Challenges for ΛCDM and Growth of Dark Energy Perturbations in Scalar-Tensor Cosmologies

L. Perivolaropoulos
http://leandros.physics.uoi.gr
Department of Physics
University of Ioannina

Main Points

The consistency level of LCDM with geometrical data probes has been increasing with time during the last decade.

There are some puzzling conflicts between ΛCDM predictions and dynamical data probes
(bulk flows, alignment and magnitude of low CMB multipoles,
alignment of quasar optical polarization vectors, cluster halo profiles)

The amplified dark energy clustering properties that emerge in
Scalar-Tensor cosmology
may help resolve the puzzles related to
amplified bulk flows and cluster halo profiles.

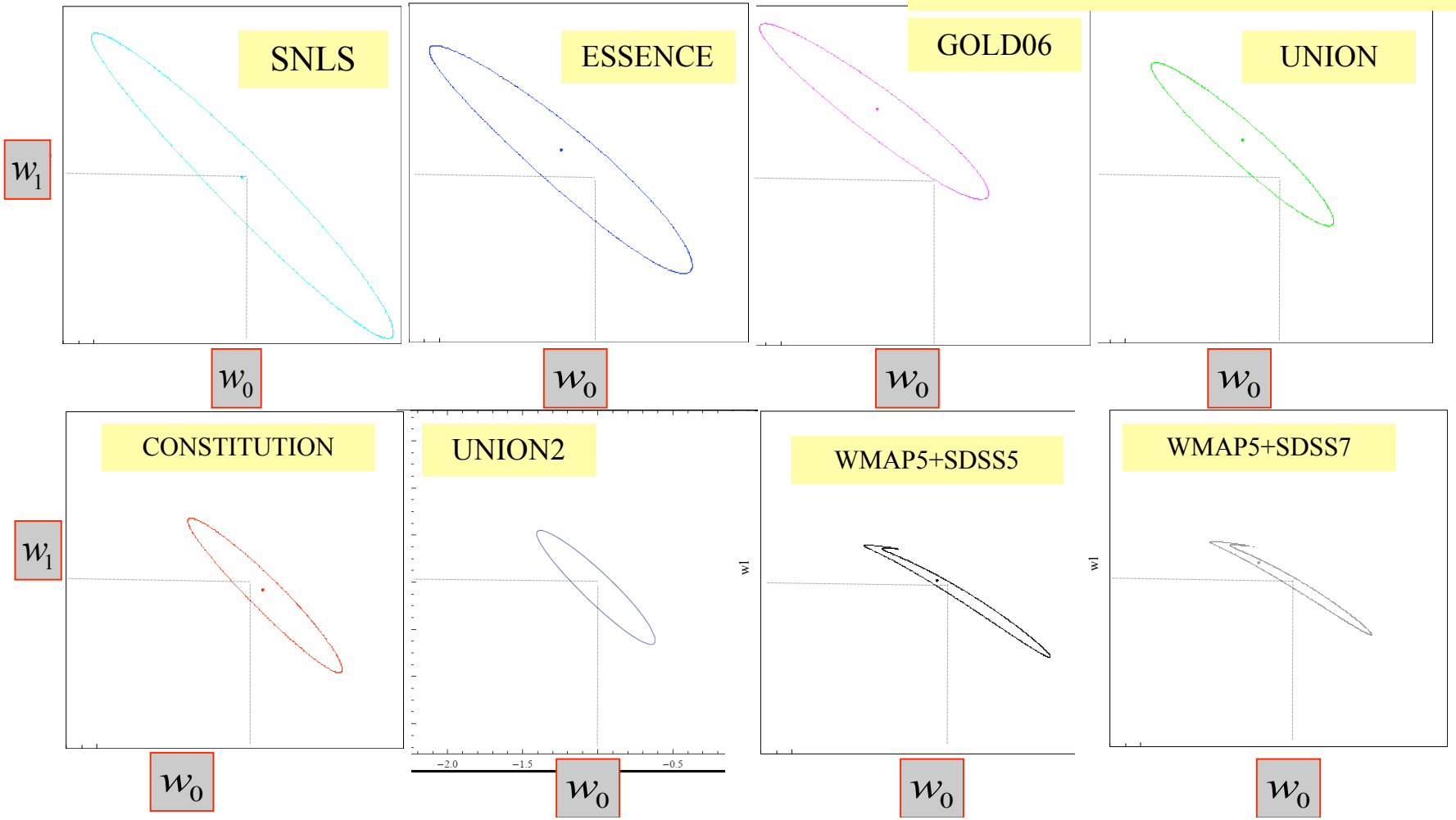
$\Omega_{0m} = 0.28$

Consistency of ΛCDM with Geometric Probes

$$w(z) = w_0 + w_1 \frac{z}{1+z}$$

2σ CPL parameter contour for recent standard candle (SnIa) and Standard Ruler (CMB+BAO) datasets.

J. C. Bueno Sanchez, S. Nesseris, LP,
JCAP 0911:029,2009, 0908.2636



Approaches in Cosmology Research

A1:

a. Focus on majority of data which are consistent with ΛCDM.

b. Assume validity of ΛCDM and constrain standard model parameters with best possible accuracy

A2:

a. Focus on Theoretical Motivation and construct more general models.

b. Use data to constrain the larger space of parameters.

A3:

a. Focus on minority of data that are inconsistent with ΛCDM at a level more than 2-3σ.

b. Identify common features of these data and construct theoretical models consistent with these features.

c. Make non-trivial predictions using these models.

Are there data inconsistent with ΛCDM?

