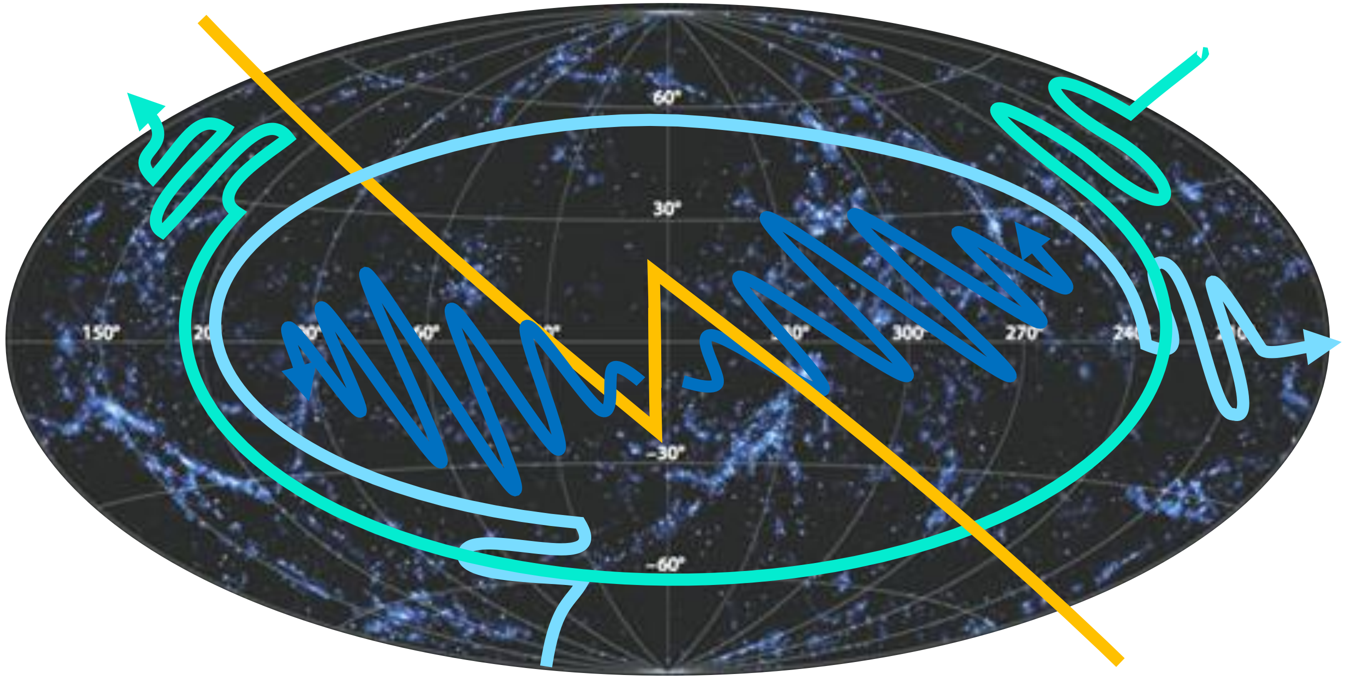
Hybrid Cosmological Collider of Axion



Lingfeng Li

Brown University

Jun, 2023

Cosmology from Home

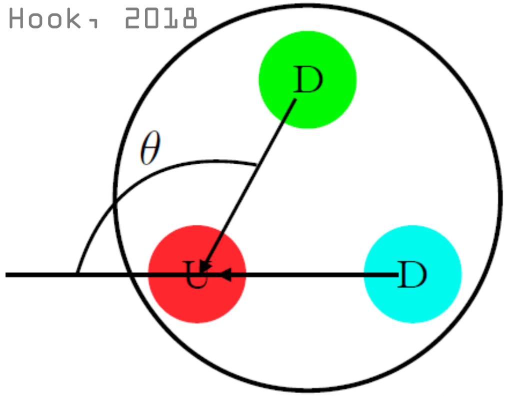
Based on

2303.03406, With Xingang Chen & JiJi Fan

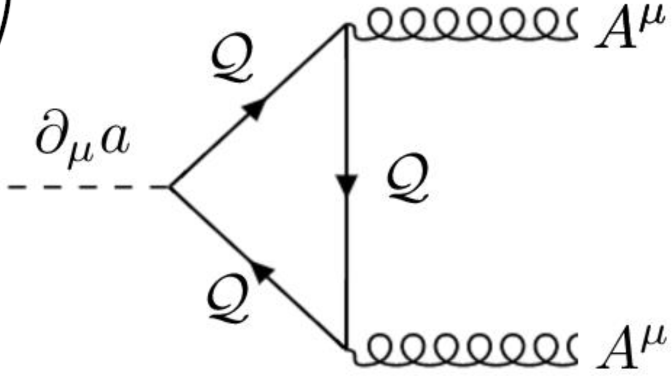
Strong CP, QCD Axion, & DM

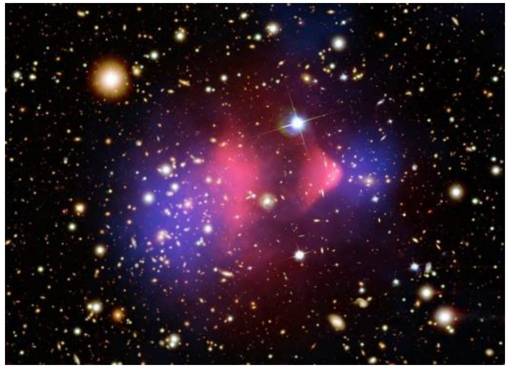
QCD axion: A pseudo Nambu-Goldstone Boson (pNGB) of a the Peccei-Quinn symmetry, the strong CP θ angle are set to zero at the minima

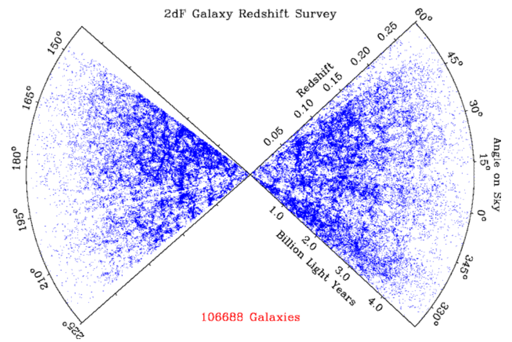
A. Hook, 2018

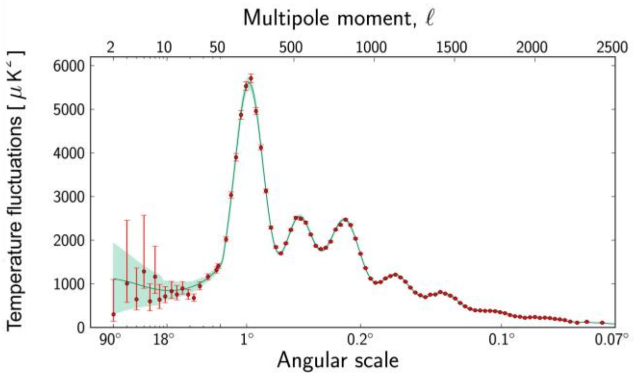


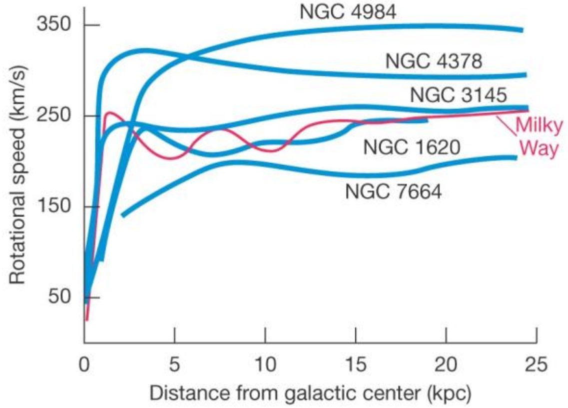
$$\mathcal{L} \supset \theta \frac{g^2}{32\pi^2} G\tilde{G}$$









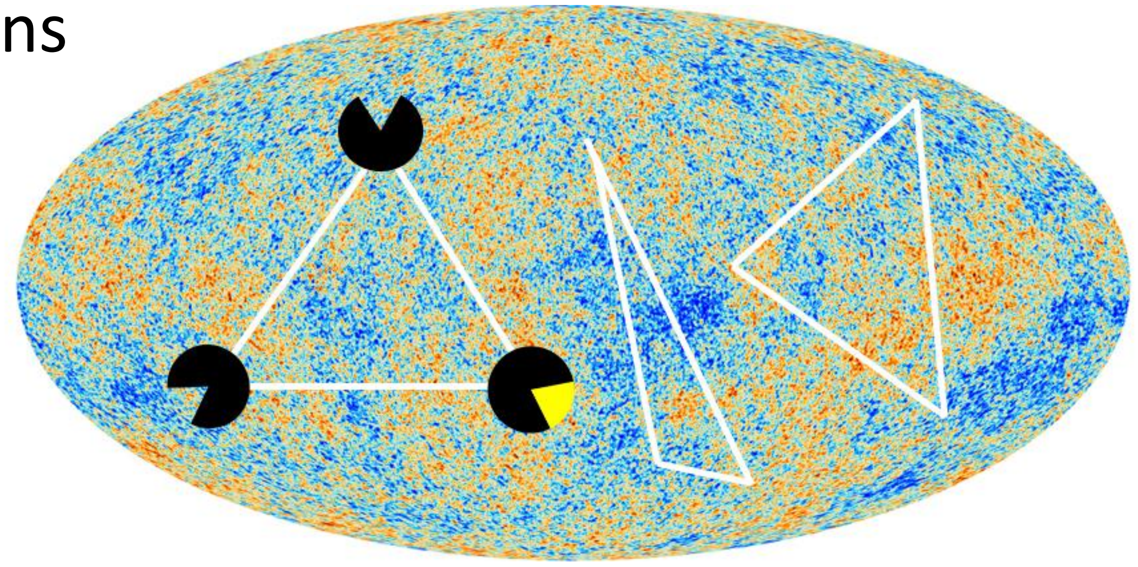


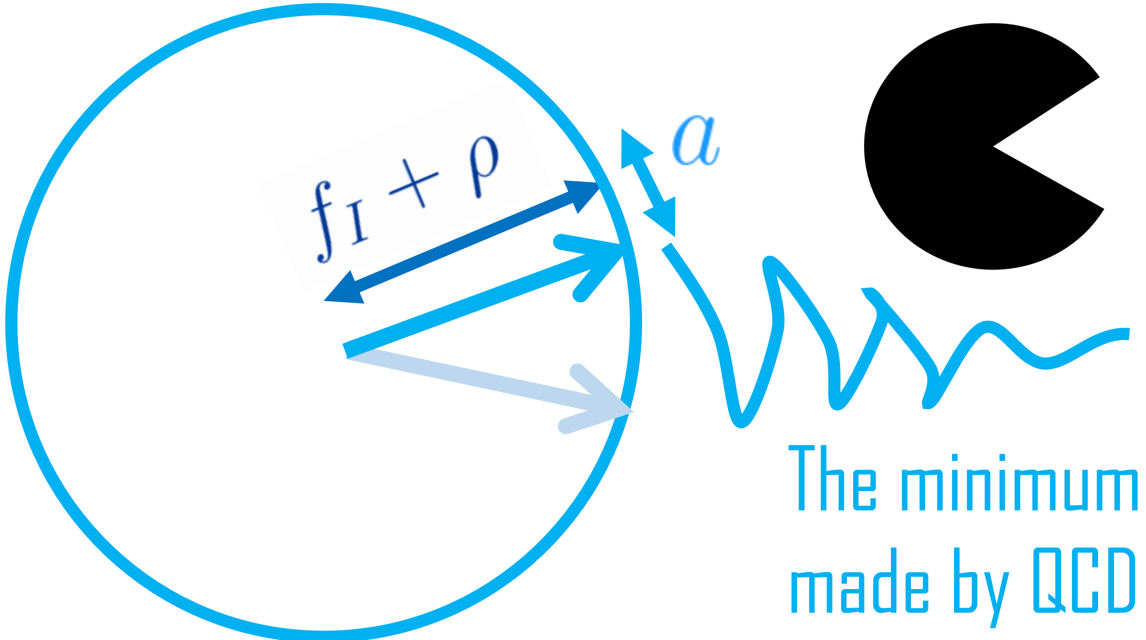
Peccei, Quinn; Weinberg; Wilczek; Kim; Shifman, Vainshtein, Zakharov; Zhitnitsky; Dine, Fischler, Srednicki, 1977-1981

