The effects of peculiar motions on the deceleration parameter

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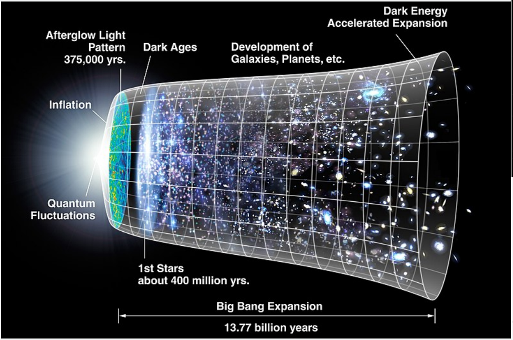
The Standard Model of Cosmology : ΛCDM



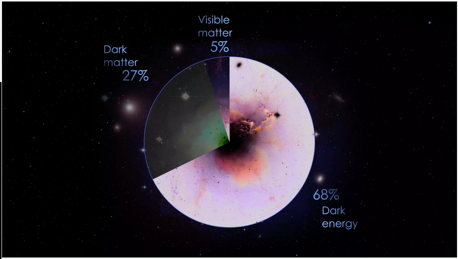
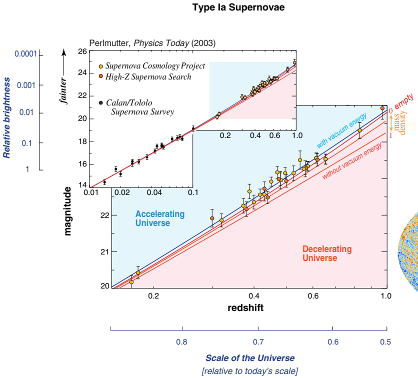


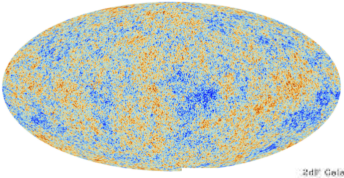
Image credit: NASA Goddard

The universe is dominated by dark energy, parametrized by the cosmological constant, Λ

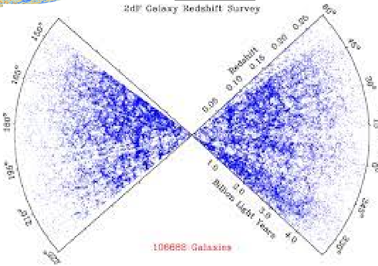
Accelerating expansion of the universe



CMB



LSS



Λ fits well all the observational data but lacks physical explanation

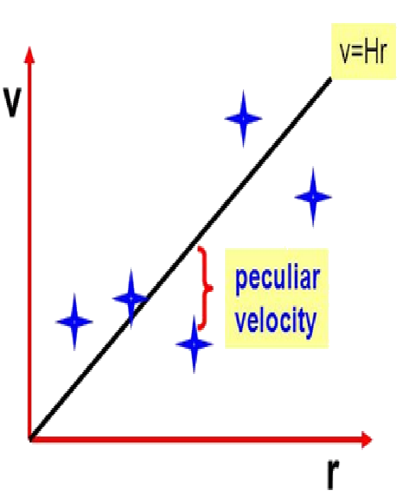
Motivation for the tilted model

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

The tilted cosmological scenario can in principle explain the late-time cosmic acceleration <u>without</u> the need of dark energy/modified gravity or new physics

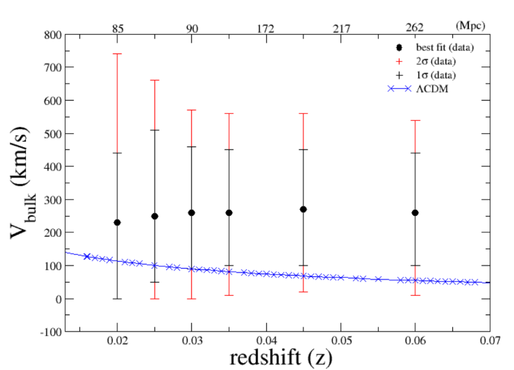
Peculiar velocities

- $1 + z_{obs} = (1 + z_{cosm})(1 + \frac{v_{pec}}{c})$



- Bulk flows

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



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

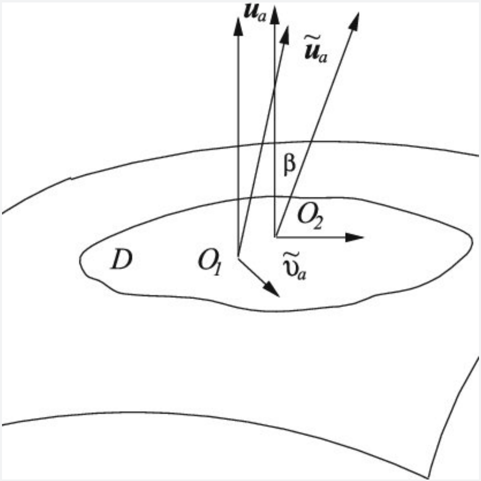
Bulk flows or Dark flows : Challenge for standard ΛCDM model?

