Generalizing ΛCDM with Inhomogenous Dark Energy: Observational Constraints

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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 dynamical data probes
(bulk flows, alignment and magnitude of low CMB multipoles, alignment of quasar optical polarization vectors, cluster halo profiles)

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 of dark energy)

Geometric Probes: Recent SnIa Datasets

Dataset	Date Released	Redshift Range	# of SnIa	Filtered subsets included
SNLS1	2005	$0.015 \leq z \leq 1.01$	115	SNLS, LR
Gold06	2006	$0.024 \leq z \leq 1.76$	182	SNLS1, HST, SCP, HZSST
ESSENCE	2007	$0.016 \leq z \leq 1.76$	192	SNLS1, HST, ESSENCE,
Union	2008	$0.015 \leq z \leq 1.55$	307	Gold06, ESSENCE
Constitution	2009	$0.015 \leq z \leq 1.55$	397	Union, CfA3
SDSS	2009	$0.022 \leq z \leq 1.55$	288	Nearby, SDSS-II, ESSENCE, SNLS , HST
Union2	2010	$0.015 \leq z \leq 1.4$	557	Union, CfA3, SDSS-II

Q1: What is the Figure of Merit of each dataset?

Q2: What is the consistency of each dataset with ΛCDM?

Q3: What is the consistency of each dataset with Standard Rulers?

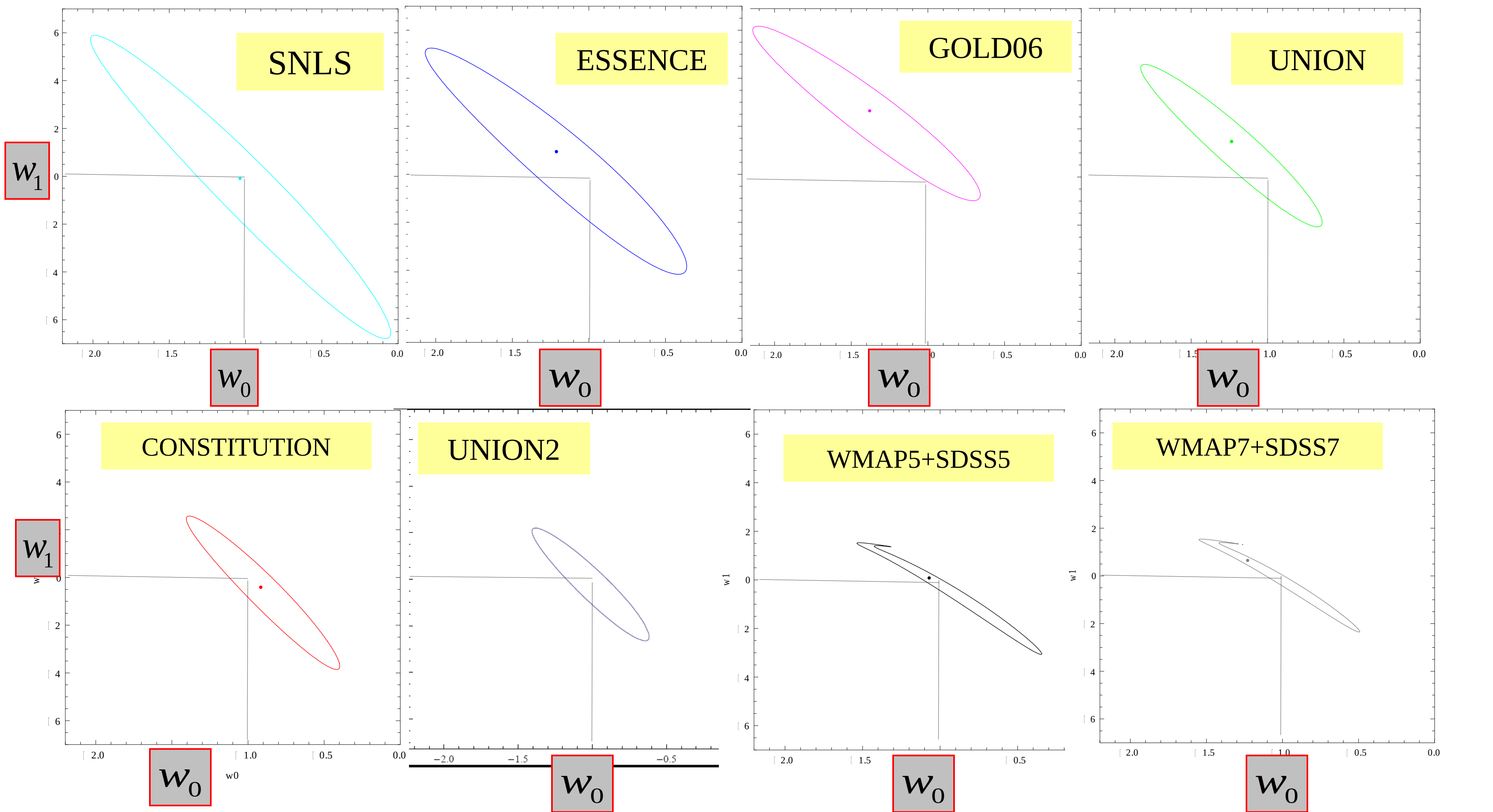
J. C. Bueno Sanchez, S. Nesseris, LP,
JCAP 0911:029,2009, 0908.2636

$\Omega_{0m} = 0.28$

Figures of Merit

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

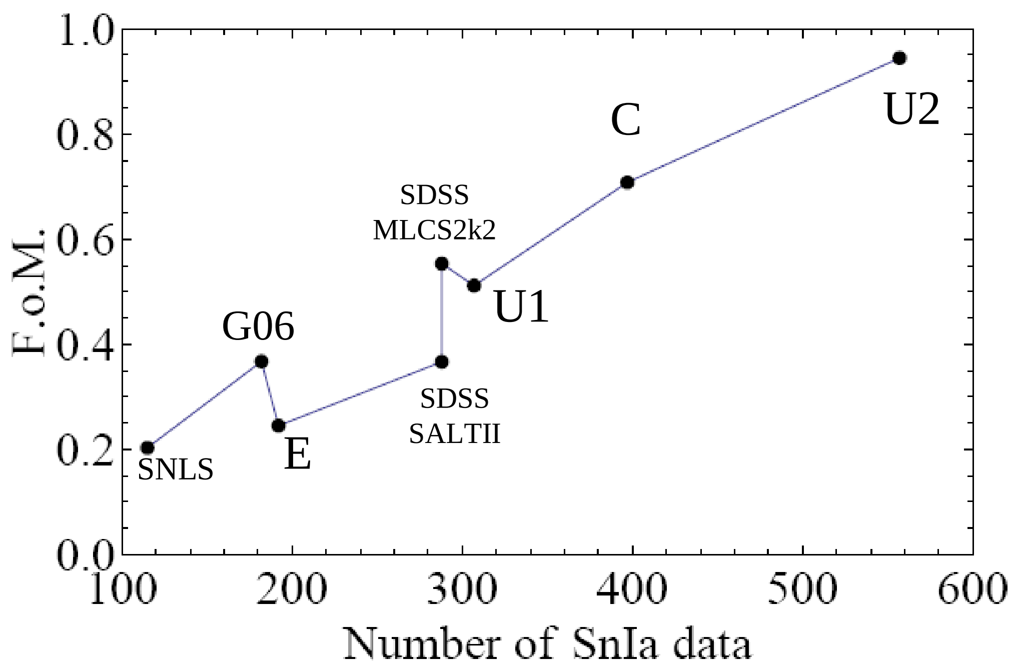
The Figure of Merit: Inverse area of the 2σ CPL parameter contour.
A measure of the effectiveness of the dataset in constraining the given parameters.



Figures of Merit

The Figure of Merit: Inverse area of the 2σ CPL parameter contour.
A measure of the effectiveness of the dataset in constraining the given parameters.

Dataset	# of SnIa	Figure of Merit
SNLS1	115	0.208
Gold06	182	0.367
ESSENCE	192	0.245
SDSS-II (SALT2)	288	0.366
SDSS-II (MLCS2k2)	288	0.553
Union	307	0.512
Constitution (SALT2)	397	0.708
Union2	557	0.95
CMB+SDSS5	-	2.028
CMB+SDSS7	-	2.541



SDSS5 → **Percival et. al.** arXiv:0705.3323

SDSS7 → **Percival et. al.** arXiv:0907.1660

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.

Puzzles for ΛCDM

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

Large Scale Velocity Flows

R. Watkins et. al. , **Mon.Not.Roy.Astron.Soc.392:743-756,2009**, 0809.4041.
A. Kashlinsky et. al. **Astrophys.J.686:L49-L52,2009 arXiv:0809.3734**

- 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),**
Copi et. al. **Adv.Astron.2010:847541,2010**.

- Predicted: Orientations of coordinate systems that maximize planarity ($|a_{ll}|^2 + |a_{l-l}|^2$) of CMB maps should be independent of the multipole l .
- Observed: Orientations of l=2 and l=3 systems 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 and Galaxy 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: **3-5%**

Proximity of Axes Directions

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

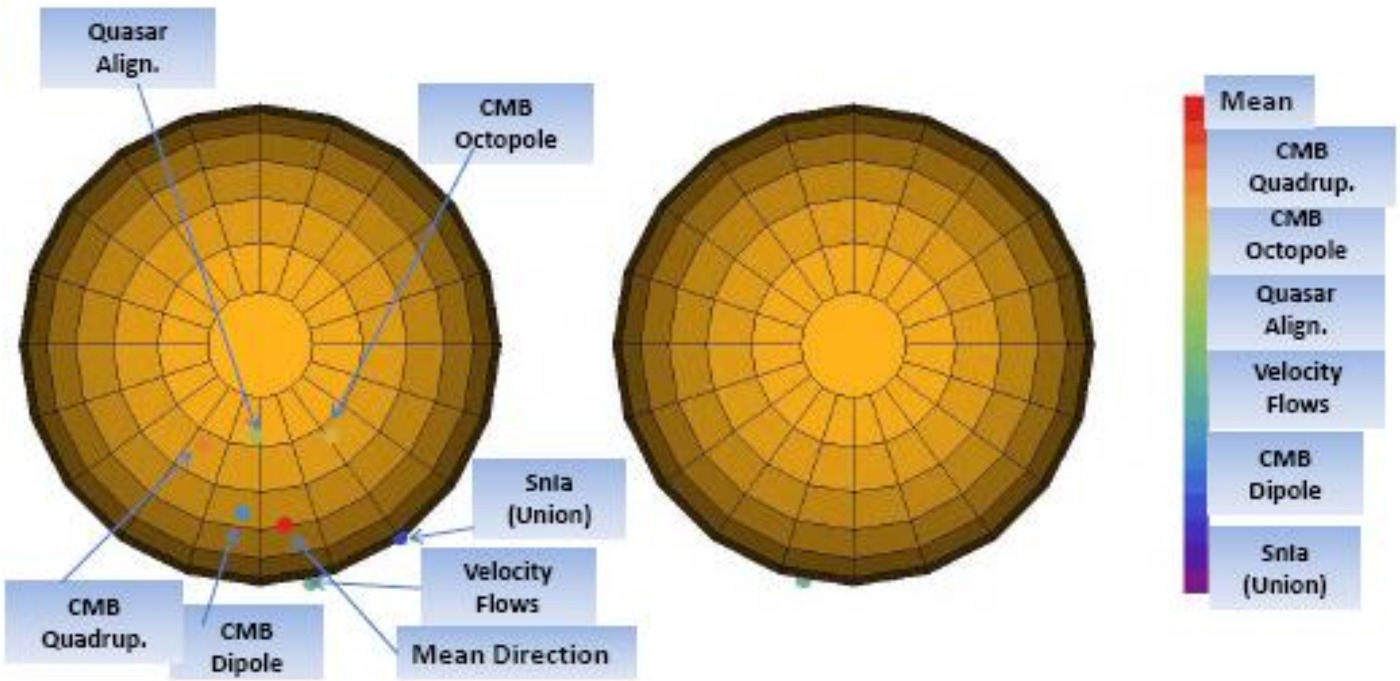
Q: What is the probability that these independent axes lie so close in the sky?

