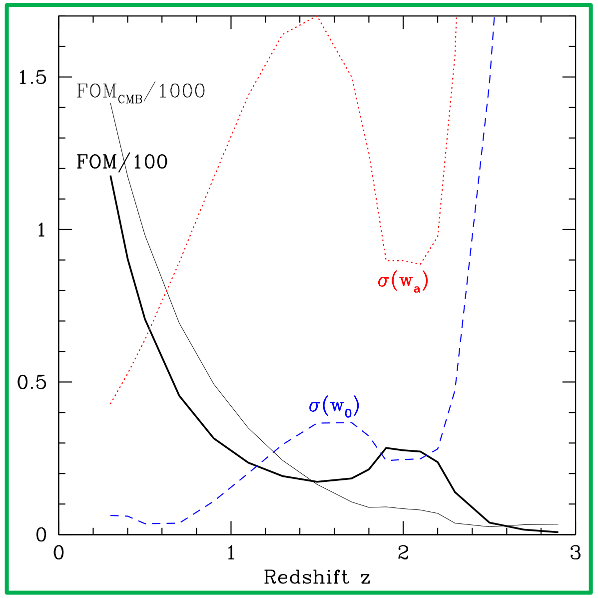
The Future of Dark Energy

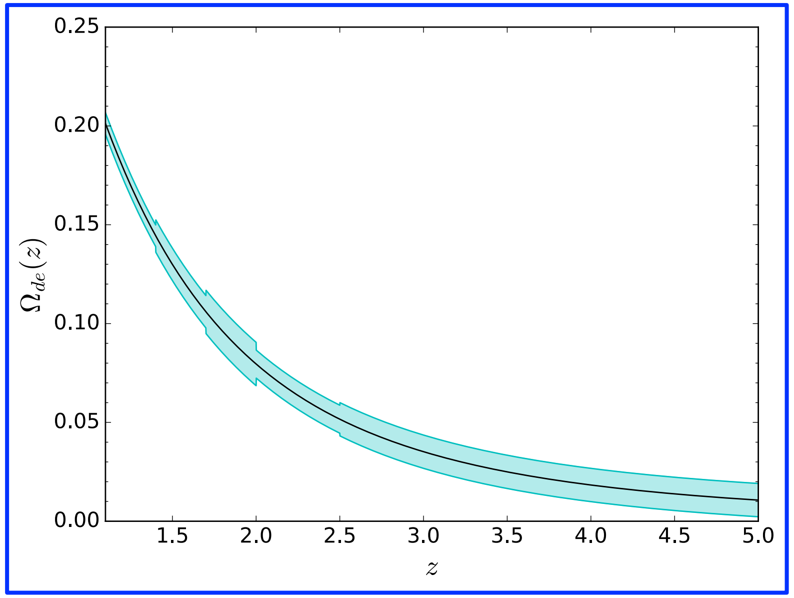
Eric Linder

UC Berkeley

PONT Avignon

4 May 2023





Dark Energy's Future

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Will DE stay just as it is (Λ)?

Will DE approach de Sitter ($w \to -1$)?

Will DE lead to cosmic doomsday ($\rho_{DE} < 0$)?

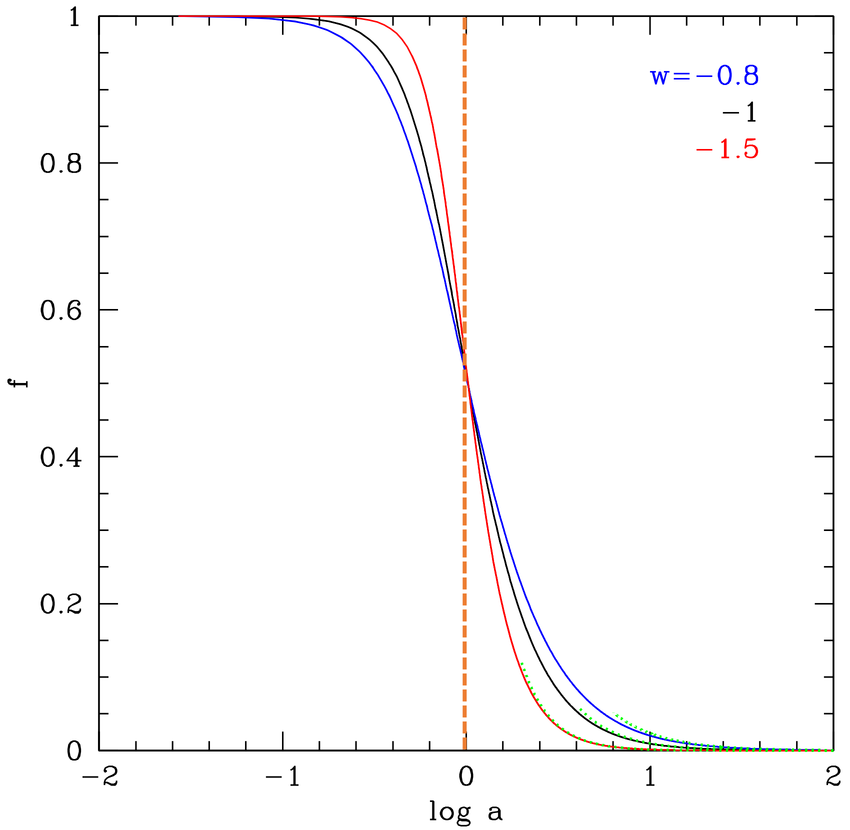
Will DE vanish ($\rho_{DE} \to 0$)?

