Title: Cosmological Foundations revisited with Pantheon+

Speakers: Antonia Seifert

Collection/Series: Cosmology and Gravitation

Subject: Cosmology

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Abstract:

The standard model of cosmology is built upon the assumptions of homogeneity and isotropy. Invoking backreaction of inhomogeneities leads to an alternative model, the timescape cosmology. It is homogeneous and isotropic on a statistical level but departs from average Friedmann-Lemaître-Robertson-Walker evolution and replaces dark energy by kinetic gravitational energy and its gradients.

In this talk, I will give an overview of the timescape cosmology and present a statistical analysis of the Pantheon+ Type Ia Supernovae spectroscopic comparing the timescape and spatially flat ΛCDM cosmological models. This analysis is based on the Tripp equation for supernova standardisation alone, thereby avoiding any potential correlation in the stretch and colour distributions and finds very strong evidence (ln B > 5) in favour of timescape over ΛCDM when considering the entire Pantheon+ sample.

Cosmological Foundations revisited with Pantheon+

Antonia Seifert

Cosmology Group Seminar
January 28, 2025

work with Zachary Lane, Marco Galoppo,
Ryan Ridden-Harper and David Wiltshire

arXiv:2311.01438
MNRAS, 536, 1752

MNRAS 000, 1–26 (2024) Preprint 8 November 2024 Compiled using MNRAS LaTeX style file v3.2

Cosmological foundations revisited in Pantheon+

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arXiv:2412.15143
MNRAS: Letters, 537, L55

MNRAS 000, 1–6 (2024) Preprint 8 November 2024 Compiled using MNRAS LaTeX style file v3.2

Supernovae evidence for foundational change to cosmological models

Antonia Seifert[1,2], Zachary G. Lane[1]*, Marco Galoppo[1]
Ryan Ridden-Harper[1], and David L. Wiltshire[1]
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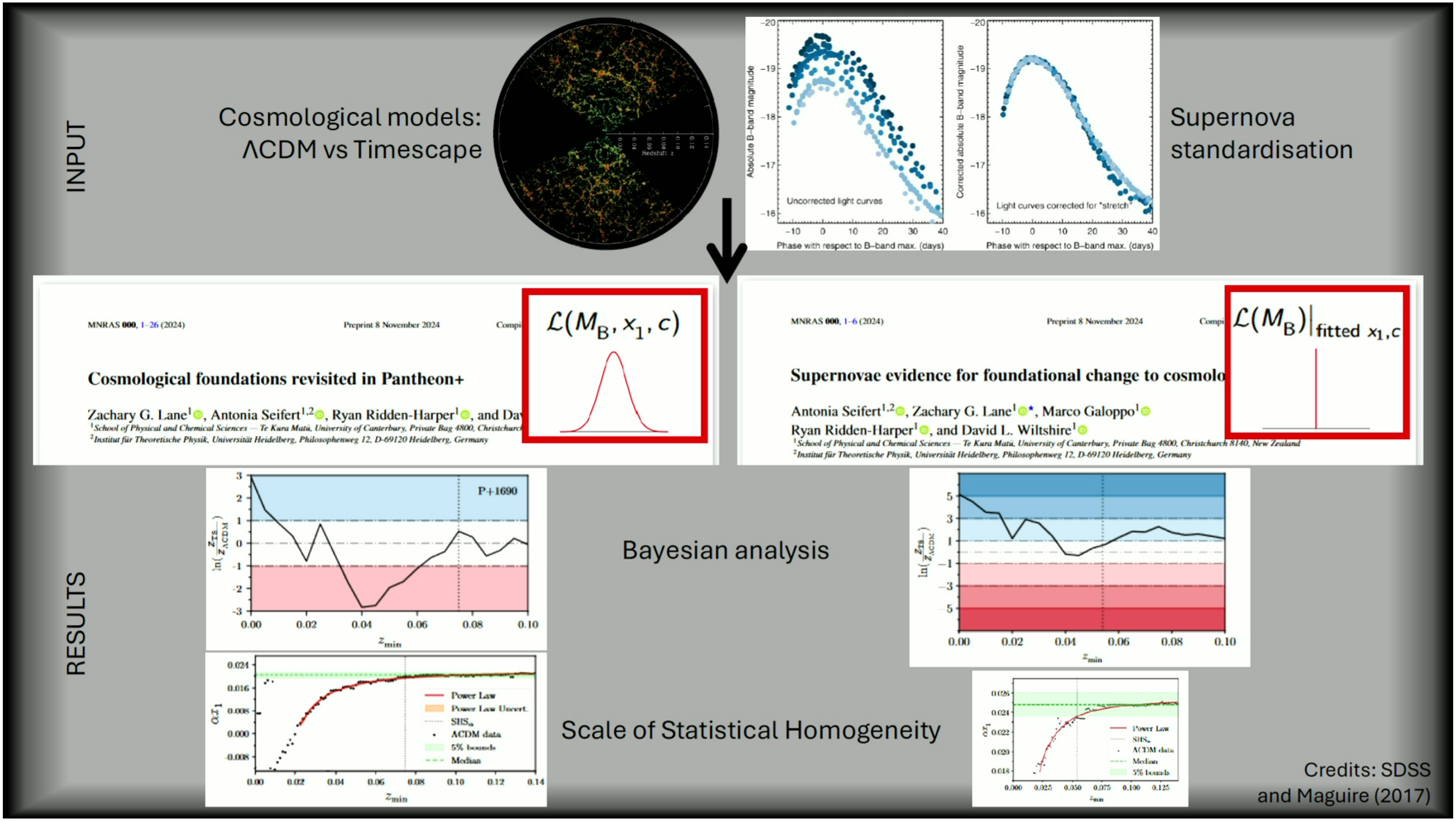
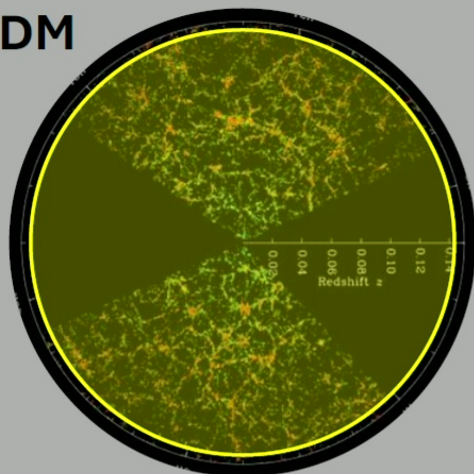
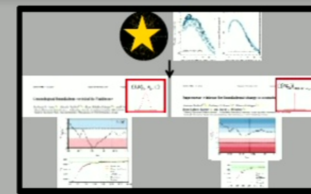

INPUT
Cosmological models:
ΛCDM vs Timescape
Supernova
standardisation
Uncorrected light curves
Light curves corrected for "stretch"
Absolute B–band magnitude
Corrected absolute B–band magnitude
Phase with respect to B–band max. (days)
MNRAS 000, 1–26 (2024)
Preprint 8 November 2024
Cosmological foundations revisited in Pantheon+
Zachary G. Lane[1], Antonia Seifert[1,2], Ryan Ridden-Harper[1], and Da
$\mathcal{L}(M_B, x_1, c)$
MNRAS 000, 1–6 (2024)
Preprint 8 November 2024
Supernovae evidence for foundational change to cosmolo
Antonia Seifert[1,2], Zachary G. Lane[1]*, Marco Galoppo[1]
Ryan Ridden-Harper[1], and David L. Wiltshire[1]
$\mathcal{L}(M_B)|_{\text{fitted } x_1, c}$
RESULTS
P+1690
$\ln\left(\frac{Z_{TS}}{Z_{\Lambda CDM}}\right)$
z_{min}
Bayesian analysis
Power Law
Power Law Uncert.
SHS_a
ΛCDM data
5% bounds
Median
Scale of Statistical Homogeneity
Credits: SDSS
and Maguire (2017)

Cosmological models

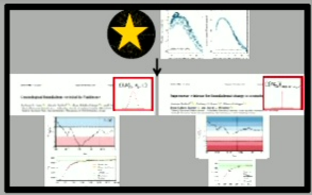
Spatially flat ΛCDM

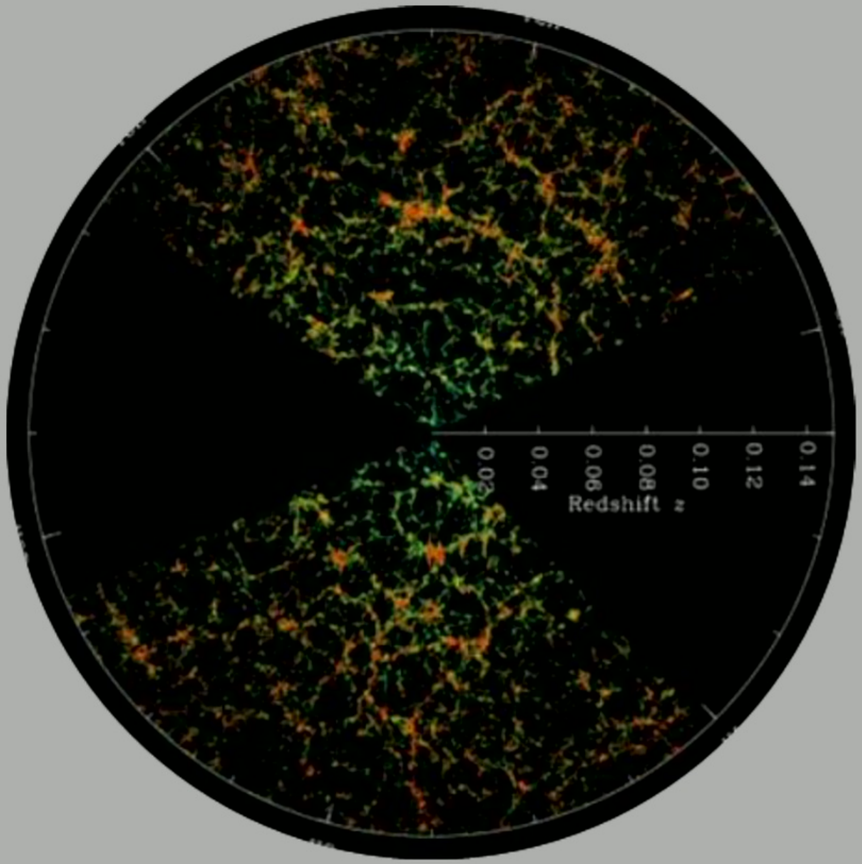


- same metric everywhere
- flat
- homogeneous & isotropic

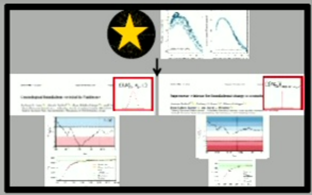


Cosmological models



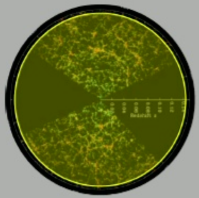


Credit: SDSS



Cosmological models

Spatially flat ΛCDM



- spatially flat metric:

$$ds^2 = -dt^2 + a(t)(dr^2 + r^2 d\Omega)$$

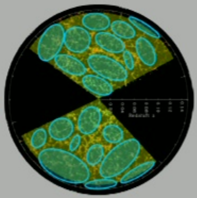
- Friedmann equations:

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

$$\frac{\ddot{a}}{a} = -\frac{4\pi G(1+3w)\rho}{3} + \frac{\Lambda}{3}$$

- model parameter $\Omega_{\mathrm{M}} = \frac{8\pi G\rho}{3H^2} = 1 - \Omega_\Lambda$ for $k = 0$

Timescape



- wall metric:

$$ds^2 = -d\tau_w^2 + a_w(\tau_w)(d\eta_w^2 + \eta_w^2 d\Omega)$$

- void metric:

$$ds^2 = -d\tau_v^2 + a_v(\tau_v)(d\eta_v^2 + \sinh^2(\eta_v)\, d\Omega)$$

- volume average weighted with void fraction f_v (Buchert 2000, Wiltshire 2007)

$$\bar{a}^3 = \frac{V(t)}{V(t_0)} = f_{vi} a_v^3 + (1 - f_{vi}) a_w^3$$

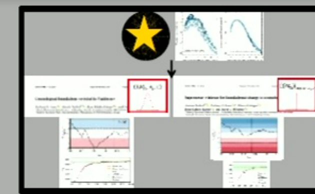
- Friedmann-like evolution equations:

$$\frac{\dot{\bar{a}}^2}{\bar{a}^2} = \frac{8\pi G\langle\rho\rangle}{3} - \frac{\langle\mathcal{R}\rangle}{6} - \frac{\mathcal{Q}}{6}$$

$$\frac{\ddot{\bar{a}}}{\bar{a}} = -\frac{4\pi G\langle\rho\rangle}{3} + \frac{\mathcal{Q}}{3}$$

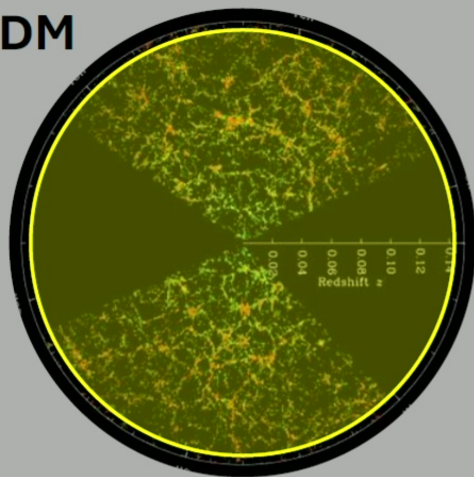
- $\langle\mathcal{R}\rangle$ and backreaction $\mathcal{Q} = \frac{2\dot{f}_v^2}{3f_v(1-f_v)}$ functions of f_v

Credit: D. Wiltshire



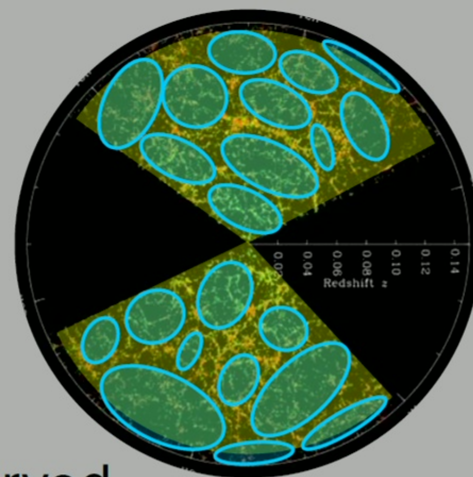
Cosmological models

Spatially flat ΛCDM



- same metric everywhere
- flat
- homogeneous & isotropic
- model parameter: Ω_{M}

Timescape

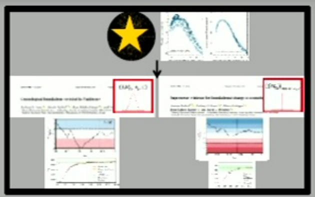


- wall metric: flat
- void metric: negatively curved
- not homogeneous
- model parameter: f_v

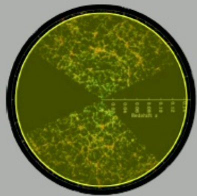
metric(s) $\mathrm{d}s^2$ → luminosity distance d_L

Credit: SDSS

Cosmological models



Spatially flat ΛCDM



- Luminosity distance d_L:

$$\frac{d_L}{(1+z)^2} = d_A = \frac{a_0 \chi(r)}{1+z}$$

- Spatially flat: $\chi(r) = r$

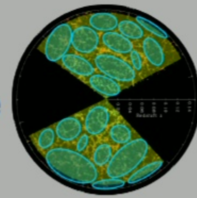
- From geometry:

$$ds^2 = -dt^2 + a(t)(dr^2 + \chi^2(r)\, d\Omega)$$

$$a\, dr = dt$$

$$\chi(r) = r = \int_t^{t_0} \frac{dt}{a} = \int_t^{t_0} \frac{da}{a\, H(a)}$$

Timescape



- Luminosity distance d_L:

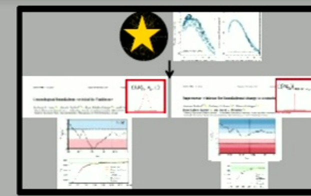
$$\frac{d_L}{(1+z)^2} = d_A = \frac{a_0 r_w}{1+z}$$

- Volume-averaged geometry:
  conformal time $\bar{a}\, d\bar{\eta} = dt = \bar{\gamma}\, d\tau_w = \bar{\gamma}\, \underbrace{\bar{a} \left(\frac{1-f_v}{f_{wi}}\right)^{\frac{1}{3}}}_{a_w} d\eta_w$

- Observer in wall: $ds^2 = -d\tau_w^2 + a_w(\tau_w)(d\eta_w^2 + \eta_w^2 d\Omega)$

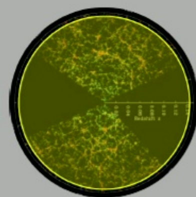
$$ds^2 = -\frac{dt^2}{\bar{\gamma}} + \frac{\bar{a}}{\bar{\gamma}}\left(d\bar{\eta}^2 + \underbrace{\left(\frac{\bar{\gamma}(1-f_v)^{\frac{1}{3}}}{f_{wi}^{\frac{1}{3}}} \eta_w \right)^2}_{r_w} d\Omega \right)$$

Credit: D. Wiltshire



Cosmological models

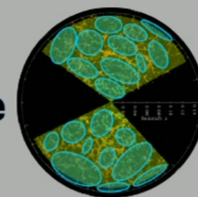
Spatially flat ΛCDM



- Luminosity distance d_L:

$$\frac{d_L}{(1+z)^2} = d_A = \frac{a_0 \chi(r)}{1+z}$$

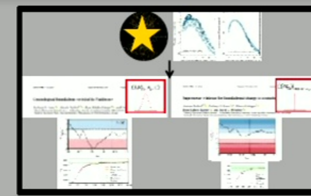
Timescape



- Luminosity distance d_L:

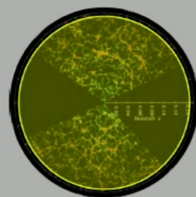
$$\frac{d_L}{(1+z)^2} = d_A = \frac{a_0 r_w}{1+z}$$

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



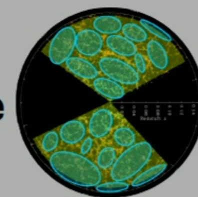
Cosmological models

Spatially flat ΛCDM



- Luminosity distance d_L:
$$\frac{d_L}{(1+z)^2} = d_A = \frac{a_0\chi(r)}{1+z}$$
- Spatially flat: $\chi(r) = r$
- From geometry:
$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a(t)(\mathrm{d}r^2 + \chi^2(r)\,\mathrm{d}\Omega)$$
$$a\,\mathrm{d}r = \mathrm{d}t$$
$$\chi(r) = r = \int_t^{t_0}\frac{\mathrm{d}t}{a} = \int_t^{t_0}\frac{\mathrm{d}a}{a\,H(a)}$$

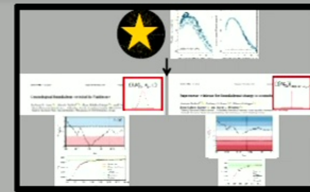
Timescape



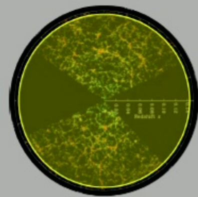
- Luminosity distance d_L:
$$\frac{d_L}{(1+z)^2} = d_A = \frac{a_0 r_w}{1+z}$$
- Volume-averaged geometry: conformal time $\bar{a}\,\mathrm{d}\bar{\eta} = \mathrm{d}t = \bar{\gamma}\,\mathrm{d}\tau_w = \bar{\gamma}\,\underbrace{\bar{a}\left(\frac{1-f_v}{f_{wi}}\right)^{\frac{1}{3}}}_{a_w}\mathrm{d}\eta_w$
- Observer in wall: $\mathrm{d}s^2 = -\mathrm{d}\tau_w^2 + a_w(\tau_w)(\mathrm{d}\eta_w^2 + \eta_w^2\mathrm{d}\Omega)$
$$\mathrm{d}s^2 = -\frac{\mathrm{d}t^2}{\bar{\gamma}} + \frac{\bar{a}}{\bar{\gamma}}\left(\mathrm{d}\bar{\eta}^2 + \underbrace{\left(\frac{\bar{\gamma}(1-f_v)^{\frac{1}{3}}}{f_{wi}^{\frac{1}{3}}}\eta_w\right)^2}_{r_w}\mathrm{d}\Omega\right)$$
$$r_w = \frac{\bar{\gamma}(1-f_v)^{\frac{1}{3}}}{f_{wi}^{\frac{1}{3}}}\int \mathrm{d}\eta_w = \bar{\gamma}(1-f_v)^{\frac{1}{3}}\int_t^{t_0}\frac{\mathrm{d}t}{\bar{\gamma}(1-f_v)^{\frac{1}{3}}\bar{a}}$$

Credit: D. Wiltshire

Cosmological models



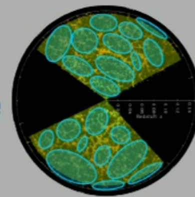
Spatially flat ΛCDM



- Luminosity distance d_L:

$$\frac{d_L}{(1+z)^2} = d_A = \frac{a_0 \chi(r)}{1+z}$$

Timescape



- Luminosity distance d_L:

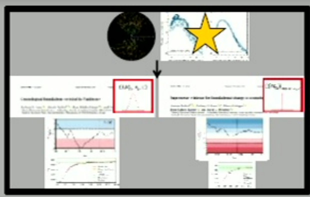
$$\frac{d_L}{(1+z)^2} = d_A = \frac{a_0 r_w}{1+z}$$

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

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

$$\mu_{\Lambda\mathrm{CDM}} = \mu_0(z) + \frac{5}{\ln 10}\left\{(1 - \tfrac{3}{4}\Omega_{M0})z - \left[\tfrac{1}{2} + \tfrac{1}{2}\Omega_{M0} - \tfrac{27}{32}\Omega_{M0}^2\right] z^2 + \left[\tfrac{1}{3} - \tfrac{1}{8}\Omega_{M0} + \tfrac{21}{16}\Omega_{M0}^2 - \tfrac{45}{32}\Omega_{M0}^3\right] z^3 + \dots\right\}.$$

