Title: The reconstruction of the CMB lensing bispectrum

Speakers: Alba Kalaja

Series: Cosmology & Gravitation

Date: October 11, 2022 - 11:00 AM

URL: https://pirsa.org/22100104

Abstract: Weak gravitational lensing by the intervening large-scale structure (LSS) of the Universe is the leading non-linear effect on the anisotropies of the cosmic microwave background (CMB). The integrated line-of-sight gravitational potential that causes the distortion can be reconstructed from the lensed temperature and polarization anisotropies via estimators quadratic in the CMB modes. While previous studies have focused on the lensing power spectrum, upcoming experiments will be sensitive to the bispectrum of the lensing field, sourced by the non-linear evolution of structure. The detection of such a signal would provide additional information on late-time cosmological evolution, complementary to the power spectrum.

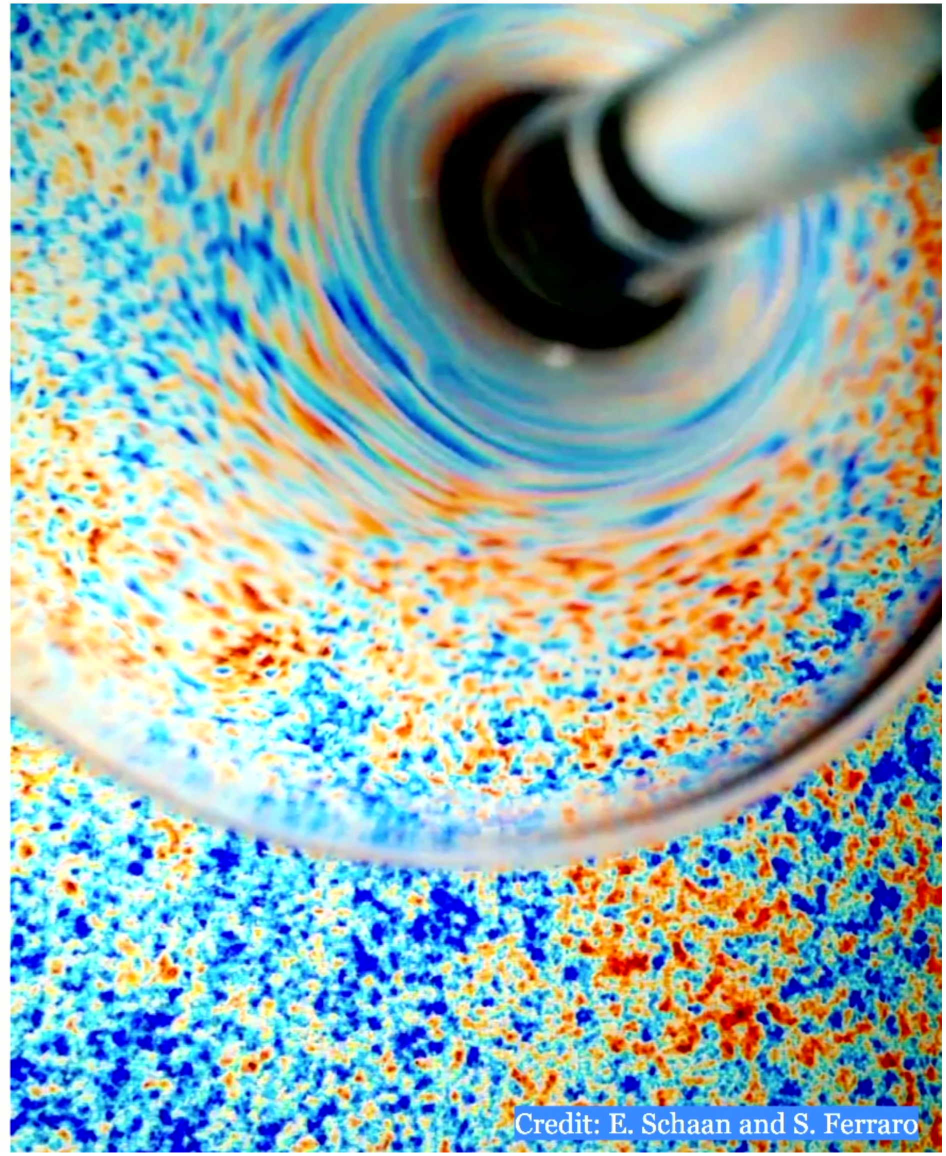
Zoom link: https://pitp.zoom.us/j/94880169487?pwd=dzRWcVRwQ2dVdWZ3N2RjOWU2RDUyZz09

THE RECONSTRUCTION OF THE CMB LENSING BISPECTRUM

Alba Kalaja

with Giorgio Orlando and Daan Meerburg (Groningen U.),
Aleksandr Bowkis and Anthony Challinor (Cambridge U.),
Toshiya Namikawa (IPMU, Tokyo U.)

Perimeter Institute - 11/10/2022



OUTLINE

Focus: reconstruction noise biases and challenges in measuring the lensing bispectrum.

- ★ Introduction: weak lensing of the cosmic microwave background (CMB).
- ★ Beyond the Gaussian assumption.
- ★ Lensing reconstruction from CMB anisotropies.
- ★ Feynman diagrams for lensing: analytical results and validation with simulations.
- ★ Conclusions and future directions.

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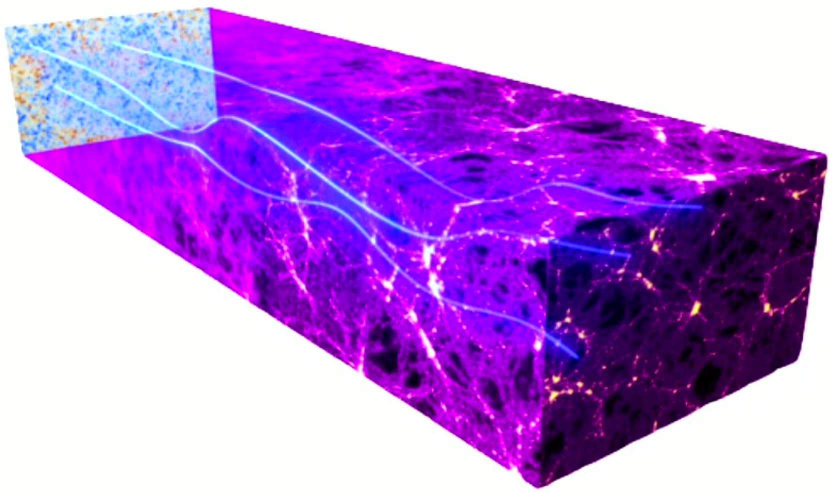
★ Introduction: weak lensing of the cosmic microwave background (CMB).

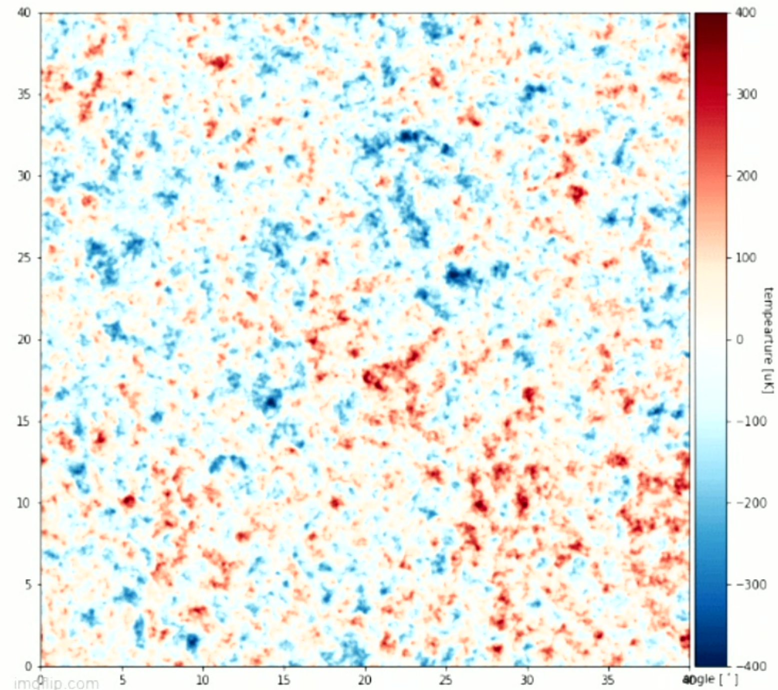
★ Beyond the Gaussian assumption.

