Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Fast Generation of Covariance Matrices for Weak Lensing

RS, Réfrégier, Amara, Nicola 2018 (1801.05745)

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Institute for Particle Physics and Astrophysics

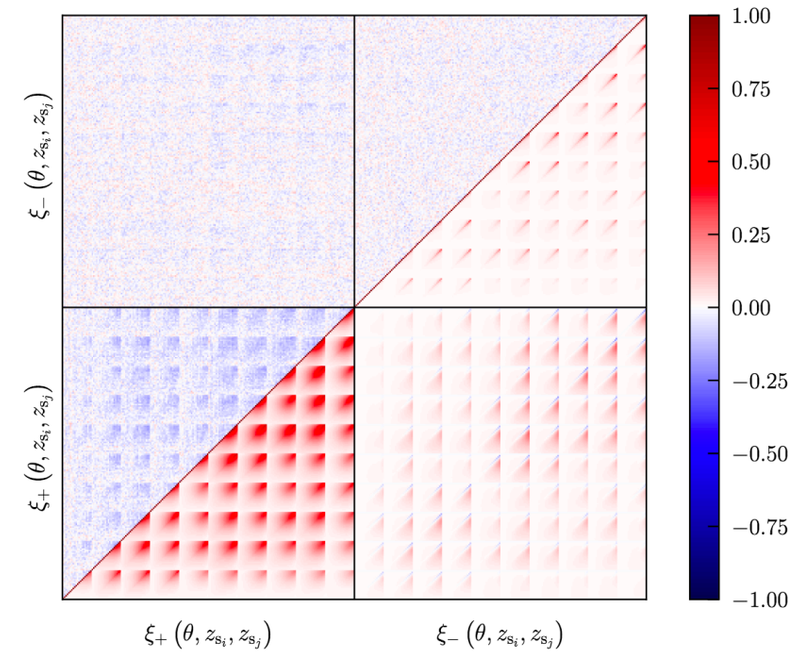
Cosmo-18
August 27 - 31, 2018

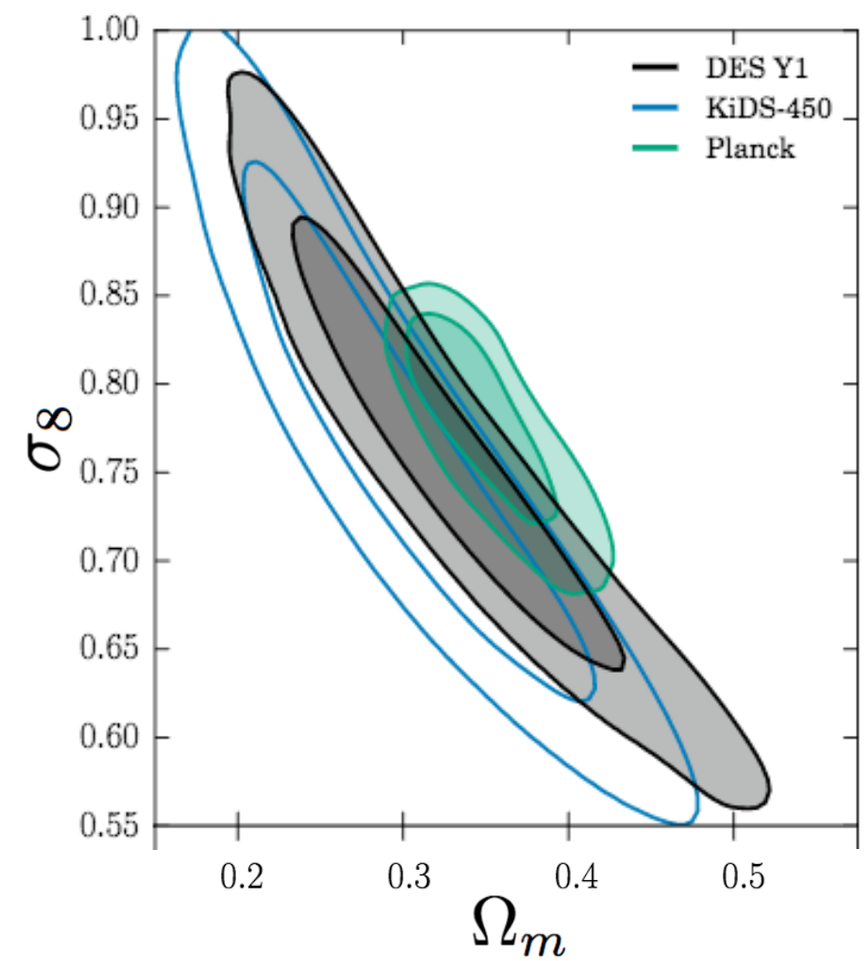
Motivation

- Interpretation of LSS data.

$$\mathcal{L}(D|\theta) \propto e^{-\frac{1}{2}(X^{\mathrm{D}}-X^{\mathrm{M}})^{\mathrm{T}}\mathrm{cov}^{-1}(X^{\mathrm{D}}-X^{\mathrm{M}})}$$

- large ensemble of N-Body simulations needed for a well-converged covariance matrix





DES collaboration 2017 (1708.0153)

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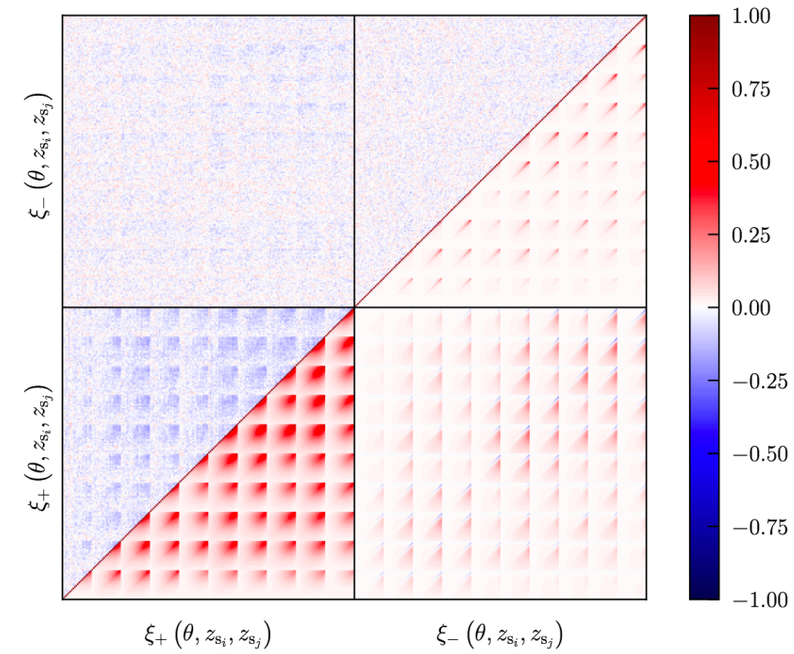
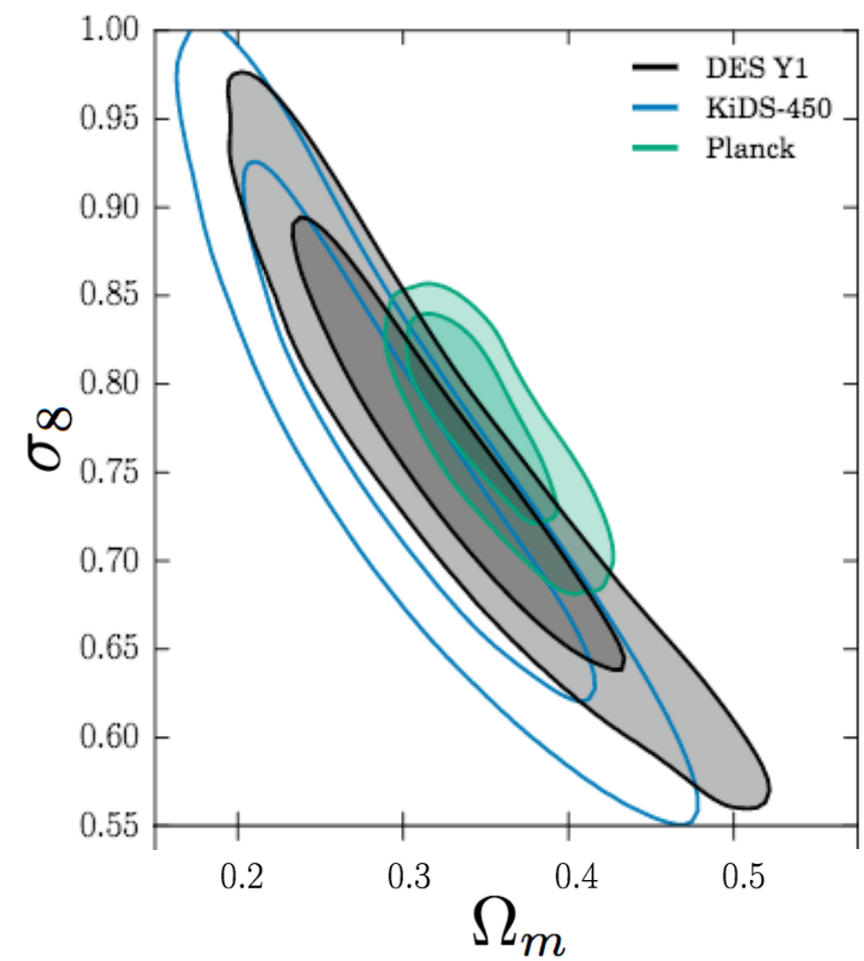
- large ensemble of N-Body simulations needed for a well-converged covariance matrix

↓

Computational Power ⚡ Resolution





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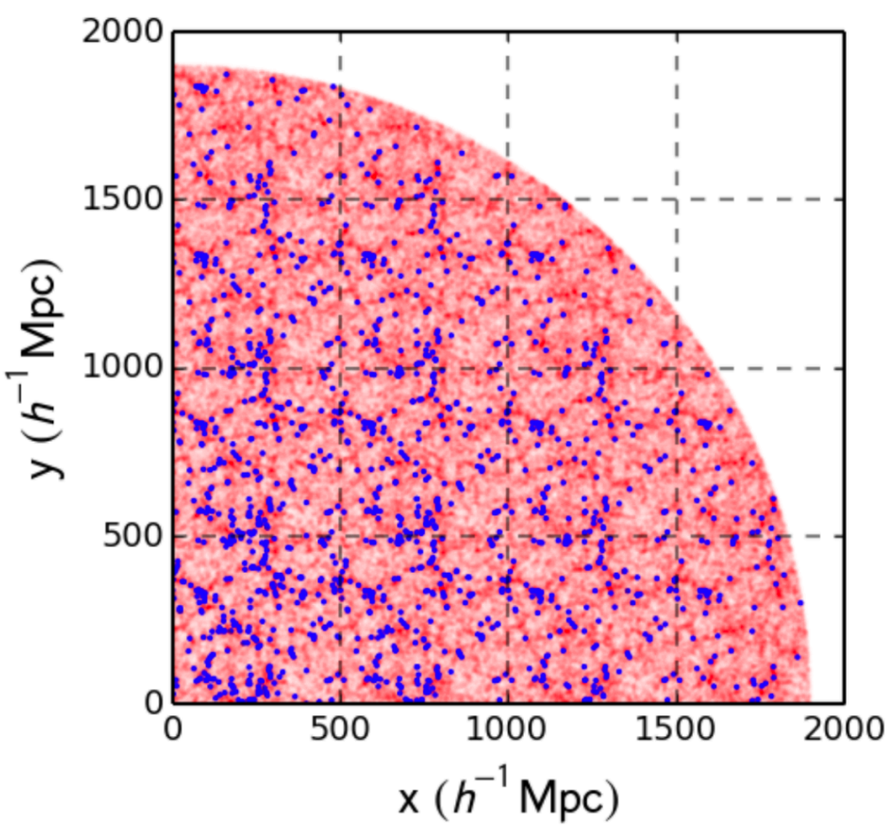
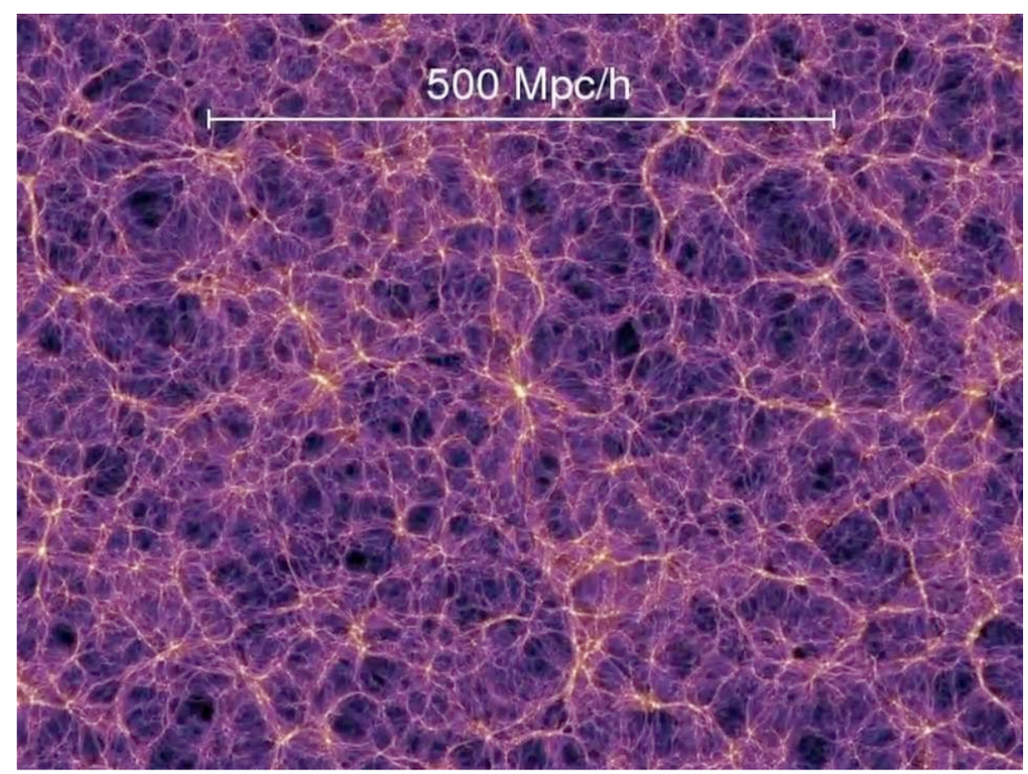
N-Body Simulations