Calculate:

$$< |cos\theta_{ij}| >=< |\hat{r}_i \cdot \hat{r}_j| >= \sum_{i,j=1, j\neq i}^{N} \frac{|\hat{r}_i \cdot \hat{r}_j|}{N(N-1)}$$

Compare 6 real directions with 6 random directions

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	$277^\circ \pm 26^\circ$	$44^\circ \pm 27^\circ$



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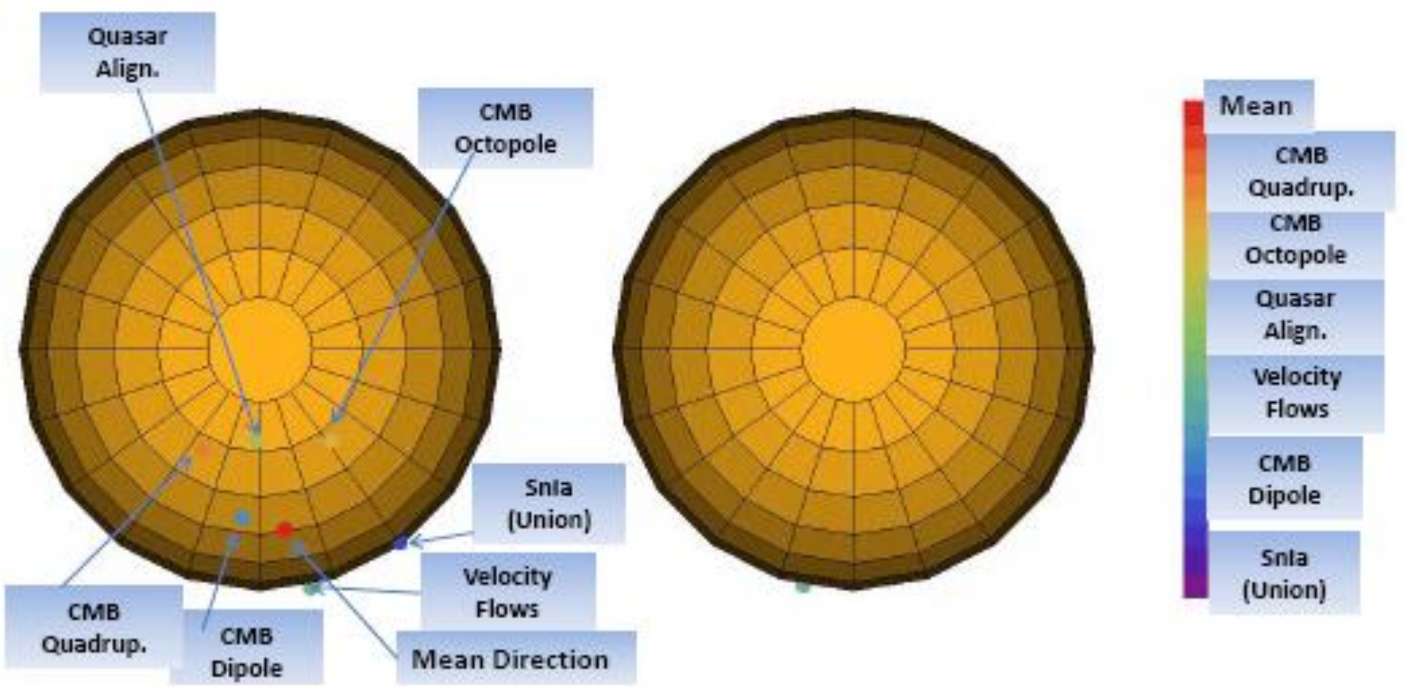
Compare 6 real directions with 6 random directions

Simulated 6 Random Directions:

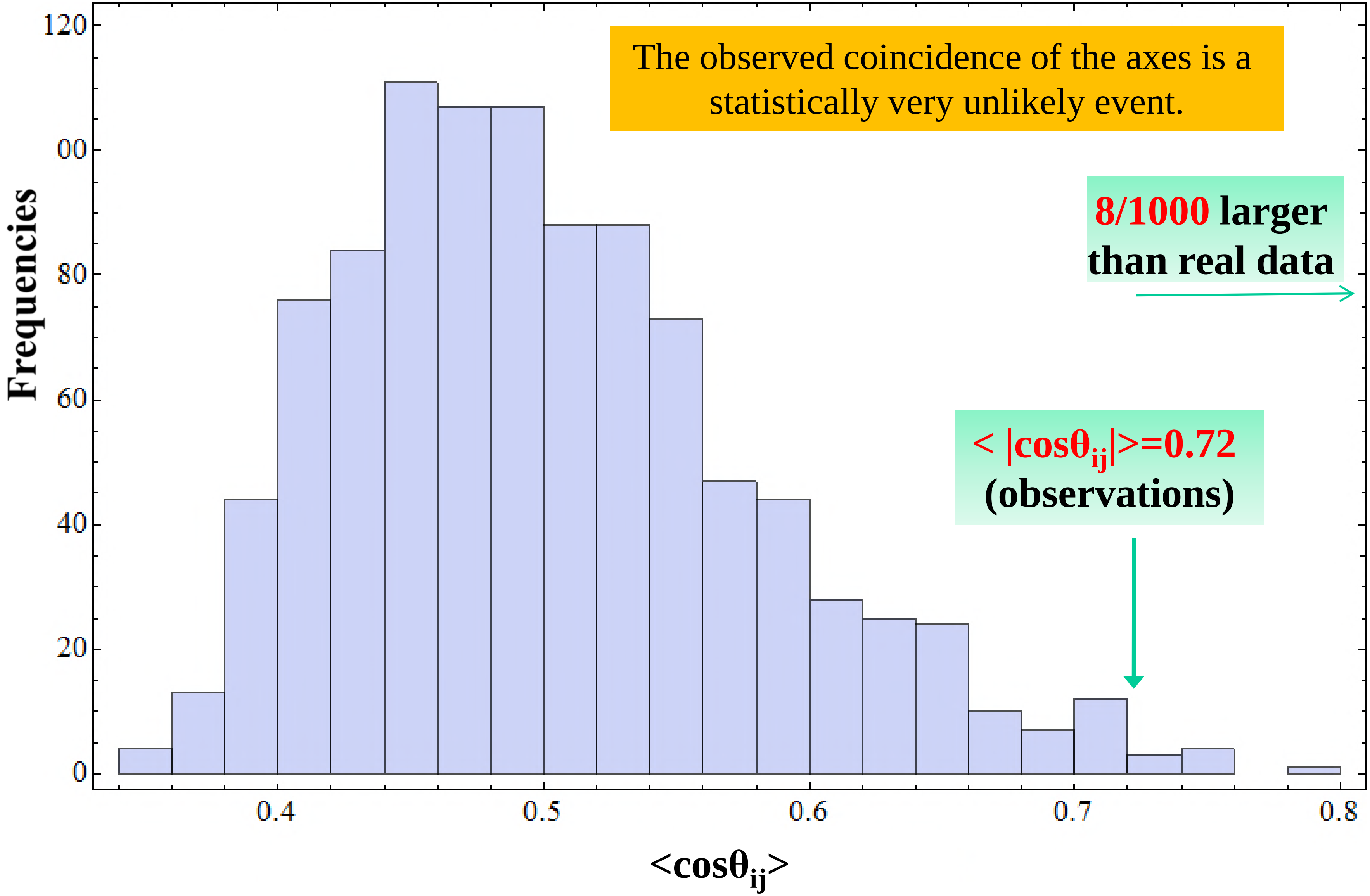
$$< |cos\theta_{ij}| >= 0.5 \pm 0.072$$

6 Real Directions (3σ away from mean value):

$$< |cos\theta_{ij}| >= 0.72$$



Distribution of Mean Inner Product of Six Preferred Directions (CMB included)



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))

- 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))

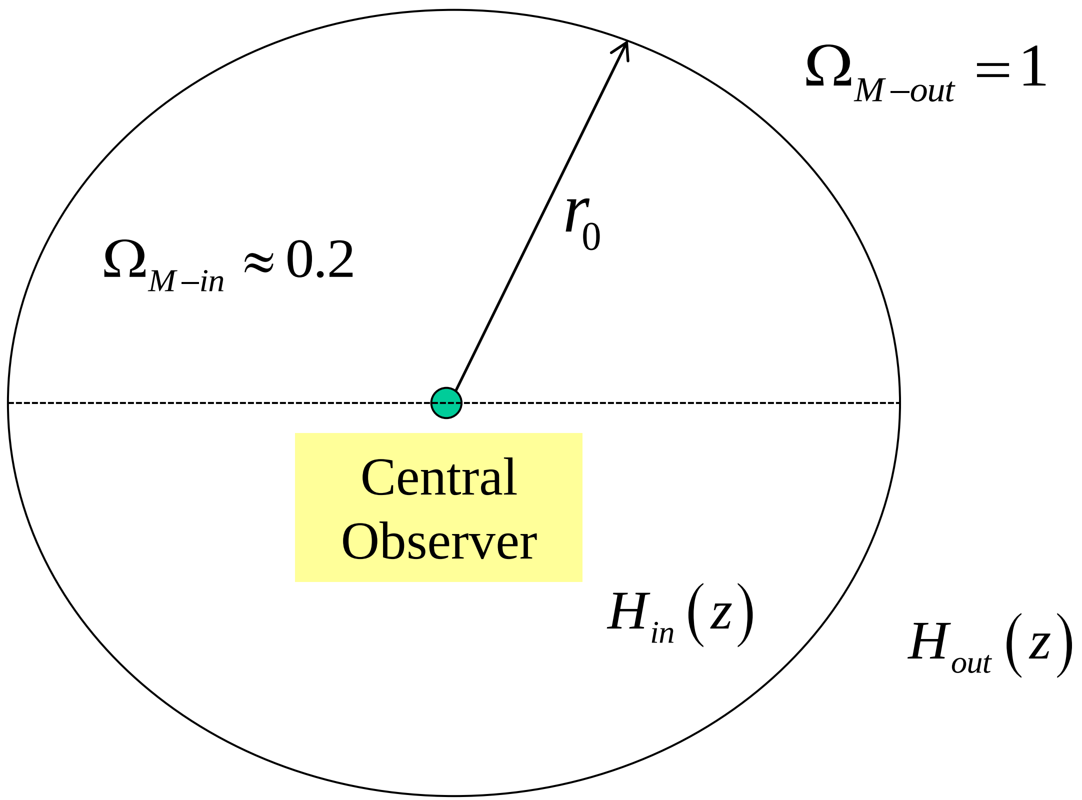
- Statistically Anisotropic Primordial Perturbations (eg vector field inflation)
  (A. R. Pullen and M. Kamionkowski (2007), L. Ackerman, S. M. Carroll and M. B. Wise (2007), K. Dimopoulos, M. Karciauskas, D. H. Lyth and Y. Ro-driguez (2009))

- Horizon Scale Primordial Magnetic Field.
  (T. Kahniashvili, G. Lavrelashvili and B. Ratra (2008), L. Campanelli (2009), J. Kim and P. Naselsky (2009))

- **Horizon Scale Dark Matter or Dark Energy Perturbations (eg few 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))

Simplest Model: Lematre-Tolman-Bondi

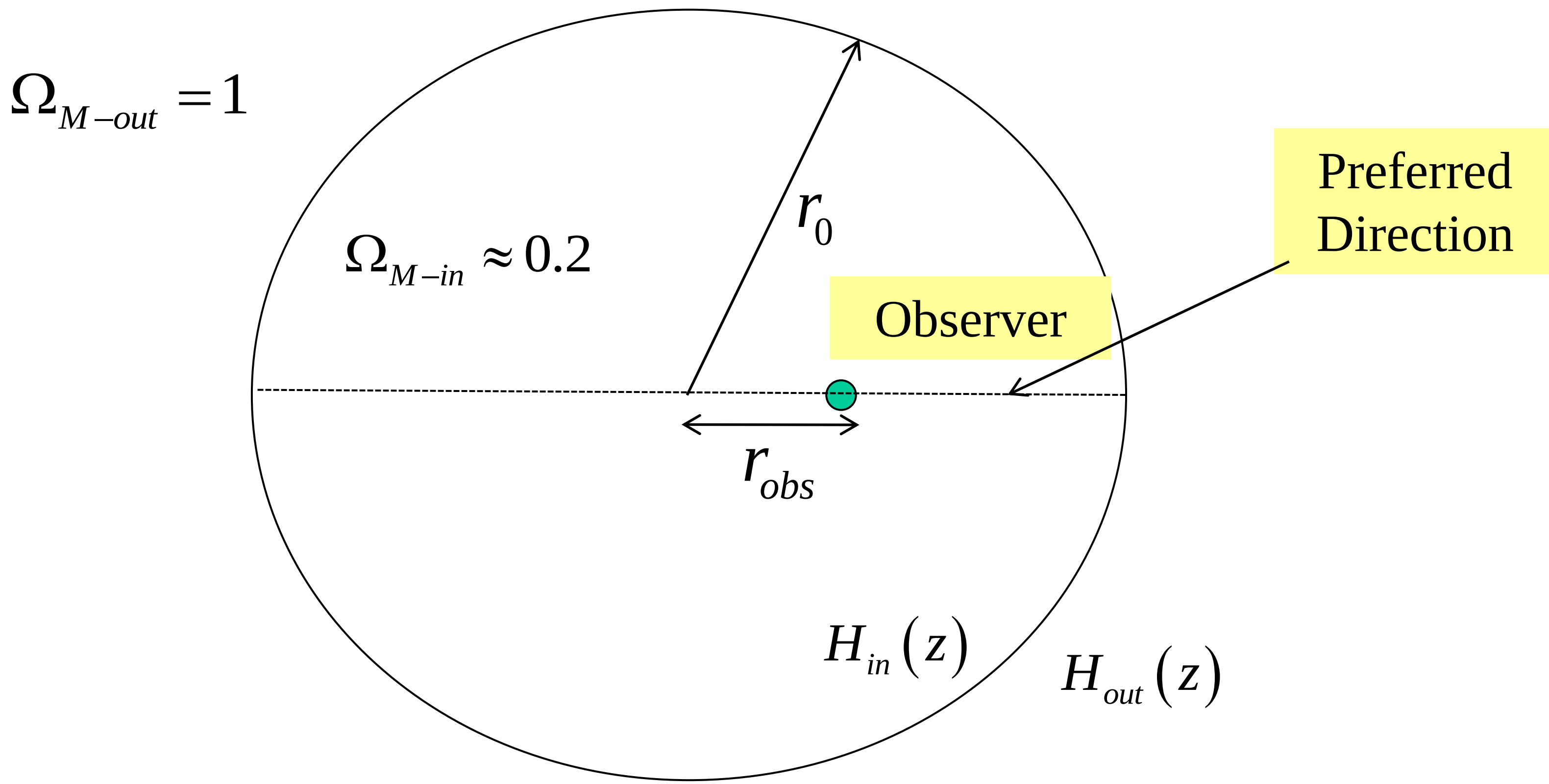
Local spherical underdensity of matter (Void), no dark energy



