Title: Probing Parity in the Cosmic Microwave Background (CMB)

Speakers: Cyril Creque-Sarbinowski

Collection/Series: Cosmology and Gravitation

Subject: Cosmology

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Abstract:

Deviations from a parity-symmetric Universe would strongly signal the presence of new physics beyond the Standard Model. The lowest-order scalar observable sensitive to parity in a homogeneous and isotropic Universe is the connected four-point function of a given cosmological field. Geometrically, this function is described by a suitable average of this field over many tetrahedral configurations. As the CMB represents a spherical projection of three-dimensional curvature fluctuations, its four-point function serves as a unique, but potentially limited, probe of this fundamental symmetry. In this talk, I will discuss progress in rigorously understanding the CMB's sensitivity to parity-violating physics from both early- and late-time sources.

Probing Parity in the Cosmic Microwave Background

Center for Computational Astrophysics (CCA)

Cyril Creque-Sarbinowski with Kendrick Smith and Stephon Alexander

11/26/2024

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Review

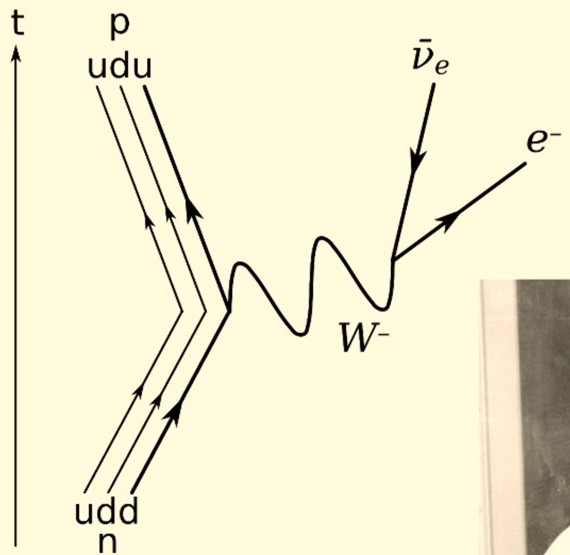
Signal

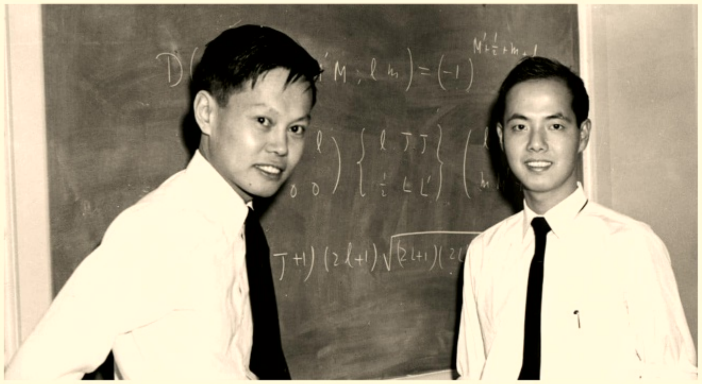
Sensitivity

Comment

Parity in Particle Physics

$$\mathbb{P}\mathbf{x} = -\mathbf{x}, \mathbb{P}\varphi(\mathbf{x}) = \pm\varphi(-\mathbf{x})$$

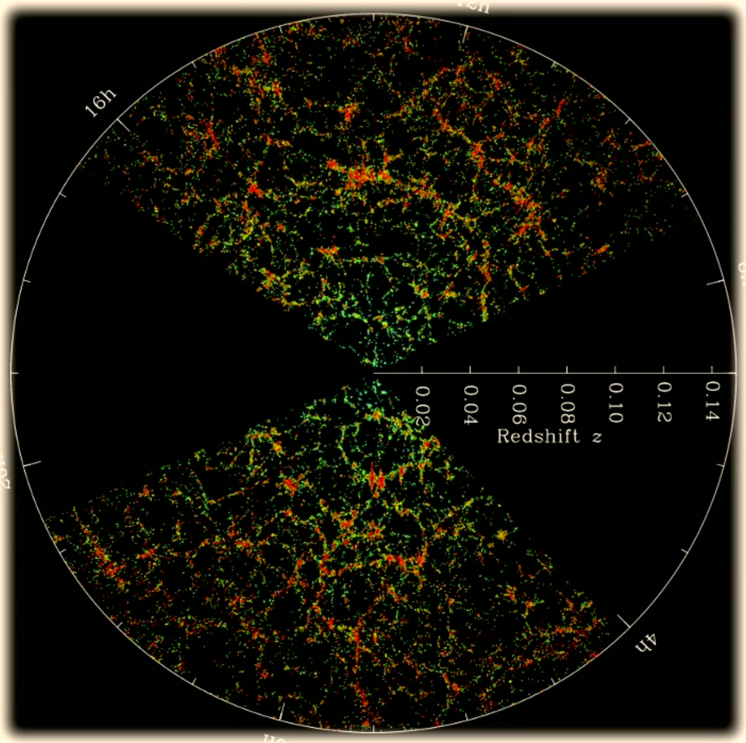


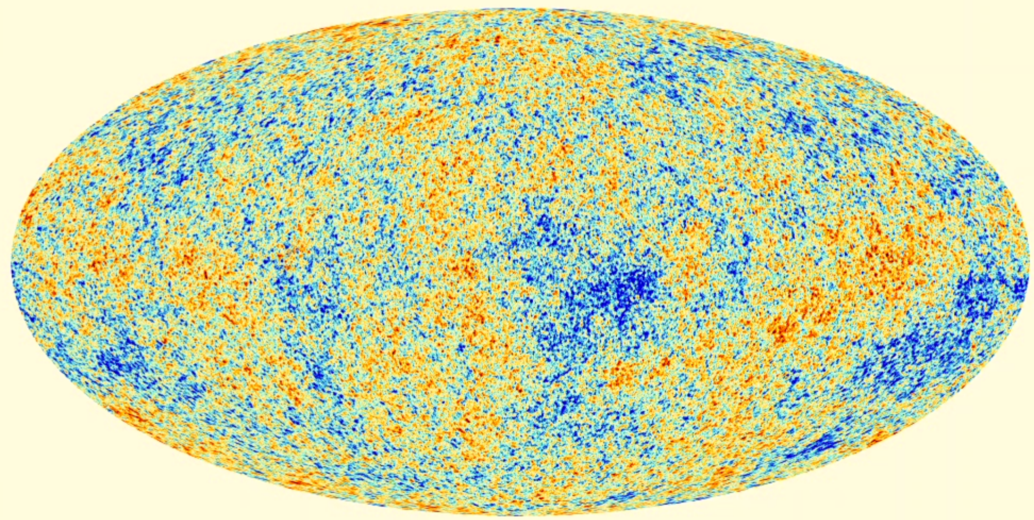


[Lee & Yang (1956), Wu et al (1957)]

Parity in Cosmology

$$\mathbb{P}\mathbf{x} = -\mathbf{x}, \mathbb{P}\delta(\mathbf{x}) = \pm\delta(-\mathbf{x})$$





[Lue, Wang, Kamionkowski (1998)]

Statistical Imprints

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N-Point Functions!

