

The Future of Cosmological Physics:

Dark Energy



Wayne Hu
Chicago, January 2016

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Dystopian Future:
Theory

$$(10^{120}+2)-10^{120}$$

$$(10^{120}+1)-10^{120}$$



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Dystopian Future:
Observations

2017

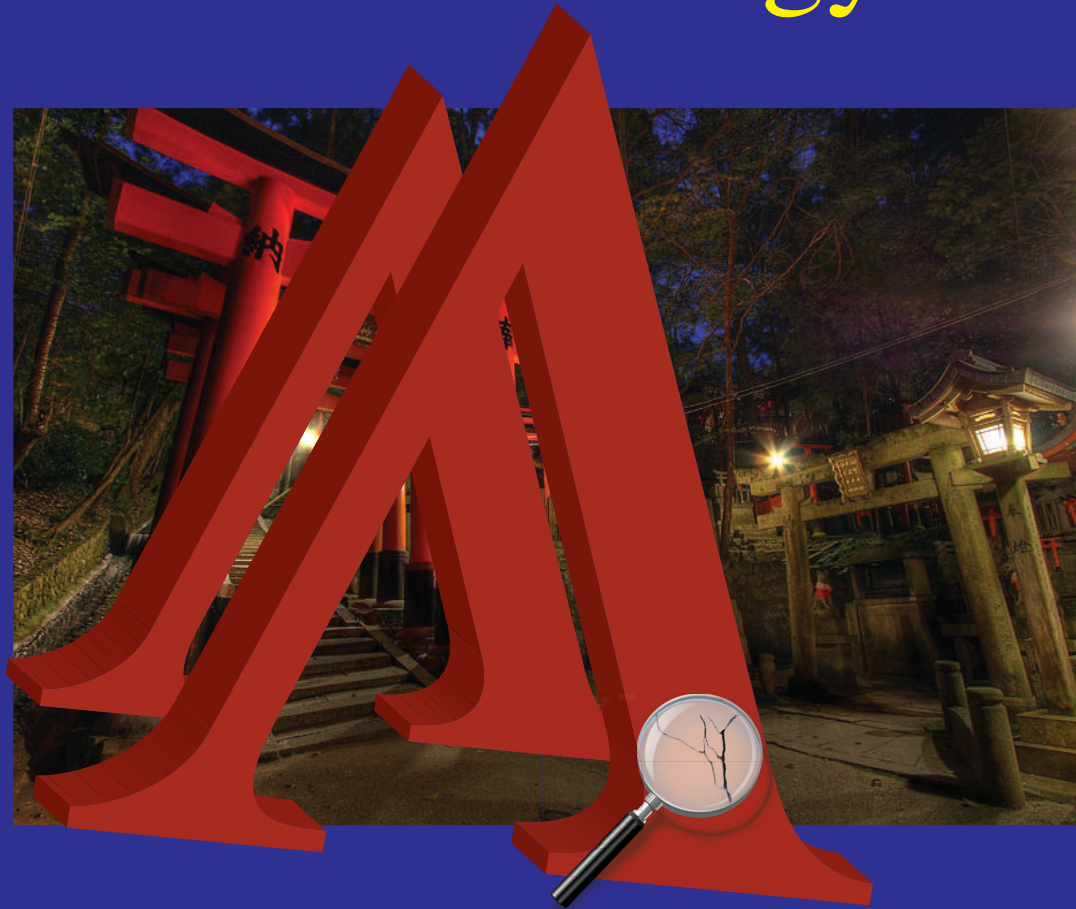
2016



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Goldstone Boson
of Spontaneously
Broken Time Translation
Symmetry

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Accelerated Expansion

Accelerating Expansion: Distance-Redshift

- Photons travel on null geodesics in the FRW spacetime

$$D = \int \frac{dt}{a} = \int \frac{da}{aH} = \int \frac{dz}{H}$$

- D quantifies light travel time, whereas scale factor $a=1/(1+z)$ quantifies the expansion or size of universe



inferring
distance:
standard
candles
&
rulers

Accelerating Expansion: Distance-Redshift

- SNIa as standard candle: relative distance from high to low z
- High z SNIa dimmer than expected, H more constant than expected in decelerating universe Riess et al (1998); Perlmutter et al (1998)
- Sound horizon as standard ruler: angular size in CMB is larger than expected in an open universe Boomerang, Maxima, DASI



Accelerating Expansion: Distance-Redshift

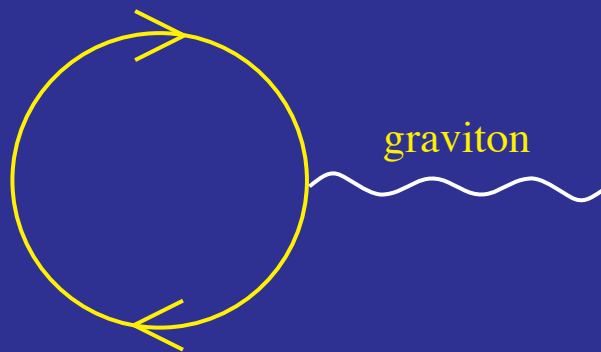
- Cosmological constant: energy density remains constant as Universe expands
- Friedmann equation: H goes to a constant, spacetime approaches deSitter

$$H^2 = 8\pi G\rho/3$$

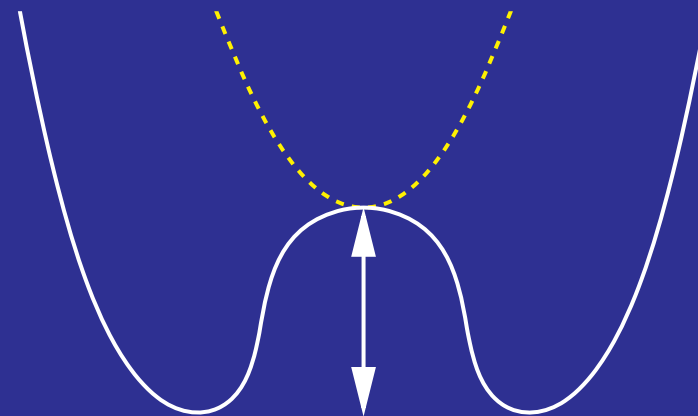


Simple \neq Natural

- Simplest possibility, consistent with all data to date, is a constant: Einstein's Cosmological Constant
- Particle physics provides sources for such a constant



Zero Point Energy

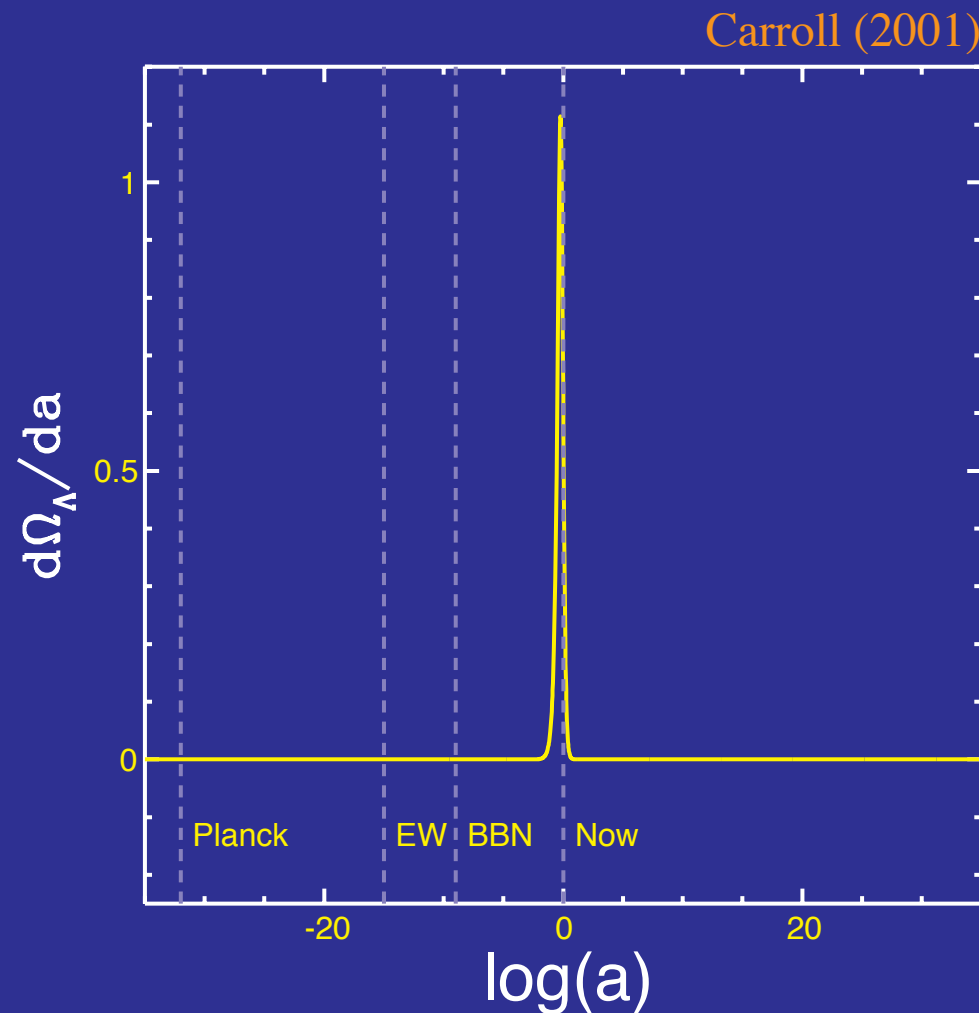


Phase Transitions

- But the energy scales associated with particle physics scale cutoffs and transitions give energy densities ($\rho \sim E^4$) at least ~ 60 orders of magnitude too large
- For a bare CC to cancel these contributions would seem to require exquisite fine tuning

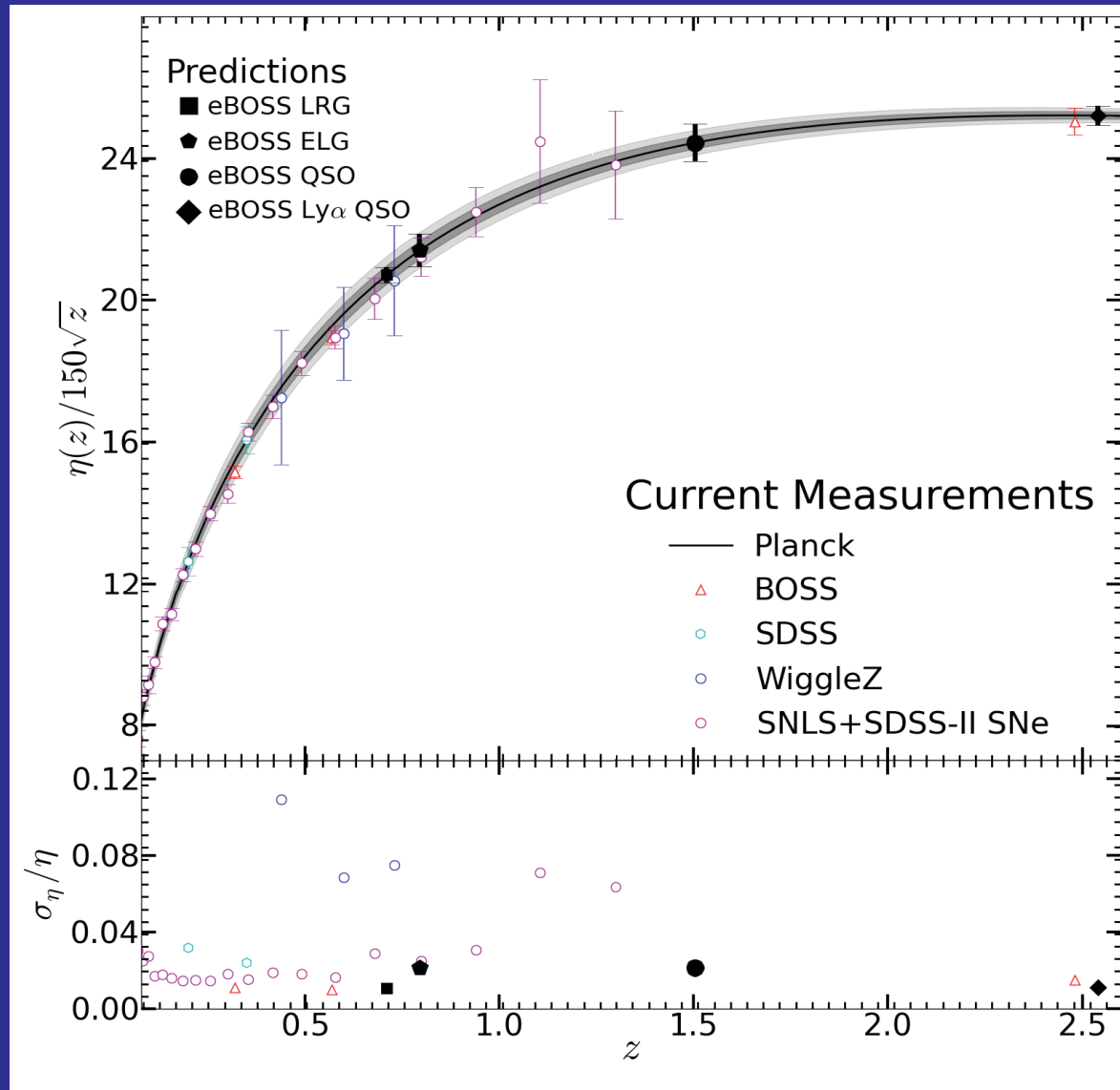
Coincidence

- Coincidence problem:
 - matter/radiation dilutes with expansion
 - dark energy constant or slowly diluting
 - only comparable today