Faster expansion rate at low redshifts
(local space equivalent to recent times)

Shifted Observer: Preferred Direction

Local spherical underdensity of matter (Void)



Faster expansion rate at low redshifts
(local space equivalent to recent times)

Constraints: Union2 Data – Central Observer

Metric:

FRW limit: $A(r,t) = r\,a(t), \quad k(r) = k$

$$ds^2 = -dt^2 + \frac{(A'(r,t))^2}{1-k(r)}dr^2 + A^2(r,t)\left(d\theta^2 + \sin^2\theta d\varphi^2\right)$$

Cosmological Equation:

0

$$1 - \Omega_M(r) = -\frac{k(r)}{H_0(r)^2 A(r,t_0)^2}$$

$$H^2(r,t) = H_0^2(r)\left[\Omega_M(r)\left(\frac{A_0}{A}\right)^3 + \Omega_X(r) + \Omega_c(r)\left(\frac{A_0}{A}\right)^2\right]$$

$$H(r,t) \equiv \frac{\dot{A}(r,t)}{A(r,t)}$$

1

$$\Omega_M(r) = \Omega_{M,\text{out}} + (\Omega_{M,\text{in}} - \Omega_{M,\text{out}})\frac{1-\tanh[(r-r_0)/2\Delta r]}{1+\tanh(r_0/2\Delta r)}$$

$$H_0(r) = \frac{1}{t_0}\int_0^1 \frac{dx}{\sqrt{\Omega_M(r)x^{-1} + \Omega_X(r)x^2 + \Omega_c(r)}}$$

Geodesics:

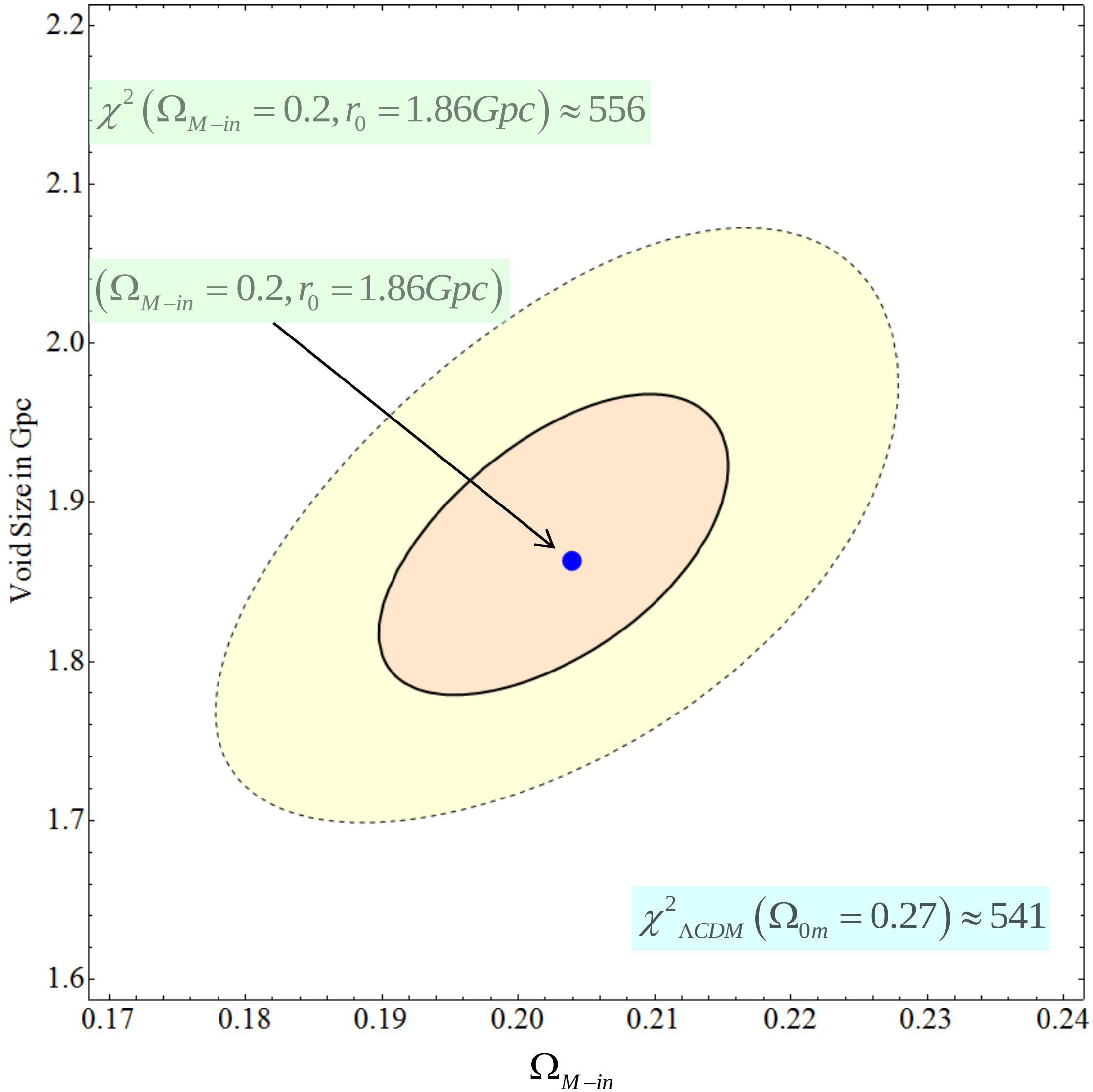
$$\frac{dt}{dz} = -\frac{A'(r,t)}{(1+z)\dot{A}'(r,t)}$$

$$\frac{dr}{dz} = \frac{c\sqrt{1-k(r)}}{(1+z)\dot{A}'(r,t)}$$

Luminosity Distance:

$$d_L(z, r_0, \Omega_{\text{M,in}}) = (1+z)^2\, A(r(z), t(z))$$

Constraints: Union2 Data – Central Observer



Advantages:

1. No need for dark energy.
2. Natural Preferred Axis.
3. Coincidence Problem

Problems:

1. No simple mechanism to create such large voids.
2. Off-Center Observer produces too large CMB Dipole.
3. Worse Fit than LCDM.
4. Ruled out (Zibin,Bull,Stebbins)

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

Inhomogeneous Dark Energy: Why Consider?

Coincidence Problem:

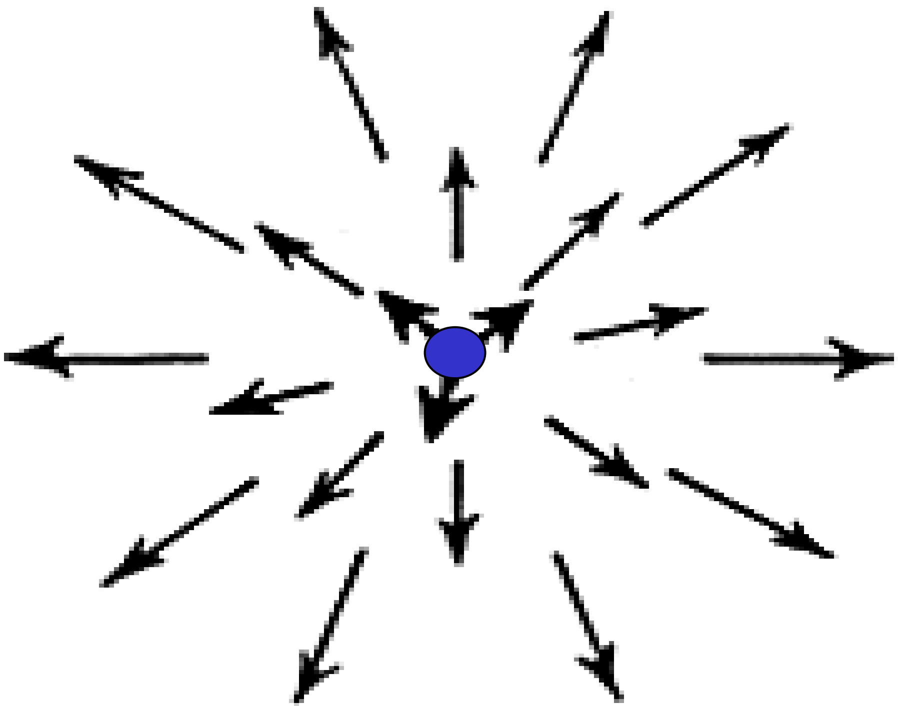
Why Now? ⟶ Time Dependent Dark Energy

Alternatively:

Why Here? ⟶ Inhomogeneous Dark Energy

Standard Model (ΛCDM):

1. Homogeneous - Isotropic Dark and Baryonic Matter.
2. Homogeneous-Isotropic-Constant Dark Energy (Cosmological Constant)
3. General Relativity



Consider Because:

1. New generic generalization of ΛCDM (breaks homogeneity of dark energy). Includes ΛCDM as special case.
2. Natural emergence of preferred axis (off – center observers)
3. Well defined physical mechanism (topological quintessence with Hubble scale global monopoles).

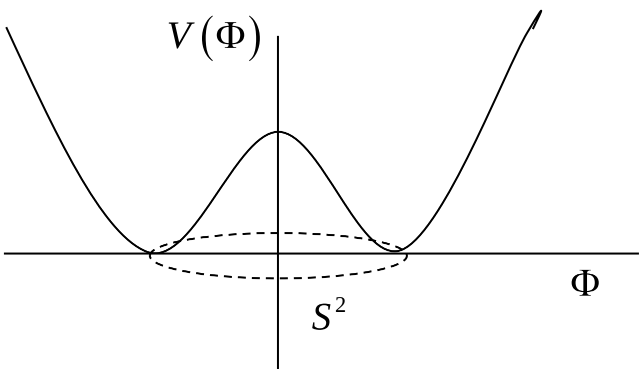
J. Grande, L.P., Phys. Rev. D **84**, 023514 (2011).

J. B. Sanchez, LP, in preparation.

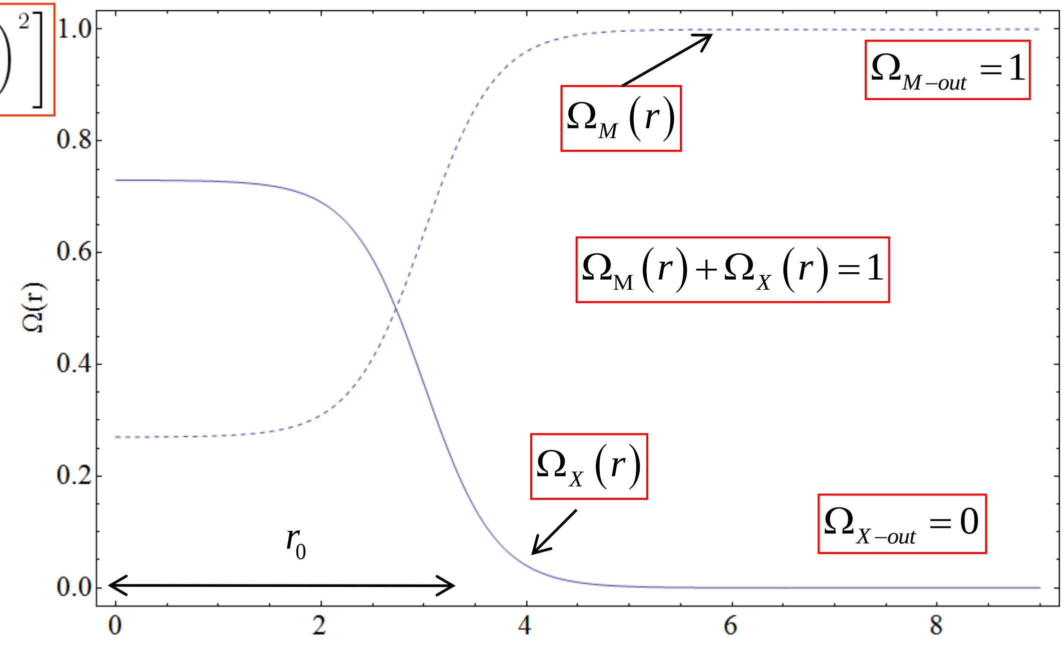
Generalized LTB: Inhomogeneous Dark Energy

Cosmological Equation:

$$H^2(r,t) = H_0^2(r)\left[\Omega_M(r)\left(\frac{A_0}{A}\right)^3 + \Omega_X(r) + \overset{\nearrow\, 0}{\Omega_c(r)}\left(\frac{A_0}{A}\right)^2\right]$$



Isocurvature Profiles (Flat):



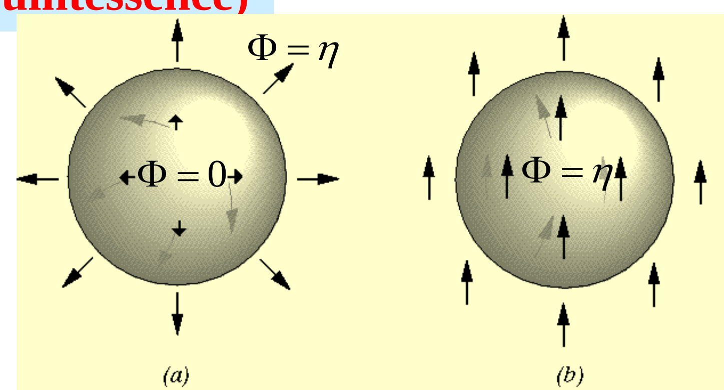
Physical Motivation:

Global Monopole with Hubble scale Core **(Topological Quintessence)**

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

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

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



Constraints for On-Center Observer

Geodesics:

Luminosity Distance:

$$d_L(z, r_0, \Omega_{X,\mathrm{in}}) = (1+z)^2 \, A(r(z), t(z))$$

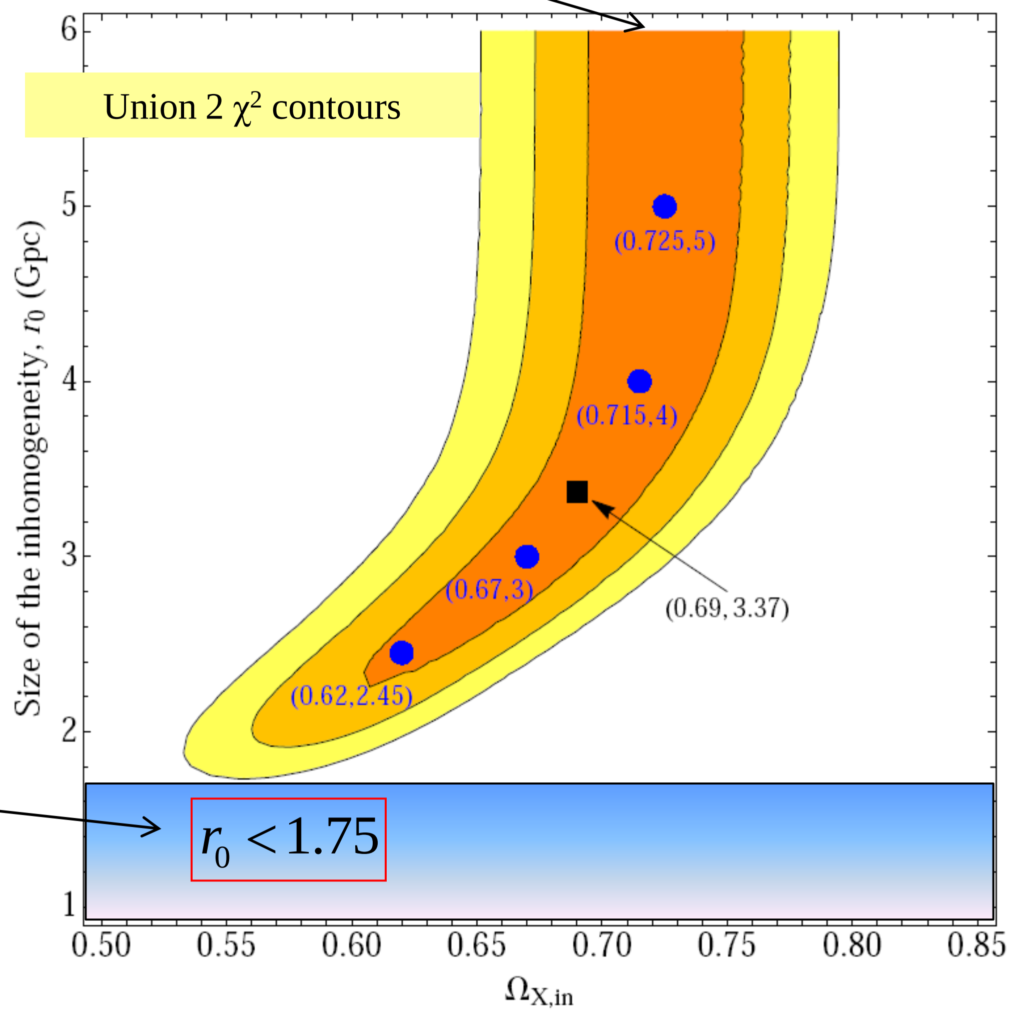
$$\chi^2 \left(r_0, \Omega_{X-in} \right)$$

ΛCDM limit

Union 2 χ^2 contours

Ruled out region at 3σ

$r_0 < 1.75$



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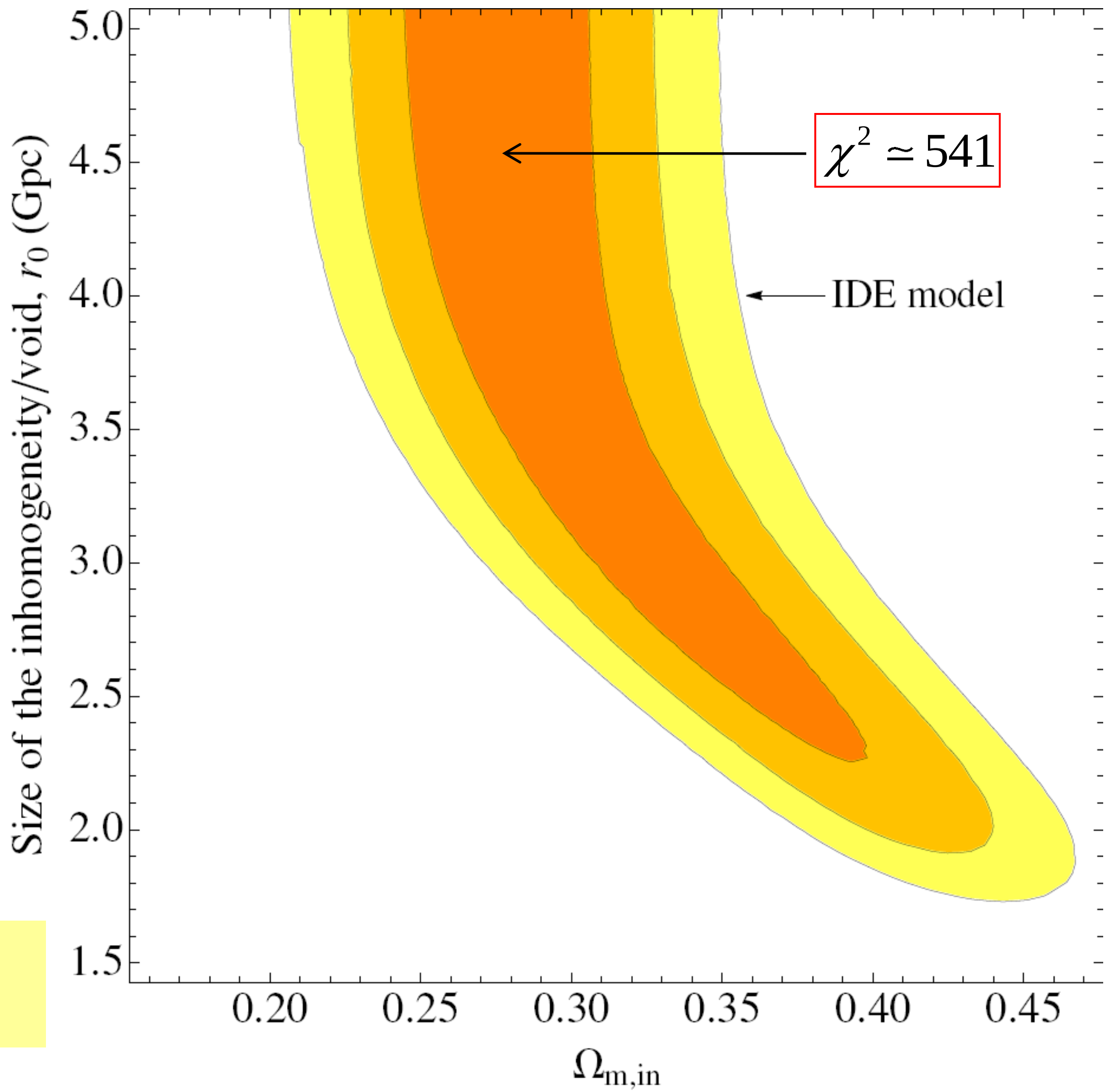
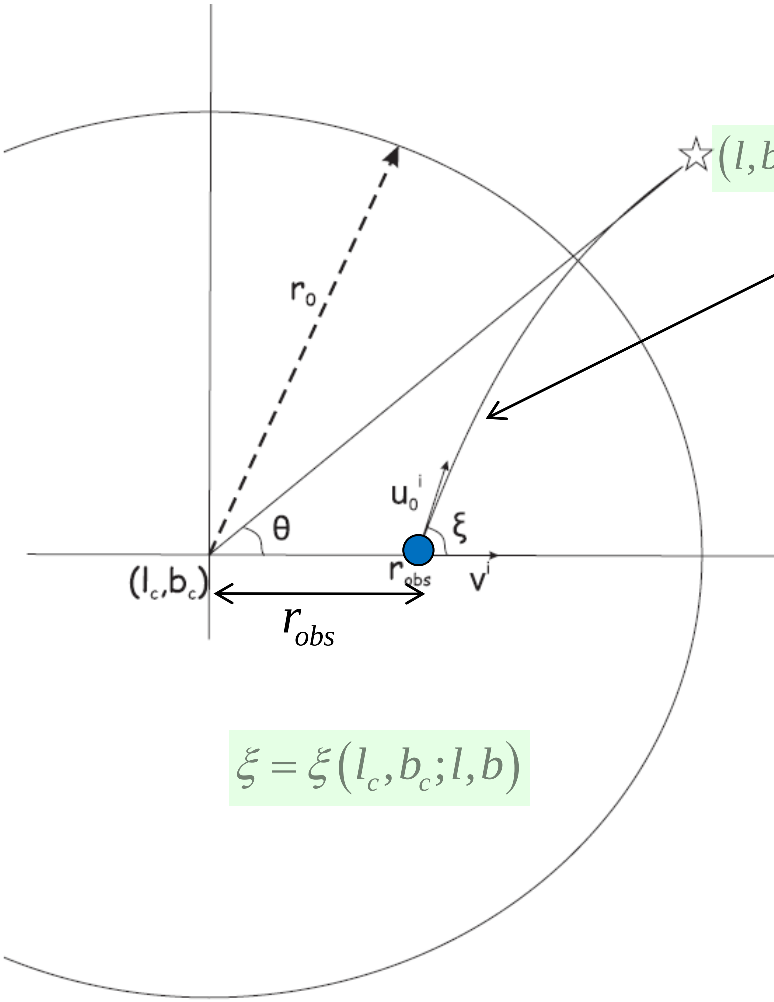
$$\chi^2\left(r_0, \Omega_{X-in}\right)$$



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

Off-Center Observer



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

Geodesics

↓

Luminosity Distance

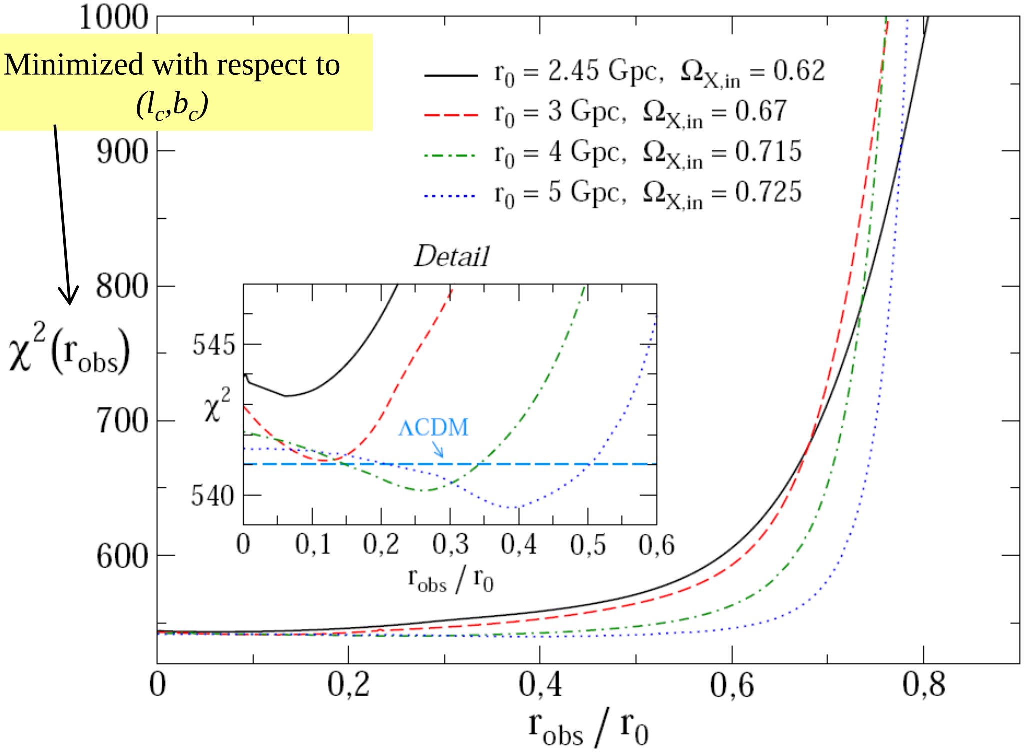
$$d_L\left(z, r_0, \Omega_{X-in}; \xi, r_{obs}\right)$$

