

Hybrid Cosmological Collider of Axion

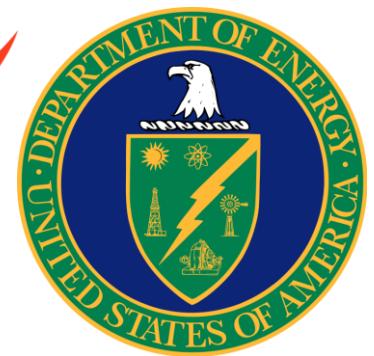
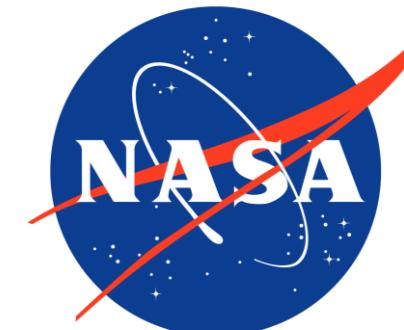
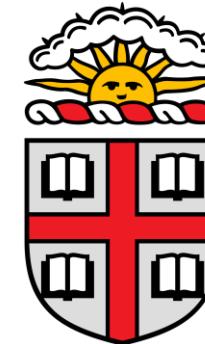
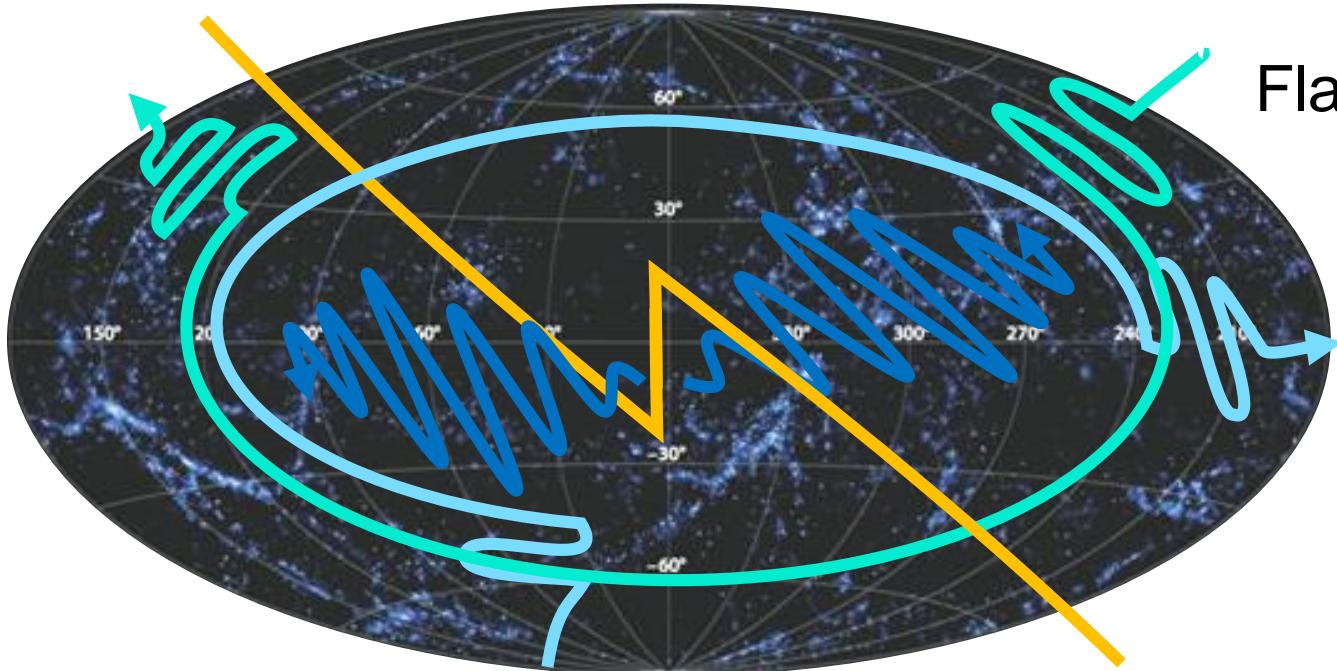
Lingfeng Li (Brown University)

Prospecting for New Physics through
Flavor, Dark Matter, and Machine Learning

Mar. 28, 2023, Aspen

Based on

2303.03406, With Xingang Chen & JiJi Fan

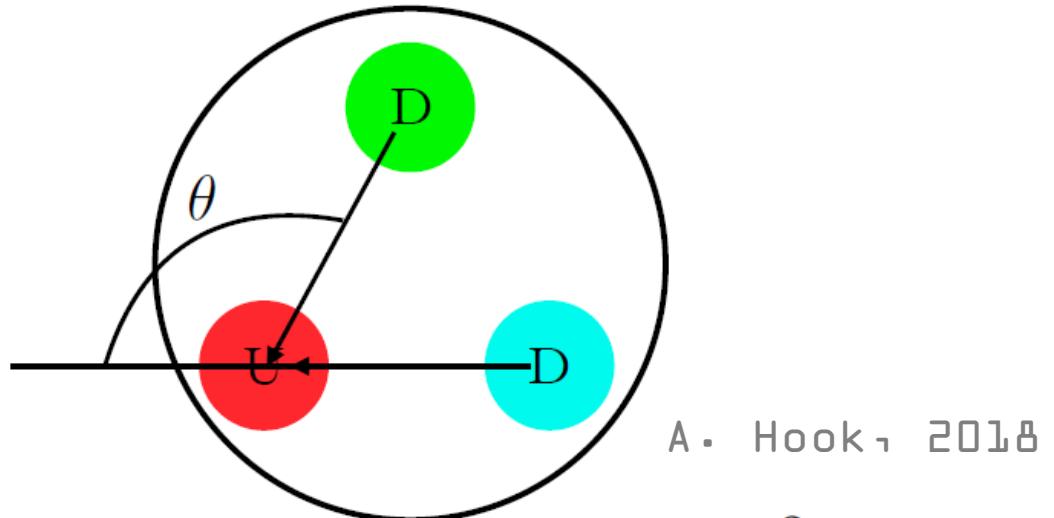


Strong CP and QCD Axion

Experimental hints: neutron EDM

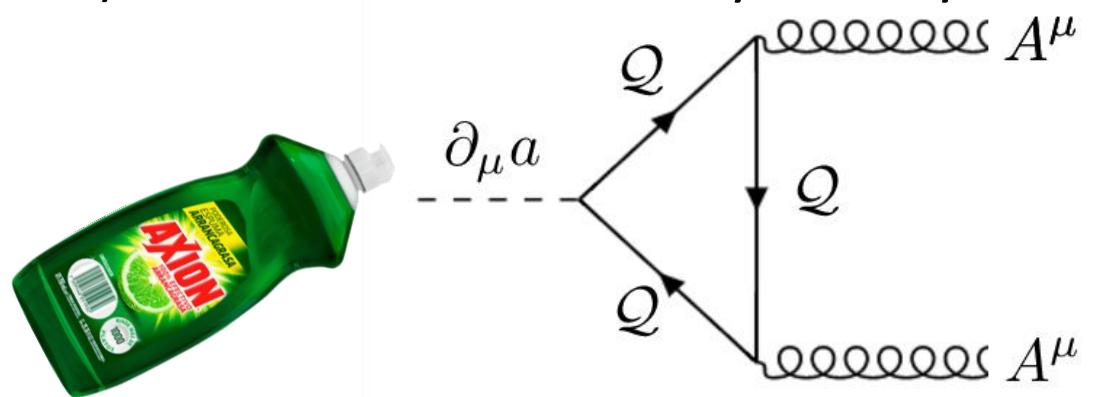
Naive expectation: $O(Q \times fm) \approx 10^{-13} e\text{ cm}$

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



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

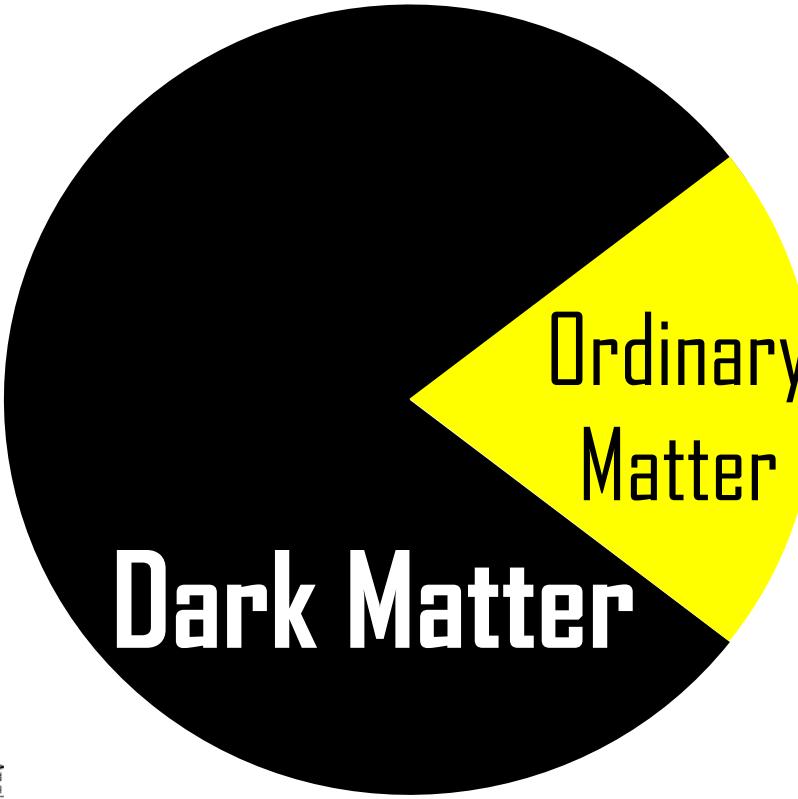
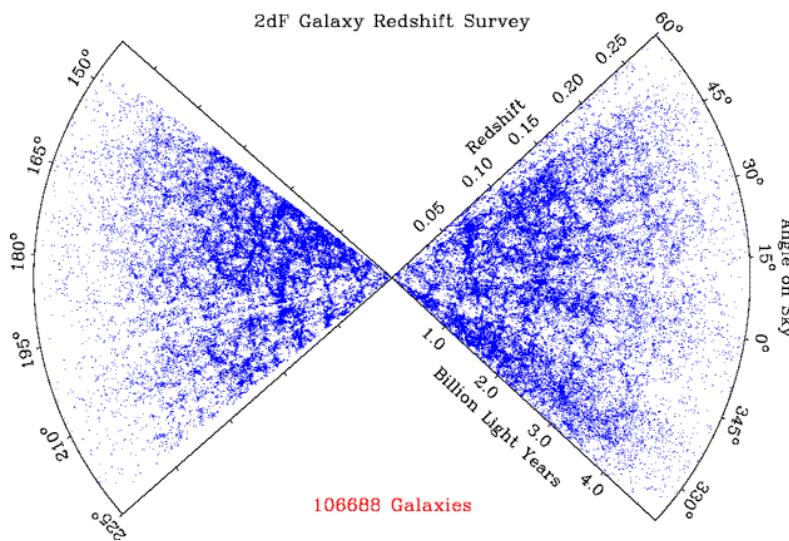
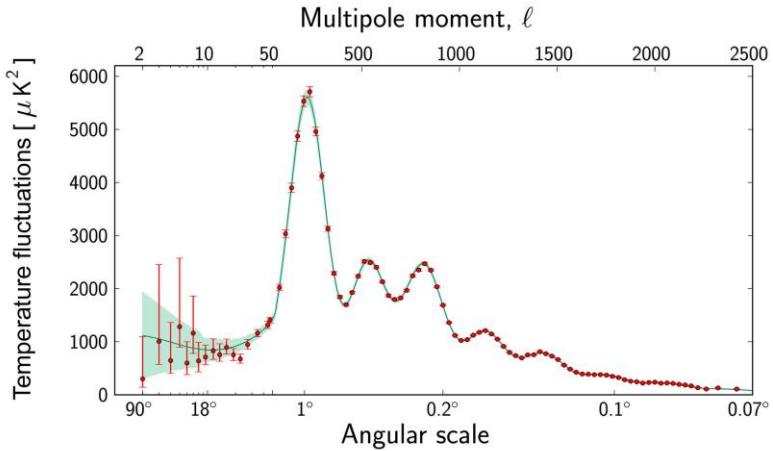
QCD axion: A pseudo Nambu-Goldstone Boson (pNGB) of a the Peccei-Quinn symmetry



