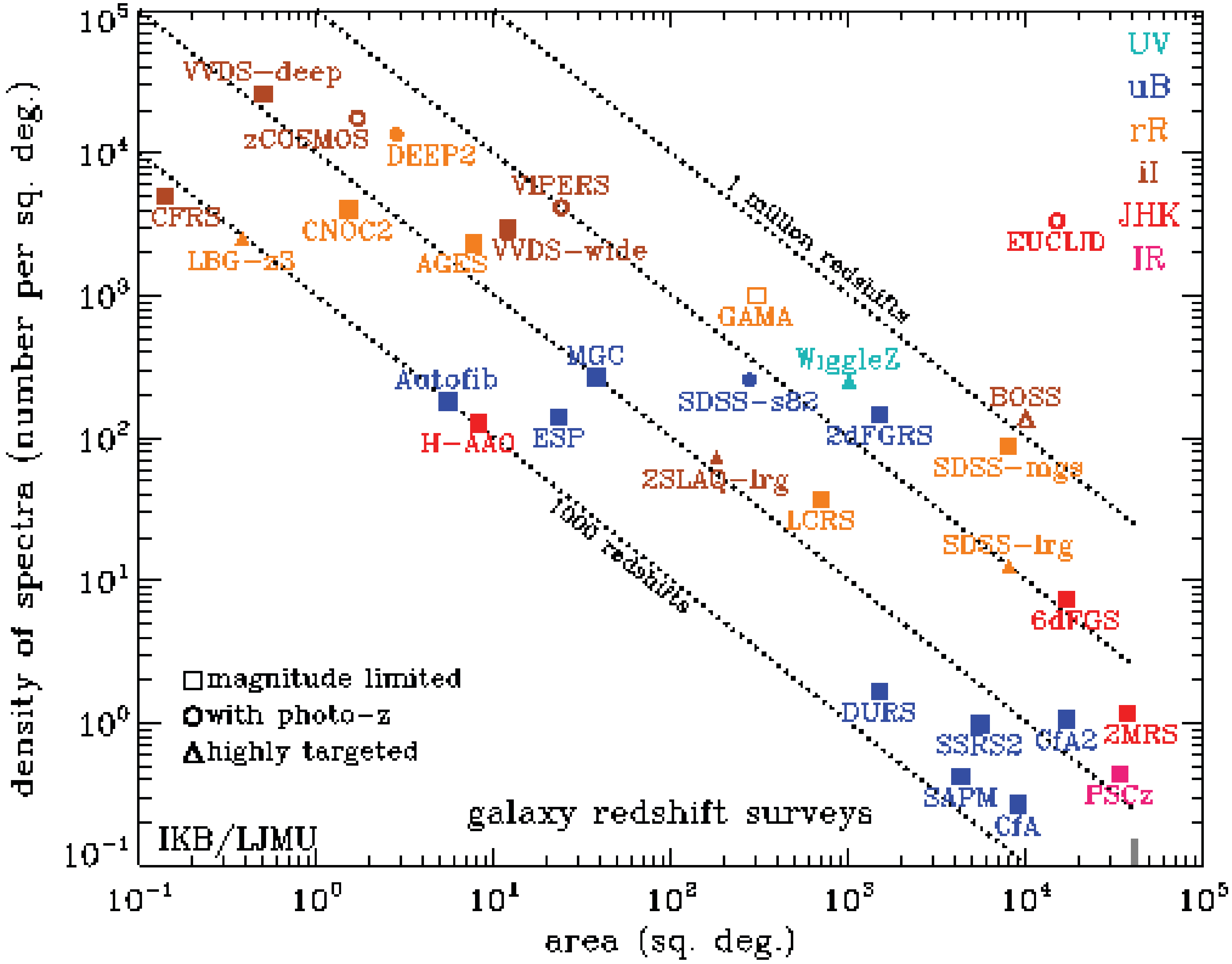
- BOSS & eBOSS

Dark Energy Spectroscopic Instrument (DESI) Survey

- Hardware
- Science
- Data Systems



Galaxy Redshift Surveys



http://www.astro.ljmu.ac.uk/~ikb/research/galaxy-redshift-surveys.html

Comparison between galaxy redshift surveys: *squares* represent predominantly magnitude-limited surveys; *circles* represent surveys involving colour cuts for photometric redshift selection; while *triangles* represent highly targeted surveys. Filled symbols show completed surveys. The grey region shows the parameter space covered by magnitude-limited surveys. Surveys are colour coded according to selection wavelength. The dotted lines correspond to surveys of 1000, 10^4, 10^5 and 10^6 galaxies.

What's out there?
- fundamental astro

Where is it?
- cosmic rulers

How is it moving?
- universe expansion, redshift space distortions

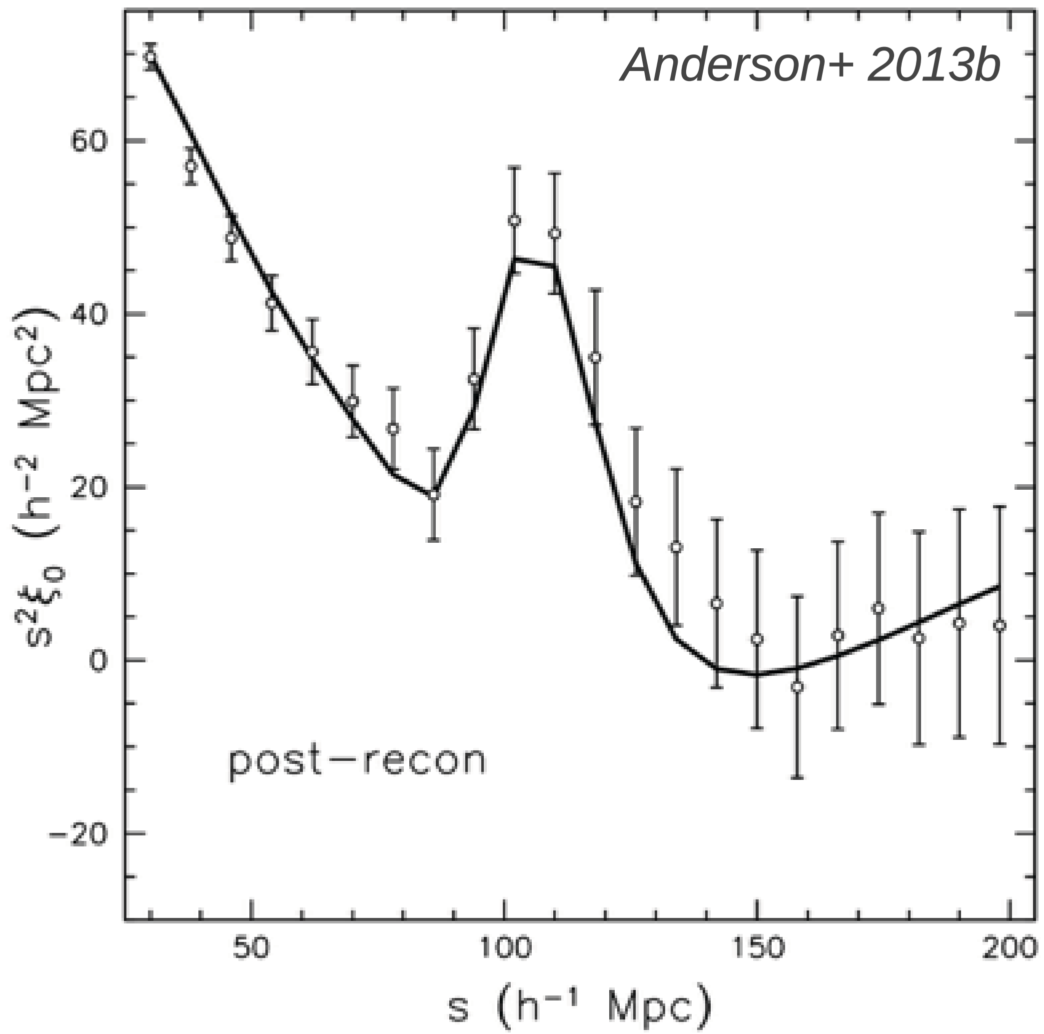
Baryon Acoustic Oscillations

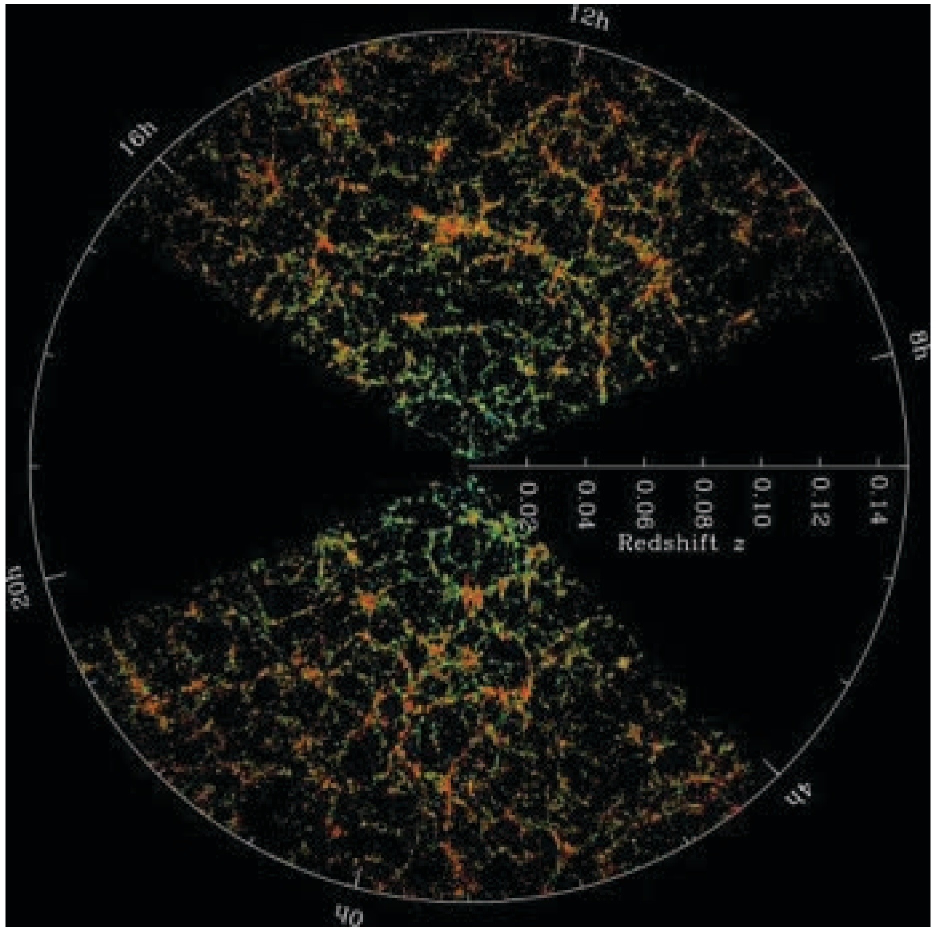
Frozen sound waves from early universe

Seeds of large scale structure

Observable signature

- Excess probability of galaxies separated by ~100 Mpc/h





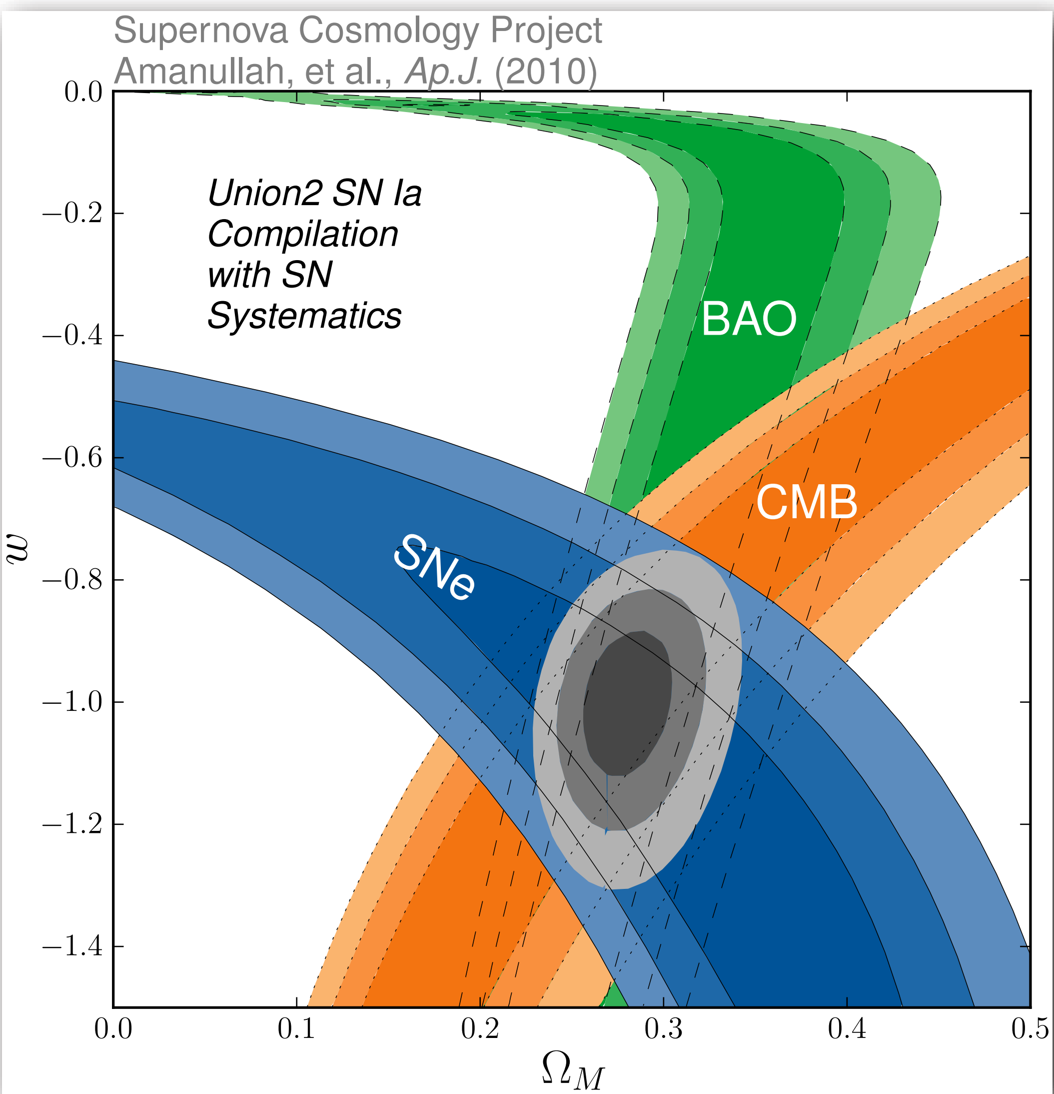
Why BAO?

$$d_L(z) = (1+z)\frac{c}{H_0}\int dz'\left(\Omega_M(1+z')^3 + \Omega_k(1+z)^2 + \Omega_X \exp\left(\int_0^z 3\frac{1+w(z')}{1+z'}dz'\right)\right)^{-1/2}$$

Distance

Redshift

Cosmology parameters



Standard ruler to measure expansion of universe.

Nicely complementary to other cosmology probes.

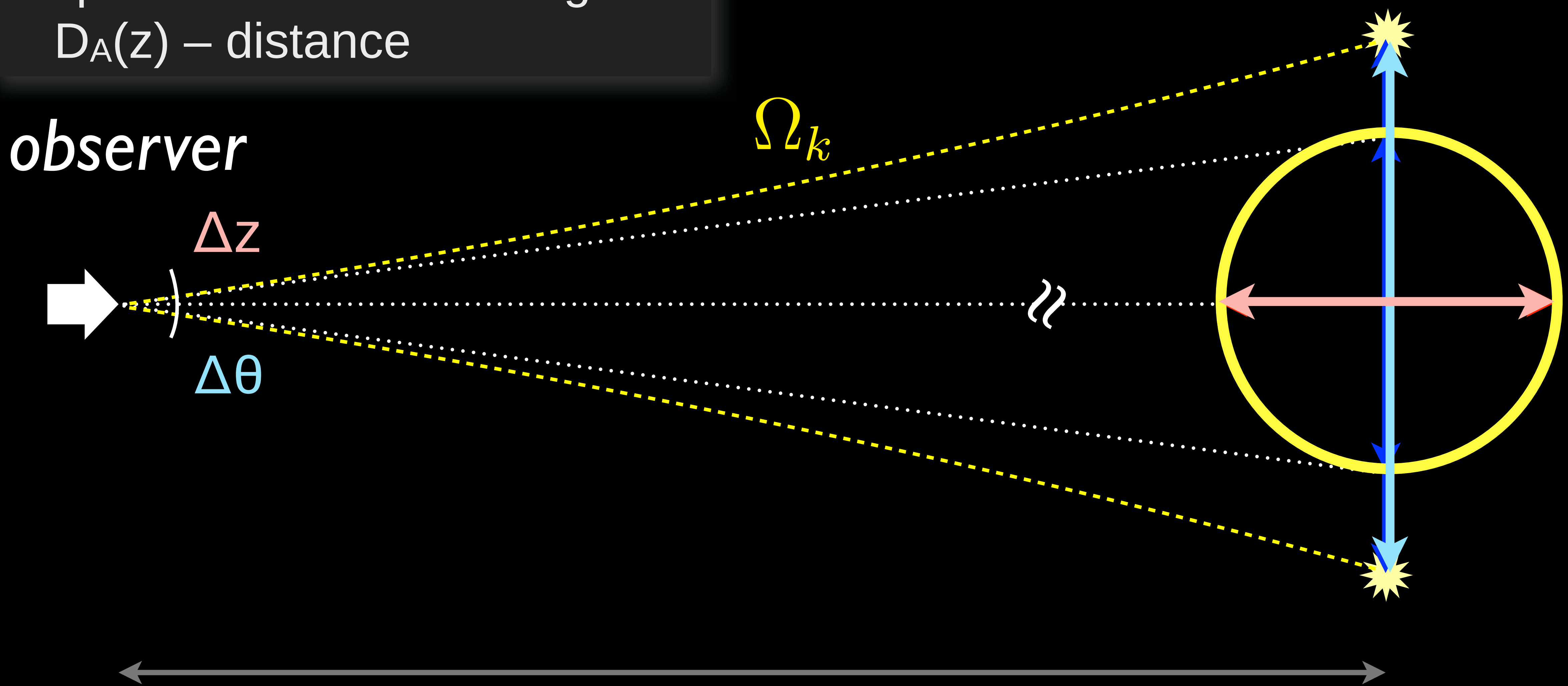
3D BAO

Parallel to line of sight:
- H(z) – expansion of universe

Perpendicular to line-of-sight:
- $D_A(z)$ – distance

$$\Delta r_{\parallel} = \frac{c}{H(z)} \Delta z$$

$$\Delta r_{\perp} = (1+z)\, D_A(z)\, \Delta\theta$$

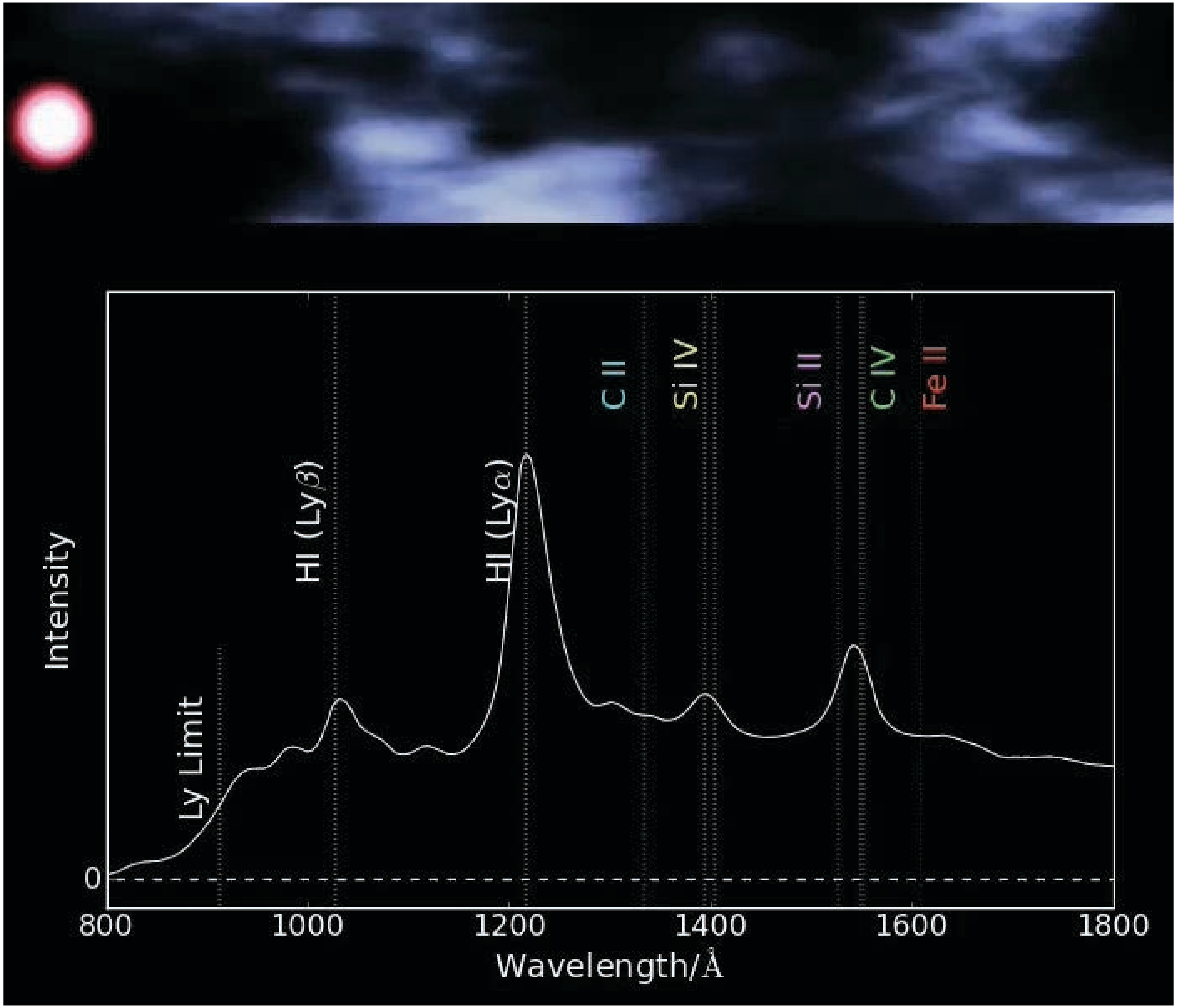


$$r_{\parallel}(z) = \int_0^z \frac{c}{H(z')} dz'$$

Graphics compliments of D. Kirkby, UC Irvine

St

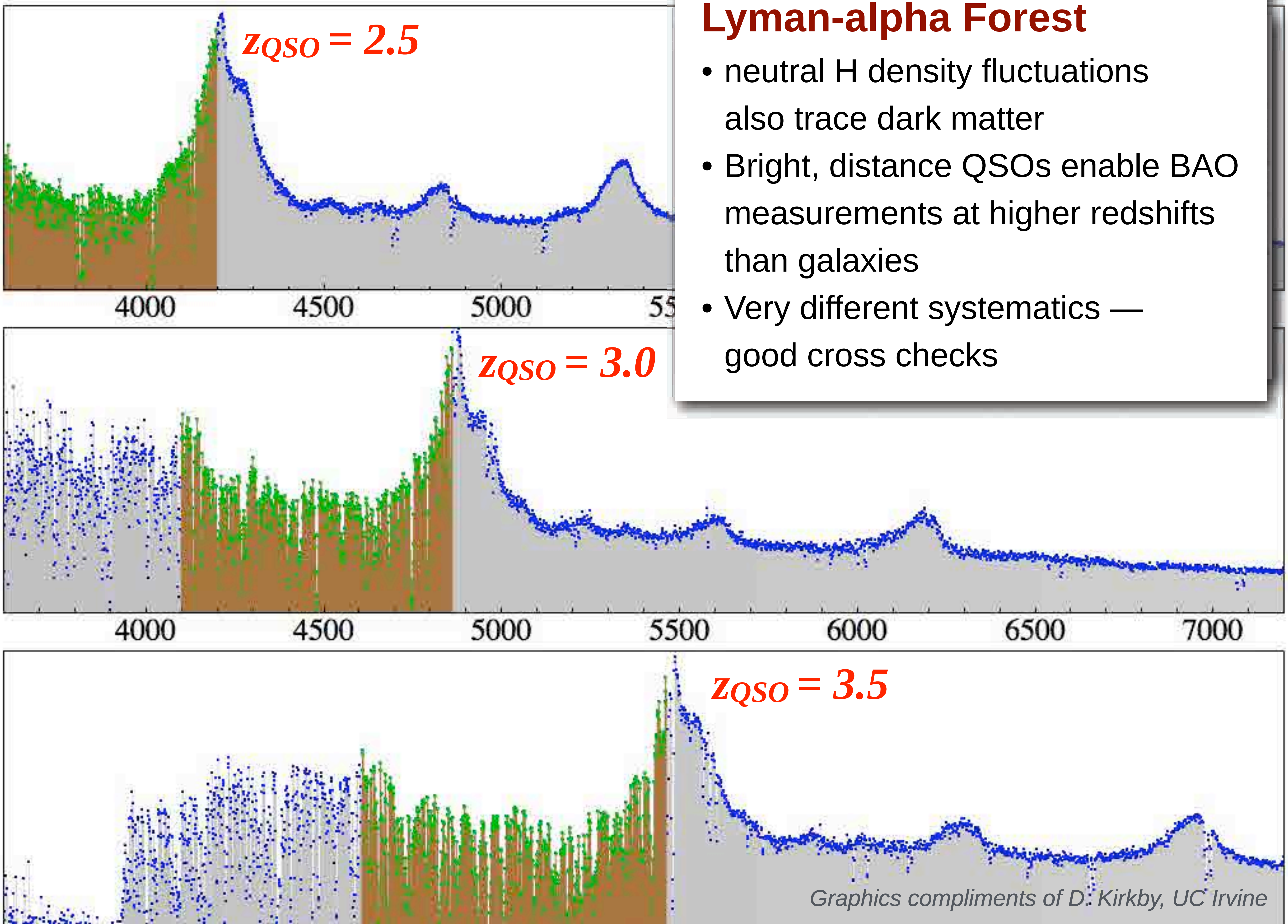
Lyman-alpha Forest



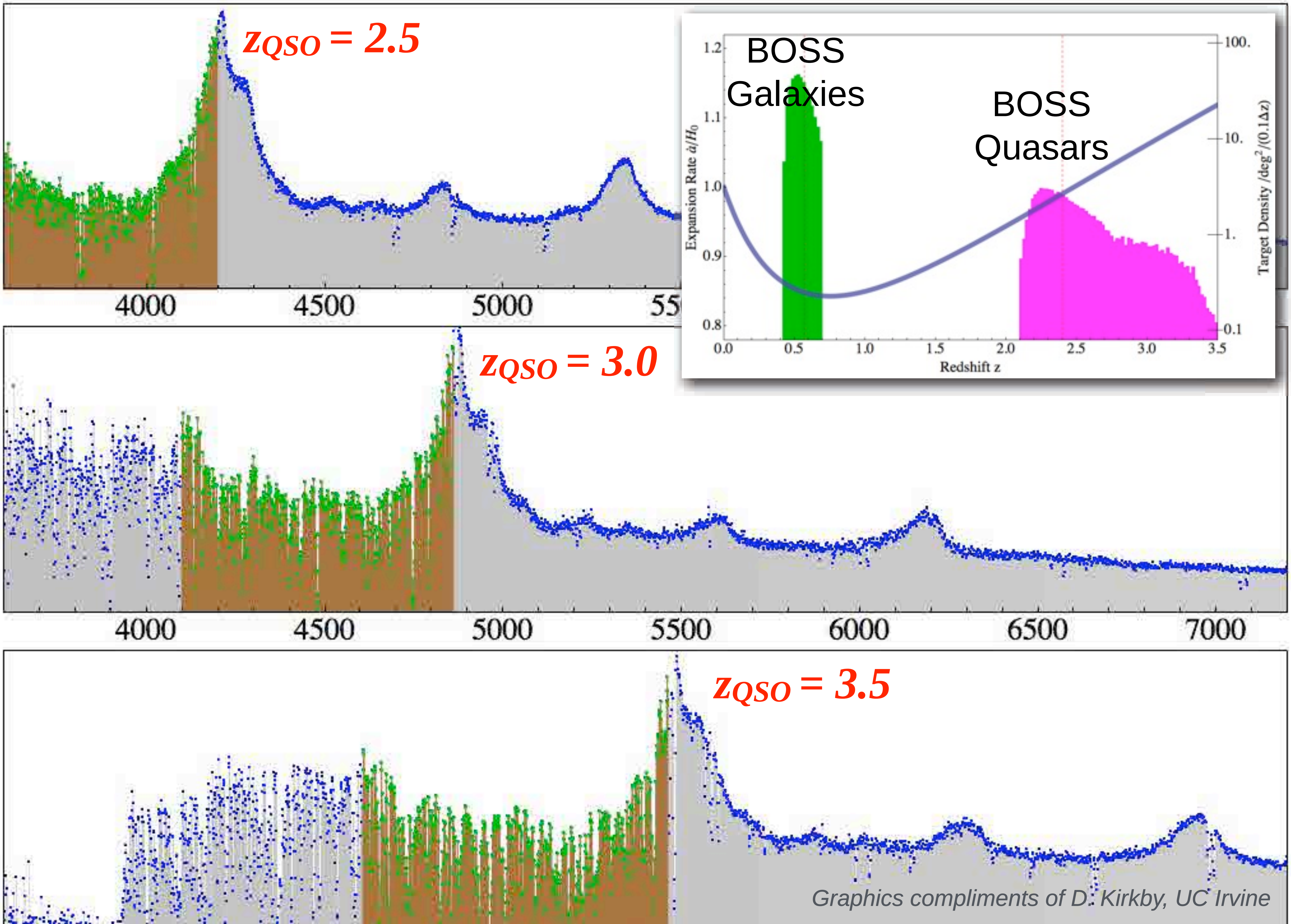
Credit: Andrew Pontzen

Lyman-alpha Forest

- neutral H density fluctuations also trace dark matter
- Bright, distance QSOs enable BAO measurements at higher redshifts than galaxies
- Very different systematics — good cross checks



Graphics compliments of D. Kirkby, UC Irvine



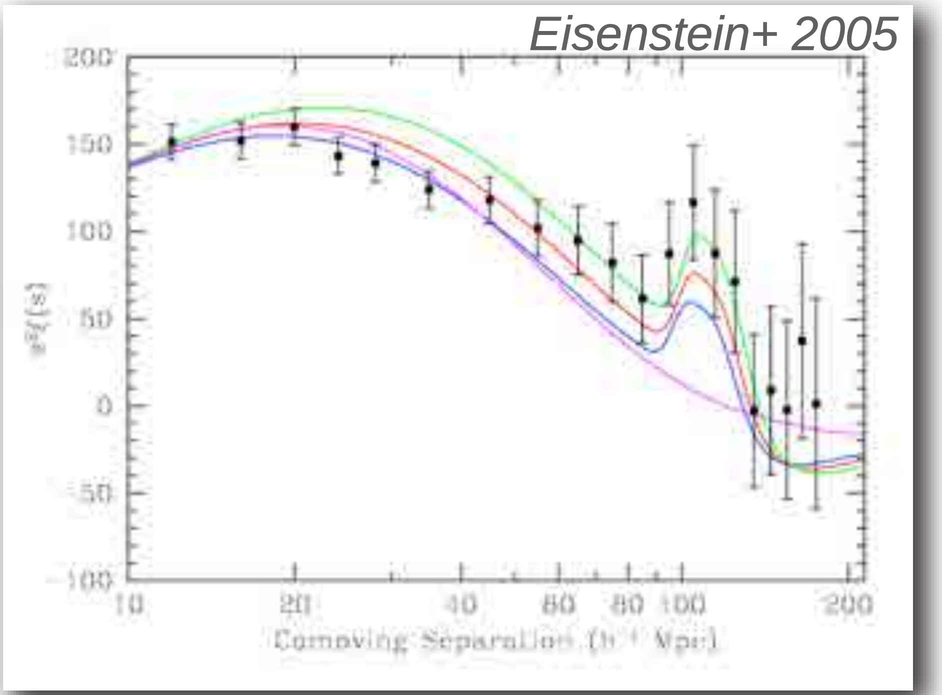
z_QSO = 2.5
z_QSO = 3.0
z_QSO = 3.5
4000
4500
5000
5500
6000
6500
7000
BOSS Galaxies
BOSS Quasars
Expansion Rate ȧ/H0
Target Density /deg²/(0.1Δz)
Redshift z
1.2
1.1
1.0
0.9
0.8
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
100.
10.
1.
0.1
Graphics compliments of D. Kirkby, UC Irvine

