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

arXiv:2209.06733 & the near future
Image: personal archive


SISSA DATASCIENCE
Machine Learning for the Natural Sciences

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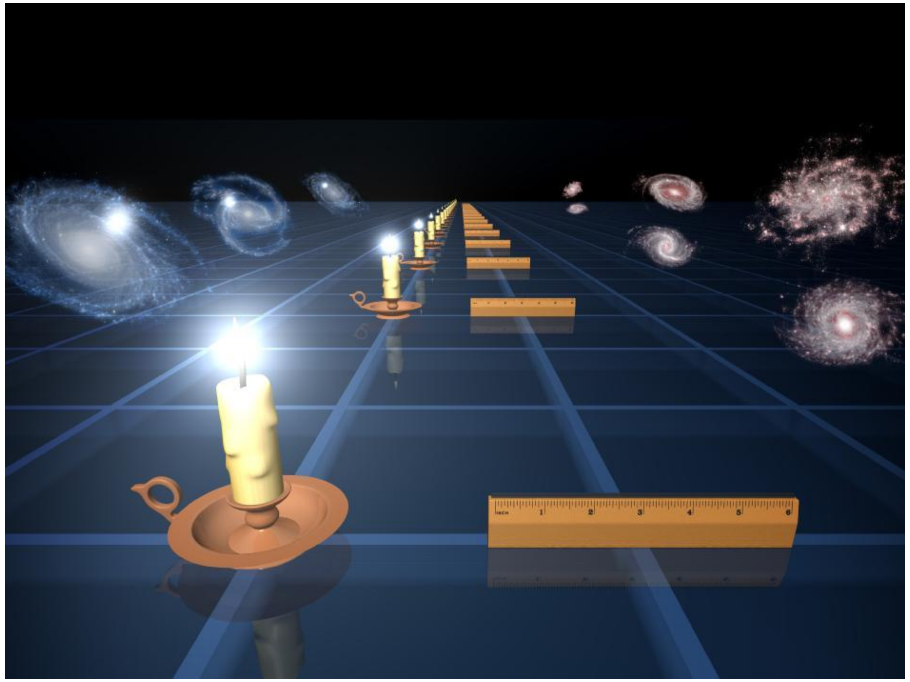
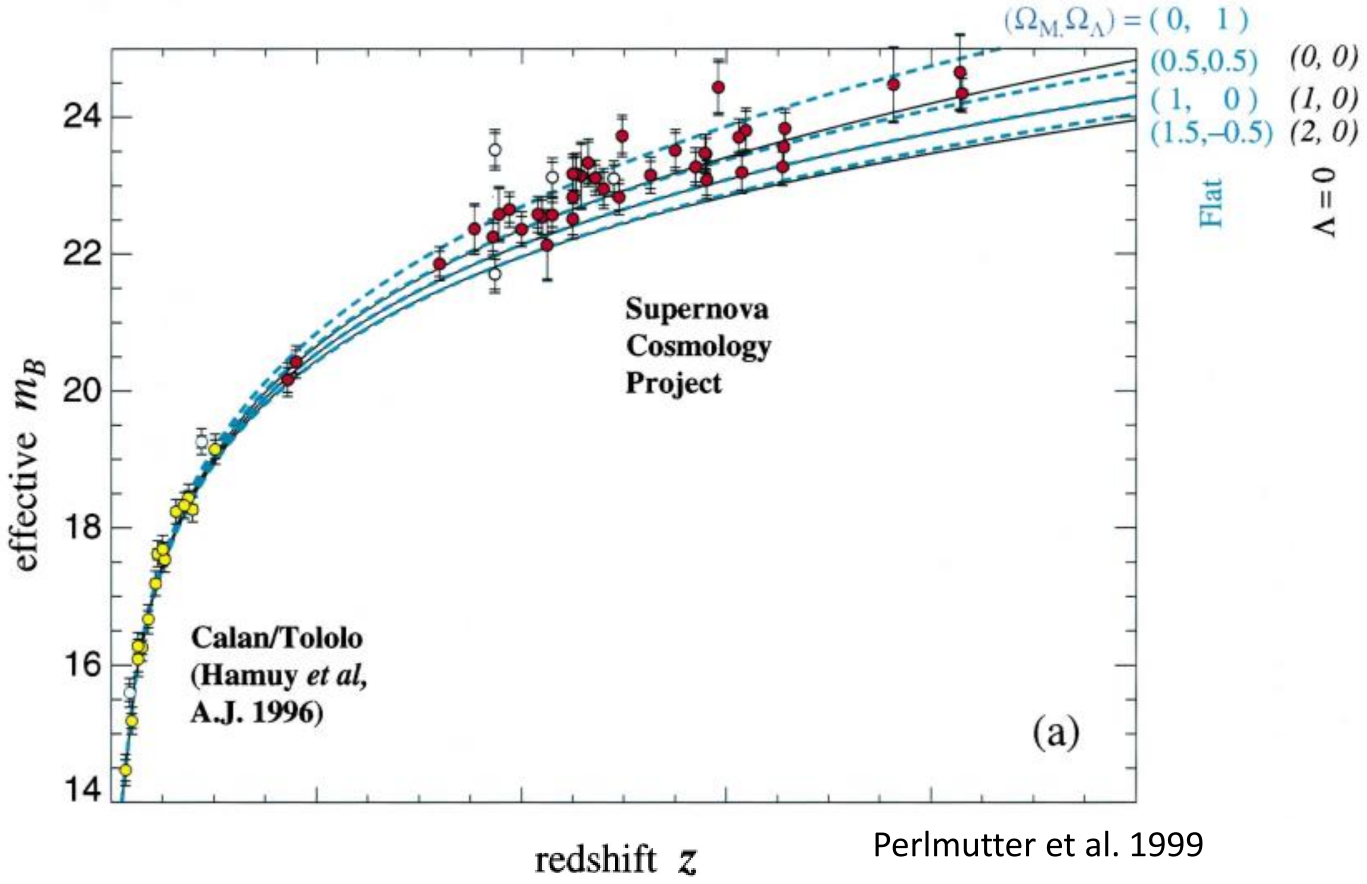
Cosmology 2023 in Miramare
2023-08-31

