# RECENT COSMOLOGICAL EVOLUTION: DARK ENERGY OR MODIFIED GRAVITY?

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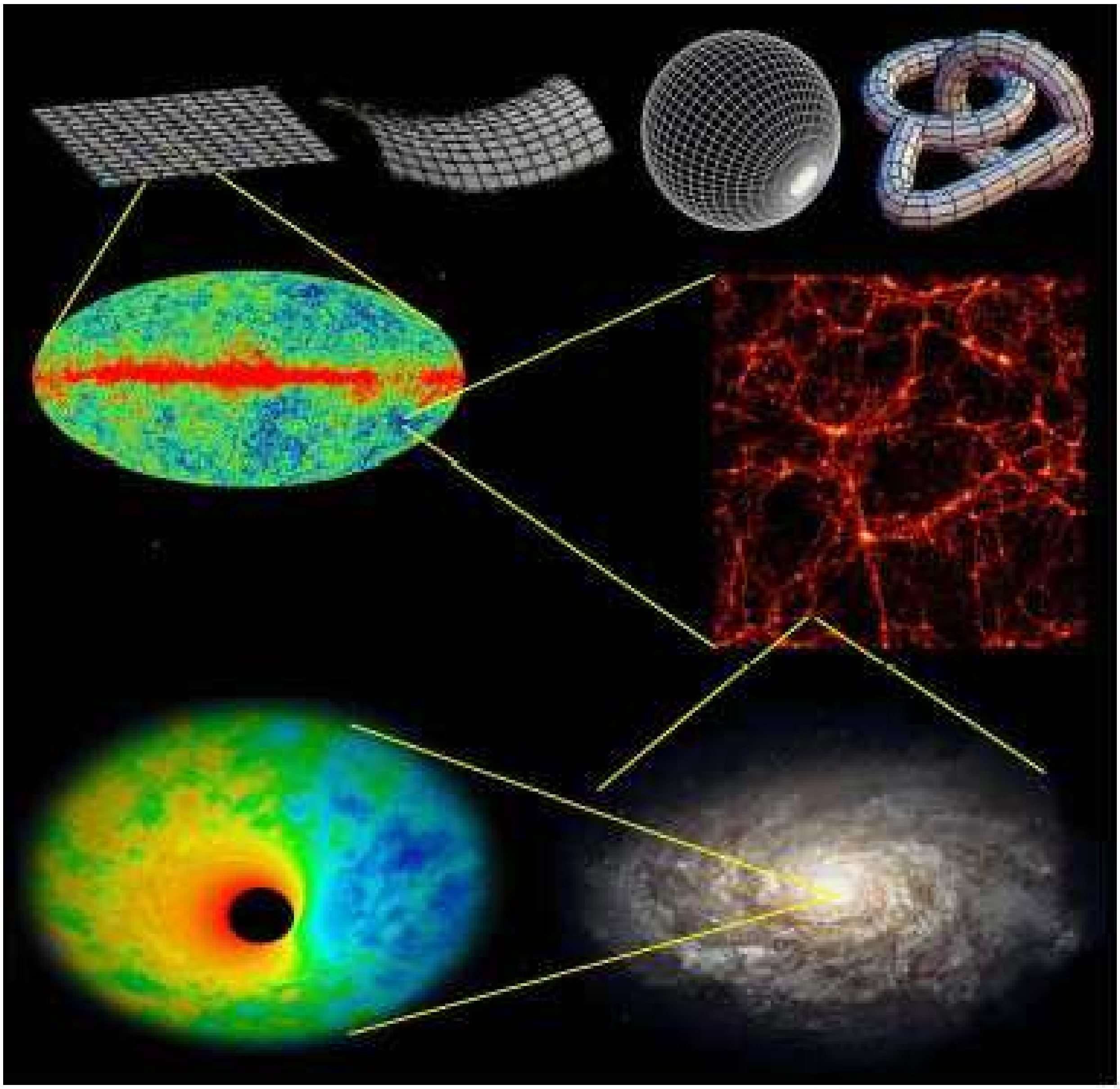


FIG. 1. Summary of the spacetime issues discussed in this article. One can use photons and astronomical objects as test particles to measure spacetime over 22 orders of magnitude in scale, ranging from the cosmic horizon (probing the global topology of and curvature of space — top) down to galaxies (giving evidence for dark matter), galactic nuclei and binary stellar systems (giving evidence for black holes). The figure illustrates how spacetime ripples at the $10^{-5}$ level will be imaged by the cosmic microwave background satellite MAP [6] and has grown via gravitational instability into cosmic large-scale structure [7], galaxies and, it seems, black holes [8].

**The Cosmological Parameters (p.210)**

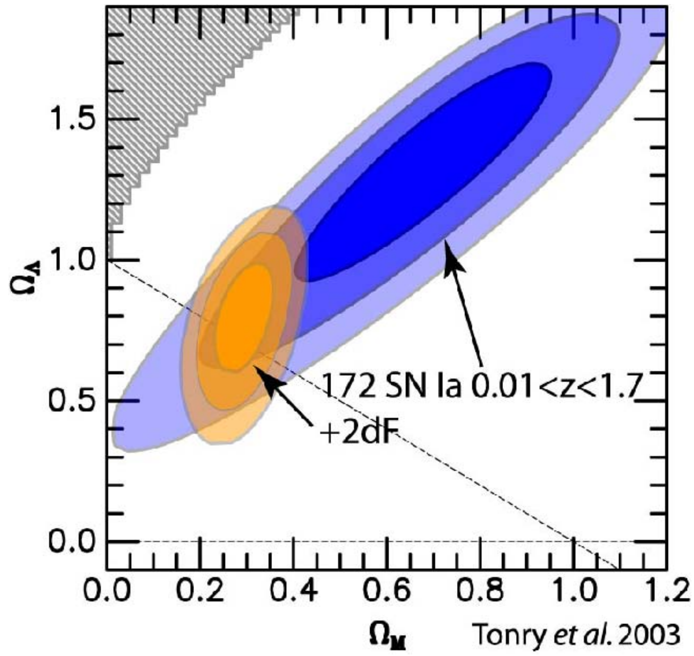



**Figure 21.1:** This shows the preferred region in the $\Omega_m$–$\Omega_\Lambda$ plane from a study of 172 supernovae, and also how the constraints tighten when the 2dF galaxy redshift survey power spectrum is added as an additional constraint. [Reproduced with permission from Tonry *et al.* [16].]

