Title: Parity-Violation in Gravity: New Constructions and Inflationary Signals

Speakers: Cyril Creque-Sarbinowski

Series: Quantum Gravity

Date: April 13, 2023 - 2:30 PM

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Abstract: I will talk about new constructions to the parity-violating sector of gravity that can yield large observables, in particular those from inflation. Within this framework, I will demonstrate the potential for seeking gravitational parity-violation in uncharted regions of parameter space and give hints to novel methods of probing baryogenesis. I will also comment on a few interesting theoretical aspects regarding inflationary correlators.

Zoom link: https://pitp.zoom.us/j/95924890817?pwd=MkRyWmV2a3g1dndPNFhoVlQvb3Ixdz09

Parity Violation in Gravity: New Constructions and Inflationary Signals

Cyril Creque-Sarbinowski

Quantum Gravity Seminar - Perimeter 2023

Based on 2207.05094 w/ Stephon Alexander
and 2303.04815 with Stephon, Marc Kamionkowski, & Oliver Philcox

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Roadmap

I will…

I) Demonstrate two new constructions (i.e types of UV completions) of dynamical Chern-Simons (dCS) gravity that encompass a wide range of EFT scales

II) Show that dCS gravity yields a parity-violating primordial scalar trispectrum that can be made large.

III) Demonstrate that ratios of odd and even trispectra contain direct information about spin.

IV) Quantify how well upcoming and future experiments can constrain scalar trispectra.

V) Hint to how parity-violating trispectra can constrain baryogenesis.

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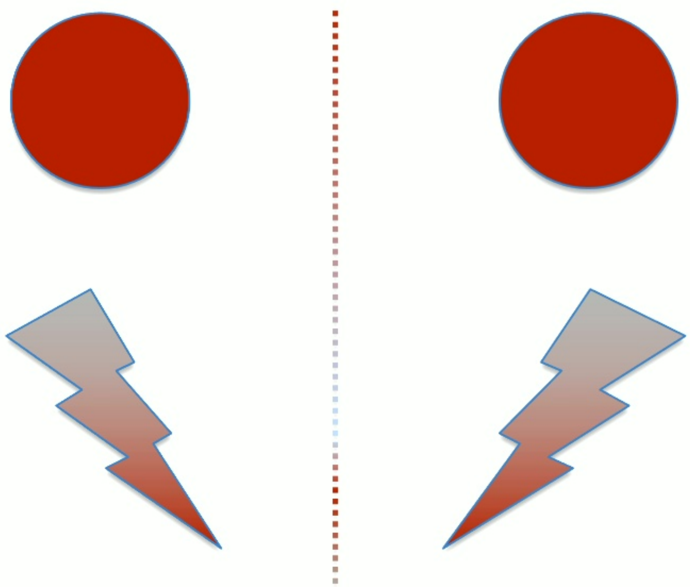
What is $\mathbb{P}$arity? How can Gravity violate it?

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



$$A_L - A_R$$

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What is [dynamical] Chern-Simons (dCS) Gravity?

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{2}g^{\mu\nu}\left(\partial_\mu\phi\right)\left(\partial_\nu\phi\right) + \frac{M_{\rm pl}^2}{2}R - \frac{\phi}{4f}{}^*RR\right]$$

Spacetime Metric, Lorentzian Signature

dCS pseudo-scalar

Einstein-Hilbert Term

dCS Decay Constant

Pontryagin Density

$${}^*R\,R = {}^*R^\rho{}_\sigma{}^{\mu\nu}R^\sigma{}_{\rho\mu\nu}$$

$${}^*R^\rho{}_\sigma{}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}R^\rho{}_{\sigma\alpha\beta}$$

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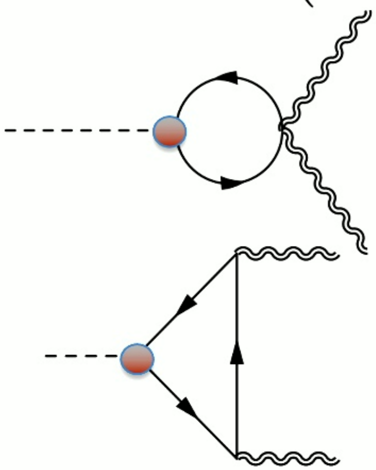
New Construction 1: Spontaneous Symmetry Breaking

$$\Phi = (1/\sqrt{2})(F + \sigma)\exp[ia(x)/F]$$

$$\mathcal{L}_\Phi = \sum_{j=L,R} i\bar{\Psi}_j\gamma^\mu\partial_\mu\Psi_j - \tilde{m}_\Psi\left(\bar{\Psi}_R\Psi_L + \bar{\Psi}_L\Psi_R\right) + \partial_\mu\Phi\partial^\mu\Phi^* - V\left(|\Phi|^2\right) - (y_\Phi\Phi\bar{\Psi}_L\Psi_R + \text{h.c.})$$

$$\mathcal{L}_\Phi = \bar{\Psi}\left[i\gamma^\mu\partial_\mu - \left(\tilde{m}_\Psi + \frac{y_\Phi F}{\sqrt{2}}\right)\right]\Psi + \frac{1}{2}\partial_\mu a\partial^\mu a - \frac{y_\Phi}{\sqrt{2}}a\bar{\Psi}\gamma^5\Psi,$$



$$\mathcal{L}_g^{\text{eff}} = -\frac{g}{384\pi^2}\frac{a}{2m_\Psi}{}^*RR \longrightarrow f = 192\sqrt{2}\pi^2\frac{m_\Psi}{y_\Phi}$$

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arXiv: 2207.05094, Collaborator: Stephon Alexander

New Construction 2: Dynamical Symmetry Breaking

$$\mathcal{L}_\Psi = \bar{\Psi}\left(i\gamma^\mu\partial_\mu - \tilde{m}_\Psi\right)\Psi - \lambda\bar{\Psi}\Psi\bar{\Psi}\Psi$$

