Towards precision tests of the cosmological principle

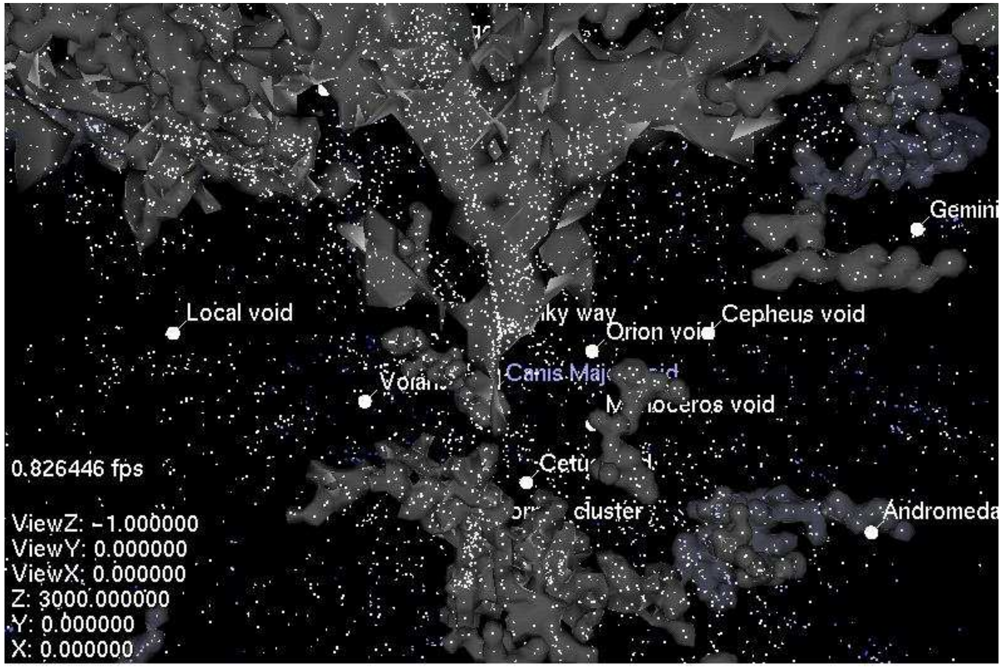
David L. Wiltshire (University of Canterbury, NZ)

L.H. Dam, A. Heinesen & DLW:

MNRAS 472 (2017) 835

A. Heinesen, C. Blake, Y-Z. Li & DLW:

JCAP 03 (2019) 003



Key elements of talk

- *“All homogeneous universes are alike, but every inhomogeneous universe is inhomogeneous in its own way.”* (Asta Heinesen)
- Friedmann evolution can be falsified by precision of Euclid, LSST, . . . within 6–10 years
- Must remove FLRW model assumptions from analysis of supernovae, BAO, CMB, . . .
- H_0 tensions naturally resolved [e.g., Bolejko PR D 97 (2018) 103529], considering scales $\lesssim 100\,h^{-1}$Mpc
- *This talk:* average expansion on $\gtrsim 100\,h^{-1}$Mpc scales
- Timescape model: *Dark energy is a misidentification of gradients in quasilocal gravitational energy in geometry of a complex evolving web of matter inhomogeneities*

General relativity: theory

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \qquad U^\nu \nabla_\nu U^\mu = 0$$

- *Matter tells space how to curve; Space tells matter how to move*
- Matter and geometry are dynamically coupled

$$\nabla^\nu T_{\mu\nu} = 0$$

- *Energy is not absolutely conserved*: rather energy-momentum tensor is covariantly conserved
- On account of the strong equivalence principle, $T_{\mu\nu}$ contains localizable energy–momentum only
- Gravitational energy is dynamical, nonlocal; integrated over a region it is *quasilocal*

Standard cosmology: practice

$$\frac{\dot{a}^2}{a^2} + \frac{kc^2}{a^2} - \frac{1}{3}\Lambda c^2 = \frac{8\pi G\rho}{3}$$

- *Friedmann tells space how to curve;* (rigidly)

$$\mathbf{v}(\mathbf{r}) = \frac{H_0 \Omega_{\mathrm{M0}}^{0.55}}{4\pi} \int \mathrm{d}^3\mathbf{r}'\, \delta_m(\mathbf{r}')\, \frac{(\mathbf{r}' - \mathbf{r})}{|\mathbf{r}' - \mathbf{r}|^3}$$

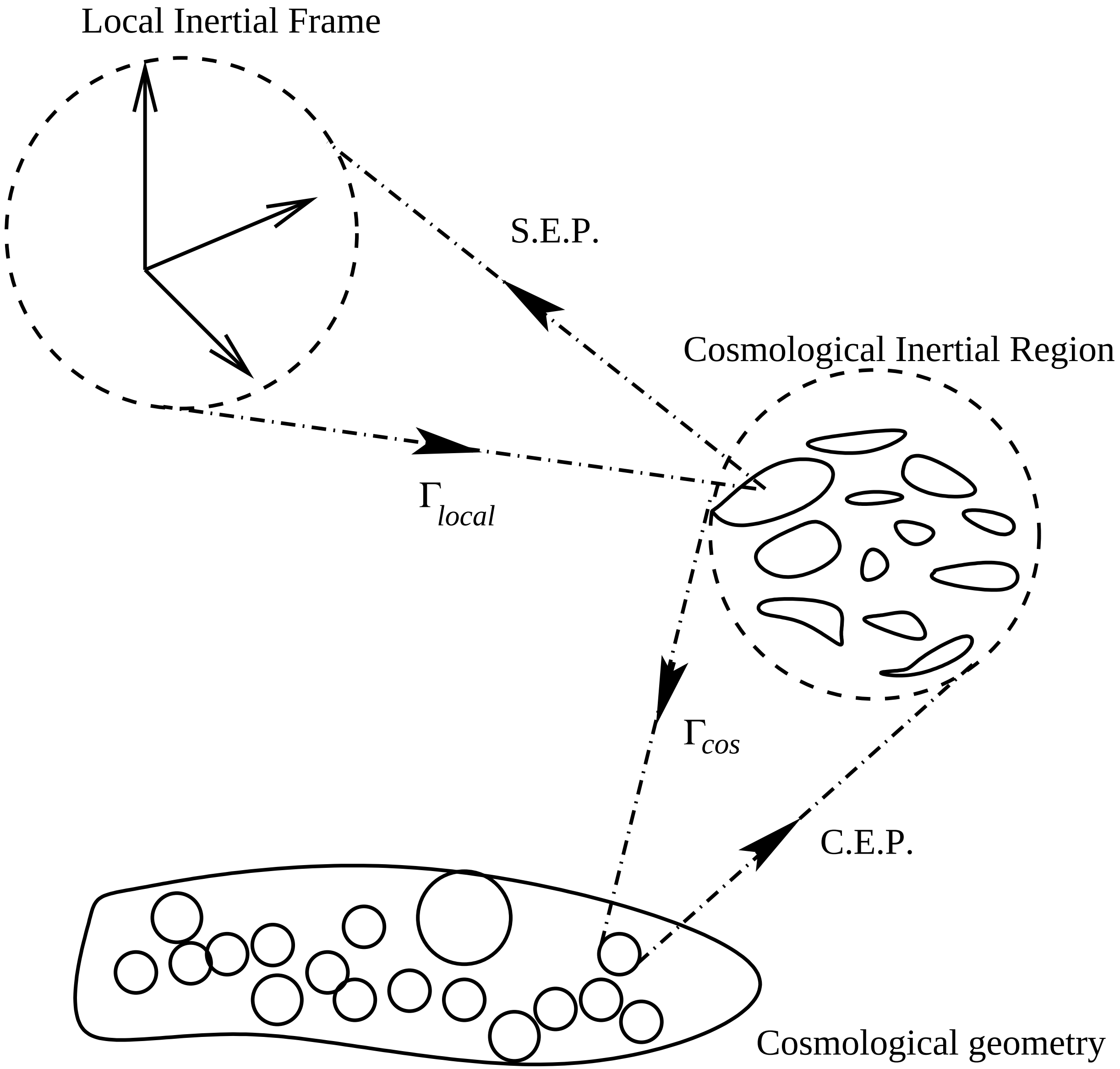
- *Newton tells matter how to move;* non-linearly in N-body simulations
- Dynamical energy of background fixed; Newtonian gravitational energy conserved
- Dynamical coupling of matter and geometry on small scales assumed irrelevant for cosmology

What is a cosmological particle (dust)?