**The Cosmological Parameters (p.213)**

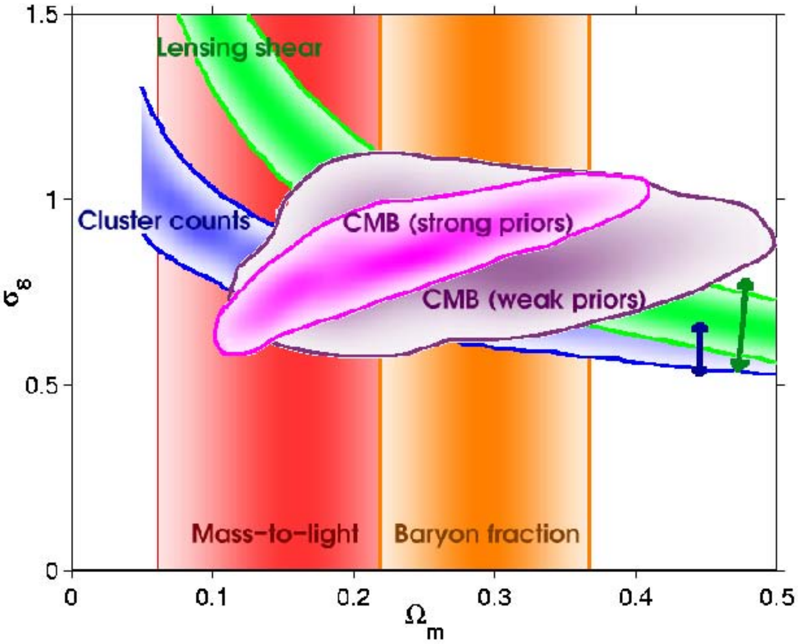



**Figure 21.4:** Various constraints shown in the $\Omega_m$–$\sigma_8$ plane. [Figure provided by Sarah Bridle; see also Ref. 42.]

# I. PRESENT UNIVERSE: FLAT, DOMINATED BY DARK ENERGY: STATIC OR NEARLY STATIC?

Assuming GR:

1. Universe is expanding $H_0 = 70\ km/sec/Mpc = 1.47610^{-33}\ eV = 0.610^{-60} M_P$

2. Universe is flat, density critical $\rho_{cr0} \equiv 3M_P^2 H_0^2 = 1.1 \times 10^{-120} M_P^4 \ll$ Planck energy density

3. Only 27% of matter clusters: $\Omega_{B0} = 0.045 \qquad \Omega_{DM} = 0.225$

4. Remainder=homogeneous **Dark Energy** with Cosmological Parameters (WMAP, LSS, Supernovae, Cosmic Shear):

$$\Omega_\Lambda = 0.70 \pm 0.04, \quad h \equiv H_0/100 = 0.70^{+0.04}_{-0.03}, \quad t_0 \approx 13.5Gyr$$

Hubble radius:$c/H_0 = 4280$

comoving distances back to inflation, recombination:$14,300Mpc$, $14,000Mpc$

5. DE does not cluster on scales $<$ supercluster $\approx 100\ Mpc$: any quantum field mass $< 10^{-31}eV$.

Tegmark et al, Phys. Rev. D **69** 10351(2004): WMAPext+SDSS

mass spectrum shape $\Gamma \equiv h\Omega_m = 0.21 \pm 0.03$

6. Direct observation of DE by comoving distances to:

- Standard Candles $d_L(z) = (1+z)\eta$
- Standard Rods $d_A(z) = \eta/(1+z)$

shows expansion is accelerating:

$$w_{Q0} = -1.02^{+0.13}_{-0.19} < -0.78 \ (95\% \ CL), \qquad w_{Q1} \equiv (dw_Q/dz)_0 = 0.6 \pm 0.5$$

Riess et al,astro-ph/0402512

(a) High Red Shift Supernova

- Early ($z \gtrsim 0.5$) SN Ia are dimmer: luminosity distances appear larger.
- Cross-over to DE dominance $DM \to DE$ about $z = 0.46 \pm 0.13$
- Present EOS consistent with both $\Lambda CDM$ ($w_Q = -1$) and with $w_Q(z)$ now rapidly decreasing towards -1

