MEASURING DARK ENERGY PARAMETERS TO SELECT THEORETICAL MODELS

I. Cosmology: Test Bed for Gravitational Theories

II. Parametrization of Current SN, CBR, BAO Observations

III. Beyond the Concordance Model

IV. Critique of Dark Energy/Dark Gravity Theories

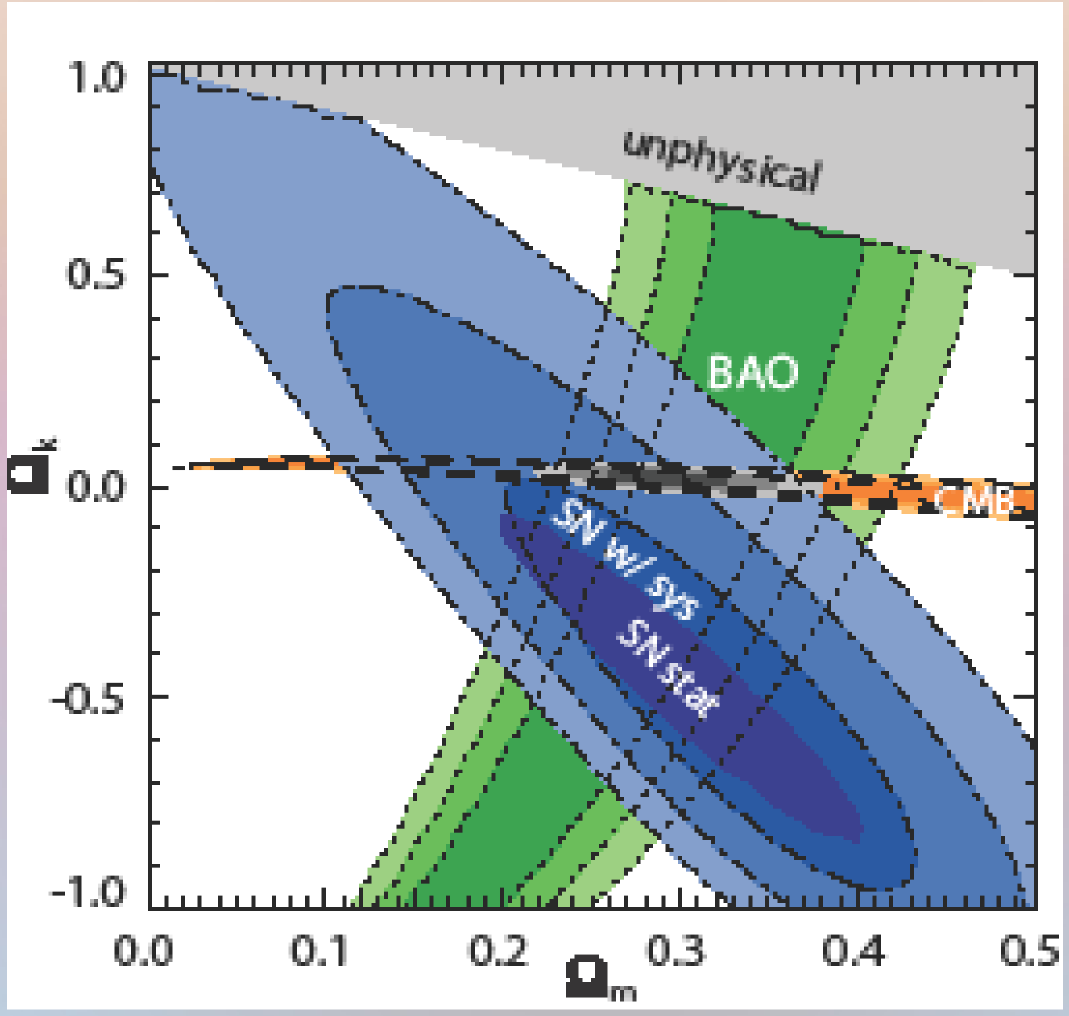
V. Conclusions: Phenomenological and Epistemological

I.HOMOGENEOUS/ISOTROPIC UNIVERSE: FRW

- A. Anisotropic about us: otherwise would distort Sunyaev-Zeldovich spectrum from distant sources
- B. Inhomogeneity:is poorly tested at large scale:
  - Small-scale inhomogeneity: would effect Friedman expansion eqn, effect light propagation in lumpy universe.
  - Large-scale inhomogeneity (Lemaitre-Tolman-Bondi): We may live near center of a large bubble extending to z~0.08 !!!
- C. Cosmological Principle assumes homogeneity->

Friedman-Robertson-Walker Cosmology .

FLATNESS:BEST CONSTRAINT FROM CMB



Kinematics=Cosmography=Description of Homogeneous Evolution in Space-Time)

1) Red-Shift cosmological, has nothing to do with motion of source or observer

$$dt = a\,d\eta = d\eta/1+z, \qquad \lambda = (1+z)\lambda_{proper} \;.$$

2) Positive/negative frequencies evolve differently into future/past-> particle production/annihilation in accelerating universe.

KINEMATICS OF FRWCOSMOLOGY

Conformal (comoving) time: $d\eta = dt/a(t)$

Hubble Expansion Rate: $H := da/adt$

Comoving Hubble Expansion Rate: $\mathcal{H} = da/dt = aH$

Deceleration

$$q(t) \equiv -a\ddot{a}/\dot{a}^2 \equiv -1 - \dot{H}/H^2$$

PROPER DISTANCE MEASUREMENTS DETERMINE EXPANSION RATE H(t)

Proper Distance $ds^2 = -dt^2 = -a^2 \ d\eta^2$

1. Luminous Flux $L = F/4\pi \ d_L^{\,2}(z), \qquad d_L(z) = (1+z)\eta$

Apparent dimming of SN fluxes measures luminosity distances back to "standard candles".

2. Angular Size $\theta_A = r_s(z)/d_A(z), \qquad d_A(z) = \eta \ /(1+z)$

Acoustic oscillations in baryon-photon fluid (CMB) at z=1089, luminous red galaxies at z~0.35 measure angular sizes, distances back to "standard rulers".

II.COSMOLOGICAL MEASUREMENTS

- A. GEOMETRIC (KINEMATIC, GRAVITATIONAL)
  - 1. SNIa magnitude-redshshift relation->$d_L(z)$
  - 2. CBR last scattering surface $\eta(z=1100)$
  - 3. BAO ->transverse size $d_A(z)$, $H(z)$

B. PHYSICAL (DYNAMIC)

1. Dynamical age of Universe

2. Galaxy Clustering: power spectrum, growth factor

3. CMB Power Spectrum

- 4. Gravitational Lensing: strong, weak (cosmic shear)

What is Dark Energy?

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3P\right) + \frac{\Lambda}{3}$$

We observe ä>0 about z~0.4, which can happen in 3 ways:

- ΛCDM: Non-zero cosmological constant: $\Lambda > 0$
- Dark Energy: Universe is dominated by some particle or field with: $\rho + 3P < 0$

  $$w = (P/\rho) < -(1/3)$$

- Above GR equation must be modified: Dark Gravity

HOW DO WE OBSERVE ACCELERATION?