Misalignment & Cosmological Collider

- $f_a > H_I / 2\pi$ with inflationary Hubble and PQ symmetry is not restored during (p)reheating
- DM created when $H \lesssim m_a$, non-relativistic particle created by coherent field oscillations
- CDM isocurvature given by quantum fluctuations of the axionic phase

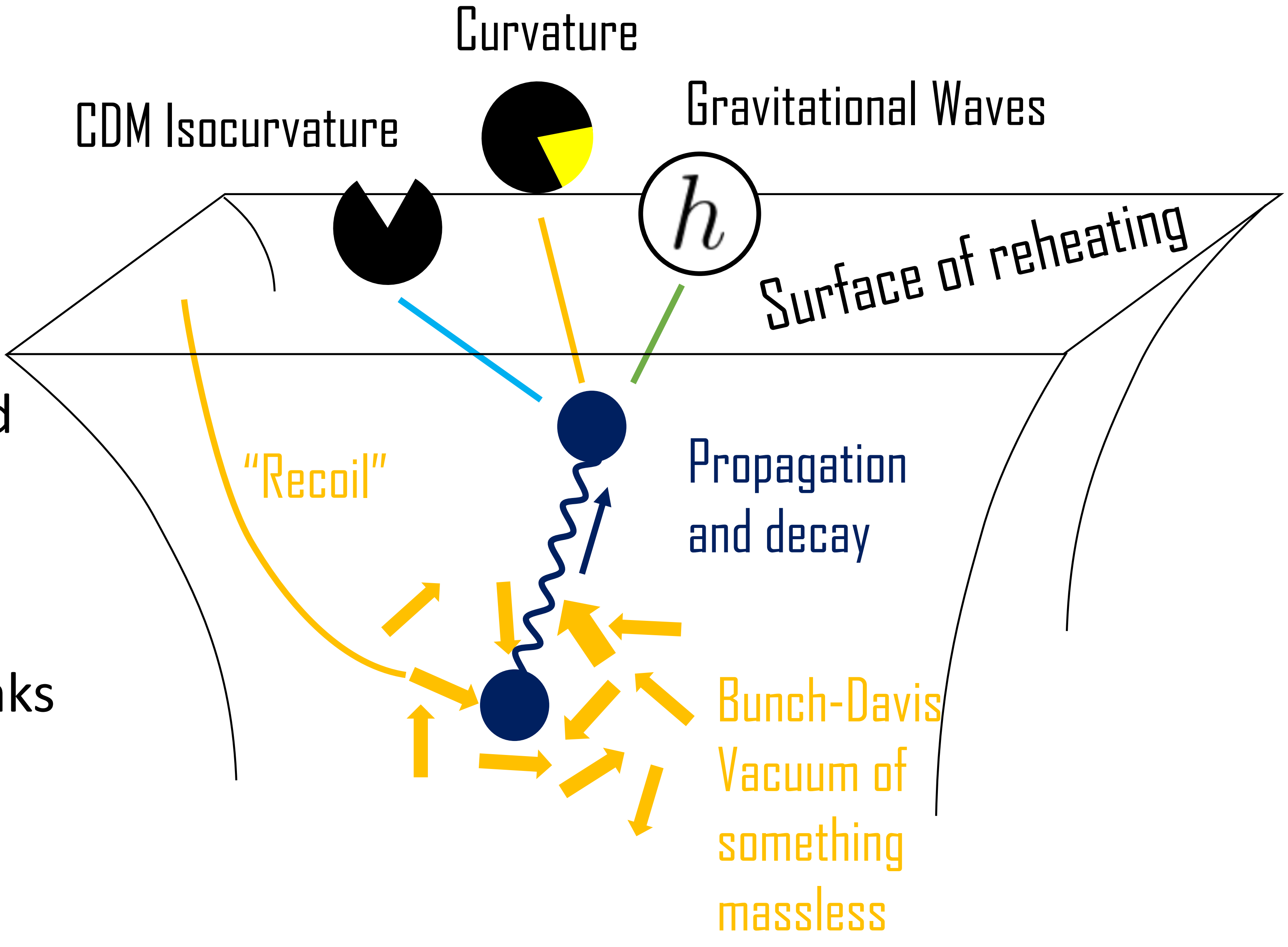
X. Chen, Y. Wang, 2009; Arkani-Hamed, Maldacena, 2015





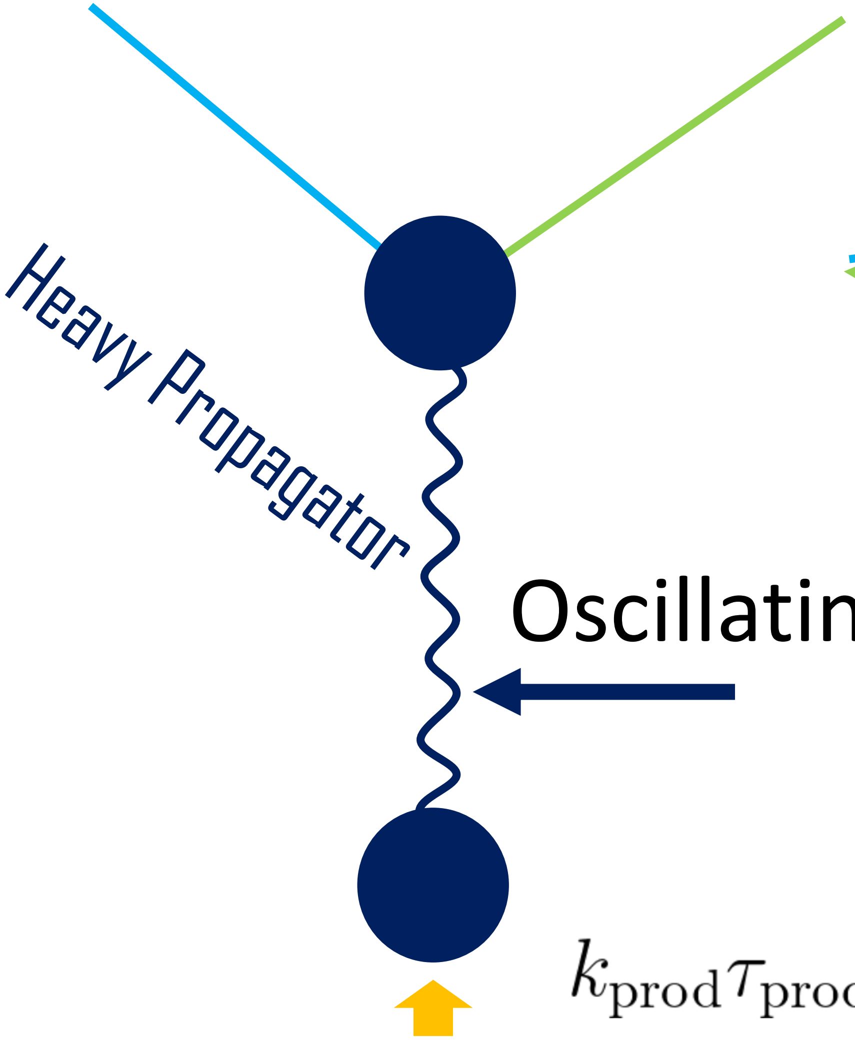
Specific (hybrid) correlators involving CDM isocurvature modes across the sky: a (hybrid) isocurvature collider

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



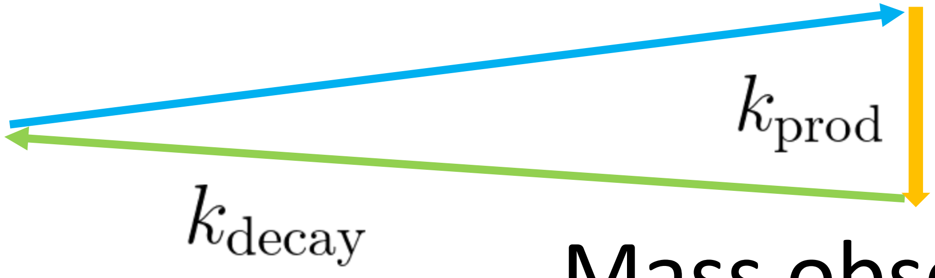
Sketch of a Cosmological Collider

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



Oscillating as: e^{imt}

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



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

Mass observed through phases:

