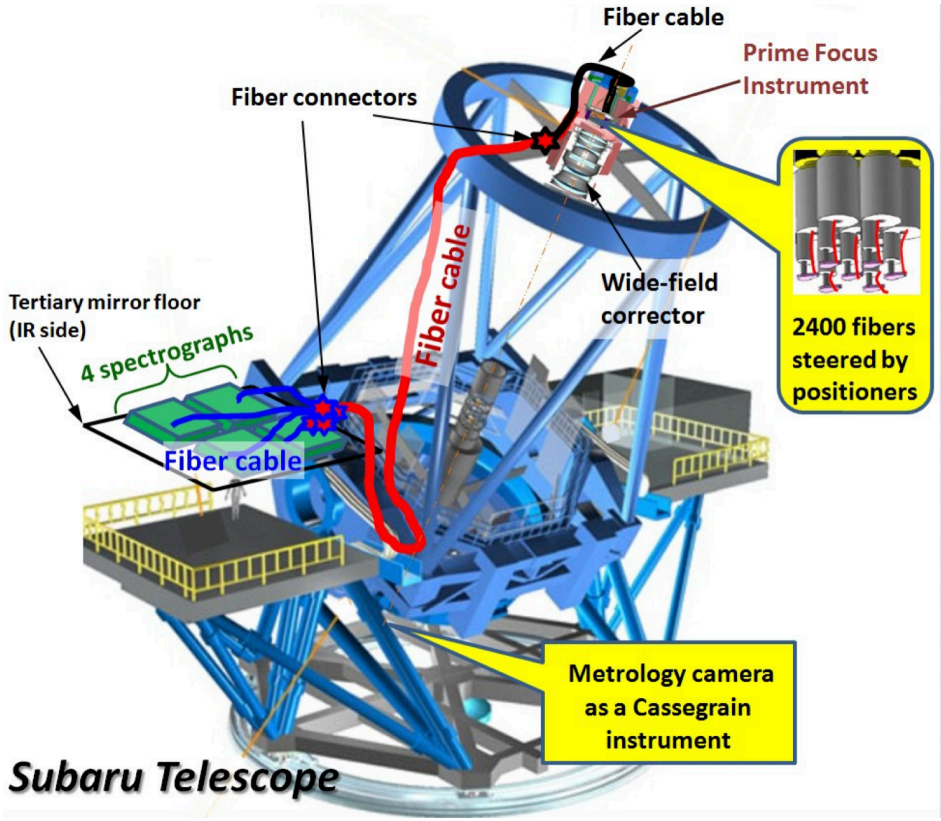
Subaru Prime Focus Spectrograph (PFS) Cosmology Program

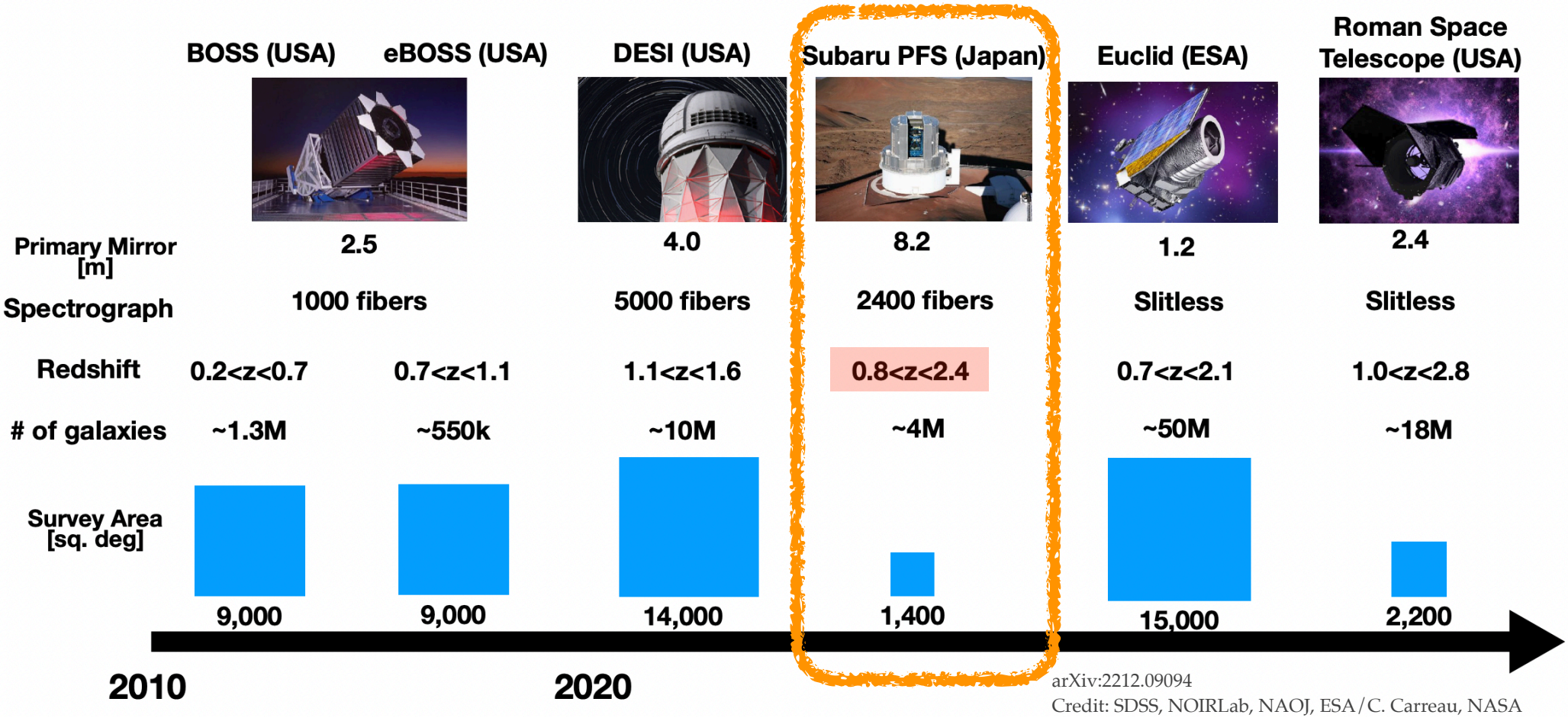
~Current and future prospects with Subaru PFS/HSC



Tomomi Sunayama (ASIAA); co-leader with ChangHoon Hahn (U. Texas Austin) on behalf of the PFS Cosmology WG

Timeline of spectroscopic galaxy surveys

Stage-III Dark Energy Experiments (BOSS, eBOSS) are finished, DESI started, and Euclid is launched…



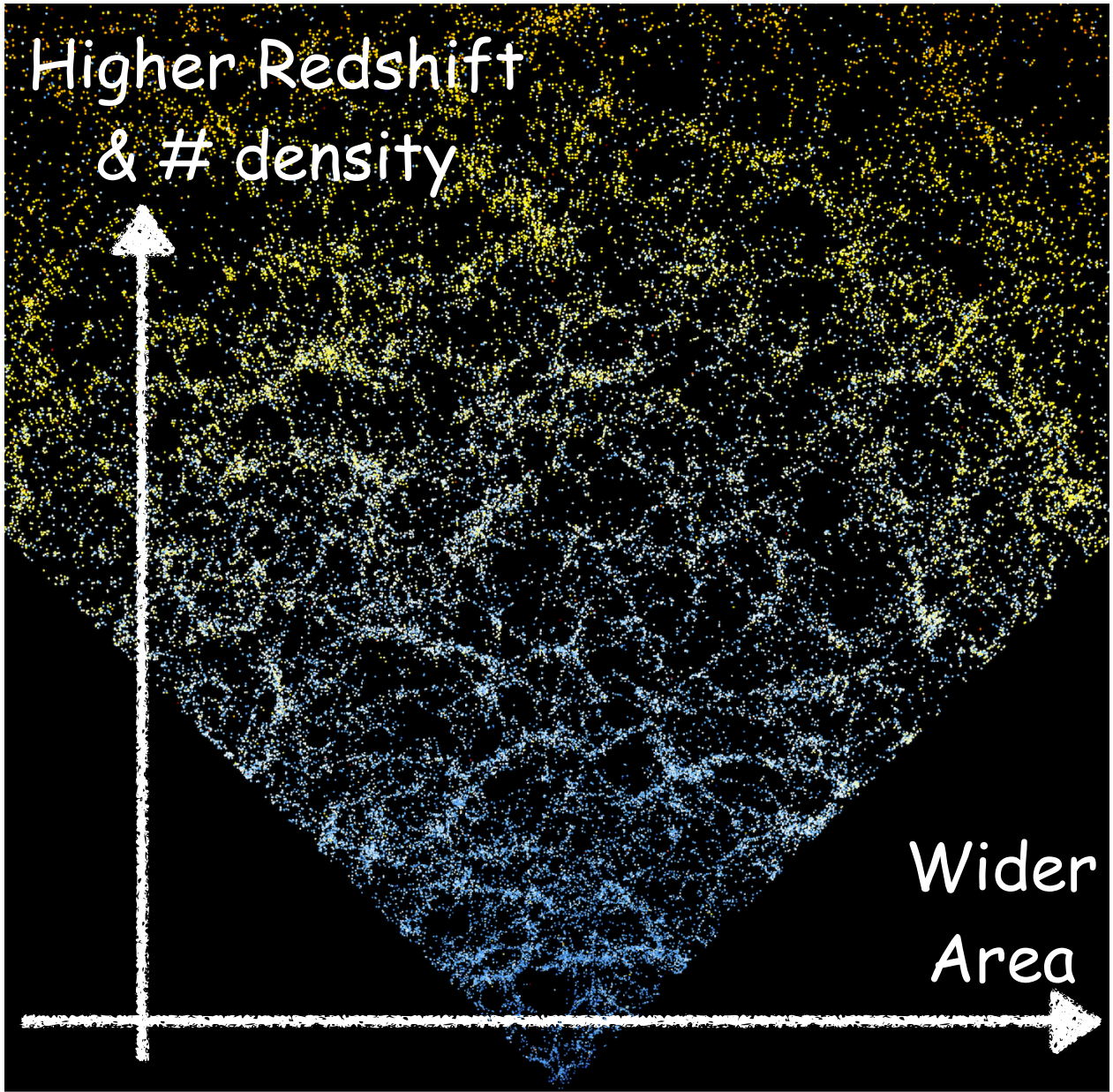
arXiv:2212.09094

Credit: SDSS, NOIRLab, NAOJ, ESA/C. Carreau, NASA

Galaxy Map: Spectroscopic Survey Design

PFS

Roman

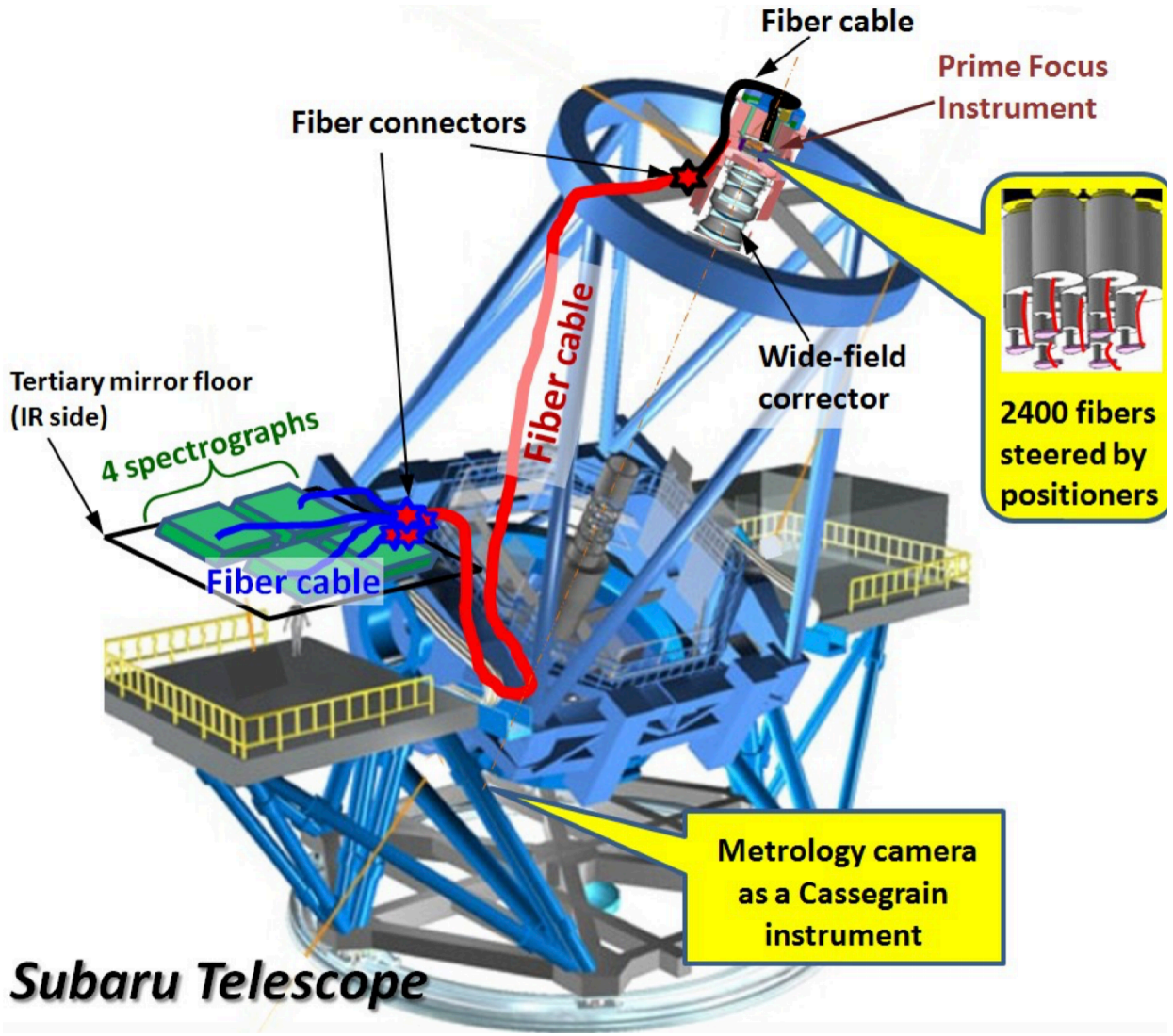


DESI

Euclid

Subaru Prime Focus Spectrograph (PFS)