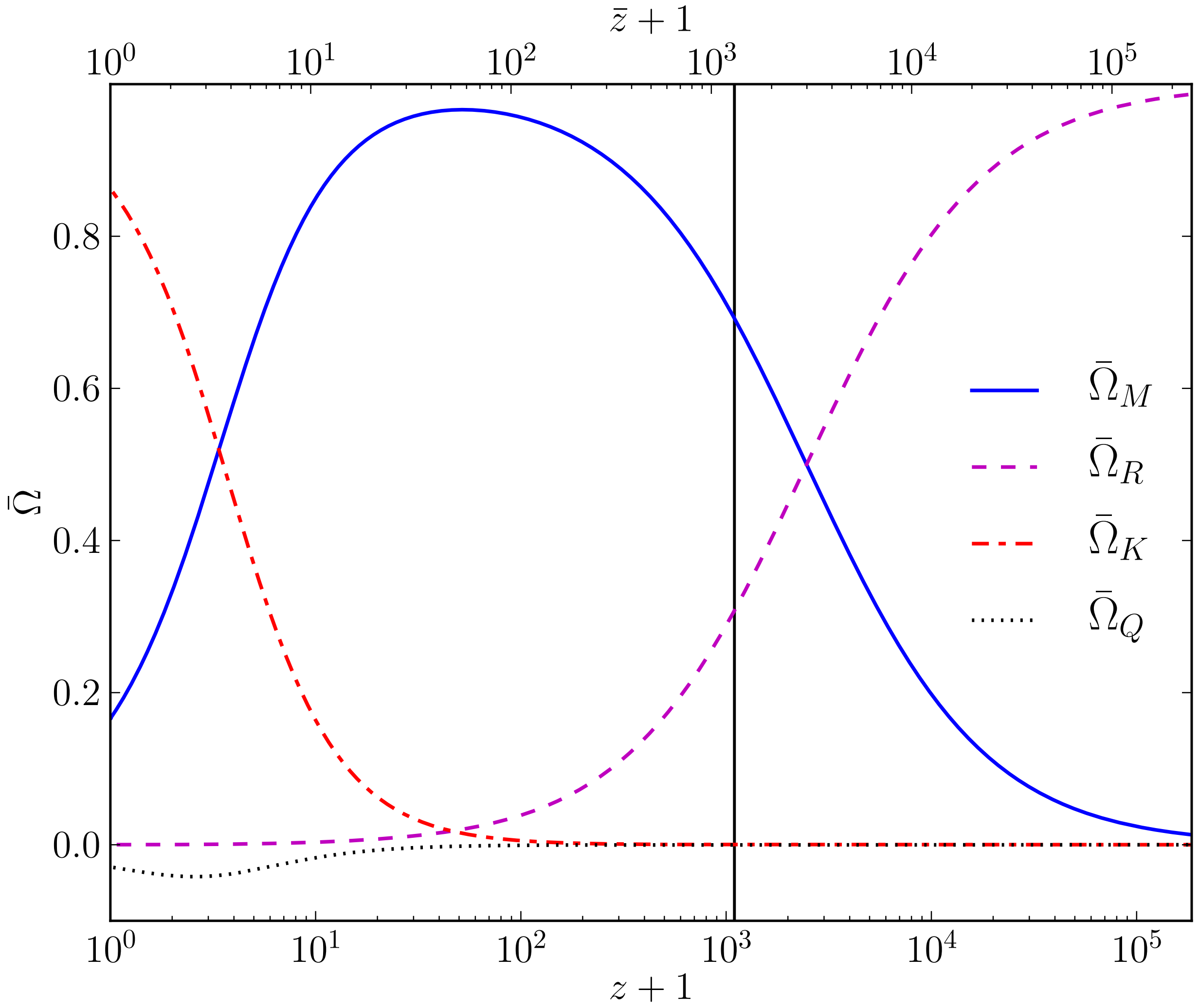
- In FLRW one takes observers “comoving with the dust”
- Traditionally galaxies were regarded as dust. However,
  - Galaxies, clusters not homogeneously distributed today
  - Dust particles should have (on average) invariant masses over the timescale of the problem
- Must coarse-grain over expanding fluid elements larger than the largest typical structures [voids of diameter $30\,h^{-1}$Mpc with $\delta_\rho \sim -0.95$ are $\gtrsim 40$% of $z = 0$ universe]

$$g_{\mu\nu}^{\rm stellar} \to g_{\mu\nu}^{\rm galaxy} \to g_{\mu\nu}^{\rm cluster} \to \left.\begin{matrix} g_{\mu\nu}^{\rm wall} \\ \vdots \\ g_{\mu\nu}^{\rm void} \end{matrix}\right\} \to g_{\mu\nu}^{\rm universe}$$

Statistical geometry…



Timescape: bare parameters



J.A.G. Duley, M.A. Nazer & DLW, CQG 30 (2013) 175006: full numerical solution with matter, radiation

Apparent cosmic acceleration

- Volume average observer sees no apparent cosmic acceleration

  $$\bar{q} = \frac{2\,(1-f_{\rm v})^2}{(2+f_{\rm v})^2}\,.$$

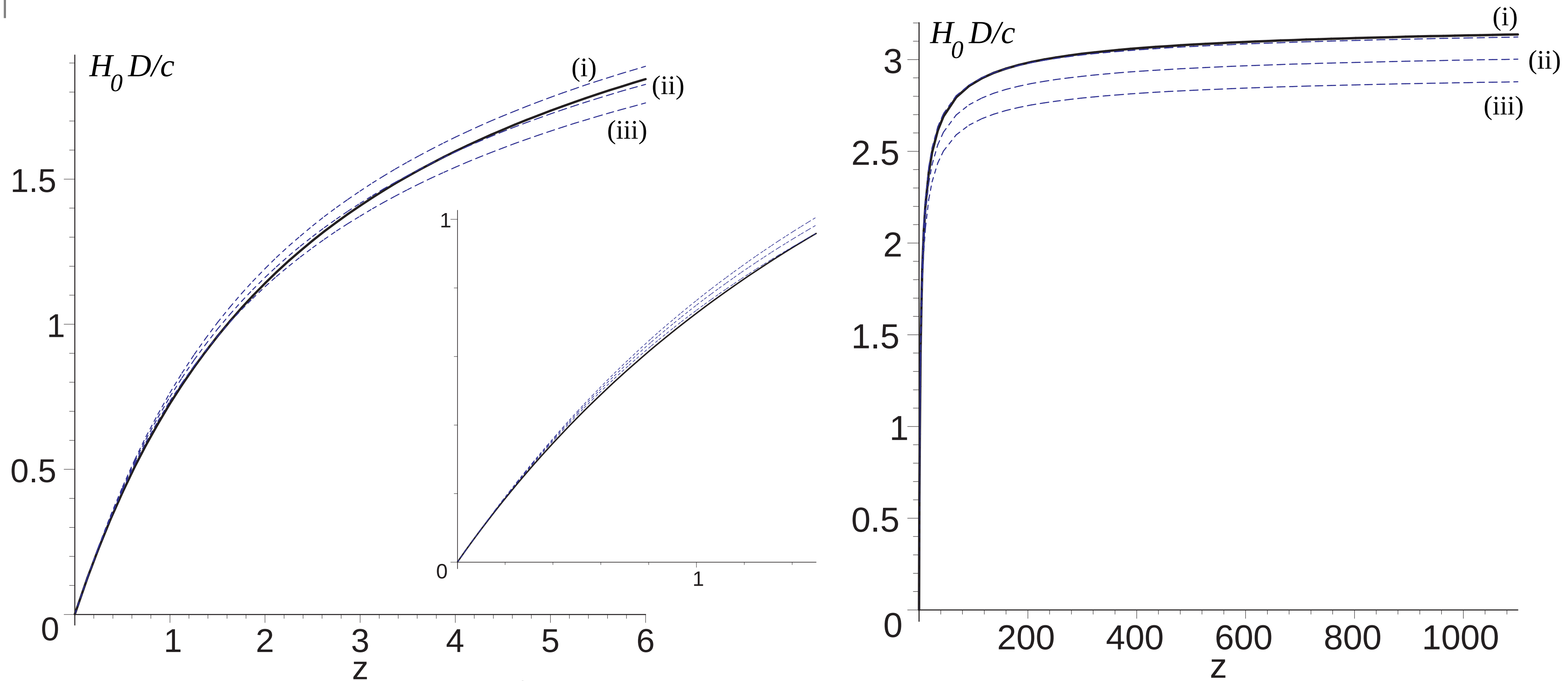
  As $t \to \infty$, $f_{\rm v} \to 1$ and $\bar{q} \to 0^+$.

- A wall observer registers apparent cosmic acceleration

  $$q = \frac{-\,(1-f_{\rm v})\,(8{f_{\rm v}}^3 + 39{f_{\rm v}}^2 - 12f_{\rm v} - 8)}{\left(4 + f_{\rm v} + 4{f_{\rm v}}^2\right)^2}\,,$$

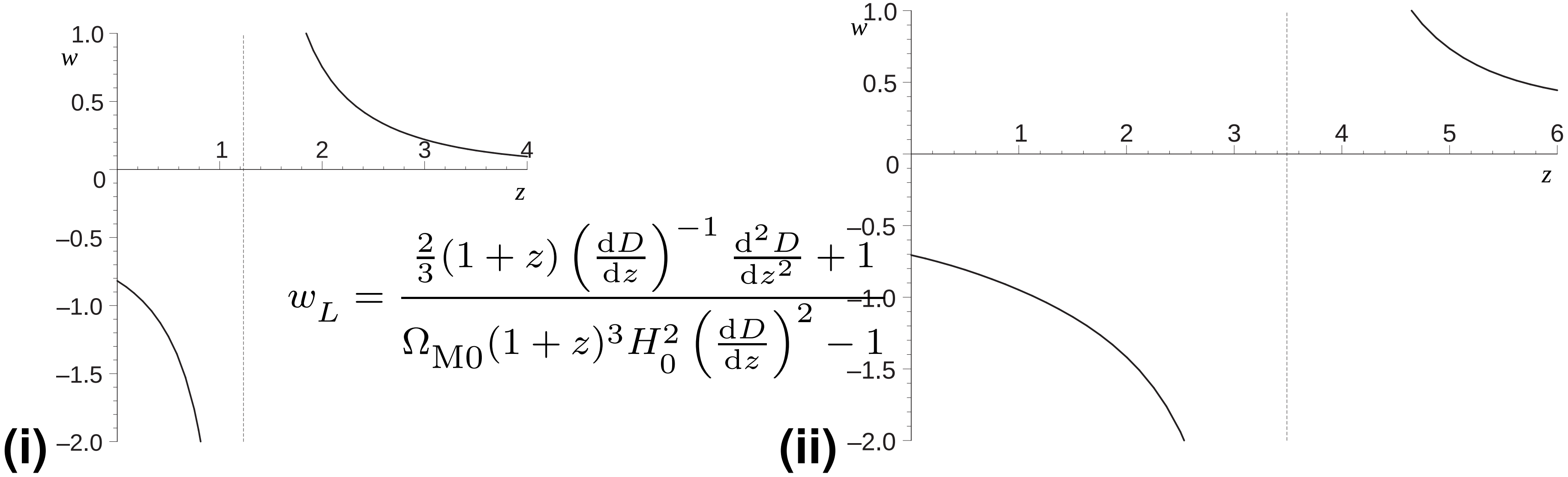
  Effective deceleration parameter starts at $q \sim \frac{1}{2}$, for small $f_{\rm v}$; changes sign when $f_{\rm v} = 0.5867\ldots$, and approaches $q \to 0^-$ at late times.