Current Status: Distance-Redshift

- [CMB-] BAO-SN and the inverse distance ladder

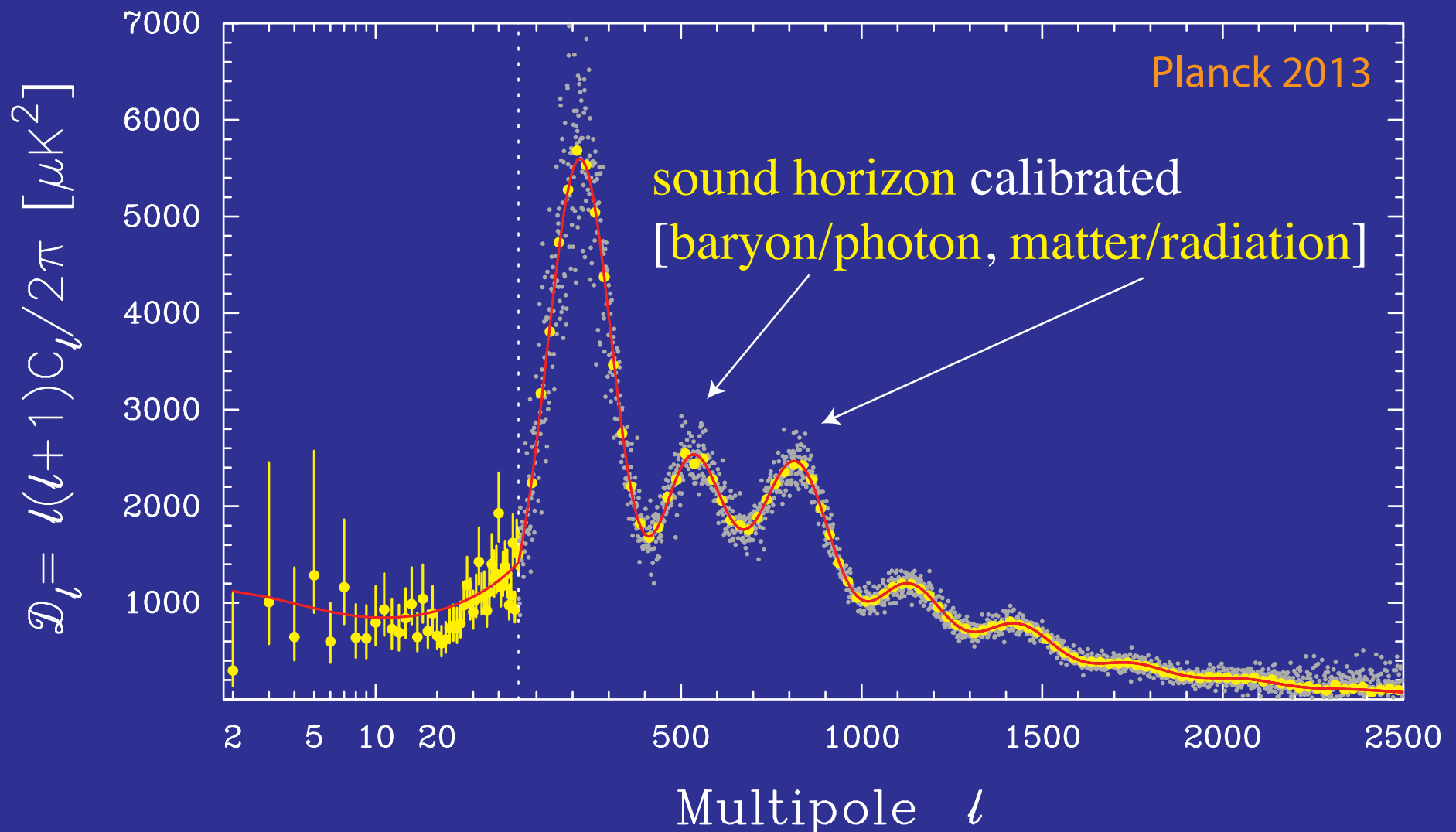


%level
precision

eBOSS Collab (2015)

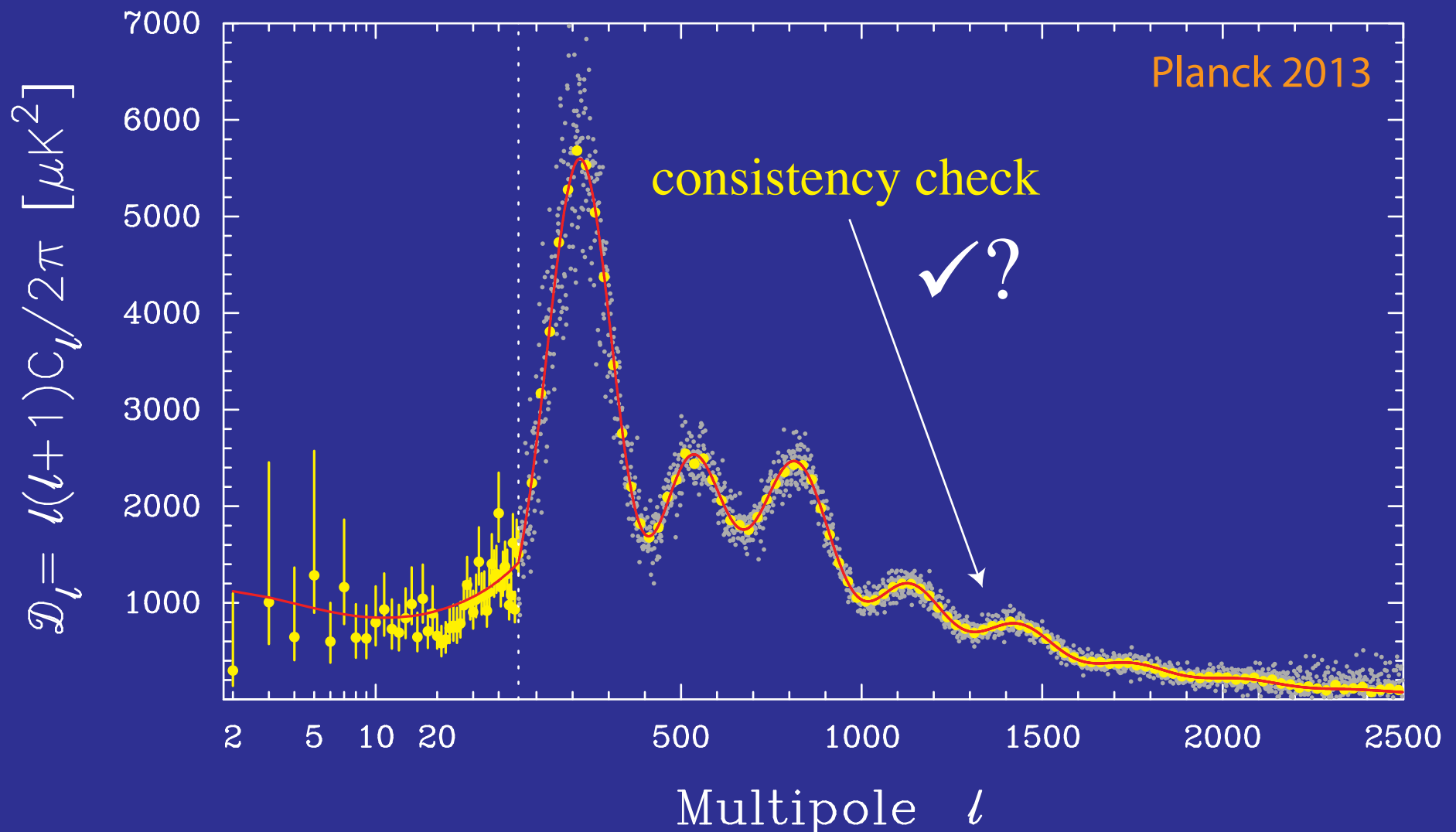
Sound Horizon

- **Standard ruler** $D(z_*)$: **sound horizon** at recombination z_* calibrated through measuring the ordinary matter content
- In **flat Λ CDM**, angular size **measures** only remaining density, Λ



Checking for Cracks

- **Standard ruler** $D(z_*)$: sound horizon at recombination z_*
- **Diffusion scale** provides **consistency check** on sound horizon calibration: new physics at **recombination**, while **BAO** on **acceleration**



Falsifying Λ CDM

- CMB determination of **matter density** controls all determinations in the **deceleration** (matter dominated) epoch
- **Planck**: $\Omega_m h^2 = 0.1426 \pm 0.0025 \rightarrow 1.7\%$
- **Distance** to recombination D_* determined to $\frac{1}{4}1.7\% \approx 0.43\%$ (Λ CDM result 0.46%; $\Delta h/h \approx -\Delta\Omega_m h^2/\Omega_m h^2$)
[more general: $-0.11\Delta w - 0.48\Delta \ln h - 0.15\Delta \ln \Omega_m - 1.4\Delta \ln \Omega_{\text{tot}} = 0$]
- **Expansion rate** during any redshift in the deceleration epoch determined to $\frac{1}{2}1.7\%$
- **Distance** to **any redshift** in the deceleration epoch determined as

$$D(z) = D_* - \int_z^{z_*} \frac{dz}{H(z)}$$

- **Volumes** determined by a combination $dV = D_A^2 d\Omega dz / H(z)$
- **Structure** also determined by growth of fluctuations from z_*

Value of Local Measurements

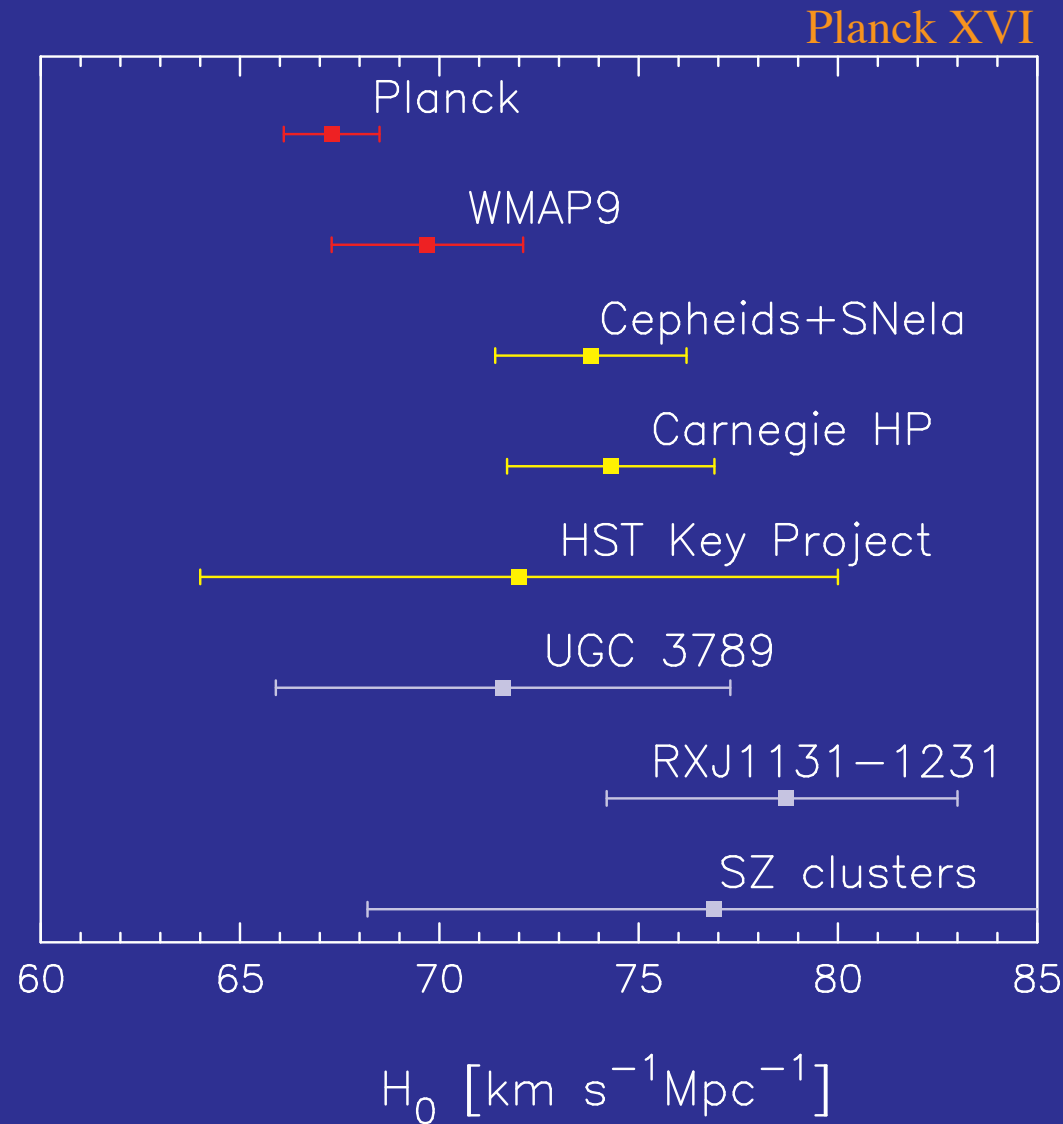
- With high redshifts fixed, the **largest deviations** from the dark energy appear at **low redshift** $z \sim 0$
- By the **Friedmann equation** $H^2 \propto \rho$ and difference between $H(z)$ extrapolated from the CMB $H_0 = 38$ and 67 is entirely due to the **dark energy** density in a flat universe
- With the dark energy density fixed by H_0 , the deviation from the CMB observed D_* from the Λ CDM prediction measures the **equation of state** (or evolution of the dark energy density)

$$p_{\text{DE}} = w\rho_{\text{DE}}$$

- Likewise current amplitude of structure, e.g. **local cluster abundance**, tests the smooth dark energy paradigm