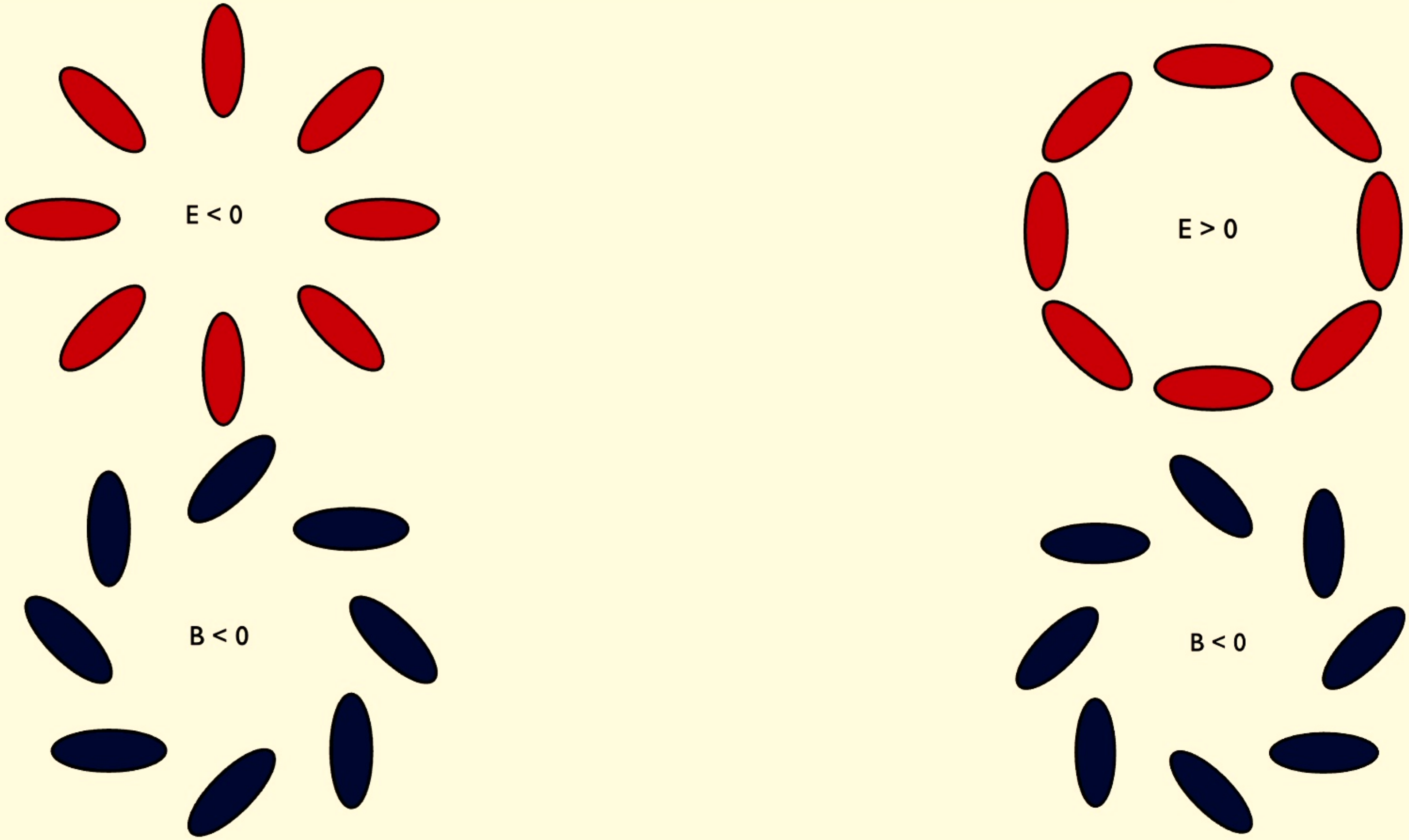
$$\delta_g(\mathbf{x}) = \frac{n_g(\mathbf{x}) - \bar{n}_g}{\bar{n}_g}$$

$$\langle \delta(\mathbf{x}) \rangle_c = 0$$

$$\langle \delta(\mathbf{x}_1)\delta(\mathbf{x}_2) \rangle_c = \xi_2(\mathbf{x}_1, \mathbf{x}_2) = \xi_2(|\mathbf{x}_1 - \mathbf{x}_2|)$$

$$\langle \delta(\mathbf{x}_1) \ldots \delta(\mathbf{x}_N) \rangle_c = \xi_N(\mathbf{x}_1, \ldots, \mathbf{x}_N)$$