Mass resolution: $$m = \frac{V}{N} \cdot \rho_{\mathrm{crit}} \cdot \Omega_{\mathrm{m}}$$



L-PICOLA simulation code
Howlett et al. 2015 (1506.03737)

$$N = 2160^3 \quad V = 500\,\mathrm{Mpc}/h$$

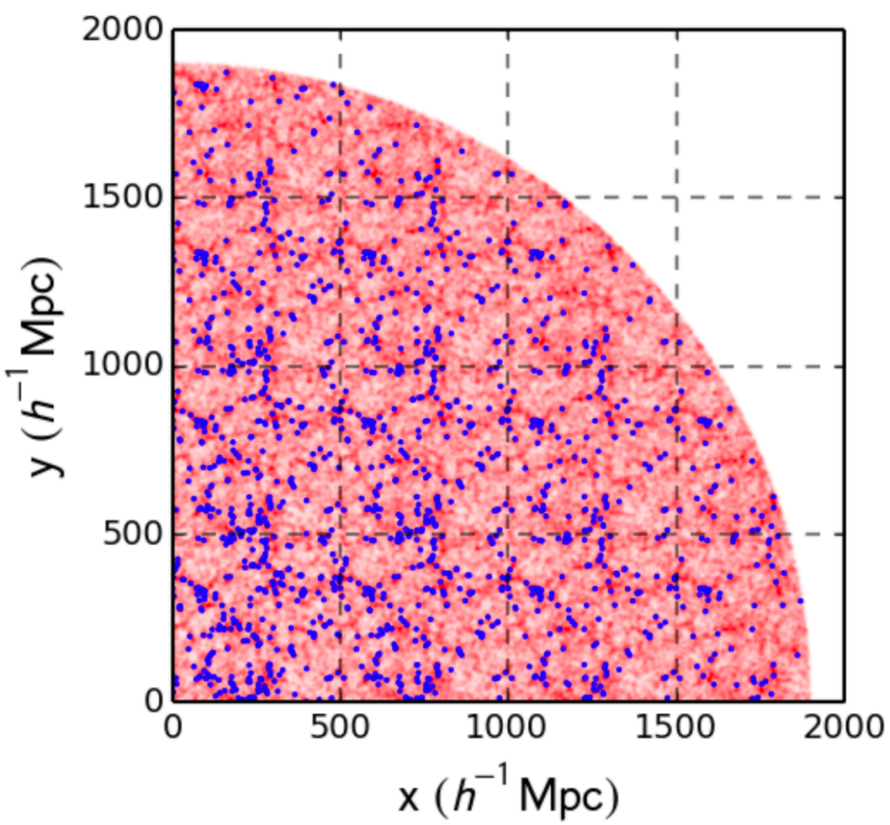


Millennium Simulation (MPA Garching)

N-Body Simulations

Mass resolution: $$m = \frac{V}{N} \cdot \rho_{\rm crit} \cdot \Omega_{\rm m}$$

→ Use large V in order to avoid replications and avoid dealing with SSC.



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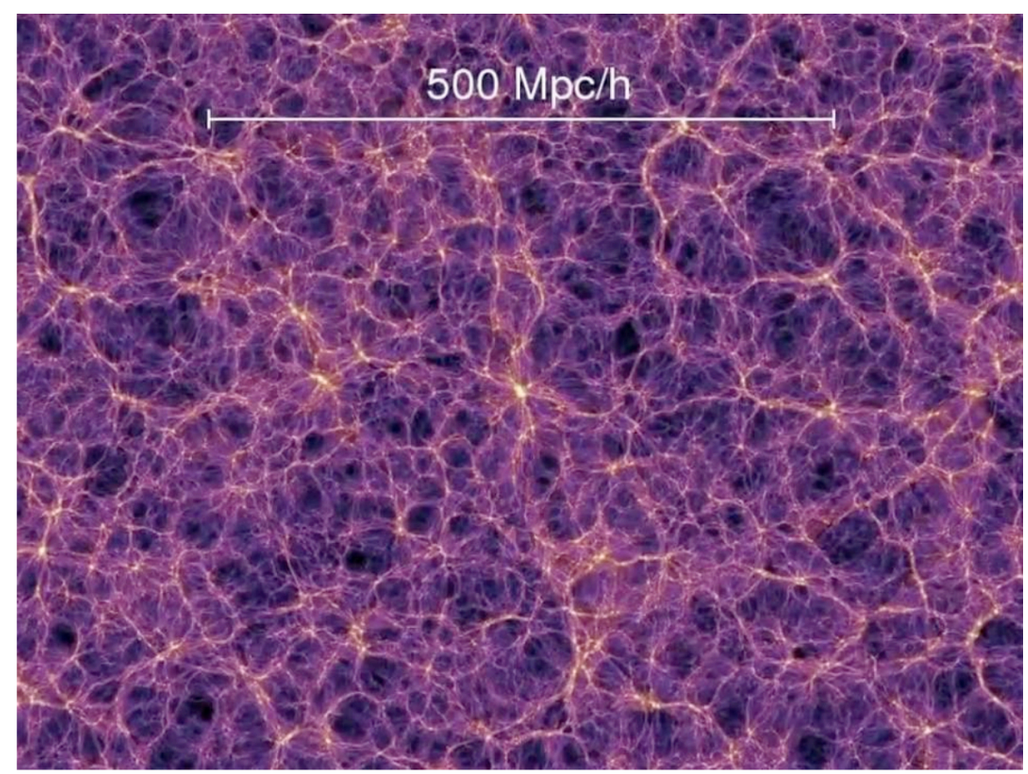

Millennium Simulation (MPA Garching)

L-PICOLA

N-Body code	Lagrangian Perturbation Theory
➕ recovers non-linear regime	➕ exact results on large scales
➖ computationally expensive	➖ PT breaks down at k_{NL}

L-PICOLA

N-Body code

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Lagrangian Perturbation Theory

- ➕ exact results on large scales
- ➖ PT breaks down at k_{NL}

COLA

Tassev, Zaldarriaga, Eisenstein 2013 (1301.0322)

calculate LSS exactly with 2LTP

N-Body code (PM) solves small scales

L-PICOLA

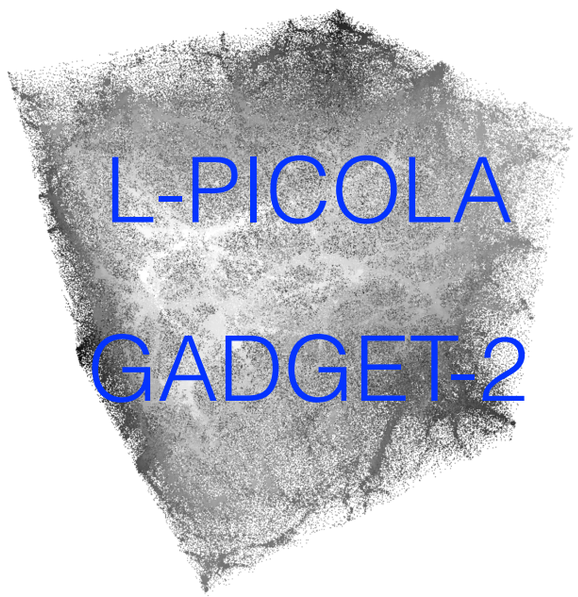
Howlett et al. 2015 (1506.03737)

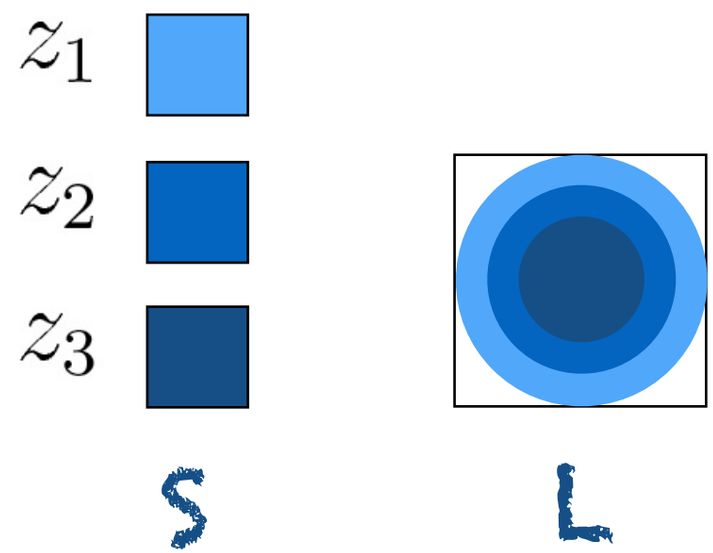
see also: ICE-COLA

Izard et al. 2015 (1509.04685) & 2017 (1707.06312)

Can we use L-PICOLA to efficiently and accurately generate covariance matrices for weak lensing?

Simulations and Lightcone

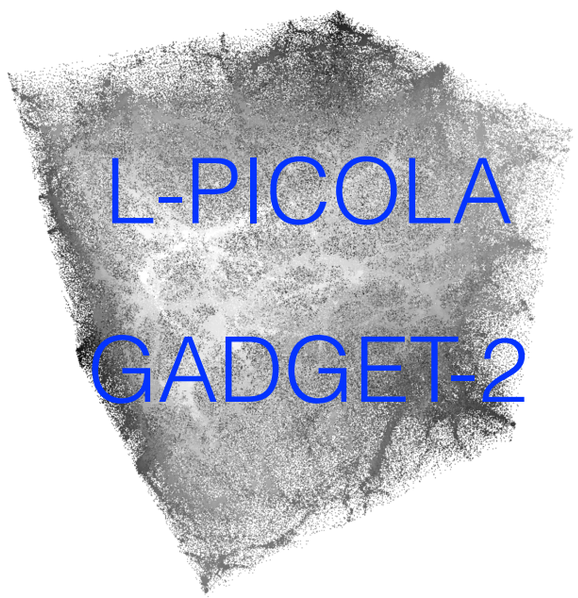


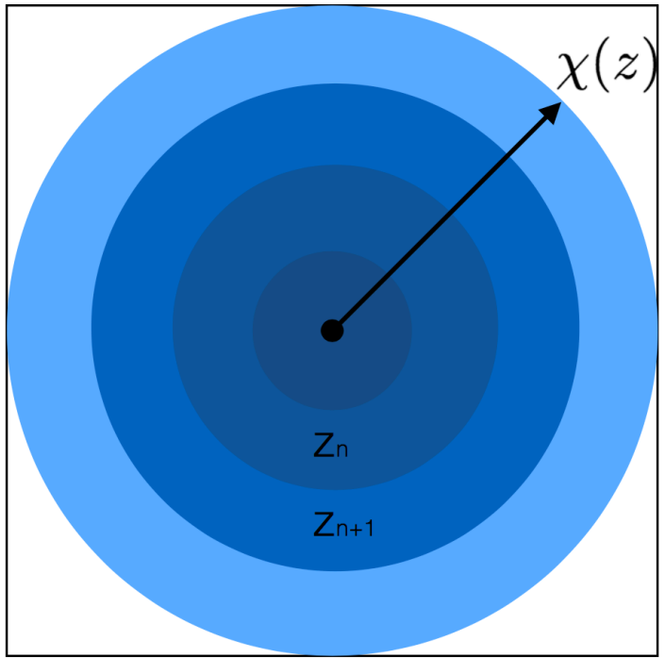


- 1 GADGET-2 and L-PICOLA sims in snapshot mode
- 150 L-PICOLA sims in lightcone mode