- **Asymptotic minimum of potential?**
- **Oscillate around minimum (w diverges from -1)?**

The End of Cosmic Growth

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

We live in a special time for cosmic growth.
We can detect its suppression, but growth is continuing.
This won't happen forever!



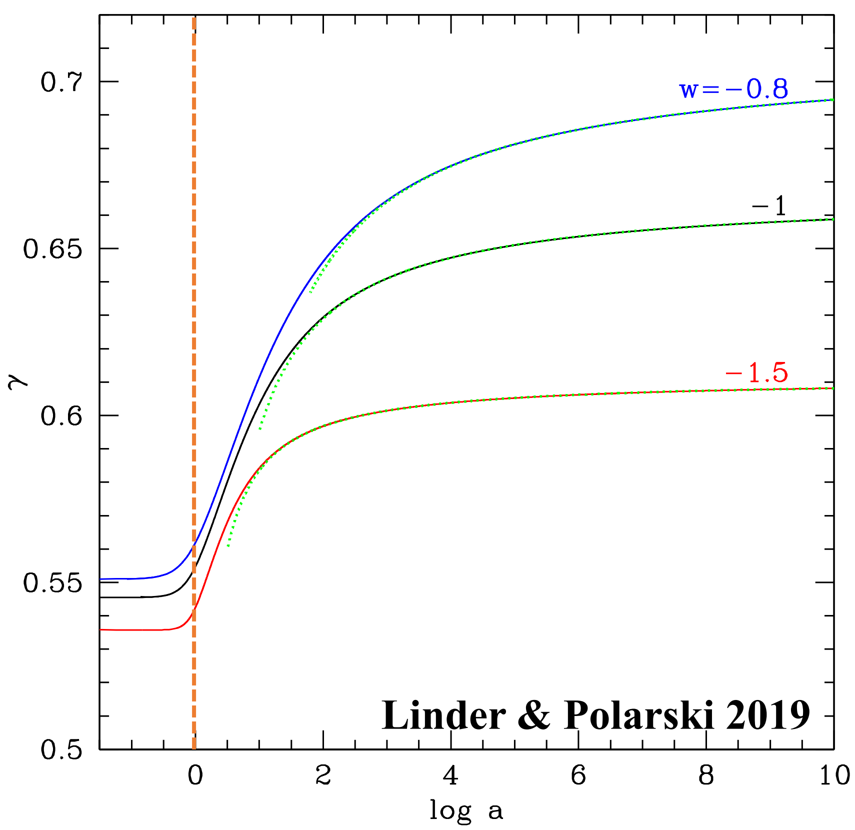
Growth rate f

$$f = \frac{dD}{d\ln a} \sim a^{-(1-3w)/2}$$

$$f \approx \Omega_m(a)^\gamma \Rightarrow \gamma \equiv \frac{d\ln f}{d\ln \Omega_m(a)}$$

$$\gamma(a\to\infty) \approx \frac{3w-1}{6w}$$

e.g. in ΛCDM, $f{\sim}a^{-2}$, γ_∞=2/3



The Future of (Our Learning about) Dark Energy

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

How do we answer the questions about dark energy's future?
(assuming we don't want to wait a Hubble time or two)

Let's rephrase the questions to make them more definite for comparison to observations (phenomenology).

- **Dynamics**
- **The Long Past**
- **Growth**

Dynamics of Dark Energy

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Cosmic acceleration needs DE equation of state $w=P/\rho < -1/3$.

The only "natural" constant w values are -1 (Λ), -2/3 (domain walls).
Observations clearly rule out w=-2/3 at $>5\sigma$: success!

We need w(a). Fortunately, $w(a)=w_0+w_a(1-a)$ is accurate to ~0.1% on observables (d,D). **[Full EOM physics, not Taylor expansion!]**

Natural values of $\dot{w}$ are 0 or 1/H, i.e. $w' \sim 1 \sim w_a$.
Seek 5σ distinction, so seek $\sigma(w_a)\sim 0.2$.

