Observational indications of an apparent cosmic acceleration from the SNIa data

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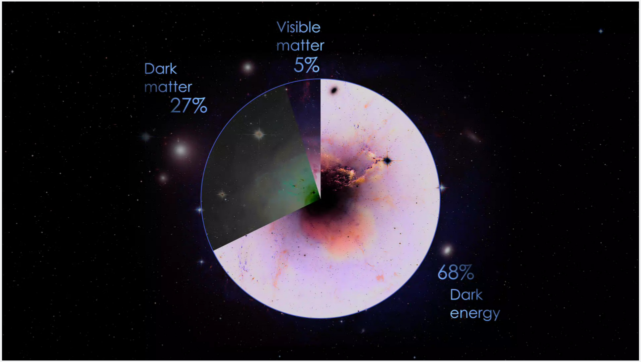
The Standard Model of Cosmology : ΛCDM



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

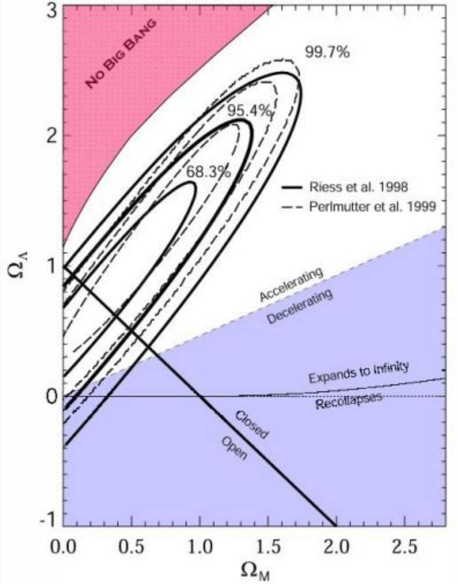
First Evidence for Acceleration from high-z supernovae

"high redshift supernovae were found to be dimmer (15% in flux) than the low redshift supernovae (compared to what would be expected in a $\Lambda = 0$ universe)"

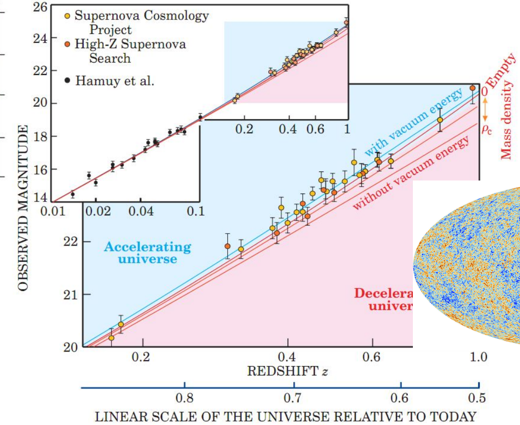
Results : Ω_M vs Ω_Λ from < 100 SNIa

The data favour a flat low-mass universe with Λ

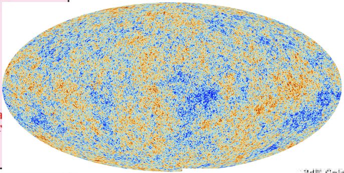
$\Omega_M = 0.28, \ \Omega_\Lambda = 0.72$



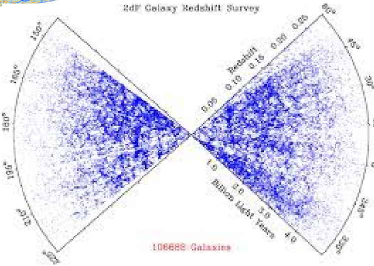
Accelerating expansion of the universe



CMB



LSS



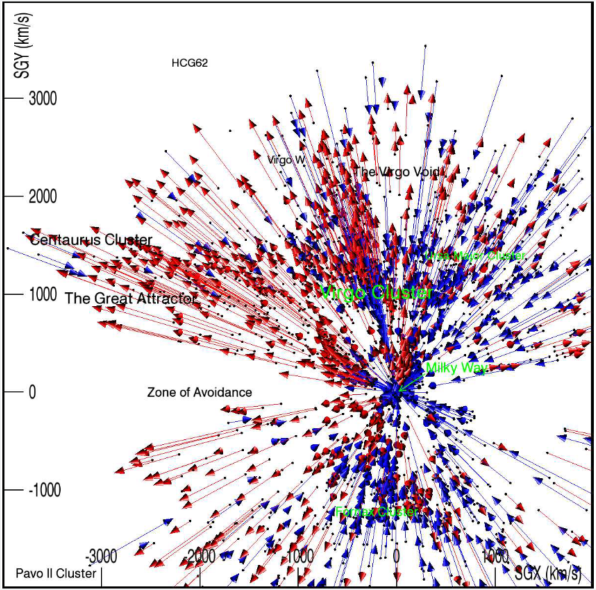
Λ fits well all the observational data but lacks physical explanation

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 widely taken into account and when they do their analysis is Newtionian
- No robust relativistic analysis of the peculiar velocity fields/effects

The tilted cosmological scenario can in principle explain the late-time cosmic acceleration <u>without</u> dark energy/Λ, modified gravity, or abandoning the FRW models.

