COSMOLOGY WITH THE LYMAN-ALPHA FOREST:

BEYOND TWO-POINT STATISTICS
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DESI INSTRUMENTATION

Suk Sien Tie

Ohio State University

Lawrence Berkeley National Lab (LBNL) | Dec 6, 2019

COSMOLOGY WITH THE LYMAN-ALPHA FOREST:

BEYOND TWO-POINT STATISTICS

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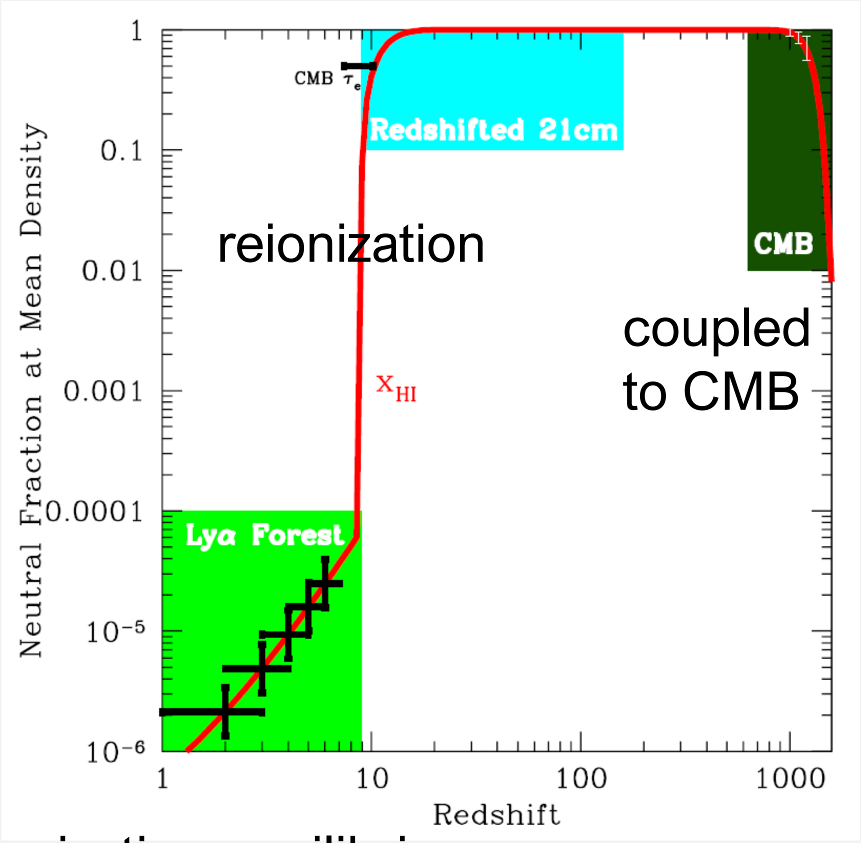
DESI INSTRUMENTATION

in collaboration with:

David Weinberg, Paul Martini, Wei Zhu, Sebastien Peirani, Teresita Suarez, and Stephane Colombi

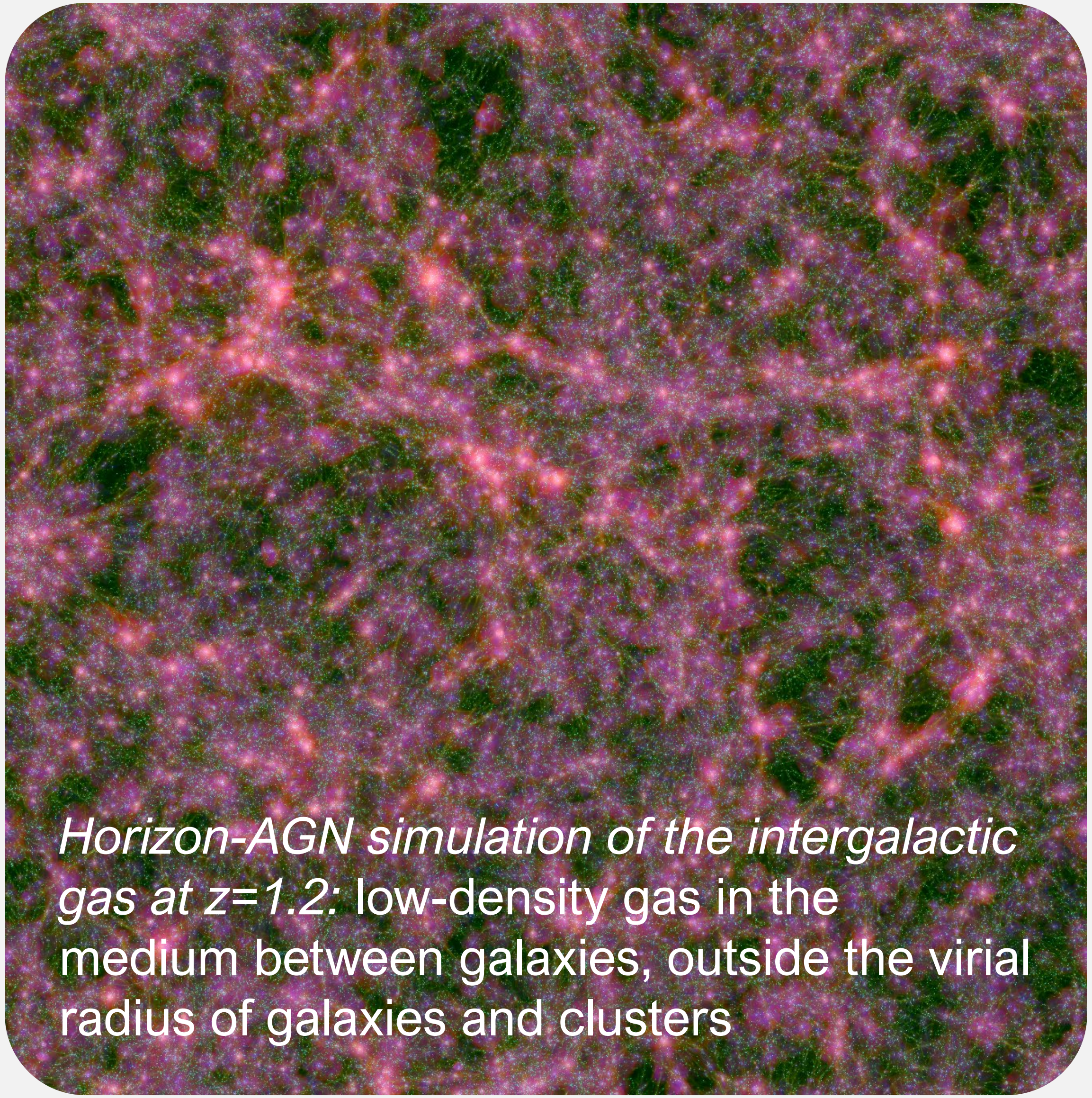
the Lyα forest of the Intergalactic Medium

Undergoes **thermal and phase changes**



photoionization equilibrium

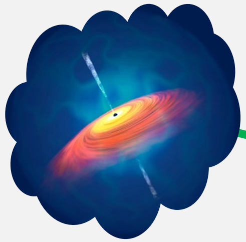
McQuinn et al. (2015)

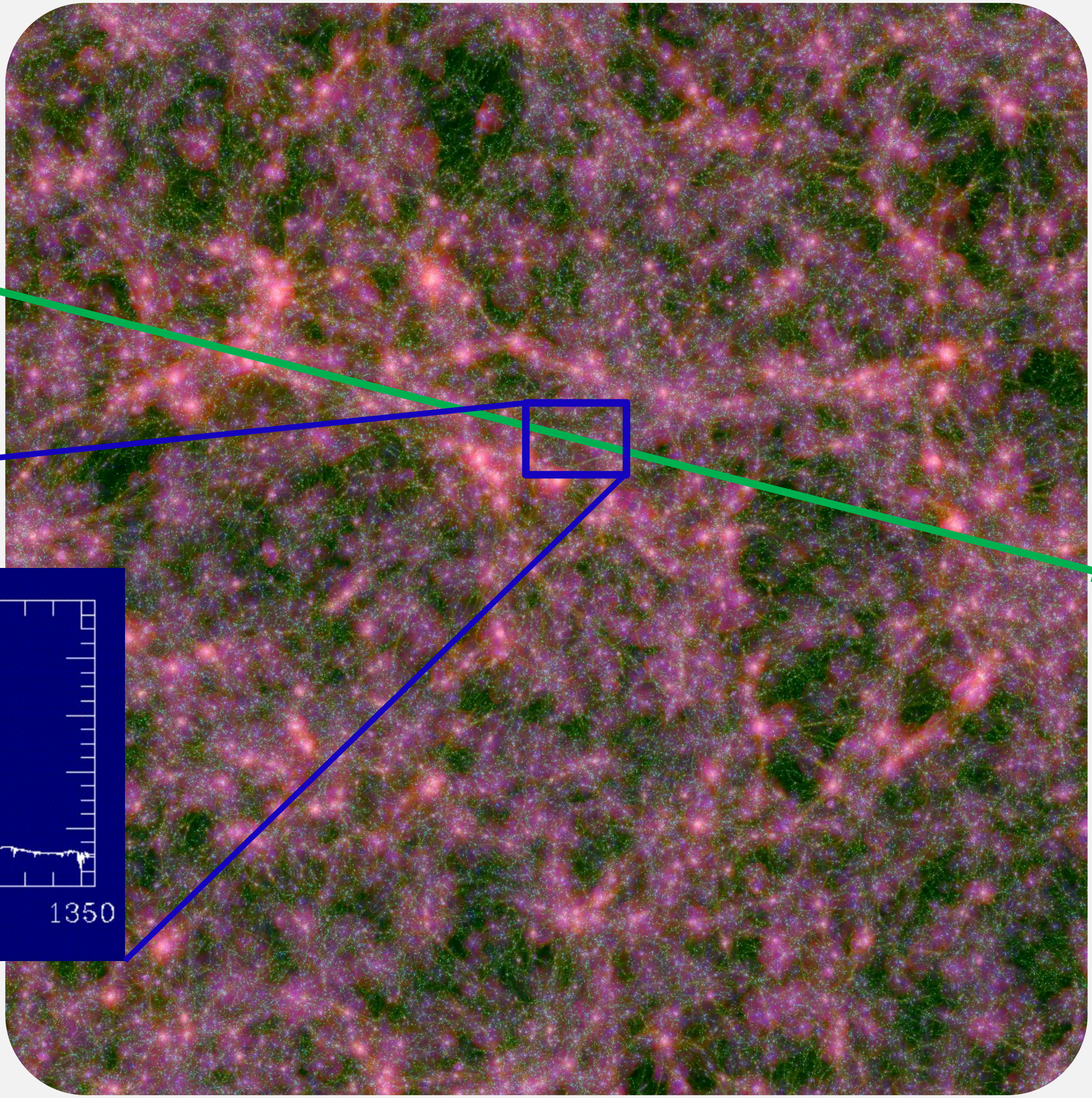


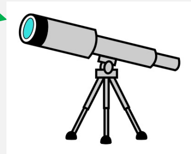
Horizon-AGN simulation of the intergalactic gas at z=1.2: low-density gas in the medium between galaxies, outside the virial radius of galaxies and clusters

the Lyα forest of the Intergalactic Medium

Observationally, the forest is a series of absorption lines between the LyA (1216 A) and LyB (1026 A) emission lines.







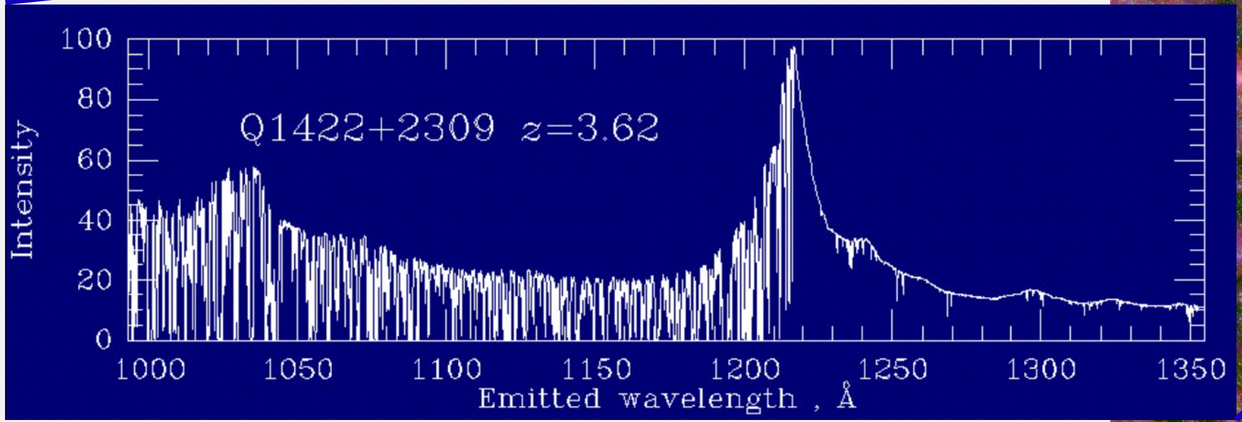


Figure from William Keel (Songaila & Cowie, 1996)

THE DISTRIBUTION OF LYMAN-ALPHA ABSORPTION LINES IN THE SPECTRA OF SIX QSOs: EVIDENCE FOR AN INTERGALACTIC ORIGIN

WALLACE L. W. SARGENT AND PETER J. YOUNG
Hale Observatories,[1] California Institute of Technology

AND

A. BOKSENBERG AND DAVID TYTLER
Department of Physics and Astronomy, University College London
Received 1979 February 26; accepted 1979 June 11

We conclude that the single Lα absorption lines and the metal line systems arise from physically distinct populations of clouds. Both types of system are produced by cosmologically distributed intervening material not associated with QSOs. The metal line systems probably arise in galaxy halos, and the Lα clouds must be an intergalactic population which is not associated with galaxies.

from intergalactic clouds…

…to a tracer of the matter field

THE LYMAN-ALPHA FOREST IN THE COLD DARK MATTER MODEL

Lars Hernquist[1,2], Neal Katz[3], David H. Weinberg[4,5], Jordi Miralda-Escudé[5]
E-mail: lars@helios.ucsc.edu, nsk@astro.washington.edu, dhw@payne.mps.ohio-state.edu, jordi@sns.ias.edu

ABSTRACT

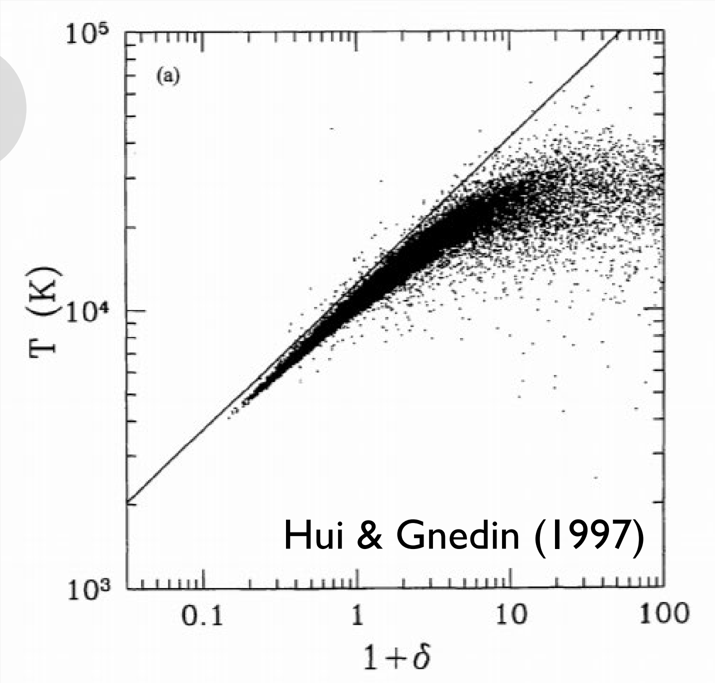
Cosmological simulations with gas provide a detailed description of the intergalactic medium, making possible predictions of neutral hydrogen absorption in the spectra of background QSOs. We present results from a high-resolution calculation of an $\Omega = 1$ cold dark matter model. Our simulation reproduces many of the observed properties of the Lyα forest surprisingly well.

The distribution of HI column densities agrees with existing data to within a factor of $\sim$ two over most of the range from $10^{14}\ \mathrm{cm}^{-2}$ to $10^{22}\ \mathrm{cm}^{-2}$; i.e., from unsaturated Lyα forest lines to damped Lyα systems. The equivalent width distribution matches the observed exponential form with a characteristic width $W_* \approx 0.3$ Å. The distribution of b-parameters appears consistent with that derived from QSO spectra. Most of the low column density absorption arises in large, flattened structures of moderate or even relatively low overdensity, so there is no sharp distinction between the Lyα forest and the "Gunn-Peterson" absorption produced by the smooth intergalactic medium.

Our results demonstrate that a Lyα forest like that observed develops naturally in a hierarchical clustering scenario with a photoionizing background. Comparison

i Gas in photoionization equilibrium with the ionizing background radiation

ii Tight temperature-density relation



iii Connection between flux and dark matter density field (fluctuating Gunn-Peterson approximation):

$$\tau_F \propto (1+\delta)^{1.6}$$

$$F \approx e^{-\tau}$$

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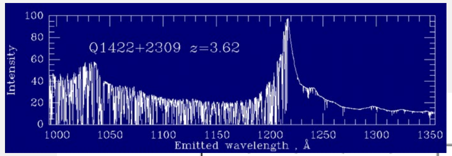

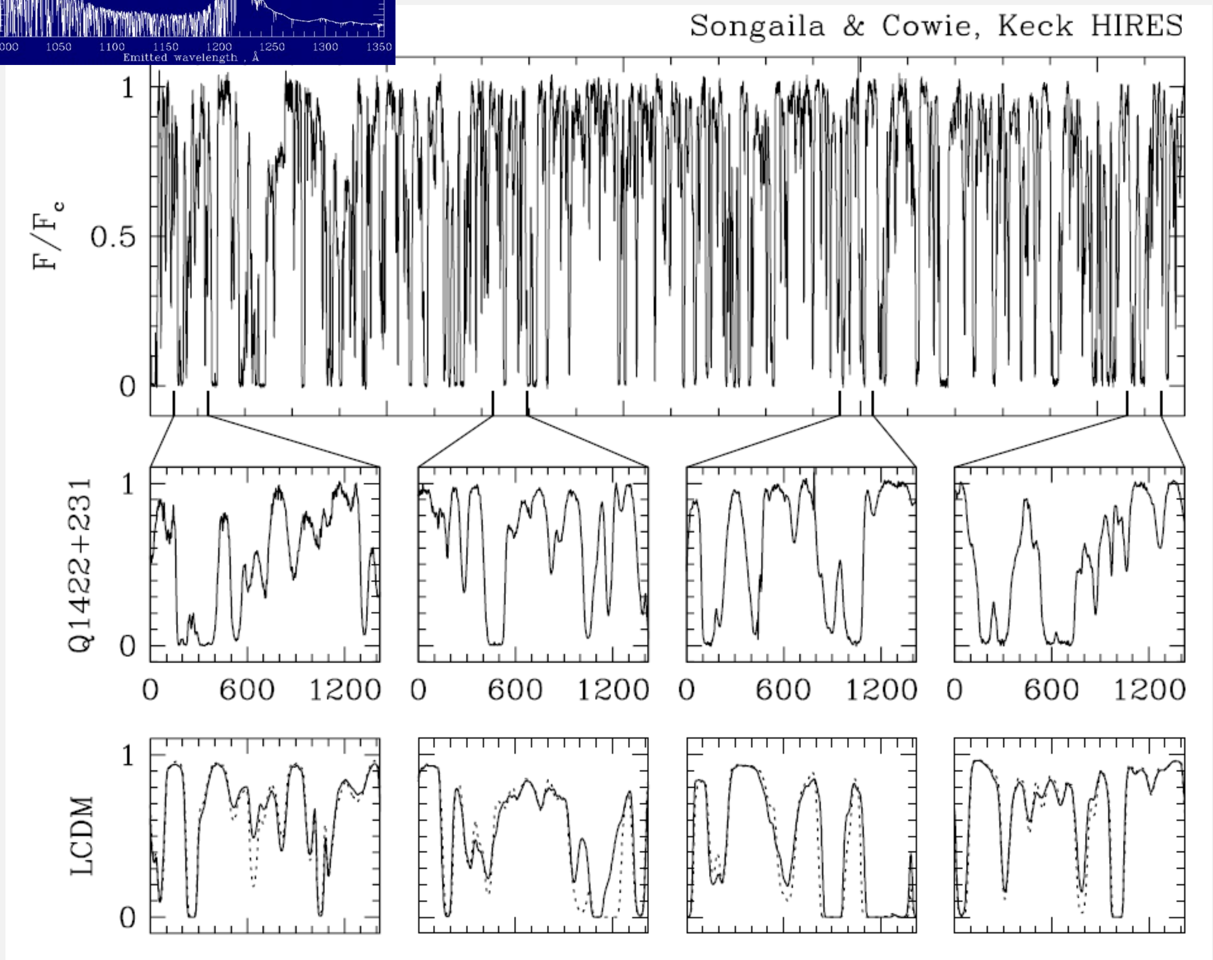

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Weinberg et al. (2003)

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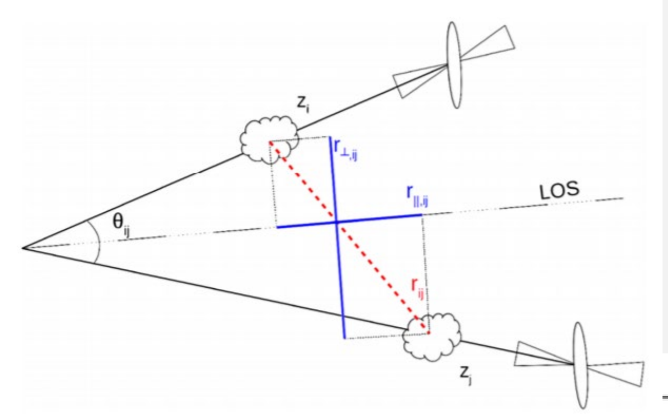
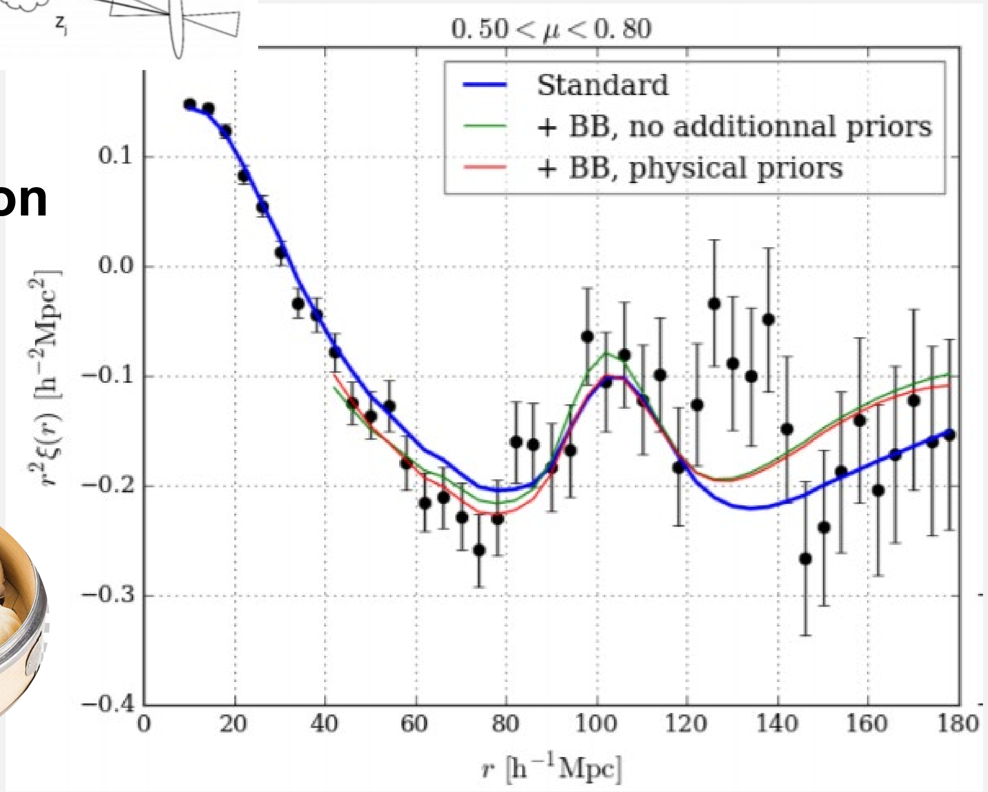
the Lyα forest as a cosmological tool



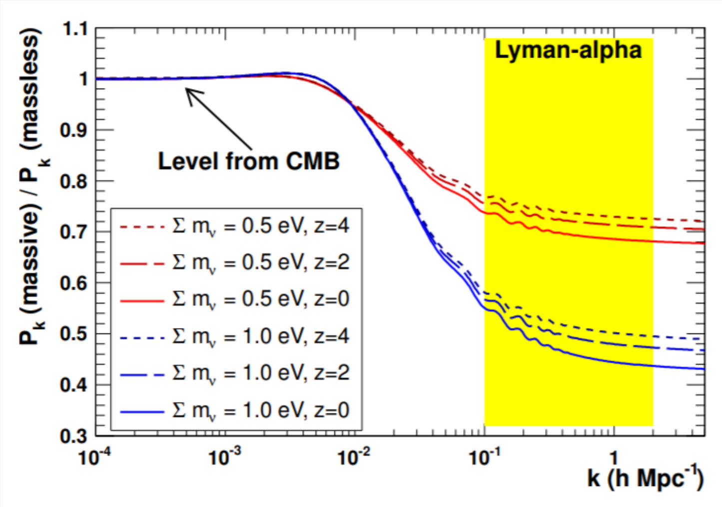
Cosmic expansion history via BAO

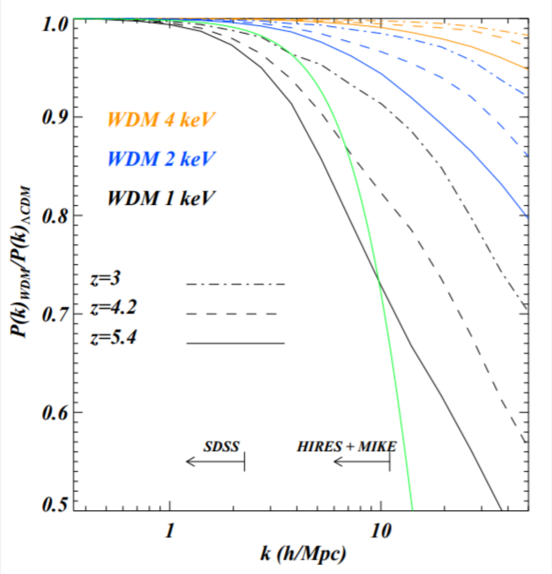
de Sainte Agathe
et al. (2019)



Neutrino mass

Palanque-Delabrouille
et al. (2015)

