A BayeSN view of the environmental step in the ZTF DR2

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ZTF Cosmo @ LPNHE - 29th September 2026

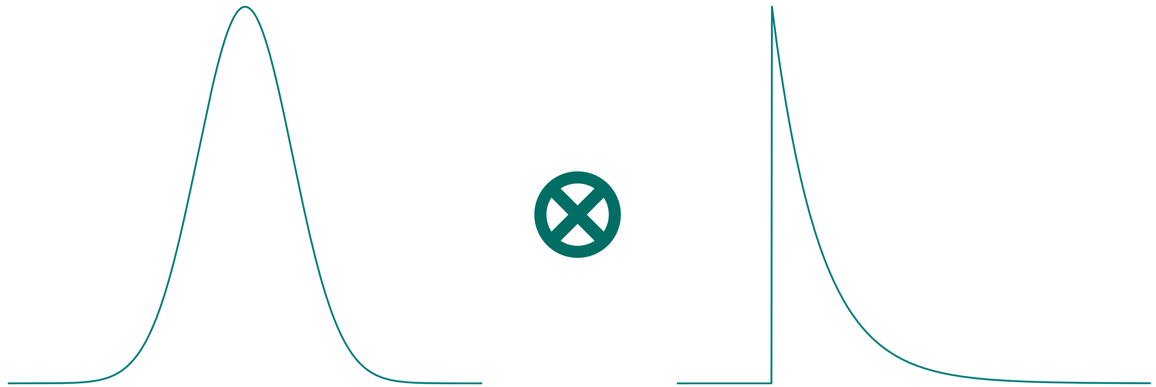
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SALT colour

Instrinsic + dust model

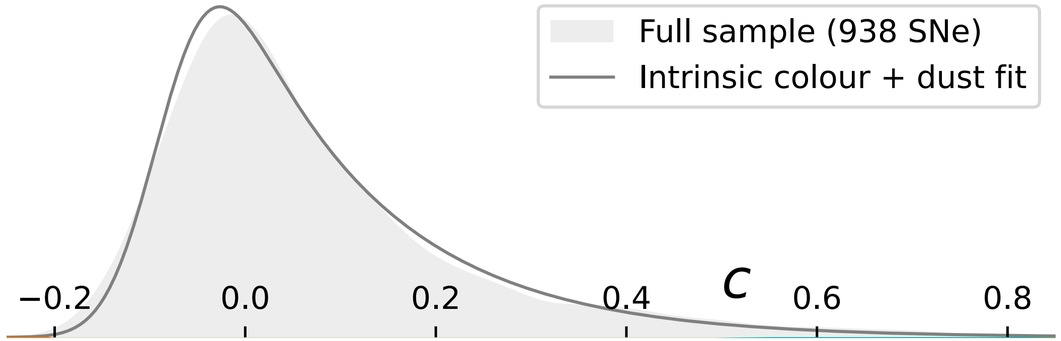
Intrinsic colour

Dust reddening



$\mathcal{N}(c, c_{\text{int}}, \sigma_c)$

$e^{-c\tau}$

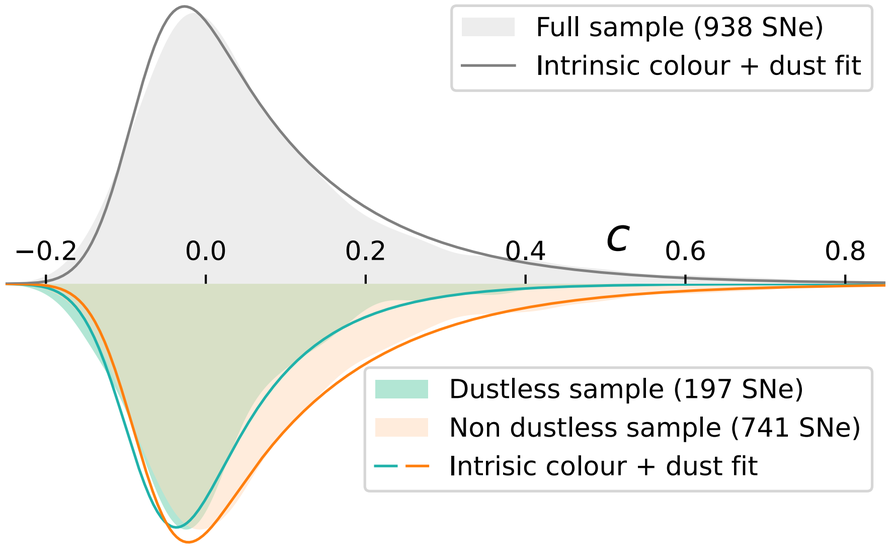


Jha+2007
Mandel+2011
Brout & Scolnic 2021

Ginolin+25a: Colour

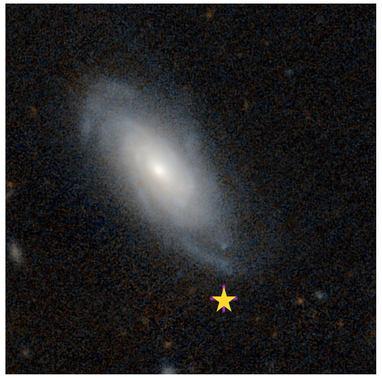
SALT colour

Dependence on environment



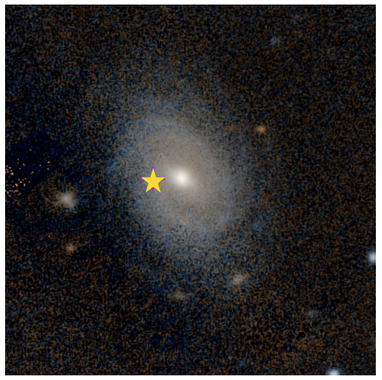
Ginolin+25a: Colour

« Dustless » example



ZTF18aahfzea

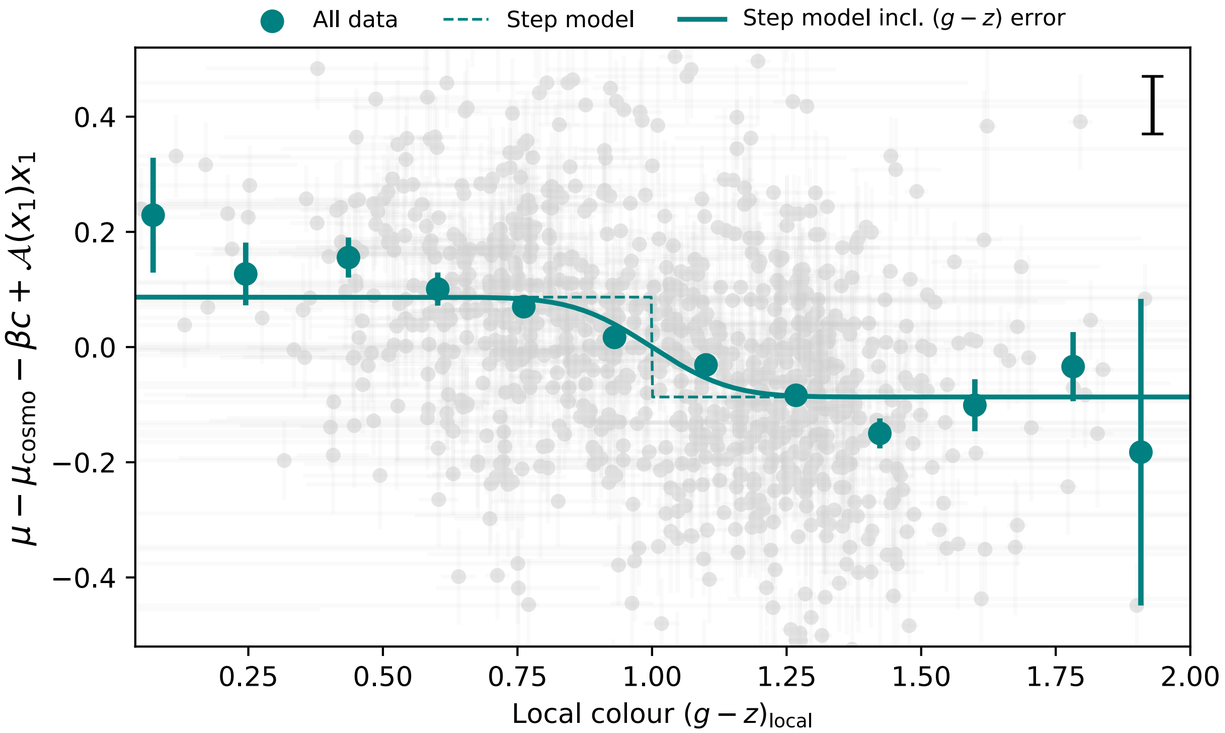
« Non dustless » example



ZTF18aaqfziz

Sample	$c_{\rm int}$	σ_c	τ
Full sample	-0.085 ± 0.004	0.030 ± 0.005	0.155 ± 0.007
Dustless* sample	-0.087 ± 0.008	0.033 ± 0.008	0.102 ± 0.010
Non dustless sample	-0.082 ± 0.005	0.029 ± 0.006	0.166 ± 0.008