Thawing vs Freezing

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

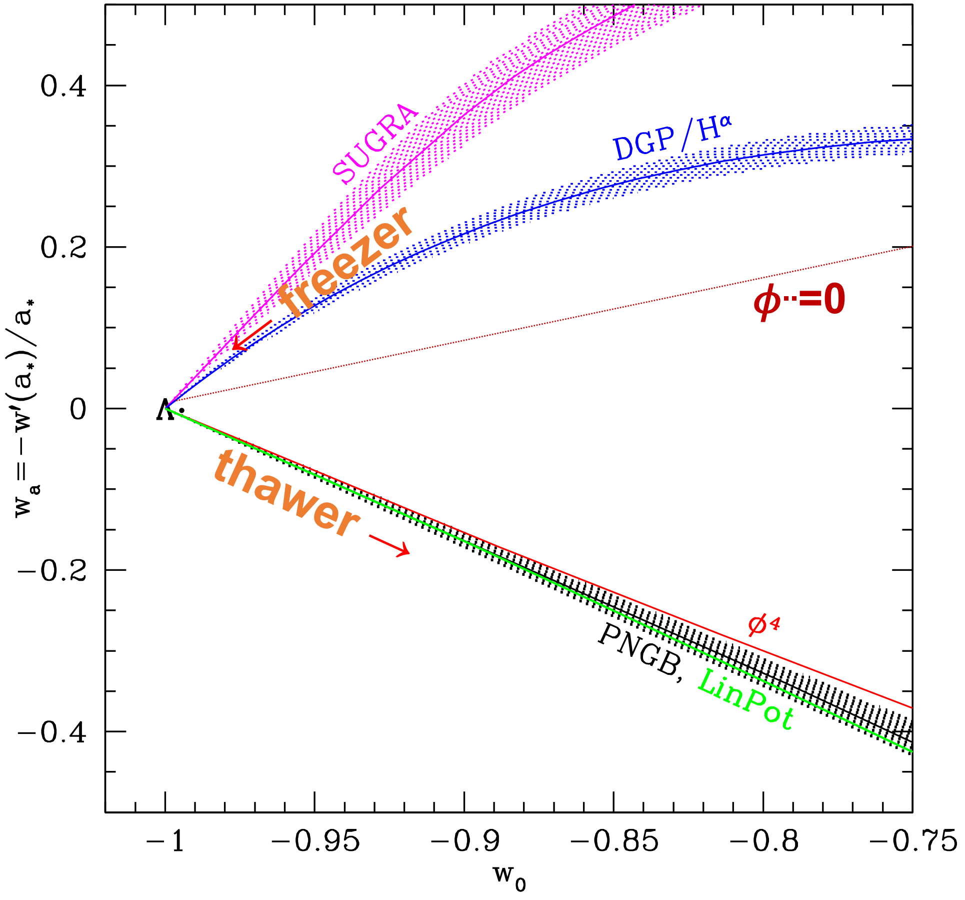
Two broad classes of dynamics: evolving away from Λ (thawing), or evolving toward Λ (freezing).

Well separated in w_0-w_a.

Valley in between "unnatural" because would fine tune to $\ddot{\phi}=0$.

Distinction if $\sigma(w_a)< 2.5\times\sigma(w_0)$.
Thus want $\sigma(w_0)\sim0.08$, $\sigma(w_a)<0.2$.

Stage 4 Dark Energy experiments!



Stage 5 Dark Energy Goals

5σ distinction on w_a between 0 and 1 is "modest". Let's aim high.

CMB experiments aim for 5σ on Starobinsky inflation. This is an α-attractor model that can connect to late time DE (e.g. Akrami+ 2018).

$$r_{GW} = 12\alpha/N^2 \quad , \quad w_{future} = -1 + 2/(9\alpha)$$

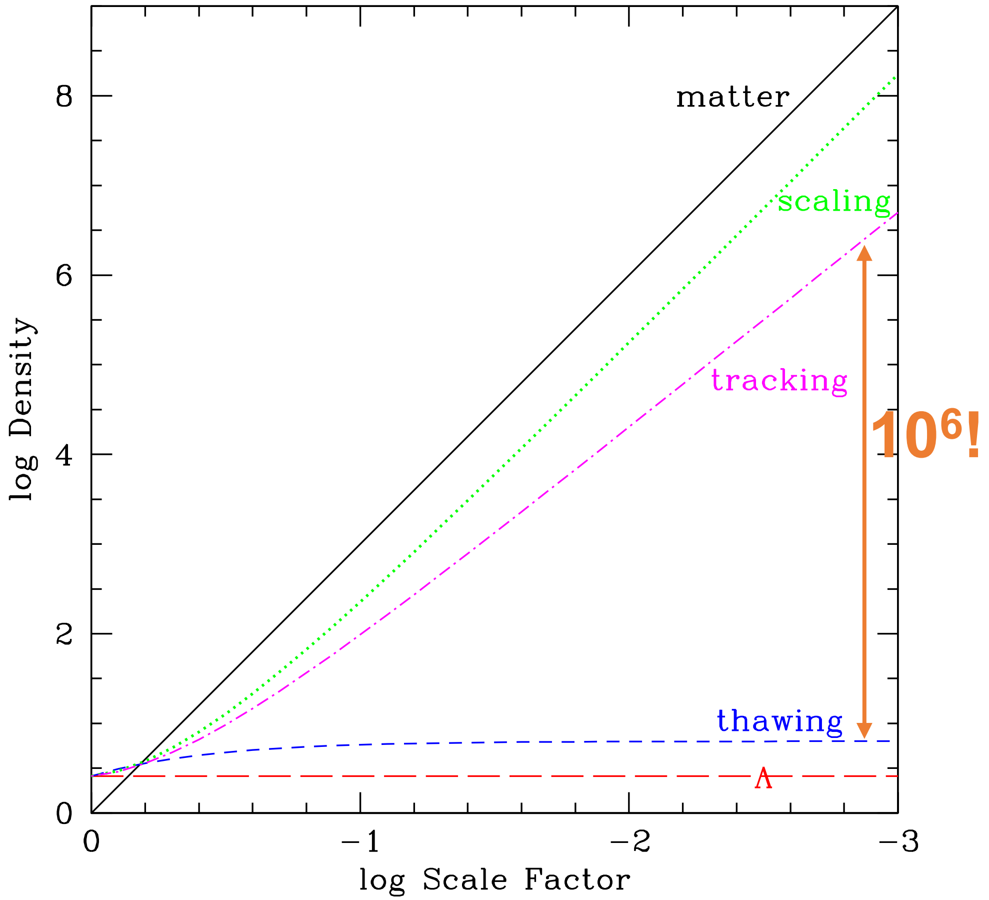
To match 5σ CMB constraint, seek $\sigma(w_0)=0.02$.