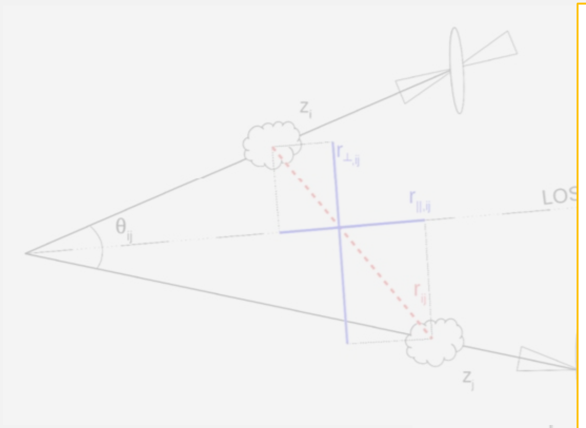


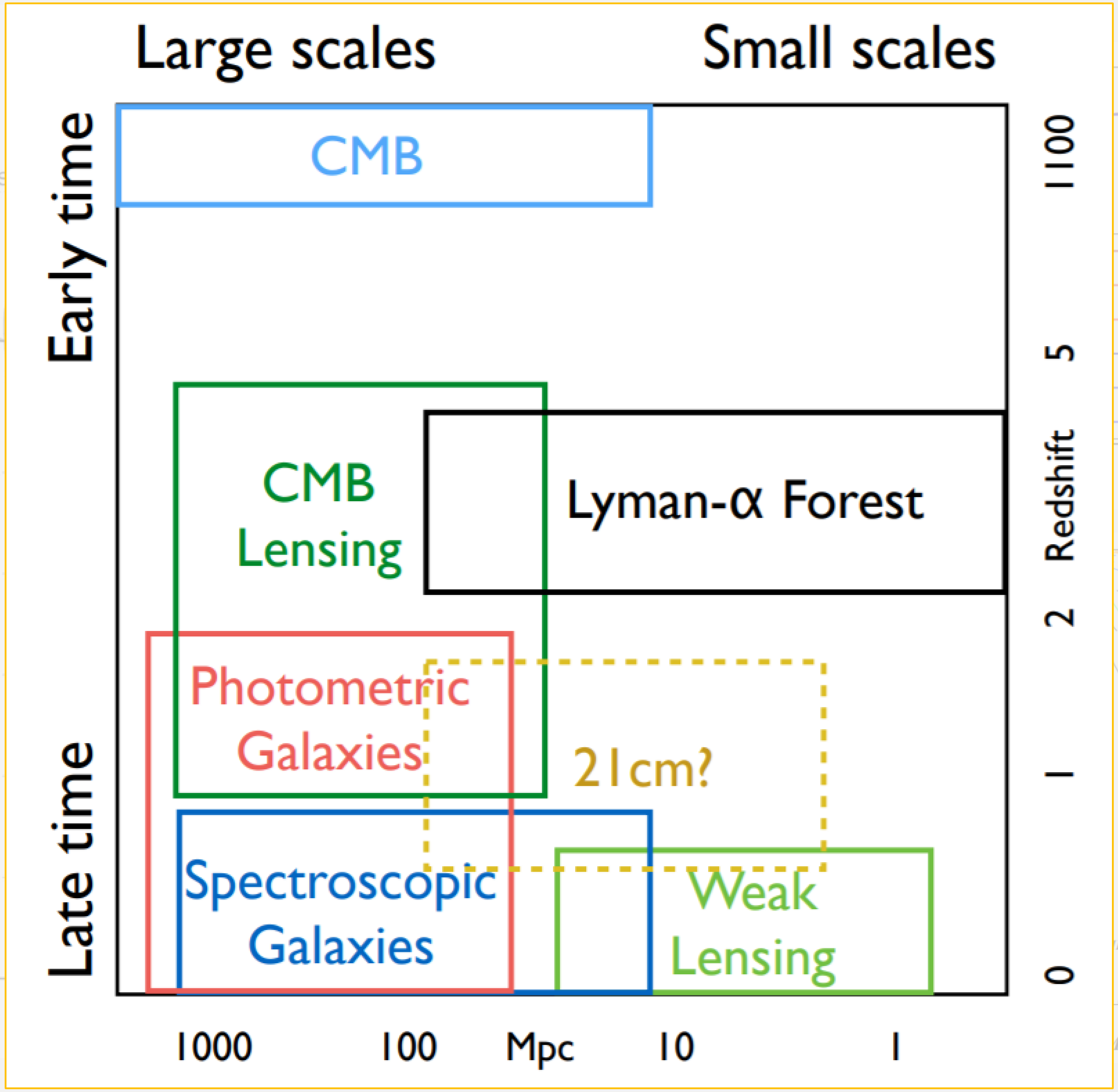


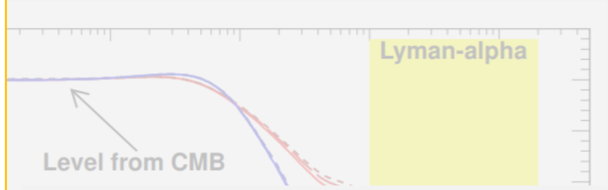
Small-scale DM physics

Viel et al. (2013)

the Lyα forest as a cosmological tool

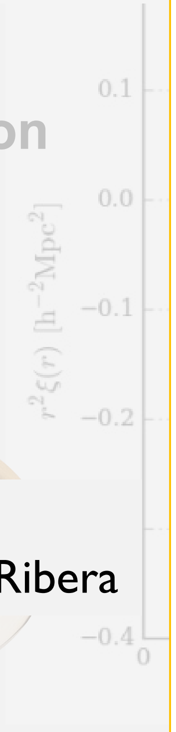






Marginalizing over systematic effects from:

- continuum estimation
- correlation from other absorbers
- reionization history
- IGM state



Cosmic expansion history via BAO

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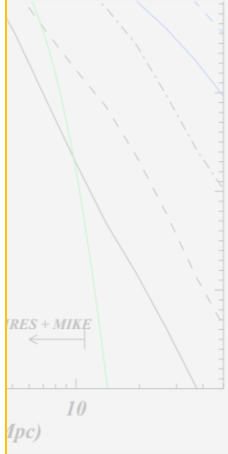
Figure from Andreu Font-Ribera



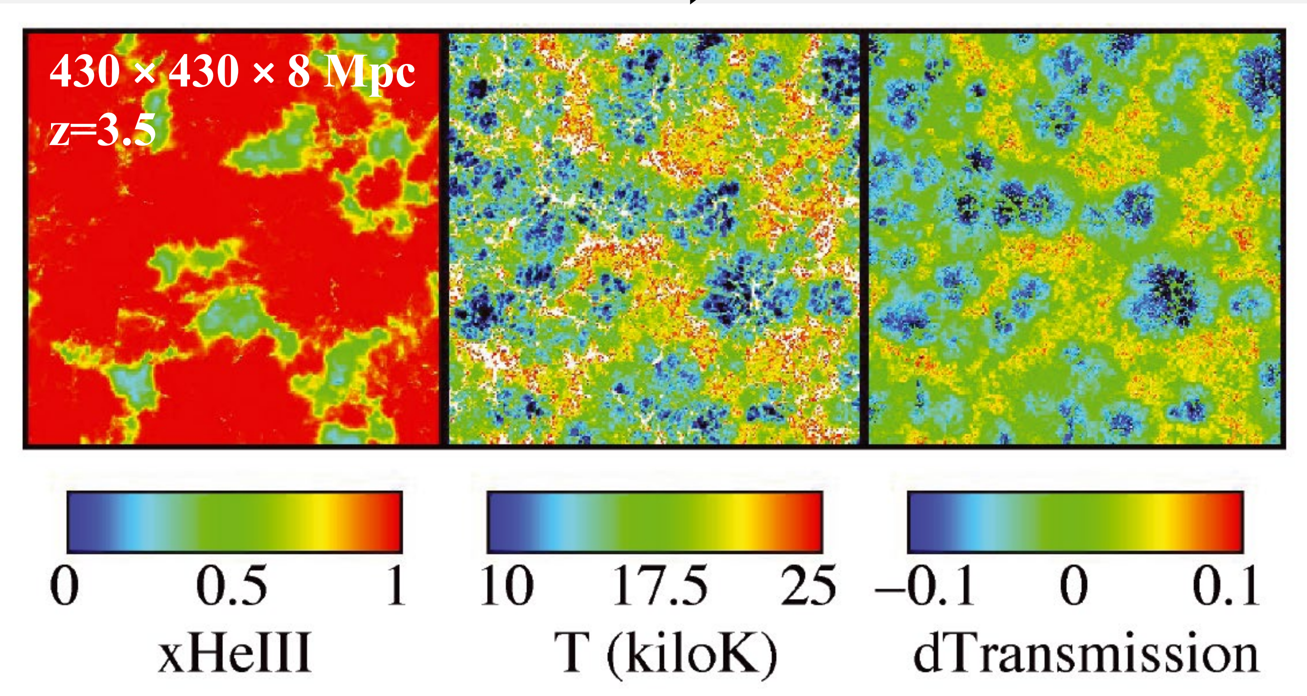
Small-scale DM physics

Viel et al. (2013)

the Lyα forest is affected by IGM state

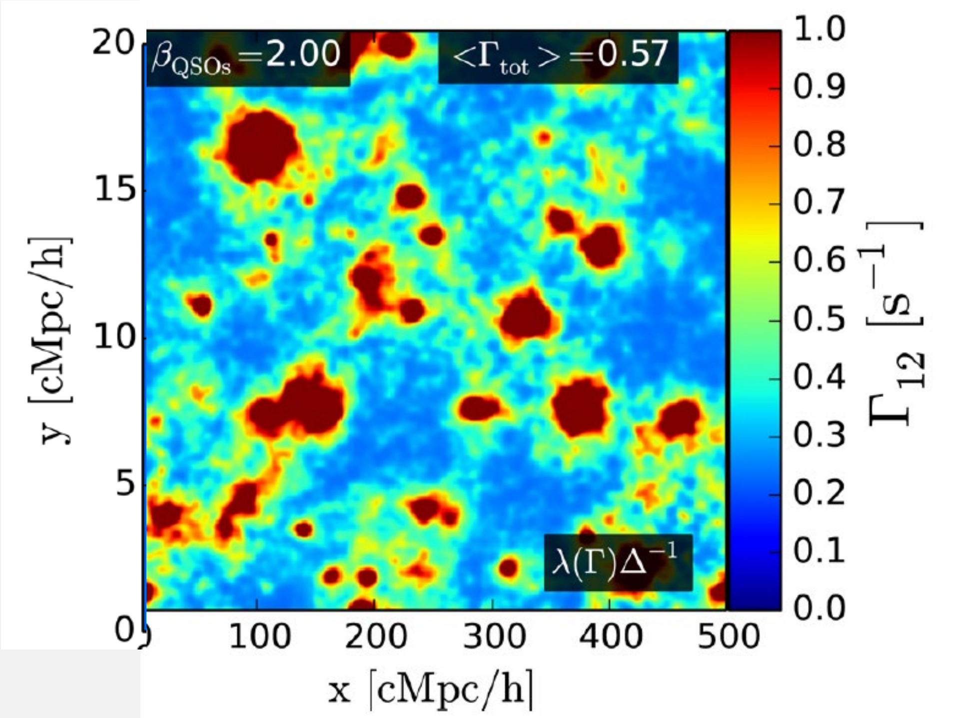
FGP approximation: $\tau_F \propto (1+\delta)^{1.6}\, T^{-0.7}\, \Gamma^{-1}$

McQuinn et al. (2009)



temperature fluctuations are unavoidable by-products of reionization

Chardin et al. (2017)



ionizing fluctuations arise from discrete sources and a finite mean free path

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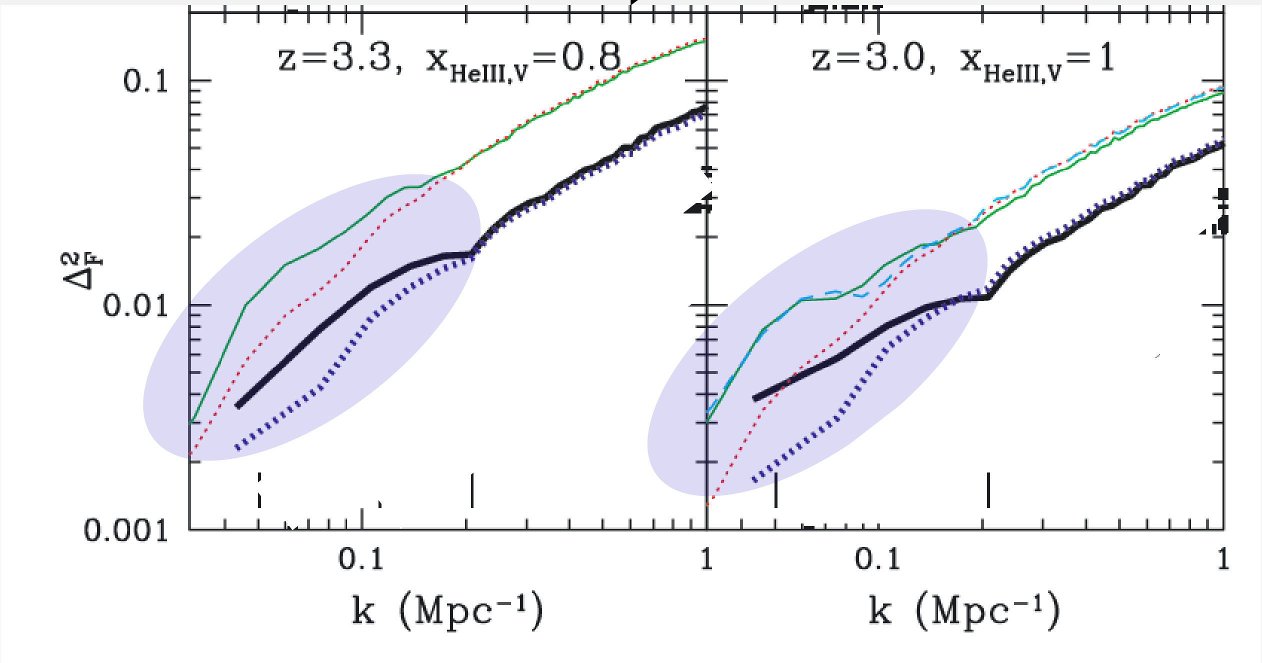
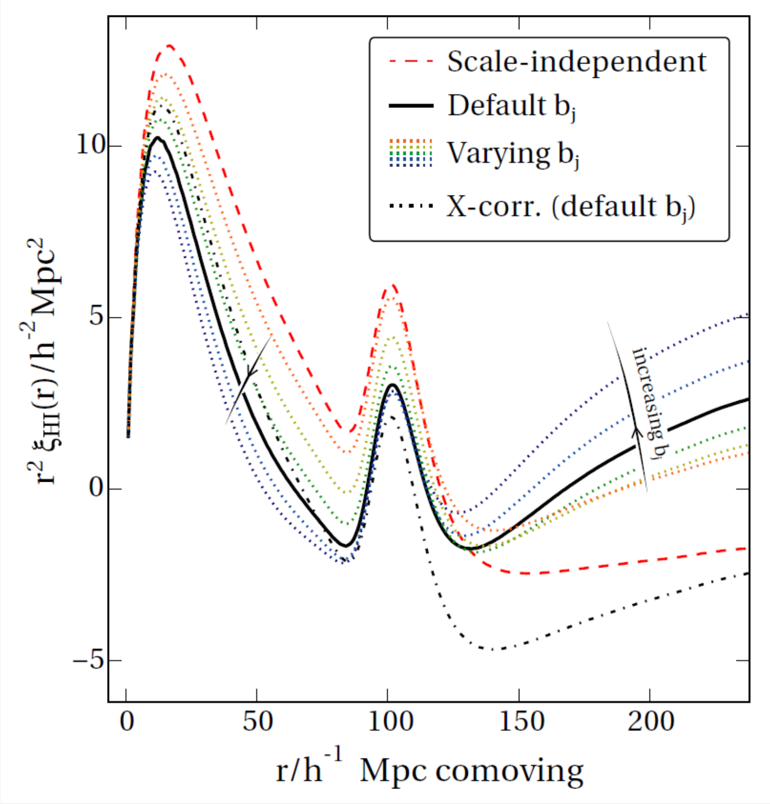
McQuinn et al. (2011)



temperature fluctuations increase 3D power by a factor of 1-2

Pontzen (2014)



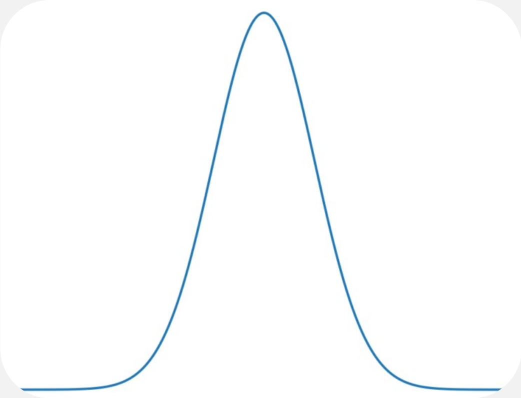
ionizing fluctuations distort 2PCF of the gas

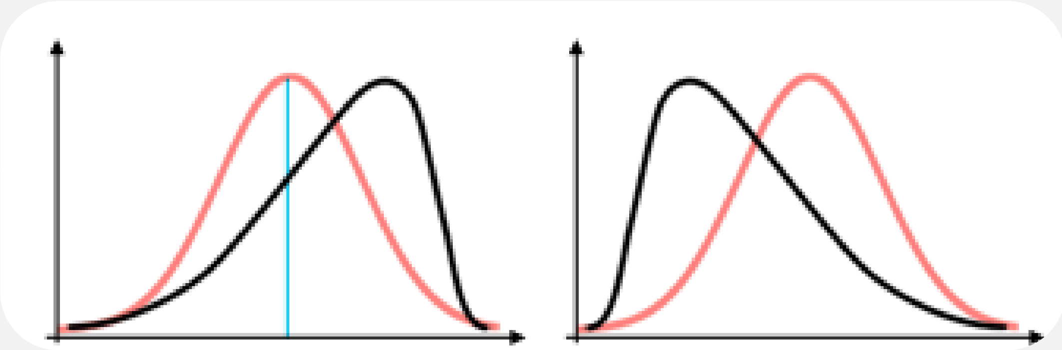
Hierarchical behavior of *n*-point correlation functions from gravitational instability

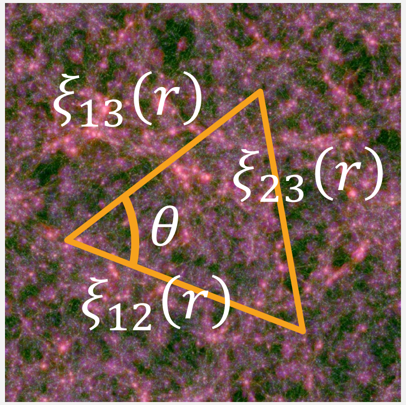
Three-point correlation function

$$Q = \frac{\xi_{123}(r_{12}, r_{13}, \theta)}{\xi_{12}(r)\xi_{13}(r) + \xi_{13}(r)\xi_{23}(r) + \xi_{12}(r)\xi_{23}(r)}$$

cyclic combination of two-point correlation function







Can we use higher-order statistics as a diagnostic of IGM state?

Hierarchical behavior of *n*-point correlation functions from gravitational instability

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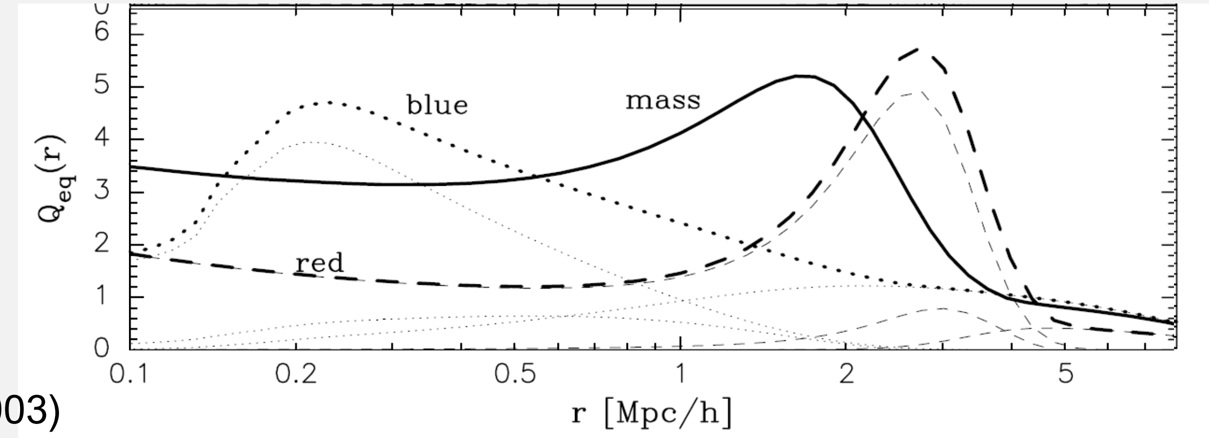
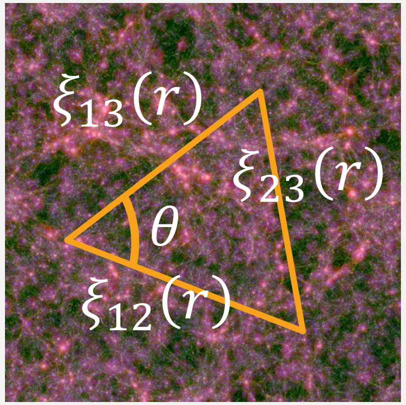


Takada & Jain (2003)



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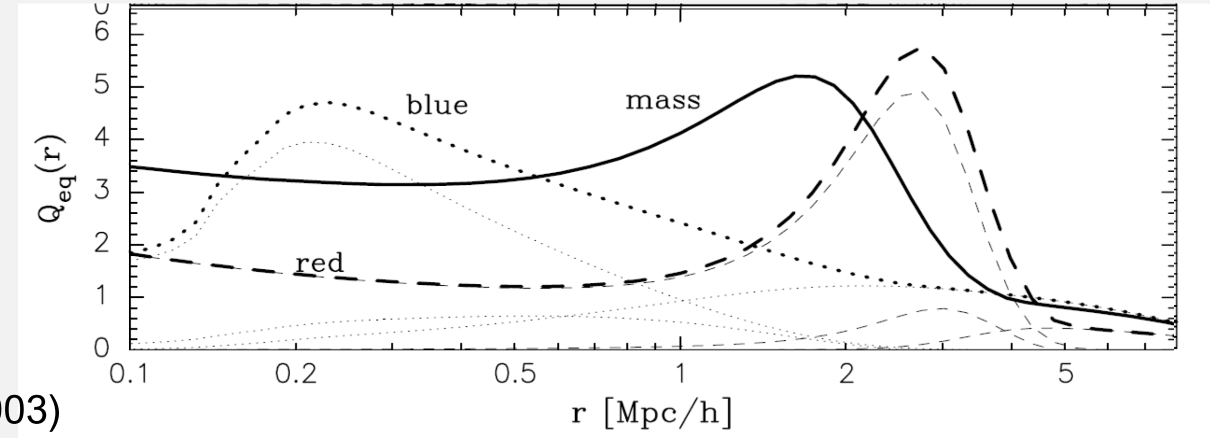

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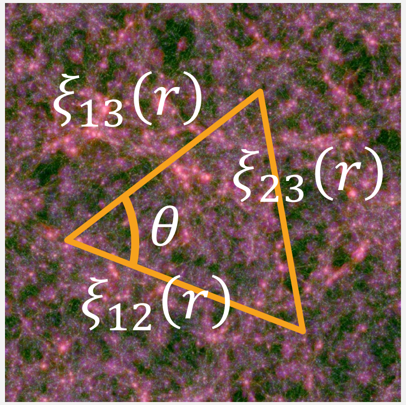


Can we use higher-order statistics as a diagnostic of IGM state?

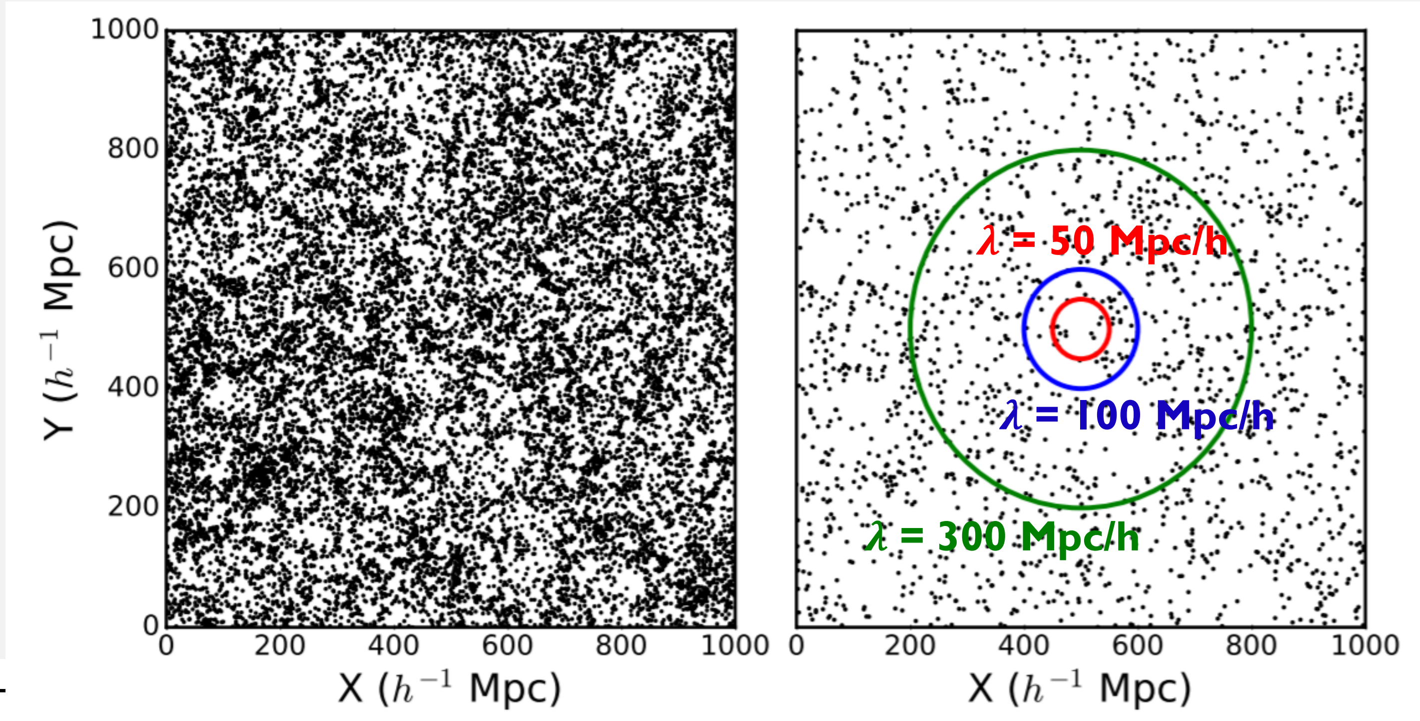
Create models of a fluctuating ionizing background

Generate Lyα flux from these models

Measure the clustering

E.g. Might Q give some hints on the scale of the fluctuating UVB?