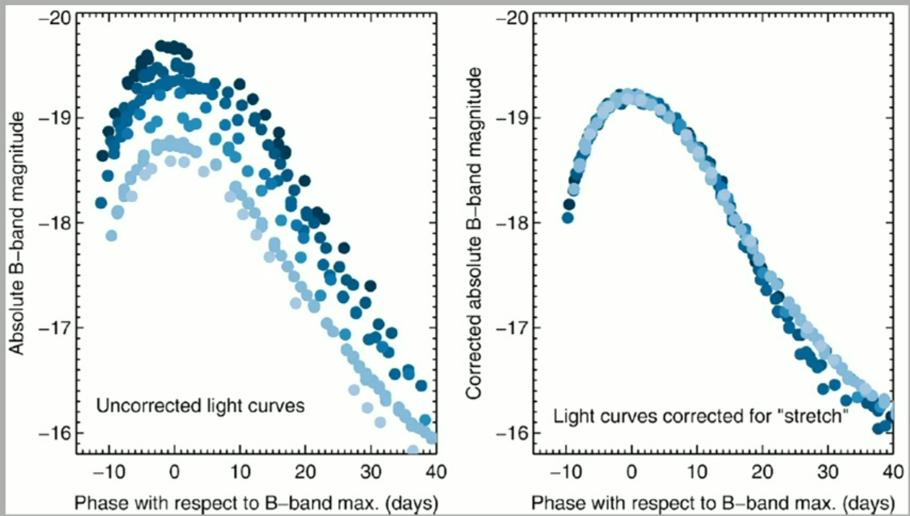
Credit: D. Wiltshire



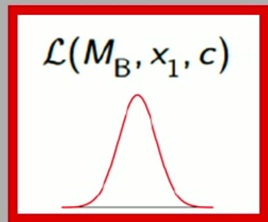
Supernova standardisation

- Tripp equation:
  $$\mu = m_{\mathrm{B}}^{*} - M_{\mathrm{B}} + \alpha x_1 - \beta c$$

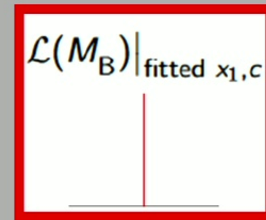
- Distance modulus
- SALT2 fit variables
- Cosmology constants
- Absolute magnitude (*B* filter)

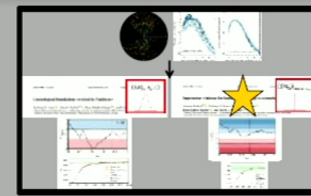


Credit: Maguire (2017)



Likelihood



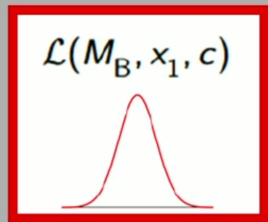


- Assumption:
  the fit values of all supernovae follow the same Gaussian
- 3N-dimensional Gaussian distribution for fitted values

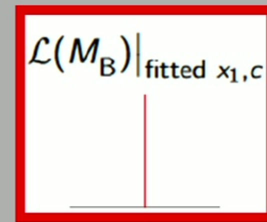
$$X - \hat{X} = \begin{pmatrix} M_\mathrm{B} - \alpha x_1 + \beta c \\ x_1 \\ c \end{pmatrix} - \begin{pmatrix} \mu - \widehat{m}_\mathrm{B}^* \\ \hat{x}_1 \\ \hat{c} \end{pmatrix}$$

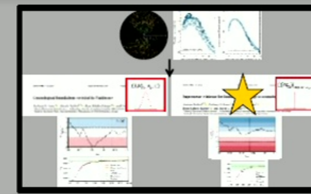
- No assumptions on the gaussianity of the SALT2 parameters
- Take the fit values as true values in the Tripp equation

$$X - \hat{X} = (M_\mathrm{B} - \alpha \hat{x}_1 + \beta \hat{c}) - (\mu - \widehat{m}_\mathrm{B}^*)$$



Likelihood

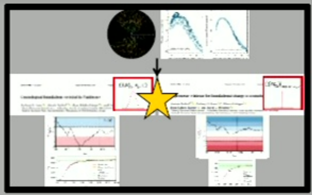


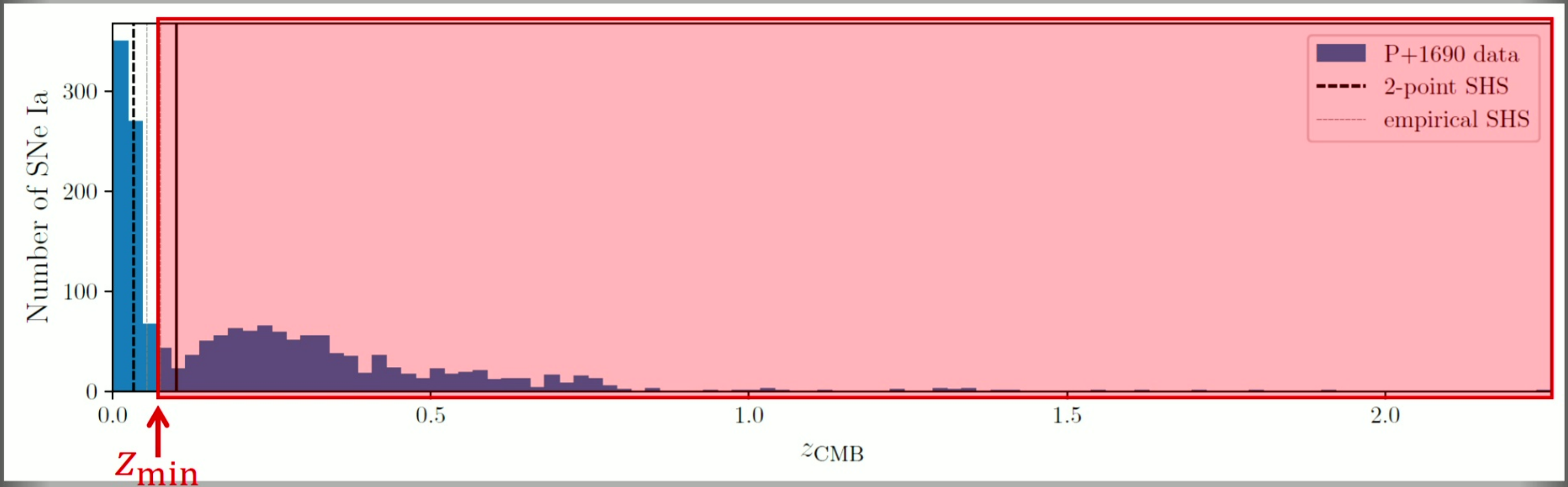


$$X - \hat{X} = \begin{pmatrix} M_\mathrm{B} - \alpha x_1 + \beta c \\ x_1 \\ c \end{pmatrix} - \begin{pmatrix} \mu - \hat{m}_\mathrm{B}^* \\ \hat{x}_1 \\ \hat{c} \end{pmatrix} \quad \Bigg| \quad X - \hat{X} = (M_\mathrm{B} - \alpha \hat{x}_1 + \beta \hat{c}) - (\mu - \hat{m}_\mathrm{B}^*)$$

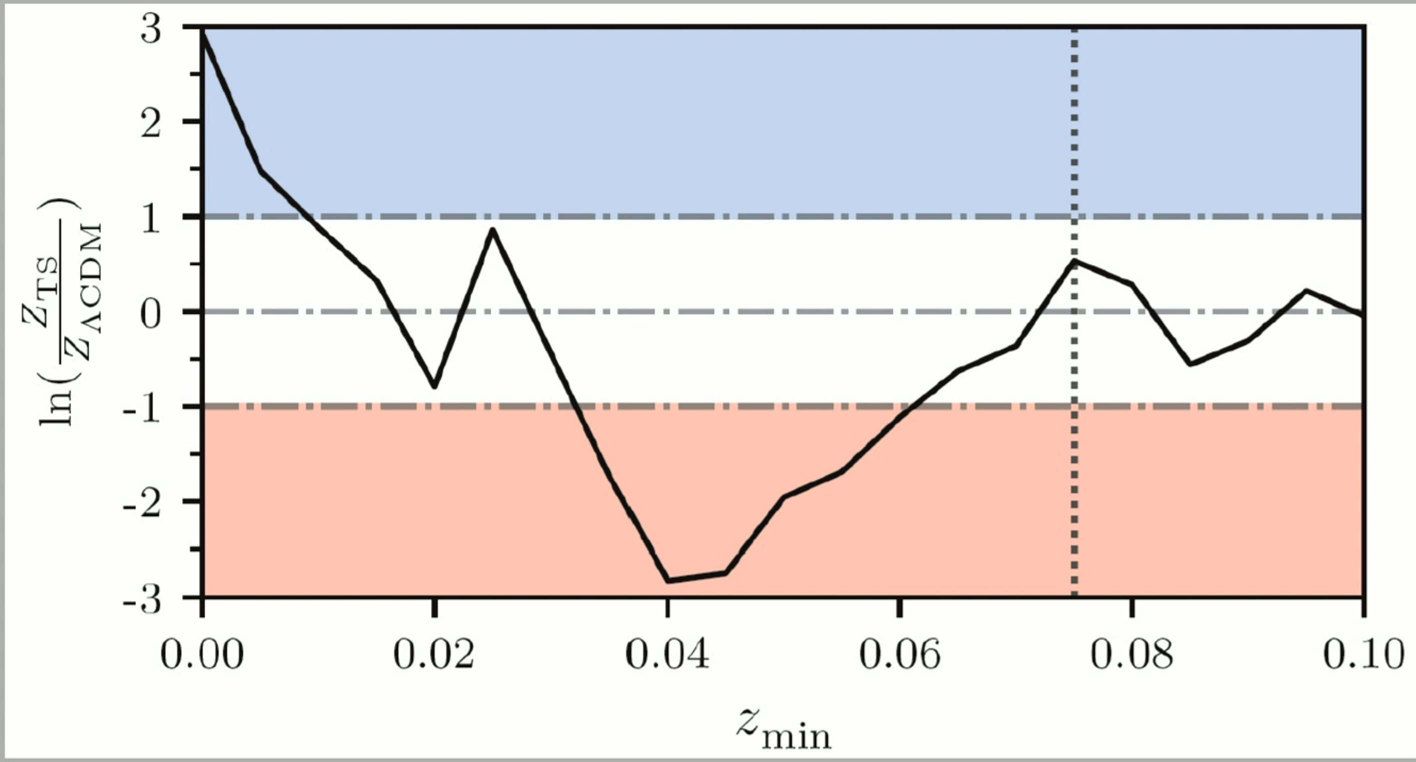
- Likelihood $\mathcal{L} \propto \exp\left(-\frac{(X-\hat{X})^T \Sigma^{-1} (X-\hat{X})}{2}\right)$
- Covariance Σ:
  - Gaussian variance $\sigma_{M_B}^2, \sigma_{x_1}^2, \sigma_c^2$
  - Statistical covariance (SALT2 fit)
  - Systematics:
    - Bias corrections
    - Gravitational lensing
    - Redshift measurement uncertainty
    - Peculiar velocities