Environmental steps

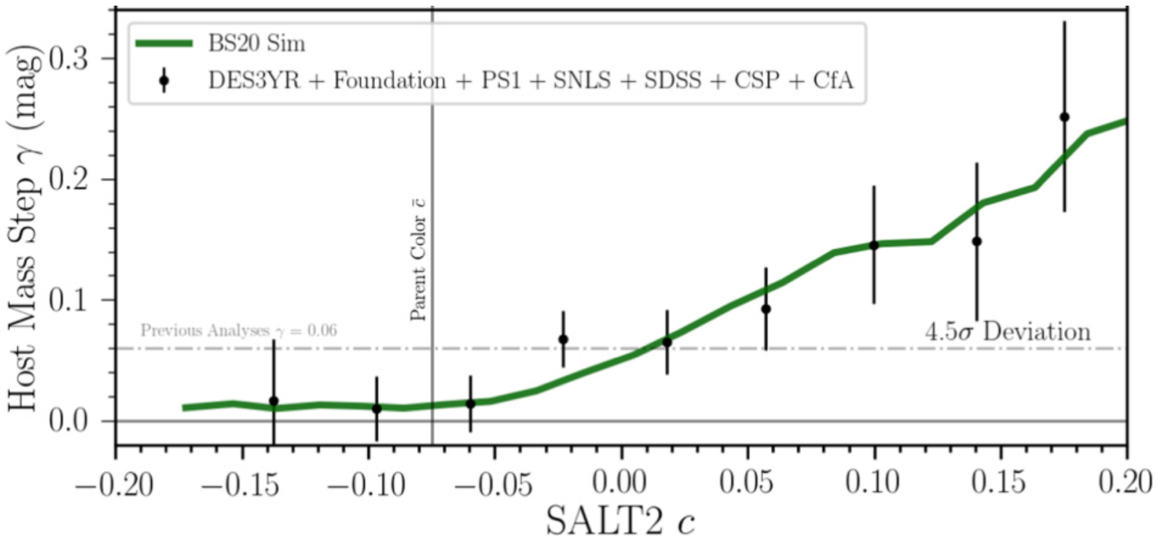


Tracer	γ [mag]	$\gamma_{\rm broken-\alpha}$ [mag]
$(g-z)_{\rm local}$	$0.143 \pm 0.025\ (5.6\,\sigma)$	$0.175 \pm 0.010\ (18.4\,\sigma)$
$(g-z)_{\rm global}$	$0.120 \pm 0.022\ (5.5\,\sigma)$	$0.149 \pm 0.009\ (16.0\,\sigma)$
$\log(M_\star/M_\odot)_{\rm local}$	$0.120 \pm 0.022\ (5.5\,\sigma)$	$0.149 \pm 0.010\ (14.9\,\sigma)$
$\log(M_\star/M_\odot)_{\rm global}$	$0.145 \pm 0.021\ (6.8\,\sigma)$	$0.153 \pm 0.013\ (12.0\,\sigma)$

Ginolin+25b: Stretch

Environmental steps

Dependence on colour



Brout & Scolnic 21

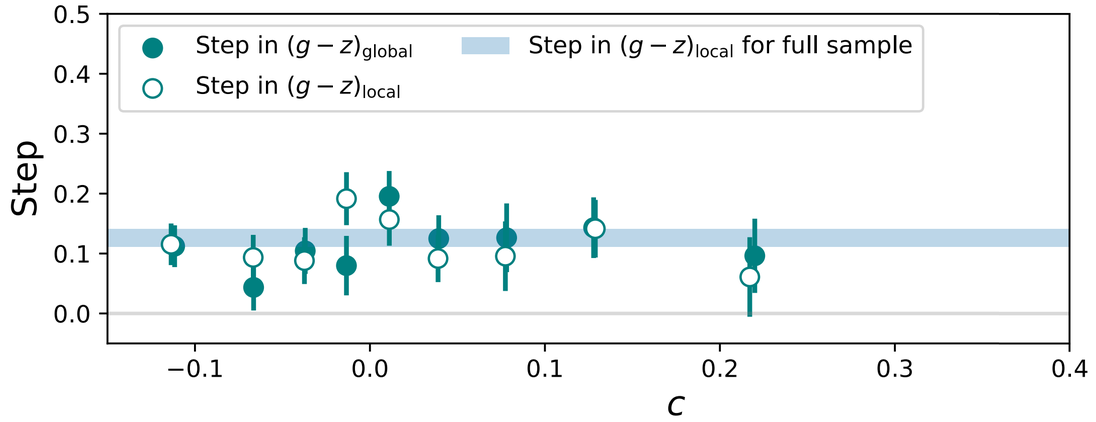


Table 3. Parameters of the step evolution with SN colour: slope of the fit and ΔAIC between an affine function and a constant.

Tracer	Slope	ΔAIC
$(g-z)_{\rm local}$	0.05 ± 0.11 (0.5σ)	1.8
$(g-z)_{\rm global}$	0.02 ± 0.12 (0.2σ)	2.0
$\log(M_\star/M_\odot)_{\rm local}$	-0.11 ± 0.12 (0.9σ)	1.2
$\log(M_\star/M_\odot)_{\rm global}$	0.02 ± 0.11 (0.1σ)	2.0

Ginolin+25a: Colour

Other ZTF analyses

Table 1. Comparison of different models and their performances.

#	Model	Indicator	Cut	α	β	γ	nMAD	$\sum\chi^2$	N_{param}	$\Delta\chi^2_{1\to i}$	$\Delta\chi^2_{step\to i}$
0	No correction	-	-	-	-	-	0.375	4312.2	0	-	
1	2-param Tripp	-	-	0.141	3.006	-	0.185	901.1	2	$58.3^a\sigma$	
2	Tripp + step (G25a)	local color	1.0	0.161	3.050	0.143	0.172	837.1	2+2	7.6σ	-
3	Tripp + step (fit)	local color	1.0	0.173	3.061	0.153	0.174	839.2	2+2	7.5σ	-
4	Tripp + BS21-lite	local color	1.0	0.173	3.061	$(0.079)^b$	0.165	815.1	2+8	7.8σ	3.3σ
5	Tripp + Host2D	local color	-	0.141	3.006	-	0.174	818.2	2+11	7.2σ	2.2σ
6	Tripp + step	global color	1.0	0.174	3.062	0.147	0.177	836.9	2+2	7.6σ	-
7	Tripp + BS21-lite	global color	1.0	0.174	3.062	$(0.081)^b$	0.177	817.0	2+8	7.7σ	2.8σ
8	Tripp + Host2D	global color	-	0.141	3.006	-	0.171	825.8	2+11	6.7σ	0.4σ
9	Tripp + step	local mass	8.9	0.157	3.145	0.108	0.184	875.2	2+2	4.6σ	-
10	Tripp + BS21-lite	local mass	8.9	0.157	3.145	$(0.054)^b$	0.174	846.1	2+8	5.8σ	3.9σ
11	Tripp + Host2D	local mass	-	0.141	3.006	-	0.171	821.2	2+11	7.0σ	5.5σ
12	Tripp + step	global mass	10	0.165	3.022	0.127	0.180	841.7	2+2	7.3σ	-
13	Tripp + BS21-lite	global mass	10	0.165	3.022	$(0.073)^b$	0.168	823.7	2+8	7.3σ	2.5σ
14	**Tripp + Host2D**	global mass	-	0.141	3.006	-	0.173	**804.9**	2+11	$\mathbf{7.9\sigma}$	$\mathbf{4.0\sigma}$
15	Tripp + step + Host2D	global mass	10	0.165	3.022	0.127	0.170	807.6	2+2+11	7.5σ	3.4σ

NOTE—The best-fit parameters, residuals, and chi-square values for 796 SNe Ia. χ^2 are calculated with a fixed uncertainty calculated at $\alpha = 0.150$, $\beta = 3.00$, and $\sigma_{int} = 0.170$. The last two columns ($\Delta\chi^2$) show the sigma-significance of improvement each model achieves compared to the baseline model #1 and the step model, respectively. [a]For model #1 only, the shown value is a comparison against the no-correction case (model #0). [b] These numbers represent the separation between low-mass and high-mass populations after the color dependency is corrected, but this term is included in the polynomial functions and is not a fitted parameter.

Murakami & Scolnic 2025

Giunta+2026

Parameter	Simple–BayeSN	Ginolin et al. (2025a)
τ	0.148 ± 0.006	0.155 ± 0.007
R_B	3.260 ± 0.055	–
x_0	-0.274 ± 0.035	–
σ_x	1.032 ± 0.025	–
c_0^{int}	-0.083 ± 0.004	-0.085 ± 0.004
α_c^{int}	-0.006 ± 0.003	–
$\sigma_{c,int}$	0.038 ± 0.004	0.030 ± 0.005
M_0^{int}	-19.483 ± 0.053	–
α	-0.159 ± 0.011	–
β_{int}	-0.360 ± 0.533	–
σ_{int}	0.113 ± 0.015	–

Table 3. Posterior means and standard deviations for all Simple-BayeSN population parameters inferred from the ZTF HQ VL sample used in this work (902 SNe). For comparison, we also report the values of c_0^{int}, $\sigma_{c,int}$ and τ from the "full sample" entry in Tab. 1 of Ginolin et al. (2025a), who fit the same Gaussian–exponential convolution to the empirical colour distribution of a similar ZTF subset (938 SNe).