Claims for bulk flows inconsistent with ΛCDM

- Kashlinsky et al., 2008 $(600-1000km/s)$ at $r \geqslant 300h^{-1}$
- Watkins et al., 2009 $(407 \pm 81km/s)$ and Feldman et al., 2010 $(416 \pm 78km/s)$ within a region of radius $r \approx 100h^{-1}$ Mpc
- Macaulay et al., 2012 $(380^{+99}_{-132}km/s)$ at $r \approx 33h^{-1}$ Mpc
- Ma and Pan, 2013 $(290 \pm 30km/s)$ at $r \approx 58h^{-1}$ Mpc
- Watkins et al., 2023 $(419 \pm 36km/s)$ at $r \approx 200h^{-1}$ Mpc

They all approximately agree with the direction of the bulk flow (close to the CMB dipole) but not with the scale and the amplitude.

The Tilted Cosmological Model



Employ General Relativity

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 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 regime).

$\tilde{\Theta} \neq \Theta$ 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:

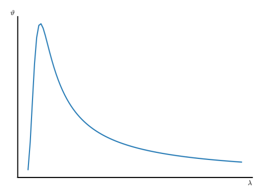
$$\tilde{q} = q + \frac{1}{9}\left(\frac{\lambda_H}{\lambda}\right)^2 \frac{\tilde{\vartheta}}{H} \quad \text{with } \lambda_H = 1/H \text{ and } |\tilde{\vartheta}|/H \ll 1 \tag{3}$$

- 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 ($\tilde{\vartheta} < 0$), $\tilde{q} < 0 \longrightarrow$ local apparent 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 $\tilde{\vartheta}$

- We assume that locally the bulk flow contracts $(\tilde{\vartheta} < 0)$ and $q = \frac{1}{2}$
- A more qualitative form [1] of the volume scalar is $|\tilde{\theta}| = \frac{\sqrt{3}\langle v \rangle}{\lambda}$
- We consider a form of the local volume scalar $\tilde{\vartheta}$ in the tilted frame [2]



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

- The deceleration parameter in the tilted frame now becomes

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

[1] Tsagas, Kadiltzoglou, Phys. Rev. D 92, 043515

[2] K. Asvesta, L. Kazantzidis, L. Perivolaropoulos, C. Tsagas, 2022, DOI: 10.1093/mnras/stac922

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

Eq.5 can take the form

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

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

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

- The Hubble free luminosity distance of the SNIa :

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

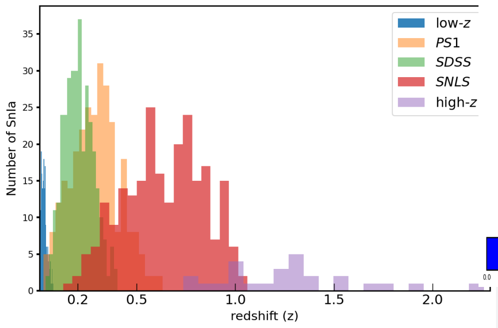
- The theoretically predicted apparent magnitude :

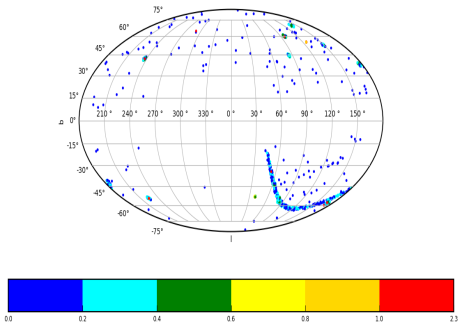
$$m_{th}(z) = M + 5\log_{10}\tilde{D}_L(z) + 5\log_{10}\left(\frac{c/H_0}{1Mpc}\right) + 25 = \mathcal{M} + 5\log_{10}\tilde{D}_L(z) \qquad (9)$$

