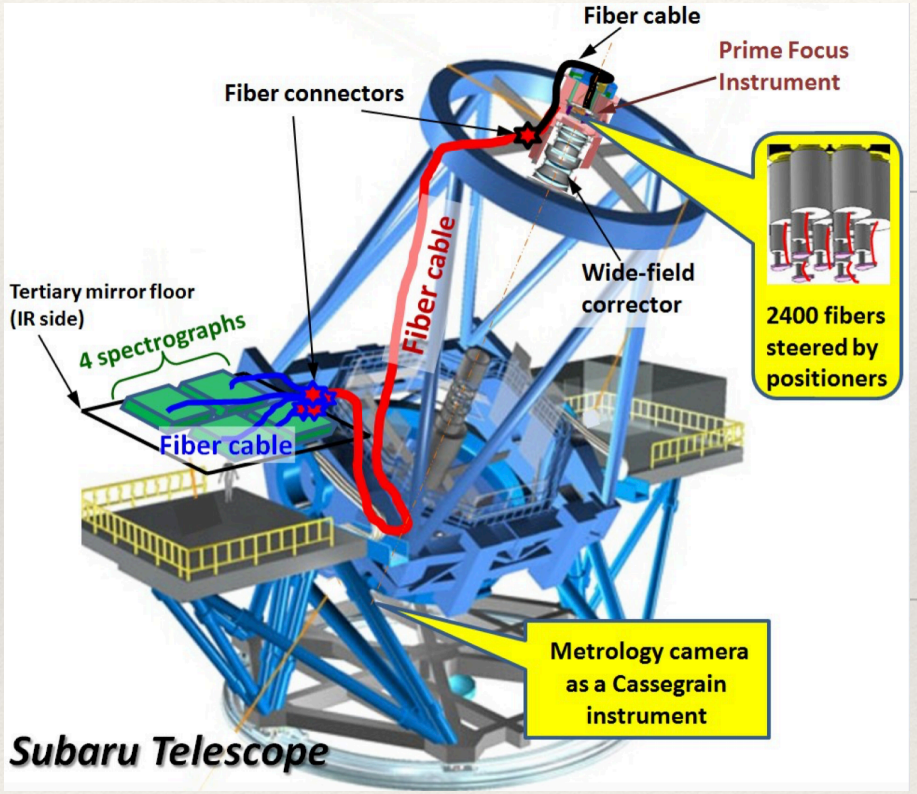
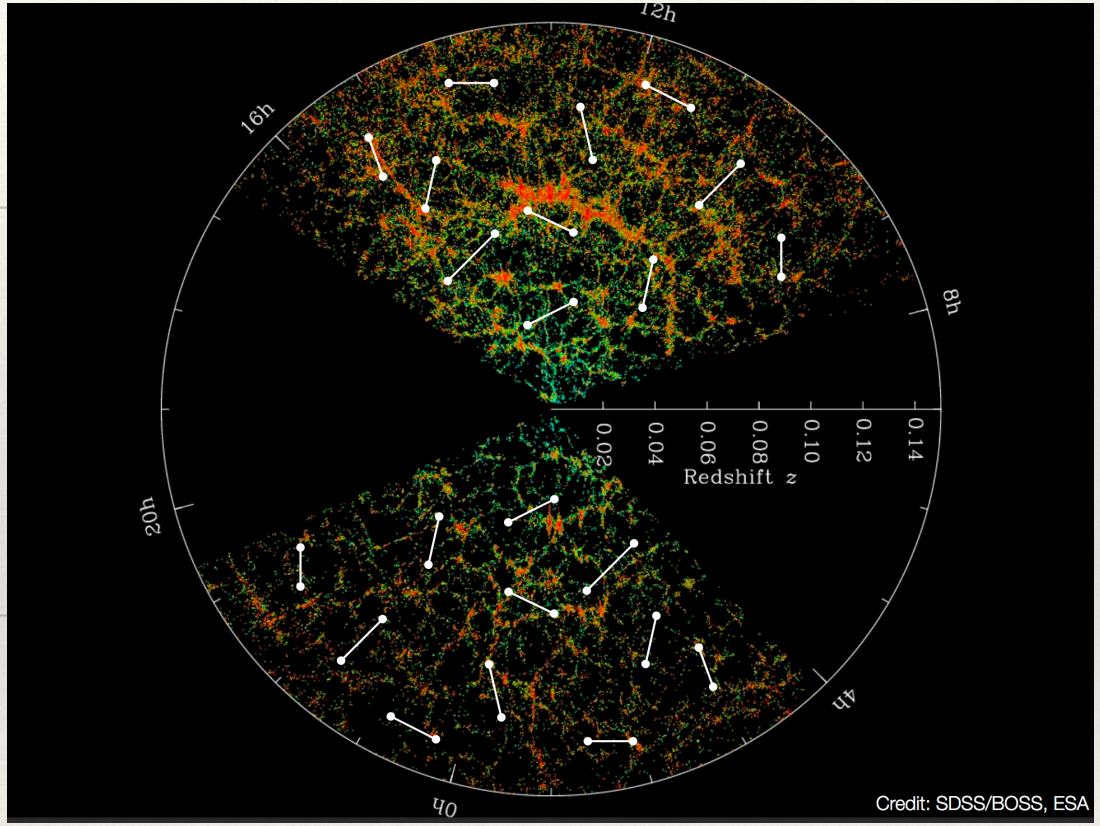
Subaru PFS Cosmology

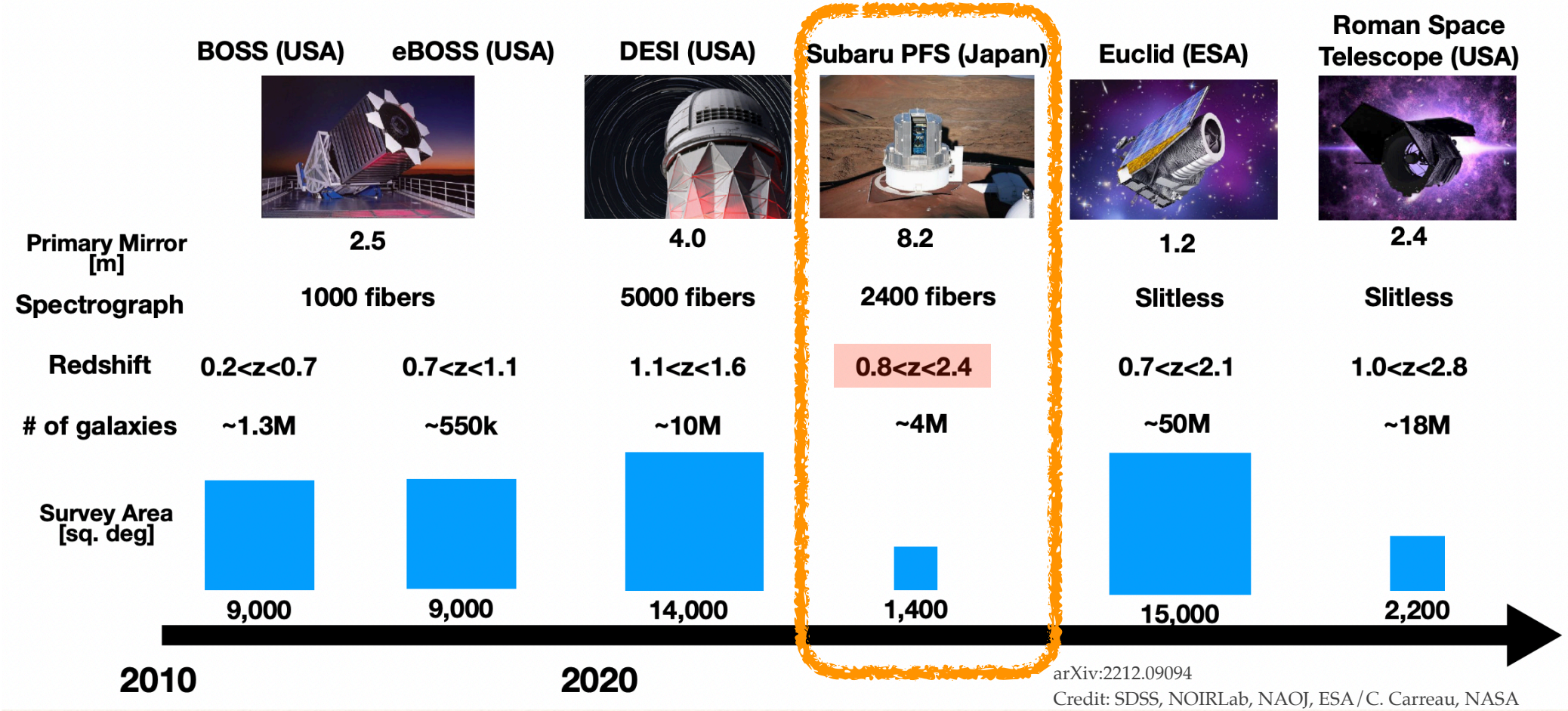




Tomomi Sunayama (U. Arizona): On behalf of PFS Cosmology WG

Timeline of spectroscopic galaxy surveys

- Stage-III Dark Energy Experiments (BOSS, eBOSS) are finished and now DESI and Subaru PFS will start taking data…

