# SICRET:
# Supernova Ia Cosmology
## with
# (TMN) Ratio EsTimation

arXiv:2209.06733
& the near future


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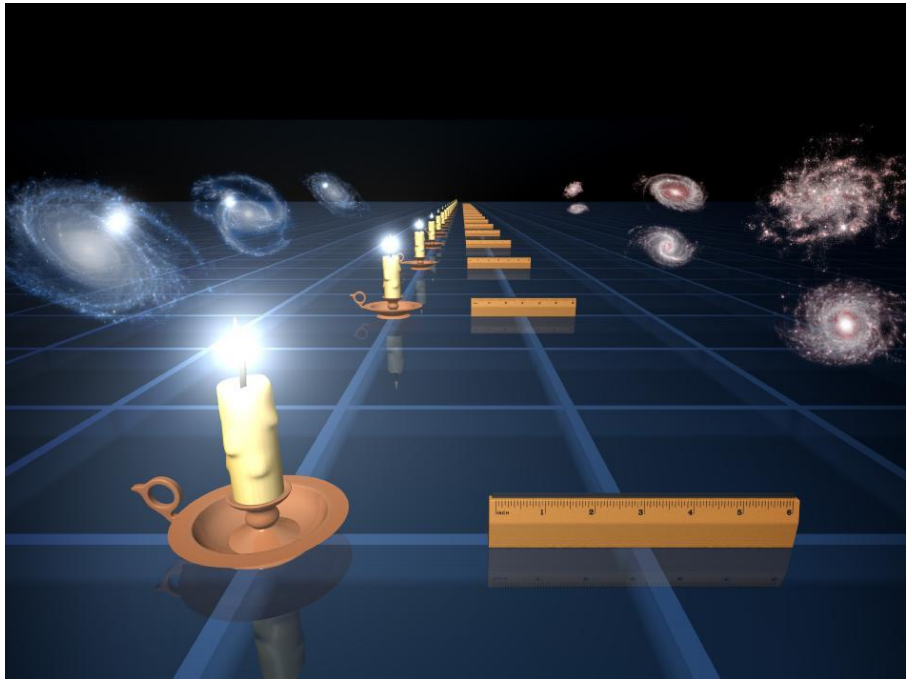
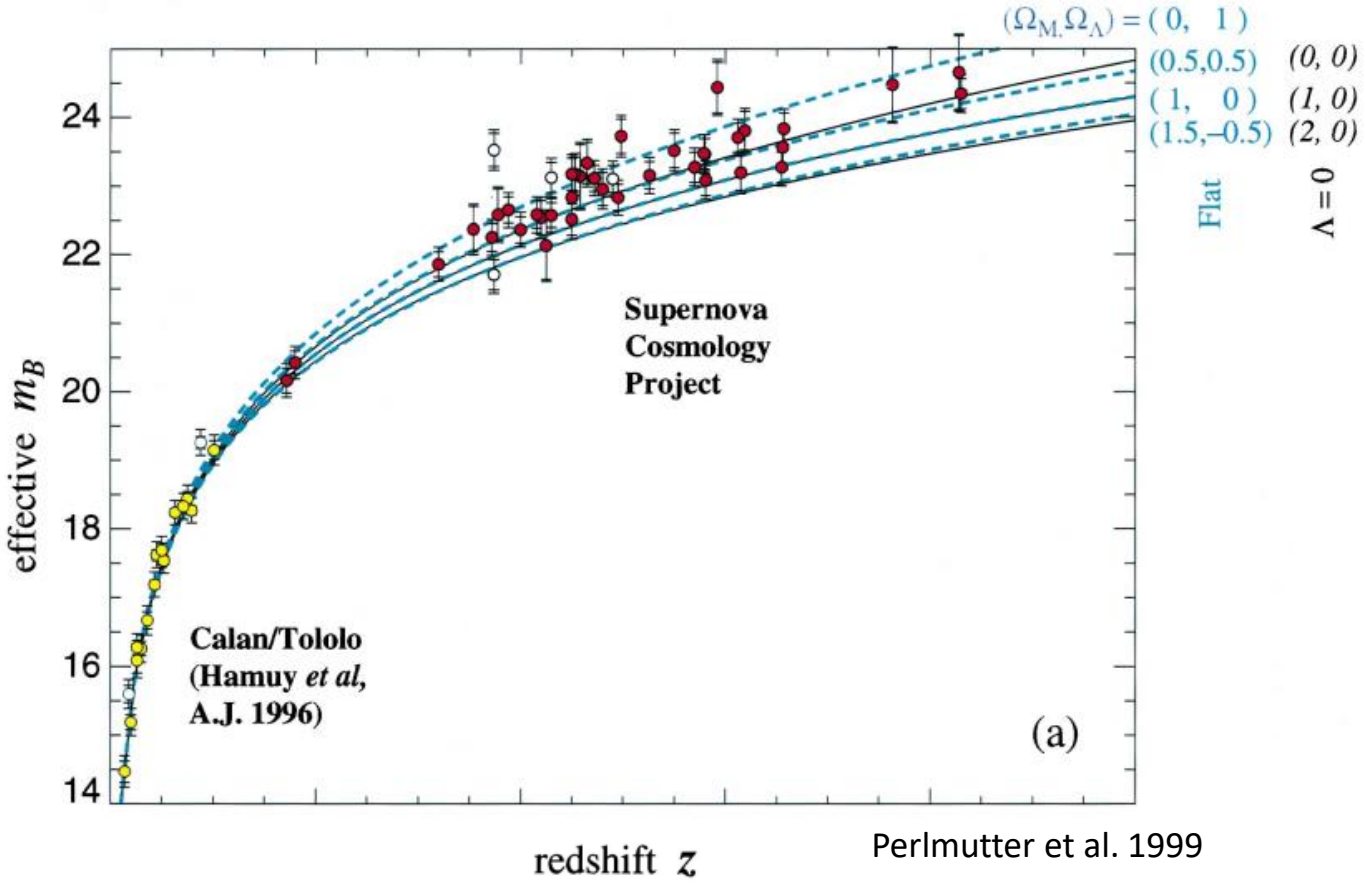
SISSA DATASCIENCE
Machine Learning for the Natural Sciences

