ACCEL² simulation

Growth rate from SNIa peculiar velocity and galaxy density field

Corentin Ravoux - CNRS/LPCA Clermont-Ferrand

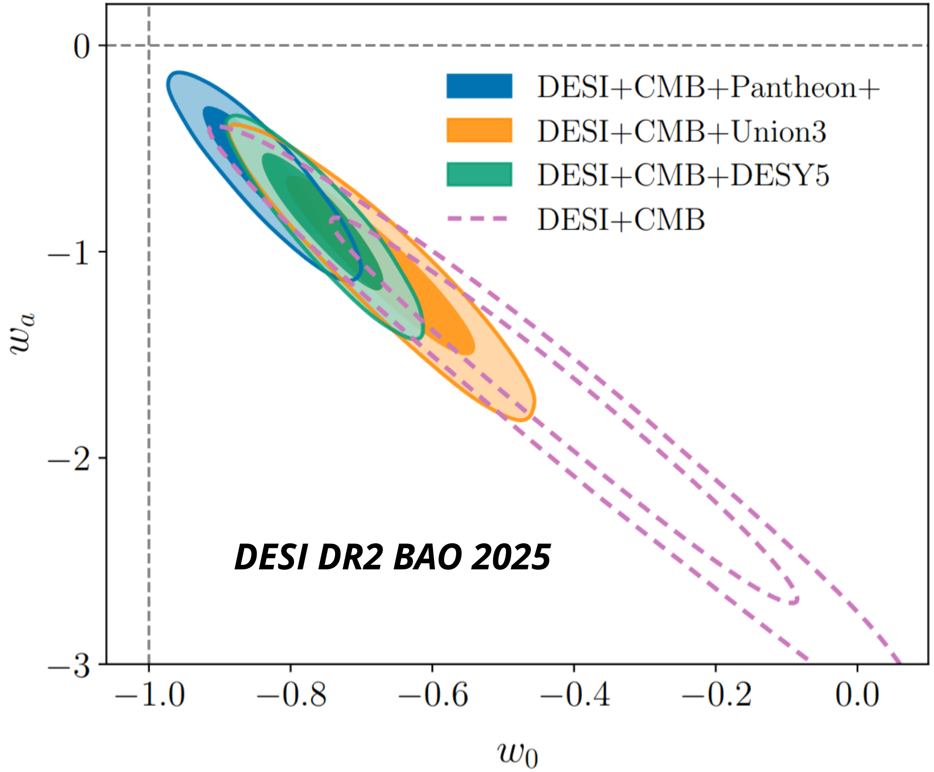
with Bastien Carreres, Julian Bautista, Damiano Rosselli, Alex Kim and many others

Synergistic power of combined cosmological observables - 29 October 2025

Dark Energy

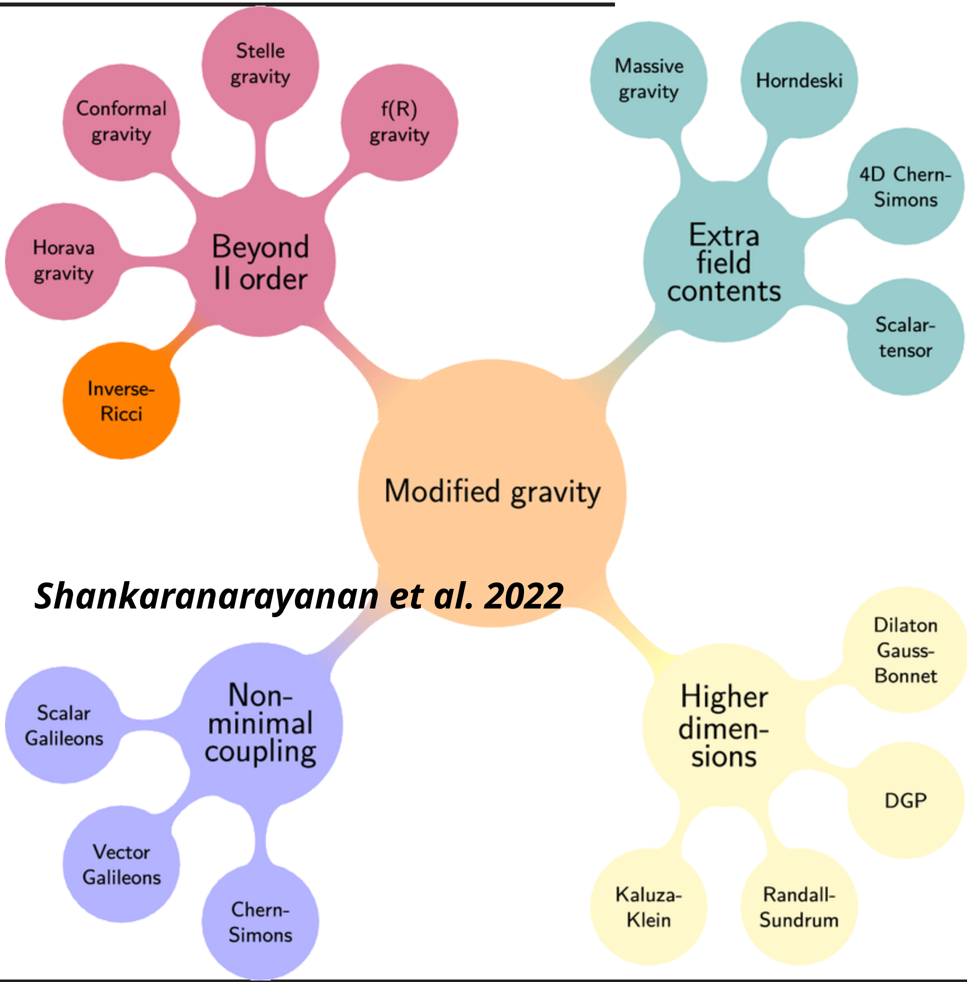
- What is the nature of dark energy ?
- Cosmological constant model (Λ) not very satisfying

Recent DESI DR2 BAO + CMB + SNIa results: stronger hints for varying dark energy



Dark Energy

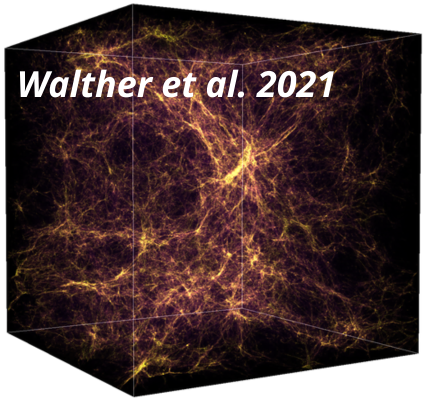
- What is the nature of dark energy ?
- Cosmological constant model (Λ) not very satisfying
- **Other models** :
  - Fifth force, additional field ?
  - Modified gravity theories ?
- **Our current objective**: Probing large-scale structure formation to constrain dark energy/modified gravity.

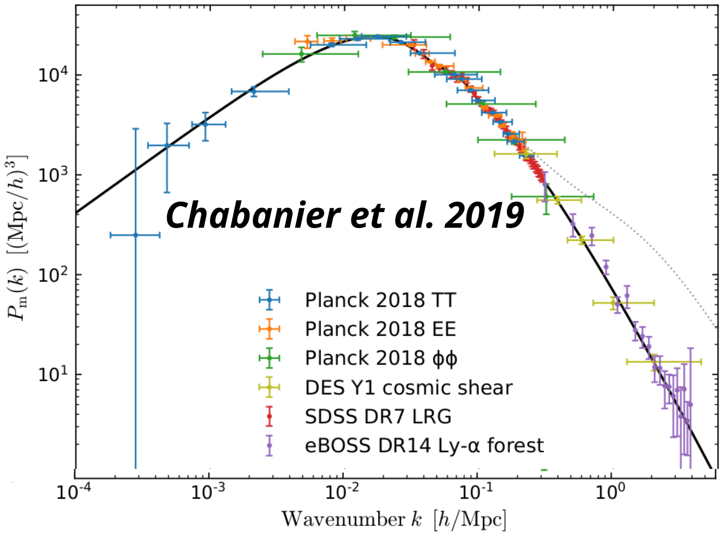


Shankaranarayanan et al. 2022

Cosmic web

- Matter perturbations in the primordial Universe grew to form the cosmic web
- **Static description**: matter density contrast (δ) follows a linear power spectrum at large-scales
- **Dynamic description**: Cosmic web peculiar velocities (v_p) caused by gravitation





fσ8 parameter

- Linear perturbation theory:

Cosmic web velocities

Normalized matter overdensity

$$\nabla \cdot \boxed{\mathbf{v}(\mathbf{r})} \propto -aH(f\sigma_8)\boxed{\hat{\delta}(\mathbf{r})}$$

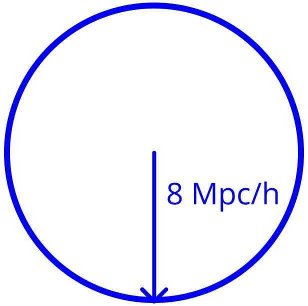
fσ8 parameter

- Linear perturbation theory:

Cosmic web velocities

Normalized matter overdensity

$$\nabla \cdot \boxed{\mathbf{v}(\mathbf{r})} \propto -aH(\boxed{f}\boxed{\sigma_8})\boxed{\hat{\delta}(\mathbf{r})}$$



Logarithmic growth rate of linear perturbations

$$f = \frac{d \log \delta_+}{d \log a} \simeq \Omega_{\mathrm{m}}^{0.55}$$ in GR

Amplitude of the matter perturbations in spheres of 8 Mpc/h comoving radius (matter power spectrum amplitude)

Measuring fσ8

Peculiar velocities (PV)	Redshift Space Distortions (RSD)

Peculiar velocities (PV)

- Direct estimation of velocities

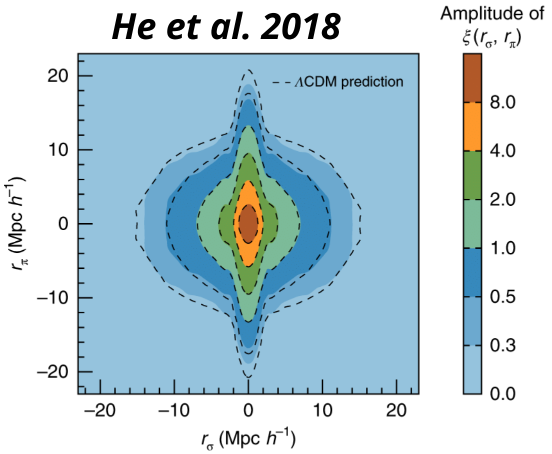
$$1 + z_{\mathrm{obs}} = (1 + z_{\cos})(1 + v_{\mathrm{p}}/c)$$

- Need an estimate of redshift (z_{obs}) and distance (decoupling $z_{\cos}$ from v_{p})
- Compute statistics from PV

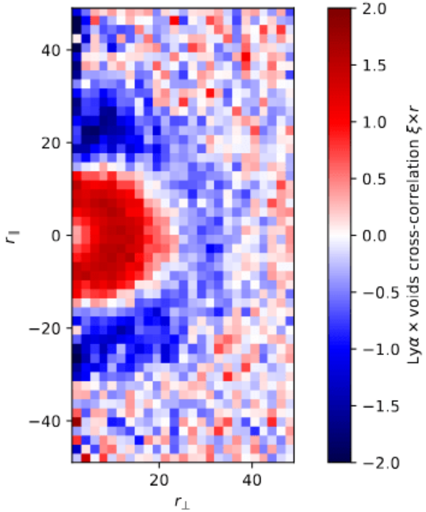
Redshift Space Distortions (RSD)

- Impact of PV on measurements
- **Example**: galaxy auto-correlation, void cross-correlation, ...

He et al. 2018

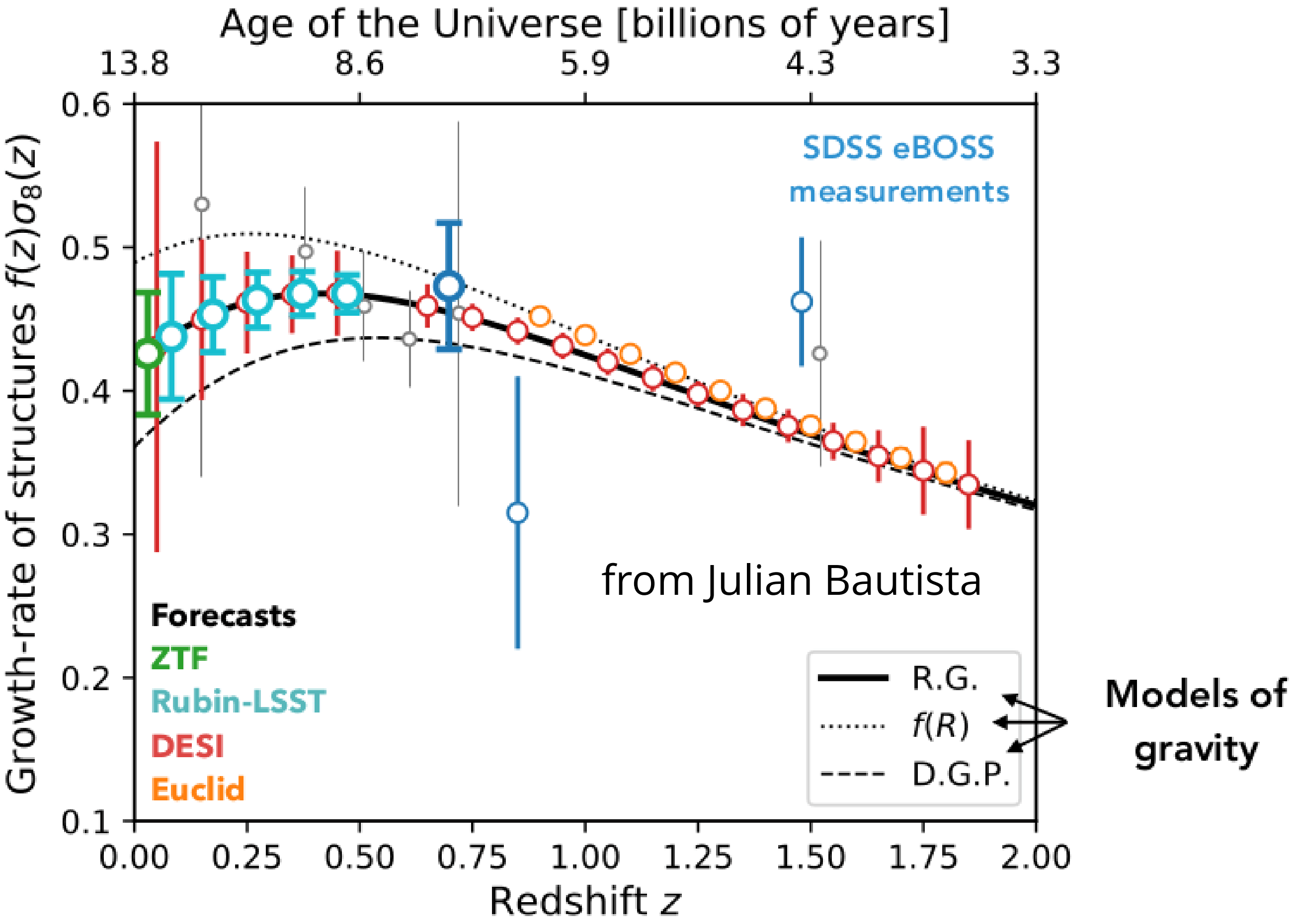


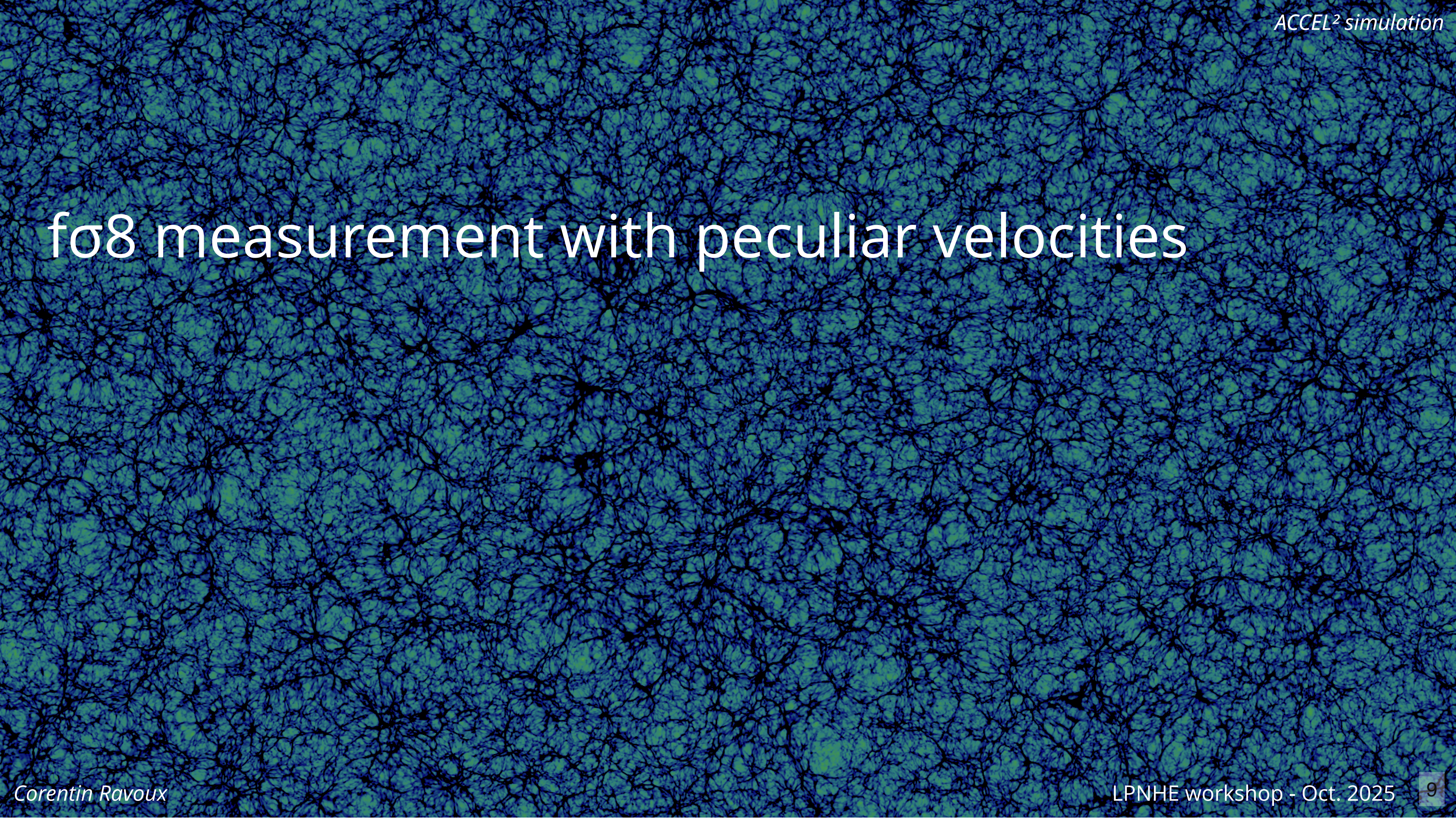
Ravoux et al. 2022



fσ8 constraints

- Constrain modified gravity models
- **RSD** very effective for high redshift
- **PV** for low redshift
- Improvement with method combination