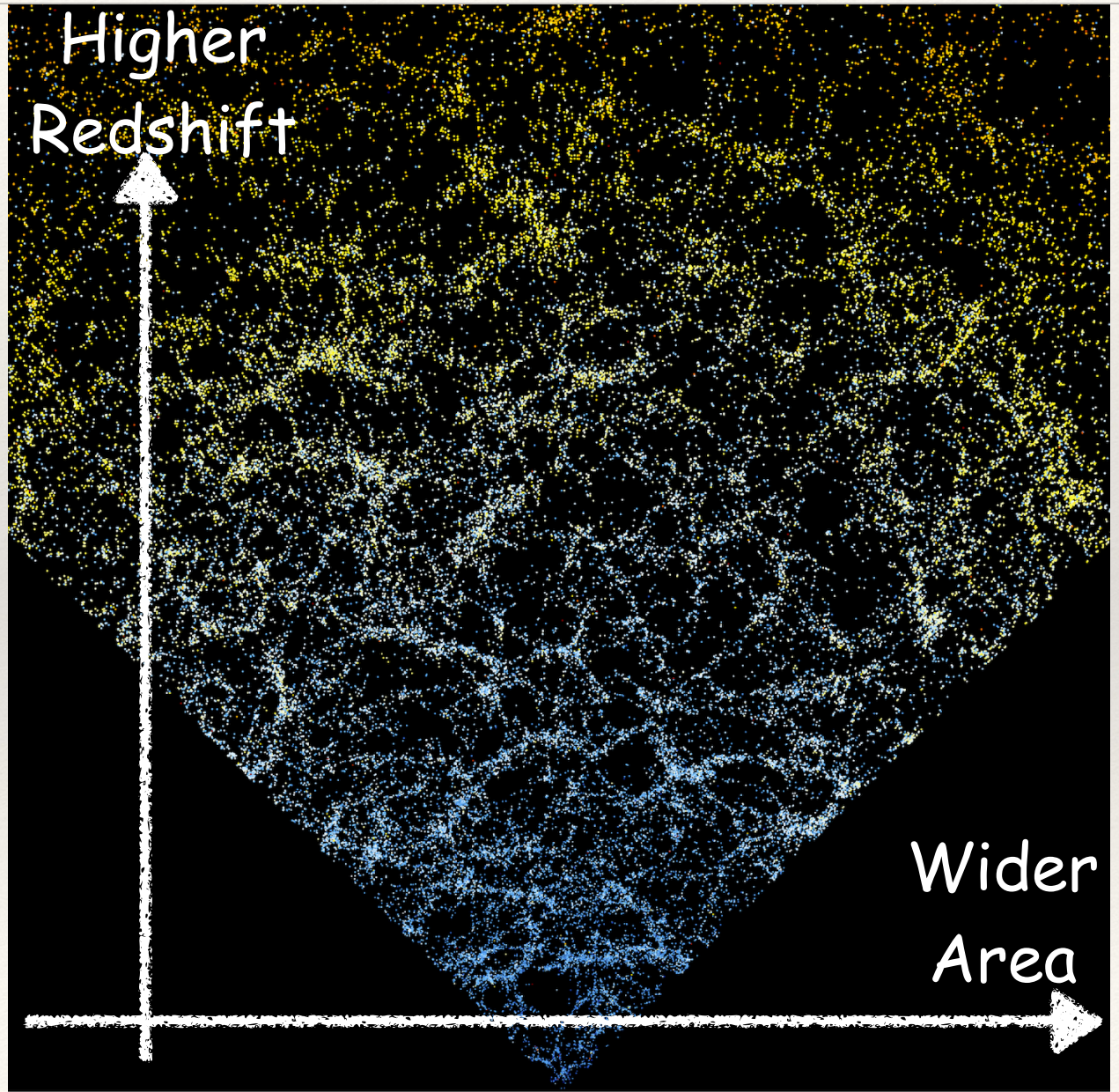


arXiv:2212.09094

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

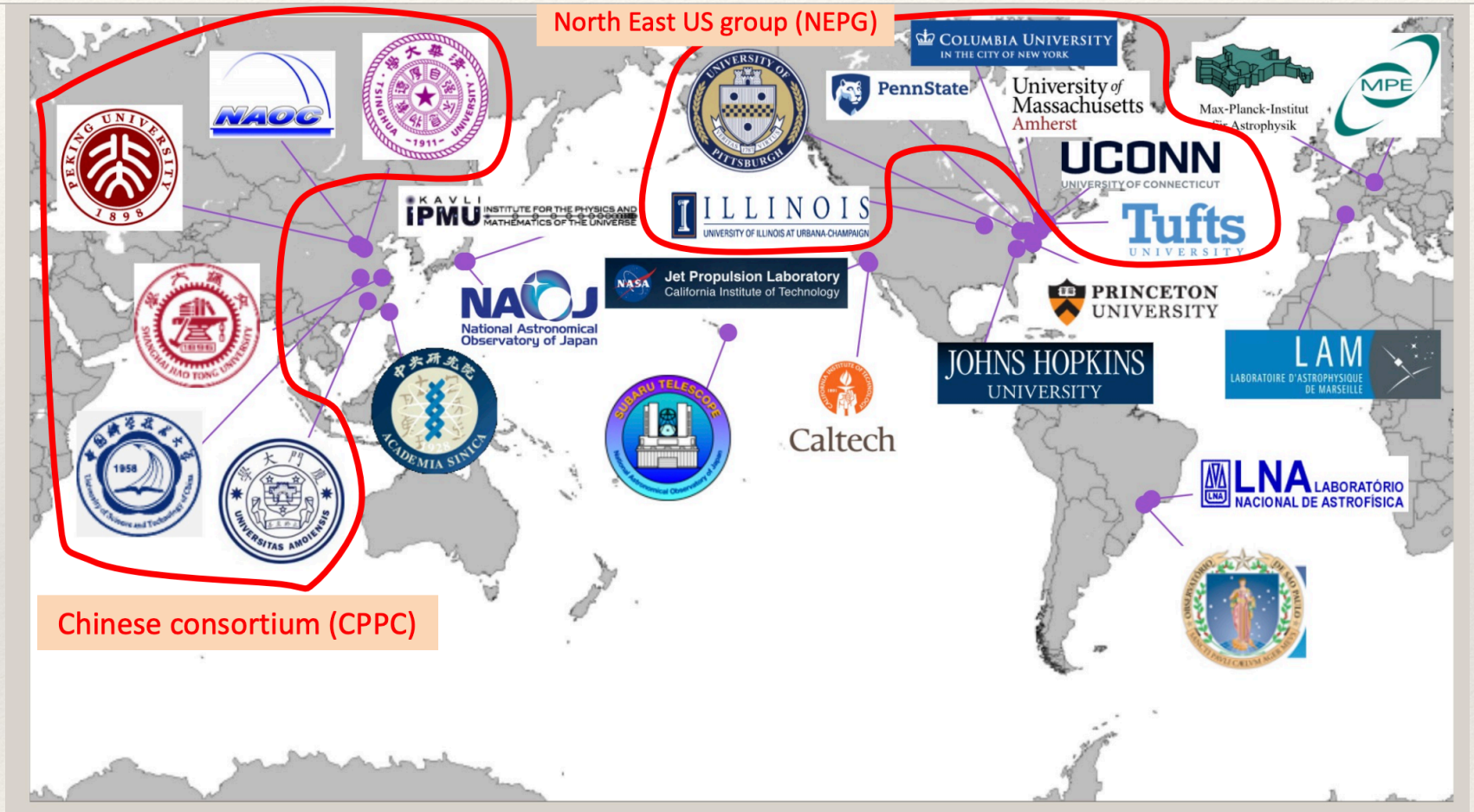
Galaxy Map: Spectroscopic Survey Design

PFS
Roman



DESI
Euclid

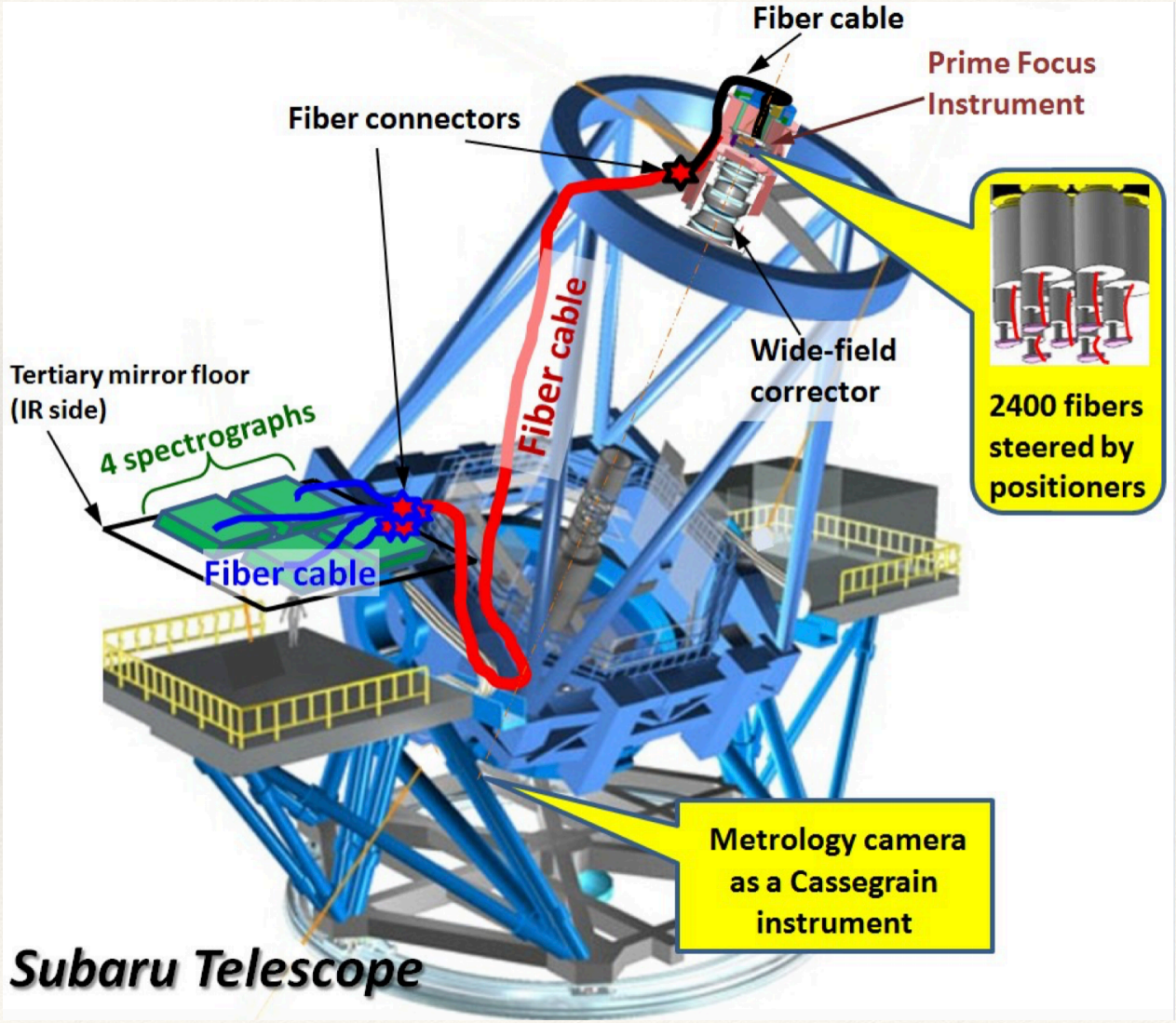
The growing PFS Collaboration



- PI: Hitoshi Murayama (Kavli IPMU/UC Berkeley)
- Project Office: Kavli IPMU, Kashiwa, Japan
- Technical work: Princeton, JHU, ASIAA (Taiwan), Caltech, LNA (Brazil), LAM (France), Nat'l Astronomical Observatories of Japan (NAOJ)

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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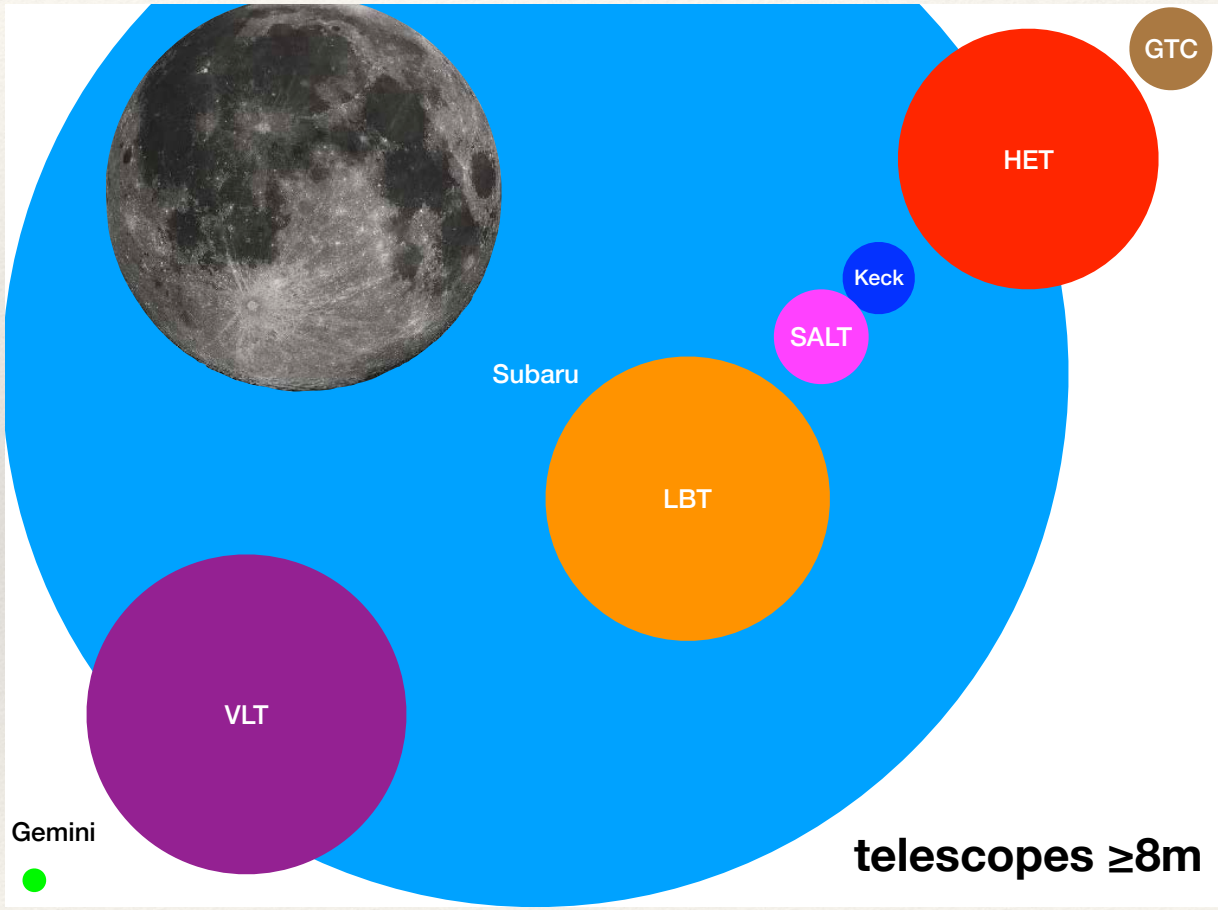

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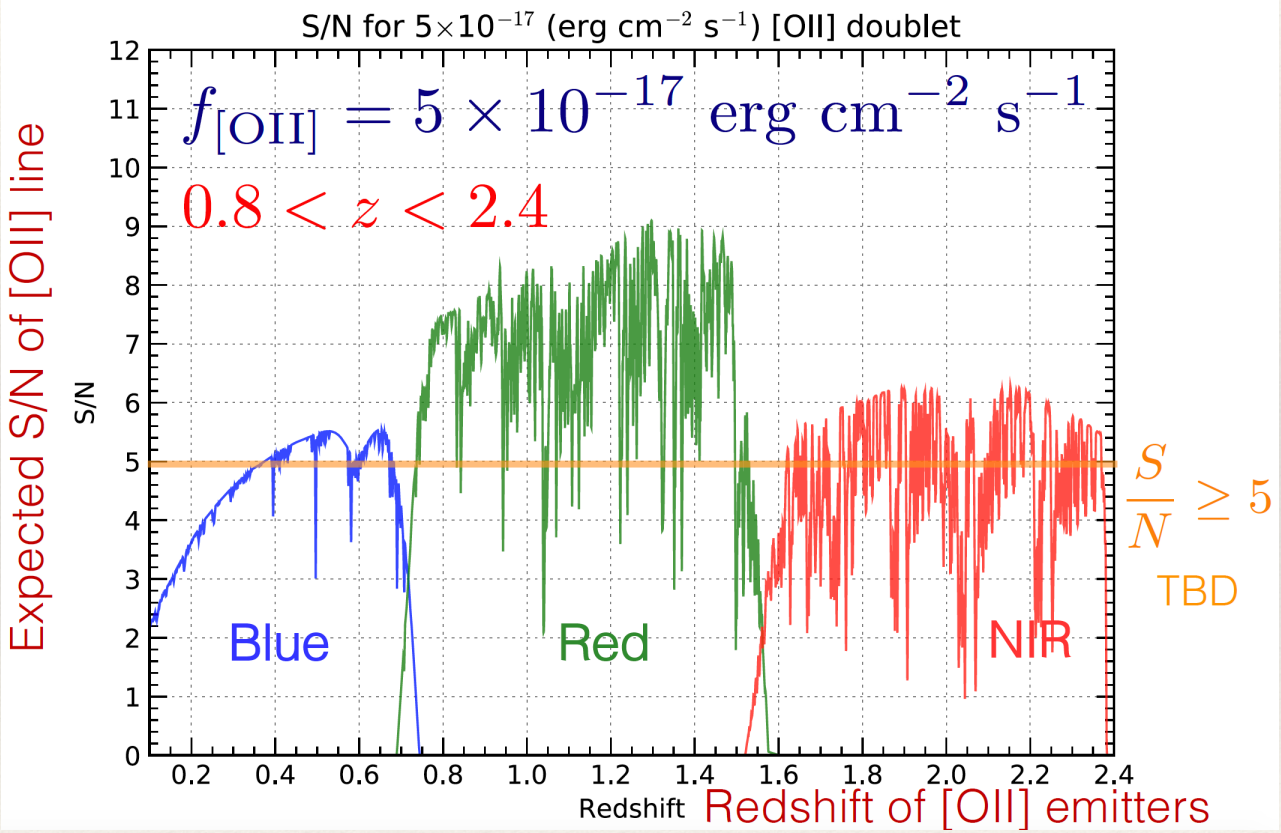
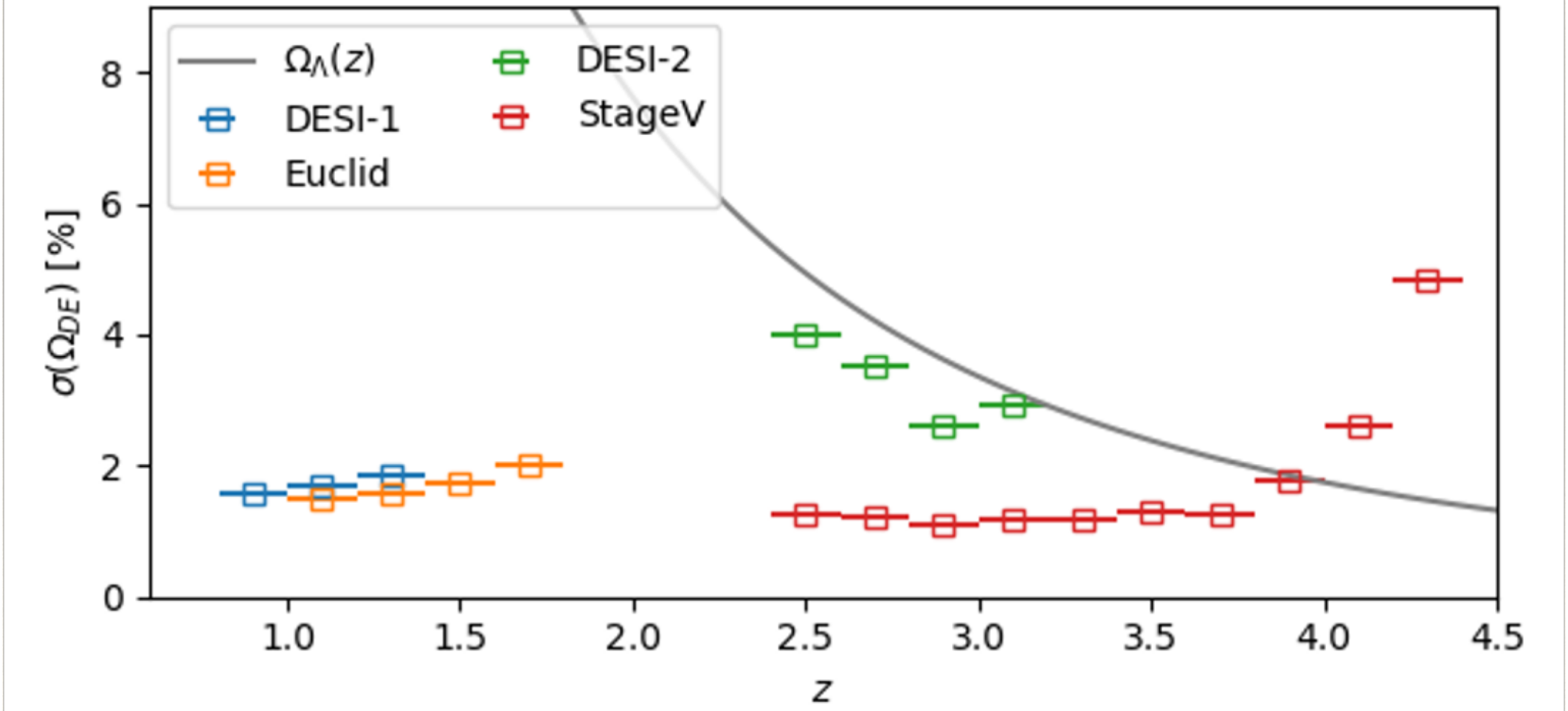


