Is there a Fundamental Cosmic Dipole?

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Main Points

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

There are some puzzling conflicts between ΛCDM predictions and specific observation
(bulk flows, alignment and magnitude of low CMB multipoles,
alignment of quasar optical polarization, fine structure dipole,dark energy dipole)

From LP, 0811.4684,
I. Antoniou, LP, **JCAP 1012:012, 2010,** arxiv:1007.4347

Most of these puzzles are related to the existence of preferred anisotropy axes which appear to be surprisingly close to each other!

The simplest mechanism that can give rise to a **cosmological preferred axis** is based on an **off-center observer** in a spherical energy inhomogeneity (dark matter or dark energy)

Topological Quintessence is a simple physical mechanism that can give rise **to a Hubble scale dark energy inhomogeneity.**

Cosmic Dipoles

Quasar absorption line spectra can determine the value of the fine structure constant at various redshifts and directions. The Keck+VLT sample consists of 295 absorbers with $0<z<4.2$ indicates a dipole angular distribution of the fine structure constant at 4.1σ confidence level.

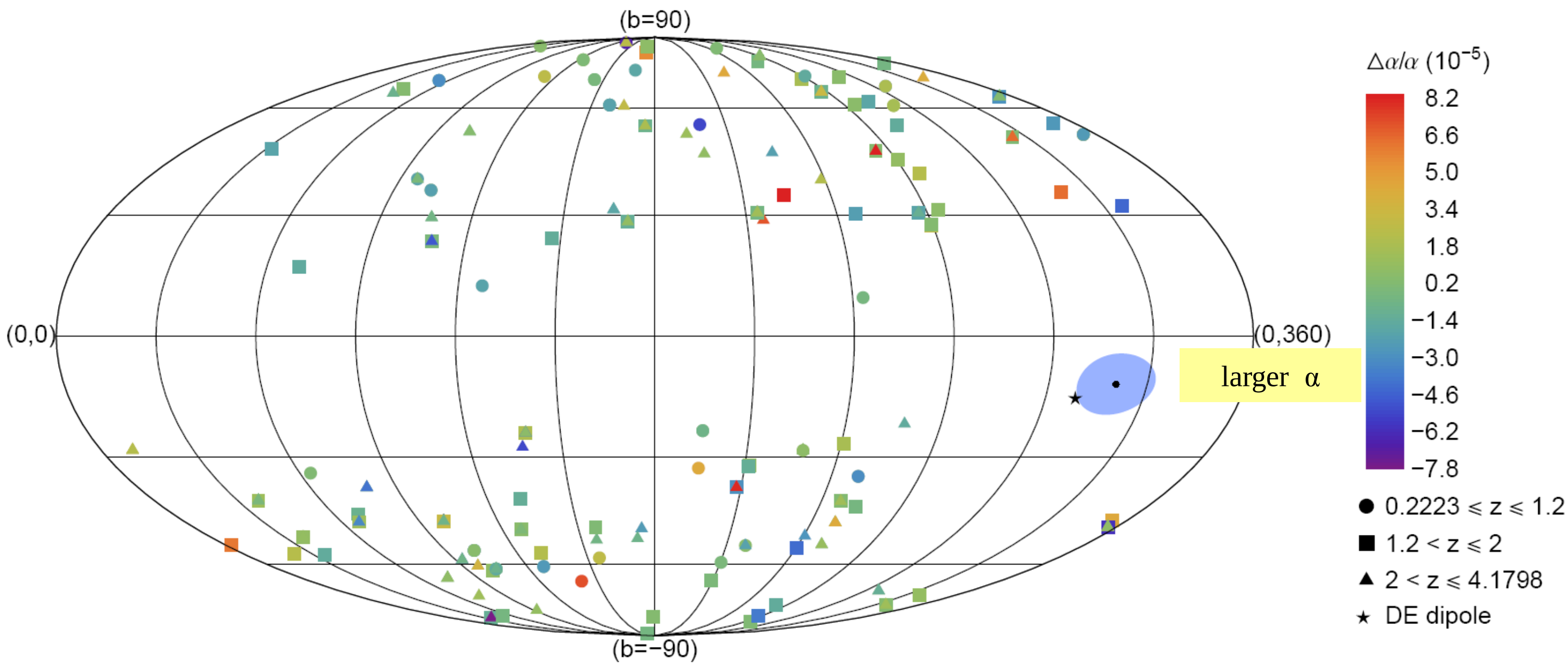
King et. al. , arXiv:1202.4758

A. Μαριανο, L.P., arxiv:1206.4055

The distance moduli residuals from the ΛCDM best fit also exhibit a dipole anisotropy at the 2σ confidence level ($0<z<1.4$). This Dark energy dipole obtained from the 557 SnIa of the Union2 sample has a direction that almost coincides with the fine structure dipole.

A. Μαριανο, L.P., arxiv:1206.4055

Fine Structure Constant Dipole



Dipole+Monopole Maximum Likelihood Fit:

$$\chi^2(\vec{D}, B) = \sum_{i=1}^{295} \frac{\left[\left(\frac{\Delta\alpha}{\alpha}\right)_i - A\cos\theta_i - B\right]^2}{\sigma_i^2 + \sigma_{rand}^2}$$

$$\hat{n}_i \cdot \vec{D} = A\cos\theta_i$$

$A_{fs} = (1.02 \pm 0.25) \times 10^{-5}$ $\quad B_{fs} = (-2.2 \pm 1.0) \times 10^{-6}$.

Monte Carlo Analysis: Magnitude of Keck+VLT dipole

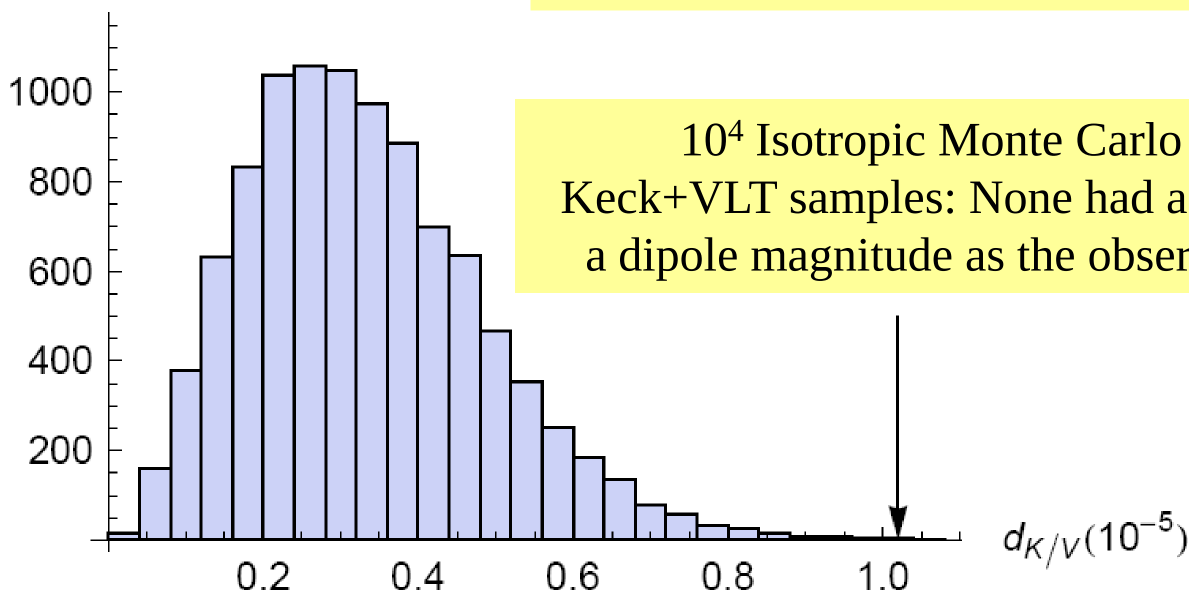
$$\chi^2(\vec{D}, B) = \sum_{i=1}^{295} \frac{\left[\left(\frac{\Delta\alpha}{\alpha}\right)_i - A\cos\theta_i - B\right]^2}{\sigma_i^2 + \sigma_{rand}^2}$$