- 2 indirect observables:
  - Distance-redshift relation for SN, BAO, CBR: comoving distance $\eta(z) \equiv$

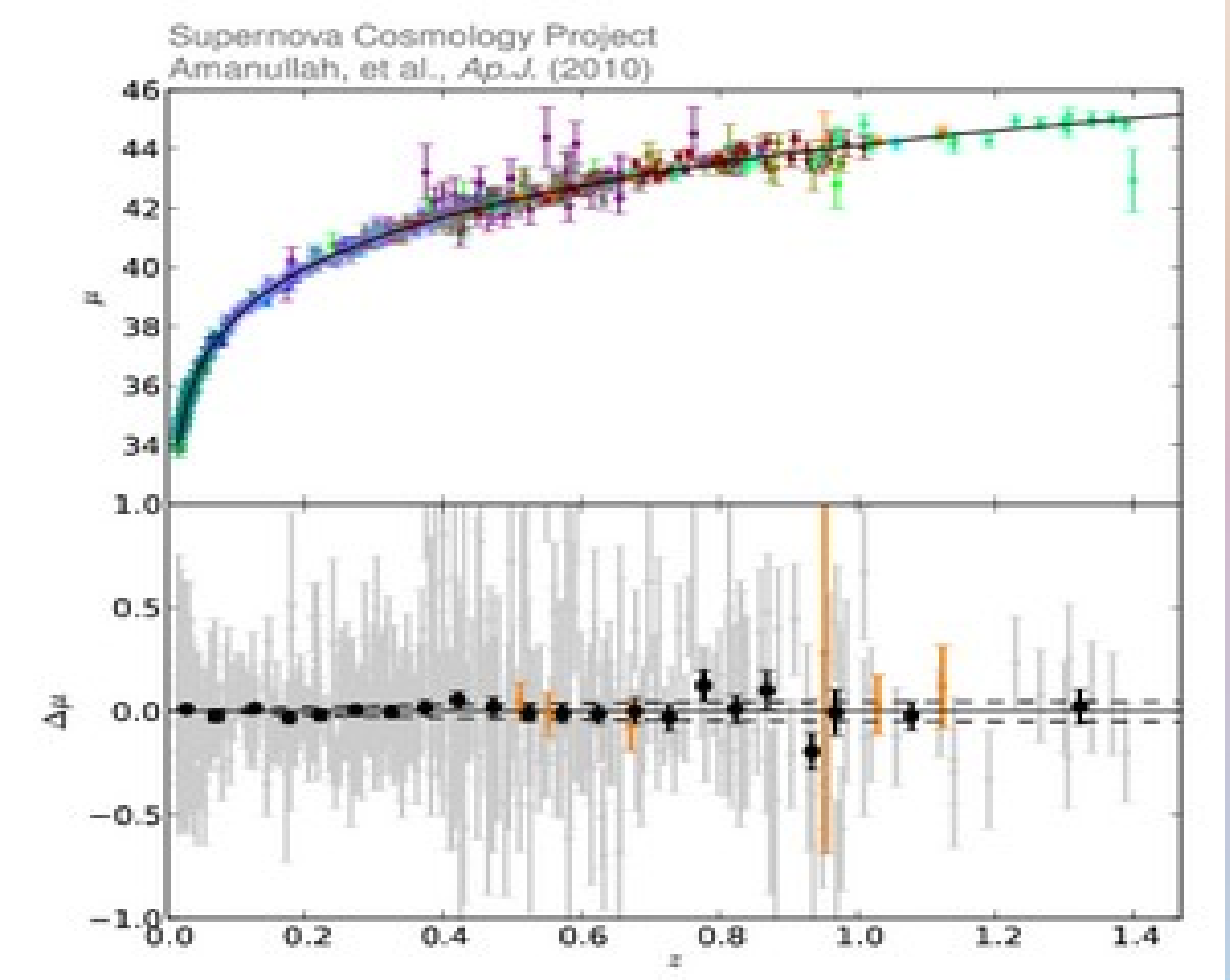
$$D(z) = \int_0^r \frac{dr'}{\sqrt{1-kr'^2}} = \int_t^{t_0} \frac{dt'}{a(t')} = \int_0^z \frac{dz'}{H(z')}.$$

    - Luminosity Distance $d_L(z)=(1+z)\eta$: "standard candles"
    - Angular Diameter Distance $d_A(z)=\eta/(1+z)$: "standard rulers"
- If GR is correct, both should agree $d_L(z)\, d_A(z)=\eta(z)^2$
  - Growth of structure:
    - Gravitational collapse competes with expansion
    - Parametrized as a function of redshift by a "growth factor", the mass function of clusters, amplitude of PS, etc

How do we measure DE?

- A. Supernovae:
  - use SN as “standard candles”.
- B. Baryon Acoustic Oscillations:
  - use the size of the sound horizon of pre-recombination acoustic waves in the CMB as a “standard ruler”.
- C.CLUSTERS
  - Use the “cluster mass function” as a function of redshift to measure the growth of structure.
- D. WEAK LENSING
  - Measure the “shear field” statistically-> both expansion history and growth history.
- FULL POWER SPECTRUM MODELLING