So Stage 5 Dark Energy goal:

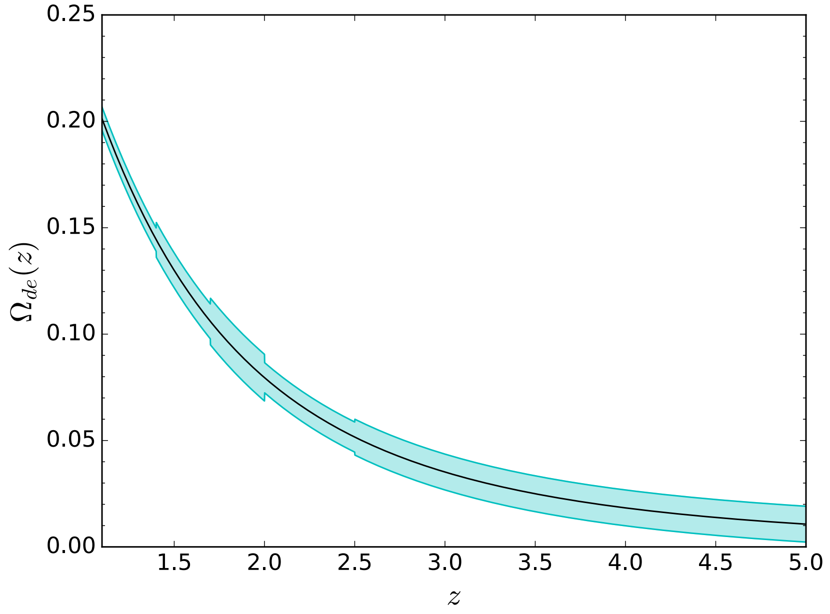
$$\sigma(w_0)=0.02 \ , \ \sigma(w_a)=0.05$$

The Long Past

ρ_{DE} can vary by >10^6 between Λ and current limits at recombination.
Seek to map it out to z~5 (Stage 5).



Even Λ has Ω_{DE}=8% (1%) at z=2 (5).



Density Benchmark:

$$\sigma\left(\frac{\rho_{\rm de}}{\rho_{\rm crit}}\right) \equiv \sigma(\Omega_{\rm de}(z)) < \frac{1}{3}\,\Omega_\Lambda(z)\,,\text{for } z<5$$

Cosmic Growth

Gravitational growth index γ accurate to 0.2% on observables.
(in linear, subhorizon, scale independent regime)

Distinguishes mod-GR where growth not governed purely by expansion. 5σ distinction of f(R) growth at z=1 from GR: $\sigma(\gamma)$~0.013.

Seek scale dependence, light propagation: $G_{matter}(a,k)$, $G_{light}(a,k)$.
Model independent approach in 3x2 bins.

$$\sigma(G_{\mathrm{matter,low}\ k,\mathrm{high}\ a}) < 0.02$$
$$\sigma(G_{\mathrm{matter,high}\ k,\mathrm{high}\ a}) < 0.05$$

k_{low}~0.055, k_{high}~0.125, a_{high}~0.75

For full nonlinearity, choose full theory (two, different screenings?).

Stage 4 Experiments will Advance

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Rubin Observatory Legacy Survey of Space and Time (LSST)

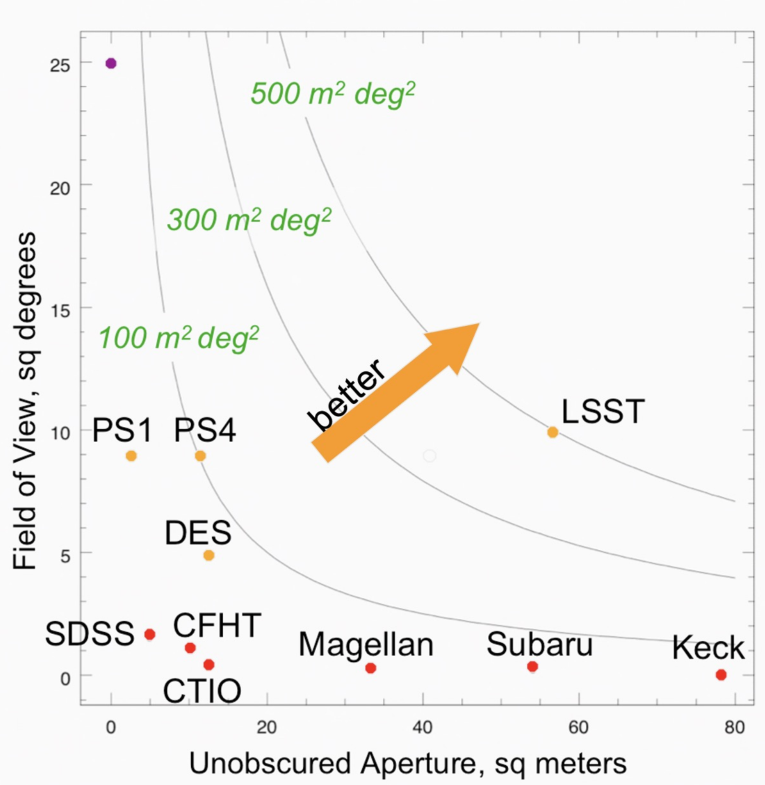
Imaging, Time Domain (Clustering, Lensing, Supernovae) ~2024-2034

