BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Dark Energy

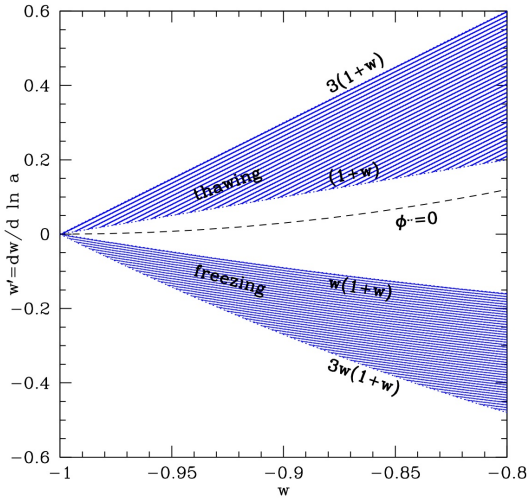
The Push, Pull, and Wiggle of Gravity

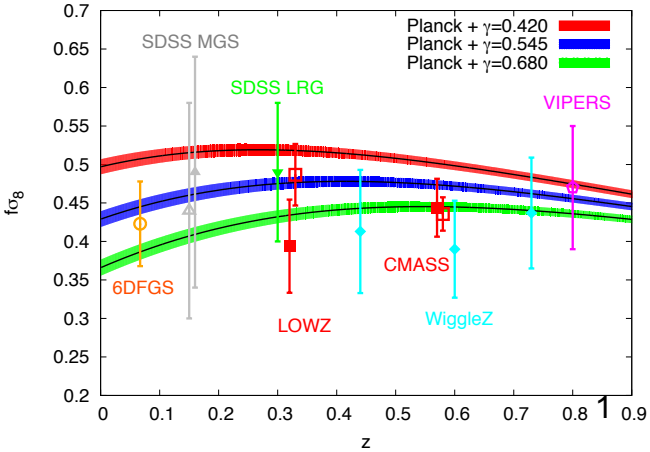
COSPA 2016

Sydney

Eric Linder

UC Berkeley/Berkeley Lab/ECL





Dark Energy and Gravity

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

The Push of Gravity –

Cosmic Acceleration and Dark Energy

The Pull of Gravity –

Growth of Structure and Lensing

The Wiggle of Gravity –

The Tensor Sector and Gravitational Waves

Future Cosmic Surveys

The Push of Gravity

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Rene Magritte
The Treachery of Images

"This is not dark energy."

Physics of Dark Energy

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

There is no equivalent of the Standard Model of particle physics to guide us for dark energy.

But if there was, should we expect it to be less complicated, i.e. just a single, canonical, minimally coupled scalar field?

Early approach – choose a model

Standard approach – phenomenological

New approach – Effective Field Theory

Gubitosi, Piazza, Vernizzi 1210.0201
Bloomfield, Flanagan, Park, Watson 1211.7054
Gleyzes, Langlois, Piazza, Vernizzi 1304.4840
Bellini & Sawicki 1404.3713
Linder, Sengor, Watson 1512.06180

Model Approach

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Very little motivation. Highly arbitrary. Lots of fine tuning, subject to quantum corrections.

Observations rule out (push to Λ) tracker models that relieve initial fine tuning.

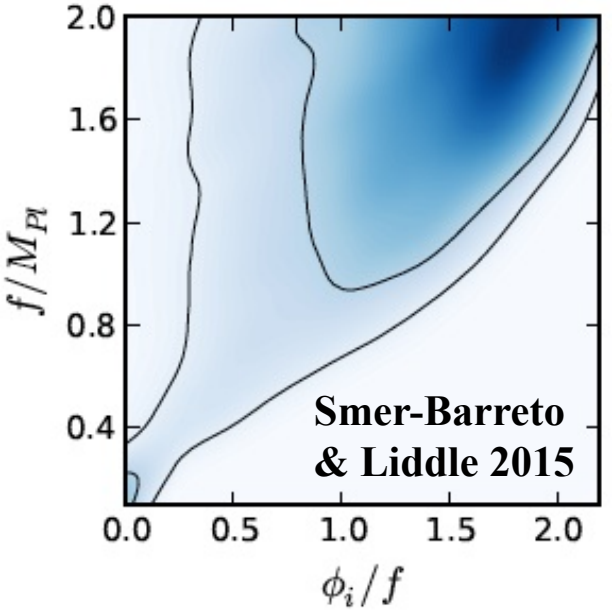
One model I still have some fondness for:

PNGB (pseudo-Nambu Goldstone boson)

$$V(\phi) = M^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right]$$

Frieman, Hill, Stebbins, Waga 1995

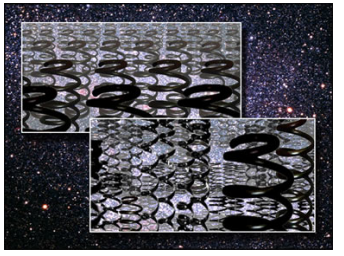
Has a shift symmetry giving technical naturalness. Connections with axion physics. In excellent agreement with observations.