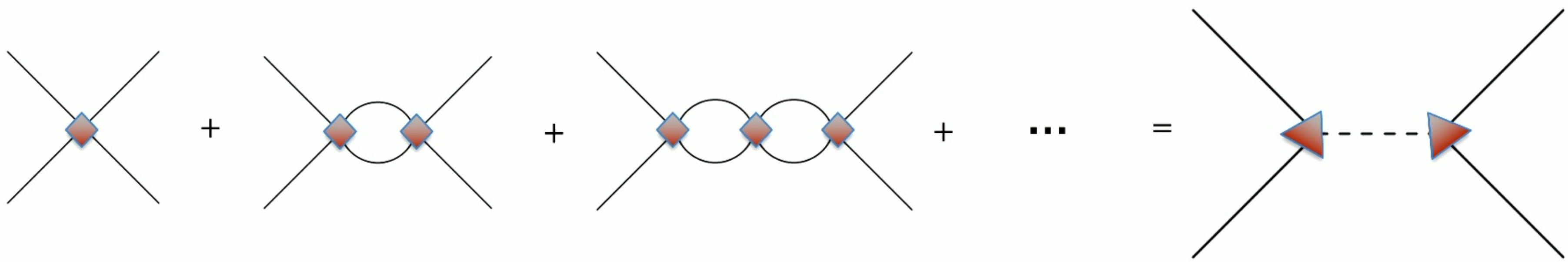
Cutoff Λ

Dirac Gamma Matrices

``bare'' mass

Dirac Fermion

(Attractive) Fermion Self-Coupling Constant



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arXiv: 2207.05094, Collaborator: Stephon Alexander

New Construction 2: Dynamical Symmetry Breaking

$$Z_\alpha = \int \mathcal{D}\alpha \mathcal{D}\bar{\alpha} \exp\left(-\int d^4x\ \tilde{m}_\Phi^2 \bar{\alpha}\alpha\right)$$

$$+$$

$$\Psi = \Psi_\ell + \Psi_s$$

$$\Phi = \alpha - \tilde{m}_\Phi^{-2} \bar{\Psi}_s \Psi_s$$

$$+$$

$$\text{Integrate Out Short} - \text{Scale Modes}$$

$$\Longrightarrow$$

$$\tilde{\mathcal{L}}_\Psi = \bar{\Psi}(i\gamma^\mu \partial_\mu - \tilde{m}_\Psi)\Psi - \lambda \bar{\Psi}\Psi\bar{\Psi}\Psi$$
$$+ (\partial_\mu \Phi^*)\ (\partial^\mu \Phi) - \underline{y_\Phi\ (\Phi\bar{\Psi}\Psi + \text{h.c.})}$$
$$+ m_\Phi^2\ |\Phi|^2 - \frac{\lambda_\Phi}{4}|\Phi|^4,$$

$$y_\Phi \sim \lambda\Lambda^2$$

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arXiv: 2207.05094, Collaborator: Stephon Alexander

What are Observable Signatures of dCS?

1) Compact Binary Coalescence (CBC) Waveform-Modification
2) Birefringence of CBC Gravitational Waves
3) Modification of Orbits around Earth

$f \ll \mathrm{eV}$ } Late-Time

4) Polarized Primordial Gravitational Waves
5) Primordial Imprints on Galaxy Clustering and the CMB

} Early-Time

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How is Galaxy Clustering Described?

Galaxy N-Point Functions!

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

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

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

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

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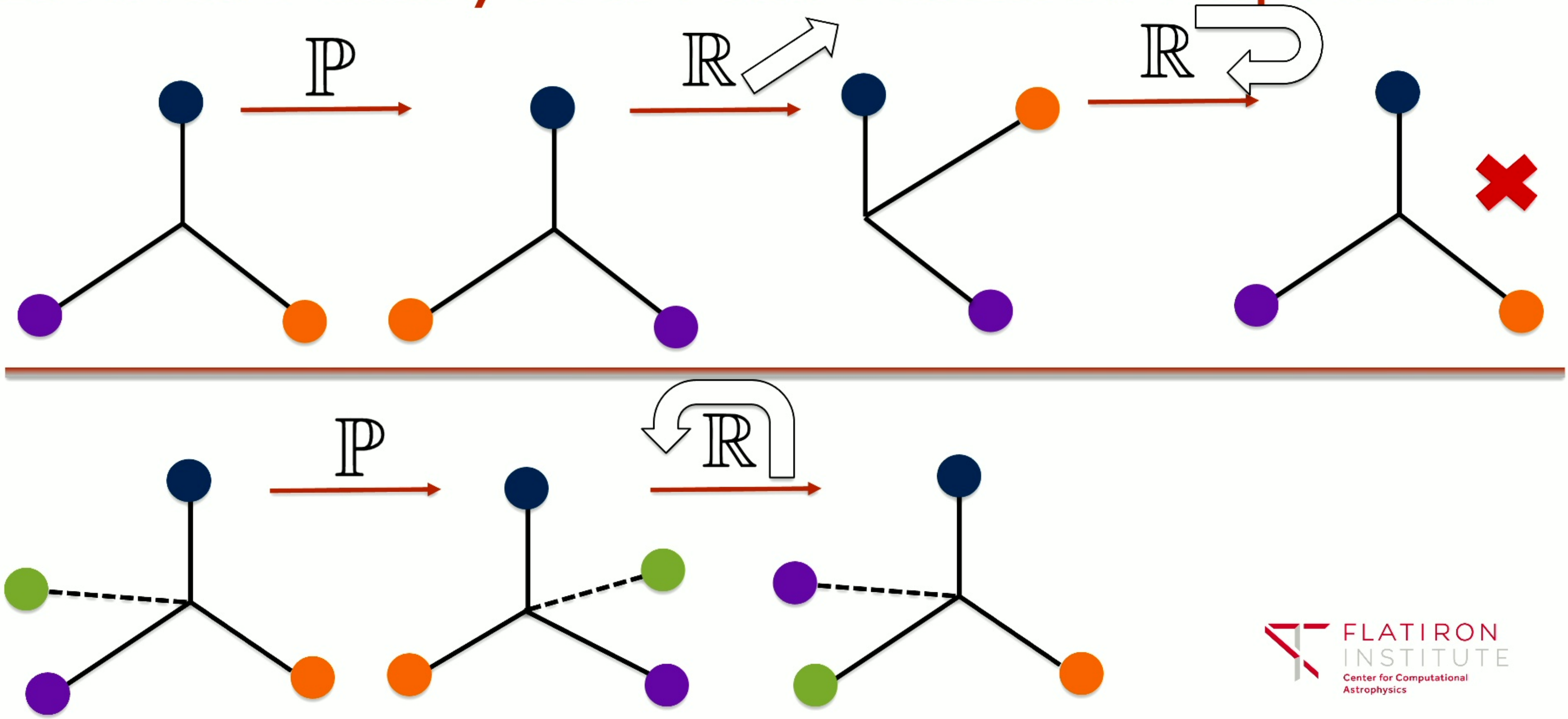
Enter: The Galaxy Four Point Function / Trispectrum