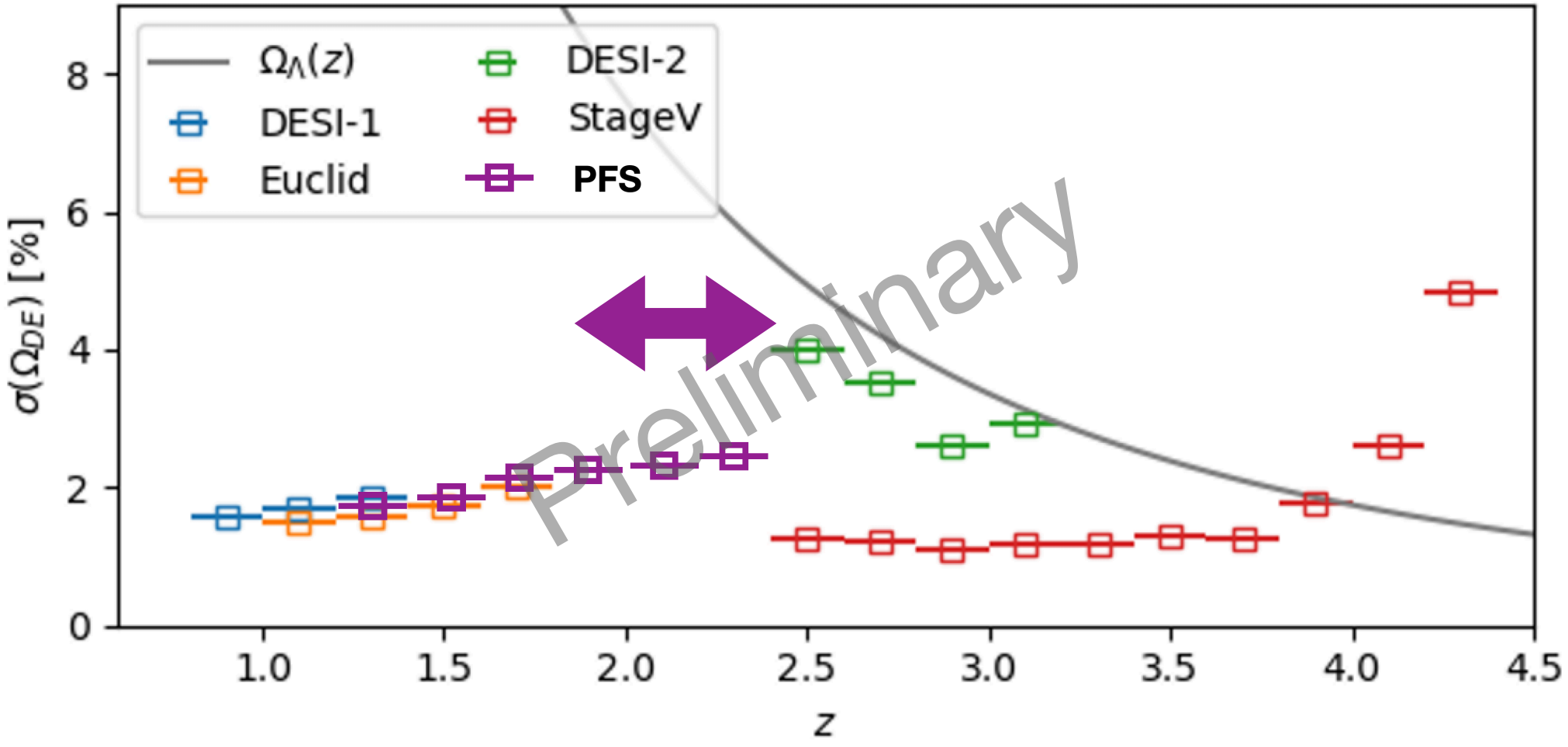
Complementarity with DESI-II/Spec-S5

- DESI is observing ELGs at z<1.6 and DESI-II is planning to observe LBGs at z>2.5

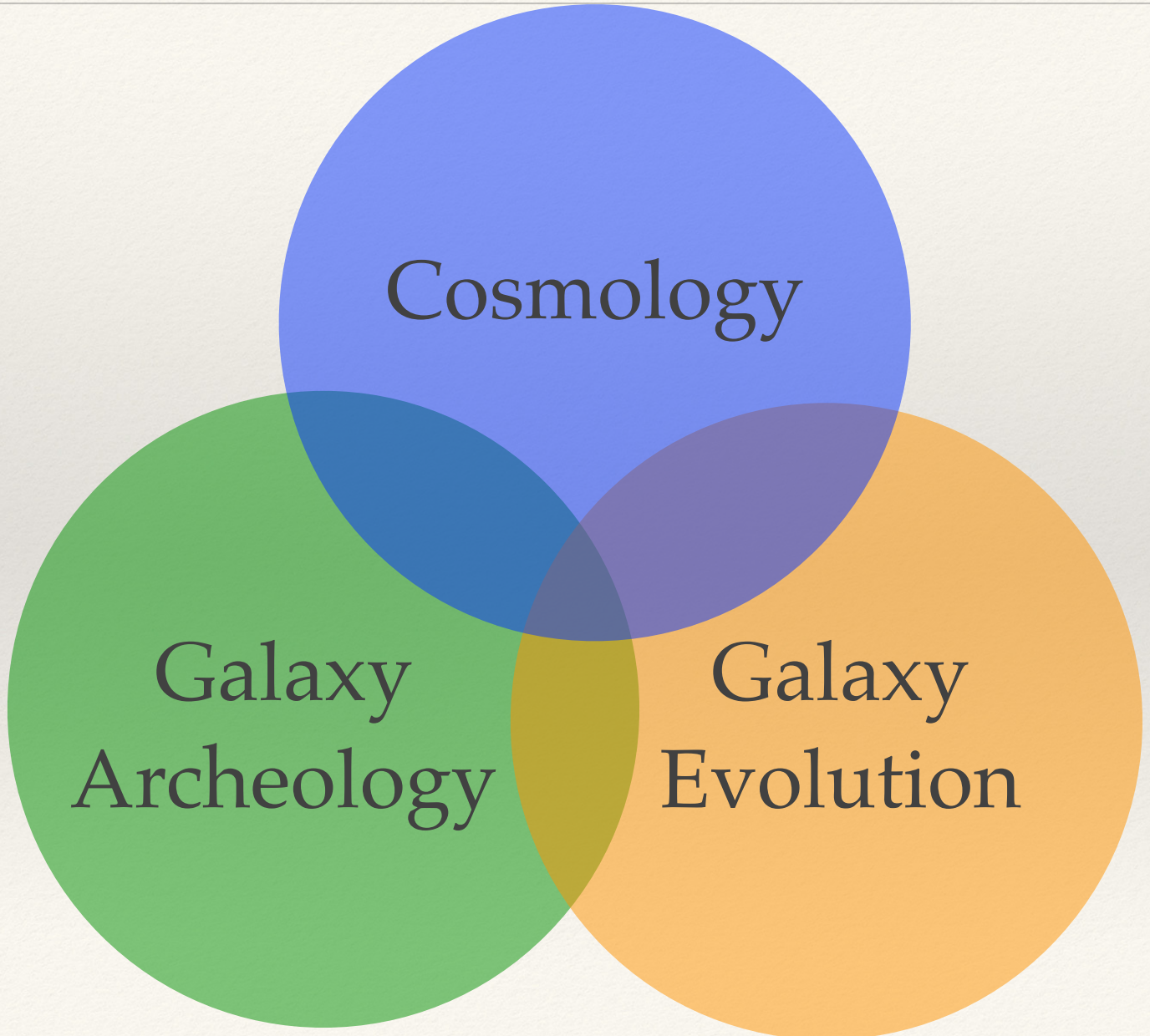


Complementarity with DESI-II/Spec-S5

- PFS can bridge the gap between DESI and DESI-II with comparable constraining power!



Scientific Themes of PFS Survey



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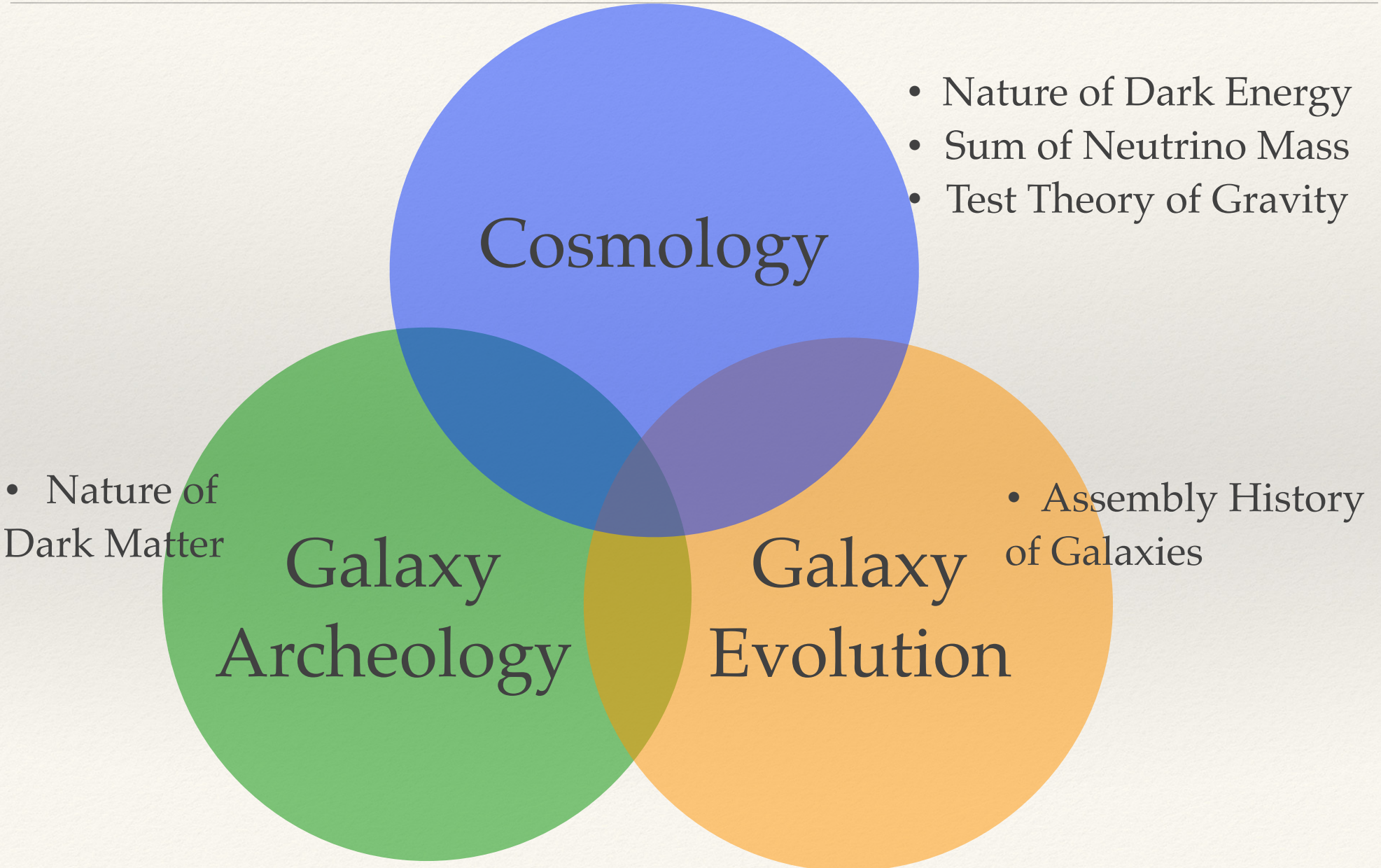


Scientific Themes of PFS

	Testing ΛCDM	Assembly history of galaxies	Importance of IGM
CO	• Nature & role of neutrinos • Expansion rate via BAO up to z=2.4 • PFS+HSC tests of GR	• PFS+HSC galaxy association • Absorption probes with PFS/SDSS QSOs around PFS/HSC host galaxies	• Search for emission from stacked spectra
GA	• Curvature of space: Ω_K • Primordial power spectrum • Nature of DM (dSphs)	• Stellar kinematics and chemical abundances – MW & M31 assembly history	• dSph as relic probe of reionization feedback • Past massive star IMF from element abundances
GE	• Search of MW dark halo • Small-scale tests of structure growth	• Halo-galaxy connection: $M_*/M_{\rm halo}$ • Outflows & inflows of gas • Environment-dependent evolution	• Physics of cosmic reionization via LAEs & 21cm studies • Tomography of gas & DM

Cosmology survey (~1400 sq. degs.): ~4M emission-line galaxy spectra

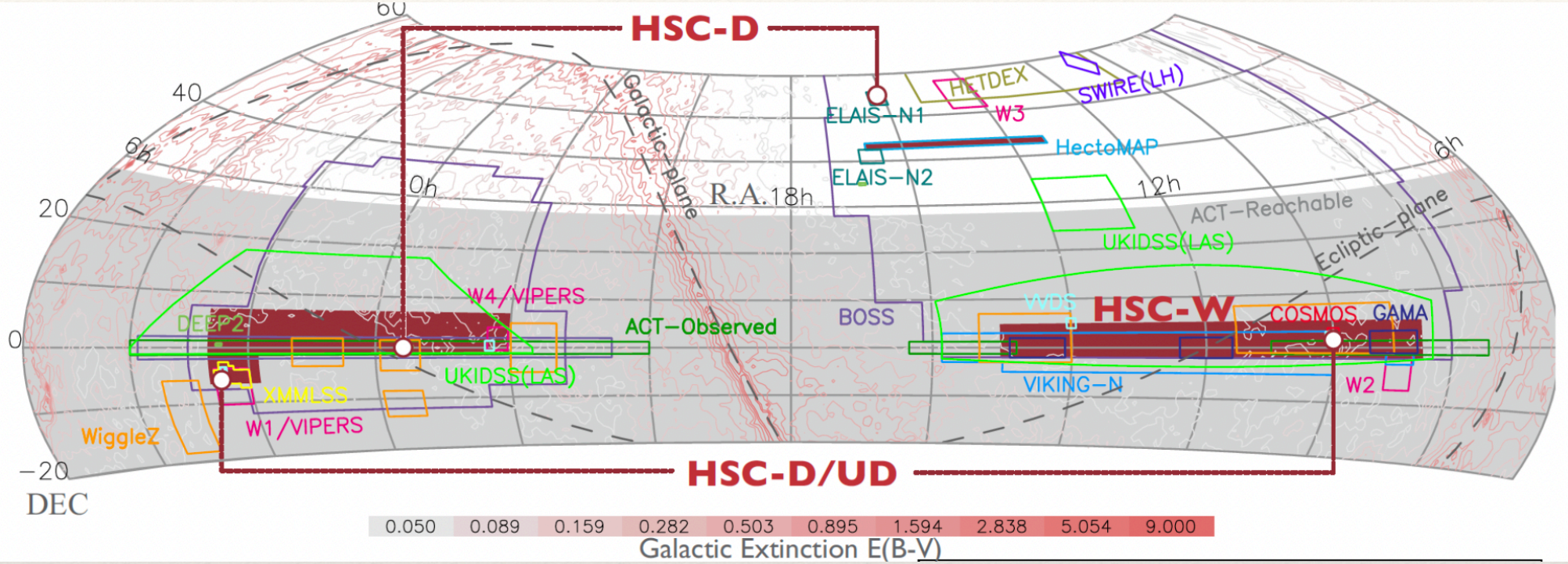
Galactic Archaeology: stars in dSphs, streams, and disk in MW and M31

Galaxy survey (~15 sq. degs.): ~a few 10^5 high S/N galaxy spectra

Target selection is based on the **HSC data**

From PFS-SSP proposal

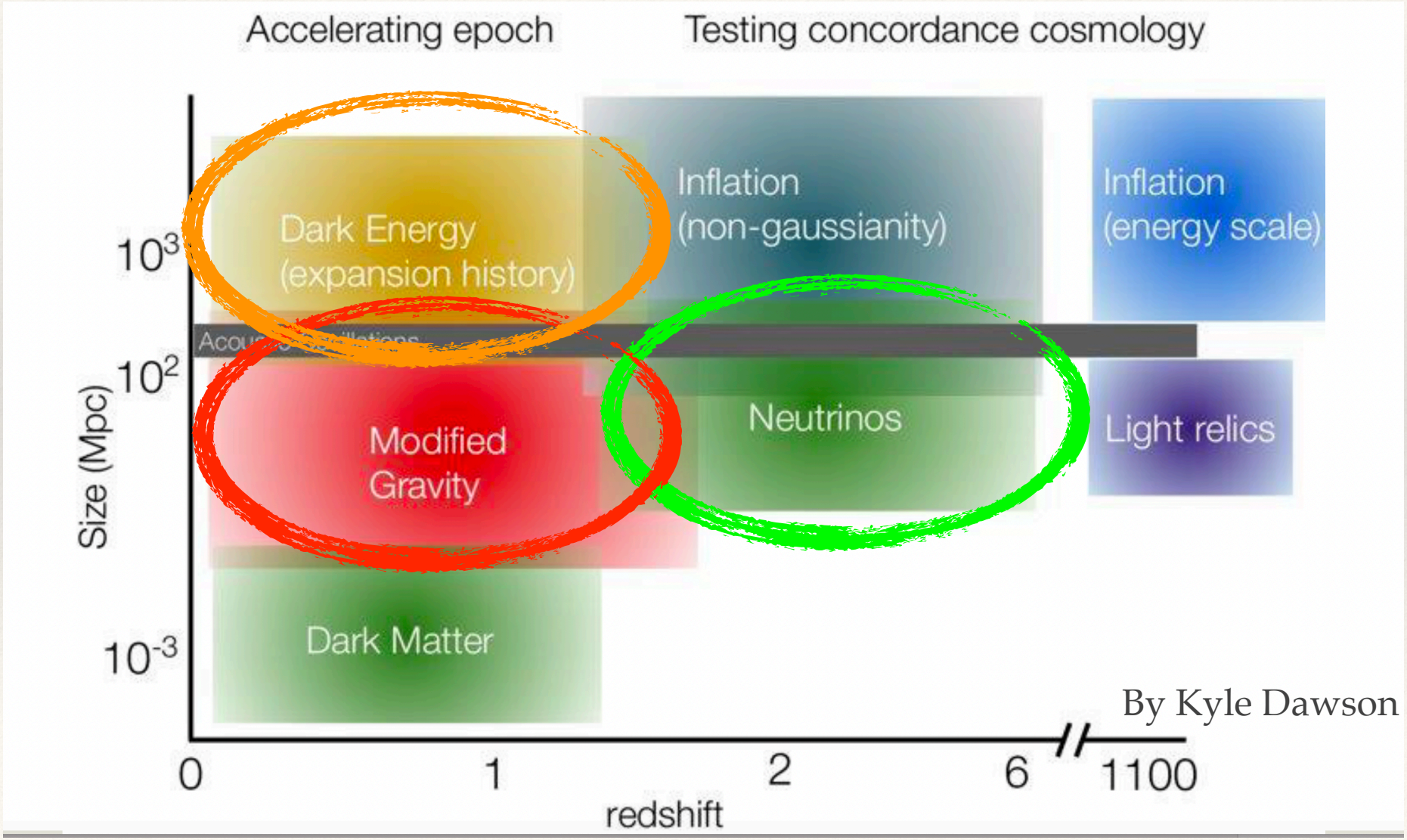
Survey Design of PFS Cosmology Program



- 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 $1200\mathrm{deg}^2$
- Other galaxy surveys only go to z=1.6 (DESI) and z=2 (Euclid), meaning 2<z<2.4 is a unique territory of PFS

Discovery Space: galaxy surveys are trying to explore…

- Why do we spend time and money for these large galaxy surveys?



