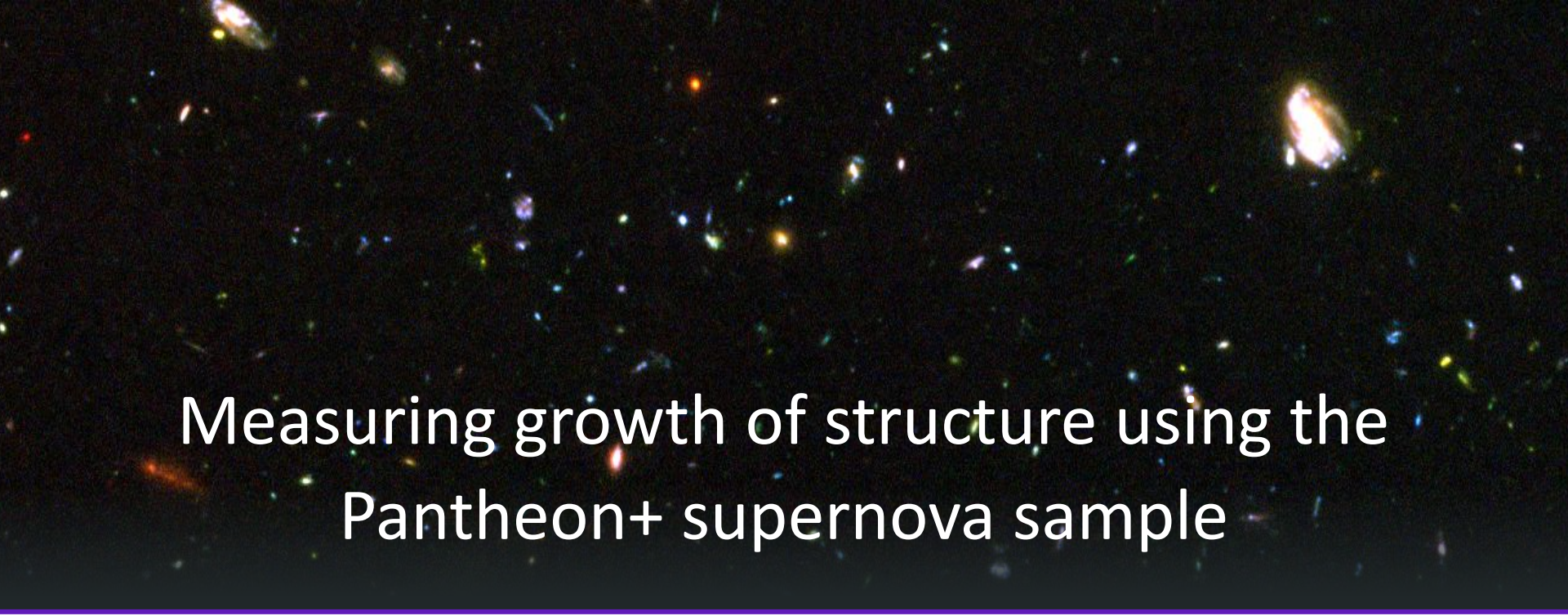


Measuring growth of structure using the Pantheon+ supernova sample

Anthony Carr (KASI)

11th KIAS Workshop, 경주시

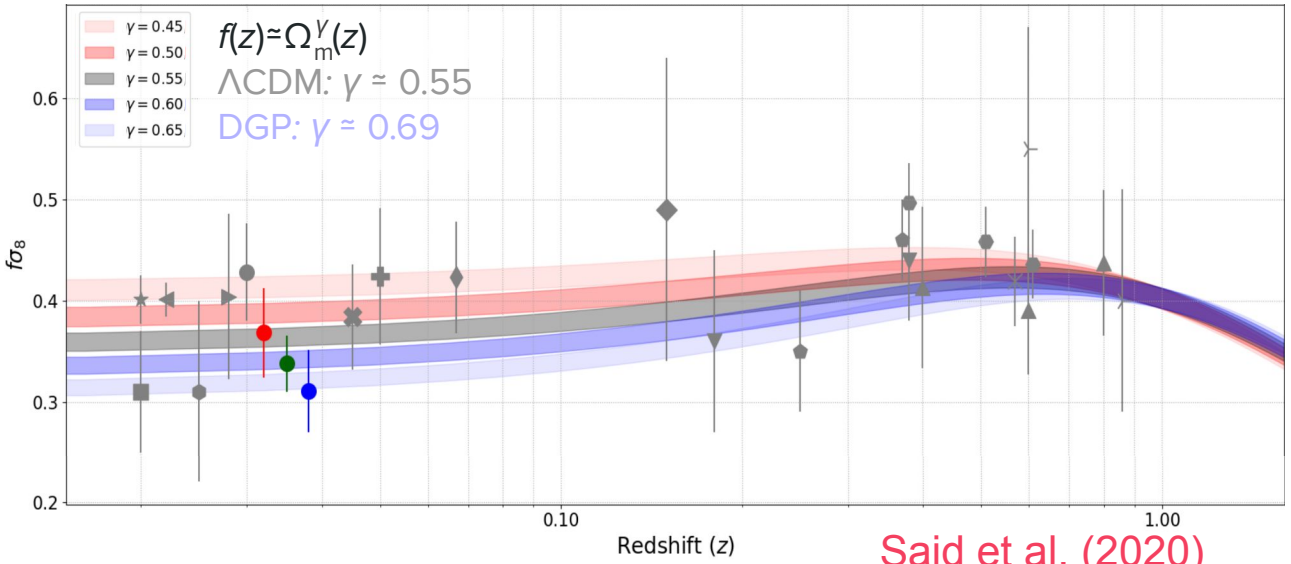
31/10/2024

Why supernova PVs? Why $f\sigma_8$?