DESC Primary Science Goals

LSST DESC Dark Energy Science Collaboration

LSST DESC is planning to carry out full cosmology analyses (dark energy, dark matter, neutrinos, inflation, …)

- Goal #1: Cosmological constraints from Rubin-only data from shear and clustering (3x2pt), clusters of galaxies and supernovae
- Goal #2: Consistency checks between different Rubin DESC probes
- Goal #3: Cosmological constraints and tensions from Rubin + External Data Sets
- Goal #4: Be prepared for serendipity
- Goal #5: Assess possibly needed changes in observing strategy, processing for upcoming data releases in the earlier years



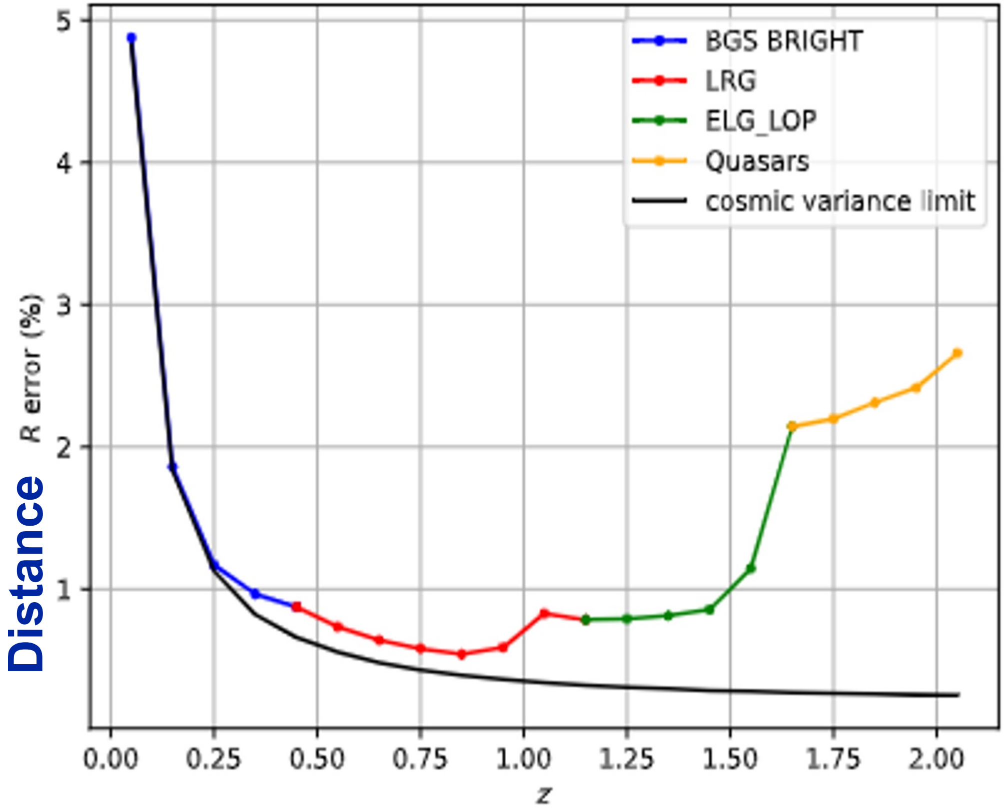
Stubbs at P5

Dark Energy Spectroscopic Instrument

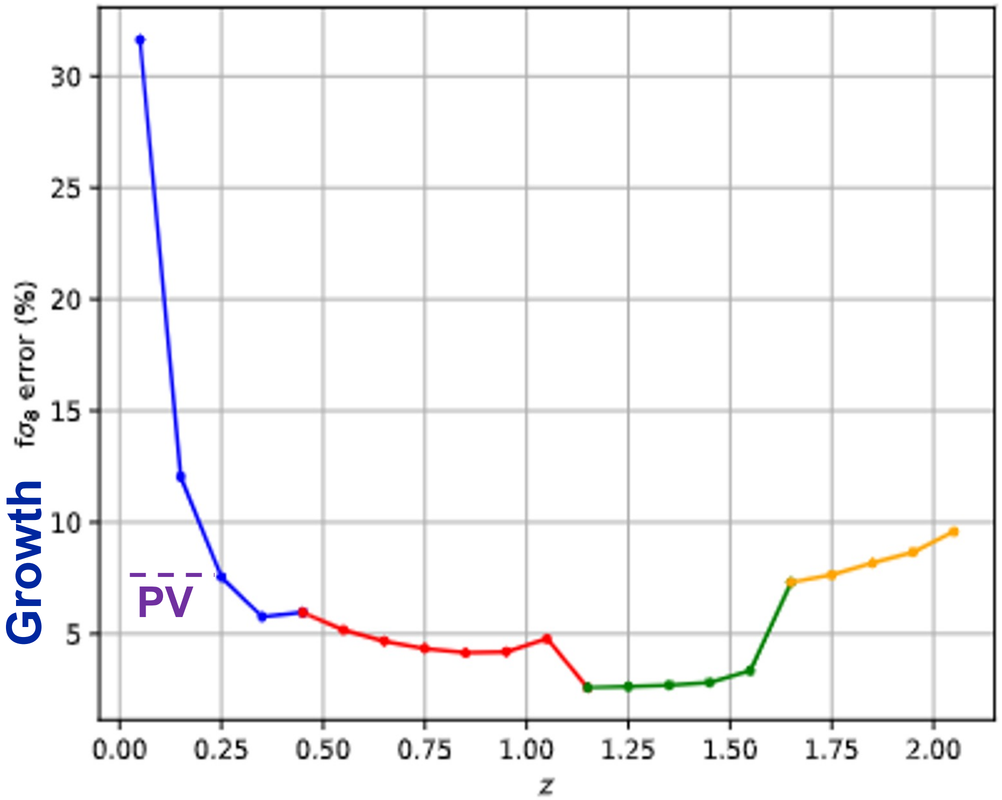
BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Stage 4 survey operating (2021-2026). Early Data Release imminent.