From LP, 0811.4684,
I. Antoniou, LP 1007.4347

Large Scale Velocity Flows

R. Watkins et. al. , 0809.4041

- Predicted: On scale larger than 50 h^{-1}Mpc Dipole Flows of 110km/sec or less.
- Observed: Dipole Flows of more than 400km/sec on scales 50 h^{-1}Mpc or larger.
- Probability of Consistency: **1%**

Alignment of Low CMB Spectrum Multipoles

M. Tegmark et. al., PRD 68, 123523 (2003), astro-ph/0302496

- Predicted: Orientations of planes that maximize perturbation power of CMB maps should be independent of the multipole l .
- Observed: Orientations of l=2 and l=3 planes are unlikely close to each other.
- Probability of Consistency: **1%**

Large Scale Alignment of QSO Optical Polarization Data

D. Hutsemekers et. al.. AAS, 441,915 (2005), astro-ph/0507274

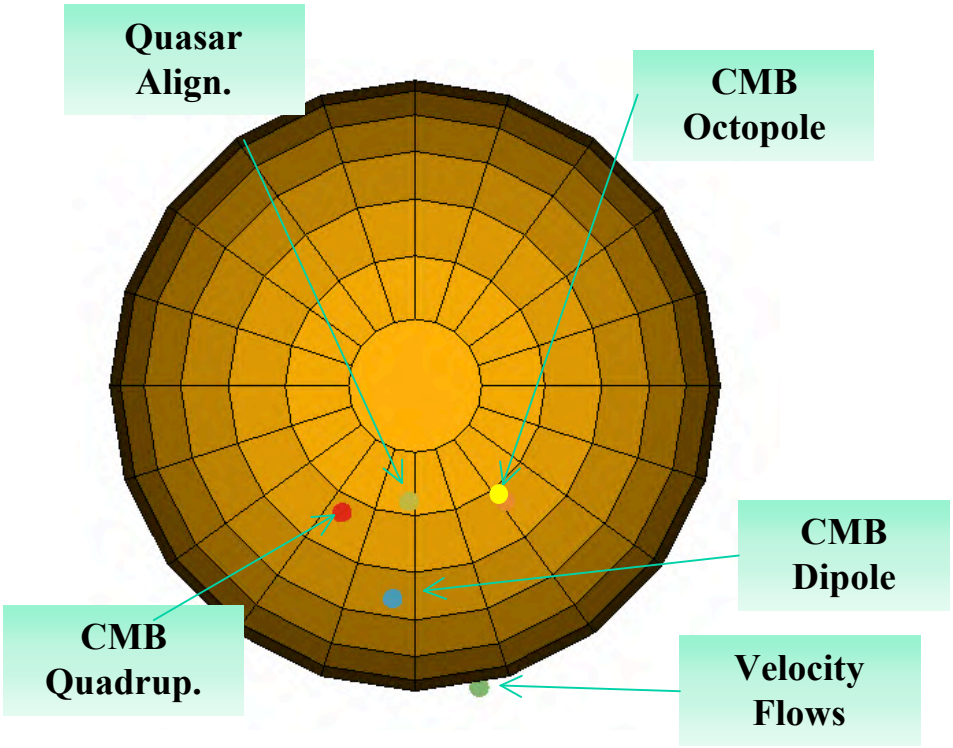
- Predicted: Optical Polarization of QSOs should be randomly oriented
- Observed: Optical polarization vectors are aligned over 1Gpc scale along a preferred axis.
- Probability of Consistency: **1%**

Cluster Halo Profiles:

Broadhurst et. al. ,ApJ 685, L5, 2008, 0805.2617,
S. Basilakos, J.C. Bueno Sanchez, LP., 0908.1333, PRD, 80, 043530, 2009.

- Predicted: Shallow, low-concentration mass profiles $(c_{vir} \sim 4-5)$
- Observed: Highly concentrated, dense halos $(c_{vir} \sim 10-15)$
- Probability of Consistency: **1-3%**

Preferred Axes

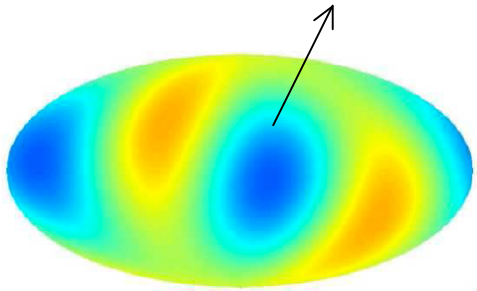


Q1: Are there other cosmological data with hints towards a preferred axis?

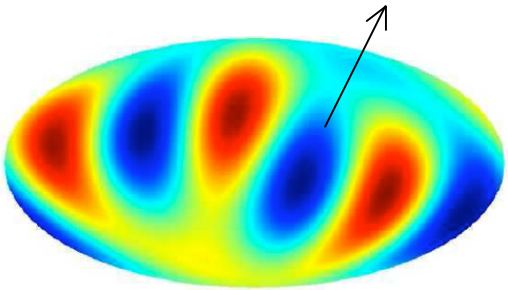
Q2: What is the probability that these independent axes lie so close in the sky?