WEAK LENSING OF THE CMB

The CMB photons travel through the Large Scale Structure (LSS) and are deflected by the distribution of matter.



[Credit: ESA and the Planck Collaboration]



WEAK LENSING OF THE CMB

$$\widetilde{T}(\boldsymbol{x}) = T(\boldsymbol{x}') = T(\boldsymbol{x} + \nabla\phi(\boldsymbol{x}))$$

$$\widetilde{T}(\boldsymbol{x}) = T(\boldsymbol{x}) + \nabla T(\boldsymbol{x}) \cdot \nabla\phi(\boldsymbol{x}) + \frac{1}{2}\nabla_i\nabla_j T(\boldsymbol{x})\ \nabla^i\phi(\boldsymbol{x})\,\nabla^j\phi(\boldsymbol{x}) + \mathcal{O}(\phi^3)$$

$$\phi(\hat{\boldsymbol{n}}) = -2\int_0^{\chi_*} \mathrm{d}\chi\, \frac{\chi_* - \chi}{\chi_*\chi}\,\Psi(\chi\hat{\boldsymbol{n}};\eta(\chi))$$

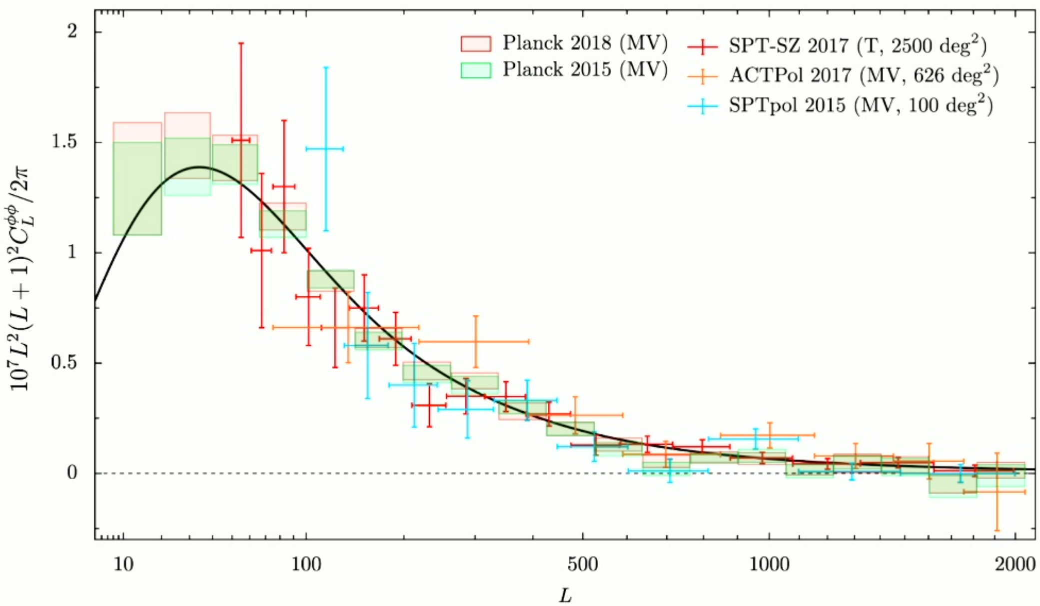
Probe of the growth of LSS, neutrino mass hierarchy, dark energy models.

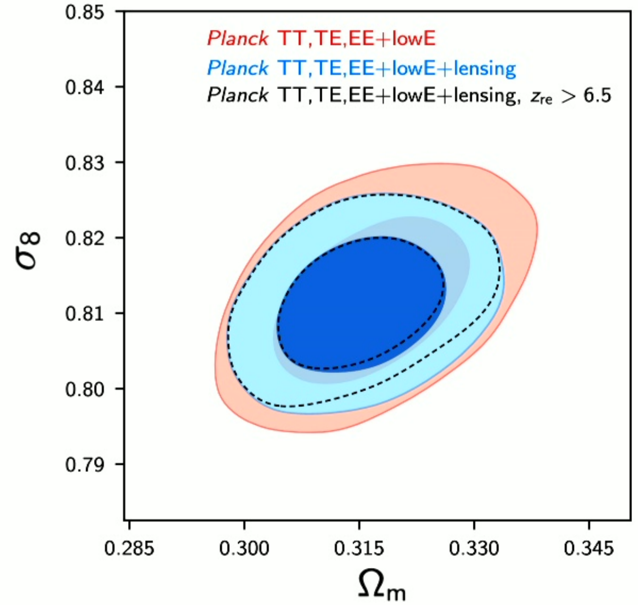
➔ Gravitational effect: it induces new (secondary) *non-Gaussianity* in the CMB anisotropies.

➔ The lensing potential can be **reconstructed** from the **lensed CMB**.

THE LENSING POWER SPECTRUM

Planck '18 temperature and polarization data have provided a detection of the lensing signal at $40\,\sigma$.



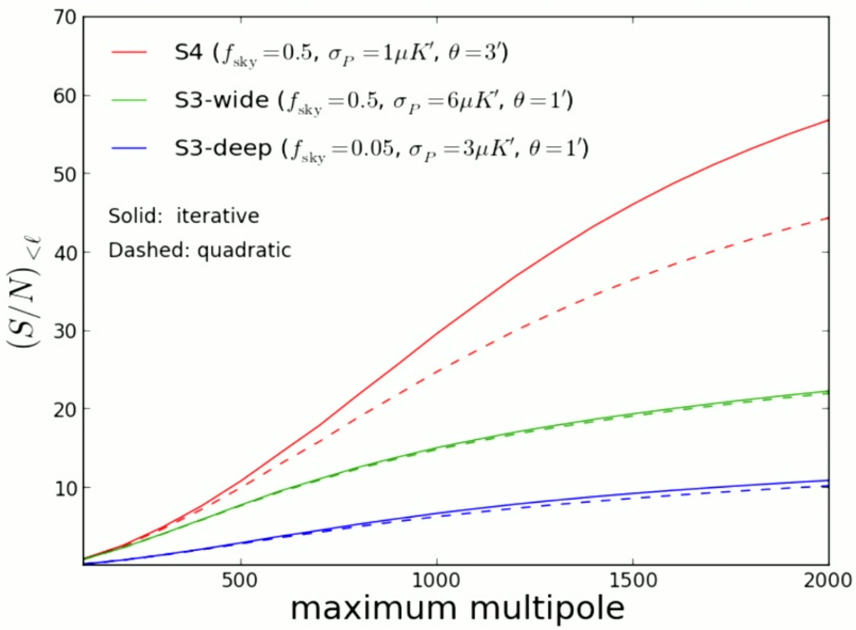


[Planck collaboration, *A&A 641 (Sep, 2020) A8*]

BEYOND THE GAUSSIAN ASSUMPTION

Late-time nonlinear clustering generates non-Gaussianity that induces a non-zero **bispectrum of ϕ**.

Cumulative signal-to-noise ratio of the bispectrum



➔ The lensing bispectrum will be detectable with next-generation CMB experiments.

➔ The combination of power spectrum and bispectrum improves constraints on the sum of neutrino masses and dark energy EoS by **30-35%** (wrt to power spectrum alone).