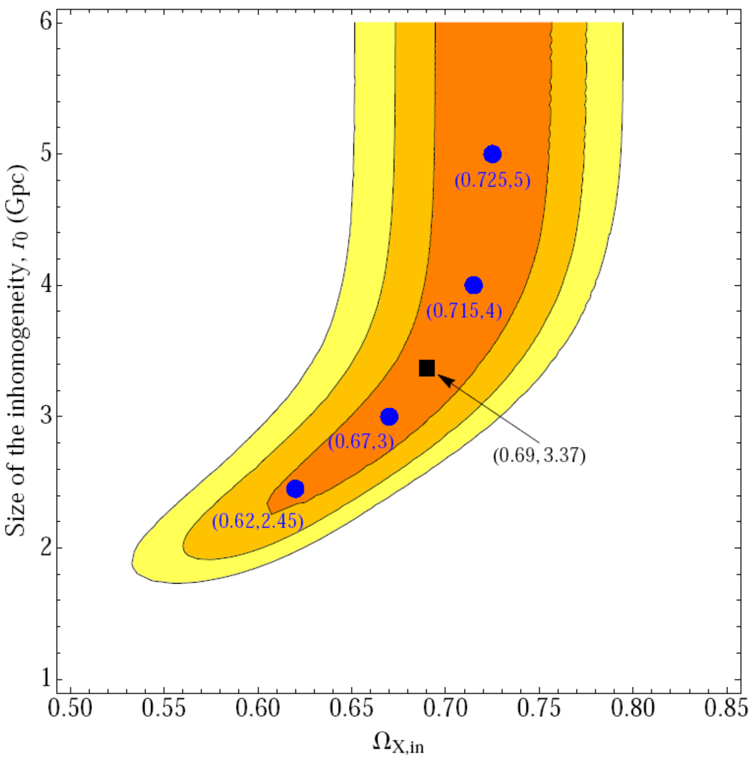
↓

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

Off-Center Observer: Union2 Constraints

Minimized with respect to (l_c, b_c)

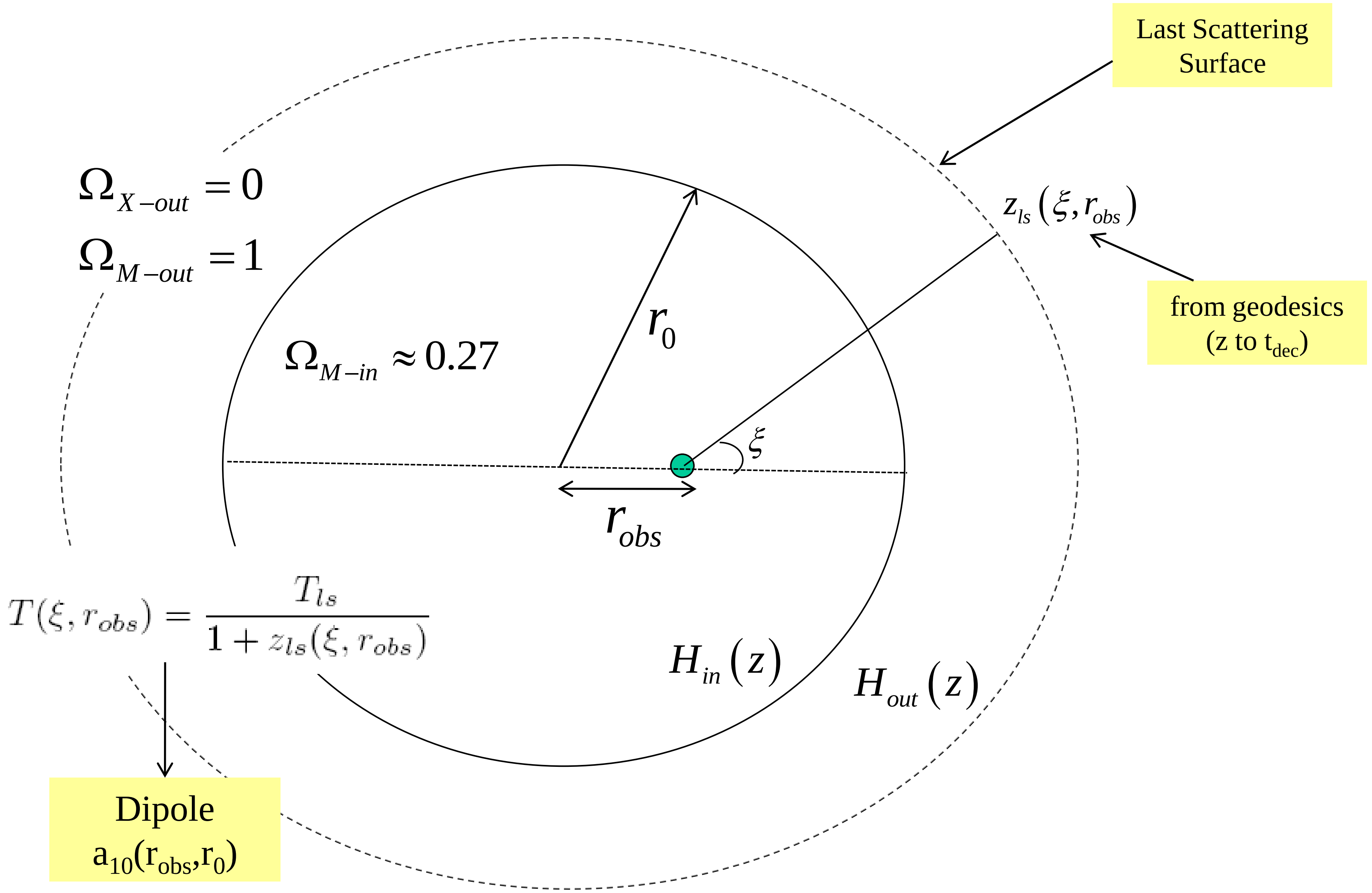




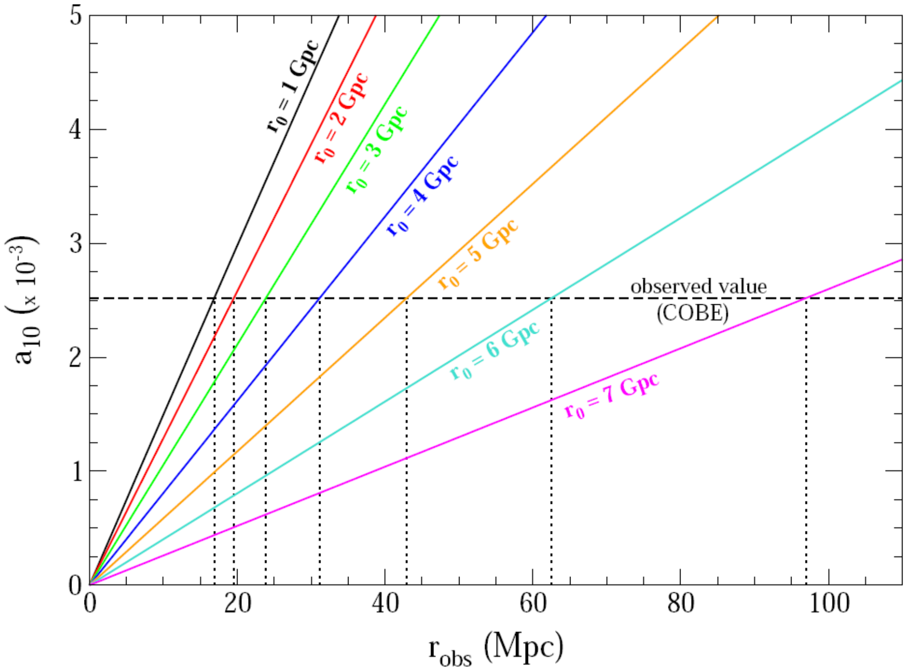
Minor improvement (if any) in quality of fit over ΛCDM, despite four additional parameters.

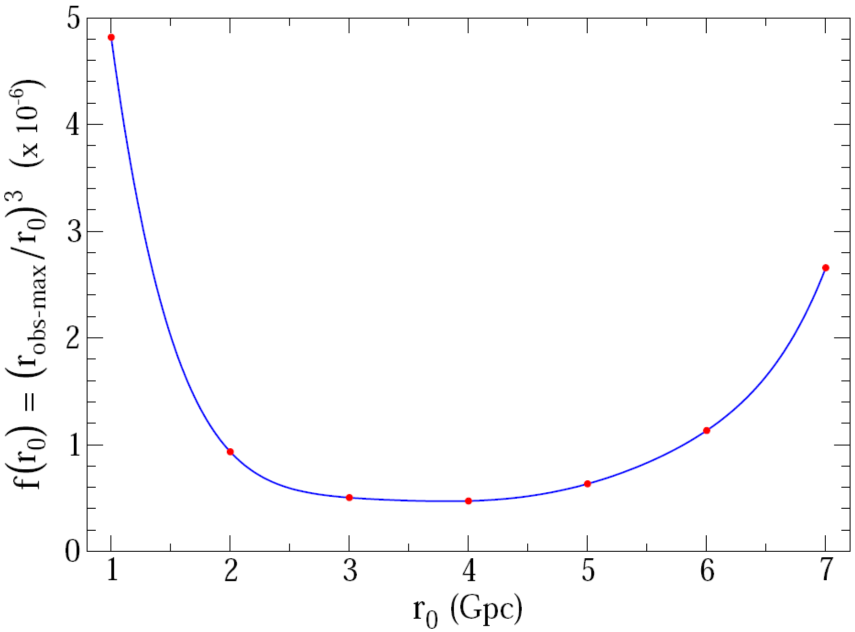
Copernican Principle Respected (r_{obs}/r_0 as large as 0.7).

Off-Center Observer: CMB dipole Constraints



Off-Center Observer: CMB dipole Constraints

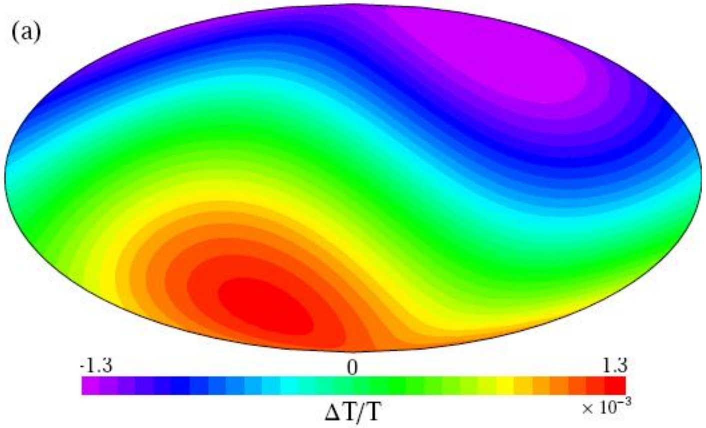




Problem with Copernican Principle ($(r_{obs}/r_0)^3 < 10^{-5}$).

Expected to be alleviated for $r_0 \sim r_{ls}$

Off-Center Observer: CMB multipoles alignment



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)

Such a mechanism can give rise to **aligned CMB multipoles** and **large scale velocity flows**. If the inhomogeneity is attributed to a Hubble scale global monopole with a Hubble scale core other interesting effects may occur (direction dependent variation of fine structure constant, quasar polarization alignment etc).

Standard Cosmological Models

Static Universe with Matter

↓ Einstein (1917)

Static Universe with Matter and Cosmological Constant

↓ Hubble (1930)

Expanding Universe with Visible Matter

↓ Zwicki 1933 Coma galaxy cluster (virial theorem)

Expanding Universe with Dark Baryonic Matter

↓ late 70s to mid 80s (low CMB perts + experiment of 20eV neutrino,inflation)

Flat Expanding Universe with Hot Dark Matter (Neutrinos)

↓ free streaming-top down structure formation (1984)

Flat Expanding Universe with Cold Dark Matter (Exotic)

↓ $\Omega_{dyn} < 1$, too much small scale structure, SnIa data, age problem (1998)

Flat Expanding Universe with Cold Dark Matter (Exotic) and Cosmological Constant (ΛCDM)

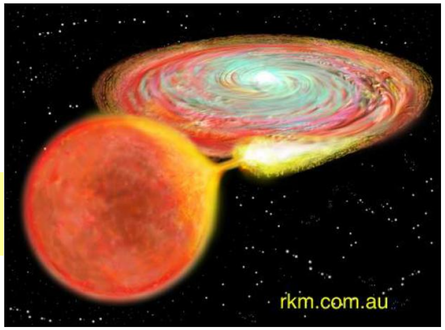
↓ ?

?