A. SUPERNOVA HUBBLE DIAGRAM: MAGNITUDE DIMINISHING WITH REDSHIFT

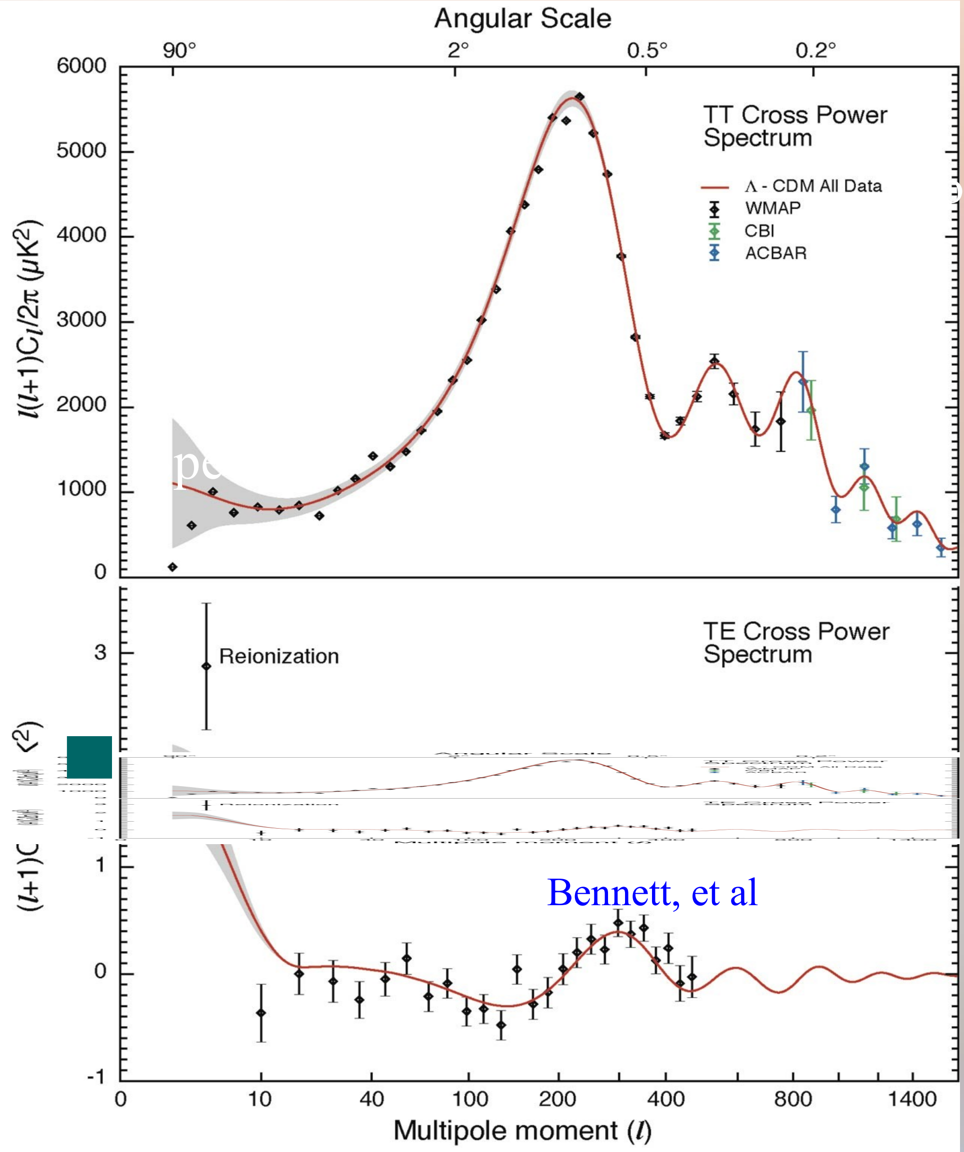


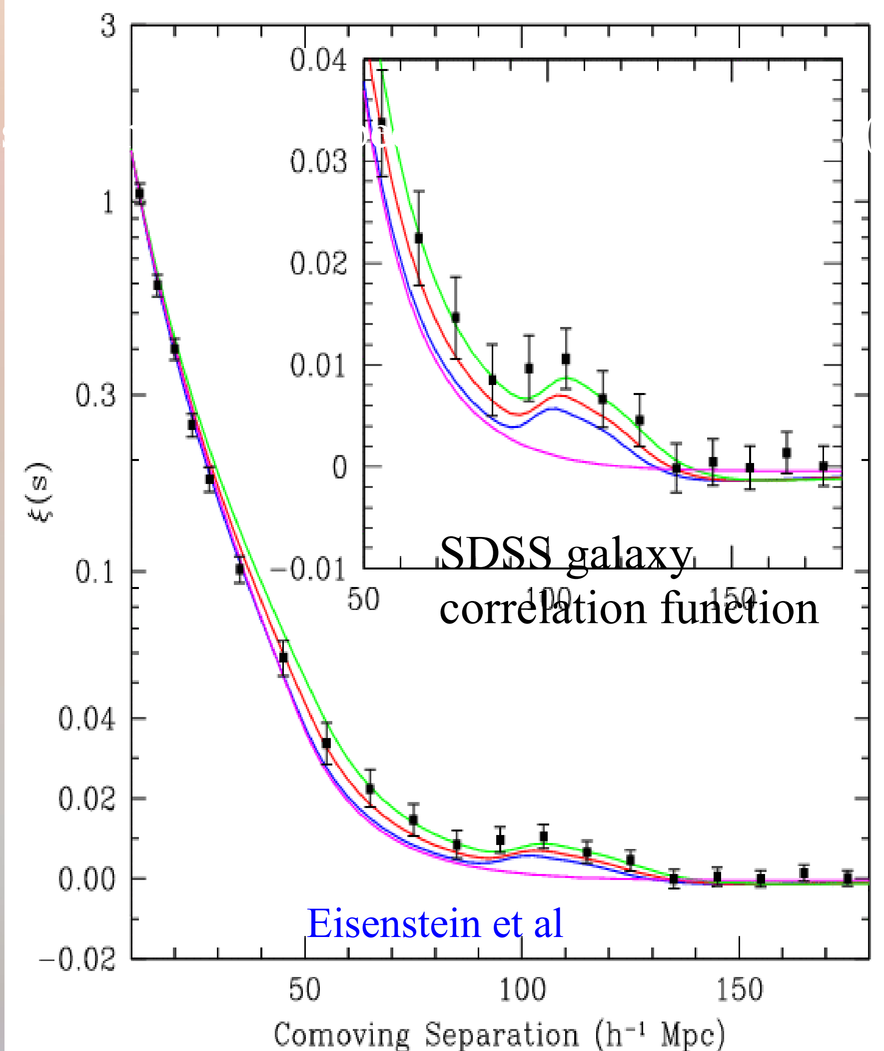
B.BARYON ACOUSTIC OSCILLATIONS IN LUMINOUS RED GALAXIES

- Baryons decouple from photon expansion at z_{decoup}=1089
- Baryon acoustic waves stall, imprint themselves on CBR as density excess at sound horizon =146.8±1.8 Mpc =standard ruler
- $d_A(z)$, H(z) are observed at z=0.2, 0.35 in LRG
- Amplitude bump reveals growth function of baryons+dark matter