[Namikawa T., *Phys. Rev. D 93, 121301 (2016)*]

THE NOISE BIASES

An efficient and optimal way to reconstruct lensing from CMB anisotropies is by using the **quadratic estimator (QE)**

normalization

$$\hat{\phi}(\boldsymbol{L}) = A_L \int_{\boldsymbol{\ell}_1,\boldsymbol{\ell}_2} (2\pi)^2 \delta^{(2)}(\boldsymbol{L}-\boldsymbol{\ell}_1-\boldsymbol{\ell}_2) F(\boldsymbol{\ell}_1,\boldsymbol{\ell}_2) \widetilde{T}(\boldsymbol{\ell}_1)\widetilde{T}(\boldsymbol{\ell}_2)$$

filter function

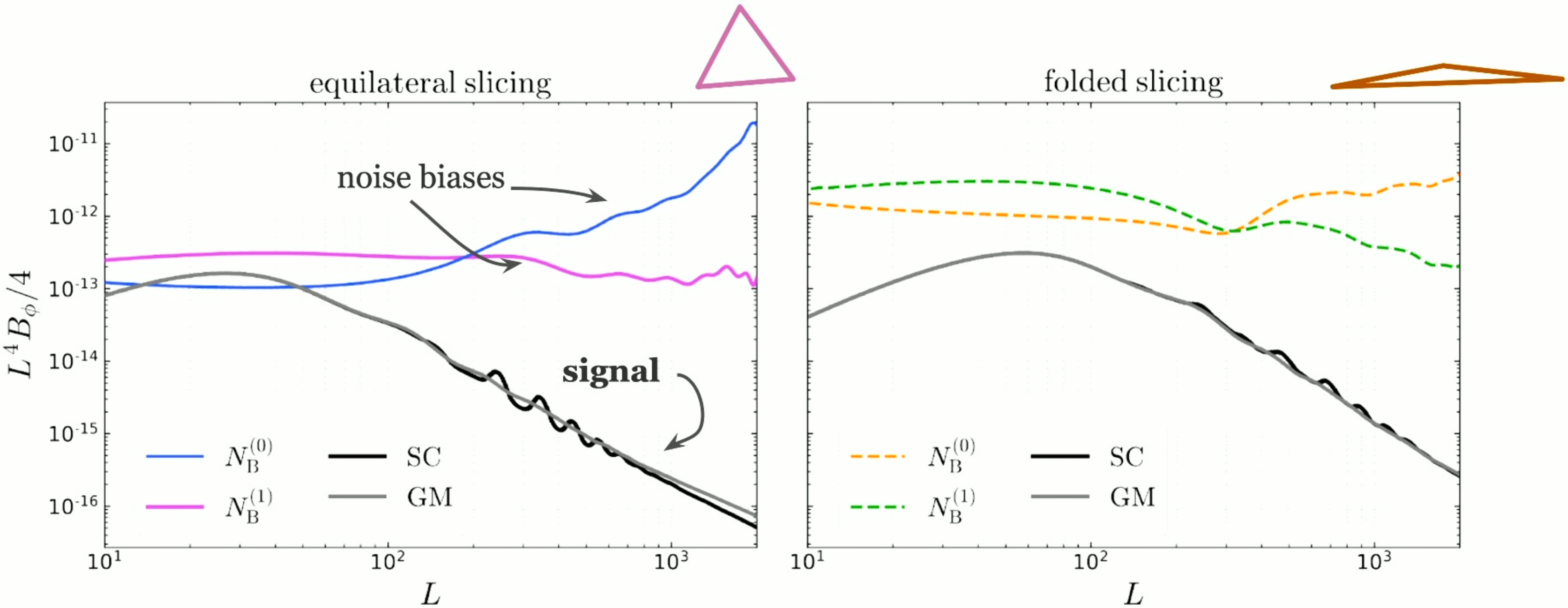
bispectrum

$$\langle \hat{\phi}(\boldsymbol{L}_1)\hat{\phi}(\boldsymbol{L}_2)\hat{\phi}(\boldsymbol{L}_3)\rangle \propto \int\int\int (\dots) \underbrace{\langle \widetilde{T}(\boldsymbol{\ell}_1)\widetilde{T}(\boldsymbol{L}_1-\boldsymbol{\ell}_1)\widetilde{T}(\boldsymbol{\ell}_2)\widetilde{T}(\boldsymbol{L}_2-\boldsymbol{\ell}_2)\widetilde{T}(\boldsymbol{\ell}_3)\widetilde{T}(\boldsymbol{L}_3-\boldsymbol{\ell}_3)\rangle}_{\text{6pt correlation function}}$$

➔ Perturbatively: $\langle \hat{\phi}(\boldsymbol{L}_1)\hat{\phi}(\boldsymbol{L}_2)\hat{\phi}(\boldsymbol{L}_3)\rangle \propto \textbf{signal} + N_{\rm B}^{(0)} + N_{\rm B}^{(1)} + N_{\rm B}^{(3/2)} + N_{\rm B}^{(2)} + \dots$

order of lensing power spectrum

THE NOISE BIASES



[SC: Scoccimarro R., *Mon.Not.Roy.Astron.Soc. 325 (2001)*] **[GM: Gil-Marin H., *JCAP02(2012)047*]**

QUICK RECAP

- ➔ Upcoming CMB experiment will be sensitive to the bispectrum of the lensing potential ϕ.
- ➔ Tighten constraints on late-time cosmology (when combined with the lensing power spectrum).
- ➔ The signal is buried in reconstruction noise (even if ϕ is Gaussian).

Goal: quantify the magnitude of reconstruction noise biases

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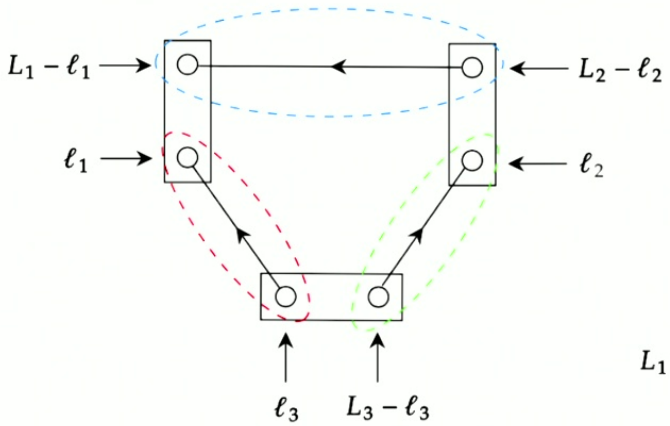
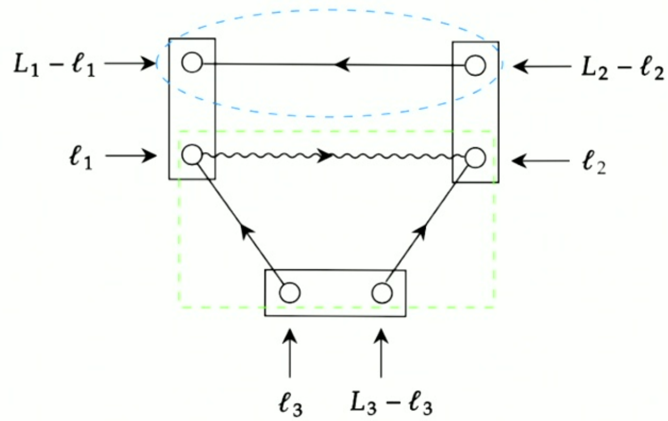
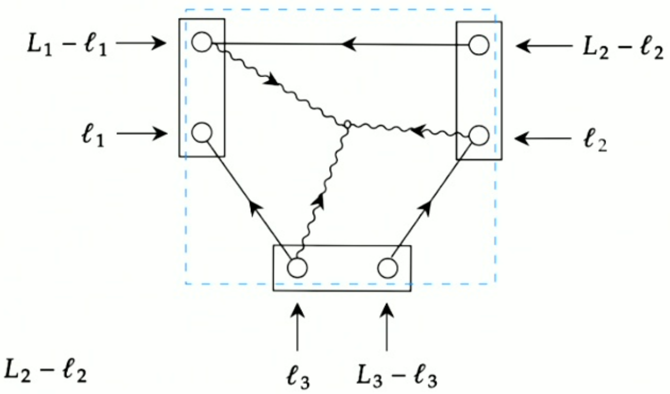


$2_C \times 2_C \times 2_C$



$4_C \times 2_C$



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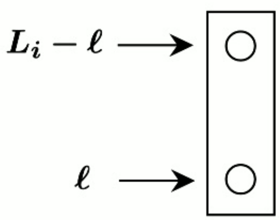
THE FEYNMAN APPROACH - FLAT SKY LIMIT

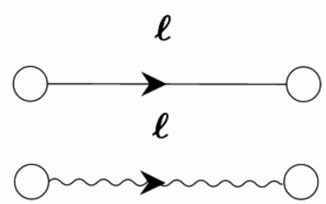
Basic rules:

"building block"



$$= A_{\boldsymbol{L}_i} F(\boldsymbol{\ell}\,, \boldsymbol{L}_i - \boldsymbol{\ell})$$

"propagators"



$$= C_\ell^{TT}$$

$$= C_\ell^{\phi\phi}$$

At each vertex there's *momentum conservation*.