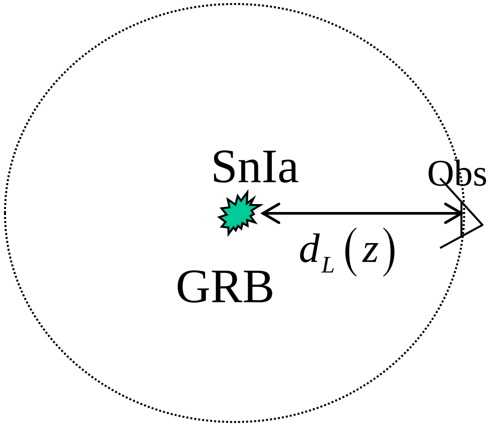
Direct Probes of the Cosmic Metric:

Geometric Observational Probes

Direct Probes of H(z):



Luminosity Distance (standard candles: SnIa,GRB):



$$l=\frac{L}{4\pi d_L^2}$$

$$d_L(z)_{th}=c(1+z)\int_0^z\frac{dz'}{H(z')}$$

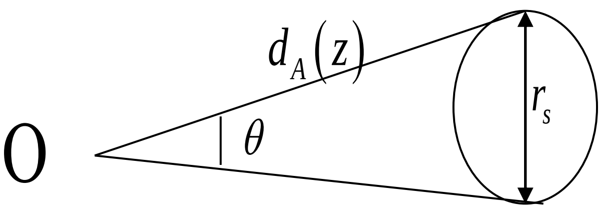
flat

$$SnIa: z\in(0,1.7]$$

$$GRB: z\in[0.1,6]$$

Significantly less accurate probes
S. Basilakos, LP, **MBRAS ,391**, 411, 2008
arXiv:0805.0875

Angular Diameter Distance (standard rulers: CMB sound horizon, clusters):



$$d_A(z)=\frac{r_s}{\theta}$$

$$d_A(z)_{th}=\frac{c}{(1+z)}\int_0^z\frac{dz'}{H(z')}$$

$$BAO: z=0.35,\ z=0.2$$

$$CMB\ Spectrum:\ z=1089$$

Geometric Constraints

Parametrize H(z):

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

Chevallier, Pollarski, Linder

$$\begin{aligned} H^2(z) &= H_0^2[\Omega_{0\mathrm{m}}(1+z)^3 + \\ &+ (1-\Omega_{0\mathrm{m}})(1+z)^{3(1+w_0+w_1)} e^{\frac{-3w_1 z}{(1+z)}}] \end{aligned}$$

$$\Lambda CDM \rightarrow (w_0, w_1) = (-1, 0)$$

Minimize:

$$\chi^2(\Omega_m, w_0, w_1) = \sum_{i=1}^{N} \frac{\left[5\log_{10}\left(d_{L,A}(z_i)_{obs}\right) - 5\log\left(d_{L,A}(z_i; w_0, w_1)_{th}\right)\right]^2}{\sigma_i^2} = \min$$

SALT-II
light curve fitter

$$\mu_i = m^*_{Bi} - M + \alpha \cdot x_{1,i} - \beta \cdot c_i$$

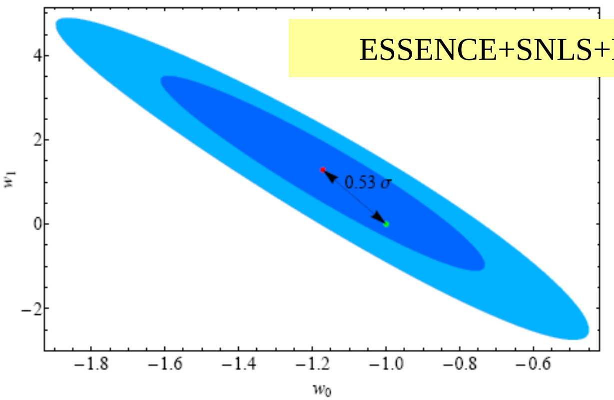
R. Amanullah, et. al. **(Union2)**
Astrophys.J.716:712-738,2010,

$$\chi^2_{\mathrm{stat}} = \sum_{\mathrm{SNe}} \frac{[\mu_B(\alpha, \beta, M) - \mu(z; \Omega_M, \Omega_w, w)]^2}{\sigma^2_{\mathrm{ext}} + \sigma^2_{\mathrm{sys}} + \sigma^2_{\mathrm{lc}}}$$

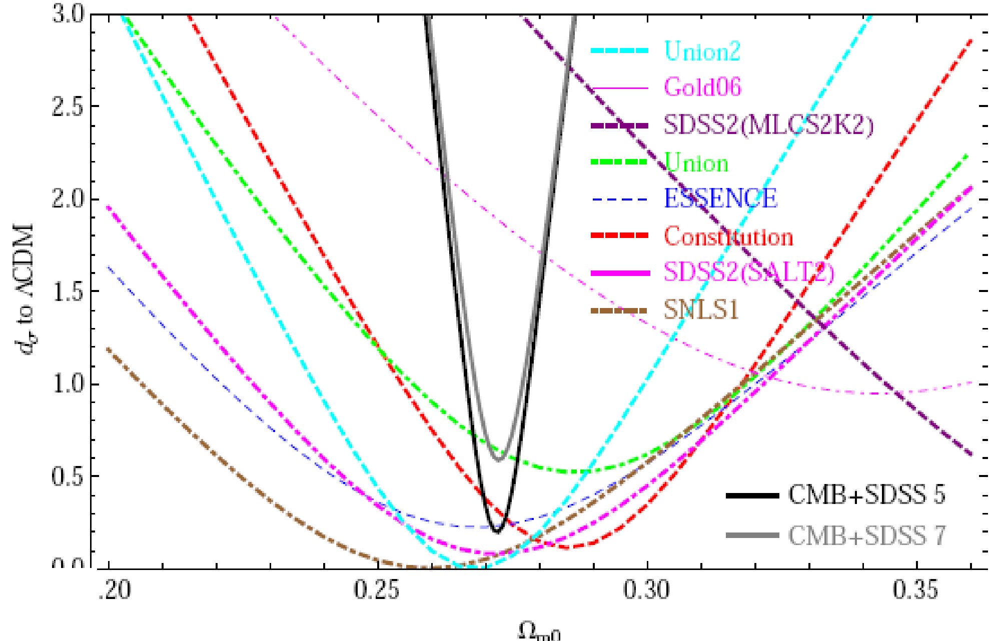
MLCS2k2
light curve fitter

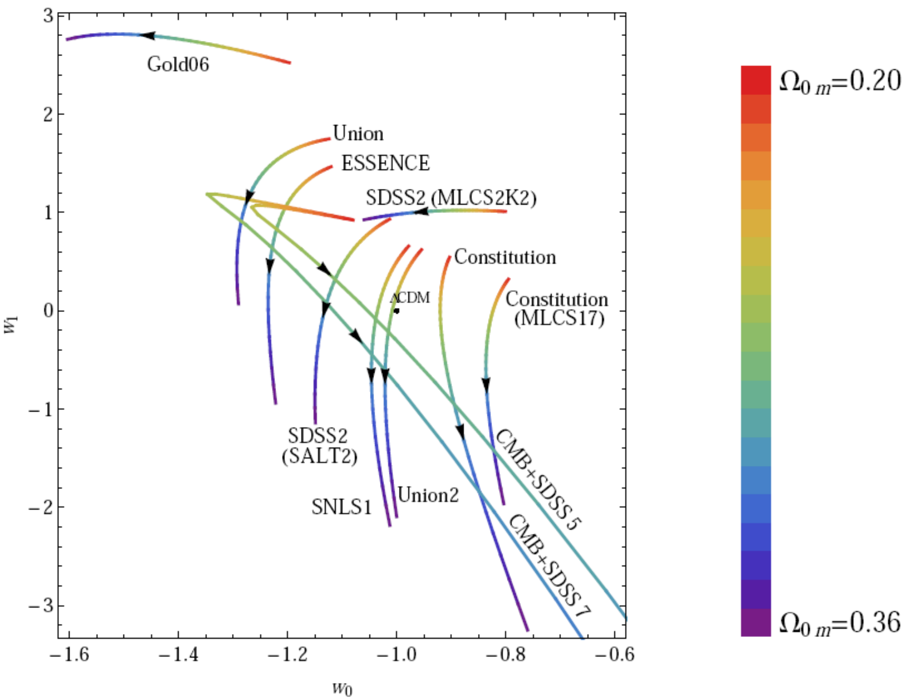
$$\chi^2_\mu = \left\{ \sum_i \frac{[\mu_i - \mu(z_i; w, \Omega_{\mathrm{M}}, \Omega_{\mathrm{DE}}, H_0)]^2}{{\sigma_\mu}^2} \right\}$$

The σ-distance to ΛCDM



Trajectories of Best Fit Parameter Point

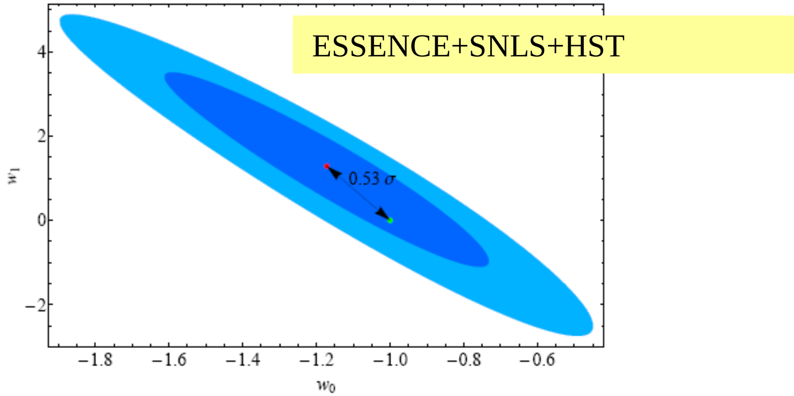


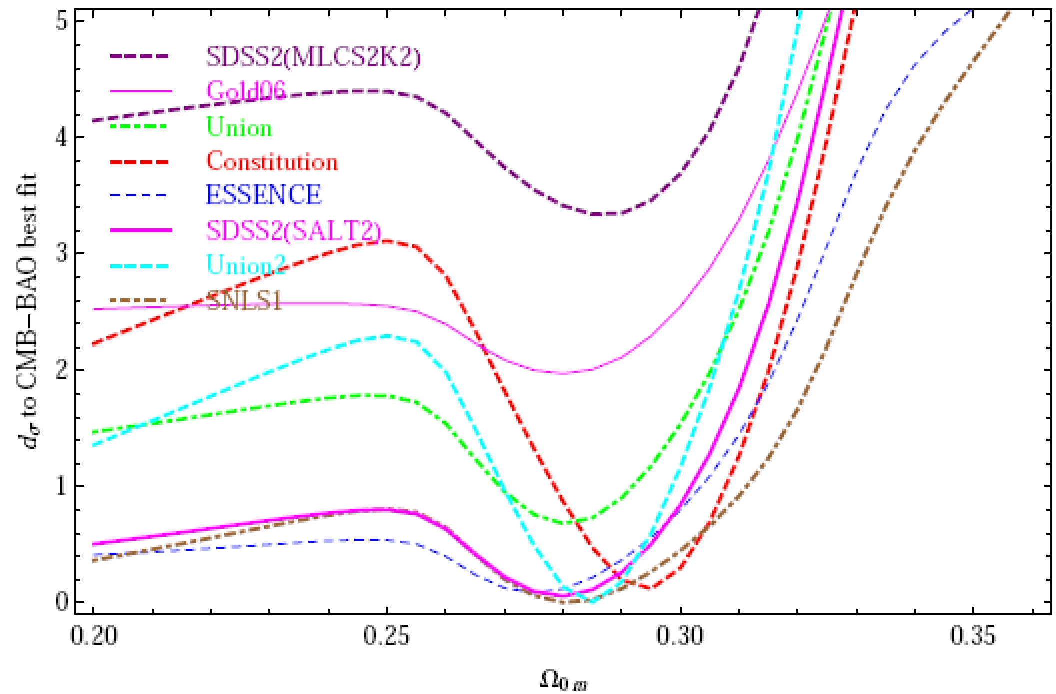


Consistency with ΛCDM Ranking:

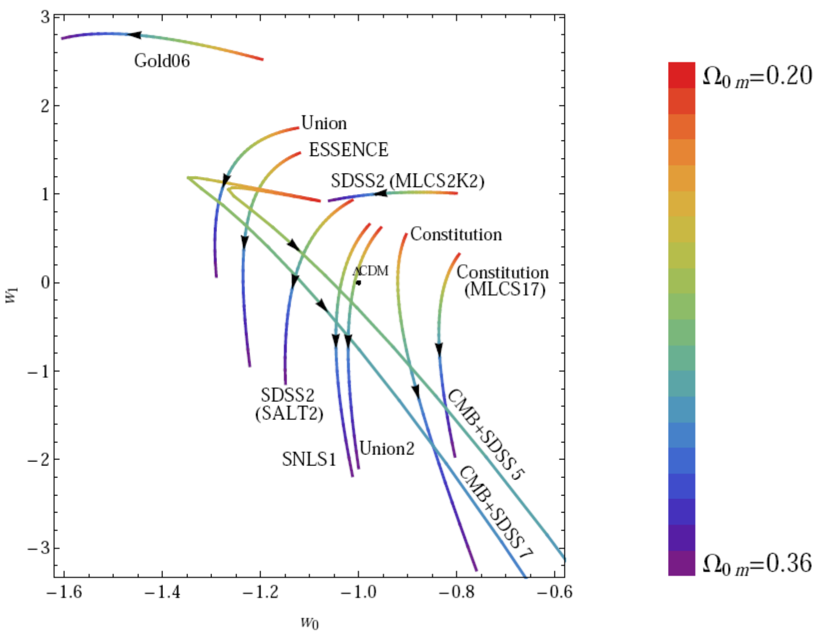
Dataset	d_σ^{min}	Ω_{0m}^{min}	w_0	w_1
Union2	0.001	0.270	-1.01	0.01
SNLS1	0.004	0.260	-1.03	0.16
SDSS-II (SALT2)	0.084	0.270	-1.09	0.51
Constitution	0.114	0.285	-0.91	-0.54
ESSENCE	0.227	0.270	-1.20	1.04
Union	0.525	0.285	-1.25	1.40
SDSS-II (MLCS2K2)	0.623	0.360	-1.06	0.93
Gold06	0.950	0.345	-1.56	2.80
CMB+BAO (SDSS5)	0.200	0.272	-1.15	0.51
CMB+BAO (SDSS7)	0.588	0.272	-1.30	0.97