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

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

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

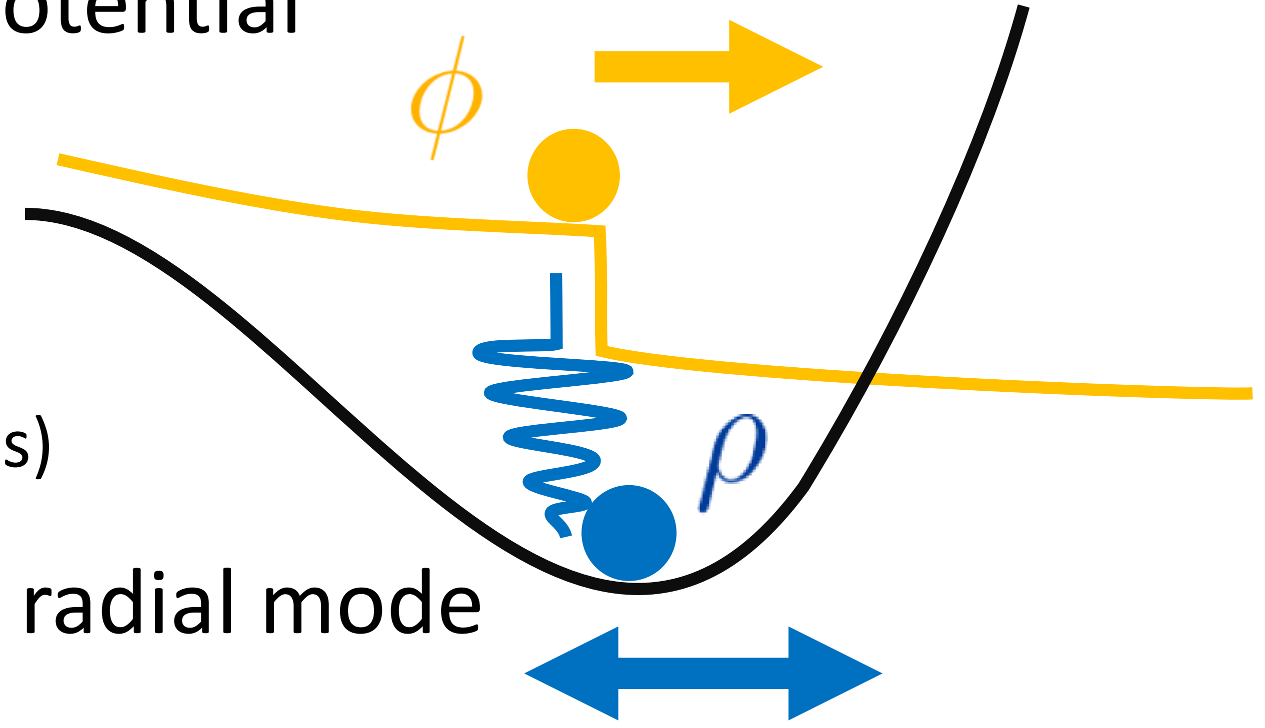
Scenario 1: Classical Feature

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

+ Toy feature: a step in potential

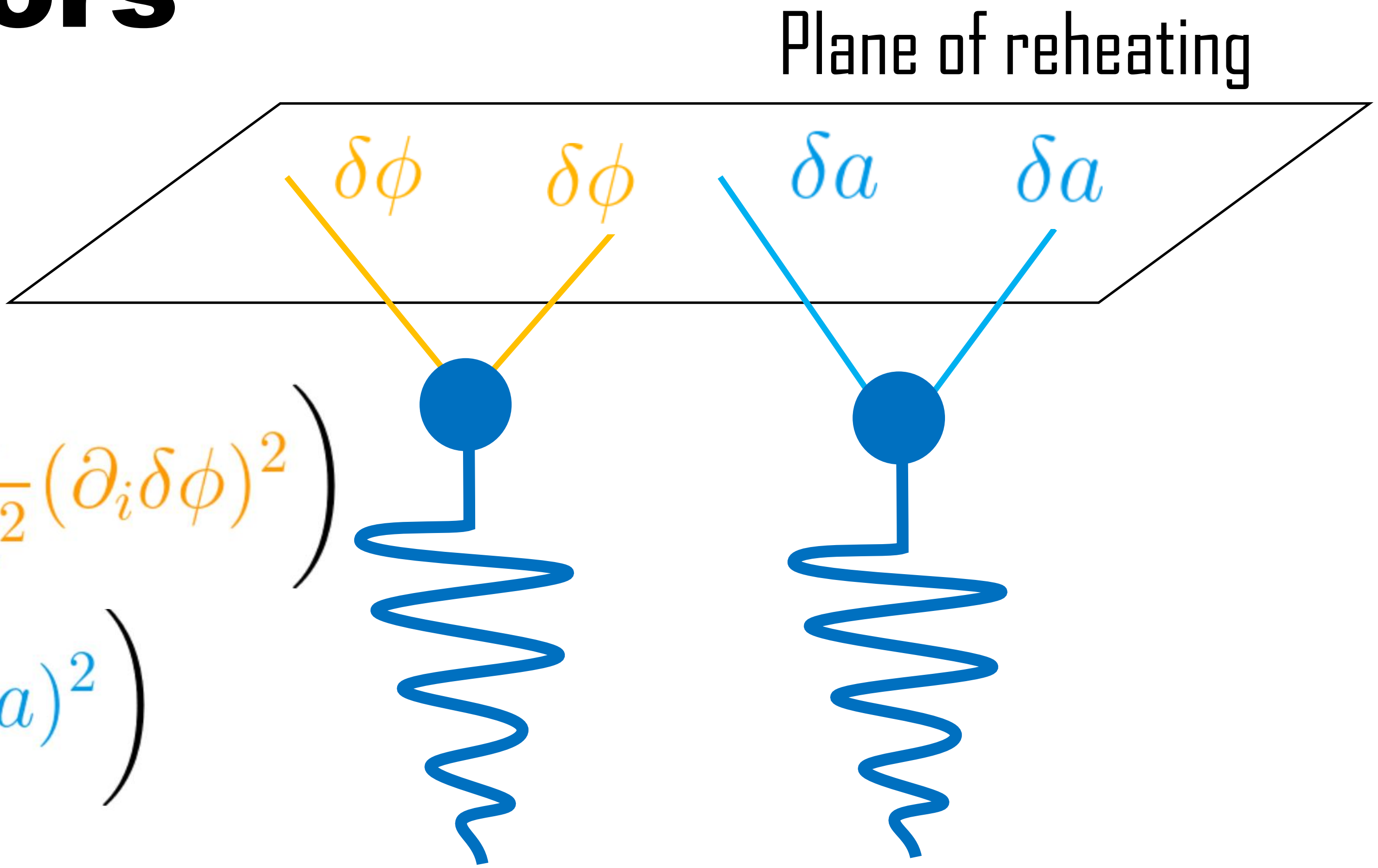
$$V_{\phi 1}(\phi) = -bV_{\phi 0}\,\theta(\phi - \phi_s)$$

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



Mediator excited: ρ the radial mode

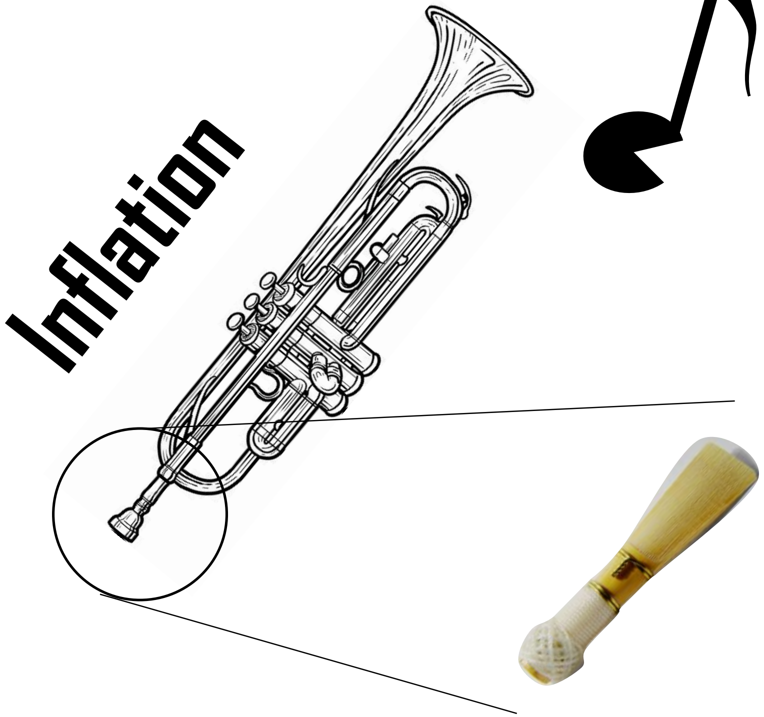
2-PT Correlators

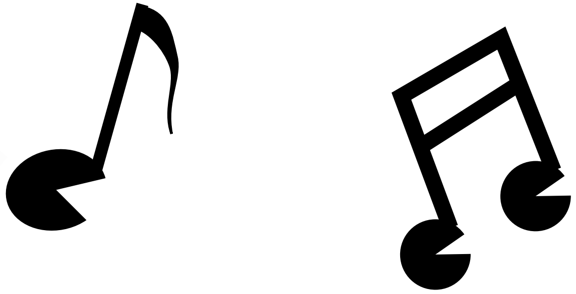


$$\mathcal{L}_1^{(2)} \supset \frac{c f_I^2}{\Lambda^2}\frac{\rho_{\rm bkg}}{f_I}\left((\delta\dot{\phi})^2 - \frac{1}{R^2}(\partial_i\delta\phi)^2\right) + \frac{\rho_{\rm bkg}}{f_I}\left((\delta\dot{a})^2 - \frac{1}{R^2}(\partial_i\delta a)^2\right)$$