[Jenkins E. et al, ***Phys. Lett. B 736 (2014)***]

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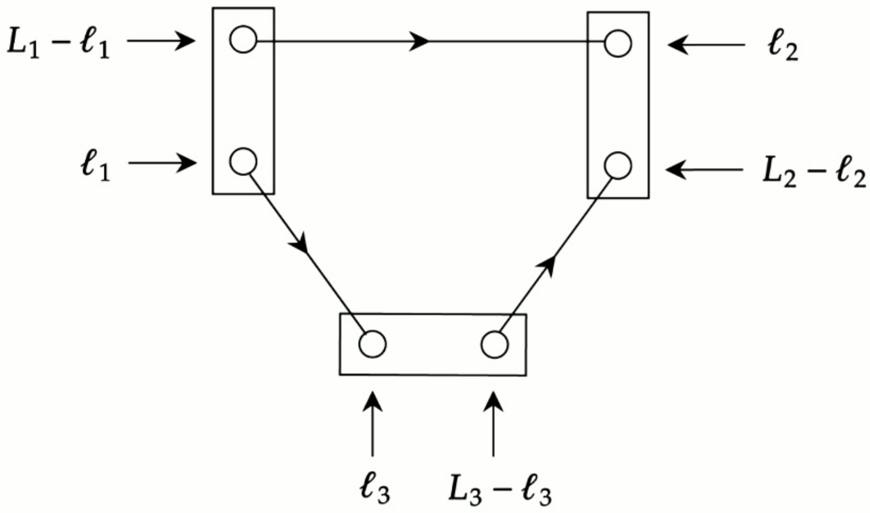

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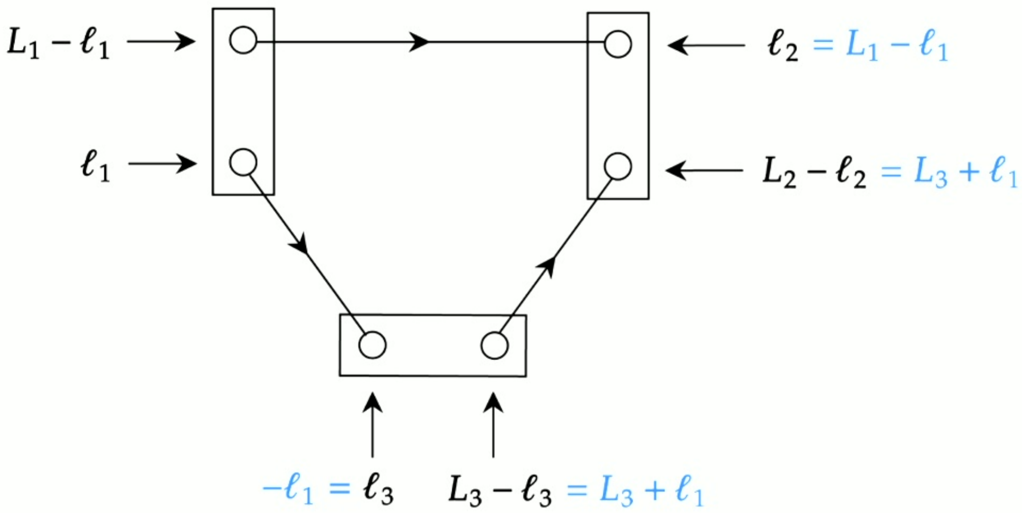

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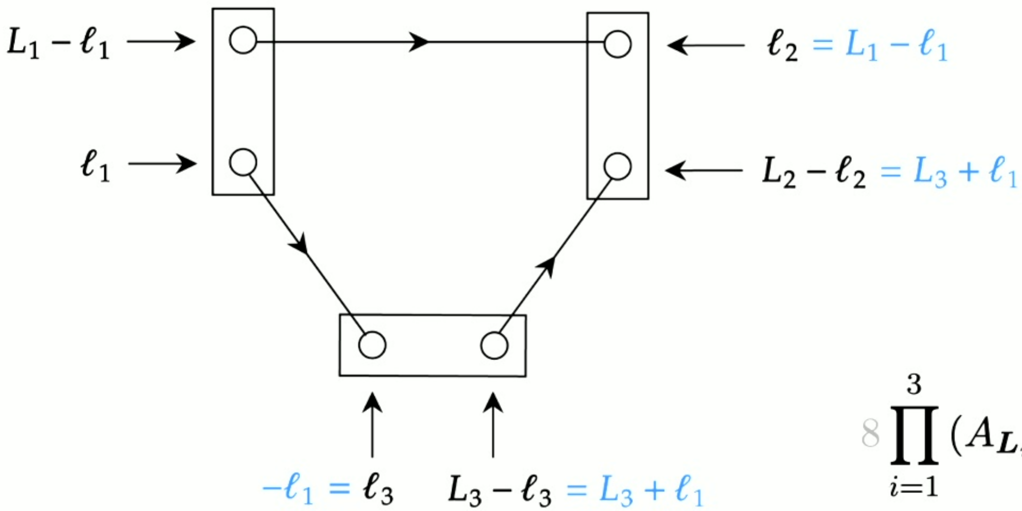

$$8\prod_{i=1}^{3}(A_{\boldsymbol{L}_i})\int_{\boldsymbol{\ell}_1} F(\boldsymbol{\ell}_1,\boldsymbol{L}_1-\boldsymbol{\ell}_1)\,F(\boldsymbol{L}_3+\boldsymbol{\ell}_1,\boldsymbol{L}_1-\boldsymbol{\ell}_1)\times$$

$$\times\ F(-\boldsymbol{\ell}_1,\boldsymbol{L}_3+\boldsymbol{\ell}_1)C^{TT}_{\ell_1}\,C^{TT}_{|\boldsymbol{L}_1-\boldsymbol{\ell}_1|}\,C^{TT}_{|\boldsymbol{L}_3+\boldsymbol{\ell}_1|}$$

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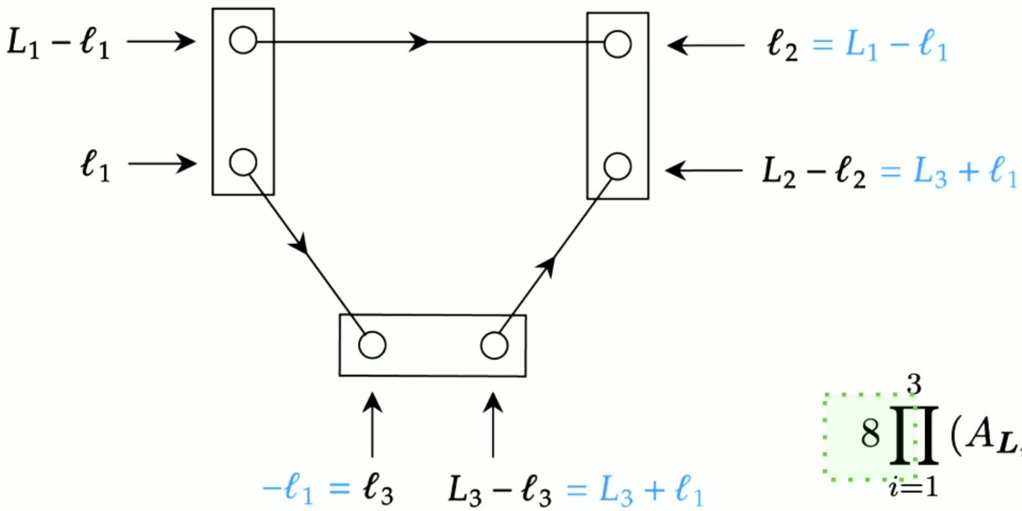