$$A = 0.$$

$$B_{fs-m} = (-0.19 \pm 0.10) \times 10^{-5}$$

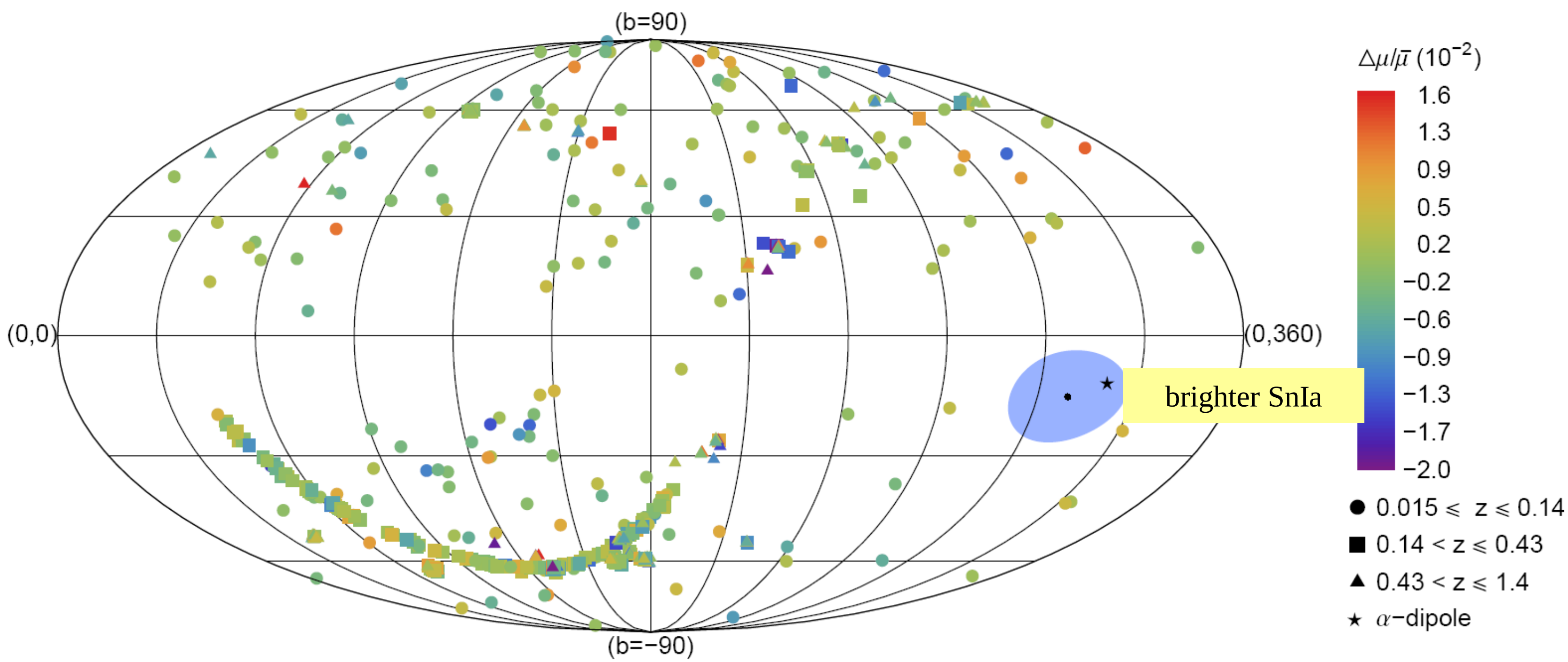
$$\left(\frac{\Delta\alpha}{\alpha}\right)_i^{MC} = g(B_{fs-m}, \sigma_i) + g(0, \sigma_{rand})$$

Random number from Gaussian probability distribution



10^4 Isotropic Monte Carlo Keck+VLT samples: None had as large a dipole magnitude as the observed!

Dark Energy Dipole



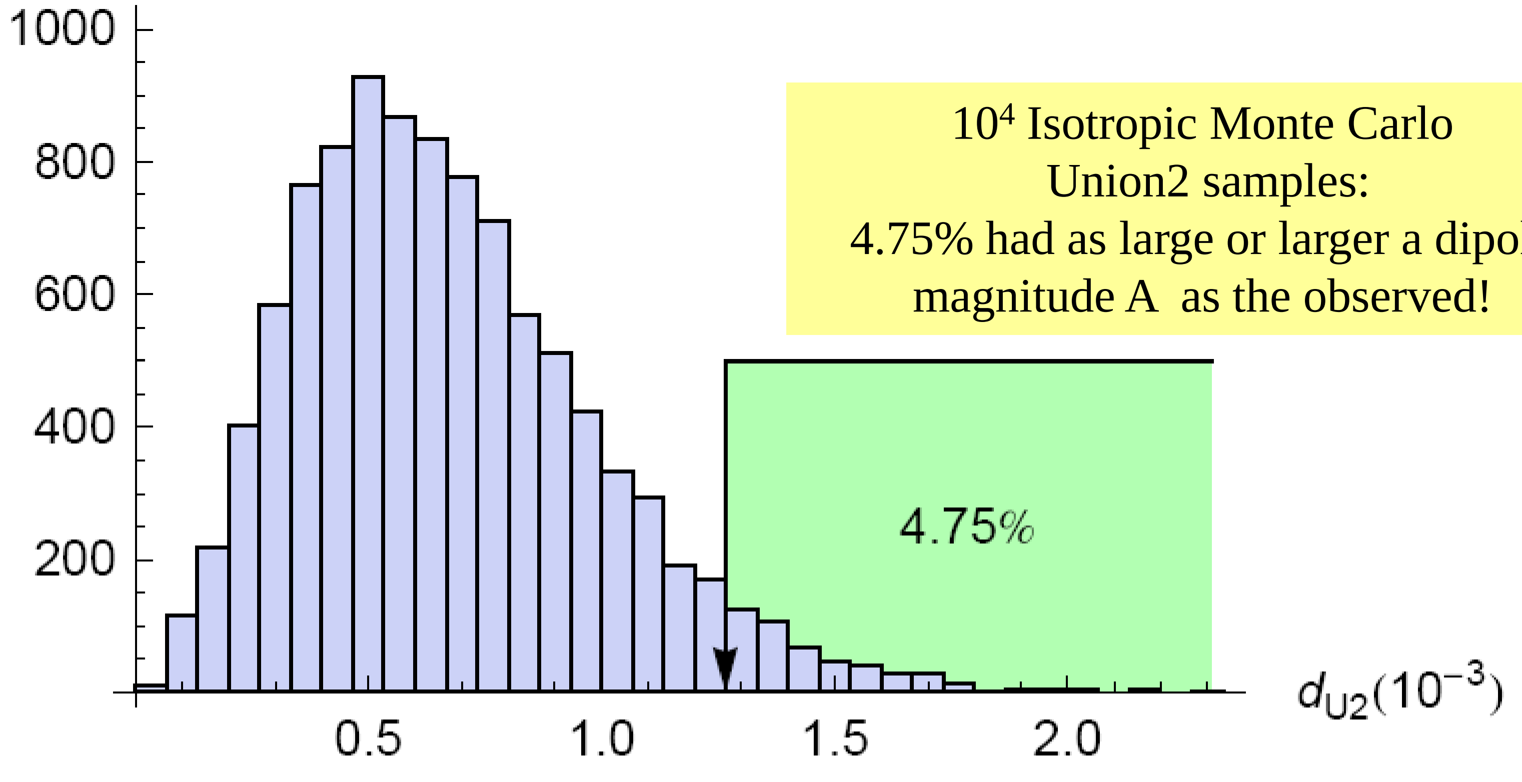
$$\left(\frac{\Delta\alpha}{\alpha}\right) = A\cos\theta + B \quad \Longrightarrow \quad \left(\frac{\Delta\mu(z_i)}{\bar{\mu}(z_i)}\right)_{obs} \equiv \frac{\bar{\mu}(z_i) - \mu(z_i)}{\bar{\mu}(z_i)}$$