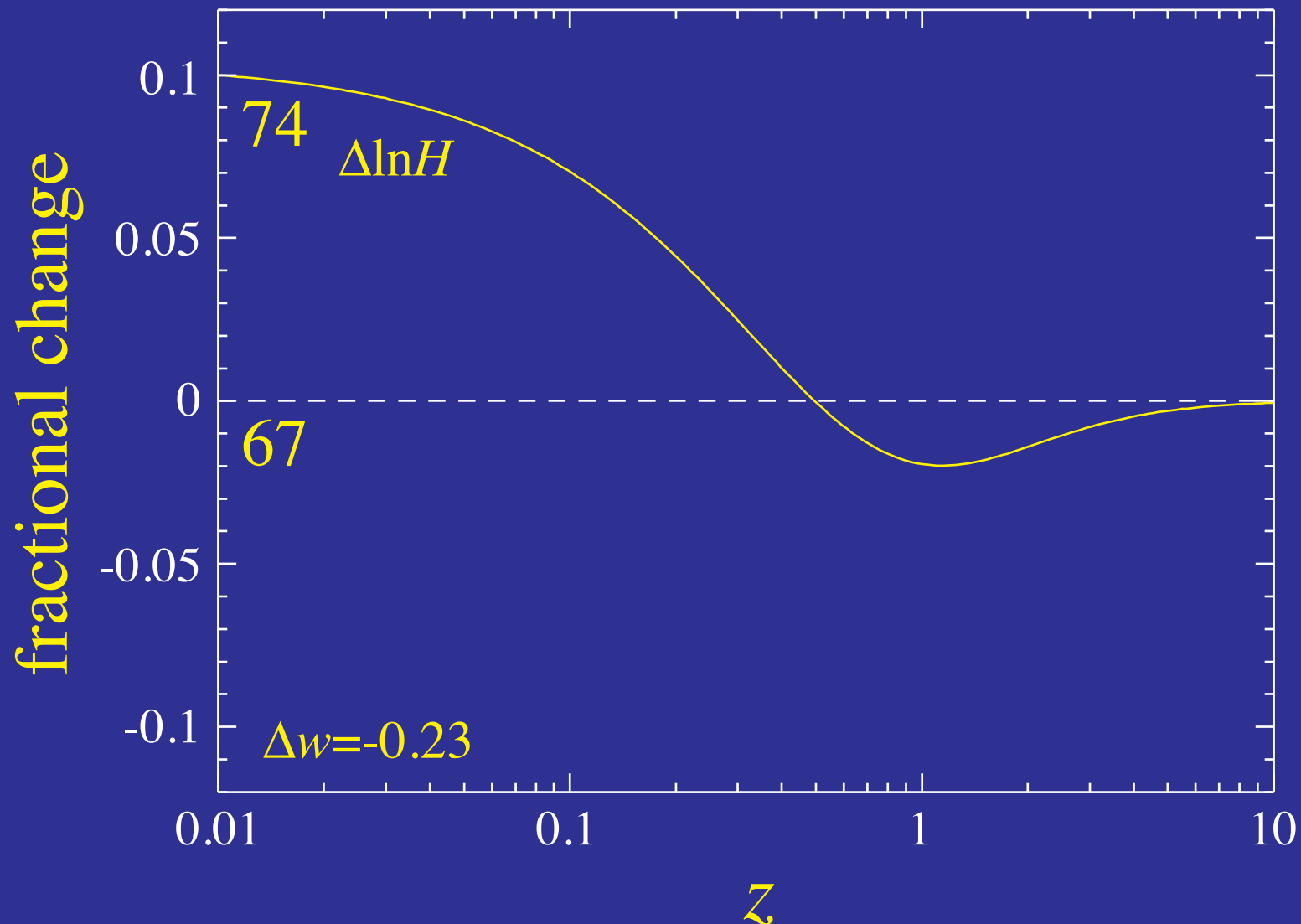
H_0 is for Hints

- Actual distance ladder measurements prefer larger value



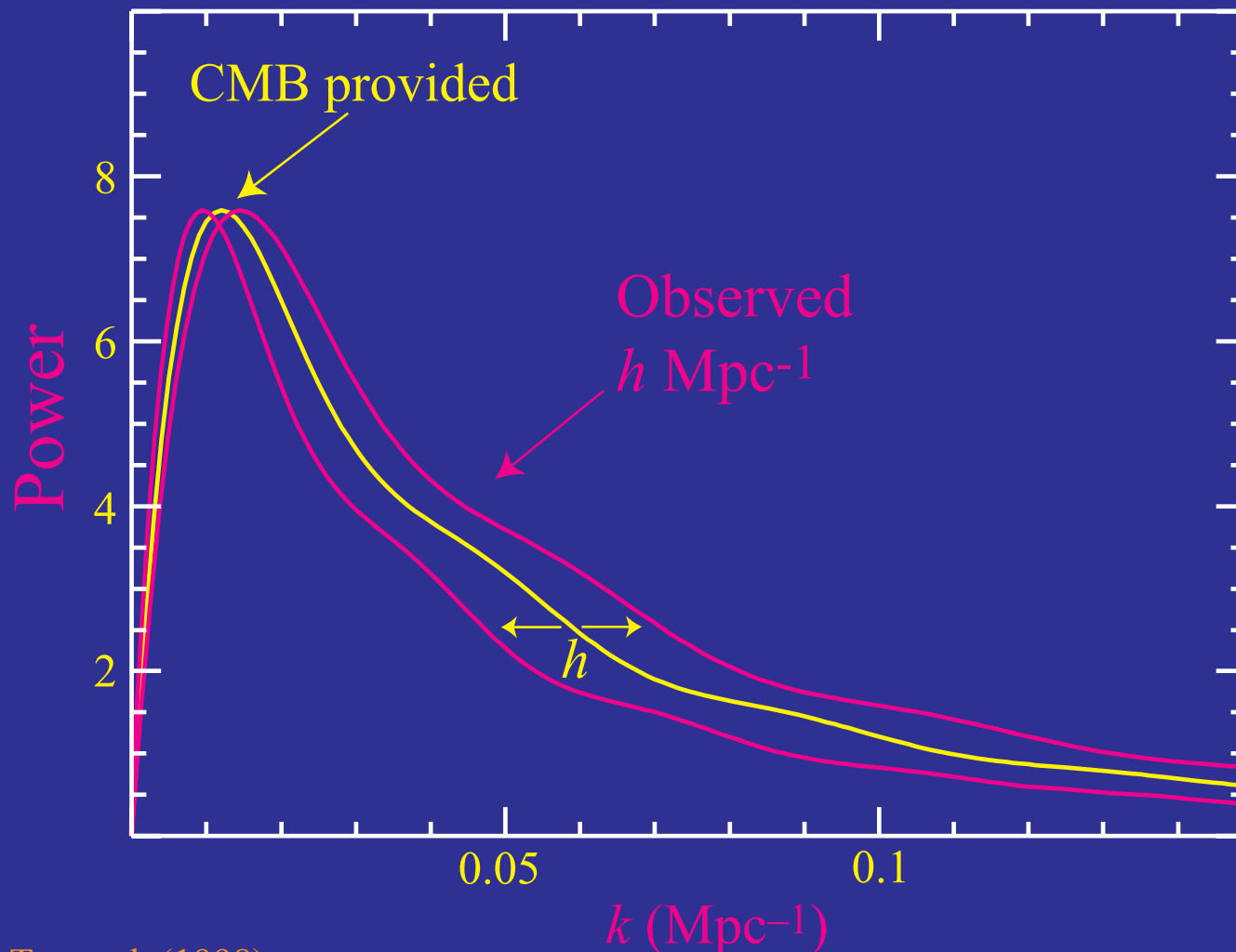
Dark Energy & H_0

- Change the dark energy, change CMB inference for H_0
- But simultaneously change expansion rate at intermediate z



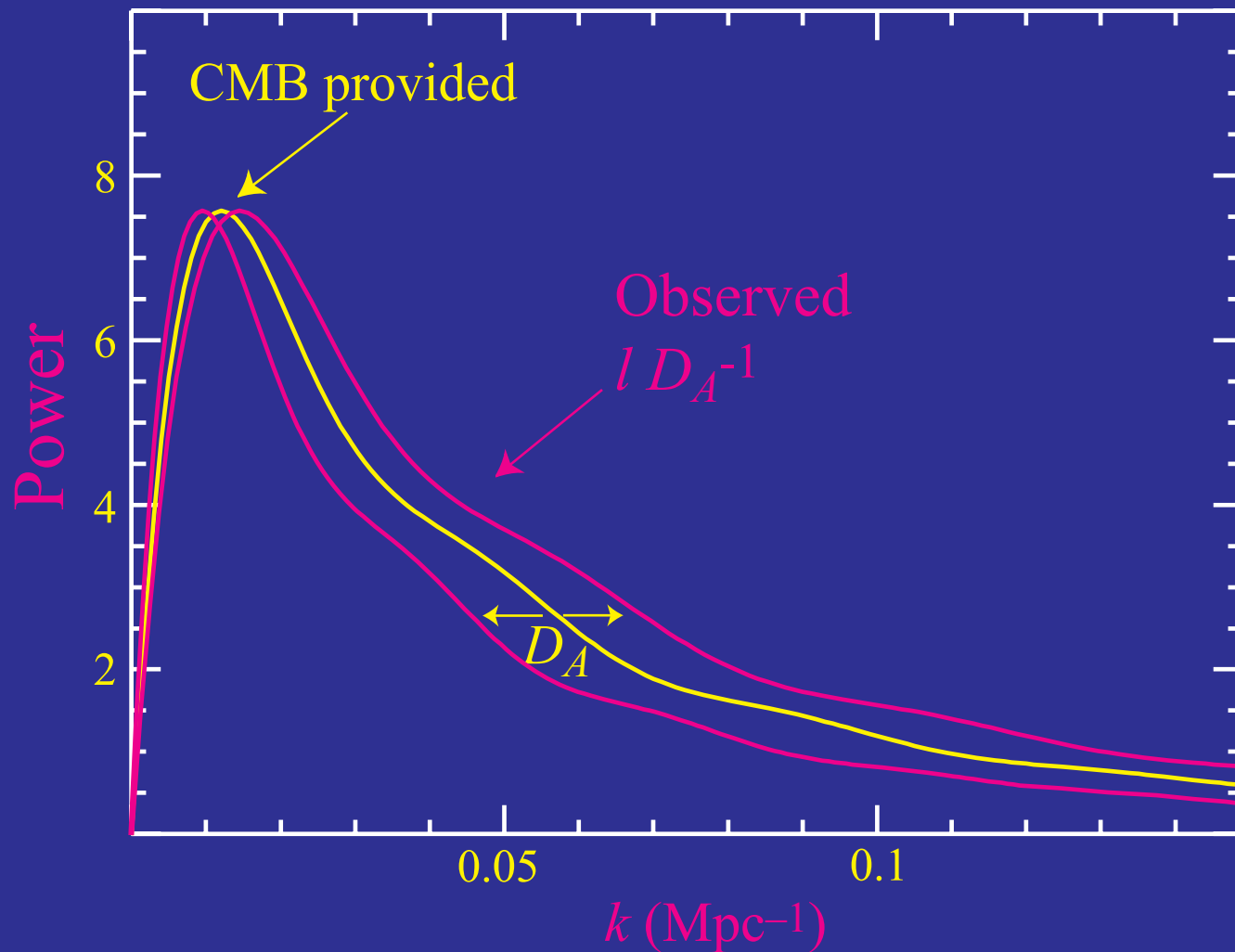
Local BAO

- Locally $D_A = \Delta z/H_0$, and the observed power spectrum is isotropic in $h \text{ Mpc}^{-1}$ space
- Template matching the features yields the Hubble constant