2-Point Functions



4-Point Functions

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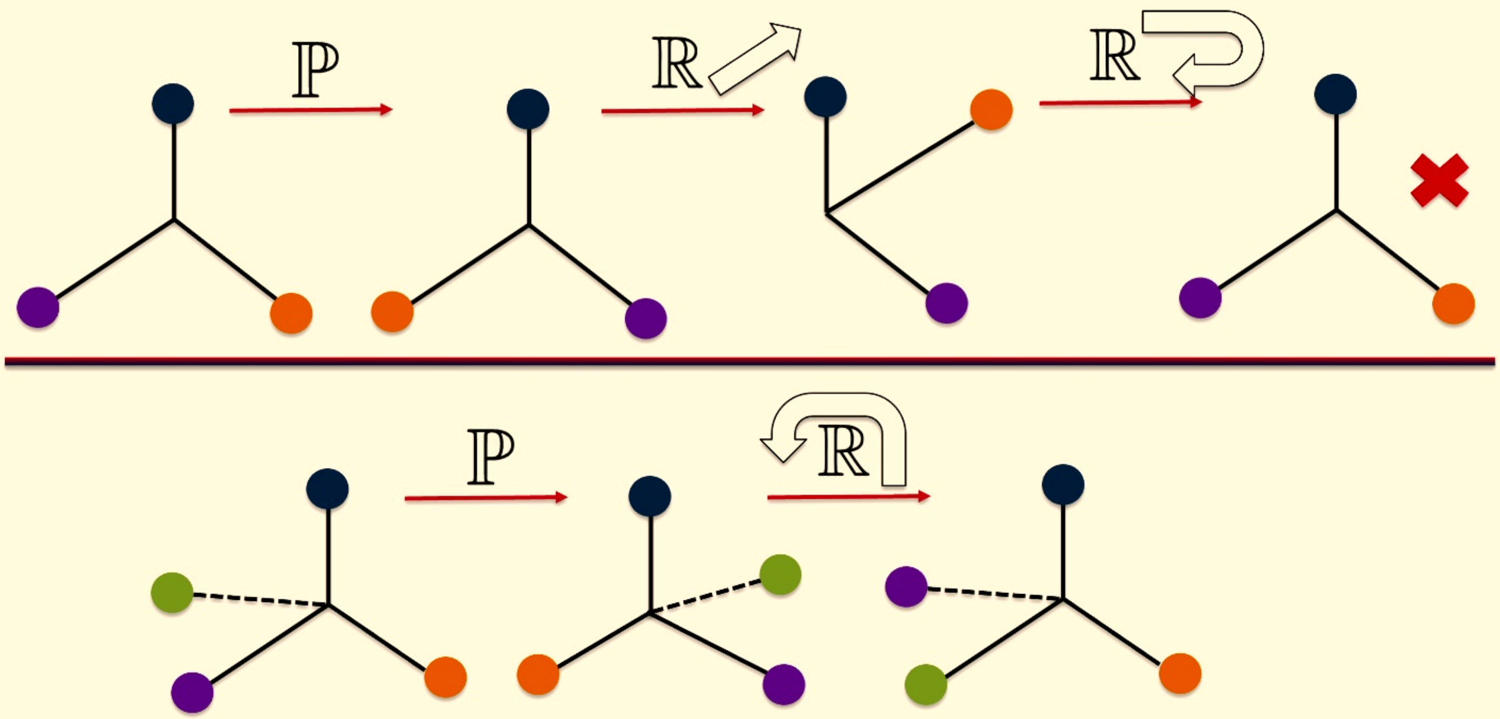

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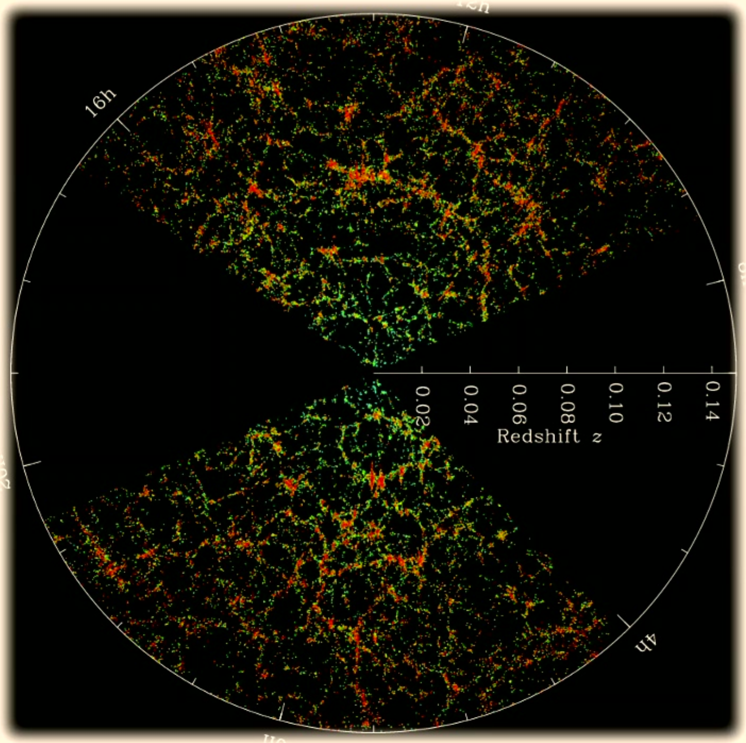
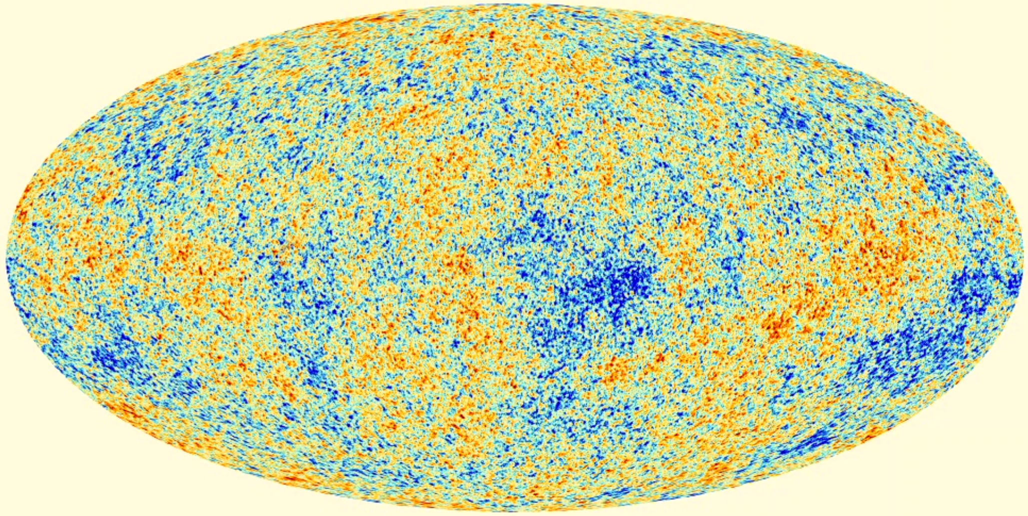
Parity Detection in Cosmology?

[Philcox (2022), Hou et al (2022)]
[Krowleski, May, Smith, Hopkins (2024)]

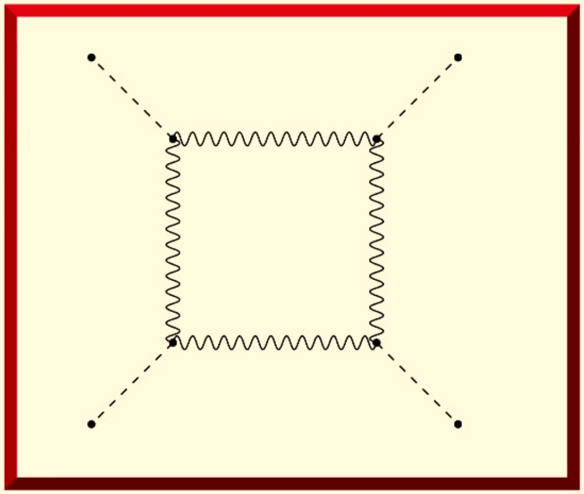


[Minami & Komatsu (2020)]
[Eskilt (2022)]