The Pantheon compilation

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

1048 SnIa out to redshift $z \sim 2.3$





K. Asvesta, L. Kazantzidis, L. Perivolaropoulos, C. Tsagas, 2022, DOI: 10.1093/mnras/stac922

Results

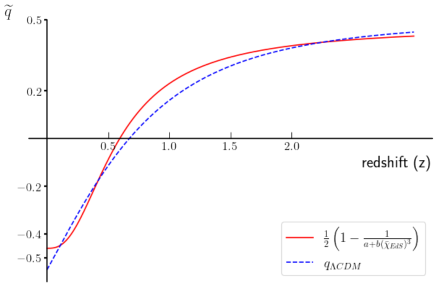
✓ **Extract the best-fit parameters of the model by performing Monte Carlo Markov Chain (MCMC) statistical method**

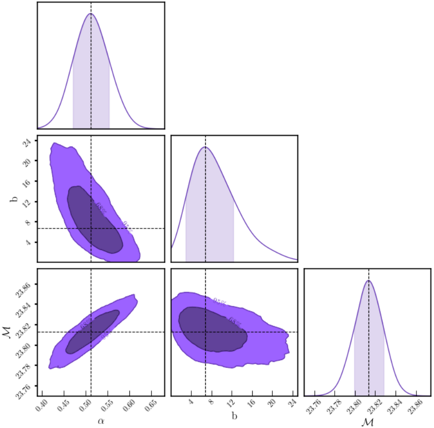
Model	$\mathcal{M}$	α	b	Ω_{0m}	$\chi^2_{\rm min}$	$\chi^2_{\rm red}$
ΛCDM	$\mathbf{23.809 \pm 0.011}$	–	–	$\mathbf{0.299 \pm 0.022}$	**1026.67**	**0.981**
T-EdS	$\mathbf{23.813^{+0.015}_{-0.014}}$	$\mathbf{0.512 \pm 0.041}$	$\mathbf{6.7^{+5.6}_{-3.8}}$	**1.0**	**1026.76**	**0.982**

K. Asvesta, L. Kazantzidis, L. Perivolaropoulos, C. Tsagas, 2022, DOI: 10.1093/mnras/stac922

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

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





K. Asvesta, L. Kazantzidis, L. Perivolaropoulos, C. Tsagas, 2022, DOI: 10.1093/mnras/stac922

The profile of $\tilde{q}$ is very close to the one of ΛCDM

Fit the SNIa data to the tilted model and found an apparent late-time cosmic acceleration without the need of dark energy

The Dipole of the Pantheon+SH0ES Data

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Abstract. In this paper we determine the dipole in the Pantheon+ data. We find that, while its amplitude roughly agrees with the dipole found in the cosmic microwave background which is attributed to the motion of the solar system with respect to the cosmic rest frame, the direction is different at very high significance. While the amplitude depends on the lower redshift cutoff, the direction is quite stable. For redshift cuts of order $z_{\rm cut} \simeq 0.05$ and higher, the dipole is no longer detected with high statistical significant. An important rôle seems to be played by the redshift corrections for peculiar velocities.

Tensions between the Early and the Late Universe
Kavli Institute for Theoretical Physics, July 2019
Verde, L., Treu, T., Riess, A.G.

Tensions between t...

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[1] ICREA & ICC UB ...
[2] University of Ca...

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MNRAS **000**, 1–12 (2022) Preprint 26 May 2022 Compiled using MNRAS LaTeX style file v3.0

The quadrupole in the local Hubble parameter: first constraints using Type Ia supernova data and forecasts for future surveys

Suhail Dhawan,[1★] Antonin Borderies,[2] Hayley J. Macpherson,[3] Asta Heinesen[2]
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ABSTRACT
The cosmological principle asserts that the Universe looks spatially homogeneous and isotropic on sufficiently large scales. Given the fundamental implications of the cosmological principle, it is important to empirically test its validity on various scales. In this paper, we use the Type Ia supernova (SN Ia) magnitude-redshift relation, from both the Pantheon and JLA compilations, ... constrain theoretically motivated anisotropies in the Hubble flow. In particular, we constrain the quadrupole moment in the ... Hubble parameter and the dipole moment in the effective deceleration parameter. We find no significant quadrupole ... less of the redshift frame we use. Our results are consistent with the theoretical expectation of a quadrupole moment ... al scales of $\sim 100\, h^{-1}$ Mpc. We place an upper limit of a $\sim 10\%$ quadrupole amplitude relative to the monopole. ... We find that we can detect a $\sim 7\%$ quadrupole moment at the 5σ level, for a forecast low-z sample of 1055 ... ntially decaying dipole moment of the deceleration parameter varies in significance depending on the ... eliocentric frame, as expected, it is detected at $\sim 3\sigma$ significance. In the rest-frame of the cosmic ... find a marginal $\sim 2\sigma$ dipole, however, after applying peculiar velocity corrections, the dipole ... fit frame of rest relative to the supernovae to differ from that of the CMB.
... ce scale – dark energy