- 8.2m diameter telescope on Maunakea, Hawaii (median seeing 0.6 arcsec)
- Fiber-fed spectrograph fed by Subaru wide-field corrector
- 2400 fibers over 1.25 sq deg FOV at prime focus
- Optical-NIR coverage from 380nm-1260nm
- Facility instrument for Subaru Telescope (anyone with Subaru access can apply)
- ~4x greater spectroscopic efficiency than DESI (N_{fiber} x Mirror Area / D_{fiber}^2)



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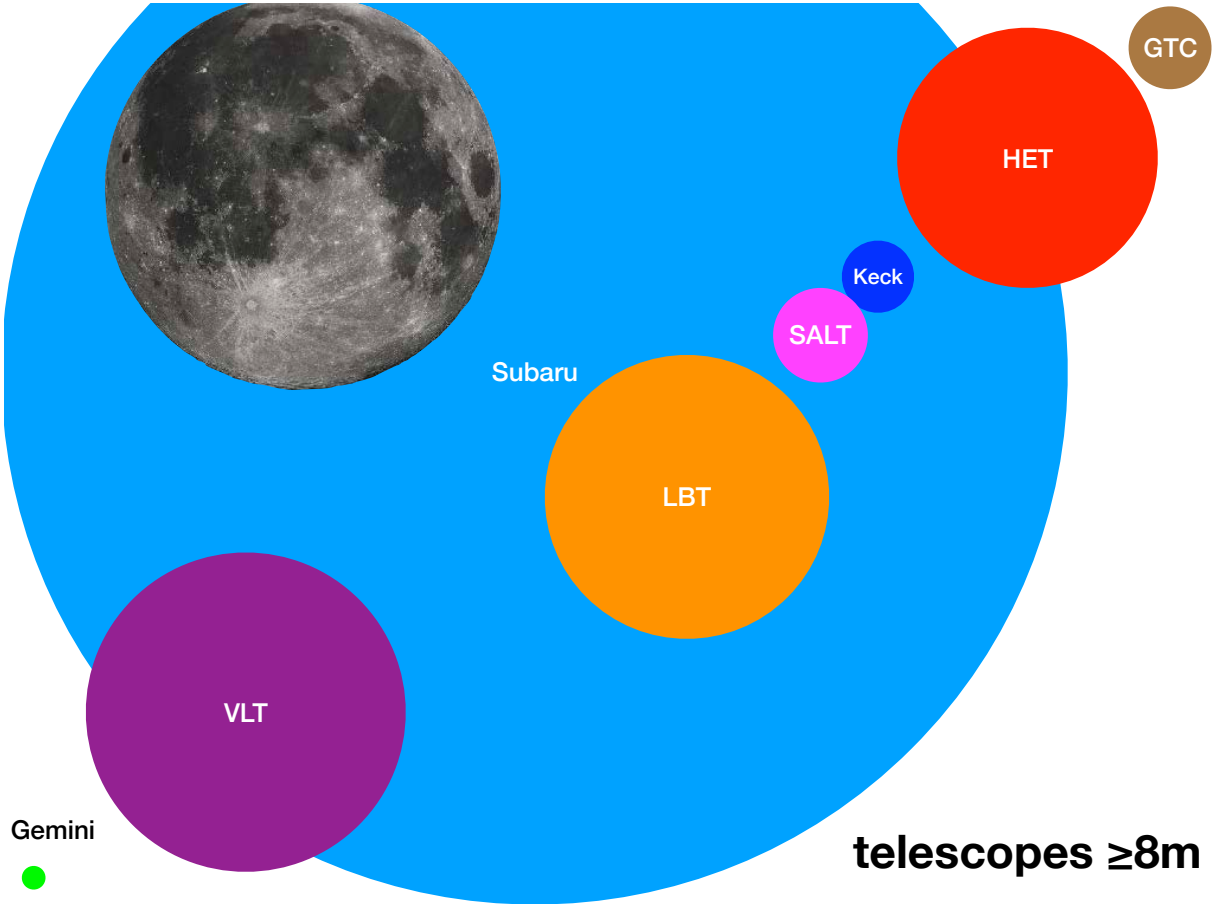

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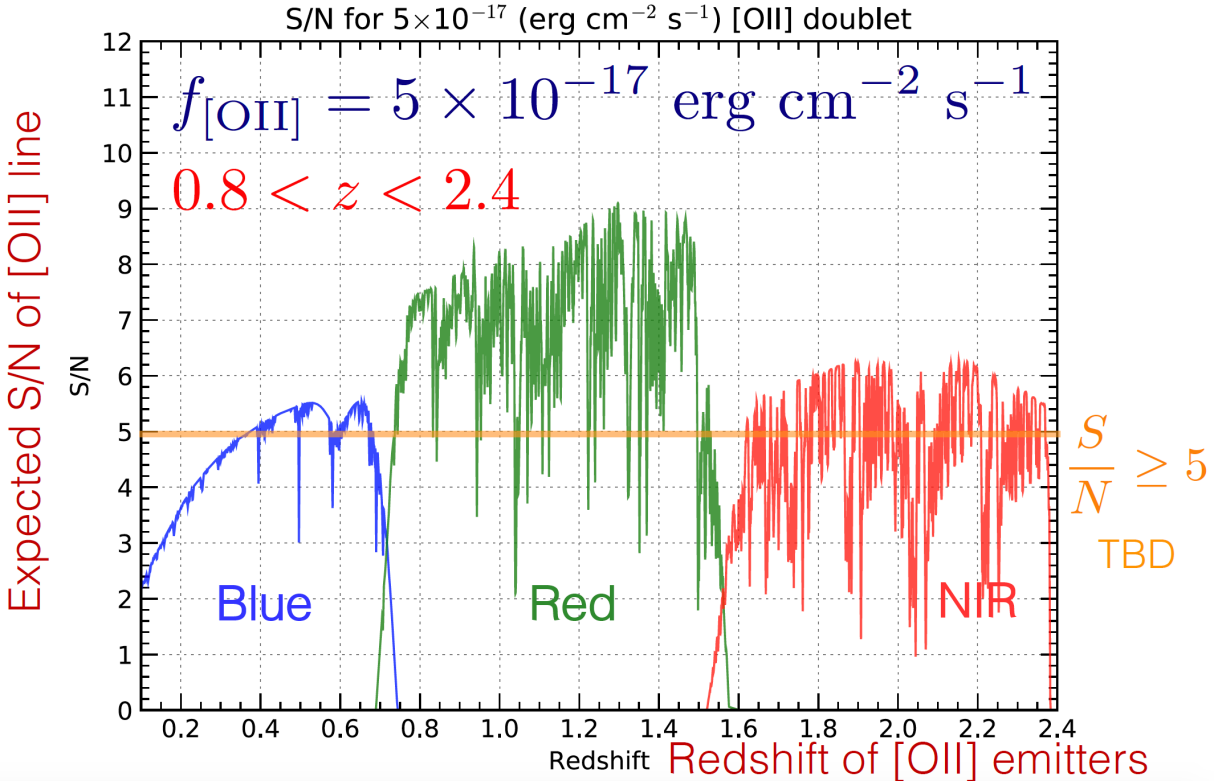
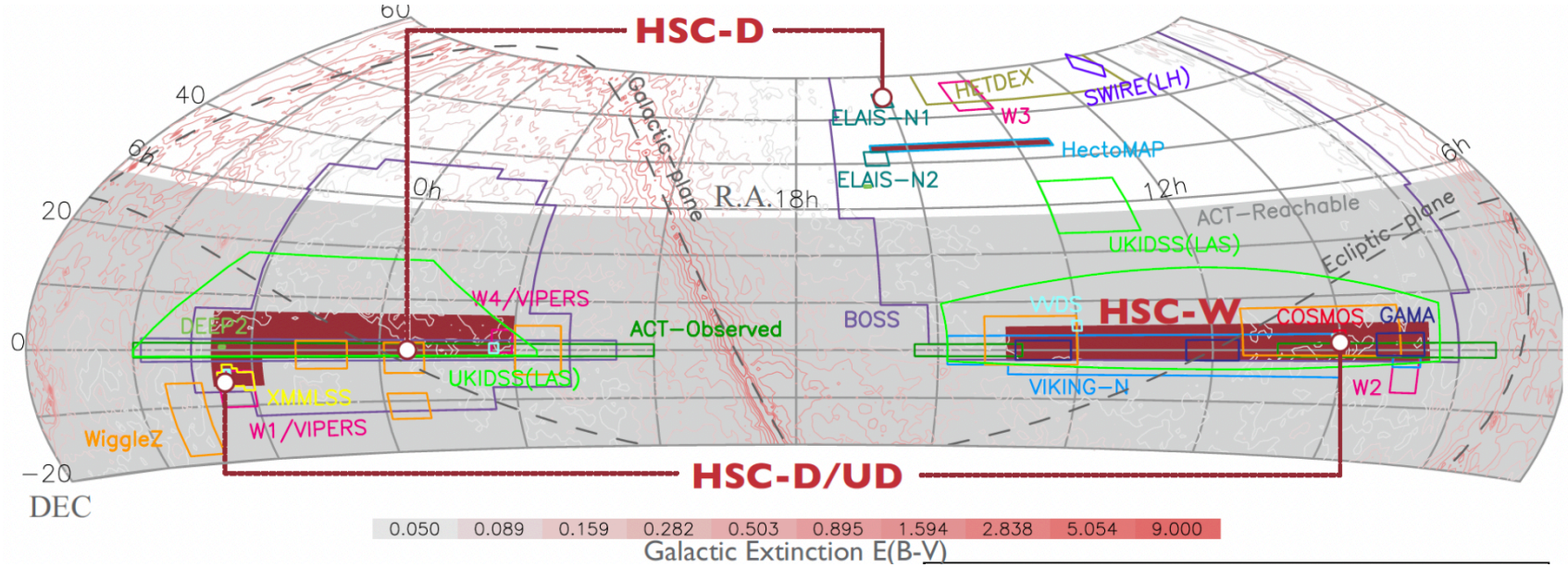
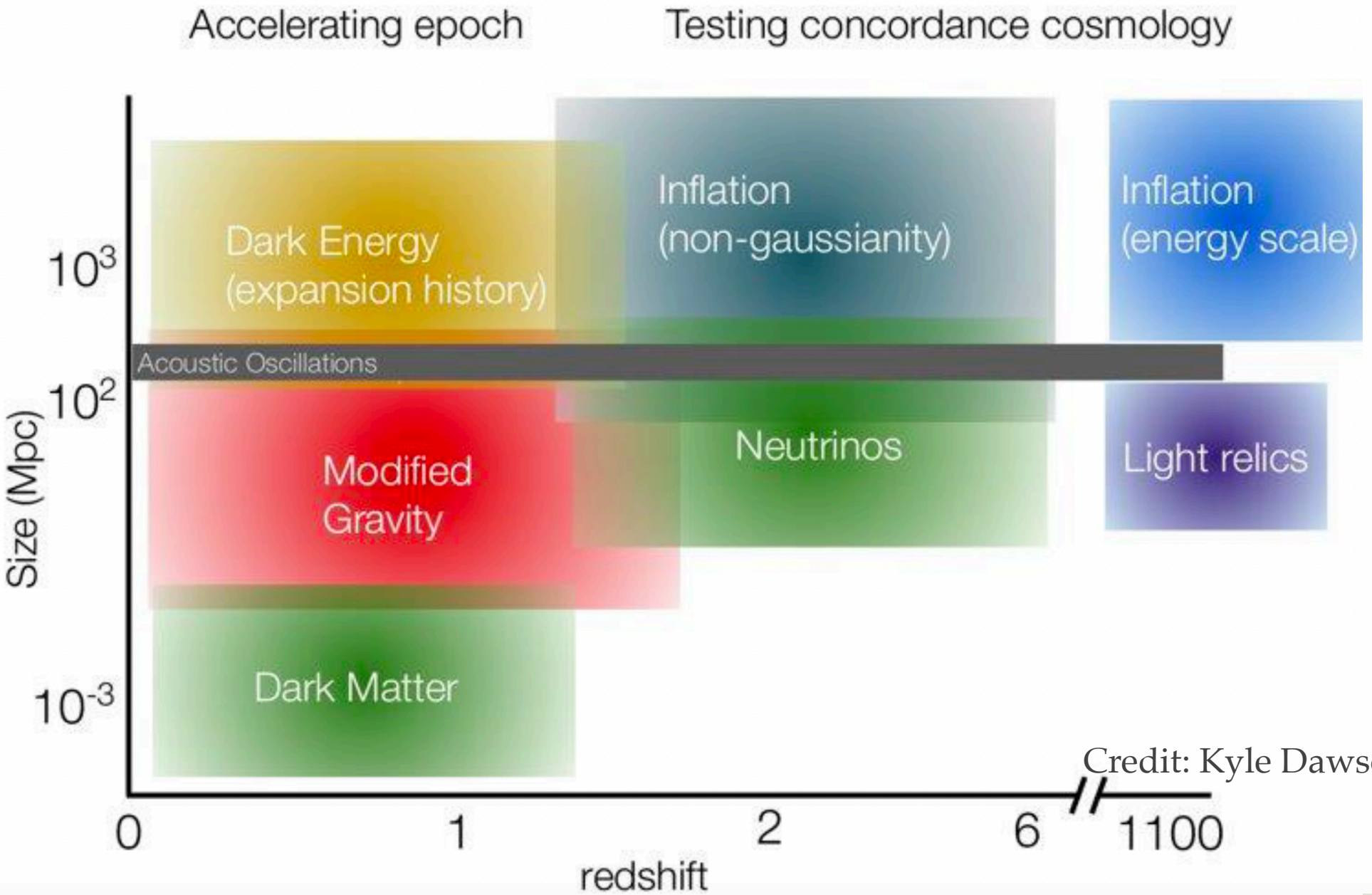