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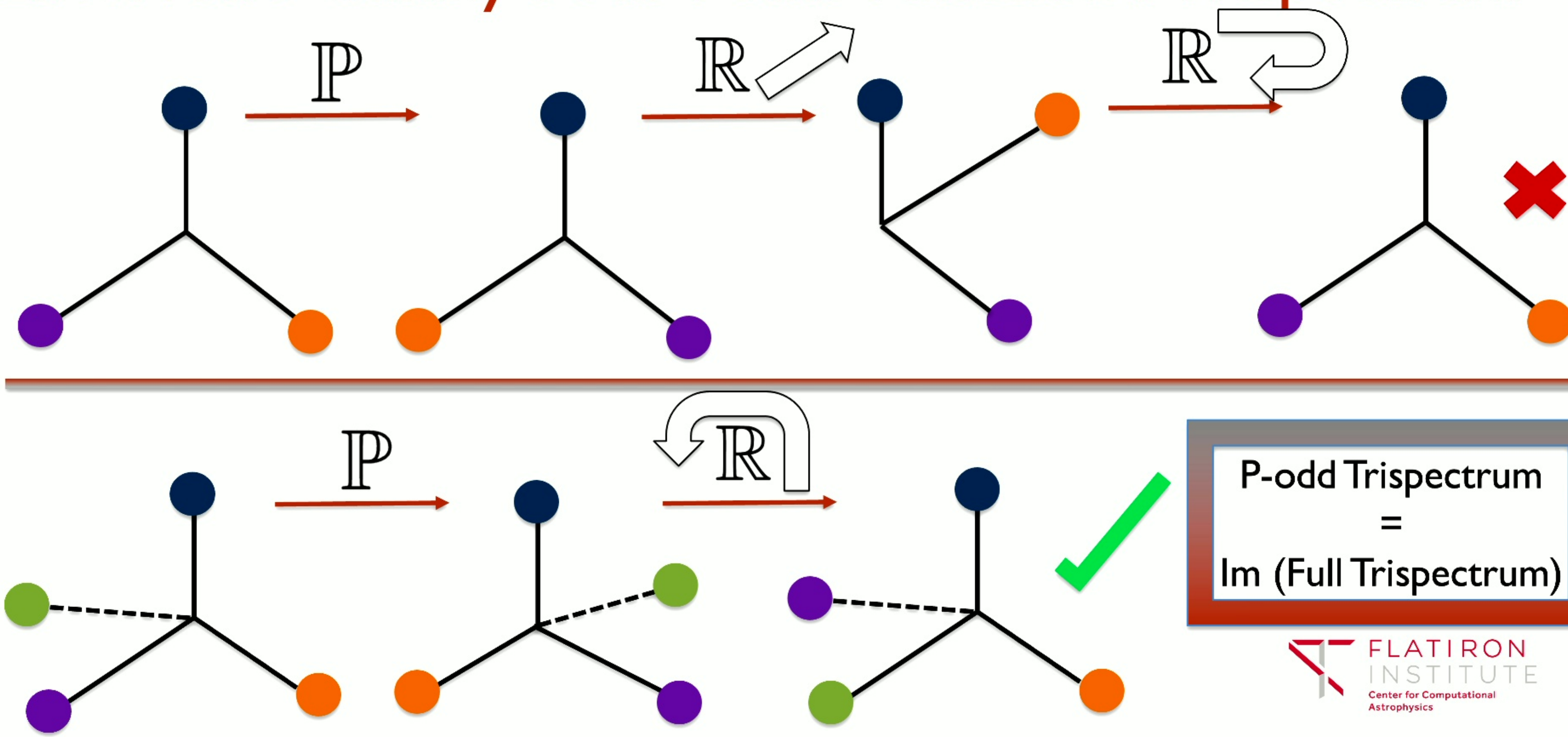
Enter: The Galaxy Four Point Function / Trispectrum



P-odd Trispectrum = Im (Full Trispectrum)

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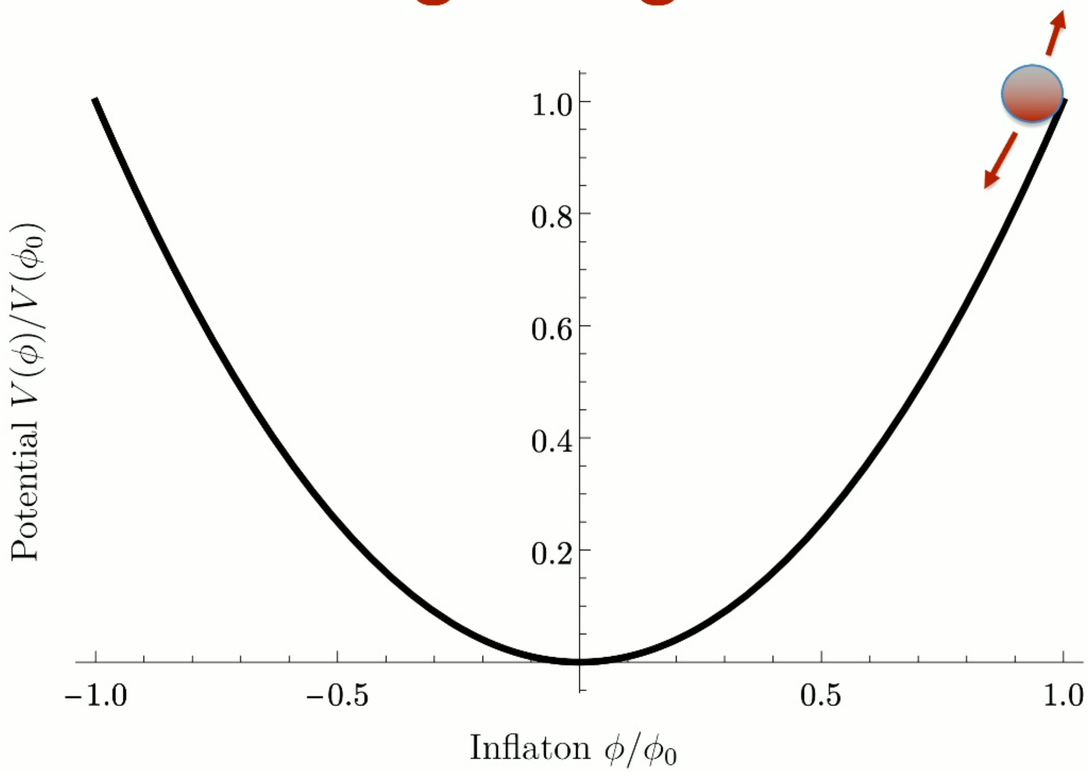
Inflation: A Lightning Review