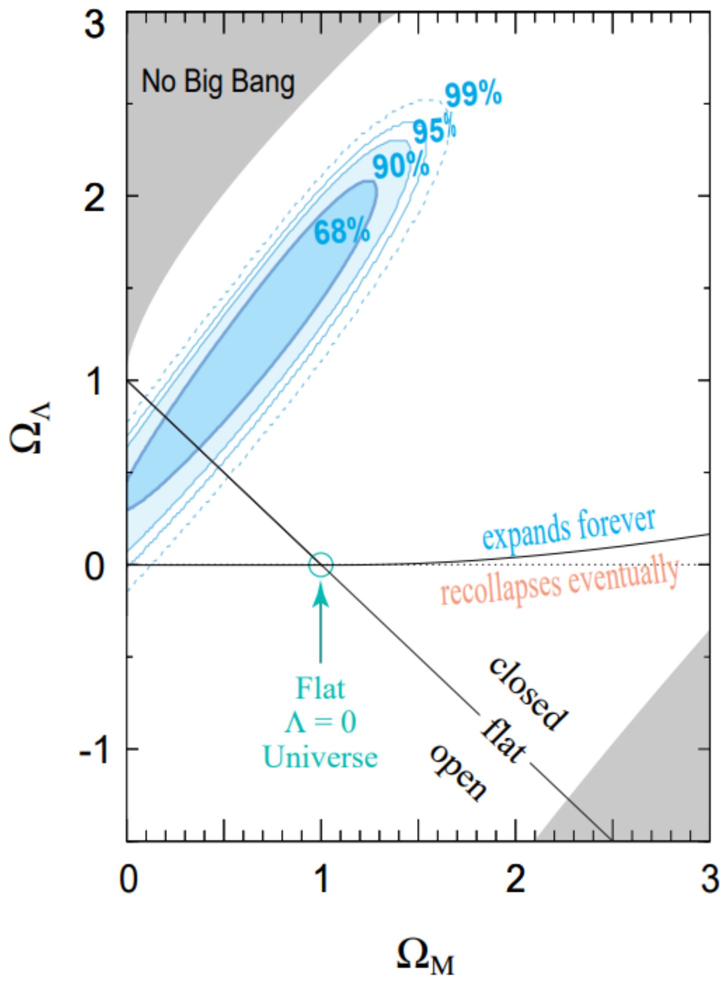
# Cosmology with standard candles



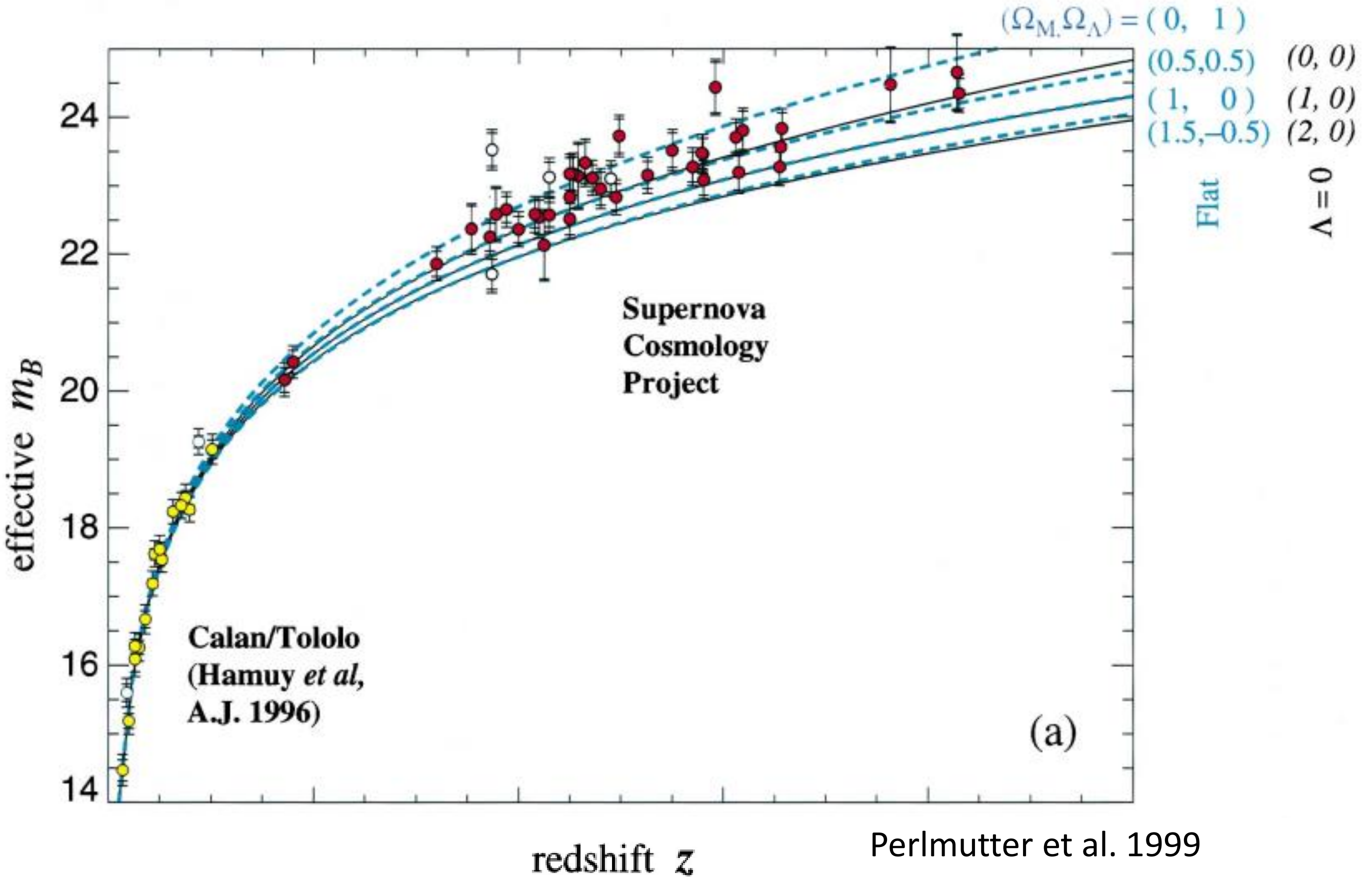



Perlmutter et al. 1999

# Cosmology with standard candles

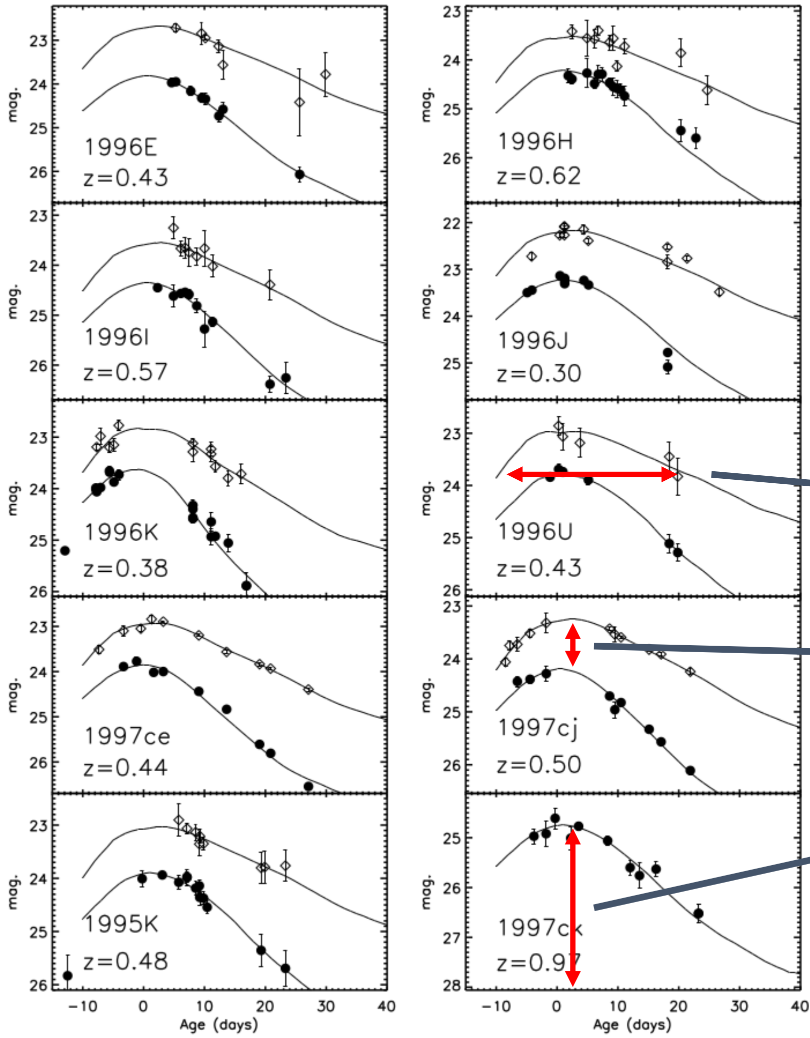



Perlmutter et al. 1999




Perlmutter et al. 1999

# SN Ia cosmology: a Nobel prize



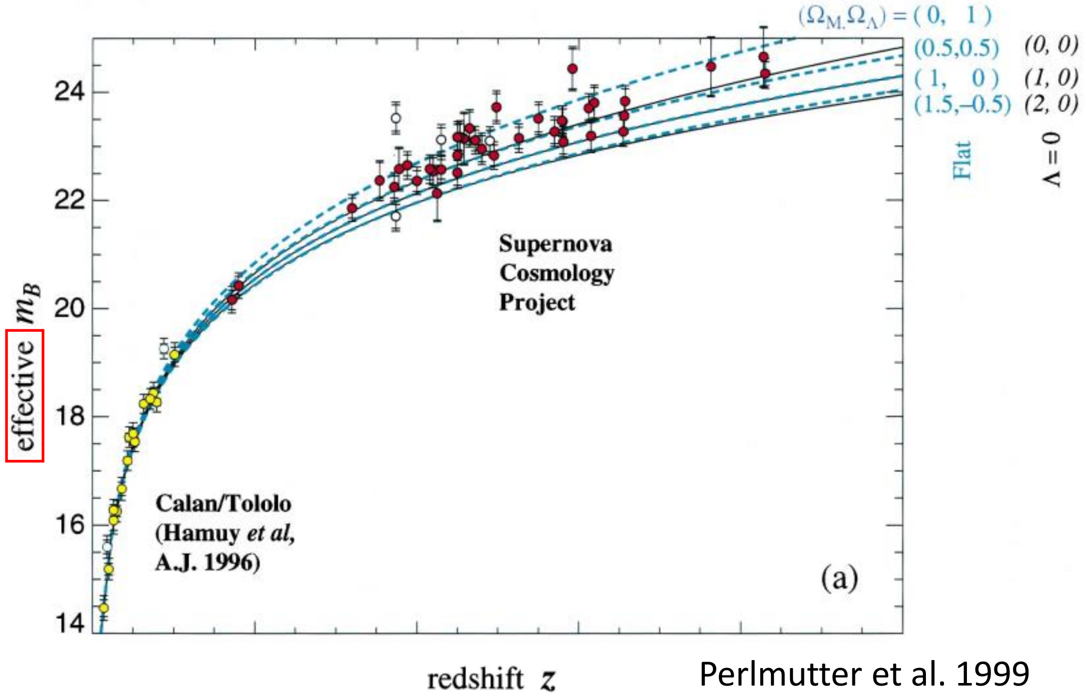

Riess et al. 1999

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

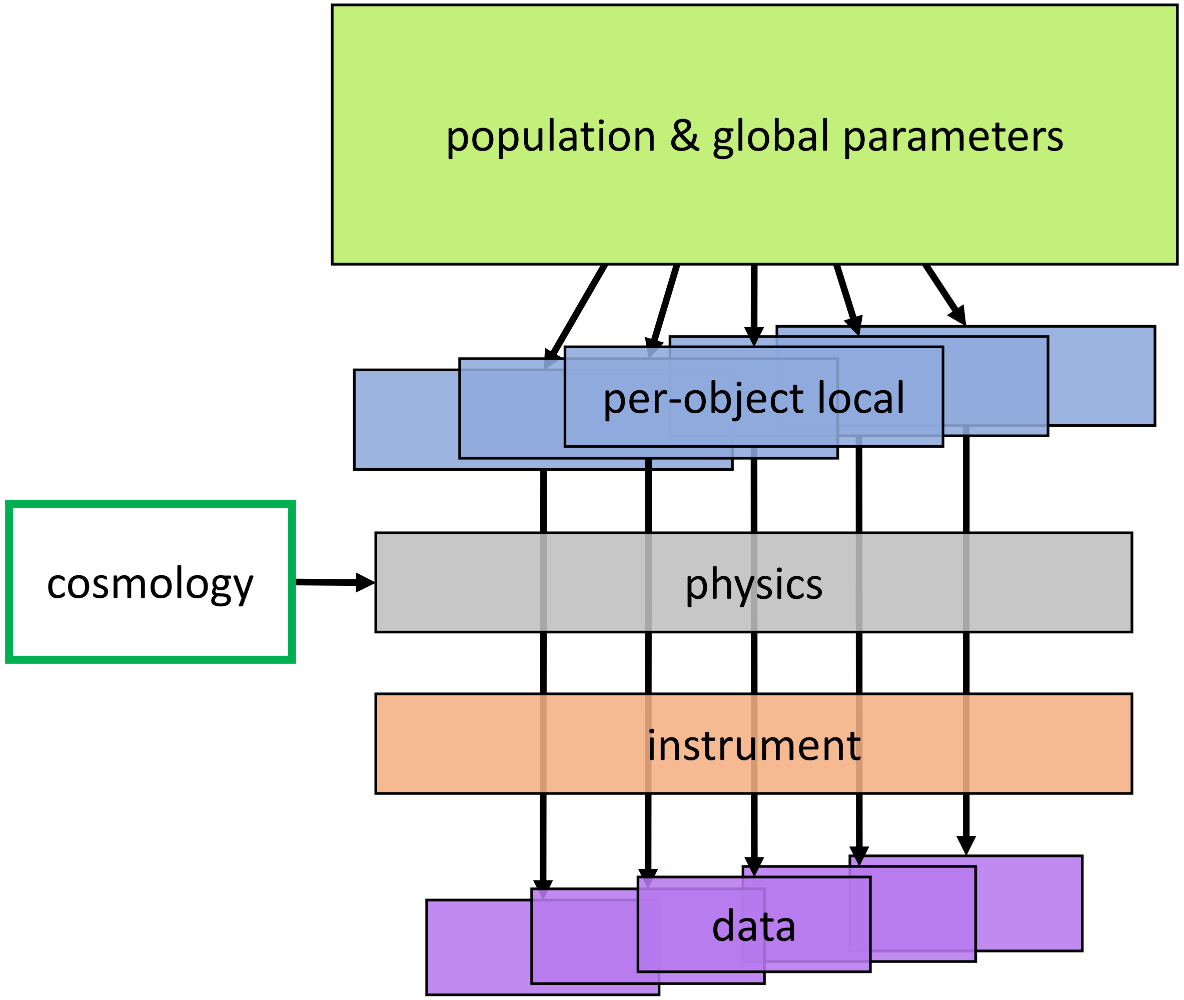


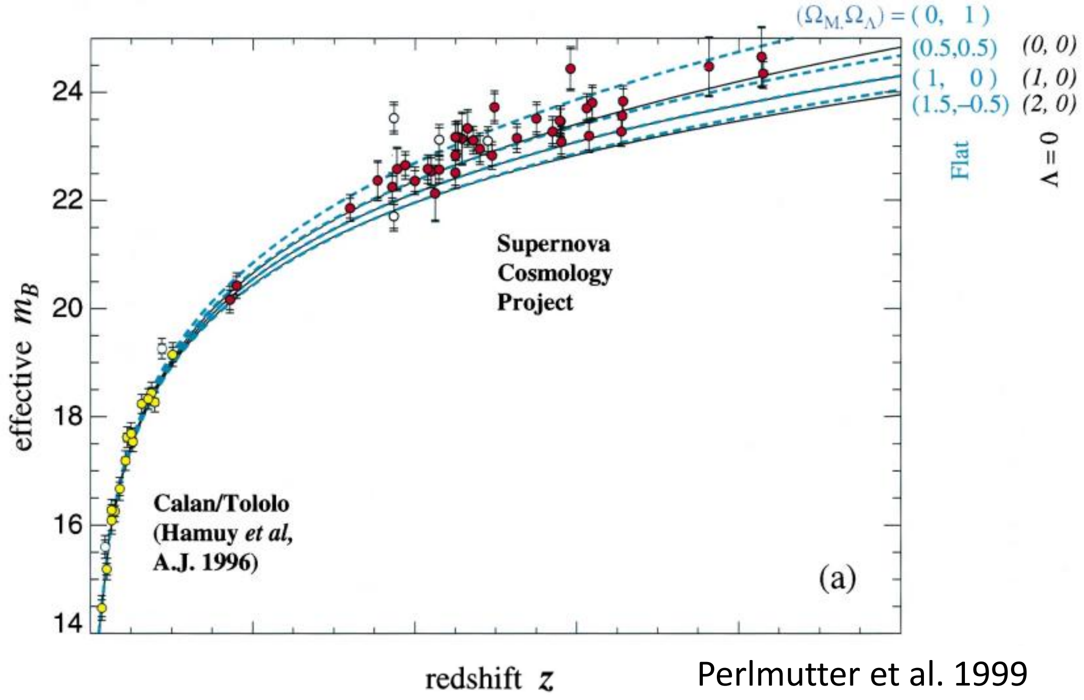

Perlmutter et al. 1999

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

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

# Hierarchical SN Ia cosmology



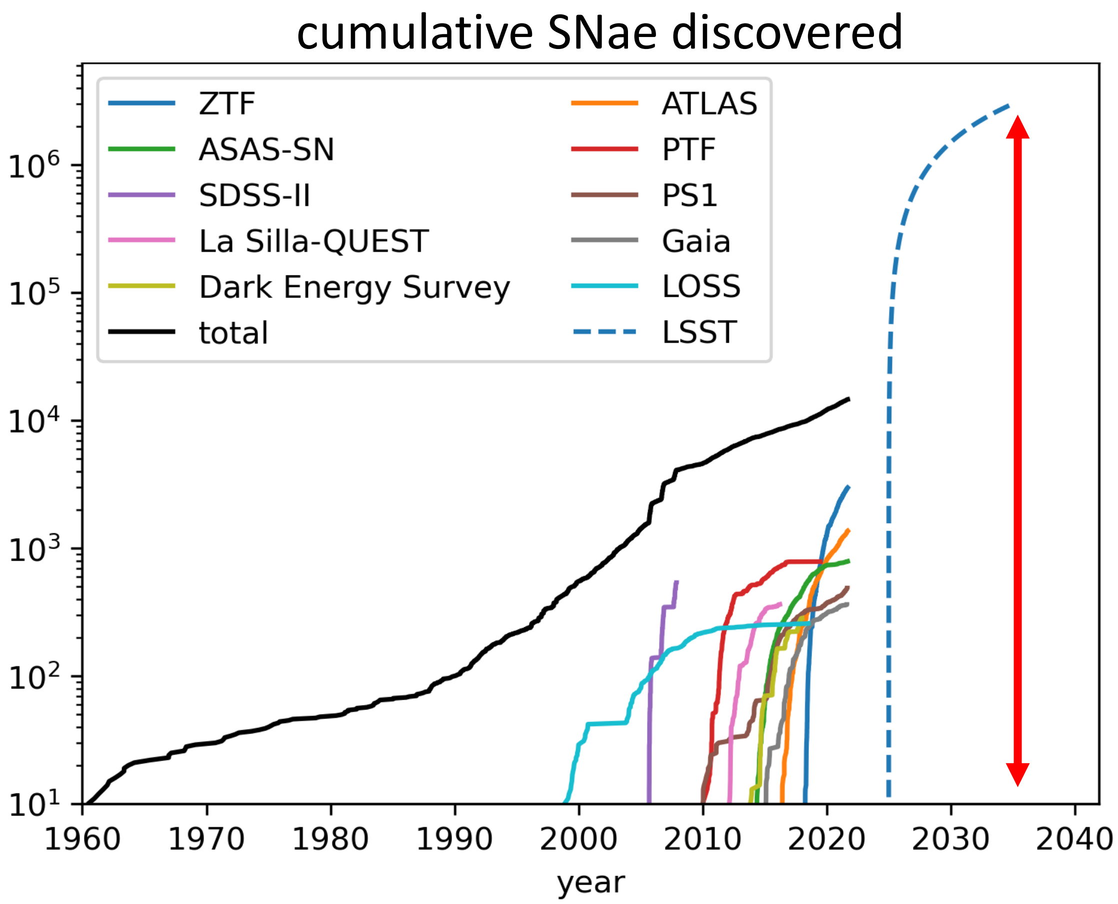




Perlmutter et al. 1999

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

population priors

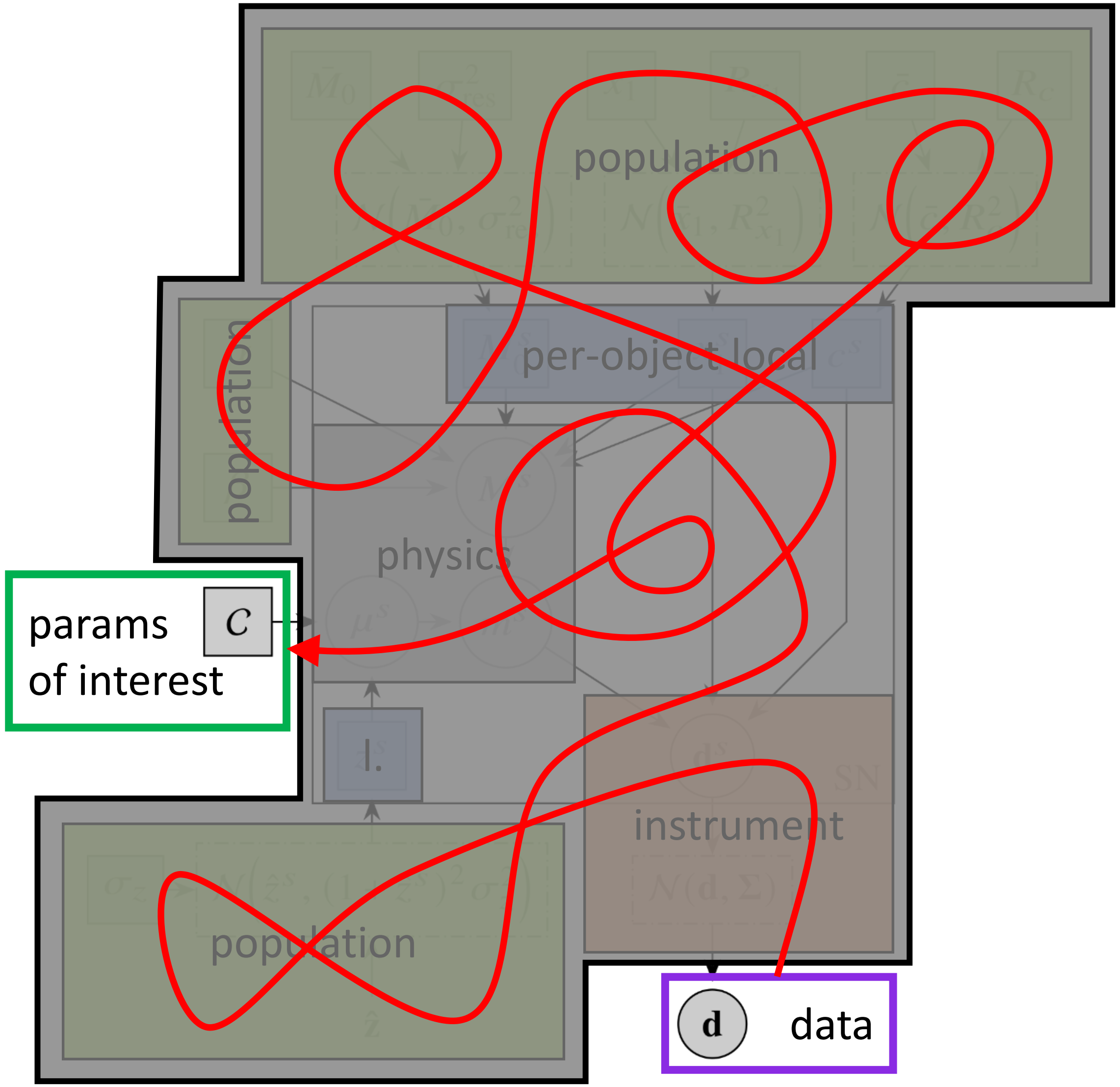
# SN Ia cosmology: *future*




$\sim 10^5$ SNæ Ia
$\sim 10^6$ "contaminants"

