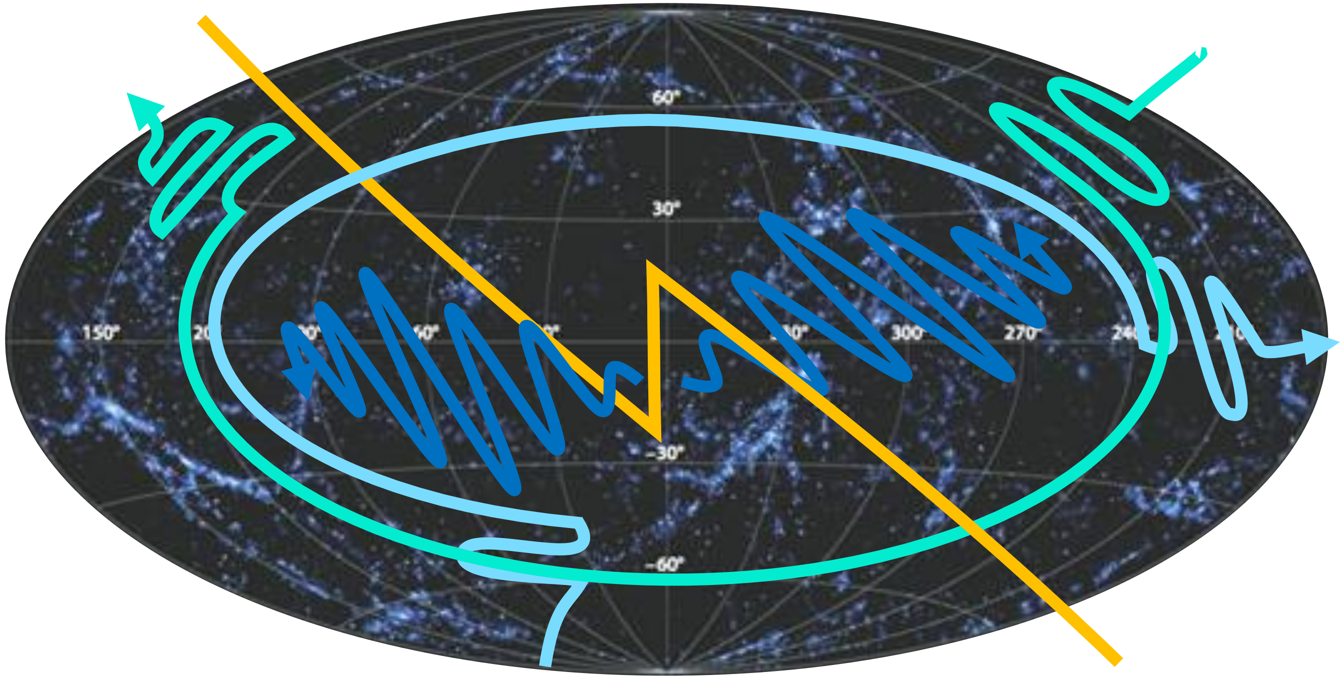
New Inflationary probes of Axion & Hybrid Cosmology Colliders



Lingfeng Li

Brown University

Oct 22, 2023, U. Florida

The Early Universe: Window to New Physics

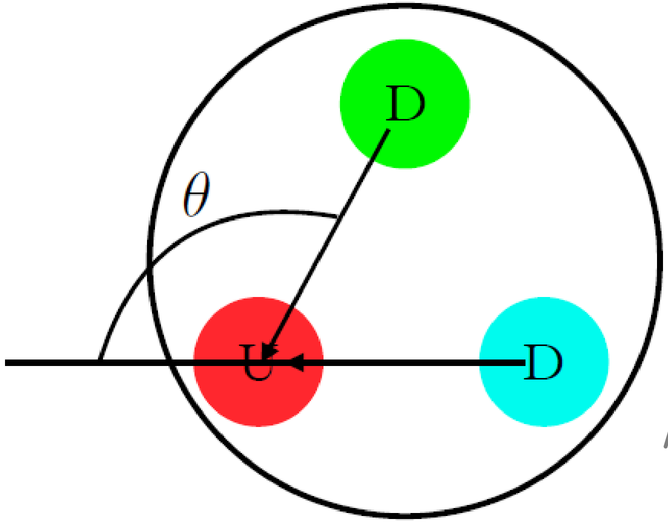
2303.03406, With Xingang Chen & JiJi Fan

Strong CP and QCD Axion

Experimental hints: neutron EDM

Naive expectation: O(Q × fm) ≈ 10^{-13} e cm

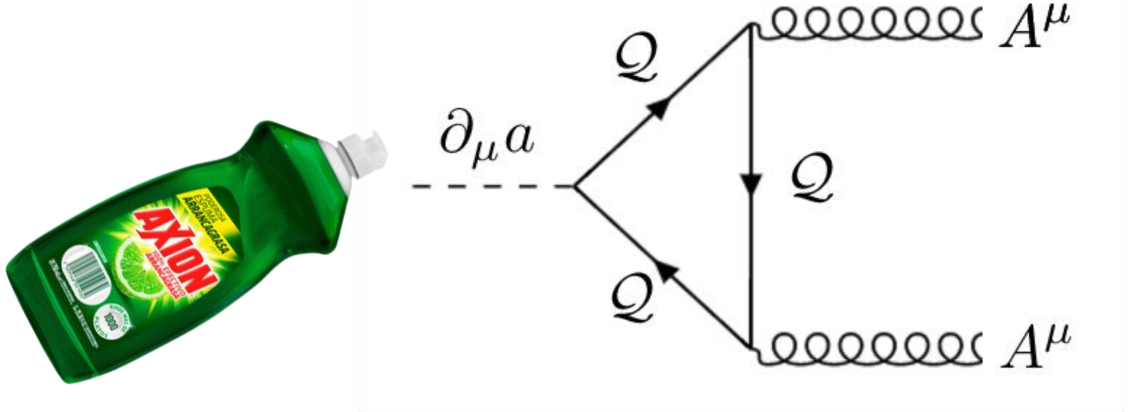
Experimental result $\lesssim 10^{-26}$ e cm, $\theta \lesssim 10^{-10}$



A. Hook, 2018

$$\mathcal{L} \supset \theta \frac{g^2}{32\pi^2} G\tilde{G}$$

QCD axion: A pseudo Nambu-Goldstone Boson (pNGB) of a the Peccei-Quinn symmetry

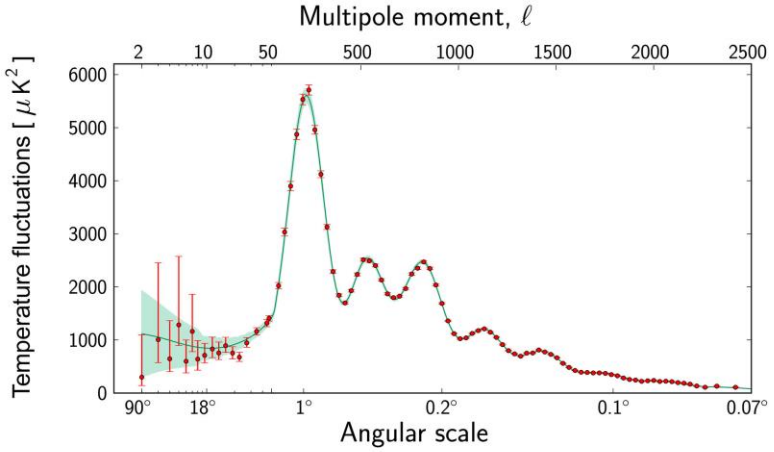


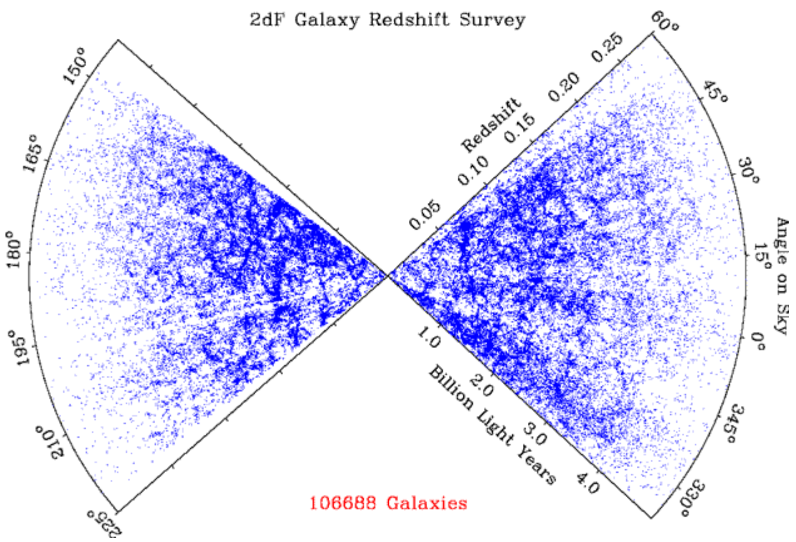
The strong CP θ angle are set to zero at the minima

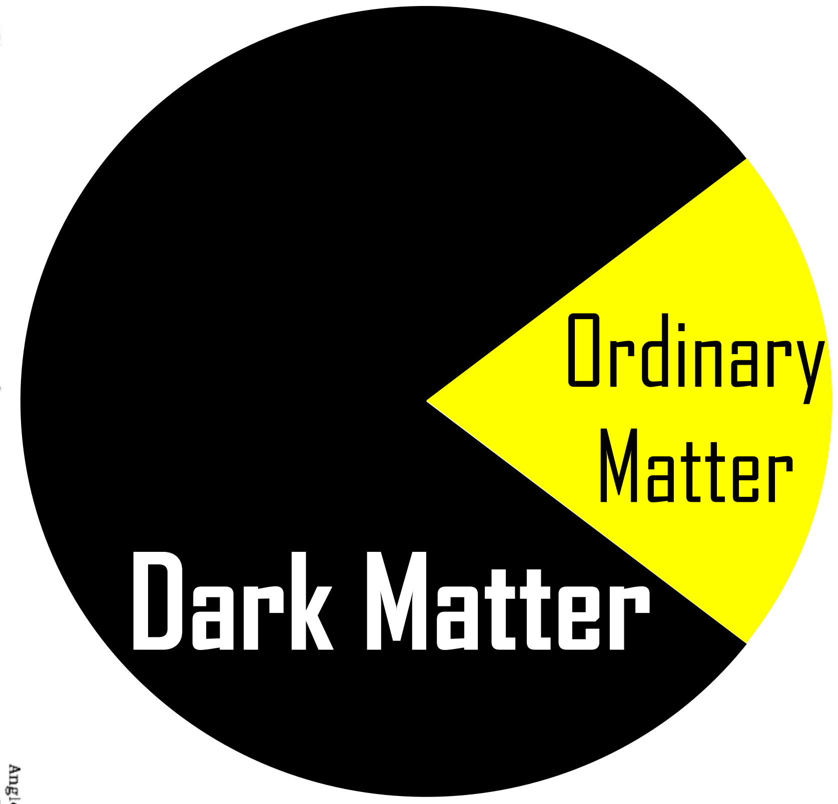
$$V = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2} \sin^2\left(\frac{a}{2f_a} + \frac{\bar{\theta}}{2}\right)}$$

Peccei, Quinn; Weinberg; Wilczek; Kim; Shifman, Vainshtein, Zakharov; Zhitnitsky; Dine, Fischler, Srednicki; L.F. Abbott, P. Sikivie 1977-1982

