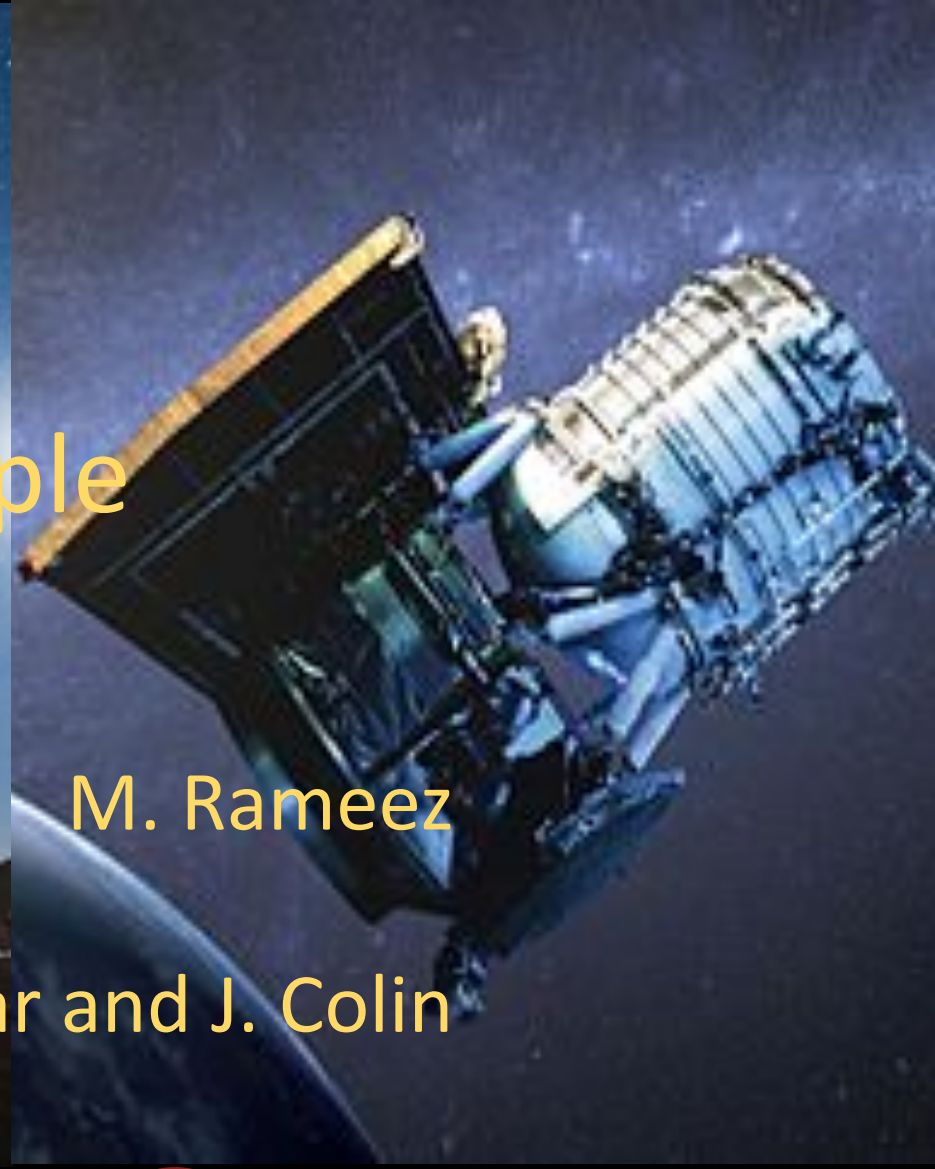
CARLSBERGFONDET



Testing the Cosmological principle

M. Rameez

Includes work with R. Mohayaee, S. Sarkar and J. Colin

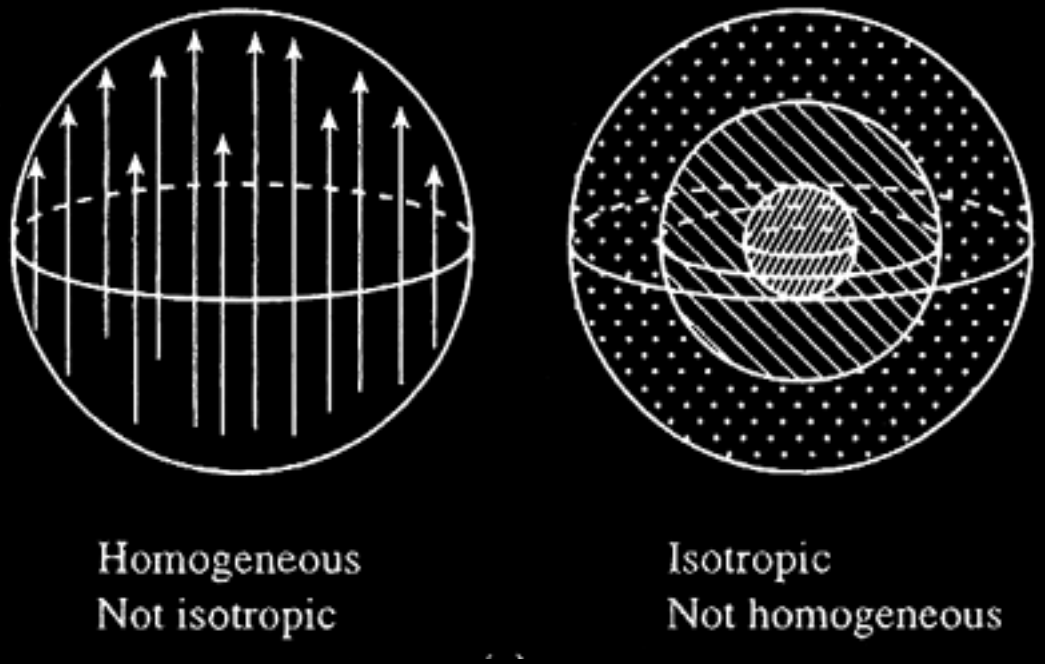
The Niels Bohr International Academy

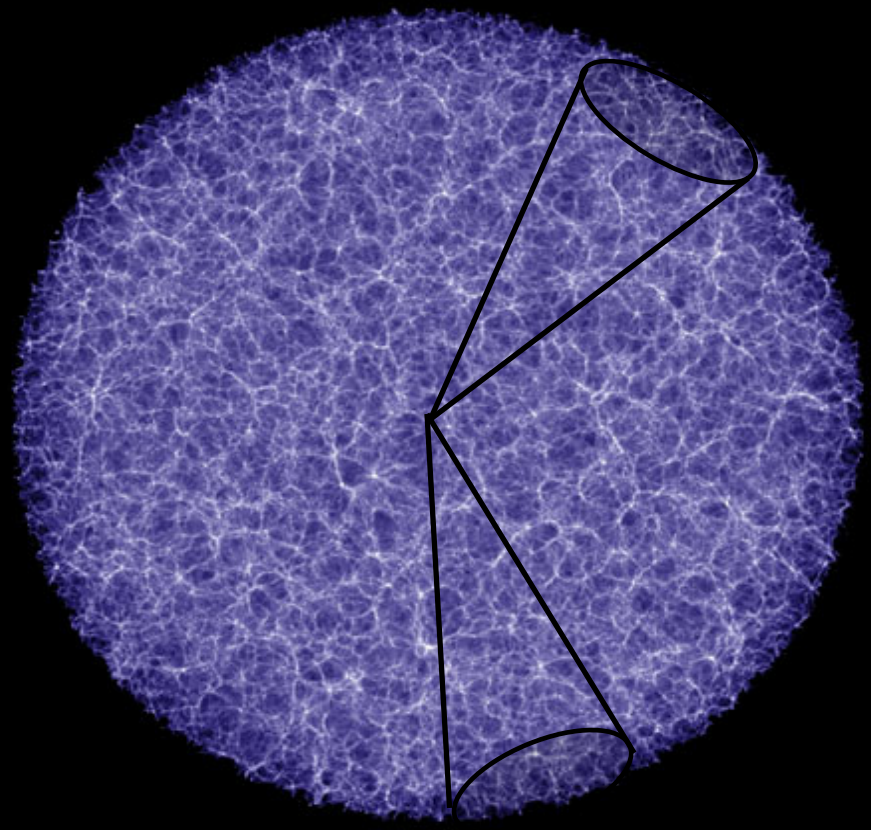
UNIVERSITY OF COPENHAGEN

VIA Lecture
APC Paris

The cosmological principle

The Universe is (statistically) isotropic and homogenous (on large scales).





No special positions or directions in the Universe.

Stationary observer:

- Sees same number of sources per solid angle in all directions
- Large angles, deep enough survey

The (ideal) FLRW Universe

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T\mu\nu$$

Isotropy and Homogeneity **at all scales**:

$$ds^2 = a(t)^2\, d\Sigma^2 \; - c^2 dt^2$$

$$H(a) = \frac{\dot{a}}{a} = H_0\sqrt{\Omega_m a^{-3} + \Omega_r a^{-4} + \Omega_k a^{-2} + \Omega_\Lambda}$$

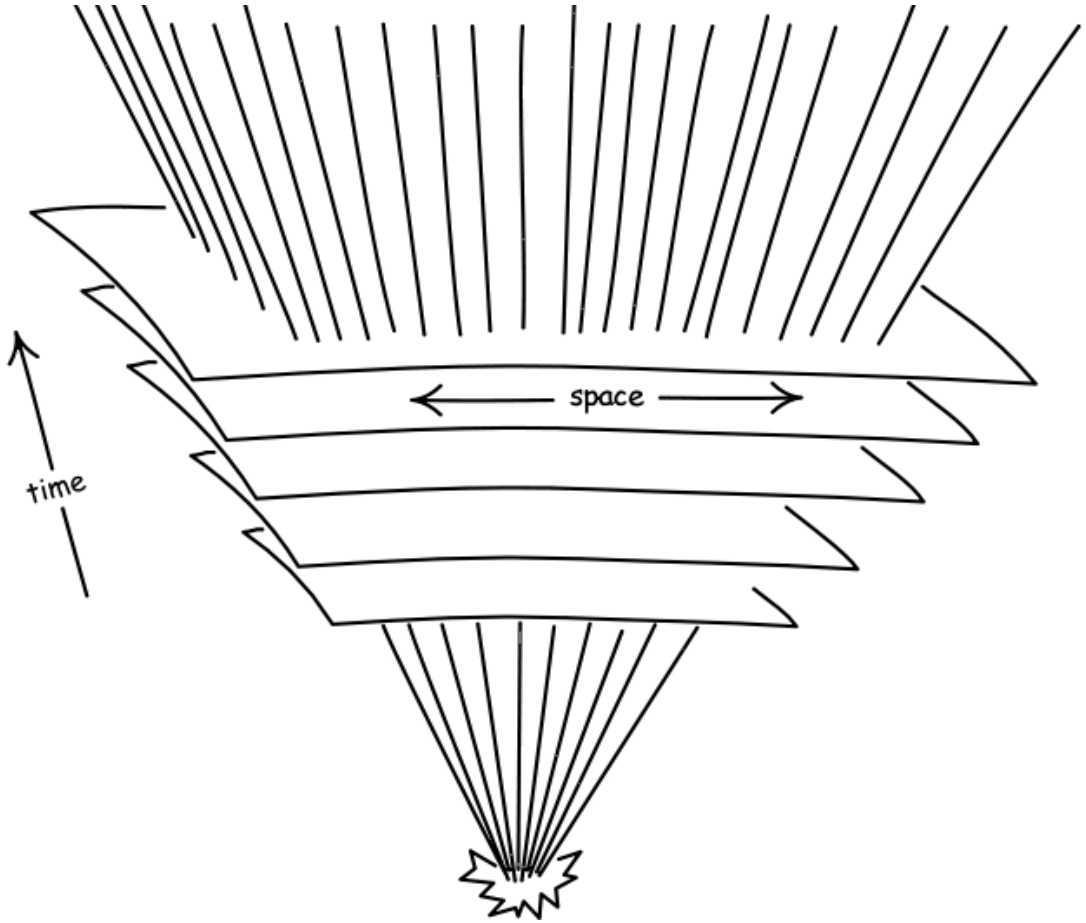
$\Omega_r \sim 10^{-4}$, usually ignored.

$$\Omega_k + \Omega_\Lambda + \Omega_m = 1$$

(Flat) ΛCDM is a (1) 2 parameter model for $a(t)$ (or equivalently, D(z))

No structure, no peculiar (non Hubble) motion, all clocks remain synchronized. Surfaces of constant time exist

Spacetime is locally Flat Minkowski

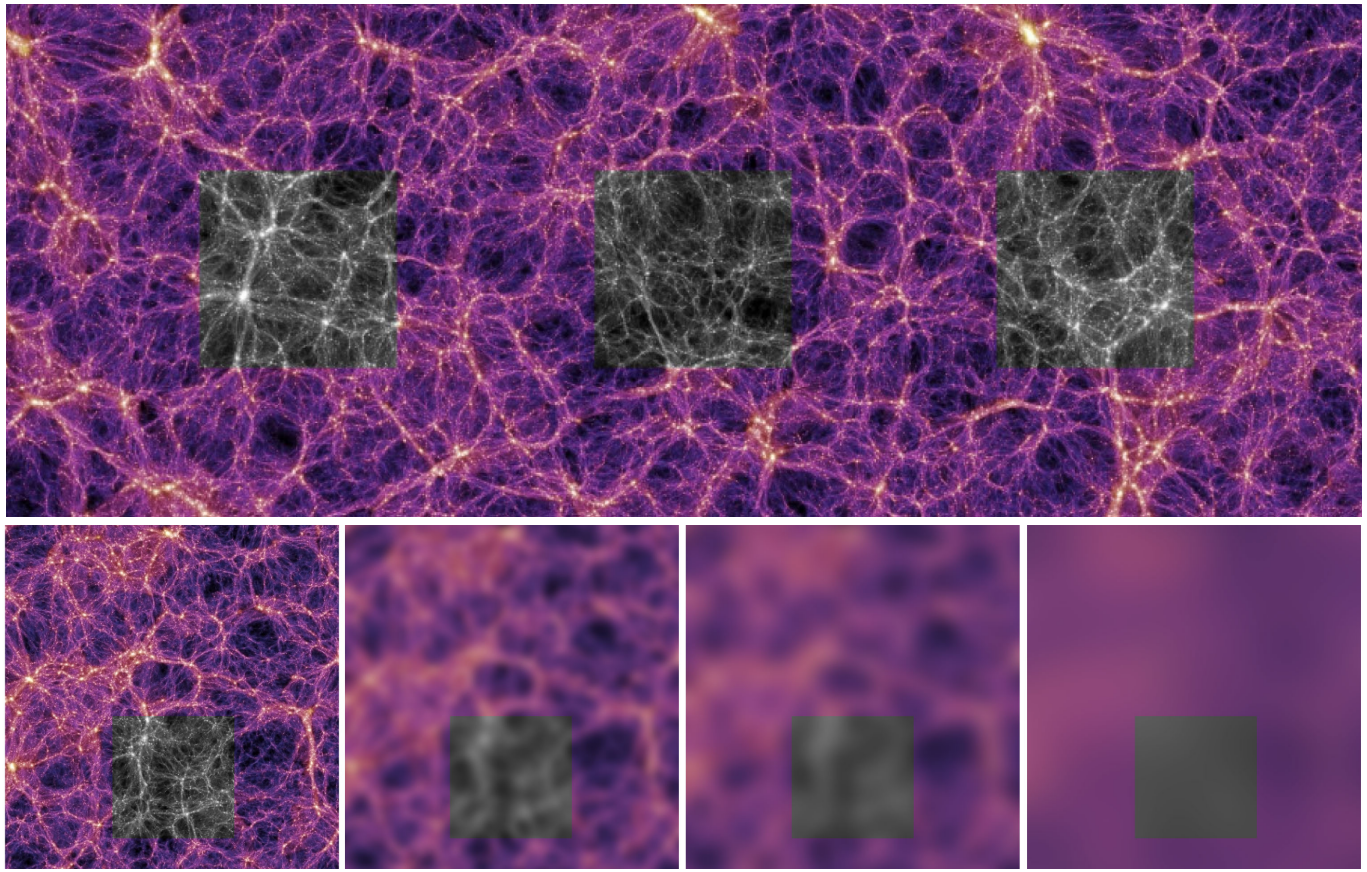


But the real Universe is not homogenous at all scales

The real, inhomogeneous Universe

Excellent review : Clarkson et al Rept.Prog.Phys. 74 (2011) 112901 https://arxiv.org/abs/1109.2314

Does the growth of structure affect our dynamical models of the universe? The averaging, backreaction and fitting problems in cosmology.



What is the length scale at which Universe approaches FLRW?

"In essence, it is an assumption that Einstein's equations also hold for an averaged geometry, as well as a local one. In fact, it is not clear that the whole machinery of GR holds after averaging – e.g., concepts such as spacetime and objects such as tensors need to be assumed to make sense after coarse graining."

Over and under densities arise in matter, leading to peculiar (non Hubble) velocities

Can constant time hypersurfaces be constructed for these moving observers? (Open problem)

Averaging procedures are non commutative.

Does fitting cosmological observations, which are on the lightcone (null hypersurface) let you infer properties of the Universe when it was FLRW?

The Fitting problem

"One can do a spacetime fitting, asking which FLRW model is best if we average invariant quantities in a spatial or spacetime volume: e.g., the energy density of particles and their velocities (when the matter averaging maybe represented by kinetic theory); one may choose to smooth the metric or scalar invariants on the geometry side. **Alternatively, one can do a null fitting, where one in effect averages astronomical observations."**

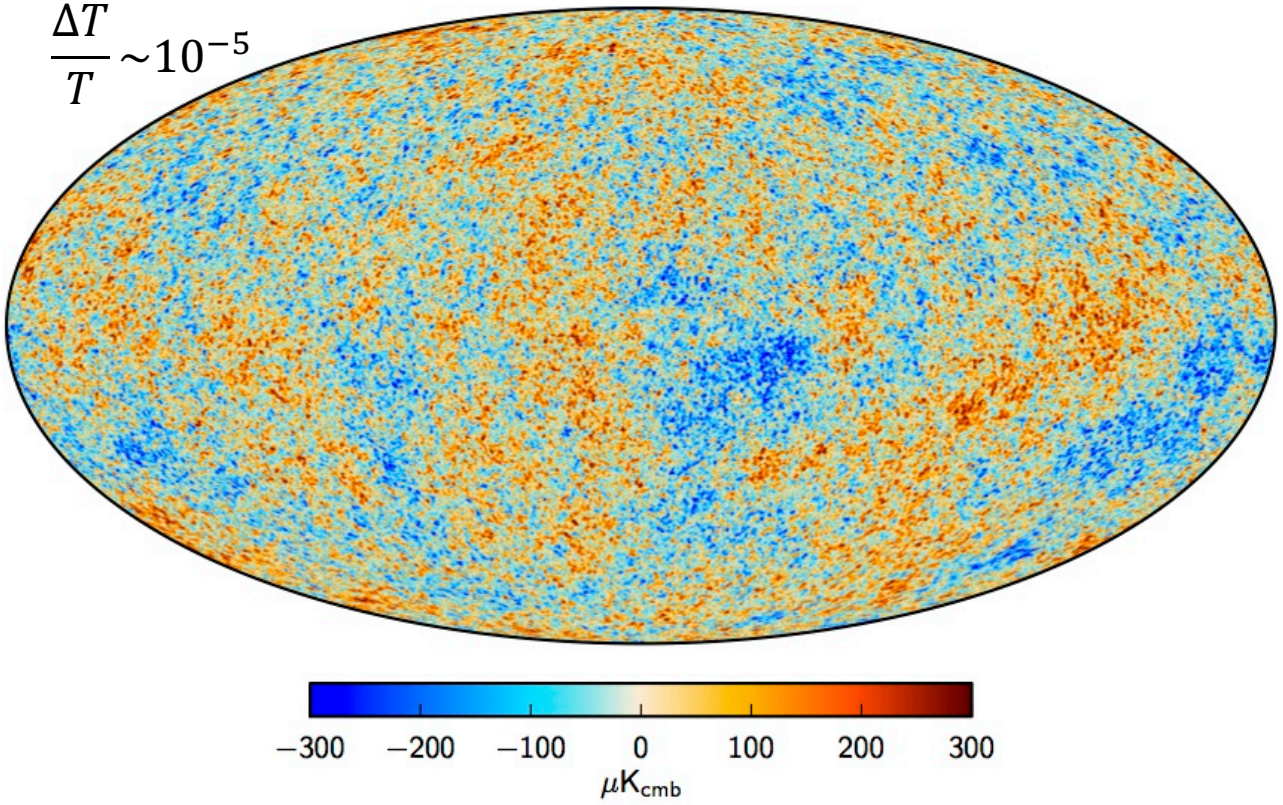
"How do we appropriately fit an idealized model to observations made from one location in a lumpy universe, given that this 'background' [FLRW] does not in fact exist?"

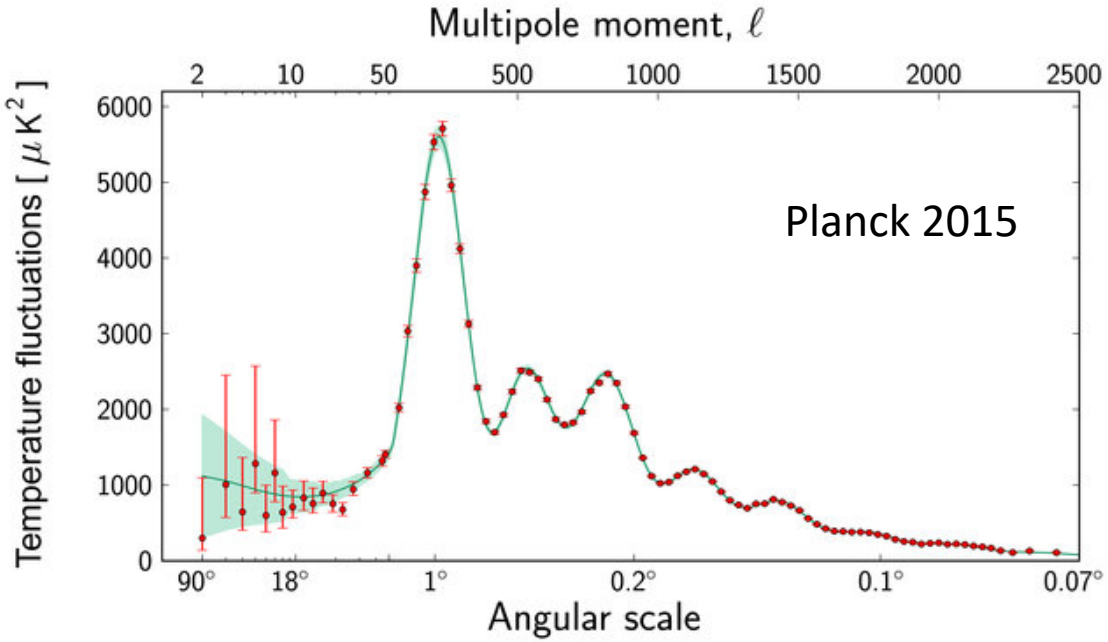
Clarkson et al Rept.Prog.Phys. 74 (2011) 112901 https://arxiv.org/abs/1109.2314

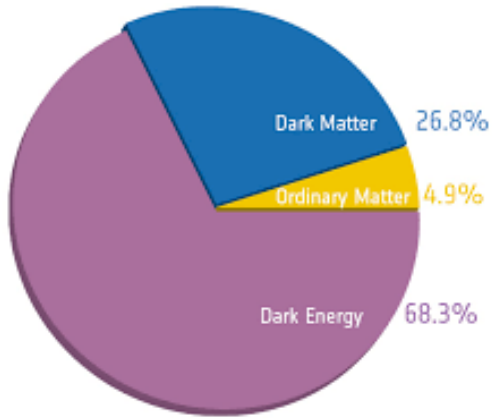
"Data from the Planck satellite show the universe to be highly isotropic" (Wikipedia)

T = 2.725 K

$\frac{\Delta T}{T} \sim 10^{-5}$

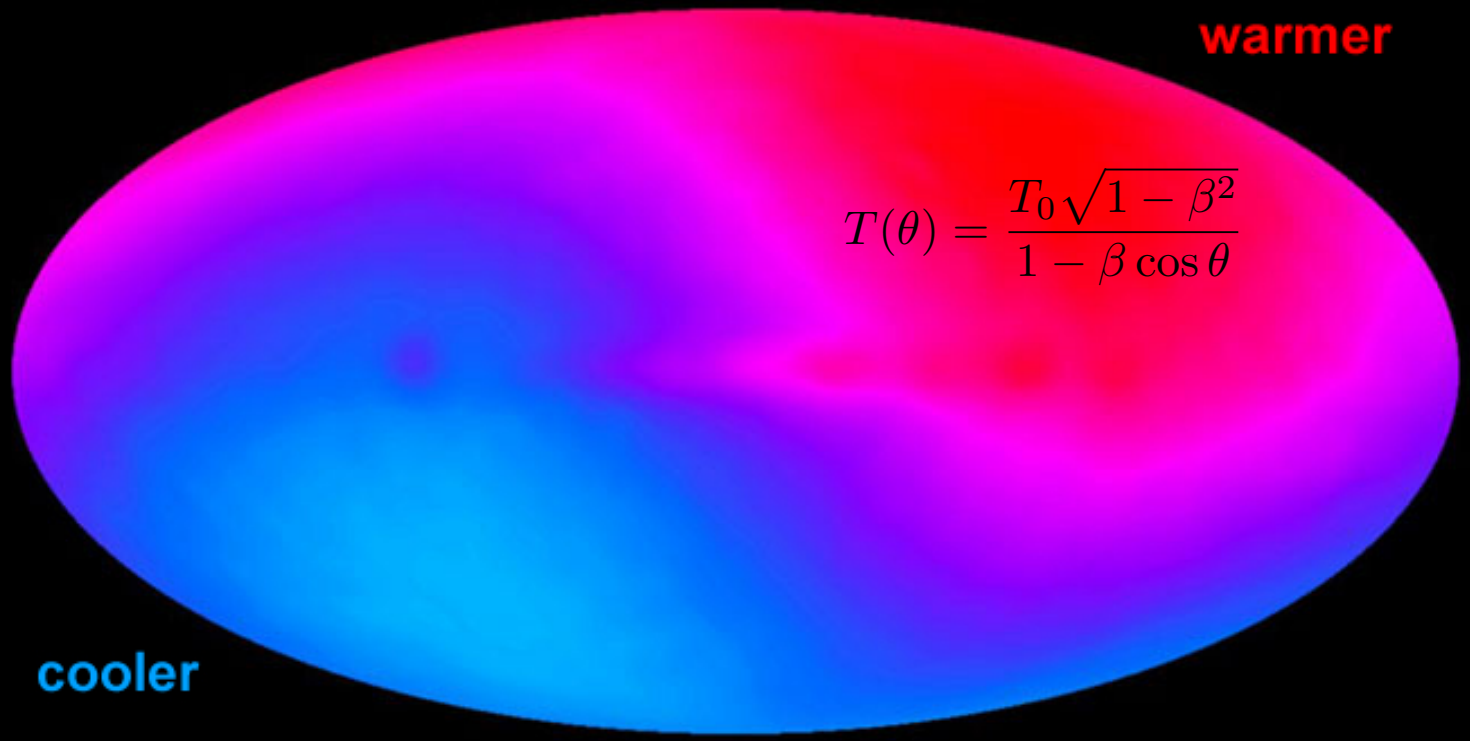






We observe a statistically isotropic* Gaussian random field of small temperature fluctuations (fully quantified by the 2-point correlations ➛ angular power spectrum)

The CMB Dipole: Our motion through the cosmos?



COBE Experiment, 1996
Planck 2015

$$\frac{\Delta T}{T} \sim 10^{-3}$$

Net motion of the Solar System barycentre: 369 +/- 2 km/s w.r.t CMB rest frame towards

R.A = 168.0, DEC = -7.0

- Motion of the Sun around the Galaxy ~225 +/- 18 km/s
- The motion of the Local Group 627+/-22 km/s ApJ, 709, 483

What is the origin of this motion?

This talk:

Dipole in radio catalogue of galaxies, NVSS and SUMSS

~600000 galaxies

z ~ 1, deep survey . $\vec{\mathcal{S}}$ (D(z)) $\rightarrow 0$

High redshift radio galaxies and divergence from the CMB dipole
J. Colin, R. Mohayaee, M. R. and S.Sarkar
MNRAS 471 (2017) no.1, 1045-1055 arXiv:1703.09376

Dipole in catalogue of galaxies from infrared survey, Wide Field Infrared Survey Explorer (WISE)
~2.4 million
z~0.14, shallow survey

The dipole anisotropy of AllWISE galaxies
M.R. , R. Mohayaee, S.Sarkar and J. Colin
MNRAS 477 (2018) no.2, 1772-1781 arXiv:1712.03444

A dipole in the deceleration parameter?
The SDSS-II/SNLS3 Joing Lightcurve Analysis sample of SN1a
740 SN1a, z=0.01 to z=1.4

Apparent cosmic acceleration due to local bulk flow
J. Colin, R. Mohayaee, M. R. and S.Sarkar
Submitted to Nature Sci Rep , arXiv:1808.04597

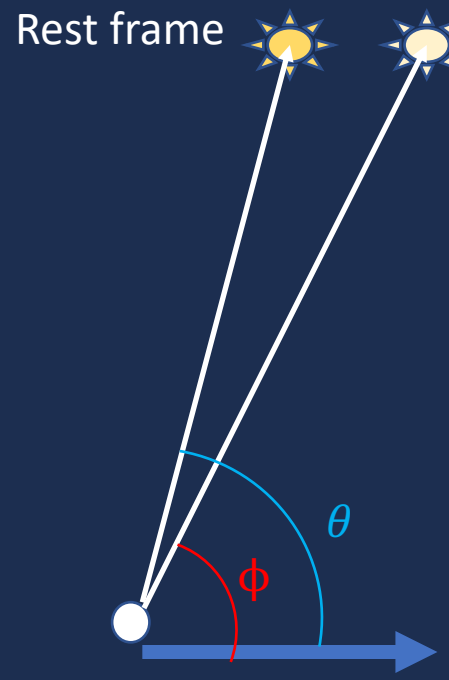
Also see https://arxiv.org/pdf/1905.00221.pdf "Concerns about the reliability of publicly available SN1a data"

https://github.com/rameez3333/ Dipole_JLA and catana repositories.