- large datasets
  - high-dimensional inference
- photometric redshift uncertainty
  - non-Gaussian, non-linearities
- non-Ia contamination
- selection effects

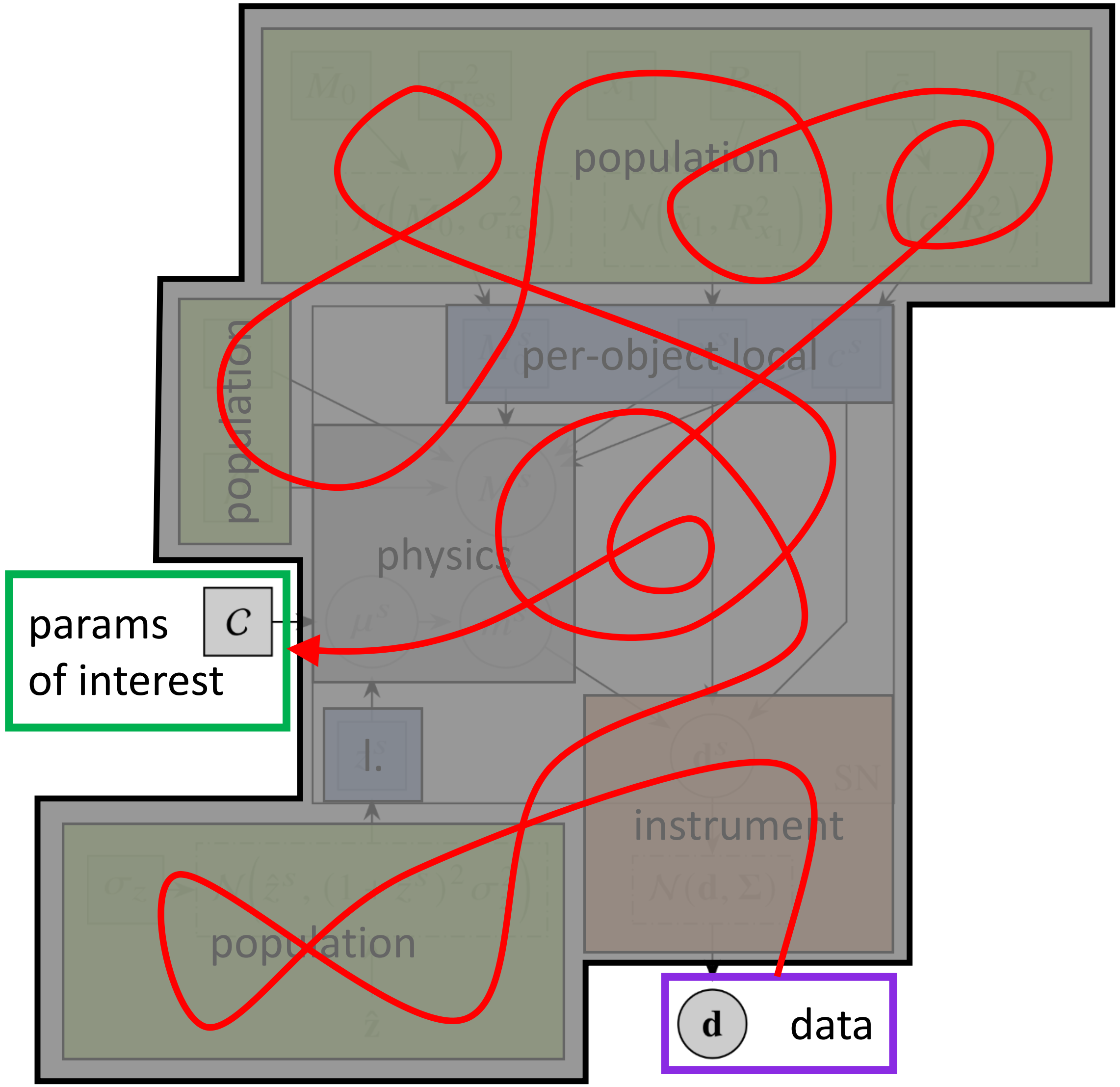
# Likelihood-based SN Ia cosmology




Inference is painful:

- large datasets
    - high-dimensional inference
- photometric redshift uncertainty
    - non-Gaussian, non-linearities
- non-Ia contamination
- selection effects

# Likelihood-based SN Ia cosmology



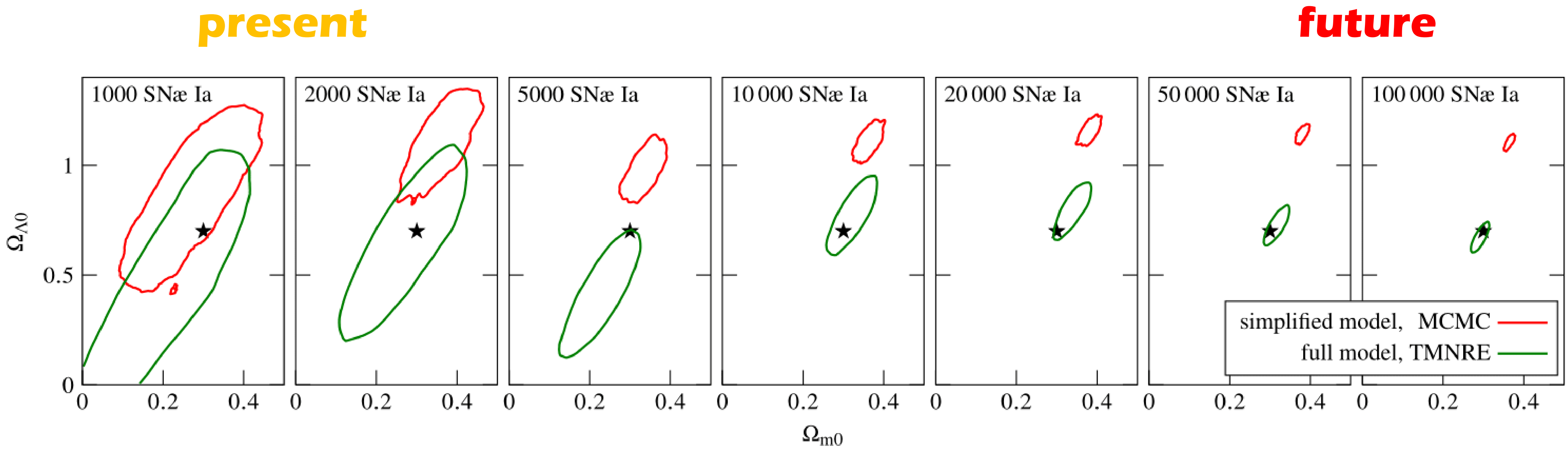

Realism is painful:

- lightcurve population
- environmental effects & dust
- Instrument model

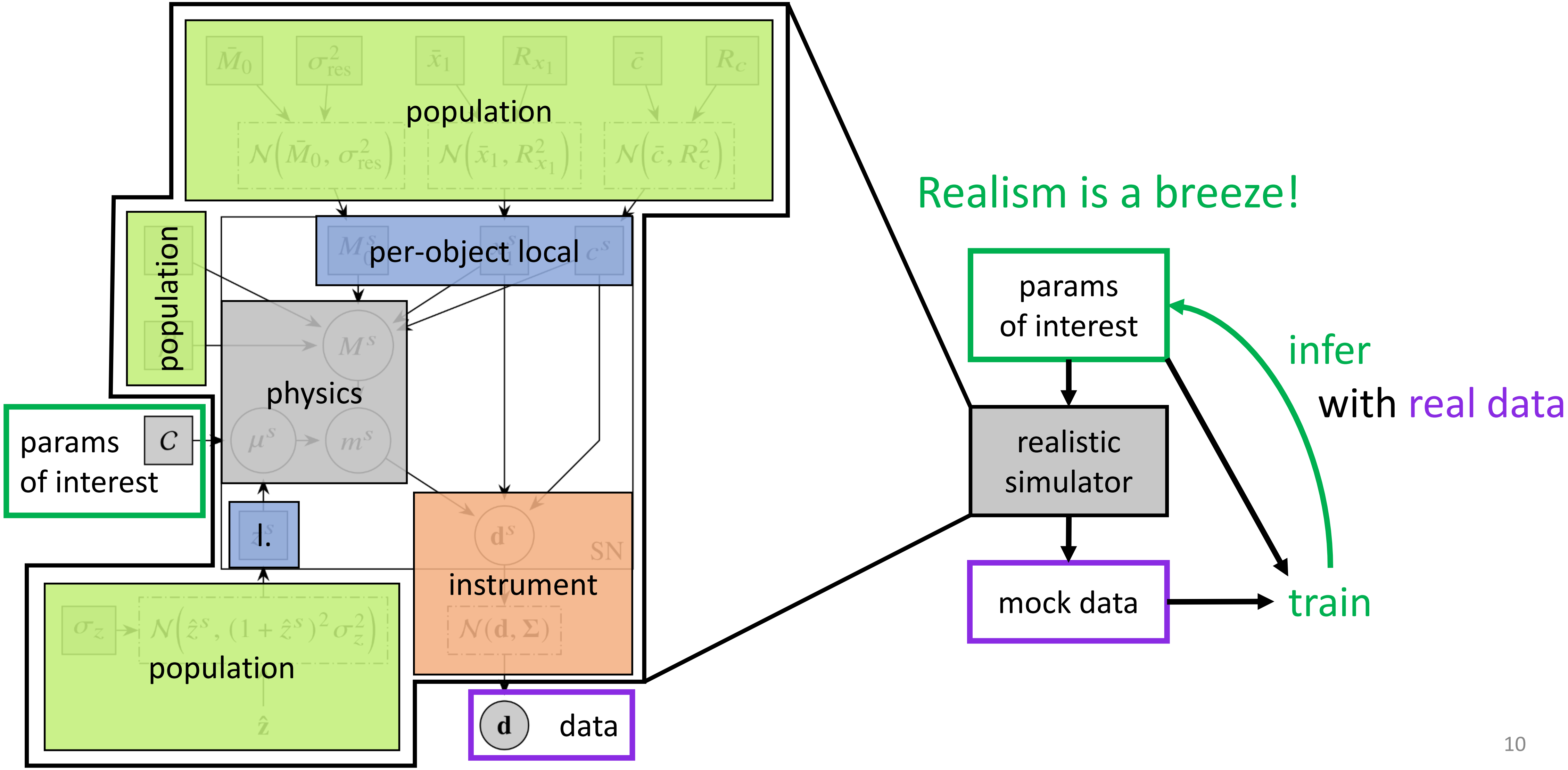
Inference is painful:

- large datasets
  - high-dimensional inference
- photometric redshift uncertainty
  - non-Gaussian, non-linearities
- non-Ia contamination
- selection effects

