Dark Energy and Dark Matter:

Cosmology with Large Redshift Surveys

Segev BenZvi

Department of Physics and Astronomy

University of Rochester

Key Points

1. Dark energy is measured using the expansion of the universe and the growth of structure. Large-scale structure also provides evidence for dark matter.

2. **All current evidence** for dark energy & dark matter comes from astrophysical datasets.

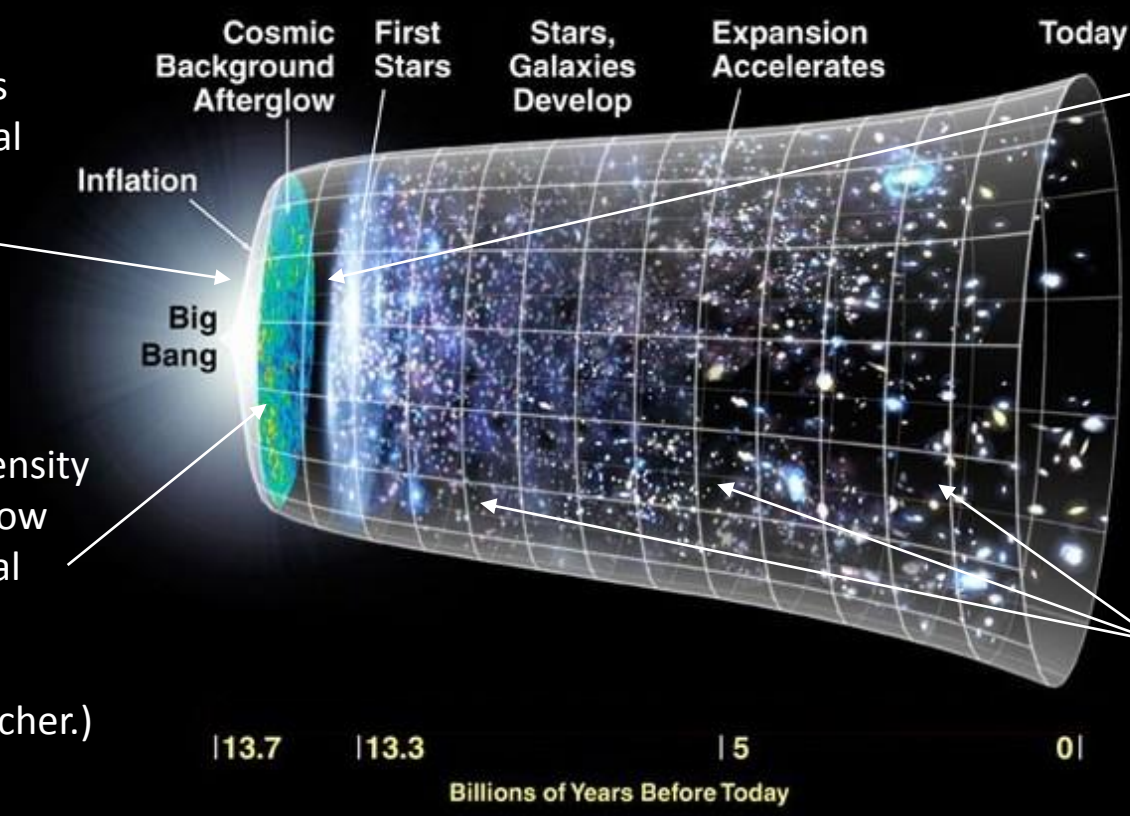
3. These measurements are sensitive to the microphysics of elementary particles.

Cosmology: the Current Picture

Inflation smooths out the primordial plasma.

Microscopic density fluctuations grow via gravitational attraction.

(The rich get richer.)



Photons decouple from baryons and free stream as the **cosmic-microwave background**

Large scale structure evolves via gravitational collapse; affected by dark energy.

ΛCDM

- On cosmic scales, the universe is a homogeneous fluid in expanding space, governed by GR. "Equation of motion":

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

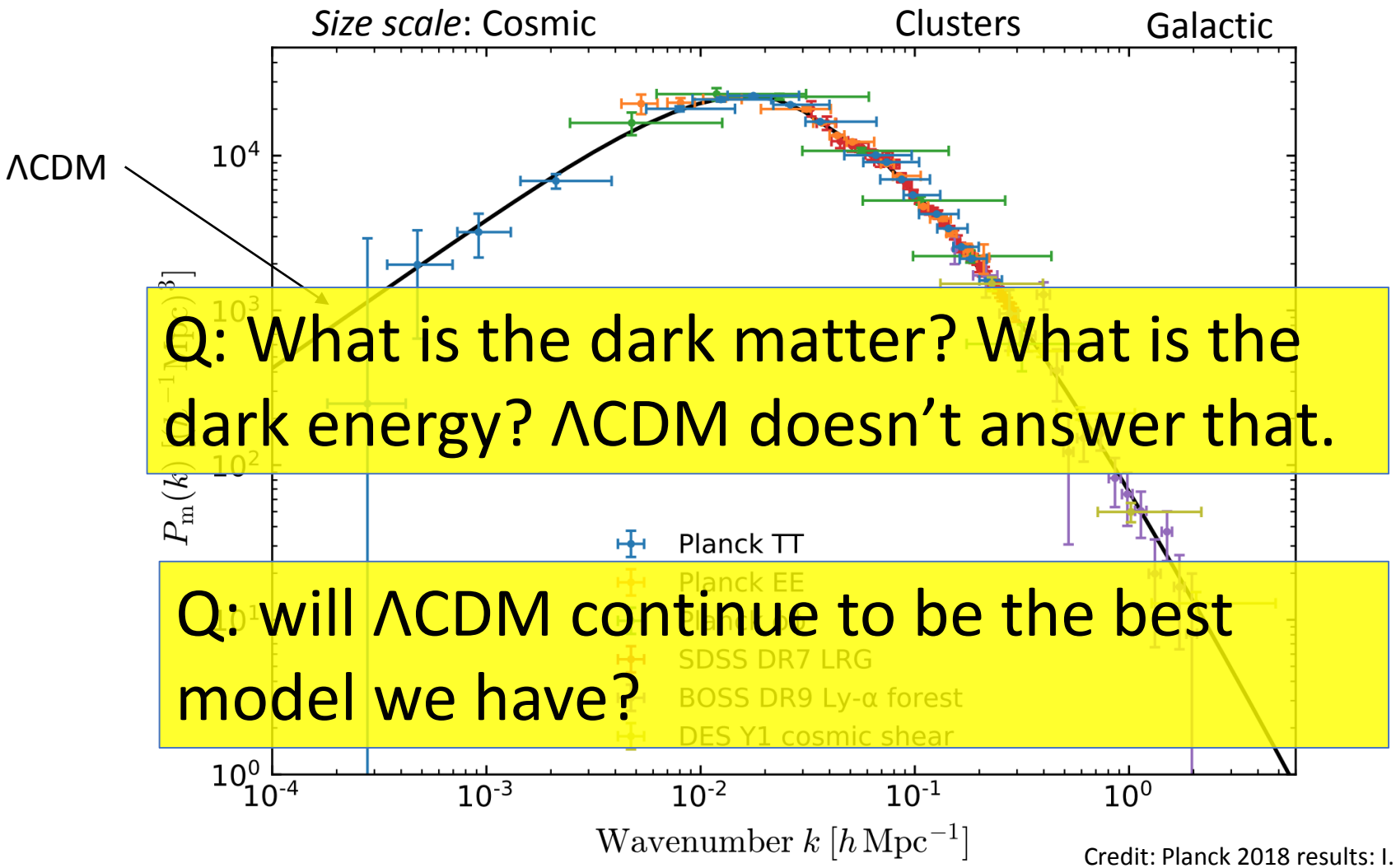
scale factor

mean matter density
$\Omega_c + \Omega_b$

dark energy
E.O.S. w=-1

- Additional parameters (some fixed, some calculated):
  - $\boldsymbol{\sigma_8}$: amplitude of density fluctuations in matter power spectrum.
  - $\boldsymbol{\Sigma m_\nu}$: sum of neutrino masses.
  - $\boldsymbol{N_{eff}}$: number of neutrino (& other light relic) species.
  - $\boldsymbol{n_s}$: spectral index of primordial density fluctuations.
  - $\boldsymbol{H_0}$: expansion rate of the universe today.

ΛCDM + Data: Matter Power Spectrum

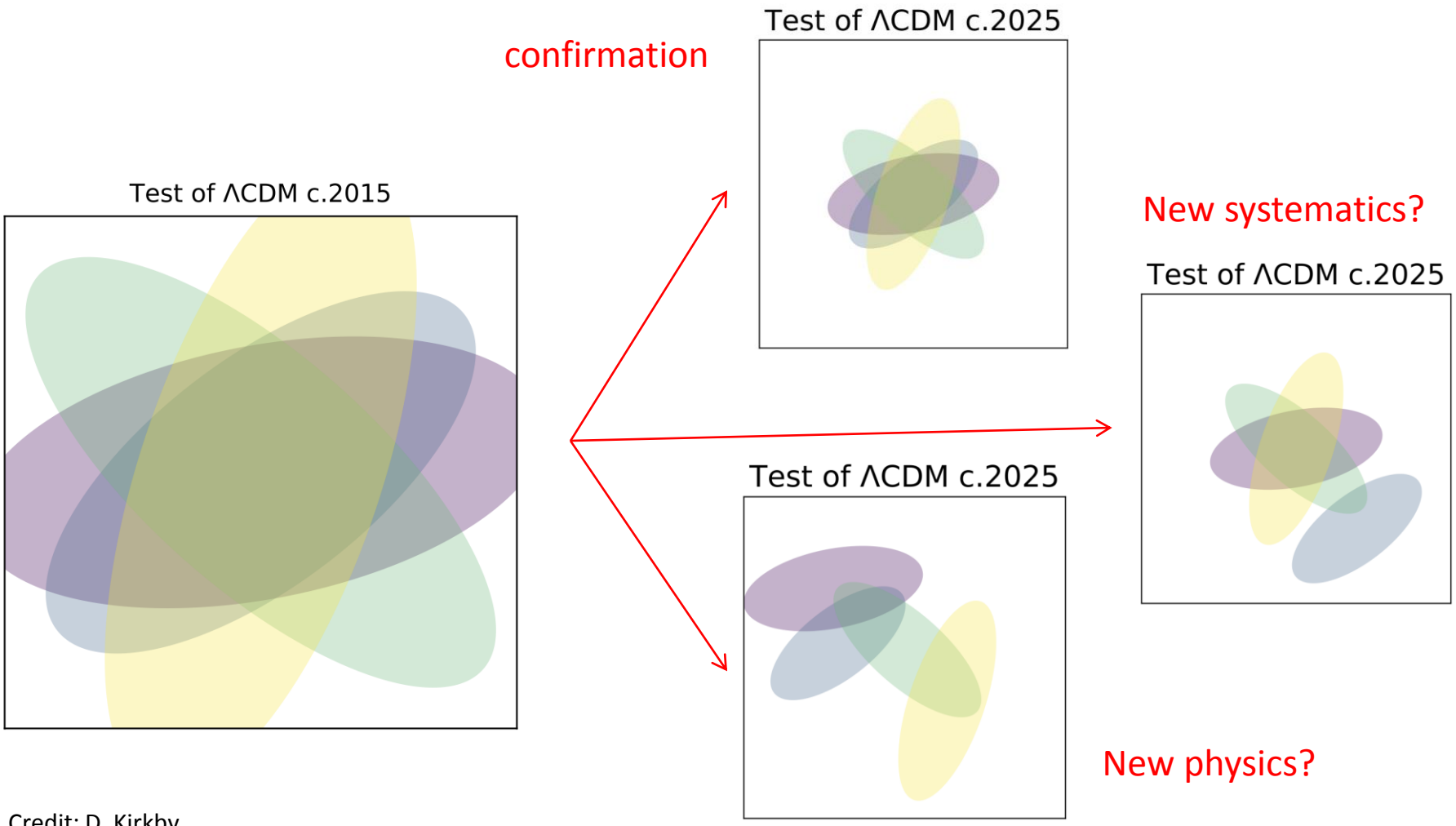


Q: What is the dark matter? What is the dark energy? ΛCDM doesn't answer that.

Q: will ΛCDM continue to be the best model we have?

Credit: Planck 2018 results: I. Overview

Testing ΛCDM: The Next 5 Years



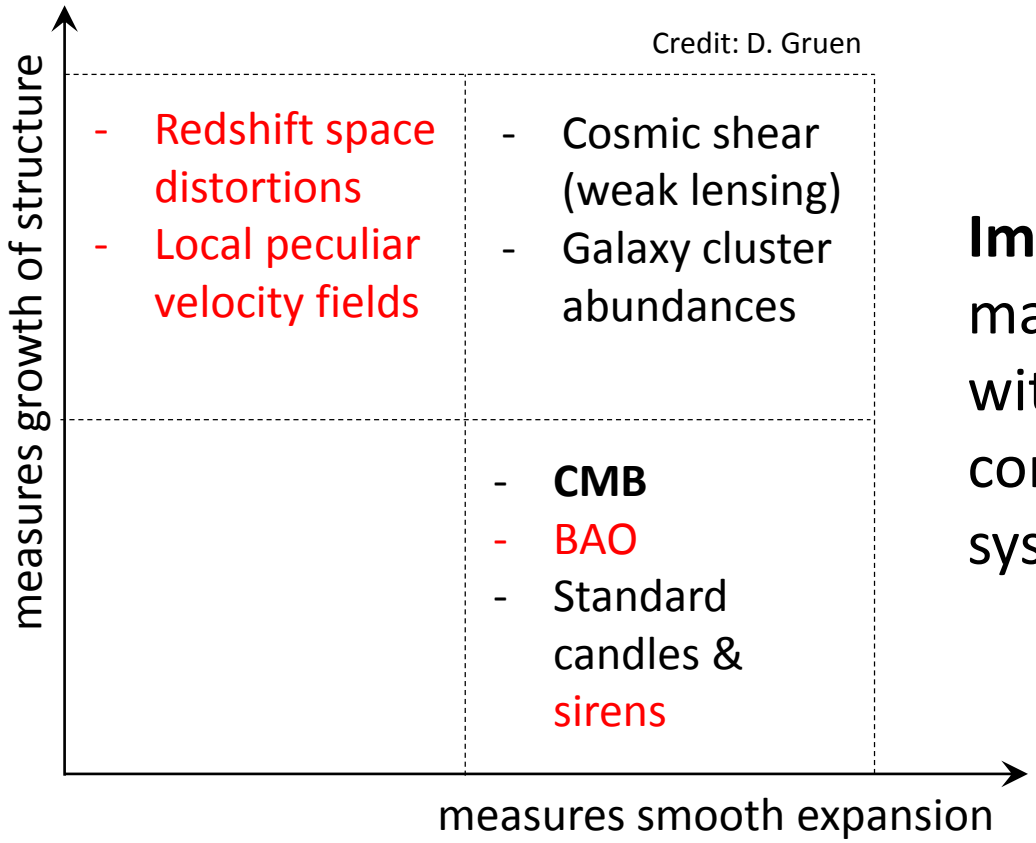
Credit: D. Kirkby

Measuring Dark Energy

Focus on Redshift Surveys and the

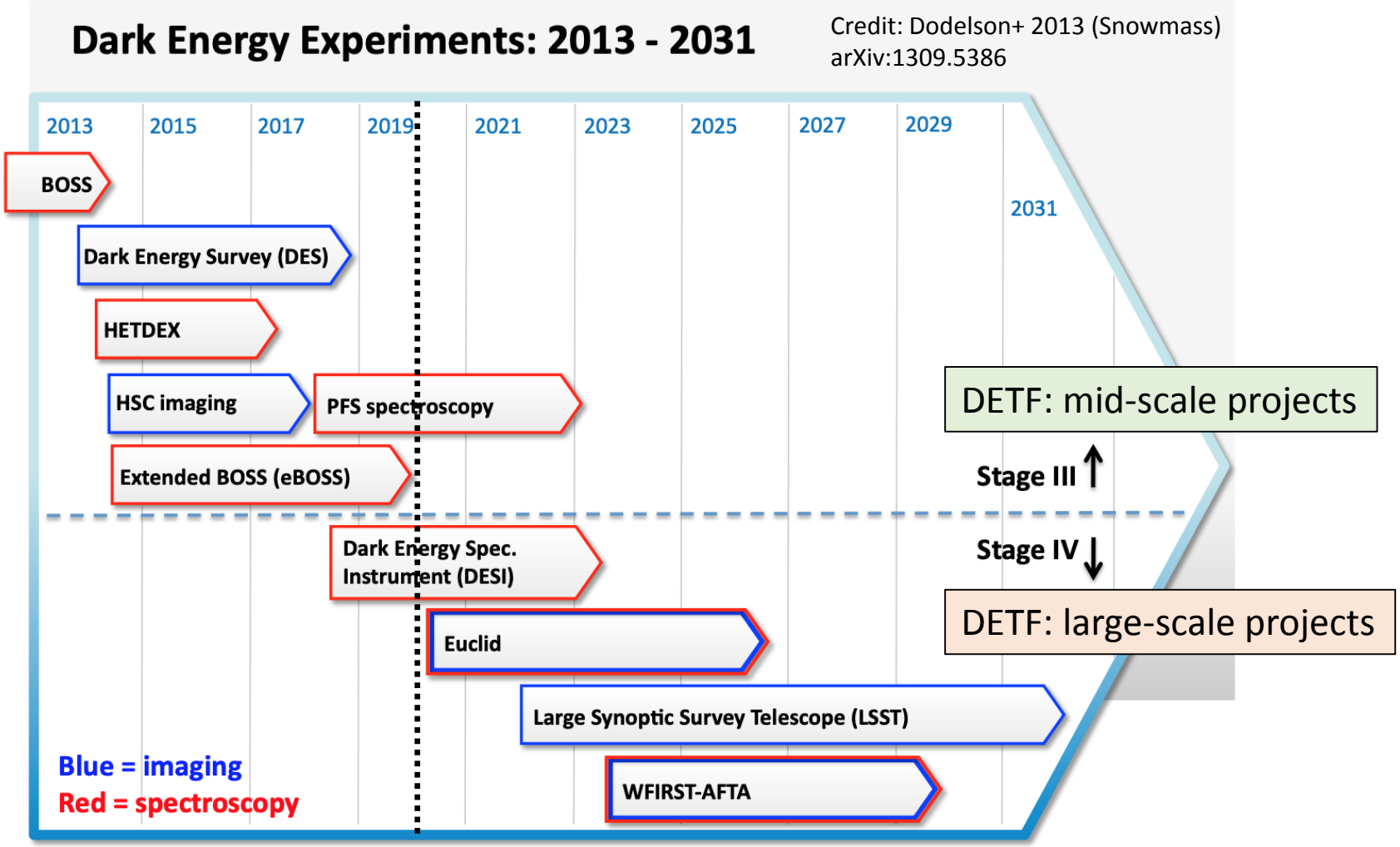
Dark Energy Spectroscopic Instrument (DESI)

Probing Dark Energy



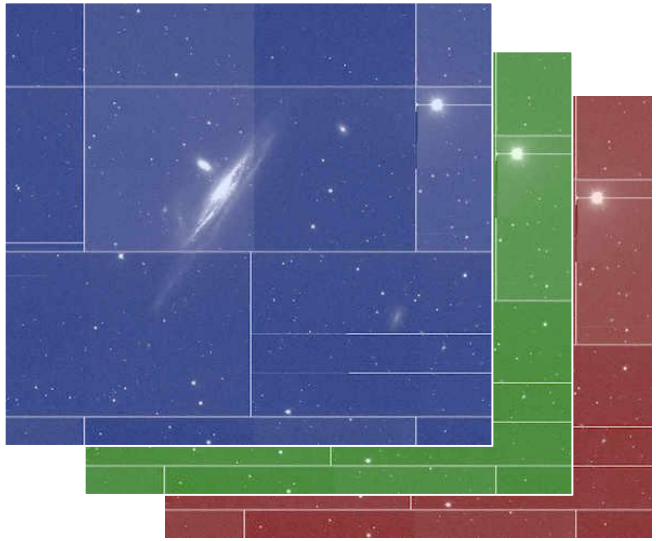
Important:
many observational probes with different (and often complementary) systematic uncertainties.

Dark Energy Program (US-Centric)

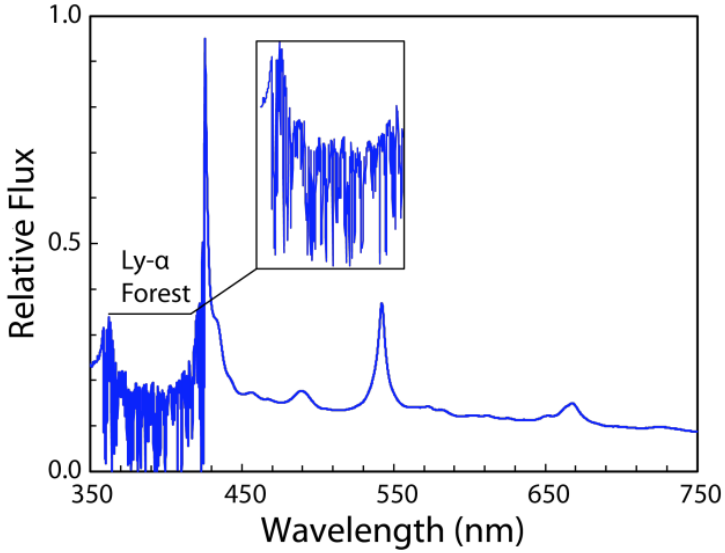


Photometry vs. Spectroscopy

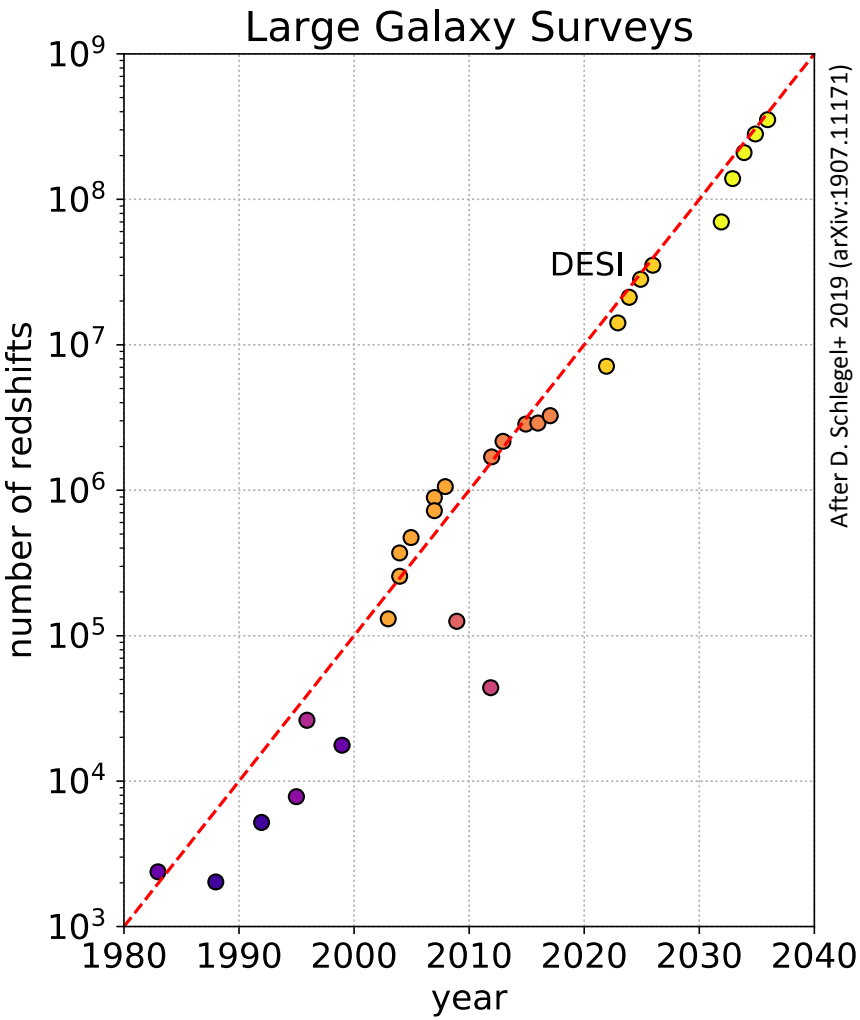
- **Photometry**: record intensity of light passed through colored filters
- **Advantages**:
  - Identify spatial features.
  - Object discovery – e.g., dwarf galaxies around the Milky Way.
  - High cadence & throughput.