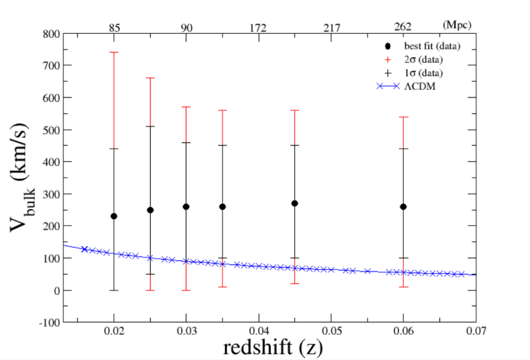
How the local universe looks like?



Hélène M. Courtois et al 2013 AJ 146 69

Peculiar velocities

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



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

Bulk flows

Typical size: $\sim 10^2$ Mpc

Typical velocity: $\sim 10^2$ km/sec

Bulk flows: Challenge for standard ΛCDM model?

Claims for bulk flows inconsistent with ΛCDM

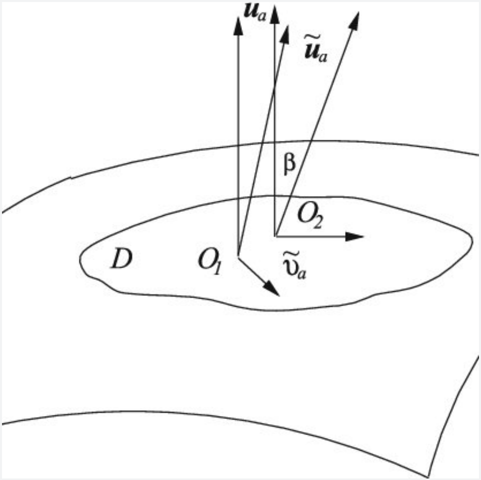
- Watkins et al., 2009 $(407 \pm 81 km/s)$ and Feldman et al., 2010 $(416 \pm 78 km/s)$ within a region of radius $r \approx 100 h^{-1}$ Mpc
- Colin et al. 2011 $(260 km/s)$ at $r \approx 180 h^{-1}$ Mpc
- Macaulay et al., 2012 $(380^{+99}_{-132} km/s)$ at $r \approx 33 h^{-1}$ Mpc
- Ma and Pan, 2013 $(290 \pm 30 km/s)$ at $r \approx 58 h^{-1}$ Mpc
- Watkins et al., 2023 $(419 \pm 36 km/s)$ at $r \approx 200 h^{-1}$ Mpc

Claims for "dark flows" : Kashlinsky et al., 2008 $(600 - 1000 km/s)$ at $r \geqslant 300 h^{-1}$

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

Tilted Cosmological Model

Tilted Model - Two Frames



Employ General Relativity

Observers O_1 in the CMB frame with 4-velocity u_a
idealised observers

Observers O_2 in the tilted/matter frame with 4-velocity $\tilde{v}_a$
real observers

$\rightarrow \; \tilde{u}_a = u_a + \tilde{v}_a$

The kinematics of the three 4-velocity fields

CMB reference frame

$$\nabla_b u_a = \frac{1}{3}\,\Theta h_{ab} + \sigma_{ab} + \omega_{ab} - A_a u_b, \quad \Theta = 3H > 0$$

where $\Theta > 0$, σ_{ab} and ω_{ab}, A^a are the *expansion*, *shear*, *vorticity* and *4-acceleration* of the idealised observer respectively.

Tilted frame

$$\nabla_b \tilde{u}_a = \frac{1}{3}\tilde{\Theta}\tilde{h}_{ab} + \tilde{\sigma}_{ab} + \tilde{\omega}_{ab} - \tilde{A}_a \tilde{u}_b, \quad \tilde{\Theta} > 0$$

Bulk peculiar flow

$$D_b \tilde{v}_a = \frac{1}{3}\tilde{\vartheta}\tilde{h}_{ab} + \tilde{\varsigma}_{ab} + \tilde{\varpi}_{ab}, \quad \tilde{\vartheta} = \tilde{D}^a \tilde{v}_a \gtrless 0$$

The dynamics in the two reference frames

In the case of non-relativistic peculiar motions ($\tilde{v}^a \ll 1$) and assuming a decelerating Einstein-de Sitter background, the linear relations of the dynamic quantities in the two reference frames are:

$$\tilde{\rho} = \rho, \quad \tilde{p} = p = 0, \quad \tilde{\pi}_{ab} = \pi_{ab} = 0, \quad \tilde{q}_a = q_a - \rho\tilde{v}_a$$

where ρ is the density, p is the pressure, π_{ab} the viscosity and q_a is the flux.