A moving observer - Kinematic Dipole

$$\sigma(\theta)_{obs} = \sigma_{rest}[1 + [2 + x(1+\alpha)]\frac{v}{c}\cos(\theta)]$$

Aberration



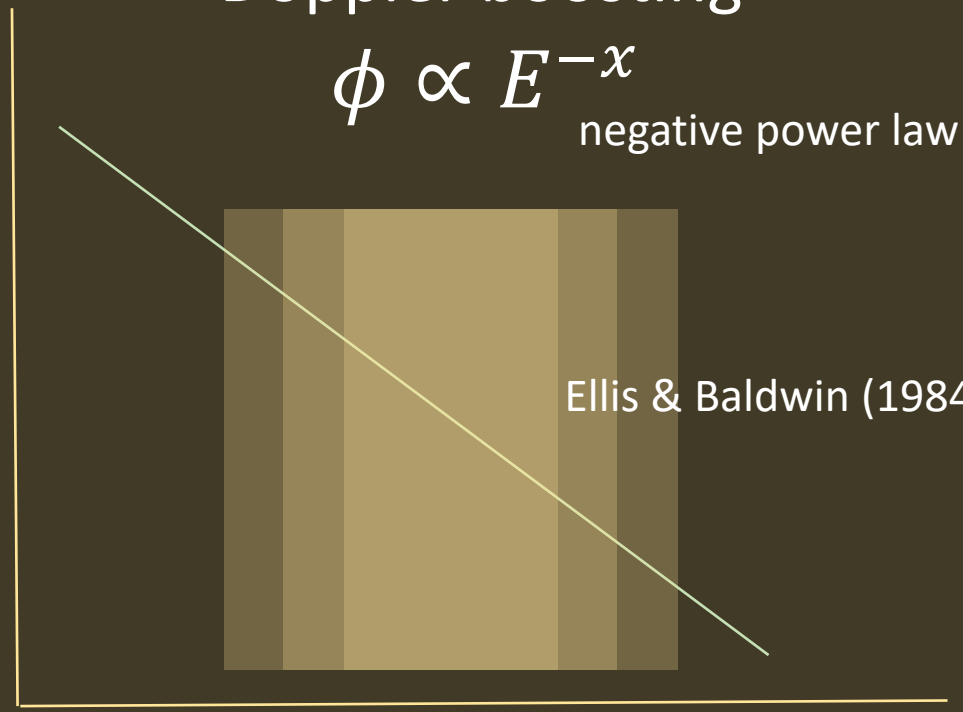
$$\tan\phi = \frac{\sin\theta}{\gamma * cos\theta - \frac{v}{c}}$$

+

Doppler boosting

$$\phi \propto E^{-x}$$

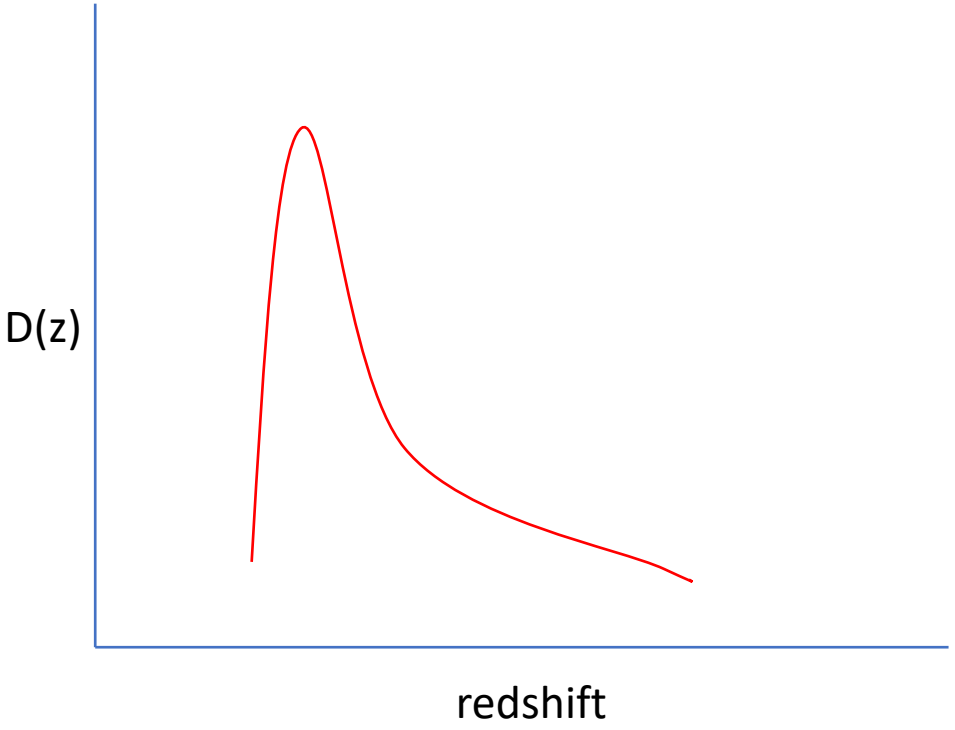
negative power law



Flux limited catalog -> more sources in direction of motion

Dipoles in a catalogue of galaxies

In an all-sky catalogue with sources of redshift distribution D(z) from directionally unbiased survey with N sources



$$\vec{\delta} = \vec{\mathcal{K}}\,(\vec{v}_{obs}, x, \alpha) + \vec{\mathcal{R}}\,(\mathrm{N}) + \vec{\mathcal{S}}\,(\mathrm{D(z)}) + \vec{\mathcal{F}}$$

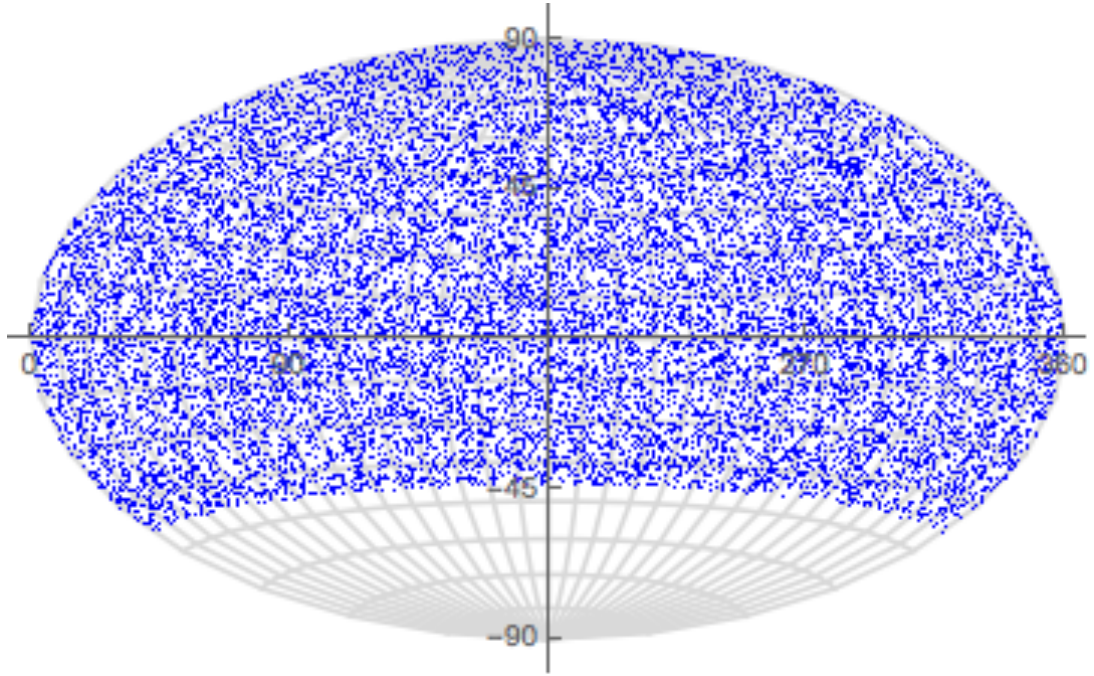
$\vec{\mathcal{K}} \rightarrow$ **The Kinematic dipole,** depends on source spectrum, source flux function, observer velocity

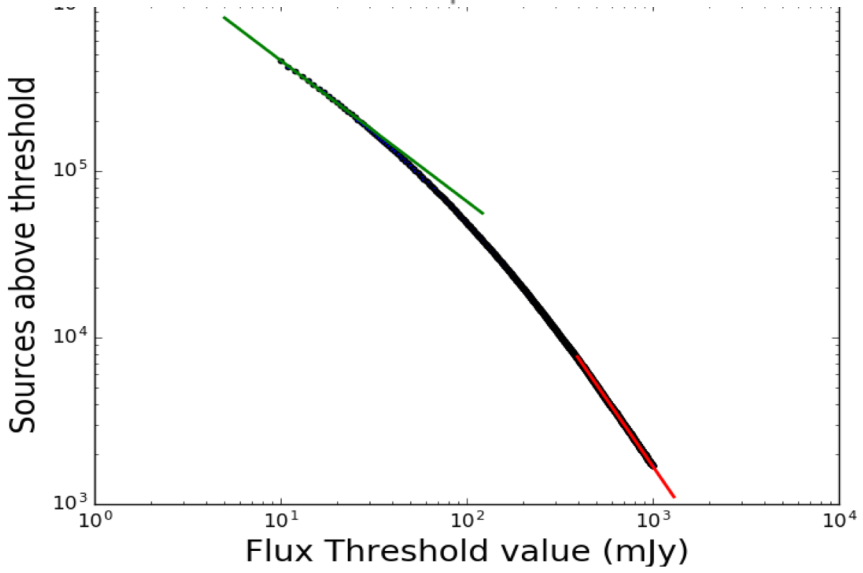
$\vec{\mathcal{R}} \rightarrow$ **The random dipole,** $\propto 1/\sqrt{N}$, isotropically distributed in direction

$\vec{\mathcal{S}} \rightarrow$ **The clustering dipole,** local anisotropy due to growing structure (which causes the motion in the first place)

$\vec{\mathcal{F}} \rightarrow$ **Foregrounds,** mainly stars and other Galactic contamination

The NRAO VLA Sky Survey (NVSS)



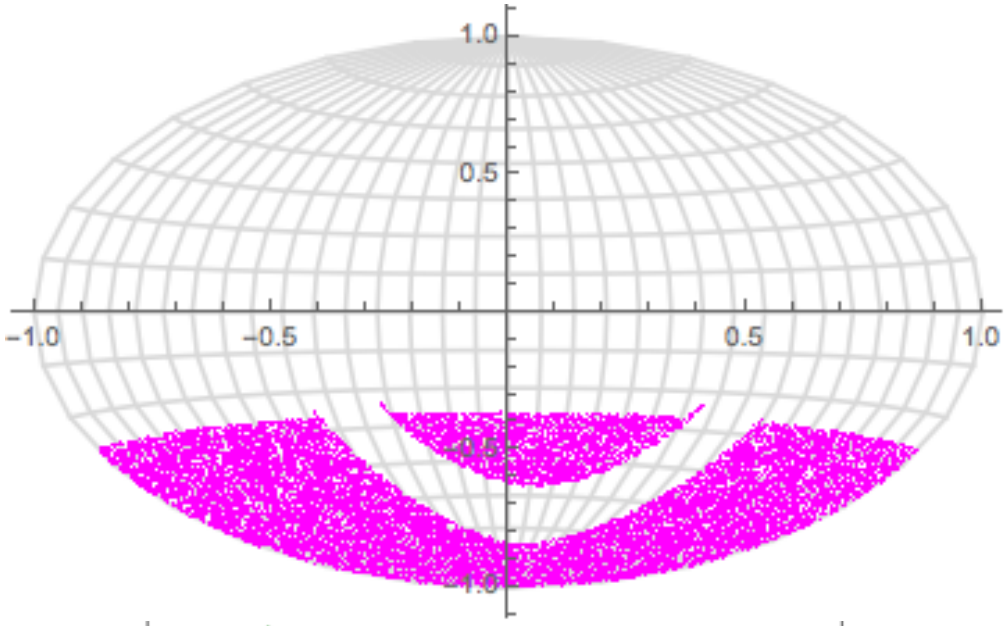


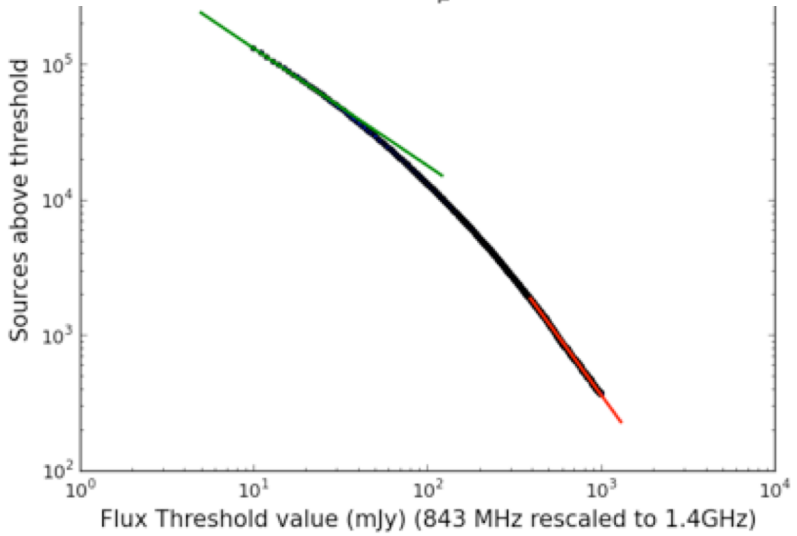
1.4 GHz survey of the Northern sky, by the National Radio Astronomy Observatory. Down to dec = -40.4^o

1,773,488 sources above 2.5 mJy. But ‘complete’ with uniform sky exposure only above 10 mJy

Phys. Rev. D, 78, 043519

Sydney University Molonglo Sky Survey (SUMSS)

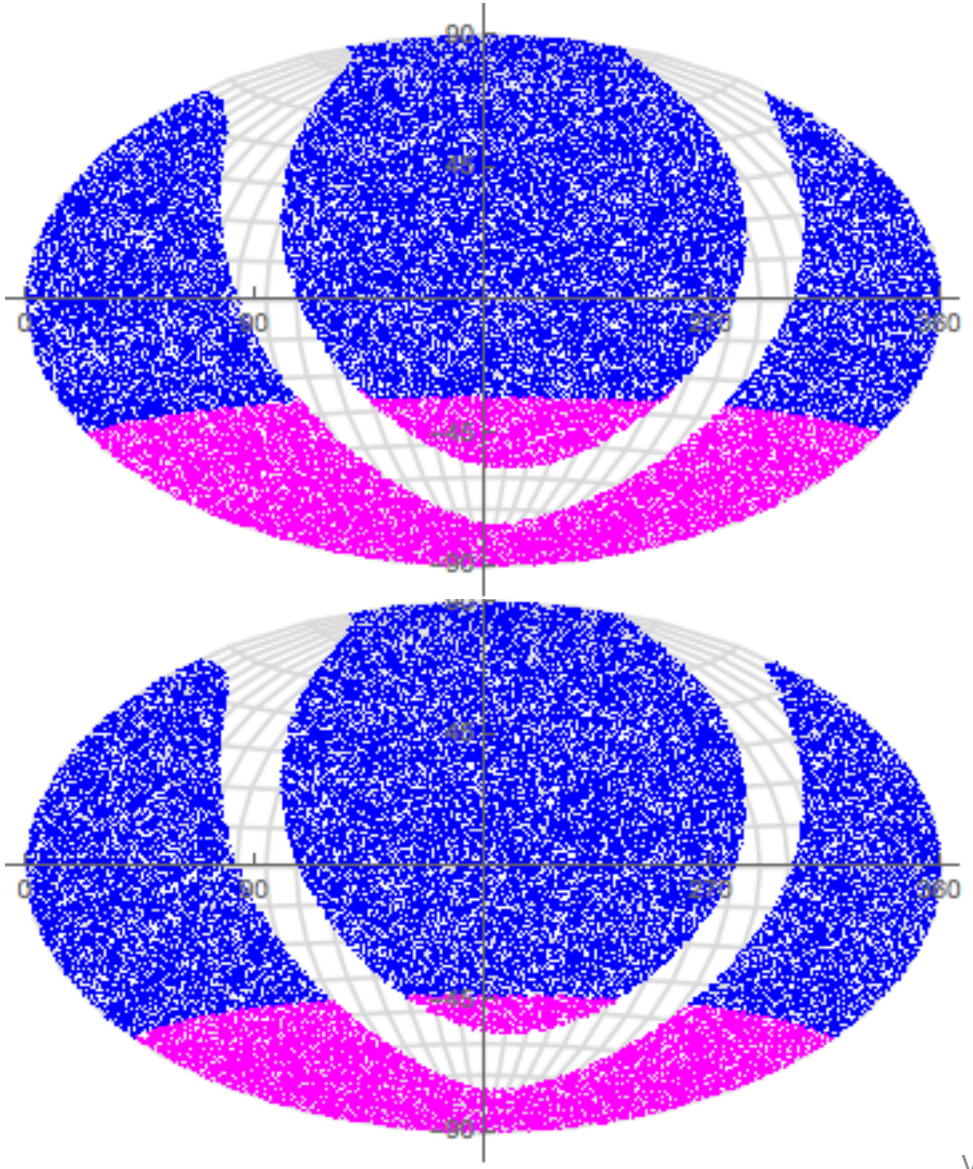




843 MHz survey of the Southern sky, by the Molonglo Observatory Synthesis telescope. Dec < -30.0^o

211050 radio sources. Similar sensitivity and resolution to NVSS

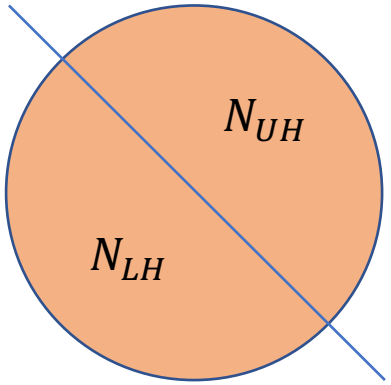
The NVSUMSS-Combined All Sky catalog



- Rescale SUMSS fluxes by $(843/1400)^{-0.75}$
- Remove Galactic Plane at +/-10 degree in NVSS
- Remove NVSS sources below and SUMSS sources above dec -30 (or -40)
- Apply common threshold flux cut on both samples
- z~1, <120 sources at z<0.3 at 90%C.L.

Estimators for the Dipole

$$\vec{D}_H = \hat{z} * \frac{N_{UH} - N_{LH}}{N_{UH} + N_{LH}}$$



Vary the direction of the hemispheres until maximum asymmetry is observed

Easy visualization

High Bias and statistical error $2.6/\sqrt{N}$

$$\vec{D}_H = \frac{\hat{z}}{N} \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\pi} \sigma(\theta) \frac{|cos\theta|}{cos\theta} sin\theta d\theta d\phi$$

$$\vec{D}_{3D} = \frac{1}{N} \sum_{i=1}^{N} \hat{r}_i$$

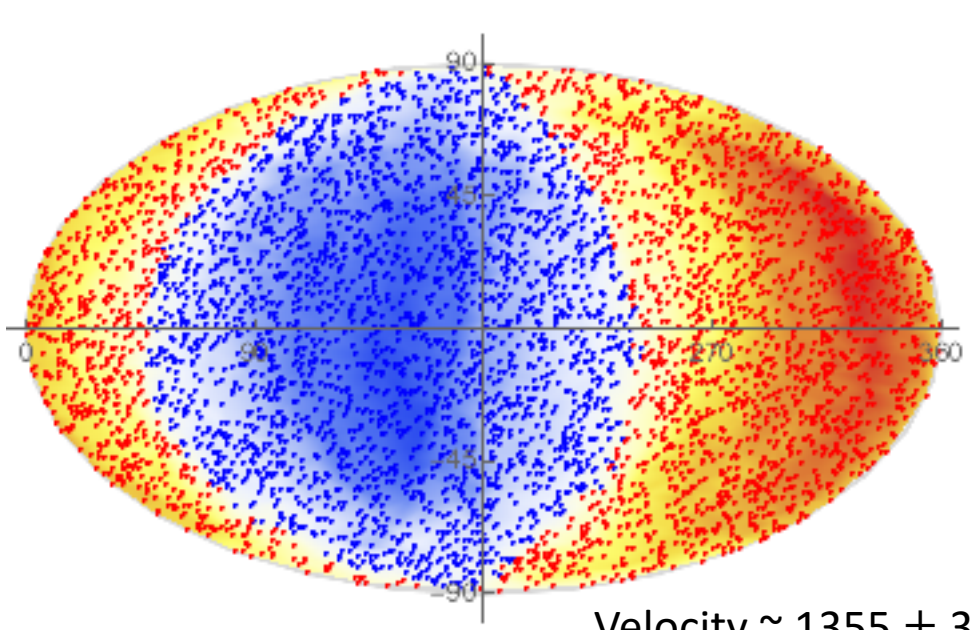
Add up unit vectors corresponding to directions in the sky for every source

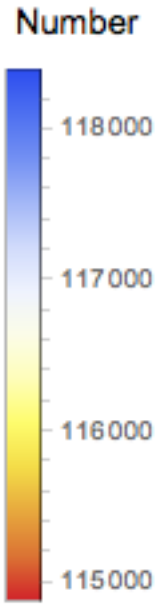
Relatively lower bias and statistical error $1/\sqrt{N}$

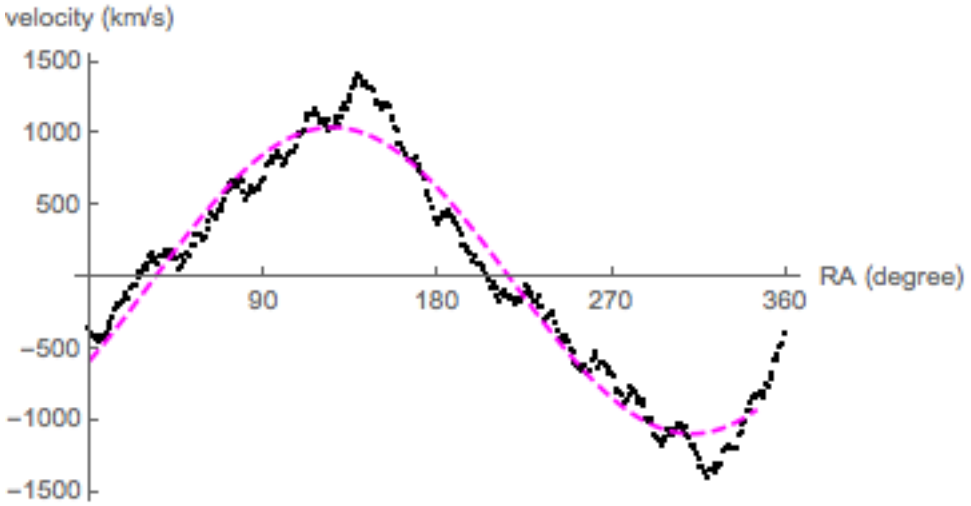
Rubart and Schwarz 2013

$$\vec{D}_C = \frac{\hat{z}}{N} \int_{\phi=0}^{\phi=2\pi} \int_{\theta=0}^{\theta=\pi} \sigma(\theta) cos\theta sin\theta d\theta d\phi$$

Results







Velocity ~ 1355 $\pm$ 351 km/s, Dir within 10° of CMB dipole direction.

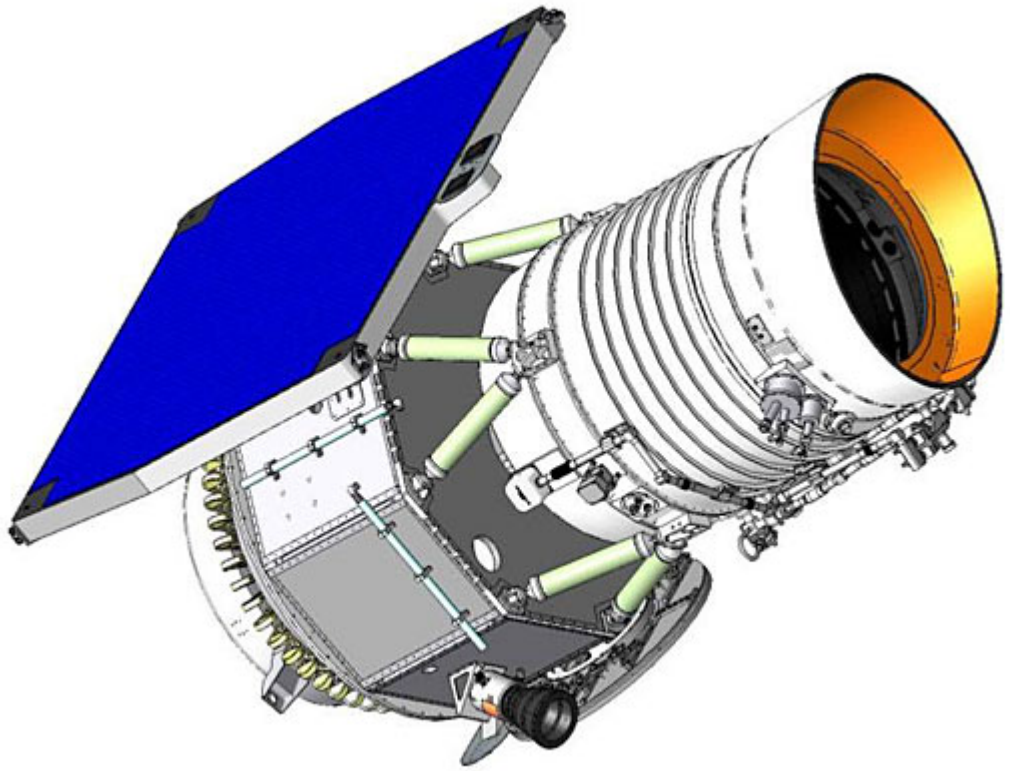
Statistical significance, ~2.81 Sigma, with the 3D linear estimator, constrained mainly by the catalogue size

Bengaly et al 2018 JCAP 1804 (2018) no.04, 031 find a 5.1 sigma dipole in TGNSS !

Could be due to unknown systematics

SKA phase 1 measurement ~10%
Bengaly (et al) 2018 : 1810.04960v1

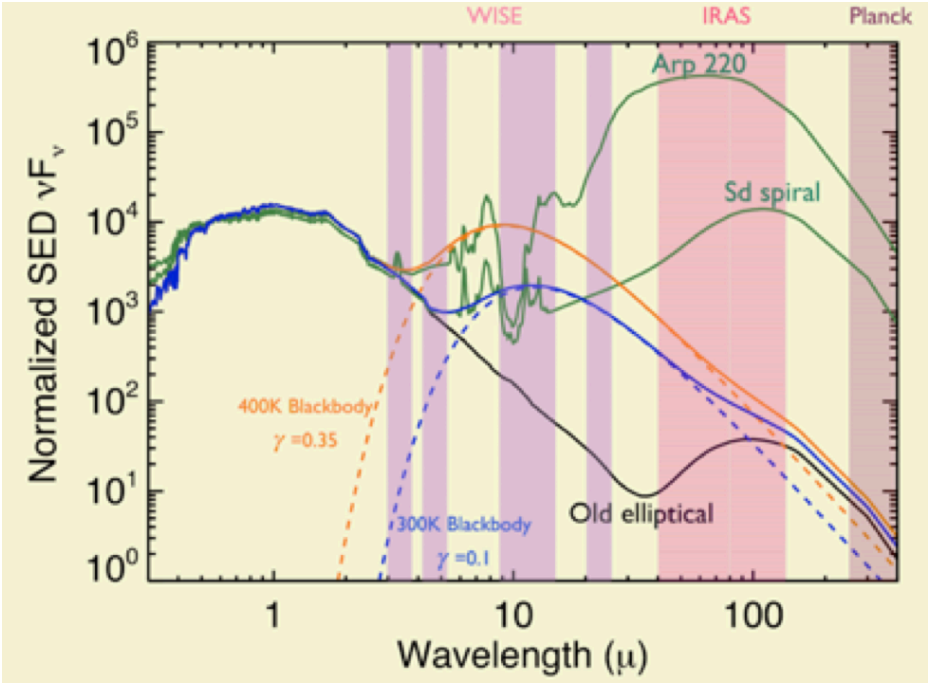
The Widefield Infrared Survey Explorer



All sky infrared survey over 10 months, in the bands 3.4, 4.6, 12 and 22 μm using a 40 cm diameter telescope

Generated a catalog of 746 million+ objects, most of which are stars.

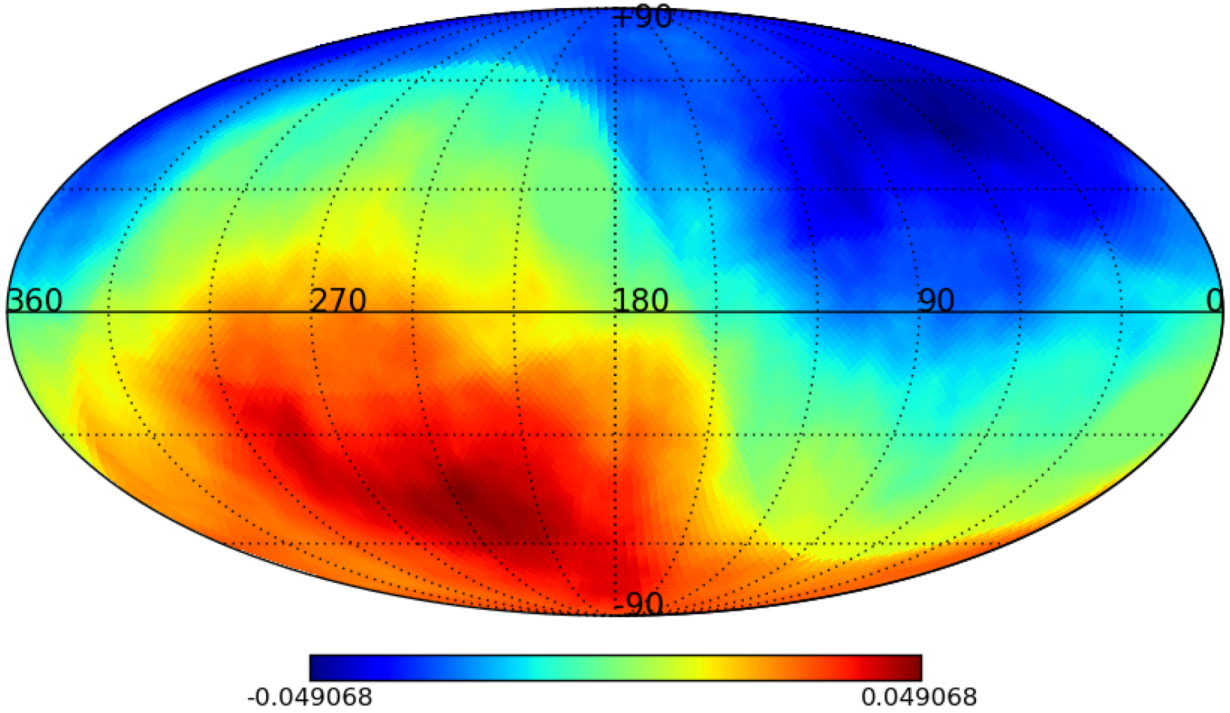
Directionally unbiased survey strategy, arc second angular resolution, multi band photometry.