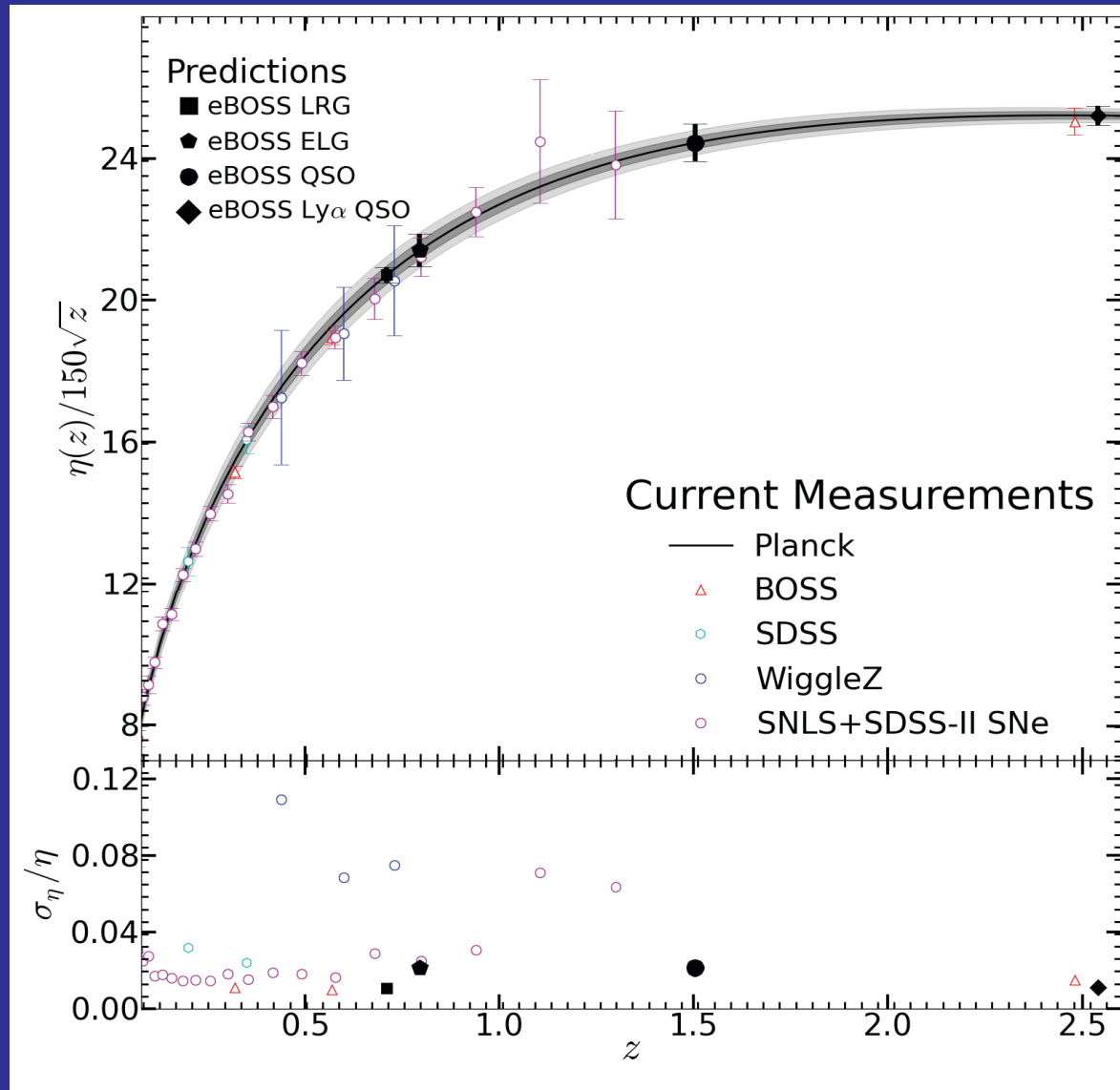
Cosmological Distances

- Modes perpendicular to line of sight measure angular diameter distance



Current Status: Distance-Redshift

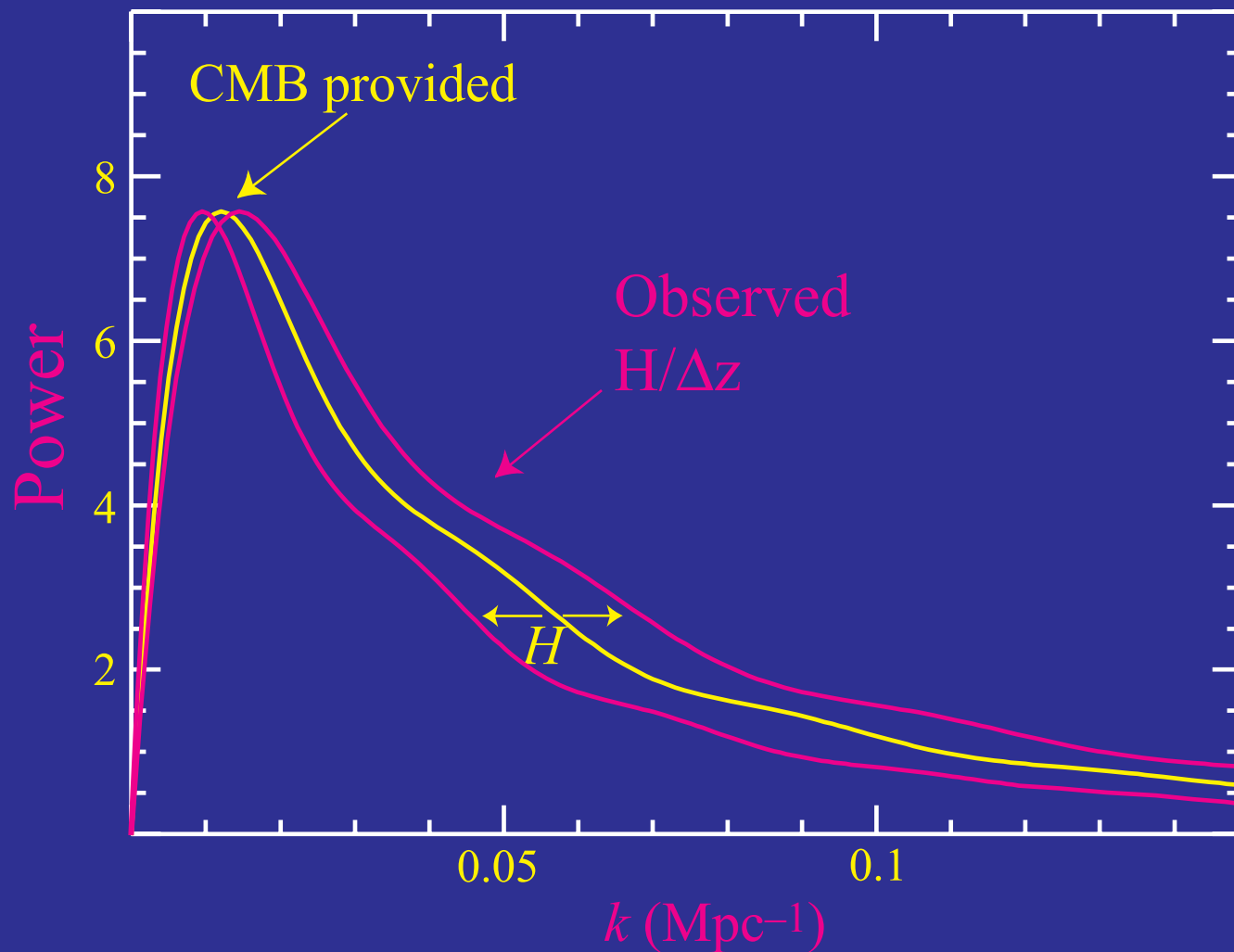
- BAO-SN and the inverse distance ladder



eBOSS Collab (2015)

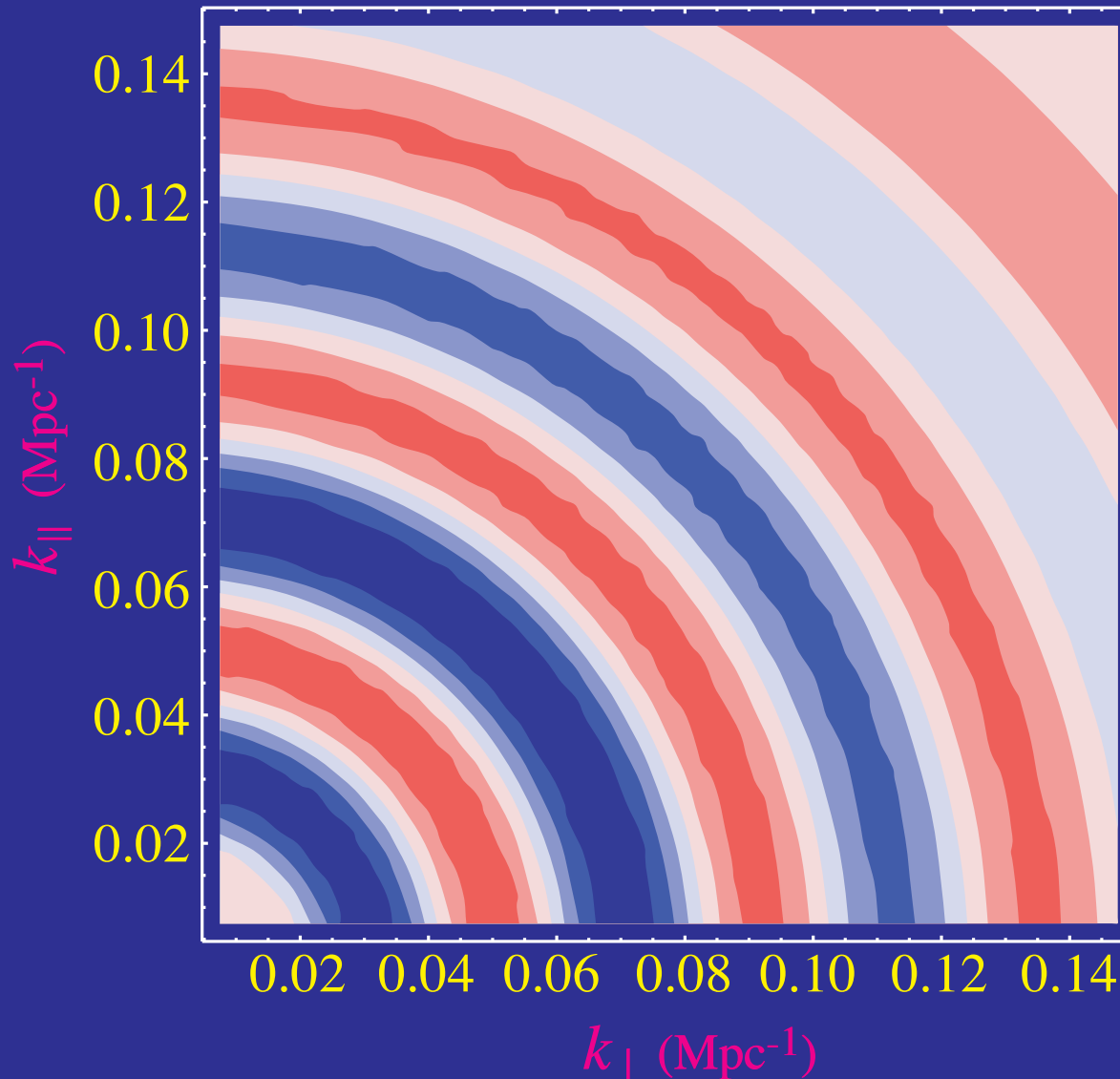
Cosmological Distances

- Modes parallel to line of sight measure the Hubble parameter



Acoustic Rings

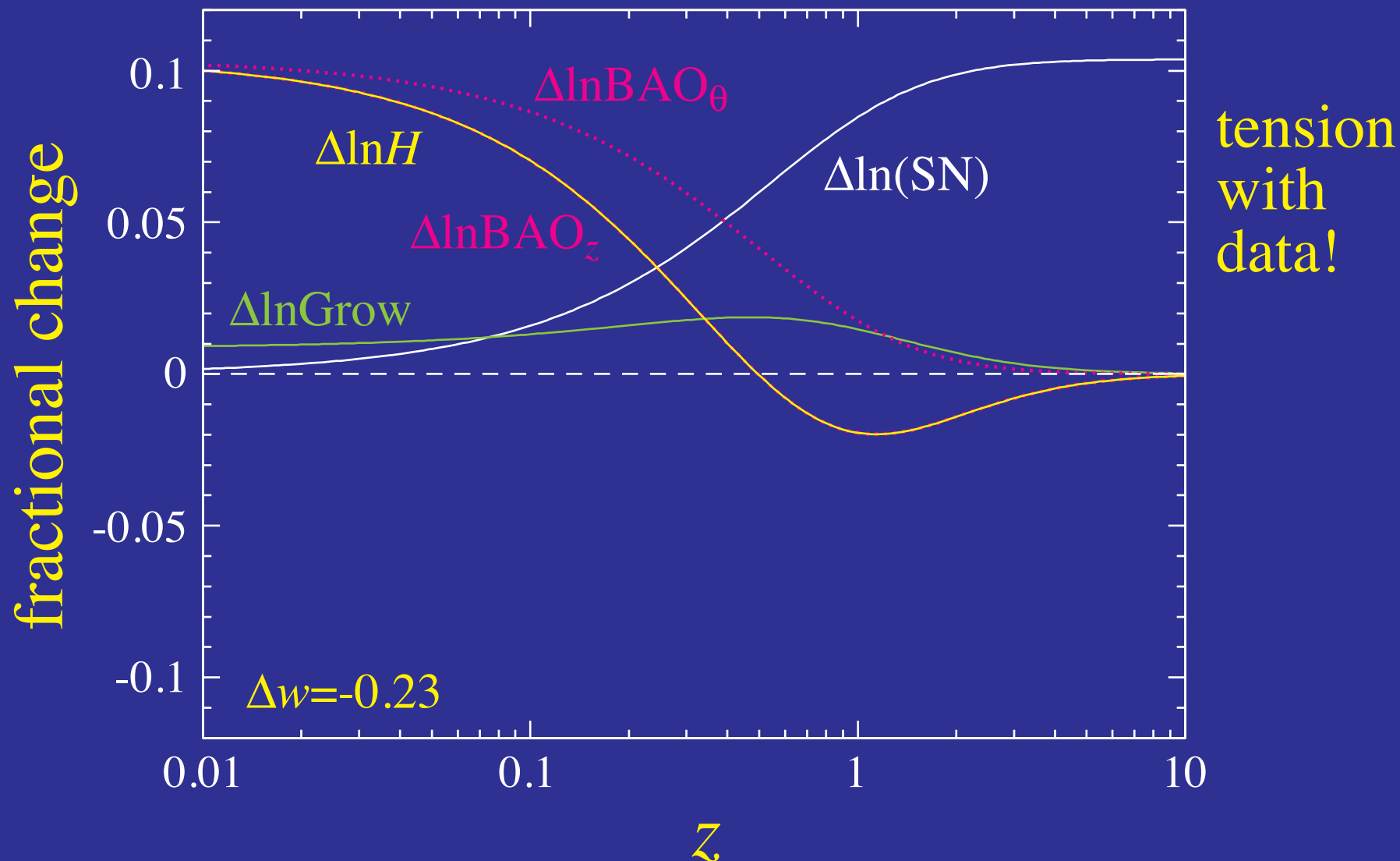
- Baryon oscillations appear as rings in a 2D power spectrum with modes parallel and perpendicular to the line of sight



~10% peak to trough

Dark Energy

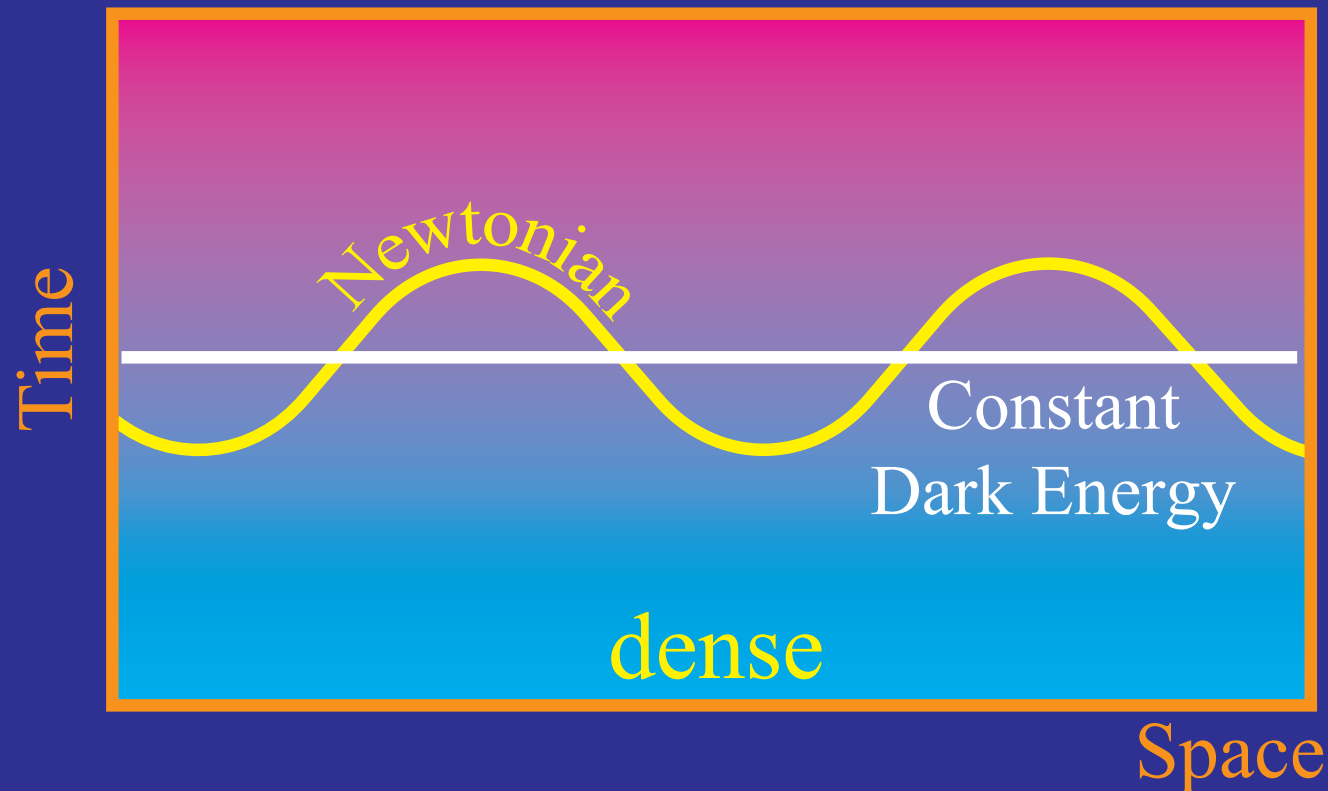
- Predicts larger **BAO** (θ) **angular** and **radial** (z) **scale**;
larger **SN**= $H_0 D_A$ relative luminosity distance;
larger **linear growth**