$$A_{de} = (1.3 \pm 0.6) \times 10^{-3}$$
$$B_{de} = (2.0 \pm 2.2) \times 10^{-4}$$

Monte Carlo Analysis: Magnitude of Union2 Dipole

$$\mu_{MC}(z_i) = g(\bar{\mu}(z_i), \sigma_i)$$

Random number from Gaussian probability distribution



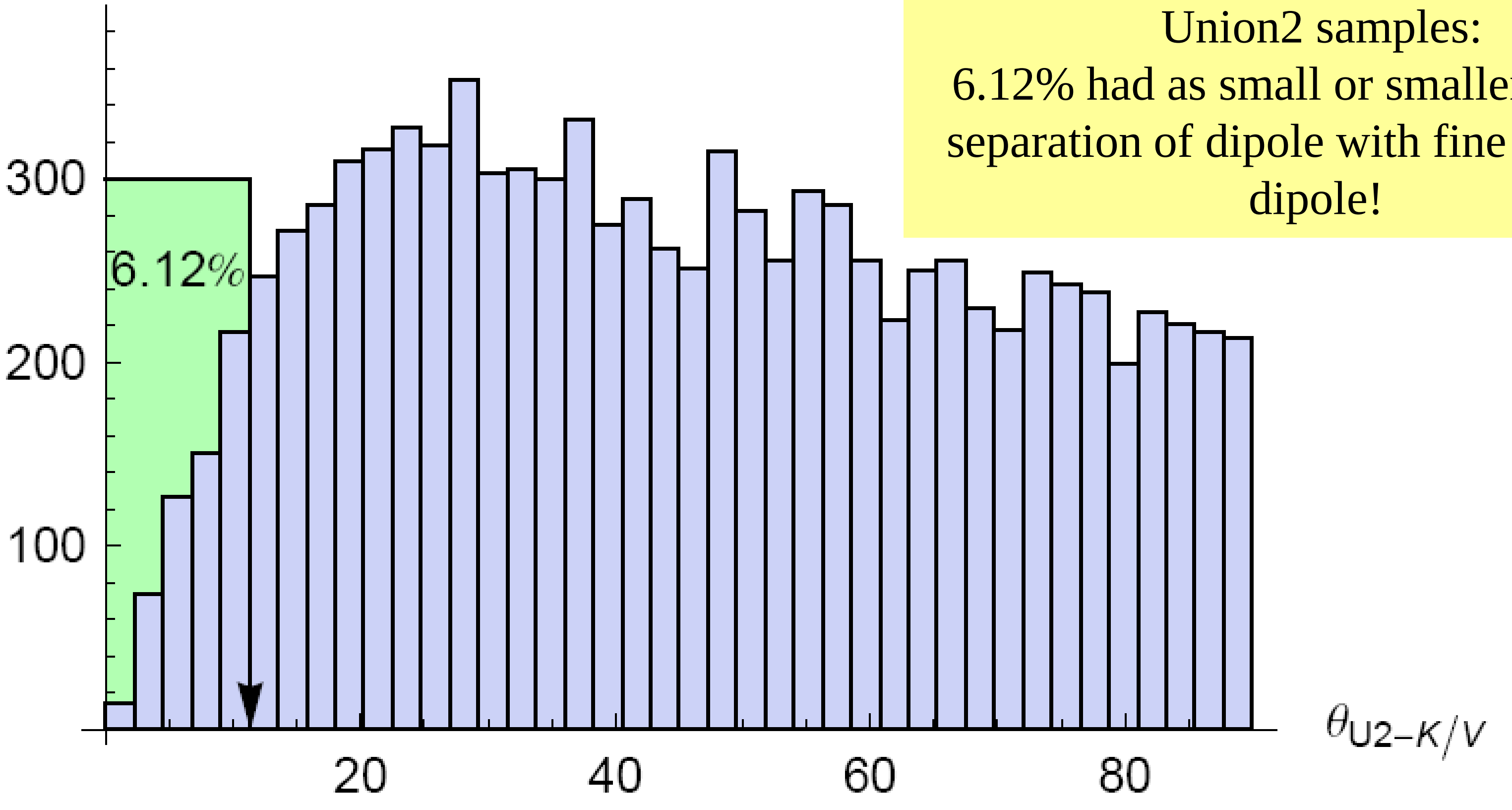
10^4 Isotropic Monte Carlo Union2 samples:
4.75% had as large or larger a dipole magnitude A as the observed!