# The importance of model realism

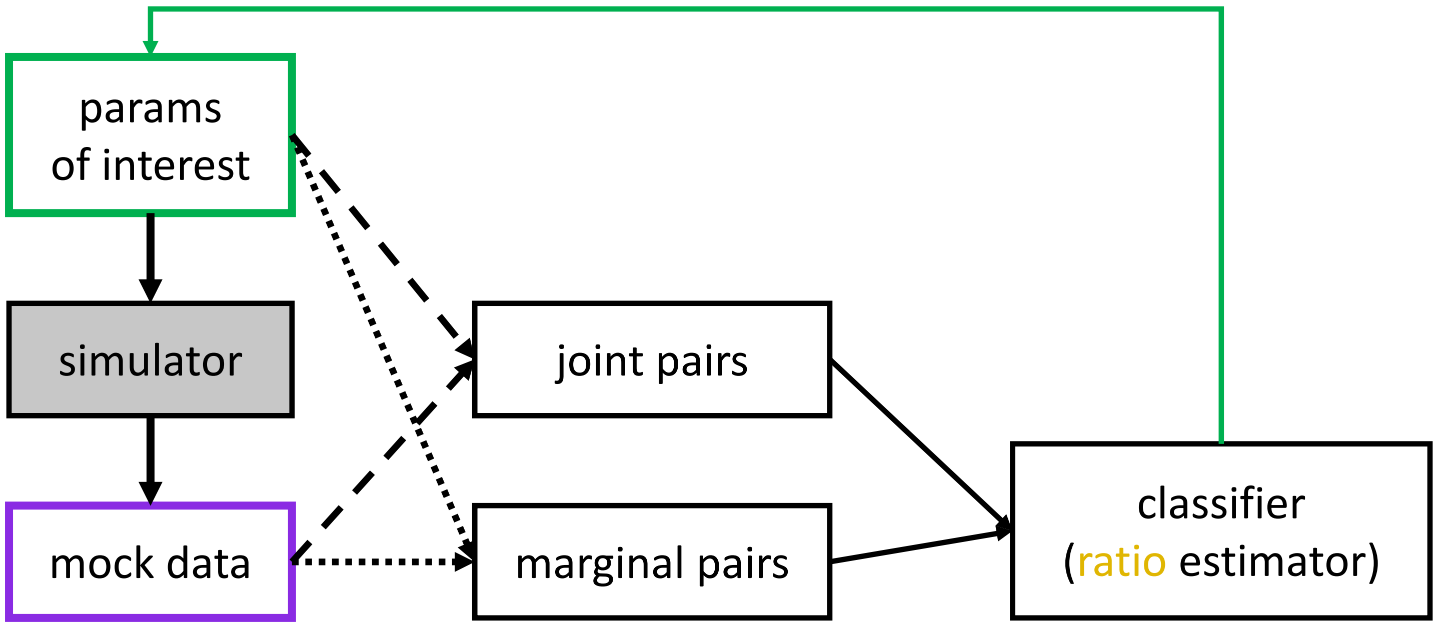


# Simulation-based SN Ia cosmology



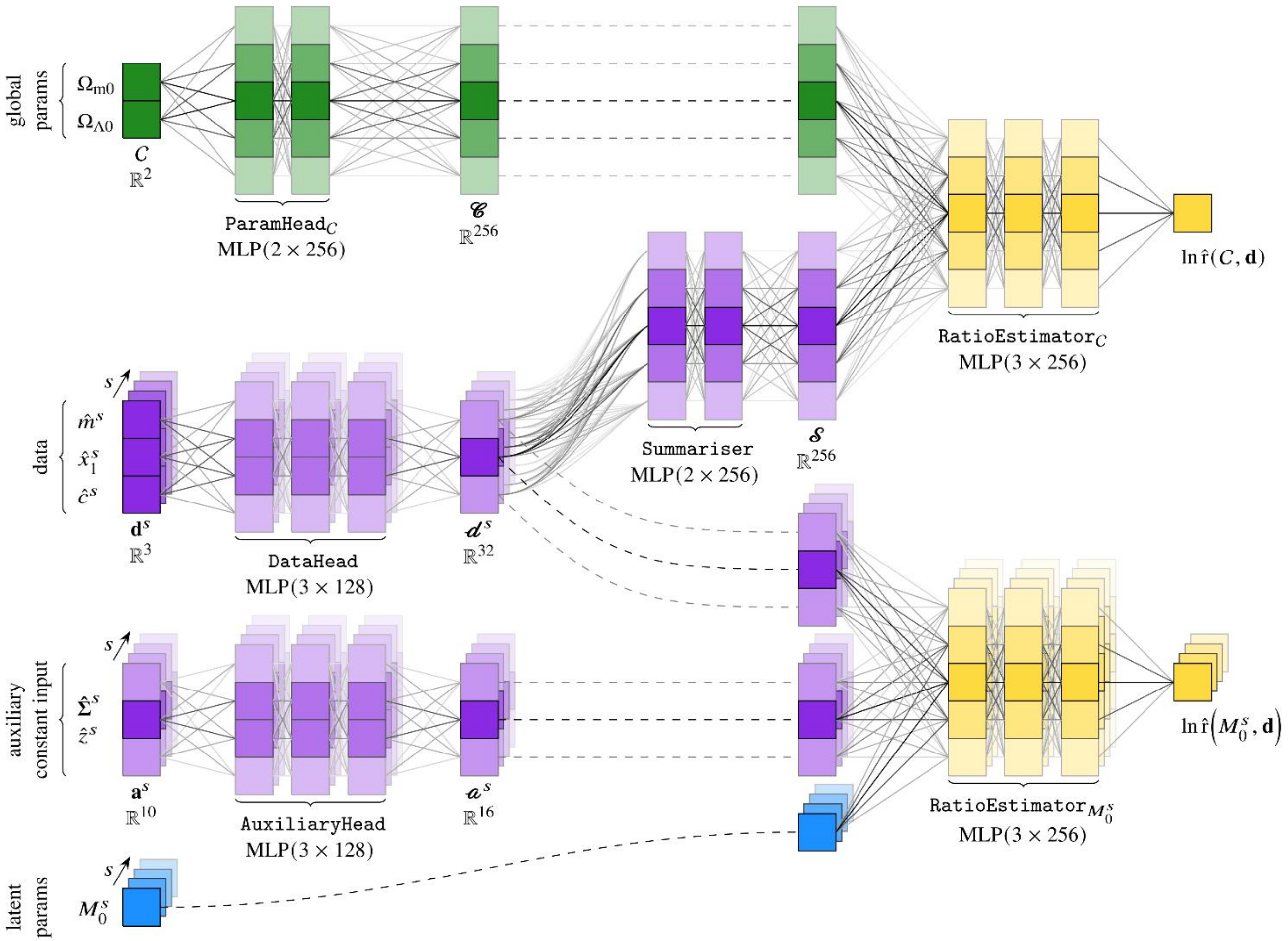
# Ratio Estimation: Bayes theorem

$$\frac{p(\theta|d)}{p(\theta)} = \frac{p(\theta,d)}{p(\theta)p(d)} \equiv r(\theta,d)$$




Hermans, Begy & Louppe 2019
Miller et al. 2021 → truncated

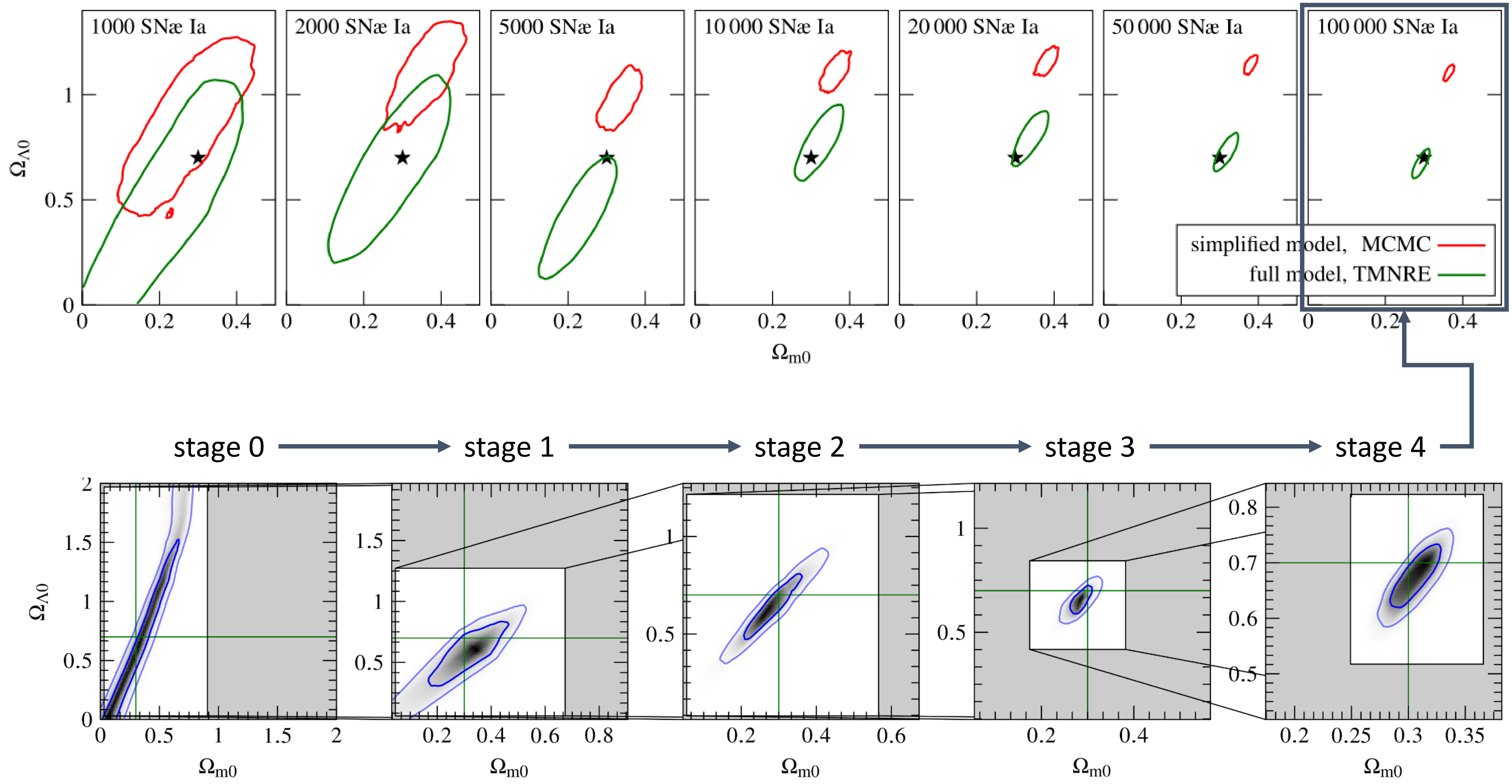
# Marginal Neural Ratio Estimation




data ($10^5$ SNæ Ia)

cosmology

$\mathcal{O}(10^5)$ SN latent parameters



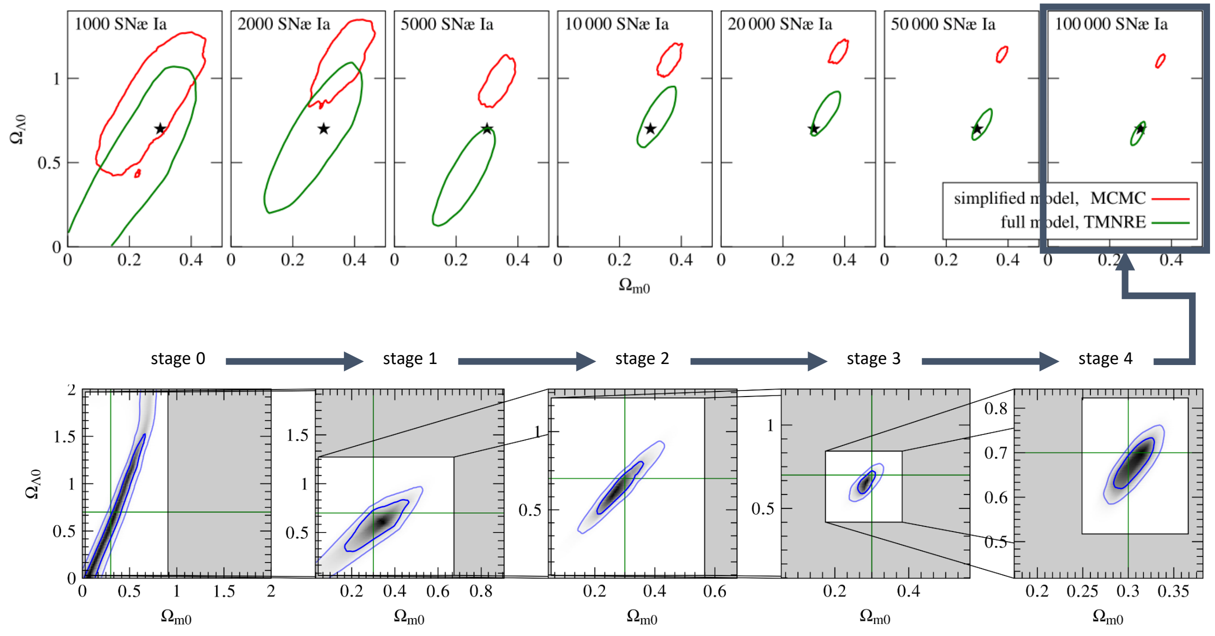

train (∼2 h)

truncate global params …

progressively home in on true values

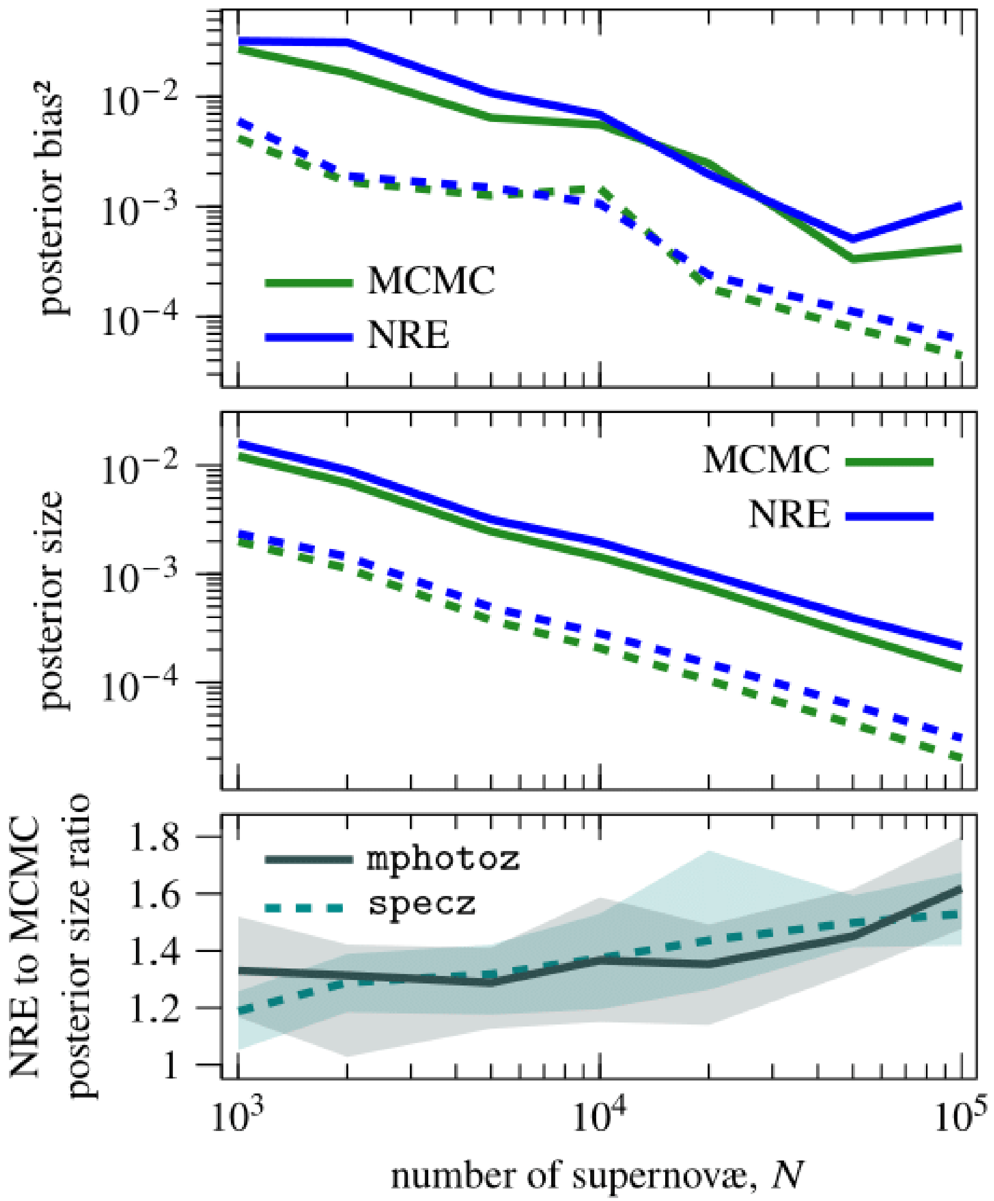
# Global inference

- scaling to $\mathcal{O}(10^5)$ observations




train (~2 h)
truncate global params
...

