SN Ia Siblings & Rubin

Sam M. Ward, Stephen Thorp, Kaisey Mandel, Suhail Dhawan & many more!

Young Supernova Experiment

Institute of Astronomy, University of Cambridge

Next generation surveys in the Rubin-LSST era

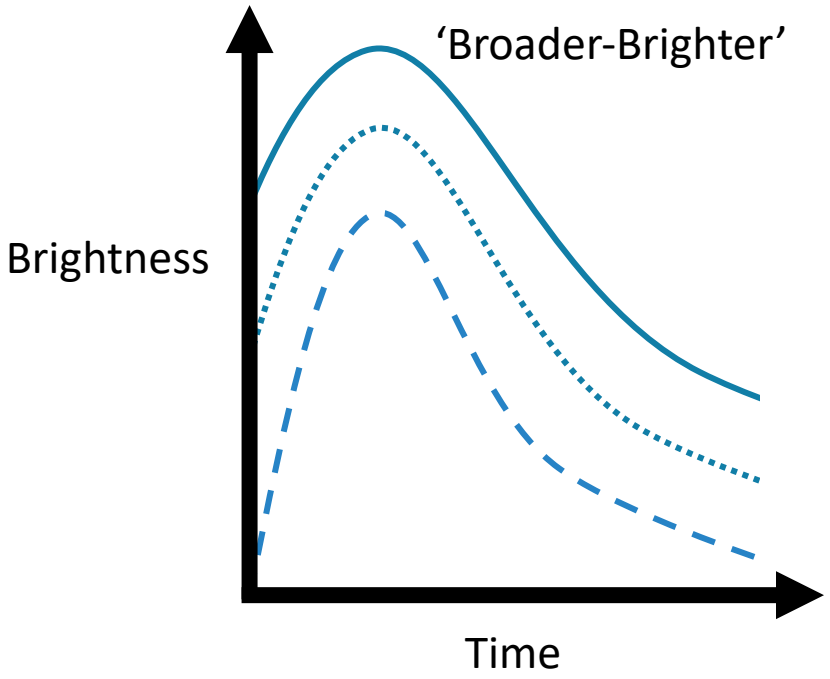
27th March 2023

UNIVERSITY OF CAMBRIDGE

ioa

SNe Ia & Systematics

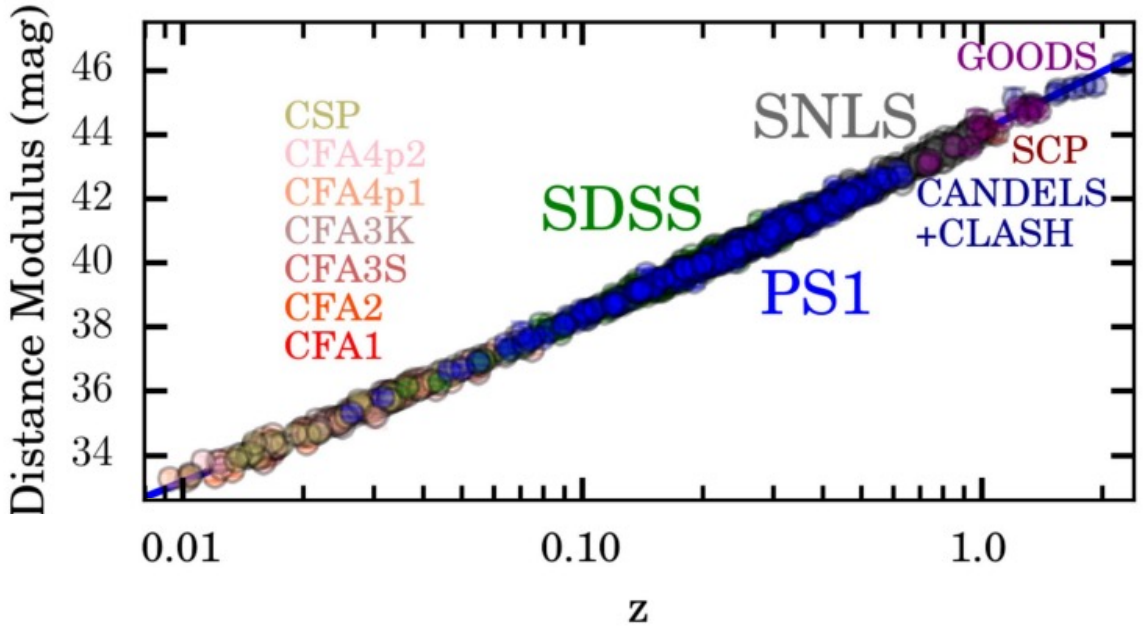
SNe Ia are Standardisable Candles

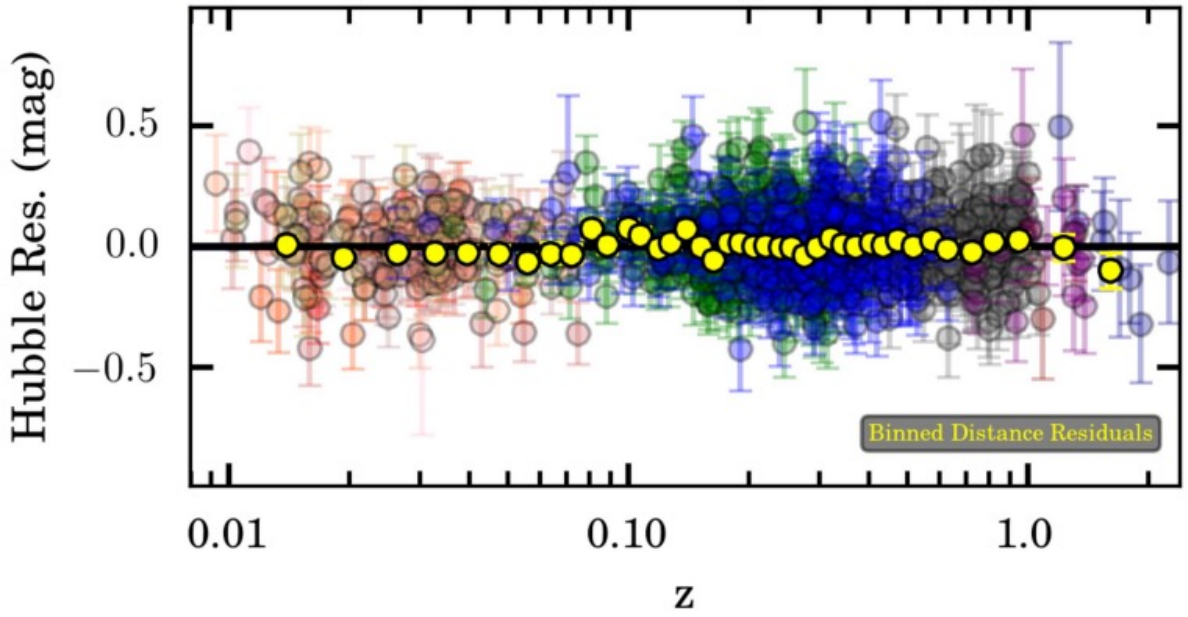


(Pskovskii77, Phillips 93)

(Riess+96,Tripp 98)

Luminosity Distances Constrain Cosmology

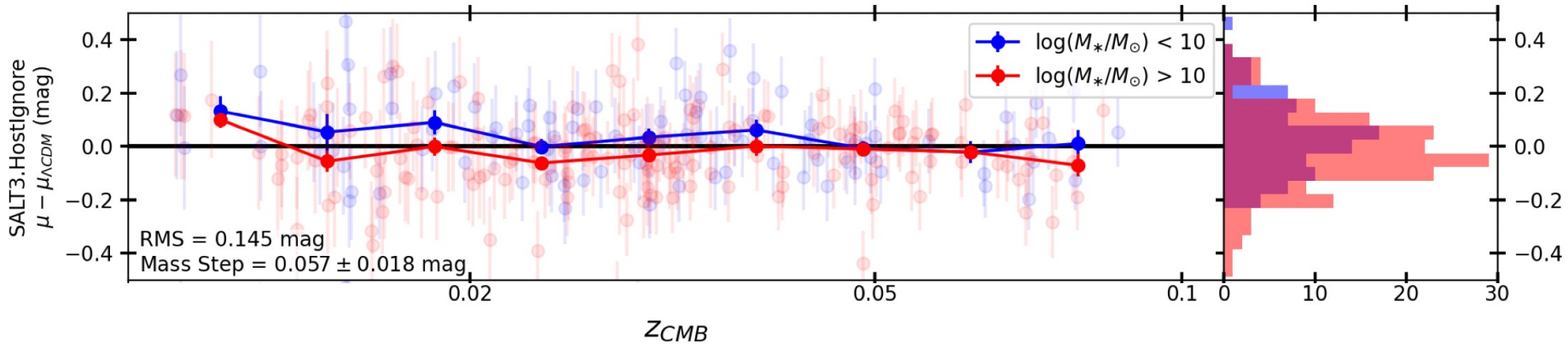




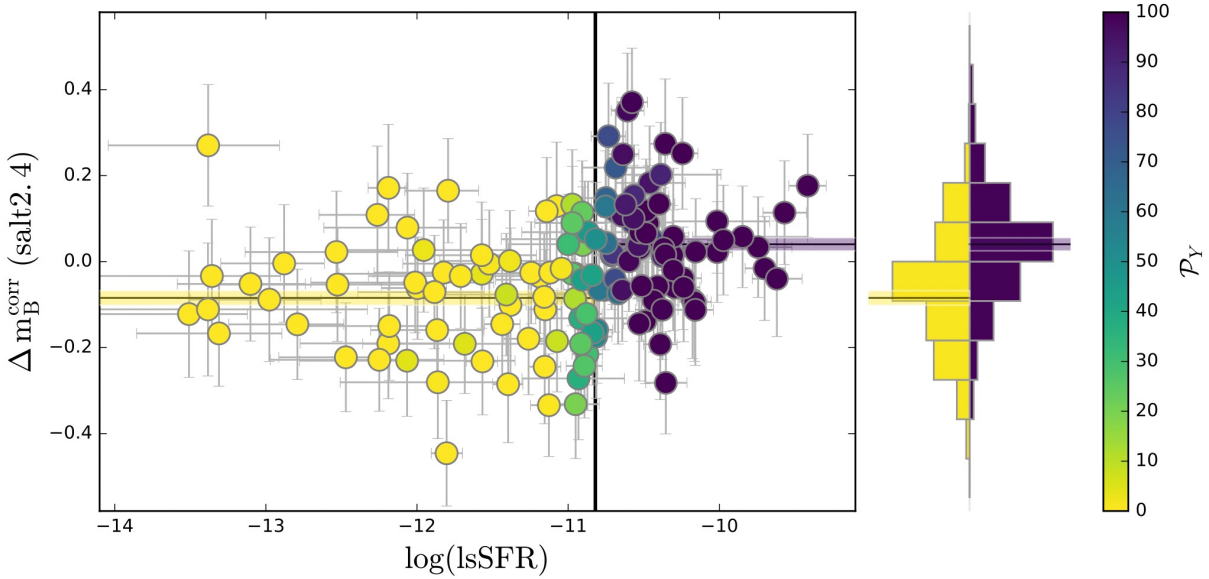
Goal is to improve SN Ia standardisation for accurate and precise constraints on e.g. w, H0, $f\sigma_8$ etc.

(Scolnic+18)

What systematics now dominate?



Step in
Global Property:
Host Galaxy
Stellar Mass



Step in
Local Property:
Local specific Star
Formation Rate

(Jones+22, Rigault+20)

Why are SN Ia Siblings Useful?

Why are Supernova Siblings Important?

SN Siblings are those that occur in the same host galaxy

Advantages: Common Distance

Common Host-Galaxy Properties (Type, Mass…)

Common Peculiar Velocity, Redshift

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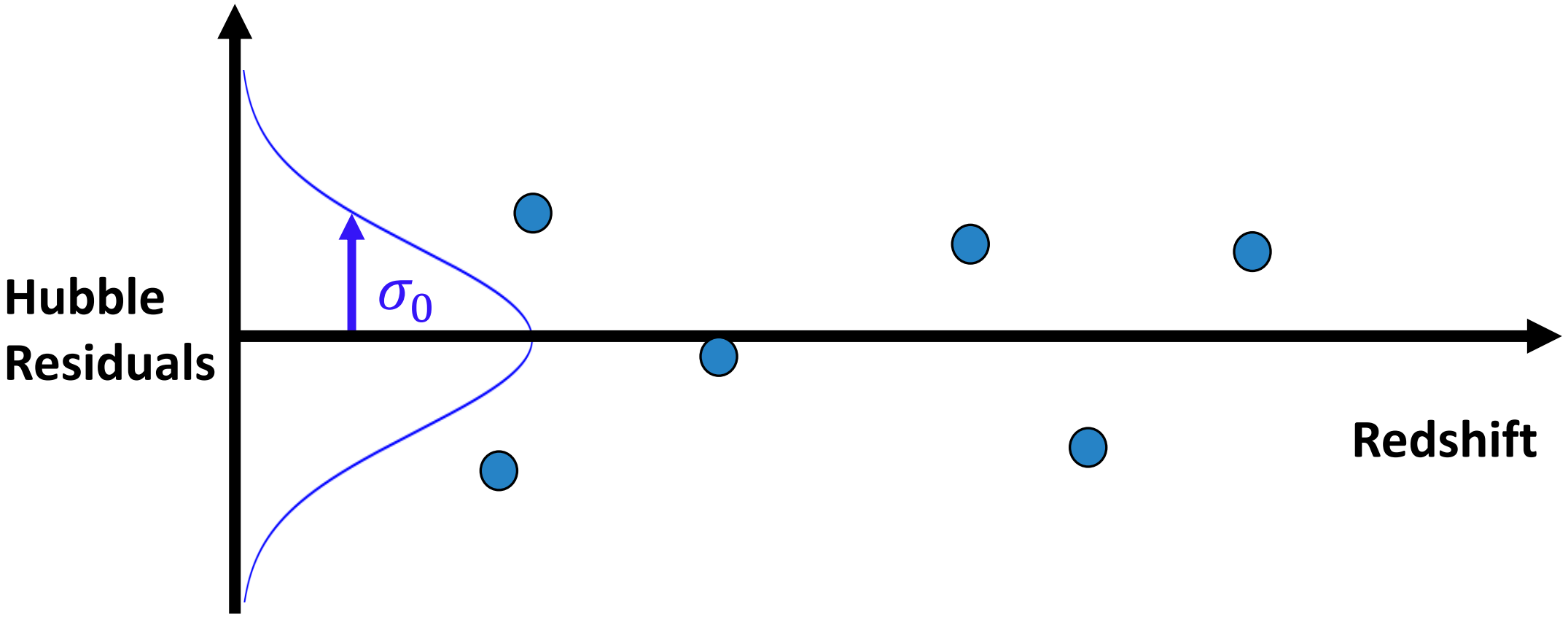
Common Peculiar Velocity, Redshift

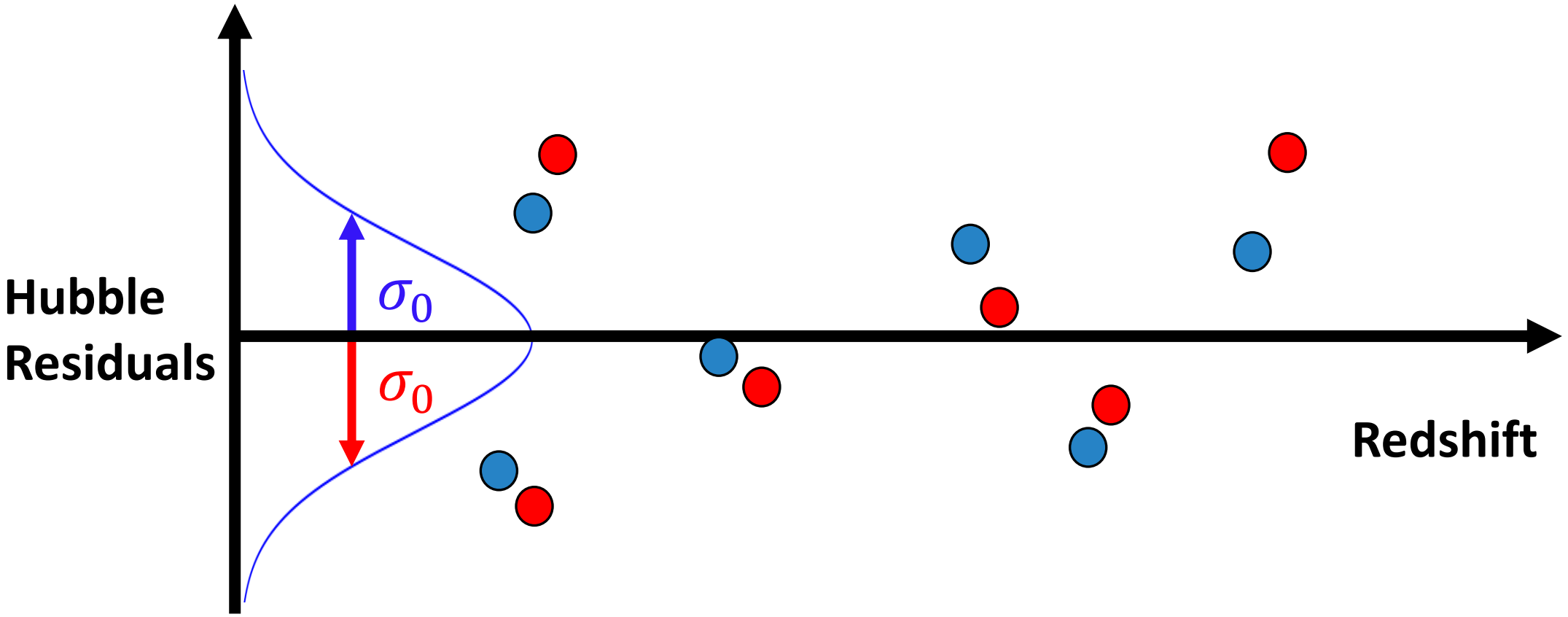
Variations between siblings: intrinsic SED, dust, local host galaxy properties, etc.