Table 1: Best-fit parameters of the prior probability distribution for the two supernova populations and their host galaxies.

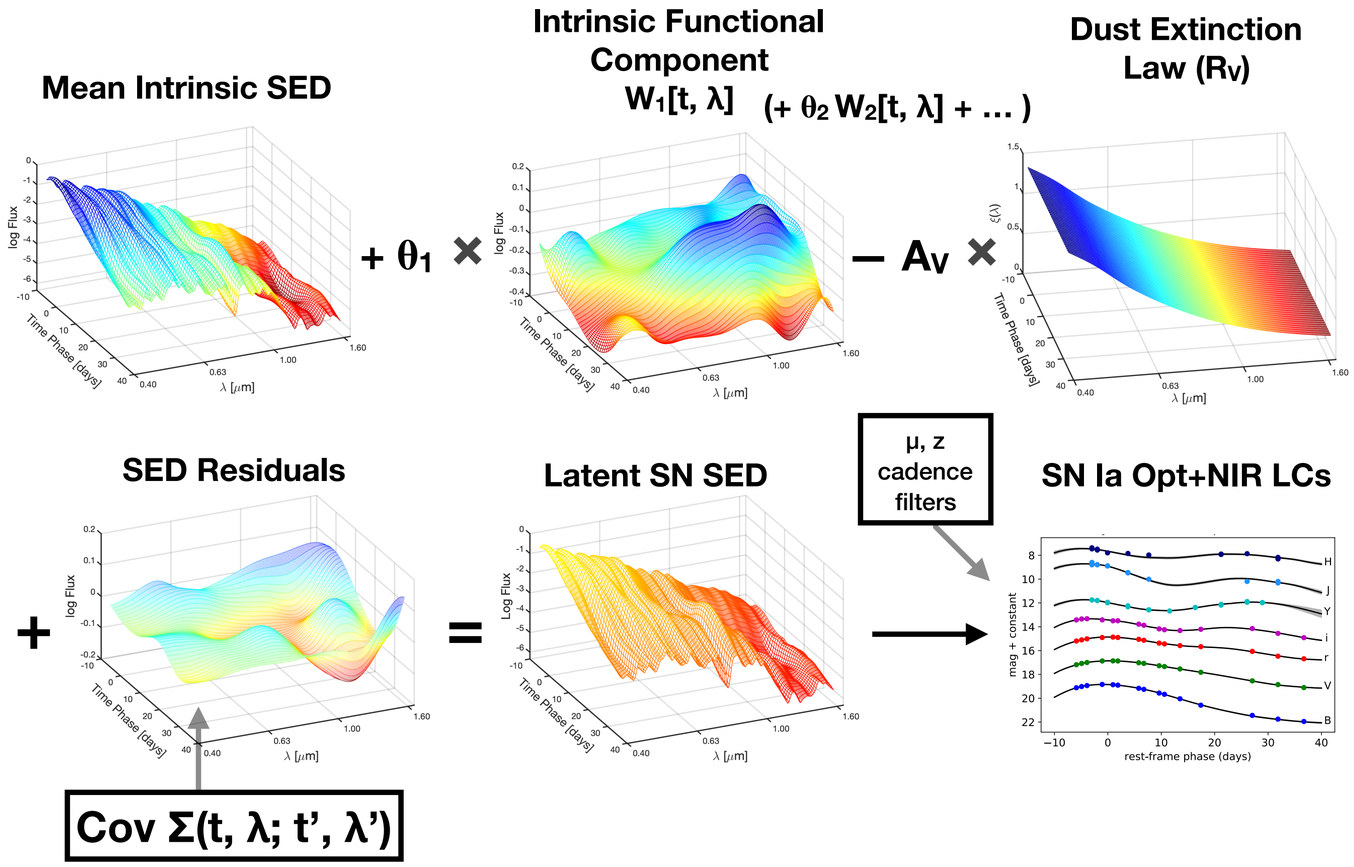
	low-x_1 SNe	high-x_1 SNe	
$\widehat{M_B}$ [mag]	$-19.32^{+0.04}_{-0.05}$	$-19.18^{+0.05}_{-0.05}$	
σ_{M_B} [mag]	$0.113^{+0.012}_{-0.011}$	$0.059^{+0.014}_{-0.014}$	
$\widehat{x_1}$	$-1.02^{+0.08}_{-0.08}$	$0.50^{+0.05}_{-0.05}$	
σ_{x_1}	$0.79^{+0.05}_{-0.05}$	$0.55^{+0.03}_{-0.03}$	
α	$0.227^{+0.016}_{-0.016}$	$0.163^{+0.018}_{-0.018}$	
$\widehat{c_{int}}$ [mag]	$-0.068^{+0.007}_{-0.007}$	$-0.080^{+0.008}_{-0.008}$	
$\sigma_{c_{int}}$ [mag]	$0.029^{+0.008}_{-0.008}$	$0.035^{+0.007}_{-0.007}$	
$\beta \equiv \beta_{low-x_1} \equiv \beta_{high-x_1}$	$2.06^{+0.45}_{-0.45}$		
$f_{low-x_1}, f_{high-x_1} \equiv 1 - f_{low-x_1}$	$0.481^{+0.036}_{-0.037}$	$0.519^{+0.037}_{-0.036}$	
	red, massive hosts		blue, less massive hosts
	low-x_1 SNe	high-x_1 SNe	high-x_1 SNe
$f_{red}, f_{blue} \equiv 1 - f_{red}$	–	$0.319^{+0.048}_{-0.048}$	$0.681^{+0.048}_{-0.048}$
$\widehat{R_B}$	$3.06^{+0.12}_{-0.12}$	$3.09^{+0.09}_{-0.09}$	$3.89^{+0.30}_{-0.29}$
σ_{R_B}	$0.62^{+0.10}_{-0.10}$	$0.31^{+0.07}_{-0.07}$	$0.63^{+0.19}_{-0.19}$
τ [mag]	$0.135^{+0.011}_{-0.011}$	$0.273^{+0.030}_{-0.031}$	$0.091^{+0.015}_{-0.015}$
$\log_{10}(\widehat{M_\star/M_\odot})$	$10.31^{+0.03}_{-0.03}$		$9.27^{+0.07}_{-0.07}$
$\sigma_{\log_{10}(M_\star/M_\odot)}$	$0.43^{+0.02}_{-0.02}$		$0.72^{+0.04}_{-0.04}$
$\widehat{(g-z)}$ [mag]	$1.18^{+0.02}_{-0.02}$		$0.71^{+0.02}_{-0.02}$
σ_{g-z} [mag]	$0.19^{+0.01}_{-0.01}$		$0.19^{+0.01}_{-0.01}$
q	$0.53^{+0.04}_{-0.04}$		$0.46^{+0.07}_{-0.07}$
	global nuisance paramaters		
$f_{host\ outlier}$	$0.035^{+0.009}_{-0.009}$		
Δ_{x_1} (pocket effect)	$0.061^{+0.045}_{-0.046}$		
$a_{pocket} \equiv dm_B/dm_{B,ZTF}$ (pocket effect)	$0.011^{+0.011}_{-0.011}$		

Wojtak+2026

See also Banana split (Rubin+25)

BayeSN

Overview of the model



Mandel+22, Thorp+21

Main differences from SALT

- Explicit dust treatment
- Already standardised SNe
- Training can be cosmology dependent

BayeSN

Overview of the model

Intrinsic scatter

$$\delta M^s \sim \mathcal{N}(0, \sigma_0^2)$$

Dust modelling

$$A_V^s \sim \tau_A^{-1} \exp(-A_V^s / \tau_A)$$

$$-2.5 \log\left(\frac{S^s(t,\lambda)}{S^0(t,\lambda)}\right) = M_0 + \delta M^s + W_0(t,\lambda) + \theta_1^s W_1(t,\lambda) + A_V^s \xi(\lambda, R_V) + \epsilon^s(t,\lambda)$$

Hsiao+07 template

PCA-like component

$$\theta_1^s \sim \mathcal{N}(0,1)$$

Intrisic colour variation from knots $\mathbf{e}^s \sim \mathcal{N}(0, \mathbf{\Sigma}_\epsilon)$

Mandel+22
Thorp+21
Grayling+26

BayeSN
Use cases - Training

Population hyperparameters

Per-SN parameters

Intrinsic scatter

$$\delta M^s \sim \mathcal{N}(0, \sigma_0^2)$$

Dust modelling

$$A_V^s \sim \tau_A^{-1} \exp(-A_V^s/\tau_A)$$

$$-2.5 \log\left(\frac{S^s(t,\lambda)}{S^0(t,\lambda)}\right) = M_0 + \delta M^s + W_0(t,\lambda) + \theta_1^s W_1(t,\lambda) + A_V^s \xi(\lambda, R_V) + \epsilon^s(t,\lambda)$$