Getting rid of the stars

following from MNRAS448,1305–1313 (2015)

- Magnitude cuts in different bands, Galactic plane cut at +/-15 degrees
  - Sample of 2.46 million Galaxies, 76% complete, with 1.8% star contamination



Cross correlate with deep surveys over a very narrow sky (SDSS, GAMA) to determine how many are stars and how many are Galaxies

The maximum is in the direction (AllWISE)
237.4° RA, -46.6 ° Dec
331.9° l 6.02° b

110 degrees from the CMB direction

Dipole magnitude ~0.049

Fully kinematic interpretation ~ 6000 km/s

in agreement with MNRAS 445 (2014) L60-L64

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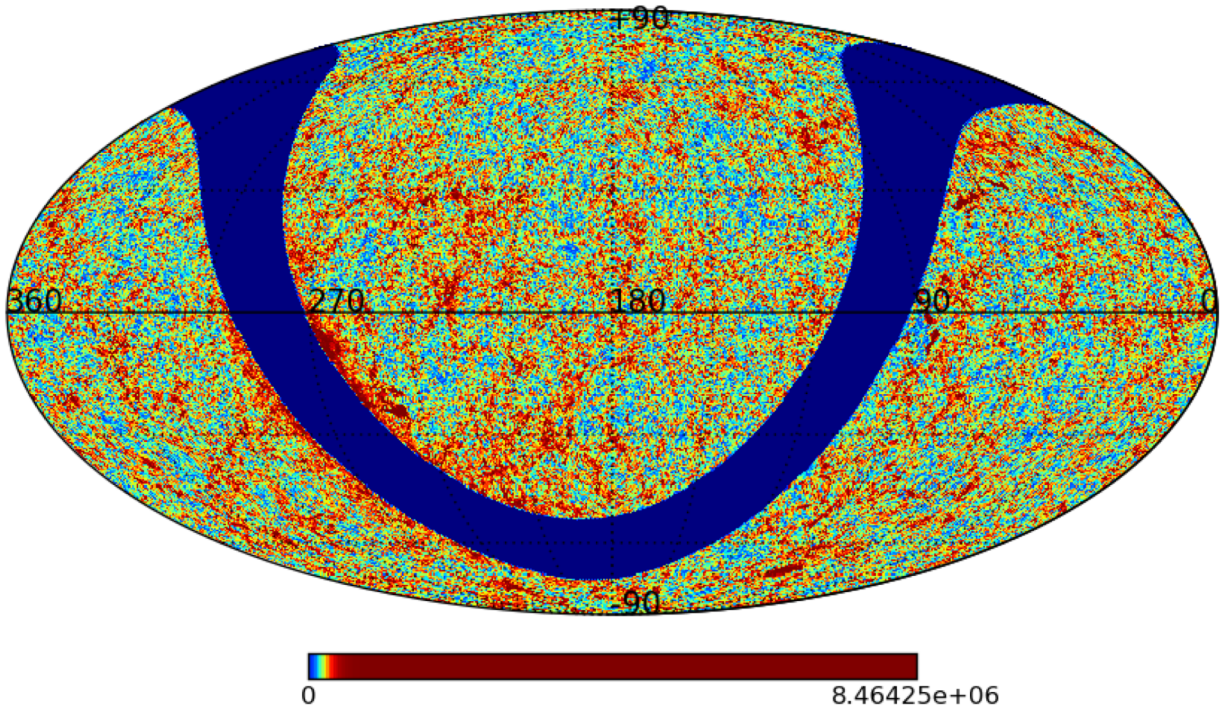

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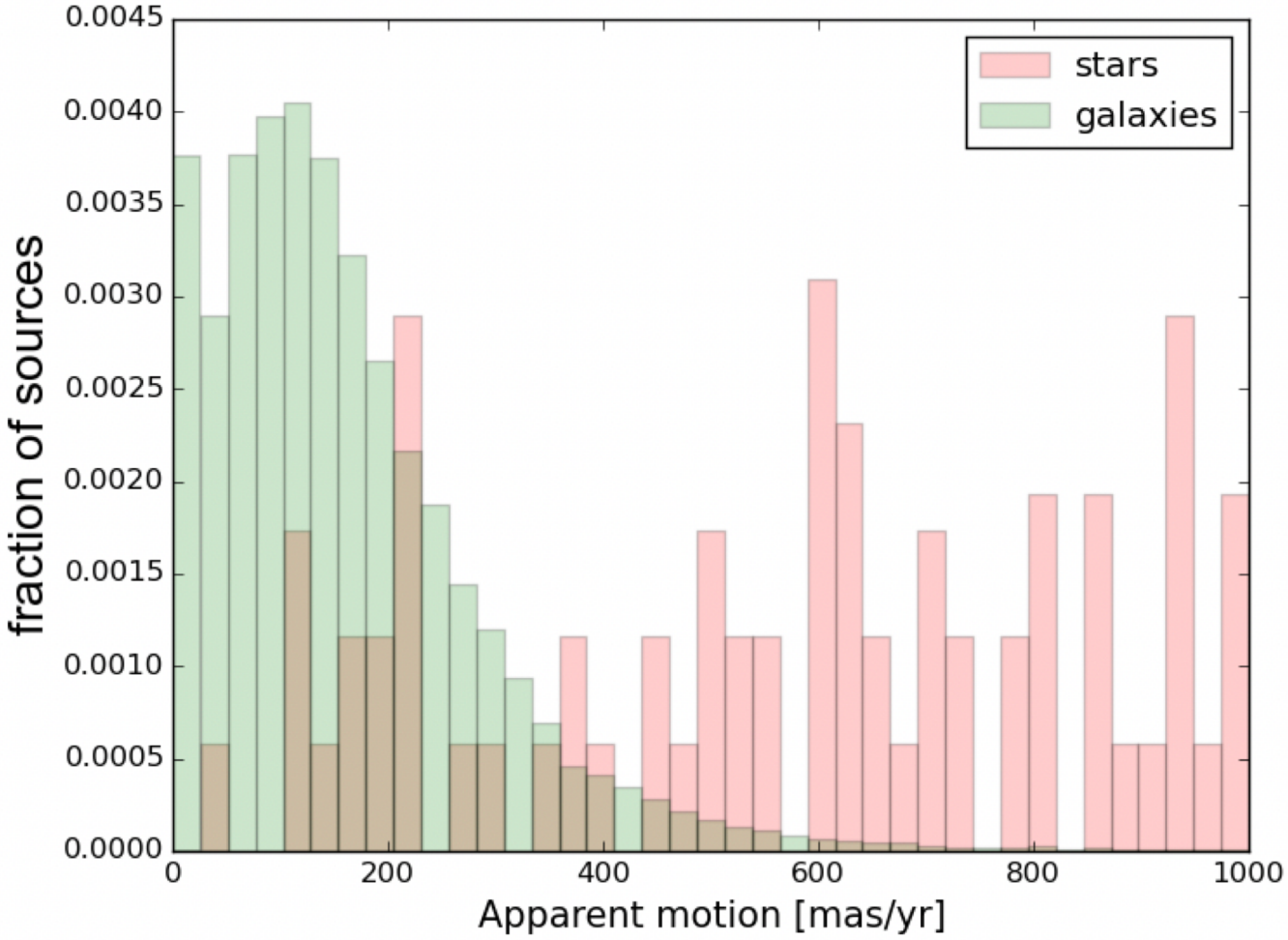
110 degrees from the CMB direction

Dipole magnitude ~0.049

Fully kinematic interpretation ~6000 km/s

in agreement with MNRAS 445 (2014) L60-L64

Getting rid of even more stars



Apparent motion = parallax + proper motion

Stars in the Galaxy have higher apparent motions 400 mas/yr up to many arc seconds/ year

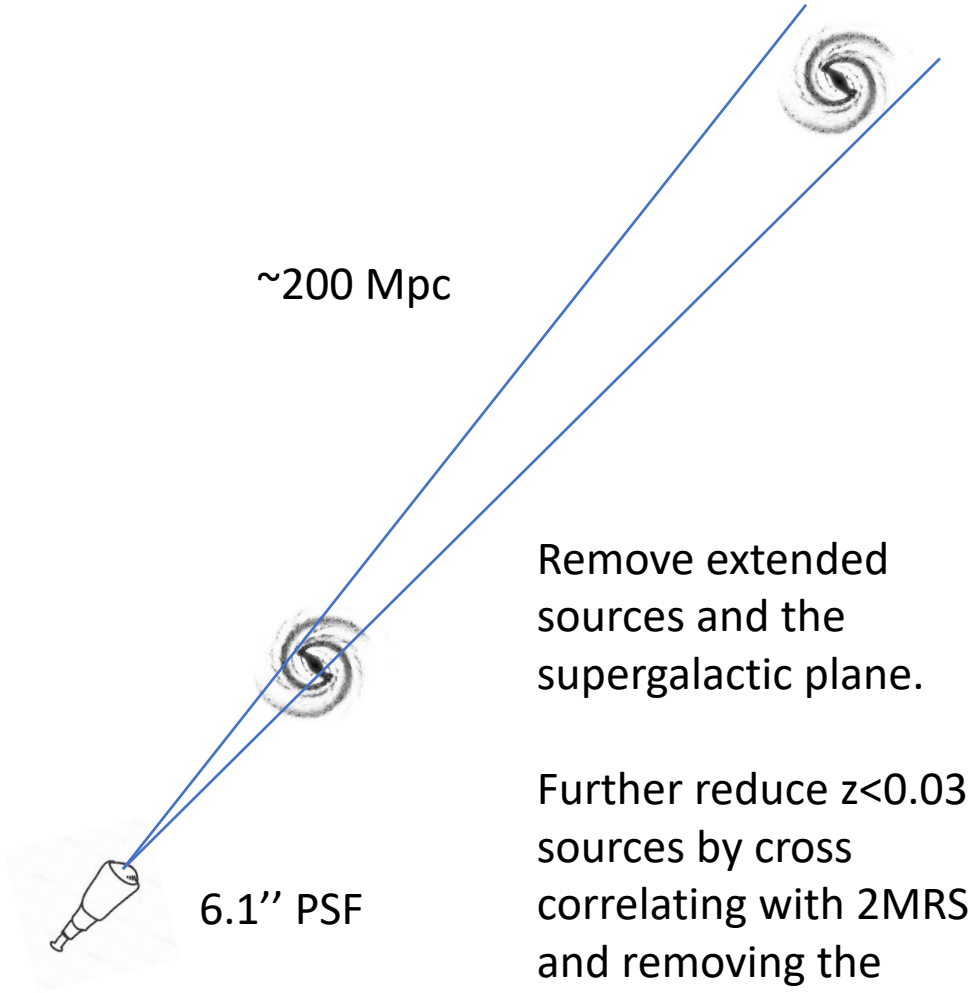
Cuts on apparent motion can bring star contamination down to 0.1%, while still keeping ~1.8 millin galaxies.

182.9° RA, -55.6° DEC, 50.1° from the CMB

Dipole magnitude reduces to 0.014

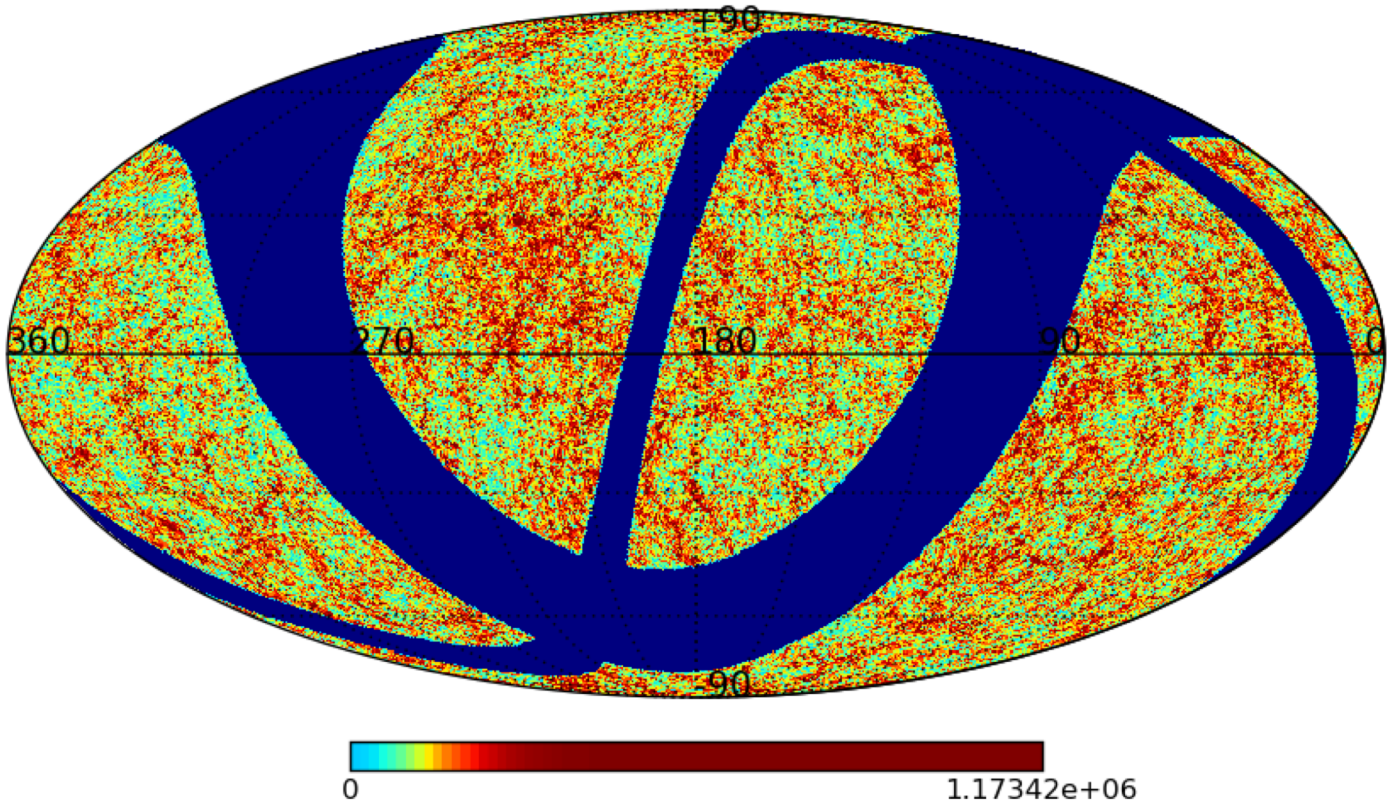
Star galaxy identification by cross correlating with SDSS

Suppressing local anisotropies

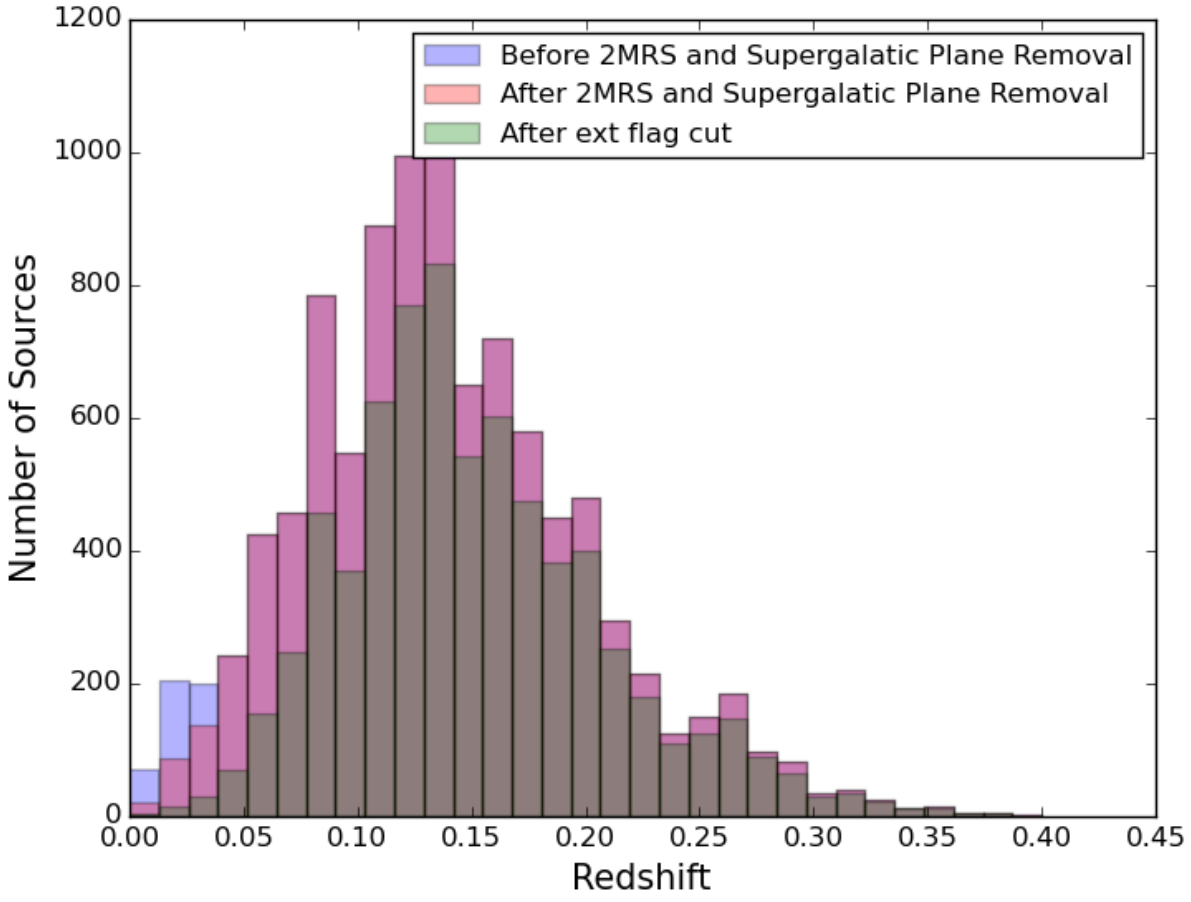


Remove extended sources and the supergalactic plane.

Further reduce z<0.03 sources by cross correlating with 2MRS and removing the correlated sources.



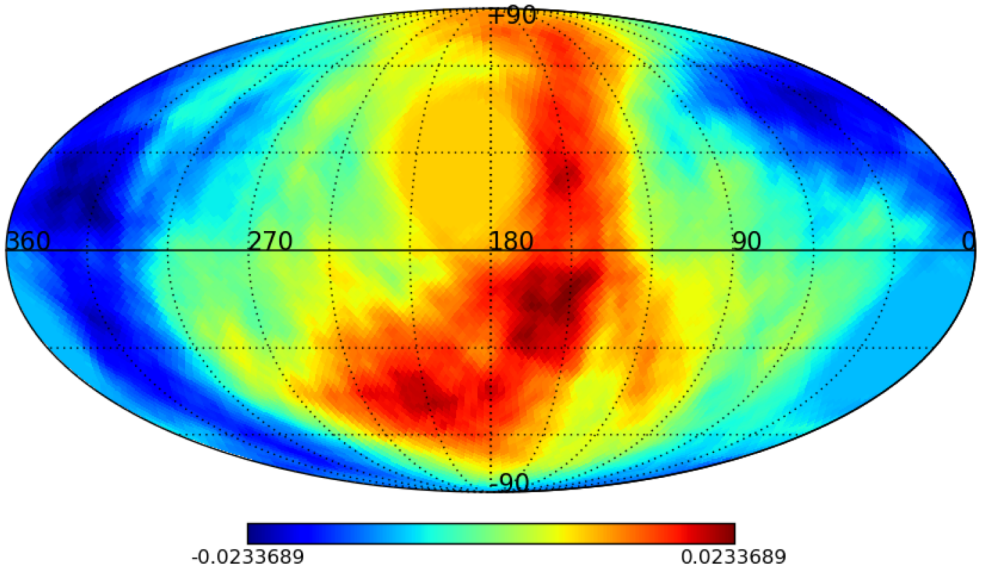
Redshift distribution of the sample



d = 0.0124 > 3600 km/s if fully kinematic

172.6° RA, -6.6° Dec (~4.5° from CMB)

Total dipole is at least 4.6σ statistically significant.



By cross correlating with Galaxy and Mass Assembly

Residual clustering dipole

- For a Copernican observer:
- $\langle D_{cls} \rangle = \sqrt{\frac{9}{4\pi} C_1}$
- $C_l = b^2 \frac{2}{\pi} \int_0^\infty f_l(k)^2 P(k) k^2 dk$
- $f_l(k) = \int_0^\infty j_l(kr) f(r) dr$
- $f(r) = \frac{H(z)}{H_0 r_0} \frac{dN}{dz}$

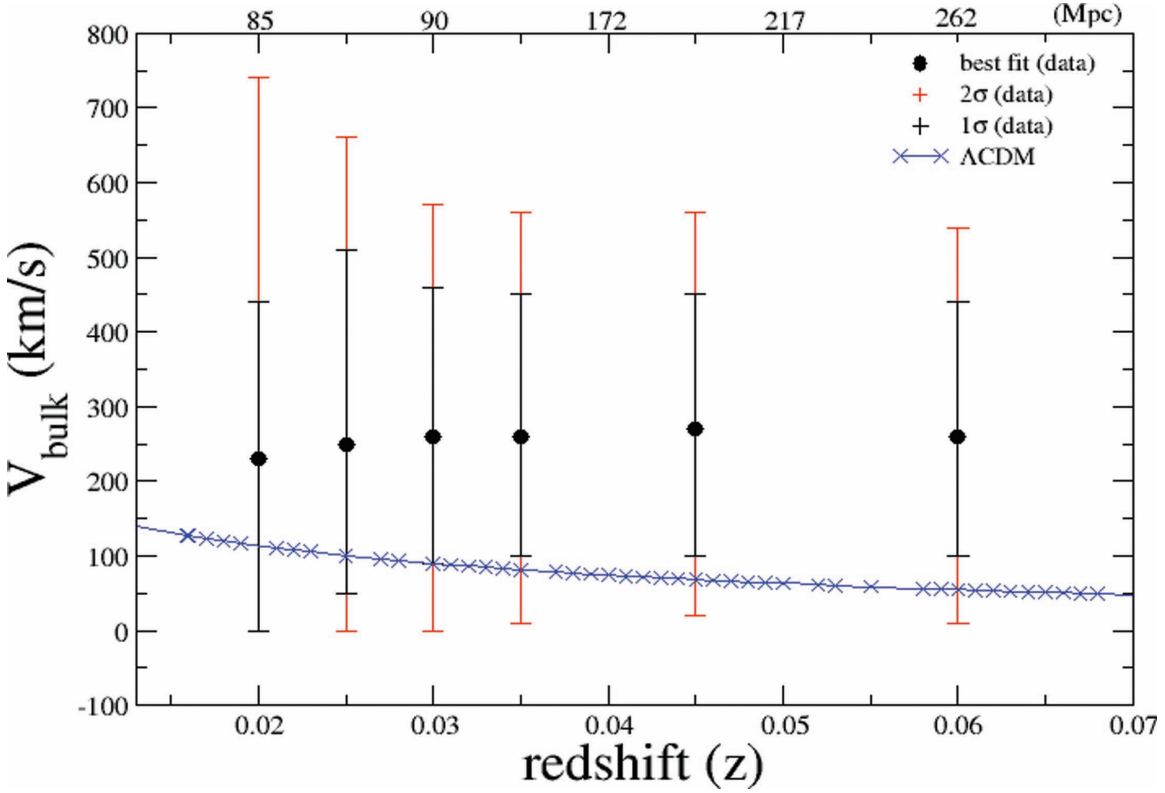
Using Planck 2015 cosmological parameters and astropy, using the the redshift distribution as dN/dz

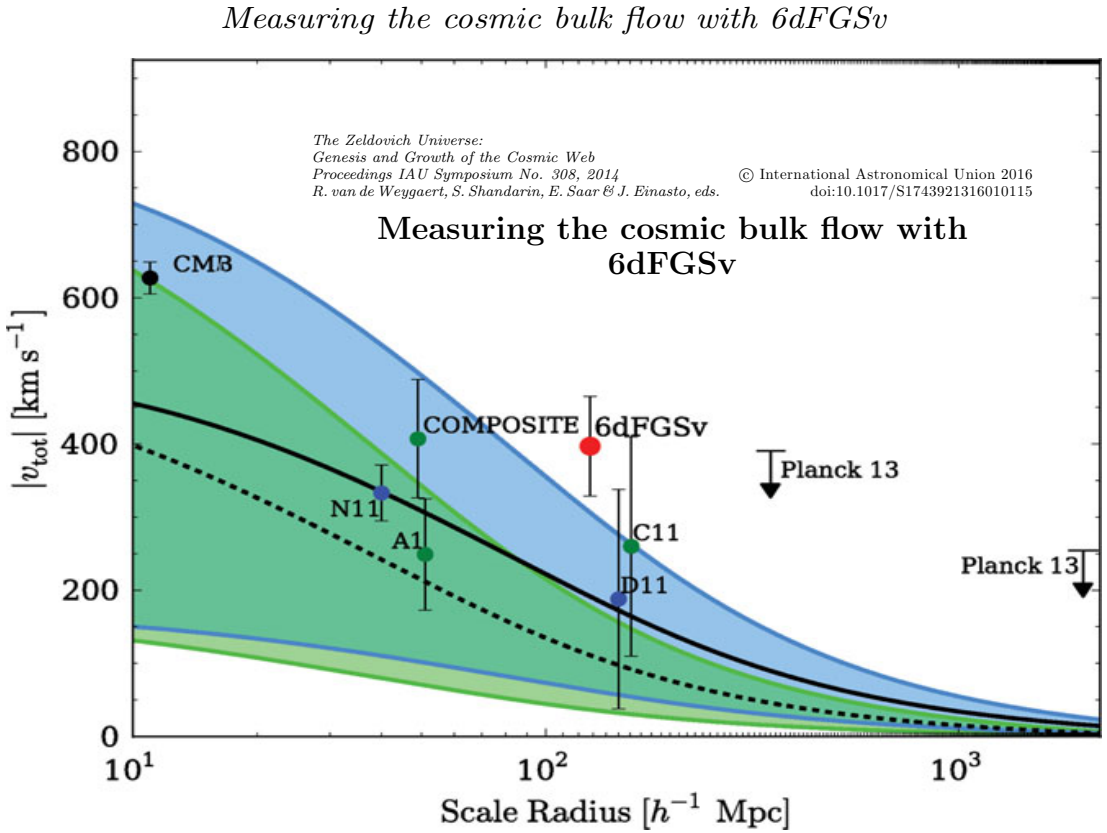
$\langle D_{cls} \rangle \quad < \ 0.0018$
In the final sample

$D_{kin} = 0.0106$

Velocity of ~3000 km/s

Hints that we are not a Copernican Observer

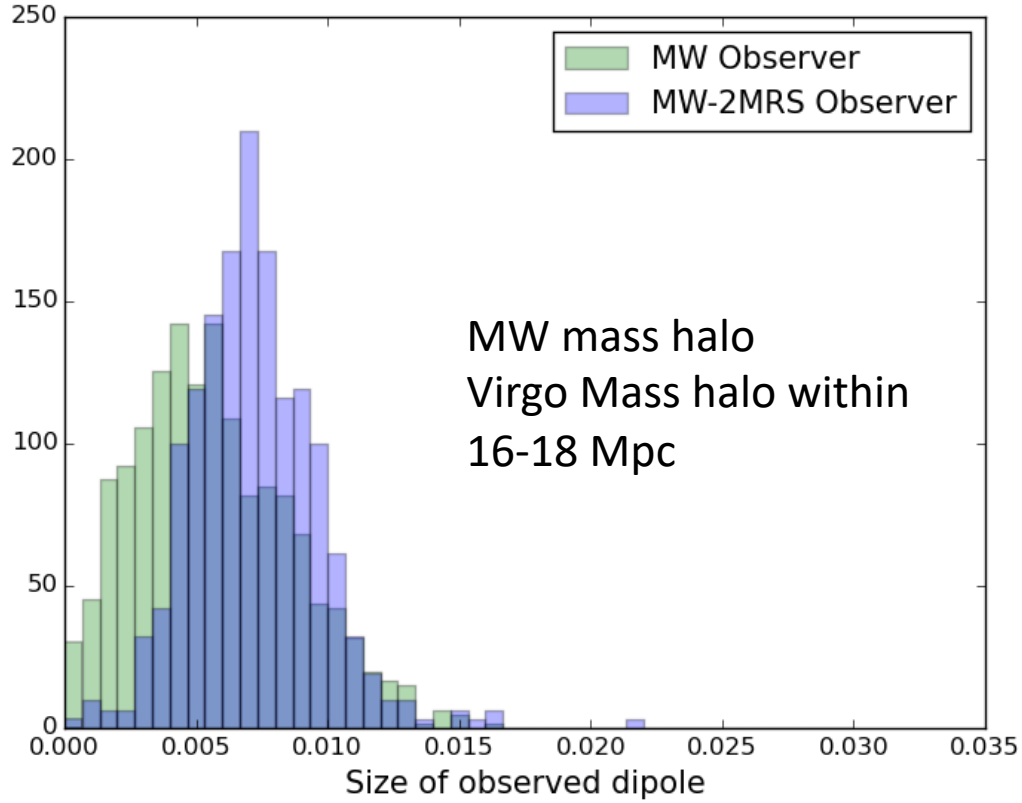


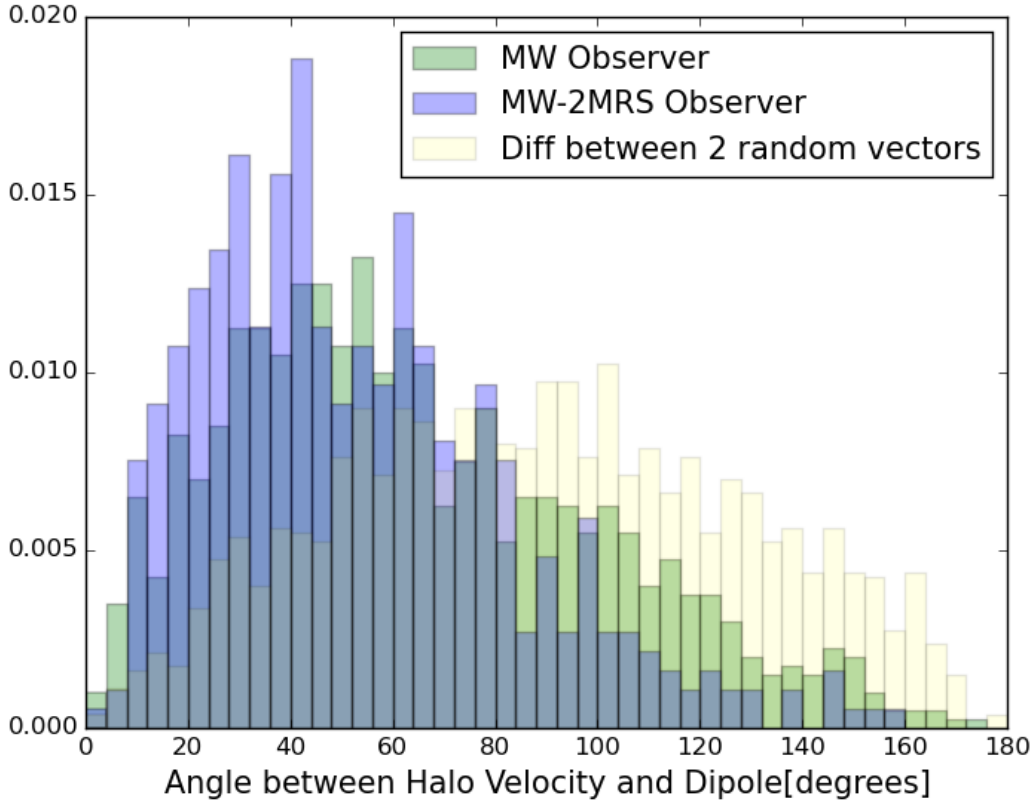


Colin J., Mohayaee R., Sarkar S. & Shafieloo A., 2011, MNRAS, 414, 264

Dark Sky N Body Simulations

First trillion particle simulation of the ΛCDM universe.