$L_{\rm Box}$ (h^{-1} Mpc)	$N_{\rm Part}$	$N_{\rm Mesh}$	mass resolution (h^{-1} $M_\odot$)	z-range	$z_{\rm init}$
700	1024	2048	2.6×10^{10}	0.0 - 0.1	9
4200	1024	2048	5.3×10^{12}	0.1 - 0.8	9
6300	1024	2048	1.8×10^{13}	0.8 - 1.5	9

Simulations and Lightcone





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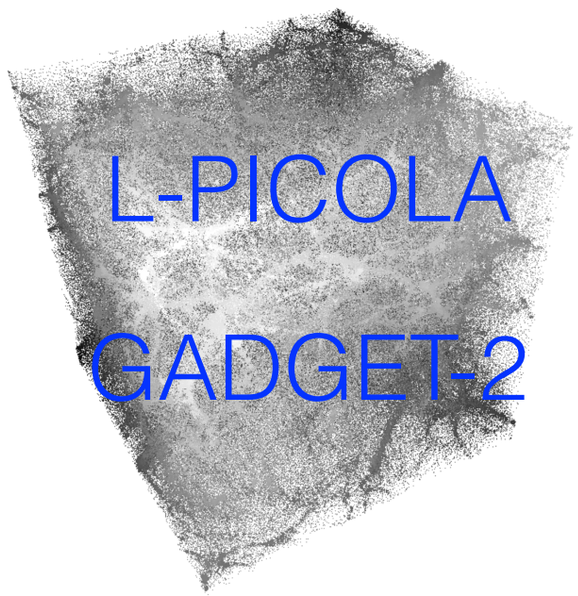

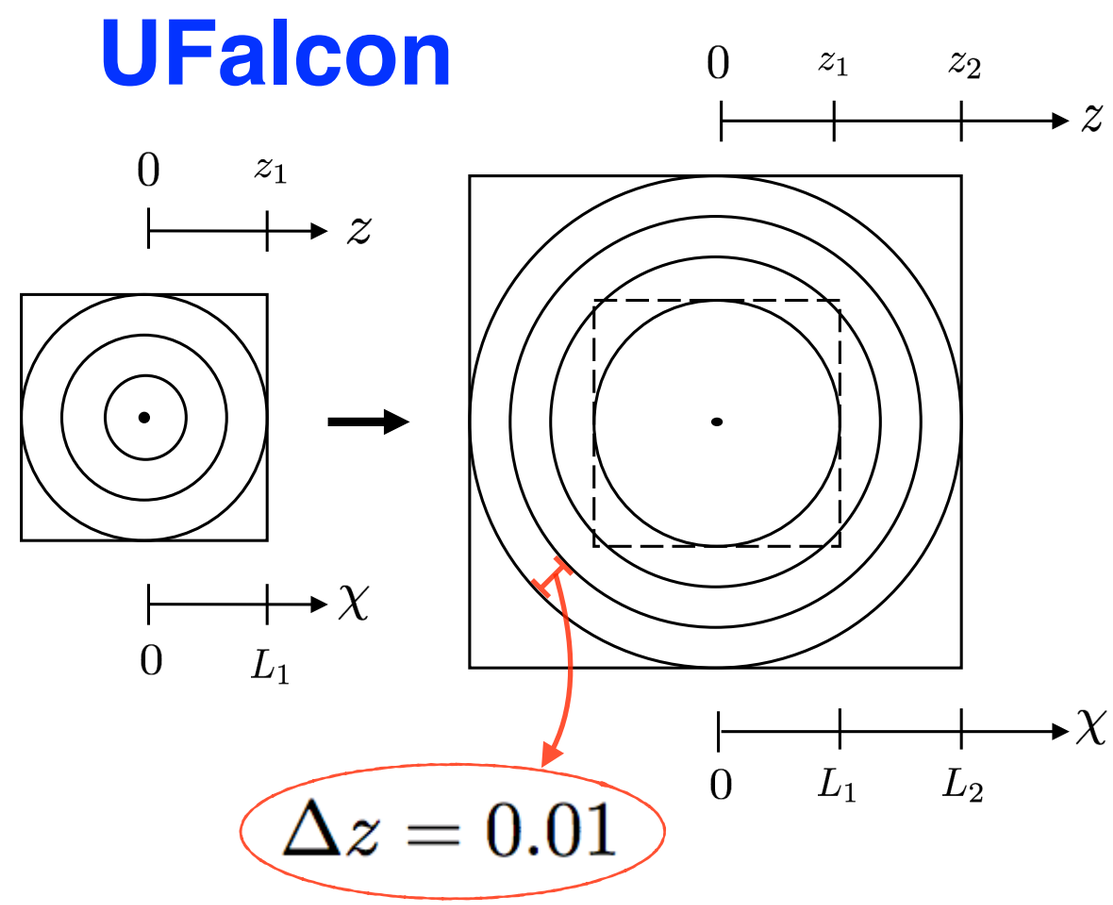

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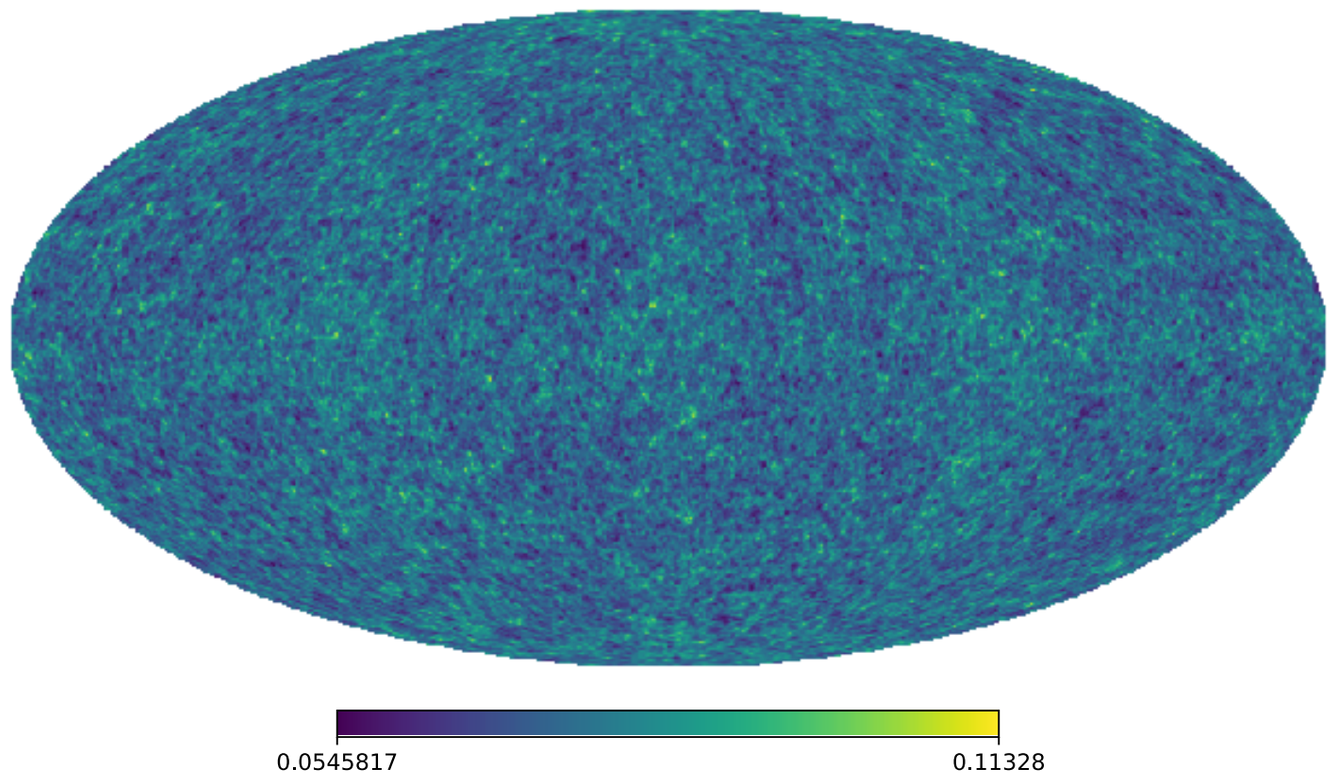
Simulations and Lightcone

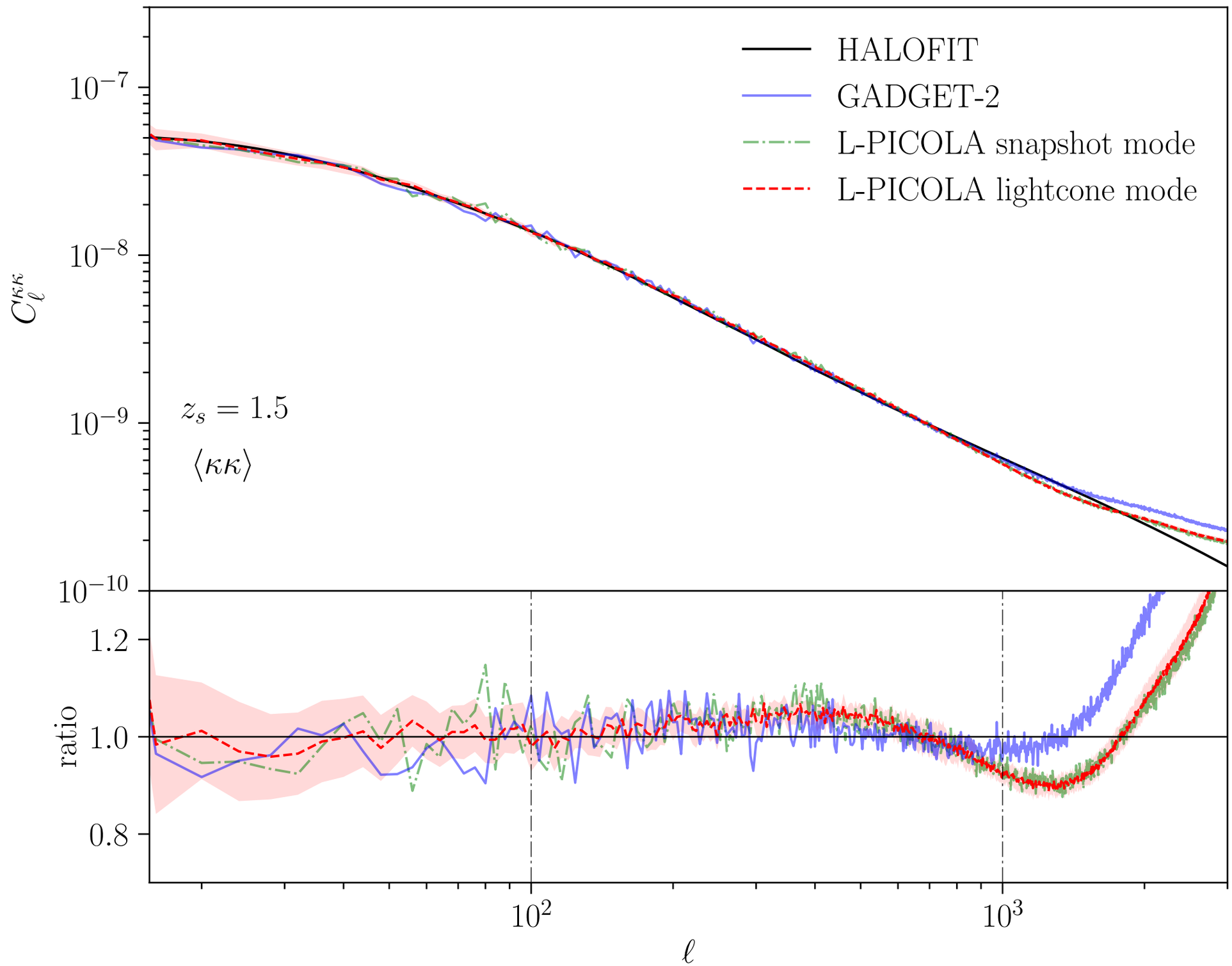
full-sky convergence map



$$\kappa(\theta_{\rm pix}) \approx \frac{3}{2}\Omega_m \sum_b W_b \frac{H_0}{c}\left[\frac{N_{\rm pix}}{4\pi}\frac{V_{\rm sim}}{N_{\rm part}^{\rm sim}}\left(\frac{H_0}{c}\right)^2 \frac{n_p(\theta_{\rm pix},\Delta\chi_b)}{\mathcal{D}^2(z_b)} - \left(\frac{c}{H_0}\Delta\mathcal{D}_b\right)\right]$$