Survey Design of PFS Cosmology Program



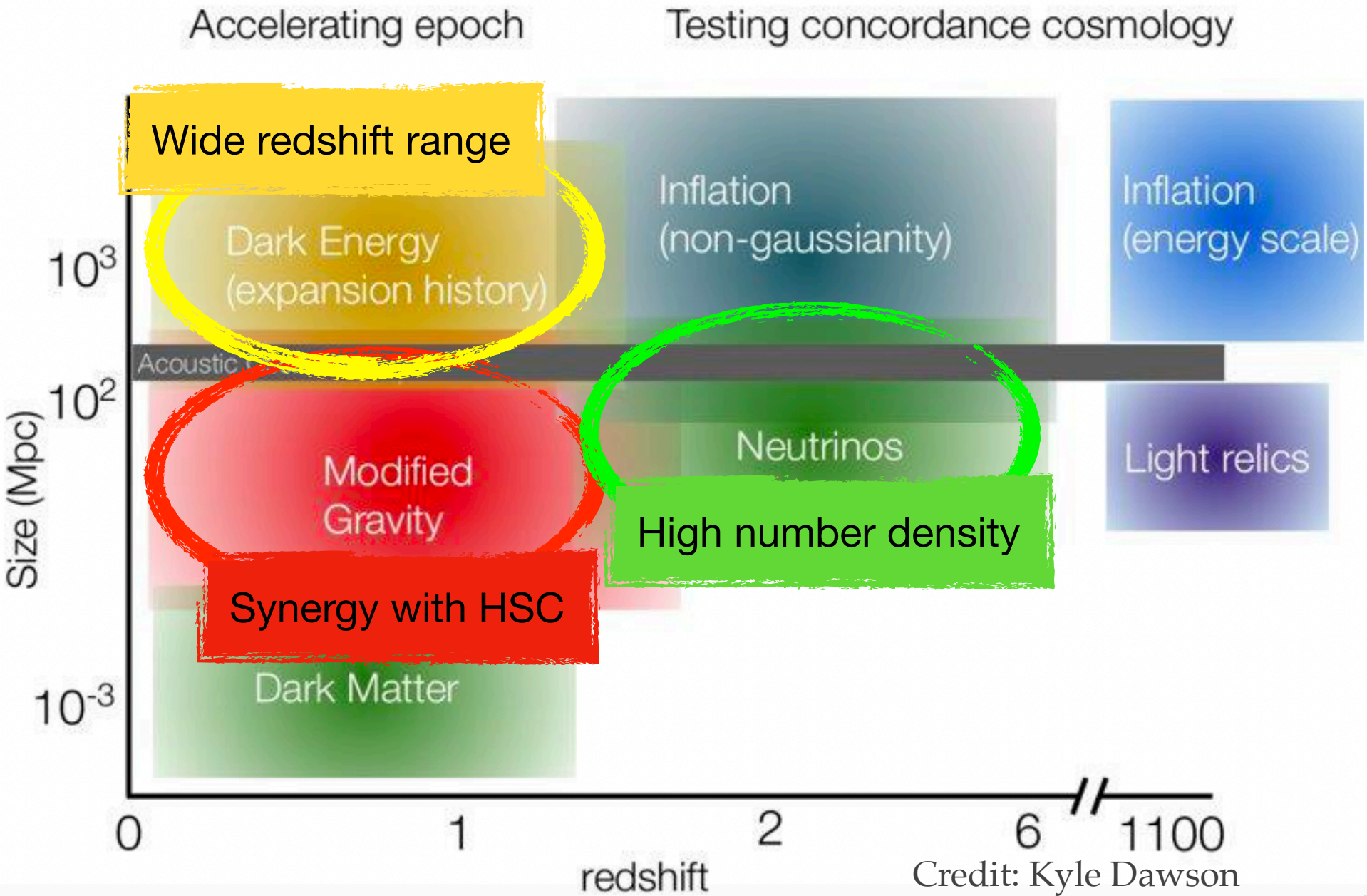
- Accurate and robust cosmological constraints using the single tracer (4 million [OII] emission line galaxies) to map evolution of the large-scale structure of the Universe in a wide range of redshifts, $0.6 < z < 2.4$, over 1200 deg^2
- With 100 nights, we will visit the same area twice with 15mins of exposure time
- Other galaxy surveys only go to z=1.6 (DESI) and z=2.0 (Euclid), meaning 2<z<2.4 is a unique redshift range of the PFS cosmology program thanks to NIR camera

Discovery Space: galaxy surveys are trying to explore…



Credit: Kyle Dawson

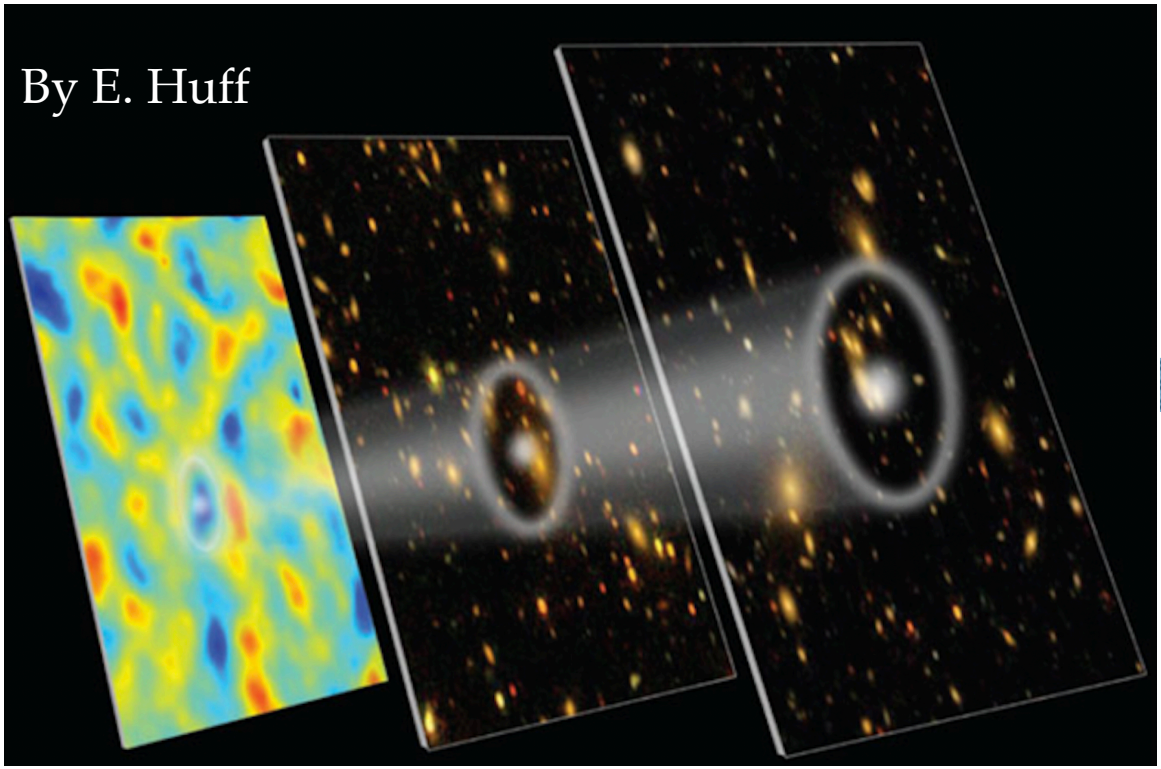
Three unique aspects of PFS cosmology program

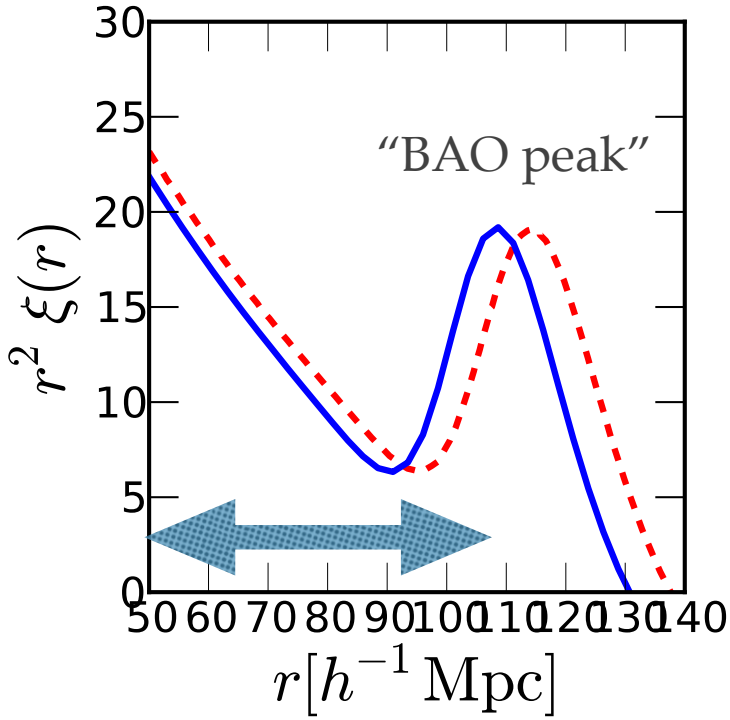


Credit: Kyle Dawson

Baryon Acoustic Oscillations (BAO)

Standard Ruler

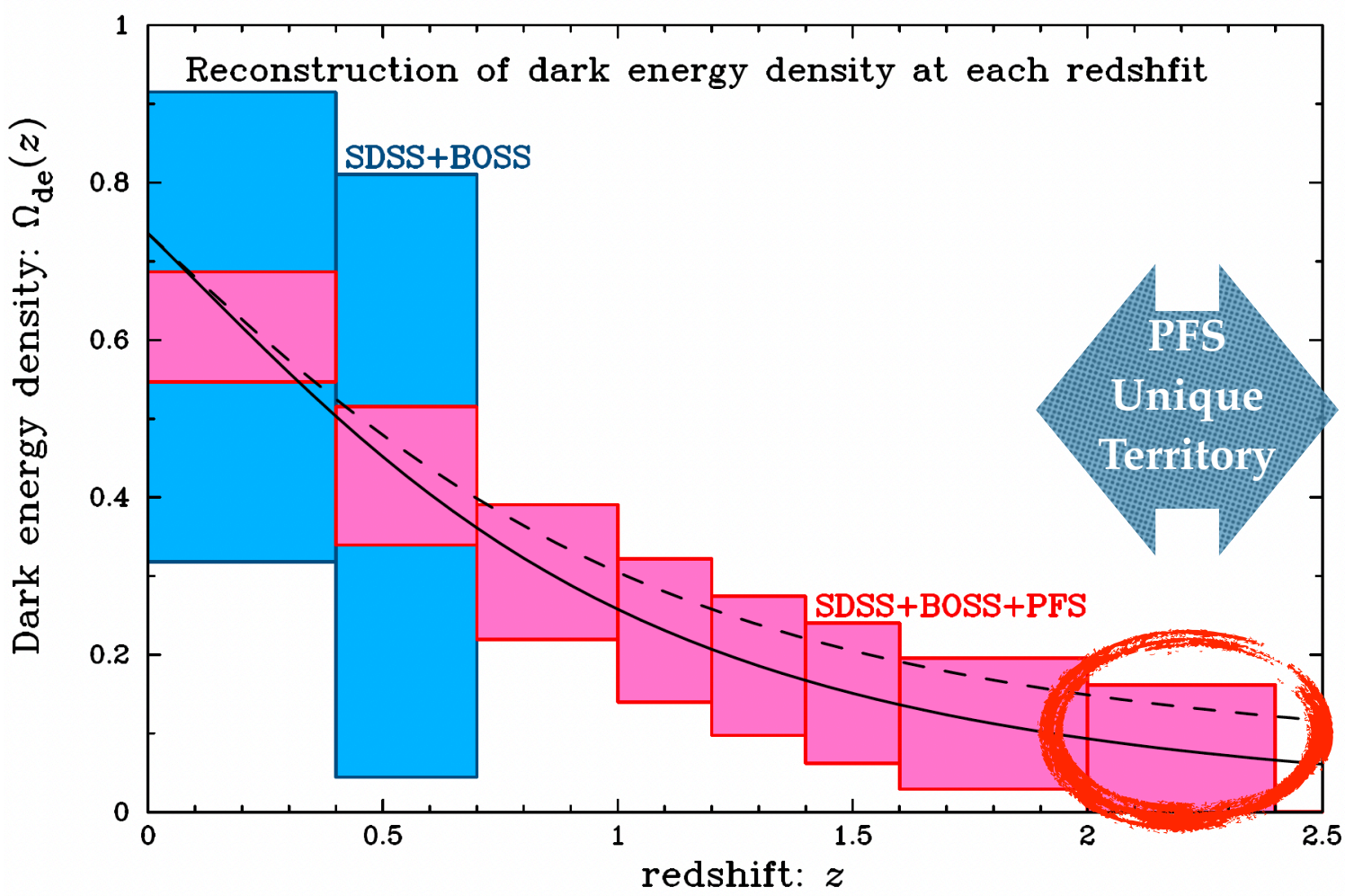




- Imprint of sound waves frozen in the early Universe
- Scale set by sound horizon and does not change in time, but depends on the amount of dark energy

PFS can measure Dark Energy…

- $\Omega_{\rm DE}(z)$ to about 7% accuracy in each redshift bin
- We can test the evolution of the Universe with a single tracer!