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symmetry

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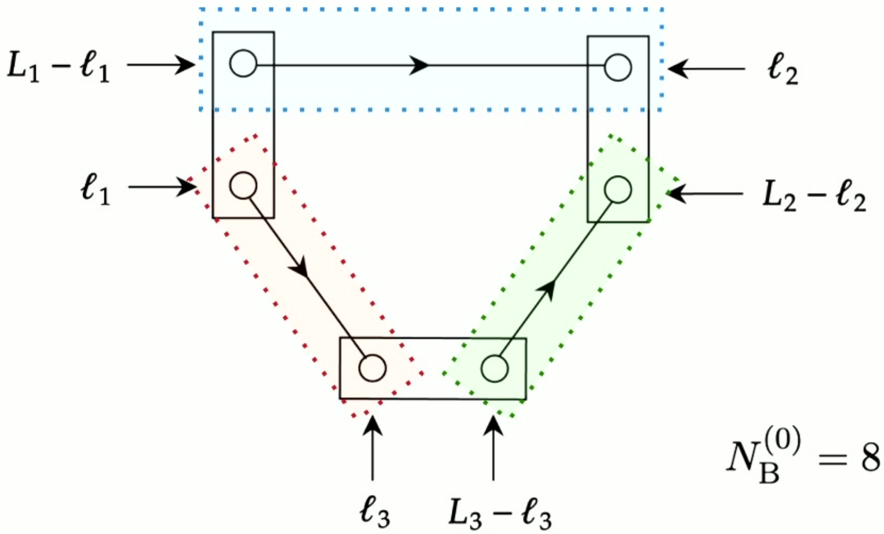

$$\langle (T)^2 \rangle \langle (T)^2 \rangle \langle (T)^2 \rangle$$

$$N_{\rm B}^{(0)} = 8 \prod_{i=1}^{3} (A_{\boldsymbol{L}_i}) \int_{\boldsymbol{\ell}_1} F(\boldsymbol{\ell}_1, \boldsymbol{L}_1 - \boldsymbol{\ell}_1)\, F(\boldsymbol{L}_3 + \boldsymbol{\ell}_1, \boldsymbol{L}_1 - \boldsymbol{\ell}_1) \times$$
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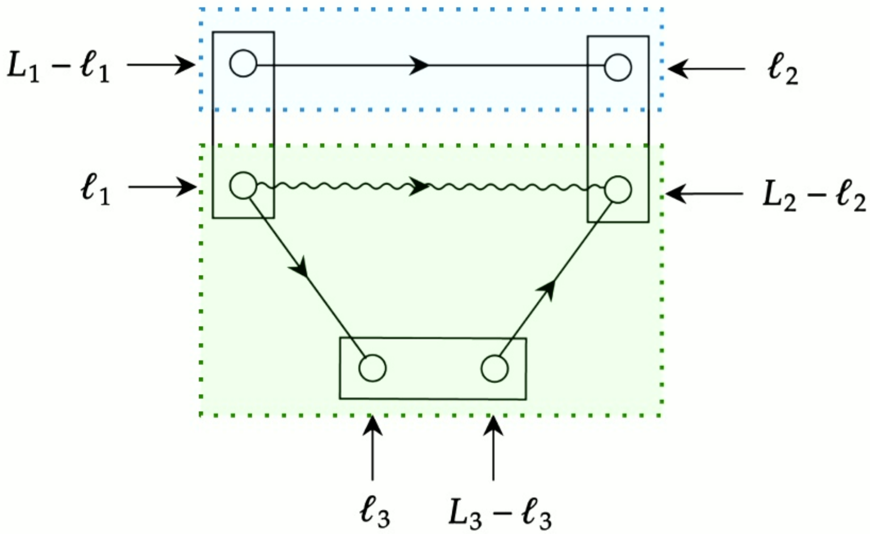

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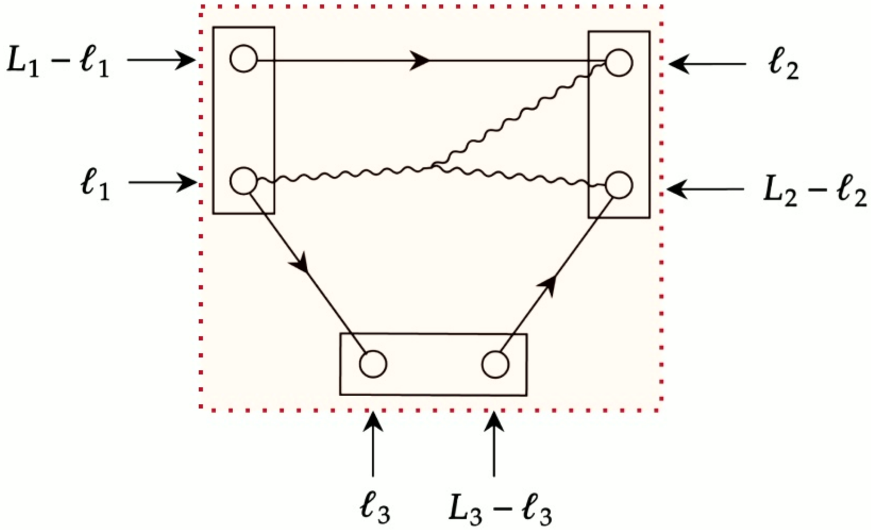

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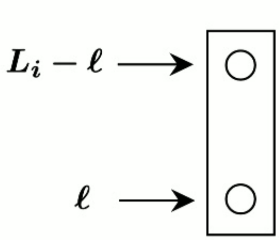

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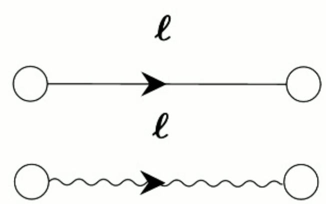

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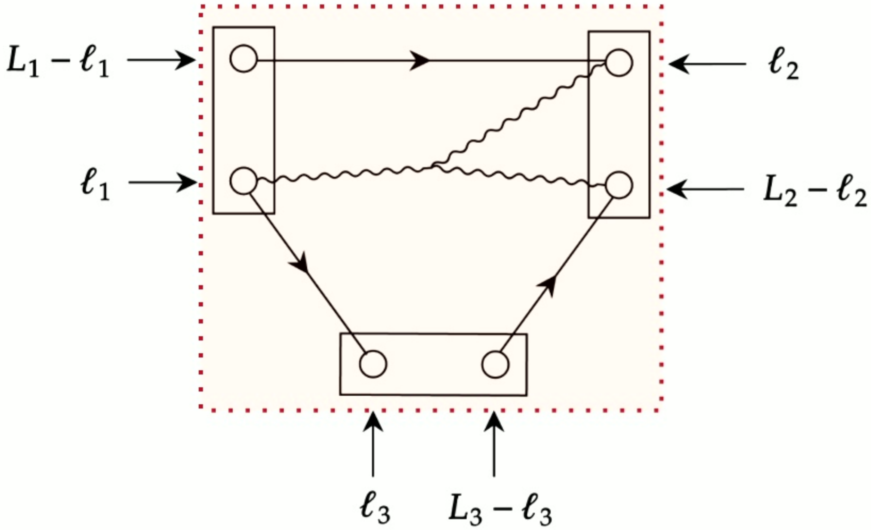