CBR CORRELATION FUNCTION SHOWS ACOUSTIC OSCILLATIONS IN PHOTON AND BARYON FLUIDS

comoving sound horizon r_s=148 Mpc at last scattering surface z_{ls}=1089





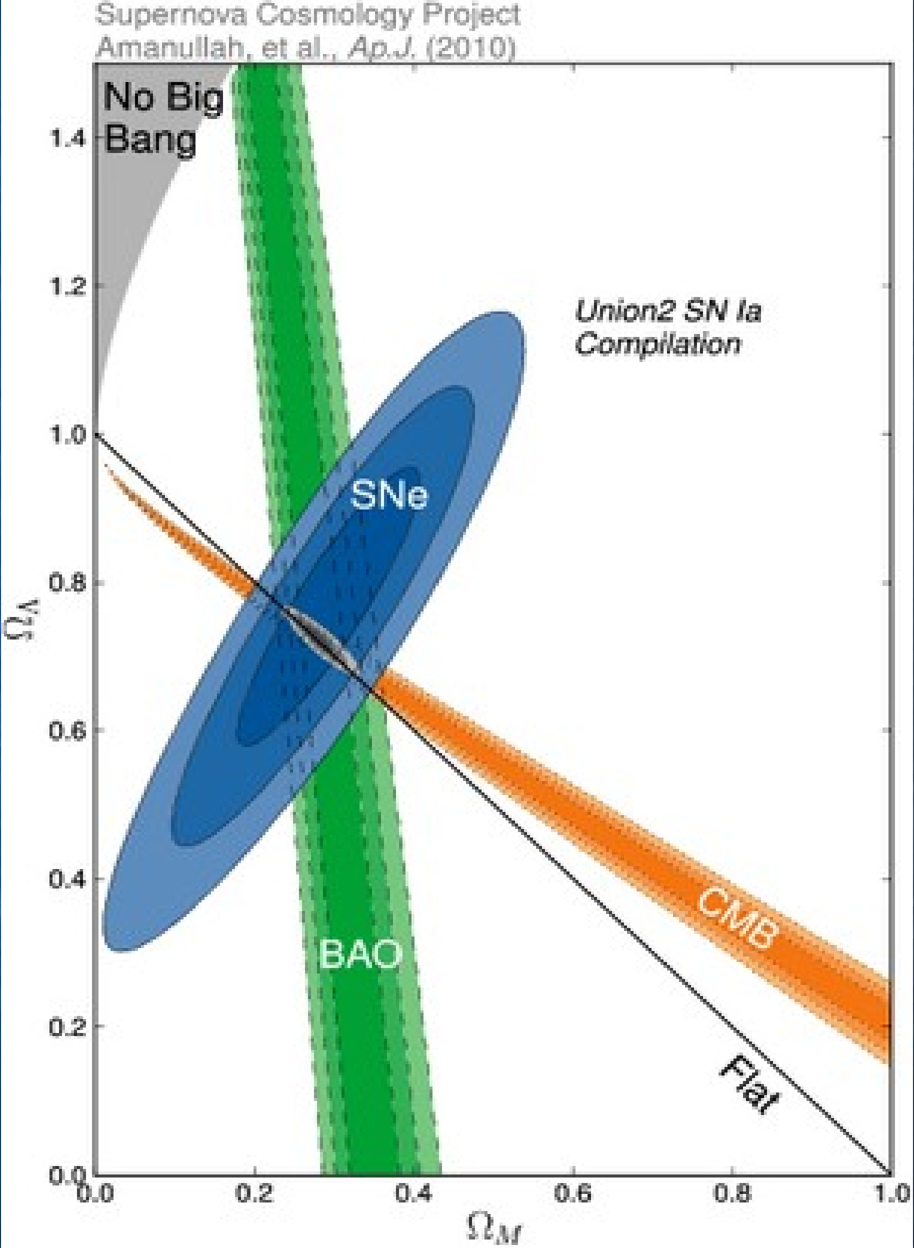
PARAMETRIZING DE MODELS

A. No Parameters Beyond Present Ω_M: flat ΛCDM

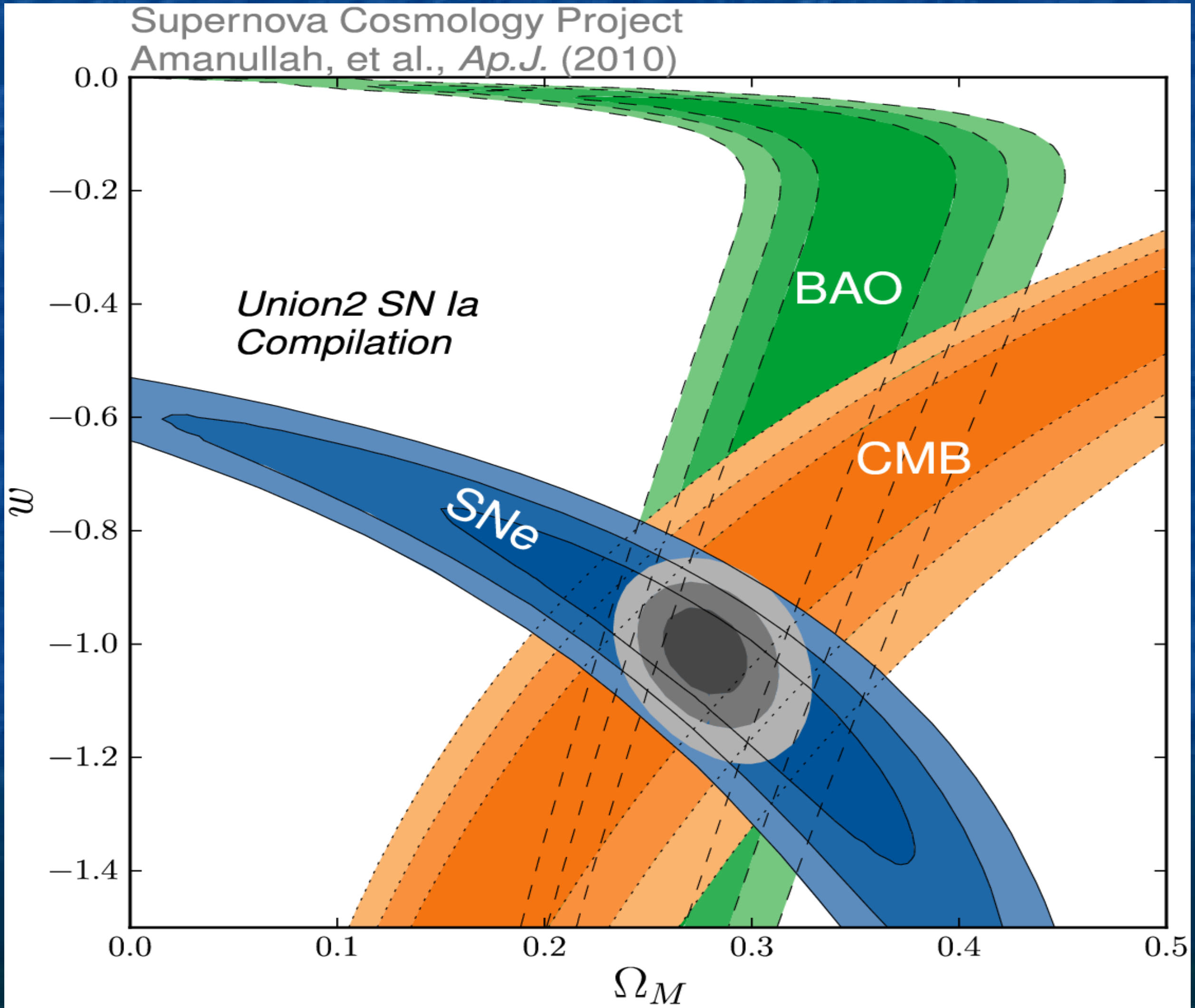
- B. One Additional Parameter: constant $w_{DE}\neq-1$, DGP r_c: Present data insensitive to any development on Hubble time scale
- C. Two Additional Parameters
  - 1. Scalar Field Models: Quintessence, k-essence
  - 2. Two models (parametrized Ricci scalar, thawing): slightly better fit than ΛCDM, but no physical motivation
  - 3. Brane Cosmology: DGP->bad fit to combined data
- D. More parameters cannot be fixed, even in projected observations.

Rubin et al , Ap. J. 695, 391-403 (2009), Table 1, maximum likelihood without Baysian selection criteria.

ΛCDM: SN, CMB, BAO CONSTRAINTS ON Ω_M-Ω_Λ



Sne, CMB, BAO CONSTRAINTS ON CONSTANT w(z)