Parity Looking Forward/Backward

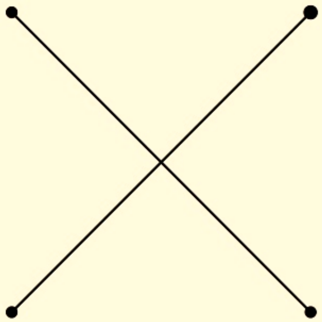
Experiments							
Name	$[z_{\rm min}, z_{\rm max}]$	$f_{\rm sky}$	$[k_{\rm min}, k_{\rm max}]$ $[h/{\rm Mpc}]$	$\bar{n}$ $[(h/{\rm Mpc})^3]$	$\bar{b}$	V $[({\rm Gpc}/h)^3]$	$N_{\rm modes}$
BOSS[a] [112, 113]	$[0.43, 0.7]$	0.23	$[0.01, 0.24]$	3×10^{-4}	2.0	3.6	10^5
DESI[a] [115]	$[0.6, 1.7]$	0.34	$[0.003, 0.31]$	3.8×10^{-4}	1.4	45	8×10^5
Euclid[a] [114]	$[0.9, 1.8]$	0.36	$[0.003, 0.34]$	4.3×10^{-4}	1.7	44	10^6
MegaMapper[a] [116, 117]	$[2, 5]$	0.34	$[0.003, 0.64]$	2.5×10^{-4}	3.8	155	7×10^6
MSE[a] [120]	$[1.6, 4]$	0.24	$[0.003, 0.54]$	2.8×10^{-4}	3.7	91	6×10^6
SPHEREx[a] [118, 119]	$[0.1, 4.3]$	0.65	$[0.003, 0.46]$	2.0×10^{-3}	1.1	360	2×10^7
HIRAX[b] [121]	$[0.8, 2.5]$	0.36	$[(0.01, 0.1), 0.38]$	10^{-3}	1.9	88	3×10^6
PUMA-32K[b] [122]	$[2, 6]$	0.5	$[(0.01, 0.1), 0.71]$	7.6×10^{-3}	6.3	290	7×10^7



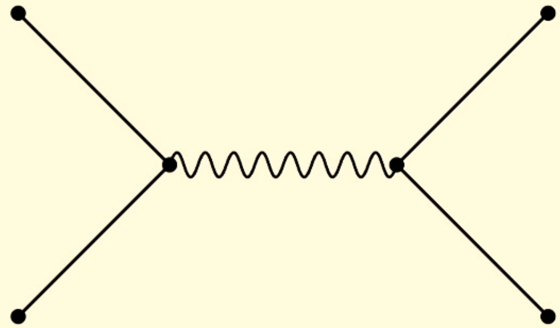
[Sailer et al. (2021), **CCS** et al. (2023)]

I. Early-Time

No-Go Theorem



Contact



Exchange

Yes-Go: non-BD, Scale-Invariance [IR Divergences, c(t)], Massive Spinning

[Liu et al (2019), Cabass et al. (2023)]

Ghost Inflation

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$$S^{(\mathrm{LO})}_{\pi\pi\pi\pi} = \frac{1}{M_{\mathrm{PO}}}\int \mathrm{d}^4x\,\sqrt{-g}\,a^{-9}\epsilon_{ijk}\partial_m\partial_n\pi\partial_n\partial_i\pi\partial_m\partial_l\partial_j\pi\partial_l\partial_k\pi$$

$$\begin{pmatrix}\ell_1 & \ell_2 & L\\ -1 & -1 & 2\end{pmatrix}\begin{pmatrix}\ell_3 & \ell_4 & L\\ -1 & -1 & 2\end{pmatrix} t^{\ell_1\ell_2}_{\ell_3\ell_4}(L) = 2(4\pi)^7\; A^{(\mathrm{Ghost-I})}(-1)^L \sum_{l_1l_2l_3l_4l'} c_{l_1l_2(l')l_3l_4}\mathcal{C}_{l_1l_2l_3l_4l'}\sum_{L'}(2L'+1)$$
$$\times\,\mathrm{Im}\int x^2dx\int d\lambda\,\lambda^{11}$$
$$\times\left[\sum_{L_1L_2} i^{\ell_{12}-L_{12}}(2L_1+1)(2L_2+1)\begin{pmatrix}L_1 & L_2 & L'\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}L_1 & l_1 & \ell_1\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}L_2 & l_2 & \ell_2\\ 0 & 0 & 0\end{pmatrix}\begin{Bmatrix}L_1 & L_2 & L'\\ l_1 & l_2 & l'\\ \ell_1 & \ell_2 & L\end{Bmatrix} h^{\ell_1L_1}_{0,1/2}(x,\lambda)h^{\ell_2L_2}_{0,3/2}(x,\lambda)\right]$$
$$\times\left[\sum_{L_3L_4} i^{\ell_{34}-L_{34}}(2L_3+1)(2L_4+1)\begin{pmatrix}L_3 & L_4 & L'\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}L_3 & l_3 & \ell_3\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}L_4 & l_4 & \ell_4\\ 0 & 0 & 0\end{pmatrix}\begin{Bmatrix}L' & L_3 & L_4\\ l' & l_3 & l_4\\ L & \ell_3 & \ell_4\end{Bmatrix} h^{\ell_3L_3}_{0,1/2}(x,\lambda)h^{\ell_4L_4}_{0,1/2}(x,\lambda)\right]$$

[Cabass et al. (2023), Philcox (2023)]

Trispectrum Symmetries

$$T(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4) \xrightarrow{\mathbb{P}} \pm T(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4)$$

$$T(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4) \xrightarrow{S_4} T(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4)$$

Build-A-Parity-Odd-Trispectrum

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$$\tilde{T}\,(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4) = Af(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4)\det\begin{pmatrix} g_1(\mathbf{k}_1) & \dots & g_1(\mathbf{k}_4) \\ \vdots & & \vdots \\ g_4(\mathbf{k}_1) & \dots & g_4(\mathbf{k}_4) \end{pmatrix}[\mathbf{k}_1 \cdot (\mathbf{k}_2 \times \mathbf{k}_3)]$$

$\mathbb{P}$	$+$	$+$	$-$
S_4	$+$	$-$	$-$

Power-Law Trispectra

$$T_{\text{even}}\left(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4\right)=\frac{1}{4!}k_1^{\alpha_1}k_2^{\alpha_2}k_3^{\alpha_3}k_4^{\alpha_4}+(23\text{ perms.})$$

$$T_{\text{odd}}\left(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4\right)=\frac{\mathrm{i}}{4!}\left[k_1^{\beta_1}k_2^{\beta_2}k_3^{\beta_3}k_4^{\beta_4}+(23\text{ perms.})\right]\left[\mathbf{k}_1\cdot(\mathbf{k}_2\times\mathbf{k}_3)\right]$$