Dressed “comoving distance” $D(z)$



TS model, with $f_{\rm v0} = 0.695$, **(black)** compared to 3 spatially flat ΛCDM models (blue): **(i)** $\Omega_{\rm M0} = 0.3175$ (best-fit ΛCDM model to Planck); (ii) $\Omega_{\rm M0} = 0.35$; **(iii)** $\Omega_{\rm M0} = 0.388$.

Equivalent “equation of state”?



$$w_L = \frac{\frac{2}{3}(1+z)\left(\frac{\mathrm{d}D}{\mathrm{d}z}\right)^{-1}\frac{\mathrm{d}^2D}{\mathrm{d}z^2}+1}{\Omega_{\mathrm{M}0}(1+z)^3H_0^2\left(\frac{\mathrm{d}D}{\mathrm{d}z}\right)^2-1}$$

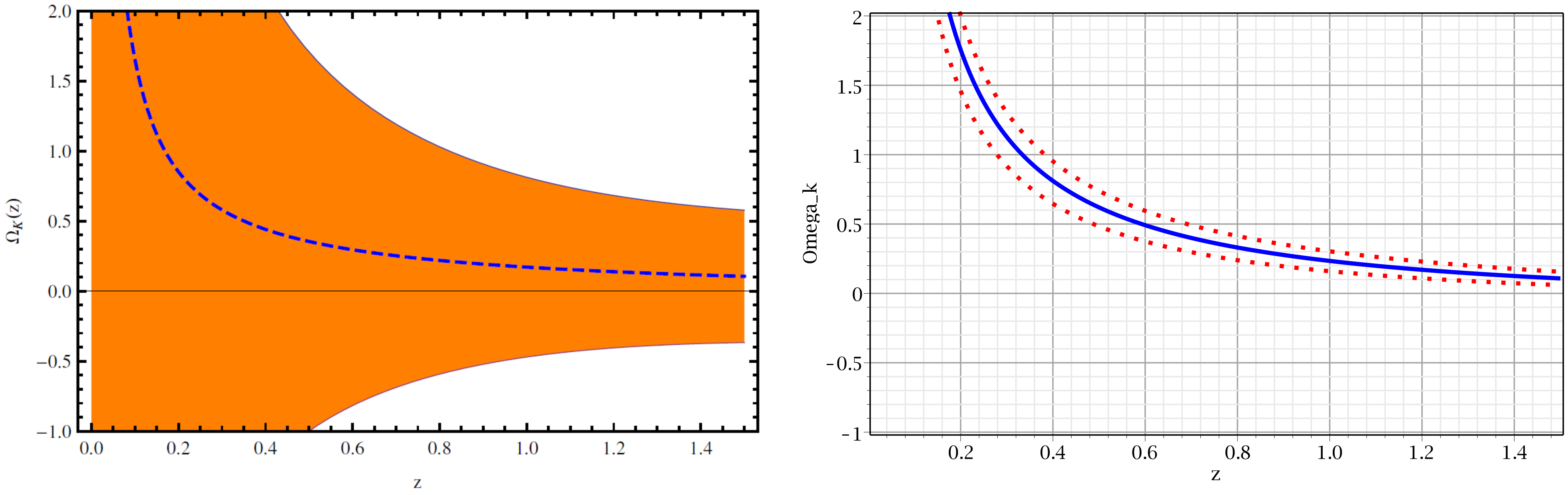
A formal “dark energy equation of state” $w_L(z)$ for the TS model, with $f_{\mathrm{v}0} = 0.695$, calculated directly from $r_w(z)$: **(i)** $\Omega_{\mathrm{M}0} = 0.41$; **(ii)** $\Omega_{\mathrm{M}0} = 0.3175$.

- Description by a “dark energy equation of state” makes no sense when there’s no physics behind it; but average value $w_L \simeq -1$ for $z < 0.7$ makes empirical sense.

Clarkson Bassett Lu test $\Omega_k(z)$

- For Friedmann equation a statistic constant for all z

$$\Omega_{\rm k0} = \Omega_k(z) = \frac{[c^{-1}H(z)D'(z)]^2 - 1}{[c^{-1}H_0 D(z)]^2}$$

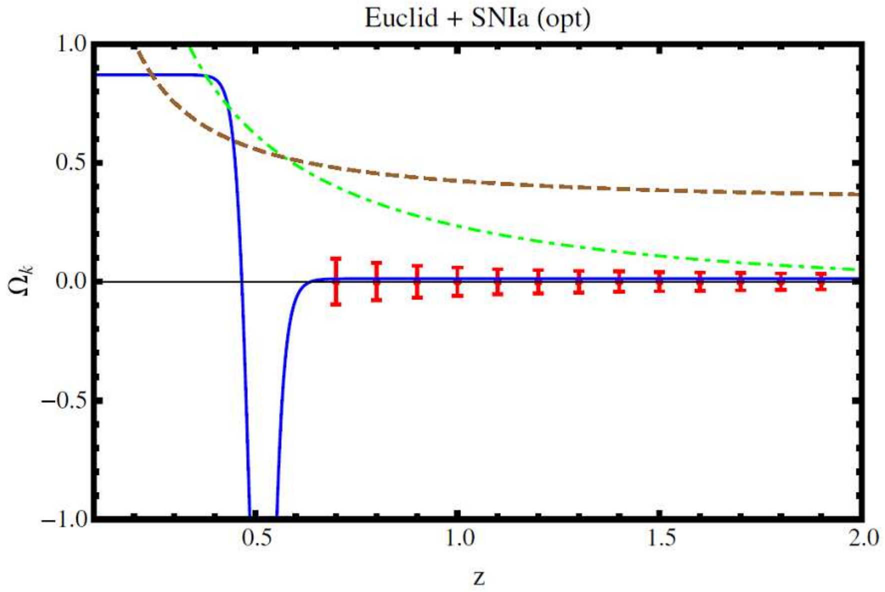


Left panel: CBL statistic from Sapone, Majerotto and Nesseris, PRD 90, 023012 (2014) Fig 8,

using existing data from SneIa (Union2) and passively evolving galaxies for $H(z)$.

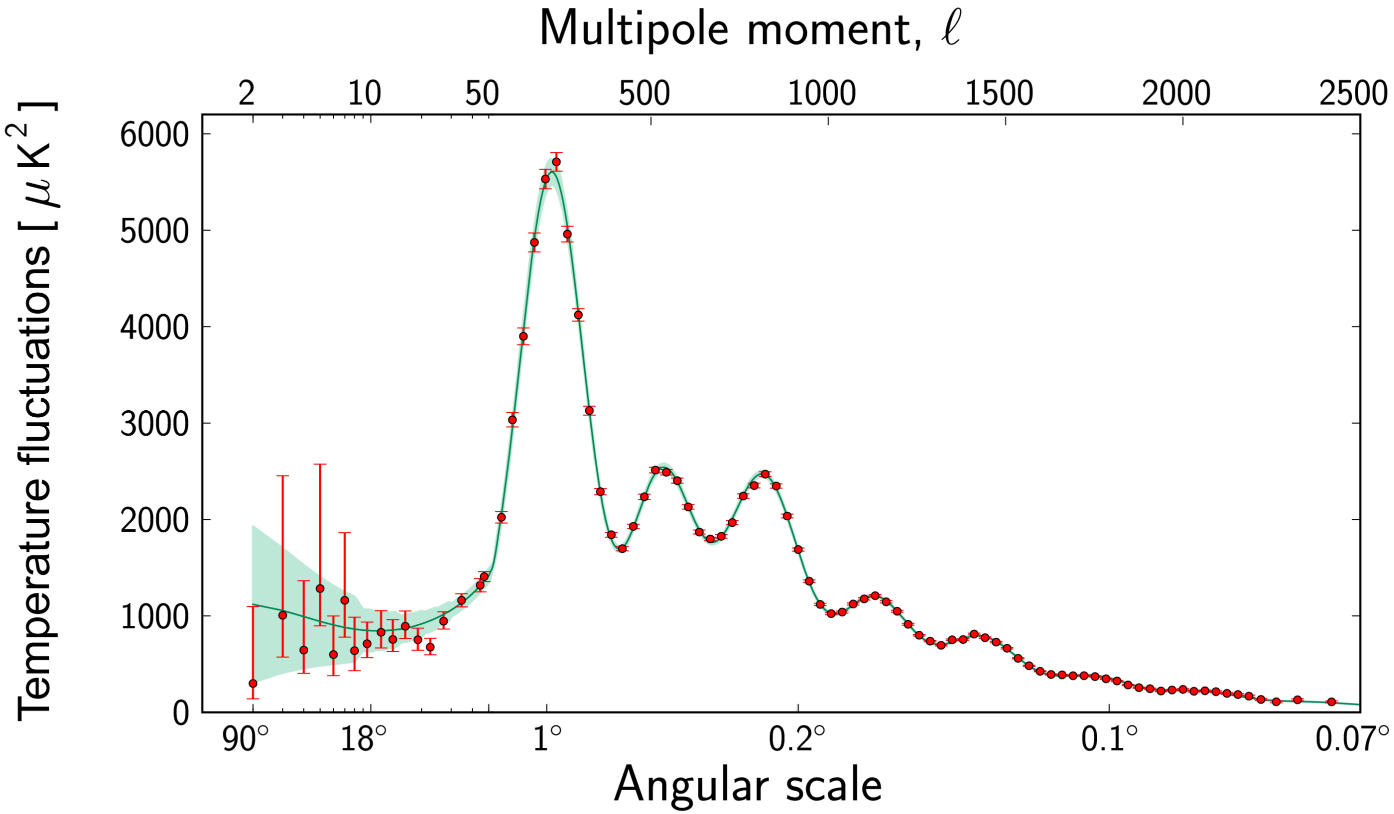
Right panel: TS prediction, with $f_{\rm v0} = 0.695^{+0.041}_{-0.051}$.