Kavli Institute for Cosmology Cambridge
KICC

2023-06-01

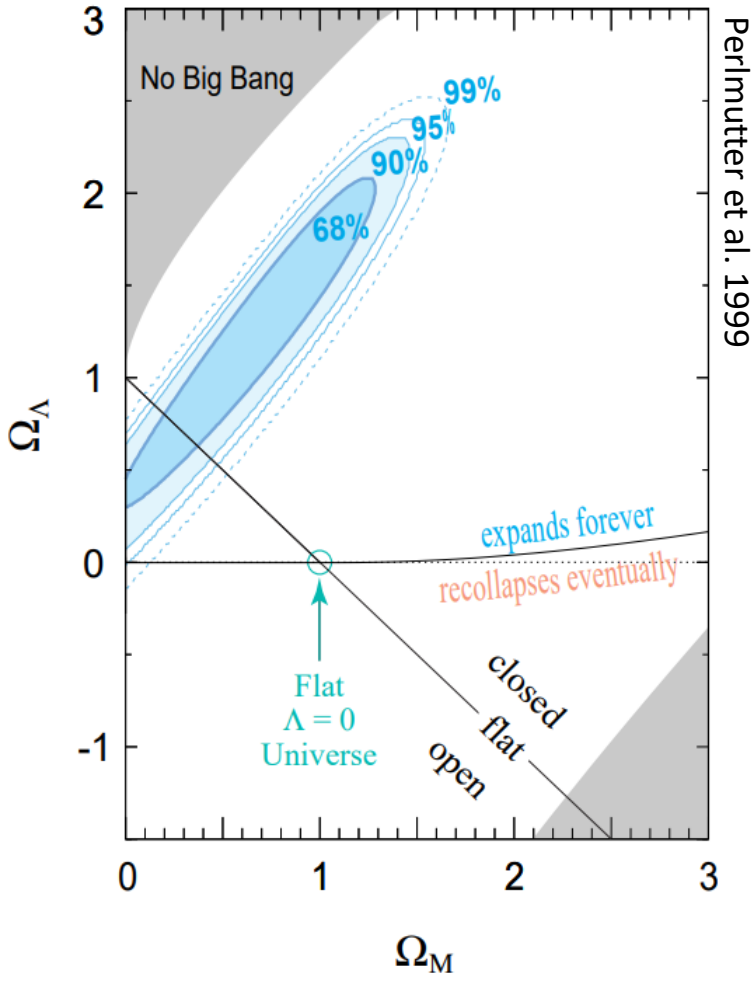
# Cosmology with standard candles



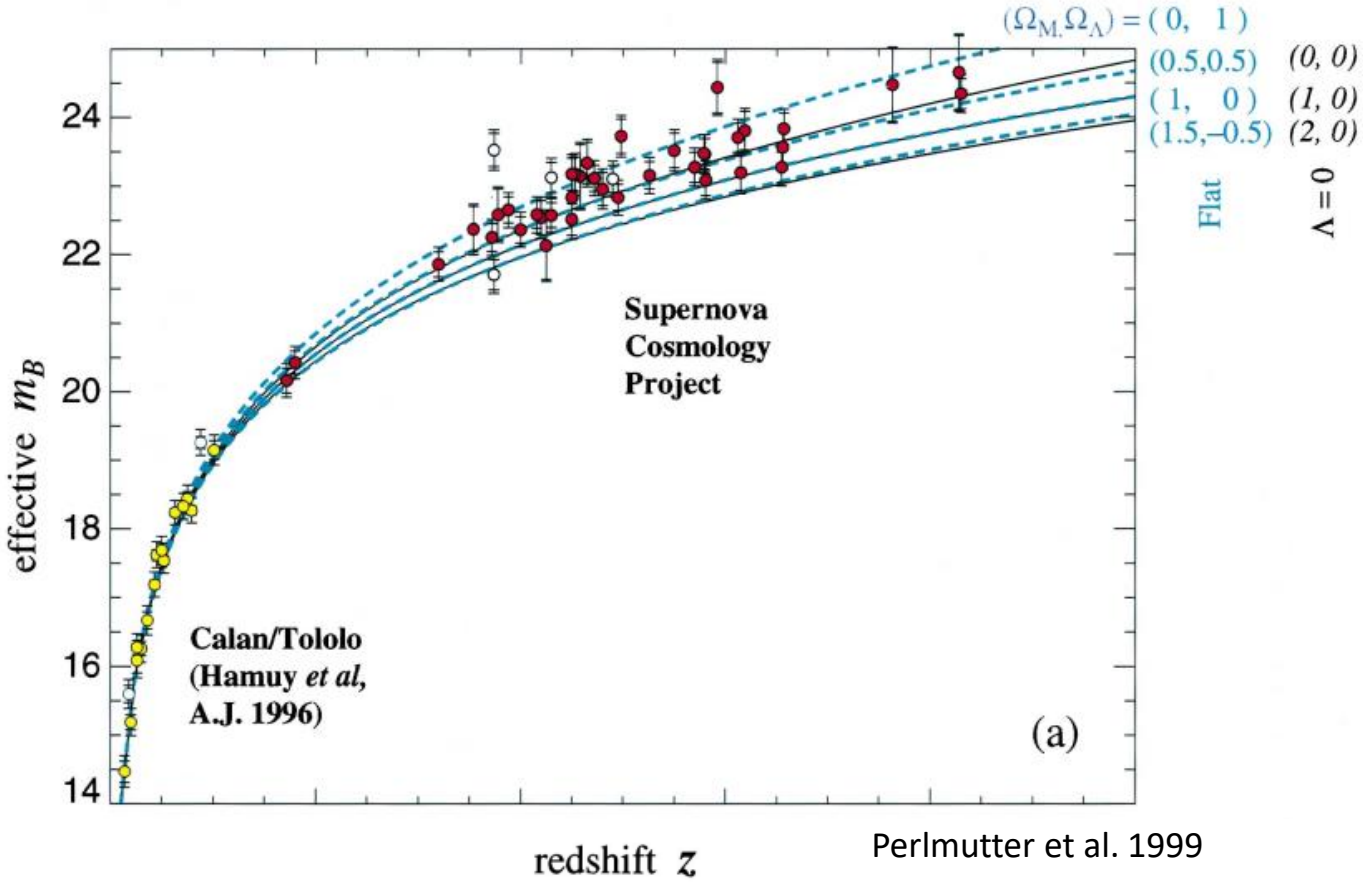



Perlmutter et al. 1999

# Cosmology with standard candles

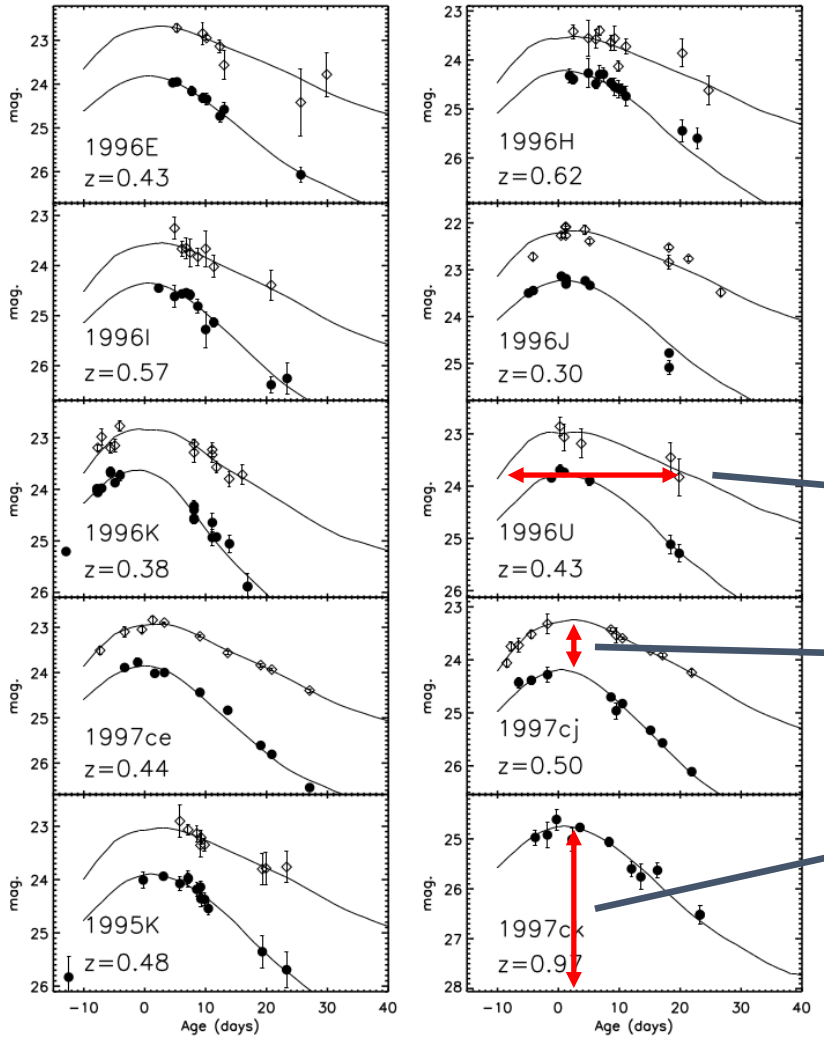



Perlmutter et al. 1999




Perlmutter et al. 1999

# SN Ia cosmology: a Nobel prize



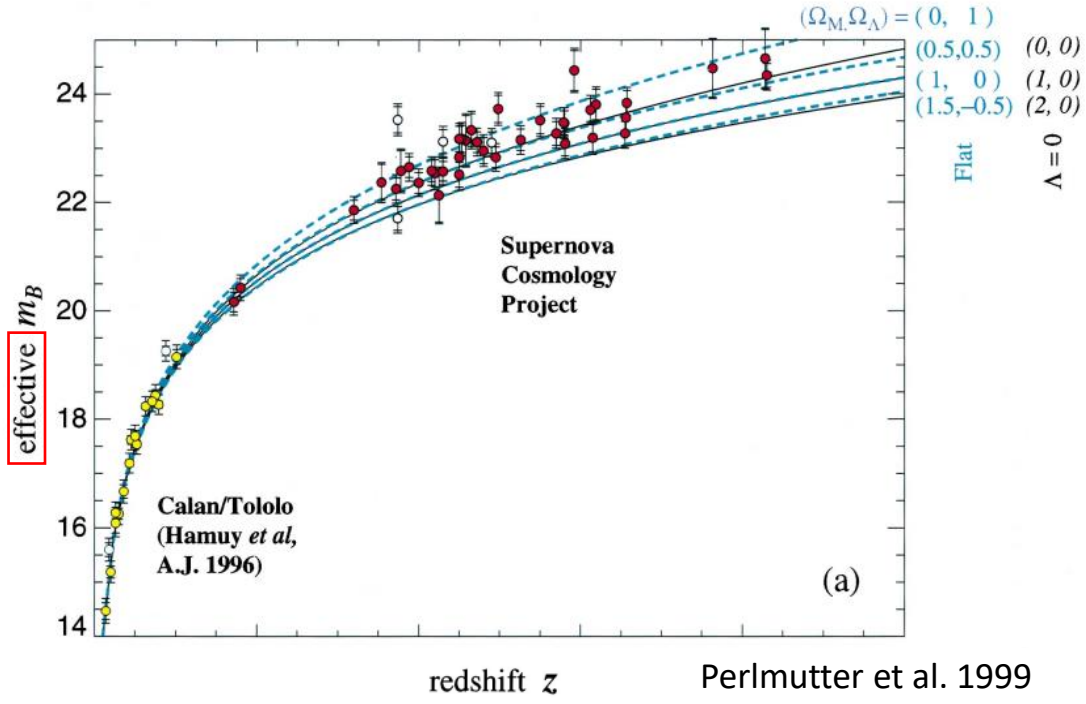

Riess et al. 1999

hand-crafted summaries

$x_1^s \pm \sigma_{x_1}^s$
"stretch"

$c^s \pm \sigma_c^s$
"colour"

