Mapping the large-scale structure of the Universe with emission-line galaxies from z=0.6 to 3.5: HETDEX and PFS

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OATs Seminar, Osservatorio Astronomico di Trieste
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Why Large-scale Structure?

- **“End-to-end Test of the Universe”**
- *Cosmology as an initial-value problem*
  - The initial fluctuation is constrained quite well by the cosmic microwave background data
  - **We then evolve the initial fluctuation forward, assuming a cosmological model and gravitational theory**
  - Does the prediction agree with what we see in the data in a late-time Universe?

State-of-the-art

- There is an indication that **the E2E test is failing for a flat ΛCDM model**
    - H_0
    - Amplitude of matter fluctuations in a low-z universe
- There is also an indication that the current large-scale structure data sets may not be consistent with each other

arXiv.org > astro-ph > arXiv:1907.04869

Search...

Help | Advance

Astrophysics > Cosmology and Nongalactic Astrophysics

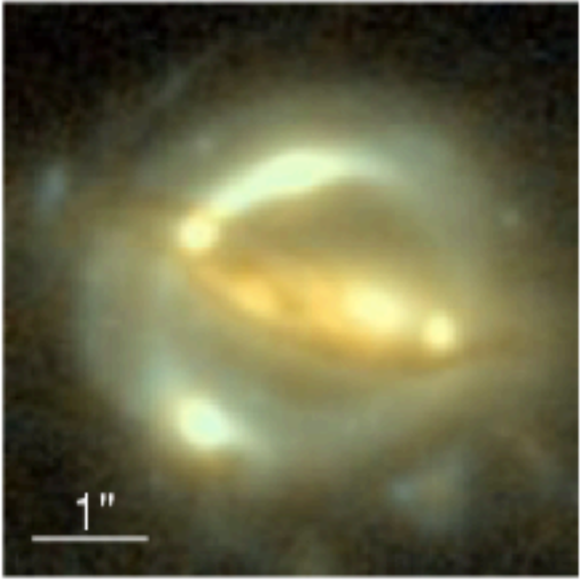
H0LiCOW XIII. A 2.4% measurement of H_0 from lensed quasars: 5.3σ tension between early and late-Universe probes

Kenneth C. Wong, Sherry H. Suyu, Geoff C.-F. Chen, Cristian E. Rusu, Martin Millon, Dominique Sluse, Vivien Bonvin, Christopher D. Fassnacht, Stefan Taubenberger, Matthew W. Auger, Simon Birrer, James H. H. Chan, Frederic Courbin, Stefan Hilbert, Olga Tihhonova, Tommaso Treu, Adriano Agnello, Xuheng Ding, Inh Jee, Eiichiro Komatsu, Anowar J. Shajib, Alessandro Sonnenfeld, Roger D. Blandford, Leon V. E. Koopmans, Philip J. Marshall, Georges Meylan

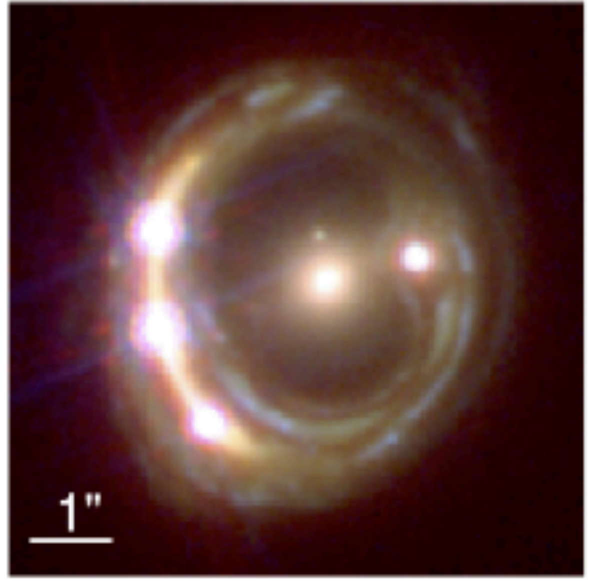
(Submitted on 10 Jul 2019)

appeared on July 12

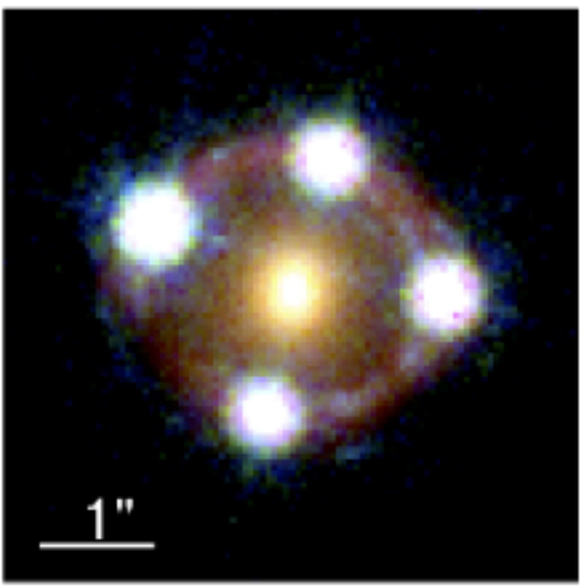
We present a measurement of the Hubble constant (H_0) and other cosmological parameters from a joint analysis of six gravitationally lensed quasars with measured time delays. All lenses except the first are analyzed blindly with respect to the cosmological parameters. In a flat ΛCDM cosmology, we find $H_0 = 73.3^{+1.7}_{-1.8}$, a 2.4% precision measurement, in agreement with local measurements of H_0 from type Ia supernovae calibrated by the distance ladder, but in 3.1σ tension with *Planck* observations of the cosmic microwave background (CMB). This method is completely independent of both the supernovae and CMB analyses. A combination of time-delay cosmography and the distance ladder results is in 5.3σ tension with *Planck* CMB determinations of H_0 in flat ΛCDM. We compute Bayes factors to verify that all lenses give statistically consistent results, showing that we are not underestimating our uncertainties and are able to control our systematics. We explore extensions to flat ΛCDM using constraints from time-delay cosmography alone, as well as combinations with other cosmological probes, including CMB observations from *Planck*, baryon acoustic oscillations, and type Ia supernovae. Time-delay cosmography improves the precision of the other probes, demonstrating the strong complementarity. Using the distance constraints from time-delay cosmography to anchor the type Ia supernova distance scale, we reduce the sensitivity of our H_0 inference to cosmological model assumptions. For six different cosmological models, our combined inference on H_0 ranges from 73–78 $\mathrm{km\ s^{-1}\ Mpc^{-1}}$, which is consistent with the local distance ladder constraints.



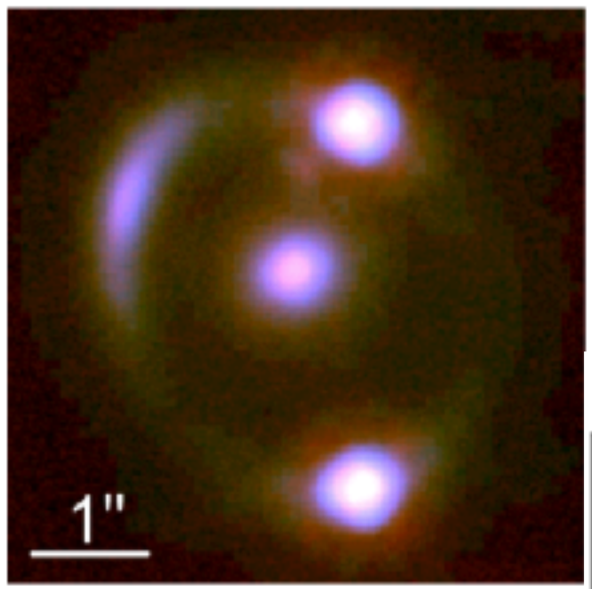
(a) B1608+656



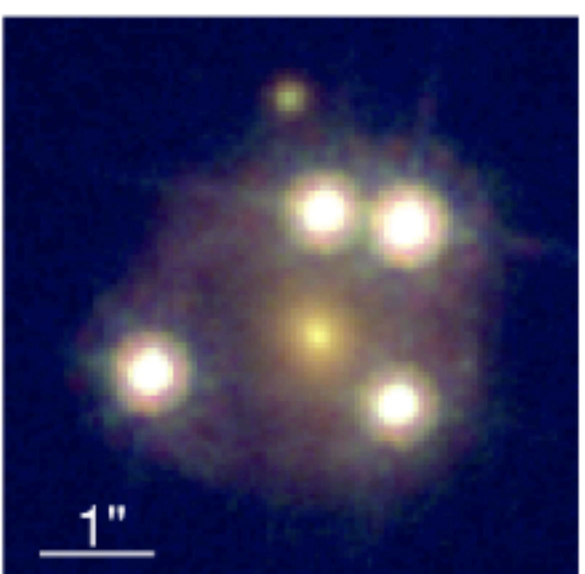
(b) RXJ1131−1231



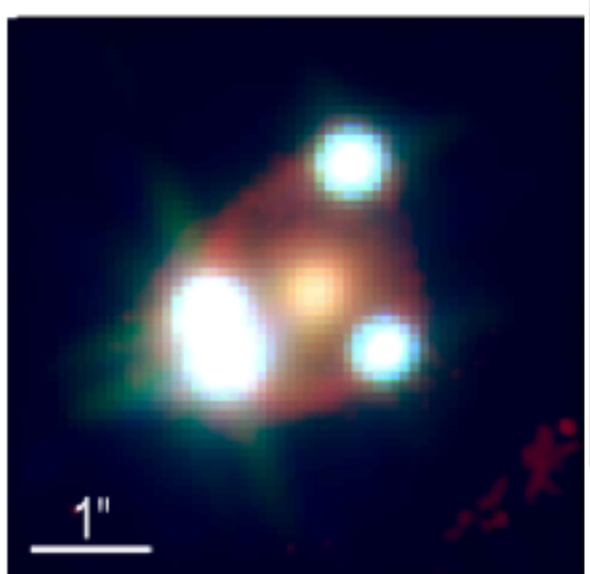
(c) HE 0435−1223



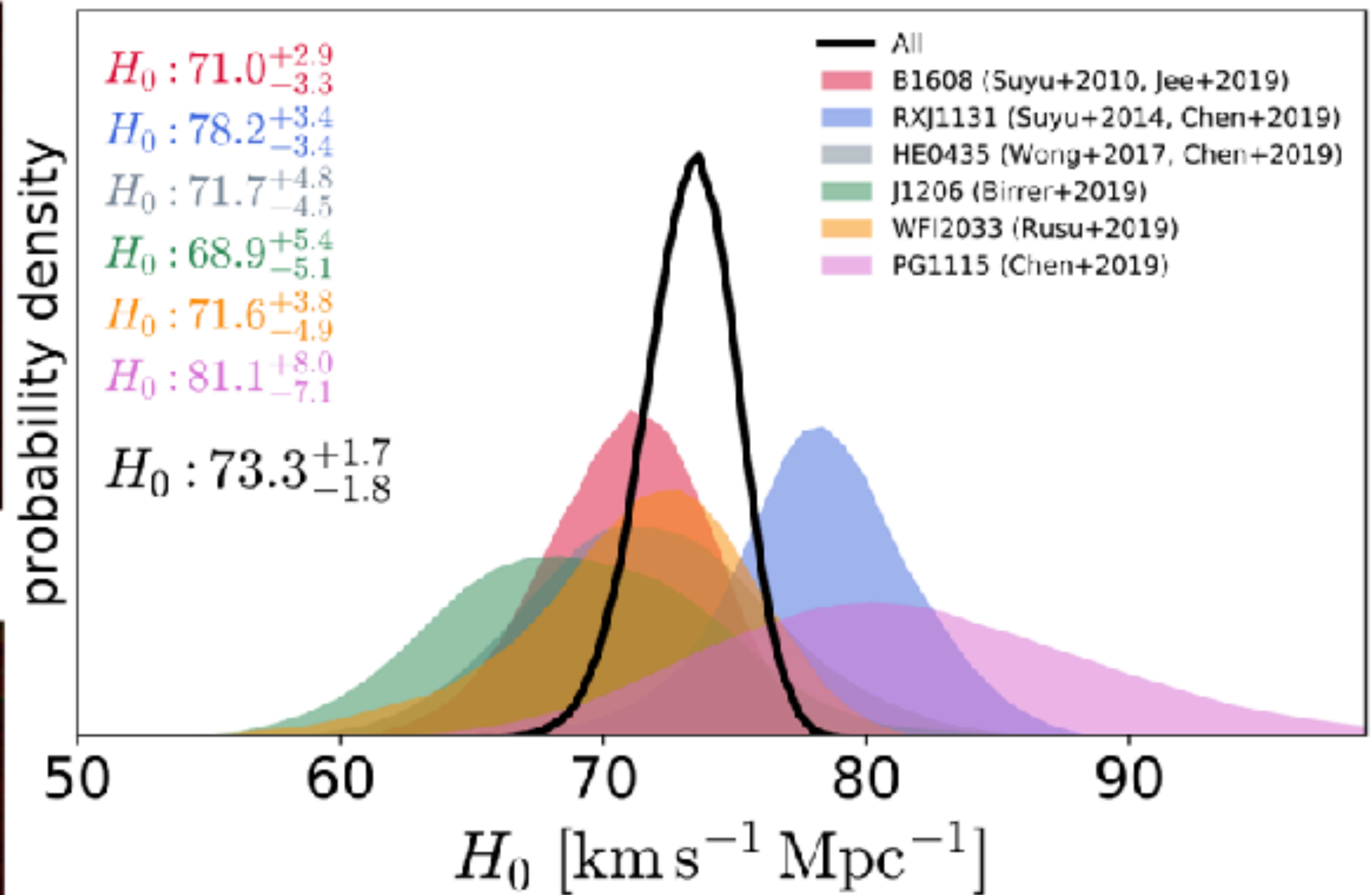
(d) SDSS 1206+4332



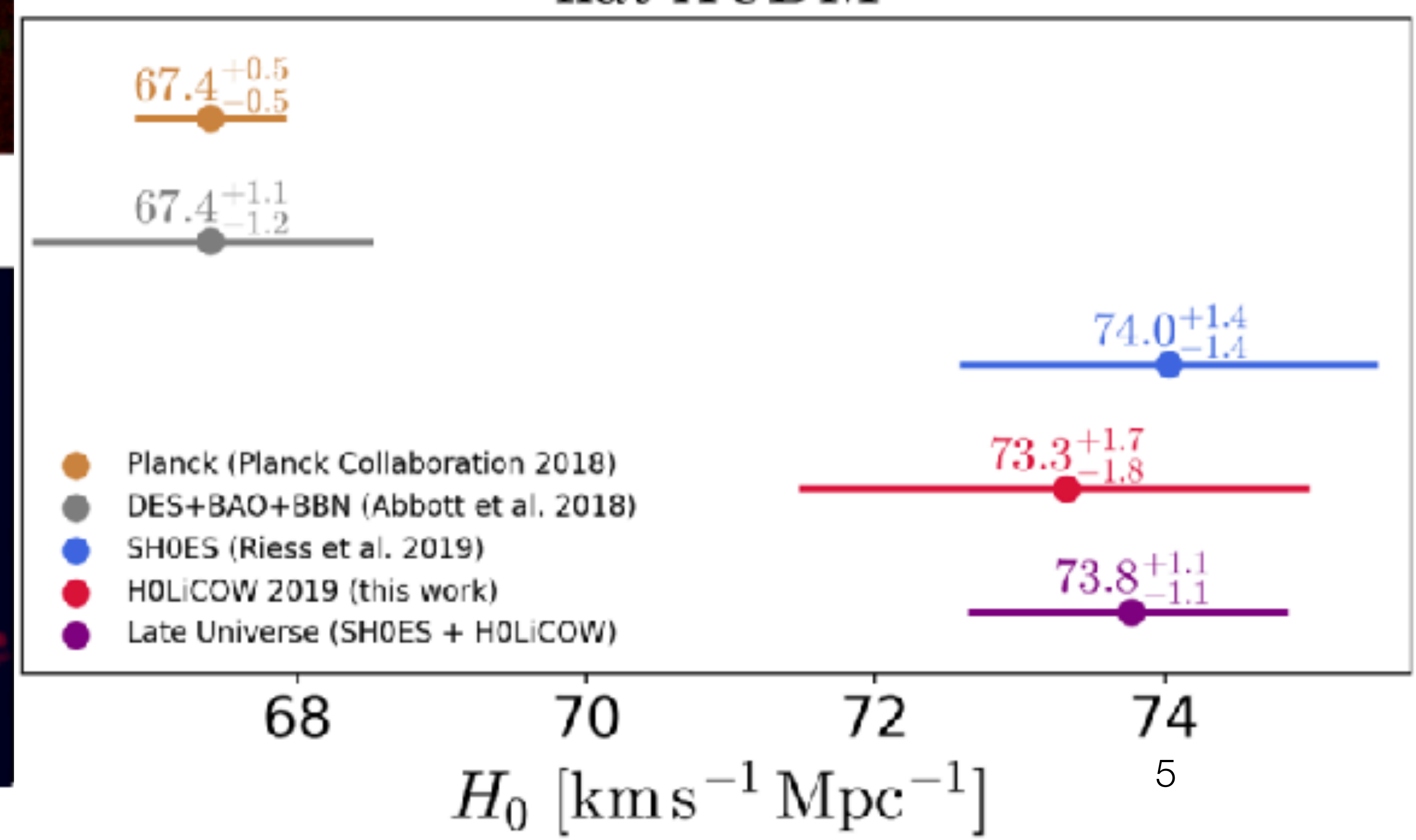
(e) WFI2033−4723



(f) PG 1115+080



flat ΛCDM



How do we explain this?

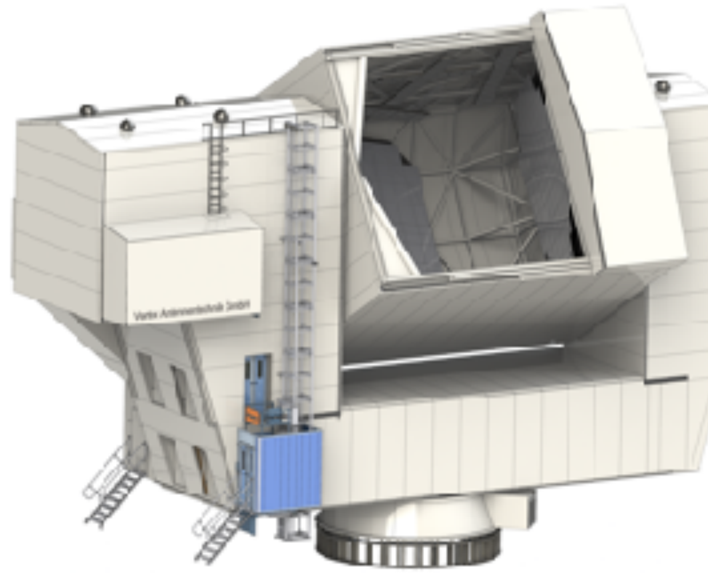
- Insomma, non so come…
- This is the "***Early Universe Probe vs Late Universe Probe***" tension
    - My approach is to "*ask the sky*". We keep cross-checking them with more data, until we find new explanation(s)
- In fact, it may not be just H_0…
    - The amplitude of matter density fluctuations in the late time Universe measured by the large-scale structure seems low compared to what we infer from CMB
    - Not yet too significant (~3σ), but it is persistent
- **More data on both early and late Universe probes are necessary**

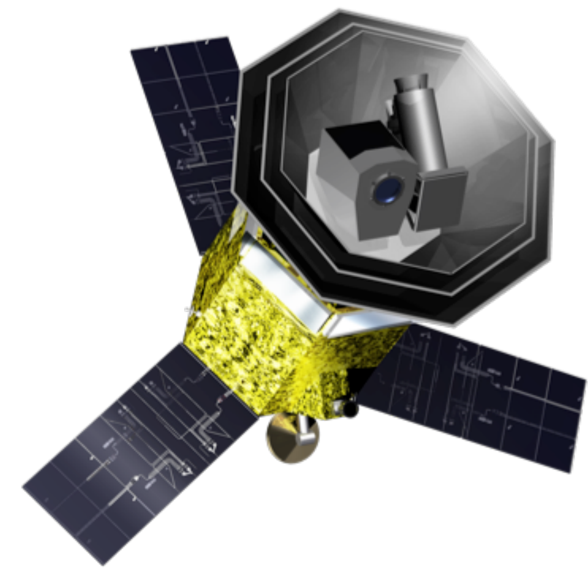
CCAT-prime
[2021–]

LiteBIRD
[JFY 2027–]

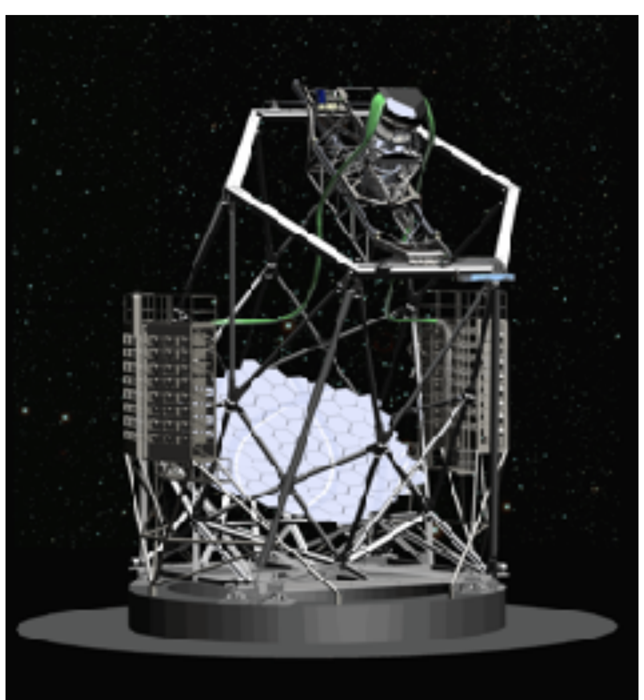
I talked about these 4 weeks ago

CMB:
Early Universe
Probe

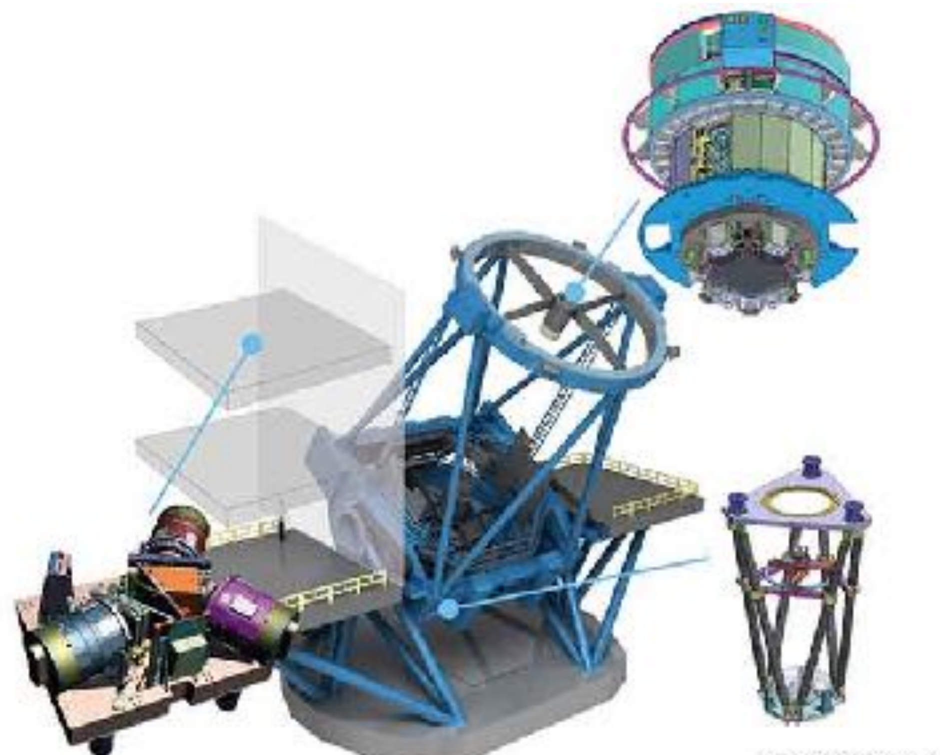




2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028



HETDEX
[2017–2023]



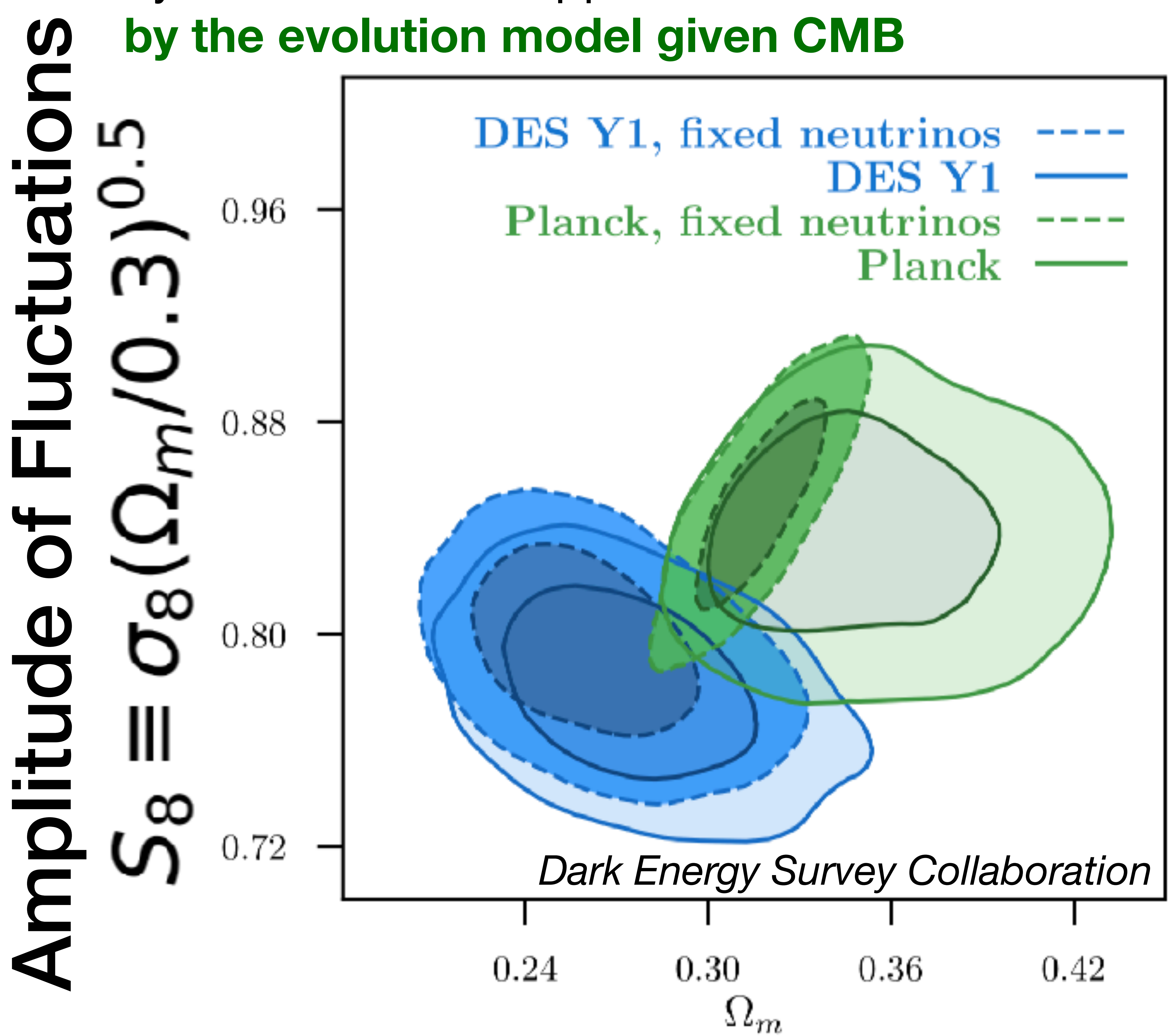
PFS
[2022–]

Today's topic

LSS:
Late Universe
Probe

Amplitude of Fluctuations

- The present-day amplitude of the matter fluctuation constrained by **the low-z data** appears to be smaller than the one **predicted by the evolution model given CMB**