- **Spectroscopy**: record intensity of light passed through dispersive grating.
- **Advantages**:
  - Narrow absorption & emission features.
  - High-res measurements of redshift.
  - *Gold standard for object classification!*

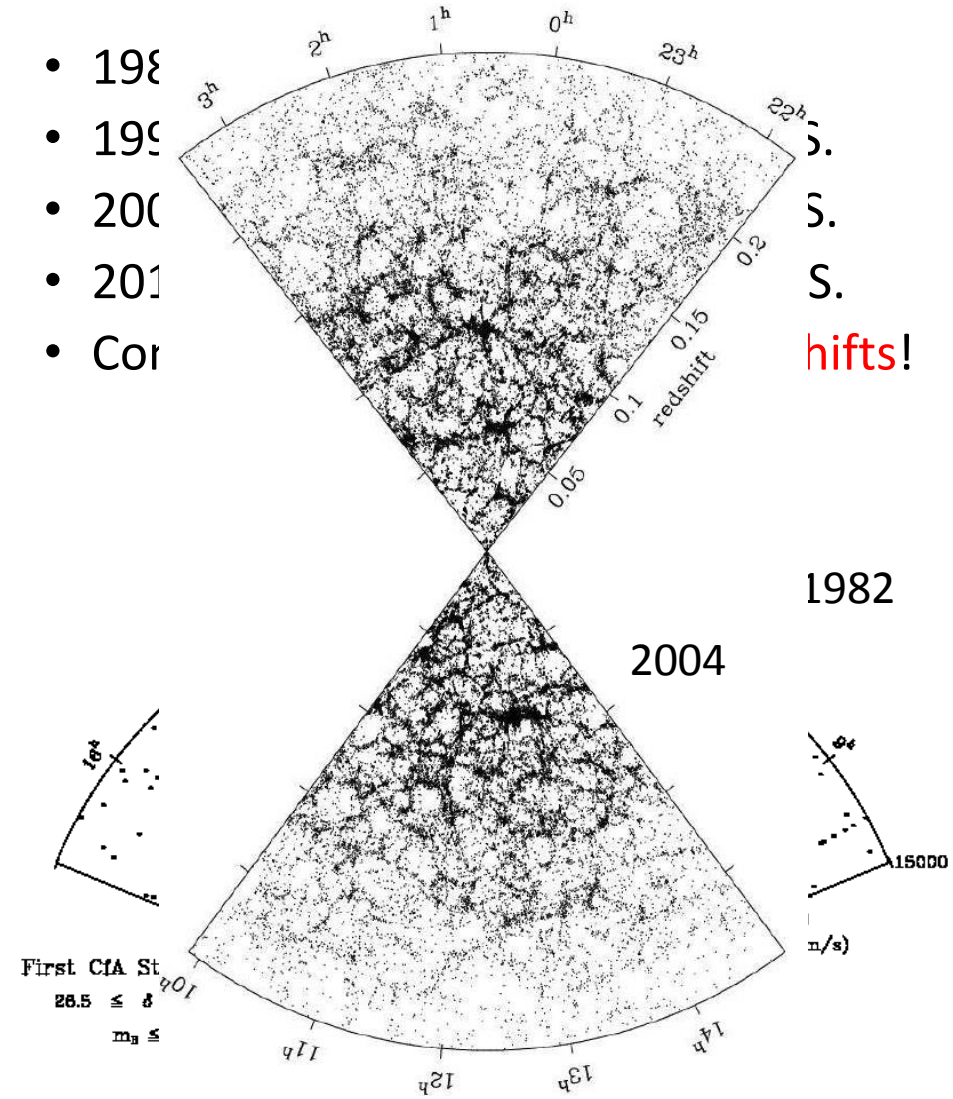


Redshift Surveys: 1980s to Today

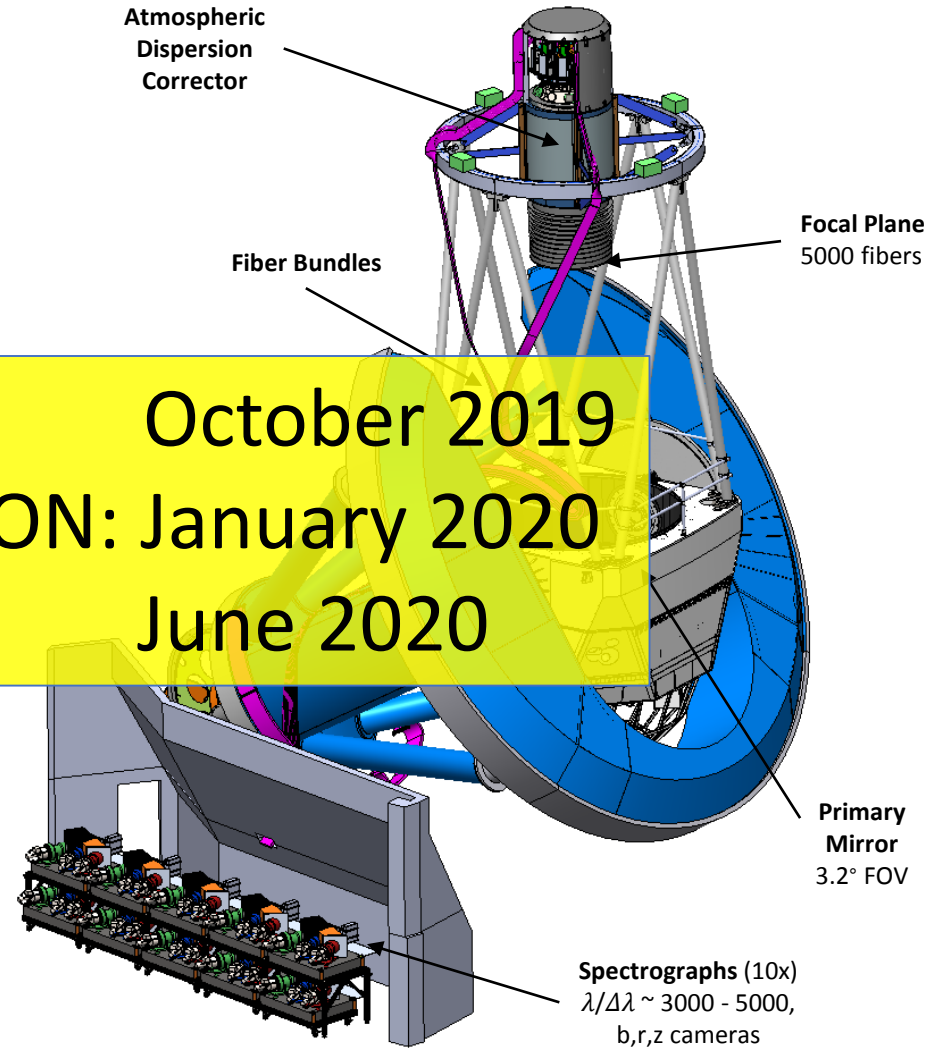


After D. Schlegel+ 2019 (arXiv:1907.11171)

- 198
- 199 S.
- 200 S.
- 201 S.
- Cor hifts!

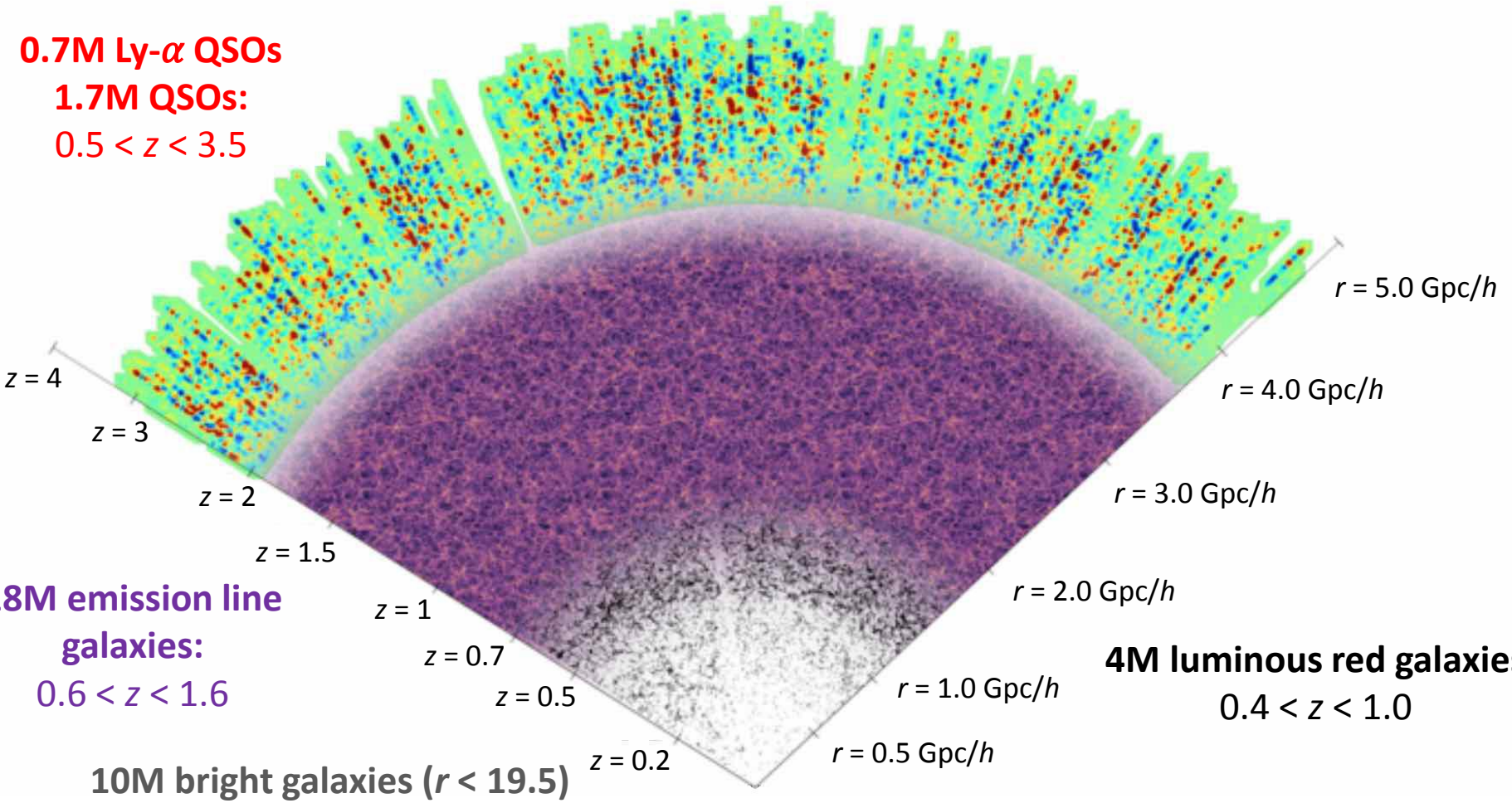


Stage IV Redshift Survey: *D*ark *E*nergy *S*pectroscopic *I*nstrument



COMISSIONING: October 2019
SURVEY VALIDATION: January 2020
SURVEY START: June 2020