- **Runtime**: **~1.5h** for simulation + **< 30 min** for lightcone
- both parts parallelized on Cluster

Power Spectrum



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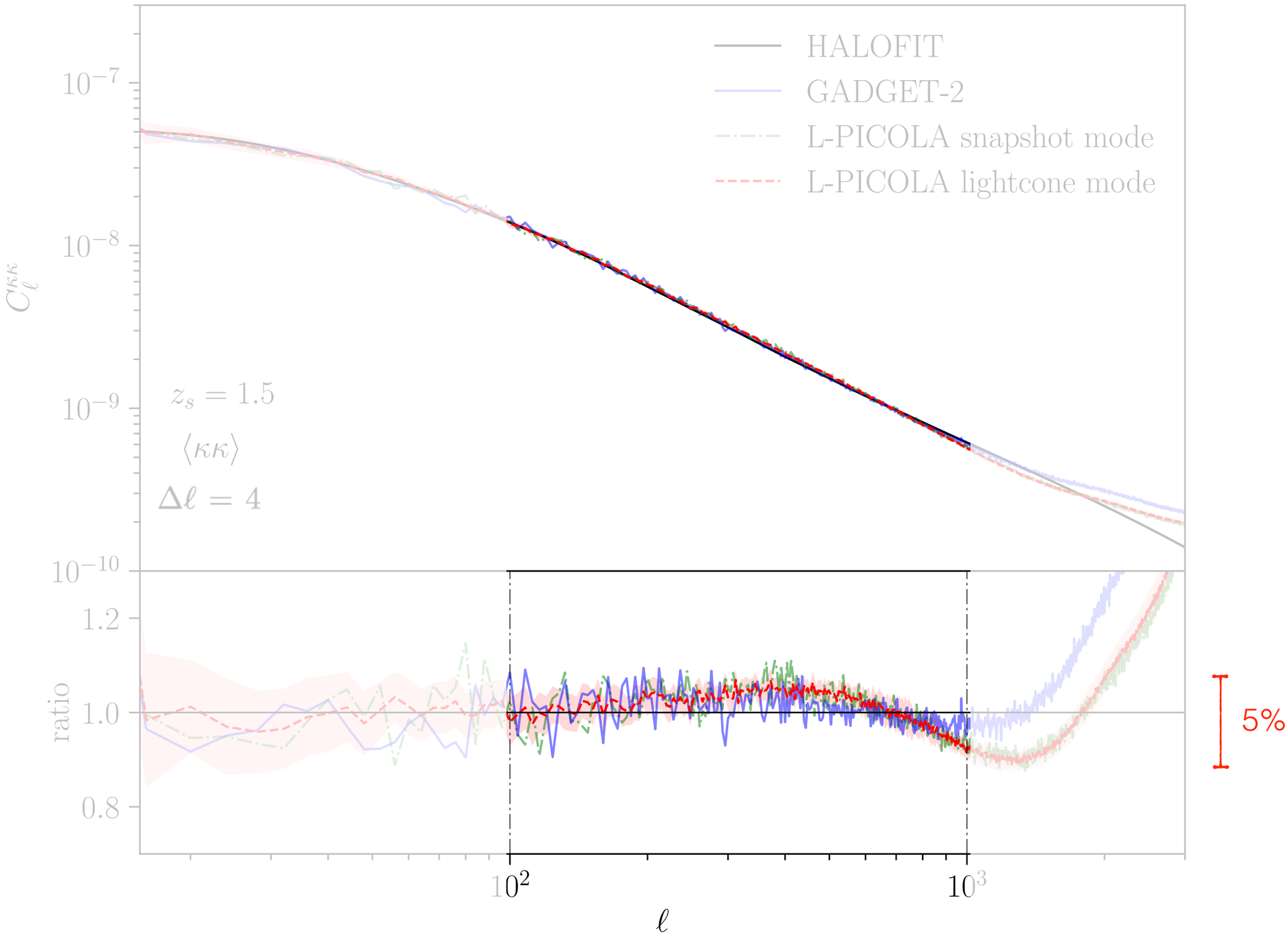
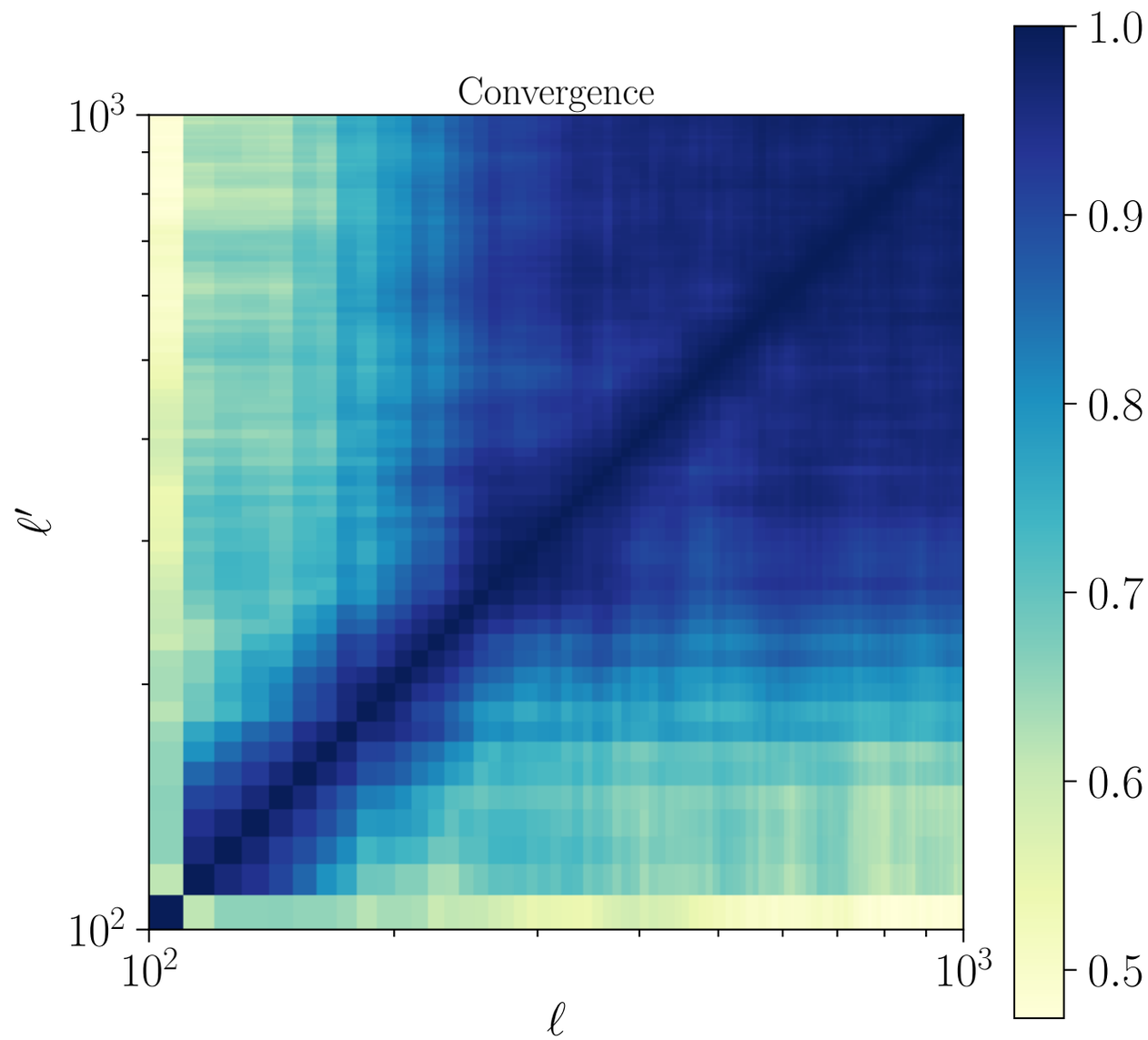


Covariance Matrix

Covariance matrix for scales $10^2 < \ell < 10^3$ using 150 UFalcon maps.

$$\mathrm{corr}(\ell, \ell') = \frac{\mathrm{cov}(\ell, \ell')}{\sqrt{\mathrm{cov}(\ell, \ell)\mathrm{cov}(\ell', \ell')}}$$



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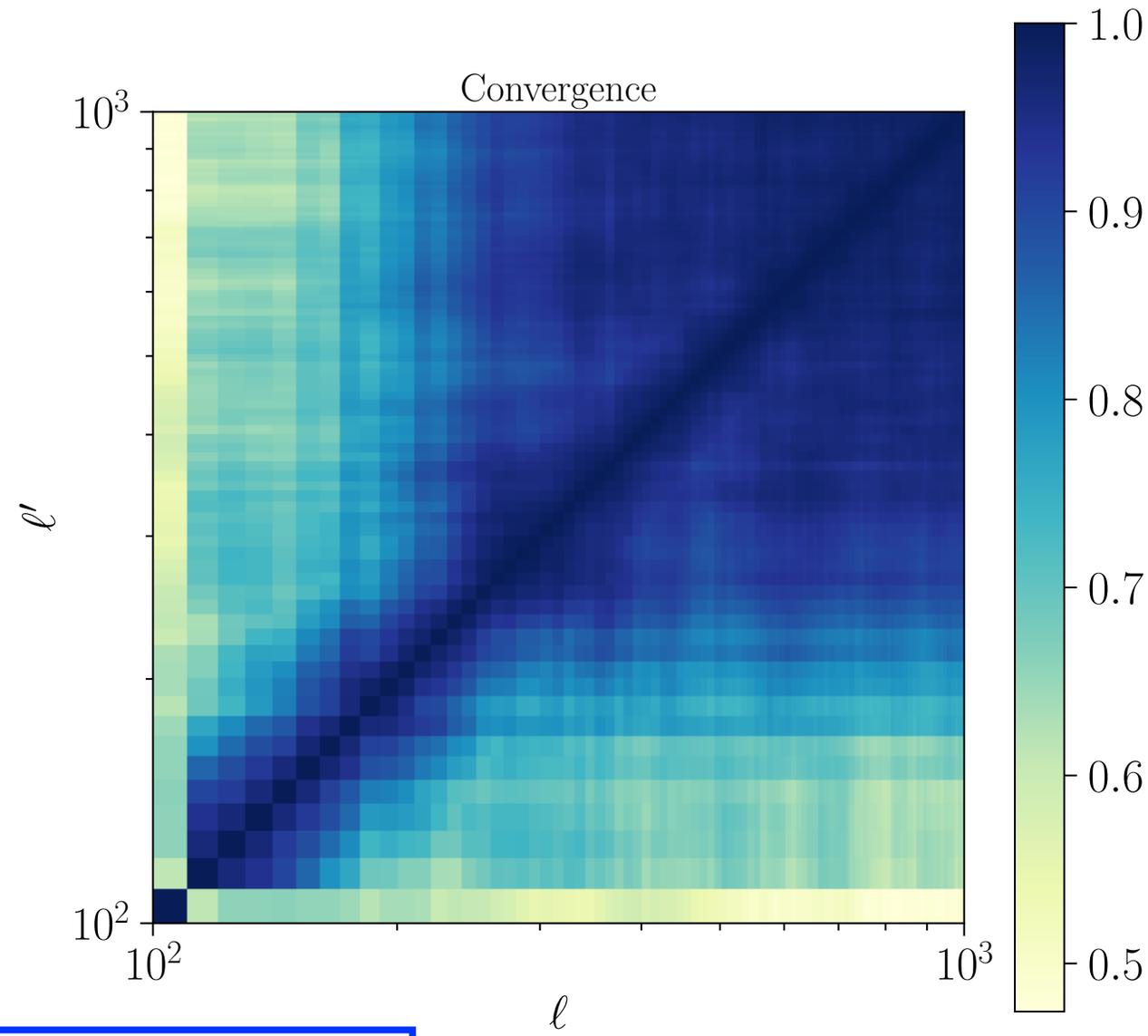
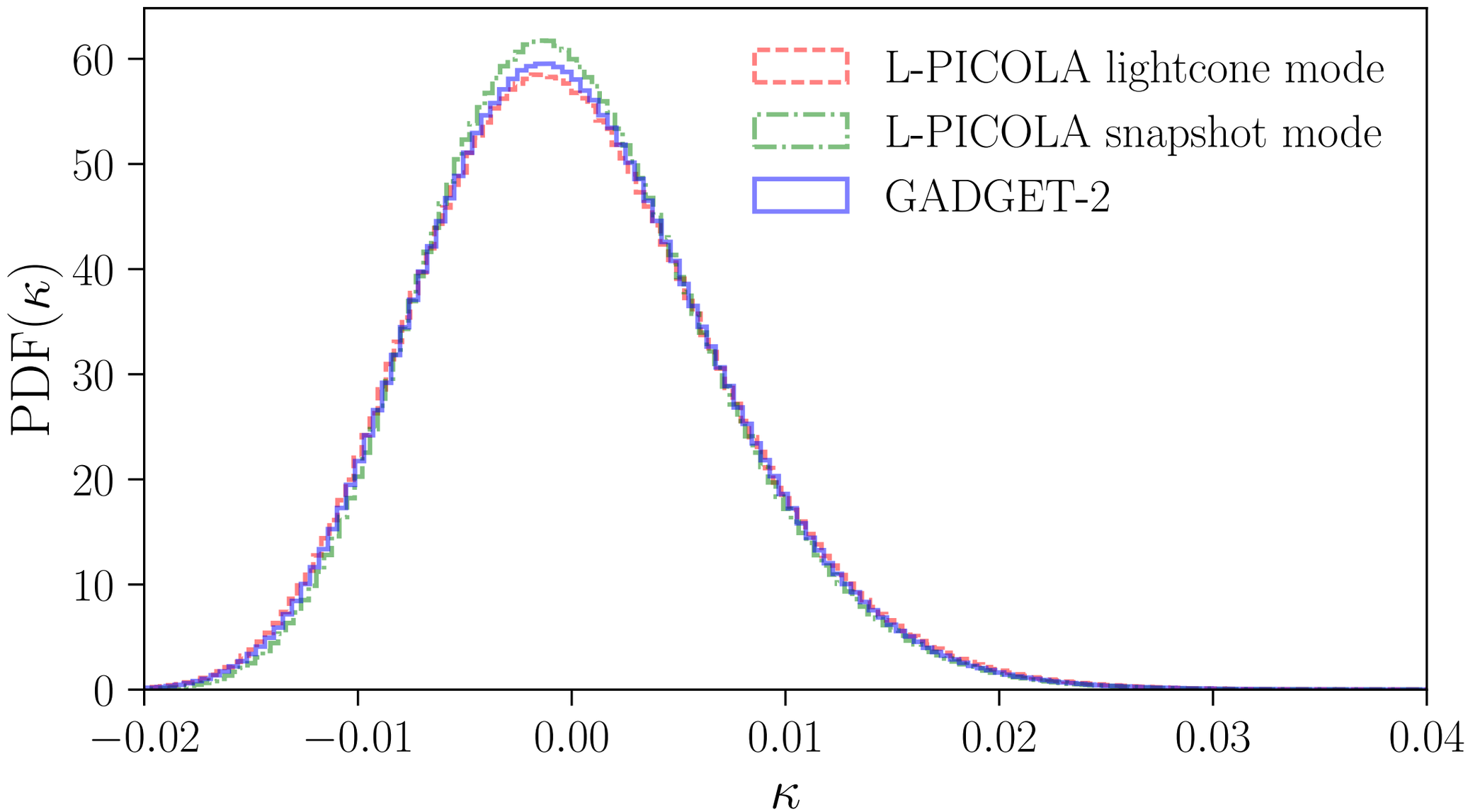