PCA-like component

$$\theta_1^s \sim \mathcal{N}(0,1)$$

Intrisic colour variation from knots $\mathbf{e}^s \sim \mathcal{N}(0, \mathbf{\Sigma}_\epsilon)$

~ 15 mins to run on 4 GPU
(on the Thorp+21 sample, 157 SNe)

BayeSN

Use cases - Inferring dust properties

Population hyperparameters

Per-SN parameters

Intrinsic scatter

$$\delta M^s \sim \mathcal{N}(0, \sigma_0^2)$$

Dust modelling

$$A_V^s \sim \tau_A^{-1} \exp(-A_V^s / \tau_A)$$

$$-2.5 \log\left(\frac{S^s(t,\lambda)}{S^0(t,\lambda)}\right) = M_0 + \delta M^s + W_0(t,\lambda) + \theta_1^s W_1(t,\lambda) + A_V^s \xi(\lambda, R_V) + \epsilon^s(t,\lambda)$$

PCA-like component

$$\theta_1^s \sim \mathcal{N}(0,1)$$

Intrisic colour variation from knots $\mathbf{e}^s \sim \mathcal{N}(0, \mathbf{\Sigma}_\epsilon)$

~ 45 mins to run on 4 GPU on Perlmutter
(on the ZTF volume-limited sample, ~1000 SNe)

BayeSN

Use cases - Light curve fitting

Population hyperparameters

Per-SN parameters

Intrinsic scatter

$$\delta M^s \sim \mathcal{N}(0, \sigma_0^2)$$

Dust modelling

$$A_V^s \sim \tau_A^{-1} \exp(-A_V^s / \tau_A)$$

$$-2.5 \log\left(\frac{S^s(t,\lambda)}{S^0(t,\lambda)}\right) = M_0 + \delta M^s + W_0(t,\lambda) + \theta_1^s W_1(t,\lambda) + A_V^s \xi(\lambda, R_V) + \epsilon^s(t,\lambda)$$

PCA-like component

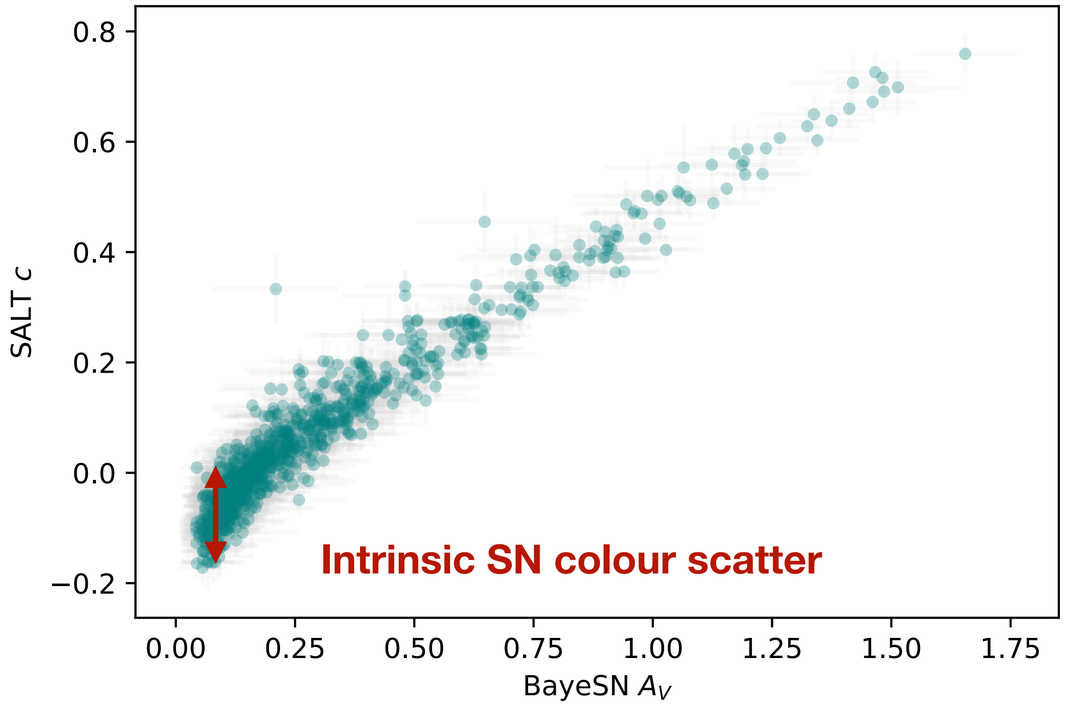
$$\theta_1^s \sim \mathcal{N}(0,1)$$

Intrisic colour variation from knots $\mathbf{e}^s \sim \mathcal{N}(0, \mathbf{\Sigma}_\epsilon)$

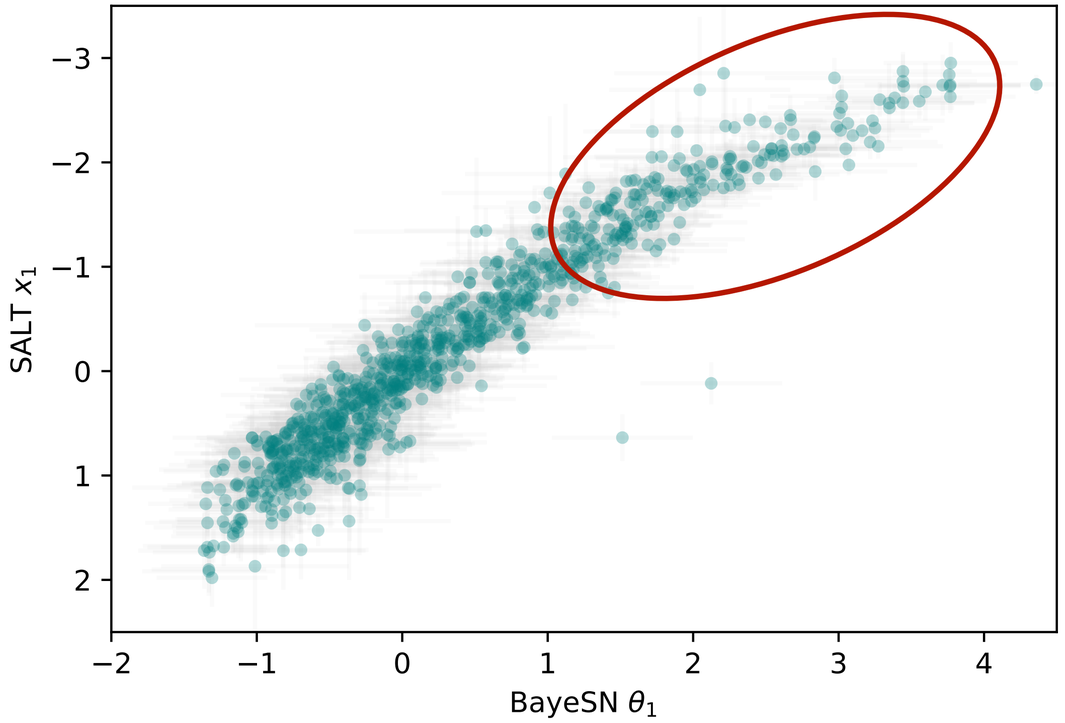
~ 30 mins to run on 4 GPU on ZTF
Can be accelerated with Variational Inference (~30-40 SNe/s)

BayeSN x ZTF DR2

Light curve parameters



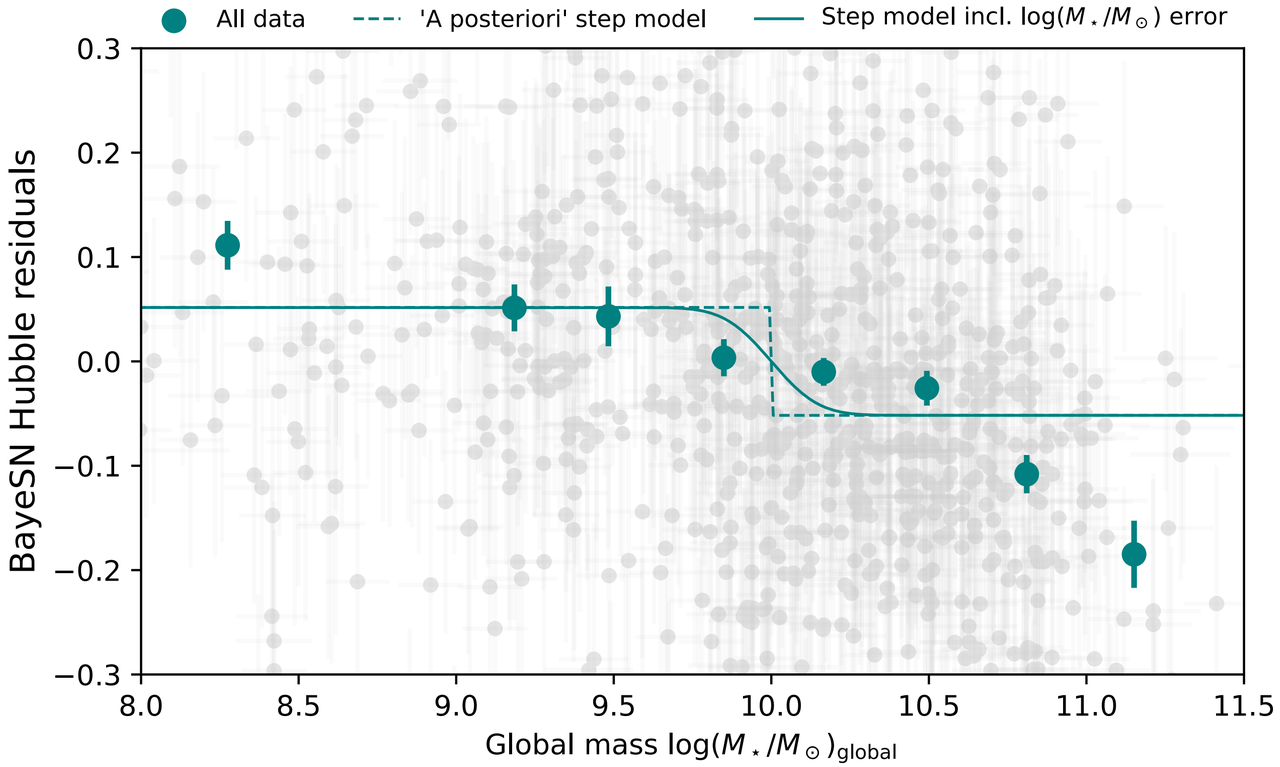
Non linearity related to the broken-α?