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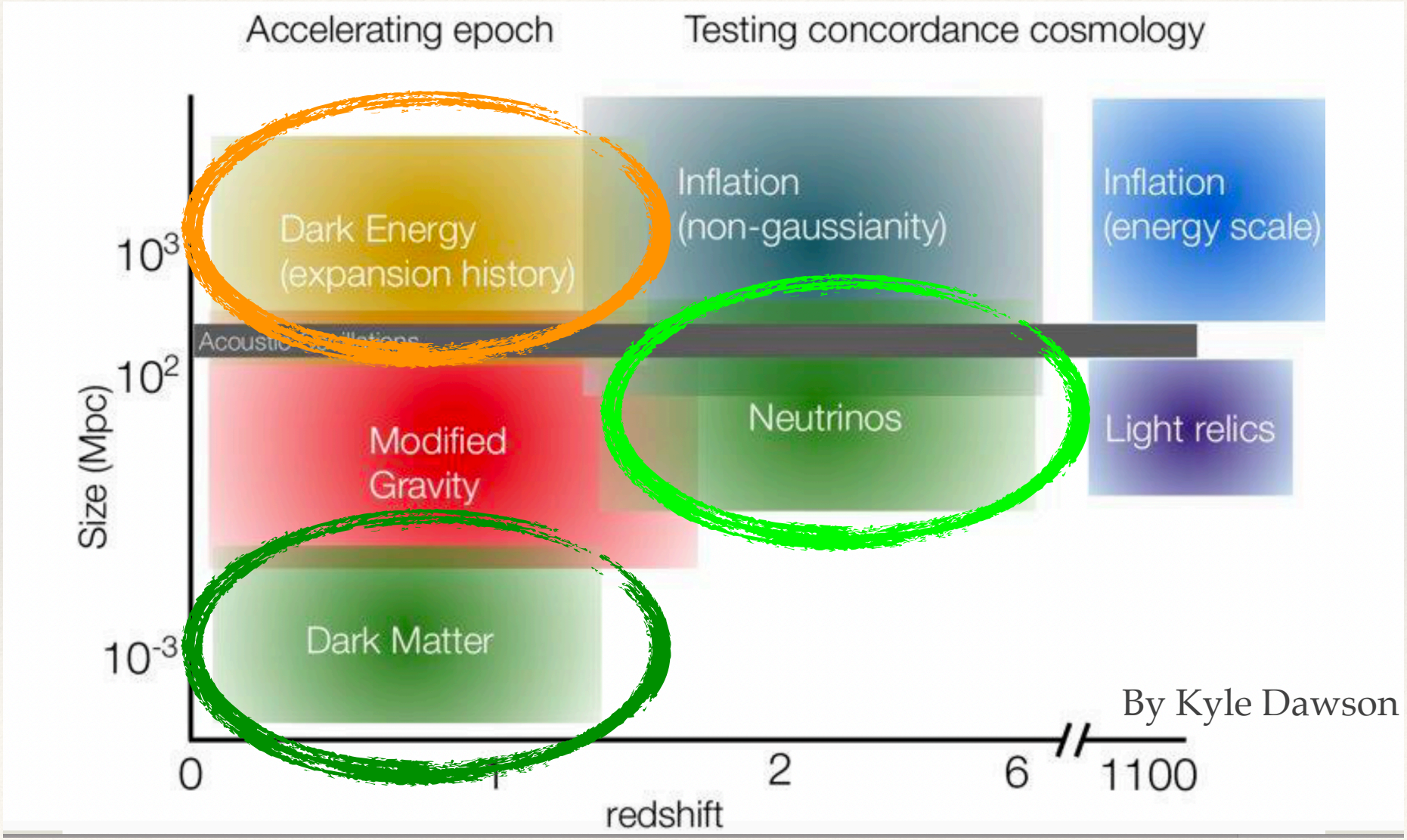

Overview

- What is Subaru Prime Focus Spectrograph (PFS) Survey?
  - PFS Instrument/Collaboration
  - The strength and uniqueness of PFS
  - Scientific Goals from three programs
- What are we trying to do in the cosmology program?
  - Constraining sum of neutrino mass
  - Measuring Dark Energy
  - Testing theory of gravity
- Where can we do to constrain DM models?

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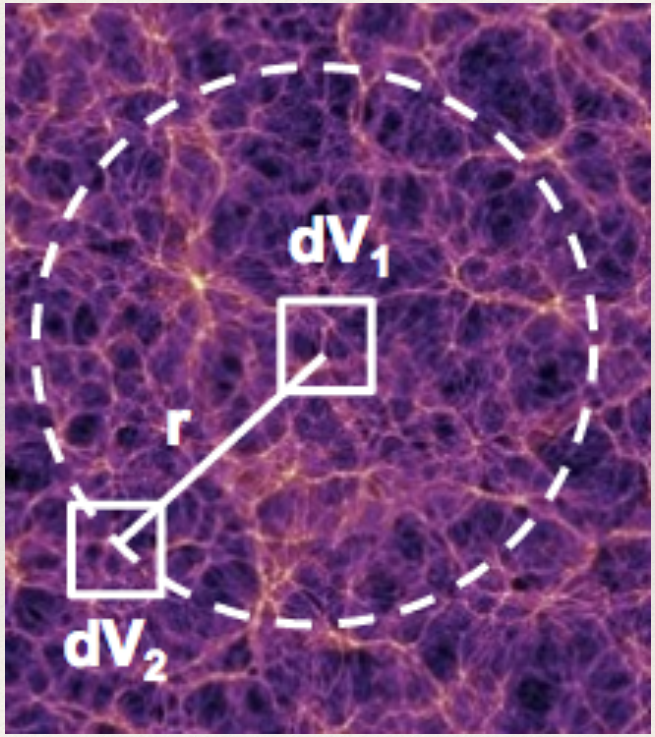
  - Constraining sum of neutrino mass → High number density of ELGs
  - Measuring Dark Energy → Wide redshift range
  - Testing theory of gravity → Synergy with Subaru HSC survey
- Where can we do to constrain DM models?

Correlation Functions: Statistical tool to quantify galaxy distribution

- Galaxy correlation functions measure an excess probability (relative to Poisson) of galaxy pairs separated by distance r.



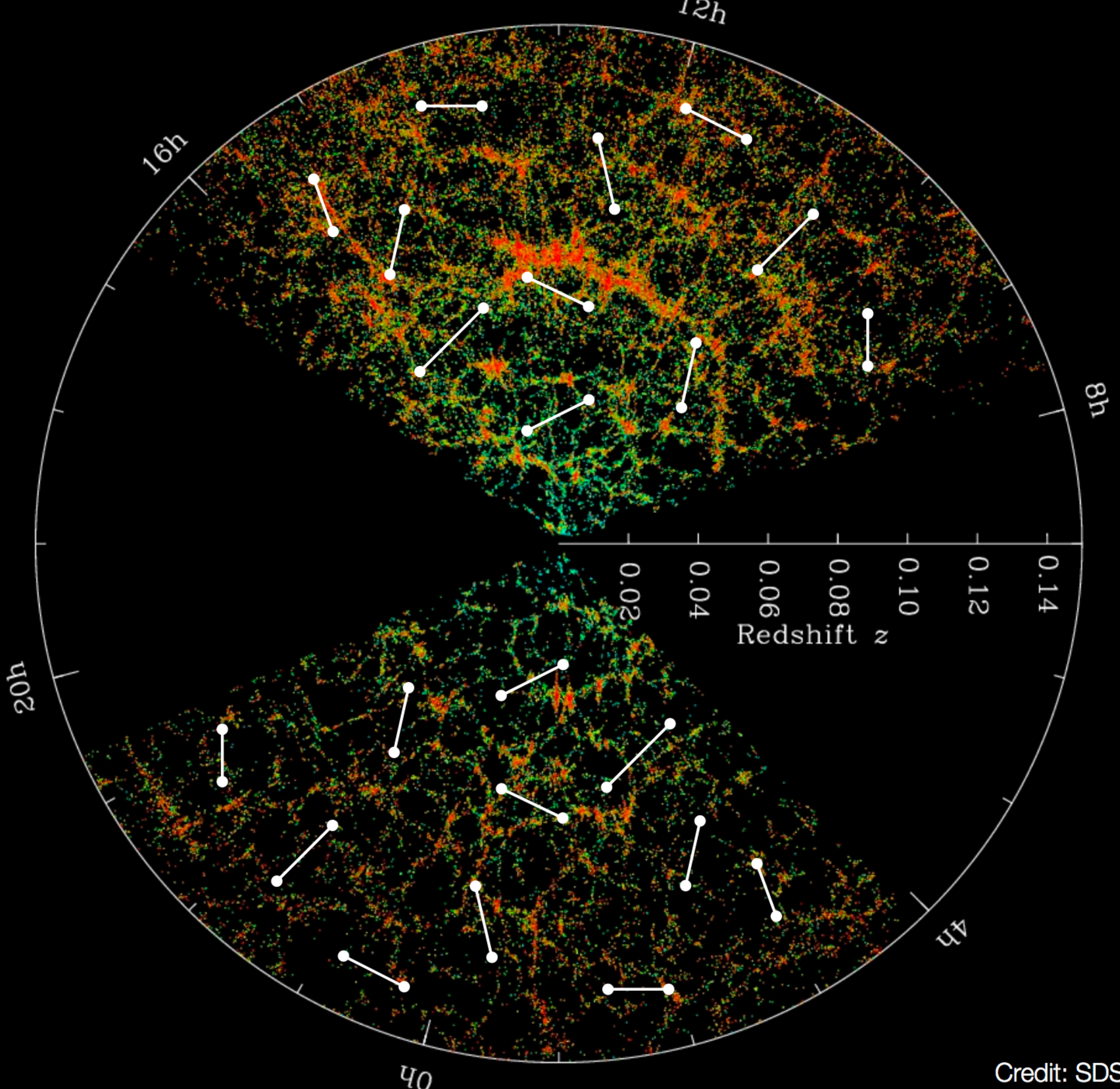
$$dP = n^2(1 + \xi(r))dV_1 dV_2$$

"Correlation Function"

$$\xi(r) = \int \frac{d^3k}{(2\pi)^3} P(k) e^{ik\cdot r}$$

"Power Spectrum"

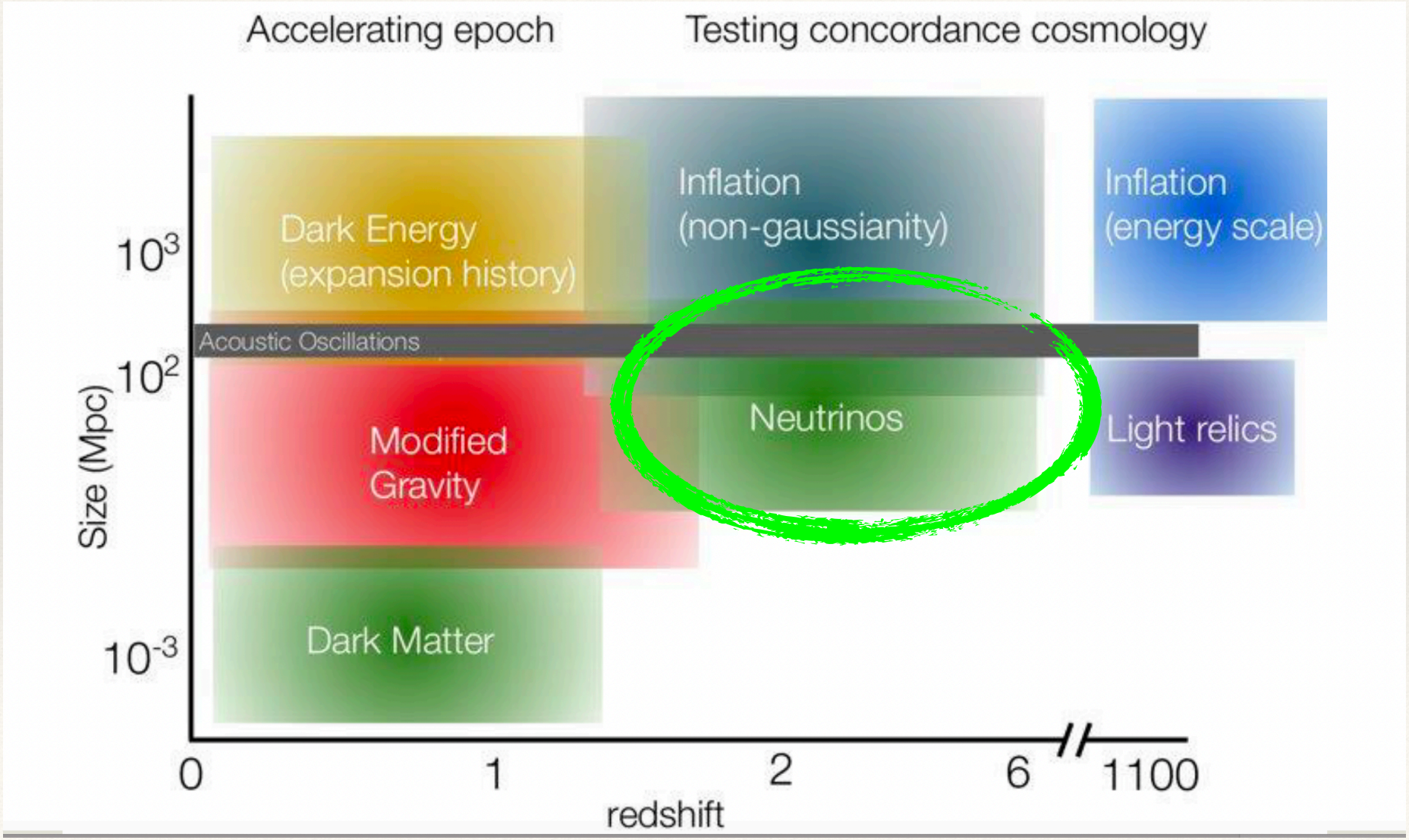
- If the density field is a random Gaussian, it can be fully characterized by the correlation functions.