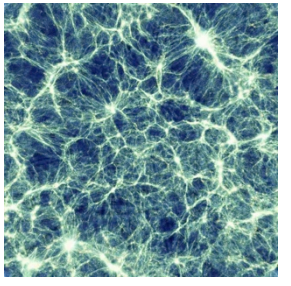
Phenomenological Approach

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

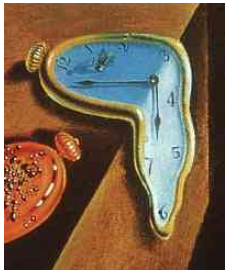
Handles on dark energy:



Expansion history → eq of state w(z)



Clustering → sound speed $c_s(z)$



Growth vs expansion → modified gravity, DE clustering, DE coupling, neutrinos

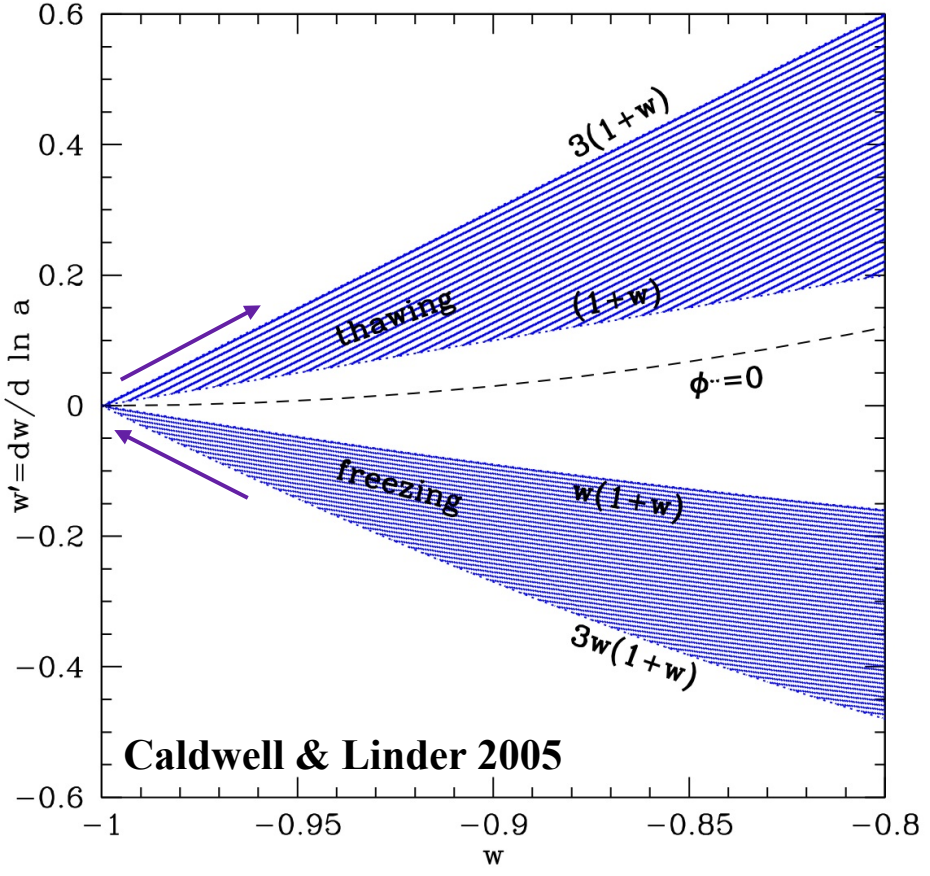
These help determine whether dark energy is a physical (scalar) field, or a modification of gravity.

Cosmic Expansion History

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Expansion history a(t) is completely equivalent to an (effective) dark energy equation of state w(z).

The phase space w-w′ has distinct regions corresponding to different physics.



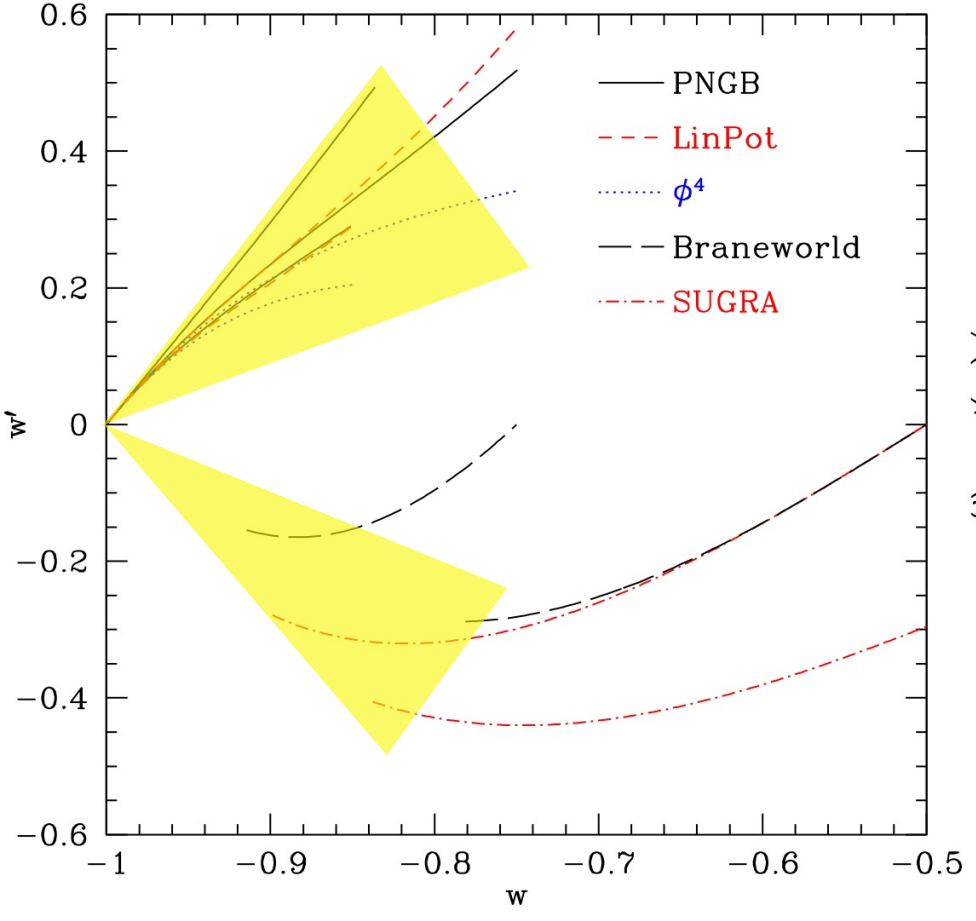
Entire "thawing" region looks like <w> ~ -1 ± 0.05.