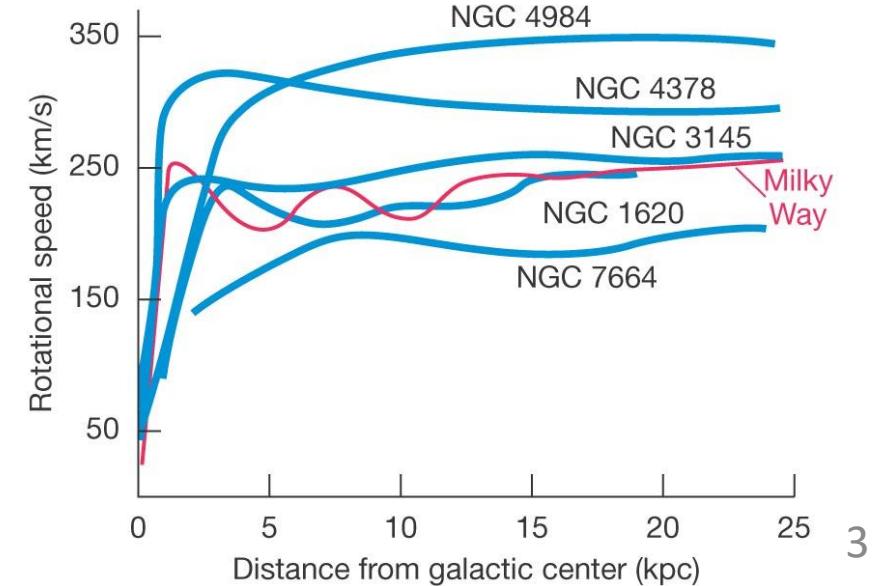
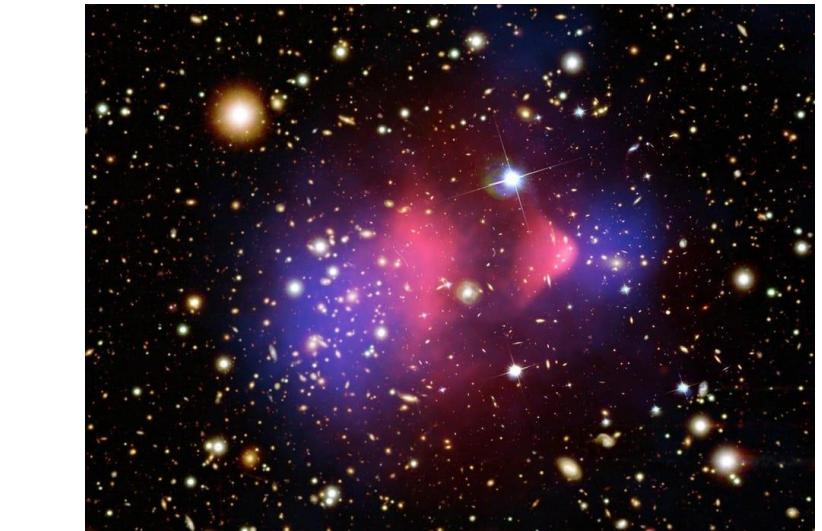
The strong CP θ angle are set to zero at the minima

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

Dark Matter Exists



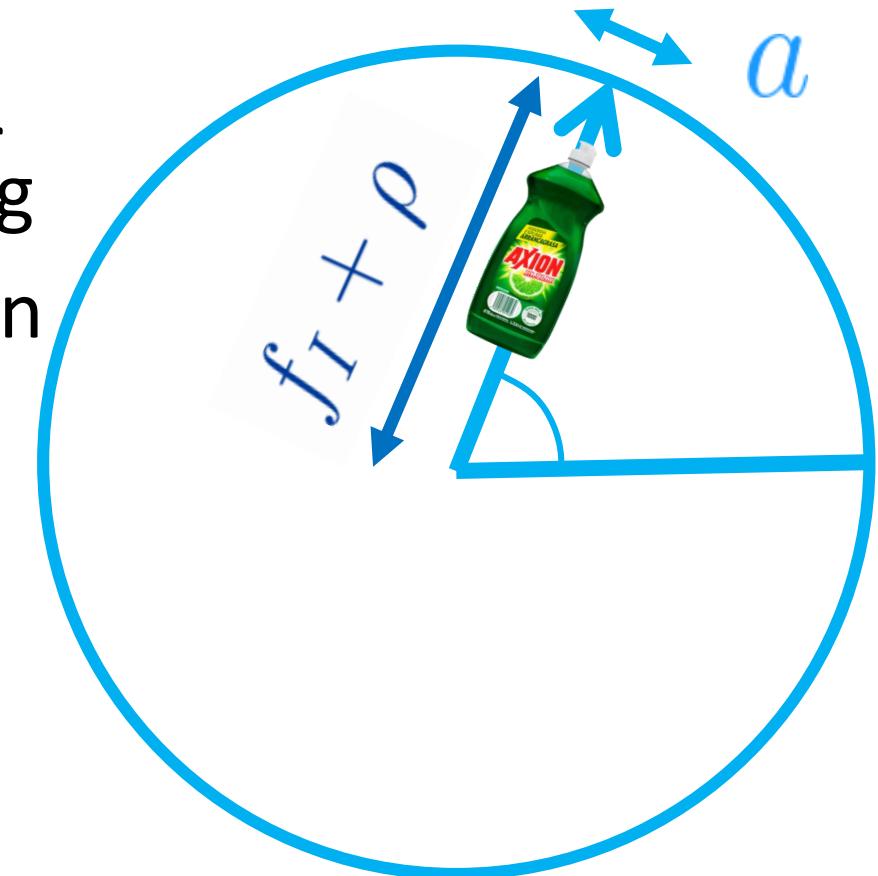
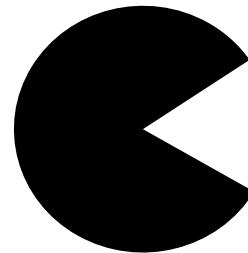
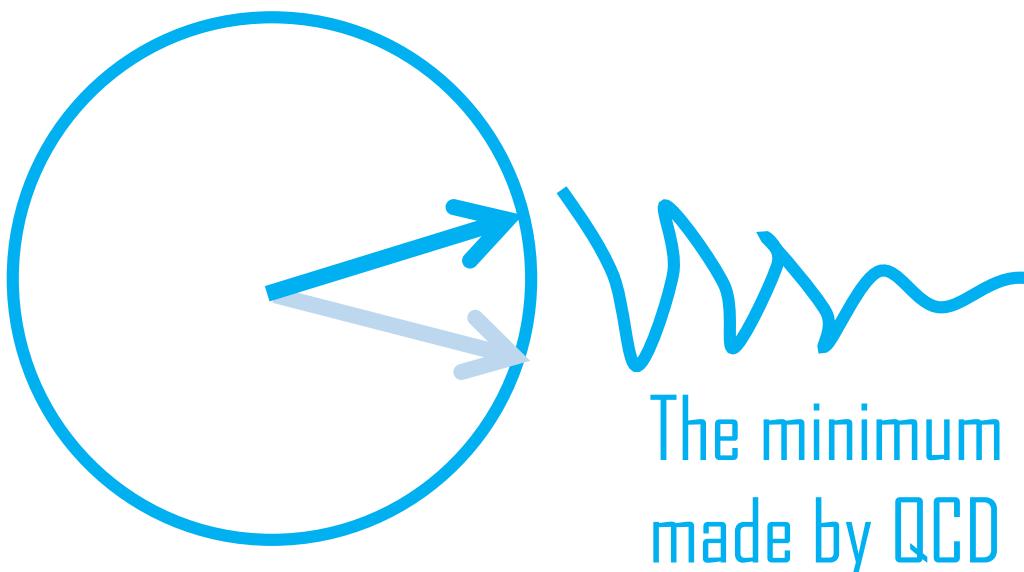
The matter budget of
our universe