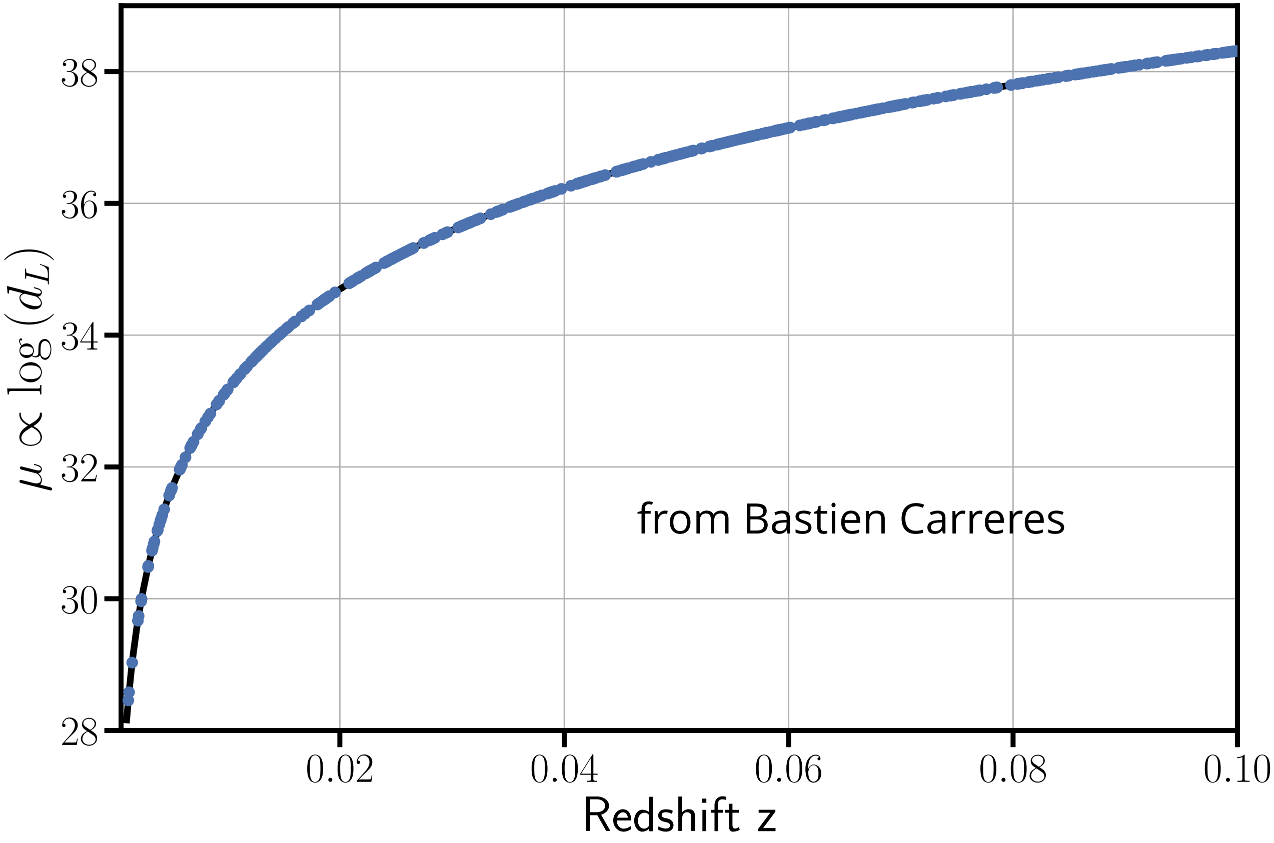



ACCEL² simulation

fσ8 measurement with peculiar velocities

Hubble diagram

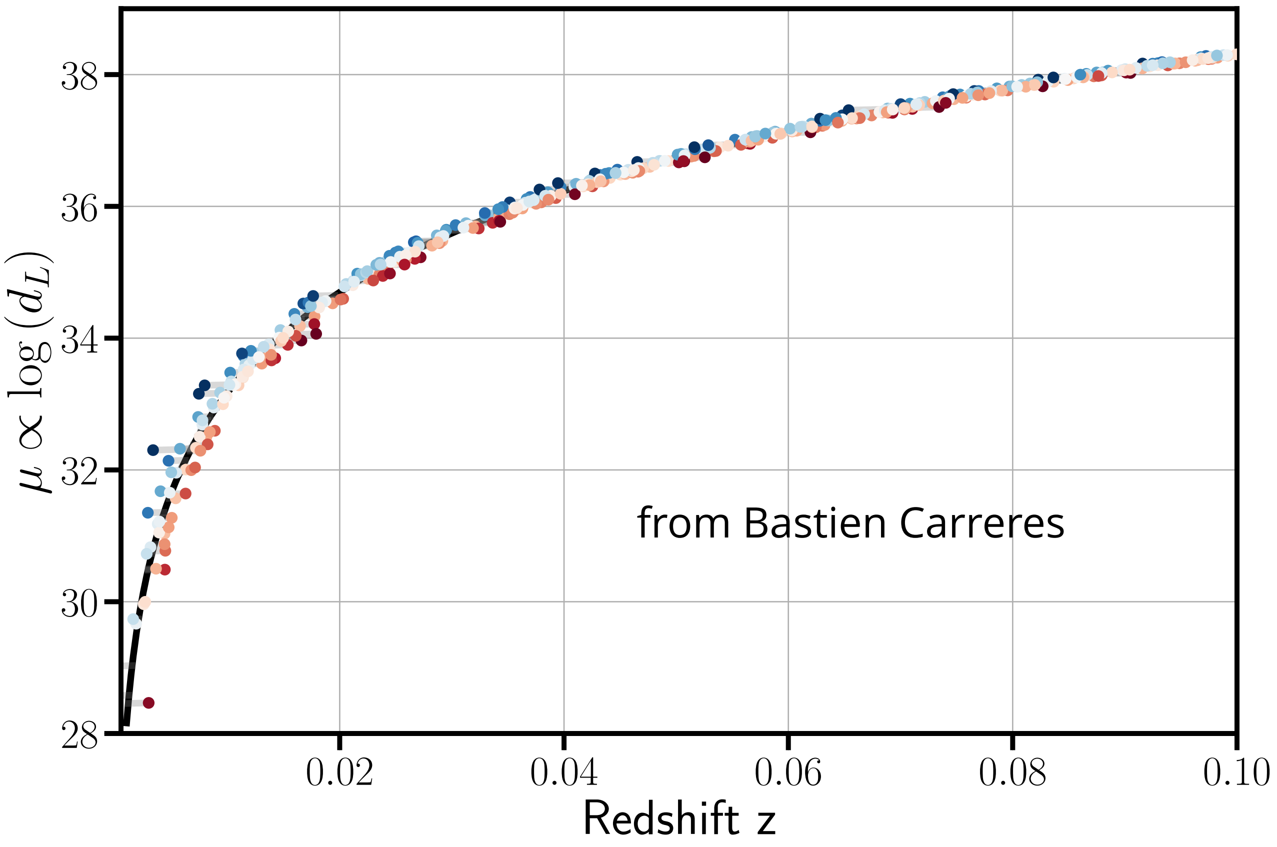
Perfect standard candle in an expanding Universe



Standard candle = object with fixed luminosity

Hubble diagram

Perfect standard candle in an expanding Universe



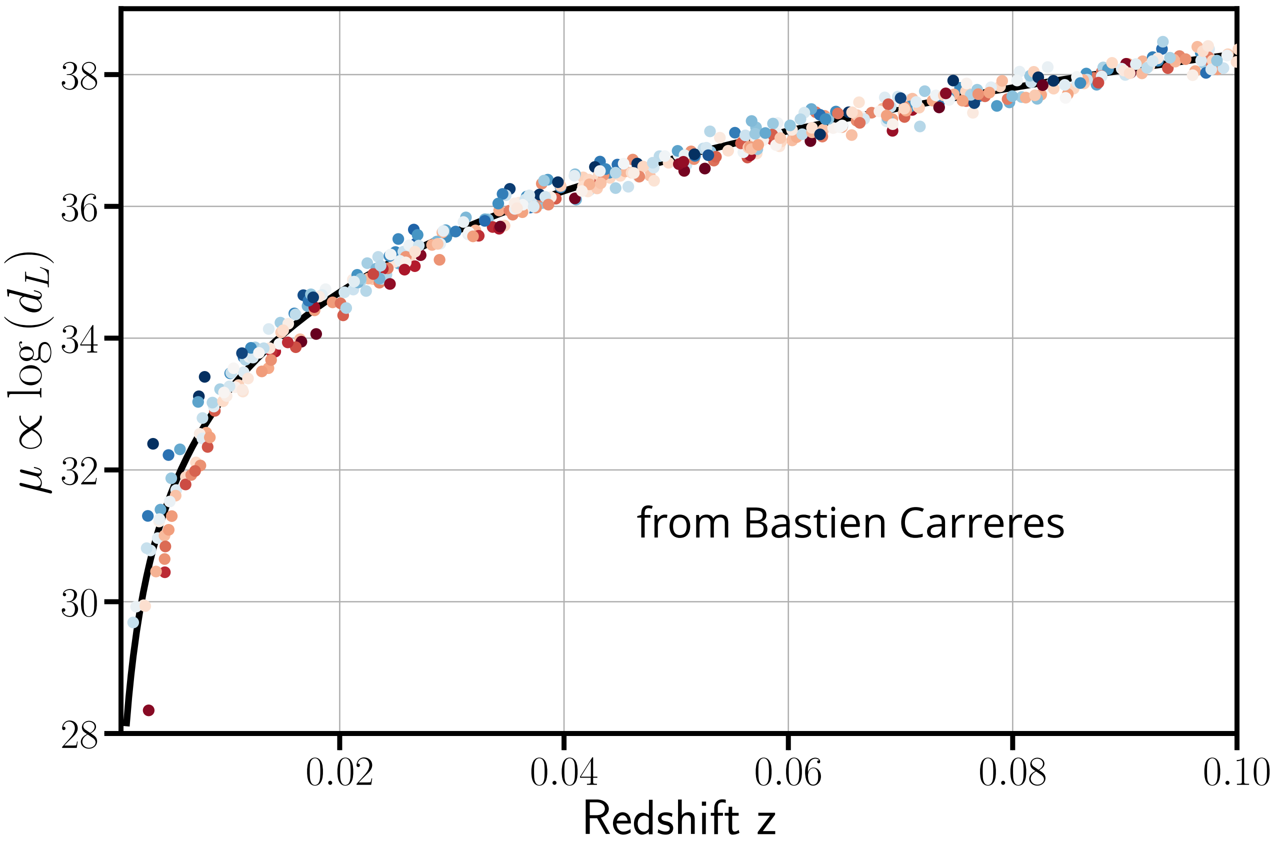
Peculiar velocities

Hubble diagram

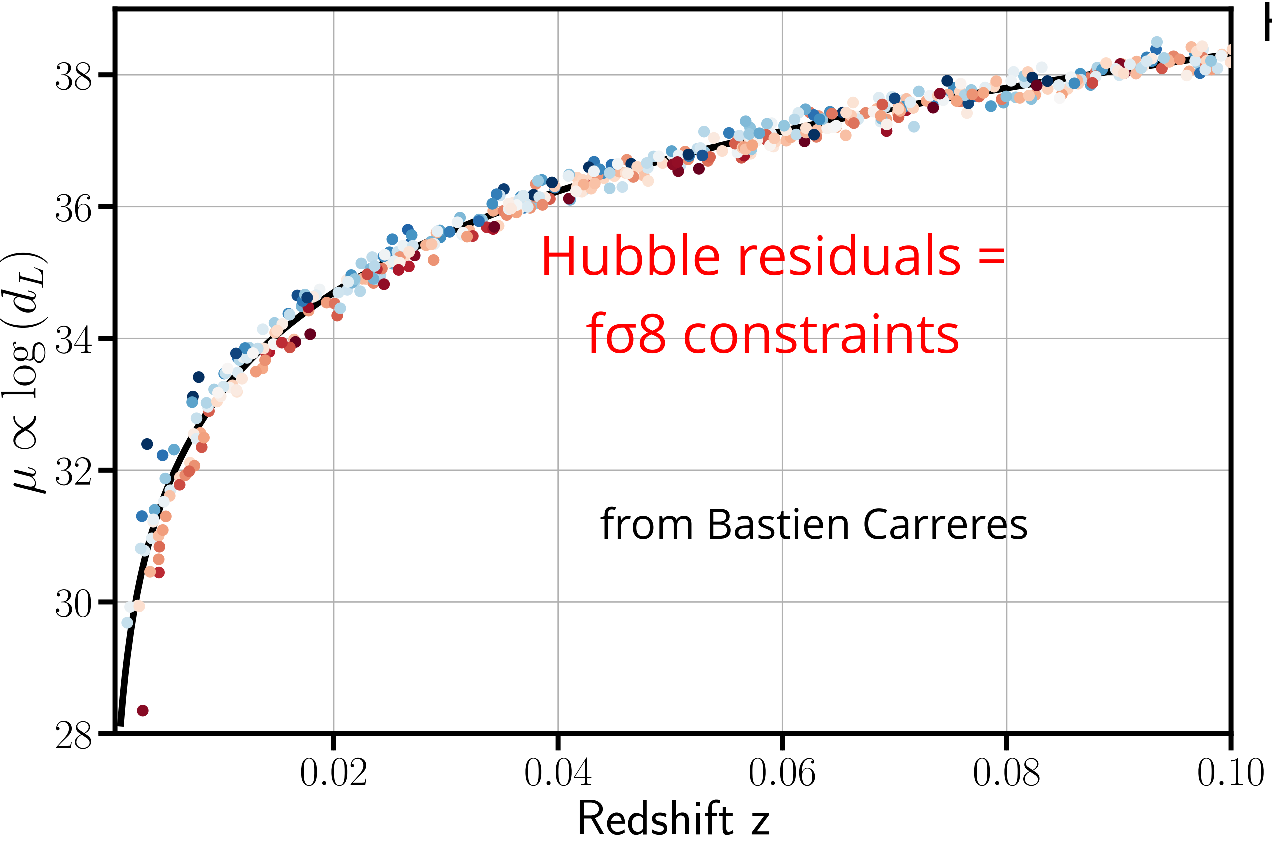
Standardizable candle in an expanding Universe

Noise sources (intrinsic scatter, local environment, instruments...)

Peculiar velocities



Hubble diagram



High redshifts = dark energy constraints (*w*, or *w0,wa*)

Low redshifts + calibration of the candle luminosity = H0 constraints

Type Ia supernovae

- **SNe Ia**: Thermonuclear explosion a white dwarf reaching Chandrasekhar mass

- Distance modulus:

$$\mu_{\mathrm{obs},i} = m_{\mathrm{B},i} - M_{\mathrm{B},i}$$

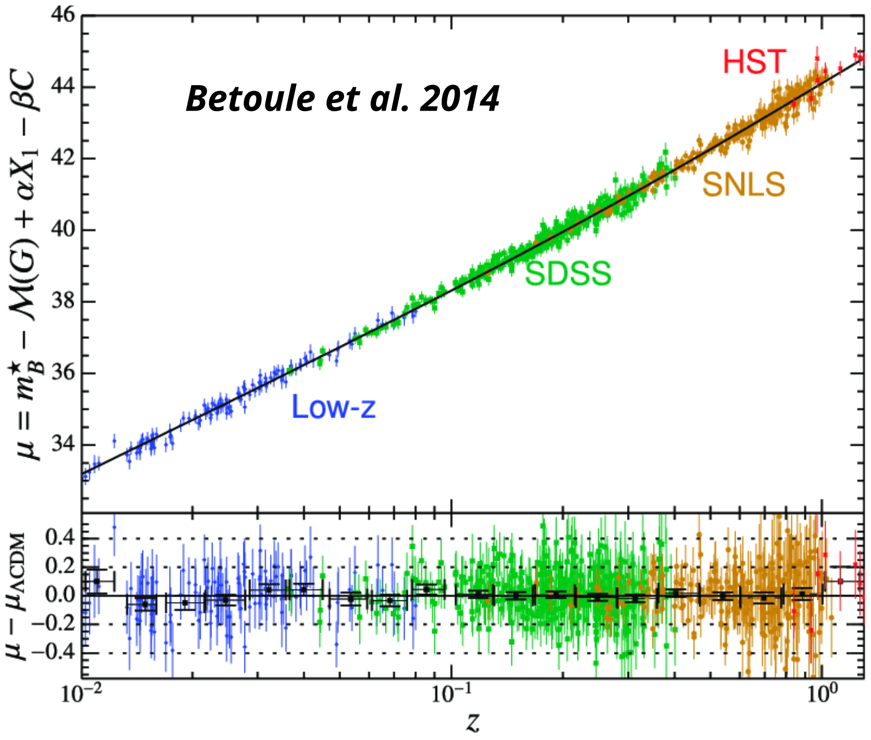
- SNe Ia standardization = Tripp relation

$$M_{\mathrm{B},i} = \boxed{M_0} - \boxed{\alpha}\boxed{x_{1,i}} + \boxed{\beta}\boxed{c_i} + (\mathrm{opt})$$

Parameters common for all SN Ia

Light-curve stretch
"Luminous fade slowly"

SN color
"Redder is fainter"



$$\sigma_D / D \sim 7\%$$

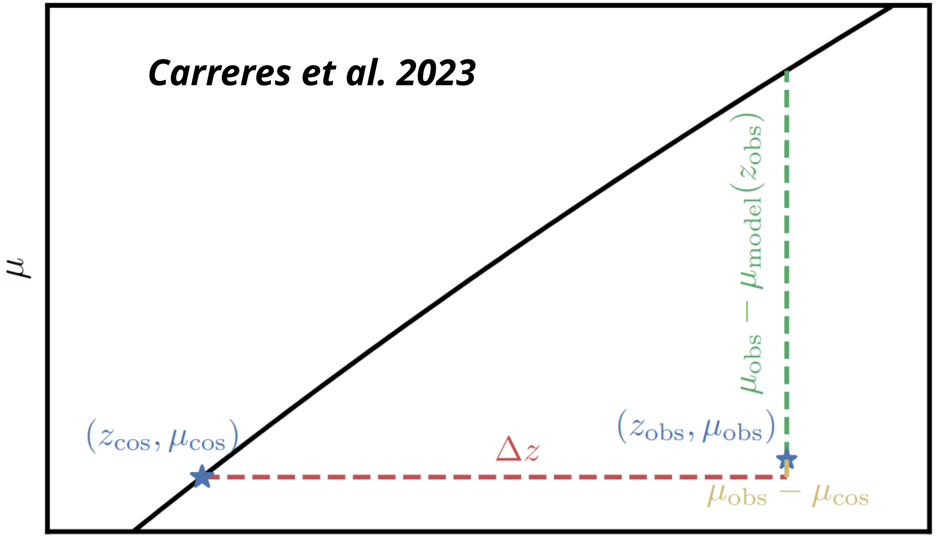
Type Ia supernovae

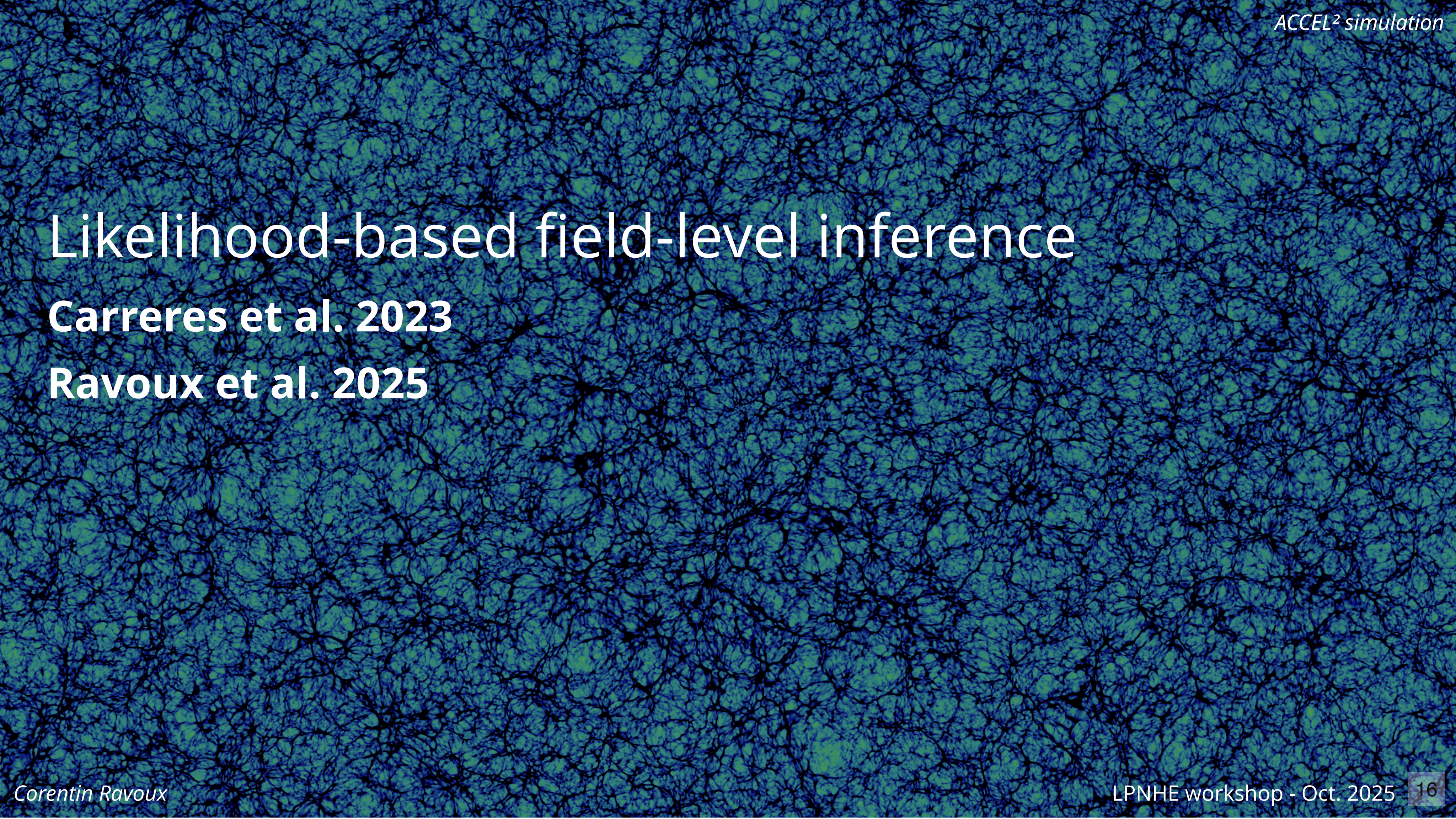
- Hubble residuals:

$$\Delta\mu_i = \mu_{\mathrm{obs},i} - \mu_{\mathrm{model}}(z_{\mathrm{obs},i}) = \mu_{\mathrm{obs},i} - 5\log\left(\frac{d_{\mathrm{L}}(z_{\mathrm{obs},i})}{10\mathrm{pc}}\right)$$