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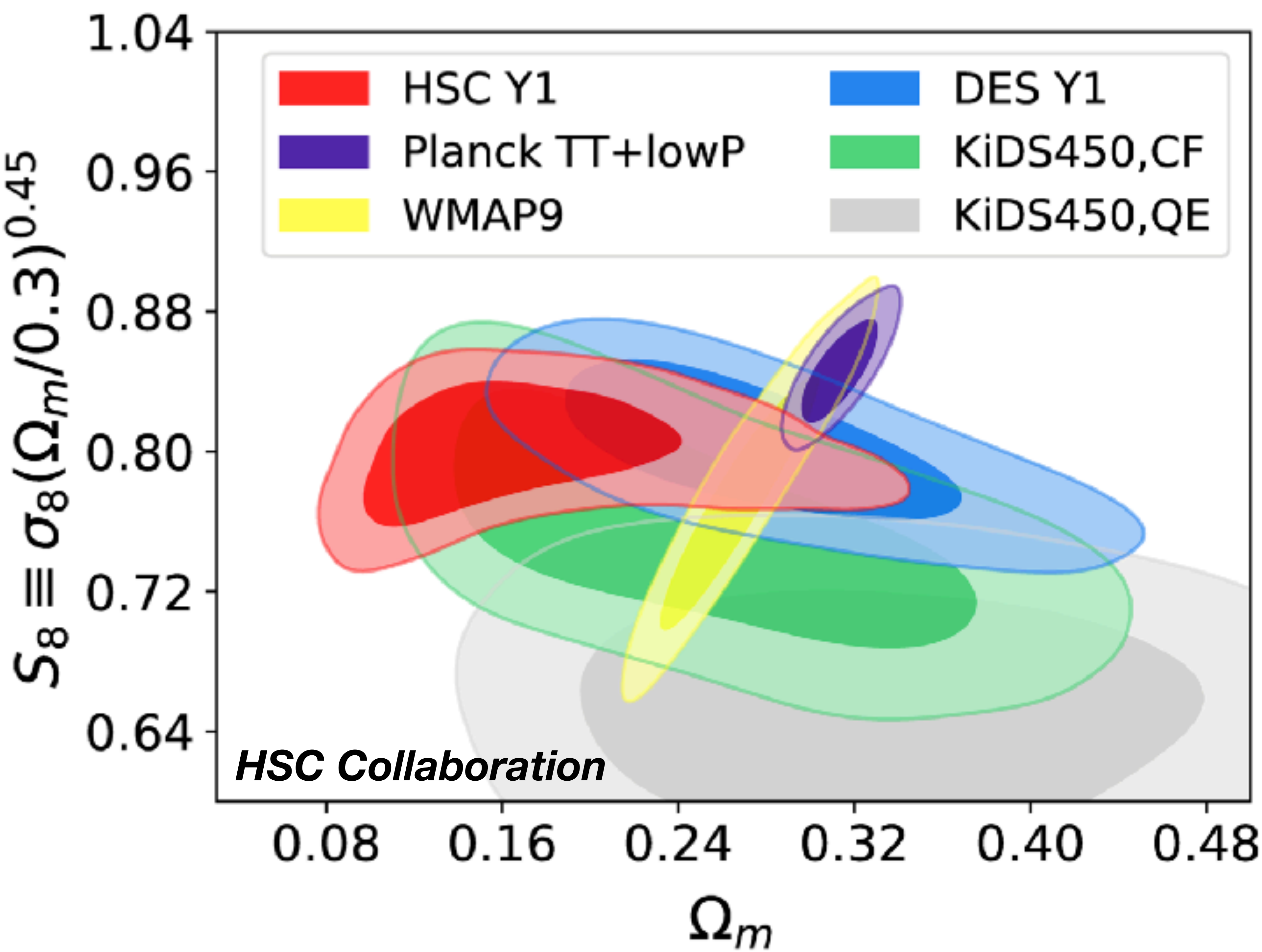
Amplitude of Fluctuations



Amplitude of Fluctuations

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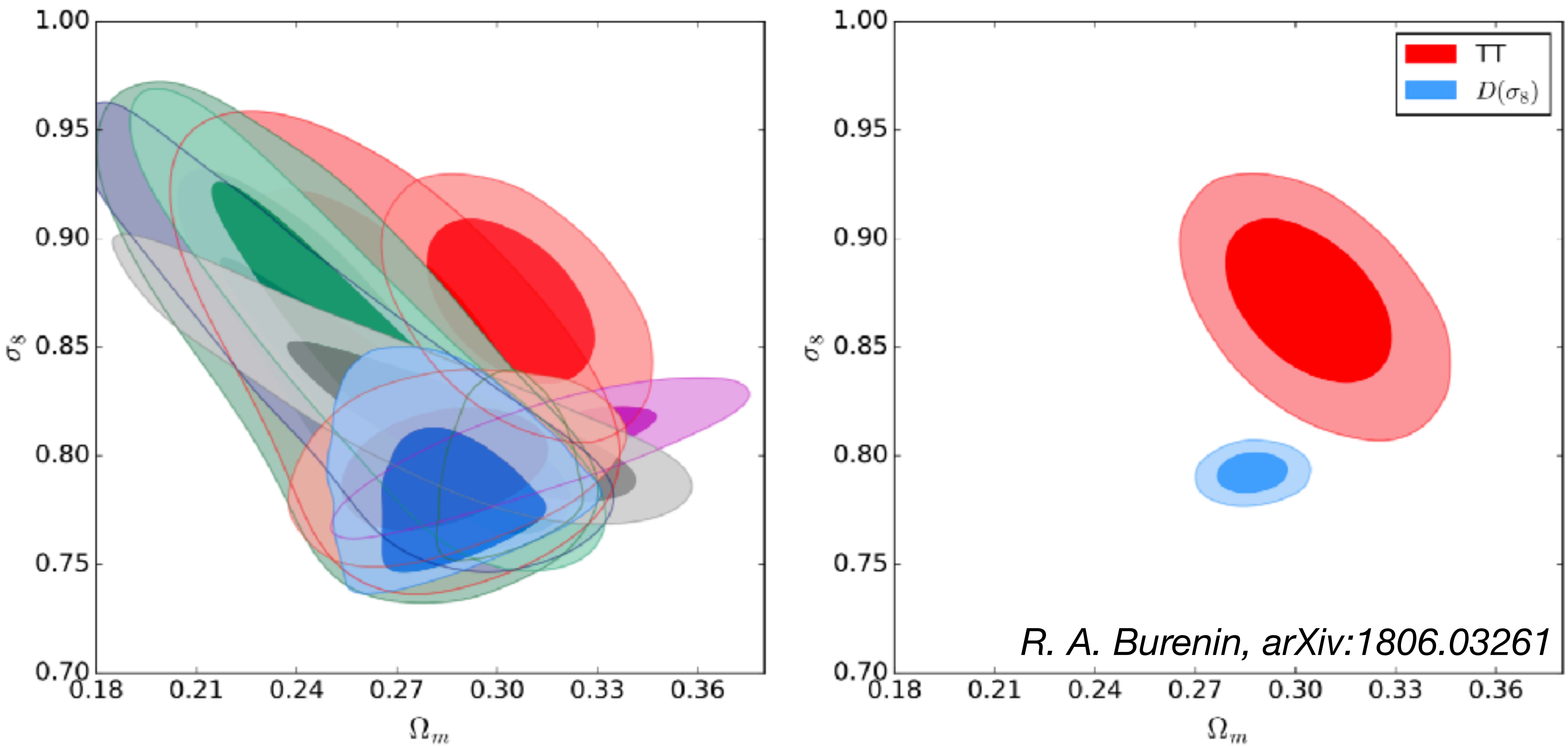


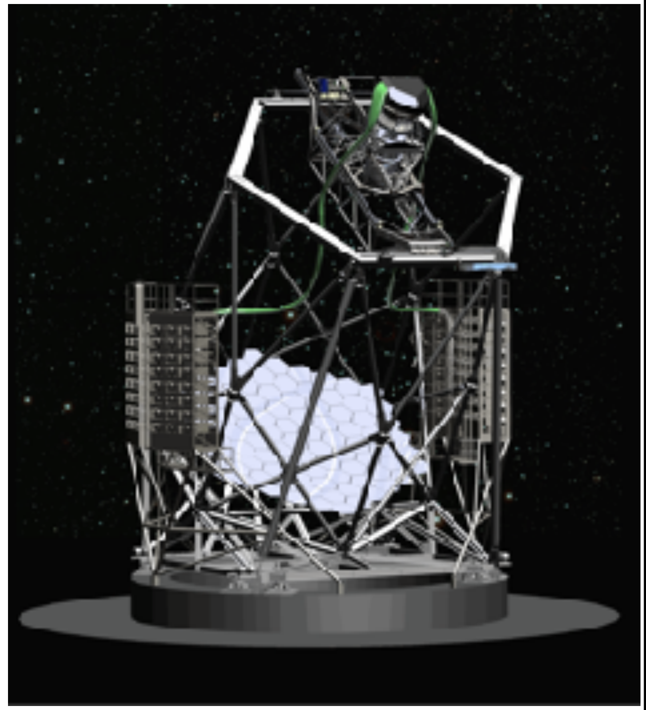
Two known low-z effects

- So, there is some evidence that the end-to-end test is failing. Namely:
  - The locally measured H_0 appears to be larger than that predicted by the CMB+
  - The locally measured amplitude of fluctuations appears to be lower than that predicted by the CMB+
- **Two effects that are known** to influence the low-z evolution:
  - **Neutrino mass**
  - **Dark energy/modified gravity**

} **Large-scale structure!**

HETDEX
Hobby-Eberly Telescope Dark Energy Experiment
Illuminating the Darkness

Hobby-Eberly Telescope Dark Energy Experiment



Location
McDonald Observatory (West Texas)

Primary Mirror Size
10 m

Wavelength Coverage
350–550 nm (Δλ=6.2Å)

Redshift (Lyα)
z=1.9–3.5

Spectrograph Type
Integral Field Unit (IFU)

# of fibers
34,944

Field of View
0.1 deg² (22’ diam.)
~20 Mpc in one go!

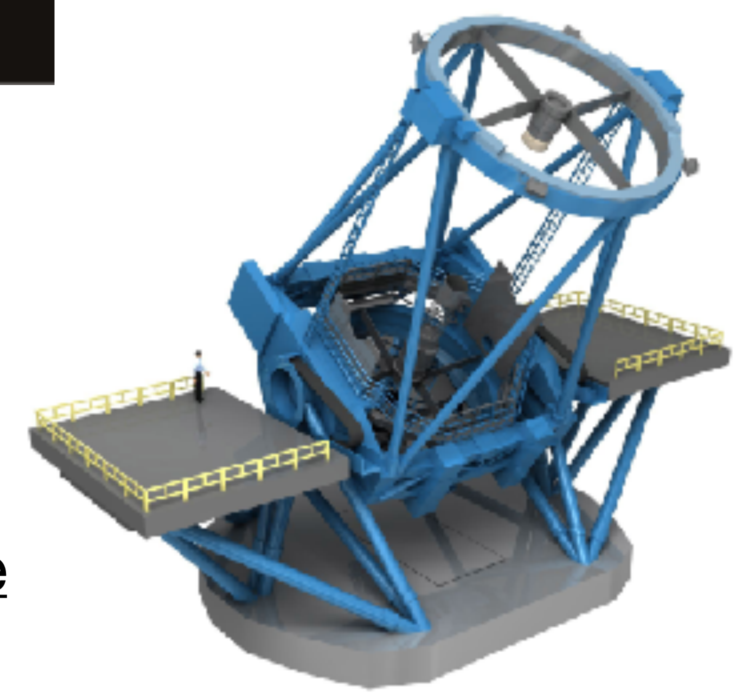
Fiber Diameter
1.5 arcsec

Survey Volume
2.8 (Gpc/h)³

Survey Type
Blind

Prime Focus Spectrograph
SuMIRe

PFS



Location
Subaru Telescope (Hawaii)

Primary Mirror Size
8.2 m

Wavelength Coverage	Redshift ([OII])
Blue: 380–650 nm (Δλ=2.1Å)	z=0.02–0.74
Red(LR): 630–970 nm (Δλ=2.7Å)	**z=0.69–1.60**
Red(HR): 710–885 nm (Δλ=1.6Å)	z=0.90–1.37
NIR: 940–1260 nm (Δλ=2.4Å)	**z=1.52–2.38**

Spectrograph Type
Robotic Multi Object Fiber-fed

# of fibers
2,394 + 96

Field of View
1.25 deg² (1.38 deg diam.)

Fiber Diameter
1.2 arcsec

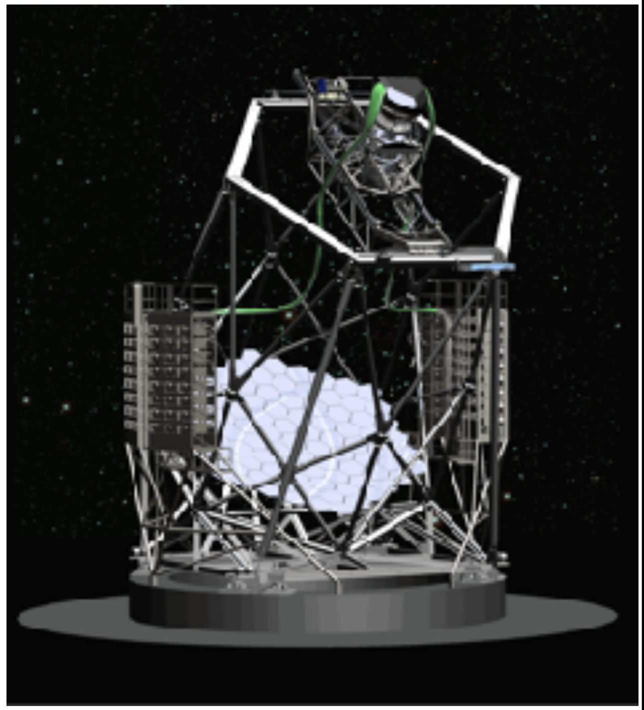
Survey Volume
8.2 (Gpc/h)³

Survey Type
Traditional

HETDEX Illuminating the Darkness
Hobby-Eberly Telescope Dark Energy Experiment

Hobby-Eberly Telescope Dark Energy Experiment

Texas-led
$42M experiment



The University of Texas at Austin
McDonald Observatory, The University of Texas at Austin
Penn State 1855
Institut für Astrophysik Göttingen
LMU USM
MPE
AIP
ATM
NSF
University of Oxford
Max-Planck-Institut für Astrophysik
東京大学 The University of Tokyo
Missouri S&T University of Science & Technology

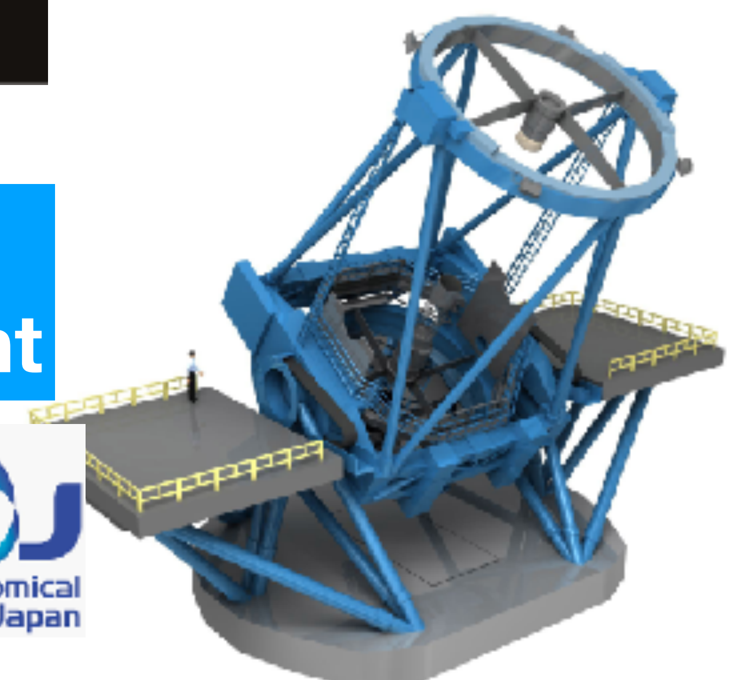
Main Objective:
Cosmology

But, we can do:
- Properties of Lyman-alpha emitting galaxies
- ***Blind survey:*** Unbiased survey of everything

Prime Focus Spectrograph
SuMIRe

PFS

Japan-led
$85M instrument



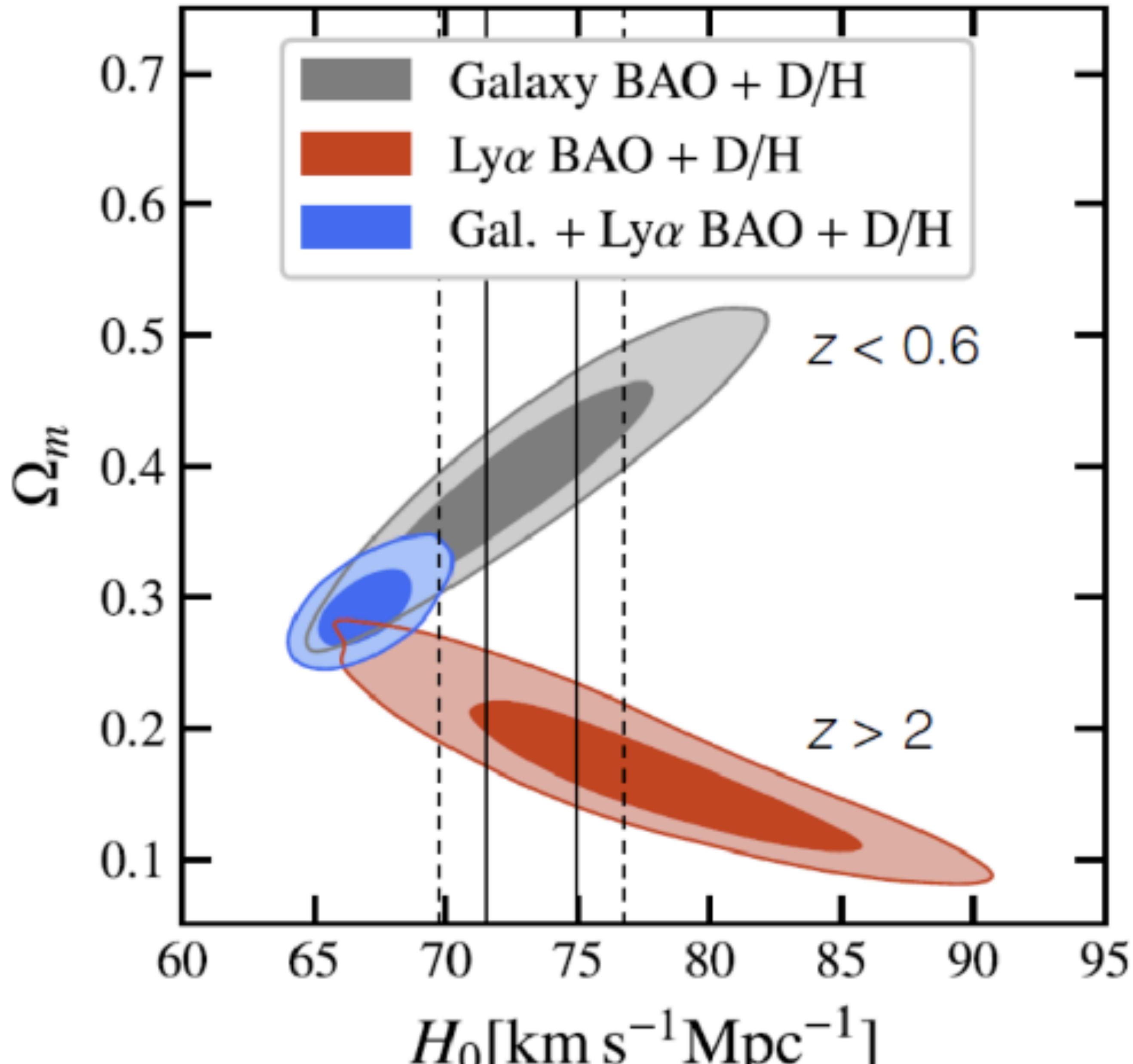
Kavli IPMU
国立天文台 NAOJ National Astronomical Observatory of Japan
JPL Jet Propulsion Laboratory, California Institute of Technology
California Institute of Technology
LAM Laboratoire d'Astrophysique de Marseille
LNA Laboratório Nacional de Astrofísica
Universidade de São Paulo
ASIAA
Max-Planck-Institut für Astrophysik
MPE
CPPC
NEPG

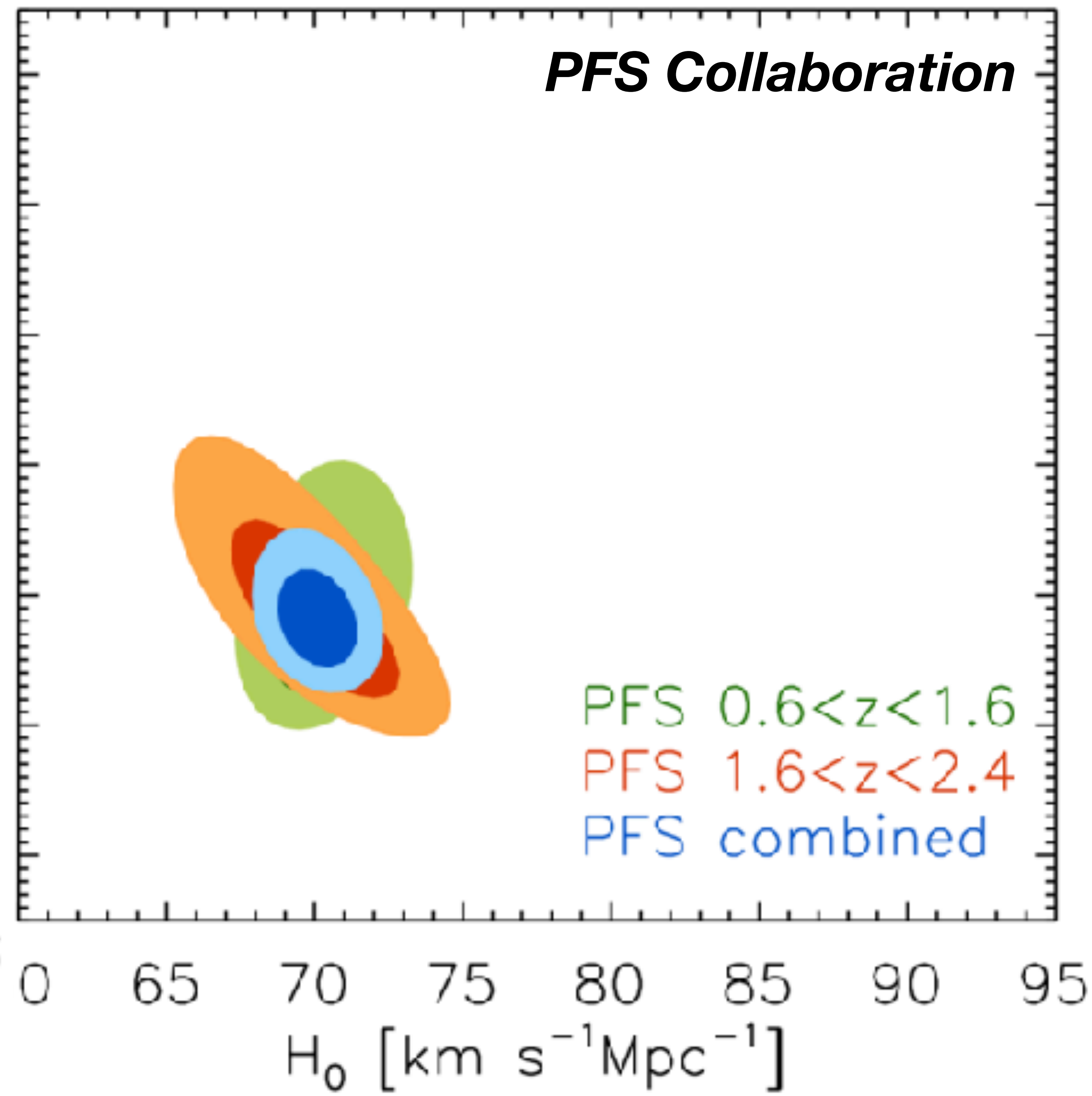
Main Objective:
Spectroscopic follow-up of targets detected by the imaging survey of Hyper Suprime Cam

Three major science programs:
- Cosmology
- Galaxy Evolution
- Galactic Archeology

Large Redshift Lever Arm: One Example

Addison et al. (2018)



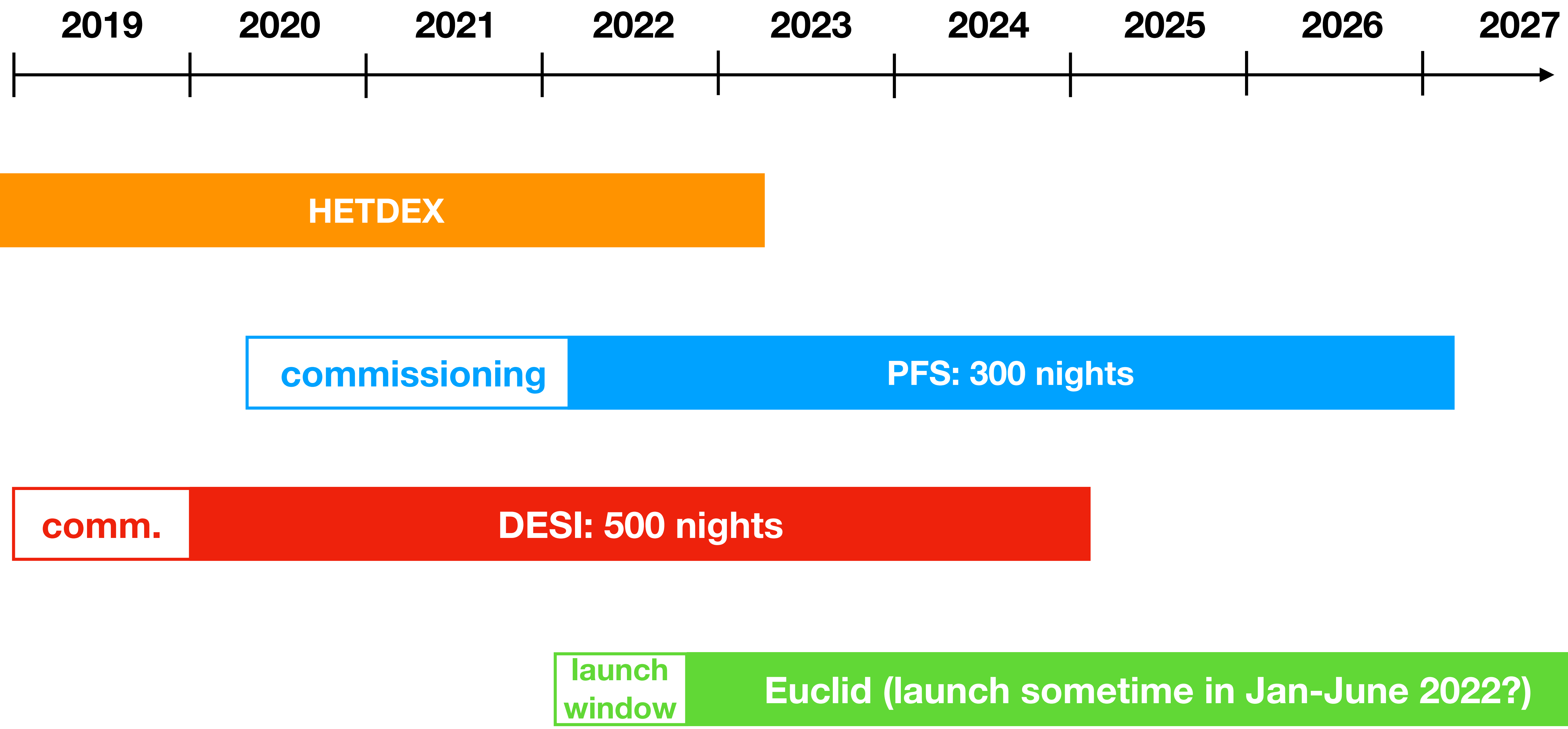


- We want **accurate** and **robust** cosmology! (not just precision)

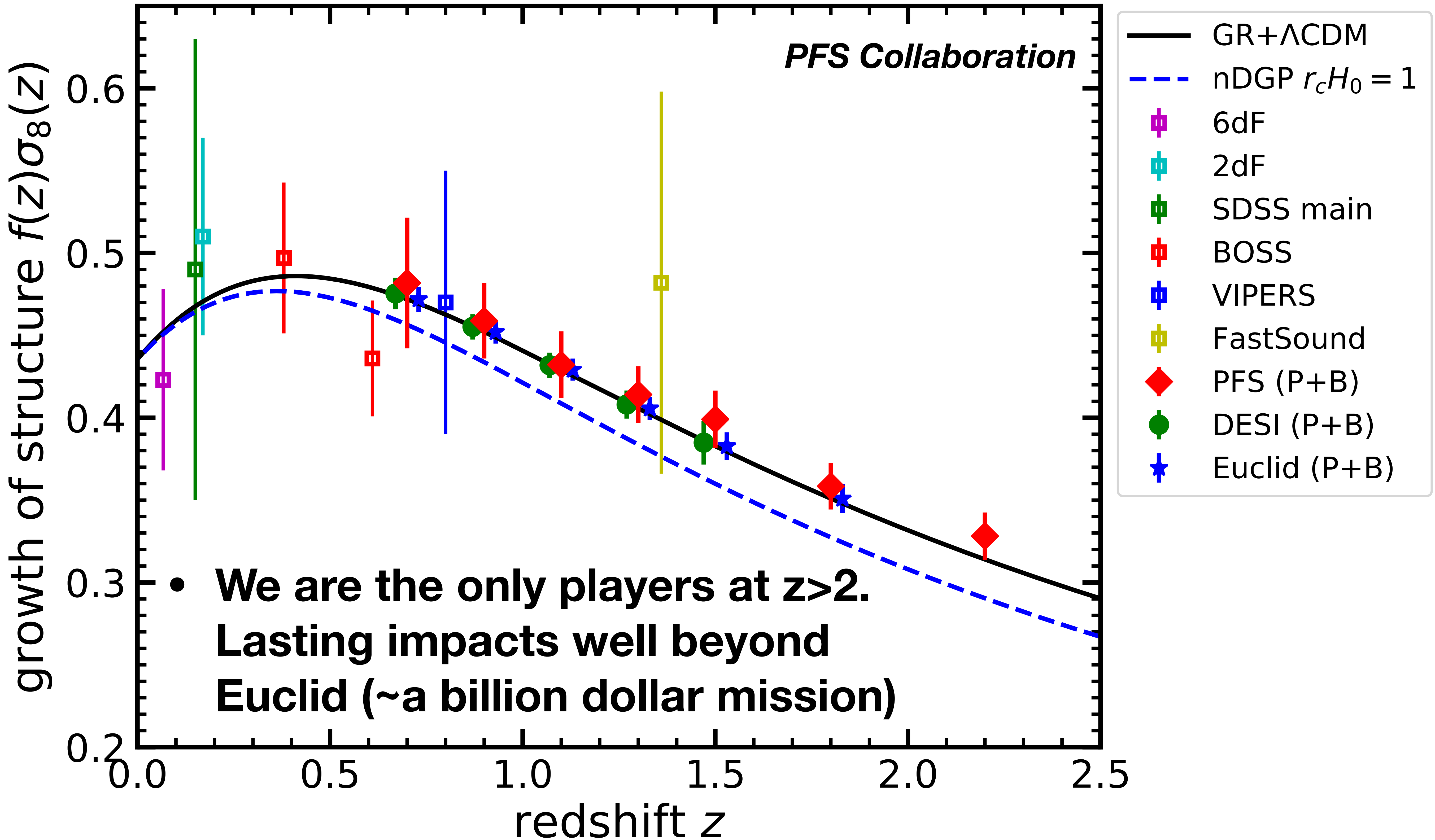
Science Cases (Cosmology)