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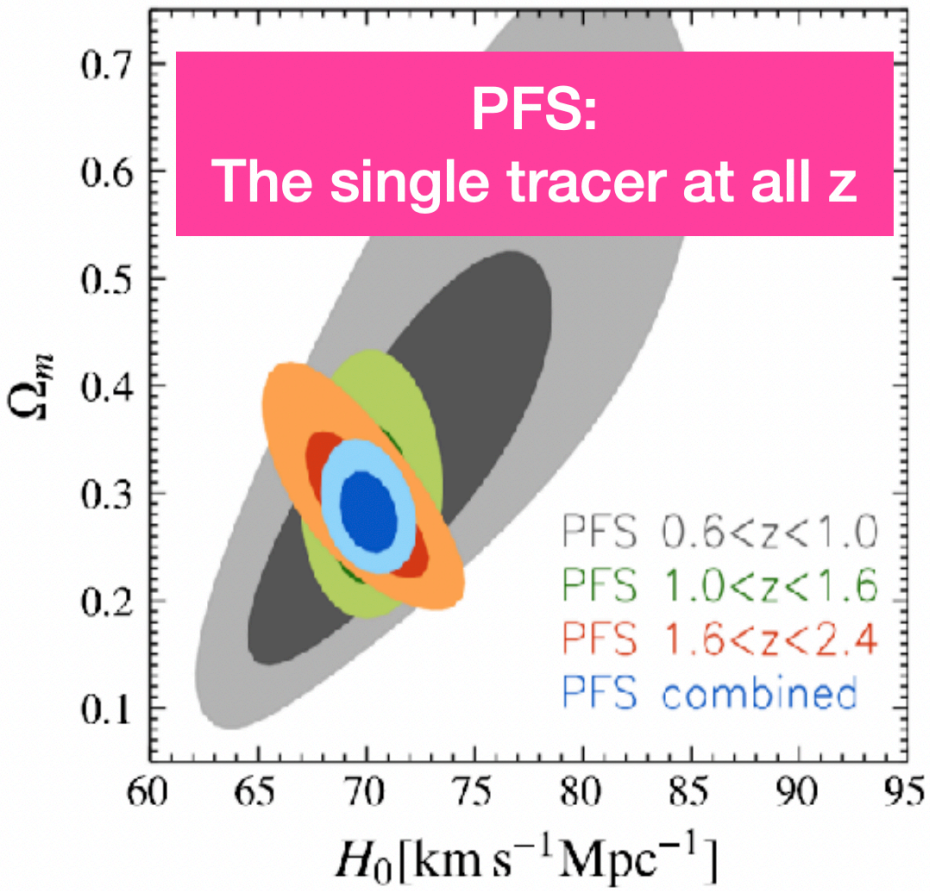
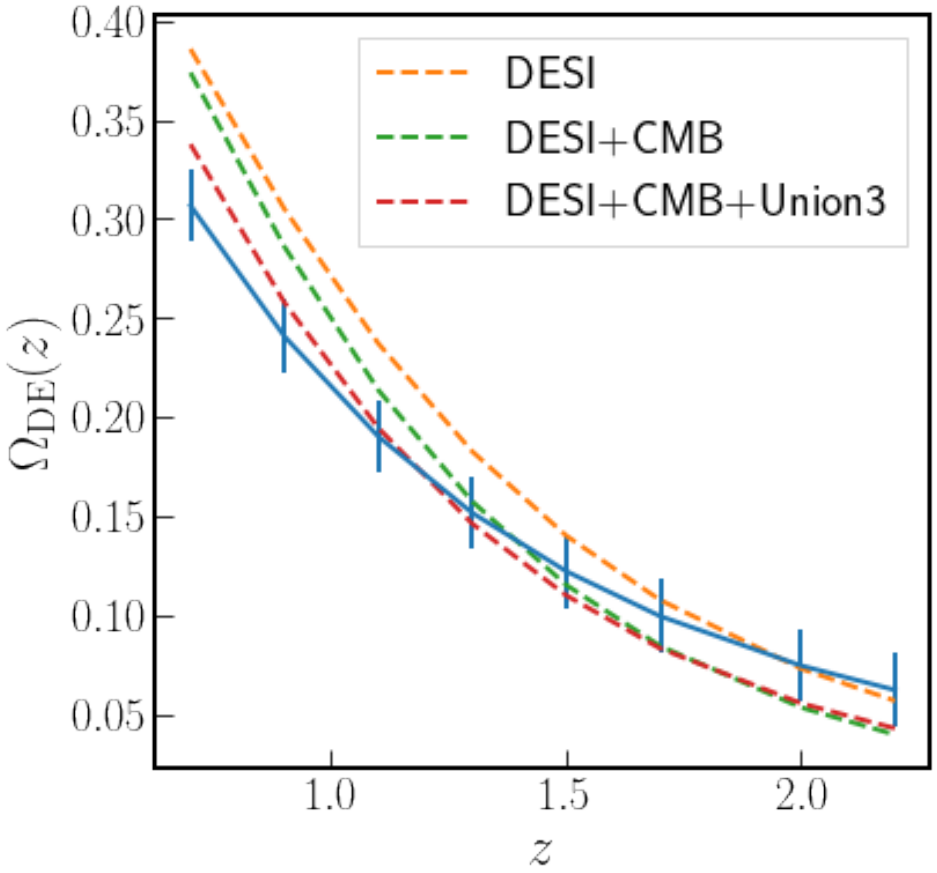
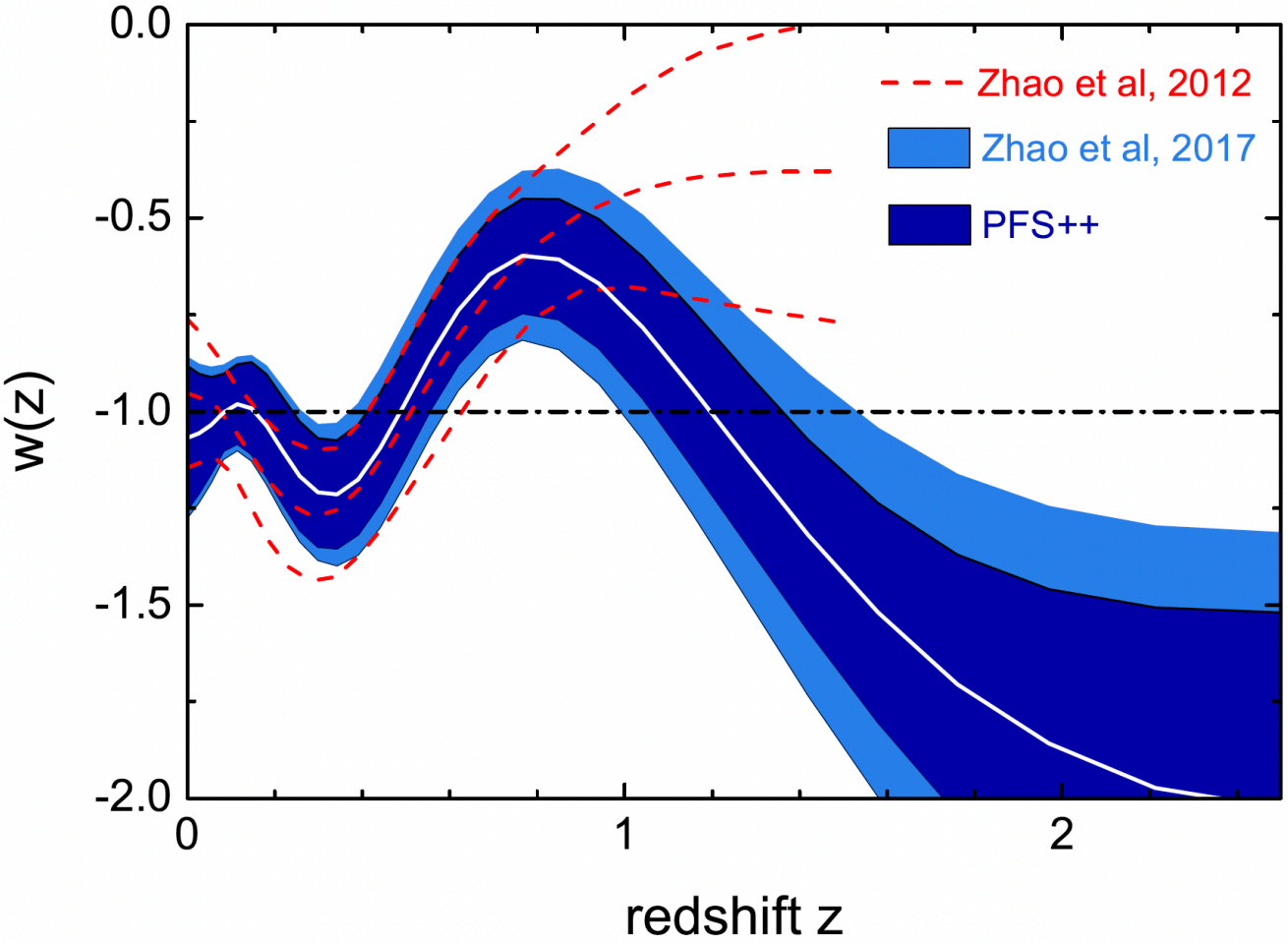


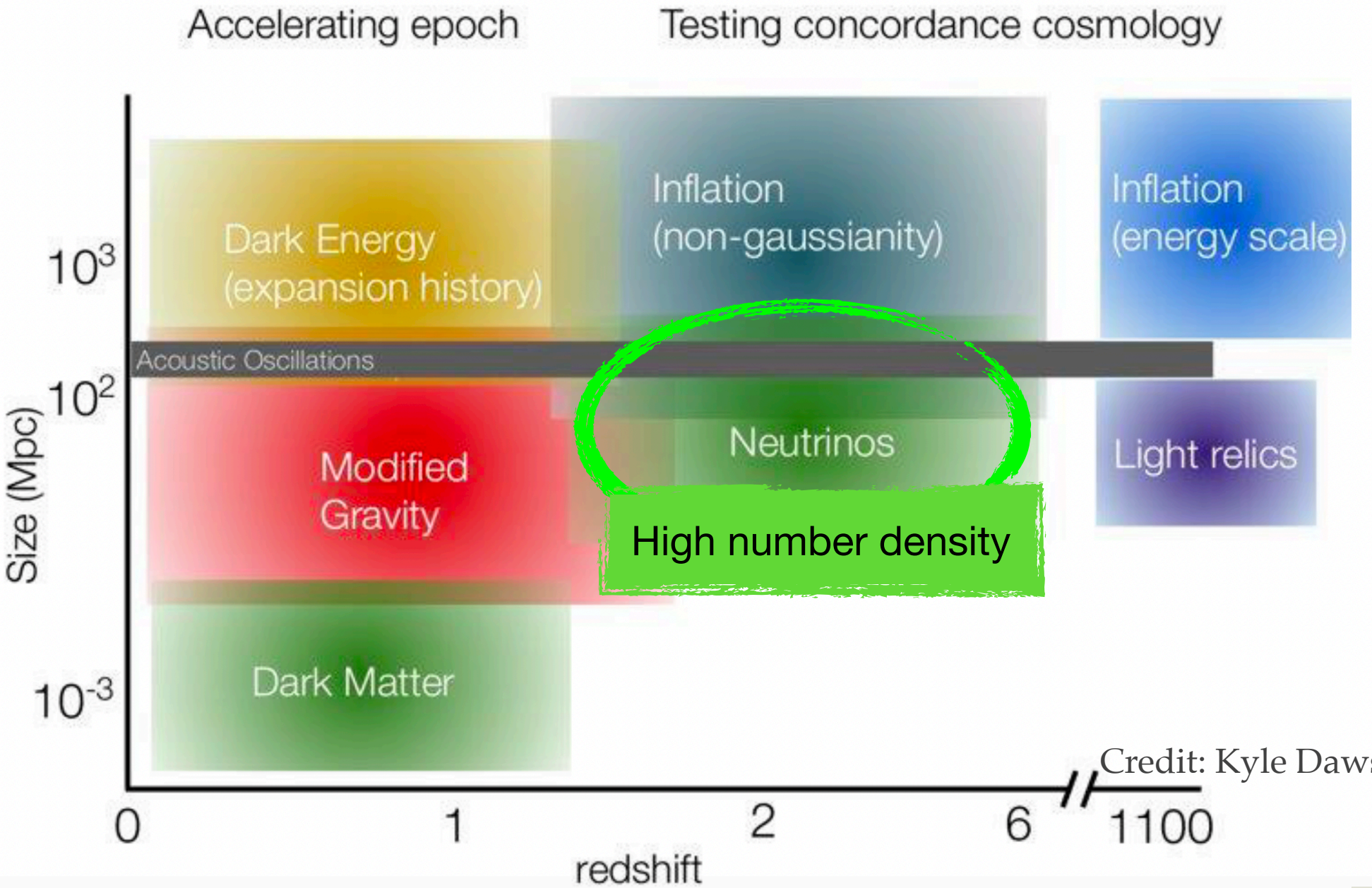


Discovery Potential: Time Evolving Dark Energy

There is a significant theoretical motivation for dark energy potentials with periodic modulations.