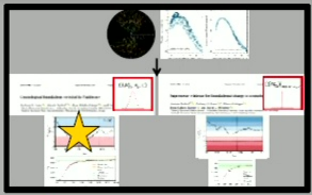
Bayesian Analysis

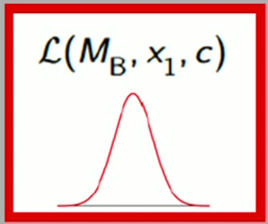




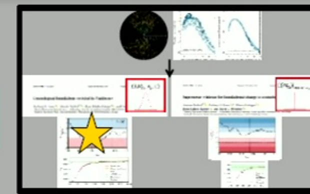
Bayesian Analysis: Gaussian Likelihood

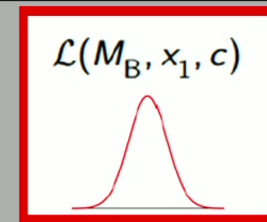


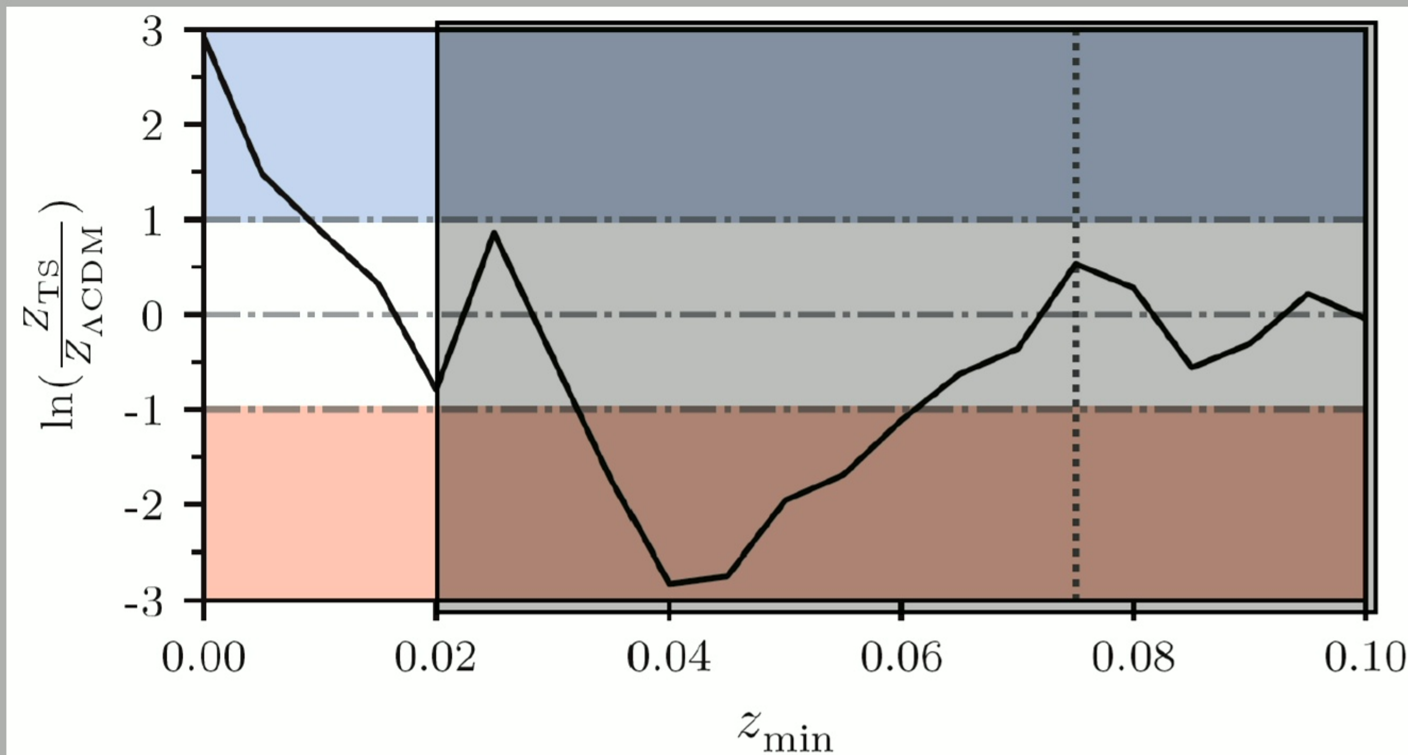




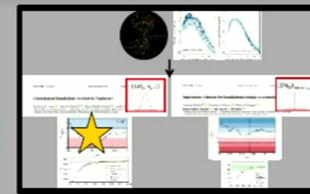
Bayesian Analysis: Gaussian Likelihood

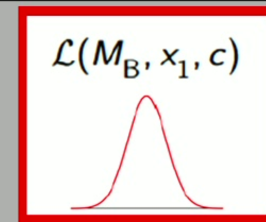


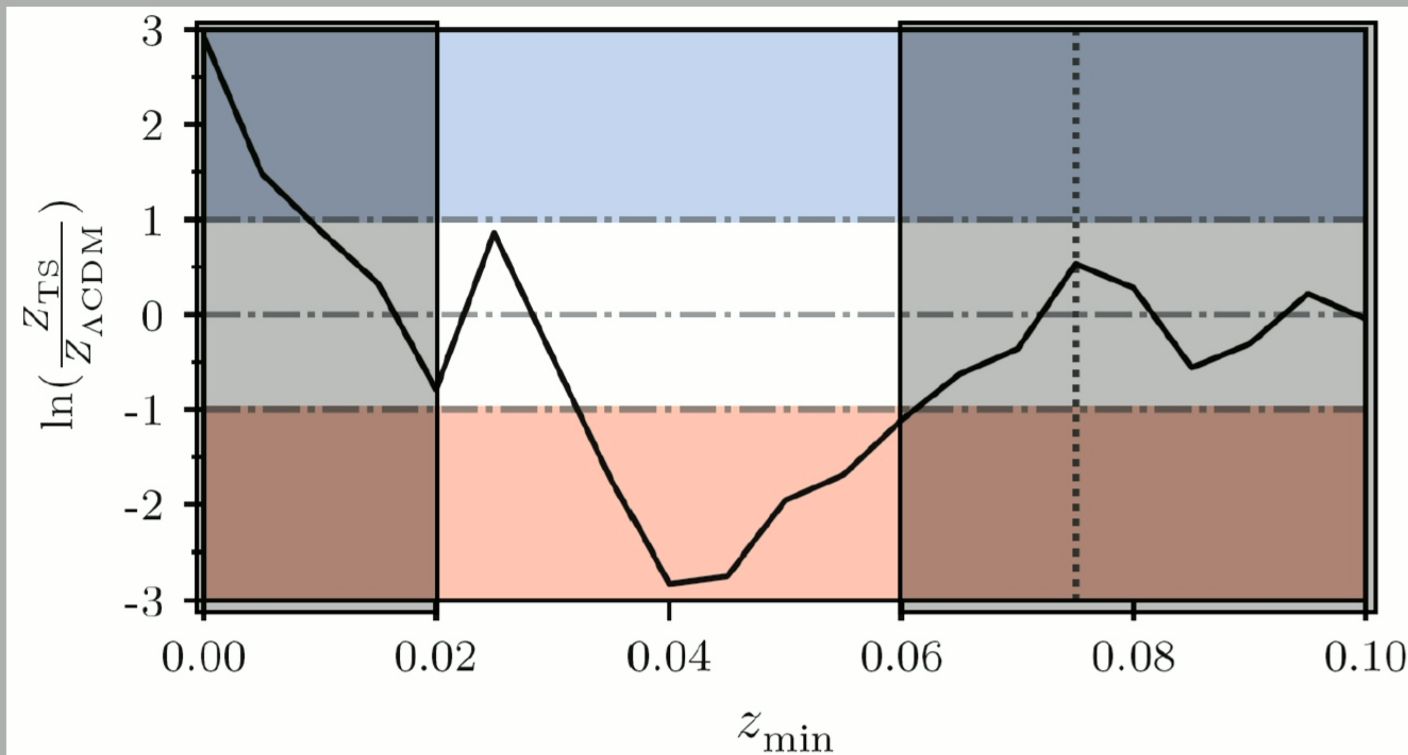




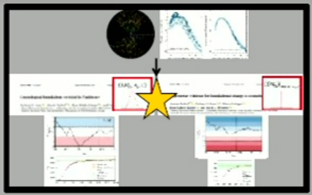
Bayesian Analysis: Gaussian Likelihood

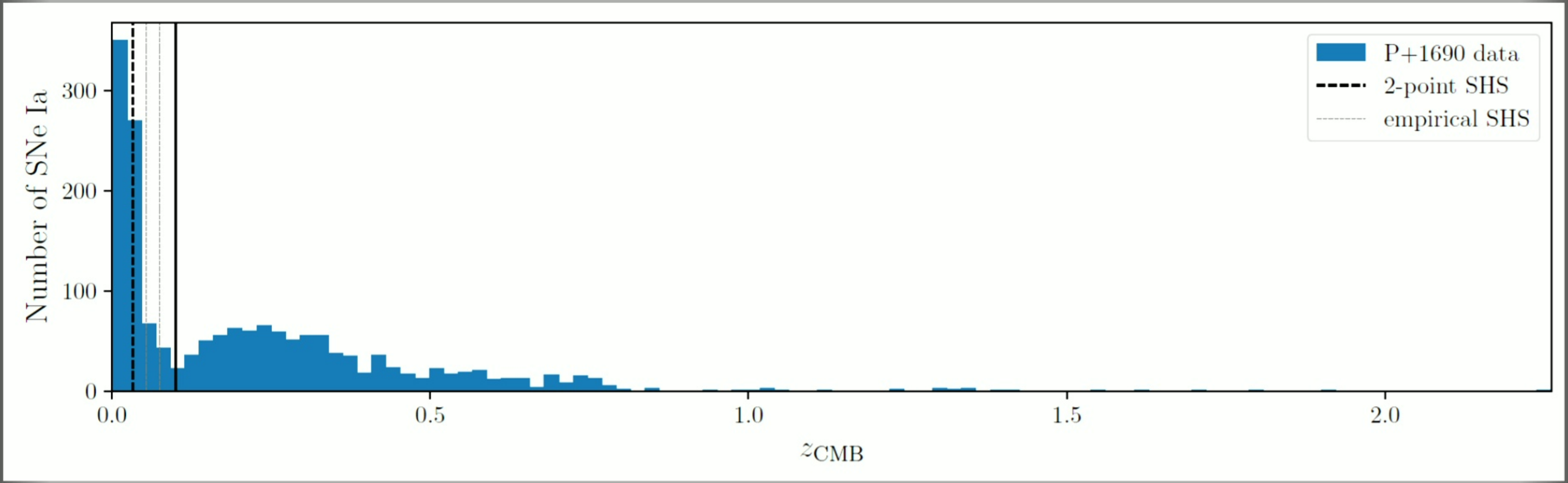






Bayesian Analysis





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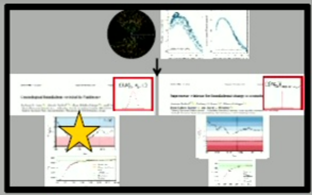
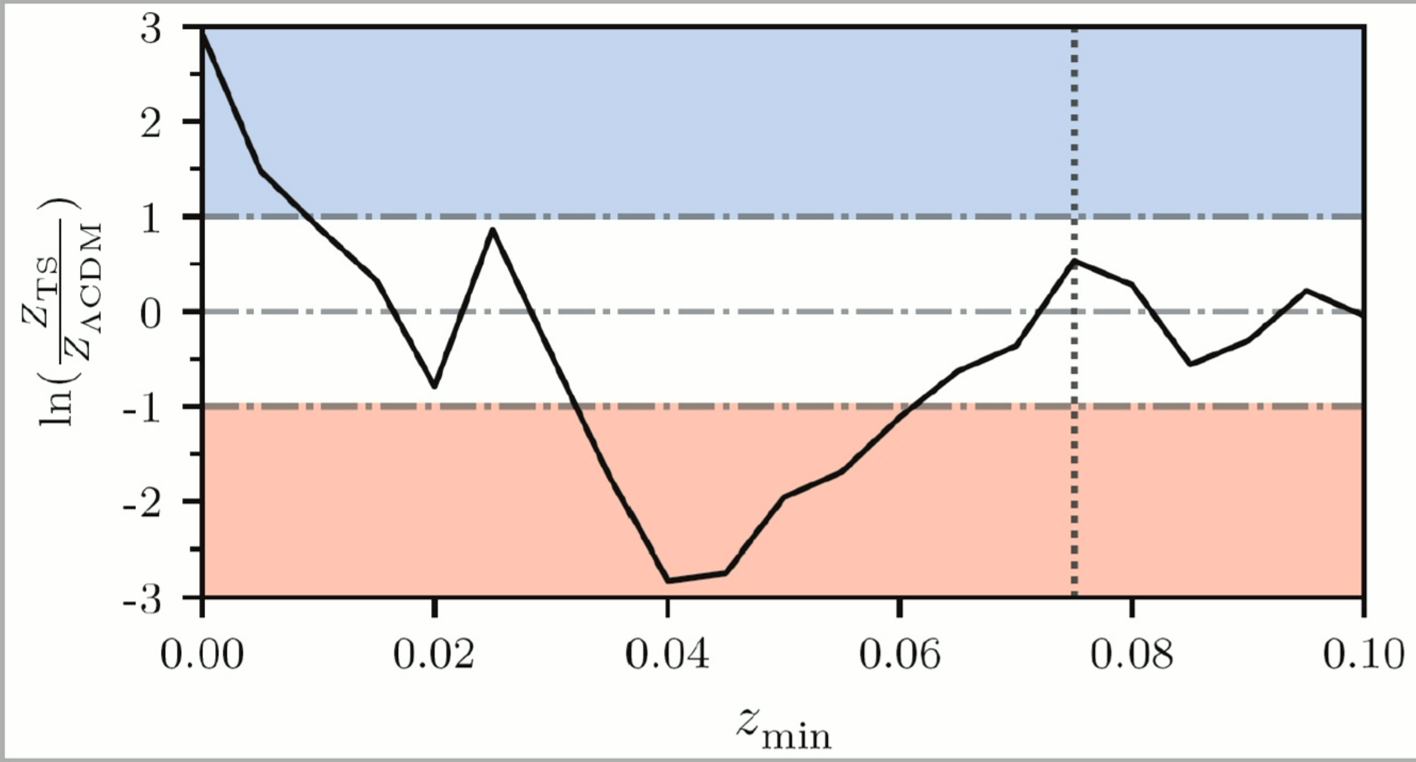
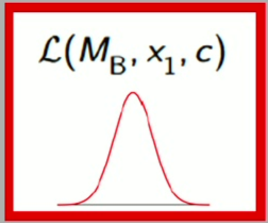
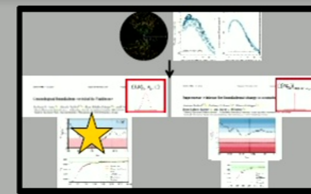
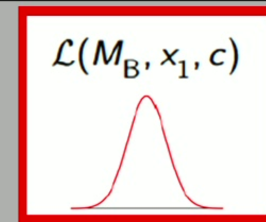






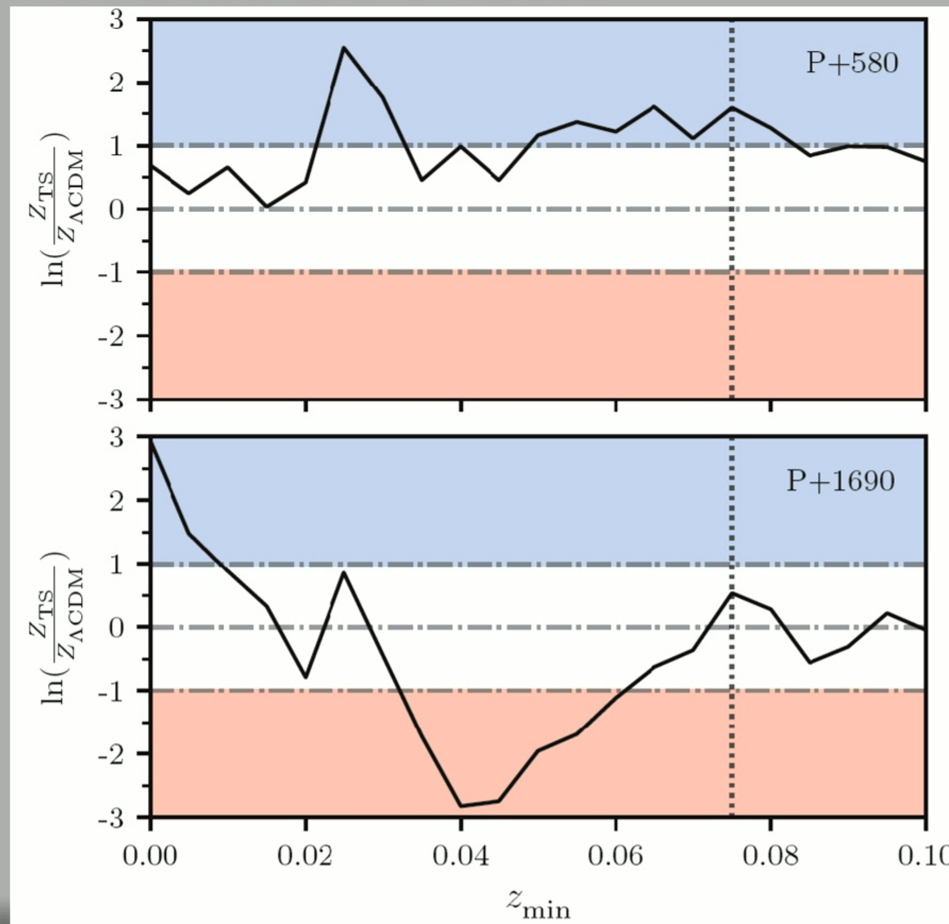
Comparison to Previous Work

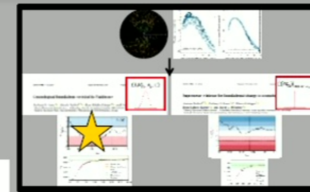


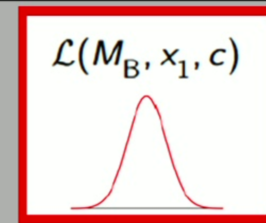


- Dam et al. 2017: JLA catalogue, Gaussian likelihood
- less clear evidence ($-1 < \ln B \leq 1$)
- Consider common subsample JLA/Pantheon+ for comparison