- Not just testing tensions in H_0 and the amplitude of fluctuations!
- **To rule out the standard ΛCDM model** (or to put the tightest limits on deviations)
  - If ΛCDM, HETDEX can detect Λ at z>2 for the first time
- **To rule out the inverted hierarchy of the neutrino mass** (or to discover it)
- And, we do a lot of non-cosmological projects too!
  - **I would love to discuss other ideas with you today. These instruments are really amazing**

Experimental Landscape

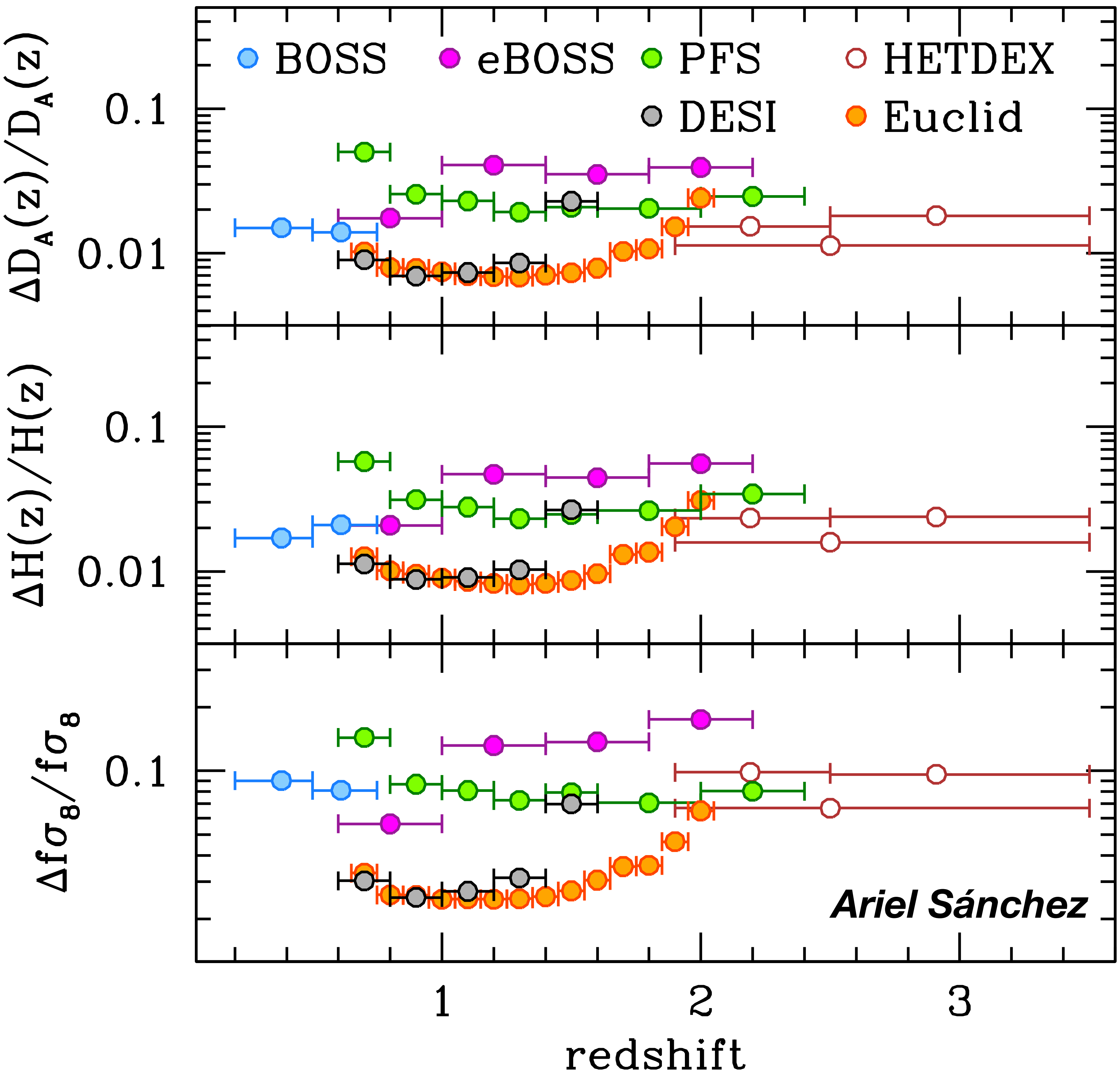


Experimental Landscape



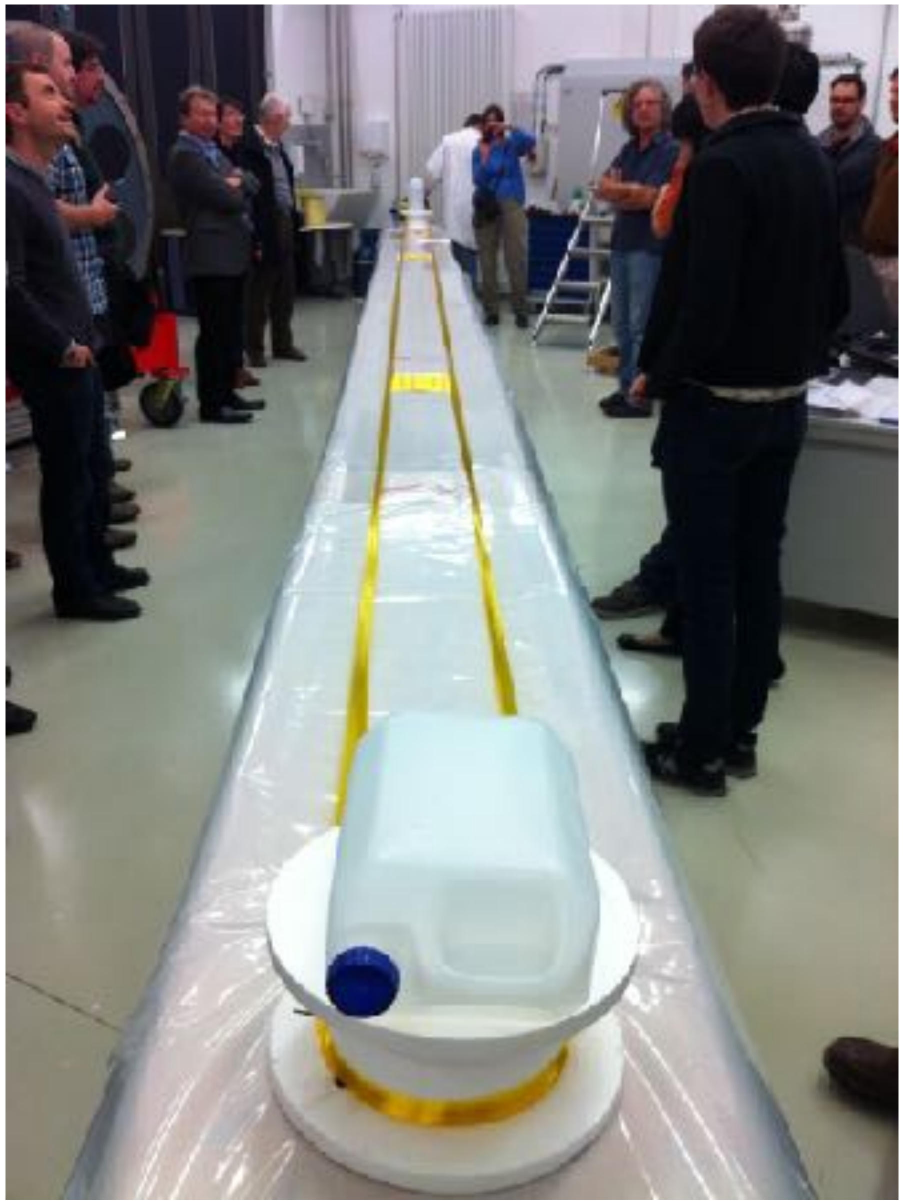
- **We are the only players at z>2. Lasting impacts well beyond Euclid (~a billion dollar mission)**

Experimental Landscape



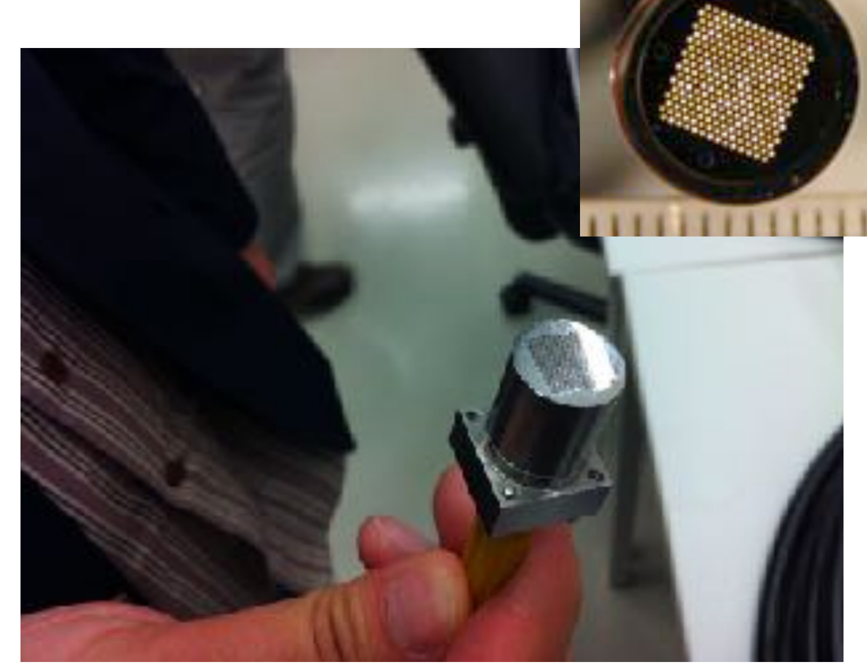
- **We are the only players at z>2**
- **Lasting impacts well beyond Euclid (~a billion dollar mission)**

IFUs fabricated at AIP

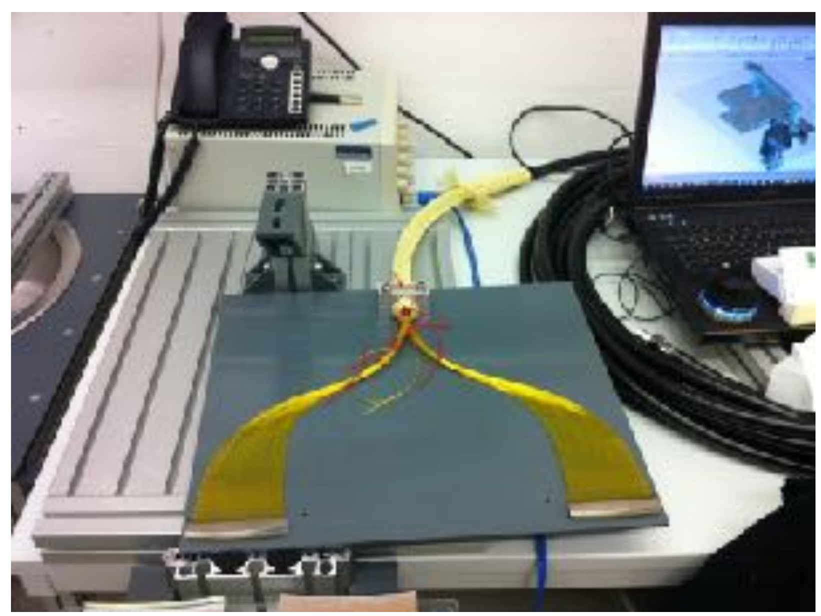


Long fibers!
(Each fiber sees 1.5")

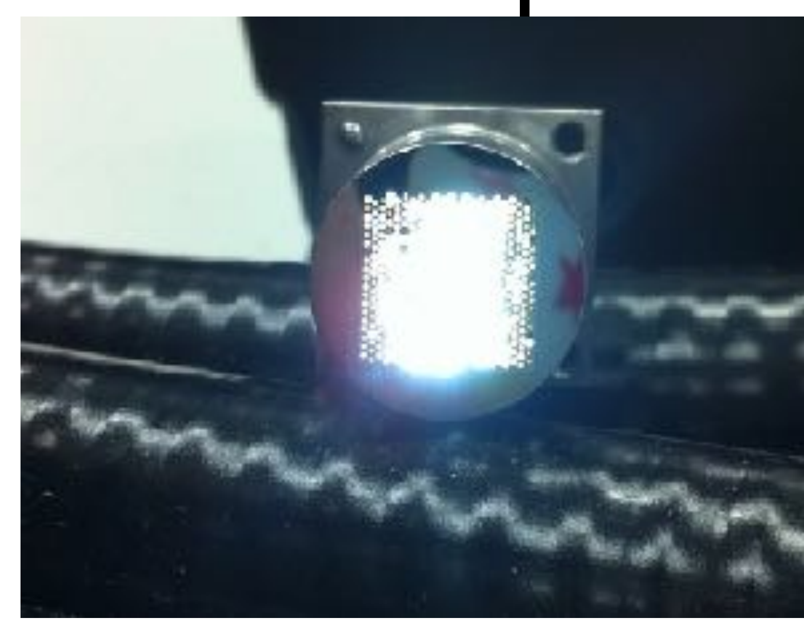
Put into cables...



448 fibers per IFU

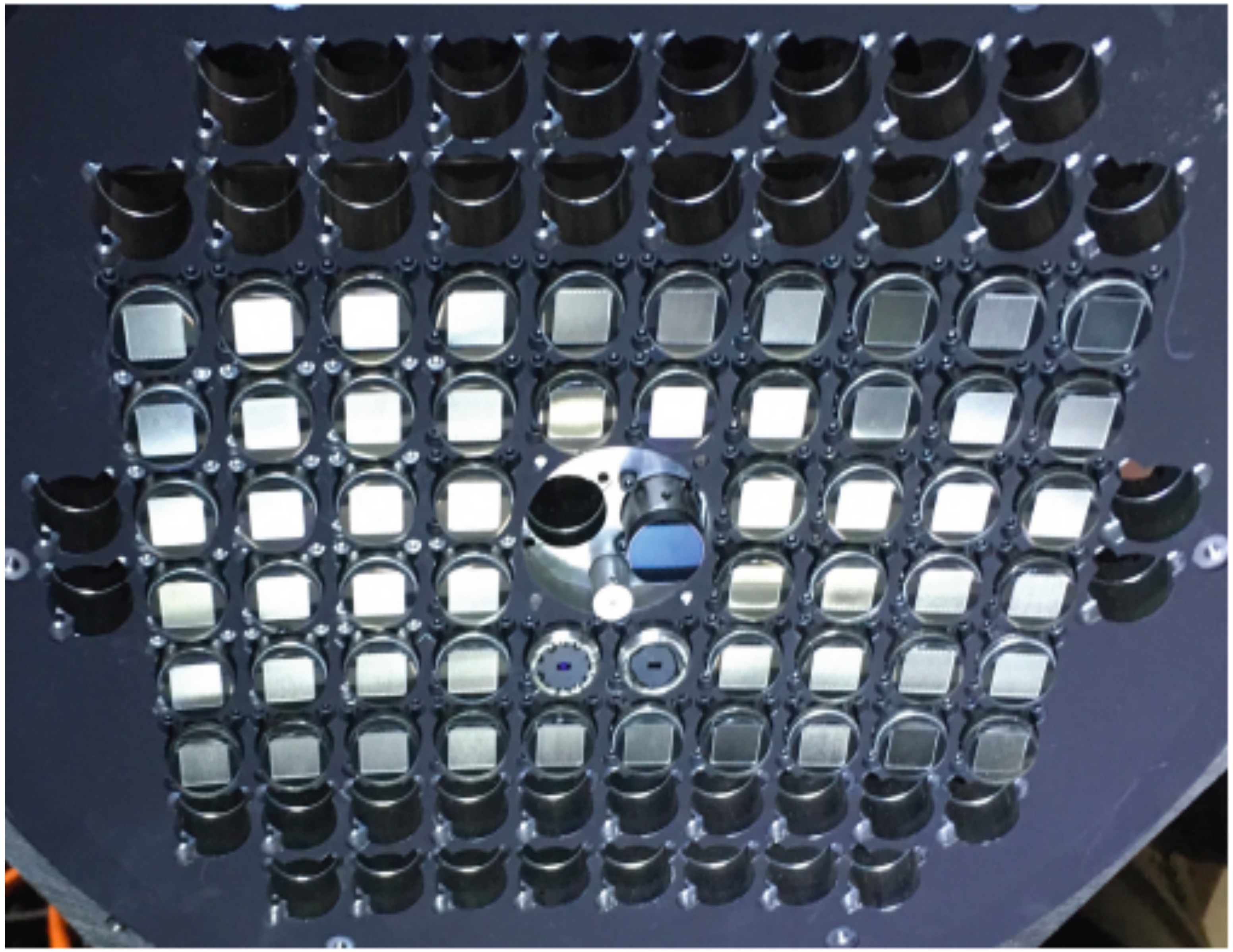


One IFU feeds two spectrographs



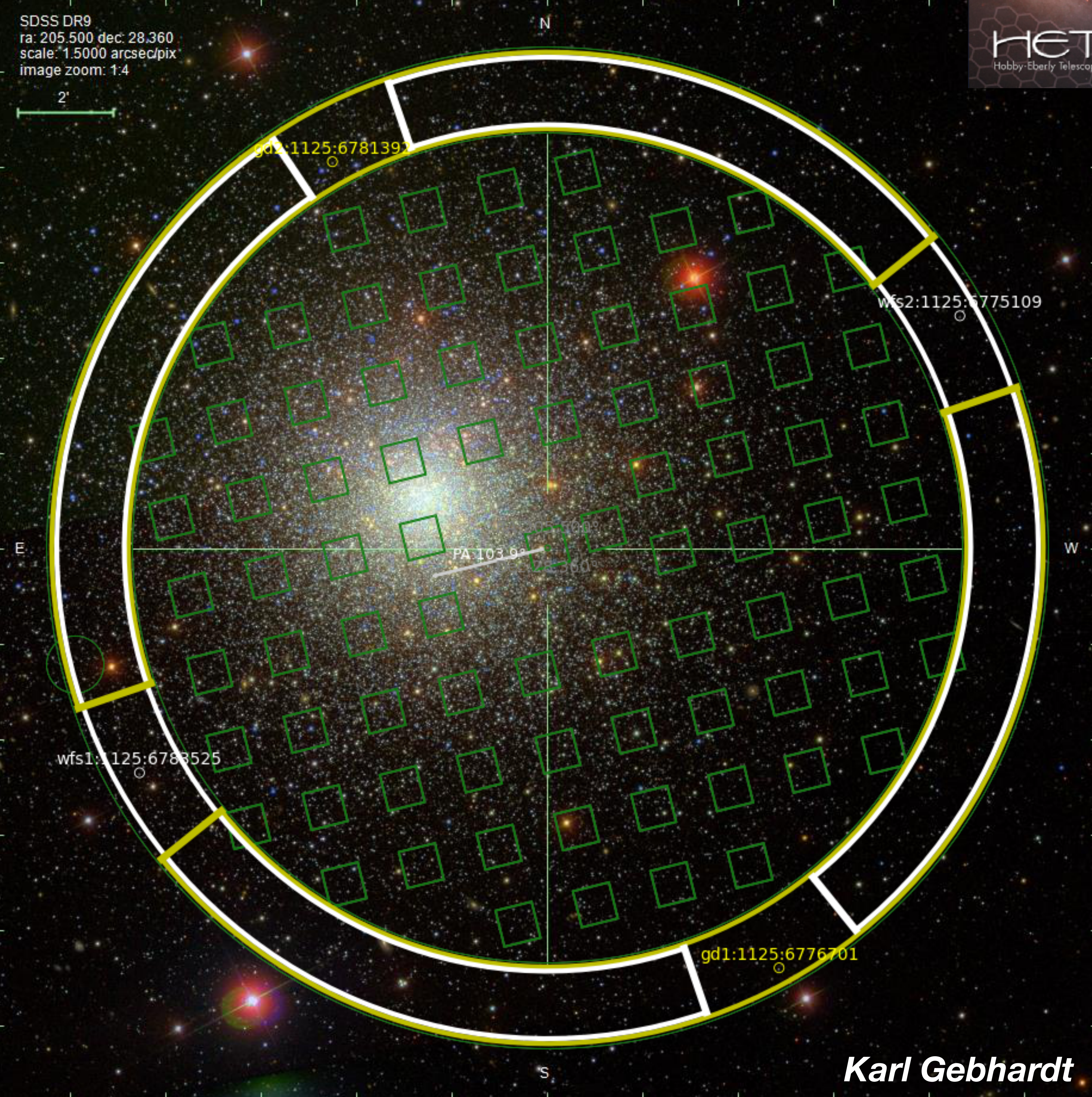
A test IFU being lit

Current VIRUS

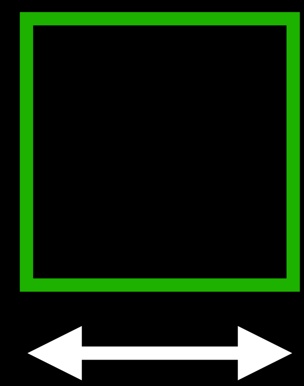


- 47 IFUs (out of 78) are active now. More IFUs will be installed as they are built (at the rate of 3 units per month)

- 47 x 448 = **21,056** fibers! And this is the open-use instrument



Example of full field on M3. Green boxes are the IFU locations.



~1 arcmin, completely filled by fibers (after 3 dither)

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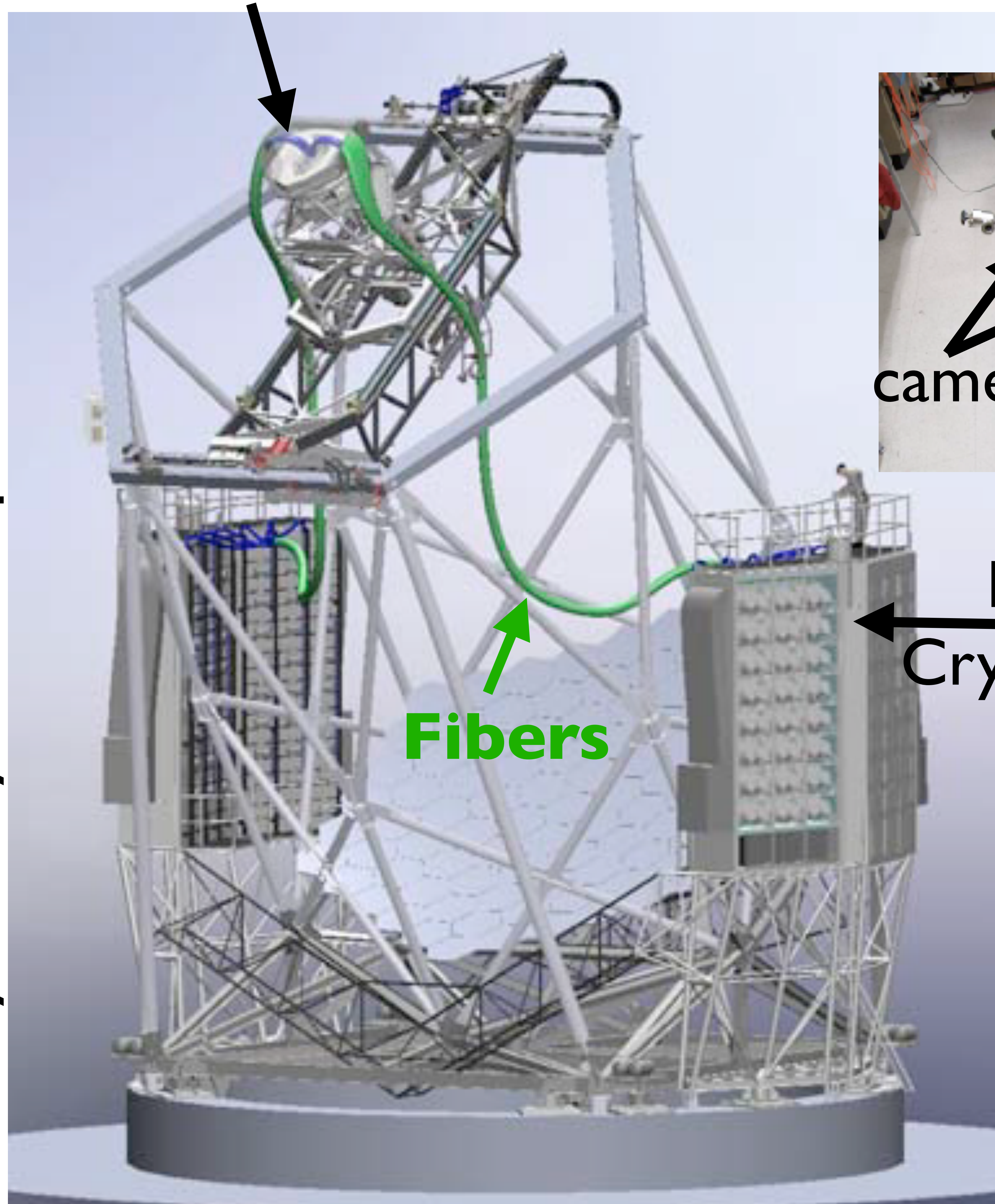
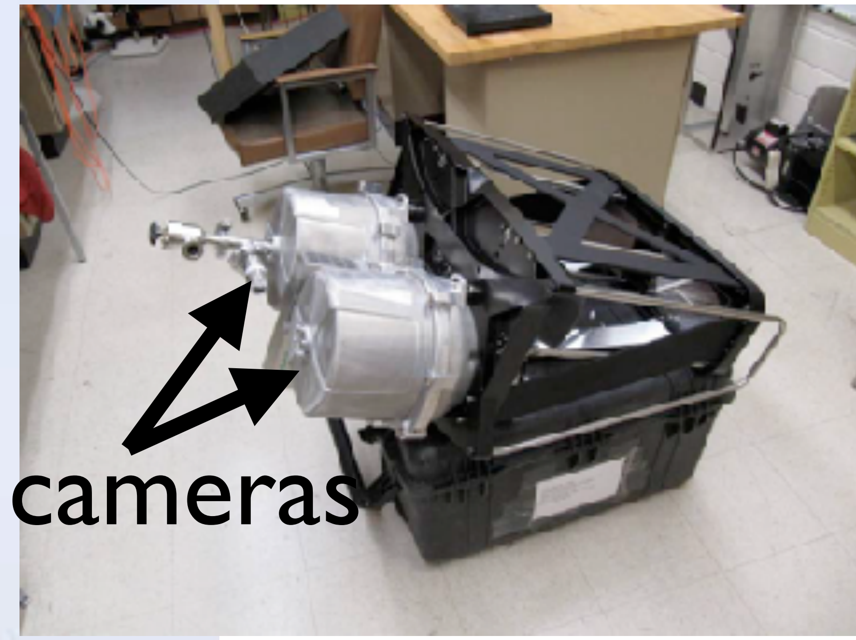
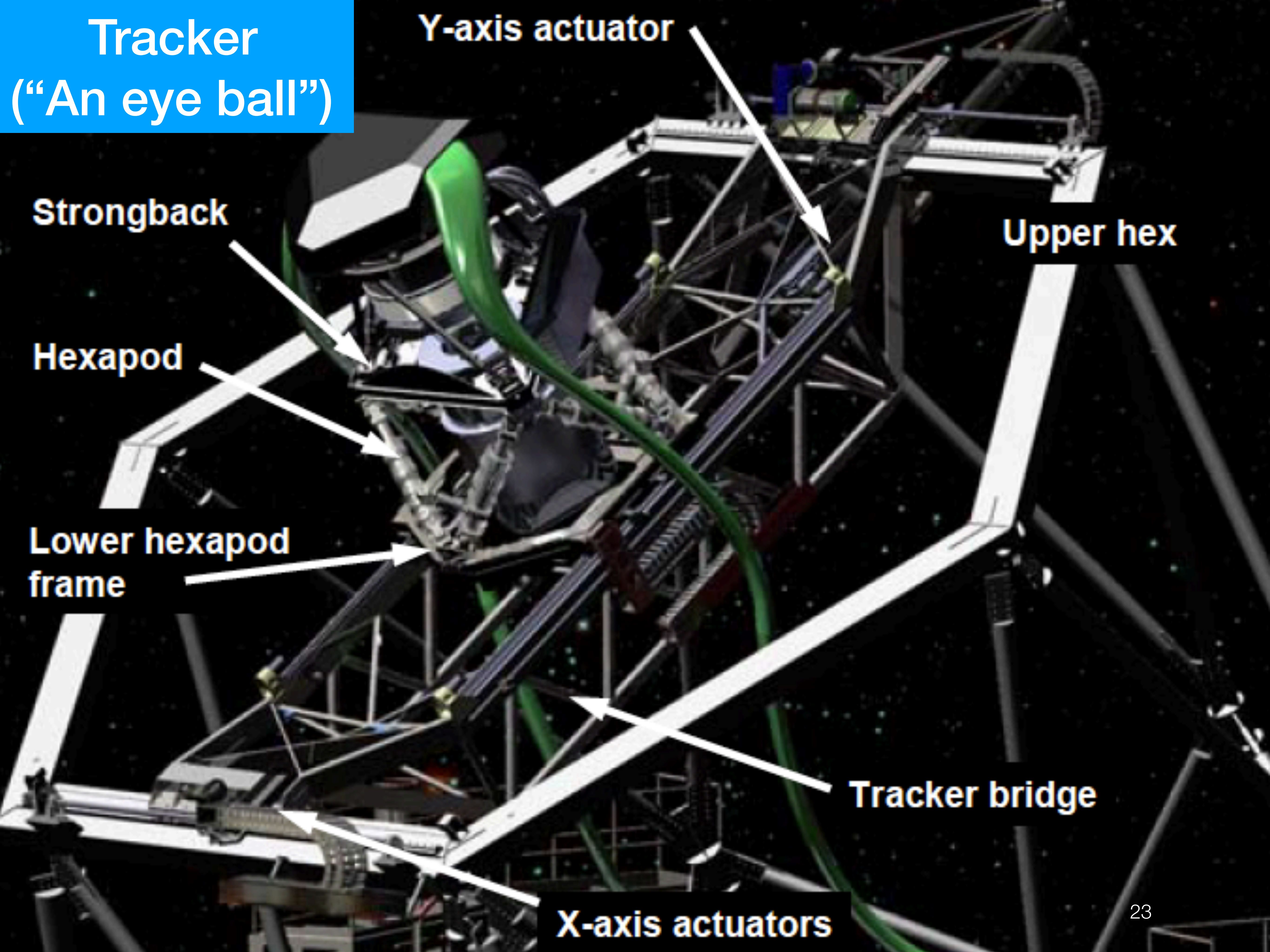
Hobby-Eberly Telescope with VIRUS