→ accurate enough for weak lensing?

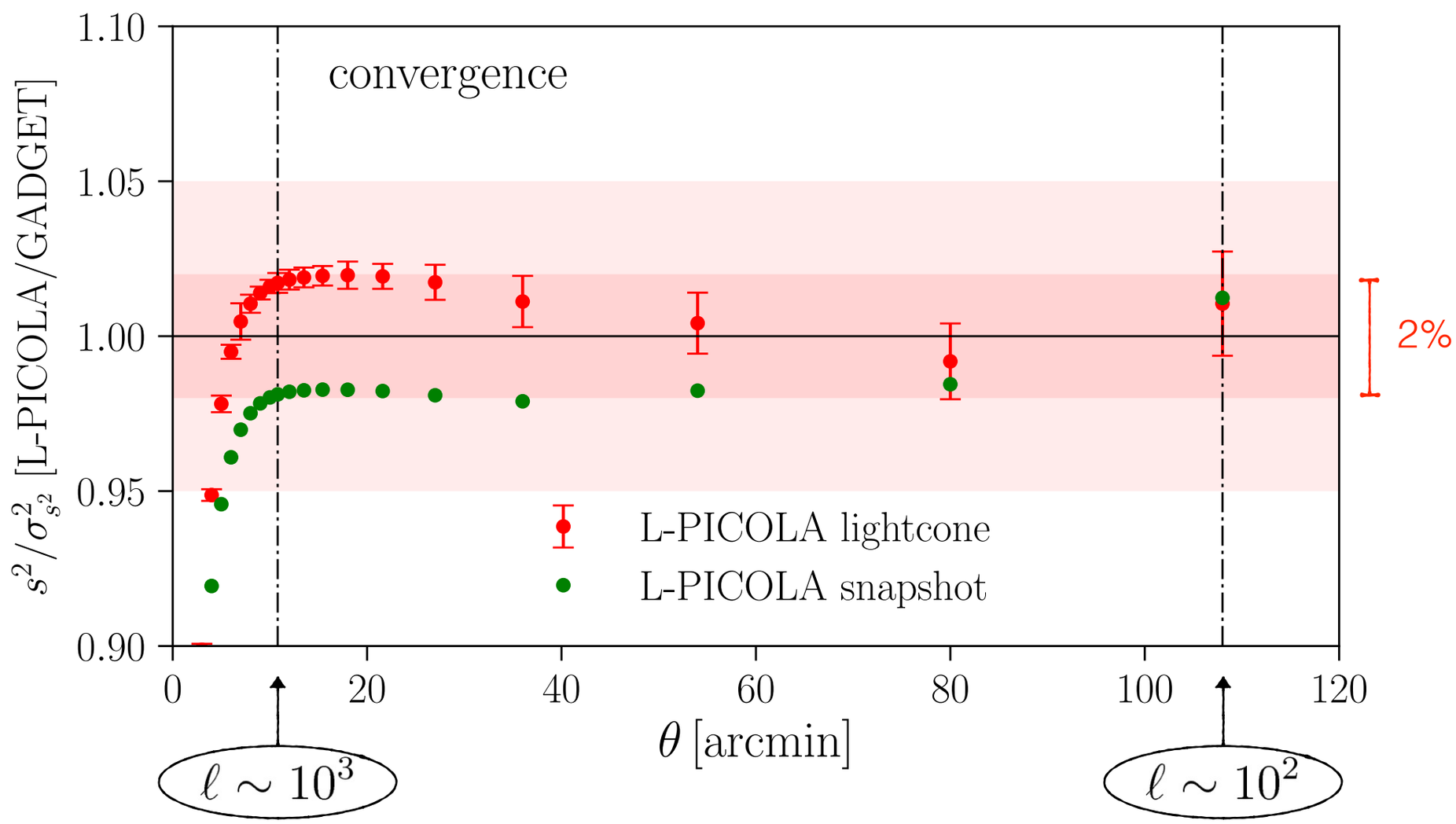
1-Point Distribution



1-Point Distribution

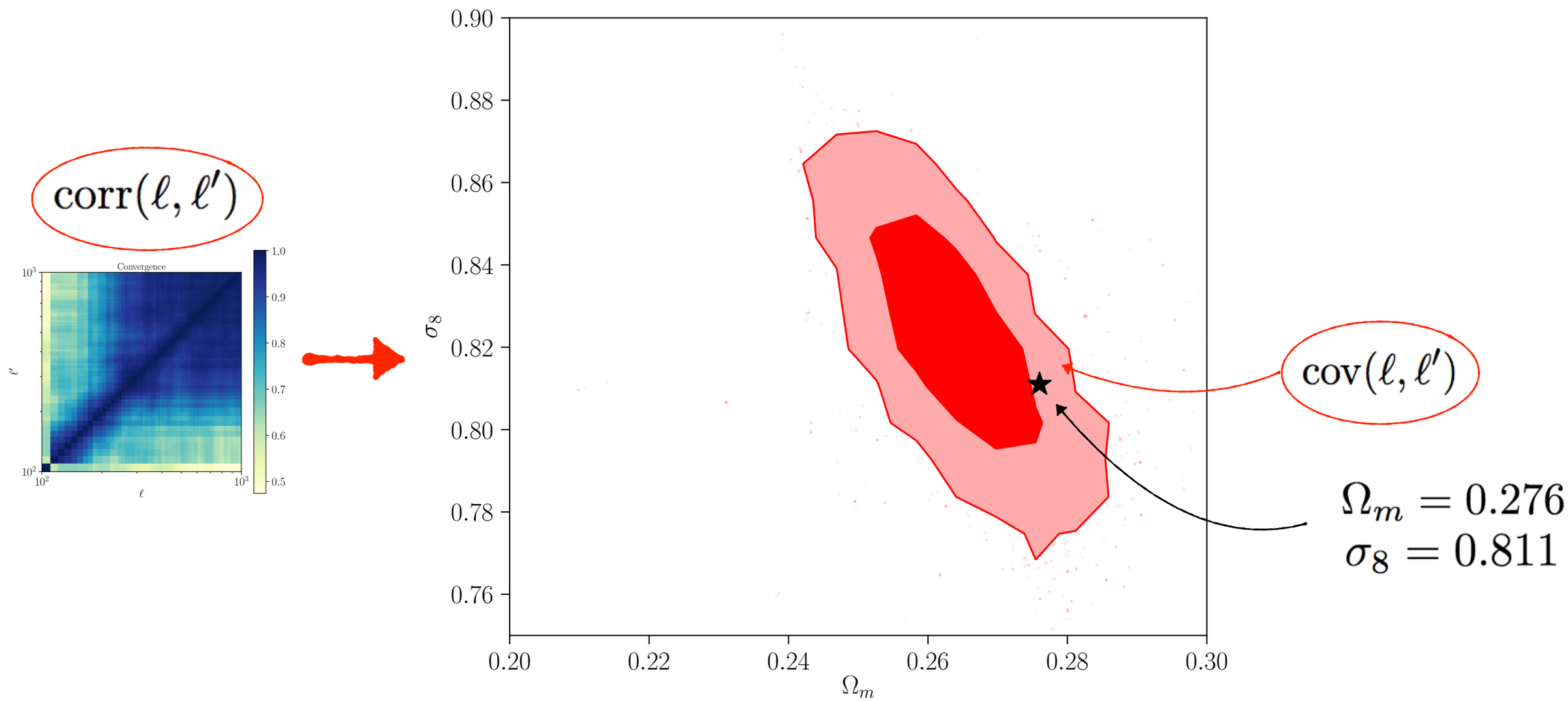
Variance of sample variance as a measure of non-Gaussianity.

$$\sigma^2_{s^2} = \frac{(N-1)^2}{N^3}\mu_4 - \frac{(N-1)(N-3)}{N^3}\mu_2^2 \sim \boxed{\frac{1}{N}(\mu_4 - \mu_2^2)}$$



Parameter Constraints

- Sample $\Omega_{\rm m}$ and σ_8 with a Monte Carlo Markov Chain (MCMC) on scales $10^2 < \ell < 10^3$.