May 2022

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Kavli Institute for Theoretical …
Verde, L., Treu, T., Riess, A…

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…on Contemporary Issues in High Energy…
…Conference Series **481** (2014) 01200…
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The Astrophysical Journal Letters, 908:L51 (6pp), 2021 February 20 https://doi.org/10.3847/2041…

A Test of the Cosmological Principle with Quasars

Nathan J. Secrest[1], Sebastian von Hausegger[2,3,4], Mohamed Rameez[5], Roya Mohayaee[3], Subir Sarkar[4], and Jacques Colin[3]

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Received 2020 September 29; revised 2021 January 18; accepted 2021 January 19; published 2021 February 25

Abstract

We study the large-scale anisotropy of the universe by measuring the dipole in the angular distribution of a flux-limited, all-sky sample of 1.36 million quasars observed by the Wide-field Infrared Survey Explorer (WISE). This sample is derived from the new CatWISE2020 catalog, which contains deep photometric measurements at 3.4 and 4.6 μm from the cryogenic, post-cryogenic, and reactivation phases of the WISE mission. While the direction of the dipole in the quasar sky is similar to that of the cosmic microwave background (CMB), its amplitude is over twice as large as expected, rejecting the canonical, exclusively kinematic interpretation of the CMB dipole with a p-value of 5×10^{-7} (4.9σ for a normal distribution, one-sided), the highest significance achieved to date in such studies. Our results are in conflict with the cosmological principle, a foundational assumption of the concordance ΛCDM model.

Unified Astronomy Thesaurus concepts: Large-scale structure of the universe (902); Cosmic microwave background radiation (322); Observational cosmology (1146); Infrared astronomy (786); Quasar… galactic nuclei (16); Cosmology (343)

1. Introduction

The standard Friedmann–Lemaître–Robertson–Walker (FLRW) cosmology is based on the "cosmological principle," which … that the universe is homogeneous and isotropic on l… This assumption is supported by the smo… which has temperature fluctuations … small angular scales. These … power spectrum are … created in the … which …

than $\gtrsim$10…


Tensions between the Early an...
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Verde, L., Treu, T., Riess, A...

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...847/2041...

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https://doi.org/10.1051/0004-6361/201936373

Letter to the Editor

Evidence for anisotropy of cosmic acceleration★

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Received 22 July 2019 / Accepted 18 October 2019

ABSTRACT

...a "bulk flow" in the local Universe which is faster and extends to much larger scales than are expected around a ...tandard ΛCDM cosmology. This is expected to result in a scale-dependent dipolar modulation of the accel- ...inferred from observations of objects within the bulk flow. From a maximum-likelihood analysis of the ...ue of Type Ia supernovae, we find that the deceleration parameter, in addition to a small monopole, ...onent aligned with the cosmic microwave background dipole, which falls exponentially with ...best fit to data yields $q_d = -8.03$ and $S = 0.0262$ ($\Rightarrow d \sim 100$ Mpc), rejecting isotropy ...$q_m = -0.157$ and consistent with no acceleration ($q_m = 0$) at 1.4σ. Thus the cosmic ...fact of our being non-Copernican observers, rather than evidence for a dominant

...le structure of Universe

...s; nevertheless there is no consensus yet ...
...ture or their origin (Schwarz et al. 20...
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Dipole in the deceleration parameter in the Pantheon+ SNIa compilation

- We add a dipole term in the previous form of the deceleration parameter
- We make a redshift cut in the Pantheon+ sample and we analyze SnIa with $z_{hel} >= 0.020 \sim 82 Mpc$
- We fix the dipole direction to coincide with the CMB dipole
- The anisotropic deceleration parameter in the tilted frame becomes

$$\tilde{q} = \tilde{q}_m(z) + q_d(\mathbf{n}_{SN} \cdot \mathbf{n}_{dip})\mathcal{F}_{dip} \tag{10}$$

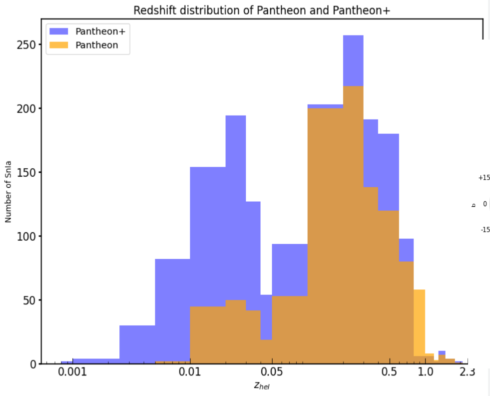
where $\tilde{q}_m(z) = \frac{1}{2}\left(1 - \frac{1}{\alpha + b\,\chi^3_{EdS}(z)}\right)$