Clarkson Bassett Lu test with *Euclid*



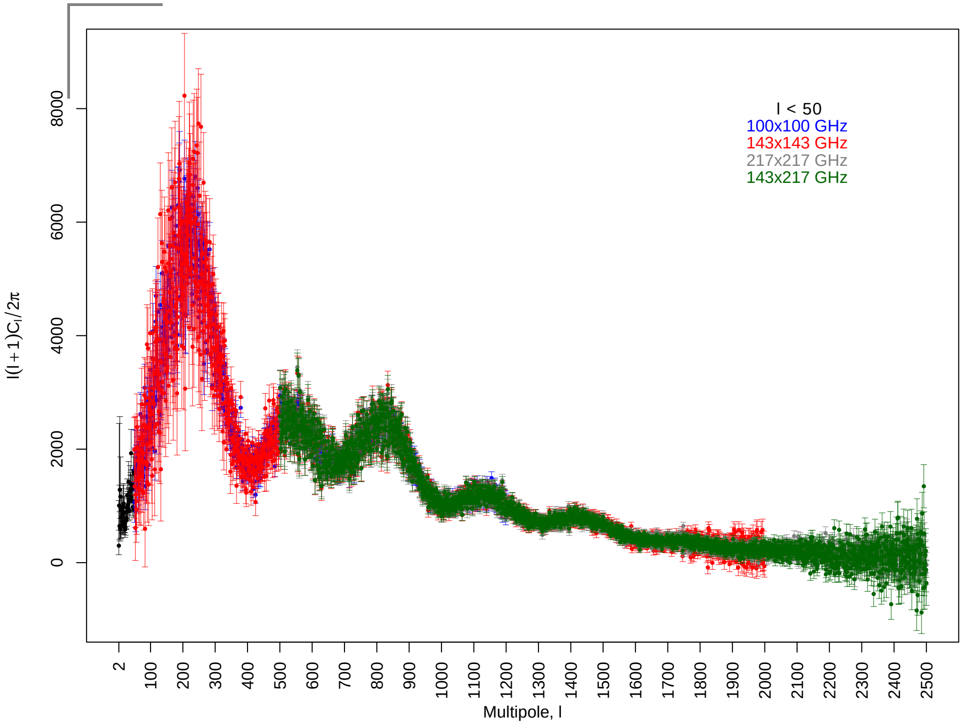
- Projected uncertainties for ΛCDM, with *Euclid* $+$ 1000 SneIa, Sapone *et al*, PRD 90, 023012 (2014) Fig 10
- Timescape prediction (green), compared to non-Copernican Gpc void model (blue), and *tardis* cosmology, Lavinto *et al* JCAP 12 (2013) 051 (brown).
- Timescape prediction becomes greater than uncertainties for $z \lesssim 1.5$. (Falsfiable.)

Planck data ΛCDM parametric fit

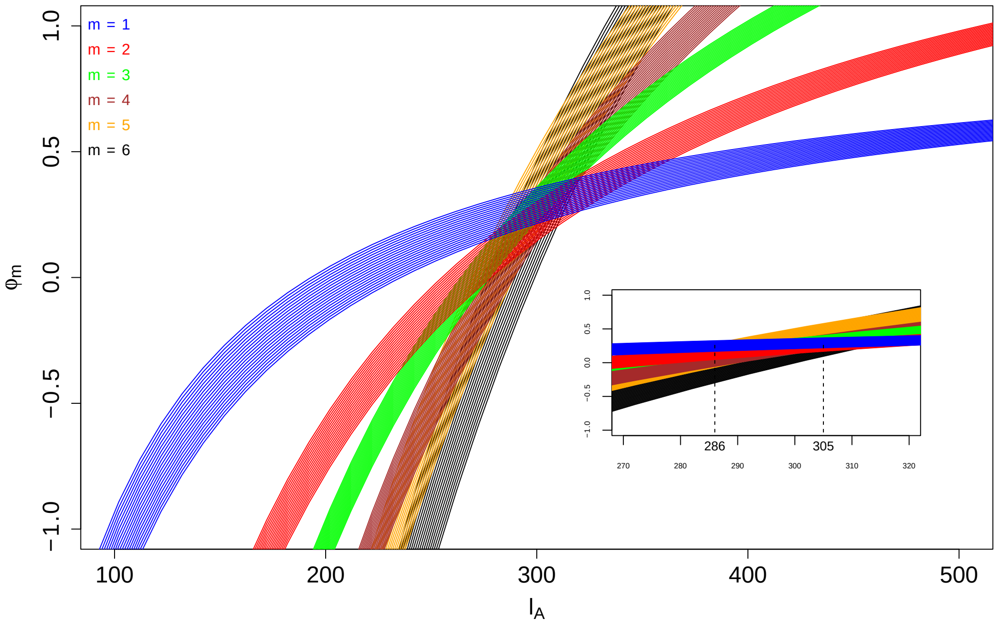


- Can fit angular scale, baryon drag scale from ΛCDM Planck values in non-FLRW models, but not robust
- Initial $|\Omega_{\mathcal{Q}}| \lesssim 10^{-5} \Rightarrow$ 8–13% present epoch parameter uncertainties [Nazer & DLW, PR D91 (2015) 063519]