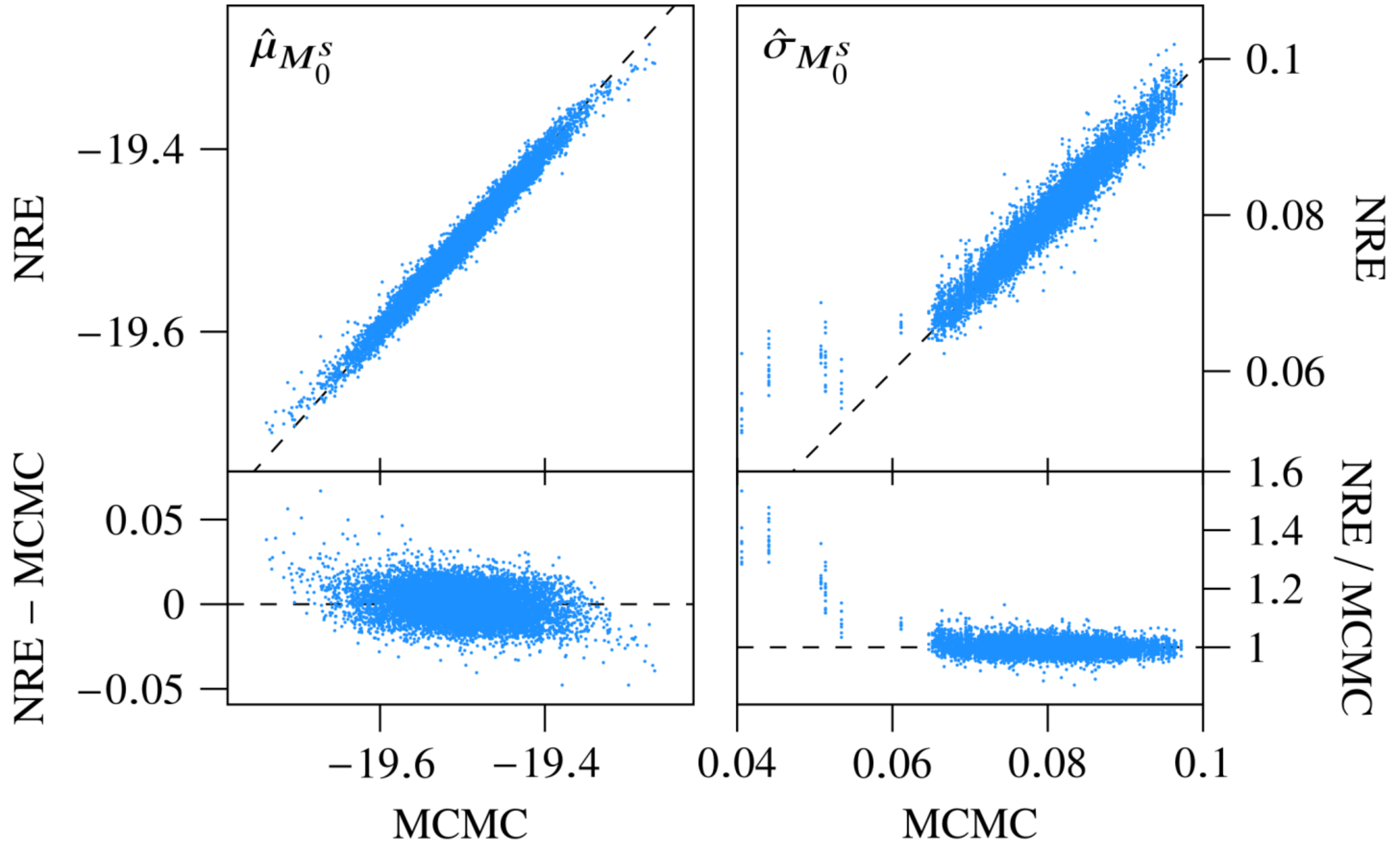
progressively home in
on true values



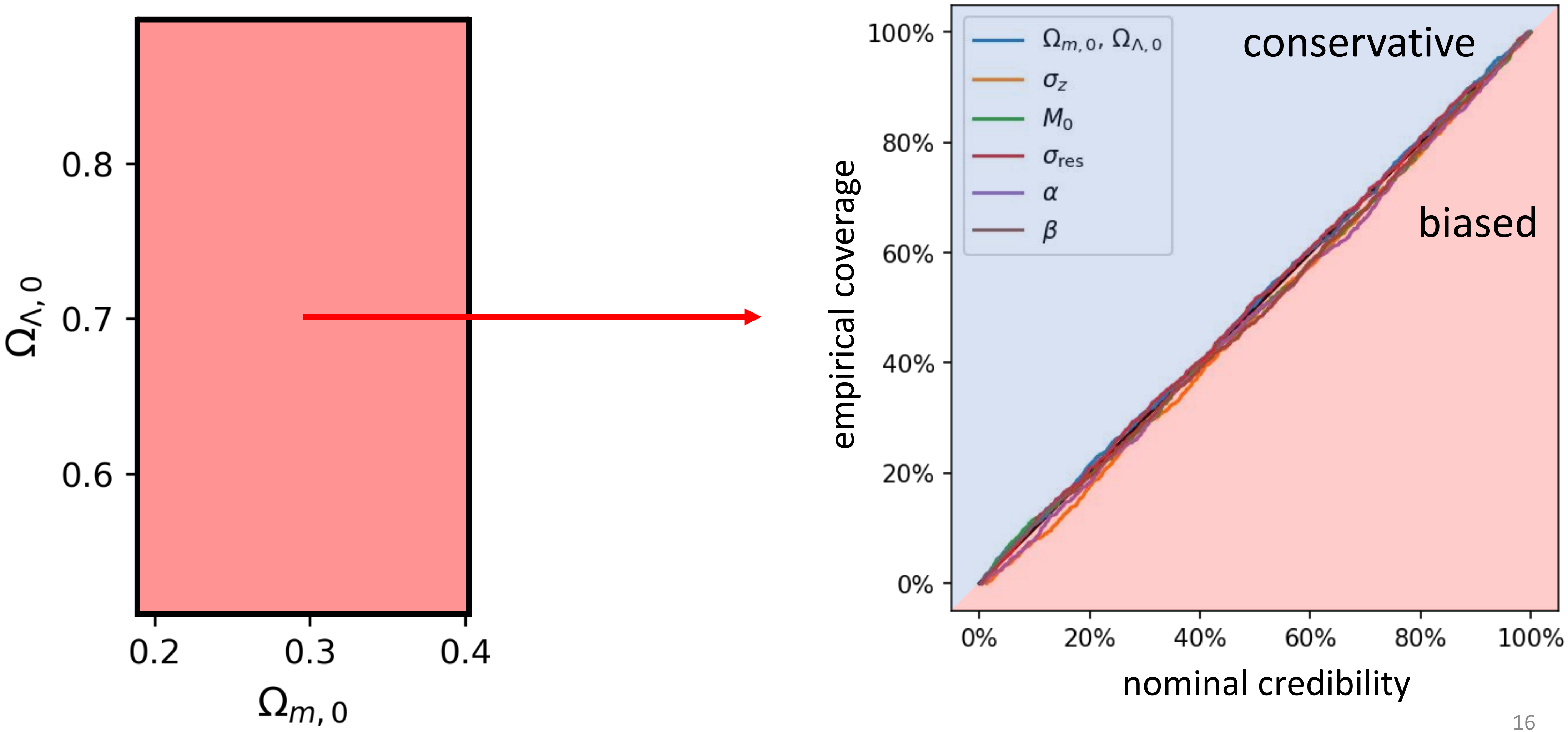
# Local variable inference

## MALFOI: MArginal Likelihood-Free Object-level Inference

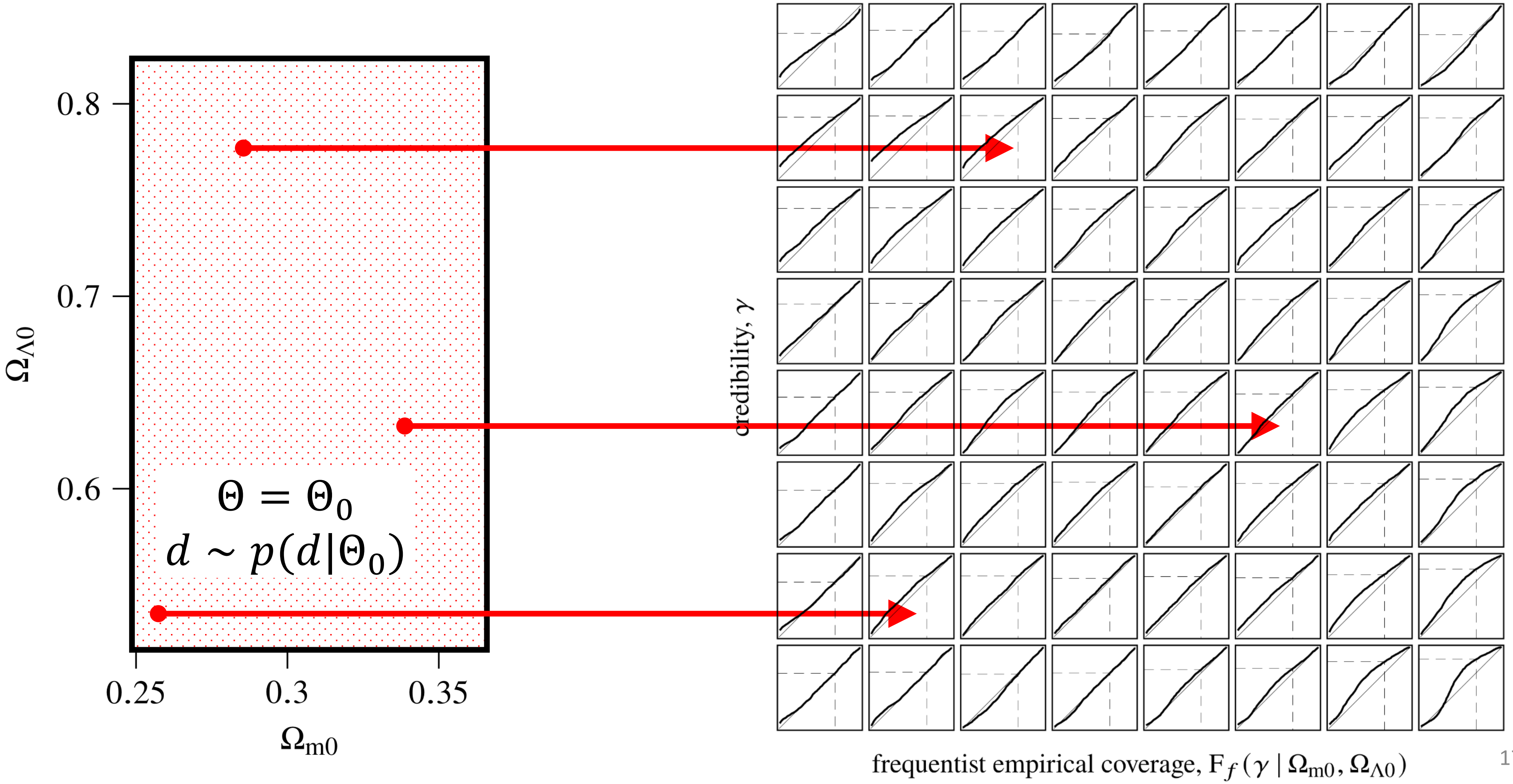
- $\mathcal{O}(10^5)$ marginal posteriors simultaneously