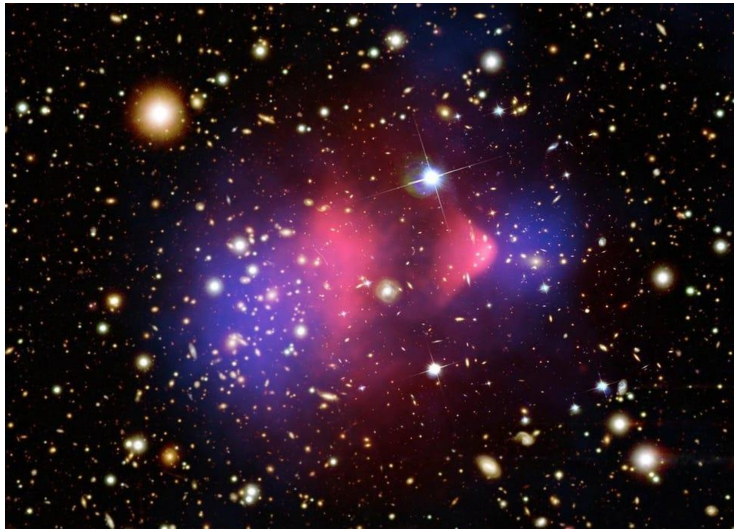
Dark Matter Exists

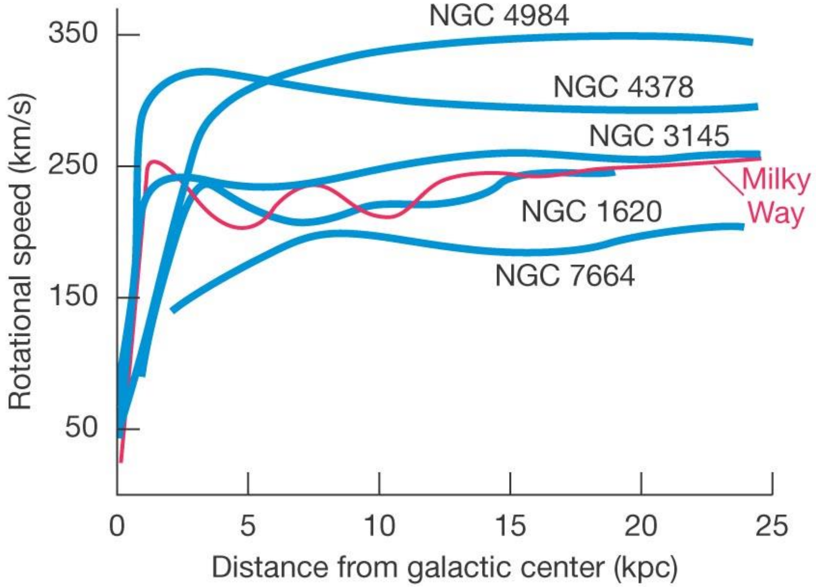






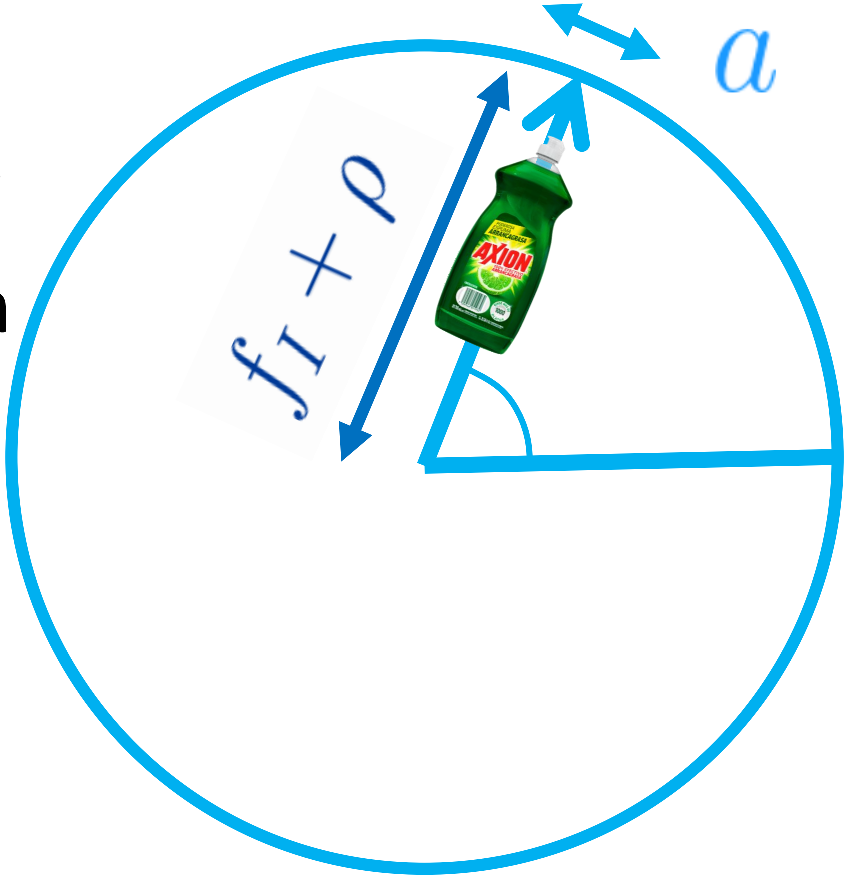
The matter budget of our universe





Axion DM from Misalignment

$$\delta\theta \simeq H/2\pi f_a \ll 1$$



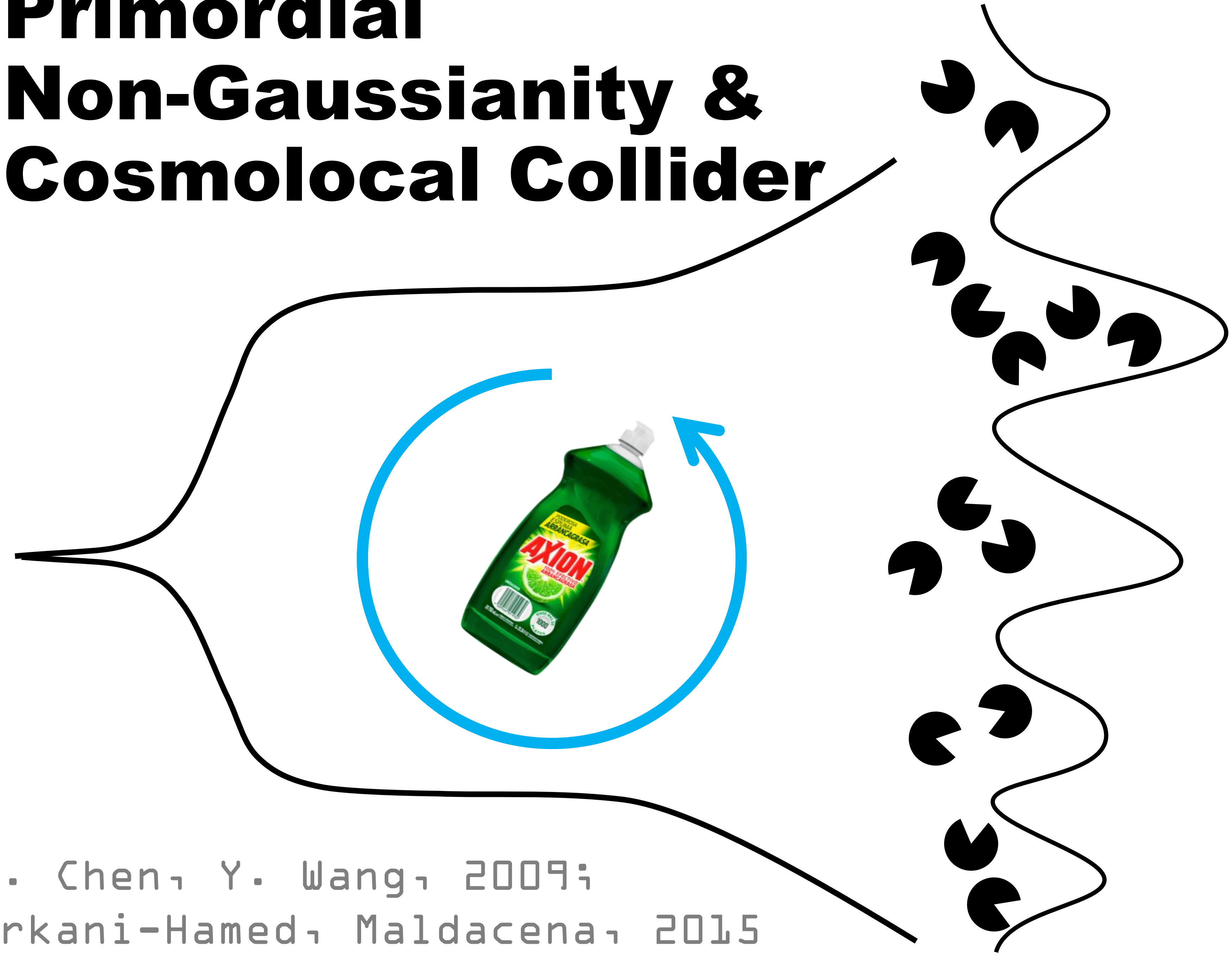
- ❑ $f_a > H_I / 2\pi$ with inflationary Hubble and PQ symmetry is not restored during (p)reheating
- ❑ DM created when $H \lesssim m_a$, isocurvature given by quantum fluctuations of a

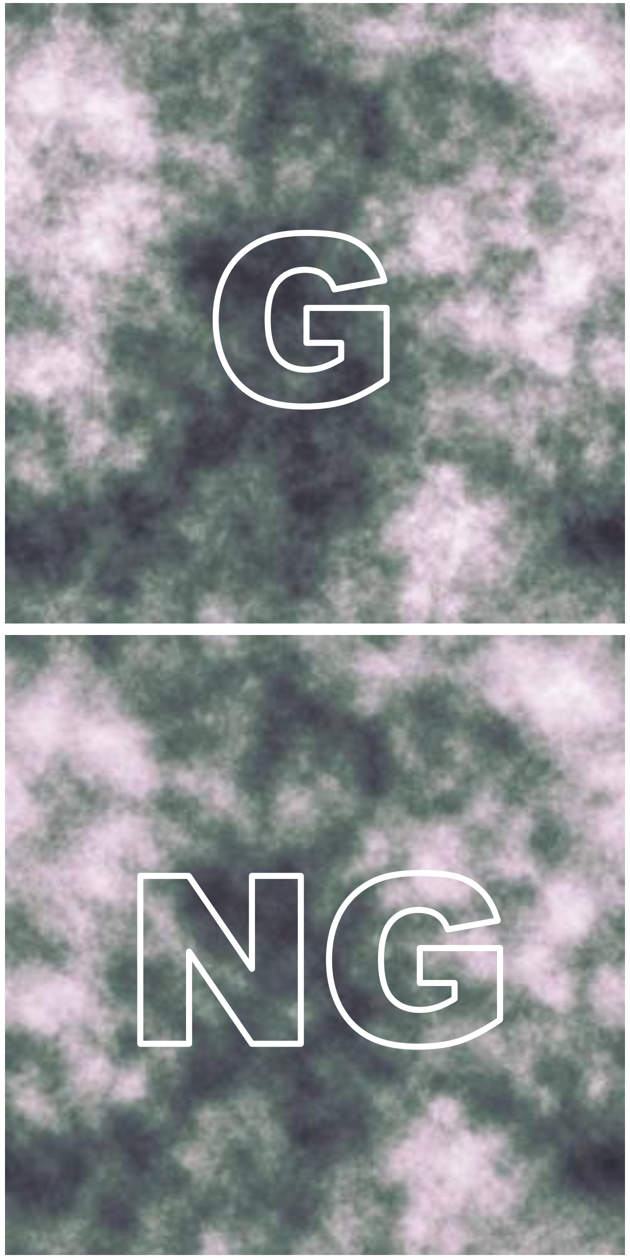
Reverse story:

Y. Bao, J. Fan, LL, 2022

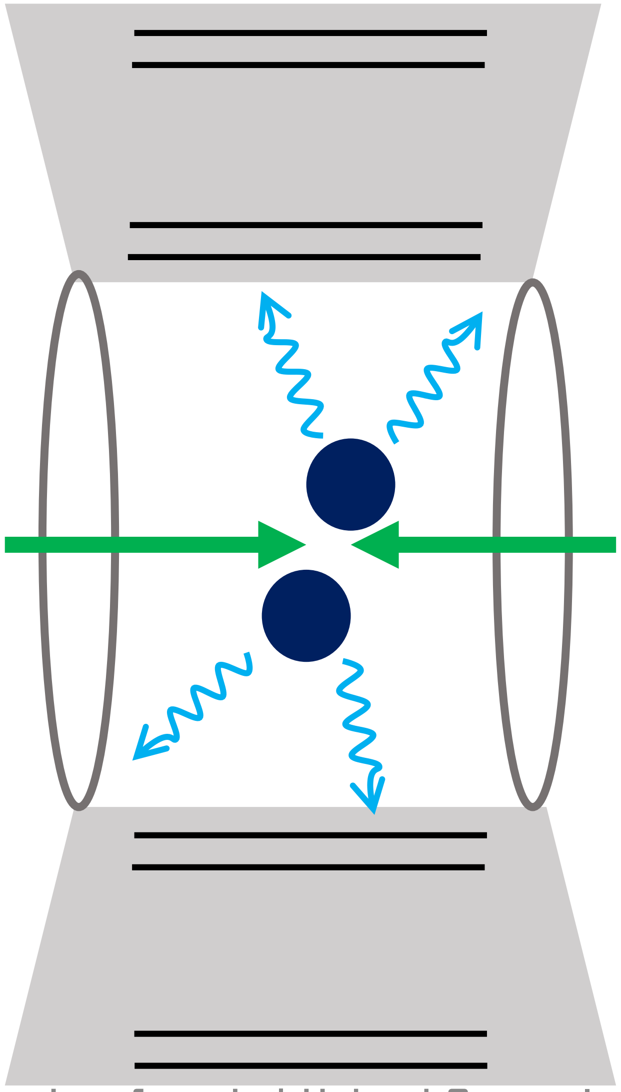
*Oscillating field creates non-relativistic, coherent axion particles

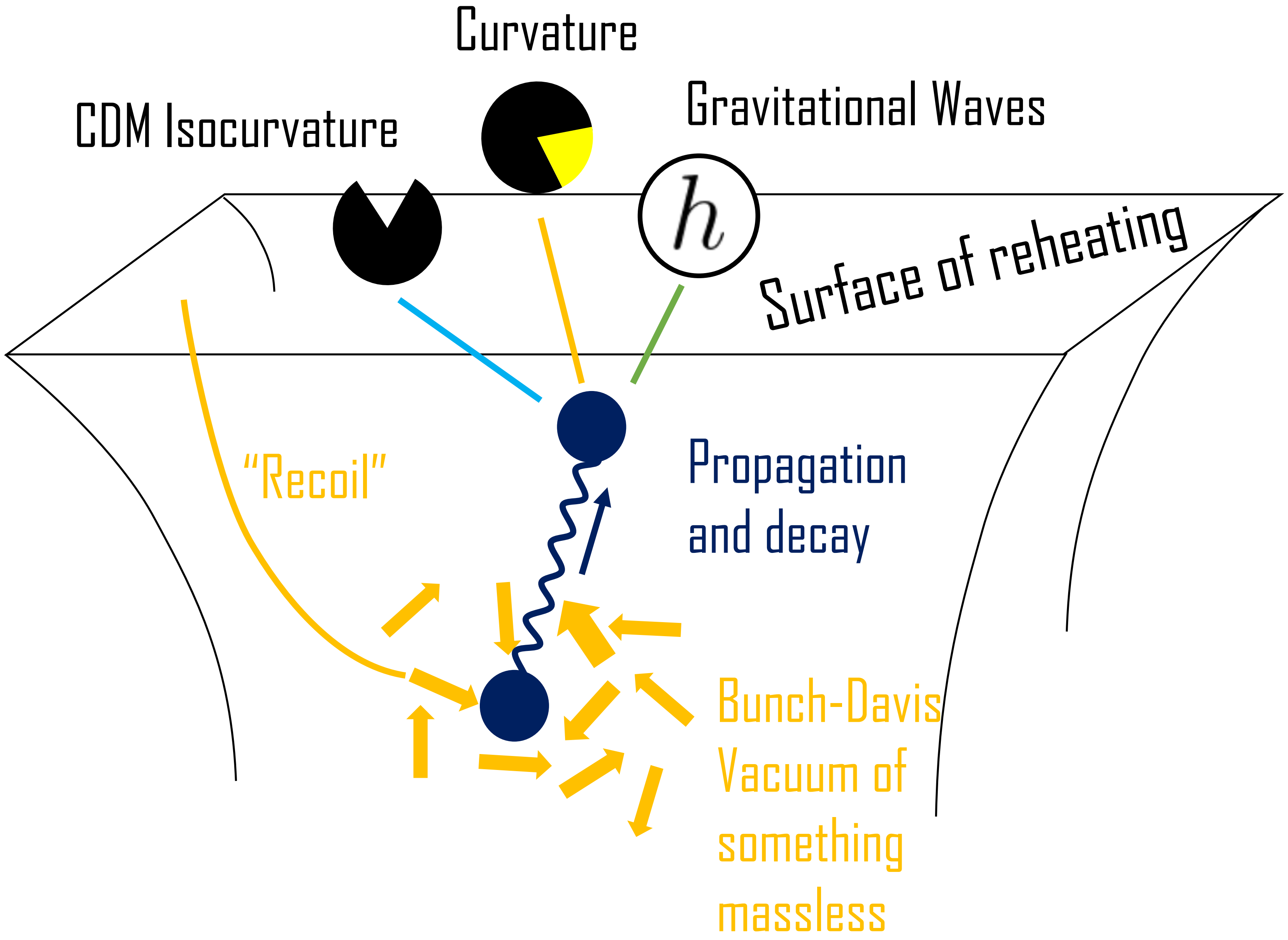
Primordial Non-Gaussianity & Cosmolocal Collider