Axion DM from Misalignment

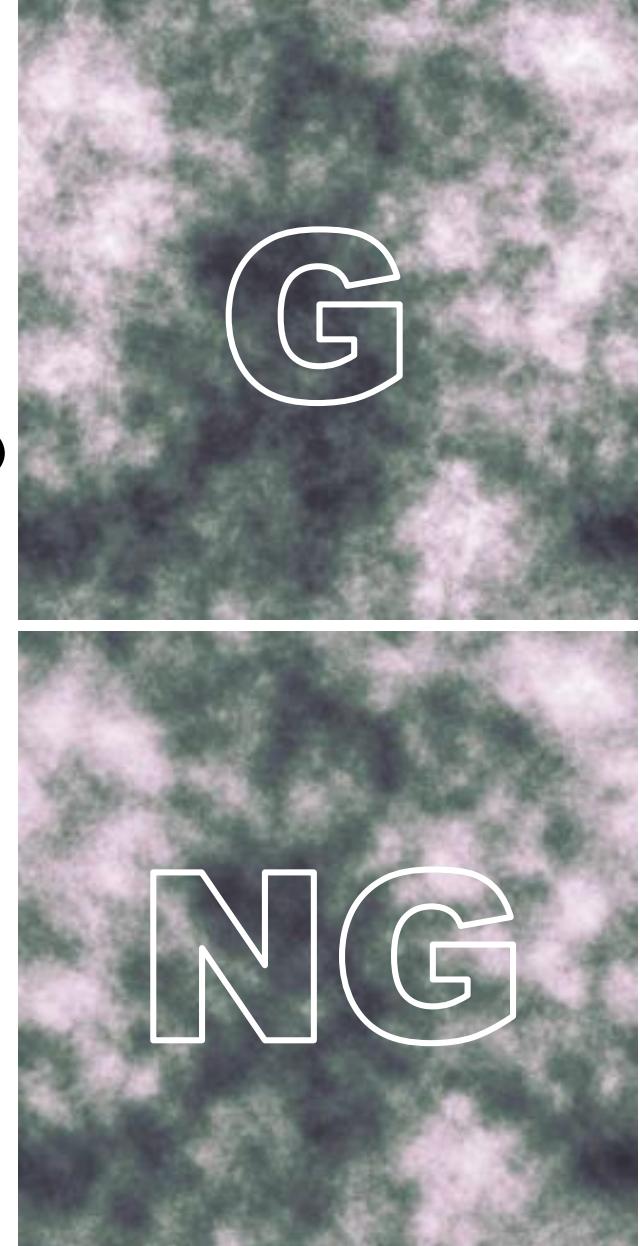
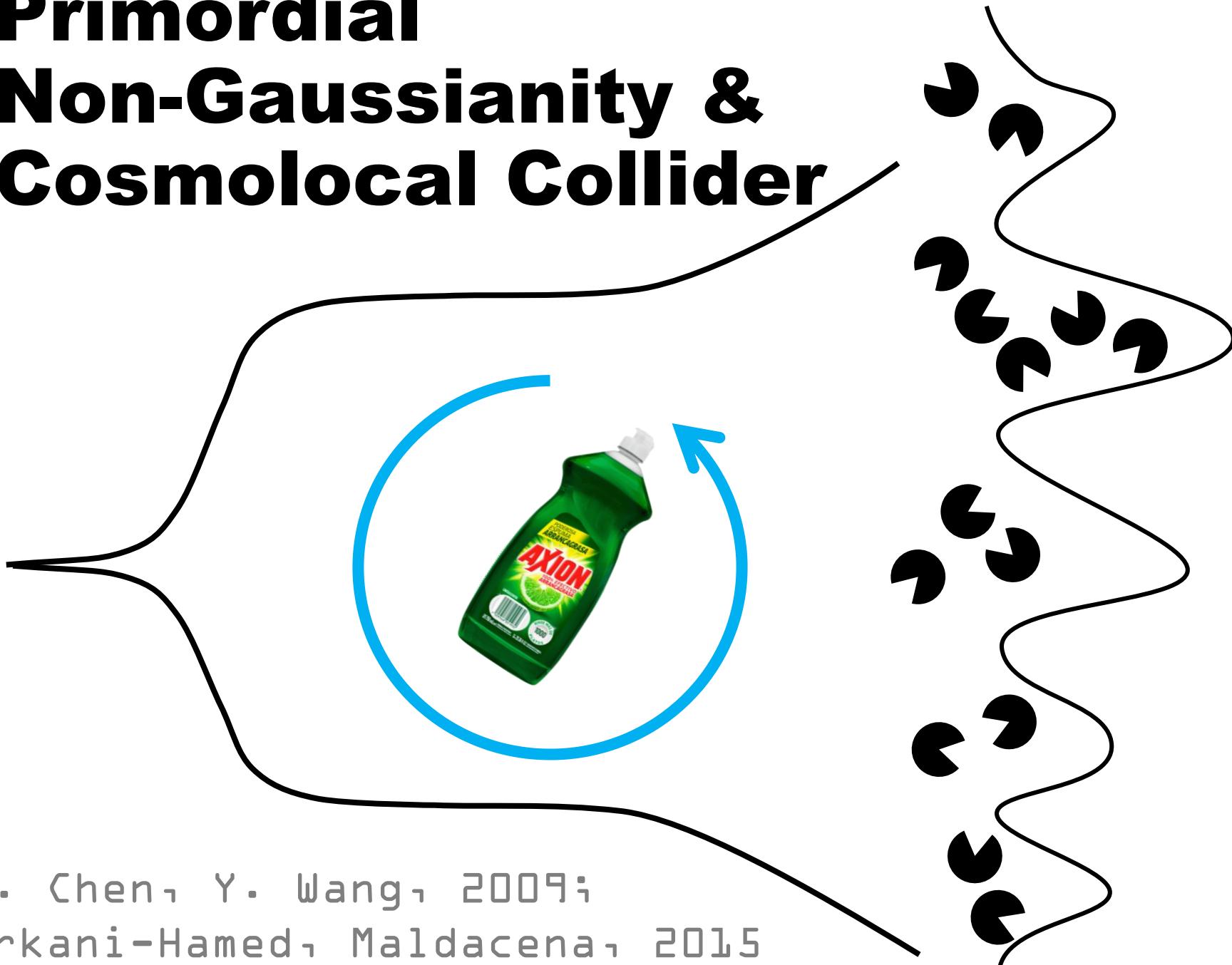
$$\delta\theta \simeq H/2\pi f_a \ll 1$$

- $f_a > H_I / 2\pi$ 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



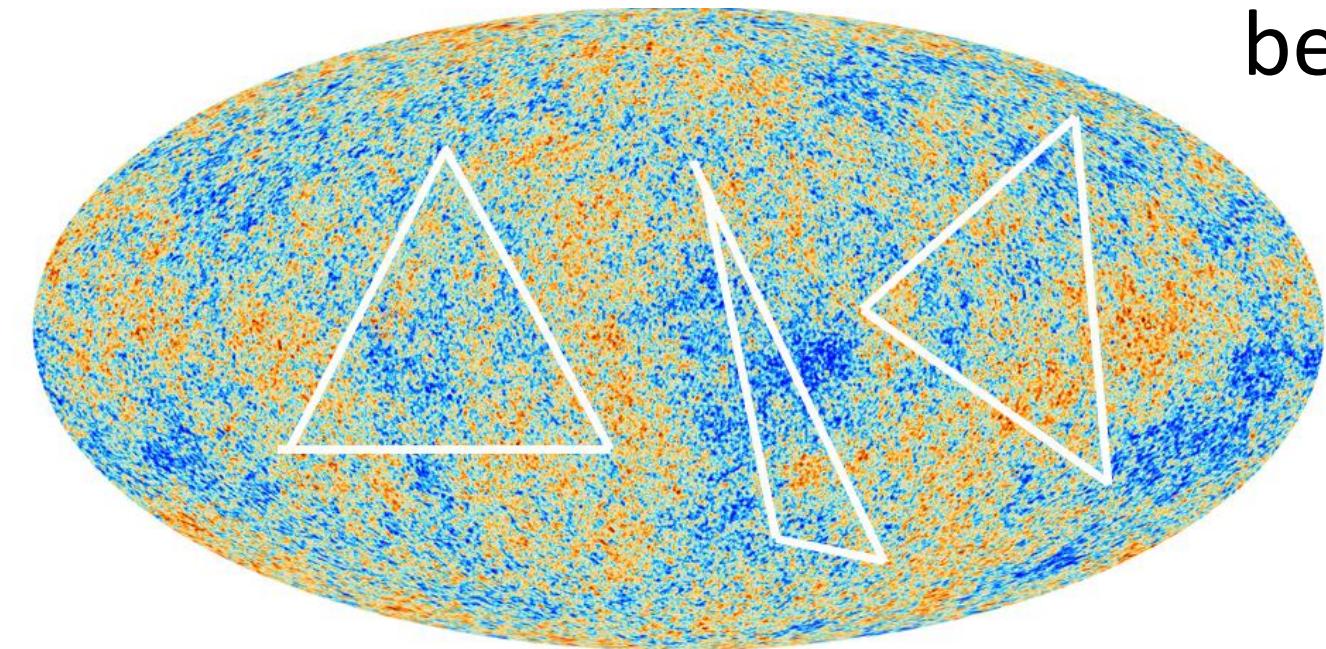
*Oscillating field creates non-relativistic, coherent axion particles

Primordial Non-Gaussianity & Cosmolocal Collider



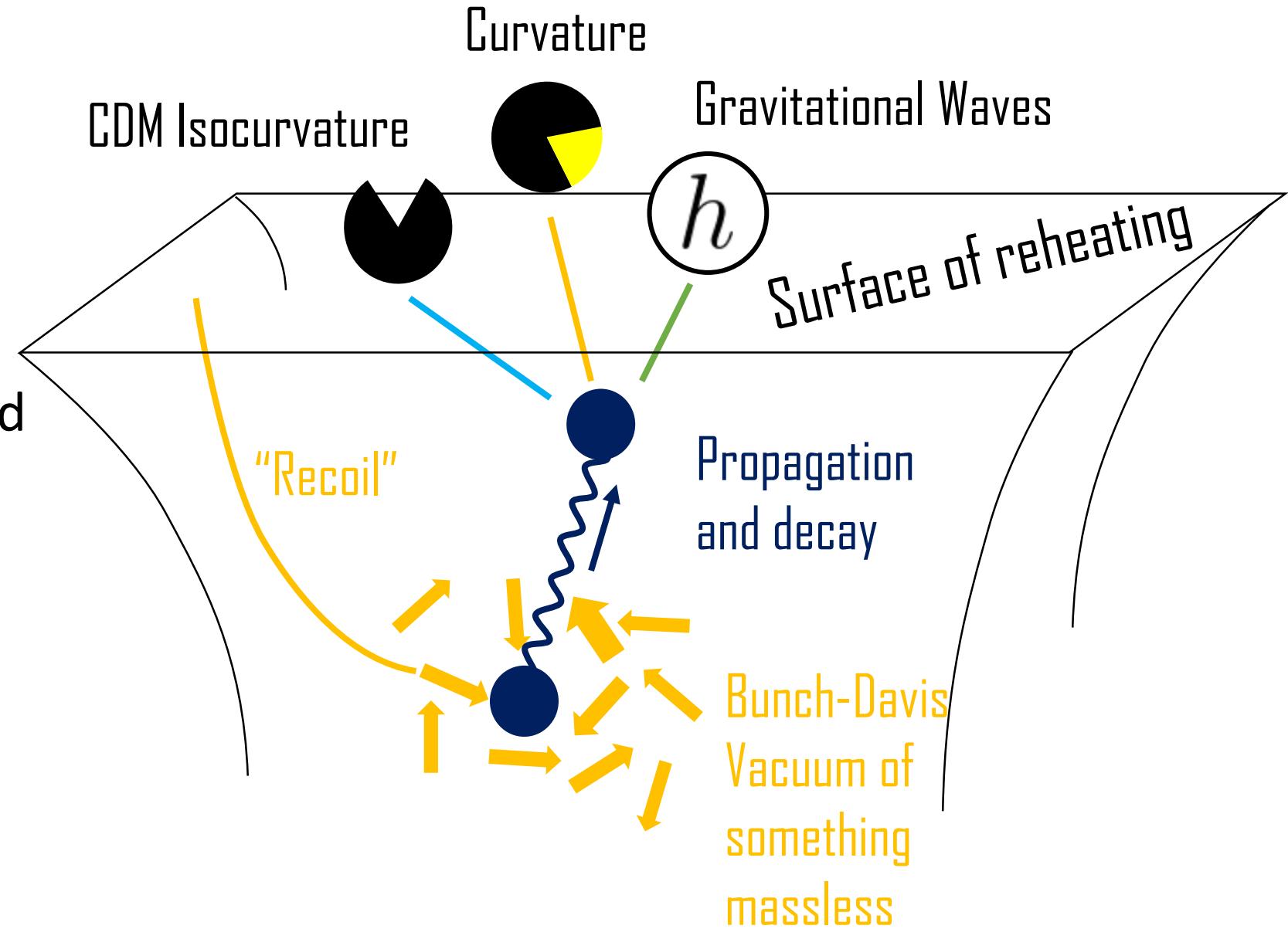
$$\langle \delta\phi(\mathbf{k}_1)\delta\phi(\mathbf{k}_2)\delta\phi(\mathbf{k}_3) \rangle \propto \delta(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) \langle \delta\phi \delta\phi \rangle^2 \times f_{\text{NL}}$$

Wouldn't happen if everything
behave as free fields!