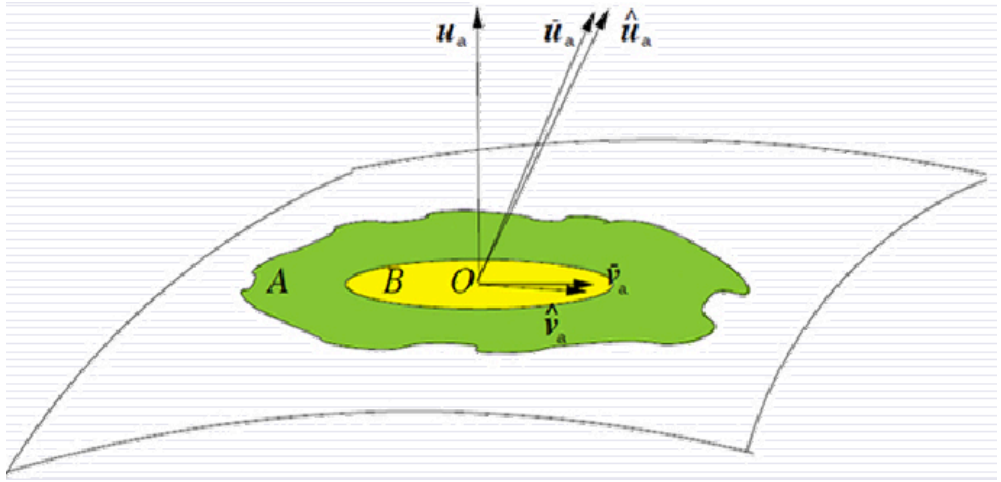
Only ~<1% of halos with MW-like mass and velocity are inside bulk flows > 240 km/s on scales exceeding 260 Mpcs

$\langle D_{cls} \rangle$ = 0.0076 +/- 0.0022

$\langle D_{kin} \rangle$ = 0.0048 +/- 0.0024

V = 1260 $\pm$ 629 km/s

The tilted Friedmann Universe



If we are inside a large local 'bulk flow'.

(Tsagas 2010, 2011, 2012; Tsagas & Kadiltzoglou 2015)

… if so there should be a dipole asymmetry in the inferred deceleration parameter in the same direction – i.e. towards the CMB dipole

The patch A has mean peculiar velocity $\tilde{v}_a$ with $\vartheta = \tilde{\mathrm{D}}^a v_a \gtrless 0$ and $\dot{\vartheta} \gtrless 0$
(the sign depending on whether the bulk flow is accelerating or decelerating)

Inside region B, the r.h.s. of the expression

$$1+\tilde{q} = (1+q)\left(1+\frac{\vartheta}{\Theta}\right)^{-2} - \frac{3\dot{\vartheta}}{\Theta^2}\left(1+\frac{\vartheta}{\Theta}\right)^{-2}, \quad \tilde{\Theta} = \Theta + \vartheta,$$

drops below 1 and the comoving observer 'measures' *negative* deceleration parameter in one direction of the sky

The FLRW Universe in Kinematics

"Cosmology is the search for two numbers. The Hubble parameter H_0 and the deceleration parameter q_0" – Alan Sandage

- $H = \frac{\dot{a}}{a}$
- $q \overset{\text{def}}{=} -\frac{\ddot{a}a}{\dot{a}^2}$ (defined with a minus to be positive for a decelerating universe)
- $j = \frac{\dddot{a}}{aH^3}$

$q = \frac{\Omega_M}{2} - \Omega_\Lambda$ (in ΛCDM)

Matt Visser 2004

$$d_L(z) = \frac{cz}{H_0}\left\{1 + \frac{1}{2}[1 - q_0]z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0 + \frac{kc^2}{H_0^2 a_0^2}\right]z^2 + O(z^3)\right\}$$

Tilt : $q_0 \rightarrow q_m + q_d \cos(\theta_{|cmb-SN|}) F(S)$

The Fitting problem

Ideal standard candle : No intrinsic dispersion

Ideal observations : No observational uncertainties

Each SC observation is a point in the D-z space.

Perfect FLRW Universe :

We need only 3 standard candle observations to estimate Ω_M, Ω_Λ to infinite precision.
Directions don't matter, redshift ranges don't matter.

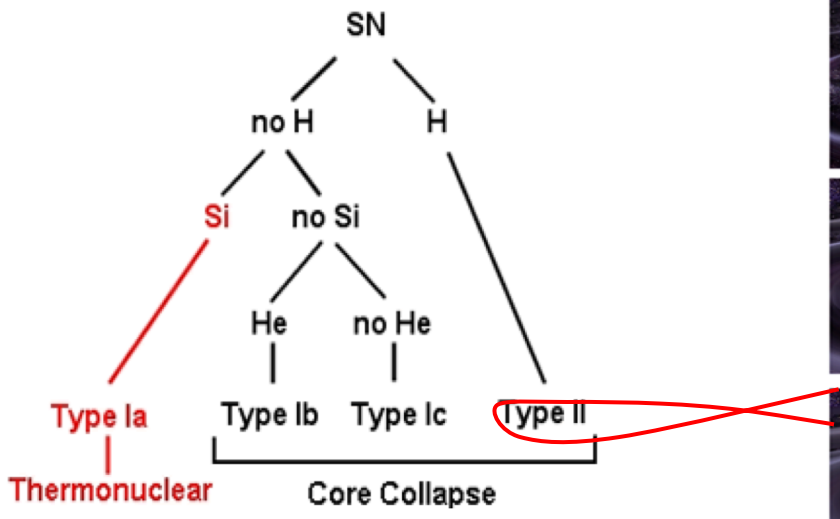
The real lumpy Universe (still ideal observations of ideal SCs) :

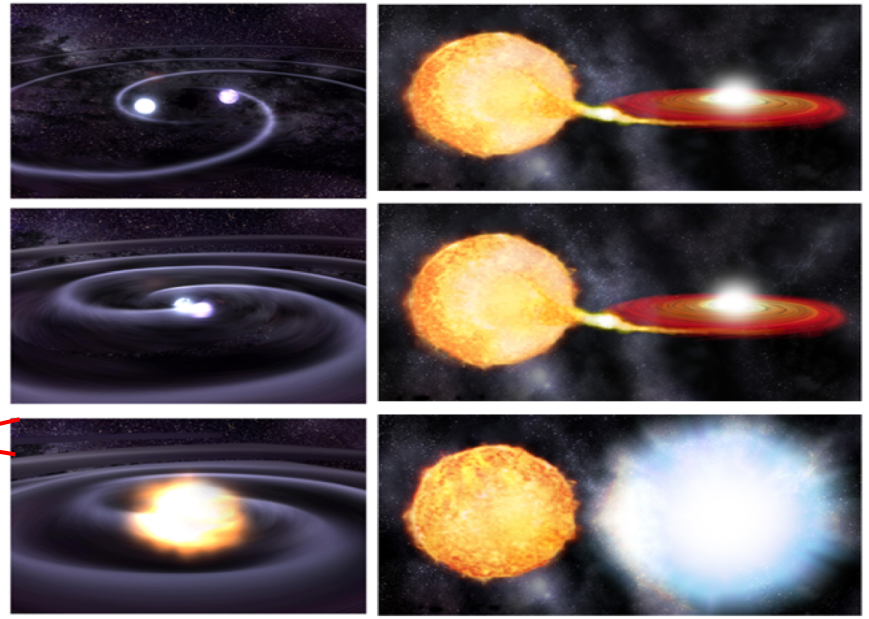
Are Ω_M, Ω_Λ inferred from 3 SCs observed in one specific direction in the sky and specific redshift range the same as those observed in another direction and redshift range?

How far out in redshift should we go before directions matter?

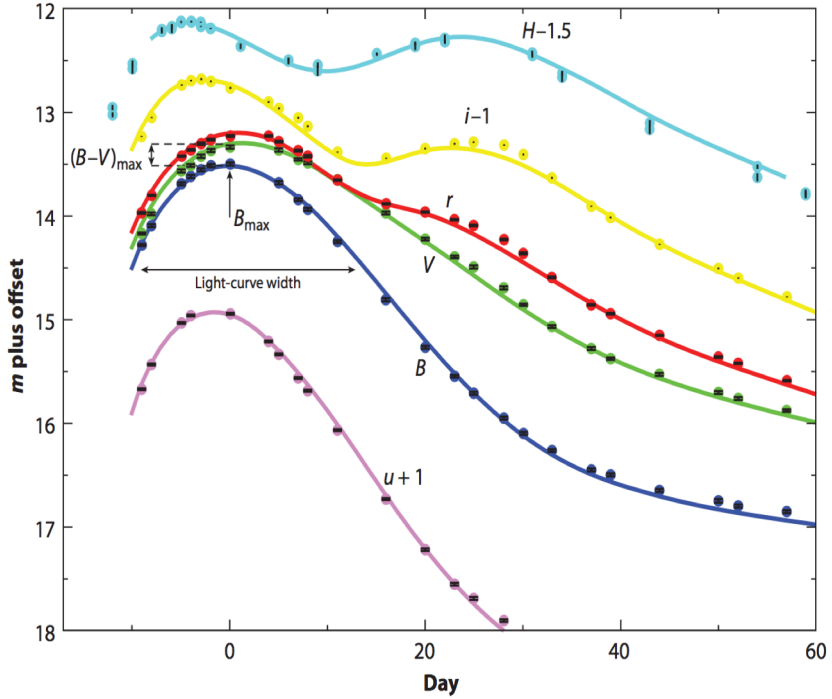
Real SNe data are a lot more complicated.

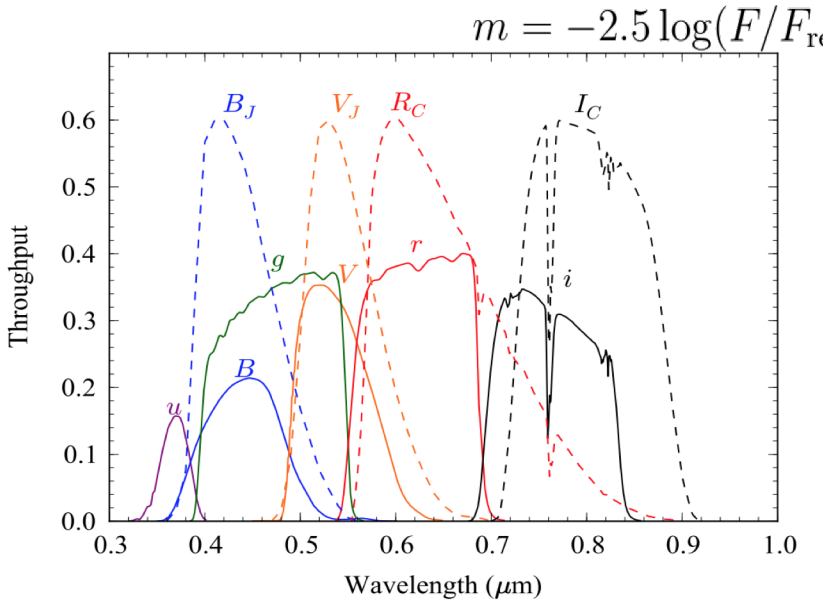
What are Type Ia supernovae?





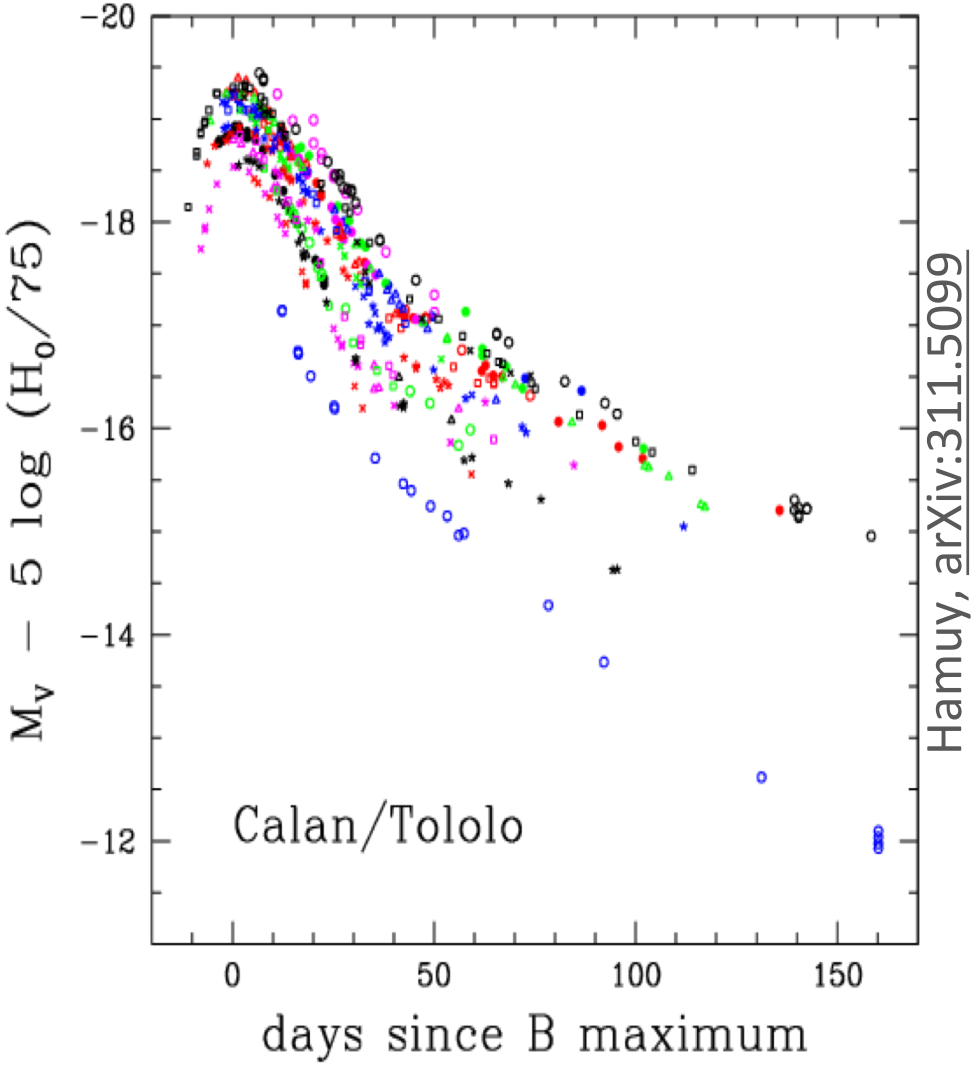
A white dwarf accreting matter from a binary companion, reignites when crossing ~1.44 Solar Masses



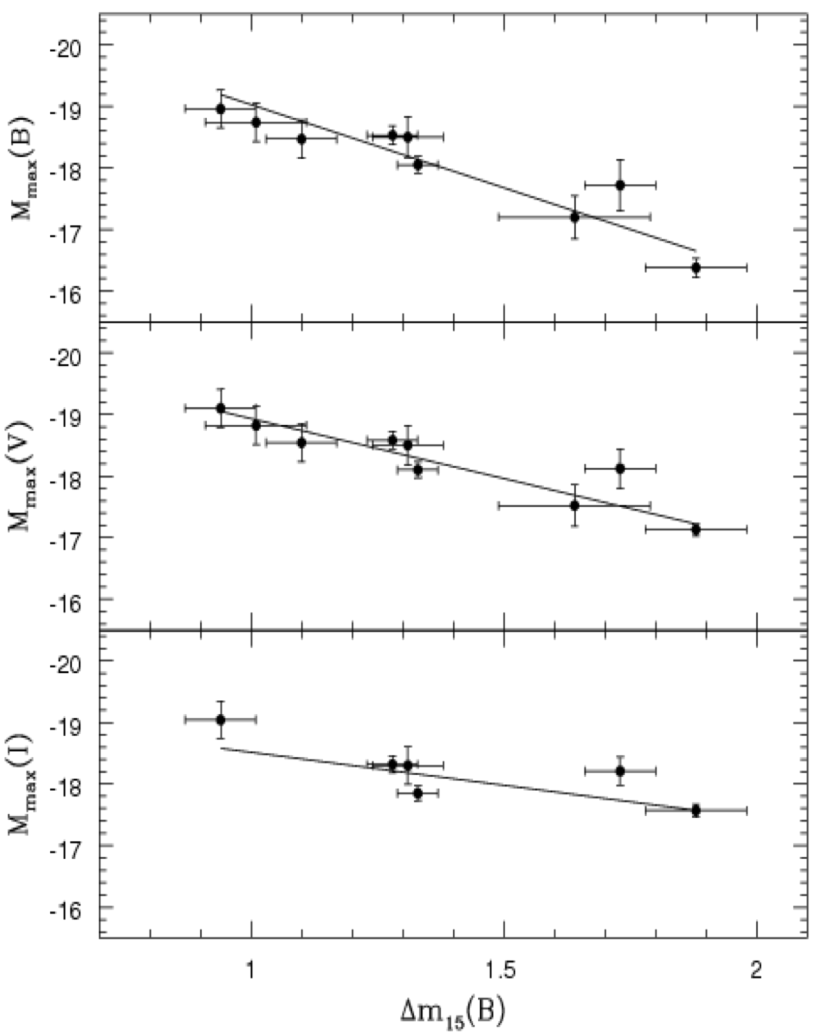


Goobar & Leibundgut, arXiv:1102.1431

They are certainly *not* 'standard candles'



Hamuy, arXiv:311.5099

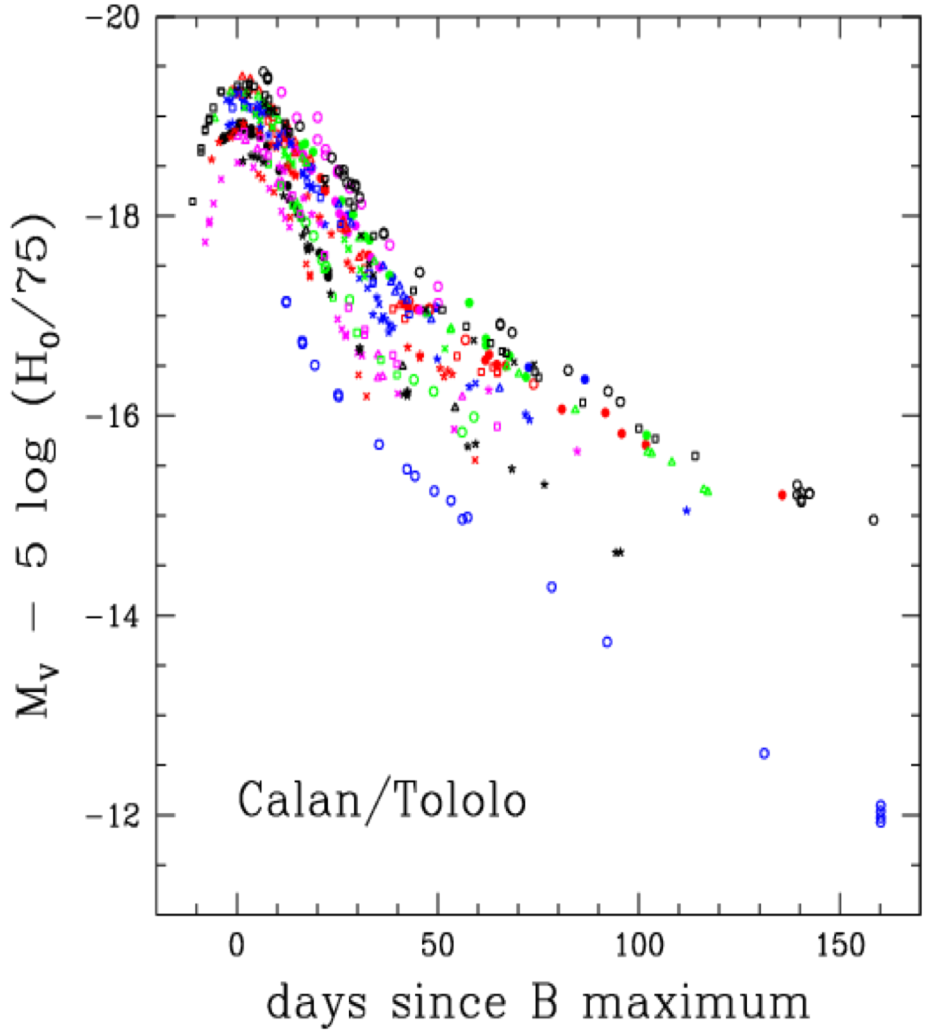


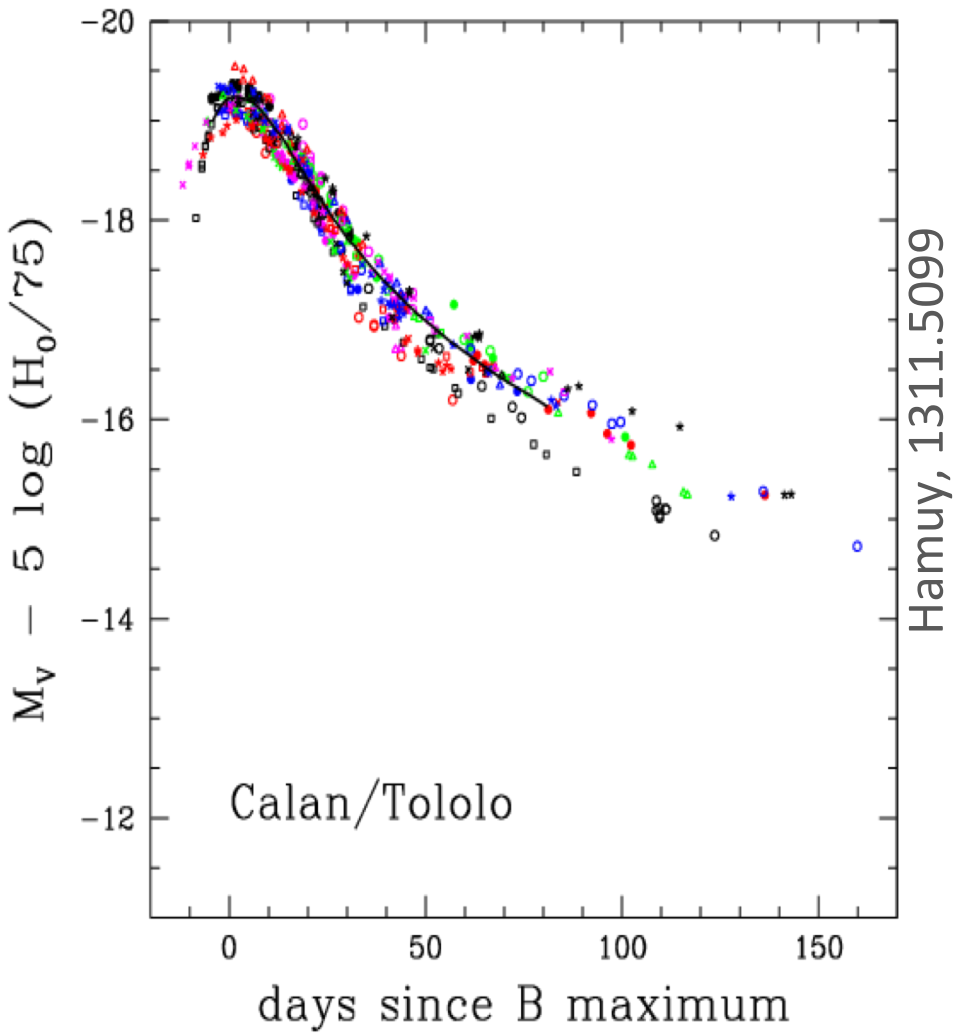
Phillips, ApJ **413**:L105, 1993

But they can be 'standardised' using the observed correlation between their peak magnitude and light-curve width (NB: this is *not* understood theoretically)

Type Ia supernovae as 'standardisable candles'

Corrected data





Hamuy, 1311.5099

Distance modulus $\mu_B = m_B^* - M + \alpha X_1 - \beta \mathcal{C}$ $= 25 + 5 \log_{10} \frac{d_L}{Mpc}$

Use a standard template (e.g. SALT 2) to make 'stretch' and 'colour' corrections …

Spectral Adaptive Lightcurve Template

(For making 'stretch' and 'colour' corrections to the observed lightcurves)

$$\mu_B = m_B^* - M + \alpha X_1 - \beta C$$

B-band

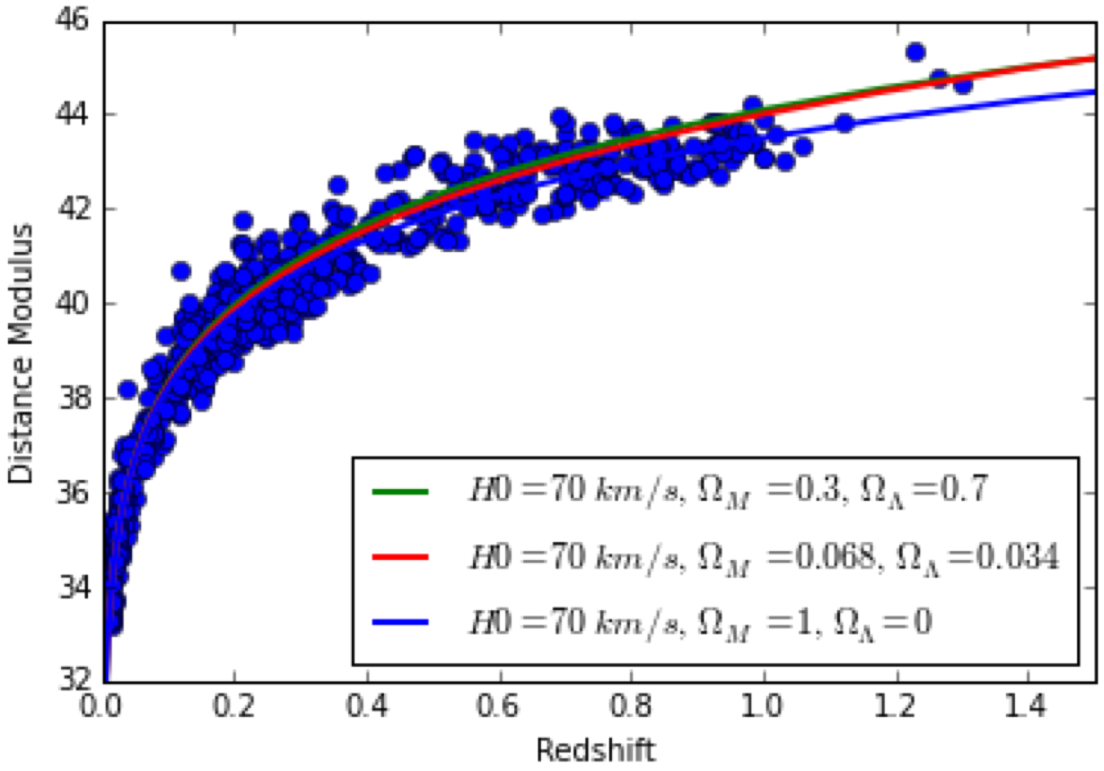
SALT 2 parameters

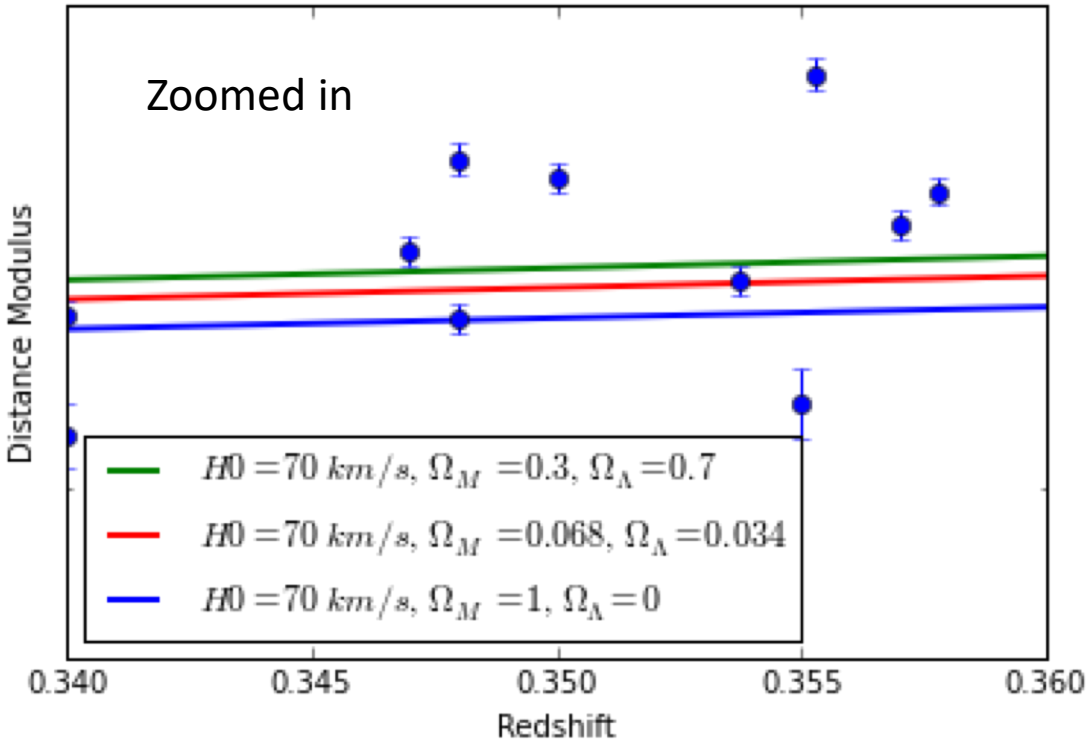
Betoule *et al.*, A&A **568**:A22,2014

Name	z_{cmb}	$m_B^\star$	X_1	C	$M_{stellar}$	?
03D1ar	0.002	23.941 ± 0.033	-0.945 ± 0.209	0.266 ± 0.035	10.1 ± 0.5	?
03D1au	0.503	23.002 ± 0.088	1.273 ± 0.150	-0.012 ± 0.030	9.5 ± 0.1	?
03D1aw	0.581	23.574 ± 0.090	0.974 ± 0.274	-0.025 ± 0.037	9.2 ± 0.1	?
03D1ax	0.495	22.960 ± 0.088	-0.729 ± 0.102	-0.100 ± 0.030	11.6 ± 0.1	?
03D1bp	0.346	22.398 ± 0.087	-1.155 ± 0.113	-0.041 ± 0.027	10.8 ± 0.1	?
03D1co	0.678	24.078 ± 0.098	0.619 ± 0.404	-0.039 ± 0.067	8.6 ± 0.3	?
03D1dt	0.611	23.285 ± 0.093	-1.162 ± 1.641	-0.095 ± 0.050	9.7 ± 0.1	
03D1ew	0.866	24.354 ± 0.106	0.376 ± 0.348	-0.063 ± 0.068	8.5 ± 0.8	
03D1fc	0.331	21.861 ± 0.086	0.650 ± 0.119	-0.018 ± 0.024	10.4 ± 0.0	
03D1fq	0.799	24.510 ± 0.102	-1.057 ± 0.407	-0.056 ± 0.065	10.7 ± 0.1	
03D3aw	0.450	22.667 ± 0.092	0.810 ± 0.232	-0.086 ± 0.038	10.7 ± 0.0	
03D3ay	0.371	22.273 ± 0.091	0.570 ± 0.198	-0.054 ± 0.033	10.2 ± 0.1	
03D3ba	0.292	21.961 ± 0.093	0.761 ± 0.173	0.116 ± 0.035	10.2 ± 0.1	
03D3bl	0.356	22.927 ± 0.087	0.056 ± 0.193	0.205 ± 0.030	10.8 ± 0.1	