Need experiments sensitive to σ(w′)≈2(1+w).

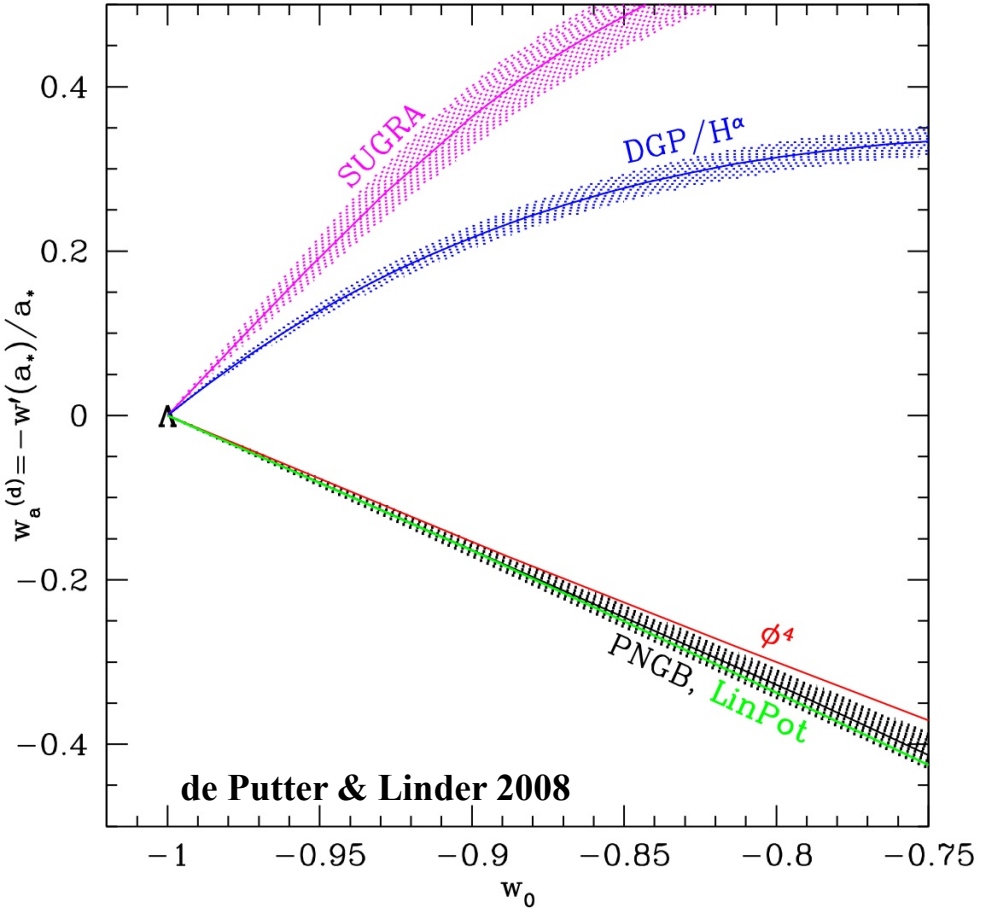
Calibrating Dark Energy

BERKELEY CENTER for COSMOLOGICAL PHYSICS

Models have a diversity of behavior, within thawing and freezing regions.



But we can calibrate w′ by "stretching" it: w′→ w′(a*)/a*. Calibrated parameters w_0, w_a.



All You Need to Know About: Cosmic Acceleration

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

The two parameters w_0, w_a achieve 10^{-3} level accuracy on observables d(z), H(z).