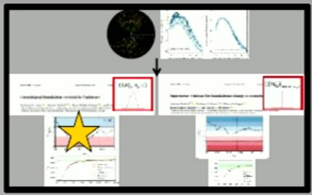
Comparison to Previous Work

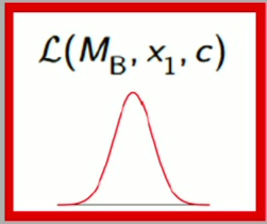


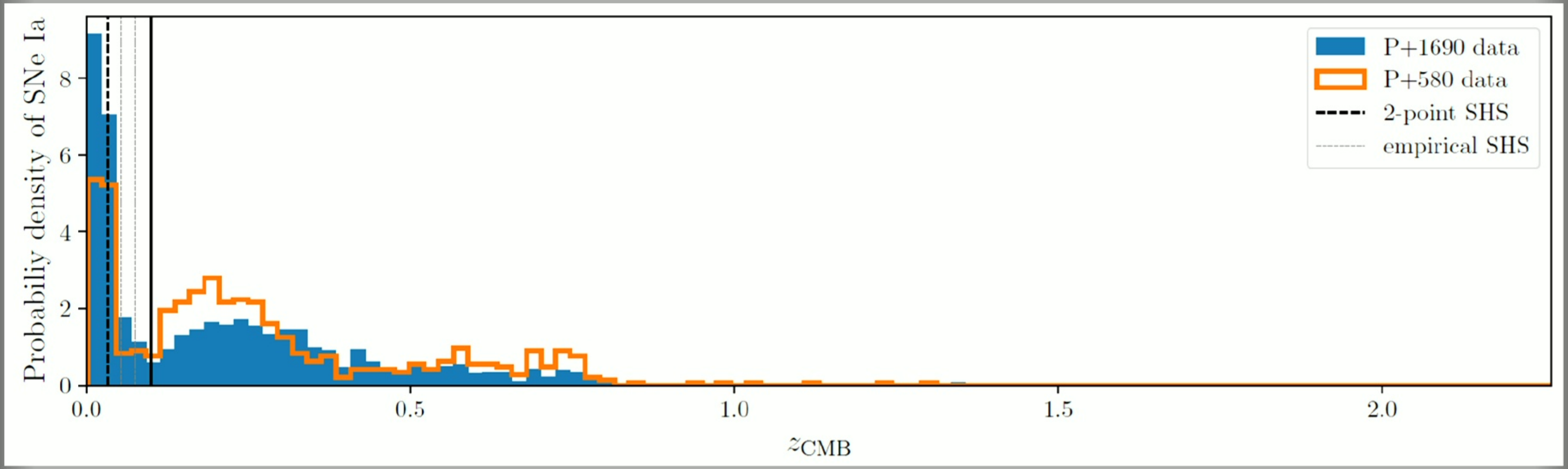




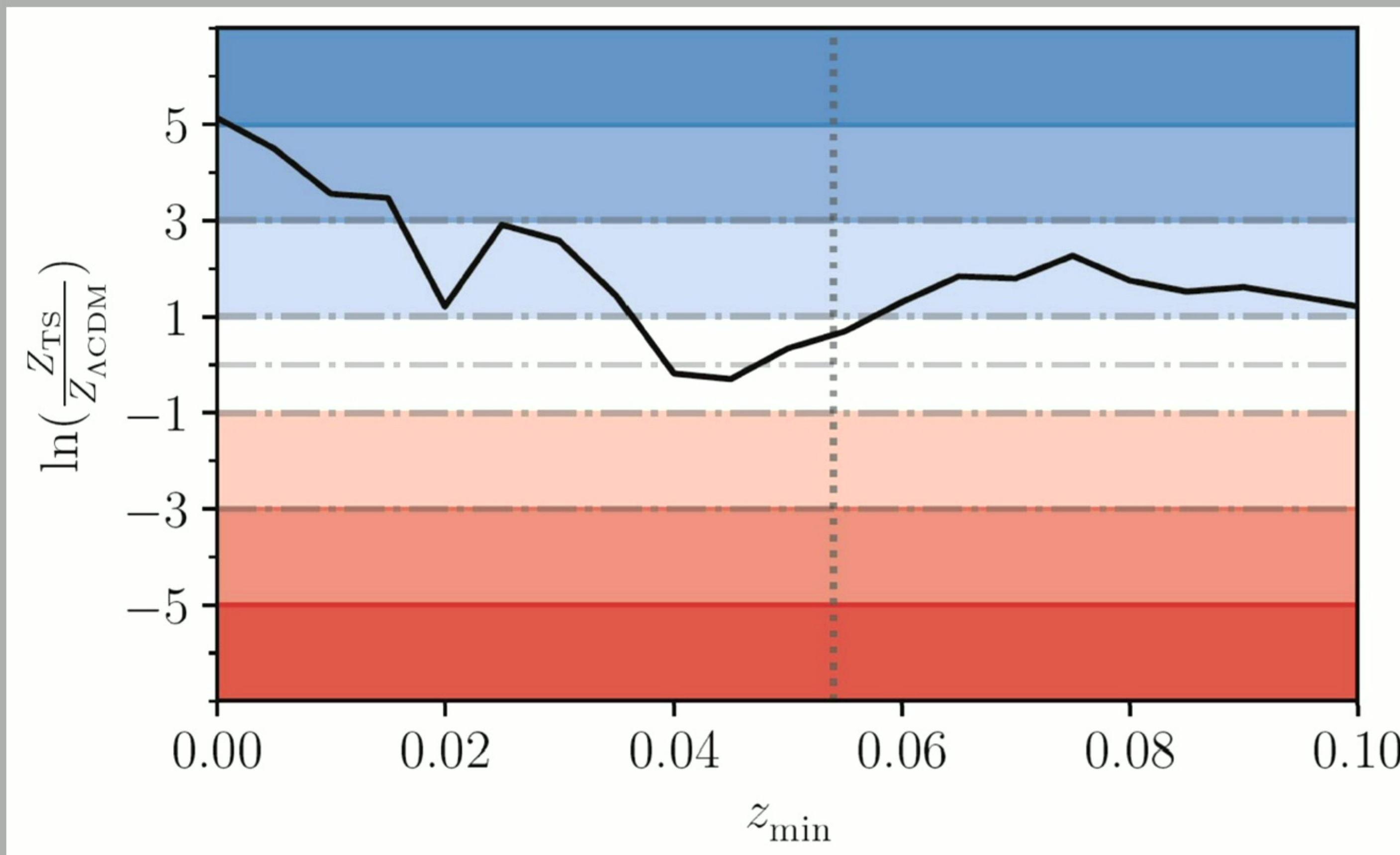
Sample Dependence

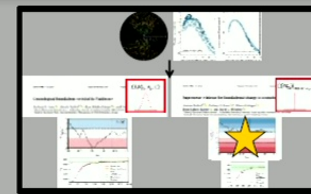


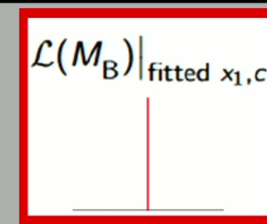




Bayesian Analysis: Fit Likelihood