$m^s \pm \sigma_m^s$
brightness

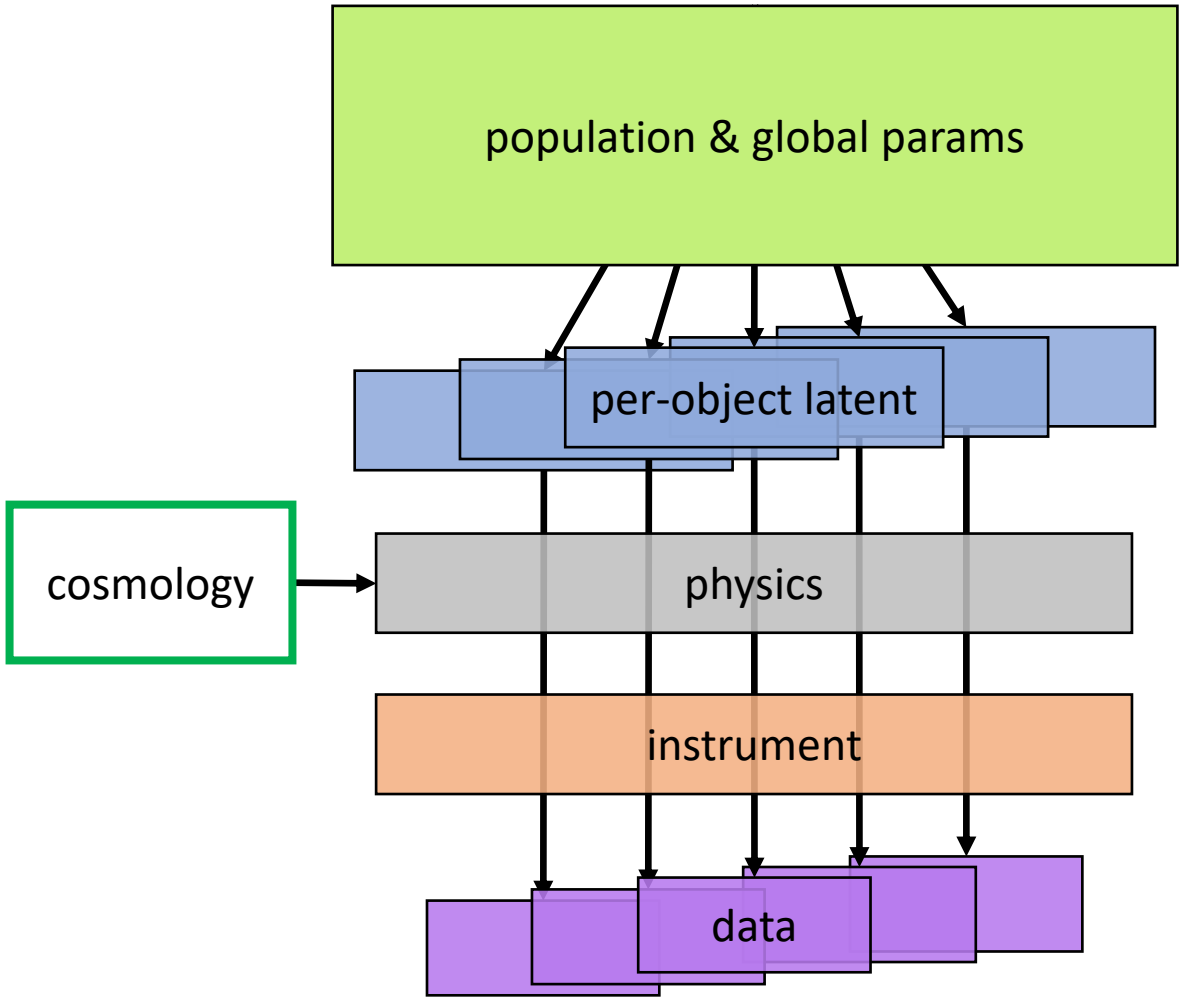


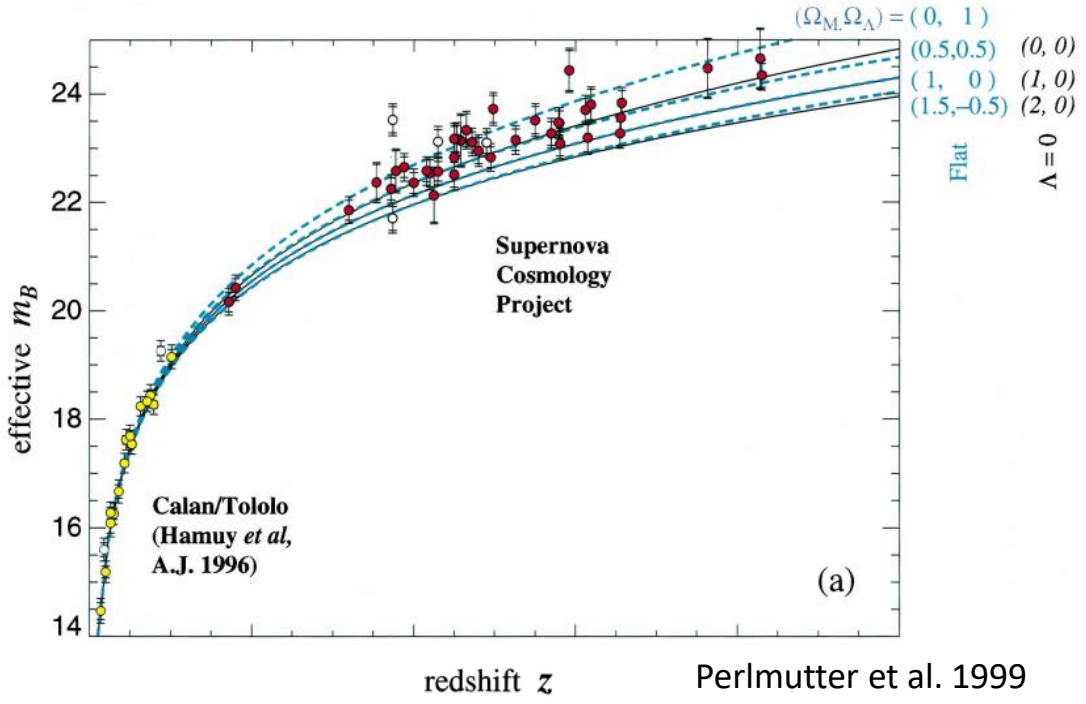

Perlmutter et al. 1999

$$m^s + \alpha x_1^s - \beta c^s = M + \mu(z^s, \mathcal{C}) + \text{"noise"}$$

$\mathcal{C} \pm \sigma_{\mathcal{C}}$
posterior

# Hierarchical SN Ia cosmology



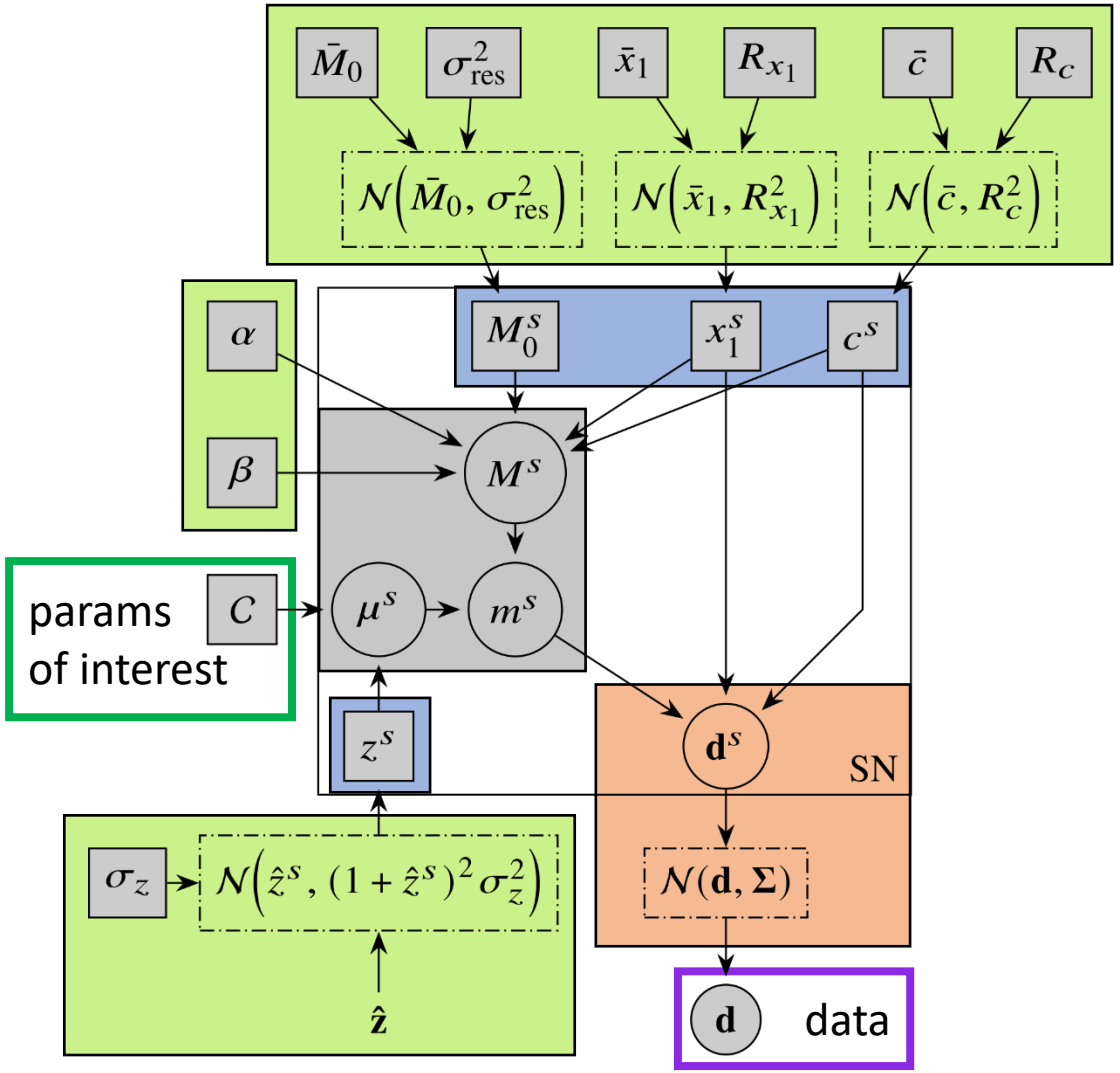



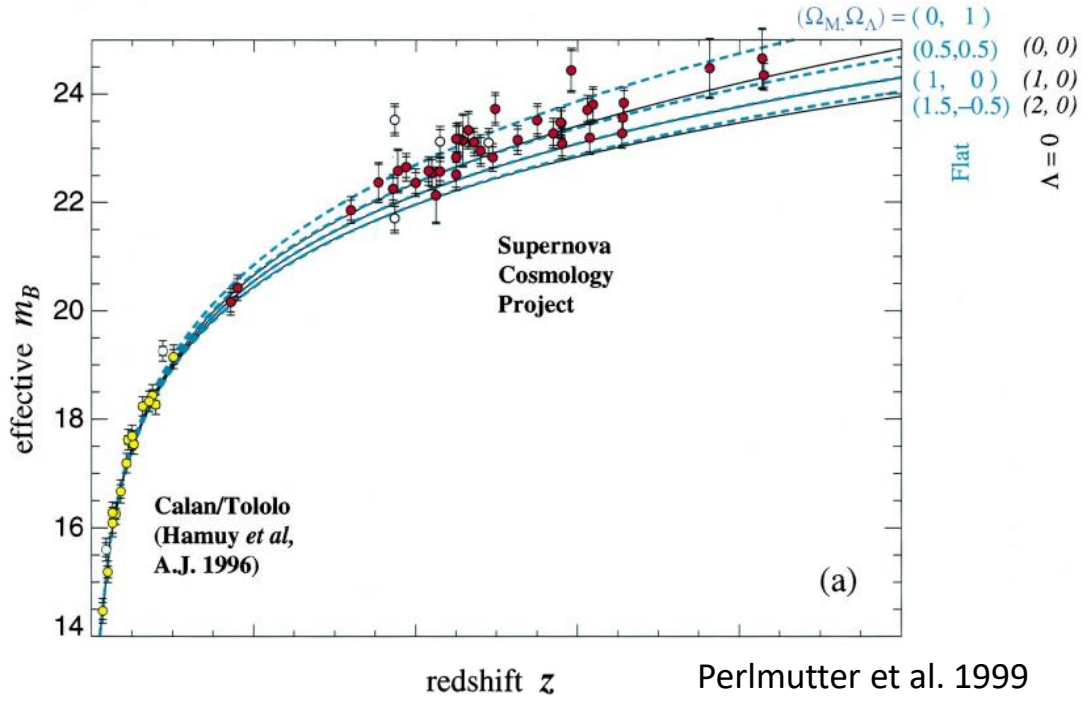

Perlmutter et al. 1999

$$m^s + \alpha x_1^s - \beta c^s = M_0^s + \mu(z^s, \mathcal{C}) + \text{"noise"}$$