Ginolin+26

BayeSN x ZTF DR2

A posteriori step



Step tracer	BayeSN	SALT
$(g-z)_{\rm local}$	$0.086 \pm 0.010\ (8.3\sigma)$	$0.089 \pm 0.010\ (8.5\sigma)$
$(g-z)_{\rm global}$	$0.080 \pm 0.010\ (7.8\sigma)$	$0.083 \pm 0.010\ (7.9\sigma)$
$\log(M_\star/M_\odot)_{\rm local}$	$0.070 \pm 0.010\ (6.8\sigma)$	$0.087 \pm 0.011\ (8.2\sigma)$
$\log(M_\star/M_\odot)_{\rm global}$	$0.103 \pm 0.010\ (10.1\sigma)$	$0.099 \pm 0.010\ (9.5\sigma)$

Ginolin+26

BayeSN x ZTF DR2

Intrinsic step

$$-2.5\log\left(\frac{S^s(t,\lambda)}{S^0(t,\lambda)}\right) = M_0 + \delta M^s + W_0(t,\lambda) + \theta_1^s W_1(t,\lambda) + A_V^s \xi(\lambda, R_V^s) + \epsilon^s(t,\lambda)$$

Achromatic mass step

$$\delta M^s = \begin{cases} \mathcal{N}(\Delta M_{0,\mathrm{LM}}, \sigma^2_{0,\mathrm{LM}}) & \text{if } m \leq 10 \\ \mathcal{N}(\Delta M_{0,\mathrm{HM}}, \sigma^2_{0,\mathrm{HM}}) & \text{if } m > 10 \end{cases}$$

Environment dependent dust properties

$$A_V^s \sim \tau^{-1}_{A,\mathrm{HM/LM}} \exp(-A_V^s/\tau_{A,\mathrm{HM/LM}})$$

$$R_V^s \sim \mathrm{TN}(\mu_{R,\mathrm{HM/LM}}, \sigma^2_{R,\mathrm{HM/LM}}, 1.2, \infty)$$

Grayling+24

BayeSN x ZTF DR2

Intrinsic step

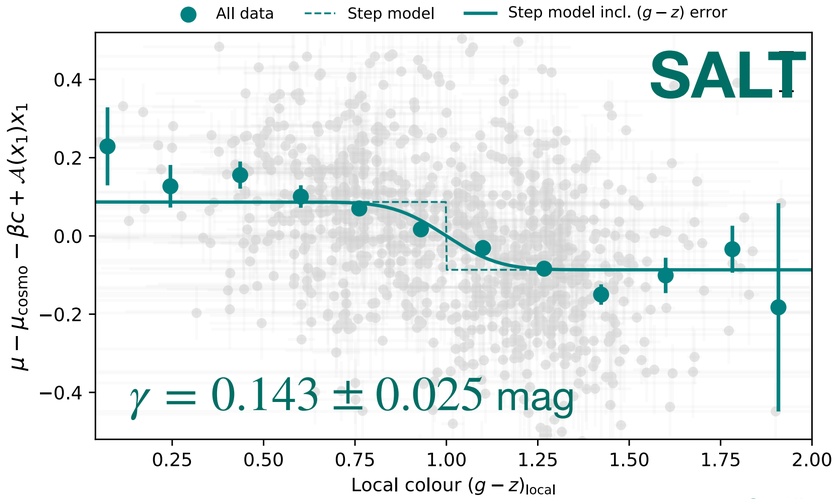
$$\gamma_{\rm int} = 0.049 \pm 0.016 \text{ mag}$$

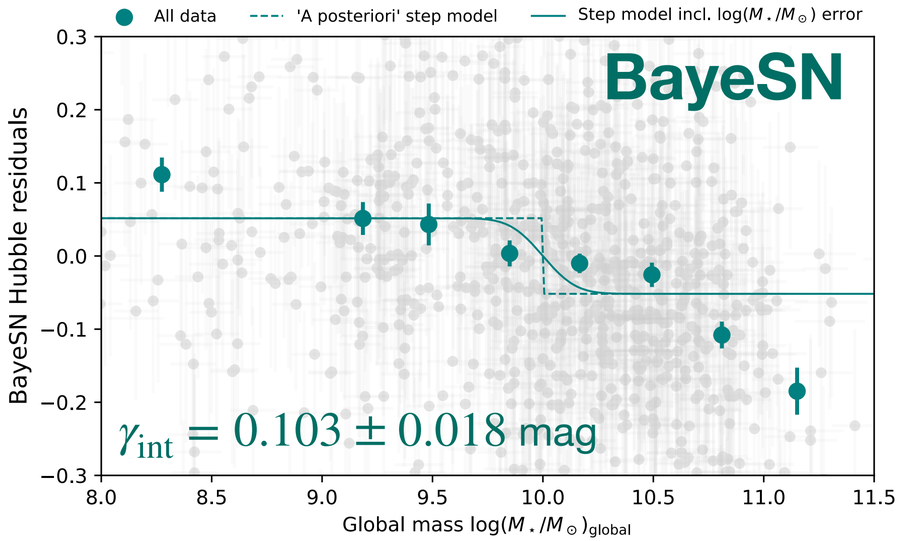
Grayling+24

Step tracer	Intrinsic step (mag)	$\Delta\mathbb{E}(R_V)$	$\Delta\tau_A$
$(g-z)_{\rm local}$	$0.085 \pm 0.019\ (4.5\sigma)$	$0.165 \pm 0.132\ (1.2\sigma)$	$-0.047 \pm 0.028\ (1.7\sigma)$
$(g-z)_{\rm global}$	$0.072 \pm 0.019\ (3.7\sigma)$	$0.155 \pm 0.126\ (1.2\sigma)$	$-0.045 \pm 0.030\ (1.5\sigma)$
$\log(M_\star/M_\odot)_{\rm local}$	$0.081 \pm 0.019\ (4.3\sigma)$	$0.086 \pm 0.148\ (0.6\sigma)$	$-0.203 \pm 0.030\ (6.8\sigma)$
$\log(M_\star/M_\odot)_{\rm global}$	$0.103 \pm 0.018\ (5.6\sigma)$	$0.146 \pm 0.139\ (1.0\sigma)$	$-0.035 \pm 0.030\ (1.2\sigma)$