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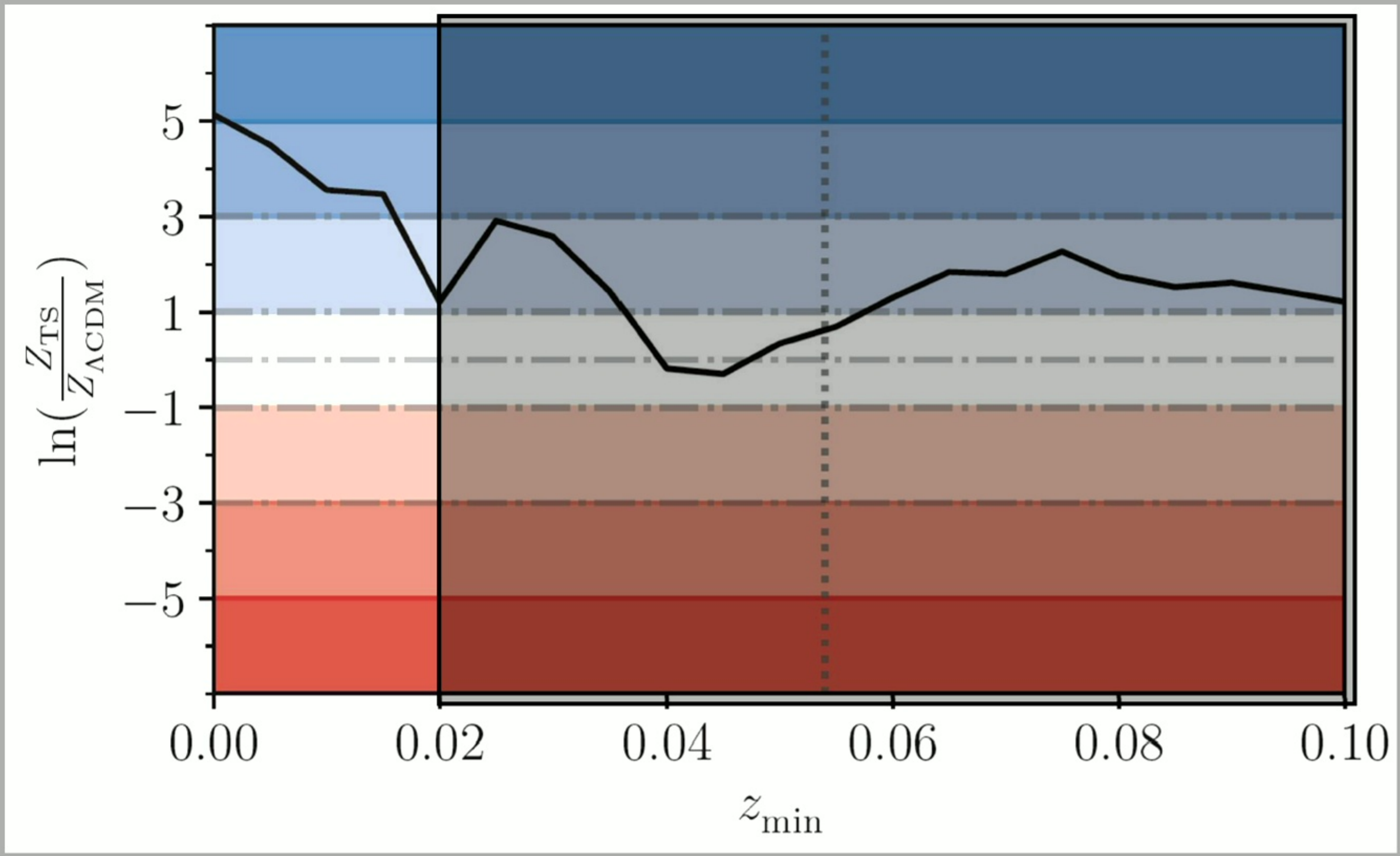

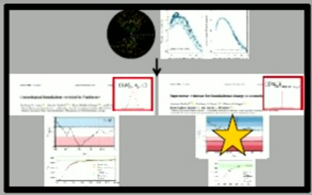

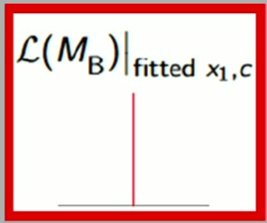

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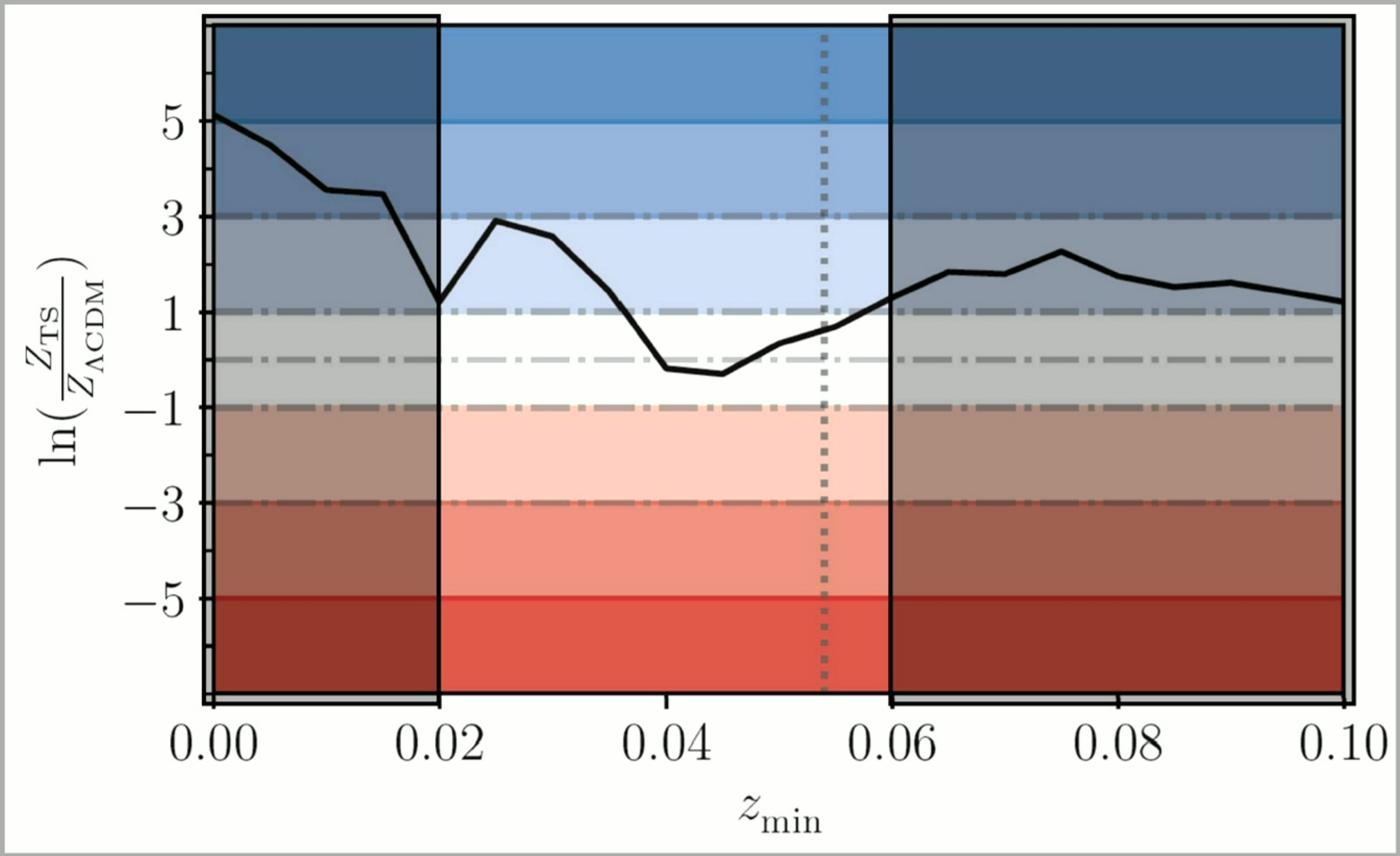
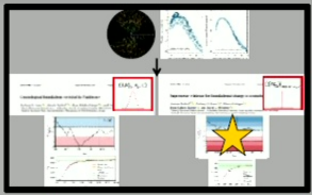
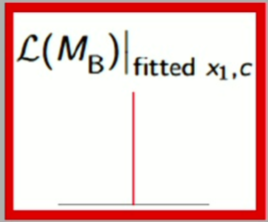
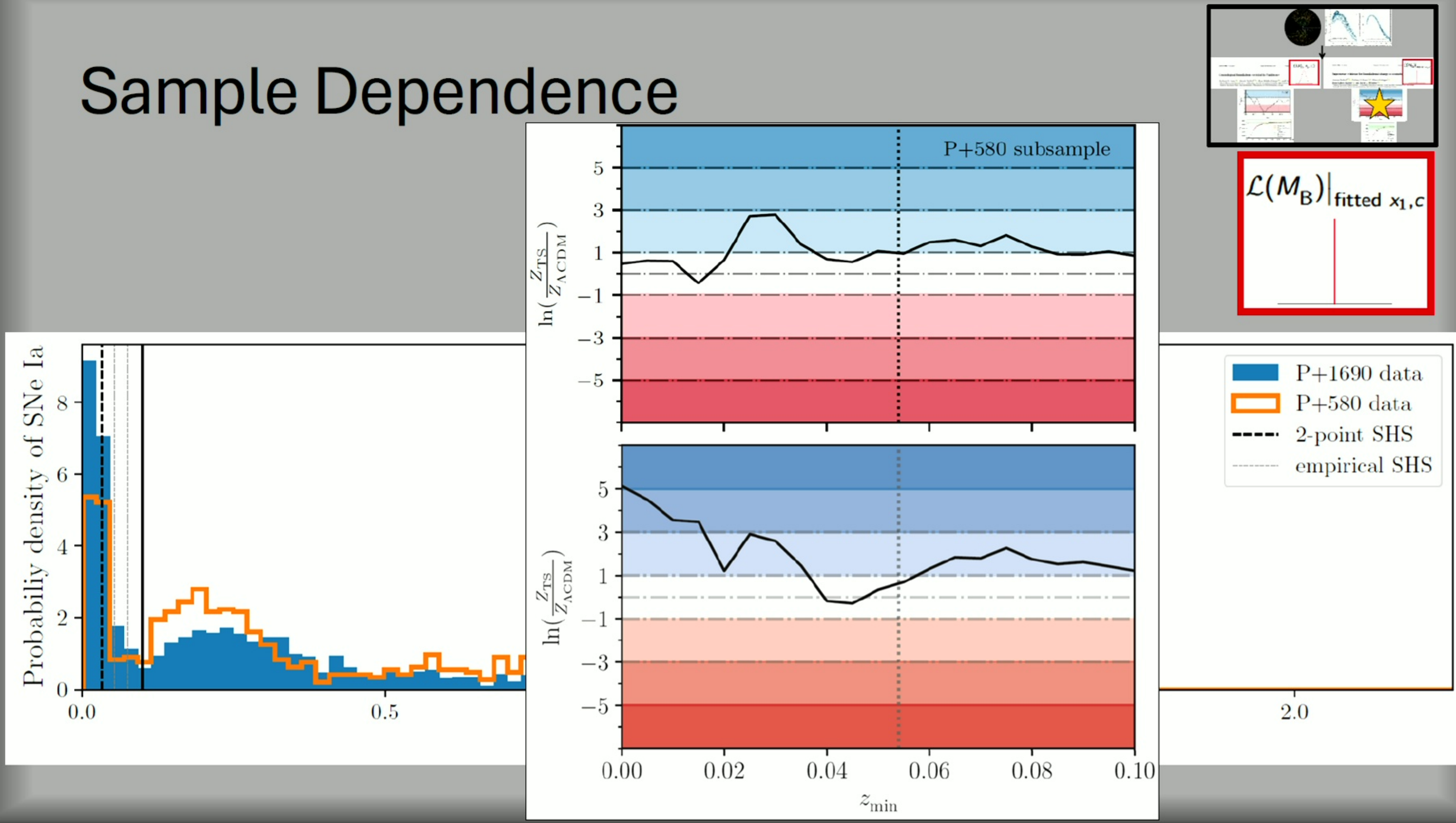