- PVs are a powerful tool at low-z
  - Probe large scales, complementary to redshift-space distortions
- Combined PV-overdensity (δ) analysis greater than the sum of its parts

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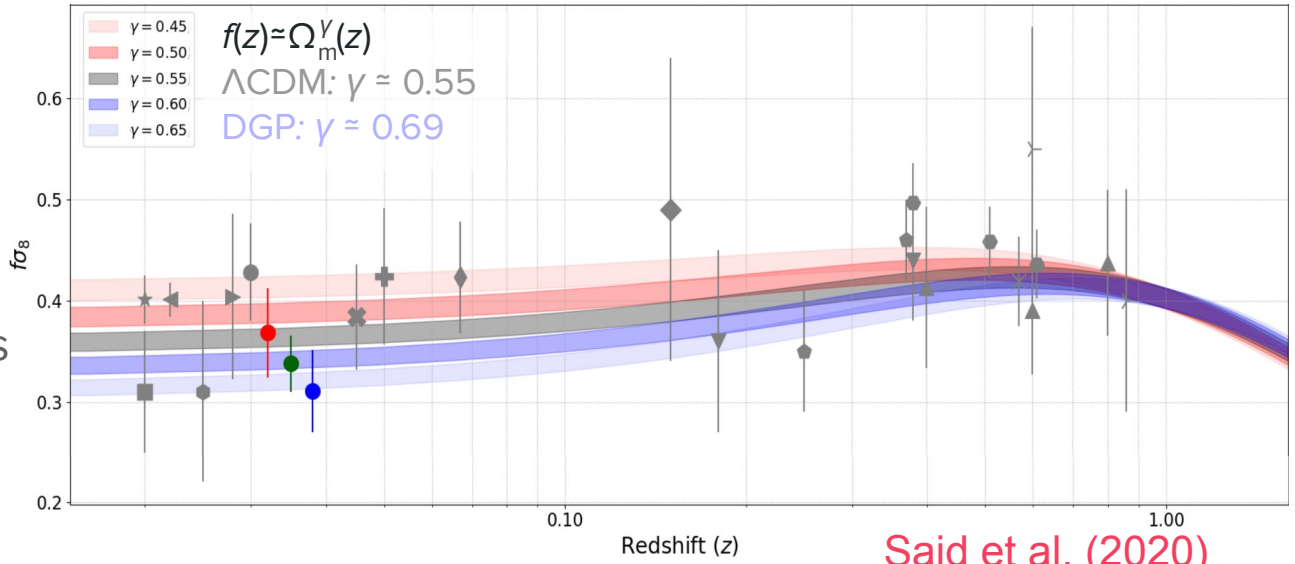
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Said et al. (2020)

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- Combined PV-overdensity (δ) analysis greater than the sum of its parts
- Tight $f\sigma_8$ constraints could distinguish modified gravity
- SNe Ia are precise, albeit rare, but 1000s more expected soon



Said et al. (2020)

How to constrain $f\sigma_8$ with PVs

- Maximise likelihood function.

$$\mathcal{L} = (2\pi)^{-N/2} |\mathbf{C}_{\rm tot}|^{-1/2} \exp\left(-\frac{1}{2} \boldsymbol{v}_{\rm p}^T \mathbf{C}_{\rm tot}^{-1} \boldsymbol{v}_{\rm p}\right)$$

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- Include measurement error and theoretical covariance ($\mathbf{C}_{\rm tot} = \mathbf{C}^{\rm meas.} + \mathbf{C}^{\rm vv}(f\sigma_8)$)

$$C_{ij}^{\rm meas.} = (\sigma_v^2 + \sigma_\mu^2)\delta_{ij}^K$$

$$or$$

$$= \sigma_v^2 \delta_{ij}^K + C_{ij}^{\rm Pantheon+}$$

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$$C_{ij}^{vv} = \langle v_{\rm p}(\boldsymbol{x}_i) v_{\rm p}^*(\boldsymbol{x}_j) \rangle$$

$$= {\rm const.} \int_0^\infty f^2 P_{\theta\theta}(k) \, {\rm window \atop func.}(k) \, {\rm d}k$$

Continuity equation links v/θ to δ field through f

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$$P_{\theta\theta}^{\rm nonlin.}(k,\sigma_8,\sigma_u) = P_{\theta\theta}^{\rm lin.}(k) B(k,\sigma_8) D_u^2(k,\sigma_u)$$

Higher order perturbation fitting formula

Strong empirical damping

$$B(k,\sigma_8) = e^{-k(a_1(\sigma_8)+a_2(\sigma_8)k+a_3(\sigma_8)k^2)}$$

Bel et al. (2019)

$$D_u(k) = \frac{\sin(k\sigma_u)}{k\sigma_u}$$

Koda et al. (2014)

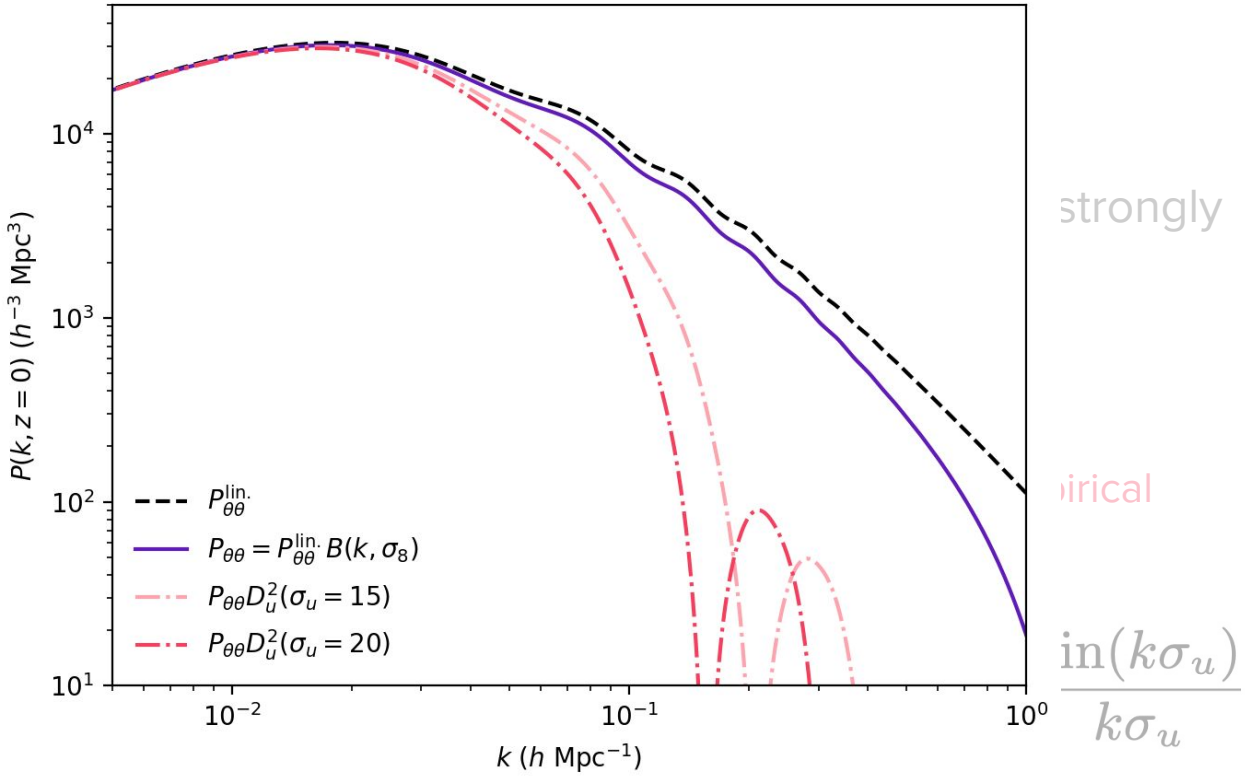
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- Large scale
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$$P_{\theta\theta}^{\rm nonlin.}(k$$