Growth of Structure

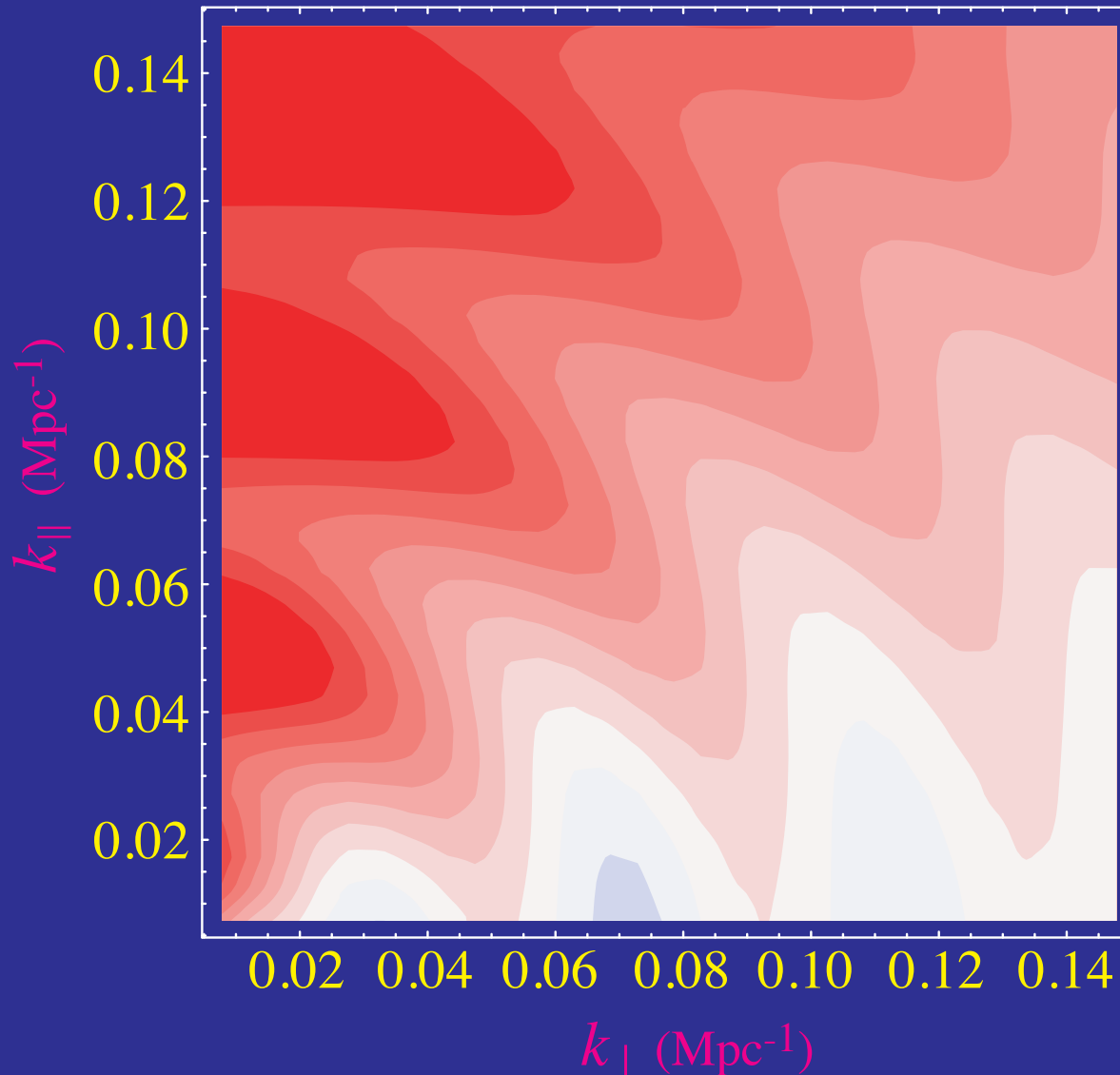
Smooth Dark Energy and Sound Speed

- Only cosmological constant is spatially smooth in all frames
- Dark energy can be smooth relative to the dark matter if relativistic stresses support it against collapse
- On scales below the sound horizon (Jeans scale), expansion history determines growth of structure: consistency relations



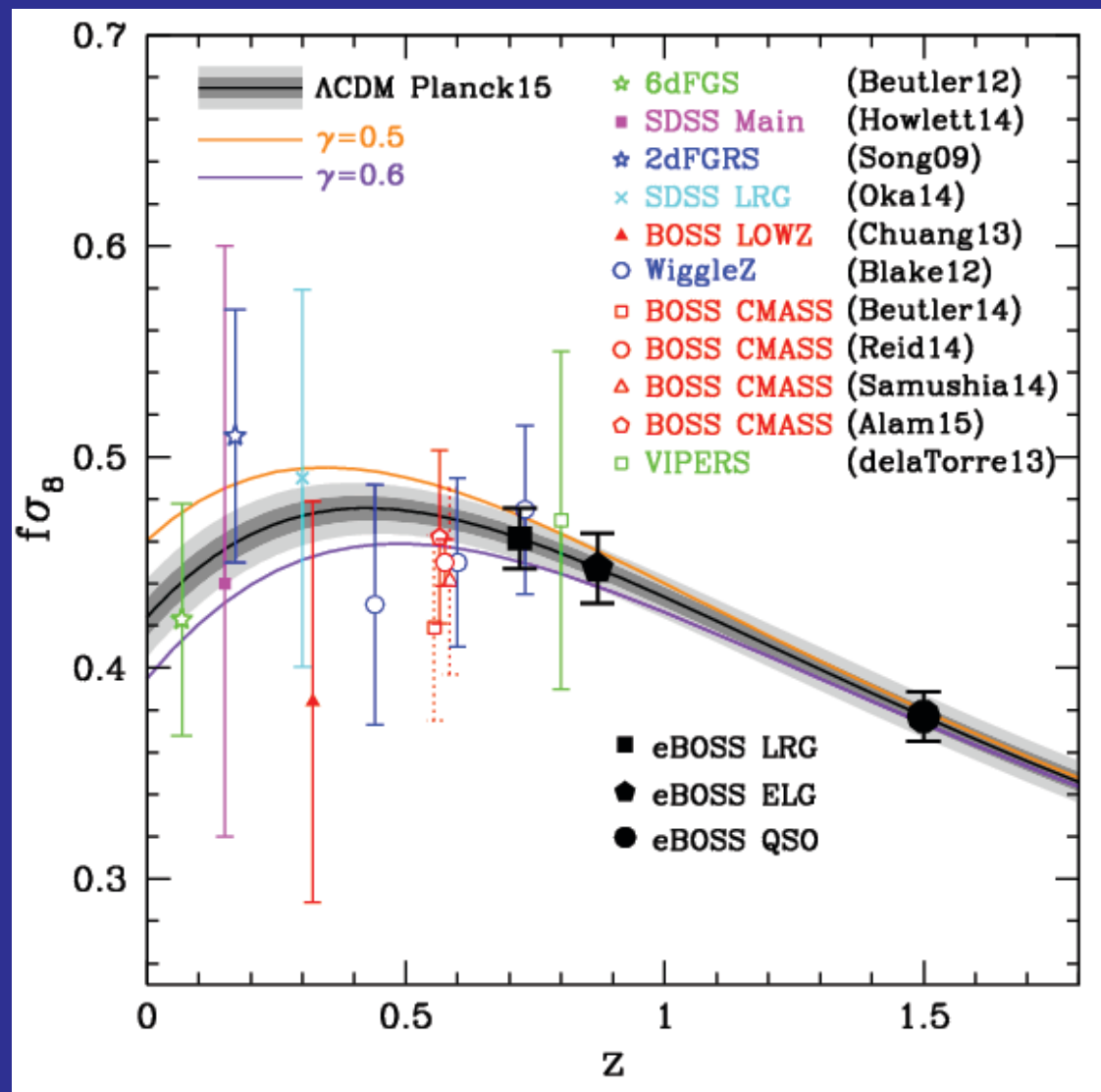
Redshift Space Distortion

- Peculiar velocities enhance parallel power and hence cause an anisotropy in the power spectrum which measures growth rate



Current Status: Redshift Space Distortions

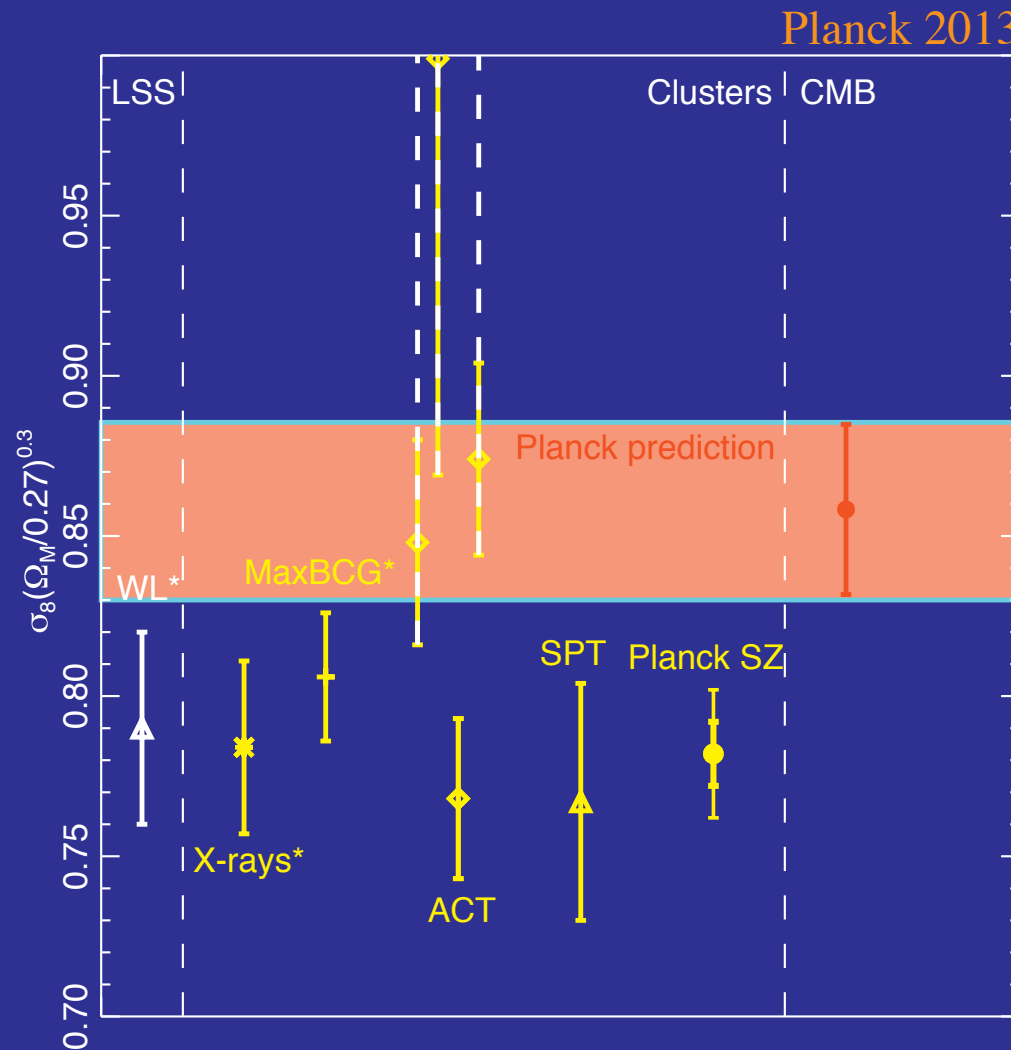
- Redshift space distortions and the growth of structure



eBOSS Collab (2015)