(b) Rich clusters of galaxies: X-ray luminosity confirms $d_L(z)$

7. Concordance Model $\Lambda CDM$. Nevertheless, we might prefer **Dynamical DE** in order to

- Explain Very Small Vacuum Energy $\rho_{vac0} = 10^{-120} M_P^4$

- Explain Coincidence Problem $\rho_{vac0} \sim \rho_{B0} \sim \rho_{cr0}$

- Dynamics May Illuminate Cosmological Phase Transitions: Inflation, RD, MD, QD

- Predict new matter

8. Dynamical Theories, Distinguishable by Sound Speed→Fluctuations

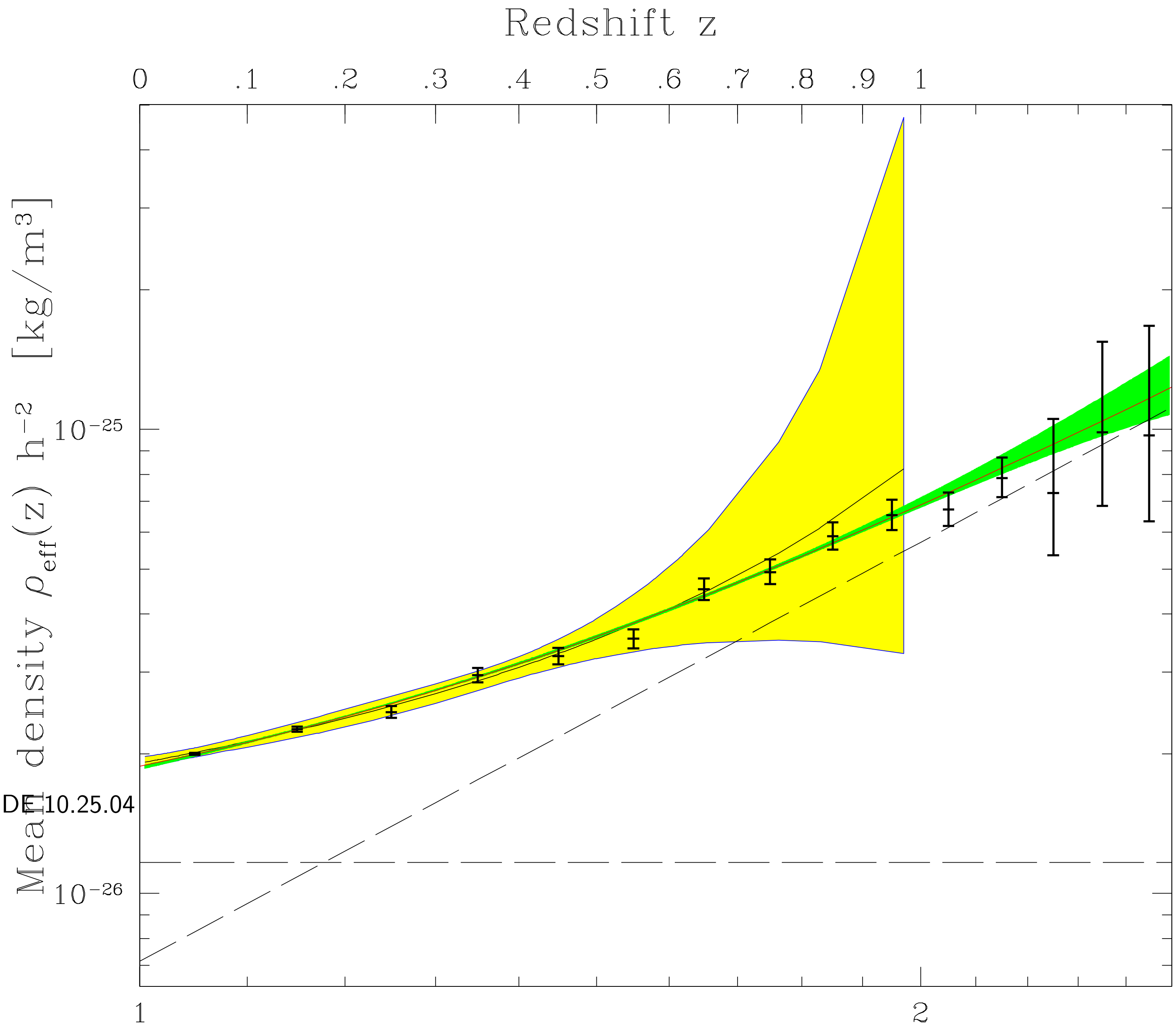
- Cosmological Fluid with EOS $P = P(\rho)$

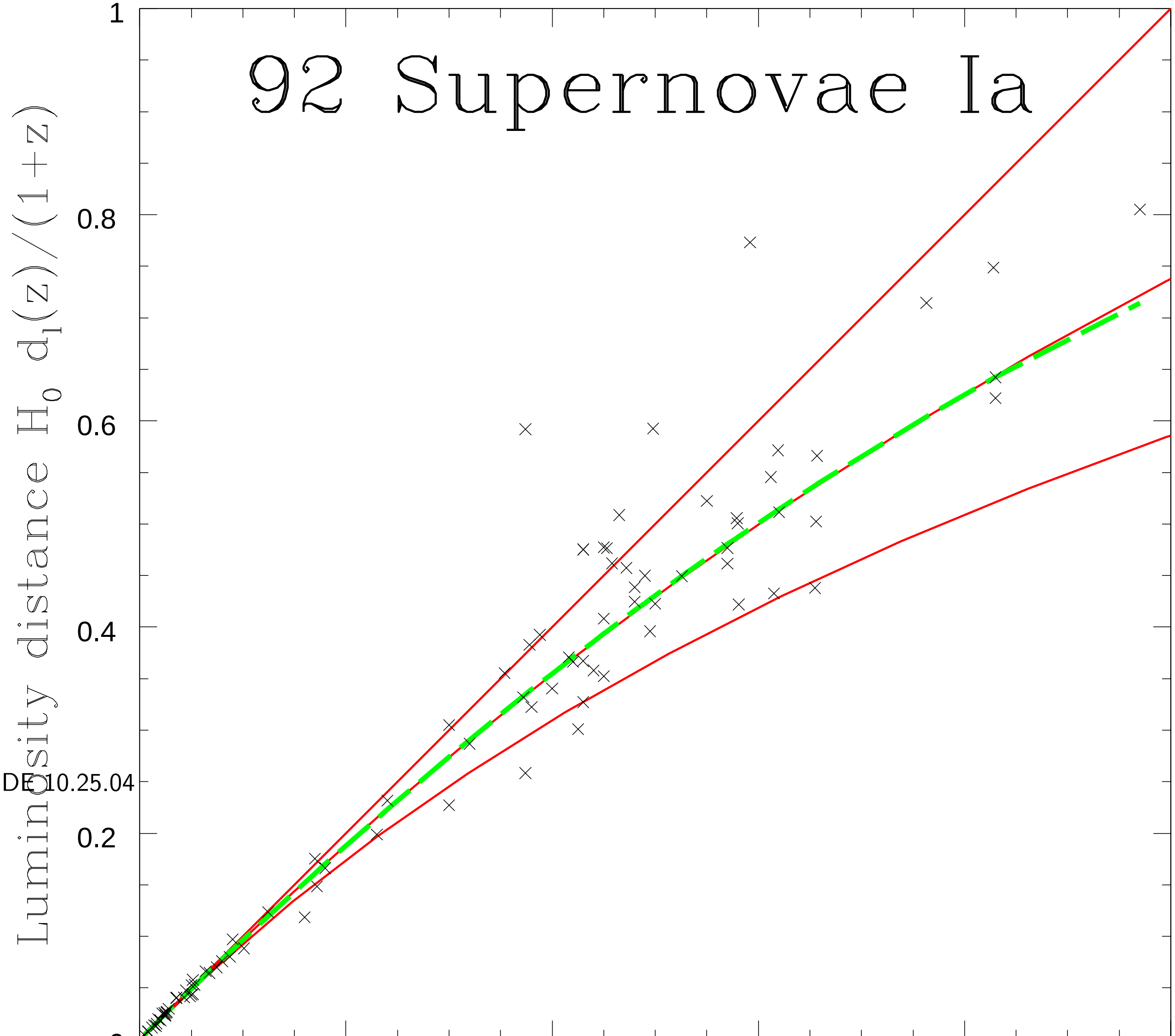
- Scalar Field with KE $=$canonical (Quintessence)/non-canonical (k-essence)