Total Intrinsic Scatter: σ_0



Total Intrinsic Scatter: σ_0

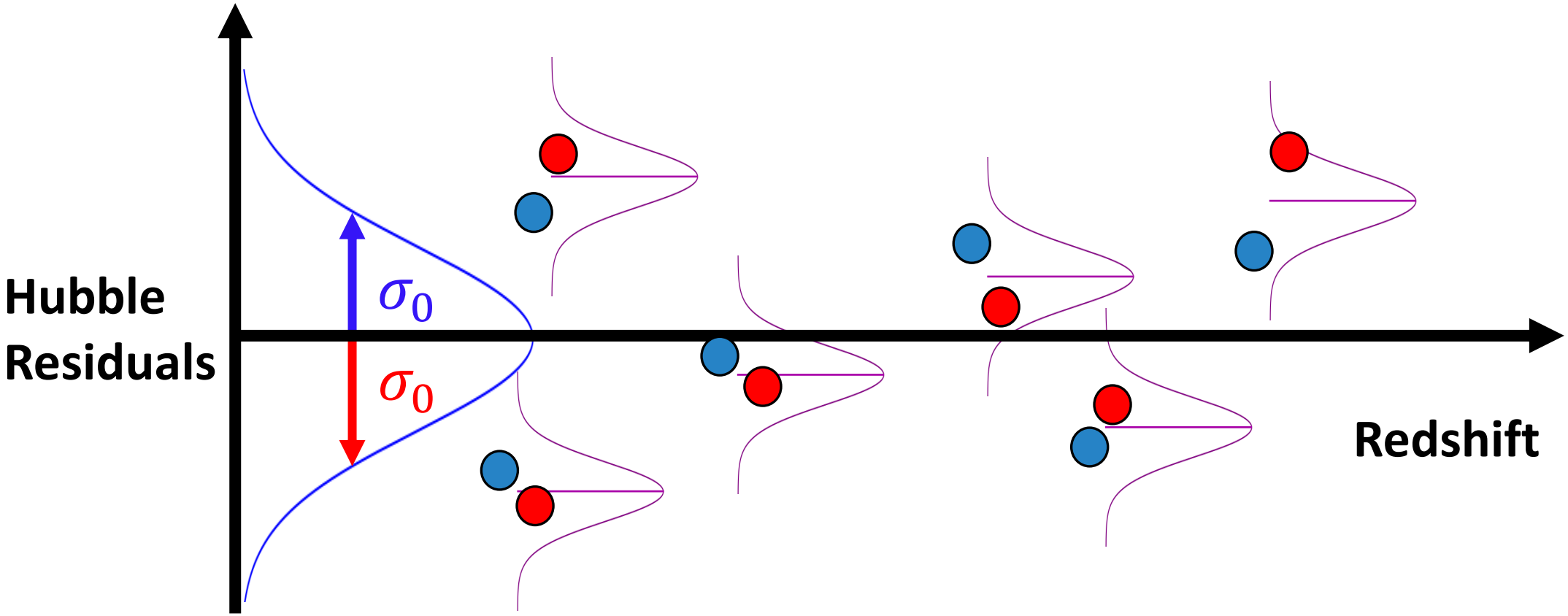
Siblings also have: σ_0



Total Intrinsic Scatter: σ_0

Relative Intrinsic Scatter: σ_{Rel}

Siblings also have: σ_0



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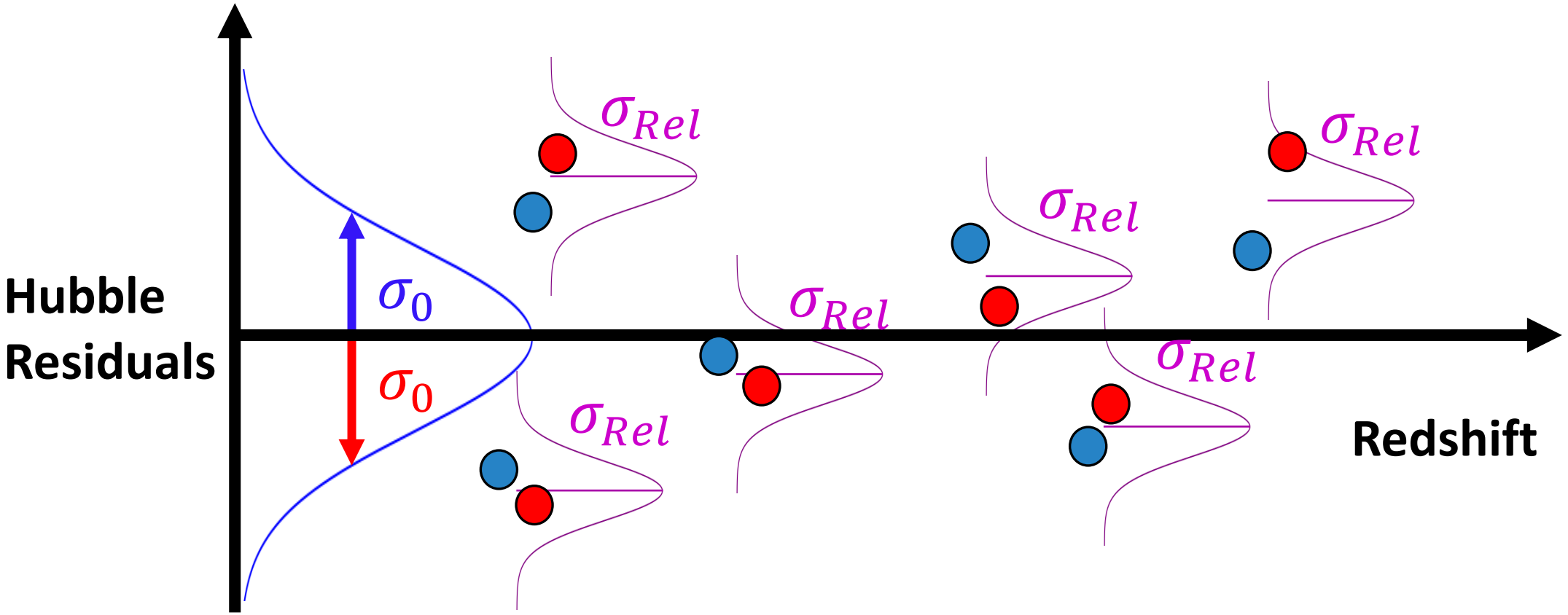

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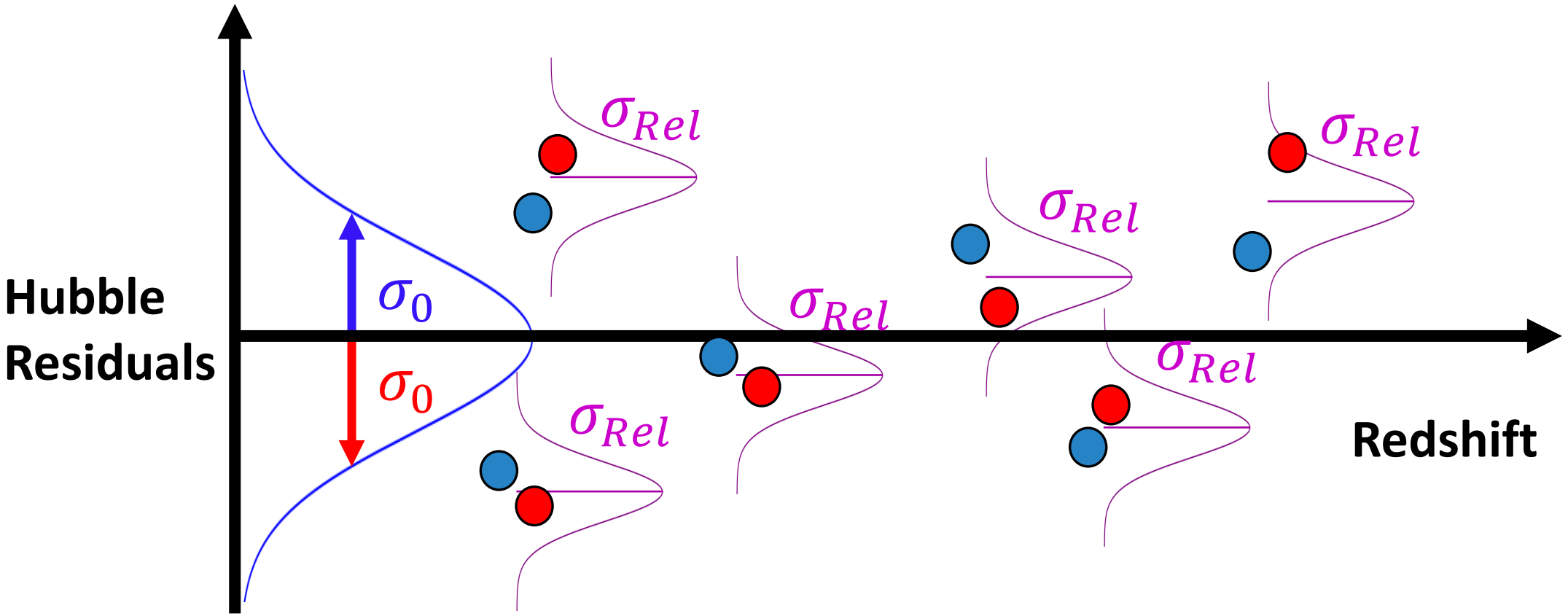
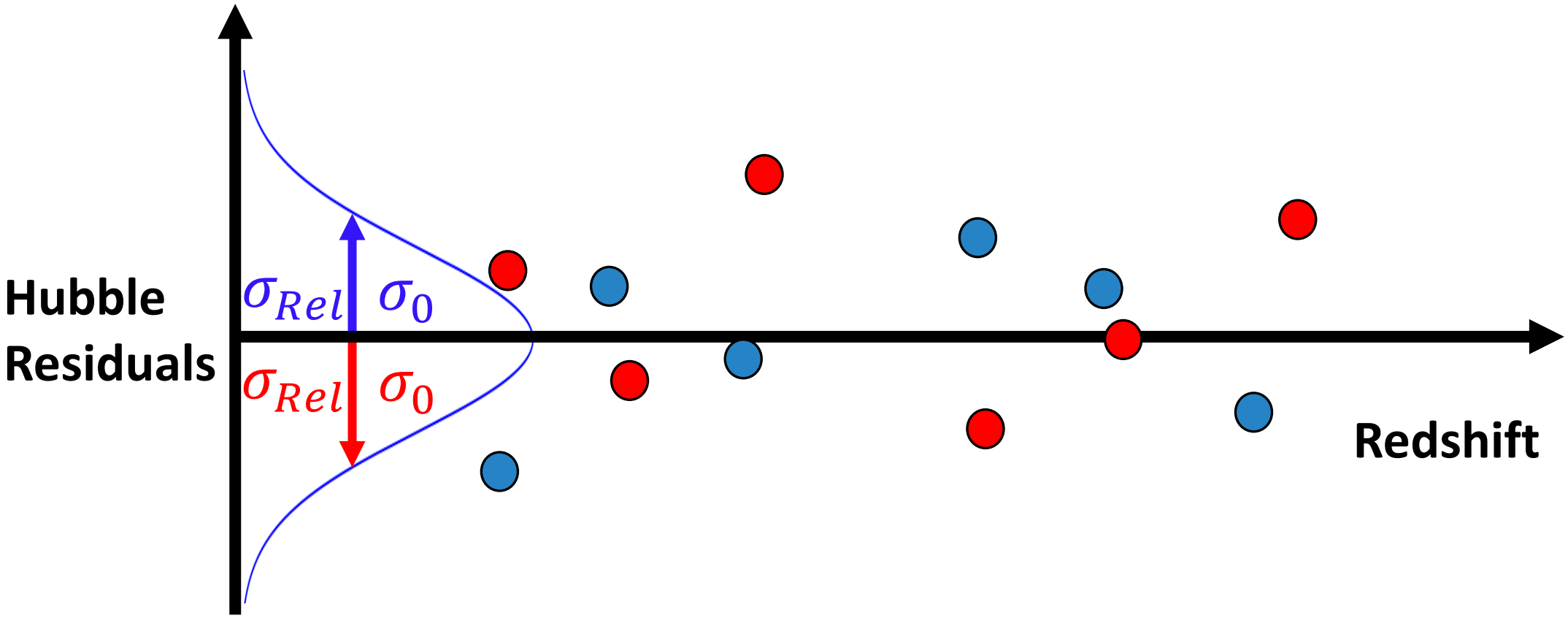


$$\sigma_{Rel} \ll \sigma_0$$

Total Intrinsic Scatter: σ_0

Relative Intrinsic Scatter: σ_{Rel}

Siblings also have: σ_0



$$\sigma_{Rel} \approx \sigma_0$$

Scenario A. $\sigma_{Rel} \ll \sigma_0$: Implies common properties dominate σ_0

Scenario B. $\sigma_{Rel} \approx \sigma_0$: Implies variations between siblings dominates σ_0

Scenario C. $\sigma_{Rel} < \sigma_0$: Both common properties and siblings variations contribute towards σ_0

Scolnic et al. (2020) with SALT2

$\sigma_{Rel} > \sigma_0/2$

We show at 2.8σ significance that at least $1/2$ of the intrinsic scatter of SNe Ia distance modulus residuals is not from common host properties.