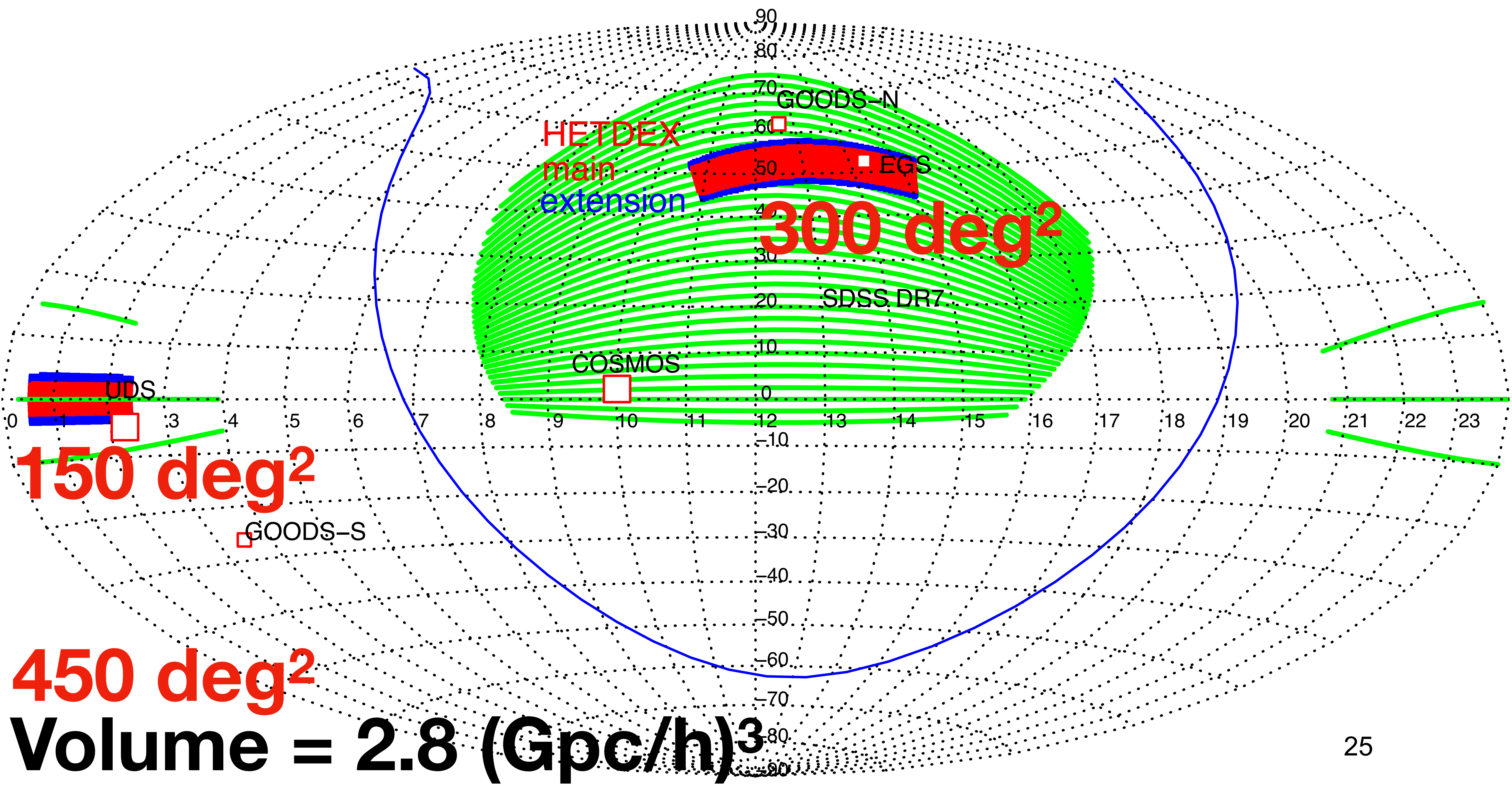
Tracker
("An eye ball")




This is the real one!

One exposure is 20 minutes

HETDEX Foot-print (in RA-DEC coordinates)

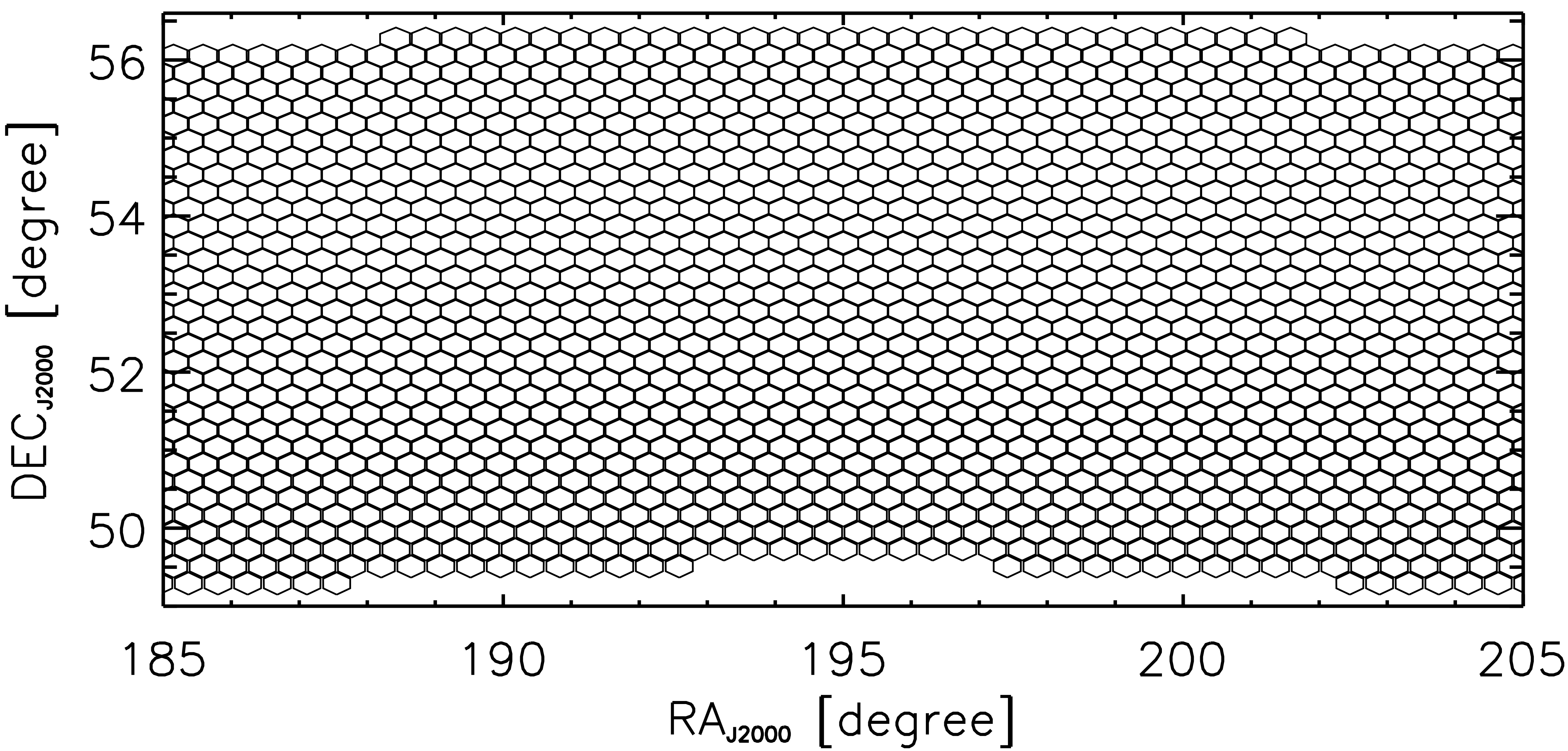


450 deg²

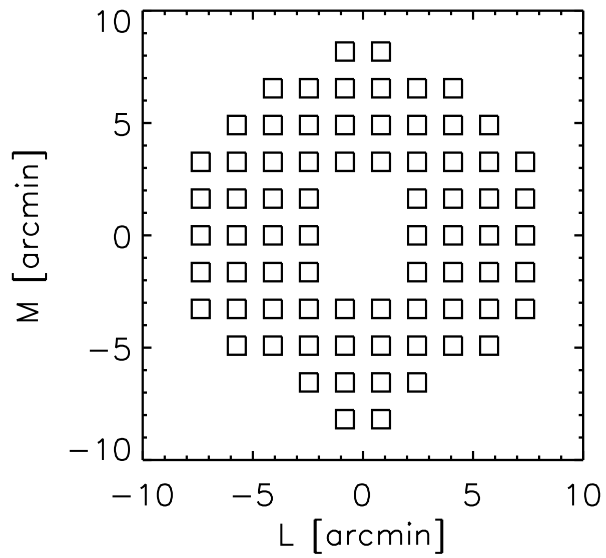
Volume = 2.8 (Gpc/h)³

Survey Strategy

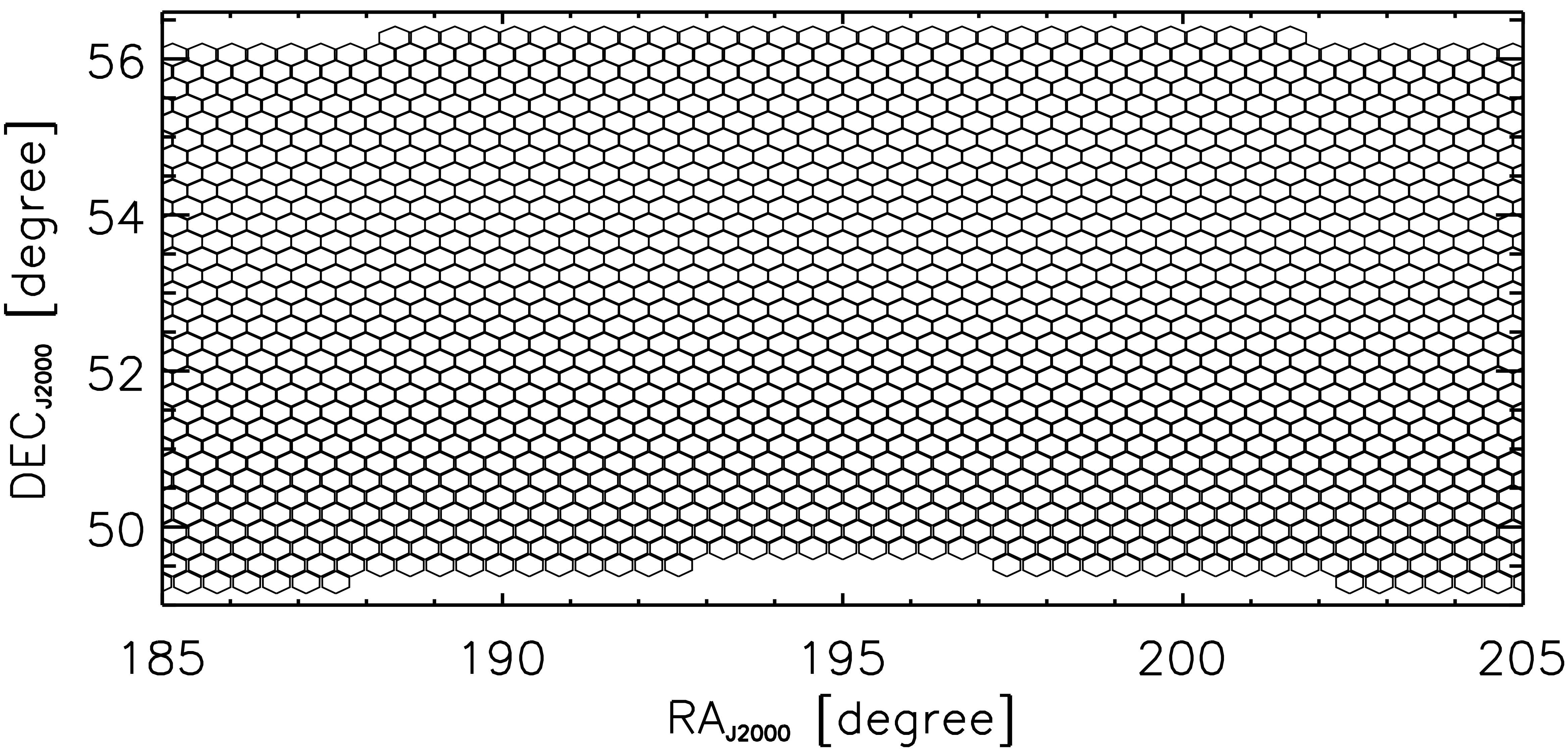
4000 shots in the northern region ("spring field")



Sparse sampling paper: Chiang et al. (2013)



- Each "shot" in the sky contains 78 IFUs
  - Spending 20 minutes per shot ~ 200 LAEs
- We do not completely fill the focal plane
  - This is the "**sparse sampling**" technique



What do we detect?

- λ=350–550nm with the resolving power of $R\sim700$ down to a flux sensitivity of a few x 10^{-17} erg/cm^2/s will give us:
  - ~1M Lyman-alpha emitting galaxies at $1.9<z<3.5$
    - 1/10 of them would be AGNs
  - ~1M [OII] emitting galaxies at $z<0.47$
  - ...and lots of other stuff, like white dwarfs, **blindly** selected/discovered

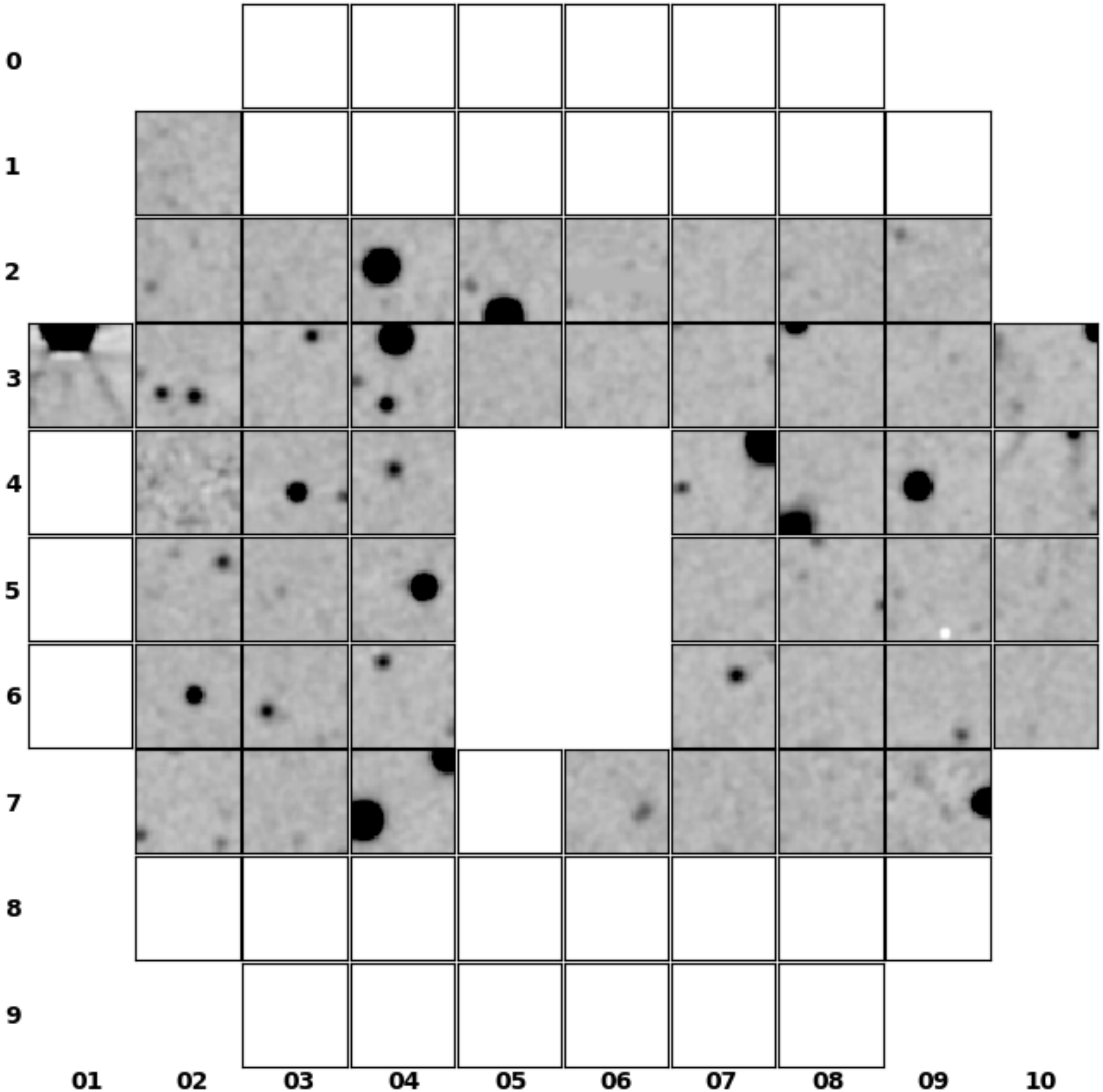
Current HETDEX Data

(~10% of the full survey data)

- *64 million* *calibrated spectra!*
    - 47,880 IFUs on the sky
    - 47,880 x 448 (# of fibers per IFU) x 3 (dither) = 64M
- And this is only 10% of the full survey data!
    - Goal: 468,000 IFUs on the sky
    - ***629M*** ***calibrated spectra*****. This is the big data!**

Karl Gebhardt

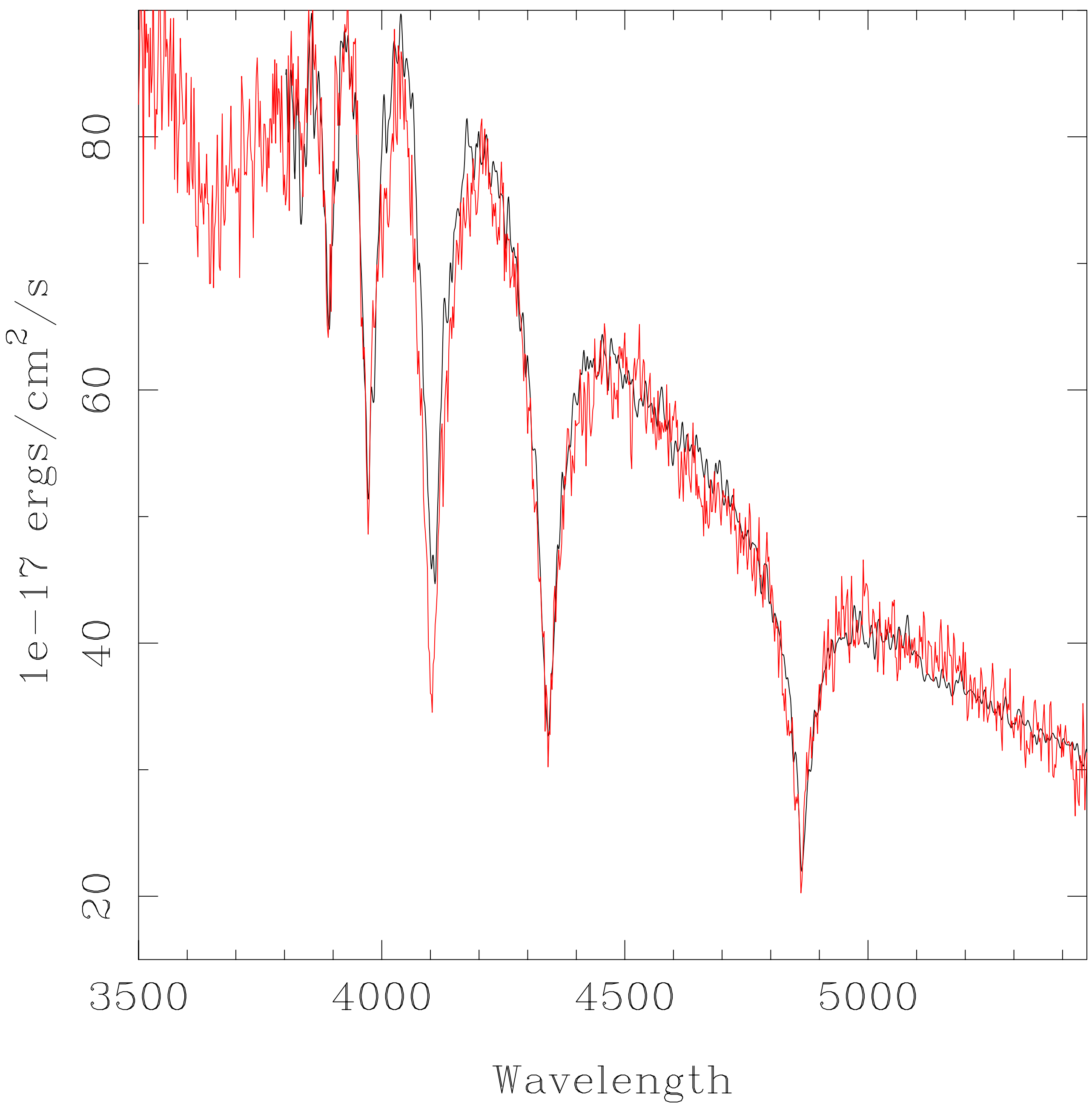
A typical hetdex field

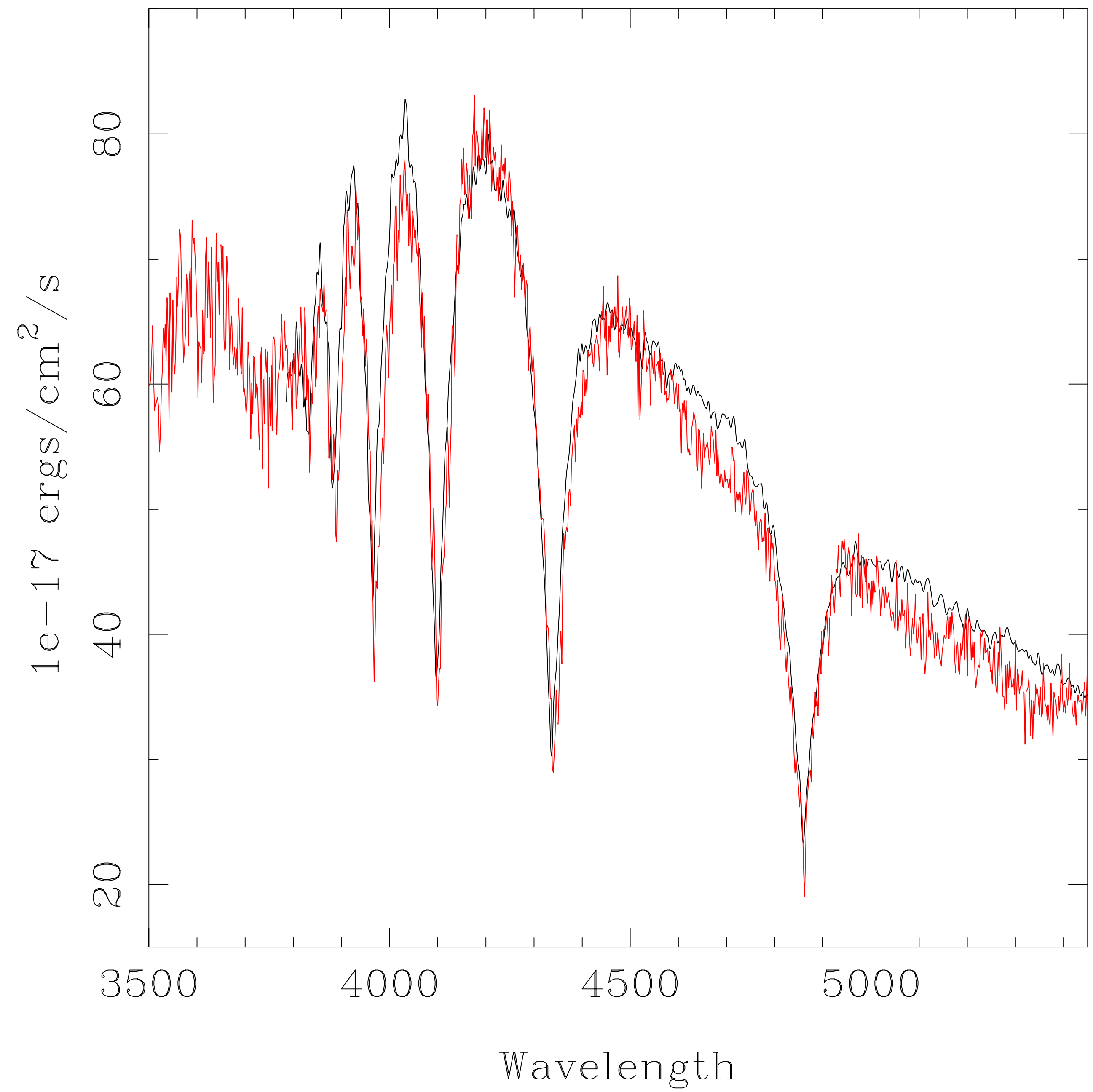


Reconstructed image of the 21k fibers. Filled squares are active IFUs, open squares are those remaining.

In this frame, we would use about 15 of the stars for astrometry and throughput measures.