population priors

# Hierarchical SN Ia cosmology



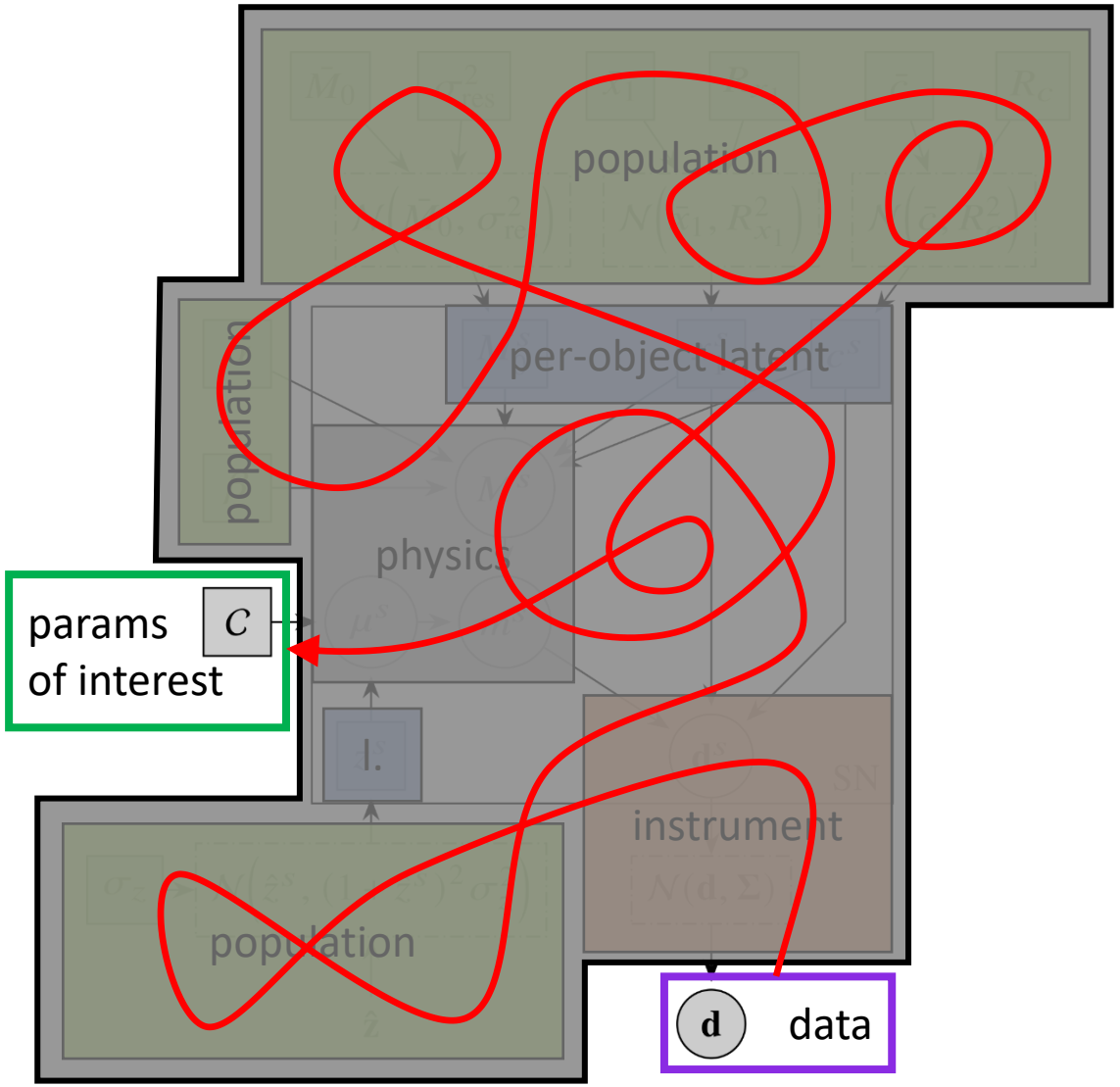




Perlmutter et al. 1999

$$m^s + \alpha x_1^s - \beta c^s = M_0^s + \mu(z^s, \mathcal{C}) + \text{"noise"}$$

population priors

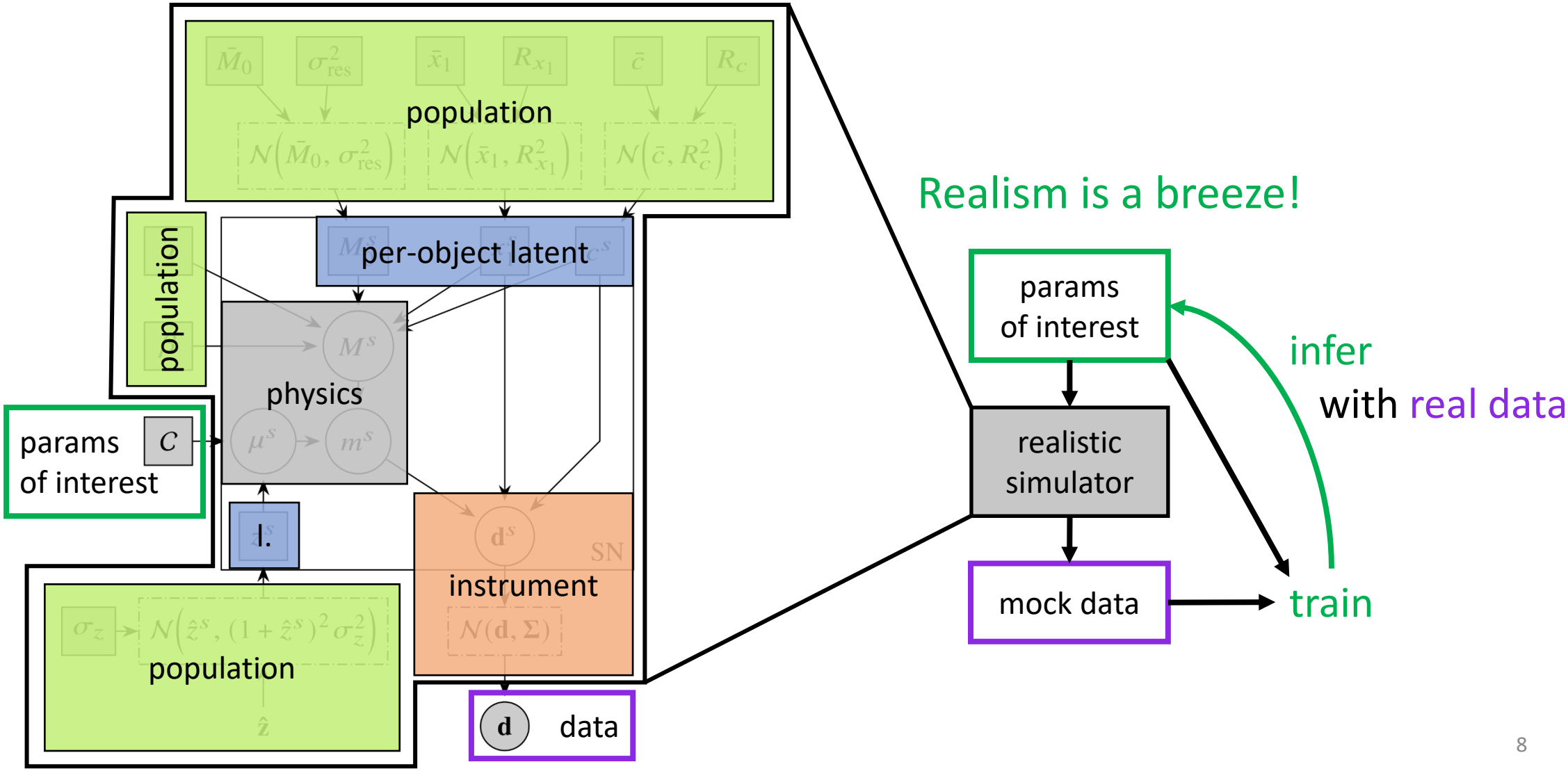
# Likelihood-based SN Ia cosmology




Realism is painful:

- lightcurve population
- environmental effects & dust
- observational uncertainty model
- photometric redshifts
- selection effects, contamination

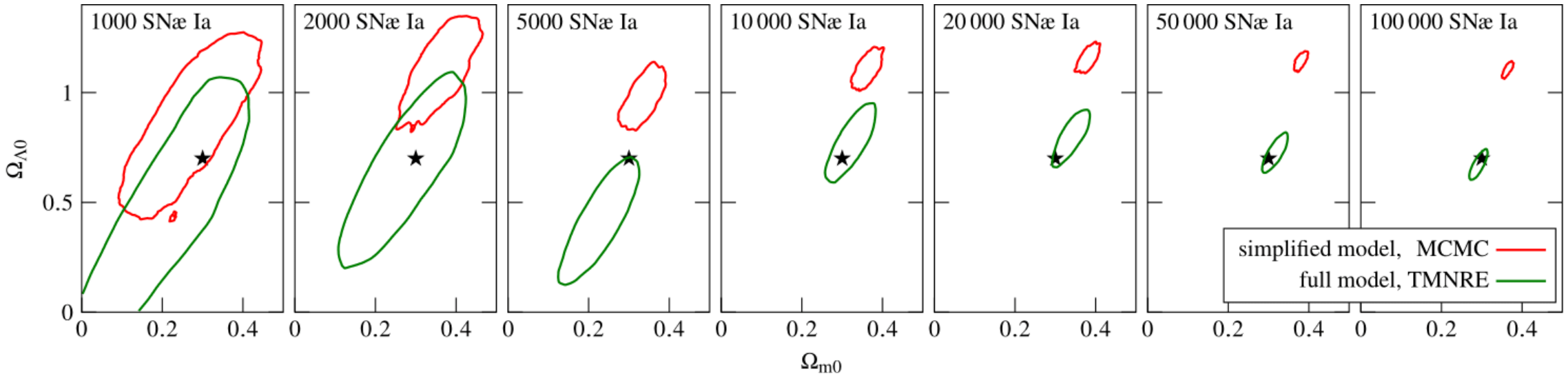
# Simulation-based SN Ia cosmology

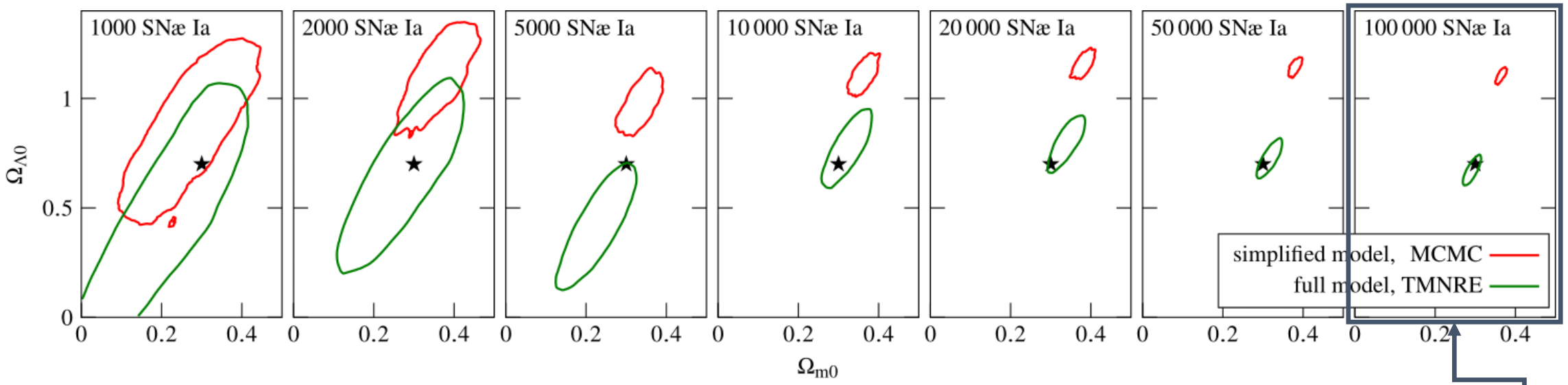


# The importance of model realism

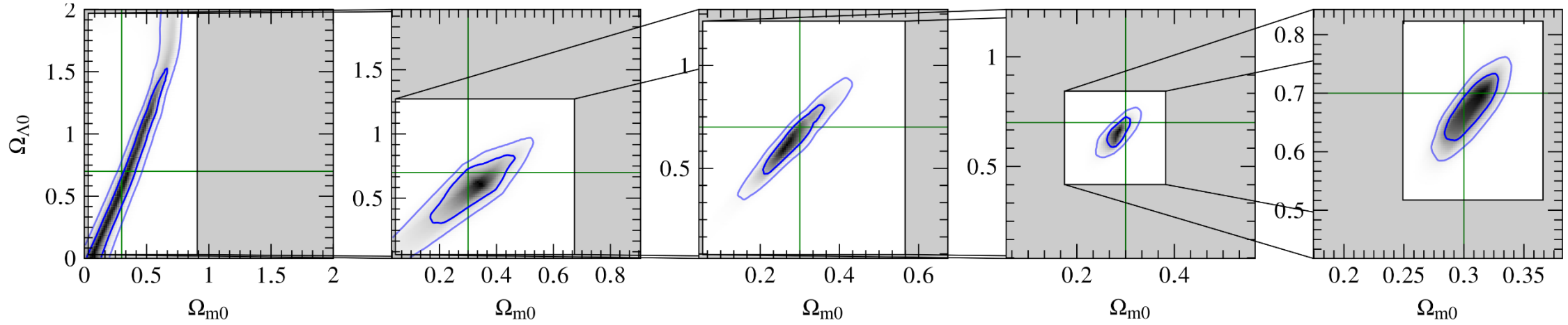
present

future






stage 0 → stage 1 → stage 2 → stage 3 → stage 4




train (~2 h)