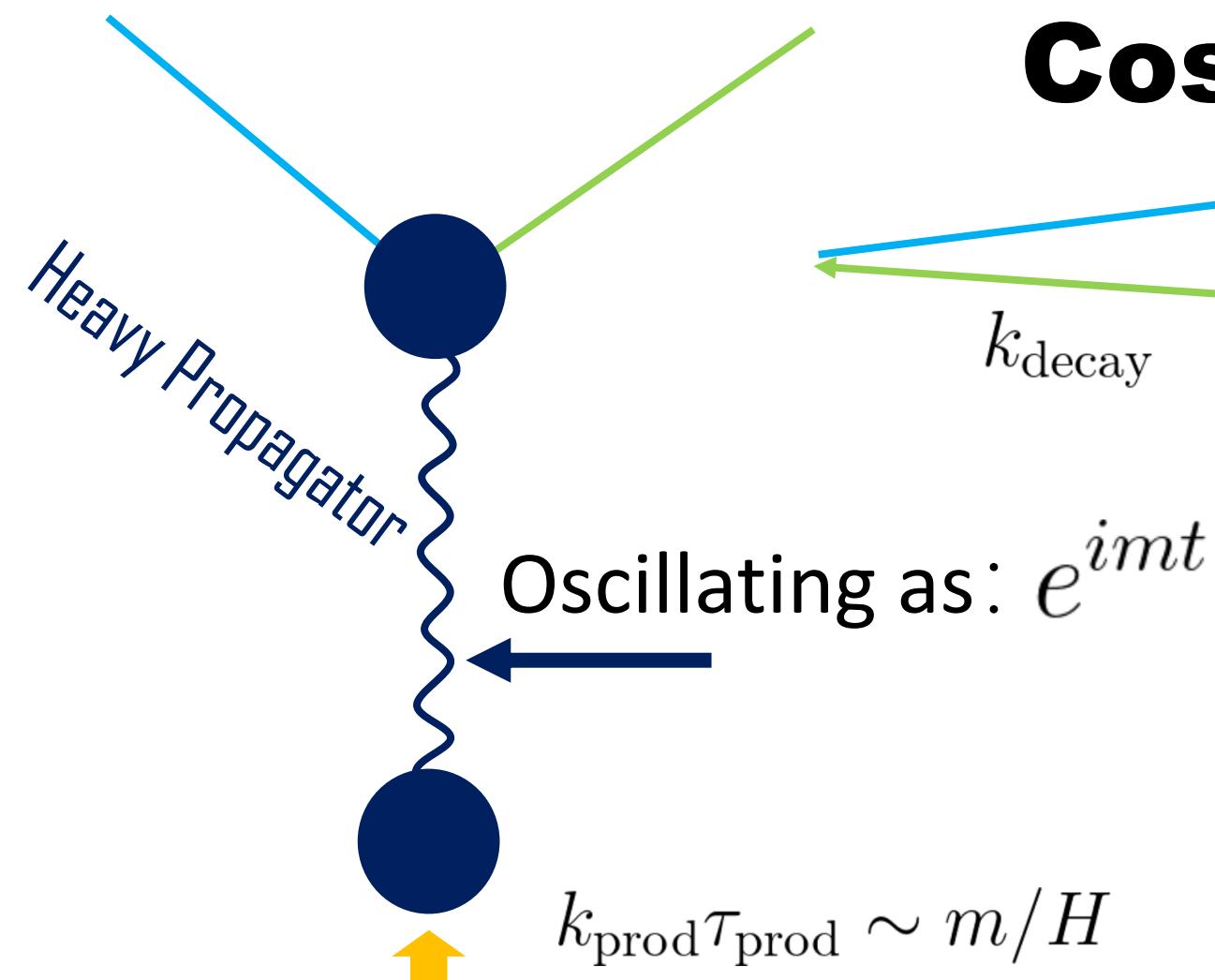
Planck limit on f_{NL} : $O(10)$ for pure curvature.

- 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

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



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

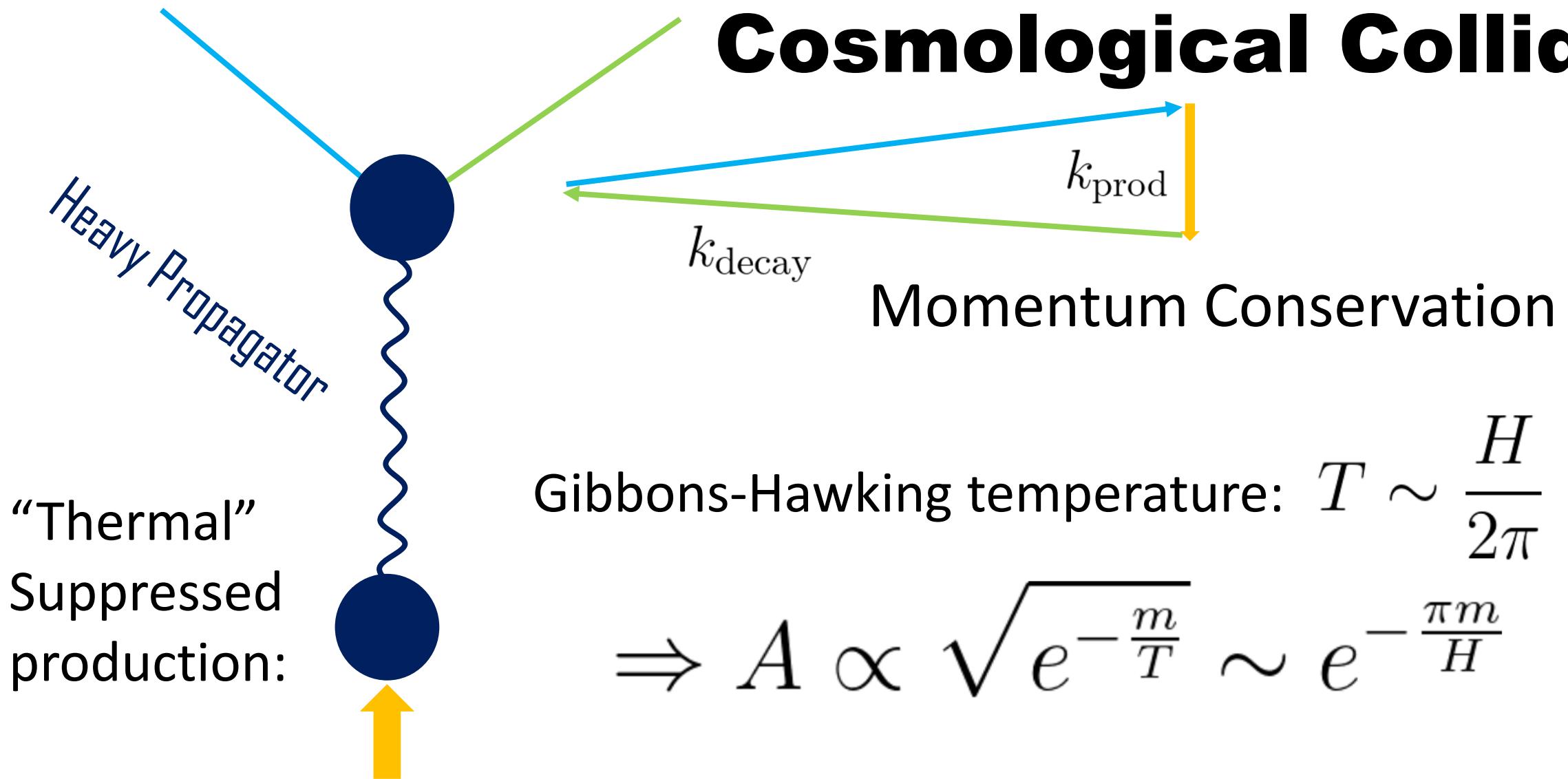
Mass observed through
phases:

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

$$t_{\text{decay}} - t_{\text{prod}} \sim \log \frac{\tau_{\text{prod}}}{\tau_{\text{decay}}}$$

