SNe Ia growth-rate measurements with Rubin-LSST simulations: intrinsic scatter systematics

B. Carreres, R. Chen, E. Peterson, D. Scolnic, C. Ravoux, D. Rosselli, M. Acevedo, J. E. Bautista, D. Fouchez, L. Galbany, B. Racine and The LSST Dark Energy Science Collaboration

arXiv 2505.13290

Duke Cosmology

LSST DESC Dark Energy Science Collaboration

$f\sigma_8$ as a probe for general relativity

Cosmological principle:
Universe is homogeneous

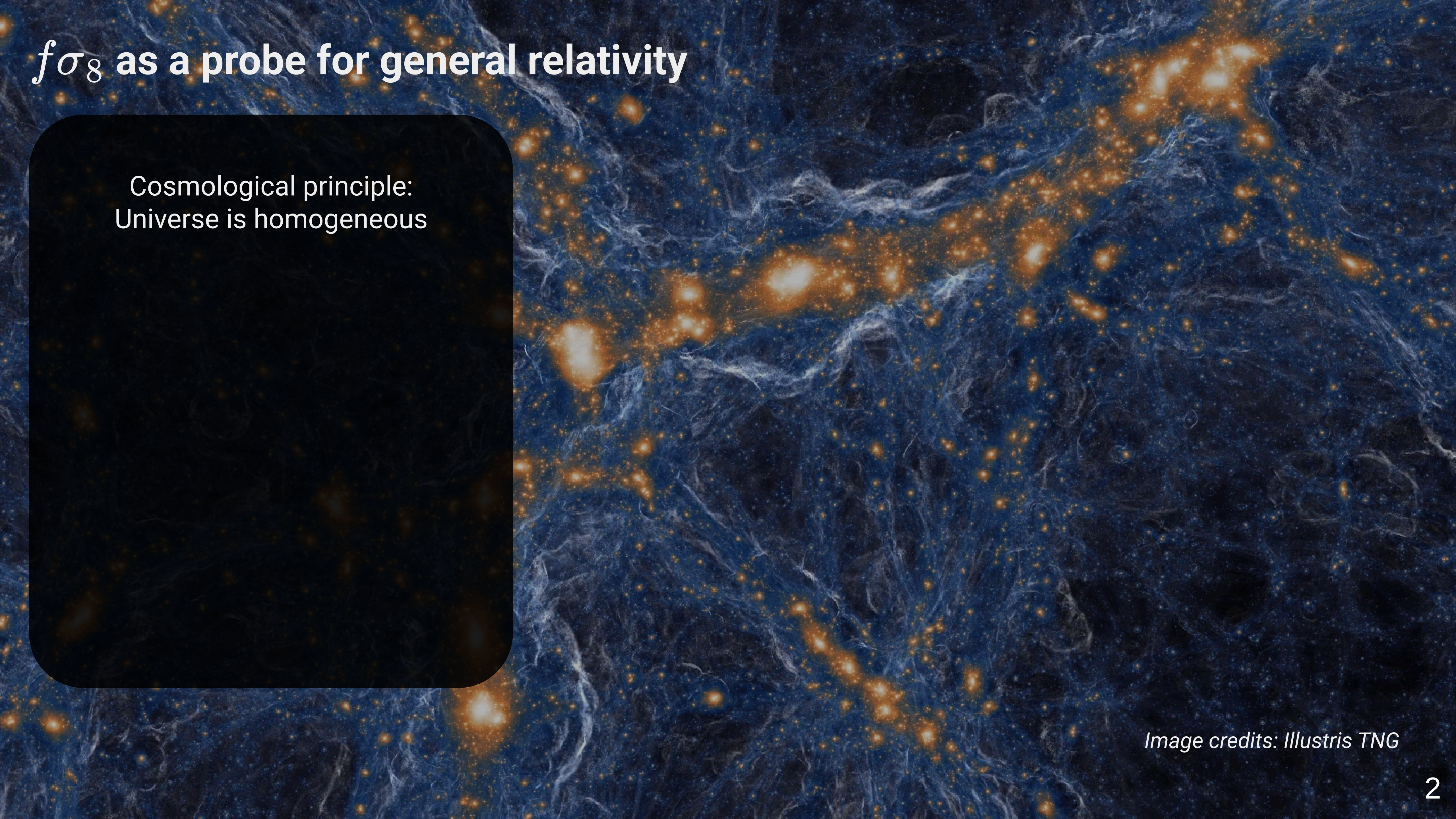

Image credits: Illustris TNG

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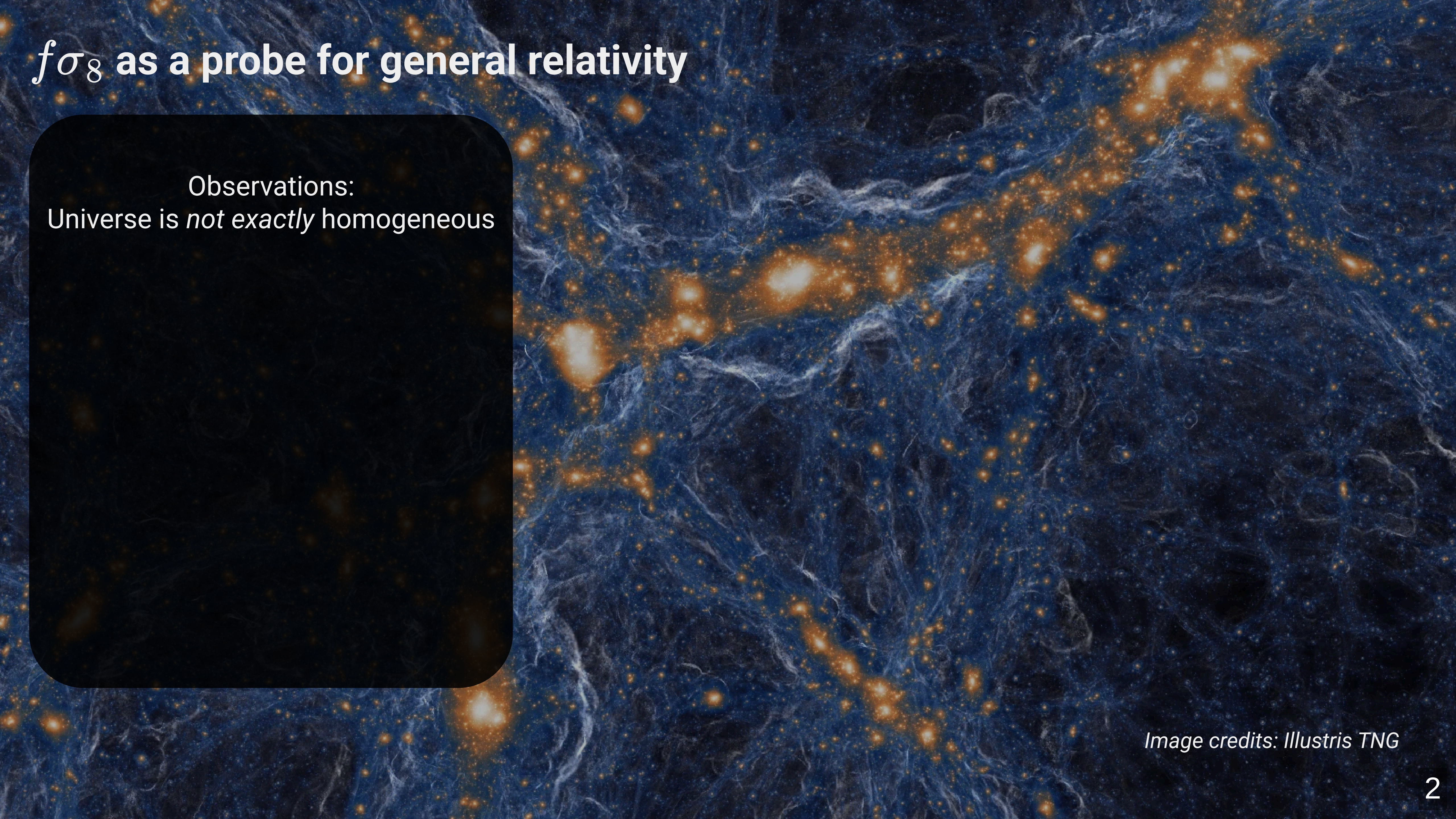

Observations:
Universe is *not exactly* homogeneous

Image credits: Illustris TNG

$f\sigma_8$ as a probe for general relativity

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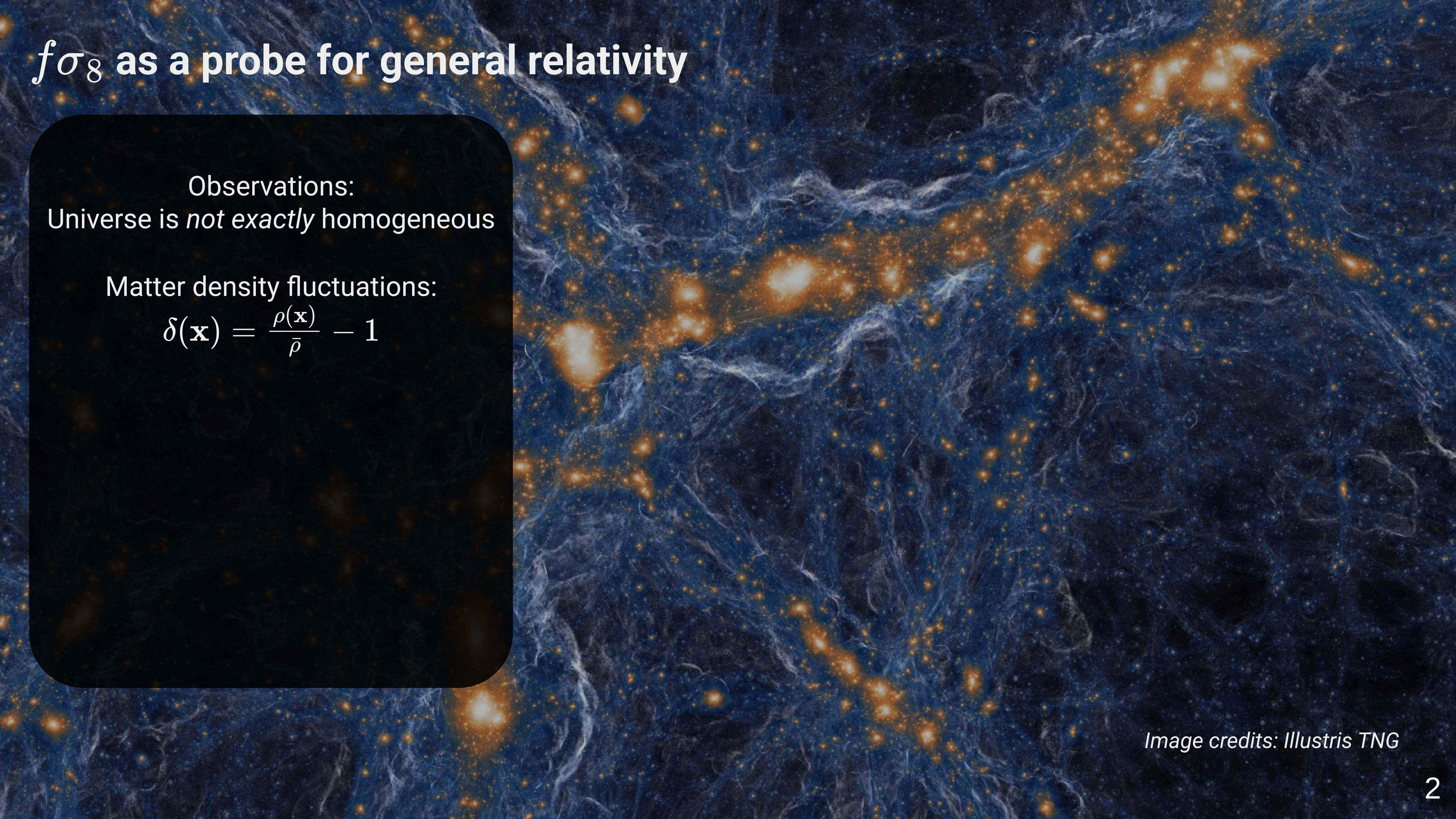
Matter density fluctuations:

$$\delta(\mathbf{x}) = \frac{\rho(\mathbf{x})}{\bar{\rho}} - 1$$



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σ_8 : fluctuation over sphere of
8 Mpc.h^{-1} radius

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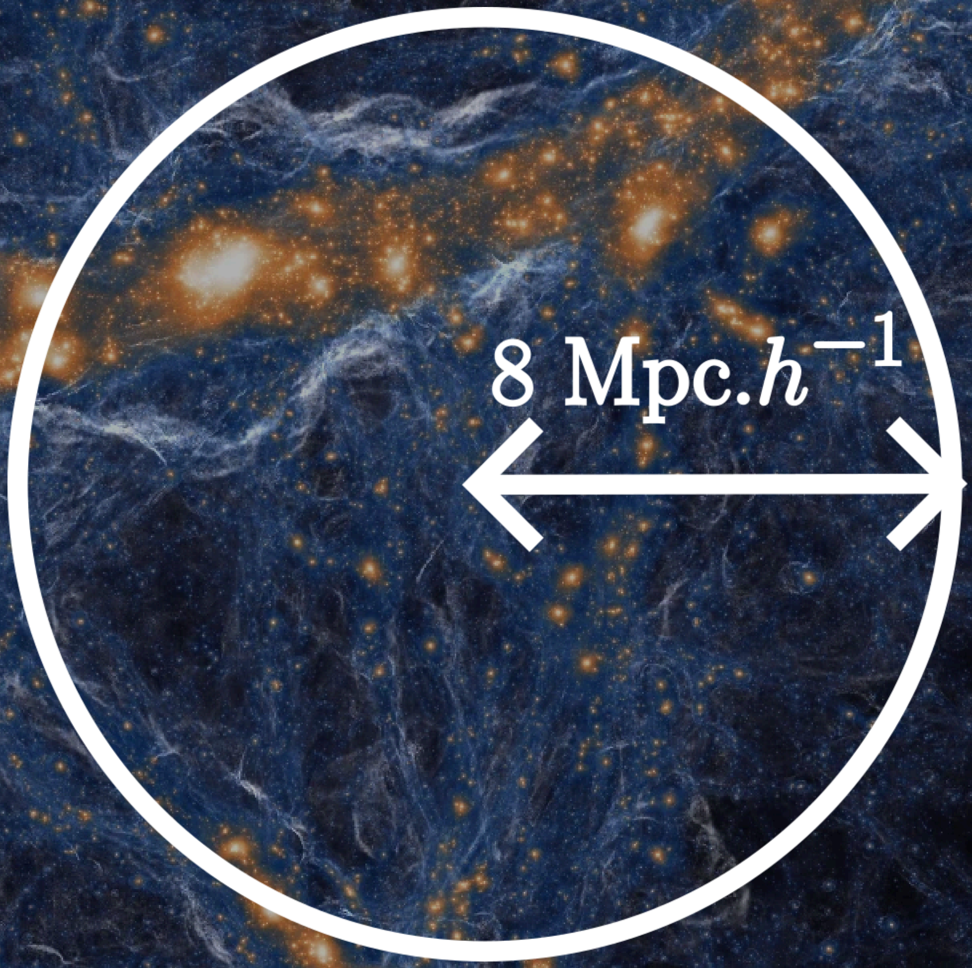

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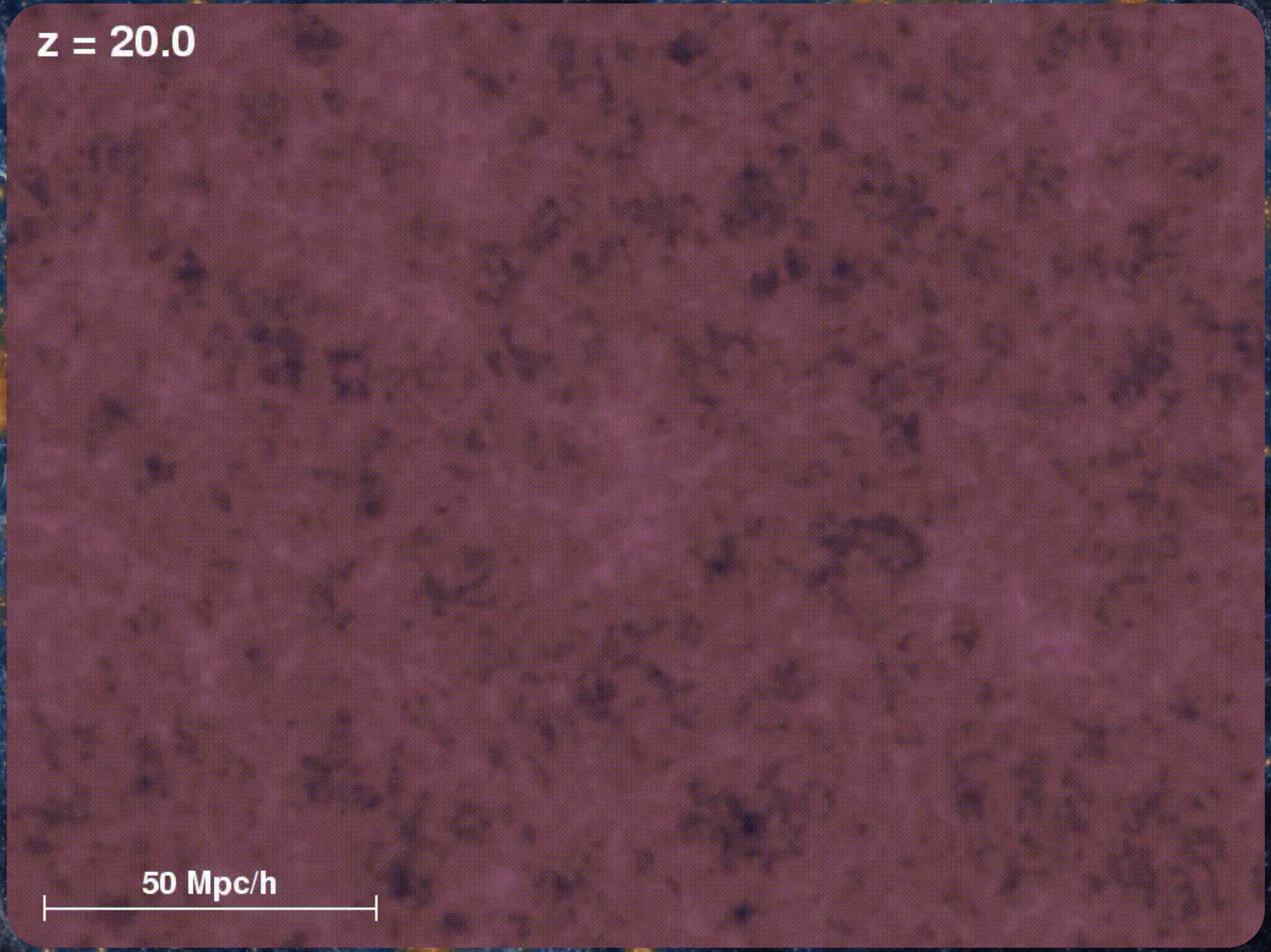
Fluctuations evolve over time

$$\delta(\mathbf{x}, t) = \delta(\mathbf{x}) D(t)$$



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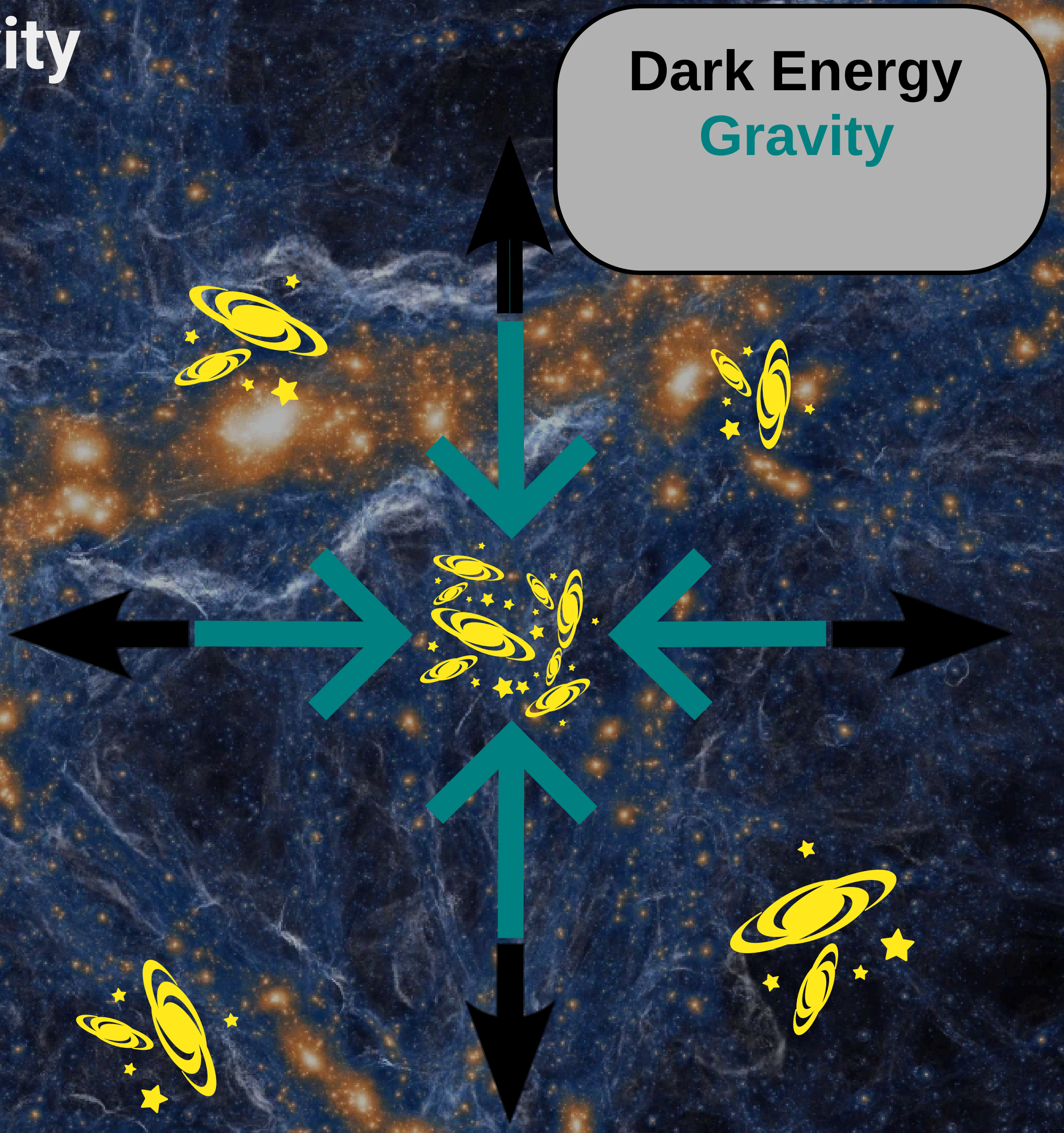
$f\sigma_8$ as a probe for general relativity

Evolution of structures:
Dark energy vs Gravity

$$f = \frac{\mathrm{d}\ln D}{\mathrm{d}\ln a}$$



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$f\sigma_8$ as a probe for general relativity