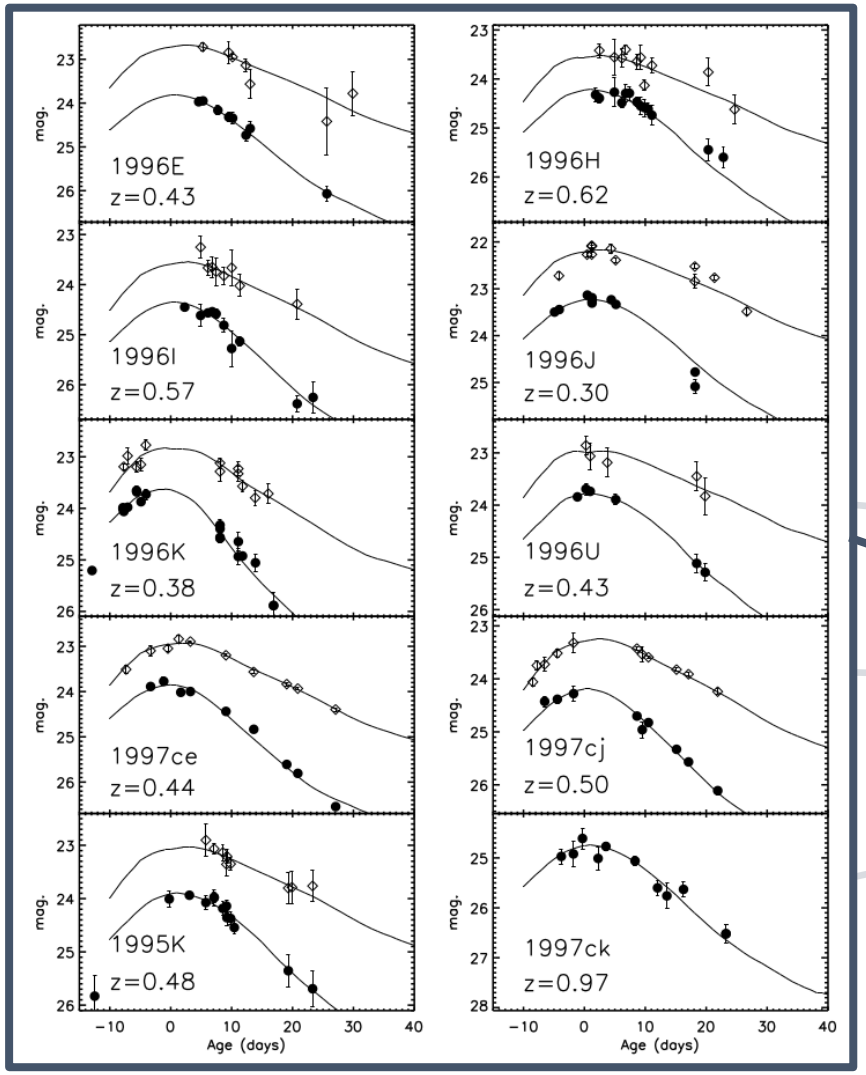
truncate global params

…

progressively home in

on true values

# Where SBI shines: realism




~~hand-crafted summaries~~

$x_1^s \pm \sigma_{x_1}^s$
"stretch"

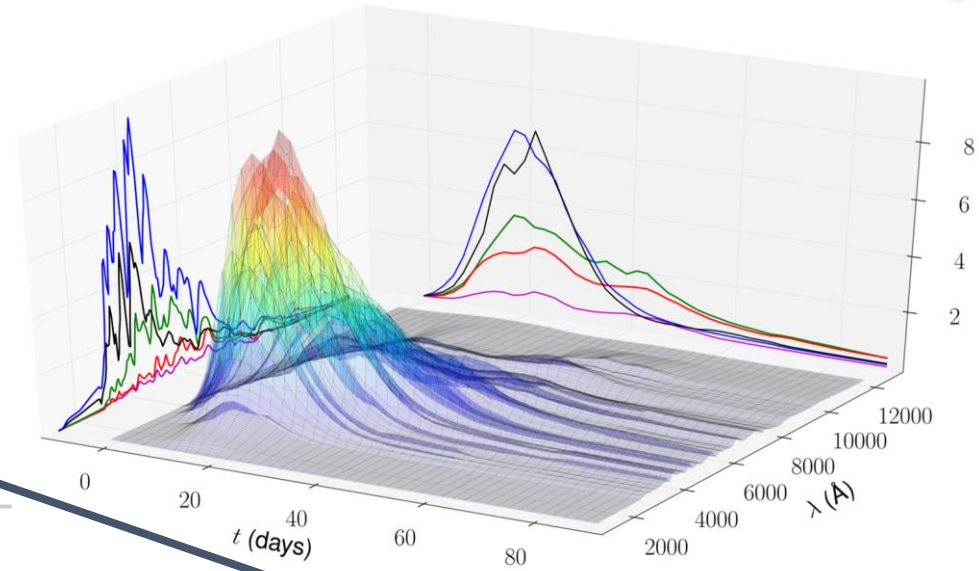
$c^s \pm \sigma_c^s$
"colour"

$m^s \pm \sigma_m^s$
brightness

$m^s +$

- lightcurve model (+ dust, host):

(pre-trained) BayeSN (Mandel et al.)




population priors

$\mathcal{C} \pm \sigma_{\mathcal{C}}$
posterior

# Where SBI shines: realism




- lightcurve model
- instrument model (+ calibration)

~~hand-crafted summaries~~

wrong: source = obs − background
correct: obs ~ **Poisson** [source + background]

$x_1^s \pm \sigma_{x_1}^s$
"stretch"

$c^s \pm \sigma_c^s$
"colour"

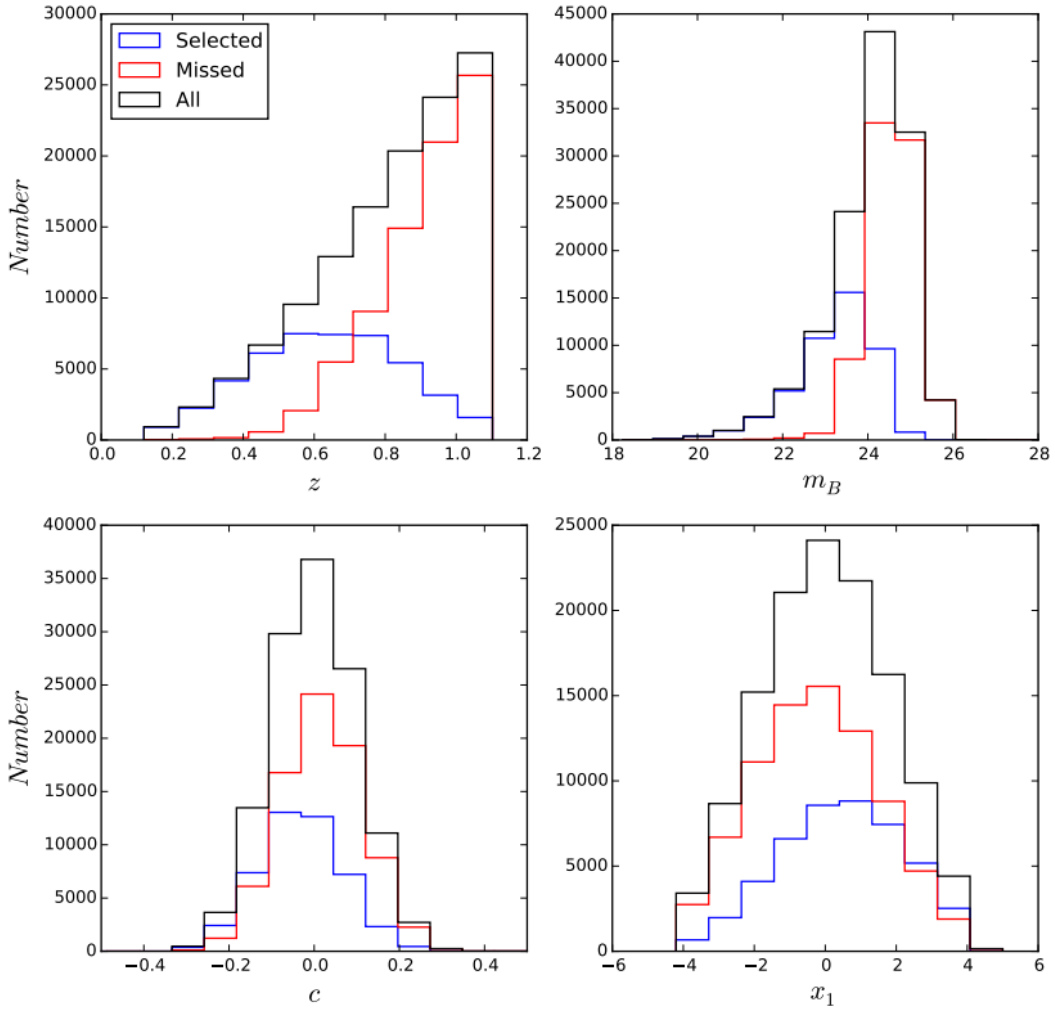
$m^s \pm \sigma_m^s$
brightness

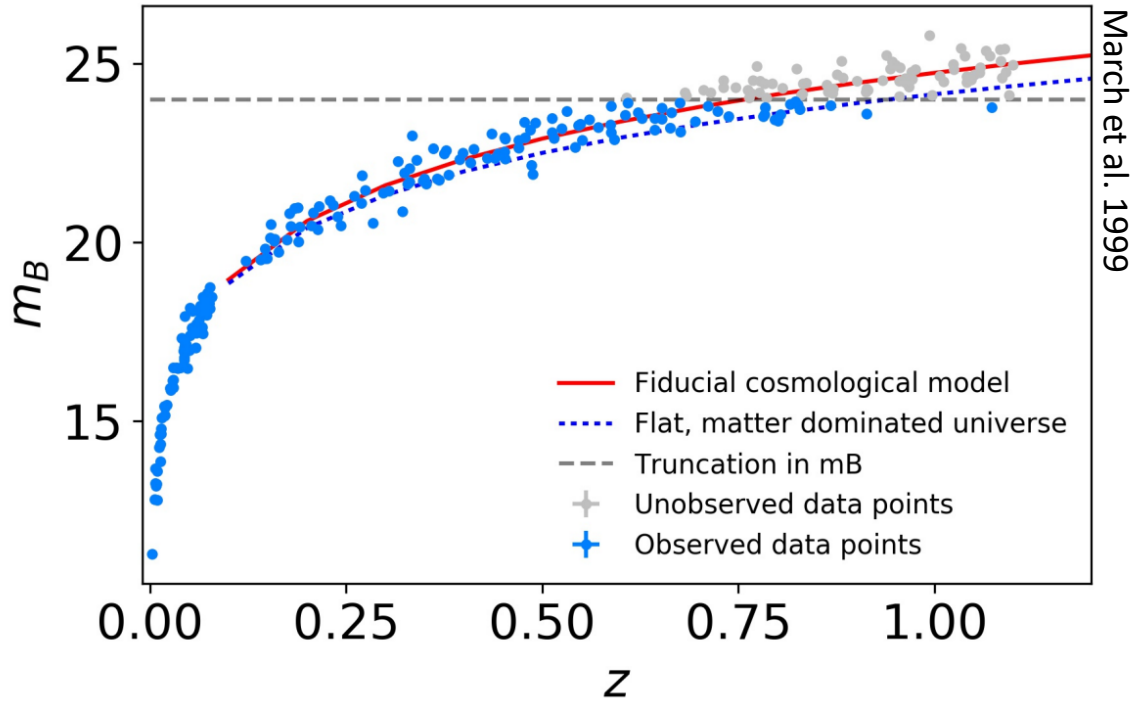
$m^s + \alpha x_1^s - \beta c^s = M_0^s + \mu(z^s, \mathcal{C}) +$ ~~"noise"~~