We set $\tilde{q}_a = 0$ in the bulk flow frame. Then, the peculiar flux in the CMB frame is: $q_a = \rho\tilde{v}_a \neq 0$, solely because of non-relativistic peculiar motions.

The peculiar flux contributes to the energy-momentum tensor and from the momentum conservation law, in the CMB frame, we get:

$$\rho A_a = -\dot{q}_a - 4Hq_a \neq 0$$

The tilted cosmological model - Deceleration parameter I

To linear order, the Raychaudhuri equations measured by the idealised and the bulk-flow observers differ:

$$3H^2\tilde{q} = \frac{1}{2}\rho, \qquad 3H^2 q = \frac{1}{2}\rho - D^a A_a$$

where the dimensionless deceleration parameter is $q = -[1 + (\dot{H}/H^2)]$.

The deceleration parameters measured in the two frames differ as well:

$$\tilde{q} = q + \frac{1}{3H^2} D^a A_a$$

The tilted cosmological model - Deceleration parameter II

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:

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

- When $\lambda \gtrsim \lambda_H$, $\tilde{q} \to q$ and the peculiar motions effects fade away in the absence of peculiar flows
- 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 crucially 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

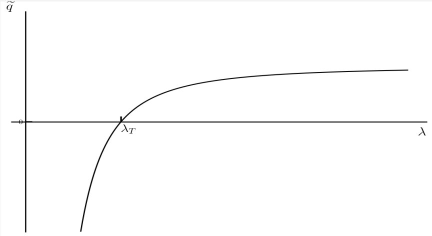
The tilted cosmological model - Transition scale

- When $\tilde{q}$ becomes zero: $\frac{1}{9}\left(\frac{\lambda_H}{\lambda}\right)^2\frac{|\tilde{\vartheta}|}{H} = q$, we get the "transition length" :

$$\lambda_T = \sqrt{\frac{1}{9q}\frac{|\tilde{\vartheta}|}{H}}\lambda_H$$

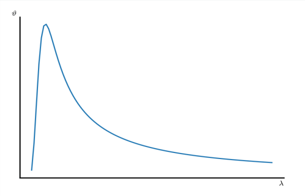
- For contracting bulk flows, the deceleration parameters in the two frames are connected through :

$$\tilde{q} = q\left[1 - \left(\frac{\lambda_T}{\lambda}\right)^2\right]$$



The tilted cosmological model - Parametrization of $\tilde{\vartheta}$

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



$$\tilde{\vartheta} = \tilde{\vartheta}(\lambda) = \frac{\lambda^2}{a + b\lambda^3}$$

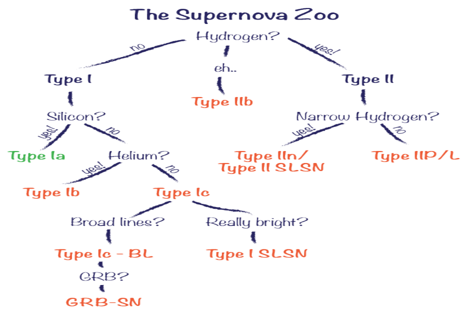
- The scale dependent deceleration parameter in the tilted frame

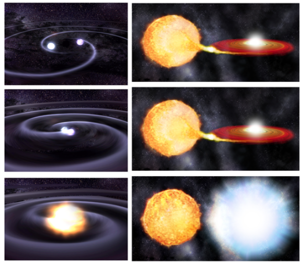
$$\tilde{q} = \tilde{q}(\lambda) = \frac{1}{2}\left(1 - \frac{1}{a + b\lambda^3}\right)$$

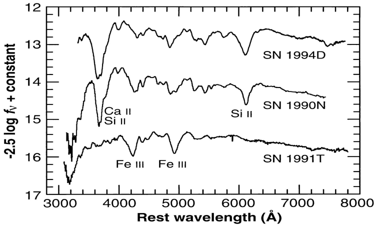
[1] K. Asvesta, L. Kazantzidis, L. Perivolaropoulos, C. Tsagas, 2022, DOI: 10.1093/mnras/stac922

Fit to the data

What are Supernovae of Type Ia ?