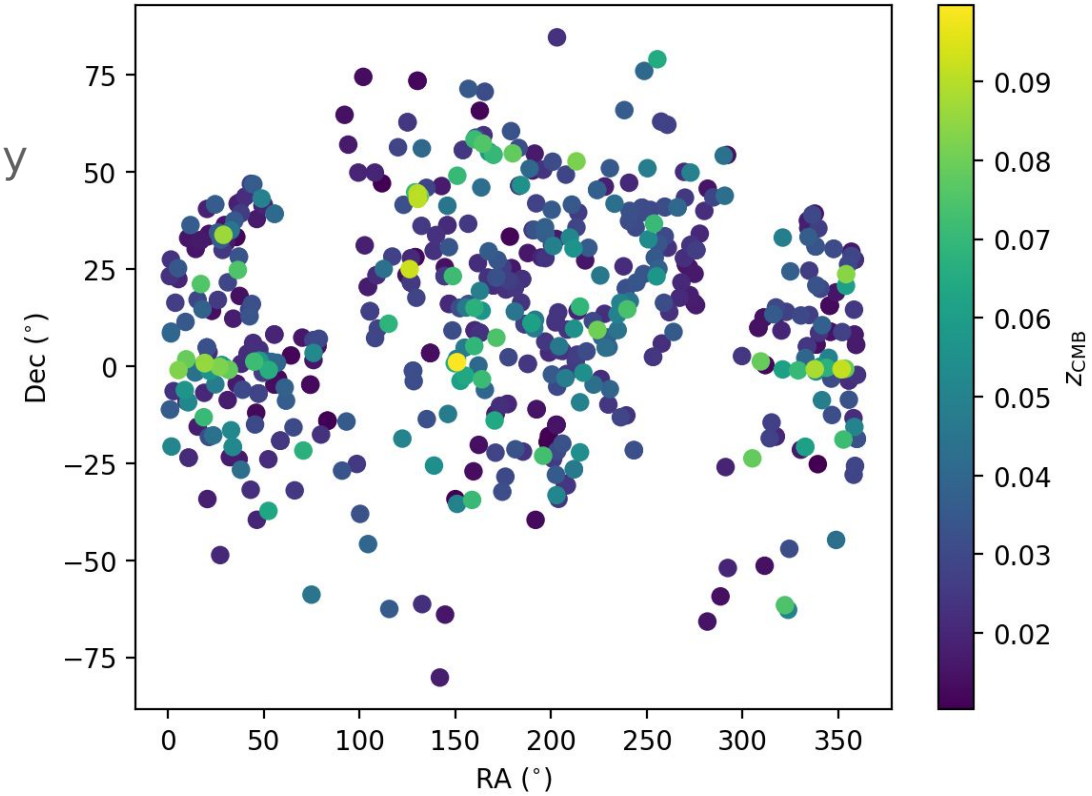
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How to constrain $f\sigma_8$ with Pantheon+

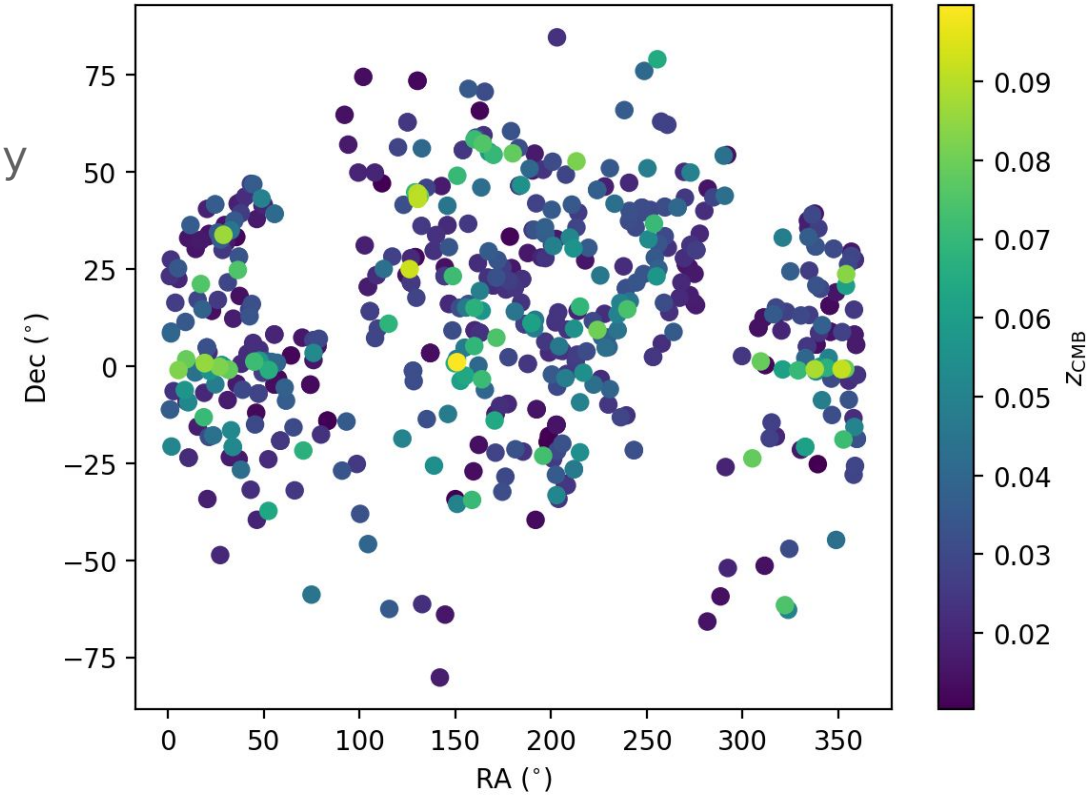
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Effective redshift ≃ 0; tomography will have to wait.



