Parity-violating Signals from Cosmological Collider

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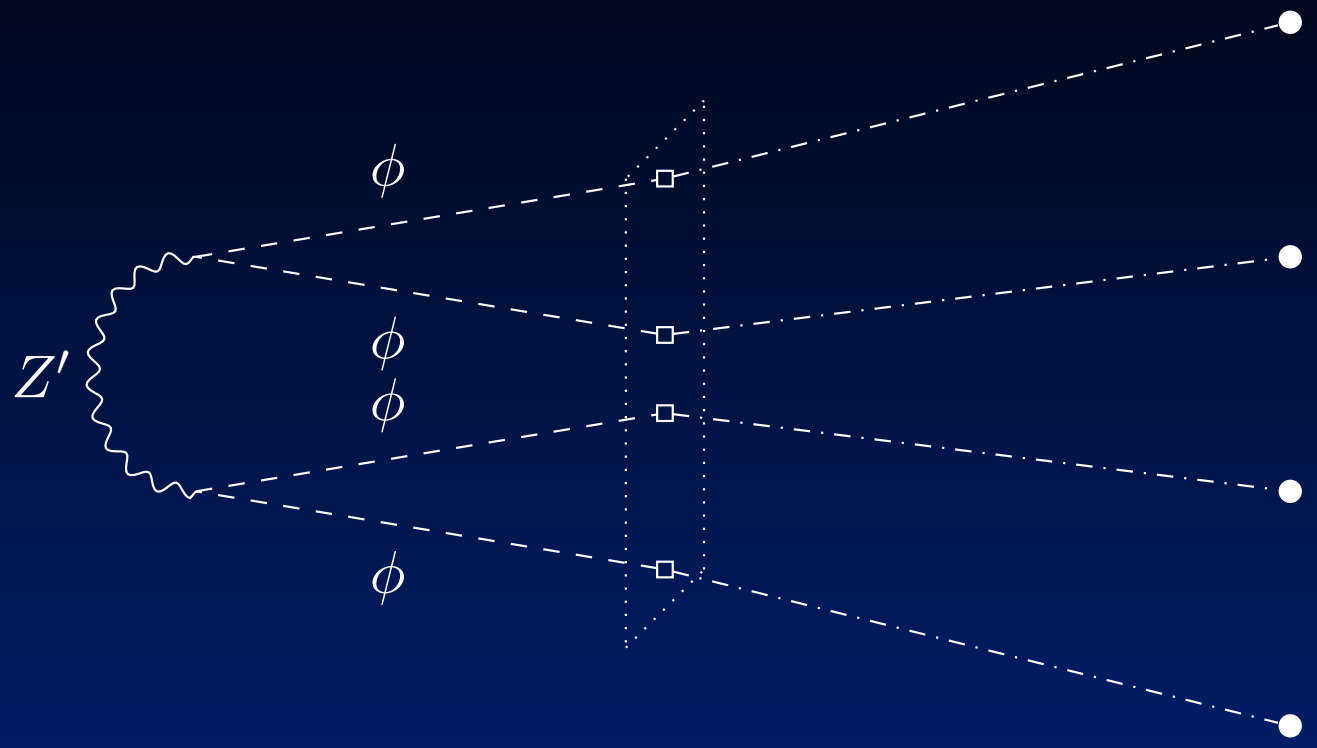
Inflation as a Probe for New Particles



inflation $\xrightarrow{\quad t \quad}$ today

$H_I \lesssim 10^{13}$ GeV

$E \sim 3\,\mathrm{K}$

Why Parity-violating Interaction?

- Potentially low background

  mock data based on structure formation model, gravity and baryonic effects on small scale should be dominantly parity-preserving

  [Hou, Slepian, Cahn: 2206.03625], [Philcox: 2206.04227], ...

- Theoretically motivated

  to produce large signal due to chemical potential enhancement

  [Wang, Xianyu: 2004.02887], [Qin, Xianyu: 2208.13790], [Creque-Sarbinowski, Alexander, Kamionkowski, Philcox: 2303.04815], ...