Non-parametric CMB constraints



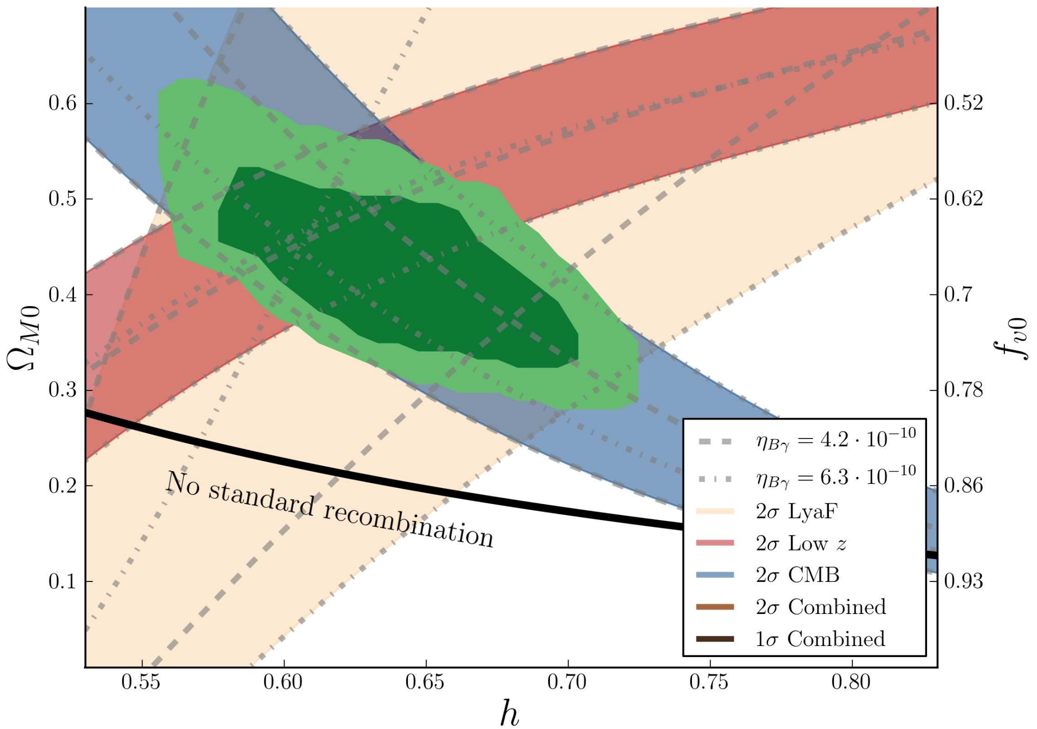
Raw Planck data



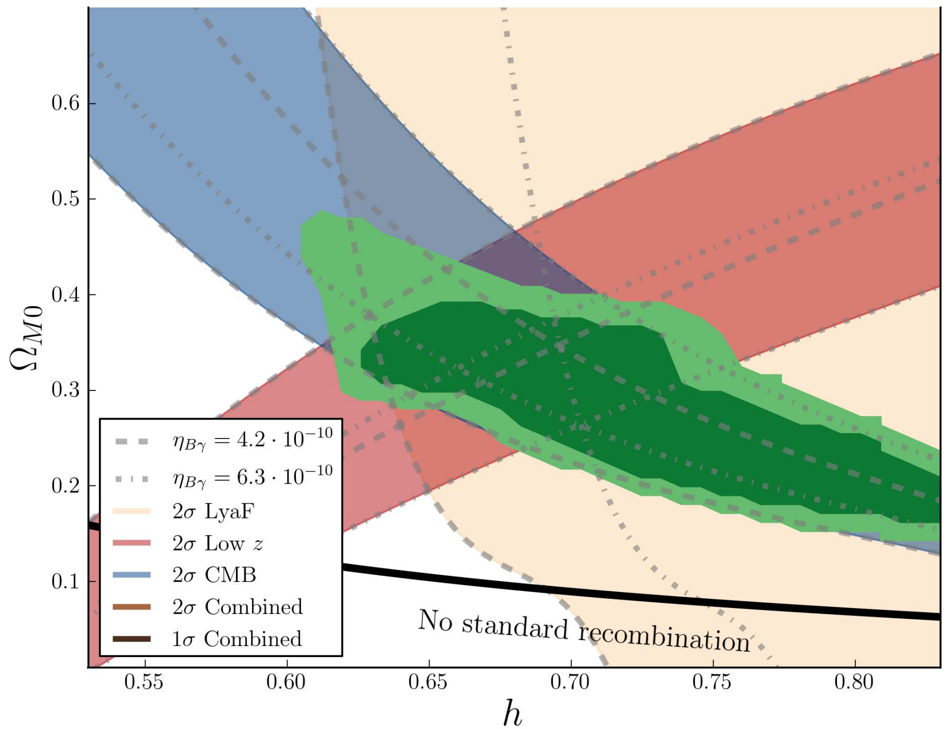
Fit to angular scale from 6 peaks

- What do we know without a cosmological model?
- $286 \leq \ell_A \leq 305$ at 95% confidence Aghamousa et al, JCAP 02(2015)007

CMB sound horizon + BAO LRG / Lyman α



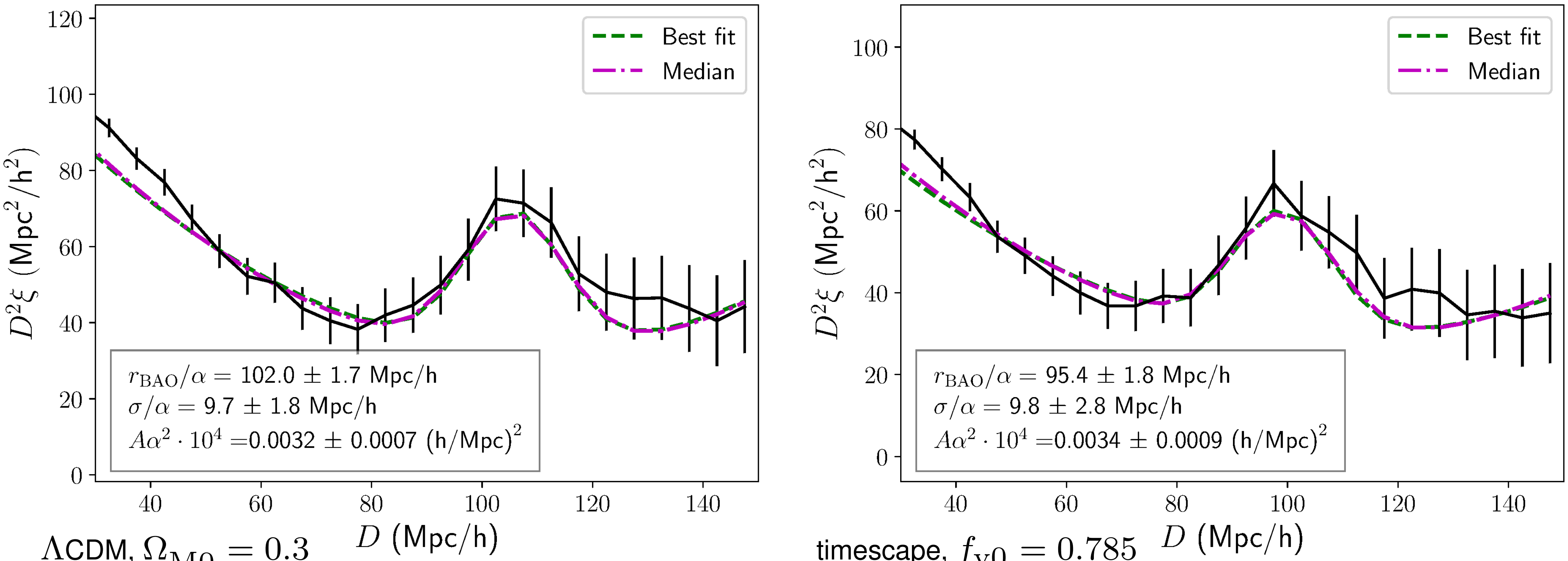
Timescape parameter constraints



Spatially flat ΛCDM parameter constraints

- Non-parametric CMB angular scale constraint (blue, 2σ)
- Baryon acoustic oscillations from BOSS (using FLRW model!) - galaxy clustering statistics $z = 0.38, 0.51, 0.61$ (red, 2σ); Lyman α forest $z = 2.34$ (pink, 2σ)