DESI Survey: 35M redshifts in 5 years



0.7M Ly-α QSOs
1.7M QSOs:
$0.5 < z < 3.5$

18M emission line galaxies:
$0.6 < z < 1.6$

4M luminous red galaxies
$0.4 < z < 1.0$

10M bright galaxies ($r < 19.5$)
$z < 0.4$

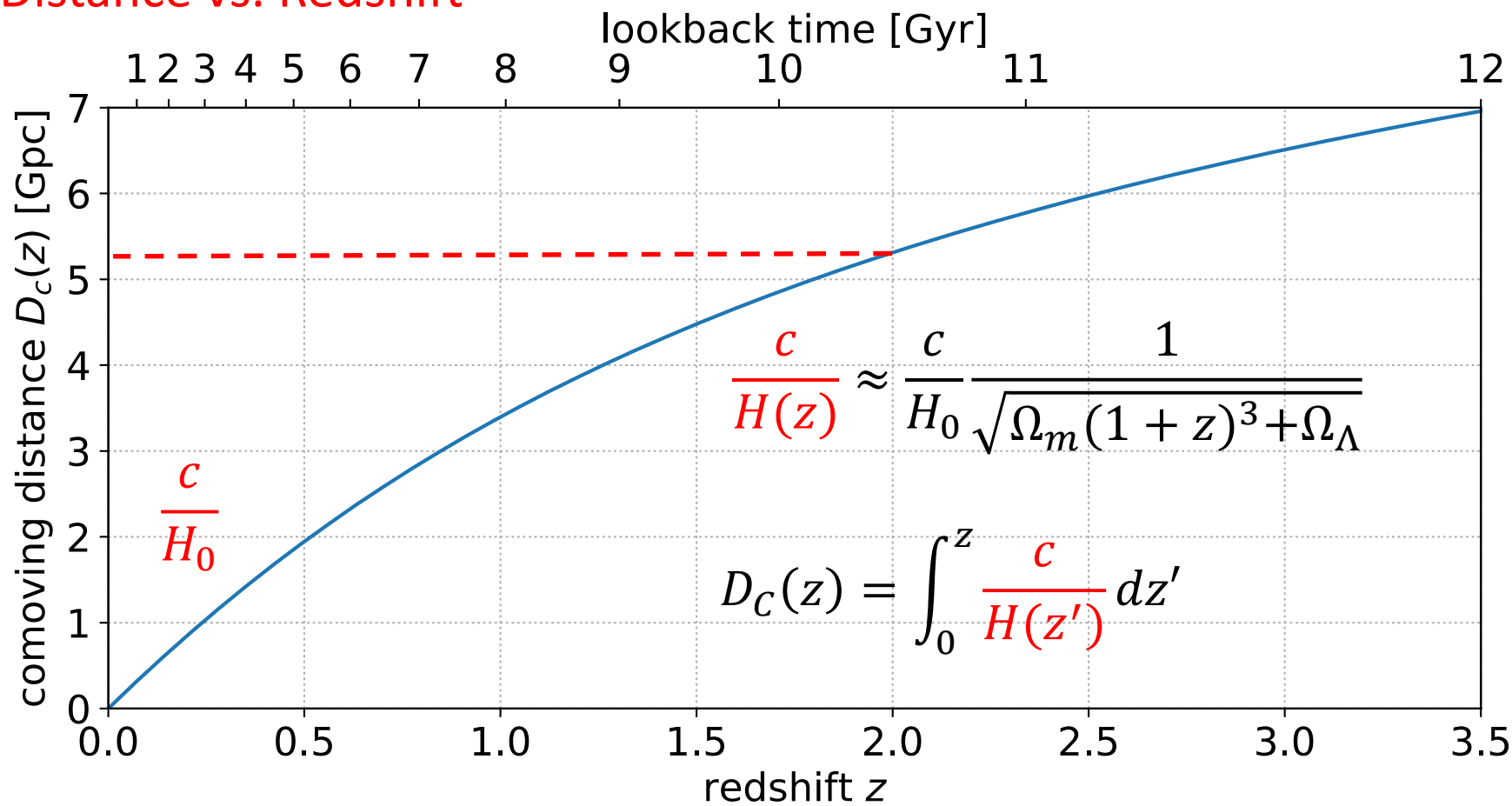
Milky Way Survey: ~10M stars

Dark Energy Part I: The Hubble Expansion

Baryon Acoustic Oscillations: a Standard Ruler

Measuring the Hubble Expansion

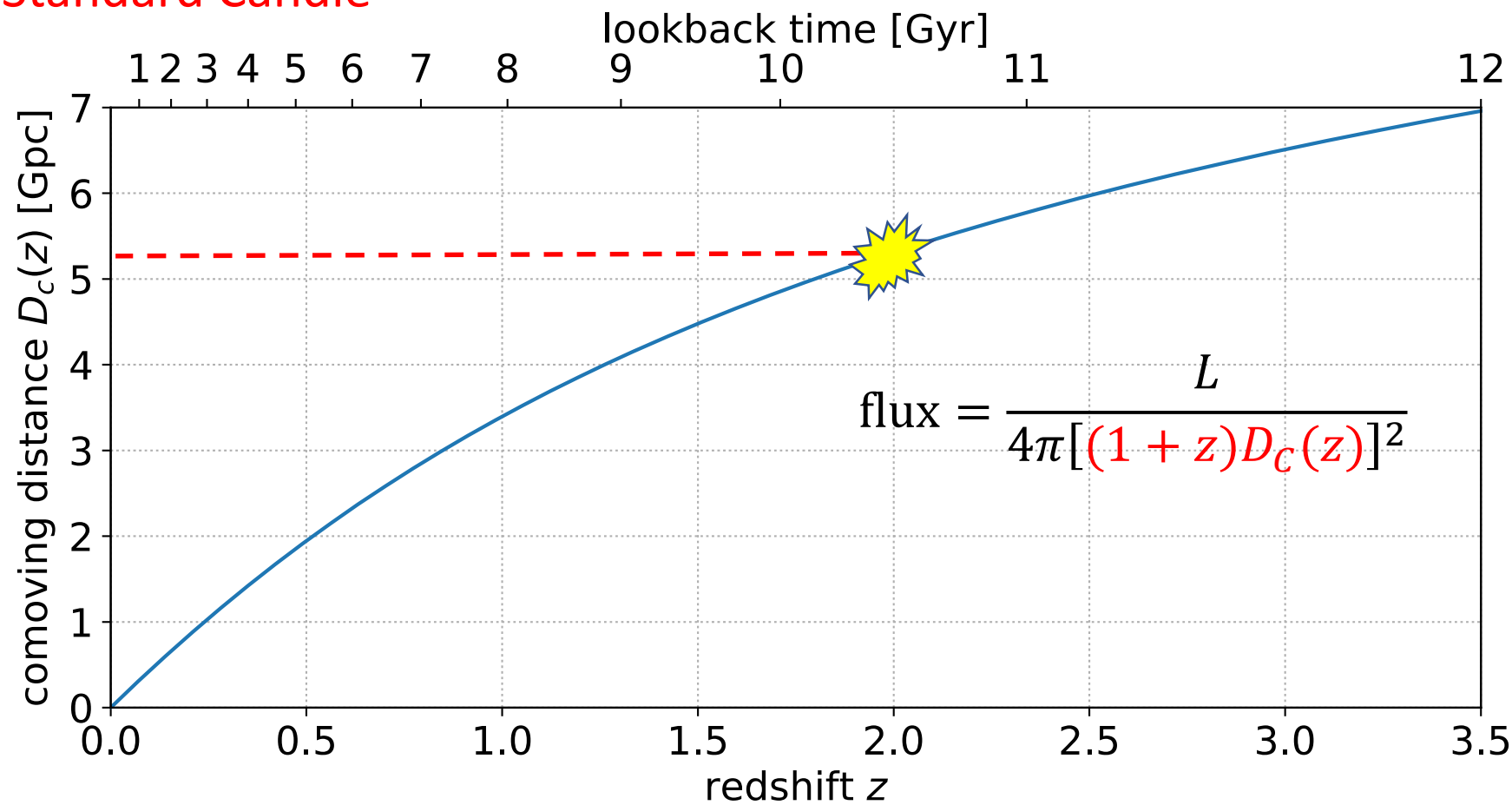
Distance vs. Redshift



Credit: D. Kirkby

Measuring the Hubble Expansion

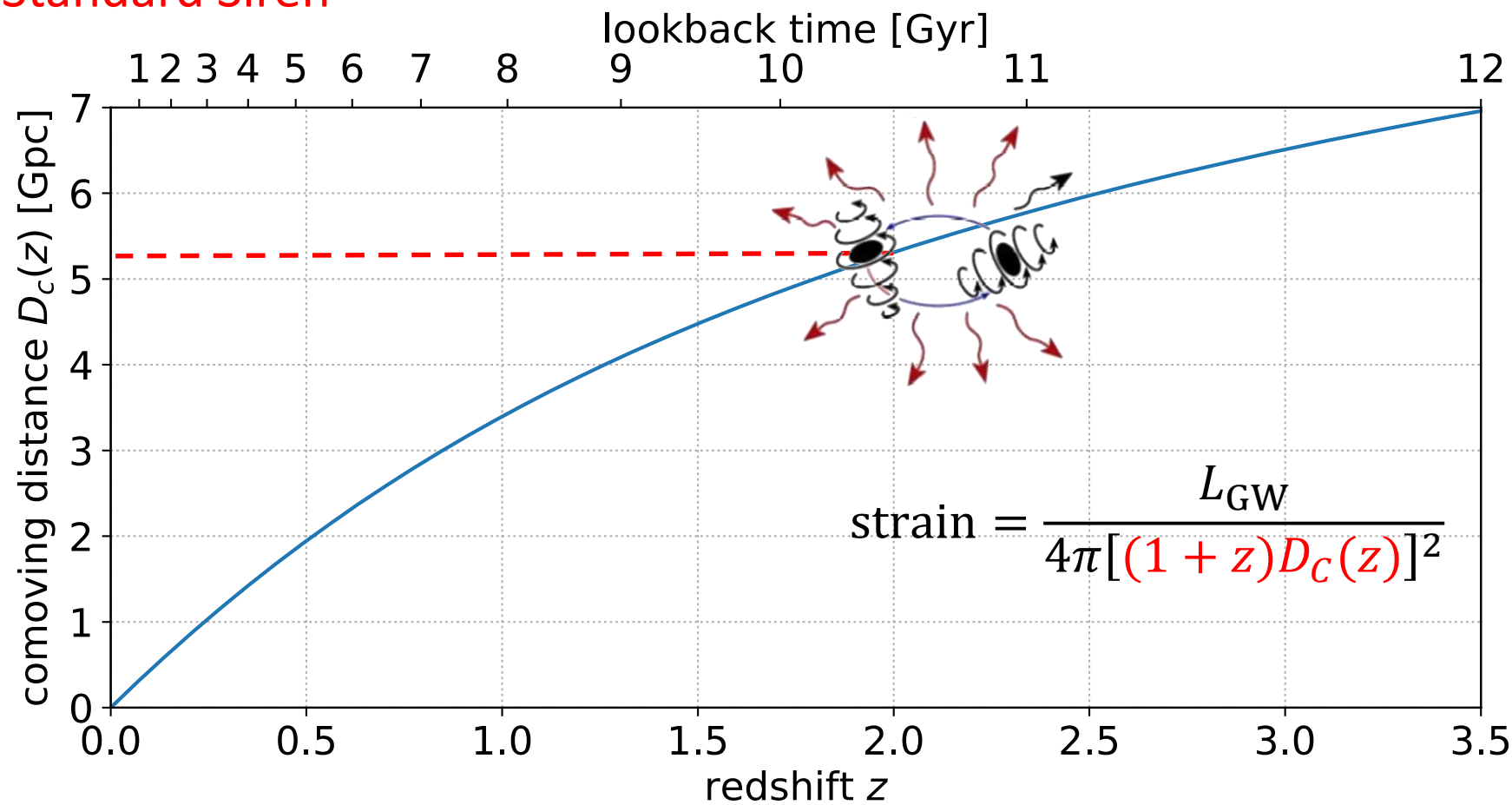
Standard Candle



Credit: D. Kirkby

Measuring the Hubble Expansion

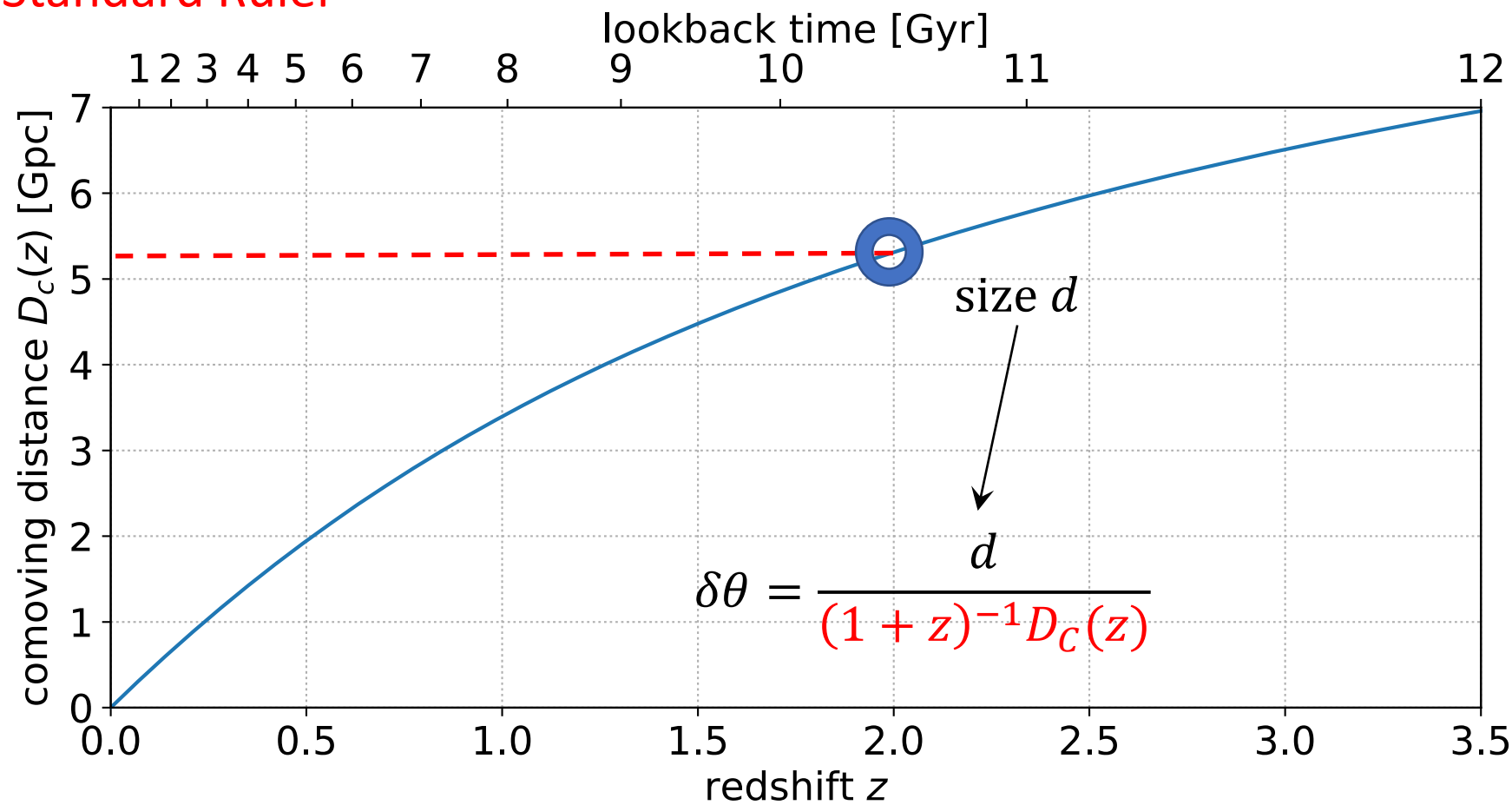
Standard Siren



Credit: D. Kirkby

Measuring the Hubble Expansion

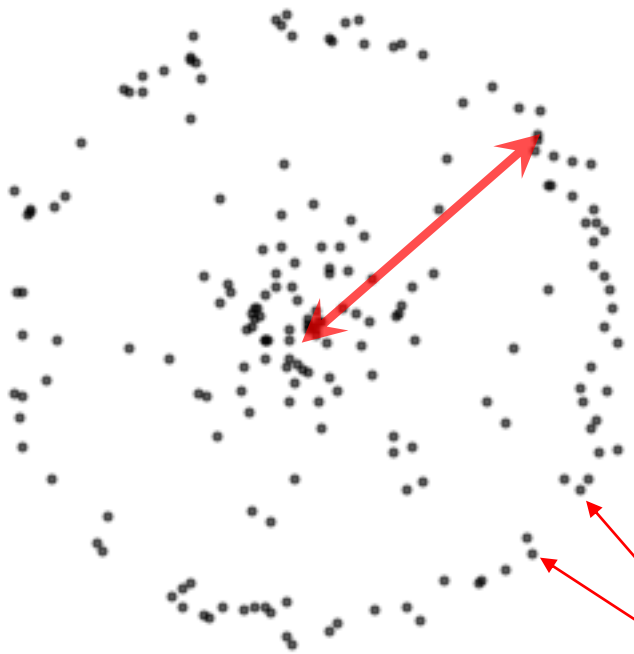
Standard Ruler



Credit: D. Kirkby

Baryon Acoustic Oscillations

- "Bubbles" embedded in large scale structure after baryon-photon decoupling. Structure today is traced by galaxies.



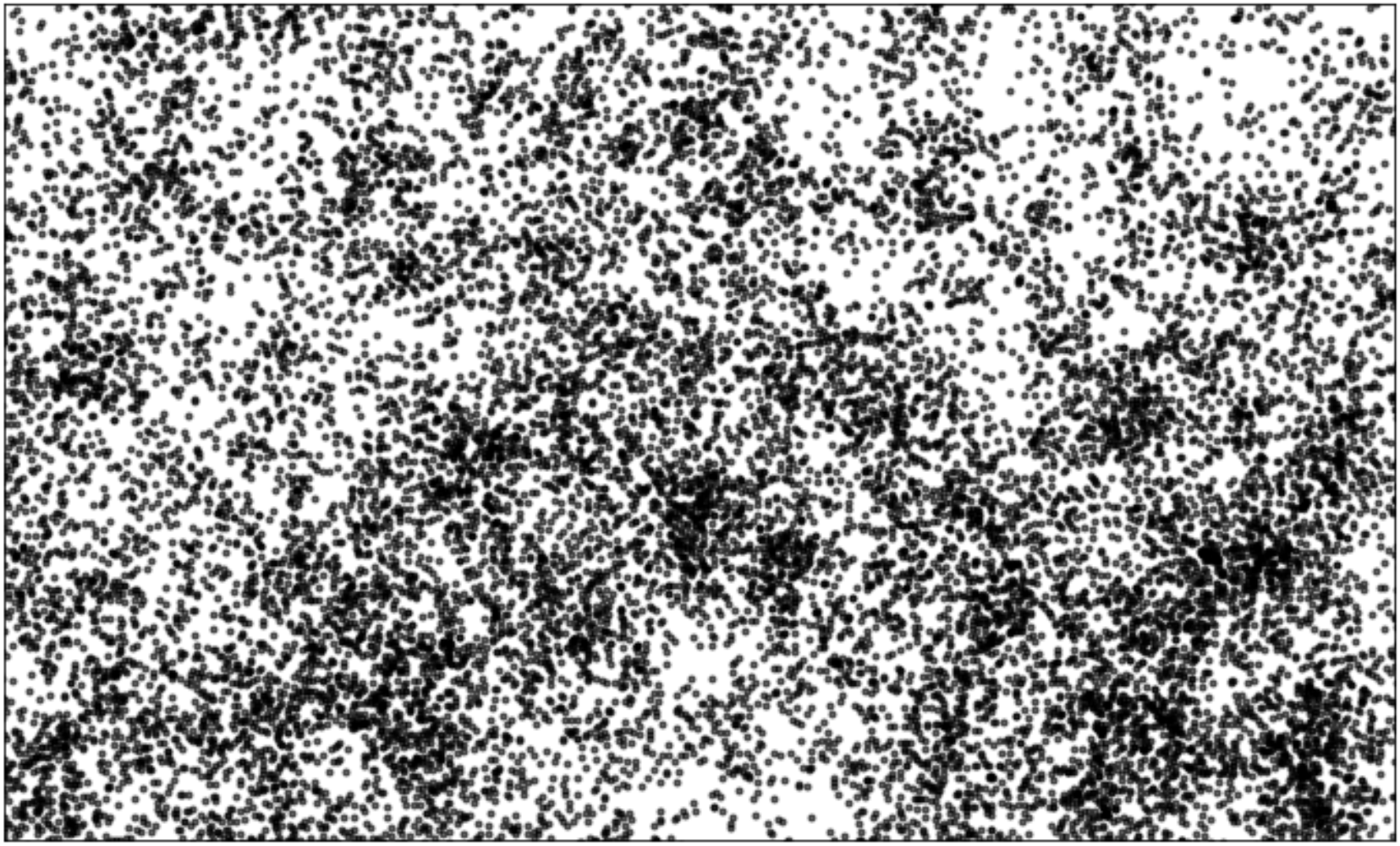
$s^* = 110$ Mpc/h:

$r_s \simeq 150$ Mpc (sound horizon)

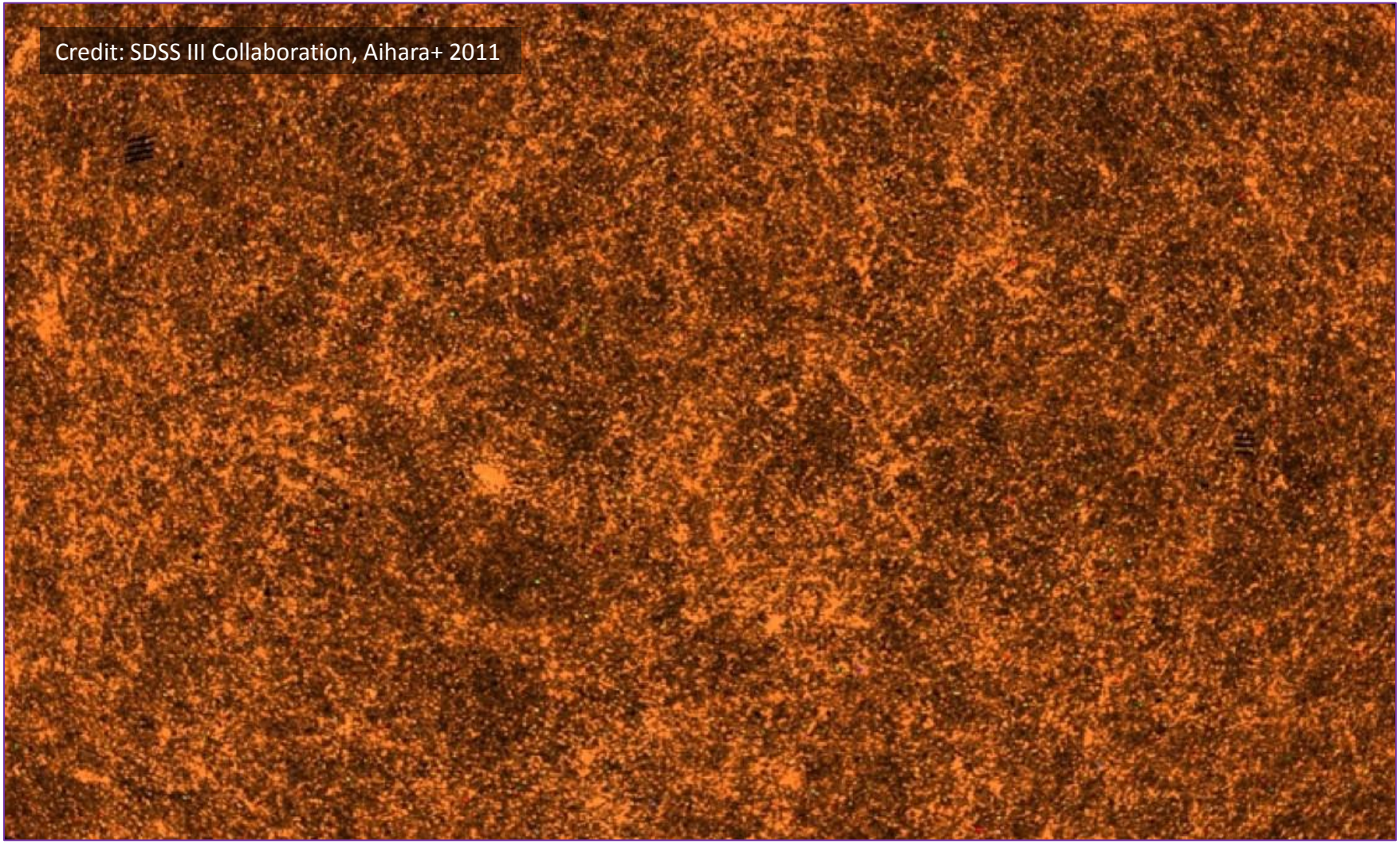
$\delta\theta \simeq 1.6^\circ$ @ $z = 2$

Tracer galaxy "test particles"

Measuring BAO



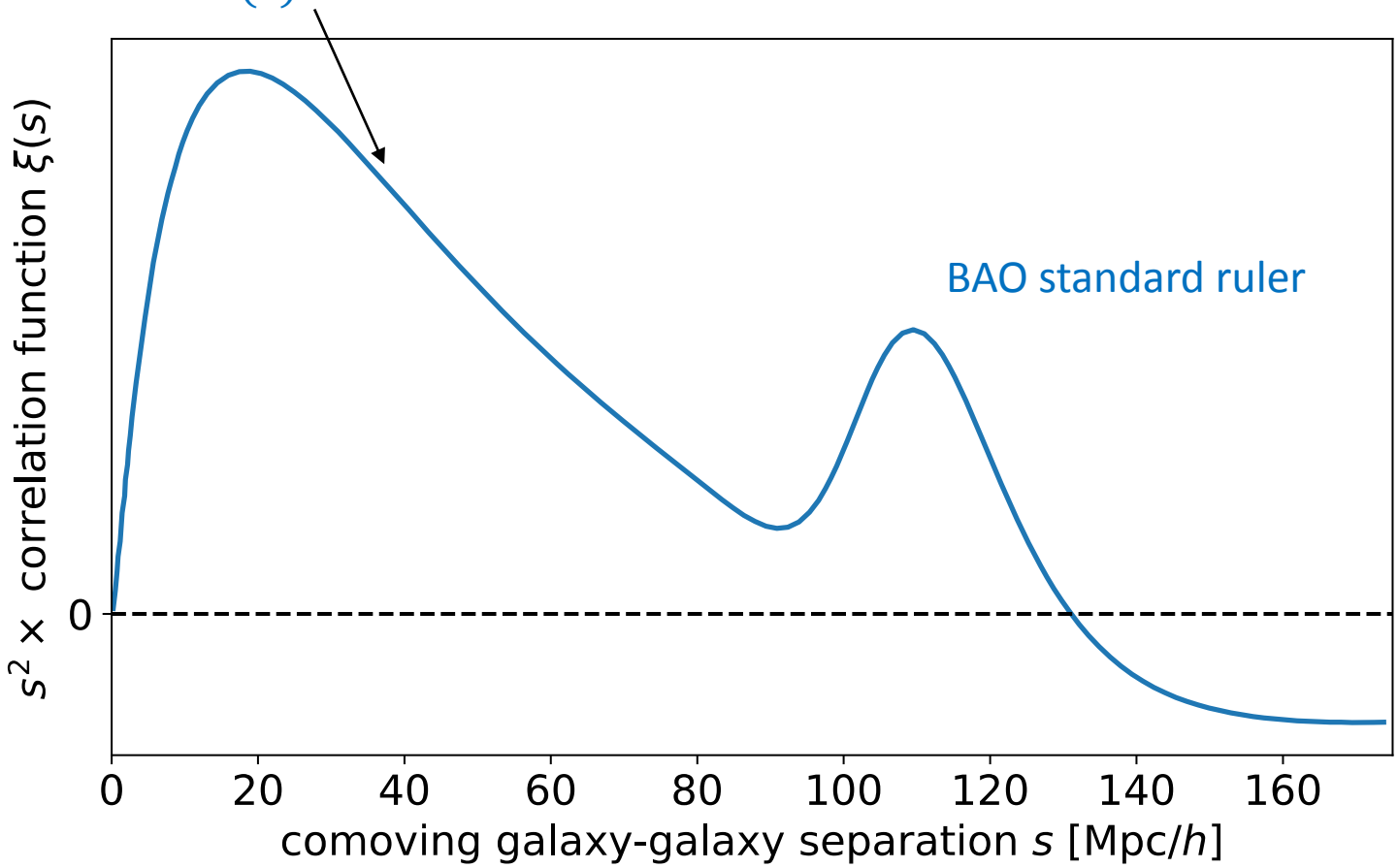
SDSS-III DR8 Northern Galactic Cap



BAO: 2-pt Correlation (angle-averaged)

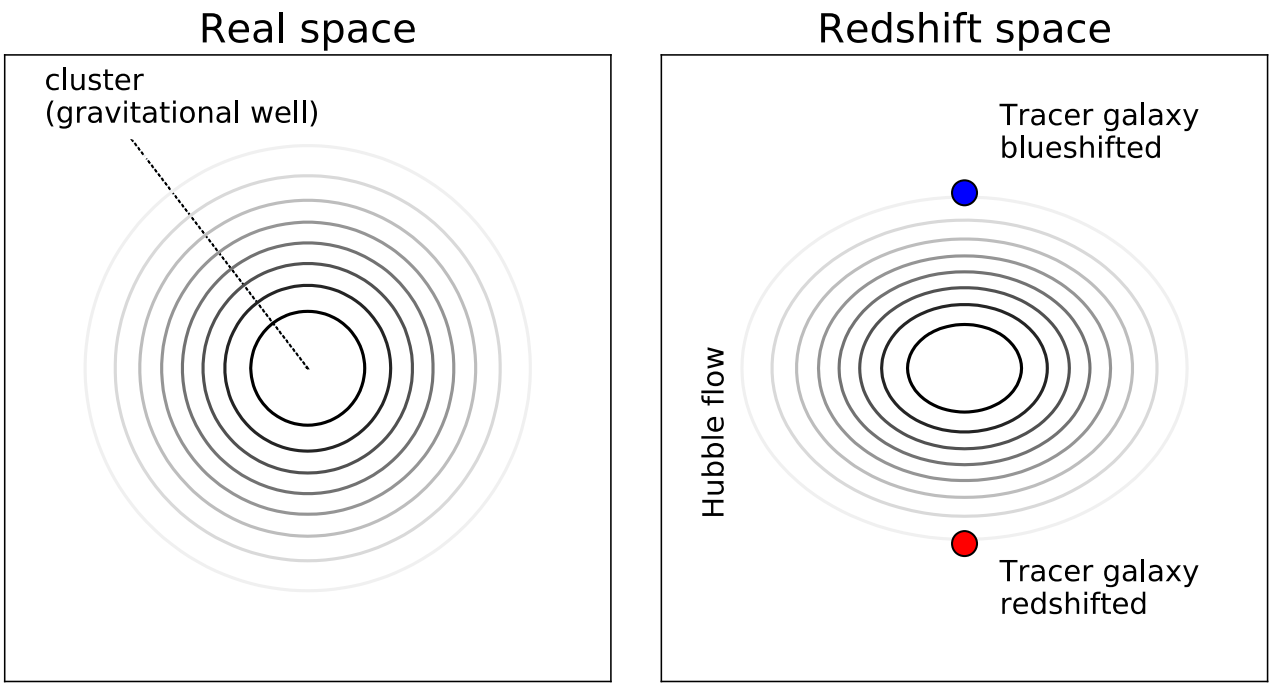
$$\xi(s) = \frac{\mathrm{DD}(s) - 2\mathrm{DR}(s) + \mathrm{RR}(s)}{\mathrm{RR}(s)} =$$

Excess galaxy pair counts in data w.r.t. random background pair counts in survey volume.