Cosmological Collider *vs.* Particle Collider

$\mathcal{L}(\phi, Z', \ldots)$

↓

Feynman rules

Schwinger-Keldysh diagrams	Feynman diagrams
↓	↓
Bispectrum, Trispectrum, *etc.*	Cross-section
↓	↓
Linear perturbation	Parton shower
↓	↓
N-point correlation function	Detector simulation

Spin-1 Model: Chemical Potential

Abelian Higgs model with coupling to some background $\theta(t)$.

$$\begin{aligned}\mathcal{L} \supset & \sqrt{-g}\left[\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + D_\mu\mathcal{H}^* D^\mu\mathcal{H}\right] + \frac{c_0\theta(t)}{4}\epsilon^{\mu\nu\rho\sigma}Z_{\mu\nu}Z_{\rho\sigma} \\ \sim & \frac{1}{2}\mathbf{Z}\left(\frac{\mathrm{d}^2}{\mathrm{d}\tau^2} + k^2 + a^2 m_Z^2\right)\mathbf{Z} + Z_i(-i\underbrace{c_0\dot{\theta}}_{\triangleq c} a\epsilon^{ijk}k_j)Z_k\end{aligned} \tag{1}$$

with $m_Z \sim H_I$.

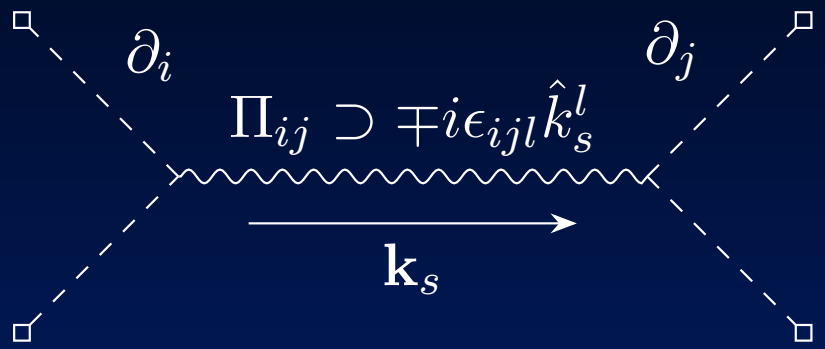
Spin-1 Model: Equation of Motion

$$
\begin{aligned}
\mathbf{Z}_- &= \boldsymbol{\epsilon}_- \cdot \exp\left(+\frac{\pi c}{2H_I}\right) \cdot f_-(m_Z, c_0\dot{\theta}; ik\tau) e^{i\mathbf{k}\cdot\mathbf{x}} \\
\mathbf{Z}_L &= \boldsymbol{\epsilon}_L \cdot \qquad 1 \qquad \cdot g(m_Z; ik\tau) e^{i\mathbf{k}\cdot\mathbf{x}} \\
\mathbf{Z}_+ &= \boldsymbol{\epsilon}_+ \cdot \exp\left(-\frac{\pi c}{2H_I}\right) \cdot f_+(m_Z, c_0\dot{\theta}; ik\tau) e^{i\mathbf{k}\cdot\mathbf{x}}
\end{aligned}
\tag{2}
$$

Chemical potential c enhances a particular polarization.

Spin-1 Model: Interaction with Inflaton

$$\mathcal{L}_{\text{int}} \propto a(\tau)\delta^{ij}\phi'\partial_i\phi Z_j. \tag{3}$$



+ permutations

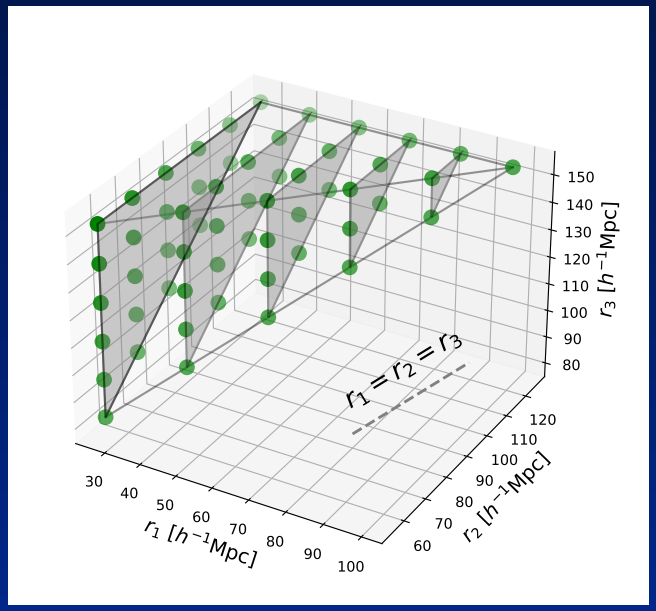
$$\langle\phi^4\rangle_{\text{full, PO}} = \mathcal{J}(k_1,\ldots,k_4,k_s)\left[i\left(\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2\right)\cdot\hat{\mathbf{k}}_s\right] + \text{permutations} \tag{4}$$