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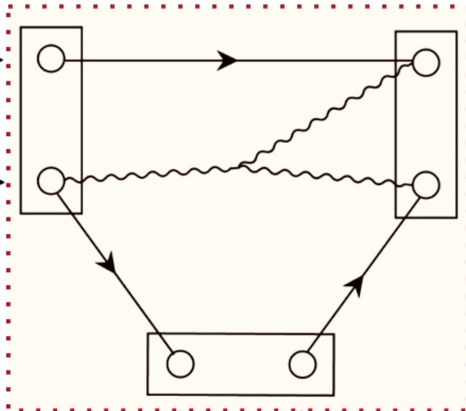

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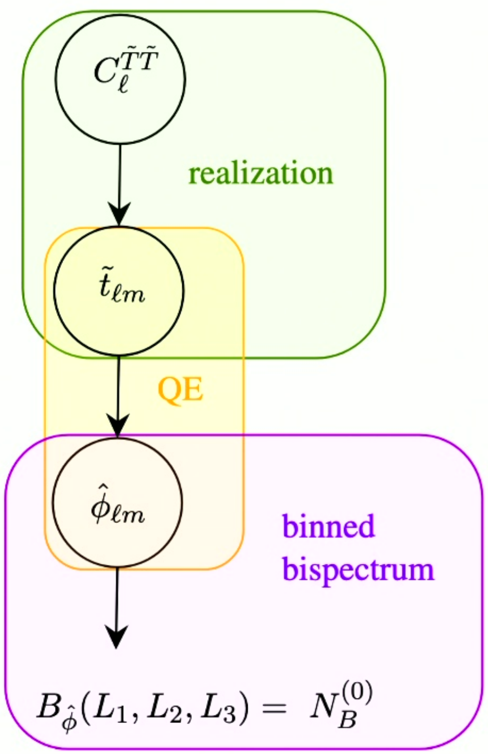
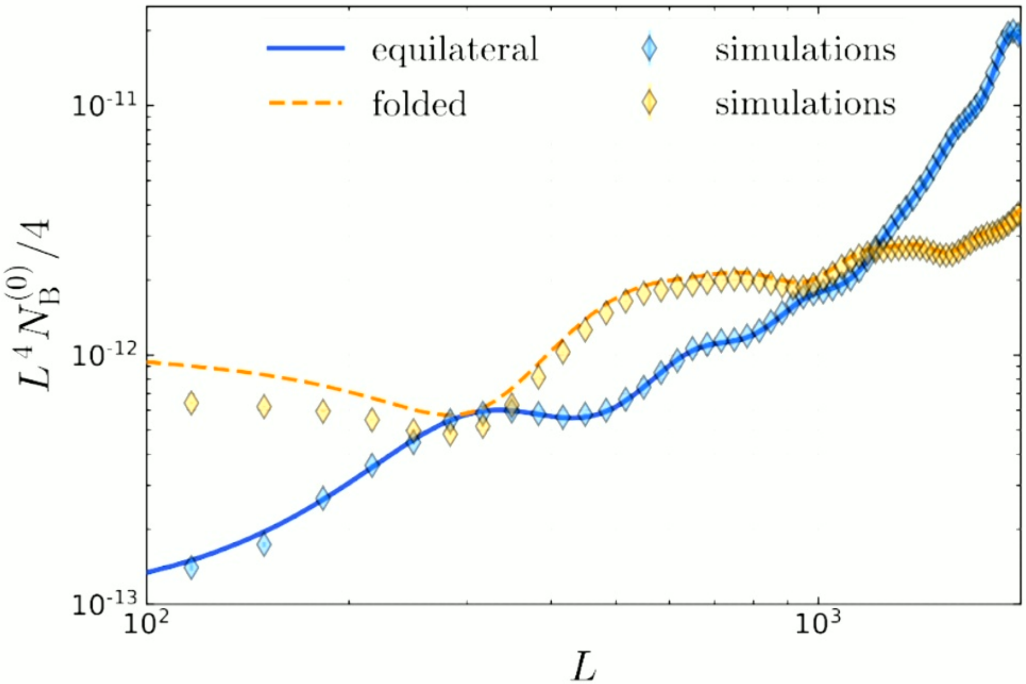


Equilateral $L_1 = L_2 = L_3 = L$

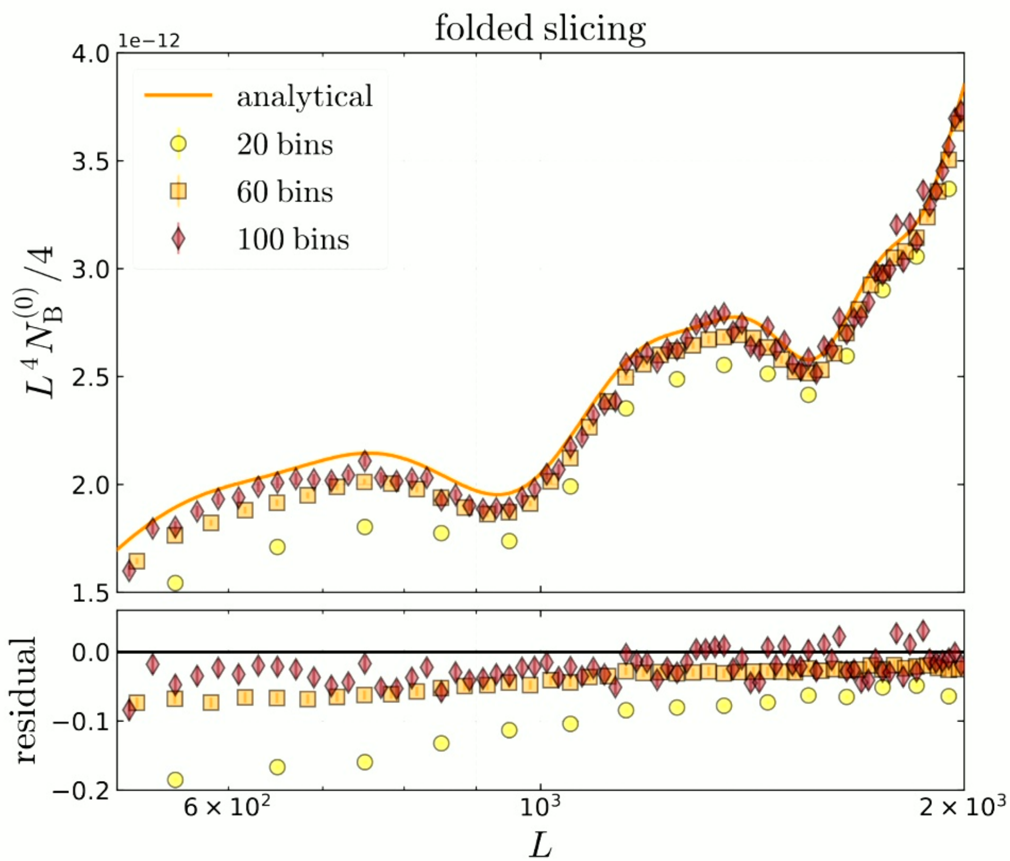
Folded $L_1 = L,\ 2L_2 = 2L_3 = L$

NUMERICAL RESULTS AND SIMULATIONS - $N^{(0)}$



➔ The folded configuration is affected by binning. **[Namikawa. et al, *Phys. Rev. D 99 (2019)*]**