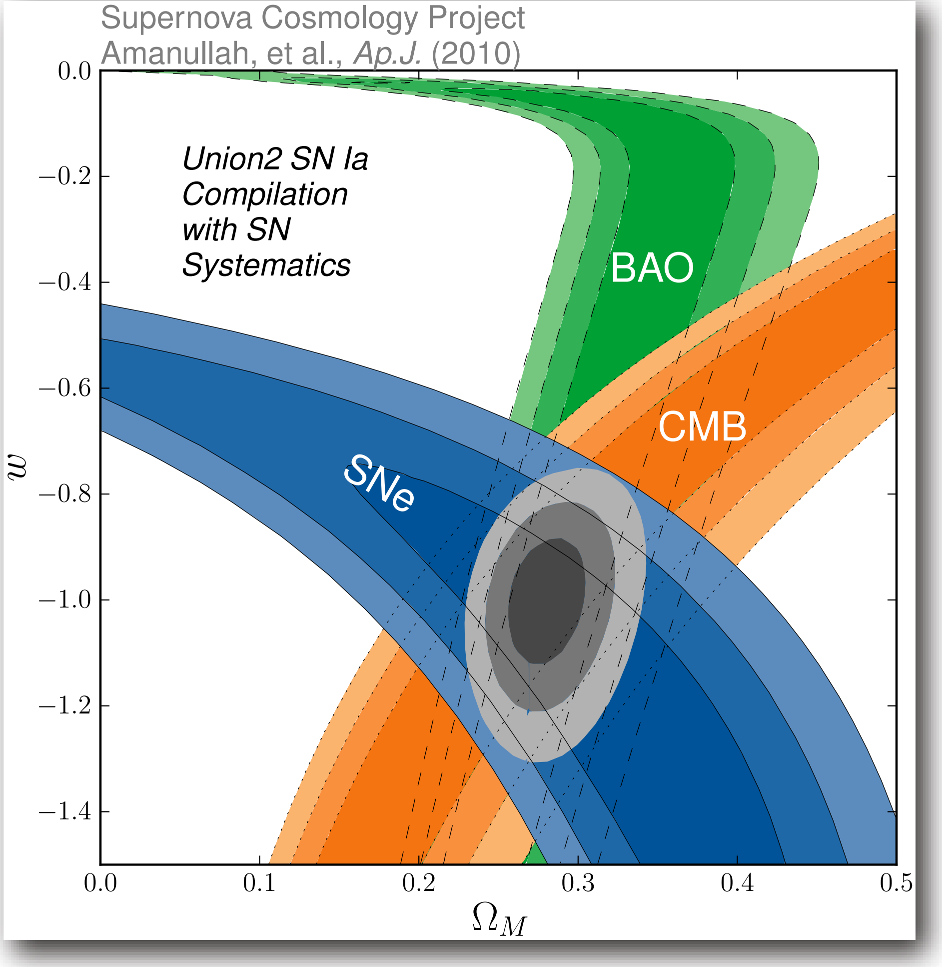
Classic BAO Results

Ties the CMB (~400k years) to galaxies (~13B years)

Provides standard ruler for cosmology measurements

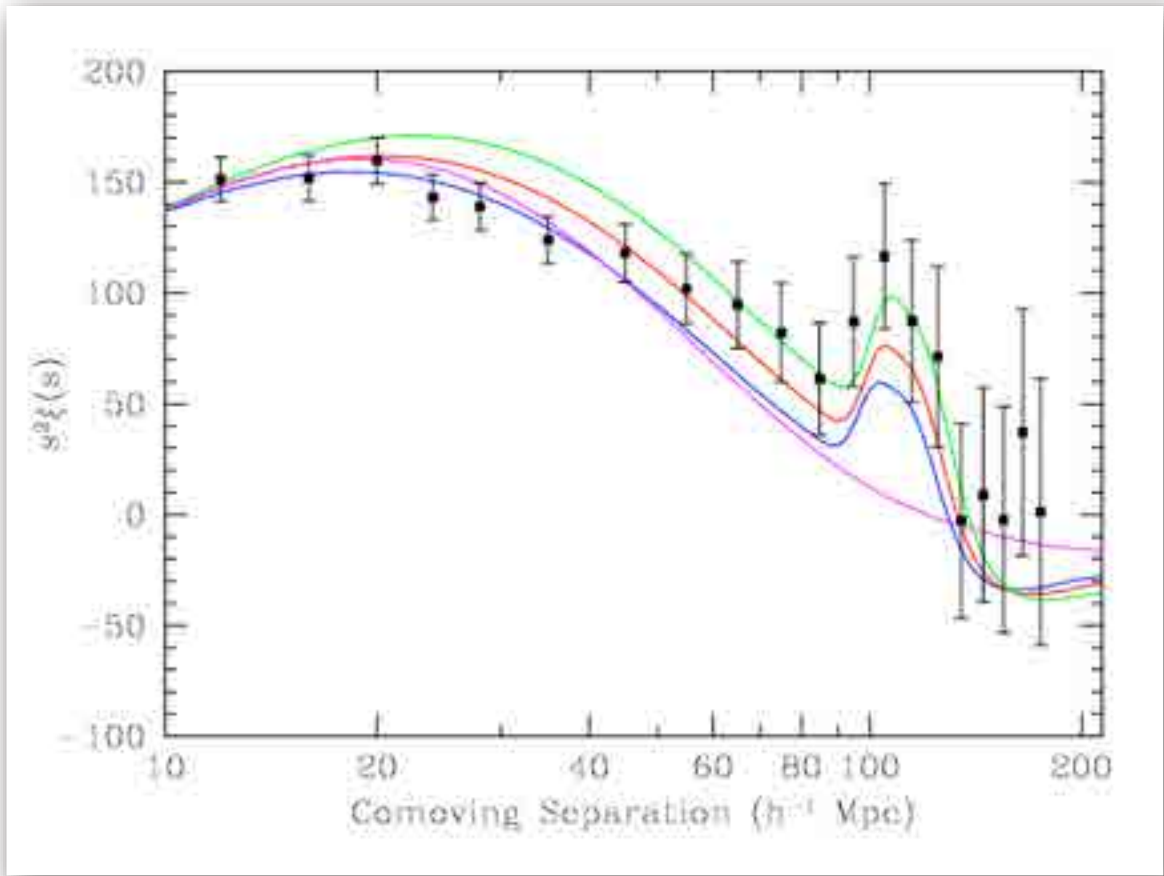
- Compliments Supernovae for Dark Energy constraints



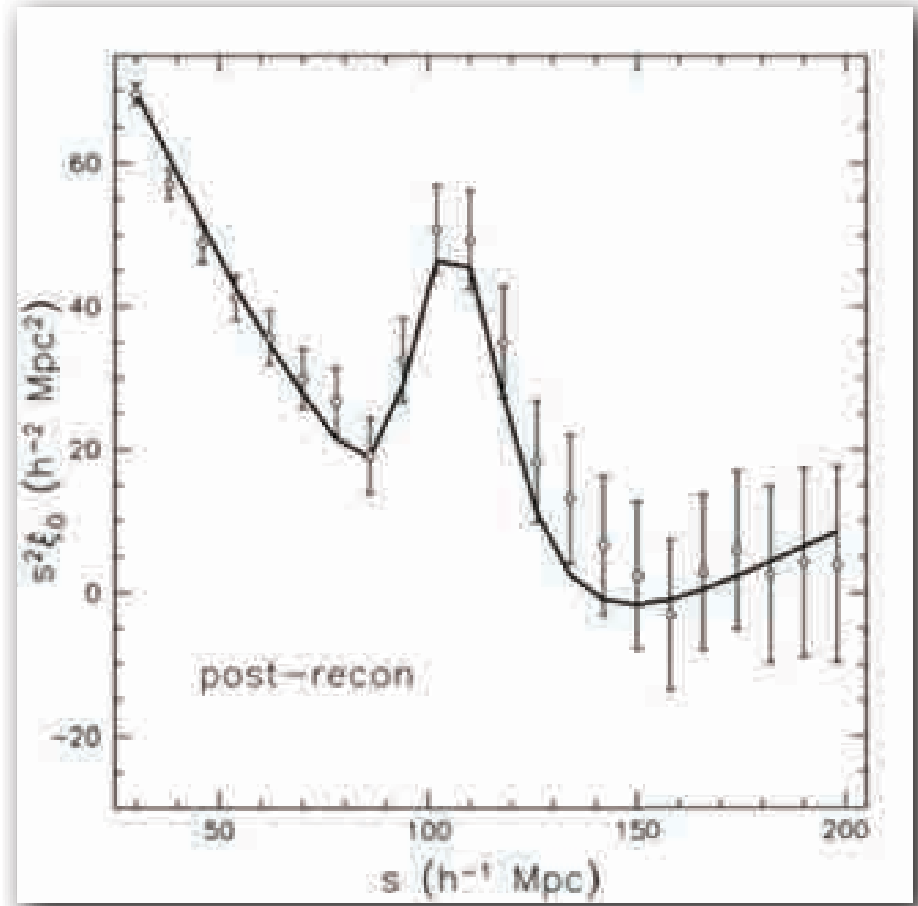


BOSS Galaxy BAO

Eisenstein+ 2005

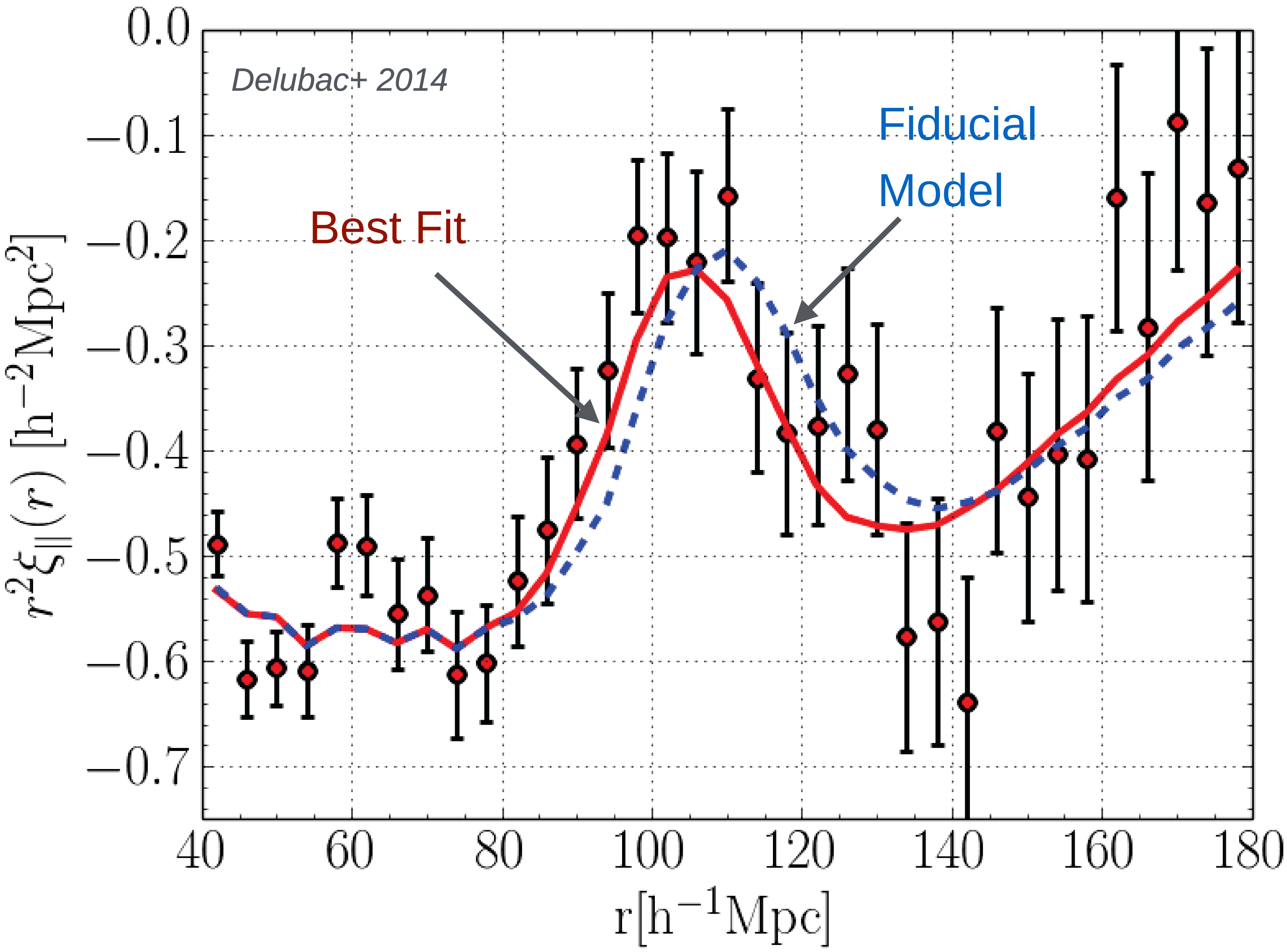


Anderson+ 2013b



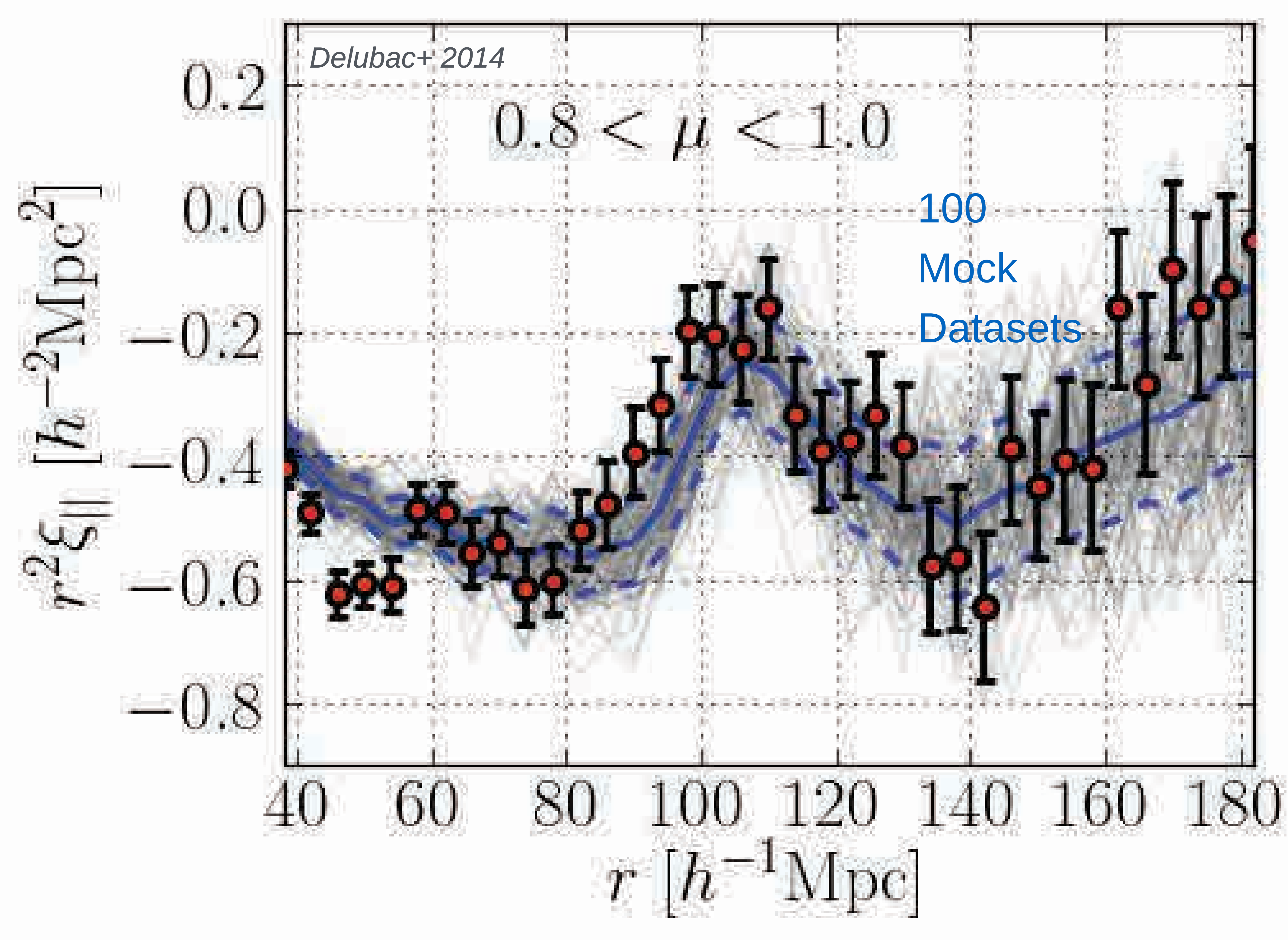
Note: error bars are correlated; do not try chi-by-eye

BAO with the Lyman-α Forest

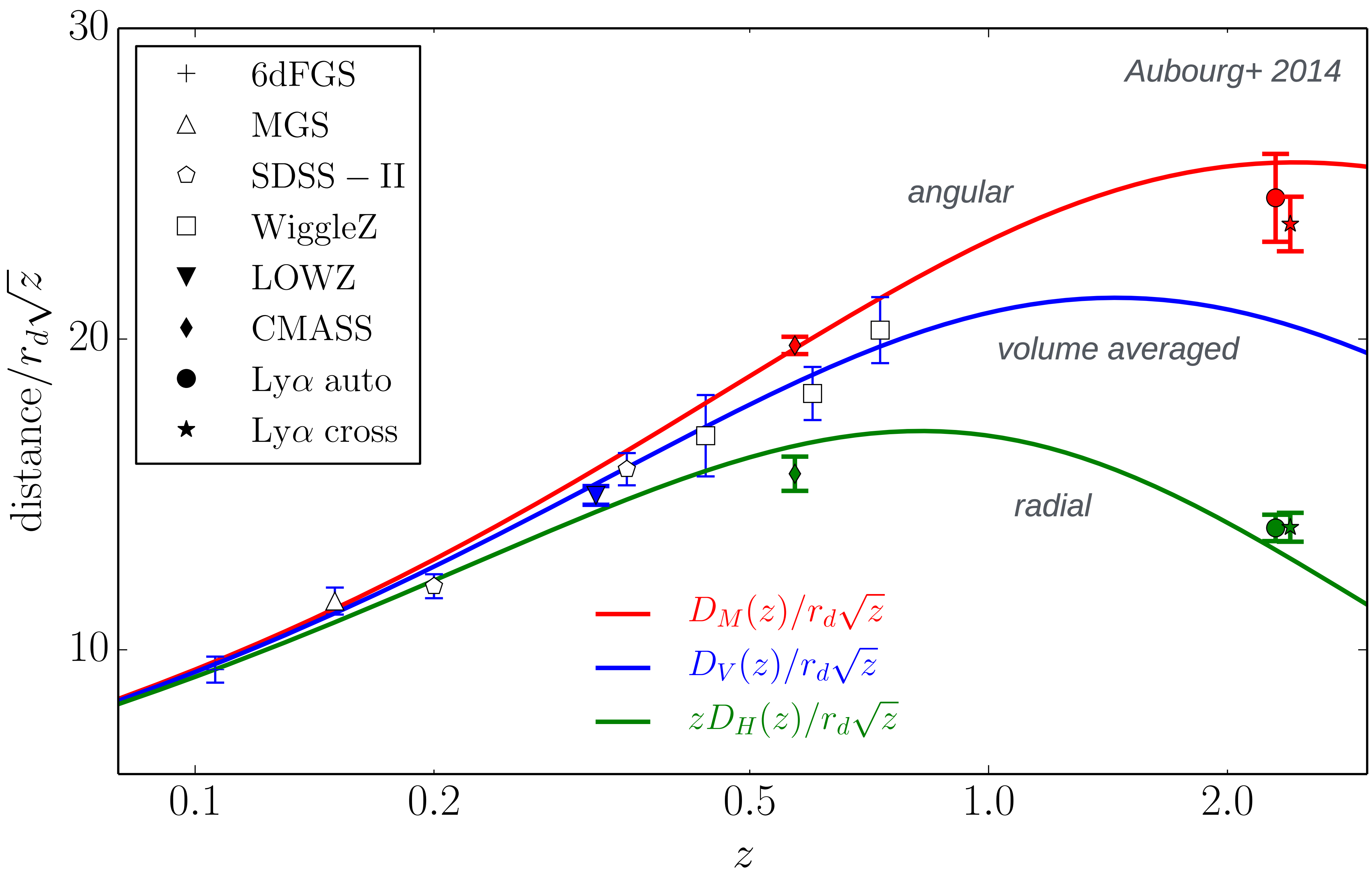


Fiducial: Flat ΛCDM Ω_m=0.27

BAO with the Lyman-α Forest



BAO Hubble Diagram

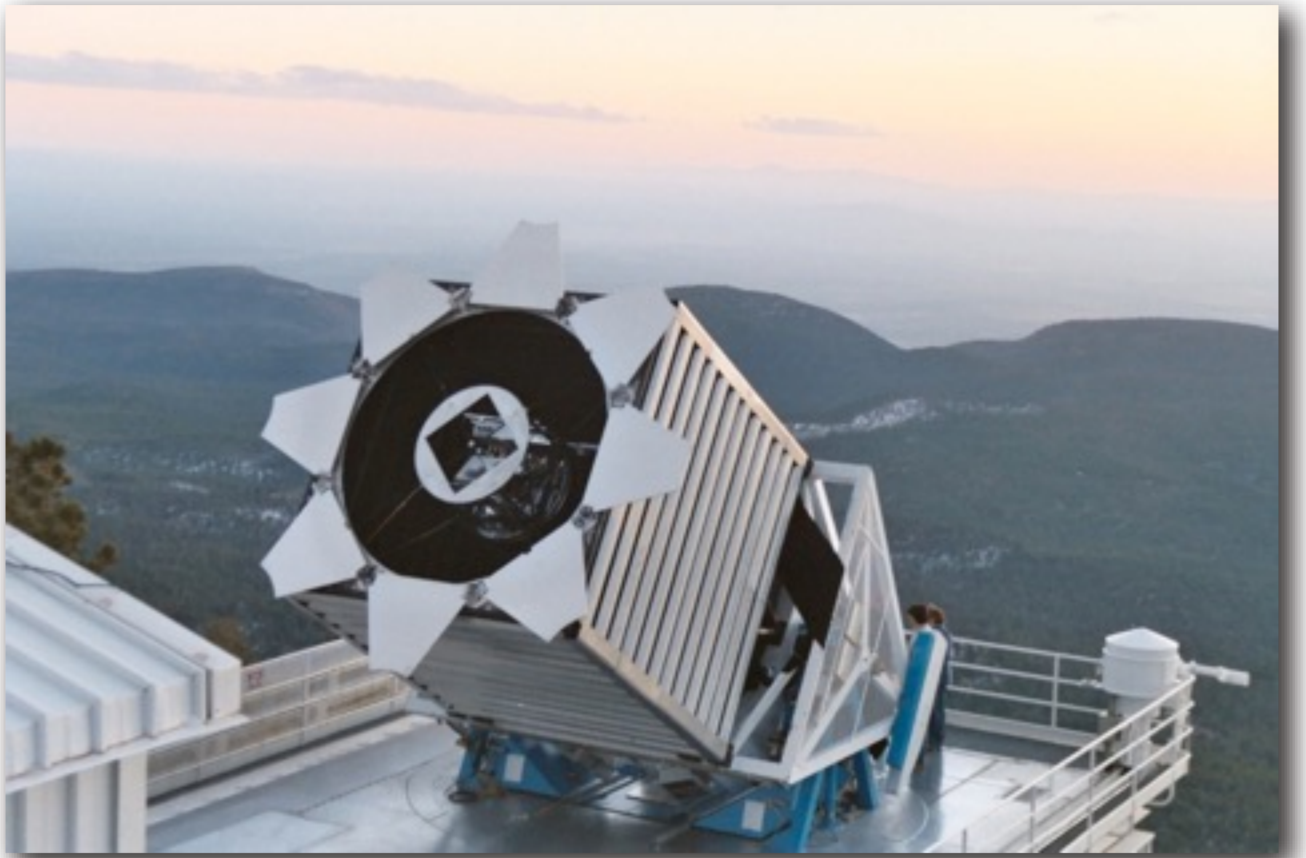


Aubourg et al. 2014 arXiv:1411.1074

Cosmological implications of baryon acoustic oscillation (BAO) measurements

BOSS: Baryon Oscillation Spectroscopic Survey

3rd Generation of Sloan Digital Sky Survey



Spectra of:

- 1.5M galaxies
- 160k quasars

2.5m telescope at Apache Point Observatory

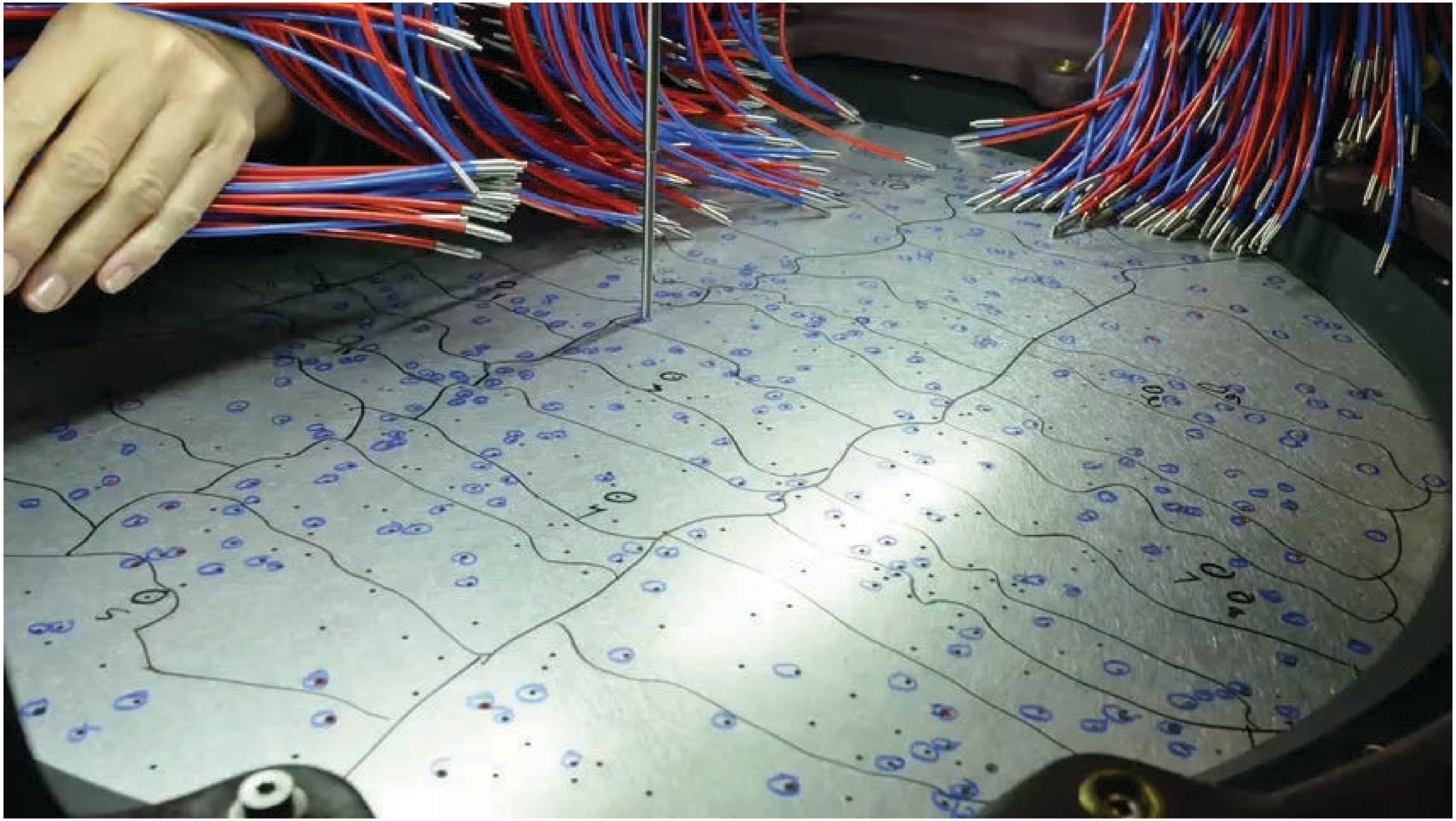
Improvements from SDSS-I & II

- More sky area (7600 → 10800 deg^2)
- Deeper redshifts ($z \sim 0.5 \rightarrow 0.7$)
- Better instrument throughput
- Denser sampling (640 →1000 fibers/plate)

Plate Plugging

- Each field is unique plate drilled with target positions
- 1000 fibers per plate plugged by hand
- Up to 9 plates per night