$\langle\phi^4\rangle_{\text{toy, PO}} =$  $\left[i\left(\hat{\mathbf{k}}_1\times\hat{\mathbf{k}}_2\right)\cdot\hat{\mathbf{k}}_s\right] + \text{permutations}$ (5)

Reading Position-space Correlation Coefficients

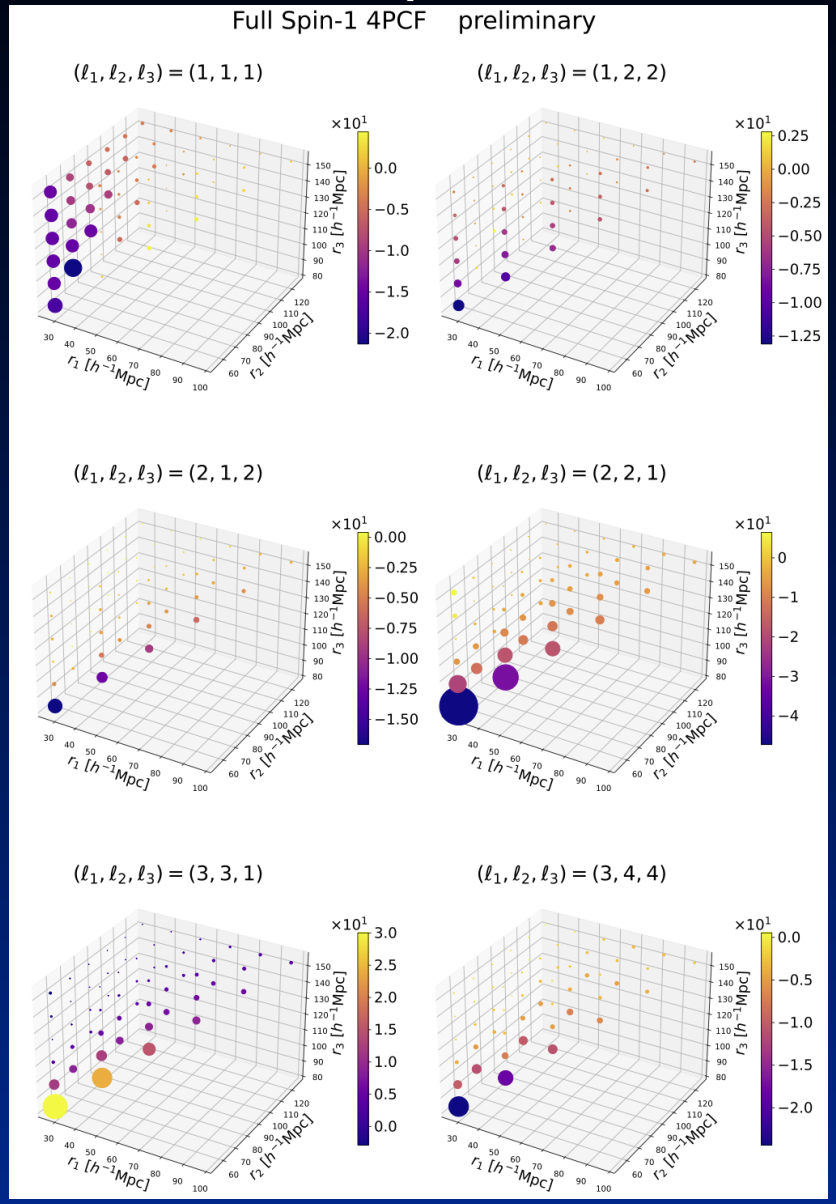
$$\left\langle \delta_g^4 \right\rangle = \left\langle \delta_g^4 \right\rangle (r_1, r_2, r_3, \theta_1, \theta_2, \theta_3),$$