Slow-Roll Parameter

$$\varepsilon = \frac{1}{2}\frac{\dot{\phi}^2}{M_{\rm pl}^2 H^2}$$

Solves:

1) The Horizon Problem
2) The Flatness Problem
3) Magnetic Monopole Problem

Quantum Inflaton Fluctuations Seed Density Perturbations

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dCS Inflation: Full Action

$$S = \int d^4x \sqrt{-g} \left[-\frac{1}{2} g^{\mu\nu} \left(\partial_\mu \phi\right) \left(\partial_\nu \phi\right) + \frac{M_{\rm pl}^2}{2} R - \frac{\phi}{4f} {}^*RR \right]$$

Spacetime Metric, Lorentzian Signature

$$g_{\mu\nu} = a^2(\tau) \begin{pmatrix} -1 & 0 \\ 0 & \delta_{ij} + h_{ij} \end{pmatrix}$$

dCS pseudoscalar/Inflaton

Einstein-Hilbert Term

dCS Decay Constant

Pontryagin Density

$${}^*R\,R = {}^*R^\rho{}_\sigma{}^{\mu\nu} R^\sigma{}_{\rho\mu\nu}$$

$${}^*R^\rho{}_\sigma{}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\alpha\beta} R^\rho{}_{\sigma\alpha\beta}$$

Inflaton Potential: $V \sim \Lambda^4$

$$\Lambda \sim \sqrt{H M_{\rm pl}} = 10^{16}\ {\rm GeV}\ [H/(10^{14}\ {\rm GeV})]^{1/2}$$

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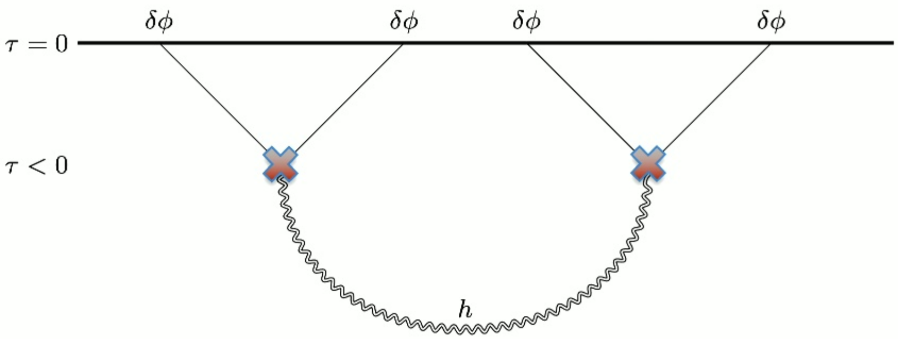
arXiv: 2303.04815, Collaborators: Oliver Philcox, Stephon Alexander, Marc Kamionkowski

Primordial Scalar Trispectrum from dCS

$$\langle \delta\phi(\mathbf{k}_1)\delta\phi(\mathbf{k}_2)\delta\phi(\mathbf{k}_3)\delta\phi(\mathbf{k}_4)\rangle_c$$



$$\propto P_{\delta\phi} P_{\delta\phi} P_h$$

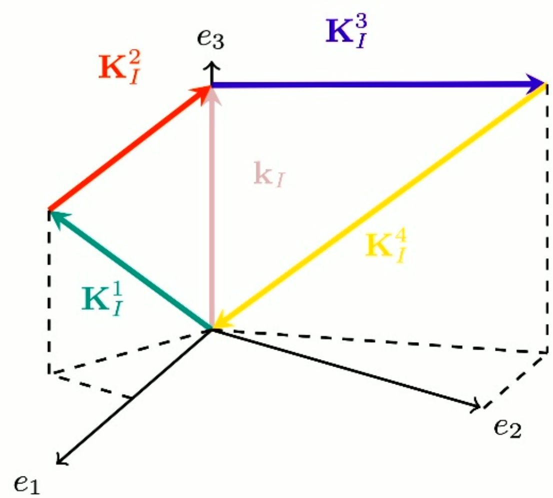
Perturbed Inflaton Kinetic Term

$$\frac{1}{2}\sqrt{-g}g^{\mu\nu}\partial_\mu\delta\phi\partial_\nu\delta\phi = \frac{1}{2}a^2\eta^{\mu\nu}\partial_\mu\delta\phi\partial_\nu\delta\phi + \boxed{\frac{1}{2}a^2 h^{ij}\partial_i\delta\phi\partial_j\delta\phi}$$

$$\mathbf{K}_s = \{\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3, \mathbf{k}_4\} \qquad \mathbf{K}_t = \{\mathbf{k}_1, \mathbf{k}_3, \mathbf{k}_2, \mathbf{k}_4\}$$

$$\mathbf{K}_u = \{\mathbf{k}_1, \mathbf{k}_4, \mathbf{k}_3, \mathbf{k}_2\} \qquad \mathbf{K}_I^1 + \mathbf{K}_I^2 = -\mathbf{K}_I^3 - \mathbf{K}_I^4 = \mathbf{k}_I$$

$$I \in \{s, t, u\}$$



$$\hat{\mathbf{e}}_1 = R_I\hat{\mathbf{x}}$$
$$\hat{\mathbf{e}}_2 = R_I\hat{\mathbf{y}}$$
$$\hat{\mathbf{e}}_3 = R_I\hat{\mathbf{z}}$$