Evolution of structures:
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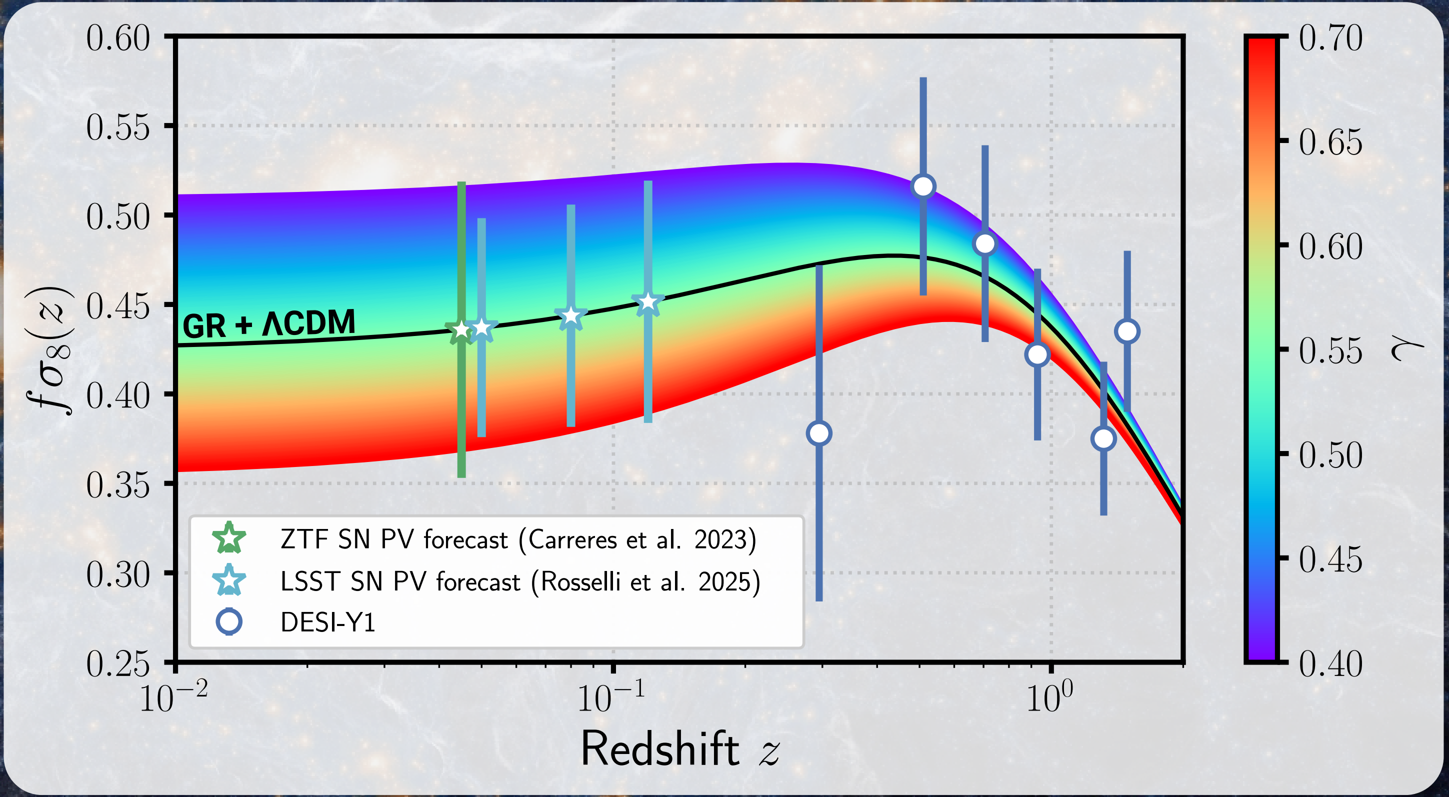
$$f = \frac{\mathrm{d}\ln D}{\mathrm{d}\ln a}$$

$$f \simeq \Omega_m^\gamma$$

General Relativity + ΛCDM: $\gamma \simeq 0.55$

$\gamma \equiv$ Growth index

f measurement is generally degenerate with σ_8 !
$\Rightarrow f\sigma_8$



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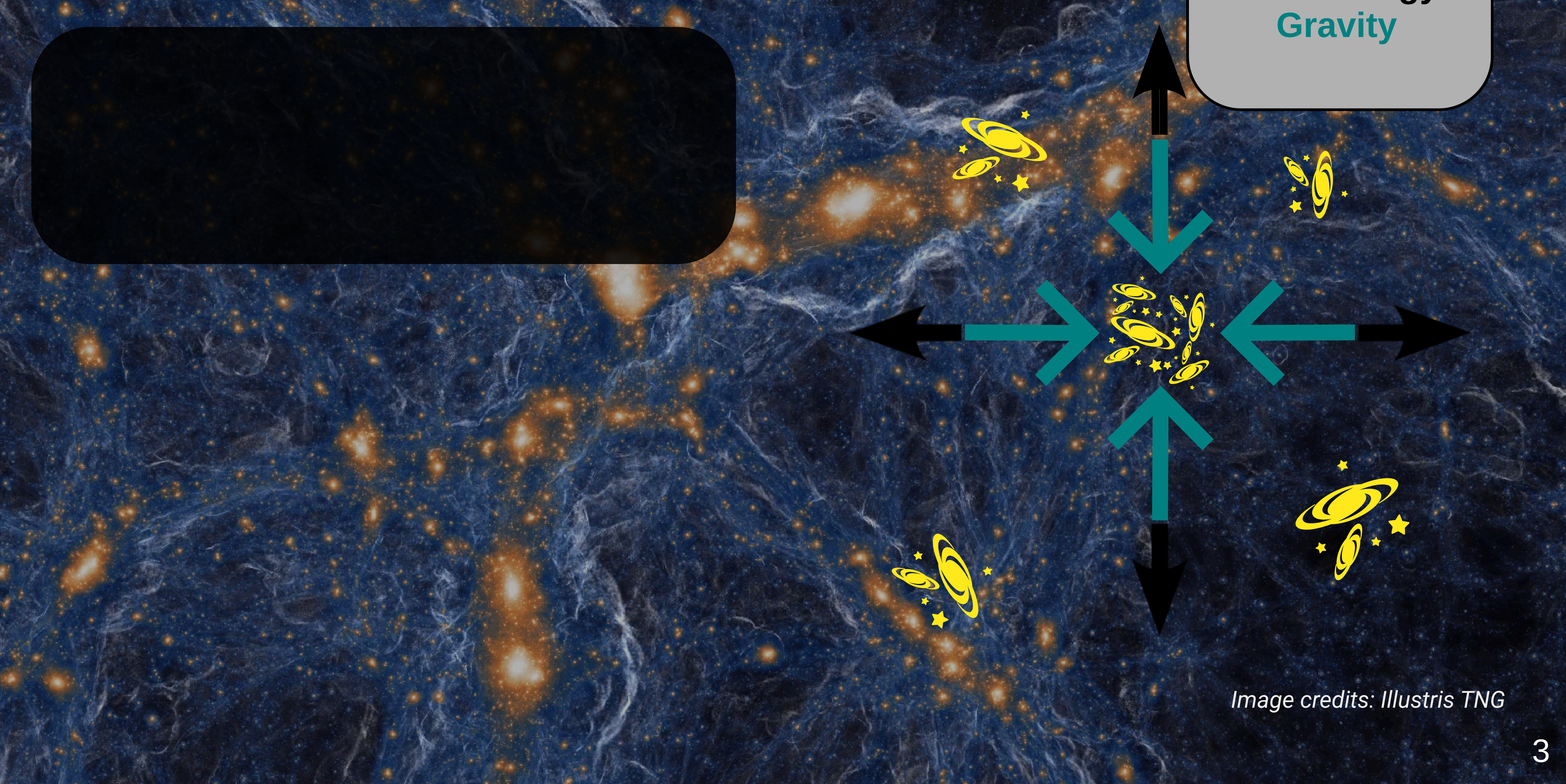
How to measure $f\sigma_8$?



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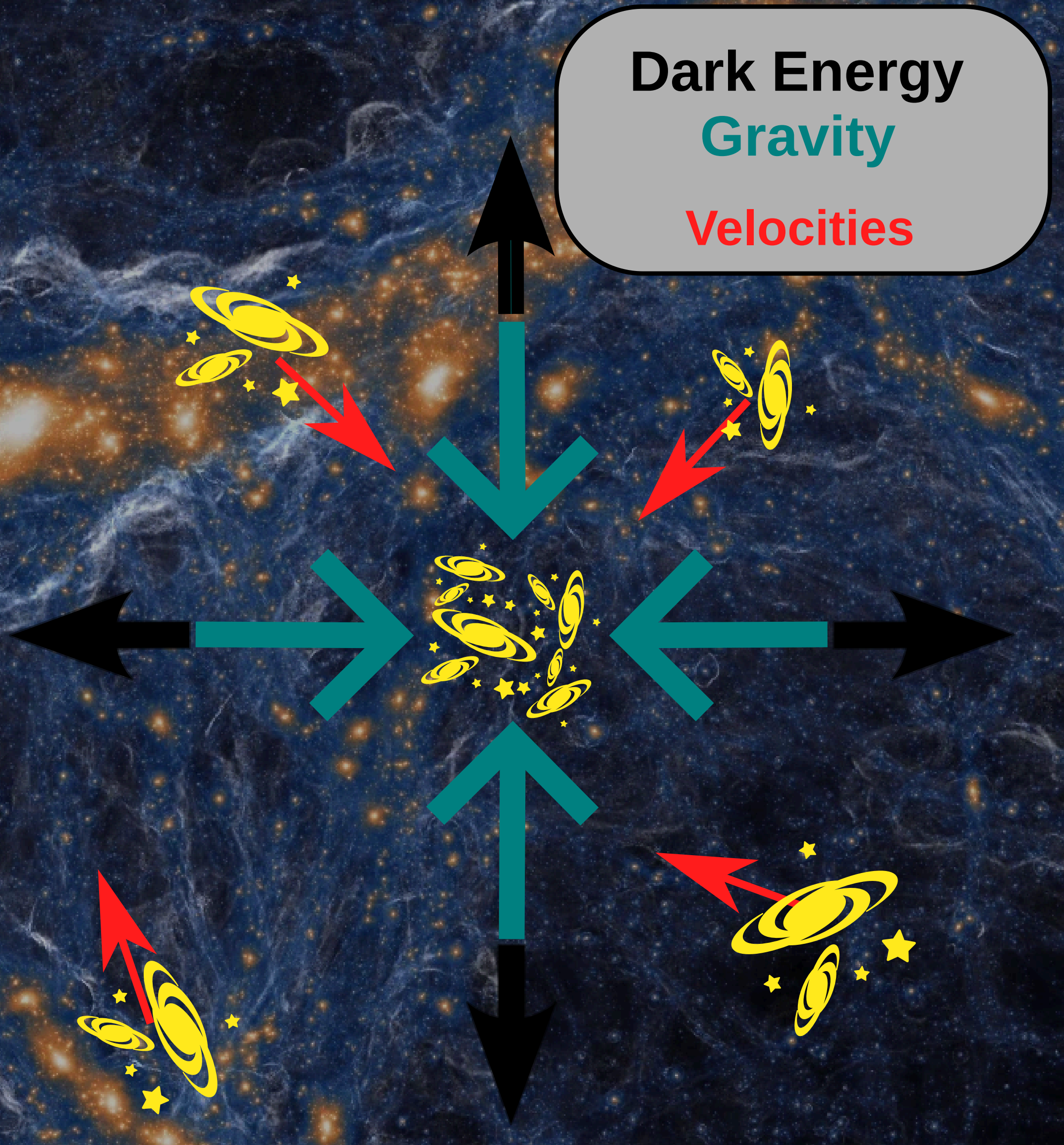
How to measure $f\sigma_8$?

Velocities are probes of $f\sigma_8$!



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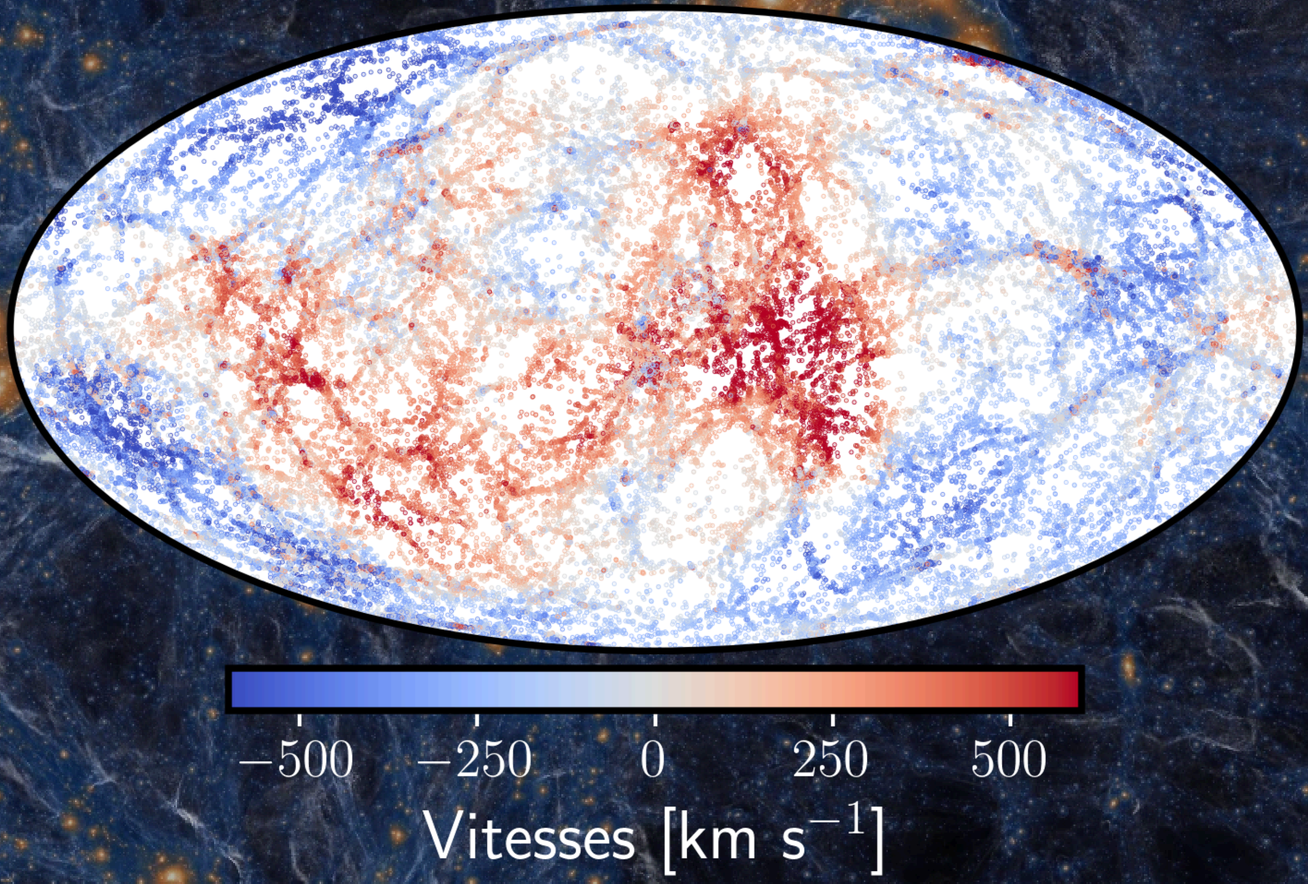
Velocity statistics directly depend on $f\sigma_8$:

$$\langle v(\mathbf{x_i})v(\mathbf{x_j})\rangle \propto (f\sigma_8)^2$$



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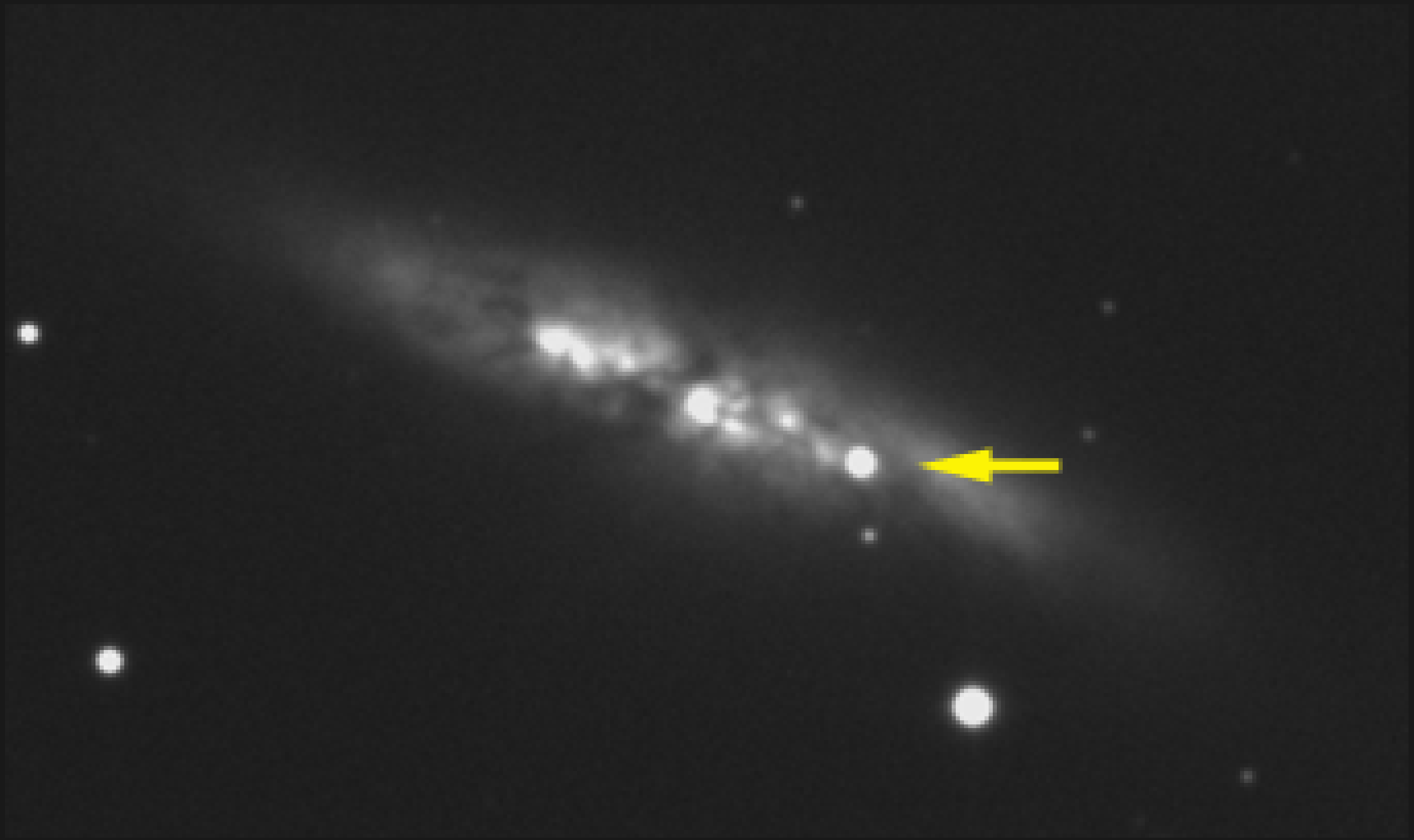
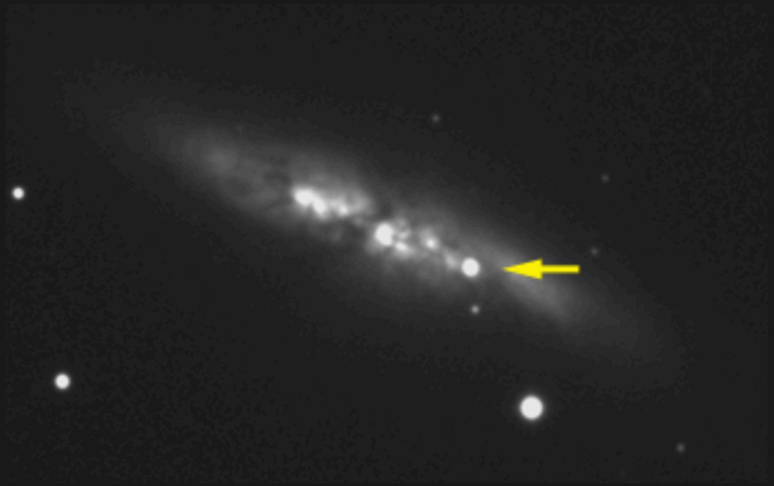
Estimating velocities from SNe Ia

Type Ia supernovae are exploding white dwarfs!

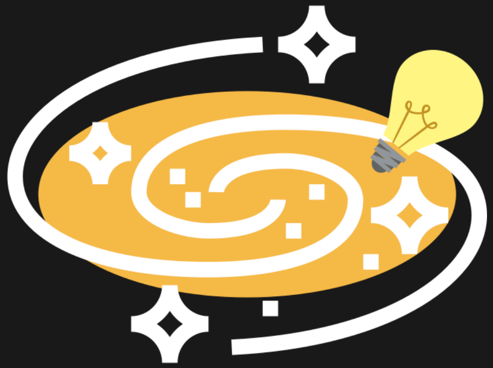


Estimating velocities from SNe Ia

Type Ia supernovae are standard candles!

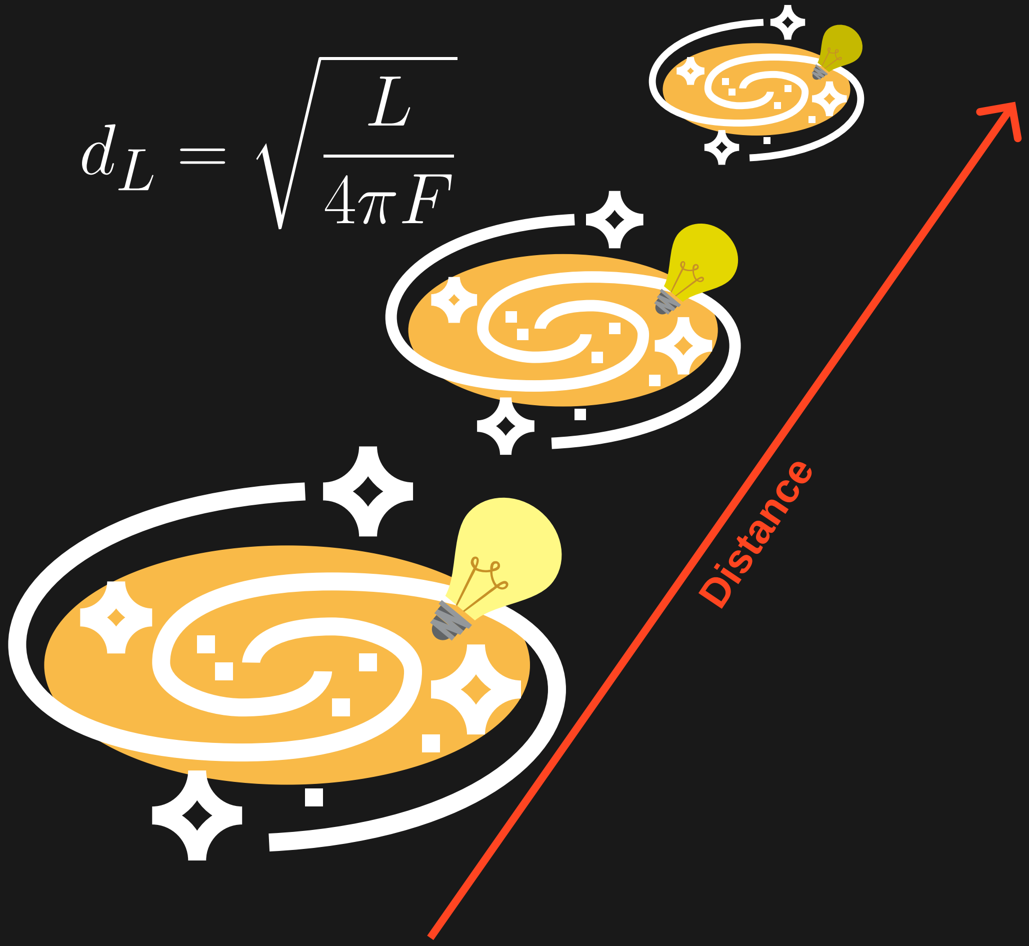


$\approx$



Estimating velocities from SNe Ia

$$d_L = \sqrt{\frac{L}{4\pi F}}$$



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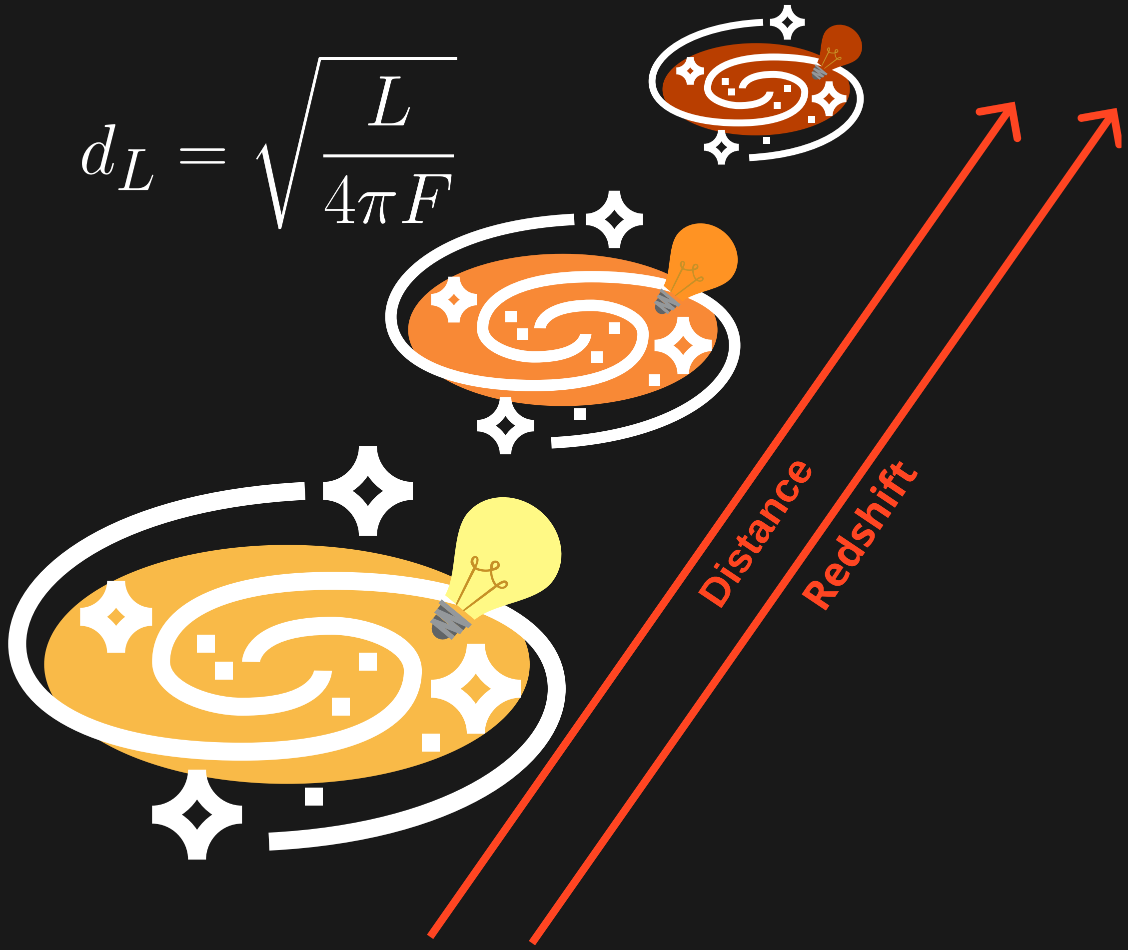

