Cosmology with the Dark Energy Spectroscopic Instrument

Segeev BenZvi, University of Rochester
on behalf of the DESI Collaboration

42nd International Symposium on Physics in Collision (PIC 2023)
Universidad de Tarapacá, Arica, Chile
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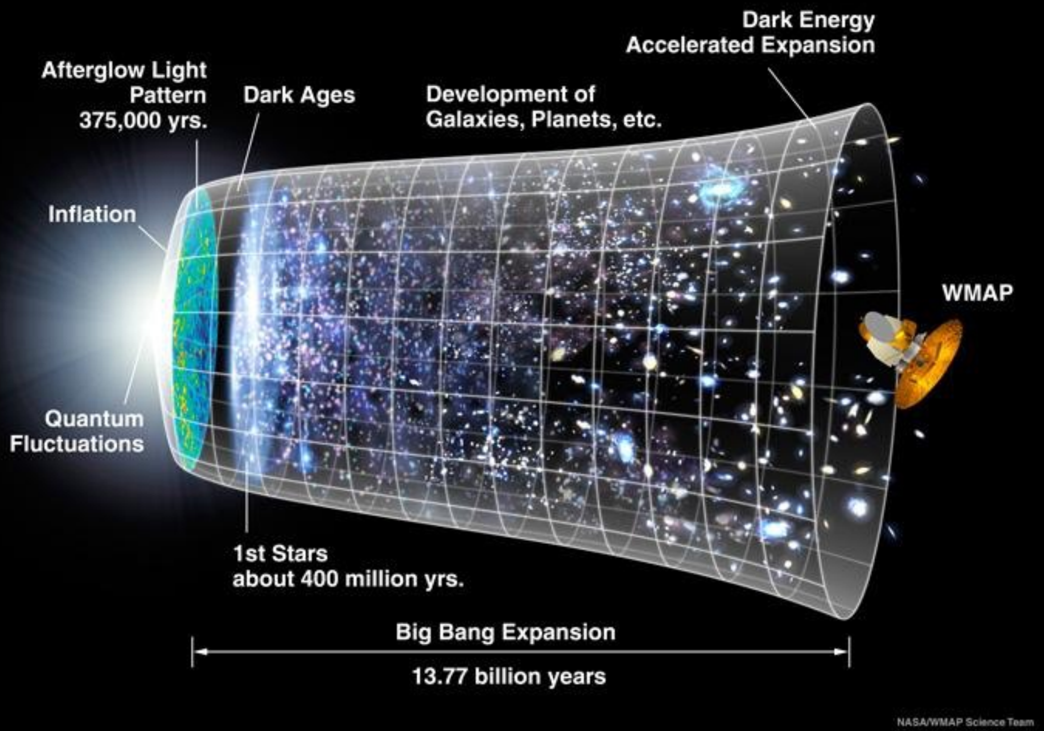
Evolution of the Universe

Initial conditions:

Big Bang + inflation.

Earliest observable is from time t_0+380 kyr: the homogeneous & isotropic (to 10^{-5} level) cosmic microwave background from last scattering surface of baryon-photon plasma.



Final state:

Large-scale structure: a "cosmic web" of luminous gas and galaxies evolved from small density perturbations in the early universe.

Credit: NASA/WMAP

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Physical Cosmology

Treating the universe as a homogeneous fluid in expanding space, the FLRW solution to field equations of General Relativity describes its growth:

$$\left(\frac{\dot{a}}{a}\right)^2 = \Omega_m a^{-3} + \Omega_\Lambda a^{-3(1+w)} + \Omega_r a^{-4} + \Omega_k a^{-2}$$

Scale factor

Matter density

Dark energy density ($w = P/\rho$ = eq. of state)

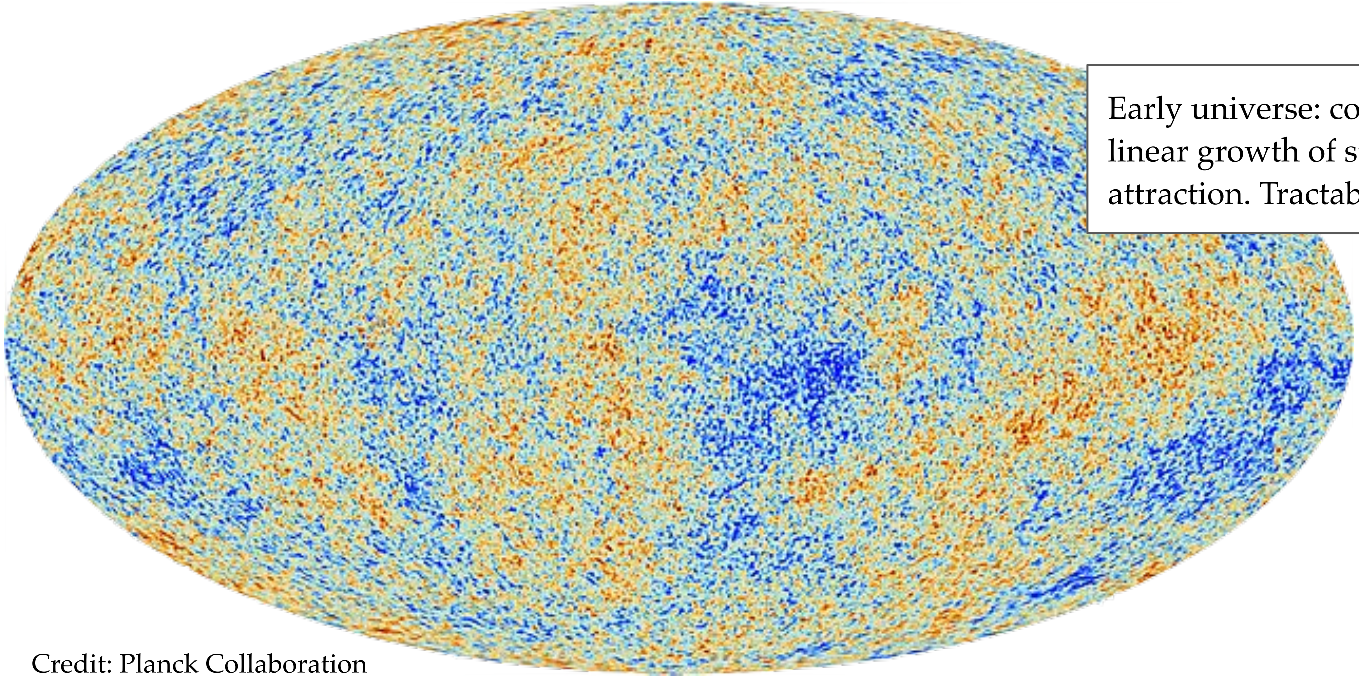
Radiation

Curvature

Cosmological parameters:

Parameters	Meaning
H_0	**Expansion rate observed today**
$\Omega_m, \Omega_\Lambda, \Omega_b$	**Matter/energy content of universe**
n_s, A_s, σ_8	**Initial conditions, inflation**
Σm_ν	**Relic neutrinos**
w_0, w_a	**Dark energy eq. of state**
f_{NL}	**Initial conditions, non-Gaussianity**

Structure Formation: Then to Now



Early universe: cosmic microwave background, linear growth of structure due to gravitational attraction. Tractable with perturbation theory.

Credit: Planck Collaboration

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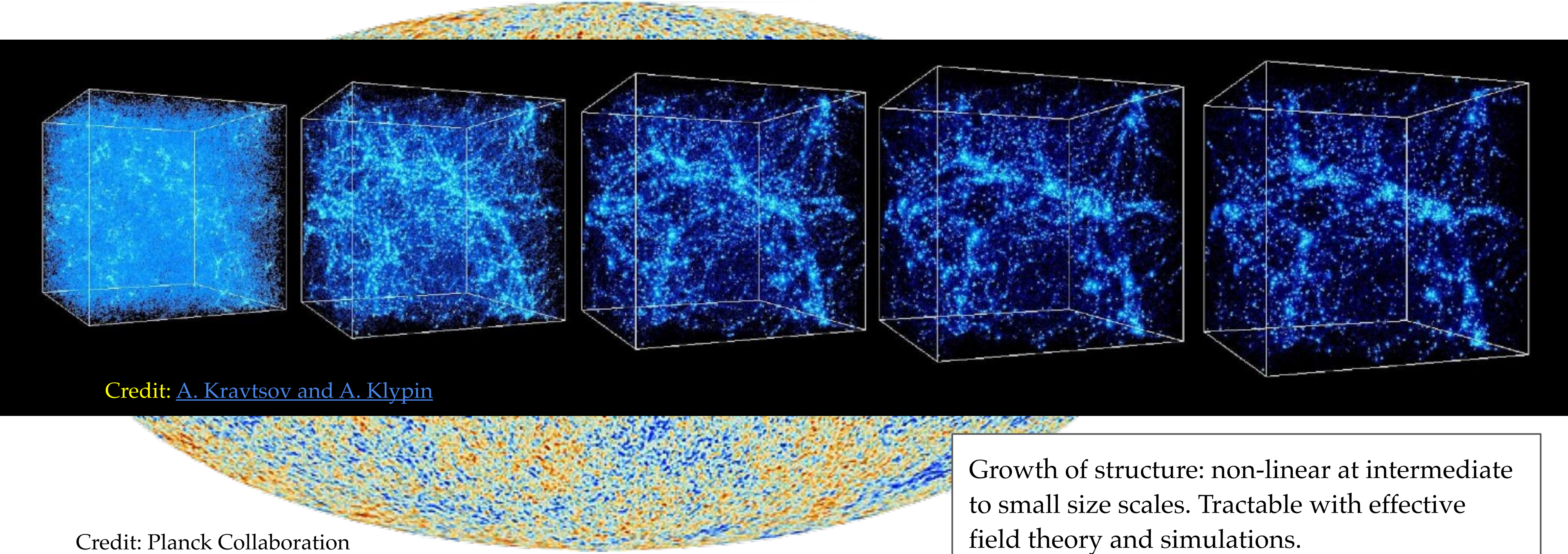
Structure Formation: Then to Now

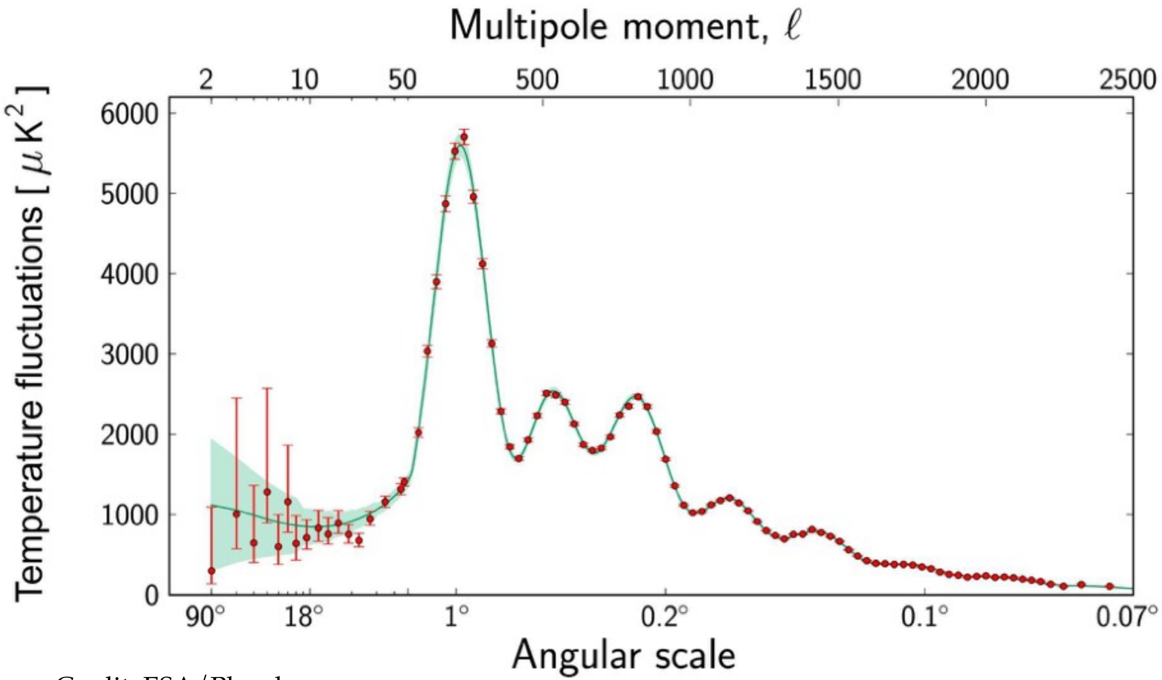


Credit: A. Kravtsov and A. Klypin

Credit: Planck Collaboration

Growth of structure: non-linear at intermediate to small size scales. Tractable with effective field theory and simulations.

Structure Formation: Then to Now



Credit: ESA/Planck

Baryon acoustic oscillations (BAO): acoustic waves in baryon-photon plasma.

Sound horizon r_s: maximum size scale of BAO, set by the speed of sound in the plasma.

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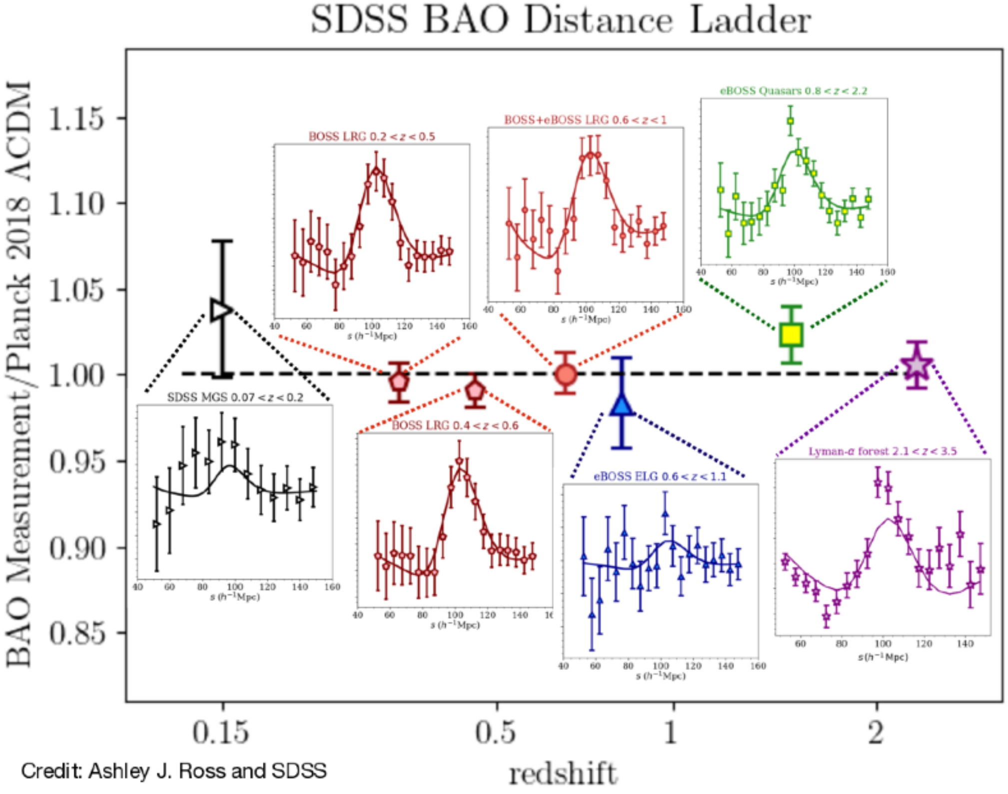
Structure Formation: Then to Now

After recombination, BAO were imprinted in the distribution of matter.

Today they are observable at low redshift as a peak in the two-point correlation function of galaxies and quasars.

The BAO can be used as a **standard ruler** to measure distances to galaxies at low *z*.



Credit: Ashley J. Ross and SDSS

Large-Scale Structure and ΛCDM

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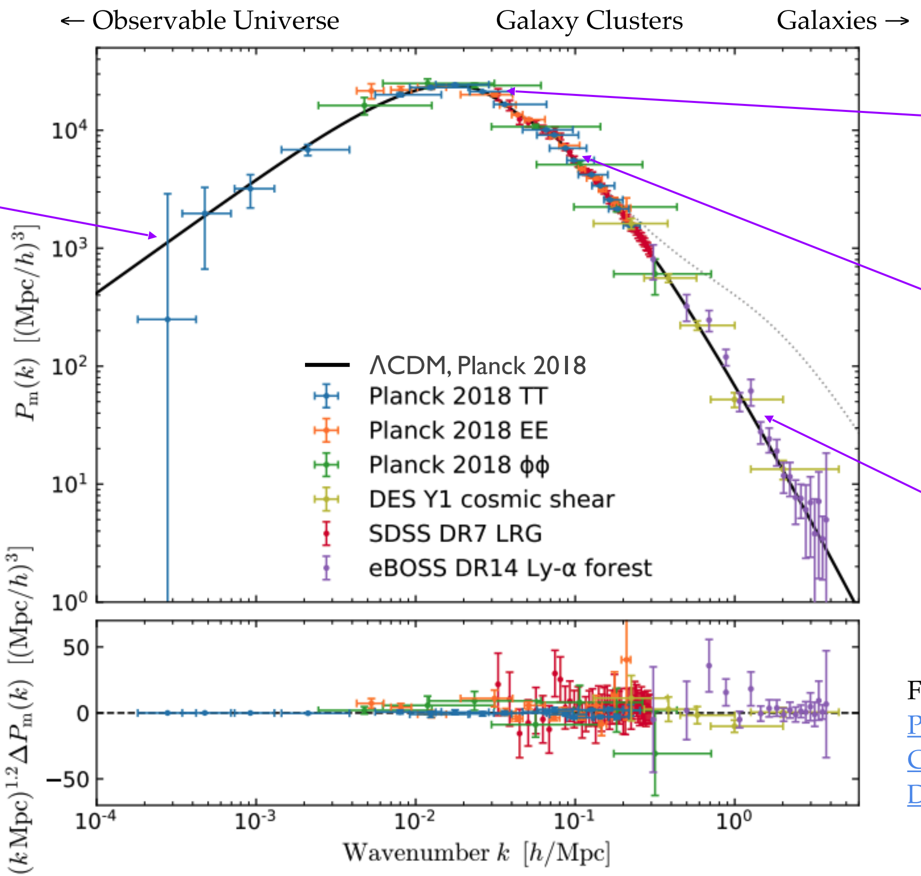
Primordial power spectrum from inflation:

$P_m(k) \propto k^{n_s}$



Peak set by horizon size at matter-radiation equality

Baryon Acoustic Oscillations (BAO): sound horizon at recombination

Small-scale spectrum:

$P_m(k) \propto k^{-2}$

Figure credit: Planck Collaboration (2018), Chabanier, Millea, and Palanque-Delabrouille (2019)

Credit: after O. Hahn, TAUP 2023

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Open Questions about ΛCDM

What is dark energy? Is it a cosmological constant with EOS w = -1? Or does it evolve as a function of scale factor such that $w = w(a)$?