THE BINNING EFFECT



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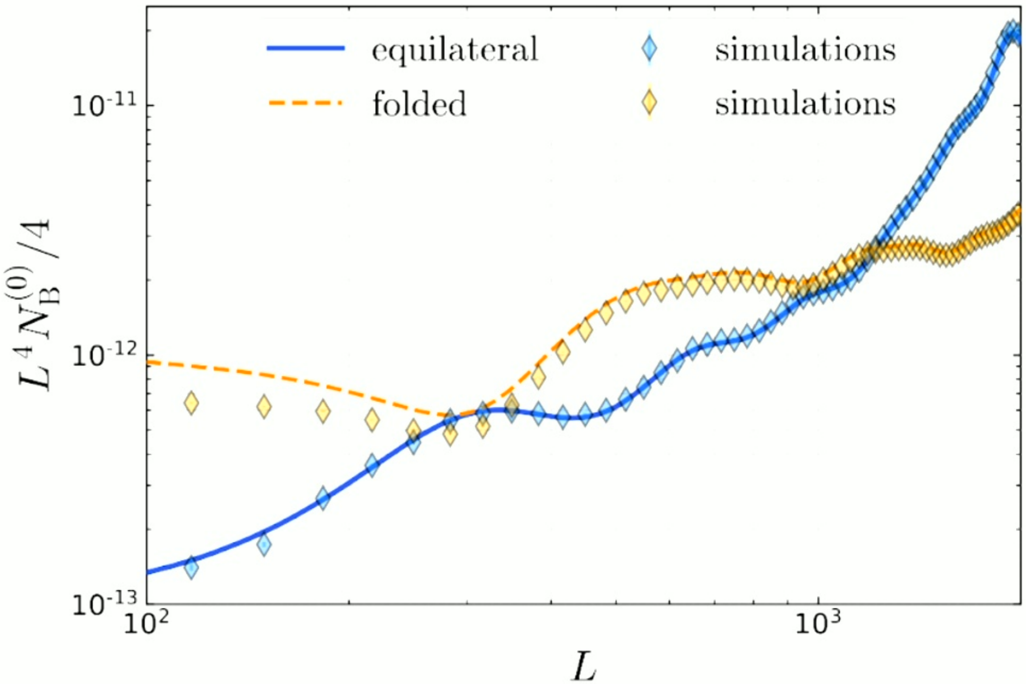

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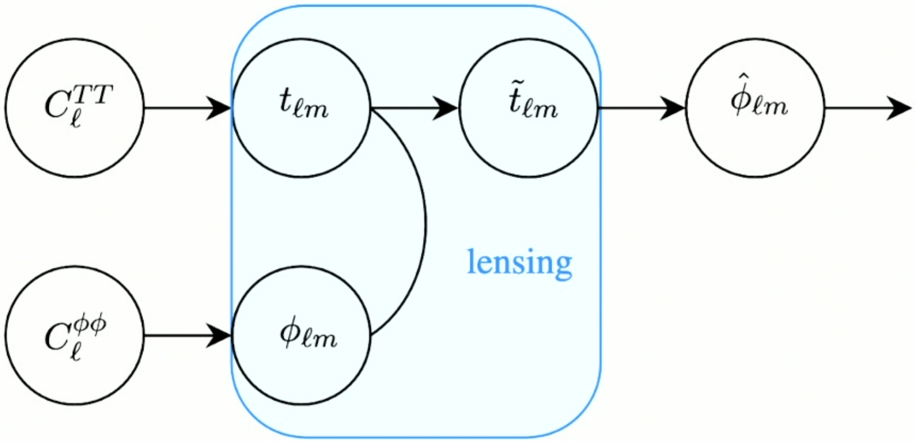
NUMERICAL RESULTS AND SIMULATIONS - N(1)



$$B_{\hat{\phi}} = N_B^{(0)} + N_B^{(1)} + N_B^{(2)}$$

We reconstruct **non-perturbatively**, then the effect of $N^{(2)}$ can be mitigated.

[Lewis A. et al, *JCAP, 03(2011)018*]

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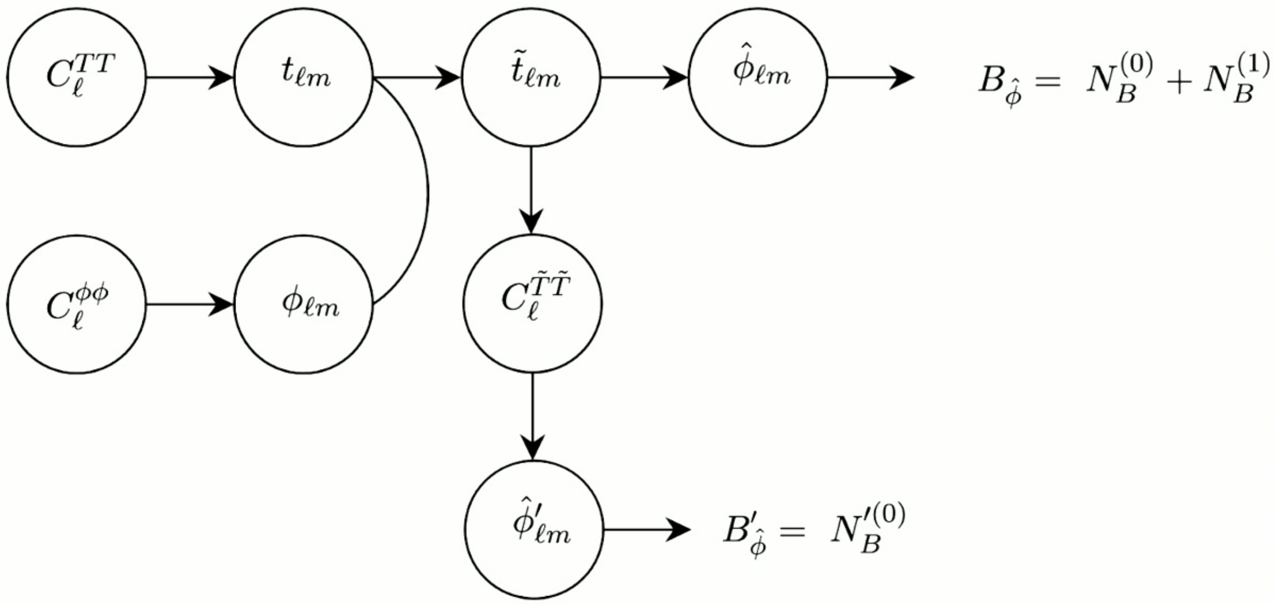

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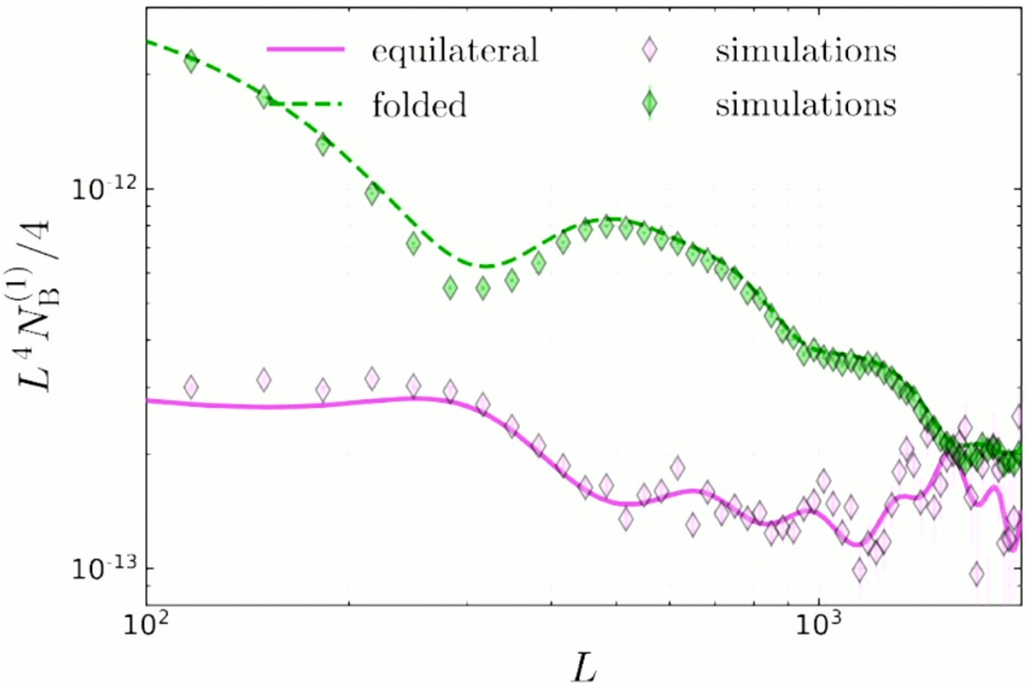