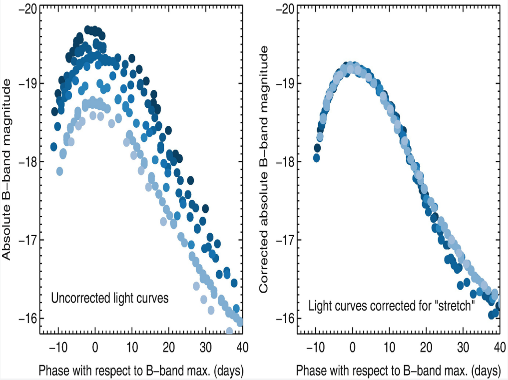




- SNIa lack of H,He and have strong Si line
- binary system of a C-O WD and a companion star or double WD
- They are exremely luminous. They can be as bright as their entire host galaxy
- almost uniform light-curves

SNIa as standardizable candles

Systematic uncertainties in SNIa distances



B-band light curves of a sample of SNe Ia with data taken from Hicken et al. (2009) and Stritzinger et al. (2011).

Corrections to the observed light-curves

- light curve shape correction ("Phillips relation")
- SNIa colour correction

Corrected Distance modulus

$\mu = m_B - M_B + \alpha X_1 - \beta C$

After corrections made, SNIa can be accurate distance indicators and used to cosmology via

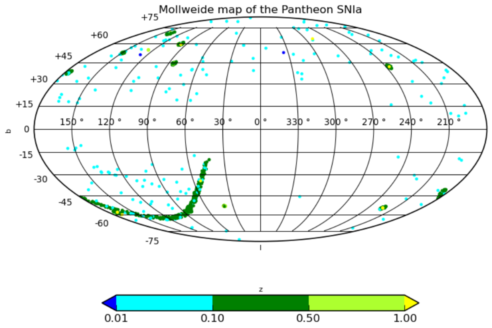
$\mu = 5 \log d_L(Mpc) + 25$

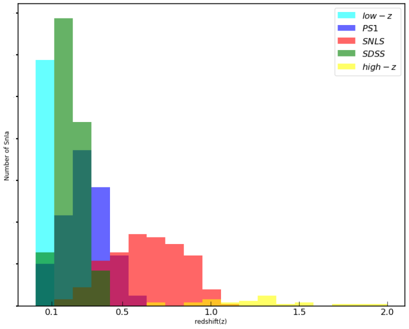
The Pantheon SNIa compilation

1048 Type Ia supernovae with redshift range $0.010 \leq z \leq 2.26$

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

The SDSS stripe dominates for $z > 0.07$





Supernova fit

- The tilted redshift-dependent deceleration parameter:

$$\tilde{q}_{(z)} = \frac{1}{2}\left(1 - \frac{1}{a + b\, d_r^3(z)}\right), \quad d_r = \frac{H_0 \bar{\chi}(z)}{c} \qquad (1)$$

where $\bar{\chi}(z)$ is the line of sight Einstein-de Sitter comoving distance

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

$$\tilde{H}(z) = H_0 \exp\left[\int_0^z \left(\frac{1+\tilde{q}(u)}{1+u}\right) du\right] \qquad (2)$$

- The luminosity distance of the SNIa (in Mpc):

$$\tilde{D}_L(z) = c\,(1+z)\int_0^z \frac{dz'}{\tilde{H}(z')} \qquad (3)$$

- The theoretical apparent magnitude :

$$m_{th}(z) = \mathcal{M} + 5\log_{10}\tilde{D}_L(z), \quad \mathcal{M} = 5\log_{10}\left(\frac{c/H_0}{1Mpc}\right) + 25 \qquad (4)$$

Supernovae fit

✓ **Extract the best-fit parameters of the model**

$$\chi^2_{min}(\mathcal{M}, \alpha, b) = (m_{obs,i}(z) - m_{th}(z))\ C^{-1}_{ij}\ (m_{obs,j}(z) - m_{th}(z)) \quad (5)$$

where $C = C_{stat} + C_{sys}$ is the total covariance matrix of the SNIa.

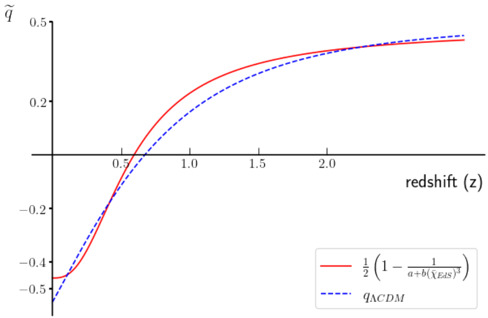
Minimization performed by employing a Bayesian Markov Chain Monte Carlo (MCMC) method. The likelihood function is $\mathcal{L} = \exp\left(-\frac{\chi^2_{min}}{2}\right)$.