Ginolin+26

Conclusion and prospects





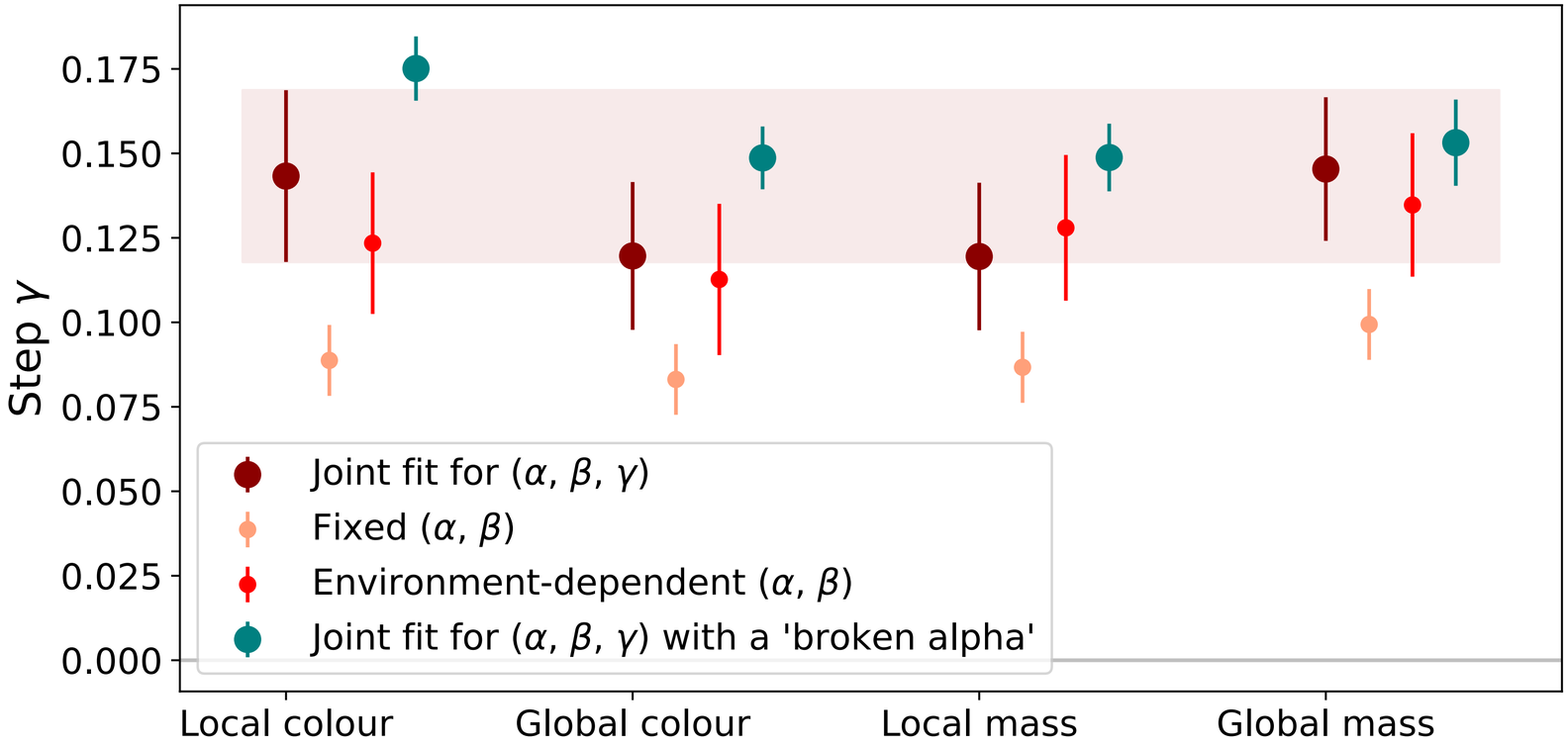
Future plans

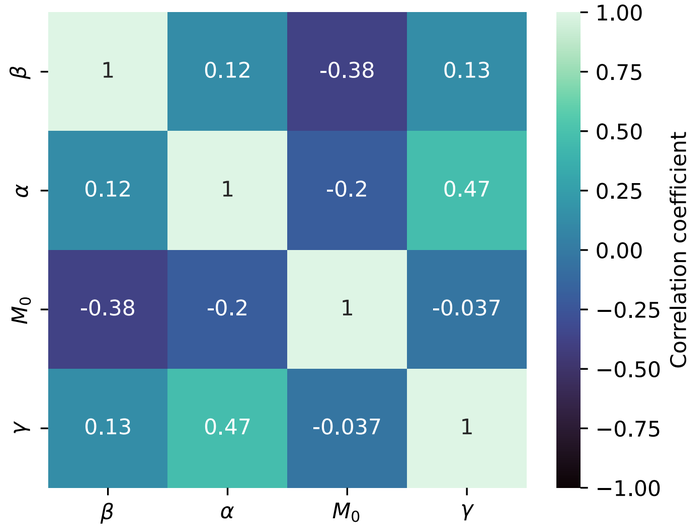
- Retraining BayeSN to jointly incorporate all effects
- Compare all models in an integrated framework (e.g. Stjornumal)