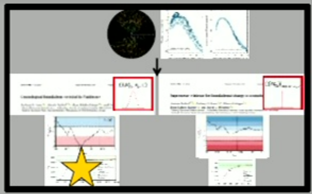


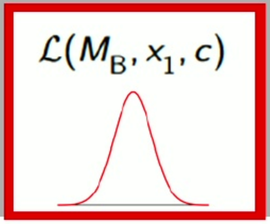


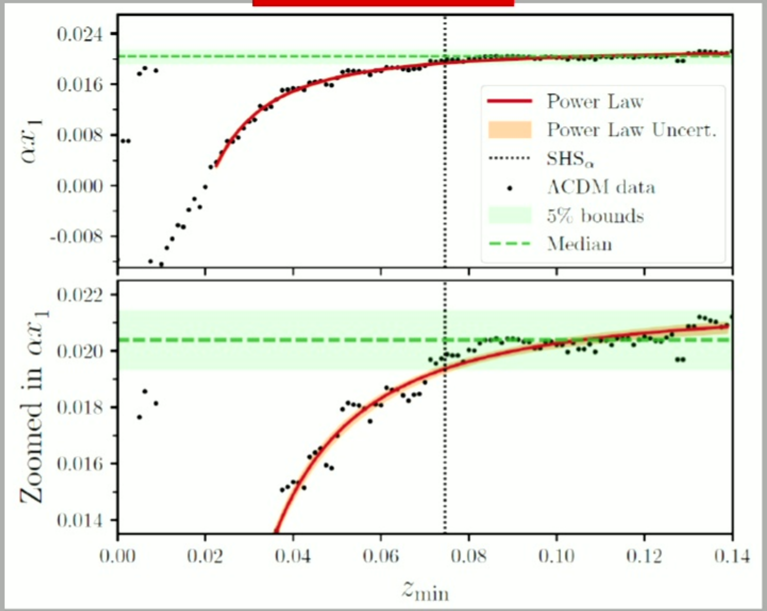
Sample Dependence



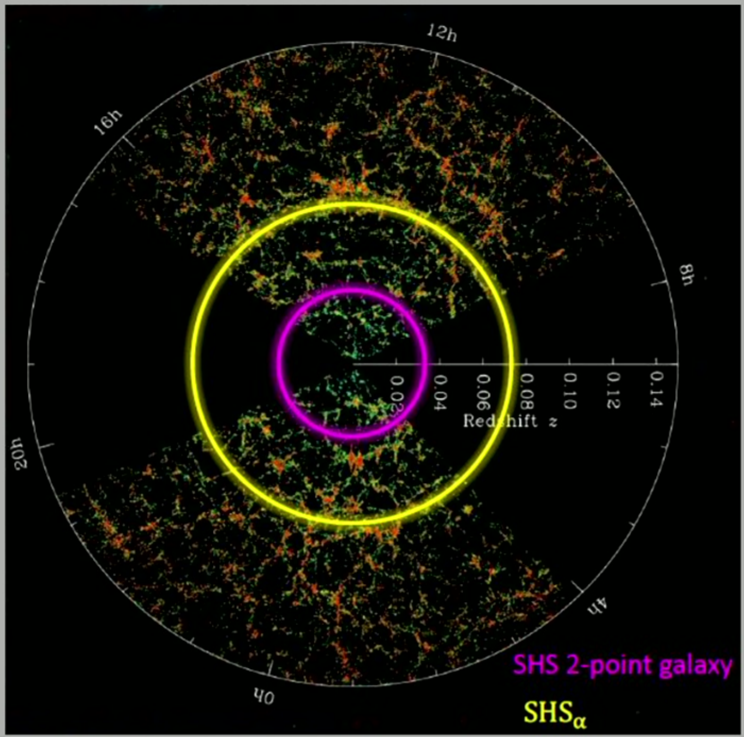
Statistical Homogeneity





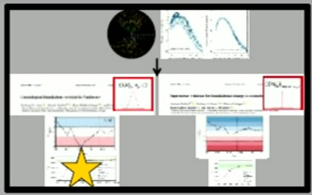


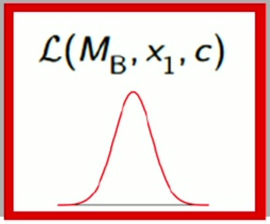
$$SHS_\alpha = 0.075^{+0.007}_{-0.009}$$

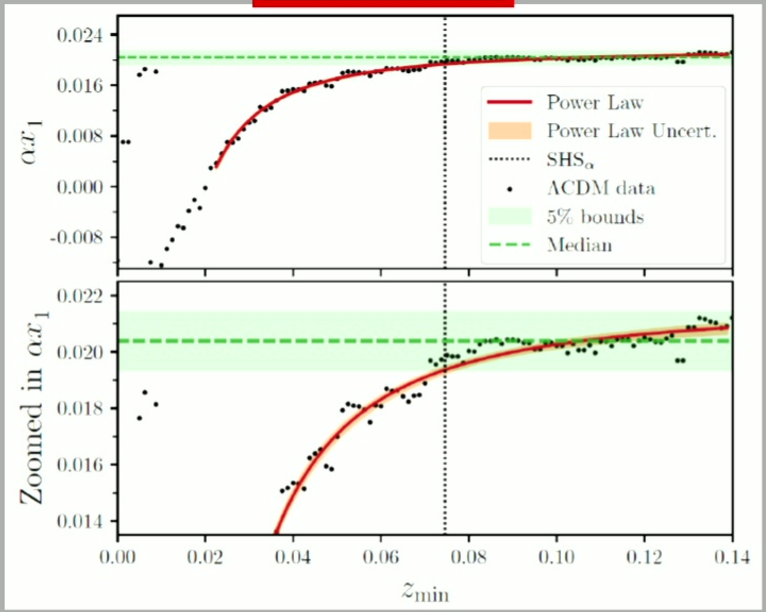


Credit: SDSS and Z. Lane

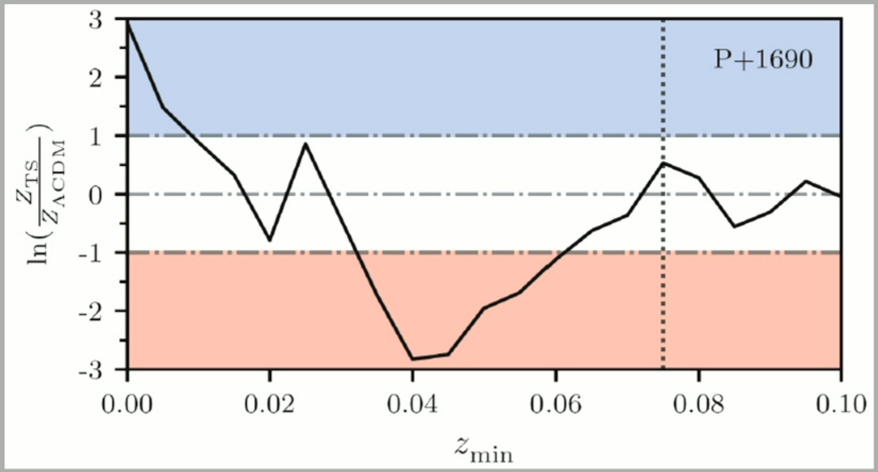
Statistical Homogeneity



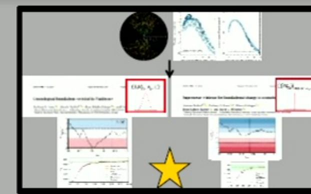


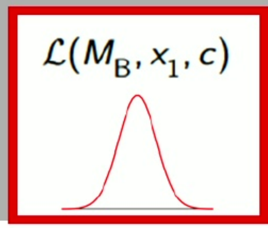


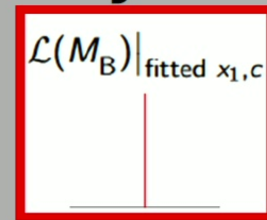
$$\mathrm{SHS}_\alpha = 0.075^{+0.007}_{-0.009}$$