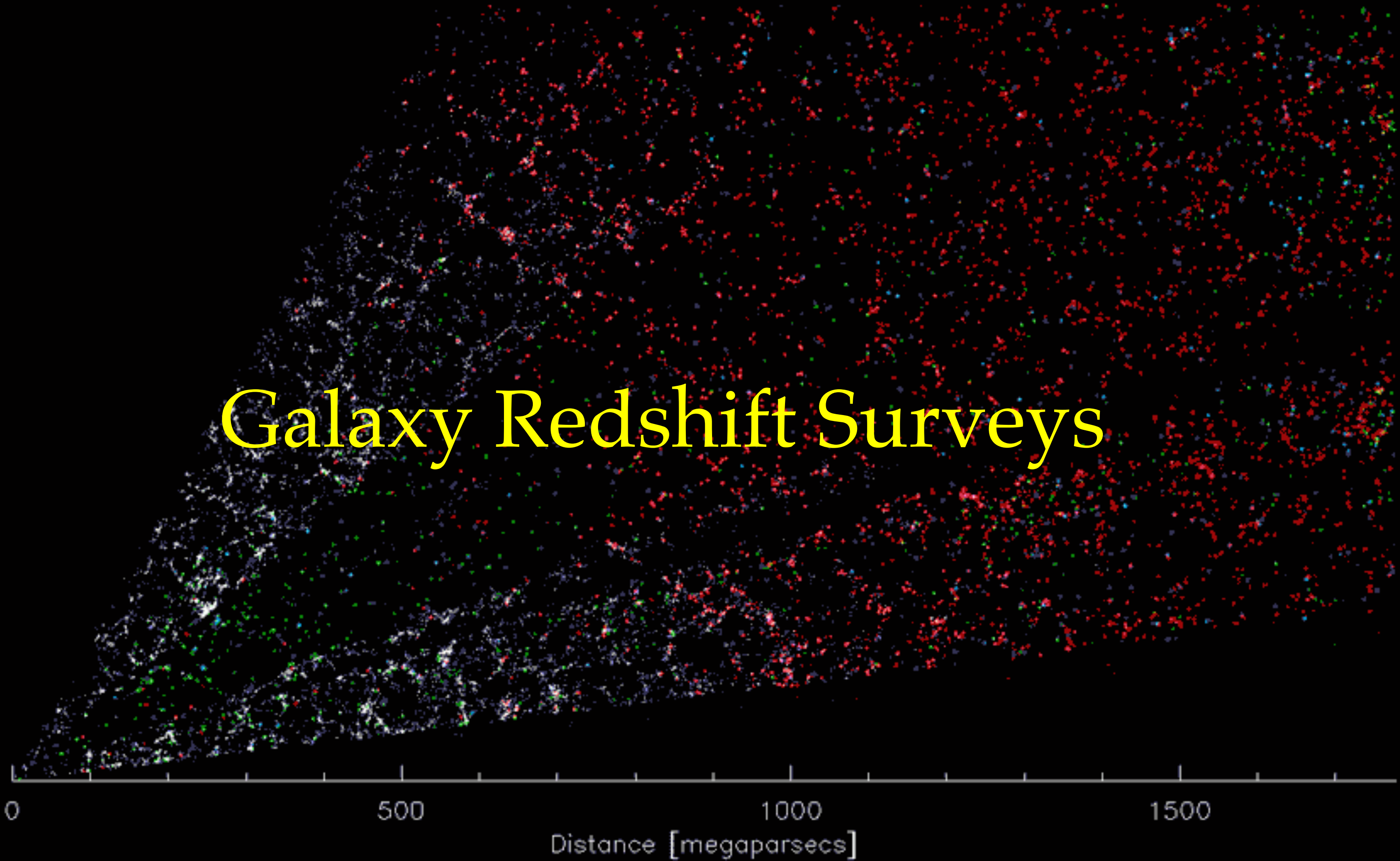
Is General Relativity correct on the largest size scales, or are observations consistent with modifications to gravity?

What were the initial conditions of the universe? Were inflationary density fluctuations Gaussian ($f_{\rm NL} = 0$) or non-Gaussian ($f_{\rm NL} \neq 0$)?

How well can we constrain the sum of the neutrino masses? Can we also constrain the neutrino mass hierarchy?

What is the nature of dark matter?

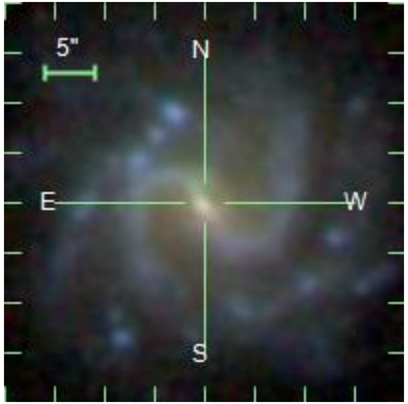
Galaxy Redshift Surveys



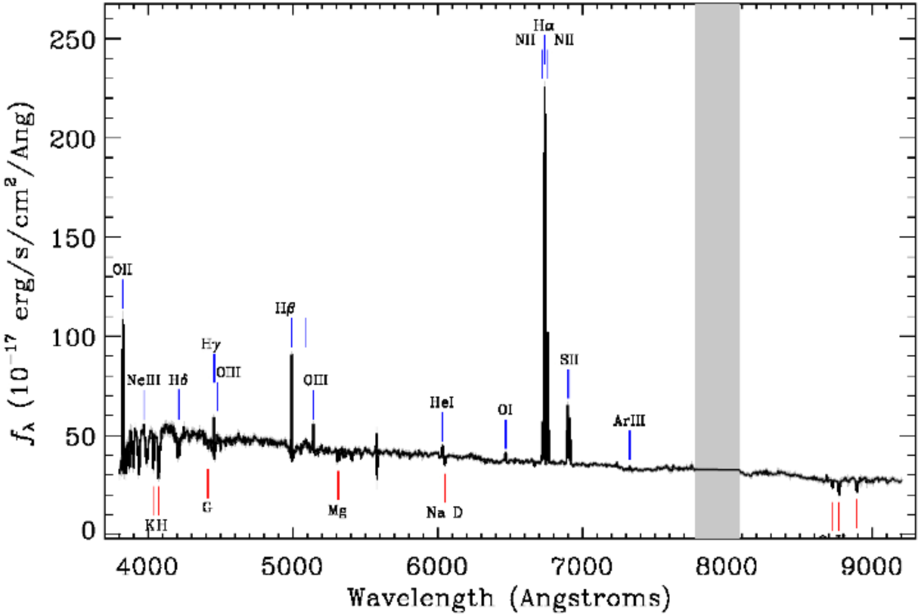
Inferring Distances to Galaxies using Redshift z

Recall your Astronomy 101: light from galaxies is increasingly redshifted with distance from Earth. The distance-redshift relation is given by the Hubble function $H(z)$.

Credit: SDSS, Dahlia Veyrat



$d = 117$ Mpc
(~400 Mly)



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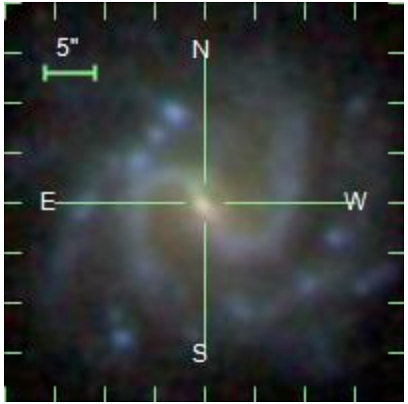

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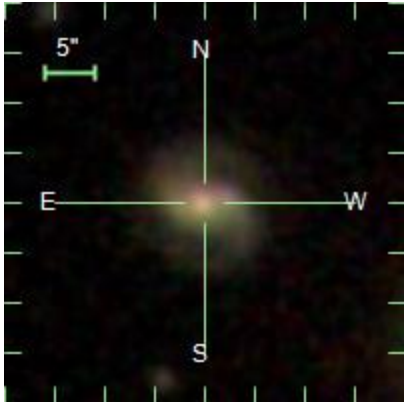
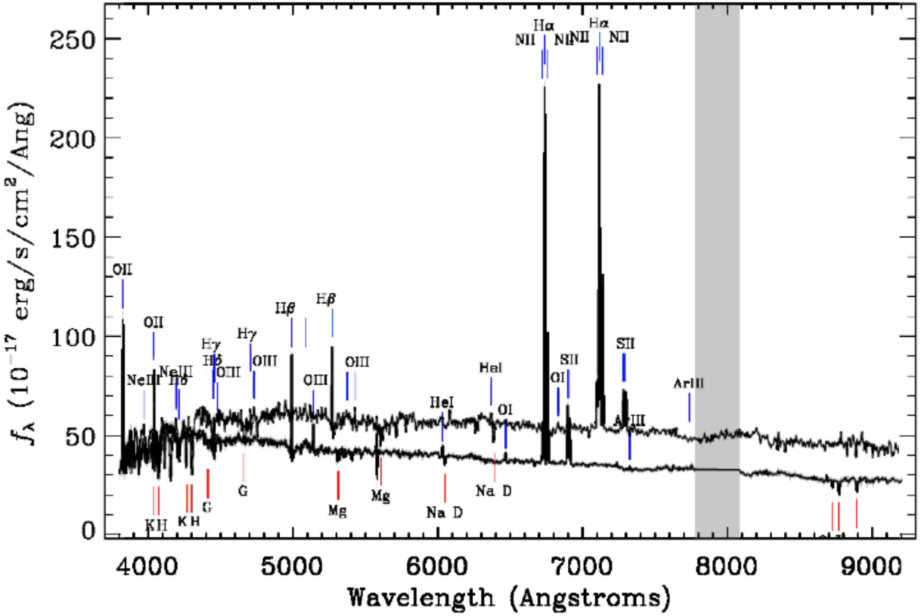
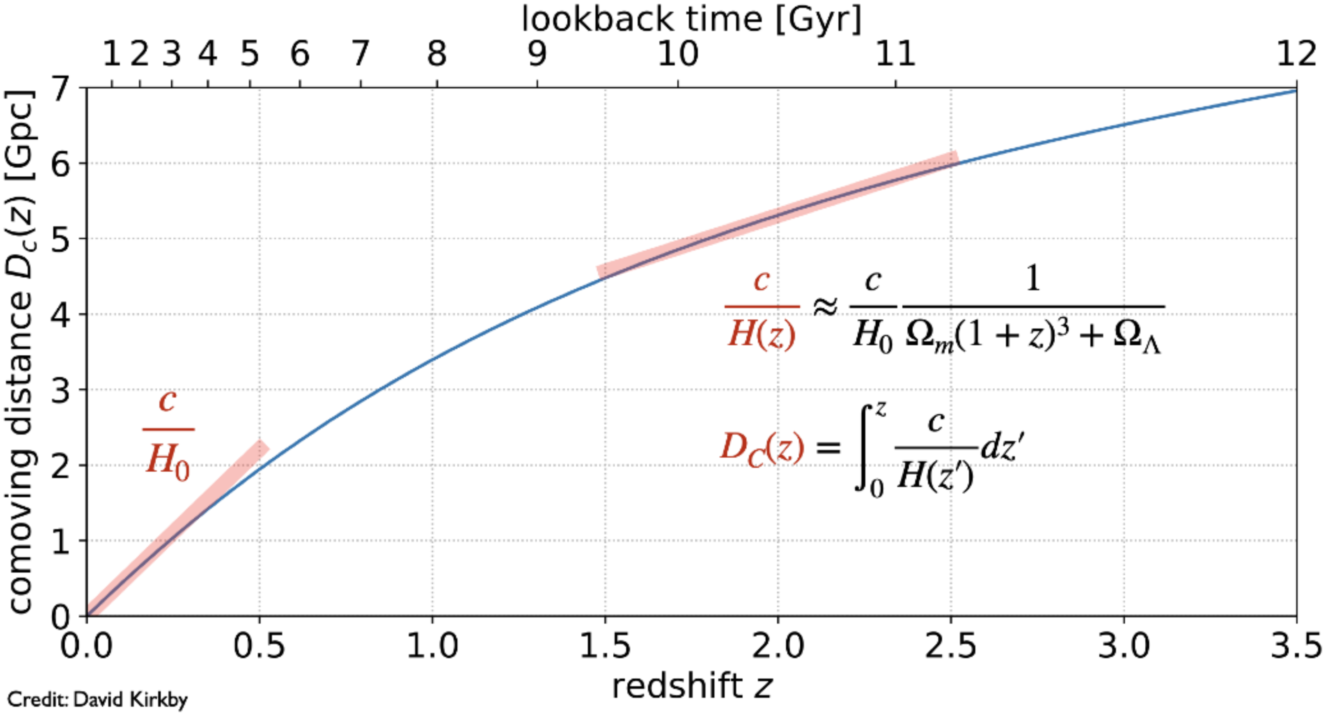


$d = 382$ Mpc
(~1200 Mly)



Measuring the Hubble Expansion $H(z)$

Distance vs. Redshift



Credit: David Kirkby

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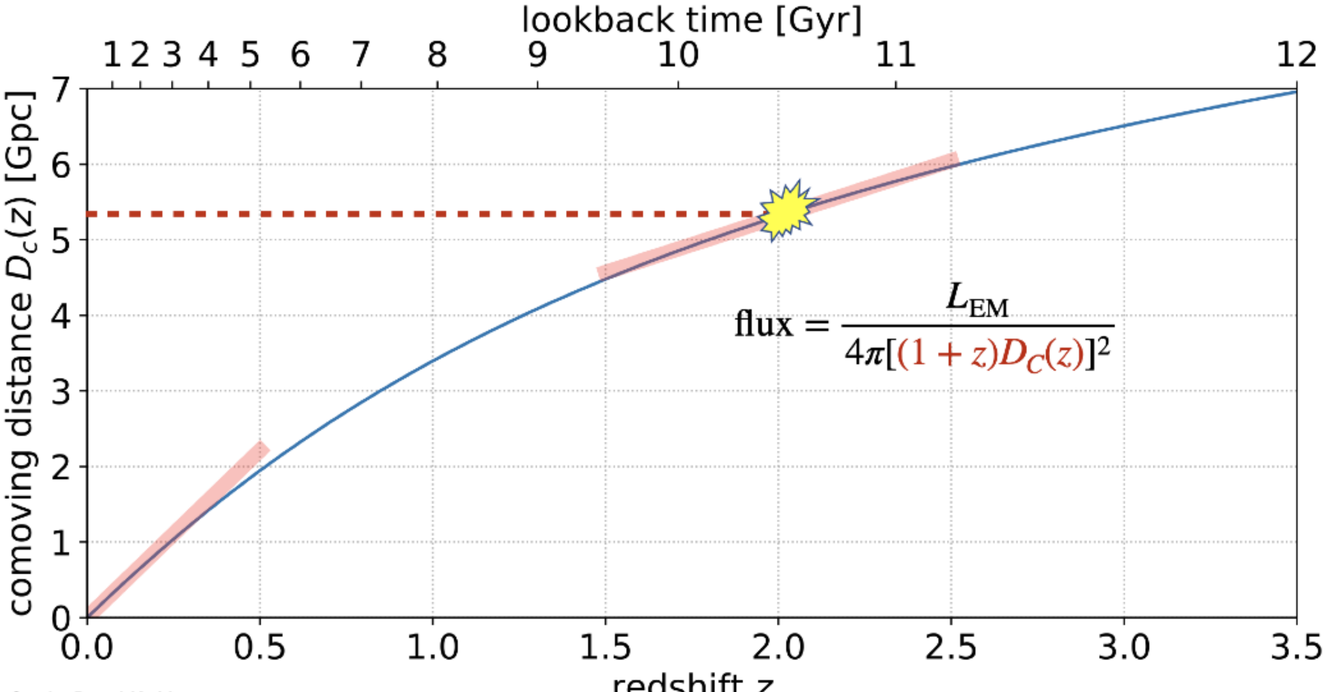
Measuring Cosmological Distances using Standard Candles