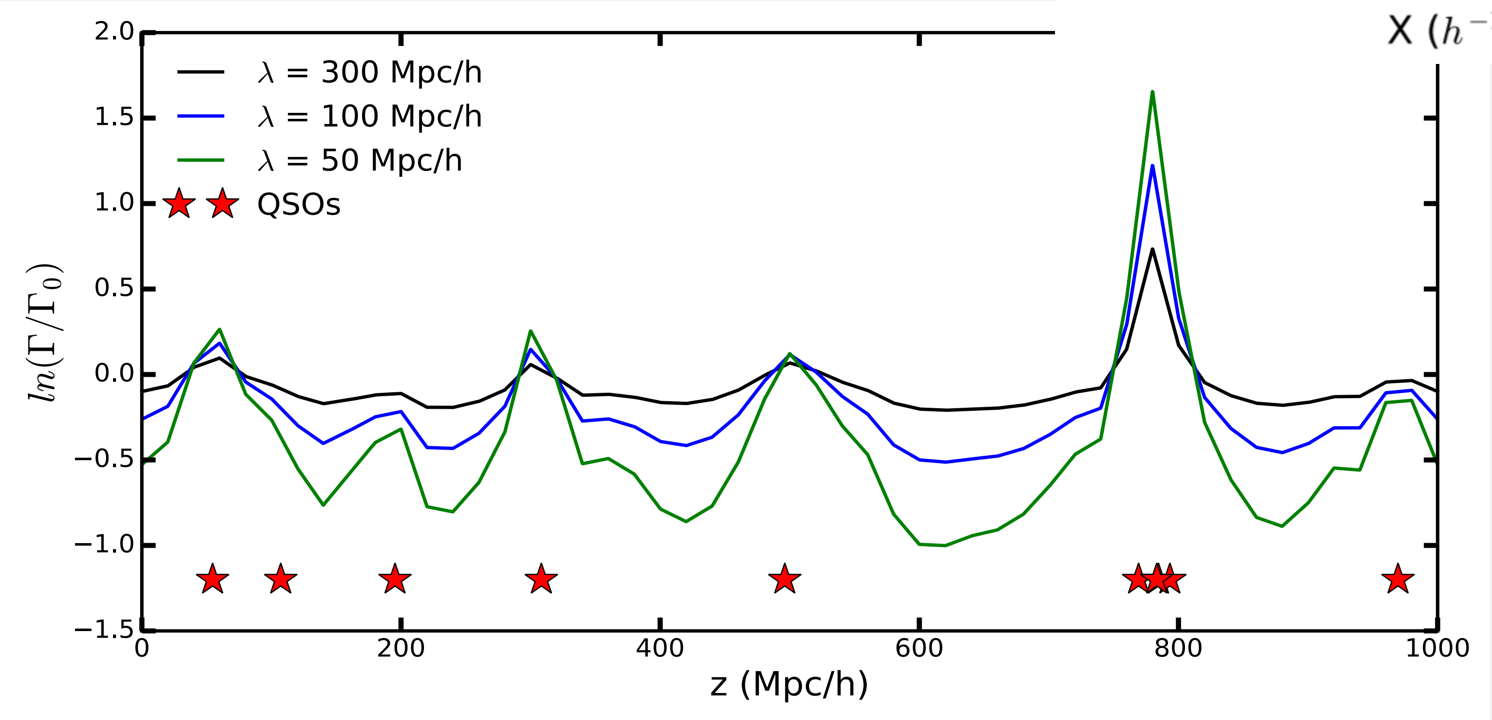
Create models of a fluctuating ionizing background



Assume quasars as ionizing sources,

i) randomly-distributed, or

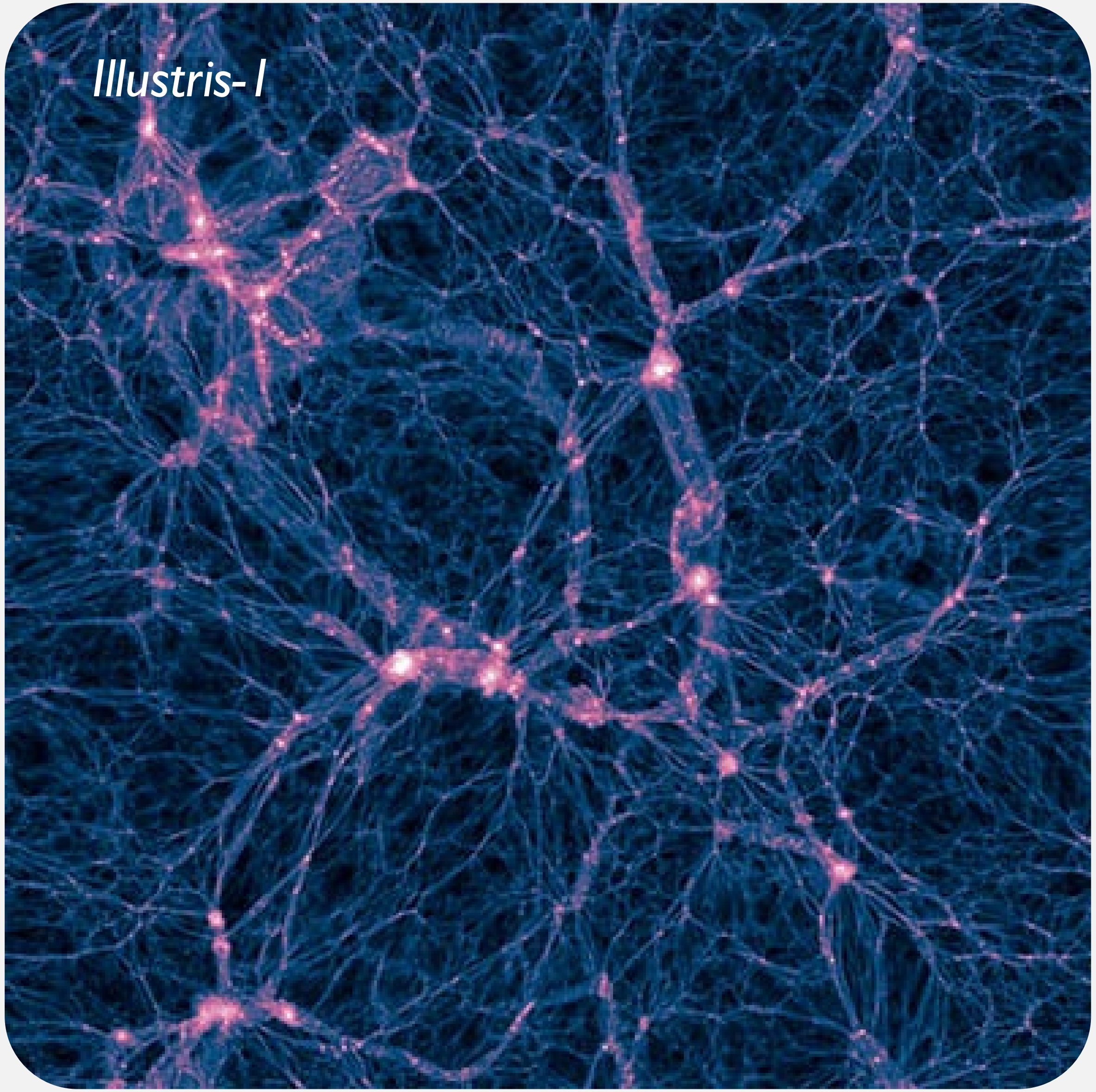
ii) found in massive halos



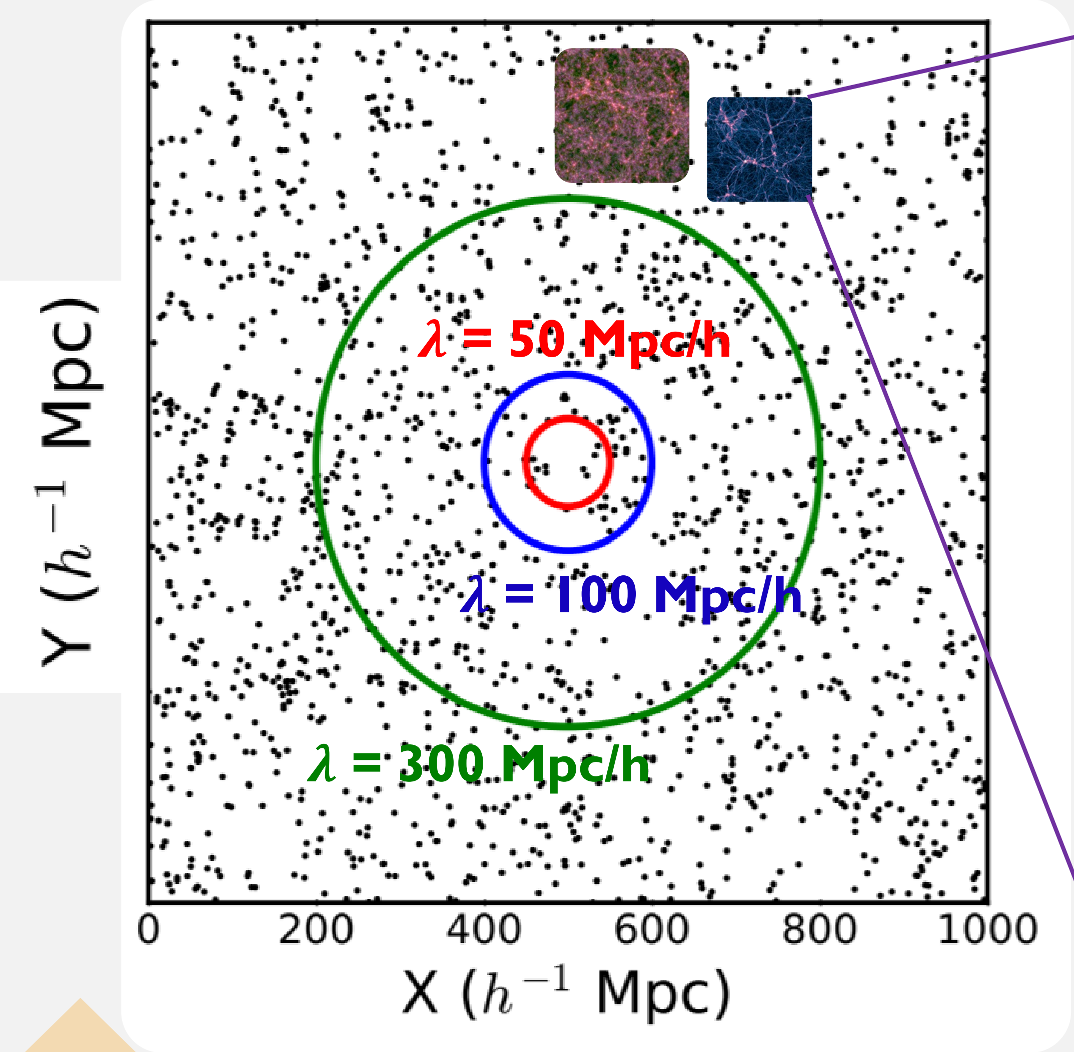
Assign certain mean free path λ for ionizing photons.

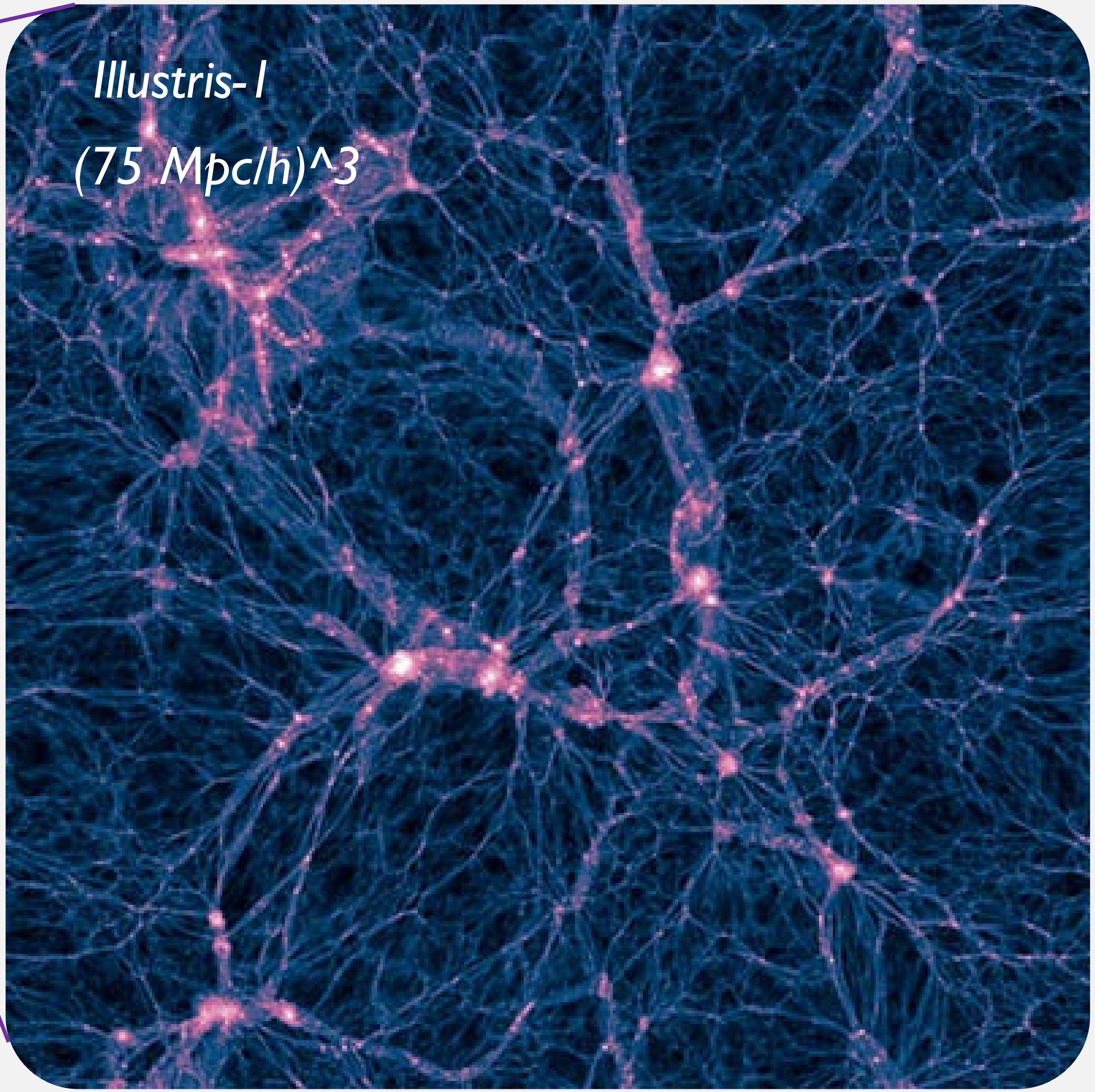
2

Generate Lyα fluxes with (....)



Hydro simulations ?





Hydro simulations ?

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Generate Lyα fluxes with (....)

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$$F \approx e^{-\tau}$$

Fluctuating Gunn-Peterson approximation

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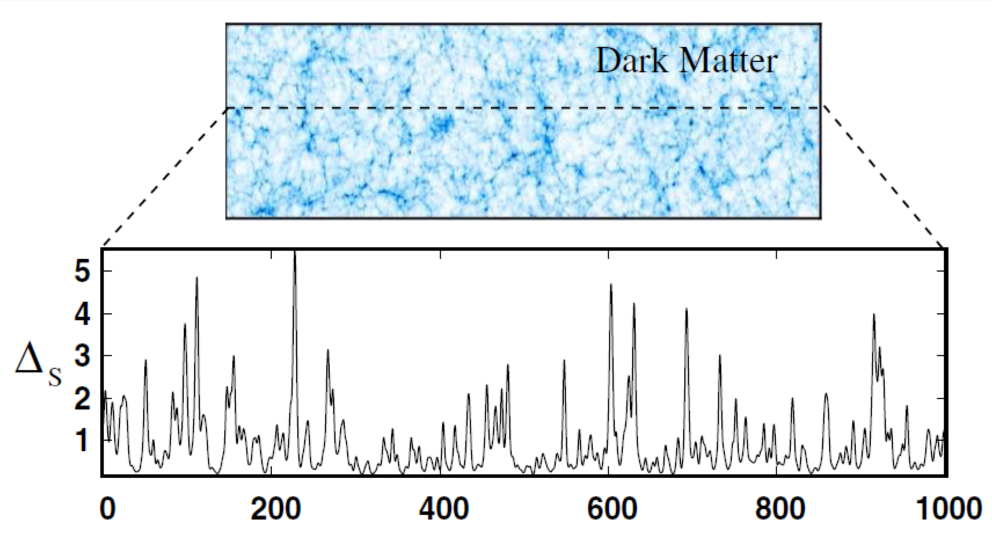
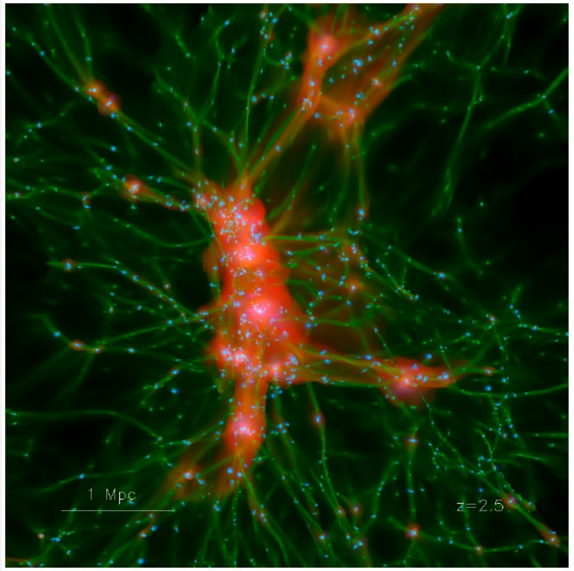
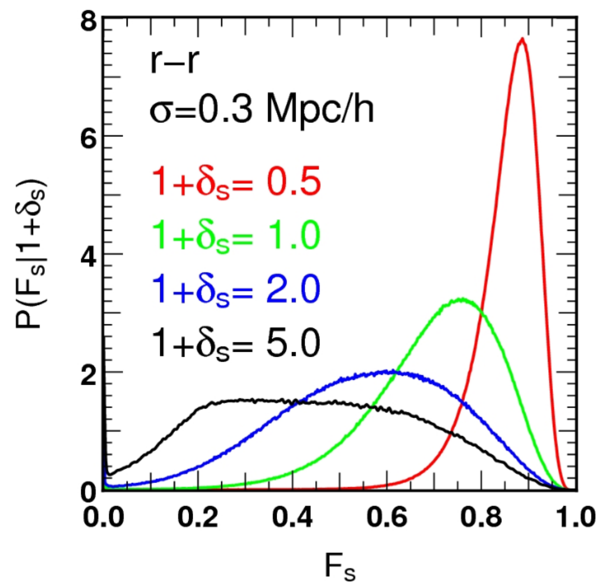


DM density from N-body sim.

2

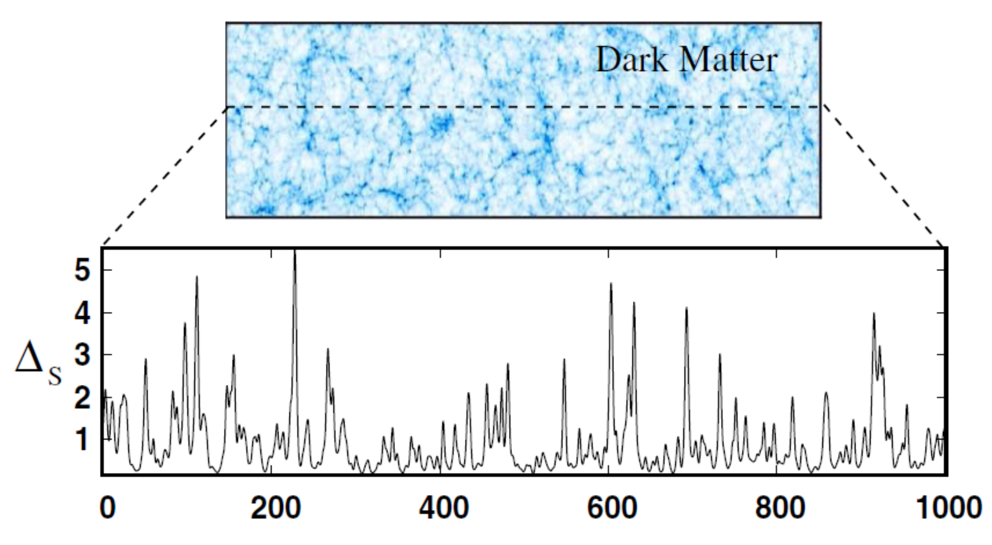
Generate Lyα fluxes with (…)





conditional PDF $P(F_s|\delta_s)$ from hydro sim.

×



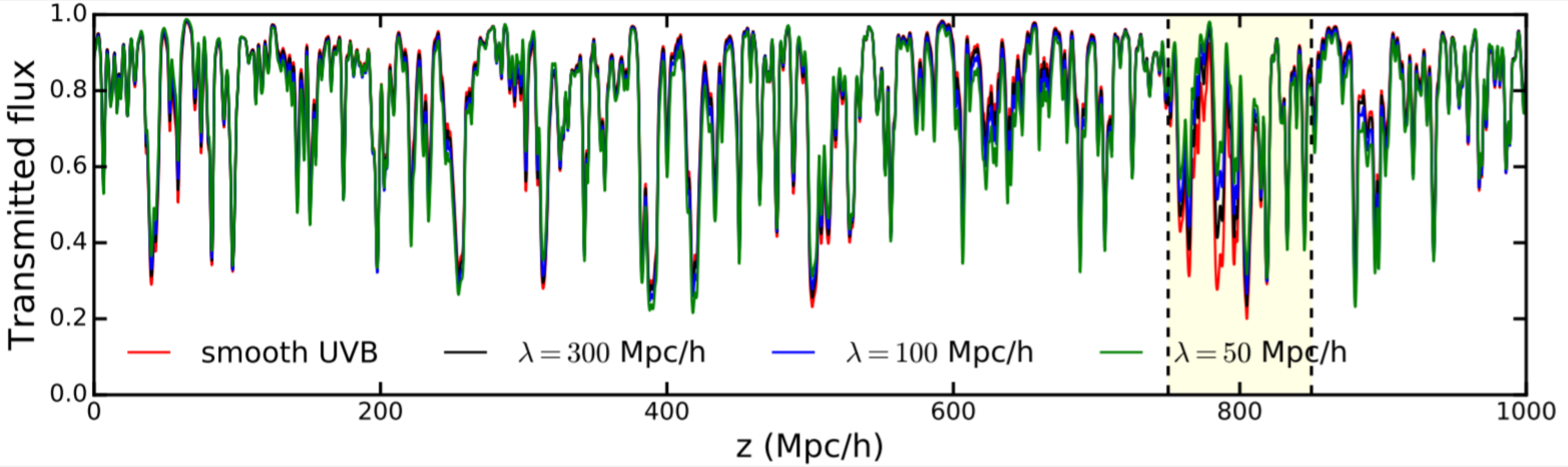
DM density from N-body sim.