$$w(a)=w_0+w_a(1-a)$$

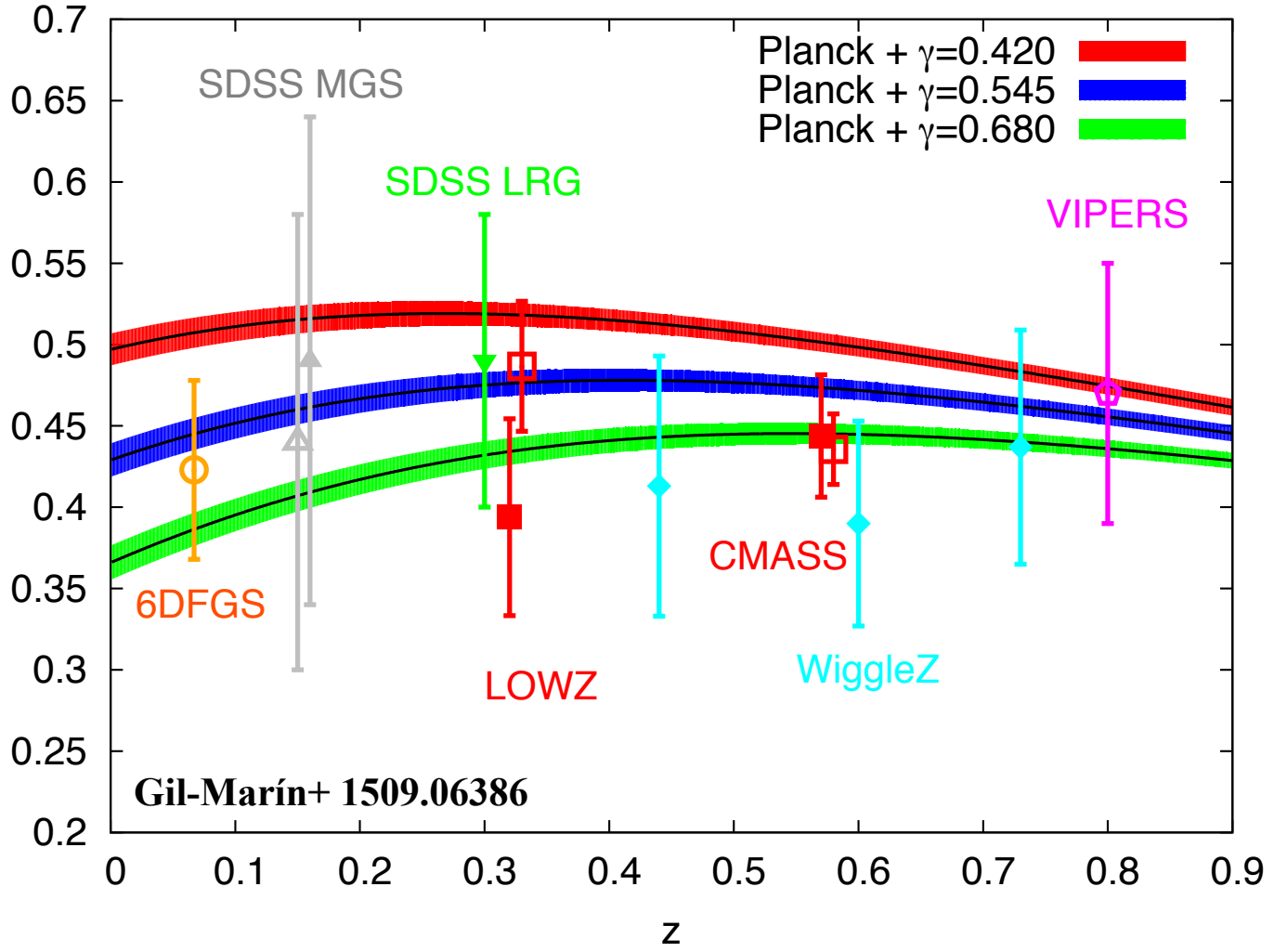
They are wholly sufficient for Stage 4 data.

They are calibration parameters arising from the physics (Klein-Gordon equations), having nothing to do with a Taylor expansion [Linder 2003].

The Pull of Gravity

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

In general relativity, (linear) growth of structure and expansion are tied together – one predicts the other. Cosmic growth tests GR.

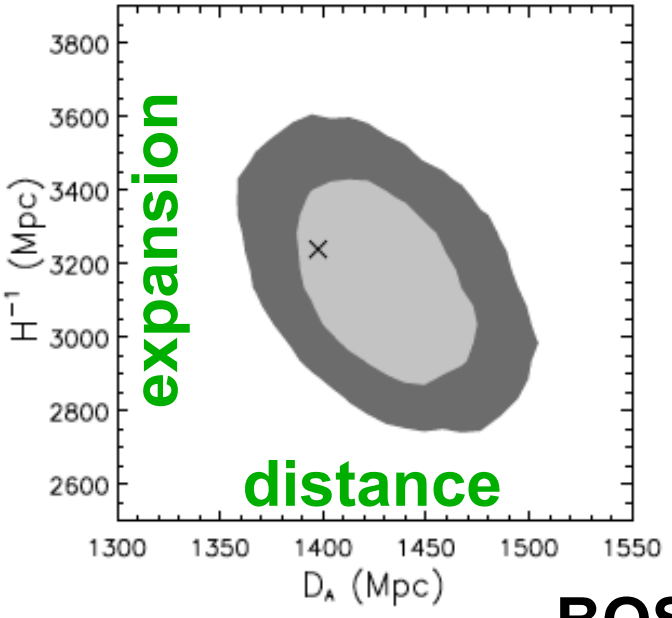


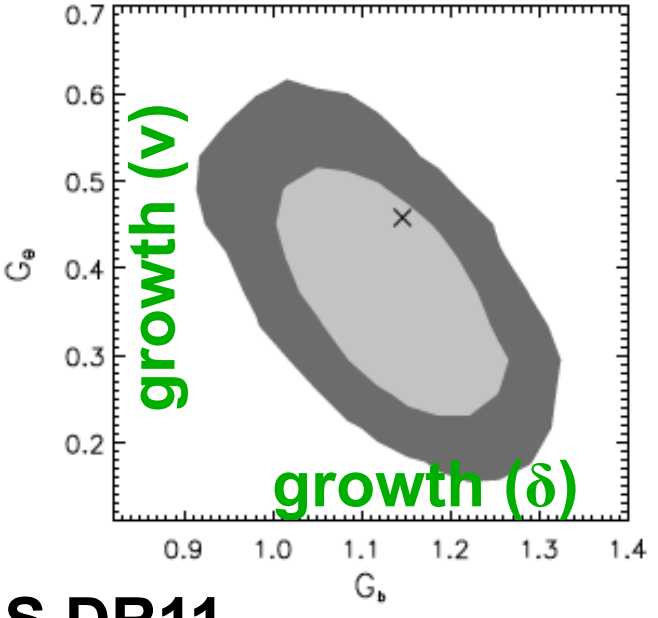
Is growth suppressed?