How to constrain $f\sigma_8$ with Pantheon+

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Effective redshift ≈ 0; tomography will have to wait.

Need to turn $\Delta\mu$ into v_p with a velocity estimator.

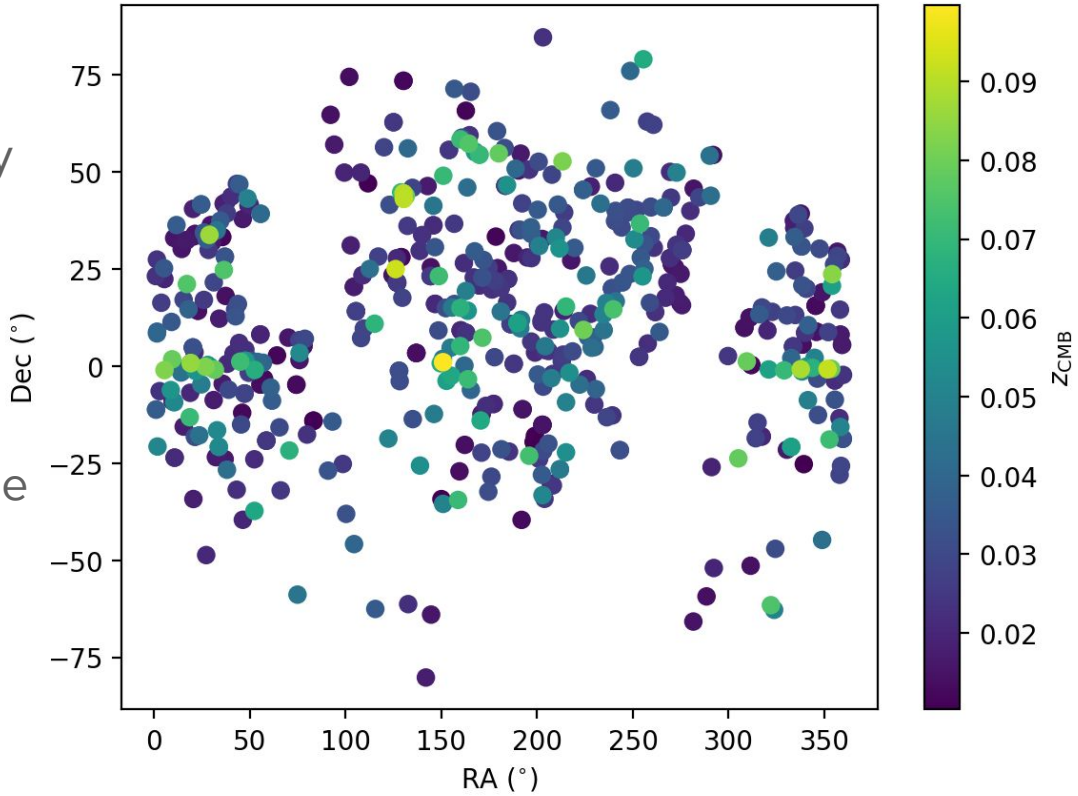


How to constrain $f\sigma_8$ with Pantheon+

618 SNe Ia, 0.01<z<0.1, all-sky. Effective redshift ≃ 0; tomography will have to wait.

Need to turn $\Delta\mu$ into v_p with a velocity estimator.

PV corrections need to be undone (in z, μ, $\mathbf{C}/\sigma_\mu$) before fitting $f\sigma_8$.



Construction of covariance matrix

$$\mathbf{C}^{\mathrm{Pantheon+}} = \mathbf{C}^{\mathrm{stat}} + \mathbf{C}^{\mathrm{syst}}$$

σ_{vpec} = 250 km/s
(converted to magnitude)

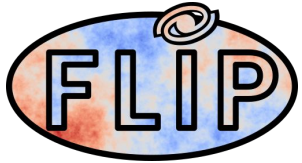
$$C_{ij}^{\mathrm{stat}} = \begin{cases} \sigma_\mu^2 = \sigma_{\mathrm{SALT}}^2 + \sigma_{\mathrm{int}}^2 + \sigma_{\mathrm{lens}}^2 \\ \qquad + \sigma_{\mathrm{z}}^2 + \sigma_{\mathrm{vpec}}^2, & i = j \\ \sigma_\mu^2 - \sigma_{\mathrm{SALT}}^2. & i \neq j \text{ and } \mathrm{SN}_i = \mathrm{SN}_j \end{cases}$$