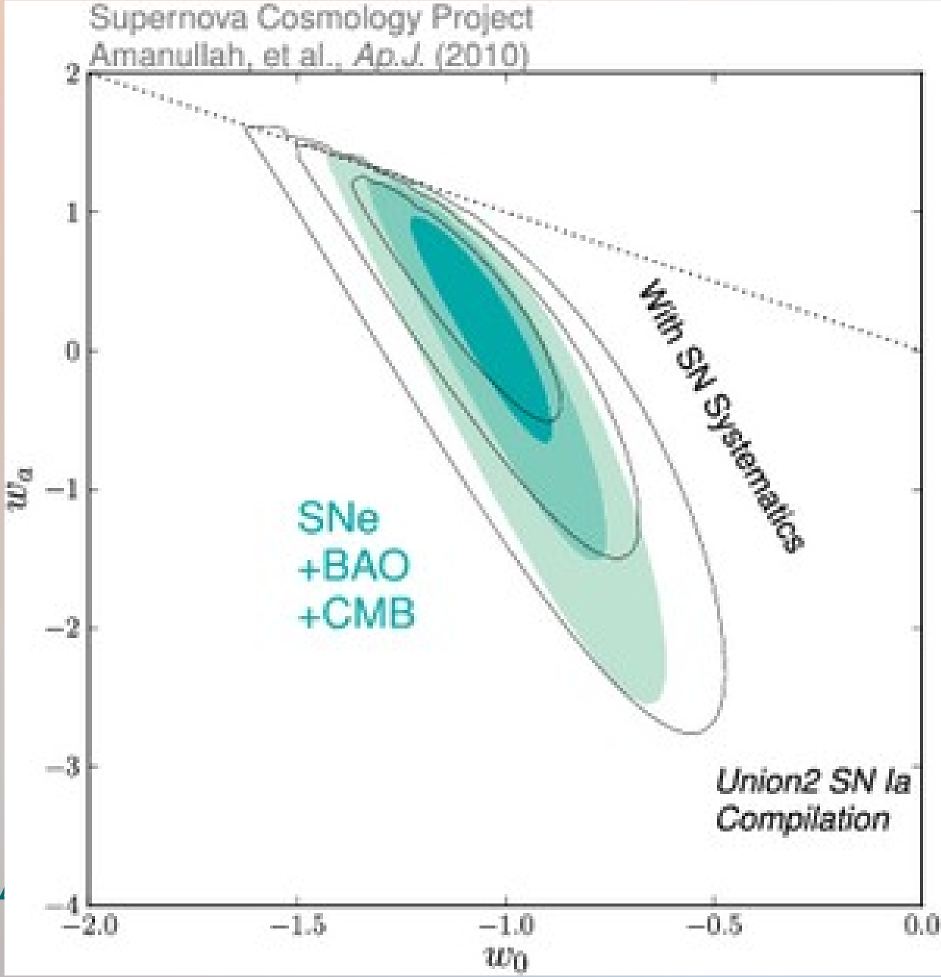
Constraints on Time-varying Dark Energy w(z

- 3-parameter model

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

No significant change in w(z)

Evidence for existence of DE is weak.



COMBINED 7WMAP+BAO+H_0+SN LIMITS ON FLATNESS, EOS, ITS EVOLUTION PARAMETERS

A. Flatness Limits, with some constant EOS w_{DE}

$$\Omega_k = -0.006^{+0.008}_{-0.007}, \; w_{DE} = -1.035^{+0.093}_{-0.097}$$

B. Limits on Any Constant EOS, assuming flatness

$$\Omega_k = 0, \quad w_{DE} = -0.997^{+0.077}_{-0.082}$$

C. Limits on Time-Varying EOS, assuming flatness

$$w(a) = -0.93 \pm 0.12 - 0.38^{+0.66}_{-0.65}$$

D. Agreement among different data sets shows absence of systematic errors

Amanullah et al (SCP), arXiv:1004.1711(2010). 68% errors are statistical+systematic

CONCORDANCE MODEL ΛCDM (EDDINGTON-LEMAITRE)

Cosmological Constant can be interpreted geometrically or materially

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = \kappa^2 T_{\mu\nu}, \quad G_{\mu\nu} = \Lambda g_{\mu\nu} + \kappa^2 T$$

as vacuum energy $\kappa^2 \rho_{vac} \equiv \Lambda$

Einstein tensor $G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}$

CLASSICAL GEOMETRIC INTERPRETATION AVOIDS QUANTUM COSMOLOGICAL CONSTANT PROBLEM

Matter vacuum fluctuations are confirmed in laboratory, but apparently do not gravitate

Cosmological Constant Problem can be side-stepped: Lambda constant of nature, an intrinsic c-number curvature, without vacuum fluctuations

Cosmological Coincidence persists: Why do we live at a late time when material energy density has diluted down to $\sim\Lambda / 2$

Cosmological Constant Problem avoided by assuming fact of nature $\rho_{vac} \approx 0$.

Cosmological Coincidence can only be solved by fine-tuning or Anthropic Reasoning

COSMOLOGICAL COINCIDENCE

Why do observers live at late time when matter has diluted down to

$$\rho_m \approx \rho_{vac} / 2$$

Suggests role of observer in fixing small Λ.

Complementarity: Observation depends on both system and observer.

Multiverses are predicted in chaotic inflationary theory, but consider unobservable domains beyond particle horizon.

Landscapes explain anthropically why observed cosmological constant is so small, but can never be tested by observation.

ANTHROPIC EXPLANATION FOR COSMOLOGICAL COINCIDENCE

Our existence sets upper limit on Λ: Among all possible material universes, we live at late time, after galaxies, planets have evolved

Multiverses are predicted in chaotic inflationary theory, but consider unobservable domains beyond particle horizon.

Landscapes explain anthropically why observed cosmological constant is so small, but can never be tested by observation.

In any case, task of physicists is to test the Concordance Model by observing DE or DG.

MULTIVERSES EXPLAIN COSMOLOGICAL CONSTANT BUT ARE NOT TESTABLE

- Proposes many universes with different Λ, outside our particle horizon
- Our observed universe only rare one of many
- Much larger Λ universe would expand faster, be far younger than observed
- Explains why our observed Λ, but not testable. An empirically-based metaphysical proposal
- Epistomology: Cosmology may be telling us to expand scope of science

III. CURRENT CONCORDANCE MODEL TESTS

Only modest improvements in 10% uncertainty in distance measurements are possible

luminosity distances $d_L=(1+z)\eta$ to SN

angular distances $d_A=\eta/(1+z)$ in BAO

Only fluctuations can distinguish

-Dynamic from static vacuum energy

-Dark energy from dark gravity

Most promising fluctuation studies:

A. Baryon Acoustic Oscillations

B. Galaxy clustering: power spectrum, spectral growth factor

C. Gravitational weak lensing

6th DECADAL SURVEY PROPOSAL PRIORITORIZES

- Ground: Synoptic Survey Telescope (2-m): weak gravitational lensing; map and record SN; near-Earth asteroids

- Space: Wide-Field Infrared Survey Telescope (Lagrangian point L2): catalogue exoplanets; precision $z \leq 1.8$ SN