BOSS Plugging

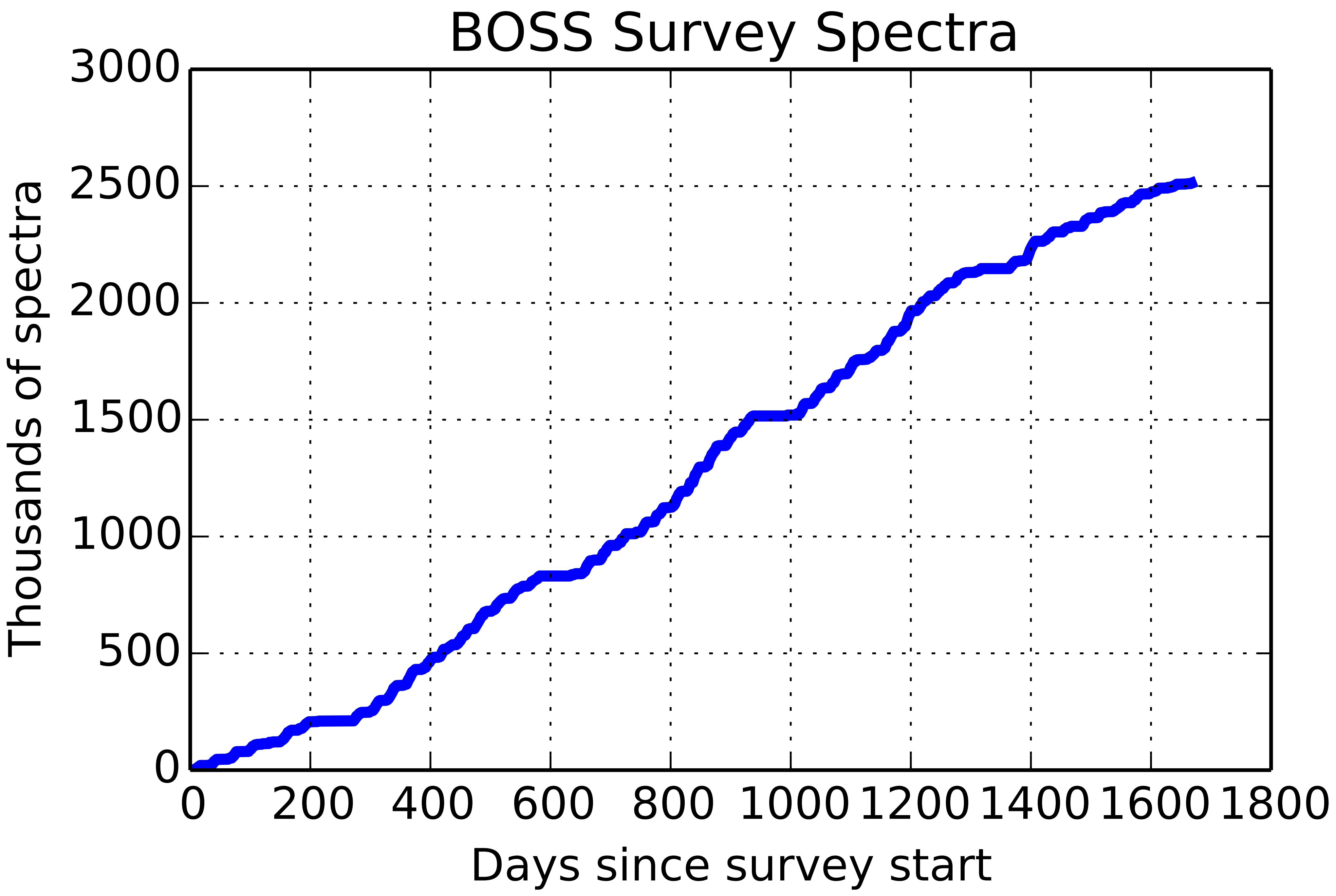


Plates are mounted on carts & changed for each field

Simple, effective, but hard to scale beyond BOSS

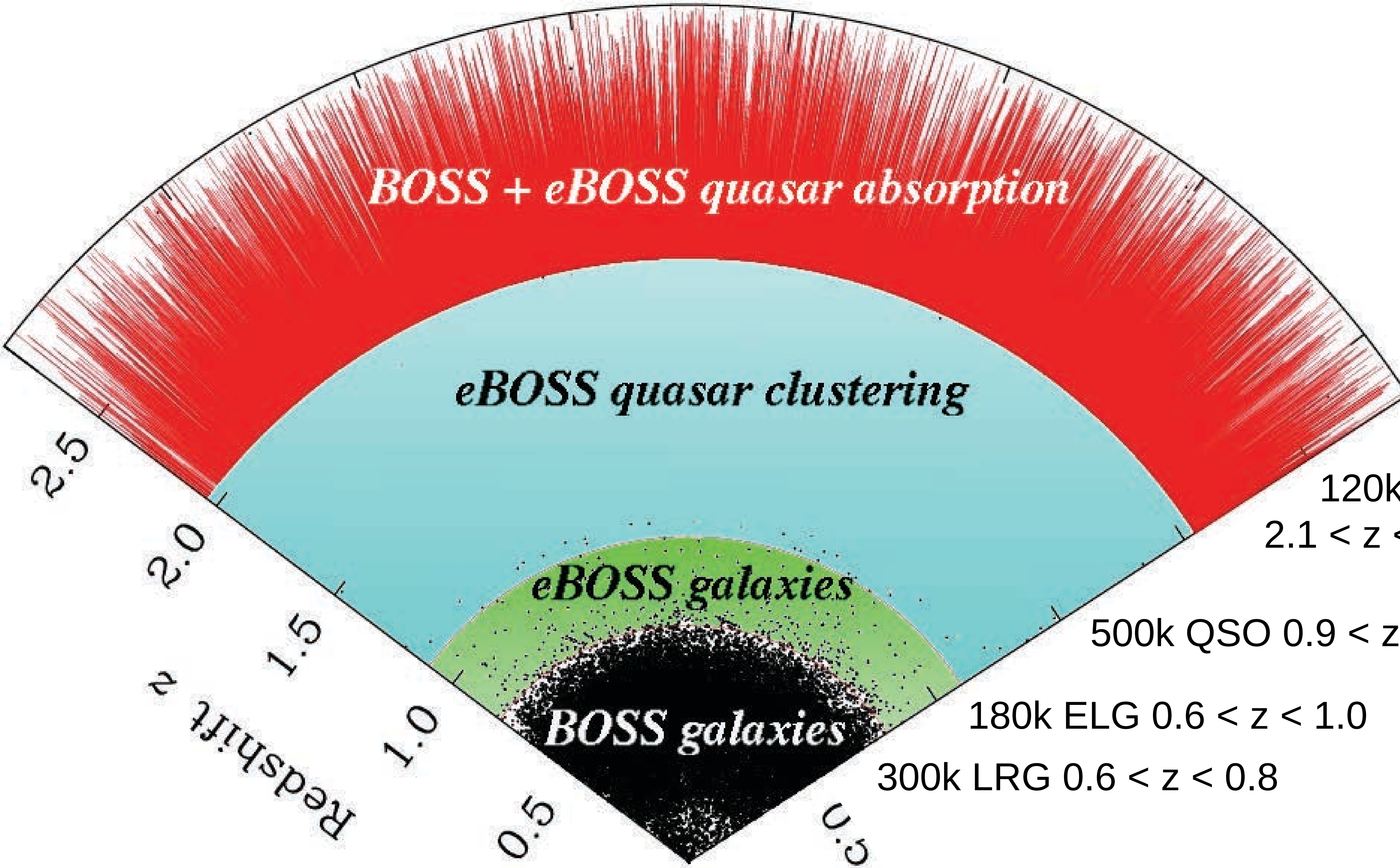
Data Release 12: >2.5M spectra

On time, under budget, great science



eBOSS: now – 2020

Same telescope & spectrographs
New targets –> higher z



120k LyA
2.1 < z < 3.5

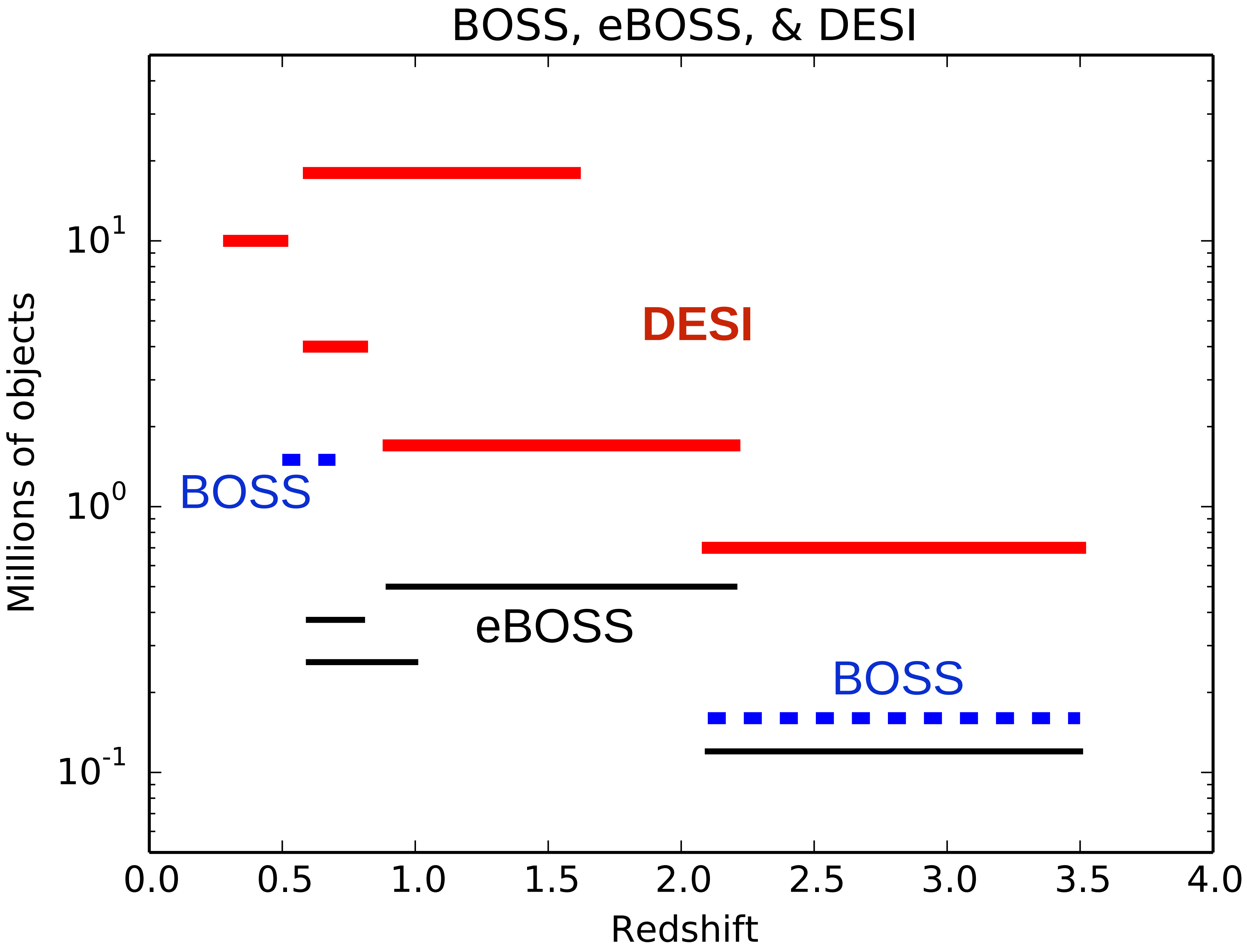
500k QSO 0.9 < z < 2.2

180k ELG 0.6 < z < 1.0

300k LRG 0.6 < z < 0.8

LRG=Luminous Red Galaxy; ELG=Emission Line Galaxy; QSO=Quasar

targets & redshifts



How to get from here to there

What	How
Higher redshift	Bigger telescope; Better throughput; Deeper imaging
Larger footprint	New imaging survey(s)
Emission Line Galaxies	Higher resolution spectrographs
More targets	More fibers
Lower S/N data	Better software

Mayall Telescope @ Kitt Peak

4-m instead of 2.5-m

One of the only 4-m telescopes that could be converted to wide field-of-view

New Corrector: 0.5 –> 8 sqdeg FOV

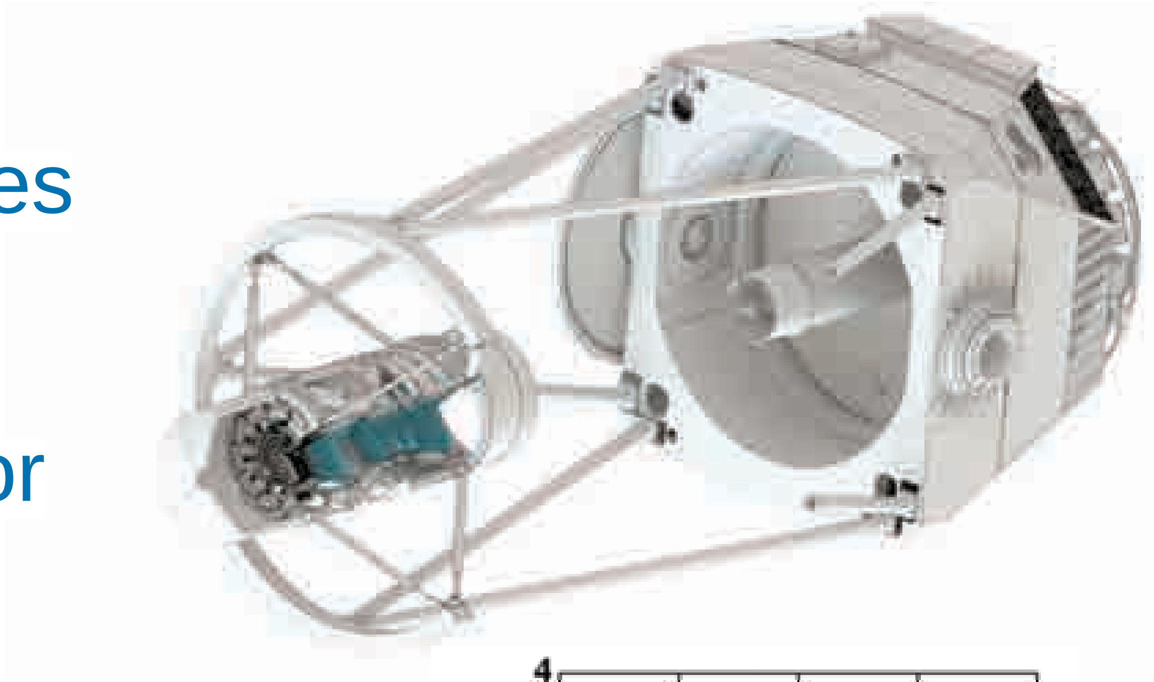
20 designs evaluated by 4 groups

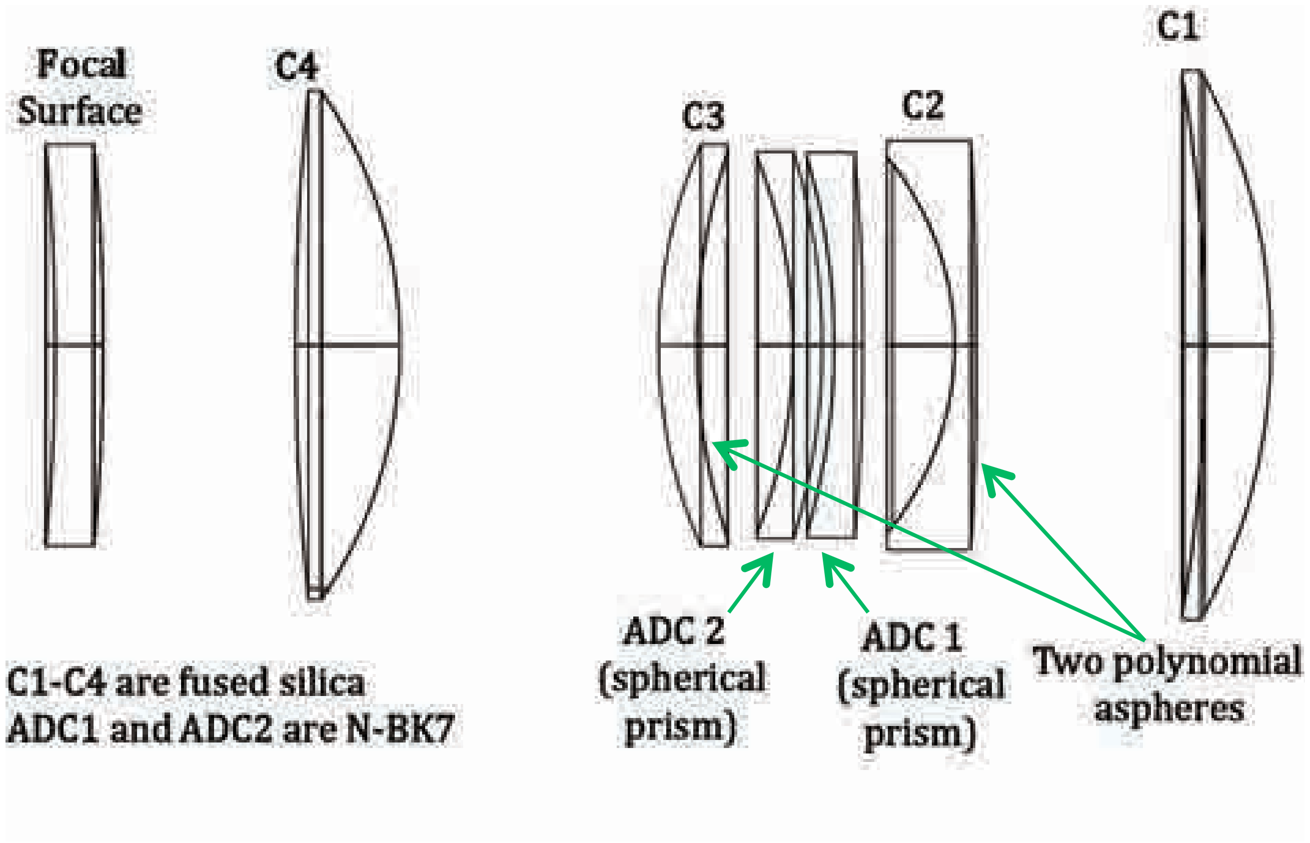
6 elements, 2 glass types, 2 aspheres

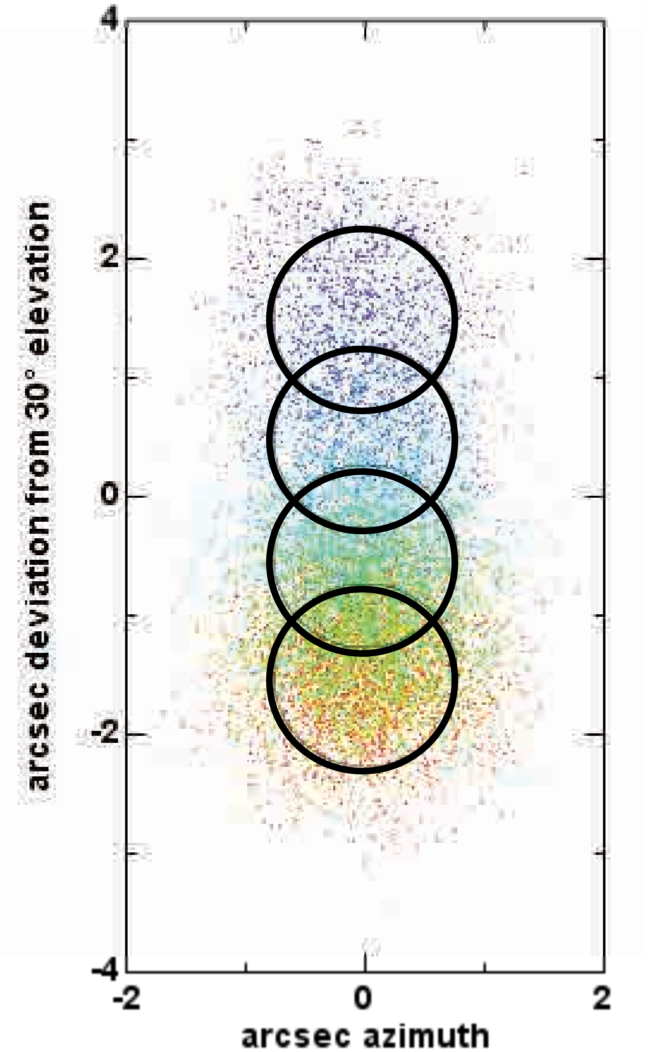
Field of view 3.2˚ linear

Atmospheric dispersion compensator

- Improves effective throughput

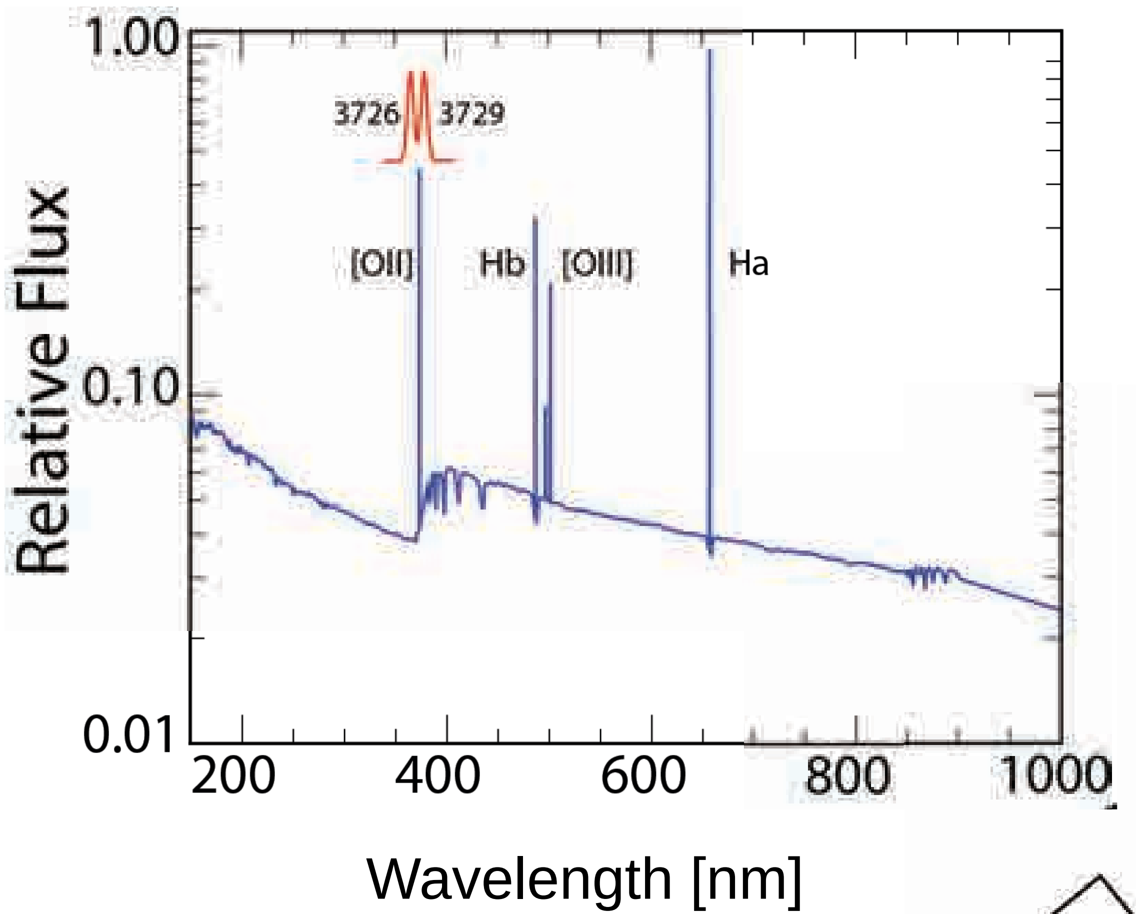




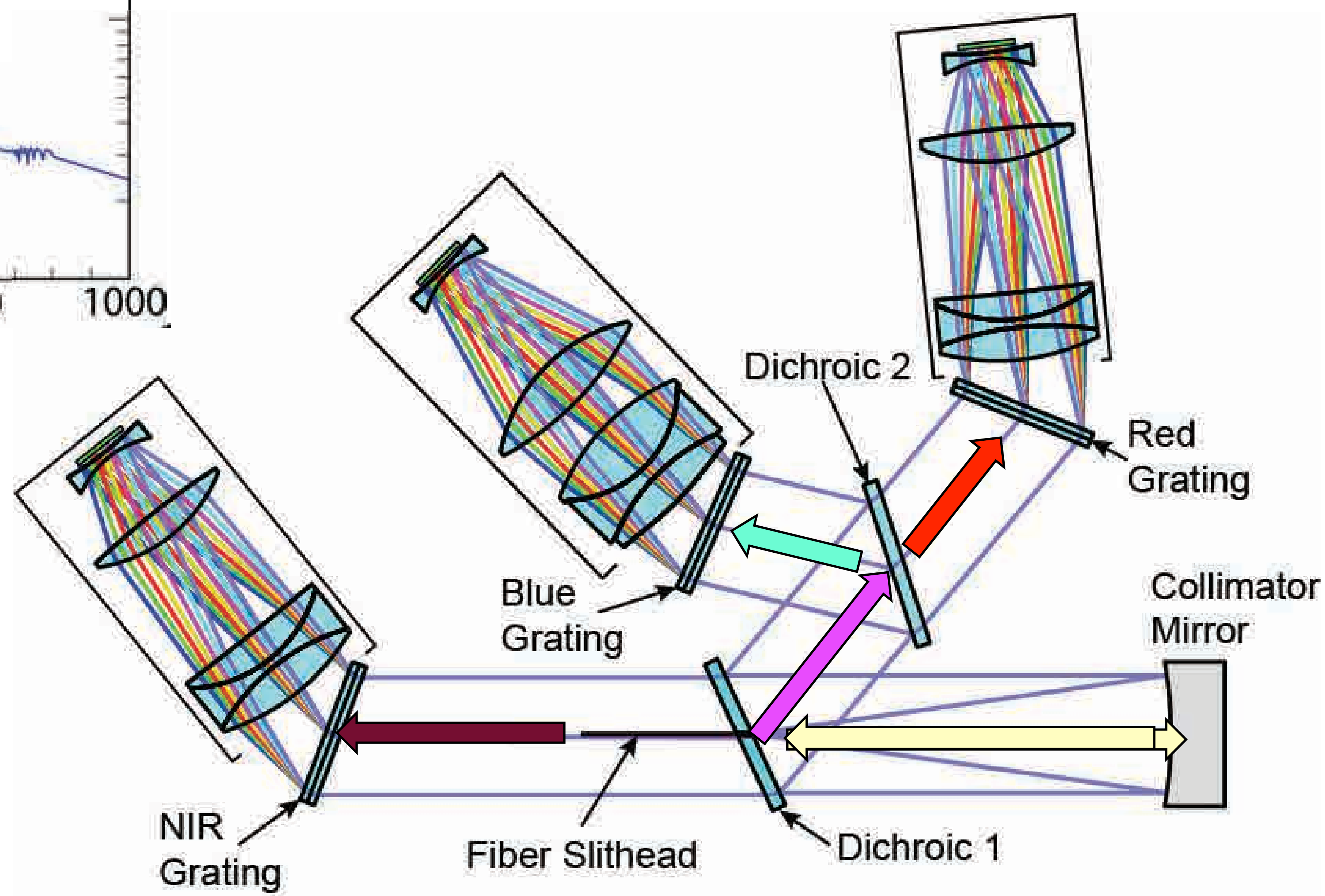


Spectrographs

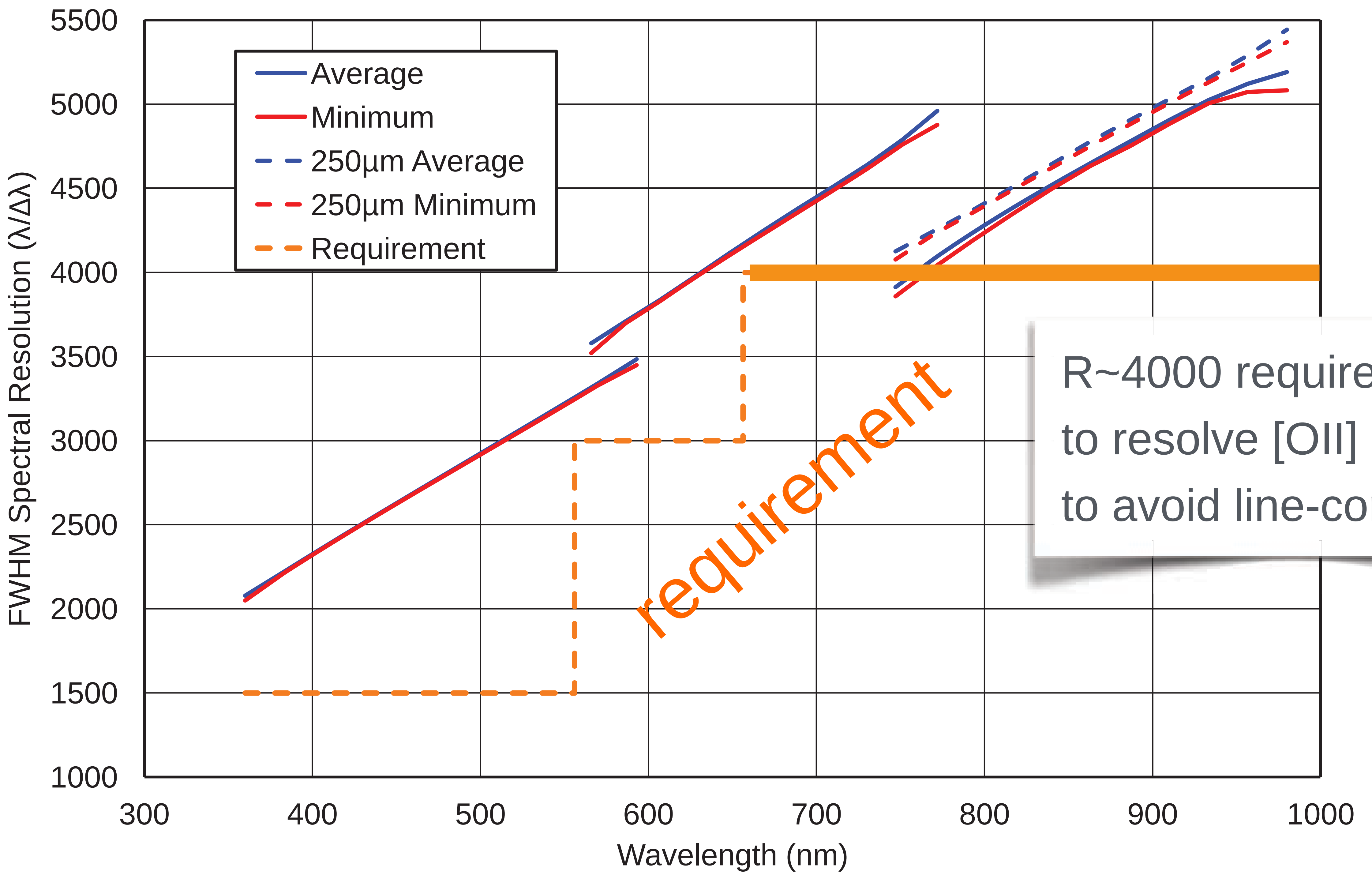
Higher resolution; better throughput



10 spectrographs
with 500 fibers each

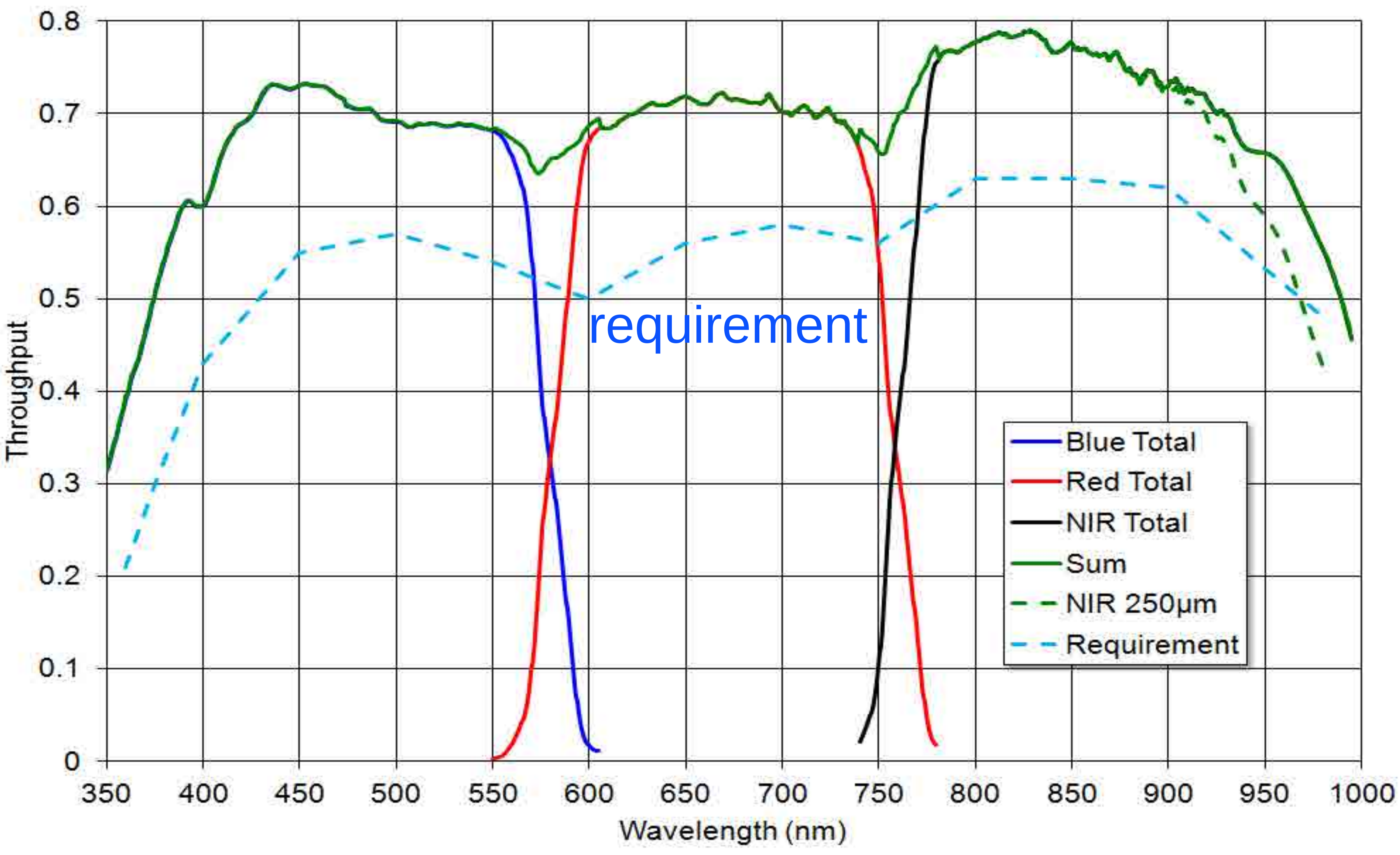


Spectrograph performance

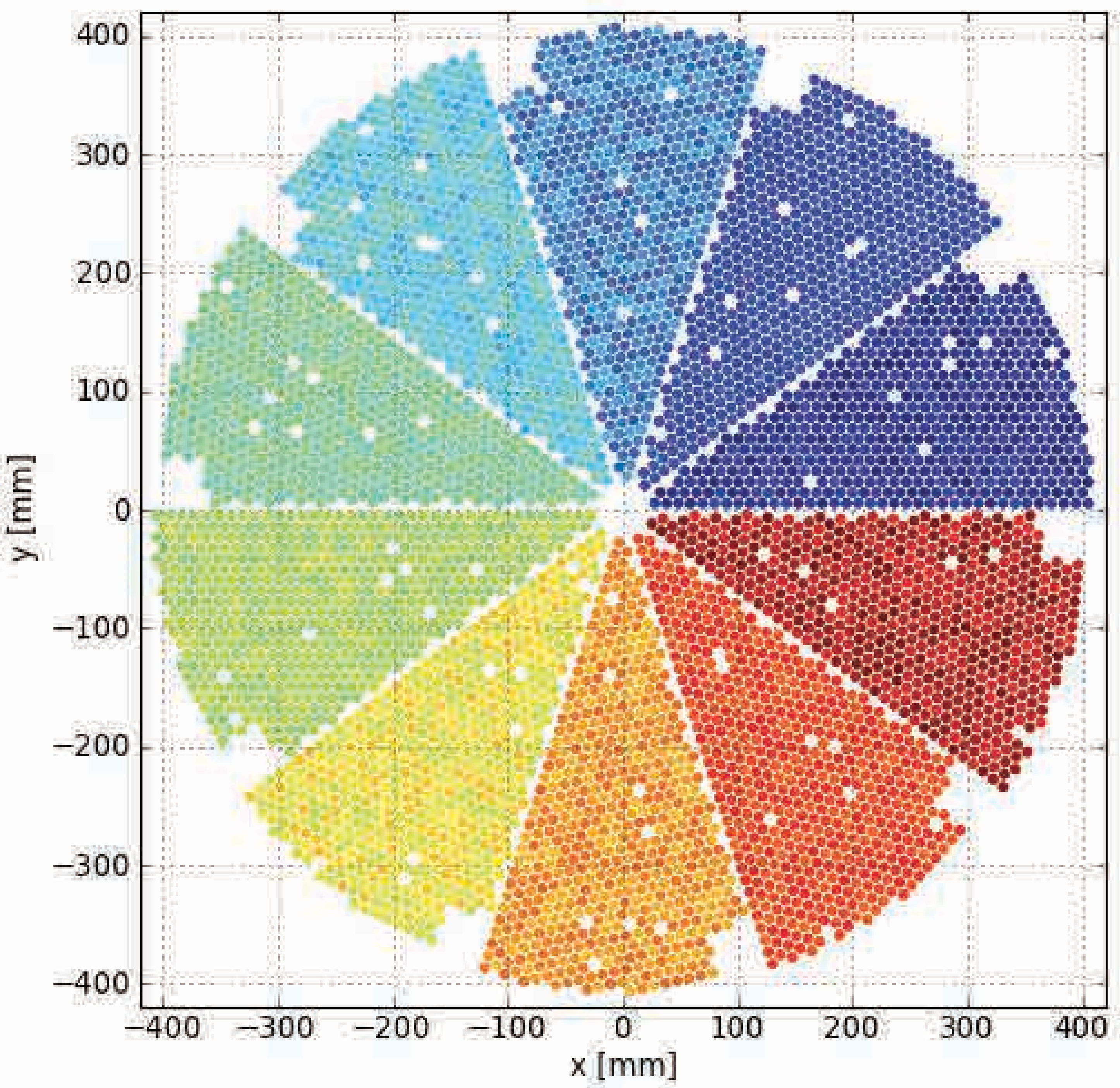


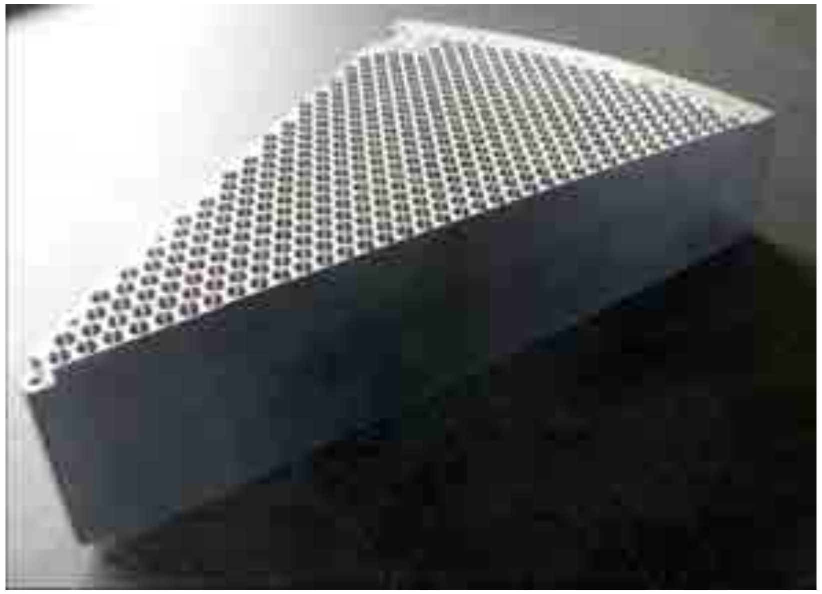
R~4000 requirement to resolve [OII] doublet to avoid line-confusion