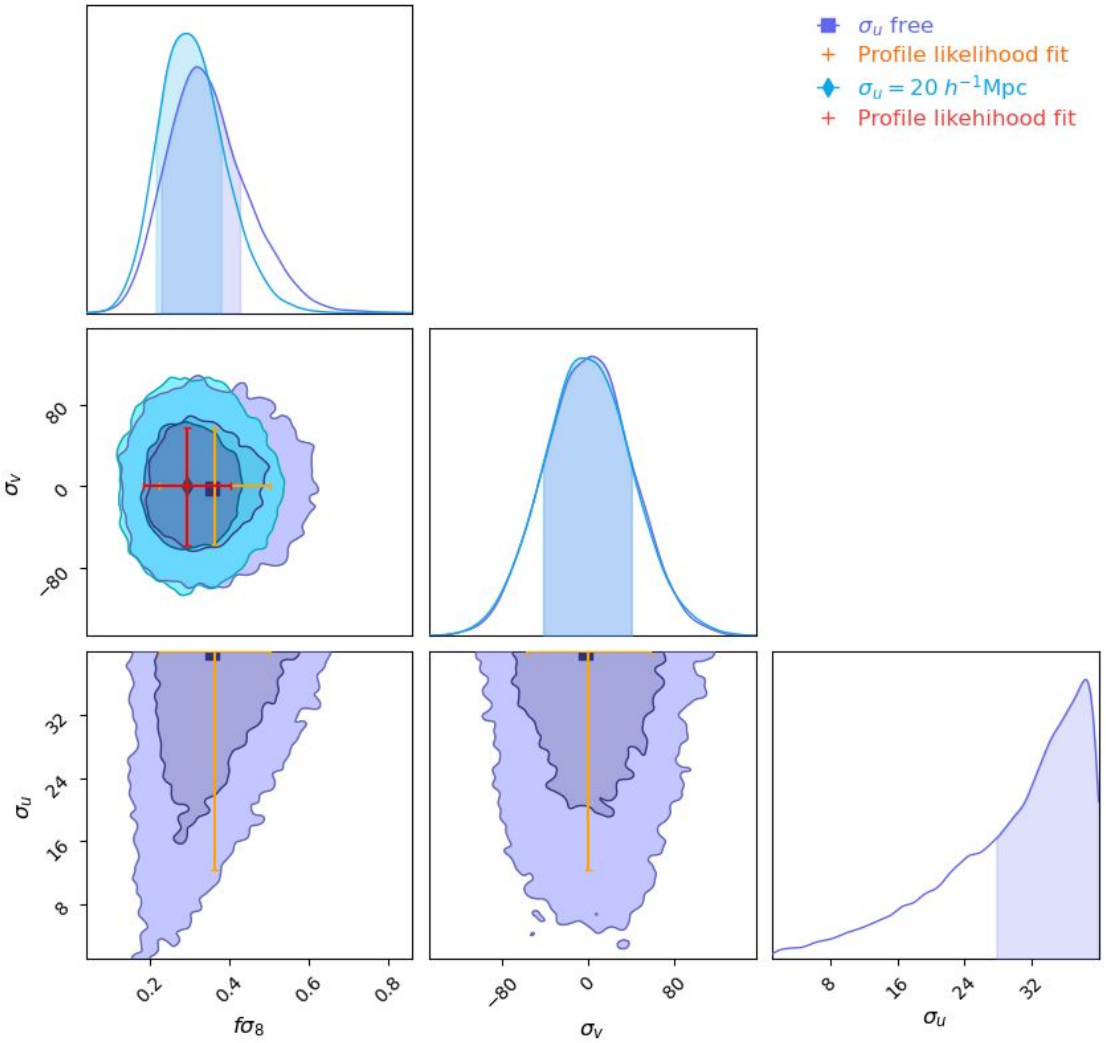
$\mathbf{C}^{\mathrm{syst}}$ is mostly non-diagonal. For PVs, leftover covariance after velocity-field reconstruction (Kenworthy et al. 2022)

So, can we measure $f\sigma_8$ from Pantheon+?

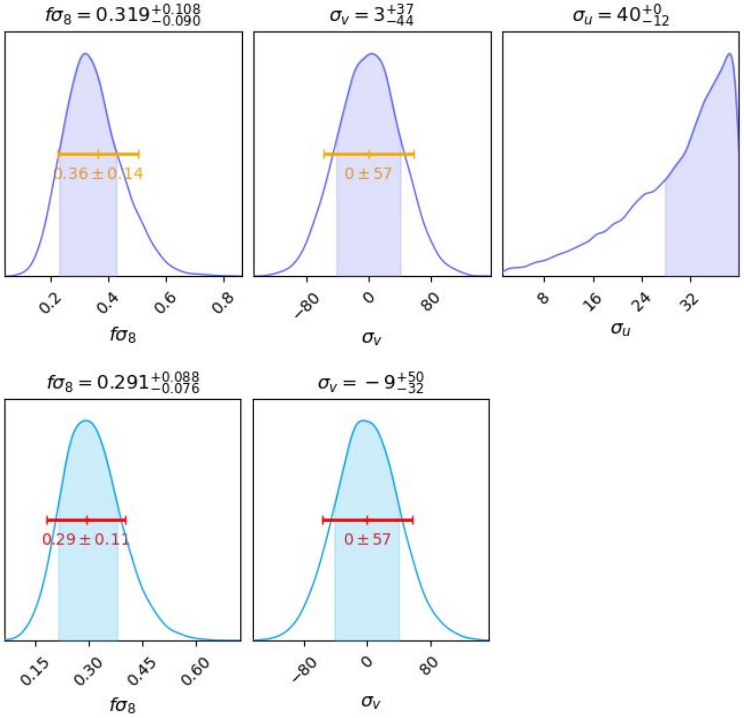
- Need to fit or fix a few parameters. $f\sigma_8$ is degenerate with σ_u.
- The Field Level Inference Package (`flip`) generates fast theoretical for velocity, density auto- and cross-covariance (and more) developed for Zwicky Transient Facility (ZTF) SN survey:

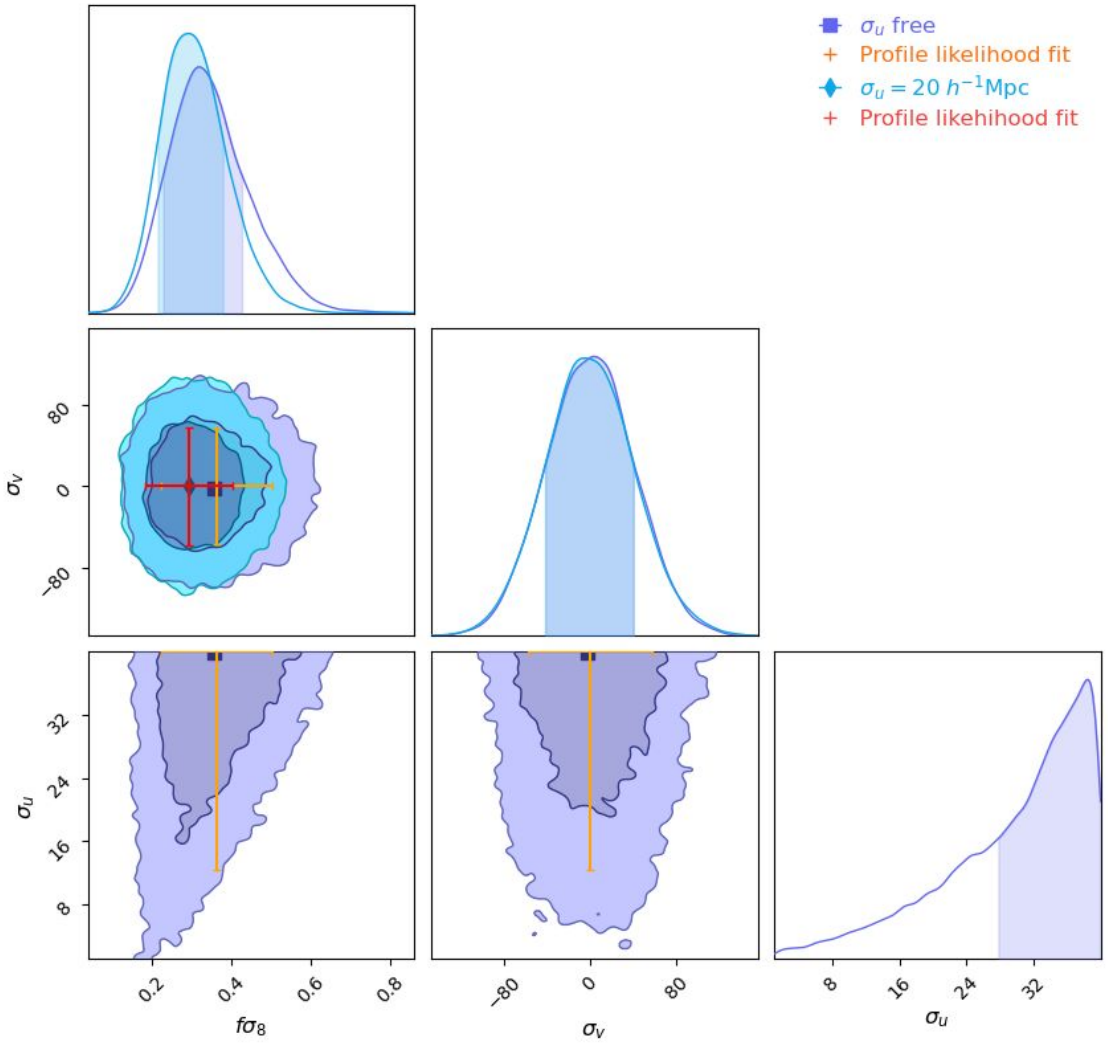
https://github.com/corentinravoux/flip



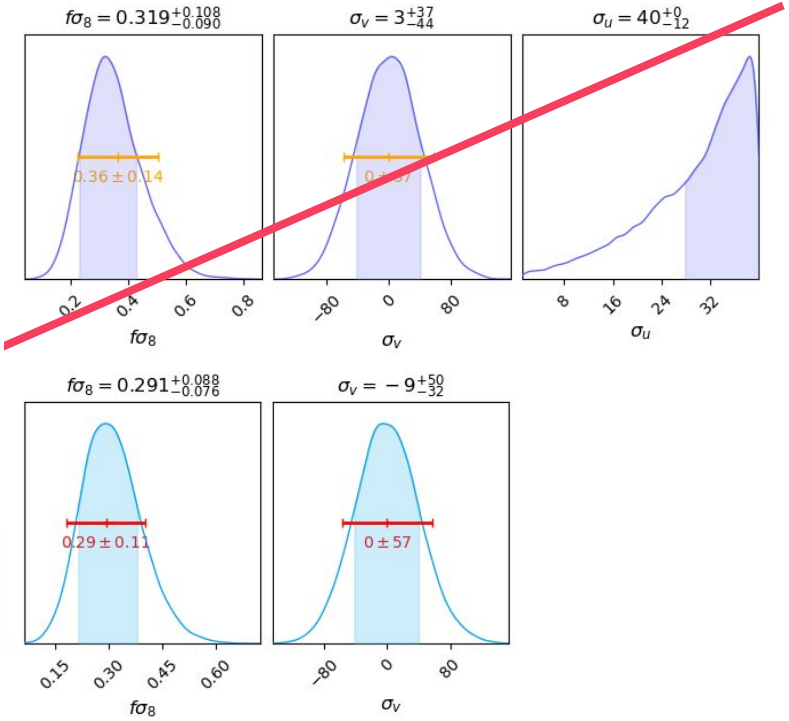


$$C_{ij}^{\text{meas.}} = (\sigma_v^2 + \sigma_\mu^2)\delta_{ij}^K$$





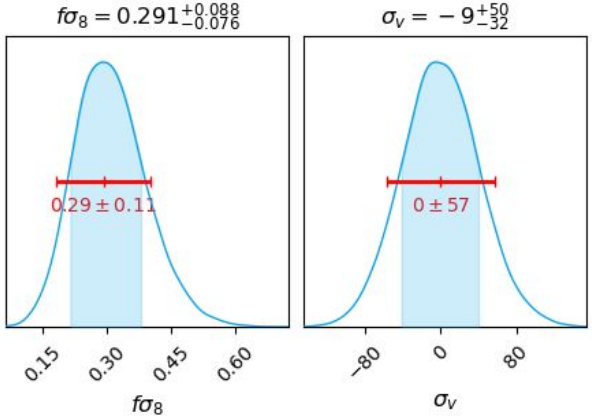
$$C_{ij}^{\text{meas.}} = (\sigma_v^2 + \sigma_\mu^2)\delta_{ij}^K$$



σ_u cannot be constrained

Summary

1. σ_u needs to be fixed for these data, but to what?
2. $C_{ij}^{\mathrm{meas.}} = \sigma_v^2 \delta_{ij}^K + C_{ij}^{\mathrm{Pantheon+}}$ may be ill-conditioned, but diagonal error only gives $f\sigma_8 = 0.29^{+0.09}_{-0.08}$.
3. Yes, we can measure $f\sigma_8$ using SNe/Pantheon+, but will only become competitive in the future, e.g. ZTF+DESI.



감사합니다!