Baryon Acoustic Oscillations



Redshift Space Distortions

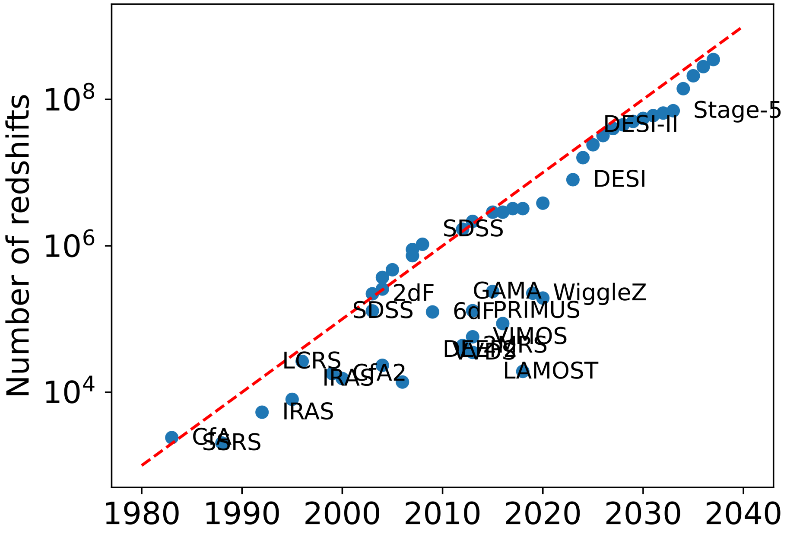


Dawson at P5

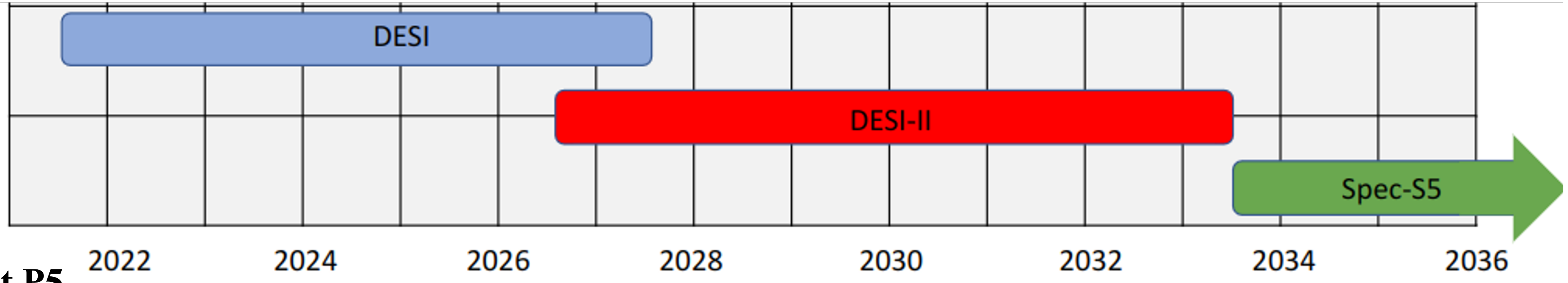
DARK ENERGY SPECTROSCOPIC INSTRUMENT
U.S. Department of Energy Office of Science

Staging Spectroscopic Surveys

- **Dark Energy Spectroscopic Instrument (DESI; primarily z<1.5)**
  - Baryon Acoustic Oscillations (BAO) and Redshift Space Distortions (RSD)
- **DESI-II (primarily z>2)**
  - As powerful as DESI, but at z>2
  - Early dark energy and growth of structure in matter-dominated regime
  - Synergies with other Cosmic Frontier experiments
- **Spec-S5**
  - Primordial physics (more constraining than the CMB in key areas)



Schlegel at P5



Dawson at P5

Achieving Stage 5 Goals

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Advances from Rubin-SpecS5-CMB synergies. Powerful, but want more!