Or is beyond linear modeling insufficient?

Cosmic Growth vs Expansion

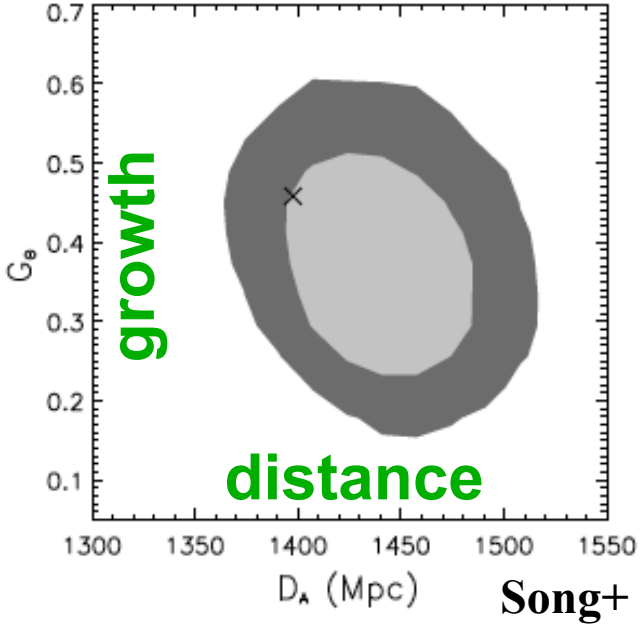
BERKELEY CENTER for COSMOLOGICAL PHYSICS

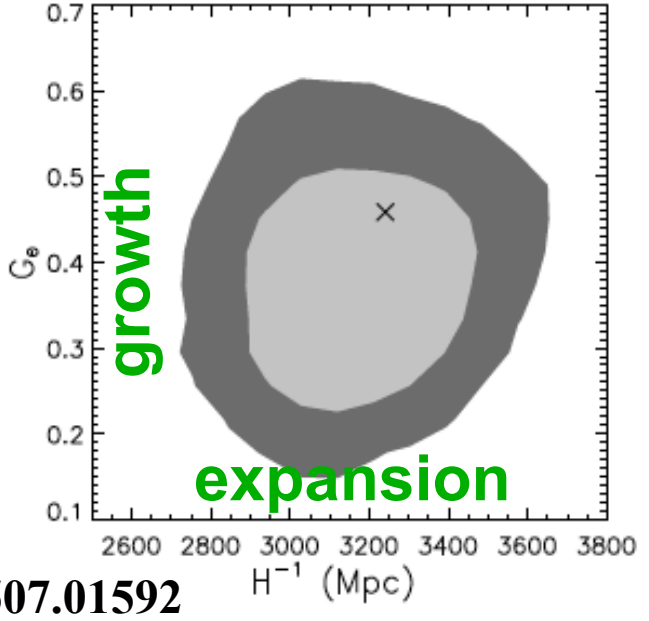




Growth vs expansion can be tested in a model independent way.

BOSS DR11





Beyond linear clustering must treat modGR consistently (perturbation theory).

Song+ 1507.01592

The Wiggle of Gravity

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

How do we parametrize the modGR time dependence and how do we capture the general physics?

A relatively new approach is the Effective Field Theory of dark energy.

This writes the most general theory possible, subject to symmetries – model independent!

One does not have to impose by hand limitations such as "no more than two derivatives". It encompasses theories beyond Horndeski.

EFTDE includes LCDM, quintessence, f(R), DGP, k-essence, Galileons, kinetic braiding, Horndeski, ghost condensate, Horava-Lifshitz, ...

Parametrizing Gravity

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Property functions give phenomenological combinations of EFT functions. Bellini & Sawicki 2014

α_B – braiding: mixing scalar and tensor sectors

α_K – kineticity: kinetic structure

α_M – running Planck mass (coupling)

α_T – tensor wave speed deviation (c_T^2-1)

All are functions of time, and 0 within GR.

Note that now the tensor sector (GW) is as important as the scalar (matter) sector!

The Richness of Gravity

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

In GR, expansion determines growth.

Note the expansion history H(z) is merely one free function of time.

For cosmic structure and growth we find that we have 5 times as many!

Cosmology much richer. Plus the tensor sector!

We have learned to fit H(z) with just a few parameters: Ω_m, w_0, w_a.