## II. COSMOGRAPHY: ACCELERATING HOMOGENEOUS ISOTROPIC FLAT UNIVERSE

**Evolution H(z)** directly observable in

- SN luminosities
- galaxy angular diameters
- weak and strong lensing
- cluster abundances/volume
- CBR radiation and mass power spectra


Redshift z
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 1
Mean density $\rho_{eff}(z)\ h^{-2}$ [kg/m$^3$]
$10^{-25}$
$10^{-26}$
1
2


92 Supernovae Ia
Luminosity distance $H_0\ d_l(z)/(1+z)$
1
0.8
0.6
0.4
0.2

1. **Kinematics in terms of** $H \equiv \dot{a}/a$, Hubble horizon $1/H \equiv -d\eta/dz$ comoving time:

$$\eta \equiv c\int_0^t dt'/a(t') = c\int_z^0 dz'/H(z').$$

## DISTANCES

Luminosity distance to **Standard Candles** $\quad d_L = (1+z)(\eta_0 - \eta)$

Angular distance to **Standard Rods** $\quad d_A = (\eta_0 - \eta)/(1+z)$

comoving Hubble horizon: $1/\mathcal{H} \equiv 1/aH = d\eta/dN$

$N \equiv \ln a, \qquad dN = -d\ln(1+z) = Hdt = \mathcal{H}d\eta$

expansion: $dV/V = 3dN = 3Hdt = 3\mathcal{H}d\eta$

Ricci space-time curvature: $\quad R \equiv -6(\dot{H} + 2H^2)$

acceleration: $\ddot{a}/a = H^2 + \dot{H}, \quad \ddot{a}/aH^2 = 1 - dH^{-1}/dt = -d(1/\mathcal{H})/d\eta$

is positive when comoving horizon shrindks with advancing time.

## 2. **First Law=Energy Conservation**

| | |
|---|---|
| energy density | $\rho_Q = \rho_Q(N)$ |
| pressure | $P = -d(\rho V)/dV = -\rho - d\rho/3dN \equiv w\rho$ |
| enthalpy | $\rho + P/c^2 = -d\rho/d\ln V = -d\rho/3dN$ |
| barotropic index | $\gamma \equiv -d\ln\rho/3dN = (\rho + P/c^2)/\rho \equiv 1 + w$ |

# GRAVITATIONAL THEORIES

1. **Einstein-Friedmann Gravity:**

$$\varkappa^2 \rho = 3H^2, \qquad \varkappa^2(\rho + P/c^2) = -2\dot{H} > 0$$
$$R = \varkappa^2(\rho - 3P/c^2), \qquad \ddot{a}a/\dot{a}^2 = -(1+3w)/2$$

requires $-1 < w \equiv P/\rho < -1/3$.

Einstein-Friedmann cosmology observationally confirmed for times $> 1$ minute by:

(a) BBN Abundance of Light Elements

(b) Evolution of primordial density fluctuations

- CBR temperature anisotropy
- LSS power spectrum

(c) Age $H_0 = \int_0^\infty d\eta/(1+z), \qquad t_0 = 13.5\ Gyr$

(d) Solar system tests

Accelerating Einstein-Friedmann universe requires Dark Energy $(w_Q \Omega_Q < -1/3,\ w_Q < -0.48$ now dominating the universe.

2. **Concordance Model** Cosmological constant $\Lambda \equiv \varkappa^2 \rho_{vac}$

$$H = H_0 t_0 \sqrt{\Omega_{m0}(1+z)^3 + \Omega_{vac}}$$

$$a(t) \propto \sinh^{2/3}(\frac{2}{3}\sqrt{\Lambda/3}ct) \to t^{2/3}, \exp(\sqrt{\Lambda/3}t$$

when matter-,vacuum dominated.

3. **Modified Gravity Theories**: Introduce an additional **low-energy ($\rho_{vac}^{1/4} = 2\ meV$), late time** scale:, require no DE, but are subject to Ötvos constraints on Weak Equivalence Principle.

1. 4-D:scalar-tensor gravity

2. branes: gravity propagates in higher dimensional bulk, matter only on branes. Gravity is modified at a new scale
   - high-density (early time): $m \sim 10^{-33}\ eV$ (Randall-Sundrum)
   - low-density (late time): $M \sim 100\ MeV$ (Defayet, Dvali, Gabadadze)

3. Usual to regard Einstein eqn: lhs=geometry, rhs=matter.

Can always **define** density $\varkappa^2\rho \equiv 3H^2$, so that modifications to Friedmann equation are regarded as extra **classical**fields, more or less physical: e.g.

- cosmological constant (l.h.s. or r.h.s. of Einstein eqn)
- scalar-tensor gravity (new geometry or non-minimally coupled scalar field)

$$\varkappa^2\rho_{eff} \equiv 3\delta H^2, \qquad \gamma_{eff} \equiv -d\ln\rho_{eff}/3dN$$

4. **Many cosmologies track towards "attractor"**, independent of ICs over more-or-less broad basin of attraction

Cosmological Acceleration. Static or Dynamic? **What constitutes DE?Potentially Observable: EOS (homogeneous) and Fluctuations (inhomogeneities)**

1. Global Homogeneous Fluid Equation of State $P = P(\rho)$. **Early Dark Energy:** Appreciable $\Omega_Q \geq .05$ back to last scattering at $z \sim 1100$. Can influence clustering of DM, baryons. SN luminosity distances are sensitive to $\Omega_Q$.
2. Material constituents (interacting or not) $\rightarrow$ **effective sound speed, viscosity**: Pressure Fluctuations=adiabatic(curvature)+isocurvature(entropic)

$$\delta P = c_{ad}^2 \delta\rho + \delta P_{nad}$$

Besides density (curvature) fluctuations, complex fluid or scalar field also supports **entropy fluctuations**:

$$\delta P_{nad} = P_{,\phi} \delta\phi$$

3. **Effective sound speed**

Effective Sound Speed: $c_s^2 \equiv \delta P/\delta\rho = \dot{P}/\dot{\rho} \qquad = c_{ad}^2 + P_{,\phi}\dot{\phi}/\dot{\rho}$