Backup

Environmental step

Different tracers and different methods

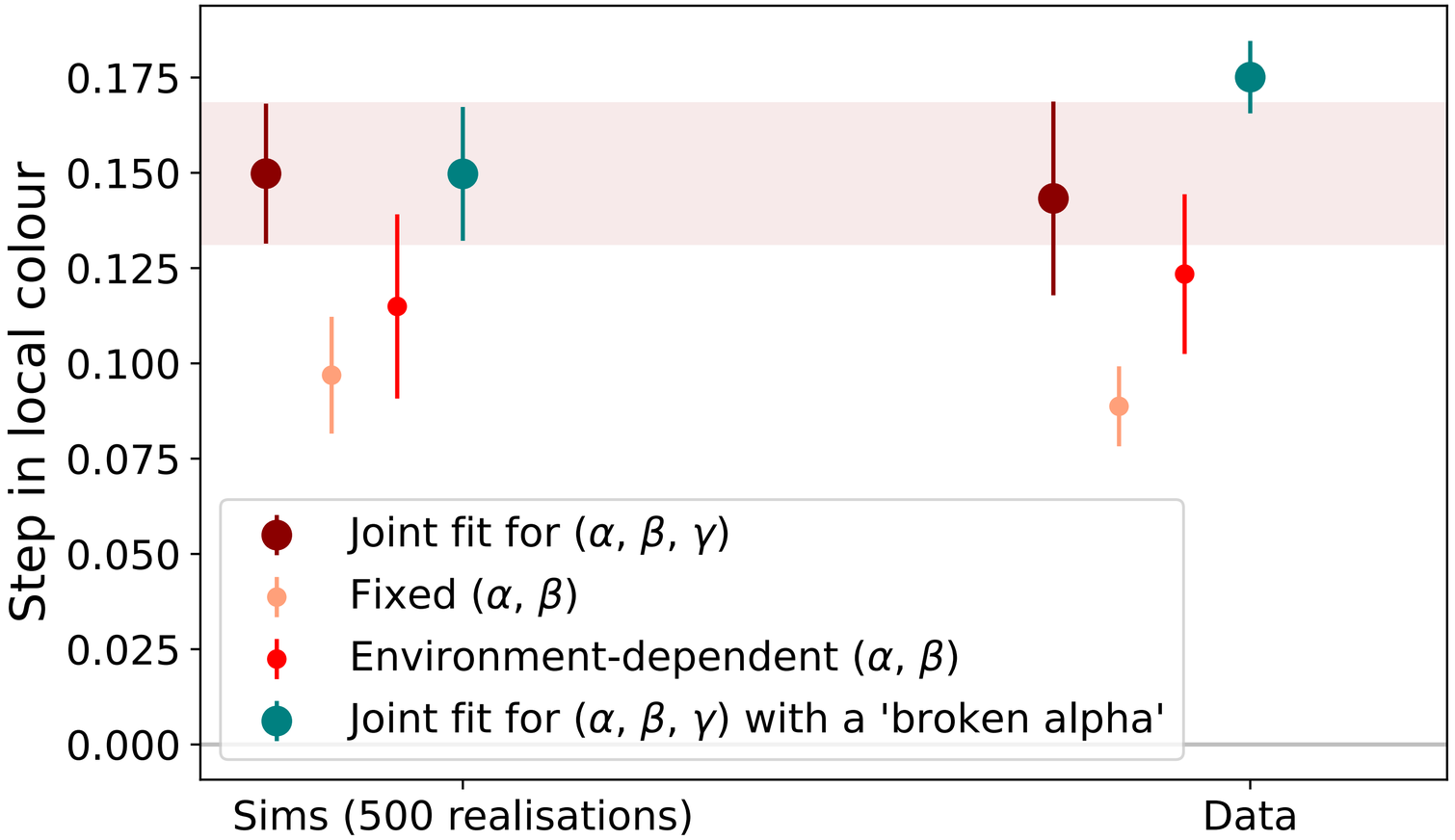




Ginolin+25b: Stretch

Environmental step

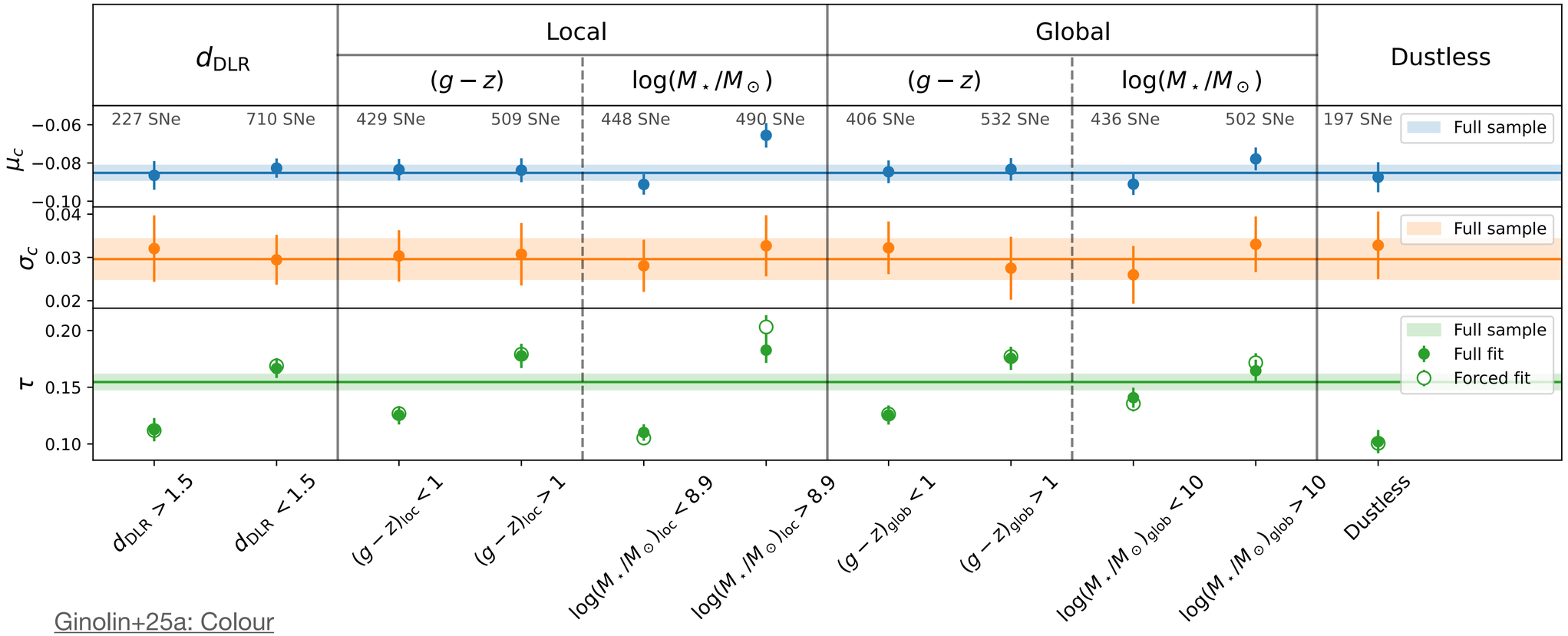
Different tracers and different methods



Ginolin+25b: Stretch

SALT colour

Dependence on environment

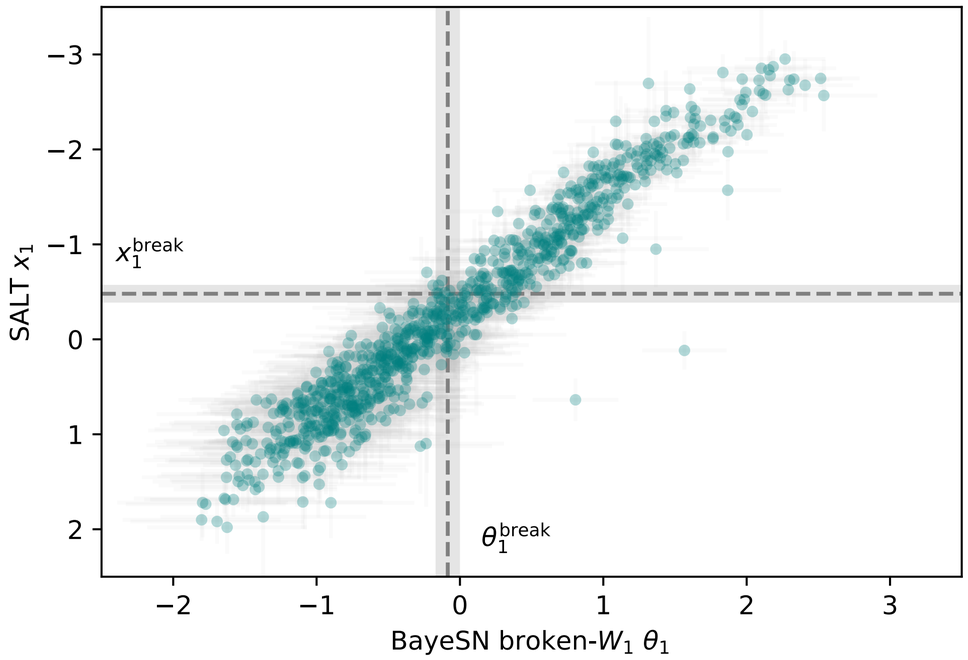


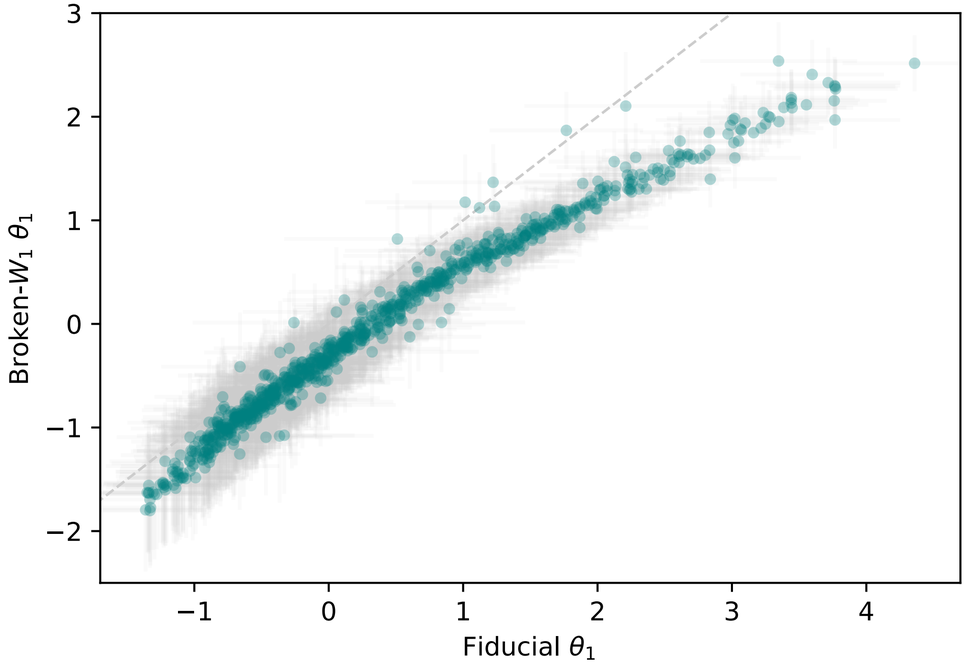
Ginolin+25a: Colour

ZTF x BayeSN

Broken-α

$$\Delta\alpha = 1.181 \pm 0.090\ (13.2\sigma)$$





Ginolin+26

ZTF x BayeSN

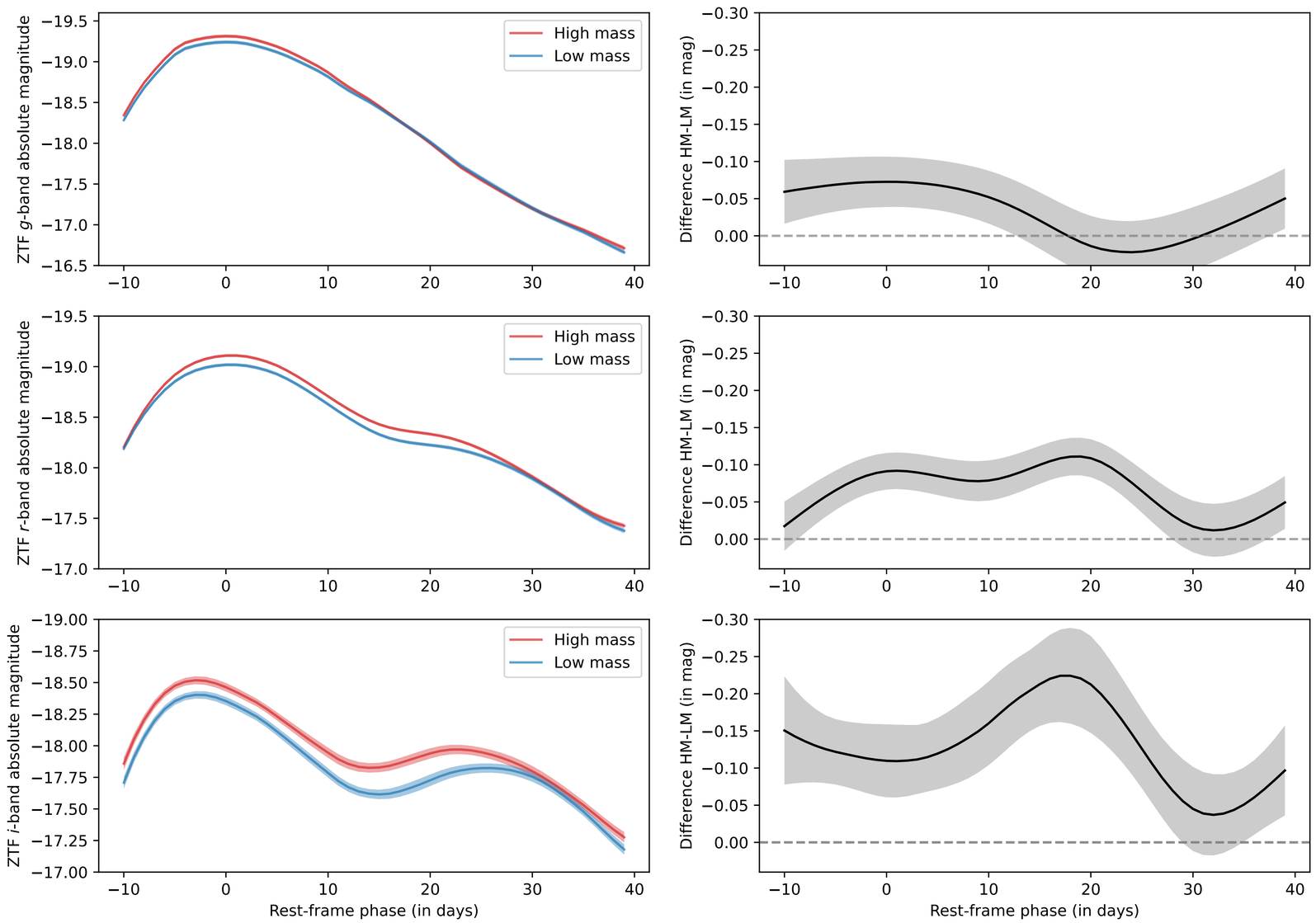
Intrinsic step - Full fit parameters

Sample	τ_A	μ_R	σ_R	$\mathbb{E}(R_V)$	$\sqrt{\mathrm{Var}(R_V)}$
$(g-z)_{\mathrm{local}} > 1$	0.389 ± 0.020	2.145 ± 0.111	0.540 ± 0.108	2.206 ± 0.076	0.488 ± 0.068
$(g-z)_{\mathrm{local}} < 1$	0.341 ± 0.020	2.325 ± 0.121	0.577 ± 0.109	2.371 ± 0.101	0.535 ± 0.077
$(g-z)_{\mathrm{global}} > 1$	0.394 ± 0.021	2.131 ± 0.134	0.551 ± 0.123	2.203 ± 0.080	0.492 ± 0.074
$(g-z)_{\mathrm{global}} < 1$	0.348 ± 0.021	2.296 ± 0.139	0.603 ± 0.123	2.358 ± 0.103	0.550 ± 0.082
$\log(M_\star/M_\odot)_{\mathrm{local}} > 8.9$	0.475 ± 0.024	2.220 ± 0.092	0.527 ± 0.088	2.261 ± 0.075	0.488 ± 0.062