Growth and Clusters

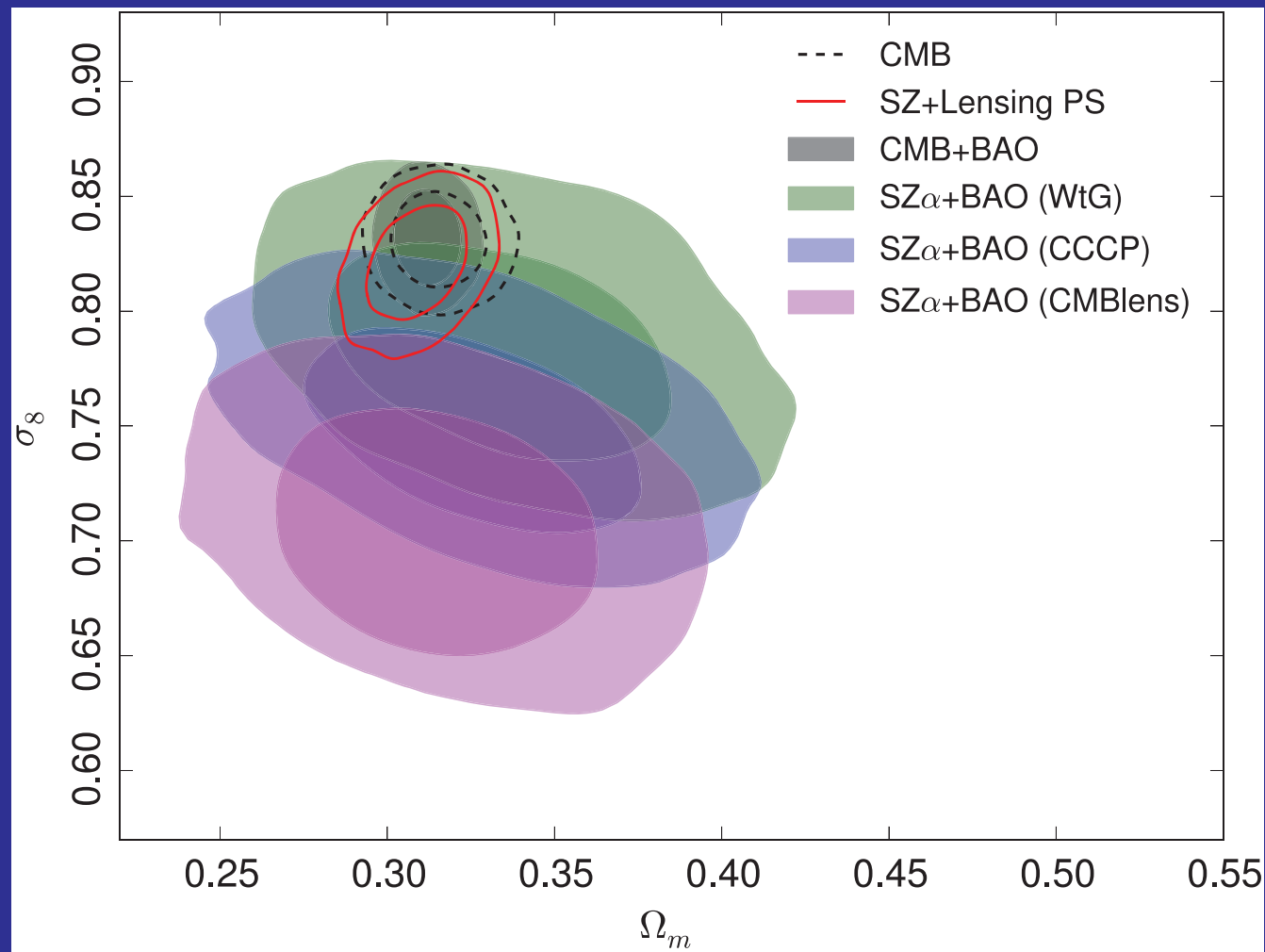
- Cluster abundance measurements vs Planck predictions



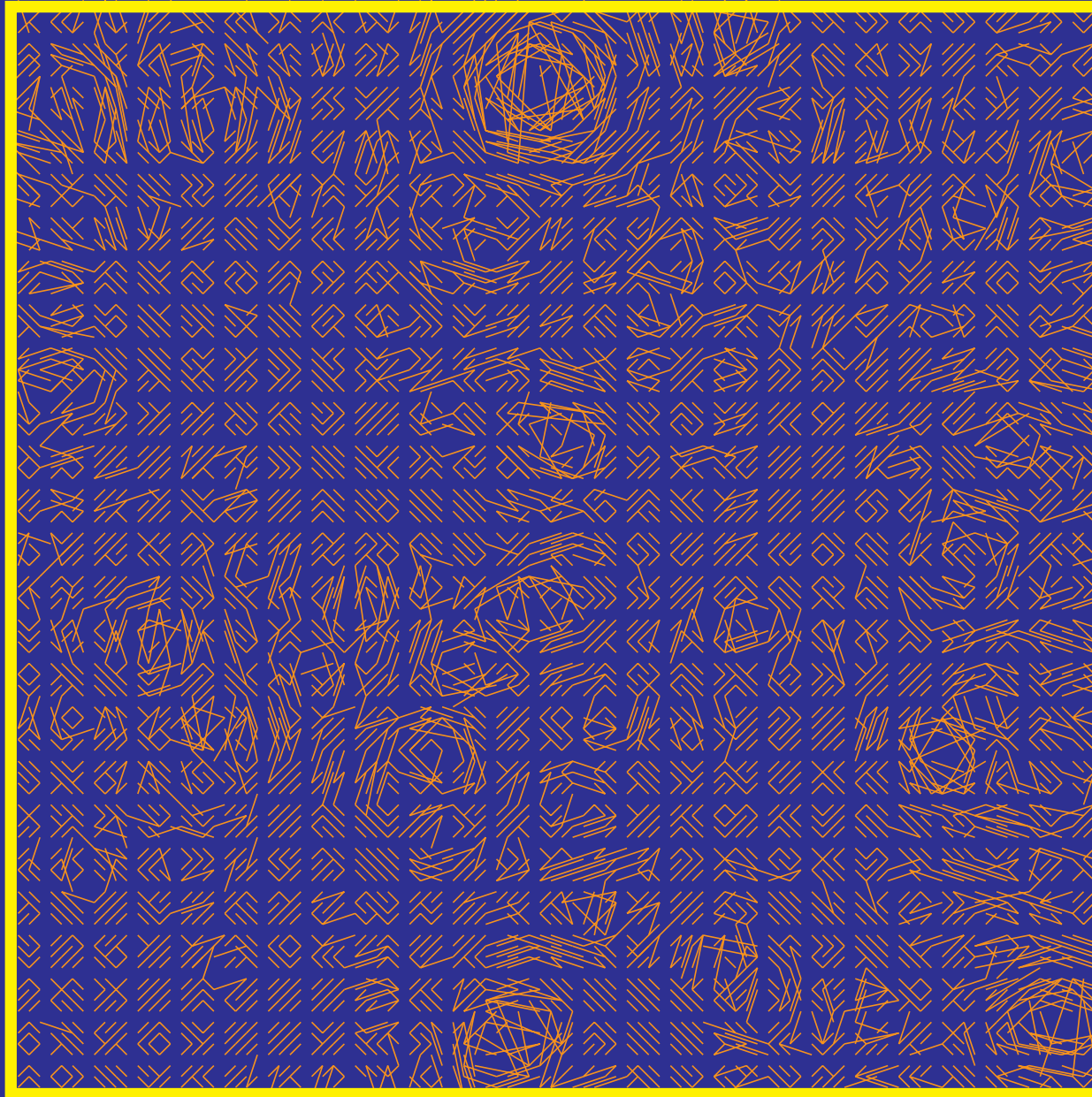
- Statistically discrepant at the $\sim 3\sigma$ level

Current Status: Cluster Abundance

- Cluster abundance, growth of structure, and the mass-observable scaling relation

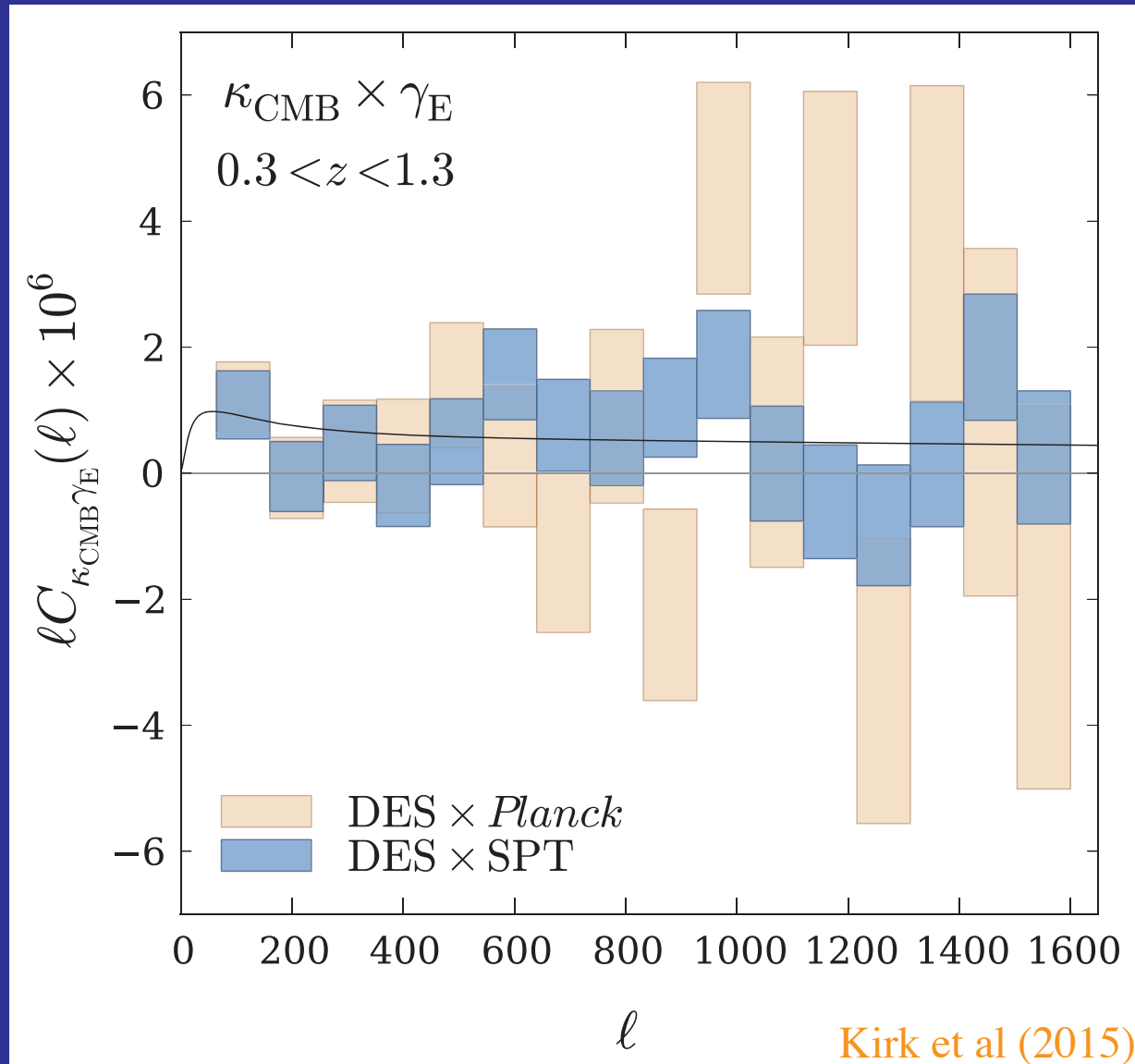


Halos and Shear



Current Status: Cosmic Shear

- Cosmic shear in DES galaxy ellipticities and CMB



Current Status: Local Cracks

- Tension between Planck high- z cosmology at local tests

Expansion rate (Hubble constant, not BAO)

Growth (cluster abundance, cosmic shear, redshift space distortions)

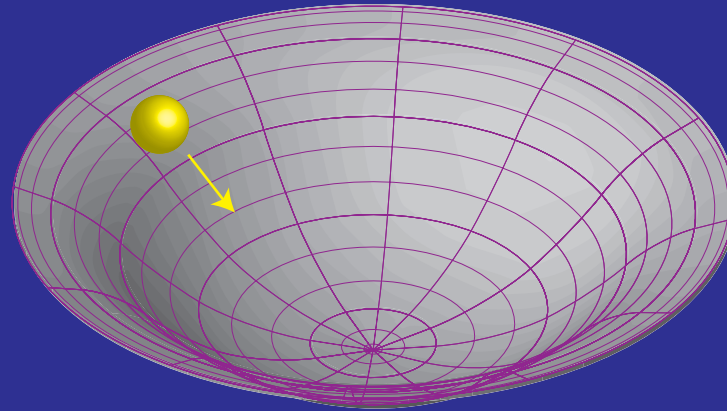
New cosmological or astro physics?

- In era of 1% precise cosmology, multiple probes and blind analyses required to assure 1% accuracy
- If new physics, a complex dark sector is required to break consistency between growth, distance and standards
- KICP is uniquely placed to resolve these observationally or theoretically

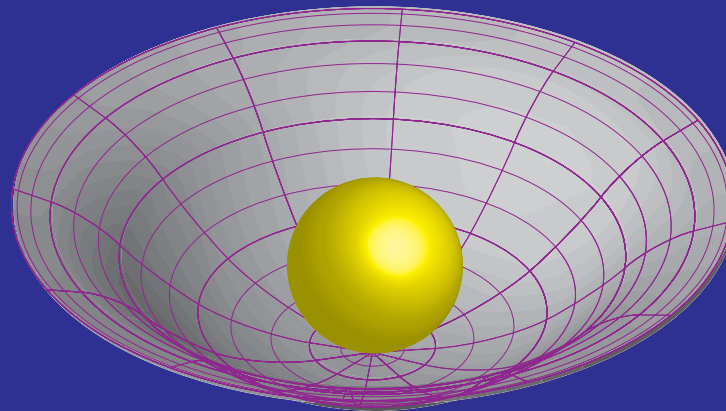
Beyond Smooth Dark Energy

Mercury or Pluto?

- General relativity says Gravity = Geometry



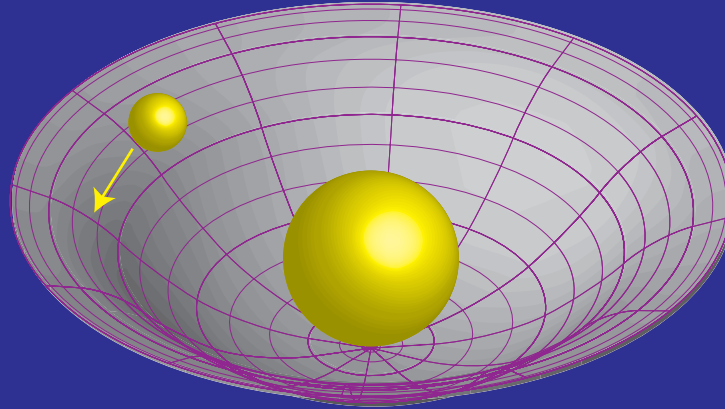
- And Geometry = Matter-Energy



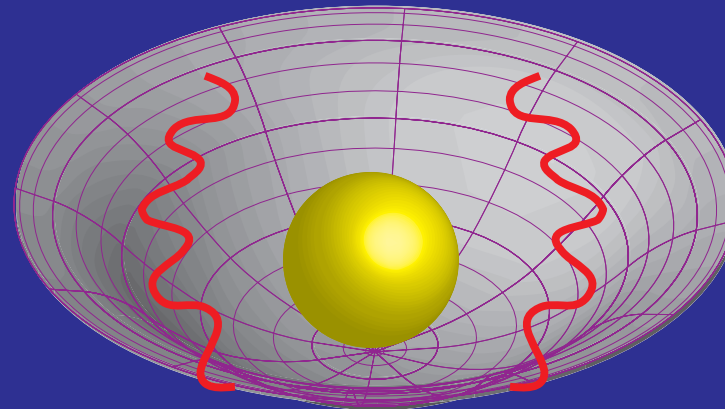
- Could the missing energy required by acceleration be an incomplete description of how matter determines geometry?