Standard Candle



Credit: David Kirkby

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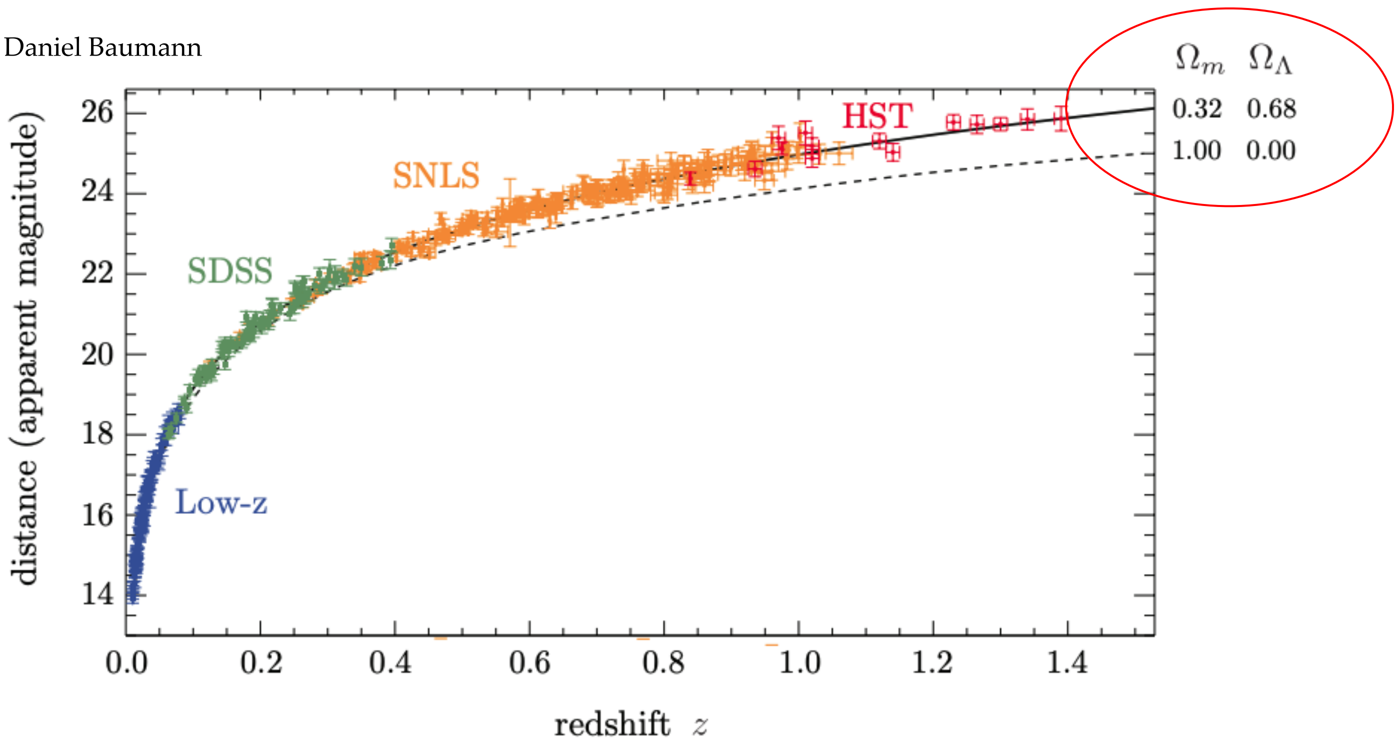
Measuring Cosmological Distances using Standard Candles

Credit: Daniel Baumann



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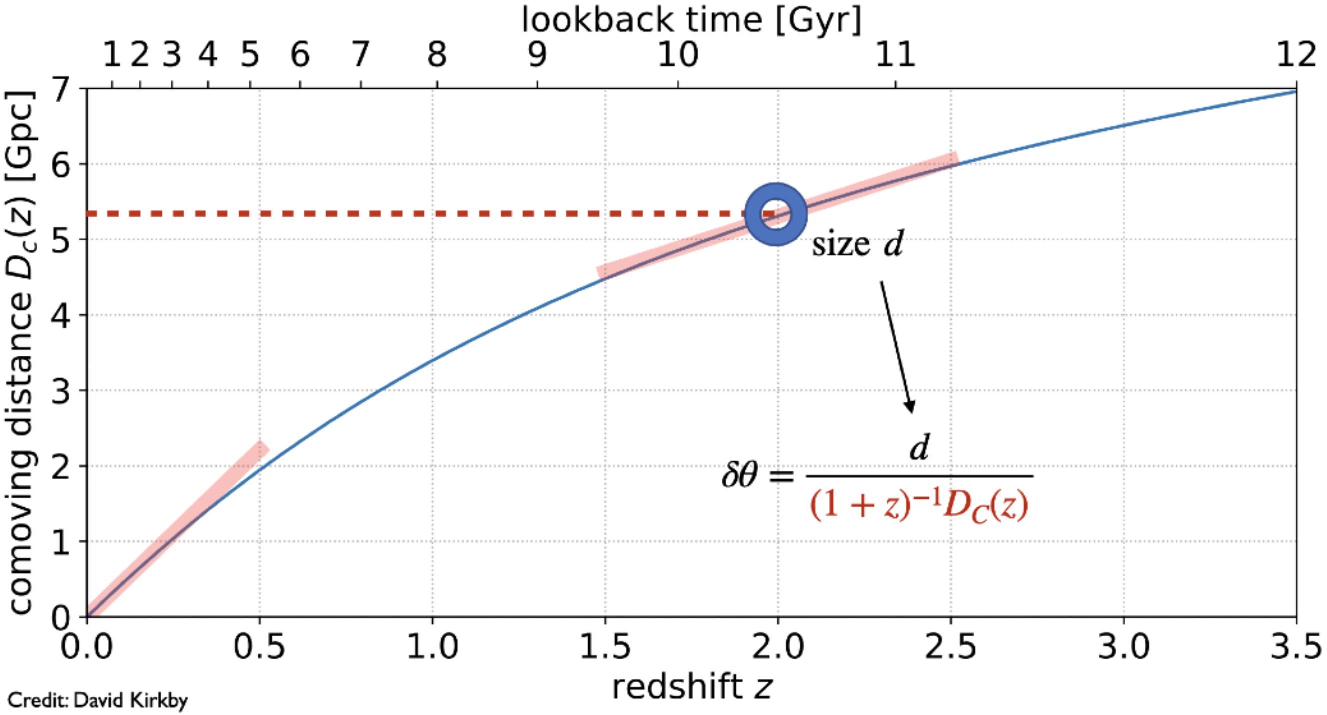
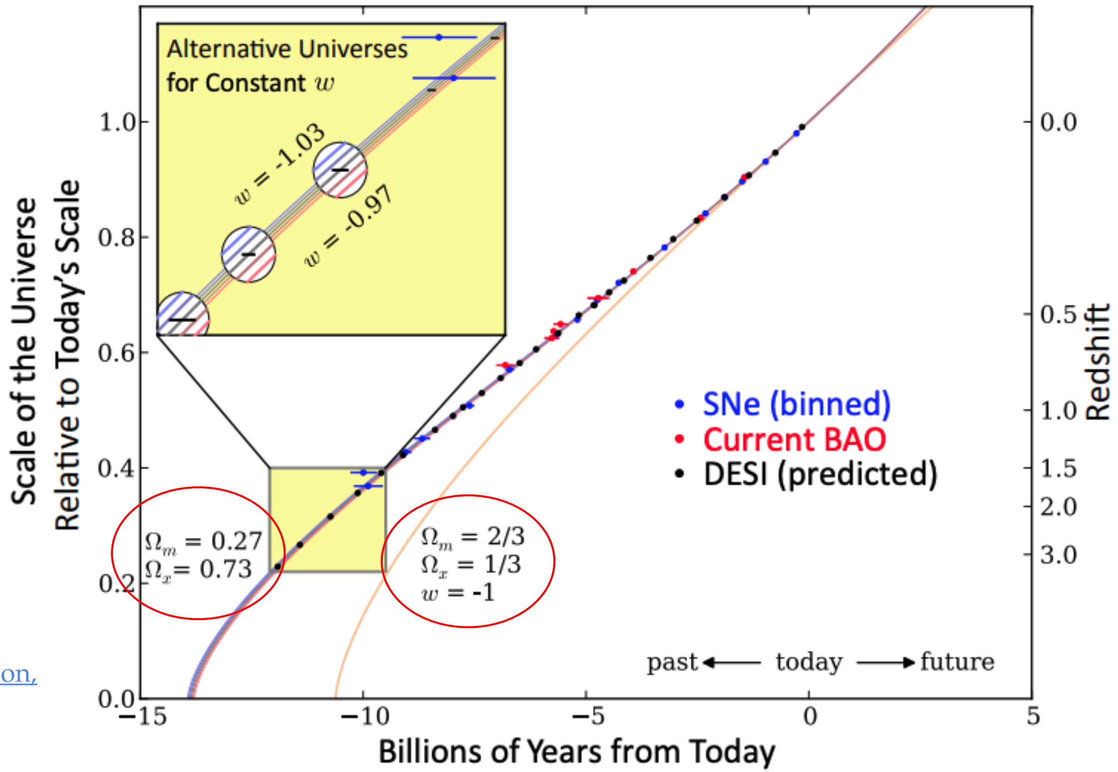
Measuring Cosmological Distances using a Standard Ruler

Standard Ruler



Credit: David Kirkby

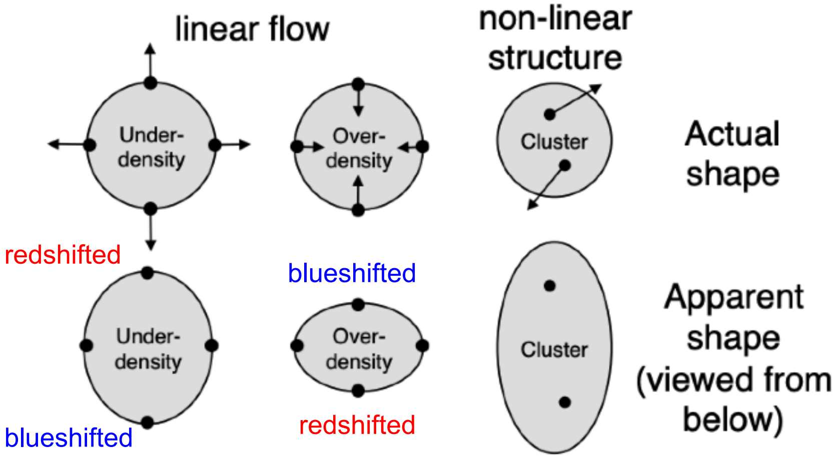
Measuring Cosmological Distances using a Standard Ruler



Credit: [DESI Collaboration, A. Aghamousa+, 2016]

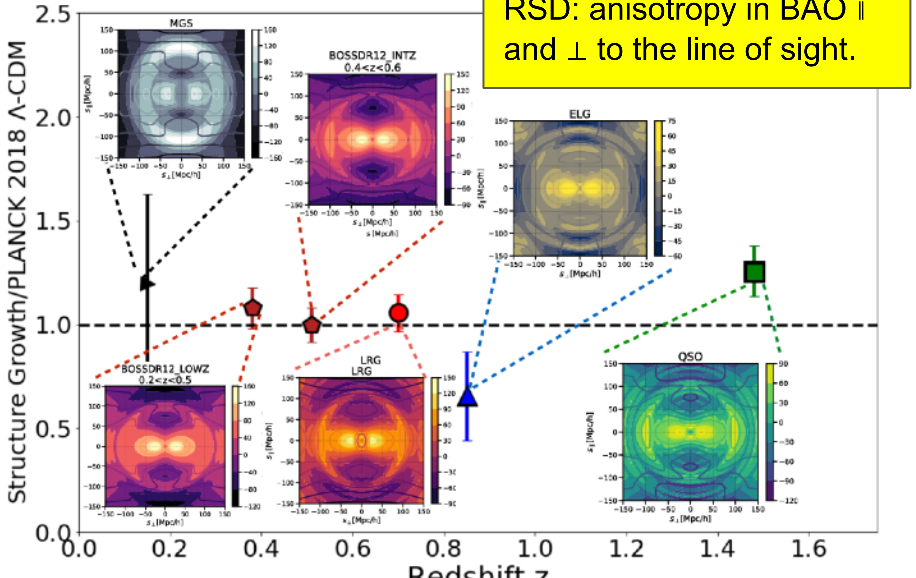
Measuring the Growth of Structure: Redshift Space Distortions (RSD)

Because we measure galaxy redshifts, not distances, peculiar motion causes deviations from the Hubble flow along the line of sight.



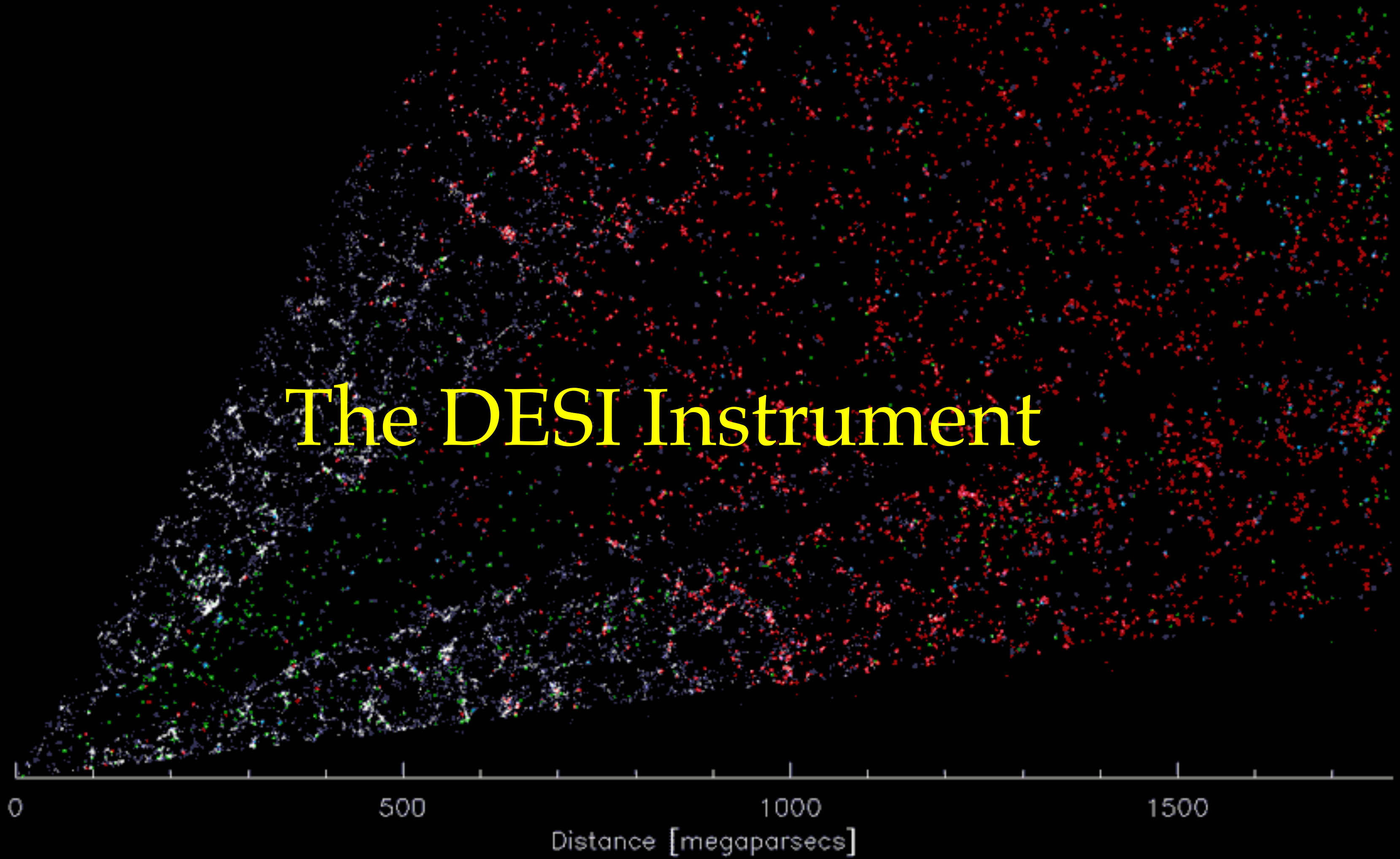
Credit: W. Percival, *Post-Planck Cosmology*, 2013

RSD: anisotropy in BAO ∥ and ⊥ to the line of sight.



Credit: M.Vargas-Magaña and SDSS.

