Tilted cosmological model as an alternative to cosmic acceleration

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The Standard Model of Cosmology : ΛCDM

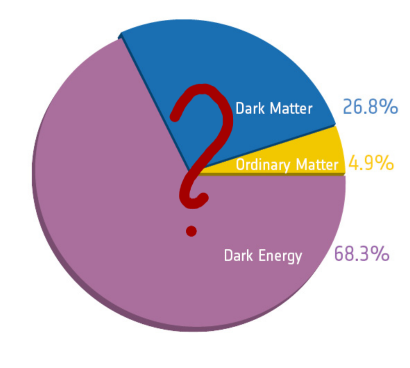


Image credit: ESA/Planck

DARK ENERGY :

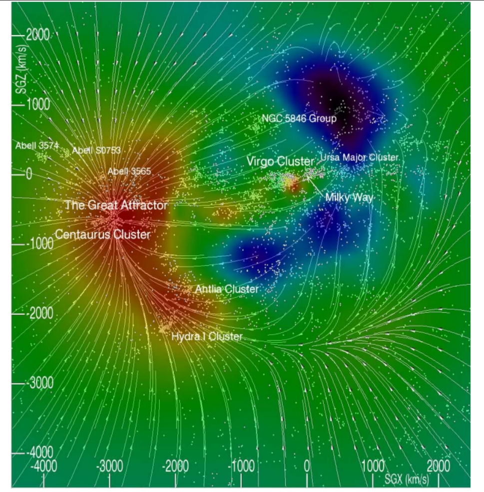
- cosmological constant (Λ)
- quintessence
- modifications of gravity
- tilted cosmological model

$$\Omega_M + \Omega_K + \Omega_\Lambda = 1$$

Peculiar velocities

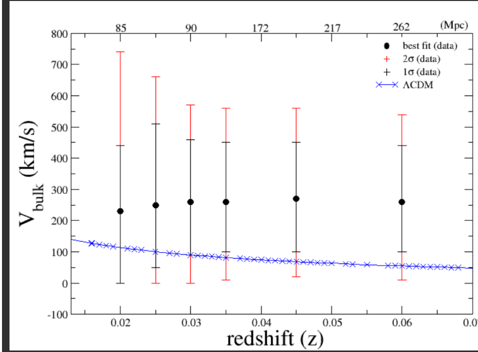
- $v_{pec} = v_{obs - H_0 d}$

Courtois et al., 2013, AJ 146 69



- Bulk flows

Size: Few hundred Mpc
Speed: Few hundred km/sec



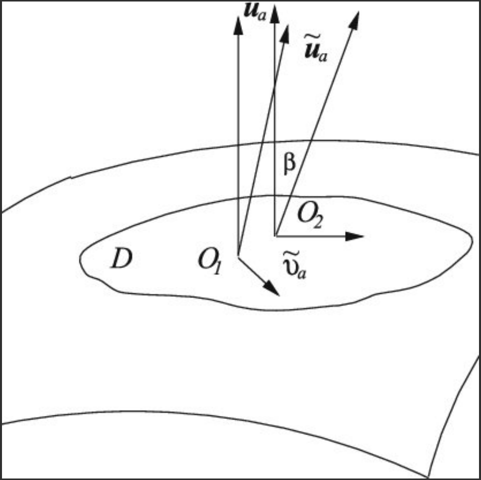
Colin, Mohayaee, Sarkar, Shafieloo., 2011, MNRAS, 414, 264-271

Motivation for the tilted model

- Several alternative cosmological models have been proposed to explain observations but most of them assume some forms of dark energy
- Large-scale peculiar motions are not taken into account
- No robust analysis of the peculiar-velocity effects

The tilted cosmological scenario can explain the late-time cosmic acceleration without the need of a dark energy or any unknown quantity

The Tilted Cosmological Model



observers with 4-velocity $u_a \rightarrow$ **idealised observers** following the smooth Hubble expansion

observers with 4-velocity $\tilde{v}_a \rightarrow$ **real observers** in galaxies like ours, moving relative to the Hubble frame

tilt angle β between them
cosh$\beta = \tilde{\gamma} = \frac{1}{\sqrt{1-\tilde{v}^2}}$

The tilted cosmological model - Kinematics (1/2)

In a perturbed FRW universe, using linear cosmological perturbation theory:

- The three velocities are related through the reduced Lorentz boost :

$$\tilde{u}_a \approx u_a + \tilde{v}_a \tag{1}$$

for non-relativistic peculiar velocities ($\tilde{v}^2 = \tilde{v}^a \tilde{v}_a \ll 1$)

- The expansion rates between the two frames are:

$$\tilde{\Theta} = \Theta + \tilde{\vartheta} \quad \text{and} \quad \tilde{\Theta}' = \dot{\Theta} + \tilde{\vartheta}' \tag{2}$$

with $\Theta = 3H$, $\tilde{\vartheta} = \tilde{D}^a \tilde{v}_a$ and $\tilde{\vartheta}/\Theta \ll 1$ (in the linear regine).