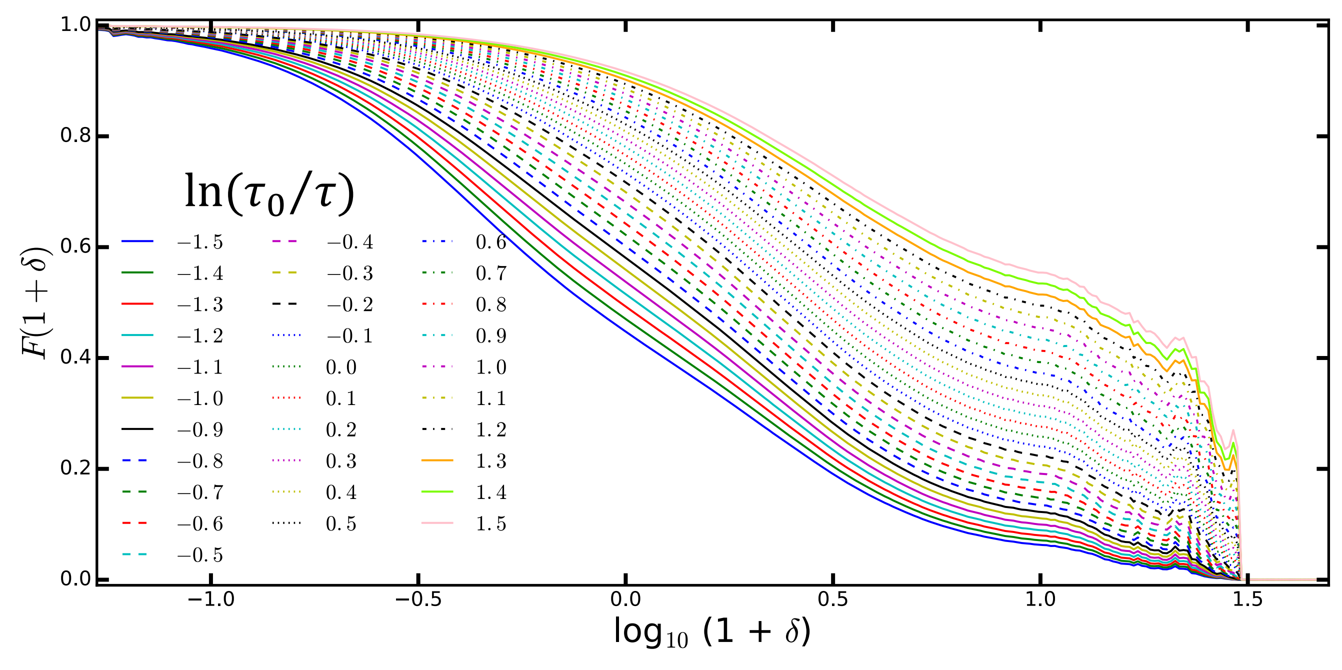
=

2

Generate Lyα fluxes with LyMAS

(Peirani et al. 2014)





Calibrate $\bar{F}(\delta) = \int F\, P(F_s|\delta_s)$ from hydro sims for a range of density and UVB intensity

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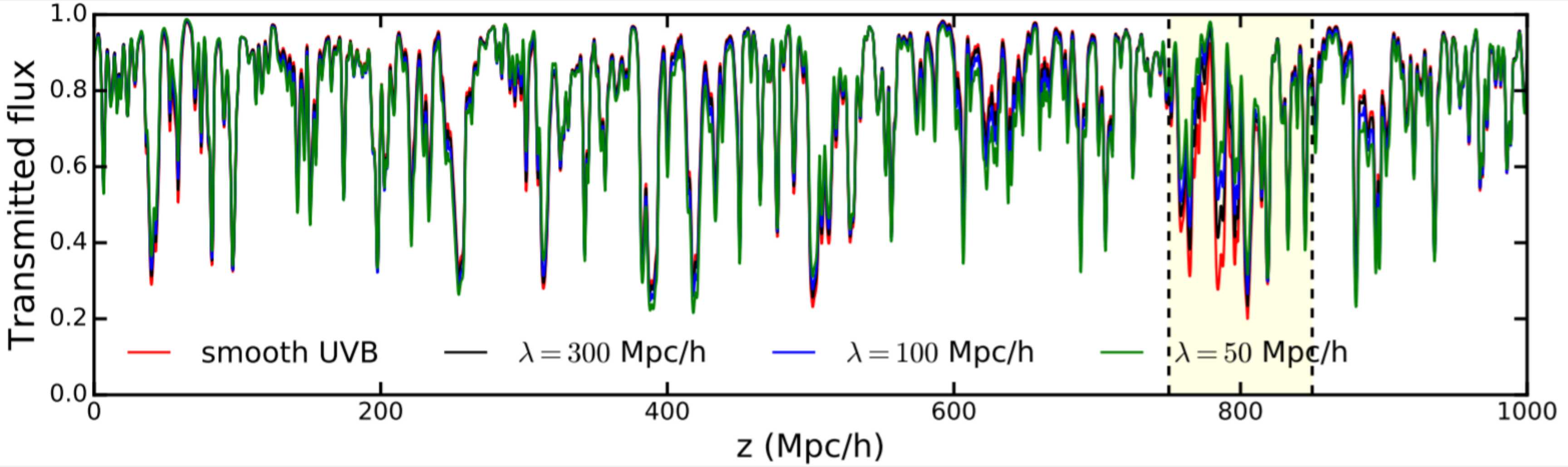
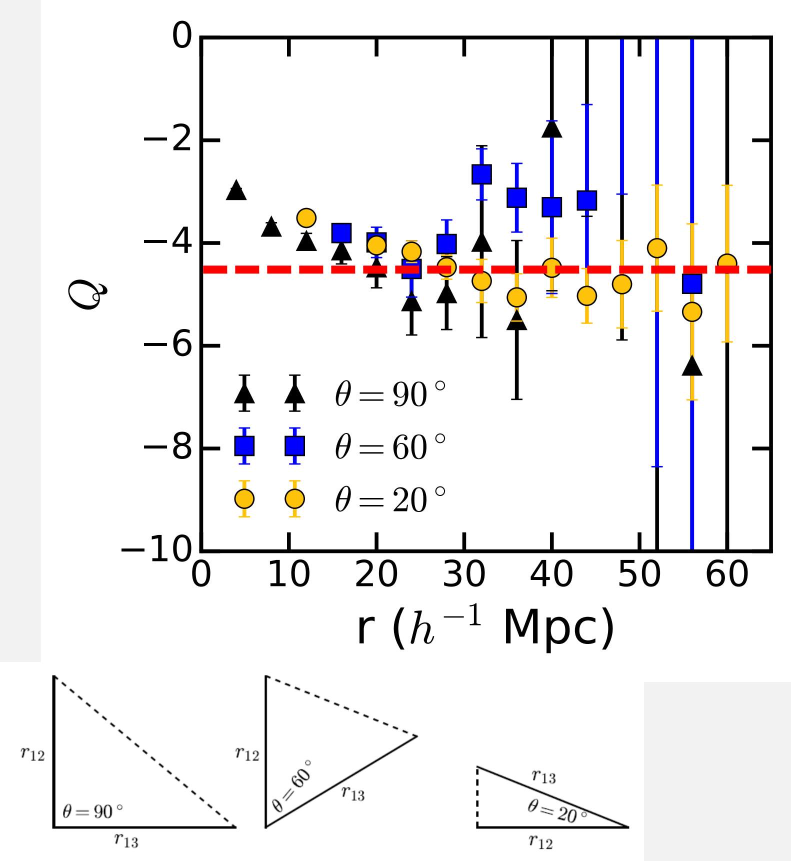
2 Generate Lyα fluxes with LyMAS

(Peirani et al. 2014)

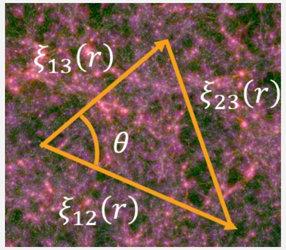




First theoretical prediction of the 3-d 3PCF of the forest

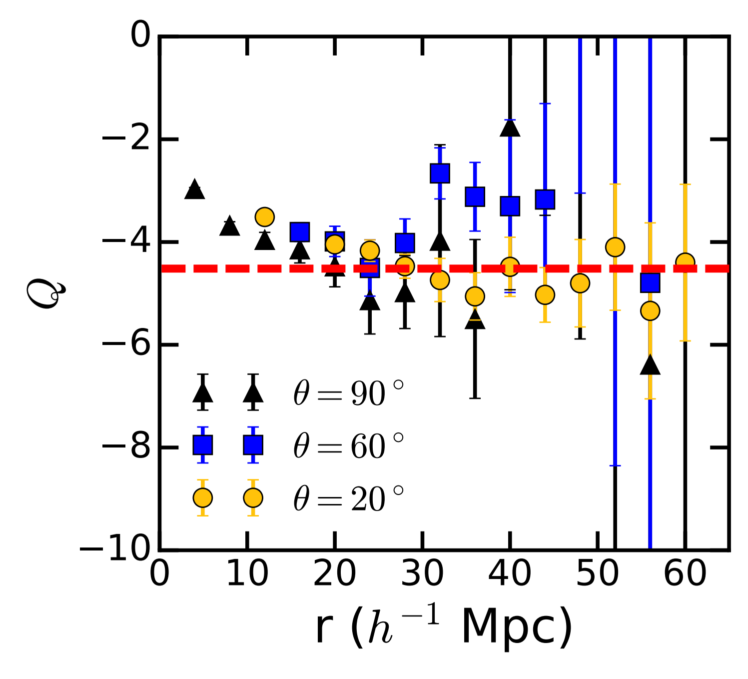
for a uniform background, Q ~ -4.5

- ✓ low bias of the forest
- ✓ anticorrelation with density



3

Clustering measurements



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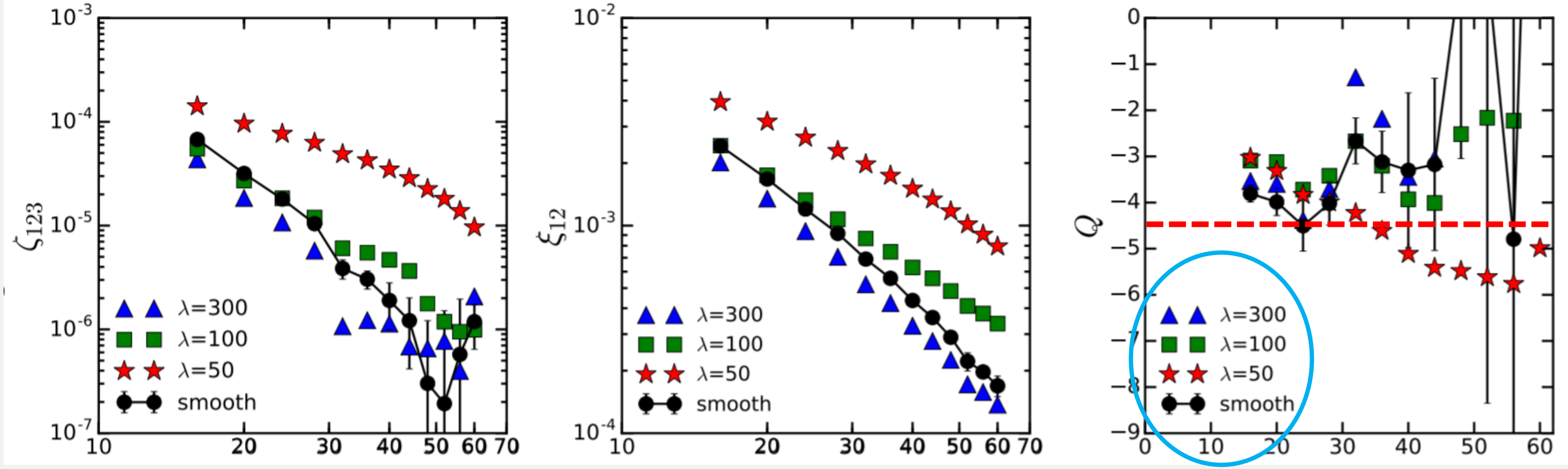
Clustering measurements

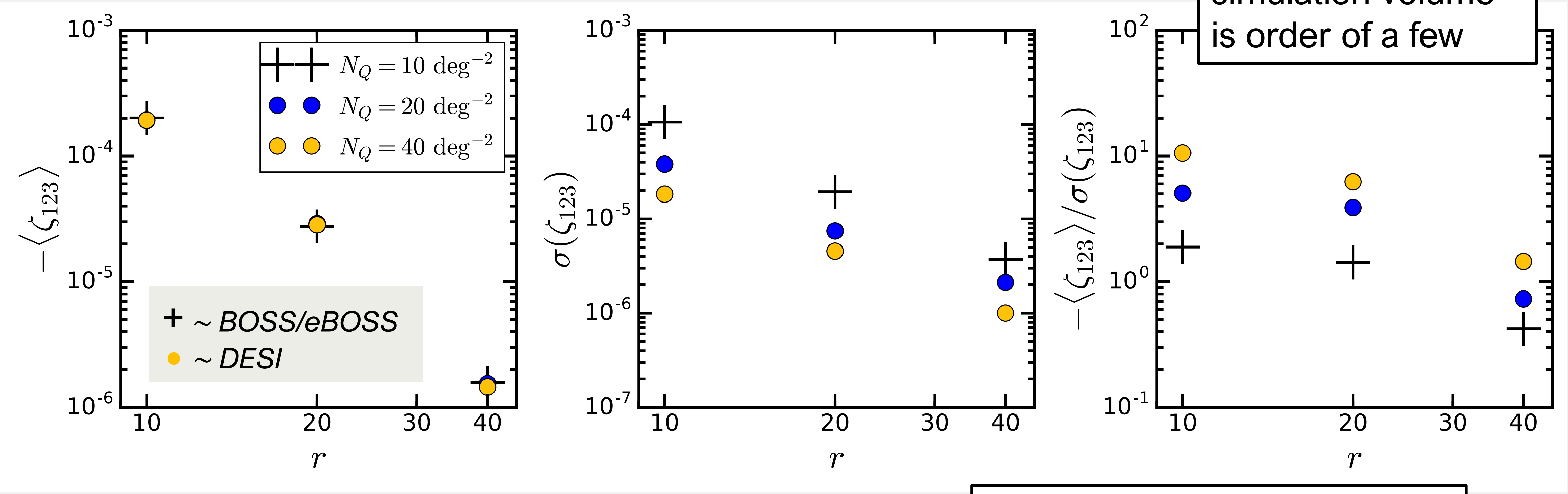
The value of Q is relatively insensitive to a fluctuating UVB within our errors.



Measurement of 3PCF from 50 realizations

Dispersion from 50 realizations

SNR for our simulation volume is order of a few

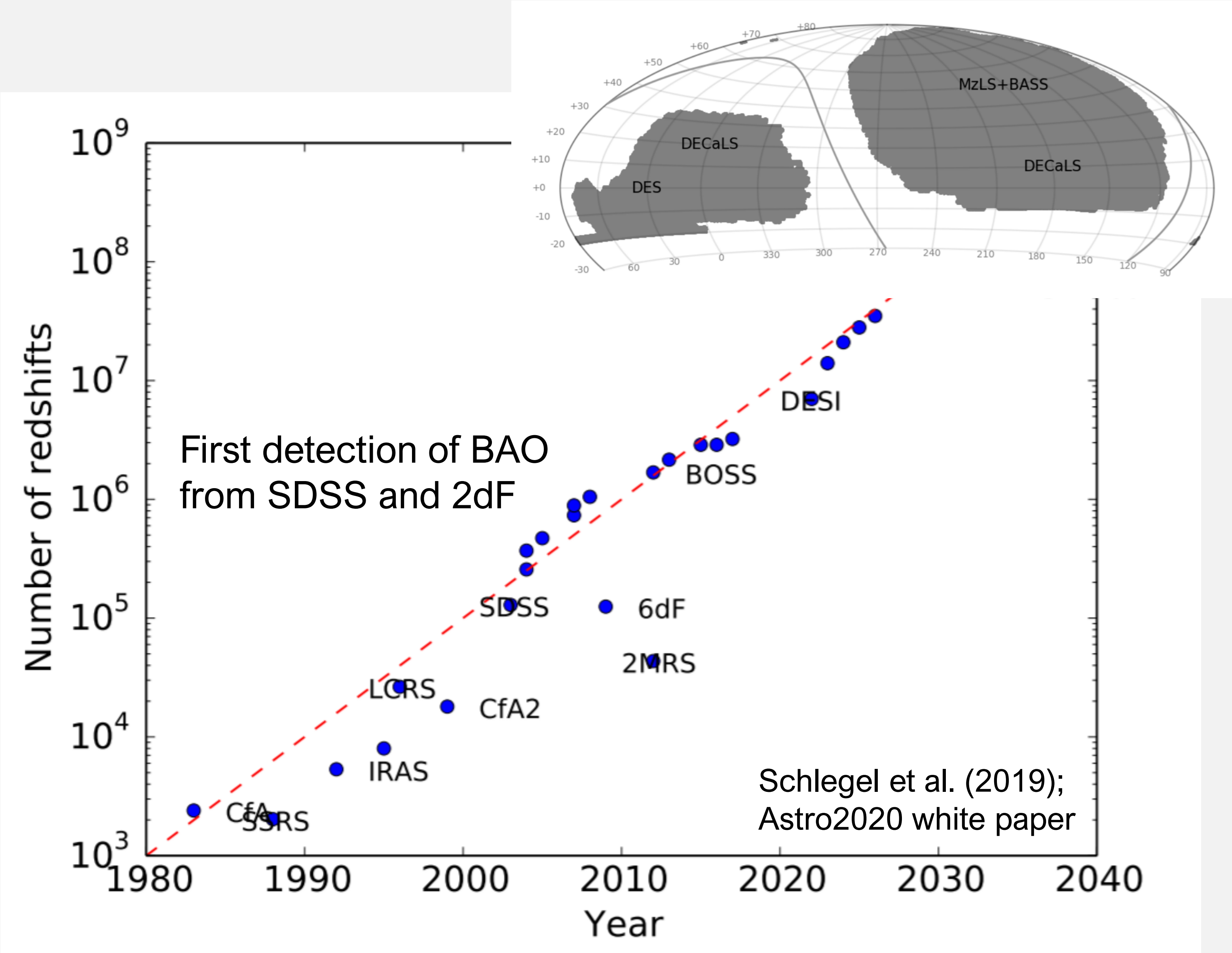


to scale to DESI, multiply yellow points by ~4.

Currently:

- ❑ studying possibility of measuring the 3PCF in eBOSS data (Debopam Som; OSU)
- ❑ improved forecasting with DESI simulation (Andreu Font-Ribera & James Farr; UCL)

DESI: towards 34 million redshifts

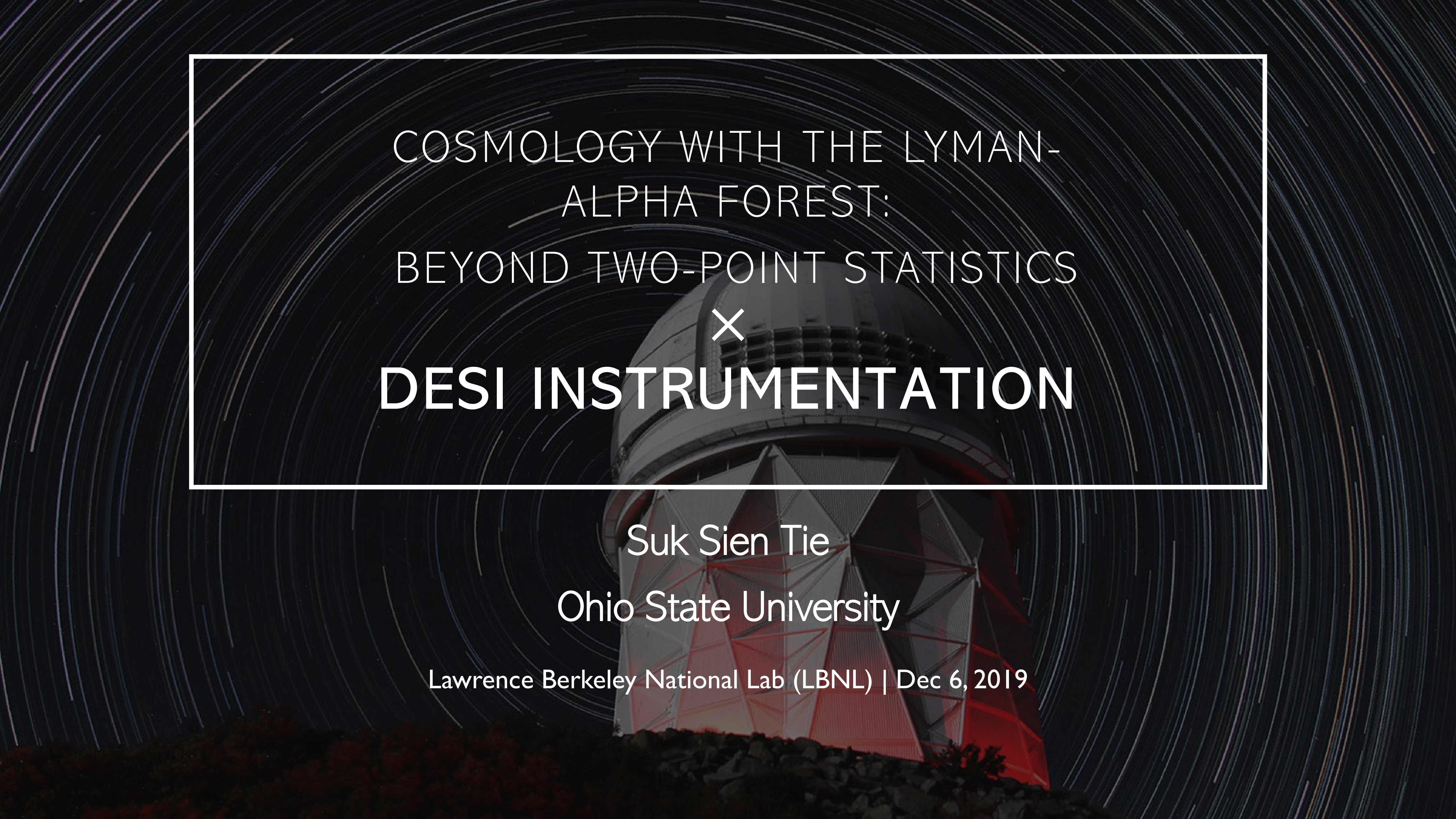


To provide sub-percent distance measurements to constrain Dark Energy

At least an OoM improvement over BOSS in survey volume and number of redshifts

~420k total Lya forest spectra (30 qso/deg^2 between z=2.1 – 2.6)

(vs. ~130k spectra from eBOSS DR 14, 14 qso/deg^2)



COSMOLOGY WITH THE LYMAN-ALPHA FOREST: BEYOND TWO-POINT STATISTICS

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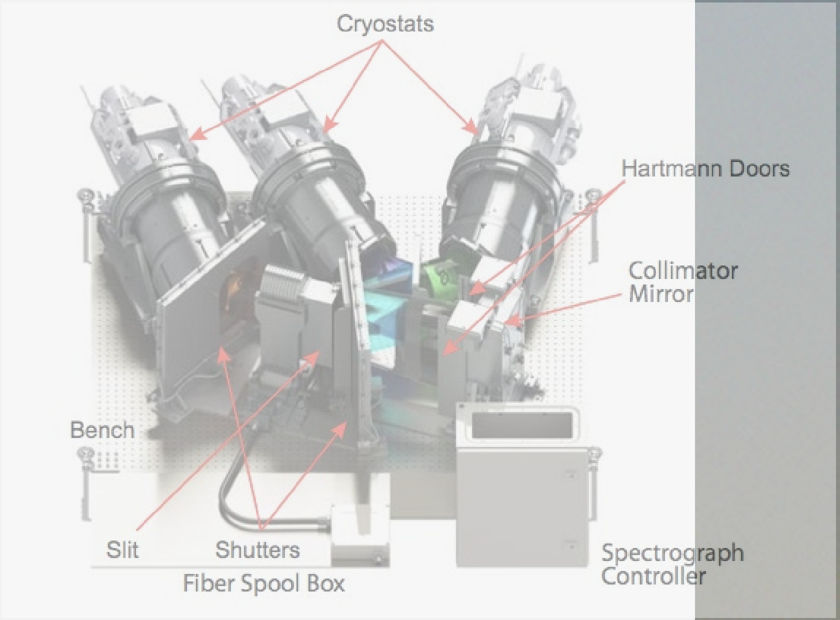
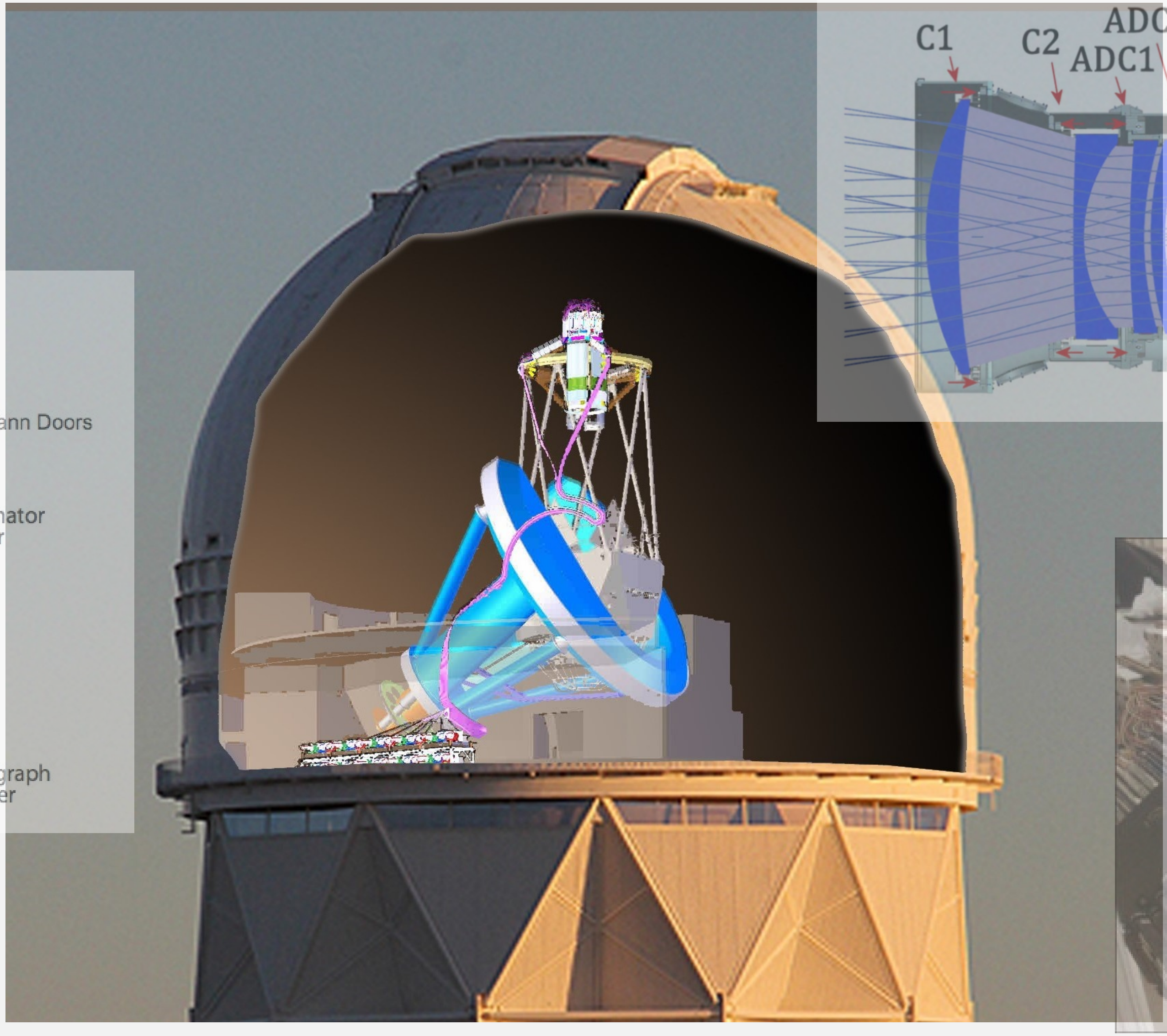
DESI INSTRUMENTATION