Adiabatic Sound Speed: $c_{ad}^2 \equiv (dP/d\rho)_{ad}$

Dispersion relation: $\omega(k)^2 = c_s^2 k^2 + V_{,\phi\phi}$

mass: $V_{\phi\phi} \geq 10^{-31} eV$

Jeans Length: $\lambda_J \equiv c_s \sqrt{\pi/G\rho}$

4. Sound speed effects

- Acoustic oscillations CMB anisotropy spectrum $(C_l)$
- Mass power spectrum $(P(k))$: linear growth factor $g(z,k) \equiv (1+z)\cdot\delta(z,k)/\delta(0,k)$

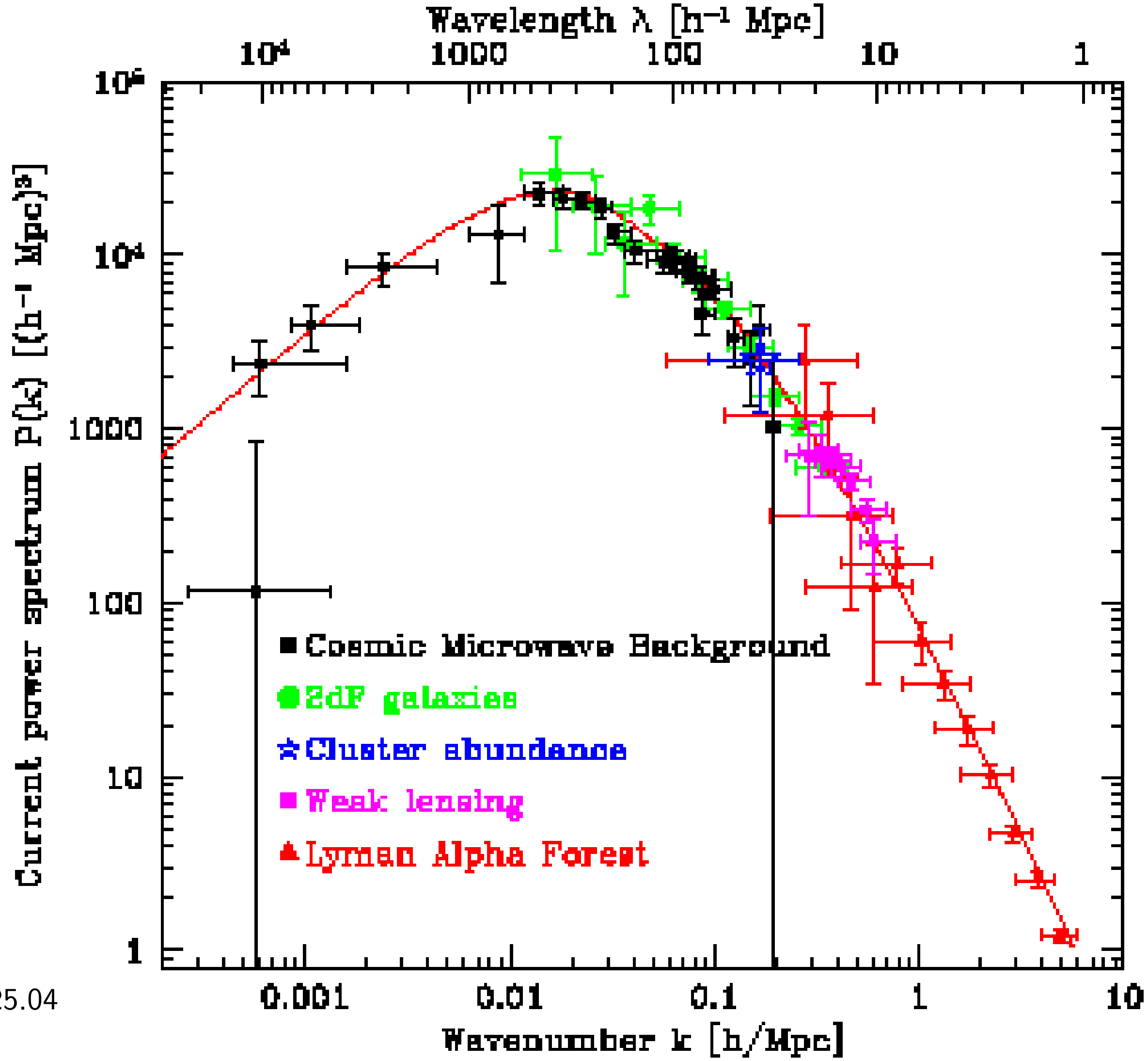







FIG. 4. Measurements of the current ($z = 0$) power spectrum of density fluctuations computed as described in [63], assuming the matter budget of [19] and reionization at $z = 8$. The CMB measurements combine the information from all

# III. DYNAMICAL MODELS FOR DE: COSMOLOGICAL FLUIDS

Simple perfect fluid $P = P(\rho)$ $w \equiv P/\rho$

two non-interacting fluids $\rho = \rho_B + \rho_Q$ $1 = \Omega_B + \Omega_Q$

$$w \equiv P/\rho = w_B \Omega_B + w_Q \Omega_Q$$

=Background+Time-Dependent Cosmological Constant

1. **Simple Perfect Polytropic Fluid**: Generalized Chaplygin Gas

$$P_{CG}(\rho) = -A/\rho^{\alpha}$$

behaves like CDM fluid $\rightarrow$ cosmological constant. Supports only adiabatic fluctuations: $\delta P_{nad} = 0$

$$w = P/\rho = 0 ... w_0, \quad c_{CG}^2 = dP/d\rho = -w\alpha < \alpha < 1$$

2. **Complex Fluid**: Dark Energy+Baryon Background expand at different rates, $\rightarrow$ out-of-equilibrium, bulk viscosity. Supports entropy fluctuations.