Model	$\mathcal{M}$	a	b	Ω_{0m}	χ^2_{min}	χ^2_{red}
ΛCDM	23.809 ± 0.011	$-$	$-$	0.299 ± 0.022	1026.67	0.981
T-EdS	23.815 ± 0.013	0.521 ± 0.030	$6.66^{+5.49}_{-3.58}$	1.0	1026.76	0.982
T-EdS(a fixed)	23.808 ± 0.006	0.5	$8.47^{+3.72}_{-2.76}$	1.0	1027.05	0.982

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

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

Evolutionary behaviour of $\tilde{q}$

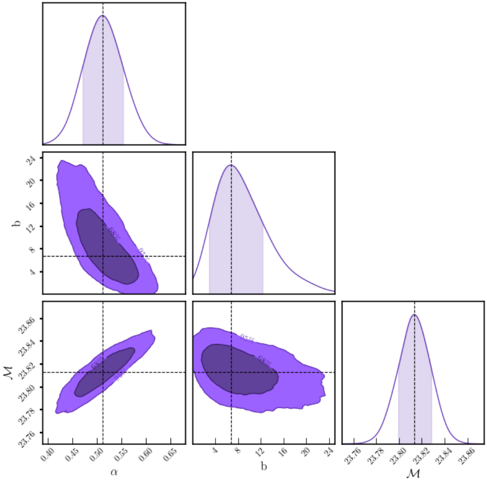


- ✓ The transition scale is close to the one from the ΛCDM model, $z_T \sim 0.6$.
- ✓ Local apparent acceleration $\tilde{q}(z=0) \sim -0.45$

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

Condidence contours of best-fit parameters

Assuming and Einstein-de Sitter bulk flow



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

Predictions of the tilted scenario

- Local apparent accelerated expansion
- Doppler-like apparent dipole in the deceleration/Hubble parameter
- The dipole should decay with redshift

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- The dipole should decay with redshift

Evidence for dipoles in cosmological parameters

[astro-ph.CO] 20 Dec 2022

Potential signature of a quadrupolar hubble expansion in Pantheon+supernovae

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ABSTRACT

The assumption of isotropy – that the Universe looks the same in all directions on large scales – is fundamental to the standard cosmological model. It is therefore critical to empirically test in which regimes this assumption holds. Anisotropies in the cosmic expansion are expected due to non-linear structures in the late Universe. However, the extent to which these anisotropies might impact our low-redshift observations remains to be fully tested. We use general relativistic simulations to determine that the expected anisotropies in the *Hubble* and deceleration parameters are quadrupolar and dipolar, respectively. We constrain these multipoles simultaneously in the new Pantheon+supernova compilation. In the rest frame of the cosmic microwave background (CMB), including peculiar velocity (PV) corrections, we find an ~2σ deviation from isotropy. We constrain the eigenvalues of the quadrupole in the *Hubble* parameter to be $\lambda_1 = 0.021 \pm 0.011$ and $\lambda_2 = 0.00 \pm 0.012$ and place a 1σ upper li... amplitude of 2.88 per cent. We find no significant dipole in the deceleration parameter, with amplitude ... in the rest frame of the CMB without PV corrections, we find a >2σ positive amplitude with ... anisotropies, the monopole of the *Hubble* parameter shifts by only 0.30 km s^{-1} M...

Key words: cosmological parameters – distance scale – cosmol...

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Letter to the Editor
Evidence for anisotropy of cosmic acceleration★
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ABSTRACT
Observations reveal a "bulk flow" in the local Universe which is faster and extends to much larger scales than are expected around a
typical observer in the standard ΛCDM cosmology. This is expected to result in a scale-dependent dipolar modulation of the acc
of the expansion rate inferred from observations of objects within the bulk flow. From a maximum-likelihood analysis of
Analysis catalogue of Type Ia supernovae, we find that the deceleration parameter, in addition to a small mono
a much bigger dipole component aligned with the cosmic microwave background dipole, which falls exponential
exp(−z/S). The best fit to data yields qd = −8.03 and S = 0.0262 (⇒ d ∼ 100 Mpc), rejecting
statistical significance, while qm = −0.157 and consistent with no acceleration (qm = 0) at 1.4σ. Thus
supernovae may be an artefact of our being non-Copernican observers, rather than evidence fo
the Universe.
dark energy – large-scale structure of Universe
The standard Frie
cosmology is based on
that the universe is homog
This assumption is supporte
which has temperature fluctuations
small angular scales. These
power spectrum are
created in the
perturbations; nevertheless there is n
their physical nature or their origin
In our real Universe there ar
the local inhomogeneity and an
These are non-negligible,
moves with respect
towards

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.