- Velocity estimator:

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




ACCEL² simulation

Likelihood-based field-level inference

Carreres et al. 2023

Ravoux et al. 2025

Likelihood-based field-level estimator

- **Purpose**: Maximizing or sampling a likelihood computed from all coordinates of the data
- *p* **= fitted parameters**: **simultaneously** cosmology (fσ8) and field parameters (e.g., Hubble diagram parameters α, β, M0 for SN)

Velocity example:

$$\mathcal{L}(\boxed{p}) \propto \exp\left[-\frac{1}{2}\boxed{v}^T(p)\boxed{C_{vv}(p)}^{-1}v(p)\right]$$

Parameters

Velocity from SNe Ia

Field covariance matrix computed from theory and coordinates

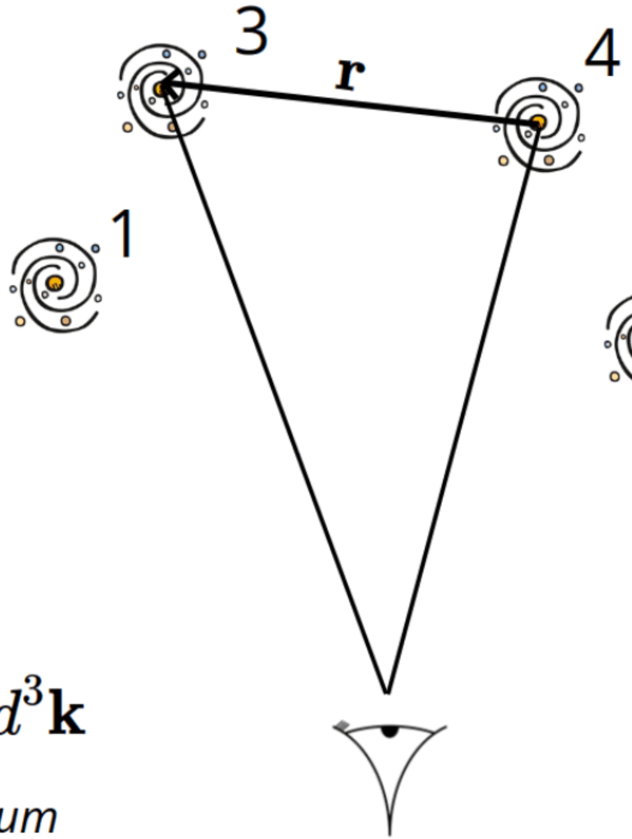
Computing the field covariance

$$\mathcal{L}(p) \propto \exp\left[-\frac{1}{2}\begin{bmatrix}1\\2\\3\\4\end{bmatrix}^T \left|\begin{matrix} & C_{12} & C_{13} & C_{14} \\ C_{21} & & C_{23} & C_{24} \\ C_{31} & C_{32} & & C_{34} \\ C_{41} & C_{42} & C_{43} & \end{matrix}\right|^{-1} \begin{bmatrix}1\\2\\3\\4\end{bmatrix}\right]$$

Field covariance

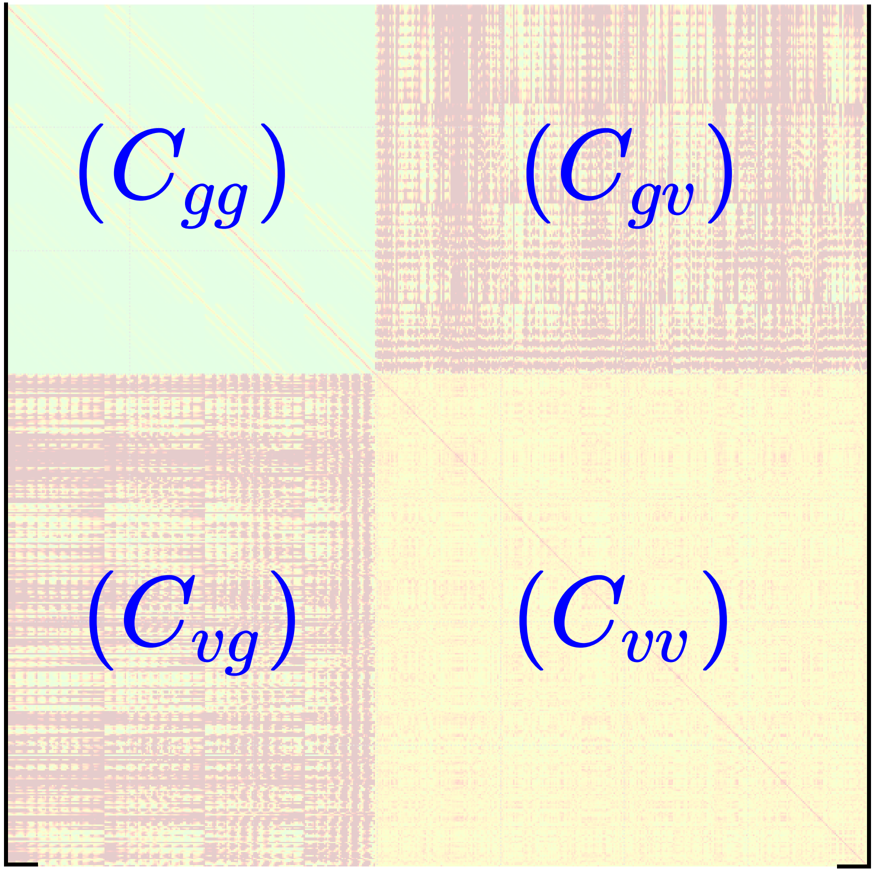
$$\boxed{C_{\mathrm{nm}}(\mathbf{r_n}, \mathbf{r_m})} = \frac{1}{(2\pi)^3}\int_{\mathbf{k}} \boxed{P_{\mathrm{nm}}(k, \mu_n, \mu_m)} e^{i\mathbf{k}.\mathbf{r}} d^3\mathbf{k}$$

Theoretical power spectrum



Combining densities (RSD) and peculiar velocities

$$\mathcal{L}(p) \propto \exp\left[-\frac{1}{2} \begin{bmatrix}\delta \\ v\end{bmatrix}^T \begin{bmatrix} (C_{gg}) & (C_{gv}) \\ (C_{vg}) & (C_{vv})\end{bmatrix}^{-1} \begin{bmatrix}\delta \\ v\end{bmatrix}\right]$$



Density field from galaxy surveys

Velocities

Full field covariance matrix

General covariance calculation

- **Objective**: Improve/Extend the likelihood-based modeling

$$C_{\mathrm{ab}}(\mathbf{r_a},\mathbf{r_b}) = \frac{1}{(2\pi)^3}\int_{\mathbf{k}} P_{\mathrm{ab}}(k,\mu_{\mathrm{a}},\mu_{\mathrm{b}})e^{i\mathbf{k.r}}d^3\mathbf{k}$$

gg, gv, vv

$$P_{\mathrm{ab}}(k,\mu_{\mathrm{a}},\mu_{\mathrm{b}}) = \sum_n w_{\mathrm{ab},n}F_{\mathrm{ab},n}(k,\mu_{\mathrm{a}},\mu_{\mathrm{b}})\mathcal{P}_{\mathrm{ab},n}(k)$$

Parameters to fit

Terms to integrate analytically

Power spectra terms to integrate numerically

- General form of field power spectrum
- **Algorithmically-oriented calculations (Hankel transforms)**
- **Wide-angle** effect accounted in the integration

flip Field Level Inference Package

- python package for likelihood-based field-level inference:

  https://github.com/corentinravoux/flip

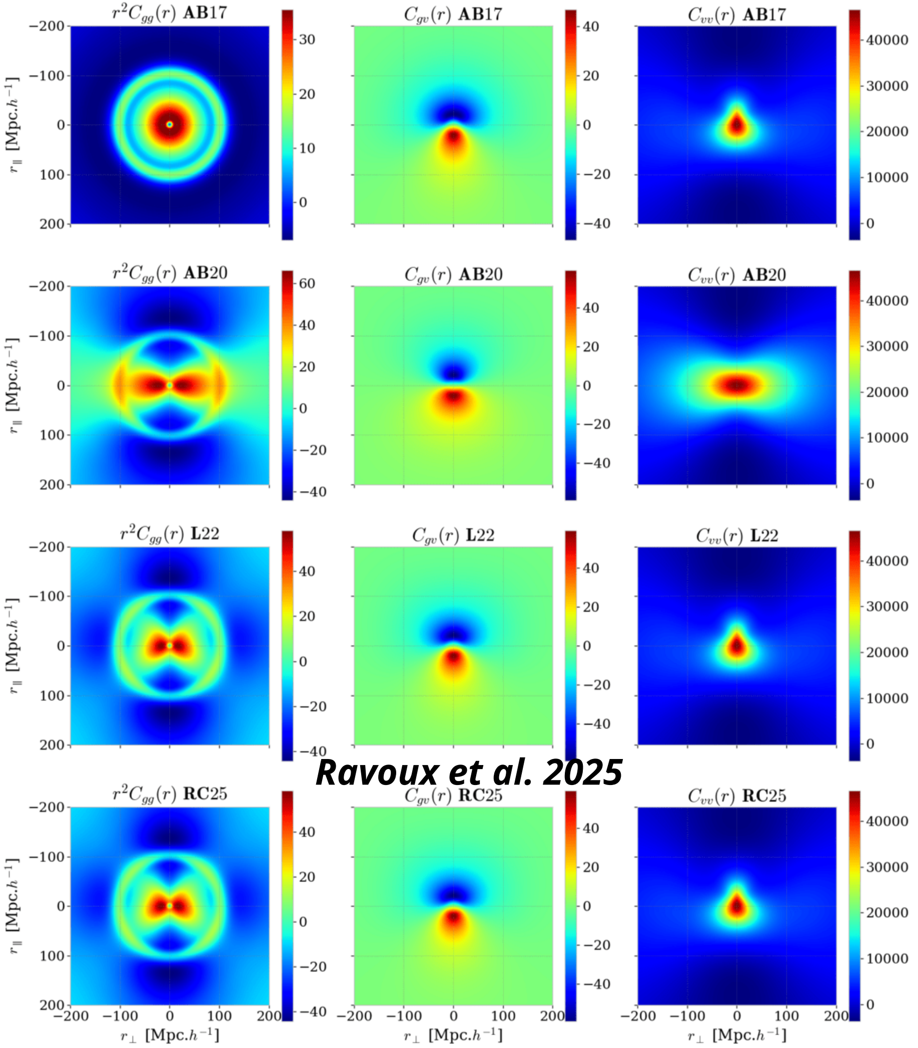
  Flip article: **arxiv:2501.16852**

- **Fast generation of field covariance**
- Symbolic code generation for covariance model
- MCMC and Minuit to fit fσ8
- General expression for vectors (SNIa, density, log distance, TF, FP...)
- Survey geometry-dependent Fisher forecast

Contributors:
Bastien Carreres,
Damiano Rosselli
and Alex G. Kim

Field covariance models

- Model comparison on a regular coordinate grid (*Adams & Blake 2017, Adams & Blake 2020, Lai et al. 2022)*
- New wide-angle model developed (**RC25**): improved stability in integration and for wider fitting parameter ranges



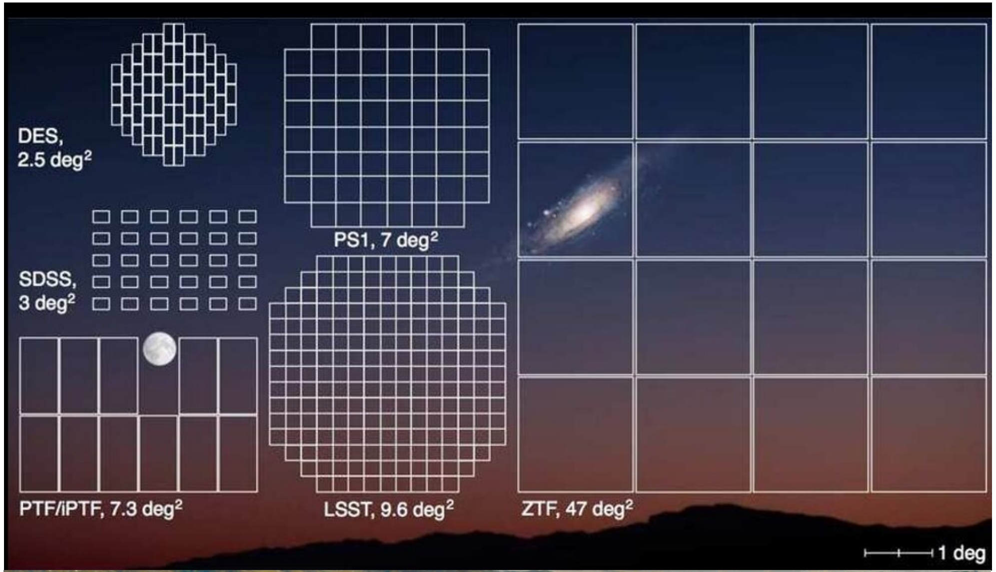
Ravoux et al. 2025

Combining DESI galaxy density and ZTF SNIa velocities on simulation

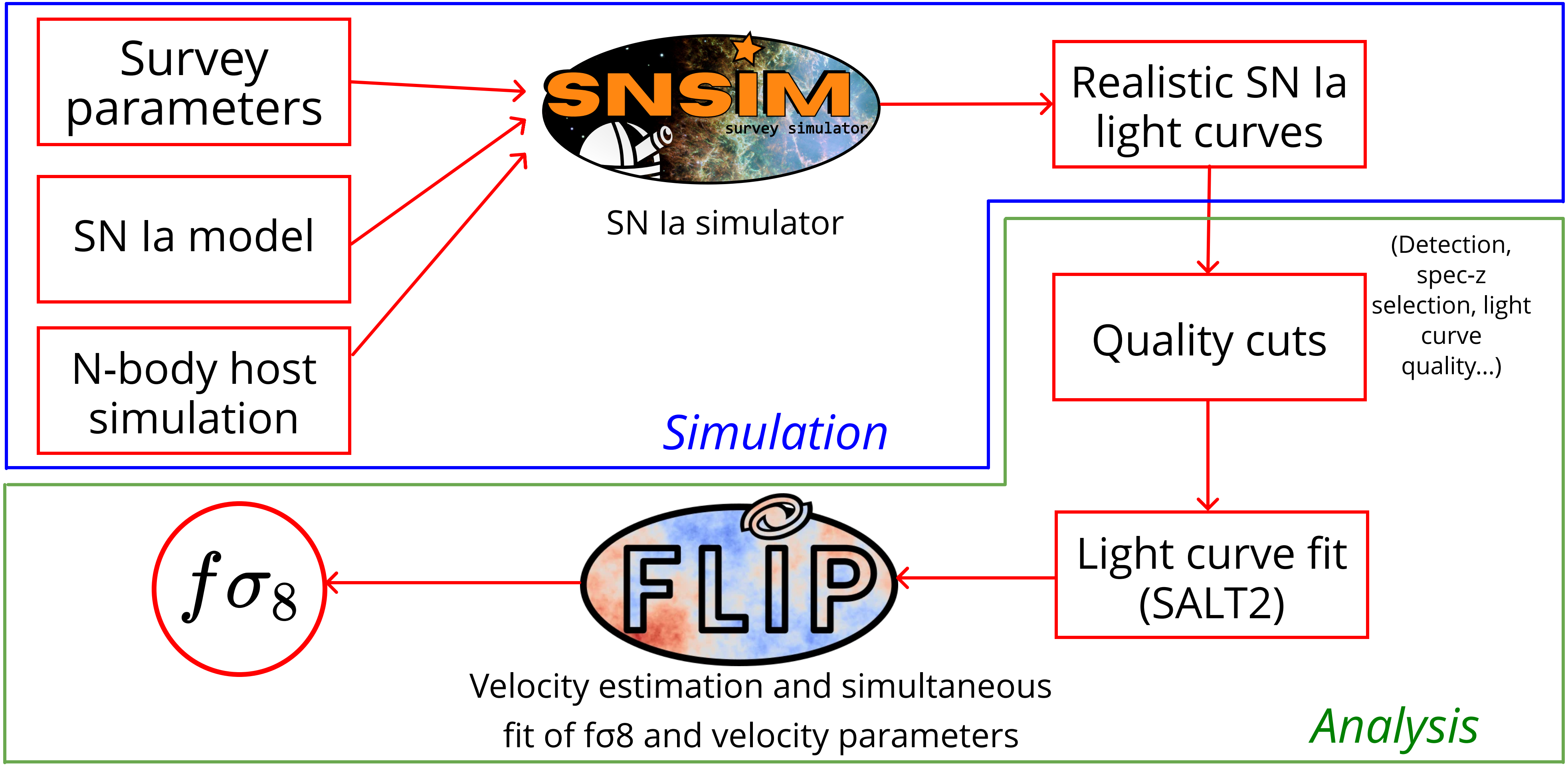
Ravoux et al. in prep

Zwicky Transient Facility (ZTF)

- ZTF = high-cadence photometric telescop in the Palomar observatory
- Very large field of view (47 deg²)
- Observing 3/4 of the sky every nights with 3 filters (g, r, i)
- **Transient sky**: Supernovae, gamma ray burst, tidal distruptive events, comets, asteroids
- Dedicated spectroscopic telescope measuring transient spectra (SEDmachine)



SN Ia simulation and analysis

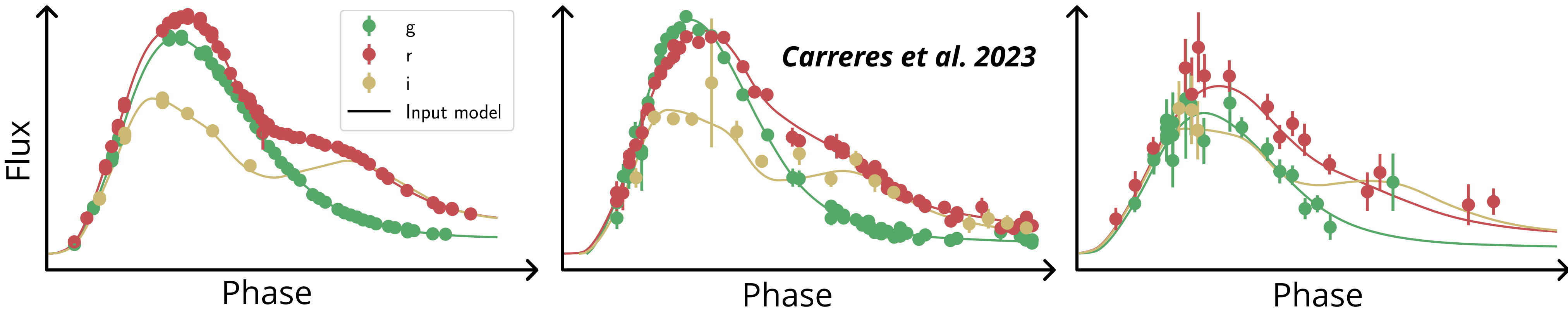


snsim

- **Survey parameters:** Cadence (ZTF, LSST), CCD gain, zero point, sky noise
- **SN Ia model:** Rate, SED, color, stretch, intrinsic scattering distributions, light-curve parameters
- **Host catalog**: Use velocities and associated clustering from N-body simulation

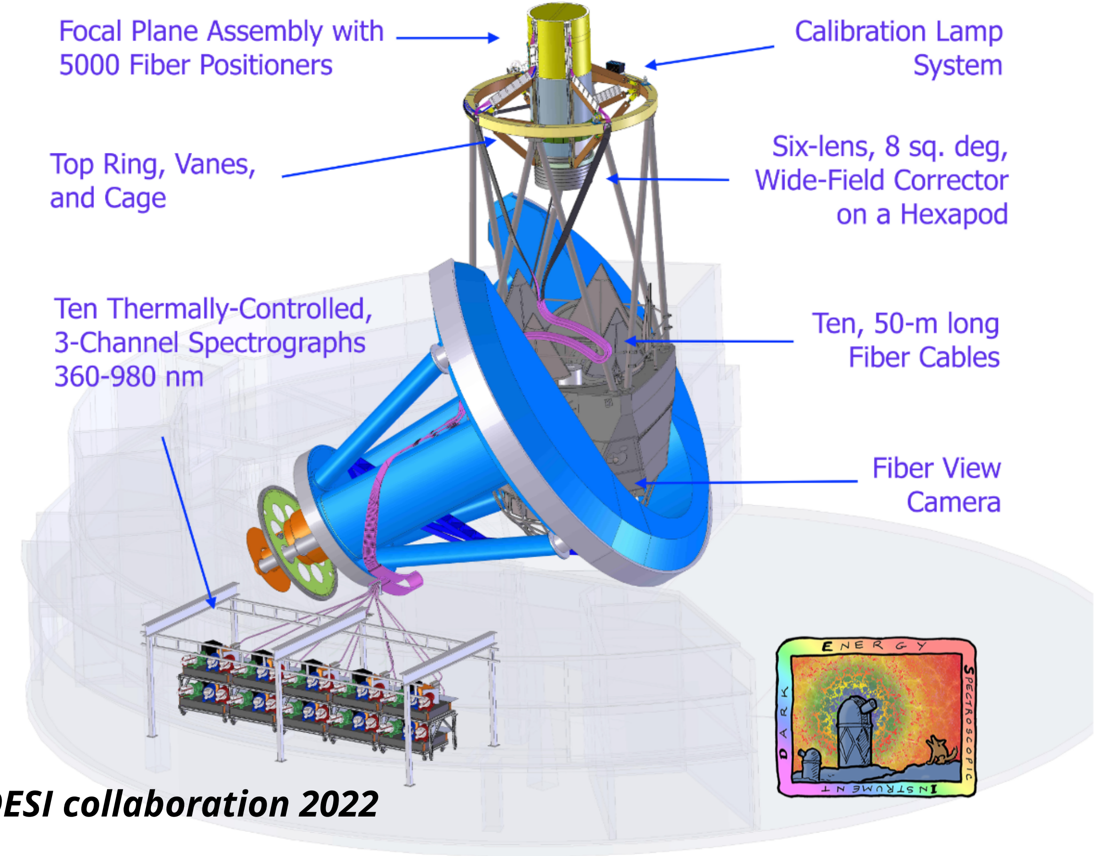
https://github.com/bastiencarreres/snsim