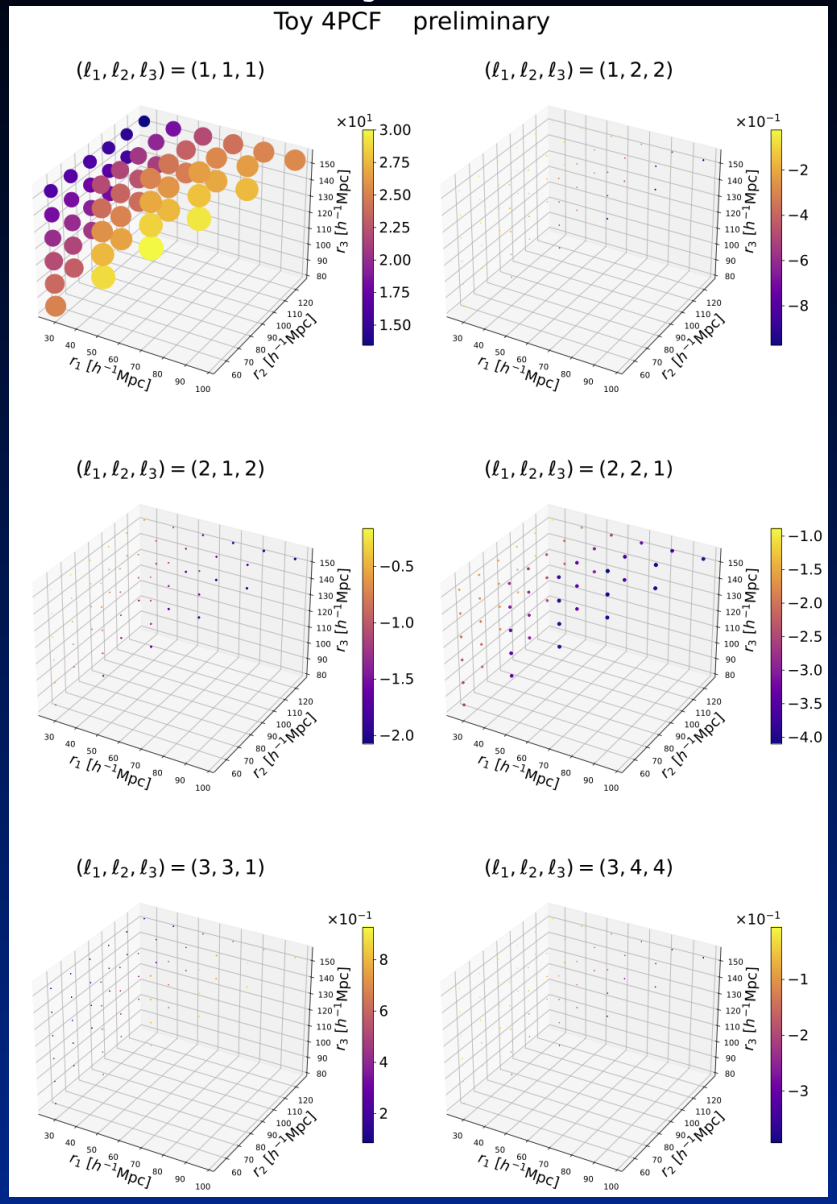
$$\implies \left\langle \delta_g^4 \right\rangle = \sum_{\ell} \zeta_{\ell_1,\ell_2,\ell_3}(r_1, r_2, r_3) \underbrace{\left[C_m^{\ell} Y_{\ell_1}^{m_1}(\theta_1) Y_{\ell_2}^{m_2}(\theta_2) Y_{\ell_3}^{m_3}(\theta_3) \right]}_{\triangleq \mathcal{P}_{\ell_1,\ell_2,\ell_3}(\theta_1,\theta_2,\theta_3)} \tag{6}$$



$$(\ell_1, \ell_2, \ell_3) = (1, 1, 1) \sim (\hat{\mathbf{r}}_1 \times \hat{\mathbf{r}}_2) \cdot \hat{\mathbf{r}}_3.$$

Full Spin-1 Model *vs.* Contact Toy Model





Summary

- Inflation offers new probes for heavy particles
- Primordial parity-violating interactions can show up in the large-scale structure survey data
- We have established a pipeline to compute the position-space correlation function from models
- Full spin-1 model shows non-trivial correlation coefficients compared to contact toy model

What's next:

- Relation between equilateral (or local) templates and full model?
- Efficient tools to perform the Fourier transform from momentum space to position space?
- Unfolding position-space data to momentum space?
- Key features to distinguish various full models in either position space or momentum space?

Why Trispectrum?

The only parity-odd invariant tensor is ϵ_{ijk}.

$$\left\langle \phi^N \right\rangle \propto \epsilon_{ijl}\left(k_1^i k_2^j k_3^l\right).$$

Momentum conservation $\implies$ at least 4 external particles, *i.e.* $\left\langle \phi^4 \right\rangle$. Alternatively,

2-point correlation  $\mapsto \#$. 3-point correlation  $\mapsto \#$.