$$\hat{\mathbf{e}}_3 = \hat{\mathbf{k}}_I$$

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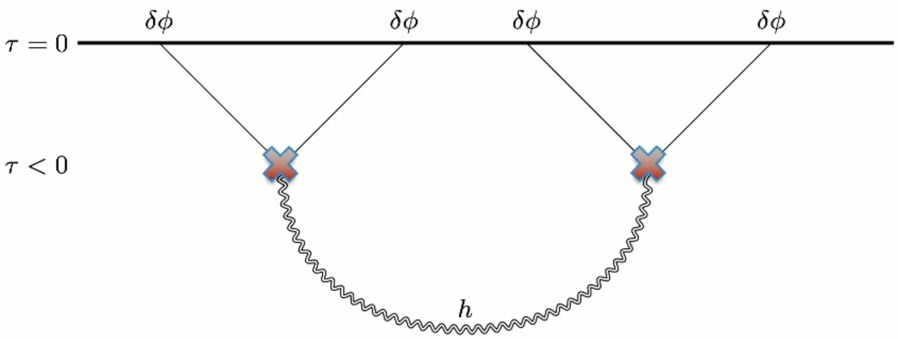

$$\propto P_{\delta\phi} P_{\delta\phi} P_h$$

$$\zeta(\mathbf{k}) = -H[\delta\phi(\mathbf{k})/\dot{\phi}]$$

Perturbed Inflaton Kinetic Term

$$\frac{1}{2}\sqrt{-g}g^{\mu\nu}\partial_\mu\delta\phi\partial_\nu\delta\phi = \frac{1}{2}a^2\eta^{\mu\nu}\partial_\mu\delta\phi\partial_\nu\delta\phi + \boxed{\frac{1}{2}a^2 h^{ij}\partial_i\delta\phi\partial_j\delta\phi}$$

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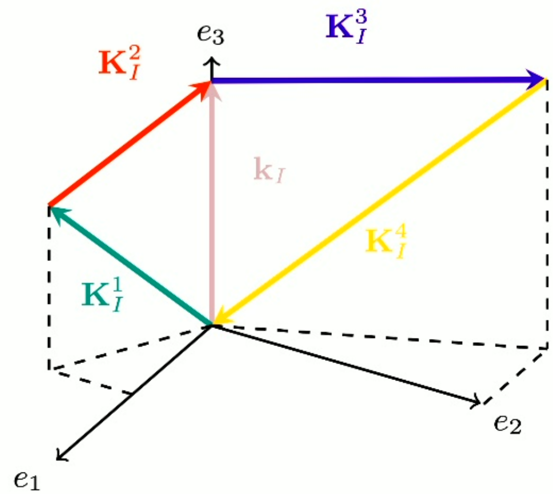
$$I \in \{s, t, u\}$$



$$\hat{\mathbf{e}}_1 = R_I\hat{\mathbf{x}}$$
$$\hat{\mathbf{e}}_2 = R_I\hat{\mathbf{y}}$$
$$\hat{\mathbf{e}}_3 = R_I\hat{\mathbf{z}}$$

$$\hat{\mathbf{e}}_3 = \hat{\mathbf{k}}_I$$

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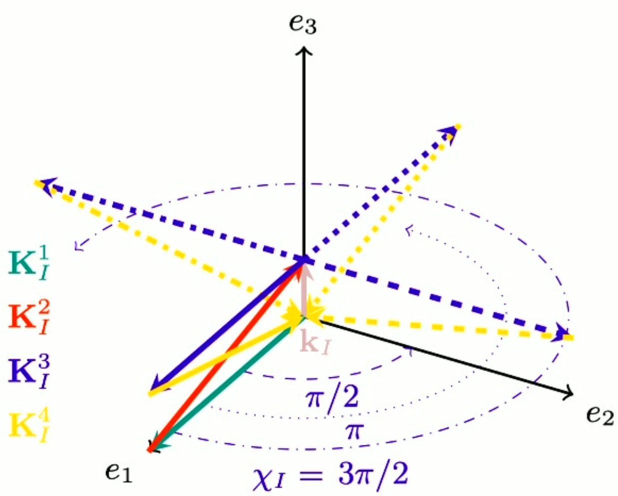
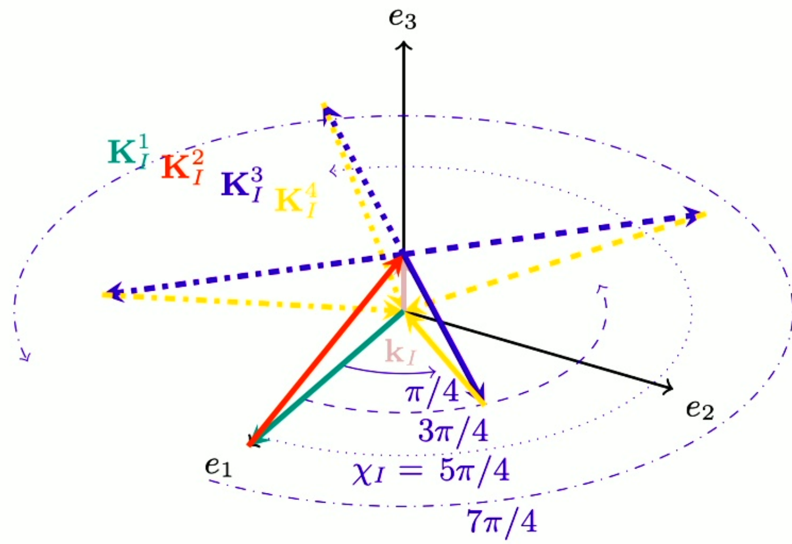
The Collapsed Limit Scalar Trispectra

$$\mathrm{Re}\left\langle \zeta\left(\mathbf{k}_1\right)\zeta\left(\mathbf{k}_1\right)\zeta\left(\mathbf{k}_3\right)\zeta\left(\mathbf{k}_4\right)\right\rangle_c^{\prime\mathrm{GE}}\Big|_{I-\mathrm{Coll.}} = \frac{9}{16} r\cos\left(2\chi_I\right)\sin^2\left(\theta_I^1\right)\sin^2\left(\theta_I^3\right)P_\zeta(k_I)P_\zeta\left(K_I^1\right)P_\zeta\left(K_I^3\right)$$

$$\mathrm{Im}\left\langle \zeta\left(\mathbf{k}_1\right)\zeta\left(\mathbf{k}_1\right)\zeta\left(\mathbf{k}_3\right)\zeta\left(\mathbf{k}_4\right)\right\rangle_c^{\prime\mathrm{GE}}\Big|_{I-\mathrm{Coll.}} = \frac{9}{16}\Pi_{\mathrm{circ}} r\sin\left(2\chi_I\right)\sin^2\left(\theta_I^1\right)\sin^2\left(\theta_I^3\right)P_\zeta(k_I)P_\zeta\left(K_I^1\right)P_\zeta\left(K_I^3\right)$$