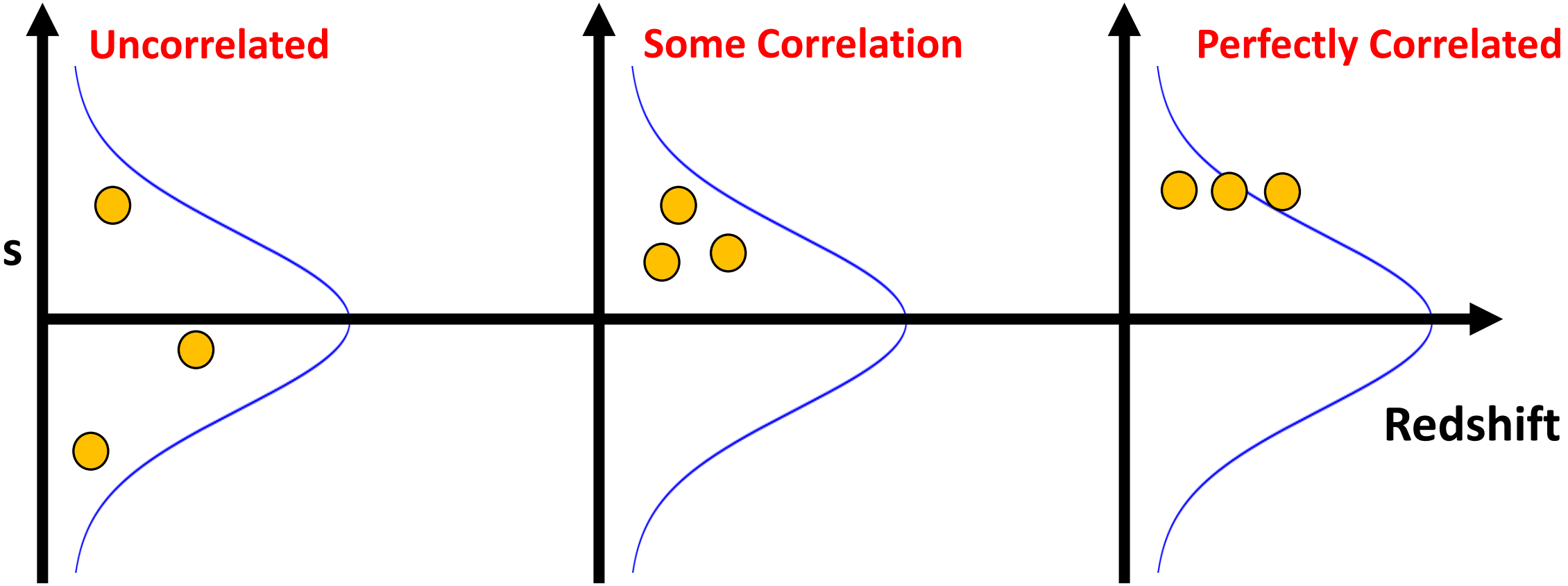
Burns et al. (2020) with SNooPy

$\sigma_{Rel} \ll \sigma_0$

Table 4
Intrinsic Dispersions in the Sibling Distances

Subsample	σ_{SN}	N_{pair}	N_{gal}
All pairs	0.14(02)	34	15
No Swift SNe	0.07(03)	28	12
$s_{BV} > 0.6$	0.12(02)	25	12
$s_{BV} > 0.6$ and no Swift SNe	<0.03 (95% conf.)	21	11

Correlation of siblings affects uncertainty on distance estimate

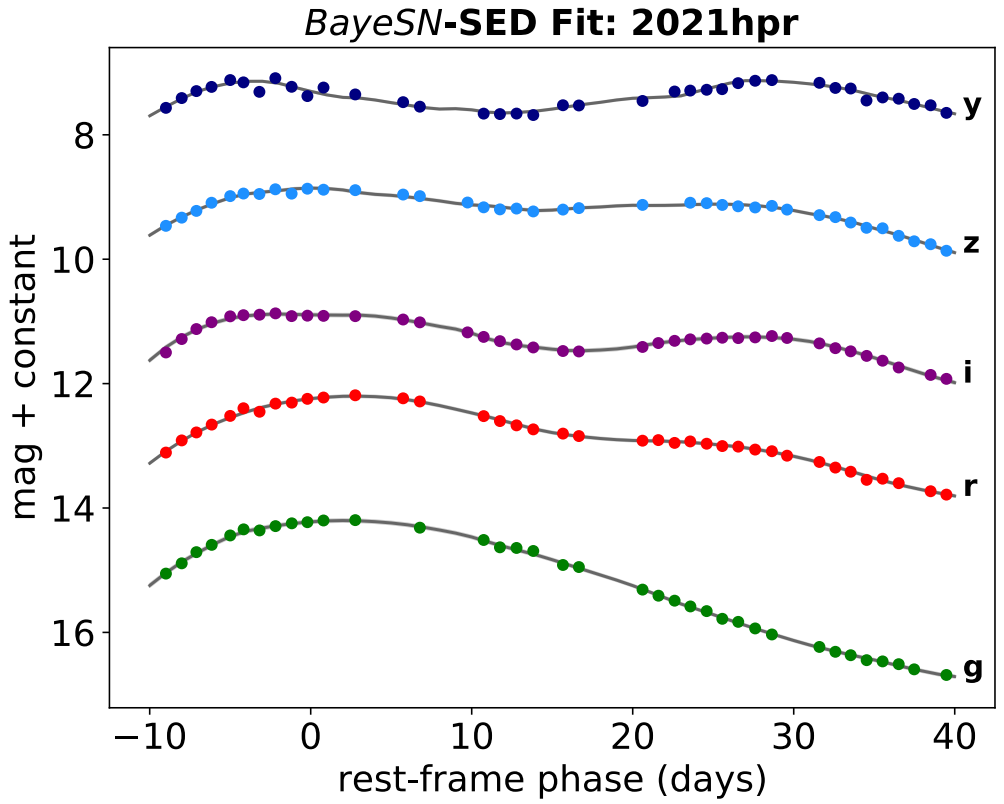


Distance Uncertainty Contribution	$\frac{\sigma_0}{\sqrt{N_{Siblings}}}$	$\sigma_0^2 - \sigma_{Rel}^2 + \frac{\sigma_{Rel}^2}{N_{Siblings}}$	σ_0

Hierarchically Modelling Siblings

(Ward et al. 2023)

Young Supernova Experiment (YSE)



(Jones+21, Aleo+22)

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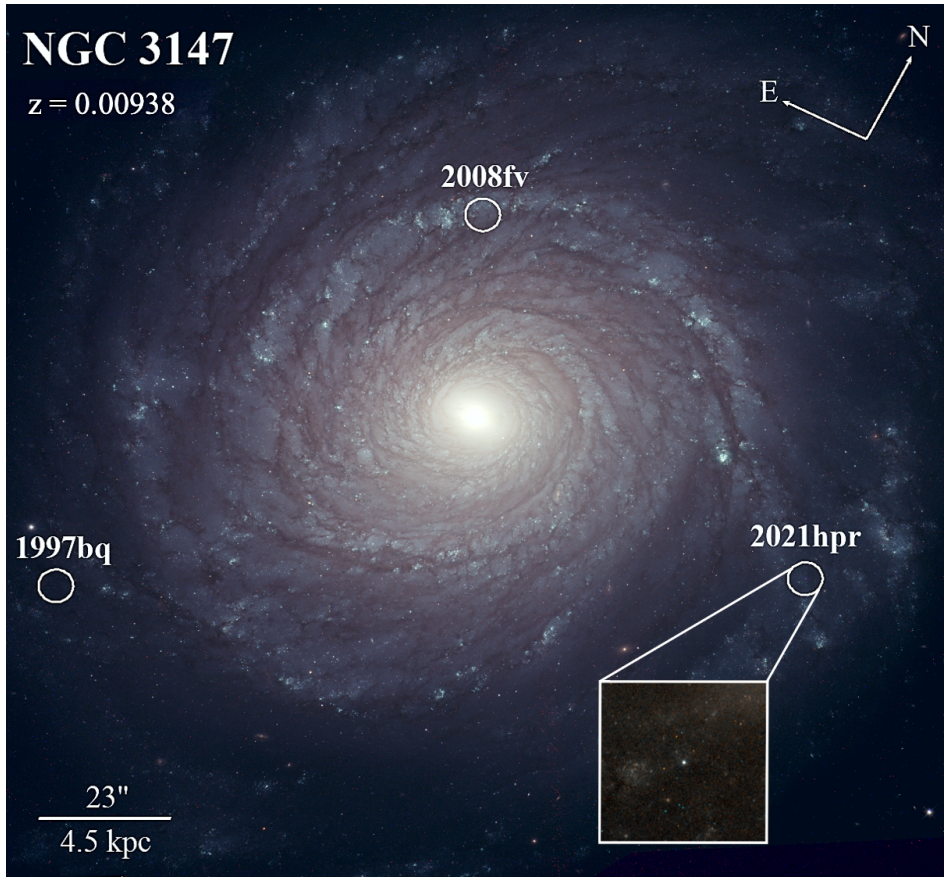
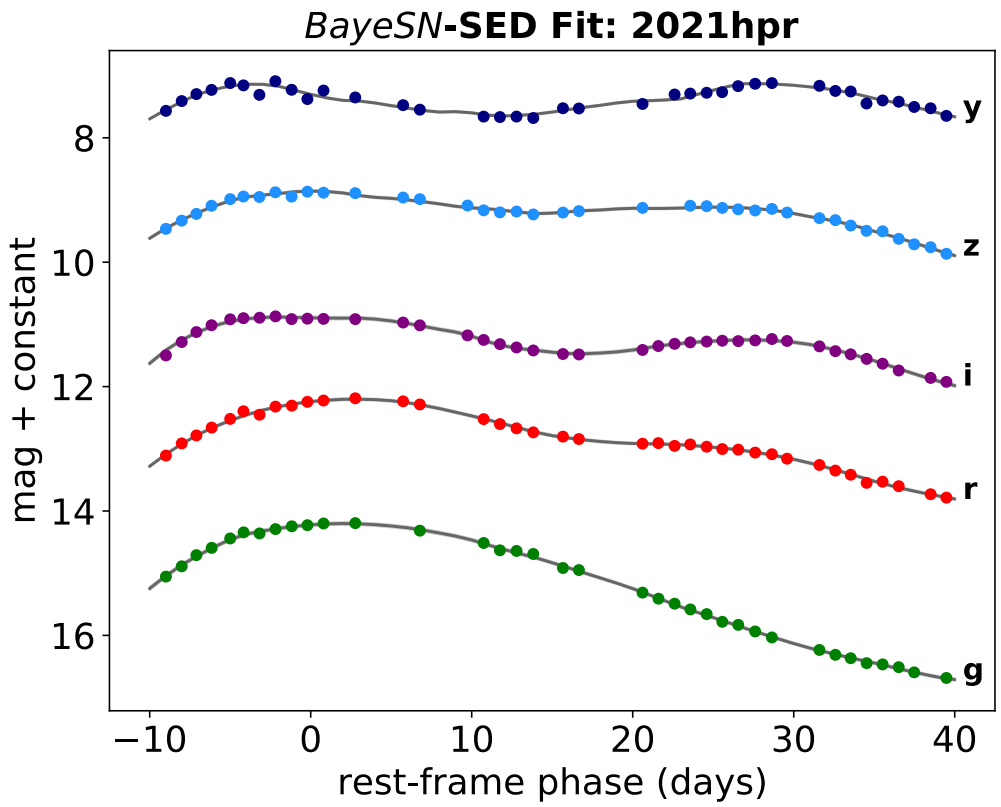
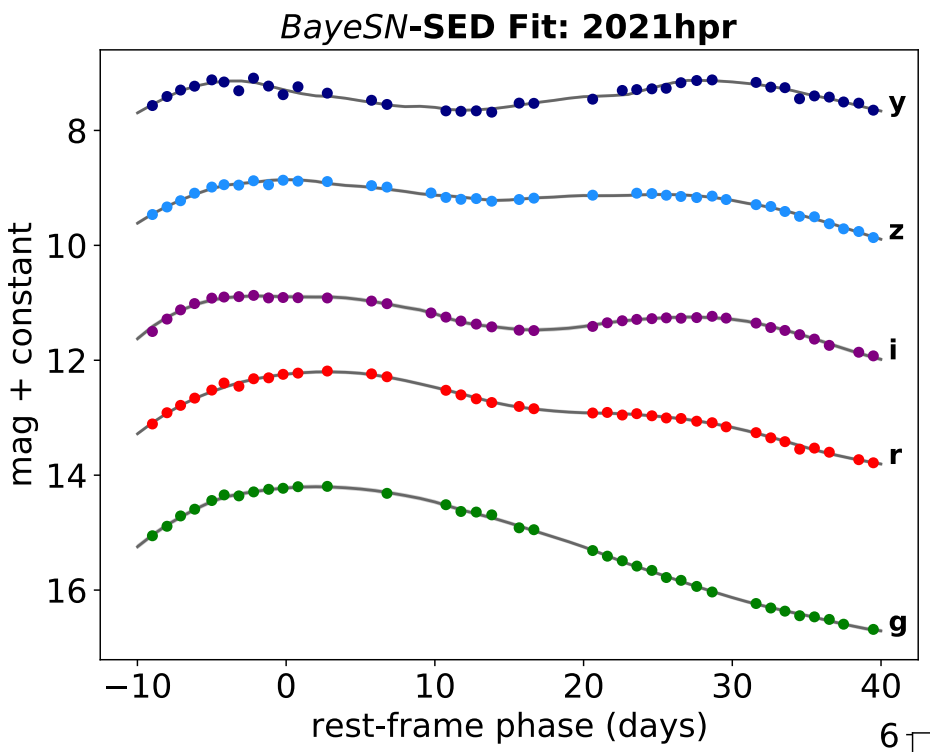




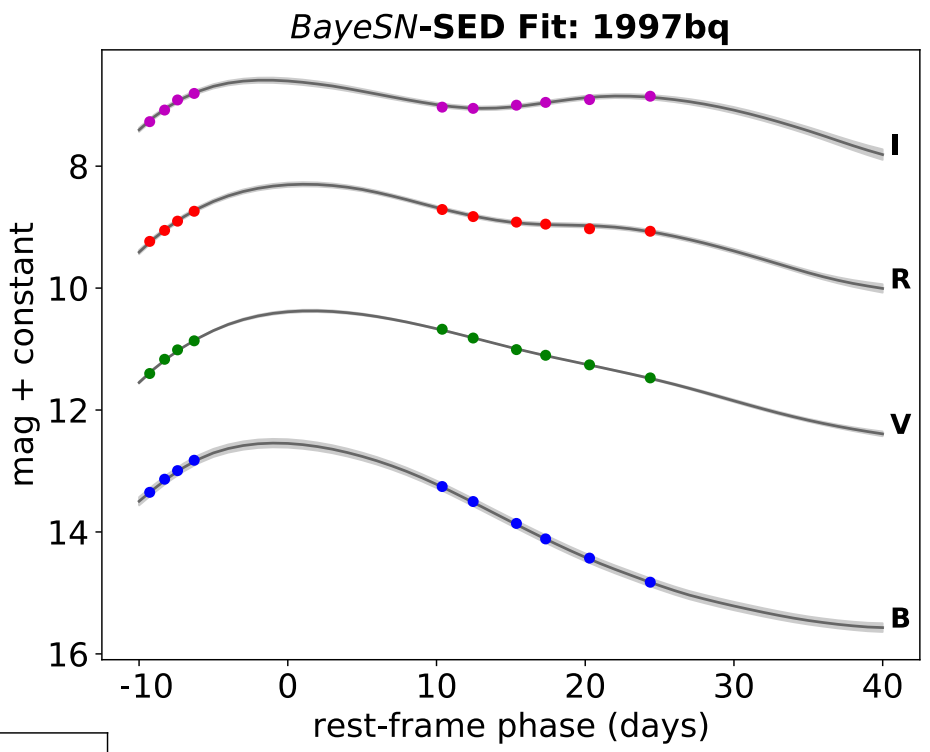
(Jones+21, Aleo+22)

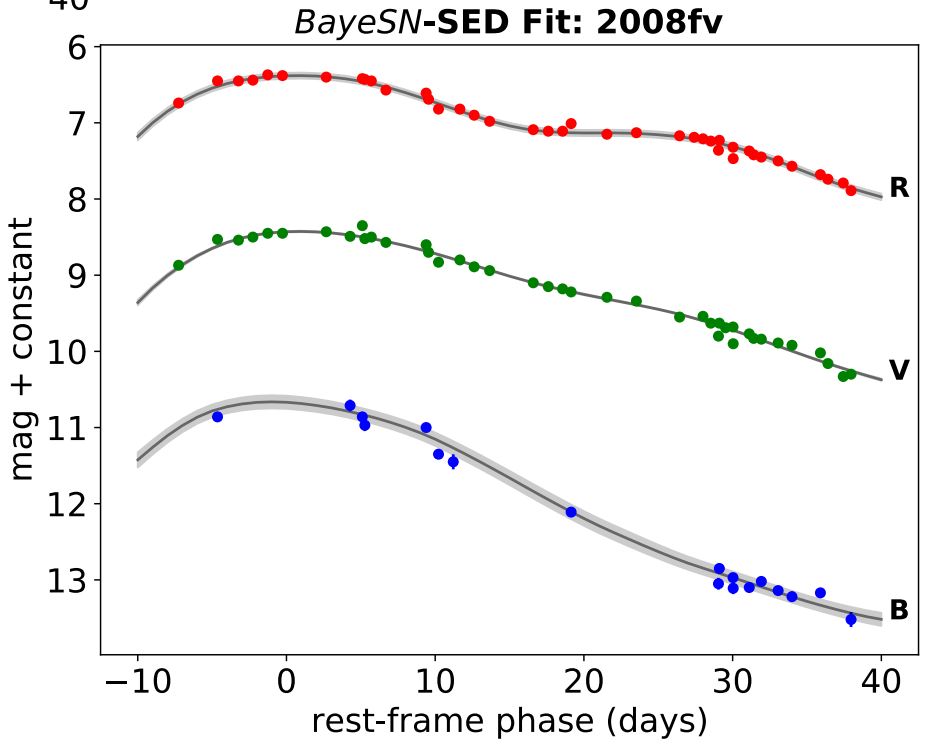


SN 2021hpr (YSE; Jones+21)