Spectrograph throughput



Focal Plane





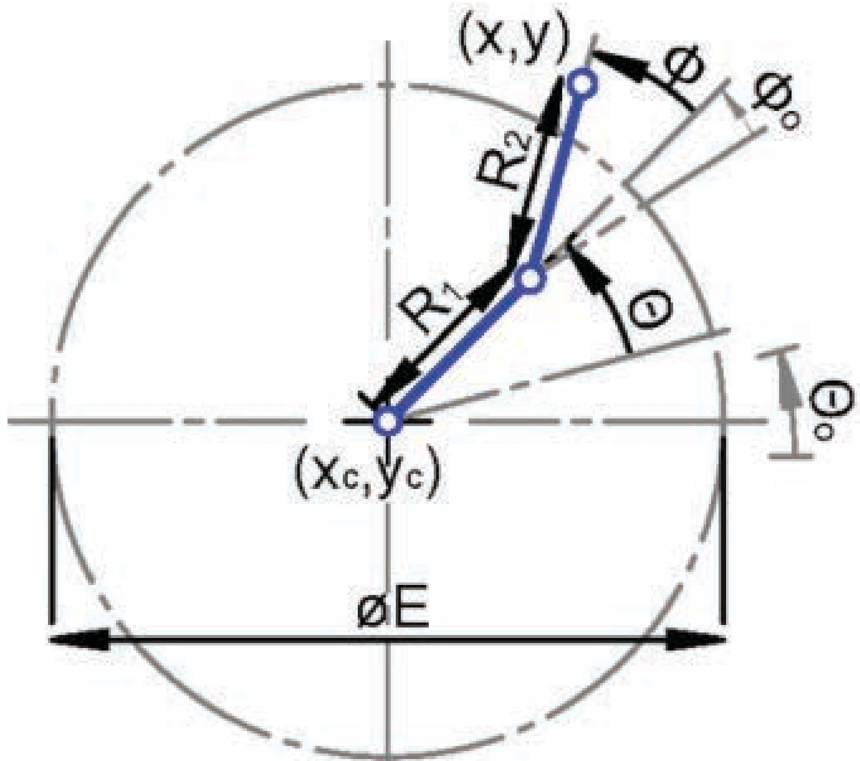
10 wedges of 500 positioners

8 sq deg field of view

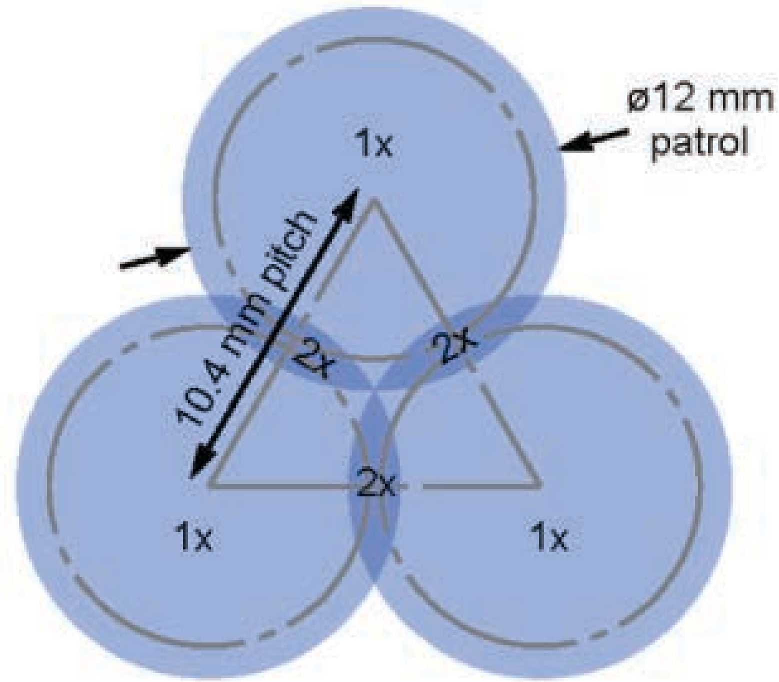
7.5 sq deg visible to fibers

Fixed fidicial fibers for
fiber view camera

5000 fiber positioner robots

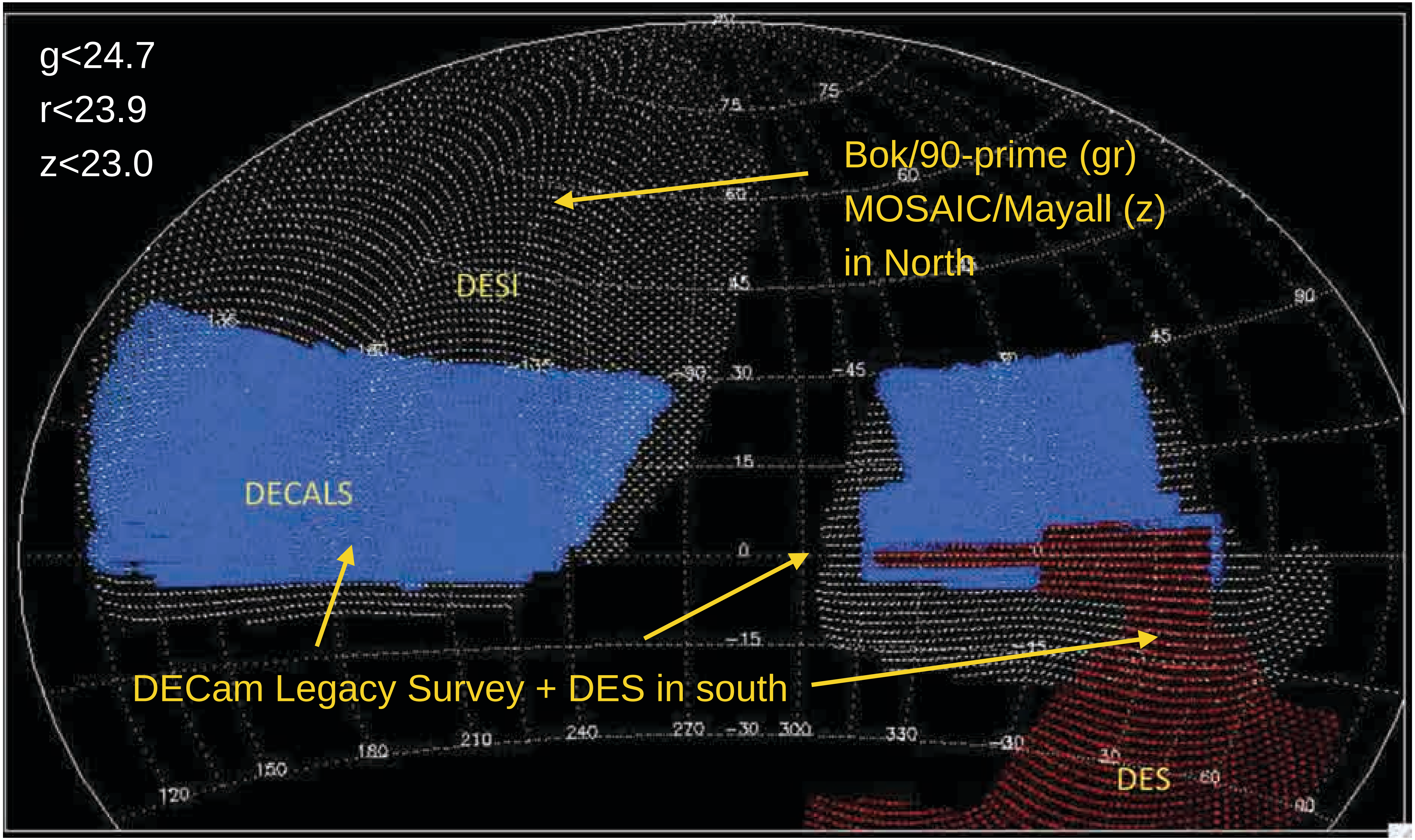


KINEMATICS /
COORDINATES



EXACT COVERAGE
R1 = R2 = 3 mm

Larger Footprint: new imaging



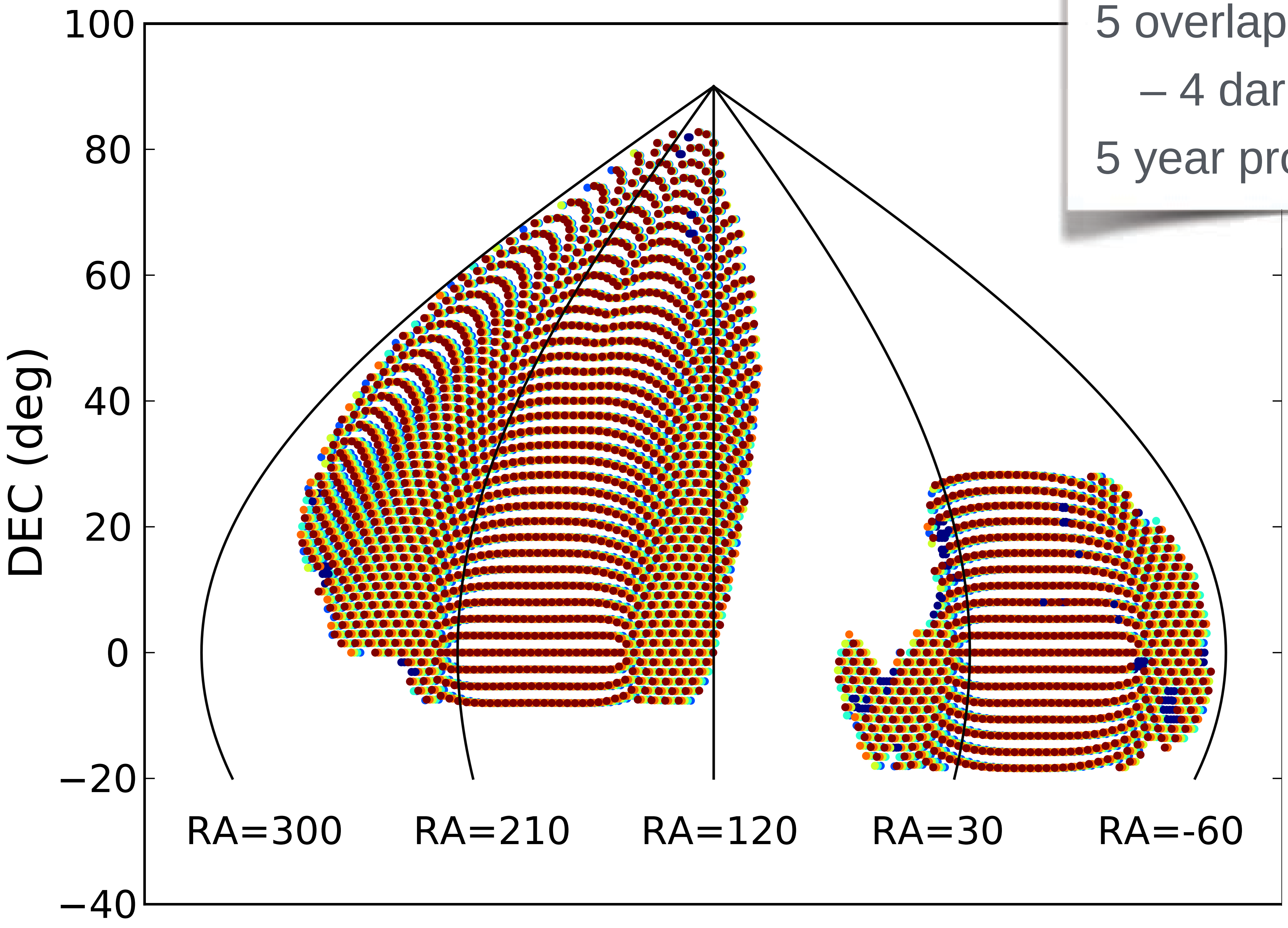
Dark Time Survey

14k sq degrees

5 overlapping layers

– 4 dark, 1 gray

5 year program



Bright Time Survey

O(10M) Galaxies to r~19.5

- Low-z BAO, clustering, SN hosts, photo-z training

O(10M) Stars

- Gaia sources
- Radial velocities, metalicities beyond what GAIA can measure

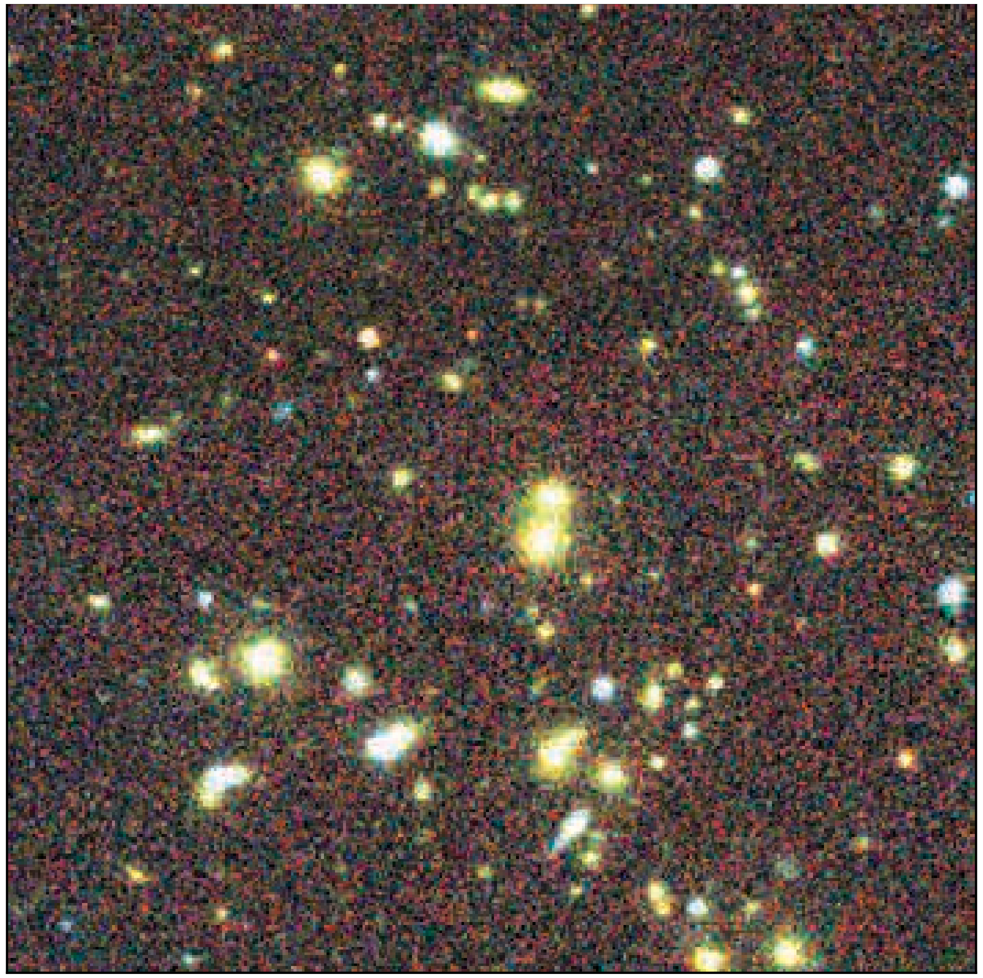
14k – 20k footprint

Deeper Imaging

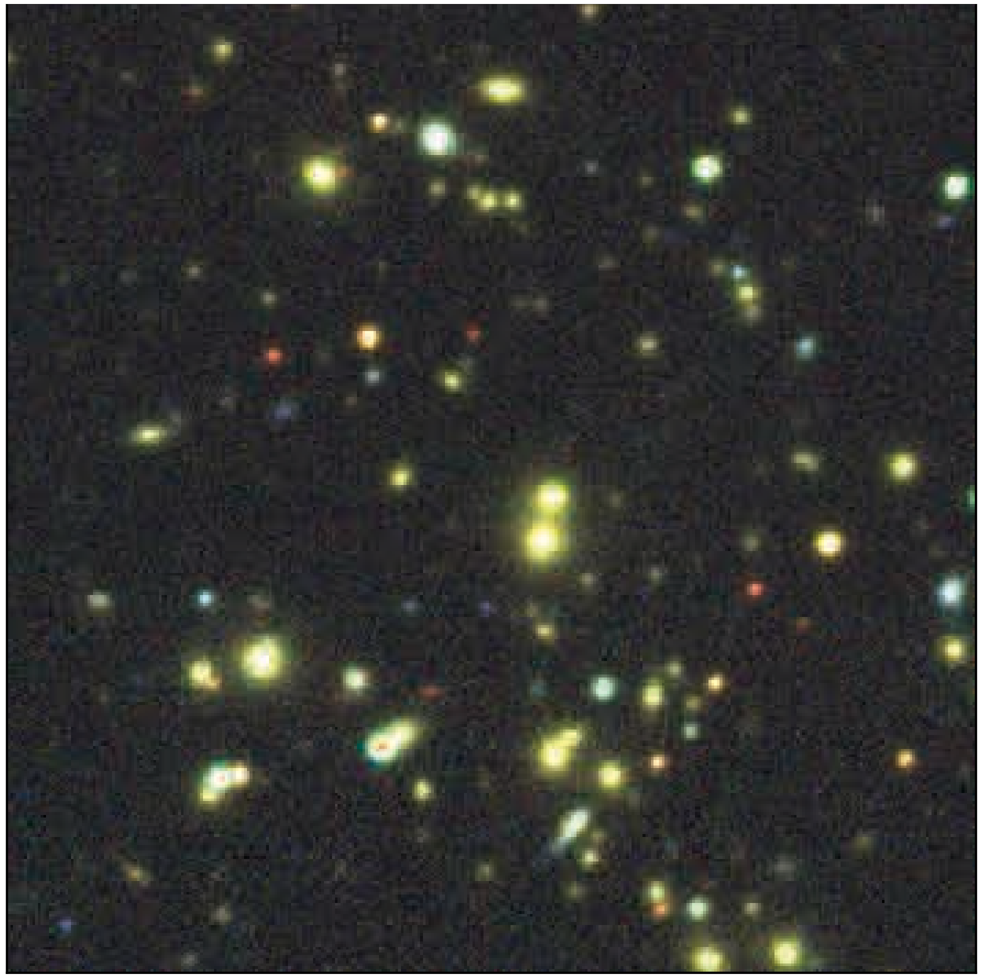
g<24.7
r<23.9
z<23.0

Both better data & better processing

Forward model all images & filters into single catalog detection



SDSS

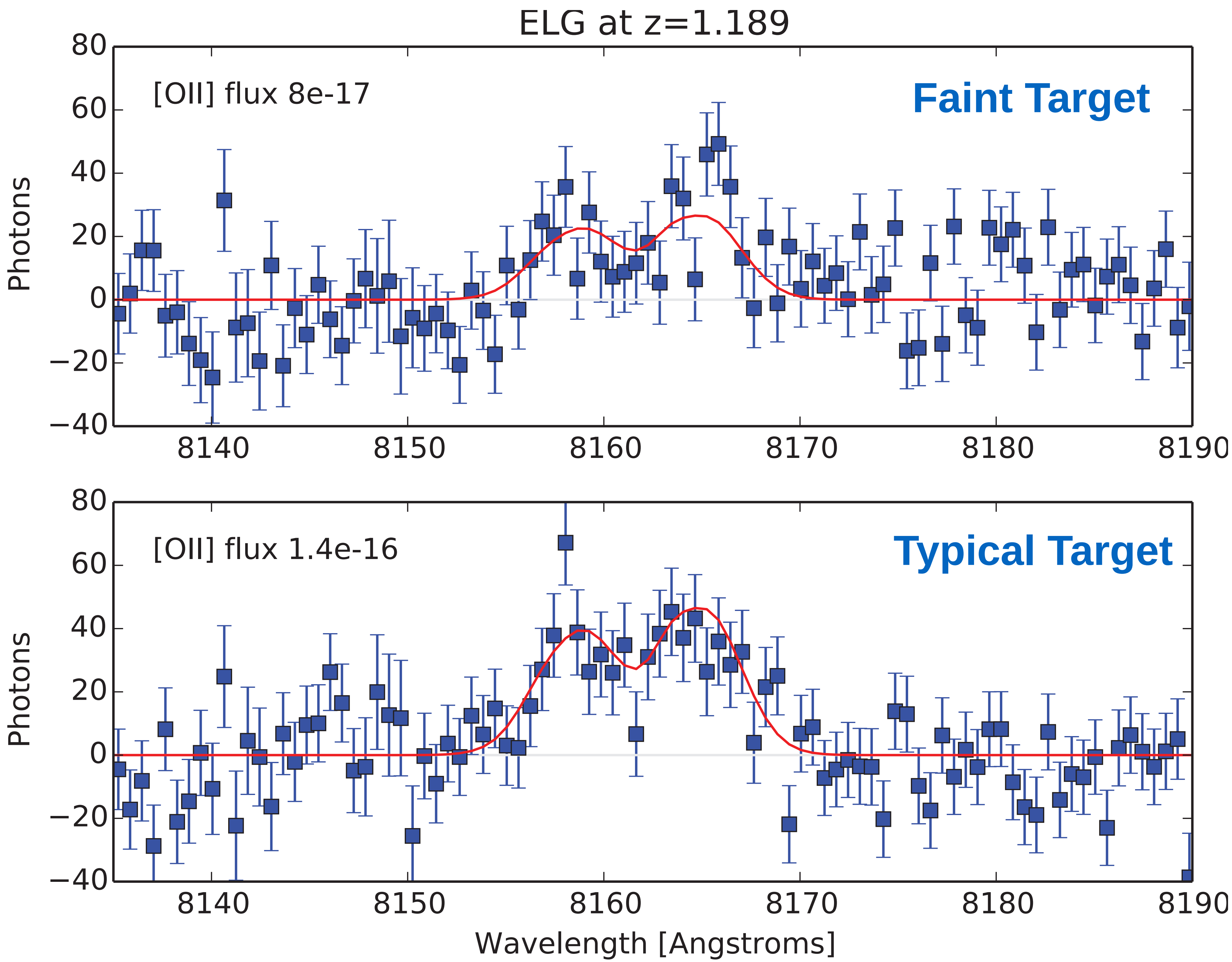


DECaLS

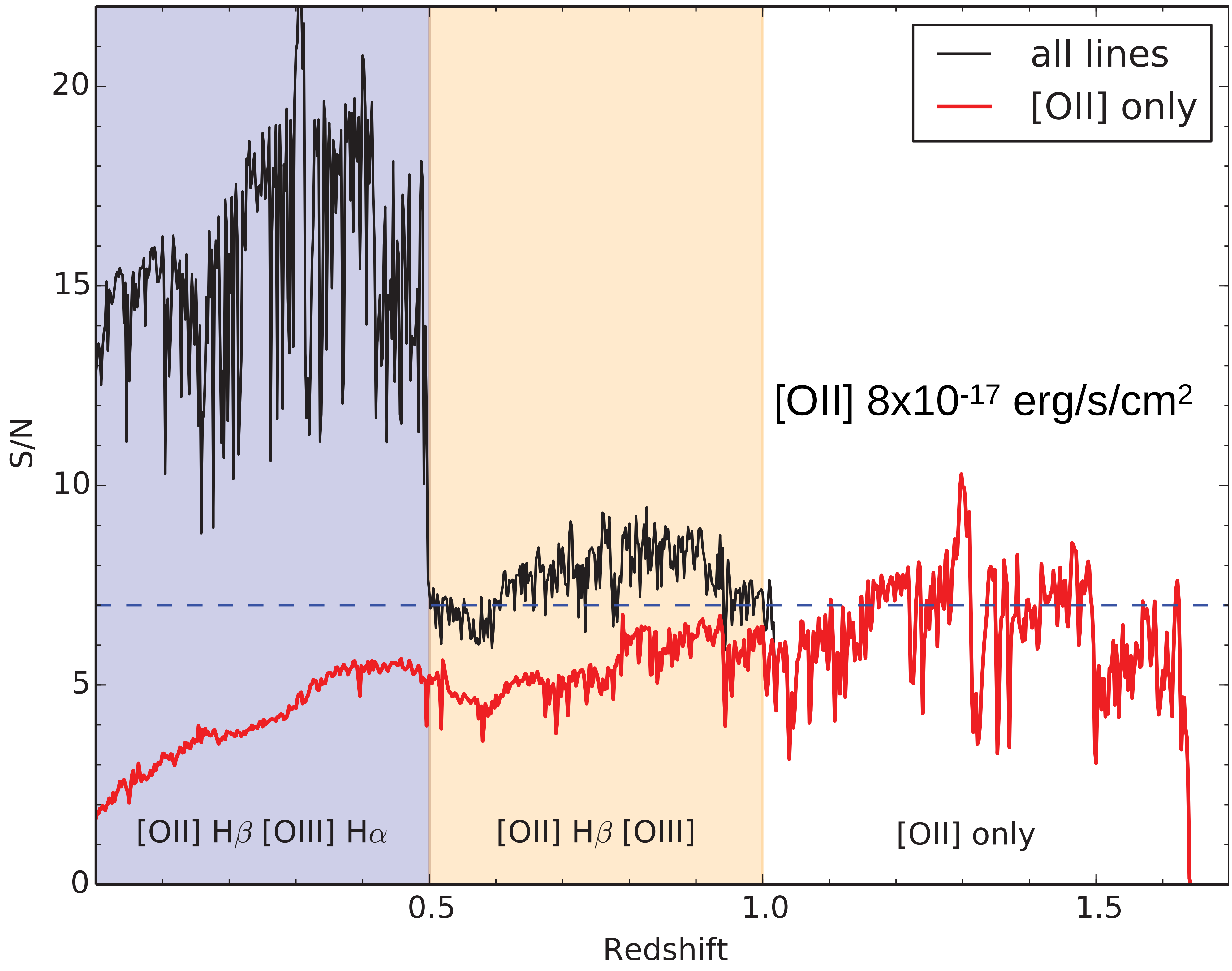
First data release April 2015: http://legacysurvey.org

[Tractor method, D. Lang+]