Monte Carlo Analysis:
Angular Separation of Dipole Directions

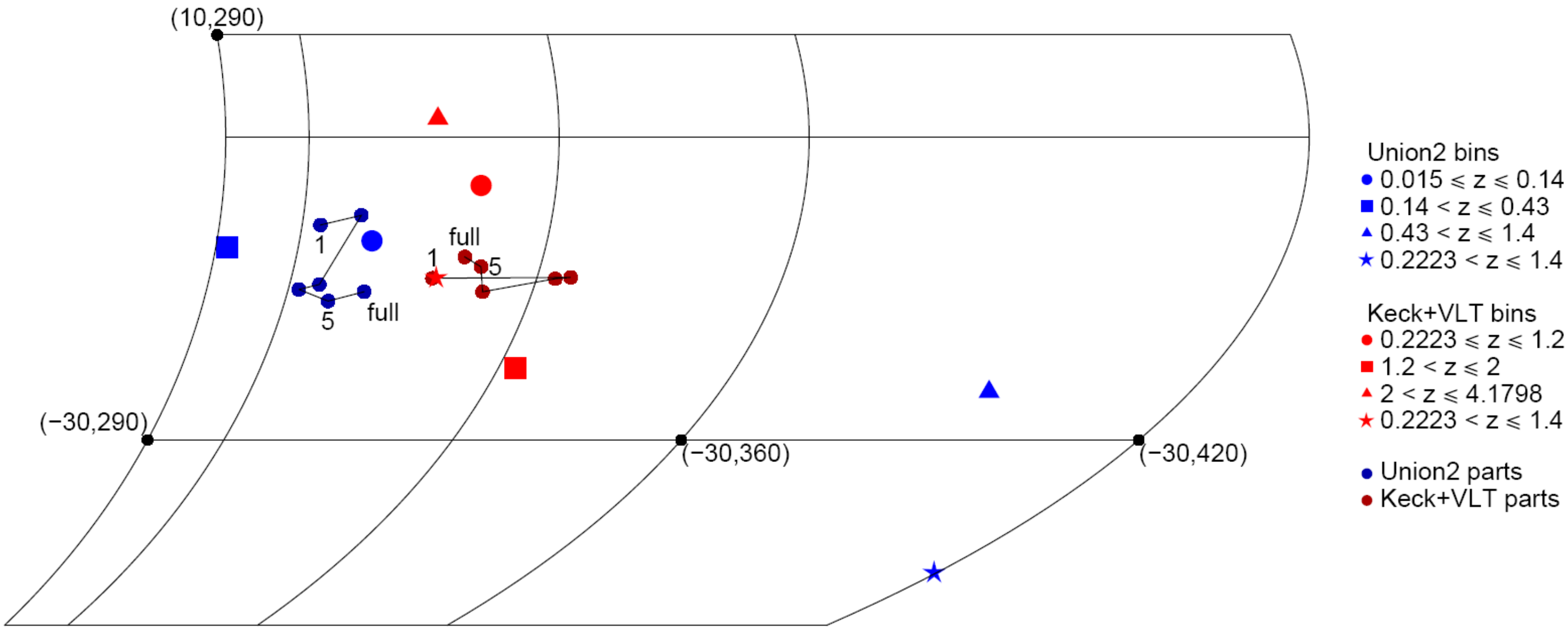
$$\mu_{MC}(z_i) = g(\bar{\mu}(z_i), \sigma_i)$$

Random number from Gaussian probability distribution

10^4 Isotropic Monte Carlo Union2 samples:
6.12% had as small or smaller angular separation of dipole with fine structure dipole!

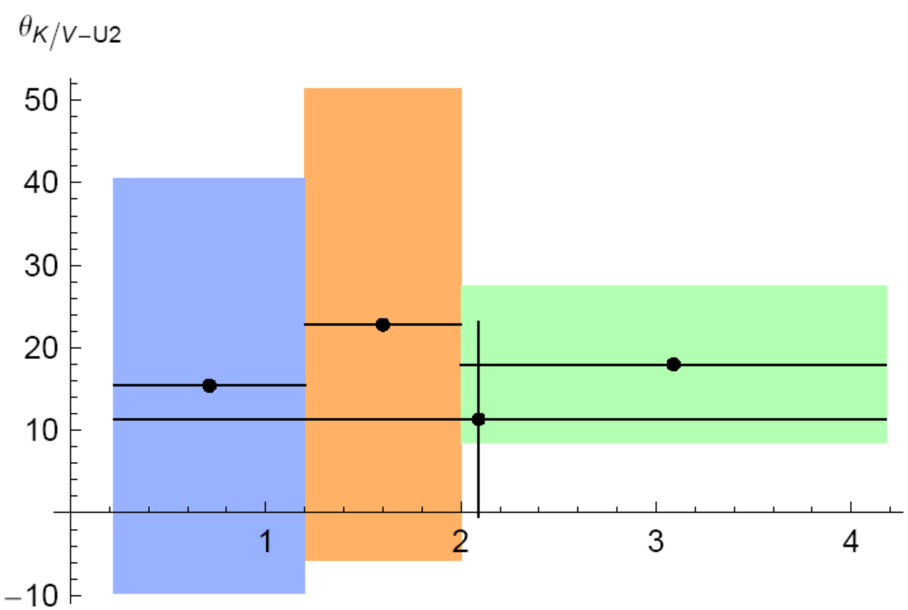


Redshift Tomography

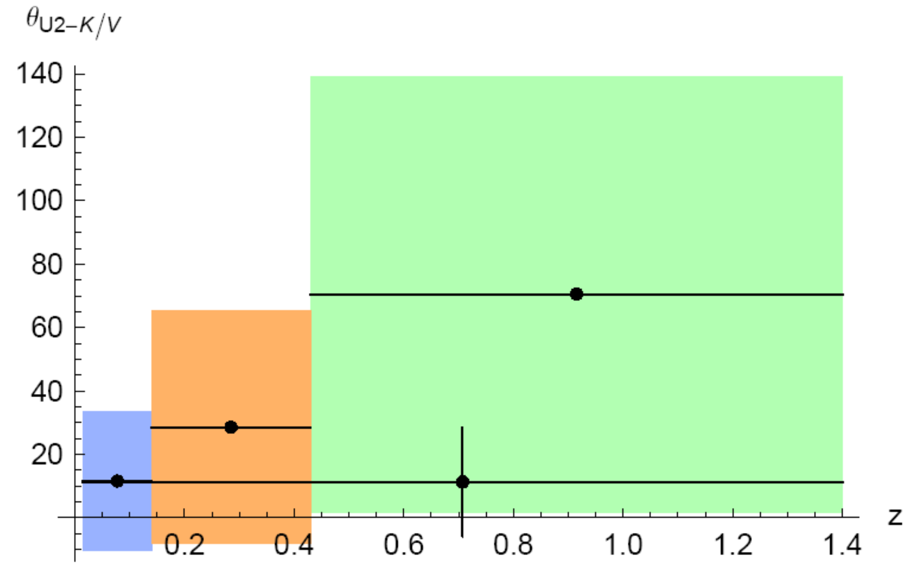


	$m_{U2}(10^{-4})$	$d_{U2}(10^{-3})$	$b_{d_{U2}}(^\circ)$	$l_{d_{U2}}(^\circ)$	$\theta_{U2-K/V}(^\circ)$	datapoints
$0.015 \leq z \leq 1.4$	2.0 ± 2.2	1.3 ± 0.6	-15.1 ± 11.5	309.4 ± 18.0	11.3 ± 17.3	557
$0.015 < z \leq 0.14$	2.6 ± 3.4	1.7 ± 0.8	-10.1 ± 15.1	308.8 ± 22.8	11.6 ± 22.1	184
$0.14 < z \leq 0.43$	2.6 ± 5.6	1.2 ± 1.9	-10.7 ± 28.7	291.4 ± 37.2	28.6 ± 36.7	186
$0.43 < z \leq 1.4$	0.7 ± 4.3	0.9 ± 0.8	-25.1 ± 30.6	34.3 ± 75.7	70.6 ± 68.7	187
$0.015 \leq z \leq 0.23$	3.3 ± 2.9	1.8 ± 0.7	-8.5 ± 12.4	302.2 ± 16.6	18.3 ± 16.0	239
$0.015 \leq z \leq 0.31$	3.8 ± 2.9	1.9 ± 0.7	-7.6 ± 11.6	307.0 ± 14.7	13.9 ± 13.8	292
$0.015 \leq z \leq 0.41$	3.0 ± 2.7	1.8 ± 0.7	-14.4 ± 10.3	303.6 ± 14.4	16.6 ± 14.1	352
$0.015 \leq z \leq 0.51$	2.2 ± 2.6	1.4 ± 0.7	-14.9 ± 12.7	301.3 ± 18.8	18.9 ± 18.2	406
$0.015 \leq z \leq 0.64$	2.1 ± 2.4	1.4 ± 0.6	-16.0 ± 11.0	305.3 ± 16.9	15.4 ± 16.2	464
$0.015 \leq z \leq 0.89$	2.2 ± 2.3	1.4 ± 0.6	-15.6 ± 10.4	309.8 ± 16.0	11.1 ± 15.3	519
$0.2223 < z \leq 1.4$	1.2 ± 2.5	0.51 ± 0.48	-44.0 ± 62.5	59.3 ± 147.6	88.2 ± 110.6	319