Bento, Bertolami & Sen, astro-ph/0407239

Amendola, Finelli, Burigana & Carturan, JCAP **0307** (2003) 005

# IV. DYNAMICAL MODELS FOR DE: SCALAR FIELDS

1. Can be made dynamic in various ways. Scalar fields may be realistic or only a way of modelling dynamics. Some scalar models do derive from supergravity, strings, M-theory.

2. Many scalar fields show **attractor** properties: from broad range of ICs, evolve to present universe, without fine tuning:

   - Fixed attractor=exponential potential $V''/V = (V'/V)^2 \equiv \lambda^2,\ \Omega_Q(z) = const$

   - Instantaneous attractors: $1/\beta(\phi) \equiv (1/\lambda)' = -\lambda'/\lambda^2 \ll 1$. Good attractors are steep, close to exponentials, but allow $\Omega_Q$ to slowly increase since BBN. (**Early Quintessence**)

- Tracking requires **fast roll** $\lambda^2 \gg -\lambda',\ w_{Qtr} \lessapprox w_B \approx 0$
- Present **slow roll** $w_Q \to -1$ requires $-\lambda' \gg 1$ (**roll-over** towards potential minimum) $\eta - \lambda^2 = -\lambda' \gg \lambda^2$ e.g. SUGRA (modified Inverse Power), Skordis-Albrecht (modified exponential)
- Can influence fluctuations, provided $c_s^2 \ll 1$ over broad range

3. Interesting Scalar Fields Generally Make *Imperfect Fluids*

$$P = P(\rho, \phi),\ w_Q = w_Q(z)$$

4. Even If EOS is Same, Perfect Fluids & Scalar Fields

- Chaplygin Perfect Fluid $P(\rho) \sim -1/\rho$
- Scalar Field $V(\phi) \sim \cosh 3\phi + 1/\cosh 3\phi$

have different pressure fluctuations, sound speeds.

5. Scalar Field Minimally Coupled to Einstein Gravity:

$$\mathcal{L} = \sqrt{-g}[2M_P^2 R + \mathcal{L}_\phi(X, \phi)], \qquad X \equiv (\partial_\mu \phi)^2/2$$

$$\mathcal{L}_\phi = P \;\; \text{Pressure,} \qquad \rho_\phi \equiv \dot{\phi}\partial\mathcal{L}_\mathcal{Q}/\partial\dot{\phi} - \mathcal{L}_\mathcal{Q} = 2XP_{,X} - P$$

For linear (canonical) kinetic energy: $P = K - V(\phi), \quad \rho_\phi = K + V(\phi)$ .

## 6. Sound speed

$$\rho_{,X} = P_{,X} + 2X \cdot P_{,XX}$$

$$\delta P = c_{ad}^2 \delta\rho + P_{,\phi}$$

total derivatives: $$\dot{P} = c_{ad}^2 \dot{\phi} + P_{,\phi}\dot{\phi}$$

effective sound speed: $$c_s^2 \equiv P_{,X}/\rho_{,X} = c_{ad}^2 + P_{,\phi}\dot{\phi}/\dot{\rho}$$

determines growth of scalar field perturbations.

# DYNAMICAL PROBES DISTINGUISH COSMOLOGICAL FLUIDS, CANONICAL/NONCANONICAL SCALAR FIELDS

1. Cosmological Fluids

- Simple perfect fluid: barotropic $\delta P = c_{ad}^2 \delta\rho, \qquad c_{ad}^2 = -w\alpha < 1$

- But complex fluids, admit entropy fluctuations.

2. Scalar Fields: $\delta P_{nad} = V_{,\phi}\delta\phi$ supports entropy fluctuations

- Linear KE: Canonical Quintessence $K = X,\ P = K - V,\ P_{,X} = 1$

$$c_s^2 = c^2, \qquad c_{ad}^2 = 1 + V_{,\phi}\dot{\phi}/\dot{\rho}$$

  Tracks, but doesn't explain "Why now?".

- Non-linear KE (higher order derivatives): $K(X) \neq X$ Sound speed is scale dependent.

$$\rho_{\phi,X} = P,X + 2XP_{,XX} > P_{,X}, \qquad c_s^2 < c^2$$

  Tracks only in Radiation Era. In Matter Era, $w \approx -1$, as observed. Allows long wavelength perturbations to grow.

# V. OBSERVATIONAL CONSTRAINTS ON DYNAMICAL MODELS

1. **CBR**: heights of 3 acoustic peaks+overall normalization+angular peak location is used to fit 6 parameters: $\Omega_\Lambda, \omega_d, \omega_b$; reionization depth $\tau$; initial conditions $A, n_s$