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arXiv: 2303.04815, Collaborators: Oliver Philcox, Stephon Alexander, Marc Kamionkowski

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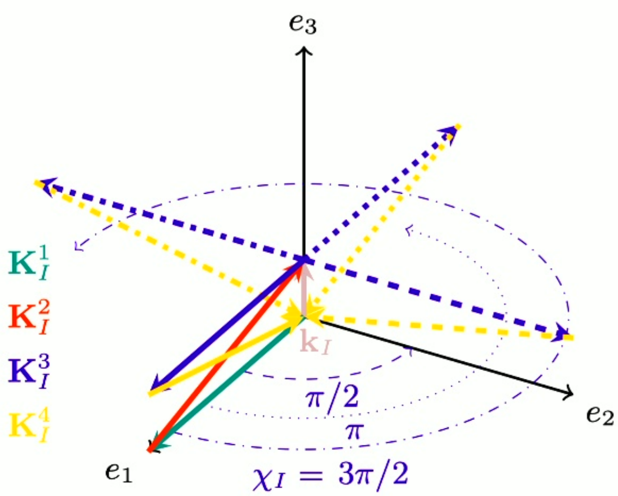
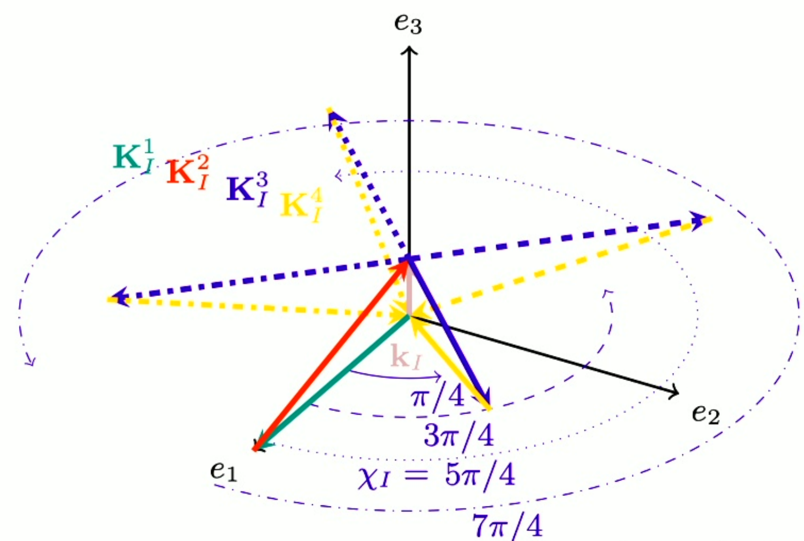
$$\mathrm{Re}\left\langle \zeta\left(\mathbf{k}_1\right)\zeta\left(\mathbf{k}_1\right)\zeta\left(\mathbf{k}_3\right)\zeta\left(\mathbf{k}_4\right)\right\rangle_c^{\prime\mathrm{GE}}\Big|_{I-\mathrm{Coll.}} = \frac{9}{16} r\cos\left(2\chi_I\right)\sin^2\left(\theta_I^1\right)\sin^2\left(\theta_I^3\right)P_\zeta(k_I)P_\zeta\left(K_I^1\right)P_\zeta\left(K_I^3\right)$$

$$\mathrm{Im}\left\langle \zeta\left(\mathbf{k}_1\right)\zeta\left(\mathbf{k}_1\right)\zeta\left(\mathbf{k}_3\right)\zeta\left(\mathbf{k}_4\right)\right\rangle_c^{\prime\mathrm{GE}}\Big|_{I-\mathrm{Coll.}} = \frac{9}{16}\Pi_{\mathrm{circ}} r\sin\left(2\chi_I\right)\sin^2\left(\theta_I^1\right)\sin^2\left(\theta_I^3\right)P_\zeta(k_I)P_\zeta\left(K_I^1\right)P_\zeta\left(K_I^3\right)$$





Graviton Spin

$$\mathrm{Odd/Even} = \Pi_{\mathrm{circ}}\cot\left(2\chi_I\right)$$

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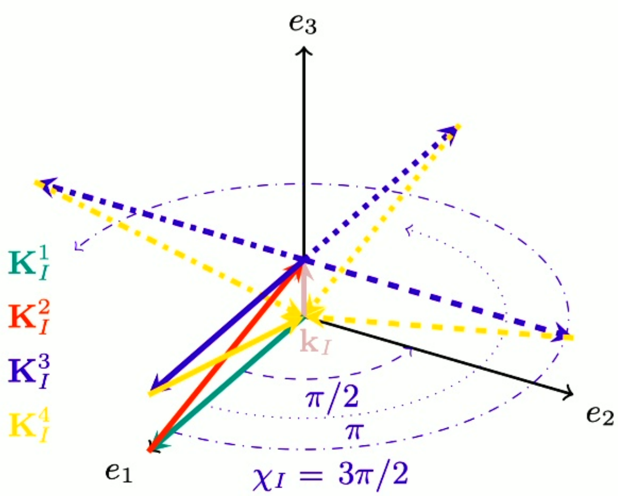
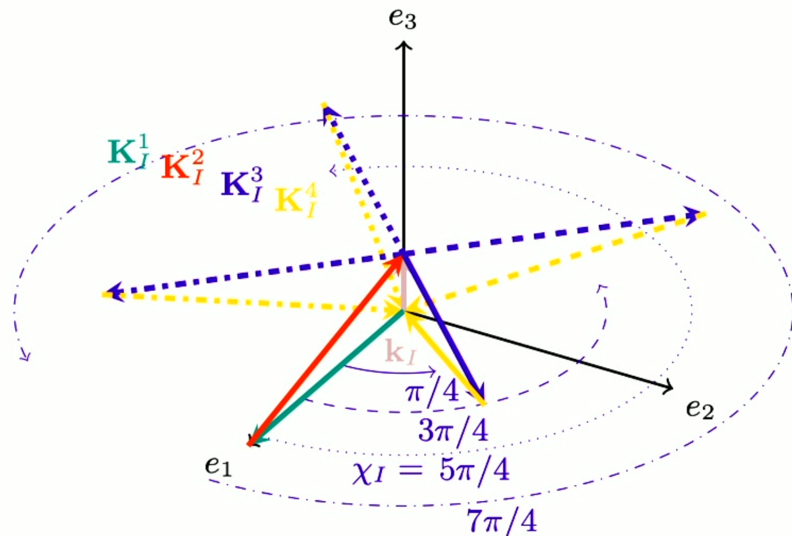
arXiv 2303.04815, Collaborators: Oliver Philcox, Stephon Alexander, Marc Kamionkowski