Redshift Tomography: Angular Separation of Dipoles



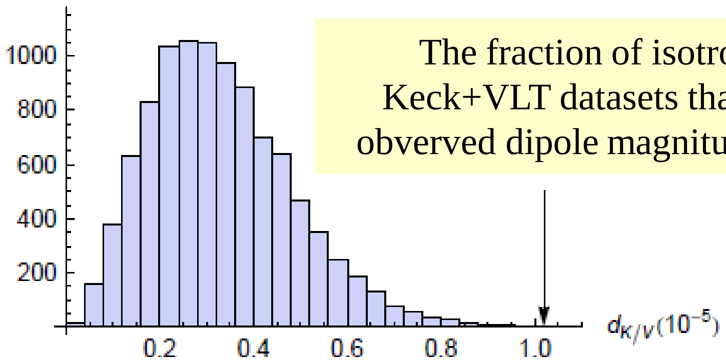
Angular separation of fine structure dipoles with full dark energy dipole in various redshift bins



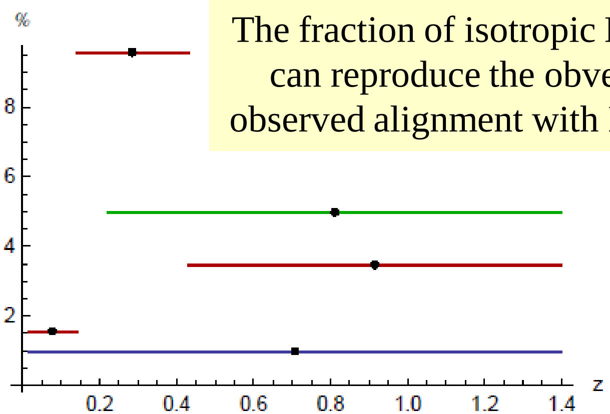
Angular separation of dark energy dipoles with full fine structure dipole in various redshift bins

Question I

What is the probability to obtain as large (or larger) dipole magnitudes with the observed alignment in an isotropic cosmological model?



The fraction of isotropic Monte Carlo Keck+VLT datasets that can reproduce the obverved dipole magnitude is less than 0.01%



The fraction of isotropic Monte Carlo Union2 datasets that can reproduce the obverved dipole magnitude and the observed alignment with Keck+VLT dipole is less than 1%

0.01% x 1% = 0.0001%

Question II

Is there a physical model that predicts the existence of such aligned dipoles?