Example calibration check, using 2 white dwarfs from SDSS (virus in red, SDSS in black)





HETDEX Hobby-Eberly Telescope Dark Energy Experiment Illuminating the Darkness

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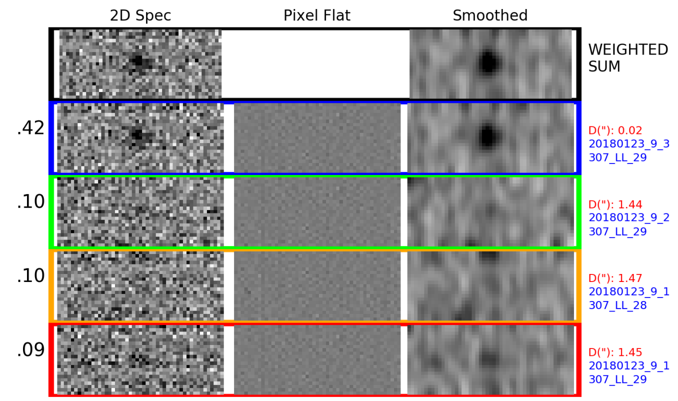
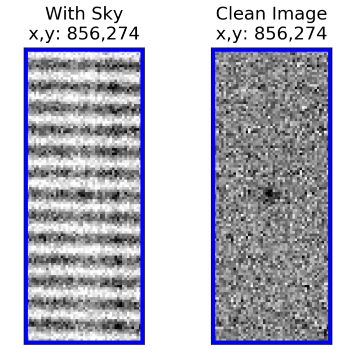
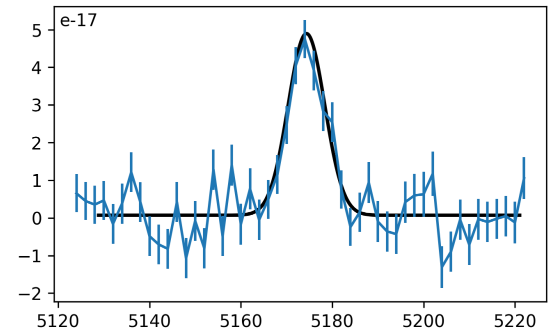
Examples from one field

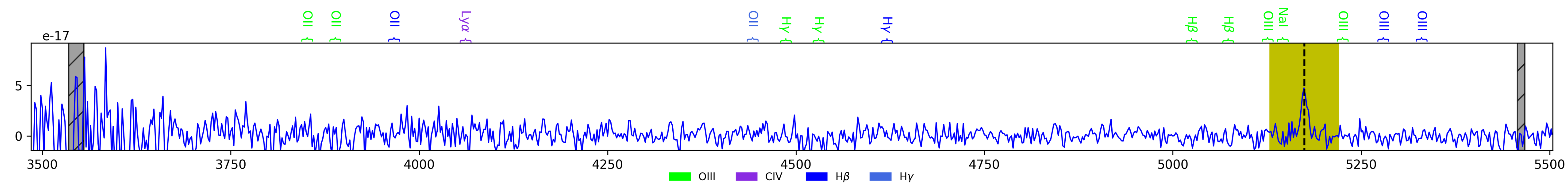
2018-10-23 13:09:51 Version 1.5.0a4

```
20180123v009_1269.pdf
Obs: 20180123v09_1
Entry# (1269), Detect ID (1)
Primary IFU Slot 074
RA,Dec (150.038250,2.127700)
λ = 5174.44Å  FWHM = 9.447Å
EstFlux = 4.58e-16
EstCont = 5e-19
EW_r(LyA) = 215Å
S/N = 20.82
P(LAE)/P(OII) = 999
LyA z = 3.2553  OII z = 0.3884
```

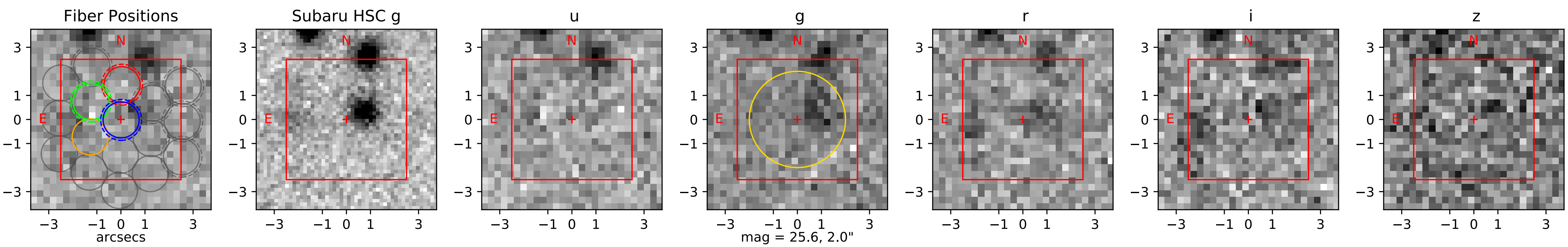




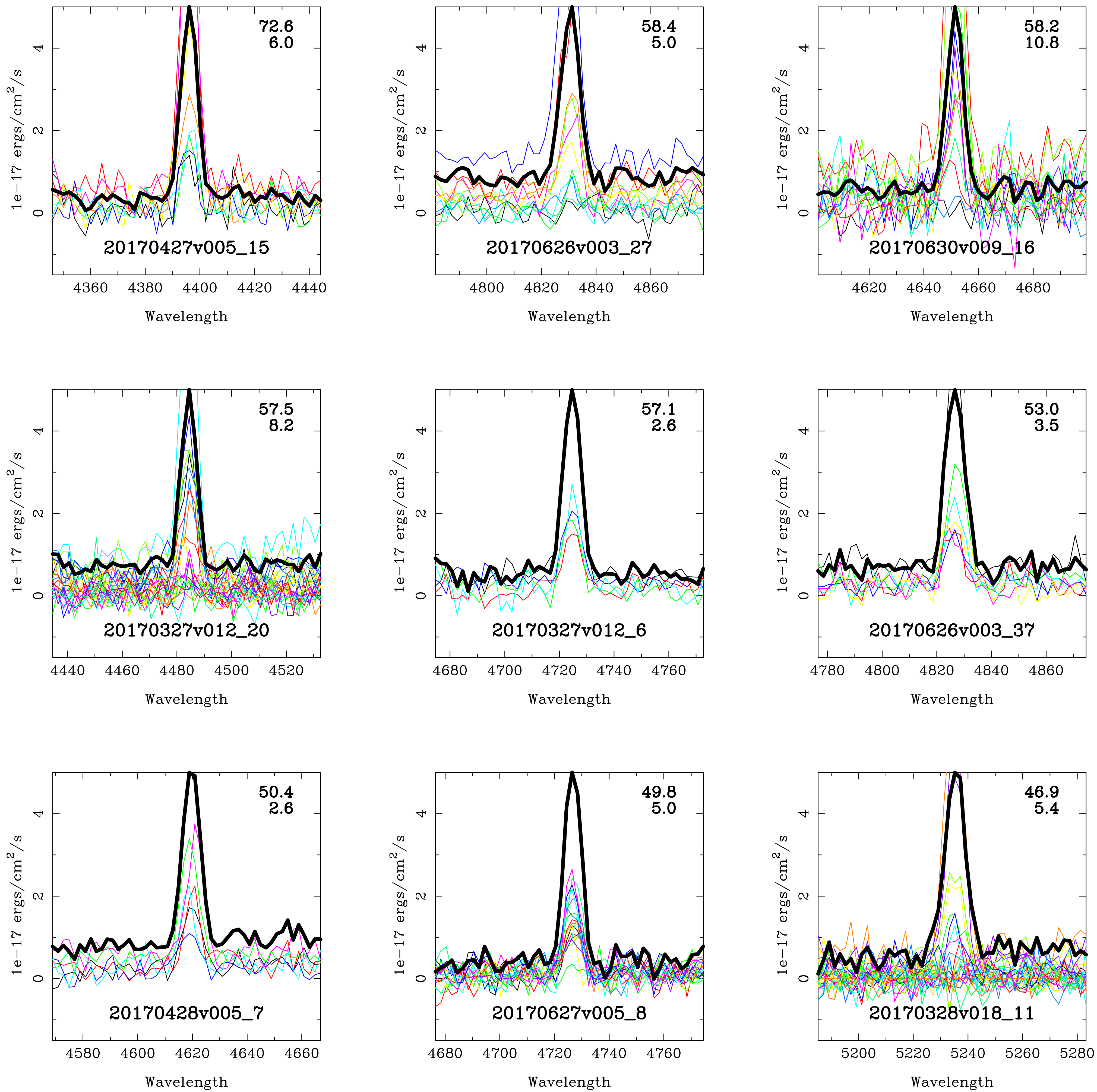


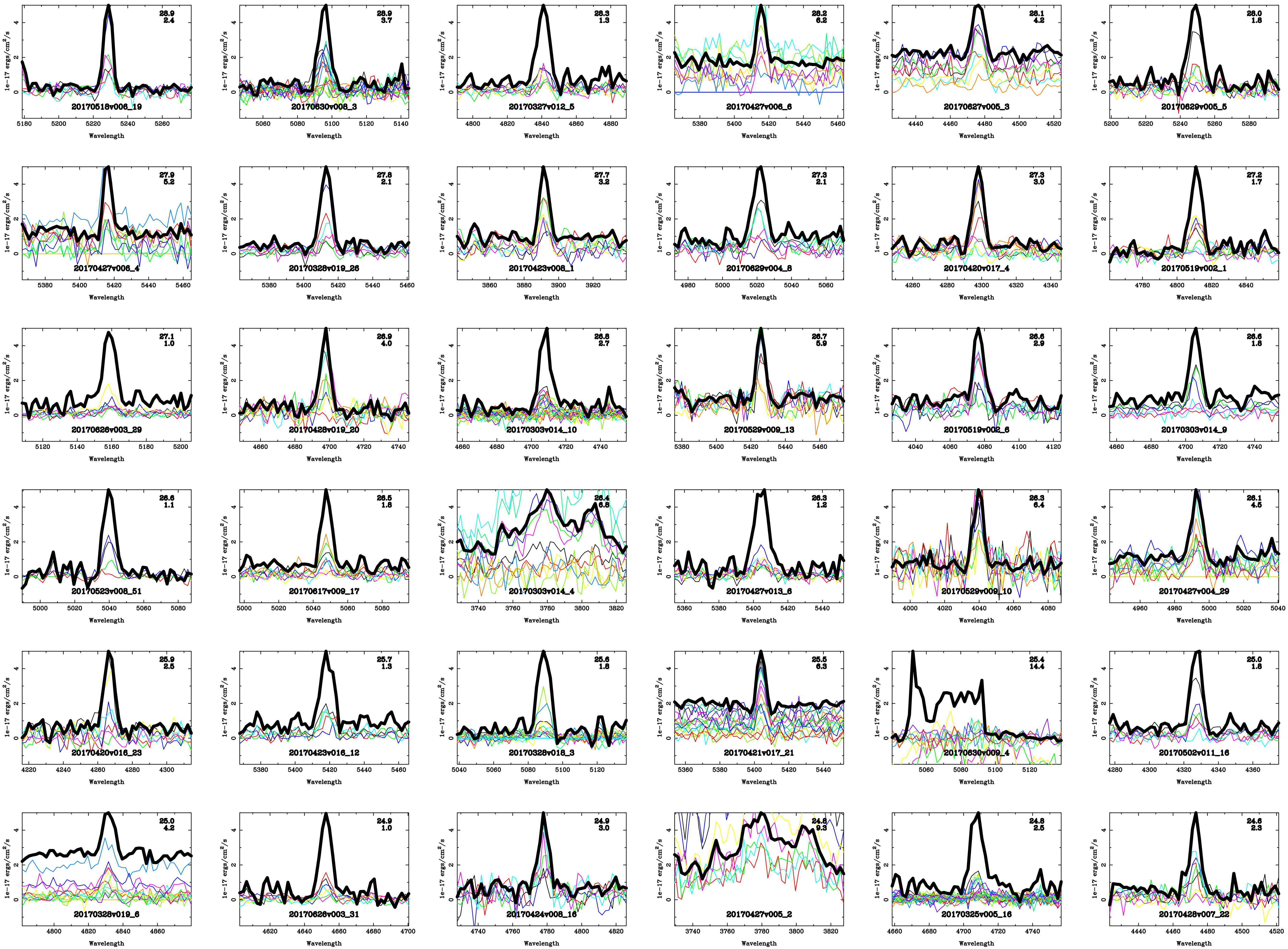


STACK_COSMOS : Possible Matches = 0 (within +/- 2.5") No continuum floor baseline defined.



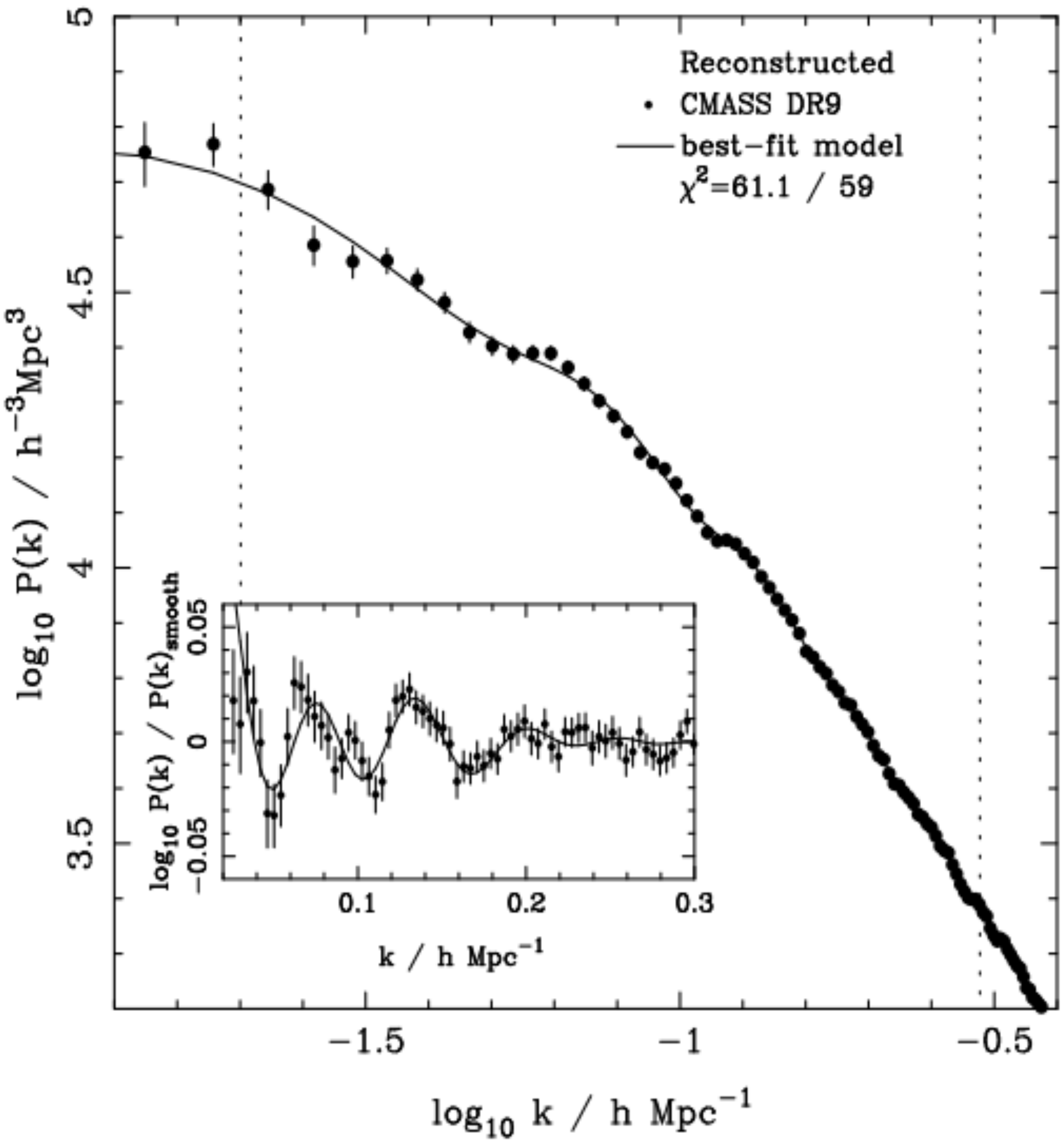
No matching targets in catalog.
Row intentionally blank.


72.6
6.0
20170427v005_15
1e−17 ergs/cm^2/s
Wavelength
4360 4380 4400 4420 4440
58.4
5.0
20170626v003_27
1e−17 ergs/cm^2/s
Wavelength
4800 4820 4840 4860
58.2
10.8
20170630v009_16
1e−17 ergs/cm^2/s
Wavelength
4620 4640 4660 4680
57.5
8.2
20170327v012_20
1e−17 ergs/cm^2/s
Wavelength
4440 4460 4480 4500 4520
57.1
2.6
20170327v012_6
1e−17 ergs/cm^2/s
Wavelength
4680 4700 4720 4740 4760
53.0
3.5
20170626v003_37
1e−17 ergs/cm^2/s
Wavelength
4780 4800 4820 4840 4860
50.4
2.6
20170428v005_7
1e−17 ergs/cm^2/s
Wavelength
4580 4600 4620 4640 4660
49.8
5.0
20170627v005_8
1e−17 ergs/cm^2/s
Wavelength
4680 4700 4720 4740 4760
46.9
5.4
20170328v018_11
1e−17 ergs/cm^2/s
Wavelength
5200 5220 5240 5260 5280
0 2 4



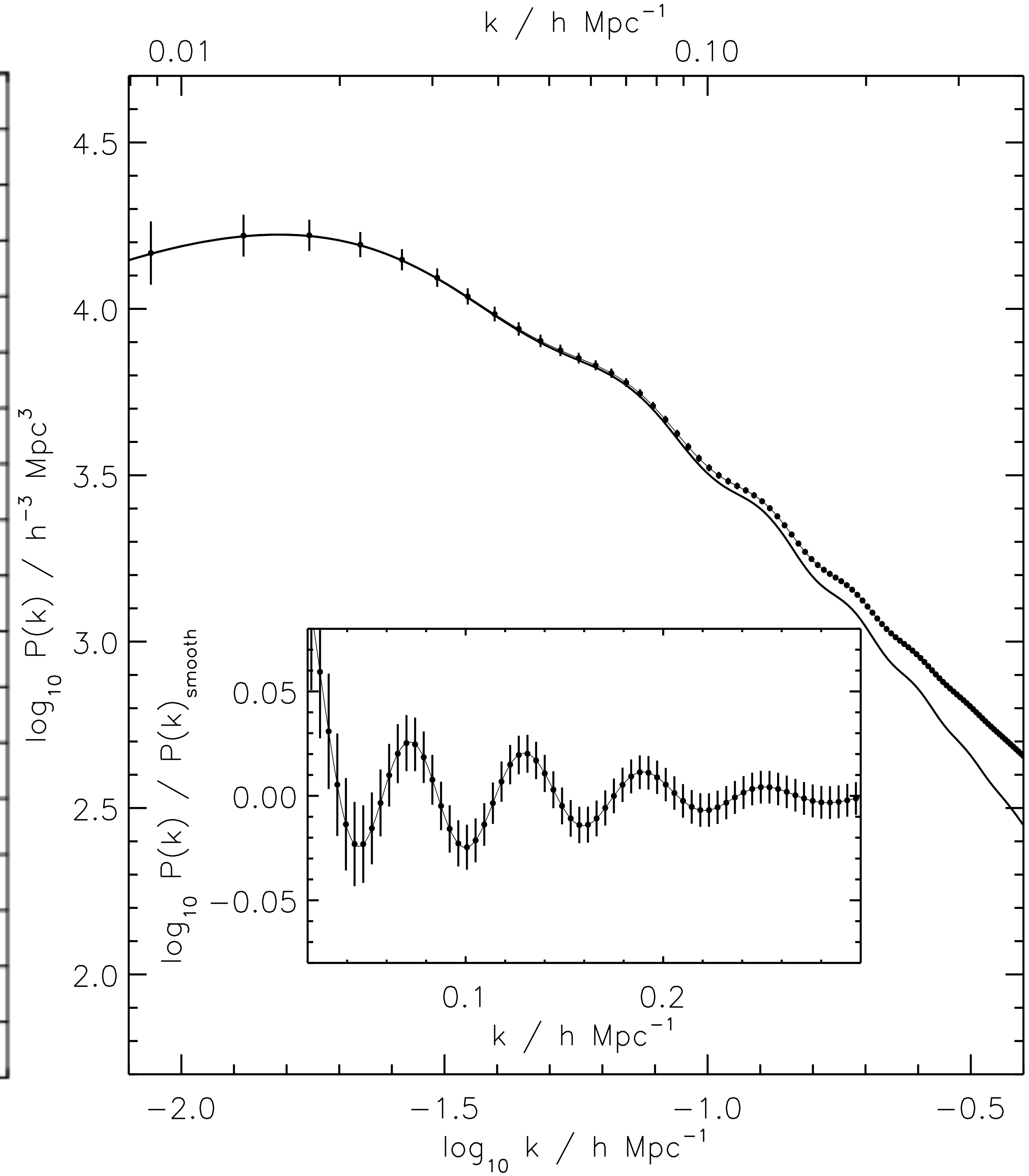
1e−17 ergs/cm^2/s
Wavelength
28.9 2.4 20170518v006_19
28.9 3.7 20170630v008_3
28.3 1.3 20170327v012_5
28.2 6.2 20170427v006_6
28.1 4.2 20170627v005_3
28.0 1.8 20170629v005_5
27.9 5.2 20170427v006_4
27.8 2.1 20170328v019_26
27.7 3.2 20170423v008_1
27.3 2.1 20170629v004_8
27.3 3.0 20170420v017_4
27.2 1.7 20170519v002_1
27.1 1.0 20170626v003_29
26.9 4.0 20170428v019_20
26.8 2.7 20170303v014_10
26.7 5.9 20170529v009_13
26.6 2.9 20170519v002_6
26.6 1.8 20170303v014_9
26.6 1.1 20170523v008_51
26.5 1.8 20170617v009_17
26.4 6.8 20170303v014_4
26.3 1.2 20170427v013_6
26.3 6.4 20170529v009_10
26.1 4.5 20170427v004_29
25.9 2.5 20170420v016_23
25.7 1.3 20170423v016_12
25.6 1.8 20170328v018_3
25.5 6.3 20170421v017_21
25.4 14.4 20170630v009_4
25.0 1.8 20170502v011_16
25.0 4.2 20170328v019_6
24.9 1.0 20170626v003_31
24.9 3.0 20170424v008_16
24.8 9.3 20170427v005_2
24.8 2.5 20170325v005_16
24.6 2.3 20170428v007_22

SDSS-III/BOSS (z=0.6)



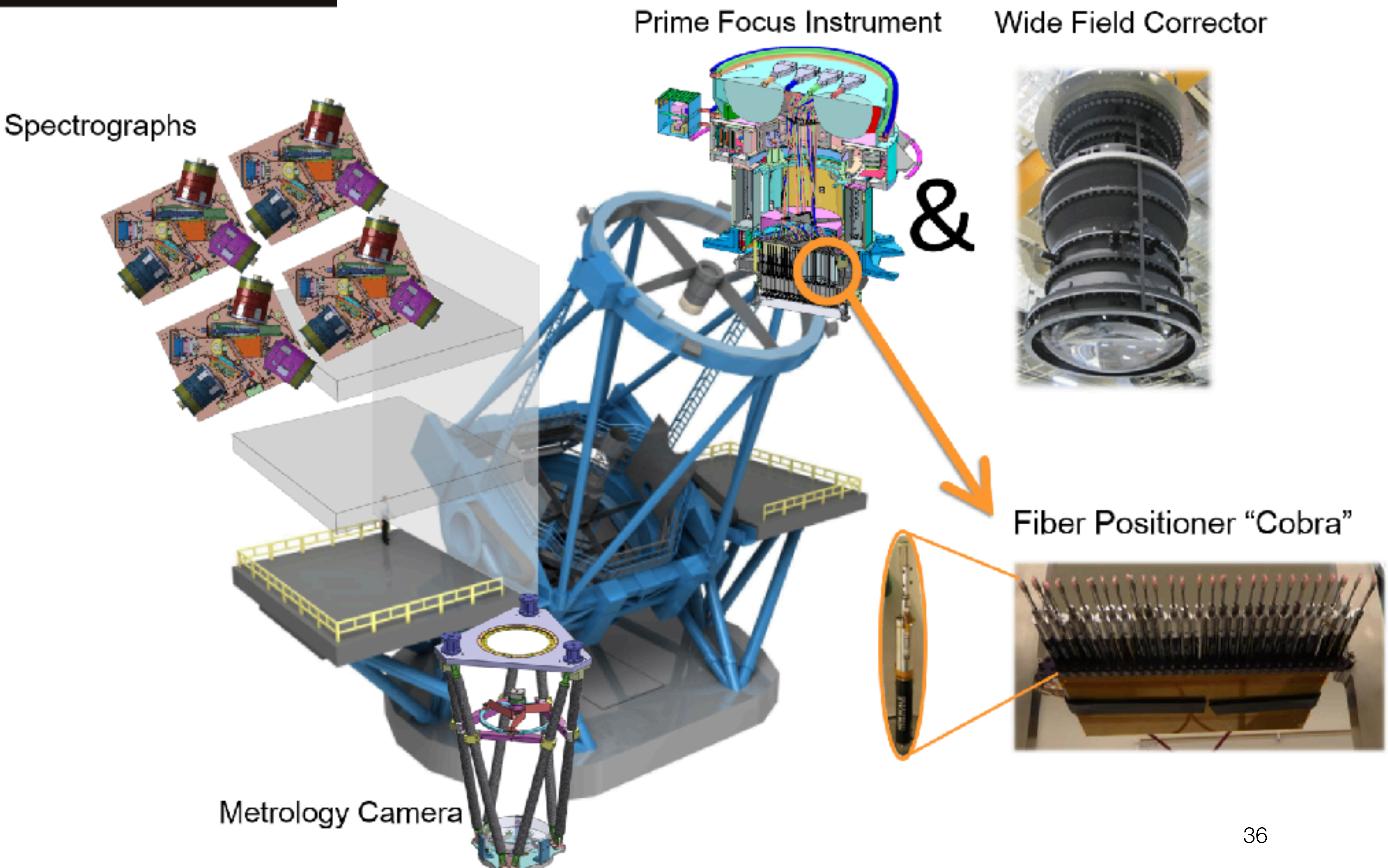
Full survey expectation for

HETDEX (z=2.5)