2. **non-CBR**: LSS, SN, weak lensing needed to remove model degeneracy

# Sound Speed→Jeans Length→ Fluctuations

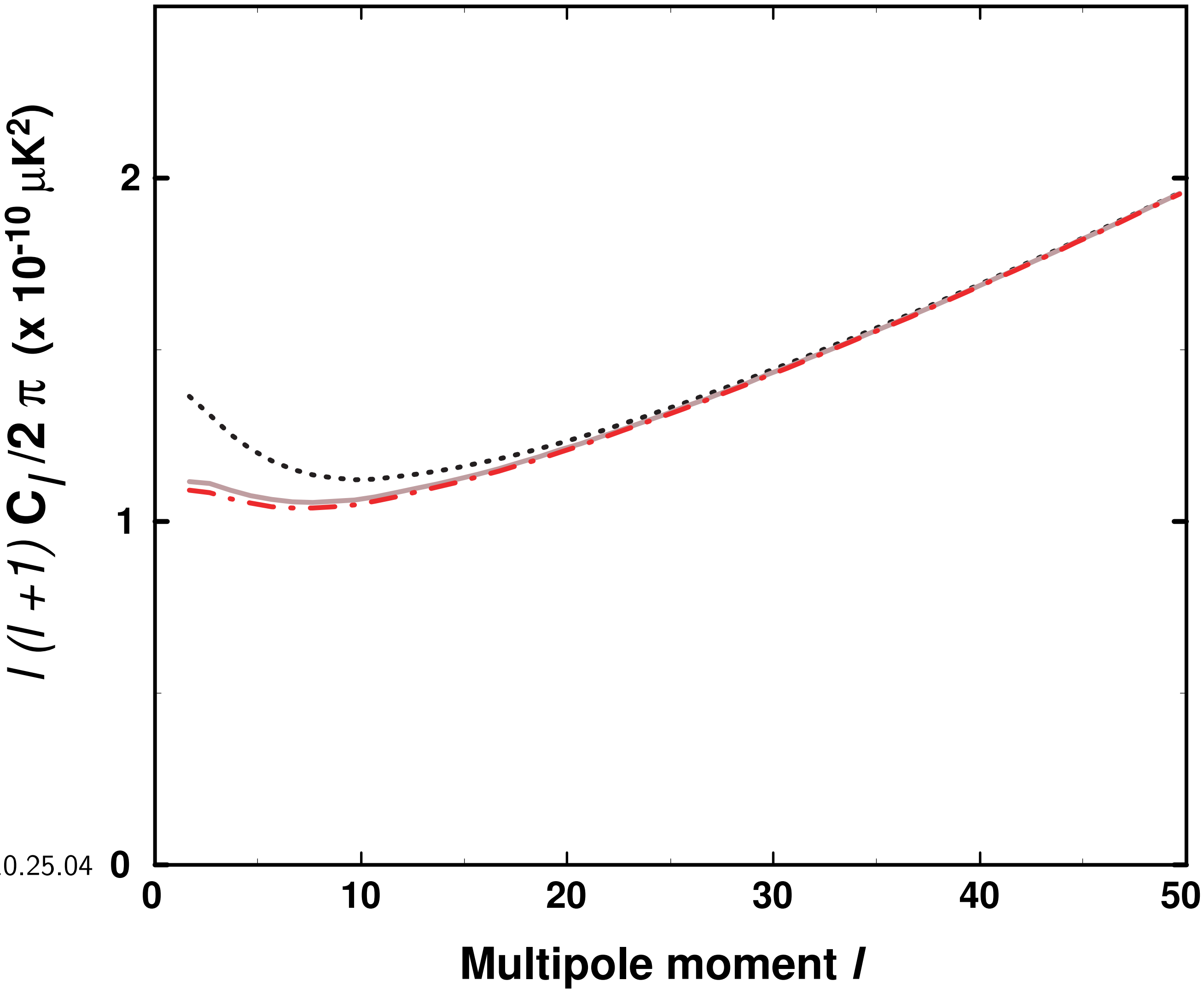
1. EOS $w(z)$ in high red-shift **supernovae** $z \lesssim 1.8$: Luminosity distances $d_L(z)$ **insensitive to EOS**

2. **CBR Temperature Fluctuations** are small, for quintessence with $w_Q < -1/3$.

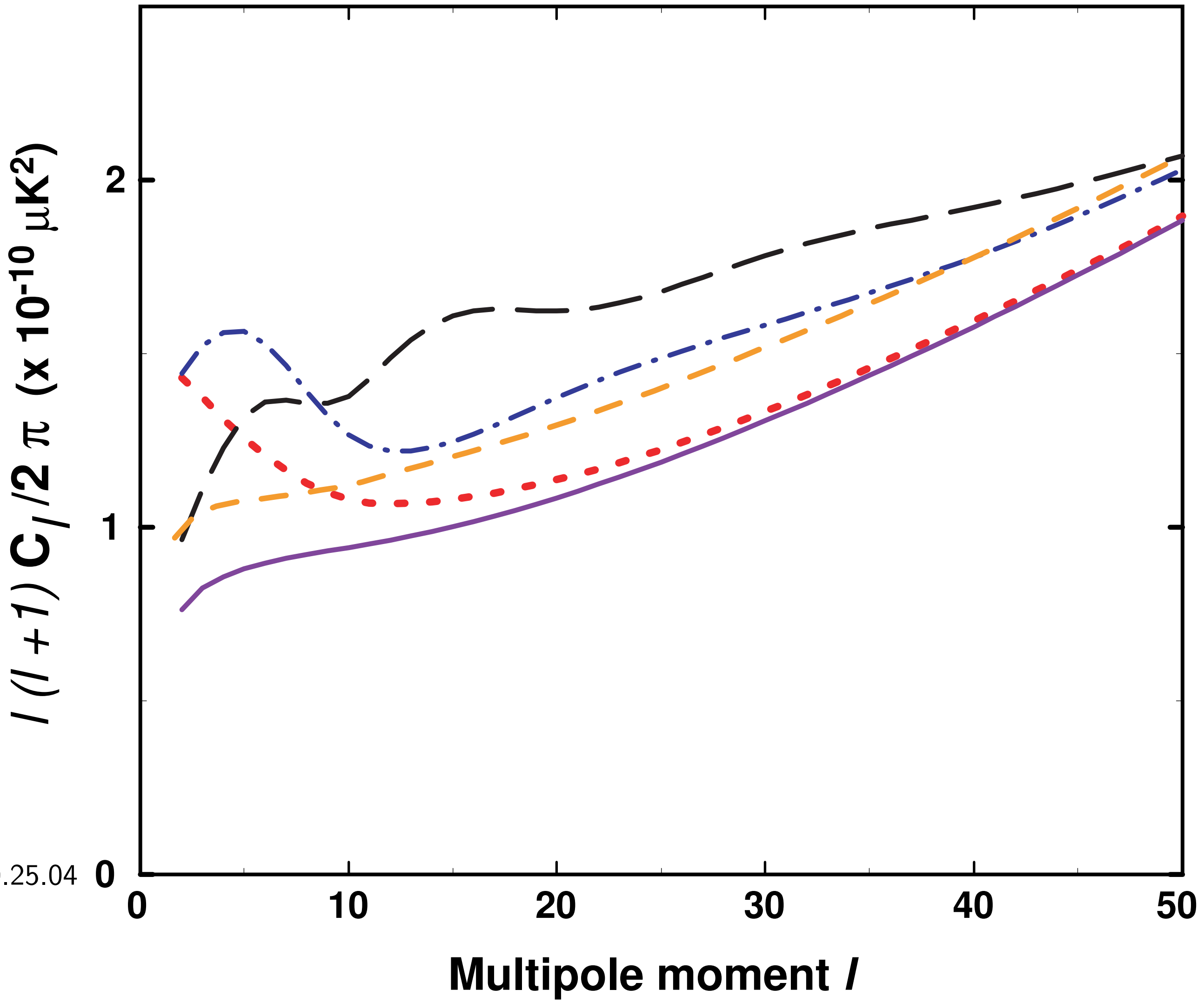
   - Small Angular Scale ($l > 400$):Fluctuations are weak when entering horizon (Fig. 3)