I. Antoniou, LP 1007.4347

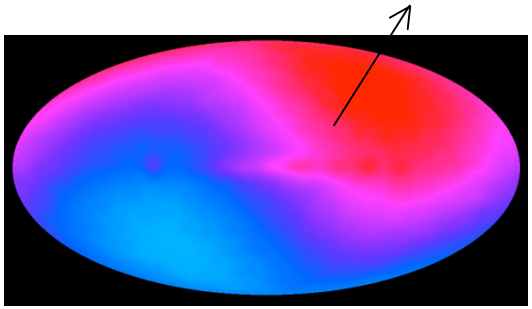
Quadrupole component of CMB map



Octopole component of CMB map



Dipole component of CMB map



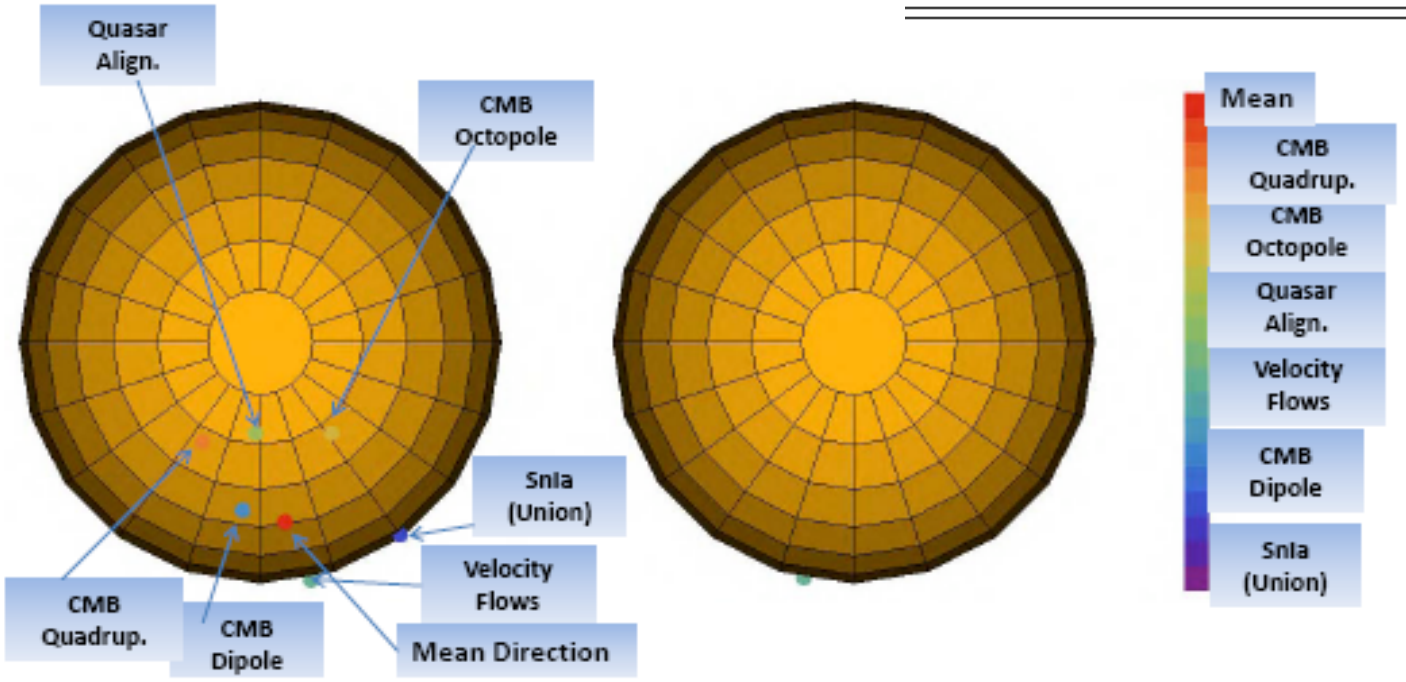
M. Tegmark et. al., PRD 68, 123523 (2003), astro-ph/0302496

Union2 Data Anisotropy Direction

Q: What is the probability that these independent axes lie so close in the sky?

It is less than 1%

Cosmological Obs.	l	b
SnIa Union2	306°	15°
CMB Dipole	264°	48°
Velocity Flows	282°	6°
Quasar Alignment	267°	69°
CMB Octopole	308°	63°
CMB Quadrupole	240°	63°
Mean	$277^\circ \pm 26^\circ$	$44^\circ \pm 27^\circ$

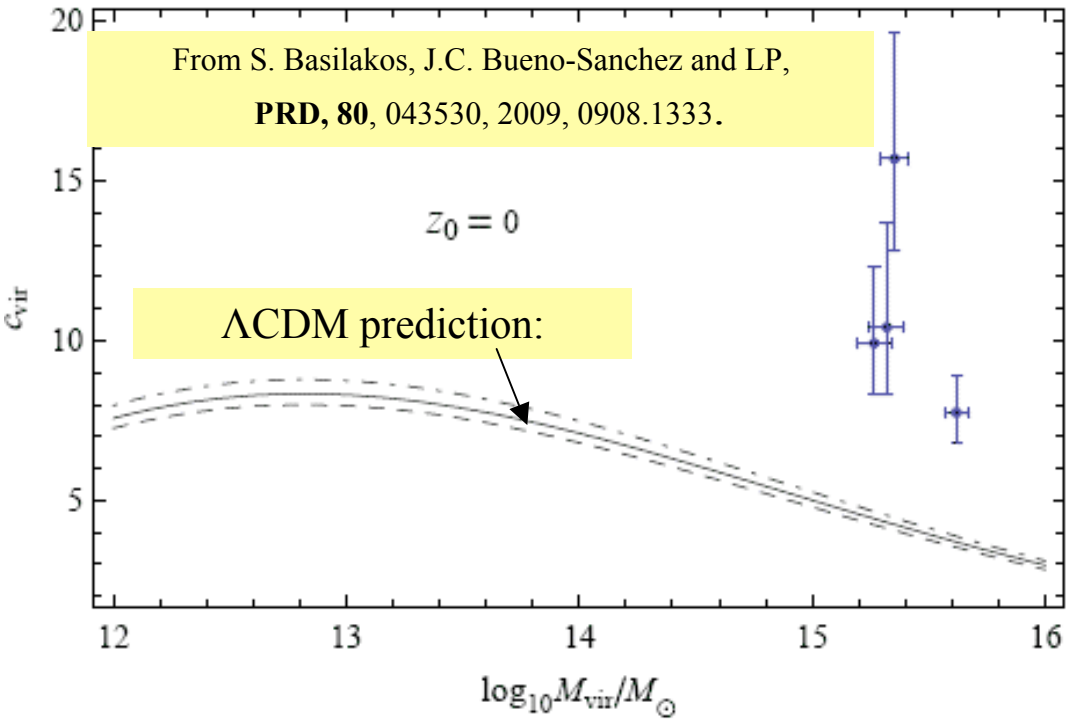


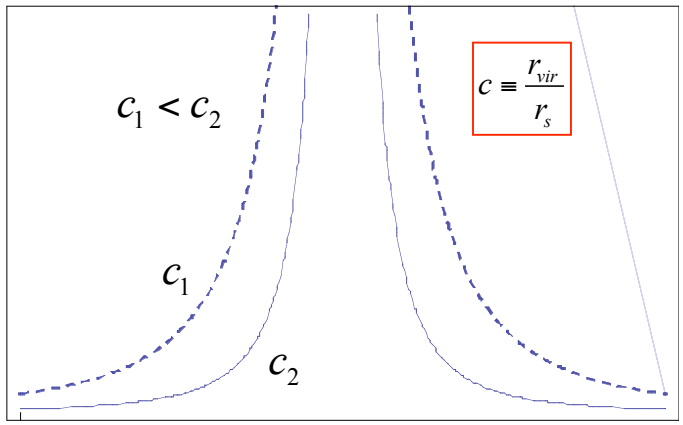
Cluster Halo Profiles

Navarro, Frenk, White, Ap.J., **463**, 563, 1996

NFW profile:

$$\rho_{NFW}(R) = \frac{\rho_s}{(R/r_s)(1+R/r_s)^2}$$





The predicted concentration parameter c_{vir} is significantly smaller than the observed.