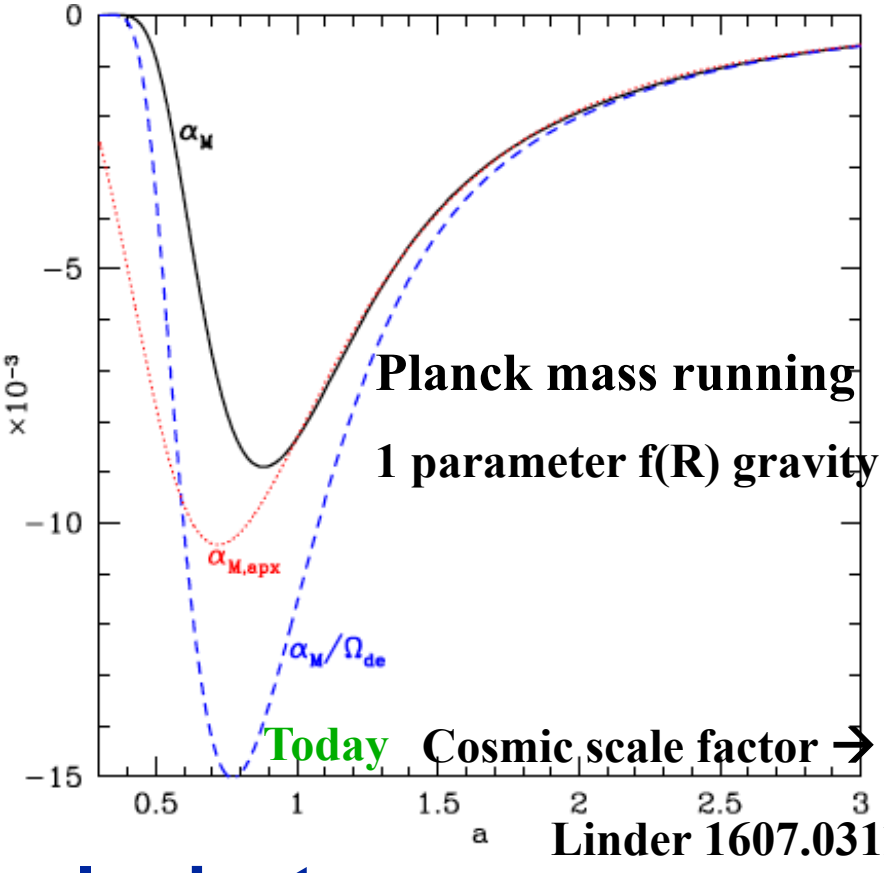
Can we do the same with gravity functions?

Need close connection between theory, computation, and data to test/interpret the results.

Testing Gravity

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Very difficult to fit these modified gravity functions of time to observations with just a few parameters, even for simple theories.



Linder 1607.03113

To reveal gravity, must also look at:

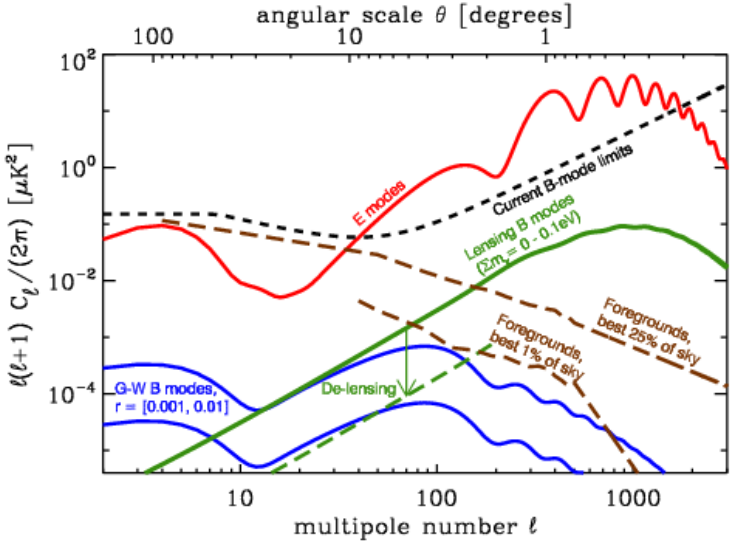
1) **Nonlinear regime and screening mechanisms**
2) **Tensor sector (gravitational waves)**
3) **Strong gravity systems (black holes)**

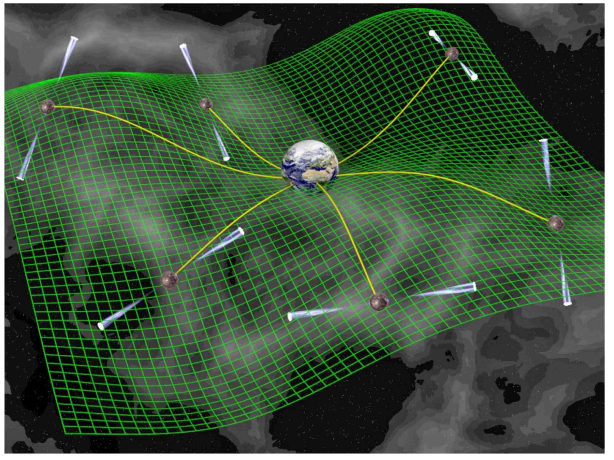
Understanding Gravity

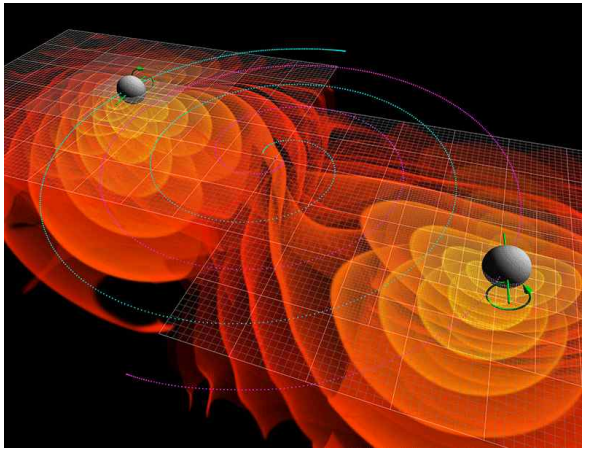
BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Unexpected synergies!

Plus, cosmology in the linear regime can't do it all.







The tensor sector is accessible through gravitational waves: CMB B-modes, pulsar timing arrays, interferometers.

Galaxy surveys have deep complementarity with CMB surveys (and PTA, LISA).