The DESI Instrument



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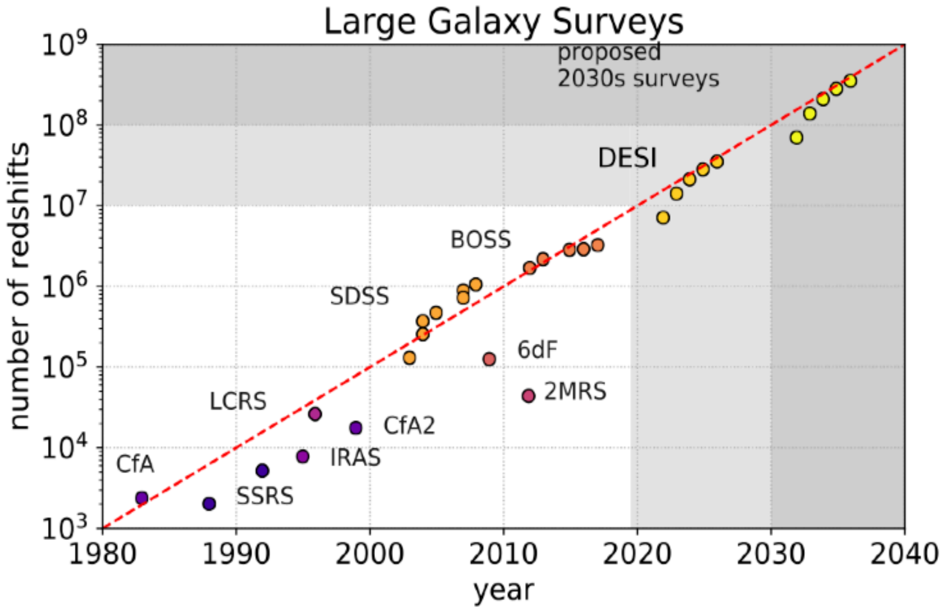
Galaxy Redshift Surveys: 1980s-2020s

Cutting-edge cosmology requires pushing the limits on survey throughput.



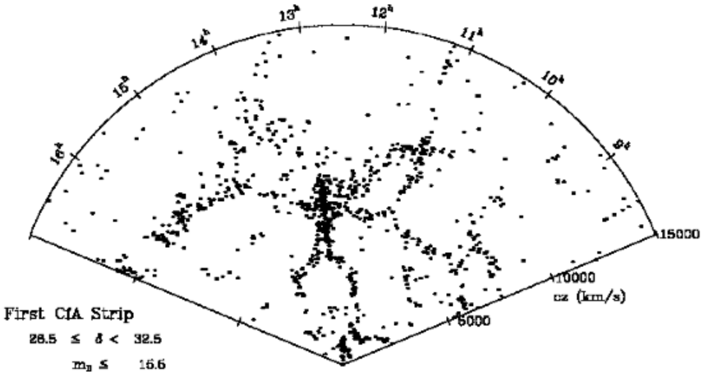
After D. Schlegel+, BAAS 51:229, 2019

1980s: ~10^3 redshifts (e.g., CFA).

1990s: ~10^4 redshifts (e.g., LCRS).

2000s: ~10^5 redshifts (e.g., SDSS).

2010s: ~10^6 redshifts (e.g., BOSS).



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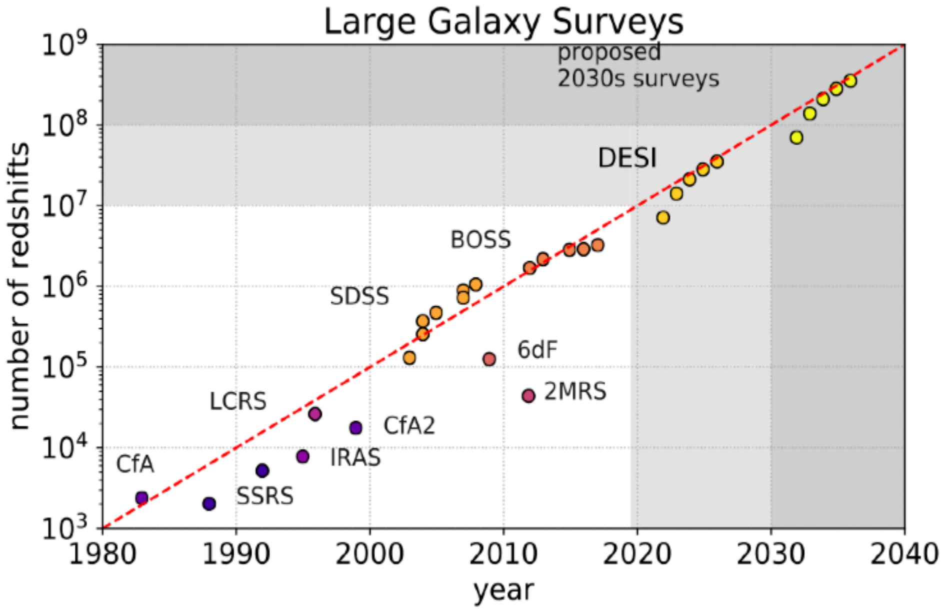

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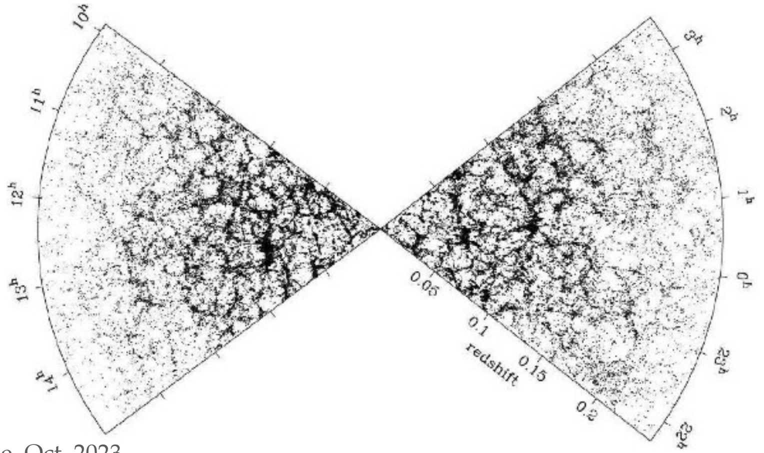

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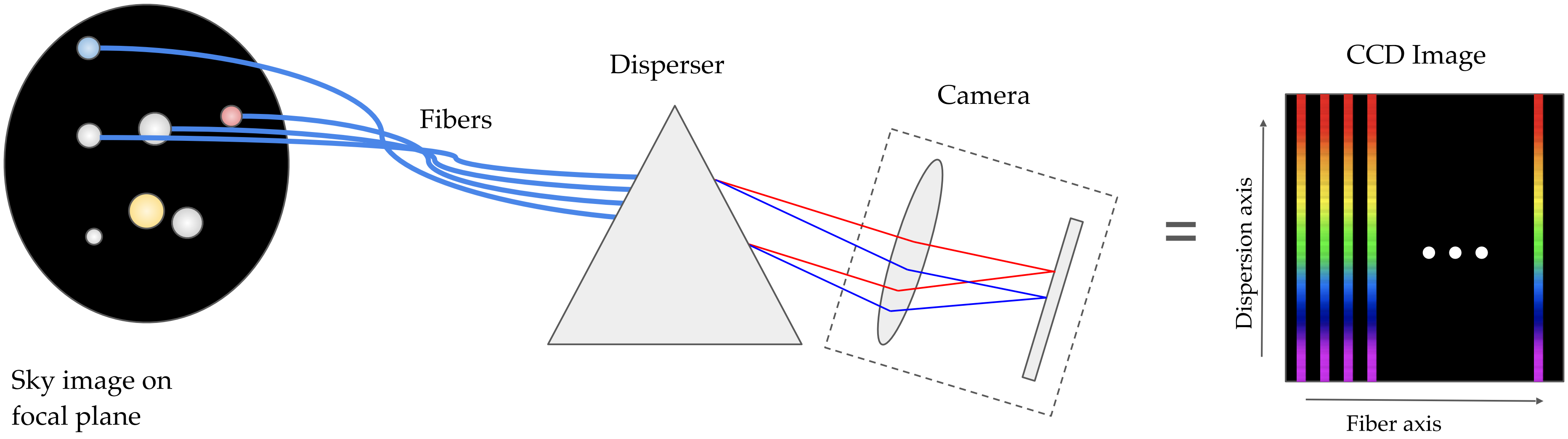
Multi-Object Spectroscopy

Multiplexed observations of many sources uses optical fibers targeted on individual objects. Light passes through a dispersing element to CCD cameras.



Credit: after D. Steeghs / U. Warwick

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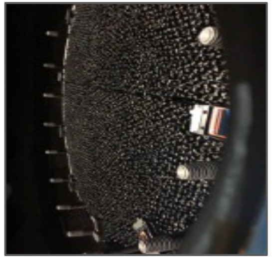
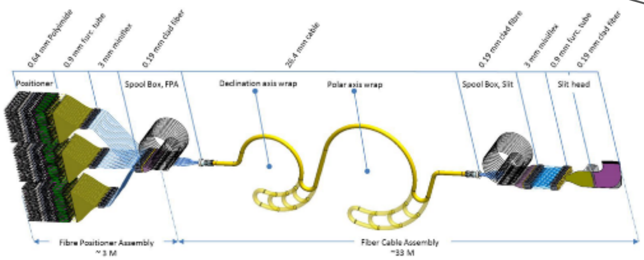
Dark Energy Spectroscopic Instrument

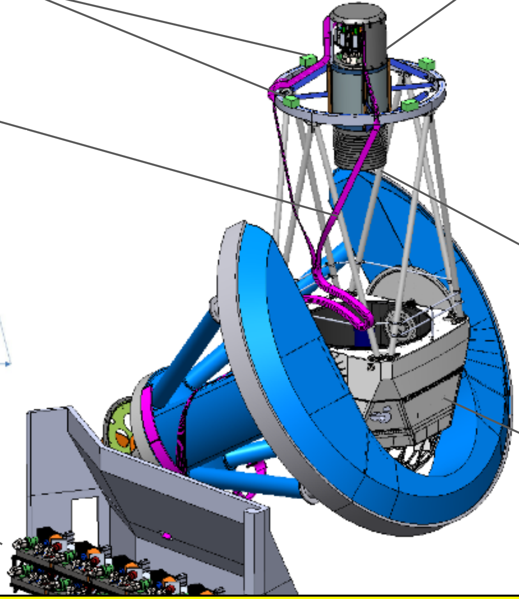
Calibration lamp system

Focal plane assembly with 5,000 fiber positioners.

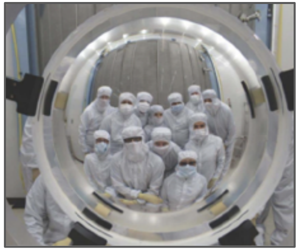


50 m, 10-cable fiber run

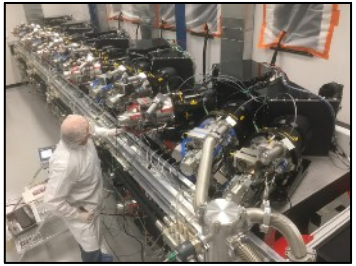




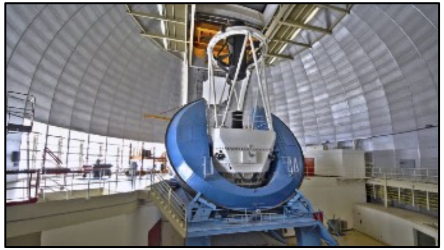
6-lens wide-field Atmospheric Dispersion Corrector



10 thermally-controlled 3-camera spectrographs, 360-980 nm



Mayall 4 m (primary mirror), Kitt Peak



More details: arXiv:2205.10939

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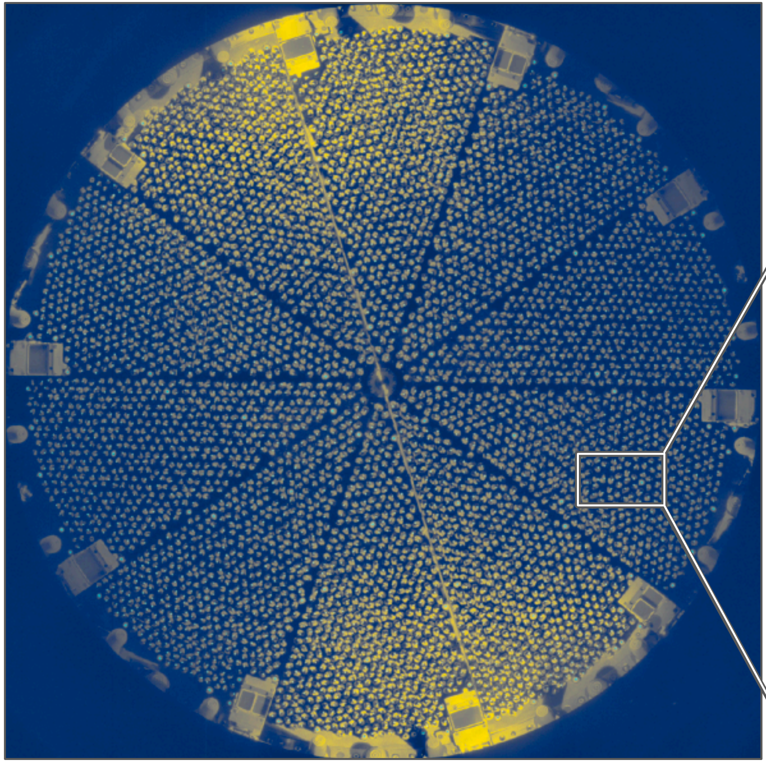
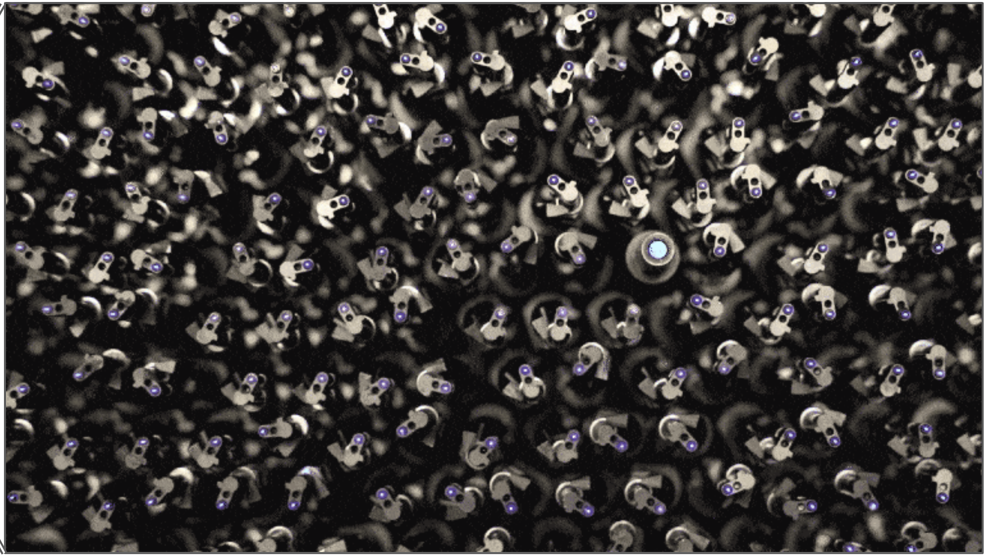
DESI Focal Plane: 10 “Petals” with 5,020 Robotic Fiber Positioners



⌀107 μm fibers (1.5″), 12 mm patrol radius

~10 s move time



Credit: C. Poppett / LBNL

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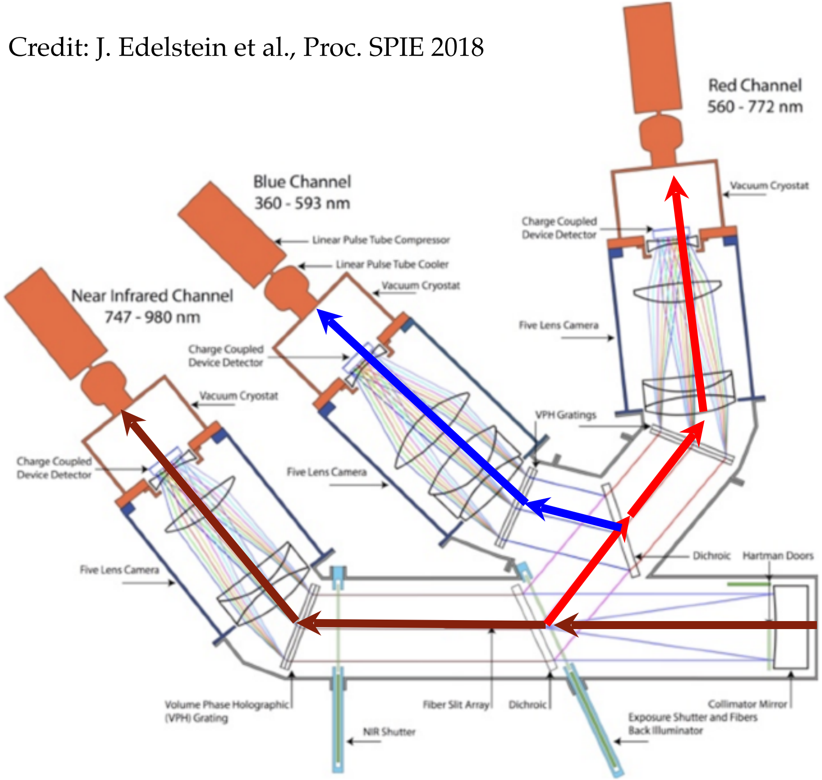
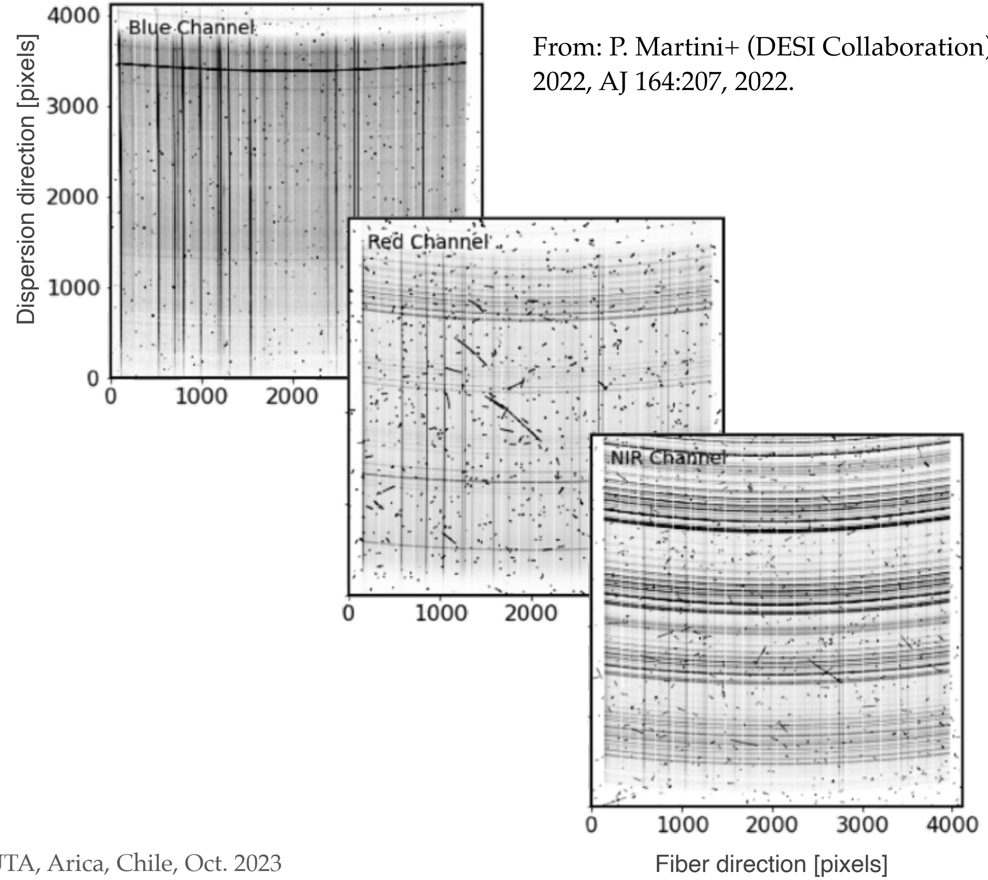
DESI Spectrographs

Credit: J. Edelstein et al., Proc. SPIE 2018



From: P. Martini+ (DESI Collaboration), 2022, AJ 164:207, 2022.