The Collapsed Limit Scalar Trispectra

$$\mathrm{Re}\,\langle\zeta(\mathbf{k}_1)\,\zeta(\mathbf{k}_1)\,\zeta(\mathbf{k}_3)\,\zeta(\mathbf{k}_4)\rangle_c^{\prime\mathrm{GE}}\Big|_{I-\mathrm{Coll.}} = \frac{9}{16} r\cos(2\chi_I)\sin^2(\theta_I^1)\sin^2(\theta_I^3)\,P_\zeta(k_I)P_\zeta(K_I^1)\,P_\zeta(K_I^3)\,\underline{\times F}$$

$$\mathrm{Im}\,\langle\zeta(\mathbf{k}_1)\,\zeta(\mathbf{k}_1)\,\zeta(\mathbf{k}_3)\,\zeta(\mathbf{k}_4)\rangle_c^{\prime\mathrm{GE}}\Big|_{I-\mathrm{Coll.}} = \frac{9}{16}\Pi_{\mathrm{circ}} r\sin(2\chi_I)\sin^2(\theta_I^1)\sin^2(\theta_I^3)\,P_\zeta(k_I)P_\zeta(K_I^1)\,P_\zeta(K_I^3)\;\underline{\times F}$$





Graviton Spin

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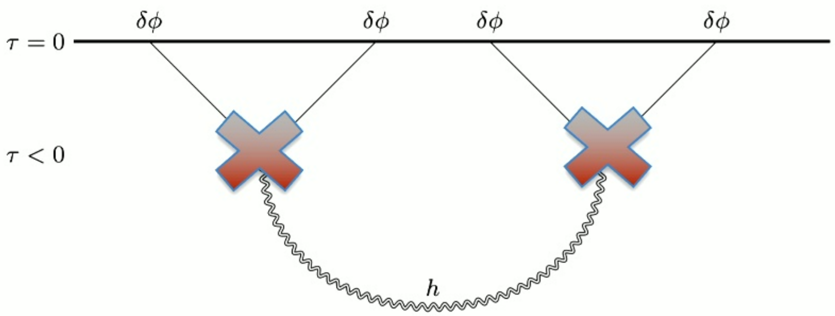
Two Examples Beyond Vanilla dCS Inflation

Superluminal Scalar Sound Speed

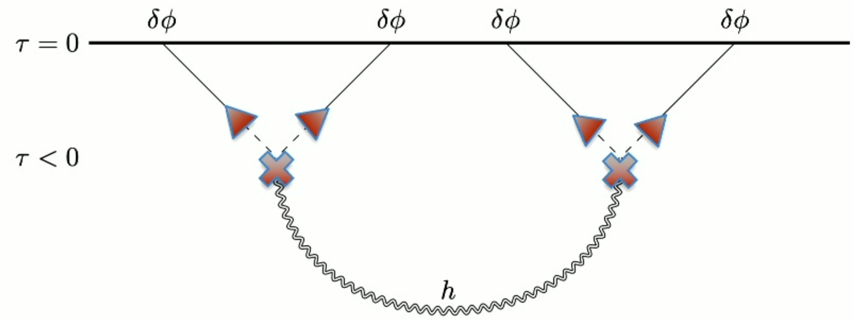
$$c_s^2 g^{ij} \left(\partial_i \phi\right) \left(\partial_j \phi\right)$$



$$F = 2 \times 10^6 \left(c_s/6\right)^8$$

Quasi-Single Field/Multi-Field

$$a^3 \lambda \delta\sigma \delta\dot{\phi} \qquad h^{ij} \partial_i(\delta\sigma) \partial_j \left(\delta\sigma\right)$$



$$F \sim 10^4 \left[w(\nu)/20\right]$$

$$\nu = \sqrt{9/4 - (m/H)^2} \lesssim 0.5$$

arXiv: 1504.05993

(Dimastrogiovanni, Fasiello, Kamionkowski)

$$F \sim 10^7 \ \left(N/60\right)^4$$

$$\nu \sim 3/2$$

arXiv: 0911.3380

(Xingang Chen, Yi Wang)

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The Trispectra can be Large

arXiv: 2303.04815, Collaborators: Oliver Philcox, Stephon Alexander, Marc Kamionkowski

How Sensitive are we to Collapsed Trispectra?

$$\left[1+\delta^P_{\rm odd}\left(\Pi_{\rm circ}-1\right)\right] r \gtrsim 0.04\left(\frac{n}{3}\right)\left(\frac{8\times10^5}{F}\right)\left(\frac{10^6}{N_{\rm modes}}\right)^{1/2}\left(\frac{k_{\rm min}}{0.003\ h/{\rm Mpc}}\right)^{3/2}\left(\frac{0.3\ h/{\rm Mpc}}{k_{\rm max}}\right)^{3/2}$$

$$f \lesssim 4\times10^9\ {\rm GeV}\left(\frac{3}{n}\right)\left(\frac{F}{8\times10^5}\right)\left(\frac{\varepsilon}{10^{-2}}\right)^{3/2}\left(\frac{H}{10^{14}\ {\rm GeV}}\right)^{2}\left(\frac{N_{\rm modes}}{10^6}\right)^{1/2}\left(\frac{0.003\ h/{\rm Mpc}}{k_{\rm min}}\right)^{3/2}\left(\frac{k_{\rm max}}{0.3\ h/{\rm Mpc}}\right)^{3/2}$$

$$N_{\rm modes} = V\int_{k_{\rm min}}^{k_{\rm max}} \frac{d^3\mathbf{k}}{(2\pi)^3}{\rm W}\left(\mathbf{k}\right)\frac{\left[G^2(\mathbf{k},\bar{z})P^{gg}_{\rm L}(\mathbf{k},\bar{z})\right]^2}{\left[P^{gg}_{\rm NL}\left(\mathbf{k},\bar{z}\right)+\bar{n}^{-1}\right]^2}$$