Data from: T. Broadhurst, K. Umetsu, E. Medezinski, M. Oguri and Y. Rephaeli, Astrophys. J. **685**, L9 (2008) [arXiv:0805.2617 [astro-ph]].

Cluster Halo Profiles

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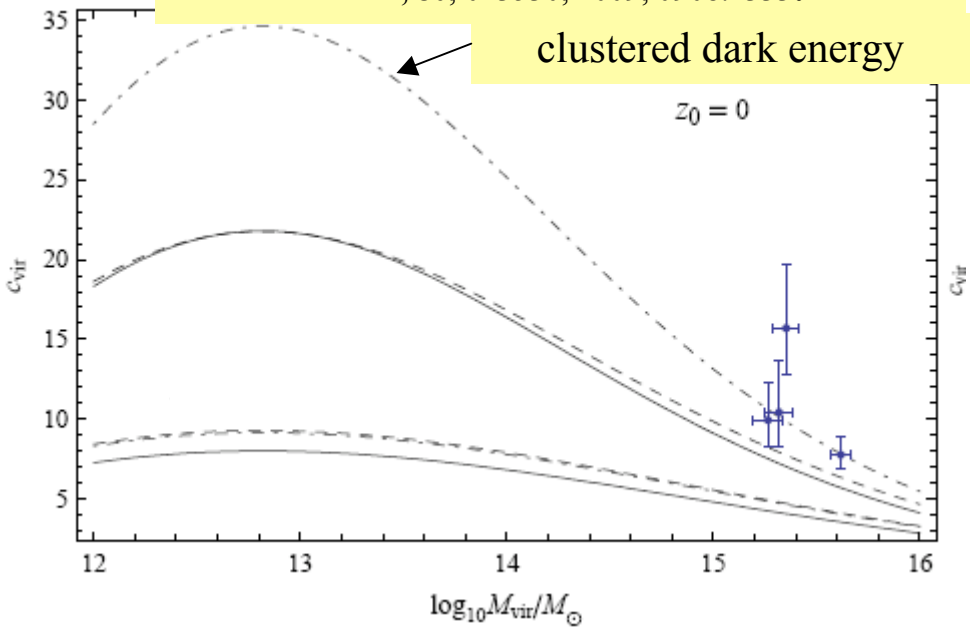

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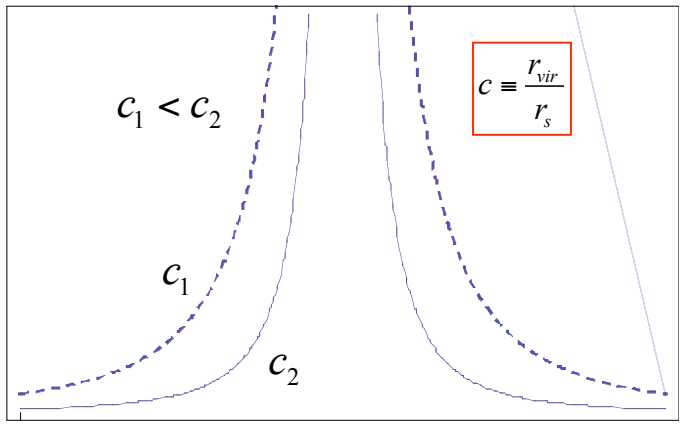


Clustered Dark Energy can produce more concentrated halo profiles

Data from:

T. Broadhurst, K. Umetsu, E. Medezinski, M. Oguri and Y. Rephaeli, Astrophys. J. **685**, L9 (2008) [arXiv:0805.2617 [astro-ph]].

Producing Dark energy Perturbations

Q: Is there a model with a similar expansion rate as ΛCDM but with significant clustering of dark energy?

A: Yes. This naturally occurs in Scalar-Tensor cosmologies due to the direct coupling of the scalar field perturbations to matter induced curvature perturbations

J. C. Bueno-Sanchez, LP,
Phys.Rev.D81:103505,2010,
(arxiv: 1002.2042)

Scalar-Tensor Theories

(ρ_m, p_m)

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\Big(F(\Phi)\ R - Z(\Phi)\ g^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi - 2U(\Phi)\Big) + S_m[\psi_m; g_{\mu\nu}]$$

Rescale Φ ⟹ $Z(\Phi)=1$

Units: $8\pi G \to 1$

General Relativity: $F(\Phi) = \Phi_0 \simeq 1$

Background Cosmological Evolution

Flat FRW metric:

$$ds^2 = -dt^2 + a^2(t)\left[dr^2 + r^2\left(d\theta^2 + \sin^2\theta\ d\phi^2\right)\right]$$

Generalized Friedman equations:

$$3F \cdot H^2 = \rho_m + \frac{1}{2}\dot{\Phi}^2 - 3H\dot{F} + U \equiv \rho_{tot}$$

$$-2F \cdot \dot{H} = \rho_m + \dot{\Phi}^2 + \ddot{F} - H\dot{F} \longrightarrow \rho_{tot} + p_{tot}$$

$$\ddot{\Phi} + 3H\dot{\Phi} = 3\frac{dF}{d\Phi}\left(\dot{H} + 2H^2\right) - \frac{dU}{d\Phi}$$

$$\dot{\rho}_m + 3H\ \rho_m = 0$$

These terms allow for superacceleration (phantom divide crossing)

Curvature (matter) drives evolution of Φ (dark energy) and of its perturbations.