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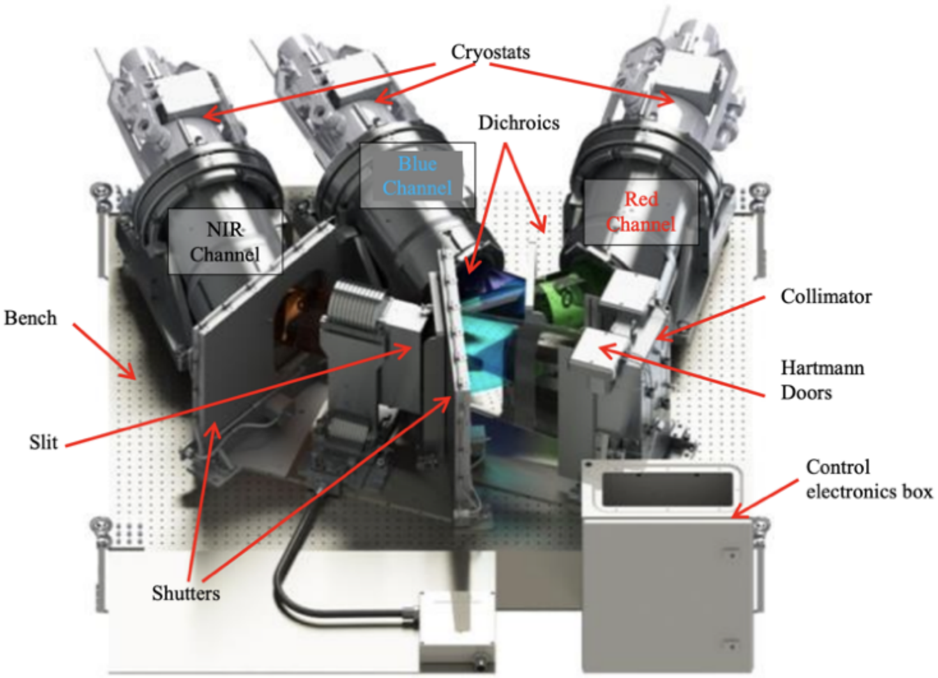
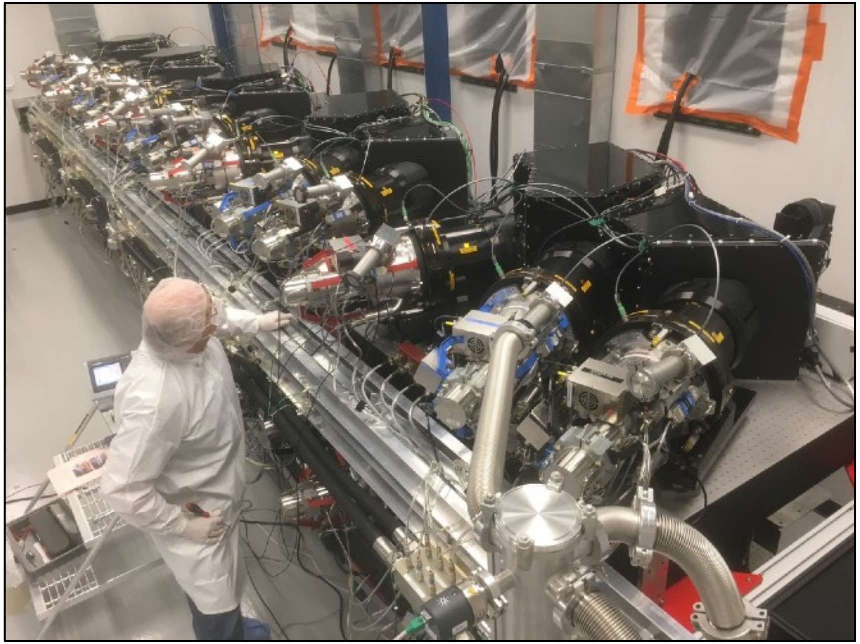
Spectrographs and "Shack"

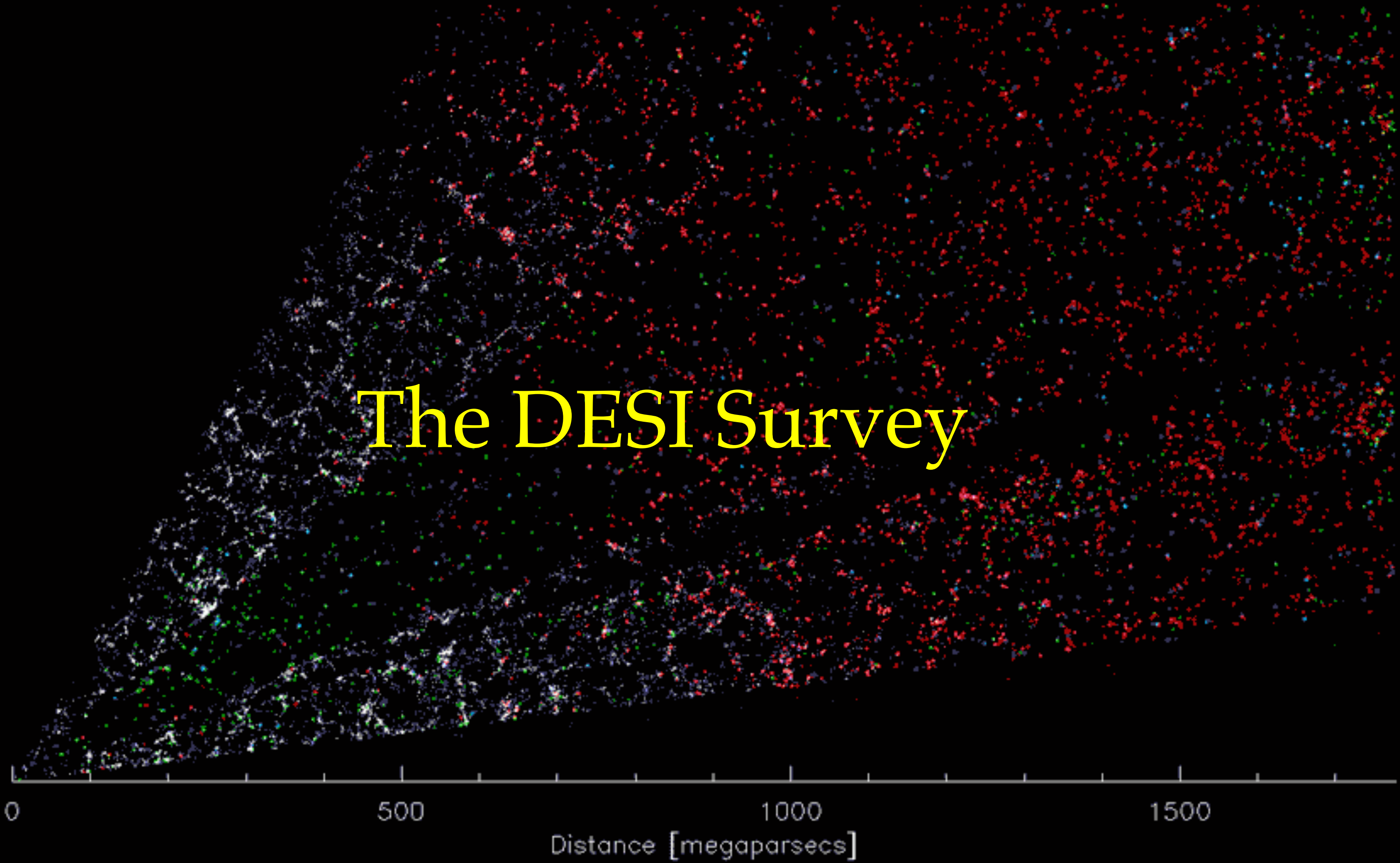


Credit: S. Perruchot et al., Proc. SPIE 2020



Credit: R. Besuner et al., Proc. SPIE 2020

The DESI Survey



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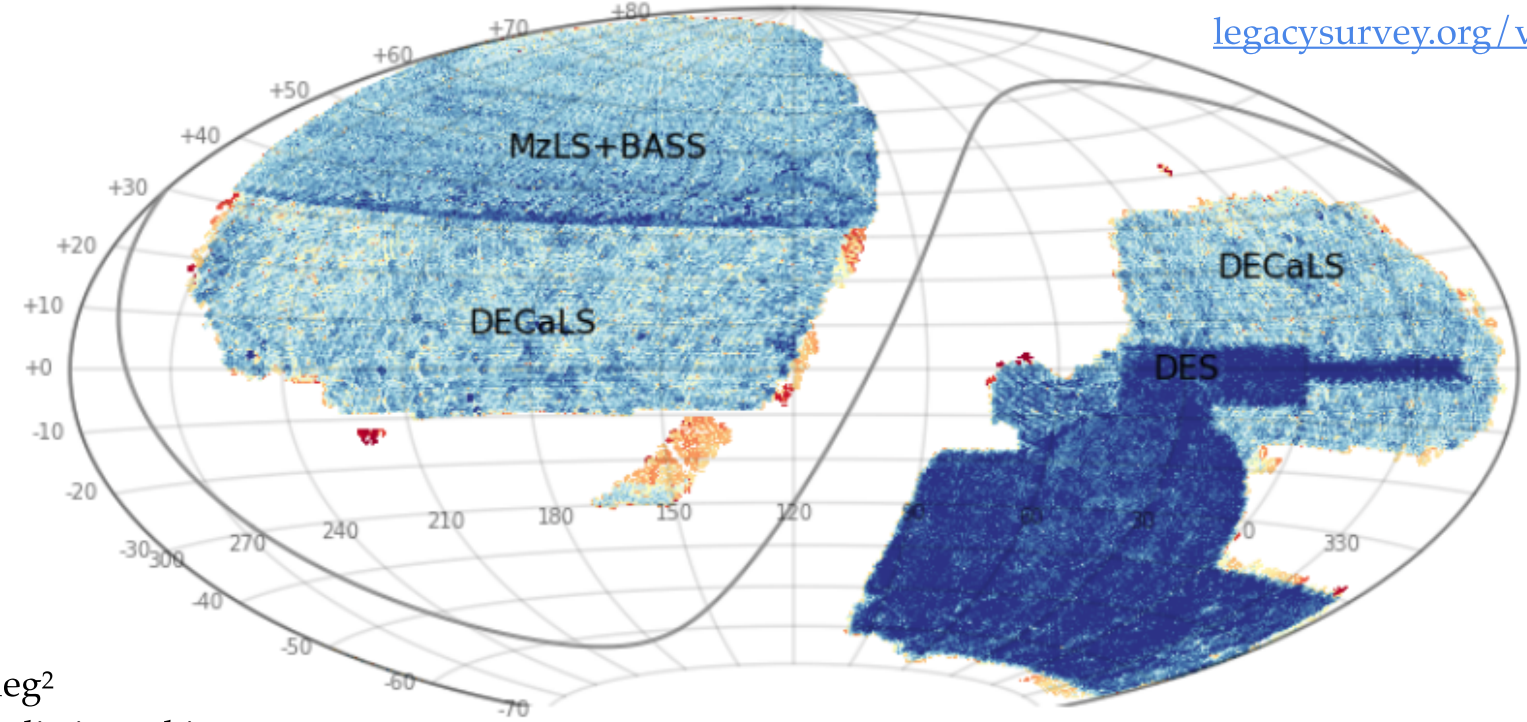
DESI Legacy Imaging Survey: Spectroscopic Target Selection

legacysurvey.org/viewer



20,000 deg^2
2 billion distinct objects

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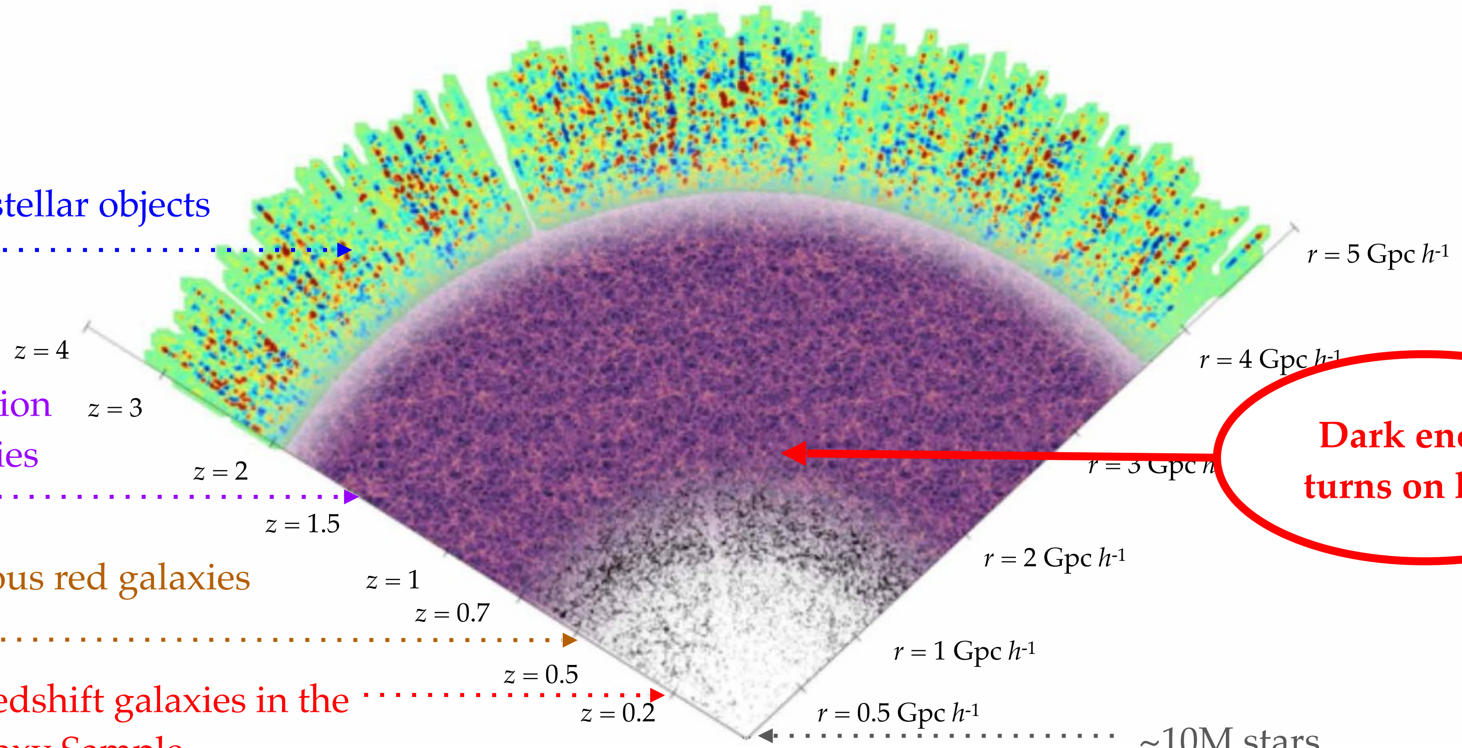
DESI Galaxy Samples: BGS, LRGs, ELGs, QSOs (+Ly-α forest)

3M quasi-stellar objects **(QSO**s)

17M emission Line galaxies **(ELG**s)

8M luminous red galaxies **(LRG**s)

14M low redshift galaxies in the Bright Galaxy Sample **(BGS)**



Dark energy turns on here?