Prime Focus Spectrograph

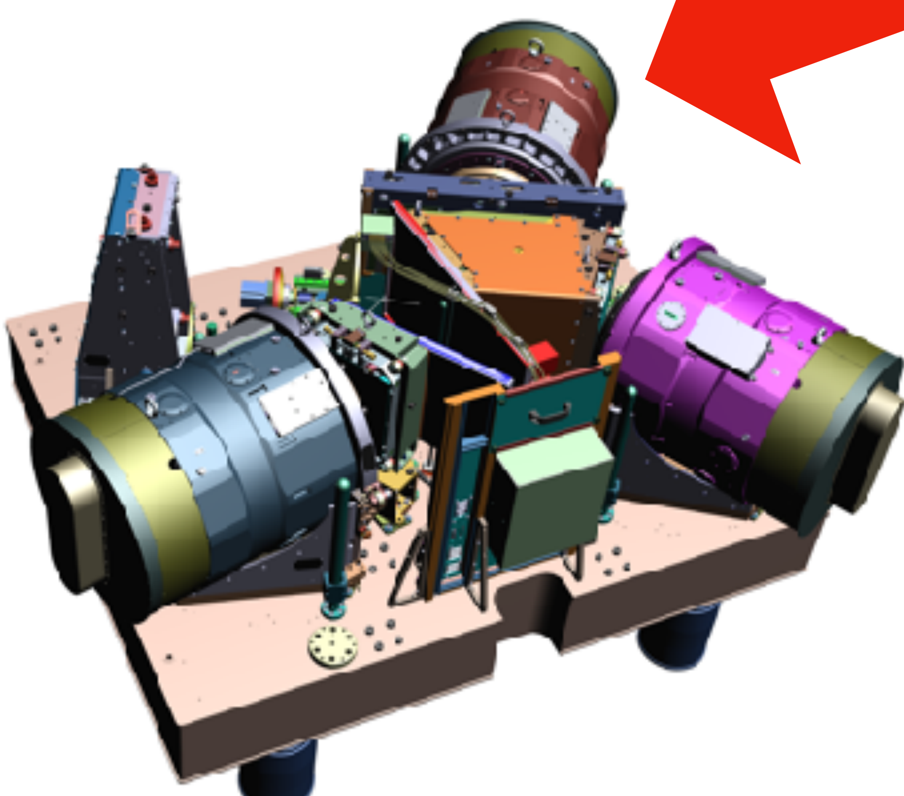
SuMIRe

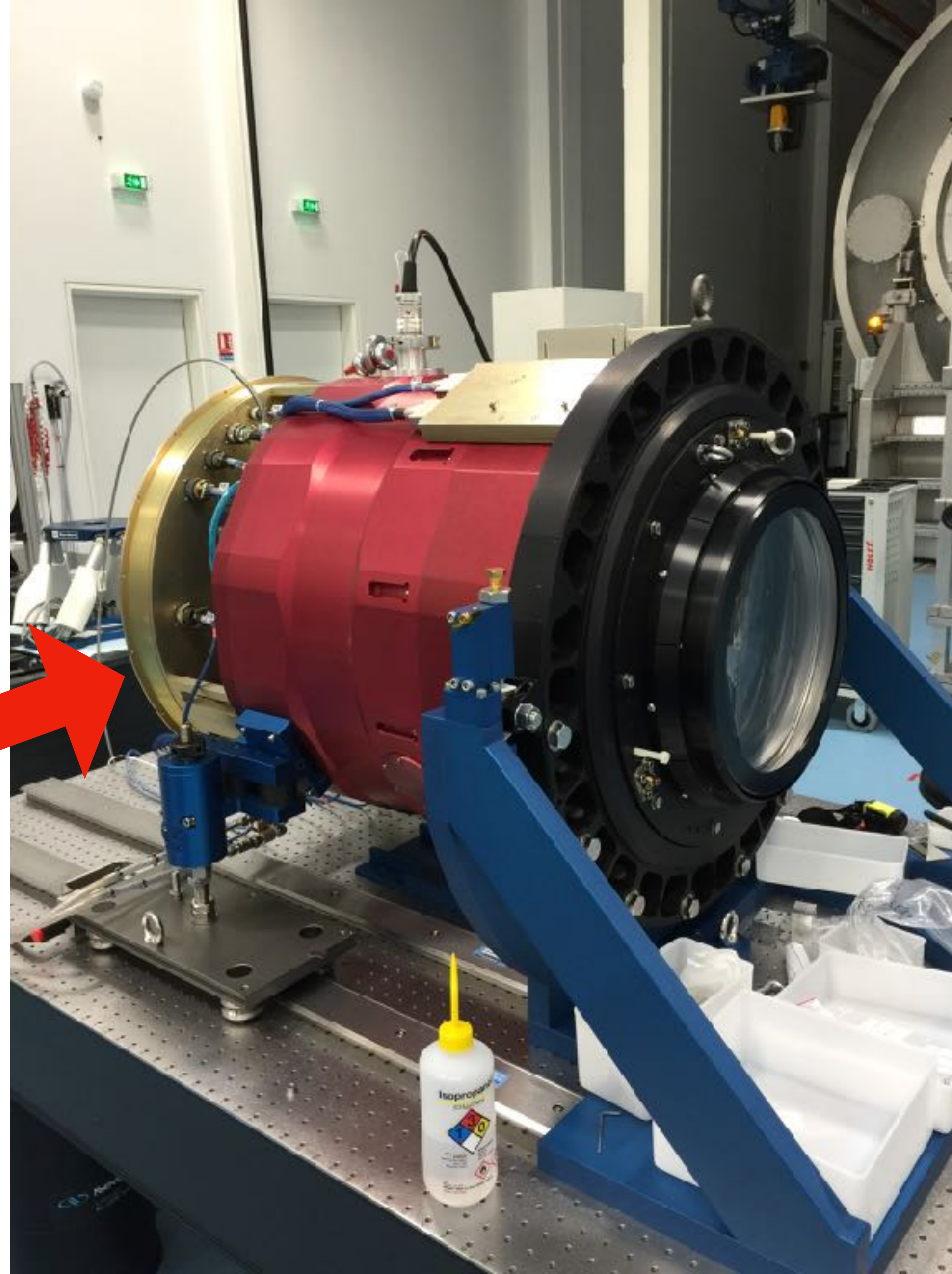


SuMIRe Prime Focus Spectrograph

One of the "Red" Spectrograph Modules being tested at LAM

LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE





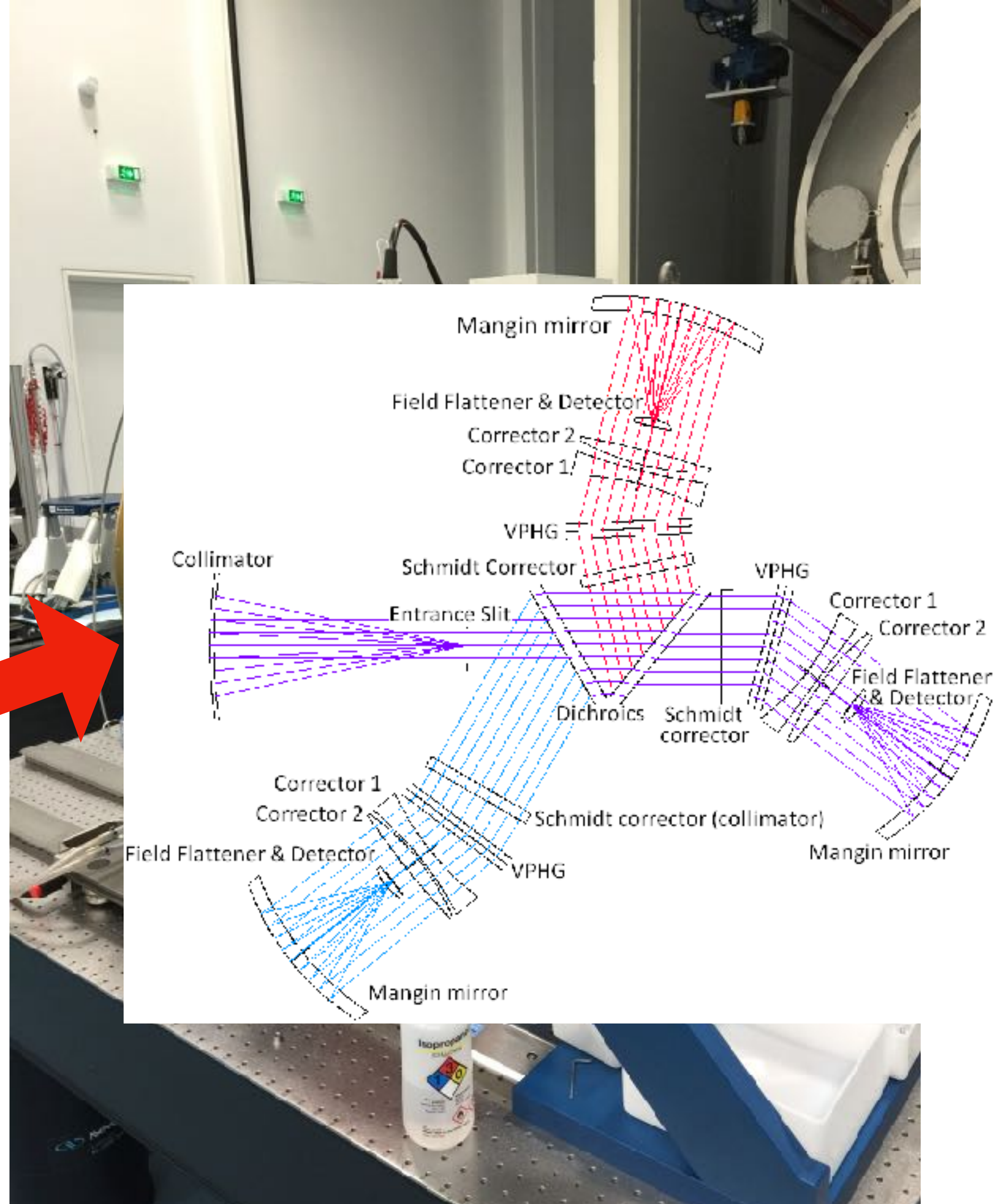
Prime Focus Spectrograph

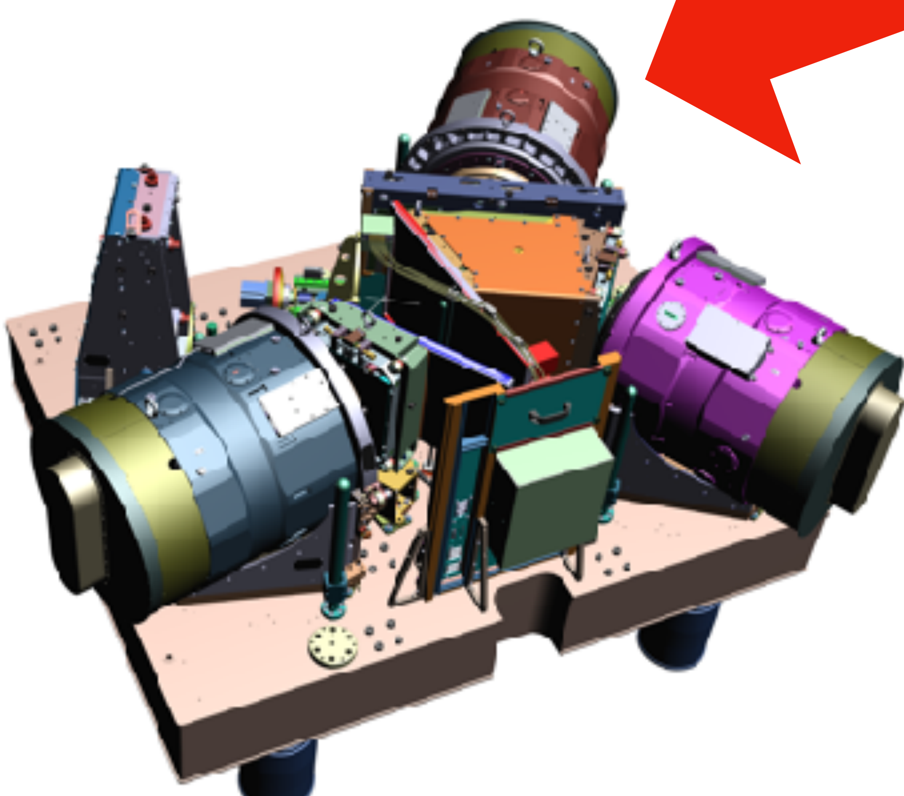
SuMIRe

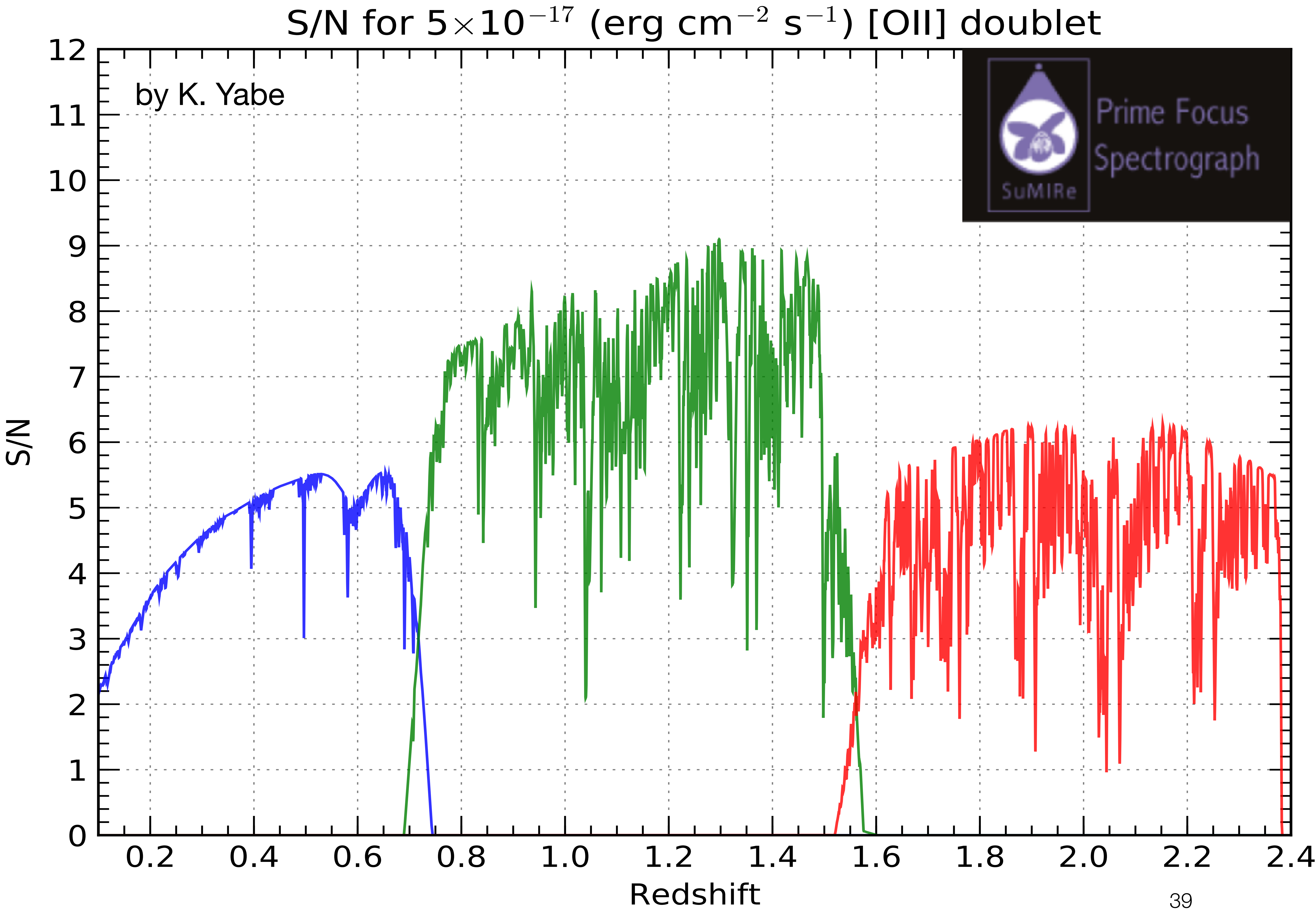
One of the “Red” Spectrograph Modules being tested at LAM

LAM

LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE





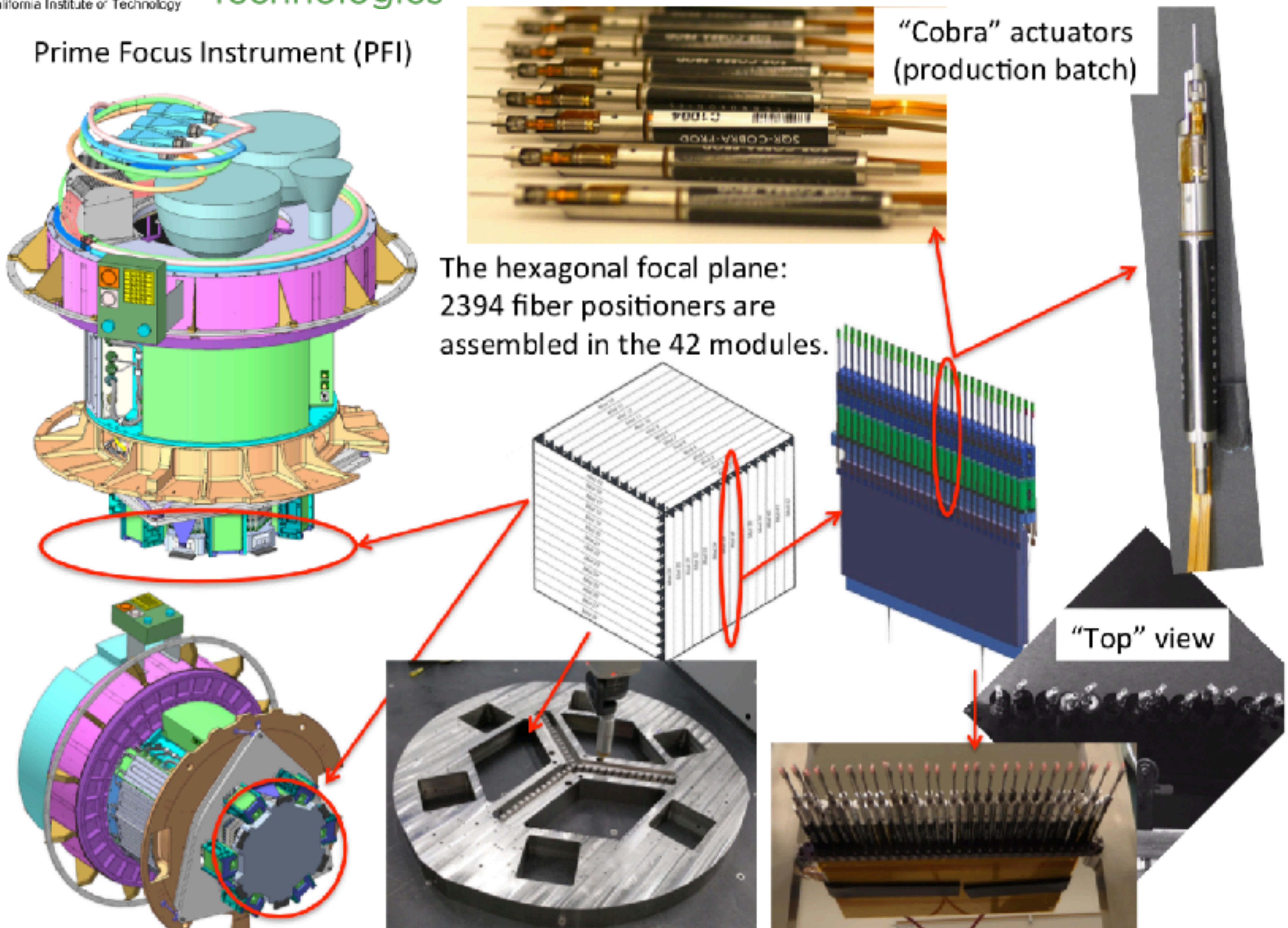


S/N for 5×10^{-17} (erg cm^{-2} s^{-1}) [OII] doublet
by K. Yabe
Prime Focus Spectrograph
SuMIRe
S/N
Redshift
0
1
2
3
4
5
6
7
8
9
10
11
12
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4

Robotic Fiber Positioner “Cobra”

JPL Jet Propulsion Laboratory California Institute of Technology

New Scale Technologies

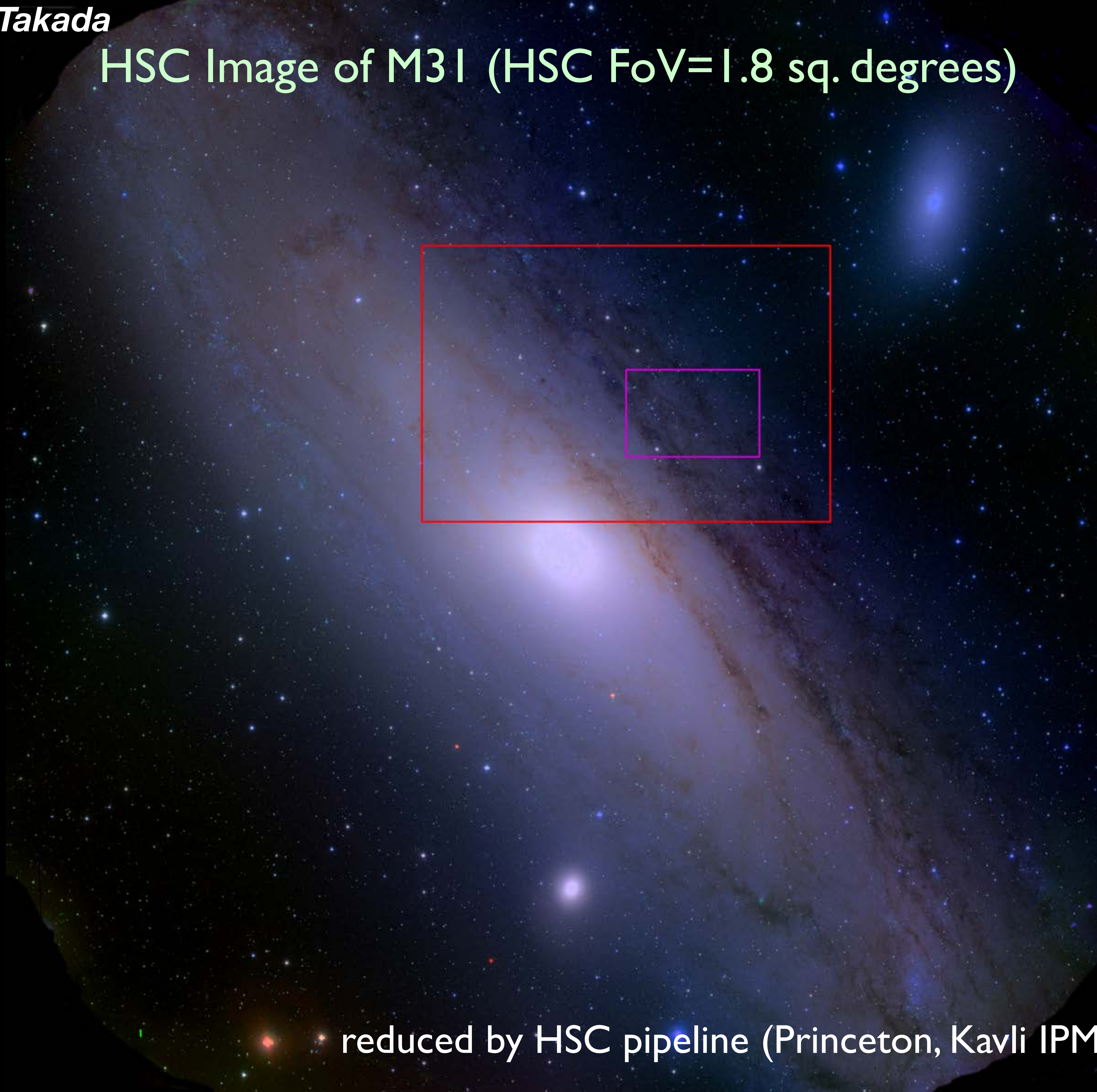


“Cobra” optical bench

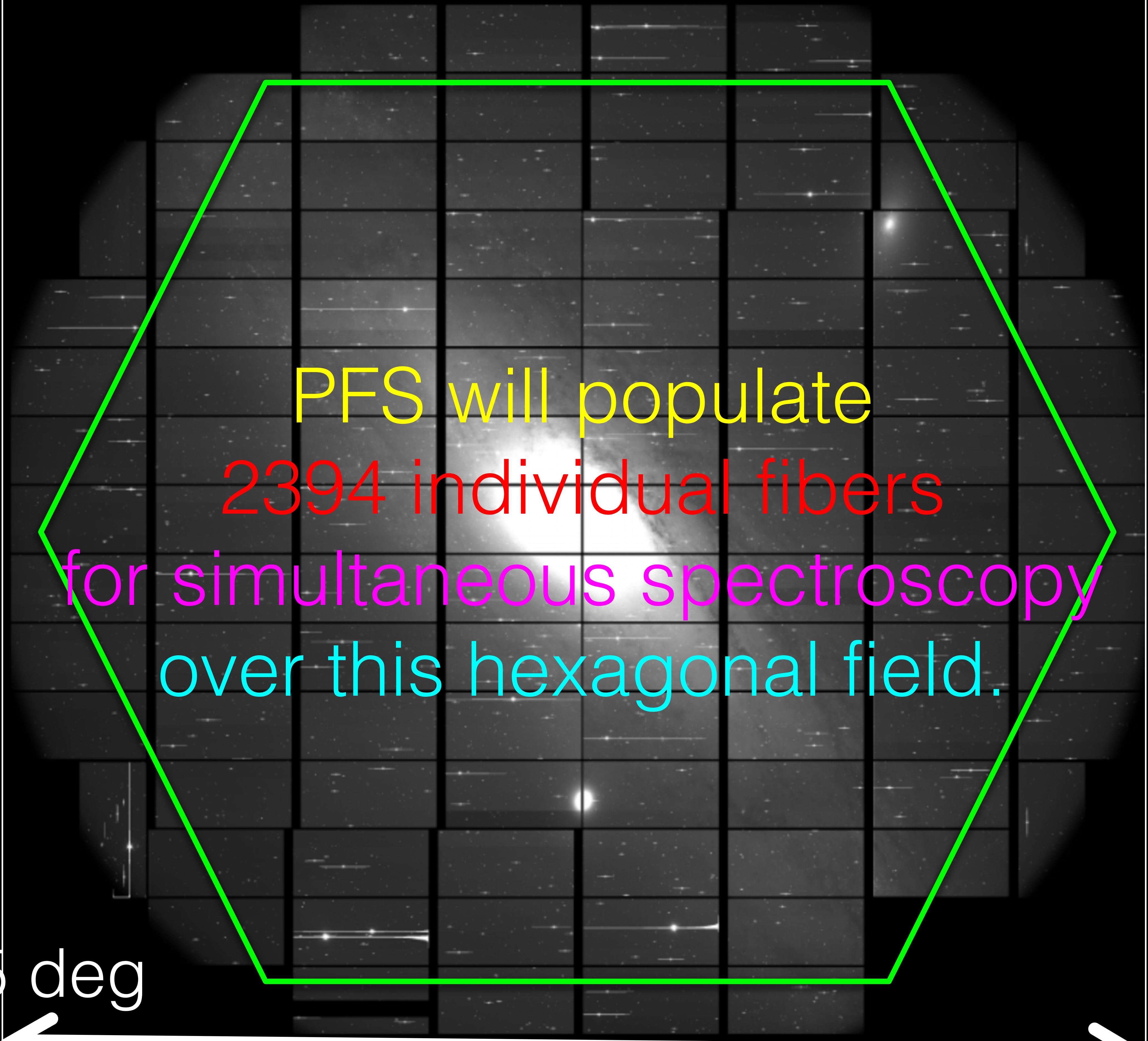
“Cobra” eng. model module

Masahiro Takada

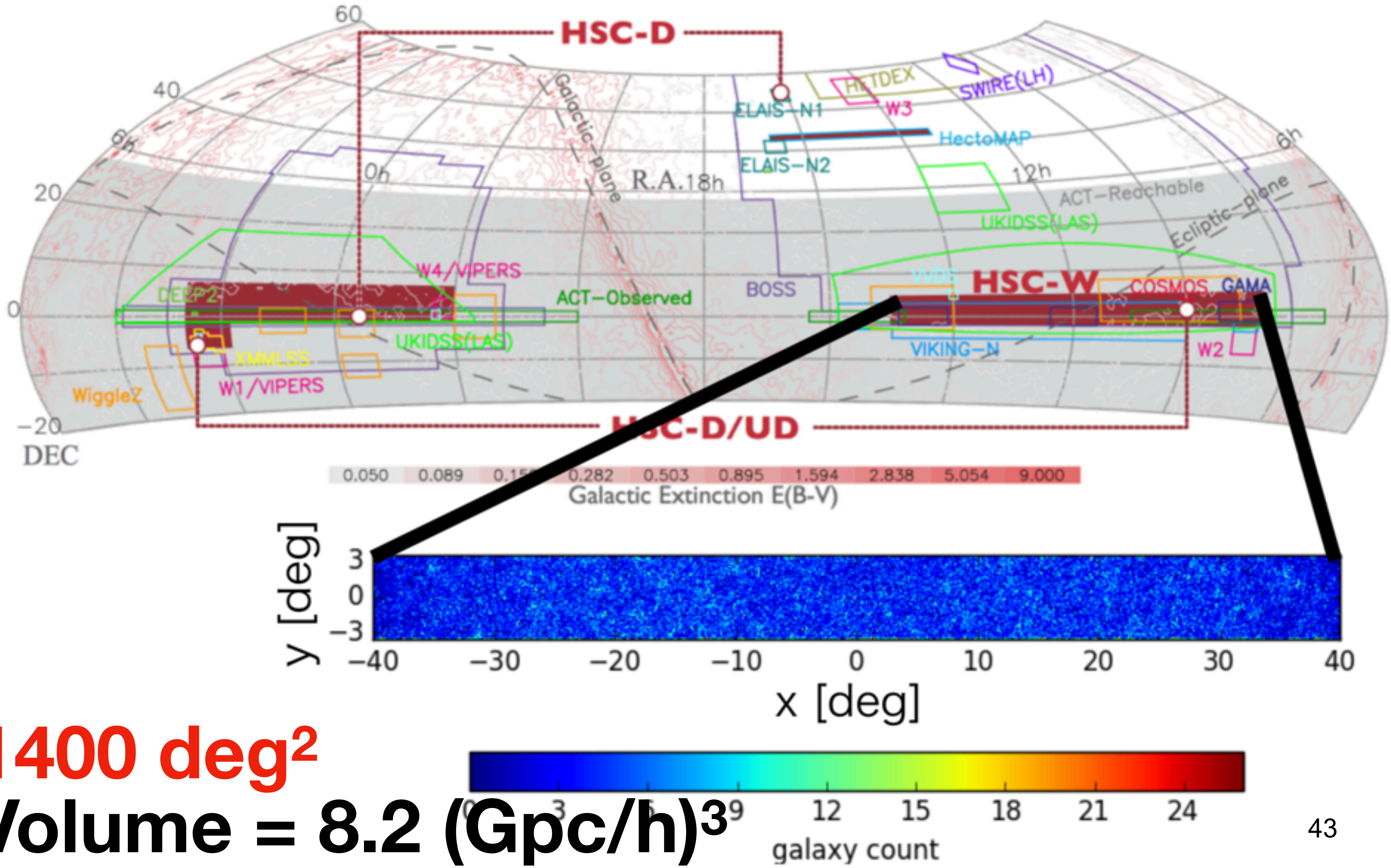
HSC Image of M31 (HSC FoV=1.8 sq. degrees)



reduced by HSC pipeline (Princeton, Kavli IPMU, NAOJ)


PFS will populate
2394 individual fibers
for simultaneous spectroscopy
over this hexagonal field.
~1.5 deg

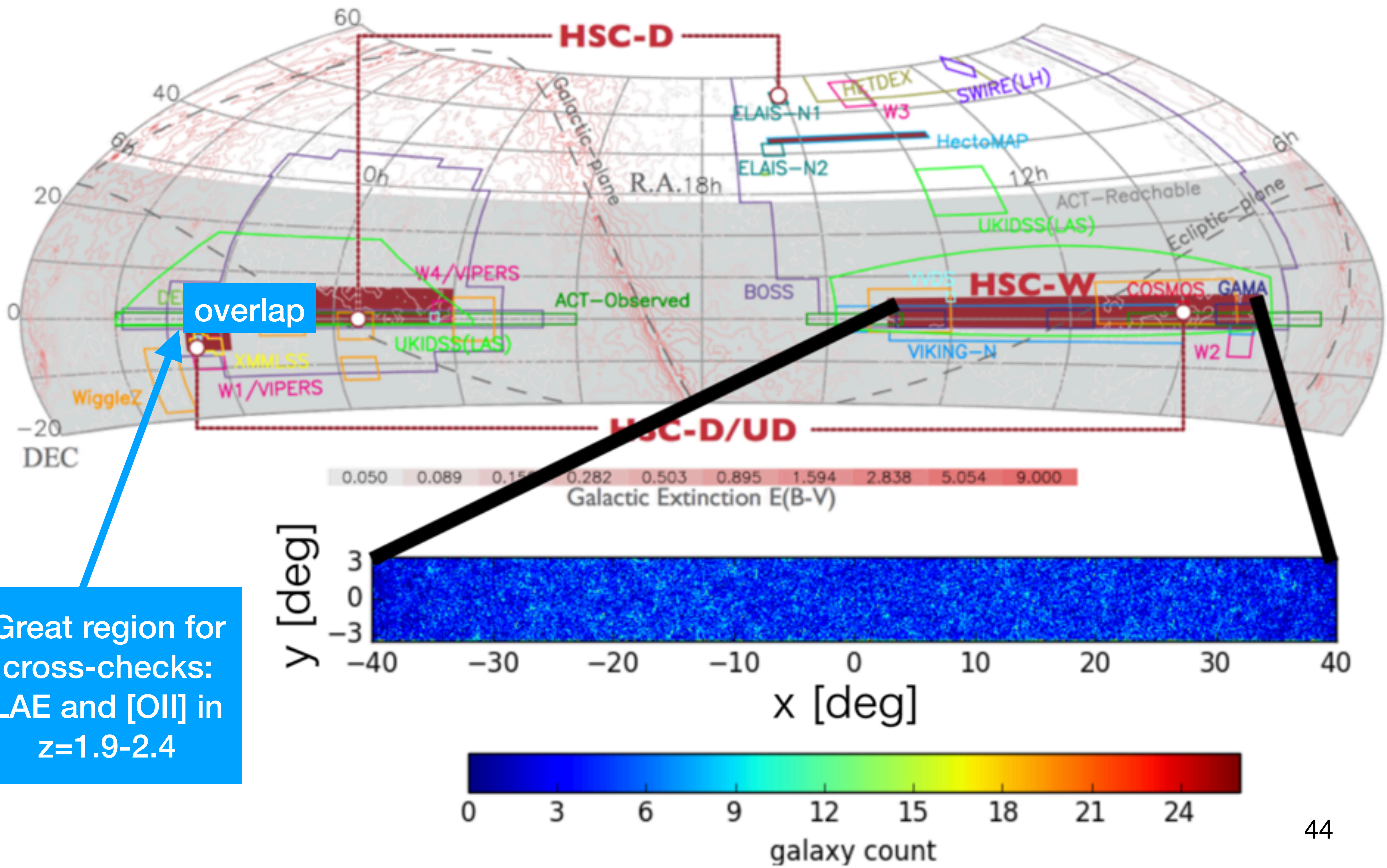
PFS Foot-print (in RA-DEC coordinates)