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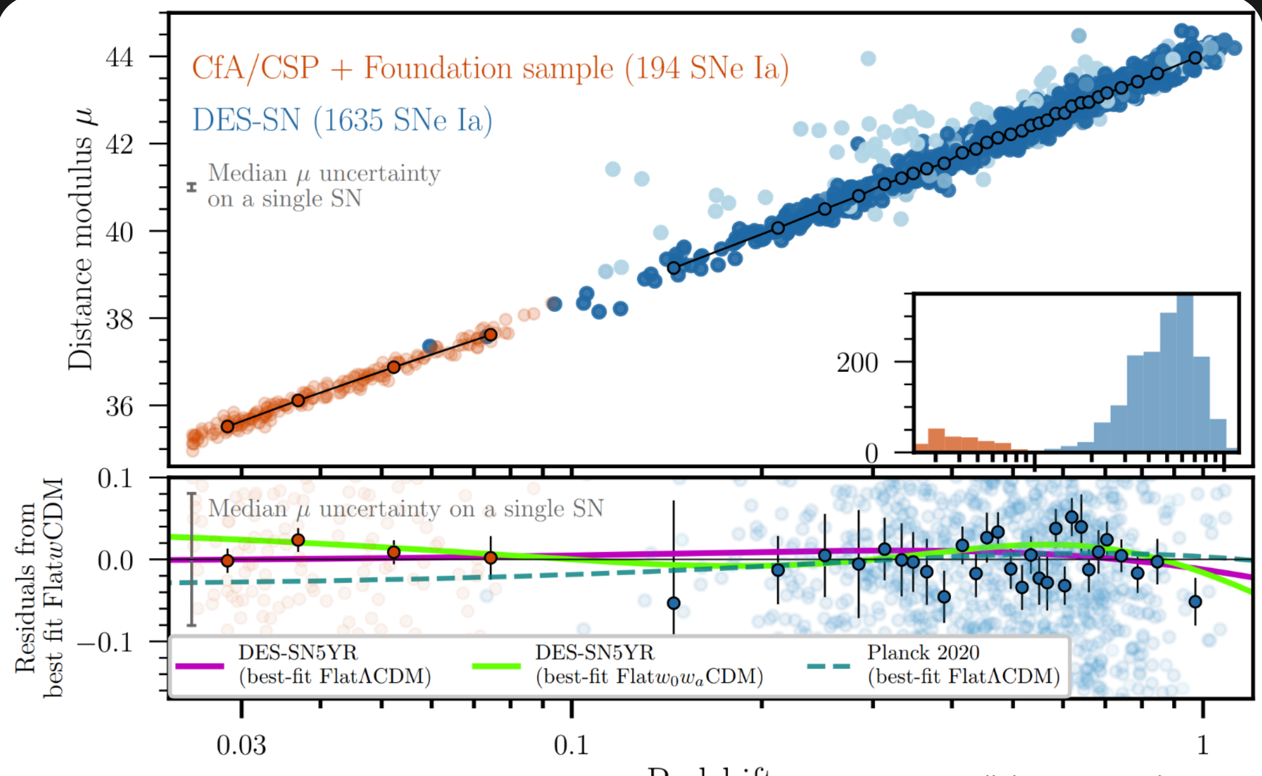
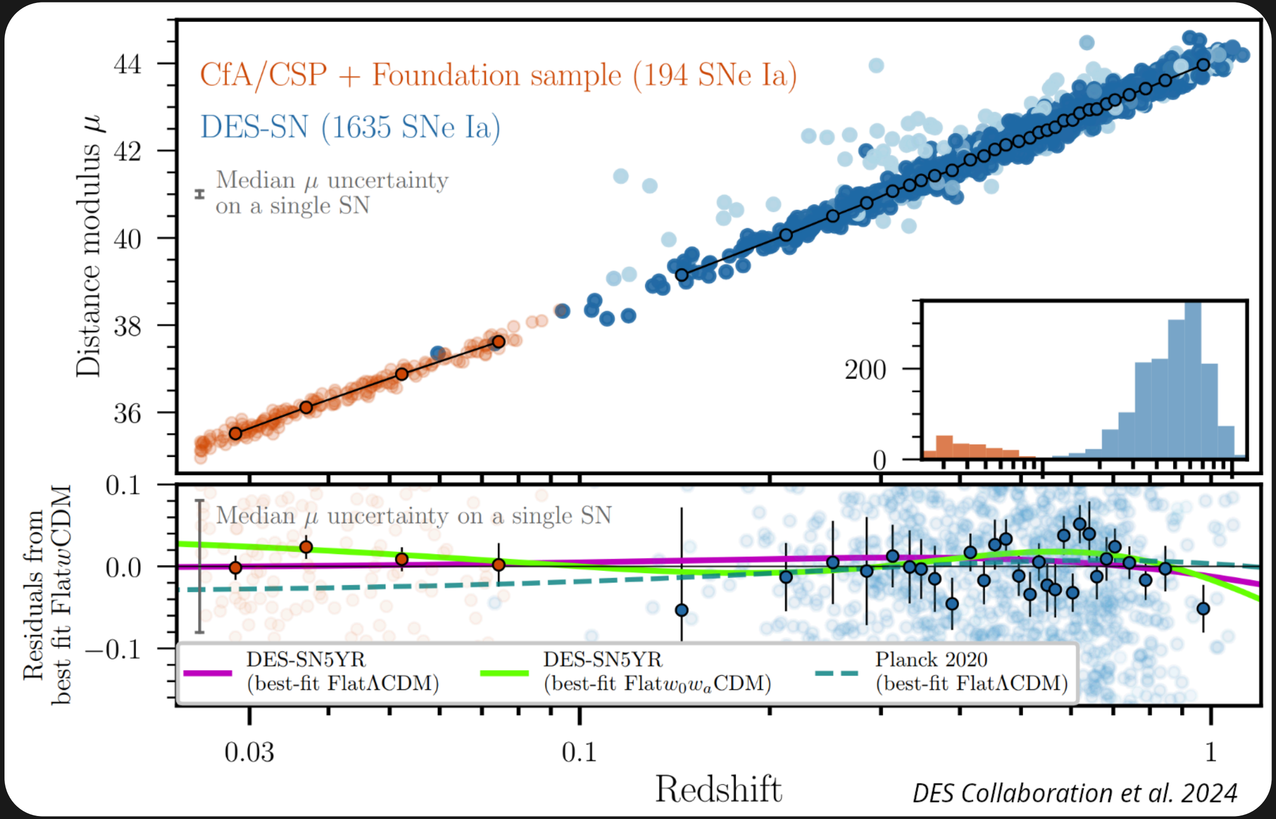


DES Collaboration et al. 2024

Estimating velocities from SNe Ia

Distance modulus:

$$\mu = 5\log\left(d_L/10\ \text{pc}\right) = m - M$$



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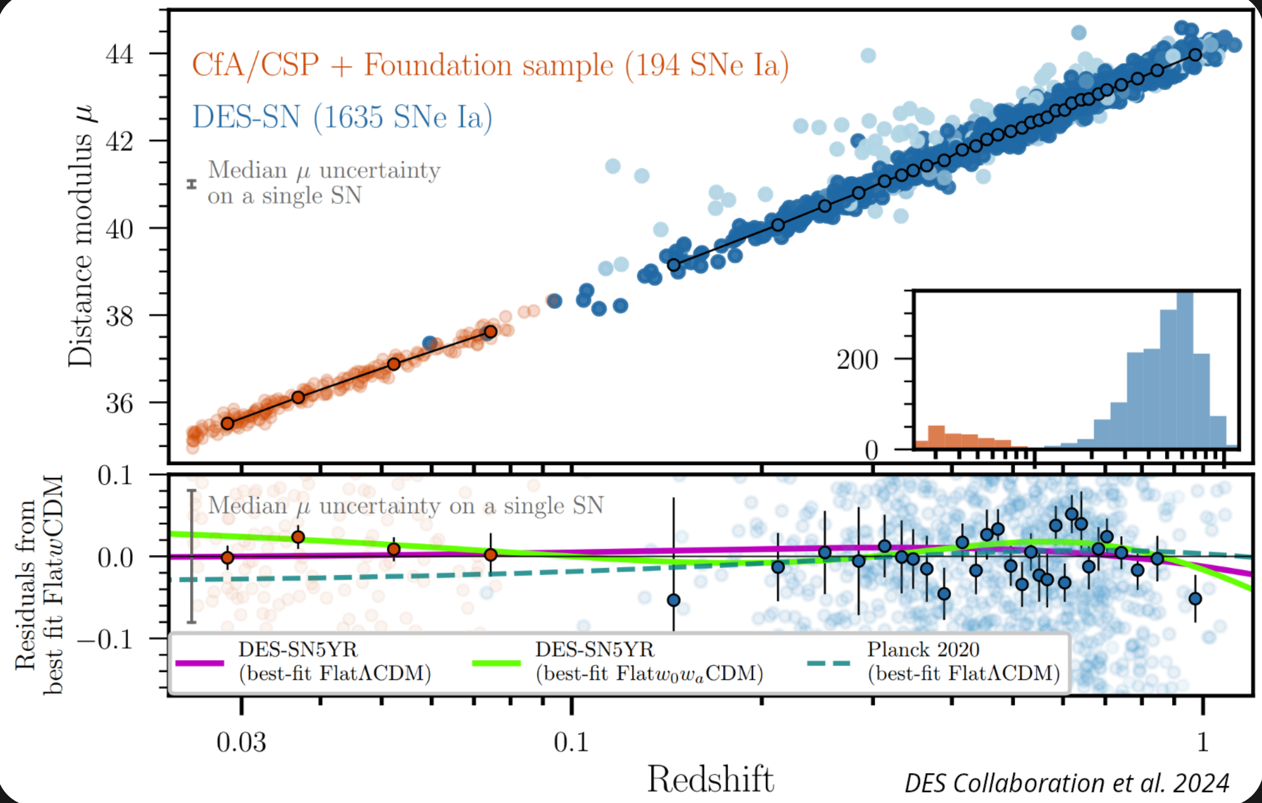
$$\mu_{\mathrm{obs}} = m_B - (M_B \qquad\qquad\qquad\qquad)$$



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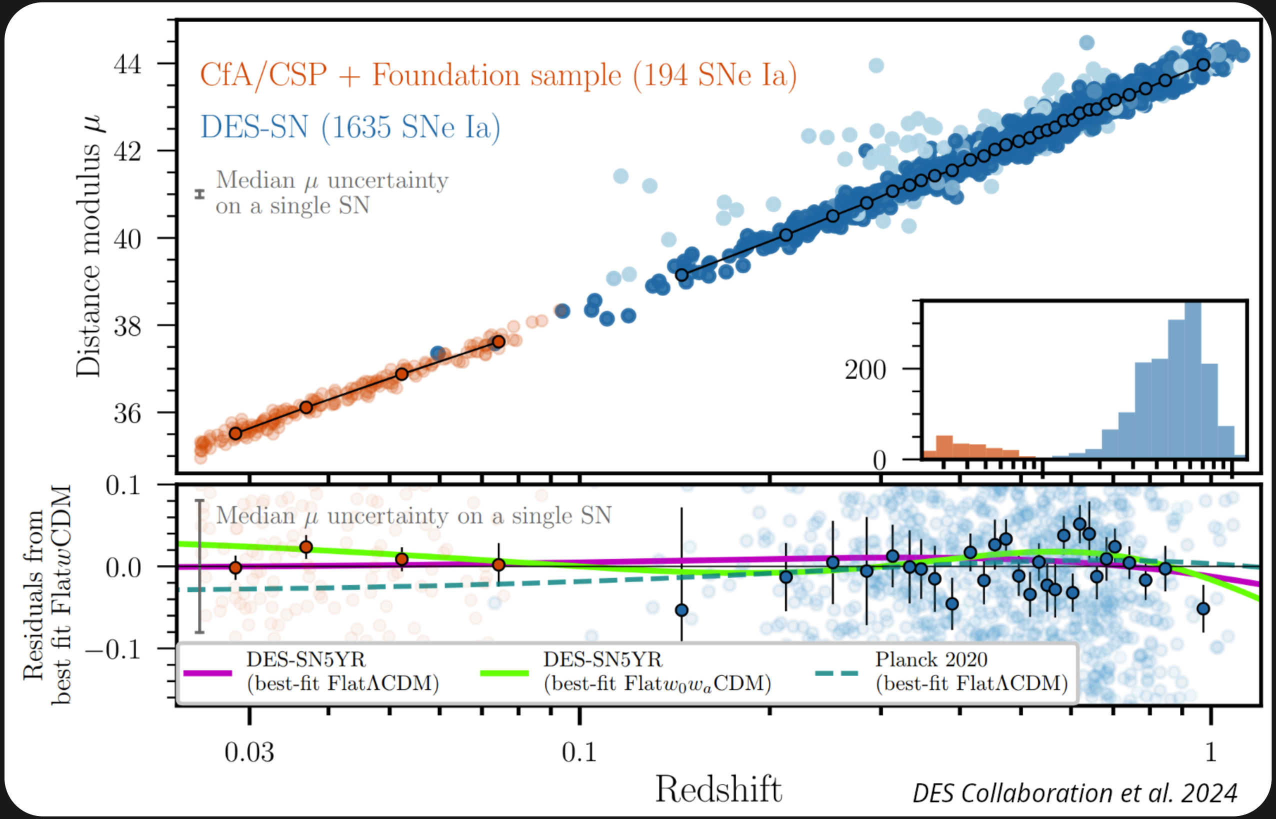

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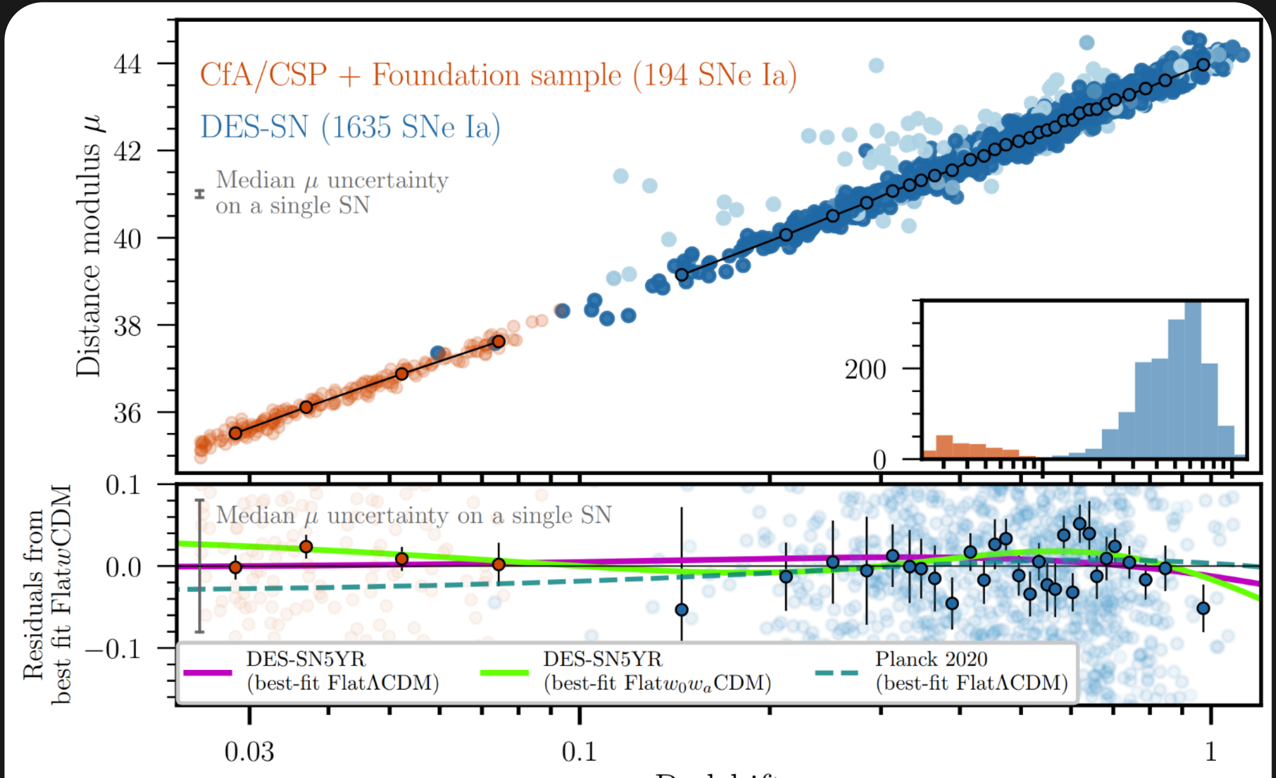

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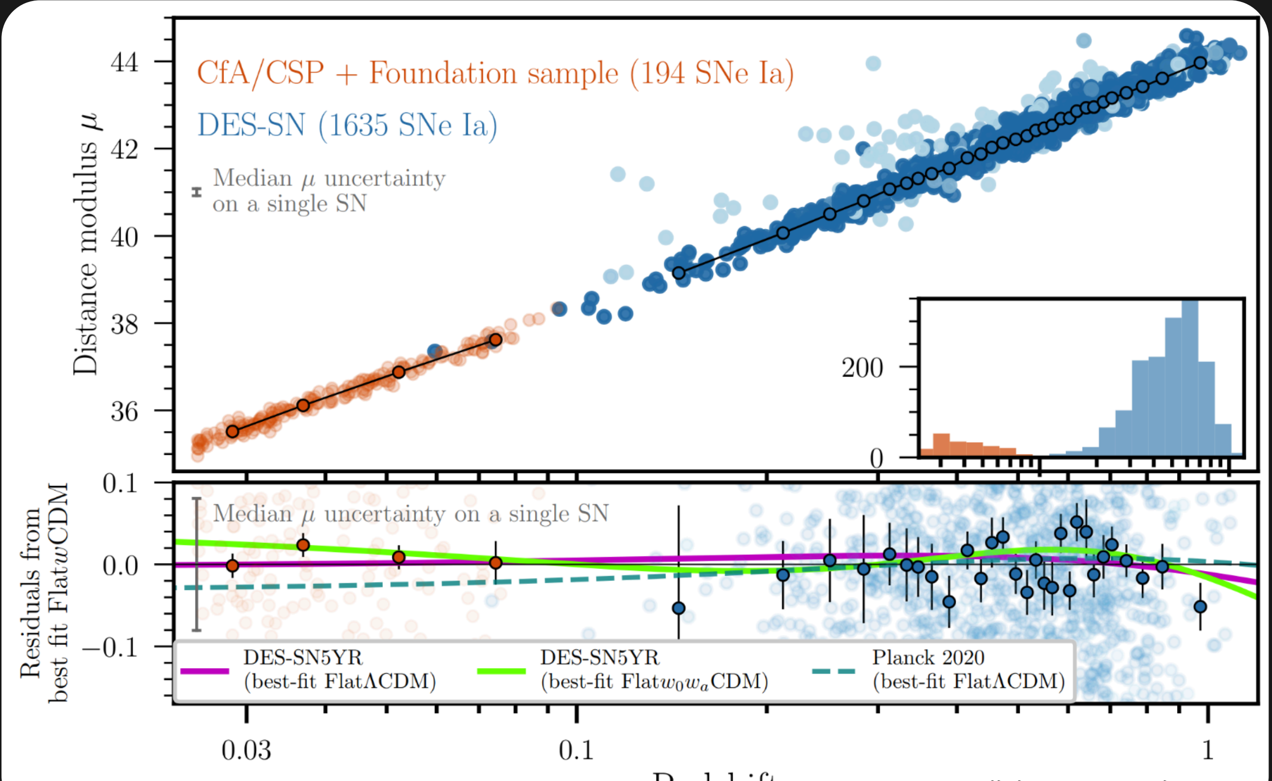

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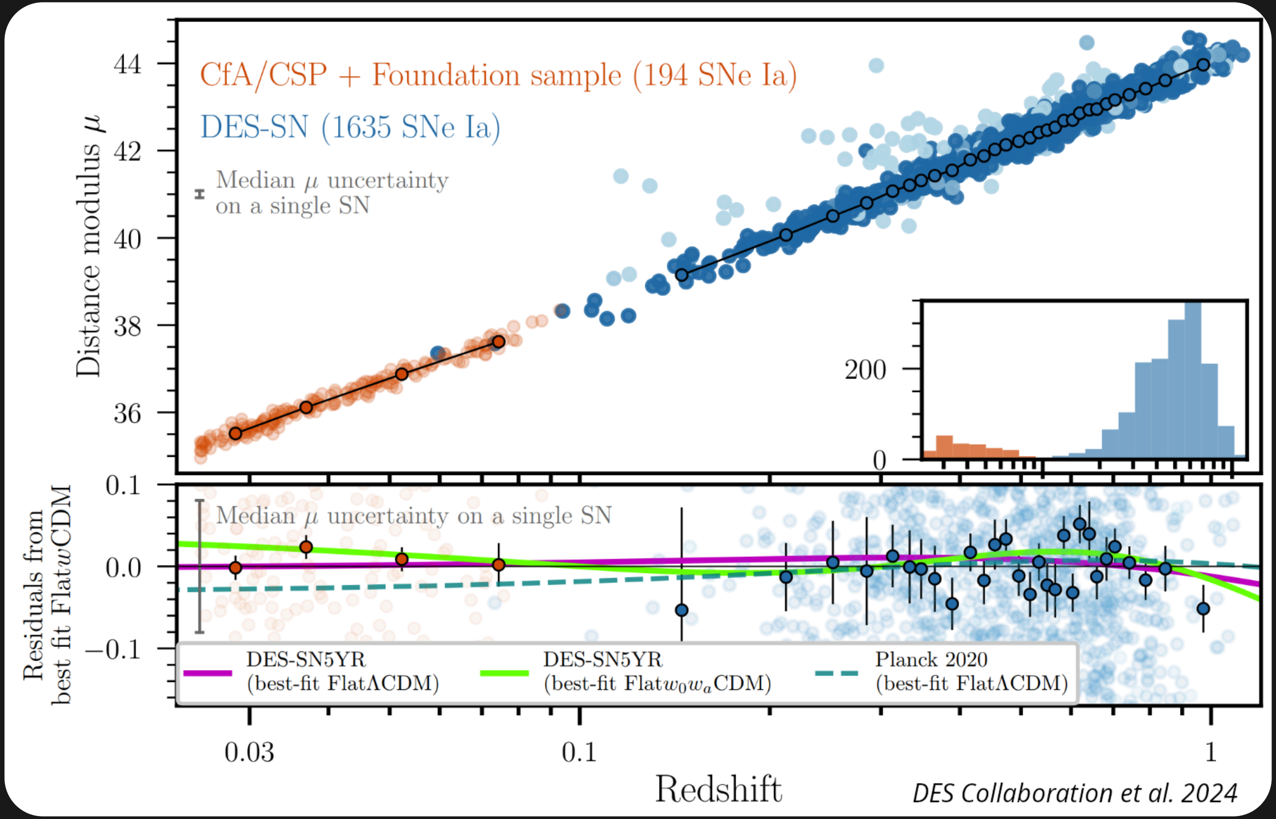
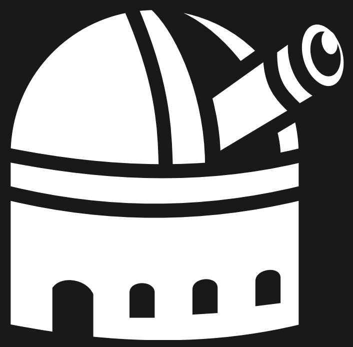
Remaining intrinsic scatter $\sigma_\mu \sim 0.12$ mag



Estimating velocities from SNe Ia

Observed redshifts:

$1 + z_{\text{obs}} = (1 + z_{\text{cos}})(1 + z_{\text{p}})$ with $z_p \simeq v_p/c$



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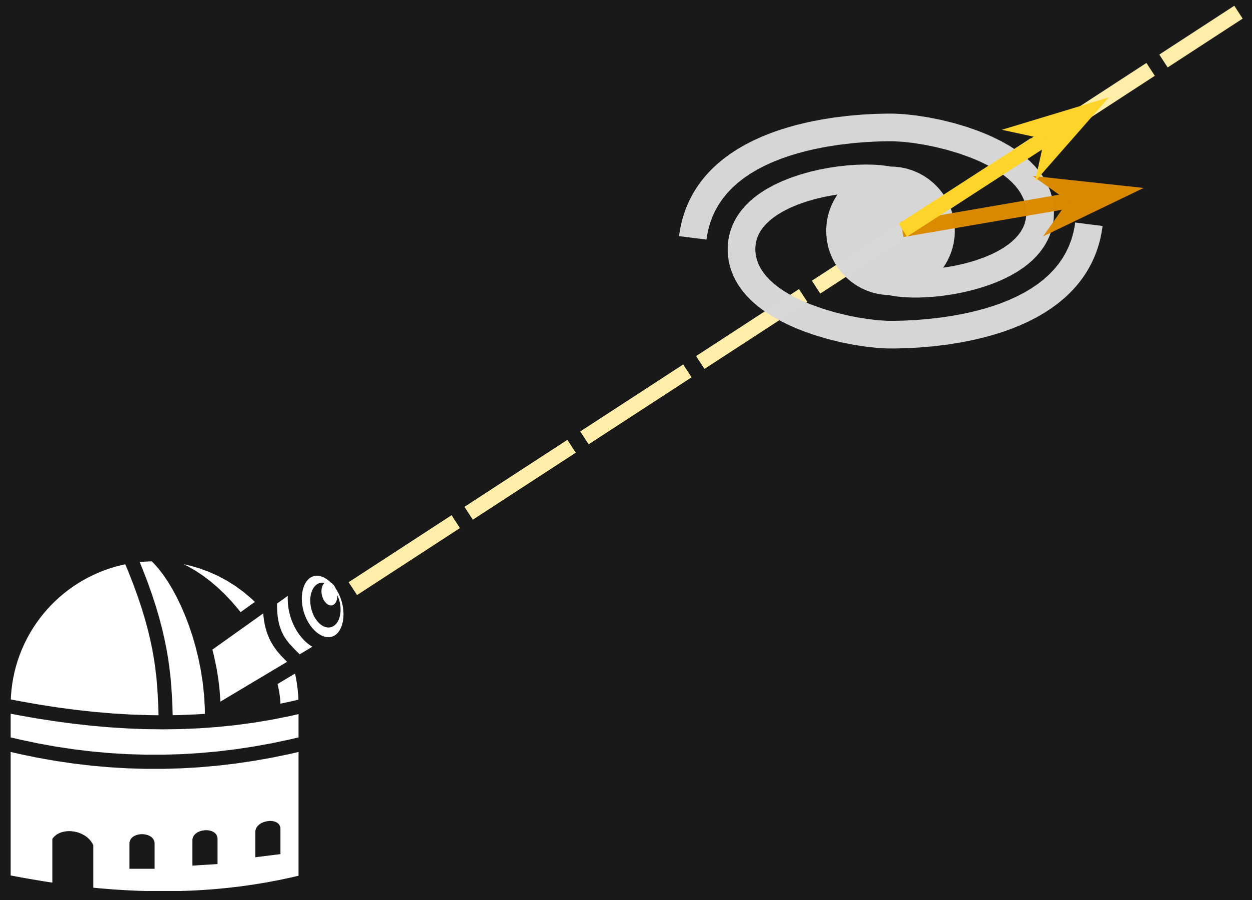

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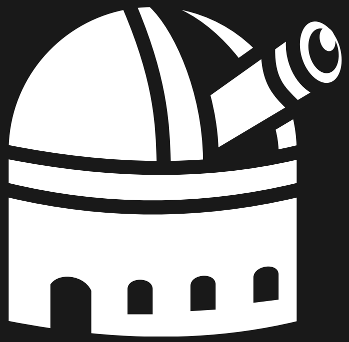