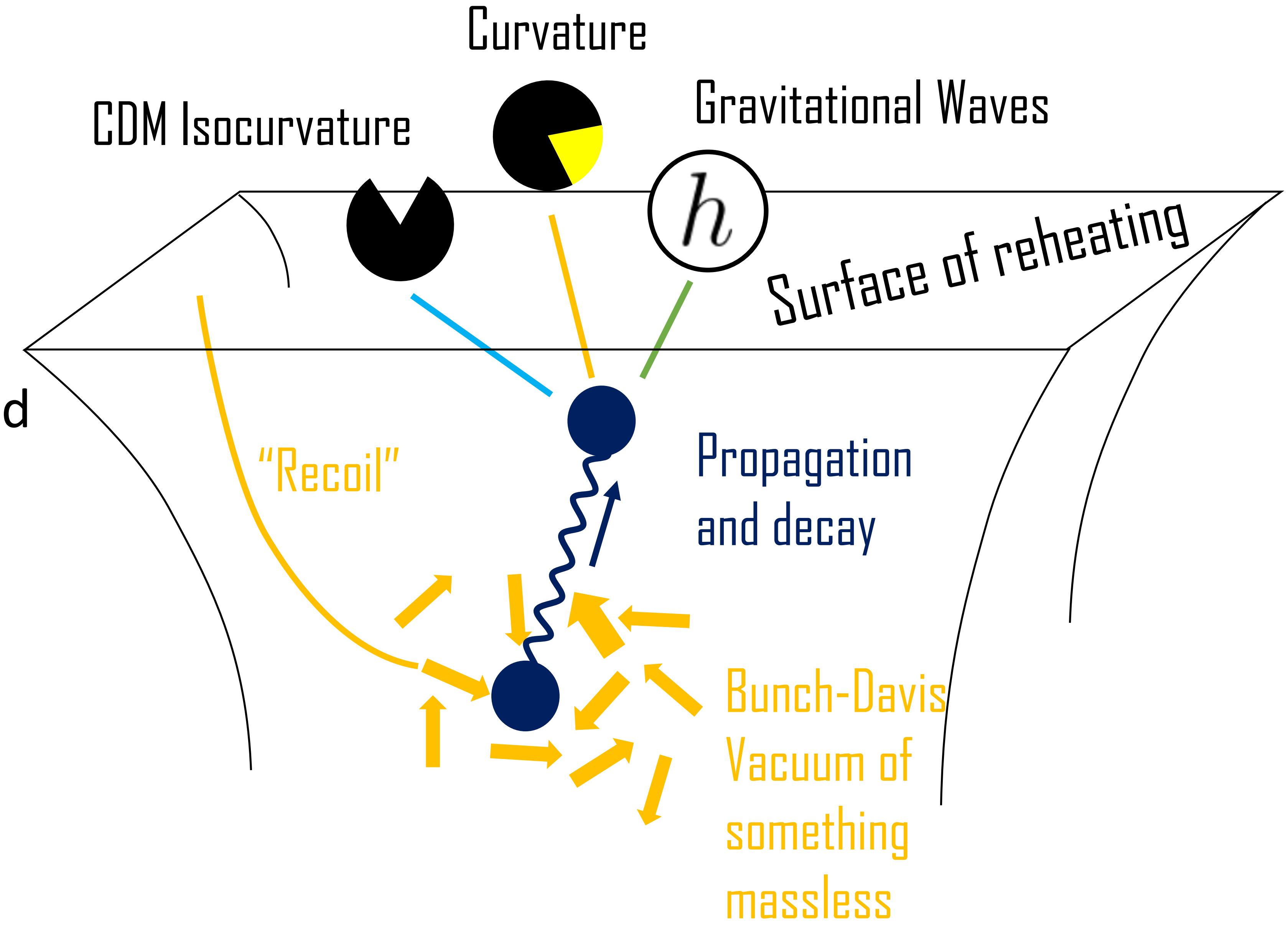


X. Chen, Y. Wang, 2009;
Arkani-Hamed, Maldacena, 2015



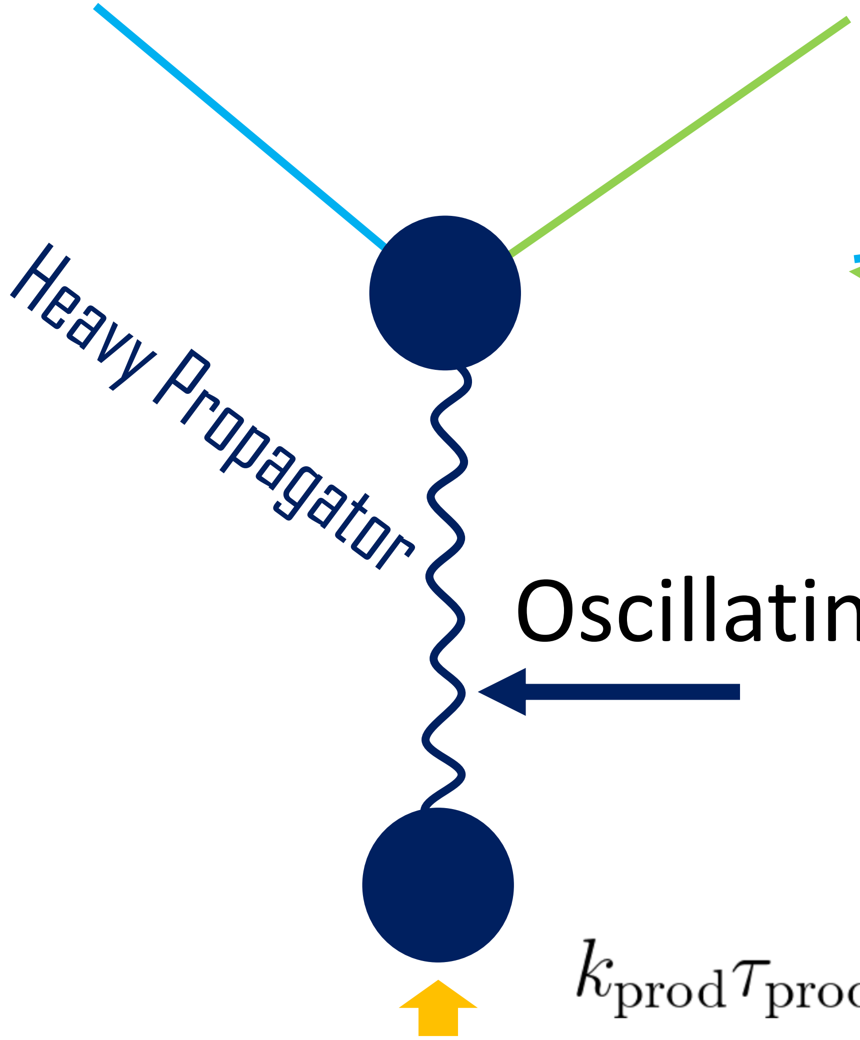

Curvature
CDM Isocurvature
Gravitational Waves
h
Surface of reheating
"Recoil"
Propagation
and decay
Bunch-Davis
Vacuum of
something
massless

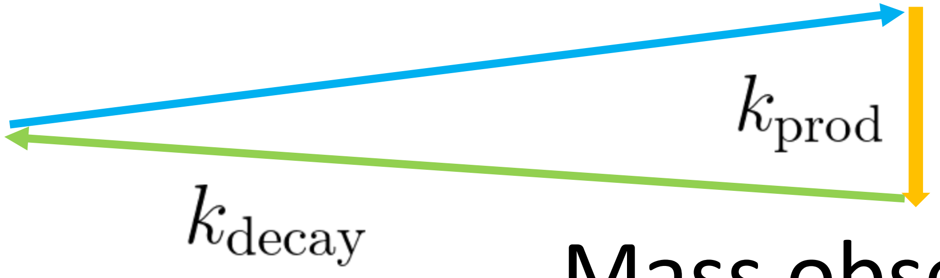
- Heavy field created by quantum fluctuations vs. Well-prepared beams
- Interfere with background fluctuations, amplitude instead of its square
- Time invariance breaks down by inflation: No invariant masses



Sketch of a Cosmological Collider

$k_{\rm decay}\tau_{\rm decay} \sim m/H$





$$k_{\rm decay} \gg k_{\rm prod}$$

Oscillating as: e^{imt}

Mass observed through phases:

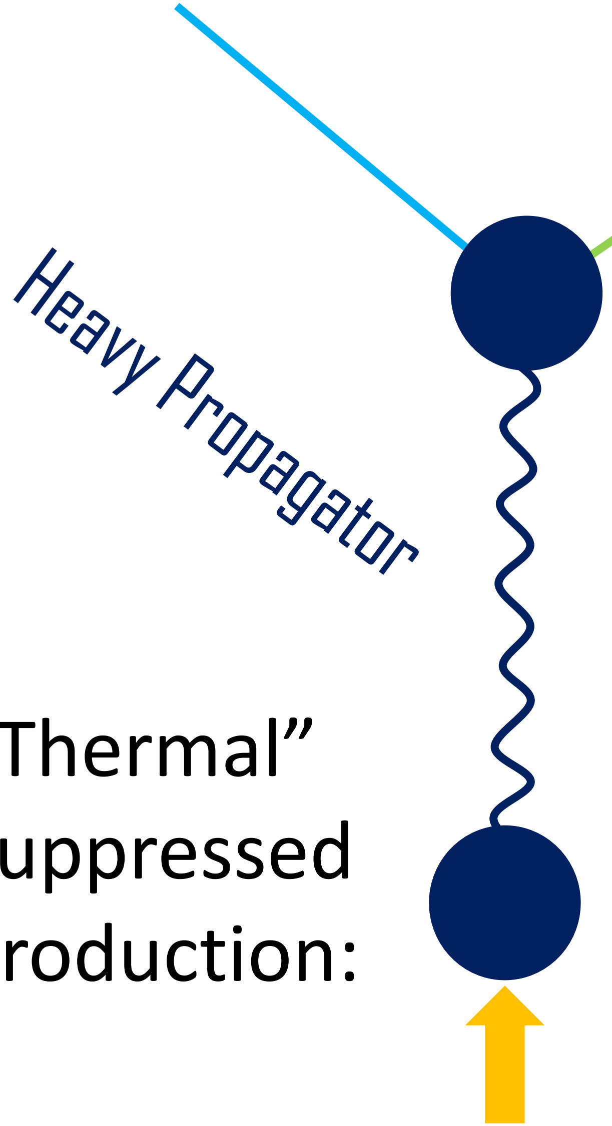
$$|\tau| \sim H^{-1}e^{-Ht} \Rightarrow$$

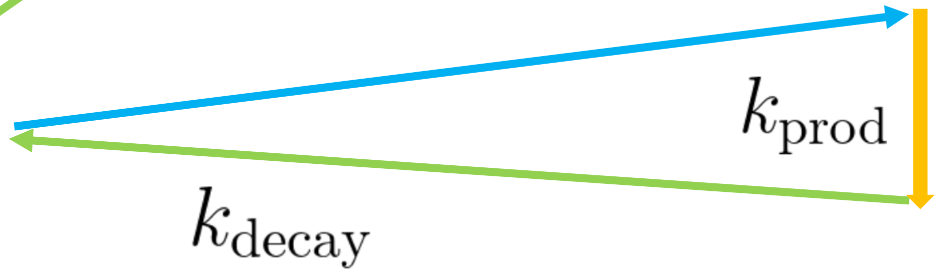
$$t_{\rm decay} - t_{\rm prod} \simeq H^{-1}\log\left|\frac{\tau_{\rm prod}}{\tau_{\rm decay}}\right|$$

$$e^{im\Delta t} \sim \left(\frac{k_{\rm decay}}{k_{\rm prod}}\right)^{im/H}$$

$k_{\rm prod}\tau_{\rm prod} \sim m/H$

Sketch of a Cosmological Collider





“Thermal” Suppressed production:

Gibbons-Hawking temperature: $T \sim \frac{H}{2\pi}$

$$\Rightarrow A \propto \sqrt{e^{-\frac{m}{T}}} \sim e^{-\frac{\pi m}{H}}$$

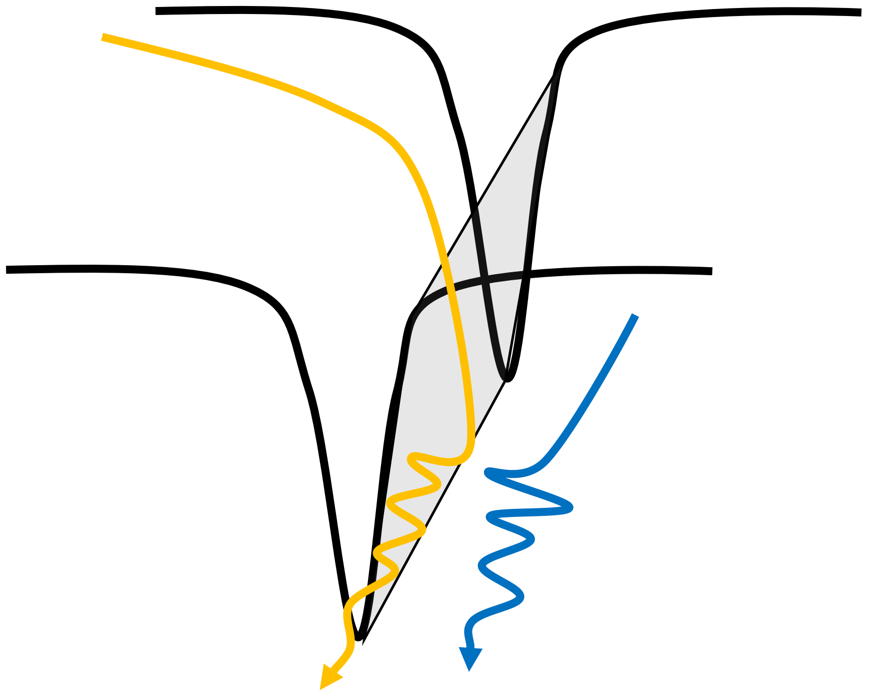
Beyond Boltzmann Suppression

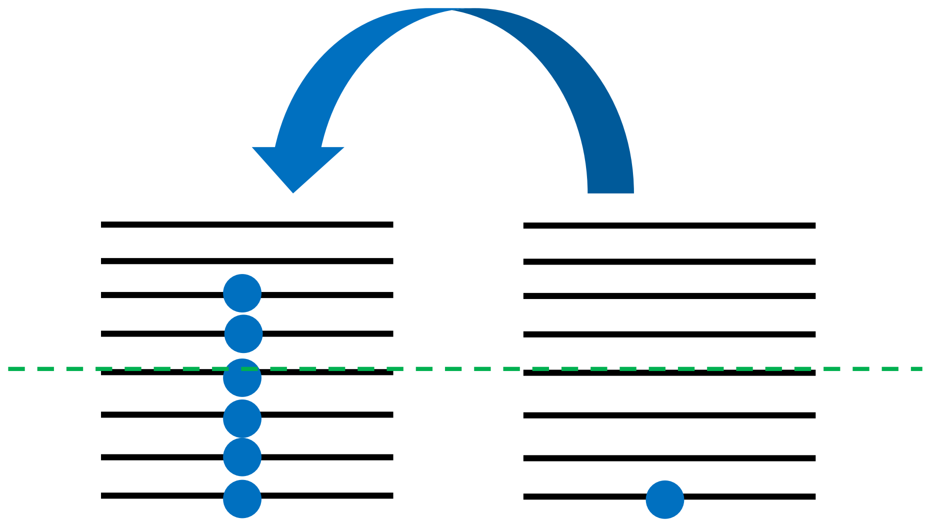
❑Classical Feature

X. Chen, 2011; X. Chen, R. Ebadi, S. Kumar, 2022; A. Bodas, R. Sundrum, 2022 …

❑Chemical potential

A. Bodas, S. Kumar, R. Sundrum, 2020; C. M. Sou, X. Tong ,Y. Wang, 2022 …





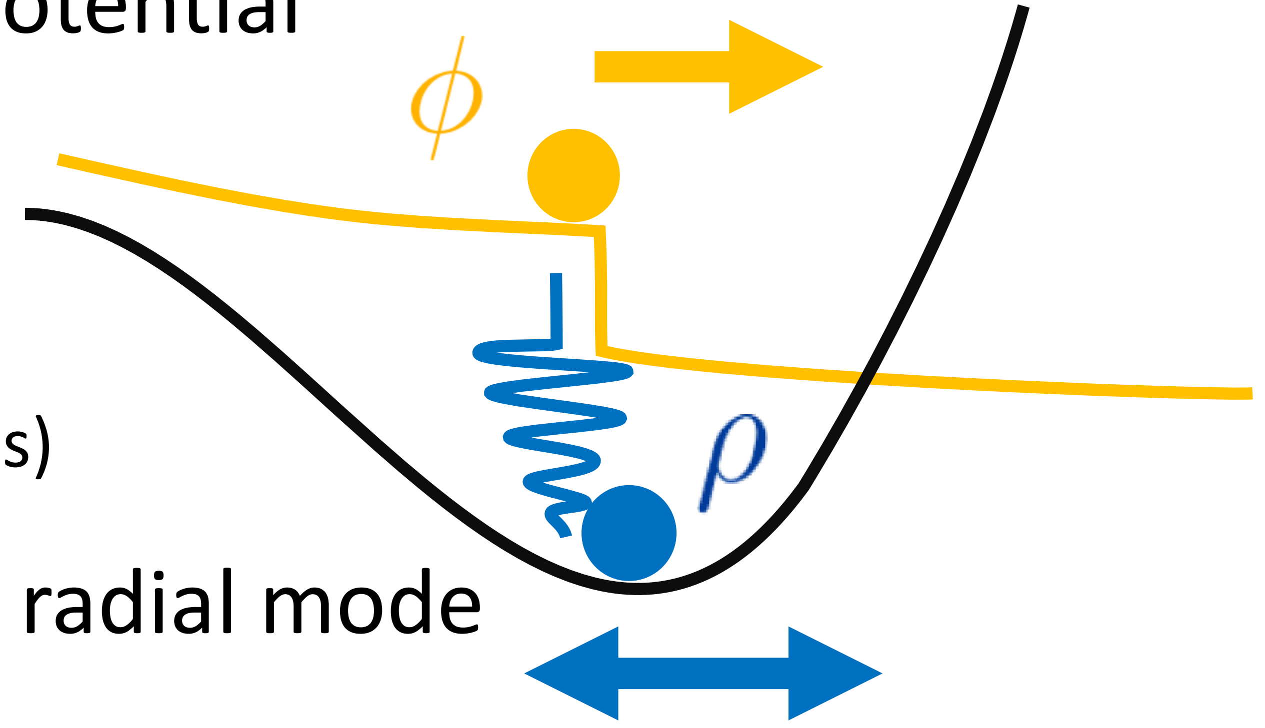
Scenario 1: Classical Feature

$$\mathcal{L}_1 = -\frac{(\partial_\mu \phi)^2}{2} - |\partial_\mu \chi|^2 - V_\phi(\phi) - V_\chi(\chi) - \frac{c}{\Lambda^2}(\partial\phi)^2|\chi|^2$$

+ Toy feature: a step in potential

$$V_{\phi 1}(\phi) = -bV_{\phi 0}\,\theta(\phi - \phi_s)$$

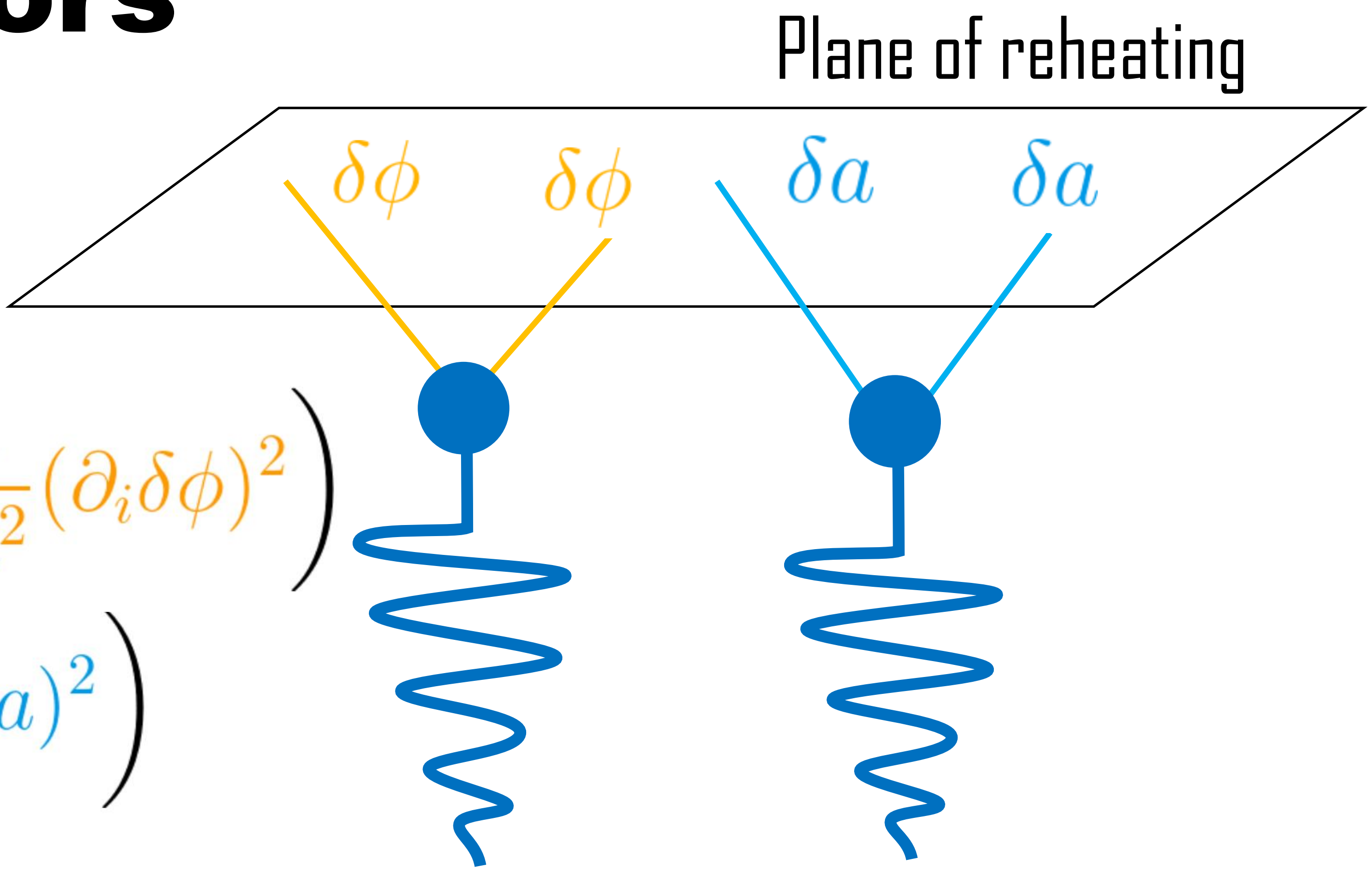
(Could be a phase transition or other more realistic approaches)



Mediator excited: ρ the radial mode

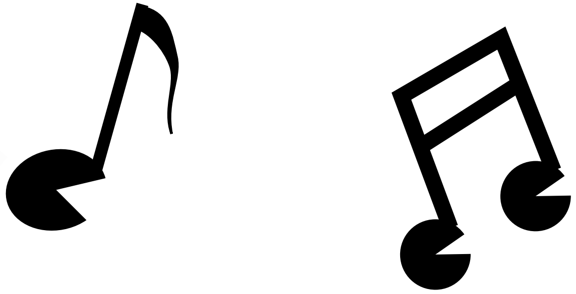
2-PT Correlators

$$\mathcal{L}_1^{(2)} \supset \frac{c f_I^2}{\Lambda^2}\frac{\rho_{\rm bkg}}{f_I}\left((\delta\dot{\phi})^2 - \frac{1}{R^2}(\partial_i\delta\phi)^2\right) + \frac{\rho_{\rm bkg}}{f_I}\left((\delta\dot{a})^2 - \frac{1}{R^2}(\partial_i\delta a)^2\right)$$



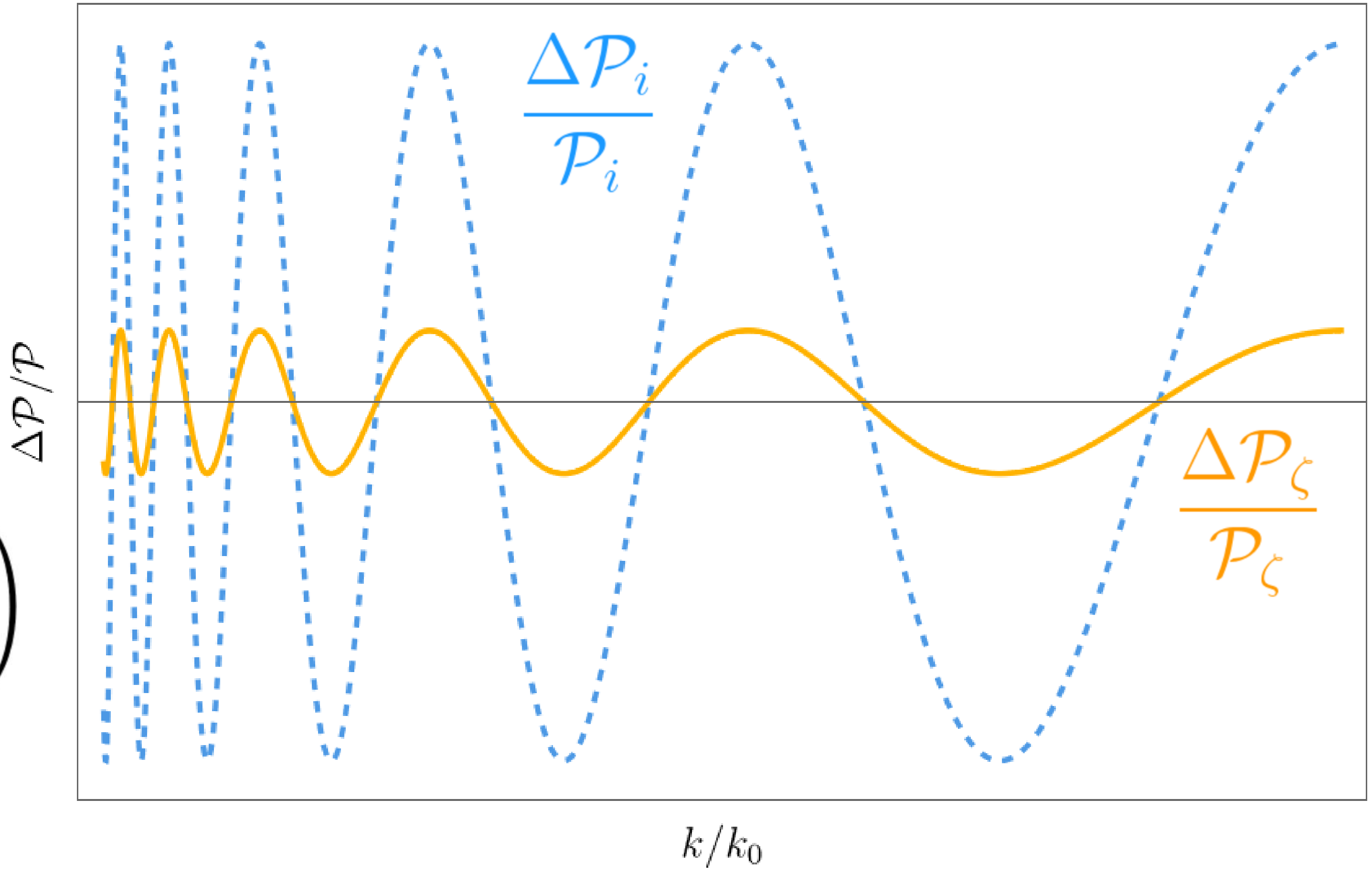
Scale-dependent oscillation in 2-pt, **LARGER** in isocurvature