Main contributors:
Bastien Carreres,
Damiano Rosselli



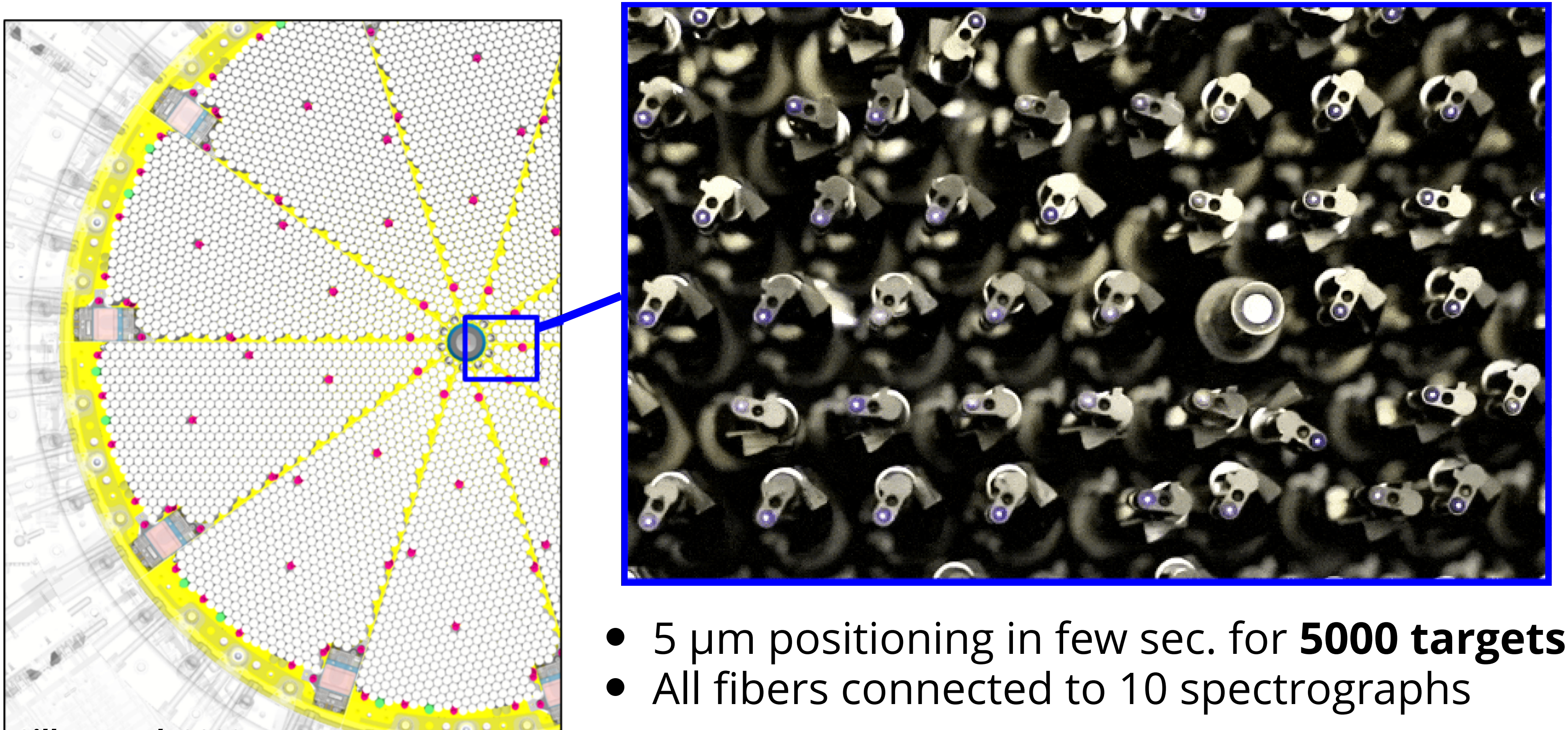
DESI

- 4m multi-object spectrograph at Kitt Peak Observatory



DESI collaboration 2022

DESI



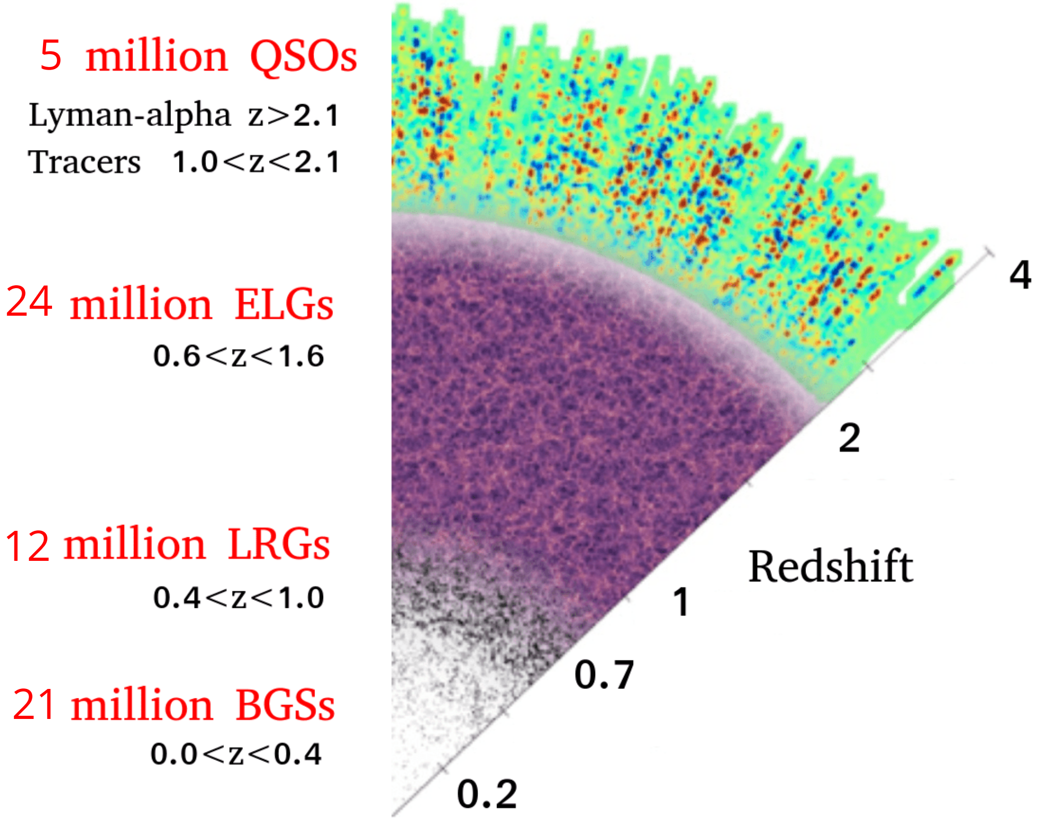
Silber et al. 2022

- 5 μm positioning in few sec. for **5000 targets**
- All fibers connected to 10 spectrographs

DESI

- **BGS**: Bright Galaxy Survey
- **LRG**: Luminous Red Galaxy
- **ELG**: Emission Line Galaxy
- **QSO**: Quasar
  - $z > 2.1$: with a Lyman-α forest
  - $z < 2.1$: as tracers

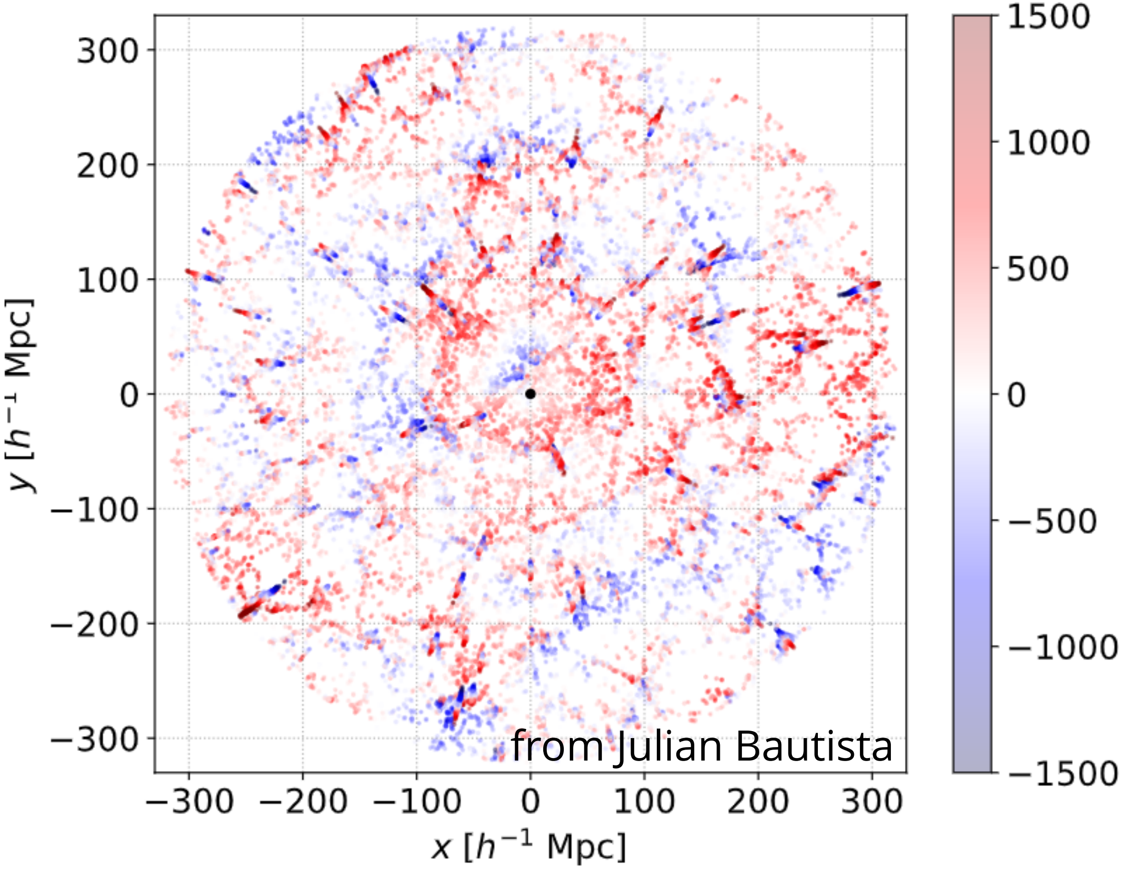
63 million redshifts in 8 years over 17,000 deg²



Primary science: BAO and RSD measurements

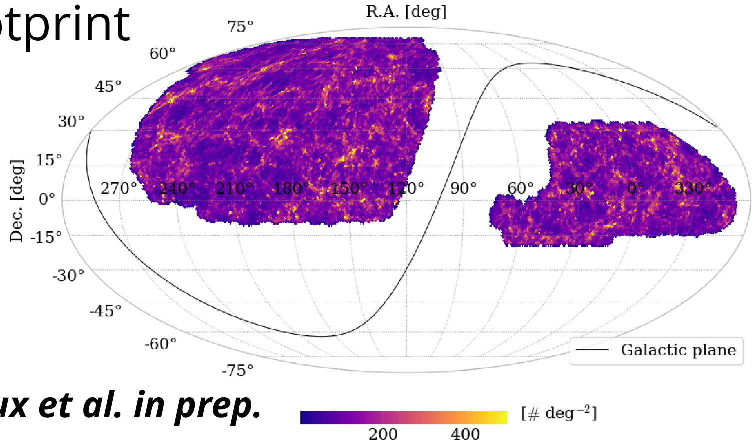
DESI x ZTF simulation

- 27 simulations from AbacusSummit (*Maksimova et al. 2019)*
- **Density**: DESI Bright Galaxy Survey (BGS) clustering matching for DR3 (J. Bautista, A. Smith)
- **Velocity:** ZTF SNIa Y6 simulation performed (following *Carreres et al. 2023*)

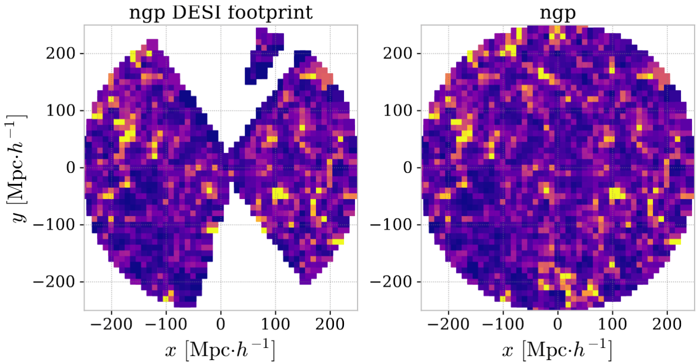


Galaxy field	Supernovae velocities

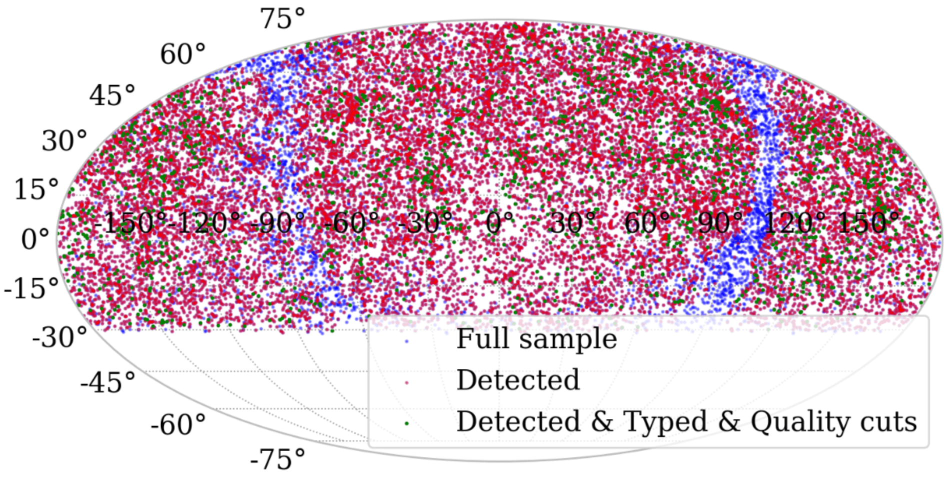
- AbacusSummit mocks matching **DESI DR3 (5 years) BGS clustering** and footprint



Ravoux et al. in prep.



- Runs of SNsim to mimic **ZTF SNIa Y6** data set (following ***Carreres et al. 2023***)



Model for density & velocity fit

- Use of the **RC25** wide-angle model implemented in *flip:*

$$P_{\mathrm{gg}} = \left[b^2 P_{\mathrm{mm}}(k) + bf(\mu_1^2 + \mu_2^2)P_{\mathrm{m}\theta}(k) + f^2\mu_1^2\mu_2^2 P_{\theta\theta}(k)\right] \exp\left[\frac{-k^2(\mu_1^2+\mu_2^2)\sigma_{\mathrm{g}}^2}{2}\right]$$

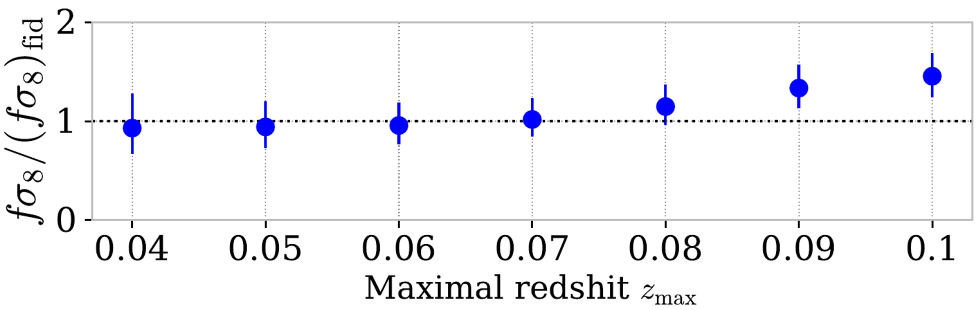
$$P_{\mathrm{gv}} = iaH\frac{\mu_2}{k^2}\left(bfP_{\mathrm{m}\theta}(k) + f^2\mu_1^2 P_{\theta\theta}(k)\right)\exp\left[\frac{-k^2\mu_1^2\sigma_{\mathrm{g}}^2}{2}\right] D_u(k,\sigma_u)$$

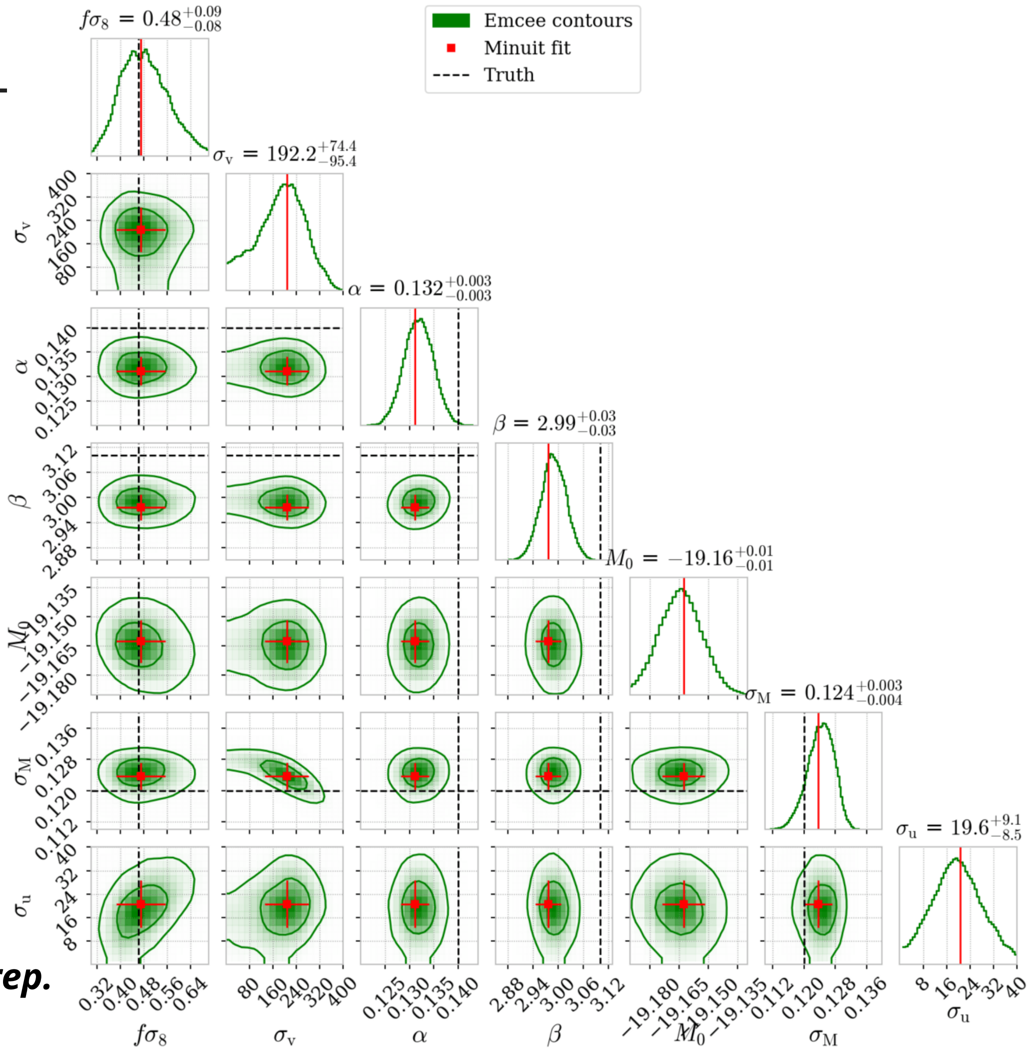
$$P_{\mathrm{vv}} = (aHf)^2\frac{\mu_1\mu_2}{k^2}P_{\theta\theta}(k)D_u^2(k,\sigma_u)$$

$$C_{\mathrm{ab}}(\mathbf{r_1},\mathbf{r_2}) = \frac{1}{(2\pi)^3}\int_{\mathbf{k}} P_{\mathrm{ab}}(k,\mu_1,\mu_2)e^{i\mathbf{k}.\mathbf{r}}d^3\mathbf{k}$$

ZTF velocity fit

- Velocity fit including Hubble diagram parameters to reproduce ***Carreres et al. 2023***
- Variation of analysis parameters (max redshift, SNIa density...)