~10M stars (Milky Way Survey)

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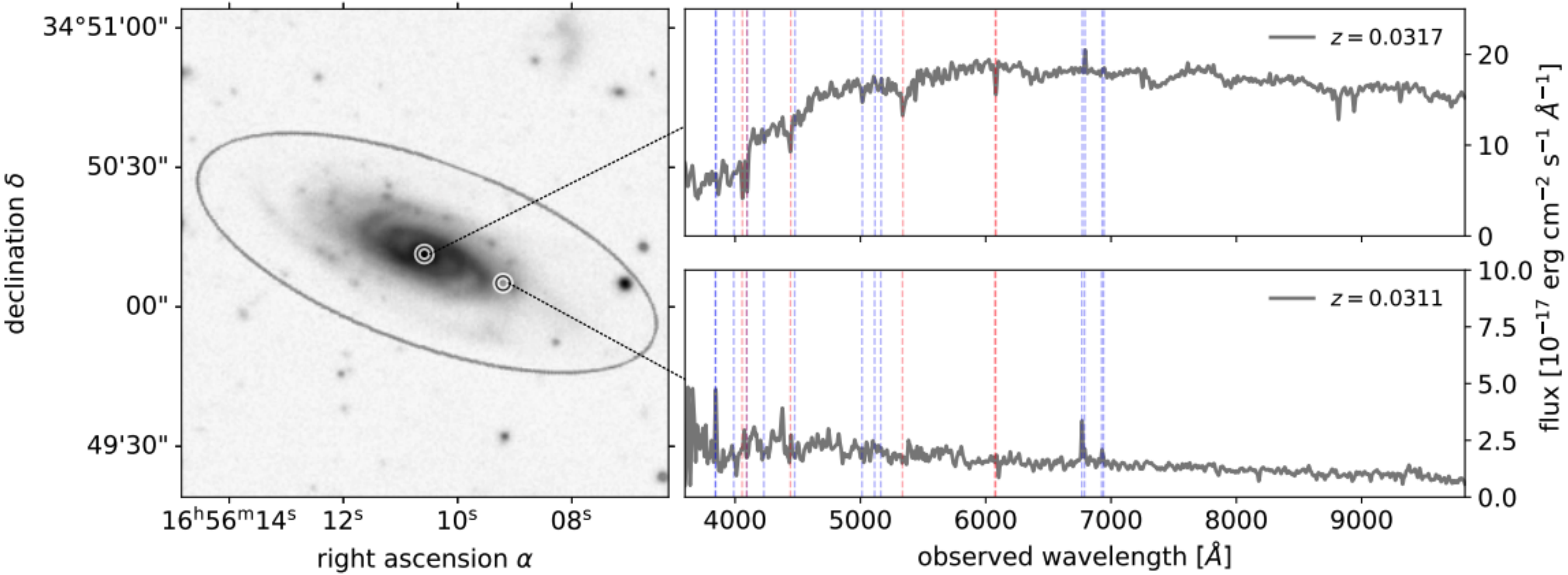
Example Spectrum: Bright Galaxy



Credit: [C. Saulder+, MNRAS 525:1106, 2023]

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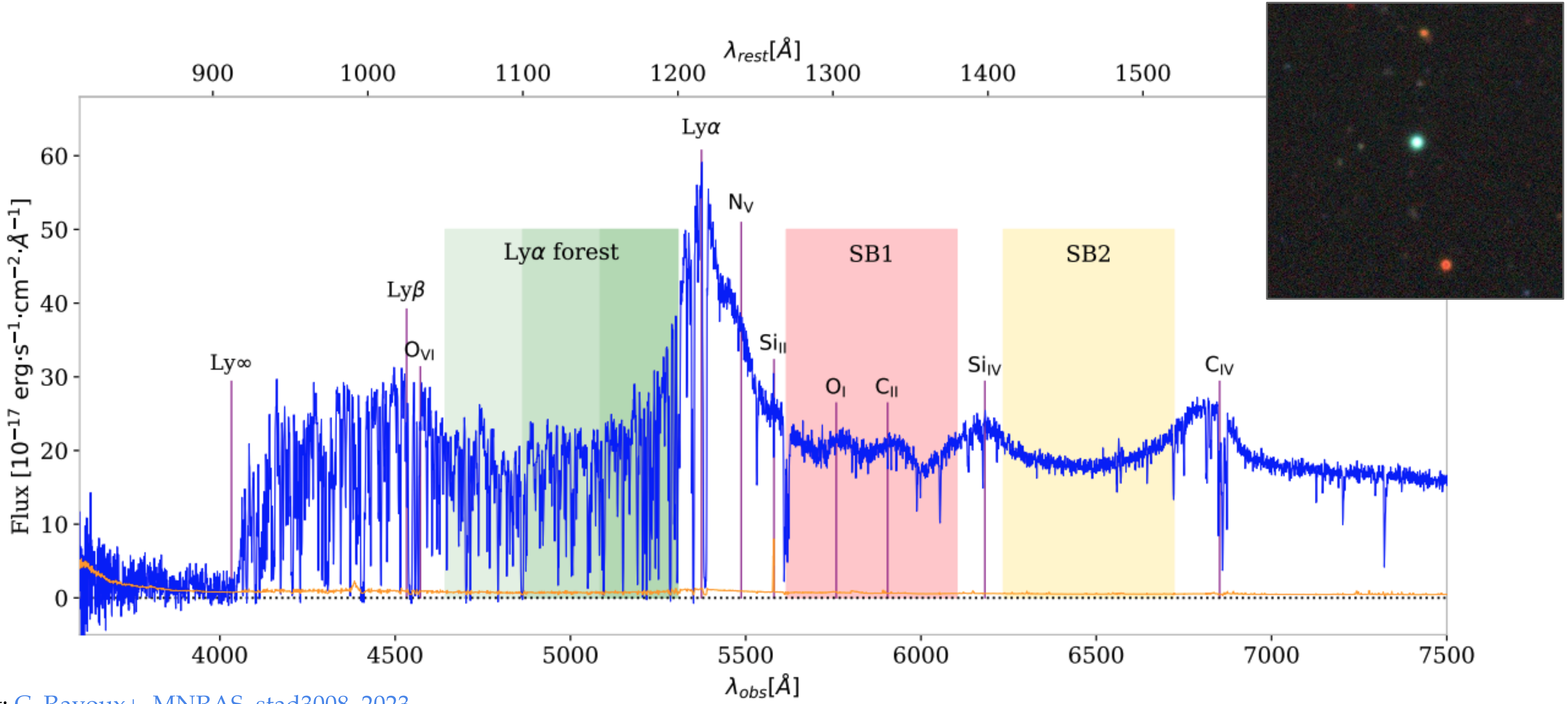
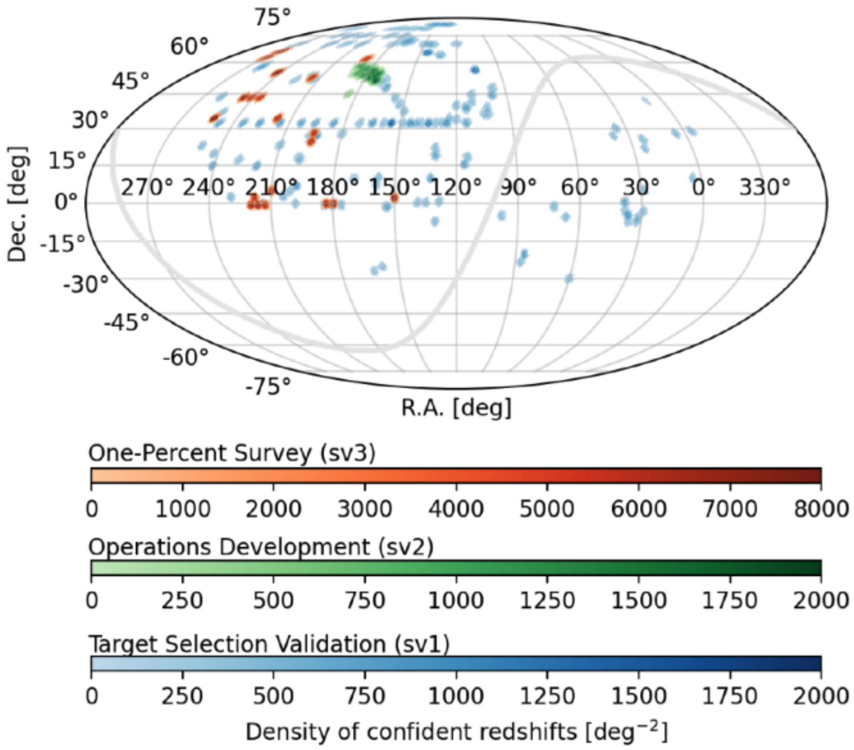
Example Spectrum: QSO + Ly-α Forest



Credit: C. Ravoux+, MNRAS, stad3008, 2023

DESI Survey Validation



Dec. 2020 - May 2021: 3 programs.

1. **SV1**: target selection validation, deep observations with 4× nominal t_{exp}, 150 tiles, ~230k spectra.
2. **SV2**: survey operations development, ~100k spectra.
3. **SV3**: 1% survey, 1.2× nominal t_{exp}, 500 tiles, ~1M spectra.

Credit: DESI Collaboration: A.G. Adame+ 2023

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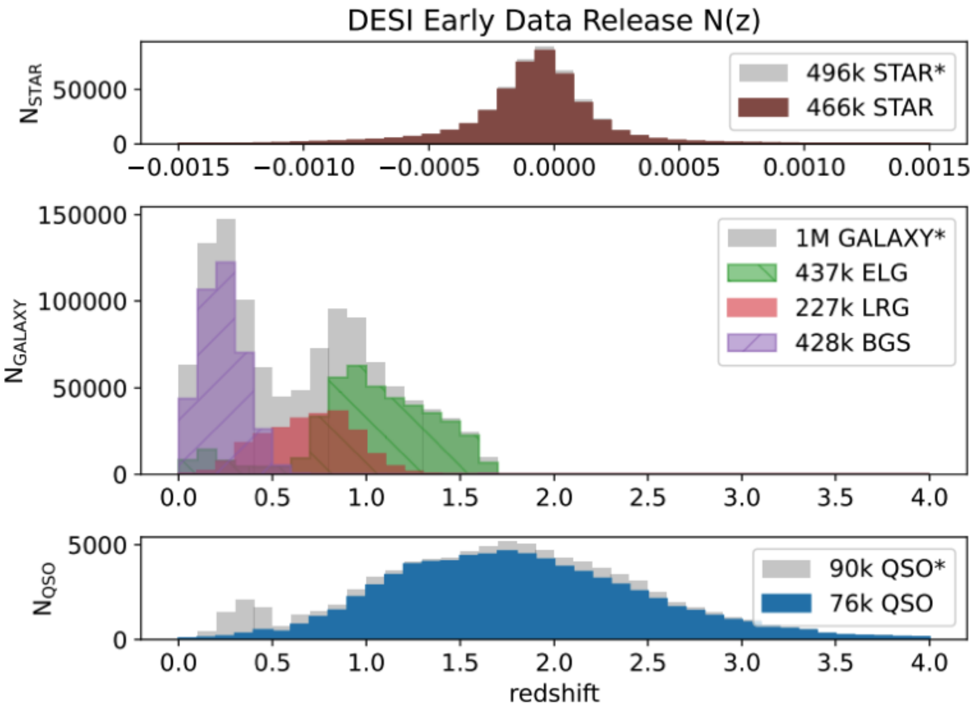
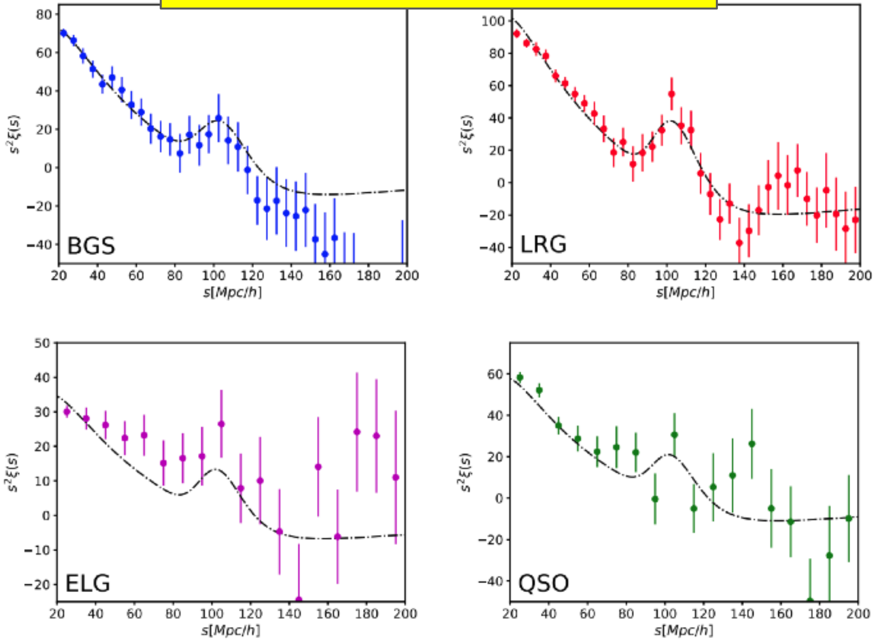
DESI Early Data Release (EDR)



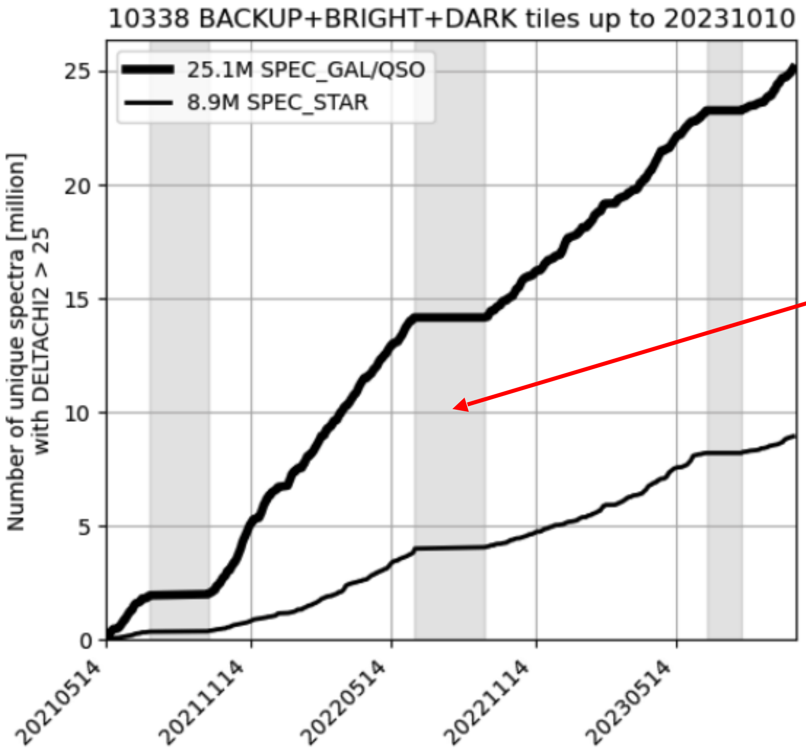
Credit: [DESI Collaboration: A.G. Adame+ 2023]

5σ BAO detection in 2 months



Credit: [J. Moon+, 2023]

DESI Survey Status: 50% Complete



Credit: A. Raichoor, DESI Collaboration

Contreras Fire: shutdown 14 June - 10 Sep. 2022. Other shutdowns due to hardware & software upgrades.