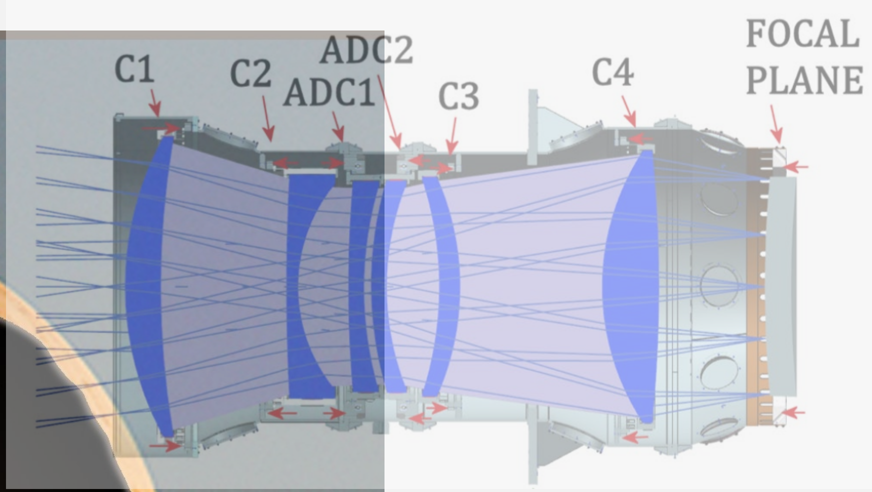
Suk Sien Tie

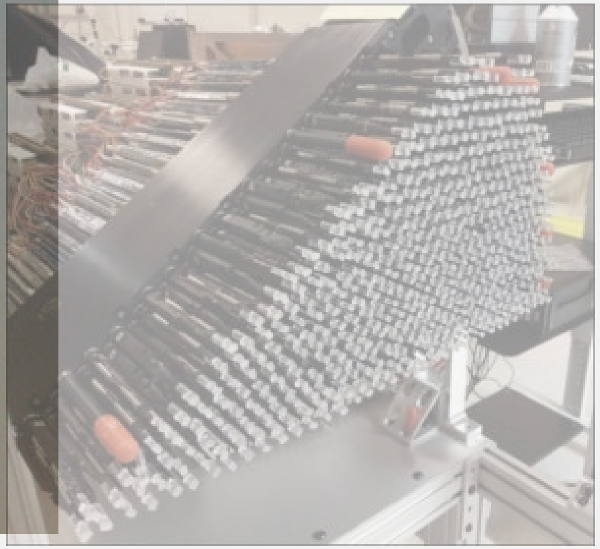
Ohio State University

Lawrence Berkeley National Lab (LBNL) | Dec 6, 2019

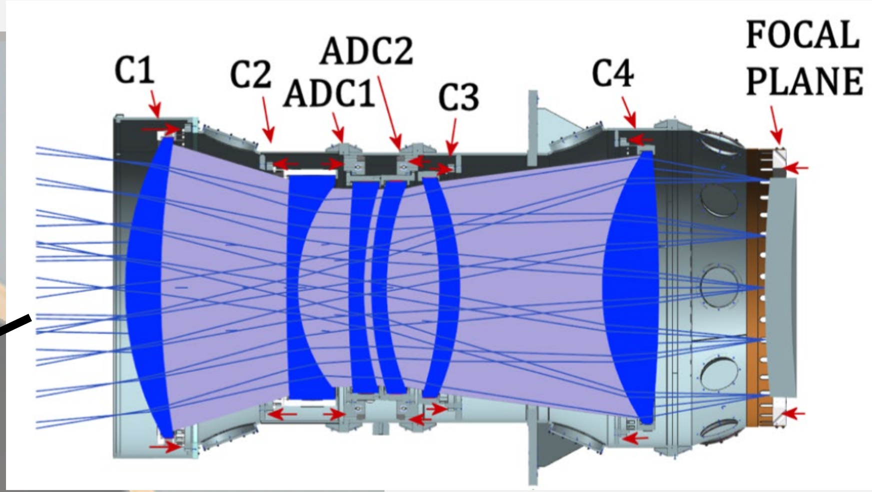




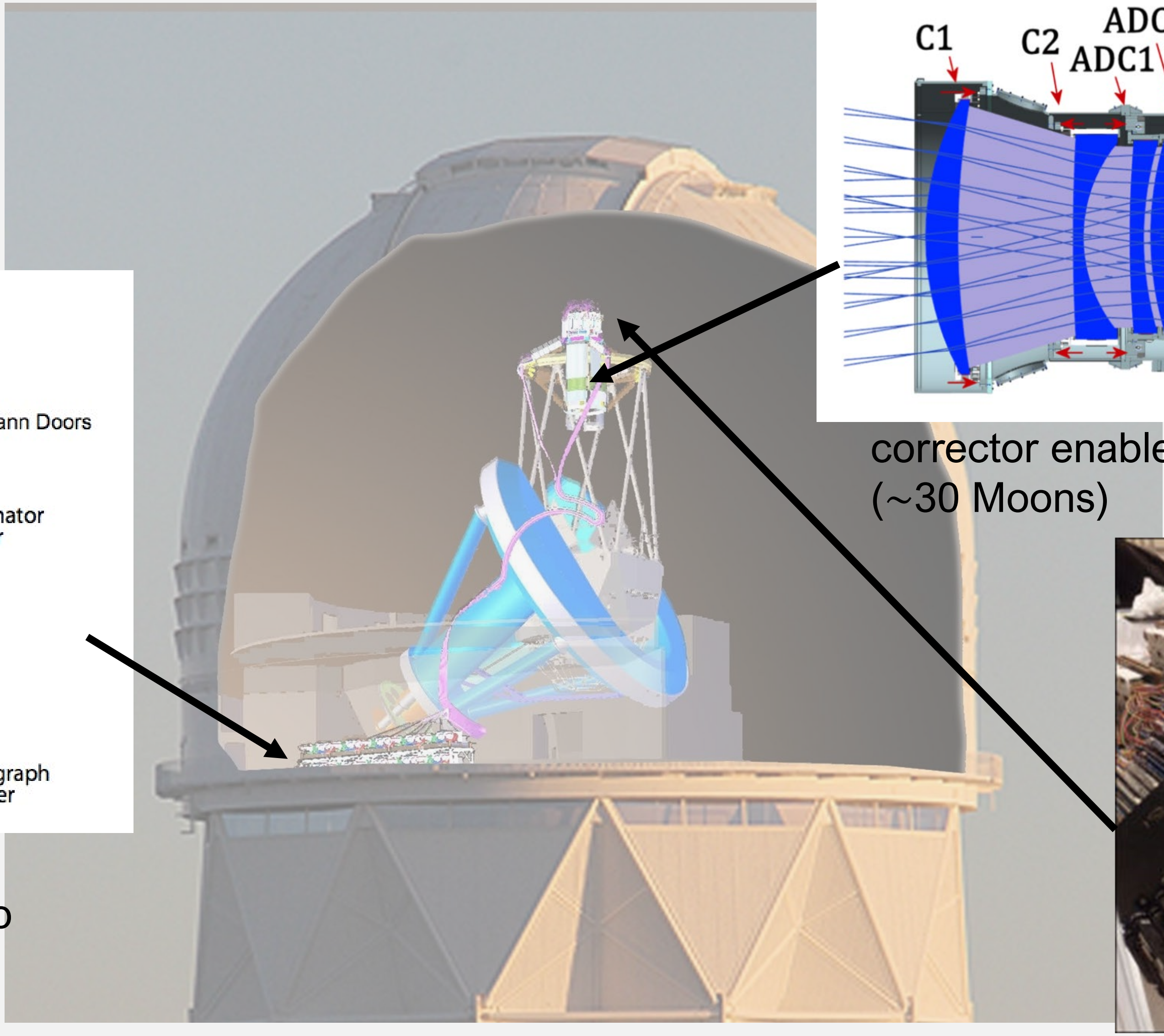


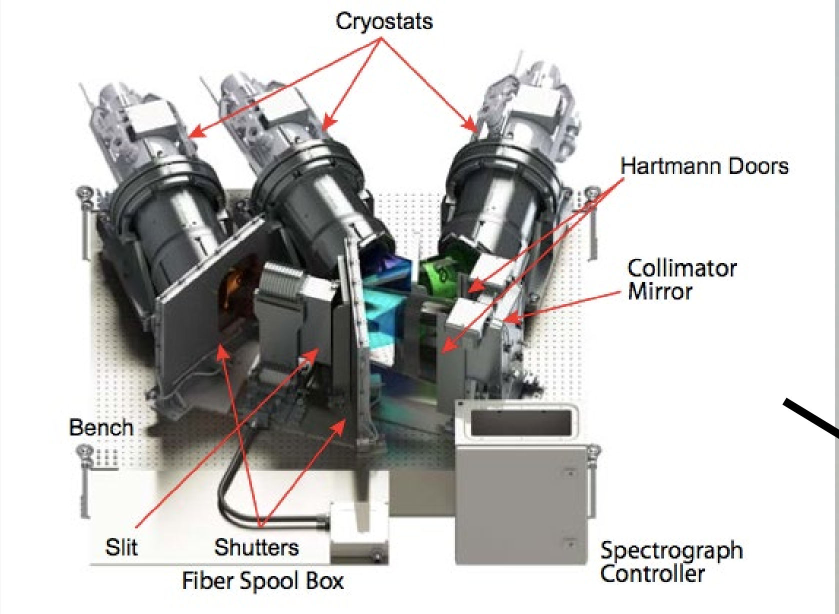


behind a great survey

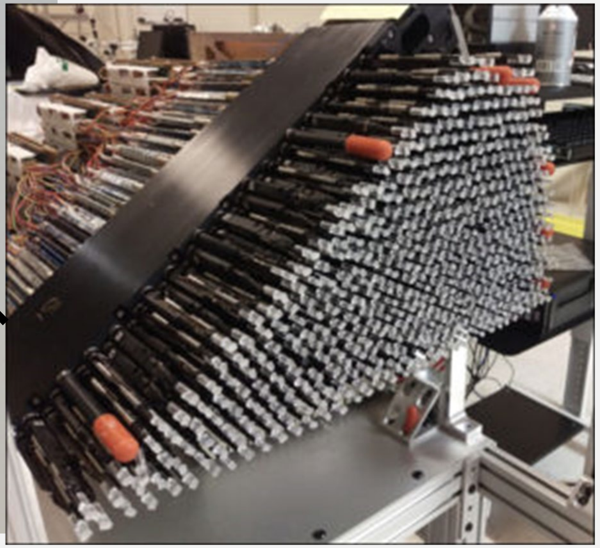


corrector enables 8 deg^2 field of view (~30 Moons)



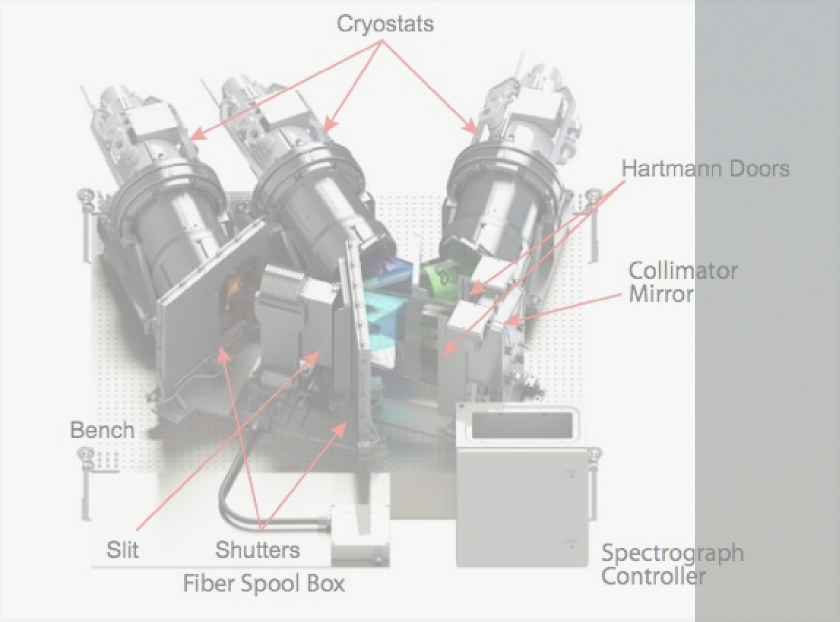


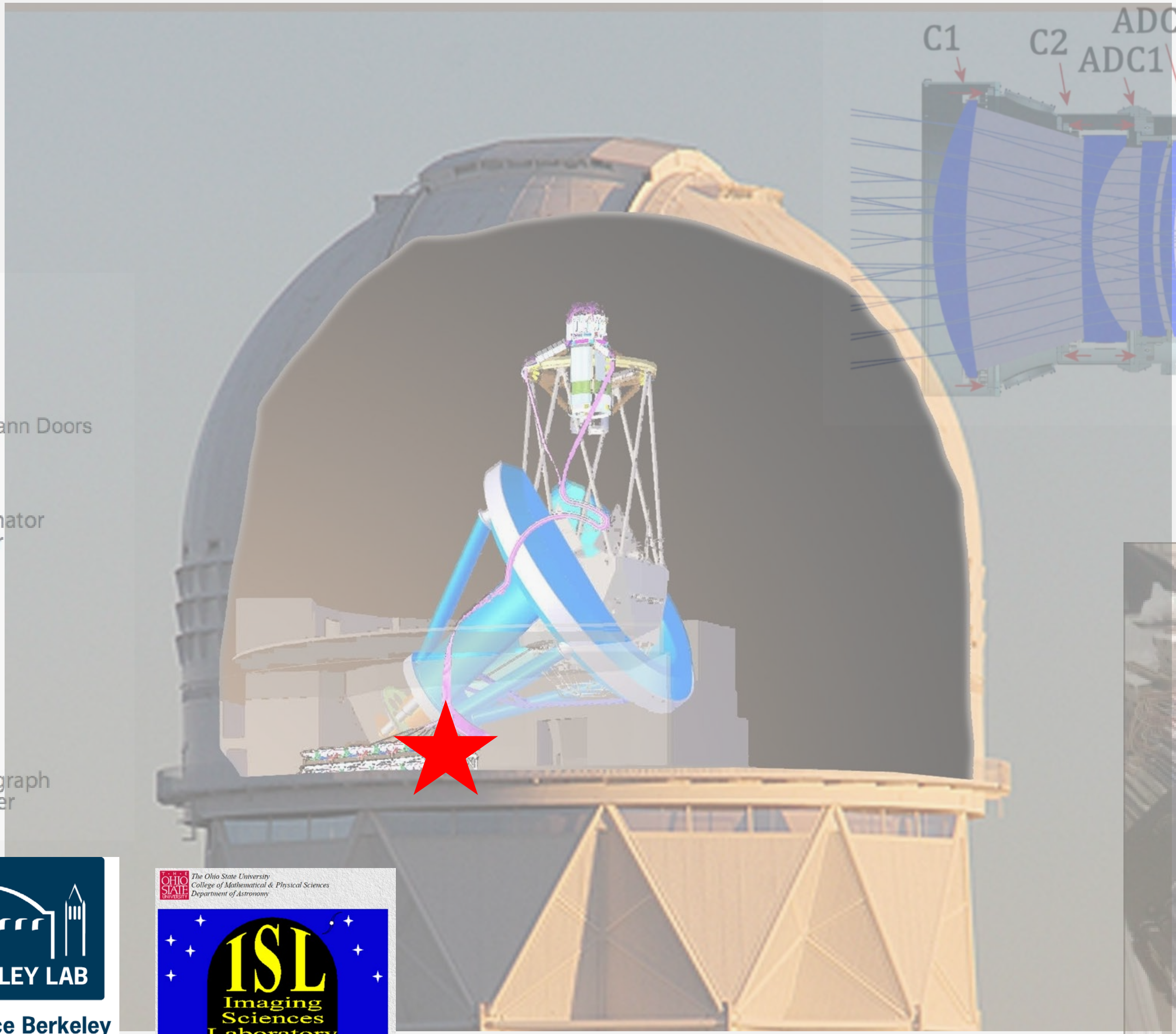
resolution of ~thousands and spectral coverage from *u*-band to ~1 micron

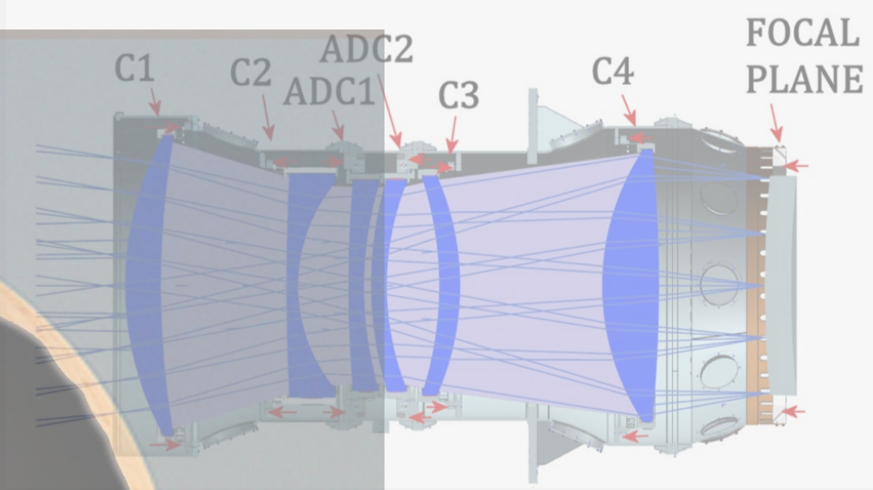


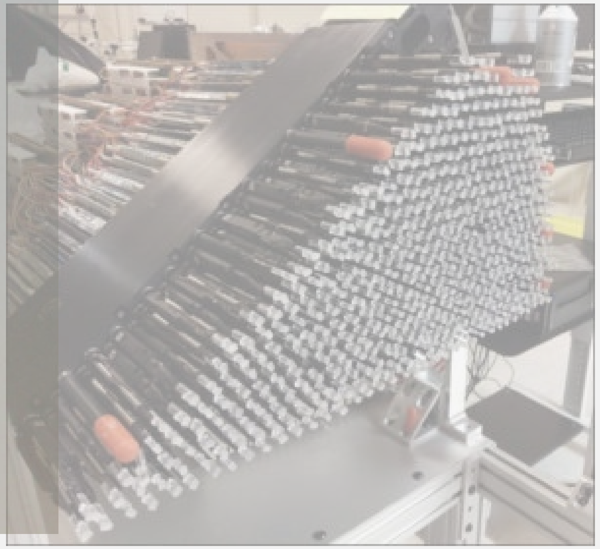
fiber positioners allow 5000 targets at once

the sum of all parts









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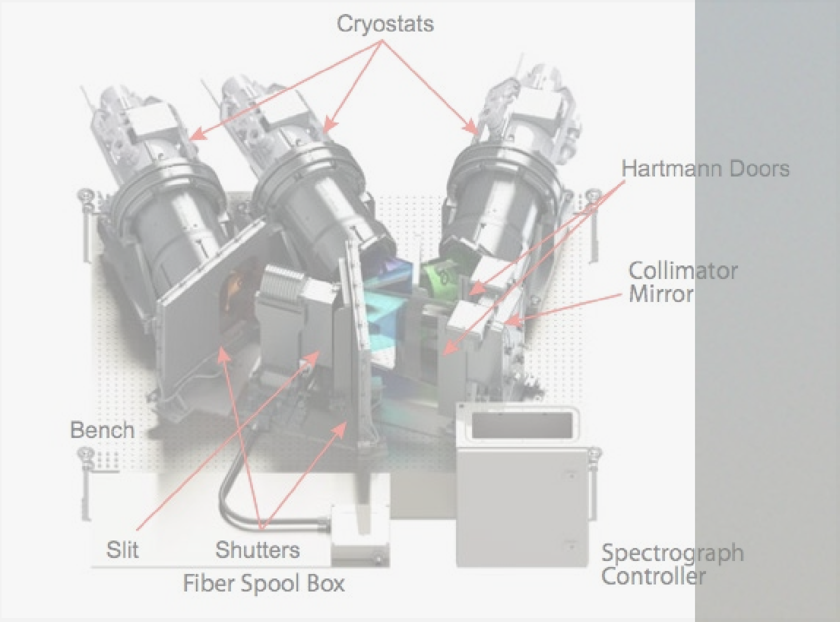
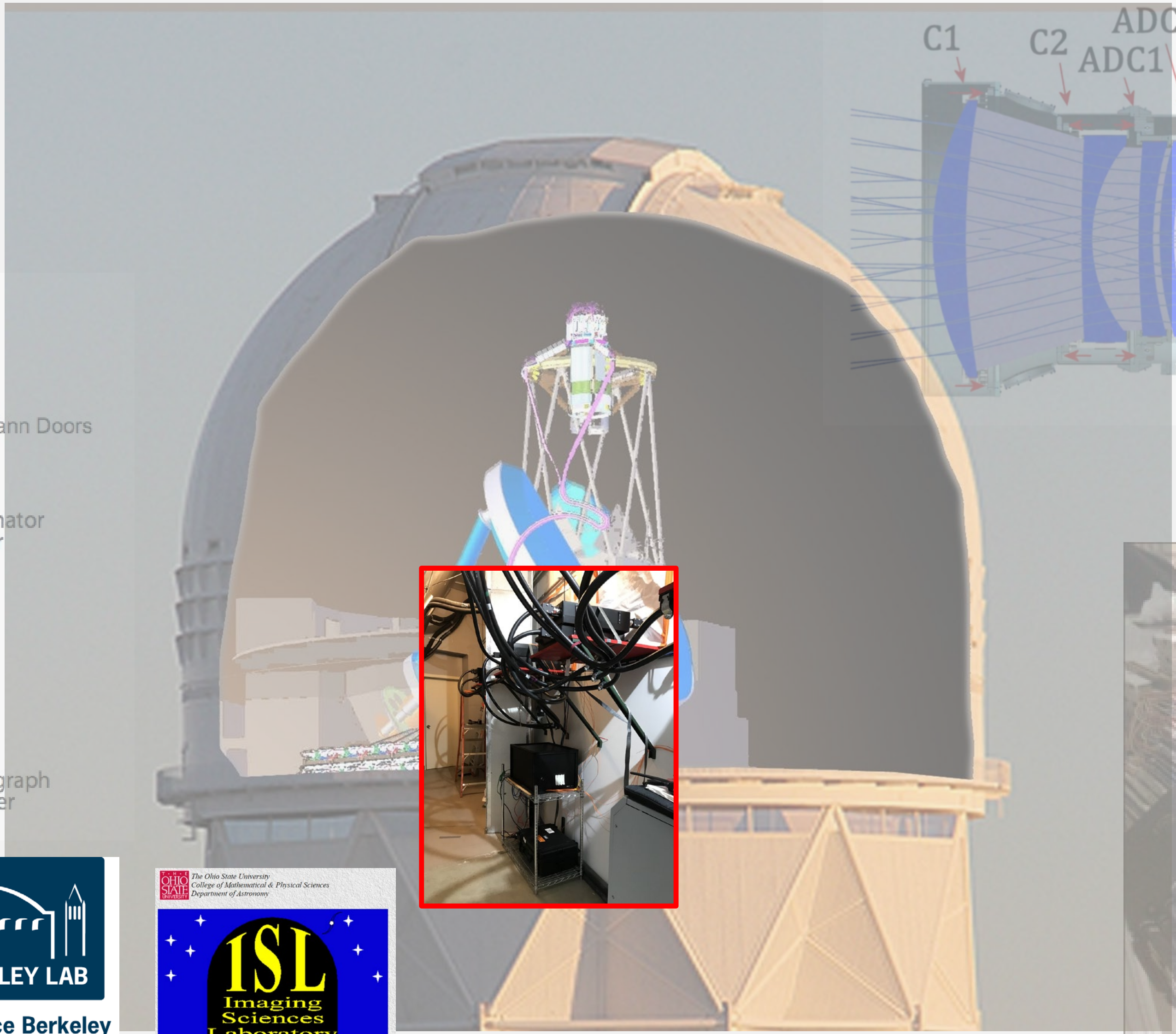
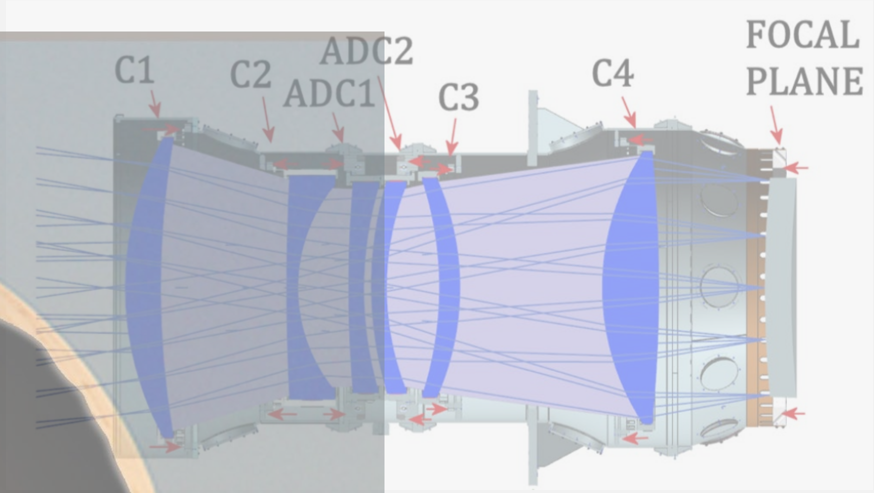
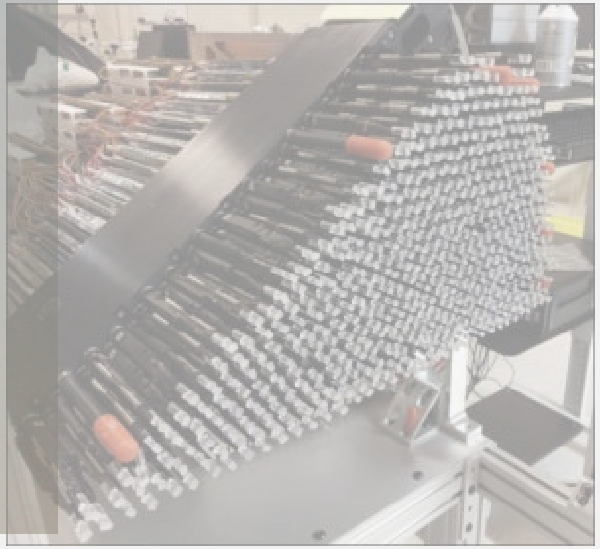
the DESI **sky camera**









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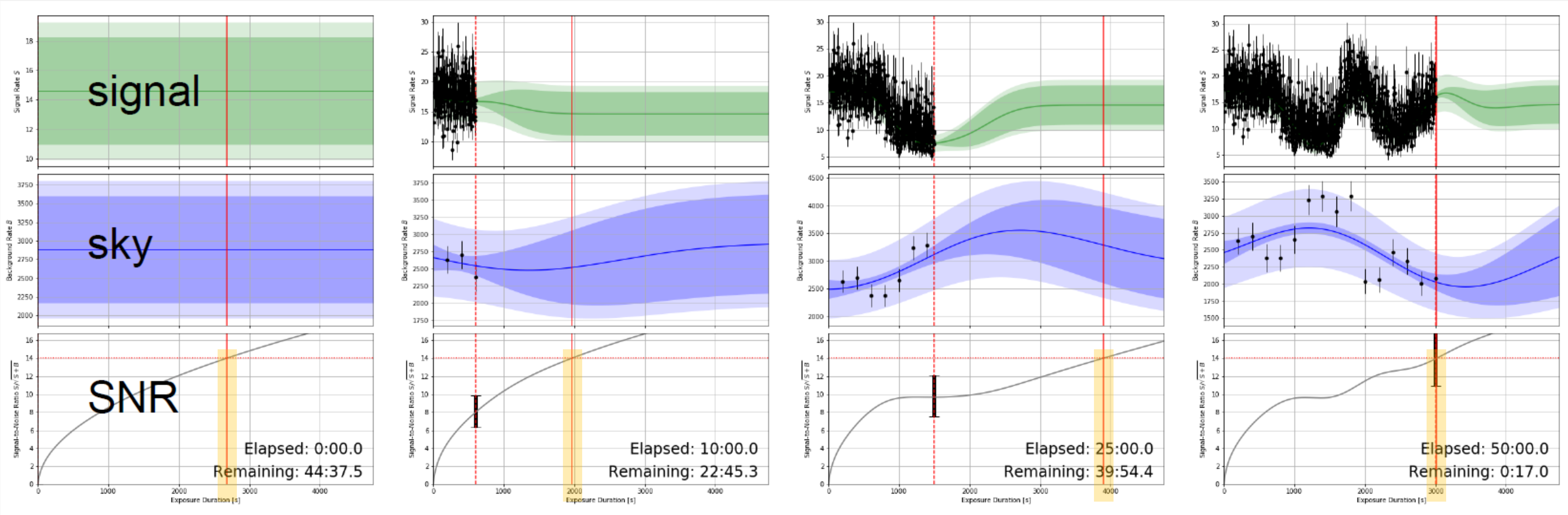
the DESI **sky camera**

the **sky camera** facilitates real-time exposure timing

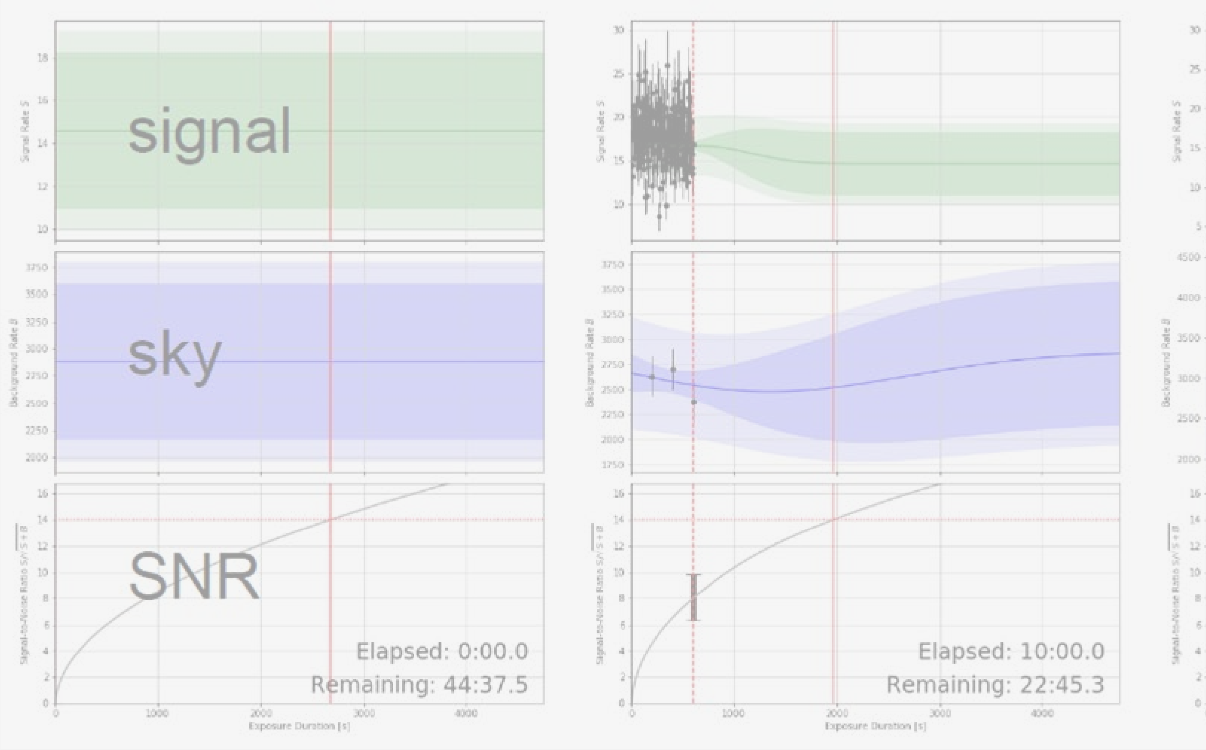
Skycam is part of the dynamic **Exposure Time Calculator (ETC)**