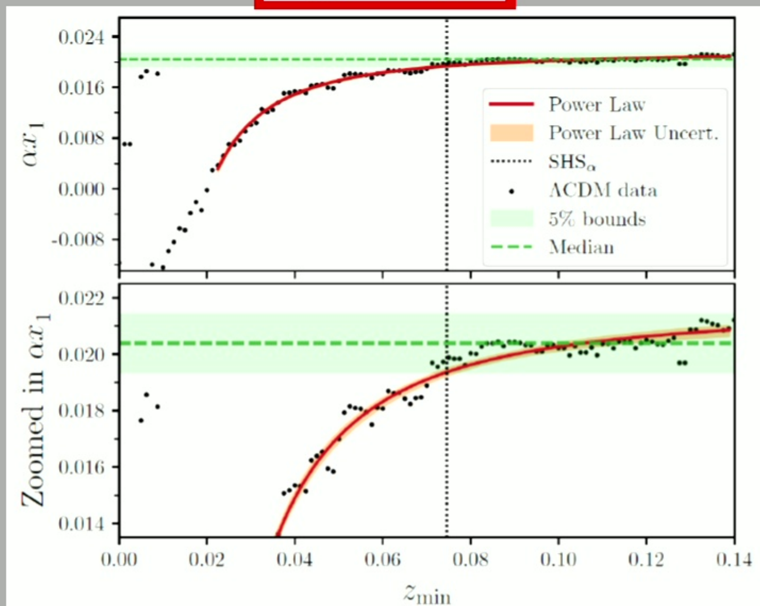


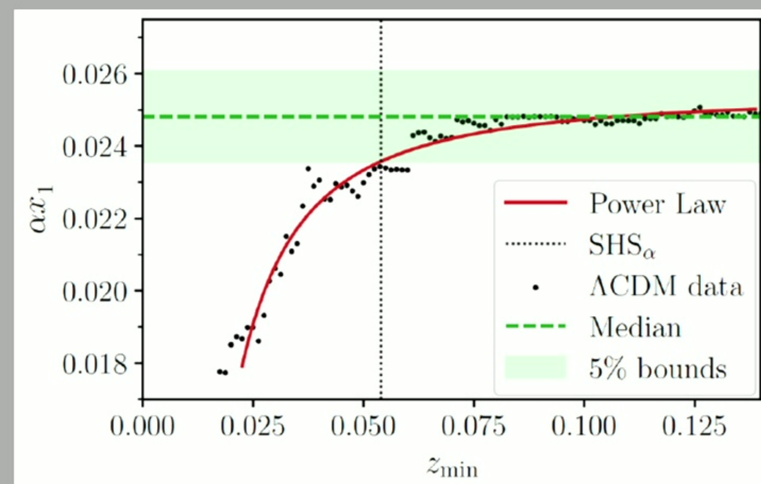
Statistical Homogeneity







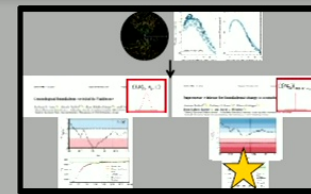


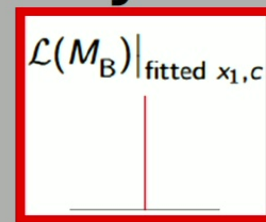


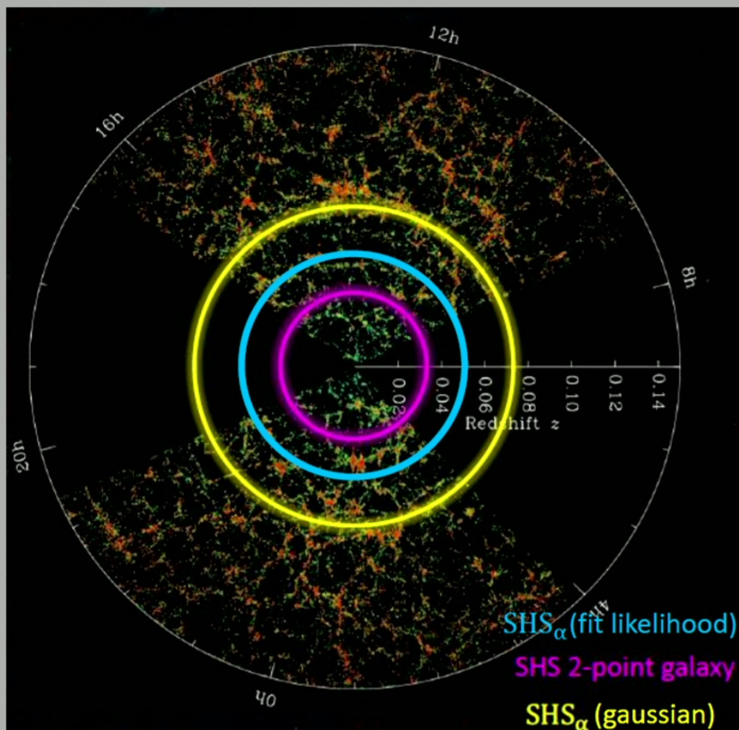
$SHS_\alpha = 0.075^{+0.007}_{-0.009}$

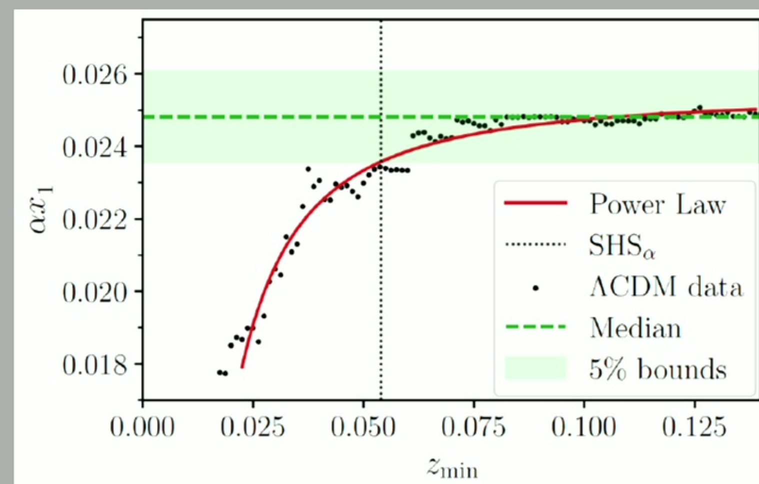
$SHS_\alpha = 0.054^{+0.007}_{-0.012}$

Statistical Homogeneity





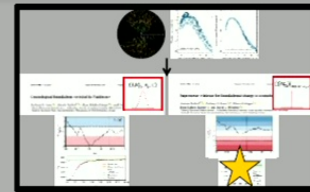


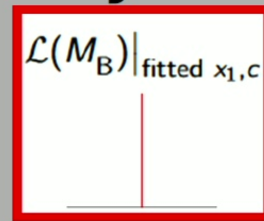


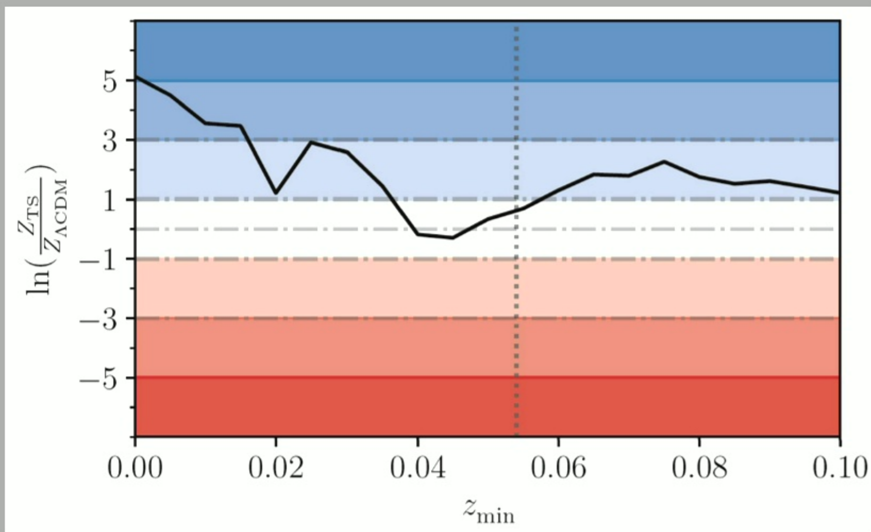
$$\mathrm{SHS}_\alpha = 0.054^{+0.007}_{-0.012}$$

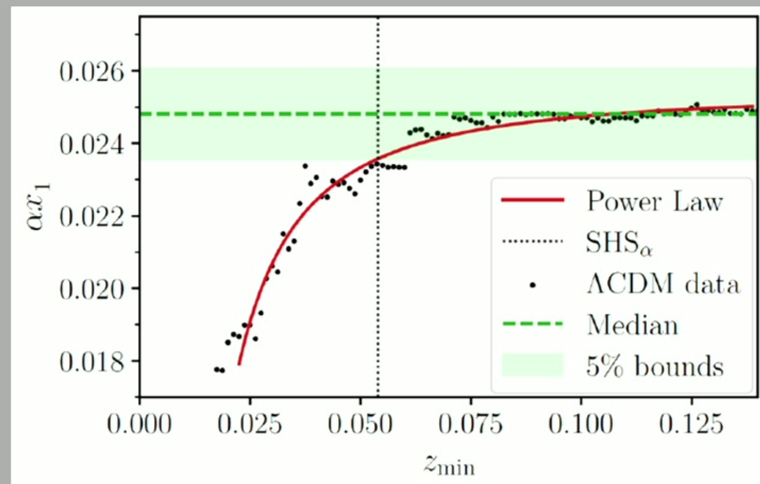
Credit: SDSS and Z. Lane

Statistical Homogeneity



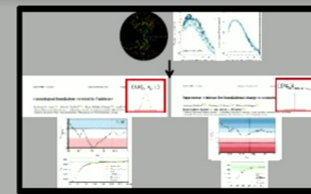






$$\text{SHS}_\alpha = 0.054^{+0.007}_{-0.012}$$

Conclusions



- Assumptions on the distribution of x_1 and c influences the Bayesian evidence
- Analysis based on fit likelihood favours timescape cosmology
- Particularly important in low-redshift regime
- Empirical SHS gives higher values than usually assumed
- Dependence on redshift-distribution of the sample: see Lane et al. (arXiv:2311.01438)
- Future work:
  - Likelihood with non-gaussian distribution
  - Reanalysis with more SNe from DES 5Y sample
  - Investigation of models to include more corrections

arXiv:2311.01438

arXiv:2412.15143