4-point correlation  $\mapsto \#$.

Some LSS Redshift Surveys

- BOSS and eBOSS (from SDSS)
- DES (CTIO)
- WiggleZ (AAT)
- KiDS (VLT)
- Euclid (ESA)
- Vera Rubin Observatory (LSST)
- Roman Space Telescope (WFIRST)
- ...

Spin-1 Model: Interaction with Inflaton

$$
\begin{aligned}
-\mathcal{L} \supset & \sqrt{-g}\left[\frac{c_1}{\Lambda}\partial_\mu\phi(\mathcal{H}^* D^\mu \mathcal{H}) + \frac{c_2}{\Lambda^2}(\partial\phi)^2|\mathcal{H}|^2 + \text{h.c.}\right] \\
\supset & \underbrace{-\operatorname{Im}\left\{\frac{c_1\dot{\phi}_0 m_Z}{\Lambda}\right\}}_{\triangleq \rho_{1,Z}} \frac{a^2}{\dot{\phi}_0}\eta^{\mu\nu}\partial_\mu\phi Z_\nu h - a^3 \underbrace{\frac{c_2 v\dot{\phi}_0}{\Lambda^2}}_{\triangleq \rho_2} \phi' h.
\end{aligned}
\tag{7}
$$

Just A Fourier Transform?

$$\left\langle \delta_g^4 \right\rangle (\mathbf{r}_1, \ldots, \mathbf{r}_4) \sim \int \prod_{i=1}^{4} \left(\frac{\mathrm{d}k_i}{2\pi} \right)^3 e^{i\mathbf{k}_i \cdot \mathbf{r}_i} \left\langle \phi^4 \right\rangle (\mathbf{k}_1, \ldots, \mathbf{k}_4) \quad (8)$$

For instance, 10 grids per dimension, 10^{12} grids in total!

Just A Fourier Transform?

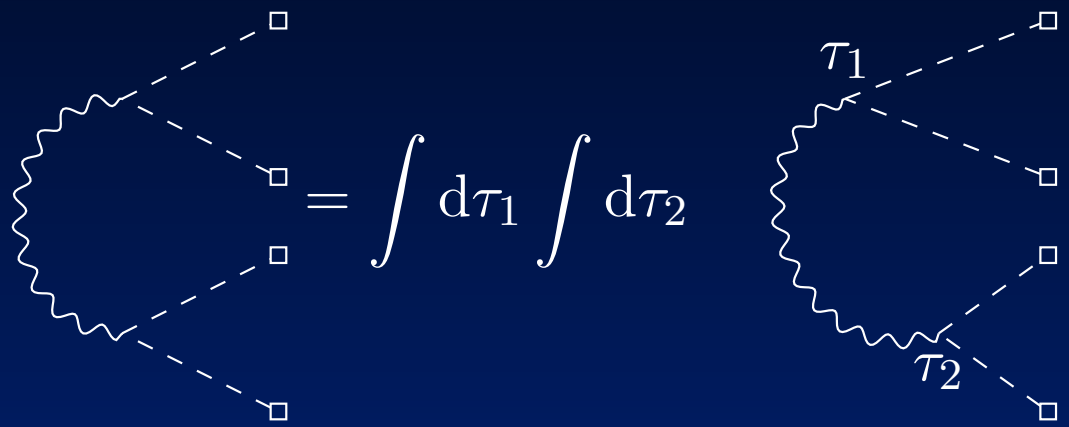
Instead, if we can "separate" $\left\langle \phi^4 \right\rangle (\mathbf{k}_1, \ldots, \mathbf{k}_4) = f_1(\mathbf{k}_1) \ldots f_4(\mathbf{k}_4)$ [Lee, Dvorkin: 2001.00584], [Smith, Senatore, Zaldarriga: 1502.00635], then

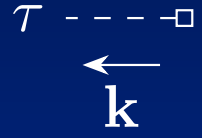
$$\left\langle \delta_g^4 \right\rangle (\mathbf{r}_1, \ldots, \mathbf{r}_4) \sim \prod_{i=1}^{4} \left[\int \left(\frac{\mathrm{d}k_i}{2\pi} \right)^3 e^{i\mathbf{k}_i \cdot \mathbf{r}_i} f_i(\mathbf{k}_i) \right]. \tag{9}$$

Then, only $4 \times 10^3 \ll 10^{12}$ grids are needed. However, $\left\langle \phi^4 \right\rangle = f_1 \ldots f_4$ is a very strict requirement.