DESI Spectra

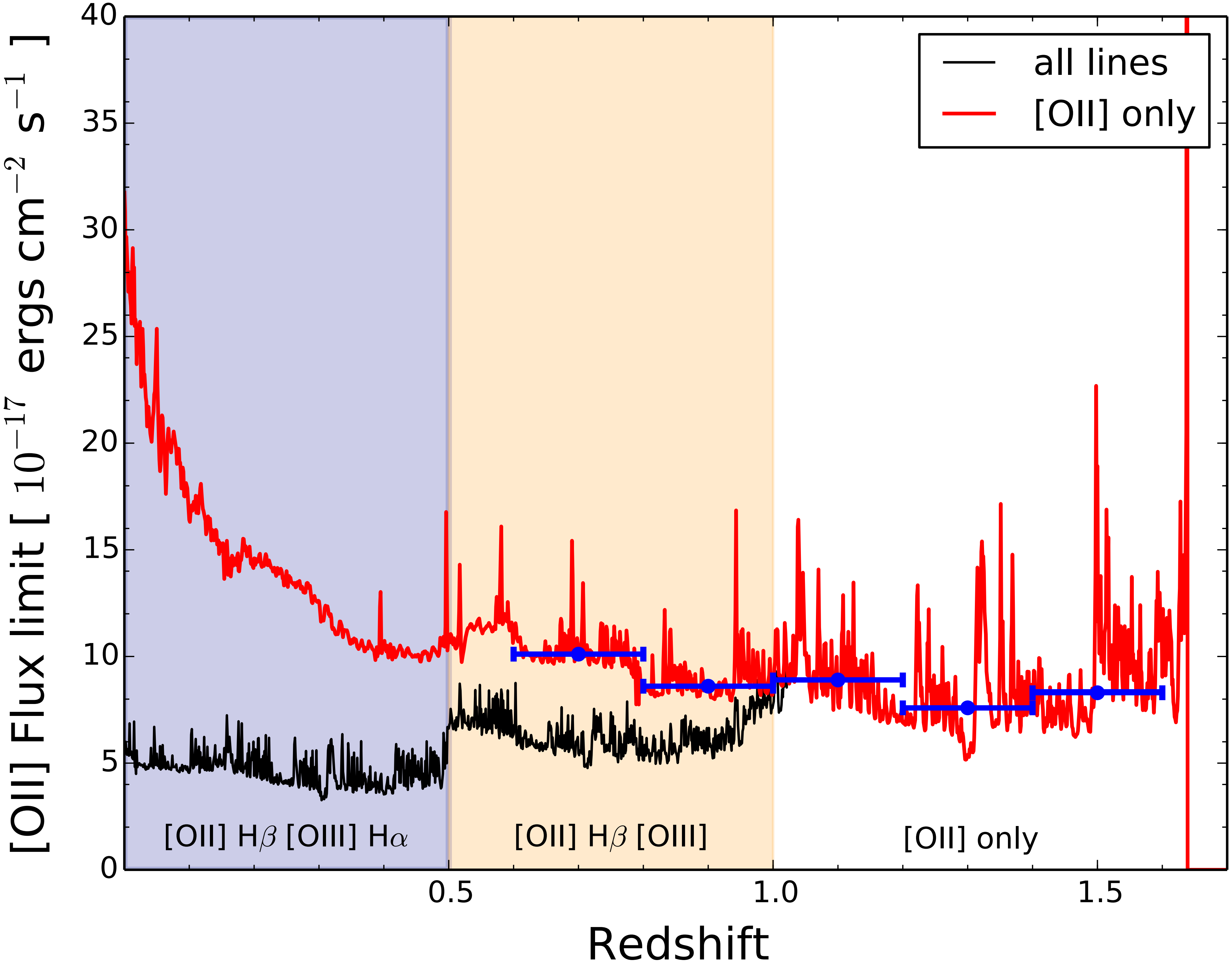


DESI ELG S/N

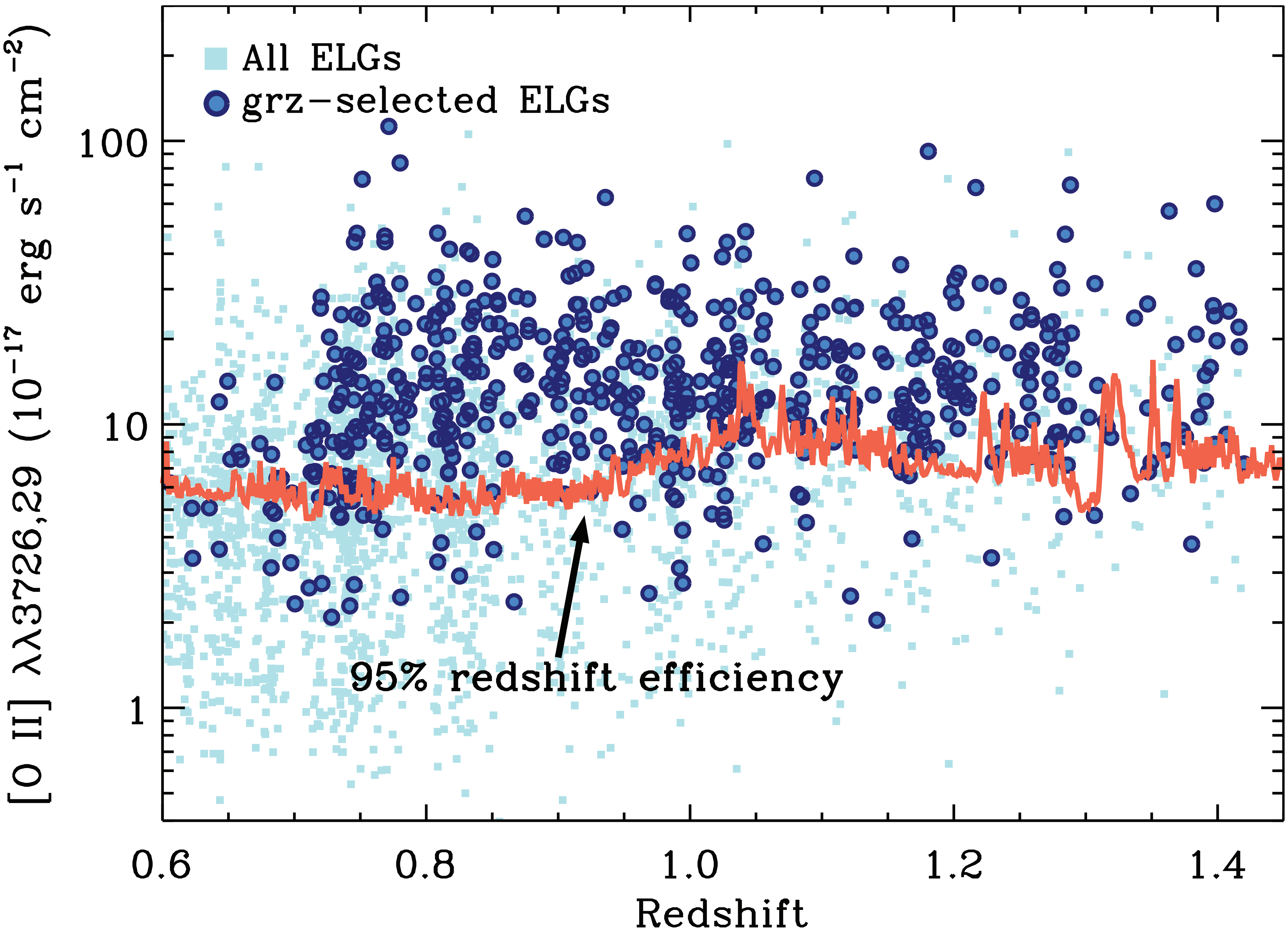


all lines
[OII] only
[OII] 8x10-17 erg/s/cm2
S/N
20
15
10
5
0
0.5
1.0
1.5
Redshift
[OII] Hβ [OIII] Hα
[OII] Hβ [OIII]
[OII] only

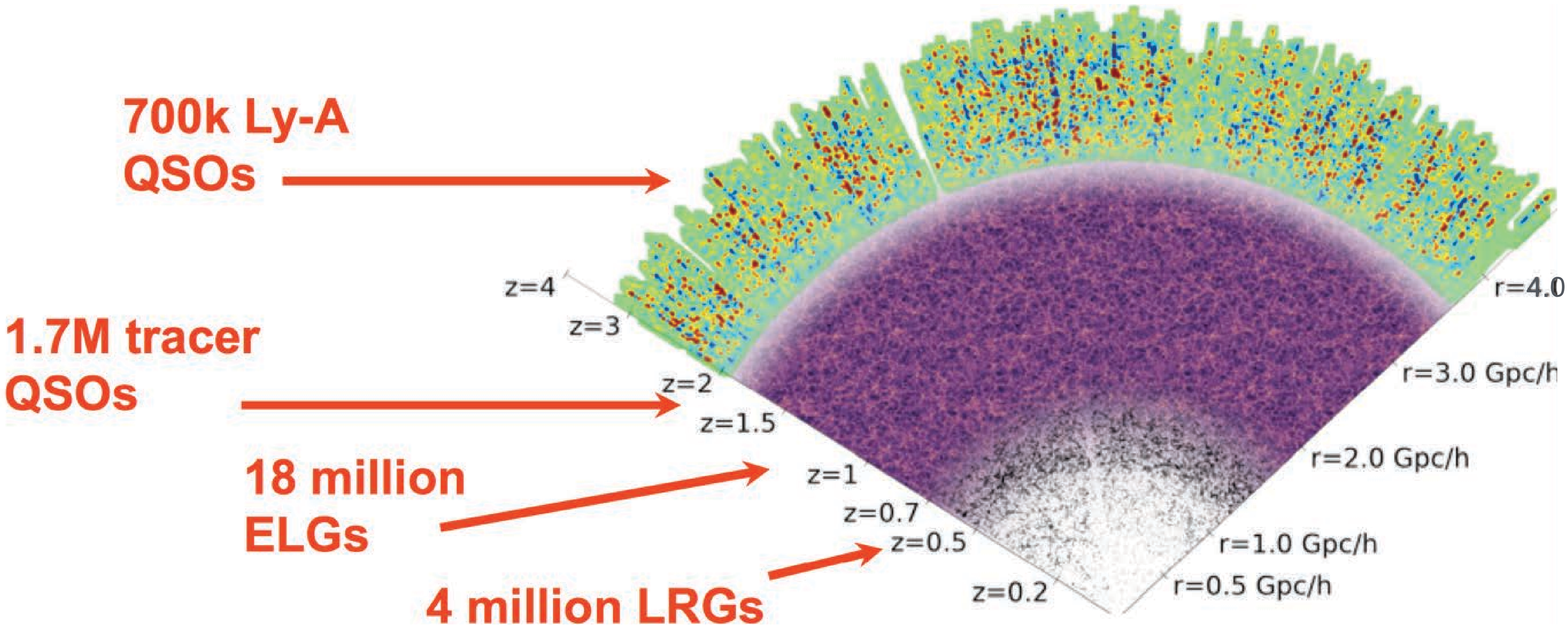
[OII] Flux limit vs. redshift



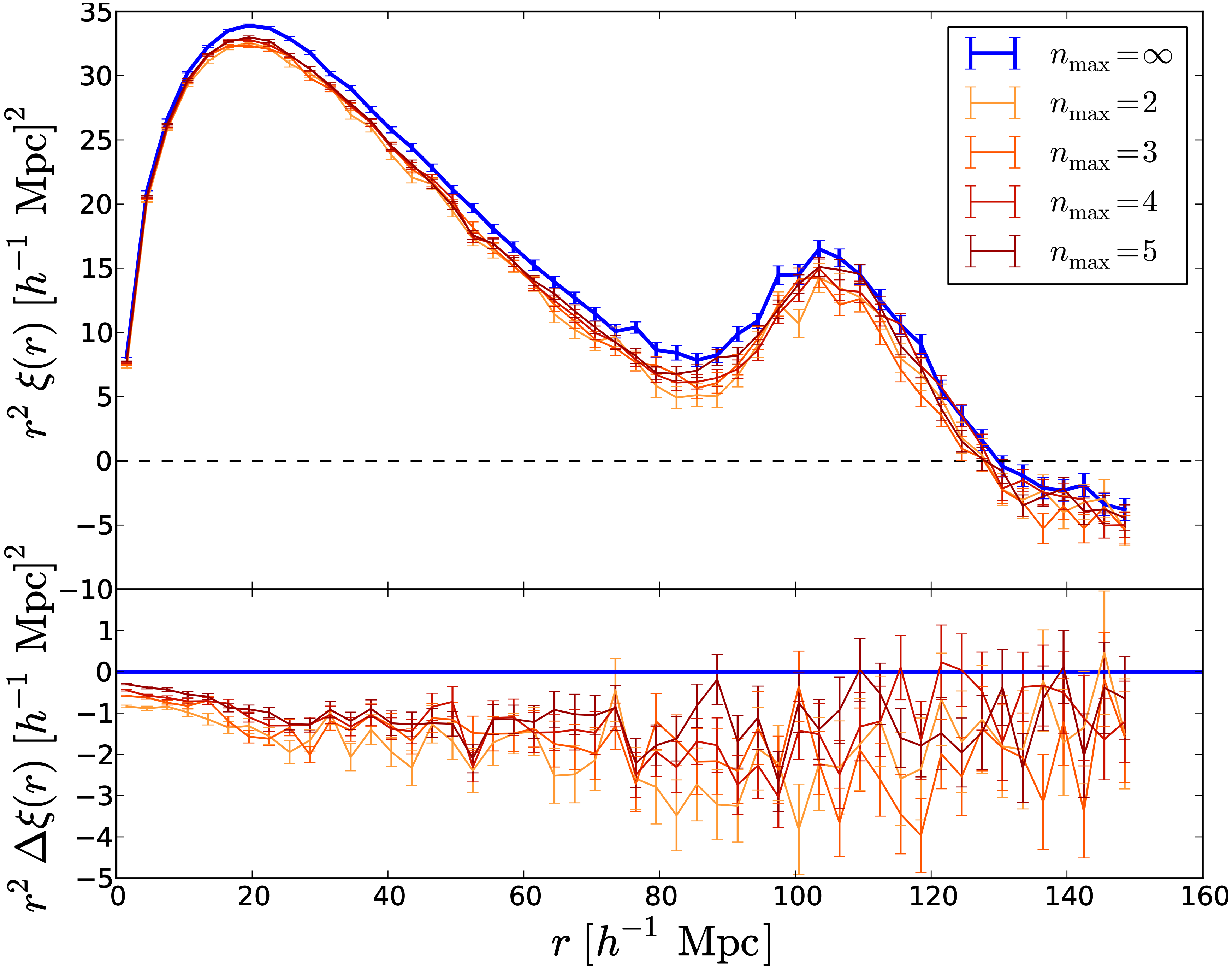
ELG Target Selection



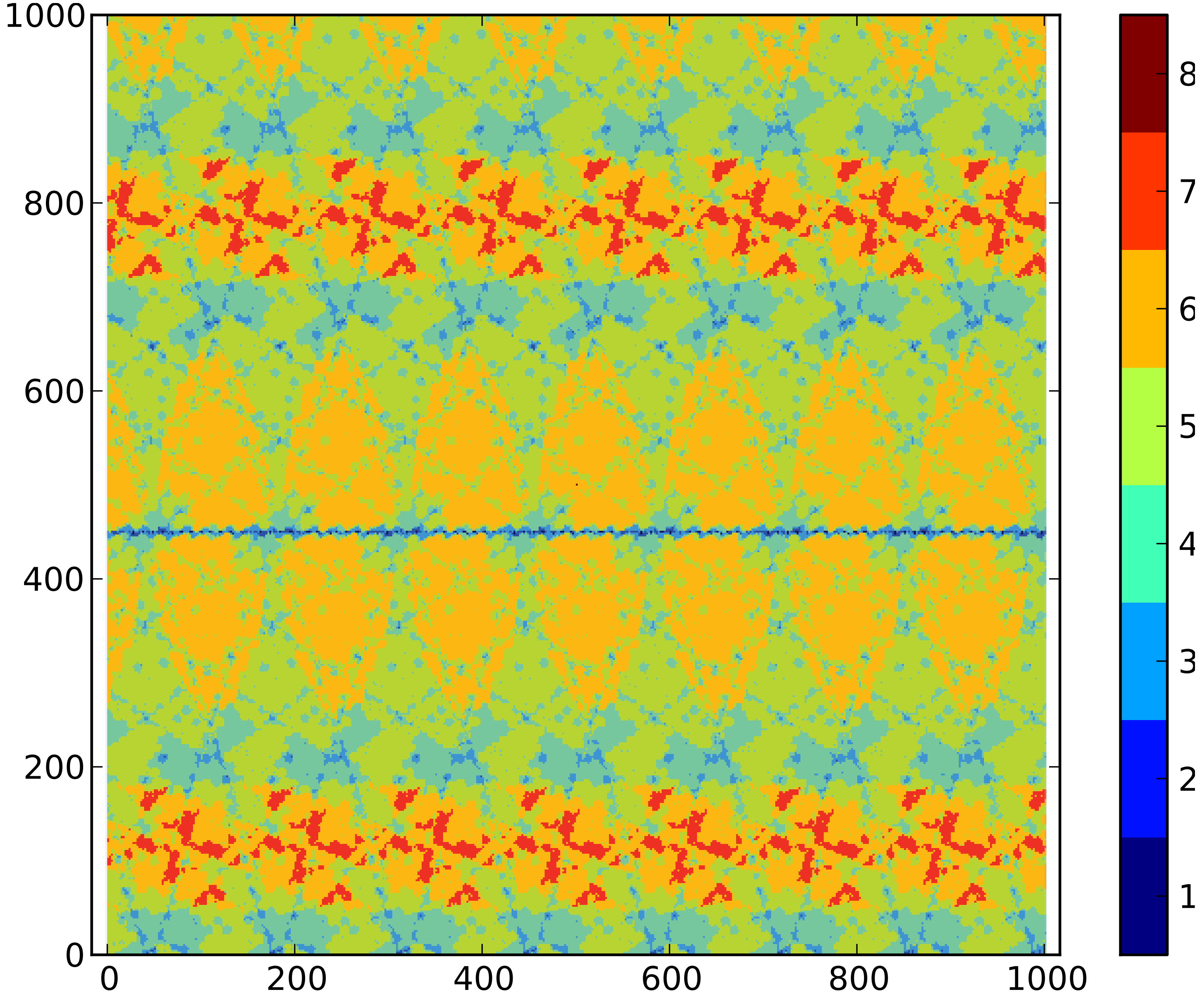
DESI Redshift Coverage



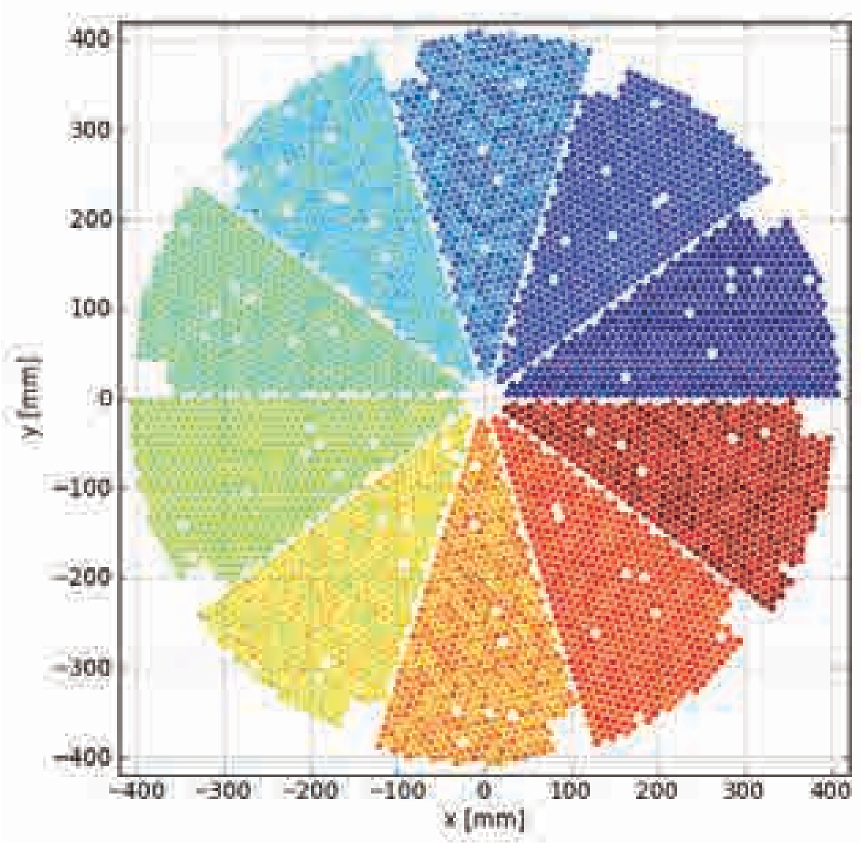
ξ(r) distortions: uniform coverage



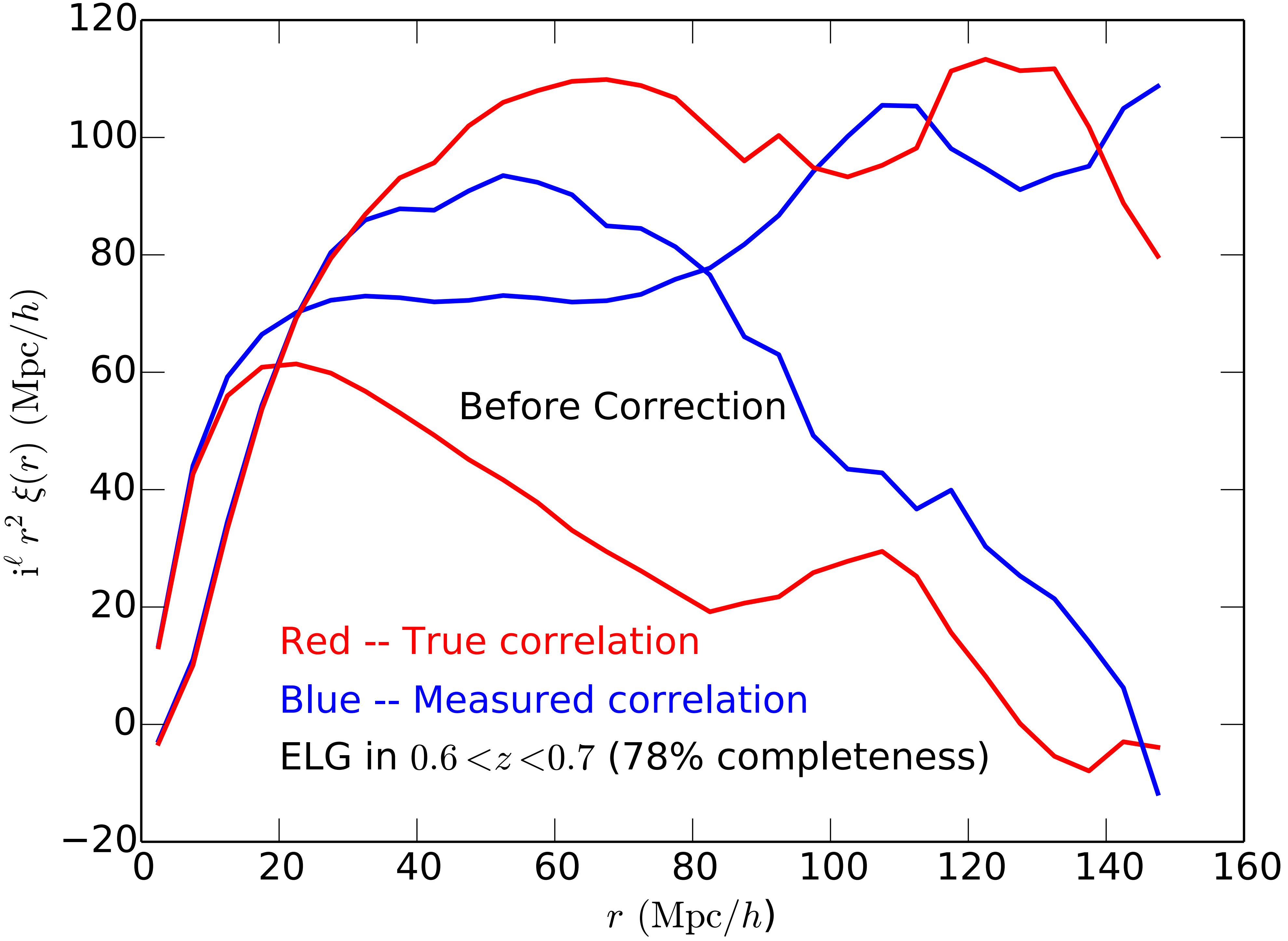
Actual Coverage



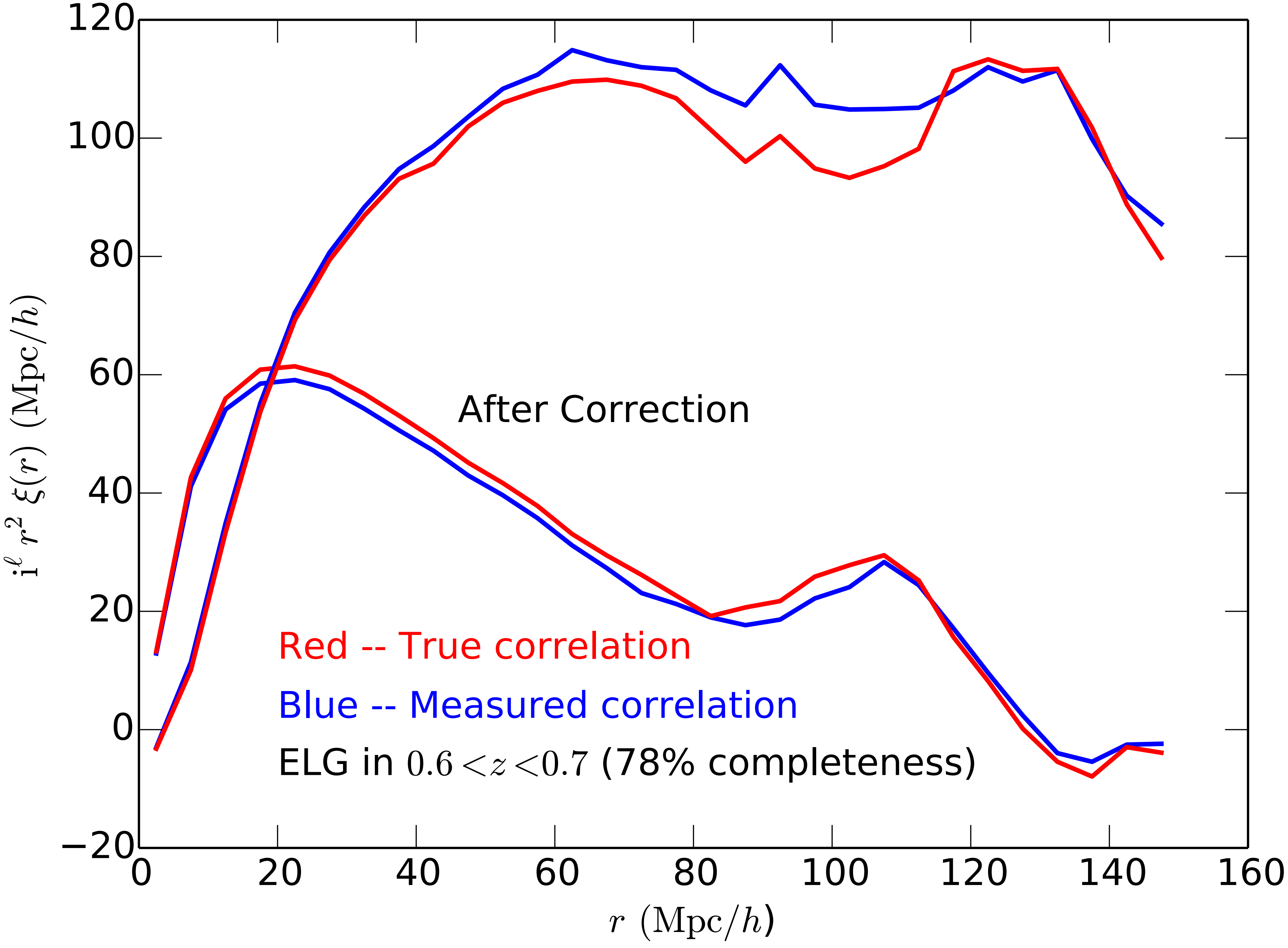
non-uniformities due to tiling pattern and focal plane coverage