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

Sketch of a Cosmological Collider

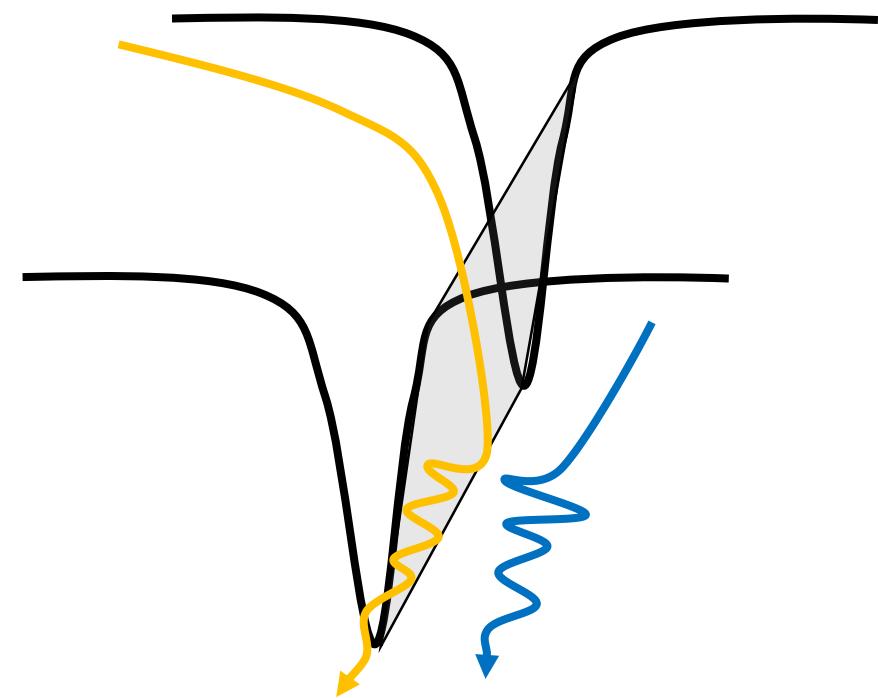


Beyond Boltzmann Suppression

□ Classical Feature

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

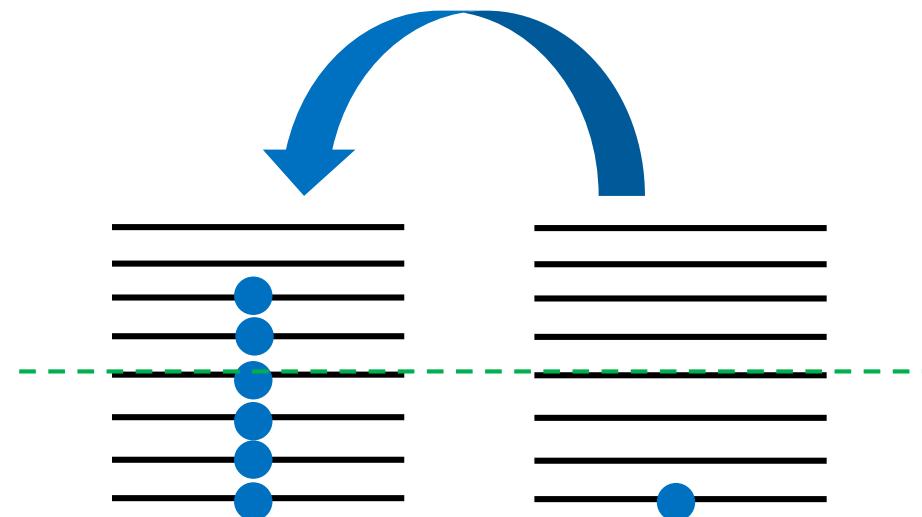
X. Chen, 2011; X. Chen, R. Ebadi, S. Kumar, 2022; A. Bodas, R. Sundrum, 2022 ...



□ 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 ...



Scenario 1: Classical Feature

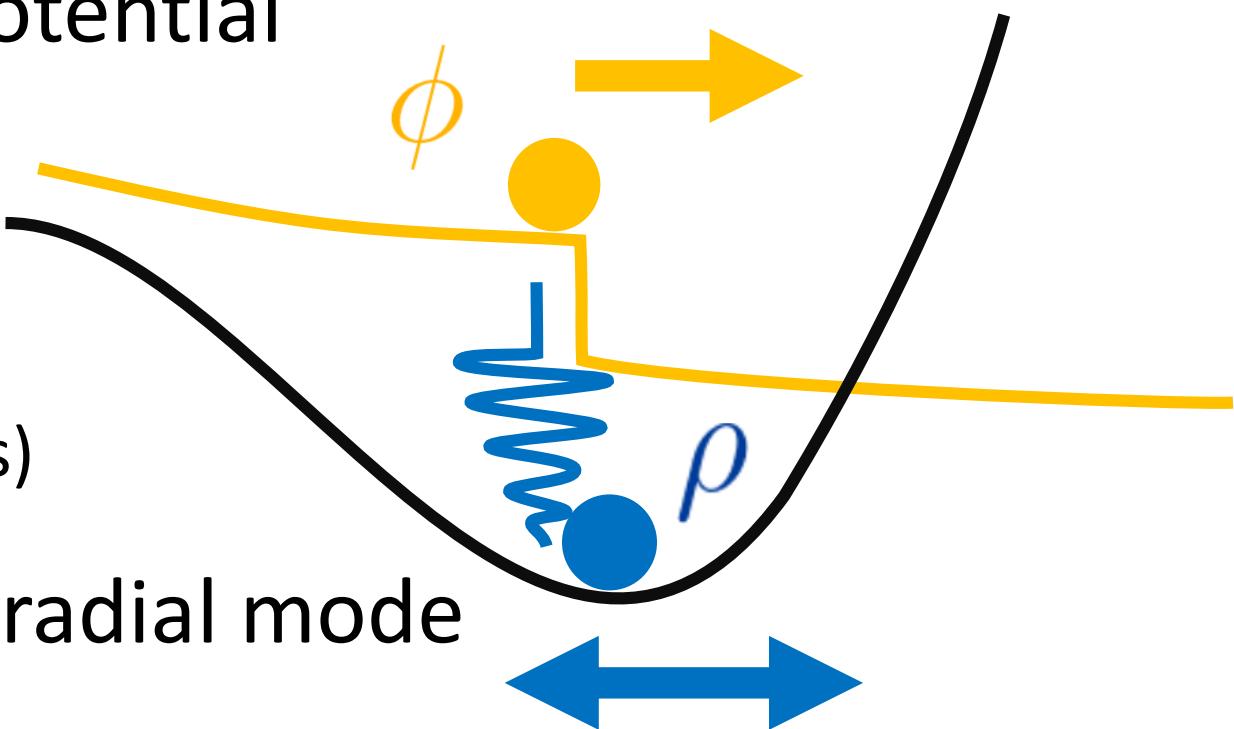
$$\mathcal{L}_1 = -\frac{(\partial_\mu \phi)^2}{2} - |\partial_\mu \chi|^2 - V_\phi(\phi) - V_\chi(\chi) - \boxed{\frac{c}{\Lambda^2} (\partial \phi)^2 |\chi|^2}$$

+ Toy feature: a step in potential

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

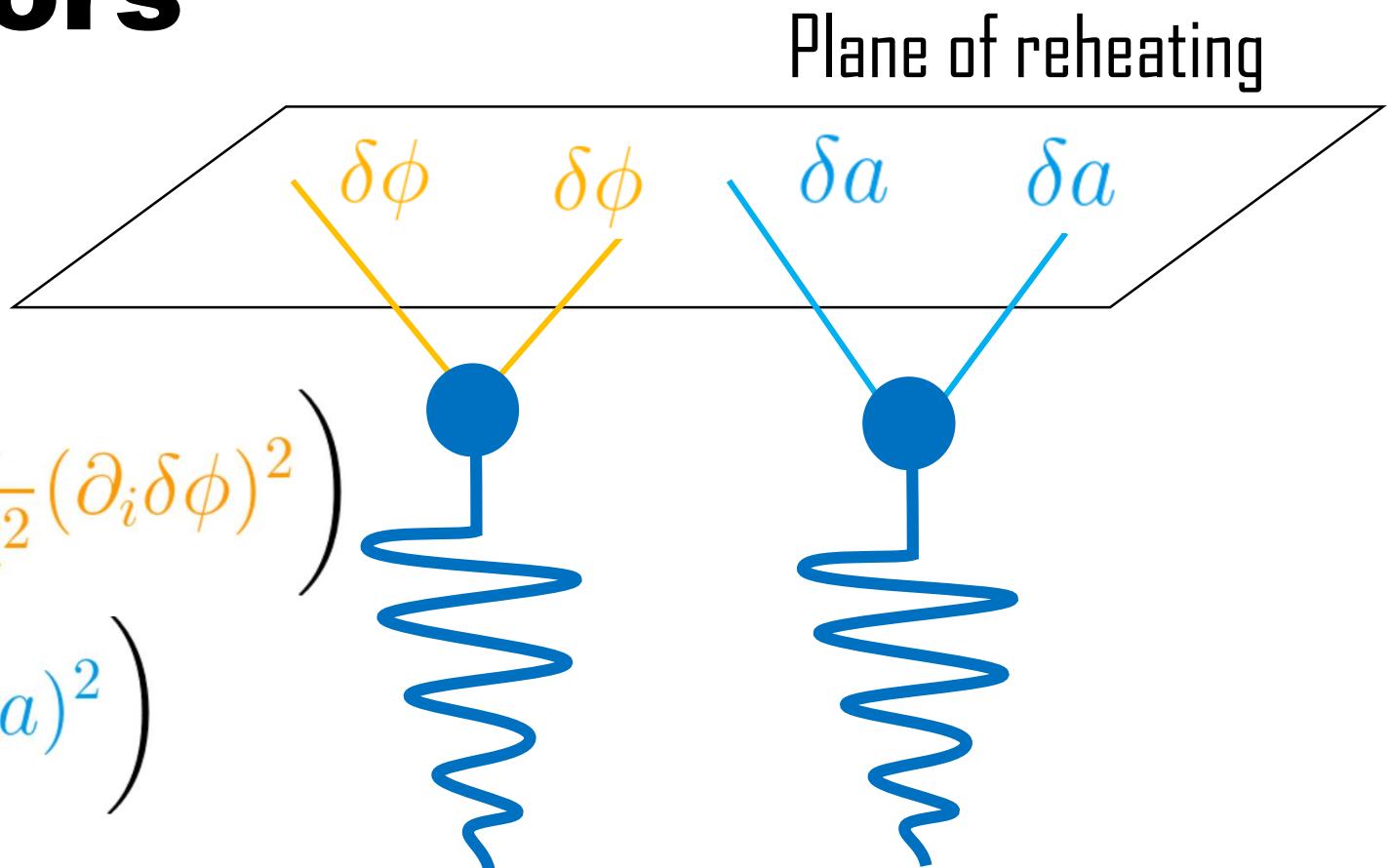
(Could be a phase transition or
other more realistic approaches)