$\log(M_\star/M_\odot)_{\mathrm{local}} < 8.9$	0.272 ± 0.018	2.274 ± 0.175	0.610 ± 0.136	2.347 ± 0.124	0.550 ± 0.086
$\log(M_\star/M_\odot)_{\mathrm{global}} > 10$	0.395 ± 0.021	2.164 ± 0.110	0.500 ± 0.100	2.207 ± 0.083	0.461 ± 0.069
$\log(M_\star/M_\odot)_{\mathrm{global}} < 10$	0.359 ± 0.021	2.249 ± 0.149	0.681 ± 0.129	2.352 ± 0.100	0.597 ± 0.078

Ginolin+26

ZTF x BayeSN

Intrinsic step



Ginolin+26

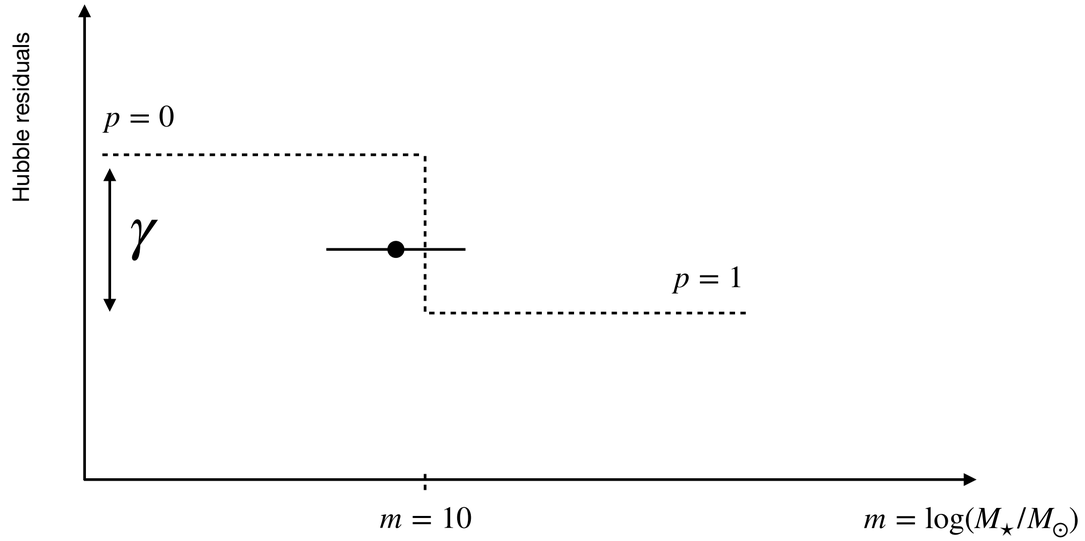
ZTF x BayeSN

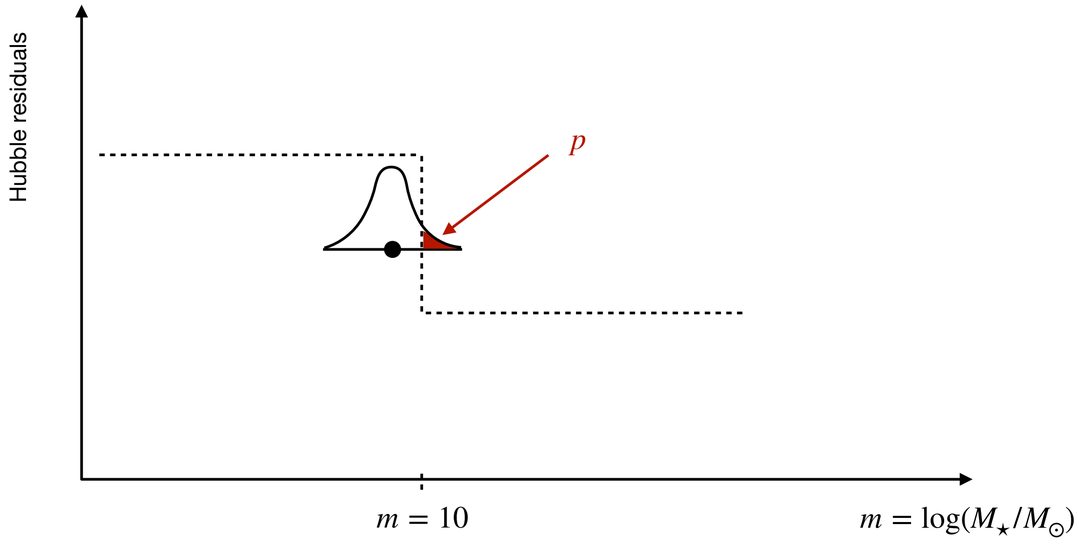
Changes from Grayling+24

SALT standardisation: $m_B + \alpha x_1 - \beta c + p\gamma$

$$p = \begin{cases} 0 & \text{if } m \leq 10 \\ 1 & \text{if } m > 10 \end{cases}$$

$$p = 1 - \int_{-\infty}^{10} \mathcal{N}(x, m, \sigma_m^2) dx$$

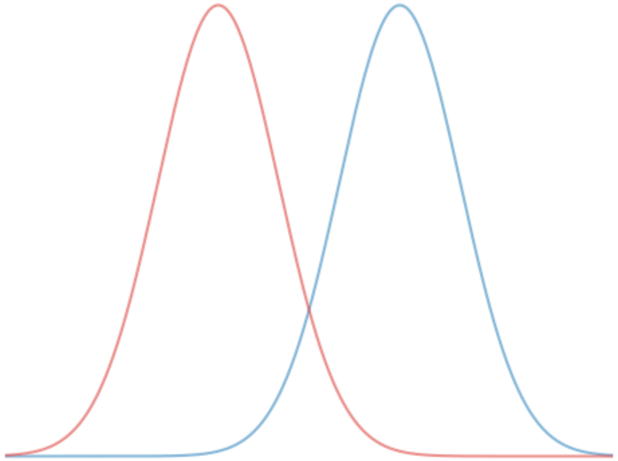




ZTF x BayeSN

Changes from Grayling+24

$$R_V^s \sim \begin{cases} \mathrm{TN}(\mu_{R,\mathrm{LM}}, \sigma^2_{R,\mathrm{LM}}, 1.2, \infty) & \text{if } \log(M_\star^s/M_\odot) \leq 10 \\ \mathrm{TN}(\mu_{R,\mathrm{HM}}, \sigma^2_{R,\mathrm{HM}}, 1.2, \infty) & \text{if } \log(M_\star^s/M_\odot) > 10 \end{cases}$$



$$R_V^s \sim p\mathrm{TN}(\mu_{R,\mathrm{LM}}, \sigma^2_{R,\mathrm{LM}}, 1.2, \infty) + (1-p)\mathrm{TN}(\mu_{R,\mathrm{HM}}, \sigma^2_{R,\mathrm{HM}}, 1.2, \infty)$$