BAO: beyond FLRW extraction

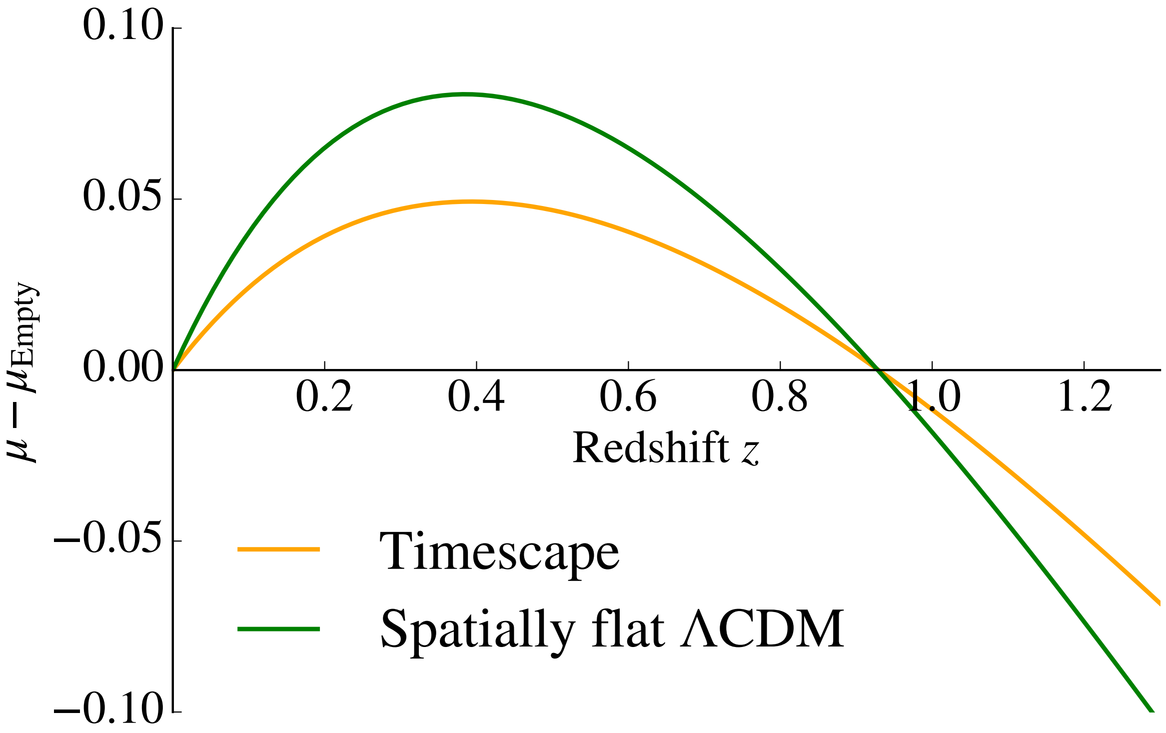


ΛCDM, $\Omega_{\rm M0} = 0.3$

timescape, $f_{\rm v0} = 0.785$

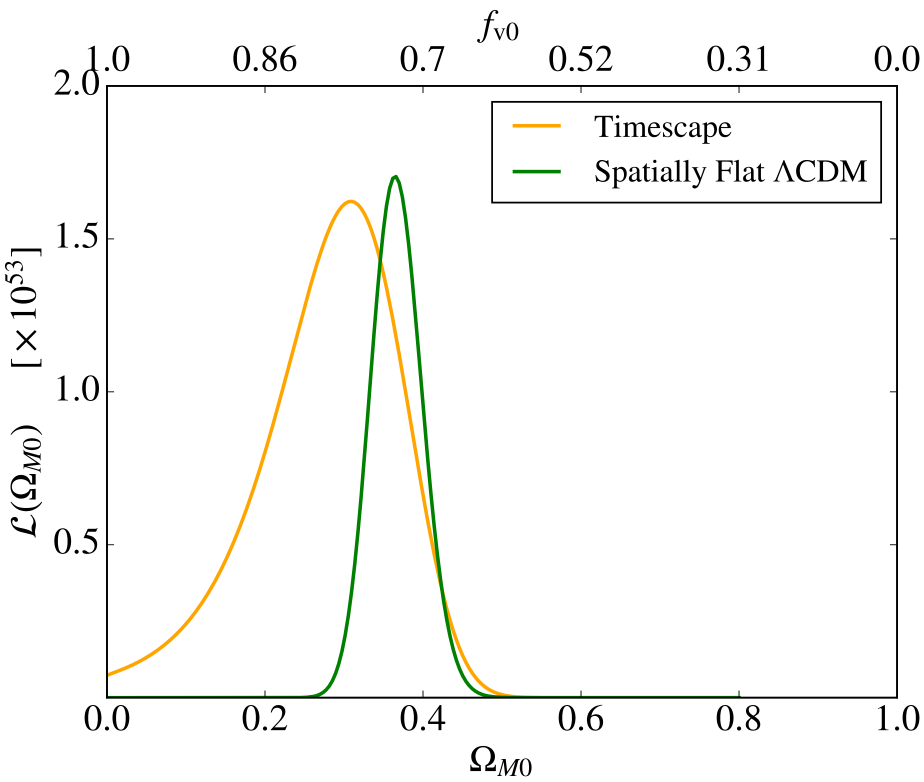
- A. Heinesen, C. Blake, Y-Z. Li, DLW: JCAP 03 (2019) 003 – new methods for generic non-FLRW evolution
- BAO scale successfully extracted for timescape model from BOSS SDSS-III data
- Parameter fits will be third paper in series

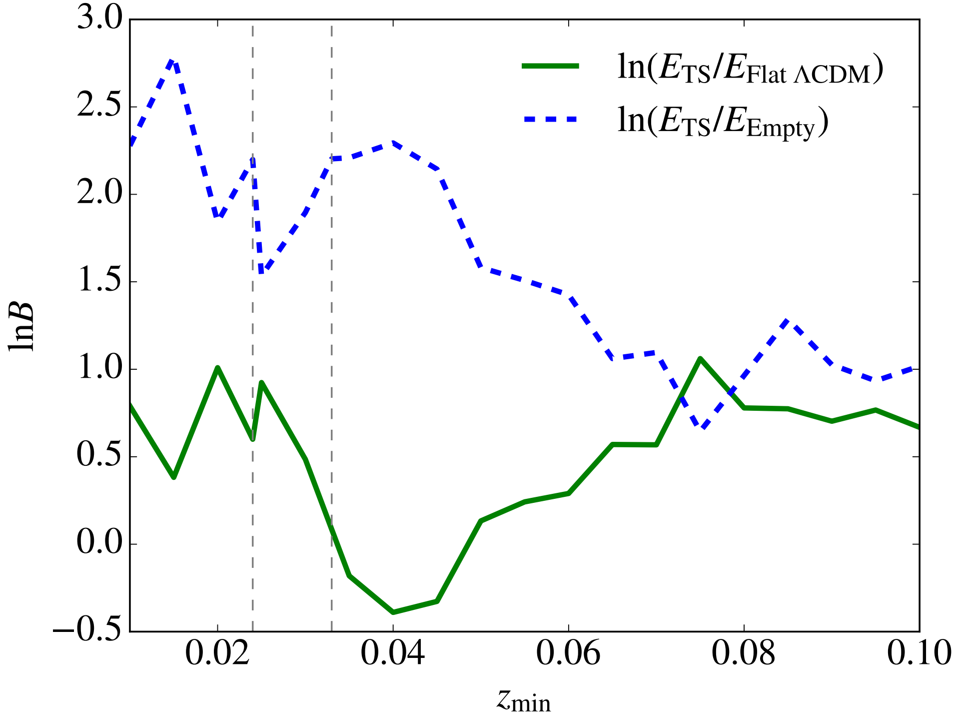
Supernovae Ia: data fits



- Dam, Heinesen + DLW, MNRAS 472 (2017) 835: SALT2 on JLA data (Betouille et al 2014), 740 SneIa, with methodology Nielsen, Guffanti & Sarkar Sci. Rep. 6 (2016) 35596

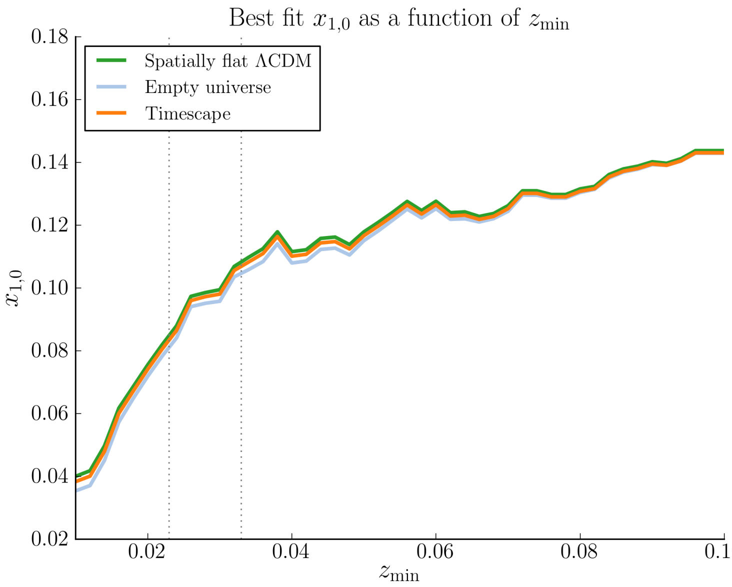
Dam, Heinesen & DLW, arXiv:1706.07236



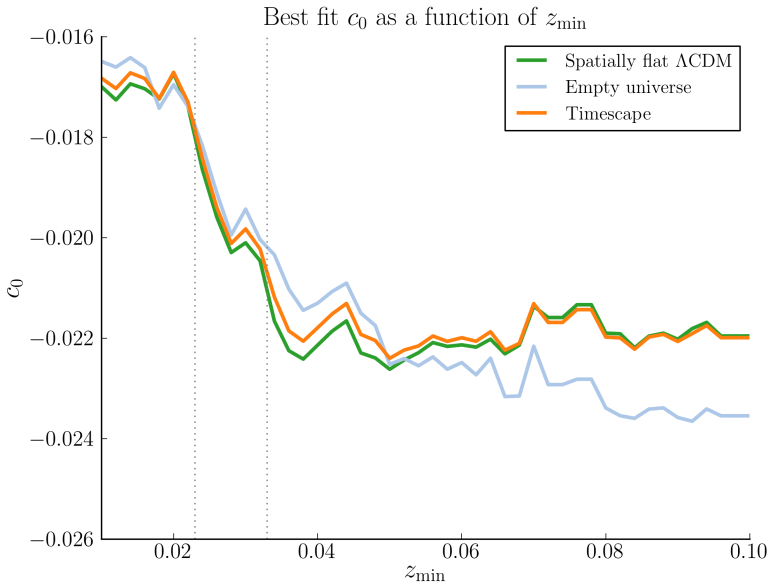


- Timescape / ΛCDM statistically indistinguishable, $\ln B =$ 0.60, 0.08 $z_{\rm min} = 0.024, 0.033$
- Best fit $f_{v0} = 0.778^{+0.063}_{-0.056}$ (or $\Omega_{\rm M0} = 0.33^{+0.06}_{-0.08}$) same as Leith, Ng & DLW, ApJ 672 (2008) L91 fit to Riess07 data

JLA data: SALT2 light curve parameters



$x_{1,0}$



c_0

- Inclusion of SneIa below statistical homogeneity scale significant issue; along with SneI systematics (dust reddening/extinction, intrinsic colour variations)
- Feature consistent with a *Statistical Homogeneity Scale* (SHS) is seen as a systematic *irrespective of model cosmology*

SALT2 systematics

$$\mu \equiv 25 + 5\log_{10}\left(\frac{d_L}{10\,\mathrm{Mpc}}\right)$$

$$\mu_{\rm SN} = m_{\rm B}^* - M_{\rm B} + \alpha x_1 - \beta c$$

- Nielsen et al criticized by Rubin & Hayden, ApJ 833 L30, (2016) who introduce 12 additional empirical parameters (differing in JLA subsamples)

$$x_{1,0} \to x_{1,0,J} + x_{z,J} z, \qquad \text{and} \qquad c_0 \to c_{0,J} + c_{z,J} z,$$

- Systematic issues in JLA Sne Ia data, but RH empirical model reveals cosmological model dependency
- Regardless of which model is better, timescape is a useful diagnostic tool