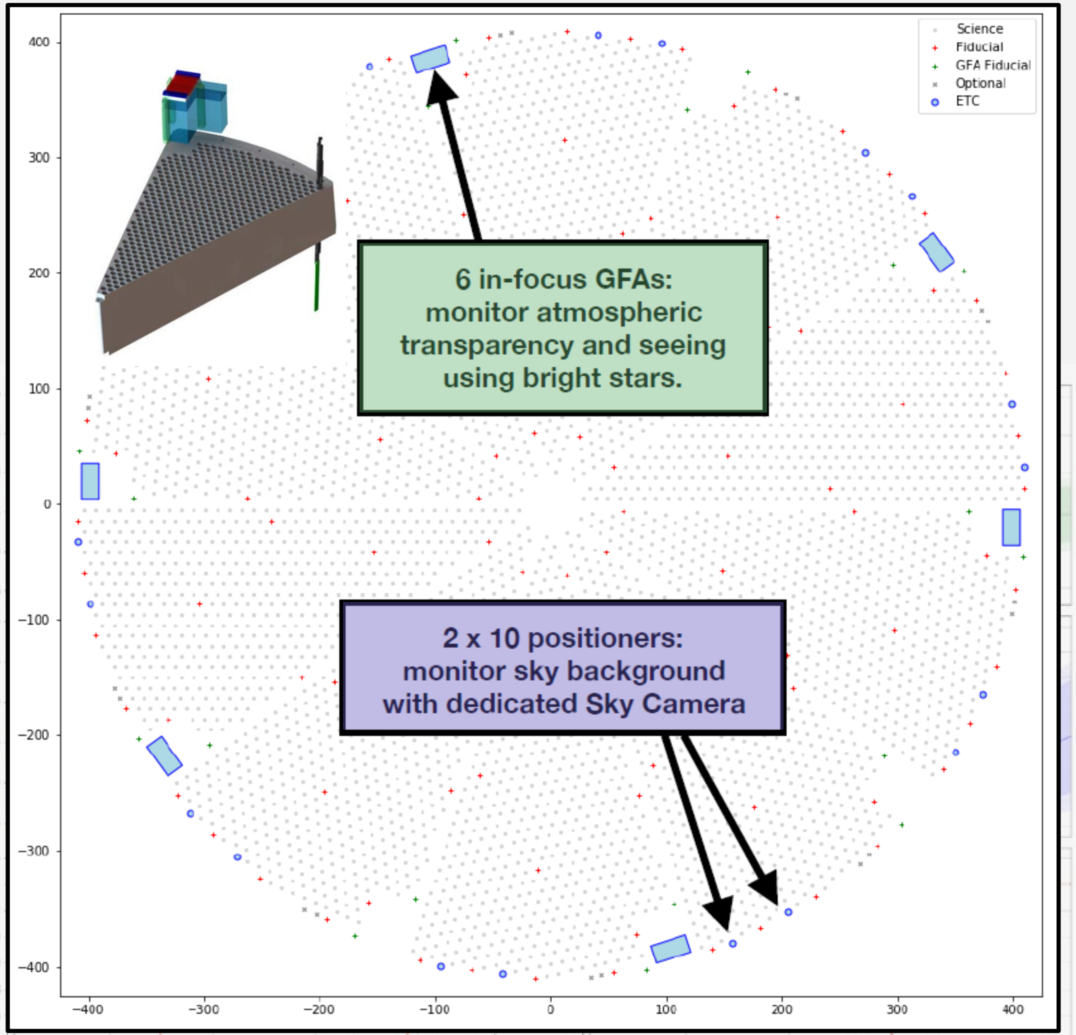
First time doing real time exposure adjustment for a cosmological survey, to maximize efficiency and ensure uniformity across a large sky for precision cosmology.



the **sky camera** facilitates real-time exposure timing

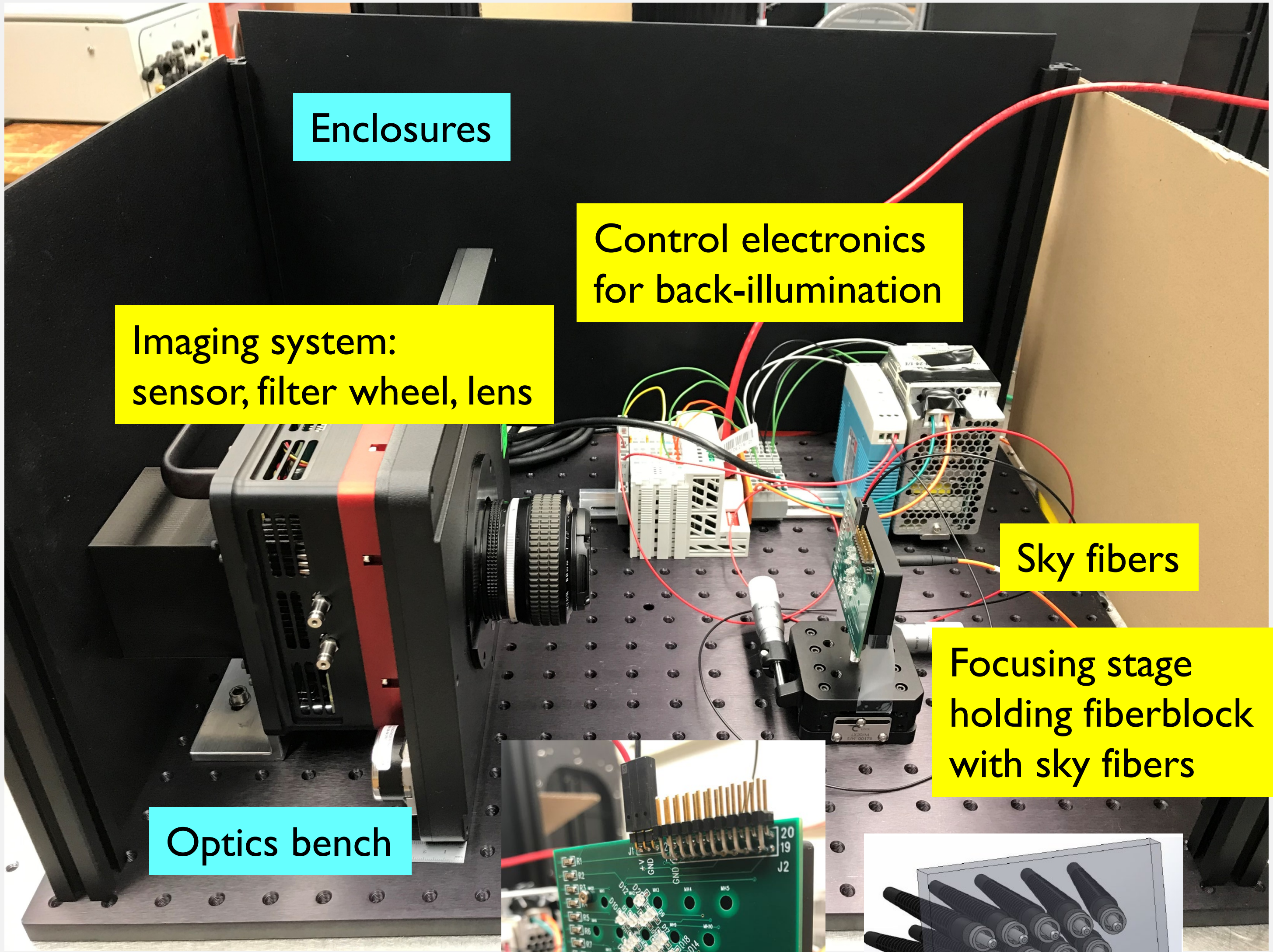
Real-time exposure timing results in ~10% gain in efficiency

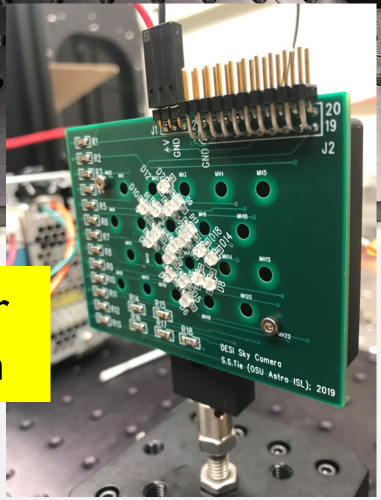




the **sky camera** in the making

99% 1%





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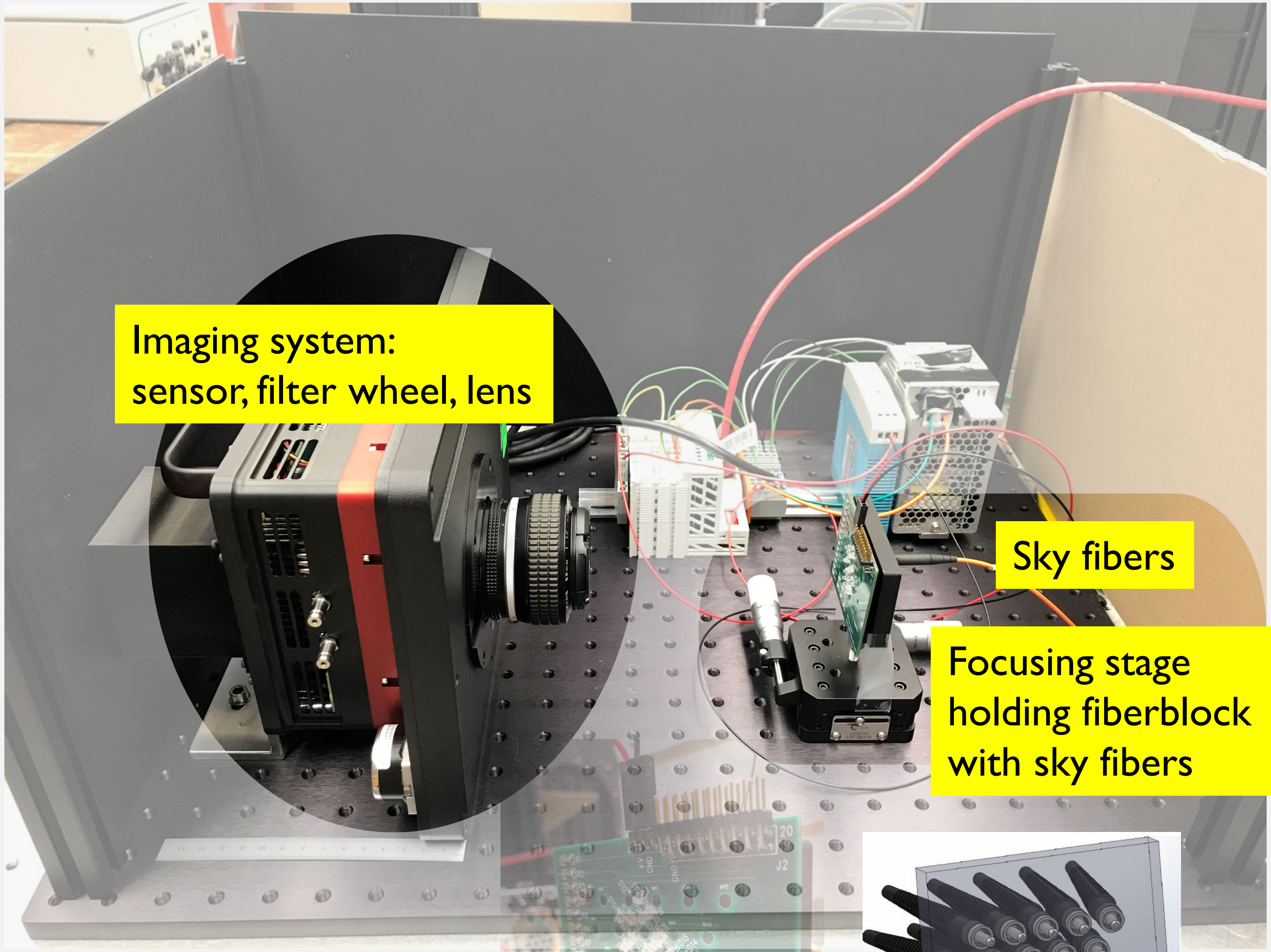
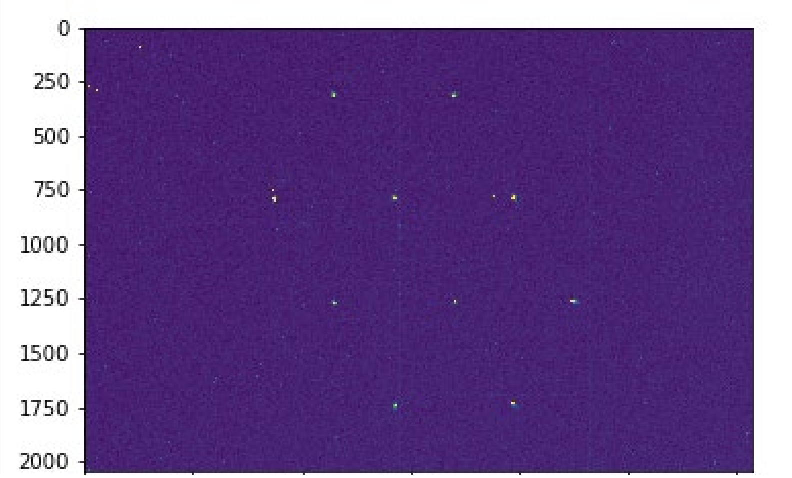
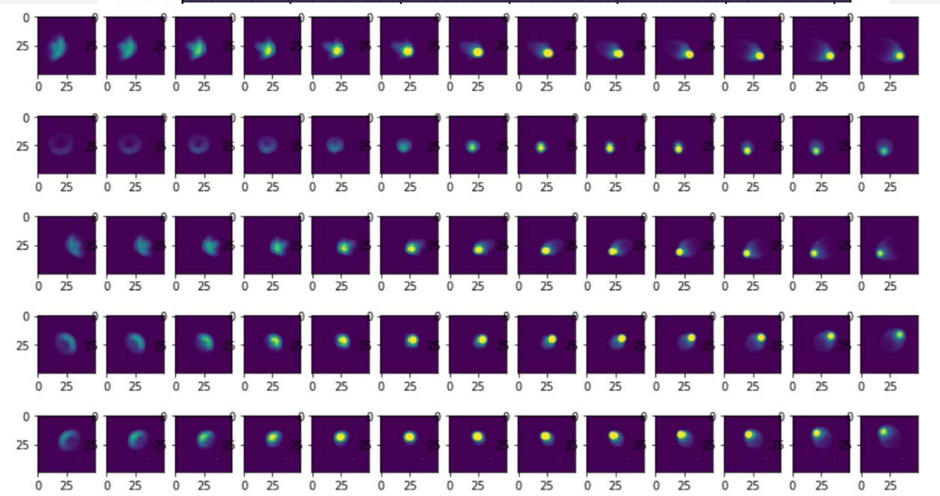
99% | 1%







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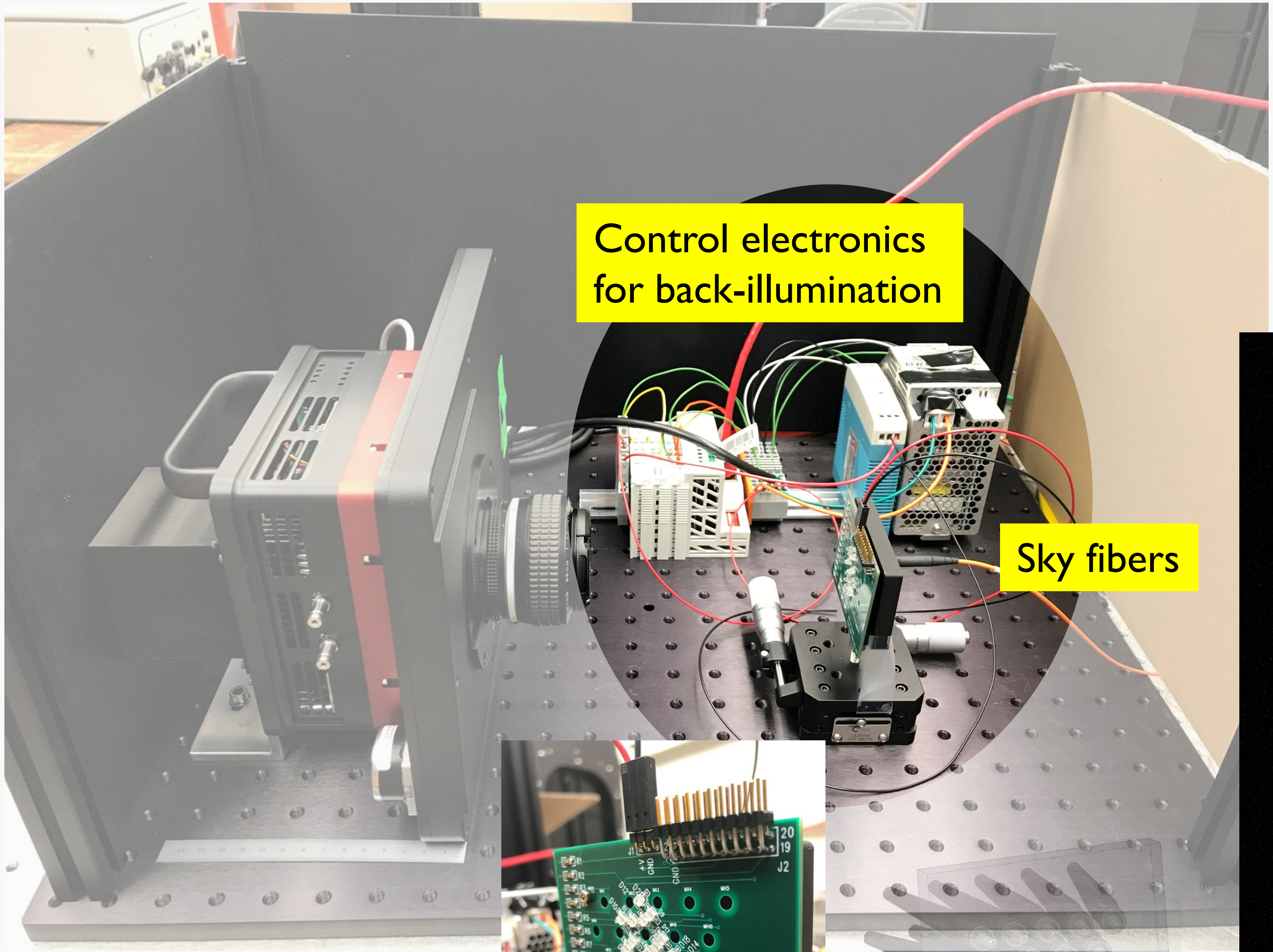
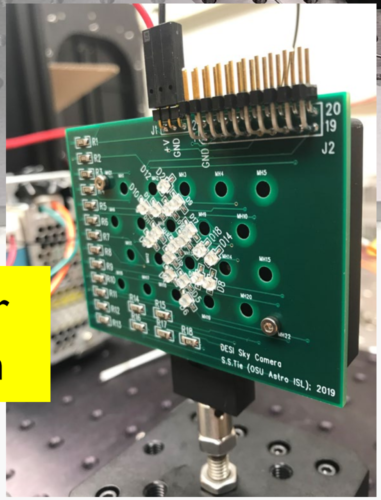
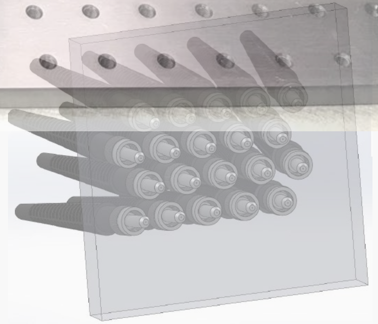
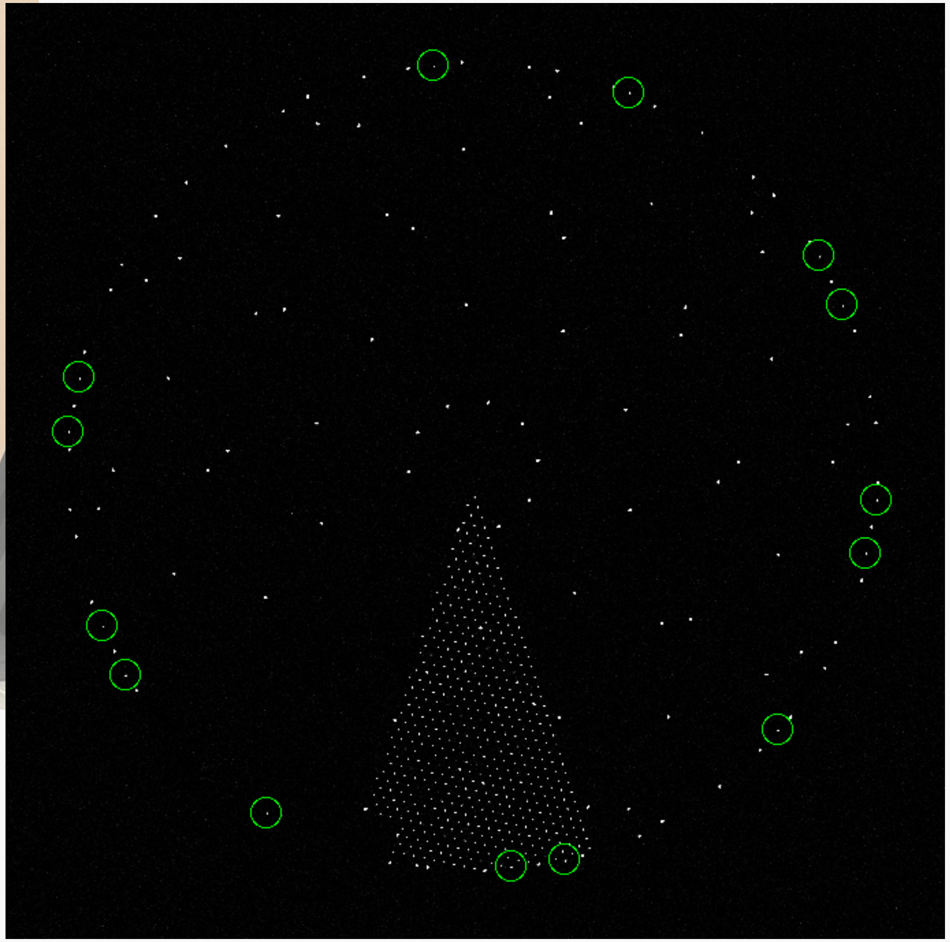
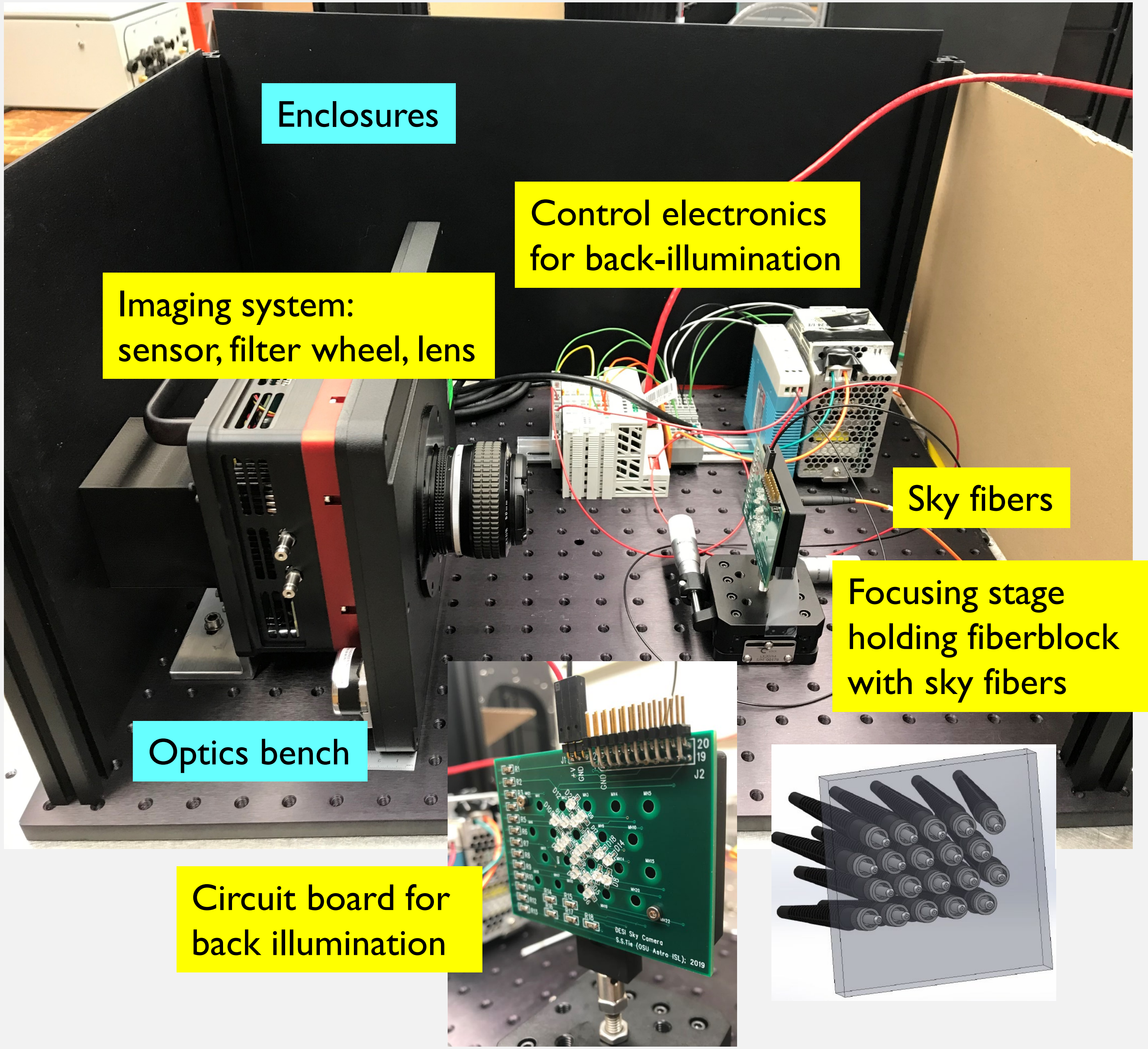