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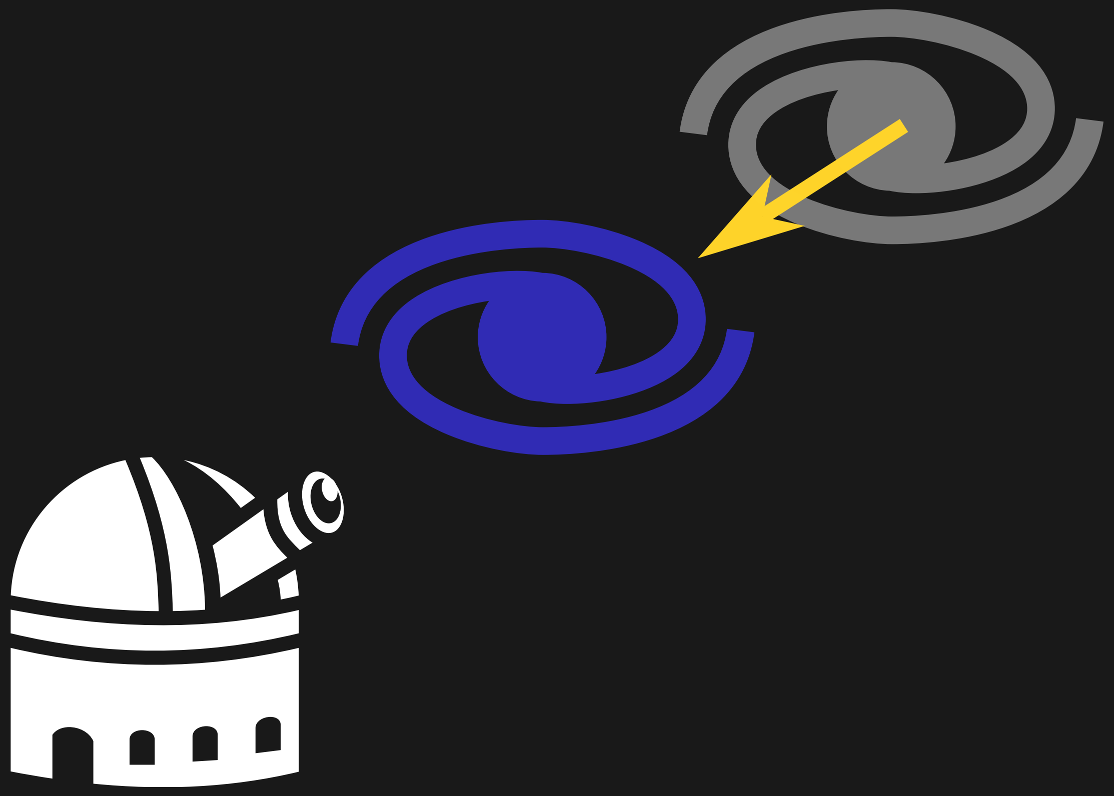

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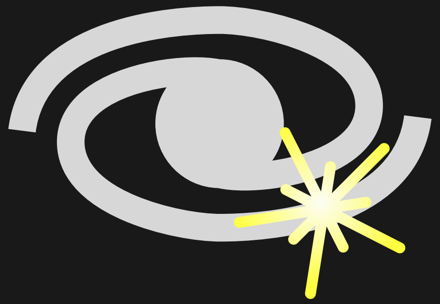

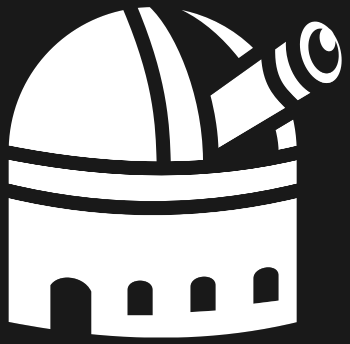

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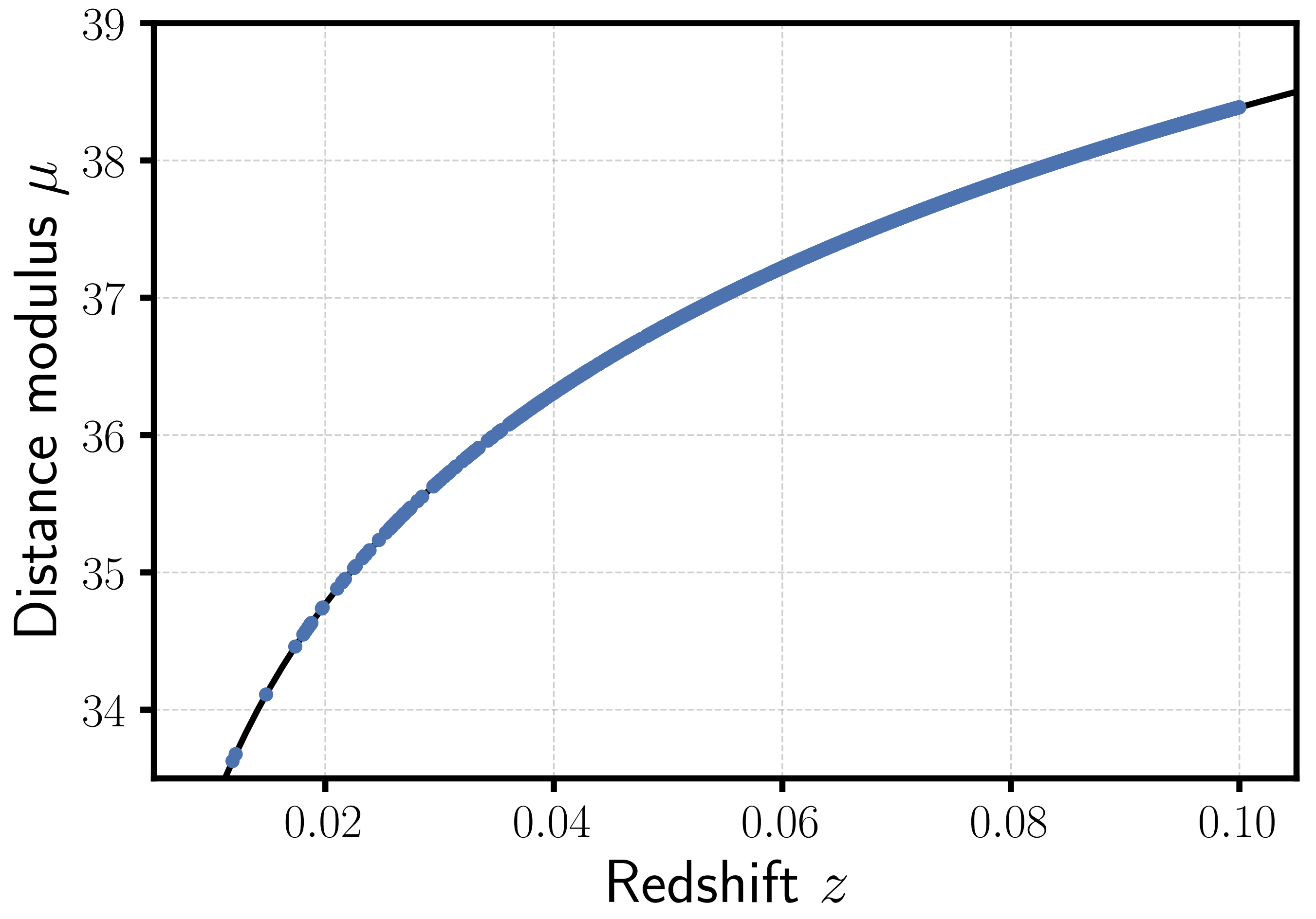

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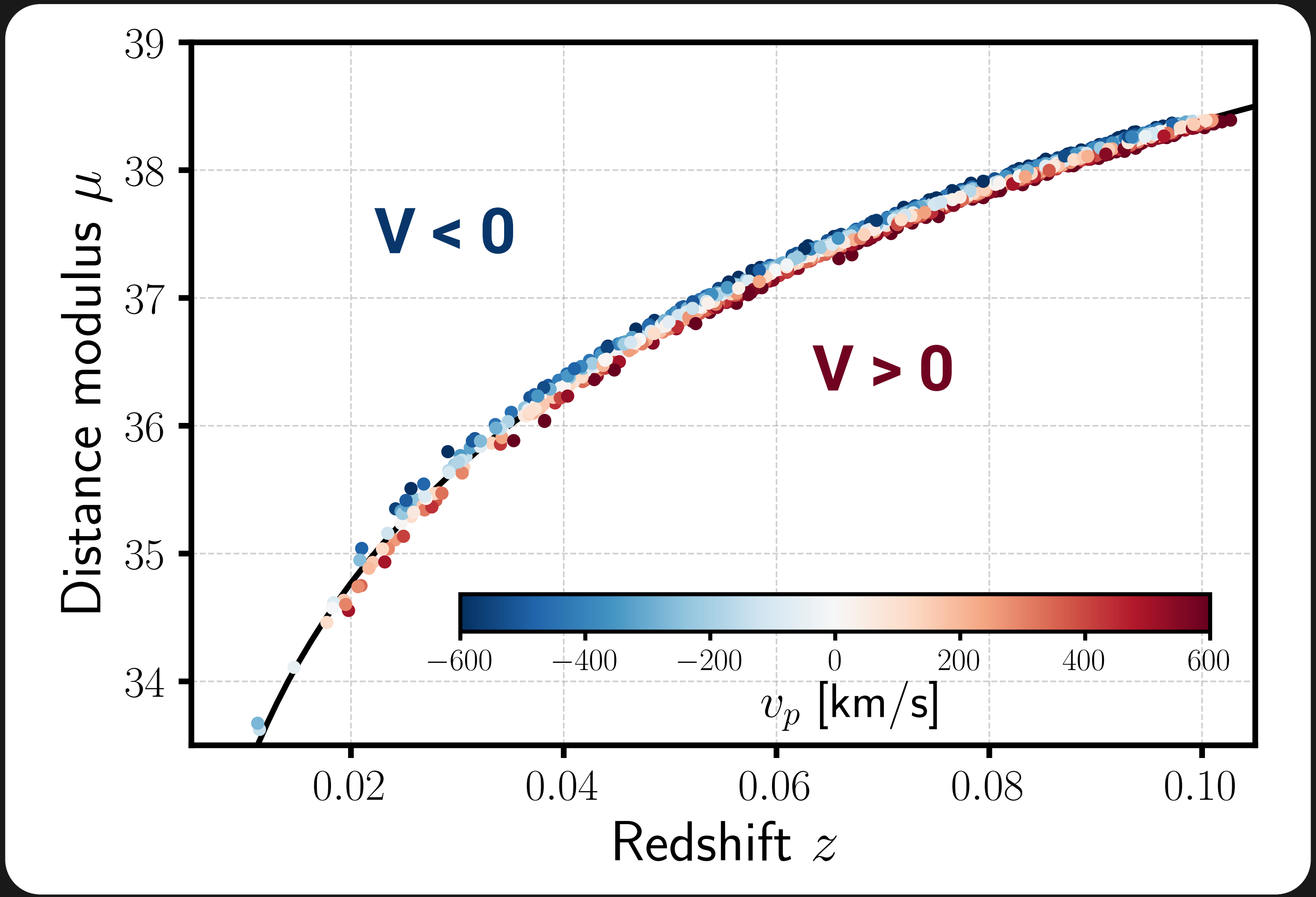

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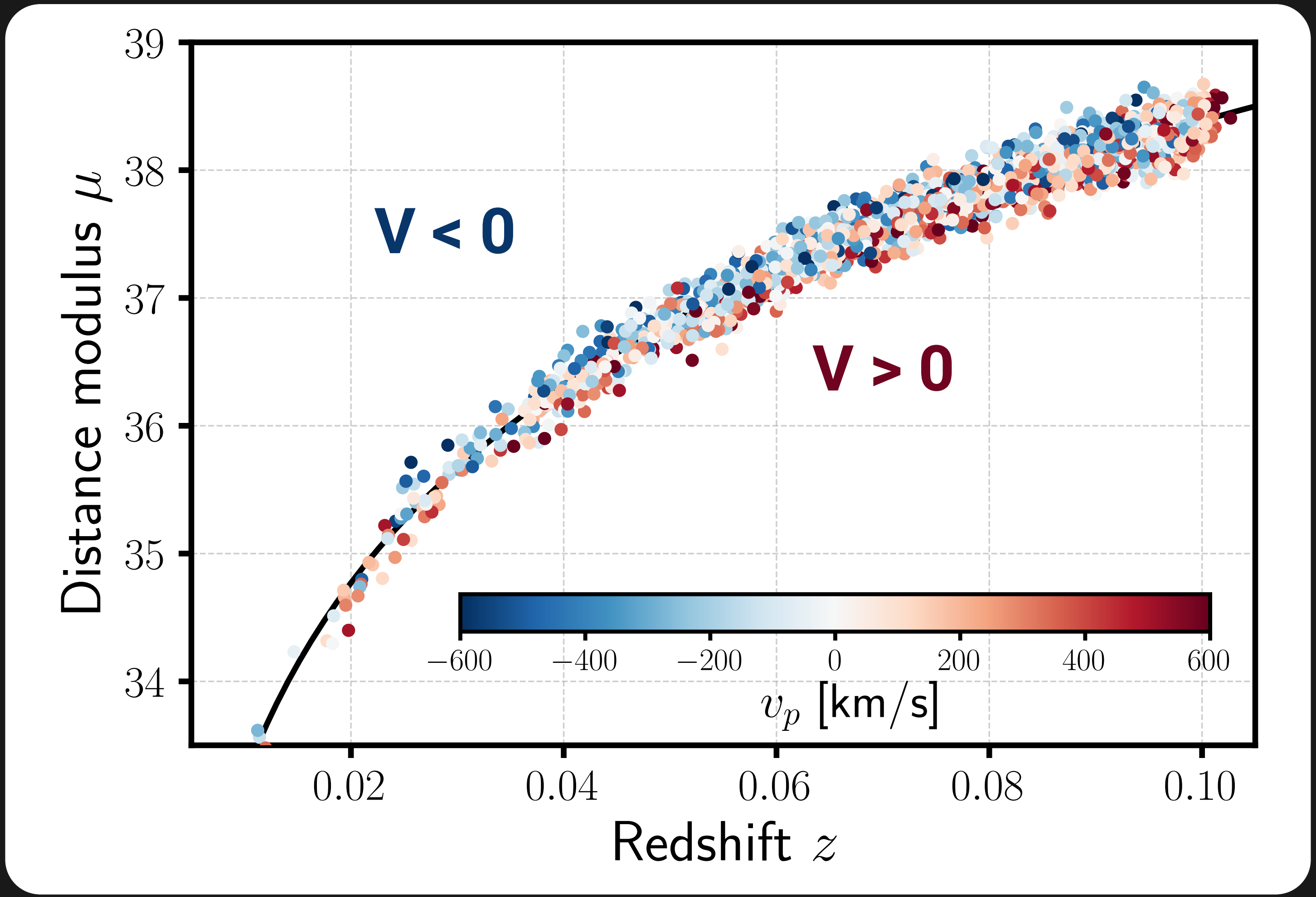
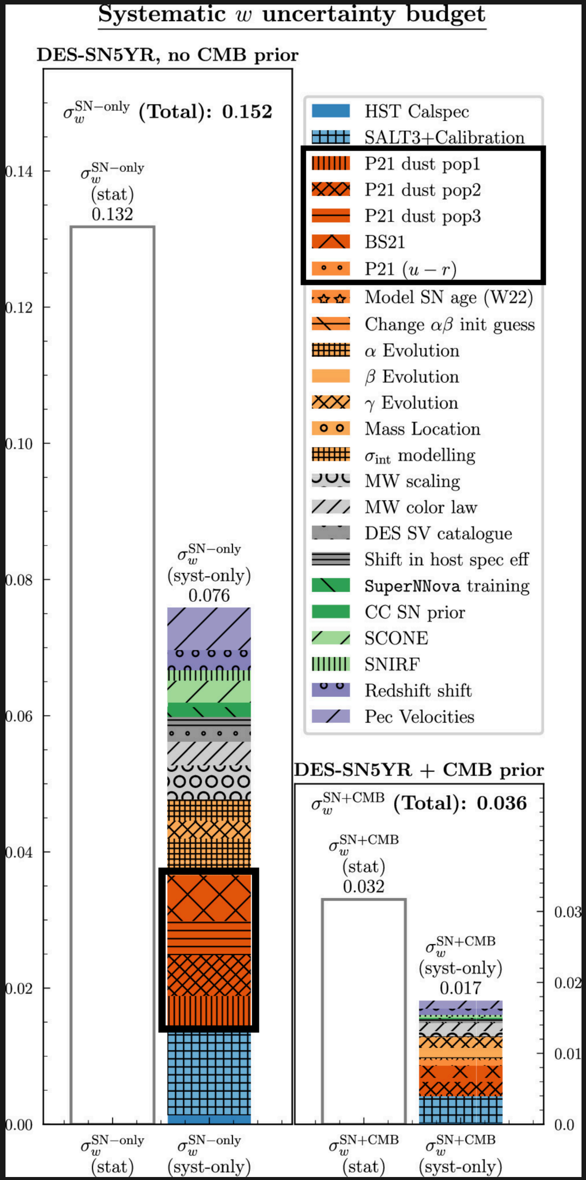


The intrinsic scatter of SNe Ia

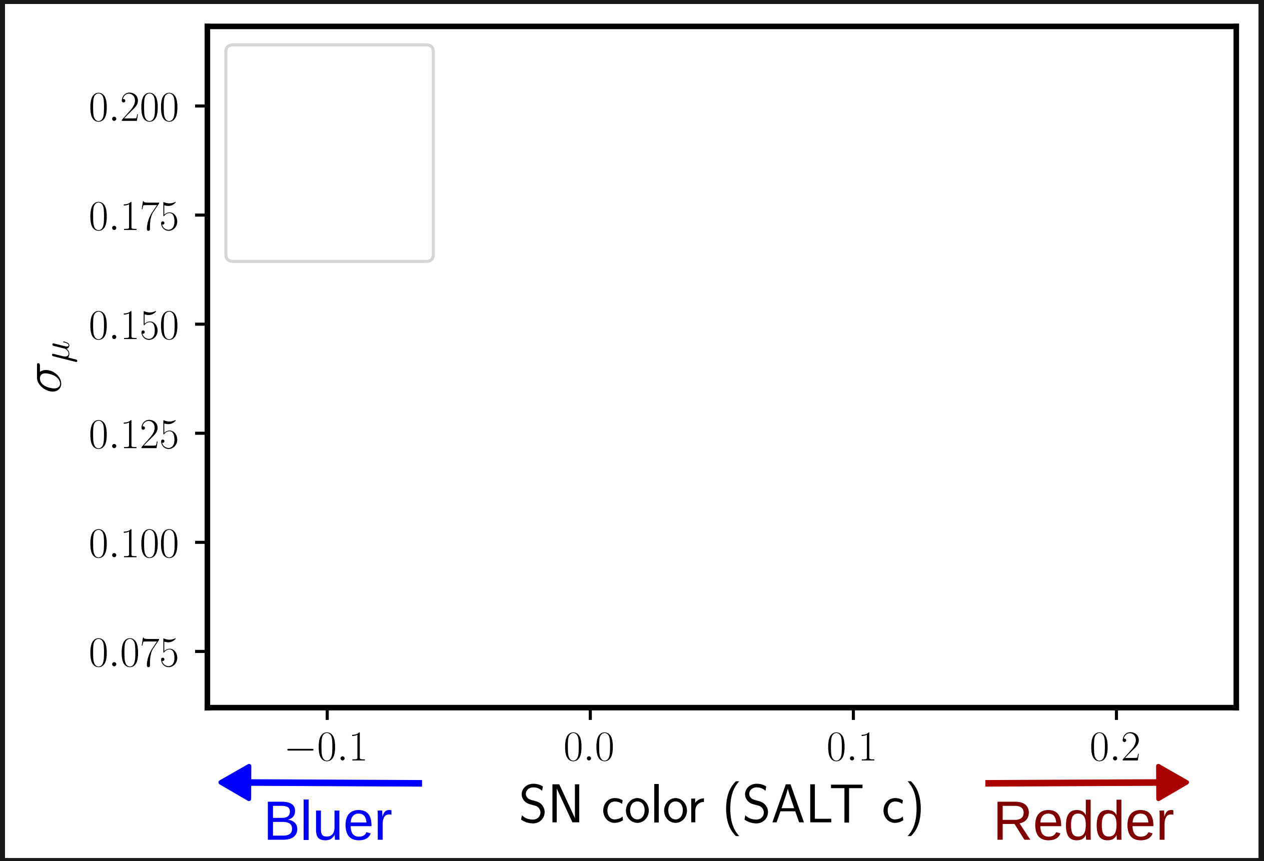
Main systematic of DES 5-year dark energy analysis (*Vincenzi et al. 2023*)!!!

What about $f\sigma_8$???



The intrinsic scatter of SNe Ia

In this work we considered 4 models of intrinsic scatter



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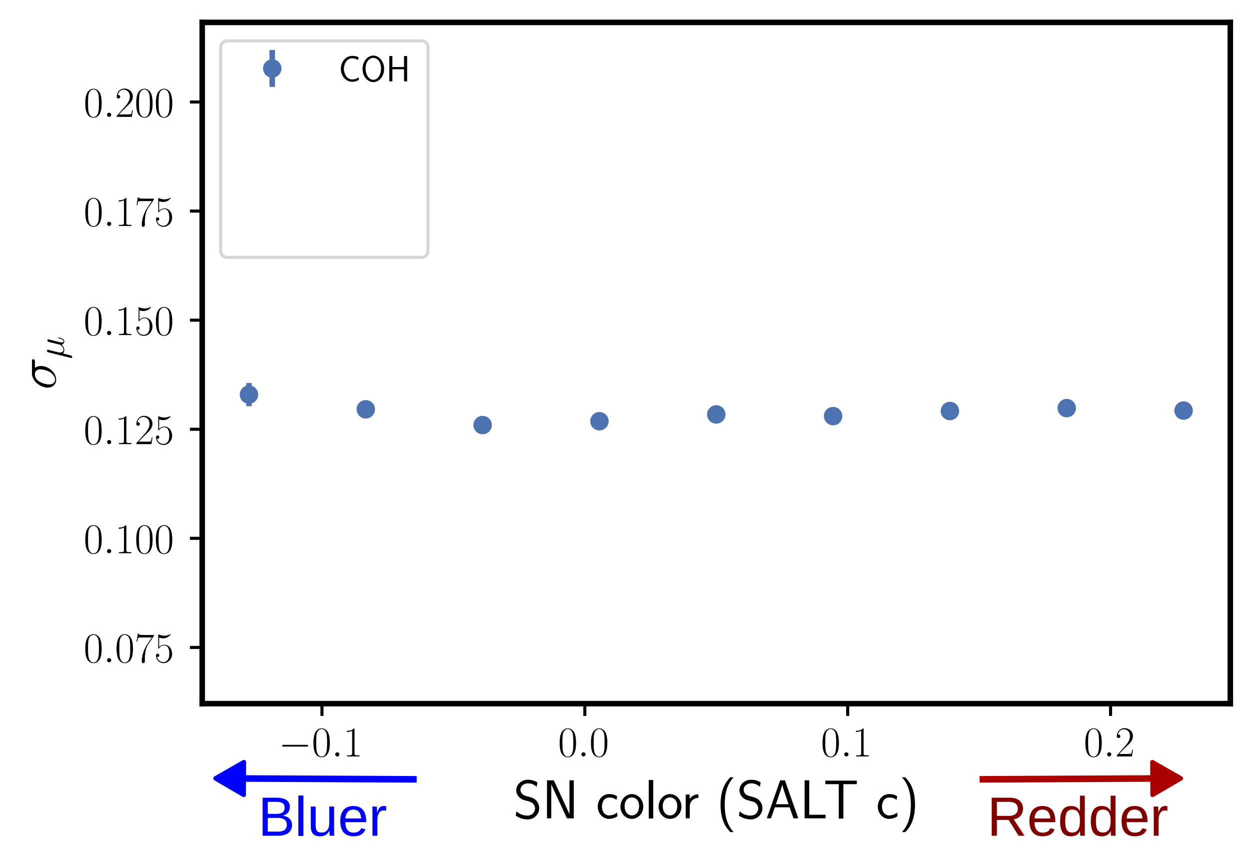
- Random coherent scatter (COH)
  Achromatic
  Unrealistic



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  $\sim 70\%$ achromatic / $\sim 30\%$ chromatic
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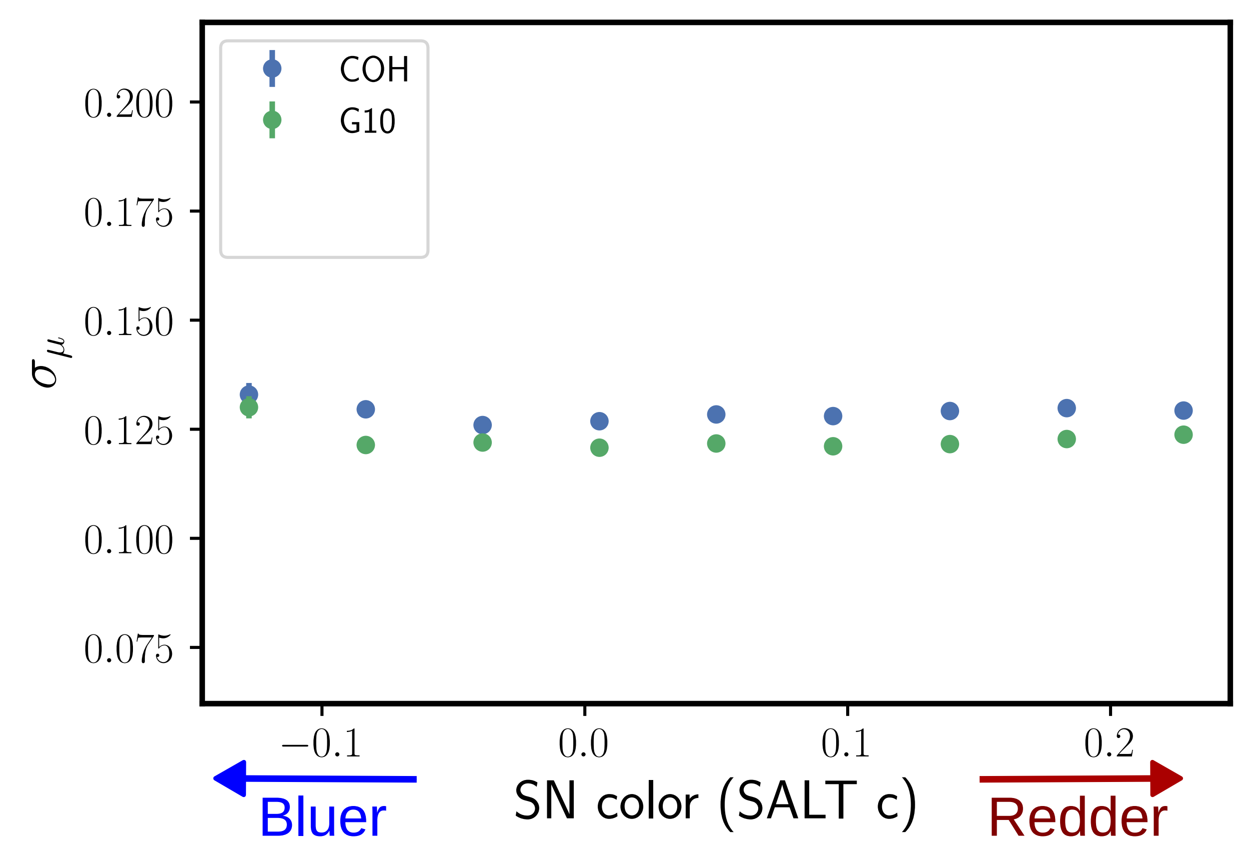