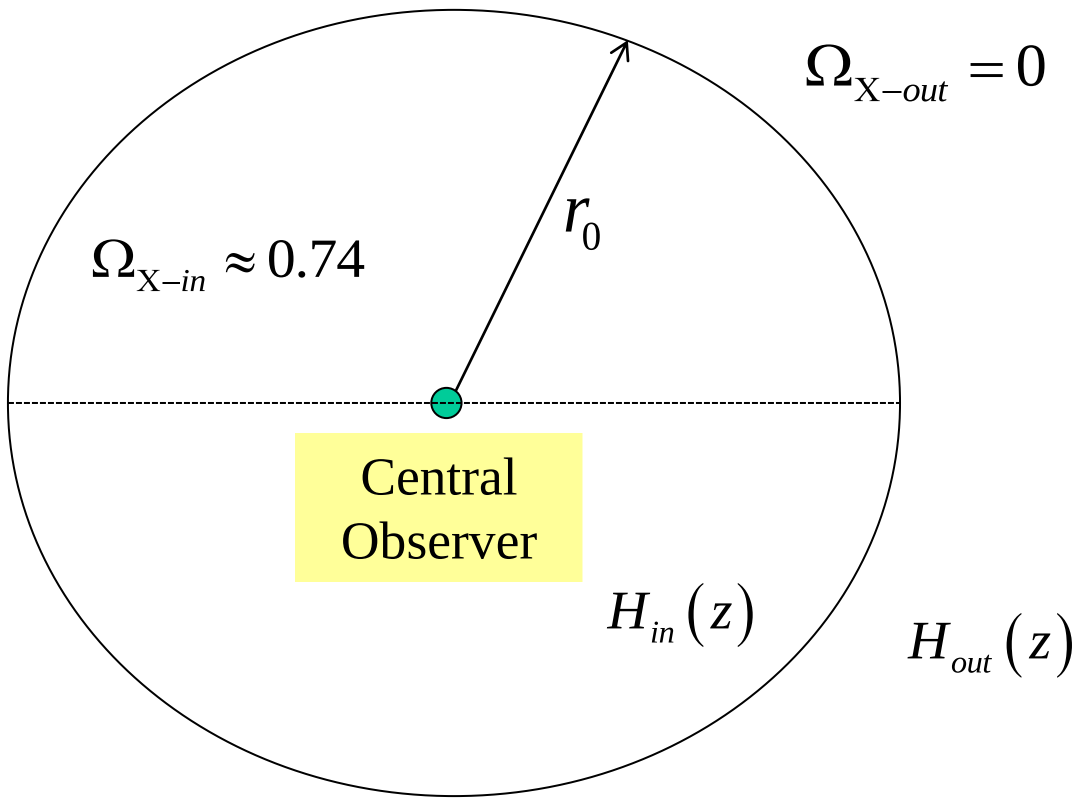
A. Μαριανο, L.P., arxiv:1206.4055

J. B. Sanchez, LP, **Phys.Rev. D84 (2011) 123516** arxix:1110.2587

J. Grande, L.P., Phys. Rev. D **84**, 023514 (2011).

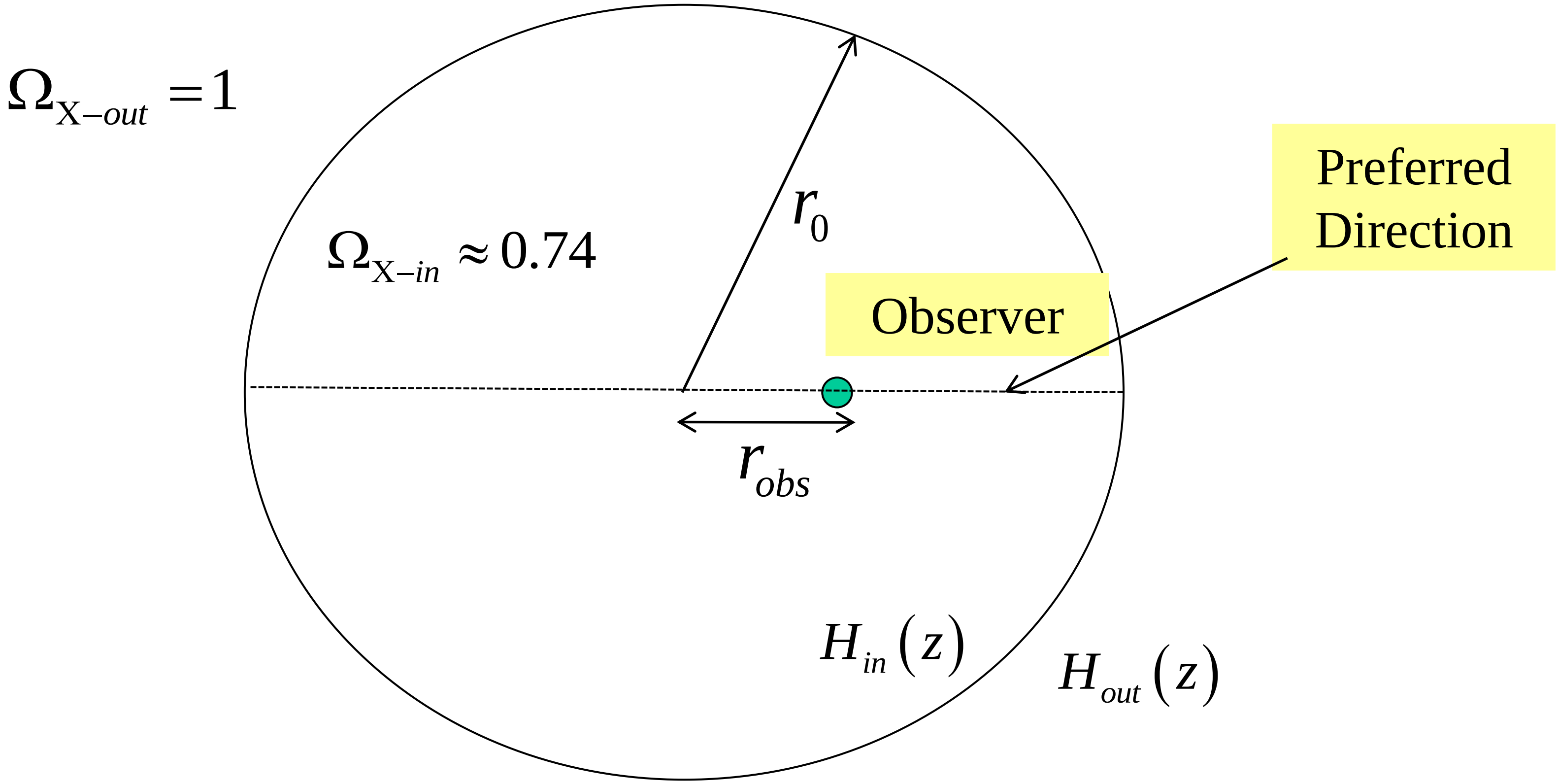
Spherical Hubble Scale Scalar Field Energy

Spherical Scalar Field (Dark Energy)v Inhomogeneity



Inhomogeneous Dark Energy Density

Shifted Observer: Preferred Direction



What Physical Mechanism can produce such Dark Energy Inhomogeneity?

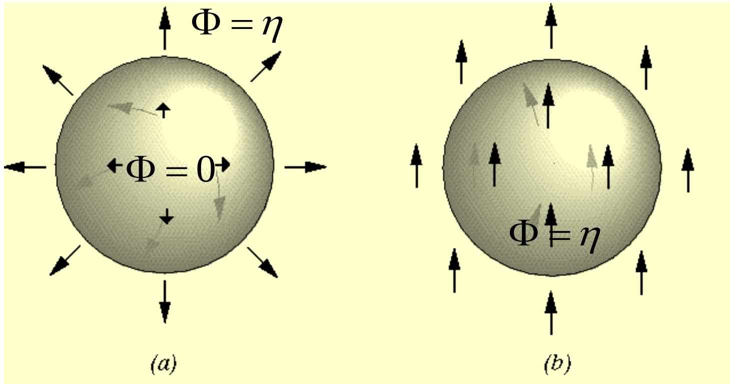
Topological Quintessence

Global Monopole with Hubble scale Core

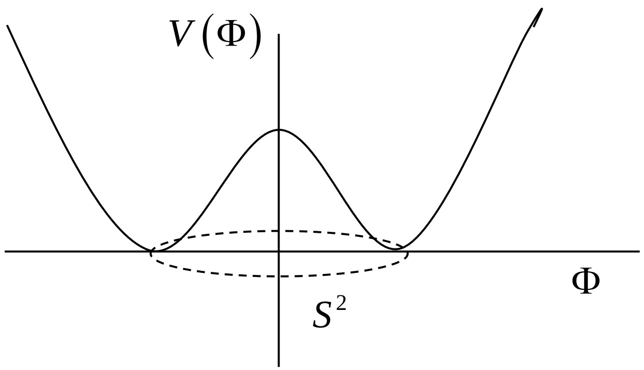
$$S = \int d^4x\sqrt{-g}\left[\frac{m_{Pl}^2}{16\pi}\mathcal{R} - \frac{1}{2}(\partial_\mu \Phi^a)^2 - V(\Phi) + \mathcal{L}_m\right]$$

$$V(\Phi) = \frac{1}{4}\lambda(\Phi^2 - \eta^2)^2, \quad \Phi \equiv \sqrt{\Phi^a \Phi^a}$$

$$\begin{aligned} \Phi(0,t) &= 0 \\ \Phi(\infty,t) &= \eta \end{aligned}$$



$$\Phi^a = \Phi(t,r)\hat{r}^a \equiv \Phi(t,r)(\sin\theta\cos\varphi, \sin\theta\sin\varphi, \cos\theta)$$



General Metric with Spherical Symmetry:

$$ds^2 = -dt^2 + A^2(r,t)dr^2 + B^2(r,t)r^2(d\theta^2 + \sin^2\theta d\varphi^2)$$

Energy – Momentum Tensor:

$$T_{\mu\nu} = \partial_\mu \Phi^a \partial_\nu \Phi^a - g_{\mu\nu}\left[\frac{1}{2}(\partial_\sigma \Phi^a)^2 + V(\Phi)\right]$$

$$T_{\mu\nu} = T_{\mu\nu}^{(mon)} + T_{\mu\nu}^{(mat)}$$

$$T_{\mu\nu}^{(mat)} = \rho^{mat} u_\mu u_\nu$$

$$u^\mu = \left(\frac{1}{\sqrt{1-v^2}}, \frac{v}{A\sqrt{1-v^2}}, 0, 0\right)$$

Full Dynamical Equations

$$-G^0_0 = K^2_2(2K - 3K^2_2) - 2\frac{B''}{A^2B} - \frac{B'^2}{A^2B^2} + 2\frac{A'B'}{A^3B} - 6\frac{B'}{A^2Br} + 2\frac{A'}{A^3r} - \frac{1}{A^2r^2} + \frac{1}{B^2r^2}$$
$$= \frac{8\pi}{m^2_{Pl}}\left[\frac{\dot{\Phi}^2}{2} + \frac{\Phi'^2}{2A^2} + \frac{\Phi^2}{B^2r^2} + \frac{\lambda}{4}(\Phi^2 - \eta^2)^2 + \frac{\rho^{mat}}{1-v^2}\right],$$

$$K^1_1 = -\frac{\dot{A}}{A}, \quad K^2_2 = K^3_3 = -\frac{\dot{B}}{B}, \quad K = K^i_i$$

$$\frac{1}{2}G_{01} = K^{2\prime}_2 + \left(\frac{B'}{B} + \frac{1}{r}\right)(3K^2_2 - K) = \frac{4\pi}{m^2_{Pl}}\left(\dot{\Phi}\Phi' - \frac{v}{1-v^2}A\,\rho^{mat}\right),$$