There may well be other variables that the magnitude correlates with …

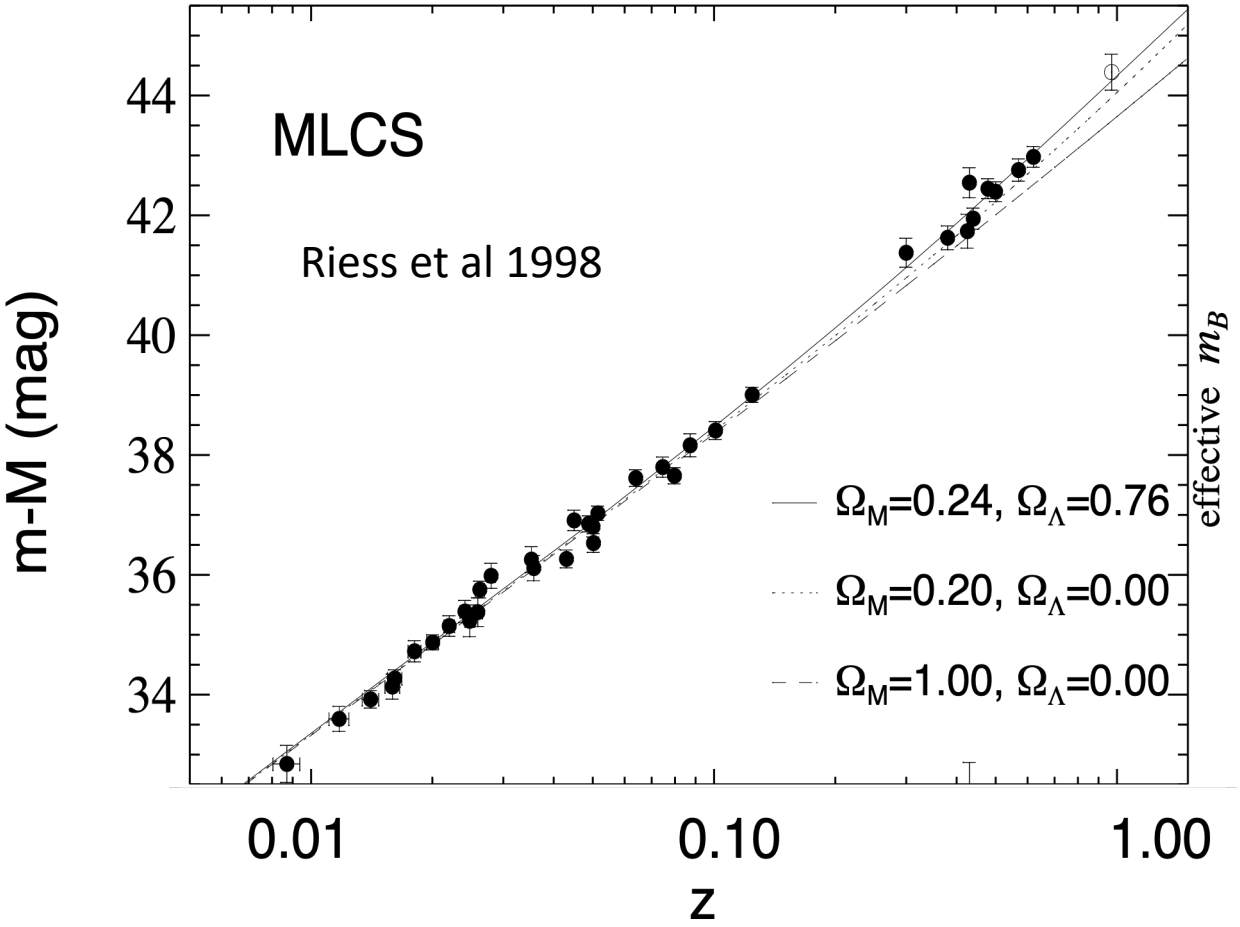
SNe Data and Cosmology

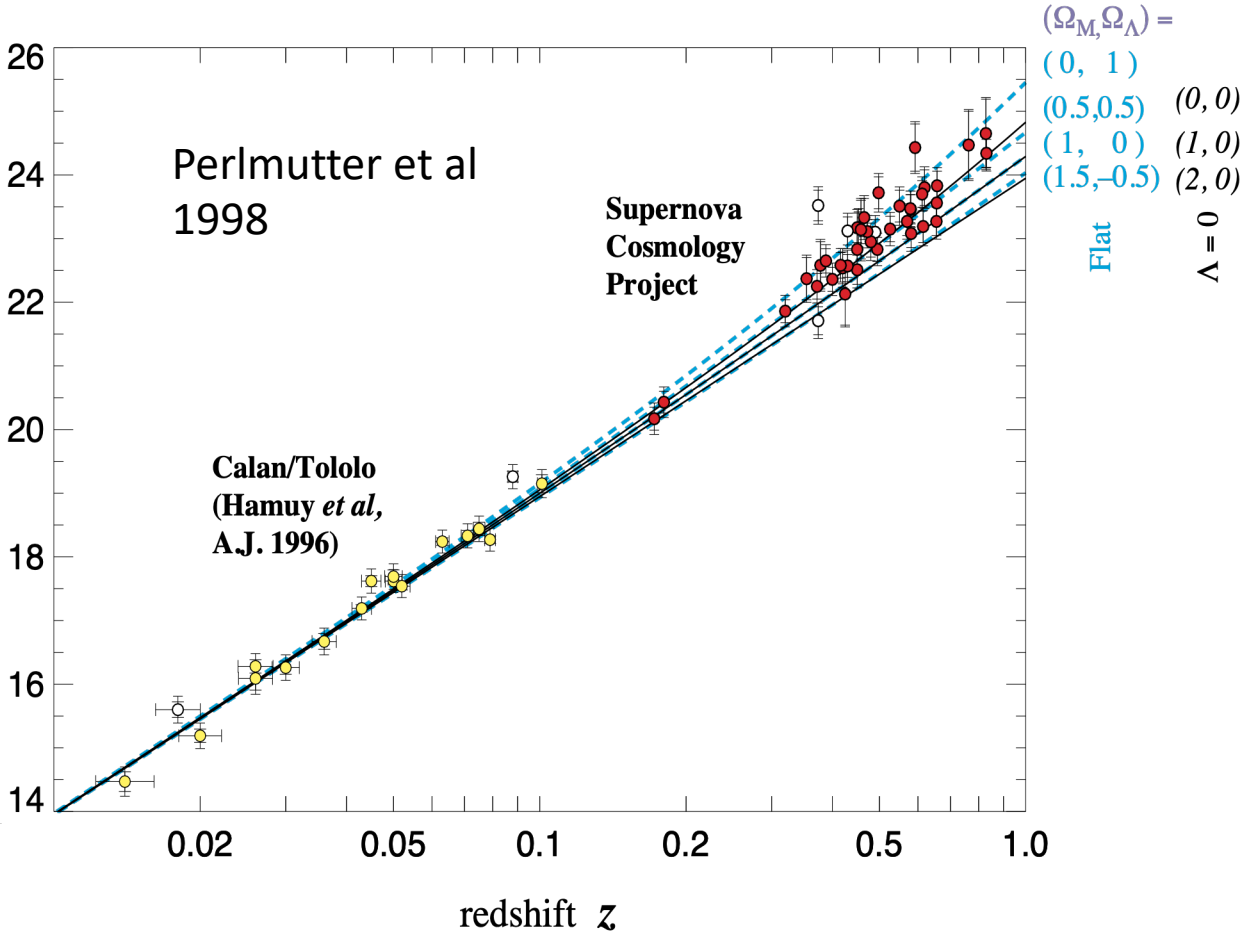




The data are intrinsically dispersed. The error bars have to be ‘enlarged’ by hand according to some statistical procedure.

SN1a breakthroughs history





No SN by SN peculiar velocity corrections in either. Null fitting.

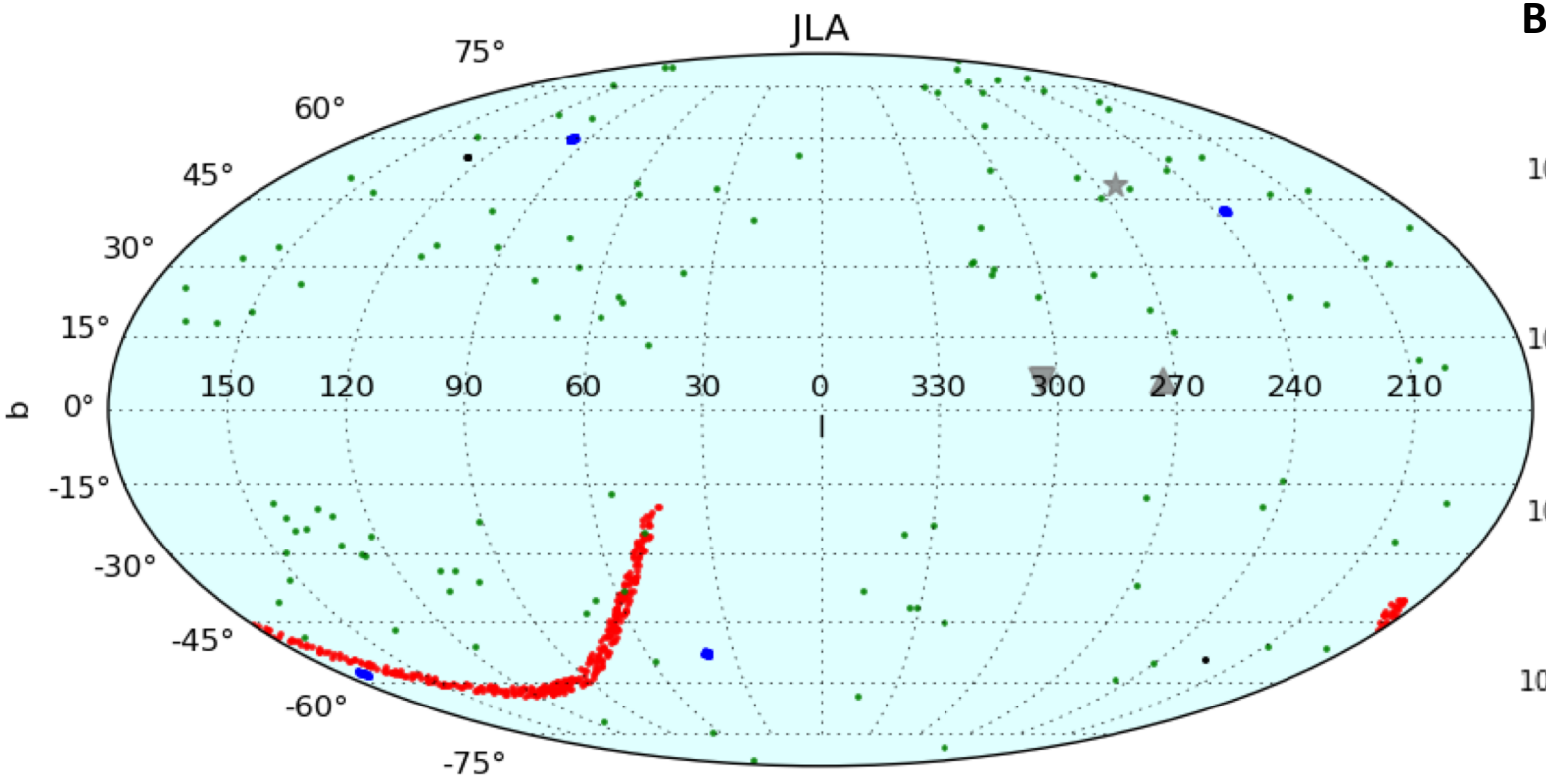
SN1a data fitting – the standard χ^2 Method

Karpenka, PhD Thesis : https://arxiv.org/pdf/1503.03844.pdf

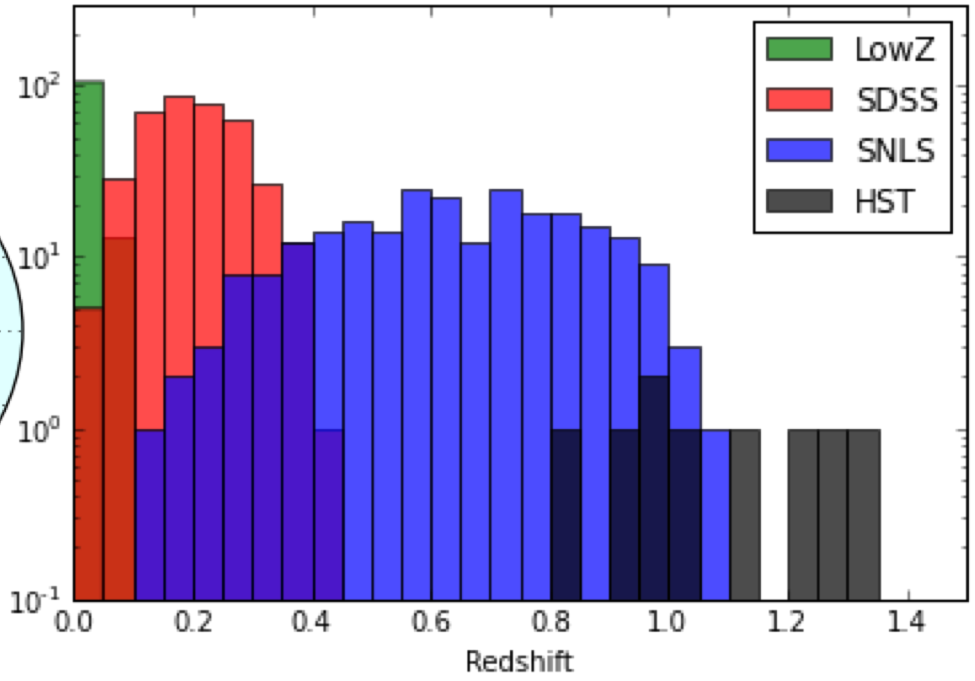
- $\chi^2(C, \alpha, \beta, M_0, \sigma_{int}) = \sum_{i=1}^{N_{SN}} \frac{\left[\mu_i^{obs}(\alpha,\beta,M_0) - \mu_i(C)\right]^2}{\sigma_i^2(\alpha,\beta,\sigma_{int})}$
- $\sigma_i^2 = \left(\sigma_{\mu,i}^z\right) + \sigma_{int}^2 + \sigma_{fit,i}^2(\alpha, \beta)$
- χ^2 is minimized w.r.t. C, α, β, M_0

  - Then σ_{int} is estimated by requiring that $\frac{\chi^2_{min}}{N_{dof}} \sim 1$
  - Not statistically well motivated, but based on empirical evidence and experience (Gull 1989)
  - Not suitable for model selection, only parameter estimation.

The Joint Lightcurve Analysis (JLA) Sample



Betoule et. al. Astron.Astrophys. 568 (2014) A22



The SDSSII/SNLSIII Joint Lightcurve Analysis (JLA) catalogue of SN1a
740 SN1a , 551 of which are in the hemisphere opp to the CMB motion
Redshifts corrected using SMAC, which has a bulk flow (gray triangle)
631 are in the opp hemisphere to SMAC BF

Peculiar velocity impact on SN1a magnitude

$$1 + z = (1 + \bar{z})\left(1 + z_{pec}^{hel}\right)\left(1 + z_{pec}^{SN}\right)$$

$$d_L(z) = \bar{d}_L(\bar{z})\left(1 + z_{pec}^{hel}\right)\left(1 + z_{pec}^{SN}\right)^2$$

Davis et. al. Astrophys.J. 741 (2011) 67

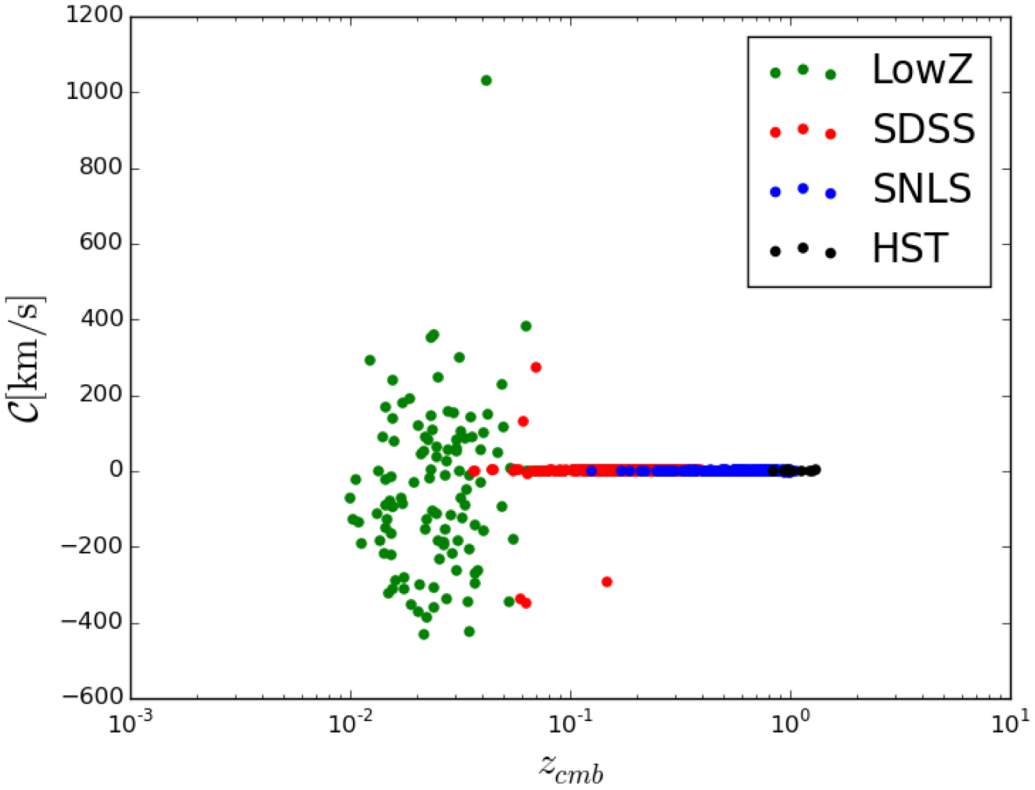
JLA (and Pantheon) redshifts and magnitudes have been corrected to account for the local bulk flow.

#name	zcmb	zhel	dz	mb	dmb	x1	dx1	color	dcolor
03D1au	0.503084	0.504300	0	23.001698	0.088031				
03D1aw	0.580724	0.582000	0	23.573937	0.090132				
03D1ax	0.494795	0.496000	0	22.960139	0.088110				
03D1bp	0.345928	0.347000	0	22.398137	0.087263				
03D1co	0.677662	0.679000	0	24.078115	0.098356				
03D1dt	0.610712	0.612000	0	23.285241	0.092877				
03D1ew	0.866494	0.868000	0	24.353678	0.106037				
03D1fc	0.330932	0.332000	0	21.861412	0.086437				
03D1fq	0.798566	0.800000	0	24.510389	0.101777				

$z_{hel} \rightarrow measured$

$z_{cmb} \rightarrow inferred\ using\ a\ flow\ model$

$$C = [(1 + z_{hel}) - (1 + z_{cmb})(1 + z_d)] \times c$$



SN1a at z>0.06 are assumed (arbitrarily) to be in the CMB rest frame. (only uncorrelated 150 km/s in error budget)
Wrong 'correction' to SDSS2308 in JLA. Many such mistakes in Pantheon (eg : SN2246).

Consequently, we use only z_{hel} and subtract out the corrections to m_B

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Davis et. al. Astrophys.J. 741 (2011) 67

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SMAC, Hudson et al MNRAS 352 61(2004)

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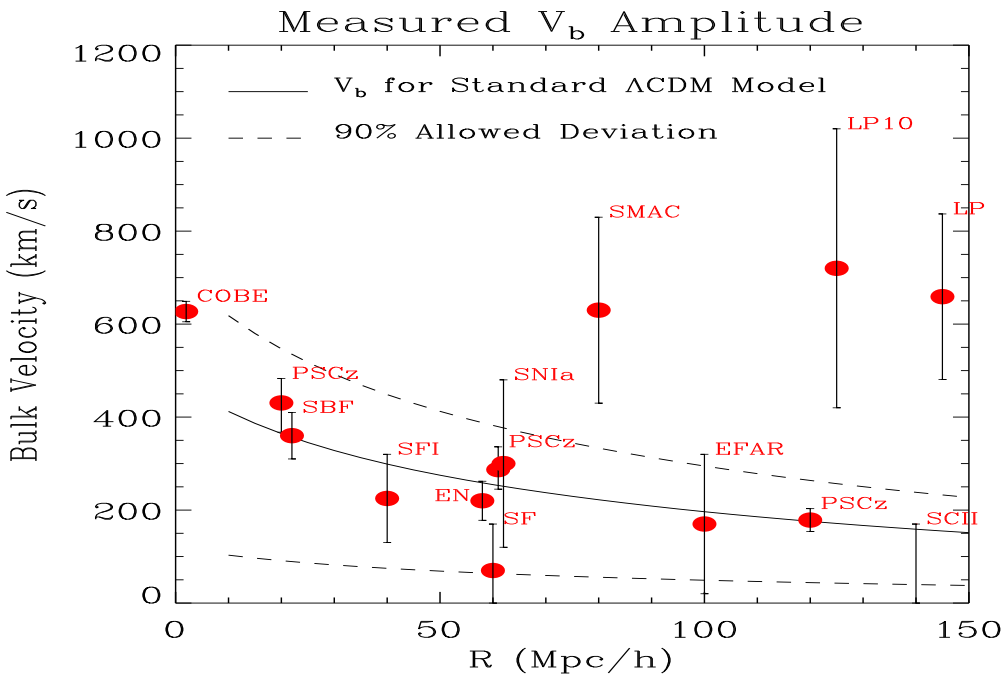

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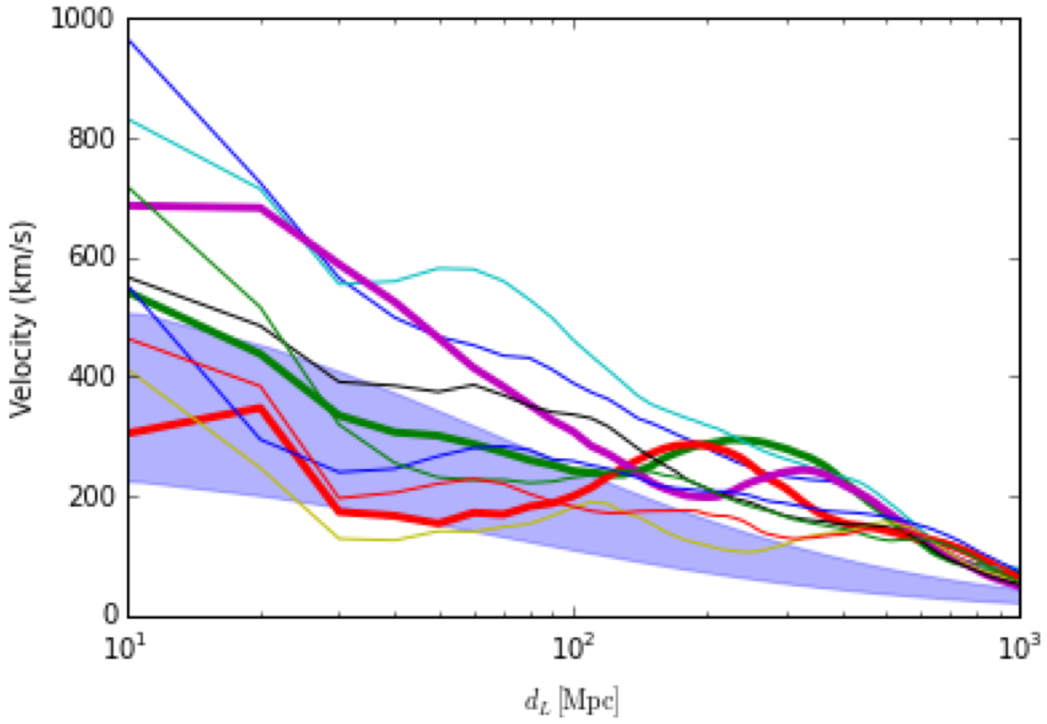

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Construct a Maximum Likelihood Estimator

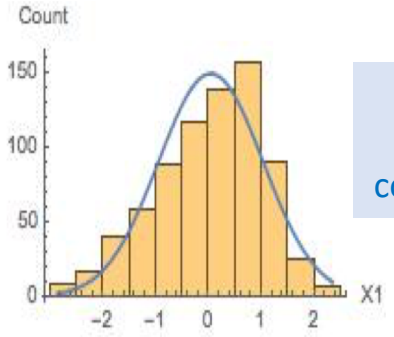
$$\mathcal{L} = \text{probability density}(\text{data}|\text{model})$$

$$\mathcal{L} = p[(\hat{m}_B^*, \hat{x}_1, \hat{c})|\theta]$$

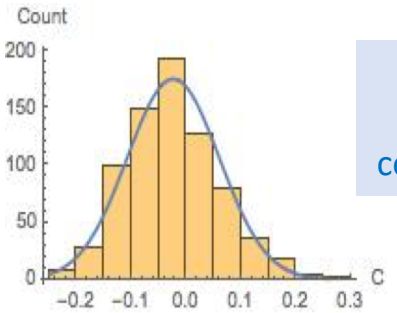
$$= \int p[(\hat{m}_B^*, \hat{x}_1, \hat{c})|(M, x_1, c), \theta_{\text{cosmo}}]$$

$$\times p[(M, x_1, c)|\theta_{\text{SN}}] dM dx_1 dc$$

Well-approximated as Gaussian



JLA data 'Stretch' corrections



JLA data 'Colour' corrections

$$p[(M, x_1, c)|\theta] = p(M|\theta)p(x_1|\theta)p(c|\theta),$$

$$p(M|\theta) = \frac{1}{\sqrt{2\pi\sigma_M^2}} \exp\left(-\left[\frac{M - M_0}{\sigma_{M0}}\right]^2 /2\right)$$

$$p(x_1|\theta) = \frac{1}{\sqrt{2\pi\sigma_{x0}^2}} \exp\left(-\left[\frac{x_1 - x_{10}}{\sigma_{x0}}\right]^2 /2\right)$$

$$p(c|\theta) = \frac{1}{\sqrt{2\pi\sigma_{c0}^2}} \exp\left(-\left[\frac{c - c_0}{\sigma_{c0}}\right]^2 /2\right)$$

Nielsen, Guffanti & Sarkar, Sci.Rep. **6**:35596,2016

Likelihood

$$p(Y|\theta) = \frac{1}{\sqrt{|2\pi\Sigma_l|}} \exp\left[-\frac{1}{2}(Y - Y_0)\Sigma_l^{-1}(Y - Y_0)^{\mathrm{T}}\right]$$

$$p(\hat{X}|X,\theta) = \frac{1}{\sqrt{|2\pi\Sigma_d|}} \exp\left[-\frac{1}{2}(\hat{X} - X)\Sigma_d^{-1}(\hat{X} - X)^{\mathrm{T}}\right]$$

$$\mathcal{L} = \frac{1}{\sqrt{|2\pi(\Sigma_d + A^{\mathrm{T}}\Sigma_l A)|}} \times \exp\left(-\frac{1}{2}(\hat{Z} - Y_0 A)(\Sigma_d + A^{\mathrm{T}}\Sigma_l A)^{-1}(\hat{Z} - Y_0 A)^{\mathrm{T}}\right)$$

intrinsic distributions

cosmology

SALT2

Simultaneously fit for

q_m
$j_0 - \Omega_k$
q_d
S
α
$x_{1,0}$
$\sigma_{x_{1,0}}$
β
c_0
σ_{c_0}
M_0
σ_{M_0}