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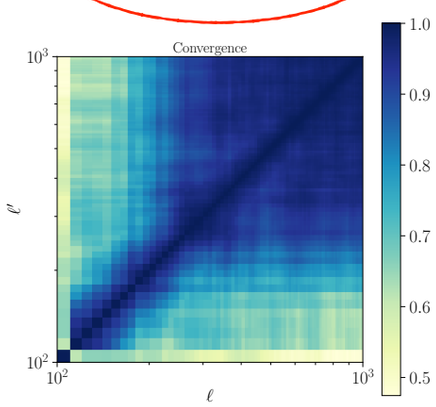
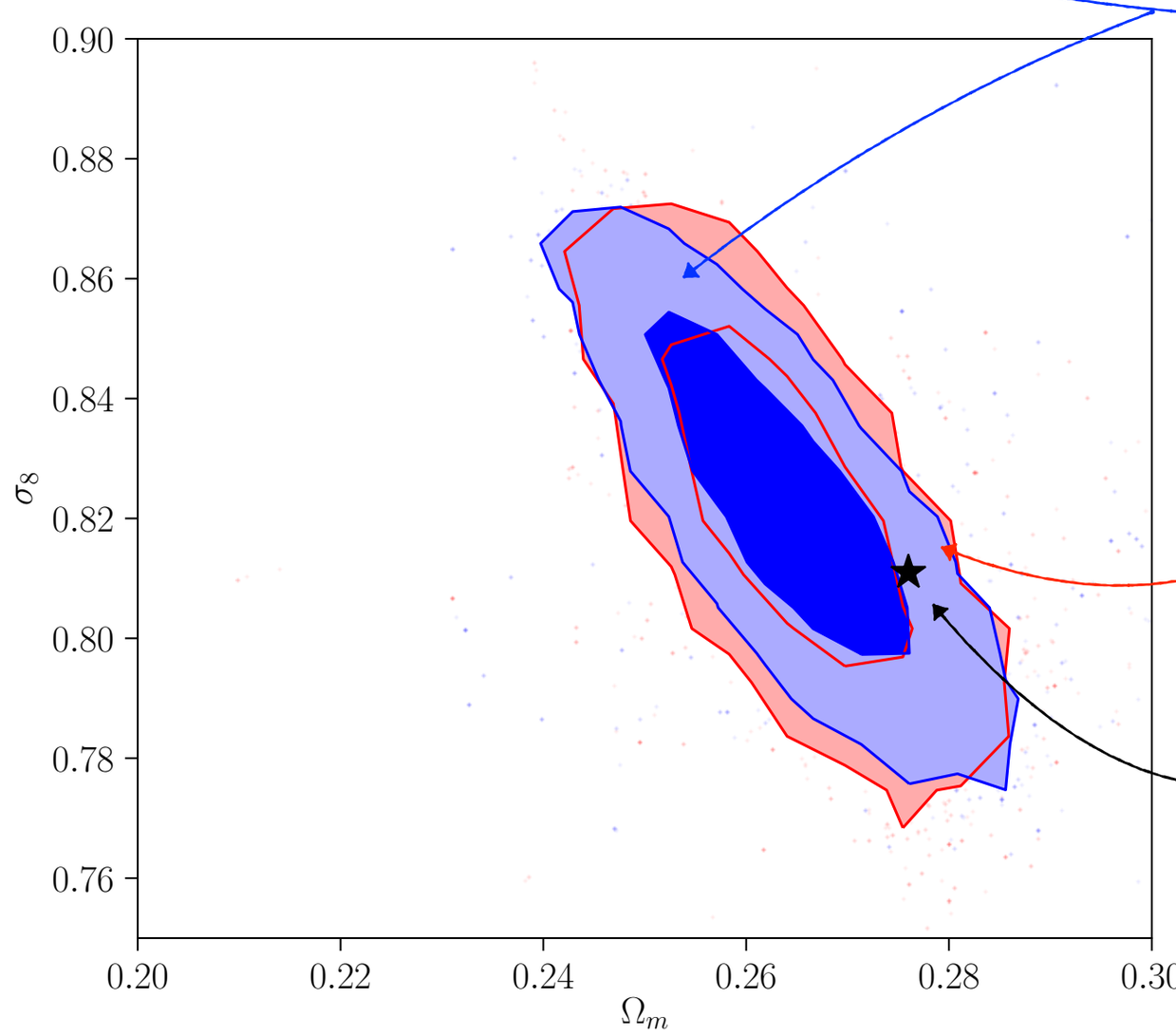
$$f(\ell) = C_\ell^{\rm GADGET-2}/C_\ell^{\rm L-PICOLA}$$

$$\widetilde{\rm cov}(\ell,\ell') \equiv f(\ell)f(\ell'){\rm cov}(\ell,\ell')$$

$${\rm corr}(\ell,\ell')$$





$${\rm cov}(\ell,\ell')$$

$$\Omega_m = 0.276$$
$$\sigma_8 = 0.811$$

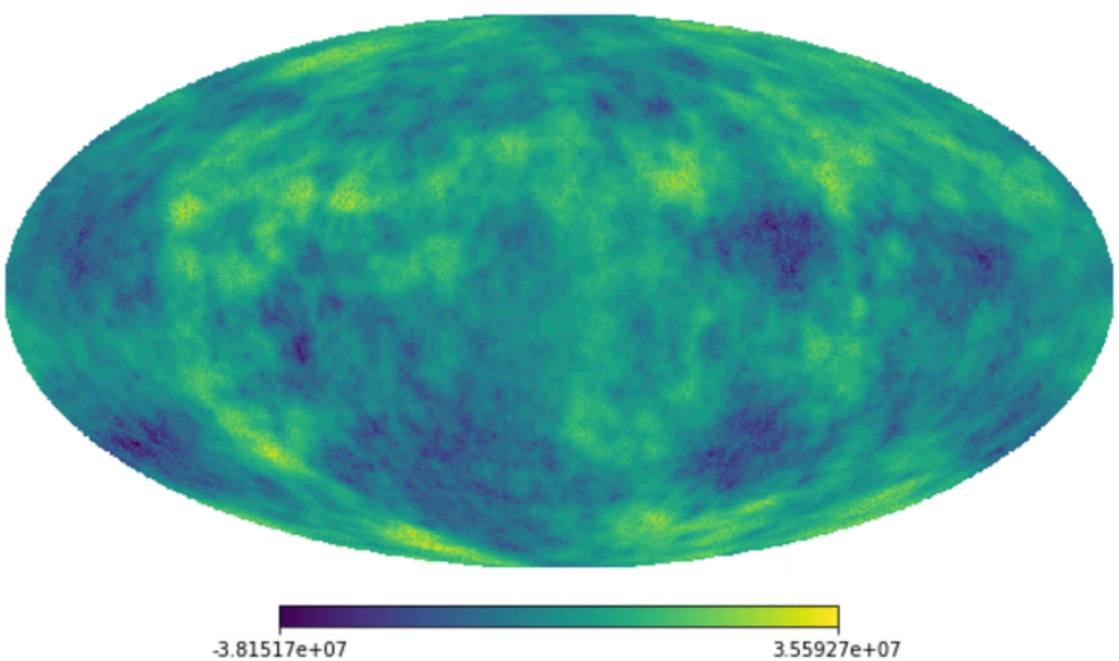
Conclusion

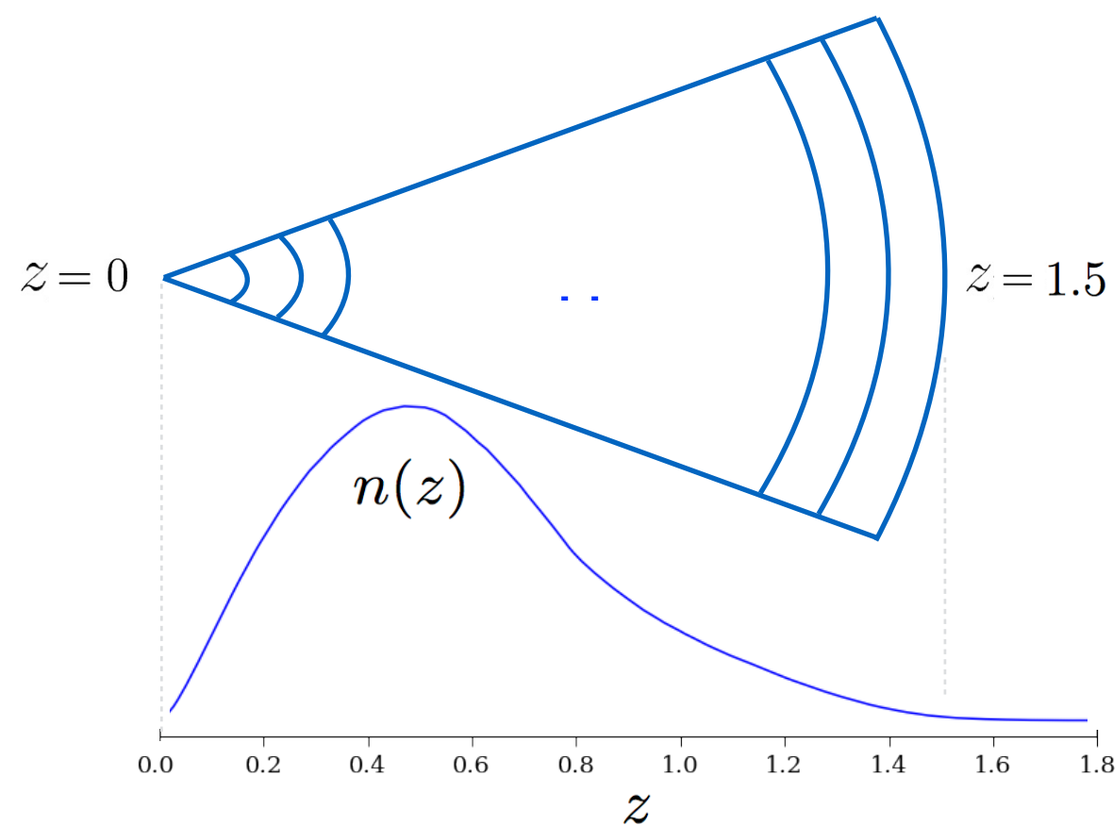
- UFalcon applied to L-PICOLA: Fast way to generate full-sky weak lensing maps up to $z_s = 1.5$.
- 5% agreement between L-PICOLA and GADGET-2 power spectra.
- 2% agreement between $s^2/\sigma^2_{s^2}$ based on L-PICOLA and GADGET-2 maps.
- Obtained constraints in the $\Omega_{\rm m} - \sigma_8$ plane are robust to changes on percent level for optimistic survey configuration.

Outlook

- Compute covariance matrix from GADGET-2 maps
- UFalcon: include other probes: CMB lensing, RSD, ISW-effect, baryonic effects
- Application of pipeline to data

Projected grav. potential from L-PICOLA





Thank you!

More Slides

COLA: working principle

- Calculates LSS exactly with 2LTP
- N-Body code (PM) solves small scales

$$\partial_t^2 \boldsymbol{x} = -\nabla\Phi$$

$$\partial_t^2 \mathbf{x}_{\rm res} = -\nabla\Phi - \partial_t^2 \mathbf{x}_{\rm LPT} \quad \text{with} \quad \mathbf{x}_{\rm res} = \mathbf{x} - \mathbf{x}_{\rm LPT}$$

discretize in PM-code

use exact 2LPT expression

Tassev, Zaldarriaga, Eisenstein 2013 (1301.0322)

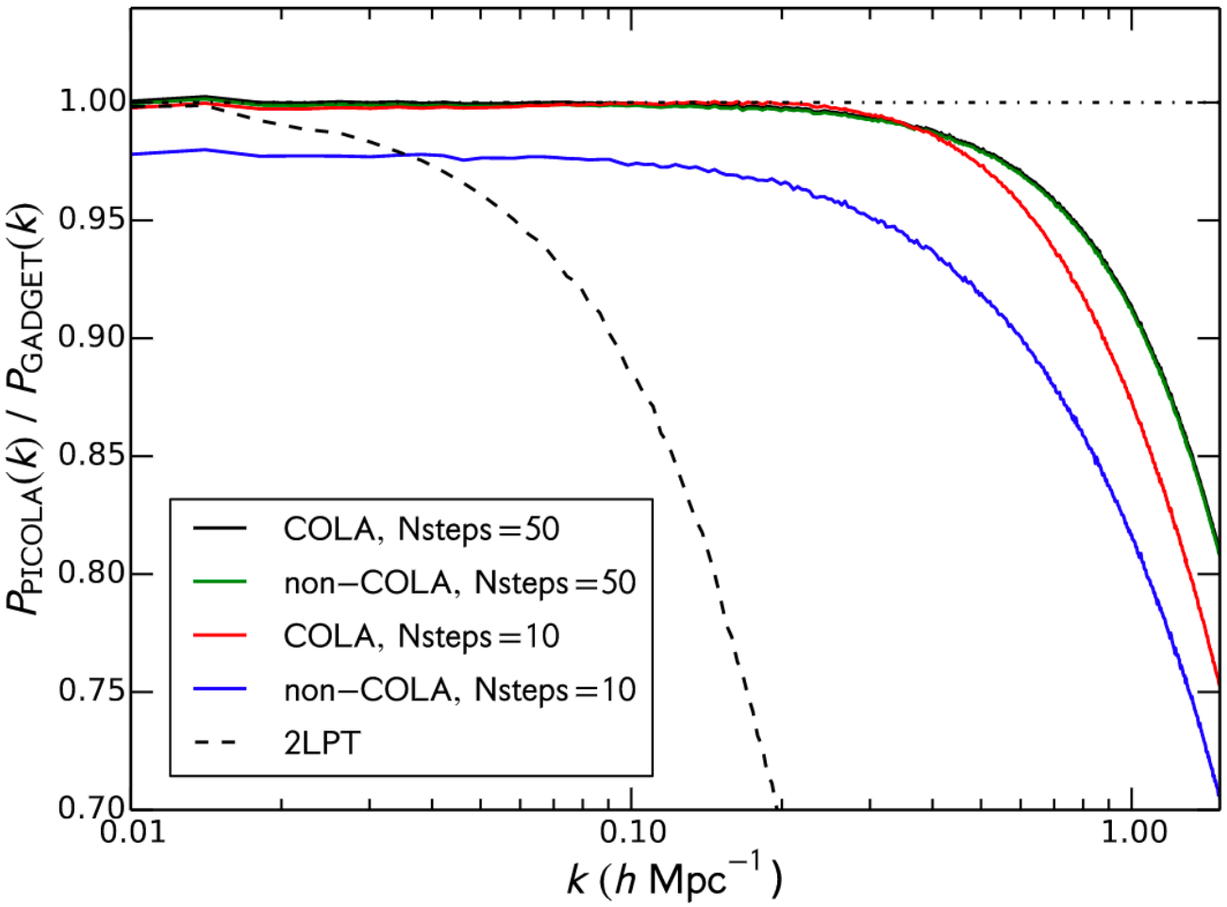
$$T[\mathbf{\Psi}_{res}] + T[D_1]\mathbf{\Psi}_1 + T[D_2]\mathbf{\Psi}_2 + \nabla\Phi = 0,$$