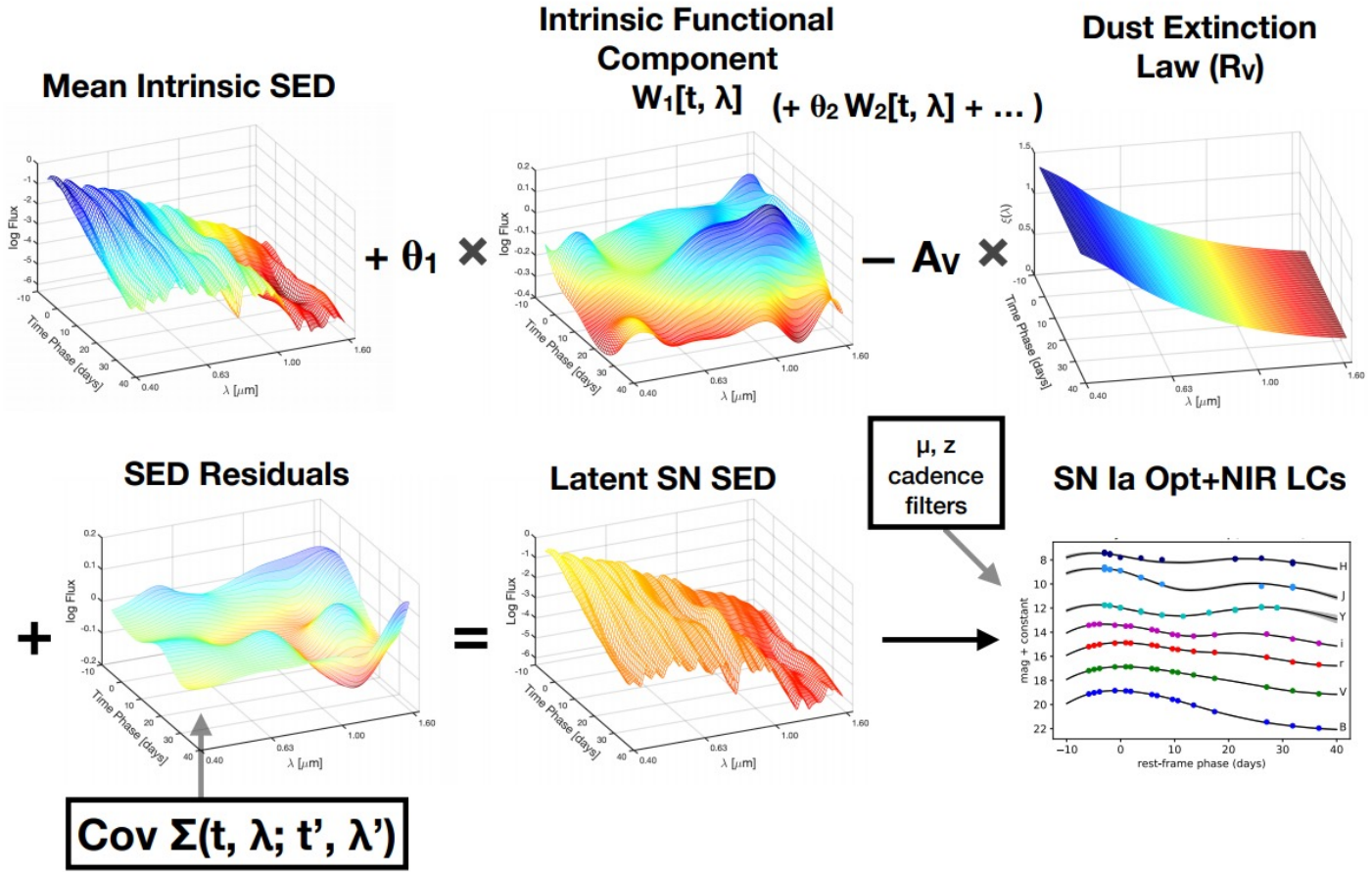
SN 2008fv (Tsvetkov+10, Biscardi+12, Friedman+15)

SN 1997bq (Jha+06)



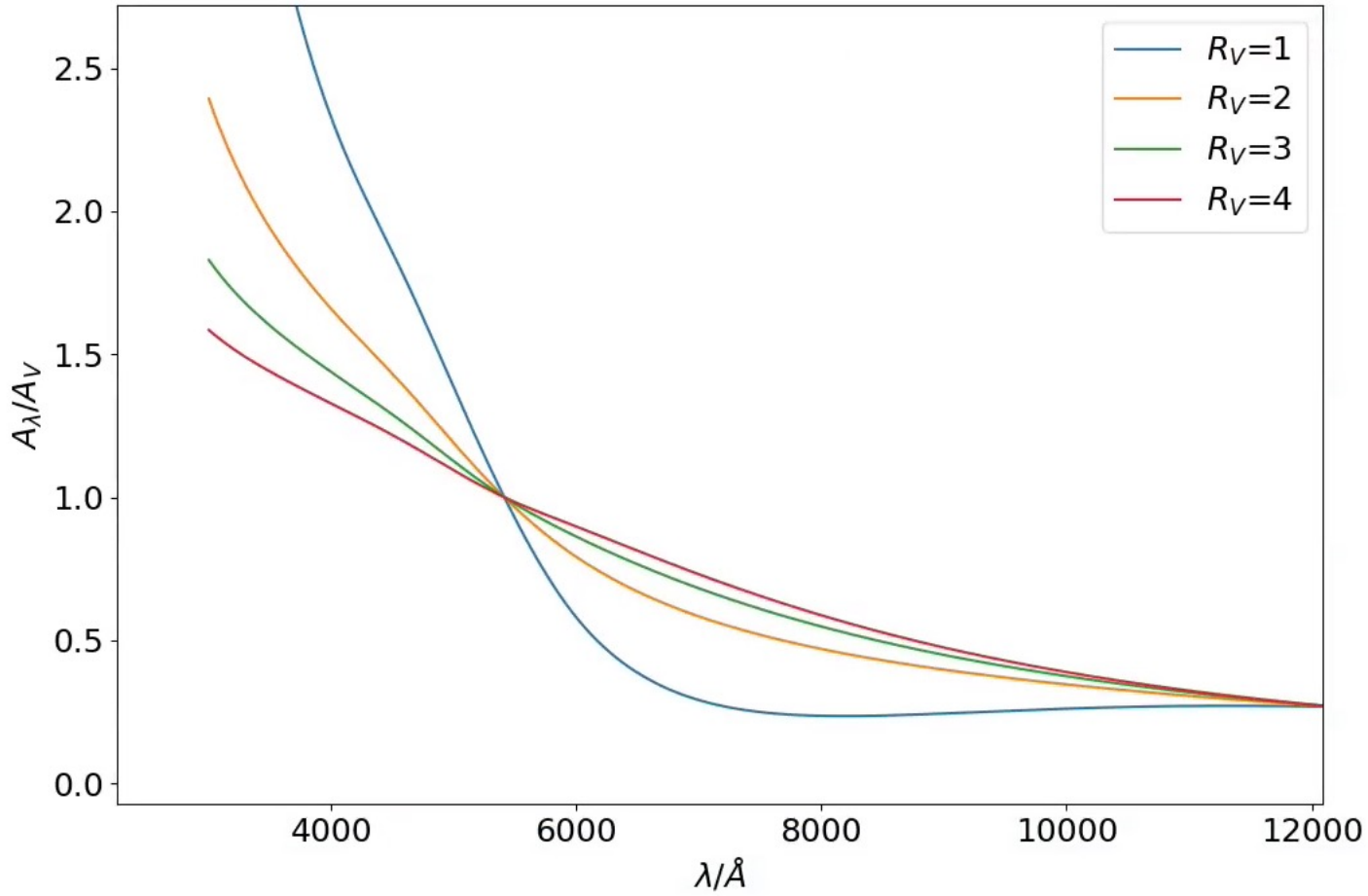


SN Ia Model: *BayeSN*



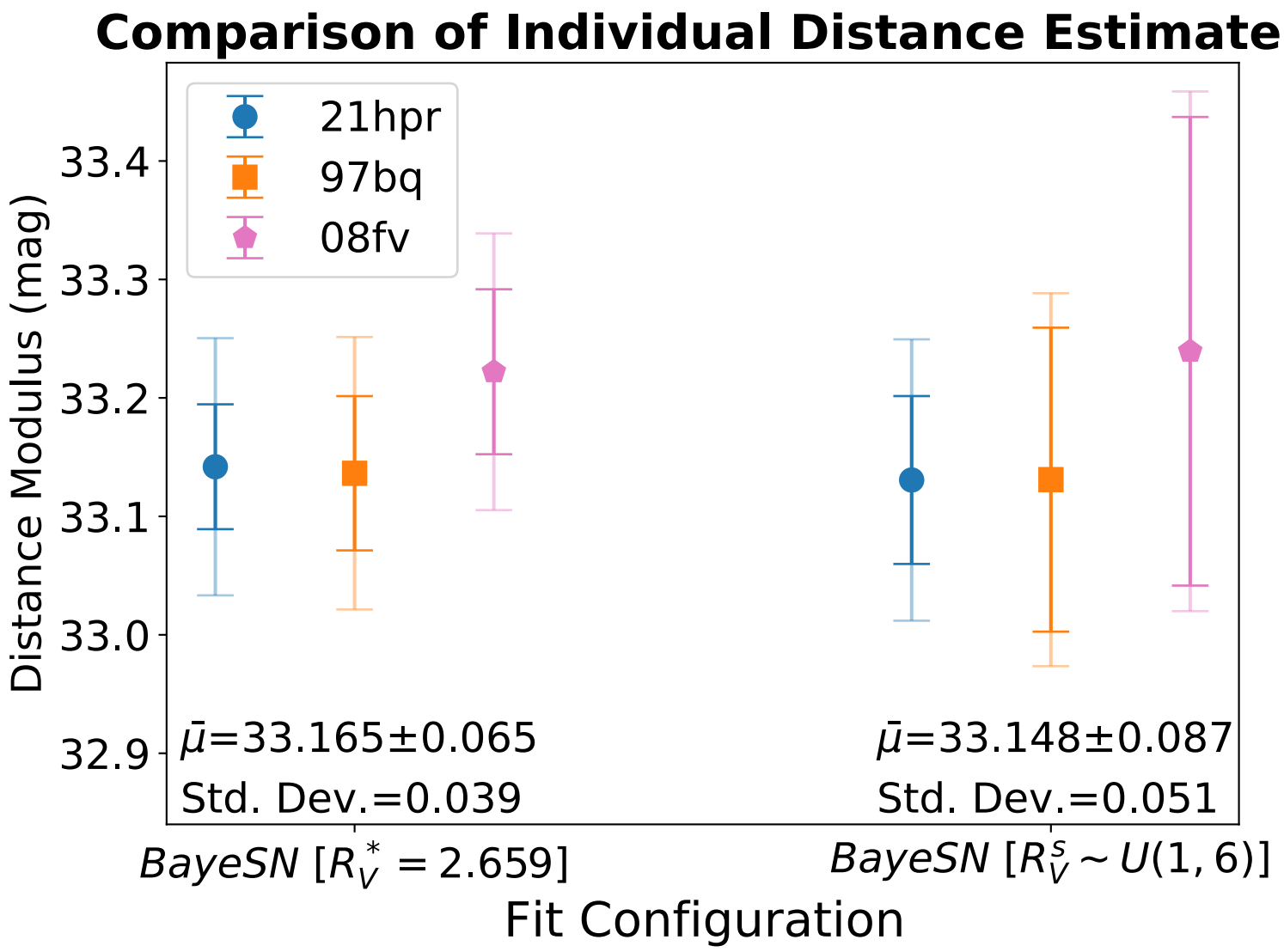
(Mandel+22, Thorp+21)

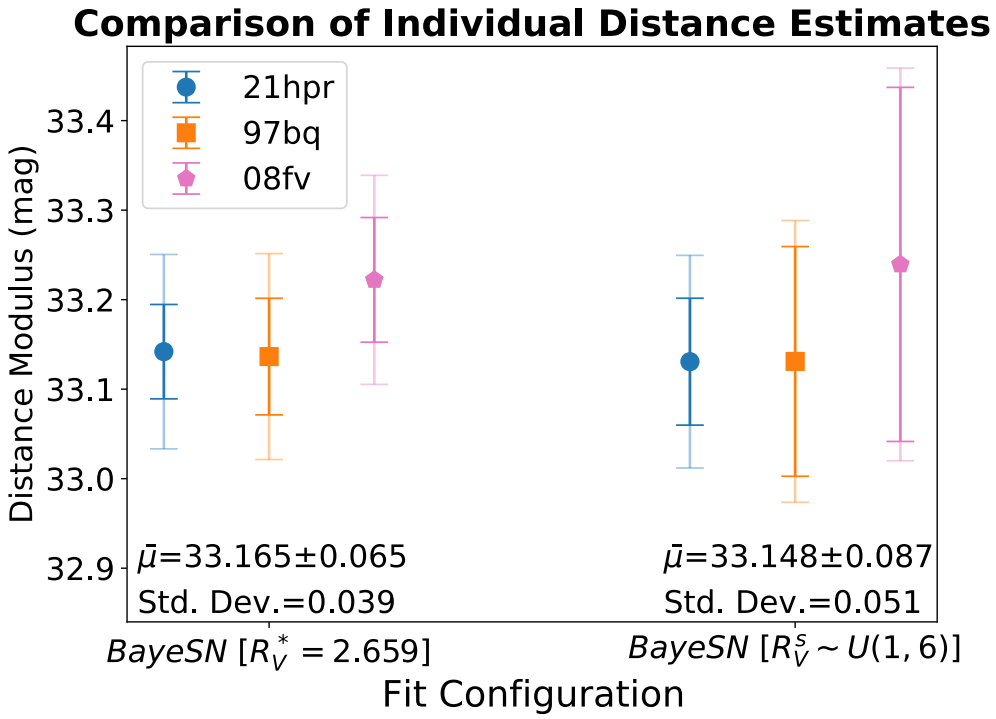
Model Parameters: Dust



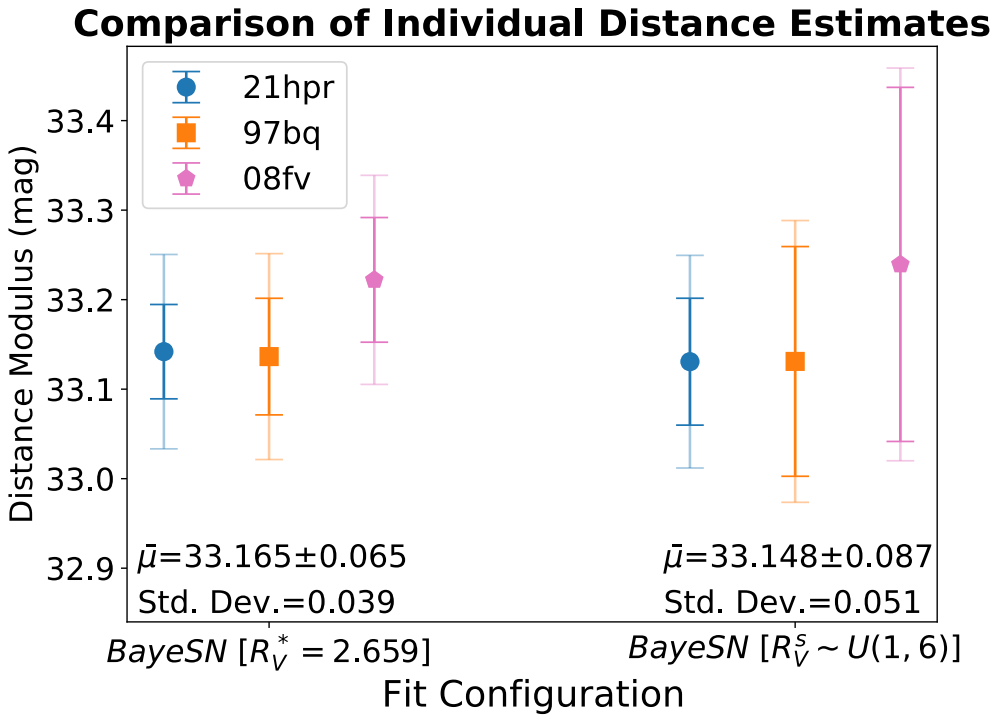
Dust Law parameterised by (A_V, R_V)