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multipoles simultaneously in the new Pantheon+supe... ...e background
(CMB), including peculiar velocity (PV) corrections, we find an ... eigenvalues of
the quadrupole in the *Hubble* parameter to be $\lambda_1 = 0.021 \pm 0.011$ and λ_2 ... ...per limit on its

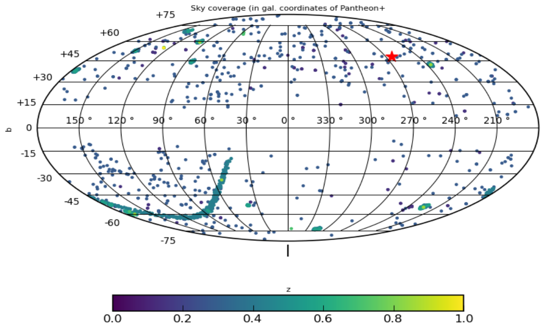
Dipole in the Pantheon+ SNIa compilation

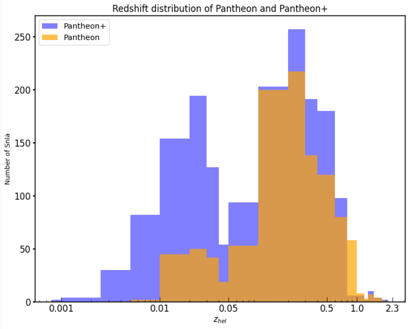
The Pantheon+ SNIa compilation

1701 Type Ia supernovae with redshift range $0.0008 \leq z \leq 2.26$

18 different surveys
727 SNIa at $z \leq 0.08$
(Dan Scolnic et al 2022 ApJ 938 113)

Pantheon+ vs Pantheon SNIa
118 SNIa at $z \leq 0.010$





Dipole in $\tilde{q}$ in the Pantheon+ SNIa compilation - I

- We make a redshift cut in the Pantheon+ sample and we analyze SnIa with $z >= 0.015 \sim 60$Mpc. In total, we have 1527 SNIa.
- The anisotropic deceleration parameter in the tilted frame becomes:

$$\tilde{q} = \tilde{q}_m(z) + q_d(\mathbf{n}_{SN} \cdot \mathbf{n}_{dip})\mathcal{F}_{dip} \tag{6}$$

$\tilde{q}_m(z) = \frac{1}{2}\left(1 - \frac{1}{a+b\,(2-\frac{2}{\sqrt{1+z}})^3}\right)$ is the monopole,
q_d is the amplitude of the dipole,
$\mathbf{n}_{SN}$ is a vector pointing to the location of the SNIa,
$\mathbf{n}_{dip}$ a vector pointing to the location of the dipole and
$\mathcal{F}_{dip}$ describes the scale-dependence of the dipole.

- We examine a form of the function of the dipole $\mathcal{F}_{dip}$ which is constant, $\mathcal{F}_{dip} = 1$ and $\mathcal{F}_{dip}(z) = \exp\left(\frac{-z}{S}\right)$

Dipole in $\tilde{q}$ in the Pantheon+ SNIa compilation - II

- The tilted redshift-dependent deceleration parameter:

$$\tilde{q}_{(z)} = \frac{1}{2}\left(1 - \frac{1}{a + b\, d_r^3(z)}\right) + q_d(\mathbf{n}_{SN} \cdot \mathbf{n}_{dip})\mathcal{F}_{dip} \tag{7}$$

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

$$\tilde{H}(z) = H_0 \exp\left[\int_0^z \left(\frac{1 + \tilde{q}(u)}{1 + u}\right) du\right] \tag{8}$$

- The luminosity distance of the SNIa (in Mpc):

$$\tilde{D}_L(z) = c\,(1 + z)\int_0^z \frac{dz'}{\tilde{H}(z')} \tag{9}$$

- The theoretical distance modulus :

$$\mu_{th}(z) = 5\log_{10} \tilde{D}_L(z) + 25 \tag{10}$$

- The minimization function:

$$\chi^2_{SN} = (\mu_{th}(z) - \mu_{SN})C^{-1}_{SN}(\mu_{th}(z) - \mu_{SN}) \tag{11}$$

K. Asvesta et al., in preparation

Tomographic analysis

To study the evolution of the dipole parameters with redshift, we employ a redshift tomographic method dividing the dataset (1527 SNIa) into 4 equal number redshift bins.