1400 deg²

Volume = 8.2 (Gpc/h)³

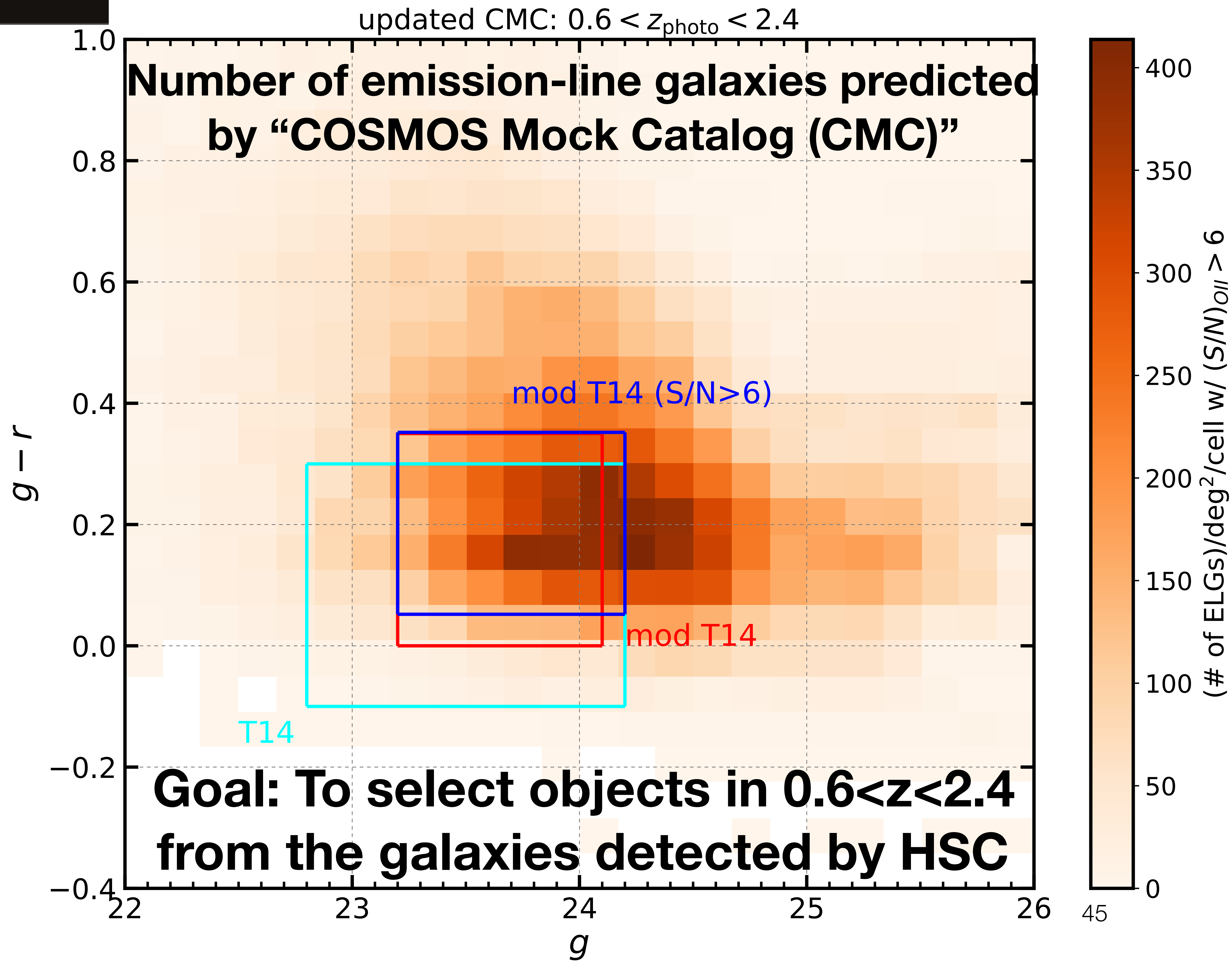
PFS Foot-print (in RA-DEC coordinates)



Great region for cross-checks: LAE and [OII] in z=1.9-2.4

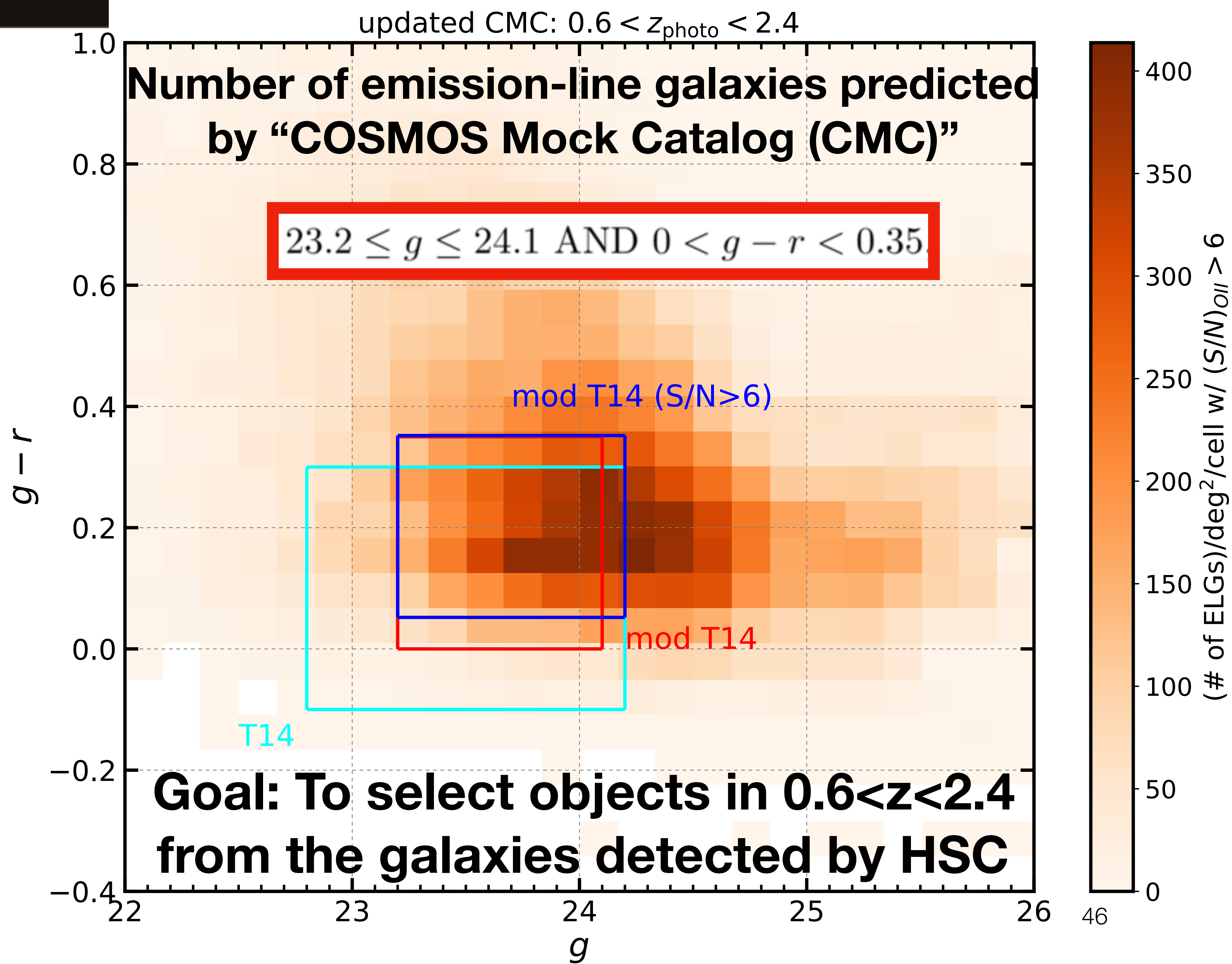
Shun Saito

Target Selection



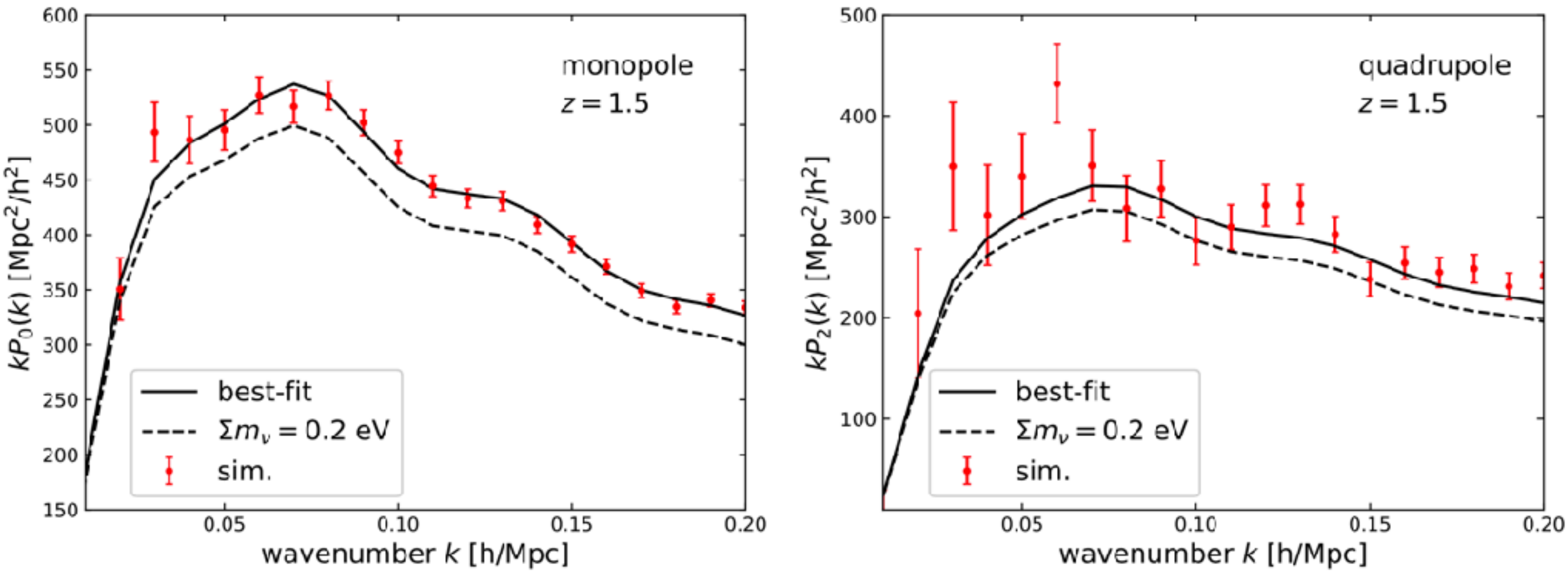
Shun Saito

Target Selection



Ryu Makiya

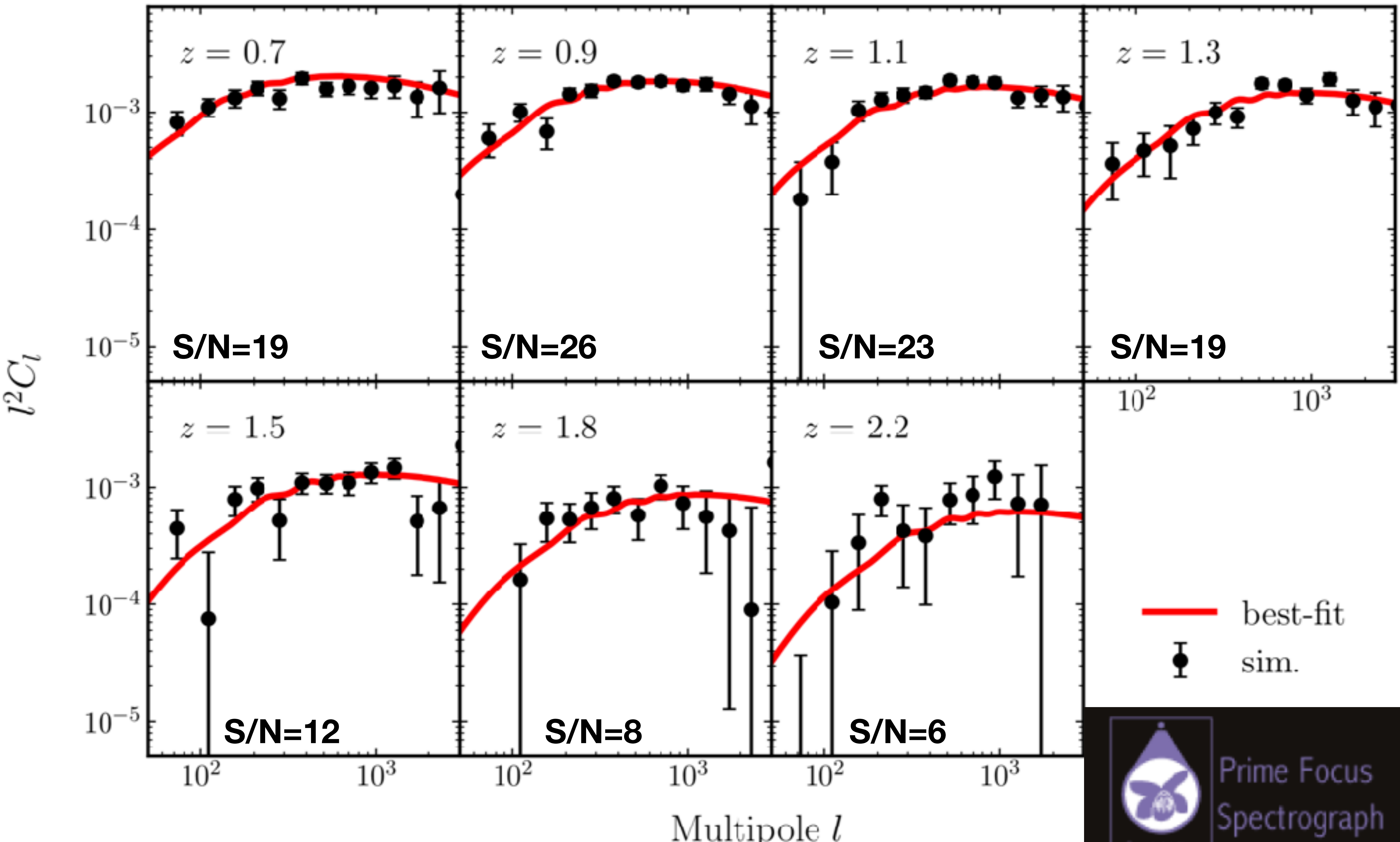
Example Deliverables: Galaxy Power Spectra



- There are six more redshift bins

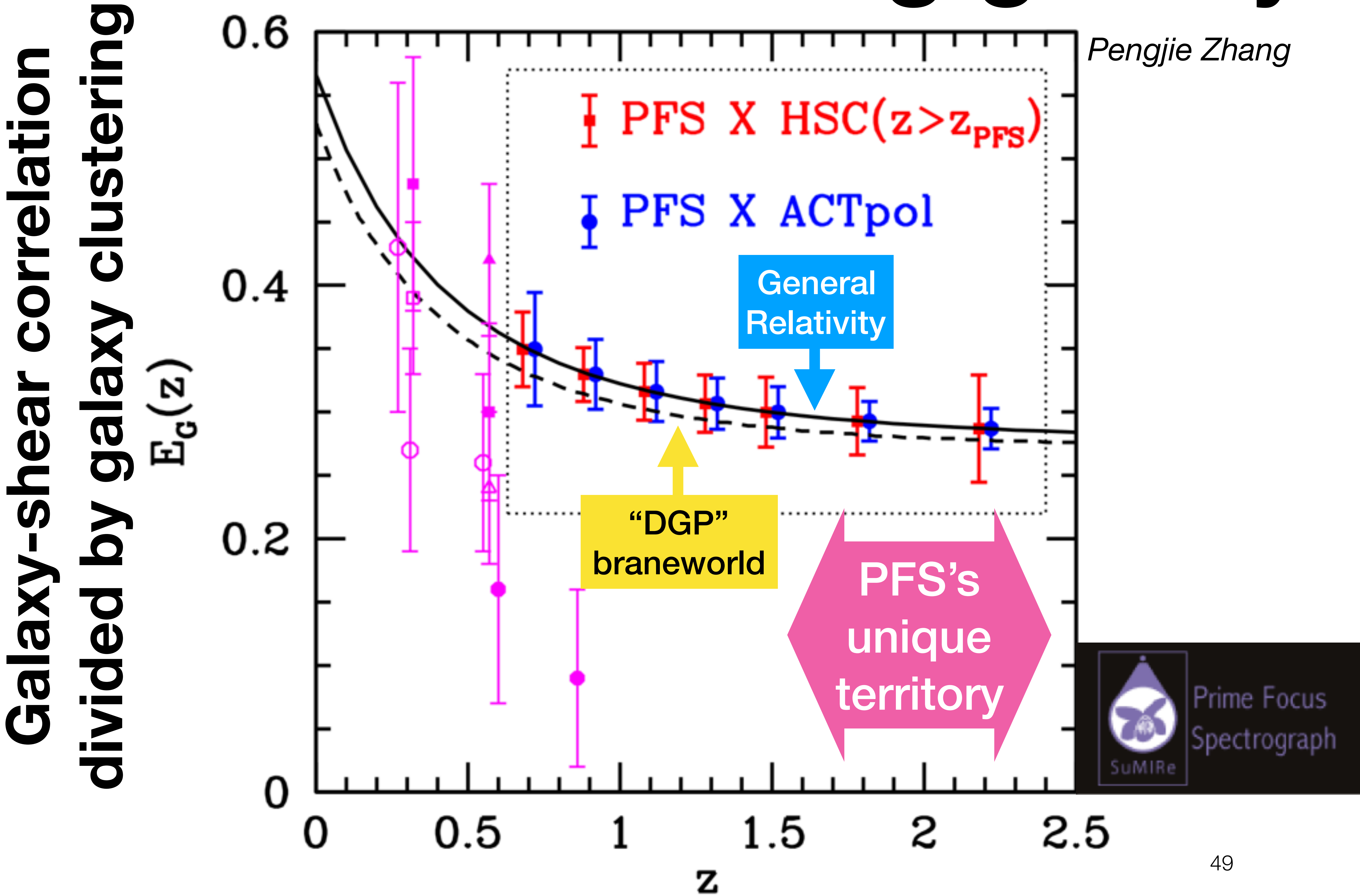
PFSxHSC: Galaxy-weak lensing Cross Spectra

Ryu Makiya



Prime Focus Spectrograph
SuMIRe

PFSxHSC: Testing gravity



Neutrino Mass

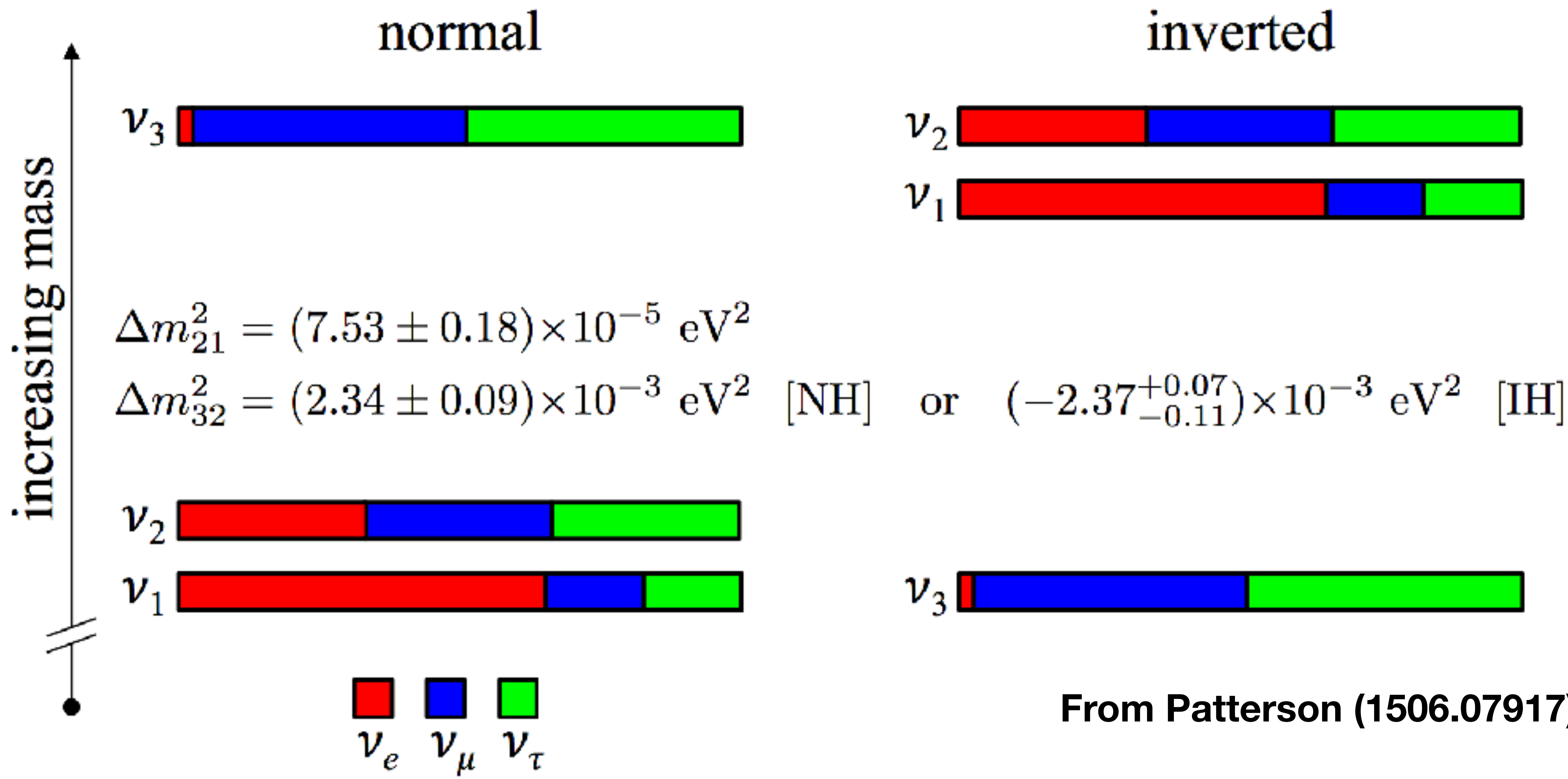
Two major goals

- *To rule out the inverted mass hierarchy of neutrino masses by measuring* ***$\sum m_\nu < 0.1$ eV*** *(95% CL)*
    - or, to determine the total mass if $\sum m_\nu > 0.1$ eV
- *To rule out the ΛCDM model by finding time evolution of dark energy density,* $\rho_{DE} = \boldsymbol{\rho_{DE}(t) \neq \Lambda}$
    - or, to confirm it with unprecedented precision to z=3.5

Why Neutrino Mass *Hierarchy*?

- We know that neutrinos have masses, but we do not know the absolute value of the mass
    - Only mass differences between three mass eigenstates are known from the neutrino oscillation experiments
- Knowing the mass would be nice, but what appears to be more fundamental is the mass **hierarchy**
    - **“Normal” vs “Inverted”**

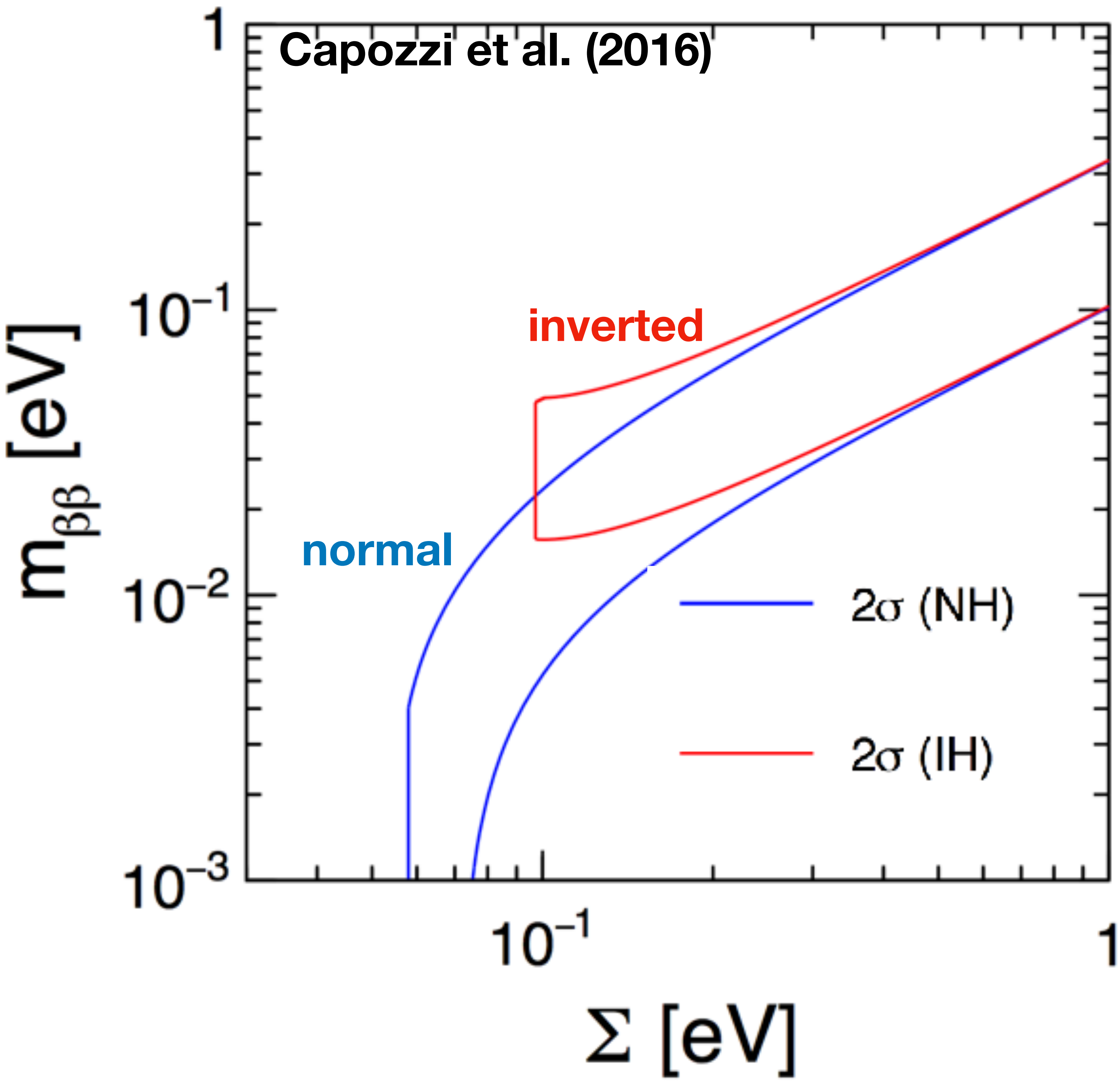
Mass Hierarchy



From Patterson (1506.07917)

- Do we have two heavy states (inverted), or just one (normal)? **$\sum m_\nu$ = 0.1 eV is the key level**

Are neutrinos Dirac or Majorana?



- Deciding the mass hierarchy sets a concrete target for the neutrino-less double beta decay experiments
- Dirac or Majorana? Fundamental importance!