population priors

$\mathcal{C} \pm \sigma_{\mathcal{C}}$
posterior

# Where SBI shines: selection effects



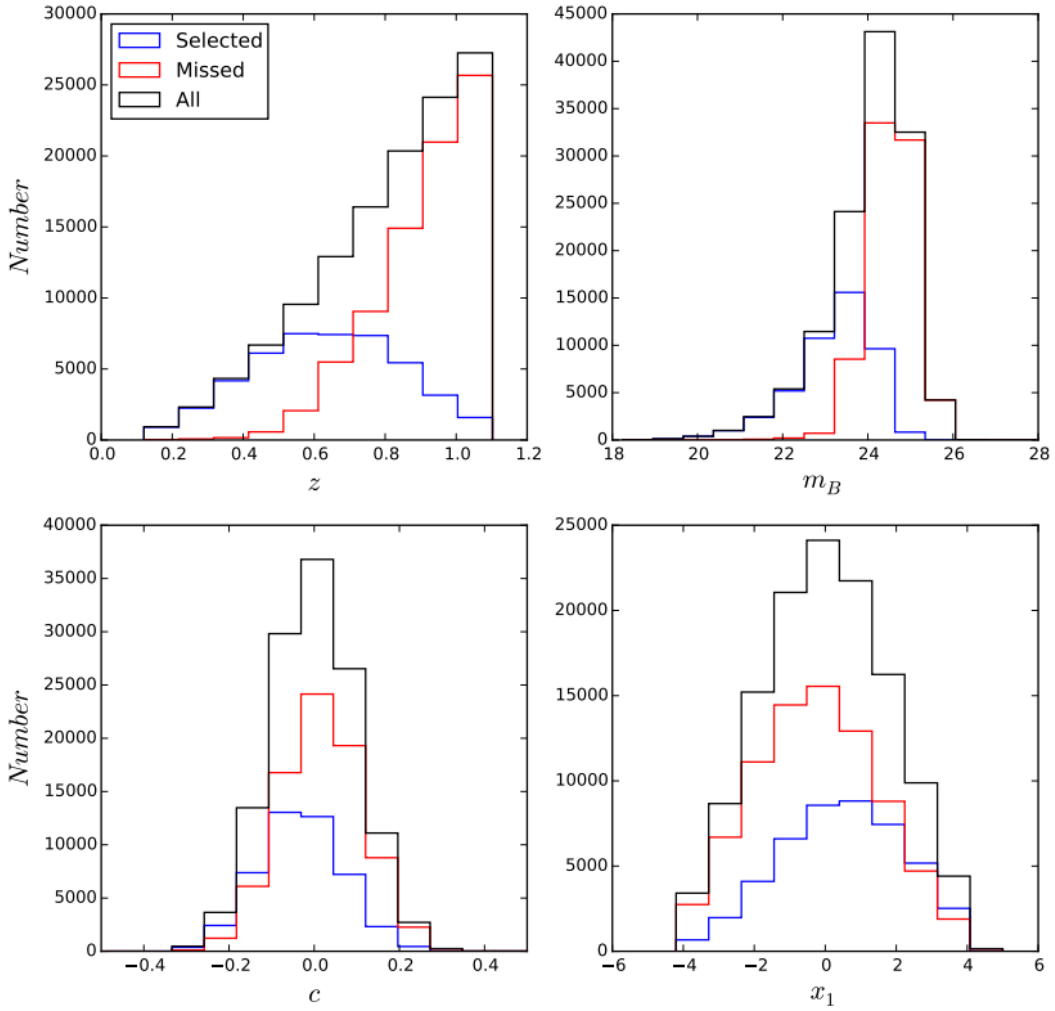



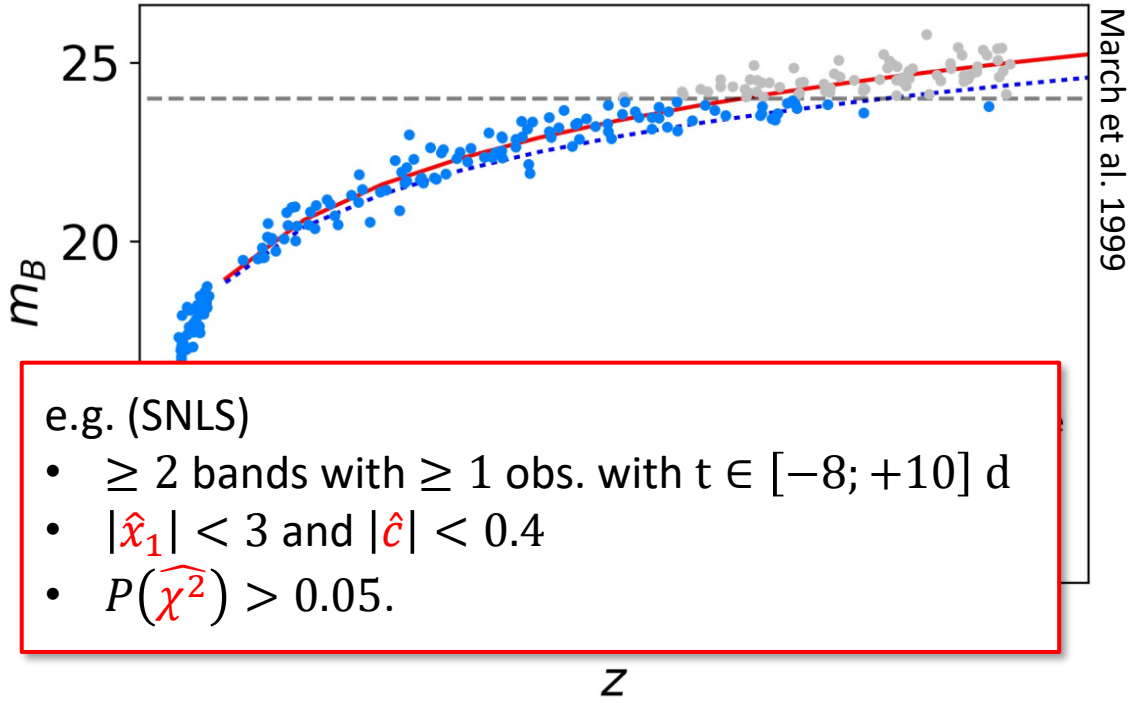

$$m^s + \alpha x_1^s - \beta c^s = M_0^s + \mu(z^s, \mathcal{C}) + \text{"noise"}$$

population priors given SN is observed

$\mathcal{C} \pm \sigma_{\mathcal{C}}$ posterior

# Where SBI shines: selection effects




e.g. (SNLS)

- $\geq 2$ bands with $\geq 1$ obs. with t $\in [-8; +10]$ d
- $|\hat{x}_1| < 3$ and $|\hat{c}| < 0.4$
- $P(\widehat{\chi^2}) > 0.05$.

$$m^s + \alpha x_1^s - \beta c^s = M_0^s + \mu(z^s, \mathcal{C}) + \text{"noise"}$$