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What about Experiments?

$$[1+\delta^P_{\rm odd}(\Pi_{\rm circ}-1)]\,r \gtrsim 0.04\left(\frac{n}{3}\right)\left(\frac{8\times10^5}{F}\right)\left(\frac{10^6}{N_{\rm modes}}\right)^{1/2}\left(\frac{k_{\rm min}}{0.003\ h/{\rm Mpc}}\right)^{3/2}\left(\frac{0.3\ h/{\rm Mpc}}{k_{\rm max}}\right)^{3/2}$$

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 $[({\rm Gpc}/h)^3]$	$N_{\rm modes}$	F
BOSS[a] [112, 113]	[0.43, 0.7]	0.23	[0.01, 0.24]	3×10^{-4}	2.0	3.6	10^5	2×10^7
DESI[a] [115]	[0.6, 1.7]	0.34	[0.003, 0.31]	3.8×10^{-4}	1.4	45	8×10^5	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	6×10^5
MegaMapper[a] [116, 117]	[2, 5]	0.34	[0.003, 0.64]	2.5×10^{-4}	3.8	155	7×10^6	10^5
MSE[a] [120]	[1.6, 4]	0.24	[0.003, 0.54]	2.8×10^{-4}	3.7	91	6×10^6	10^5
SPHEREx[a] [118, 119]	[0.1, 4.3]	0.65	[0.003, 0.46]	2.0×10^{-3}	1.1	360	2×10^7	10^5
HIRAX[b] [121]	[0.8, 2.5]	0.36	[(0.01, 0.1), 0.38]	10^{-3}	1.9	88	3×10^6	$(2\times10^6, 7\times10^7)$
PUMA-32K[b] [122]	[2, 6]	0.5	[(0.01, 0.1), 0.71]	7.6×10^{-3}	6.3	290	7×10^7	$(2\times10^5, 5\times10^6)$

[a]Spectroscopic Galaxy Survey
[b]21-cm Experiment

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arXiv 2303.04815, Collaborators: Oliver Philcox, Stephon Alexander, Marc Kamionkowski

dCS Inflation: Dynamics and Primordial Power Spectra

$$u''(\tau,\mathbf{k}) - \frac{2}{\tau}u'(\tau,\mathbf{k}) + k^2 u(\tau,\mathbf{k}) = 0$$

$$u''_{\pm}(\tau,\mathbf{k}) - \frac{2}{\tau}u'_{\pm}(\tau,\mathbf{k}) + \left(k^2 \mp \frac{2k\mu}{\tau}\right) u_{\pm}(\tau,\mathbf{k}) = 0$$

$$u(\tau,\mathbf{k}) = \frac{H}{\sqrt{2k^3}}(1+ik\tau)e^{-ik\tau}$$

$$u_{\pm}(\tau,\mathbf{k}) = \frac{H}{M_{\rm pl}\sqrt{k^3}}(1+ik\tau)e^{-ik\tau}\left[\frac{U(2\mp i\mu, 4, 2ik\tau)}{U(2,4,2ik\tau)}\right]\exp\left(\pm\frac{\pi}{2}\mu\right)$$

$$\Pi_{\rm circ} = 0.9\left(\frac{\varepsilon}{10^{-2}}\right)^{1/2}\left(\frac{H}{10^{14}\ \mathrm{GeV}}\right)^2\left(\frac{10^9\ \mathrm{GeV}}{f}\right)$$

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dCS Inflation: Lepto/Baryogenesis

$$a^4 \frac{\phi(\tau)}{4f} {}^*RR$$

$$\frac{\dot{\phi}}{4f} = \frac{1}{2}\frac{M_{\rm pl}}{H}\left[\sqrt{\frac{\varepsilon}{2}}\frac{H^2}{M_{\rm pl} f}\right] = \frac{1}{2}\frac{M_{\rm pl}^2}{H}\mu$$

$$\partial_\mu J_5^\mu = {}^*RR/(384\pi^2) \quad J_5^0 = n_L - n_R$$

Canonical Normalization

$$\sim H\mu(n_L - n_R)$$

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Conclusions/Future Extensions

1) Two new constructions of dCS, yielding a large range of decay constants
2) First example of massless spin-exchange yielding a parity-violating scalar trispectrum
3) Scalar trispectra can probe dCS decay constants at very high values
4) Odd to even ratios, in collapsed limit, (i.e. the phase of the trispectrum) give direct information about spin
5) Potential new probes of baryogenesis

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dCS Extensions

1) Removal of the dCS Ghost
2) Parity-Odd Signal for all configurations
3) Where do the trispectra peak?
4) CMB signal
5) Intermediary dCS constants? (Gravi-axion DM/DE)?

Baryogenesis Extensions

1) What type of spin-1 baryogenesis can be probed? (What vertex interactions, shapes, sensitivities, UV completions etc)

2) Other CMB/LSS probes?

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dCS Inflation: Quadratic Action

$$^*RR = \frac{2\tilde{\epsilon}^{ijk}}{a^4(\tau)}\left[h''_{il}\left(\partial_j h^l_k\right)' + \left(\partial_m h'_{li}\right)\left(\partial_j \partial^l h^m_k + \partial_k \partial^m h^l_j\right)\right]$$

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UV Completions for Fermion SI

(Scalar) Yukawa

$$\mathcal{L} \supset g_\chi \chi \bar{\Psi}\Psi$$

$$\Lambda \sim m_\chi$$

$$\lambda = (g_\chi / m_\chi)^2$$

$$f = 34 \text{ eV } g_\chi^{-2} \left(\frac{m_\Psi}{10^{-3} \text{ eV}}\right)$$

Gravitational Torsion

$$\mathcal{L} \supset (2/\gamma) R^{\mu\nu} \wedge e_\mu \wedge e_\nu$$

$$\Lambda \sim M_{\rm pl}$$

$$\lambda = 3\pi / \Lambda_T^2$$

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arXiv: 2207.05094, Collaborator: Stephon Alexander