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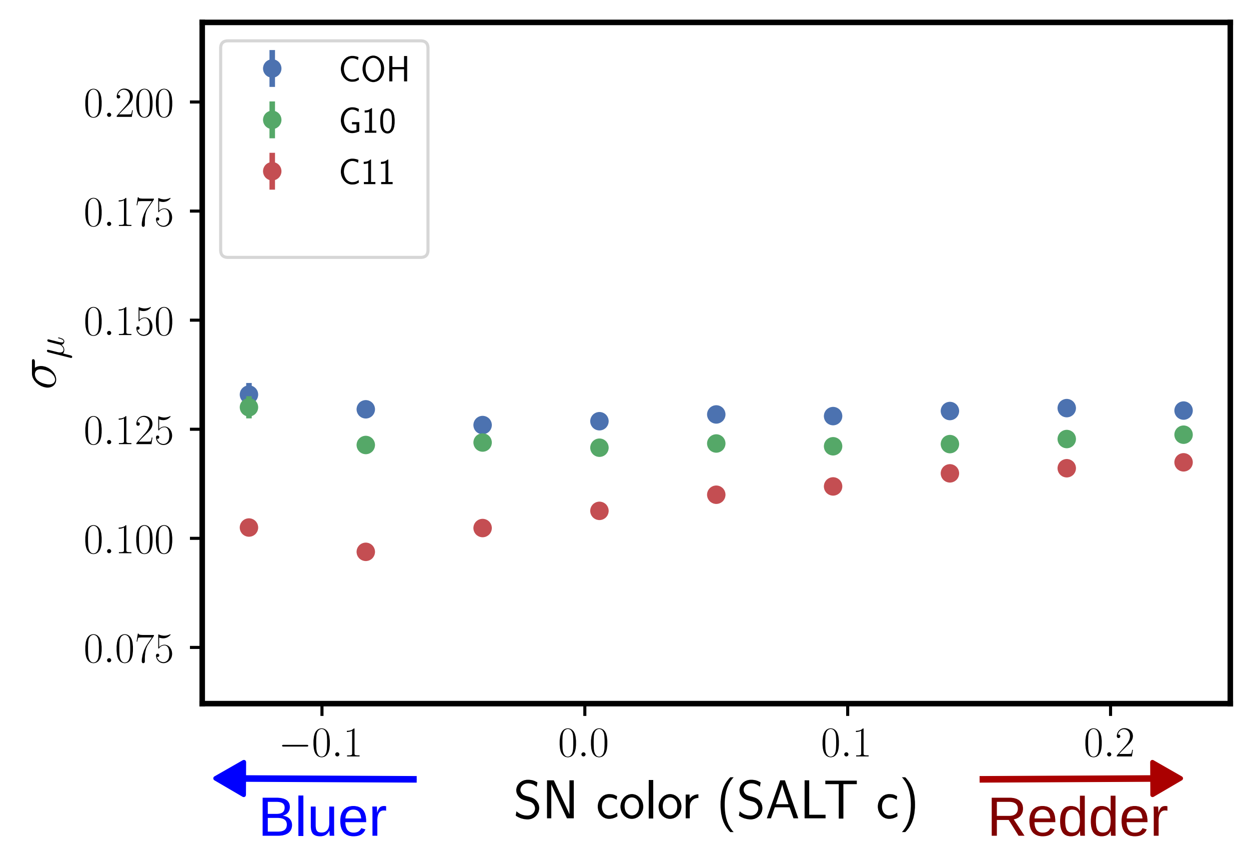

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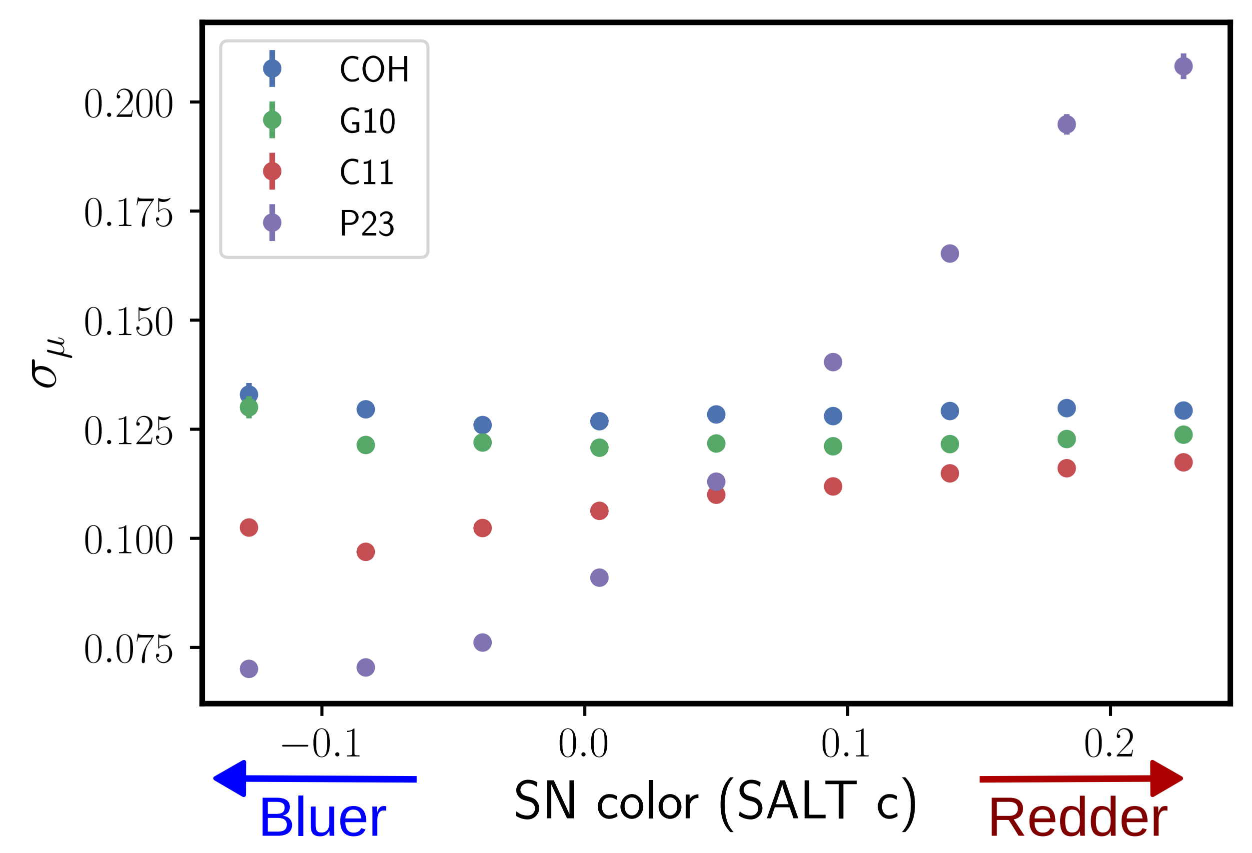
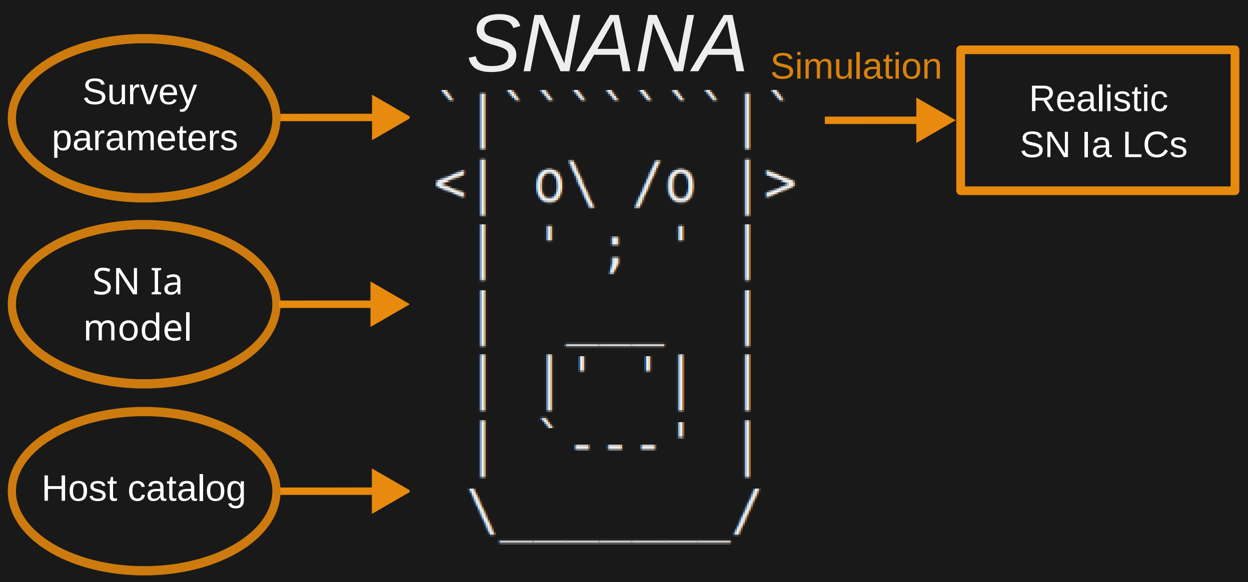
- The BS21 model (*Brout & Scolnic 2021*), parameters from *Popovic et al. 2023* (P23):
  Dust-based model
  Currently favored by data (DES 5-year)



Rubin-LSST Simulations

We used the SNANA software (*Kessler et al. 2009*) to simulate the 10 years of the Rubin-LSST survey!



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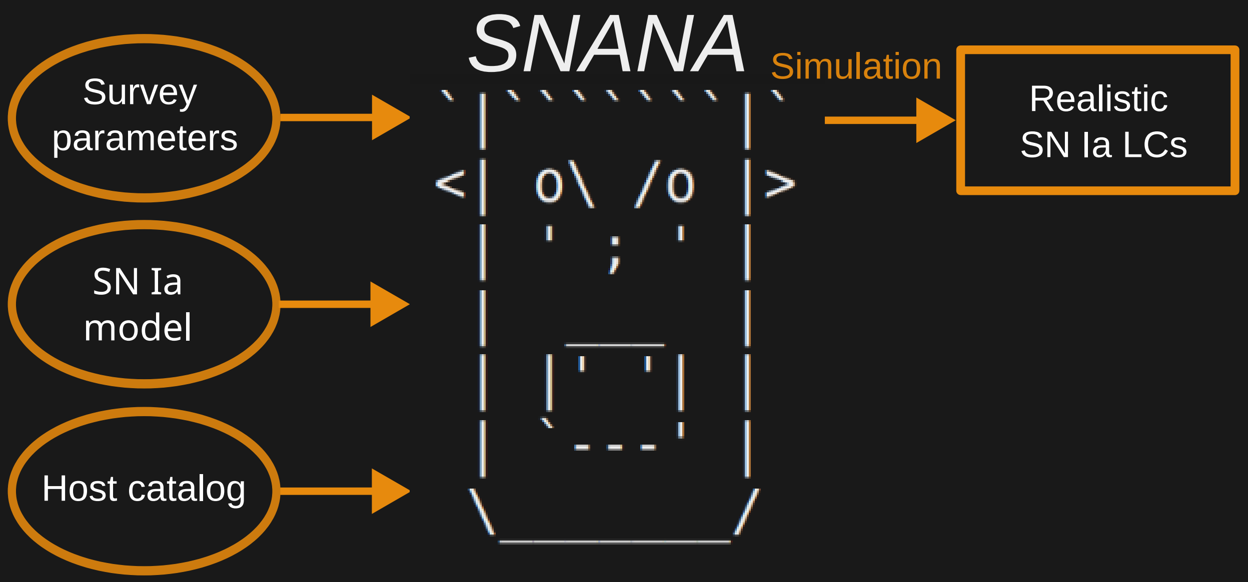

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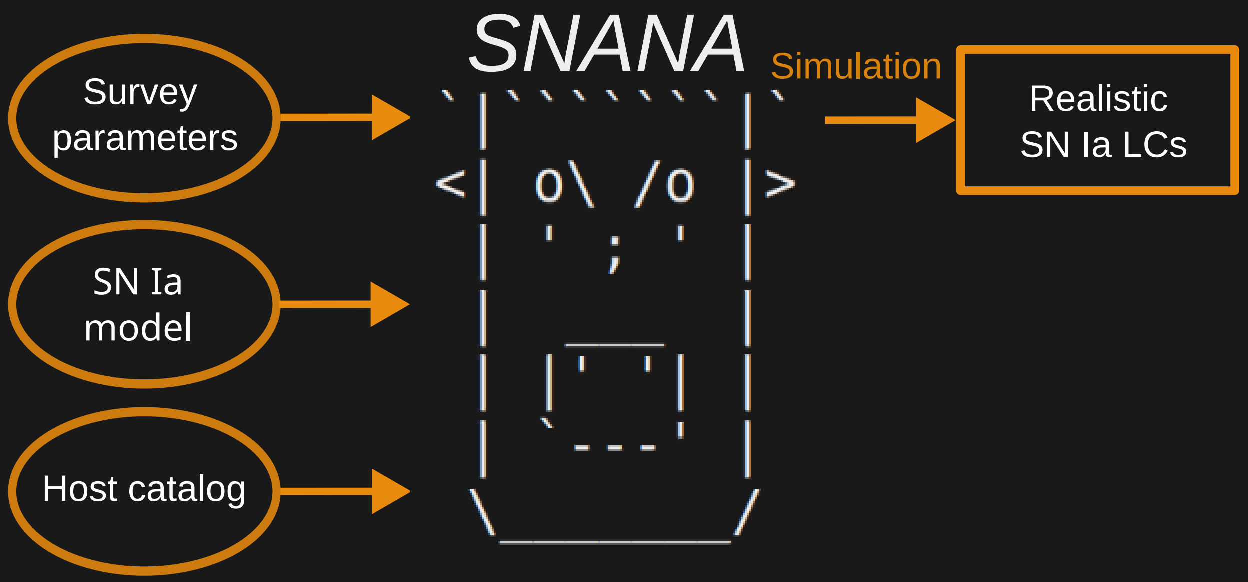

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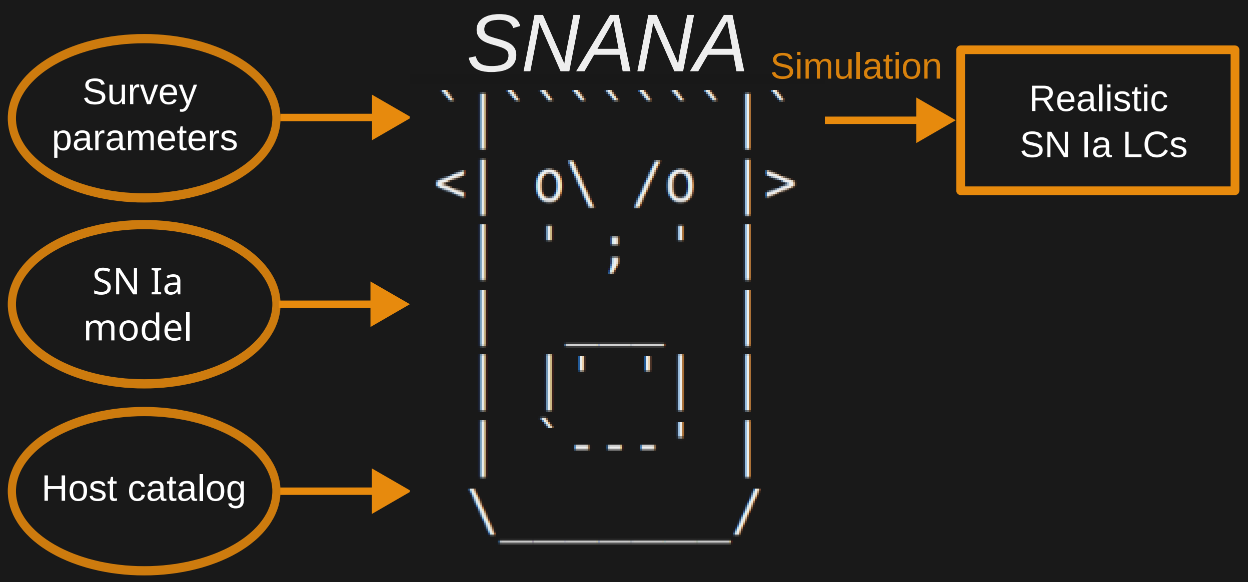

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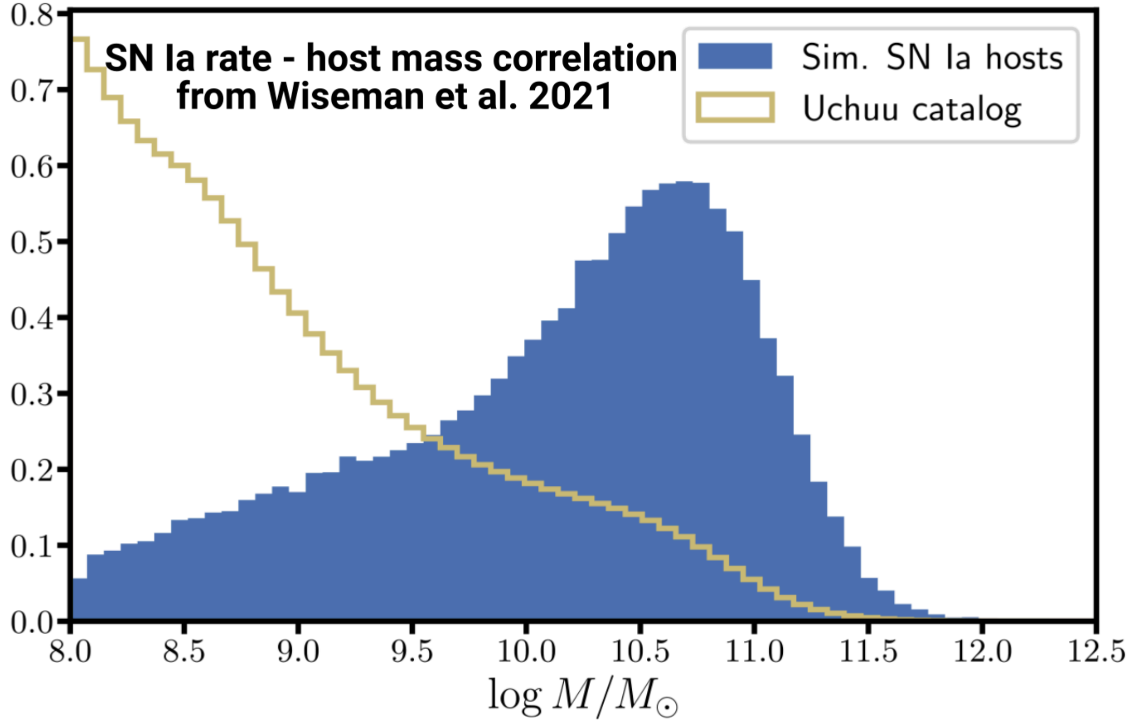
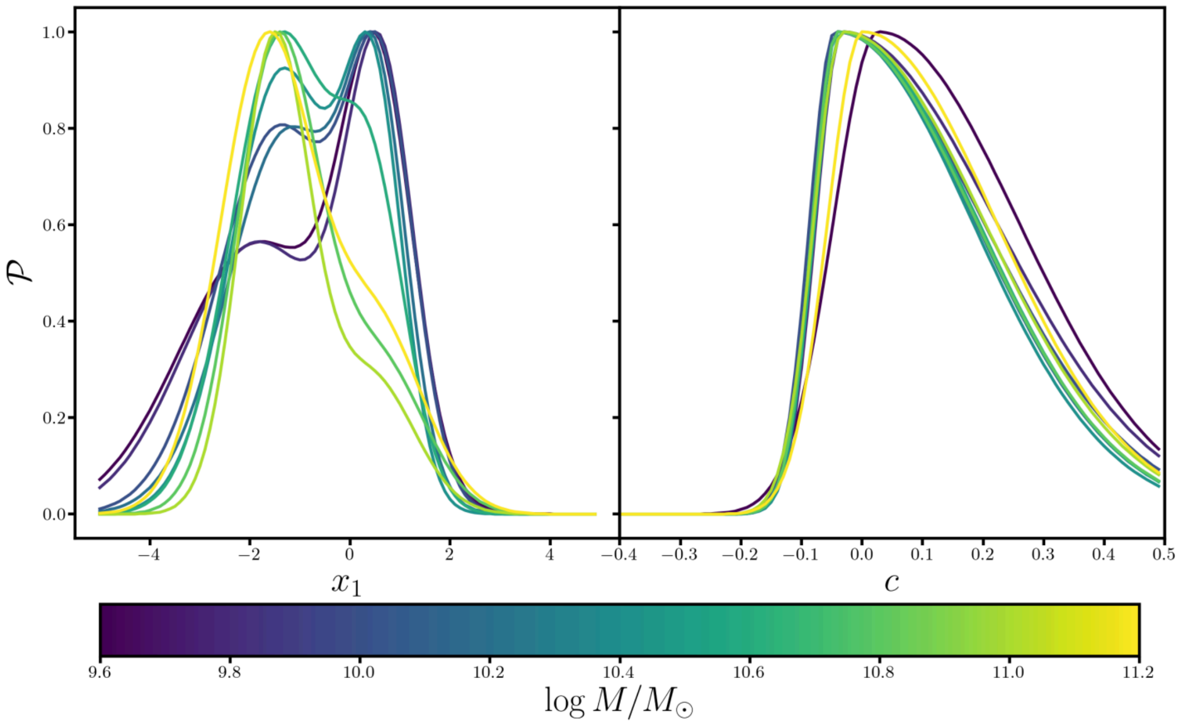
- Host catalog: Uchuu UniverseMachine N-body simulation (*Ishiyama et al. 2021*, *Aung et al. 2022*)