$\tilde{\Theta} \neq \Theta$ and $\tilde{\Theta}' \neq \dot{\Theta}$ because of peculiar motion effects only

The tilted cosmological model - Kinematics (2/2)

In a perturbed Einstein-de Sitter universe (with $p = 0$ and $\Omega = 1$ in the background) the deceleration parameter measured by the real observers is:

$$\tilde{q} = q + \frac{1}{9}\left(\frac{\lambda_H}{\lambda}\right)^2 \frac{\tilde{\vartheta}}{H} \quad \text{with } \lambda_H = 1/H \text{ and } |\tilde{\vartheta}|/H \ll 1 \tag{3}$$

- When $\lambda \gtrsim \lambda_H$, $\tilde{q} \to q$ and the peculiar motions fade away
- On subhorizon scales ($\lambda \ll \lambda_H$), $\tilde{q} \neq q$ and the difference can be large depending on the bulk flow scale
- The difference depends on the sign of $\tilde{\vartheta}$. For contracting bulk-flows ($\tilde{\vartheta} < 0$), $\tilde{q} < 0 \longrightarrow$ accelerated expansion for the real observers

Tsagas, 2011, DOI: 10.1103/PhysRevD.84.063503
Tsagas, Kadiltzoglou, 2015, DOI: 10.1103/PhysRevD.92.043515
Tsagas, 2021, Eur. Phys. J. C 81, 753

Parametrization of $\tilde{\vartheta}$

- Assume that locally the bulk flow contracts ($\tilde{\vartheta} < 0$) and $q = \frac{1}{2}$
- Consider a form of the local volume scalar $\tilde{\vartheta}$ in the tilted frame

$$\tilde{\vartheta} = \tilde{\vartheta}(\lambda) = \frac{m\lambda^2}{p + r\lambda^3} \tag{4}$$

  where m, p, r correspond to free parameters.
- The deceleration parameter in the tilted frame now becomes

$$\tilde{q} = \tilde{q}(\lambda) = \frac{1}{2}\left(1 - \frac{m}{p + r\lambda^3}\right) \tag{5}$$

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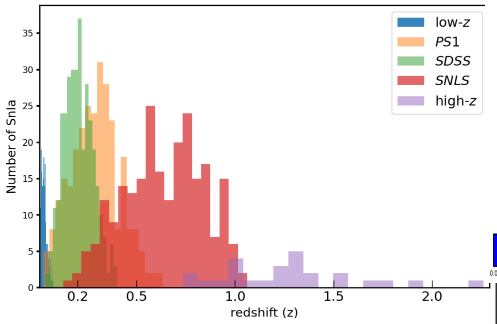
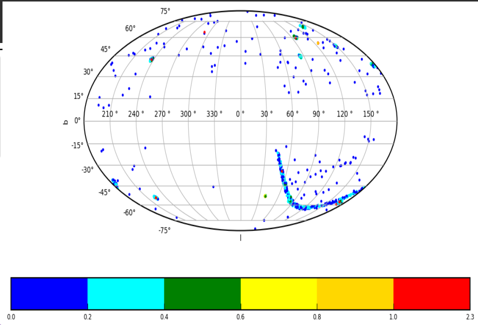
The Pantheon compilation

JLA + additional SnIa from PanStarrs and HST
(Scolnic et al. (2018) arXiv:1710.00845)

1048 SnIa out to redshift $z \sim 2.3$





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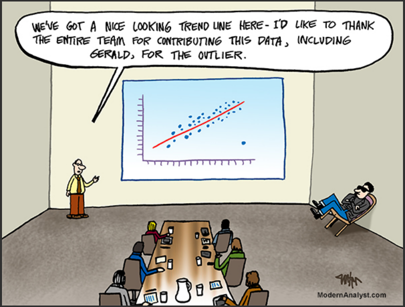
Methodology



- ✓ Construct the theoretical apparent magnitude (m_{th}) out of the studied cosmological model
- ✓ Compare it with the observed apparent magnitude (m_{obs}) taken from the SNIa data by minimizing χ^2
- ✓ Extract the best-fit parameters of the model
- ✓ Estimate the errors on these parameters and construct the posterior probability distributions of these parameters

✓ **Construct the theoretical apparent magnitude (m_{th}) out of the studied cosmological model**

Eq.5 simplifies to

$$\tilde{q}(z) = \frac{1}{2}\left(1 - \frac{1}{\alpha + b\, d_r^3(z)}\right) \quad \text{with} \quad d_r(z) = H_0\, \bar{\chi}(z)/c \tag{6}$$

- The Hubble rate at any redshift connects with the deceleration parameter through

$$\tilde{H}(z) = H_0 \exp\left[\int_0^z \left(\frac{1+\tilde{q}(u)}{1+u}\right) du\right] \tag{7}$$

- The Hubble free luminosity distance of the SNIa :

$$\tilde{D}_L(z) = H_0(1+z)\int_0^z \frac{dz'}{\tilde{H}(z')} \tag{8}$$

- The theoretically predicted apparent magnitude :

$$m_{th}(z) = M + 5\log_{10}\tilde{D}_L(z) + 5\log_{10}\left(\frac{c/H_0}{1Mpc}\right) + 25 = \mathcal{M} + 5\log_{10}\tilde{D}_L(z \tag{9}$$