“Music” of Dark Matter

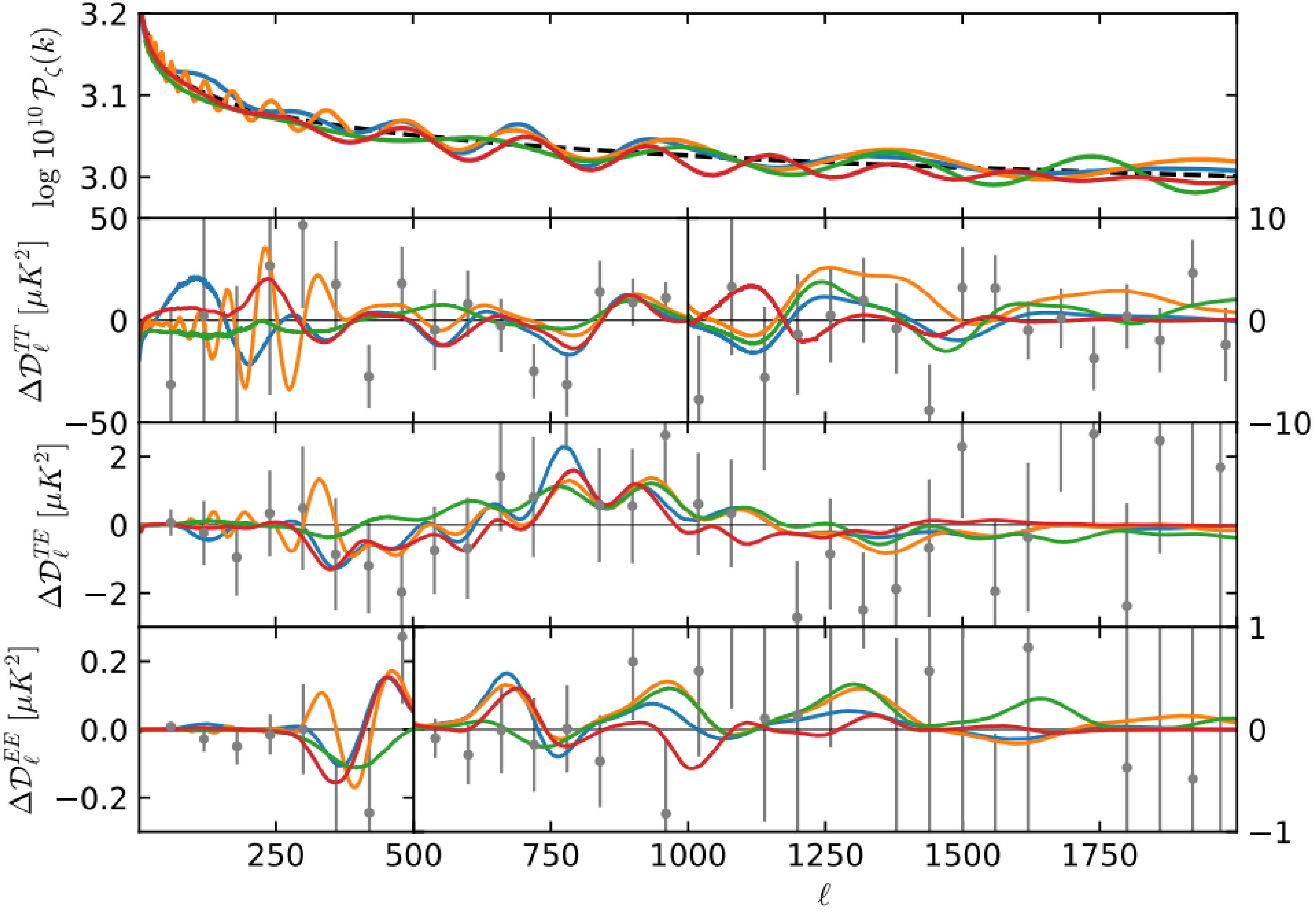


Feature ~ Reed

$$\frac{\Delta\mathcal{P}}{\mathcal{P}} \propto \sin\left(\frac{m_\rho}{H}\log\frac{k}{k_{\rm feature}}\right)$$

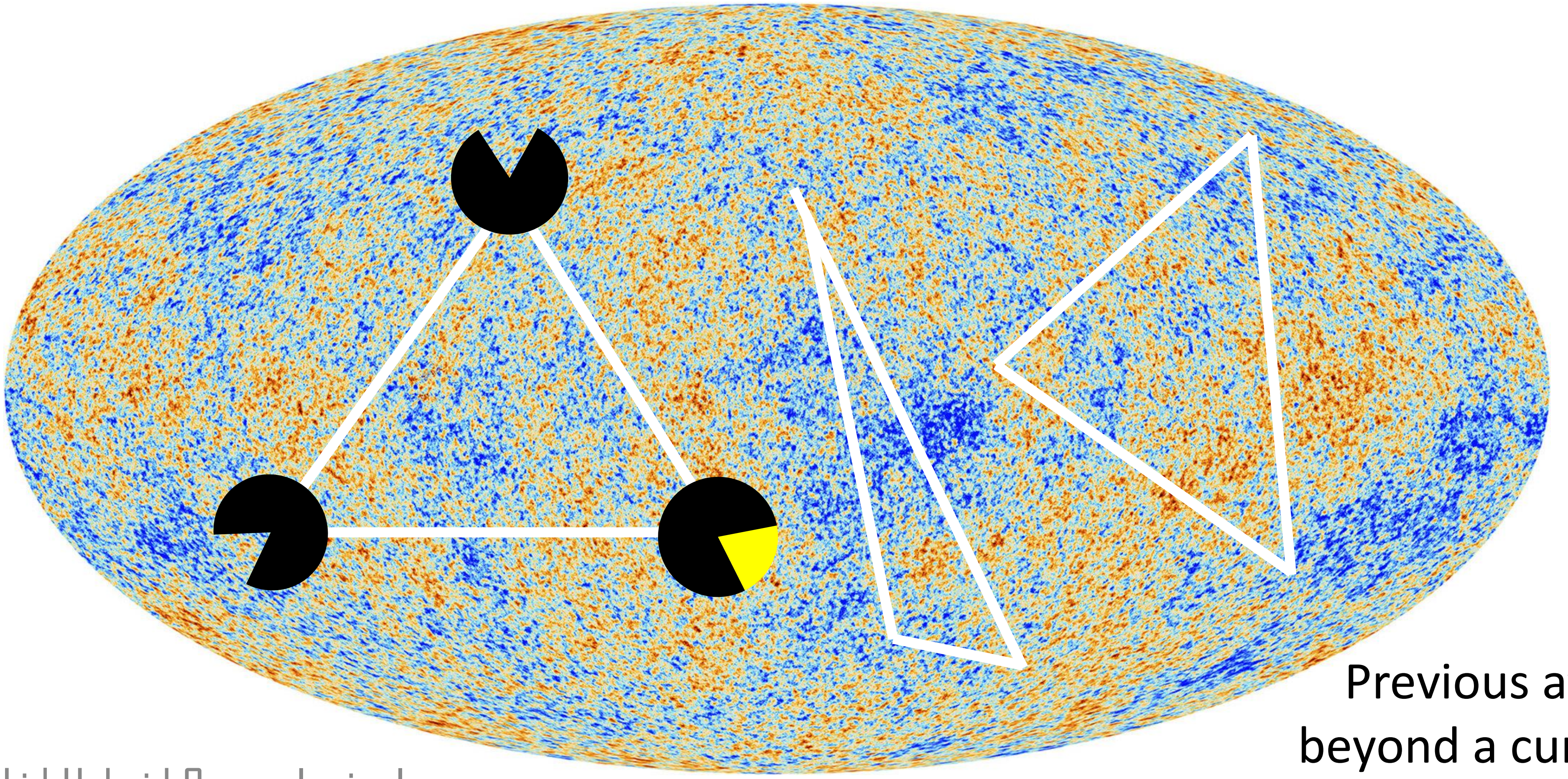


Observational Hints



M. Braglia, X. Chen and D. K. Hazra 2021; A. Antony, F. Finelli, D. K. Hazra and A. Shafieloo, 2022; M. Braglia, X. Chen, D. K. Hazra and L. Pinol, 2022

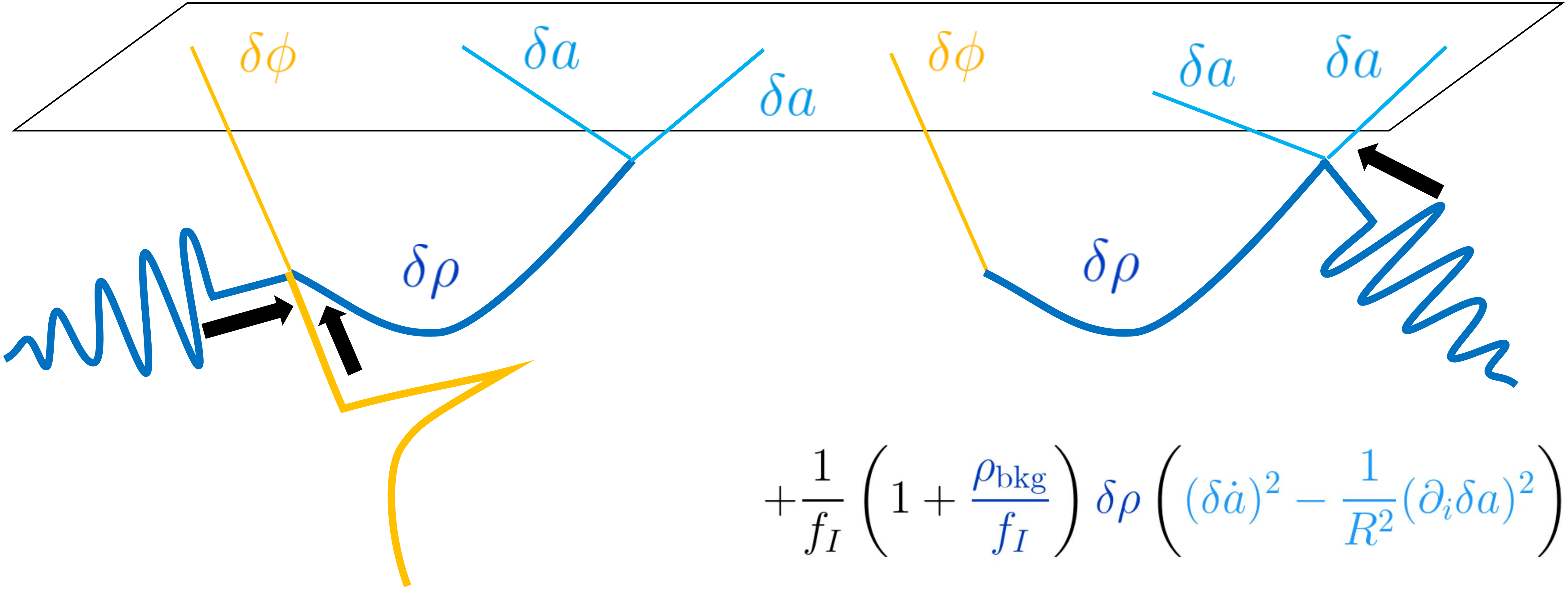
Cosmological Collider Signals of Hybrid Modes



Previous attempts to go beyond a curvature collider:

S. Lu, 2021; LL, S. Lu, Y. Wang, S. Zhou, 2021

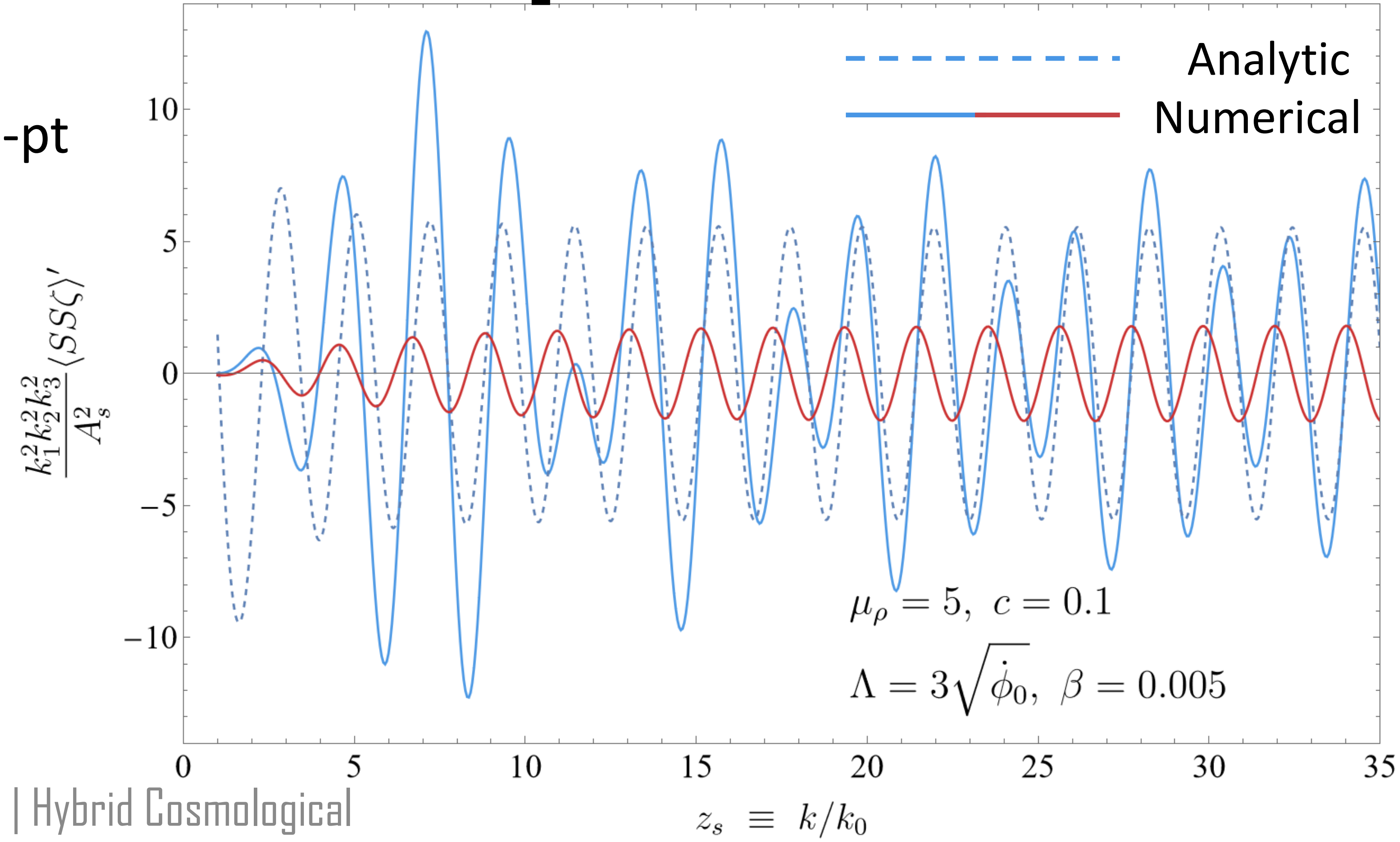
$$\frac{2cf_I\dot{\phi}_0}{\Lambda^2}\left(1+\frac{\dot{\phi}_1}{\dot{\phi}_0}+\frac{\rho_{\rm bkg}}{f_I}\right)\delta\dot{\phi}\delta\rho$$



$$+\frac{1}{f_I}\left(1+\frac{\rho_{\rm bkg}}{f_I}\right)\delta\rho\left((\delta\dot{a})^2-\frac{1}{R^2}(\partial_i\delta a)^2\right)$$