Power-Law Trispectra

$$T_{\text{even}}\left(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4\right)=\frac{1}{4!}k_1^{\alpha_1}k_2^{\alpha_2}k_3^{\alpha_3}k_4^{\alpha_4}+(23\text{ perms.})$$

$$T_{\text{odd}}\left(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4\right)=\frac{\mathrm{i}}{4!}\left[k_1^{\beta_1}k_2^{\beta_2}k_3^{\beta_3}k_4^{\beta_4}+(23\text{ perms.})\right]\left[\mathbf{k}_1\cdot(\mathbf{k}_2\times\mathbf{k}_3)\right]$$

Scale Invariant: $\sum\alpha_i=-9$ $\quad\sum\beta_i=-12$

IR Finite: $\min(\alpha_i)>-3$ $\quad\min(\beta_i)>-4$

Beyond Power-Law

$$T_{\text{odd}}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4) = \frac{\mathrm{i}}{4!} k_T^{-p}\left[k_1^{\beta_1}k_2^{\beta_2}k_3^{\beta_3}k_4^{\beta_4} + (23\text{ perms.})\right][\mathbf{k}_1\cdot(\mathbf{k}_2\times\mathbf{k}_3)]$$

$$\mathcal{L} \supset \sum_\alpha \frac{\mathcal{O}_\alpha}{\Lambda_\alpha^{D_\alpha-4}}$$

$$p = 4L + 2E - 3 + \sum_{\alpha=1}^{V}(D_\alpha - 2n_\alpha)$$

$$p = 1 + \sum_\alpha (D_\alpha - 4)$$

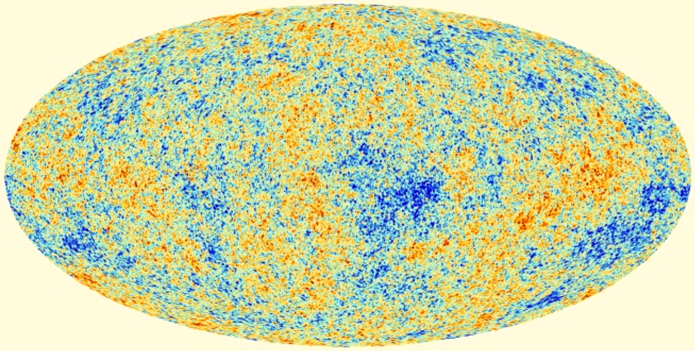
$$D = 4 + N$$

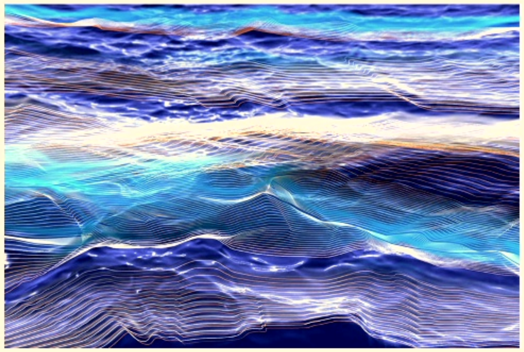
[Pajer (2020)]

I. Late-Time

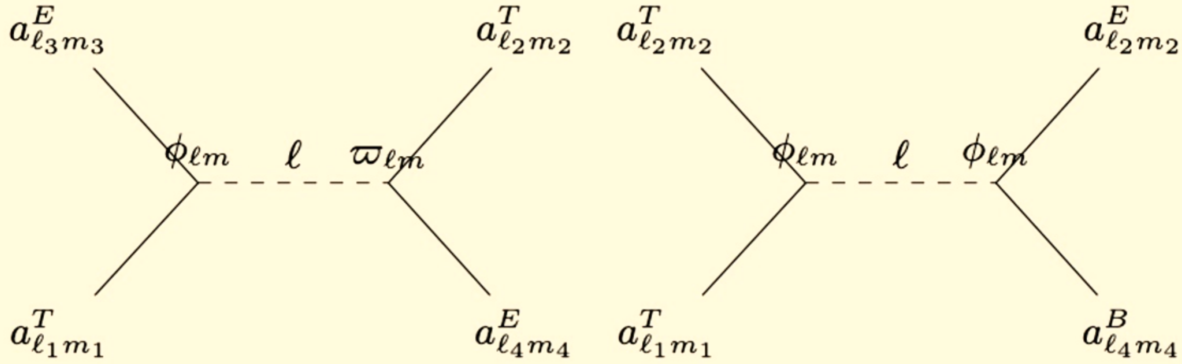
Lensing by Foreground Stochastic Fields

$$\tilde{\Theta}(\hat{\mathbf{n}}) = \Theta(\hat{\mathbf{n}}) + \left[\nabla_{\perp}\phi(\hat{\mathbf{n}}) + \hat{\mathbf{n}} \times \nabla_{\perp}\varpi(\hat{\mathbf{n}})\right] \cdot \left[\nabla_{\perp}\Theta(\hat{\mathbf{n}})\right]$$





Lensing by Foreground Stochastic Fields



Lensing by Foreground Stochastic Fields

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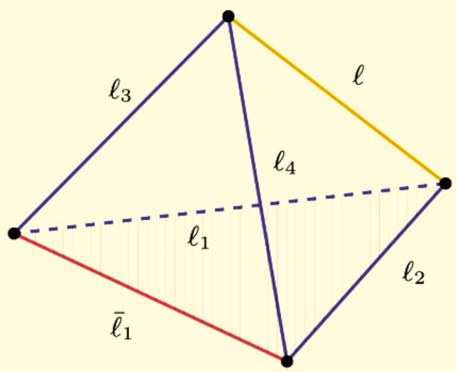
$$\mathrm{Im}\left\langle \tilde{a}^T_{\ell_1}\tilde{a}^T_{\ell_2}\tilde{a}^T_{\ell_3}\tilde{a}^T_{\ell_4}\right\rangle^{LM}_{\bar{\ell}_1\bar{\ell}_2} = (-1)^{\ell_1+\ell_2}\,\delta^{\mathrm{K}}_{\bar{\ell}_2\ell_4}\delta^{\mathrm{K}}_{L,0}\delta^{\mathrm{K}}_{M,0}\sqrt{2\bar{\ell}_1+1}\times C^{TT}_{\ell_1}C^{TT}_{\ell_2}$$
$$\times\sum_{\ell=0}^{\infty}(-1)^{\ell}\,\bar{\Phi}_{\ell_3\ell\ell_1}\bar{\Omega}_{\ell_4\ell\ell_2}\begin{Bmatrix}\ell & \ell_2 & \ell_4\\ \bar{\ell}_1 & \ell_3 & \ell_1\end{Bmatrix}C^{\phi\varpi}_{\ell} + 23\text{ perms.}$$