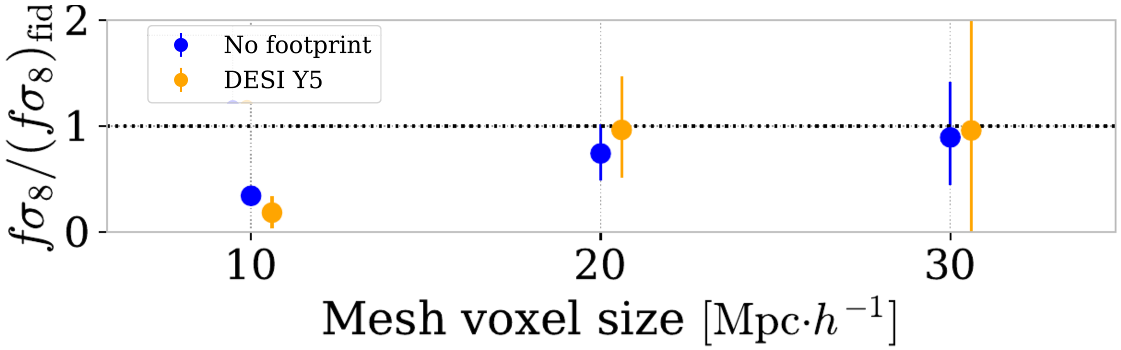




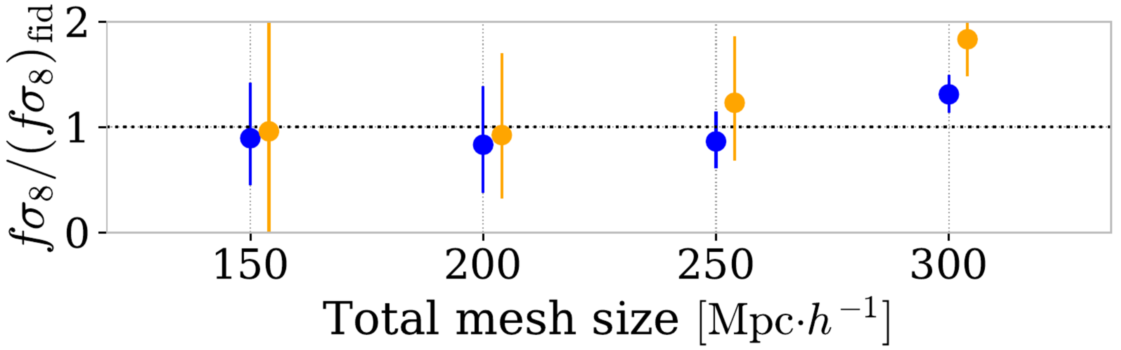
Ravoux et al. in prep.

DESI density fit

- Density grid with *pypower*
- Test varying **all density gridding parameters**: grid size, mesh cell size, interpolation scheme (NGC, CIC, TSC, PCS), footprint (DESI DR3 or no cut)
- Mean minuit fit on 27 mocks with average error bar

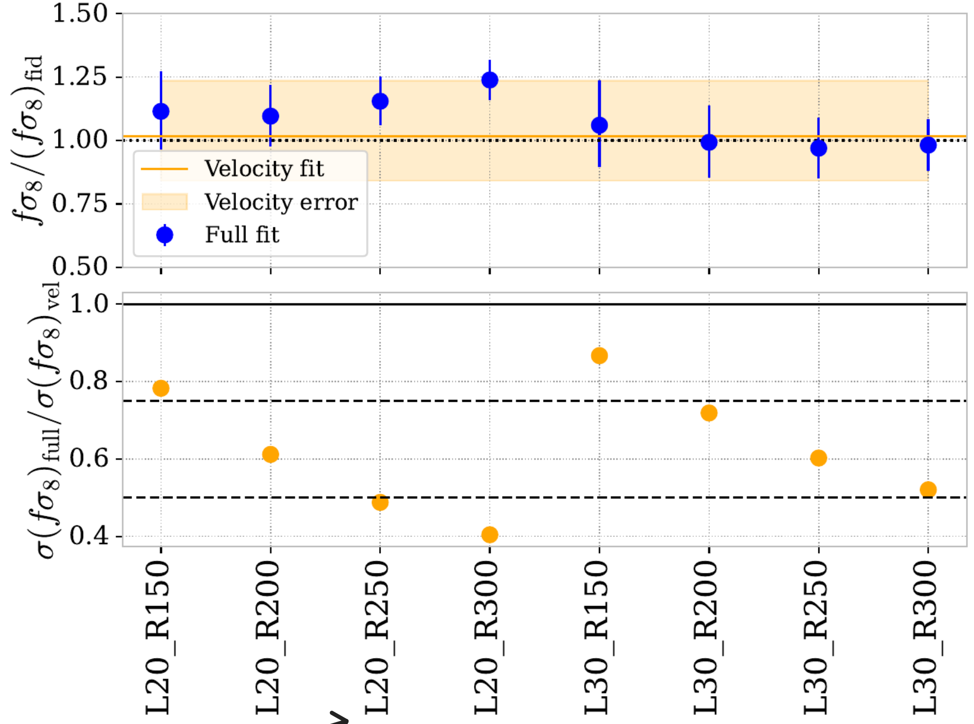


Ravoux et al. in prep.

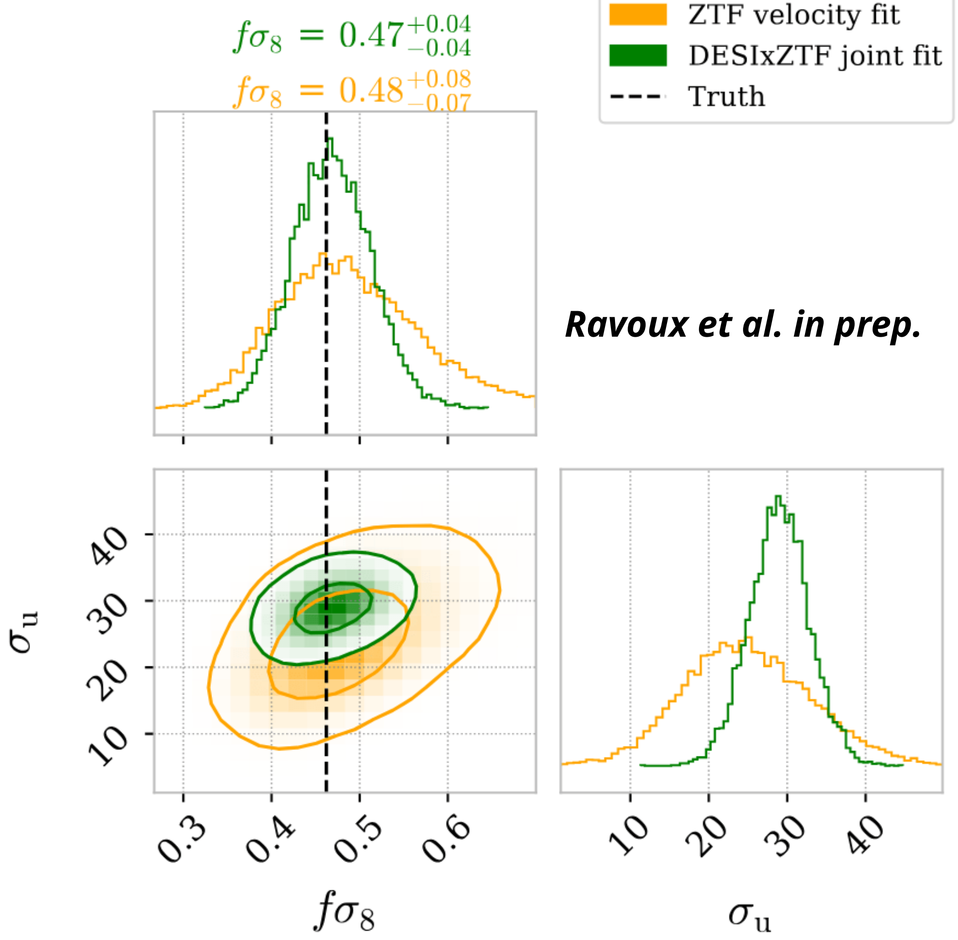


DESI x ZTF joint fit

- SNIa velocity fit with Hubble diagram parameters and density field



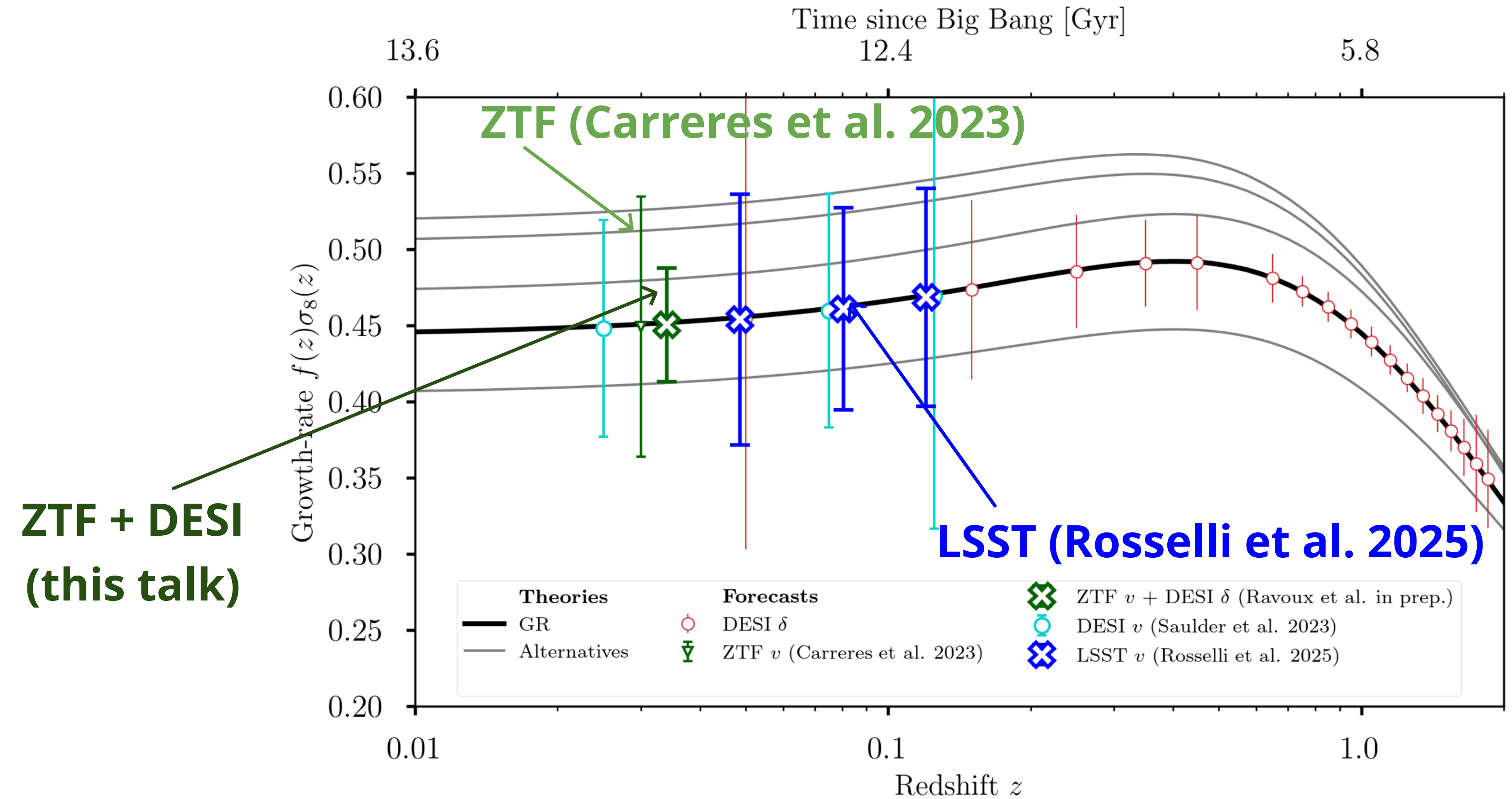
Different density configurations



Ravoux et al. in prep.

Adding density improves fs8 constraints up to 60%

Summary of PV estimations on realistic simulations



Conclusion

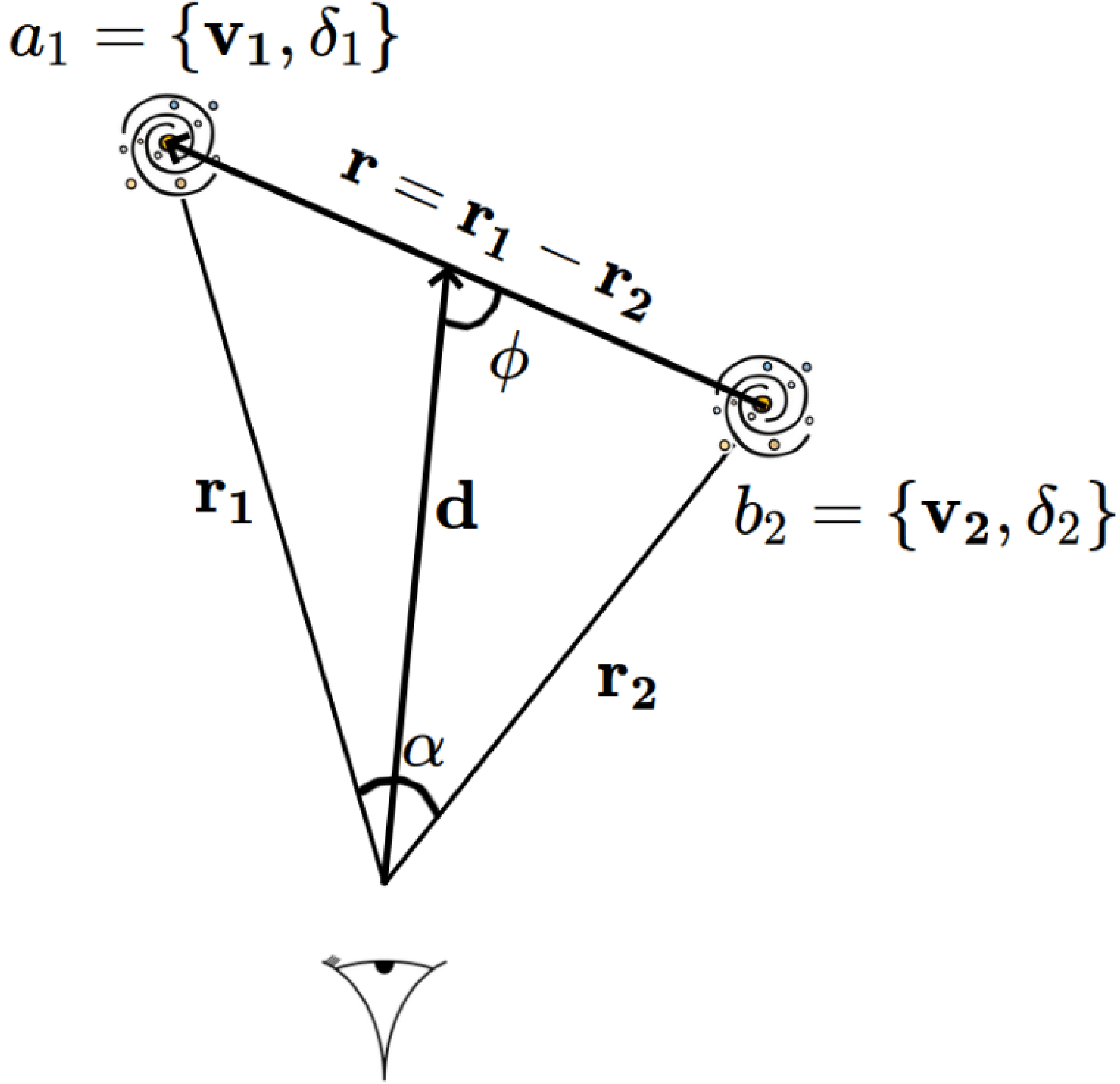
- Large modeling and simulation preparatory work for ZTF, LSST and combination with DESI density field
- Dedicated sofware for simulation *(snsim, skysurvey)* and analysis *(flip)*
- **Next steps**:
  - Application on data (Pantheon+, ZTF, DEBASS, ATLAS)
  - Simulation of all-sky combination (LSST/4HS+4MOST, ZTF+DESI)
  - Combination with other velocity tracers (DESI TF, FP)

Duke Cosmology

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

Aix*Marseille université Socialement engagée

LPC Particules pLasmas Univers applicationS Laboratoire de Physique de Clermont


$a_1 = \{\mathbf{v_1}, \delta_1\}$
$\mathbf{r} = \mathbf{r_1} - \mathbf{r_2}$
ϕ
$\mathbf{r_1}$
$\mathbf{d}$
$b_2 = \{\mathbf{v_2}, \delta_2\}$
$\mathbf{r_2}$
α

AB17 (Adams & Blake 2017) - Wide-angle model without RSD on density

Fields ab	Term number n	$w_{\mathrm{ab},n}$	$F_{\mathrm{ab},n}$	$\mathcal{P}_{\mathrm{ab},n}$
gg	0	$(b\sigma_8)^2$	1	$P_{\mathrm{mm}}(k)$
gv	0	$b\sigma_8 f\sigma_8$	$(iaH)\frac{\mu_2}{k}$	$P_{\mathrm{m}\theta}(k)D_{\mathrm{u}}(k,\sigma_{\mathrm{u}})$
vv	0	$(f\sigma_8)^2$	$(aH)^2\frac{\mu_1\mu_2}{k^2}$	$P_{\theta\theta}(k)D_{\mathrm{u}}^2(k,\sigma_{\mathrm{u}})$

AB20 (Adams & Blake 2020) - Plane-parallel model with RSD on density

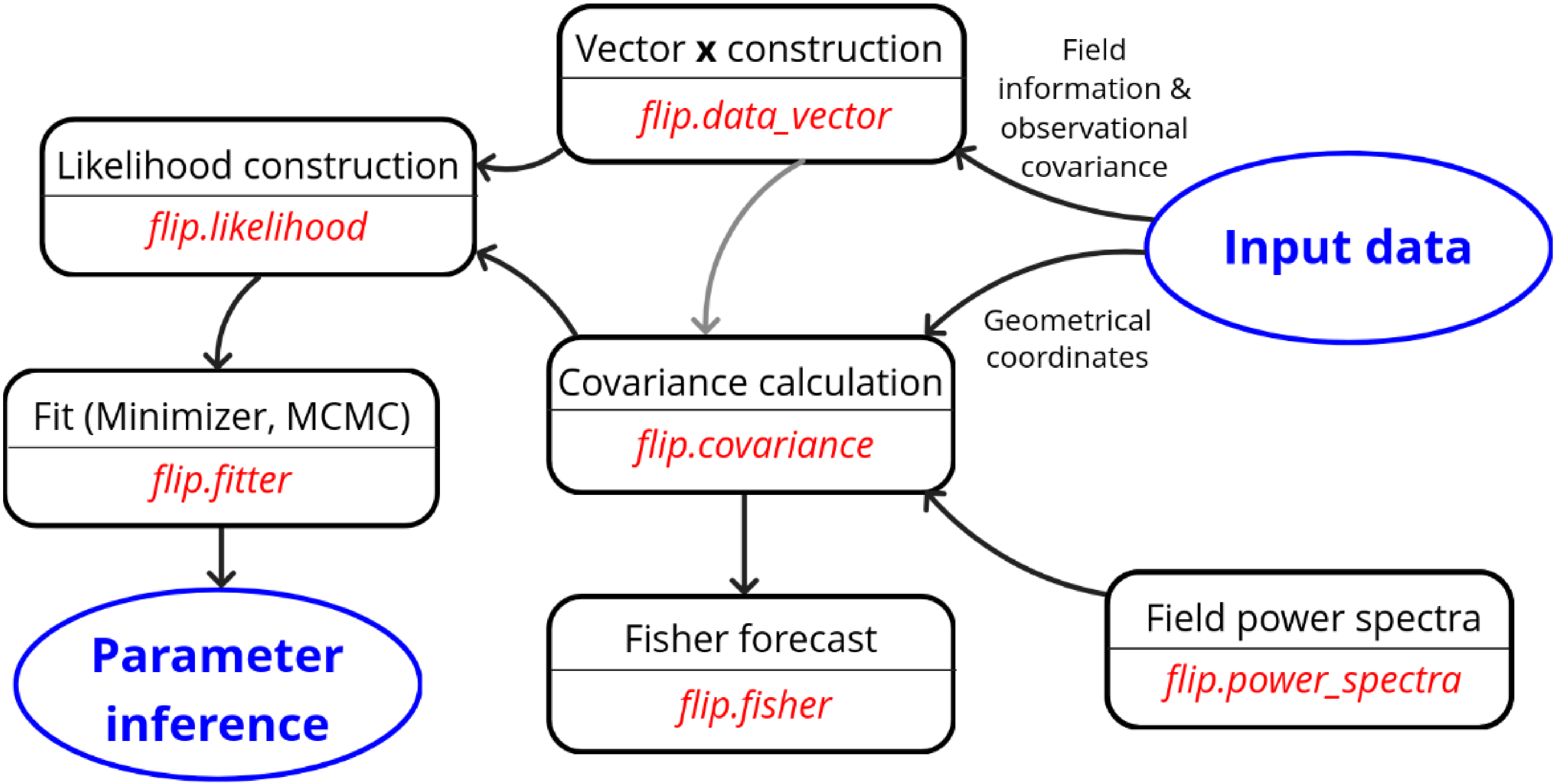
Field ab	Term n	$w_{\mathrm{ab},n}$	$F_{\mathrm{ab},n}$	$\mathcal{P}_{\mathrm{ab},n}$
gg	0	$(b\sigma_8)^2$	$\exp\left[-(k\sigma_{\mathrm{g}}\mu)^2\right]$	$P_{\mathrm{mm}}(k)$
	1	$(b\sigma_8)^2\beta_f$	$2\mu^2\exp\left[-(k\sigma_{\mathrm{g}}\mu)^2\right]$	$P_{\mathrm{m}\theta}(k)$
	2	$(b\sigma_8)^2\beta_f^2$	$\mu^4\exp\left[-(k\sigma_{\mathrm{g}}\mu)^2\right]$	$P_{\theta\theta}(k)$
gv	0	$b\sigma_8 f\sigma_8$	$(iaH)\frac{\mu}{k}\exp\left[-\frac{(k\sigma_{\mathrm{g}}\mu)^2}{2}\right]$	$P_{\mathrm{m}\theta}(k)D_{\mathrm{u}}(k,\sigma_{\mathrm{u}})$
	1	$(f\sigma_8)^2$	$(iaH)\frac{\mu^3}{k}\exp\left[-\frac{(k\sigma_{\mathrm{g}}\mu)^2}{2}\right]$	$P_{\theta\theta}(k)D_{\mathrm{u}}(k,\sigma_{\mathrm{u}})$
vv	0	$(f\sigma_8)^2$	$(aH)^2\frac{\mu^2}{k^2}$	$P_{\theta\theta}(k)D_{\mathrm{u}}^2(k,\sigma_{\mathrm{u}})$