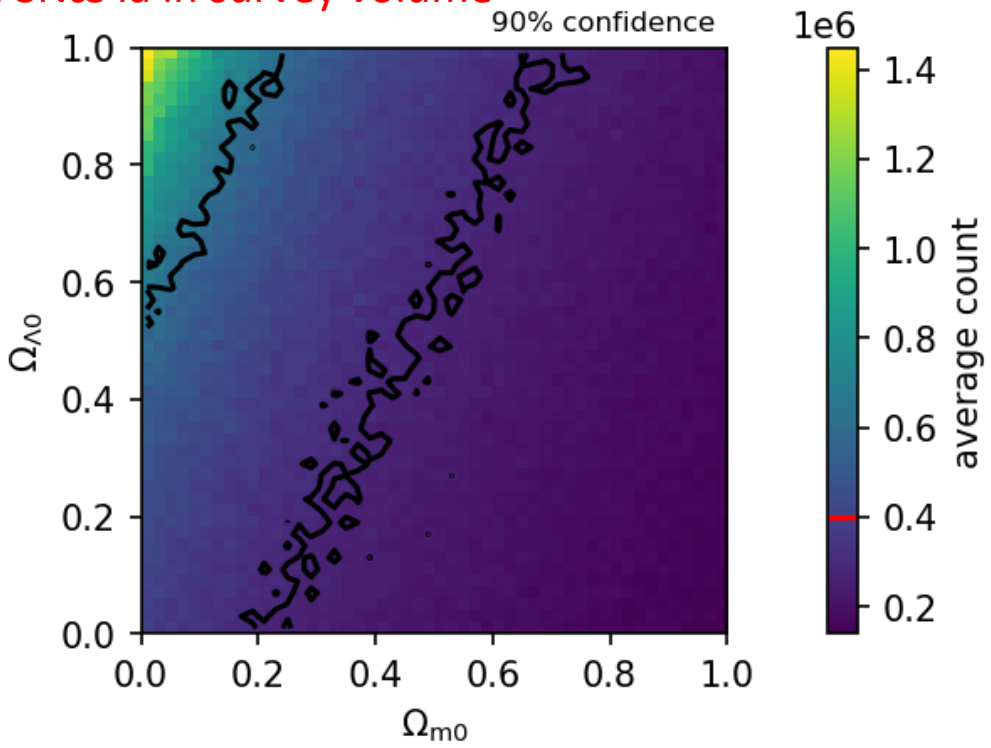
population priors given SN is observed

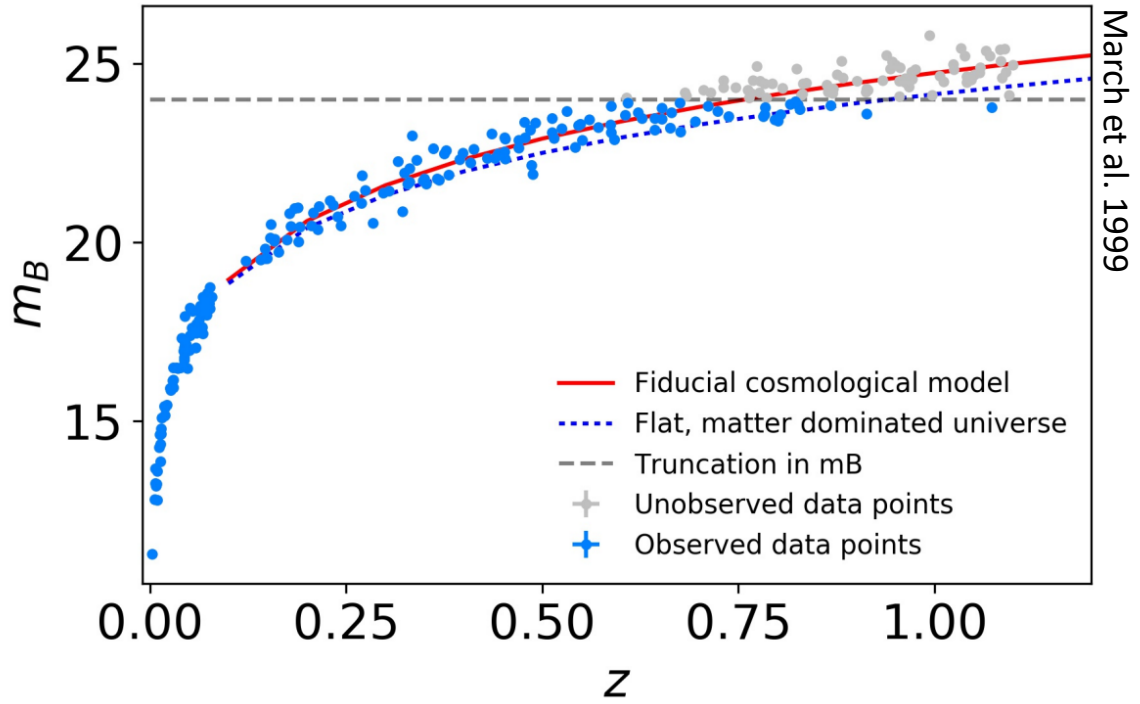
$\mathcal{C} \pm \sigma_{\mathcal{C}}$ posterior

(cf. "Detection is truncation" (Anau Montel & Weniger 2022))

# Where SBI shines: selection effects

all SNæ Ia in survey volume



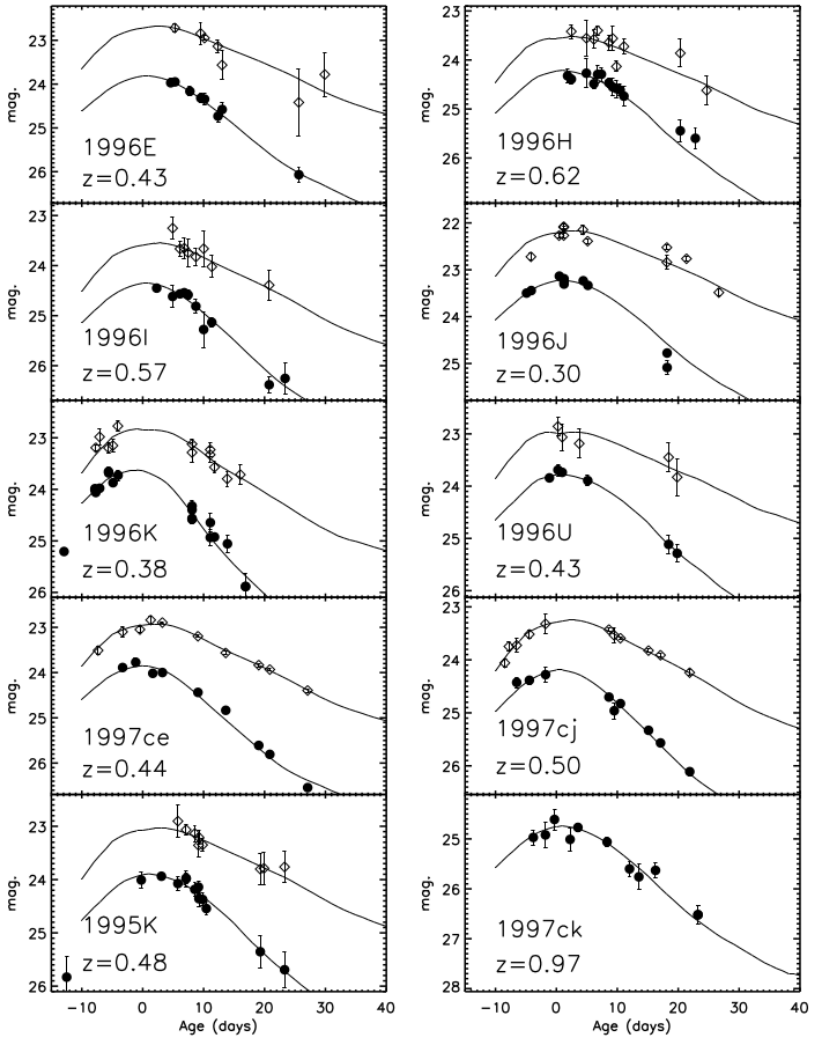

$$m^s + \alpha x_1^s - \beta c^s = M_0^s + \mu(z^s, \mathcal{C}) + \text{"noise"}$$

counts contain information

population priors given SN is observed

$\mathcal{C} \pm \sigma_{\mathcal{C}}$ posterior

# SN Ia cosmology: *a dataset*




$s^1$ $\rightarrow m^s, x_1^s, c^s, z^s$ & covar ?!

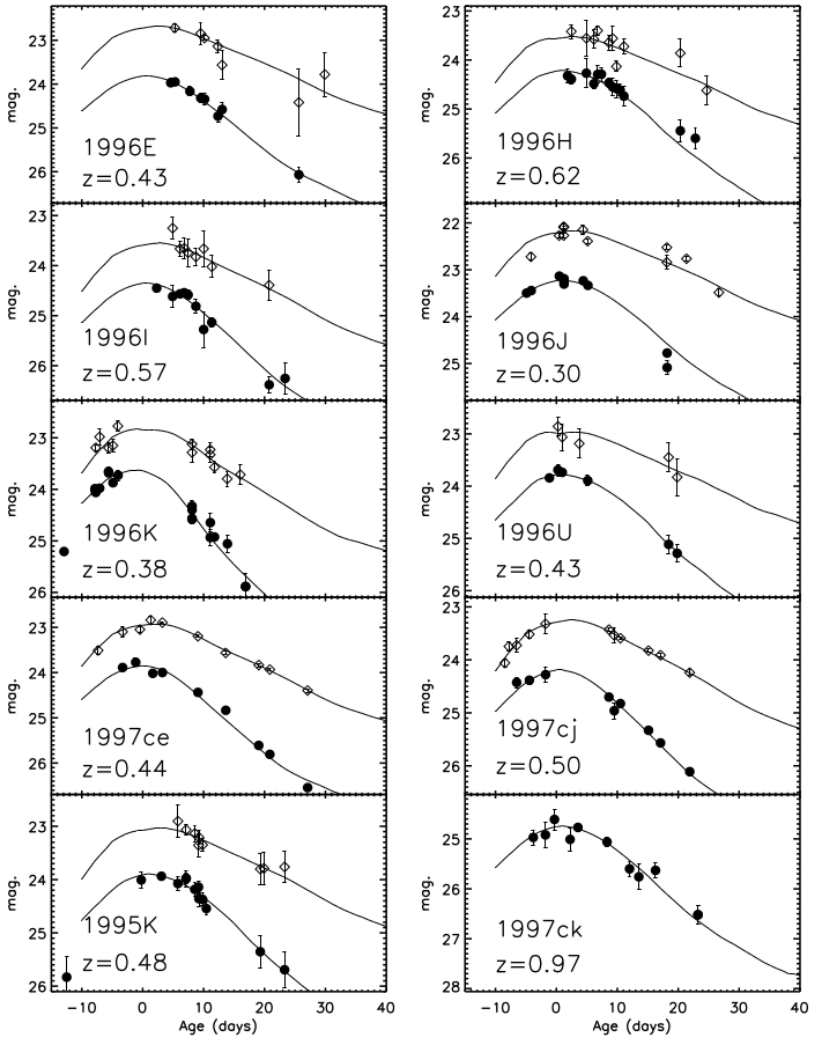
$s^2$

$s^3$

$s^4$

$s^5$

# SN Ia cosmology: *a dataset summary*




$\boldsymbol{s}^1$

$\boldsymbol{s}^2$

$\boldsymbol{s}^3$

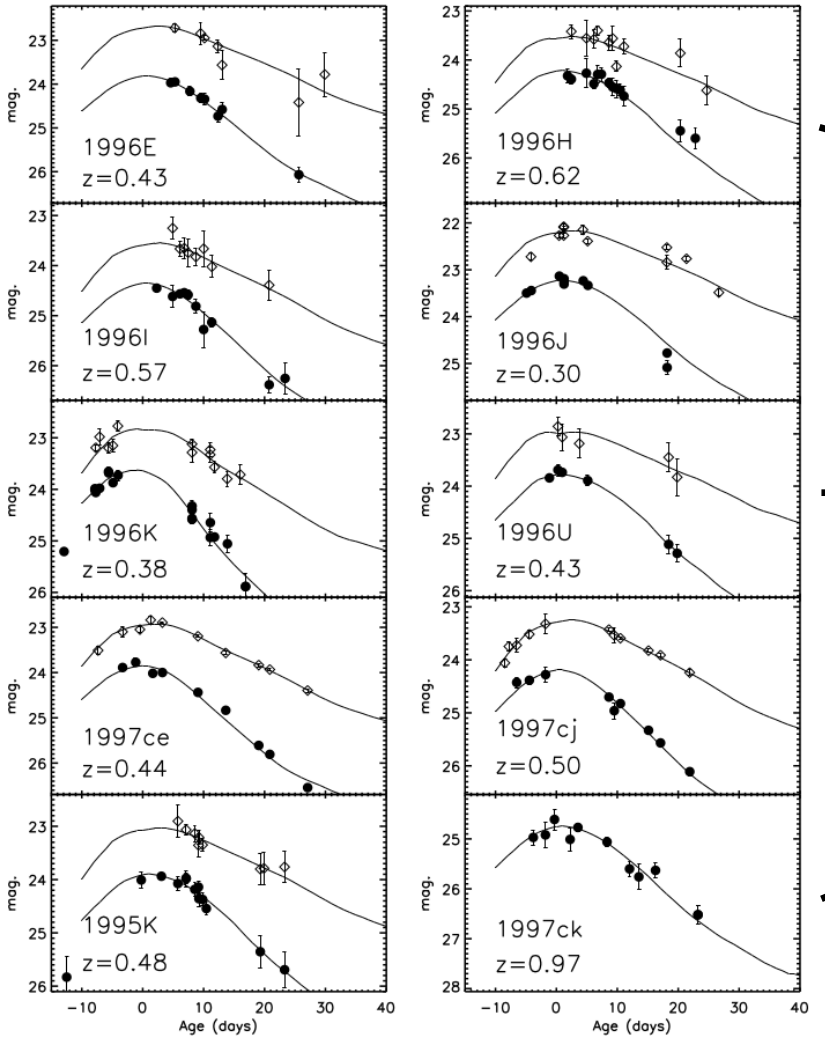
$\boldsymbol{s}^4$

$\boldsymbol{s}^5$

dataset summary: $\boldsymbol{S} = \rho_{\mathrm{NN}}\left[\sum_s \phi_{\mathrm{NN}}(\boldsymbol{s}^s)\right]$