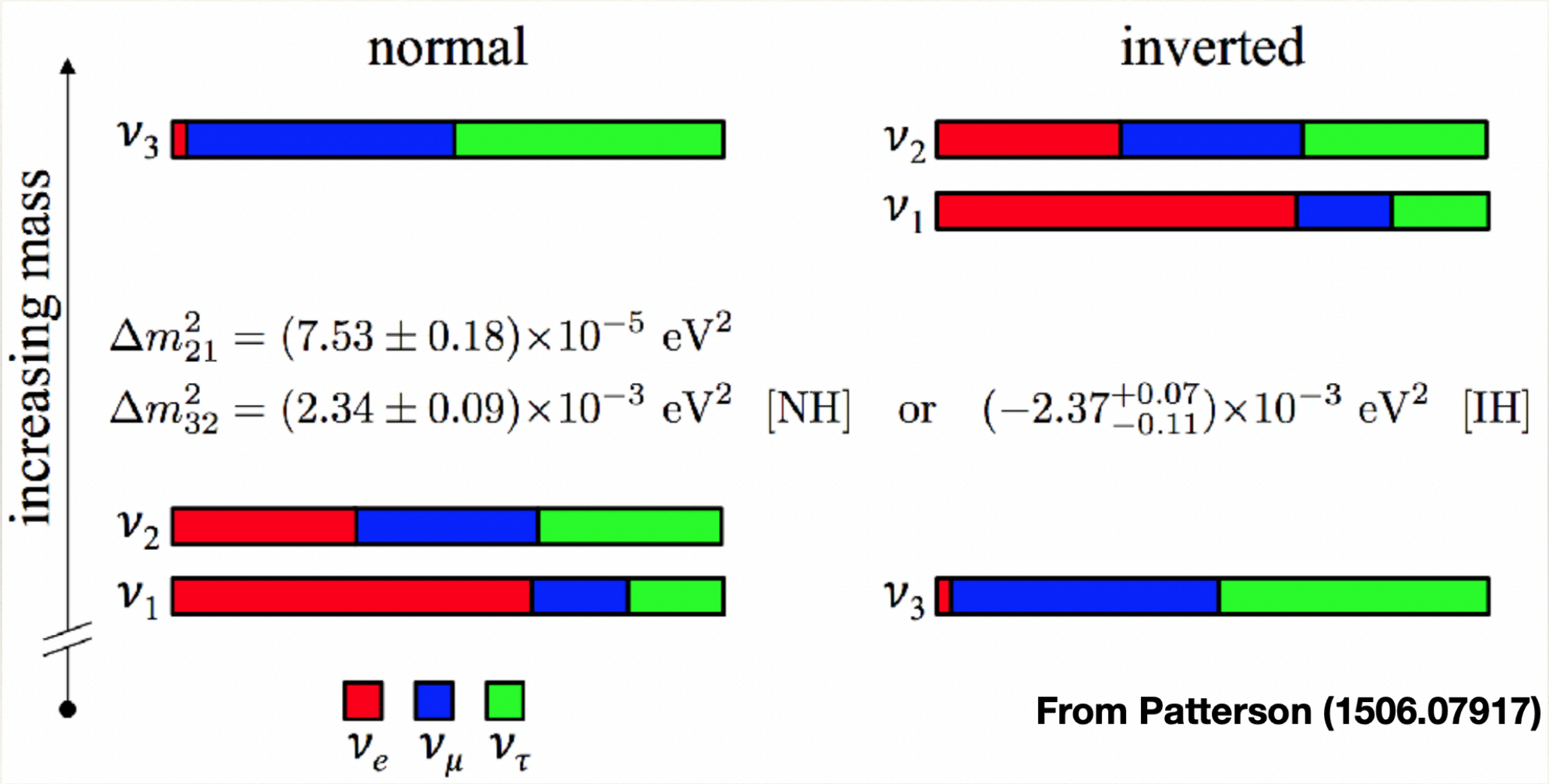
Credit: SDSS/BOSS, ESA

PFS Cosmology program will explore…

- How well can we measure the sum of neutrino mass?

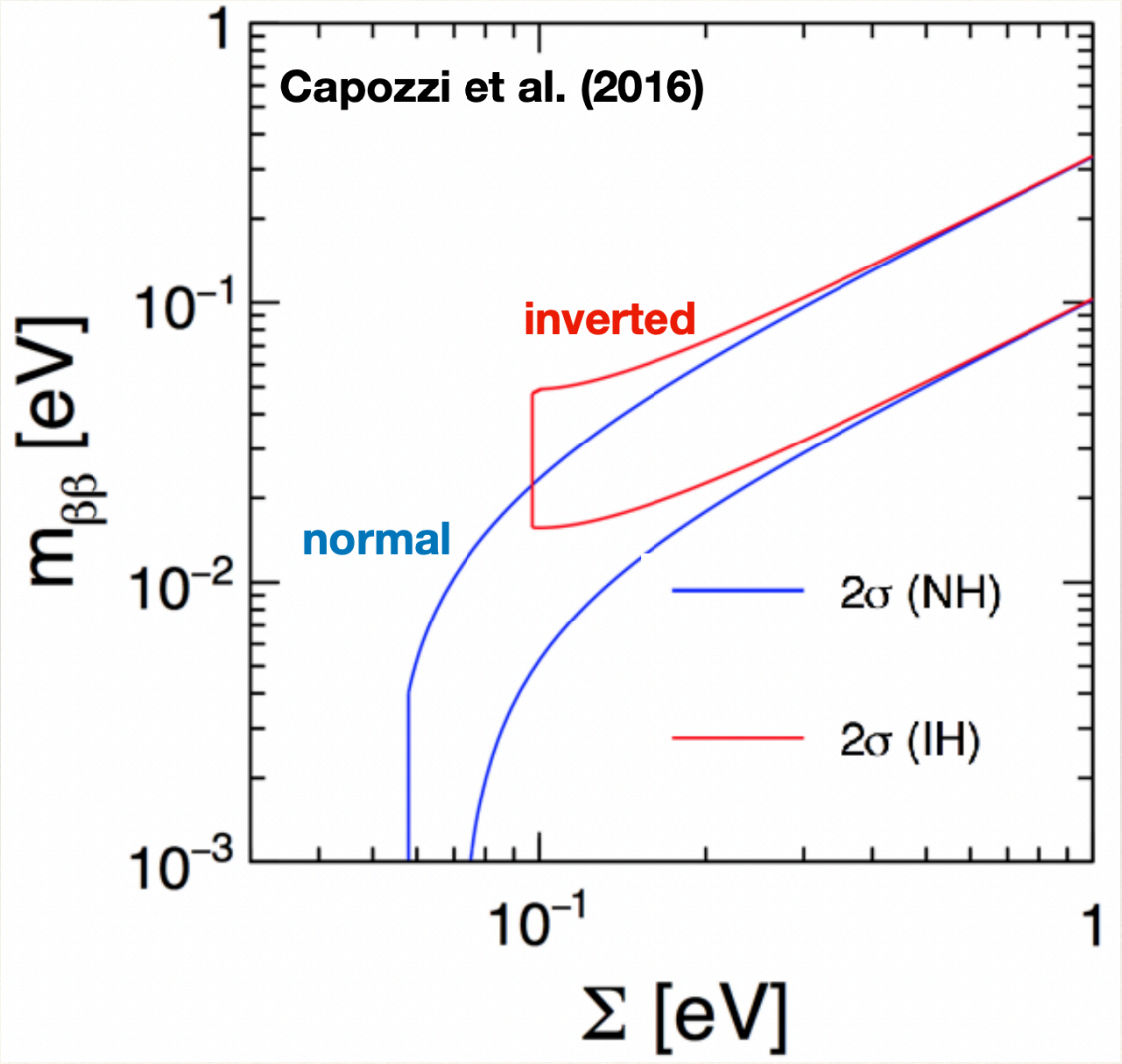


Neutrino Mass Hierarchy



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

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

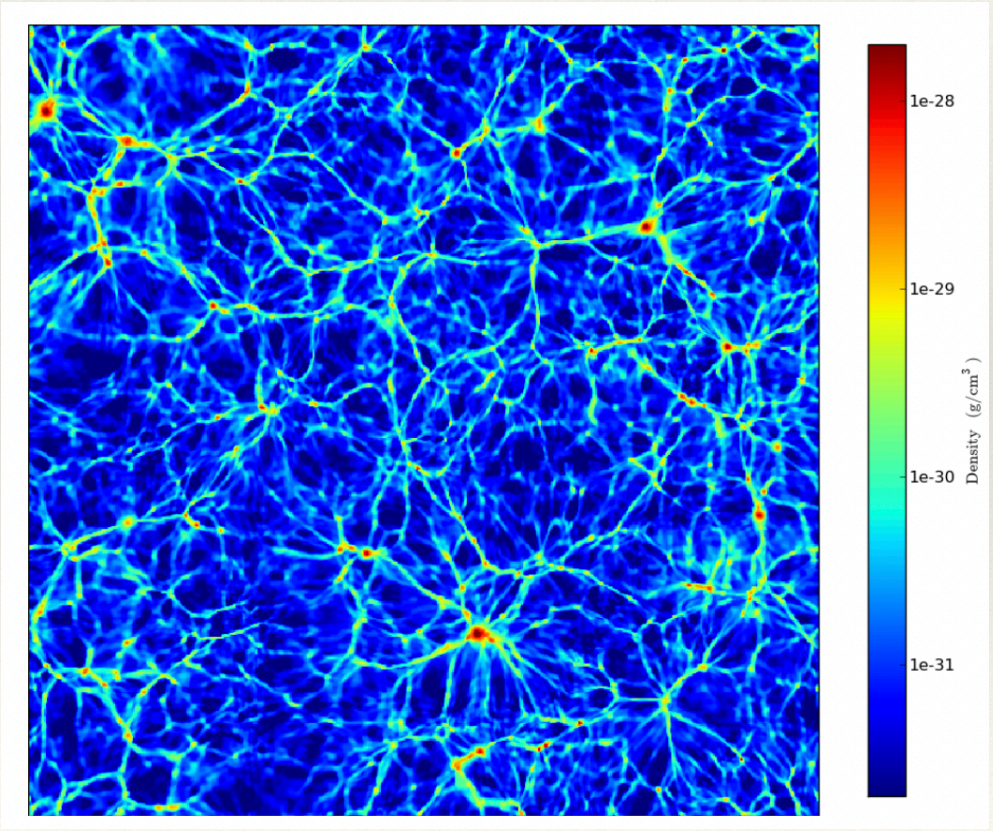


- Deciding the mass hierarchy sets a concrete target for the neutrino-less double beta decay experiments
- Can test whether neutrinos are Dirac or Majorana

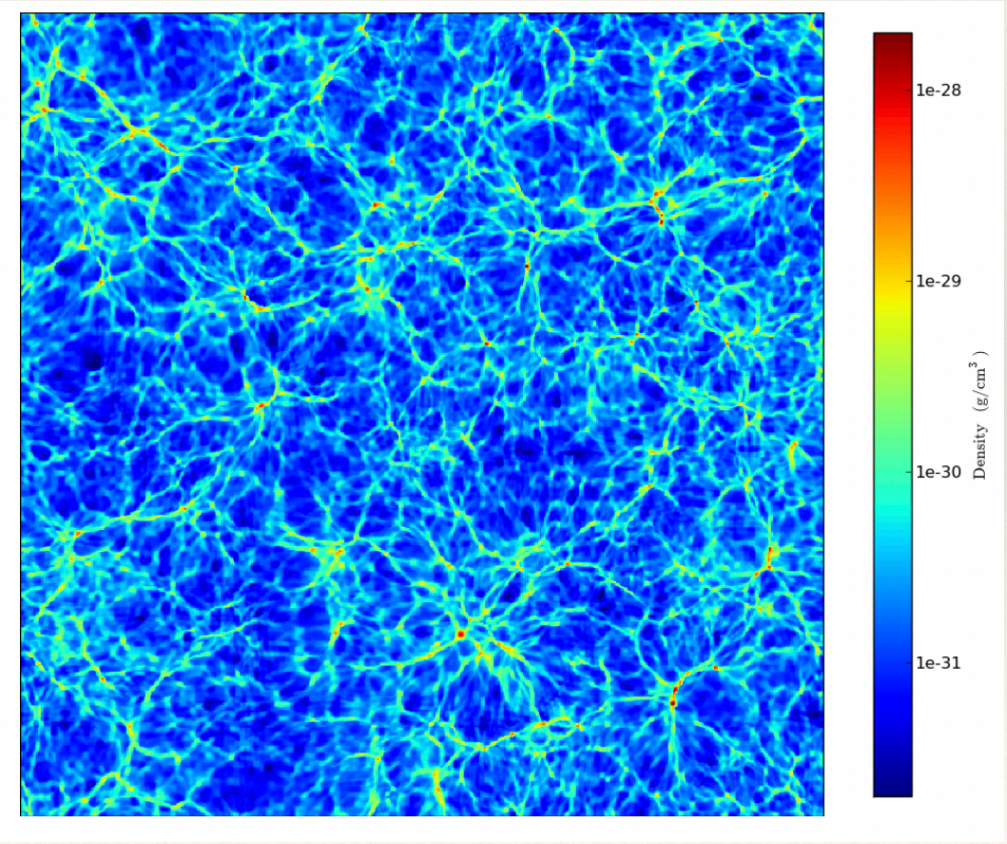
What does neutrino do on large scale structure?

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

Without Neutrinos



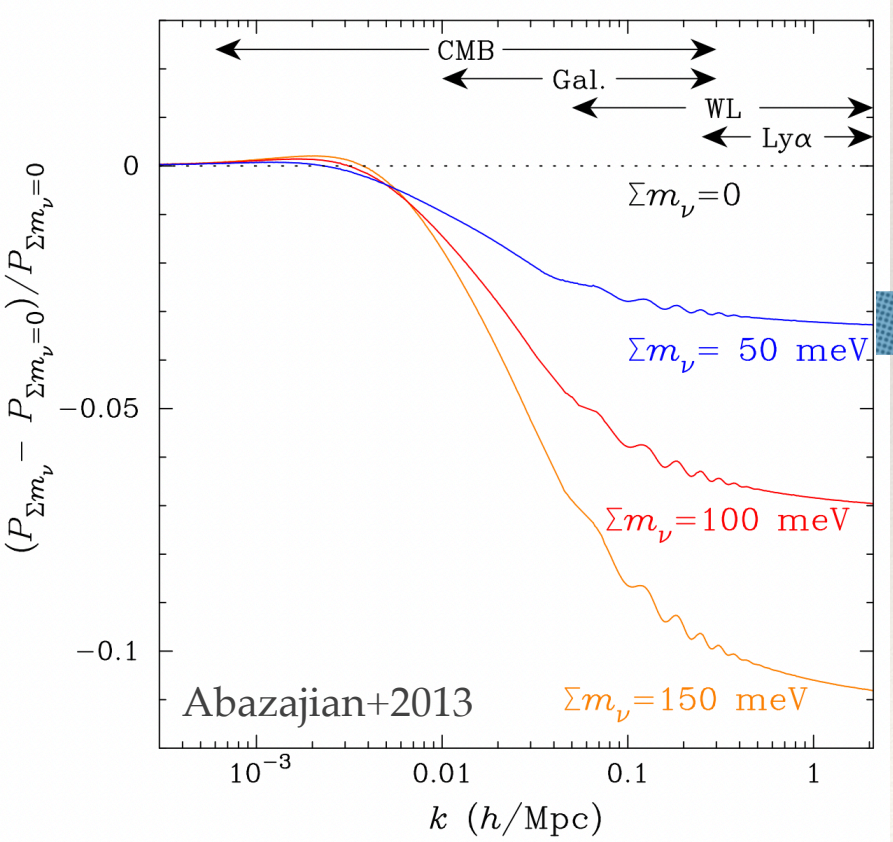
With Neutrinos

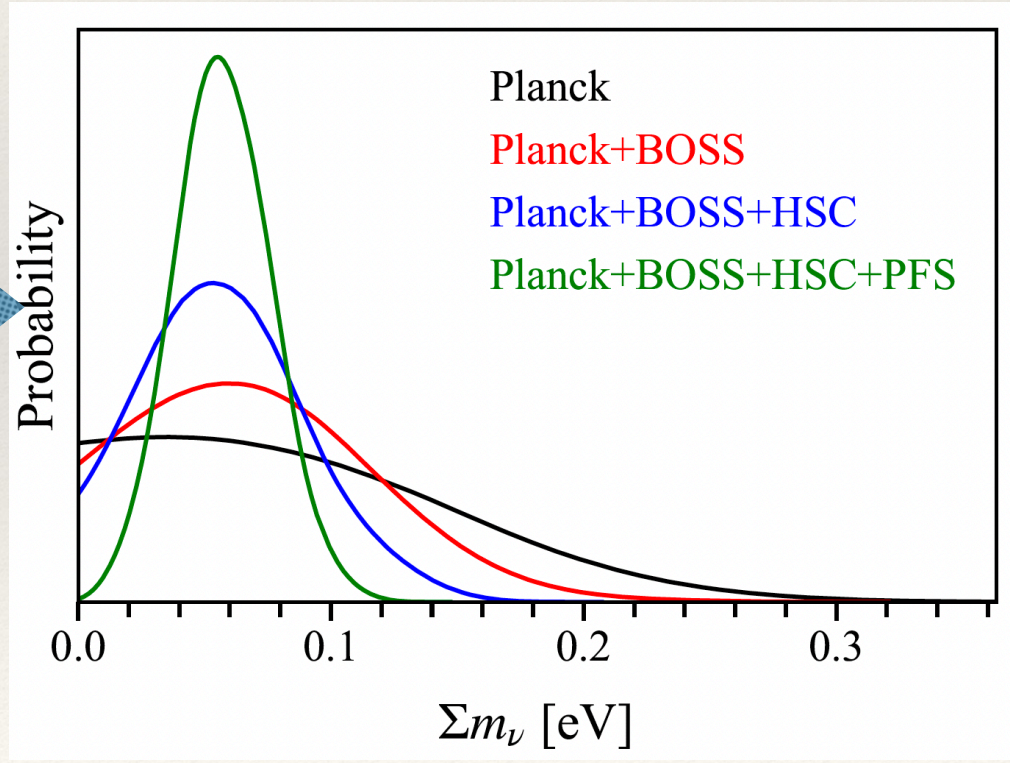


Agarwal&Feldman 2010

What does neutrino do on clustering of galaxies?