L22 (Lai et al. 2022) - Wide-angle model with RSD and Taylor expansion of FoG

Field ab	Term n	$w_{\mathrm{ab},n}$	$F_{\mathrm{ab},n}$	$\mathcal{P}_{\mathrm{ab},n}$
gg	$0,m$	$(b\sigma_8)^2\sigma_{\mathrm{g}}^{2m}$	$\sum_{p,q,p+q=m}\left(\frac{(-1)^{p+q}}{2^{p+q}p!q!}\right)k^{2(p+q)}\mu_1^{2p}\mu_2^{2q}$	$P_{\mathrm{mm}}(k)$
	$1,m$	$(b\sigma_8)^2\beta_f\sigma_{\mathrm{g}}^{2m}$	$\sum_{p,q,p+q=m}\left(\frac{(-1)^{p+q}}{2^{p+q}p!q!}\right)k^{2(p+q)}\mu_1^{2p}\mu_2^{2q}(\mu_1^2+\mu_2^2)$	$P_{\mathrm{m}\theta}(k)$
	$2,m$	$(b\sigma_8)^2\beta_f^2\sigma_{\mathrm{g}}^{2m}$	$\sum_{p,q,p+q=m}\left(\frac{(-1)^{p+q}}{2^{p+q}p!q!}\right)k^{2(p+q)}\mu_1^{2p+2}\mu_2^{2q+2}$	$P_{\theta\theta}(k)$
gv	$0,m$	$(b\sigma_8)^2\beta_f\sigma_{\mathrm{g}}^{2m}$	$(iaH)\left(\frac{(-1)^m}{2^m m!}\right)k^{2m-1}\mu_2\mu_1^{2m}$	$P_{\mathrm{m}\theta}(k)D_{\mathrm{u}}(k,\sigma_{\mathrm{u}})$
	$1,m$	$(f\sigma_8)^2\sigma_{\mathrm{g}}^{2m}$	$(iaH)\left(\frac{(-1)^m}{2^m m!}\right)k^{2m-1}\mu_2\mu_1^{2m+2}$	$P_{\theta\theta}(k)D_{\mathrm{u}}(k,\sigma_{\mathrm{u}})$
vv	0	$(f\sigma_8)^2$	$(aH)^2\frac{\mu_1\mu_2}{k^2}$	$P_{\theta\theta}(k)D_{\mathrm{u}}^2(k,\sigma_{\mathrm{u}})$

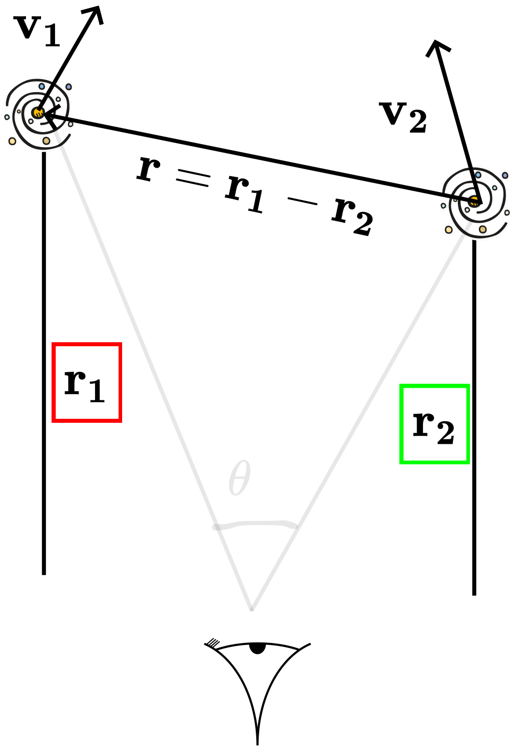
RC25 This study - Wide-angle model with RSD

Field ab	Term n	$w_{\mathrm{ab},n}$	$F_{\mathrm{ab},n}$	$\mathcal{P}_{\mathrm{ab},n}$
gg	0	$(b\sigma_8)^2$	$\exp\left[-\frac{k^2\sigma_{\mathrm{g}}^2(\mu_1^2+\mu_2^2)}{2}\right]$	$P_{\mathrm{mm}}(k)$
	1	$(b\sigma_8)^2\beta_f$	$(\mu_1^2+\mu_2^2)\exp\left[-\frac{k^2\sigma_{\mathrm{g}}^2(\mu_1^2+\mu_2^2)}{2}\right]$	$P_{\mathrm{m}\theta}(k)$
	2	$(b\sigma_8)^2\beta_f^2$	$\mu_1^2\mu_2^2\exp\left[-\frac{k^2\sigma_{\mathrm{g}}^2(\mu_1^2+\mu_2^2)}{2}\right]$	$P_{\theta\theta}(k)$
gv	0	$(b\sigma_8)^2\beta_f$	$(iaH)\frac{\mu_2}{k}\exp\left[-\frac{(k\sigma_{\mathrm{g}}\mu_1)^2}{2}\right]$	$P_{\mathrm{m}\theta}(k)D_{\mathrm{u}}(k,\sigma_{\mathrm{u}})$
	1	$(f\sigma_8)^2$	$(iaH)\frac{\mu_2\mu_1^2}{k}\exp\left[-\frac{(k\sigma_{\mathrm{g}}\mu_1)^2}{2}\right]$	$P_{\theta\theta}(k)D_{\mathrm{u}}(k,\sigma_{\mathrm{u}})$
vv	0	$(f\sigma_8)^2$	$(aH)^2\frac{\mu_1\mu_2}{k^2}$	$P_{\theta\theta}(k)D_{\mathrm{u}}^2(k,\sigma_{\mathrm{u}})$

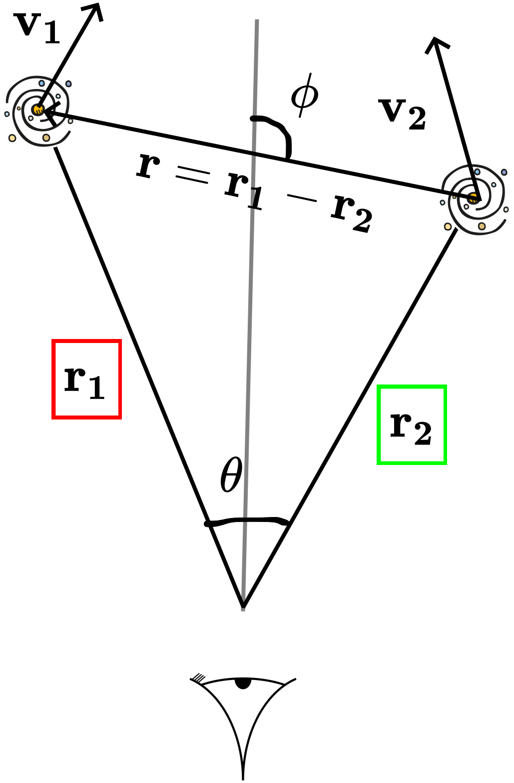

Vector x construction
flip.data_vector
Field information & observational covariance
Likelihood construction
flip.likelihood
Input data
Geometrical coordinates
Fit (Minimizer, MCMC)
flip.fitter
Covariance calculation
flip.covariance
Fisher forecast
flip.fisher
Field power spectra
flip.power_spectra
Parameter inference

A word on wide-angle in clustering

Plane parallel models	Wide angle models



$$\mu = \mu_1 = \mu_2$$



$$\mu_1 \neq \mu_2$$

$$\mu_i = \mathbf{k} \cdot \mathbf{r_i}$$

Plane parallel model

- Express power spectrum model in a general way:

$$P_{\mathrm{ab}}(k,\mu) = \sum_n \boxed{w_{\mathrm{ab},n}}\,\boxed{F_{\mathrm{ab},n}}(k,\mu)\,\boxed{\mathcal{P}_{\mathrm{ab},n}}(k)$$

Parameters to fit

Terms to integrate analytically

Power spectra terms to integrate numerically

- vv "simple" example:

$$P_{\mathrm{vv}} = \boxed{(f\sigma_8)^2} \times \boxed{\left(a^2H^2\frac{\mu^2}{k^2}\right)} \times \boxed{\left(P_{\theta\theta}(k)D_u^2(k,\sigma_u)\right)}$$

Plane parallel model

- Without loosing generality we can express the covariance:

$$C_{\mathrm{ab}}(\mathbf{r_1}, \mathbf{r_2}) = \sum_n w_{\mathrm{ab},n} \sum_\ell N_{\mathrm{ab},\ell}(\phi) \mathcal{H}_\ell \left[\mathcal{P}_{\mathrm{ab},n}(k) M^\ell_{\mathrm{ab},n}(k)\right](r)$$

$$N_{\mathrm{ab},\ell}(\phi) = (2\ell + 1) L_\ell(\cos{(\pi - \phi)})$$

$$M^\ell_{\mathrm{ab},n}(k) = \tfrac{1}{2} \int_{-1}^{1} d\mu' F_{\mathrm{ab},n}(k, \mu') L_\ell(\mu')$$

Plane parallel model

- Without loosing generality we can express the covariance:

$$C_{\mathrm{ab}}(\mathbf{r_1}, \mathbf{r_2}) = \sum_n \boxed{w_{\mathrm{ab},n}} \sum_\ell N_{\mathrm{ab},\ell}(\phi)\mathcal{H}_\ell \left[\mathcal{P}_{\mathrm{ab},n}(k) M^\ell_{\mathrm{ab},n}(k)\right](r)$$

Linear sum of matrix with parameters to fit as coefficients

Plane parallel model

- Without loosing generality we can express the covariance:

$$C_{\mathrm{ab}}(\mathbf{r_1},\mathbf{r_2}) = \sum_n w_{\mathrm{ab},n} \sum_\ell N_{\mathrm{ab},\ell}(\phi) \boxed{\mathcal{H}_\ell} \left[\mathcal{P}_{\mathrm{ab},n}(k) M^\ell_{\mathrm{ab},n}(k)\right](r)$$

Hankel transform

$$\mathcal{H}_\ell\left[f(k)\right](r) = i^\ell \int_0^\infty \frac{k^2 dk}{2\pi^2} j_\ell(kr) f(k)$$

- **Most important part**: Algorithmically optimized way to compute power spectrum integral, with FFTLog algorithm

Plane parallel model

- Without loosing generality we can express the covariance:

$$C_{\mathrm{ab}}(\mathbf{r_1},\mathbf{r_2}) = \sum_n w_{\mathrm{ab},n} \sum_\ell N_{\mathrm{ab},\ell}(\phi)\mathcal{H}_\ell\left[\mathcal{P}_{\mathrm{ab},n}(k)M^\ell_{\mathrm{ab},n}(k)\right](r)$$

$$\boxed{\begin{aligned} N_{\mathrm{ab},\ell}(\phi) &= (2\ell+1)L_\ell(\cos(\pi-\phi)) \\ M^\ell_{\mathrm{ab},n}(k) &= \tfrac{1}{2}\int_{-1}^{1} d\mu' F_{\mathrm{ab},n}(k,\mu')L_\ell(\mu') \end{aligned}}$$

Terms pre-computed analytically with symbolic code generaltion

- **More complicated formalism derived and implemented for wide-angle**

Wide angle model

$$P_{\mathrm{ab}}(k,\mu_1,\mu_2) = \sum_i A_{\mathrm{ab},i} B_{\mathrm{ab},i}(k,\mu_1,\mu_2) P_{\mathrm{ab},i}(k)$$

linear sum of matrix

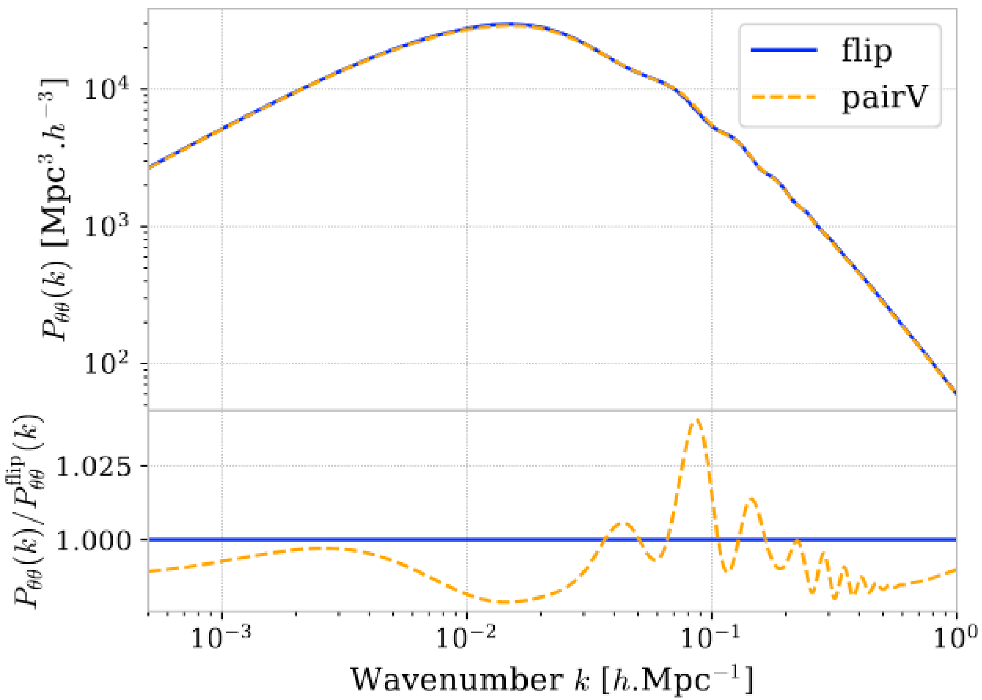
$$C_{\mathrm{ab}}(\mathbf{r_1},\mathbf{r_2}) = \sum_i A_{\mathrm{ab},i} \sum_l \xi^i_{\mathrm{ab},\ell}(r)$$

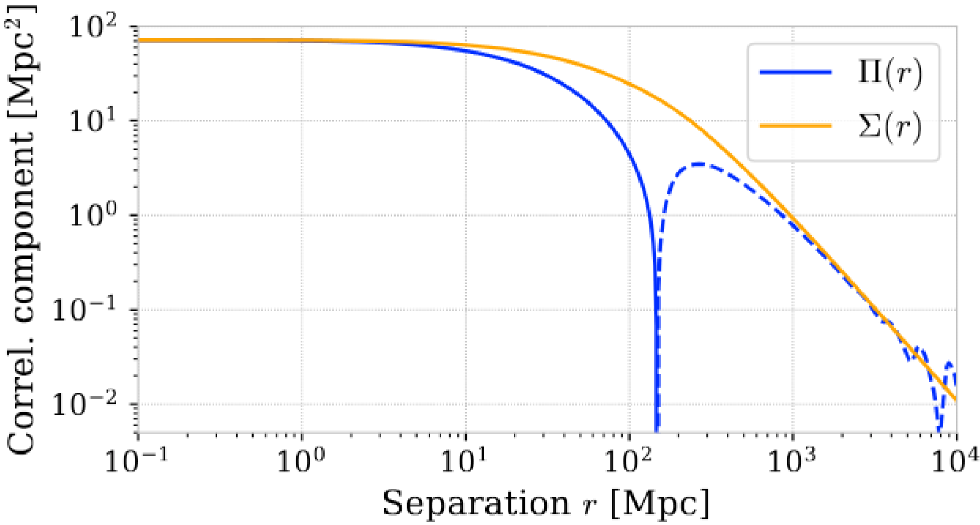
$$\xi^i_{\mathrm{ab},\ell}(r) = \sum_j N^{i,j}_{\mathrm{ab},\ell}(\theta,\phi)\left[i^\ell \int_k \frac{k^2 dk}{2\pi^2} P_{\mathrm{ab},i}(k) M^{i,j}_{\mathrm{ab},\ell}(k) j_\ell(kr)\right]$$

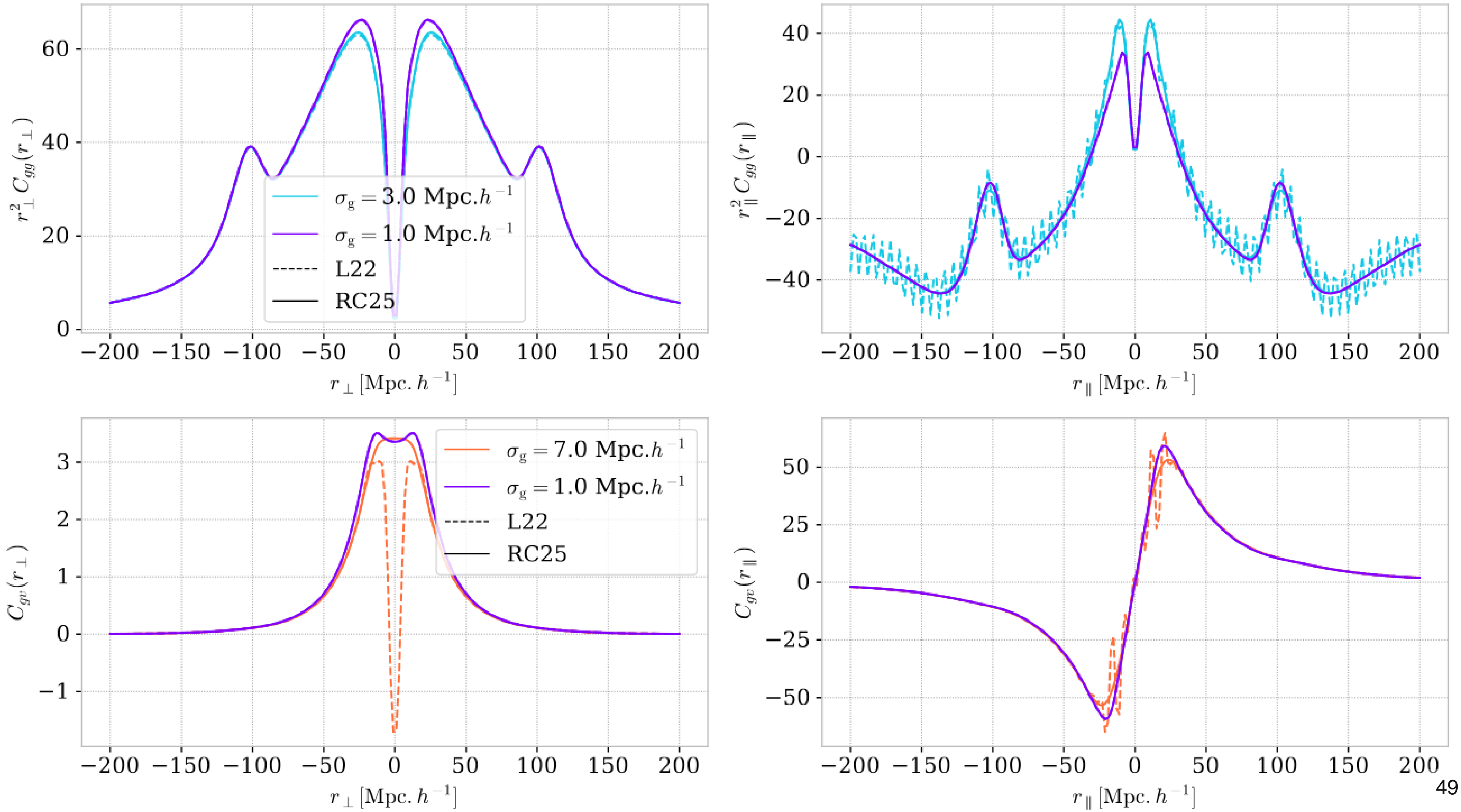
$$M^{i,j=(\ell_1,\ell_2)}_{\mathrm{ab},\ell}(k) = \int_{\mu_1=-1}^{1}\int_{\mu_2=-1}^{1} \frac{1}{4} L_{\ell_1}(\mu_1) L_{\ell_2}(\mu_2) B_{\mathrm{ab},i}(k,\mu_1,\mu_2) d\mu_1 d\mu_2$$

$$N^{i,j=(\ell_1,\ell_2)}_{\mathrm{ab},\ell}(\theta,\phi) = (4\pi)^2 \sum_{m,m_1,m_2} G^{m,m_1,m_2}_{l,l_1,l_2} Y_{\ell m}(\hat{\mathbf{r}})^* Y_{\ell_1 m_1}(\hat{\mathbf{r_1}})^* Y_{\ell_2 m_2}(\hat{\mathbf{r_2}})^*$$