NG in the Equilateral limit

Sizable hybrid 3-pt signal



Lingfeng Li | Hybrid Cosmological Collider of Axion| 2303.03406

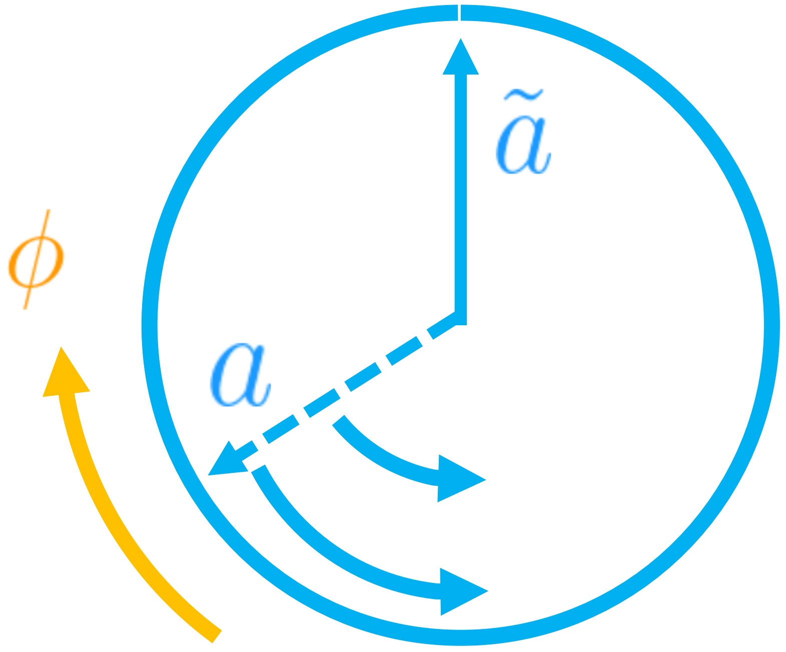
Scenario 2: Chemical Potential

$$\mathcal{L}_{\text{chem}} = -\frac{(\partial_\mu \phi)^2}{2} - |\partial_\mu \chi|^2 - V(\phi) - \frac{\lambda}{2}\left(|\chi|^2 - \frac{f_a^2}{2}\right)^2 - i\frac{\kappa \partial_\mu \phi}{\Lambda}(\chi^\dagger \partial^\mu \chi - \chi \partial^\mu \chi^\dagger)$$

Kinetic mixing between the massless axion and still massive inflaton:

$$\tilde{\rho} = \rho \ , \quad \tilde{a} = a - z\phi \ , \quad z \equiv \frac{\kappa f_I}{\Lambda}$$

$\tilde{a}$ will convert into isocurvature after the inflation ends



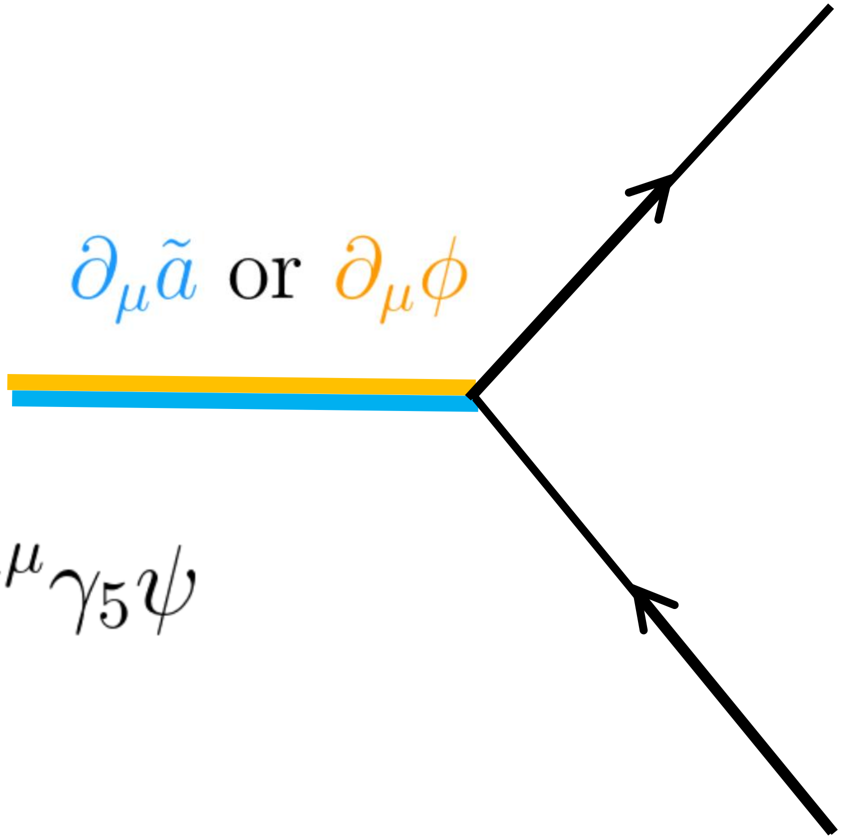
Axion-Fermion Coupling

Take a KSVZ-type theory w/ PQ symmetry

Using vector-like quarks to induce coupling to QCD:

J.E. Kim, 1979; M. A. Shifman, A. I. Vainshtein, V. I. Zakharov, 1980

"Native" in QCD axion scenarios



$$\frac{\partial_\mu a}{2f_I}\bar{\psi}\gamma^\mu\gamma_5\psi = \frac{\partial_\mu \tilde{a} + z\partial_\mu \phi}{2f_I}\bar{\psi}\gamma^\mu\gamma_5\psi$$

Chemical Potential

X. Chen, Y. Wang, and Z.-Z. Xianyu, 2018; L.-T. Wang and Z.-Z. Xianyu, 2019; A. Bodas, S. Kumar, R. Sundrum 2020; C. M. Sou, X. Tong, Y. Wang 2021

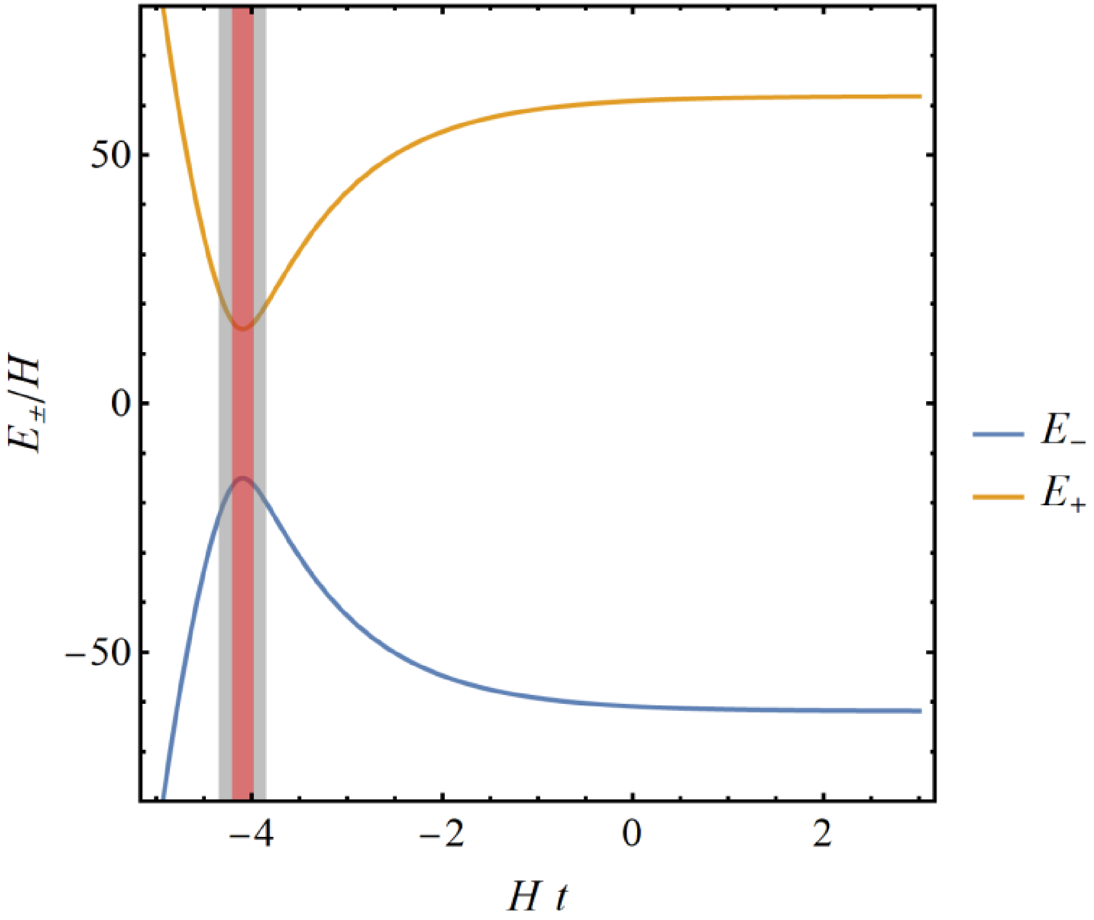
A rolling axion field introduces a chemical potential
Opposite sign for different fermion helicity

$$\frac{\partial_\mu a}{2f_I}\bar{\psi}\gamma^\mu\gamma_5\psi \quad \Rightarrow \quad \mu_c \equiv \frac{z\dot{\phi}_0}{2f_I}$$

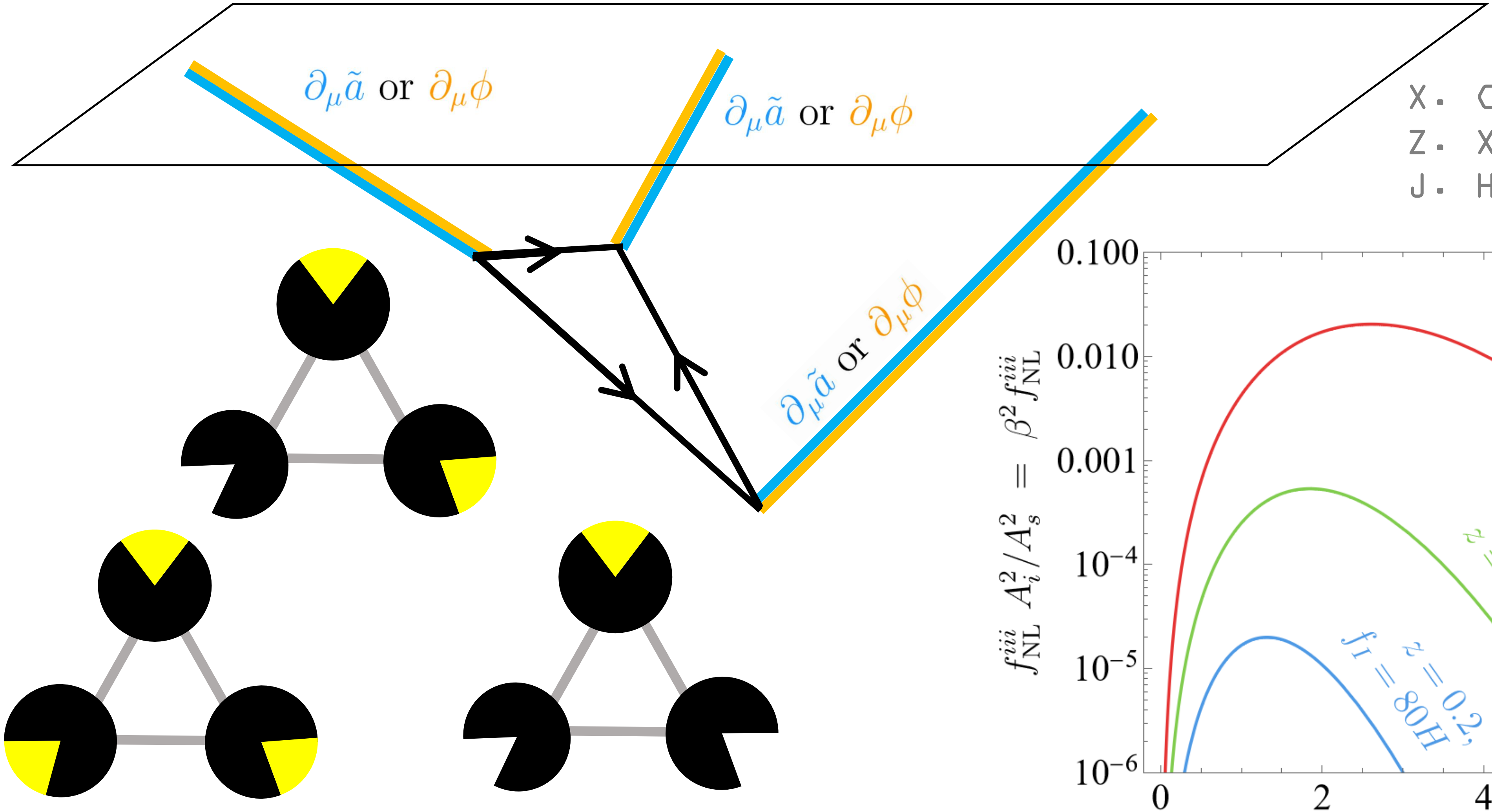
The chemical potential

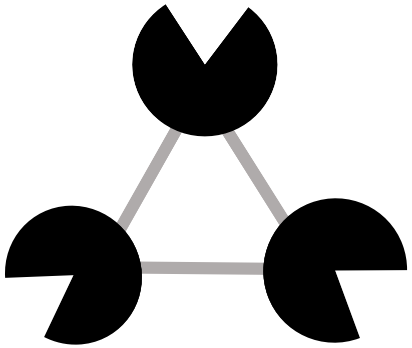
In de Sitter background, non-adiabatic transition happens with little suppression

$$\sim e^{\frac{-2\pi m_\psi}{H_I}} \Rightarrow \sim e^{\frac{-m_\psi^2}{\mu_c H_I}}$$