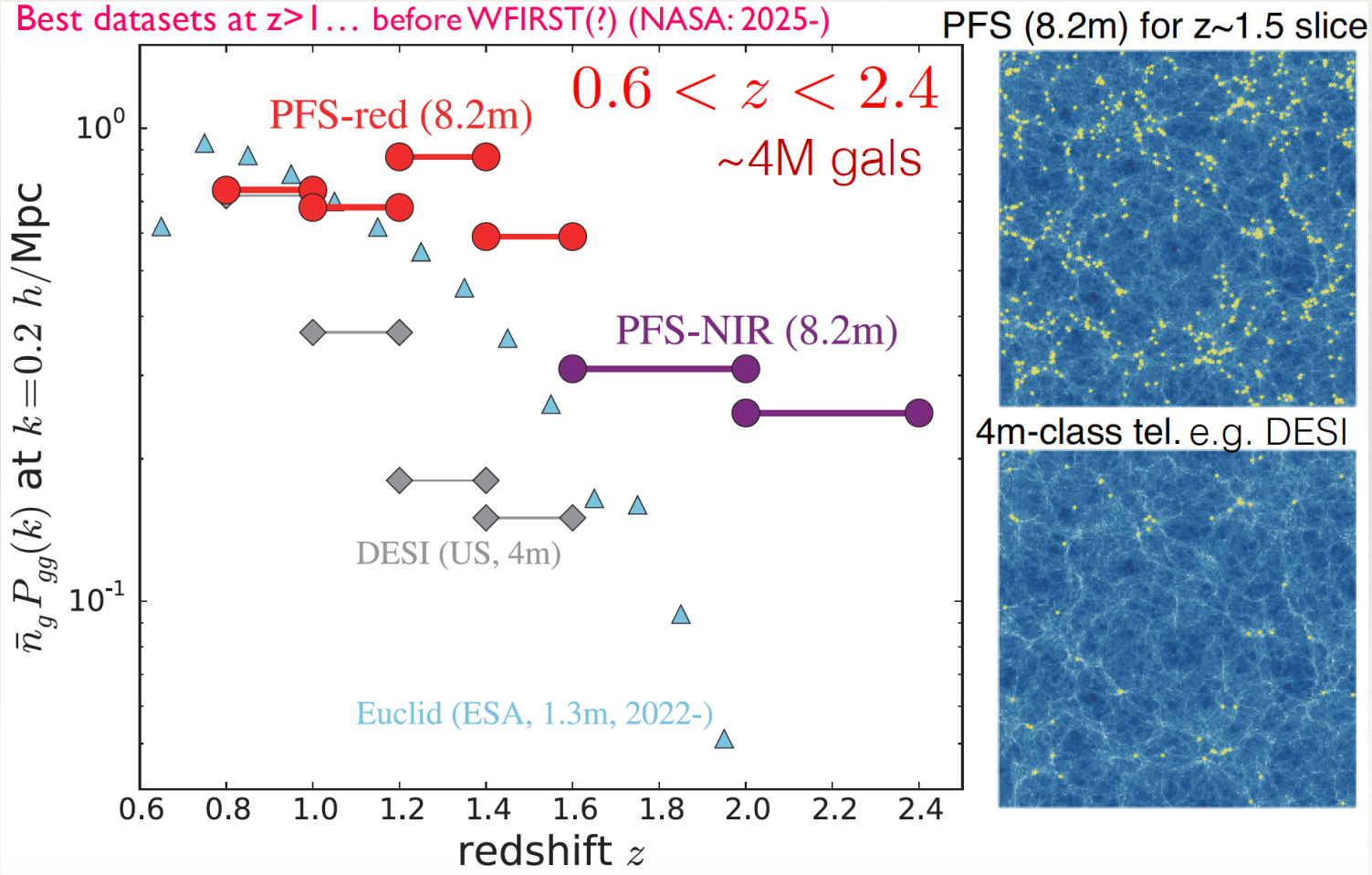
- Neutrinos suppress power spectrum (clustering of galaxies)
- PFS can achieve $\sigma(\Sigma m_\nu) = 0.02$eV!





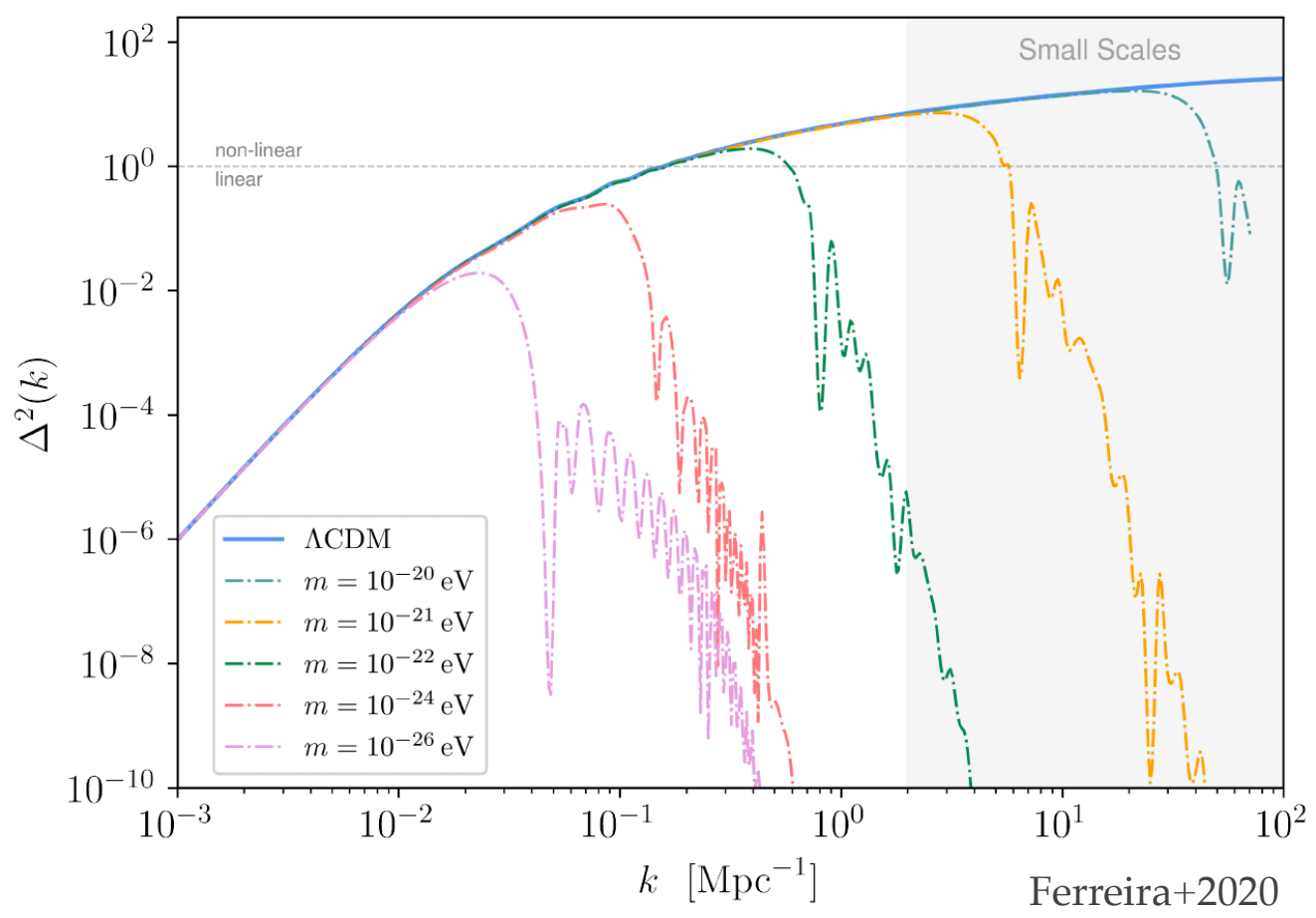
High-number density=can push to smaller scales

- PFS Cosmology program keep the high-number density at 0.6<z<2.4, which enables us to use small scale clustering.
- Going to smaller scales (k=0.5h/Mpc) can improve the neutrino mass constraint by 30%



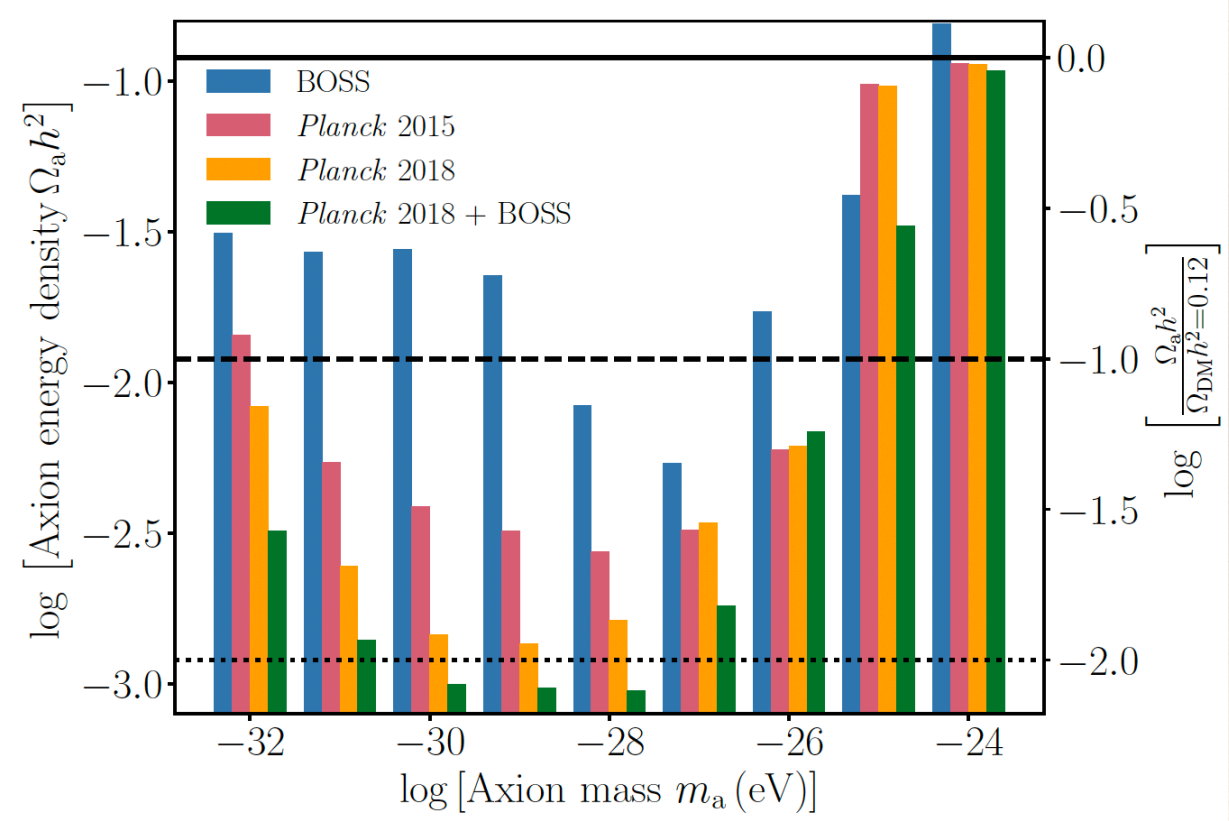
Implication on Ultra-light DM

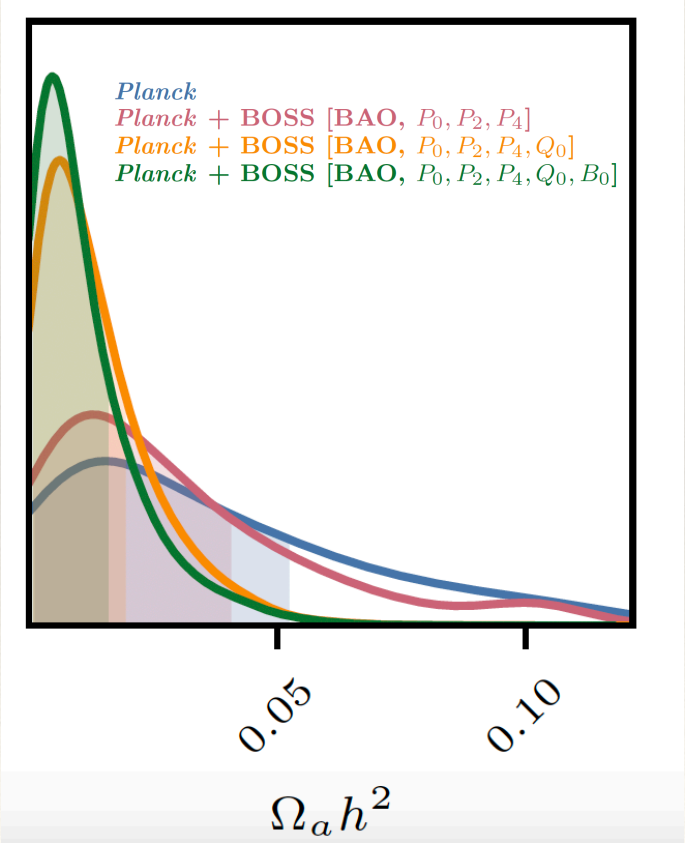
- Ultra-light DM also suppresses power spectra on small scales due to the macroscopic de Broglie wavelengths of ultra-light DM