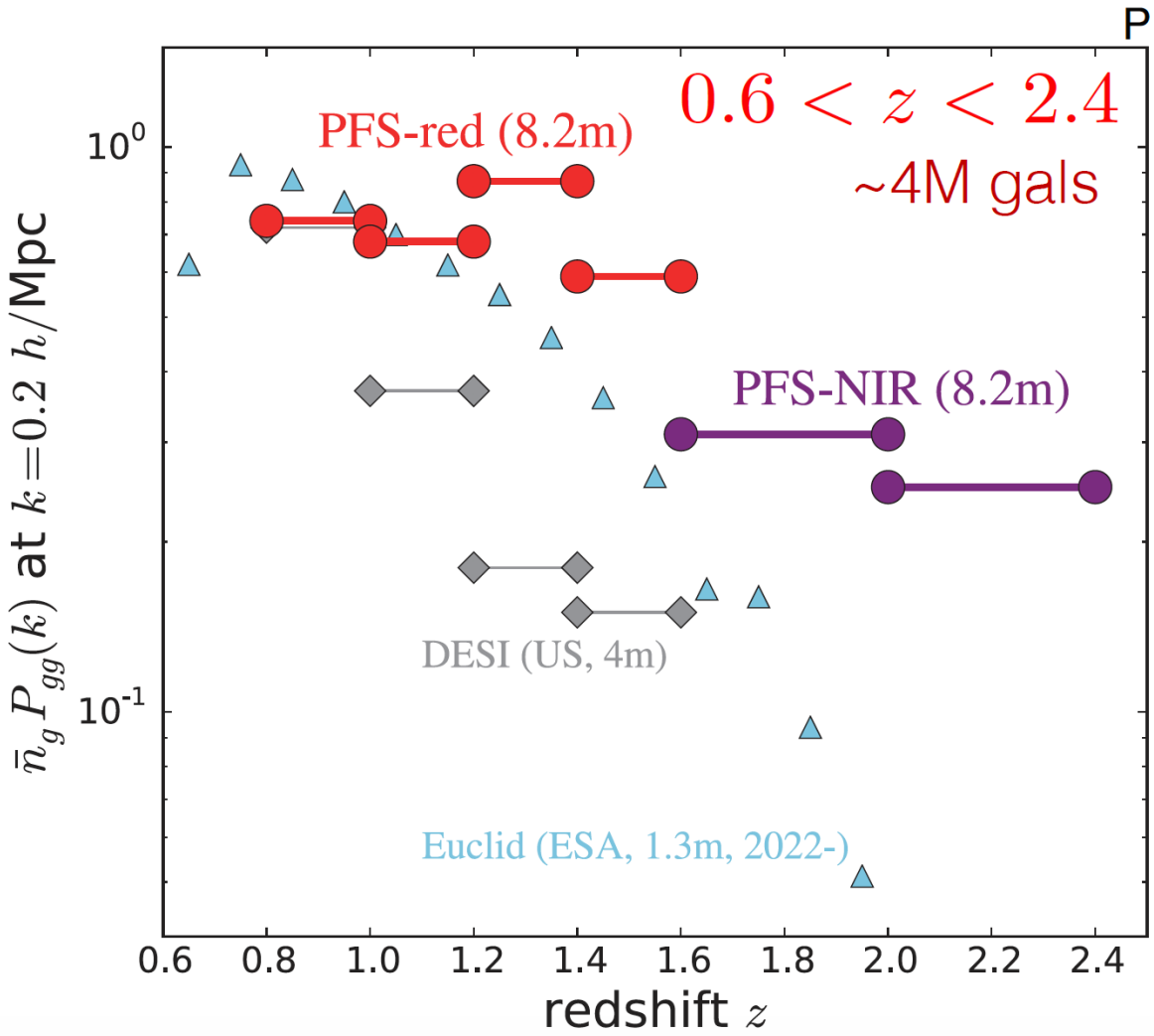
Three unique aspects of PFS cosmology program

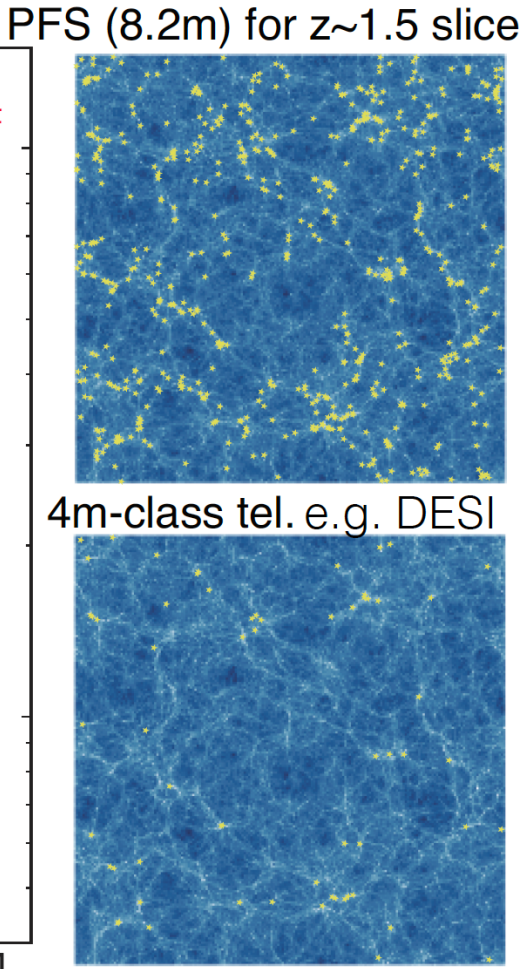


Credit: Kyle Dawson

High-number density=can push to smaller scales

- PFS Cosmology program keep the high-number density at 0.6<z<2.4, which enables us to use small scale clustering.

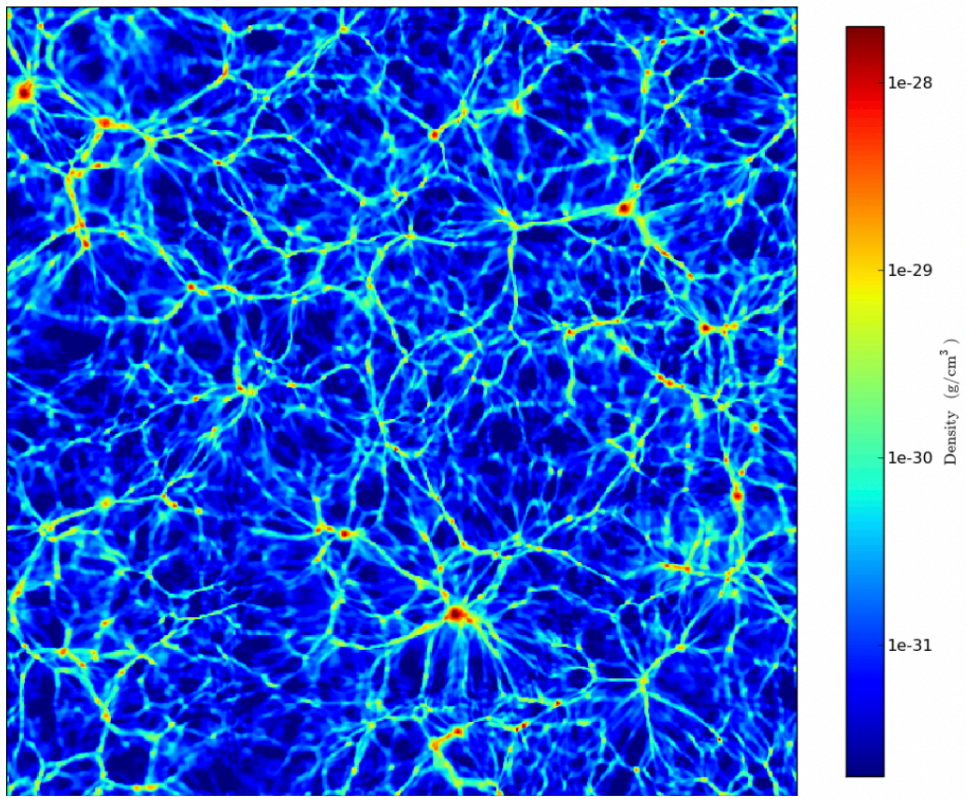




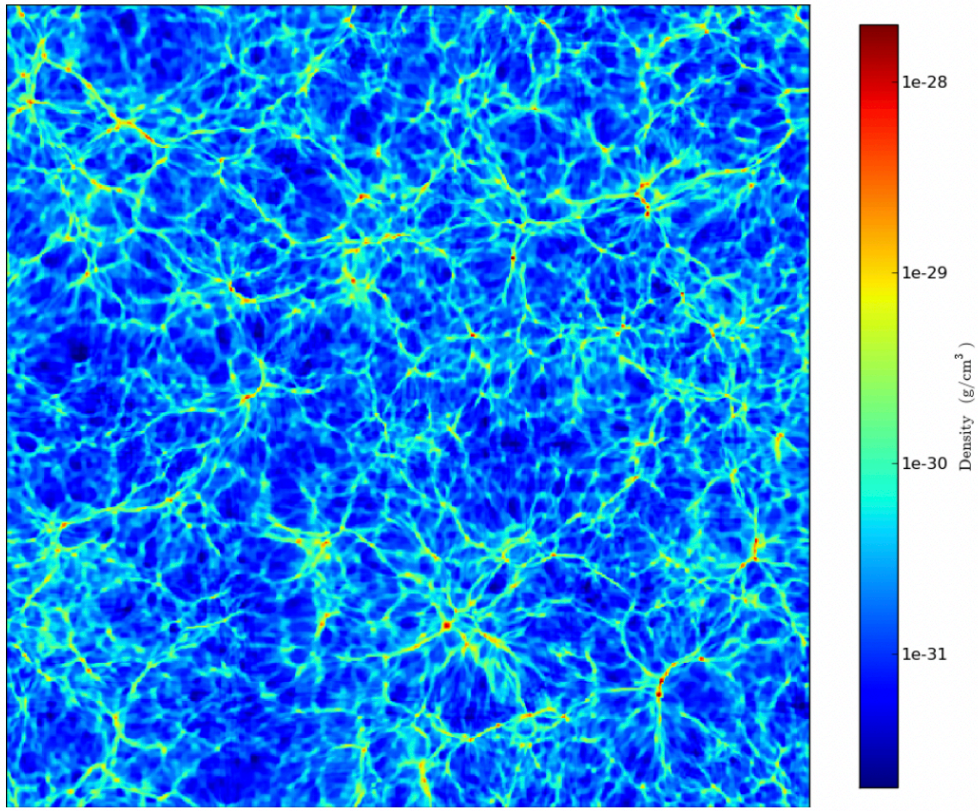
What does neutrino do on large scale structure?

Neutrinos decoupled when they were still relativistic, hence they wiped out structure on small scales