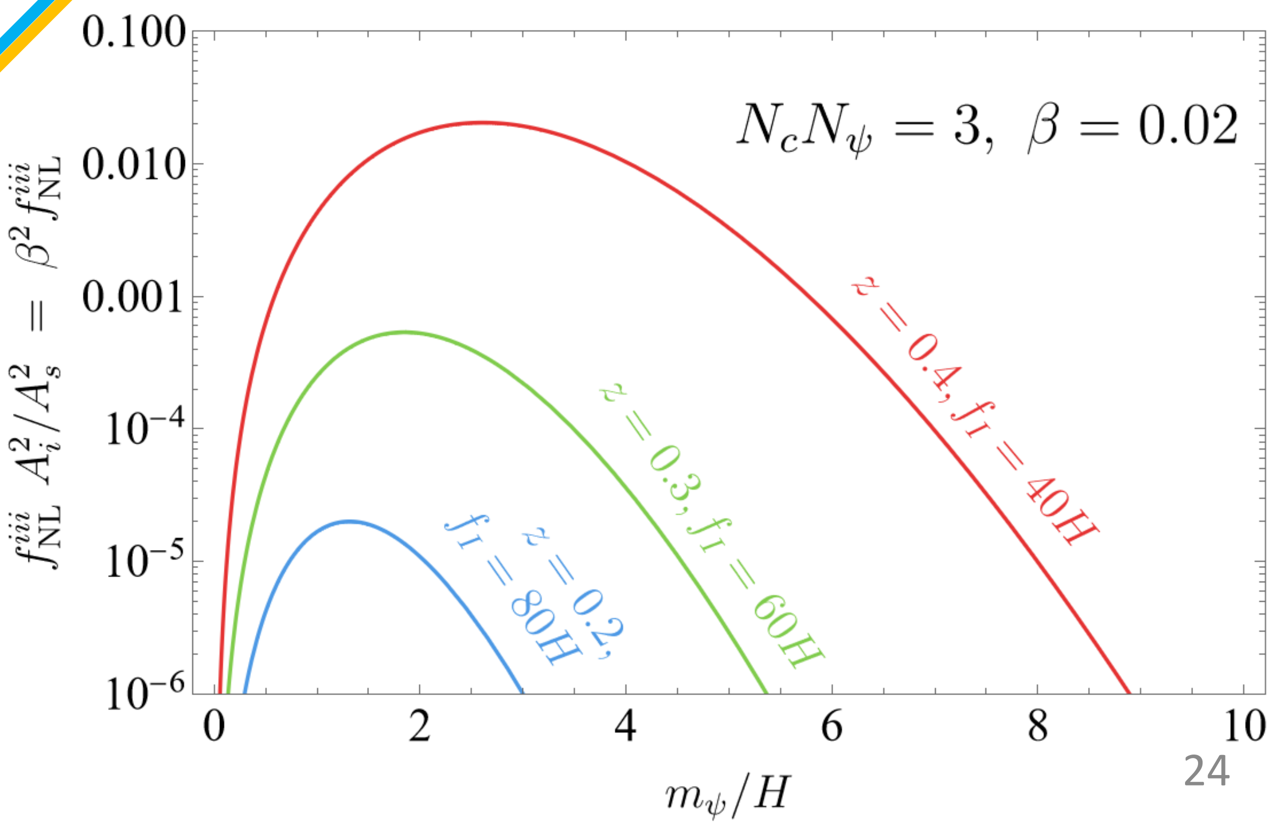


Hybrid Mode of All Types

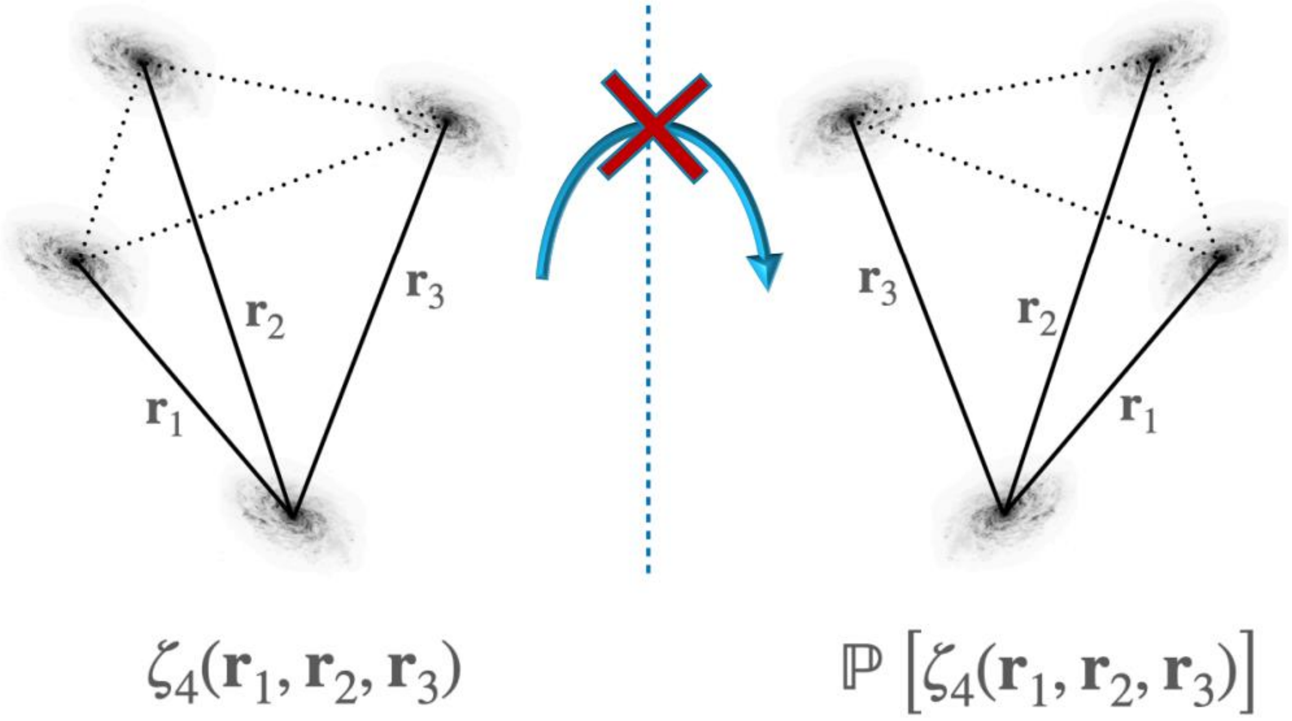


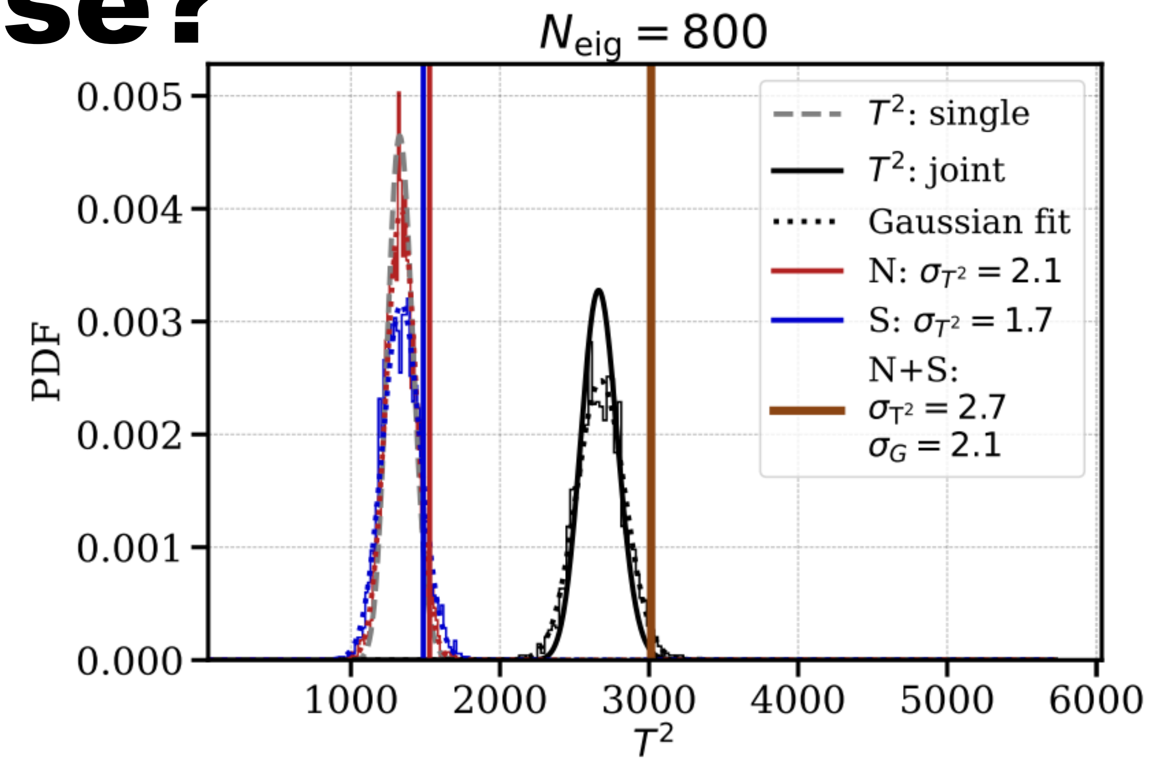


X. Chen, Y. Wang, and Z.-Z. Xianyu, 2018; A. Hook, J. Huang, D. Racco, 2019



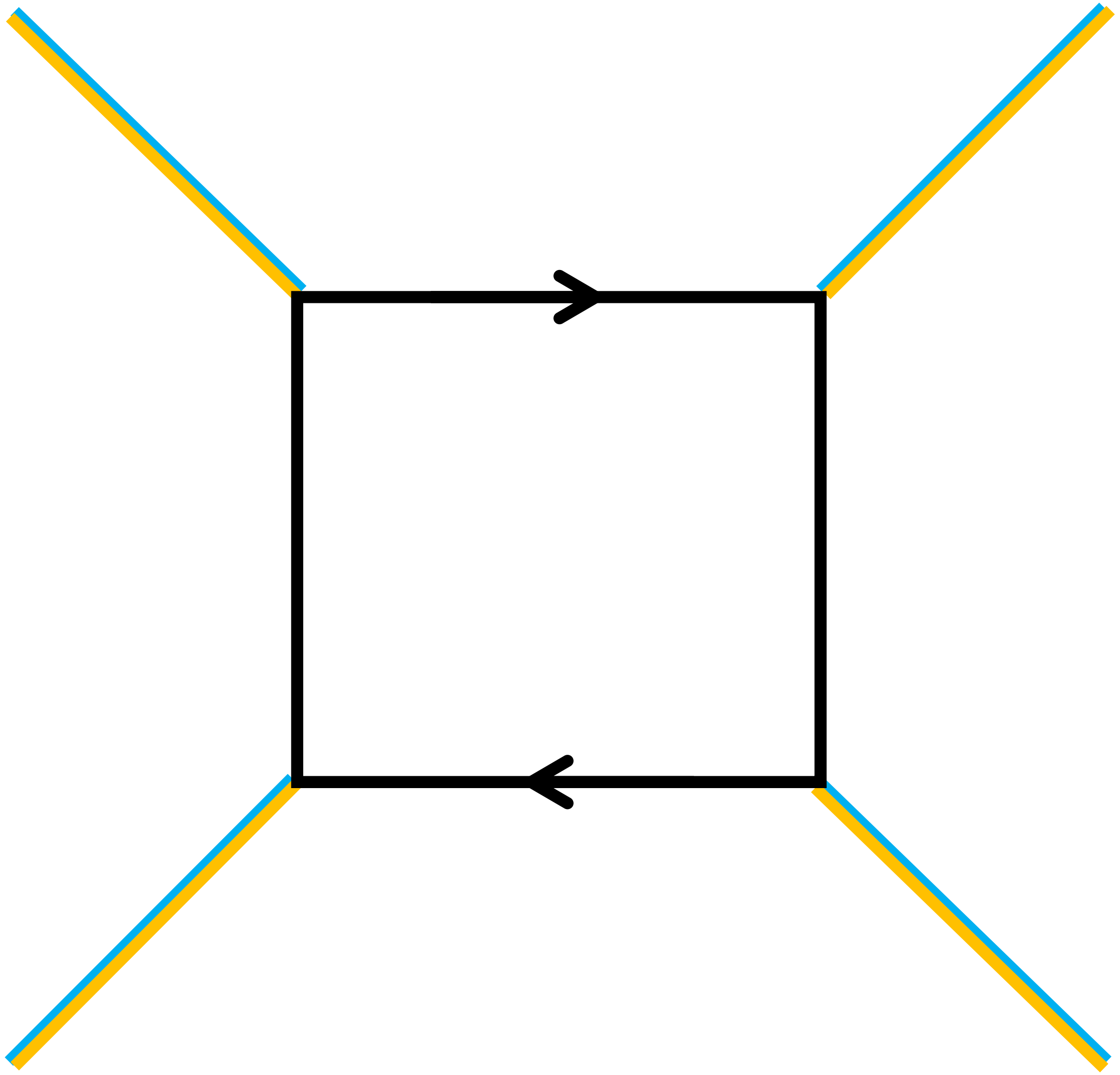
Parity Odd Universe?