IV.QUINTESSENCE MODELS FOR DARK ENERGY LACK PREDICTIVE POWER

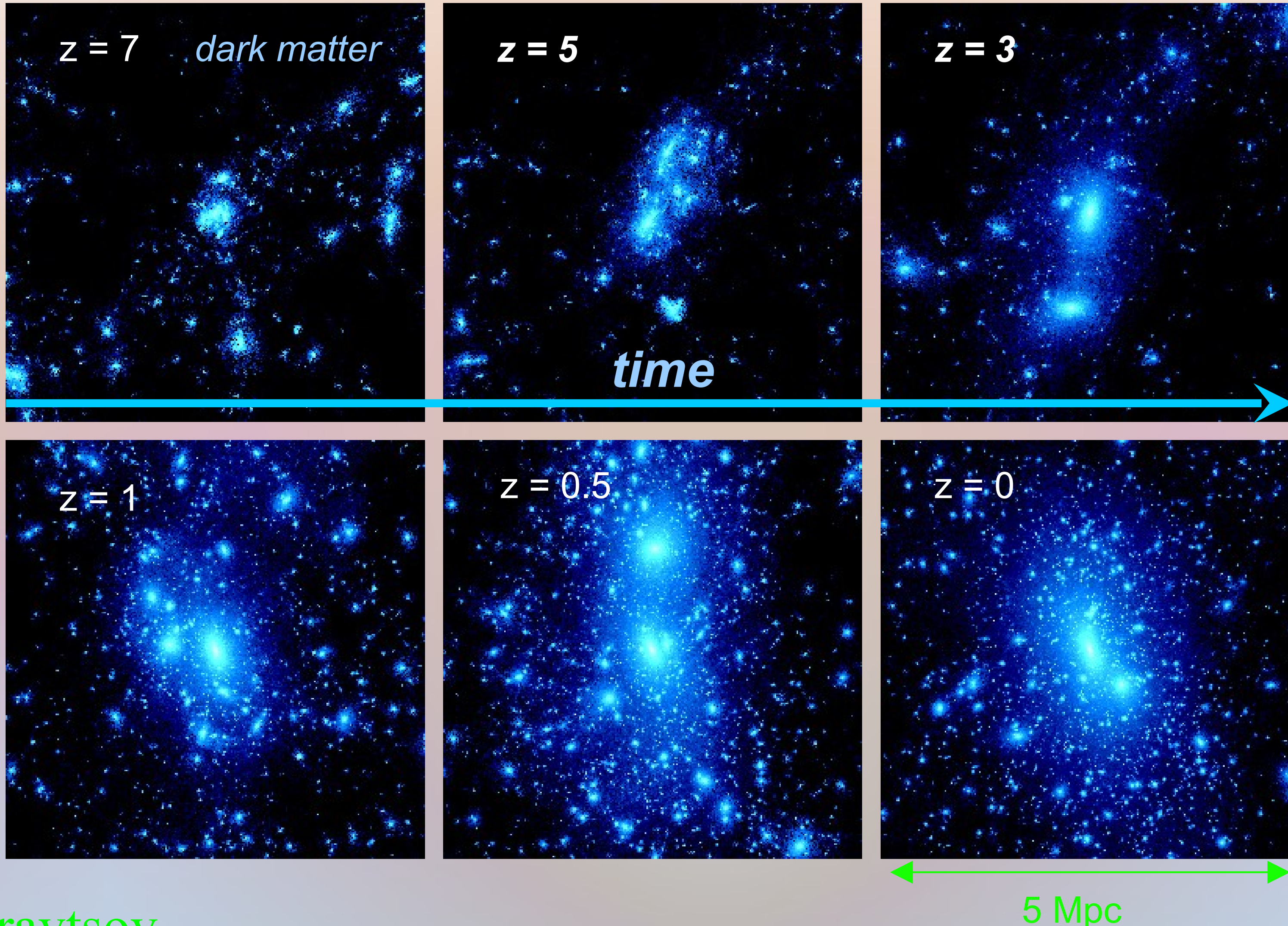
- Within GR, include exotic scalar fields φ(t): quintessence, k-essence, tachyons

$$H^2(a) = \kappa^2(\rho_m + \rho_\rho)$$

Fields are non-renormalizable, without natural justificaton: must be interpreted as effective fields.

- Every observed evolution a(t) or EOS w(a) can be modeled as some V(φ)

A.. HIERARCHICAL CLUSTER GROWTH DEPENDS ON COSMOLOGICAL BACKGROUND



Kravtsov

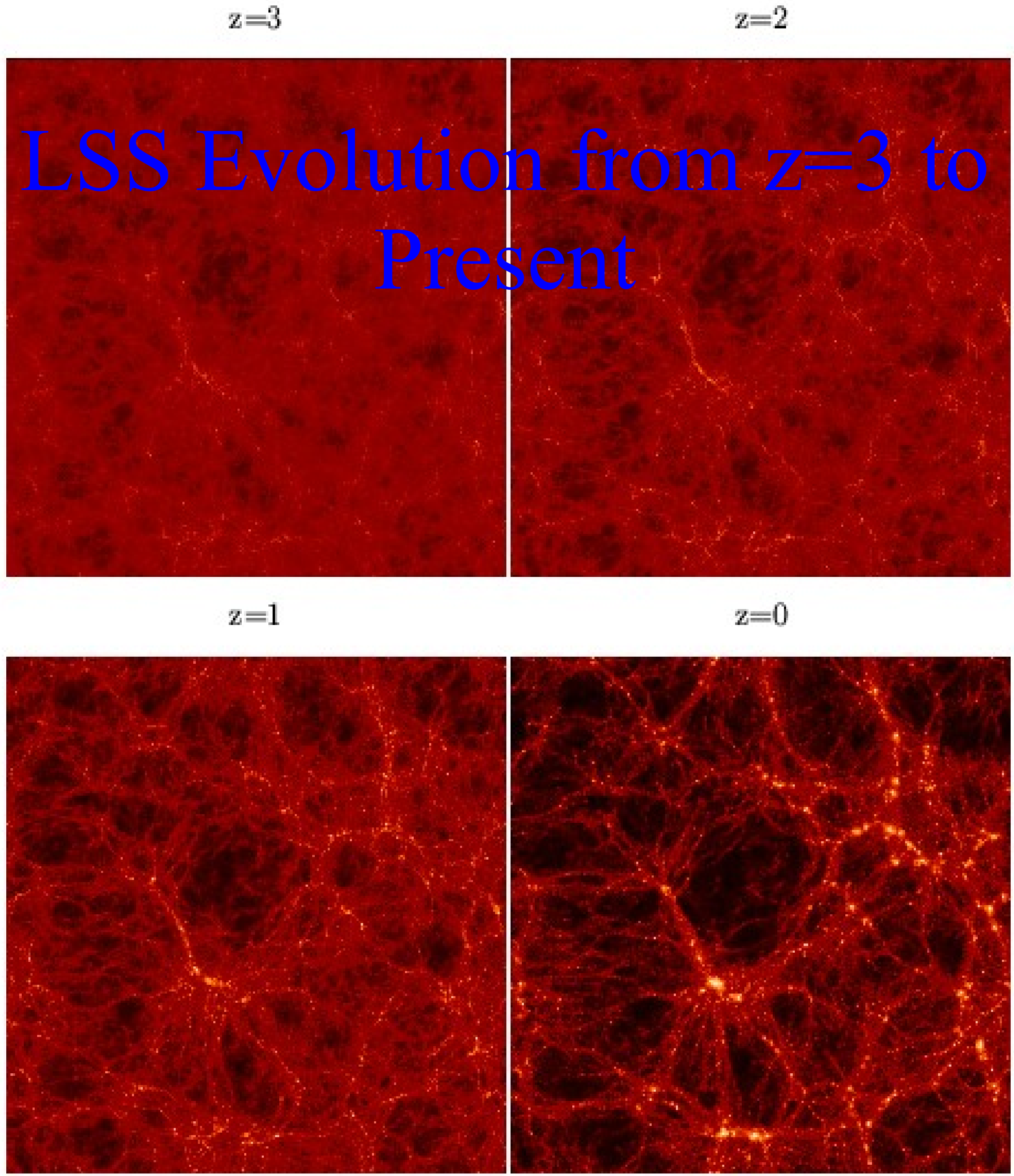
LSS GROWTH RATE g(z)