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

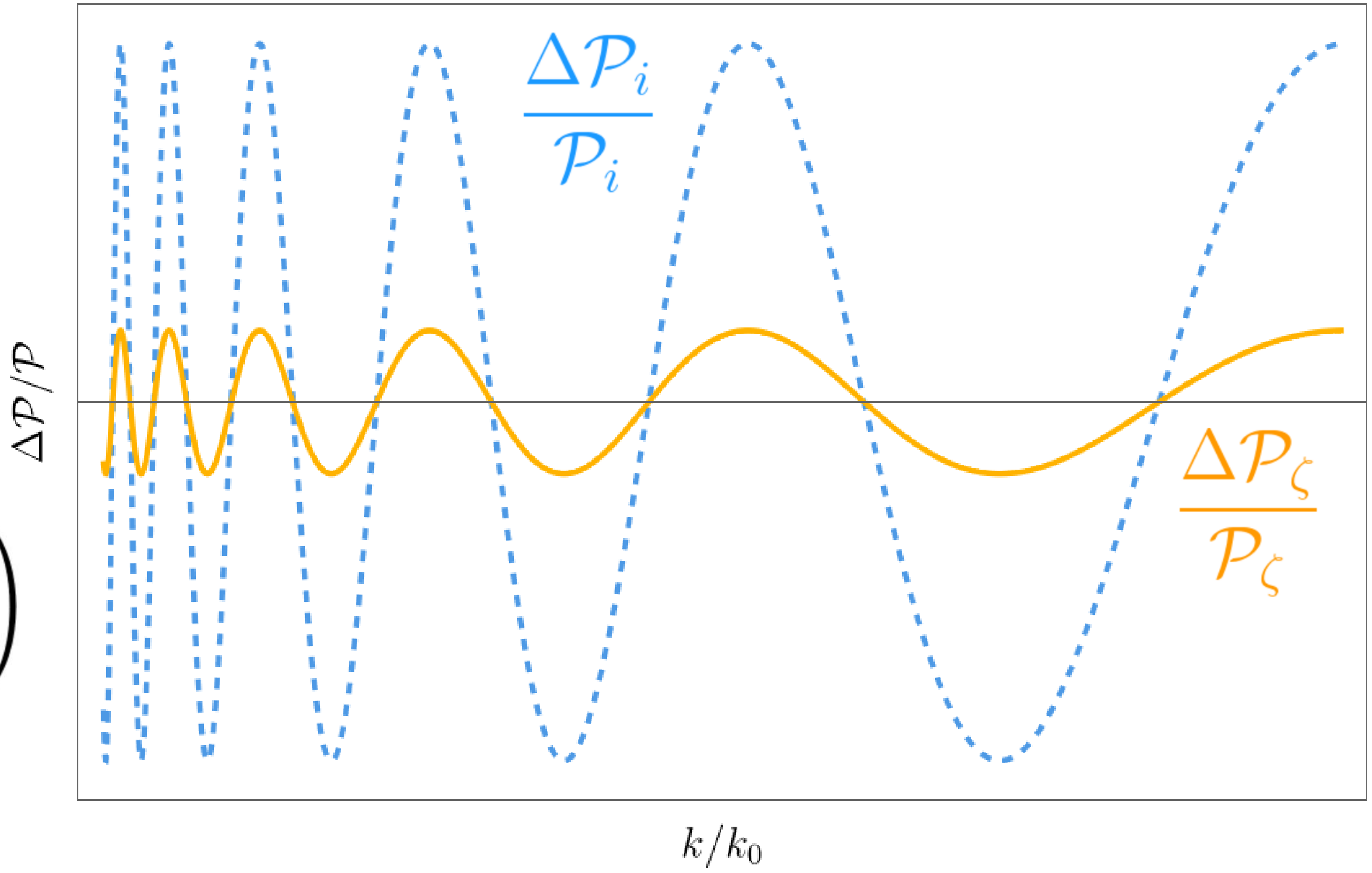
“Music” of Dark Matter





Feature ~ Reed

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



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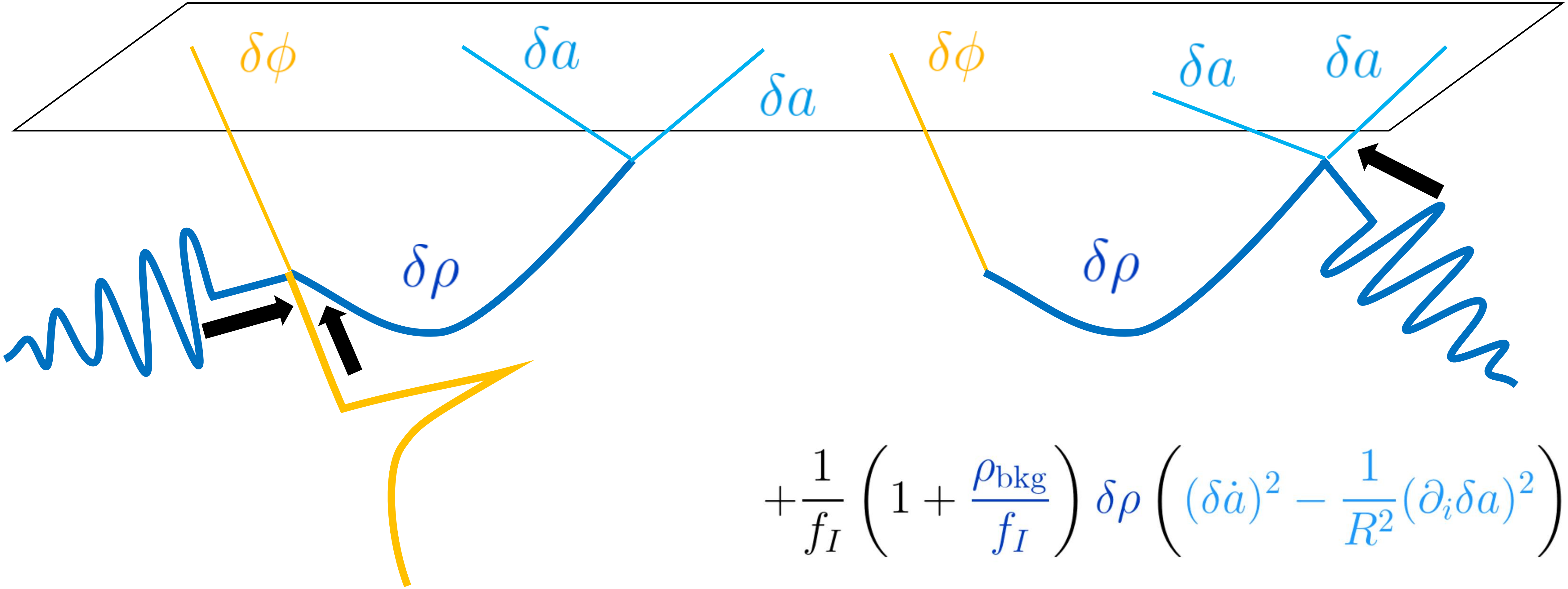
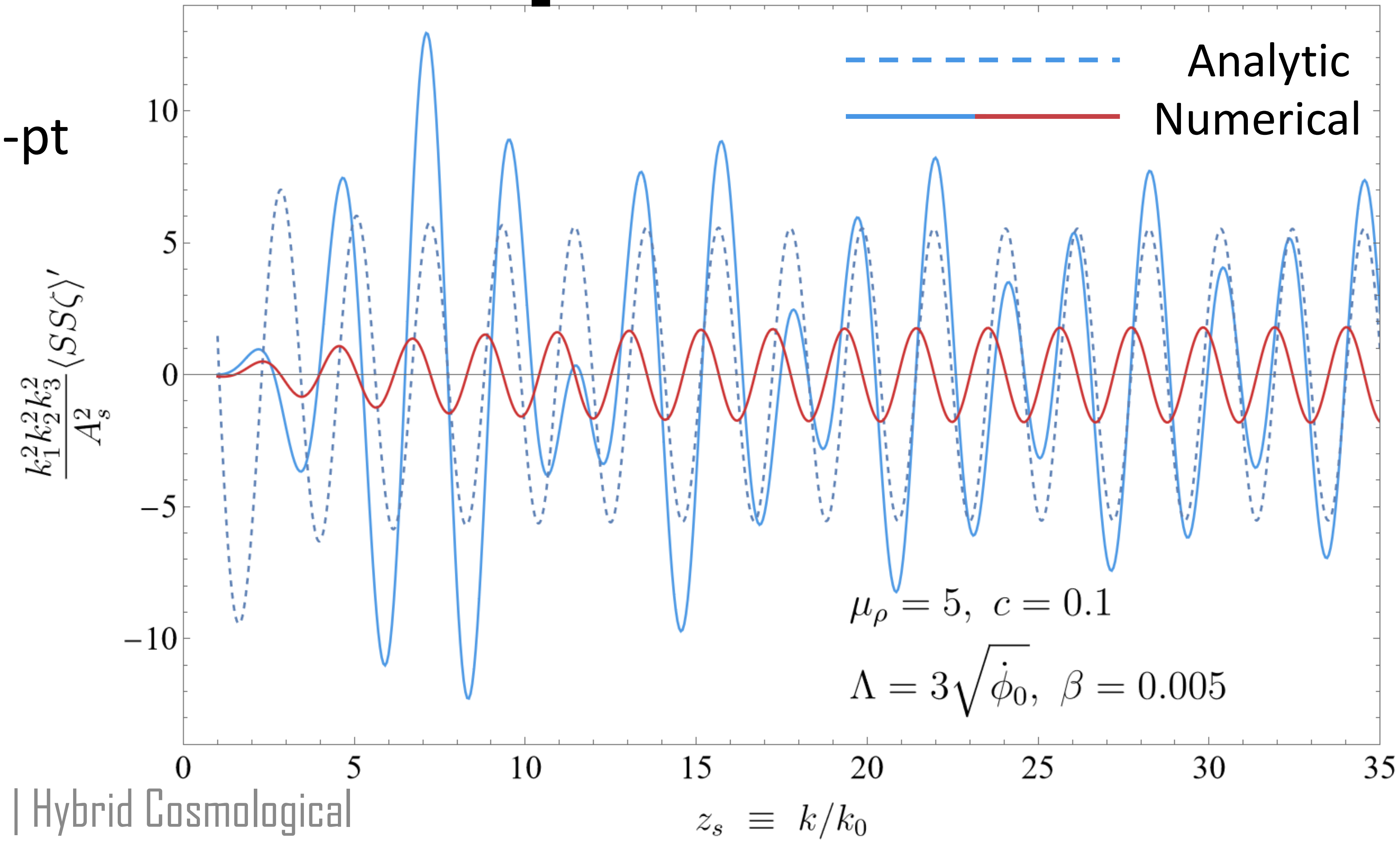
$$\frac{2cf_I\dot{\phi}_0}{\Lambda^2}\left(1+\frac{\dot{\phi}_1}{\dot{\phi}_0}+\frac{\rho_{\text{bkg}}}{f_I}\right)\delta\dot{\phi}\delta\rho$$



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

NG in the Equilateral limit

Sizable hybrid 3-pt signal



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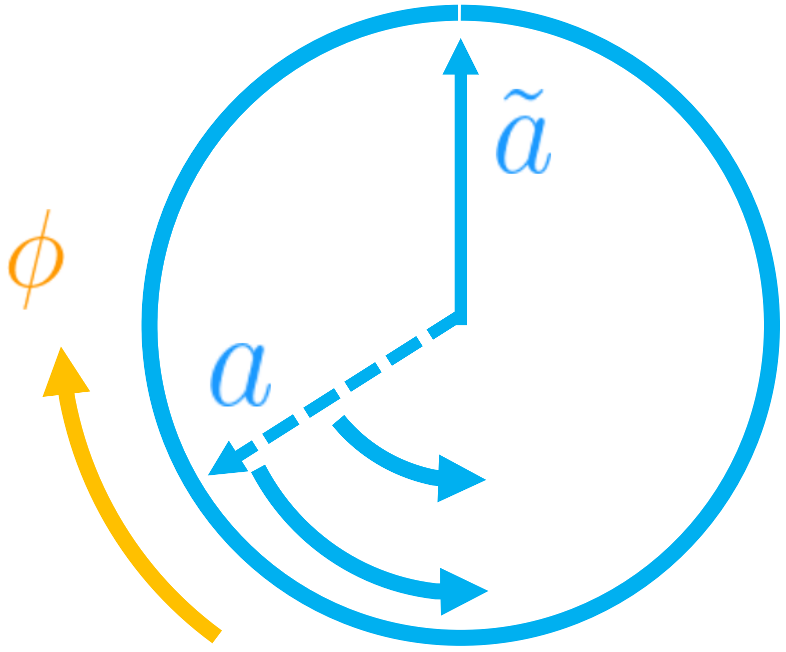
Scenario 2: Chemical Potential

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

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 later



Axion-Fermion Coupling and Chemical Potential

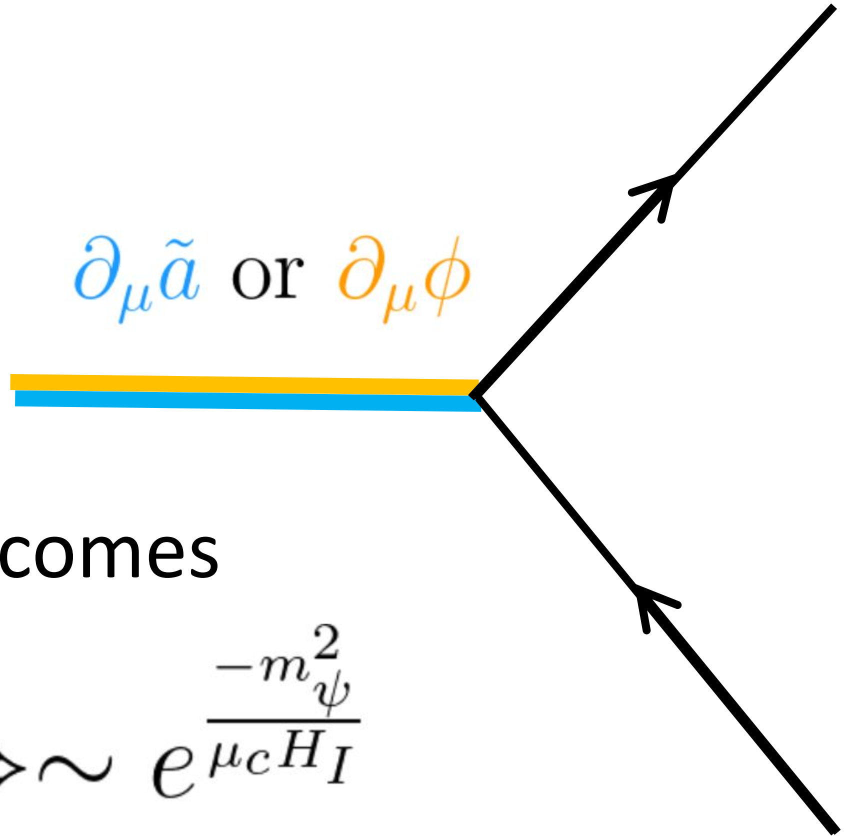
J.E. Kim, 1979; M. A. Shifman, A. I. Vainshtein, V. I. Zakharov, 1980

KSVZ-type: axion couple to vector-like quarks

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

Different helicities get different sign of chemical potential:

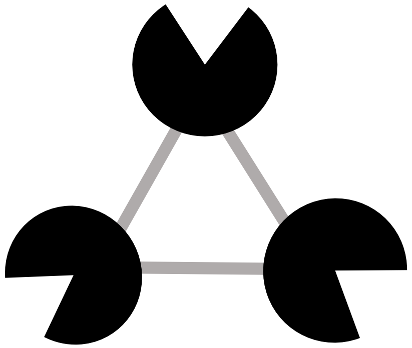
$$\mu_c \equiv \frac{z\dot{\phi}_0}{2f_I} \gg m_\psi$$