Hints from LSS that the four-point trispectrum of galaxies is parity odd

O. Philcox, 2022; J. Hou, Z. Slepian, R.N. Cahn, 2022

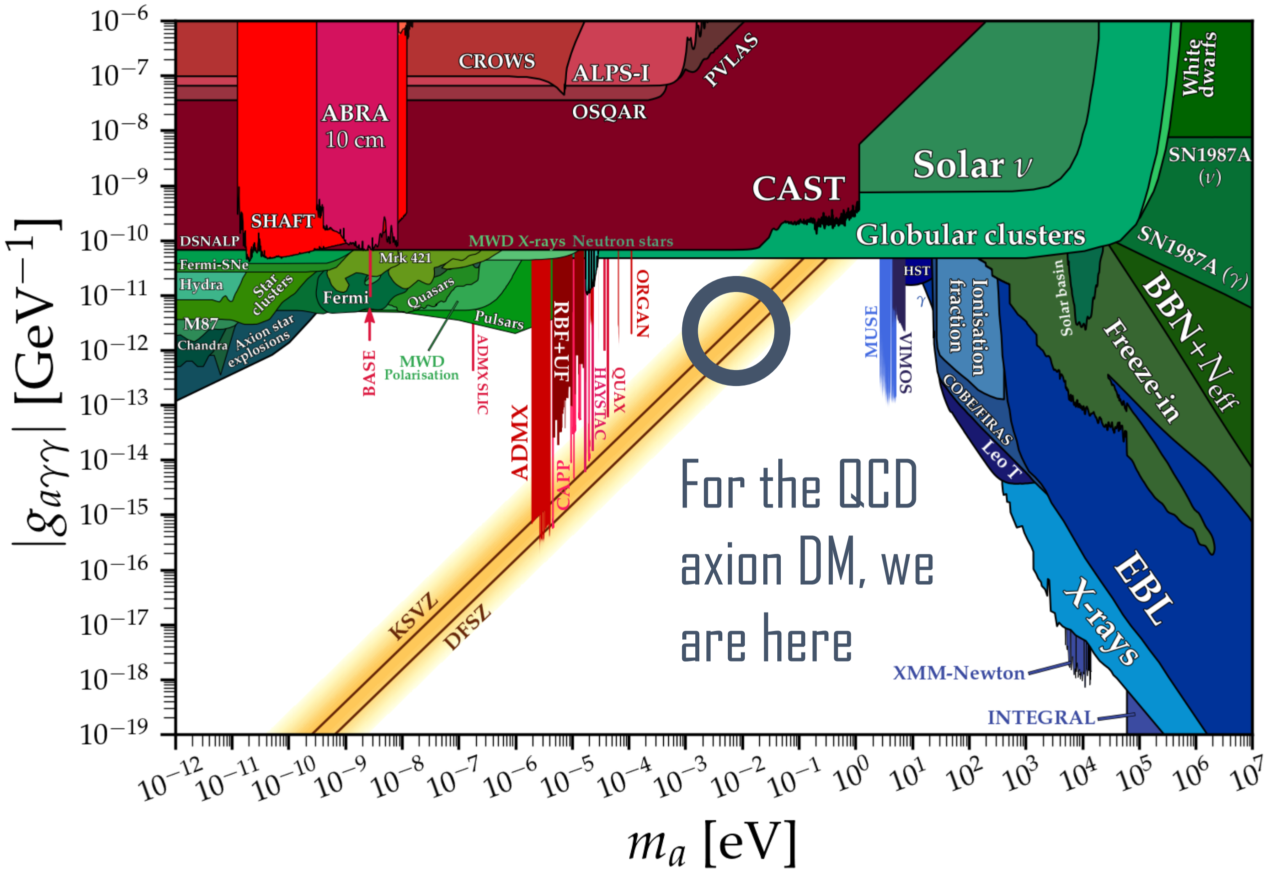


For the boson loop version, see X. Niu, M. H. Rahat, K. Sirinvasan, W. Xue 2022

See also
V. Gluscevic, M. Kamionkowski, 2010
T. Liu, X. Tong, Y. Wang , Z.-Z. Xianyu, 2019; R.N. Cahn, Z. Slepian, J. Hou, 2021; S. Jazayeri, S. Renaux-Petel, X. Tong, D. Werth, Y. Zhu, 2023

Misalignment Details

https://cajohare.github.io/AxionLimits



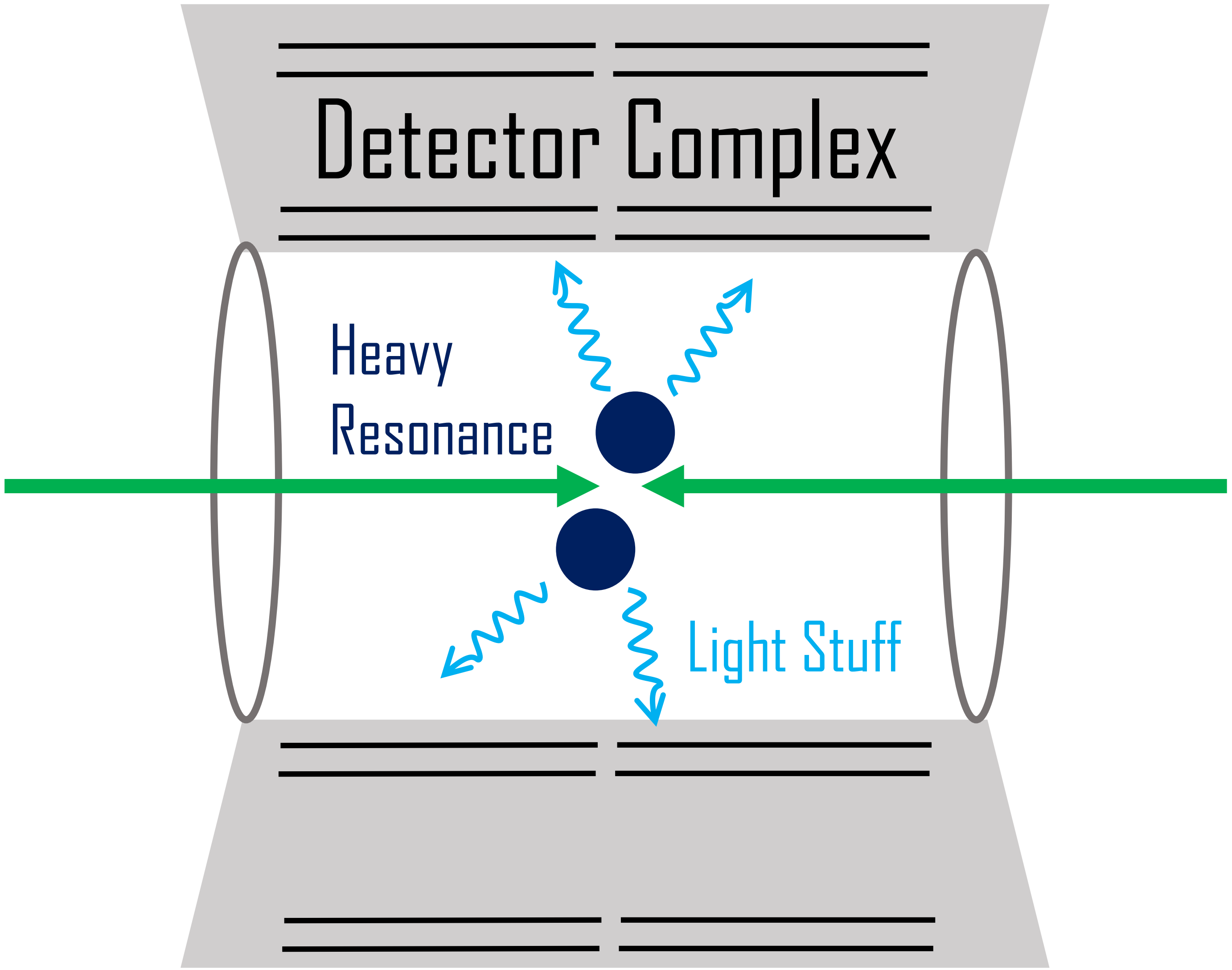
- ❑ May be a good way to pin down the inflationary scale:
  - ➢ f_a inferred from alternative methods (e.g. Helioscopes)
  - ➢ $H^2\theta^2 f^{1/3}$ from isocurvature spectrum
  - ➢ $H/(\lambda^{1/2} f_a)$ from cosmological collider

Summary

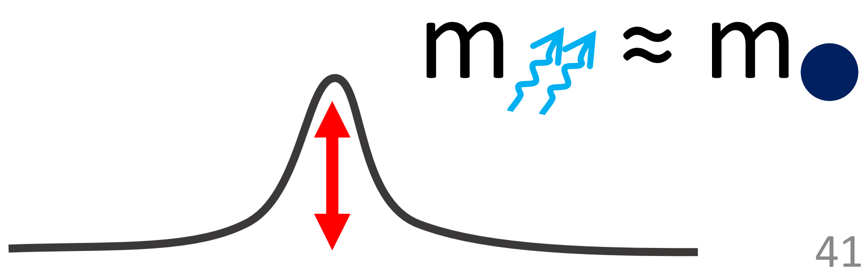
- Non-minimal coupling between the PQ field and inflaton can do a lot
- Rich cosmological signals in both curvature and isocurvature modes
- Applies to axion-like-particles
- May point out the scale of inflation
- Potential relation to the (C)P properties of our universe

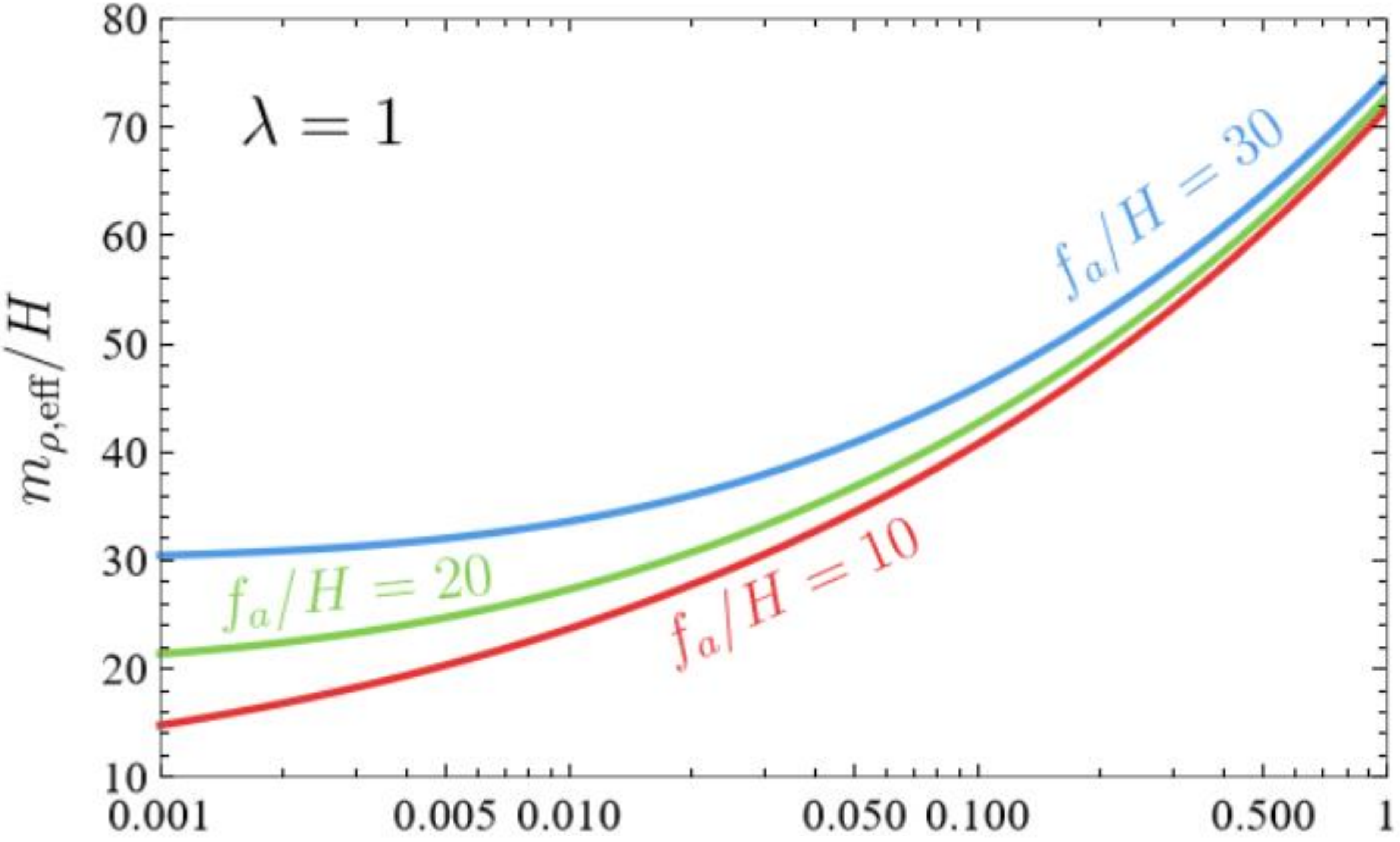
BAKCUPS &
EXTRA THOUGHTS

Cosmological Collider: Start from an Actual Collider



- Precisely prepared initial state: fixed Ecm, luminosity, direction…
- Short-lived resonances: the detector surfaces are too far compared to $m_{\bullet}^{-1}$
- Multi-species: γ, $e^{\pm}$, $\pi^{\pm}$, $K^{\pm}$ …
- Flat space time: invariant mass





$$q \equiv c f_I^2/\Lambda^2 \ll 1$$

In-in Formalism

$$\langle W(t)\rangle = \left\langle \left(Te^{-i\int_{-\infty}^{t} H_{\rm int}(t')dt'}\right)^{\dagger} \; W(t) \; \left(Te^{-i\int_{-\infty}^{t} H_{\rm int}(t'')dt''}\right)\right\rangle$$

$$\langle W(t)\rangle = \sum_{N=0}^{\infty} i^N \int_{-\infty}^{t} dt_N \int_{-\infty}^{t_N} dt_{N-1} \ldots \int_{-\infty}^{t_2} dt_1 \, \langle [H_{\rm int}(t_1), [H_{\rm int}(t_2), \ldots [H_{\rm int}(t_N), W(t)] \ldots]]\rangle$$

Numerical Benchmark

$$
\begin{aligned}
\left|\frac{\Delta P_\zeta}{P_\zeta}\right|_{\text{clock;amp}} &= \frac{2c^2 bV_{\phi 0} f_I^2}{\Lambda^4 H^2}\sqrt{\frac{2\pi}{\mu_\rho^3}} \\
&\approx\ 0.019\left(\frac{q}{0.02}\right)^2 \left(\frac{bV_{\phi 0}}{0.3\dot{\phi}_0^2}\right)\left(\frac{\dot{\phi}_0}{(60H)^2}\right)^2 \left(\frac{40H}{f_I}\right)^{7/2}\left(\frac{1}{\lambda}\right)^{3/4}
\end{aligned}
$$

$$
\begin{aligned}
\left|\frac{\Delta P_i}{P_i}\right|_{\text{clock;amp}} &\approx \frac{2cbV_{\phi 0}}{\Lambda^2 H^2}\sqrt{\frac{2\pi}{\mu_\rho^3}} \\
&\approx\ 0.96\left(\frac{q}{0.02}\right)\left(\frac{bV_{\phi 0}}{0.3\dot{\phi}_0^2}\right)\left(\frac{\dot{\phi}_0}{(60H)^2}\right)^2 \left(\frac{40H}{f_I}\right)^{7/2}\left(\frac{1}{\lambda}\right)^{3/4}
\end{aligned}
$$

Numerical Approximation

X. Chen, Y. Wang, and Z.-Z. Xianyu, 2018;
A. Hook, J. Huang, D. Racco, 2019

≥3 if QCD

$$\left|f_{\mathrm{NL}}^{iii}\right| \frac{A_i^2}{A_s^2} \simeq \frac{\boxed{N_c N_\psi} \beta^{3/2}}{6\pi\sqrt{A_s}} \left(\frac{H}{2f_I}\right)^3 \left(\frac{m_\psi}{H}\right)^3 \frac{\mu_c^2\sqrt{m_\psi^2+\mu_c^2}}{H^3}$$

$$\times \frac{e^{\pi\mu_c/H}\Gamma\left(-i\sqrt{m_\psi^2+\mu_c^2}/H\right)^2\Gamma\left(2i\sqrt{m_\psi^2+\mu_c^2}/H\right)^3}{2\pi\Gamma\left[i\left(\sqrt{m_\psi^2+\mu_c^2}+\mu_c\right)/H\right]^3\Gamma\left[1+i\left(\sqrt{m_\psi^2+\mu_c^2}-\mu_c\right)/H\right]}$$