Robustness of CDM paradigm recommends its use as a Dark Energy probe

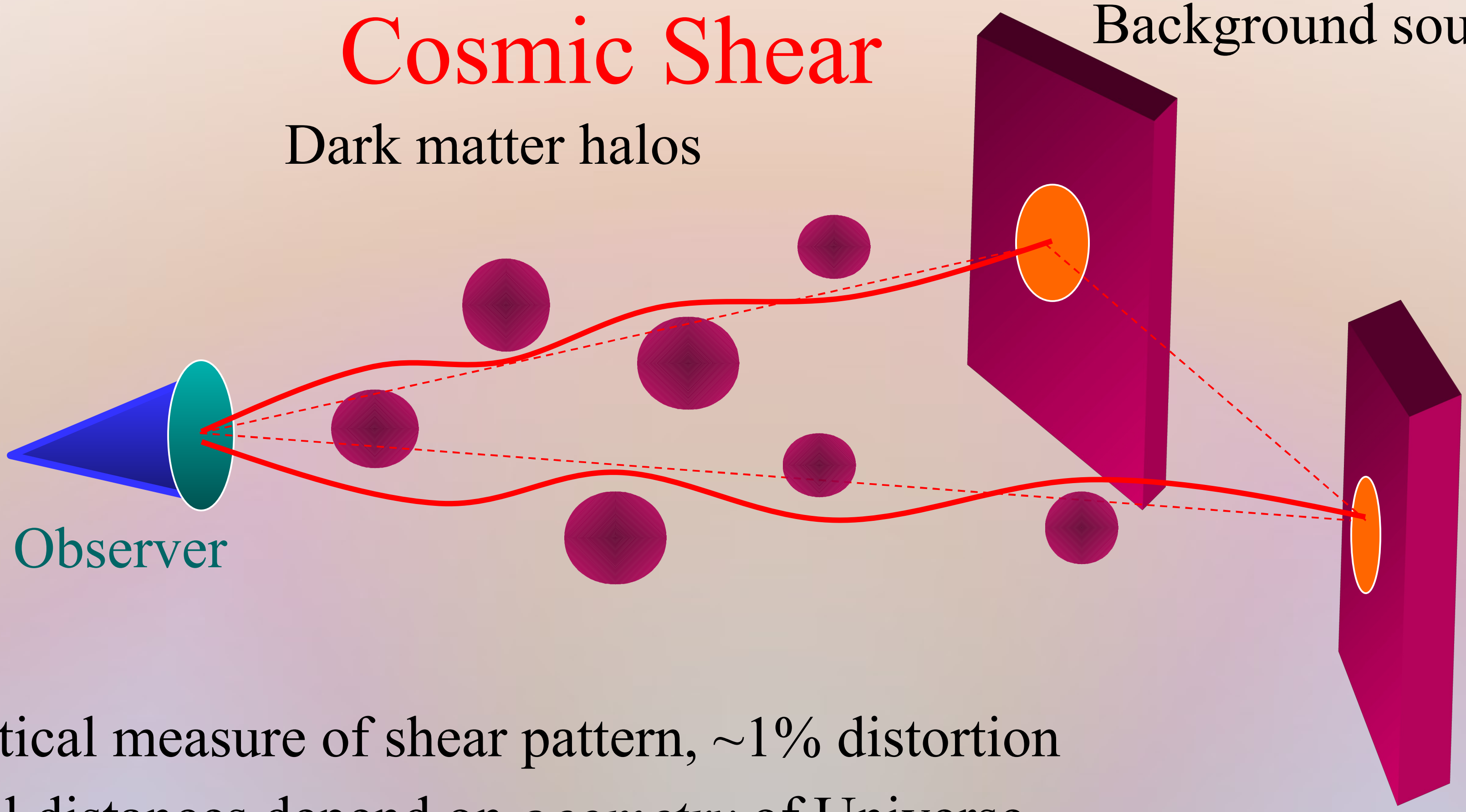
Price: depends on additional cosmological and structure formation parameters