EFT Summary

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

The study of cosmic acceleration is far richer than realized even a few years ago:

The background, i.e. expansion H(z), has 1/5 or less of the functional information!

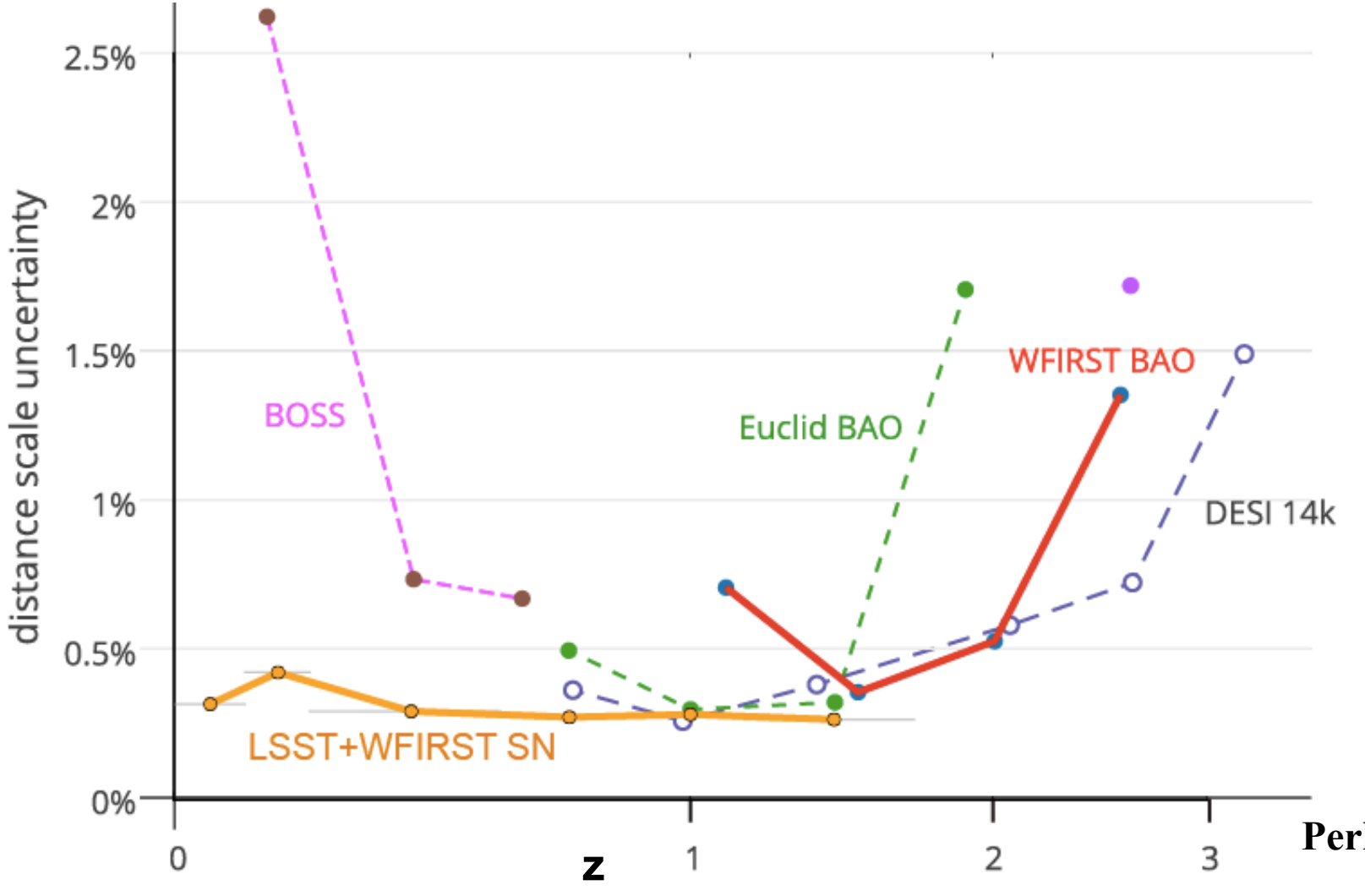
The tensor sector has equal information to the scalar sector (2 functions each)!

Don't despair! Be clever in looking for new theoretical principles and new observational regimes.

Mapping Cosmic Expansion

BERKELEY CENTER for COSMOLOGICAL PHYSICS

We will have sub% distance measurements over most of the cosmic expansion history.