Advantages and Constraints

Advantages:

- Natural generalizations of GR (superstring dilaton, Kaluza-Klein theories)
- General theories (f(R) and Brans-Dicke theories consist a special case of ST)
- Potential for Resolution of Coincidence Problem
- Natural Super-acceleration ($w_{eff}<-1$)
- **Amplified Dark Energy Perturbations**

Constraints:

Solar System $\Rightarrow$ $\left.\frac{F_{,\Phi}{}^2}{F}\right|_{t=t_0} < 10^{-4}$

Cosmology $\Rightarrow$ $\frac{F_{,\Phi}{}^2}{F} < O(1)$

Numerical Evolution

$$3F \cdot H^2 = \rho_m + \frac{1}{2}\dot{\Phi}^2 - 3H\dot{F} + U \equiv \rho_{tot}$$

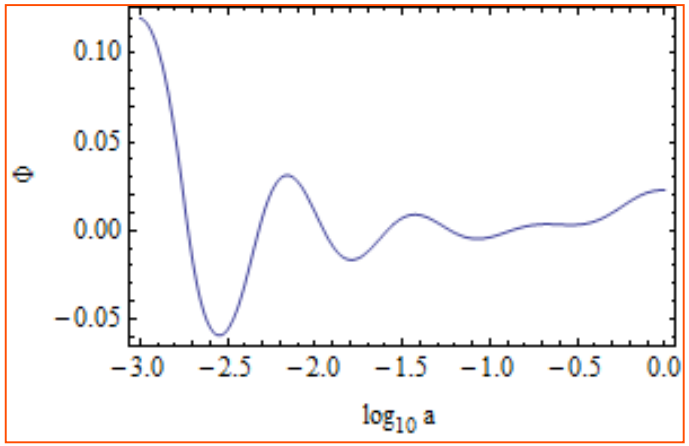
$$-2F \cdot \dot{H} = \rho_m + \dot{\Phi}^2 + \ddot{F} - H\dot{F}$$

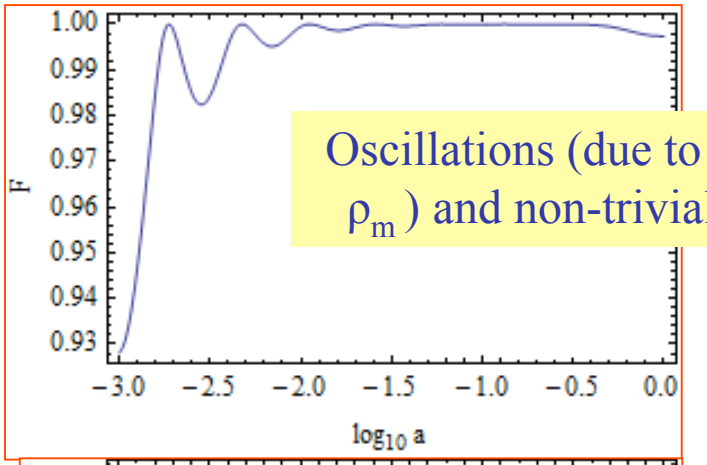
$$\ddot{\Phi} + 3H\dot{\Phi} = 3\frac{dF}{d\Phi}\left(\dot{H} + 2H^2\right) - \frac{dU}{d\Phi}$$

$$U(\Phi) = 1 + \exp(-\lambda\Phi)$$

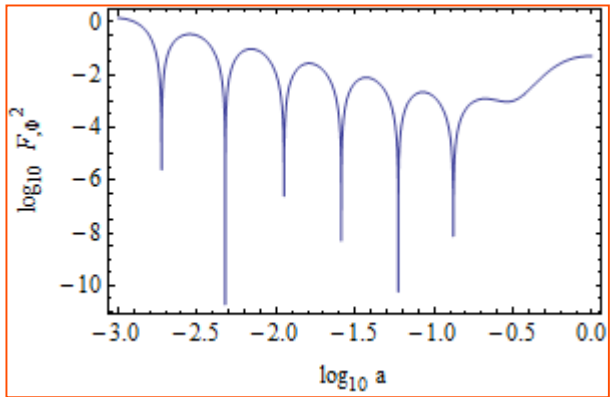
$$F(\Phi) = 1 - \lambda_f \Phi^2$$

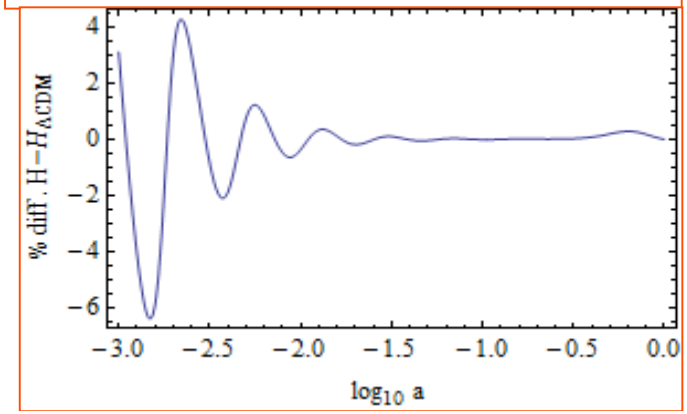
$$\lambda_f = 5, \quad \lambda = 1, \quad \Phi_i = 0.12$$