(Fitzpatrick 99)


Comparison of Individual Distance Estimates
21hpr
97bq
08fv
Distance Modulus (mag)
33.4
33.3
33.2
33.1
33.0
32.9
$\bar{\mu}$=33.165±0.065
Std. Dev.=0.039
$\bar{\mu}$=33.148±0.087
Std. Dev.=0.051
BayeSN [$R_V^* = 2.659$]
BayeSN [$R_V^s \sim U(1, 6)$]
Fit Configuration



$\sigma_{\rm Rel}$-Posterior (mag) [b]		
$\sigma_{\rm Rel} \sim \mathcal{U}(0, 0.1)$	$\sigma_{\rm Rel} \sim \mathcal{U}(0, 0.15)$	$\sigma_{\rm Rel} \sim \mathcal{U}(0, 1.0)$
< 0.056 (0.091)	< 0.073 (0.133)	< 0.130 (0.516)
< 0.062 (0.094)	< 0.086 (0.138)	< 0.209 (0.663)



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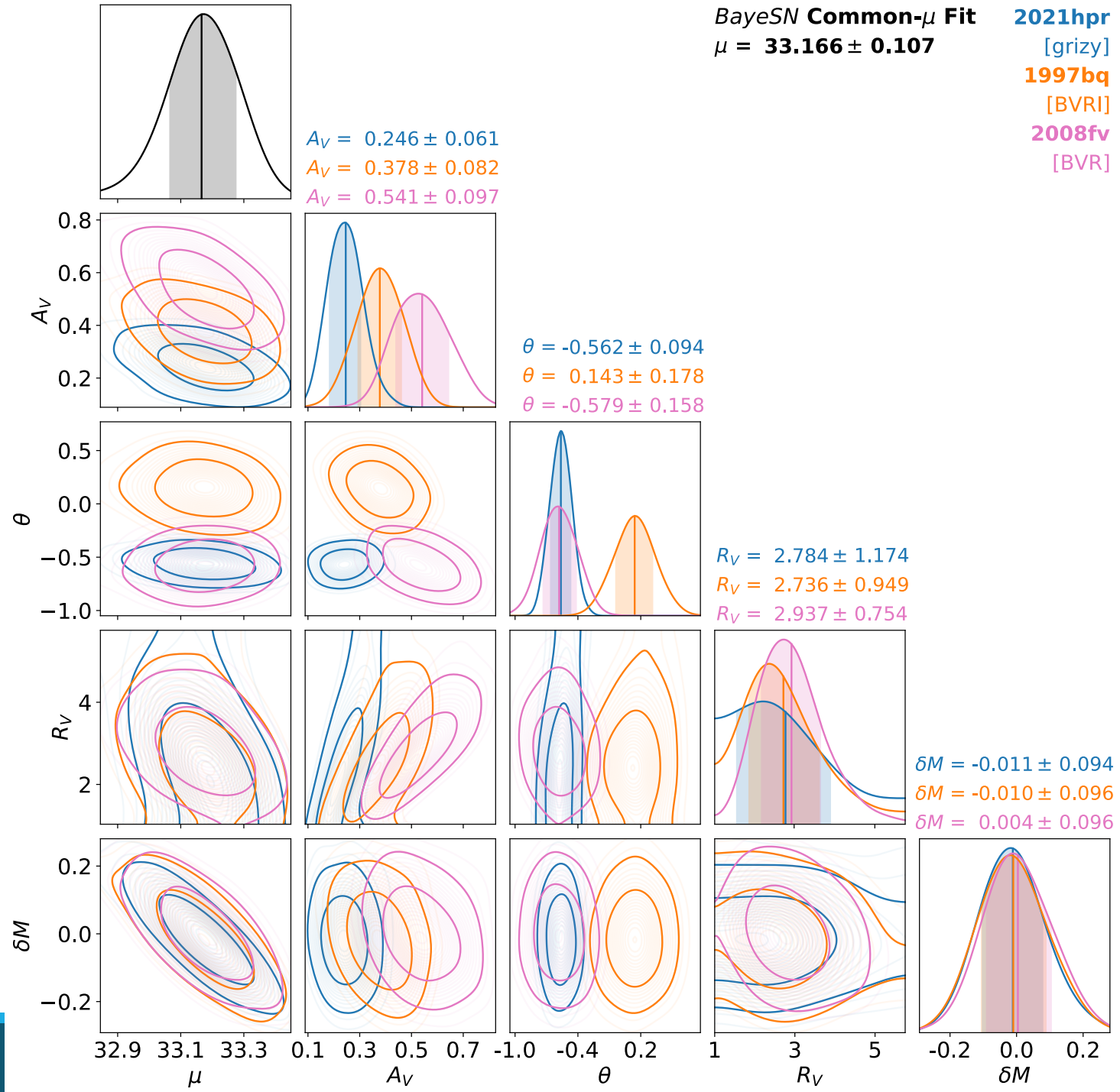
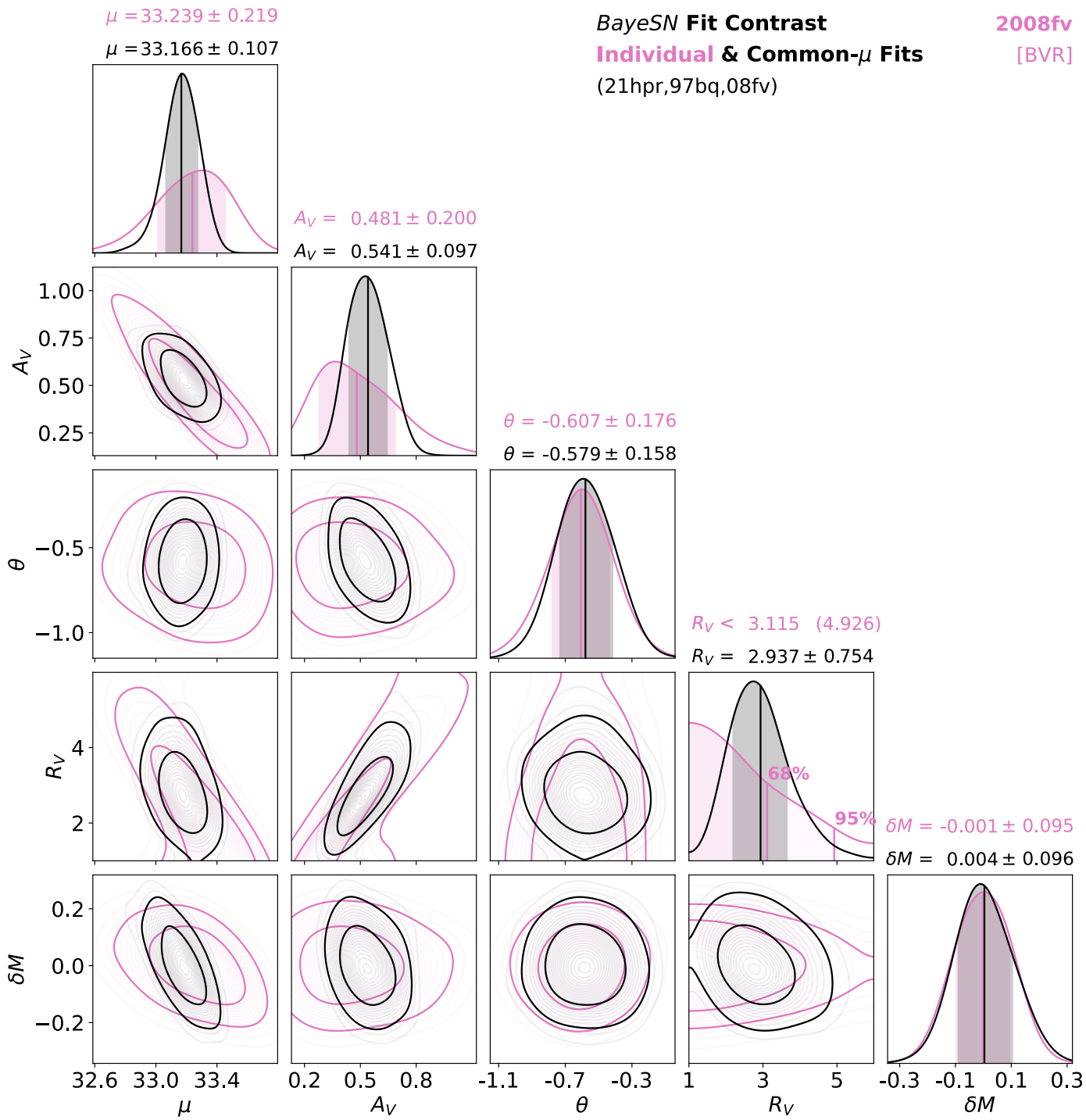
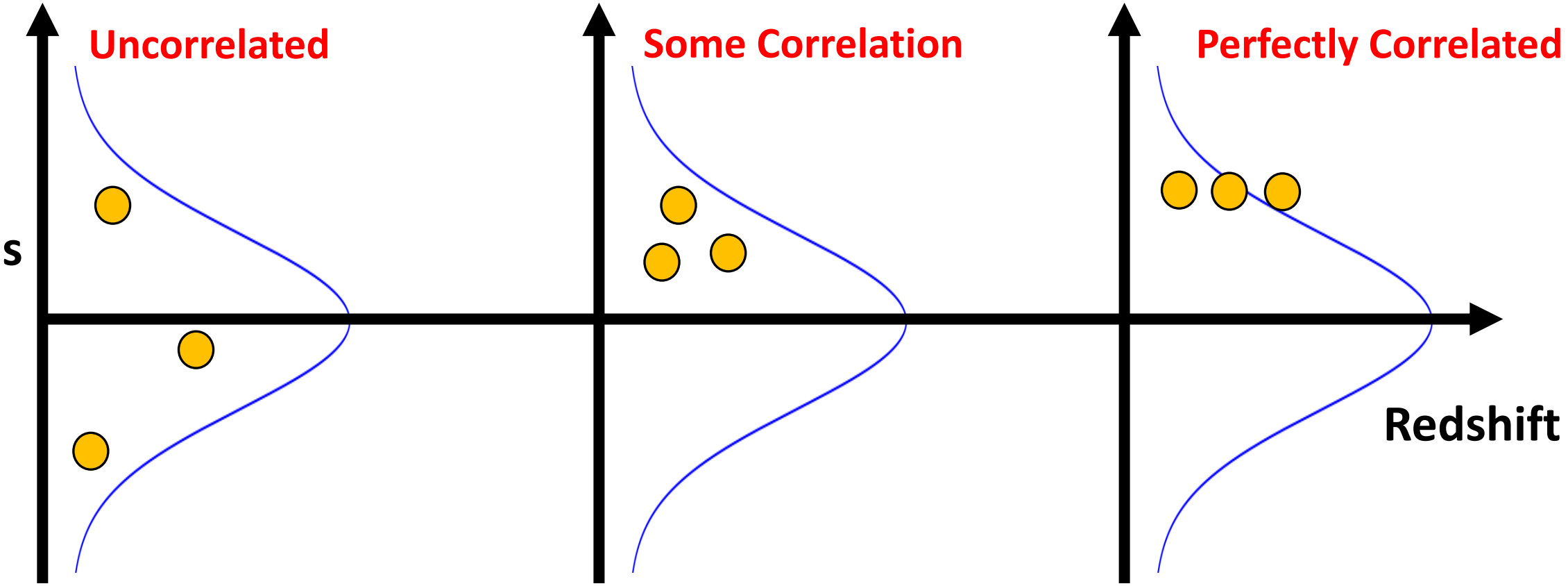
< 0.056 (0.091)	< 0.073 (0.133)	< 0.130 (0.516)
< 0.062 (0.094)	< 0.086 (0.138)	< 0.209 (0.663)

Need more siblings to constrain σ_{Rel}


BayeSN Common-μ Fit
μ = 33.166 ± 0.107
2021hpr
[grizy]
1997bq
[BVRI]
2008fv
[BVR]
A_V = 0.246 ± 0.061
A_V = 0.378 ± 0.082
A_V = 0.541 ± 0.097
θ = -0.562 ± 0.094
θ = 0.143 ± 0.178
θ = -0.579 ± 0.158
R_V = 2.784 ± 1.174
R_V = 2.736 ± 0.949
R_V = 2.937 ± 0.754
δM = -0.011 ± 0.094
δM = -0.010 ± 0.096
δM = 0.004 ± 0.096
μ
A_V
θ
R_V
δM

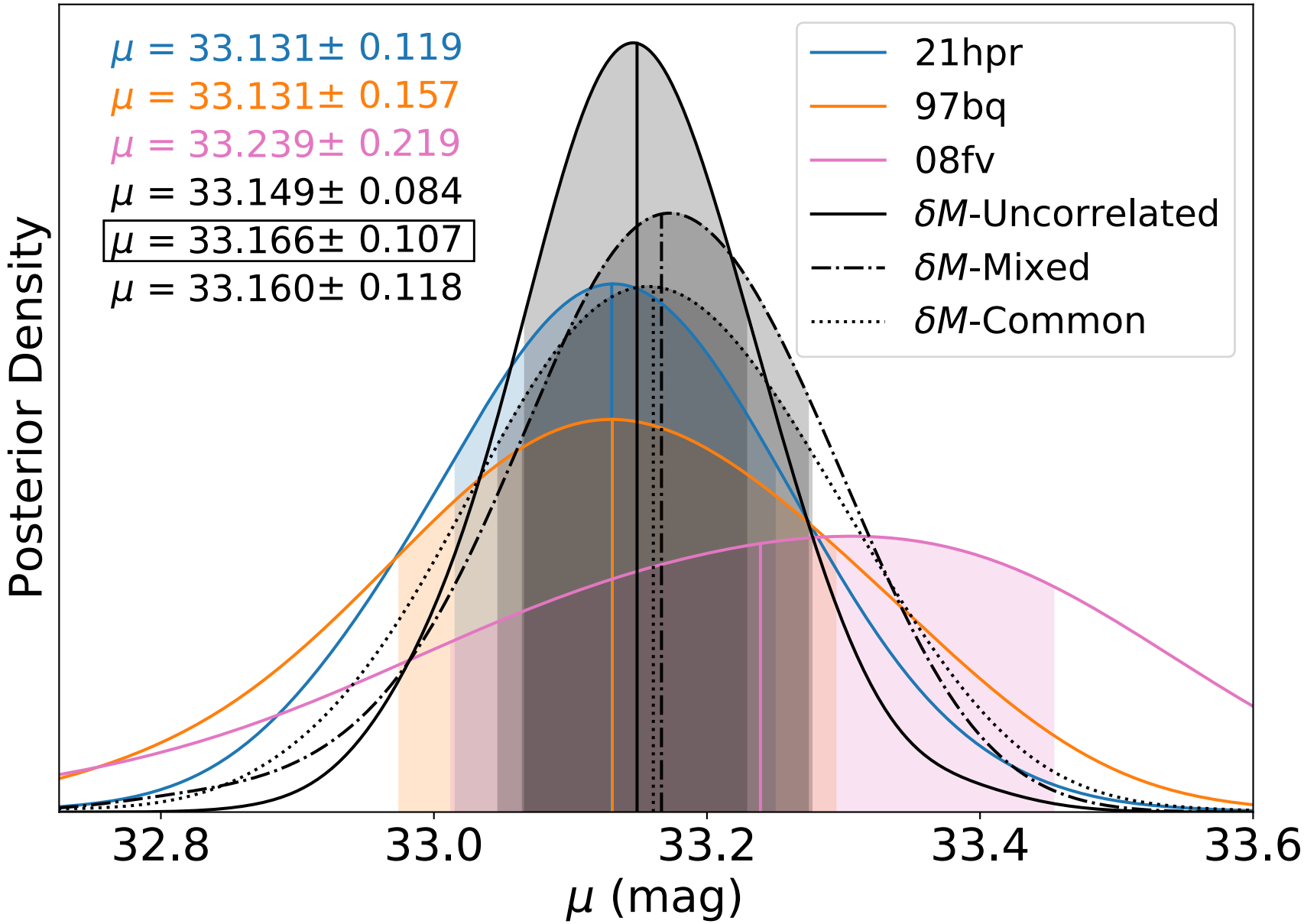

BayeSN **Fit Contrast** **2008fv**
Individual & Common-μ Fits [BVR]
(21hpr,97bq,08fv)
μ = 33.239 ± 0.219
μ = 33.166 ± 0.107
A_V = 0.481 ± 0.200
A_V = 0.541 ± 0.097
θ = -0.607 ± 0.176
θ = -0.579 ± 0.158
R_V < 3.115 (4.926)
R_V = 2.937 ± 0.754
68%
95%
δM = -0.001 ± 0.095
δM = 0.004 ± 0.096
μ
A_V
θ
R_V
δM