- We fix the monopole parameters, (a, b) to the best-fit ones from the Pantheon + SNIa, in the applied z-cut sample: **a** $= 0.512^{+0.018}_{-0.015}$ and **b** $= 8.3^{+4.3}_{-3.1}$
- The first redshift bin contains 359 SNIa with $0.015 \leq z_{hel} < 0.034$ and **mean redshift 0.024**
- The second redshift bin contains 394 SNIa with $0.034 \leq z_{hel} < 0.195$ and **mean redshift 0.10**
- The third redshift bin contains 381 SNIa with $0.195 \leq z_{hel} < 0.34$ and **mean redshift 0.265**
- The fourth redshift bin contains 393 SNIa with $0.34 \leq z_{hel} < 2.3$ and **mean redshift 0.575**

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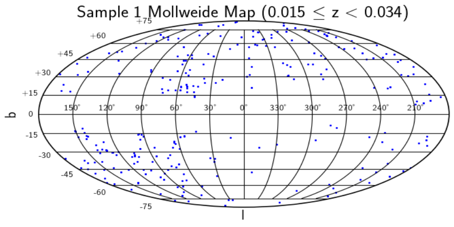
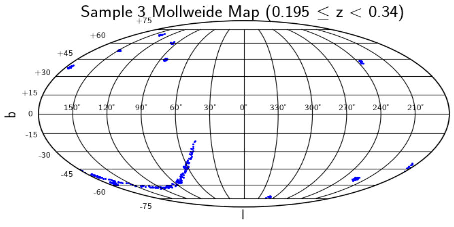
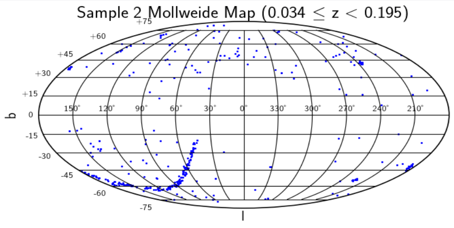
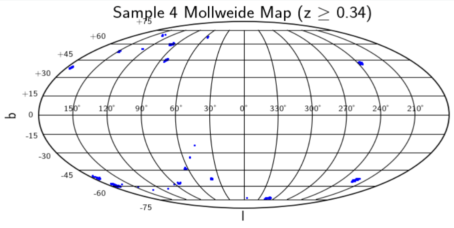
Spatial Distribution of the subsamples









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Tomographic analysis - Dipole fit in three redshift frames

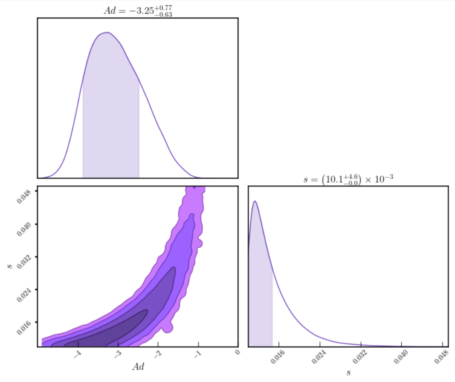
We constrain the dipole in all three redshift frames, namely the heliocentric (Hel), the CMB (CMB) and the Hubble Diagram frame (HD).

The direction of the dipole coincides with the CMB dipole.

Frame	Bin	q_{mono}	F(z,S)	q_{dip}	S
Hel	**1**	**-0.4764**	1	$\mathbf{-2.32}^{+0.51}_{-0.48}$	-
Hel	**1**	**-0.4764**	$e^{-z/S}$	$\mathbf{-2.39}^{+0.53}_{-0.58}$	unconstrained
CMB	1	-0.4764	1	2.33 ± 0.47	-
CMB	1	-0.4764	$e^{-z/S}$	$2.43^{+0.69}_{-0.62}$	unconstrained
HD	1	-0.4764	1	1.27 ± 0.47	
HD	1	-0.4764	$e^{-z/S}$	$1.11^{+0.62}_{-0.57}$	unconstrained
Hel	**2**	**-0.463**	1	$\mathbf{-0.159} \pm 0.084$	-
CMB	2	-0.463	1	0.096 ± 0.086	-
HD	2	-0.463	1	0.057 ± 0.085	-
Hel	**3**	**-0.329**	1	$\mathbf{0.058} \pm 0.047$	-
CMB	3	-0.329	1	$0.115^{+0.045}_{-0.049}$	-
HD	3	-0.329	1	0.108 ± 0.047	-
Hel	**4**	**0.032**	1	$\mathbf{0.069} \pm 0.027$	-
CMB	4	0.032	1	0.089 ± 0.028	-
HD	4	0.032	1	0.089 ± 0.028	-

Dipole in the full sample -I

The posterior distributions of the full sample $(z >= 0.015)$ when the tilted anisotropic deceleration parameter, in the heliocentric frame, is:
$\tilde{q} = -0.35 + q_d(\mathbf{n}_{SN} \cdot \mathbf{n}_{CMB}) \exp\left(\frac{-z}{S}\right)$