Current constraints on axions

- Constraints are from Planck and BOSS for various axion masses

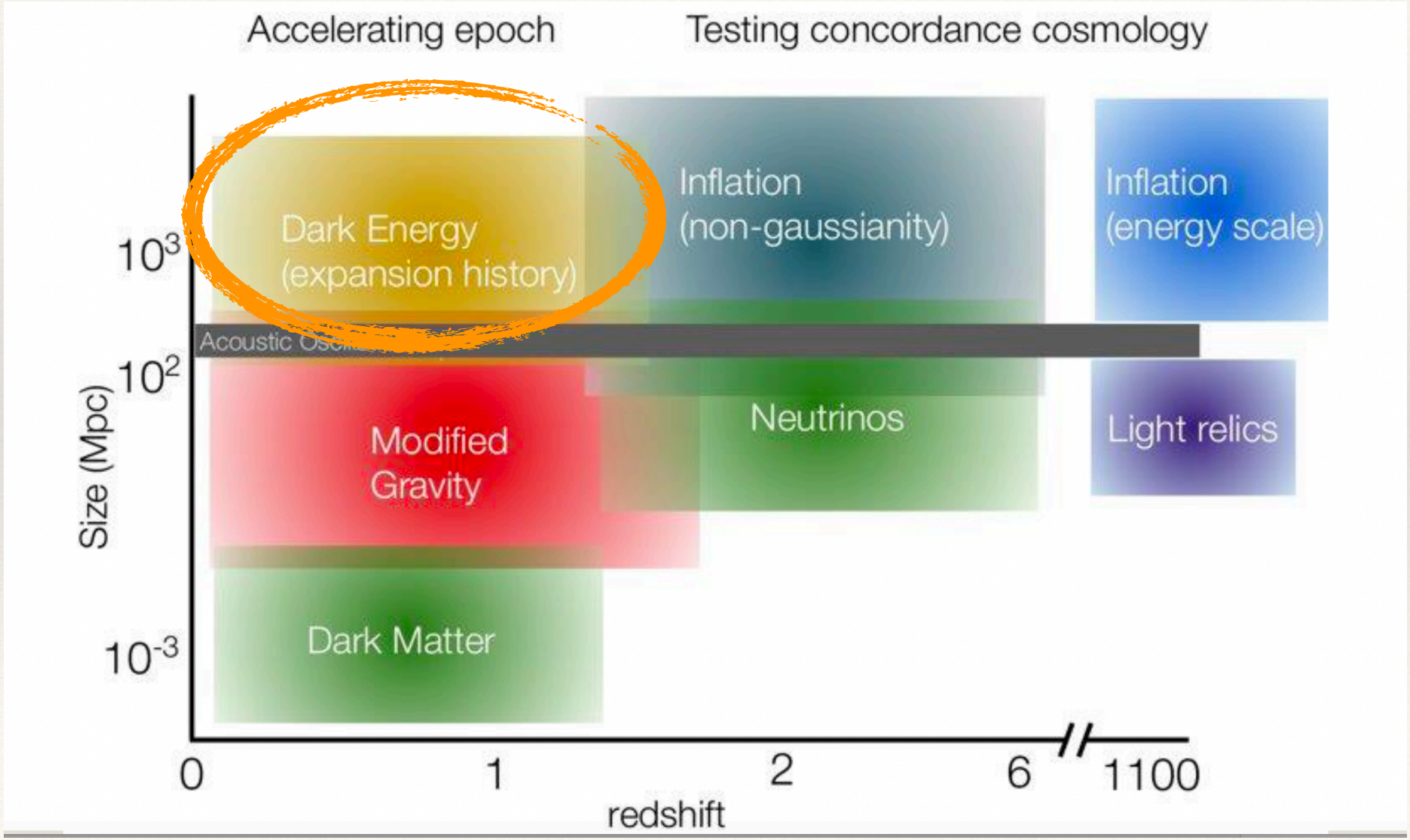




Rogers+2023

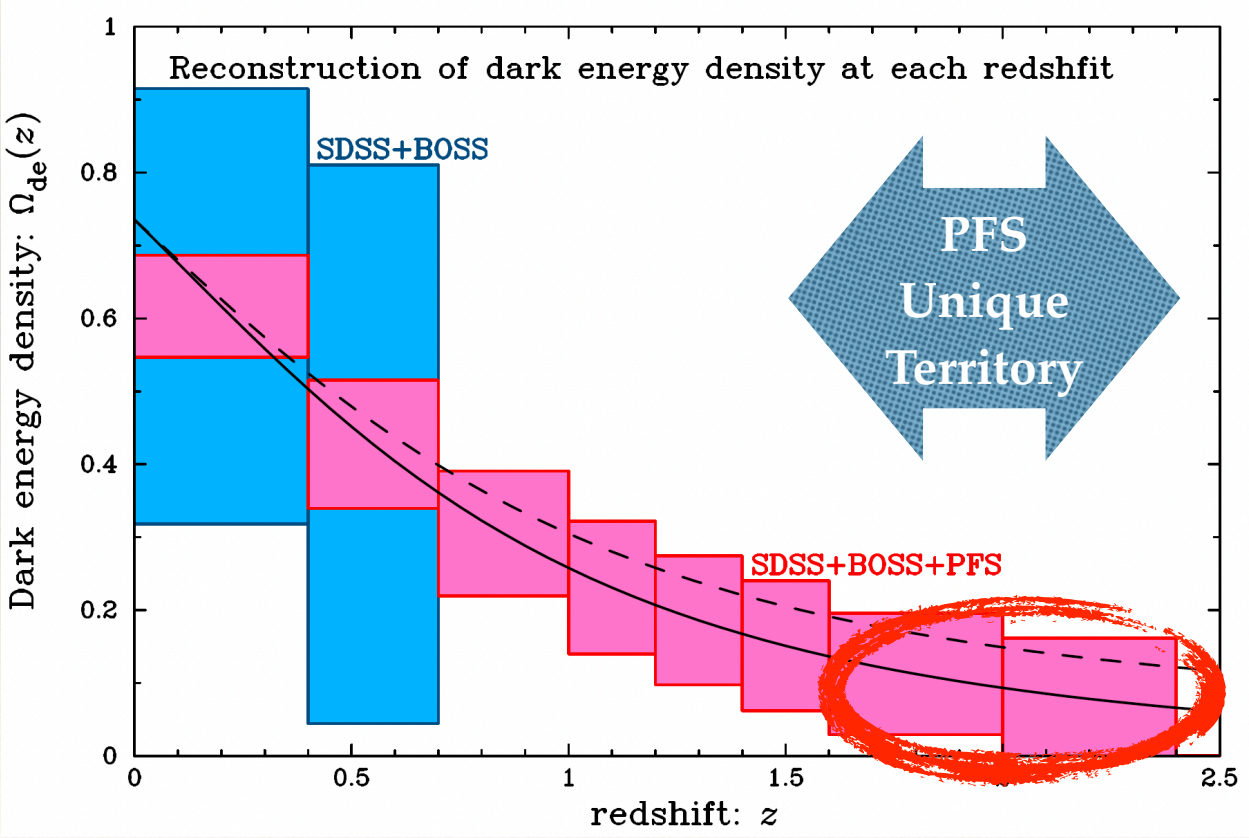
PFS Cosmology program will explore…

- What can we learn about Dark Energy?



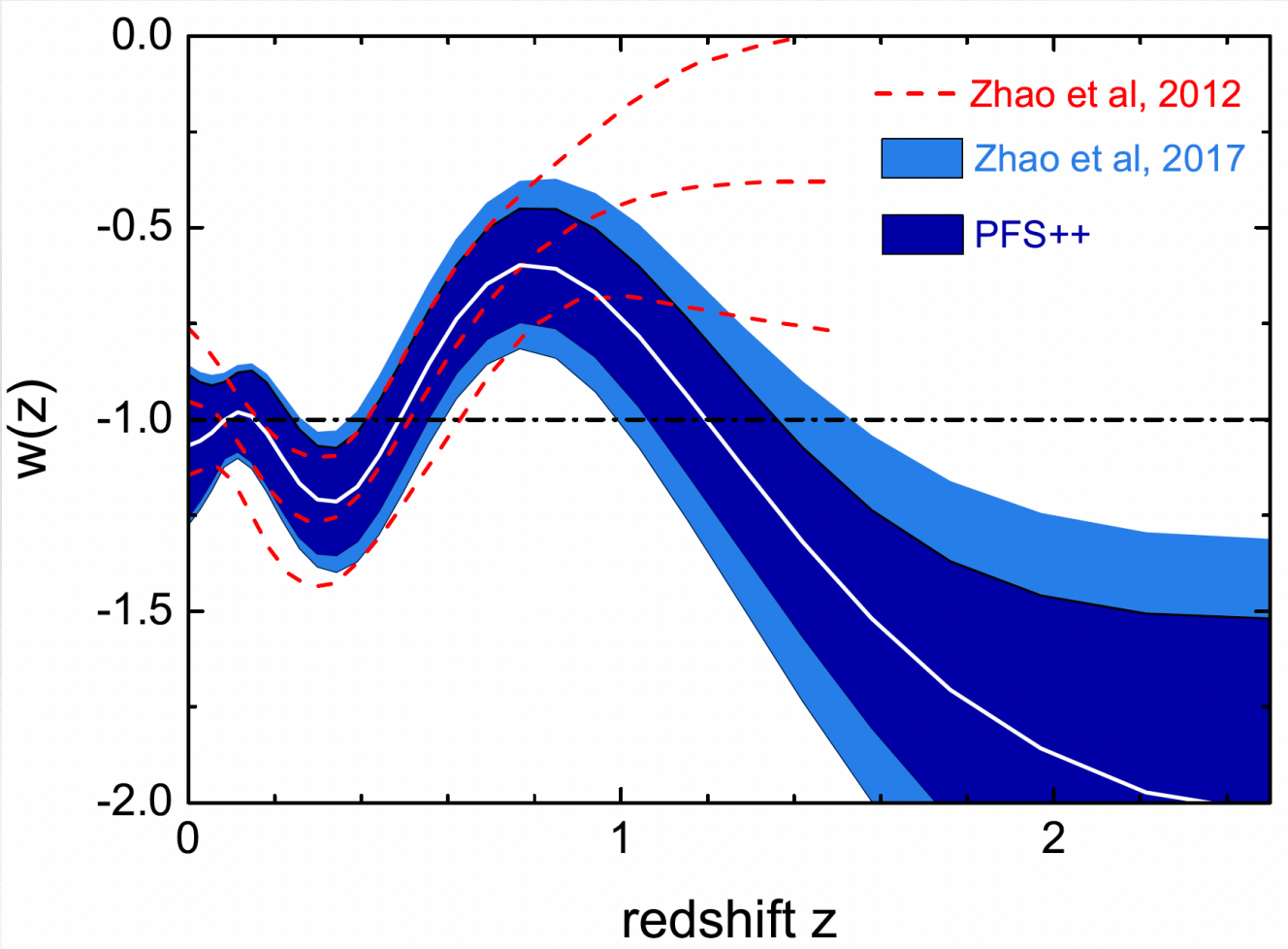
PFS can measure Dark Energy…

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



Discovery Potential: Time Evolving Dark Energy

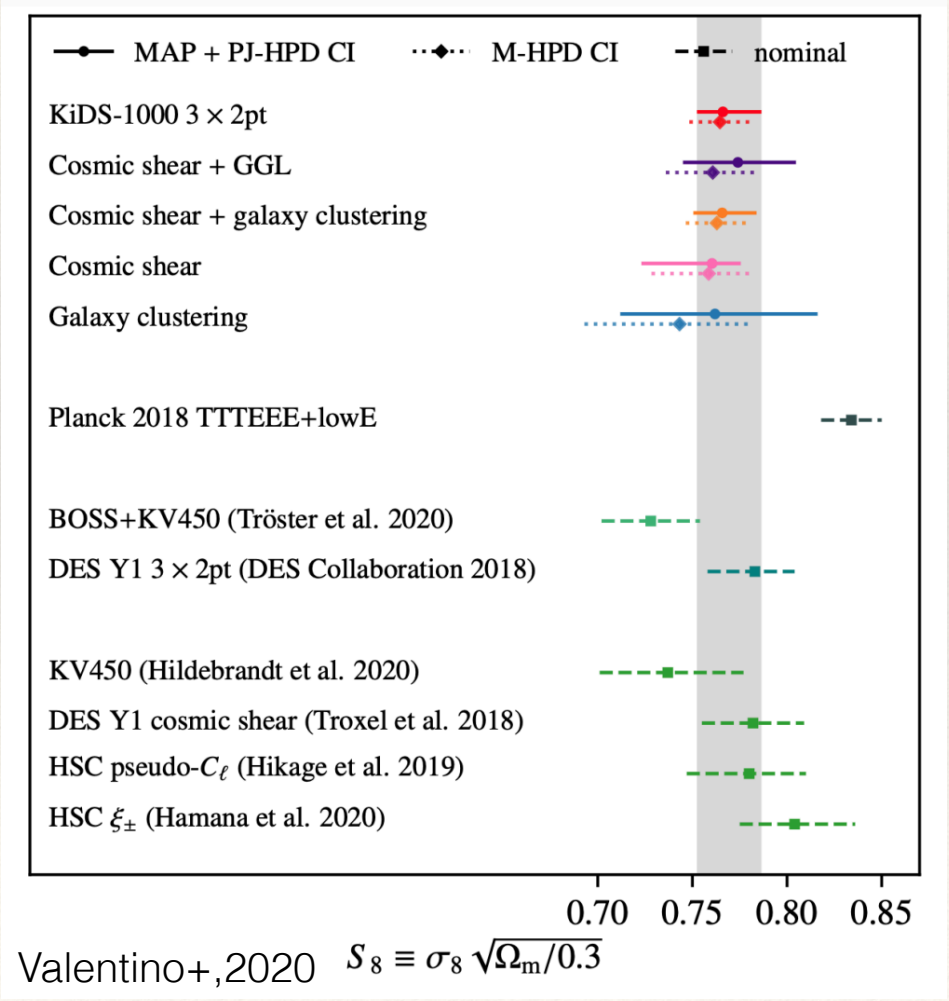
- There is a significant theoretical motivation for dark energy potentials with periodic modulations.



Where are we now? Concordance Cosmology?

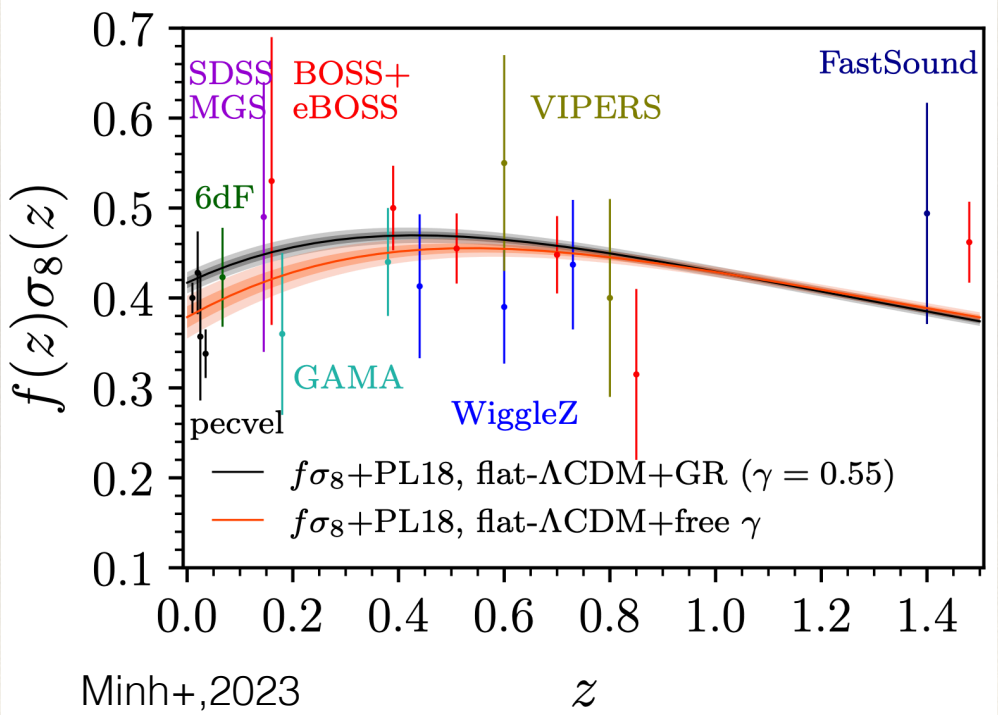
- Improvements in statistical precision reveal tensions in cosmology

Clumpiness of the density fluctuation



Valentino+,2020

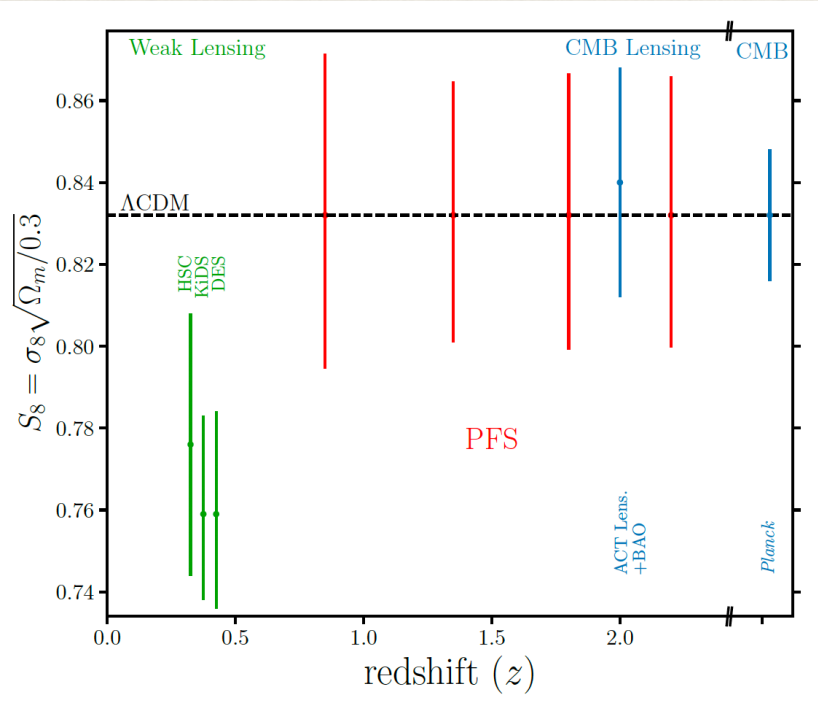
Evidence for suppression of structure growth?