Correlation of siblings affects uncertainty on distance estimate

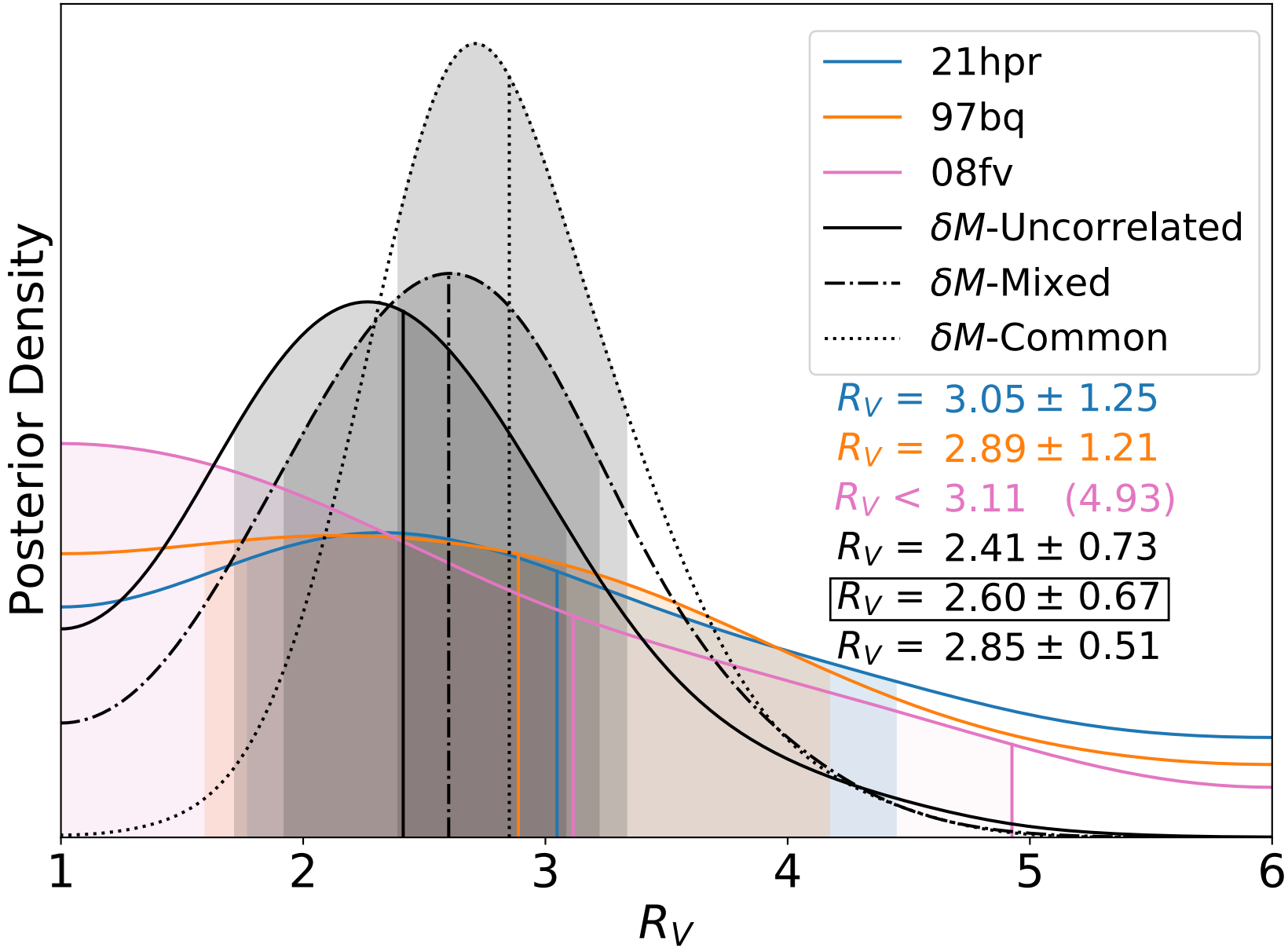


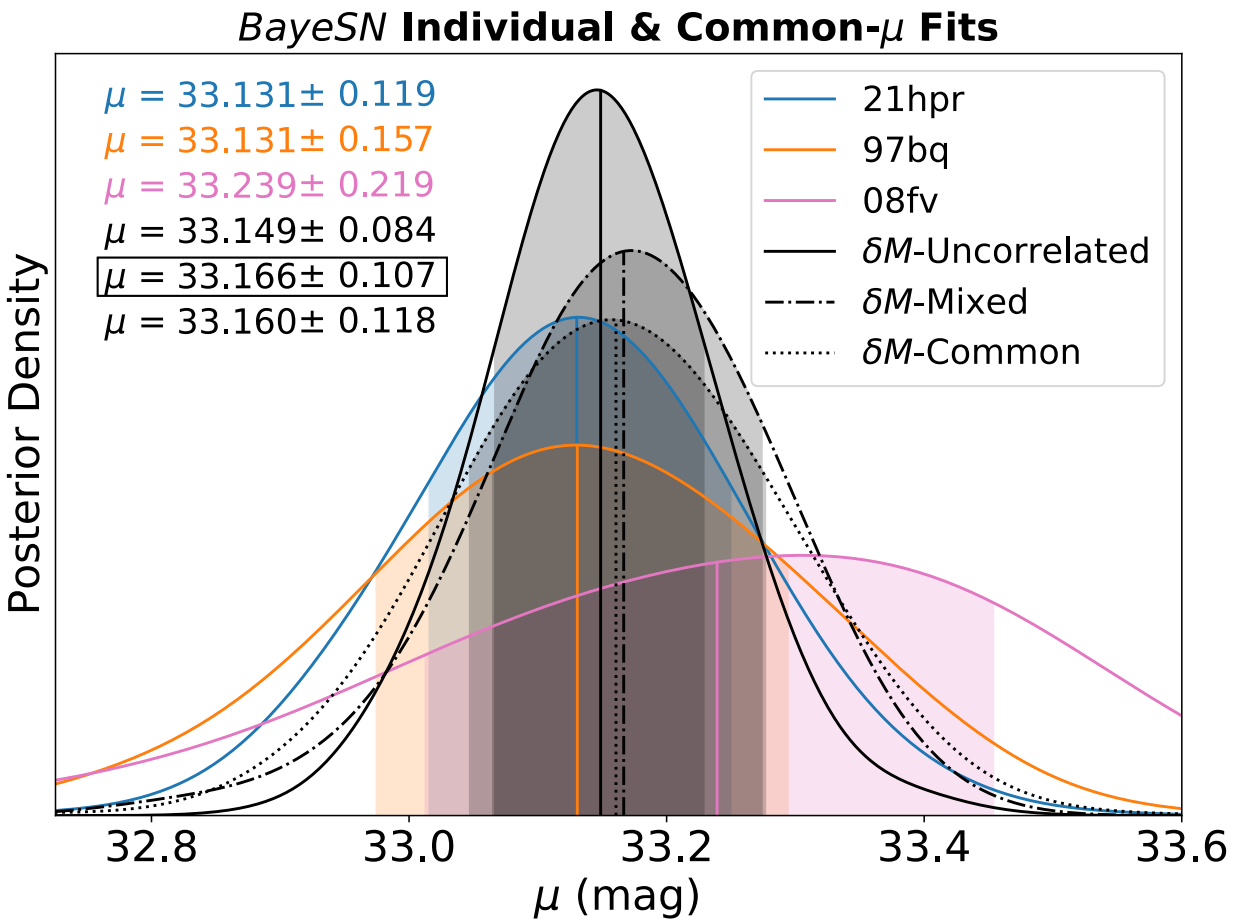
Distance Uncertainty Contribution	$\frac{\sigma_0}{\sqrt{N_{Siblings}}}$	$\sigma_0^2 - \sigma_{Rel}^2 + \frac{\sigma_{Rel}^2}{N_{Siblings}}$	σ_0

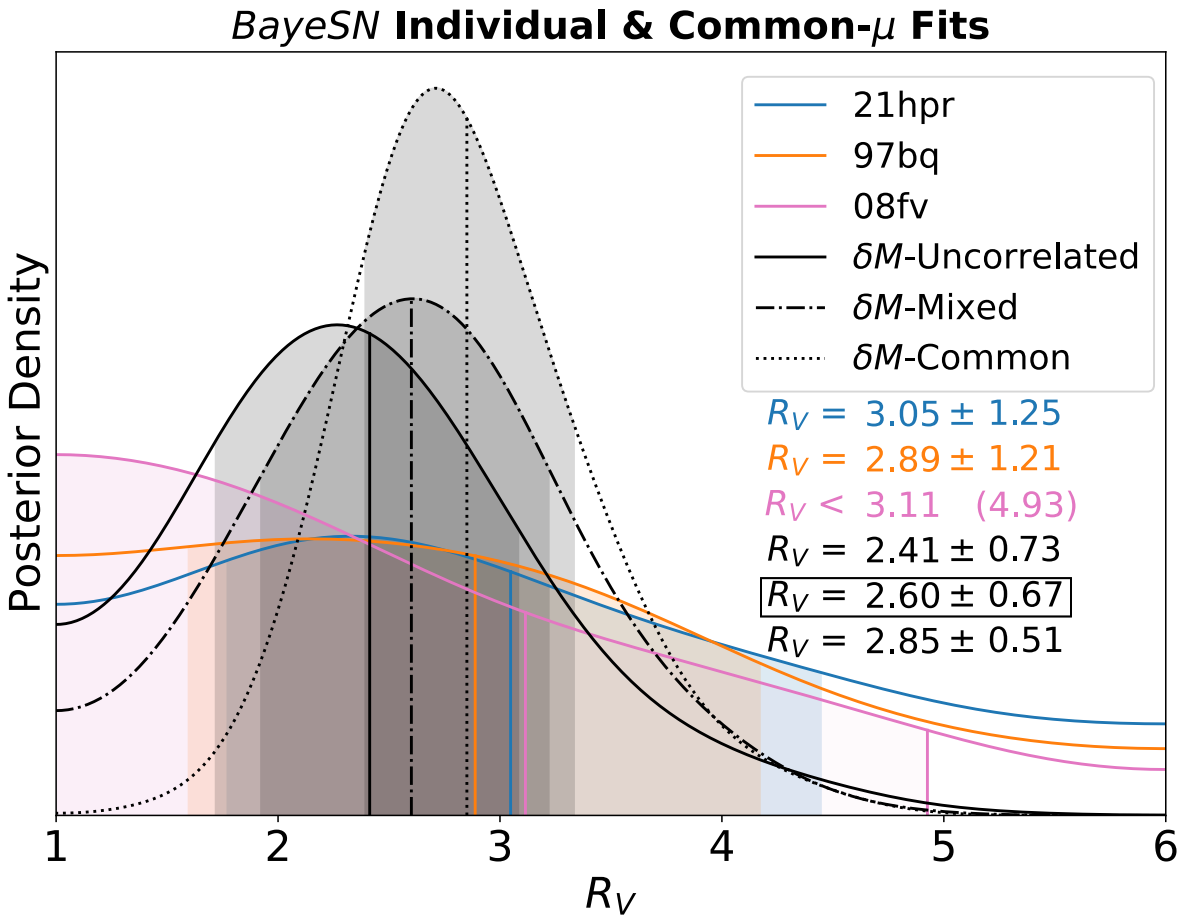
BayeSN **Individual & Common-μ Fits**

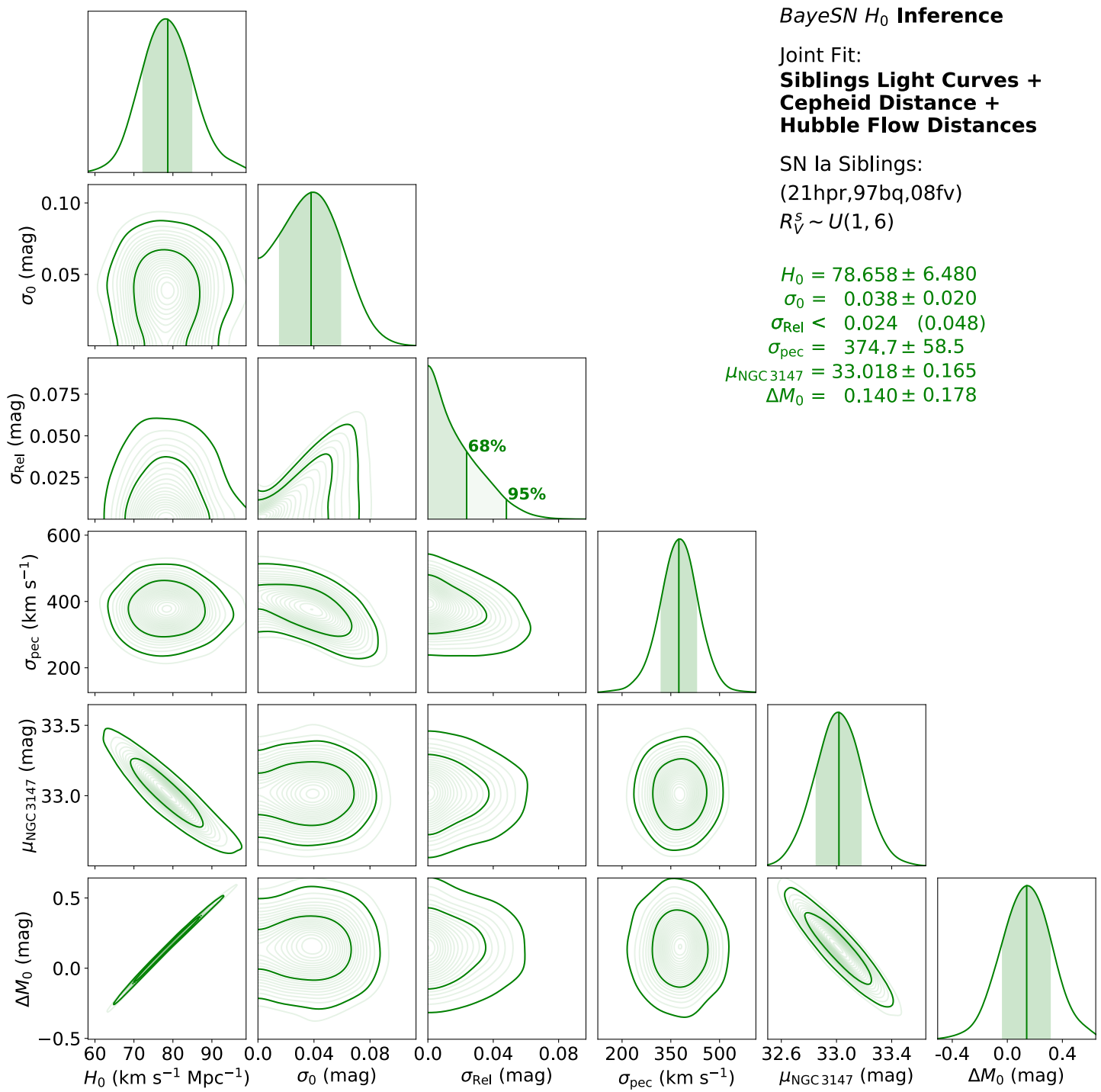


BayeSN Individual & Common-μ Fits




BayeSN **Individual & Common-μ Fits**
μ = 33.131± 0.119
μ = 33.131± 0.157
μ = 33.239± 0.219
μ = 33.149± 0.084
μ = 33.166± 0.107
μ = 33.160± 0.118
21hpr
97bq
08fv
δM-Uncorrelated
δM-Mixed
δM-Common
Posterior Density
32.8
33.0
33.2
33.4
33.6
μ (mag)