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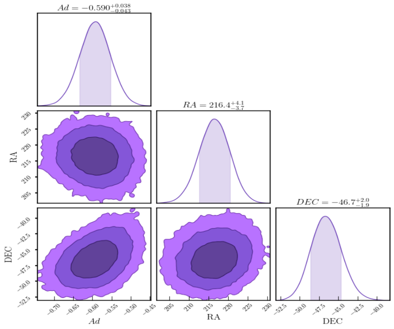
Dipole in the full sample - II

The posterior distributions of the full sample ($z >= 0.015$) when the tilted anisotropic deceleration parameter, in the heliocentric frame, is:
$\tilde{q} = -0.35 + q_d(\mathbf{n}_{SN} \cdot \mathbf{n}_{dip})$



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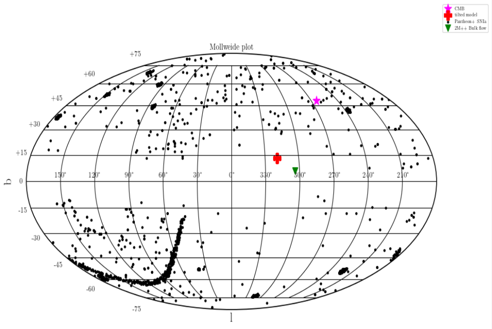

2M++ Bulk flow: Jonathan Carrick et al. 2015, MNRAS, 450, 317

Other dipoles on the sky

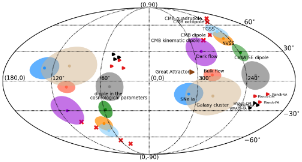

FIG. 1: Directions of anisotropy in the Universe in the Galactic (l, b) coordinates with the galactic center in the middle, as inferred from Table I. Directions from the literature are shown with different markers or ellipses (data points and their 1 σ uncertainties) with text labels.

TABLE I: Directions of anisotropy in the Universe as inferred from several data sets, the locations of the data points are shown in Fig. 1.

Data Point	(l, b)	color in Fig. 1	Ref.
Galaxy cluster	$(280° \pm 35°, -15° \pm 20°)$	tan	[99]
NVSS	$(248° \pm 12.5°, 44° \pm 8°)$	orange	[100]
TGSS	$(247° \pm 14.6°, 52° \pm 8°)$	light-blue	[101]
Dipole in the cosmological parameters	$(48.8°^{+14.3°}_{-14.4°}, -5.6°^{-17.0°}_{-17.4°})$	grey	[80]
CatWISE dipole	$(238.2°, 28.8°)$	green	[102]
CMB kinematic dipole	$(280°, 42°)$	red x	[103]
CMB dipole	$(263.99°, 48.26°)$	red x	[104]
CMB quadrupole	$(224.2°, 69.2°)$	red x	[65]
CMB octopole	$(239°, 64.3°)$	red x	[65]
Planck-VA (Variance Asymmetry)	$(212°, -13°)$	red >	[105]
Planck-DM (Dipole Modulation)	$(227°, -15°)$	red >	[105]
Planck-PA (Power Asymmetry)	$(218°, -21°)$	red >	[105]
WMAP9-VA	$(219°, -24°)$	black >	[105]
WMAP5-DM	$(224°, -22°)$	black >	[105]
WMAP9-PA	$(227°, -27°)$	black >	[105]
Great Attractor	$(307°, 9°)$	brown >	[106]
SNe Ia	$(310.6° \pm 18.2°, -13.0° \pm 11.1°)$	blue	[107]
Dark flow	$(290° \pm 20°, 30° \pm 15°)$	dark-violet	[42]
Bulk flow	$(282° \pm 11°, 6° \pm 6°)$	light-red	[108]

P.K. Aluri et al., 2023, DOI: 10.1088/1361-6382/acbefc

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:

$$q = -\left(1 + \frac{3\dot{\Theta}}{\Theta^2}\right) \quad \text{and} \quad \tilde{q} = -\left(1 + \frac{3\tilde{\Theta}'}{\tilde{\Theta}^2}\right) \tag{12}$$

$$\tilde{q} = q + \frac{\tilde{\vartheta}'}{3\dot{H}}\left(1 + \frac{1}{2}\Omega\right) \quad \text{to linear order} \tag{13}$$

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

$$\frac{\tilde{\vartheta}'}{\dot{H}} = \frac{4}{3}\left[1 + \frac{1}{6}\left(\frac{\lambda_H}{\lambda}\right)^2\right]\frac{\tilde{\vartheta}}{H} \tag{14}$$