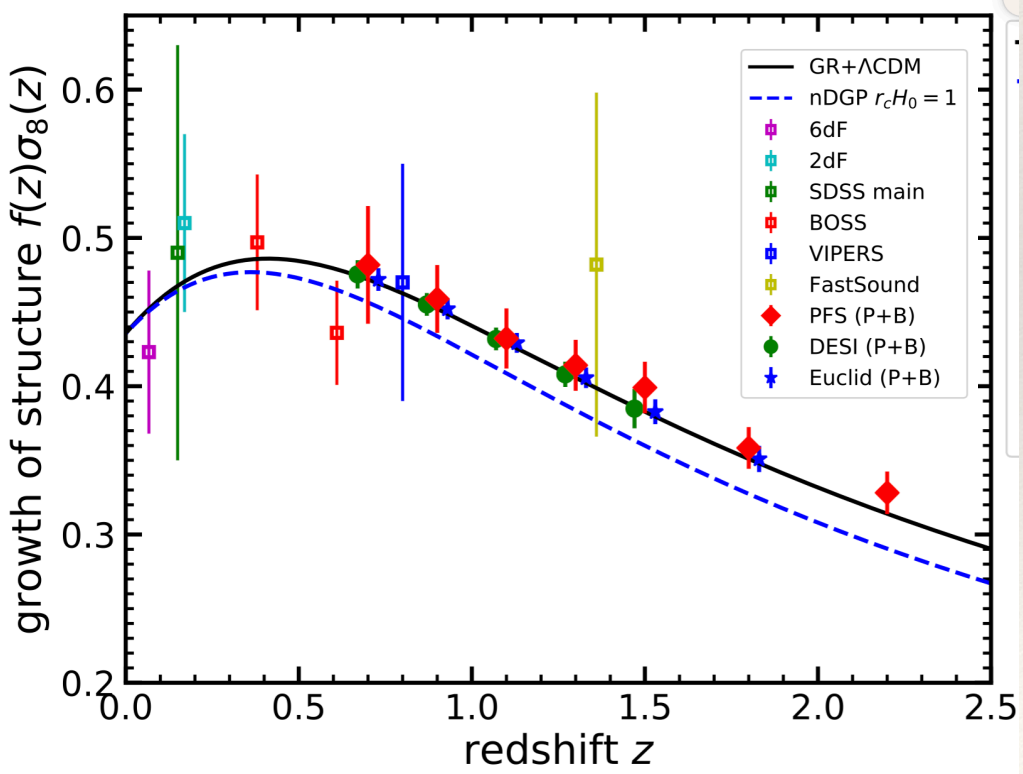


Minh+,2023

Constraints on growth of structure from PFS

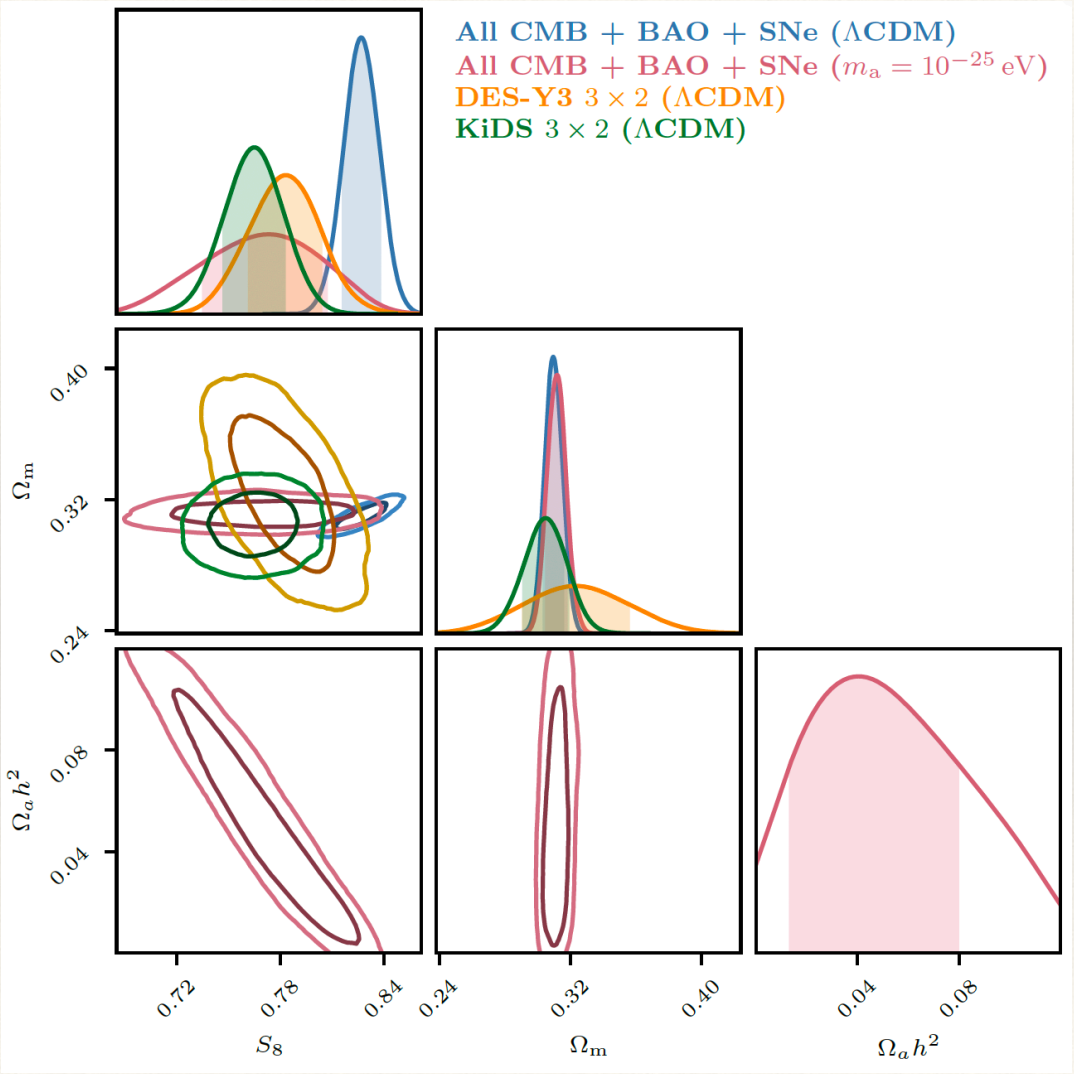
- We can constrain S_8 comparable to ACT CMB lensing measurement and growth rate of structure much more precisely than any existed measurements.





Ultra-light axions and the S_8 tension

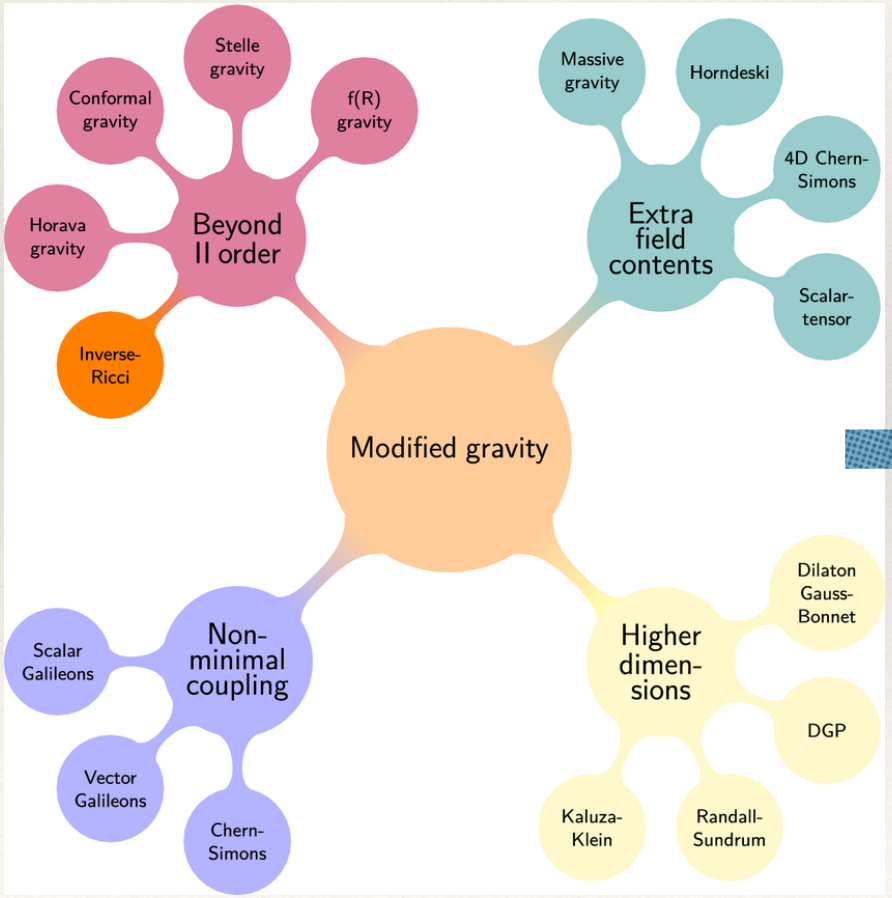
- Axions can be an explanation to the S_8 tension?
- Ω_a and S_8 are degenerate



Rogers+2023

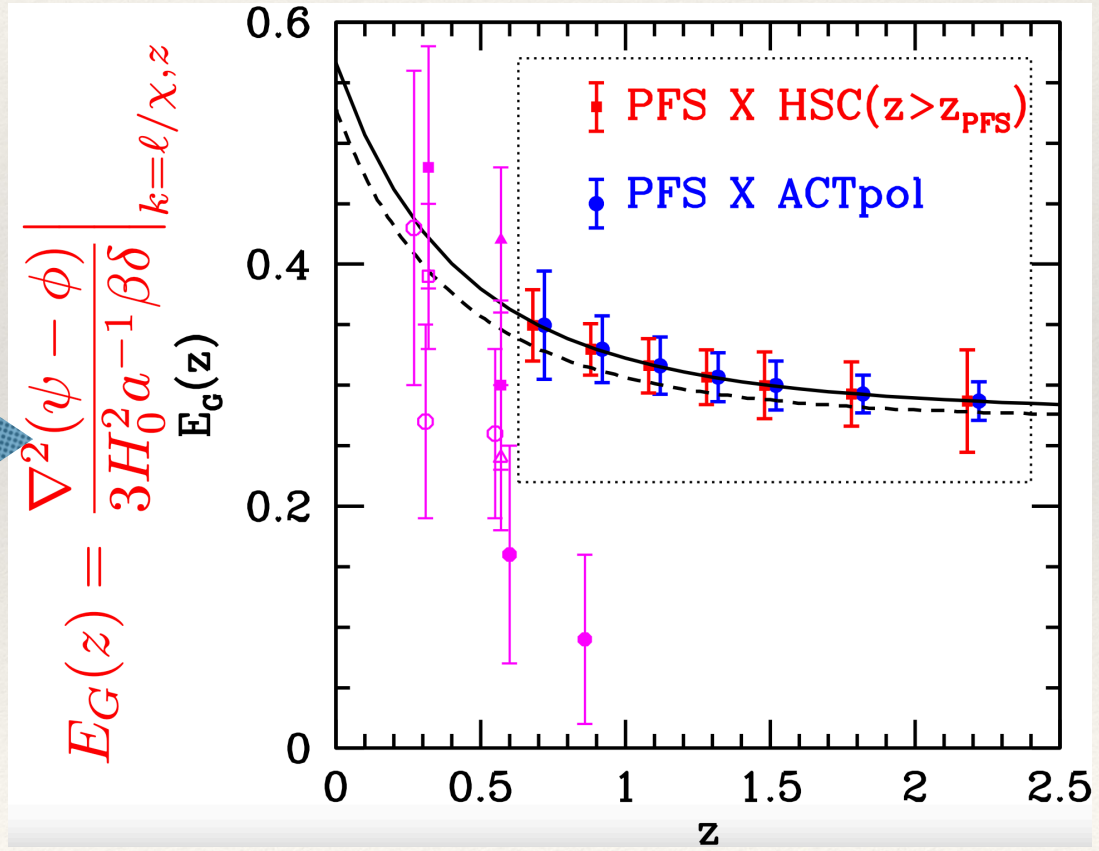
Testing theory of gravity: synergy with HSC

- Combining galaxy lensing from HSC and clustering from PFS ca be a powerful probe to test theory of gravity
- Recently, the review paper (2212.09094) is published (led by Dr. Arai, Prof. Yokoyama and Prof. Miyatake at Nagoya University/KMI)



Shankaranarayanan&Johnson2022

$$E_G(z) = \left.\frac{\nabla^2(\psi-\phi)}{3H_0^2 a^{-1}\beta\delta}\right|_{k=\ell/\chi,z}$$

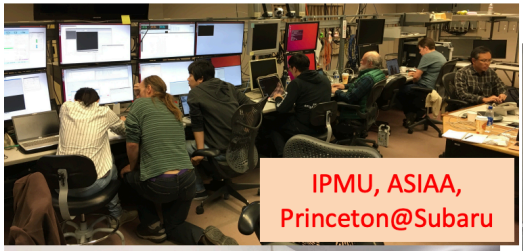


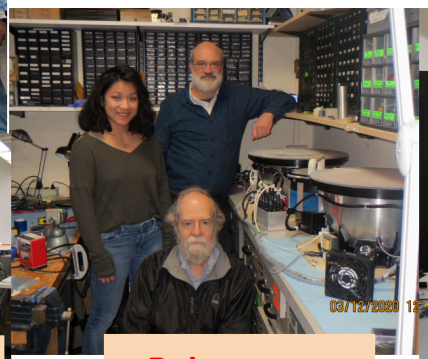
Summary

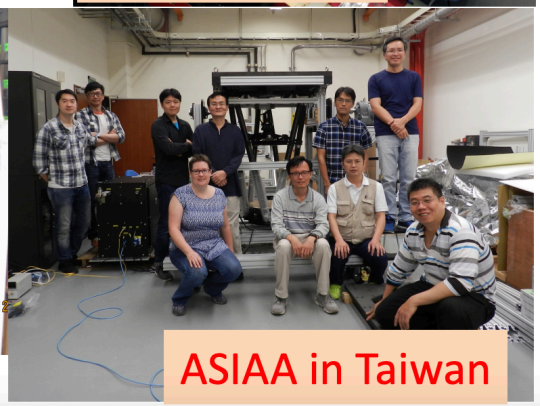
- Subaru PFS Cosmology program is unique to have a wide redshift range, high number density of ELGs, and having a synergy with Subaru HSC survey.
- PFS Cosmology program will measure the sum of neutrino mass with $\sigma(\Sigma m_\nu) = 0.02$ev, which will enable us to distinguish the mass hierarchy of neutrino.
- High number density of ELGs enables us to measure power spectra on small scales.
- Observing ELGs at z=2-2.4 is a unique strength of PFS cosmology program and enables us to trace the redshift evolution of growth of structure and dark energy density

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 (Kavli IPMU)

Prof. Yuki Moritani (U. Hawaii)

Dr. Kiyoto Yabe (Kavli IPMU)