"Deep Sets" (1703.06114)
"Set Transformers" (1810.00825)

# SN Ia cosmology: a set dataset




$$\left\{ \begin{array}{l} \boldsymbol{d}^1 \\ \boldsymbol{d}^2 \\ \dots \end{array} \right\} \quad \boldsymbol{s}^1 = \rho_{\mathrm{NN}}^{\mathrm{obs}} \left[ \sum_{i \in \mathrm{SN}^1} \phi_{\mathrm{NN}}^{\mathrm{obs}}(\boldsymbol{d}^i) \right]$$

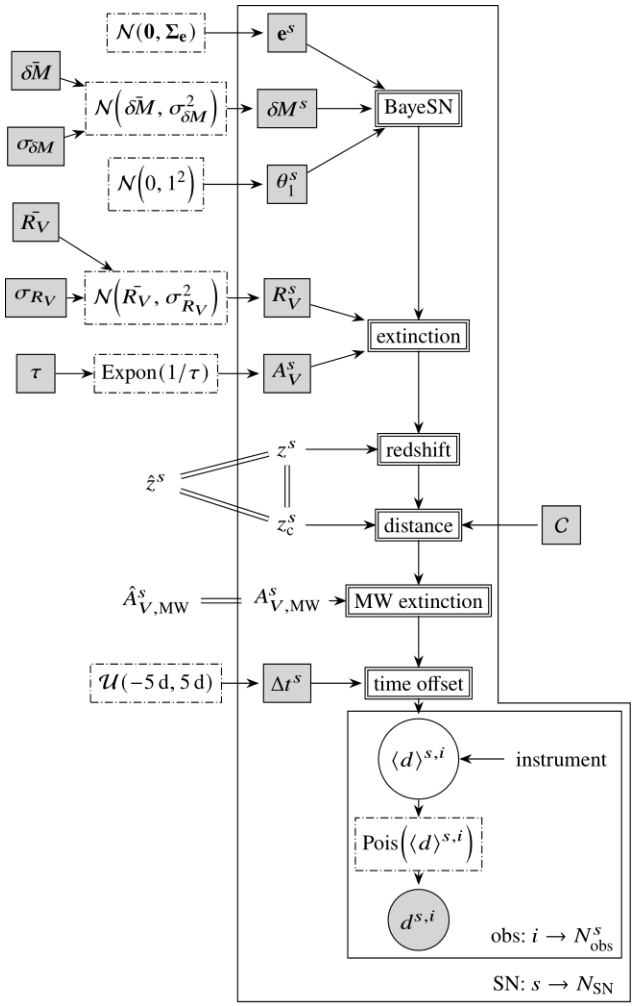
$$\left\{ \begin{array}{l} \boldsymbol{d}^{25} \\ \boldsymbol{d}^{26} \\ \dots \end{array} \right\} \quad \boldsymbol{s}^2 = \rho_{\mathrm{NN}}^{\mathrm{obs}} \left[ \sum_{i \in \mathrm{SN}^2} \phi_{\mathrm{NN}}^{\mathrm{obs}}(\boldsymbol{d}^i) \right]$$

$$\left\{ \begin{array}{l} \boldsymbol{d}^{42} \\ \boldsymbol{d}^{43} \\ \dots \end{array} \right\} \quad \boldsymbol{s}^3 = \rho_{\mathrm{NN}}^{\mathrm{obs}} \left[ \sum_{i \in \mathrm{SN}^3} \phi_{\mathrm{NN}}^{\mathrm{obs}}(\boldsymbol{d}^i) \right]$$

$$\mathbf{S} = \rho_{\mathrm{NN}} \left[ \sum_{s} \phi_{\mathrm{NN}}(\boldsymbol{S}^s) \right]$$

# State of affairs

## SIDE-real: Sn Ia Dust Extinction with real(istic) data

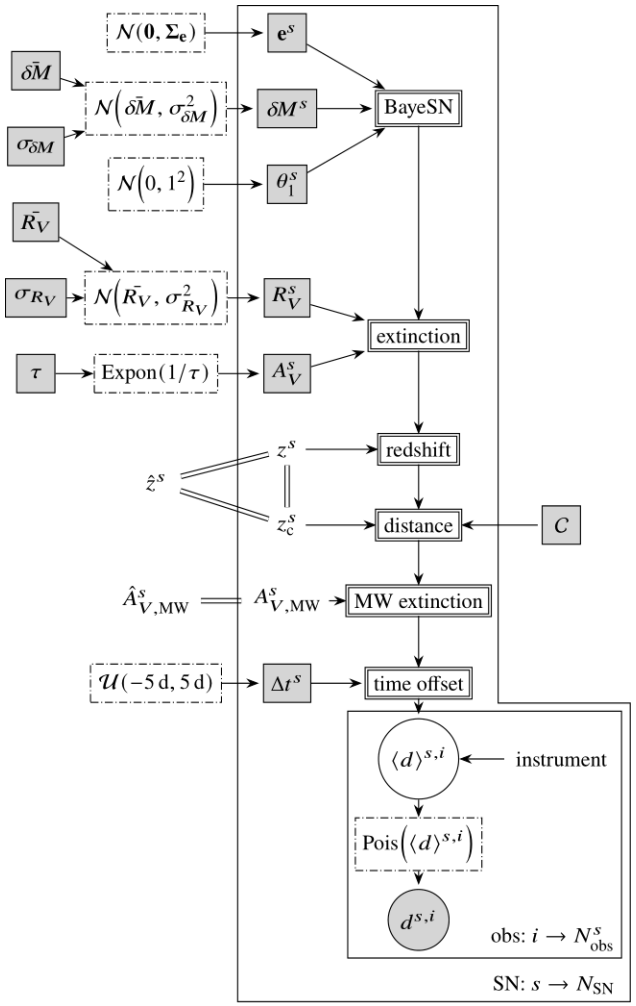


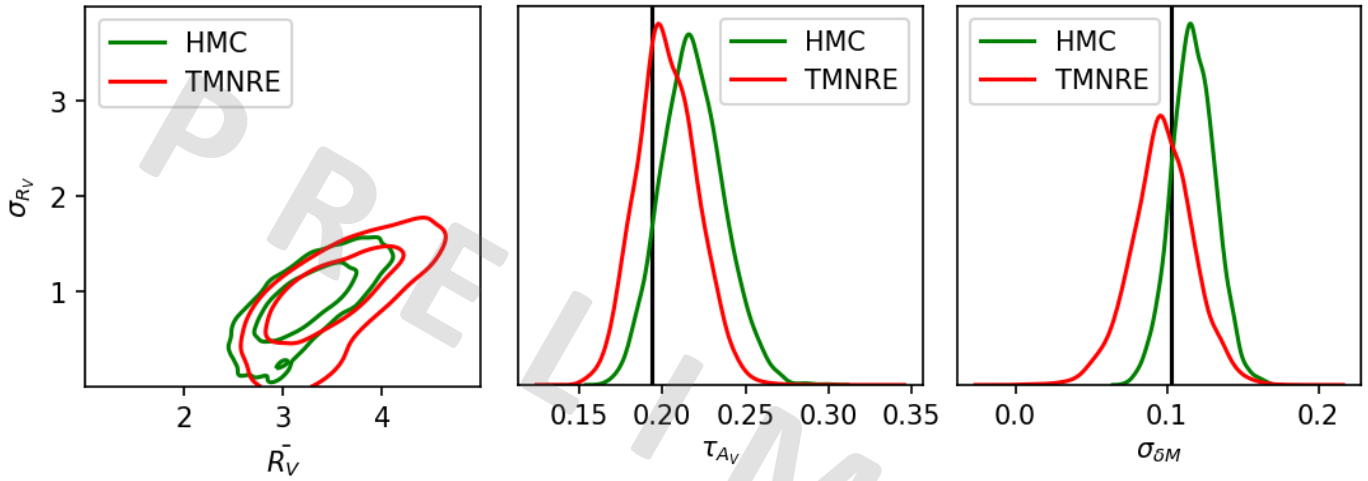

- BayeSN
  - pre-trained lightcurve model (for now?)
  - host & MW extinction
- "calibrated fluxes" (for now) vs. raw counts
- fixed redshifts and distances (for now)
- DES 3yr (for now), Foundation (Thorp et al. 2021)
  - $\sim$ 200 low-redshift SNæ Ia with spec-$z$
  - $\sim$ 10000 observations (data vector)

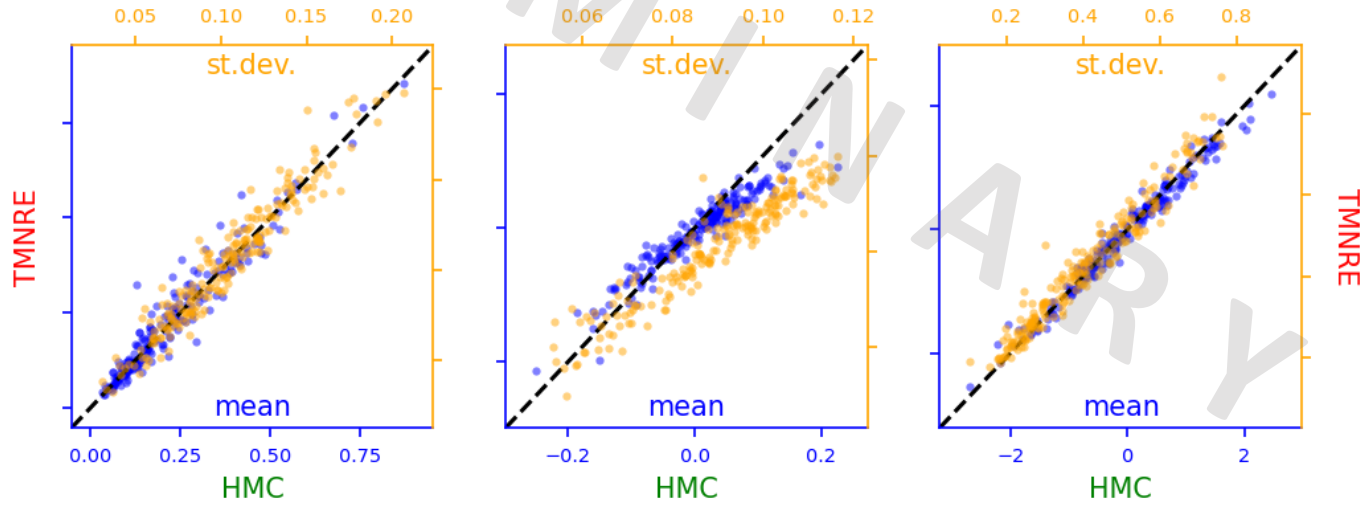
➢ tackle real data, assuming completeness

# State of affairs

## SIDE-real: Sn Ia Dust Extinction with real(istic) data




HMC by Matt Grayling using `numpyro`

# Thank you for your attention!

*“An illustration of a supernova explosion with swirling cosmic gases in the background, inspired by the surrealist paintings of Salvador Dali”*

image by DALL·E, prompt by ChatGPT