   - Large Angular Scale ($l < 20$): (Fig. 6)

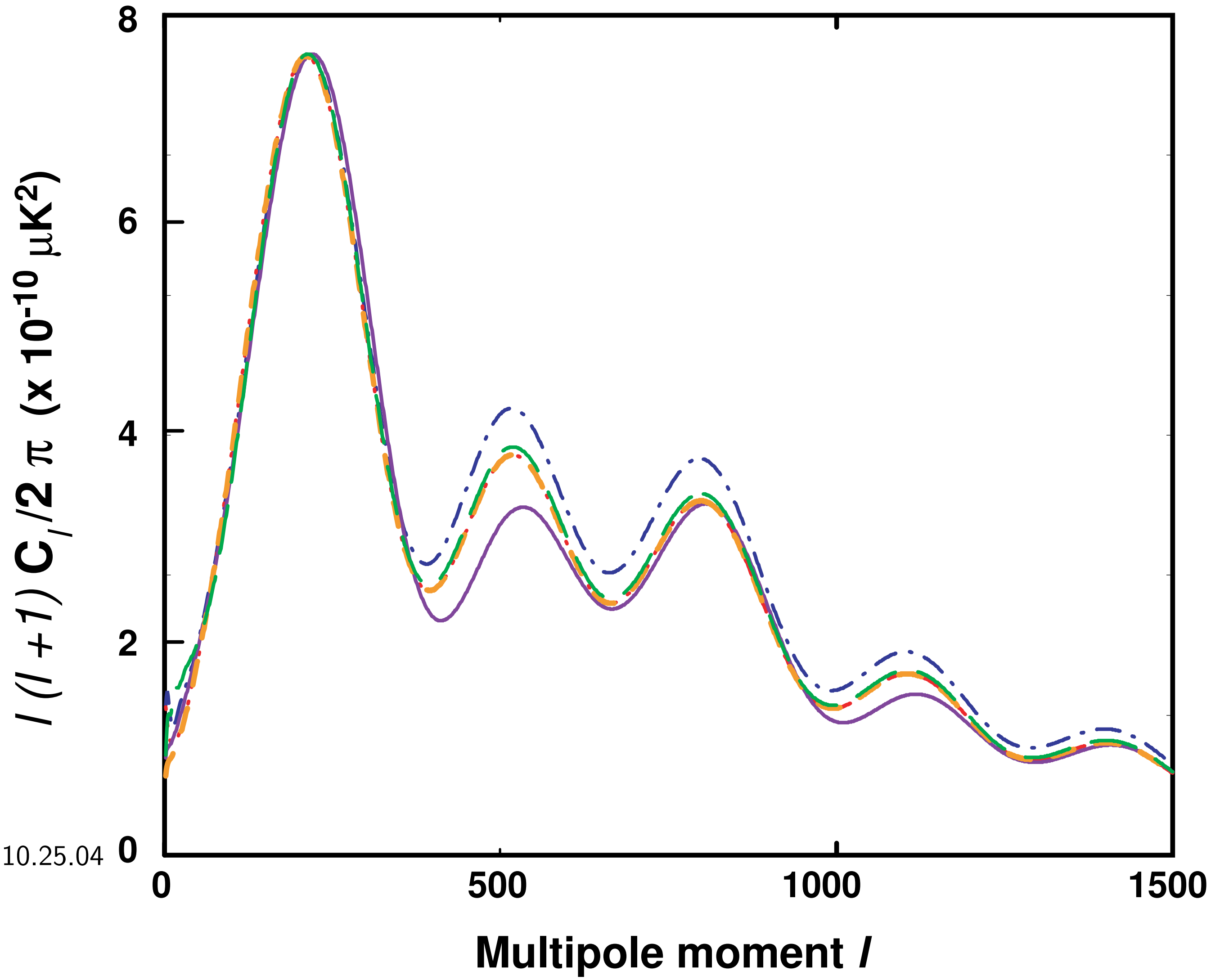
DeDeo, Caldwell & Steinhardt, Phys. Rev. D67, 103509



$l\,(l+1)\,C_l/2\pi$ (x $10^{-10}$ μK$^2$)
2
1
0
0
10
20
30
40
50
Multipole moment $l$



2
1
0
0
10
20
30
40
50
Multipole moment $l$
$l\,(l+1)\,C_l/2\pi$ (x $10^{-10}$ $\mu K^2$)


8
6
4
2
0
0
500
1000
1500
Multipole moment l
l (l +1) C_l /2 π (x 10^-10 μK^2)

3. **Small Sound speed** $c_s^2 \ll 1$, if $\Omega_Q \geq 0.01$ and **if** k-essence. Early quintessence influences DM, baryon clustering. Caldwell et al, astro-ph/0302505

   (a) **Temperature Power Spectrum**
   - Low multipole moments $l < 20$ WMAP, Planck, SDSS **may** distinguish perfect fluid or canonical/non-canonical scalar fields. But, $dw_Q/dz > 1$ already rules out k-essence?
   - Higher multipole moments $l > 400$

   (b) **Mass power spectrum shape**: Can show bumps, oscillations at small scales $< 100 Mpc$.

   (c) **CBR polarization**

# VI. CONCLUSIONS: DYNAMICAL SCALAR FIELDS, COSMOLOGICAL FLUIDS

1. Tracking Quintessence Requires **two** Cosmological Coincidences. Good trackers must have quintessence domination *and* slow-roll *both* beginning recently, as in
   - Supergravity-inspired (SUGRA) models $V \propto \phi^{-\alpha} \cdot \exp{(\kappa\phi)^2/2}$
   - Albrecht and Skordis $V \propto \phi^{\mu} \times \exp{(\lambda\phi)^{\beta}}$
   Time in which we live is special in *two* ways!

2. k-essence would explain cosmological coincidence "Why now?", but is ruled out if $dw/dz > 0$

3. Cosmological fluid without microscopic scalar field?

4. Alternative gravitational theories (higher dimensions, branes) avoid DE, but also require fine tuning of potential and/or initial conditions, that tracking hoped to avoid)