The σ-distance to Standard Rulers





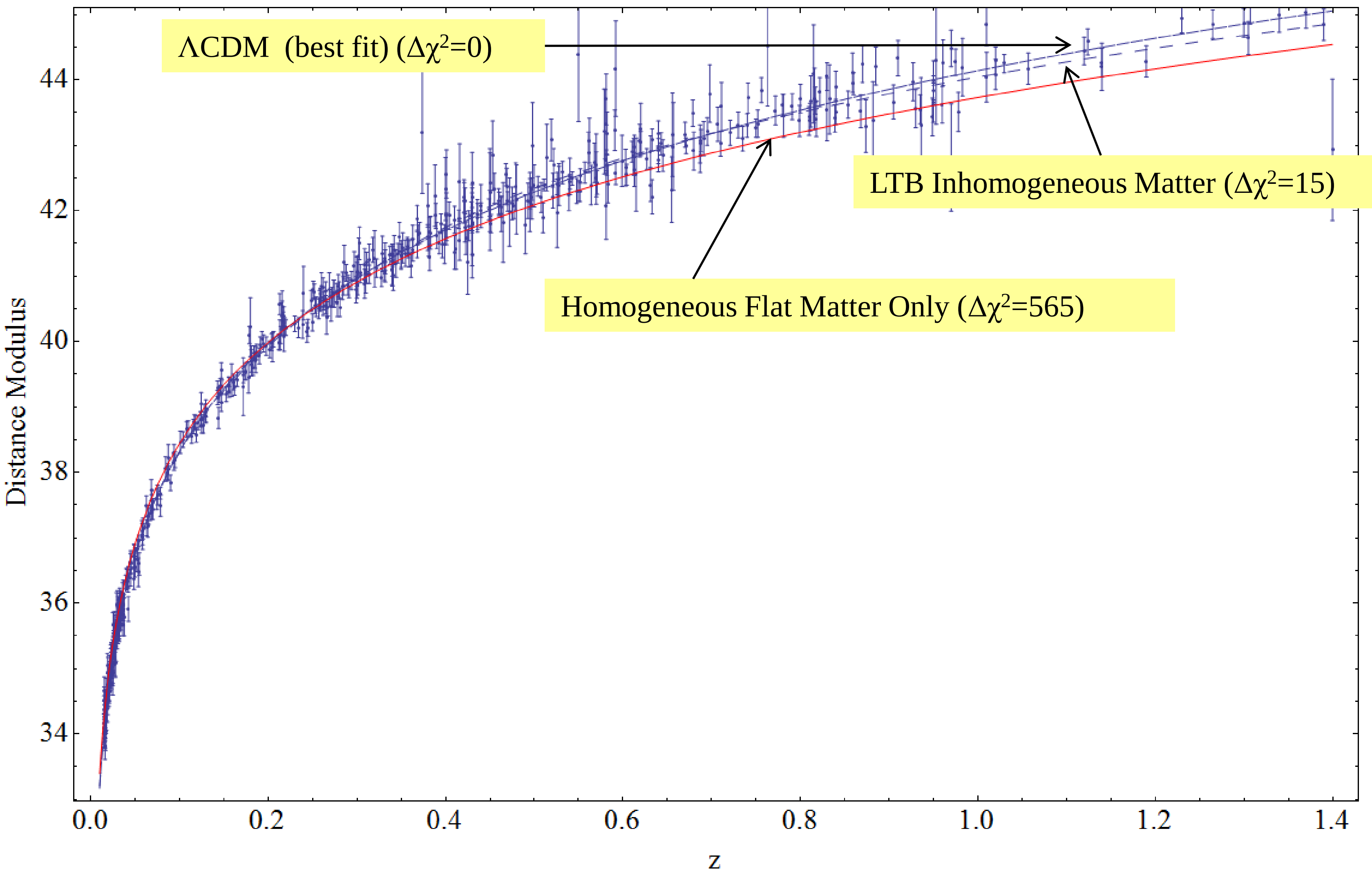
Trajectories of Best Fit Parameter Point



Consistency with Standard Rulers Ranking:

Dataset	d_σ^{min}	Ω_{0m}^{min}	w_0	w_1	w_0^{SR}	w_1^{SR}
SNLS1	0.003	0.280	-1.04	-0.10	-1.07	0.08
Union2	0.004	0.280	-1.01	-0.12	-1.07	0.08
SDSS-II (SALT2)	0.058	0.280	-1.11	0.40	-1.07	0.08
ESSENCE	0.087	0.275	-1.21	0.99	-1.12	0.38
Constitution	0.121	0.295	-0.90	-0.76	-0.84	-1.28
Union	0.681	0.280	-1.24	1.44	-1.07	0.08
Gold06	1.976	0.280	-1.38	2.75	-1.07	0.08
SDSS-II(MLCS2K2)	3.342	0.285	-0.92	1.02	-1.00	-0.28

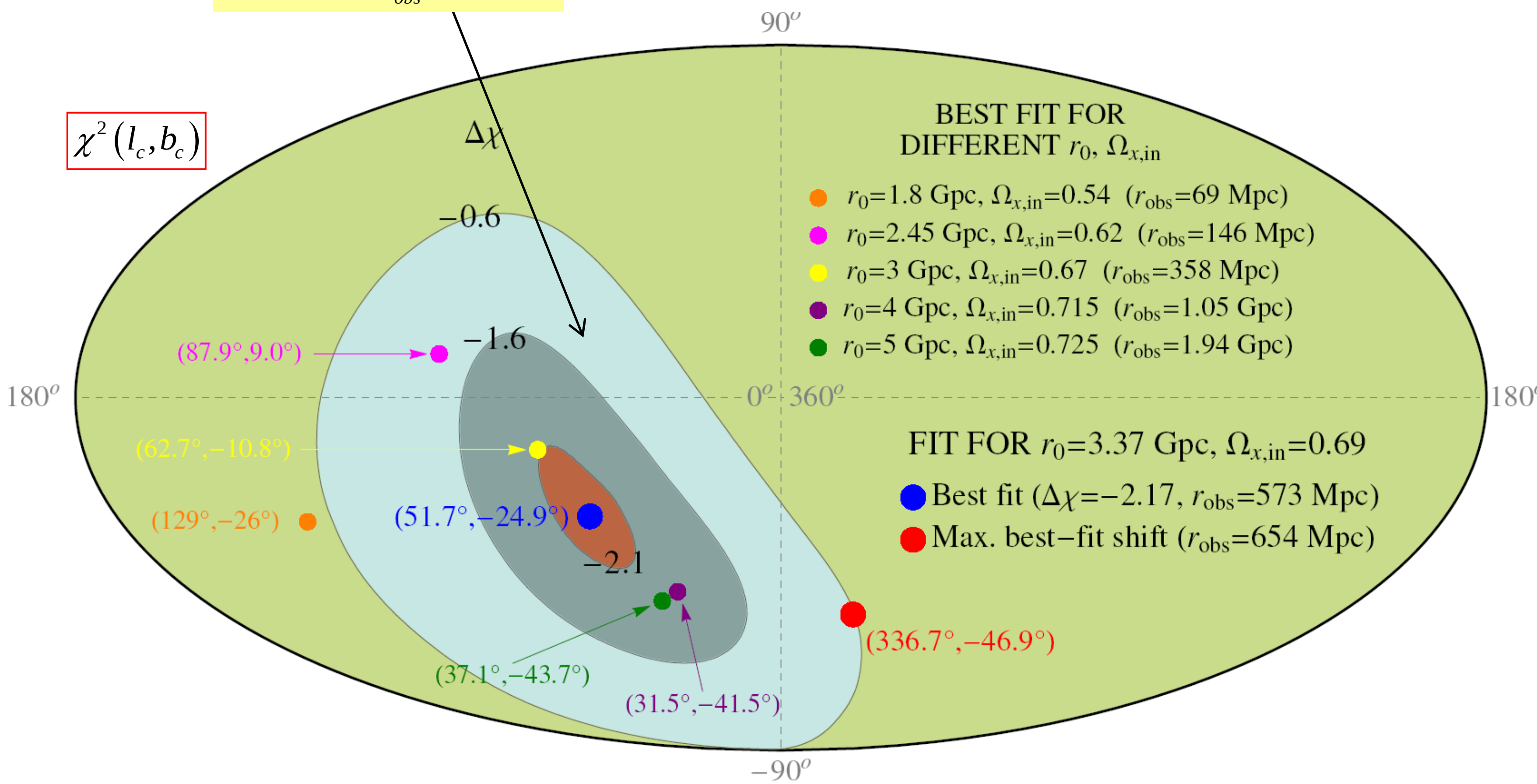
Constraints: Union2 Data – Central Observer



Off-Center Observer: Union2 Constraints II

Minimized χ^2 with respect to r_{obs}

$\chi^2(l_c, b_c)$



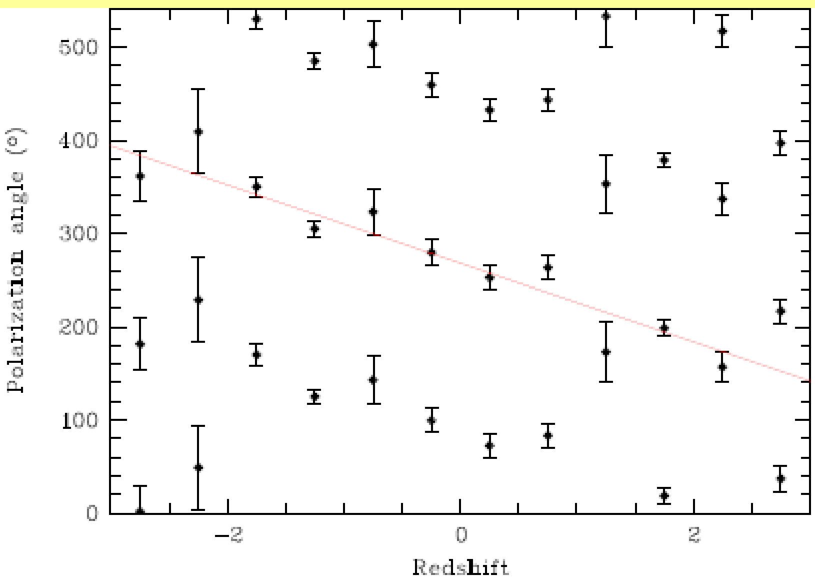
Preferred Axes

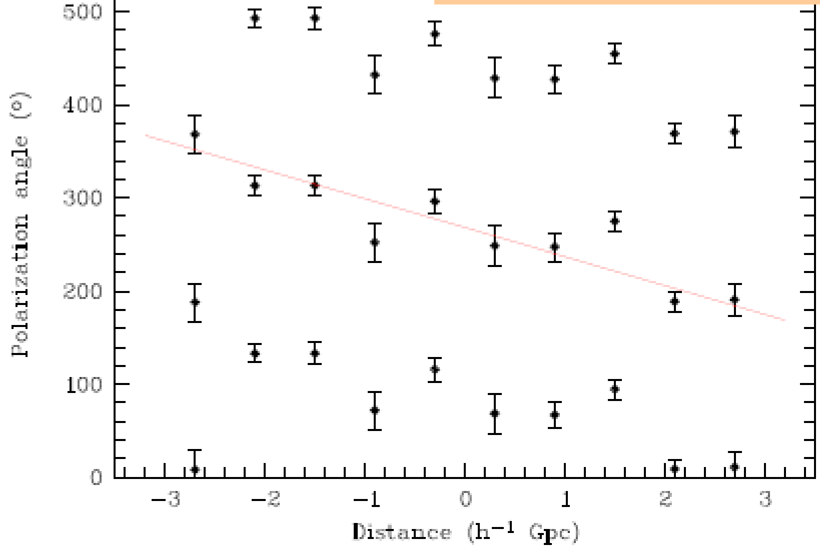
Three of the four puzzles for ΛCDM are related to the existence of a preferred axis

Cosmological Obs.	l	b
CMB Dipole	264°	48°
Velocity Flows	282°	6°
Quasar Alignment	267°	69°
CMB Octopole	308°	63°
CMB Quadrupole	240°	63°

QSO optical polarization angle along the diretction l=267°, b=69°

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





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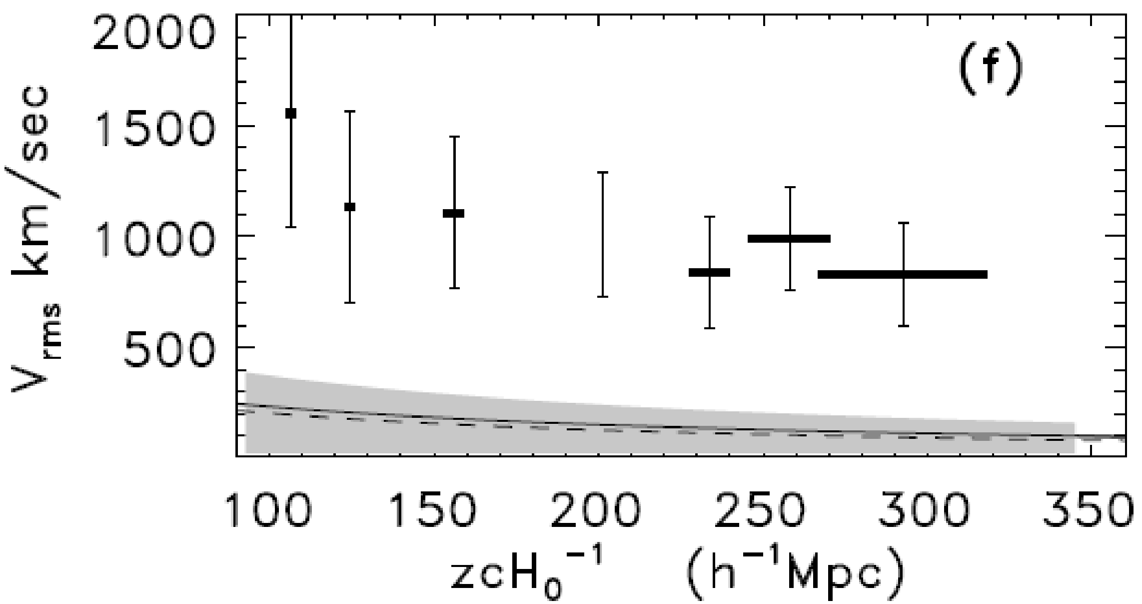
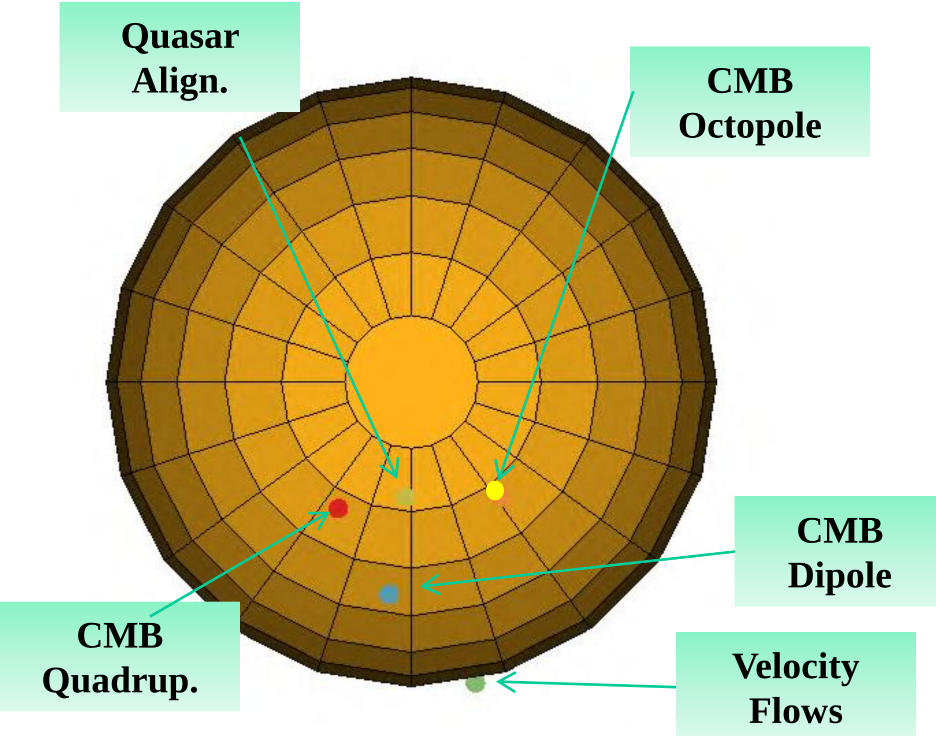
Three of the four puzzles for ΛCDM are related to the existence of a preferred axis