BayeSN **Individual & Common-μ Fits**
21hpr
97bq
08fv
δM-Uncorrelated
δM-Mixed
δM-Common
R_V = 3.05 ± 1.25
R_V = 2.89 ± 1.21
R_V < 3.11 (4.93)
R_V = 2.41 ± 0.73
R_V = 2.60 ± 0.67
R_V = 2.85 ± 0.51
Posterior Density
1
2
3
4
5
6
R_V



Siblings fitted simultaneously with **Cepheid distance** and **Hubble flow SNe Ia**, whilst marginalising over $\boldsymbol{\sigma_{Rel}}$ and siblings' **dust parameters**

σ_{Rel}-marginalisation adds $\approx 1.5\%$ to H_0 uncertainty

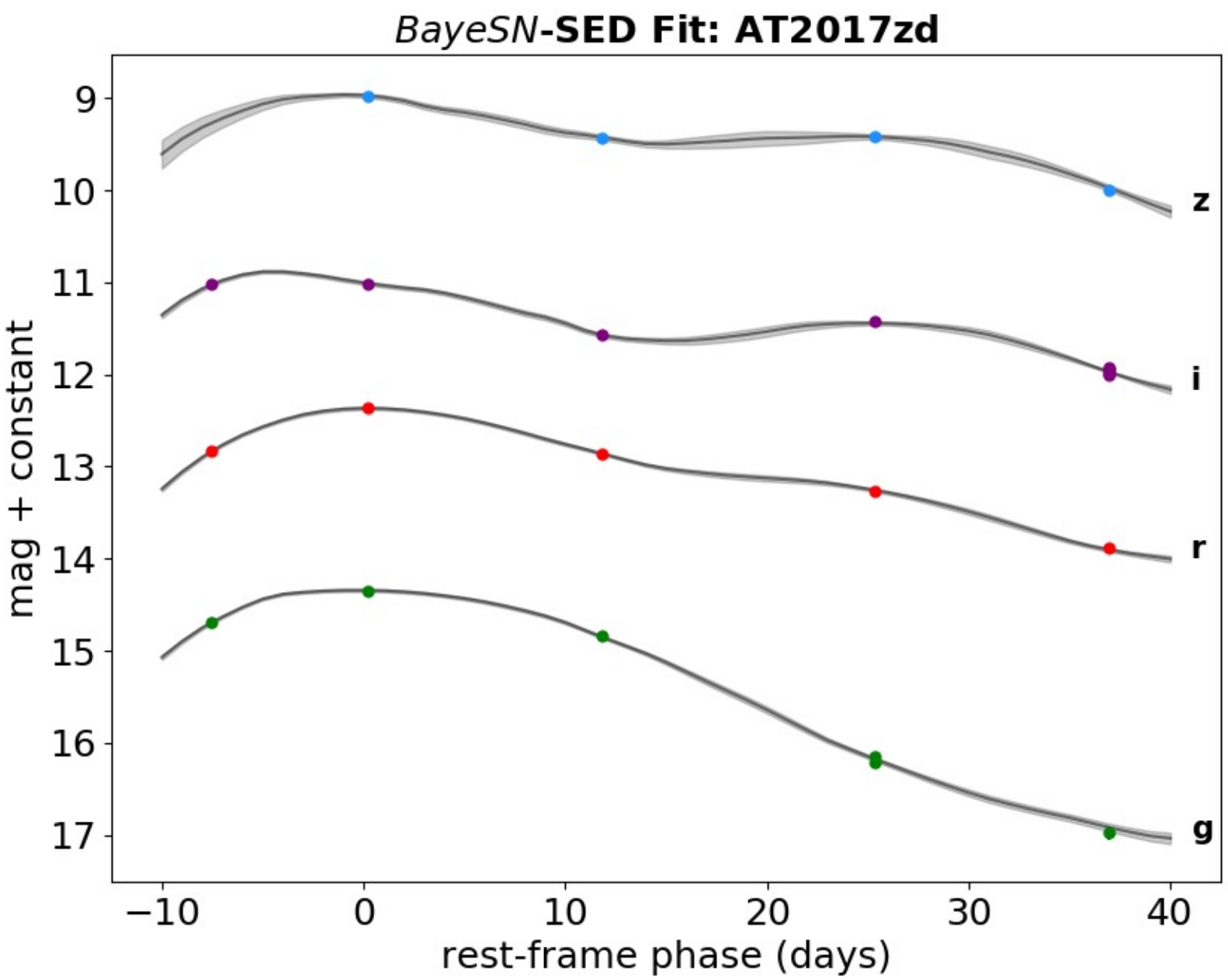
Prospects with LSST SN Ia Siblings?

What can we do with more siblings?

With more siblings we can:

- Tightly constrain σ_{Rel} and compare against σ_0
- Build model to explain how siblings' properties correlates with σ_{Rel}

Scolnic+20 estimate ***~800 galaxies*** with SN Ia sibling pairs by end of 10-year LSST
Additionally, there will be siblings pairs by combining ***archival non-LSST SNe + LSST SNe***
Largest sample to date ***158 galaxies with 327 SNe Ia*** *(Kelsey 2023)*

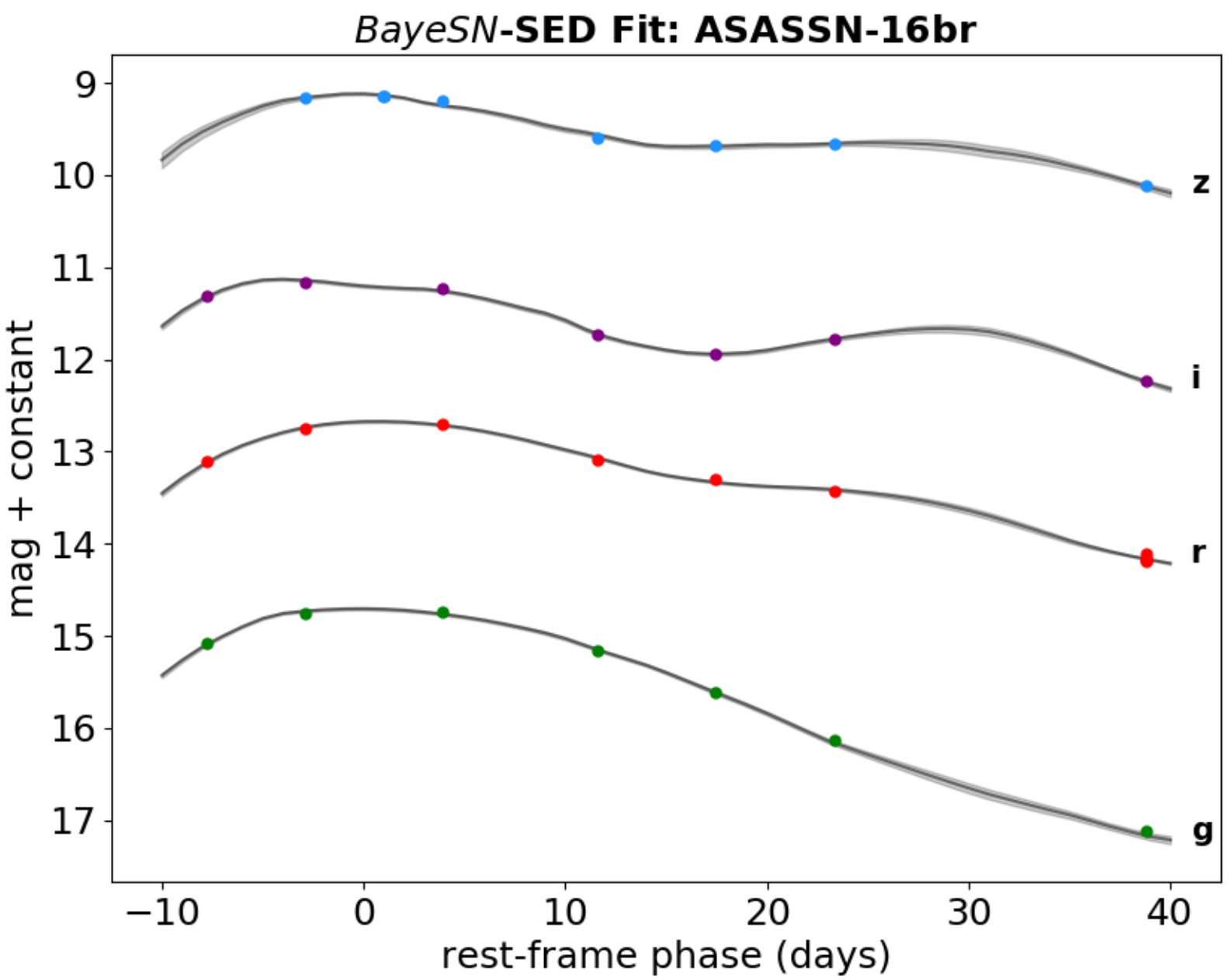


Foundation DR1 LCs

$griz$

$\boldsymbol{\Delta t \sim 7-11}$ **days**

(Foundation DR1 – Foley+18; Jones+19)



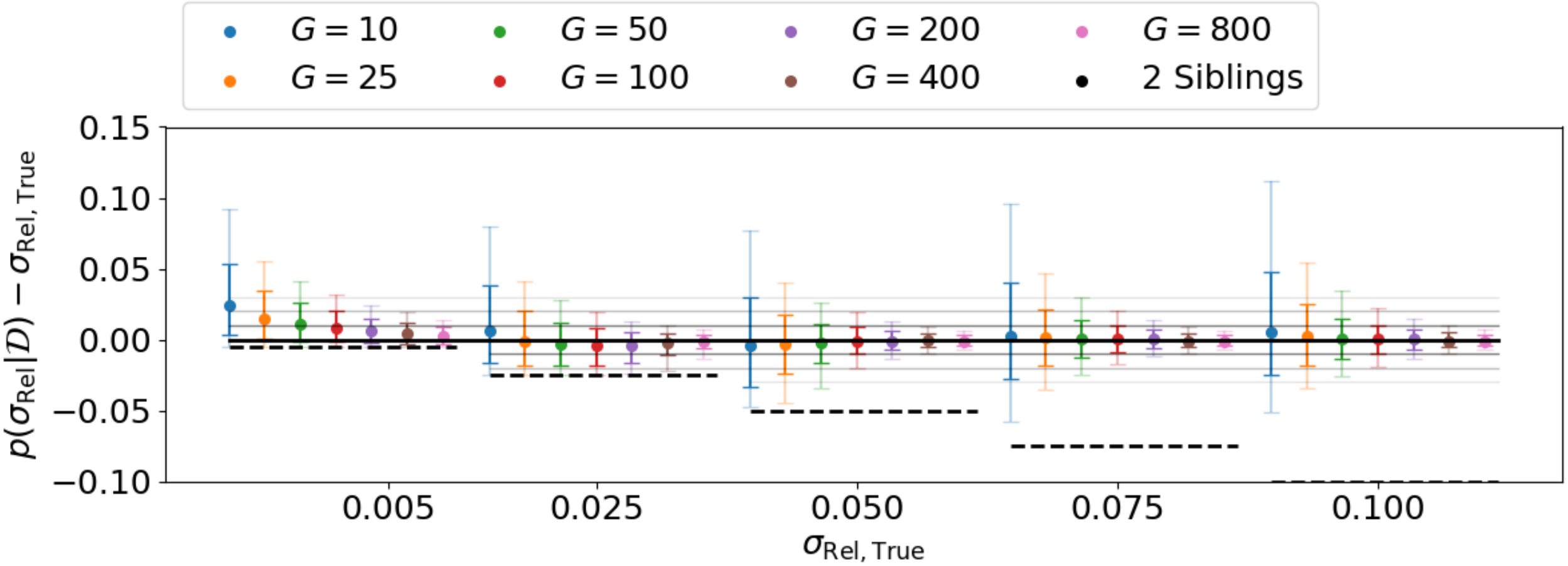
Foundation DR1 LCs

$griz$

$\boldsymbol{\Delta t \sim 7-11}$ **days**

(Foundation DR1 – Foley+18; Jones+19)

σ_{Rel} constraints from fitting **Foundation DR1** (Foley+18) sample ($\boldsymbol{griz}$ LCs, $\boldsymbol{\Delta t \sim 7-11}$ **days**)