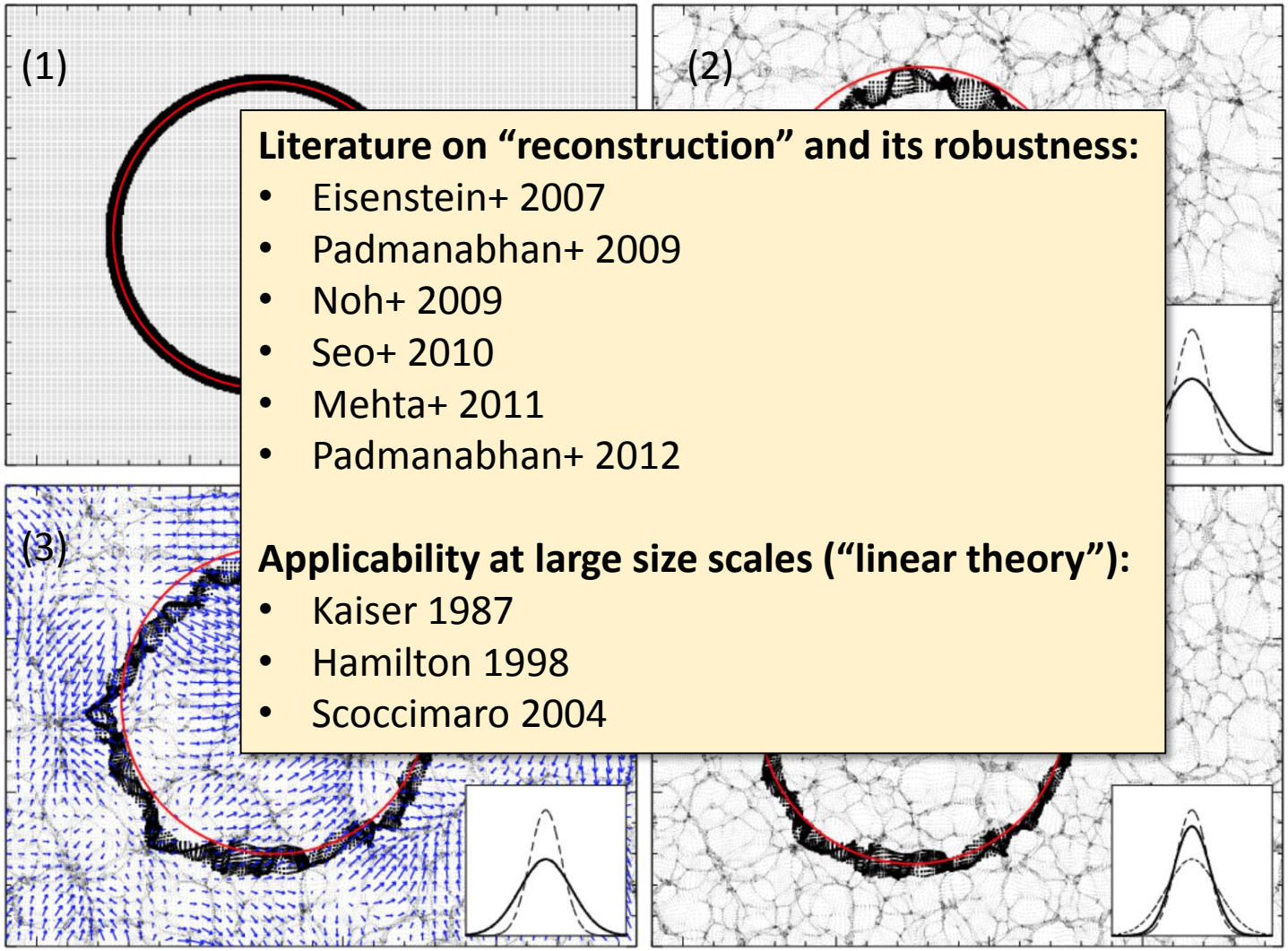


Systematics: Redshift Space Distortions

- Tracer galaxies are gravitationally attracted to clusters (peculiar motion).
- In redshift space, clusters appear squashed and voids appear stretched along the line of sight.
- Redshift space distortions (RSDs) create artificial anisotropy in the BAO.



“Reconstruction” of Displacement Field



Credit: Padmanabhan+ 2012

Literature on “reconstruction” and its robustness:

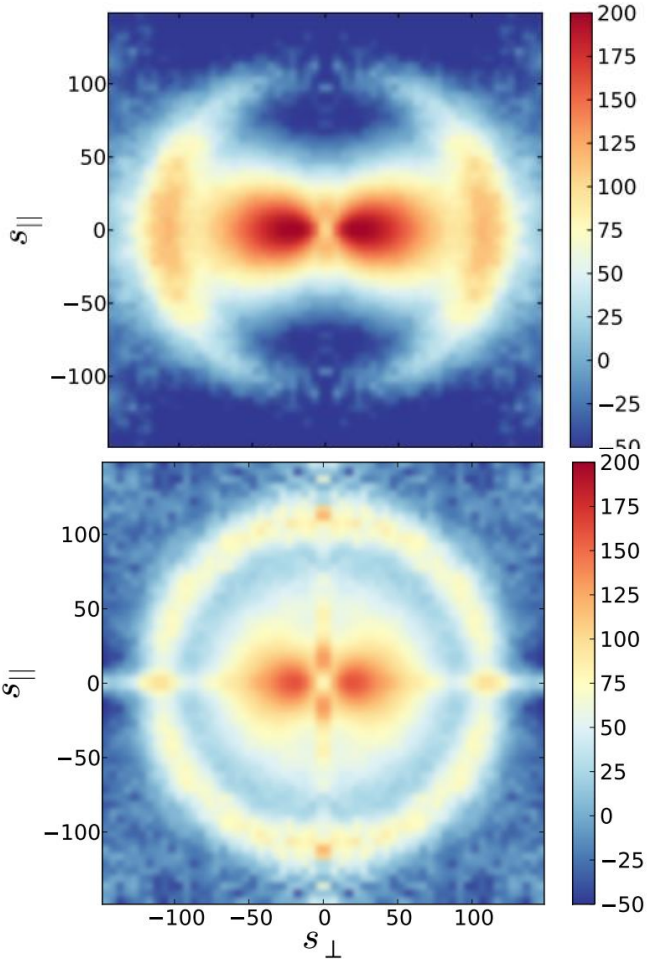
- Eisenstein+ 2007
- Padmanabhan+ 2009
- Noh+ 2009
- Seo+ 2010
- Mehta+ 2011
- Padmanabhan+ 2012

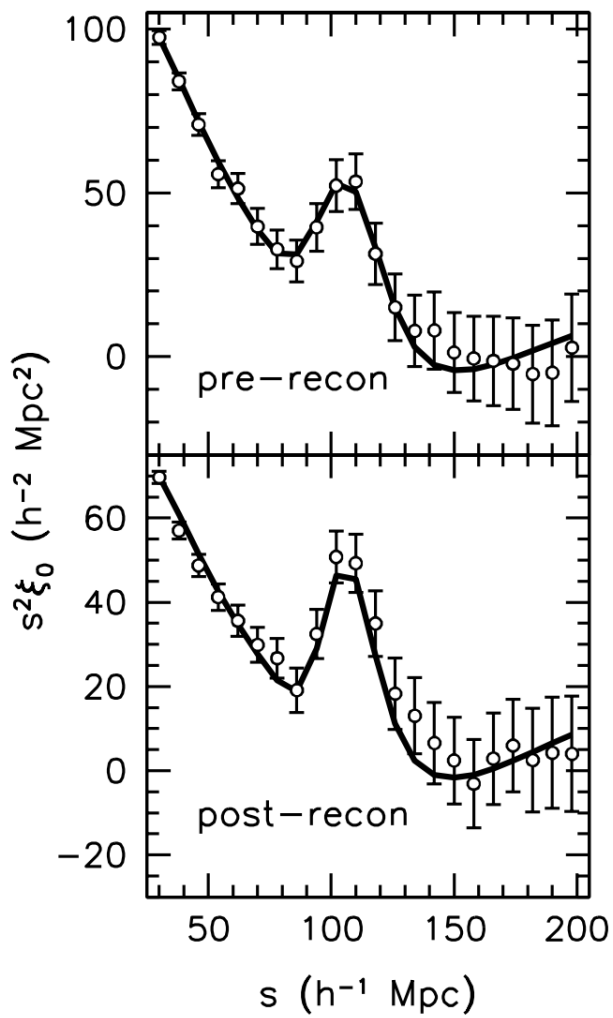
Applicability at large size scales (“linear theory”):

- Kaiser 1987
- Hamilton 1998
- Scoccimaro 2004

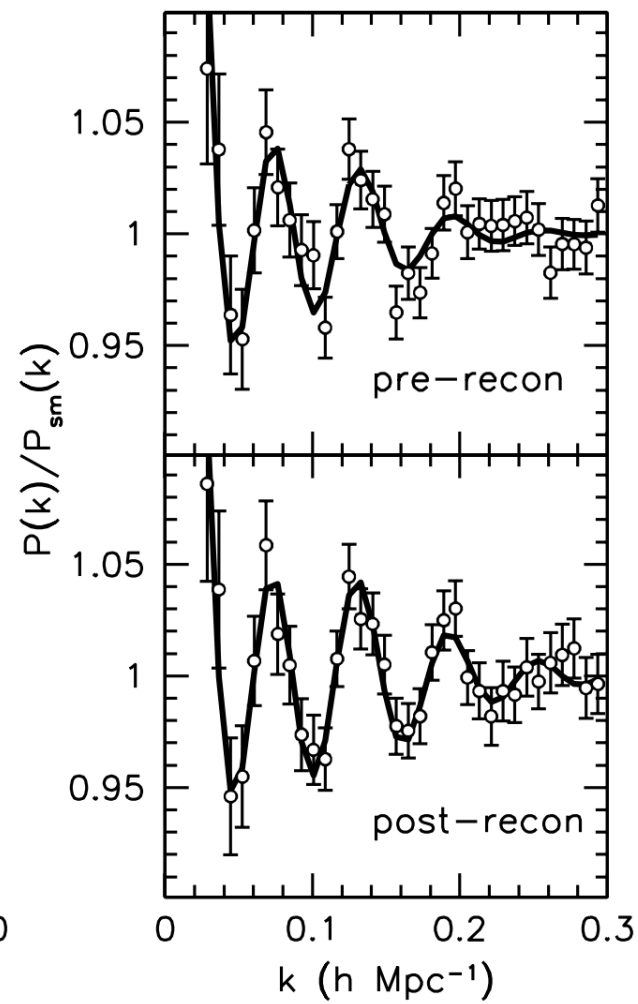
BAO after Reconstruction (BOSS DR11)

Credit: Padmanabhan+ 2012





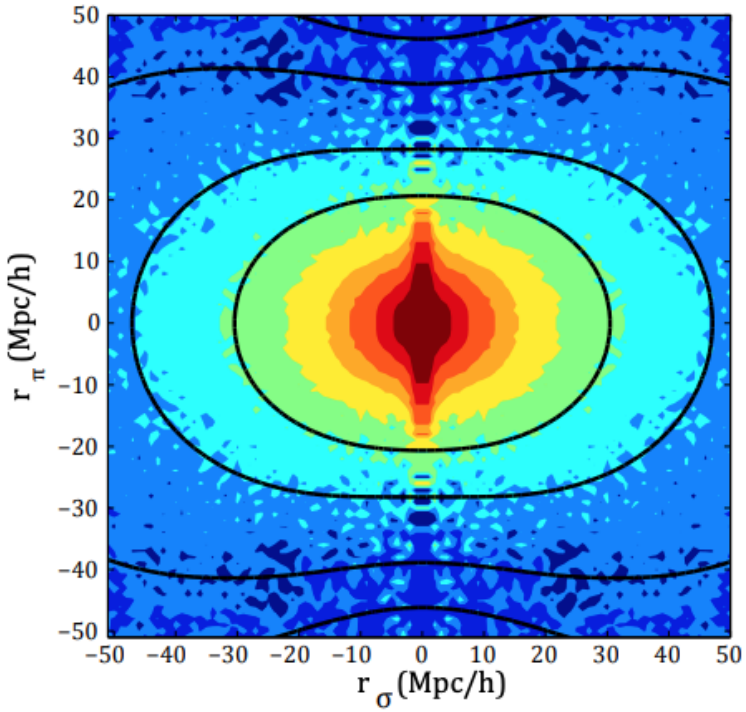
Credit: Anderson+ 2014



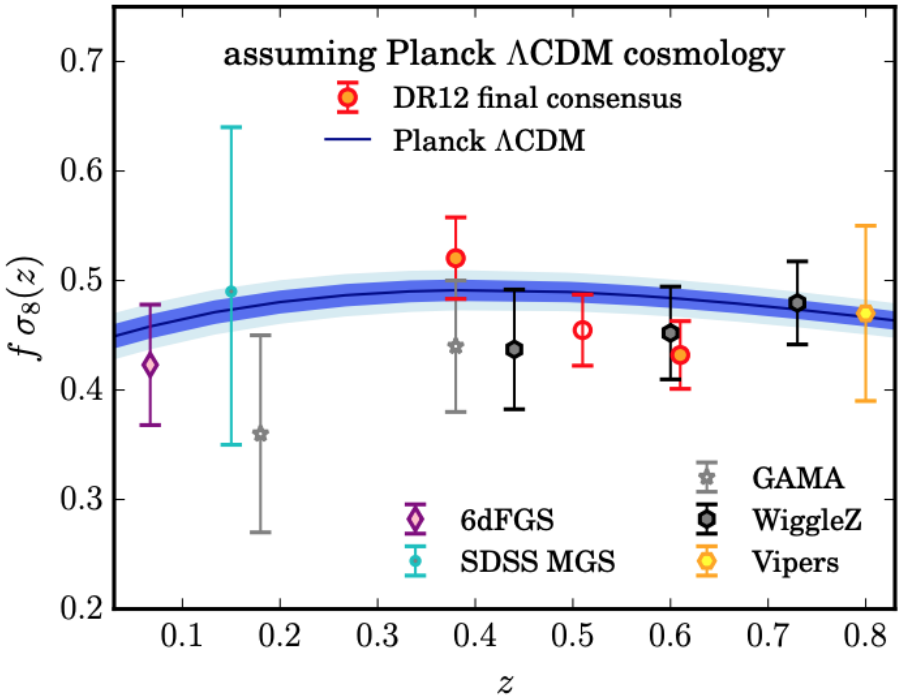
Dark Energy Part II: The Growth of Structure

More Information: Growth of Structure

- RSD must be removed to study the BAO standard ruler, but they are extremely useful in their own right!
- The anisotropy produced by RSD constrains $f\sigma_8$, where f is the growth rate of structure and σ_8 is the normalized amplitude of mass fluctuations.



Credit: BOSS Collaboration, Alam+ 2017



Growth Index: Testing General Relativity

- Q: can we add modifications to gravity (GR) that explain cosmological data without invoking a new form of energy?

- Parameterize the redshift evolution of the growth rate as

$$f(z) \approx \Omega_m(z)^{\gamma}$$

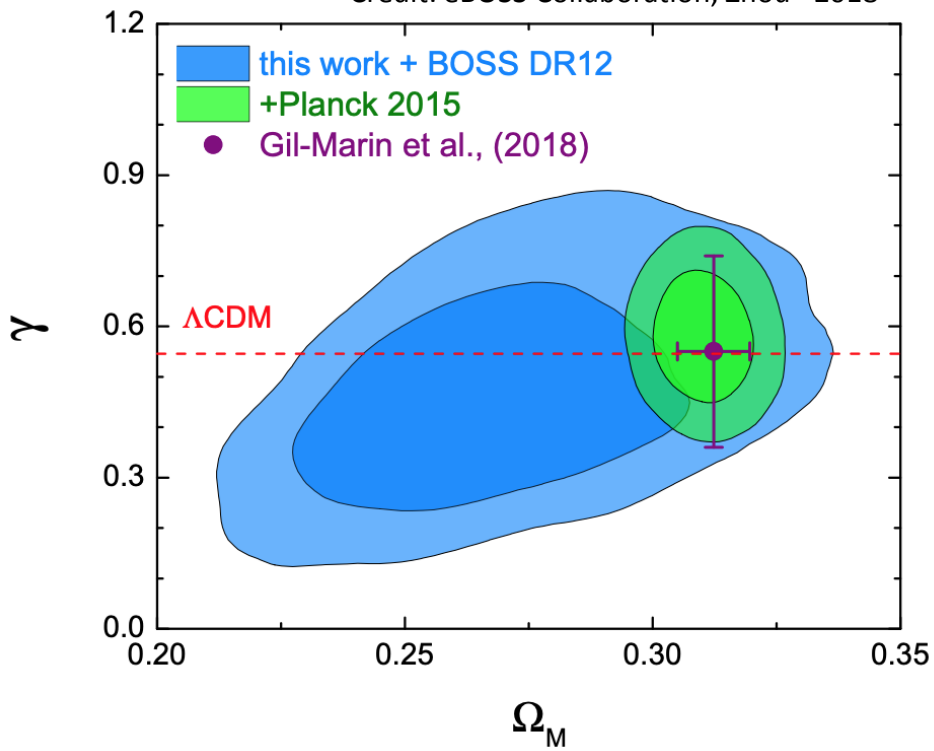
Growth rate of structure Matter density Growth index

- GR predicts $\gamma \simeq 0.55$. Significant deviations from this value would motivate alternatives to GR on cosmic scales.

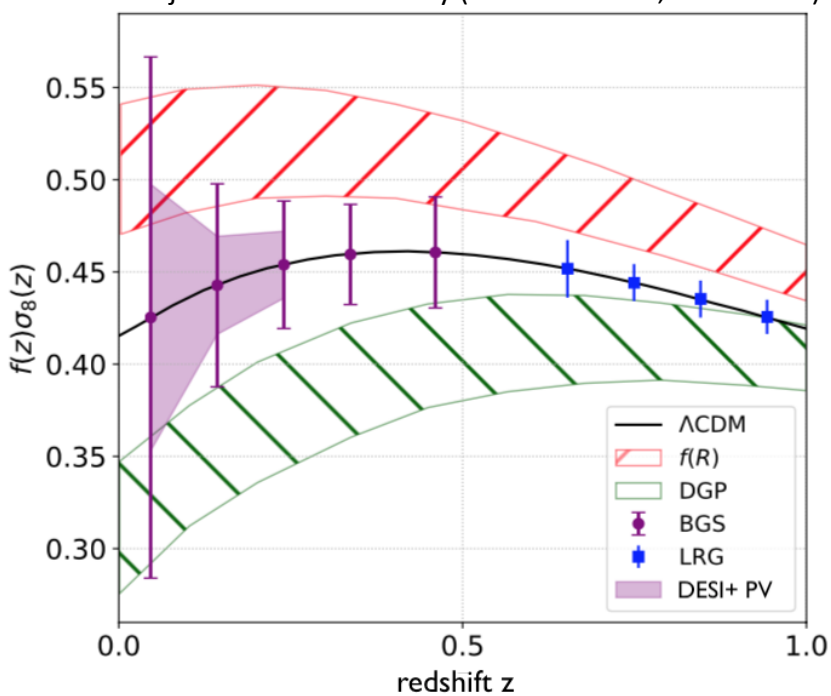
Growth Index: Testing General Relativity

- Current constraints on γ are consistent with GR.
- 2-3x improvement in constraints with DESI LRG + peculiar velocity surveys at low-z. Model discrimination at 3σ level.

Credit: eBOSS Collaboration, Zhou+ 2018

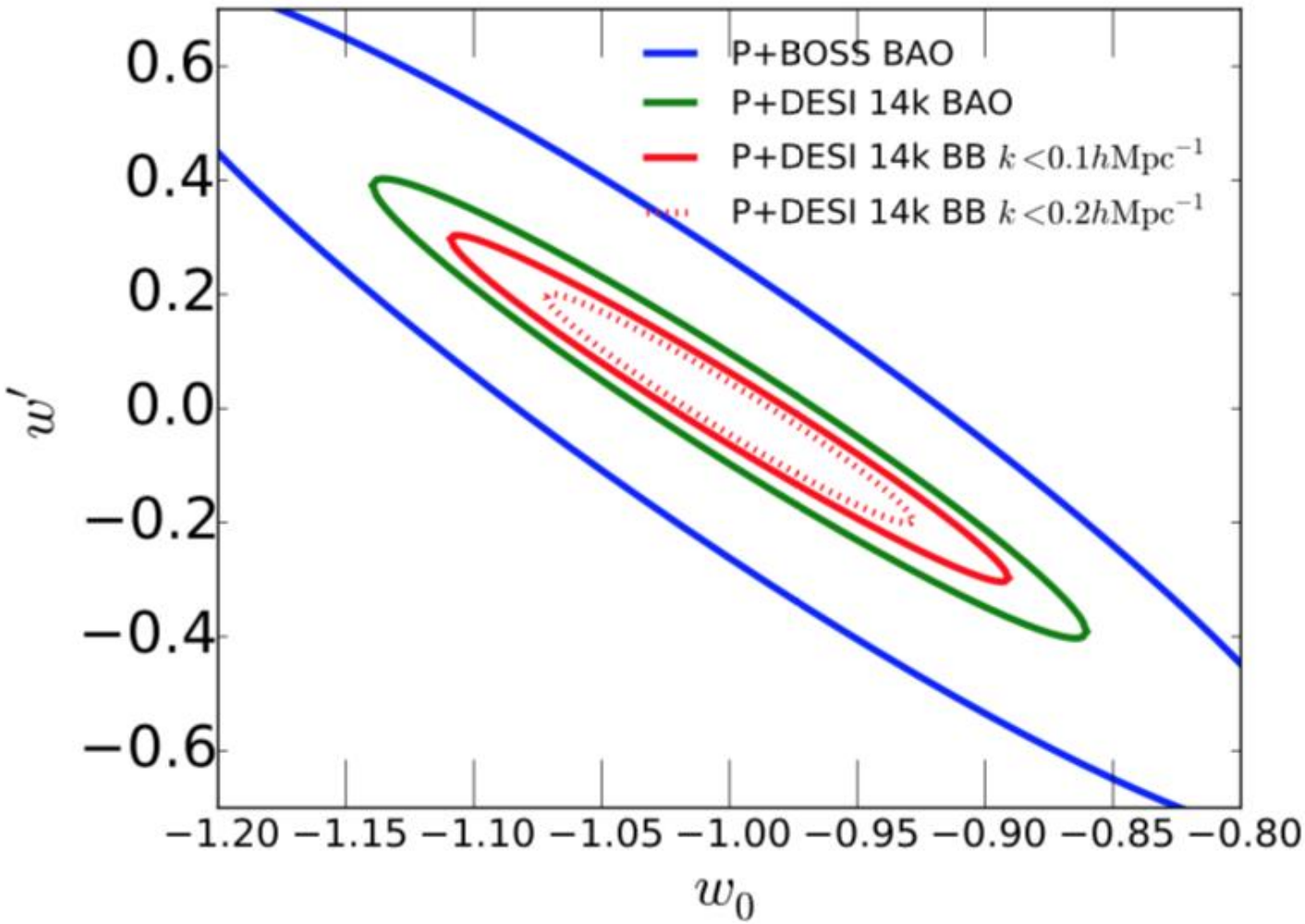


Projected DESI sensitivity (DESI FDR 2016, Kim+ 2019)



Does Dark Energy Evolve: $w = w(a)$?