Hints from Diagrams

$$\mathcal{L}_{\text{int}} \propto a(\tau)\eta^{\mu\nu}\phi'\partial_\mu\phi Z_\mu. \tag{3}$$

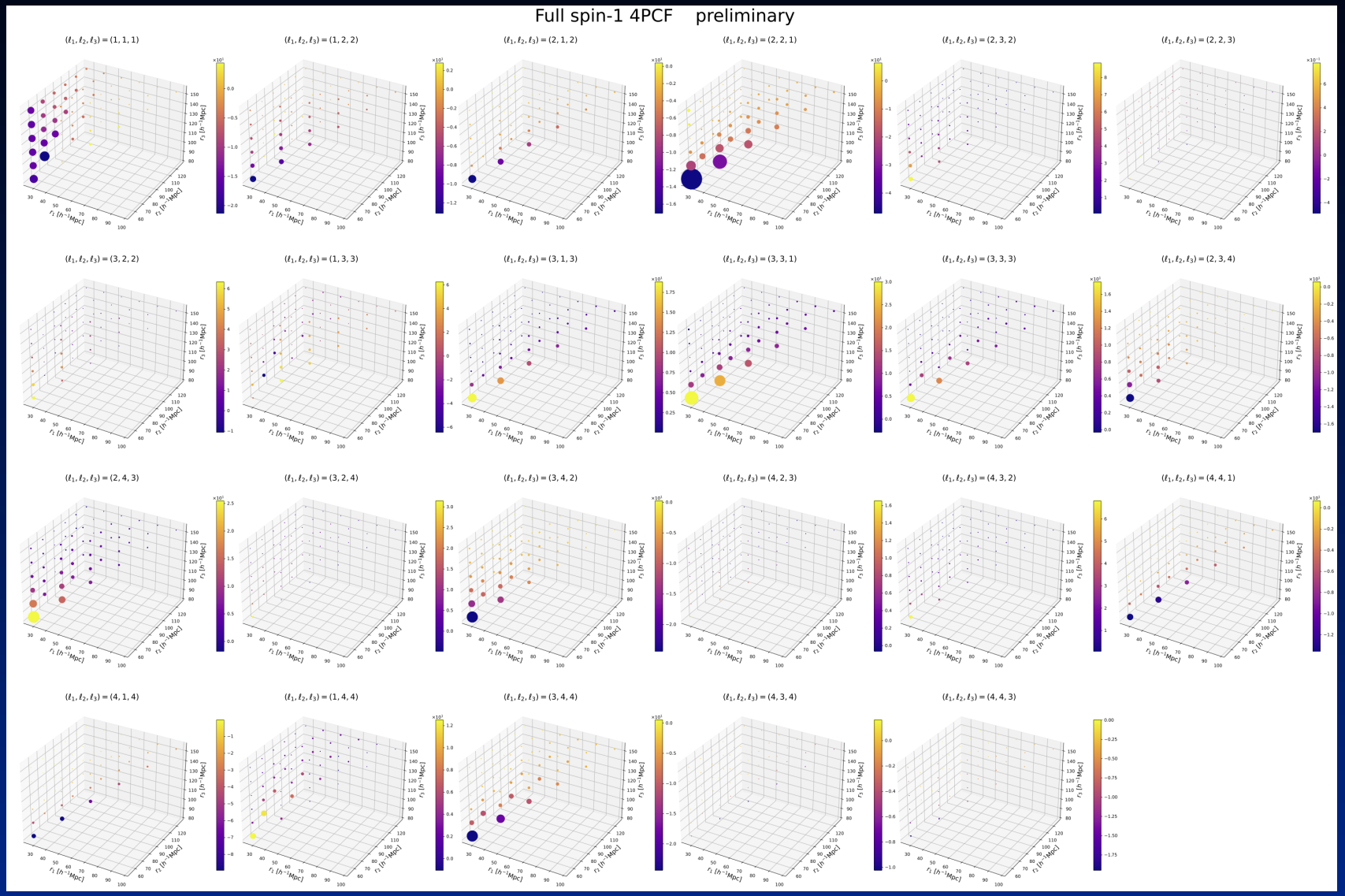




$$\sim \exp(ik\tau) \cdot \frac{(1+ik\tau)}{k^3}$$

After Wick rotation, we only need to sample over small τ.

Full Spin-1 Result



Equilateral Result