Dynamical vs Lensing Mass

- Newtonian **potential**: $\Psi = \delta g_{00} / 2g_{00}$ which non-relativistic particles feel



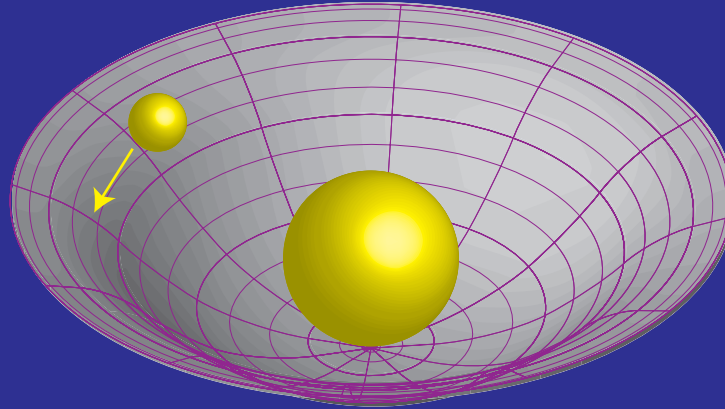
- Space **curvature**: $\Phi = \delta g_{ii} / 2g_{ii}$ which also deflects photons



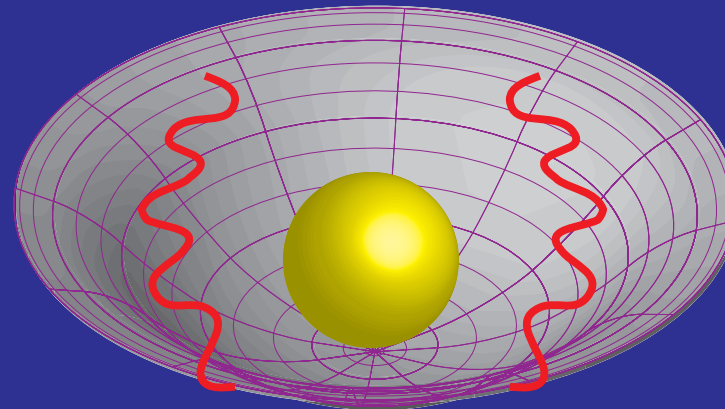
- Most of the **incisive tests** of gravity reduce to testing the **space curvature** per unit **dynamical mass**

Dynamical vs Lensing Mass

- Newtonian **potential**: $\Psi = \delta g_{00} / 2g_{00}$ which non-relativistic particles feel



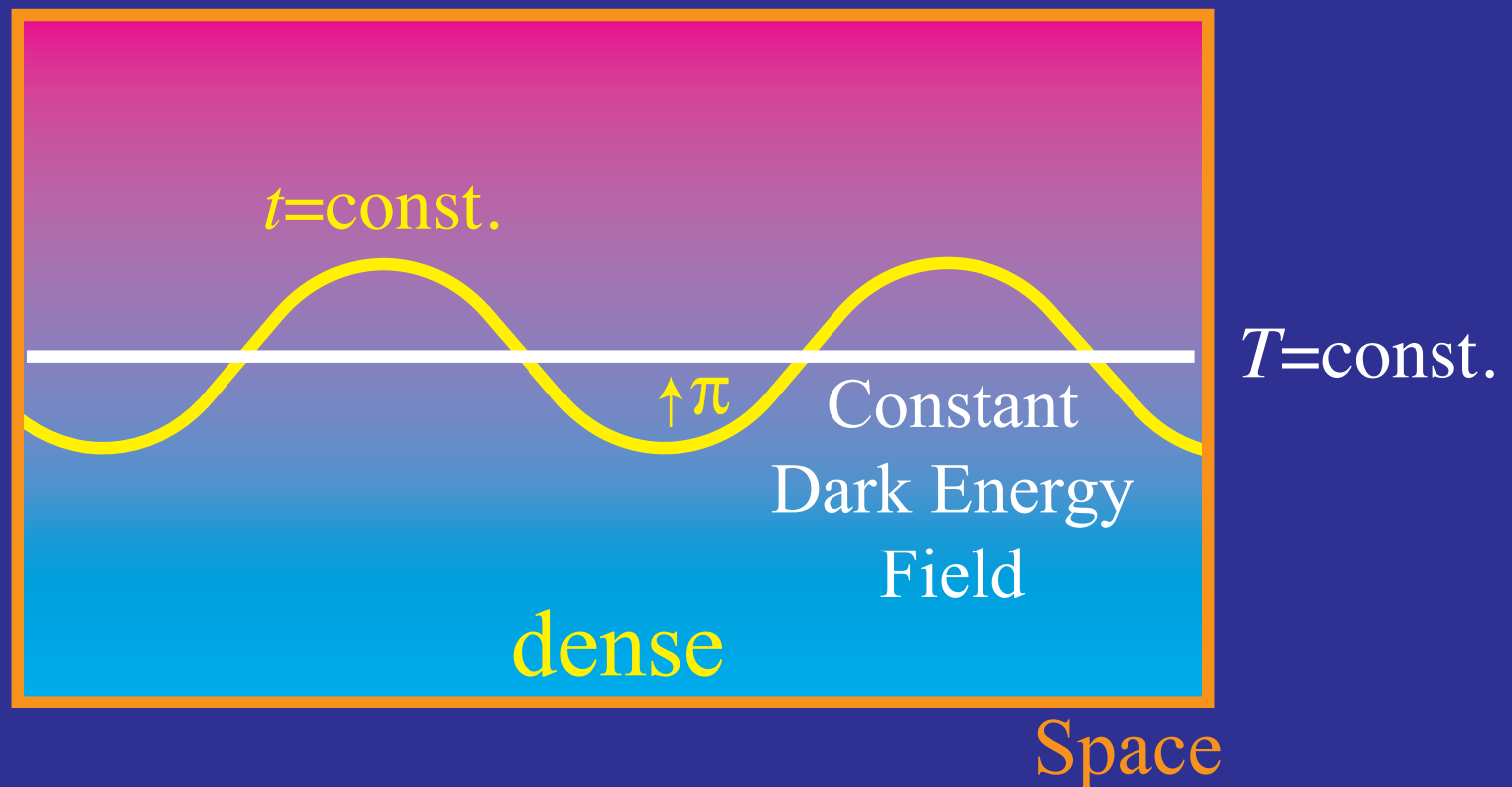
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Dark Energy as a Scalar Field

- Dark energy picks out a preferred time slicing or foliation where spatial translational invariance unbroken
- Symmetry limits the form of interactions and coupling with tensor gravity [EFT as organizing principle]
- $T=t+\pi(t,\mathbf{x})$ in a general slicing, introducing a (Stuckelberg) scalar

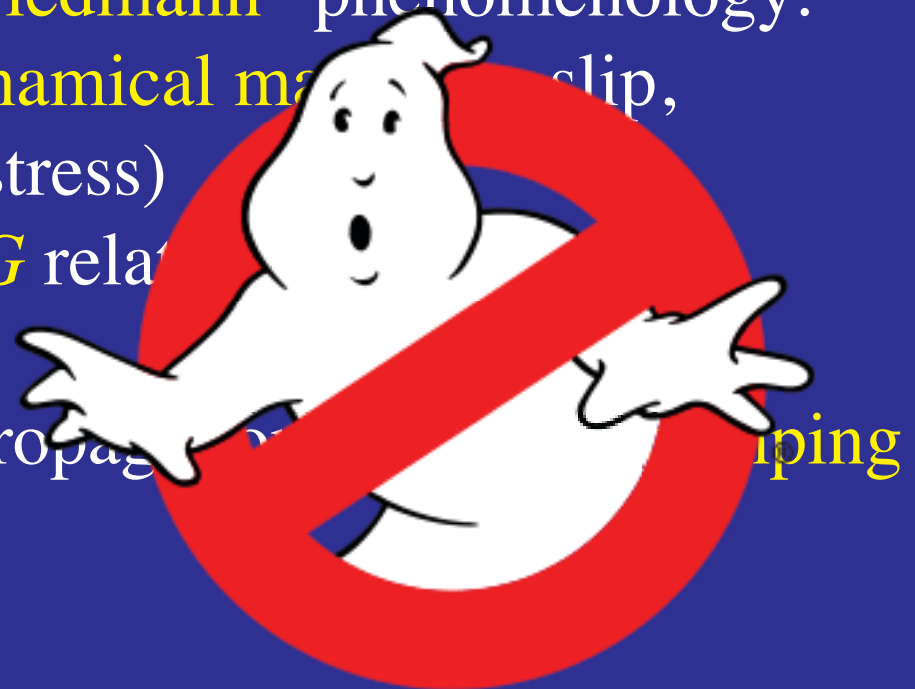


Perturbative Subhorizon Regime

- When dark energy field **nonlinearity** can be **ignored**:
Most general **scalar-tensor theory** [Horndeski++] and/or
Effective field theory
leads to
Theory with 4 free functions of time
- Specifying **perturbative “post Friedmann”** phenomenology:
Space curvature per unit dynamical mass (aka slip,
dark energy anisotropic stress)
Effective **Newton constant G** relating **potentials** to
density fluctuations
Tensor gravitational wave propagation speed and damping

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Space curvature per unit dynamical mass (slip,
dark energy anisotropic stress)
Effective **Newton constant G** relative to GR
density fluctuations
Tensor gravitational wave propagation speed (slipping)
- **Linear instabilities**:
ghost (wrong sign kinetic terms, negative energy states)
gradient instability (imaginary sound speed)



Perturbative Subhorizon Regime

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Most general **scalar-tensor theory** [Horndeski++] and/or
Effective field theory
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Theory with 4 free functions of time
- Specifying **perturbative “post Friedmann”** phenomenology:
Space curvature per unit dynamical density (dark energy anisotropic stress)
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Tensor gravitational wave propagation speed (gravitational wave trapping)
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Perturbative Subhorizon Regime

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Effective **Newton constant G** relating **potentials** to
density fluctuations
Tensor gravitational wave propagation speed and damping
- **Linearization must break down**: gravity well tested **locally**
- **Nonlinear interactions lead to screening mechanism**

Nonlinear Screening Mechanisms

- **Scalar** degree of freedom ϕ [where previously $T(\phi)$] introduces changes to the **Poisson equation(s)**

$$\nabla^2(\Phi - \Psi)/2 = -4\pi G a^2 \Delta\rho$$

$$\nabla^2\Psi = 4\pi G a^2 \Delta\rho - \frac{1}{2}\nabla^2\phi$$

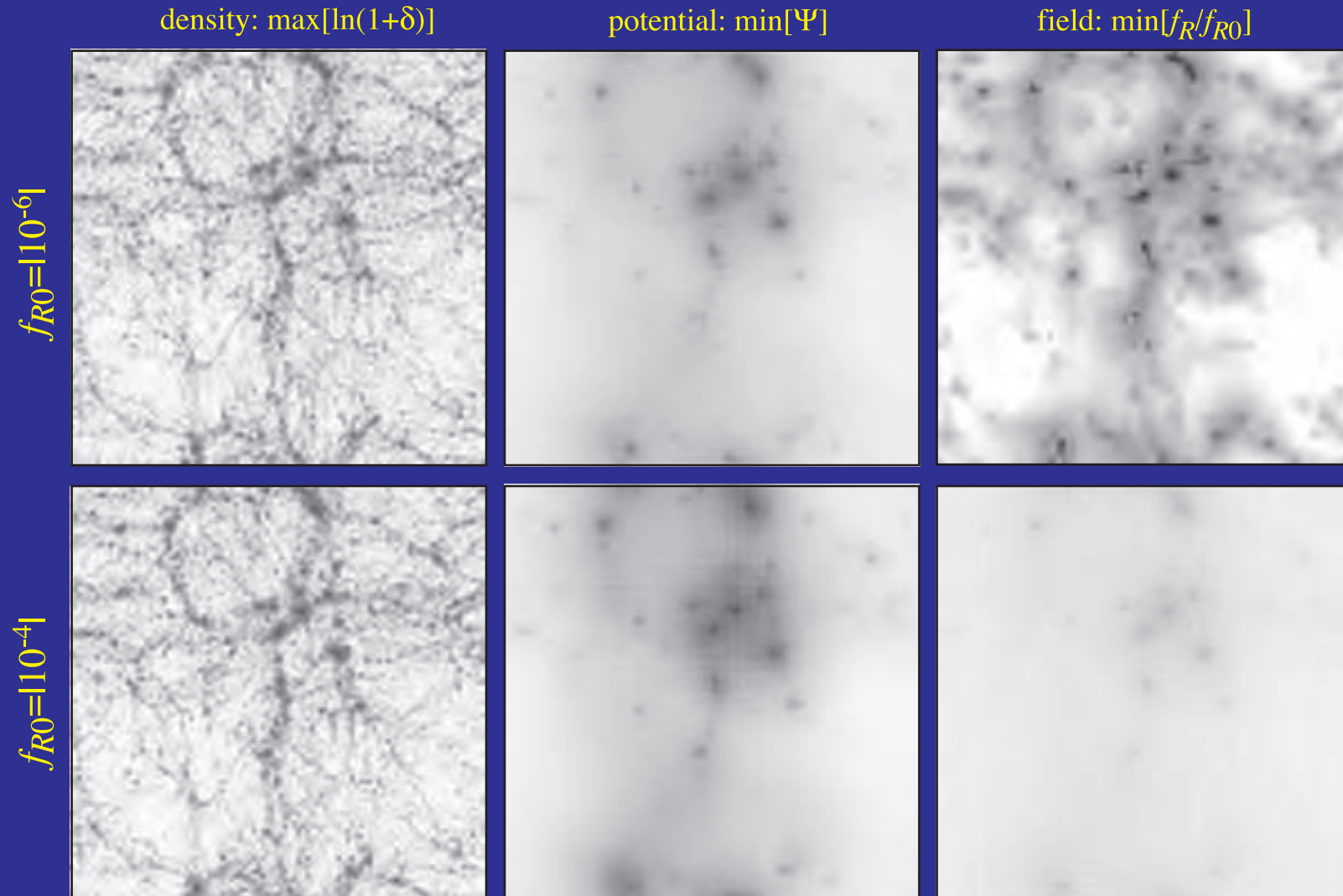
- Where ϕ depends **nonlinearly** on matter sources

$$\nabla^2\phi = g_{\text{lin}}(a)a^2 (8\pi G \Delta\rho - N[\phi])$$

- **Nonlinearity** in
 - Field: **chameleon/symmetron**
 - Field gradients: **kinetic screening**
 - Field second derivatives: **Vainshtein/galileon**
- **No superposition principle**: structure must be simulated numerically with N-body simulations