$$\bar{\Phi}_{\ell_1\ell_2\ell_3} = -\frac{1}{2}\sqrt{\ell_2(\ell_2+1)\ell_3(\ell_3+1)}I_{\ell_1\ell_2\ell_3}\left[1+(-1)^{\ell_1+\ell_2+\ell_3}\right]\begin{pmatrix}\ell_1 & \ell_2 & \ell_3\\ 0 & -1 & 1\end{pmatrix}$$
$$\bar{\Omega}_{\ell_1\ell_2\ell_3} = -\frac{1}{2}\sqrt{\ell_2(\ell_2+1)\ell_3(\ell_3+1)}I_{\ell_1\ell_2\ell_3}\left[1-(-1)^{\ell_1+\ell_2+\ell_3}\right]\begin{pmatrix}\ell_1 & \ell_2 & \ell_3\\ 0 & -1 & 1\end{pmatrix}$$

$$\begin{Bmatrix}\ell & \ell_2 & \ell_4\\ \bar{\ell}_1 & \ell_3 & \ell_1\end{Bmatrix}\sim\frac{\cos(\ldots)}{\sqrt{3\pi V/2}}$$

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Review

Signal

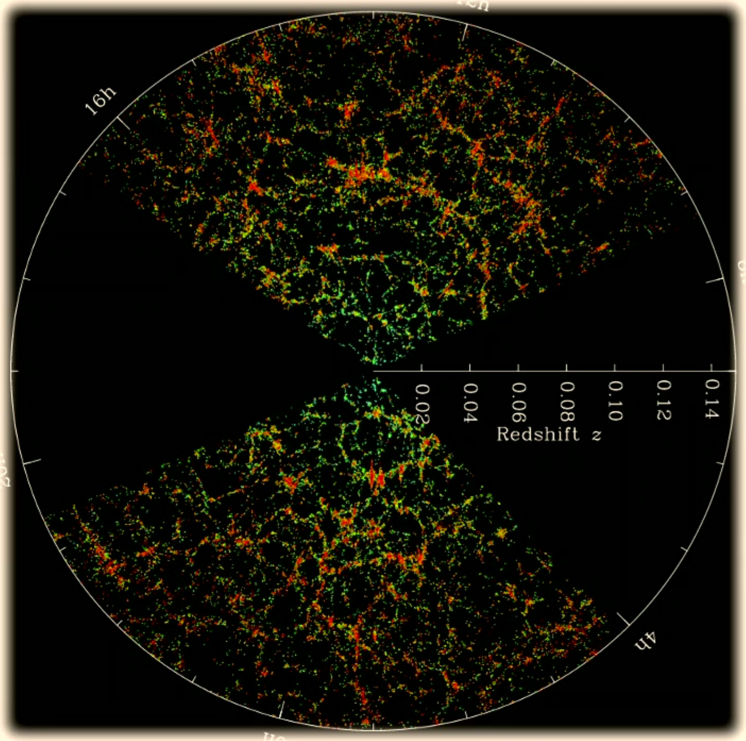
Sensitivity

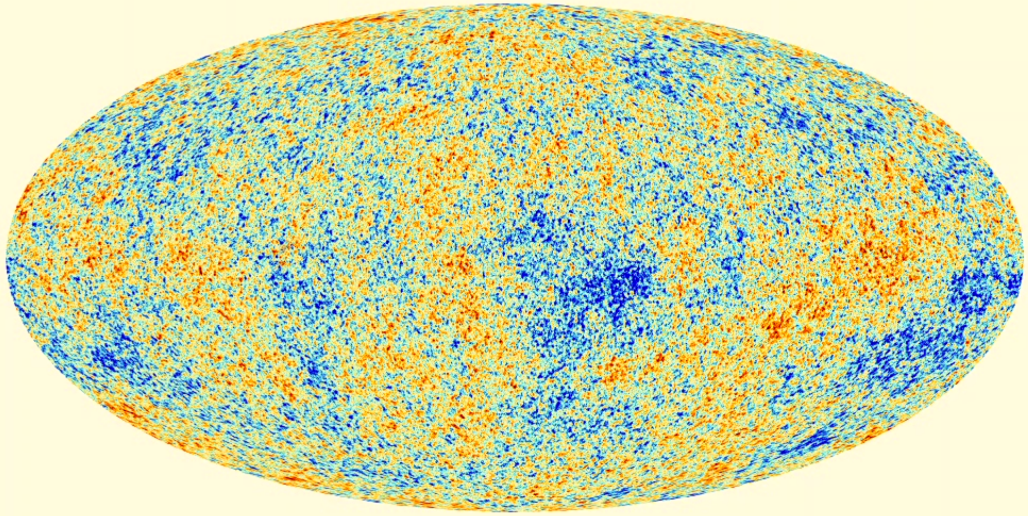
Comment

Mode Counting

$$N_{\rm modes}^{\rm LSS} = V \int_{k_{\rm min}}^{k_{\rm max}} \frac{k^2 dk}{2\pi^2} \frac{d\mu}{2} \left[\frac{G^2(k,\mu,z) P_{\rm lin}(k,\mu,z)}{P_{\rm tot}(k,\mu,z)} \right]^2$$

$$N_{\rm modes}^{\rm CMB} = f_{\rm sky} \sum_{\ell=\ell_{\rm min}}^{\ell_{\rm max}} (2\ell+1) \left[\frac{C_\ell^{\rm TT}}{C_\ell^{\rm TT} + N_\ell^{\rm TT}} \right]^2$$