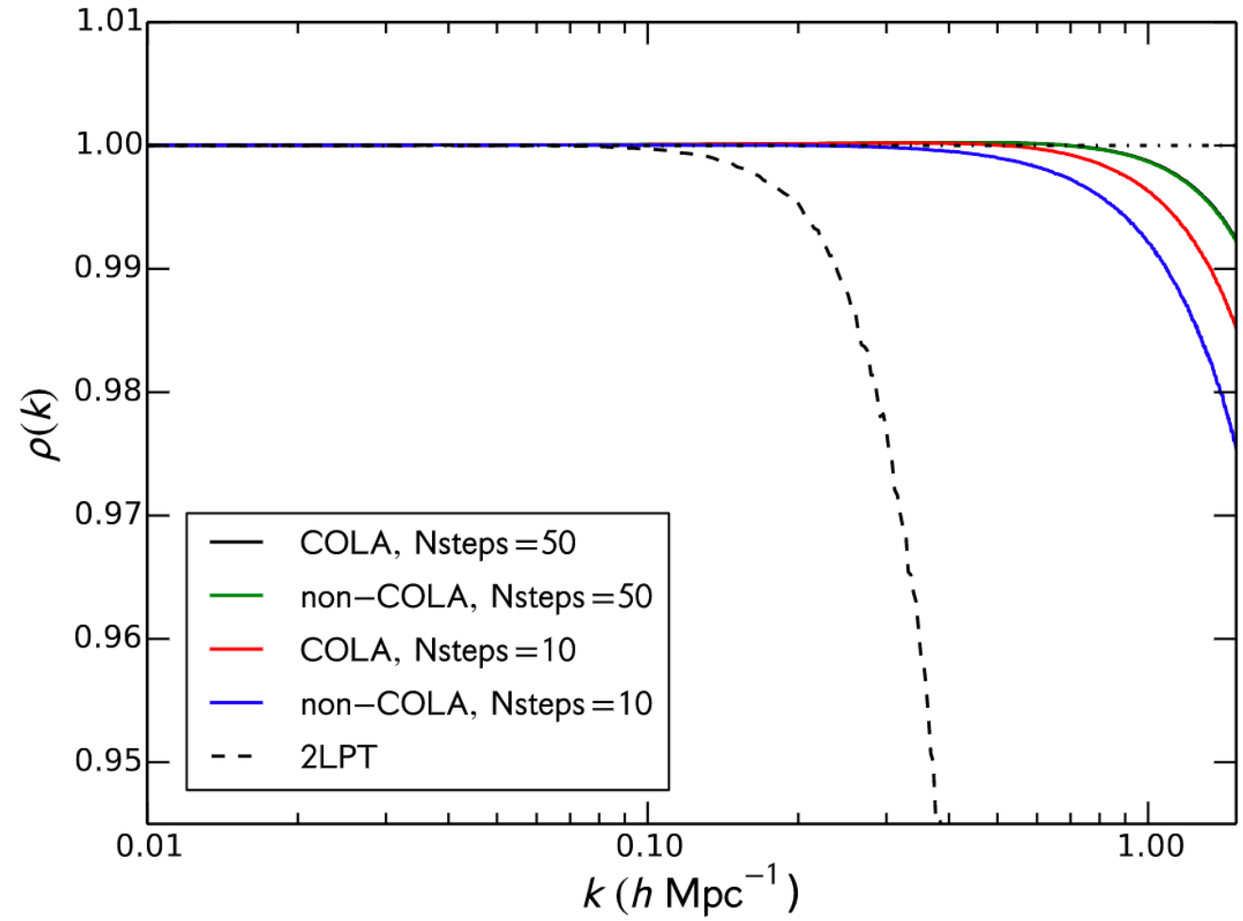
Howlett et al. 2015 (1506.03737)

$$T[X] = \frac{d^2 X}{d\tau^2} + \mathcal{H}\frac{dX}{d\tau}.$$

$$\nabla\Phi = \mathrm{IFFT}\left[\frac{3}{2}\frac{\Omega_{m,0}\boldsymbol{k}}{ak^2} \times \mathrm{FFT}[\rho(\boldsymbol{x}) - 1]\right]$$

L-PICOLA: accuracy

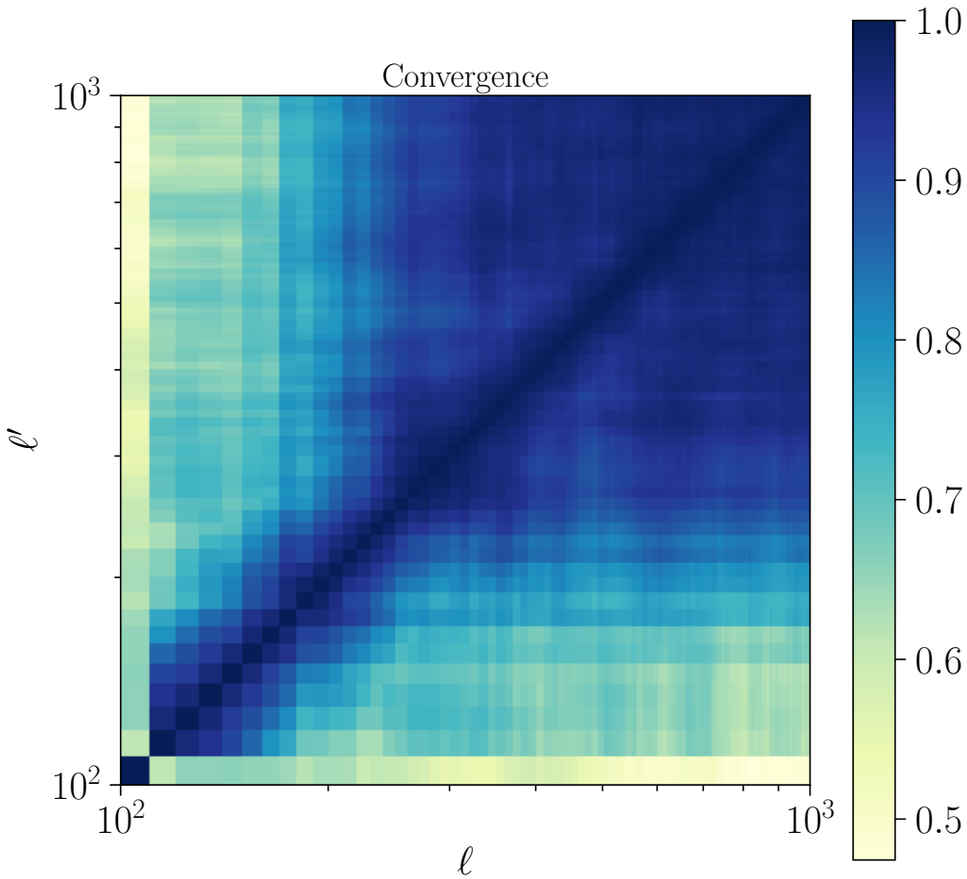




$$\rho(k) = \frac{\langle \delta(\boldsymbol{k}) \delta^*_{NL}(\boldsymbol{k}) \rangle}{\langle |\delta(\boldsymbol{k})|^2 \rangle \langle |\delta_{NL}(\boldsymbol{k})|^2 \rangle}$$

Howlett et al. 2015 (1506.03737)

Test of Non-Gaussianity

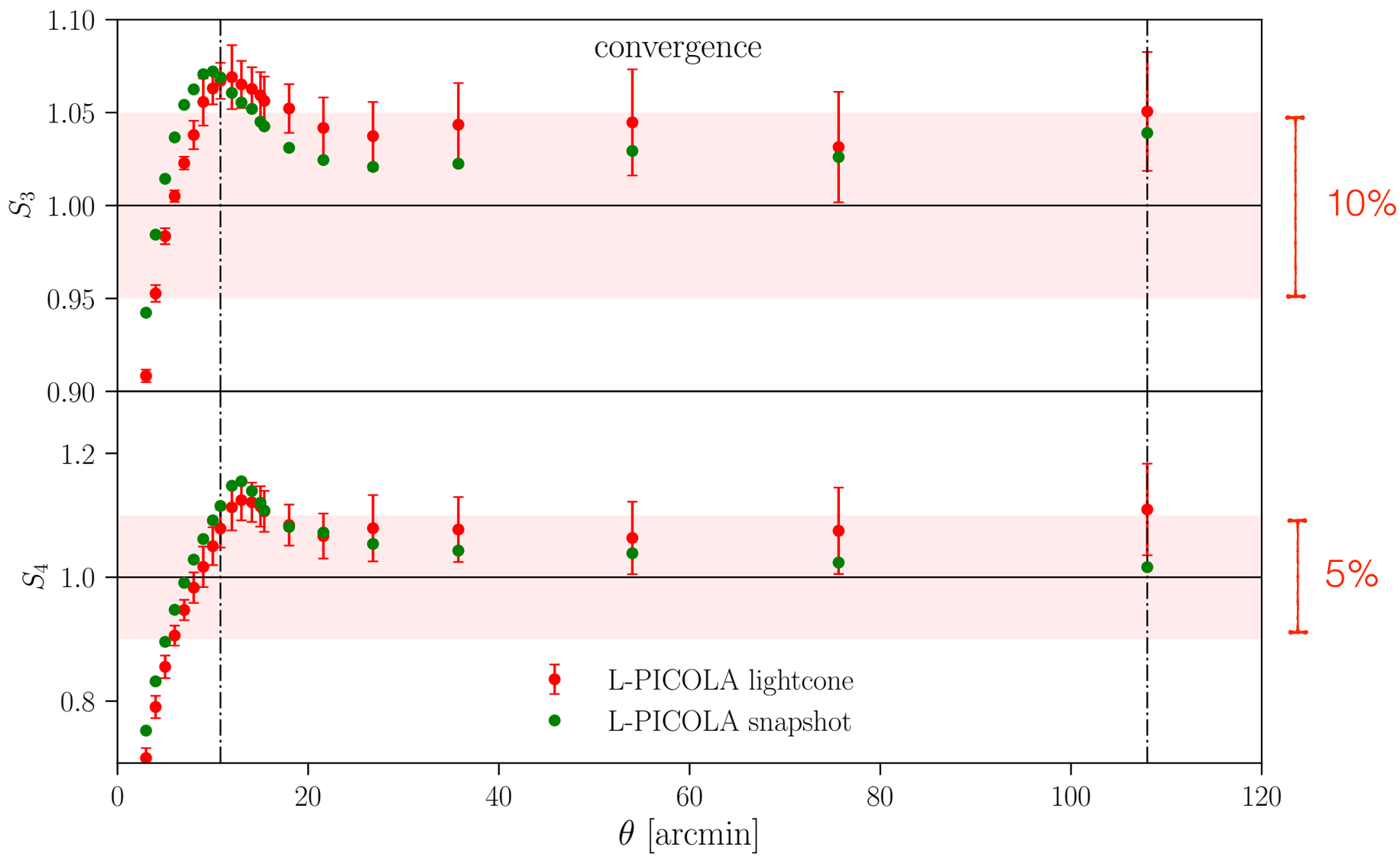


$$\mathrm{cov}(\mathcal{C}_{\ell_i}, \mathcal{C}_{\ell_j}) = A_f \left[\frac{2\mathcal{C}_{\ell_i}^2}{A_r(\ell_i)} \delta_{ij} + \bar{T}_{ij}(\ell_i, \ell_j) \right]$$

$$T^\kappa = \int \mathrm{d}\chi \frac{W(\chi, \chi_s)^4}{d_A^6} T^\delta \left(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4\right)$$

$$\bar{T}_{ij}(\ell_i, \ell_j) = (2\pi)^3 \int_{\ell_i} \frac{\mathrm{d}^2\ell}{A_r(\ell_i)} \int_{\ell_j} \frac{\mathrm{d}^2\ell}{A_r(\ell_j)} T^\kappa(\ell_i, -\ell_i, \ell_j, -\ell_j)$$