Oscillations (due to coupling to ρ_m) and non-trivial evolution





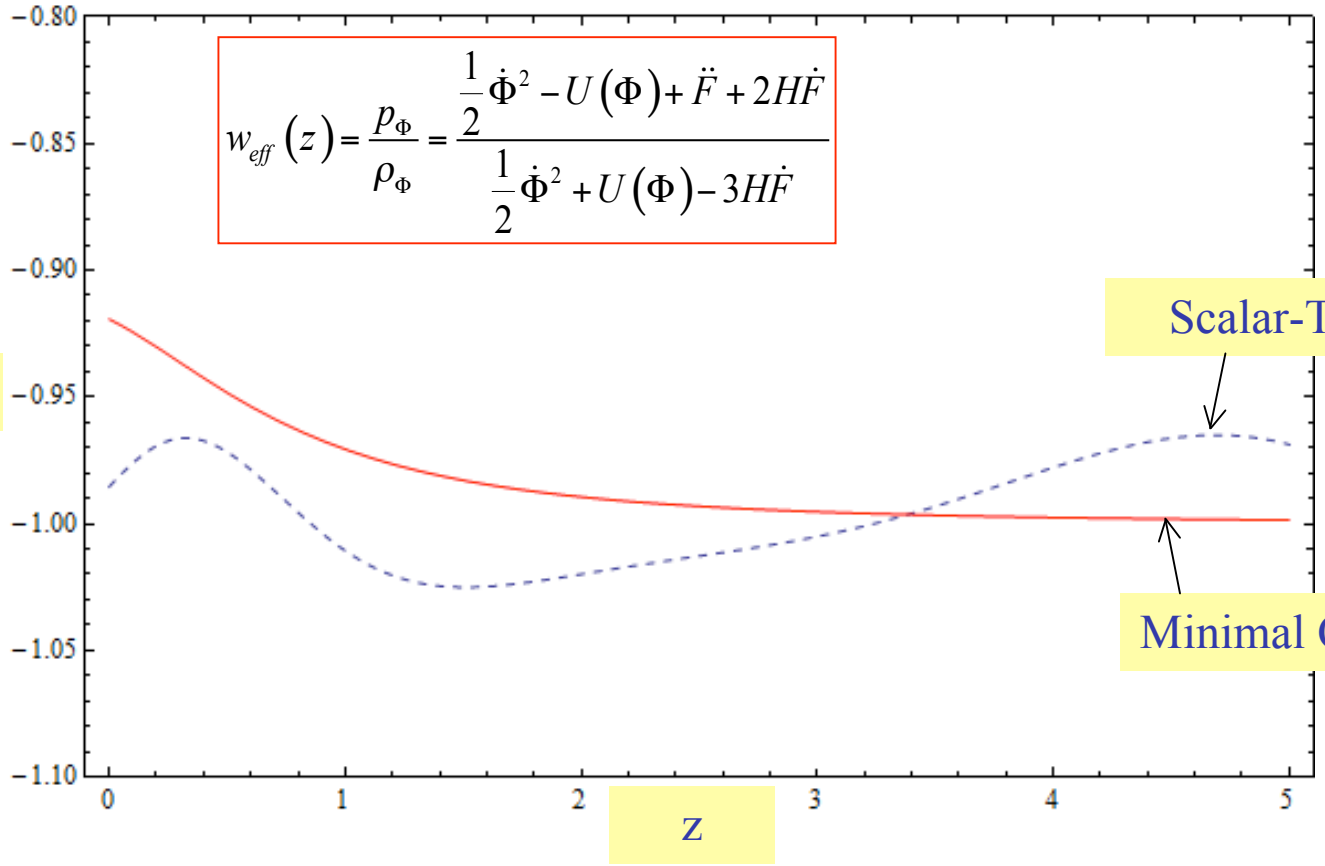
Effective Equation of State

$$3F \cdot H^2 = \rho_m + \frac{1}{2}\dot{\Phi}^2 - 3H\dot{F} + U \equiv \rho_{tot}$$

$$-2F \cdot \dot{H} = \rho_m + \dot{\Phi}^2 + \ddot{F} - H\dot{F} \equiv \rho_{tot} + p_{tot}$$

Effective Equation of State:

$$w_{eff}(z) = \frac{p_\Phi}{\rho_\Phi} = \frac{\frac{1}{2}\dot{\Phi}^2 - U(\Phi) + \ddot{F} + 2H\dot{F}}{\frac{1}{2}\dot{\Phi}^2 + U(\Phi) - 3H\dot{F}}$$



W_{eff}

Scalar-Tensor (λ_f=5)

Minimal Coupling (λ_f=0)

Perturbations: Sub-Hubble ST scales

Perturbed FRW metric (Newtonian gauge):

$$ds^2 = -(1+2\phi)dt^2 + a^2(1-2\psi)\delta_{ij}dx^i dx^j$$

Sub-Hubble ST scales: $\frac{k}{a} \simeq F_{,\Phi}^{1/2}\frac{k}{a} \gg H,\ F_{,\Phi} \gtrsim 1$

$|\dot{f}| \simeq H|f|$

J. C. Bueno-Sanchez, LP, Phys.Rev.D81:103505,2010, (arxiv: 1002.2042)

$$\delta\ddot{\Phi} + 3H\delta\dot{\Phi} + (\frac{k^2}{a^2} + U_{,\Phi\Phi} - \frac{R}{2}F_{,\Phi\Phi})\delta\Phi - \dot{\Phi}\dot{\phi} + (2\ddot{\Phi} + 3H\dot{\Phi})\phi + \dot{\Phi}\xi + \frac{F_{,\Phi}}{2}\delta R = 0$$

$|\dot{f}| \simeq H|f|$ $\quad F_{,\Phi} = O(1)$ $\quad \frac{k}{a} >> H$

$$\delta R = 2\left[\dot{\xi} - 4H\xi - (3\dot{H} - \frac{k^2}{a^2})\phi - 2\frac{k^2}{a^2}\psi\right] \longrightarrow \delta\Phi \simeq (\phi - 2\psi)F_{,\Phi}$$

$$\phi = \psi - \frac{F_{,\Phi}}{F}\delta\Phi$$

$$\delta\Phi \simeq -\psi\frac{FF_{,\Phi}}{F + F_{,\Phi}^2} \longrightarrow \frac{\delta\rho_\Phi}{\delta\rho_m} = \frac{\delta_\Phi}{\delta_m} \simeq -\frac{F_{,\Phi}^2}{3F_{,\Phi}^2 + 2F}$$

Anticorrelation

No suppression on small scales!