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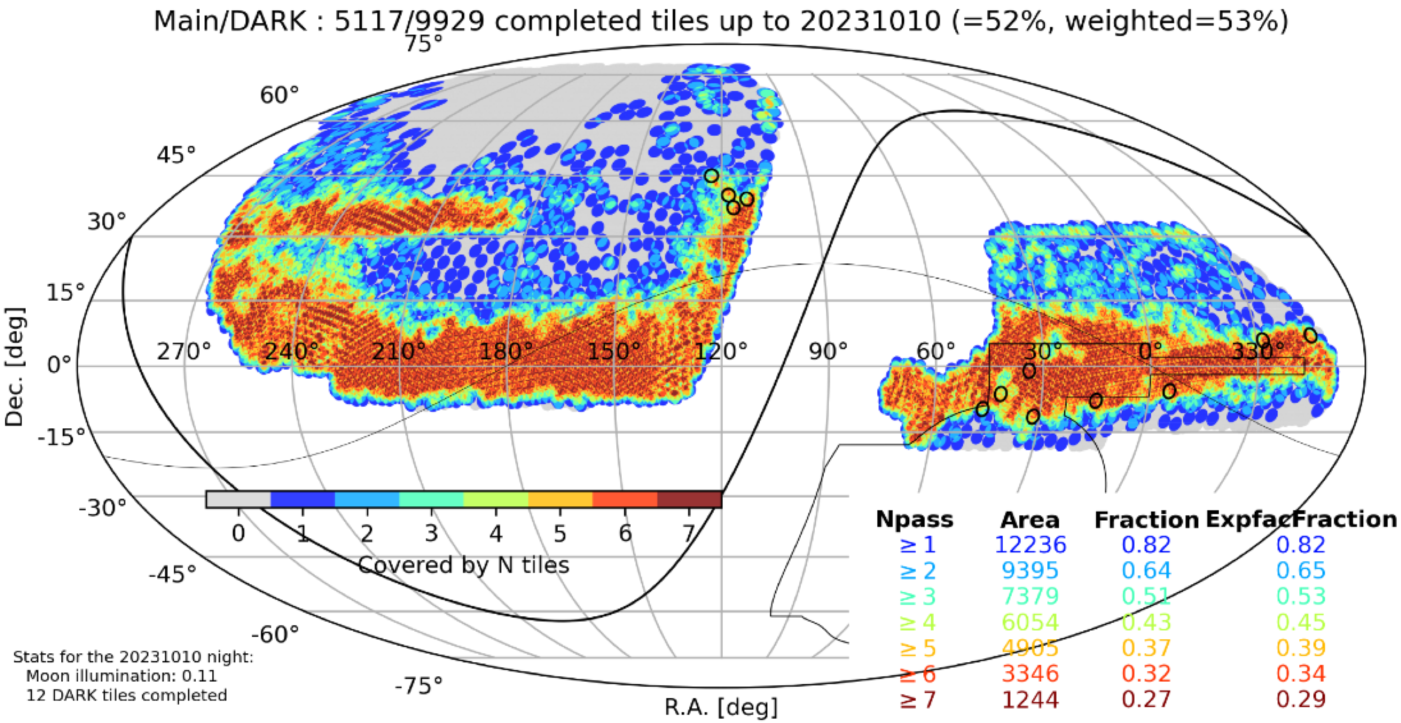
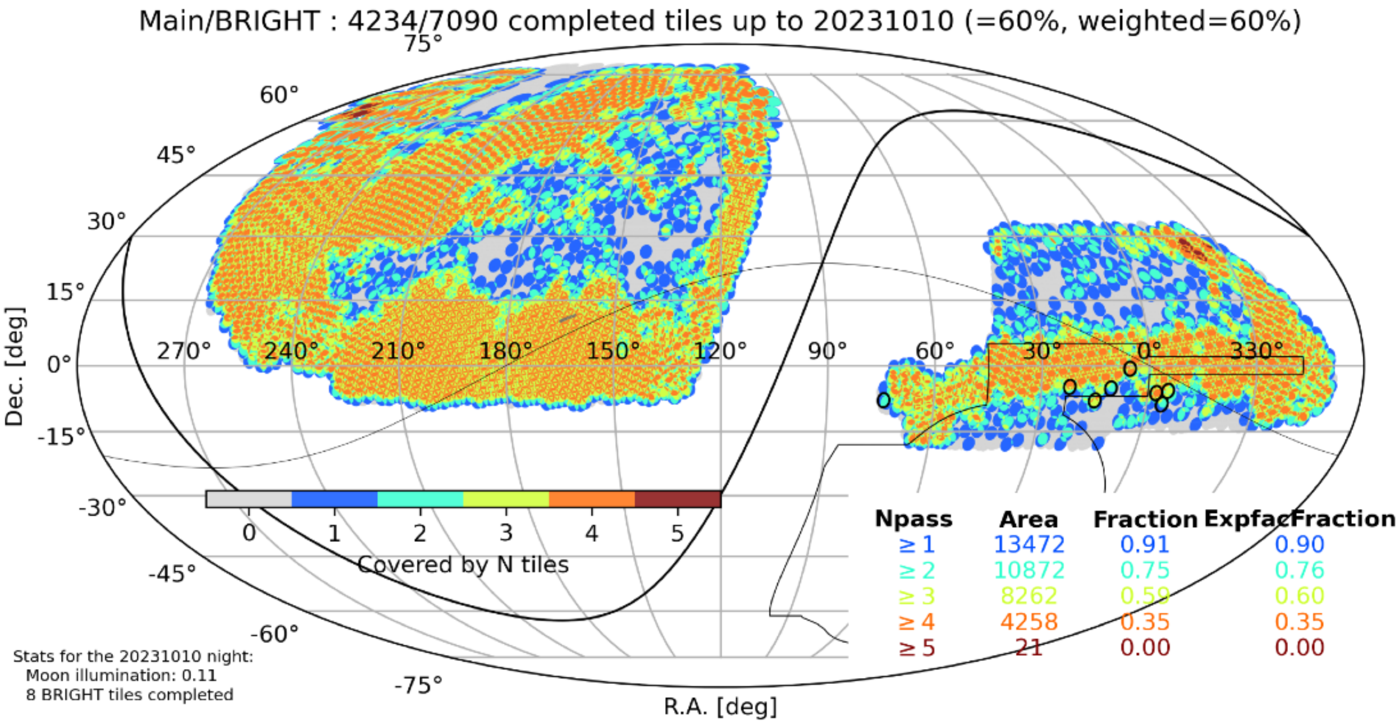
DESI Survey Status

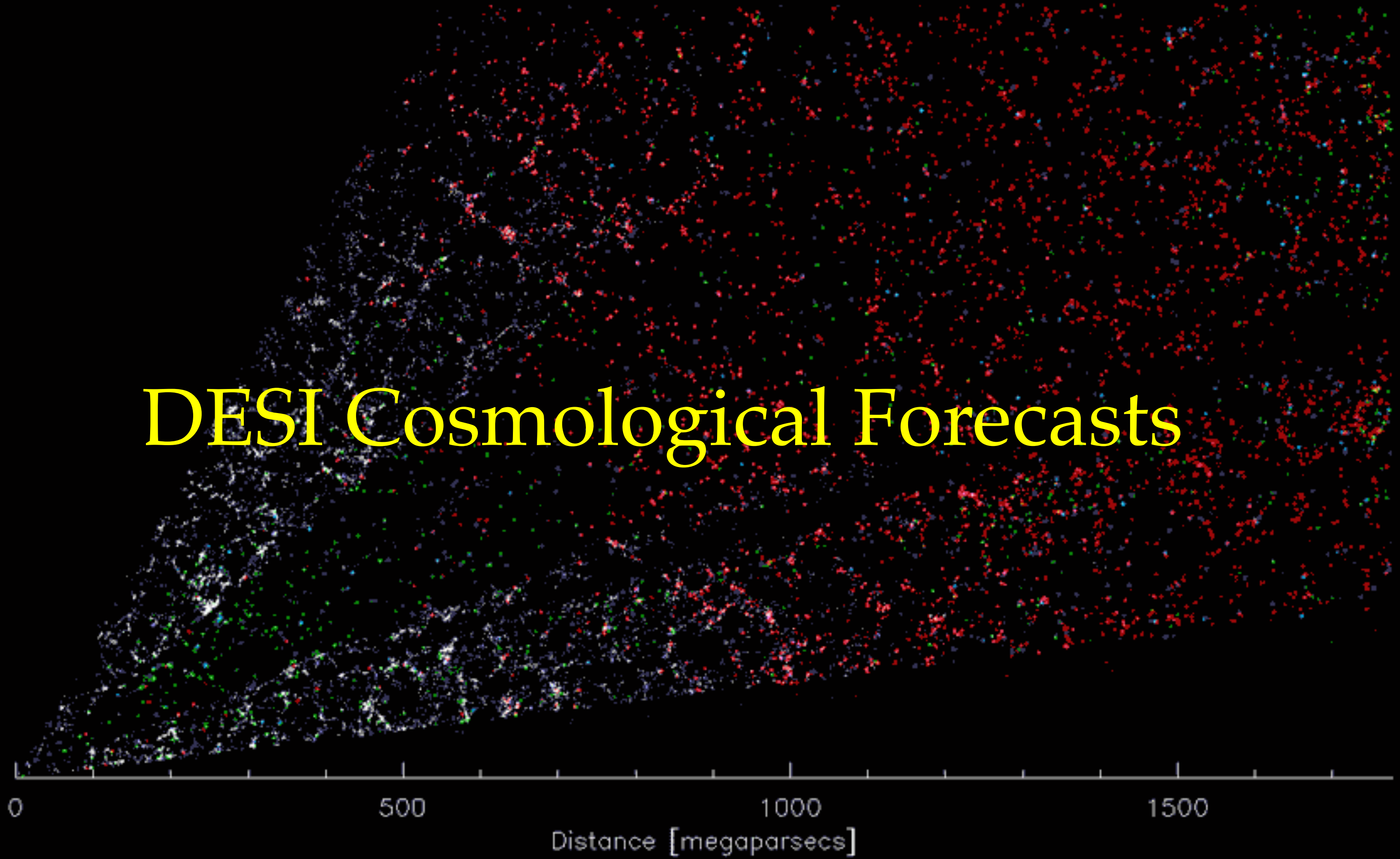


DESI Survey Status



Npass	Area	Fraction	ExpfacFraction
≥ 1	13472	0.91	0.90
≥ 2	10872	0.75	0.76
≥ 3	8262	0.59	0.60
≥ 4	4258	0.35	0.35
≥ 5	21	0.00	0.00

DESI Cosmological Forecasts



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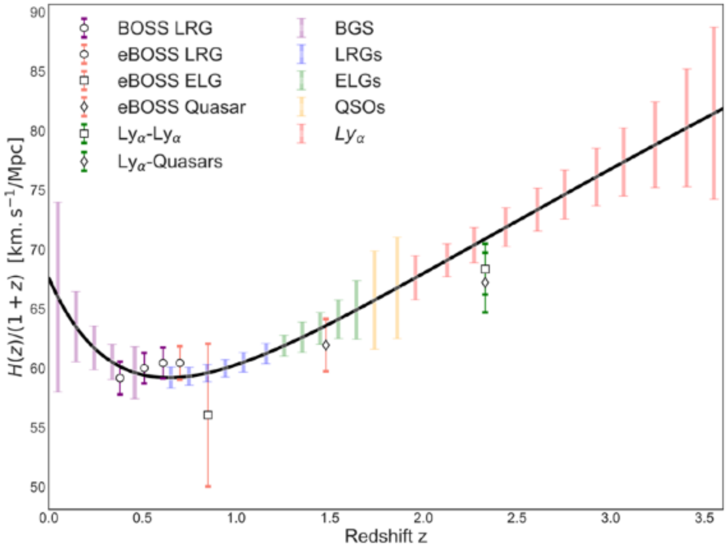
DESI main physics probes

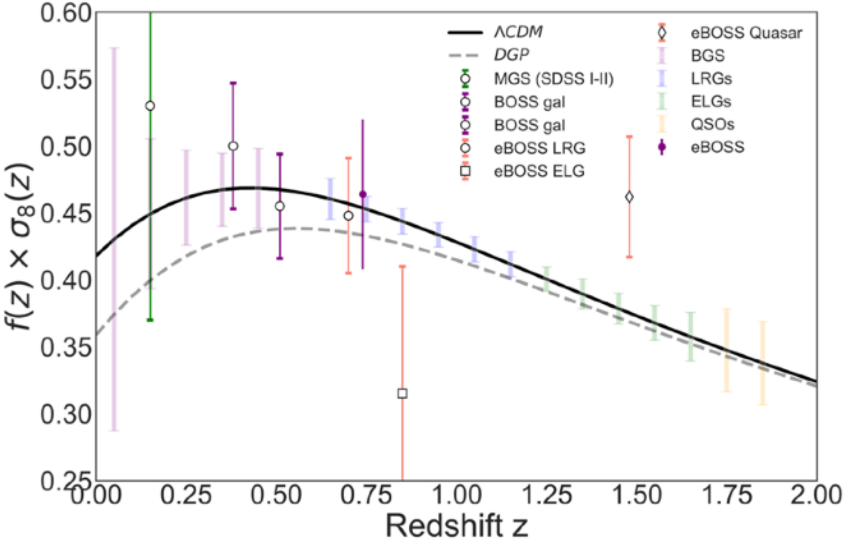
Baryon Acoustic Oscillations (BAO)

Expansion history



Redshift Space Distortions (RSD)

Growth rate of structure



Credit: M. Vargas-Magaña

Science Goal 1: Dark energy

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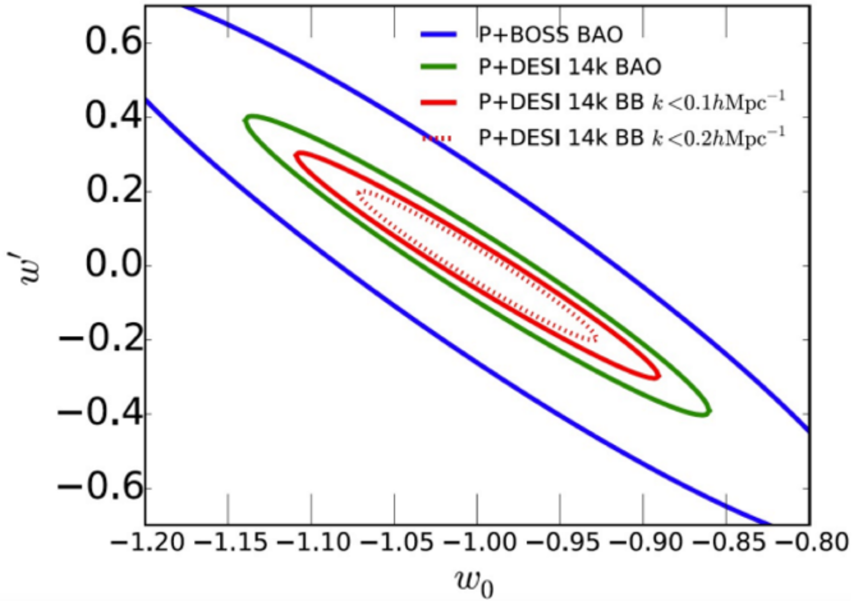
Is dark energy a cosmological constant, or dynamically evolving with $a = 1/(1+z)$?

DE equation of state for constant dark energy: $w = -1$.

DE equation of state for evolving dark energy: $w(a) = w_0 + (1 - a)w_a$.

Constraint on w_0-w_a using BAO from BOSS (a precursor survey) and DESI with priors from Planck CMB measurements.



Credit: DESI Collaboration, A. Aghamousa+, 2016

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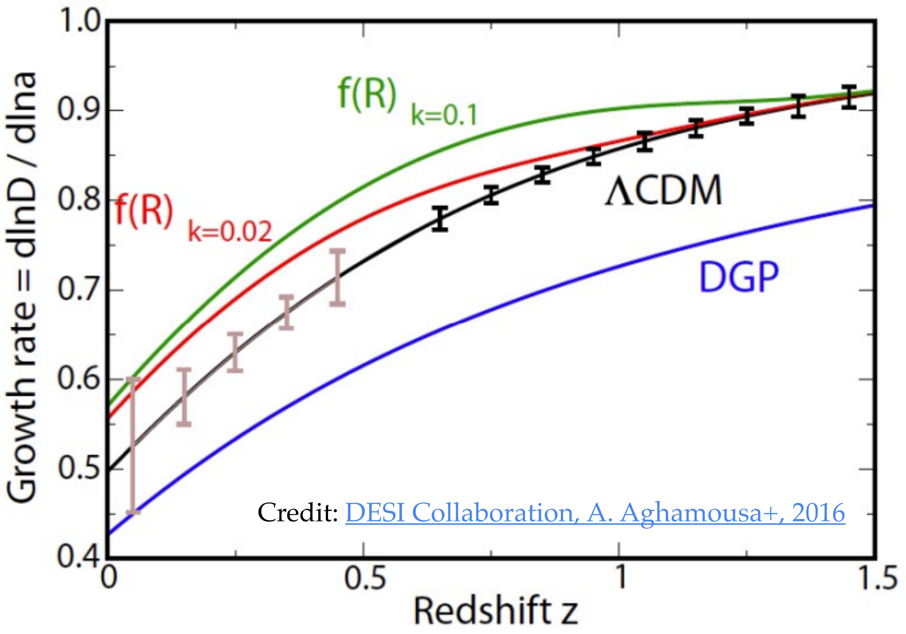
Science Goal 2: Growth of Structure

Using redshift space distortions, DESI observes the growth of structure.

Modified gravity models can mimic the acceleration attributed to dark energy.

But model selection is possible by observing the growth of structure, which differs under GR+DE vs. modified gravity.

DESI can study the growth rate with RSD and direct observations of peculiar motion due to gravitation.