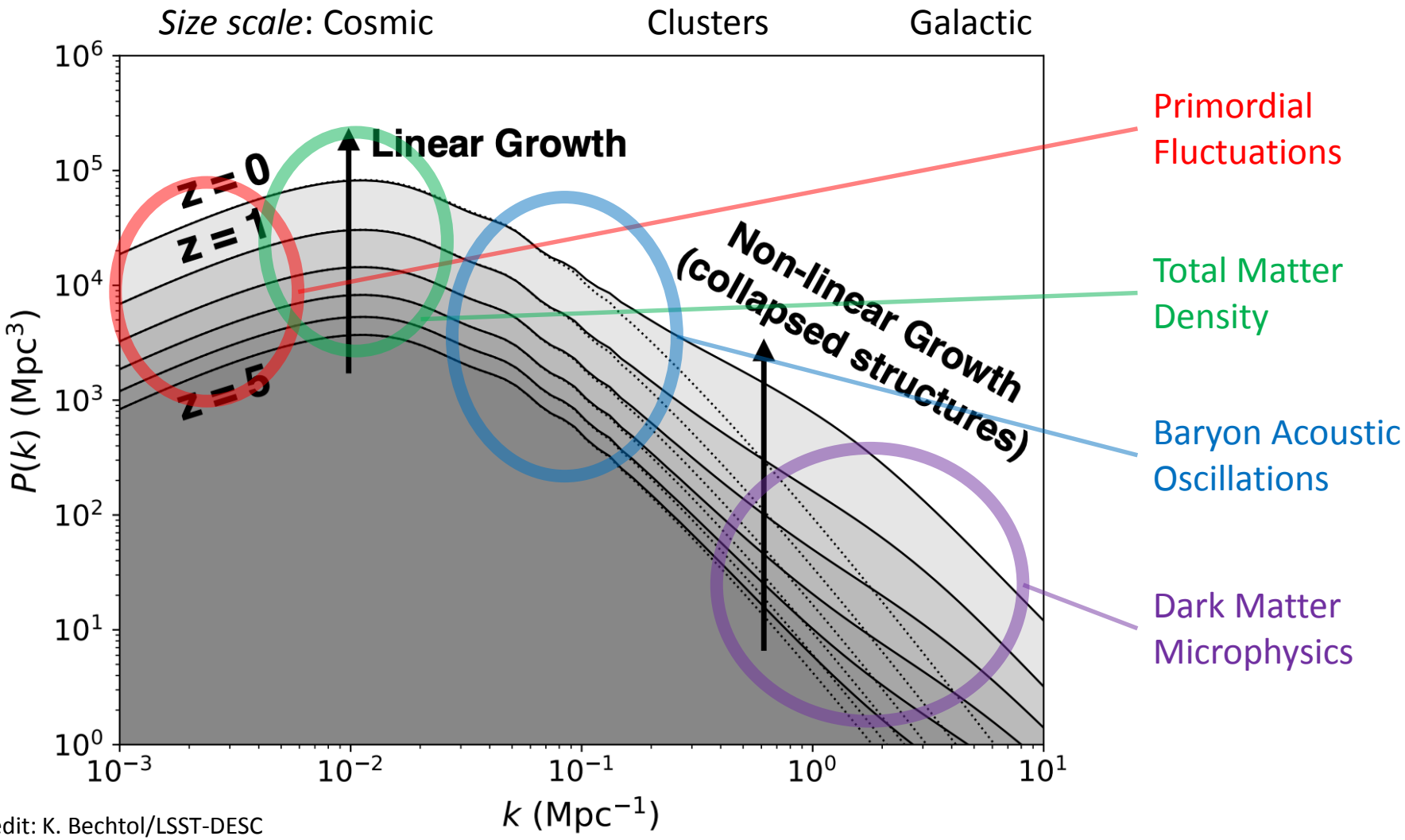
Credit: DESI Science FDR 2016; see also Linder 2005, Linder+Cahn 2007



Particle Microphysics & Large Scale Structure

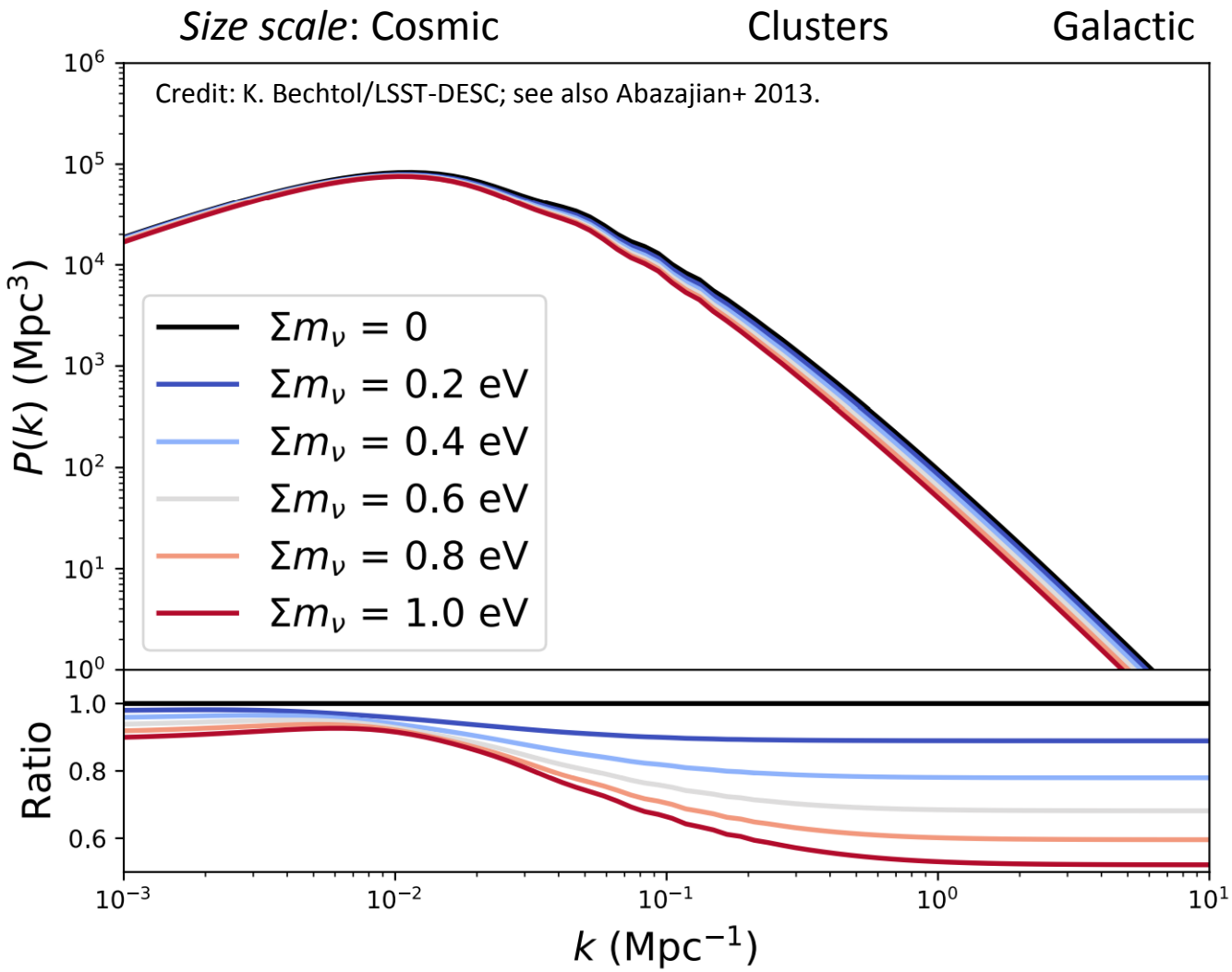
Cosmic Neutrinos (and other Light Relics)

Information in the Power Spectrum



Credit: K. Bechtol/LSST-DESC

Information from the Power Spectrum: Neutrino Mass



Massive neutrinos suppress formation of structure at small size scales.

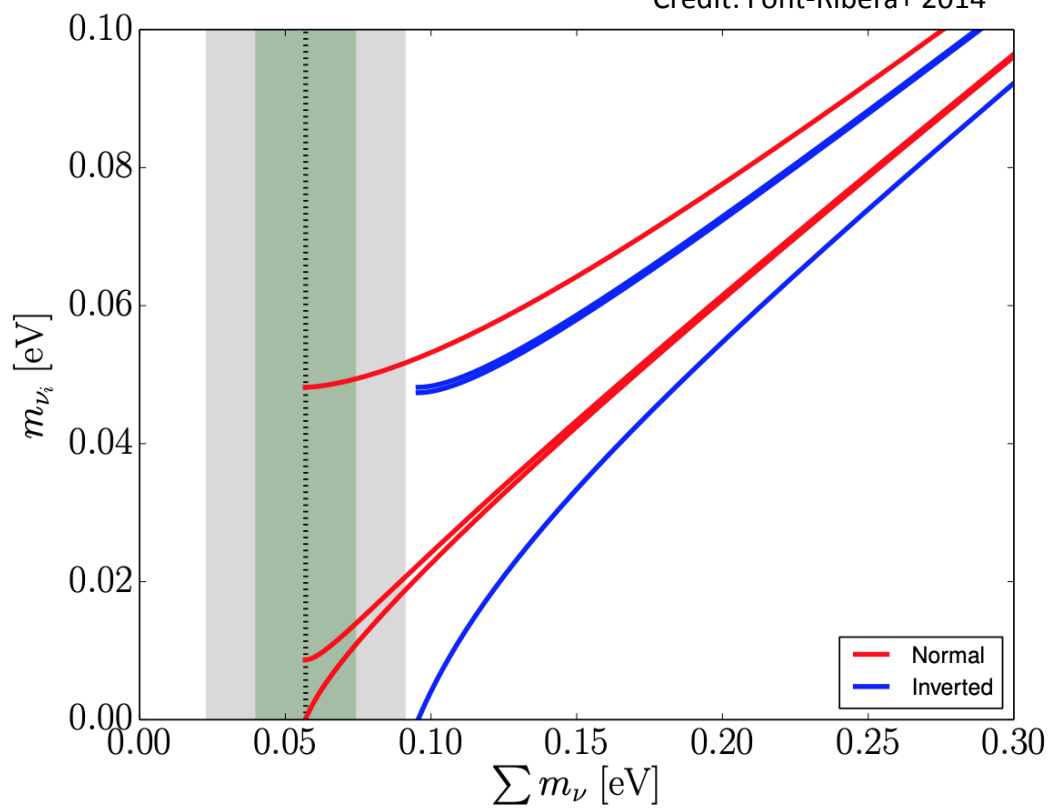
Neutrinos escape from small grav. potential wells ("free streaming").

If Ω_ν is a bigger component of Ω_m then small-scale structure is suppressed.

Limits on Σm_ν: Projected Sensitivity

- Oscillations require $\Sigma m_\nu > 59$ meV (normal hierarchy) and > 98 meV (inverted).
- Next-gen CMB+LSS: expect $\sigma_{\Sigma m} \simeq 17$ meV.
- Small Σm_ν can rule out inverted hierarchy at 3.5σ (best-case).
- Note: NH with Σm_ν well above the minimum allowed would not be distinguishable from IH.

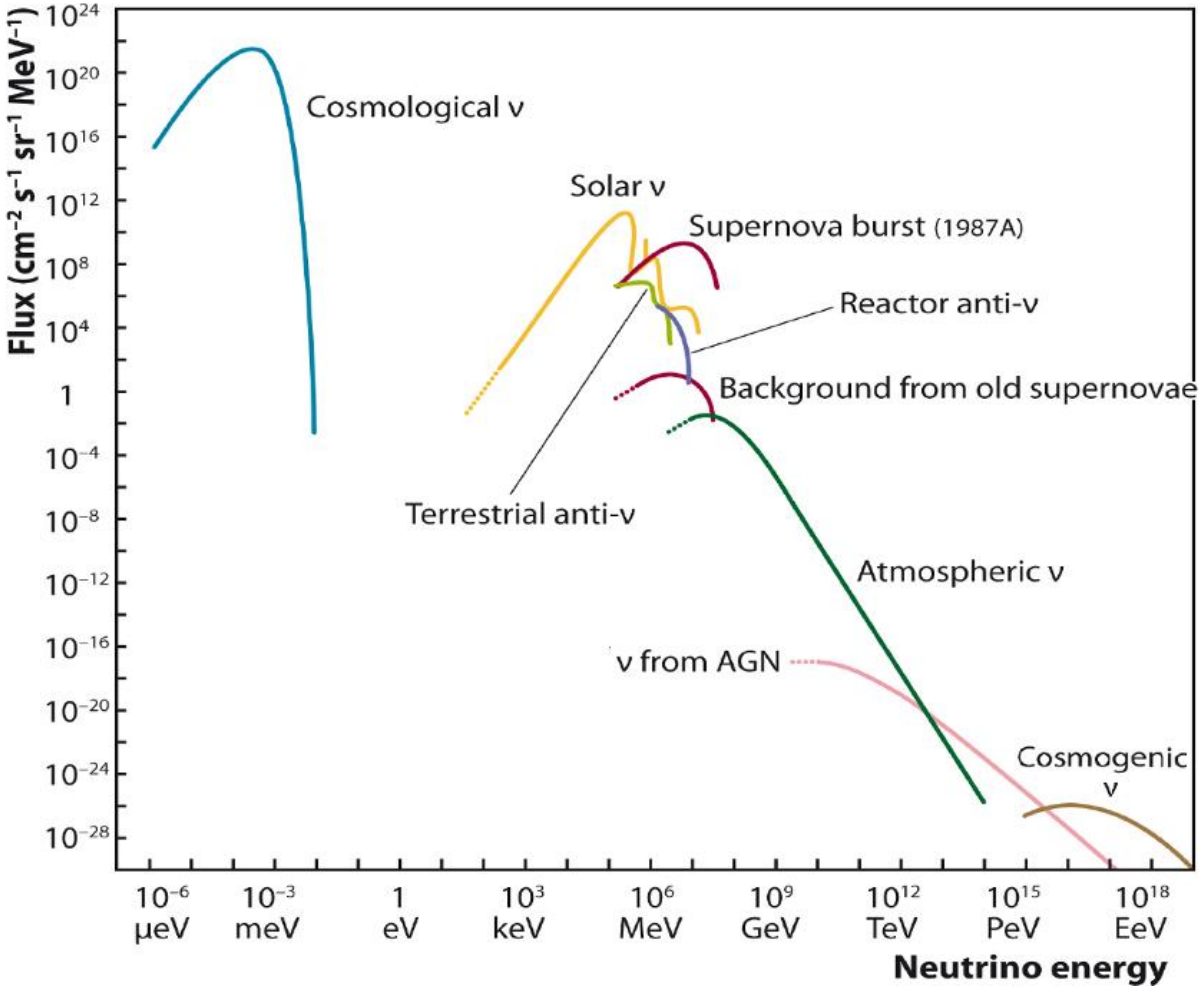
Credit: Font-Ribera+ 2014



Additional Information: N_{eff}

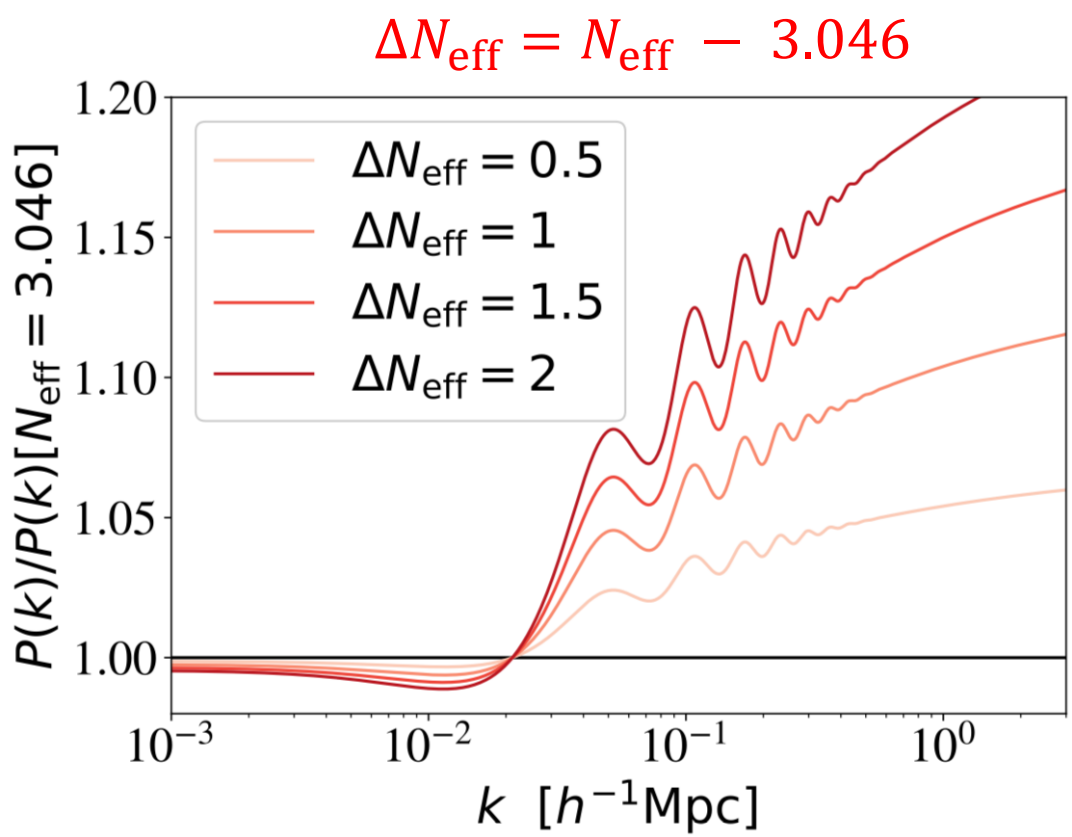
- CMB + LSS are sensitive to light relic particles.
- Very obvious candidate population: the cosmic neutrino background (CνB).
- Energy ~1 μeV; direct detection not likely…

Credit: IceCube Collaboration / NSF



$N_{\text{eff}} > 3.046$: "Dark Radiation"

- We've assumed no massless or light relic particles beyond photons and known active neutrinos.
- Expect $N_{\text{eff}} = 3.046$ from cosmological limits: gradual neutrino decoupling at $T \sim 2$ MeV + flavor oscillations (de Salas + Pastor 2016).
- Larger N_{eff} → dark radiation. E.g., a sterile neutrino or other light relic.

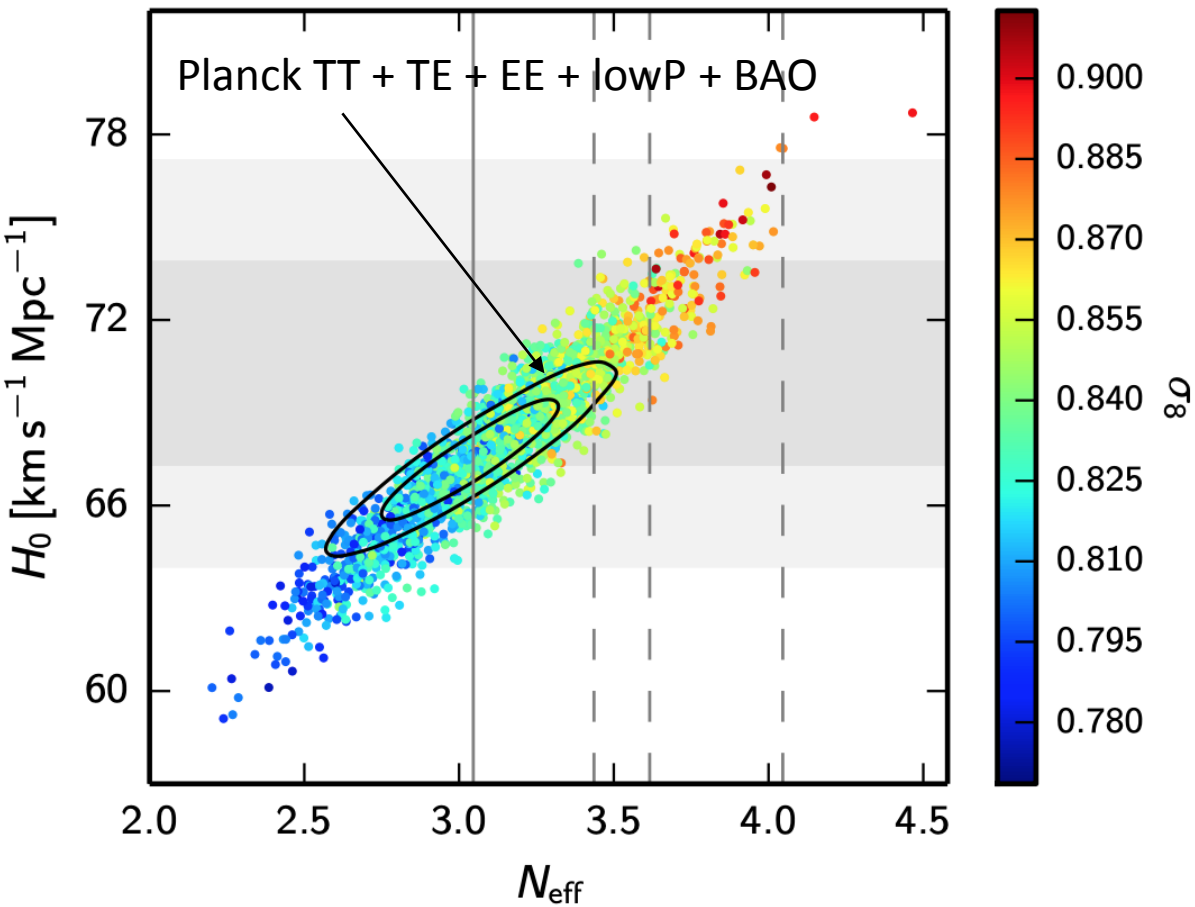


Credit: Lesgourges + Verde 2018

Present Limits on N_{eff}

- Planck 2D constraints on N_{eff} and H_0; both allowed to vary.
- $N_{\mathrm{eff}} > 3$ favors larger H_0, but also higher σ_8.
- Planck+BAO favor ΛCDM values.
- Data don't seem to justify $\Delta N_{\mathrm{eff}} > 0$ at present.