Redshift Drift (seeing the universe expand in real time: dz/dt_0) known 60 years ago, but is very very challenging.

Direct, kinematic probe of acceleration. Just like redshift, don't need to know matter density or forces.

$$\frac{dz}{dt_0} = \frac{d}{dt_0}\left[\frac{a(t_0)}{a(t_e)} - 1\right] = \frac{\dot{a}(t_0) - \dot{a}(t_e)}{a(t_e)} = (1+z)\,H_0 - H(z)$$

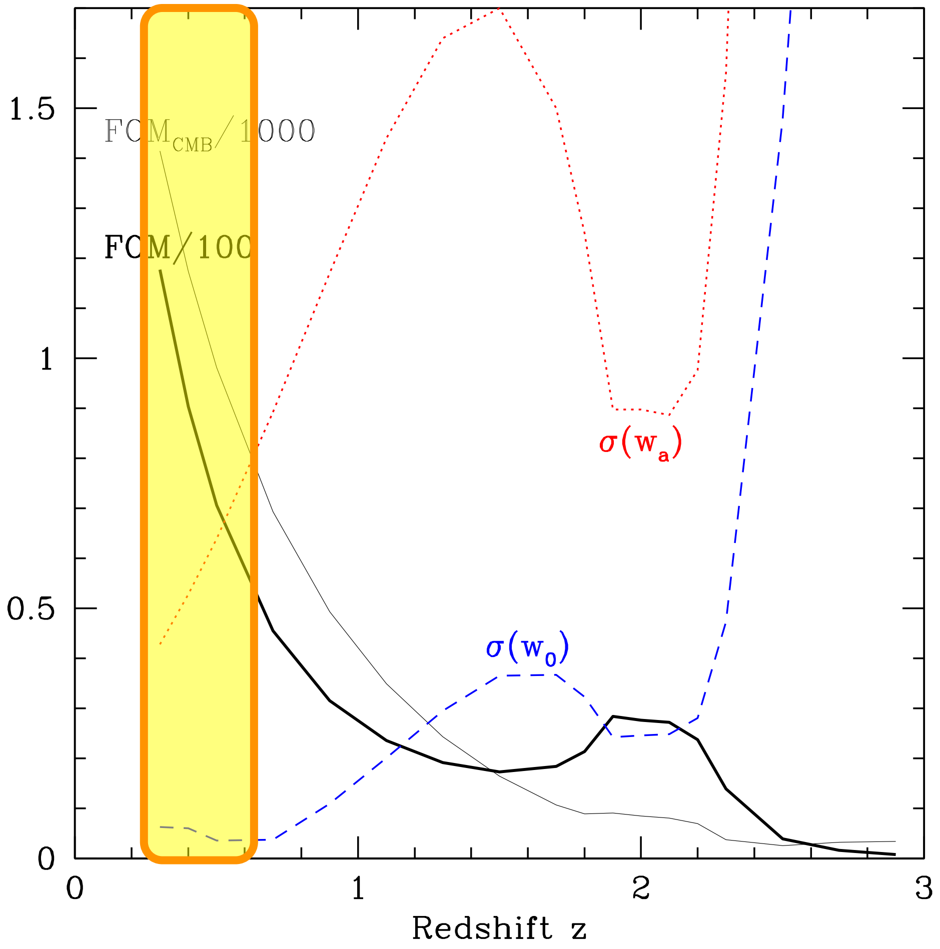
Sandage 1962, McVittie 1962

New theory, analysis, and hardware developments

Kim, Linder, Edelstein, Erskine 2015; Erskine, Linder+ 2016; and new data 2022, 2023!

Redshift Drift and Dark Energy

If redshift drift ż can be measured, it has powerful complementarity with CMB.



Leverage ranges from independent crosscheck to 3x above Stage 4.

Optimal range z<0.5.

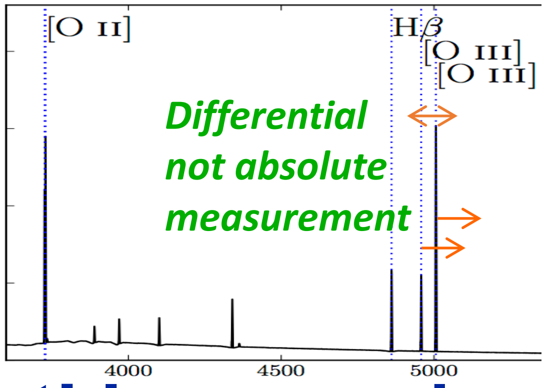
Need lots of photons, e.g. 10m or ELTs.

Redshift Drift Survey

Redshift accuracy very challenging: Δz → cm/s (Δt/3y) calibration, drift, PSF, line shape.

Strong gains from bright, well known, narrow lines.

Wavelength differences redshift the same as wavelength so measure differentially (doublet).



Low redshift ELGs with [OII], [OIII] doublets are great! In cosmology sweet spot, well surveyed, and in field (low peculiar acceleration).