J. B. Sanchez, LP, **Phys.Rev. D84 (2011) 123516** arxix:1110.2587

$$\frac{1}{2}(G^1_1 + G^2_2 + G^3_3 - G^0_0) = \dot{K} - (K^1_1)^2 - 2(K^2_2)^2$$
$$= \frac{8\pi}{m^2_{Pl}}\left[\dot{\Phi}^2 - \frac{\lambda}{4}(\Phi^2 - \eta^2)^2 + \frac{1}{2}\frac{1+v^2}{1-v^2}\rho^{mat}\right],$$

$$\ddot{\Phi} - K\dot{\Phi} - \frac{\Phi''}{A^2} - \left(-\frac{A'}{A} + \frac{2B'}{B} + \frac{2}{r}\right)\frac{\Phi'}{A^2} + \frac{2\Phi}{B^2r^2} + \lambda\Phi(\Phi^2 - \eta^2) = 0.$$

Energy-Momentum Conservation

$$\frac{\dot{v}}{v} = (v^2 - 1)\frac{\dot{A}}{A} - \frac{v'}{A},$$

$$\frac{\dot{\rho}^{mat}}{\rho^{mat}} = \frac{\dot{v}}{v} - 2\frac{\dot{B}}{B} - \frac{v}{A}\frac{(\rho^{mat})'}{\rho^{mat}} - 2\frac{v}{A}\frac{B'}{B} - \frac{2v}{r\,A}$$

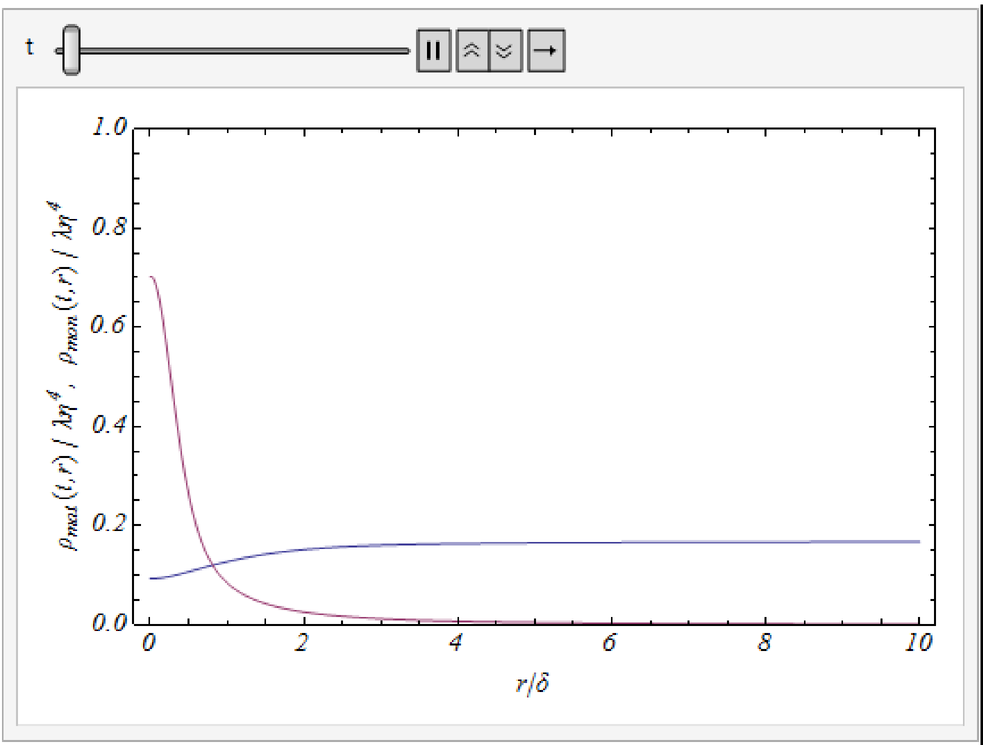
Initial-Boundary Conditions

Static Monopole Profile
(Φ=f(r))

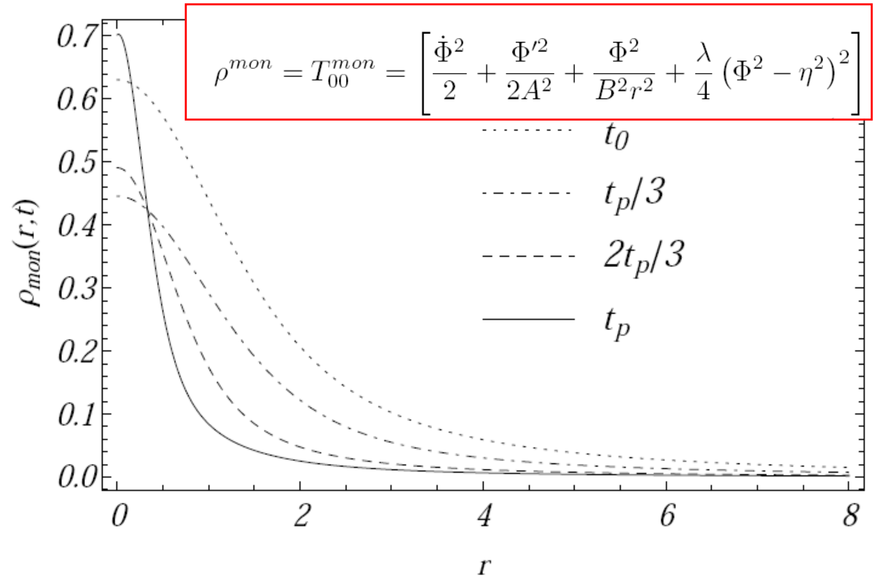
Homogeneous, Flat Matter
Dominated (A=B=1)

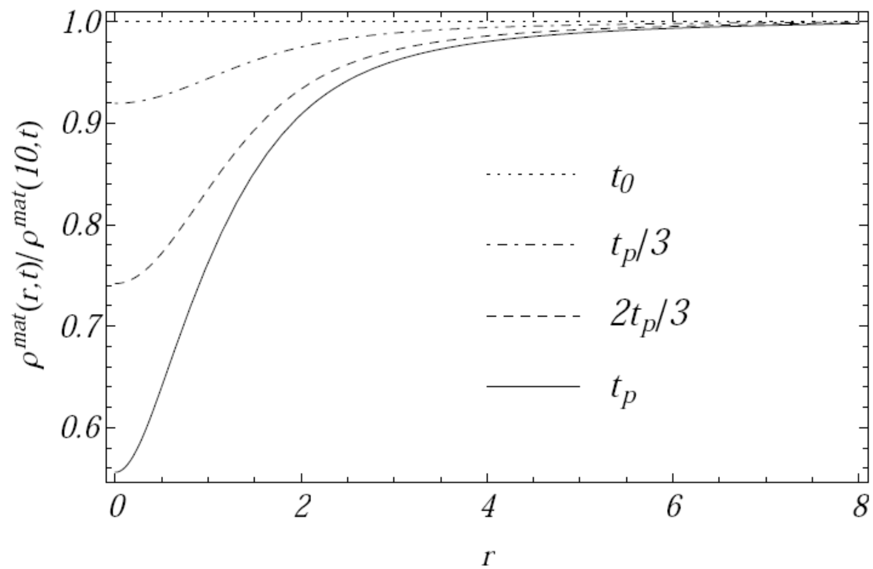
Energy Densities

1. Monopole energy density slowly shrinks and dominates at late times in the core.
2. Matter develops underdensity at the core.