Credit: Planck Collaboration, Ade+ 2016

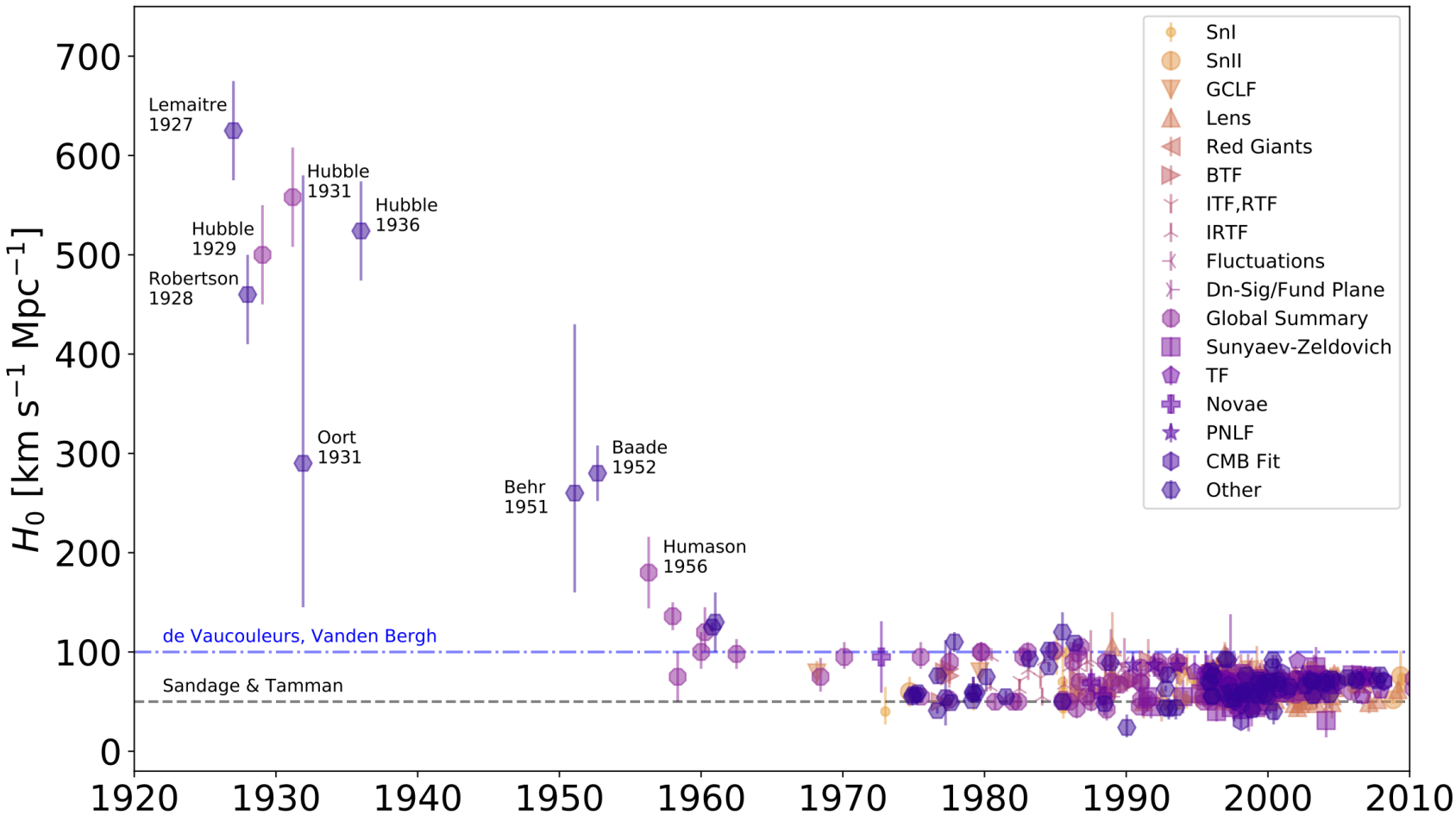


Systematic Errors, or New Physics?

A brief update on the H_0 "crisis"

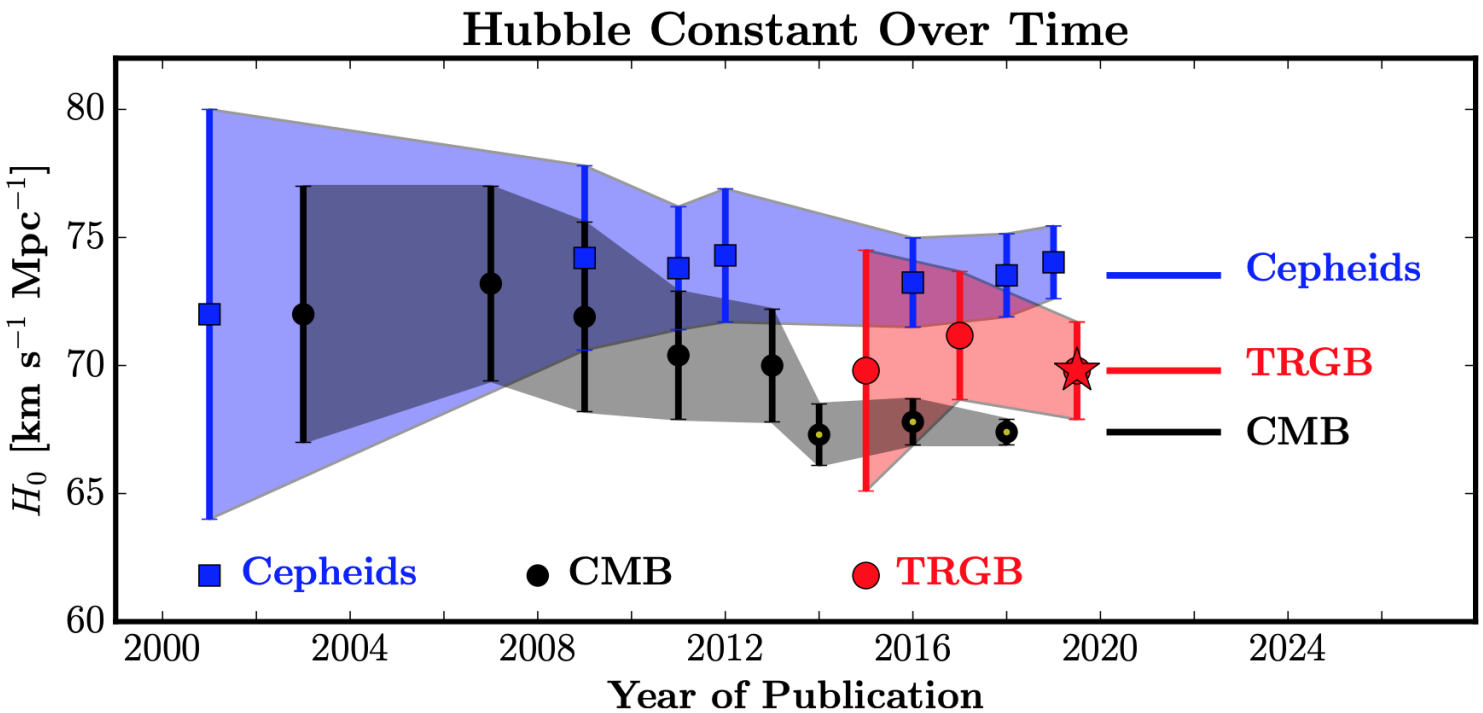
History lesson: measuring distance is hard!

Credit: compilation by J. Huchra (CfA)



Measurement Status of H_0: August 2019

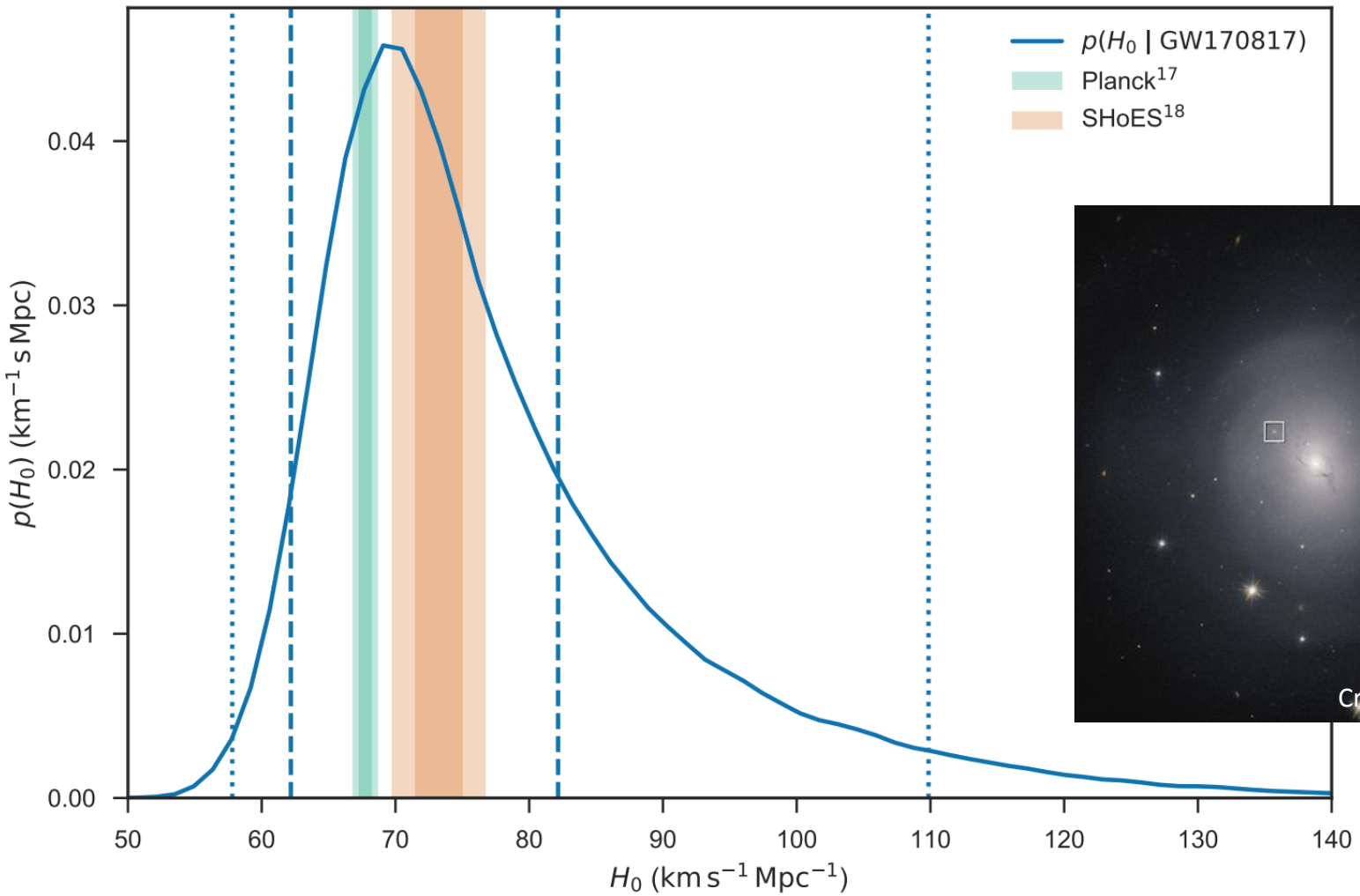
- H_0 from the tip of the Red Giant Branch (TGRB): Freedman+ 2019.

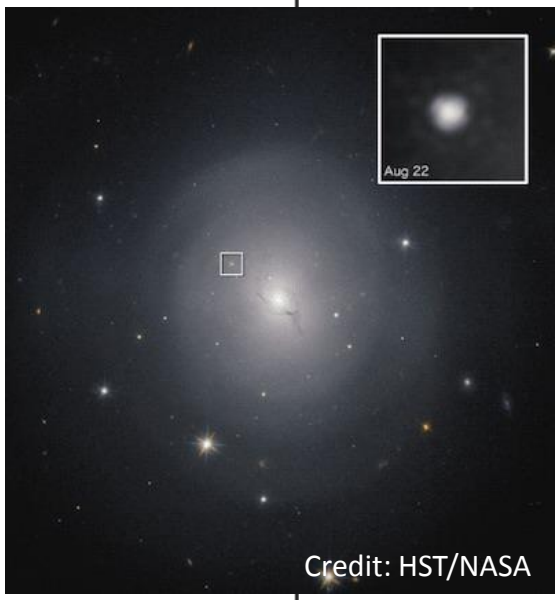


- Discrepancy between H_0 measured by CMB and local distance ladder is inspiring many new techniques with independent systematics.

H_0 from Standard Siren GW170817

Credit: Abbott+ 2017 (LIGO, Virgo, 1M2H, DES, *et al.*)

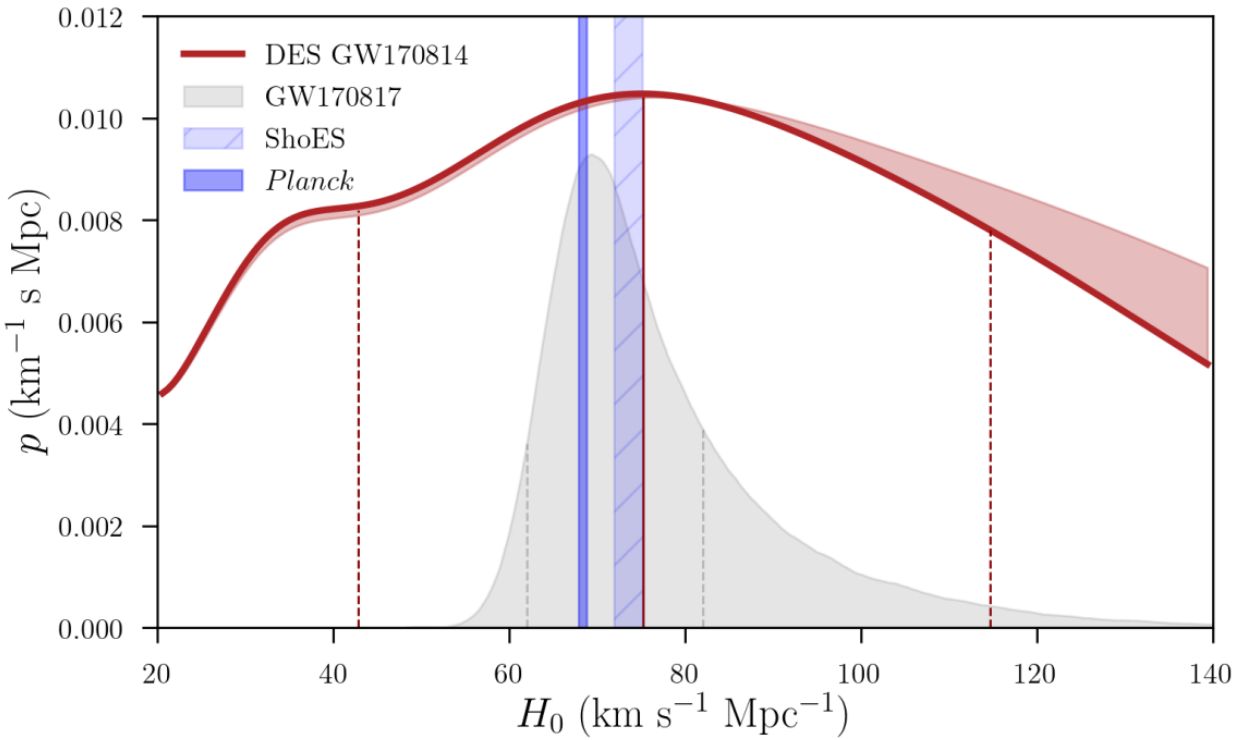




Also: H_0 from **Dark** Sirens

- H_0 from a GW with no optical counterpart ("dark siren").
- Marginalize over all hosts in localized volume around GW event.
- Try to win with statistics: 10x more BBH events than kilonovae!

Credit: Soares-Santos+ 2019 (DES, LIGO-Virgo)



Conclusion

Key Points

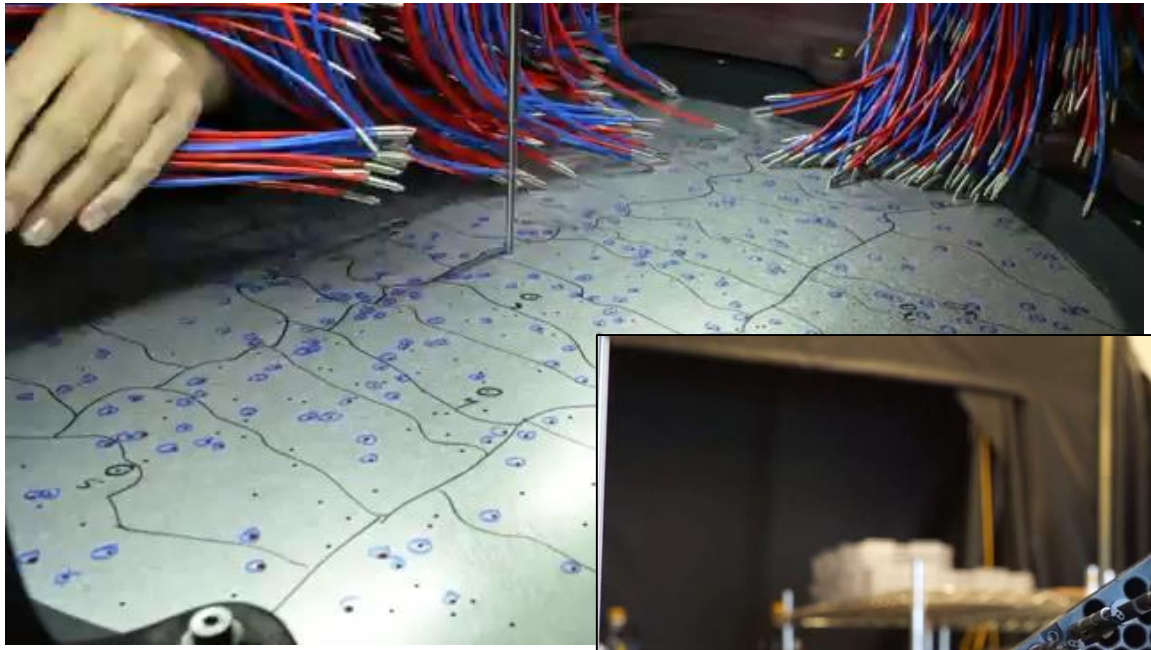
1. Dark energy is measured using the expansion of the universe and the growth of structure. Large-scale structure also provides evidence for dark matter.

2. **All current evidence** for dark energy & dark matter comes from astrophysical datasets.

3. These measurements are sensitive to the properties of elementary particles and other fundamental physics. For dark matter, there is a huge parameter space at small scales that we haven't yet explored.

4. Present data are in broad agreement with ΛCDM. Expect 5x to 10x improved precision by 2025.

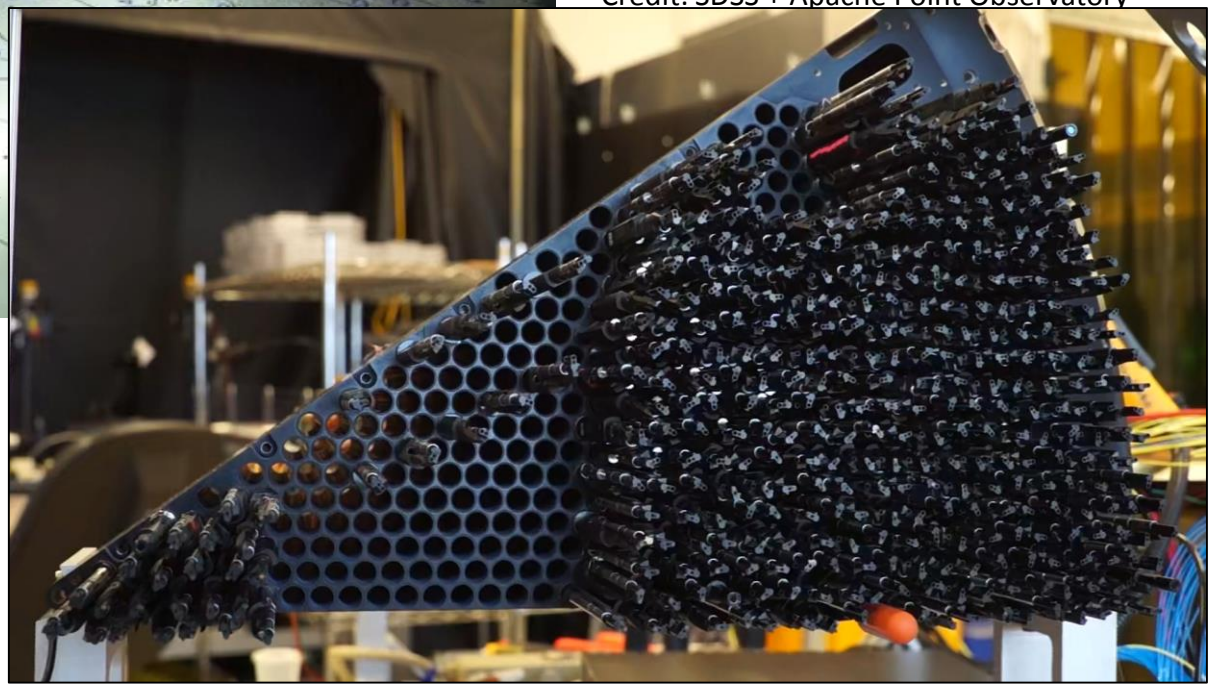
Robotic Multiplexed Spectrographs



BOSS optical fiber plug plate.

640 fibers (1999-2009)
1000 fibers (2009-2018)

Credit: SDSS + Apache Point Observatory

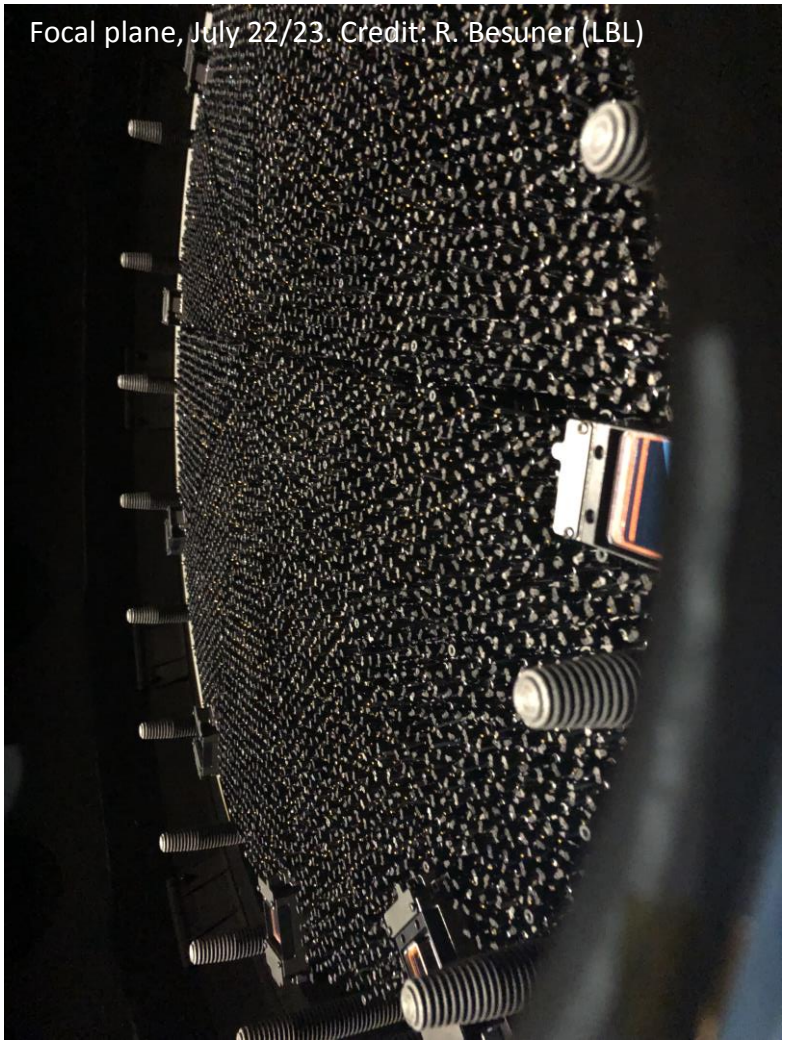


DESI petal with fiber positioners.