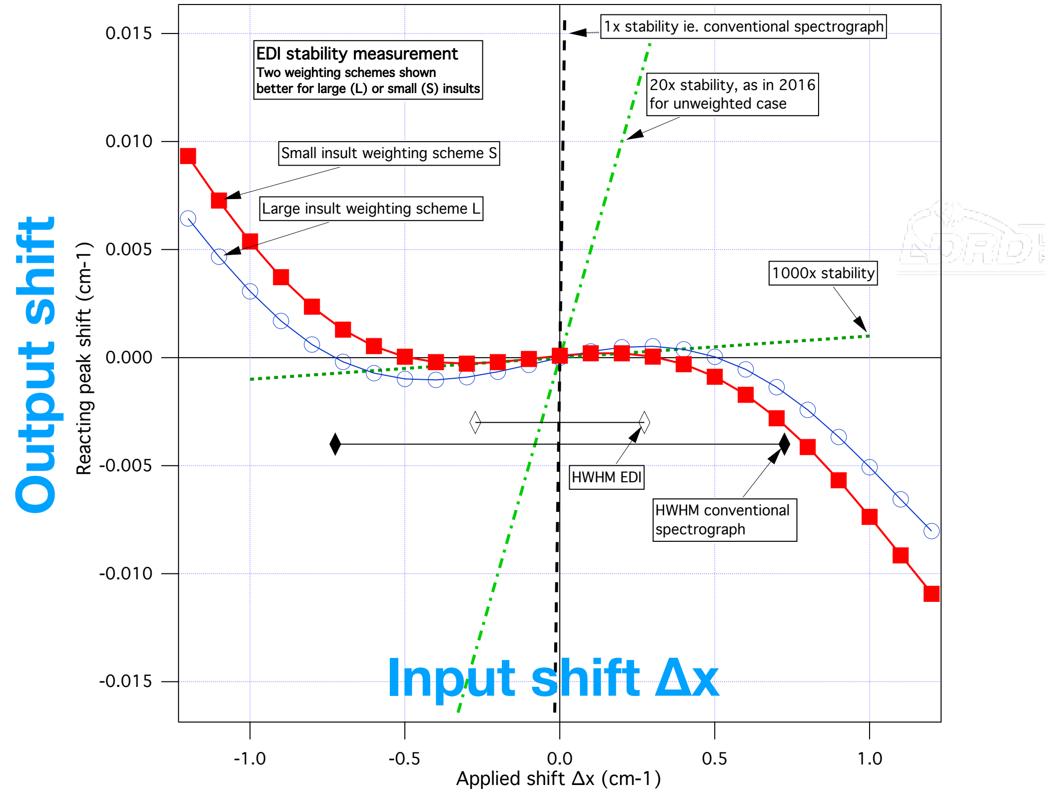
Interferometers give differential measurements that cancel some instrument systematics.

Astro2020 Erskine+ 1903.05656 ; Snowmass 2203.05924

Redshift Drift Technology

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Technology: 2016 – Hale Telescope 10x resolution gain, 20x stability gain. 2018 – GPI 100x resolution gain on biomarkers. 2019 – 1000x stability gain in lab.



1000x reduction in drift!

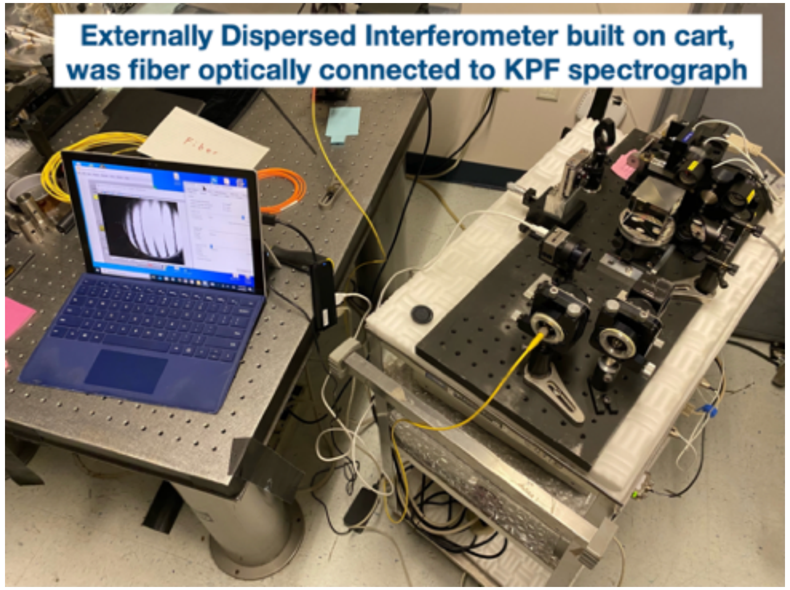


Fig. 1 Suitcase-portable EDI interferometer apparatus (on cart) we rapidly constructed and used (fiberoptically connected) on the Keck Planet Finder spectrograph during its engineering tests at UC Berkeley spring 2022.

Tested with Keck Planet Finder 2022

Erskine

https://doi.org/10.1117/1.JATIS.7.2.025006

Summary

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Stage 4 experiments (underway!) will give first major test of dark energy – dynamics and growth.

Stage 5 will address fundamental physics questions (thawer vs freezer, density, G_{matter}/G_{light}) at "natural" constraint precisions.

Experiment synergy will be key, and the direct acceleration probe of Redshift Drift is becoming a reality! (Lots of synergy with exoplanets)

Dark Energy is both an Old (2.5 decades) and New Theme in Cosmology. We see many ways to make Progress (now and soon)!