Without Neutrinos



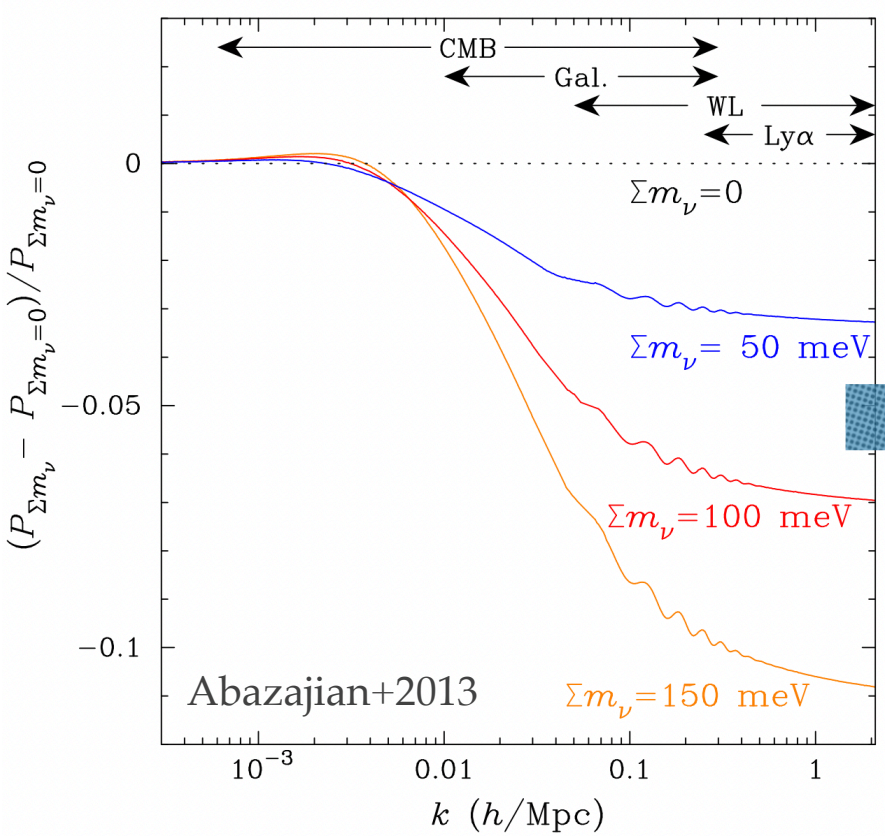
With Neutrinos

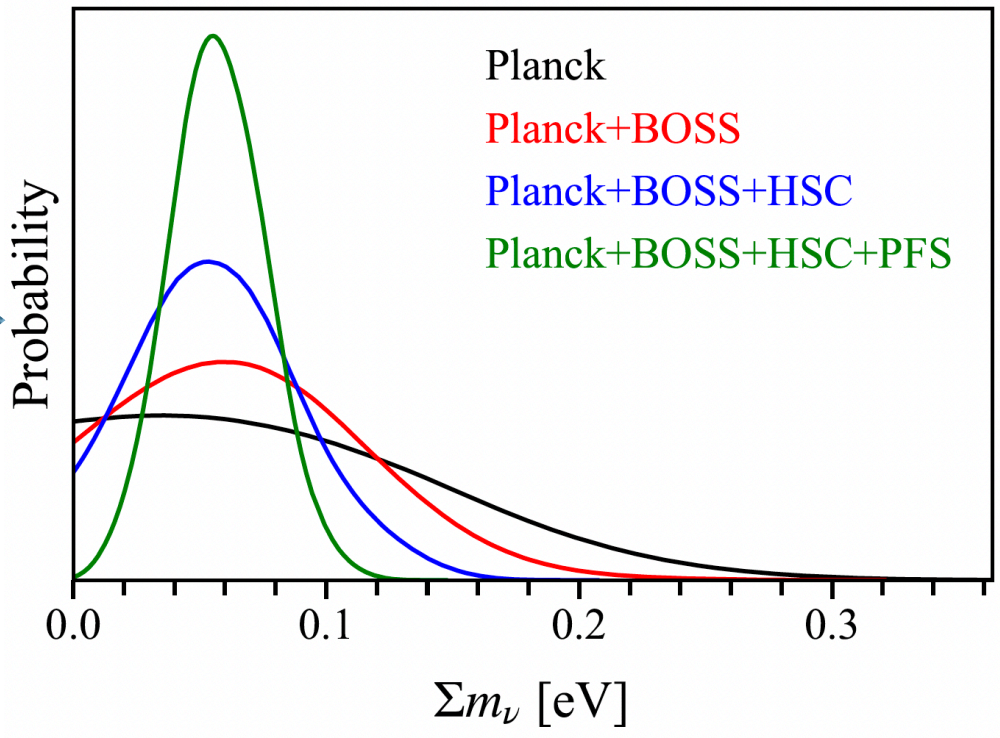


Agarwal&Feldman 2010

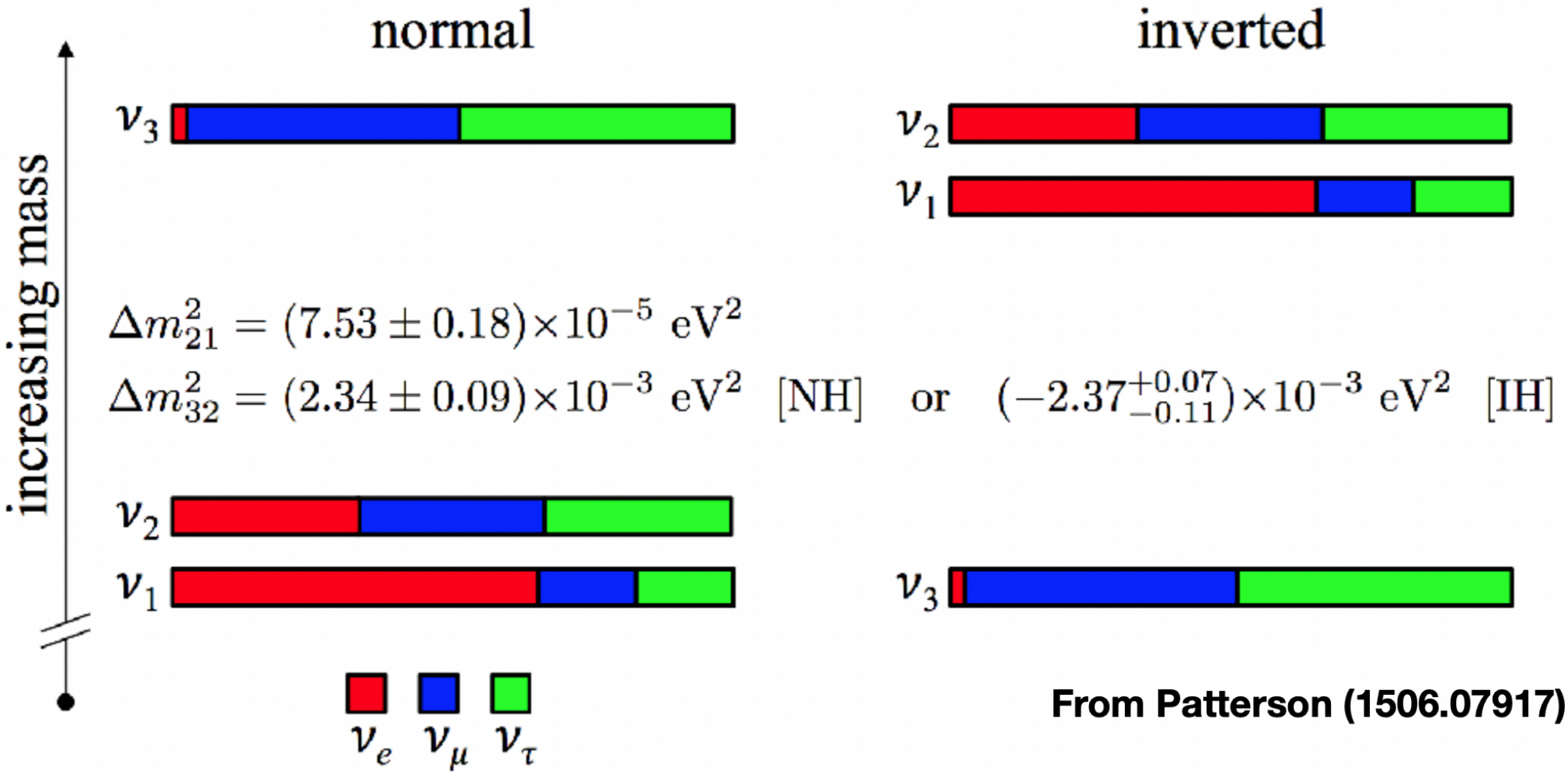
Neutrino Mass Constraint

- Neutrinos suppress power spectrum (clustering of galaxies)
- PFS can achieve $\sigma(\Sigma m_\nu) = 0.02\mathrm{eV}$!





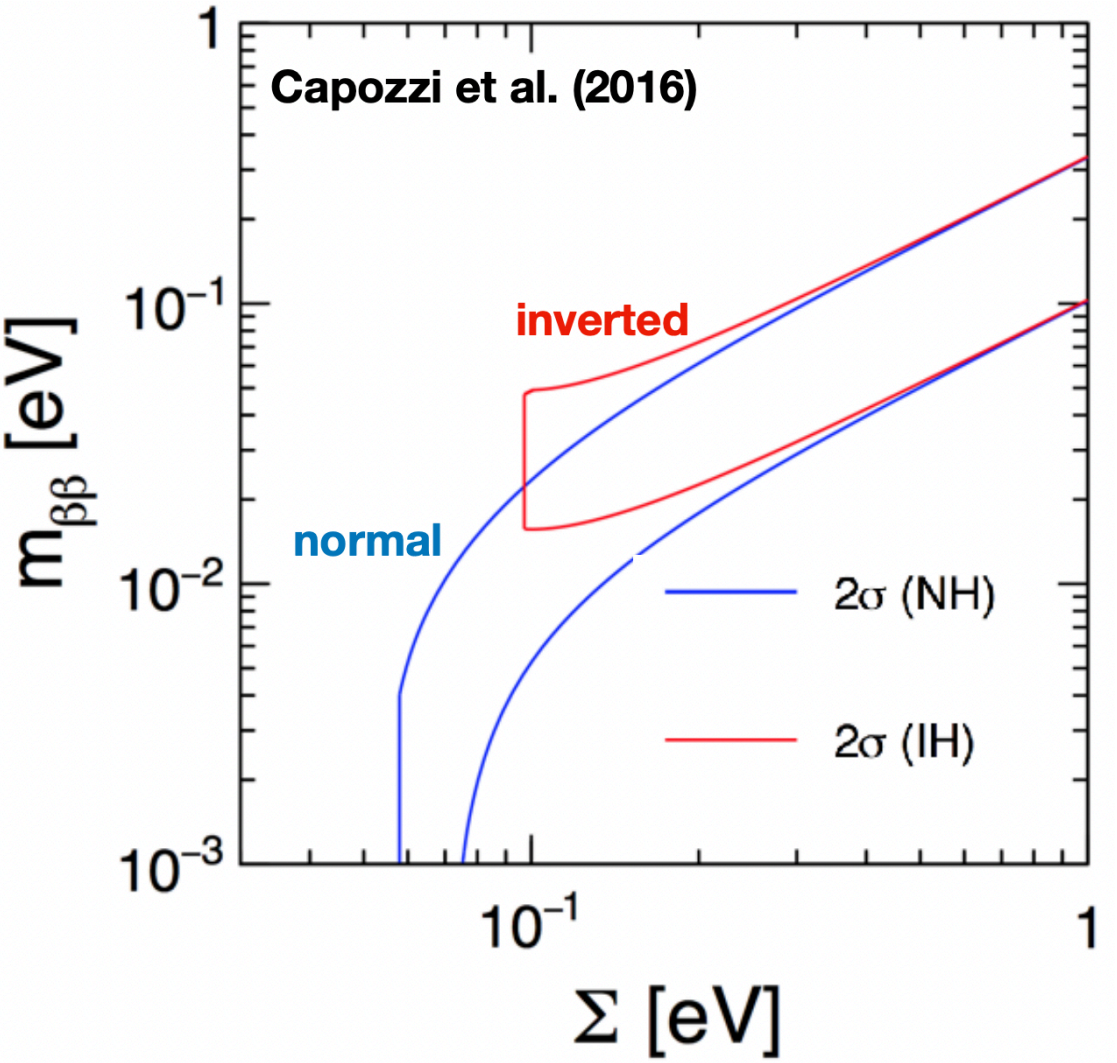
Neutrino Mass Hierarchy



From Patterson (1506.07917)

$\Sigma m_\nu = 0.06\text{eV}$ $\Sigma m_\nu = 0.1\text{eV}$

$\sum m_\nu = 0.1\mathrm{eV}$ is a key to test the hierarchy



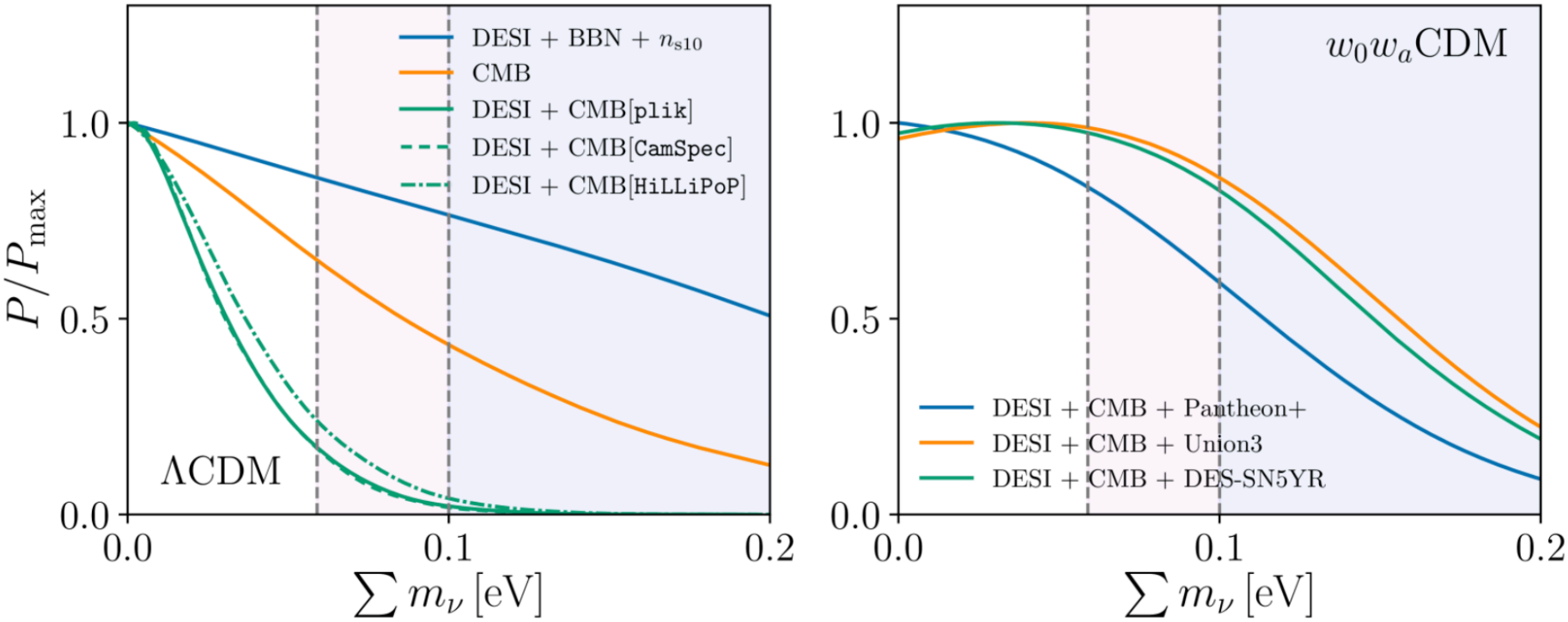
- Deciding the mass hierarchy sets a concrete target for the neutrino-less double beta decay experiments
- Can test whether neutrinos are Dirac or Majorana

Neutrino Mass Constraints

DESI Y1 Full-shape analyses

Based on the DESI Y1 BAO and full-shape analysis, the neutrino mass is constrained to

- $\sum m_\nu < 0.409$eV(95%) without CMB and $\sum m_\nu < 0.071$eV(95%) with CMB under ΛCDM
- $\sum m_\nu < 0.175$eV(95%) with CMB under w0-wa CDM