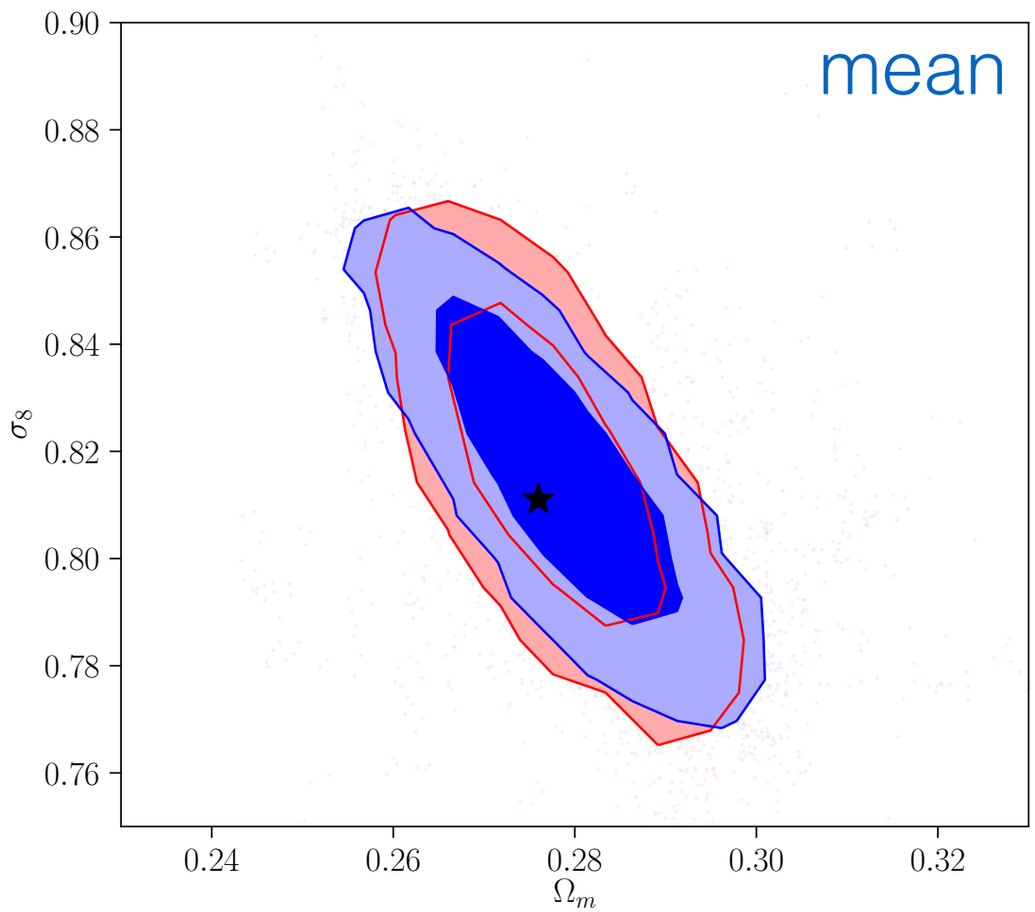
Test of Non-Gaussianity

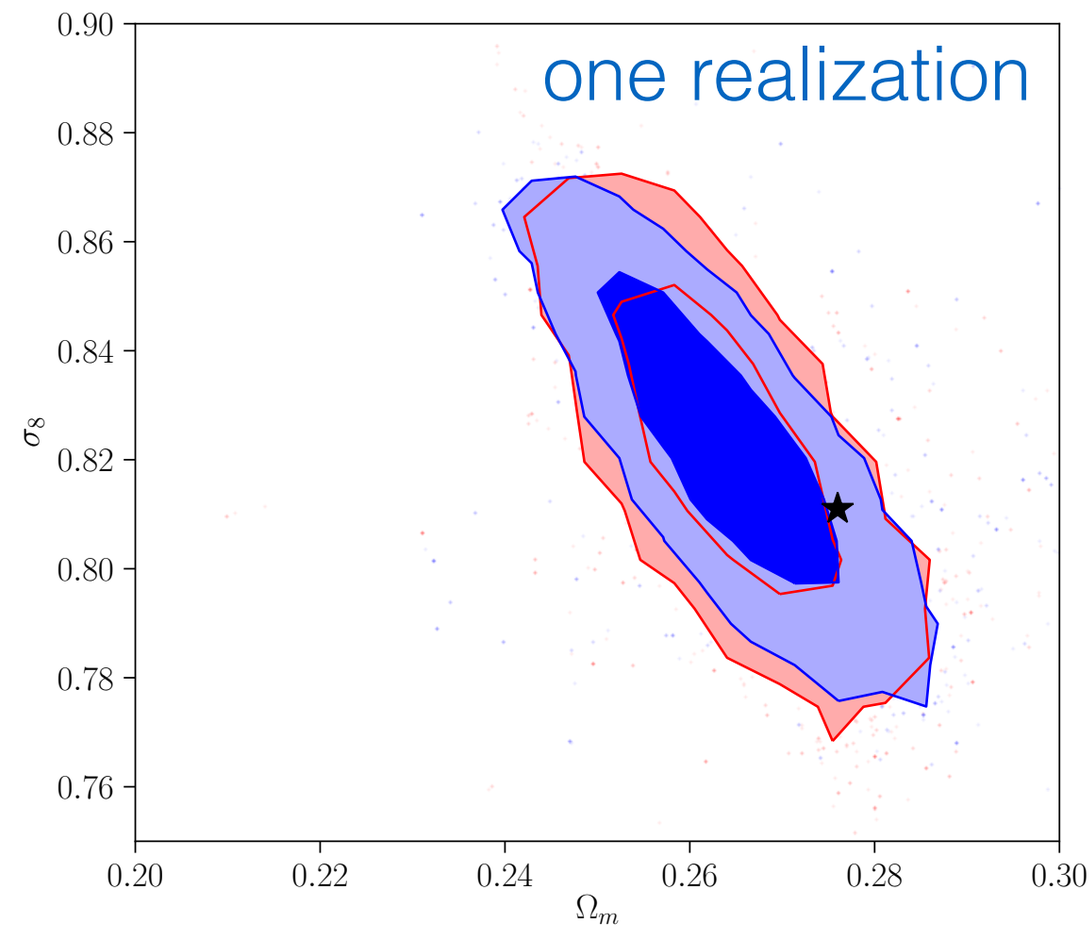


$$\langle \kappa^4(\theta_s) \rangle = \int \mathrm{d}\chi \frac{W(\chi, \chi_s)^4}{d_A^6} \int \frac{\mathrm{d}^2\ell_1}{(2\pi)^2} \frac{\mathrm{d}^2\ell_2}{(2\pi)^2} \frac{\mathrm{d}^2\ell_3}{(2\pi)^2} T^\delta\left(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, -\mathbf{k}_{123}\right) F(\ell_1) F(\ell_2) F(\ell_3) F(\ell_{123})$$

Takada & Jain 2002 (0205055)

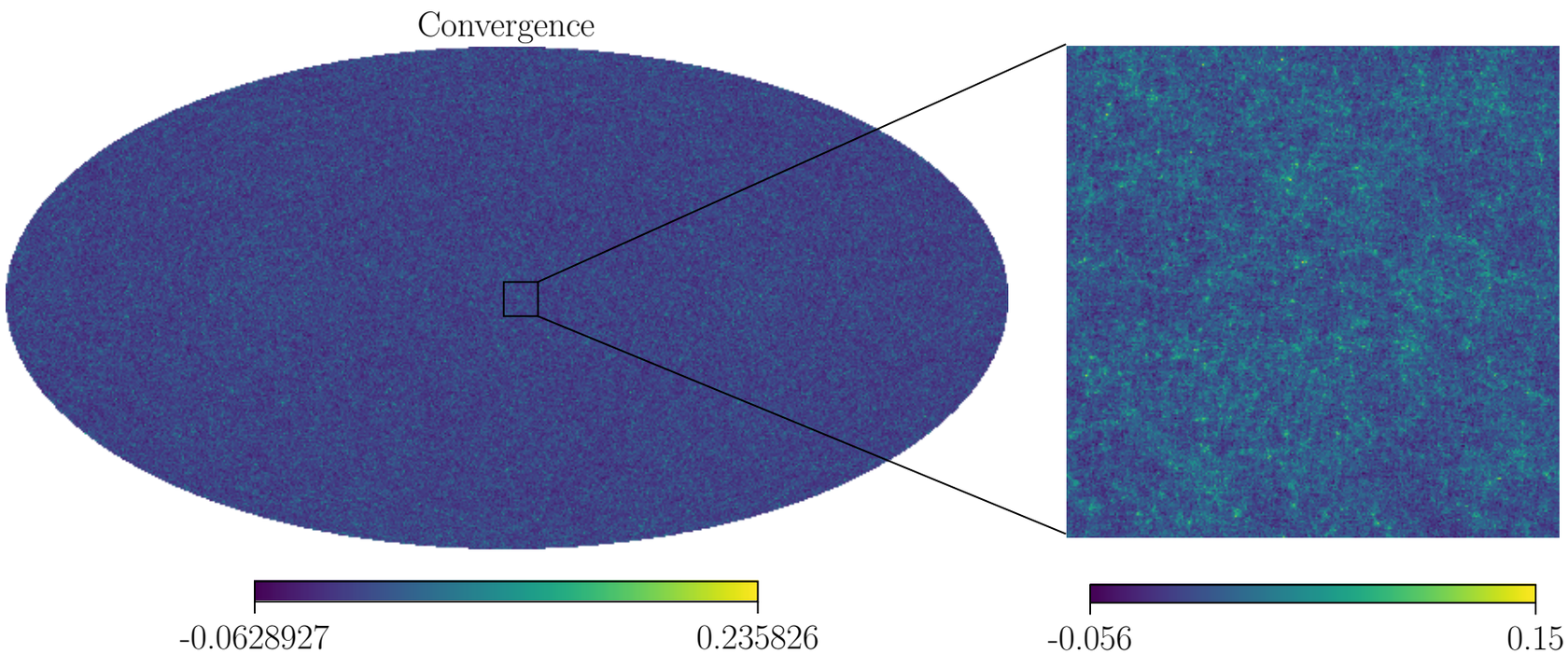
Constraints: Sample Variance





- Center of constraints for different $C_\ell^{\rm sim}$ scatter within 1σ w.r.t. fiducial values at ★

Weak Lensing Maps



$$\delta(\theta_{\rm pix}) \approx \sum_b \left[\frac{N_{\rm pix}}{4\pi} \frac{V_{\rm sim}}{N_{\rm part}^{\rm sim}} \left(\frac{H_0}{c}\right)^2 \frac{n_p(\theta_{\rm pix}, \Delta\chi_b)}{\mathcal{D}^2(z_b)} - \left(\frac{c}{H_0}\Delta\mathcal{D}_b\right)\right] / \sum_b \left(\frac{c}{H_0}\Delta\mathcal{D}_b\right)$$

$$\kappa(\theta_{\rm pix}) \approx \frac{3}{2}\Omega_m \sum_b W_b \frac{H_0}{c} \left[\frac{N_{\rm pix}}{4\pi} \frac{V_{\rm sim}}{N_{\rm part}^{\rm sim}} \left(\frac{H_0}{c}\right)^2 \frac{n_p(\theta_{\rm pix}, \Delta\chi_b)}{\mathcal{D}^2(z_b)} - \left(\frac{c}{H_0}\Delta\mathcal{D}_b\right)\right]$$

$$h = 0.7\,,\ \Omega_{\rm m} = 0.276\,,\ \Omega_{\rm b} = 0.045\,,\ n_s = 0.961\,,\ \sigma_8 = 0.811$$