Extra slides

Velocity estimators

$$\hat{v}_i = -\frac{c \ln 10}{5} \left(\frac{(1+z_i)c}{H(z_i)\chi(z_i)} - 1 \right)^{-1} \Delta\mu_i$$



$$\hat{v}_i = -\frac{c \ln 10}{5} \frac{z_{\mathrm{cosmo}}(q_0, j_0)}{1+z_i} \Delta\mu_i$$

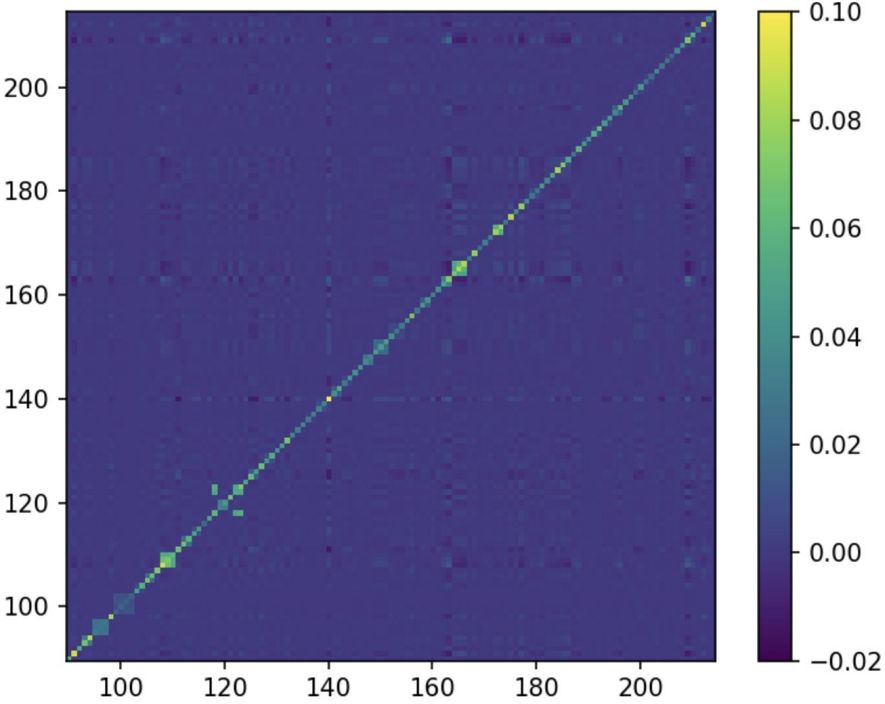
This estimator is also OK, but slightly biased.