✓ **Compare it with the observed apparent magnitude (m_{obs}) taken from the SNIa data by minimizing the χ^2**

$$\chi^2_{min}(\mathcal{M}, \alpha, b) = (m_{obs,i}(z) - m_{th}(z)) \; C^{-1}_{ij} \; (m_{obs,j}(z) - m_{th}(z)) \quad (10)$$

- C_{ij} is the total covariance matrix of the SNIa
- We calculate χ^2 for the case of an Einstein-de Sitter bulk flow model

$\rightarrow$ We fit the dimensionless model parameters α and b and $\mathcal{M}$

Results

✓ **Extract the best-fit parameters of the model by performing Monte Carlo Markov Chain (MCMC) statistical method**

Model	$\mathcal{M}$	α	b	Ω_{0m}	$\chi^2_{\rm min}$	$\chi^2_{\rm red}$
ΛCDM	**23.809 ± 0.011**	–	–	**0.299 ± 0.022**	**1026.67**	**0.981**
T-Λ	$23.815^{+0.014}_{-0.012}$	$0.517^{+0.039}_{-0.038}$	$3.9^{+3.6}_{-2.4}$	0.3	1026.69	0.982
T-Λ (α fixed)	23.808 ± 0.007	0.5	$5.20^{+2.6}_{-1.9}$	0.3	1027.21	0.982
T-EdS	$\mathbf{23.813^{+0.015}_{-0.014}}$	**0.512 ± 0.041**	$\mathbf{6.7^{+5.6}_{-3.8}}$	**1.0**	**1026.76**	**0.982**
T-EdS (α fixed)	**23.809 ± 0.007**	**0.5**	$\mathbf{8.56^{+3.8}_{-2.9}}$	**1.0**	**1027.05**	**0.982**

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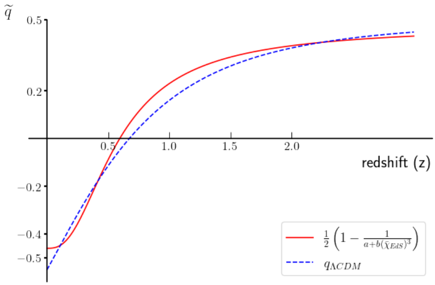
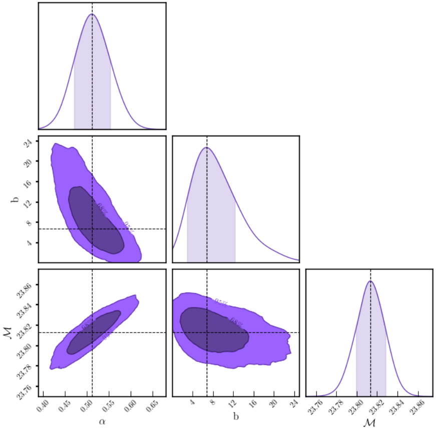
Result: The tilted cosmological model performs equally well with ΛCDM ($\chi^2_{red} \approx 1$)

Evolutionary behaviour of $\tilde{q}$ and confidence levels





Summary and Future work

- Fit the SNIa data to the tilted model and found an apparent late-time cosmic acceleration without the need of dark energy
- A prediction of the model is the presence of a dipole in the distribution of deceleration measured in the tilted frame

- Allow for a directional dependence in the spatial distribution of $\tilde{\vartheta}$ and consequently on the tilted deceleration parameter $(\tilde{q}) \rightarrow$ test for dipolar modulation on $\tilde{q}$
- Test our results with the most recent, though not yet publicly available SNIa data, named Pantheon$+$ and future SNIa surveys (LSST)
- Test our results with other cosmological probes that extend in greater redshifts such as quasars/ galaxy clusters

Thank you for listening

Back-up slides

"Cosmology is the search for two numbers. The Hubble parameter H_0 and the deceleration parameter q_0" - Allan R. Sandage

- H $= \frac{\dot{a}}{a}$
- q = - $\frac{\ddot{a}a}{\dot{a}^2}$ ($q > 0$: deceleration, $q < 0$: acceleration)

The deceleration parameters measured in the Hubble and tilted frames are:

$$q = -\left(1 + \frac{3\dot{\Theta}}{\Theta^2}\right) \quad \text{and} \quad \tilde{q} = -\left(1 + \frac{3\tilde{\Theta}'}{\tilde{\Theta}^2}\right) \tag{11}$$

$$\tilde{q} = q + \frac{\tilde{\vartheta}'}{3\dot{H}}\left(1 + \frac{1}{2}\Omega\right) \quad \text{to linear order} \tag{12}$$

In the absence of peculiar flows ($\tilde{\vartheta}' = 0$), $\tilde{q} \rightarrow q$

$$\frac{\tilde{\vartheta}'}{\dot{H}} = \frac{4}{3}\left[1 + \frac{1}{6}\left(\frac{\lambda_H}{\lambda}\right)^2\right]\frac{\tilde{\vartheta}}{H} \tag{13}$$