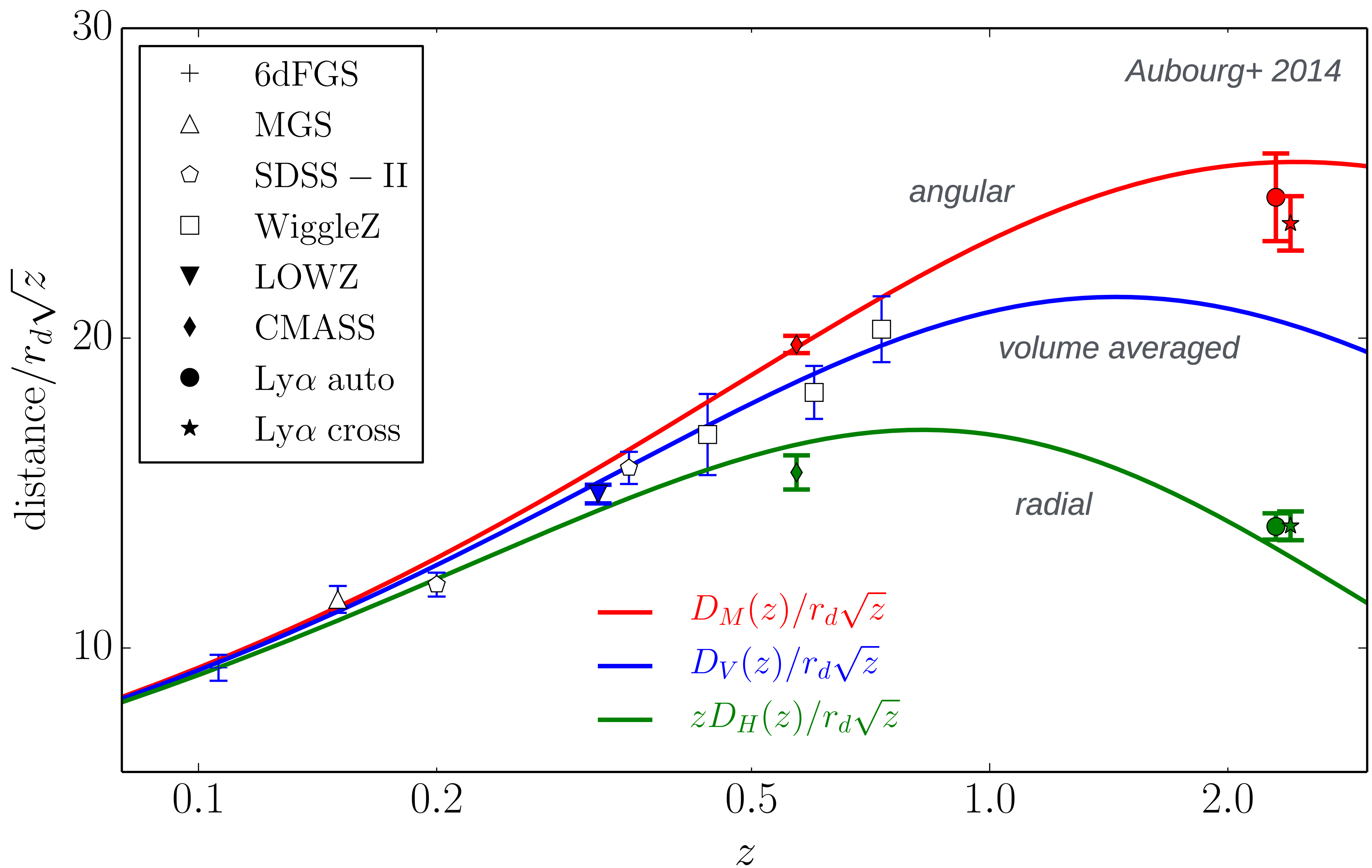
ξ(r) distortions: non-uniform coverage



ξ(r) distortions: corrected



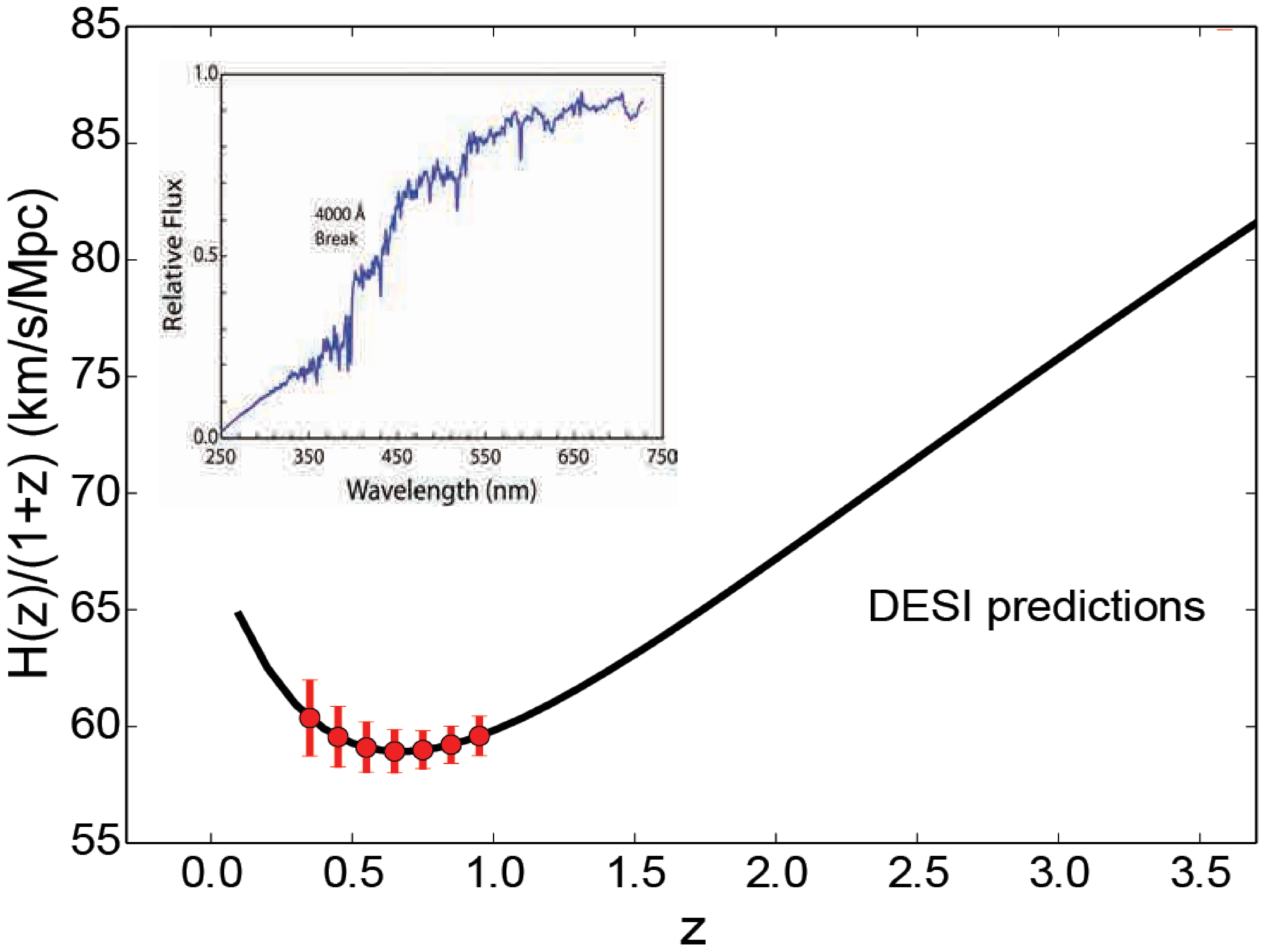
BAO Hubble Diagram



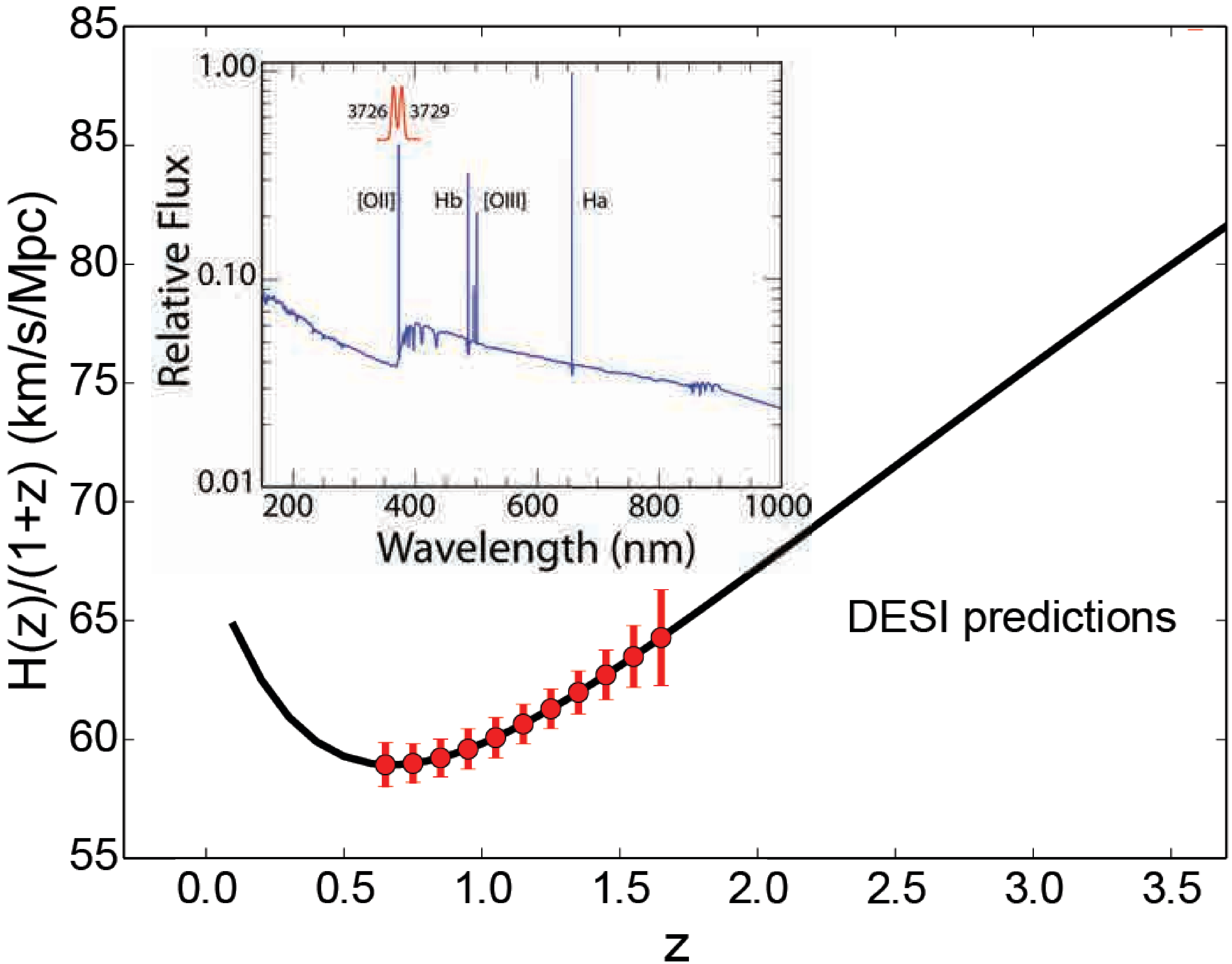
Aubourg et al. 2014 arXiv:1411.1074

Cosmological implications of baryon acoustic oscillation (BAO) measurements

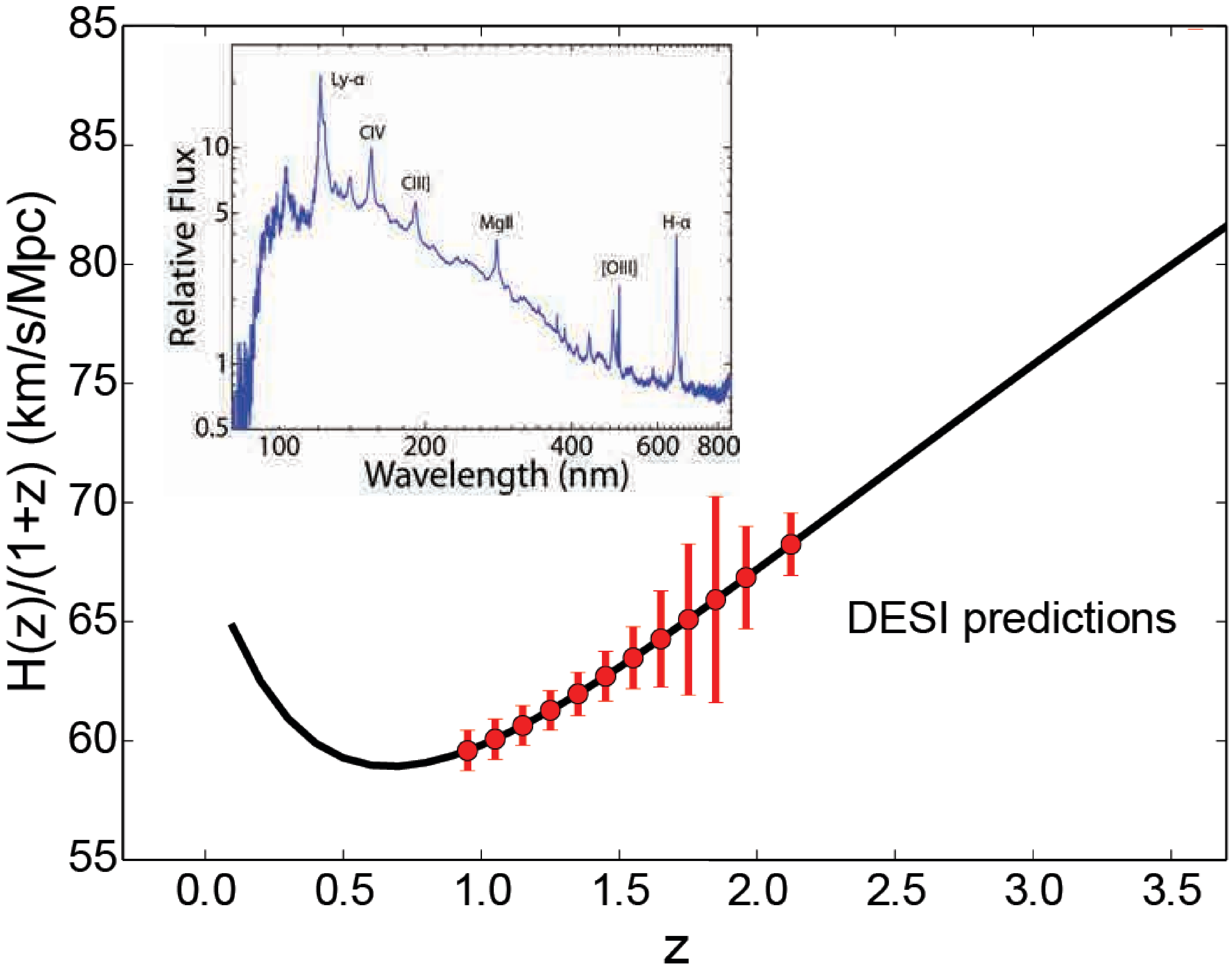
Luminous Red Galaxies



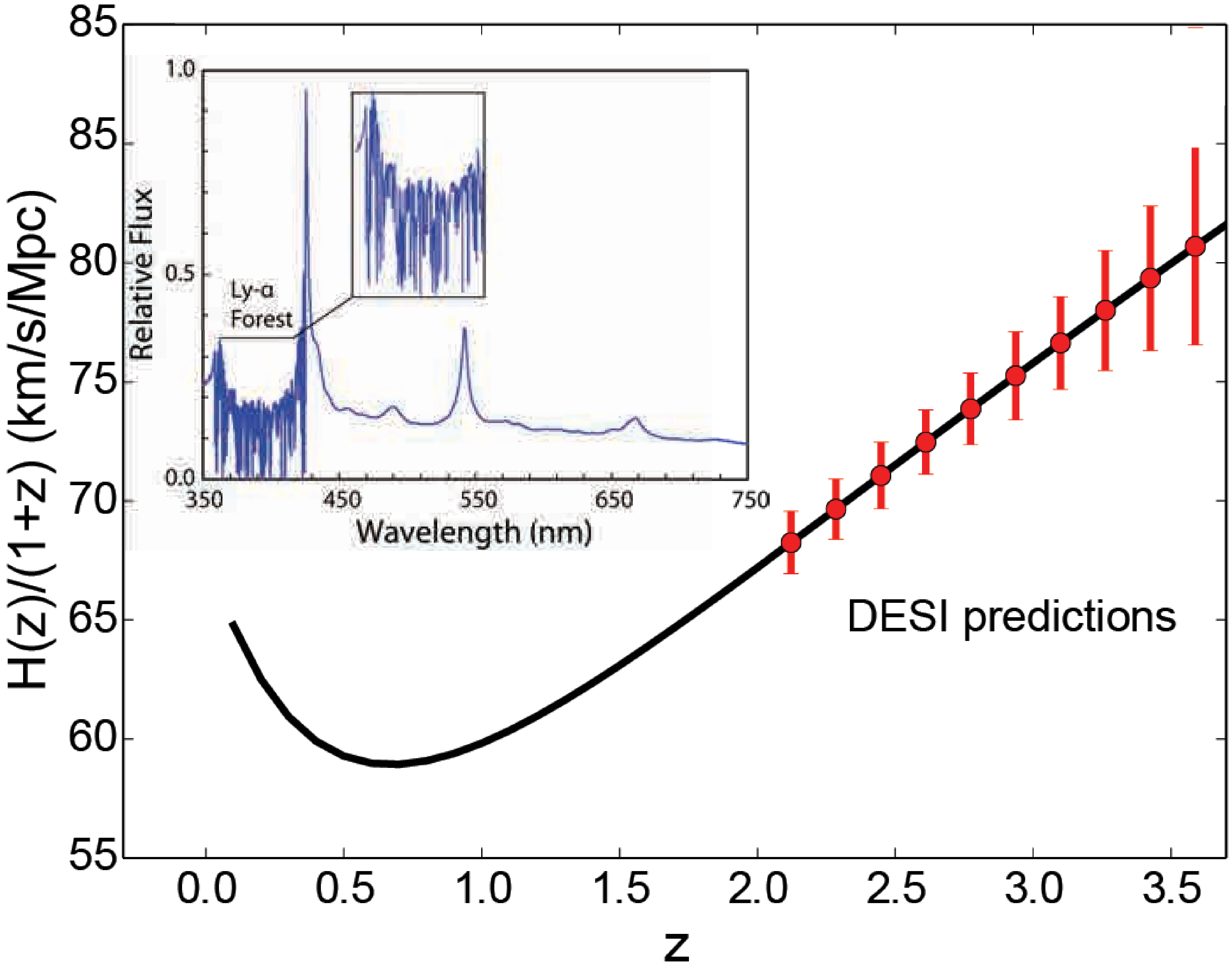
Emission Line Galaxies



Tracer QSOs

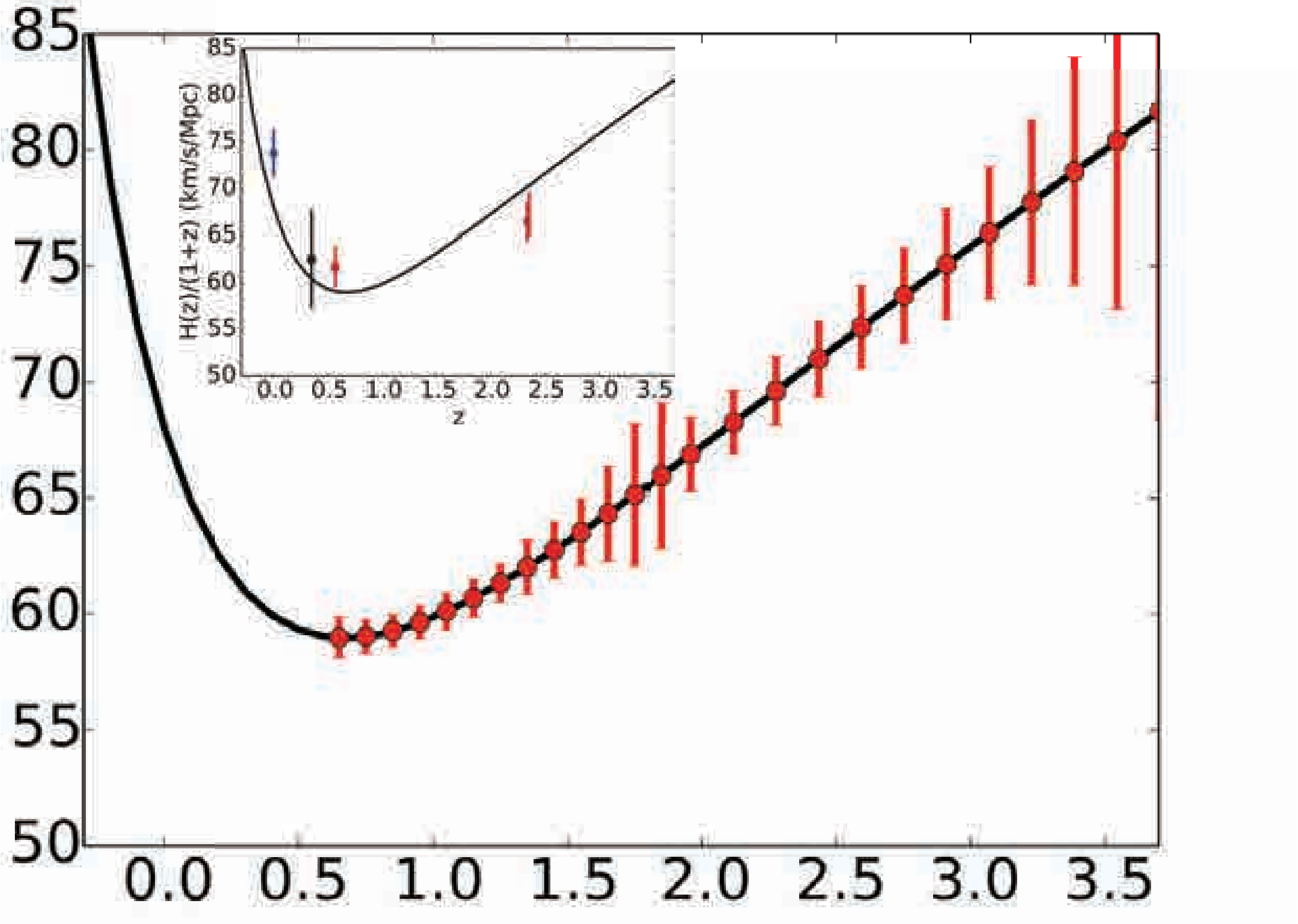

85
85
80
75
70
65
60
55
H(z)/(1+z) (km/s/Mpc)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
z
DESI predictions
Relative Flux
10
5
1
0.5
100
200
400
600
800
Wavelength (nm)
Ly-α
CIV
CIII]
MgII
[OIII]
H-α

Lyman-α forest quasars



DESI Hubble Diagram

Target type	z range	Target density deg^{-2}	Good z density deg^{-2}	$\Delta z/(1+z)$ precision	$\Delta z/(1+z)$ systematic	Bad z assignment	Complete -ness
LRG	0.4–1.0	350	300	0.0005	0.0002	< 5%	> 95%
ELG	0.6–1.6	2400	1280	0.0005	0.0002	< 5%	> 90%
QSO	< 2.1	170	120	0.0025	0.0004	< 5%	> 90%
Ly-α	> 2.1	90	50	0.0025	-	< 2%	> 72%



DESI Improvements

relative to Planck + BOSS

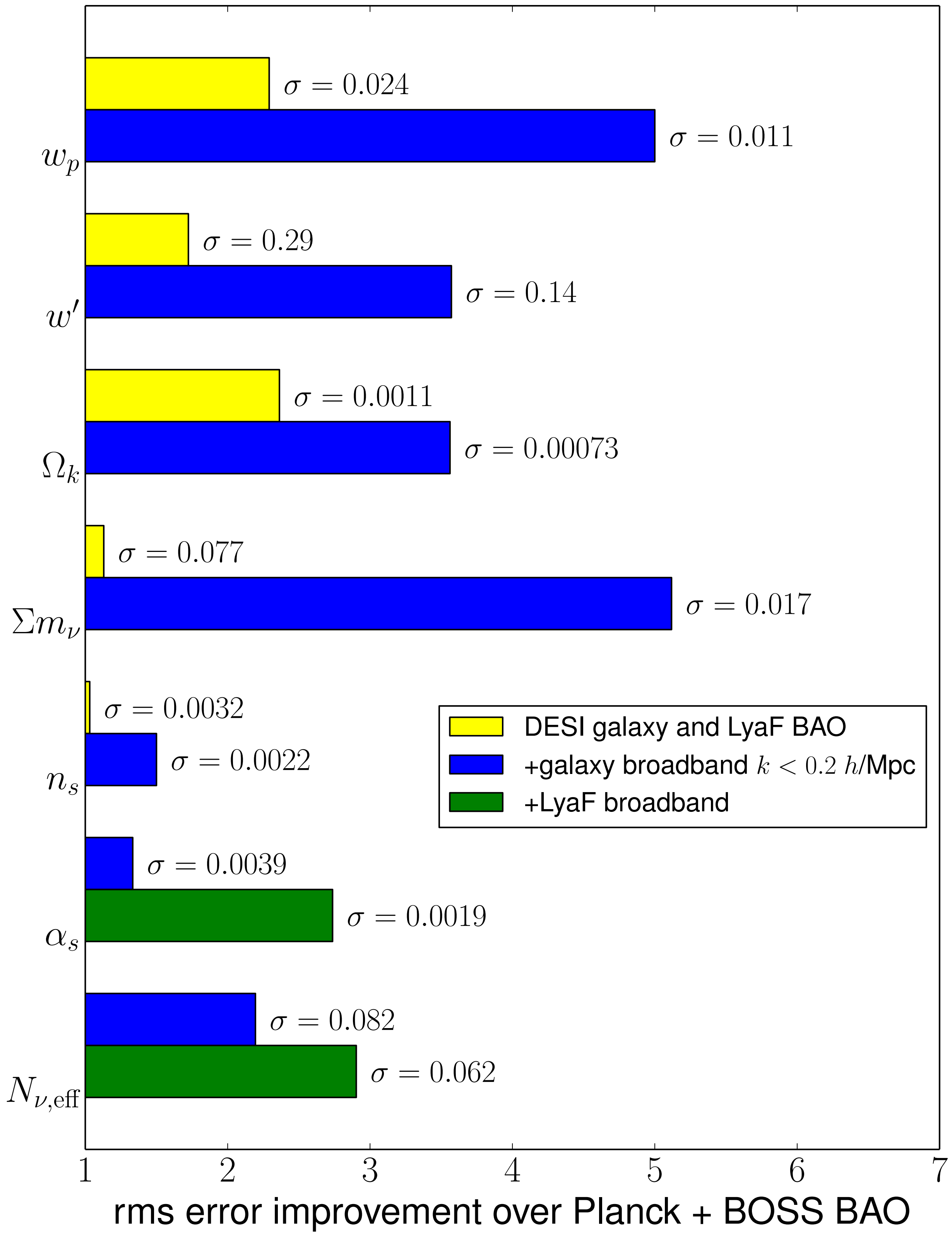
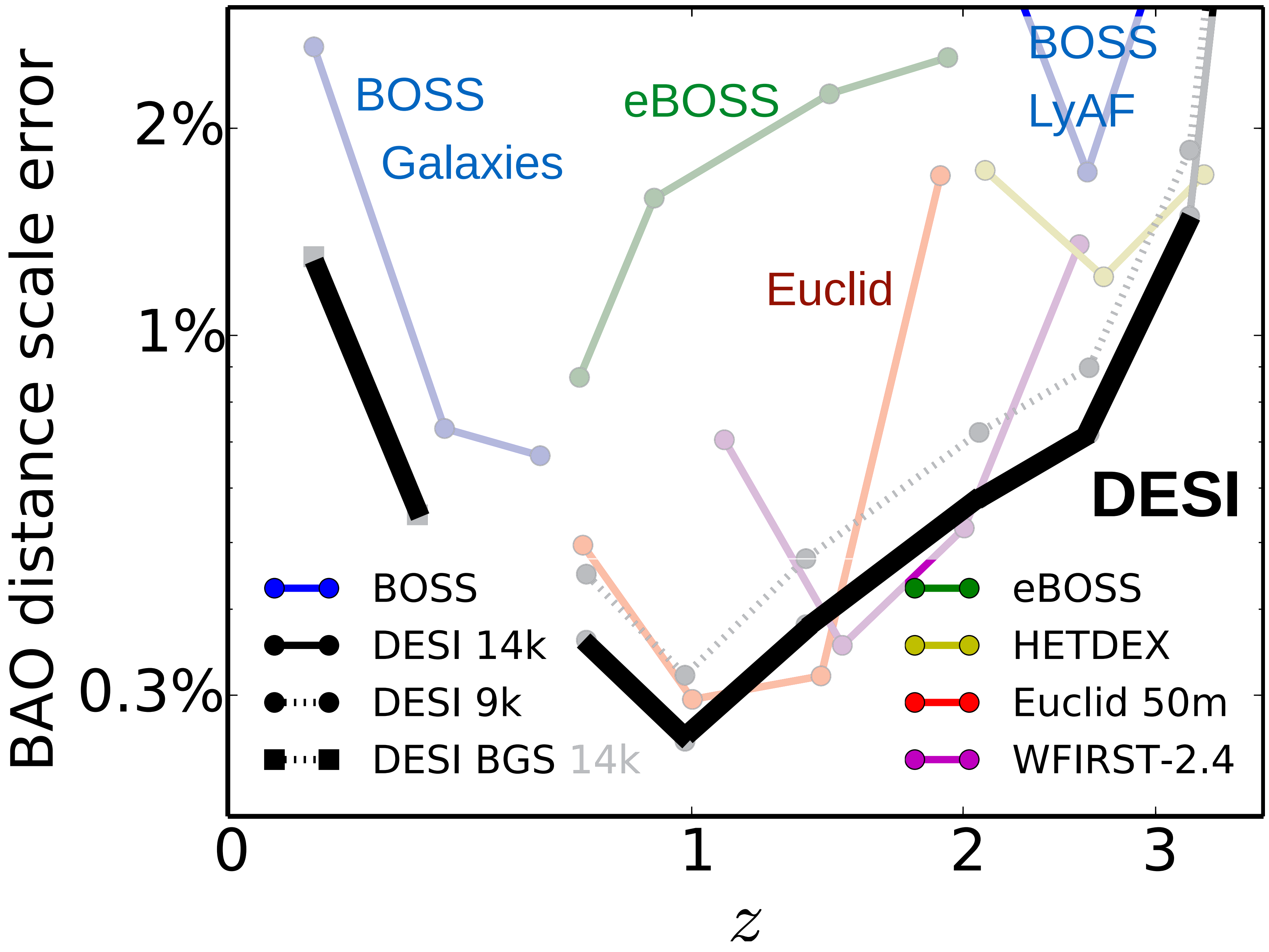


Figure 2.16: Improvement in the measurements of w_p, $w' = w_a$, Ω_k, m_ν the sum of the neutrino masses, n_s the spectral index, α_s the running of the spectral index, and $N_{\nu,eff}$ the number of neutrino-like (relativistic) species.

DESI in comparison



DESI Schedule

Nov 2012 CD0: DOE says they need a spectroscopy survey

- Merges BigBOSS and DESpec collaborations

Sept 2014 CD1: Conceptual Design Review

July 2015 CD2: Preliminary Design Review

- This secures the money

Early 2016 CD3: Another Design Review

- This gives us permission to build stuff
- Private money is already being used for long lead items

Mid 2018: Installation

Early 2019: Commissioning

Late 2019: Science verification

Late 2019 / early 2020: 5 year survey start

DESI & PFS (?)

What	DESI	PFS
Area	14k sq deg	1.4k sq deg
Field of View	7.5 sq deg	1.1 sq deg
Fibers	5000	2400
Wavelength	3600–9800	3800–12600
Telescope	4m @ 1.1” seeing	8m @ 0.8” seeing
Survey	5 years	3 x 1 years (?)
Start	2019	2017

DESI Data Systems

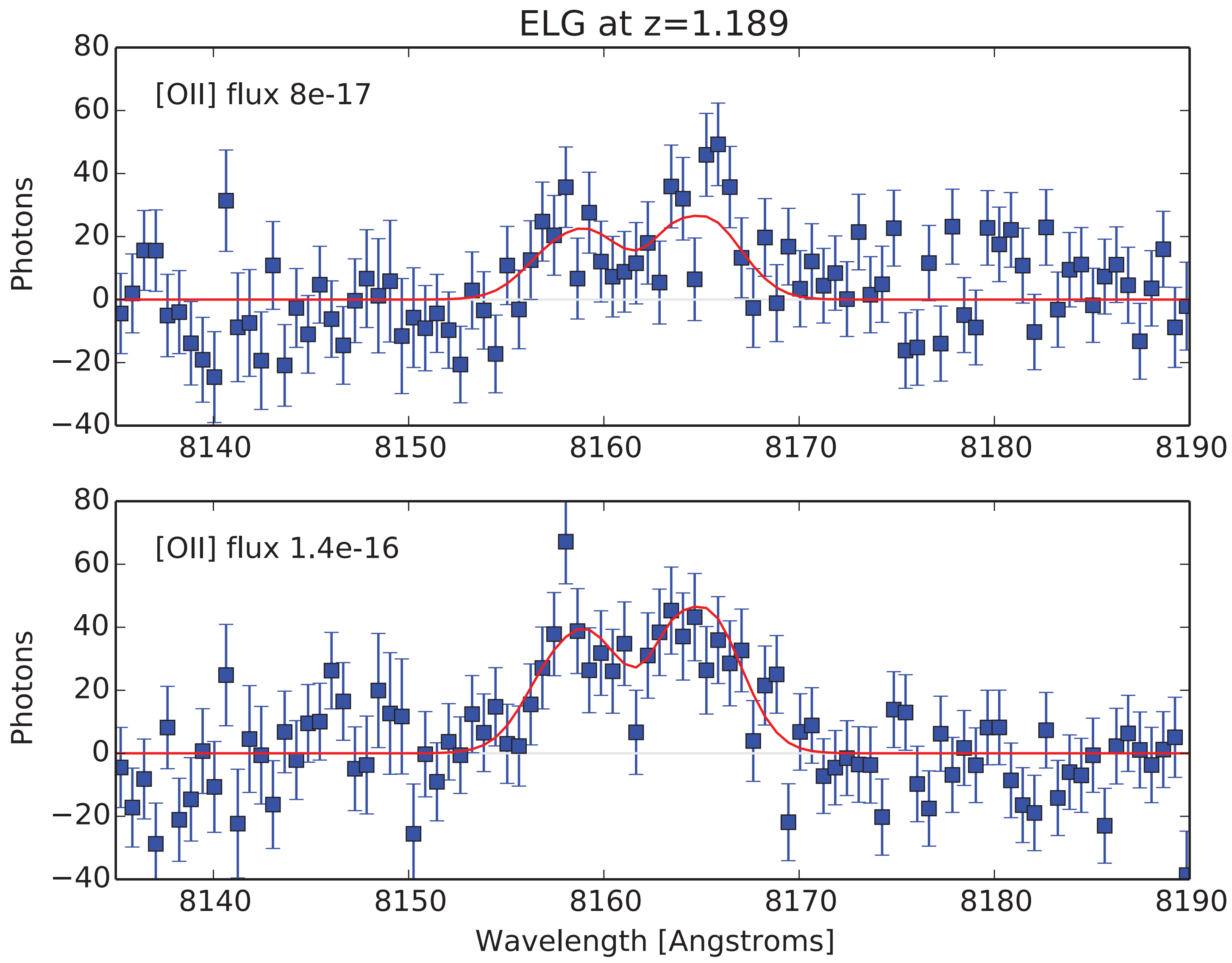
Getting the data

- Target selection
- Survey planning
- Interface with operations

Raw data –> useful data

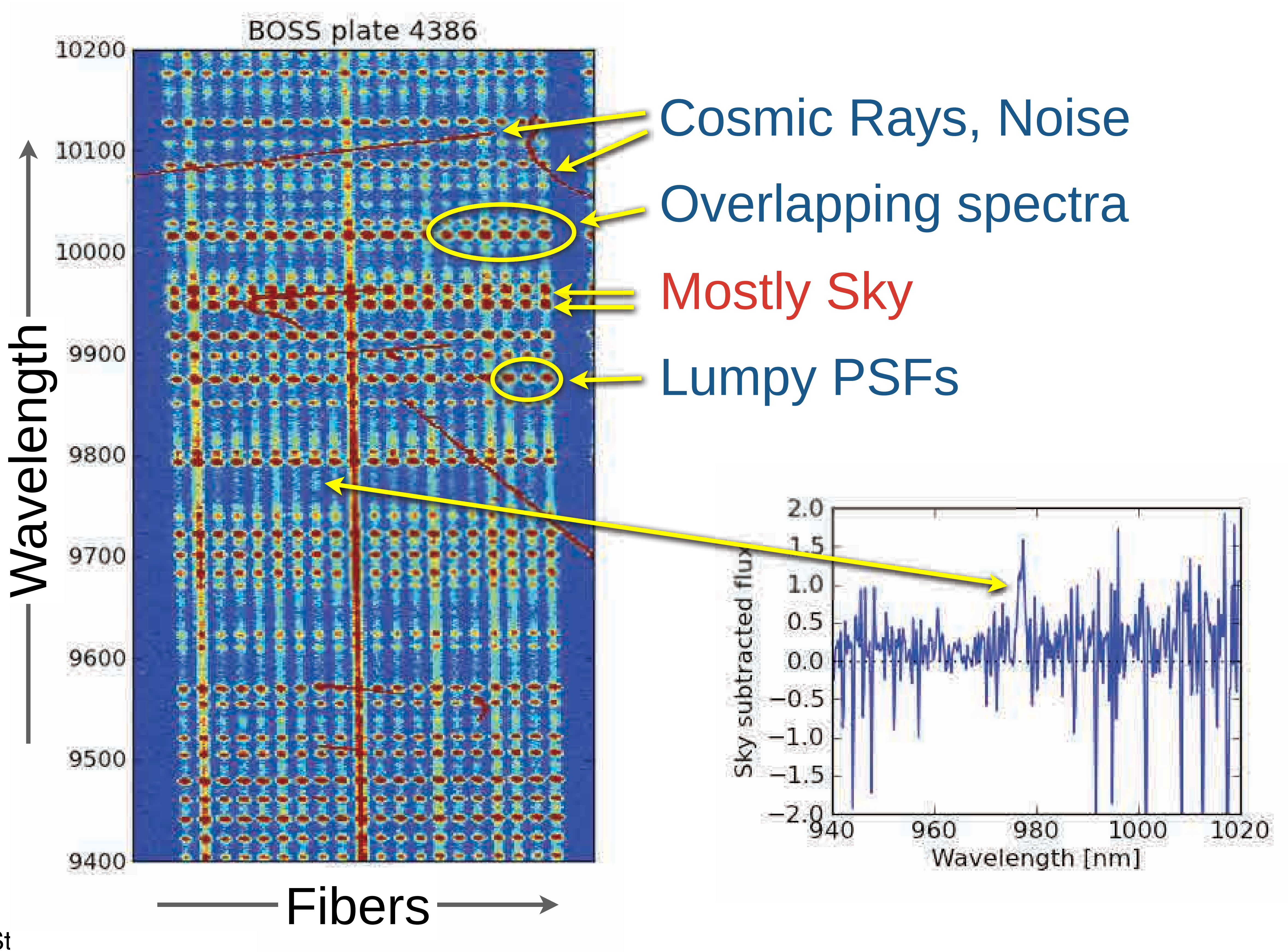
- Spectroscopic pipeline
- Data transfer & distribution

Simulations

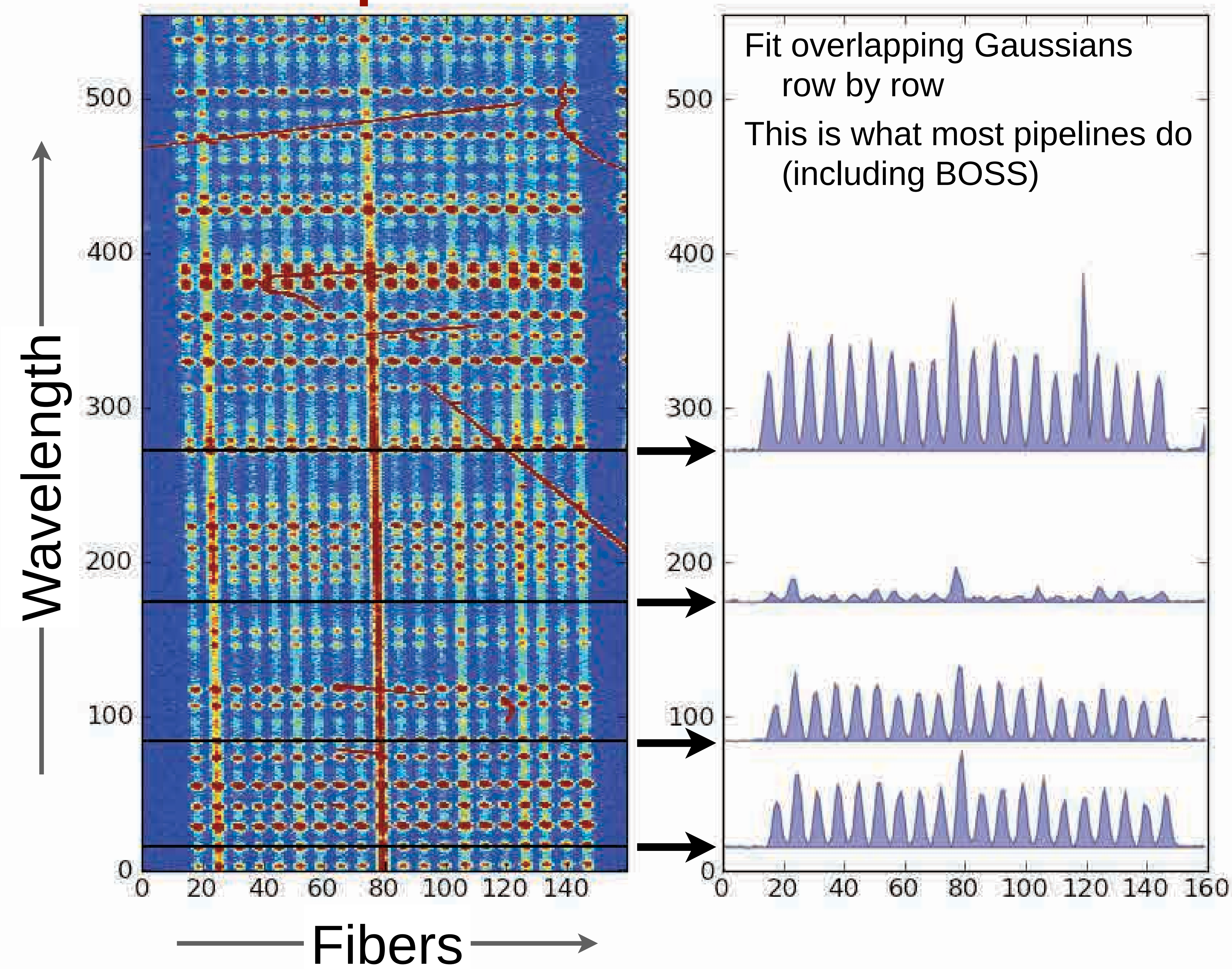


Can you find the ELG?