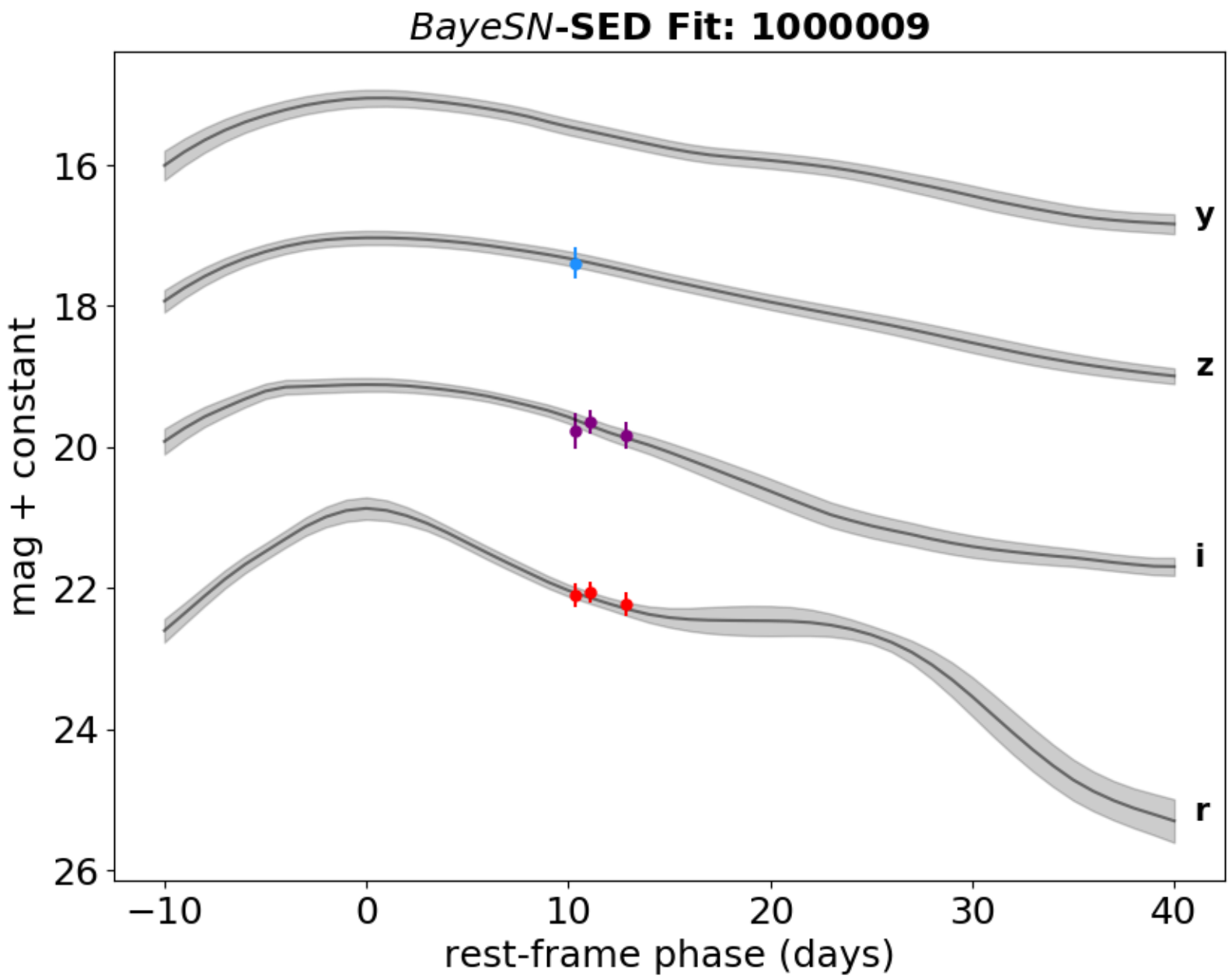


≈100 Galaxies yields ±0.01mag 68% uncertainty on σ_{Rel}

LSST-WFD LCs

$grizy$

$\boldsymbol{\Delta t \sim 5 - 25}$ **days**



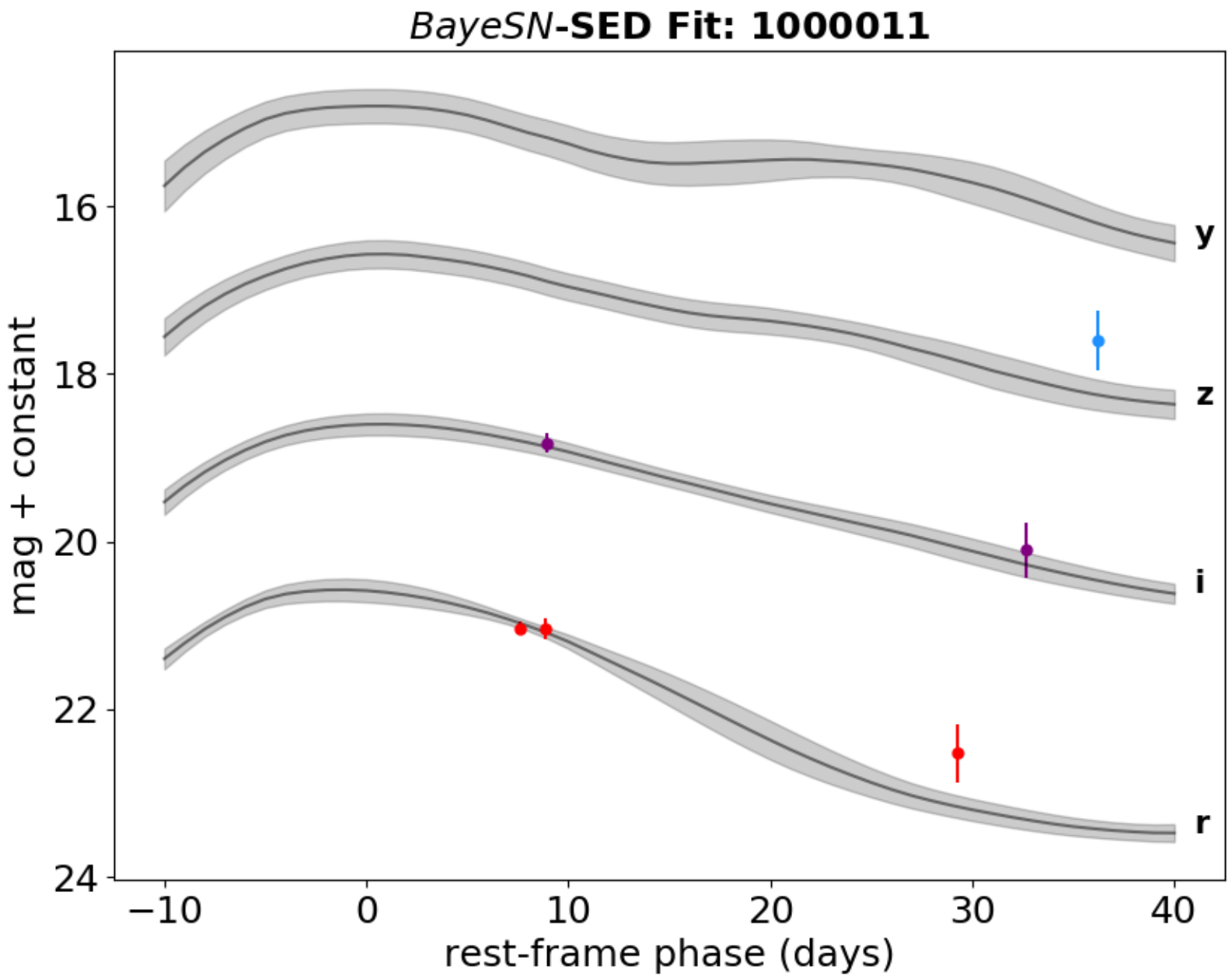
Credits: Alex Gagliano & *SCOTCH* simulations (Locken+23)

"The Simulated Catalogue of Optical Transients and Correlated Hosts"

LSST-WFD LCs

$grizy$

$\boldsymbol{\Delta t \sim 5 - 25}$ **days**



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"The Simulated Catalogue of Optical Transients and Correlated Hosts"

LSST-WFD LCs

$grizy$

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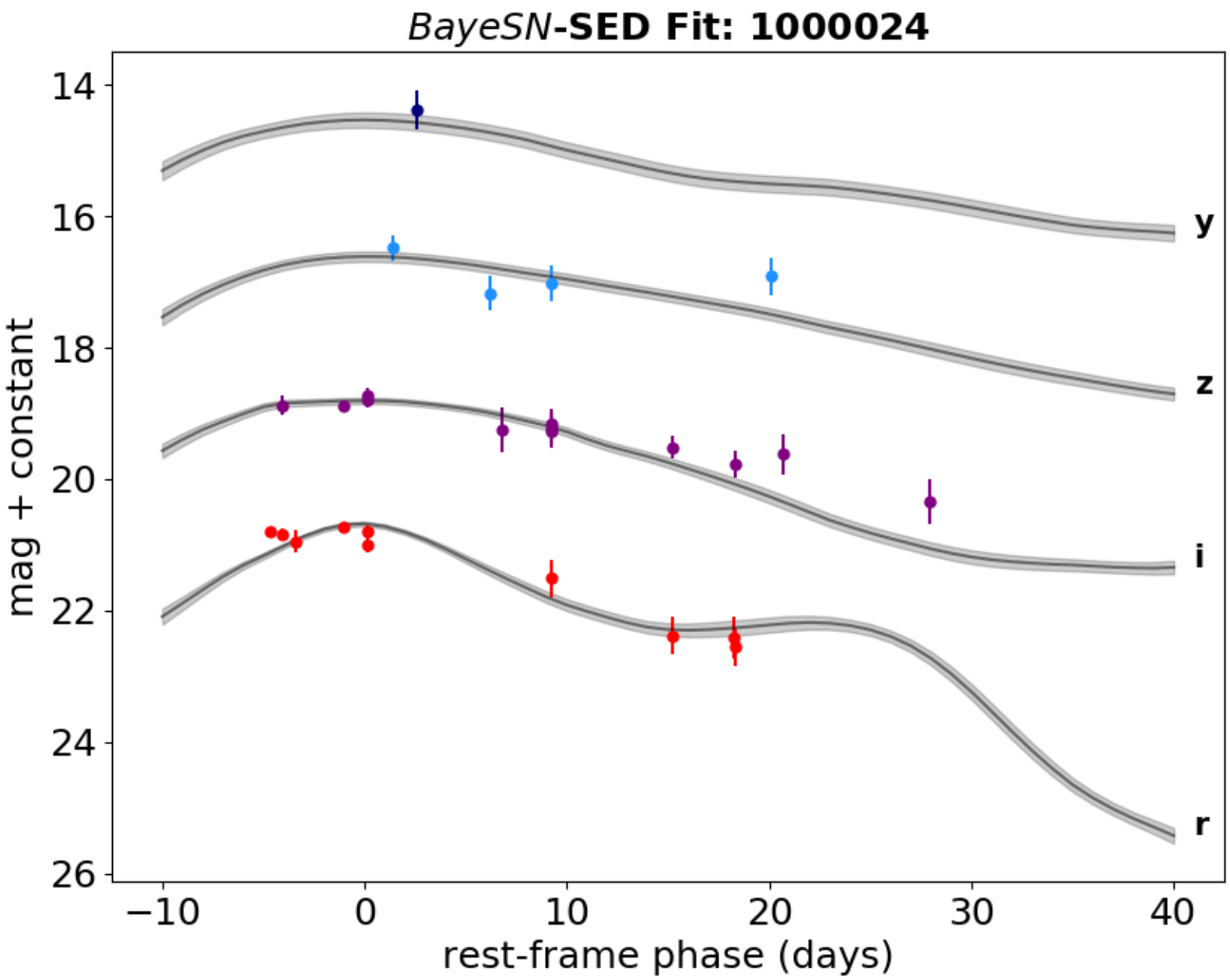
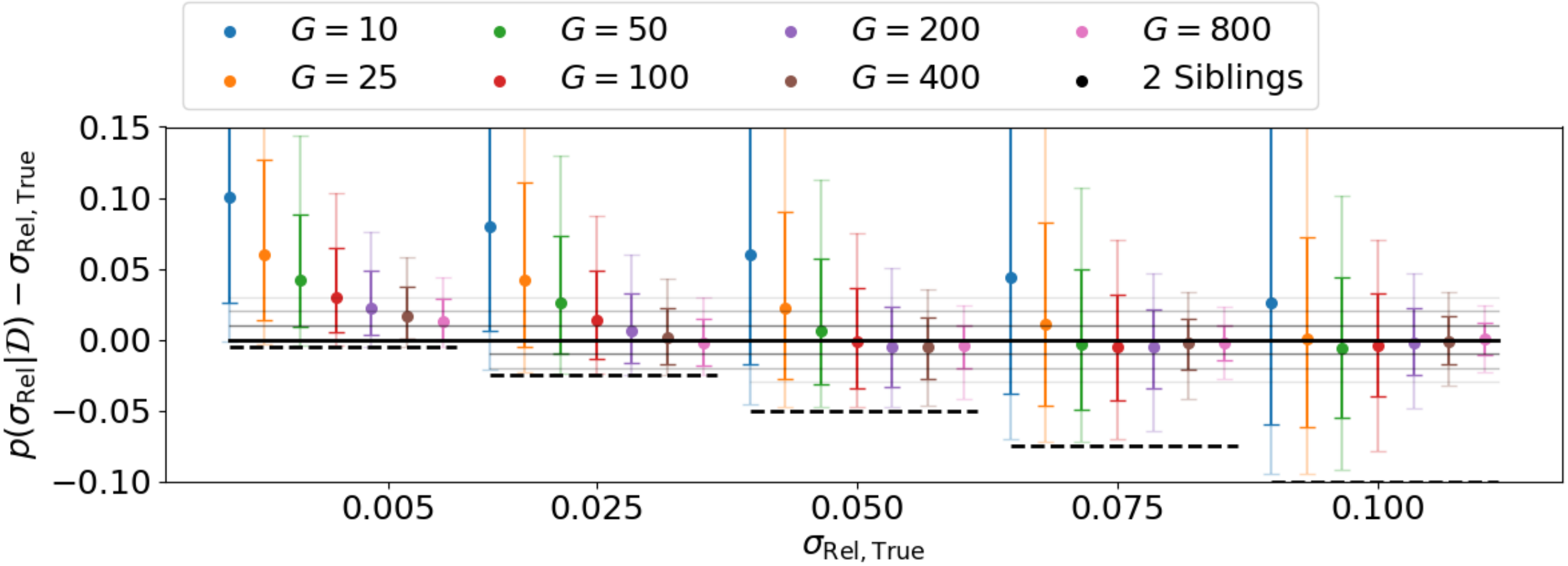


Credits: Alex Gagliano & *SCOTCH* simulations (Locken+23)

"The Simulated Catalogue of Optical Transients and Correlated Hosts"

σ_{Rel} constraints from fitting **LSST-WFD** (Locken+23) sample ($\boldsymbol{grizy}$ LCs, $\boldsymbol{\Delta t \sim 5-25}$ **days**)



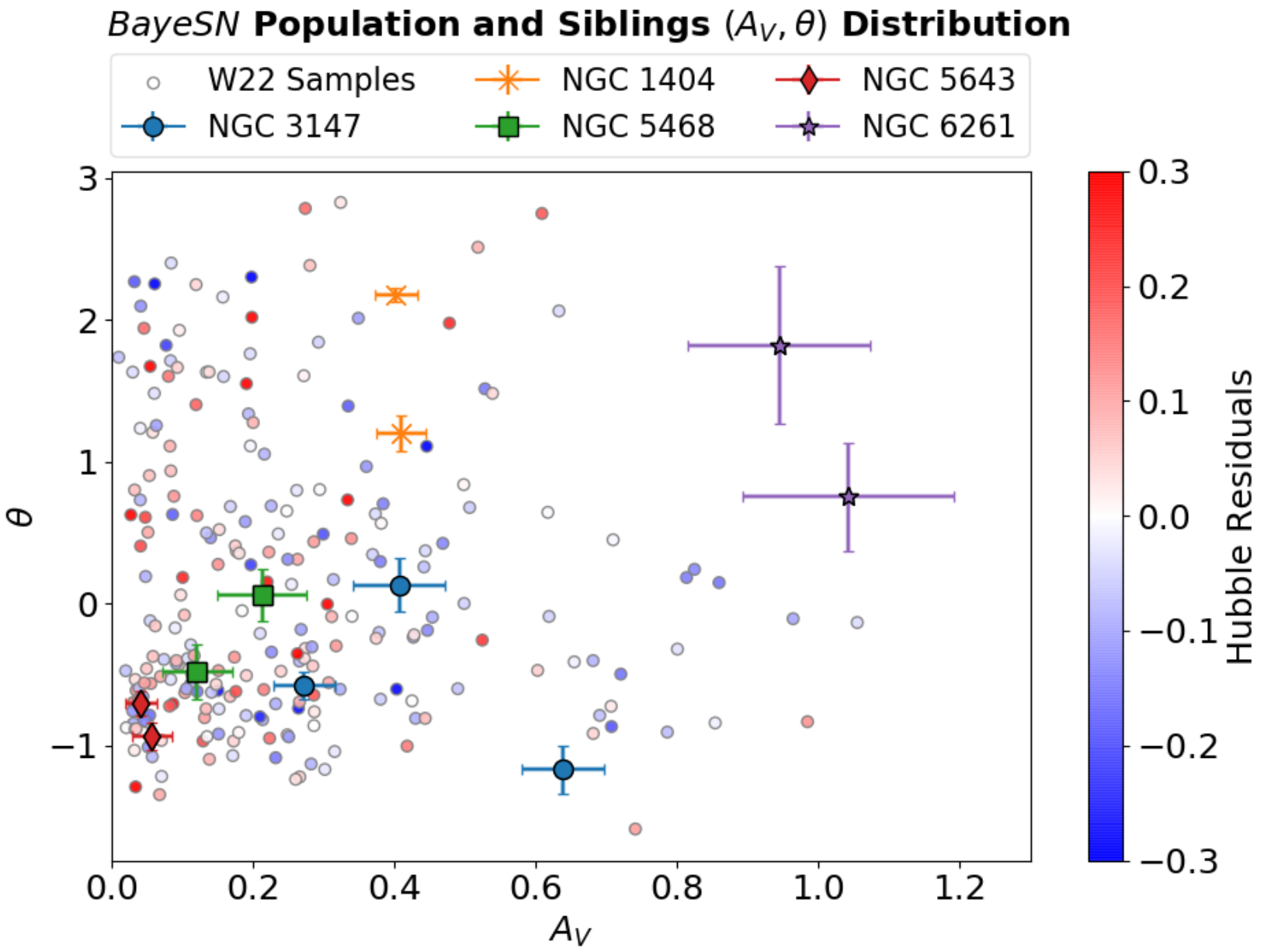
>800 Galaxies yields ±0.01mag 68% uncertainty on σ_{Rel}

Relative intrinsic scatter, σ_{Rel}:

- σ_{Rel} indicates whether common properties or within-galaxy variations dominate σ_0 in the Hubble diagram
- σ_{Rel} posterior can be computed from individual siblings distances – wide posterior for small number of galaxies
- σ_{Rel} affects joint siblings distance estimates – σ_{Rel} should be marginalised over
- σ_{Rel} also affects dust parameter estimates (in joint hierarchical fits)
- σ_{Rel} thus affects cosmological parameters, and science conclusions about siblings-host correlations

Many LSST siblings, require high-cadence photometry, focus on archival SN Ia galaxies

Multi-Galaxy Siblings Analysis



How many siblings do we need?

Method:

Simulate distances with true σ_{Rel}

Analytic posterior on σ_{Rel}, extract summary statistics

How do constraints depend on:

- Number of Siblings Galaxies
- SN Photometry (time sampling, NIR LCs)