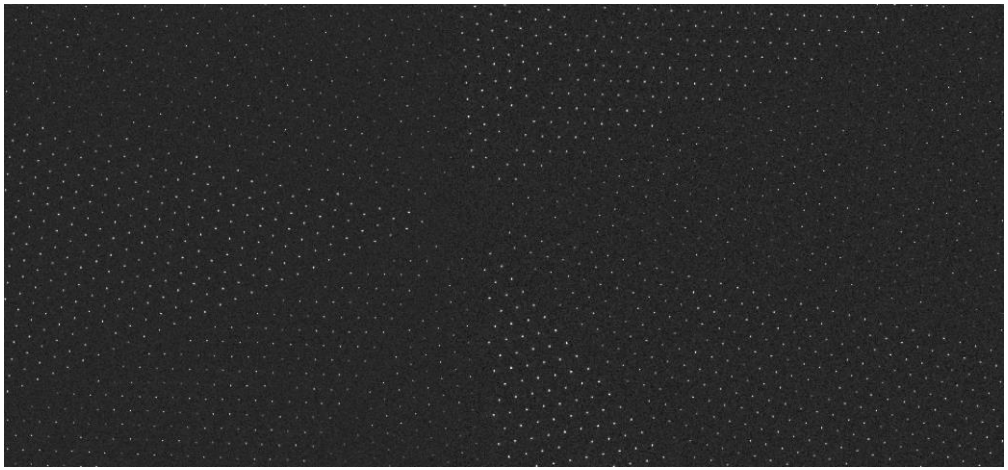
500 fibers × 10 petals,
600,000 components

Credit: DESI/LBL

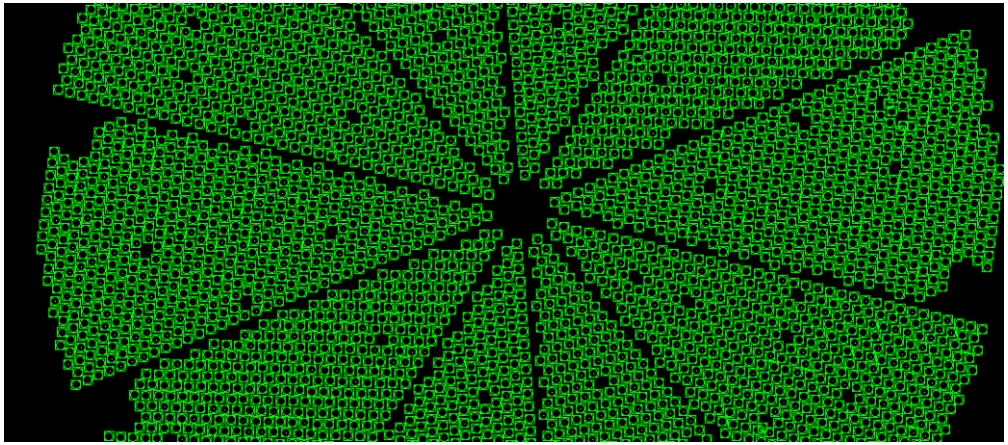
DESI Petal Installation: July 2019


Focal plane, July 22/23. Credit: R. Besuner (LBL)

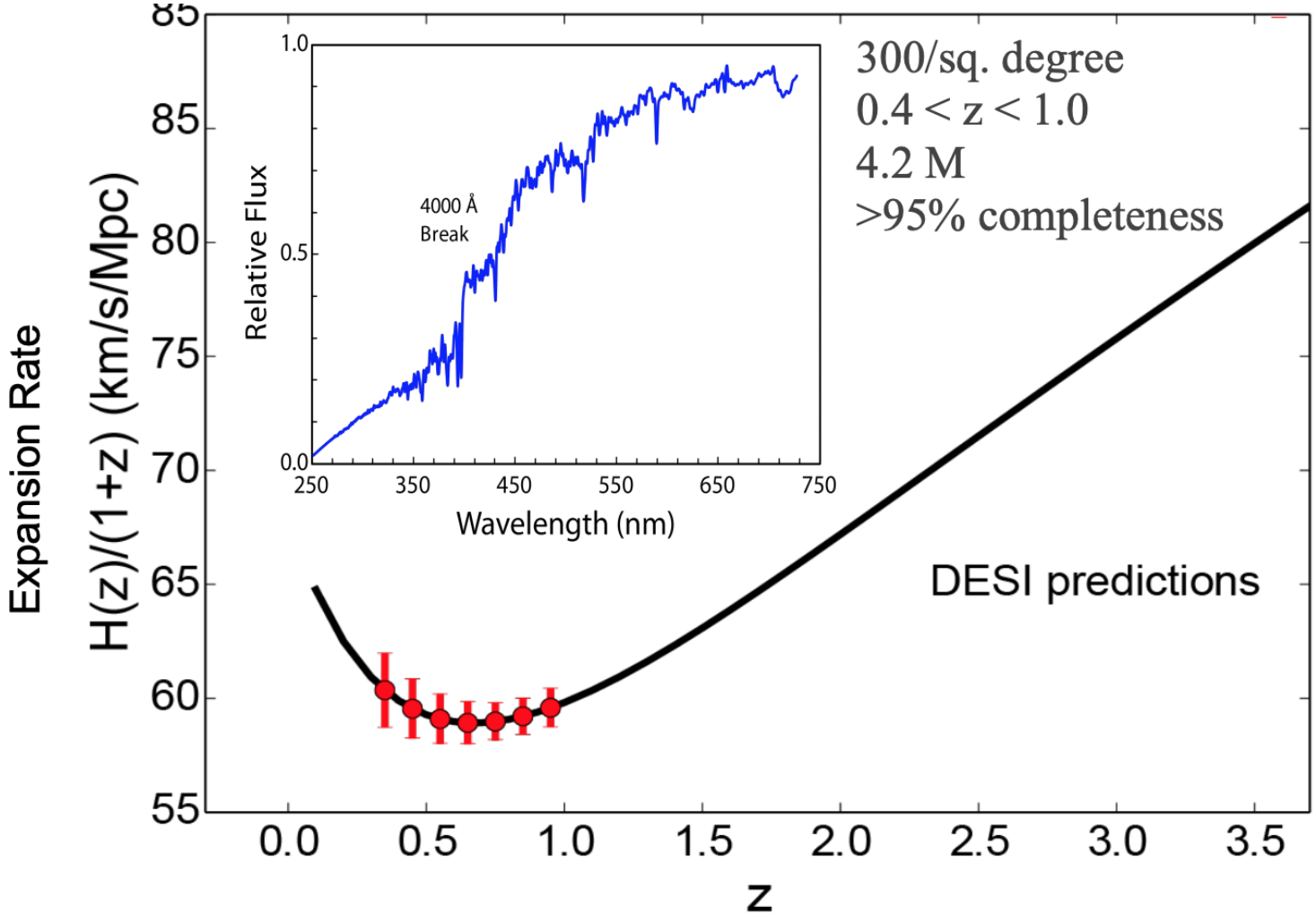
Backlit fibers, July 25/26. Credit: P. Fagrelius (LBL)



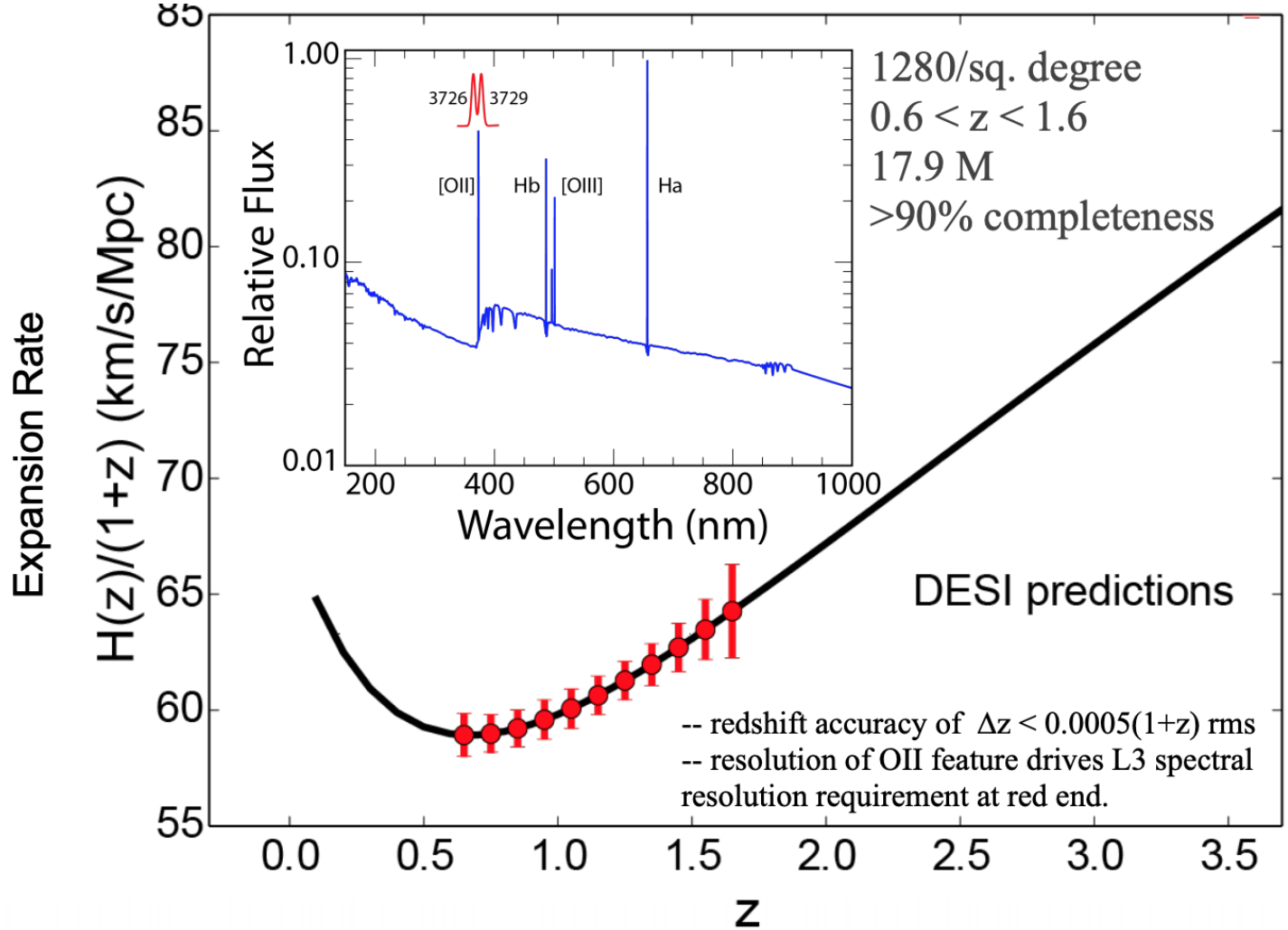
Positions in Fiber View Camera, July 25/26. Credit: P. Fagrelius (LBL)



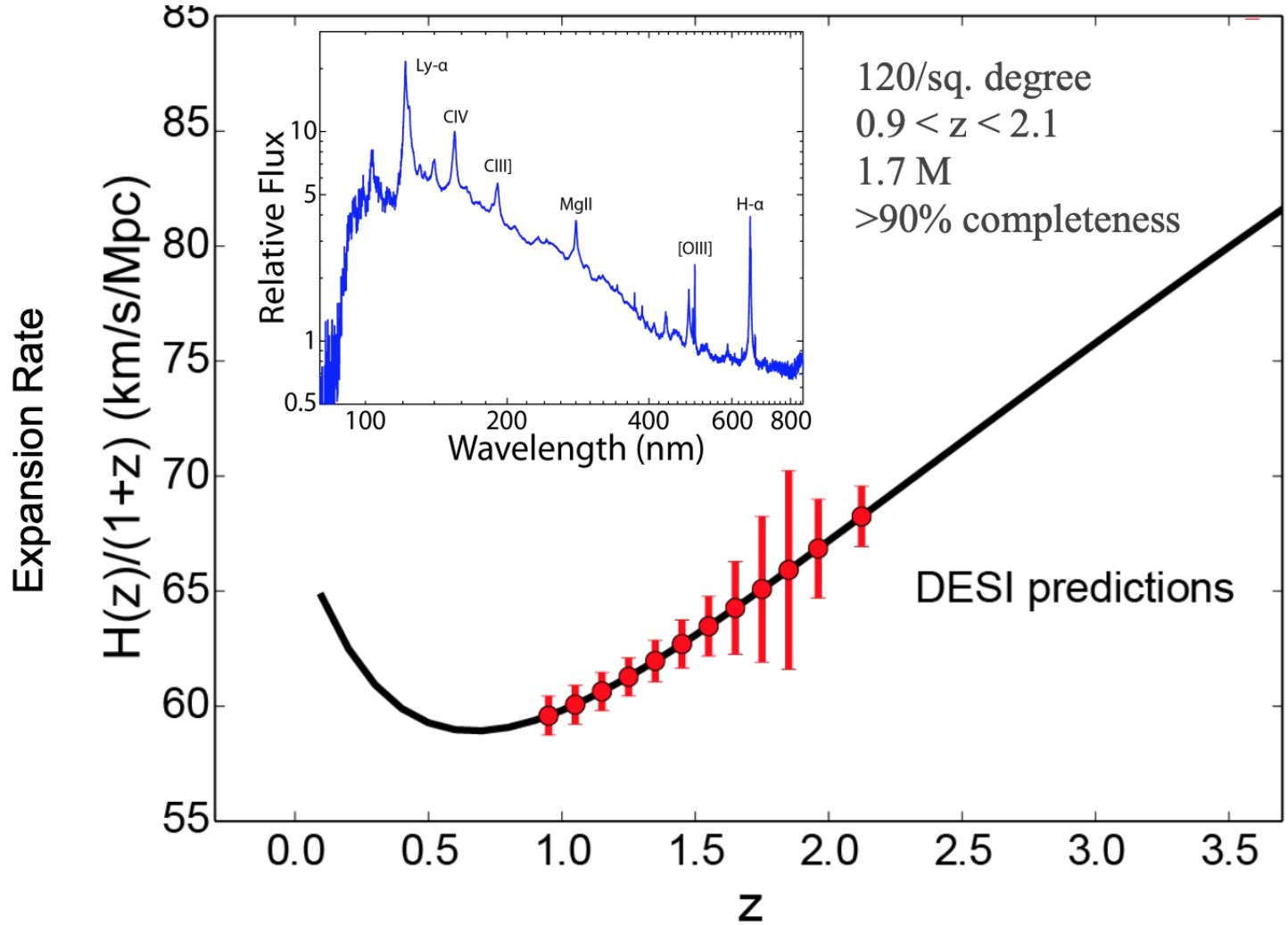
DESI Luminous Red Galaxies (LRGs)



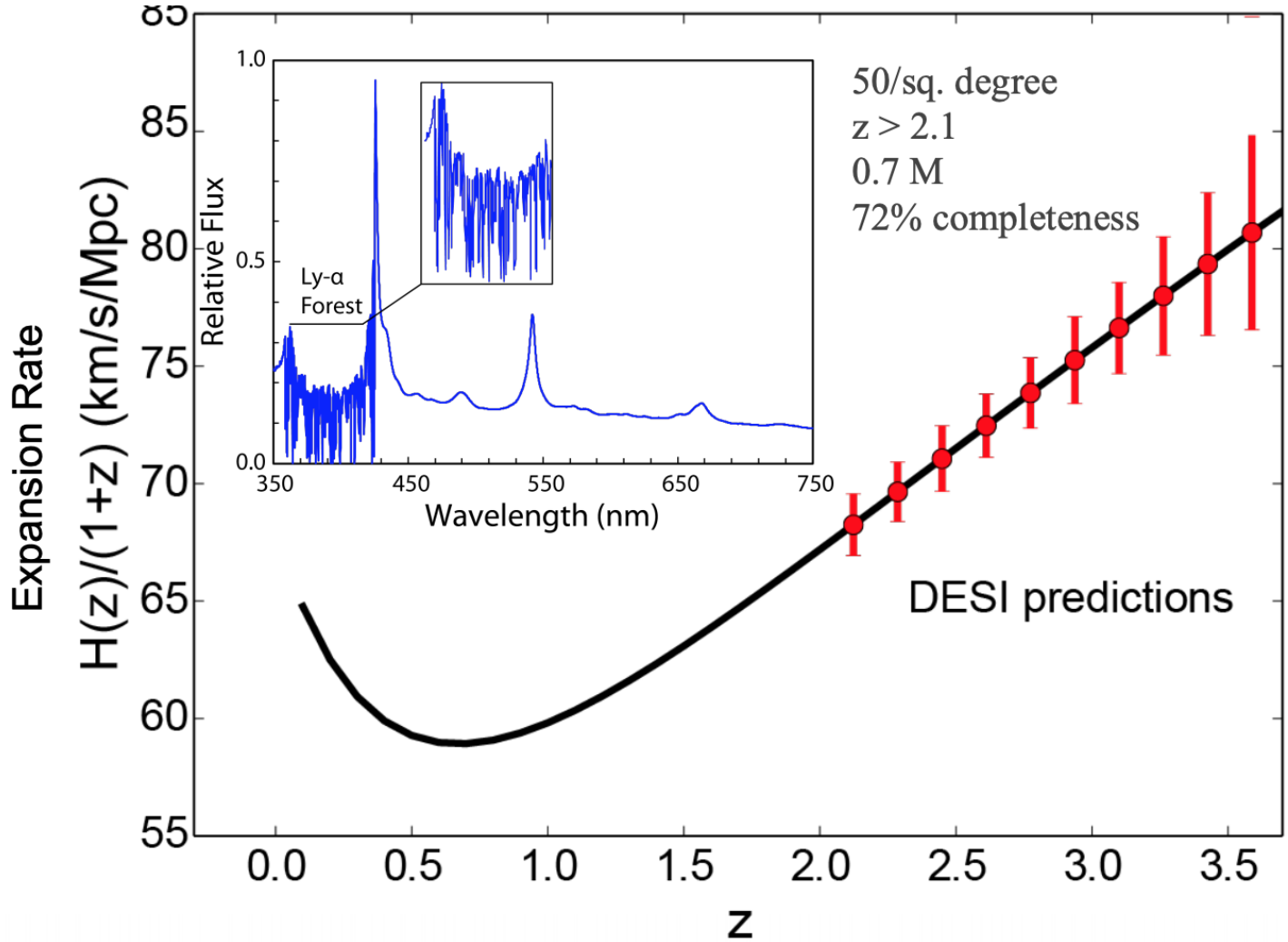
DESI Emission Line Galaxies (ELGs)



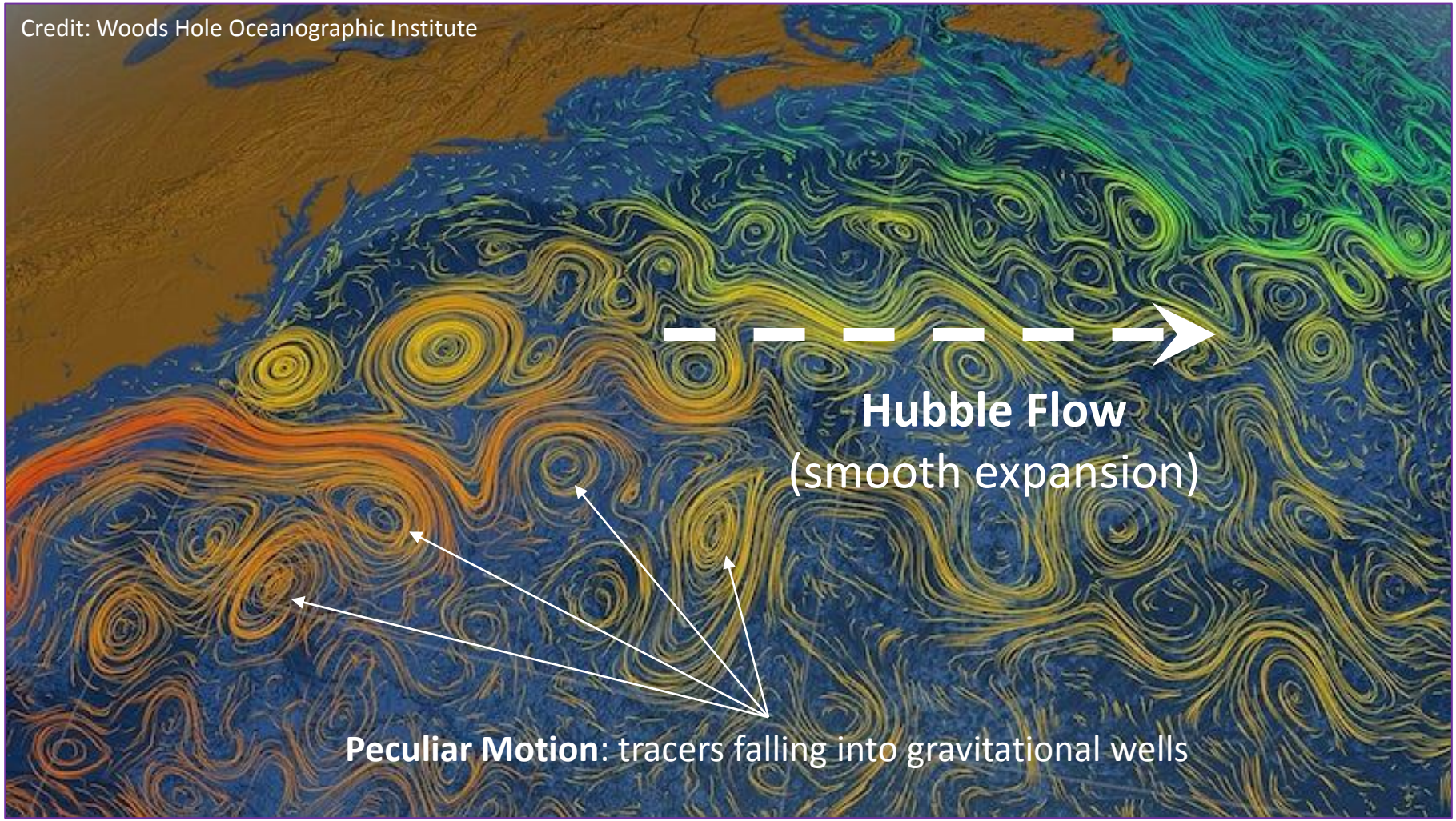
DESI Quasars (QSOs)



DESI Lyman-α Forest Quasars



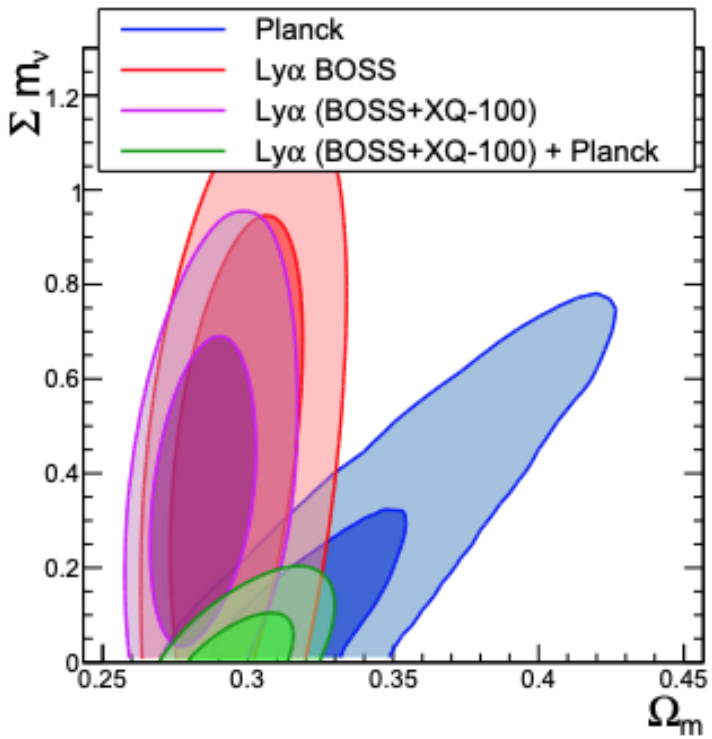
Systematics: Peculiar Velocities (PV)

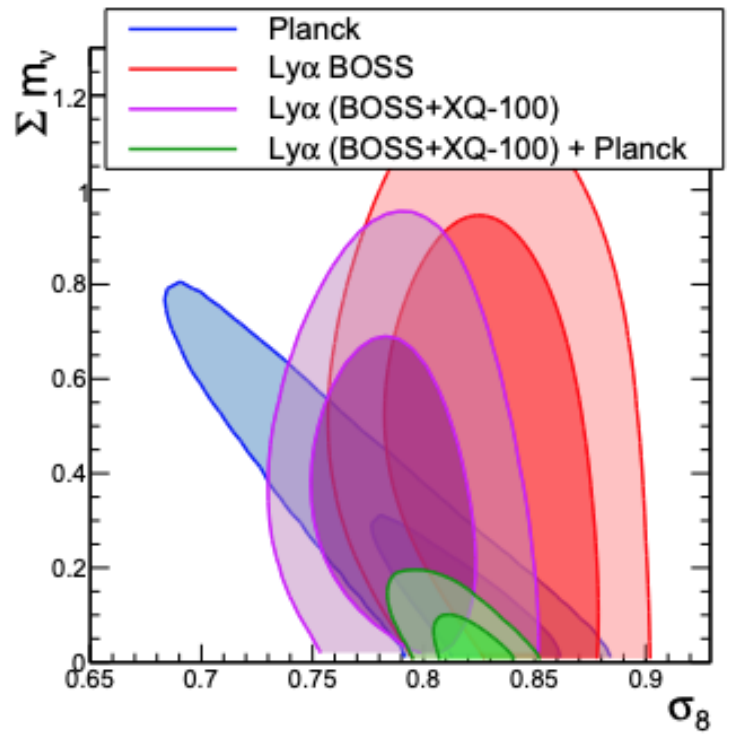


Neutrino Mass Limits: CMB + Ly-α Forest

- Push to k = 0.07 s km^{-1} using BOSS + VLT/XSHOOTER Ly-α spectra + Planck cosmological parameters.
- Ly-α constrains Ω_m and σ_8 independent of Σm_ν; compare to correlations seen in CMB constraints from Planck.