Confidence regions

$$p_{\mathrm{cov}} = \int_0^{-2\log\mathcal{L}/\mathcal{L}_{\max}} \chi^2(x;\nu)dx$$

$$\mathcal{L}_p(\theta) = \max_{\phi} \mathcal{L}(\theta,\phi)$$

1,2,3-sigma

solve for Likelihood value

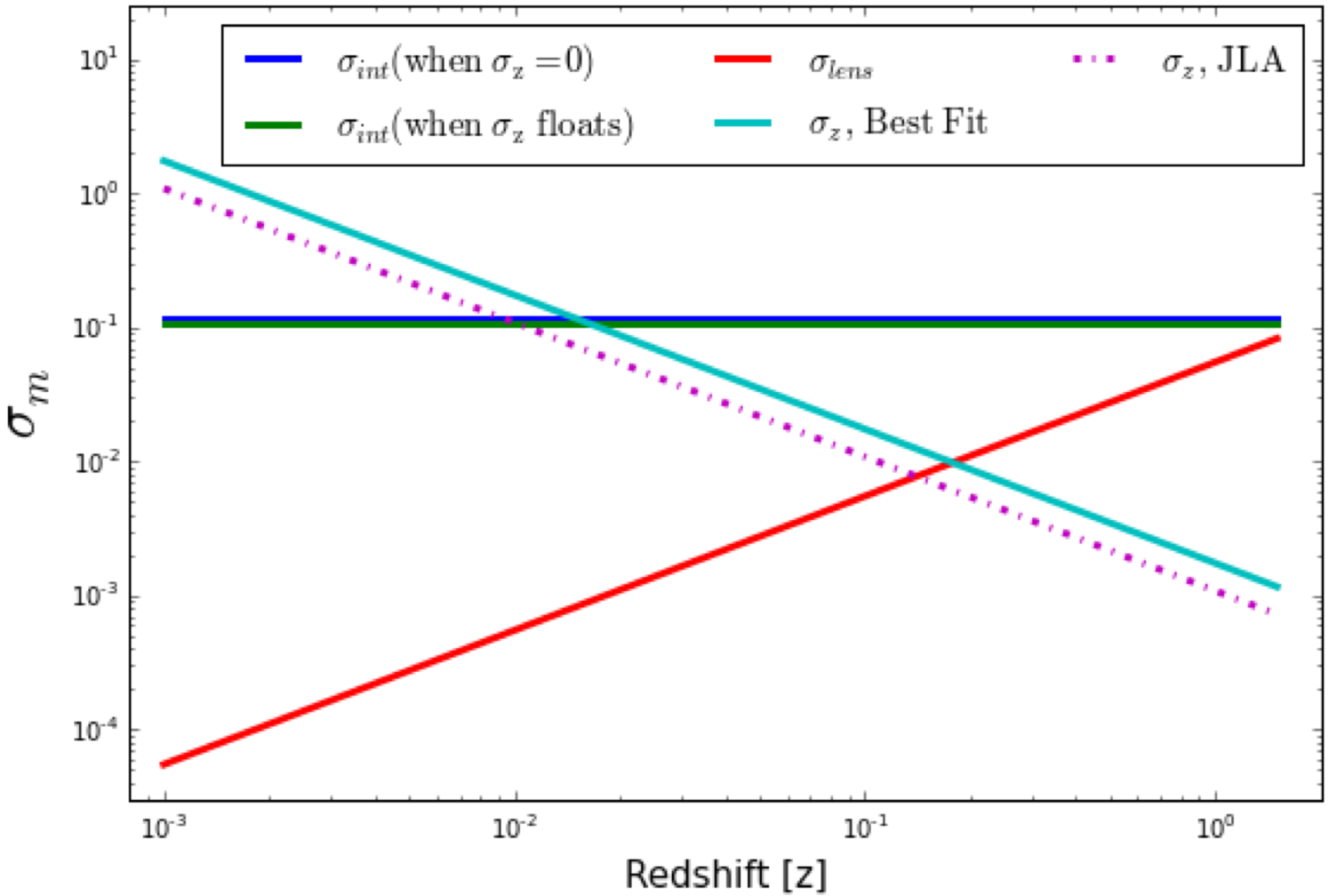
Error budget

$$\Sigma_d = \Sigma_{stat} + \Sigma_{syst}$$

$$\Sigma_{syst} = \Sigma_{cal} + \Sigma_{model} + \Sigma_{dust} + \Sigma_{lens} + \Sigma_{pecvel} + \Sigma_z$$

Observational, imposed.

Imposed dispersions



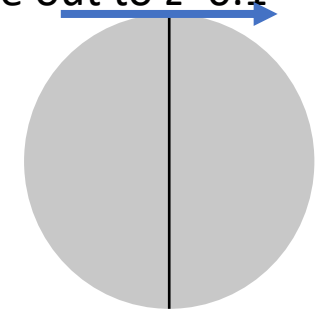
Results strongly depend on imposed uncertainties.

Results

Table 1: The tilted local universe, with $c\sigma_z = 0$.

	$-2\log\mathcal{L}_{max}$	q_m	q_d	S	$j_0 - \Omega_k$	α	$x_{1,0}$	$\sigma_{x_{1,0}}$	β	c_0	σ_{c_0}	M_0	σ_{M_0}
Tilted local universe	-208.28	-0.157	-8.03	0.0262	-0.489	0.135	0.0394	0.931	2.998	-0.0155	0.071	-19.027	0.114
„ - No Tilt ($q_d = 0$)	-189.52	-0.166	0	-	-0.460	0.133	0.0396	0.931	2.994	-0.014	0.071	-19.028	0.117
„ - No Acc ($\Omega_M/2 - \Omega_\Lambda = 0$)	-205.98	0	-6.84	0.0384	-0.836	0.134	0.0365	0.931	2.991	-0.014	0.071	-19.002	0.115

The dipolar component of q (-8) is larger than the monopole, and dominate out to z~0.1



Decelerating Universe out to z~0.1

Accelerating Universe

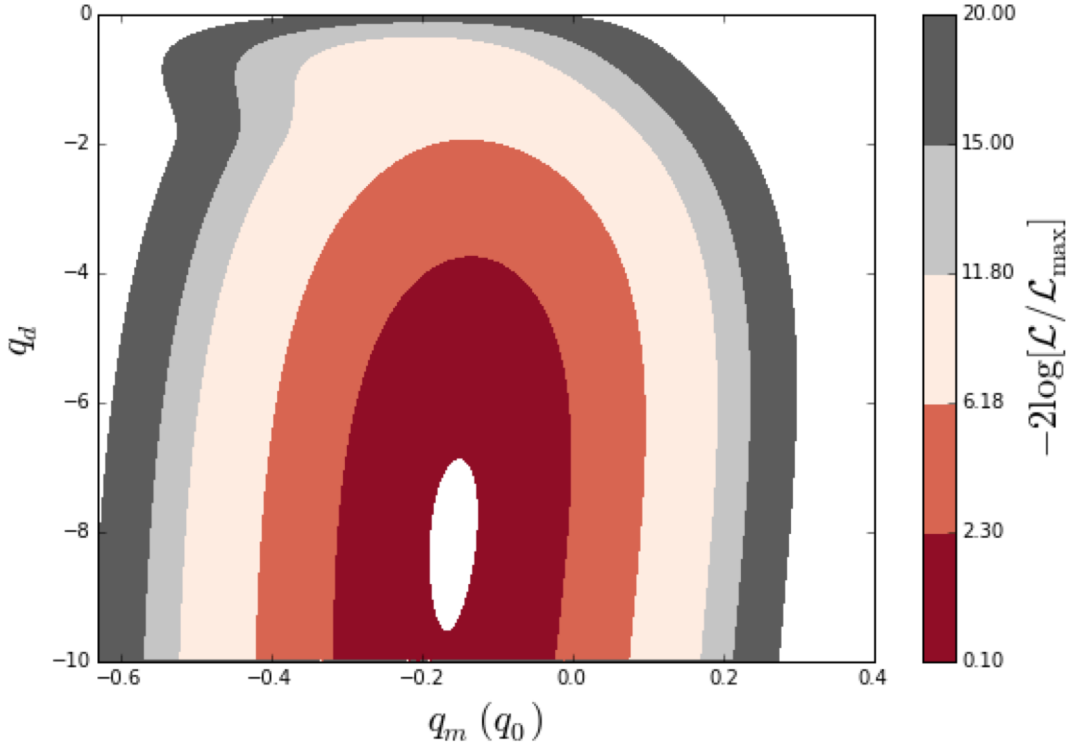
$q_d > q_m$

q_d = -8.0 , <0 at ~3.9 sigma statistical significance

The significance of q_o being negative is only 1.3σ!

Result favours lower instrinsic dispersion

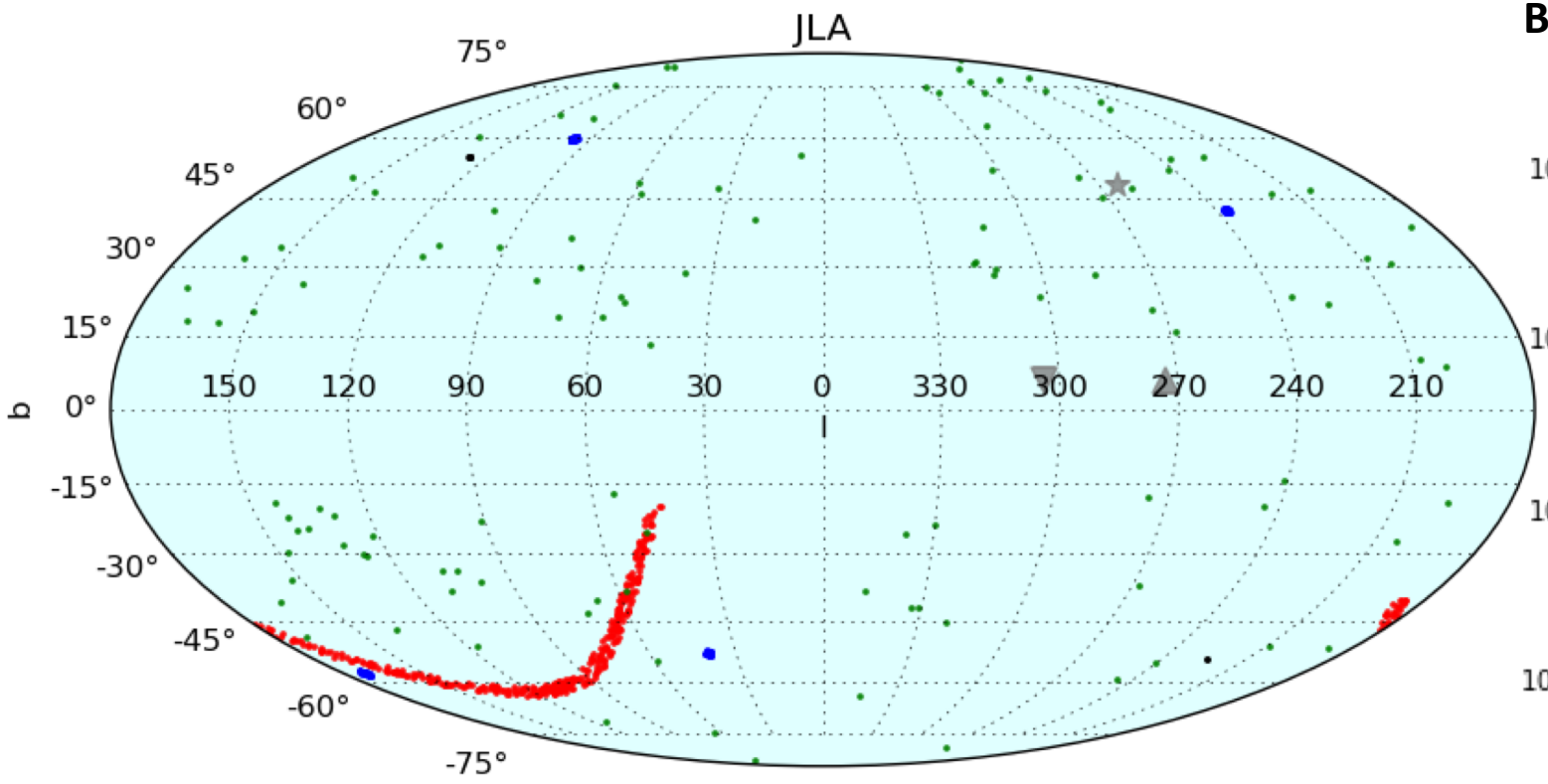
In preparation



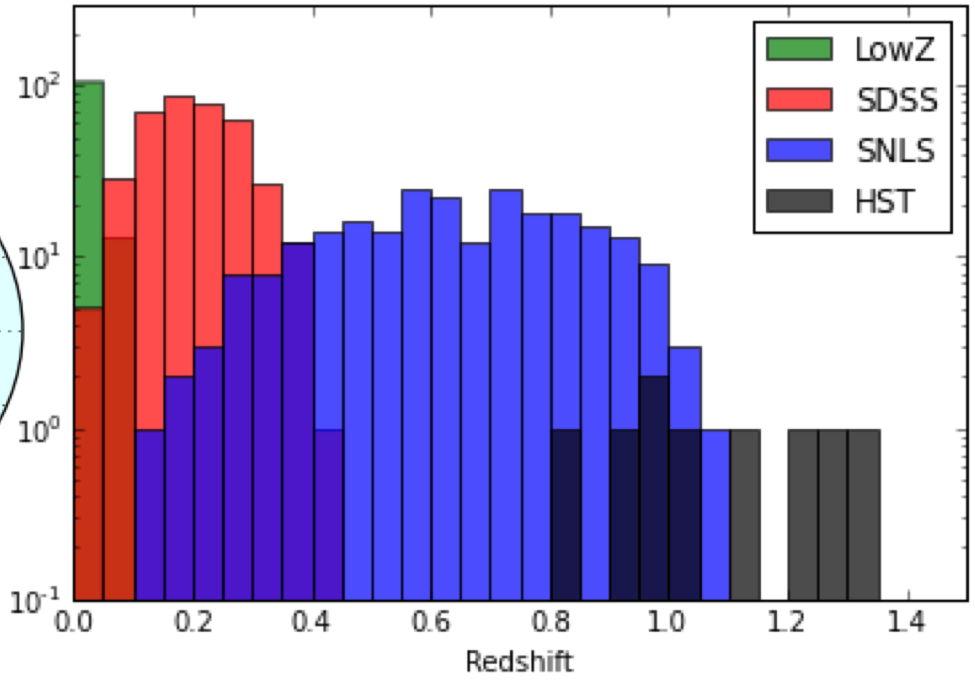
Cosmic acceleration may simply be an artefact of our being located inside a 'bulk flow'!
(and looking mostly only in one direction)

But of course, all these results assume the data are reliable!

Bizarre things about SN1a data



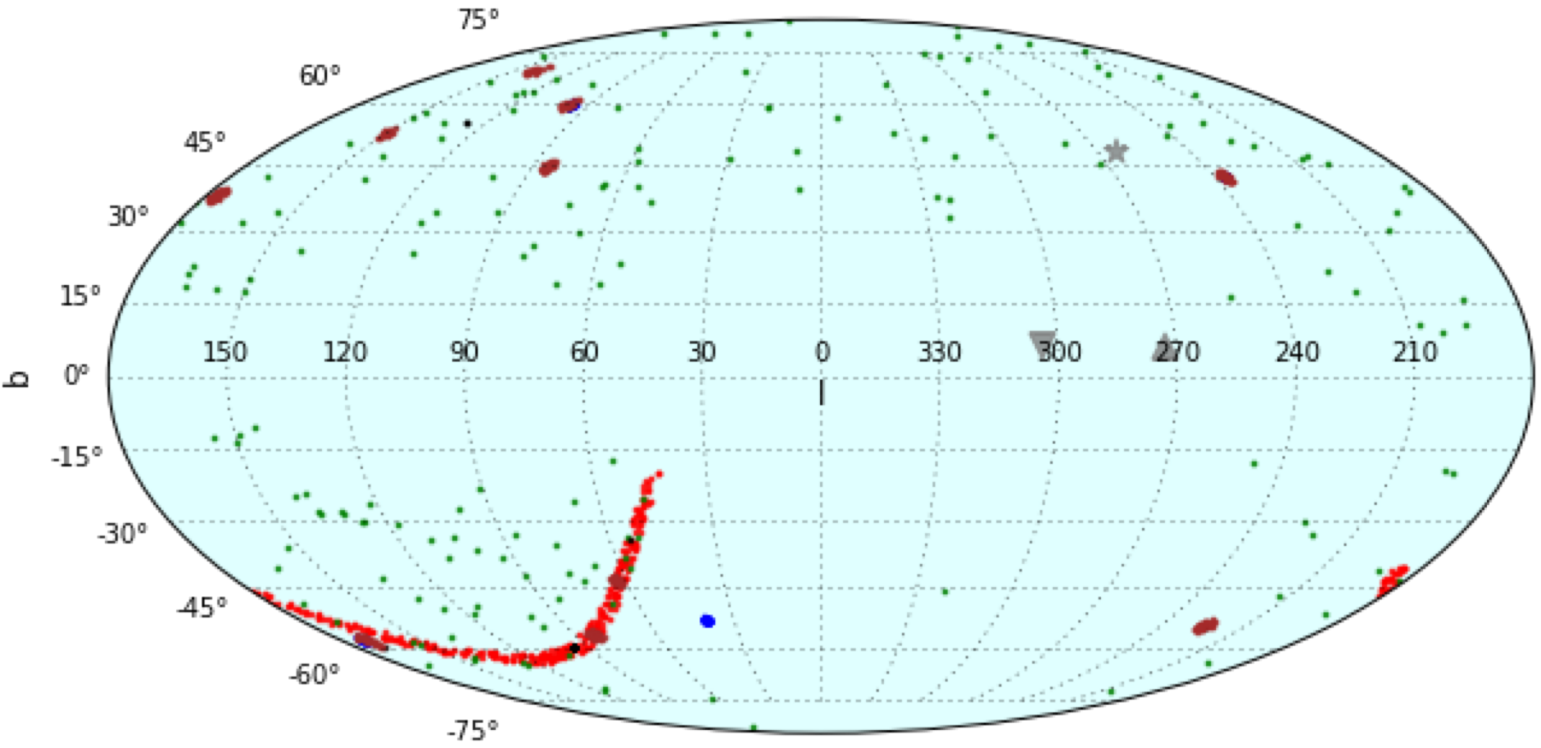
Betoule et. al. Astron.Astrophys. 568 (2014) A22

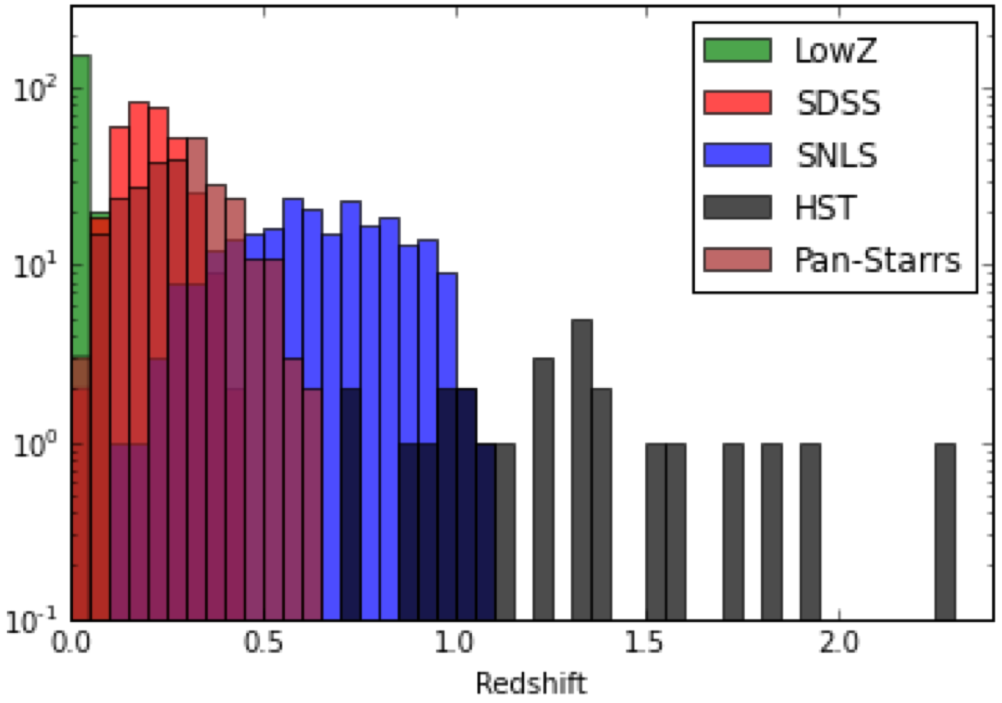


JLA has now been Superceded by Pantheon

The Pantheon compilation

Scolnic et al. Astrophys.J. 859 (2018) no.2, 101





JLA ⊆ Pantheon (mostly)

z_{hel} not available till Nov 2018

JLA + additional SN1a from Pan Starrs and HST

1048 SN1a, redshifts corrected for peculiar velocities using the 2M++ flow field

890 are in the hemisphere opposite the 2M++ bulk flow

Missing z_{hel} and wrong peculiar velocity corrections

At https://archive.stsci.edu/prepds/ps1cosmo/scolnic_datatable.html , z_{hel} and z_{cmb} columns have the exact same numbers.

The flow model used for peculiar velocity corrections, Carrick et al 2015 extends out to z~0.067, with $V_{ext} = 159 \pm 23$ km/s bulk flow for the whole volume, detected at 5.2 σ

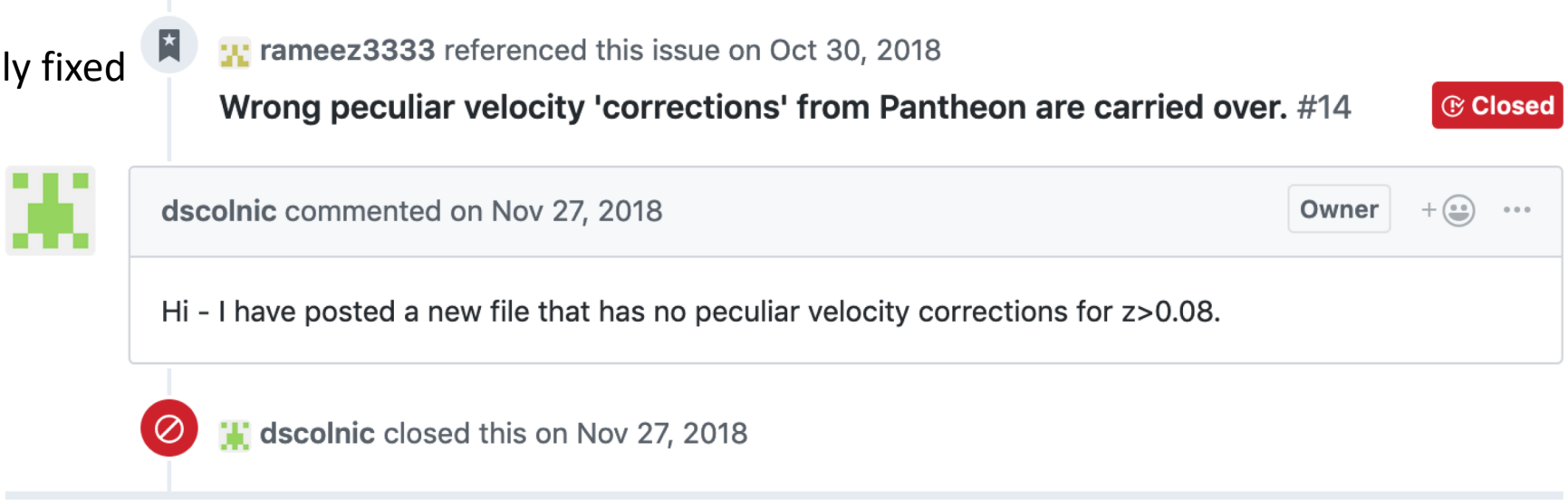
Yet the Pantheon data included 'corrections' all the way to ~0.3

https://github.com/dscolnic/Pantheon/blob/master/data_fitres/Ancillary_G10.FITRES

Illustrative example is the case of SN 2246 , which has a ZCMB of 0.19422. It seems to have a VPEC of 444.2816. The SNe is 117 degrees away from the CMB dipole, and 115 degrees away from the direction of the Vext.

Reported on github, purportedly fixed

Z_{hel} values finally submitted



Inconsistent z_{hel} values

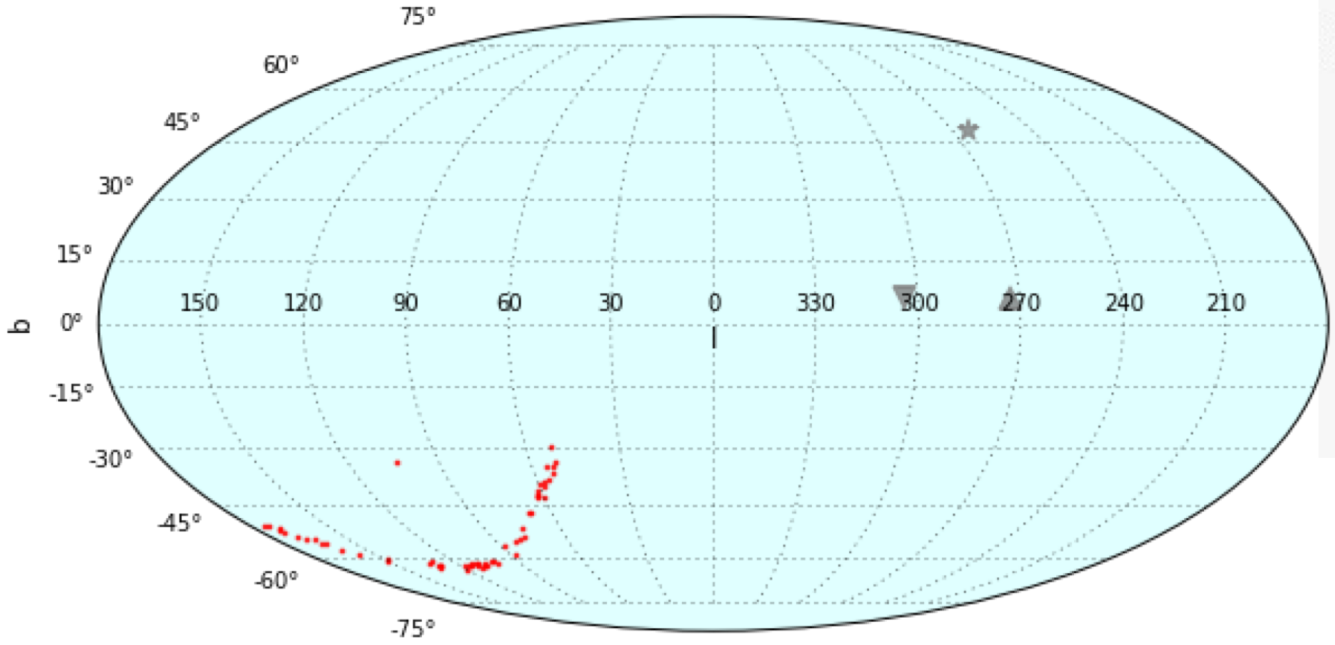
- ~150 SDSS SNe, in common between JLA and Pantheon, have different redshifts in JLA and Pantheon
- According to Astrophys. J. Suppl.185, 32 (2009) [arXiv:0908.4274 [astro-ph.CO]], the $\sigma_z = 0.0001$, 0.0005 or 0.005 (just for 34).
- Most conservatively, at least 50 SNe redshifts have changed by >5 sigma, and more than 20 by >10 sigma
- All details at https://arxiv.org/abs/1905.00221v1
- A third set of redshifts exist at https://classic.sdss.org/supernova/snlist_confirmed.html
  - Eg : According to this URL, for SN15301 the redshift is 0.29630. According to JLA it's 0.248 and according to Pantheon, it is 0.179630.
- http://skyserver.sdss.org/dr14/en/tools/explore/Summary.aspx?id=1237663458316125530
  - This URL is in agreement with Pantheon (so JLA was wrong?)
  - JLA has been cited more than 890 times and used in >400 analyses.

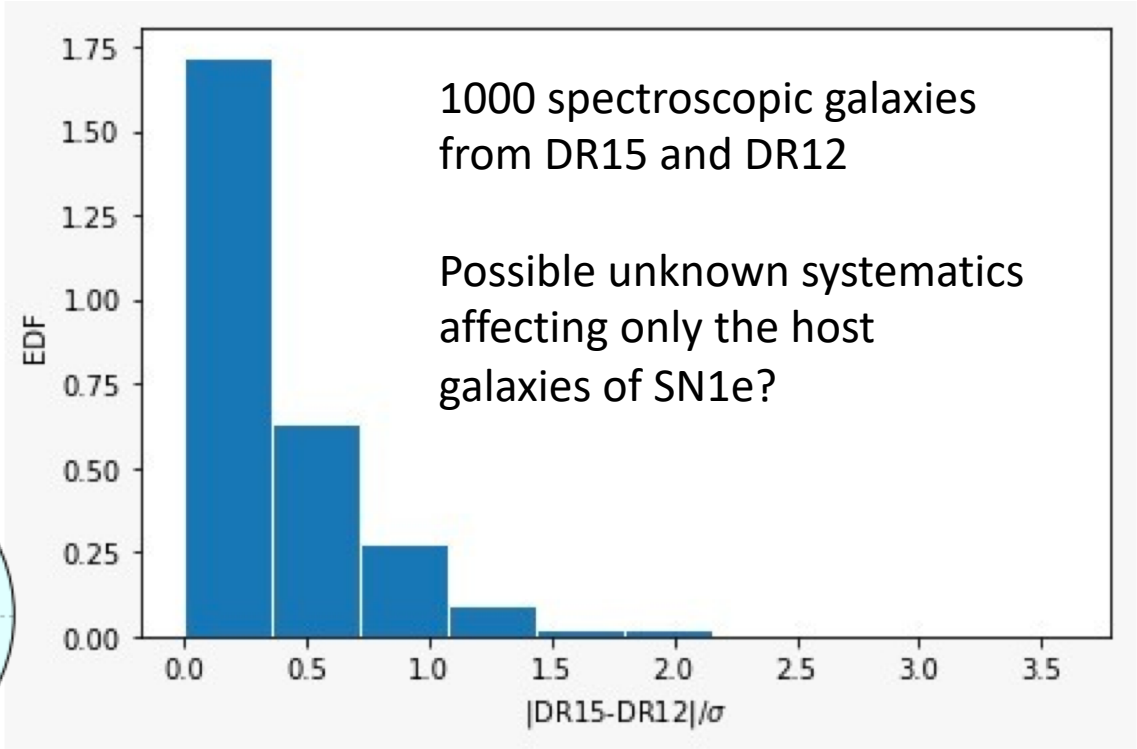
Issues with SDSS spectroscopy?