SALT2 systematics

$$\mu_{\Lambda\mathrm{CDM}} = \mu_0(z) + \tfrac{5}{\ln 10}\left\{(1-\tfrac{3}{4}\Omega_{\mathrm{M0}})z - \left[\tfrac{1}{2}+\tfrac{1}{2}\Omega_{\mathrm{M0}} - \tfrac{27}{32}\Omega_{\mathrm{M0}}^2\right]z^2 + \dots\right\}$$

$$\mu_{\mathrm{TS}} = \mu_0(z) + \tfrac{5}{\ln 10}\left\{\left[\tfrac{24\,{f_{\mathrm{v0}}}^4 - 23\,{f_{\mathrm{v0}}}^3 + 99\,{f_{\mathrm{v0}}}^2 + 8}{2(4\,{f_{\mathrm{v0}}}^2 + f_{\mathrm{v0}} + 4)^2}\right] z - \left[\tfrac{1984\,{f_{\mathrm{v0}}}^8 - 4352\,{f_{\mathrm{v0}}}^7 + 16515{f_{\mathrm{v0}}}^6 + 14770\,{f_{\mathrm{v0}}}^5 + 7819\,{f_{\mathrm{v0}}}^4 - 11328{f_{\mathrm{v0}}}^3 + 32080\,{f_{\mathrm{v0}}}^2 - 128\,f_{\mathrm{v0}} + 960}{24(4{f_{\mathrm{v0}}}^2 + f_{\mathrm{v0}} + 4)^4}\right] z^2 + \dots\right\}$$

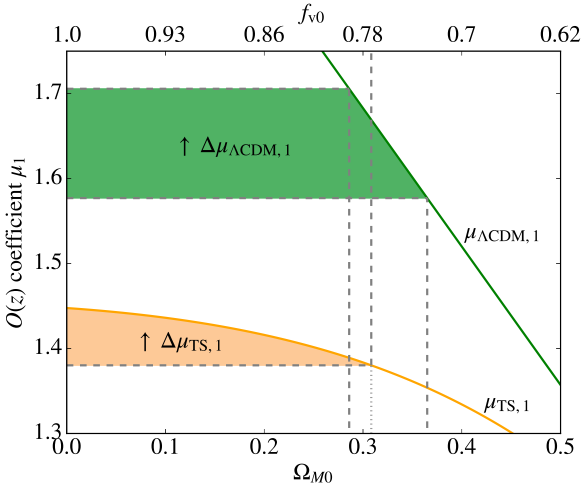
where $\mu_0(z) \equiv 25 + 5\log_{10}(2997.9\,h^{-1}) + 5\log_{10} z$

$$\mu_{\Lambda\mathrm{CDM}}(\Omega_{\mathrm{M0}} = 0.286) - \mu_{\Lambda\mathrm{CDM}}(\Omega_{\mathrm{M0}} = 0.365)$$
$$= 0.1287\,z - 0.0085\,z^2 - 0.0481\,z^3 + 0.0249\,z^4 + \dots$$

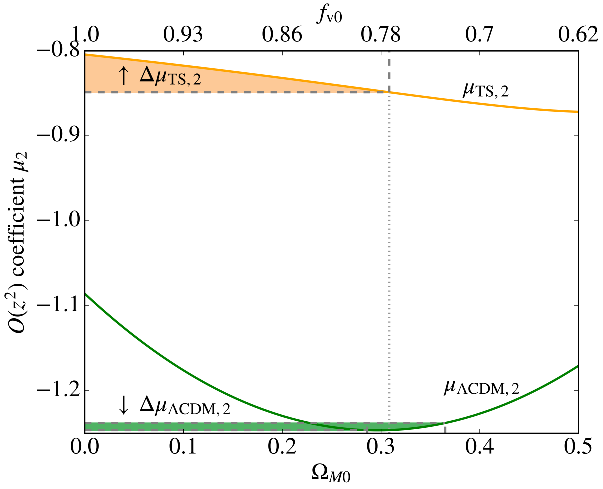
$$\mu_{\mathrm{TS}}(f_{\mathrm{v0}} = 1.0) - \mu_{\mathrm{TS}}(f_{\mathrm{v0}} = 0.778)$$
$$= 0.0674\,z + 0.0444\,z^2 - 0.0242\,z^3 + 0.0190\,z^4 + \dots$$

- ΛCDM: Changes in Ω_{M0} degenerate with SALT2 parameter c, x_1 changes linear in z, near minimum $\Omega_{\mathrm{M0}} = \frac{8}{27} = 0.296$ of O(z^2) Taylor series term.
- Not for timescape: $f_{\mathrm{v0}} \to 1$ unphysical limit.

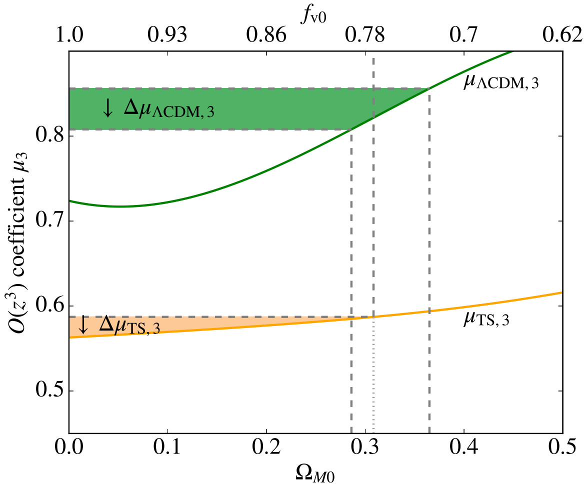
SALT2 systematics



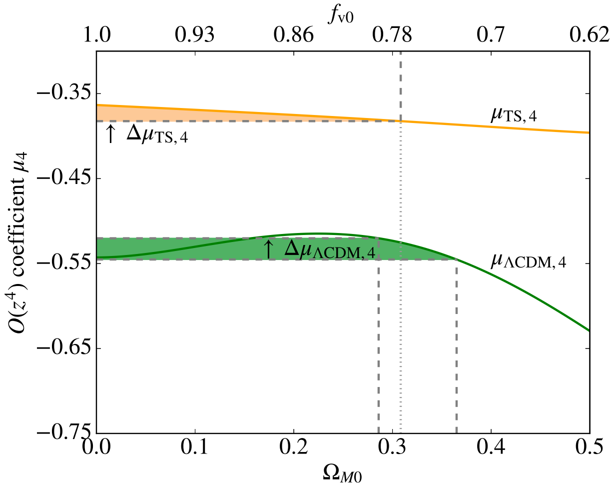
μ_1



μ_2



μ_3



μ_4

Colour parameter degeneracy drives ΛCDM deceleration parameter to particular value (with $\Omega_{\mathrm{M0}} = 8/27 = 0.296$).

Pantheon catalogue

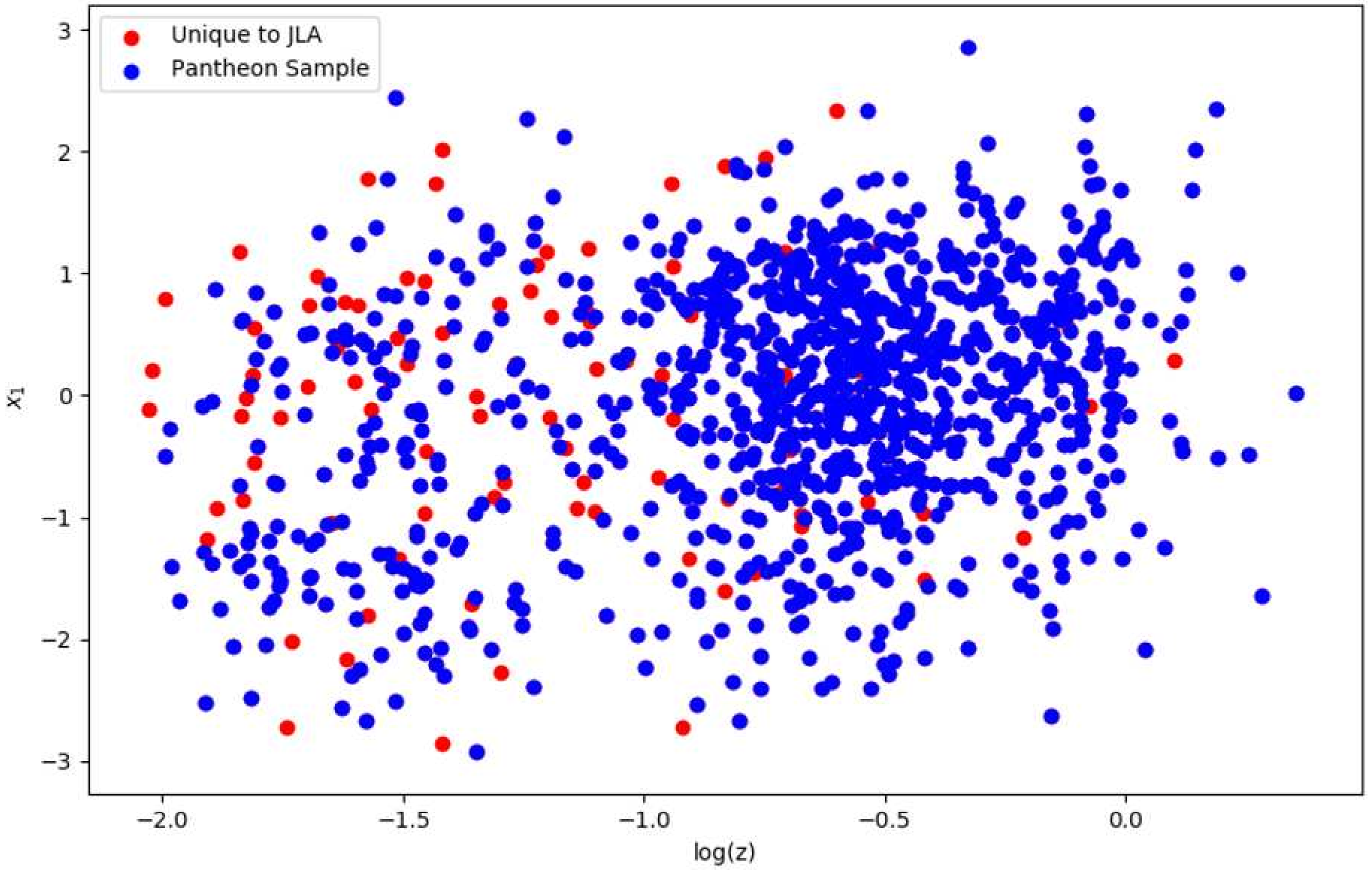
Scolnic et al, ApJ 859 (2018) 101

- 1048 SneIa compared to 740 in JLA catalogue
  - additional 269 SneIa from Pan-STARRS1
  - 646 SneIa in common with JLA (94 excluded)
- SALT2 modified to Tripp formula

$$\mu_{\rm SN} = m^*_{\rm B} - M_{\rm B} + \alpha x_1 - \beta c + \Delta_M + \Delta_B$$