Simulation: Correlations SN Ia - host

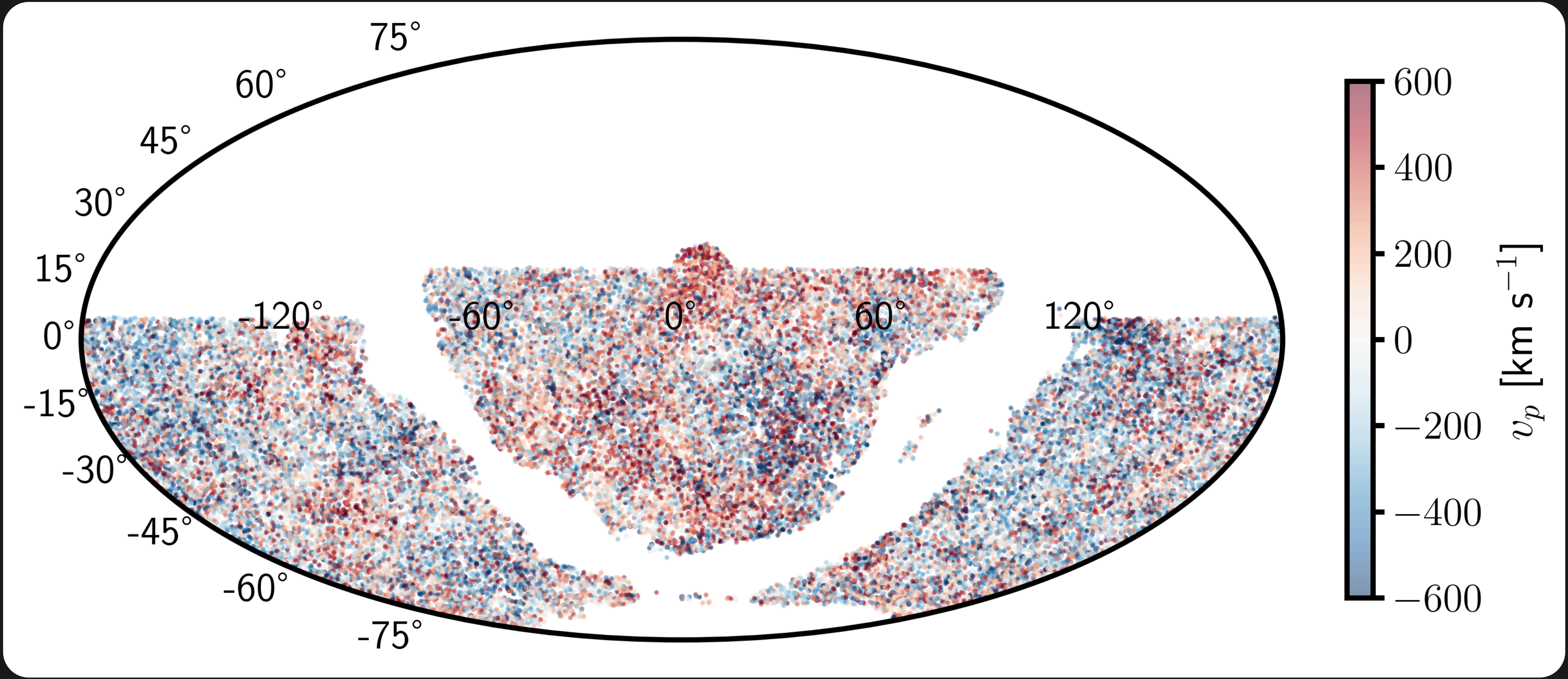


SALT parameters - host mass correlation from Popovic et al. 2021



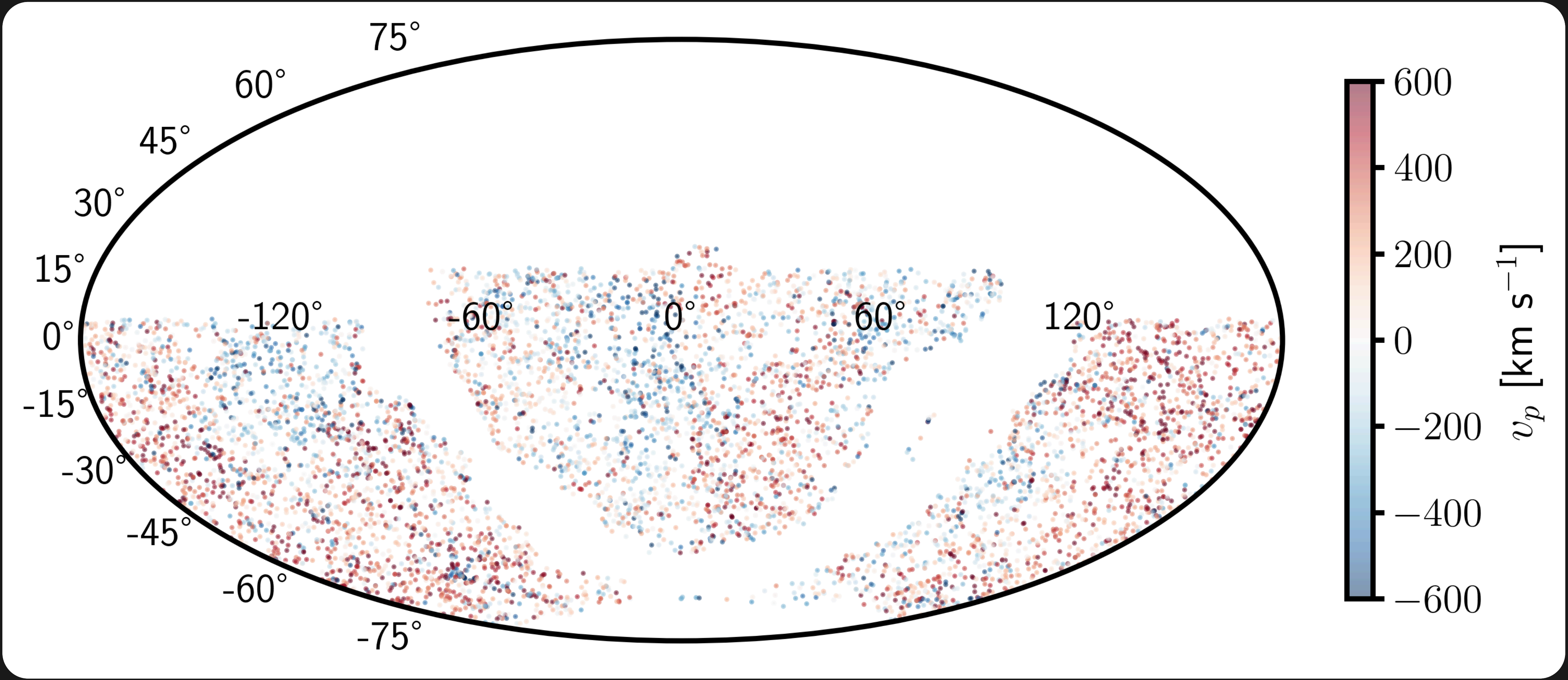
Simulation: the SNe Ia simulated sample

Simulation up to $z \sim 0.16 \Rightarrow N_{\rm SN} \sim O(50\,000)$

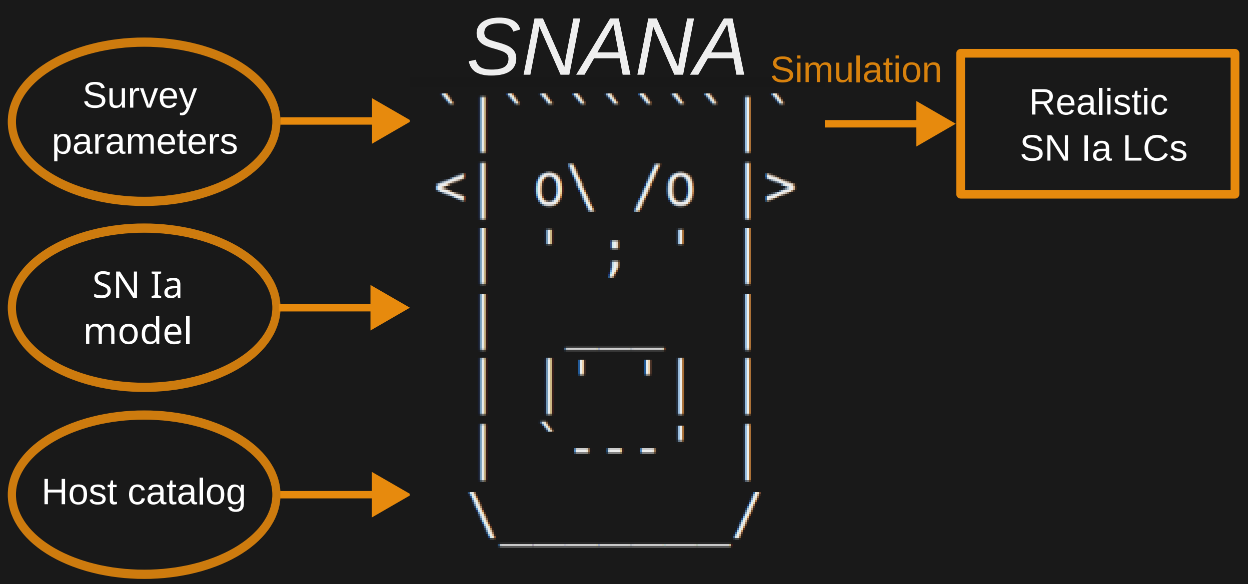


Simulation: the SNe Ia simulated sample

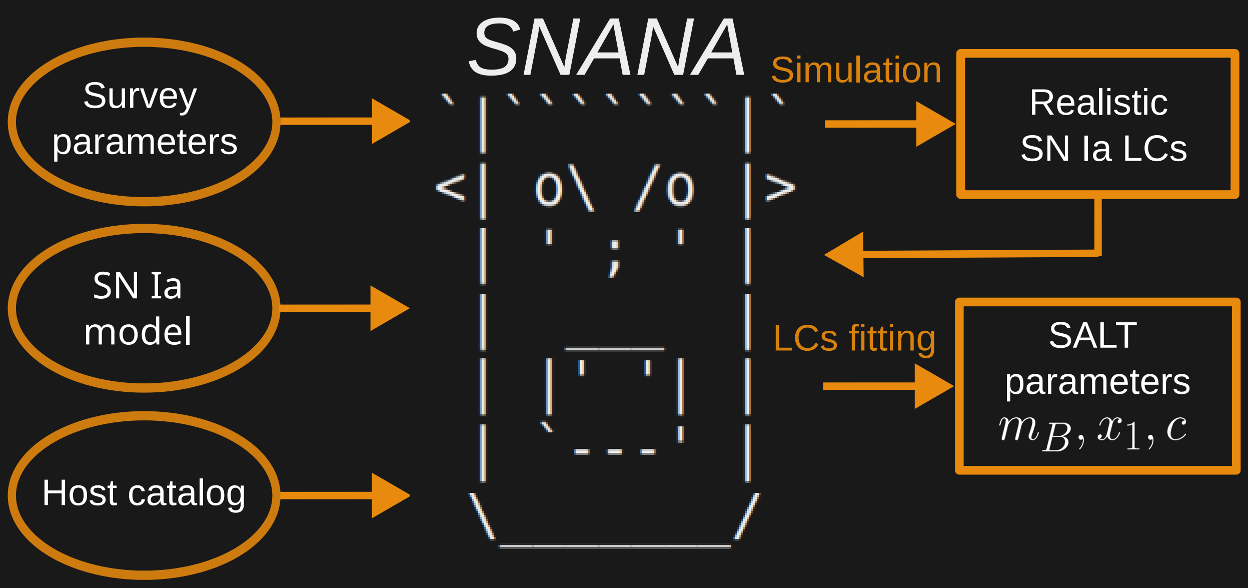
Using SNe Ia up to $z \sim 0.1 \;\Rightarrow\; N_{\rm SN} \sim O(6\,600)$



Building the Hubble diagram



Building the Hubble diagram



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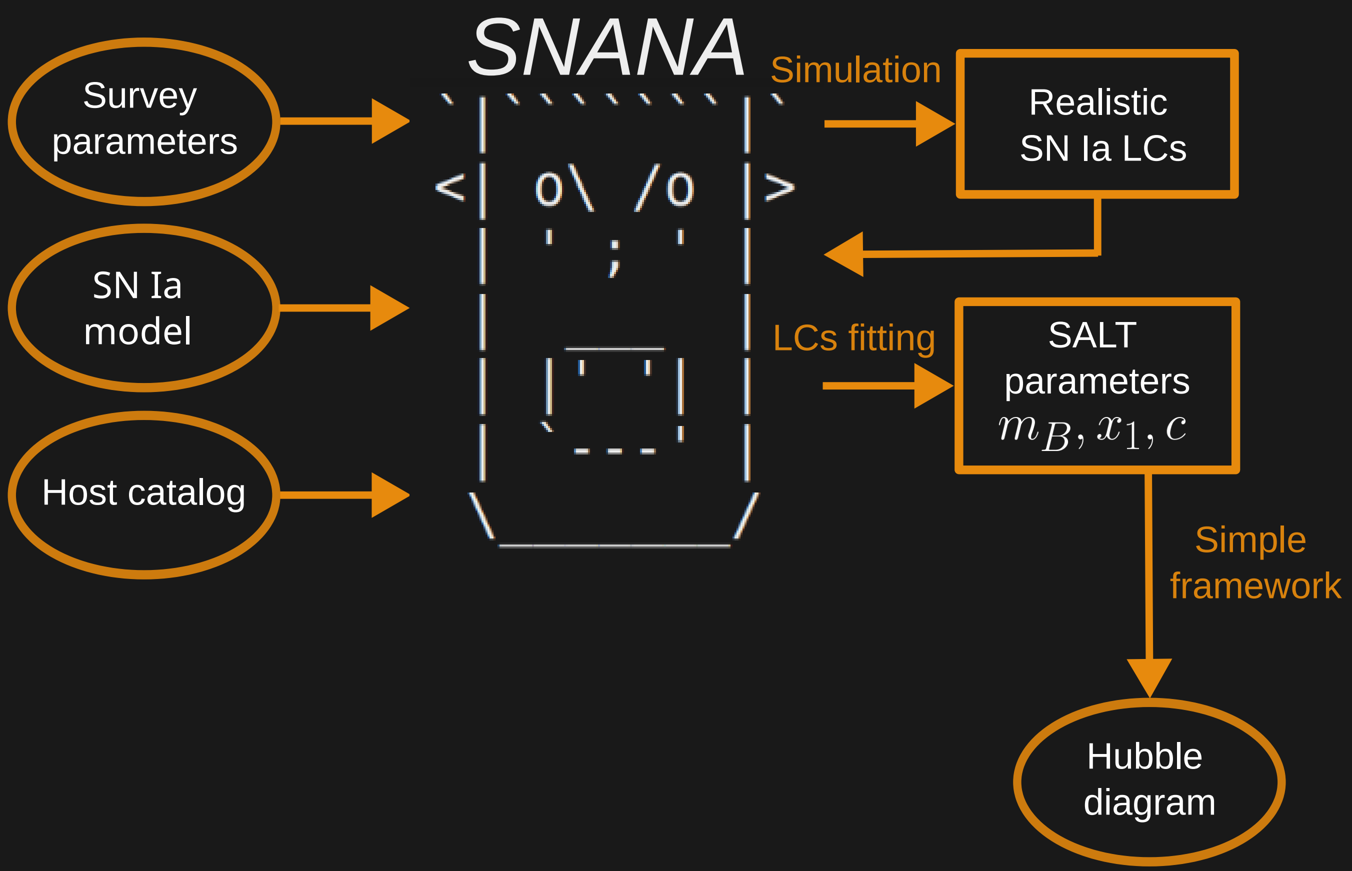


Building the Hubble diagram: simple framework

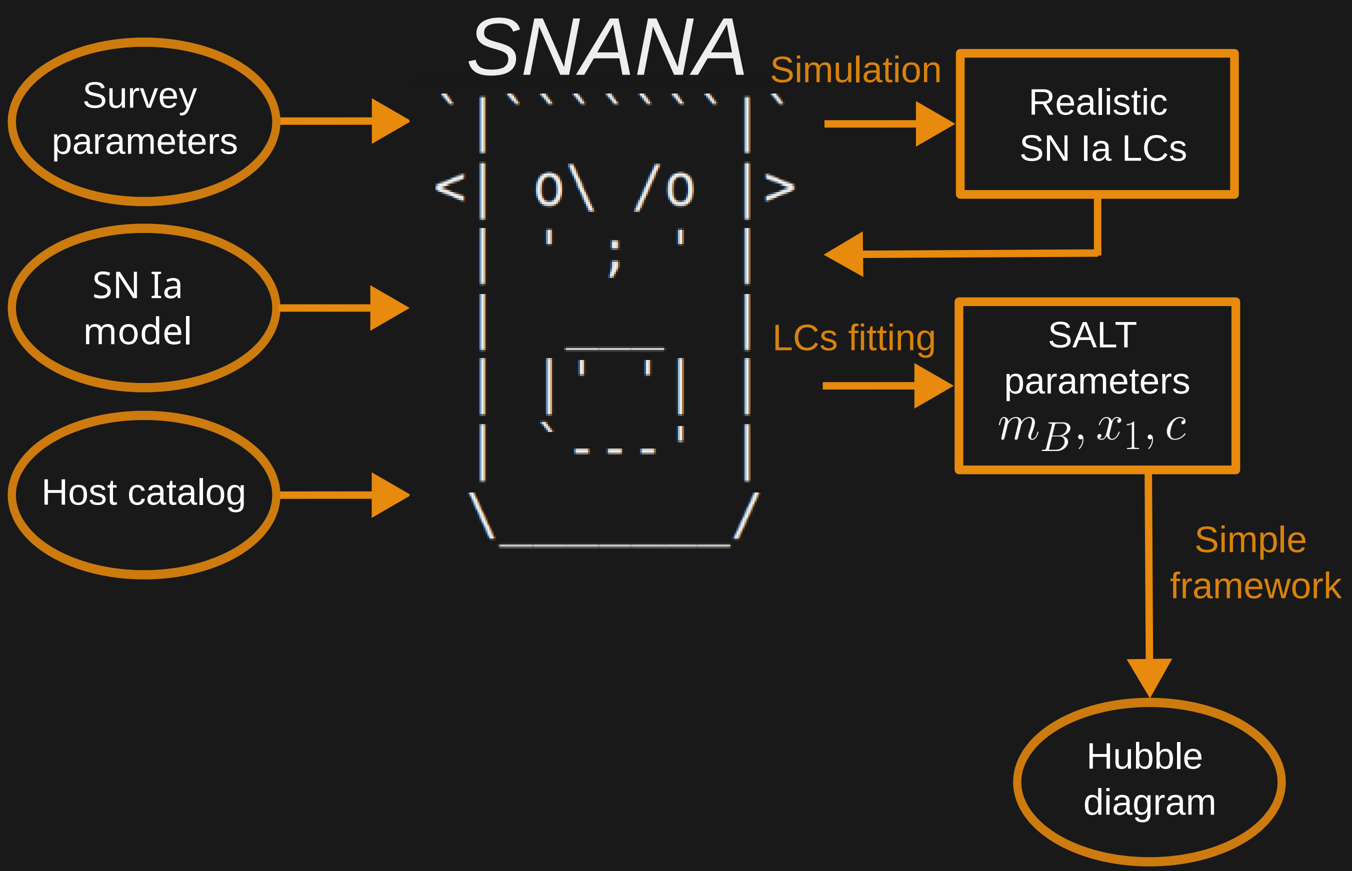
Fit for the Tripp relation along $f\sigma_8$:

$$\boldsymbol{\mu}_{\mathbf{obs}} = \boldsymbol{m}_{B} - \left(M_0 - \alpha \boldsymbol{x}_{\mathbf{1}} + \beta \boldsymbol{c} + \boldsymbol{\Delta}_{M}\left(\mathbf{M}_{\text{host}}; \gamma\right)\right)$$

$$\boldsymbol{\sigma}_{\mu}^{2} = \boldsymbol{\sigma}_{\mathbf{obs}}^{2} + {\sigma_{\text{int}}}^{2}$$

M_0, α, β, γ and σ_{int} are free parameters.

Building the Hubble diagram



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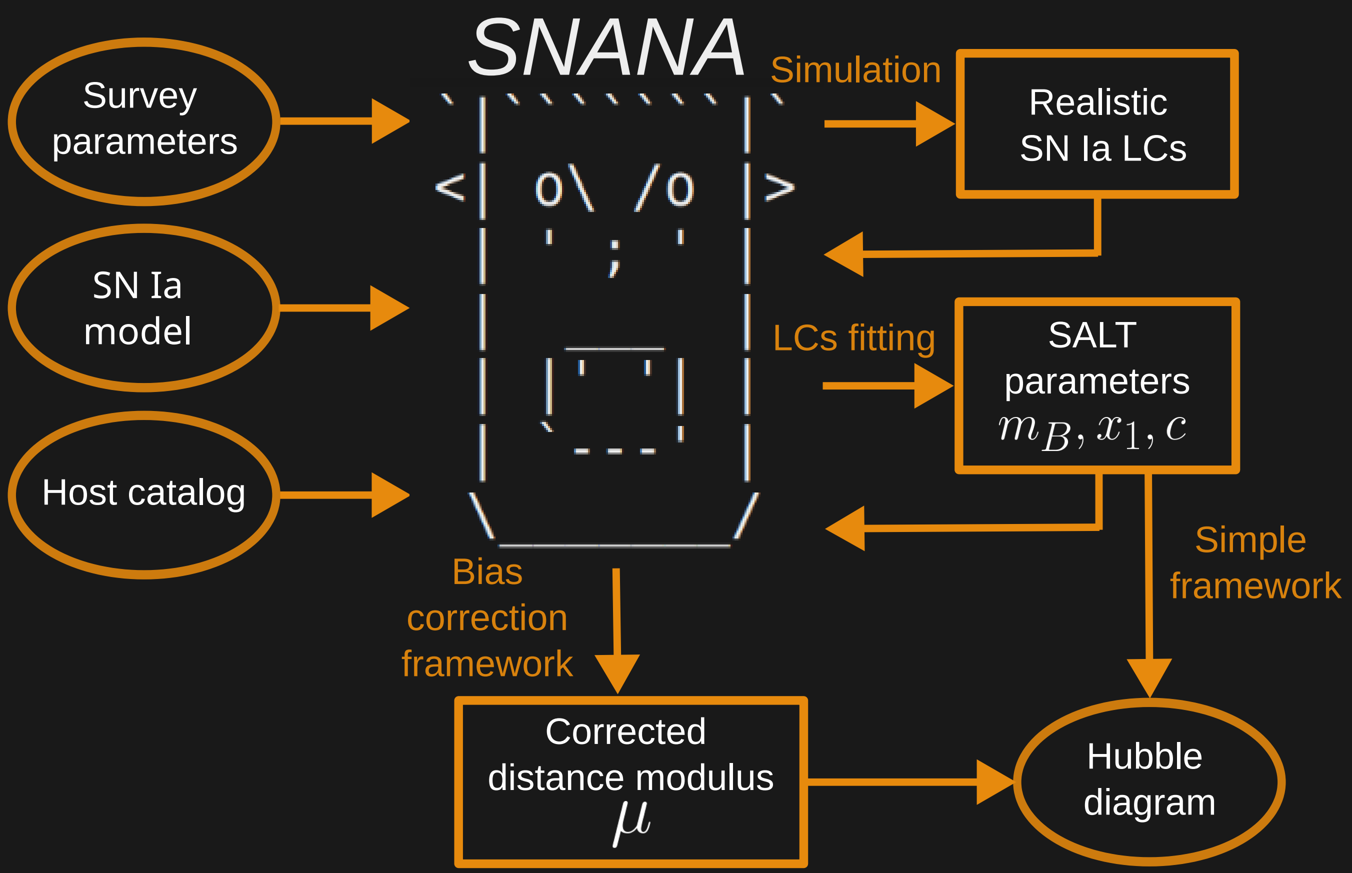

Building the Hubble diagram: BBC framework

$$\boldsymbol{\mu}_{\mathbf{obs,BBC}} = \boldsymbol{m}_{\boldsymbol{B}} - \left(M_0 - \alpha \boldsymbol{x}_{\mathbf{1}} + \beta \boldsymbol{c} + \boldsymbol{\Delta}_{\boldsymbol{M}}\left(\mathbf{M}_{\mathrm{host}}; \gamma\right)\right) + \delta_{\mathrm{corr.}}$$

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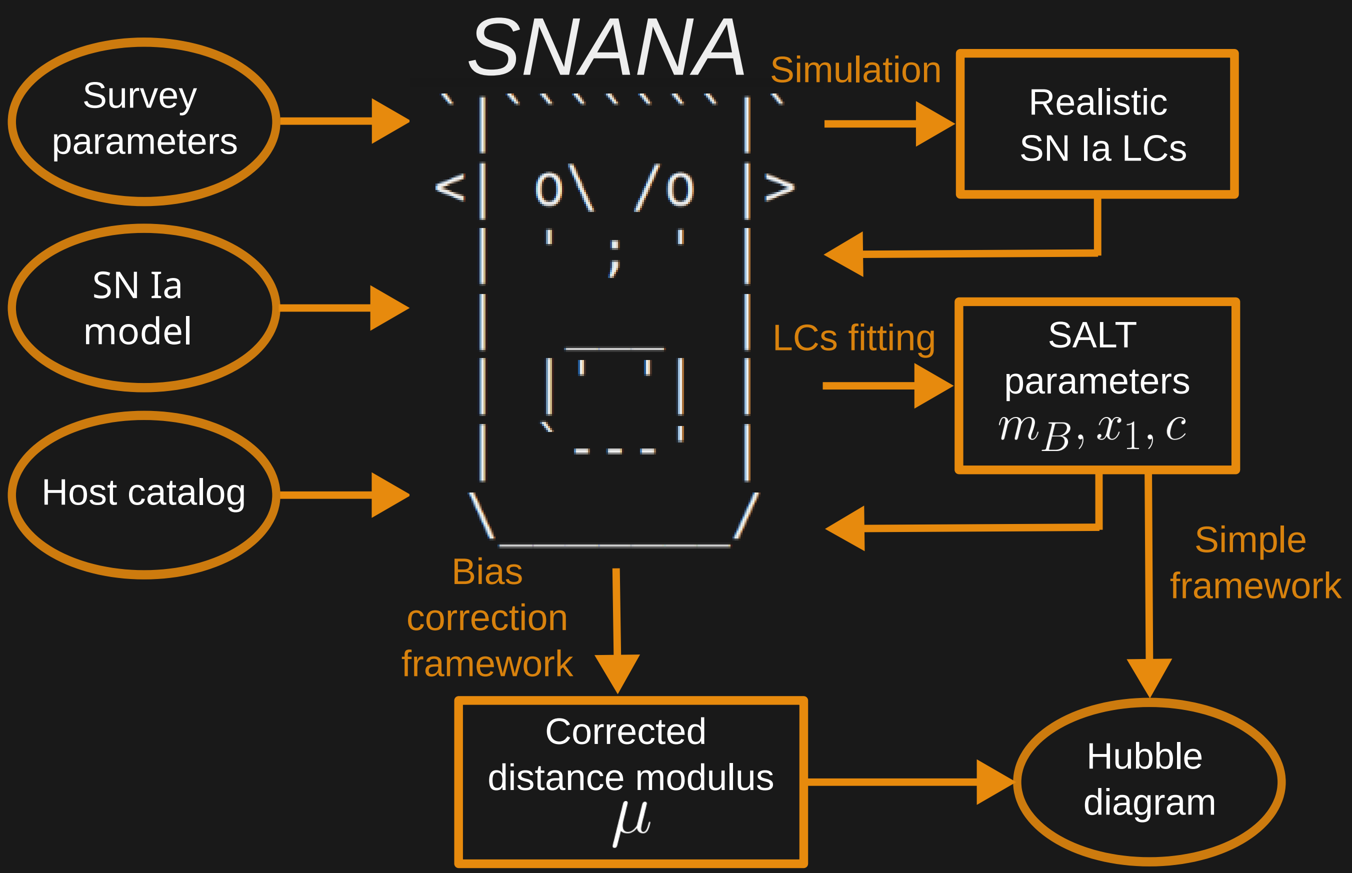
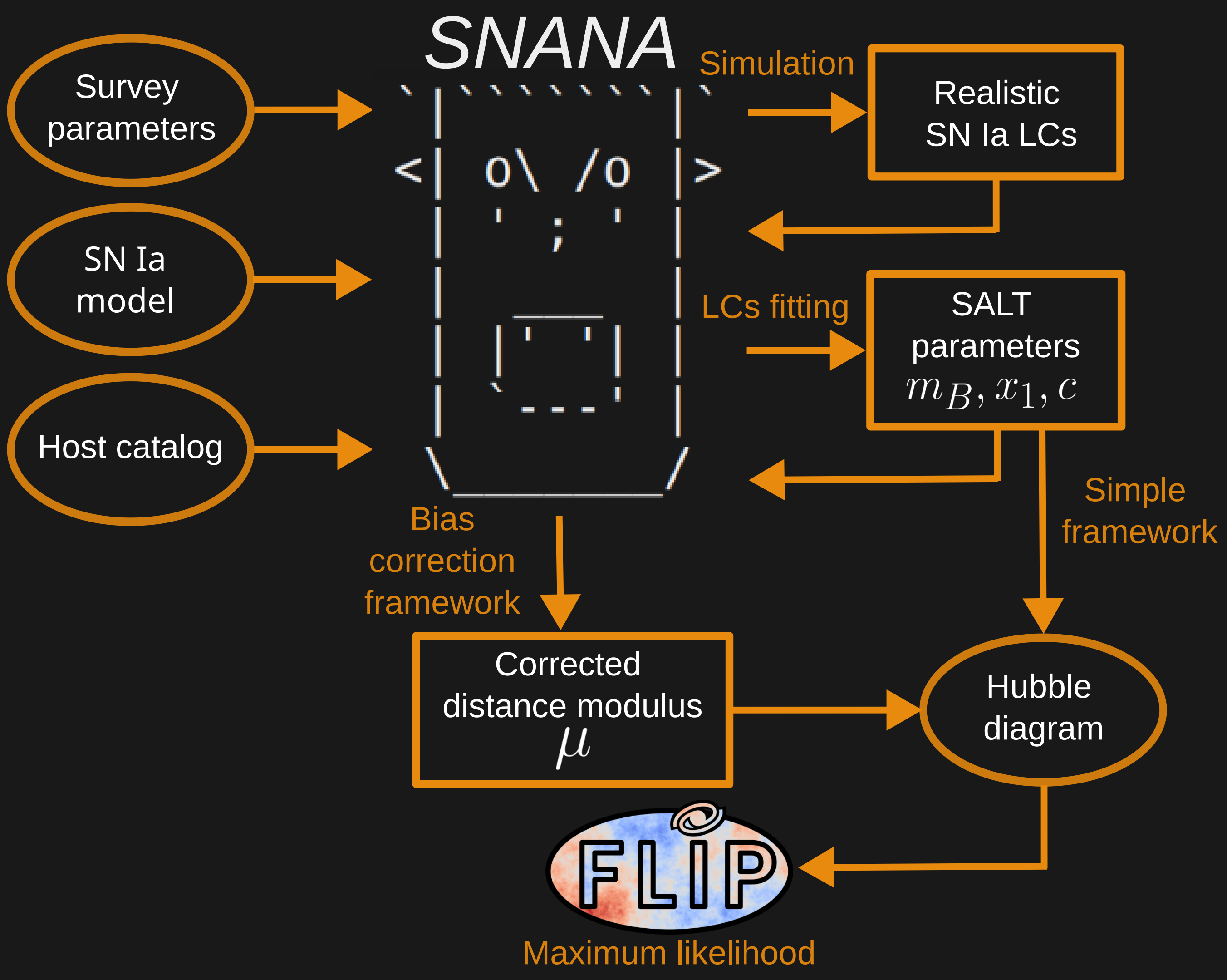
α, β, γ and σ_{int} are fitted prior to $f\sigma_8$