3x10^{-6} %
of DESI data

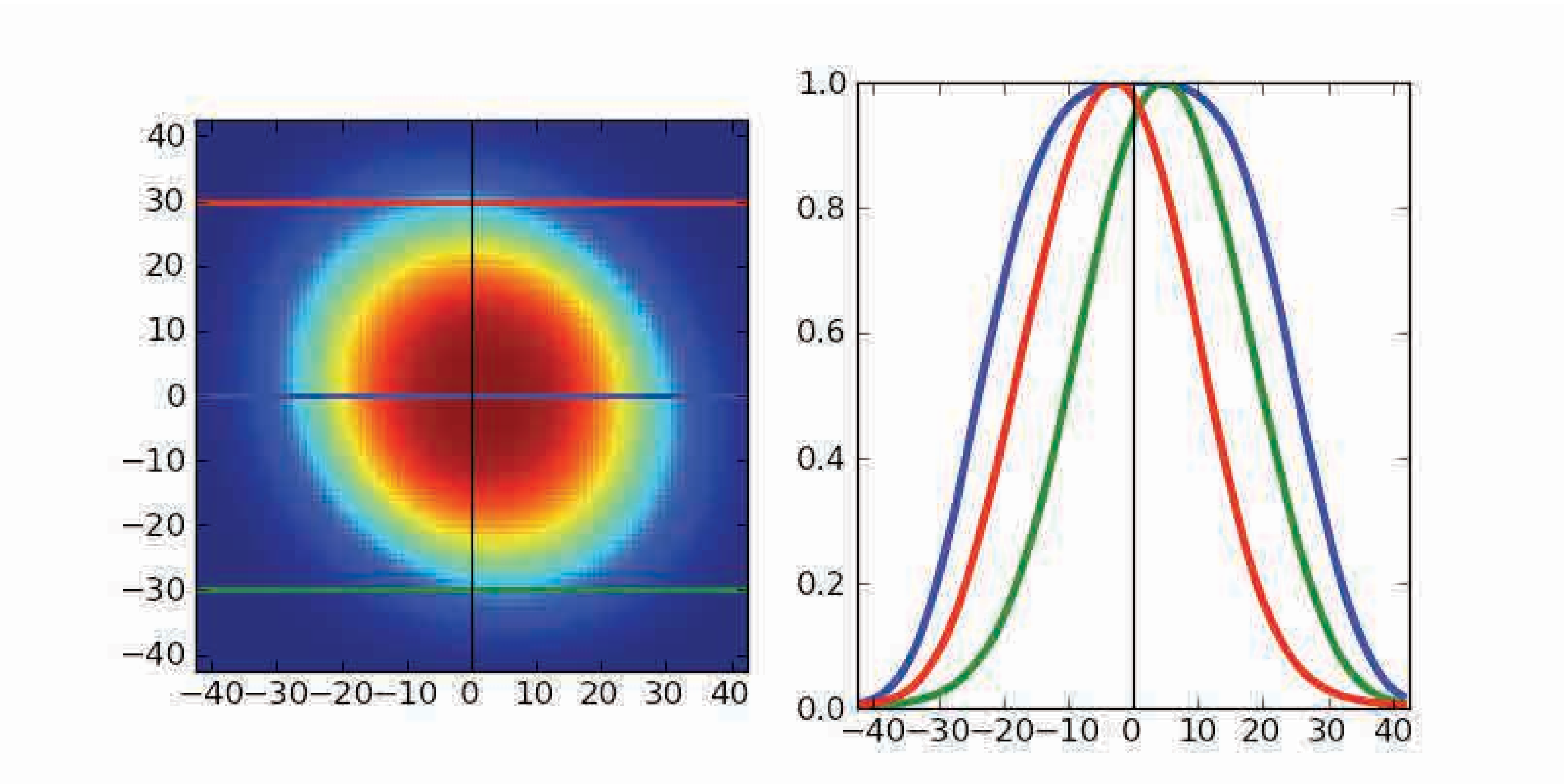


"Optimal" Extraction



"Optimal Extraction" ≠ Optimal

Only optimal if PSF(x,y) = P(x) Q(y)



Need Full 2D PSF to get this right:

"Spectroperfectionism"

Bolton & Schlegel 2010

What is a Spectrum?

Extraction as lossless data compression

Project flux to CCD pixels:

Projection Matrix: full 2D PSF

$$p = A(f_{\rm obj} + f_{\rm sky}) + \text{noise}$$

CCD pixels — *Flux for all objects*

χ^2 for model spectrum m:

$$\chi^2_p = \sum_{\rm CCD\ pix} \frac{(p - A(m + f_{\rm sky}))^2}{\sigma_p^2}$$

should be equivalent

$$\chi^2_f = \sum_\lambda \frac{(f - Rm)^2}{\sigma_f^2}$$

Resolution matrix

Model, e.g. ELG@z

Sky subtracted, Resolution convolved spectrum

Extraction products:

1. *Spectrum: sky subtracted, resolution convolved*
2. *Resolution matrix R (replaces Gaussian LSF)*
3. *Error model (full covariance)*

Spectroperfectionism in a Nutshell

2D PSF vs. spectrum and λ

$$p = Af + \text{noise}$$

Spectral flux –> CCD pixels

$$f = (A^T N^{-1} A)^{-1} A^T N^{-1} p$$

Solve for f

$$C_f = (A^T N^{-1} A)^{-1}$$

Covariance of f

$$\tilde{C} = R C_f R^T$$

Diagonalize C_f

$$\tilde{f} = R f$$

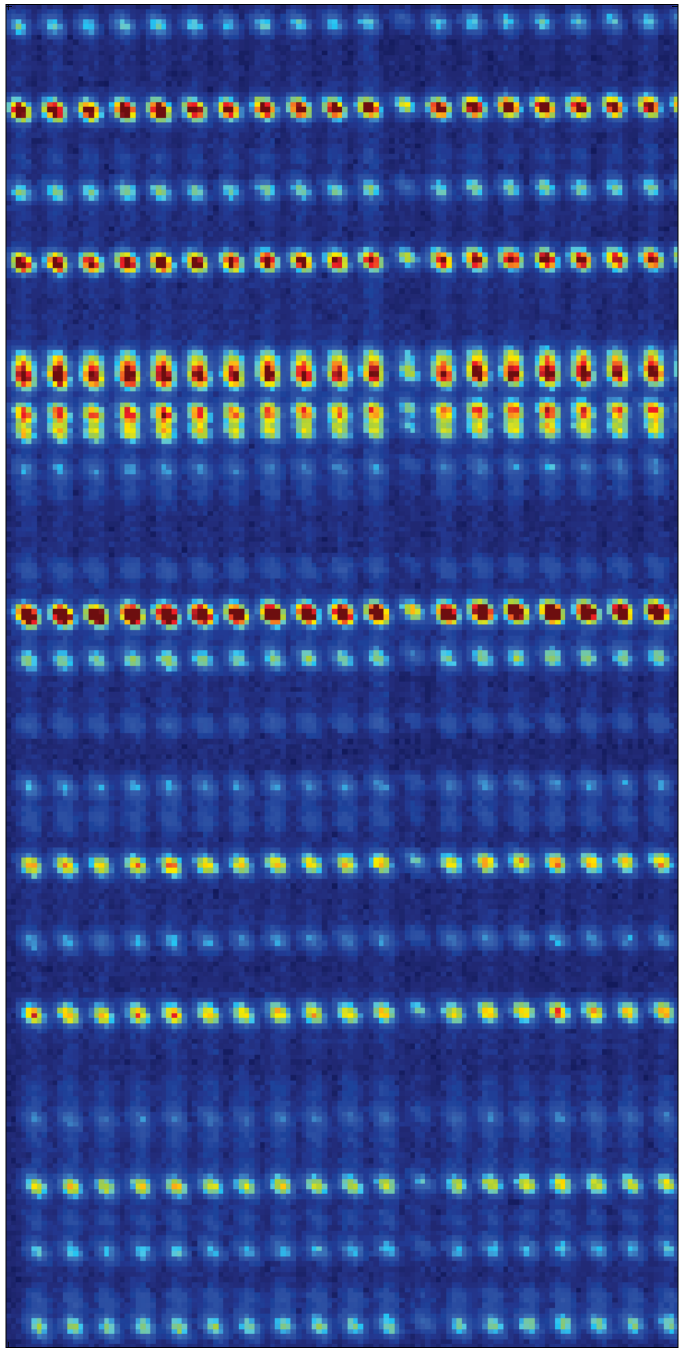
$\tilde{f}$ has diagonal error

–> Resolution equivalent to 1D spectrograph

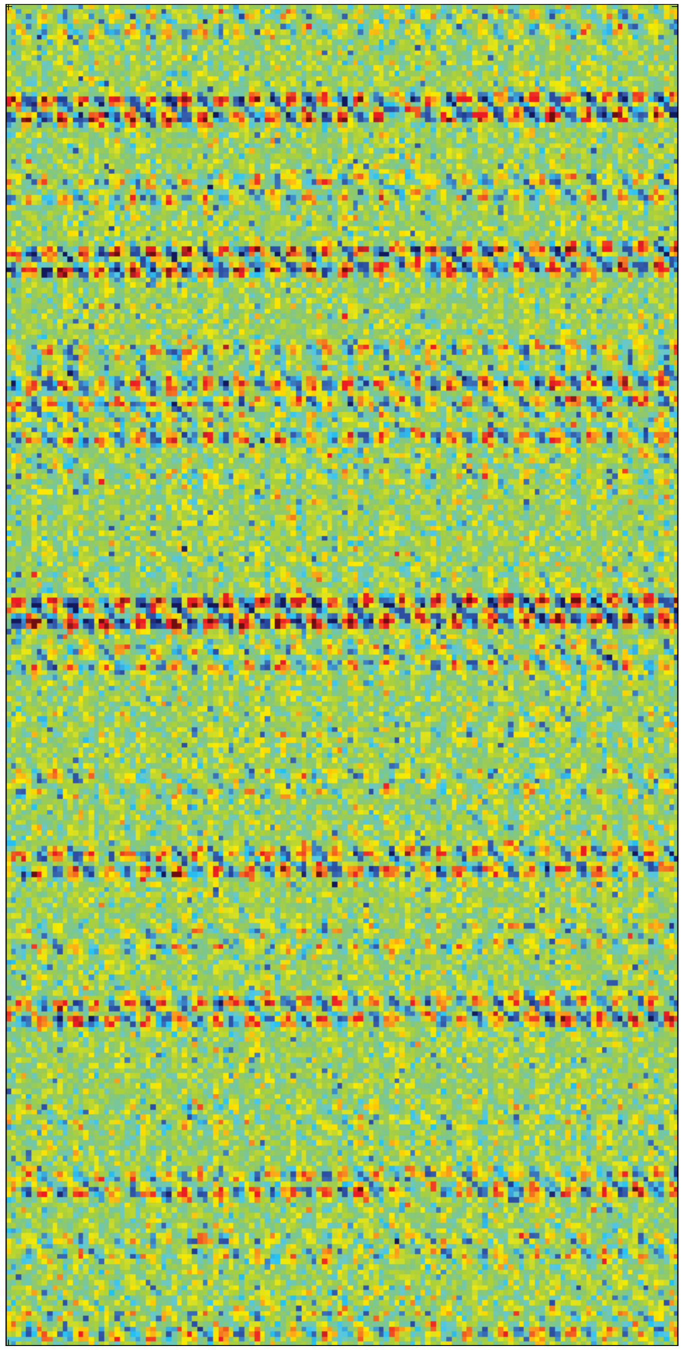
Three extraction products:

1. Spectrum (resolution convolved)
2. Resolution Matrix
3. Error model (*diagonalized* covariance)

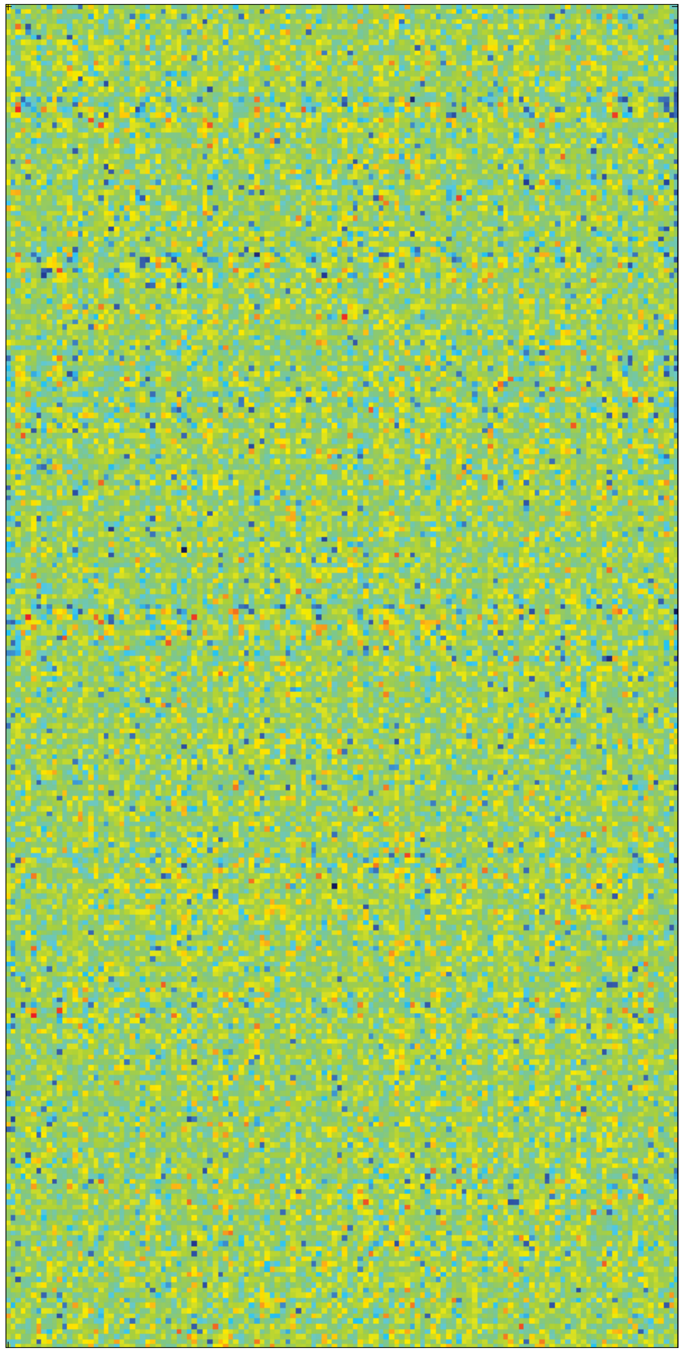
Extraction Residuals



Original Data

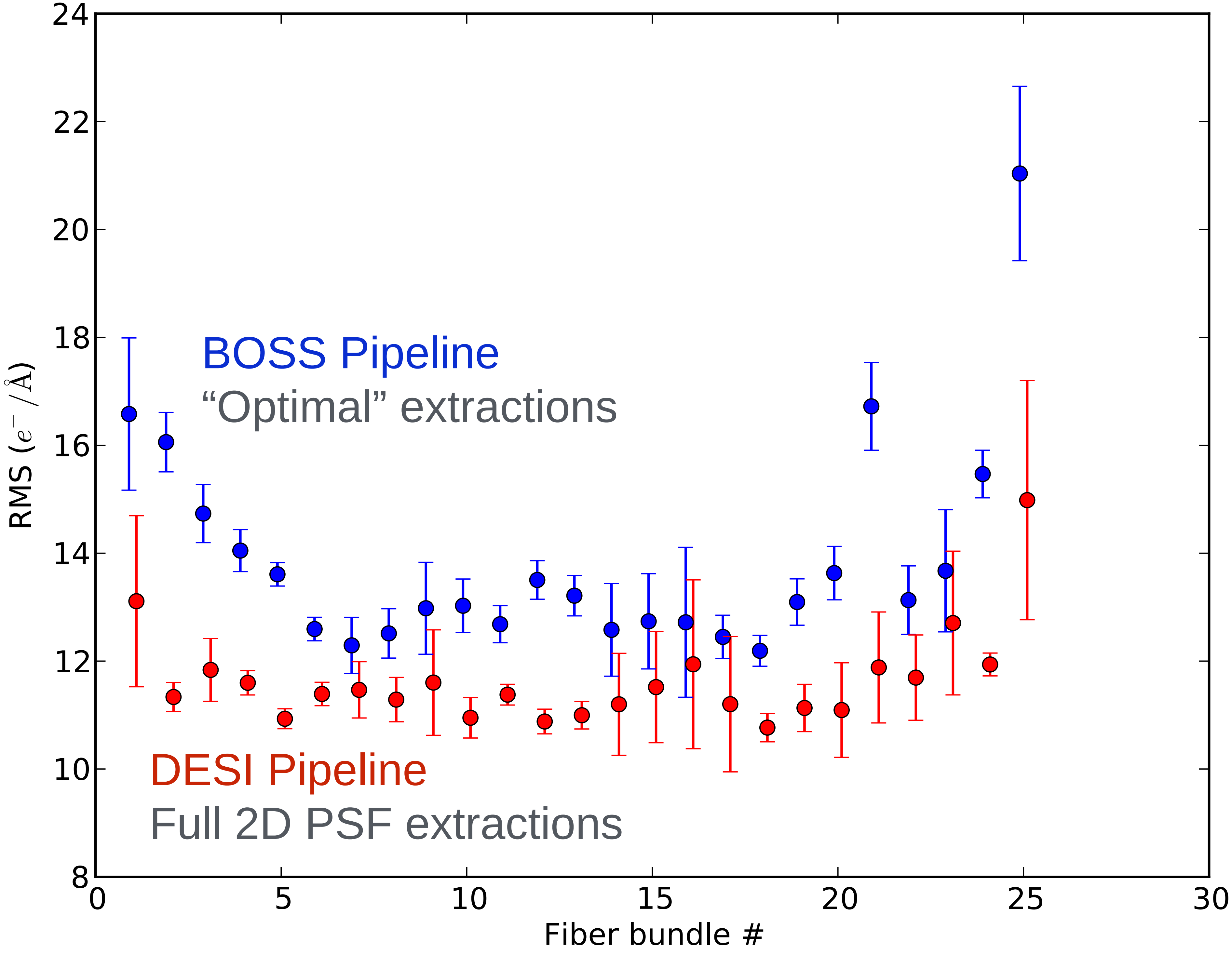


"Optimal" Residuals



Spectroperfectionism Residuals

Improved BOSS Sky Residuals



CPU Challenges

CCD pixels *Flux*

$$p = Af + \text{noise}$$

$$f = (A^T N^{-1} A)^{-1} A^T N^{-1} p$$

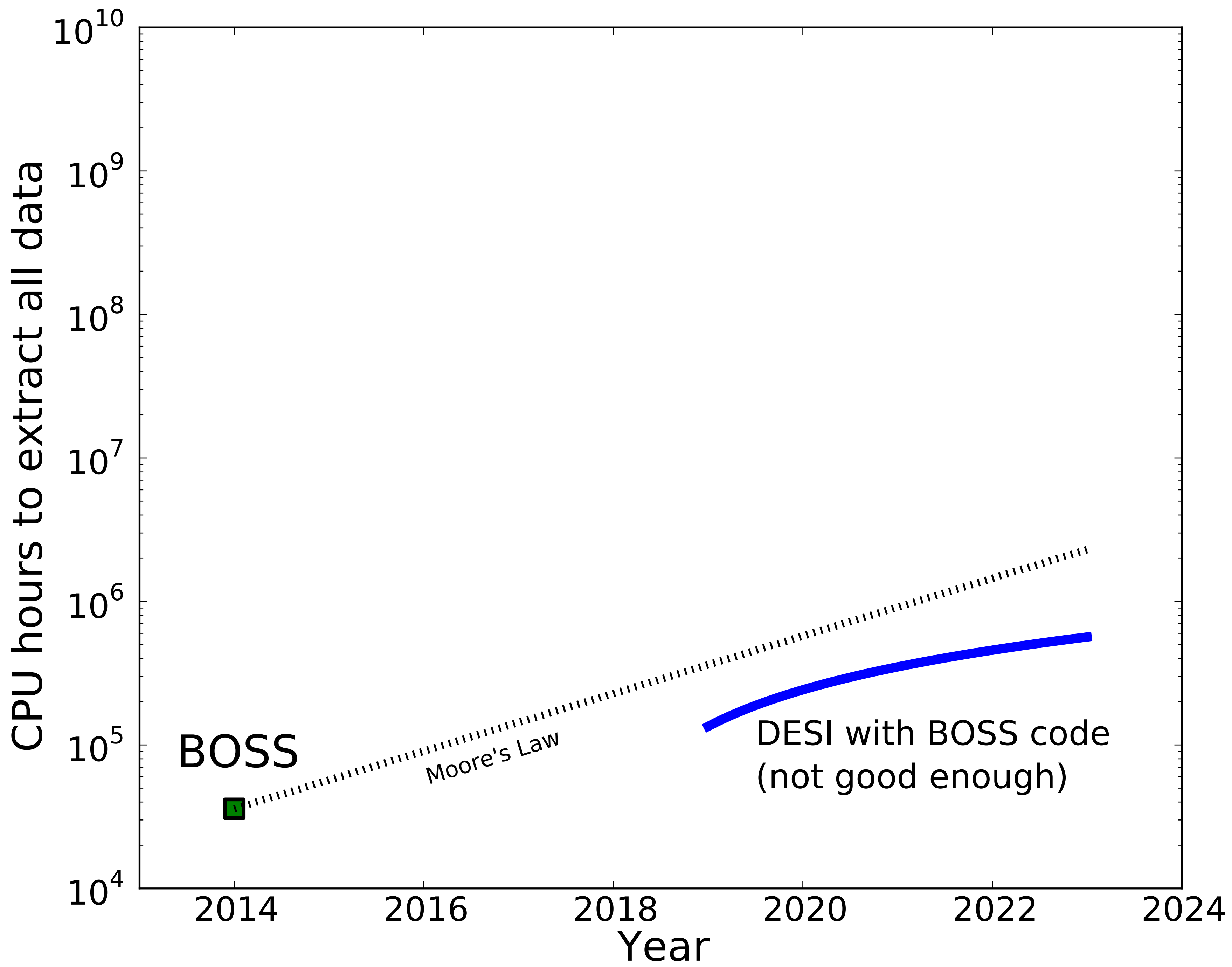
16M x 16M matrix

30 per exposure

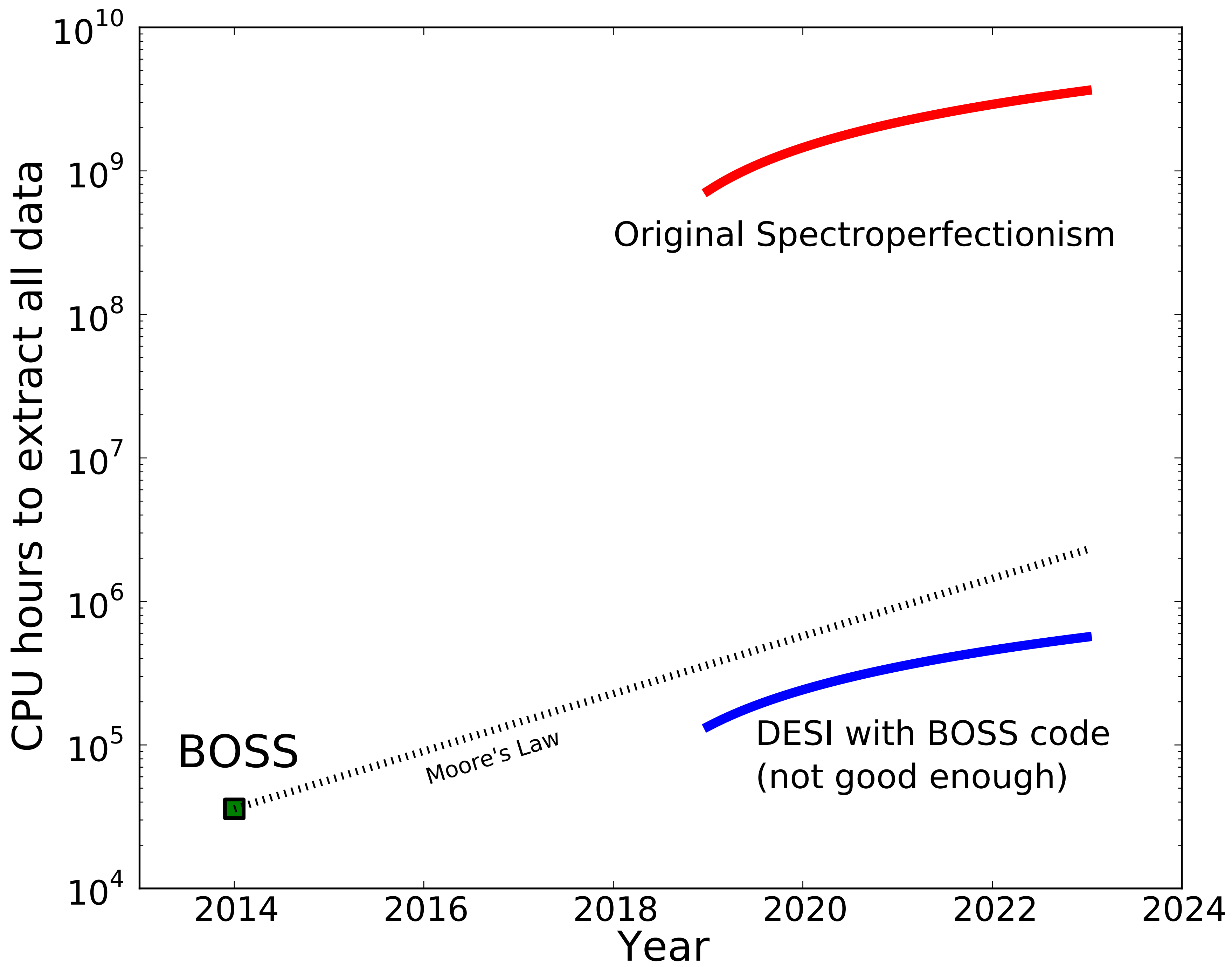
up to 100 per night

fortunately they are sparse matrices

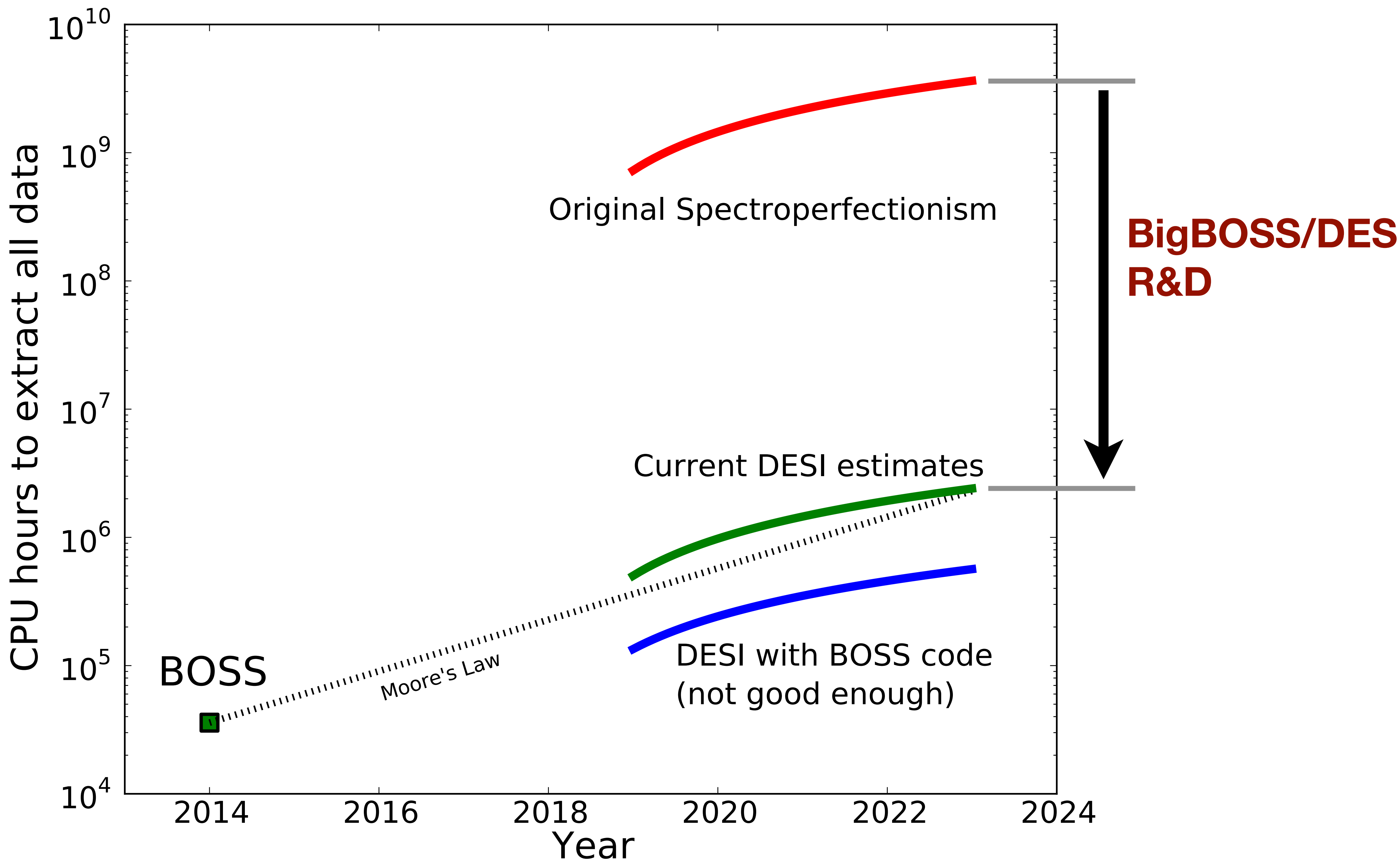
Spectral Extraction: CPU Hours



Spectral Extraction: CPU Hours

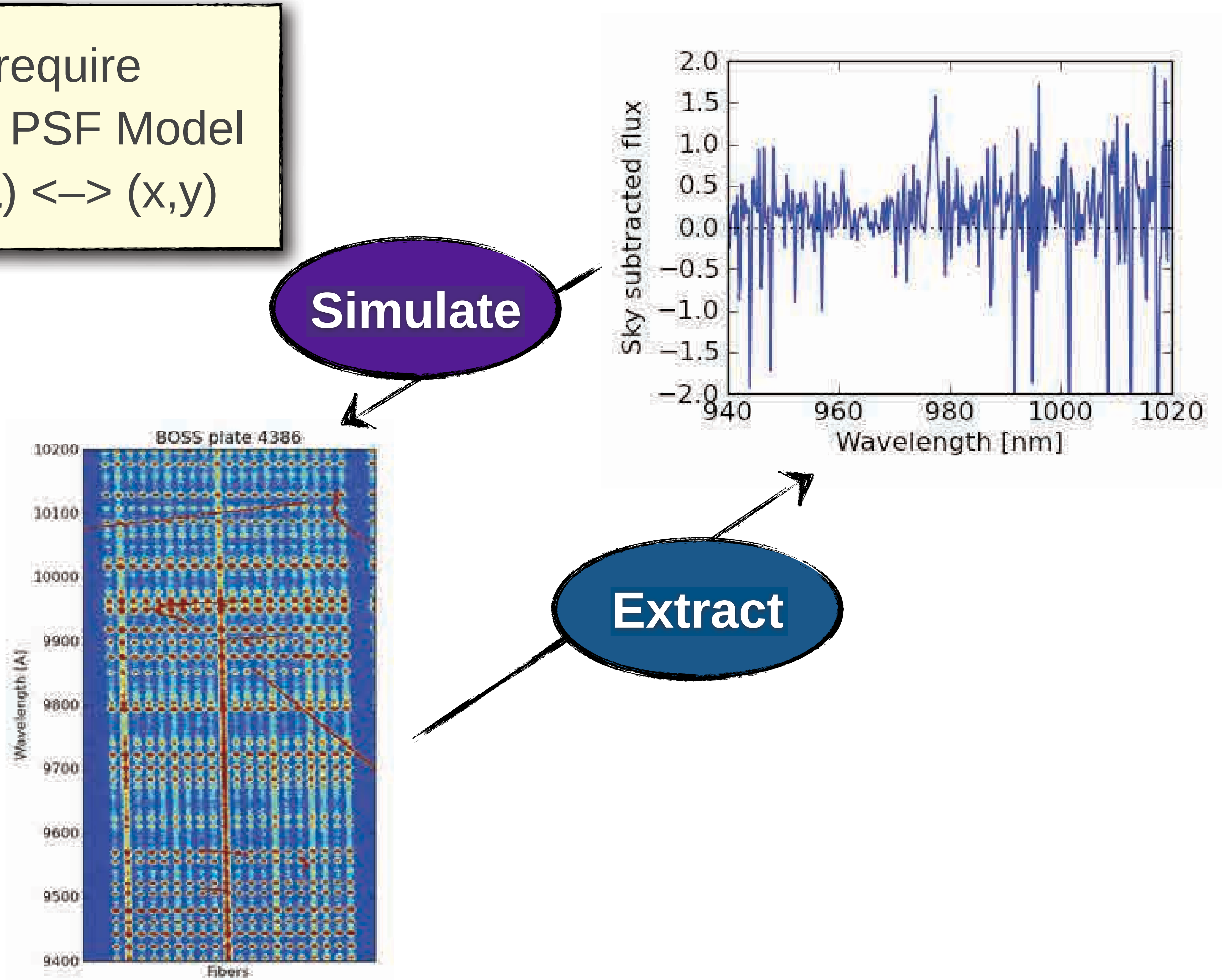


Spectral Extraction: CPU Hours

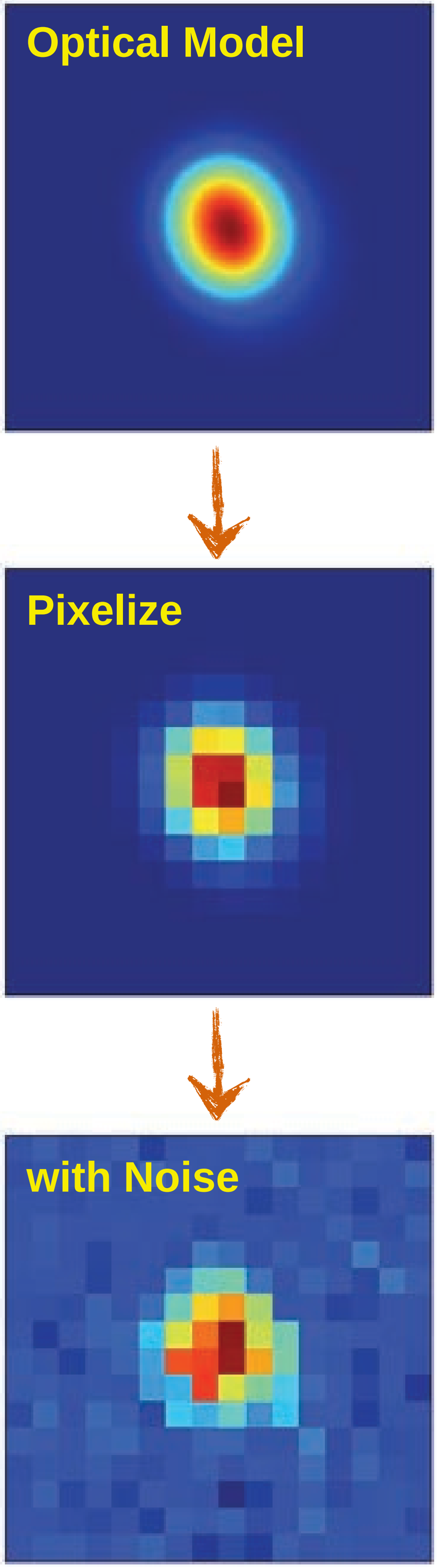


Simulation = (Extraction)$^{-1}$

Both require
- 2D PSF Model
- (i,**λ**) <–> (x,y)



Instrument Simulations



Used for:

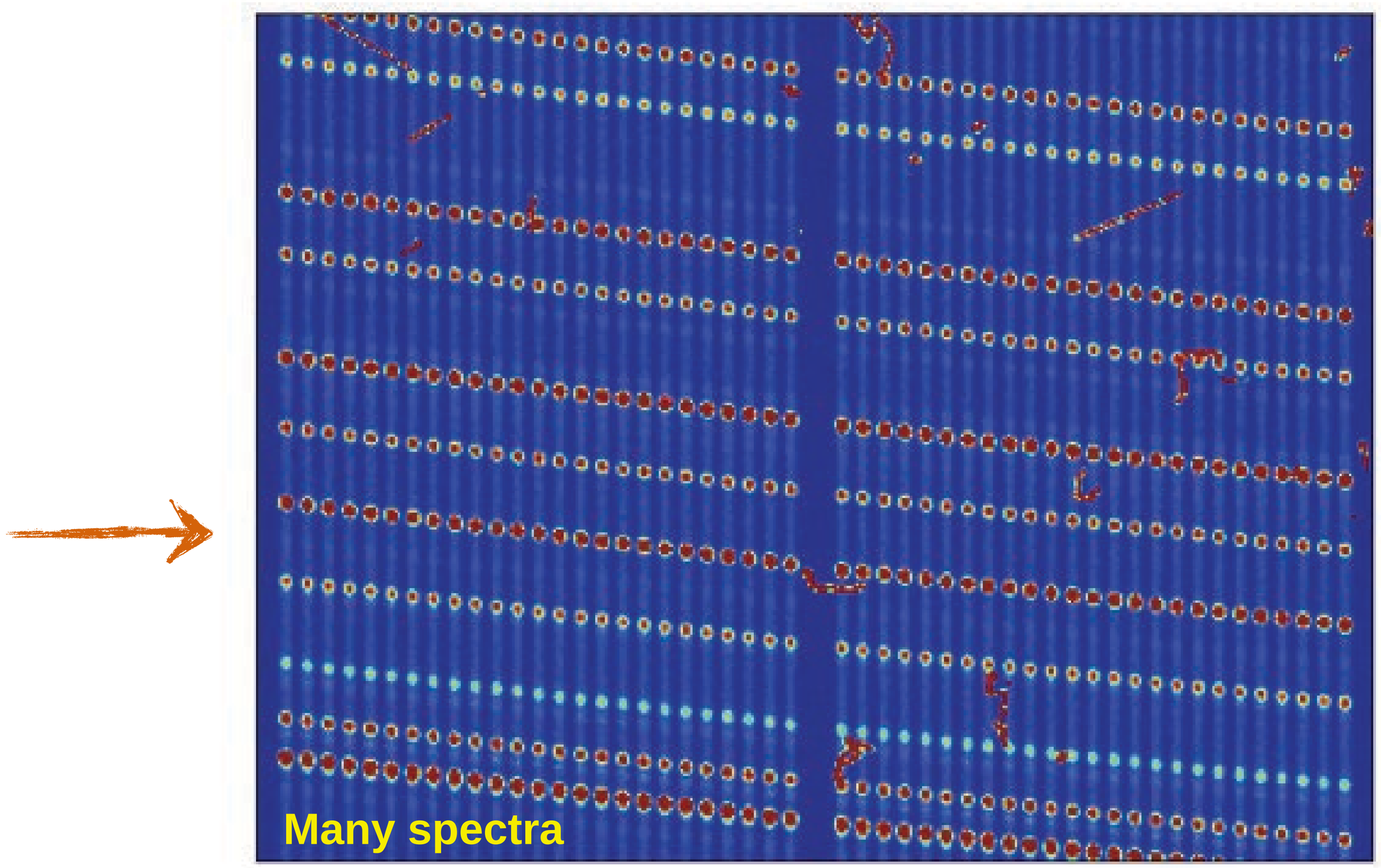
– *Science impact* of design choices

– Extraction *algorithm development*

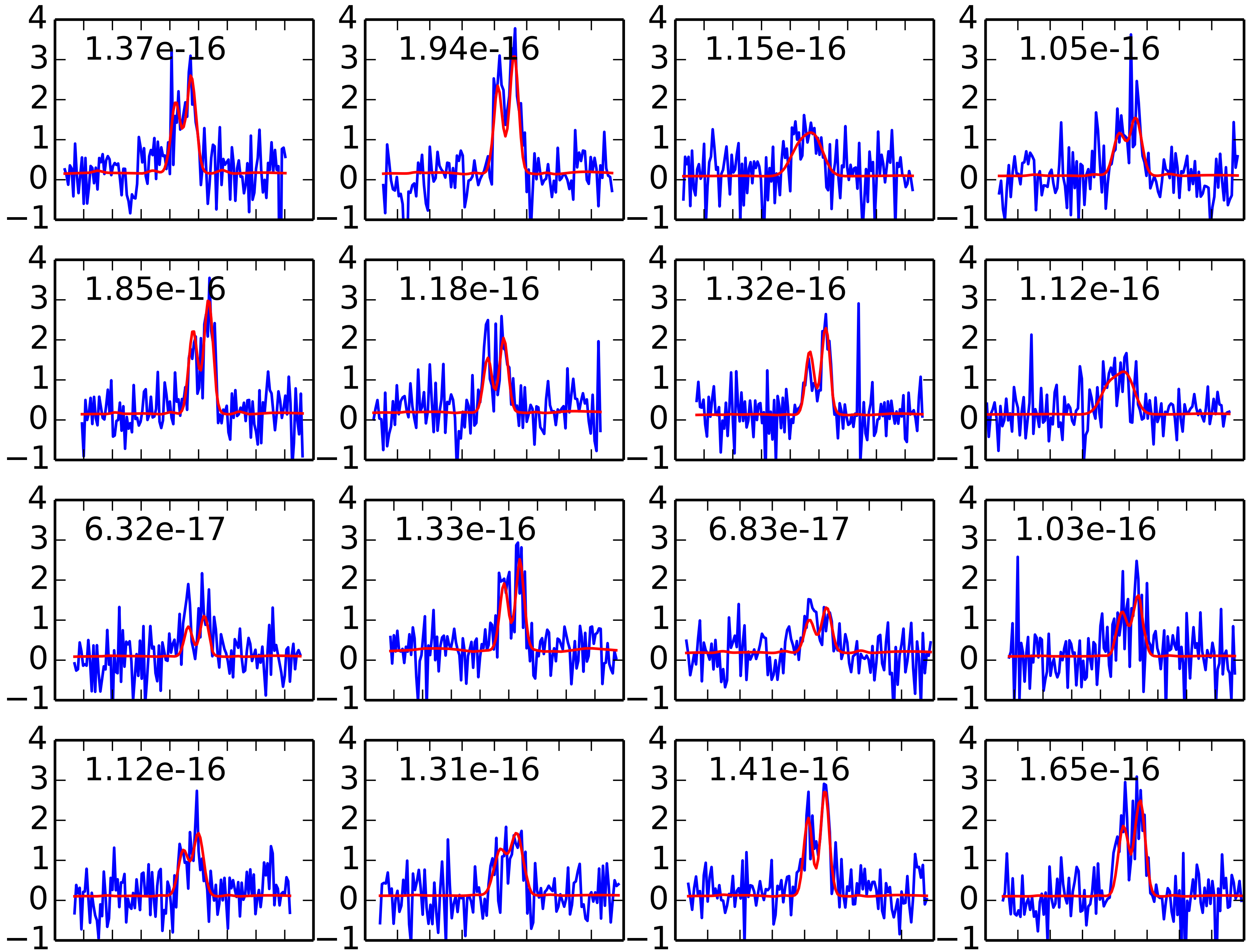
– Operations *requirements*

  – Temperature stability

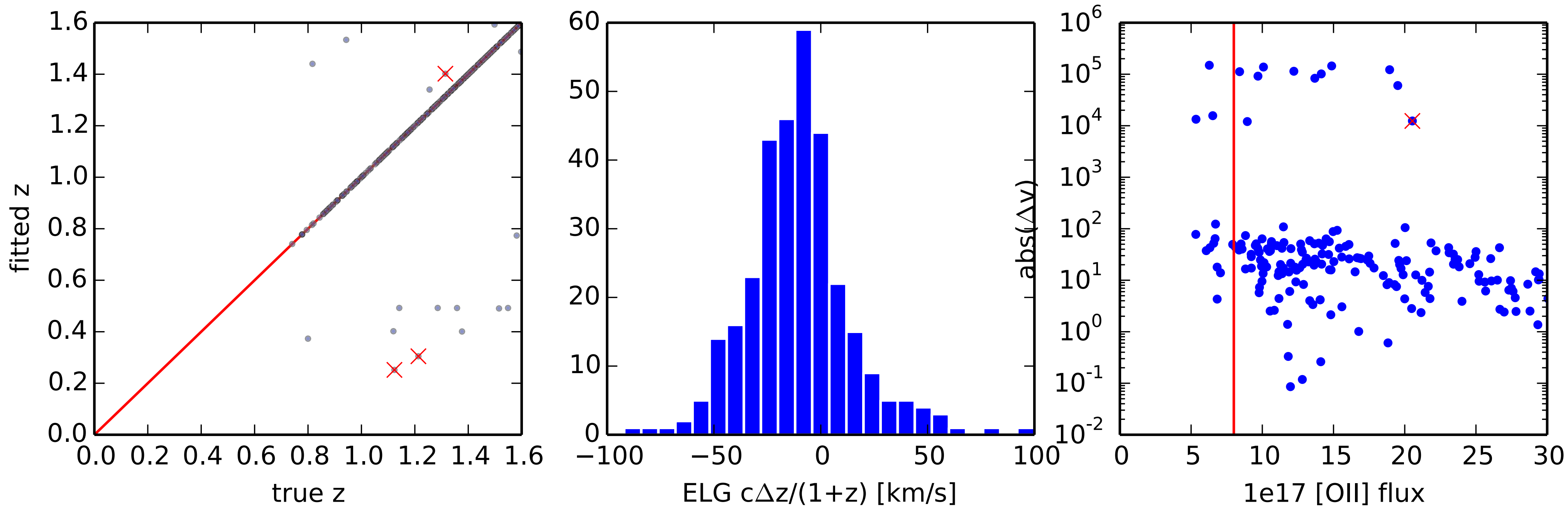
  – Calibration system



Prototype Pipeline ELGs



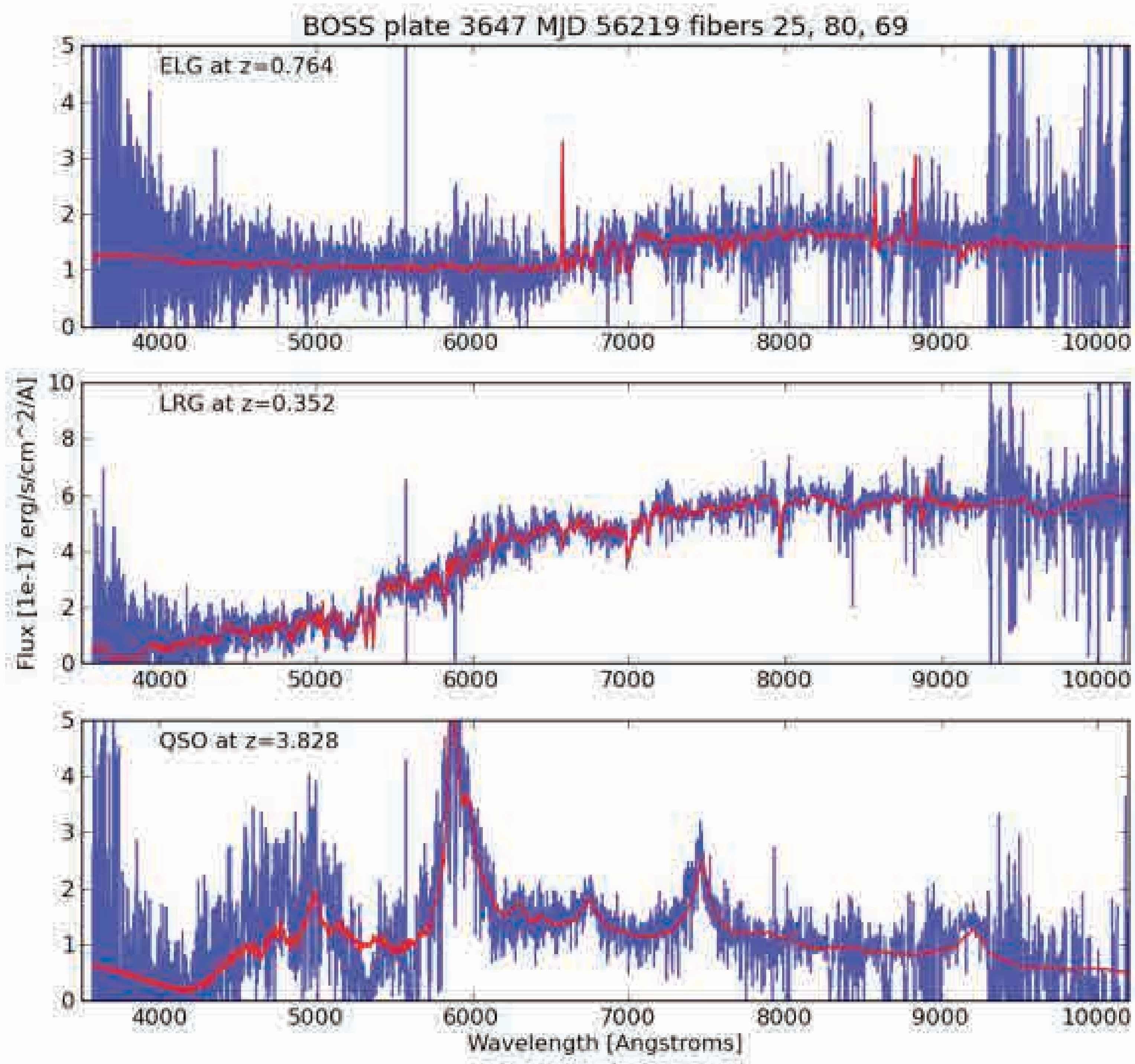
Prototype Pipeline Redshifts



SRD	Requirement	Achieved*
ELG z err	150 km/s	30 km/s
ELG z failures	<5% catastrophic	5% failures; 1% catastrophic
ELG z bias	60 km/s	10 km/s

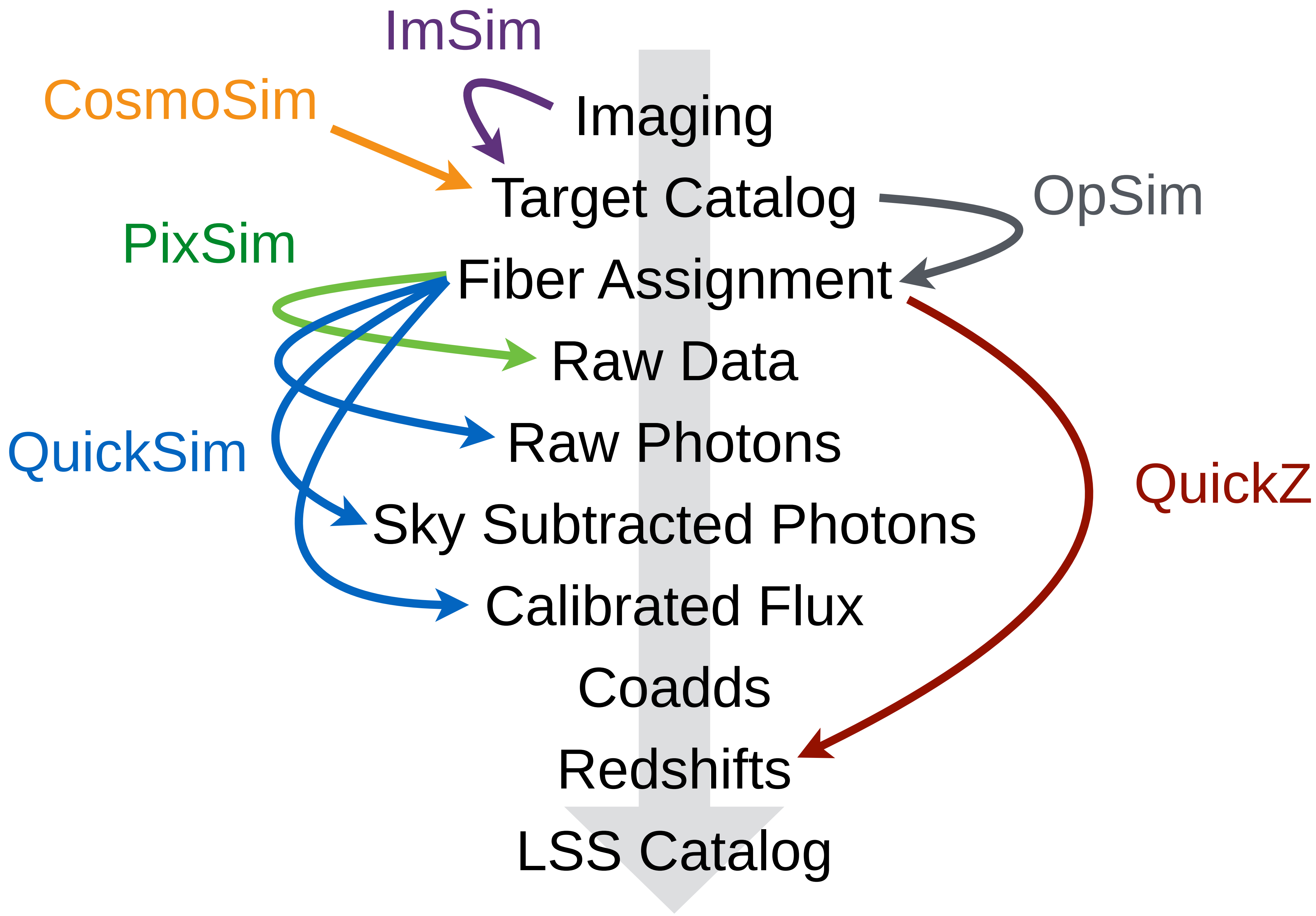
*Caveat: it can only get worse from here...

DESI applied to BOSS data



Real data keeps us honest

Simulations & Pipeline



https://github.com/sbailey/specter

DESI improvements over BOSS

Hardware

- Bigger telescope, new corrector with ADC — 2.5m –> 4m
- Higher resolution & better throughput spectrographs — R ~ 4000
- 5000 robotically positioned fibers — 1k –> 5k

Survey

- Larger footprint — 11k –> 14k
- Target selection from new, deeper imaging — 1-2 mag deeper than SDSS

Software

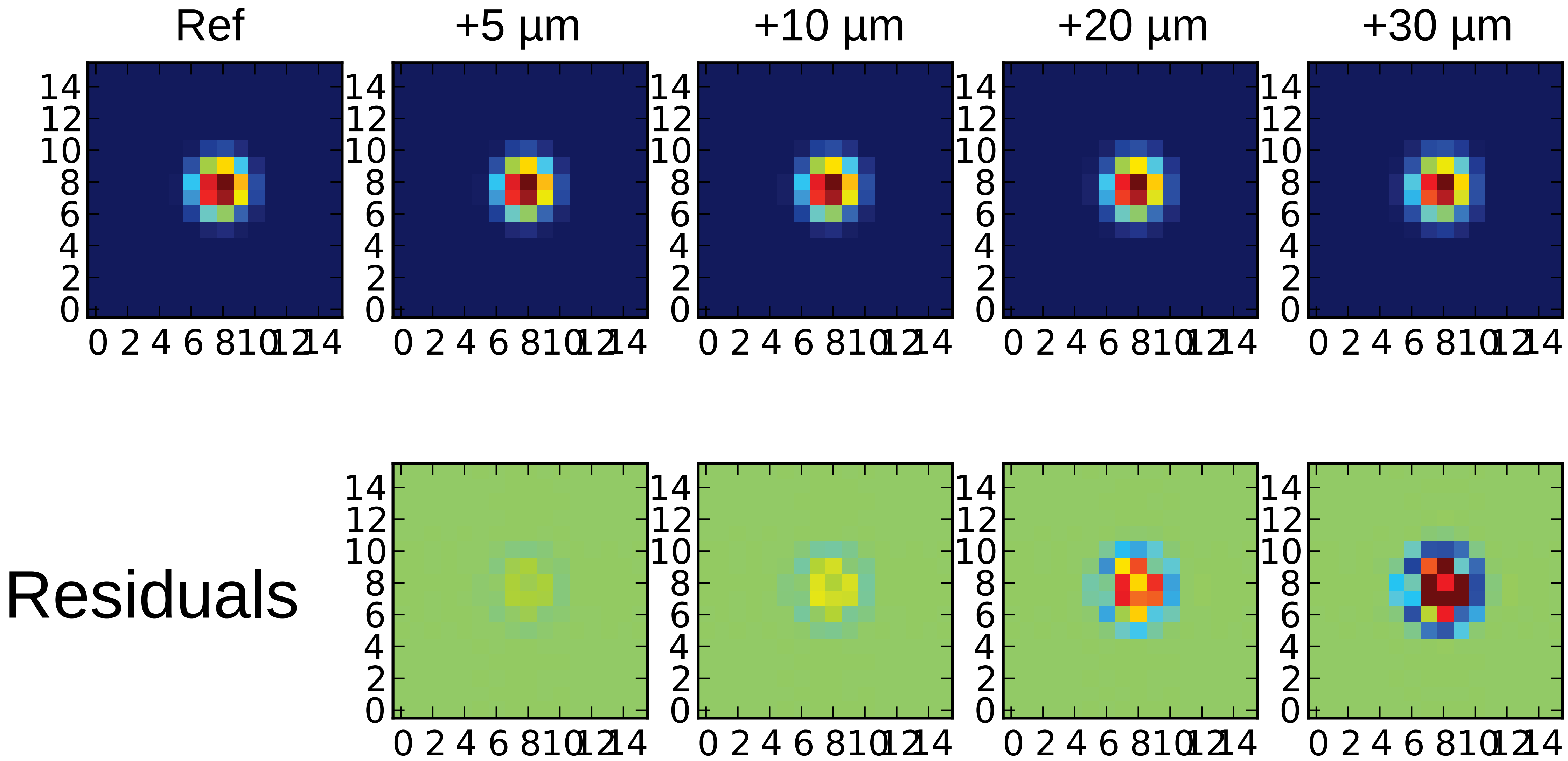
- Better algorithms to maximize the data — Full information propagation
  - Information content
  - Minimizing systematics
- Smoother data flow, learning from our experiences with SDSS

Analysis

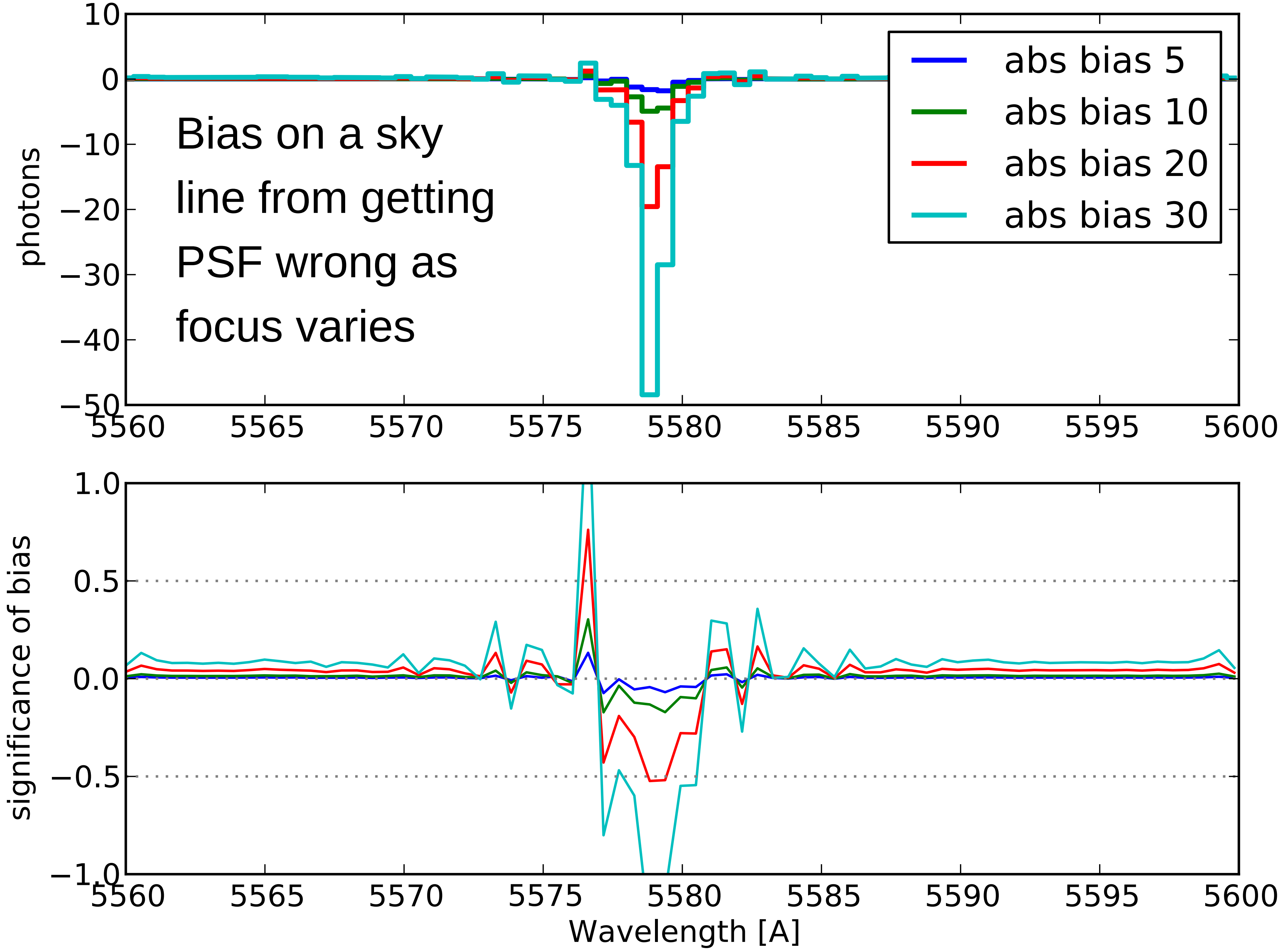
- Combining all these pieces into the definitive BAO survey

PSF Stability Requirements

Varying Focus –>



PSF Stability Requirements



Conclusions

BOSS has the world’s best BAO measurements

- Highest precision galaxy BAO
- First (and only) Lyman-alpha BAO

DESI will greatly expand this reach

- Better hardware, software, science

Complimentary to other cosmology probes & surveys

Great future for big surveys

- Let’s collaborate!