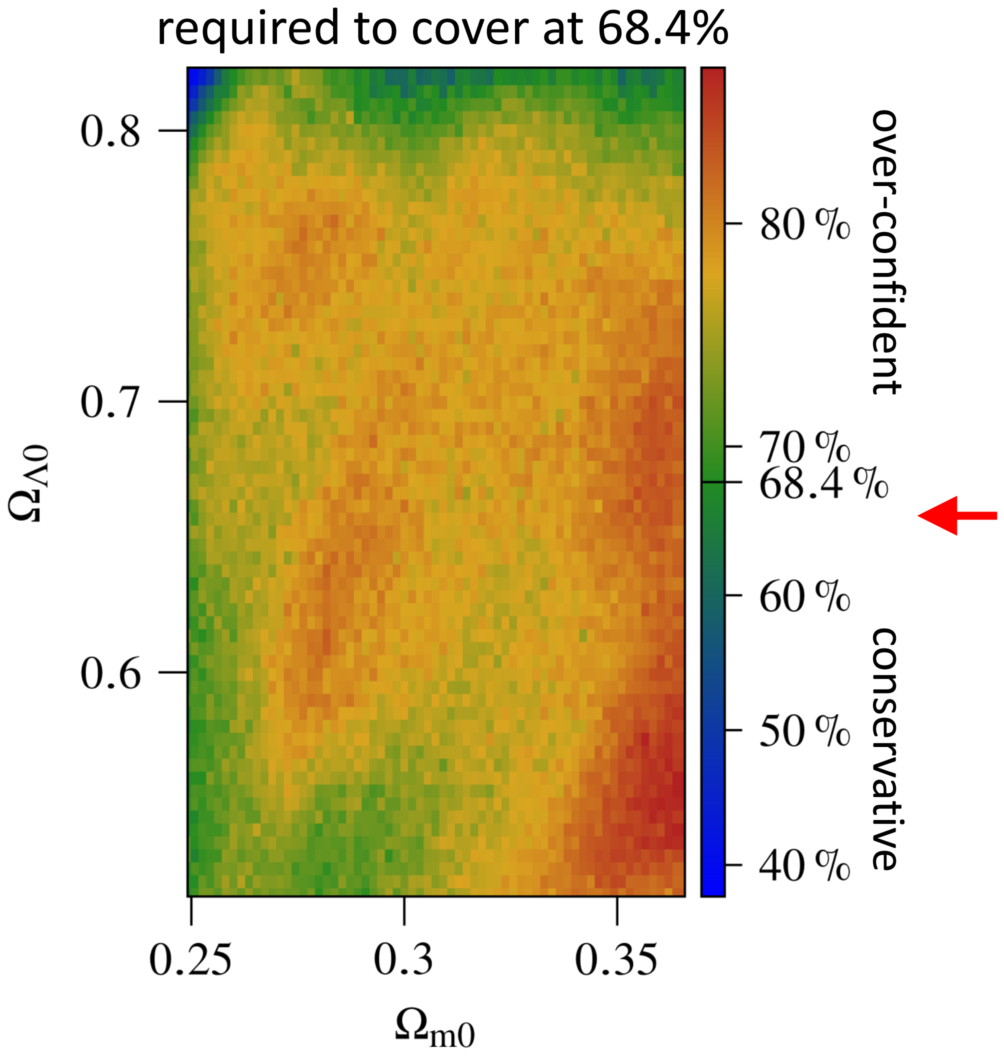
# Validation: Bayesian coverage

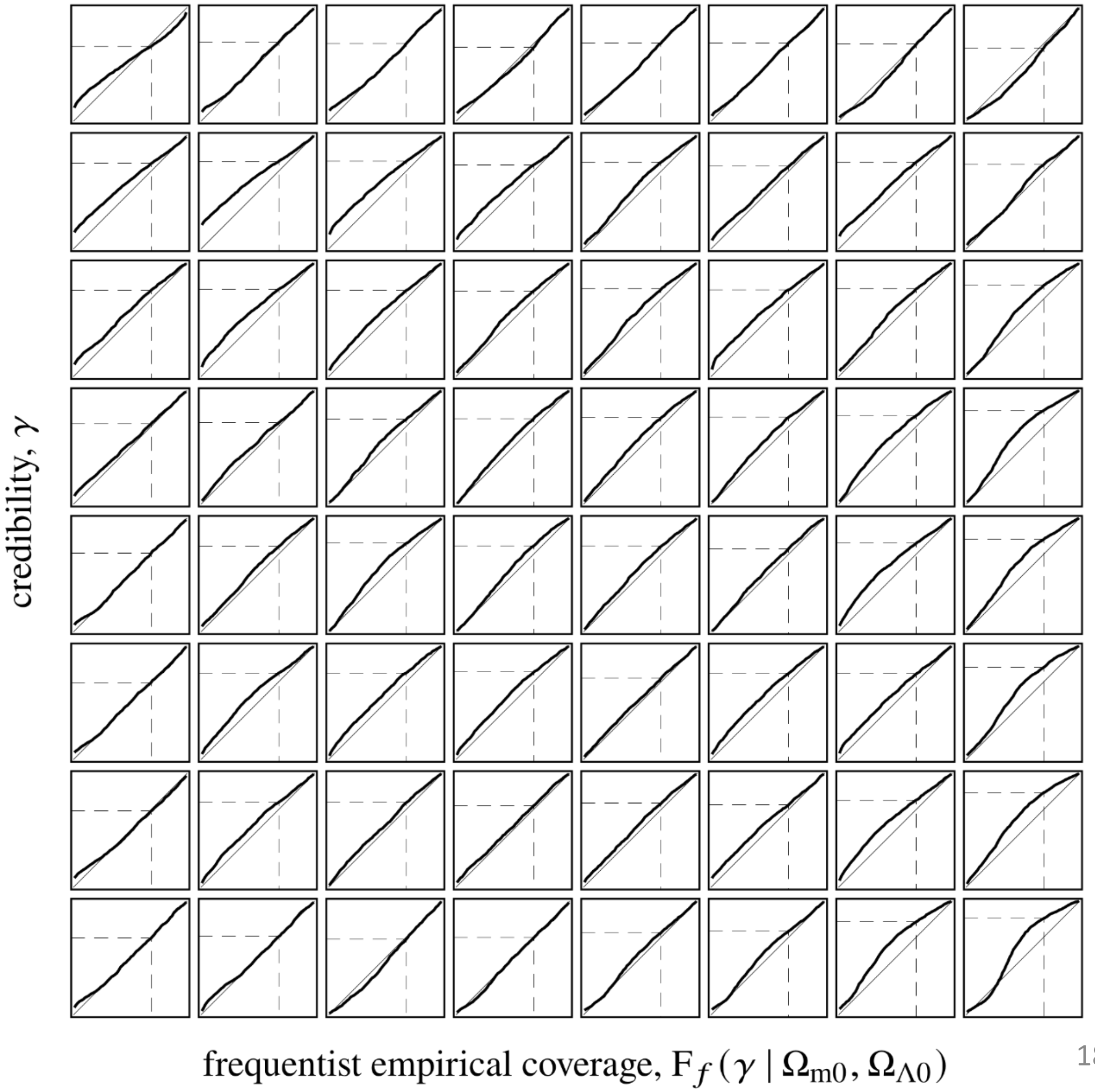


# Calibration: frequentist coverage

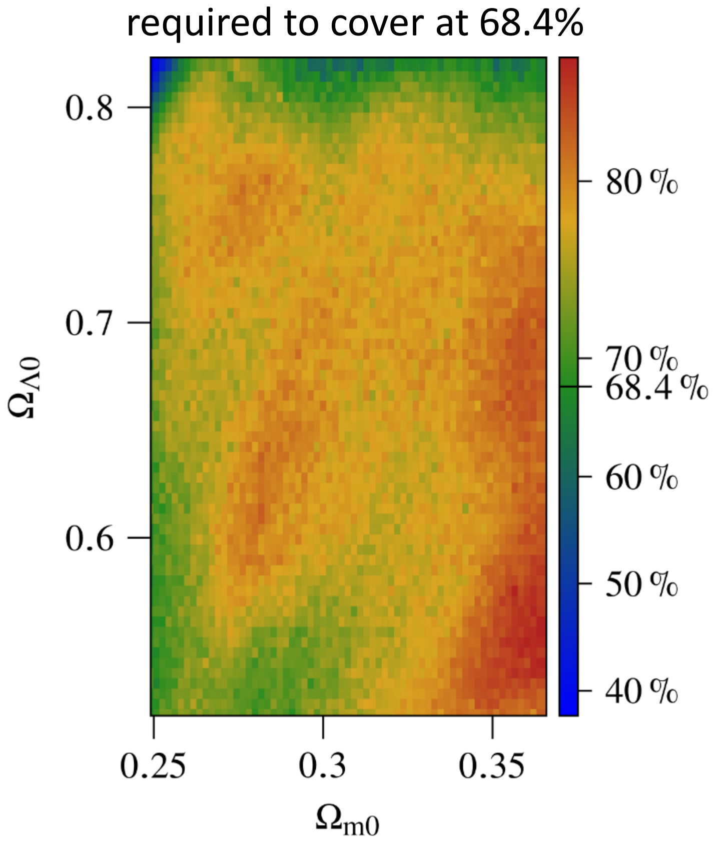


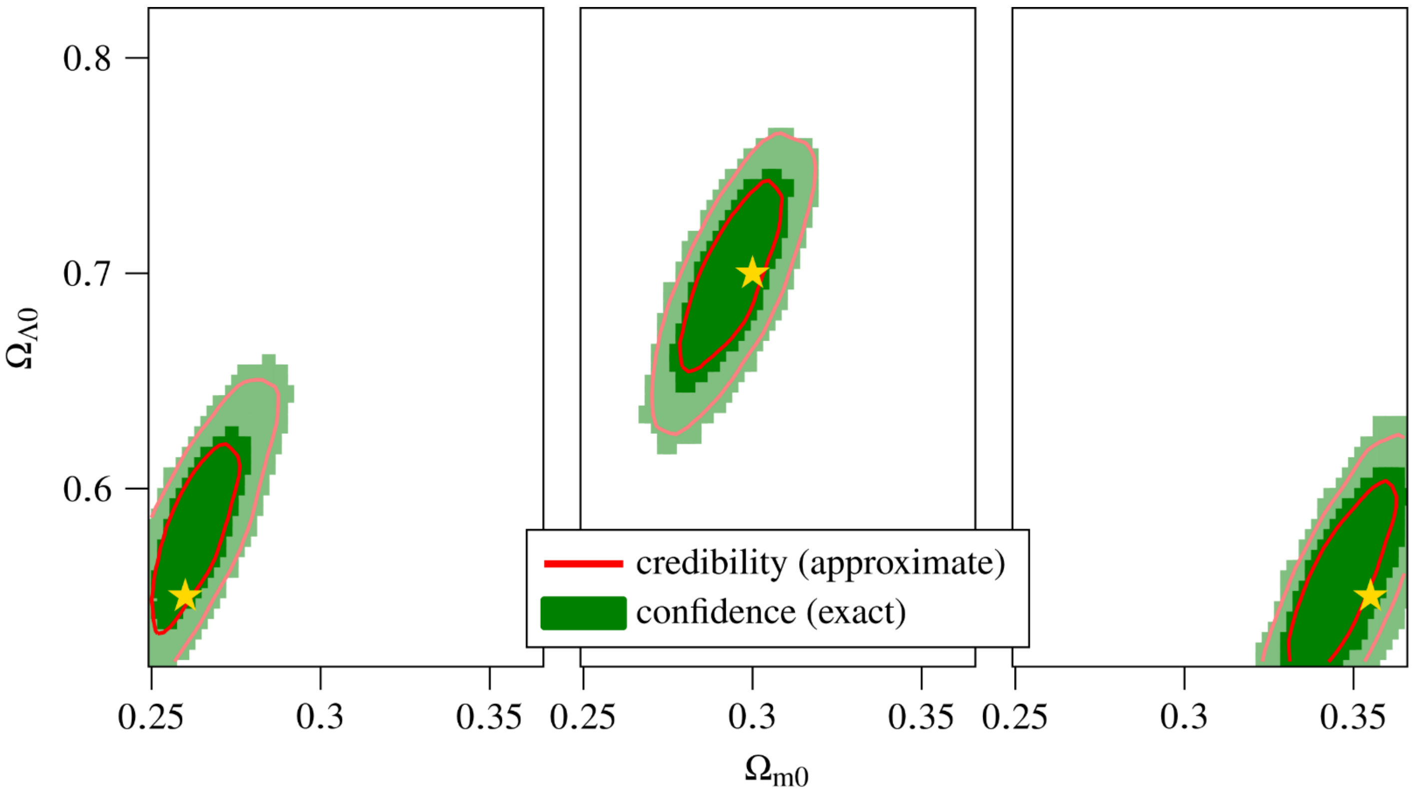
# Calibration: frequentist coverage

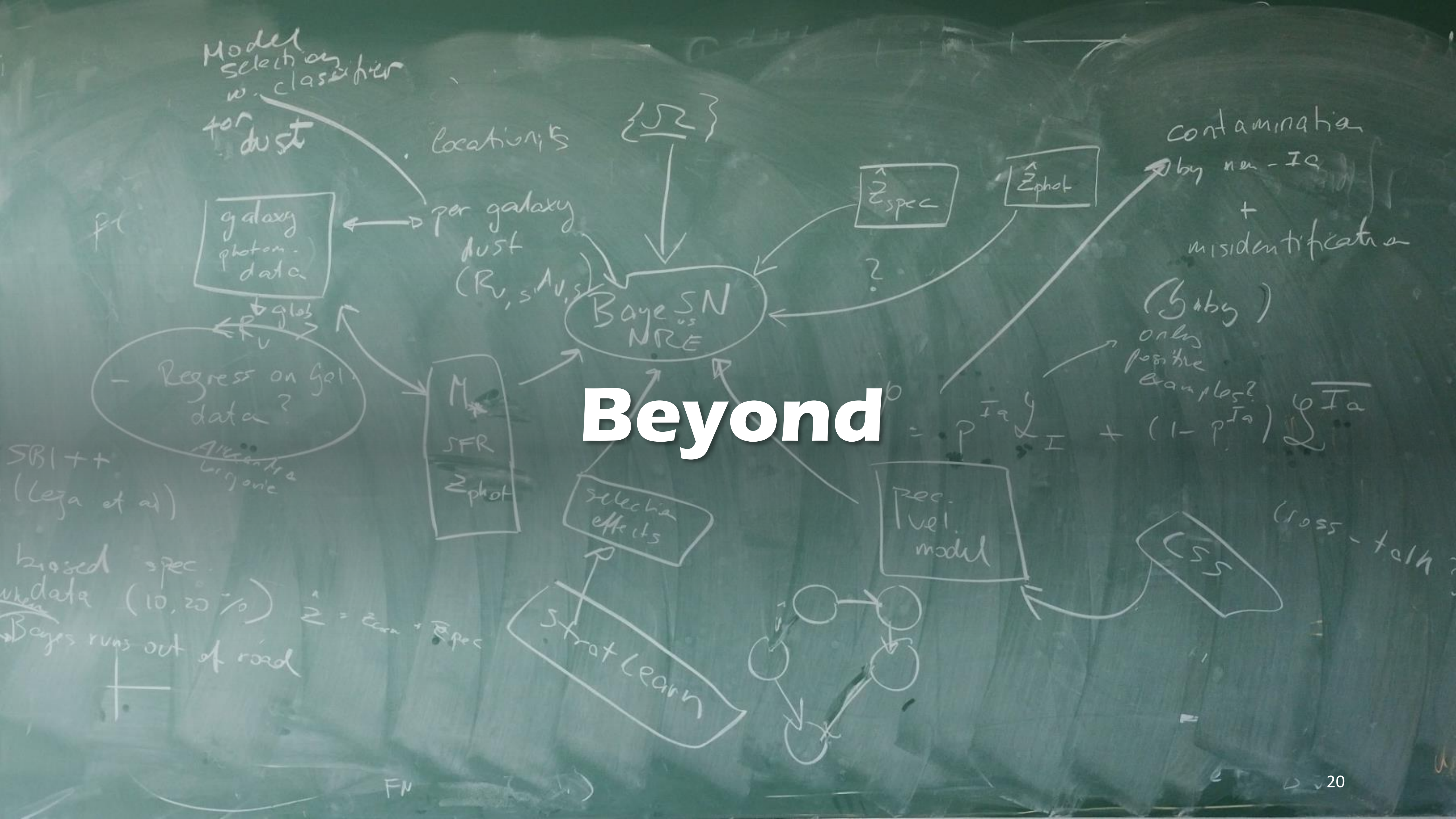


# Calibration: guaranteed coverage

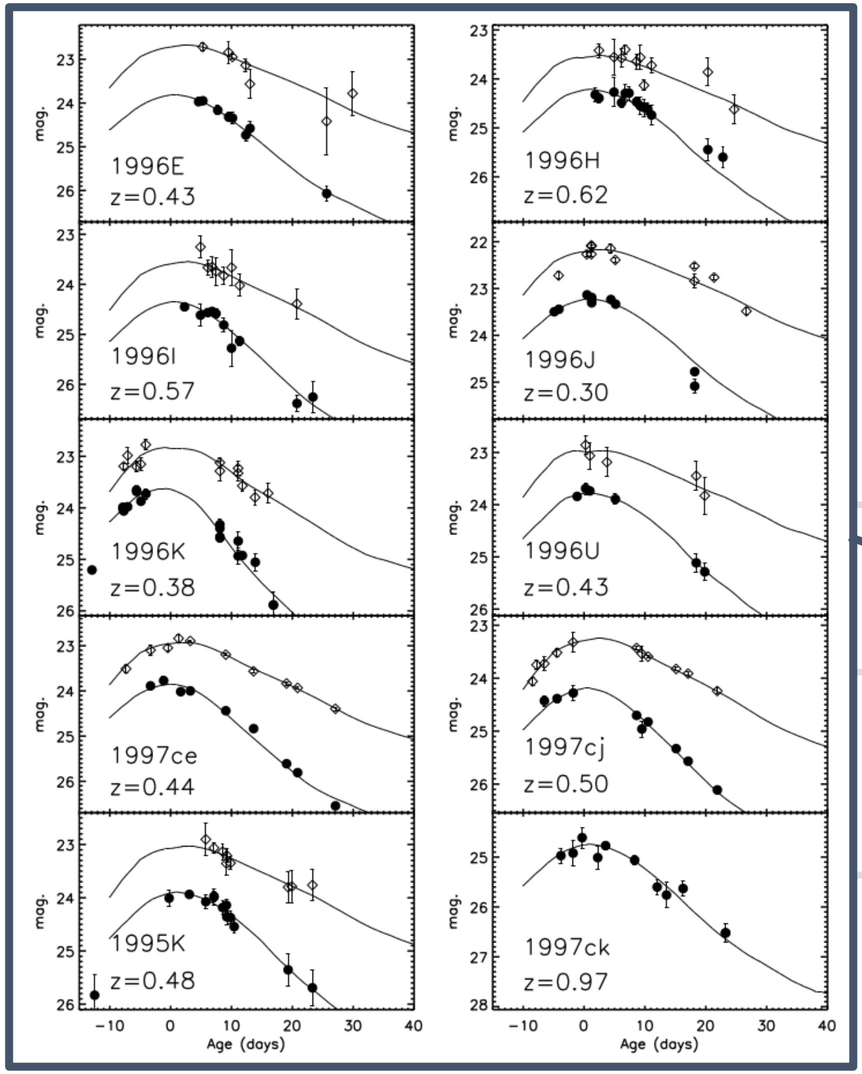



Model selection w. classifier for dust
locations
galaxy photom. data
per galaxy dust
$(R_{V,s}, A_{V,s})$
BayeSN vs NRE
$\hat{z}_{spec}$
$\hat{z}_{phot}$
contamination by non-Ia
+
misidentification
only positive examples?
Regress on gal. data?
SBI++
(Leja et al)
SFR
$z_{phot}$
selection effects
Strat Learn
pec. vel. model
CSS
cross-talk
biased spec. data (10, 20 %)
Bayes runs out of road

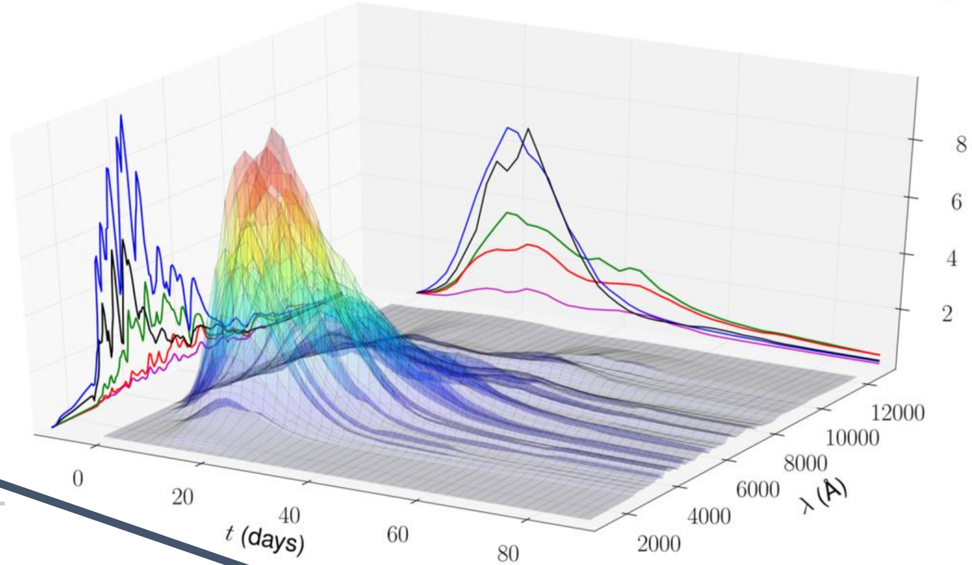
# Beyond

# Where SBI shines: realism




- lightcurve model (+ dust, host):