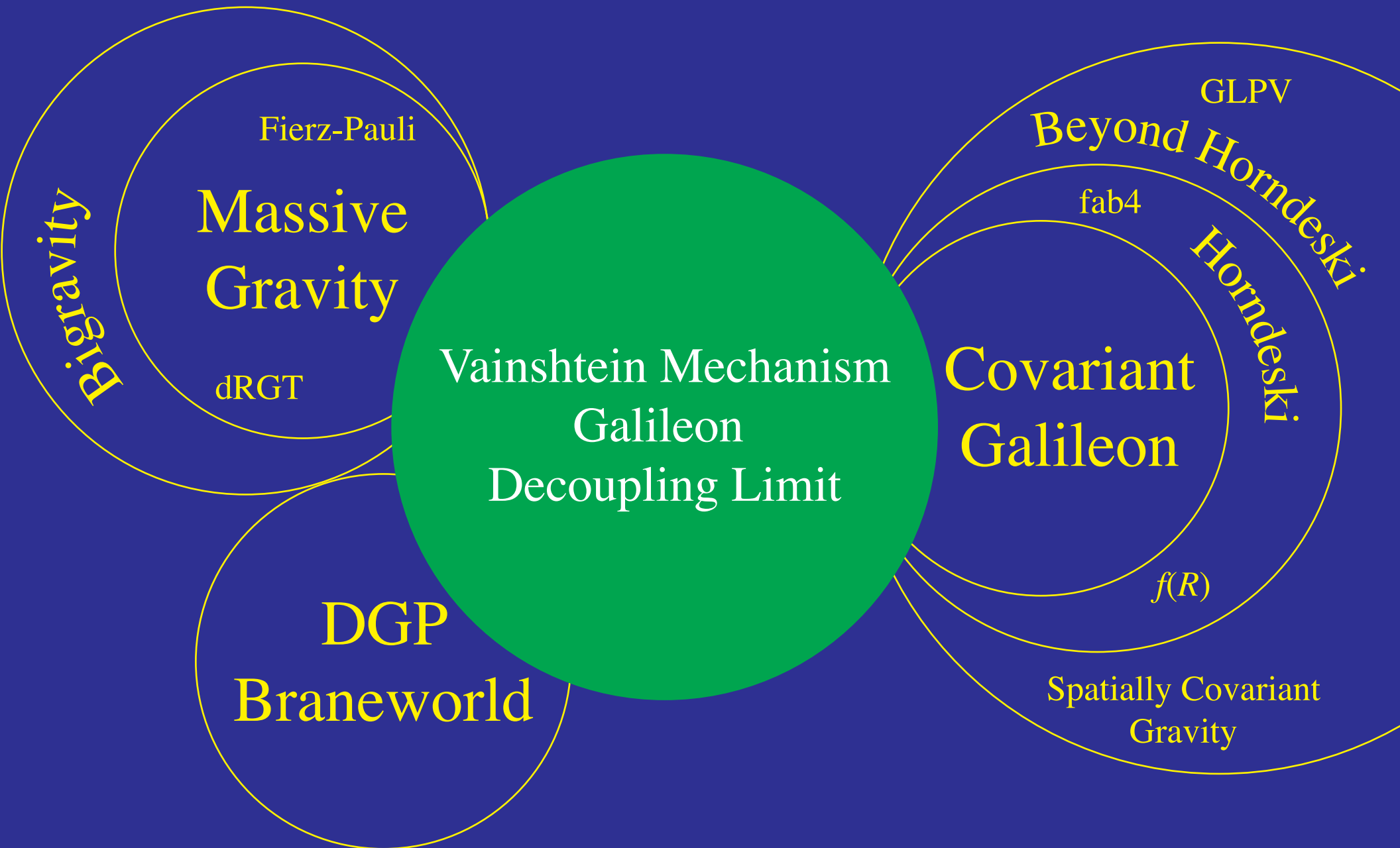
Environment Dependent Force

- For large background field, gradients in the scalar prevent the chameleon from appearing



Common Building Blocks

- Example: Vainshtein Mechanism & Galileon Symmetry

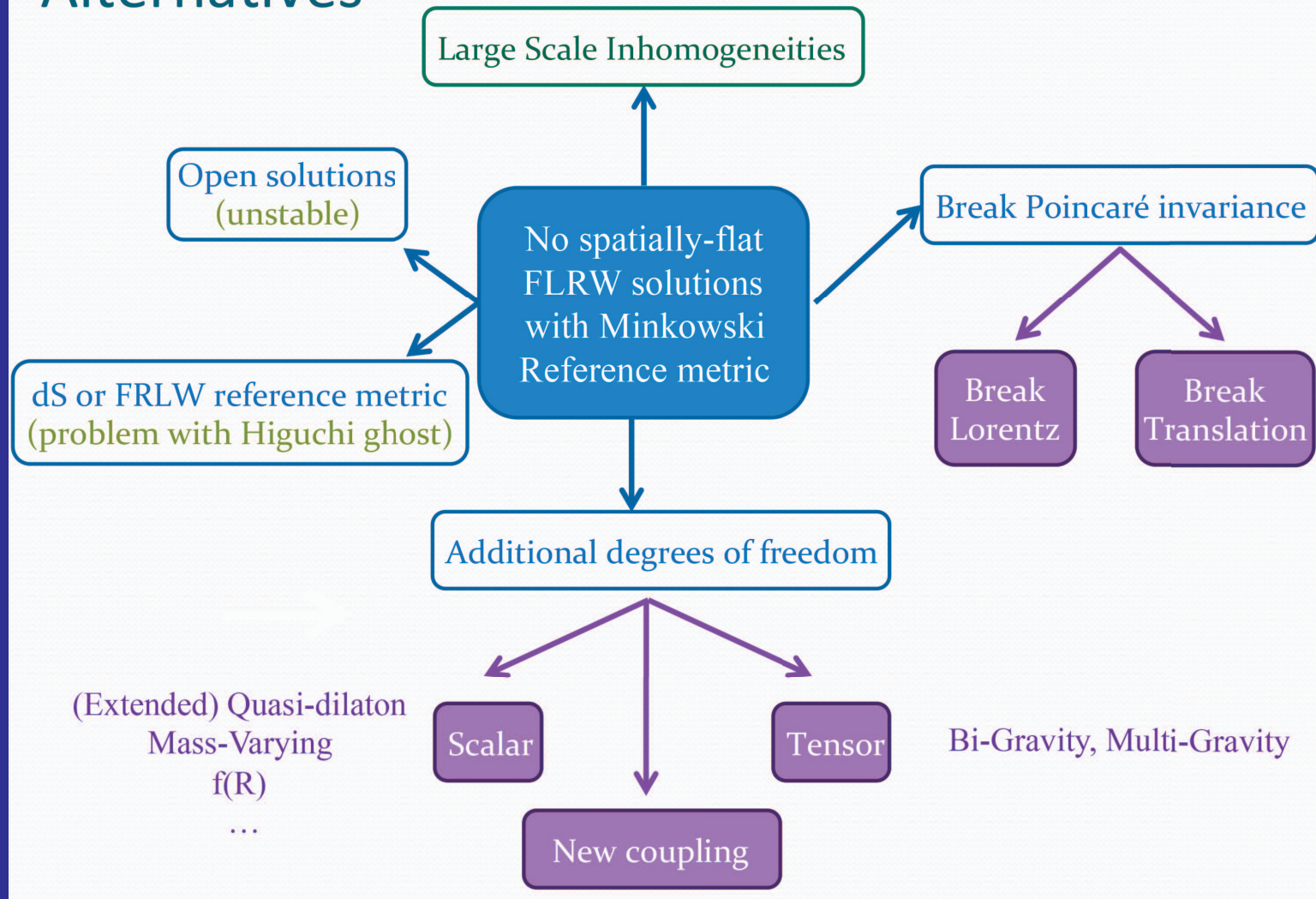


Parameterizing the Future

- General scalar-tensor and EFT akin parameterizes our current ignorance leaving future observations to guide us
Not a procedure to solve
Original Λ problem: fine tuning of vacuum energy
New Λ problem: why this finite value, why now
Not fully general: additional modes, dimensions
- Toward compelling alternative to Λ :
Provide building blocks assembled into toy models
Eliminate what cannot work
- Dark energy theory is a boom, bust field always looking for next interesting idea
- Case study: massive gravity++
Pros: degravitation, self-acceleration, Vainshtein mechanism, galileon non-renormalization, T from second metric
Cons: instabilities, strong coupling, Cauchy breakdown...

Massive Multiverse

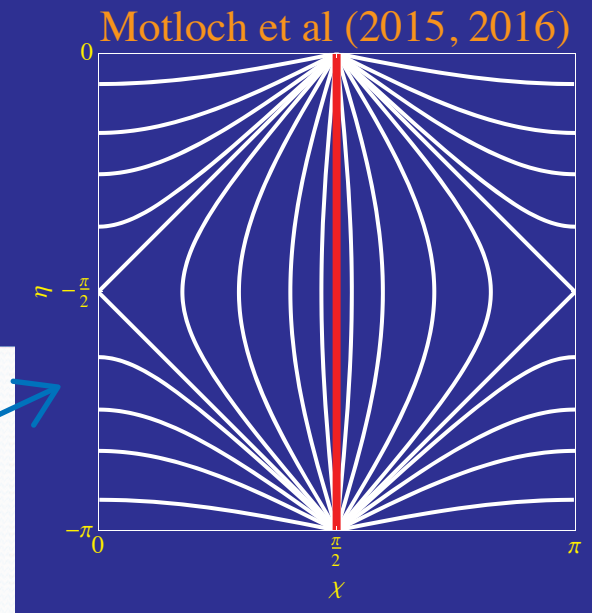
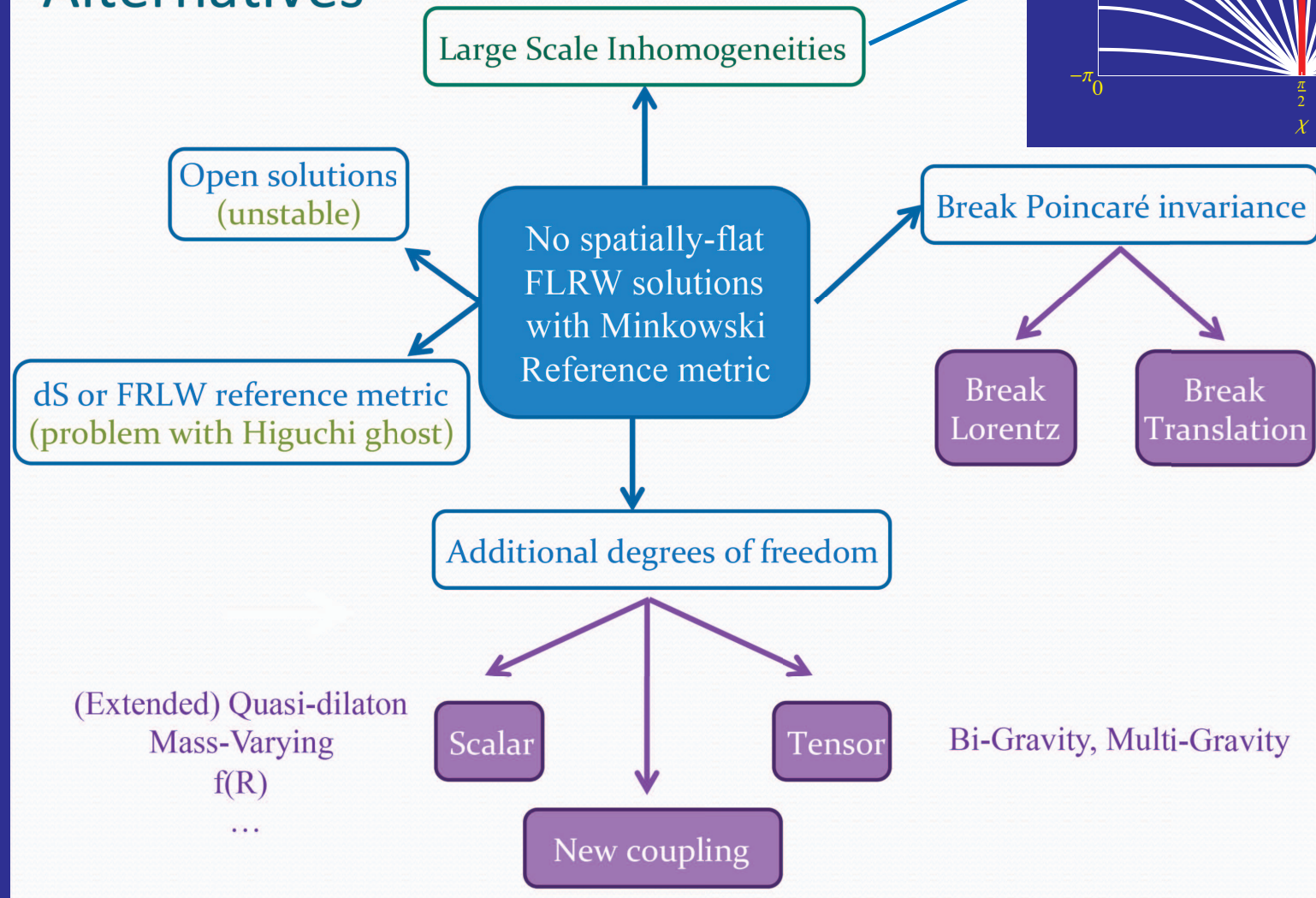
Alternatives



Massive Multiverse

Motloch et al (2015, 2016)

Alternatives



de Rham (2015)

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Stay Tuned... Josh Frieman
March 2016