Perlmutter+

CMB – Stage 4

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

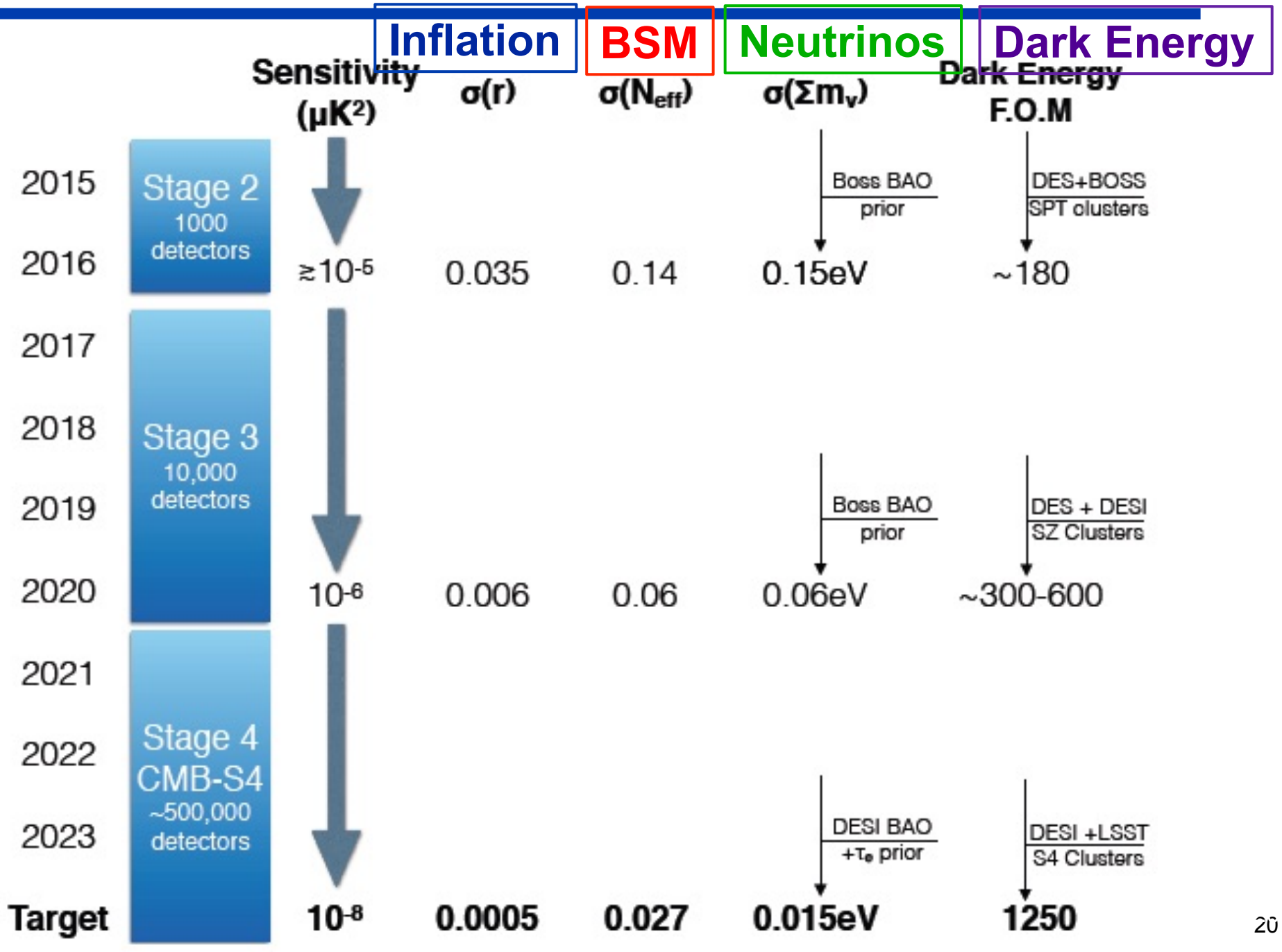
CMB-S4: a distributed array of telescopes with 0.5M detectors (Chile, South Pole,...).

Goes beyond Stage 3 (AdvACT, Simons Array, SPT-3G).
S4 test bed: Simons Observatory ($45M grant).

220 page Science Book arXiv:1610.02743

CMB-S4 Science

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS



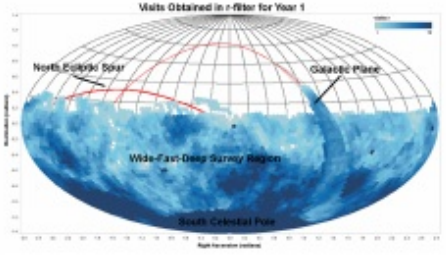
Future Cosmic Surveys

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

Beyond DESI/LSST/etc., there are already thoughts about Stage 5 Dark Energy experiments.

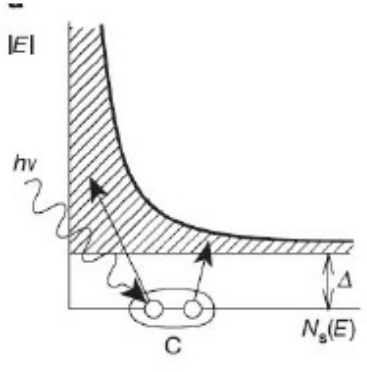
Future Cosmic Surveys **– Chicago, 21-23 Sep 2016**

Cosmic Visions: Dark Energy



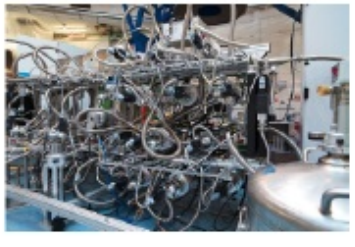
SSSI

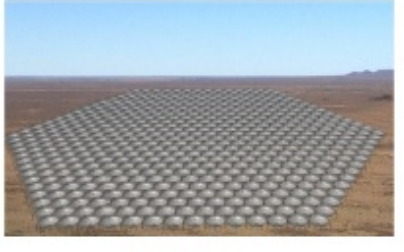
DESI-2



Low Resolution Spectroscopy

Billion Object Apparatus





21 cm

Summary & Future

BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

DESI, Euclid, LSST, WFIRST, etc. will have exciting next generation surveys. CMB polarization and lensing plays a critical role too.

Will map the expansion and growth, also need to understand them!

H(z) + 4 growth functions (including tensors). Gravity tests (CMB B-modes, PTA, interferometers).

Cosmologists are thinking now of further future surveys that can explore fundamental physics. Technology and theory developments are critical to enable these future cosmic surveys.

Your ideas are wanted!