(pre-trained) BayeSN ([Mandel et al.](#))




~~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

$m^s$ +

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"

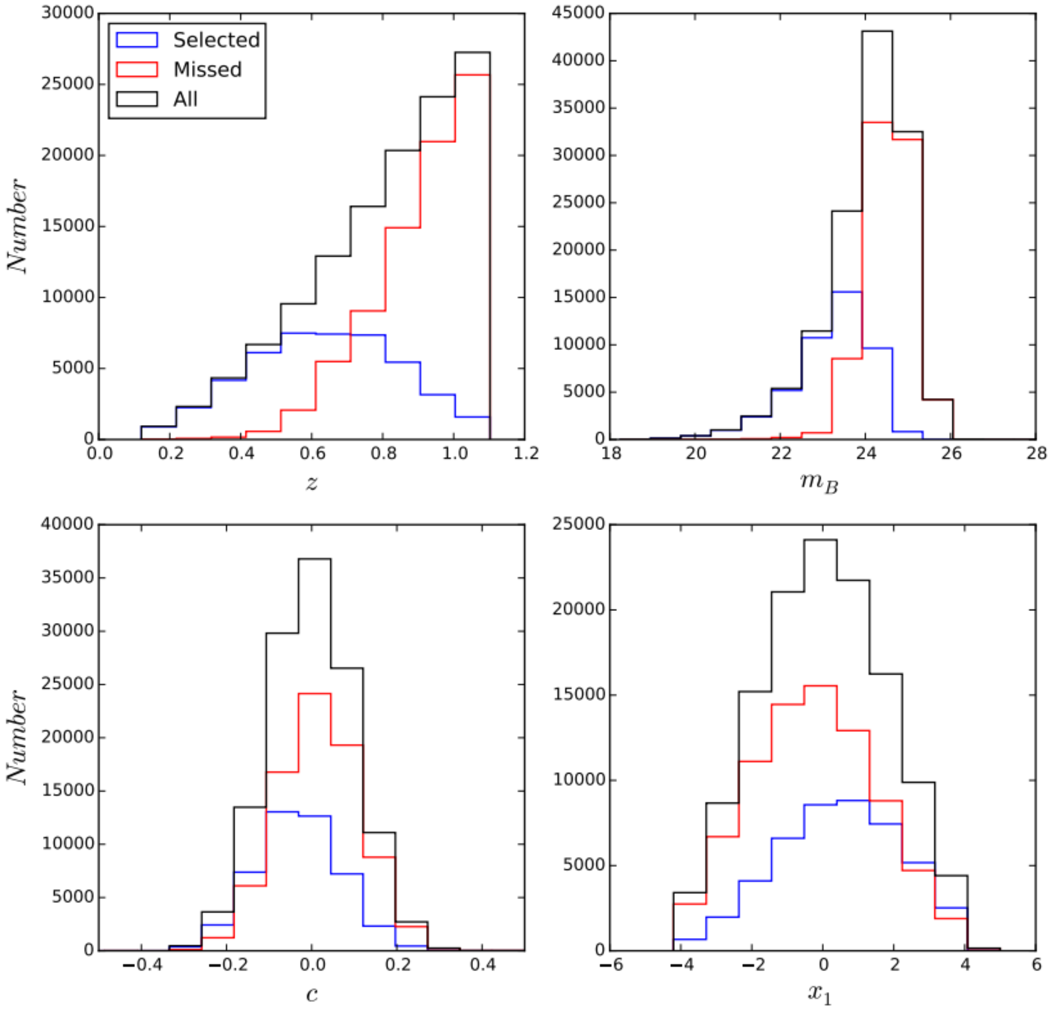
$m^s \pm \sigma_m^s$ brightness

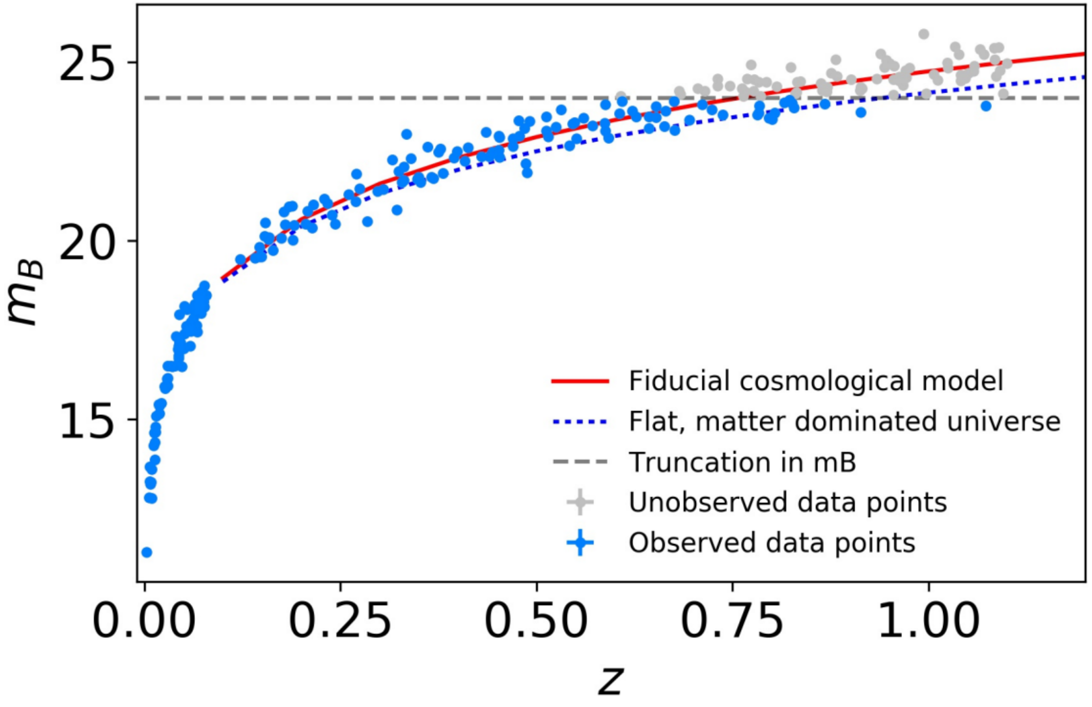
$m^s + \alpha x_1^s - \beta c^s = M_0^s + \mu(z^s, \mathcal{C}) +$ ~~"noise"~~

population priors

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

# Where SBI shines: selection effects




March et al. 1999

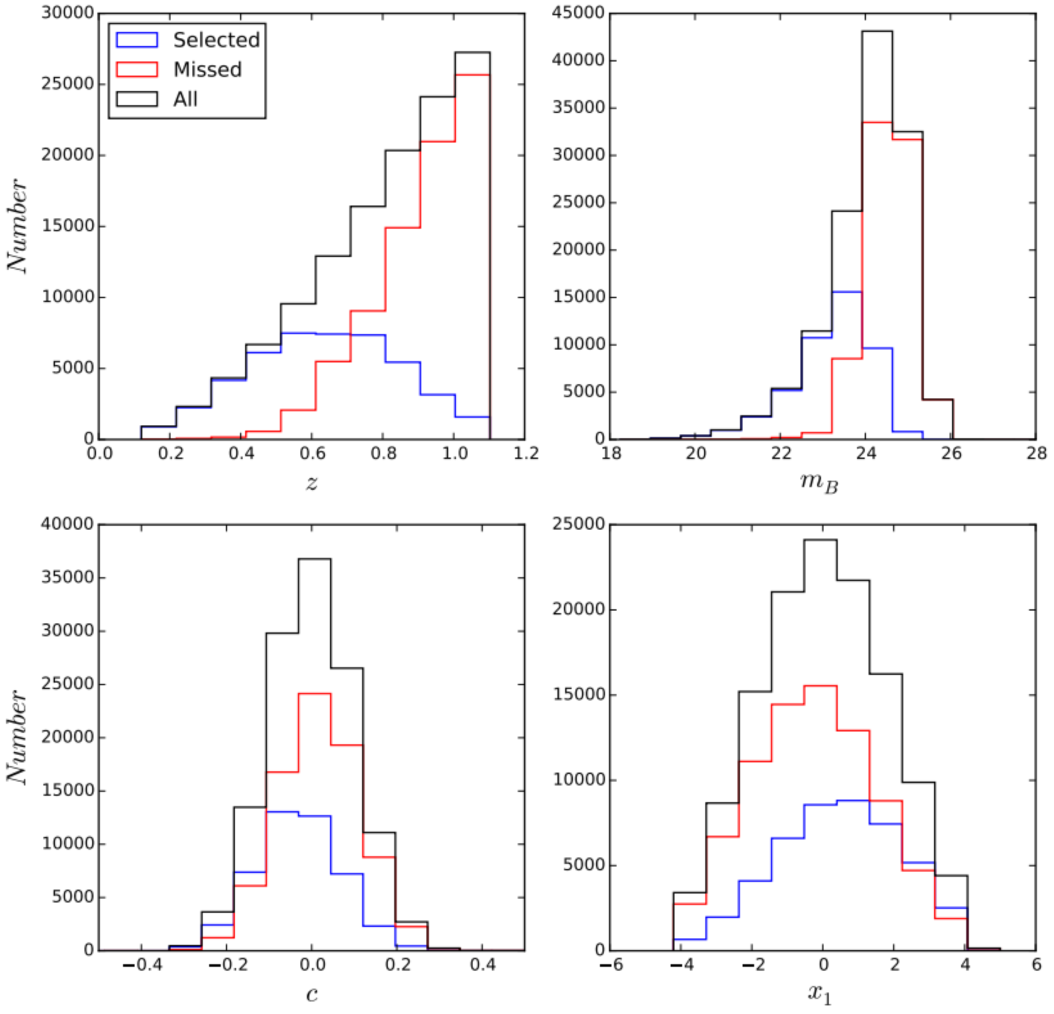
$$m^s + \alpha x_1^s - \beta c^s = M_0^s + \mu(z^s, \mathcal{C}) + \text{"noise"}$$

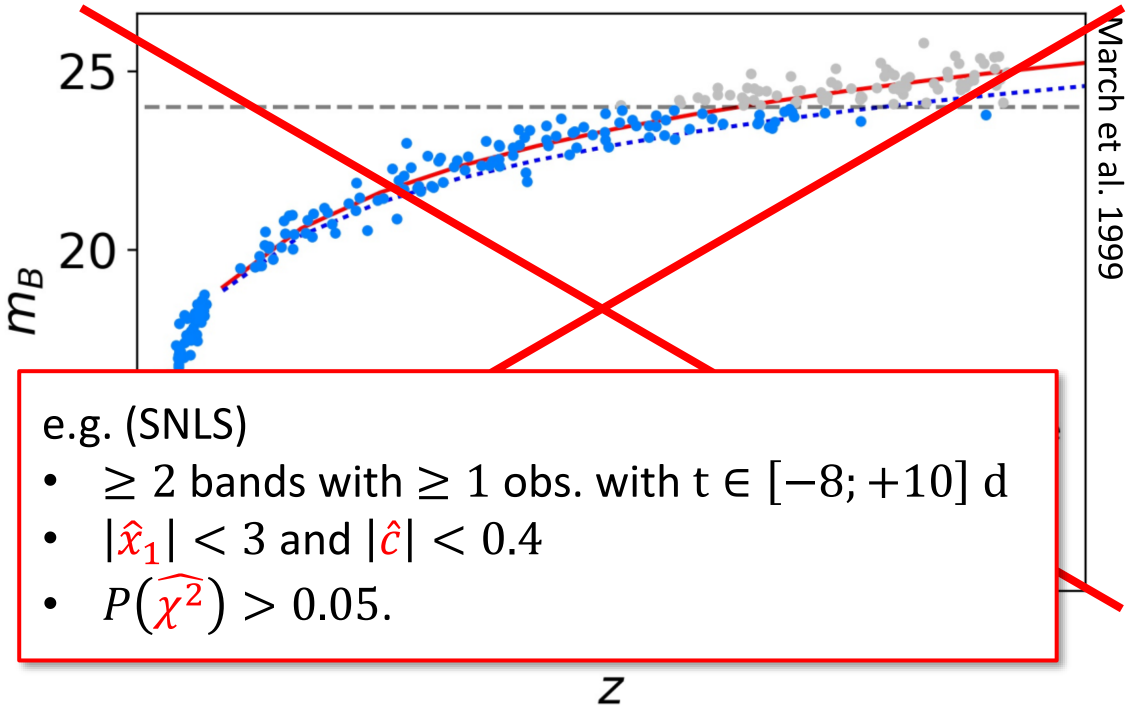
population priors
given SN is observed

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

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

# Where SBI shines: realistic ^ selection effects




e.g. (SNLS)