Circuit board for back illumination





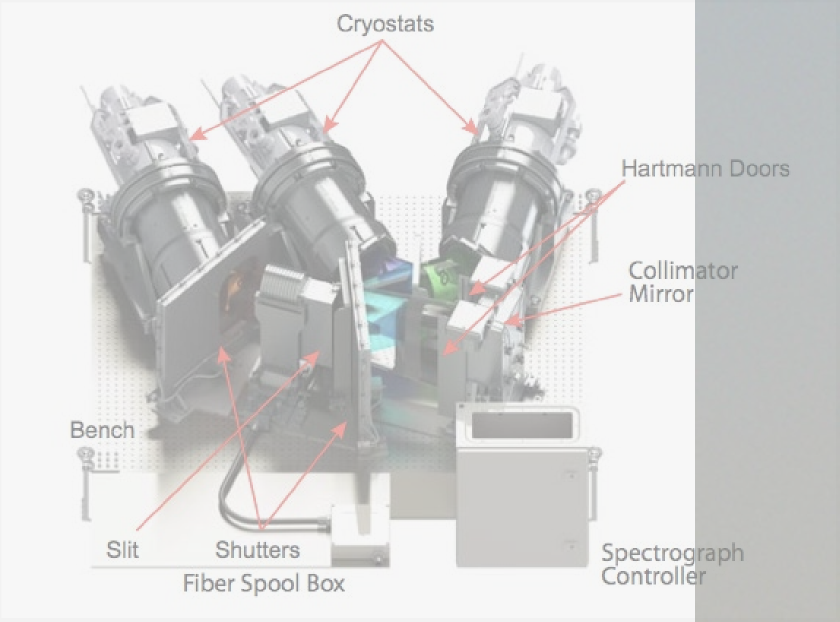


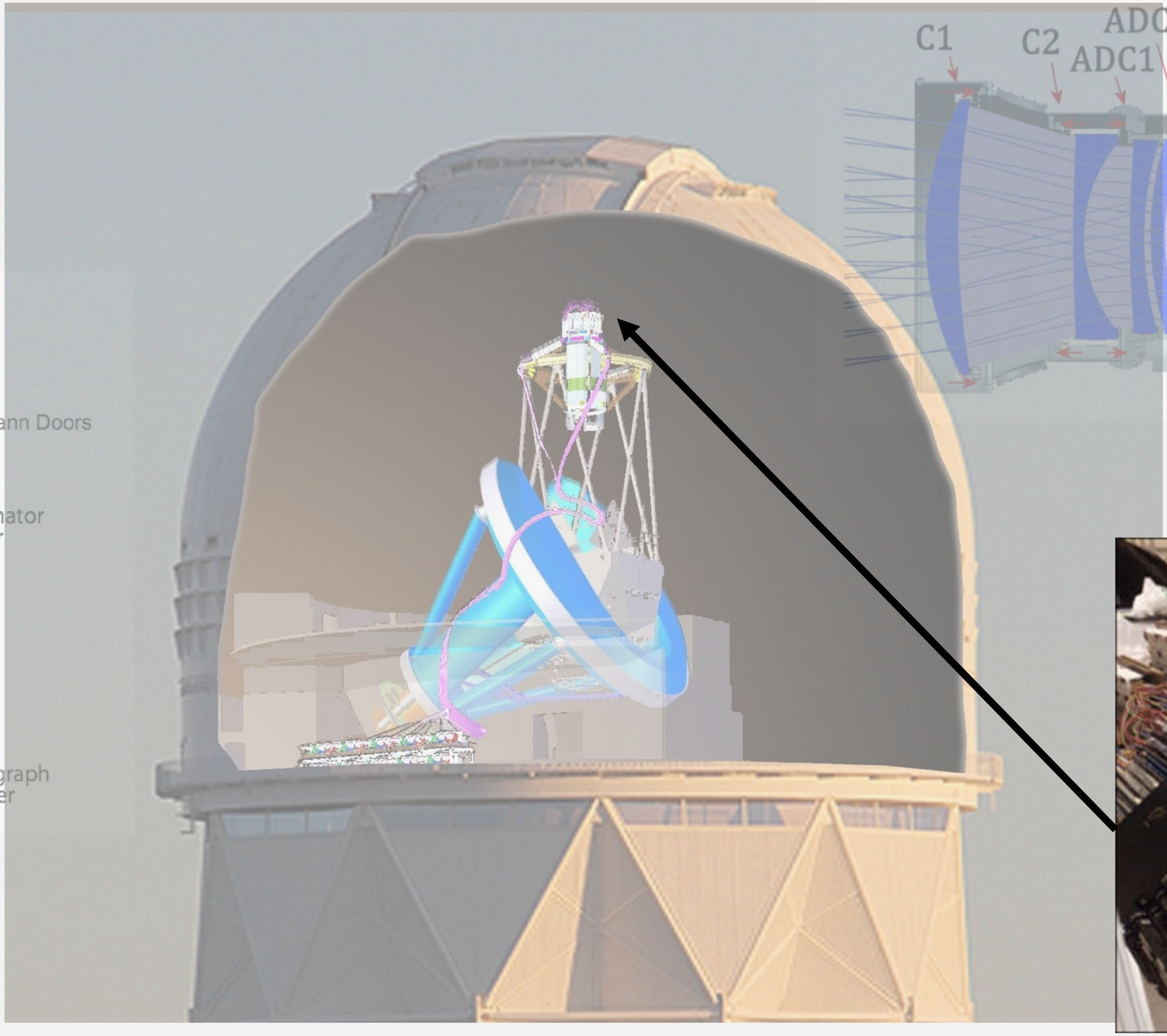
the **sky camera** in the making

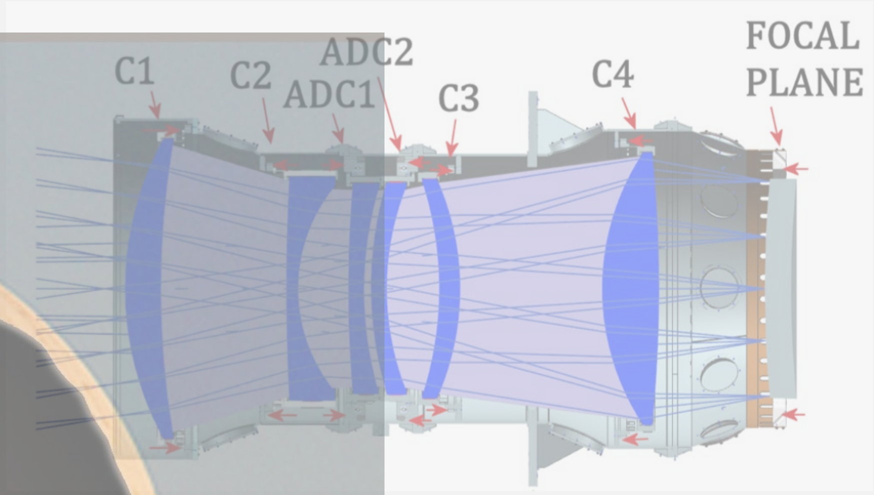
99% 1%

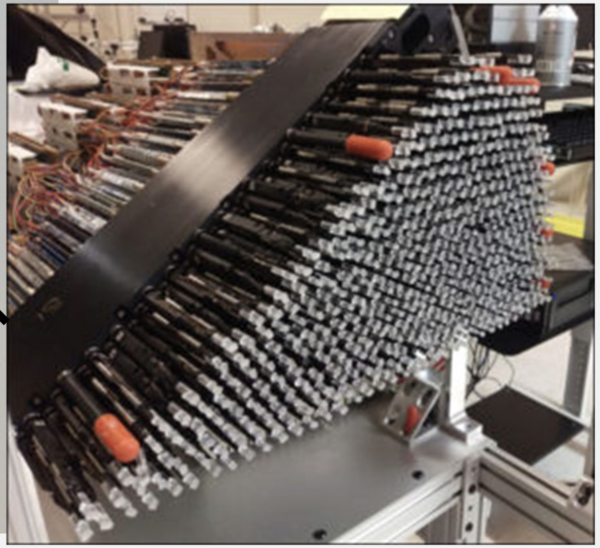
- ✓ Recently delivered to Kitt Peak
- ✓ Functional verification
- ✓ Commissioning

Anticipate commissioning with the dynamic ETC in Dec/Jan.









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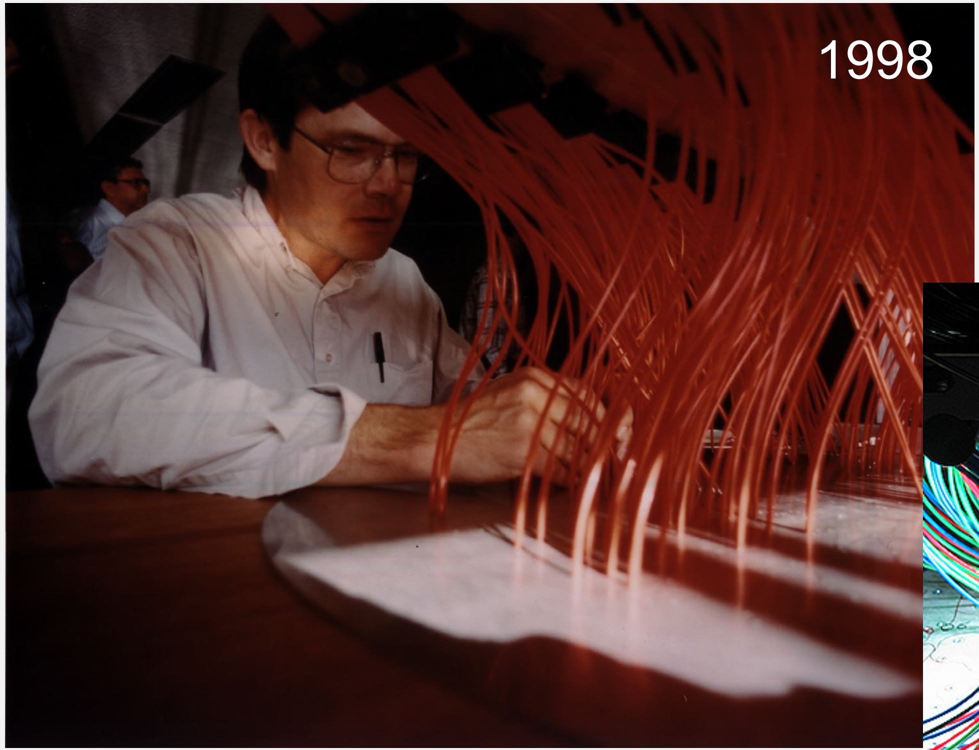
the DESI ***anti-collision algorithm***

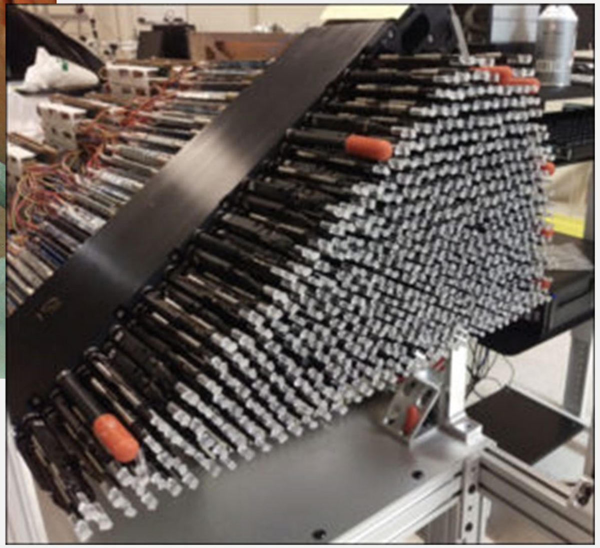
evolution of the “robots”



SDSS plug plates (640 fibers)

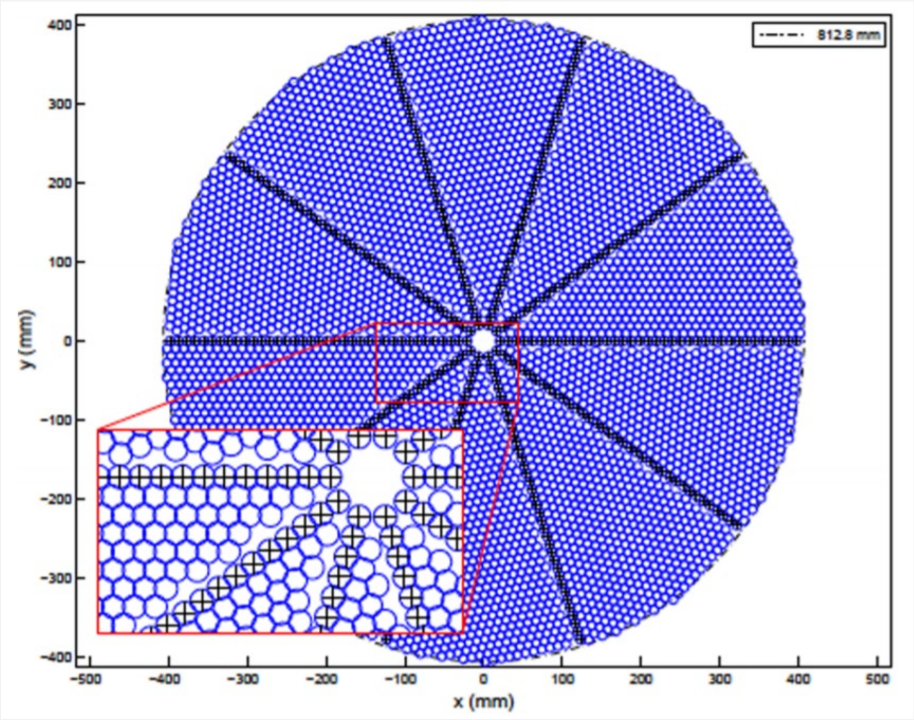
BOSS plug plates (1000 fibers)

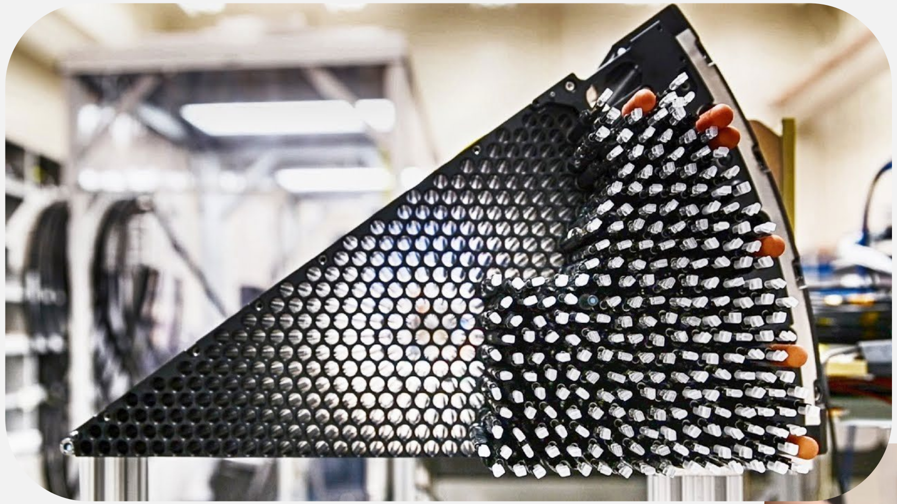
https://blog.sdss.org/2014/09/19/sdss-plates/

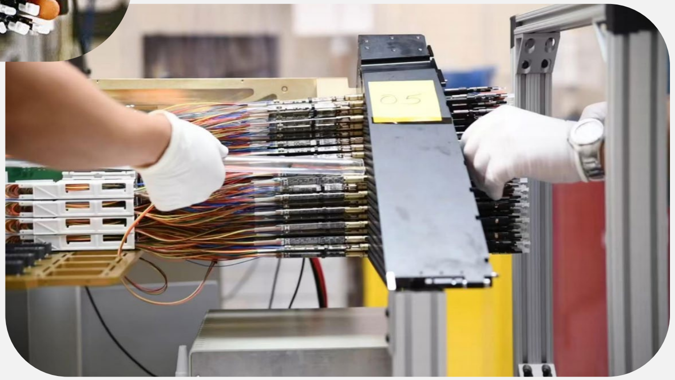


DESI robots (5000 fibers)

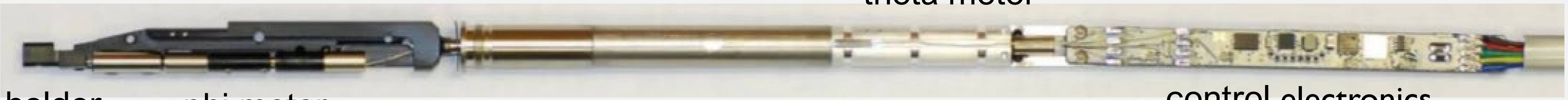
the anatomy of the DESI focal plane



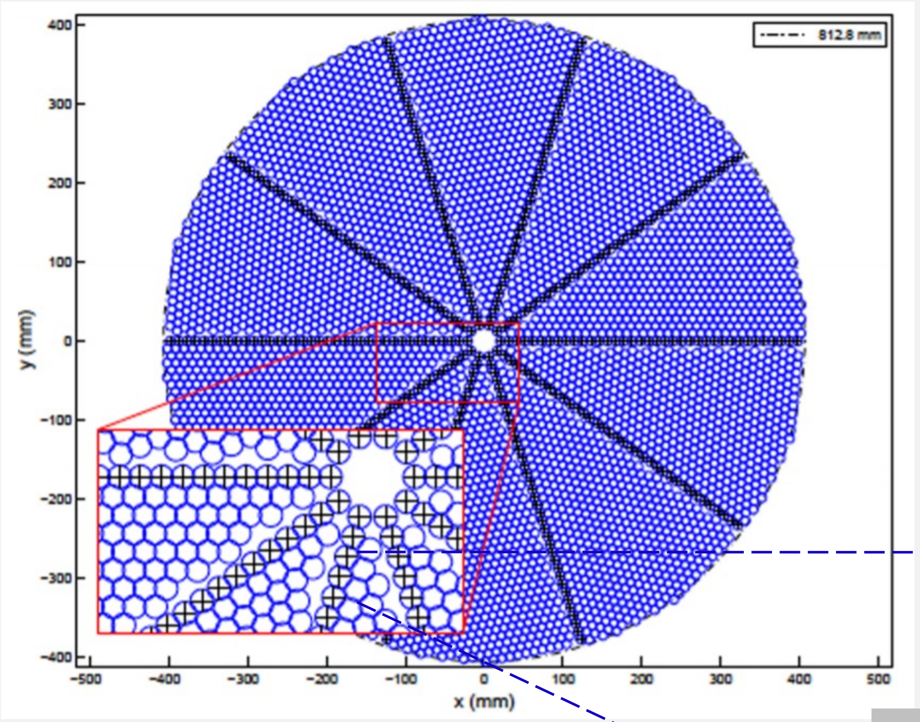




150,000 total parts for the DESI focal plane

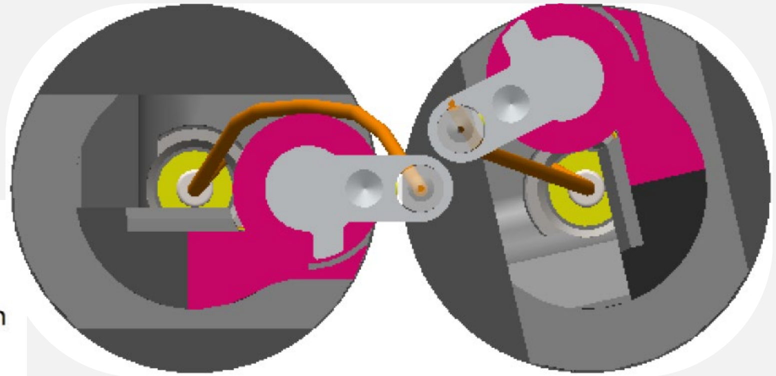


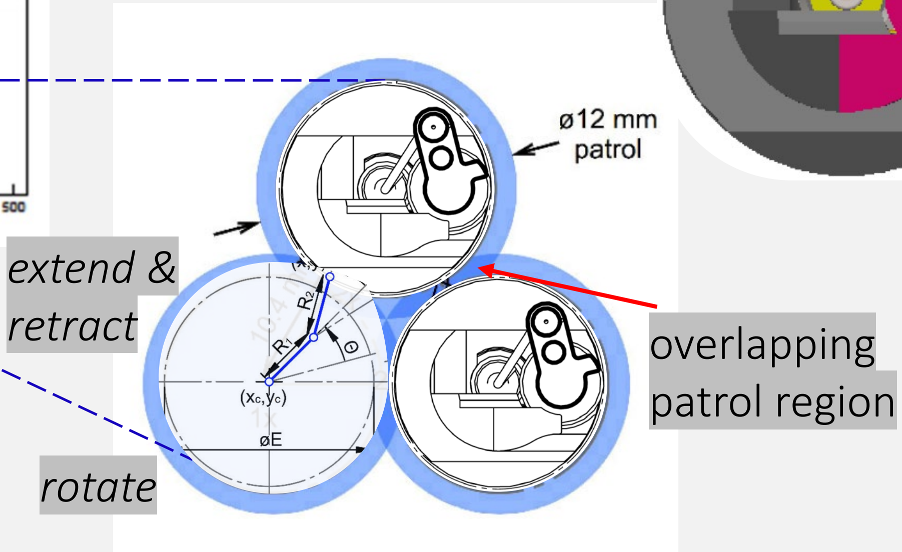
the ***anti-collision algorithm*** is the brain behind DESI



Targeting accuracy: 5 µm (10x less than hair thickness) within 1-2 minutes

Positioners can collide on the way to targets – affect targeting accuracy, can't reach target within allowed time, bad mechanically.