$$\hat{v}_i = cz_i - H_0 D(\mu)$$

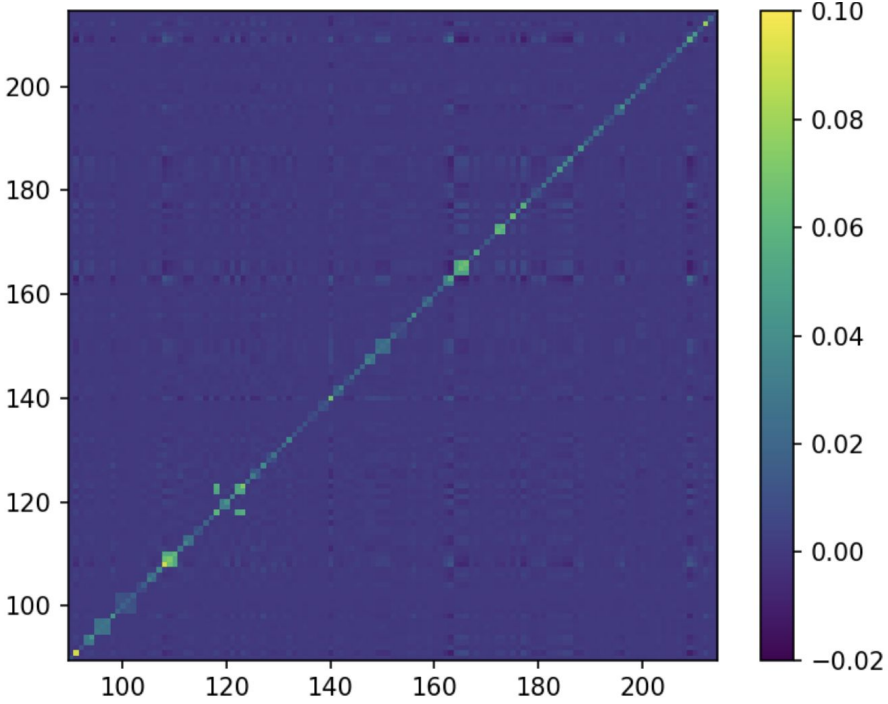


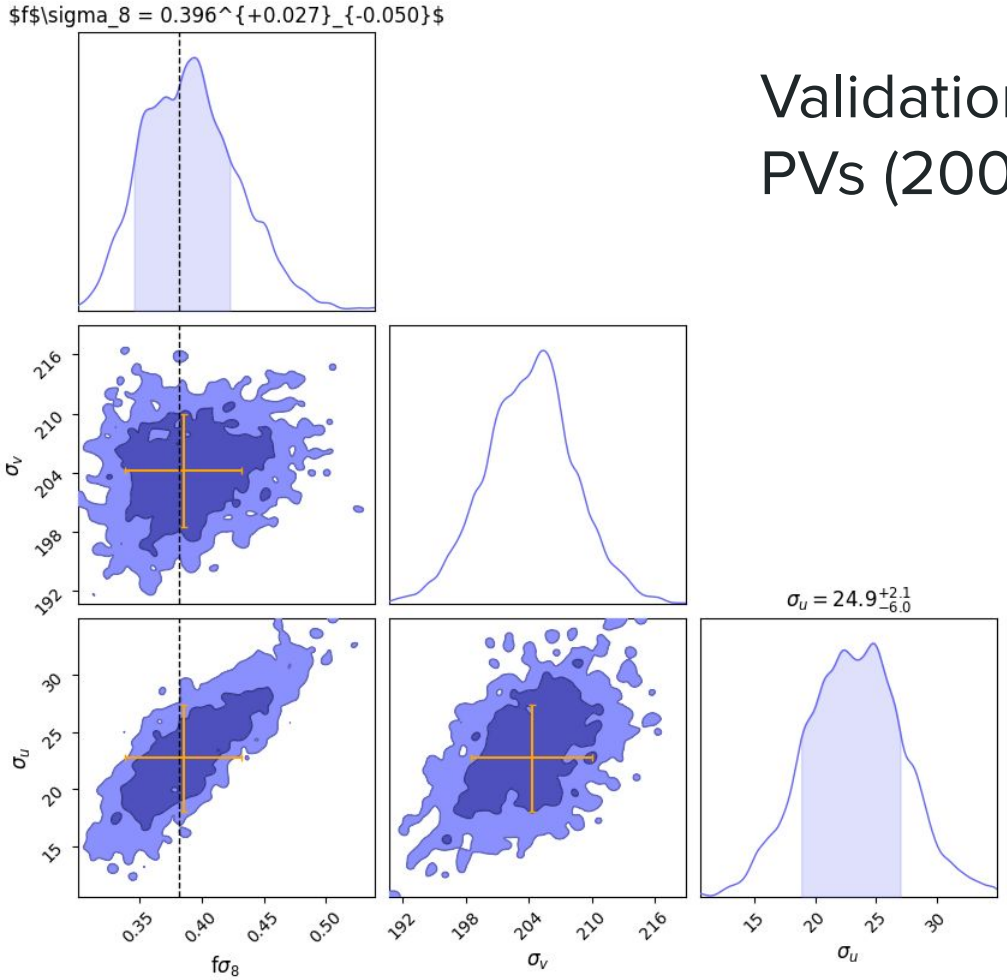
Removing PVs from Pantheon+ covariance

Low-z light curves: before

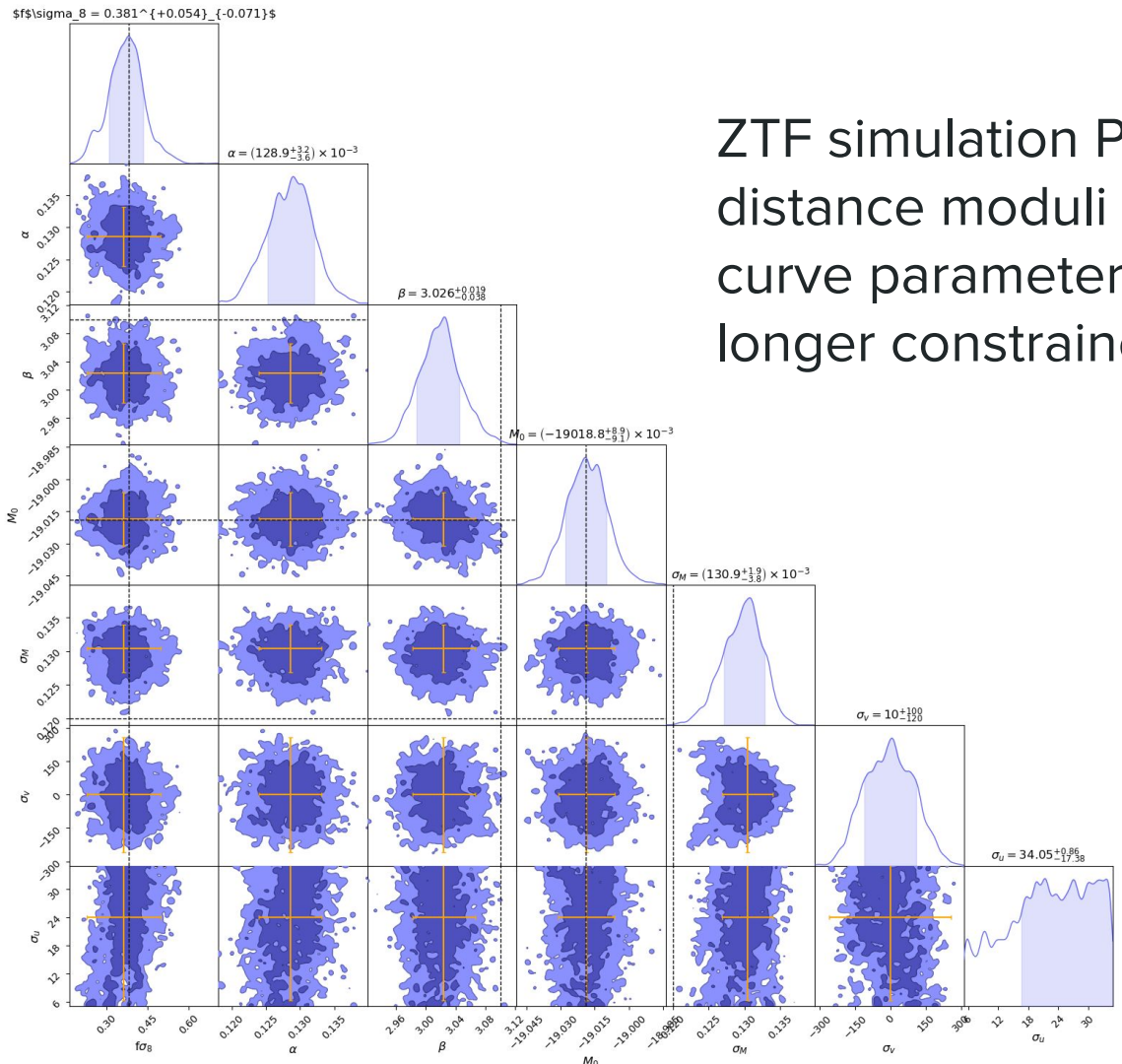


after





Validation: ZTF simulation true PVs (2000 SNe Ia)



ZTF simulation PVs estimated from distance moduli from simulated light curve parameters: σ_v disappears, σ_u no longer constrained

Construction of covariance matrix - statistical

$$C_{\text{stat+syst}} = C_{\text{stat}} + C_{\text{syst}}$$

σ^2_{vpec} = 250 km/s
(converted to magnitude)

$$C_{\text{stat}}(i,j) = \begin{cases} \sigma^2_{\mu} & i = j \\ \sigma^2_{\text{floor}} + \sigma^2_{\text{lens}} + & \\ \sigma^2_z + \sigma^2_{\text{vpec}} & i \neq j \text{ and } \text{SN}_i = \text{SN}_j \end{cases}$$

$$\sigma^2_{\mu,i} = f(z_i, c_i, M_{\star,i})\sigma^2_{\text{meas},i} + \sigma^2_{\text{floor}}(z_i, c_i, M_{\star,i}) + \sigma^2_{\text{lens},i} + \sigma^2_{z,i} + \sigma^2_{\text{vpec},i}$$

Also PV effects here?

Construction of covariance matrix - systematic

$$C_{\text{stat+syst}} = C_{\text{stat}} + C_{\text{syst}}$$

$$C^{ij}_{\text{syst}} = \sum_{\psi} \frac{\partial \Delta\mu^{i}_{\psi}}{\partial \mathrm{S}_{\psi}} \frac{\partial \Delta\mu^{j}_{\psi}}{\partial \mathrm{S}_{\psi}} \sigma^{2}_{\psi}$$

PVs are corrected using 2M++ reconstruction, so PV systematic component is the leftover covariance after correction: scales smaller than smoothing kernel and difference between 2MRS reconstruction (Kenworthy et al. 2022).