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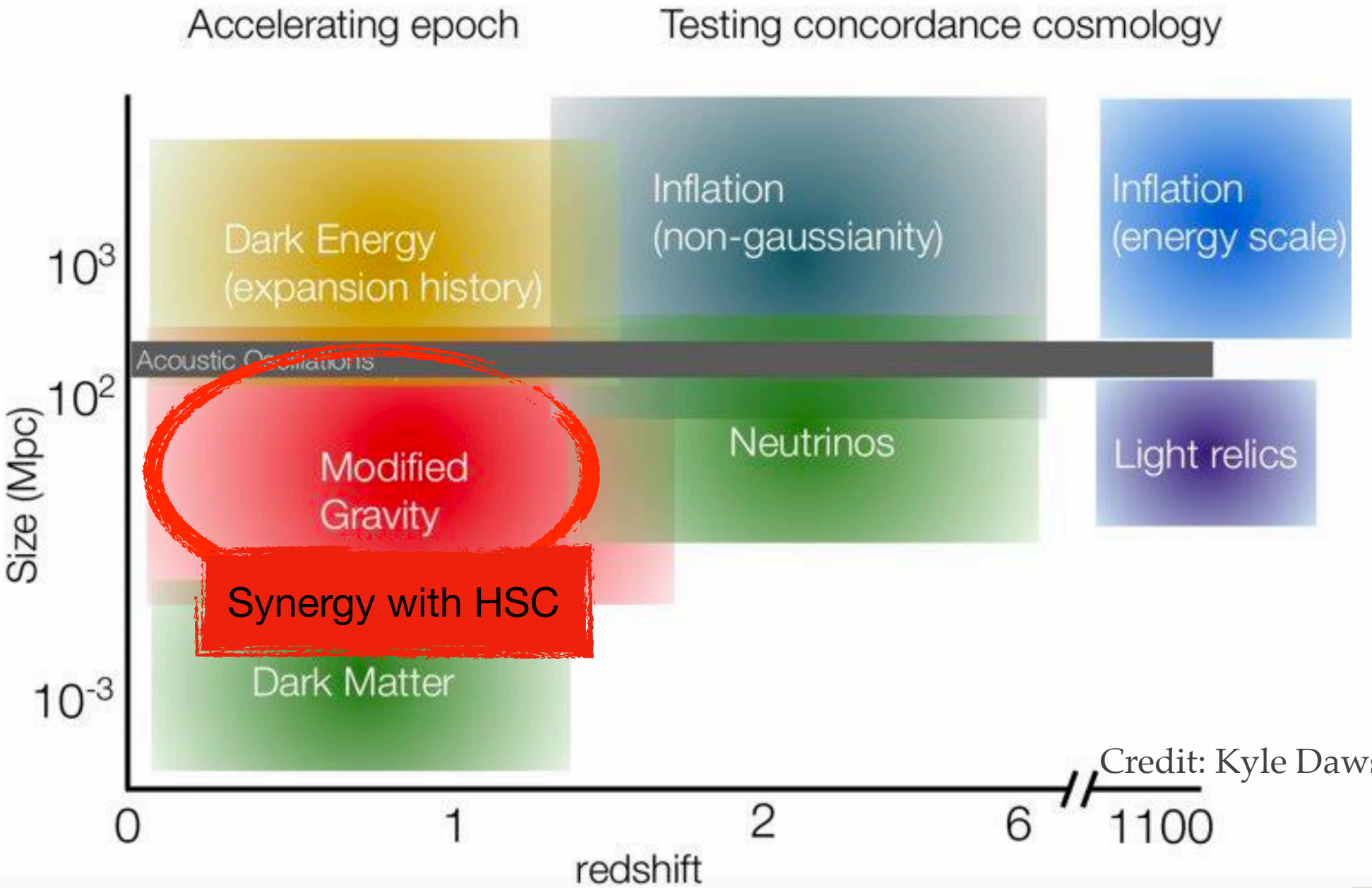


Credit: Kyle Dawson

Redshift-Space Distortion (RSD)

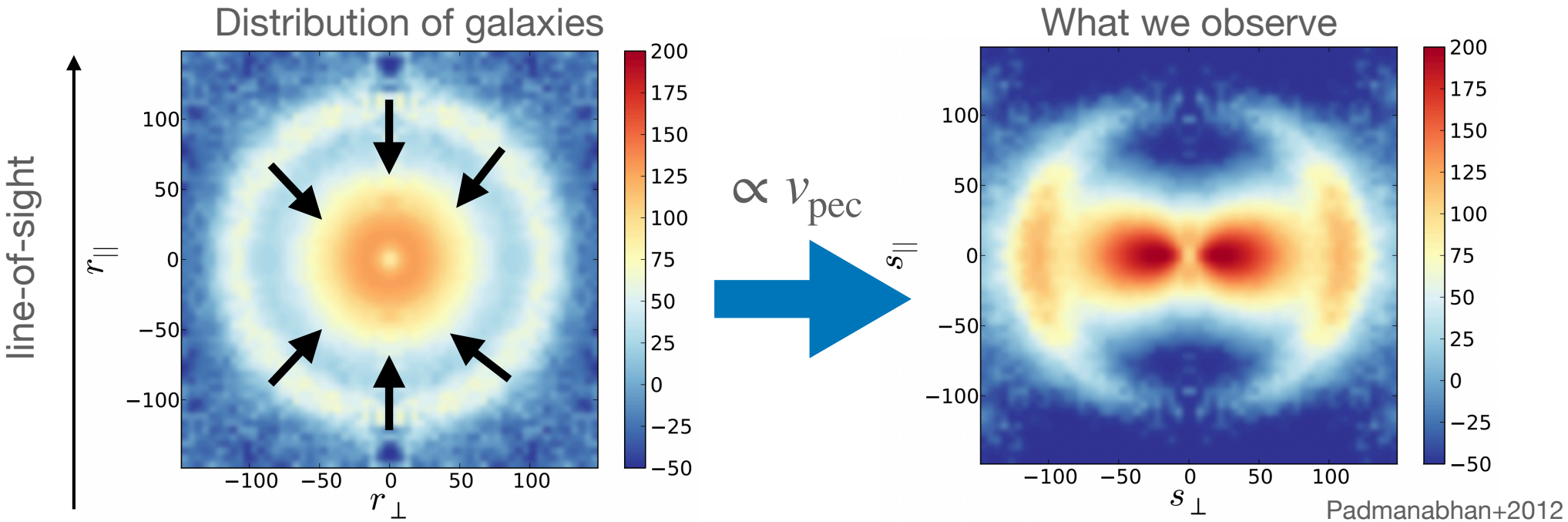
- Redshift is a combination of Hubble expansion and peculiar motion of galaxies → isotropic galaxy distribution becomes anisotropic in redshift-space

$$cz = H_0 r + v_{\rm pec}$$

Redshift "What we measure"

Expansion of the Universe

Motion of Galaxies



Padmanabhan+2012

Redshift-Space Distortion (RSD)

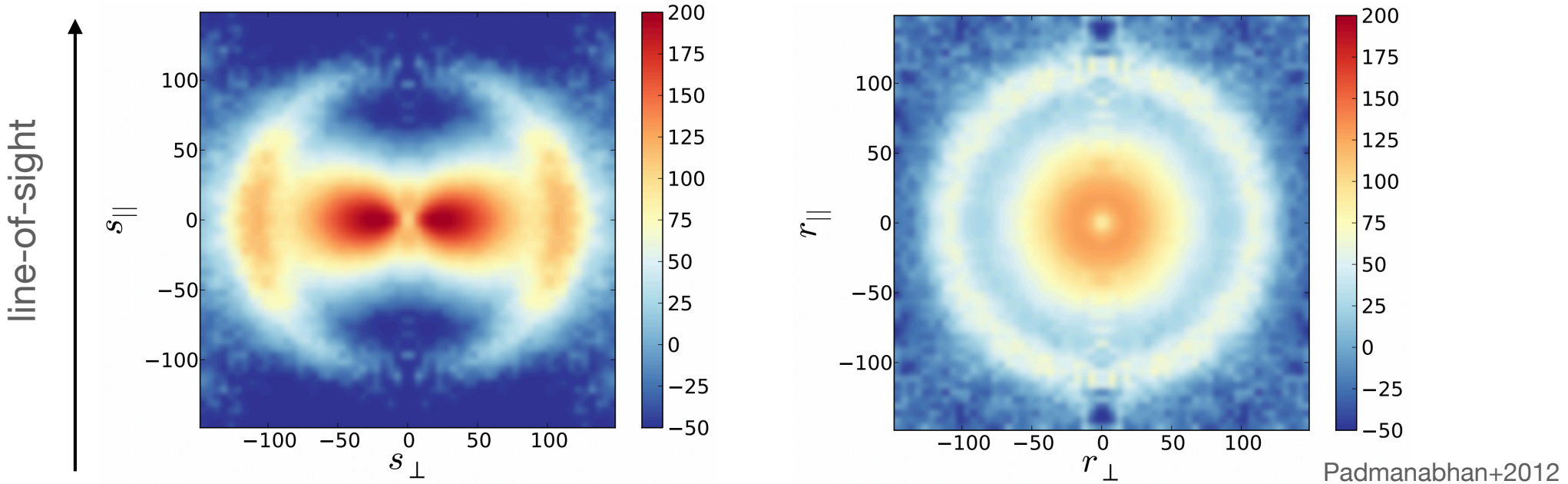
- On large scales, peculiar velocity can be computed as a function of growth rate

$$|v_{\rm pec}| \sim \frac{d\sigma_8}{d\ln a} = f\sigma_8 \quad \text{where} \quad f = \frac{d\ln\sigma_8}{d\ln a} \approx \Omega_m^{\gamma}$$

$$\delta_g^{(s)}(k,\mu) = (b + f\mu^2)\delta_m^{(r)}(k)$$

"redshift-space"(s) "real-space"(r)

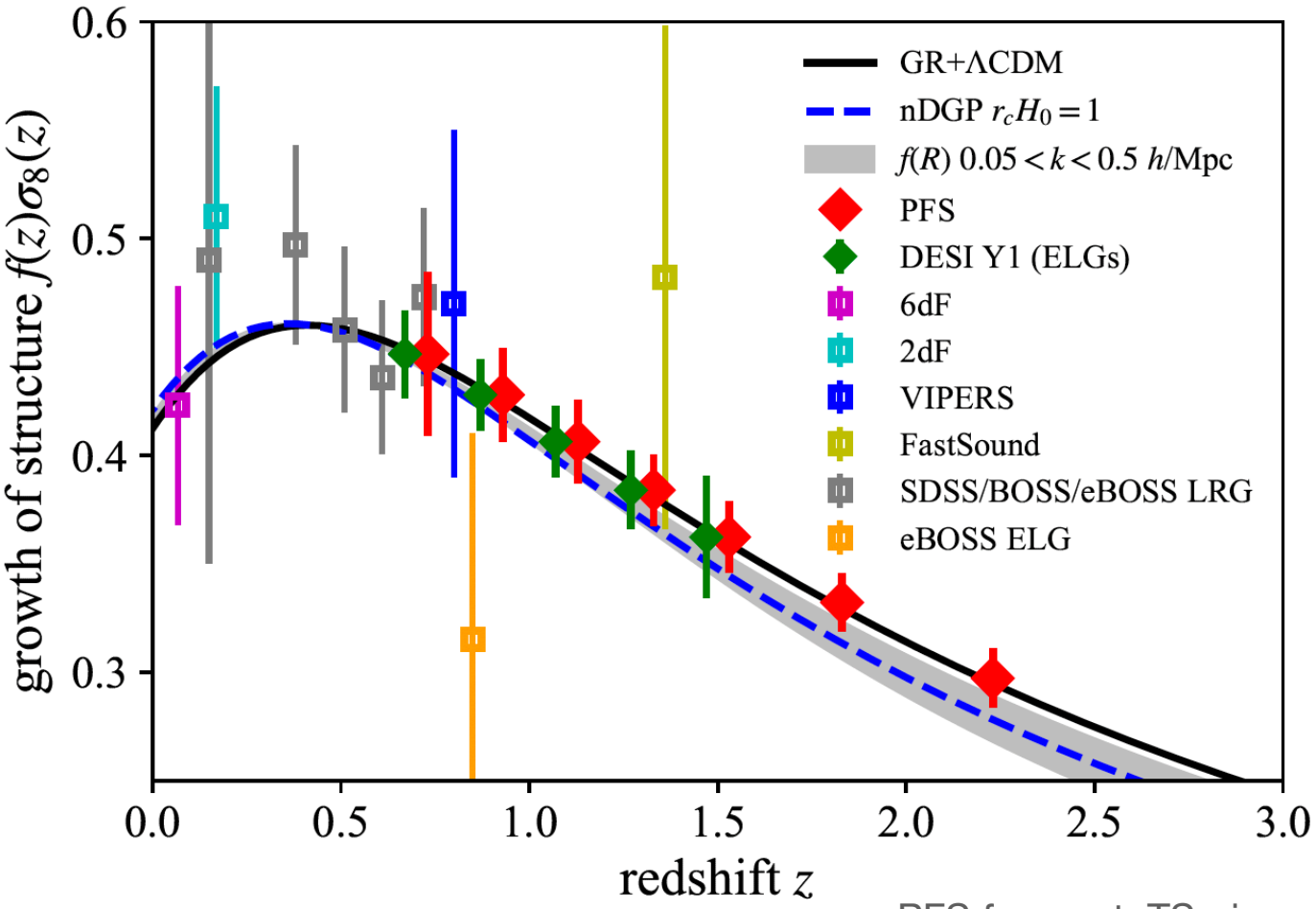
μ is angle between r and LOS



Padmanabhan+2012

Forecast for DESI Y1 and PFS in a few years

- Can constrain the growth of structure with 6% up to z~2.4

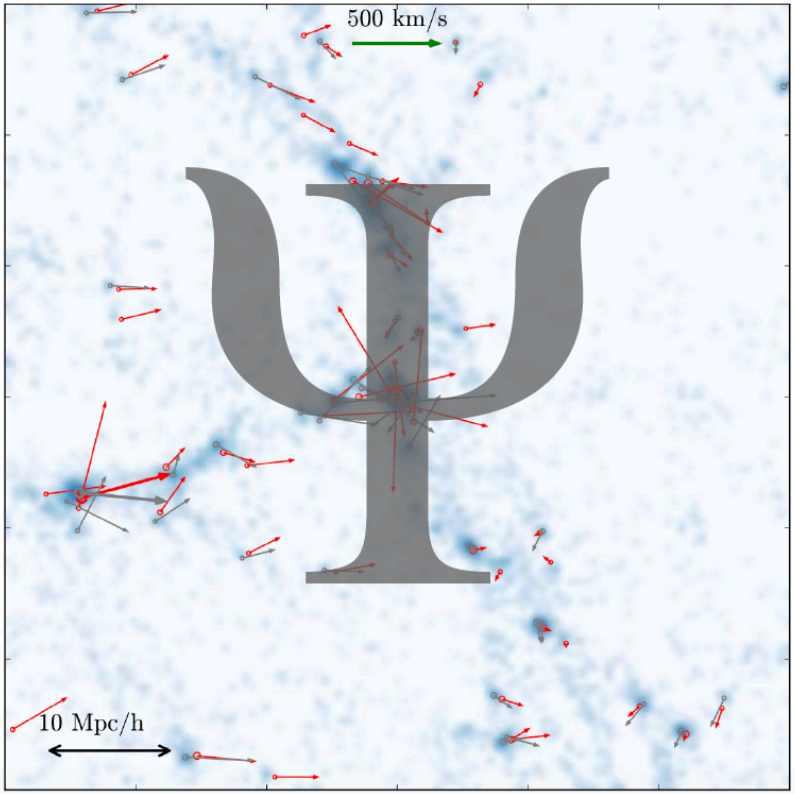


PFS forecast: TS+,in prep.