The maximum likelihood method



The maximum likelihood method



The maximum likelihood mehod

The Maximum likelihood method is implemented within the FLIP package (*Ravoux, Carreres et al. 2025*)

We want to maximize the likelihood function:

$$\mathcal{L}(f\sigma_8; v_p) \propto (2\pi)^{-\frac{N}{2}} |\mathrm{C}(f\sigma_8)|^{-\frac{1}{2}} \exp\left(-\frac{1}{2}\boldsymbol{v_p}^T \mathrm{C}(f\sigma_8)^{-1} \boldsymbol{v_p}\right)$$

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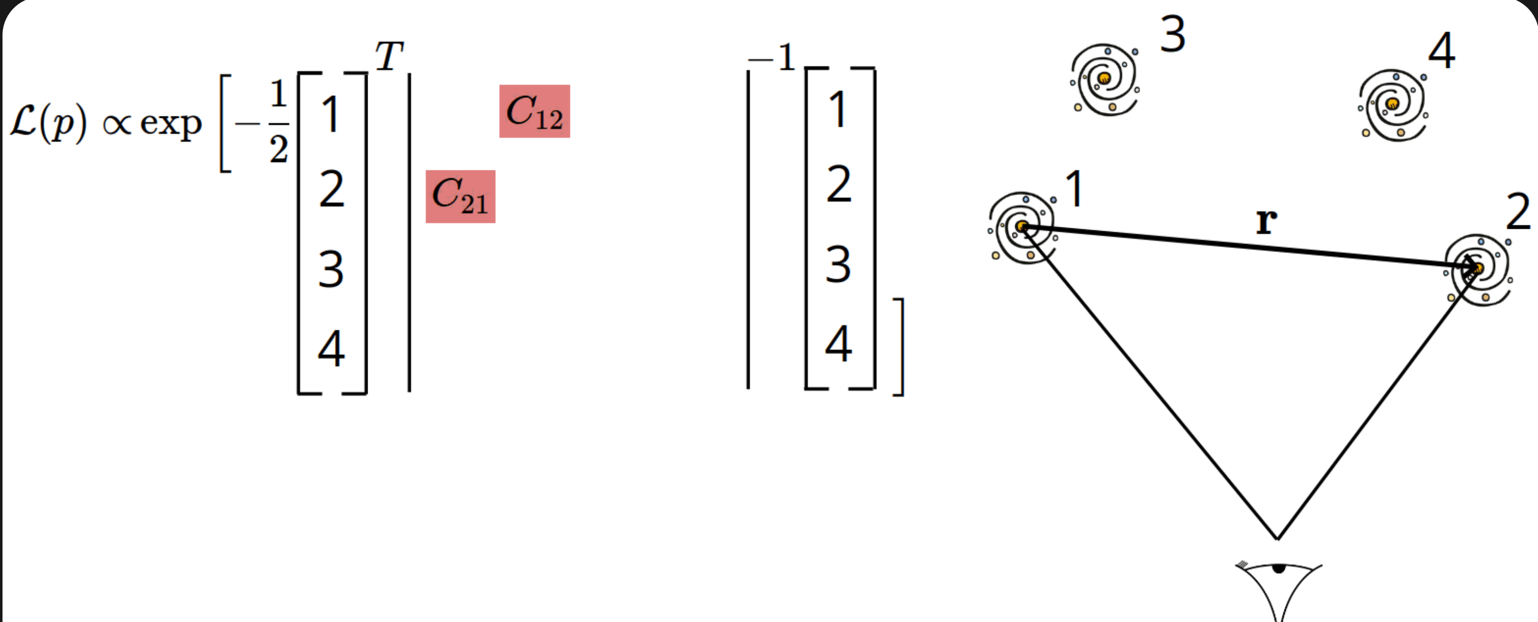
$$\mathrm{C}(f\sigma_8) = \mathrm{C}^{\mathrm{obs}} + \mathrm{C}^{vv}(f\sigma_8)$$

The maximum likelihood mehod: velocity covariance

The covariance of the velocity field is:

$$\langle v_i(\mathbf{r}_i) v_j(\mathbf{r}_j)\rangle = \mathrm{C}_{ij}^{vv} \propto (f\sigma_8)^2 \int_{k_{\min}}^{k_{\max}} P(k) W_{ij}(k; \mathbf{r}_i, \mathbf{r}_j) \mathrm{d}k$$



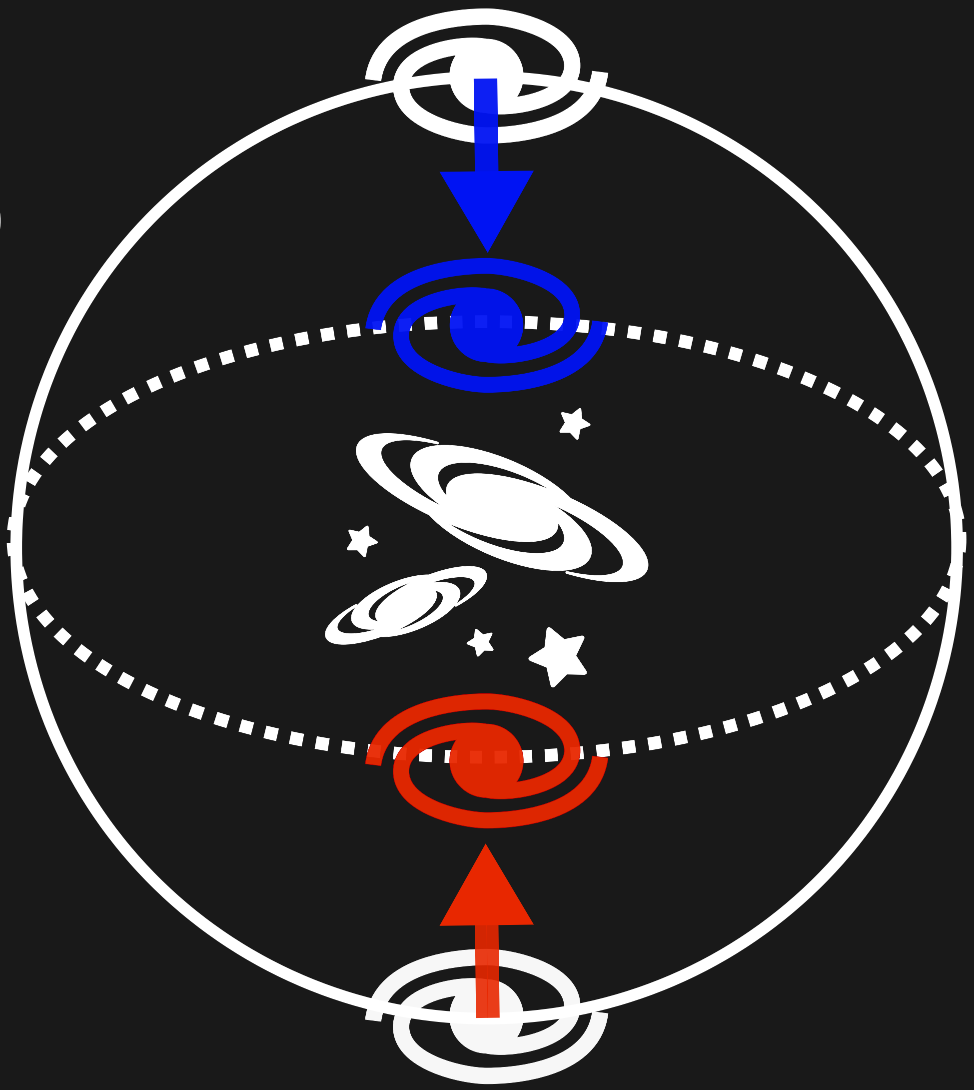
Credits: Corentin Ravoux

The σ_u redshift space parameter

Positions are evaluated using $z_{\rm obs}$ $\Rightarrow$ Redshift Space Distorsion

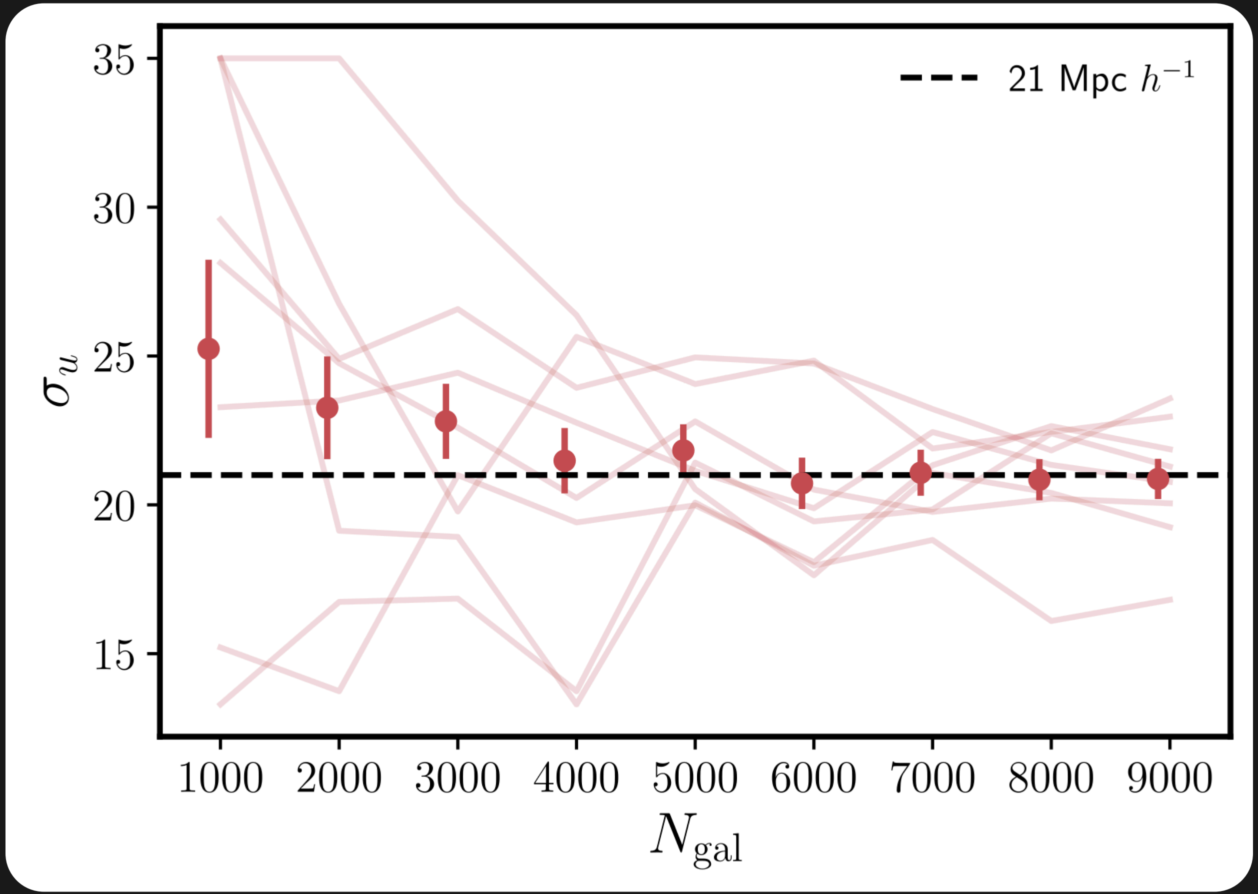
Empirical damping introduced in *Koda et al. 2014*: $D_u = \mathrm{sinc}(k\sigma_u)$

$$C_{ij}^{vv} \propto (f\sigma_8)^2 \int_{k_{\rm min}}^{k_{\rm max}} P(k) D_u(k, \sigma_u)^2 W_{ij}(k; \mathbf{r}_i, \mathbf{r}_j) \mathrm{d}k$$

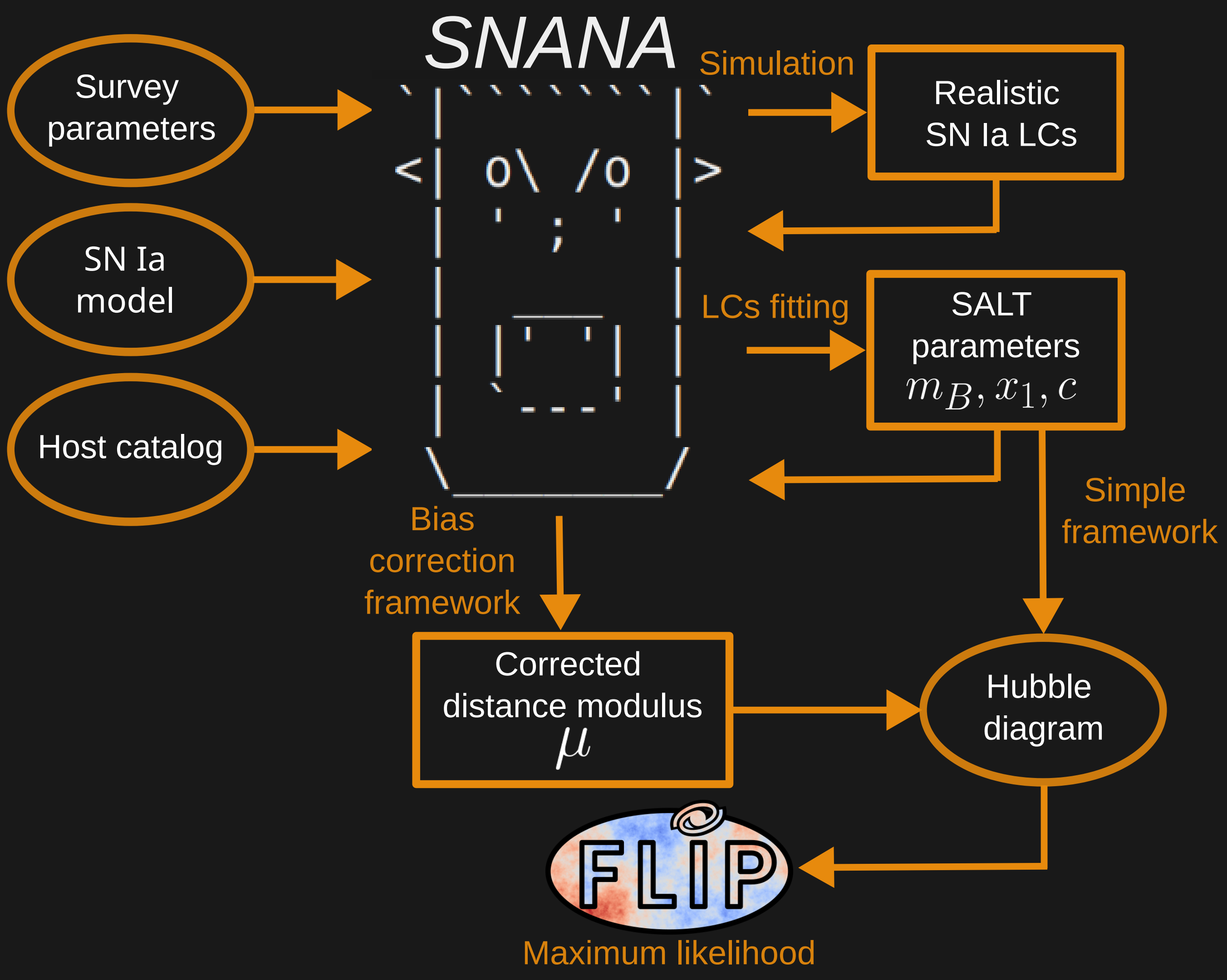


The σ_u redshift space parameter

From a fit of true vel. from randomly sampled galaxies of the Uchuu simulation we found $\sigma_u \simeq 21 \ \mathrm{Mpc}\ h^{-1}$



Fitting for $f\sigma_8$



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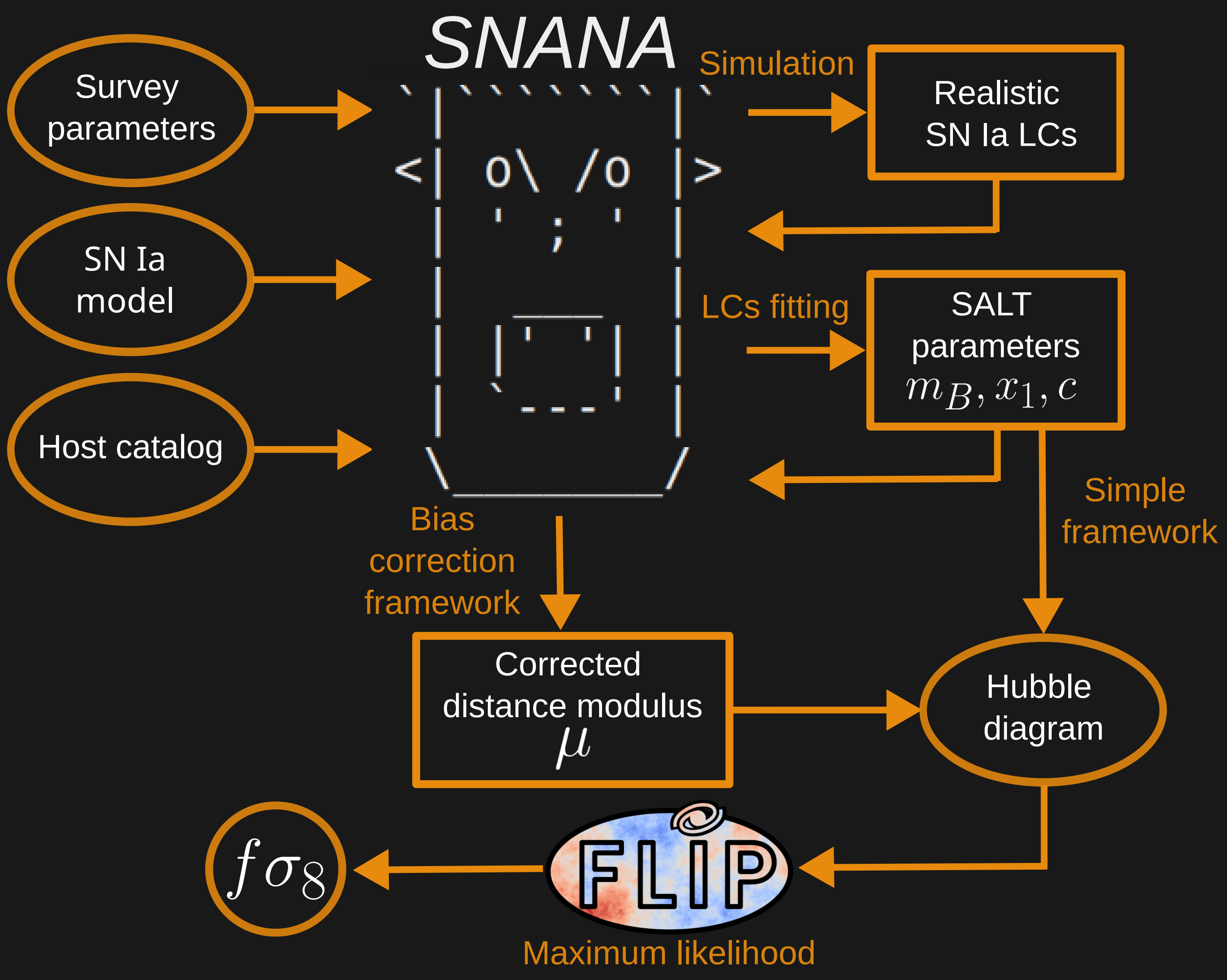
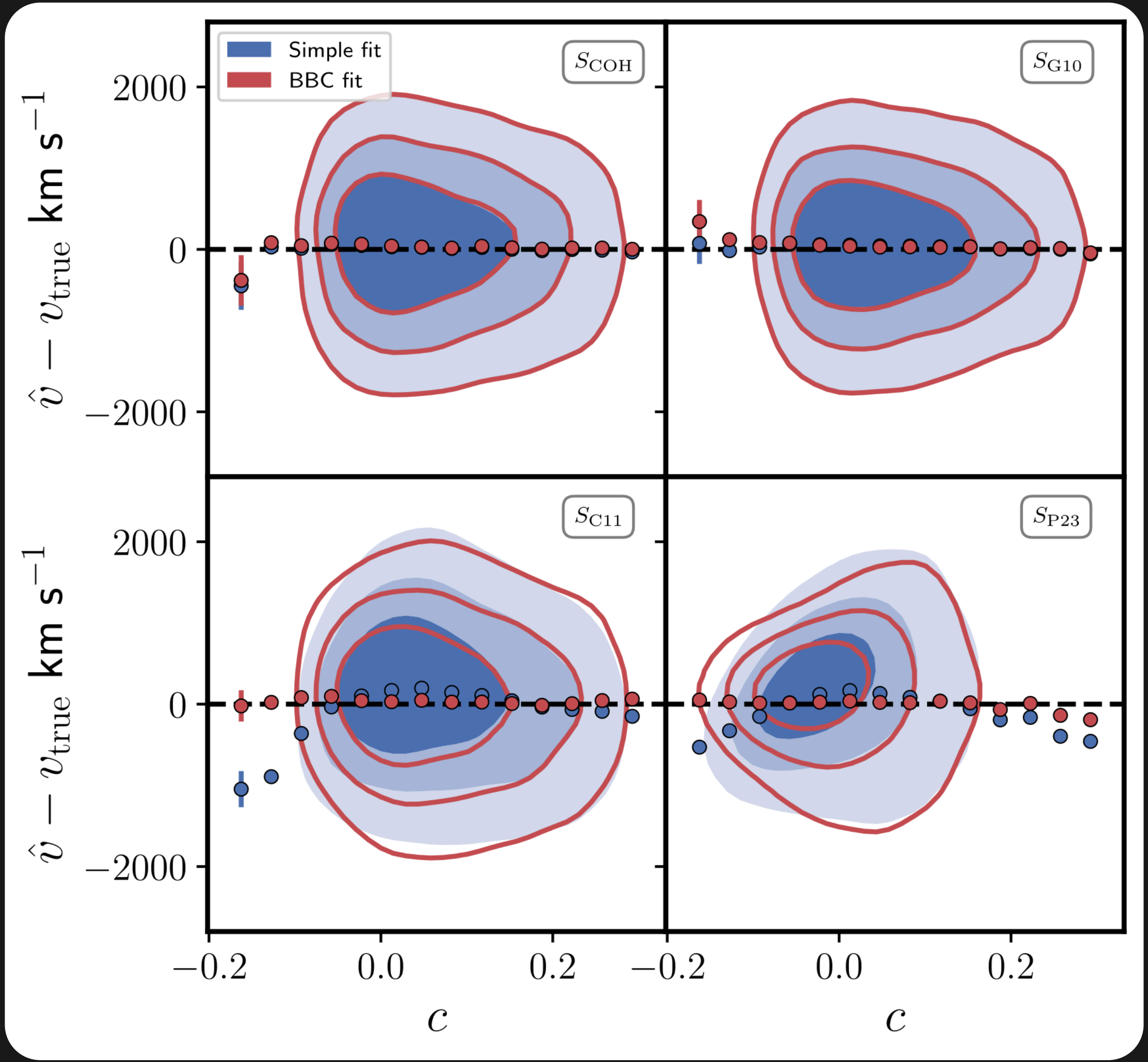