Perturbations: Sub-Hubble GR scales

Sub-Hubble GR scales $\rightarrow$ $\frac{k}{a} >> H$ $\quad F_{,\Phi} << 1$ $\quad \sqrt{F_{,\Phi}}\frac{k}{a} << H$

$$\delta\ddot{\Phi} + 3H\delta\dot{\Phi} + (\frac{k^2}{a^2} + U_{,\Phi\Phi} - \frac{R}{2}F_{,\Phi\Phi})\delta\Phi - \dot{\Phi}\dot{\phi} + (2\ddot{\Phi} + 3H\dot{\Phi})\phi + \dot{\Phi}\xi + \frac{F_{,\Phi}}{2}\delta R = 0$$

$|\dot{f}| \simeq H|f|$ $\quad \frac{k}{a} >> H$ $\quad F_{,\Phi} << 1$ $\quad \sqrt{F_{,\Phi}}\frac{k}{a} << H$

$$\delta R = 2\left[\dot{\xi} - 4H\xi - (3\dot{H} - \frac{k^2}{a^2})\phi - 2\frac{k^2}{a^2}\psi\right] \rightarrow \delta\Phi \;\square\; A\;\psi\;\frac{H^2\;a^2}{k^2}\Phi \rightarrow 0$$

Suppressed fluctuations on small scales!

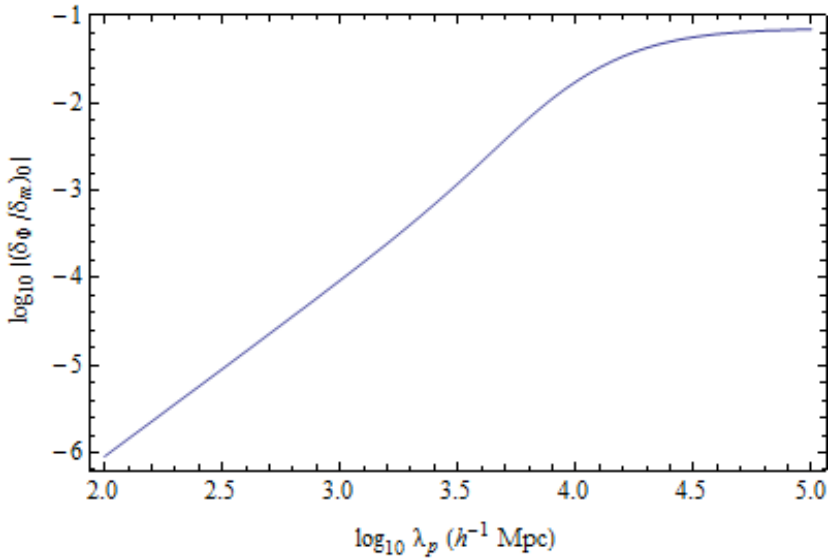
(as in minimally coupled quintessence)

Numerical Solutions

Scale Dependence of Dark Energy/Dark Matter Perturbations

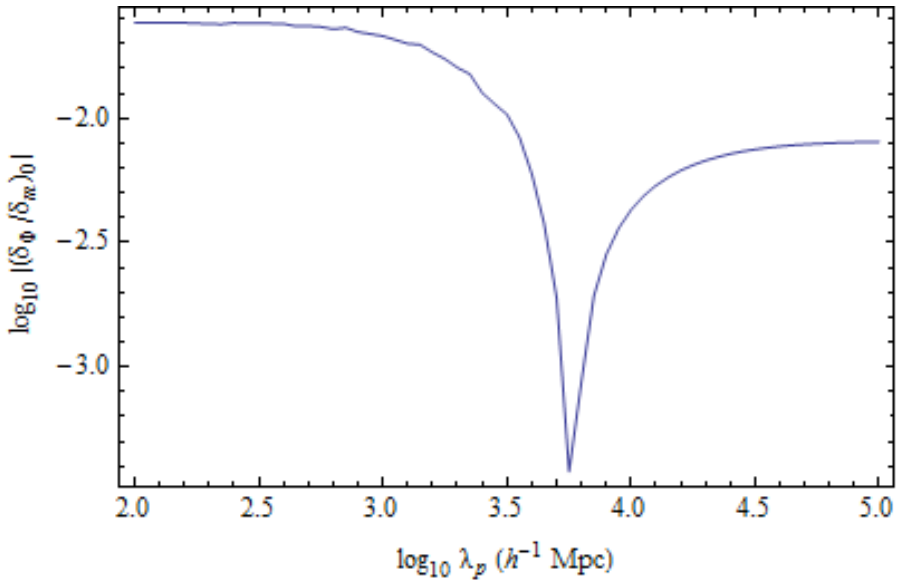
$\lambda_f = 0, \quad \lambda = 1, \; \Phi_i = 0.12$

Minimal Coupling (F=1)



$\lambda_f = 5, \quad \lambda = 1, \; \Phi_i = 0.12$

Non-Minimal Coupling ($F=1-\lambda_f \Phi^2$)



Dramatic (10^5) Amplification on sub-Hubble scales!

Summary

Early hints for **deviation from the cosmological principle** and **statistical isotropy** are being accumulated. This appears to be one of the most likely directions which may lead to new fundamental physics in the coming years.

The amplified dark energy clustering properties that emerge in
Scalar-Tensor cosmology
may help resolve the puzzles related to
amplified bulk flows and cluster halo profiles.