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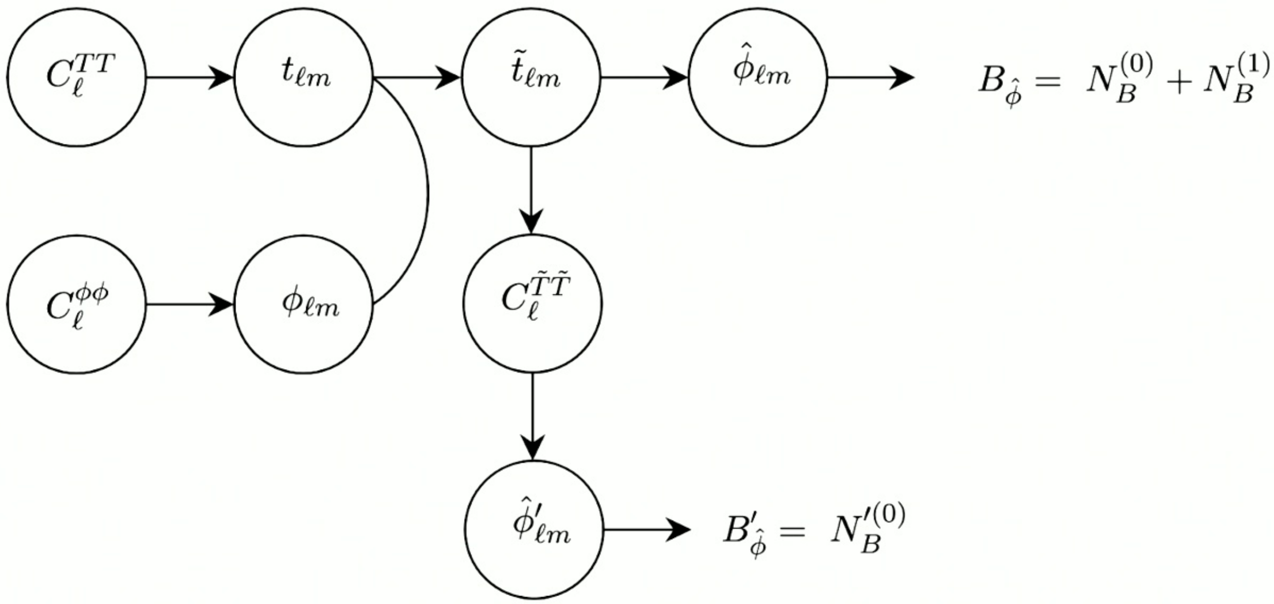

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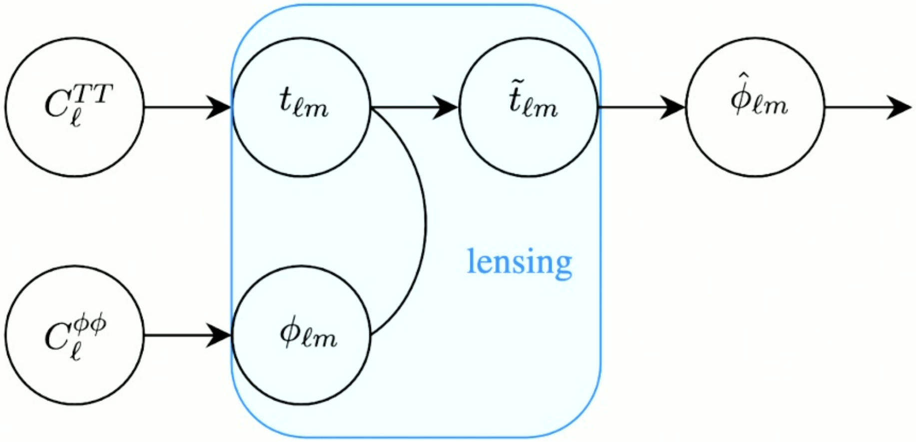

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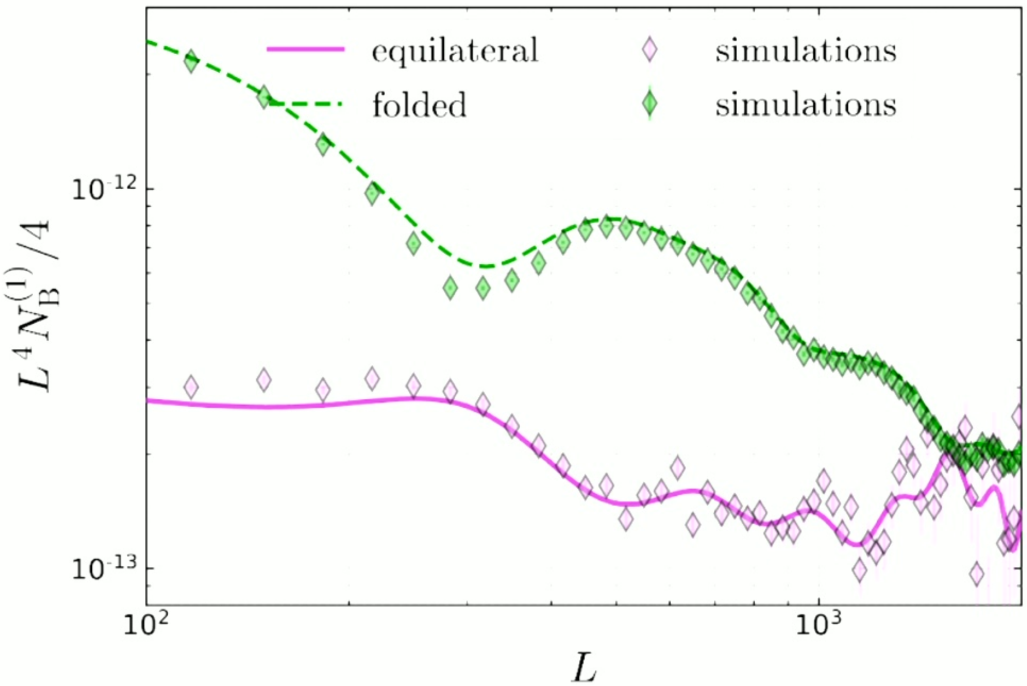

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SIMONS OBSERVATORY

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Future work:

- Include polarization data in the QE: minimum variance estimator.

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SIMONS OBSERVATORY

CONCLUSIONS AND FUTURE DIRECTIONS

- ➔ CMB lensing allows us to constrain late-time cosmology.
- ➔ Upcoming CMB experiment will be sensitive to the bispectrum of the lensing potential ϕ.
- ➔ The signal is buried in reconstruction noise: we are able to theoretically model these terms, consistently with simulations.

Future work:

- Include polarization data in the QE: minimum variance estimator.
- Perform a similar analysis for $N^{(3/2)}$ (contains the signal).
- Realization dependant analysis.

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Future work:

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- Perform a similar analysis for $N^{(3/2)}$ (contains the signal).
- Realization dependant analysis.
- Detect the bispectrum with upcoming data (Simons Observatory).

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Thank you!

★ **Bounds on the primordial curvature power spectrum with Primordial Black Holes.**
We provide new constraints on the primordial curvature power spectrum at small scales from the latest limits on PBH abundance. [**AK,** et al., *JCAP 10 (2019) 031*]

★ **Fundamental limits on constraining primordial non-Gaussianity.**
We explore the cosmic variance limit on constraining primordial non-Gaussianity (pnG) for a variety of theory-motivated shapes. [**AK,** et al., *JCAP 04 (2021) 050*]

- Machine learning applied to pnG: beyond standard estimators for pnG using neural networks.

★ **Synergies between CMB lensing and LSS.**

- Cross-correlated bispectra: break parameter degeneracies, mitigate systematics.
- Constraints from CMB x radio galaxies.

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