Many z_{hel} values have changed by as much as ~0.1 (~600 Mpc)

All SNe with shifted redshifts are in the direction directly opp to the CMB dipole

Have we discovered galaxies that accelerate by 0.1 c in a few years?





1000 spectroscopic galaxies from DR15 and DR12

Possible unknown systematics affecting only the host galaxies of SN1e?

So there are implications for all anisotropy studies with SNe

Conclusions

The low redshift Universe is inhomogenous and not FLRW at all scales.

The dipolar modulation of high redshift radio galaxies is at 2.81σ tension with the kinematic interpretation of the CMB dipole, suggesting a velocity of ~1355 km/s instead of 369 km/s

Infrared galaxies show a 4.6σ kinematic + clustering dipole in the CMB direction, favouring a velocity of ~1260 km/s, and can be reconciled with the kinematic interpretation of the CMB dipole only for a non Copernican observer rare in a ΛCDM universe at the level of <1%.

SN1a data have bizarre discrepancies that the authors do not care to elucidate on. If JLA is considered reliable, the local Universe has a dipolar modulation in the deceleration parameter, in the direction of the CMB dipole, that dominates over the monopole of the CMB dipole till z~0.1. The isotropic deceleration parameter is compatible with 0 at <1.3 sigma.

Bad data affects us all, and we must get to the bottom of this as a community before cosmology becomes post truth.

The Universe may be accelerating in some direction and volume averaged sense, but this is probably not due to a cosmological constant.

On the measurement of cosmological parameters

Rupert A. C. Croft, Matthew Dailey (CMU)

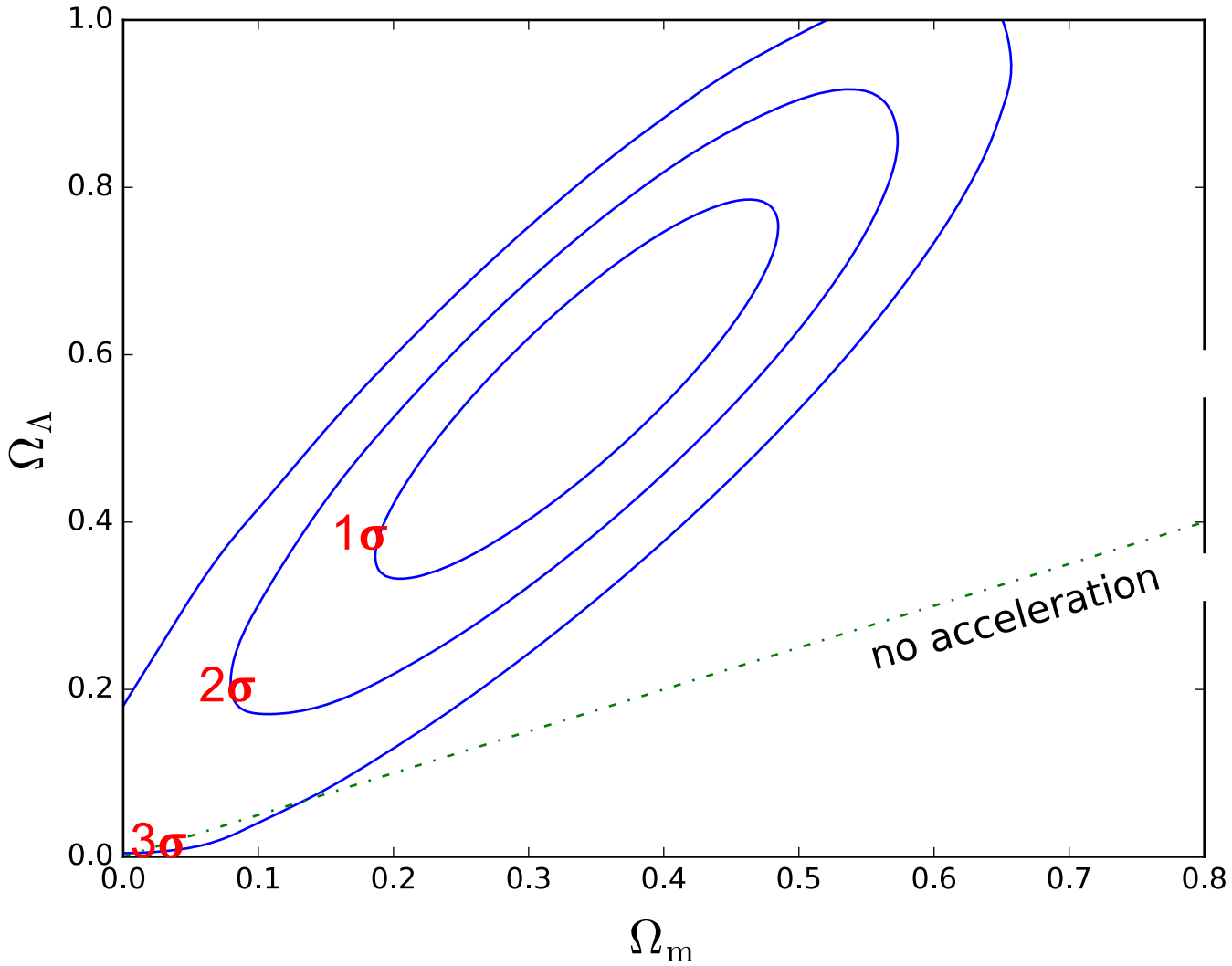
(Submitted on 14 Dec 2011 (v1), last revised 21 Jul 2015 (this version, v2))

We have catalogued and analysed cosmological parameter determinations and their error bars published between the years 1990 and 2010. Our study focuses on the number of measurements, their precision and their accuracy. The accuracy of past measurements is gauged by comparison with the WMAP7 results. The 637 measurements in our study are of 12 different parameters and we place the techniques used to carry them out into 12 different categories. We find that the number of published measurements per year in all 12 cases except for the dark energy equation of state parameter w_0 peaked between 1995 and 2004. Of the individual techniques, only BAO measurements were still rising in popularity at the end of the studied time period. The fractional error associated with most measurements has been declining relatively slowly, with several parameters, such as the amplitude of mass fluctutations sigma_8 and the Hubble constant H_0 remaining close to the 10% precision level for a 10-15 year period. The accuracy of recent parameter measurements is generally what would be expected given the quoted error bars, although before the year 2000, the accuracy was significantly worse, consistent with an average underestimate of the error bars by a factor of ~2. When used as complement to traditional forecasting techniques, our results suggest that future measurements of parameters such as fNL, and w_a will have been informed by the gradual improvment in understanding and treatment of systematic errors and are likely to be accurate. However, care must be taken to avoid the effects of confirmation bias, which may be affecting recent measurements of dark energy parameters. For example, of the 28 measurements of Omega_Lambda in our sample published since 2003, only 2 are more than 1 sigma from the WMAP results. Wider use of blind analyses in cosmology could help to avoid this.

https://arxiv.org/abs/1112.3108

Data consistent with uniform expansion @<3σ!

Opens up interesting possibilities e.g. could the cosmic fluid be *viscous* – perhaps associated with structure formation (e.g. Floerchinger *et al*, PRL **114**:091301,2015)



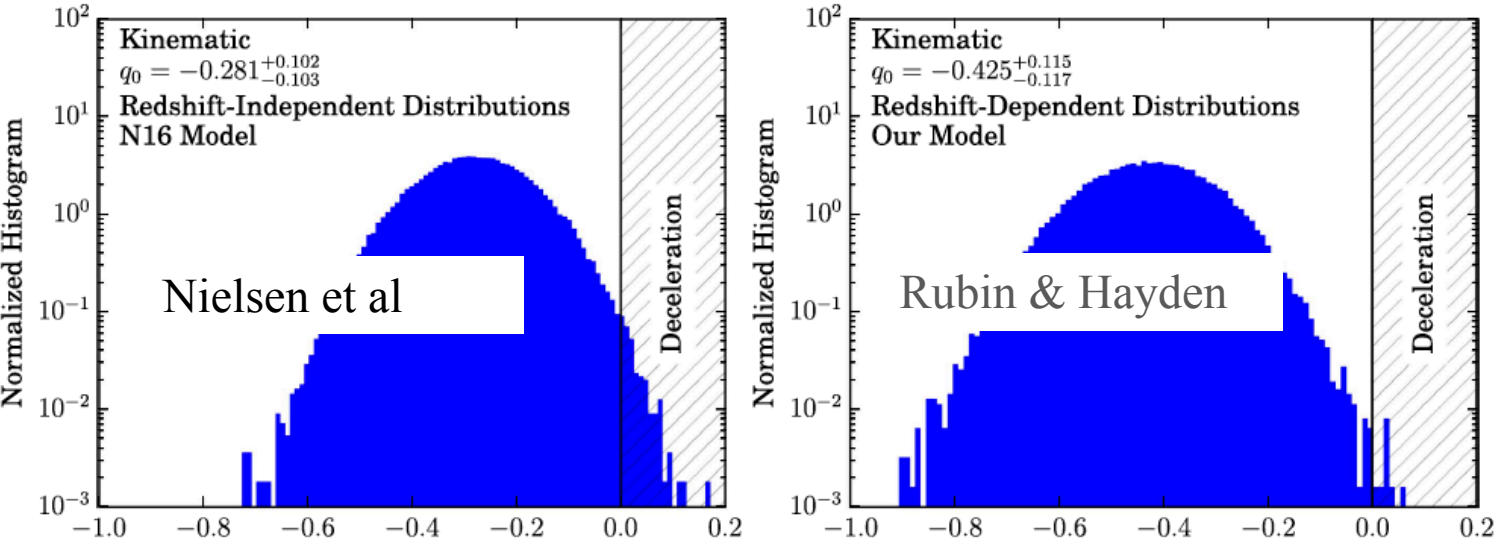
profile likelihood

MLE, *best fit*

Ω_M	0.341
Ω_Λ	0.569
α	0.134
x_0	0.038
σ^2_{x0}	0.931
β	3.058
c_0	-0.016
σ^2_{c0}	0.071
M_0	-19.05
σ^2_{M0}	0.108

Nielsen, Guffanti & Sarkar., Sci.Rep.**6**:35596,2016

Rubin & Hayden (ApJ **833**:L30,2016) verify the results of Nielsen et al
but then argue that the light-curve fit parameters may be redshift-dependent



Deceleration parameter

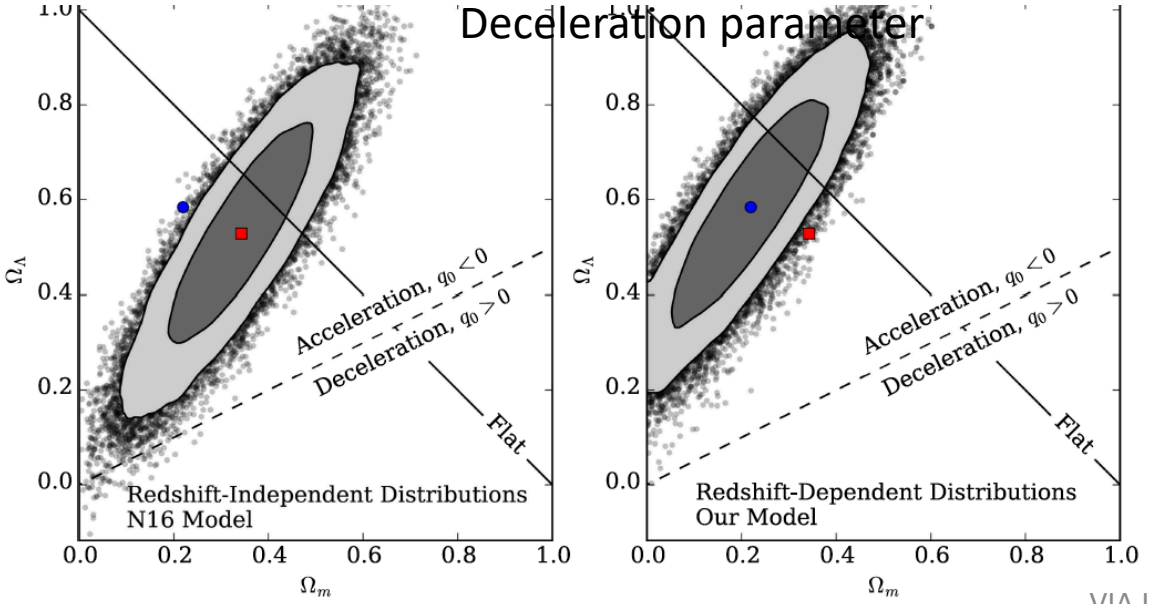
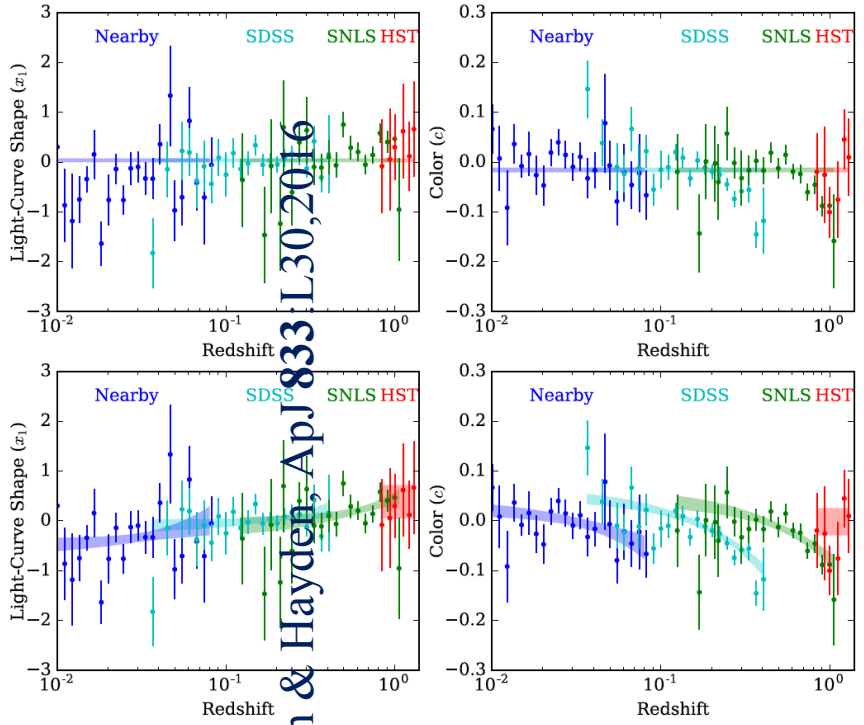


Figure 2. Ω_m–Ω_Λ constraints enclosing 68.3% and 95.4% of the samples from the posterior. Underneath, we plot all samples. The left panel shows the constraints obtained with x_1 and c distributions that are constant in redshift, as in the N16 analysis; the right panel shows the constraints from our model. The red square and blue circle show the location of the median of the samples from the respective posteriors.



Rubin & Hayden, ApJ 833:L30,2016

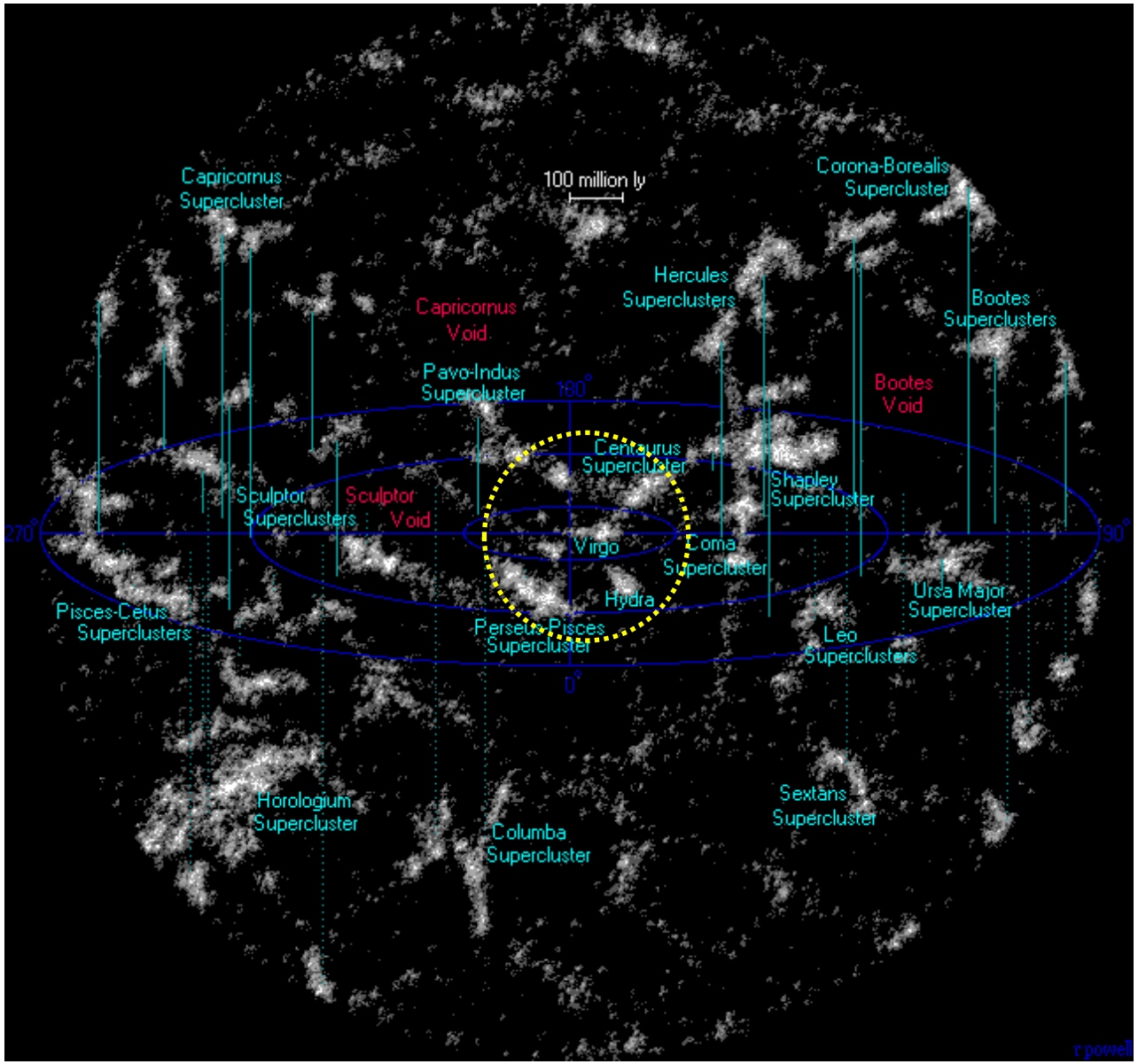
Figure 1. Binned x_1 (left panels) and c (right panels) light-curve parameters as a function of redshift for the JLA sample. The trend of color with redshift within each ground-based sample is expected due to the combination of the color-luminosity relation combined with redshift-dependent luminosity detection limits. The top panels show the 68% credible constraints on a constant-in-redshift model, as was used in N16. The bottom panels show our proposed revision. Failing to model the drift in the mean observed distributions demonstrated by the bottom panels will tend to cause high-redshift SNe to appear brighter on average, therefore reducing the significance of accelerating expansion.

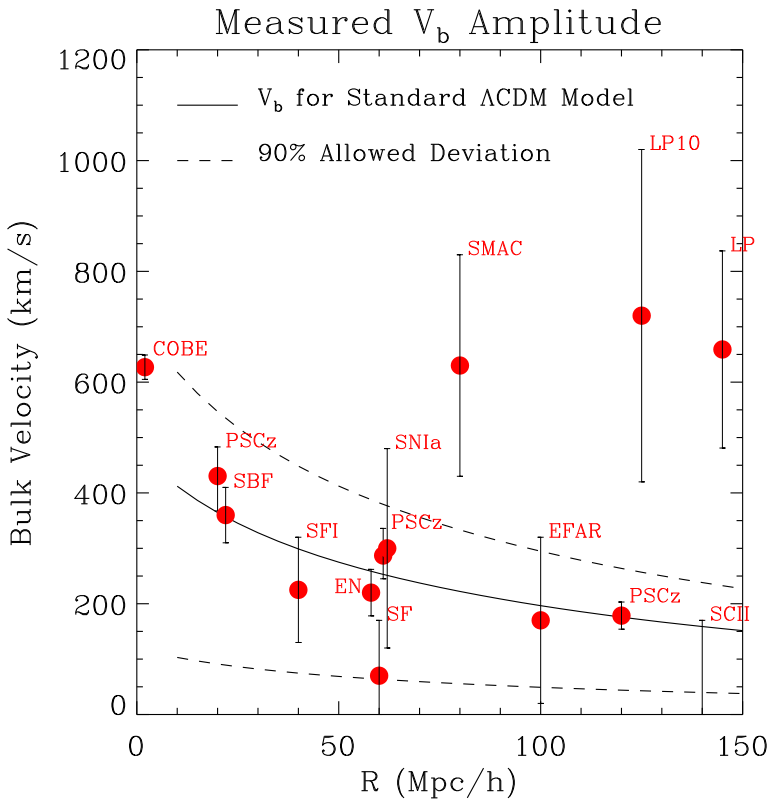
Two out of 3 parameters that go into the distance modulus have been examined by eye and made sample and redshift dependent.

Against the principles of blinded data analysis.

20 hyperparameters to standardize 740 SN1e

Even if this is justified, the significance with which a non-accelerating universe is rejected rises only to $\lesssim 4\sigma$ … still inadequate to claim a 'discovery' (even though the dataset has increased from ~50 to 740 SNe Ia in 20 yrs)!

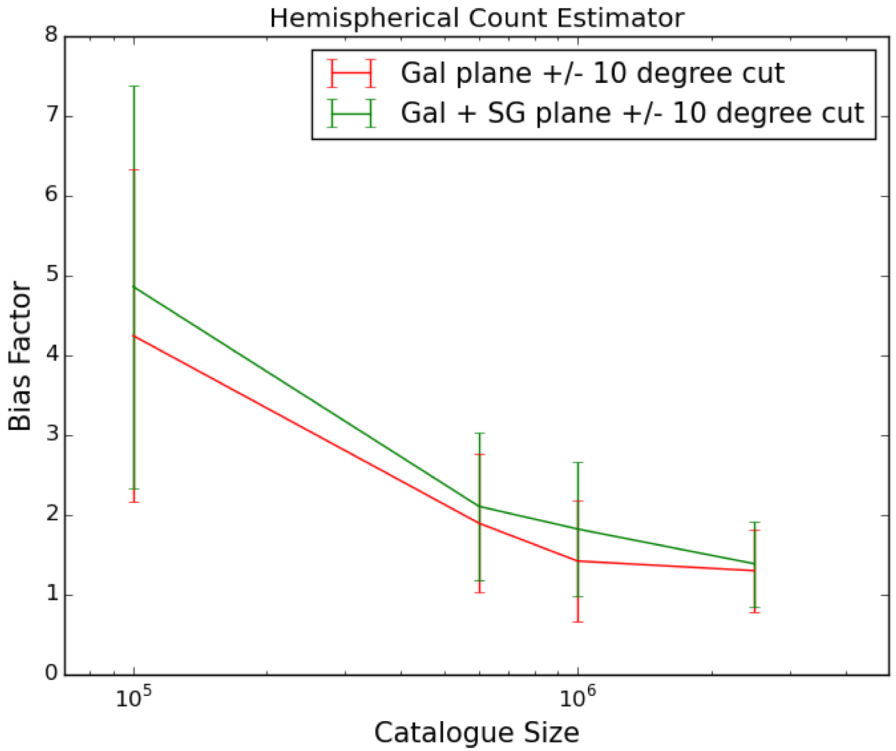

Capricornus Supercluster
100 million ly
Corona Borealis Supercluster
Hercules Superclusters
Capricornus Void
Bootes Superclusters
Pavo-Indus Supercluster
180°
Bootes Void
Centaurus Supercluster
Shapley Supercluster
Sculptor Superclusters
Sculptor Void
270°
90°
Virgo
Coma Supercluster
Hydra
Ursa Major Supercluster
Pisces-Cetus Superclusters
Perseus-Pisces Supercluster
Leo Superclusters
0°
Horologium Supercluster
Columba Supercluster
Sextans Supercluster
r powell

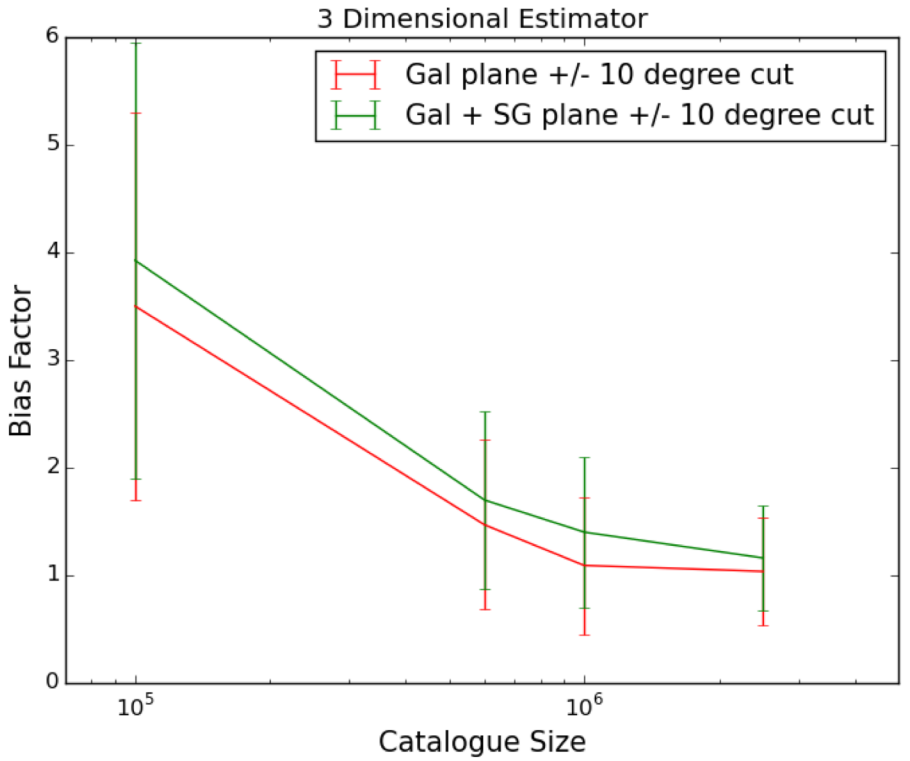

Measured V_b Amplitude
V_b for Standard ΛCDM Model
90% Allowed Deviation
Bulk Velocity (km/s)
R (Mpc/h)
0
200
400
600
800
1000
1200
0
50
100
150
COBE
SMAC
LP10
LP
PSCz
SBF
SNIa
SFI
PSCz
EFAR
EN
SF
PSCz
SCII

Estimators for the Dipole

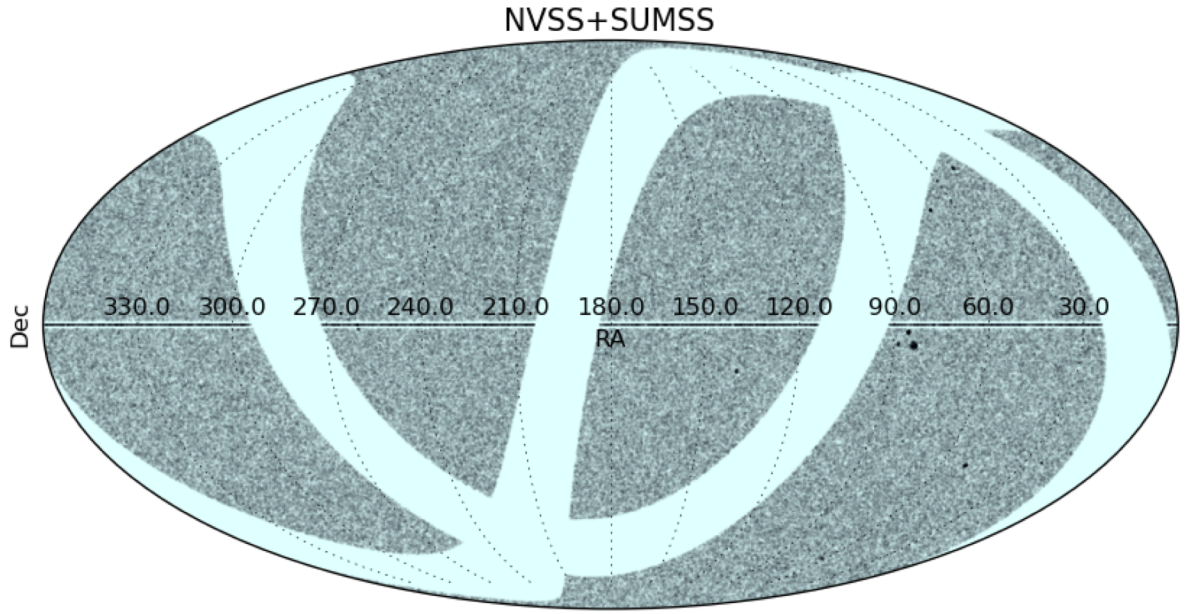
$$\vec{D}_H = \hat{z} * \frac{N_{UH} - N_{LH}}{N_{UH} + N_{LH}}$$

$$\vec{D}_{3D} = \frac{1}{N}\sum_{i=1}^{N} \hat{r}_i$$





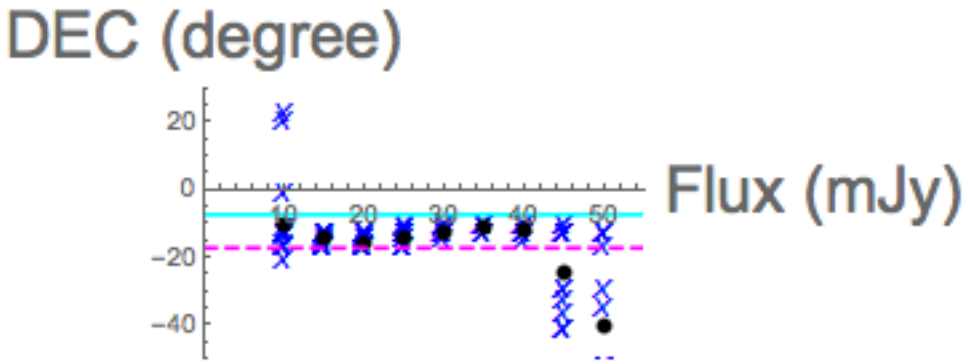
Local Sources contamination?