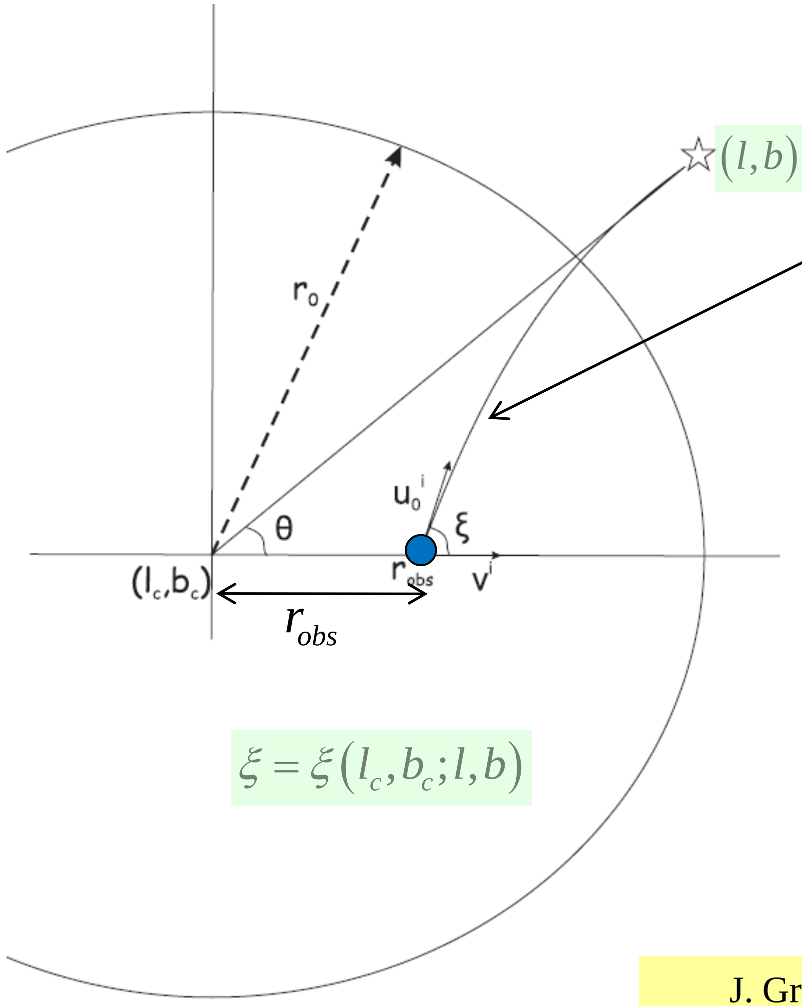


$$\rho^{mon} = T_{00}^{mon} = \left[\frac{\dot{\Phi}^2}{2} + \frac{\Phi'^2}{2A^2} + \frac{\Phi^2}{B^2 r^2} + \frac{\lambda}{4}\left(\Phi^2 - \eta^2\right)^2\right]$$





Off-Center Observer



$$\xi = \xi(l_c, b_c; l, b)$$

Geodesics

↓

Luminosity Distance

$$d_L\left(z, r_0, \Omega_{X-in}; \xi, r_{obs}\right)$$

↓

$$\chi^2\left(r_0, \Omega_{X-in}; r_{obs}, l_c, b_c\right)$$

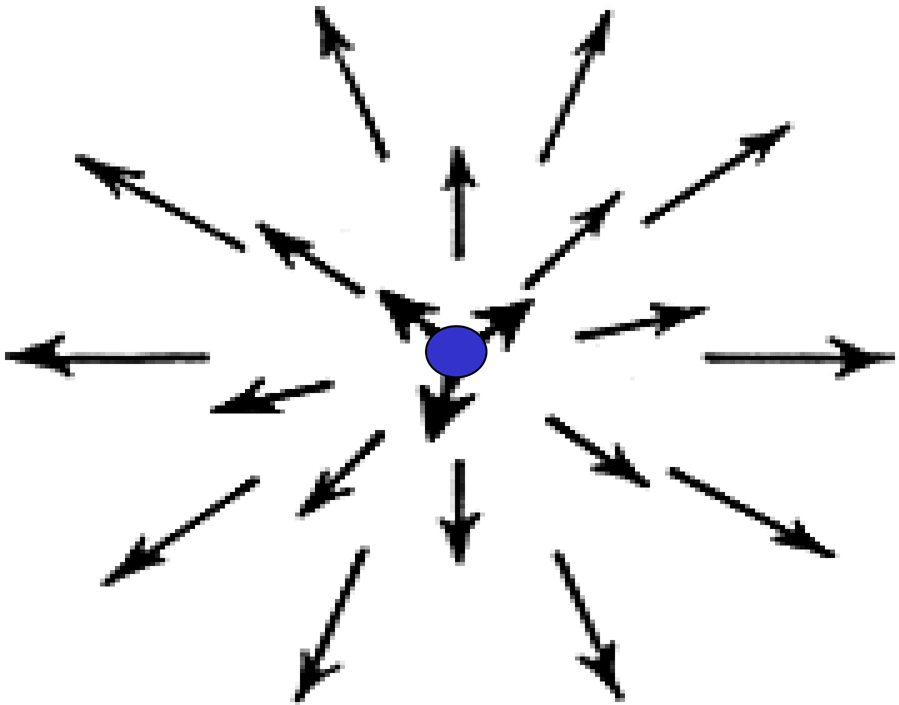
J. Grande, L.P., Phys. Rev. D **84**, 023514 (2011).

Extended Topological Quintessence

$$S = \int \left[\frac{1}{2}M_p^2 R - \frac{1}{2}(\partial_\mu \Phi^a)^2 - V(\Phi) + \right.$$
$$\left. + \frac{1}{4}B(\Phi)F_{\mu\nu}^2 + \mathcal{L}_m \right] \sqrt{-g}\,\mathrm{d}^4x, \quad \Rightarrow \quad \alpha(\Phi) = \frac{e_0^2}{4\pi B(\Phi)^2}$$

$$\Downarrow \quad B(\Phi) = \eta - \xi\Phi$$

$$\left(\frac{\Delta\alpha}{\alpha}\right) \simeq \xi\frac{\Phi}{\eta} \quad \Longrightarrow \quad \xi > 0.$$



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 simplest mechanism that can give rise to a **cosmological preferred axis** is based on an **off-center observer** in a spherical energy inhomogeneity (dark matter of dark energy)

Topological Quintessence constitutes a physical mechanism to produce Hubble scale dark energy inhomogeneities.

An extended version of such a mechanism can give rise to **aligned Fine Structure Constant and Dark Energy Dipoles**