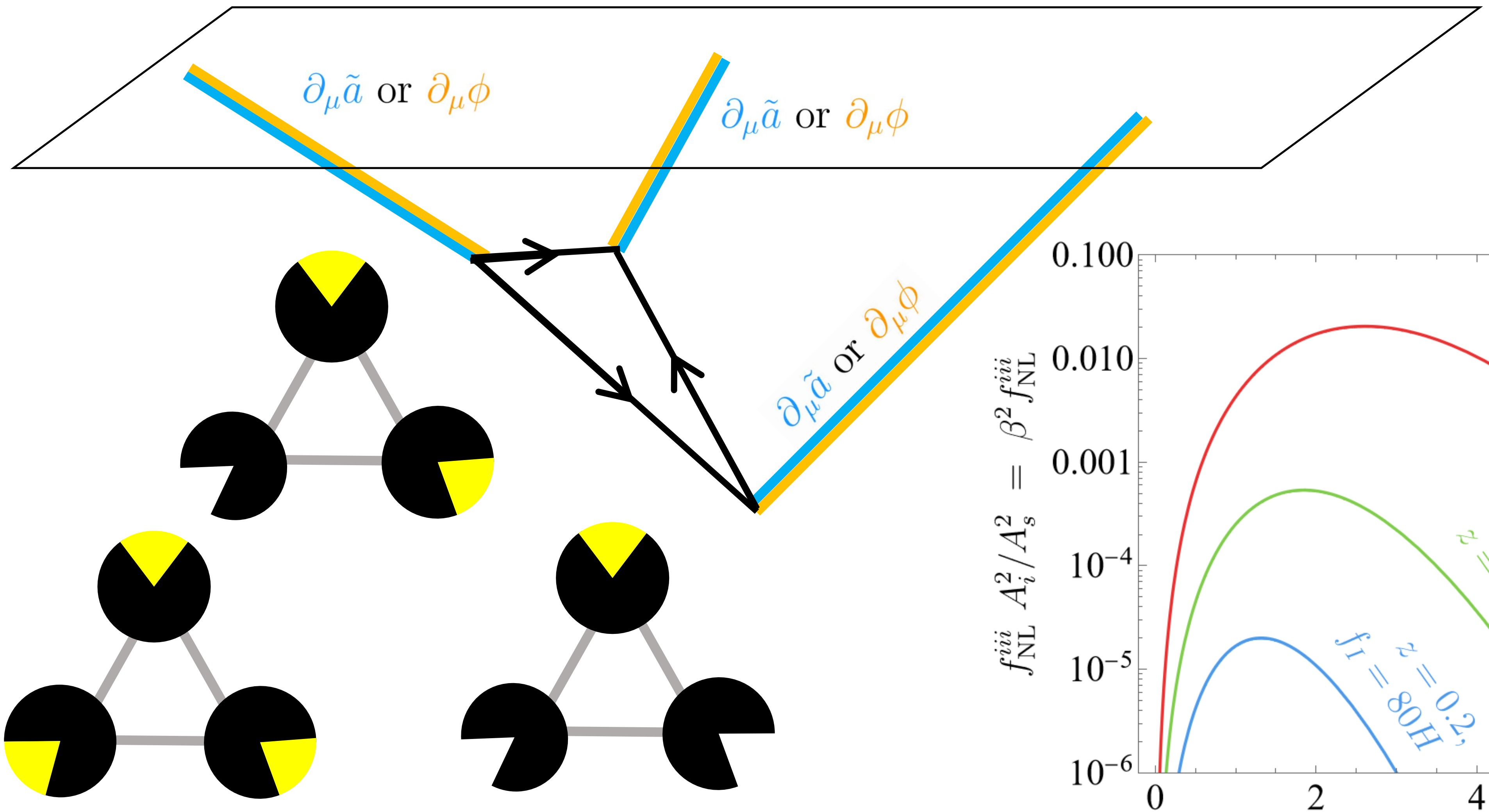


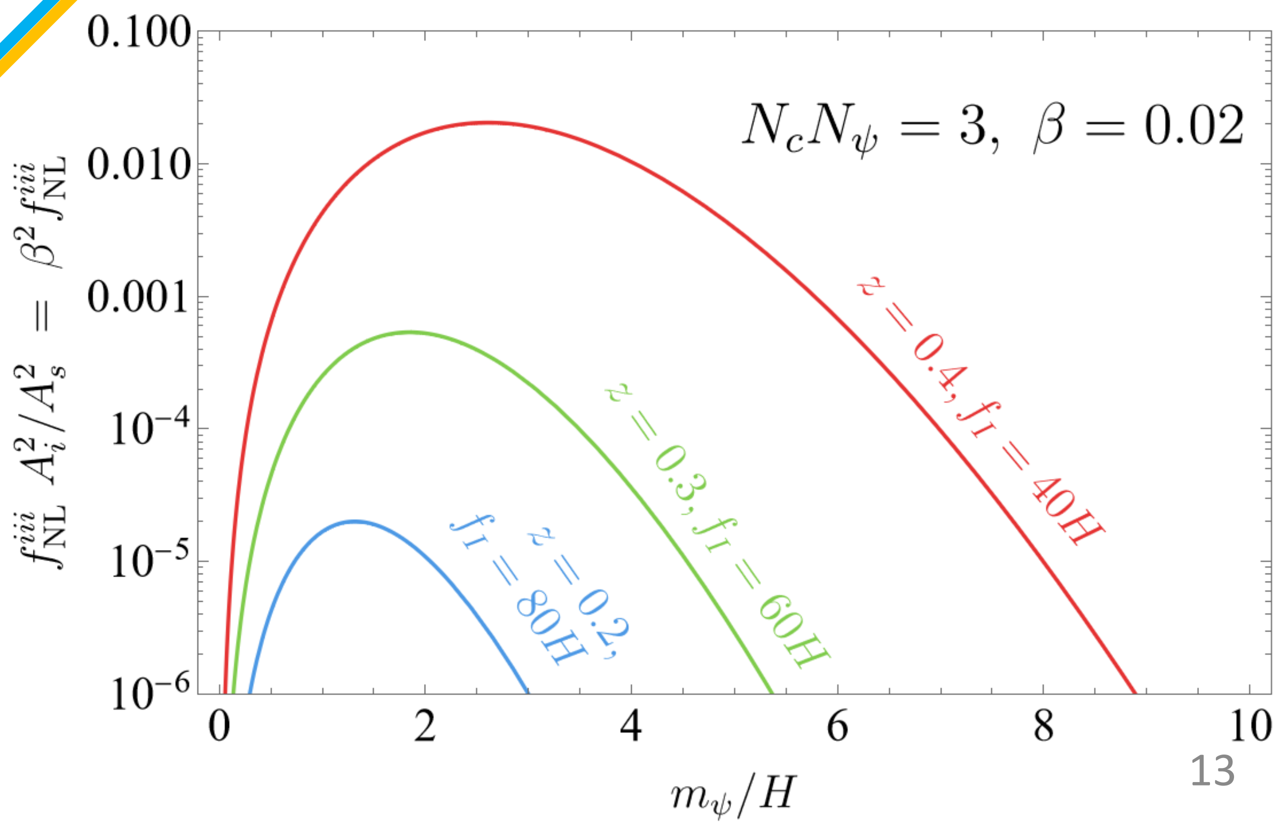
Assisted particle (pair) production that overcomes Boltzmann suppression:

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

Hybrid Mode of All Types







Summary & Outlook

- ❑Inflaton-PQ interaction could lead to big differences

e.g. restore the PQ symmetry and produce topological defects [Yunjia Bao, JiJi Fan, LL, 2209.09908]

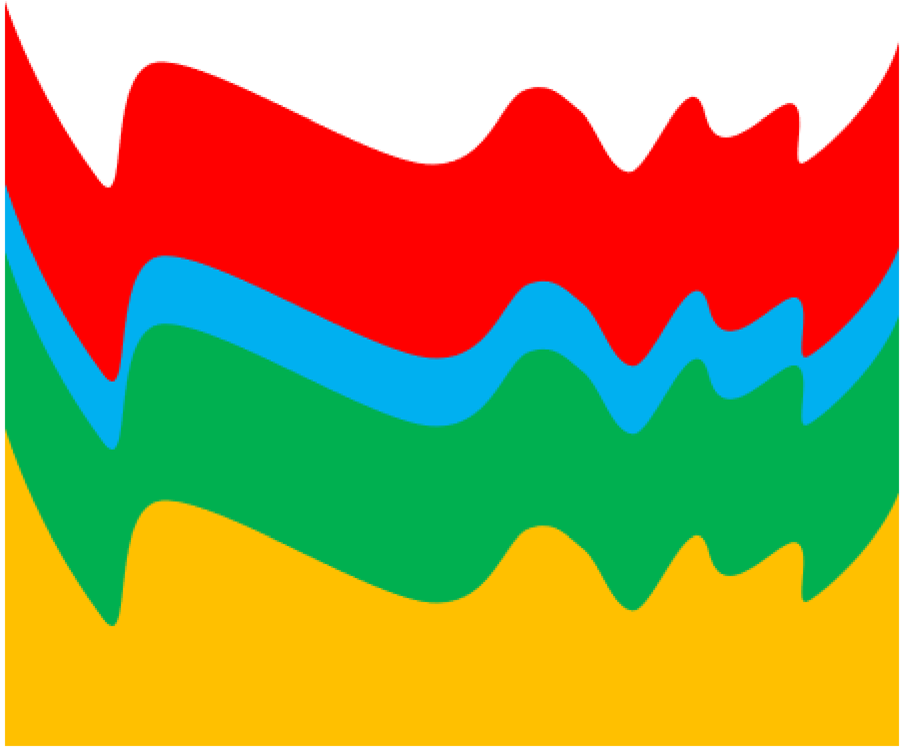
- ❑Rich cosmological signals in both curvature and isocurvature modes

- ❑Applies to axion-like-particles

- ❑May reveal the PQ radial mode and the inflationary scale

BAKCUPS & EXTRA THOUGHTS

Curvature vs. Isocurvature



Dark Matter

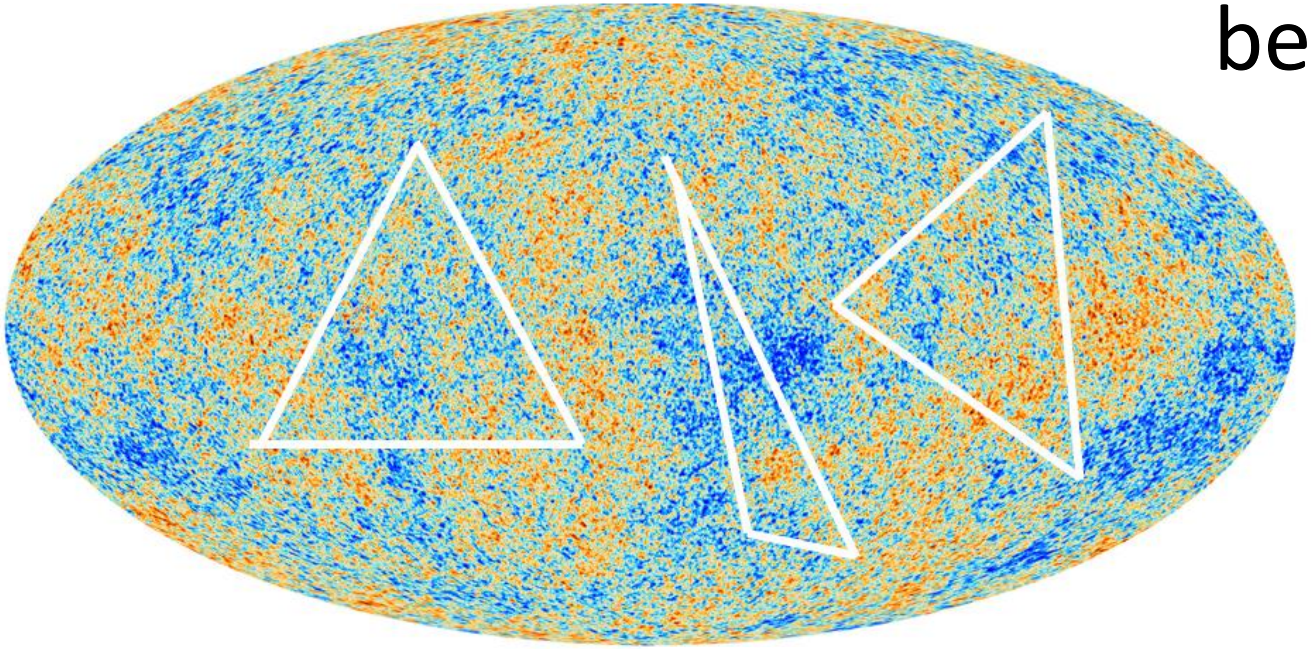
Photon

Neutrino

Baryons

$$\langle\delta\phi(\mathbf{k_1})\delta\phi(\mathbf{k_2})\delta\phi(\mathbf{k_3})\rangle \propto \delta(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})\langle\delta\phi\delta\phi\rangle^{2}\times f_{\mathrm{NL}}$$