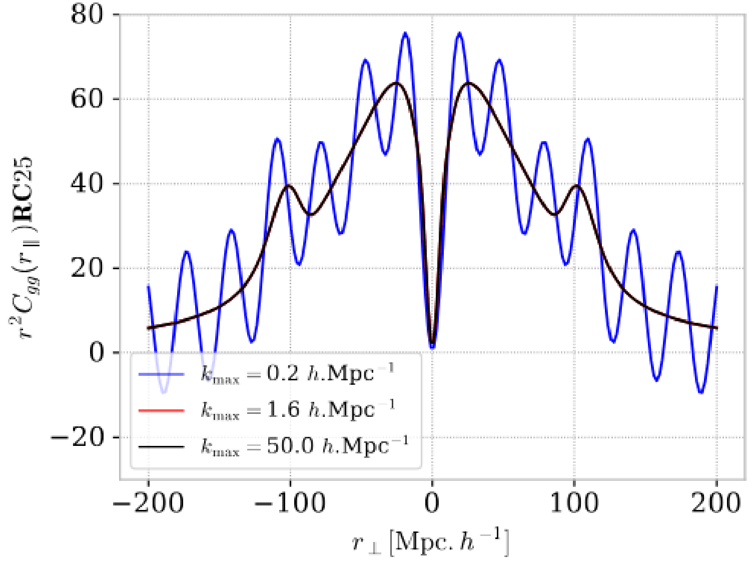
$$G^{l_1,l_2,l_3}_{m_1,m_2,m_3} = \sqrt{\frac{(2l_1+1)(2l_2+1)(2l_3+1)}{4\pi}} \begin{pmatrix} l_1 & l_2 & l_3 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} l_1 & l_2 & l_3 \\ m_1 & m_2 & m_3 \end{pmatrix}$$


flip
pairV
$P_{\theta\theta}(k)$ [Mpc^3.h^{-3}]
$P_{\theta\theta}(k)/P_{\theta\theta}^{\mathrm{flip}}(k)$
Wavenumber k [h.Mpc^{-1}]

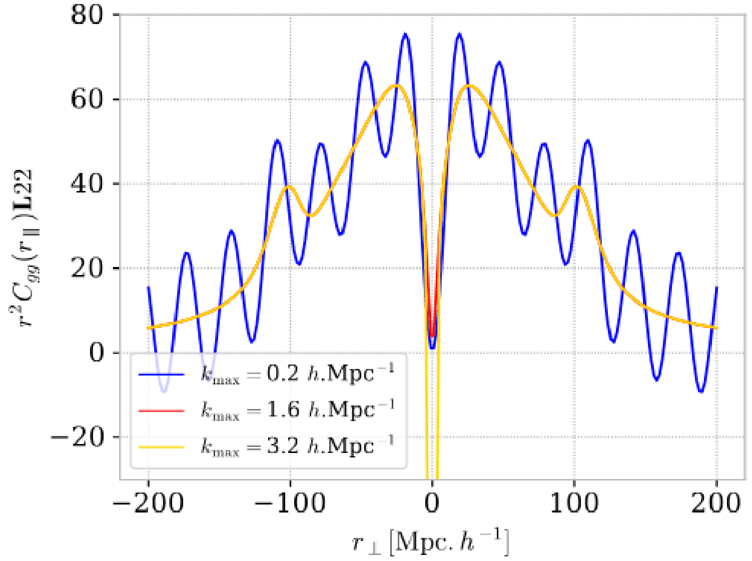

$\Pi(r)$
$\Sigma(r)$
Correl. component [Mpc^2]
Separation r [Mpc]



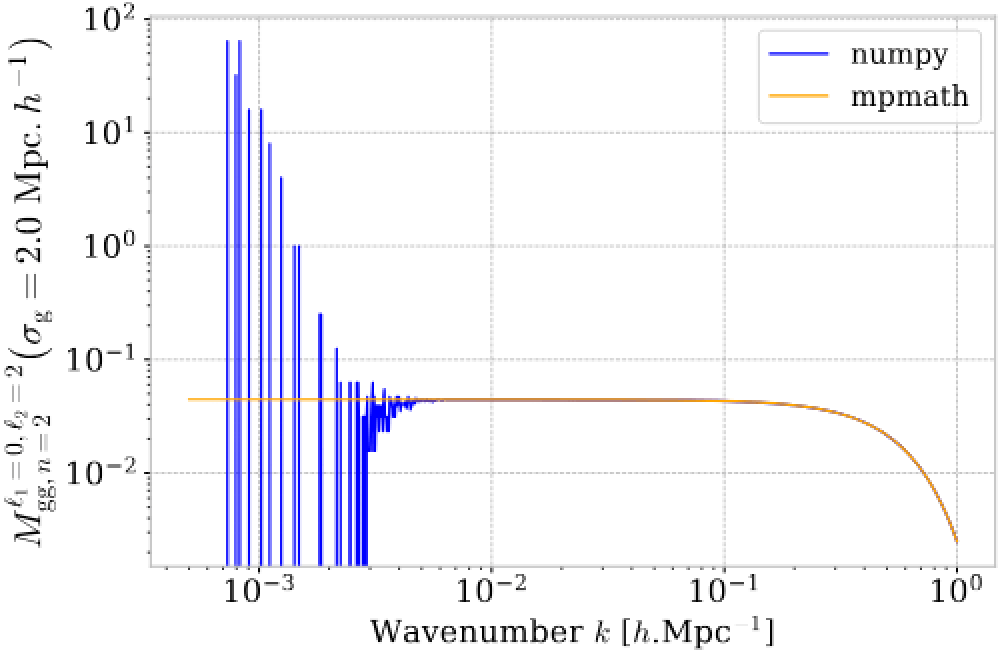
$\sigma_g = 3.0$ Mpc.h^{-1}
$\sigma_g = 1.0$ Mpc.h^{-1}
L22
RC25
$r_\perp^2 C_{gg}(r_\perp)$
$r_\perp$ [Mpc. h^{-1}]
$r_\parallel^2 C_{gg}(r_\parallel)$
$r_\parallel$ [Mpc. h^{-1}]
$\sigma_g = 7.0$ Mpc.h^{-1}
$\sigma_g = 1.0$ Mpc.h^{-1}
L22
RC25
$C_{gv}(r_\perp)$
$r_\perp$ [Mpc. h^{-1}]
$C_{gv}(r_\parallel)$
$r_\parallel$ [Mpc. h^{-1}]



$r^2 C_{gg}(r_\parallel)$ RC25
$k_{\max} = 0.2\ h.\mathrm{Mpc}^{-1}$
$k_{\max} = 1.6\ h.\mathrm{Mpc}^{-1}$
$k_{\max} = 50.0\ h.\mathrm{Mpc}^{-1}$
$r_\perp$ [Mpc. h^{-1}]



$r^2 C_{gg}(r_\parallel)$ L22
$k_{\max} = 0.2\ h.\mathrm{Mpc}^{-1}$
$k_{\max} = 1.6\ h.\mathrm{Mpc}^{-1}$
$k_{\max} = 3.2\ h.\mathrm{Mpc}^{-1}$
$r_\perp$ [Mpc. h^{-1}]



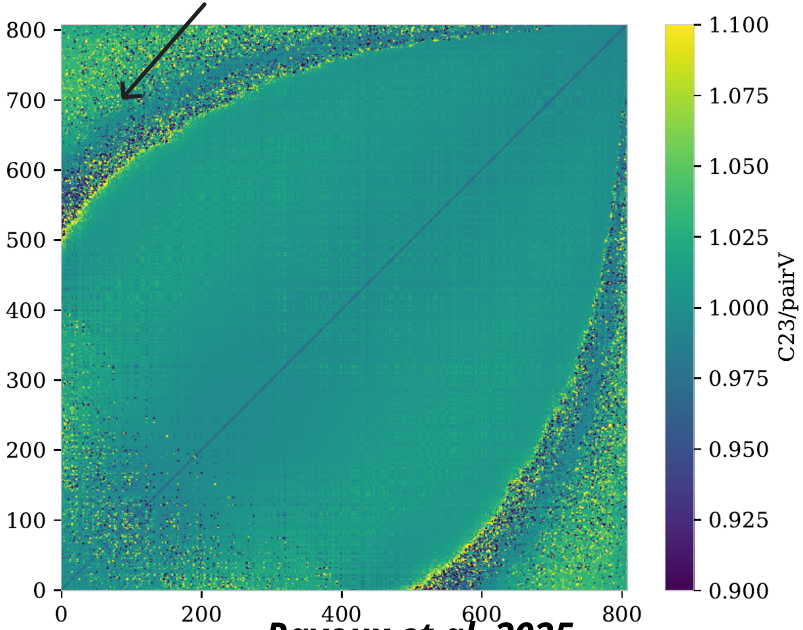
$M^{\ell_1=0,\ell_2=2}_{\mathrm{gg},n=2}(\sigma_g = 2.0\ \mathrm{Mpc}.\ h^{-1})$
numpy
mpmath
Wavenumber k [h.Mpc^{-1}]

flip validations

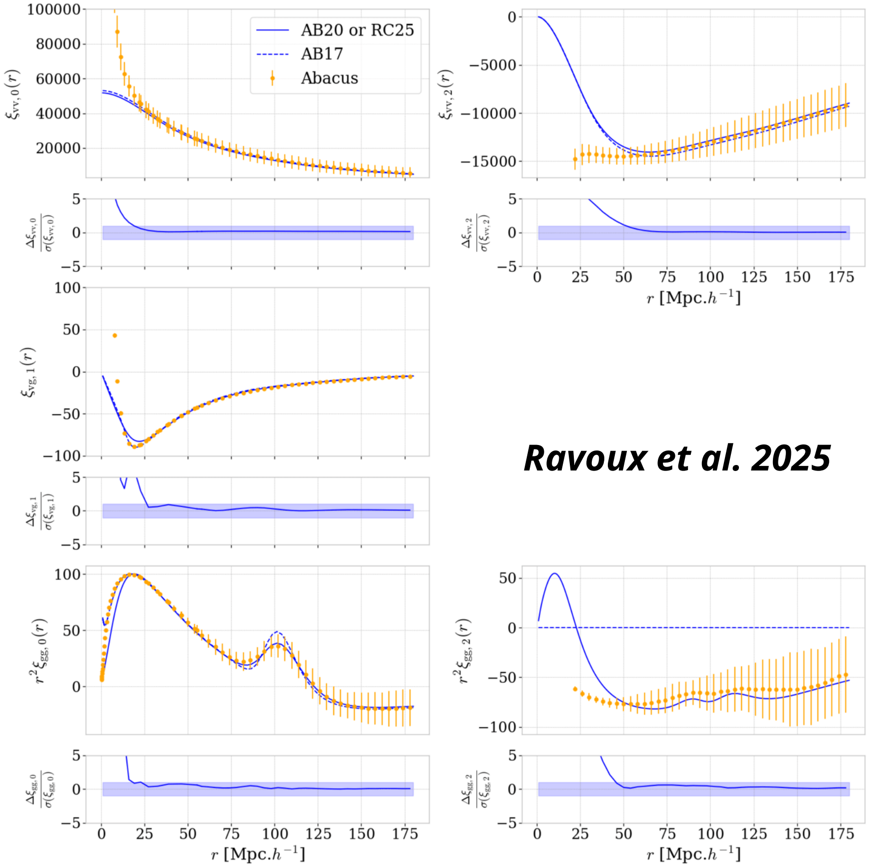
- Field covariance comparison with *pairV*

Anthony Carr & David Parkinson

Disagreement due to different power spectrum model



Ravoux et al. 2025



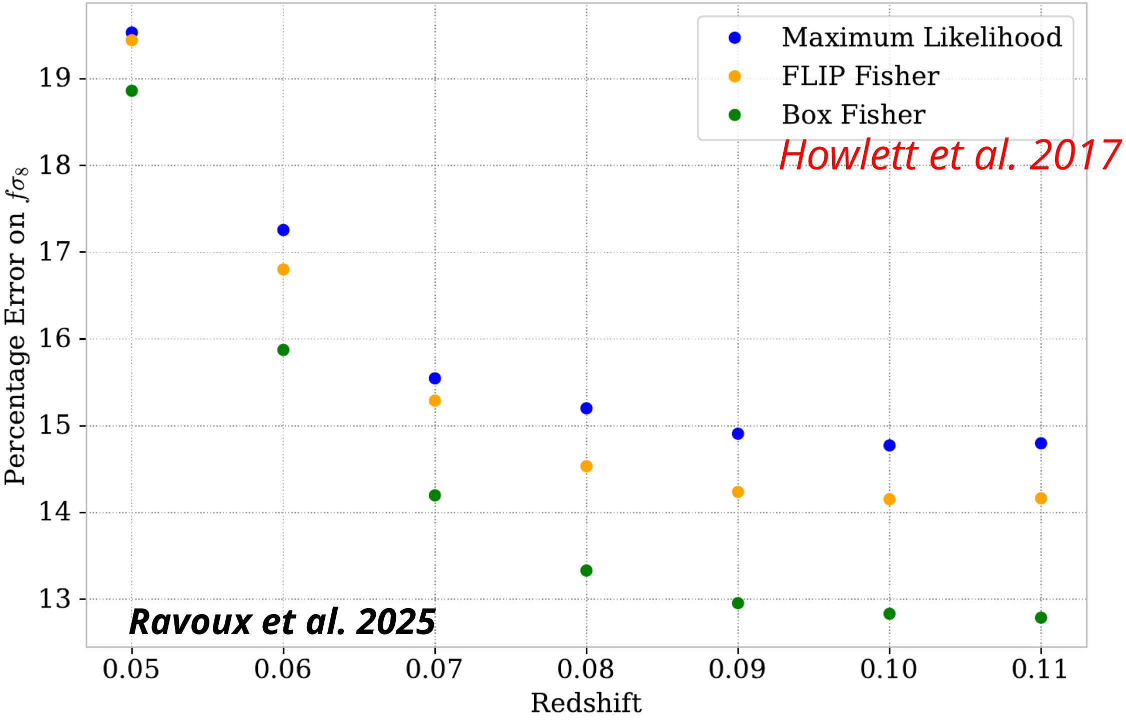
Ravoux et al. 2025

- Model validated on N-body simulations

Tyann Dummerchat

Survey dependent Fisher forecast

- Field covariance matrix accounts for survey geometry
- Comparing ZTF simulation (*Carreres et al. 2023*) with Fisher forecasts
- **Error ~ 30% closer to likelihood-based than standard Fisher**

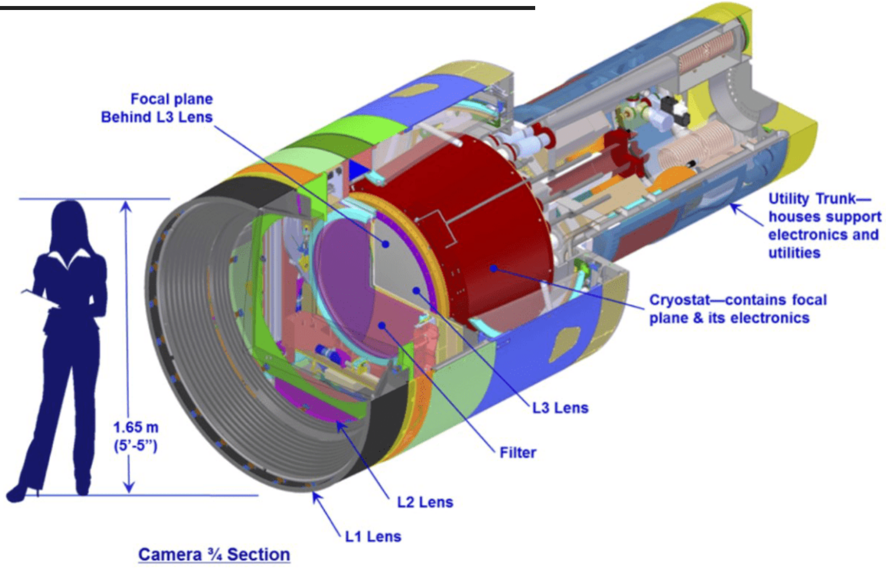


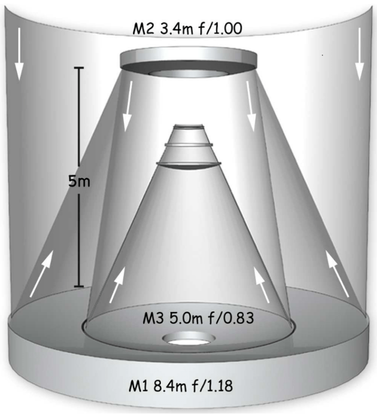
Rubin - LSST

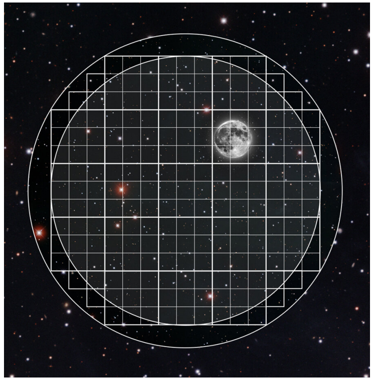

Telescope mount assembly
AuxTel: 1.2m atmospheric telescop

Rubin - LSST: instrument

- **Largest numerical camera in the world**: 3.2 Gpixels with 2s readout time
- 8.4 m primary mirror and 9.6 deg² field of view
- 6 filters: (u, g, r, i, z, y)
- 10-year photometric survey of half of the sky (~ 20 000 deg²)