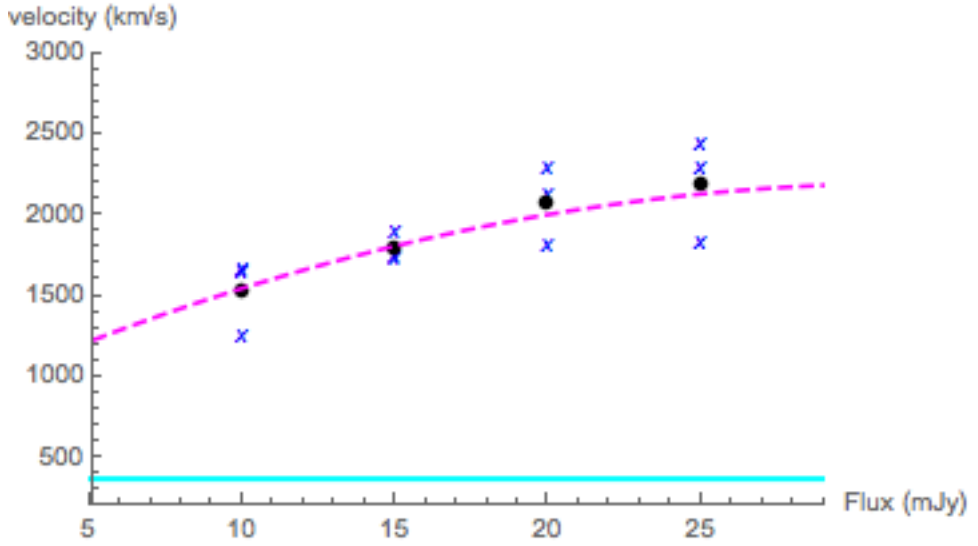


Remove the Supergalactic plane. Disk like structure containing the majority of clusters at z<0.03

Remove sources within 1 arcsecond of 2MRS z<0.03 sources

No significant impact on the velocity/direction of the dipole





	-2 log $\mathcal{L}_{\max}$	$q_{\rm m}$	$q_{\rm d}$	S	$j_0 - \Omega_k$	α	β	M_0	σ_{M_0}
Rubin & Hayden (22 param.) with no dipole	-331.6	-0.4574	–	–	0.1458	0.1345	3.067	-19.07	0.1074
As above with no acceleration ($q_{\rm m} = 0$)	-315.6	0	–	–	-1.351	0.1323	3.048	-19.01	0.1088
Rubin & Hayden (22 param.) with dipole $\propto {\rm e}^{-z/S}$	-335.9	-0.3867	-0.2325	0.1825	-0.1779	0.1337	3.028	-19.06	0.1076
As above with no acceleration ($q_{\rm m} = 0$)	-326.9	0	-2.186	0.05034	-1.333	0.1325	3.02	-19.01	0.1087
Rubin & Hayden (16 param.) with no dipole	-242.4	-0.3873	–	–	0.2937	0.1345	3.063	-19.05	0.1080
As above with no acceleration ($q_{\rm m} = 0$)	-229.9	0	–	–	-0.8444	0.1325	3.051	-19.00	0.1094
Rubin & Hayden (16 param.) with dipole $\propto {\rm e}^{-z/S}$	-250.2	-0.3329	-0.2091	0.2726	0.04258	0.1336	3.021	-19.04	0.1081
As above with no acceleration ($q_{\rm m} = 0$)	-241.2	0	-0.3585	0.1794	-0.8645	0.132	3.009	-19.00	0.1093
Rubin & Hayden (16 + 3 param.) with no dipole	-253.4	-0.09894	–	–	-0.102	0.1346	3.023	-19.07, -19.00, -18.94, -18.78	0.1082
As above with no acceleration ($q_{\rm m} = 0$)	-253	0	–	–	-0.2661	0.1344	3.016	-19.06, -18.99, -18.92, -18.77	0.1084

Even with the sample and redshift dependent treatment for $x_{1,0}$ and c_0 proposed by R&H,q_m=0 is disfavoured only at 2.4 sigma and allows for a large q_d extending to $z\sim0.18$

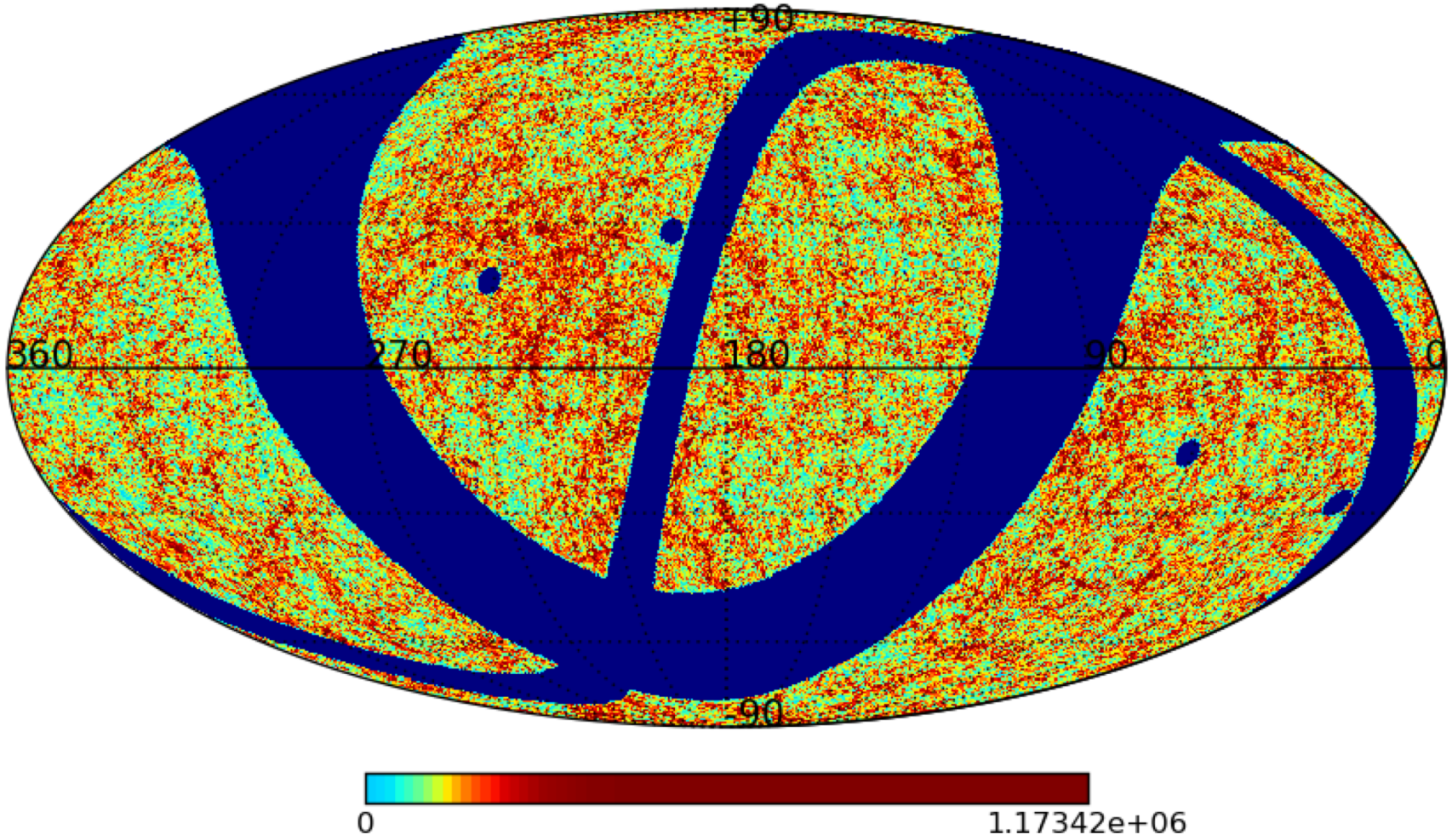
If $x_{1,0}$ and c_0 can be sample or redshift dependent, why not M_0? Undermines the use of SN1a as standard candles but justified by AIC.

Planck 2015

Parameter	*Planck* TT+lowP+lensing
$\Omega_b h^2$	0.02226 ± 0.00023
$\Omega_c h^2$	0.1186 ± 0.0020
$100\theta_{MC}$	1.04103 ± 0.00046
τ	0.066 ± 0.016
$\ln(10^{10} A_s)$	3.062 ± 0.029
n_s	0.9677 ± 0.0060
H_0	67.8 ± 0.9
Ω_m	0.308 ± 0.012
$\Omega_m h^2$	0.1415 ± 0.0019
$\Omega_m h^3$	0.09591 ± 0.00045
σ_8	0.815 ± 0.009
$\sigma_8 \Omega_m^{0.5}$	0.4521 ± 0.0088
Age/Gyr	13.799 ± 0.038
r_{drag}	147.60 ± 0.43
k_{eq}	0.01027 ± 0.00014

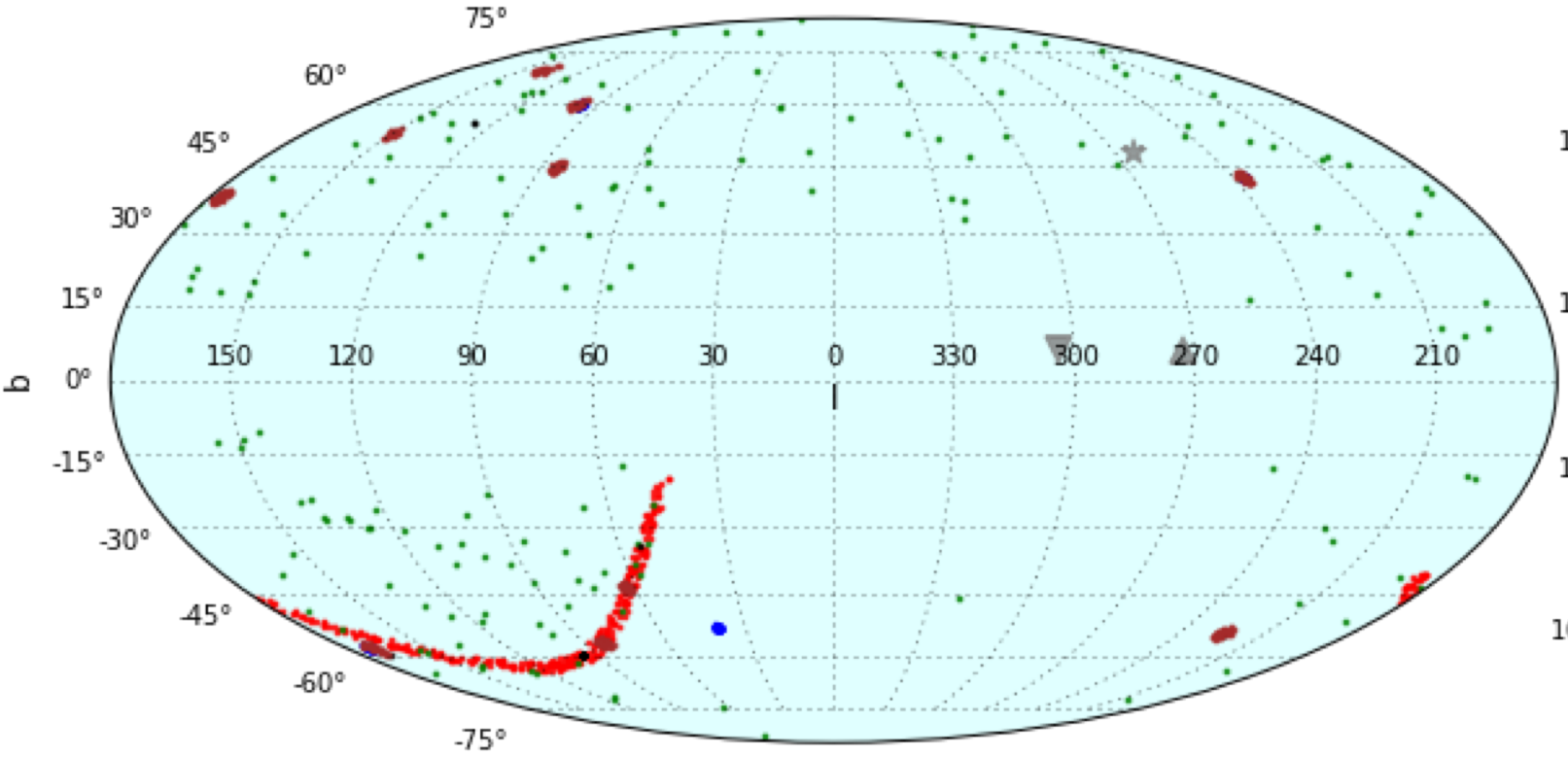
https://arxiv.org/pdf/1706.09309.pdf

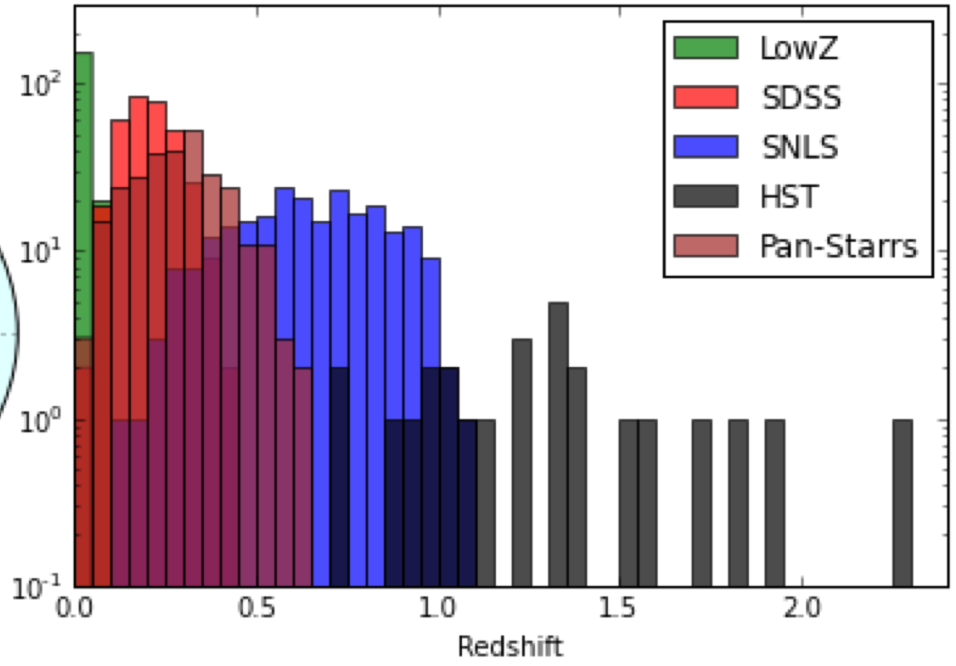
https://arxiv.org/pdf/1505.07800.pdf


+90
360
270
180
90
0
-90
0
1.17342e+06

The Pantheon compilation

Scolnic et al. Astrophys.J. 859 (2018) no.2, 101

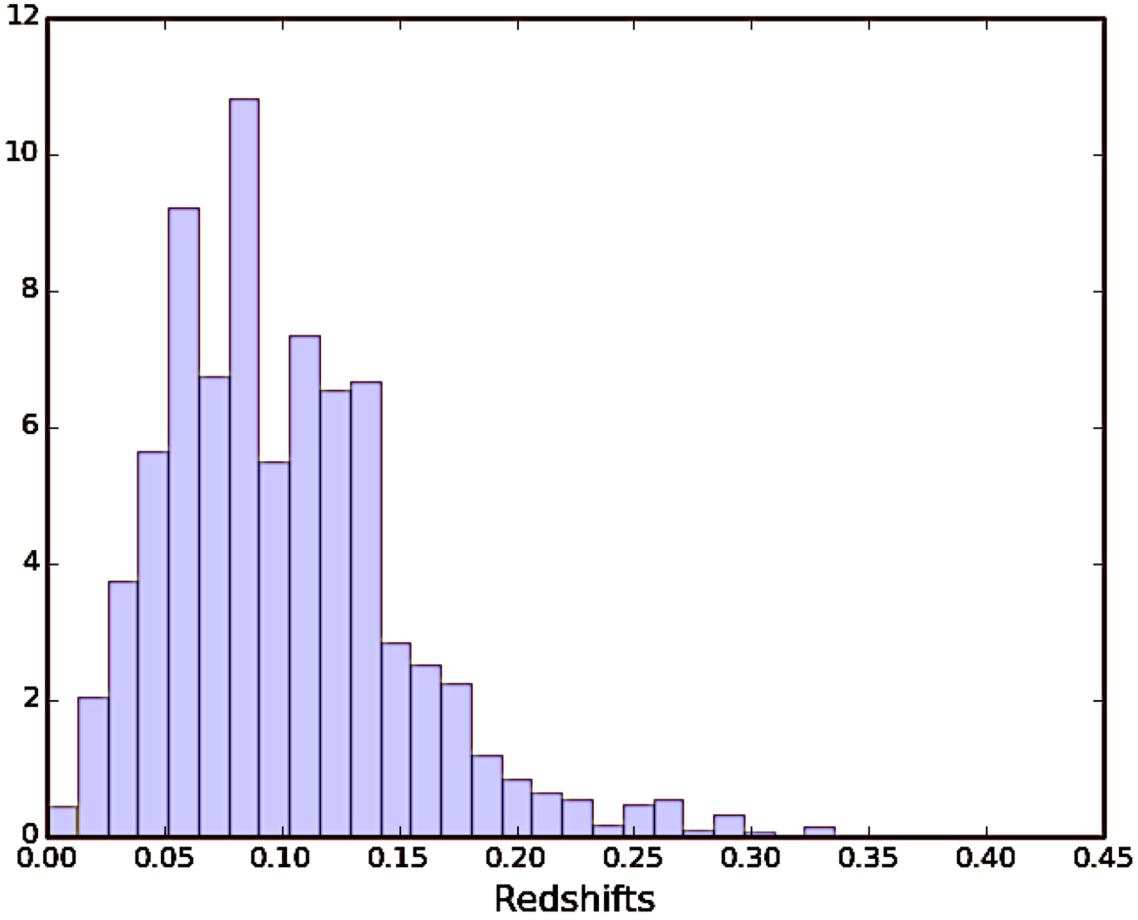




JLA + additional SN1a from Pan Starrs and HST
1048 SN1a, redshifts corrected for peculiar velocities using the 2M++ flow field
890 are in the hemisphere opposite the 2M++ bulk flow

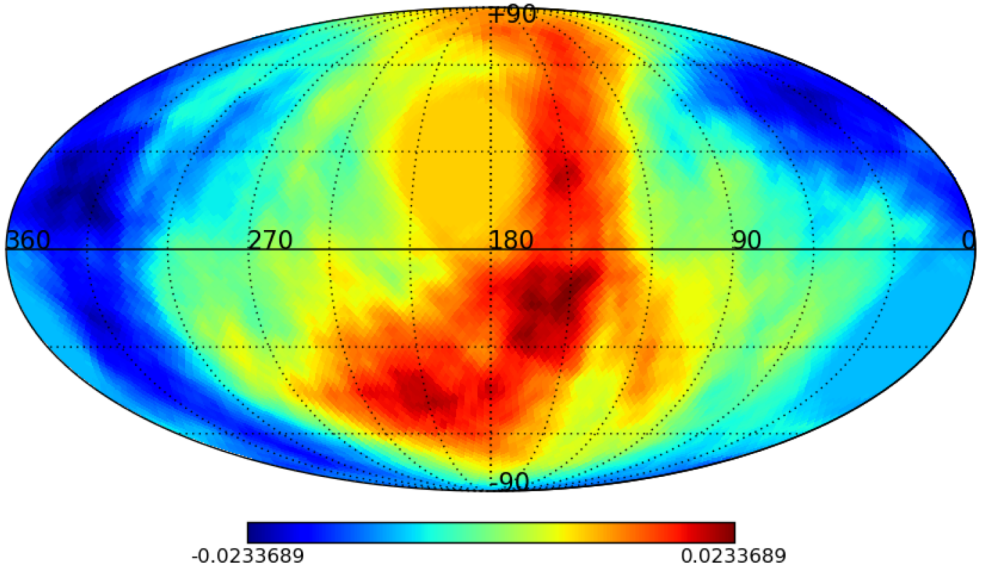
However, we use only JLA!

Redshift distribution of the removed sources

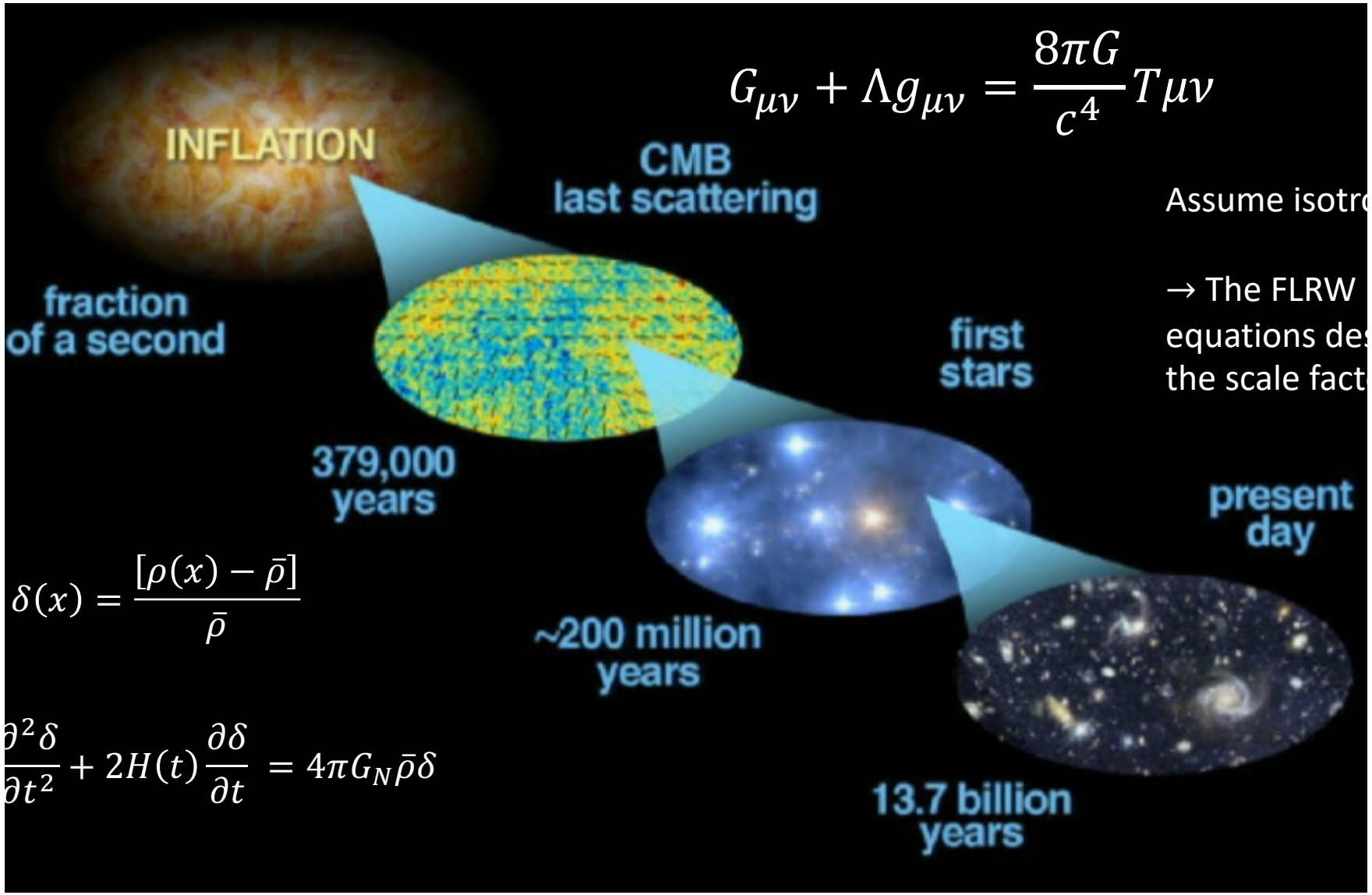


d = 0.0124 >1200 km/s if fully kinematic
172.6° RA, -6.6° Dec (~4.5° from CMB)

Total dipole is at least 4.2σ statistically significant.



By cross correlating with Galaxy and Mass Assembly



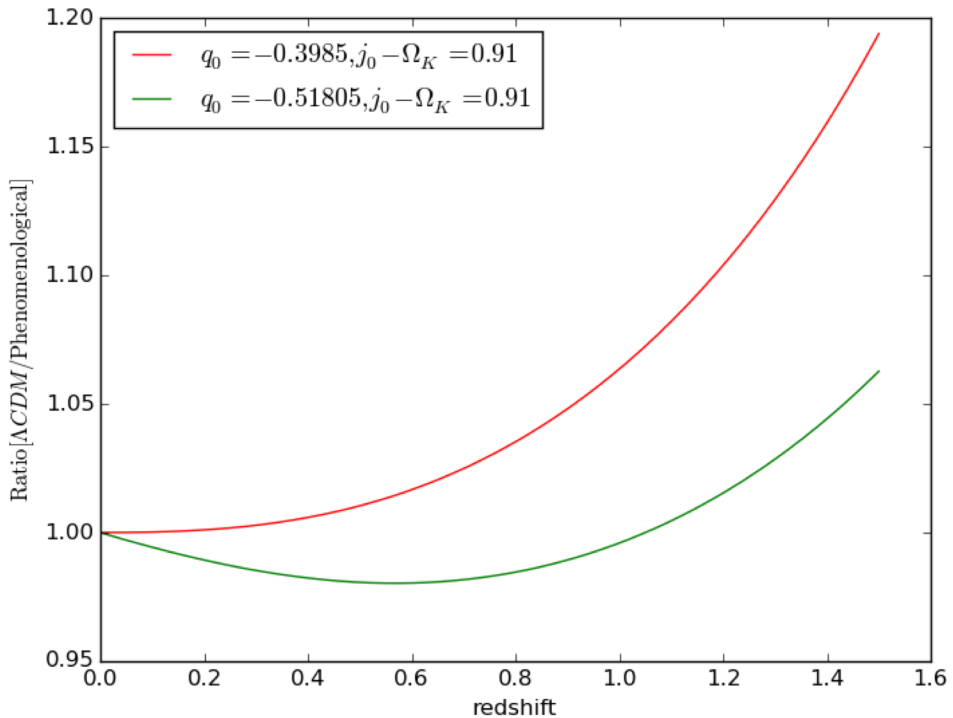
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T\mu\nu$$

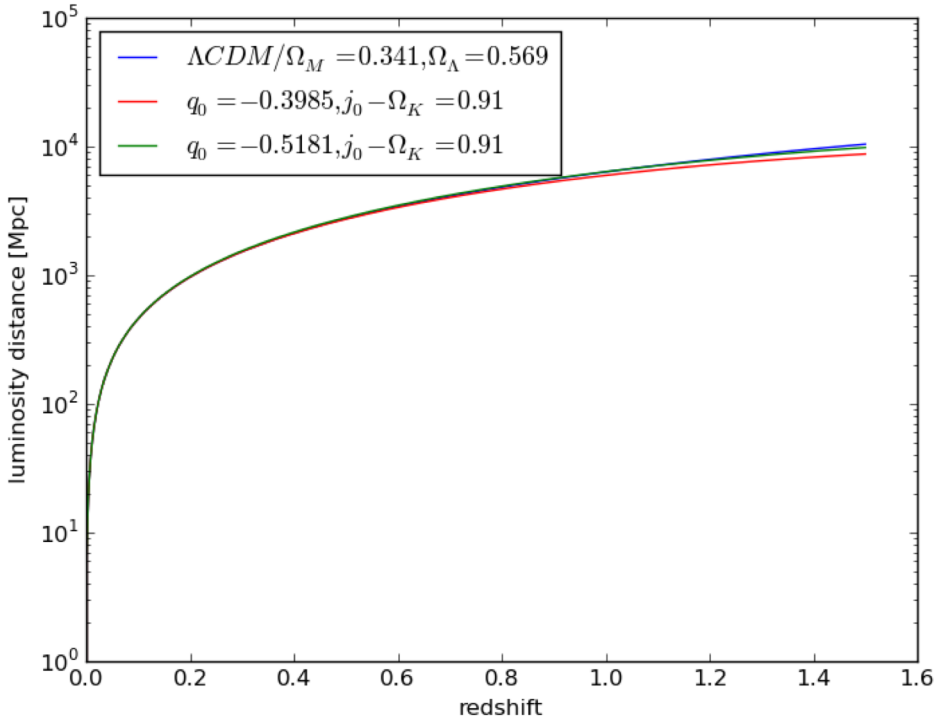
Assume isotr

→ The FLRW
equations des
the scale fact

$$\delta(x) = \frac{[\rho(x) - \bar{\rho}]}{\bar{\rho}}$$

$$\frac{\partial^2 \delta}{\partial t^2} + 2H(t)\frac{\partial \delta}{\partial t} = 4\pi G_N \bar{\rho}\delta$$


$q_0 = -0.3985, j_0 - \Omega_K = 0.91$
$q_0 = -0.51805, j_0 - \Omega_K = 0.91$
Ratio[ΛCDM/Phenomenological]
redshift


$\Lambda CDM/\Omega_M = 0.341, \Omega_\Lambda = 0.569$
$q_0 = -0.3985, j_0 - \Omega_K = 0.91$
$q_0 = -0.5181, j_0 - \Omega_K = 0.91$
luminosity distance [Mpc]
redshift