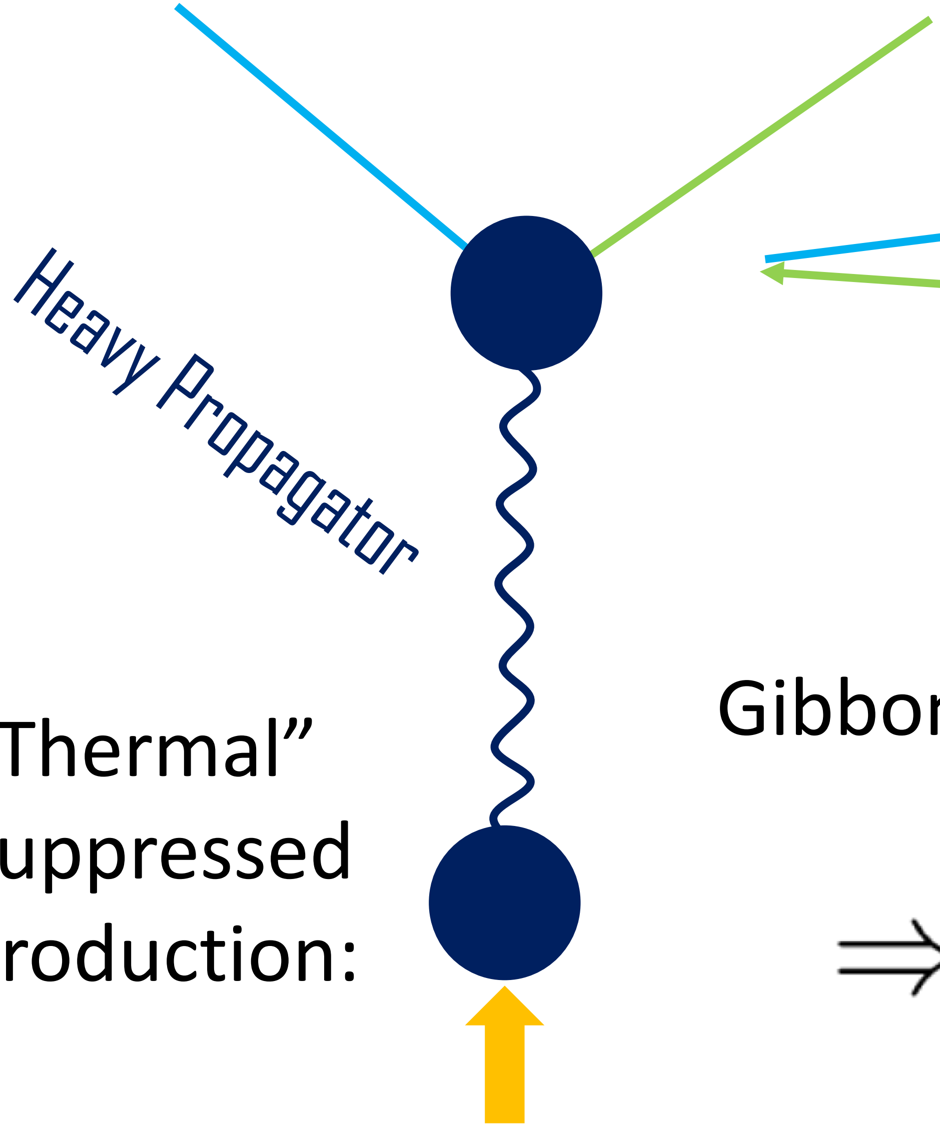
Wouldn’t happen if everything behave as free fields!



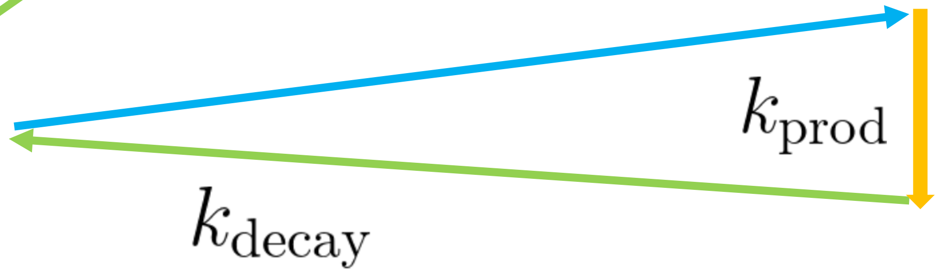
Planck limit on f_{NL}: O(10) for pure curvature.

Planck collaboration, 2018

Sketch of a Cosmological Collider



"Thermal"
Suppressed
production:

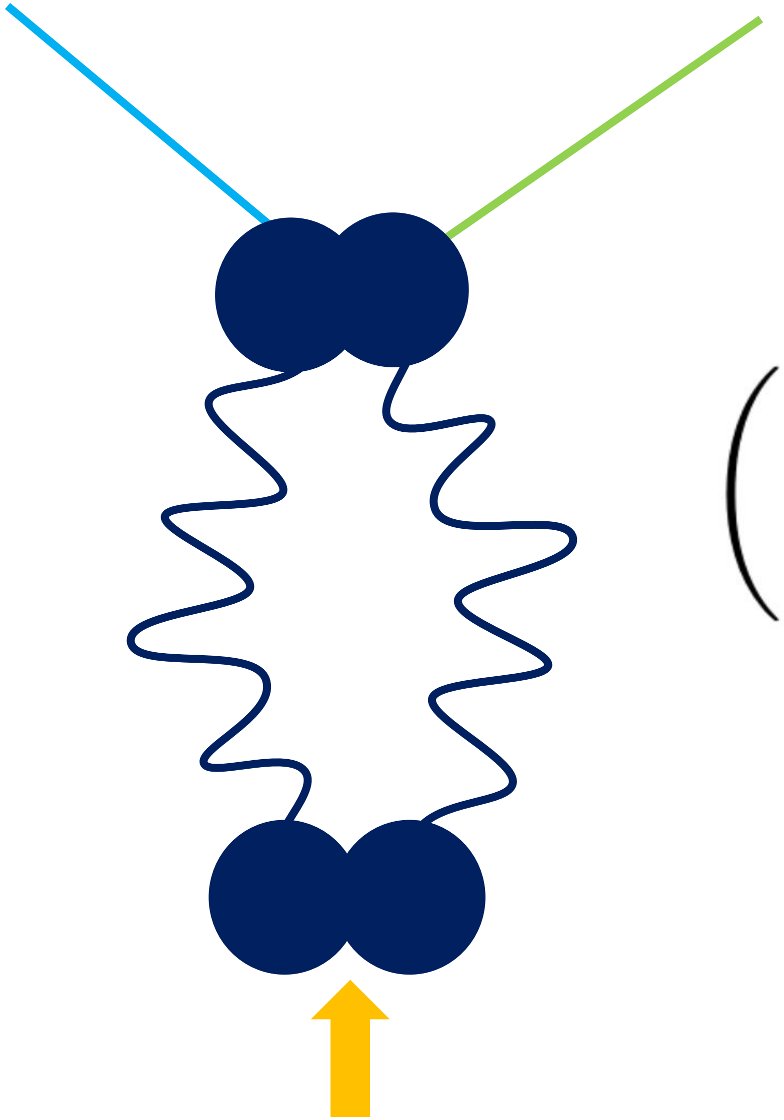


Momentum Conservation

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

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

At One Loop



$$\left(\frac{k_{\text{decay}}}{k_{\text{prod}}}\right)^{im/H} \Rightarrow \left(\frac{k_{\text{decay}}}{k_{\text{prod}}}\right)^{2im/H}$$

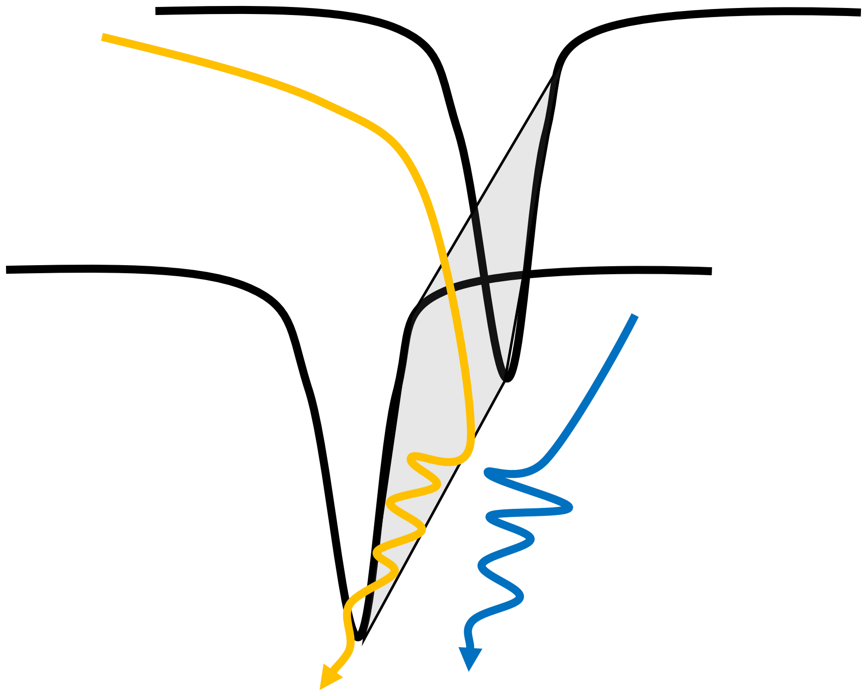
$$e^{-\frac{\pi m}{H}} \Rightarrow e^{\frac{-2\pi m}{H}}$$ and loop factors

Beyond Boltzmann Suppression

❑Classical Feature

The non-flatness in the potential excites the heavy field background classically

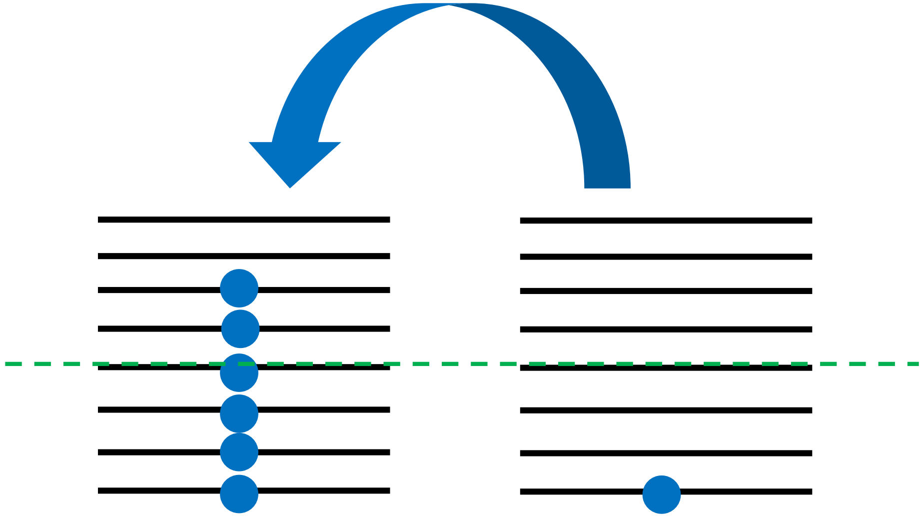
X. Chen, 2011; X. Chen, R. Ebadi, S. Kumar, 2022; A. Bodas, R. Sundrum, 2022 …