Bonus: additional structure formation Parameters

LSS Evolution from z=3 to Present



B.Most Promising: Weak Lensing of Cosmic Shear

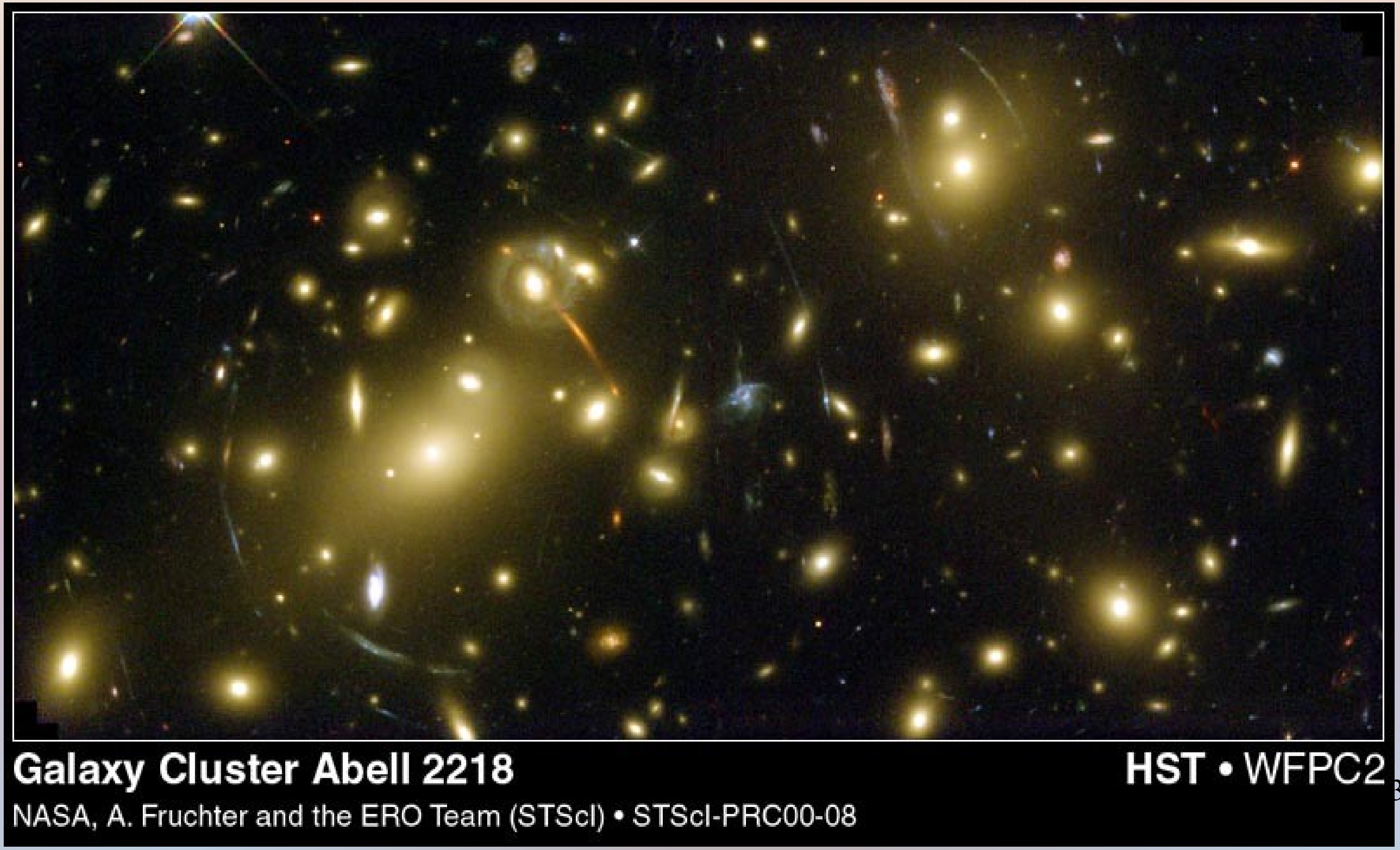


Statistical measure of shear pattern, ~1% distortion

Radial distances depend on *geometry* of Universe

Foreground mass distribution depends on *growth* of structure

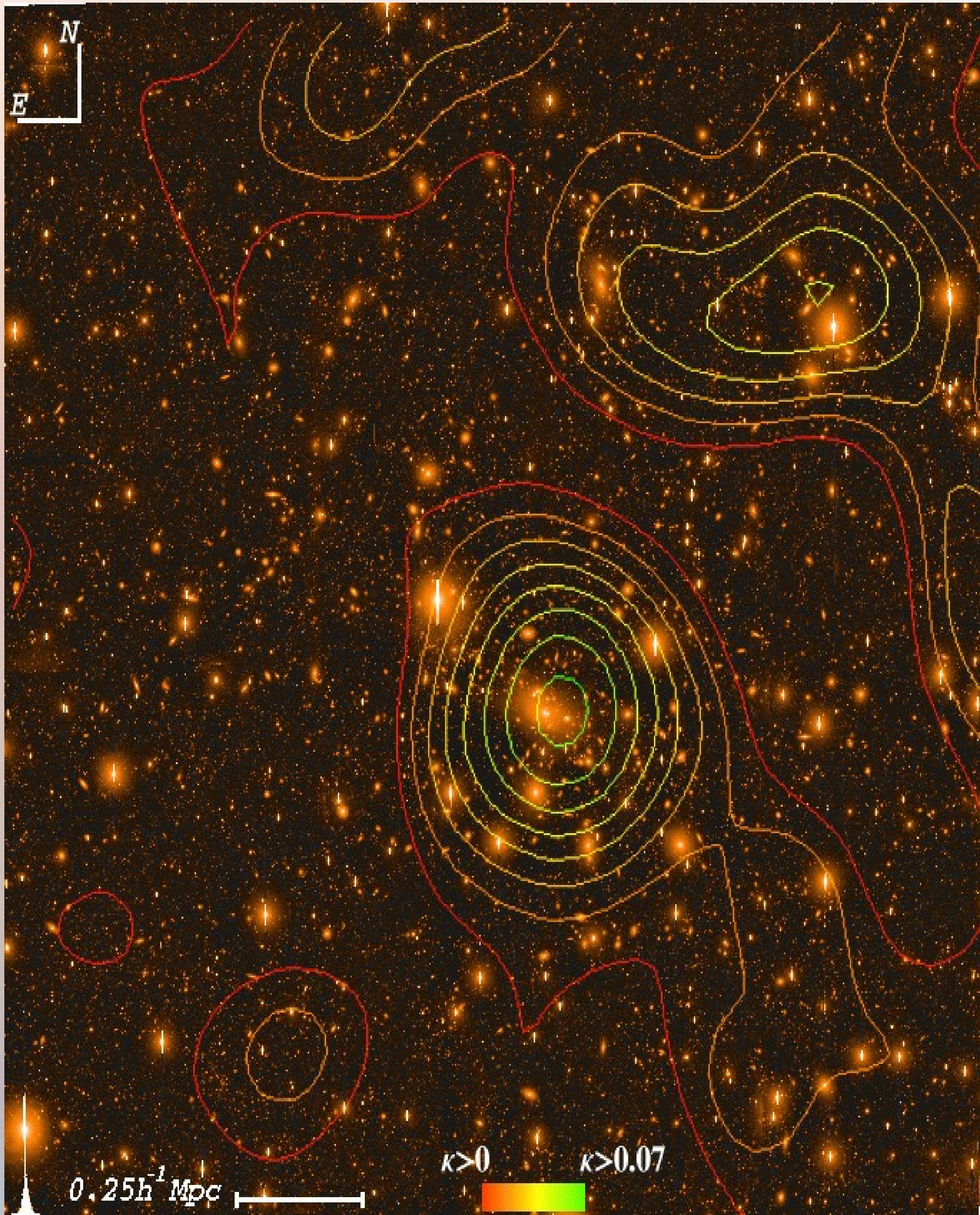
Weak Gravitational Lensing Observed in Clusters: Cosmic Shear, Magnification



Mapping the Dark Matter in a Cluster of Galaxies via Weak Gravitational Lensing

Data from Blanco 4-meter at CTIO

Joffre, etal



IR MODIFIED GRAVITY (DARK GRAVITY) THEORIES

A. Four-dimensional stable theories

- f(R)≡scalar-tensor theory in Jordon frame, with Brans-Dicke $\omega_{BD}=0$, large scalar mass m_φ
- In Einstein frame, quintessence matter coupled to scalar gravity (scalaron). DG/augmented DE describe same physics!!
- Scalaron->singularity problems in strong gravitational field (neutron stars)
- LSS growth constraints can be satisfied
- **Solar system, pulsar constraints require $\omega_{BD}=500$, small m_φ: rules out simple f(R)**

- Chamelon theories: scalaron mediated attractive fifth force->small m_φ at small scales, large m_φ at large scales

- Roy Maartens and Ruth Durrer, in Dark Energy (ed. P. Ruiz-Lapuente, Cambridge, 2010); A. Silvestri and M. Trodden, arXiv:0904.0024v2 (2009)

B. Extra-dimensional (braneworld) Theories: Gravity Crosses Over 4D->5D at Cosmological Scale r_c

- Small scales $r<r_{Vainstein}\approx$cluster scale: GR is recovered
- Intermediate scales $r_{Vainstein}<r<r$: Brans-Dicke
- Large scales $r_c<r$: gravity leaks from 4D brane->5D bulk, where it weakens

DGP ACCELERATING SOLUTON

- Late-time acceleration is produced by weakening of gravity in bulk, not by any DE
- Contradicted by WMAP observations of large-scale anisotropies (ISW), observations of growth factor
- Late-time asymptotic de Sitter solution->scalar ghosts

ALL MODELS ARE FUNDAMENTALLY FLAWED

- Can be fine-tuned to avoid instabilities and to satisfy solar system and supernova constraints.
- If tuned to observed quasi-static homogeneous evolution, then practically indistinguishable from Concordance Model.
- No theory is fundamentally consistent; all are **effective low-energy theories, requiring UV completion.**

V. PHENOMENOLOGICAL CONCLUSIONS

- Simplest Model ΛCDM=static intrinsic curvature of classical empty space-time
- Present data does not constrain w(z>1)
- Allows constant constant w_{DE}=-1 ±0.08 and some two-parameter models.
- If dynamic, Dark Gravity/Dark Gravity Degeneracy will be resolved only by *Evolution of Inhomogeneities*
- Living in large, local bubble is possible, ultimately testable.

Epistemological Questions: What is observable?

Cosmological Constant Problem requires new understanding of ‘vacuum’: only modified gravity may explain quantum material vacuum

Metaphysics: multiverse explanation of Cosmological Coincidence would extend boundaries of science by *Anthropic Reasoning*