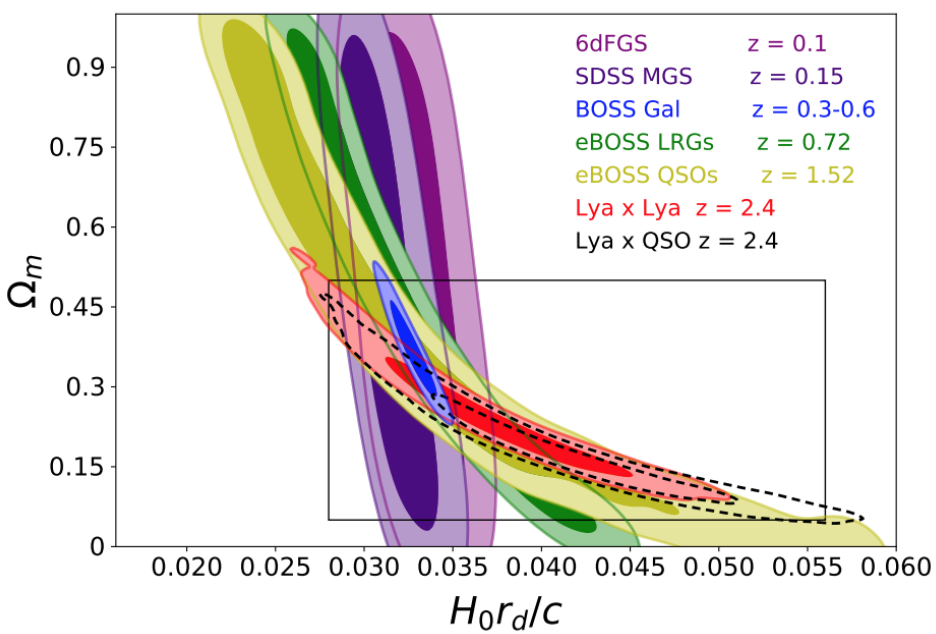
Credit: Yeche+ 2017



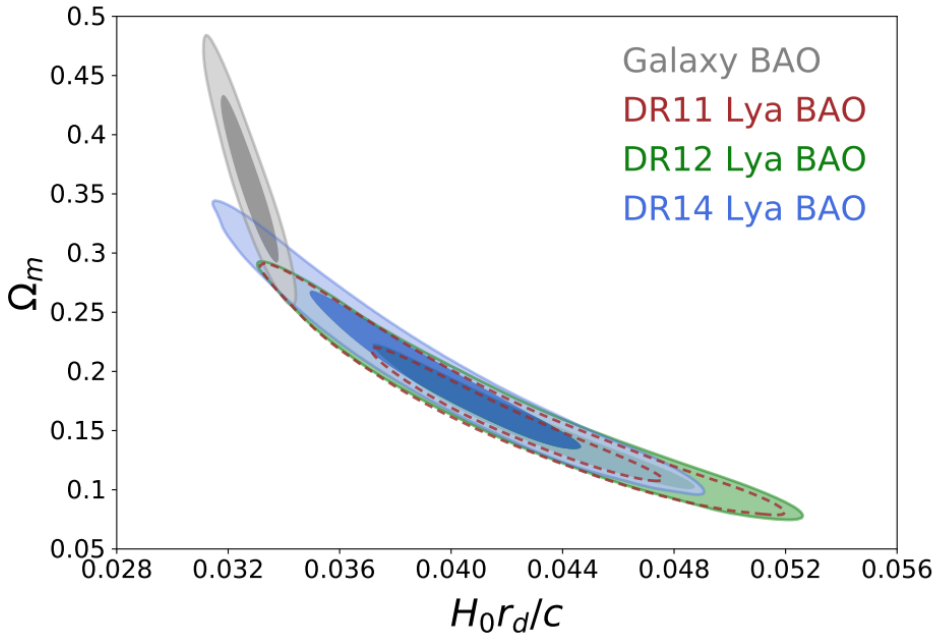


Constraints on H_0 with eBOSS

- Constraints based on redshift slices from eBOSS.
- Each slice probes a slightly different part of the Ω_m-H_0 parameter space.



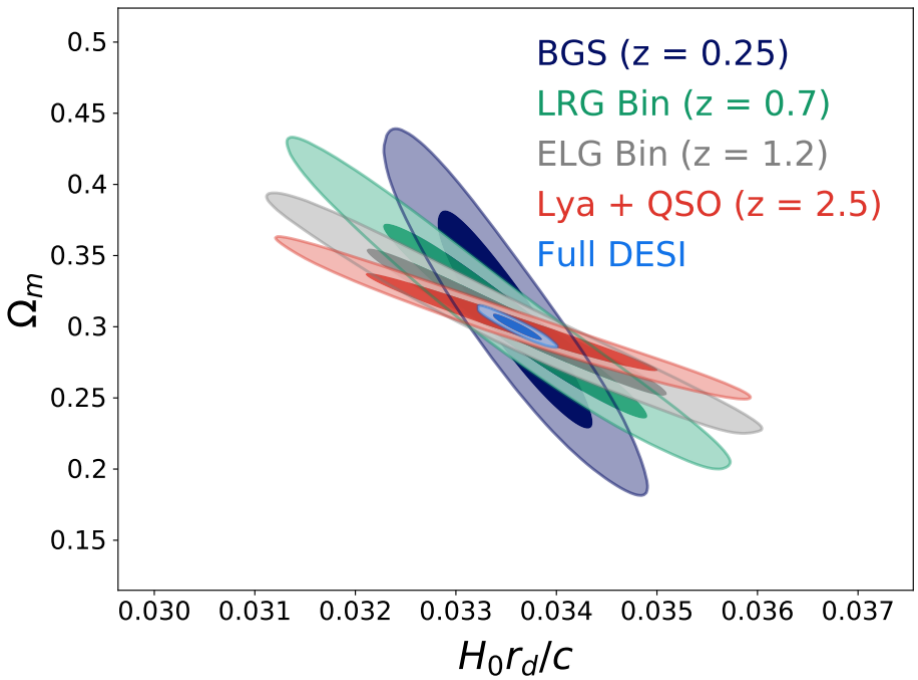
Credit: Cucei+ 2019

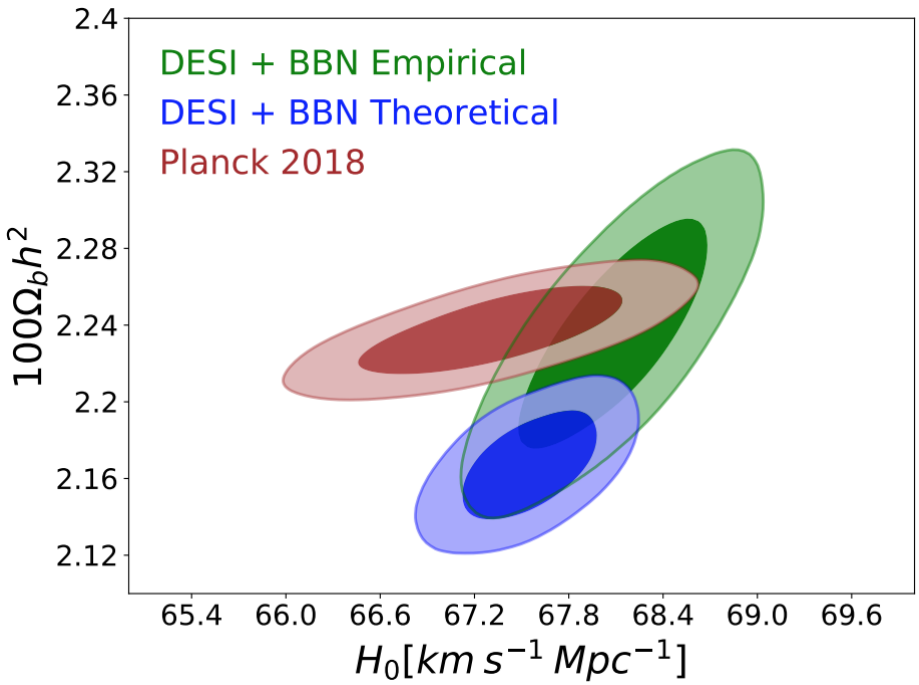


H_0 Sensitivity Forecast for DESI

- Expect much tighter contours in the Ω_m-H_0 plane with DESI due to 10x higher statistics.

Credit: Cucei+ 2019



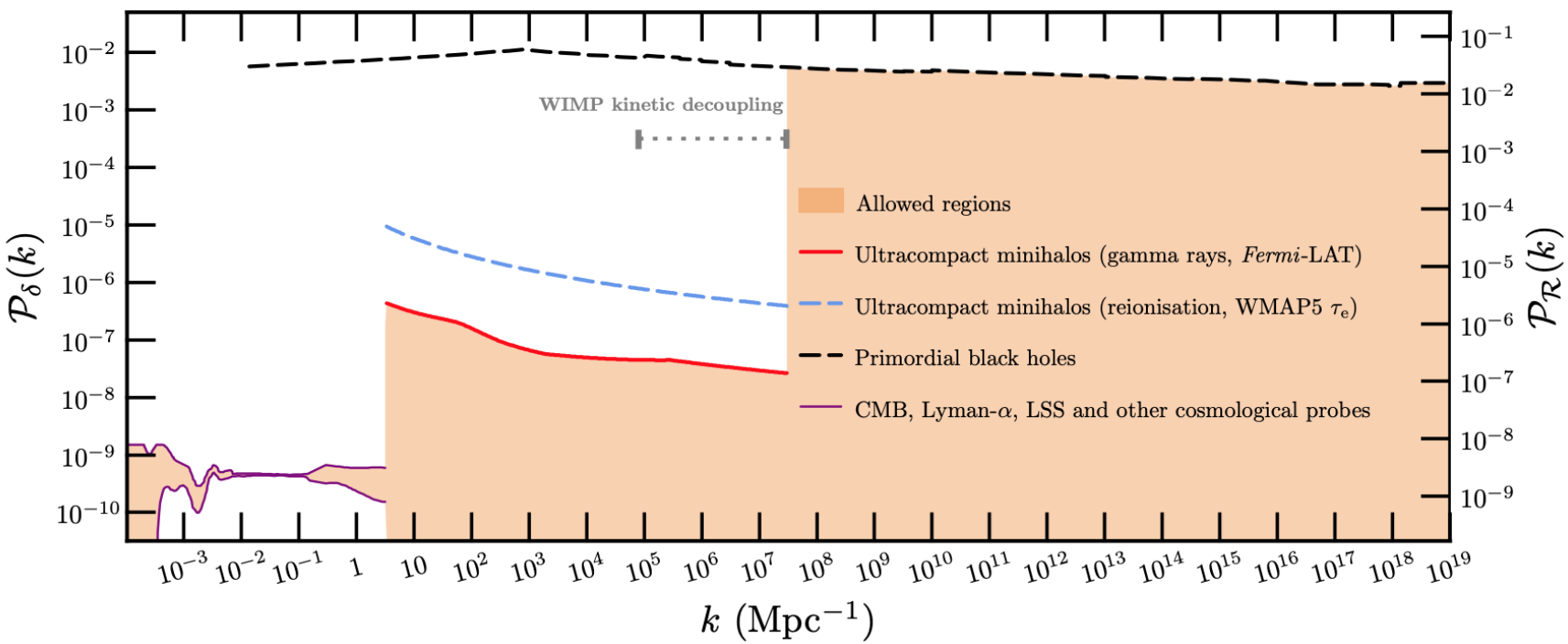


Constraints on Primordial Density Fluctuations

- Constrain primordial density perturbations using multiwavelength data.

- E.g., non-observation of evaporating primordial black holes constrains density perturbations to nearly point-like spatial scales.

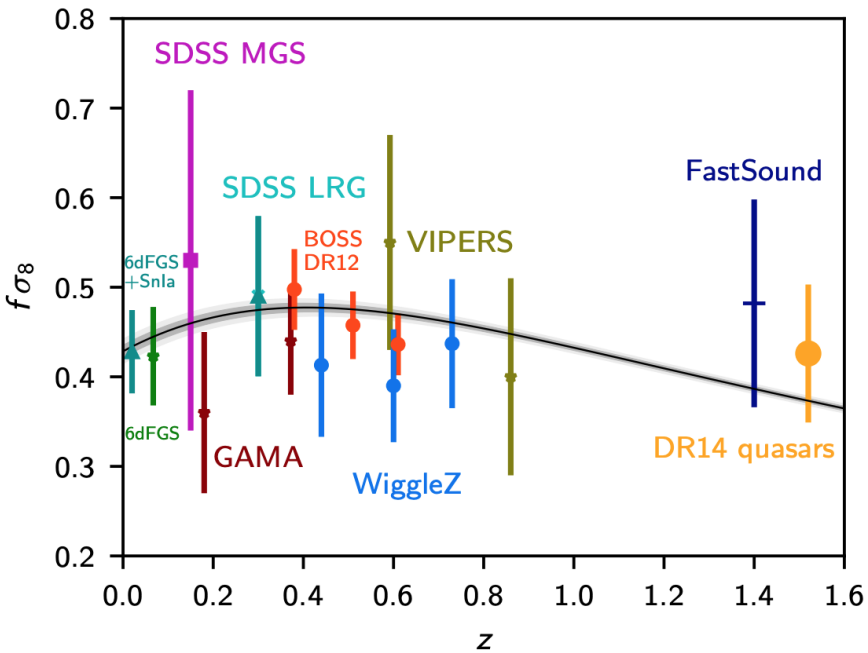
Credit: Bringmann+ 2012 (h/t K. Bechtol)



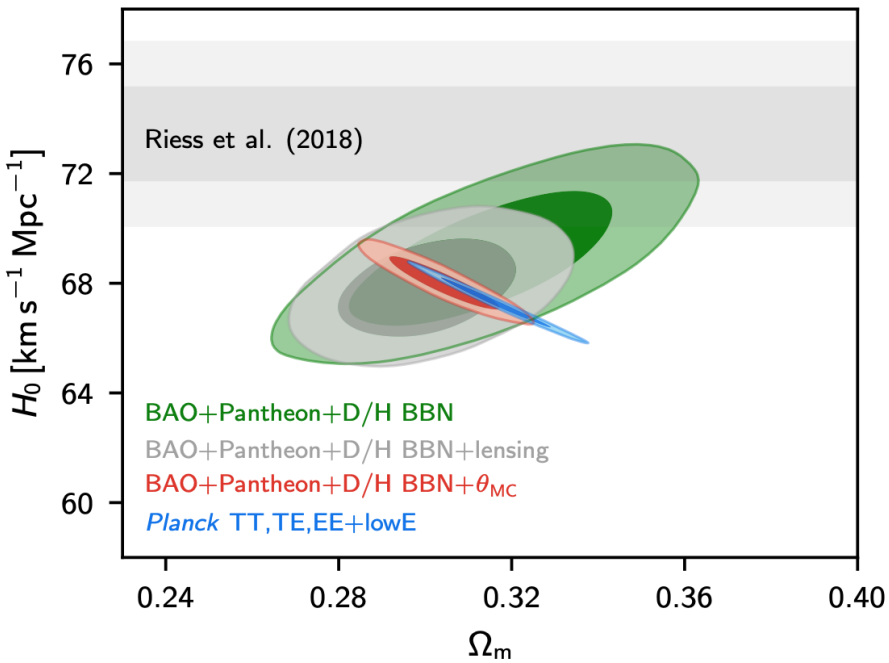
Baryon-Photon Acoustic Oscillations

Performance of ΛCDM

- Current measures of the growth of structure ($f\sigma_8$) are also still consistent with ΛCDM.
- But measurements of H_0, the expansion rate today, disagreed at >3σ in 2018; the difference today is 4.4σ (Riess+ 2019).

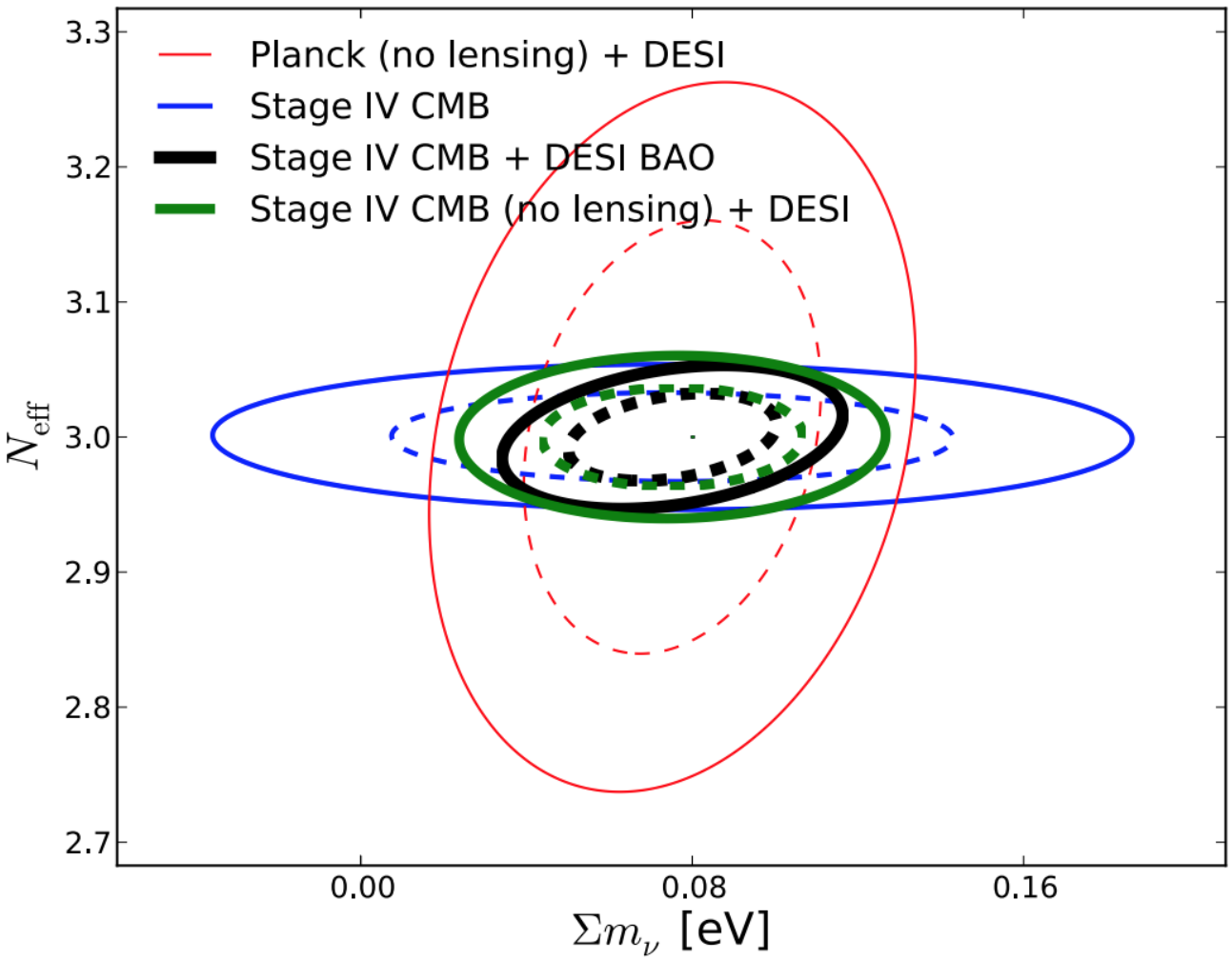


Credit: Planck 2018 results: I. Overview



Projected Sensitivity to N_{eff}

Credit: Abazajian+ 2013 (Snowmass Dark Energy + CMB WG)



H_0 from Gravitational Wave Events: Help from Spectroscopic Surveys

- Measure H_0 with sirens at $z < 0.1$: here the Hubble Law is independent of cosmology ($cz = H_0 d$).
- At low z the error $\delta z/z$ due to peculiar velocities is significant.
- **DESI**: map local peculiar velocity field with 10M bright galaxies!

Credit: after Mortlock+ 2018, Palmese + Graur 2019