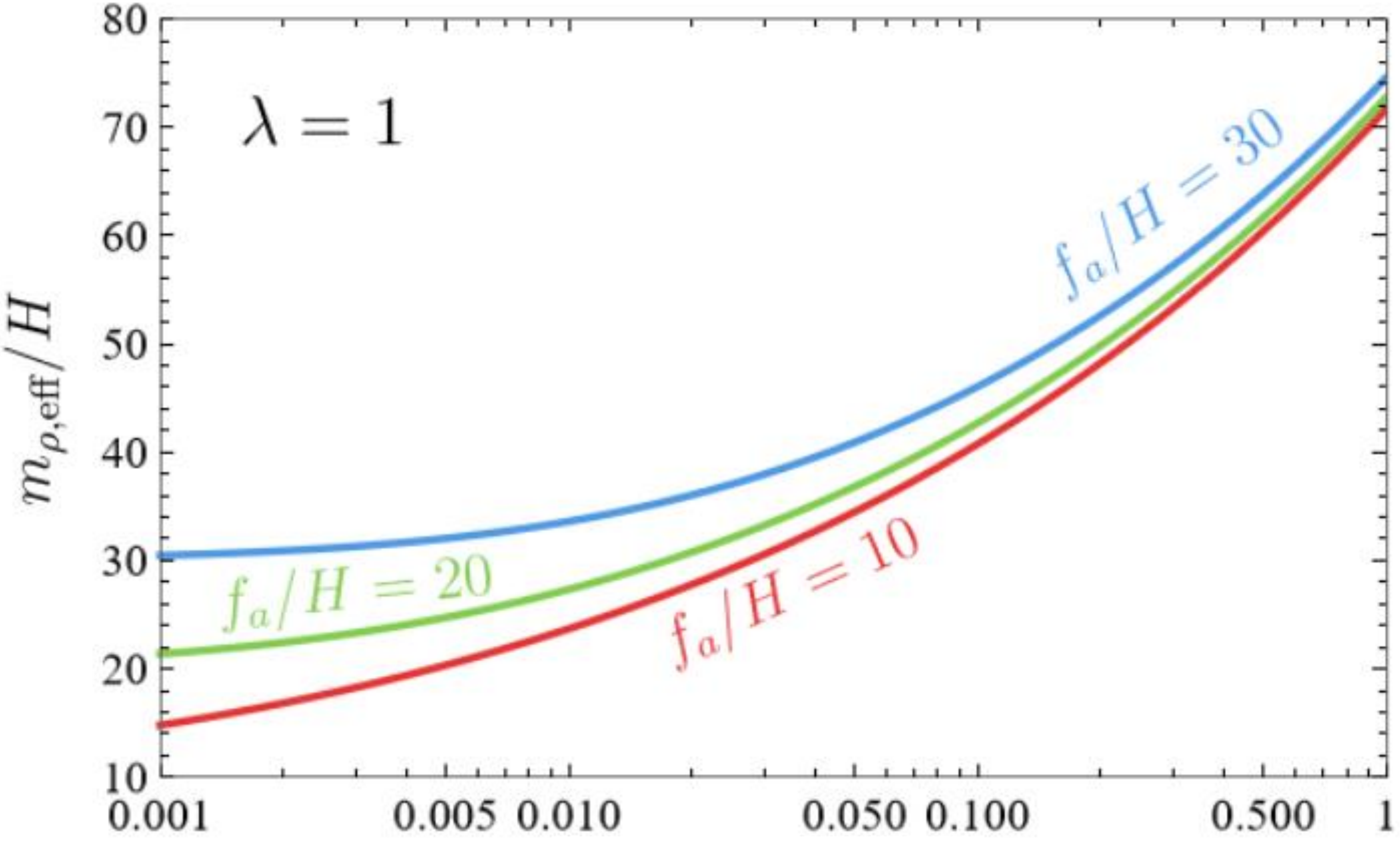


❑Chemical potential

A rolling field creates uneven chemical potential in a sector, greatly enhancing occupation number

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





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

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

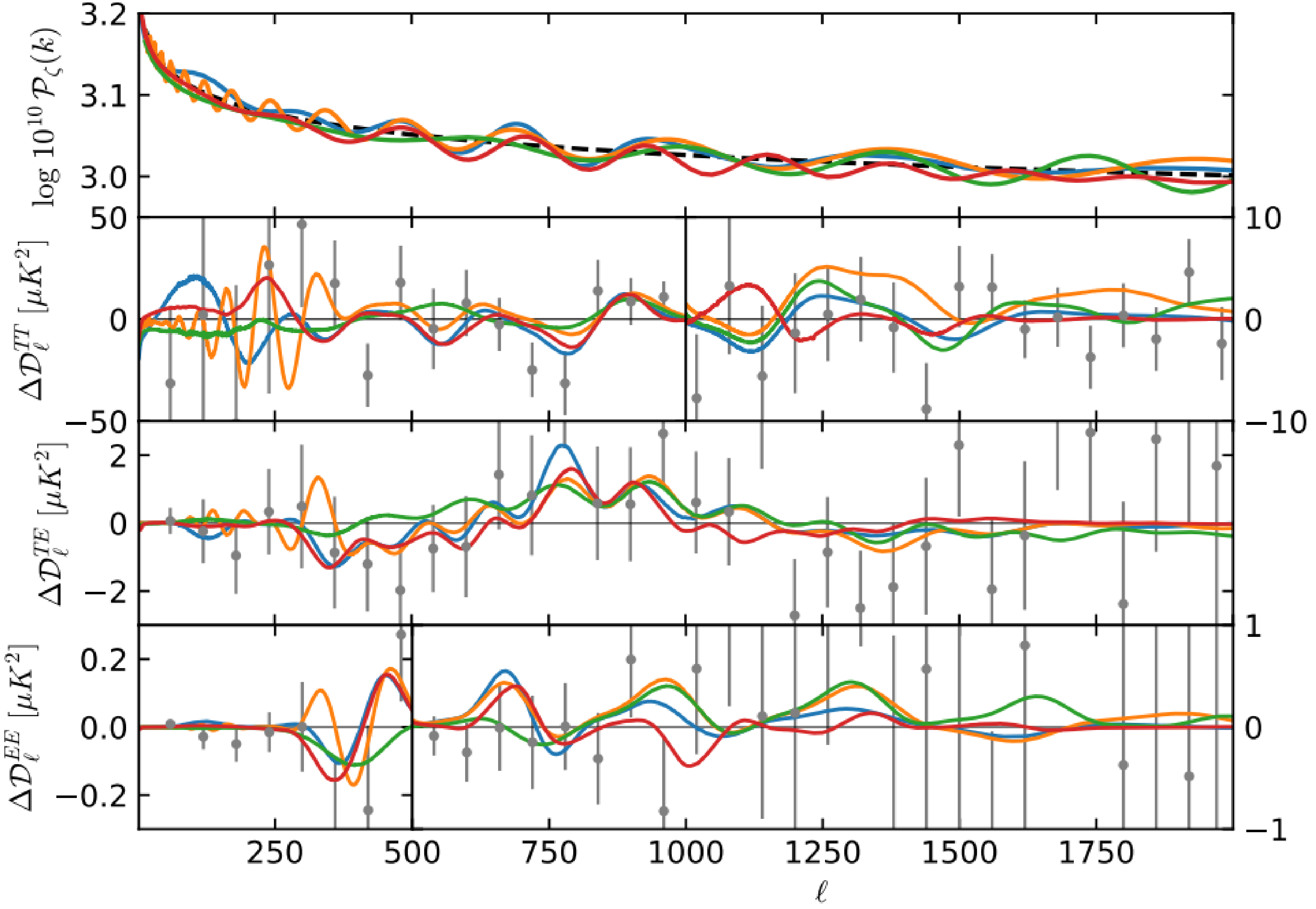
$$\left|\frac{\Delta P_\zeta}{P_\zeta}\right|_{\text{clock;amp}} = \frac{2c^2 b V_{\phi 0} f_I^2}{\Lambda^4 H^2}\sqrt{\frac{2\pi}{\mu_\rho^3}}$$

$$\approx\ 0.019\left(\frac{q}{0.02}\right)^2\left(\frac{bV_{\phi 0}}{0.3\dot{\phi}_0^2}\right)\left(\frac{\dot{\phi}_0}{(60H)^2}\right)^2\left(\frac{40H}{f_I}\right)^{7/2}\left(\frac{1}{\lambda}\right)^{3/4}$$

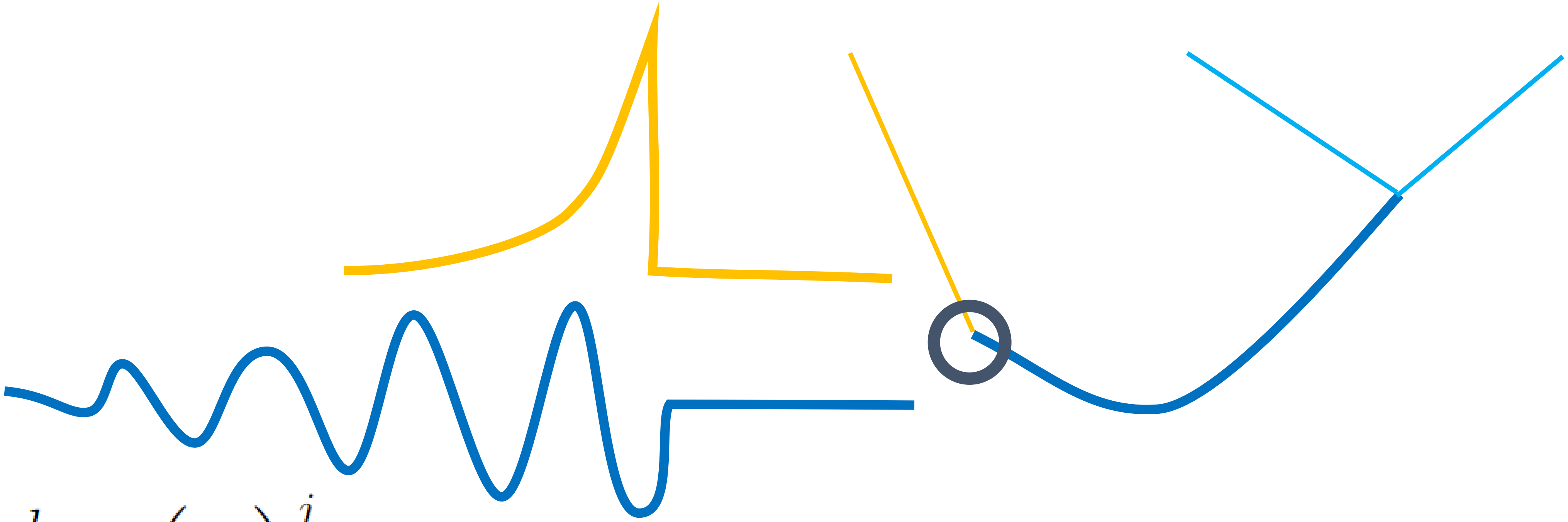
$$\left|\frac{\Delta P_i}{P_i}\right|_{\text{clock;amp}} \approx \frac{2cbV_{\phi 0}}{\Lambda^2 H^2}\sqrt{\frac{2\pi}{\mu_\rho^3}}$$

$$\approx\ 0.96\left(\frac{q}{0.02}\right)\left(\frac{bV_{\phi 0}}{0.3\dot{\phi}_0^2}\right)\left(\frac{\dot{\phi}_0}{(60H)^2}\right)^2\left(\frac{40H}{f_I}\right)^{7/2}\left(\frac{1}{\lambda}\right)^{3/4}$$

Observational Hints



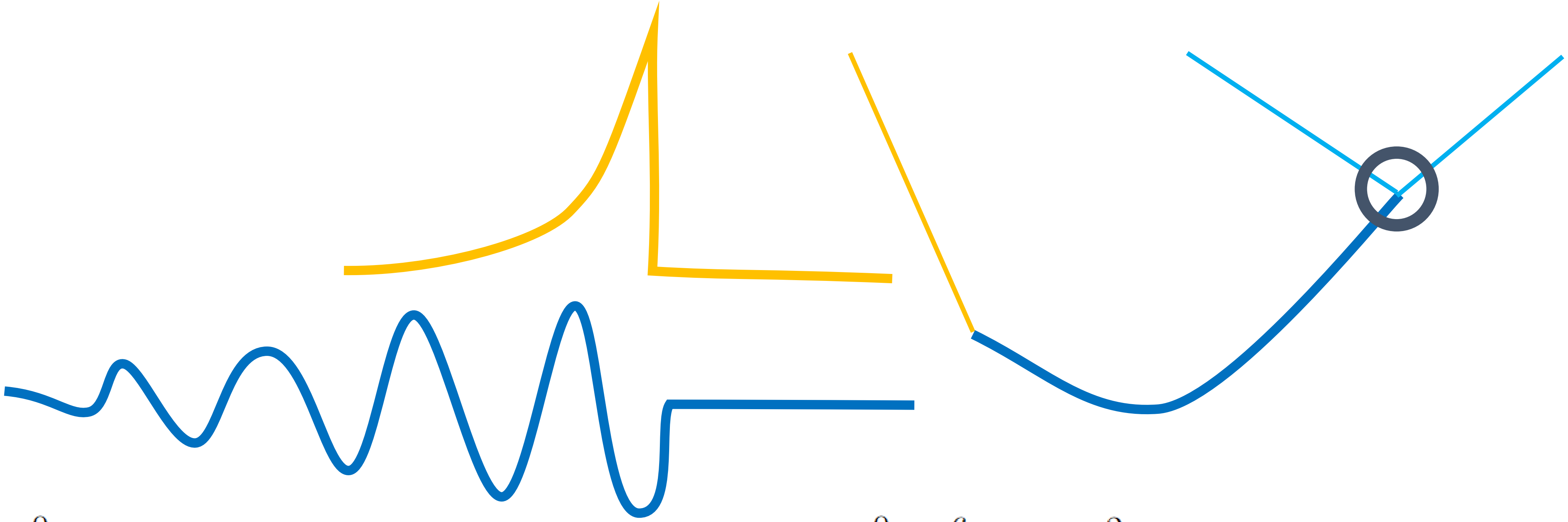
M. Braglia, X. Chen and D. K. Hazra 2021; A. Antony, F. Finelli, D. K. Hazra and A. Shafieloo, 2022; M. Braglia, X. Chen, D. K. Hazra and L. Pinol, 2022