A. Kashlinsky et. al.
Astrophys.J.686:L49-L52,2009
arXiv:0809.3734



Preferred Axes

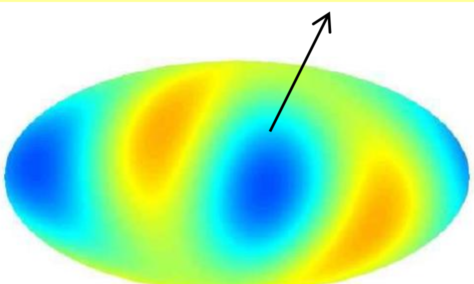


Q1: Are there other cosmological data with hints towards a preferred axis?

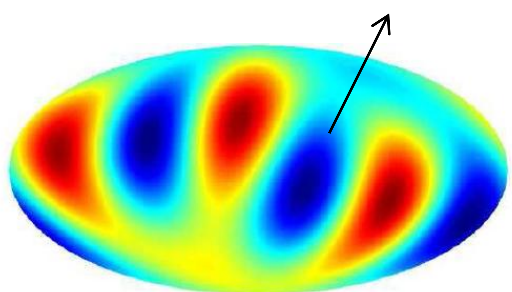
Q2: What is the probability that these independent axes lie so close in the sky?

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

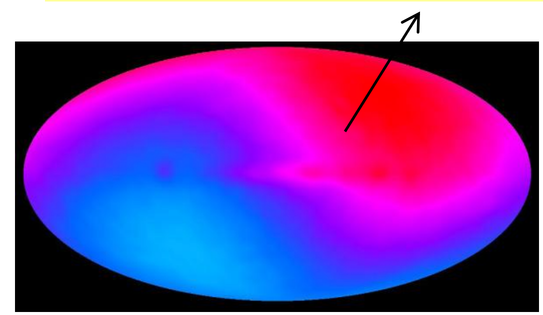
Quadrupole component of CMB map



Octopole component of CMB map



Dipole component of CMB map

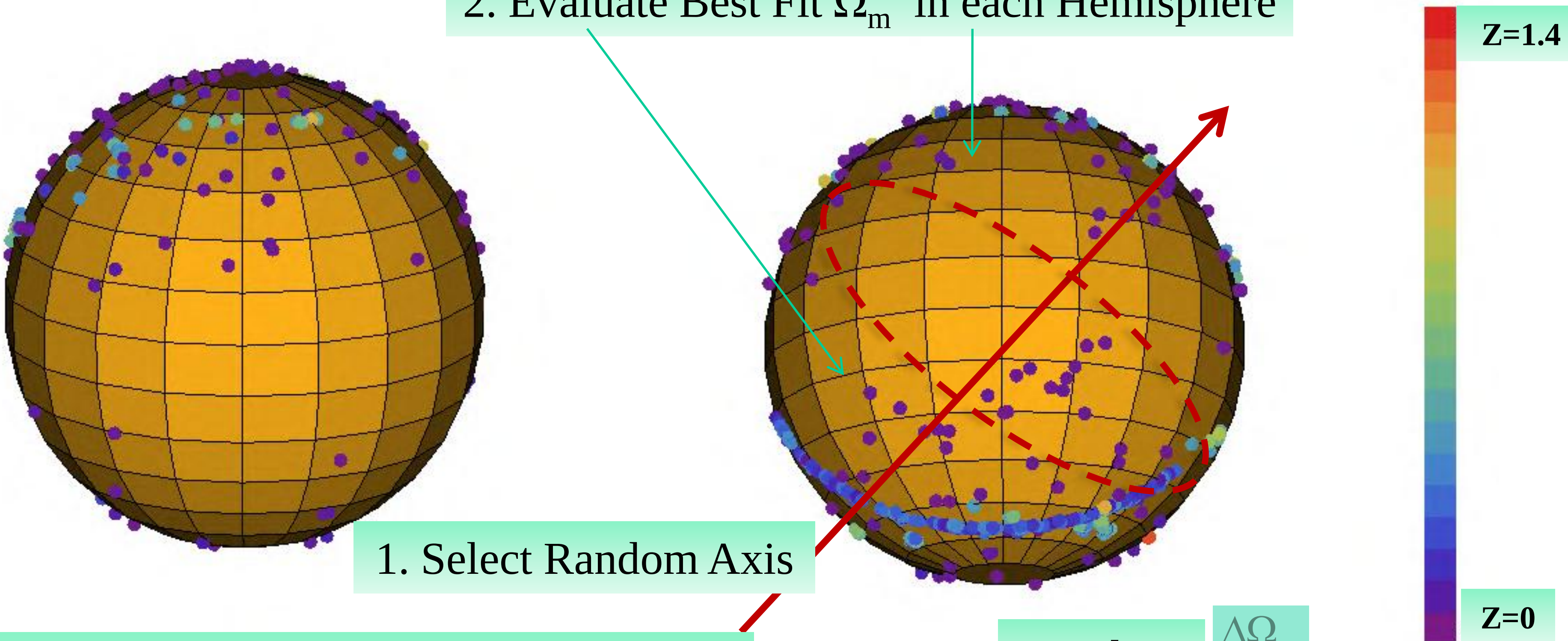


M. Tegmark et. al., **PRD 68, 123523 (2003),**
Copi et. al. **Adv.Astron.2010:847541,2010**.

Union2 Data: Hemisphere Comparison Method

Q.: How isotropic is the accelerating expansion of the universe?

2. Evaluate Best Fit Ω_m in each Hemisphere



1. Select Random Axis

3.Evaluate $\dfrac{\Delta\Omega_m}{\bar{\Omega}}$

4. Repeat with several random axes and find $\dfrac{\Delta\Omega_{max}}{\bar{\Omega}}$

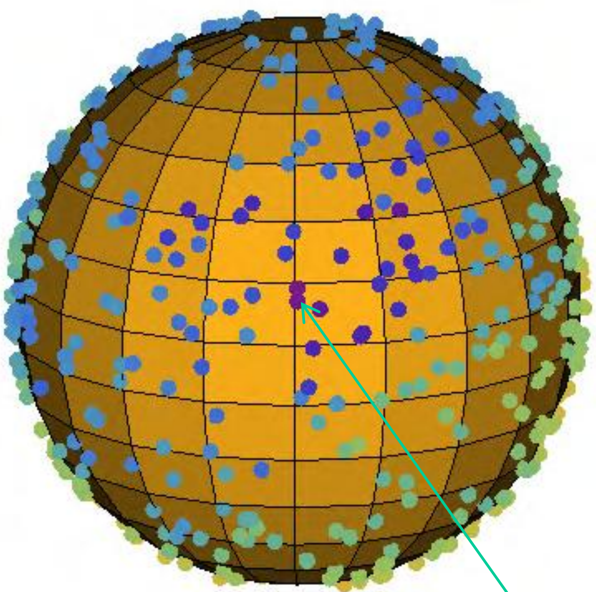
Union2 Data
Galactic Coordinates
(view of sphere from opposite directions

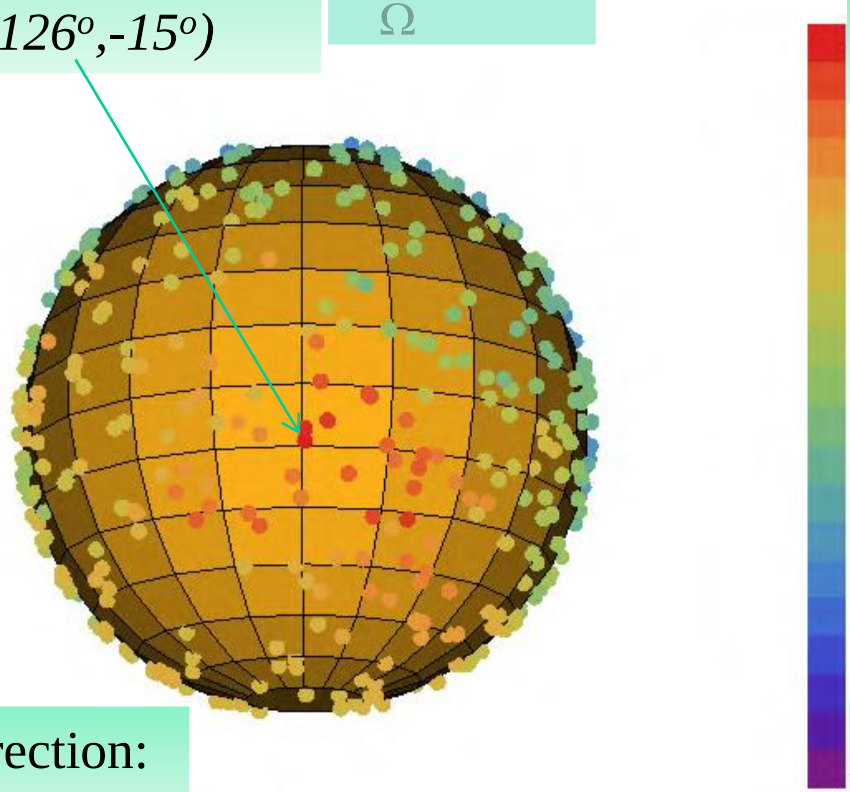
Anisotropies for Random Axes (Union2 Data)

View from above Maximum Asymmetry Axis
Galactic Coordinates

Minimum Acceleration:
(l,b)=(126º,-15º)

$$\frac{\Delta\Omega_{max}}{\bar{\Omega}} = 0.42$$





ΔΩ/Ω= 0.43

ΔΩ/Ω= -0.43

$$\frac{\Delta\Omega_{max}}{\bar{\Omega}} = -0.42$$

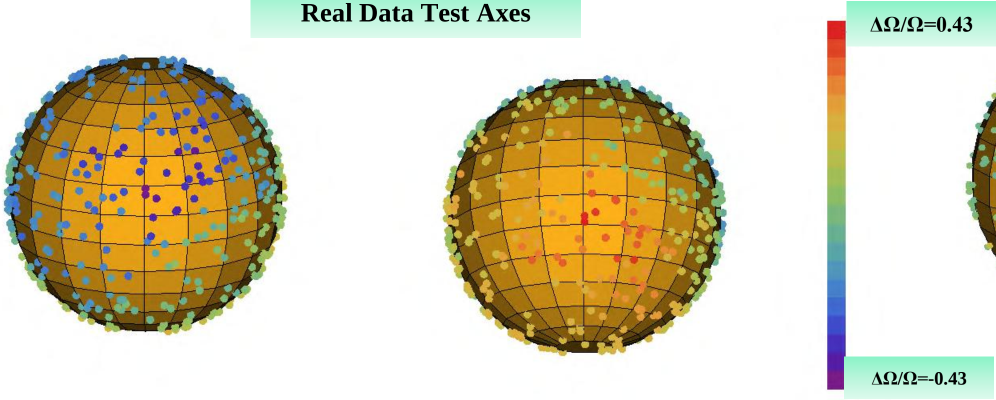
Maximum Acceleration Direction:
(l,b)=(306º,15º)

Statistical Isotropy Test: Results

There is a direction of maximum anisotropy in the Union2 data *(l,b)=(306^o,15^o).*

The level $\left(\frac{\Delta\Omega_{0m-\max}}{\Omega_{0m}}\right)^{U2}$ of this anisotropy is larger than the corresponding level of about 70% of isotropic simulated datasets but it is consistent with statistical isotropy.

Real Data Test Axes



Simulated Data Test Axes