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

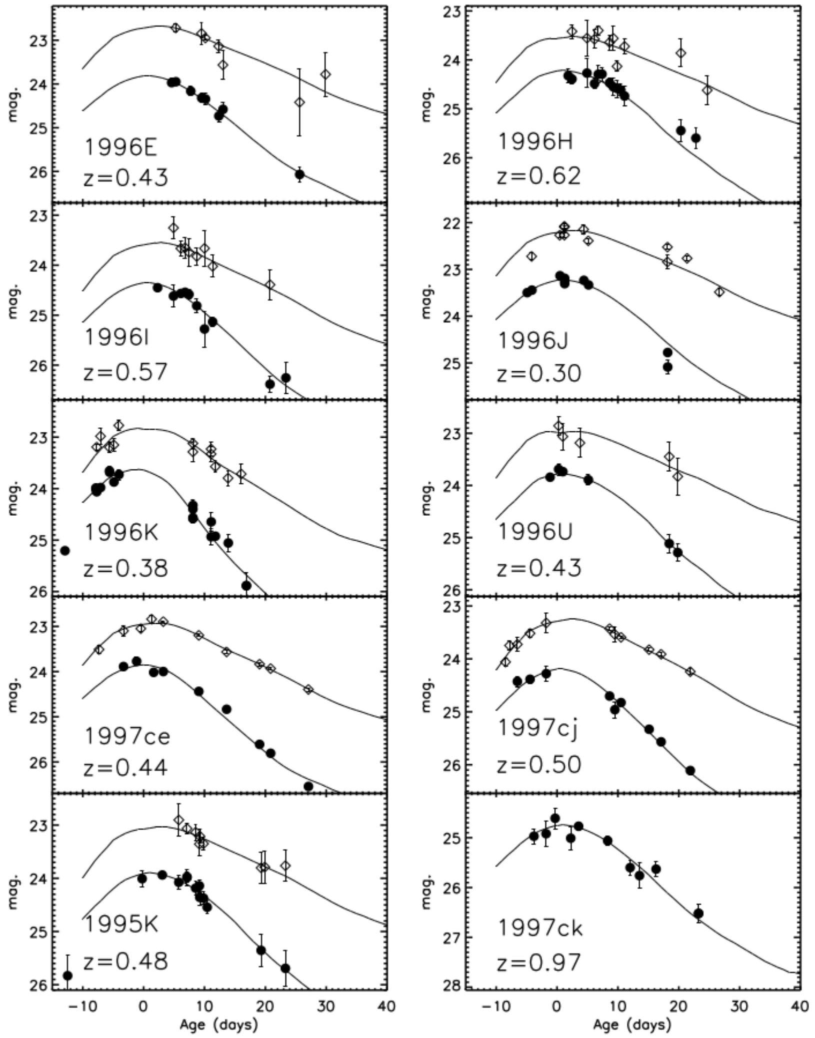
$$m^s + \alpha x_1^s - \beta c^s = M_0^s + \mu(z^s, \mathcal{C}) + \text{"noise"}$$

population priors given SN is observed

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

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

# SN Ia cosmology: a set dataset




$$\{\boldsymbol{d}^1, \boldsymbol{d}^2, \ldots\} \rightarrow \boldsymbol{S}^1 = \rho_{\mathrm{NN}}^{\mathrm{obs}}\left[\sum_{i \in \mathrm{SN}^1} \phi_{\mathrm{NN}}^{\mathrm{obs}}(\boldsymbol{d}^i)\right]$$

$$\{\boldsymbol{d}^{25}, \boldsymbol{d}^{26}, \ldots\} \rightarrow \boldsymbol{S}^2 = \rho_{\mathrm{NN}}^{\mathrm{obs}}\left[\sum_{i \in \mathrm{SN}^2} \phi_{\mathrm{NN}}^{\mathrm{obs}}(\boldsymbol{d}^i)\right]$$

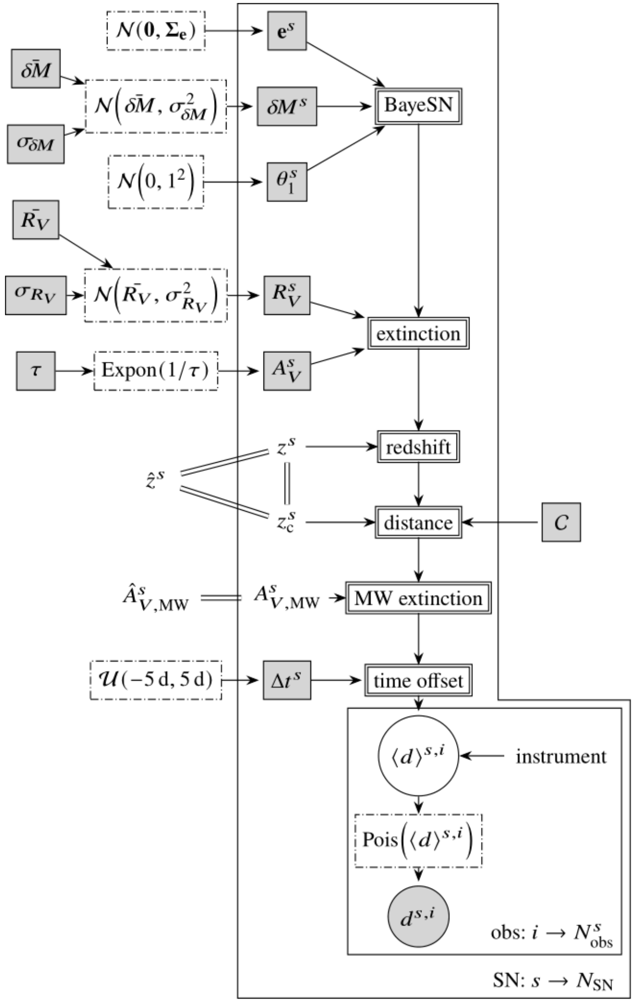
$$\{\boldsymbol{d}^{42}, \boldsymbol{d}^{43}, \ldots\} \rightarrow \boldsymbol{S}^3 = \rho_{\mathrm{NN}}^{\mathrm{obs}}\left[\sum_{i \in \mathrm{SN}^3} \phi_{\mathrm{NN}}^{\mathrm{obs}}(\boldsymbol{d}^i)\right]$$

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

"Deep Sets" (1703.06114)

# State of affairs

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

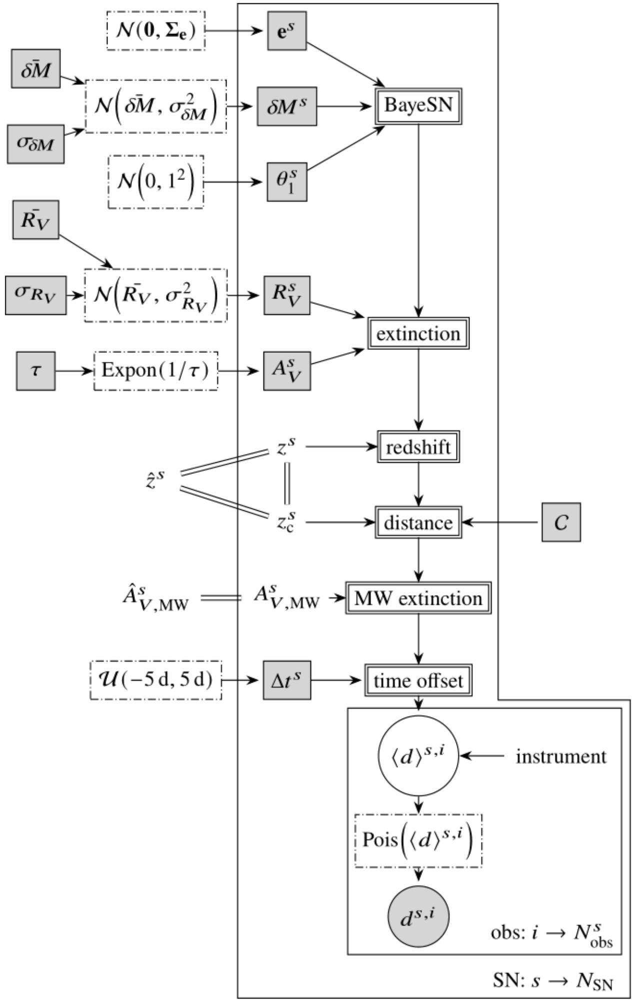


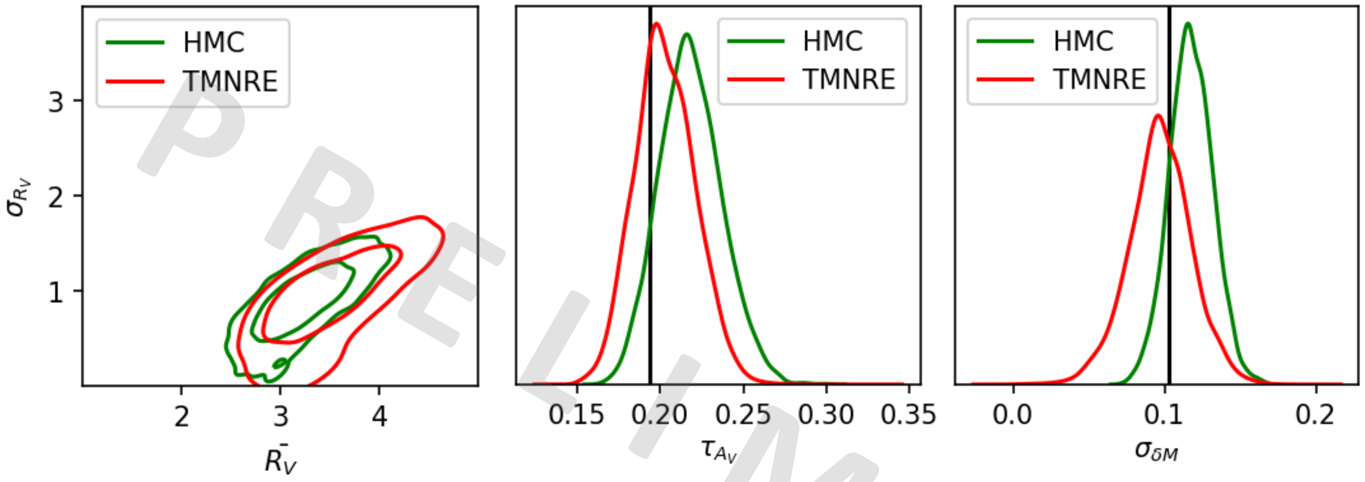

- BayeSN
  - pre-trained lightcurve model (for now?)
  - host & MW extinction
- "calibrated fluxes" (for now) vs. raw counts
- fixed redshifts and distances (for now)
- CSPDR3 (for now), Pantheon+
  - $\sim 100 - 200$ low-redshift SNæ Ia with spec-$z$
  - $\sim 10000$ observations (data vector)

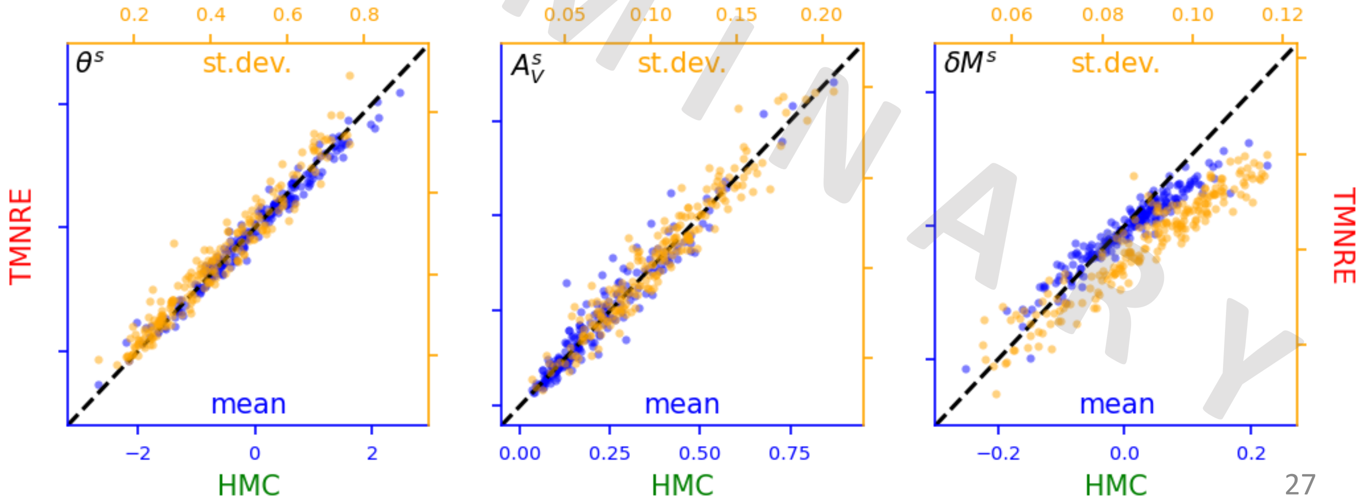
➢ tackle real data, assuming completeness

# State of affairs

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

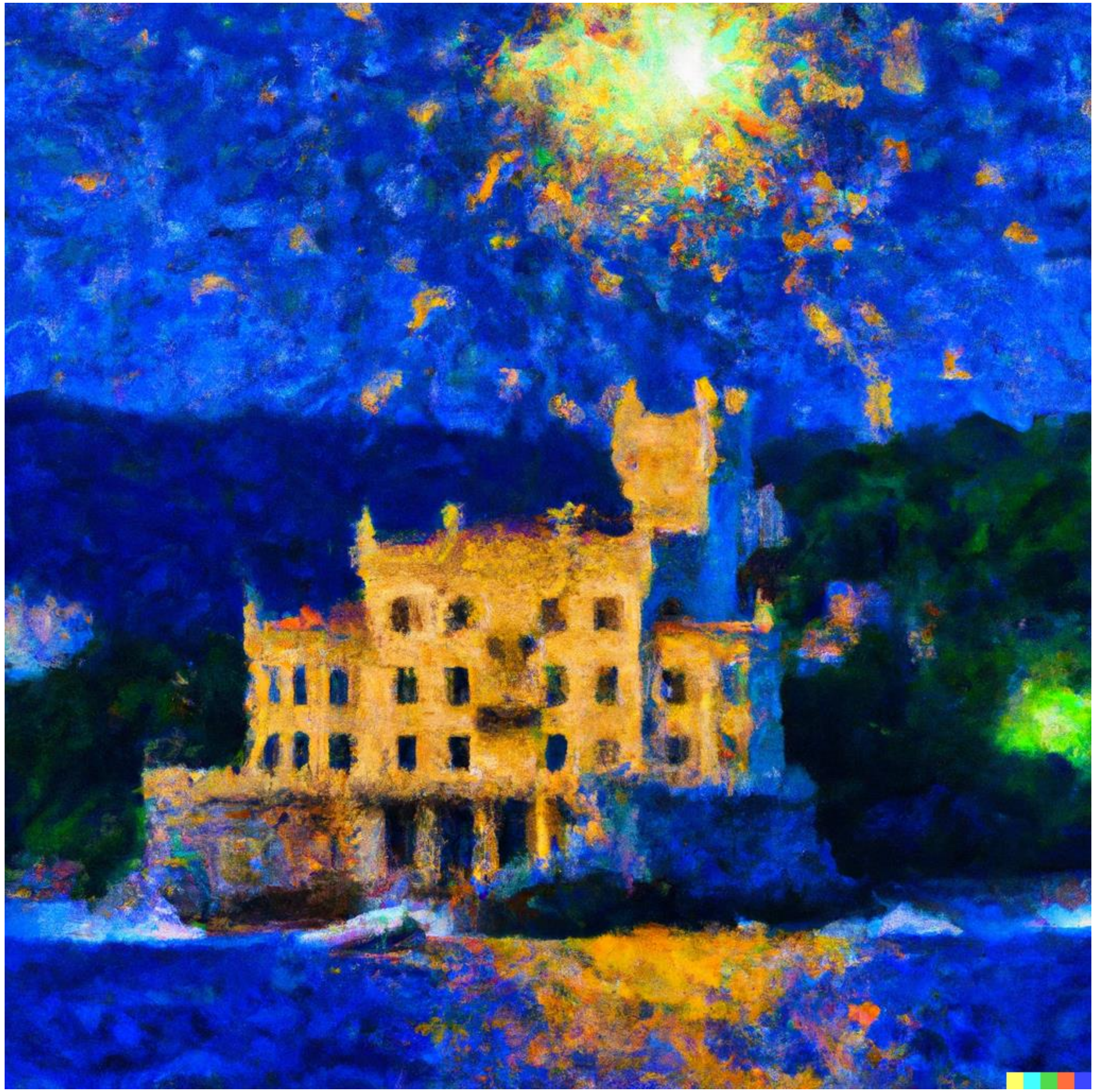



HMC by
Matt Grayling
using `numpyro`

HMC: ~ 1 h
NRE: ~ 2 h / stage
(not optimised)



# Thank you for your attention!

"A supernova explosion
over the Miramare castle;
painting in the style of Van Gogh"

image by DALL·E