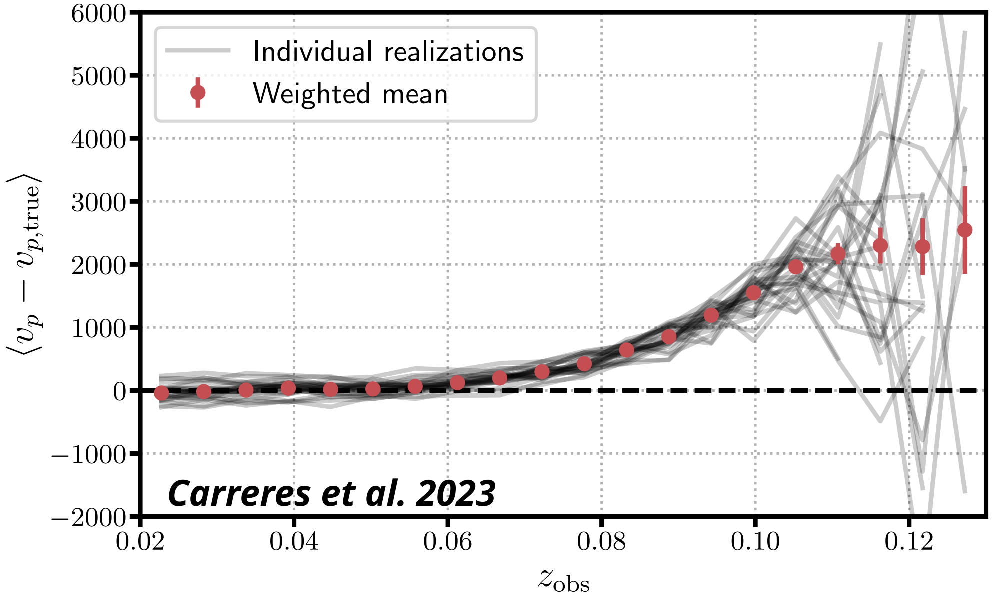


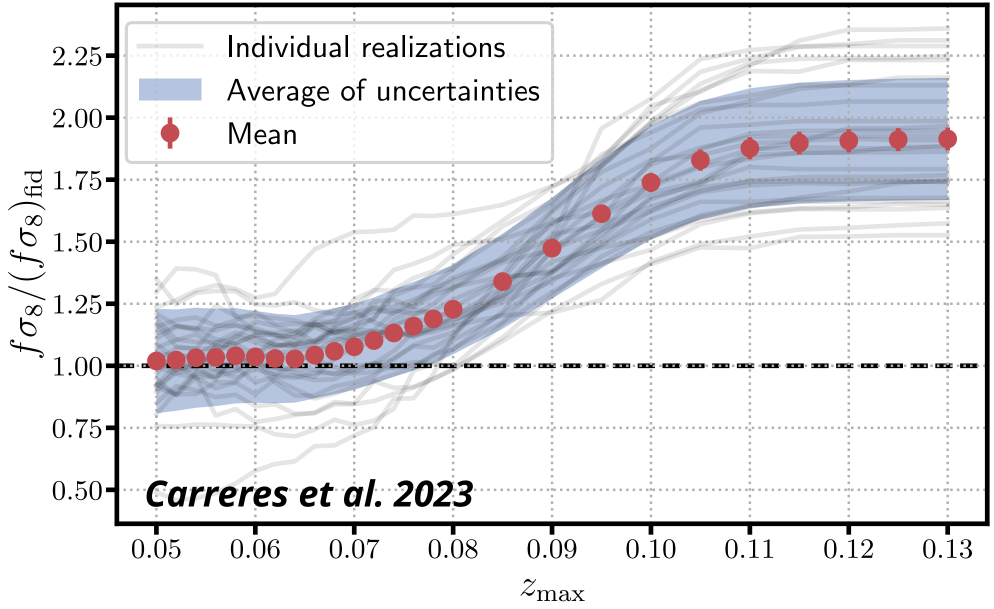




ZTF results

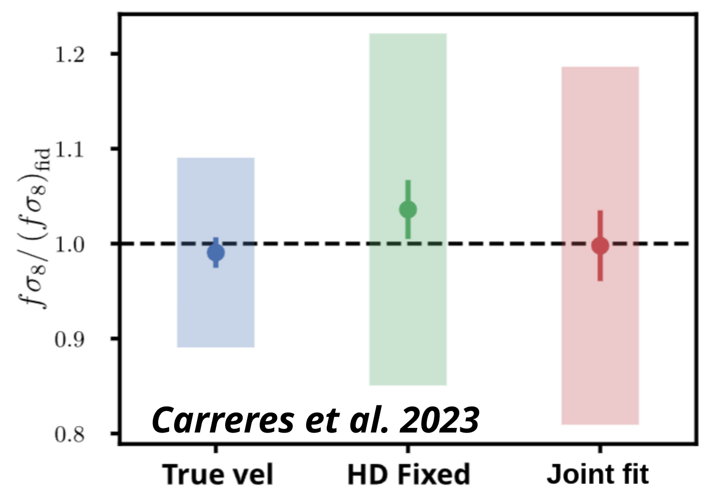
- SN Ia selection bias causes velocity & fσ8 bias at high redshift
- No fσ8 error bar improvement even with correction
- **Maximum redshift usable:** $z = 0.06$

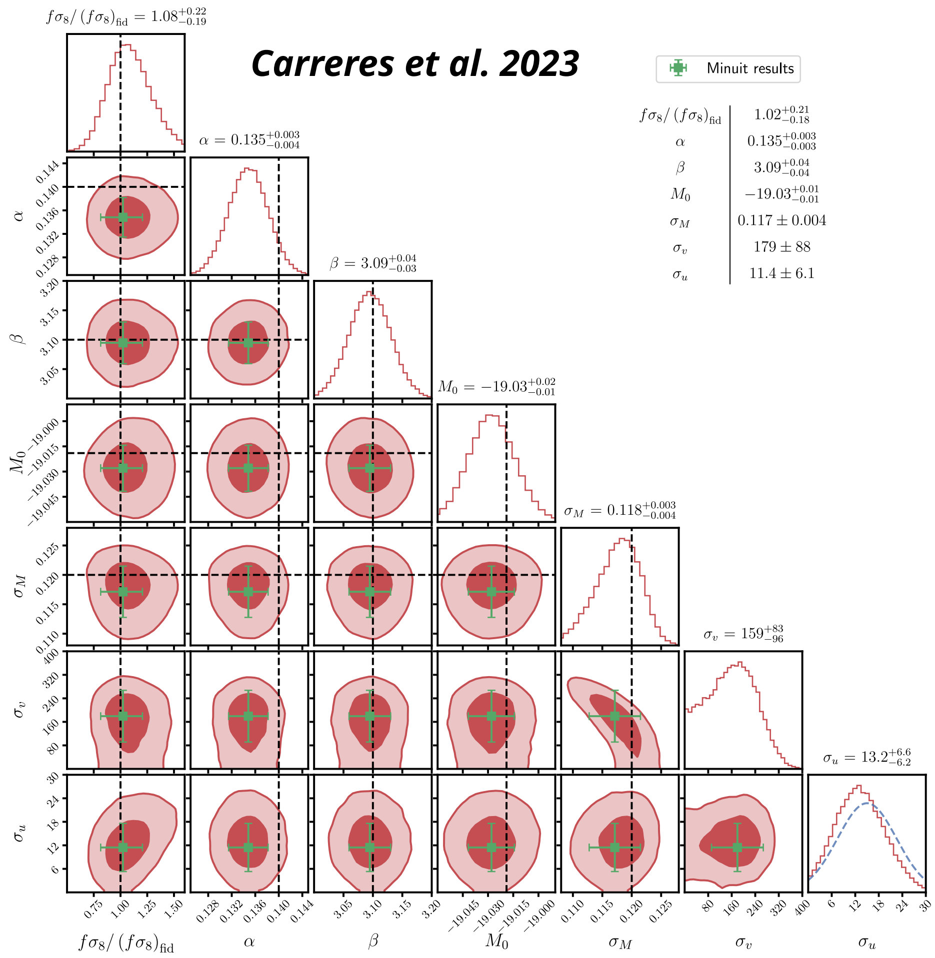




ZTF results

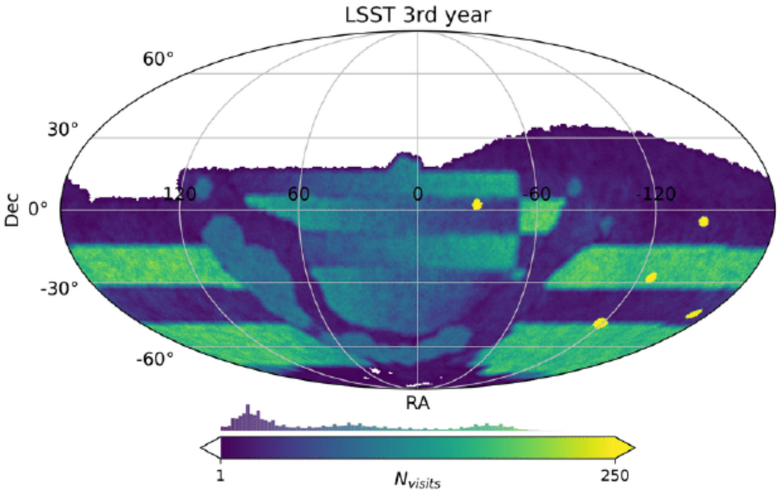
- fσ8 fit performed with Hubble diagram parameters
- no fσ8 bias on the 27 simulations
- **19 % precision measurement with only 1600 SNe Ia**



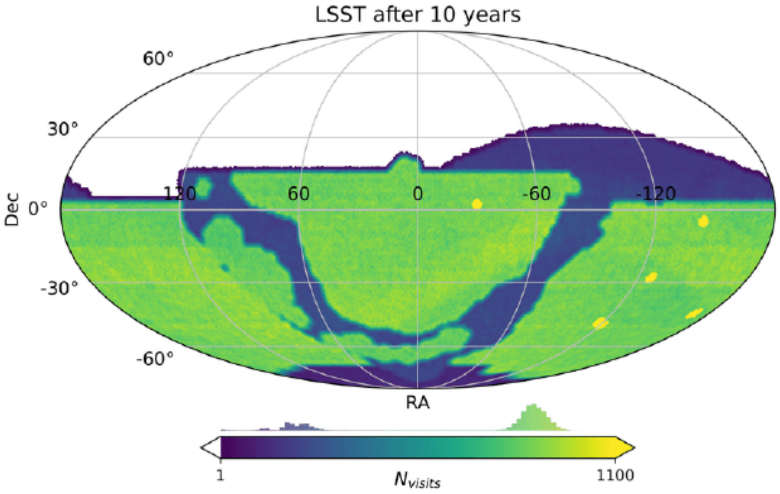


LSST simulations

- 10 year simulation from Uchuu-UniverseMachine (*Behroozi et al. 2019*)
- Cadence and instrument properties from the observing strategy simulation v3.3

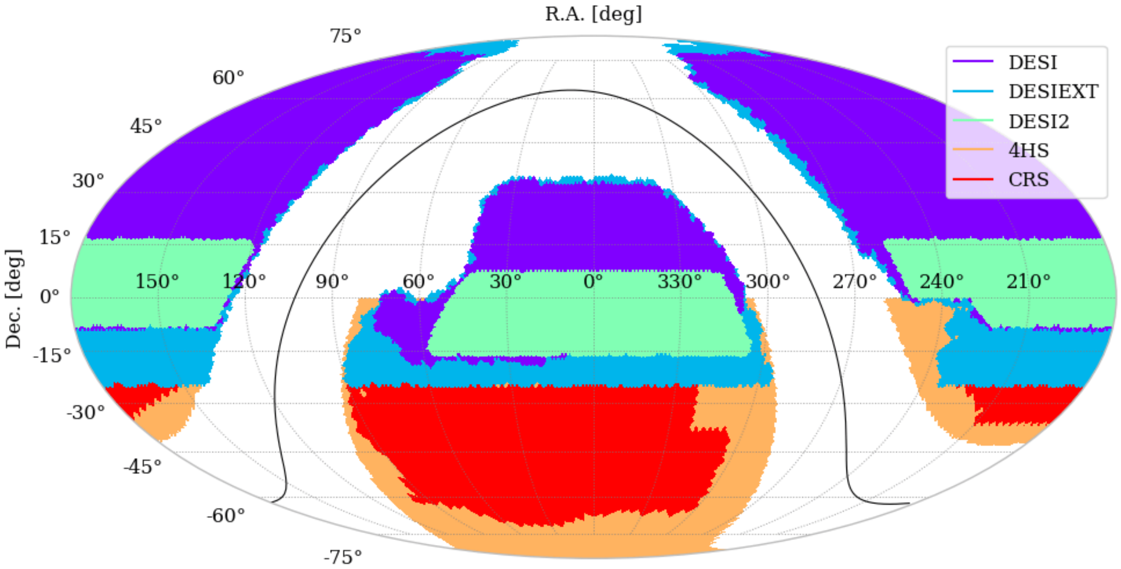


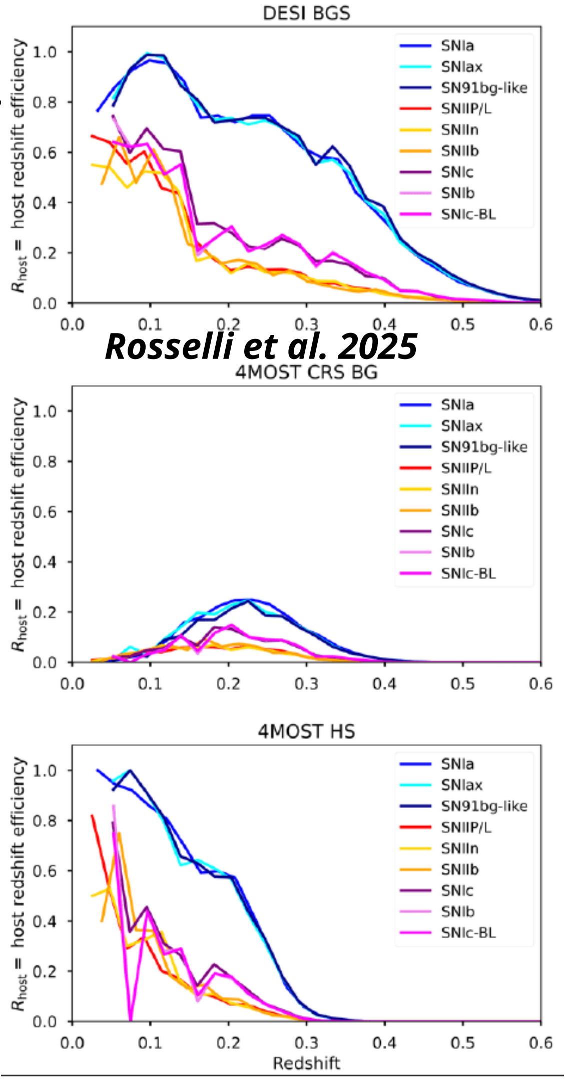
Rosselli et al. 2025



LSST simulations

- **SN host redshift efficiency** (C. Ravoux, P. Gris, D. Rosselli, J. Bautista):
  - Use of DC2 LSST simulation with galaxy properties
  - Footprint and efficiency for different spectroscopic survey
  - Considering SNe variety contamination

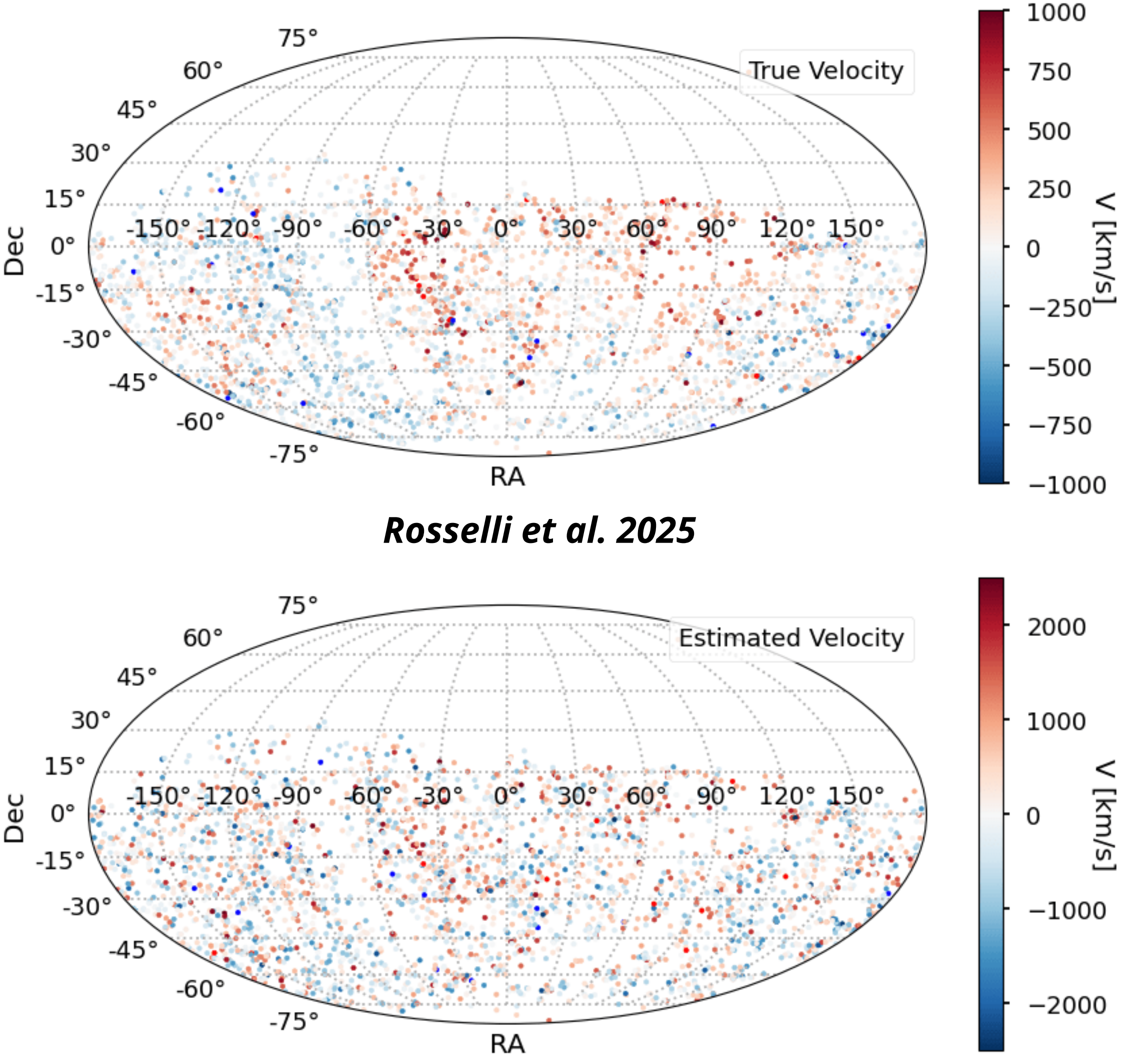




Rosselli et al. 2025

LSST simulations

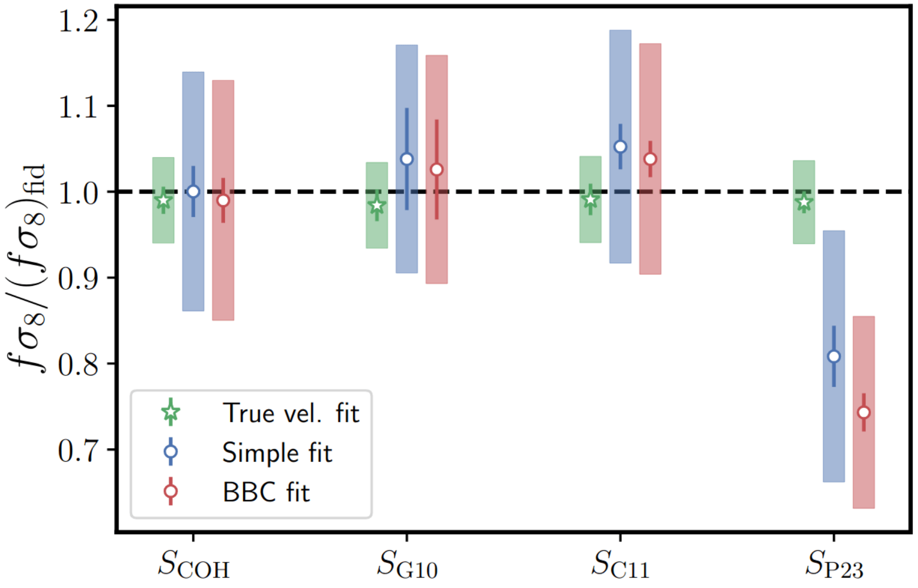
- **33,000 SNe Ia** with spectro-z at z < 0.16 (among 1M for the full sample)
- Photo-typing with *SuperNNovae* (*Moller et al. 2019*) gives **0.02% contamination from peculiar SN**

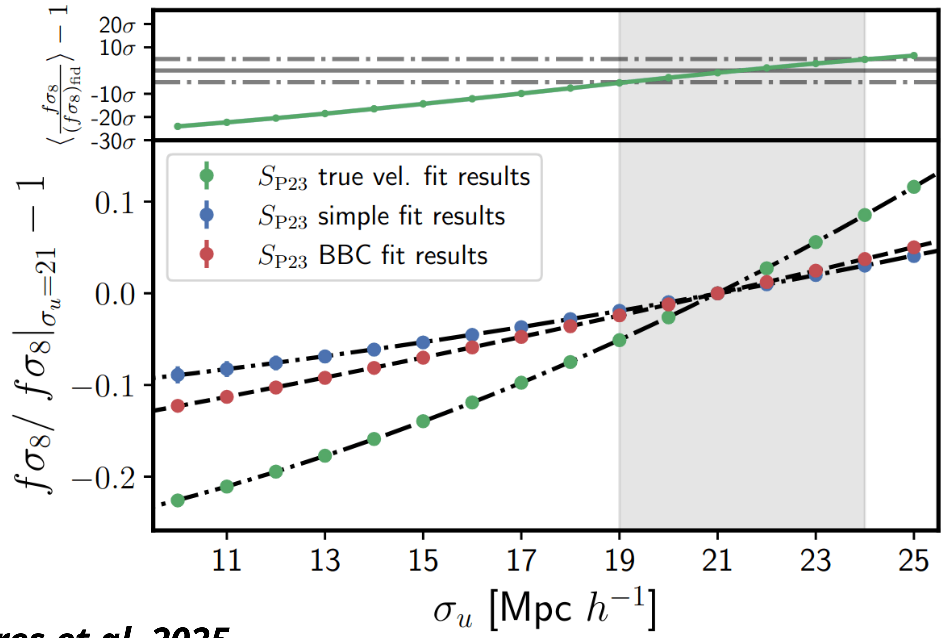


Rosselli et al. 2025

LSST results

- Dedicated study to test BBC framework and check the impact of intrinsic scatter model and nuisance parameter (σ_u = dispersion of velocity position)





Carreres et al. 2025

LSST results

- Unbiased fσ8 measurement with full Hubble diagram fit over 3 redshift points
- **How can we do better ? Combine with density field**