Results: Estimated velocities



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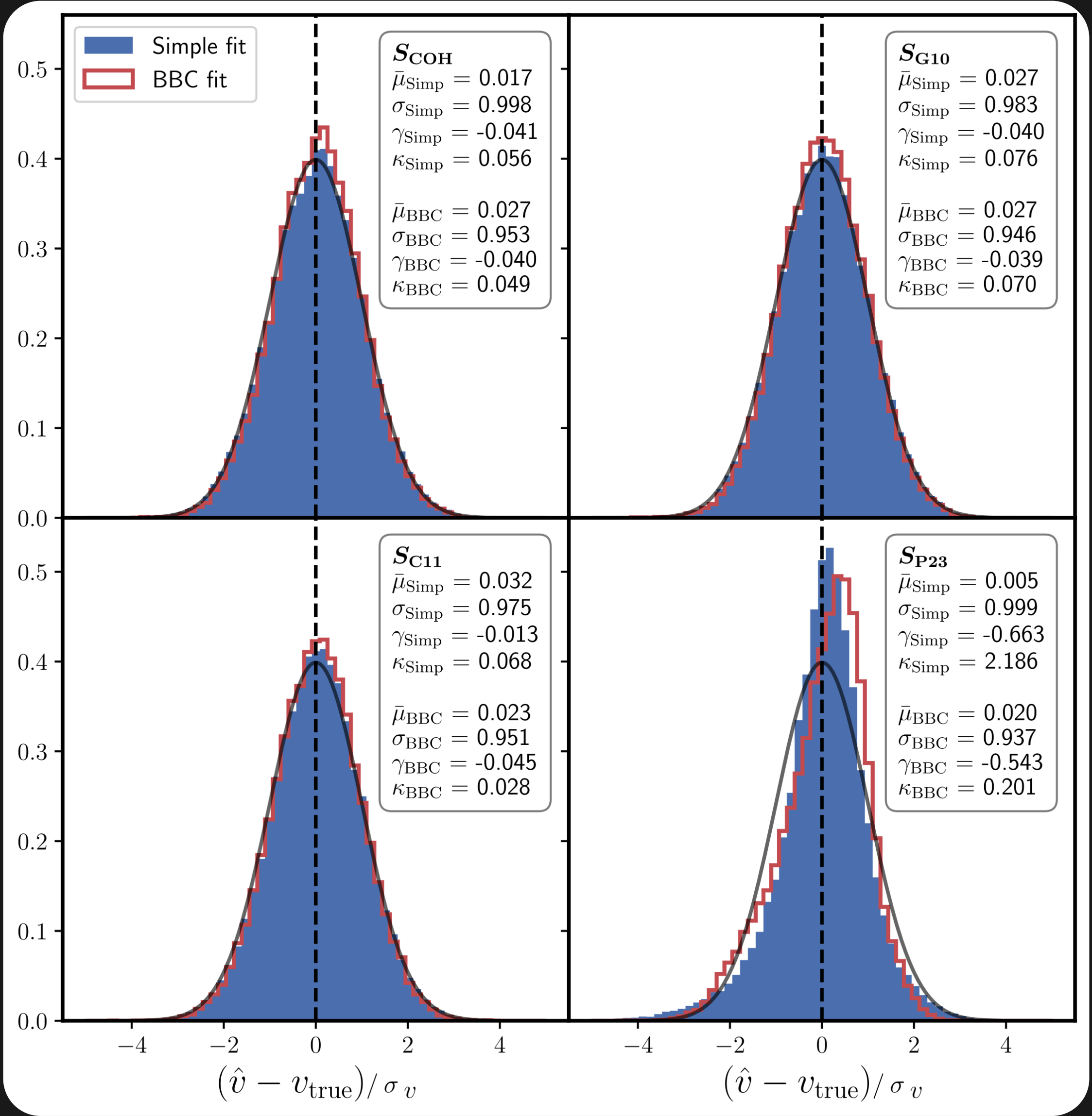
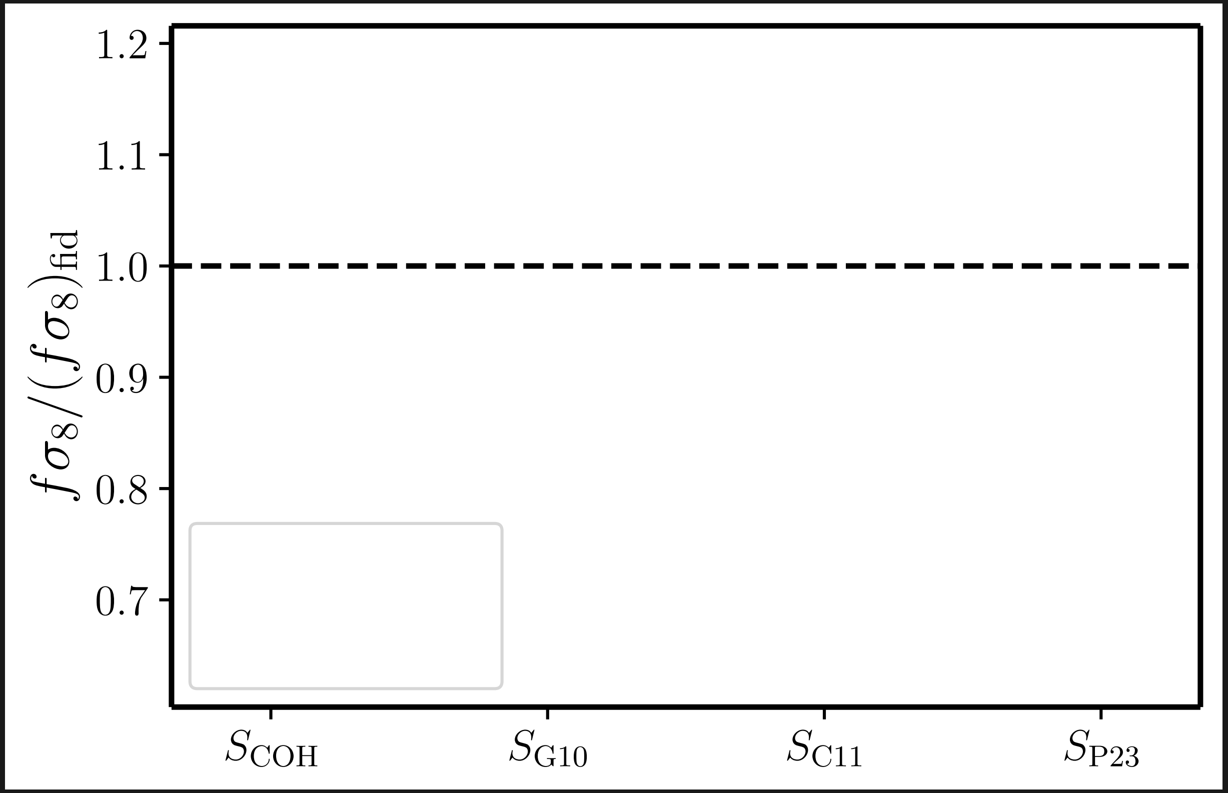


Results: $f\sigma_8$ fit for different scatter models



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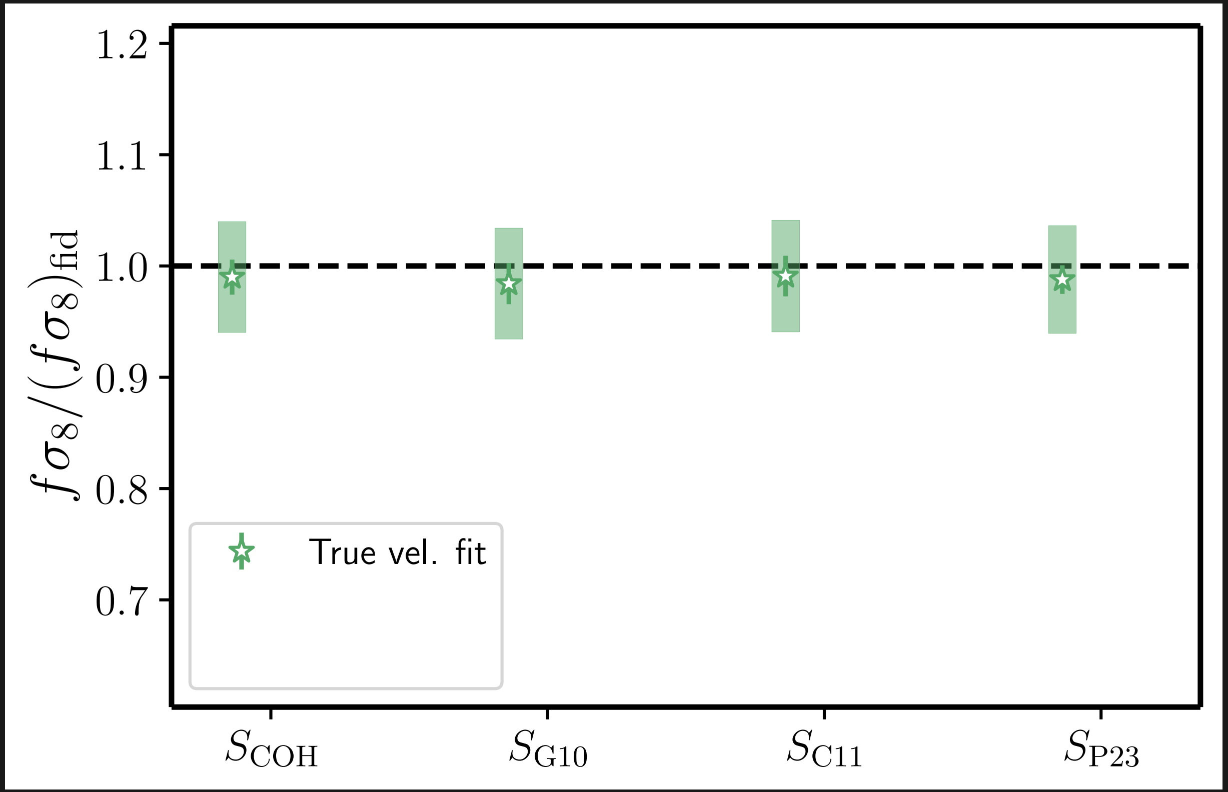
- True vel. fit:
  Unbiased $f\sigma_8$
  $\sigma_{f\sigma_8} \sim 5\%$



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  Similar results for simple and BBC fit
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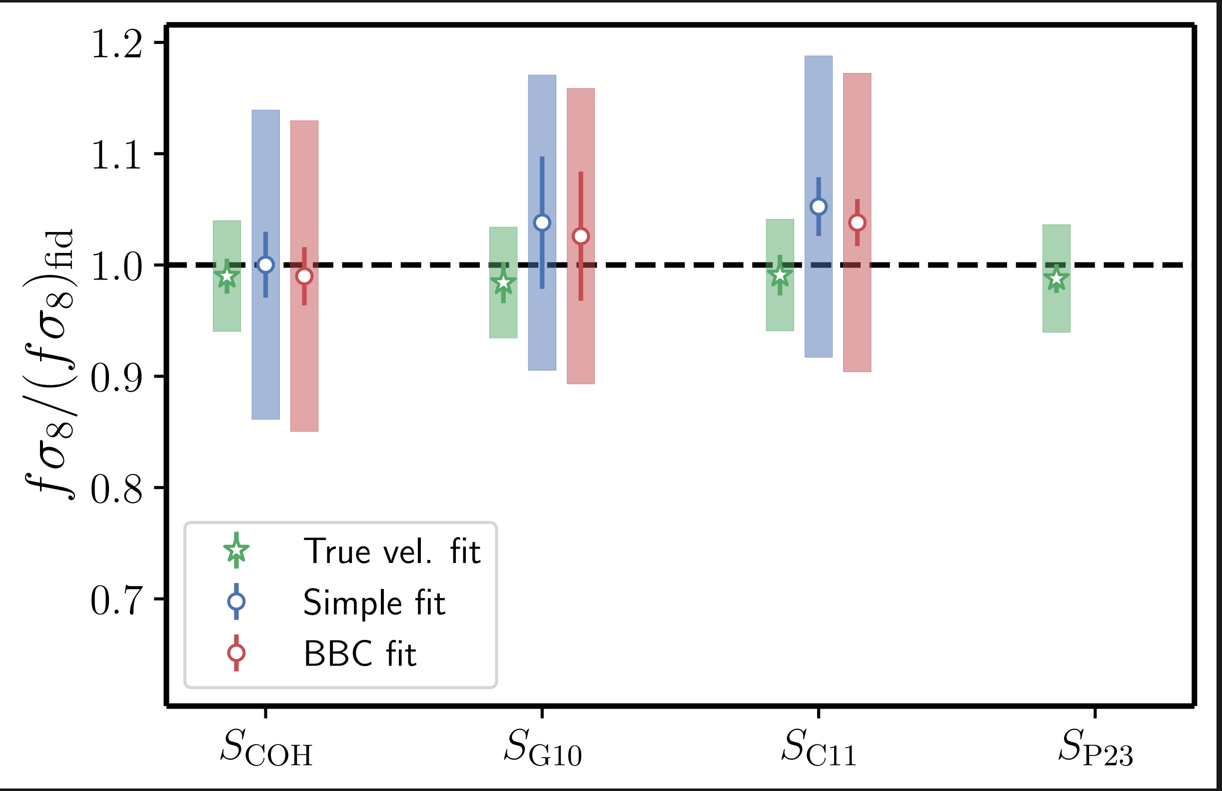

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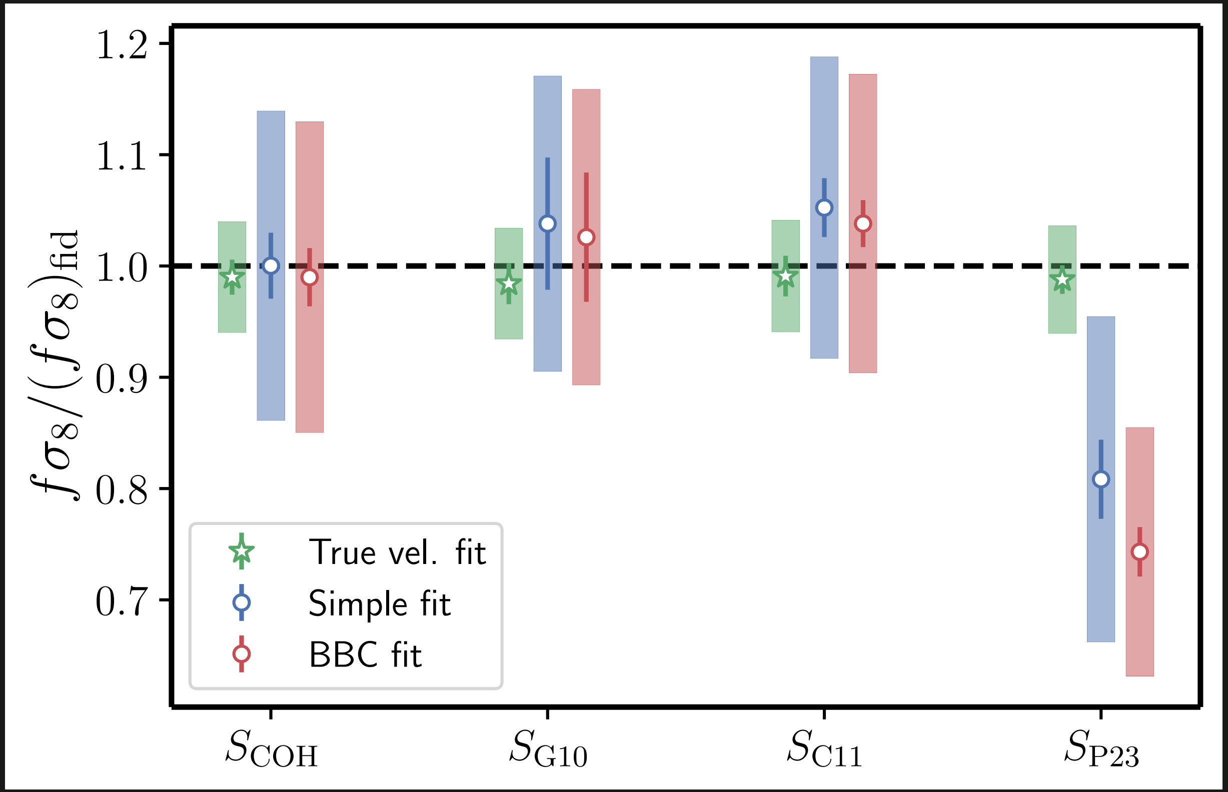
- P23 - Simple fit: $\sigma_{f\sigma_8} \sim 15\%$
  P23 - BBC fit: $\sigma_{f\sigma_8} \sim 11\%$
  Results for P23 are biased by $> 20\%$!!!



Results: Systematics - BS21 parameter variations

Errors on BS21 parameters propagated as in DES 5-year analysis (*Vincenzi et al. 2024*)

No change in $f\sigma_8$ fit!!!

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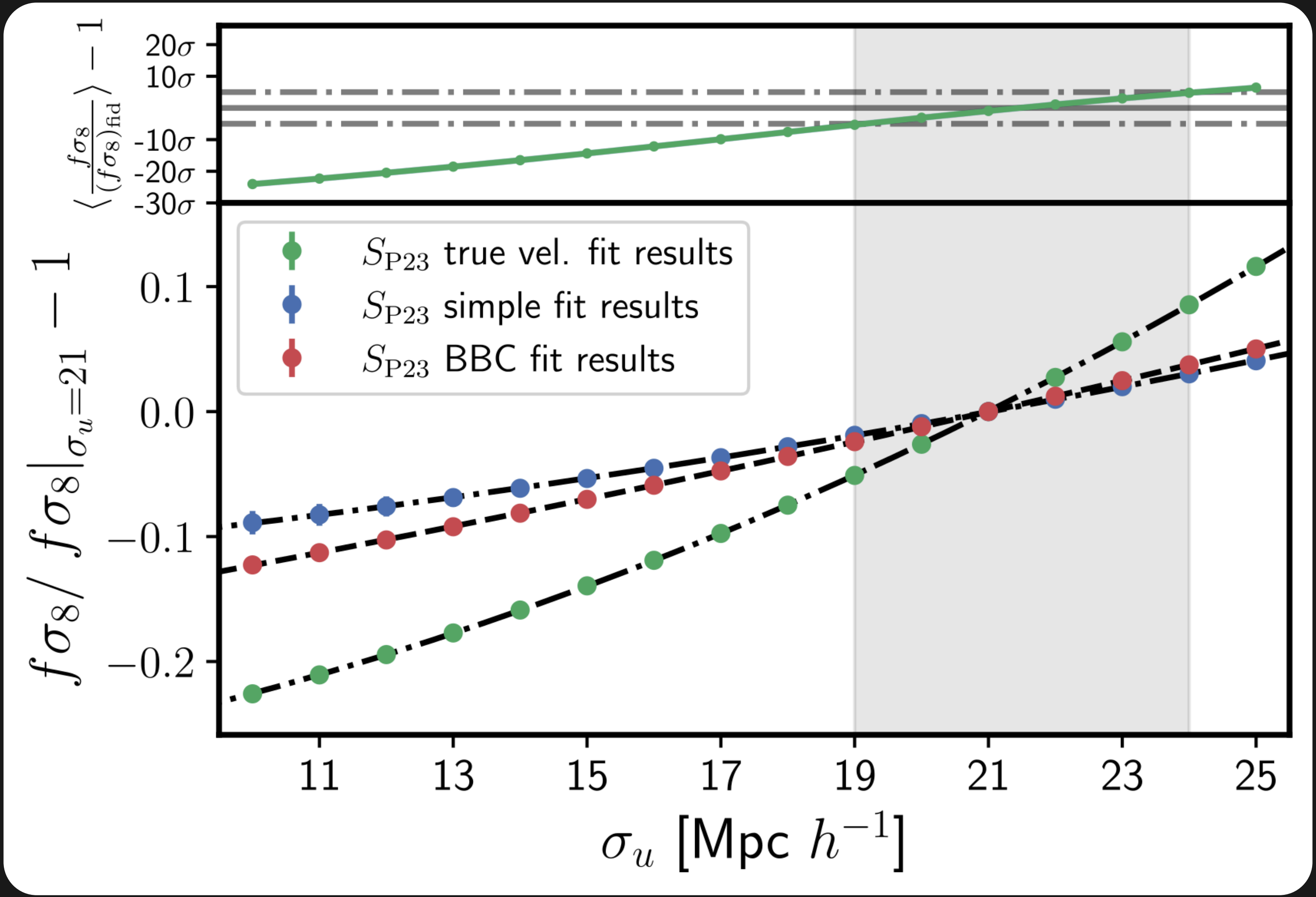
Errors on BS21 parameters propagated as in DES 5-year analysis (*Vincenzi et al. 2024*)

No change in $f\sigma_8$ fit!!!

	$\langle f\sigma_8\rangle / (f\sigma_8)_{\rm fid}$	$\sqrt{\langle \sigma^2_{f\sigma_8}\rangle}$
BBC fit	0.649 ± 0.028	12.2%
BBC + int. scat. cov fit	0.647 ± 0.028	12.2%

Results: Systematics - σ_u RSD parameter

$$\Delta\sigma_u \sim 18.5 - 23.5 \text{ Mpc } h^{-1} \Rightarrow \sigma_{f\sigma_8}^{\sigma_u} \sim 6\%$$



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What's next?

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- Is the BS21 model prediction correct? Will we see non-Gausianities in data?

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What's next?

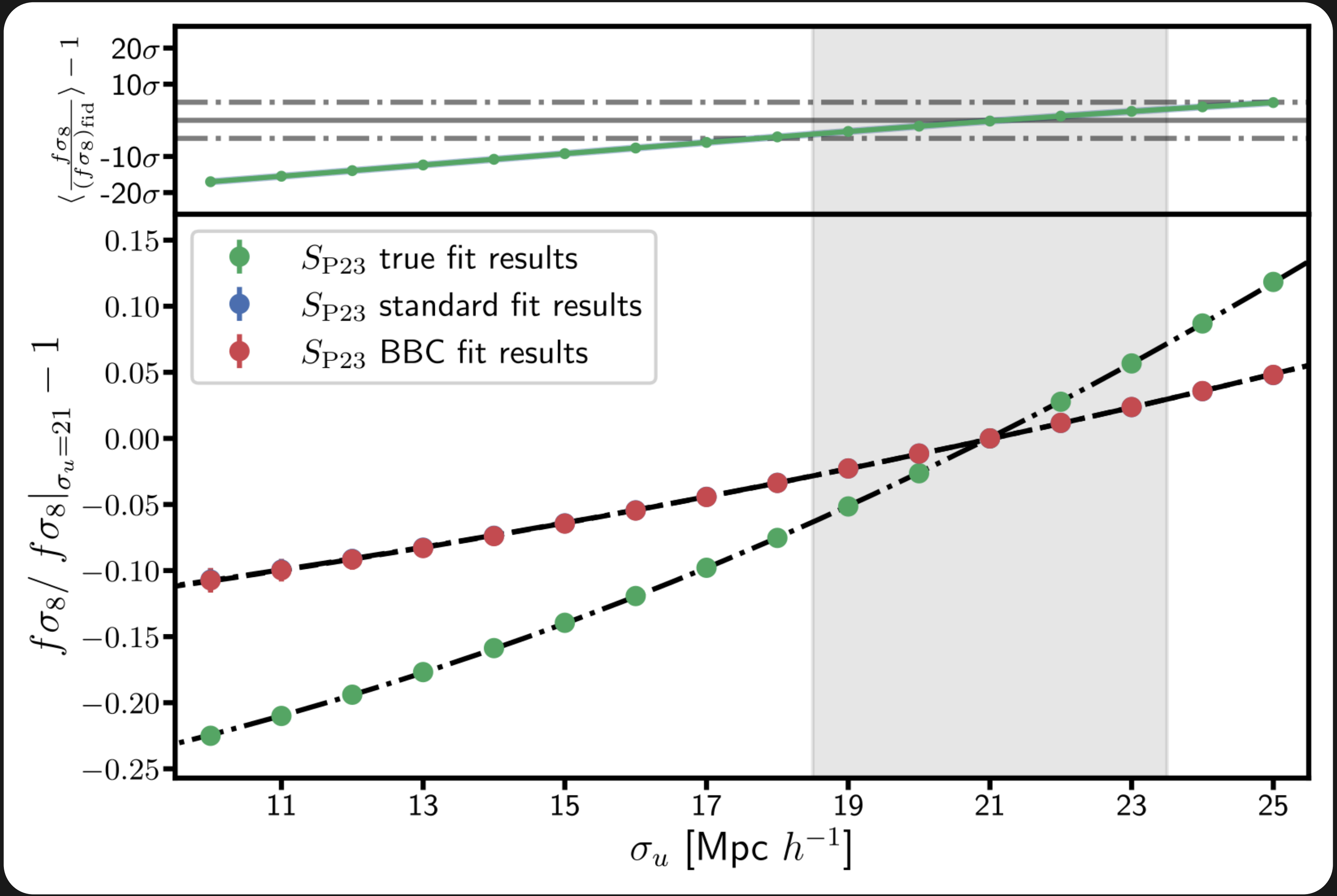
- Is the BS21 model prediction correct? Will we see non-Gausianities in data?
- Is it possible to find a better RSD parametrisation than σ_u?

Thank you for your attention !

Full $f\sigma_8$ results

Models	True fit			Standard fit			BBC fit		
	$\langle f\sigma_8\rangle / (f\sigma_8)_{\rm fid}$	$\sqrt{\langle\sigma^2_{f\sigma_8}\rangle}$ (%)	STD($f\sigma_8$) (%)	$\langle f\sigma_8\rangle / (f\sigma_8)_{\rm fid}$	$\sqrt{\langle\sigma^2_{f\sigma_8}\rangle}$ (%)	STD($f\sigma_8$) (%)	$\langle f\sigma_8\rangle / (f\sigma_8)_{\rm fid}$	$\sqrt{\langle\sigma^2_{f\sigma_8}\rangle}$ (%)	STD($f\sigma_8$) (%)
$\mathrm{S_{RND}}$	1.008 ± 0.015	4.7	4.3	0.979 ± 0.023	12.7	6.7	0.983 ± 0.024	12.5	6.8
$\mathrm{S_{G10}}$	1.000 ± 0.018	4.7	5.2	1.013 ± 0.047	12.0	13.2	1.014 ± 0.049	11.9	13.7
$\mathrm{S_{C11}}$	1.001 ± 0.017	4.7	4.9	0.999 ± 0.029	10.5	8.3	1.000 ± 0.026	10.3	7.3
$\mathrm{S_{P23}}$	0.999 ± 0.013	4.6	3.6	0.834 ± 0.035	13.6	12.0	0.805 ± 0.024	10.3	8.5

σ_u syst. for G10



HD residuals