the ***anti-collision algorithm*** is the brain behind DESI

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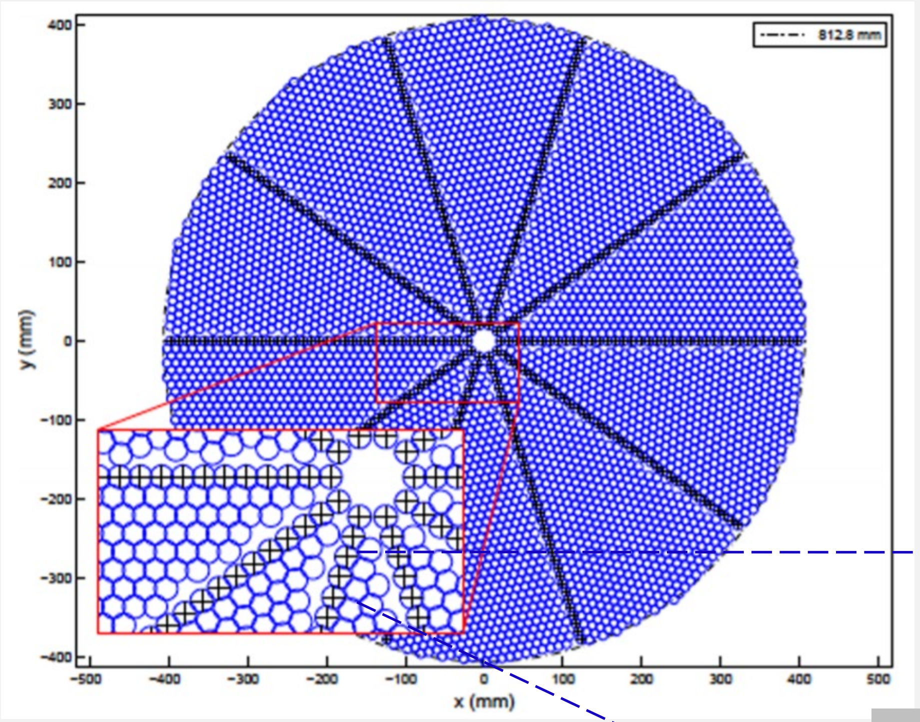
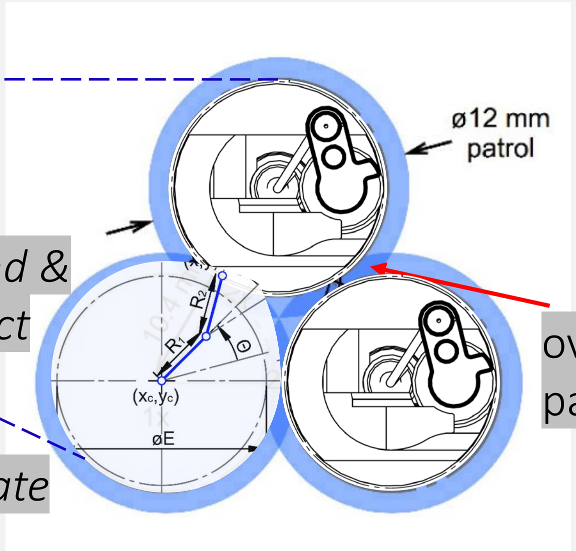
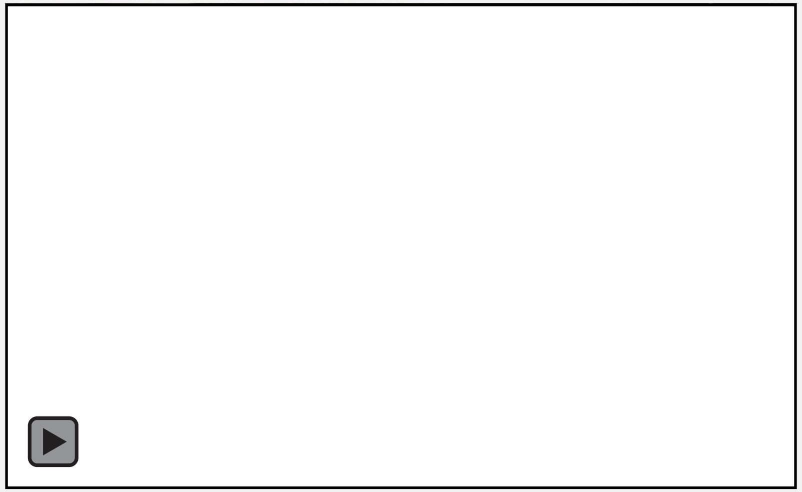
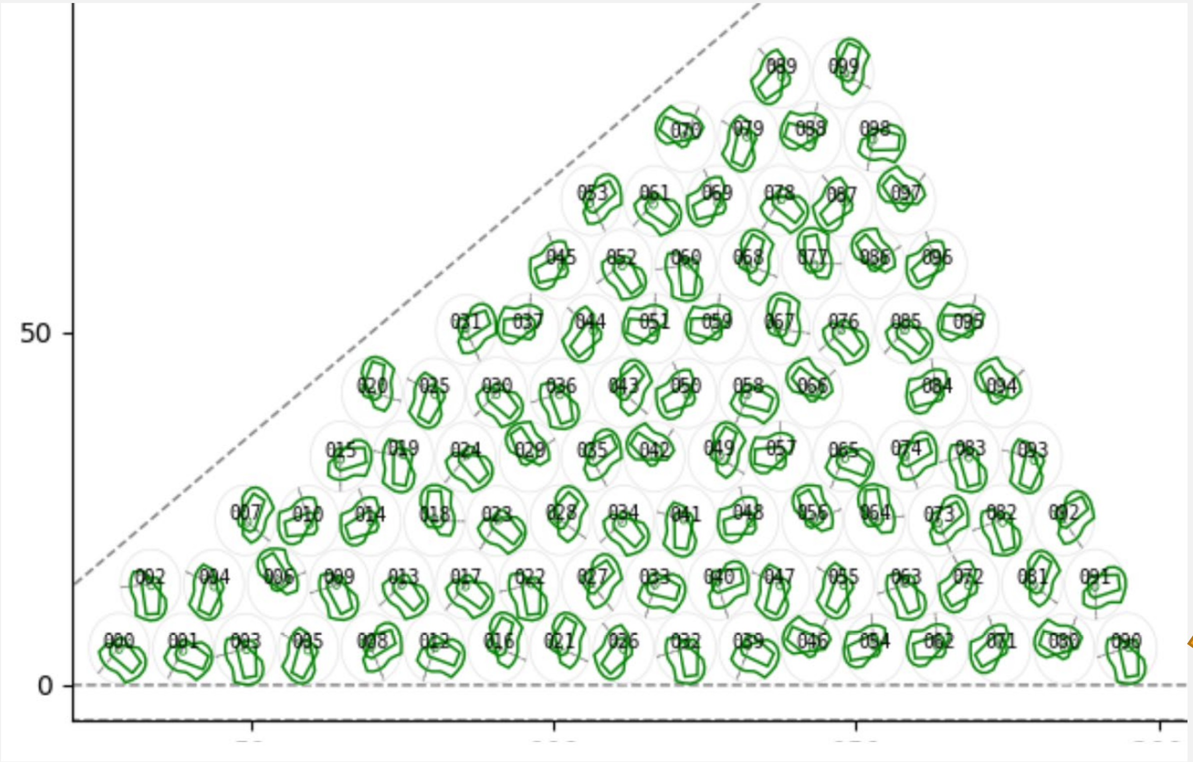
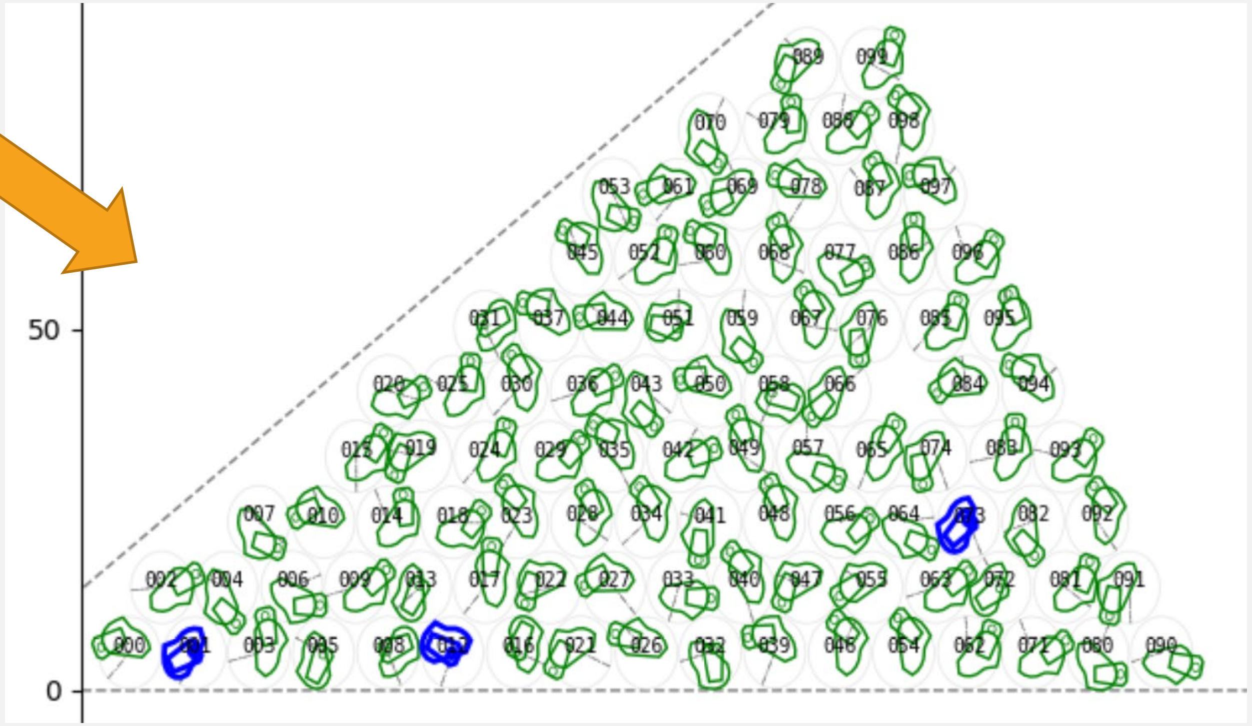








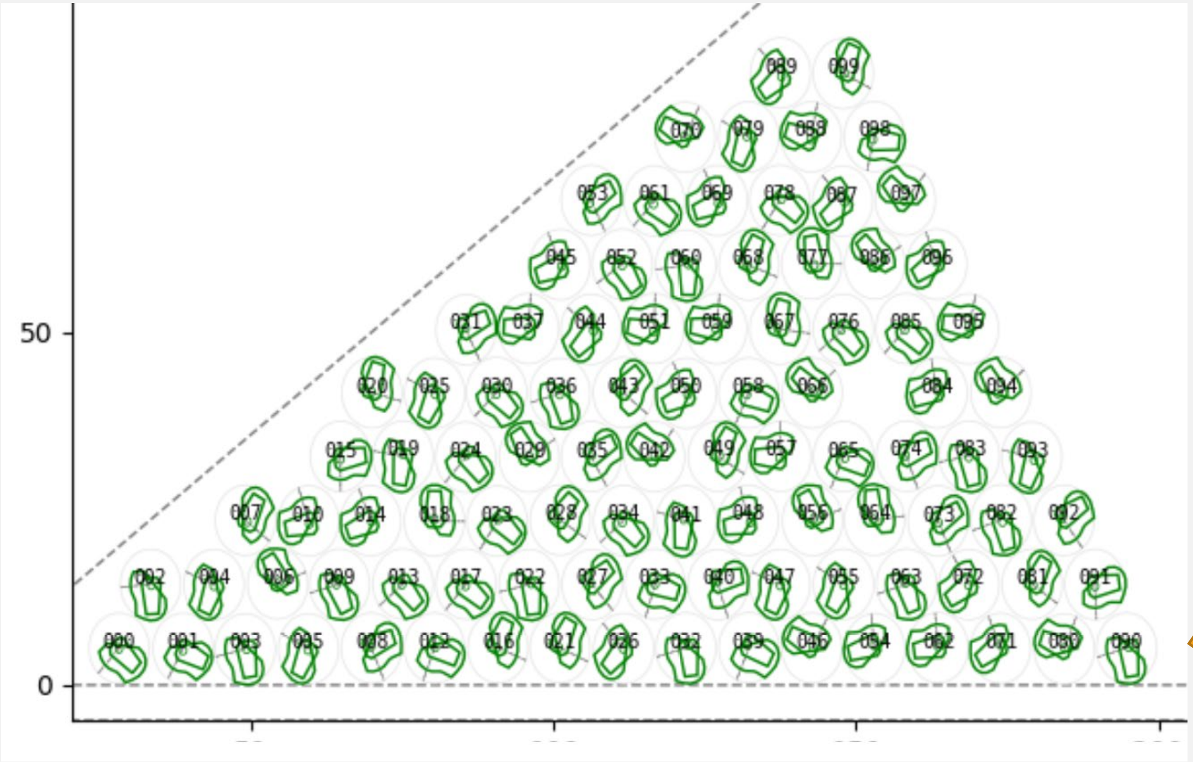
the ***a.c. algorithm***: (how) does it work?



0. Modeling of positioners and boundaries
1. Collision avoidance strategies:
    - staged arm movements + **more advanced tweaks** (ending with “freeze” if all fails)
    - distributed move sequences
    - one or two correction moves at the end

2. **Tests of (1) via simulations**
3. **End-to-end hardware test**

the ***a.c. algorithm***: in action



In **end-to-end hardware tests**, we demonstrated functionality of algorithm:

- improved algorithm
- demonstrated consistency between software prediction and hardware
- estimated collision rate to be ~few-percent

Later improvement: 10x speedup in calculation time

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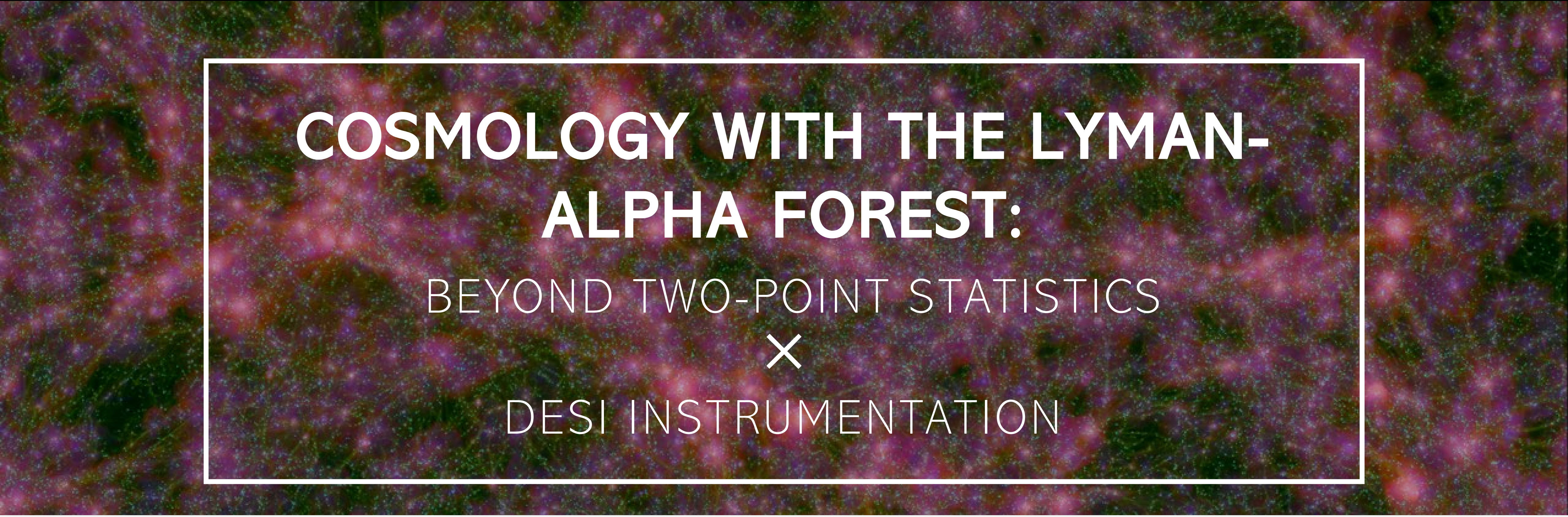

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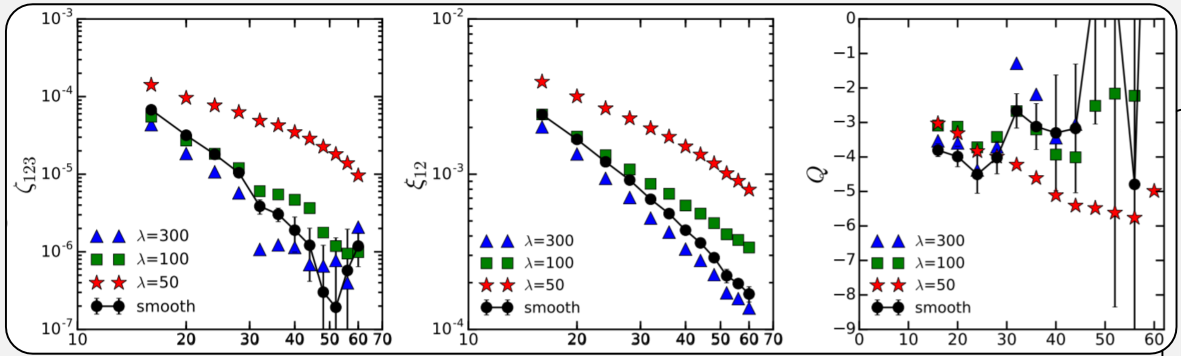
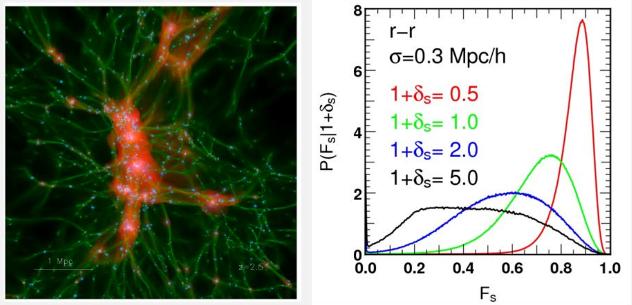


3d 3PCF of the forest

LyMAS scheme



conditional PDF $P(F_s|\delta_s)$ from hydro sim.

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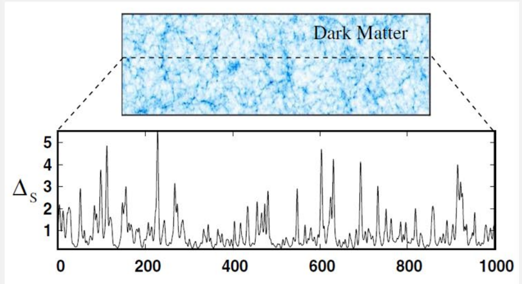

DM density from N-body sim.

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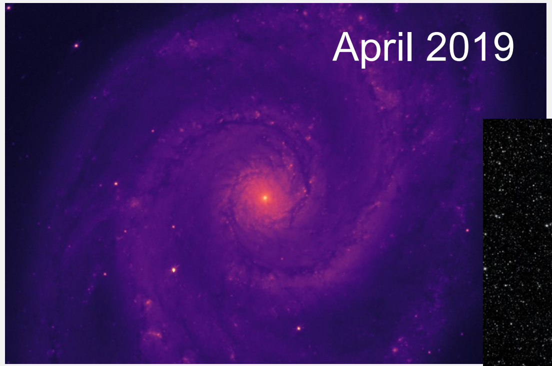
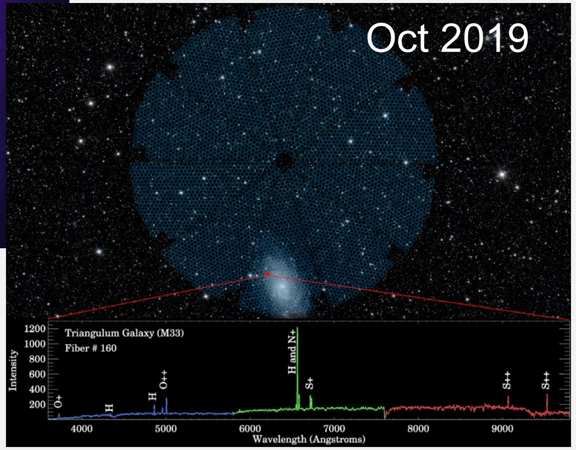
DESI will start science observations in mid-2020 and deliver 700k Lyα forest spectra over 5 years.

Early science possible with Survey Validation and 0.5-year data.

Future plans: (1) DESI measurement of the 3PCF
(2) improved simulation





EXTRA SLIDES

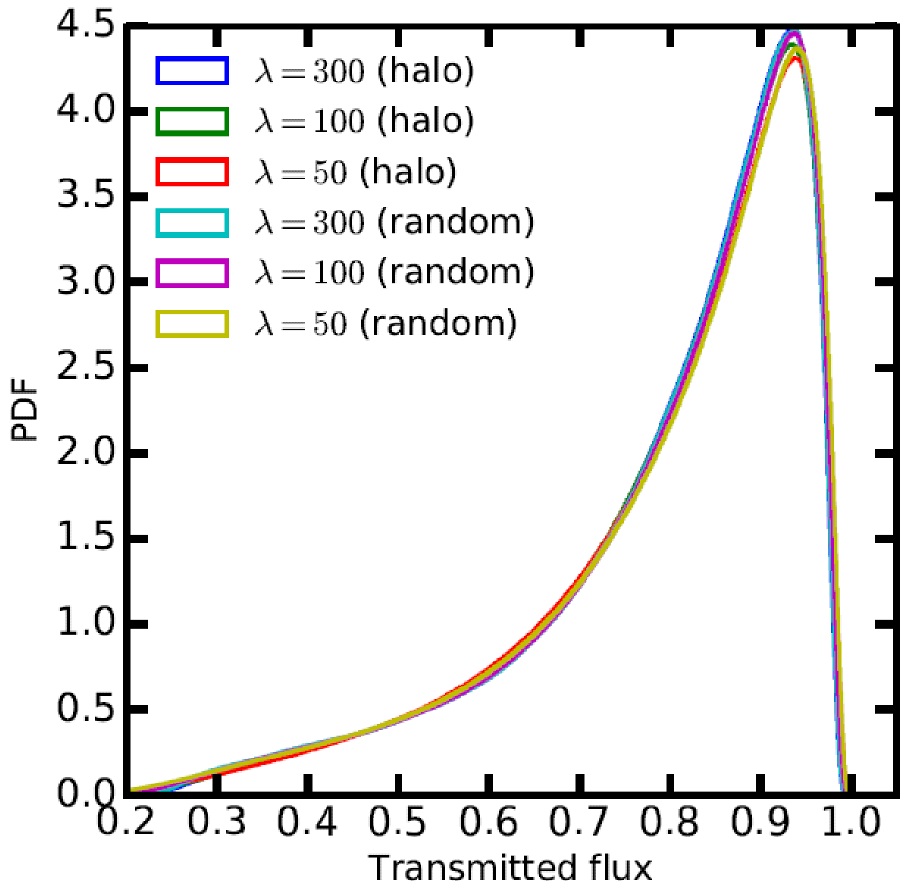


Figure 4. Distribution of forest fluxes in our $(1\ h^{-1}\ \mathrm{Gpc})^3$ box for different choices of λ for quasars found in massive halos and randomly-distributed quasars. The forest fluxes have been rescaled to the observed mean flux of $\bar{F} = 0.8$. The flux PDF is insensitive to the choices of λ.

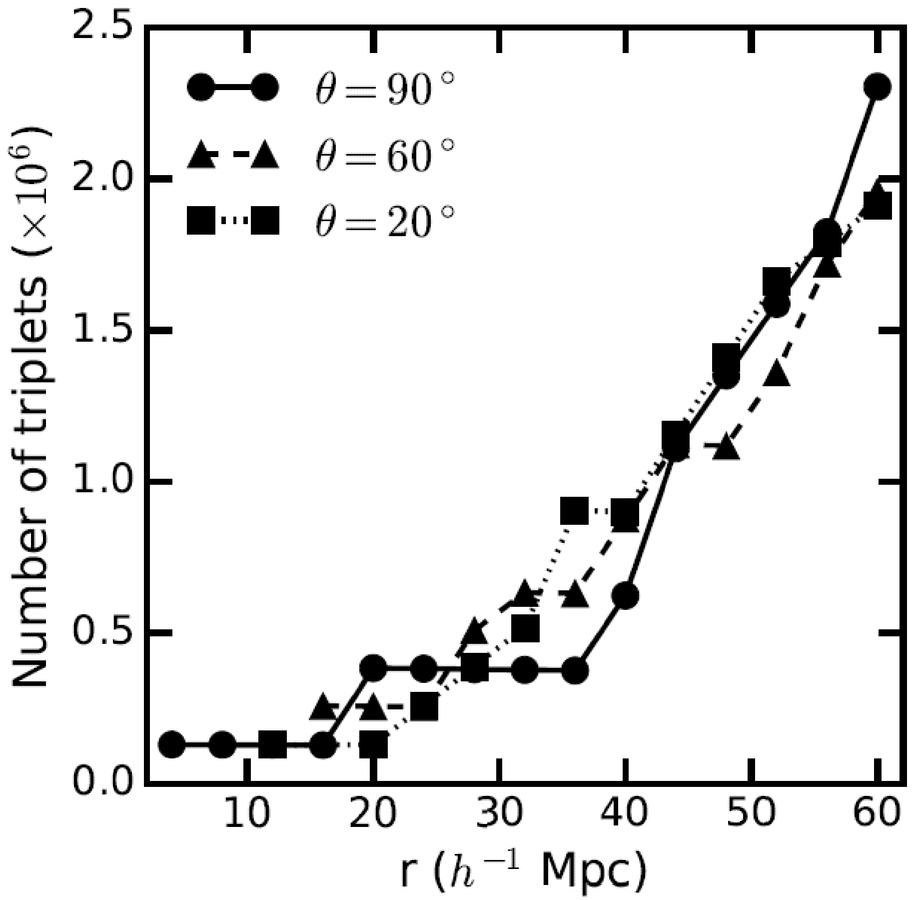


Figure 6. The total number of sight-line triplets sampled at each separation. The different lines indicate different triplet configurations. The number of available sight-lines increases with separation.

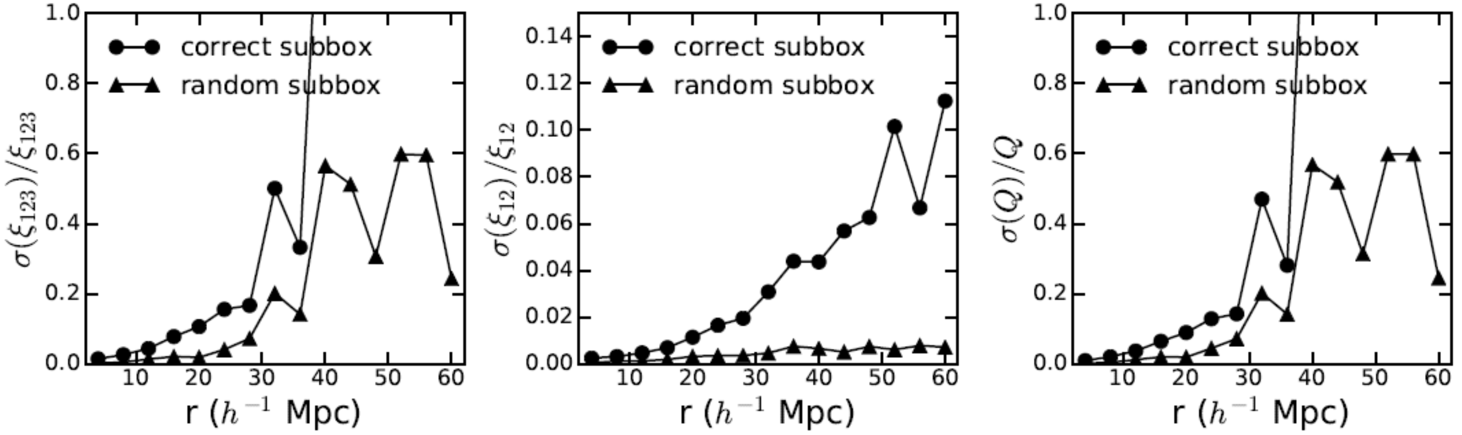


Figure 16. Fractional errors in the 3PCF (left), 2PCF (middle), and Q (right) when we assign triplets to the correct (based on the location of the primary sight-line) vs. random subvolumes. Here we use the box with a smooth UV background. Assigning triplets to random subvolumes averages out variance from large scale structure. The fractional errors of the correlation functions are larger for the "correct subbox" assignment, therefore suggesting that we are limited by cosmic variance. The errors in Q are dominated by the errors in the 3PCF.

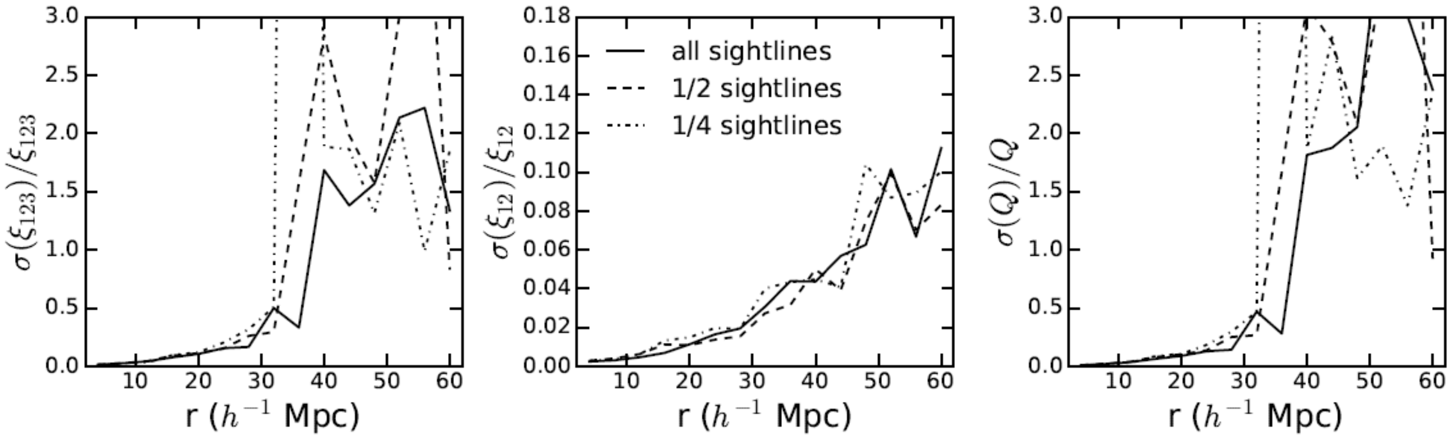


Figure 17. Fractional errors in the 3PCF (left), 2PCF (middle), and Q (right) when we vary the number of sight-lines to use in our clustering measurements. There is no significant improvement between using a quarter of or all available sight-lines in the box. This, in combination with Figure 16, suggests that our errors are mostly dominated by cosmic variance rather than by not having enough sight-lines in our box.