Numerical Solutions

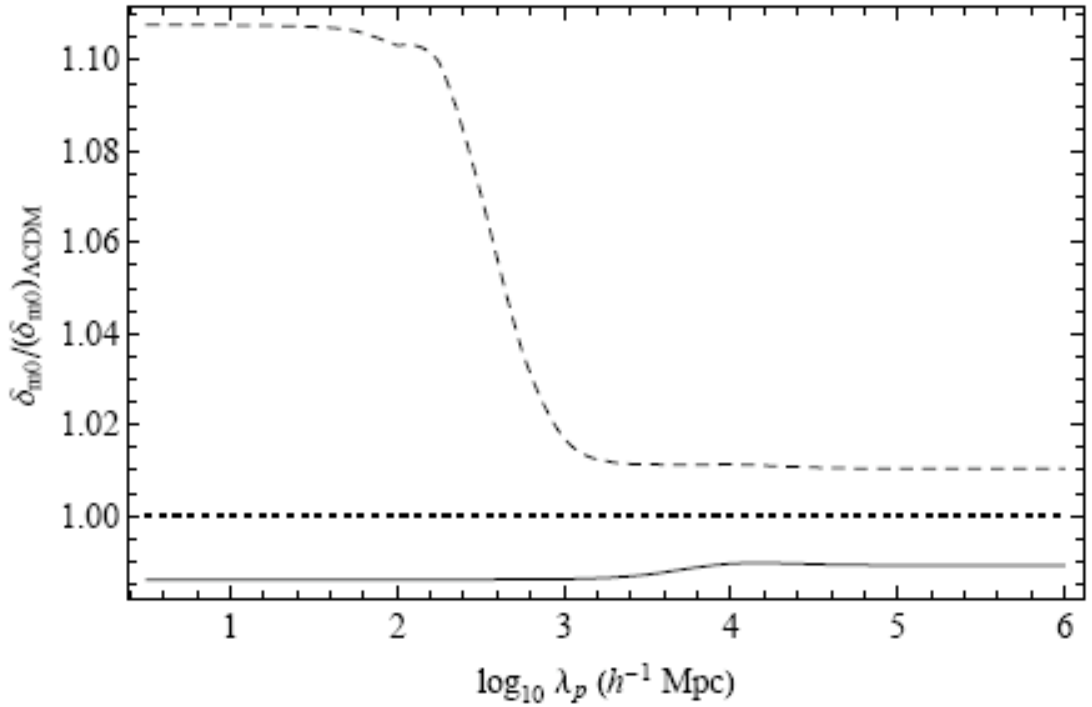
Scale Dependence of Dark Matter Perturbations

$\lambda_f = 0, \ \lambda = 1, \ \Phi_i = 0.12$

Minimal Coupling (F=1)

$\lambda_f = 5, \ \lambda = 1, \ \Phi_i = 0.12$

Non-Minimal Coupling ($F=1-\lambda_f \Phi^2$)



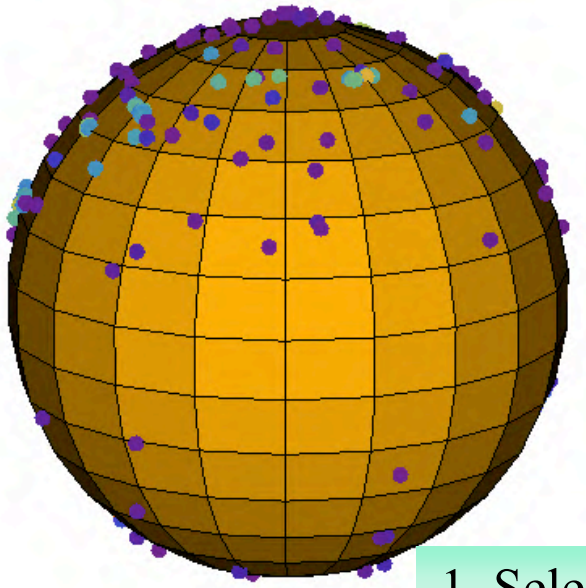
10 % Amplification of matter perturbations on sub-Hubble scales!

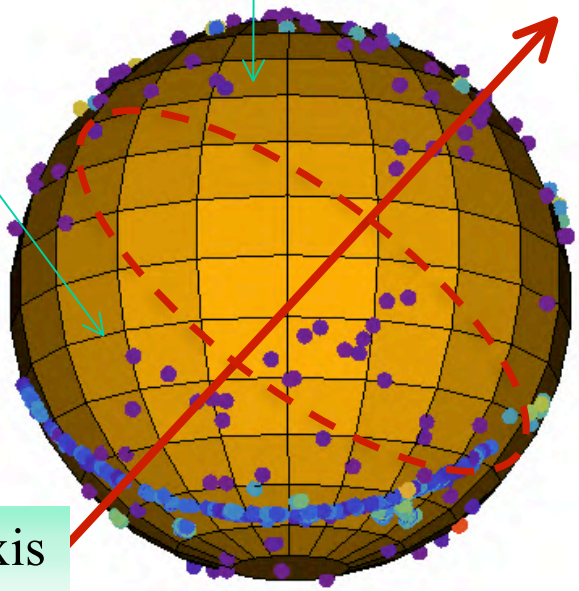
Models Predicting a Preferred Axis

- Anisotropic dark energy equation of state (eg vector fields)
  (T. Koivisto and D. Mota (2006), R. Battye and A. Moss (2009))
- Horizon Scale Dark Matter or Dark Energy Perturbations (eg 1 Gpc void)
  (J. Garcia-Bellido and T. Haugboelle (2008), P. Dunsby, N. Goheer, B. Osano and J. P. Uzan (2010), T. Biswas, A. Notari and W. Valkenburg (2010))
- Fundamentaly Modified Cosmic Topology or Geometry (rotating universe, horizon scale compact dimension, non-commutative geometry etc)
  (J. P. Luminet (2008), P. Bielewicz and A. Riazuelo (2008), E. Akofor, A. P. Balachandran, S. G. Jo, A. Joseph,B. A. Qureshi (2008), T. S. Koivisto, D. F. Mota, M. Quartin and T. G. Zlosnik (2010))
- Statistically Anisotropic Primordial Perturbations (eg vector field inflation)
  (A. R. Pullen and M. Kamionkowski (2007), L. Ackerman, S. M. Carroll and M. B. Wise (2007), K. Dimopoulos, M. Karciauskas, D. H. Lyth and Y. Ro-driguez (2009))
- Horizon Scale Primordial Magnetic Field.
  (T. Kahniashvili, G. Lavrelashvili and B. Ratra (2008), L. Campanelli (2009))

Hemisphere Comparison Method

2. Evaluate Best Fit Ω_m in each Hemisphere





1. Select Random Axis

Union2 Data
Galactic Coordinates

(view of sphere from opposite directions

3.Evaluate

4. Repeat with several random axes and find