Neutrino Mass Target in Landscape

- The current upper bound from cosmology (Planck+BOSS): **$\sum m_\nu < 0.16$ eV** (95% CL; Alam et al. 2017)

- Planned laboratory (i.e., non-cosmological) neutrino experiments would yield:

From Patterson (1506.07917)

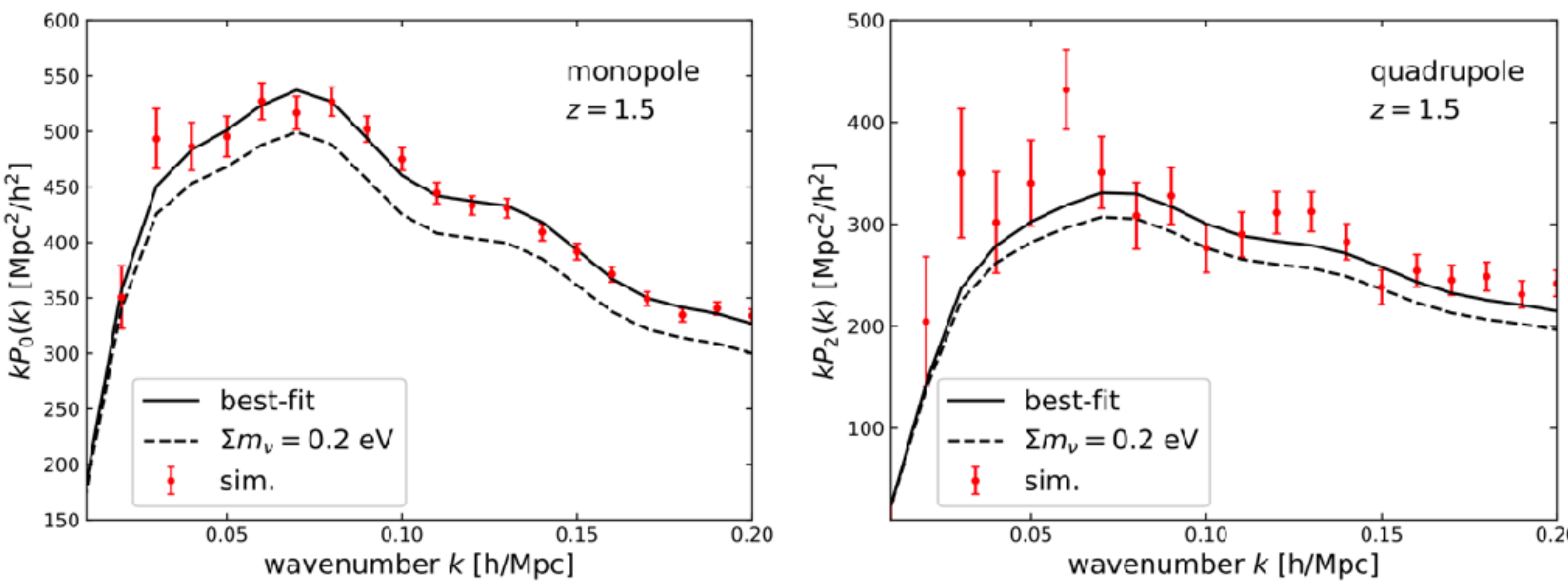
Experiment	Hierarchy sensitivity	Approximate timescale	Comments and concerns
NOνA+T2K	1–3σ	2020	currently operating below designed beam power
DUNE	3–6σ	2030	*funding, timeline*
	5–10σ	2035	
PINGU	3–6σ	2025	funding; past systematics and resolution concerns largely addressed
ORCA	3–6σ	–	insufficiently developed at present
Hyper-K	3–6σ	2030	*funding, timeline*
ICAL@INO	2–4σ	2030	timeline
JUNO	$\sim$4σ	2027	*detector performance not yet demonstrated*
RENO-50	$\sim$3σ	–	insufficiently developed at present
Cosmology	0–4σ	2027	0σ for most of allowed mass range; *requires minimal NH spectrum*

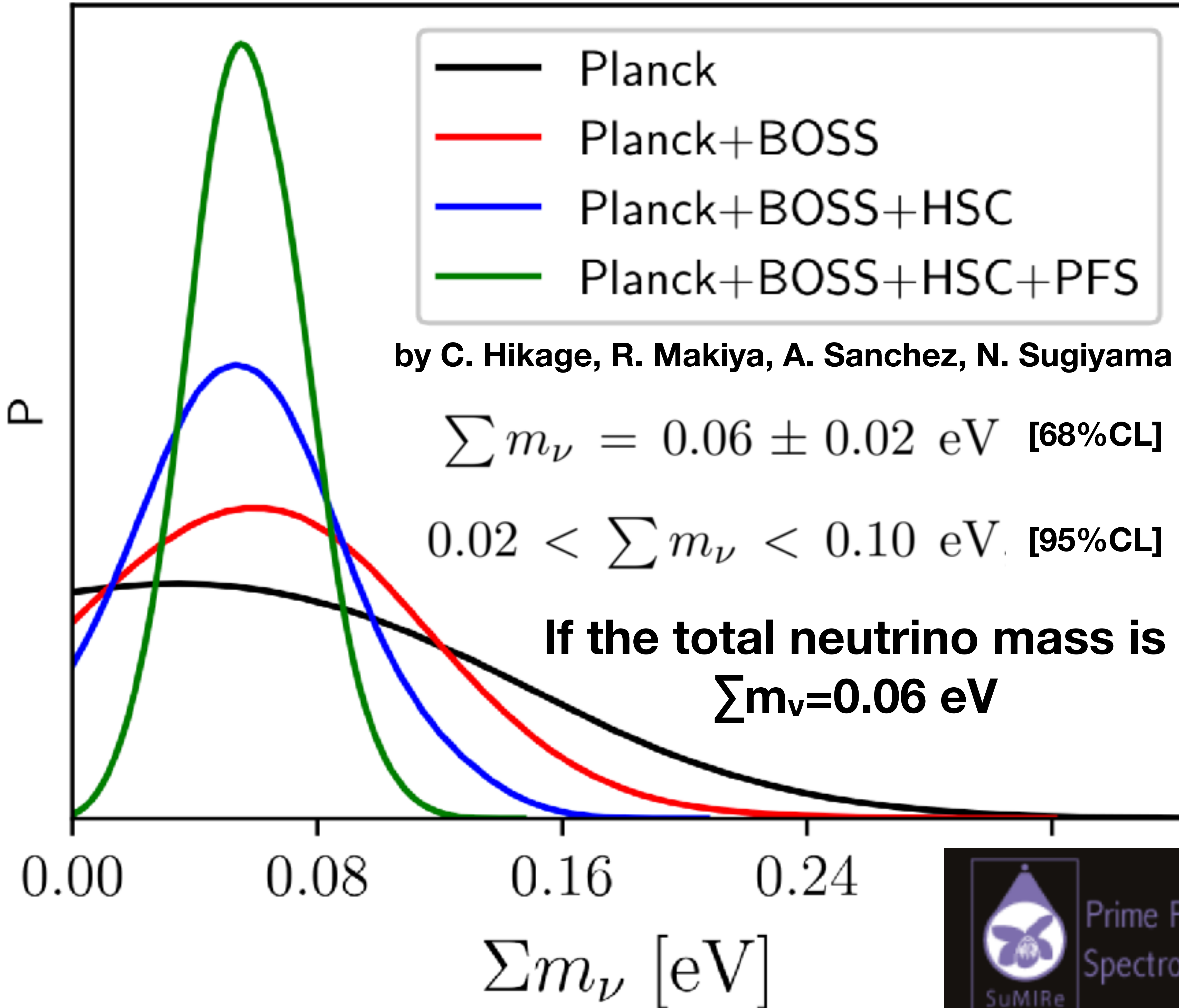
Effects of Massive Neutrinos in Cosmology

- Neutrinos do <u>two things</u>:

1. Change the expansion history of the Universe **BAO, AP**

2. Slow down the structure formation **RSD, Shape**





Planck
Planck+BOSS
Planck+BOSS+HSC
Planck+BOSS+HSC+PFS
by C. Hikage, R. Makiya, A. Sanchez, N. Sugiyama
$\sum m_\nu = 0.06 \pm 0.02$ eV [68%CL]
$0.02 < \sum m_\nu < 0.10$ eV [95%CL]
If the total neutrino mass is
$\sum m_\nu$=0.06 eV
P
0.00
0.08
0.16
0.24
Σm_ν [eV]

But, what about cosmological model-dependence?

Neutrino mass from cosmology: Model dependence!

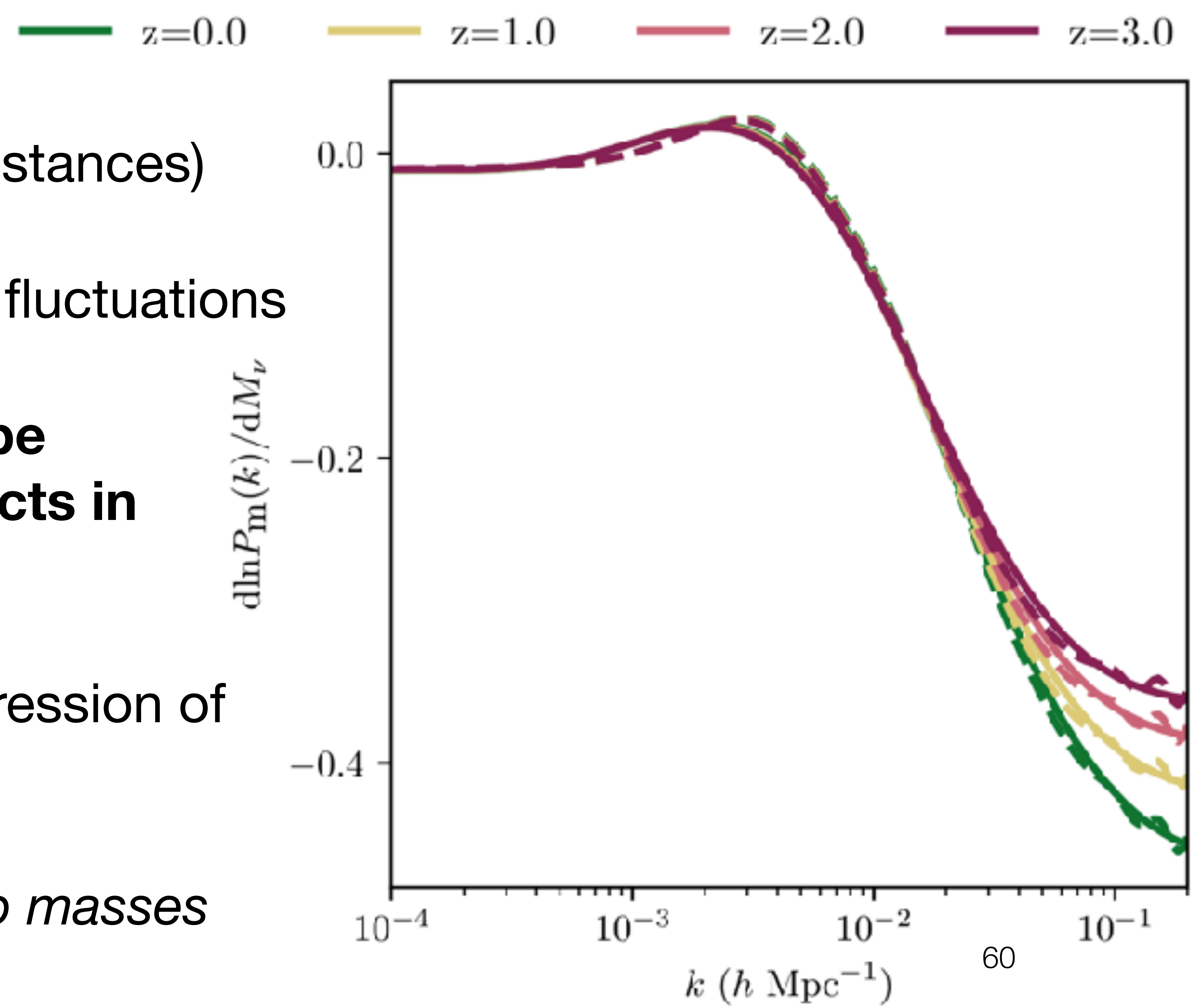
- A typical thing you see at conferences:
  - **A cosmologist**: “So, this is our measurement of the total neutrino mass from cosmology. This is much better than the laboratory experiments!”
  - **A particle physicist**: “Nice, but how dependent is your constraint on the assumed cosmological models”
  - **A cosmologist**: “Ah… Um…”
- Let’s settle this!

Aoife Boyle
(MPA)

Boyle & Komatsu (2018); Boyle (2019)

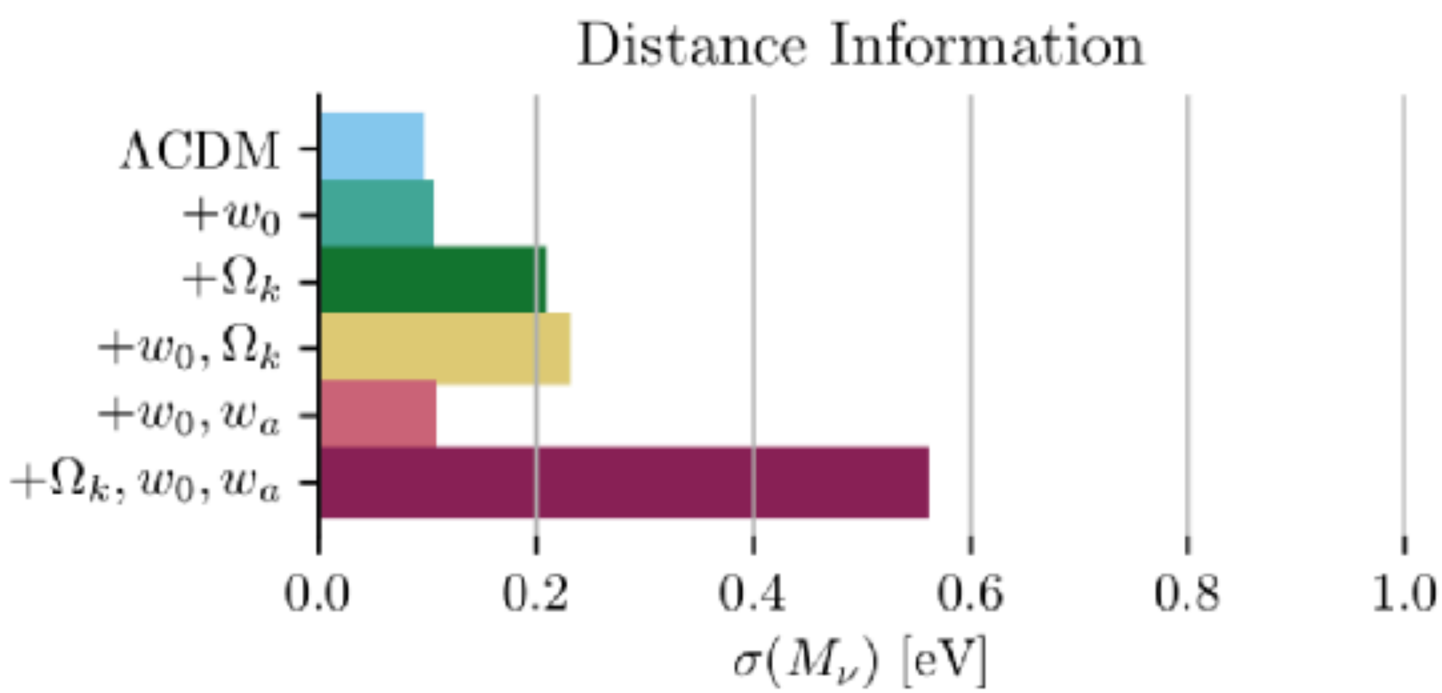
Deconstructing the neutrino mass constraint from galaxy surveys

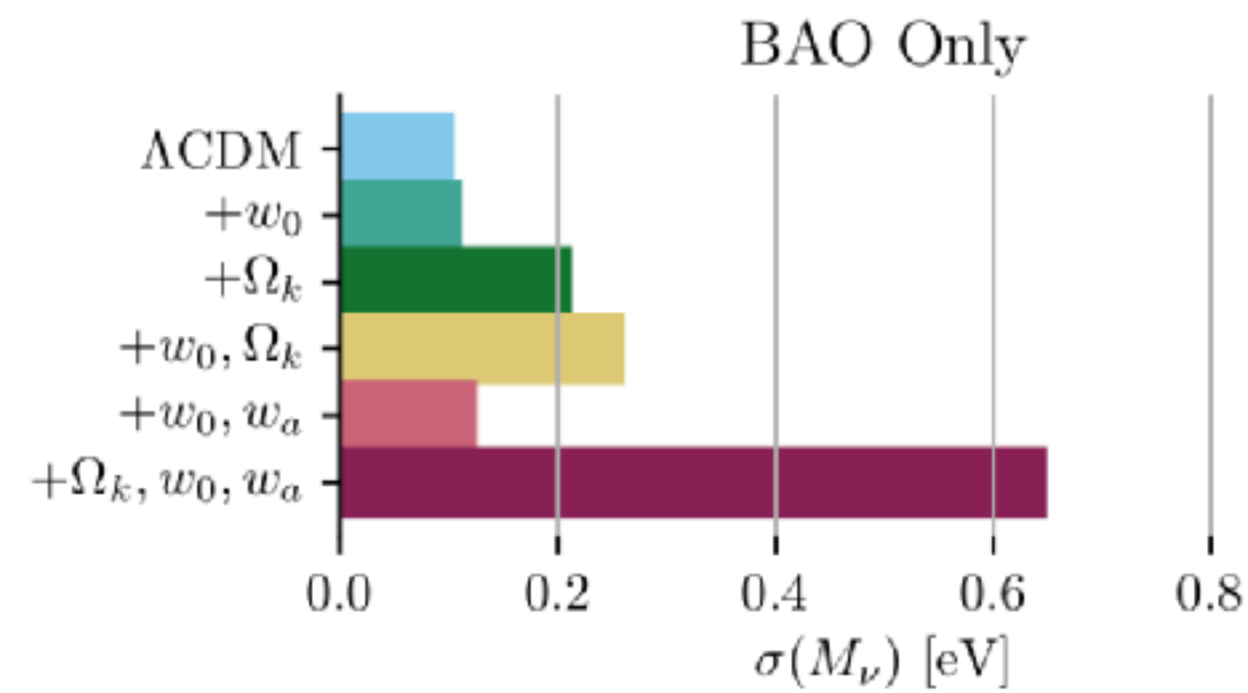
- Neutrino mass changes:
  - Expansion rate (hence distances)
  - Overall growth of matter fluctuations
  - **But, these effects can be mimicked by other effects in cosmology**
- The scale-dependent suppression of the power spectrum is not!
  - *This is unique to neutrino masses* (in General Relativity)

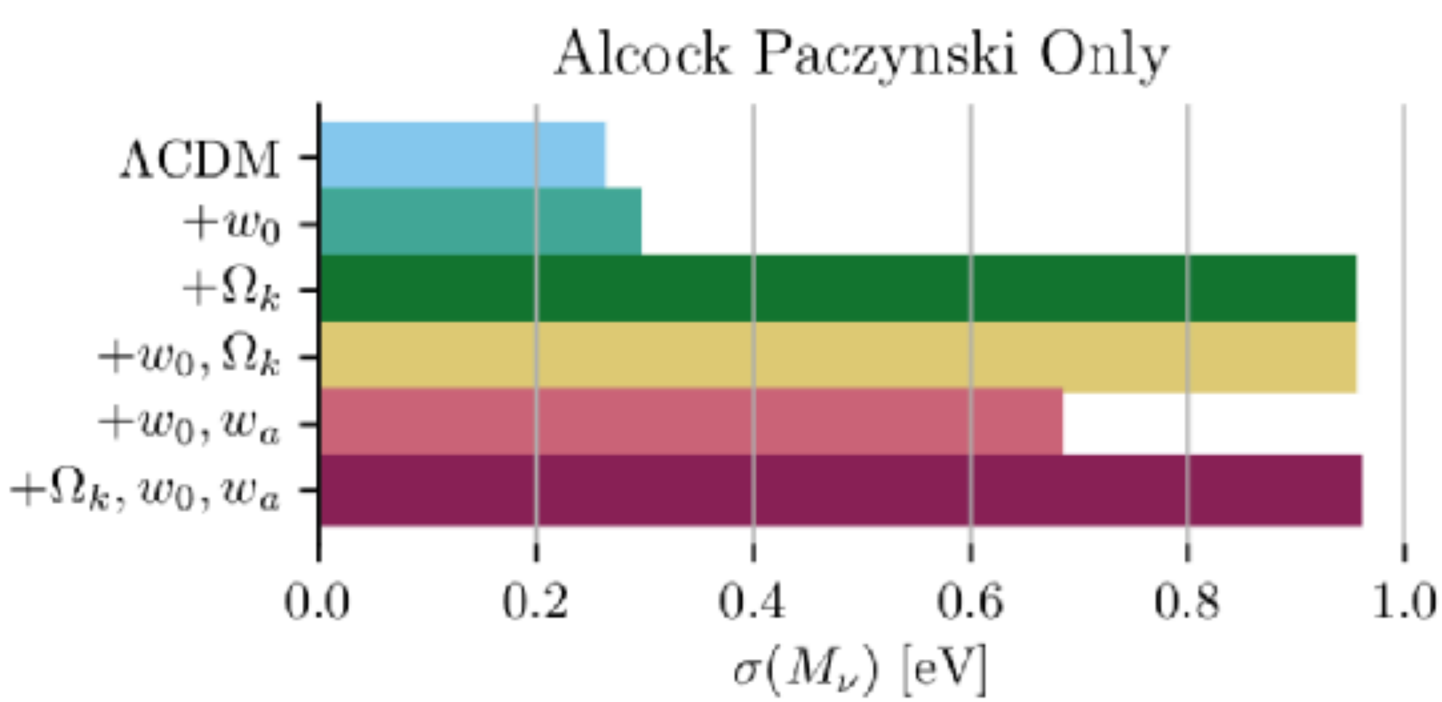


Distance Effect

[Forecast for Euclid]





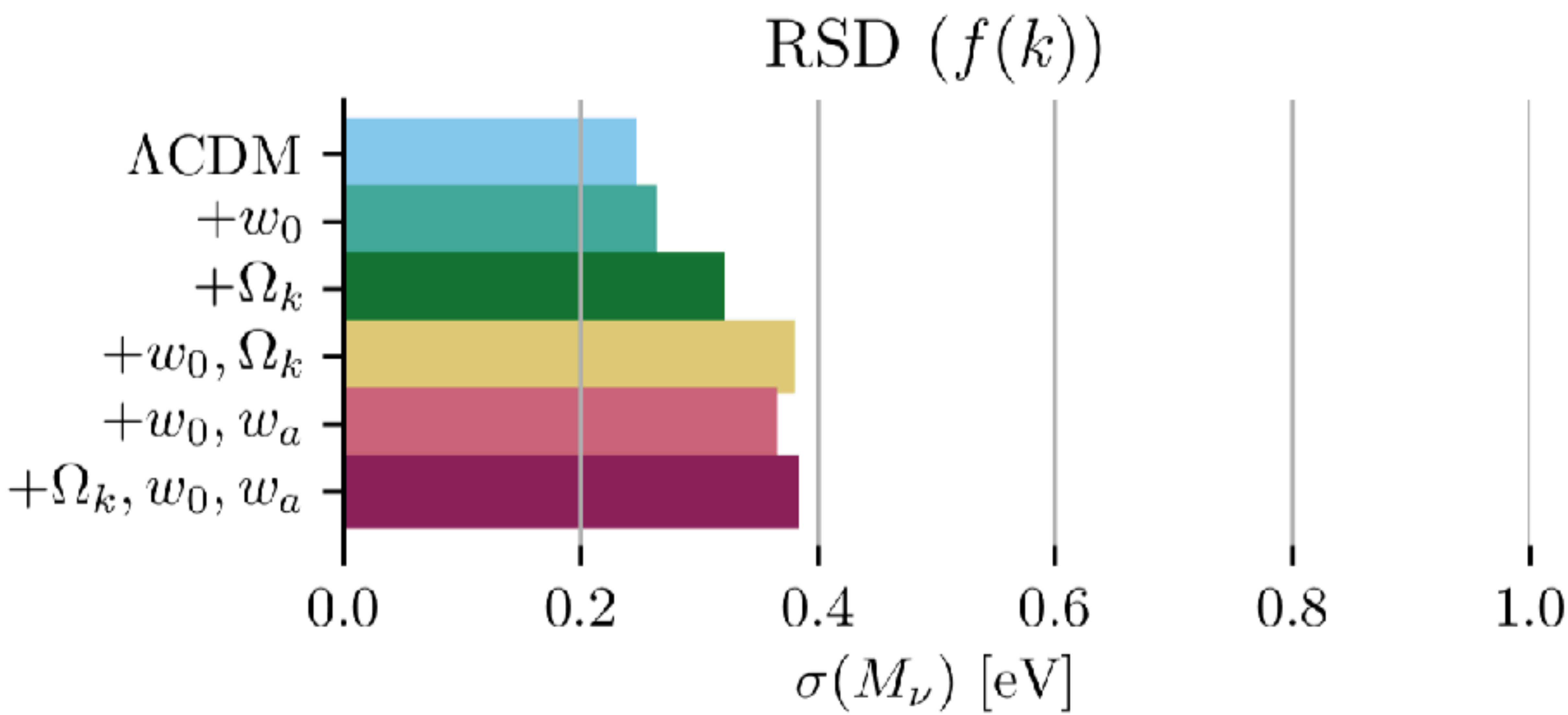


Strong dependence on the assumed cosmological models!

Boyle & Komatsu (2018); Boyle (2019)

Overall Growth Effect

[Forecast for Euclid]

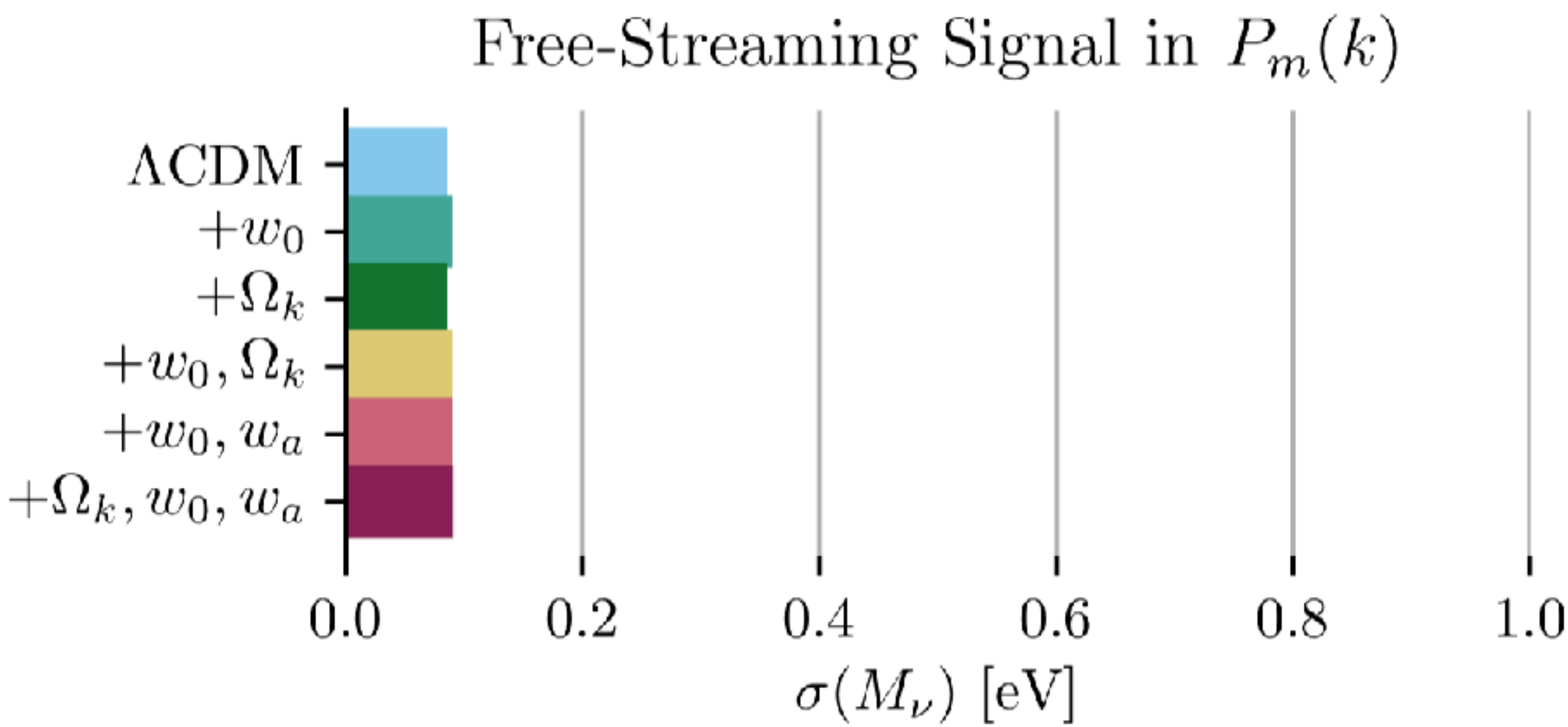


Strong dependence on the assumed cosmological models!

Boyle & Komatsu (2018); Boyle (2019)

Free-streaming Shape Only

[Forecast for Euclid]

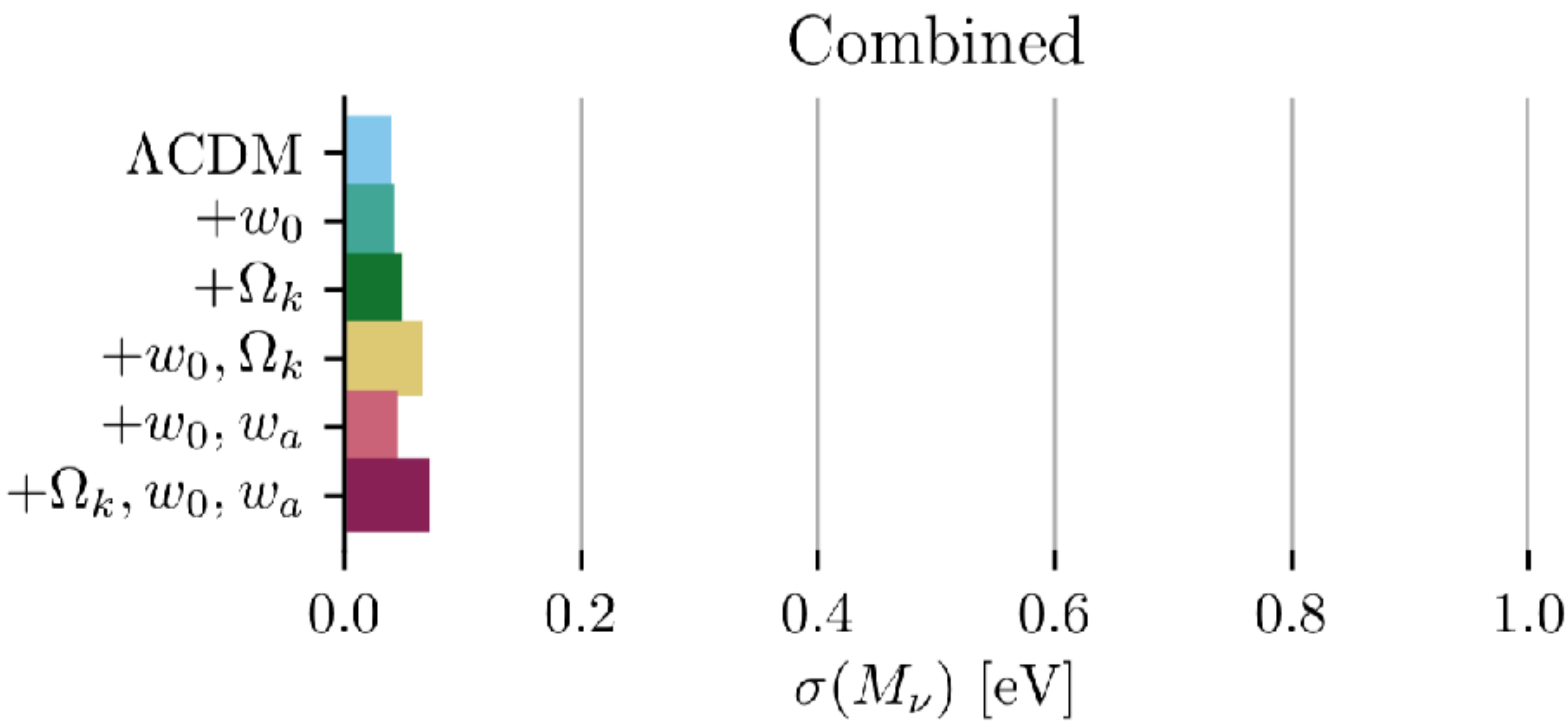


Model dependence disappears!

Boyle & Komatsu (2018); Boyle (2019)

Everything Combined

[Forecast for Euclid]



Constraints tighten, but the model dependence re-appears

Precision vs Robustness

- If we want precision, we may combine all the information and report the neutrino mass constraint
  - But, we must be honest and admit the cosmological model dependence!
- If we want robustness, we can get a model-independent constraint on the neutrino mass from the free-streaming signature in the power spectrum
  - Particle physicists would be happ(ier)?

Summary

- Galaxy surveys are going to high redshifts
    - PFS: $0.6<z<2.4$; HETDEX: $1.9<z<3.5$
    - Blind nature of HETDEX is very exciting for new discoveries
- Checking for the internal consistency of ΛCDM over a wide redshift range. Is the H_0 tension due to low-z effect?
- Measurement of the neutrino mass may be “just around the corner”
    - But beware the cosmological model dependence. The free-streaming signature is a promising way to remove the model dependence

Final Message

- **Both instruments are open-use!**
    - VIRUS (IFU used by HETDEX) is publicly available
    - PFS will be publicly available also after ~2022
- Use them! I would be very happy to talk with you about new ideas