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Goal + Benchmark Cases

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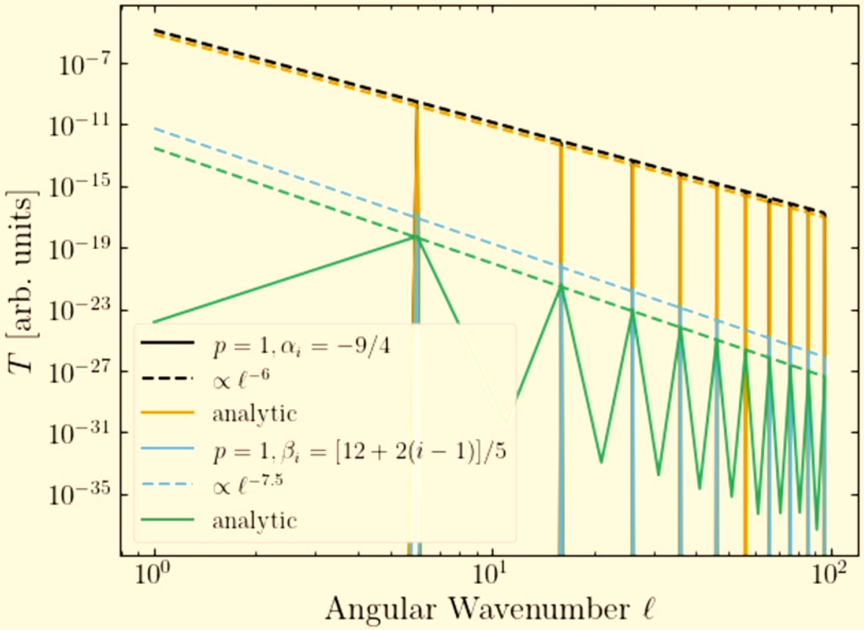
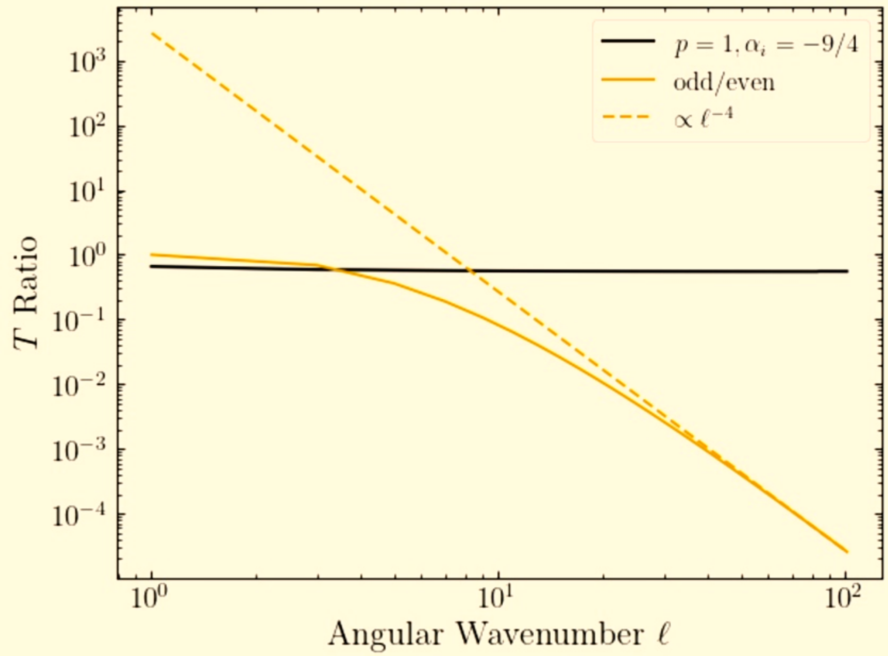
$$F_{2d}(T,T') \equiv \frac{1}{4!}\sum_{\ell_i m_i} \frac{T^{\ell_1\ell_2\ell_3\ell_4 *}_{m_1m_2m_3m_4}\, T'^{\ell_1\ell_2\ell_3\ell_4 *}_{m_1m_2m_3m_4}}{C_{\ell_1}C_{\ell_2}C_{\ell_3}C_{\ell_4}}$$

$$4\text{ short}: (\ell, \ell+1, \ell+2, \ell+4)$$
$$3\text{ short}, 1\text{ long}: (\ell, \ell+1, \ell+2, 3\ell)$$
$$2\text{ short}, 2\text{ long (1 long pair)}: (\ell, \ell+1, 2\ell, 2\ell+2)$$
$$2\text{ short}, 2\text{ long}: (\ell, \ell+1, 2\ell, 4\ell)$$
$$1\text{ short}, 3\text{ long (1 long triple)}: (\ell, 3\ell, 3\ell+1, 3\ell+2)$$
$$1\text{ short}, 3\text{ long (1 long pair)}: (\ell, 2\ell, 2\ell+1, 3\ell)$$
$$1\text{ short}, 3\text{ long}: (\ell, 2\ell, 3\ell, 4\ell+1)$$

Curvature


T [arb. units]
10^{-7}
10^{-11}
10^{-15}
10^{-19}
10^{-23}
10^{-27}
10^{-31}
10^{-35}
$p = 1, \alpha_i = -9/4$
$\propto \ell^{-6}$
analytic
$p = 1, \beta_i = [12 + 2(i-1)]/5$
$\propto \ell^{-7.5}$
analytic
10^0
10^1
10^2
Angular Wavenumber ℓ


T Ratio
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$p = 1, \alpha_i = -9/4$
odd/even
$\propto \ell^{-4}$
10^0
10^1
10^2
Angular Wavenumber ℓ

Thickness

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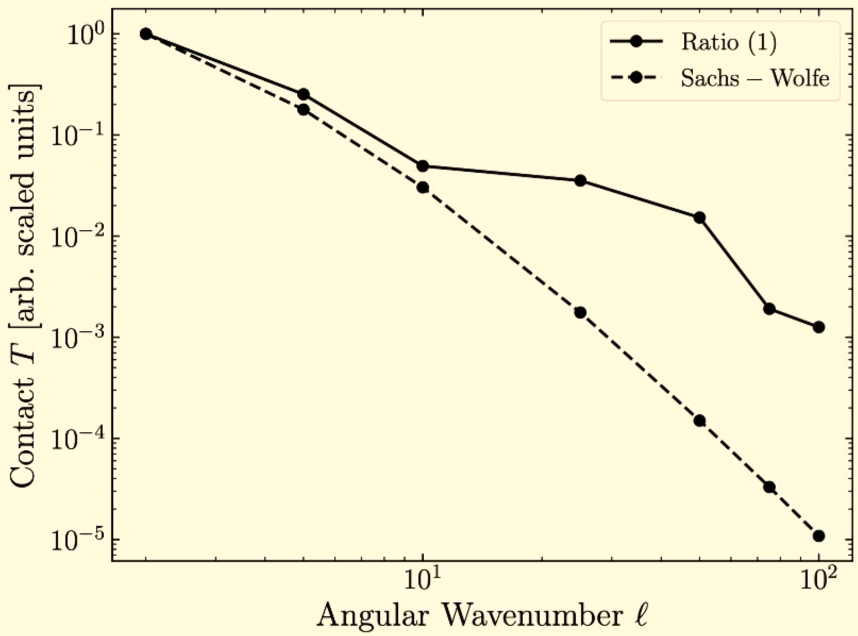