Credit: DESI Collaboration, A. Aghamousa+, 2016

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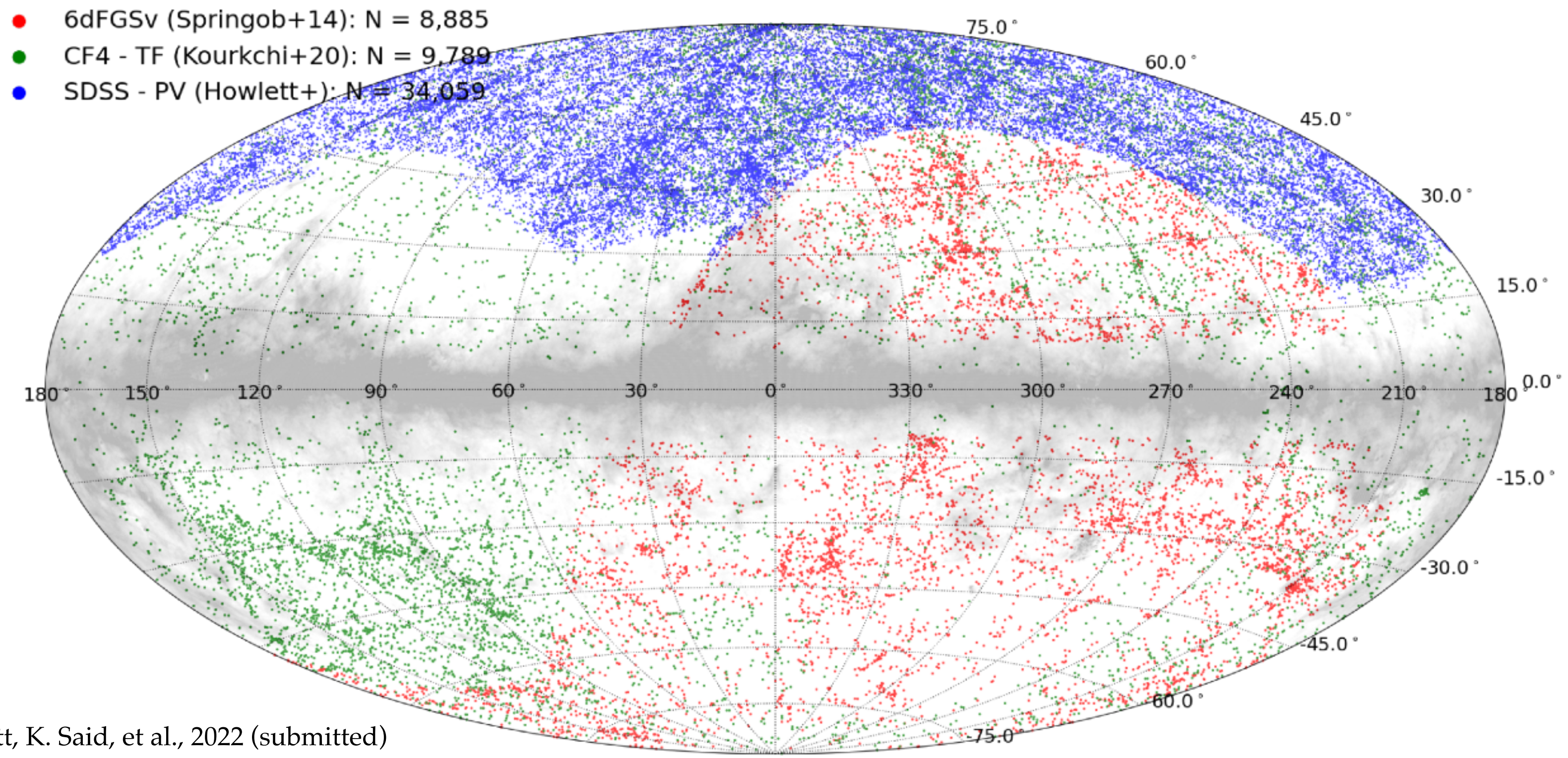
The DESI Peculiar Velocity Survey



Credits:
C. Howlett, K. Said, et al., 2022 (submitted)
C. Saulder et al. (in prep)

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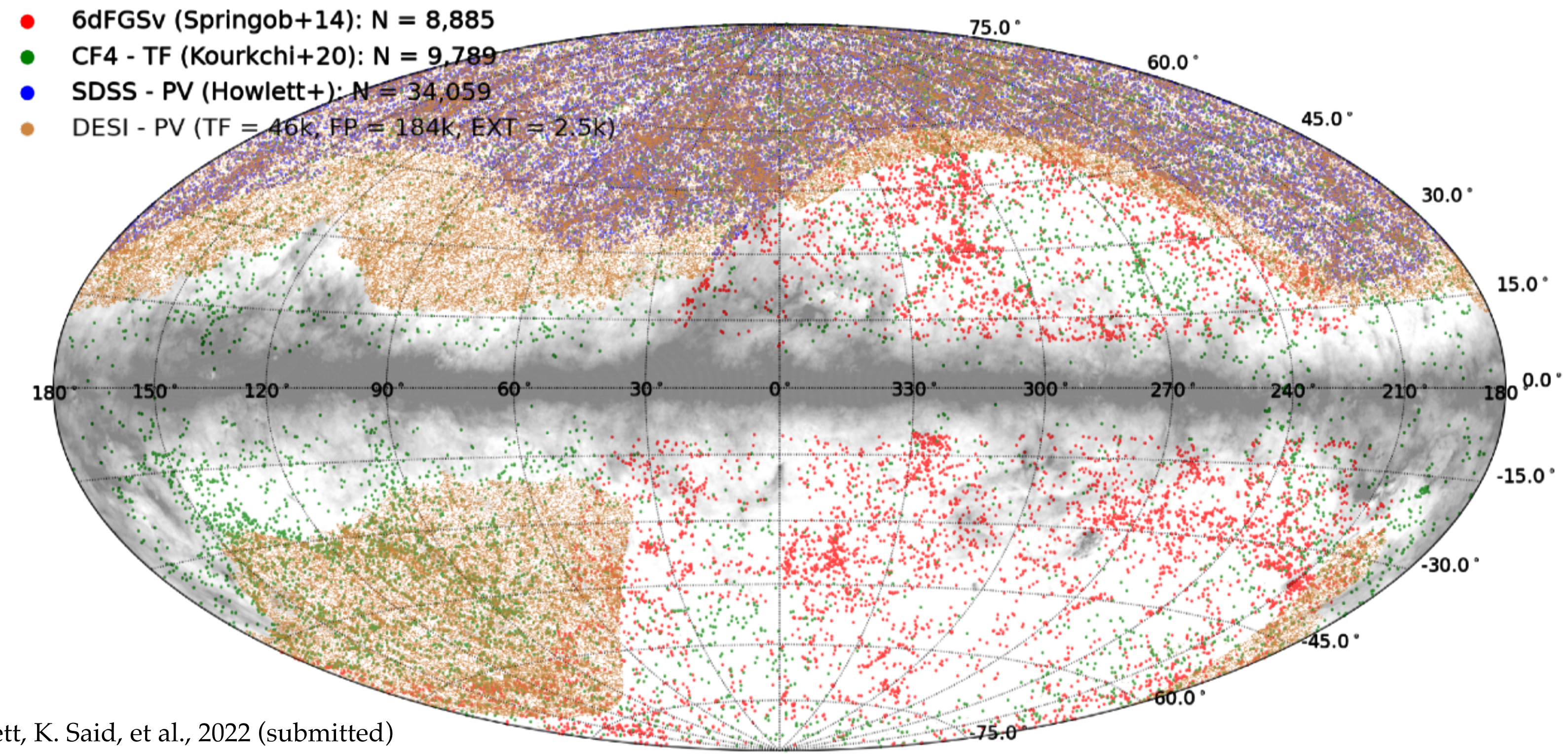

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The DESI Peculiar Velocity Survey

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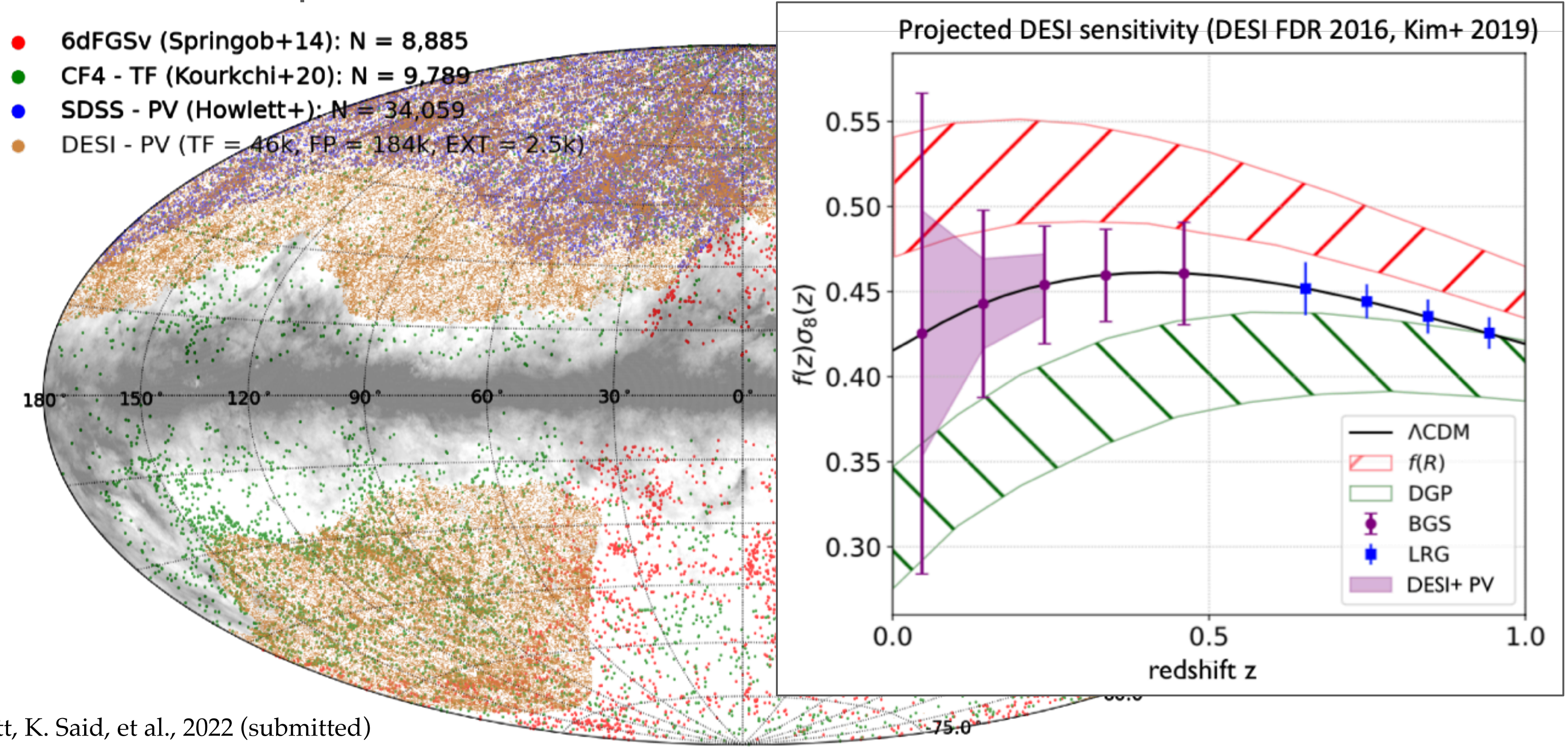

Credits:
C. Howlett, K. Said, et al., 2022 (submitted)
C. Saulder et al. (in prep)

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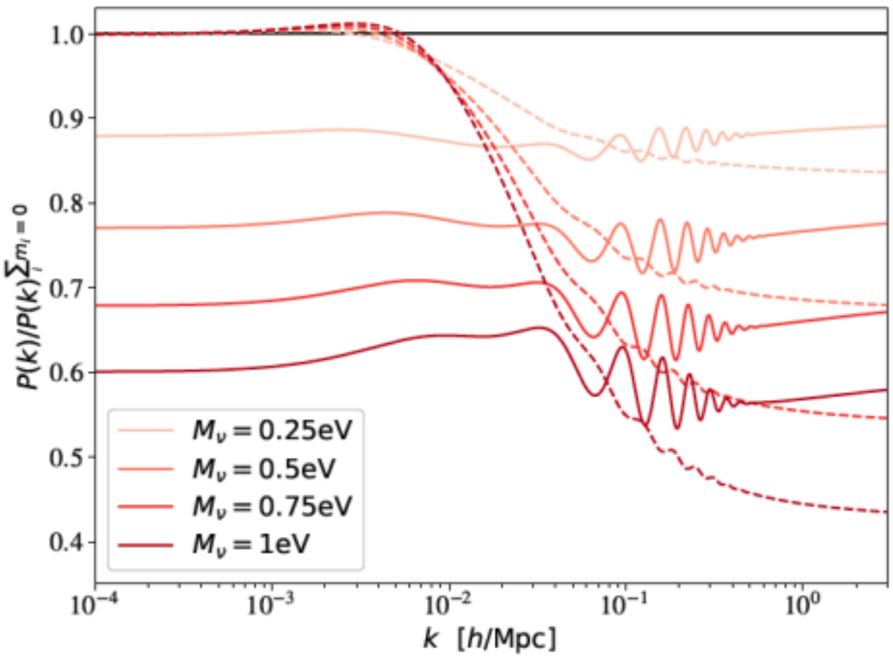
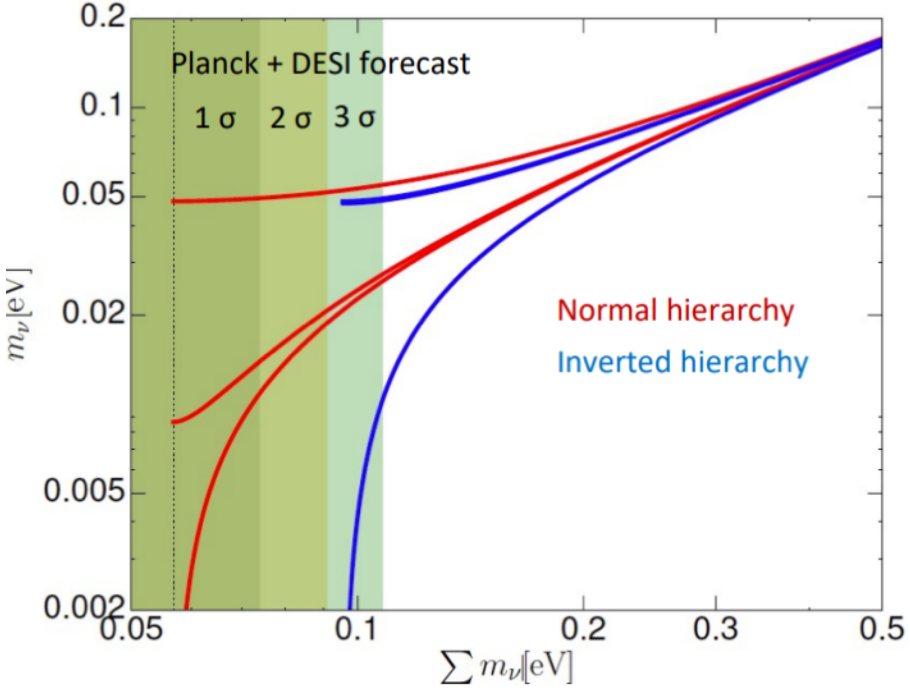
Science Goal 3: Constraining Σm_ν

Massive neutrinos suppress BAO power. Constraint on Σm_ν & the mass hierarchy.





Science Goal 4: Non-Gaussianity

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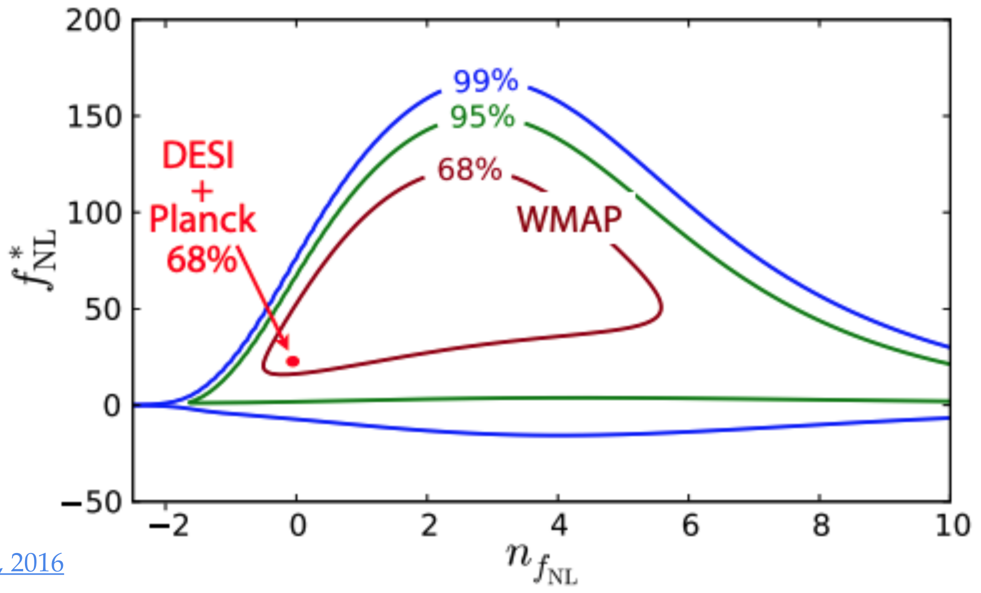
Detection of local non-Gaussianity in LSS ($f_{\rm NL} \neq 0$) rules out the simplest models of inflation. Non-detection ($f_{\rm NL} = 0$) constraints alternative inflation models.

Strongest constraints on local $f_{\rm NL}$ come from the CMB:

$$f_{\rm NL} = 0.9 \pm 5.1 \text{ (Planck 2018)}$$

DESI+Planck constraints on running $f^*_{\rm NL} \sim k^{n_{f{\rm NL}}}$ will improve significantly on past results.



Credit: DESI Collaboration, A. Aghamousa+, 2016

DESI Summary

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DESI Year 1 data release: mid-2024.

Forecasts for the Y1:

- Y1 BAO: $\boldsymbol{\sigma}(D_V/r_d) \lesssim 0.42\%$
- Y1 RSD: $\boldsymbol{\sigma}(f{\cdot}\sigma_8) \sim 1\%\text{-}1.8\%$
- Y1 massive neutrinos: $\boldsymbol{\sigma}(\Sigma m_\nu) \sim 0.063\text{eV}$
- Y1 $f_{\rm NL}$: $\boldsymbol{\sigma}(f_{\rm NL}) \sim 9$

Survey status:

- The Main Survey started about on May 14th, 2021
- Already 50% (60%) complete in dark (bright) time!

DESI will provide strong constraints on inflation, dark energy, and the presence of light primordial particles (cosmological neutrinos).

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