$$\int_{-\infty}^{\tau_1} \frac{d\tau_2}{(H\tau_2)^4}\left(\frac{\tau_2}{\tau_s}\right)^j \dot{u}^*_{k_3} v^*_{k_3}(\tau_2)\theta(\tau_2-\tau_s)$$

$$= \int_{-\infty}^{\tau_1} d\tau_2 \frac{\sqrt{\pi}(1+i)e^{\frac{\pi\mu_\rho}{2}+ik_3\tau_2}\sqrt{-k_3\tau_2}}{4H\tau_2}\left(\frac{\tau_2}{\tau_s}\right)^j H^{(2)}_{i\mu_\rho}(-k_3\tau_2)\theta(\tau_2-\tau_s)$$

$$= \frac{\sqrt{\pi}(1+i)z_s^{-j}}{4H}\int_{z_1}^{z_s} e^{\frac{\pi\mu_\rho}{2}} e^{-iz_2} z_2^{j-\frac{1}{2}} H^{(2)}_{i\mu_\rho}(z_2)dz_2 \ ,$$



$$u_{k_1}u_{k_2}(\tau_{\rm end})\int_{-\infty}^{0}\frac{d\tau_1}{(H\tau_1)^4}\partial_\mu u^*_{k_1}\partial^\mu u^*_{k_2}v_{k_3}(\tau_1)\theta(\tau_1-\tau_s)=\int_{\tau_s}^{0}\frac{H^6 d\tau_1}{(H\tau_1)^4}\frac{\tau_1^2}{4k_1^3k_2^3}v_{k_3}(\tau_1)\mathcal{D}e^{ik_{12}\tau_1}$$

$$=\frac{(-1)^{\frac{3}{4}}e^{-\pi\mu_\rho/2}H^3\sqrt{\pi}}{8k_1^3k_2^3k_3^{5/2}}\int_0^{z_s}dz_1e^{-ik_{12}z_1/k_3}\left[(k_1^2k_2^2-\mathbf{k}_1\cdot\mathbf{k}_2k_1k_2)z_1^{\frac{3}{2}}+i\mathbf{k}_1\cdot\mathbf{k}_2k_{12}k_3z_1^{\frac{1}{2}}+\mathbf{k}_1\cdot\mathbf{k}_2k_3^2/z_1^{\frac{1}{2}}\right]$$

$$\times H^{(1)}_{i\mu_\rho}(z_1),$$

$$=\frac{(-1)^{\frac{1}{4}}e^{-\pi\mu_\rho/2}H^3\sqrt{\pi}}{16k^{9/2}}\int_0^{z_s}\frac{dz_1}{\sqrt{z_1}}e^{-2iz_1}(3iz_1^2+2z_1-i)H^{(1)}_{i\mu_\rho}(z_1),$$

Chemical Potential

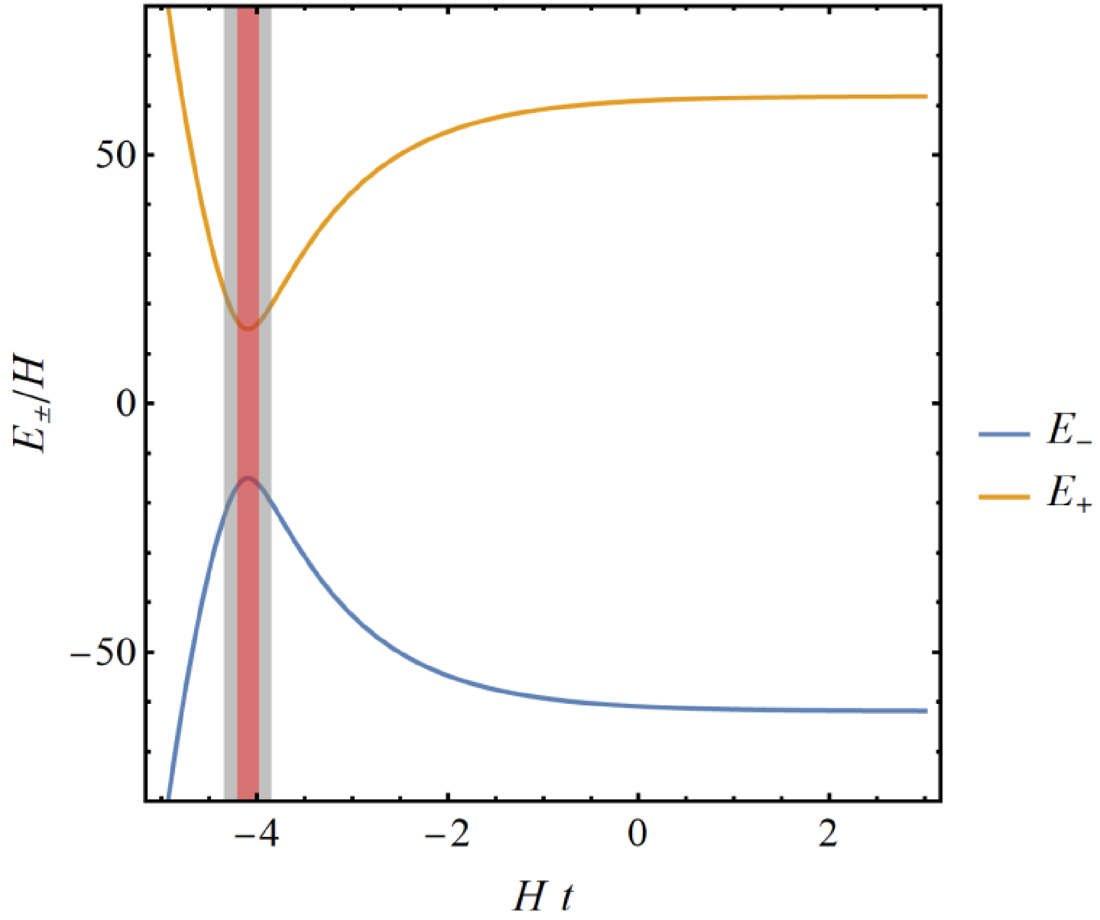
X. Chen, Y. Wang, and Z.-Z. Xianyu, 2018; L.-T. Wang and Z.-Z. Xianyu, 2019; A. Bodas, S. Kumar, R. Sundrum 2020; C. M. Sou, X. Tong, Y. Wang 2021

A rolling axion field introduces a chemical potential

Opposite sign for different fermion helicity

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

The chemical potential



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

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

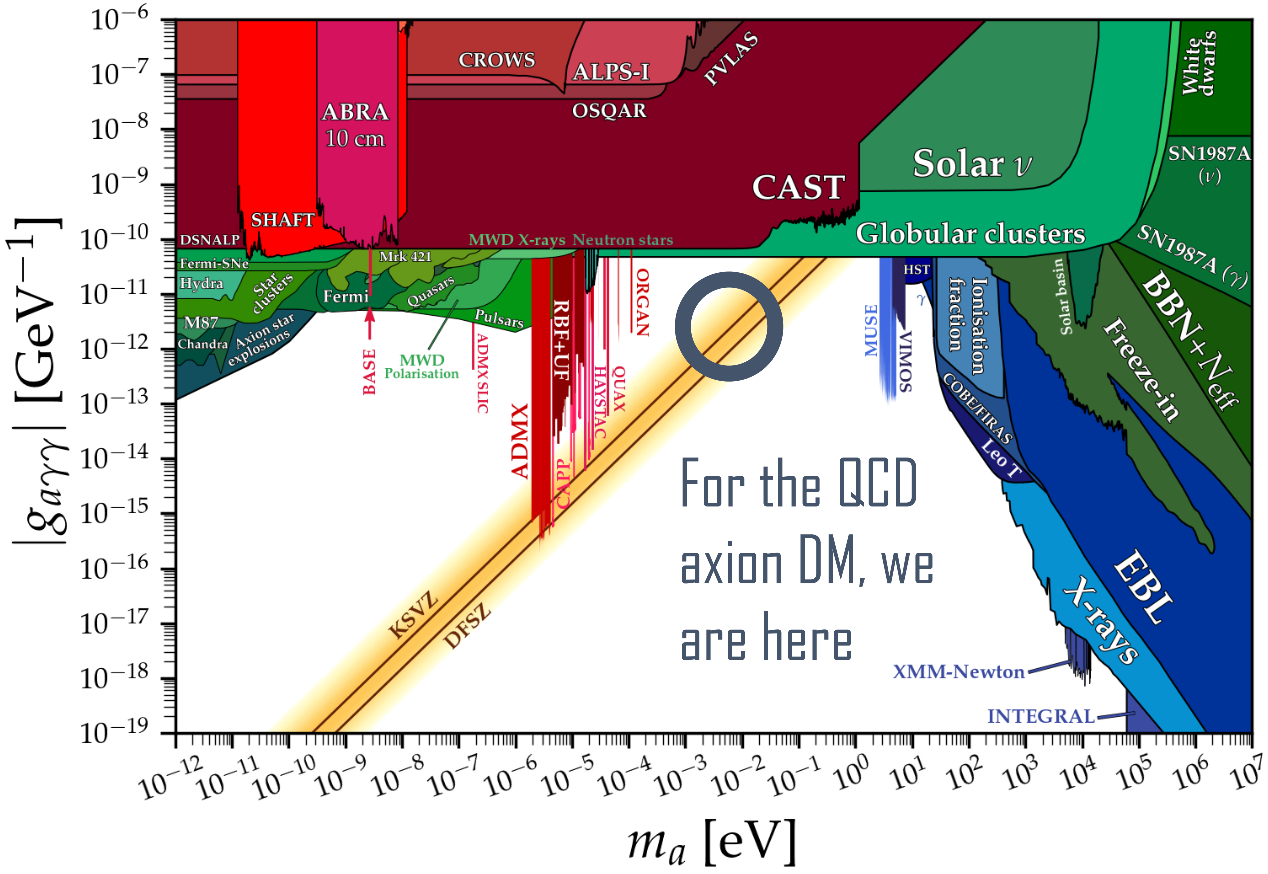
Numerical Approximation

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

≥3 if QCD

$$\left|f_{\rm NL}^{iii}\right| \frac{A_i^2}{A_s^2} \simeq \frac{\boxed{N_c N_\psi} \beta^{3/2}}{6\pi\sqrt{A_s}} \left(\frac{H}{2f_I}\right)^3 \left(\frac{m_\psi}{H}\right)^3 \frac{\mu_c^2\sqrt{m_\psi^2+\mu_c^2}}{H^3}$$
$$\times \frac{e^{\pi\mu_c/H}\Gamma\left(-i\sqrt{m_\psi^2+\mu_c^2}/H\right)^2 \Gamma\left(2i\sqrt{m_\psi^2+\mu_c^2}/H\right)^3}{2\pi\Gamma\left[i\left(\sqrt{m_\psi^2+\mu_c^2}+\mu_c\right)/H\right]^3 \Gamma\left[1+i\left(\sqrt{m_\psi^2+\mu_c^2}-\mu_c\right)/H\right]}$$

Misalignment Details



- ⚠ For sizeable isocurvature hybrid signals, need small DM faction γ of O(10^{-3}) or smaller ⚠
- May be a good way to pin down the inflationary scale

➢ Size of f_a inferred from DM direct detection (mass-coupling relation, etc.)

➢ H/f_a from cosmological collider observables