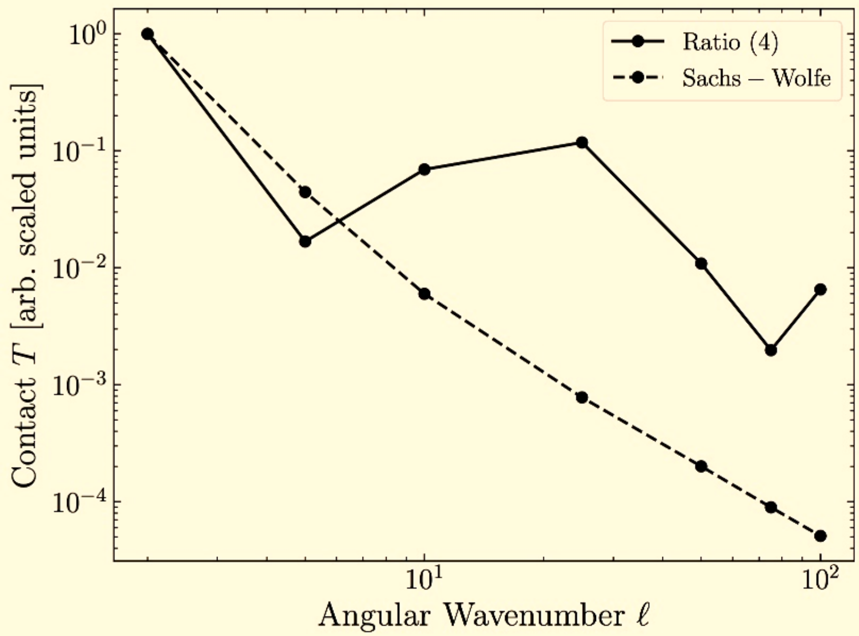

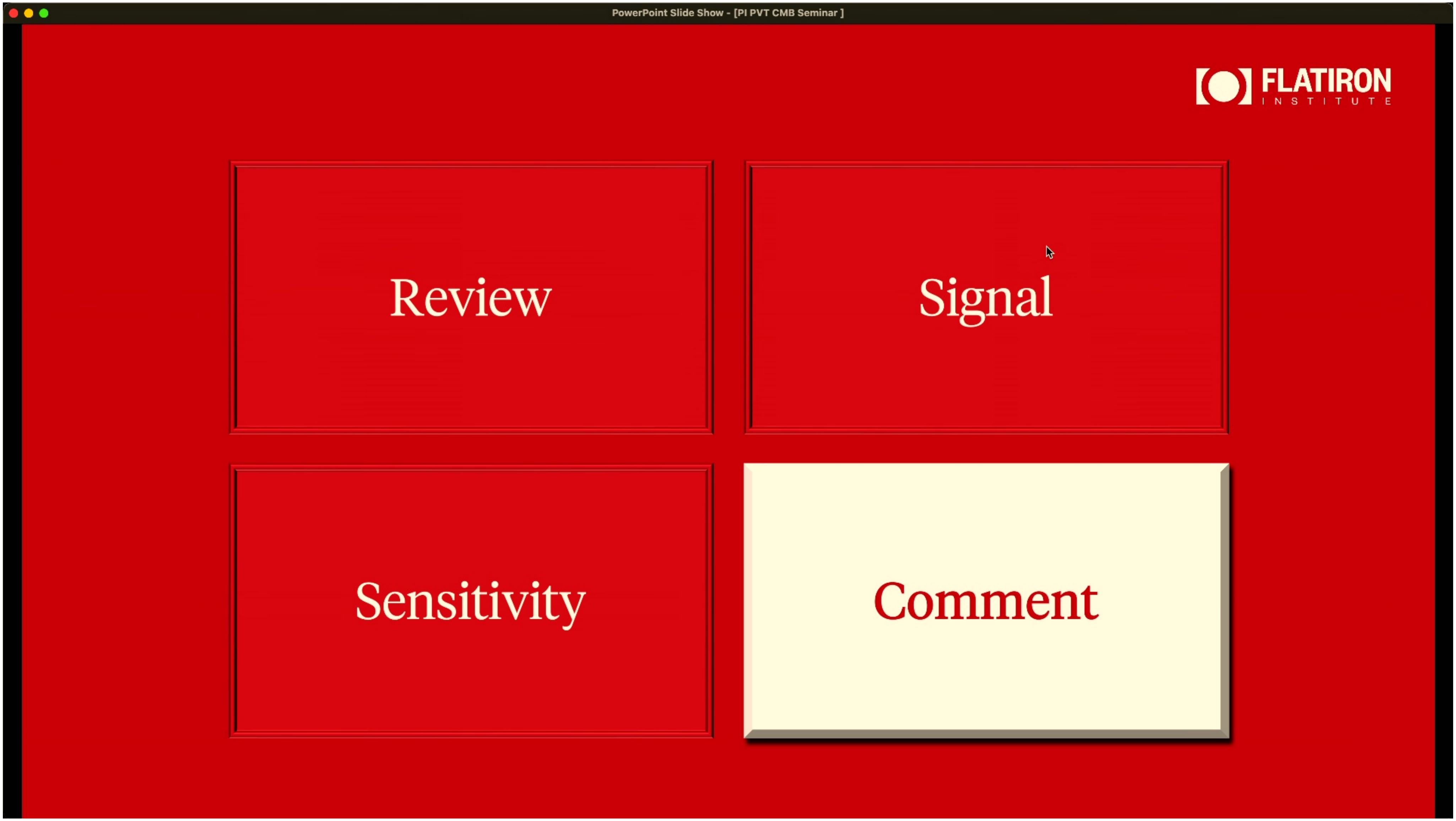
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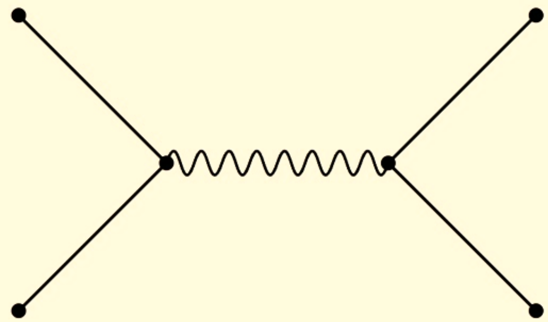
Exchange Trispectra



Exchange – Soft Internal?

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Conclusion

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- Cosmological parity can yield novel physics in upcoming surveys
- Simple geometric interpretation for exchange CMB trispectra
- CMB is most likely not sensitive to contact diagrams
- Fisher + Exchange diagram computation to be determined.

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Thank you.

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