Testing theory of gravity on cosmological scales

Combining galaxy velocities and lensing

- Photons (light rays for lensing) are sensitive to $\Phi + \Psi$, and galaxies experience the Newtonian potential Ψ
- GR predicts $\Phi = \Psi$



Subaru Hyper Suprime-Cam (HSC)

Superb image quality: PSF~0.6”

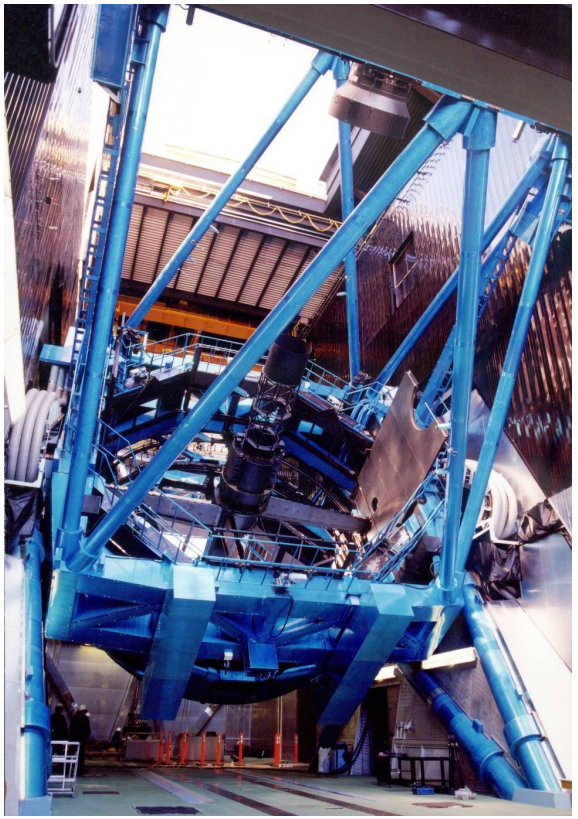
- SDSS~1.0”
- Better shape measurements

Large Field-of-View: 1.5°diameter

- ~7 x full moon
- Efficiently observe large area of sky

8.2 m primary mirror

- ~11 x light collecting power of SDSS
- Can observe high-z source galaxies



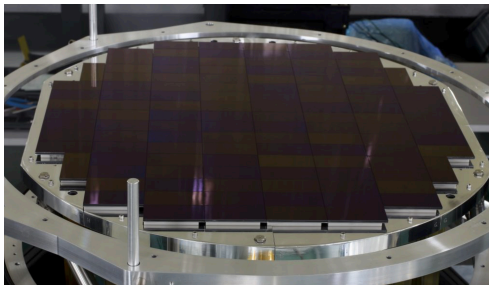
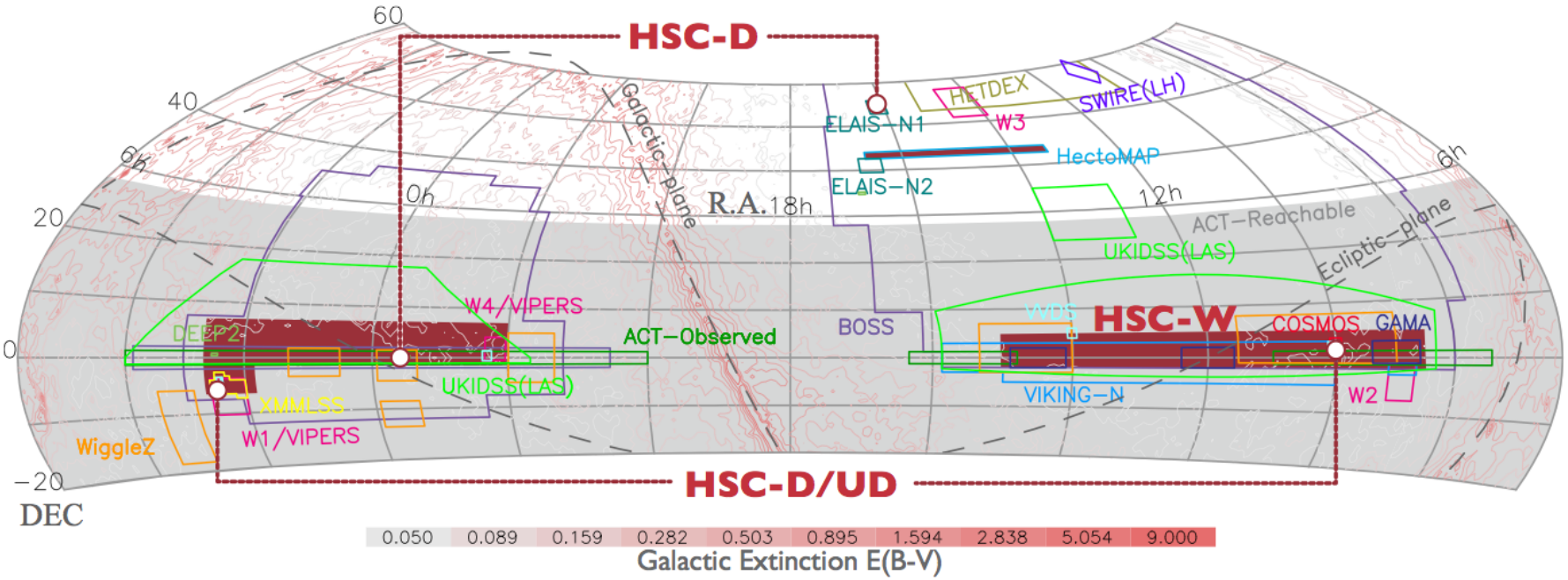


Photo credit: NAOJ, Miyazaki et al. (2018), Komiyama et al. (2018)

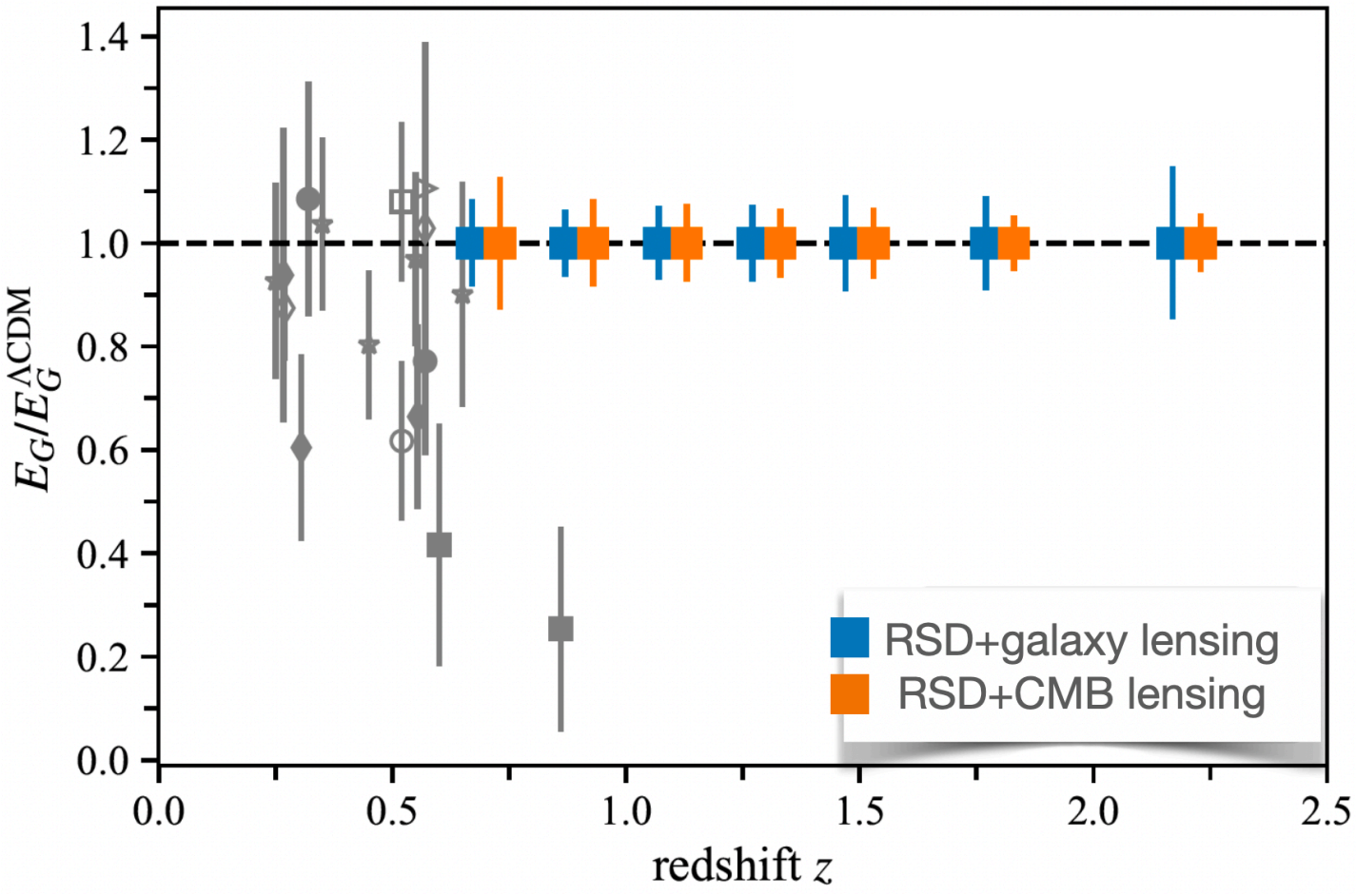
HSC SSP Survey



- Wide Layer (1,200 deg^2, grizy, i_{lim}~26) is designed for weak lensing cosmology (10^8 galaxies).
- Survey started in 2014 and completed at the end of 2021.
- **Third-year data** ~433 deg^2.
- Currently, preparing the final-year cosmology analyses.

Testing theory of General Relativity

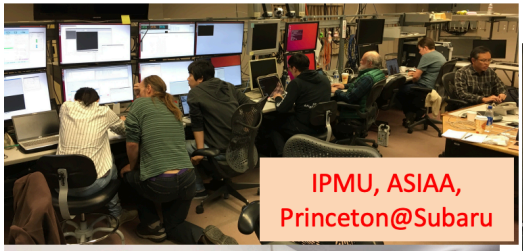
- E_G statistics combines galaxy velocity and lensing
- Spectroscopic data provides galaxy velocity information, and photometric data provides galaxy lensing measurements
- GR predicts $\Phi = \Psi$

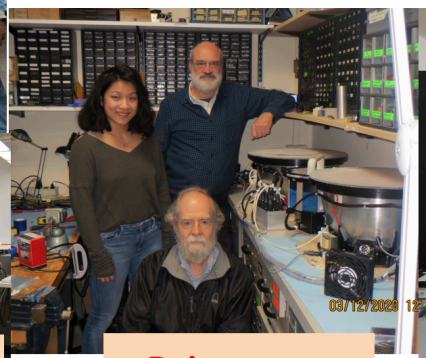


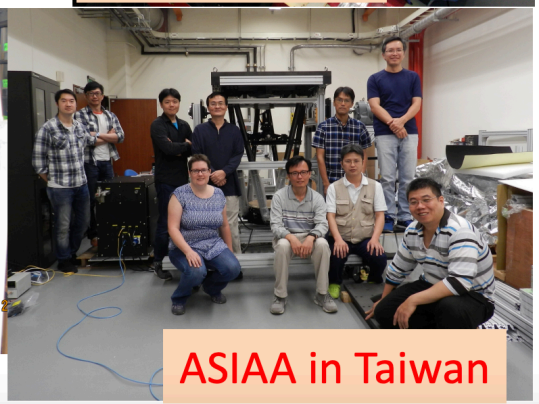
Gray points are existed constraints:
Blake+2016: WiggleZ/BOSS+CFHTLens
Pullen+2016: BOSS+Planck
delaTorre+2016: VIPERS+CFHTLenS
Alam+2016: BOSS+CFHTLenS
Amon+2018: GAMA+KiDS/2dFLens
Singh+2019: BOSS+SDSS/Planck
Jullo+2019: BOSS+CFHTLenS
Blake+2020: BOSS+KiDS-1000/2dFLen

PFS is supported by …

Without all these people, Subaru PFS will not happen and each person greatly contributes and push the project moving forward!







Prof. Naoyuki Tamura (NAOJ)

Prof. Yuki Moritani (U. Hawaii)

Dr. Kiyoto Yabe (NAOJ)

Subaru PFS has a capability to do Stage-V experiments

In all cases, the United States could envision playing a significant role in these projects through MSRI-2-level investment, which could provide up to about 20 percent of the cost of a project like MSE, SpecTel, or up to about 50 percent of MegaMapper, perhaps split with DOE. However, the time scales a such that the panel strongly encourages investment in some combination of next-generation SDSS V, DESI, and PFS through the 2020s, which could then be followed by investment in a larger dedicated facility. The panel does not believe an MREFC-level of funding is warranted in this decade.

Instrument (year)	Primary/m^2	Nfiber	Reflections	Product	Speed vs. SDSS
SDSS (1999)	3.68	640	0.9^2	1908	1.00
BOSS (2009)	3.68	1000	0.9^2	2980	1.56
DESI (2019)	9.5	5000	0.9^1	42,750	22.4
PFS (2020)	50	2400	0.9^1	108,000	56.6
4MOST (2022)	12	1624	0.9^2	15,800	8.3
MegaMapper	**28**	**20,000**	**0.9^2**	**454,000**	**238.**
Keck/FOBOS	77.9	1800	0.9^3	102,000	53.6
MSE	78	3249	0.9^1	228,000	119.
LSSTspec	35.3	8640	0.9^3	222,000	116.
SpecTel	87.9	15,000	0.9^2	1,070,000	560.

Summary

- Subaru PFS cosmology program will be complementary to other galaxy surveys like DESI and Euclid
- The unique aspects of PFS cosmology program
  - Wide redshift range → Dark Energy
  - High-number density → Sum of neutrino mass
  - Synergy with HSC → Testing theory of gravity

Thank you!