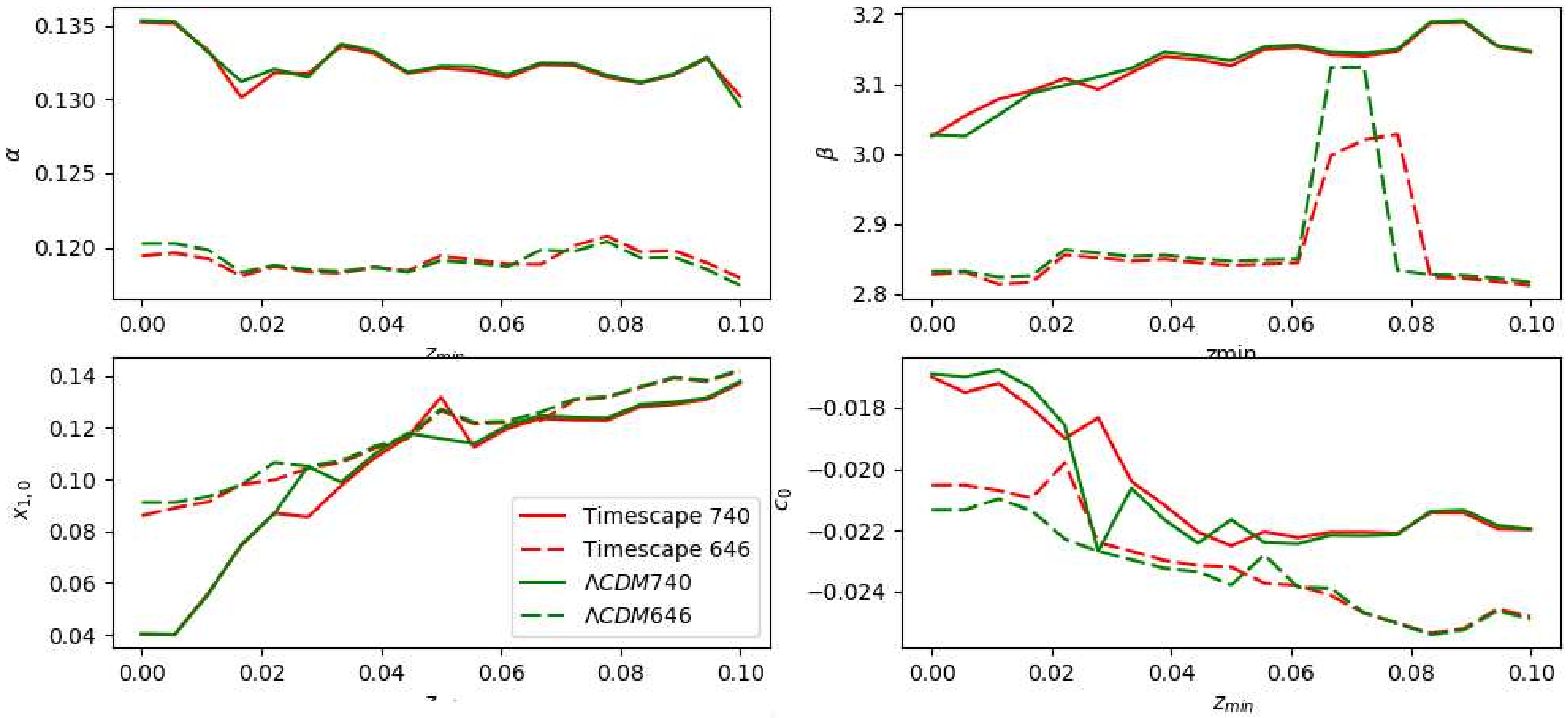
- Extra distance corrections: Δ_M host galaxy correction; Δ_B bias correction using N-body simulations
- Some heliocentric redshifts changed from JLA
- Data presented without full covariance matrix between individual SneIa: previous MLE analysis impossible

Pantheon and JLA-extra SneIa



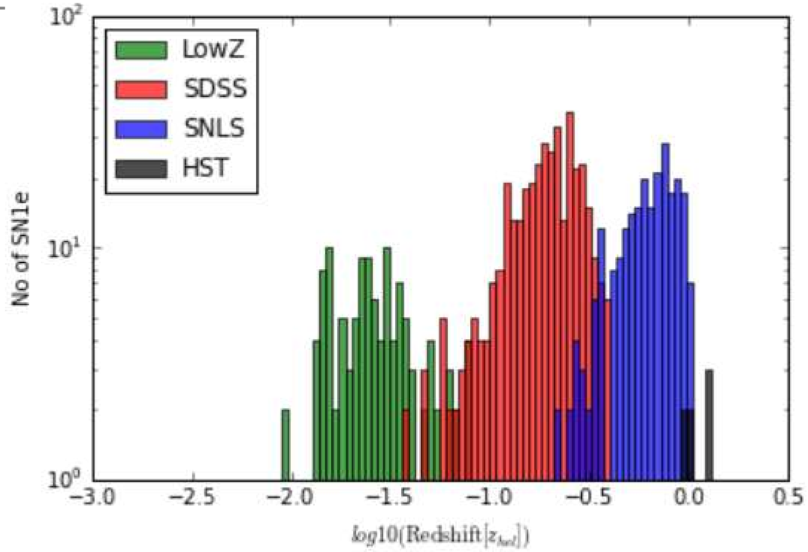
Redshift distribution of Pantheon events (blue); with additional 94 JLA SneIa in red (53 low-z, 36 SDSS, 3 SNLS, 2 HST)

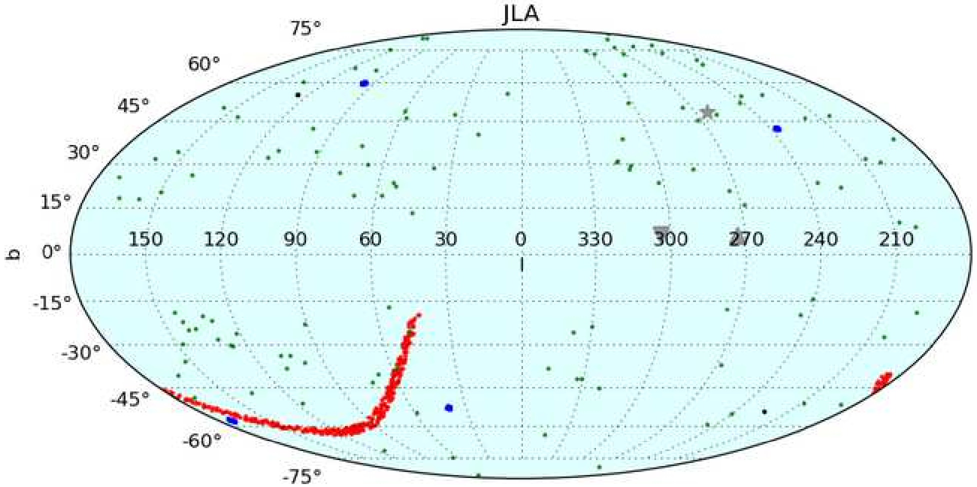
JLA common subsample (R. Gaur)



Reanalysis of JLA for 646 SneIa common to Pantheon:
with $z_{\rm min} = 0.024$ slightly raised $\ln B_{\rm TS:\Lambda CDM} = 1.43$
…but systematic changes raise concerns!

Sky distribution of JLA sample





- Similar concerns by M. Rameez, arXiv:1905.00221, also w.r.t. statistical isotropy claims from Pantheon
- Colin, Mohayaee, M. Rameez & Sarkar show a different interpretation of JLA data, arXiv:1808.04597: *“Apparent cosmic acceleration due to local bulk flow”*

Conclusion

- Friedmann equation should be falsifiable (and maybe already falsified) by GR24 in 2025
- Precision tests of this assumption require removing FLRW assumptions from analysis:
  - BAO reconstruction methods independent of LCDM Fourier space techniques…
  - Raw data needs to be presented in manner non-FLRW modelers can analyse…
  - Need Sne Ia light curved parameters without peculiar velocity modeling using N-body simulations etc
  - Statistical homogeneity scale is an issue
- Non-FLRW models (such as timescape): independent check on modeling of systematic uncertainties