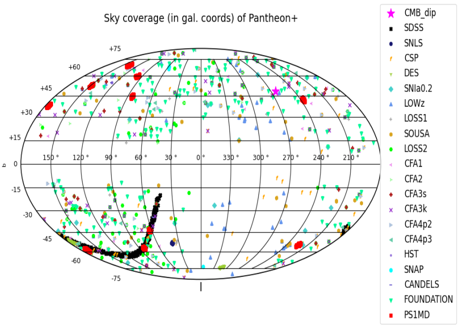
- We examine a form of the function of the dipole $\mathcal{F}_{dip}$ which is constant, $\mathcal{F}_{dip} = 1$

The Pantheon+ SnIa compilation (1/2)

Pantheon + additional SnIa from 5 low-z surveys and DES
(Scolnic et al. 2022, Astrophys.J. 938, 2, 113)

1701 SnIa with redshift range
$0.0008 < z < 2.3$

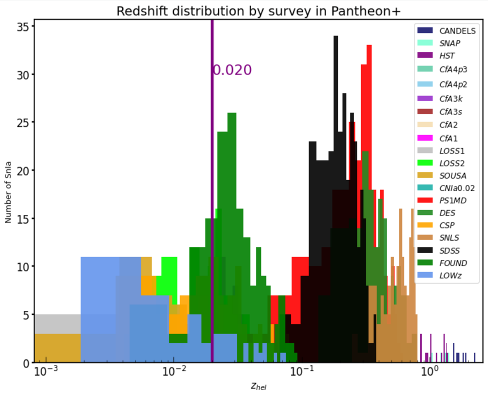


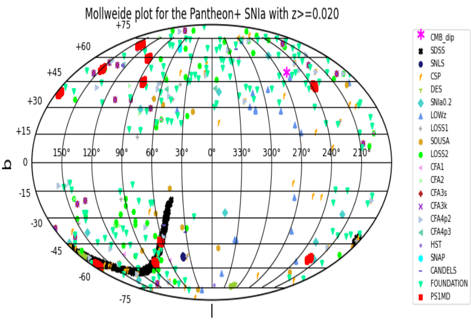


The Pantheon+ SnIa compilation (2/2)

Make a redshift cut at $z \geq 0.020$

In total 1429 SnIa





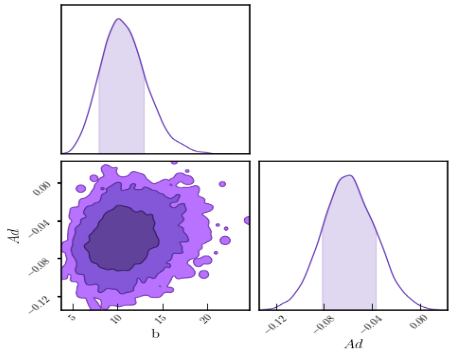
K. Asvesta + (in prep.)

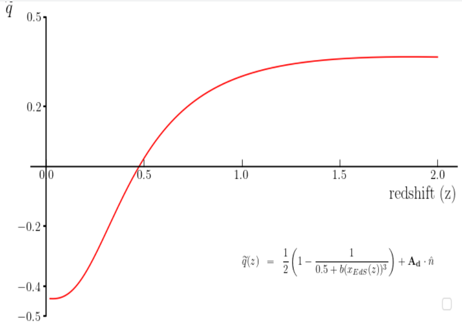
Results

$$\tilde{q} = \frac{1}{2}\left(1 - \frac{1}{\alpha + b\,\chi^3_{EdS}(z)}\right) + q_d(\mathbf{n}_{SN}\cdot\mathbf{n}_{dip})$$

where $\mathcal{F}_{dip} = 1$

The magnitude of the dipole is $> 2\sigma$ away from the ΛCDM





K. Asvesta + (in prep.)

What comes next?

- Use different parametrizations of the dipolar form and check which one fits better the data
- Enlarge the number of free parameters and let for the direction of the dipole to vary
- Do a redshift tomography of the data and check in which redshift bin the dipole becomes stronger
- Allow for a different parametrization of the local contraction rate, $\tilde{\theta}$, which is physically motivated


Thank you for your attention!

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 ($\tilde{\vartheta}' = 0$), $\tilde{q} \to q$

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