Mediator excited: ρ the radial mode



2-PT Correlators

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



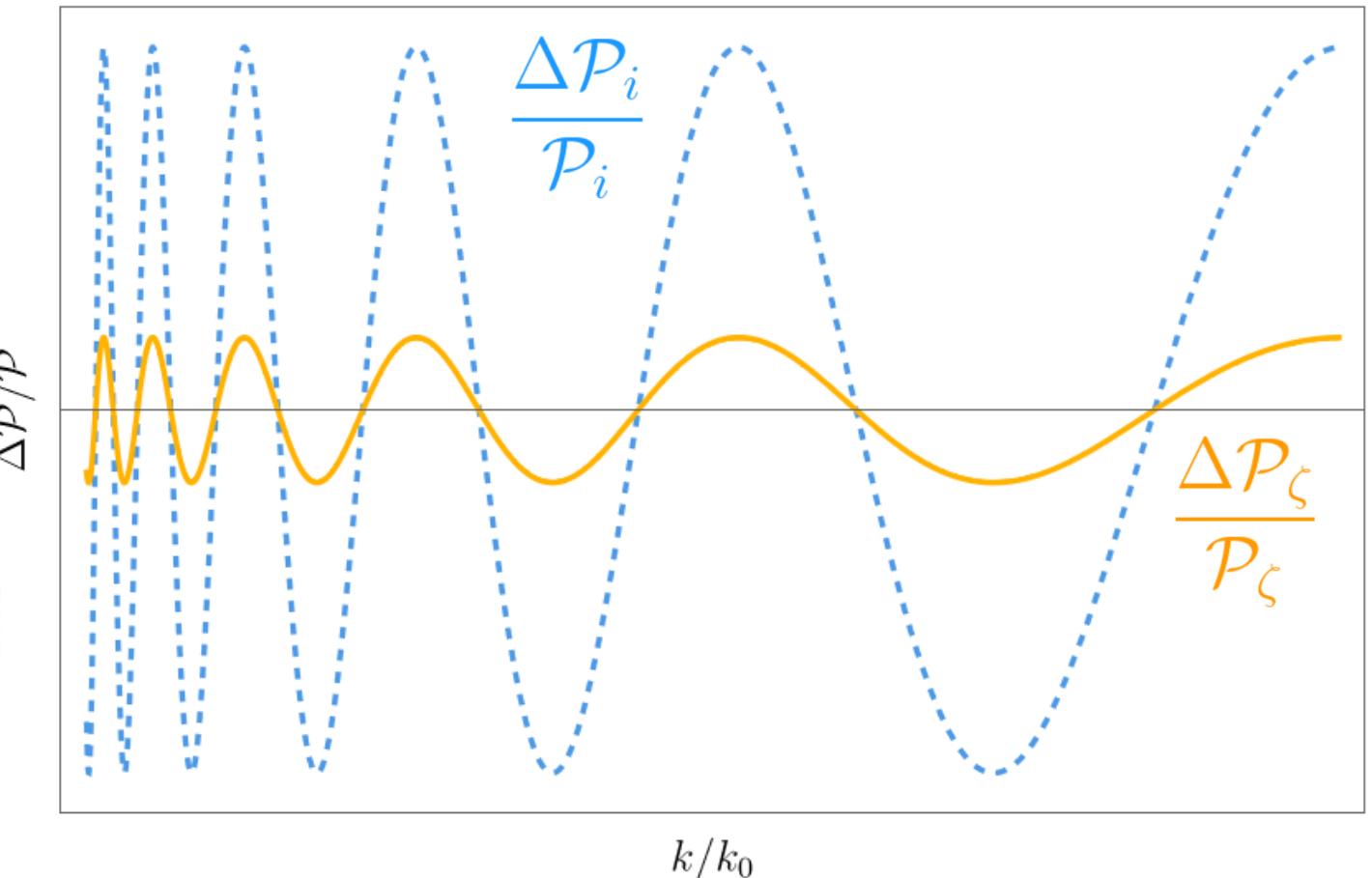
Scale-dependent oscillation in 2-pt, **LARGER** in isocurvature

“Music” of Dark Matter

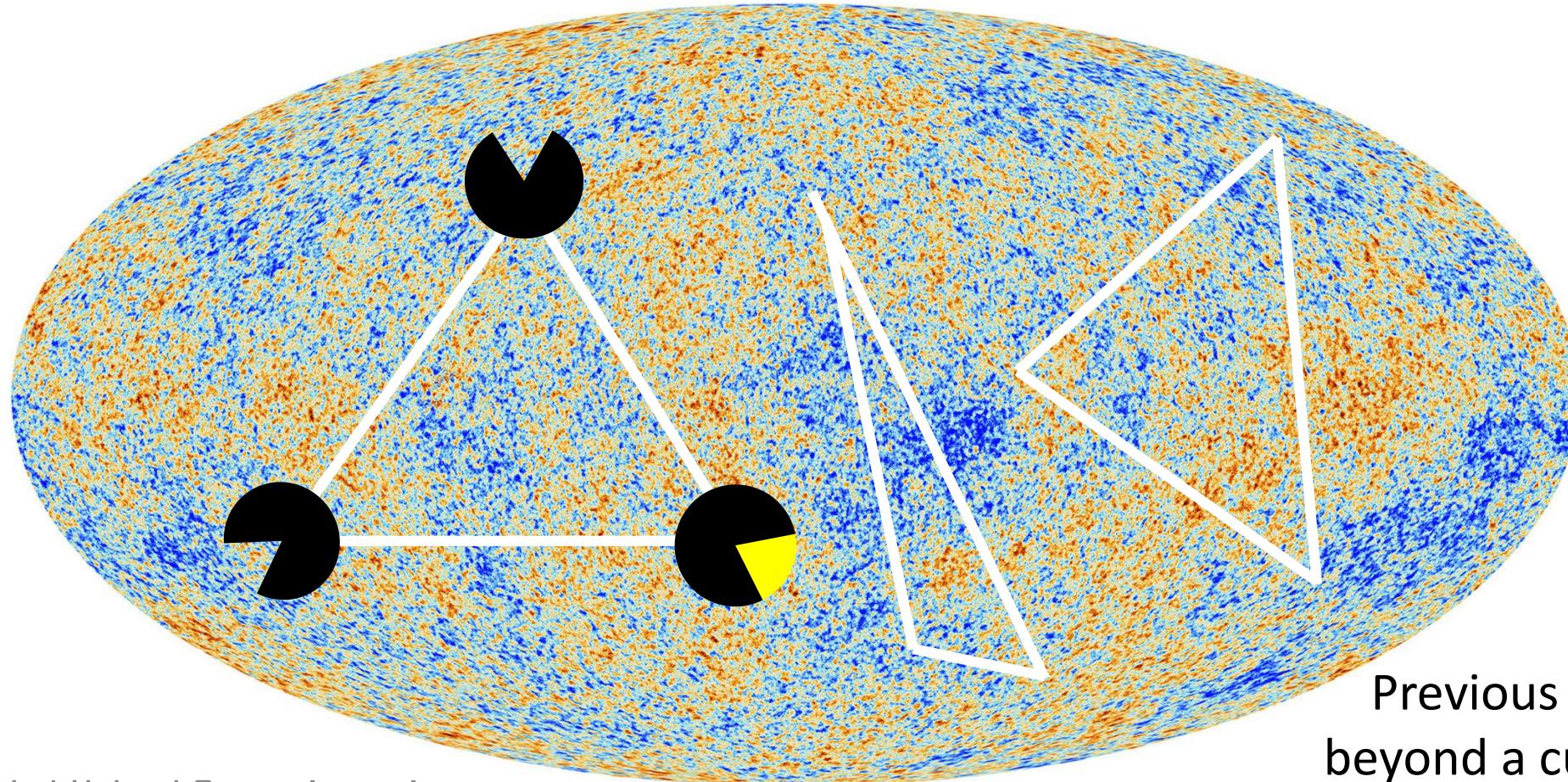


Feature ~ Reed

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



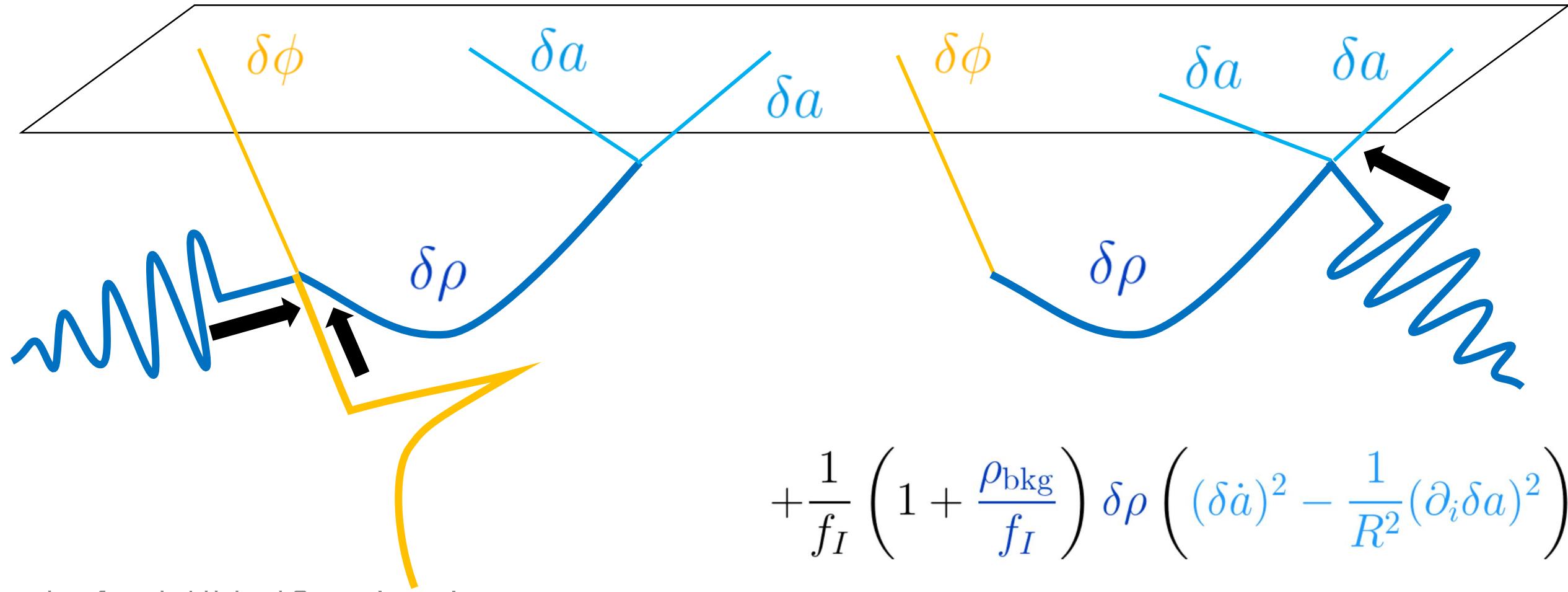
Cosmological Collider Signals of Hybrid Modes



Previous attempts to go beyond a curvature collider:

S. Lu, 2021;
Zhou, 2021

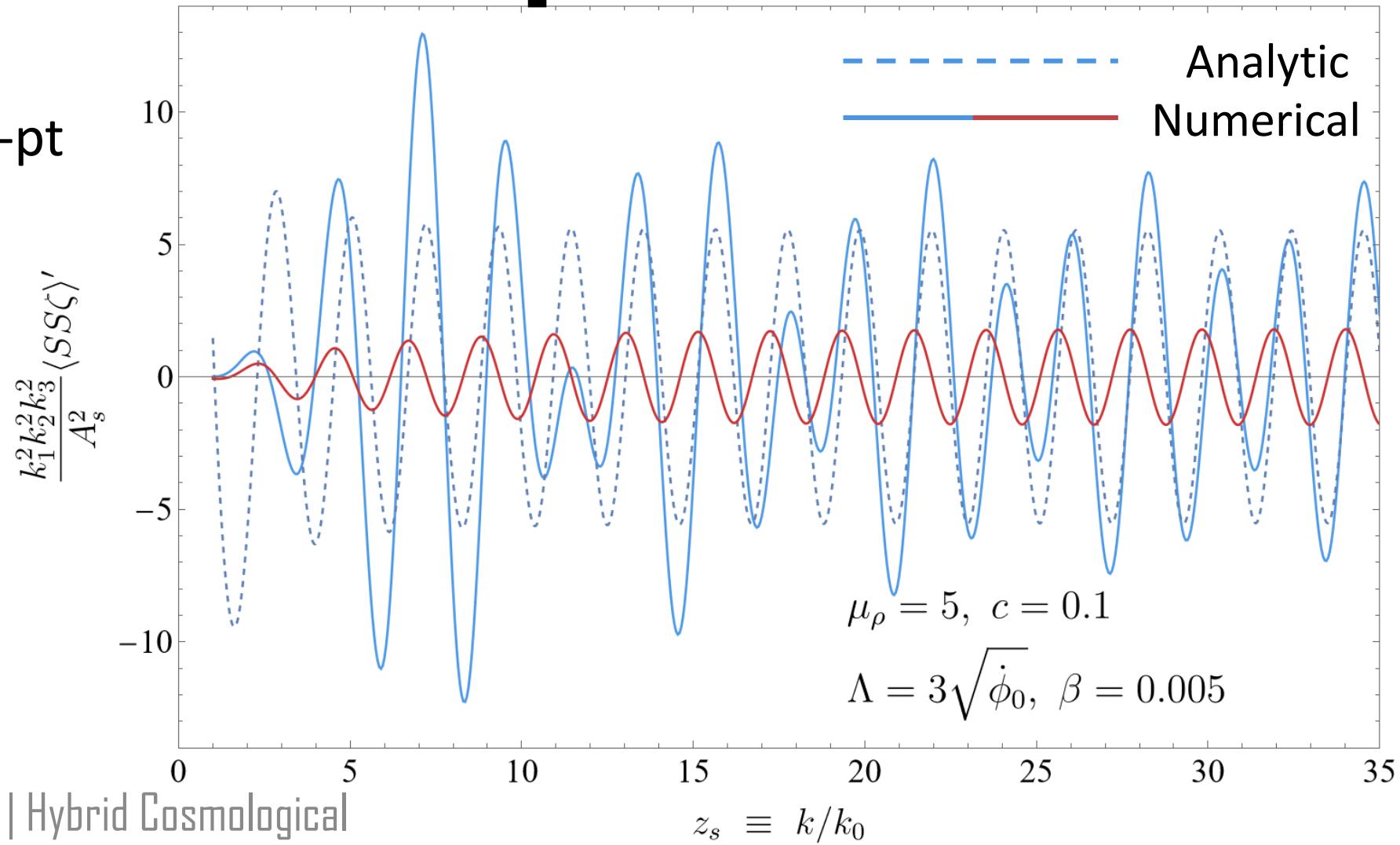
$$\frac{2c f_I \dot{\phi}_0}{\Lambda^2} \left(1 + \frac{\dot{\phi}_1}{\dot{\phi}_0} + \frac{\rho_{\text{bkg}}}{f_I} \right) \delta\dot{\phi} \delta\rho$$



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

NG in the Equilateral limit

Sizable
hybrid 3-pt
signal



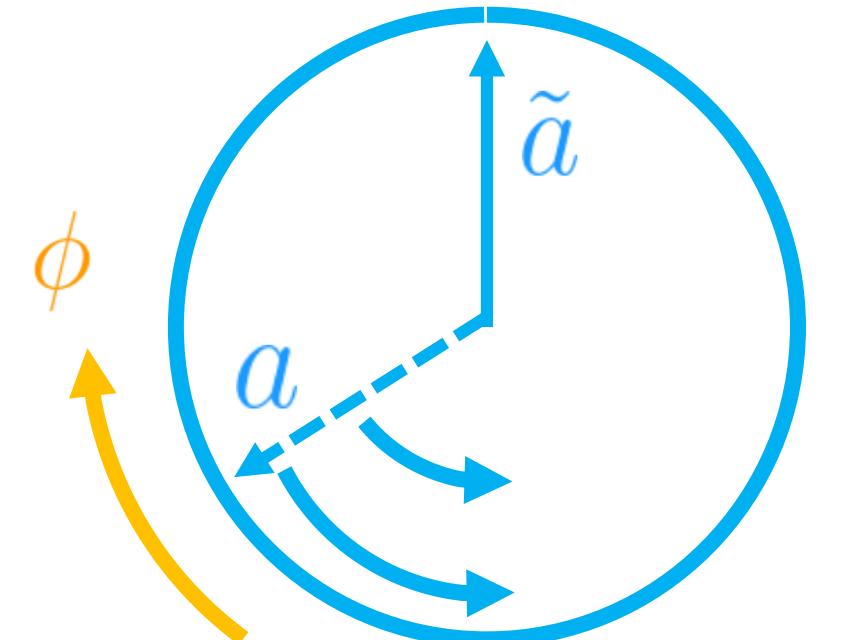
Scenario 2: Chemical Potential

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

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 later



Axion-Fermion Coupling and Chemical Potential

KSVZ-type: axion couple to vector-like quarks

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

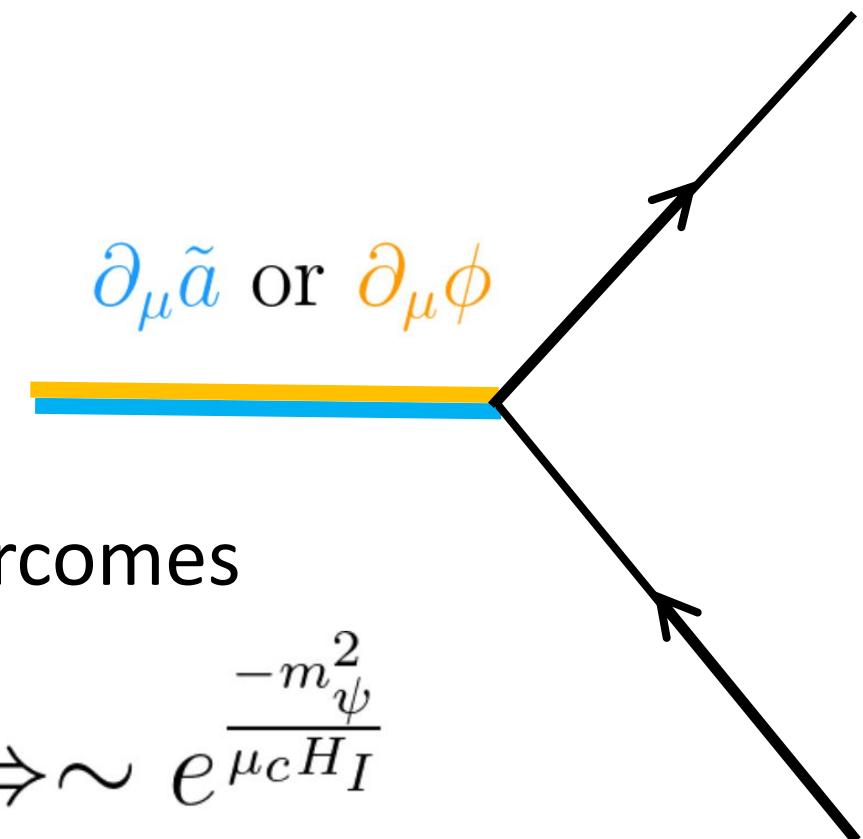
$$\frac{\partial_\mu a}{2f_I} \bar{\psi} \gamma^\mu \gamma_5 \psi = \frac{\partial_\mu \tilde{a} + z \partial_\mu \phi}{2f_I} \bar{\psi} \gamma^\mu \gamma_5 \psi$$

Different helicities get different sign of chemical potential:

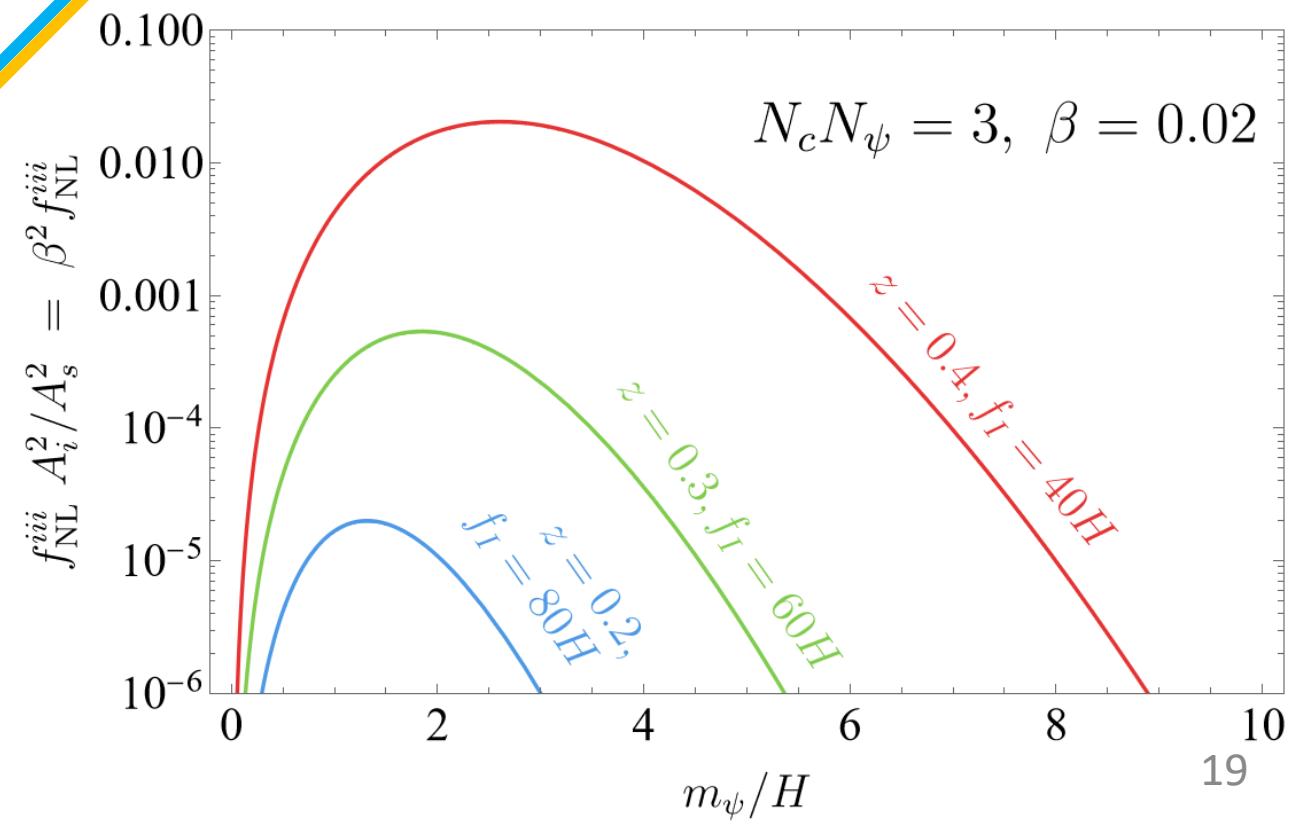
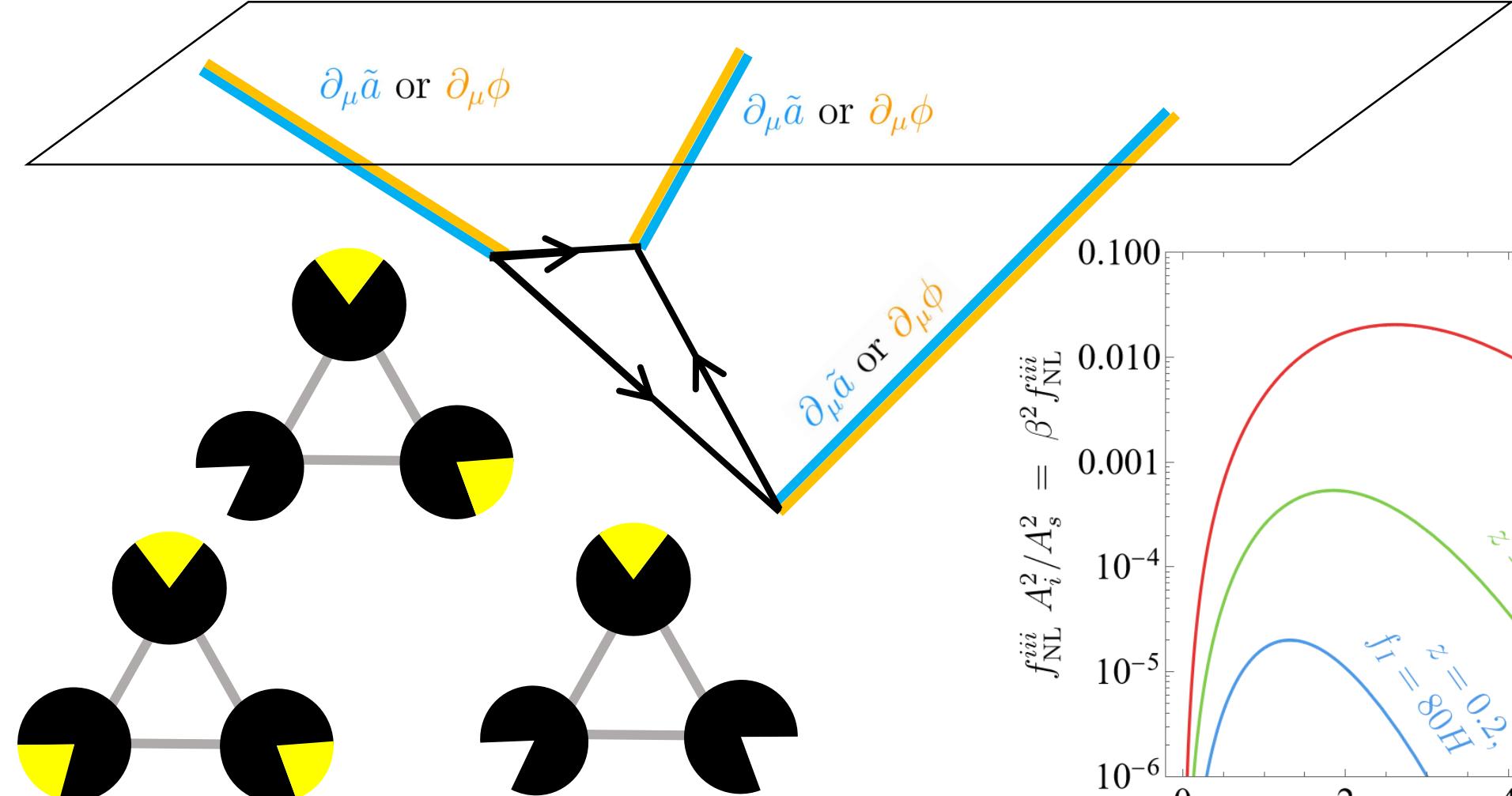
$$\mu_c \equiv \frac{z \dot{\phi}_0}{2f_I} \gg m_\psi$$

Assisted particle (pair) production that overcomes Boltzmann suppression:

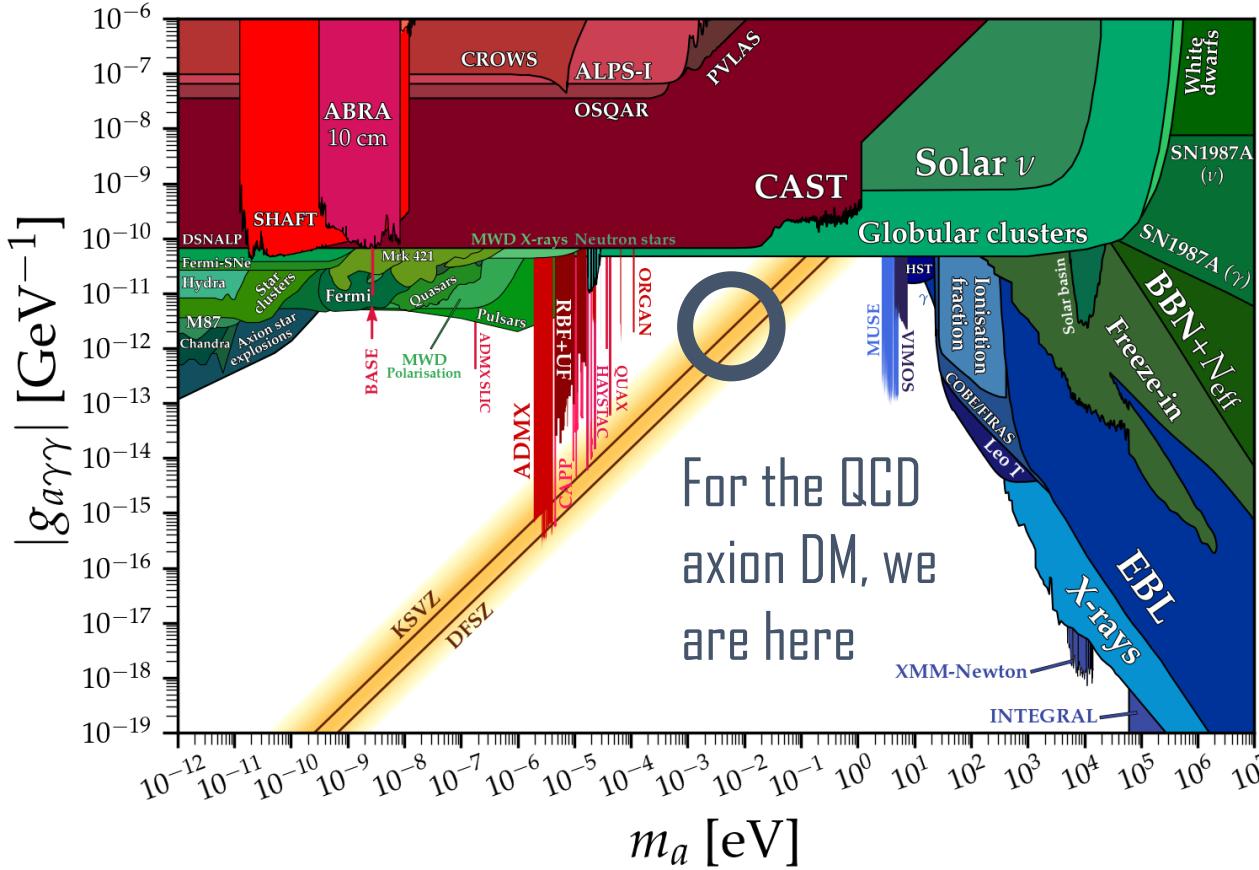
$$\sim e^{\frac{-2\pi m_\psi}{H_I}} \Rightarrow \sim e^{\frac{-m_\psi^2}{\mu_c H_I}}$$



Hybrid Mode of All Types



Misalignment Details



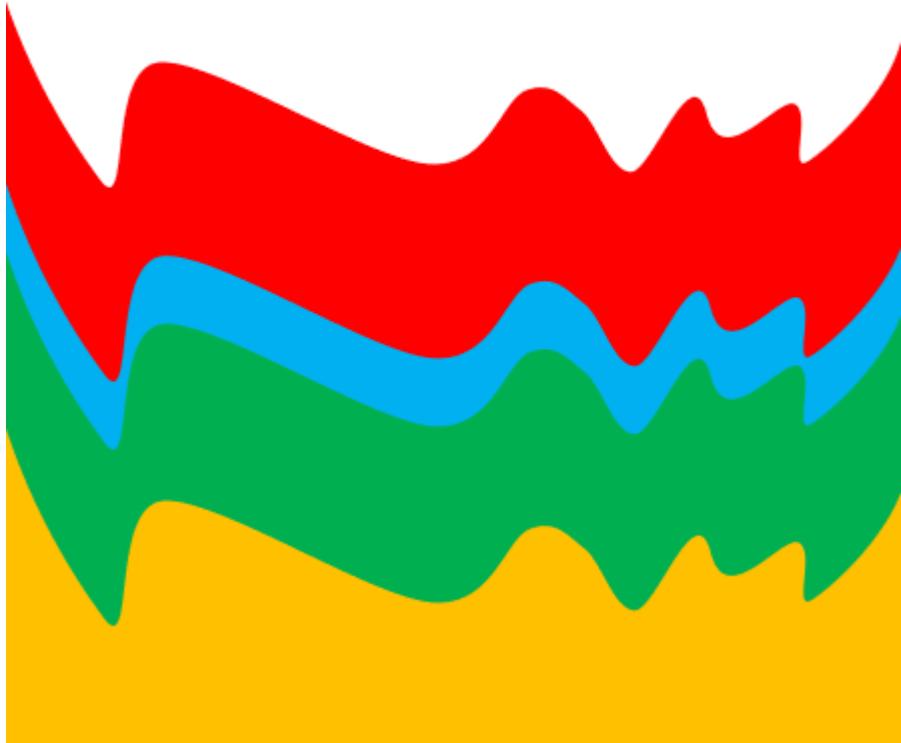
- ⚠ For sizeable isocurvature hybrid signals, need small DM fraction γ of $O(10^{-3})$ or smaller ⚠
- May be a good way to pin down the inflationary scale
 - Size of f_a inferred from DM direct detection (mass-coupling relation, etc.)
 - H/f_a from cosmological collider observables

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

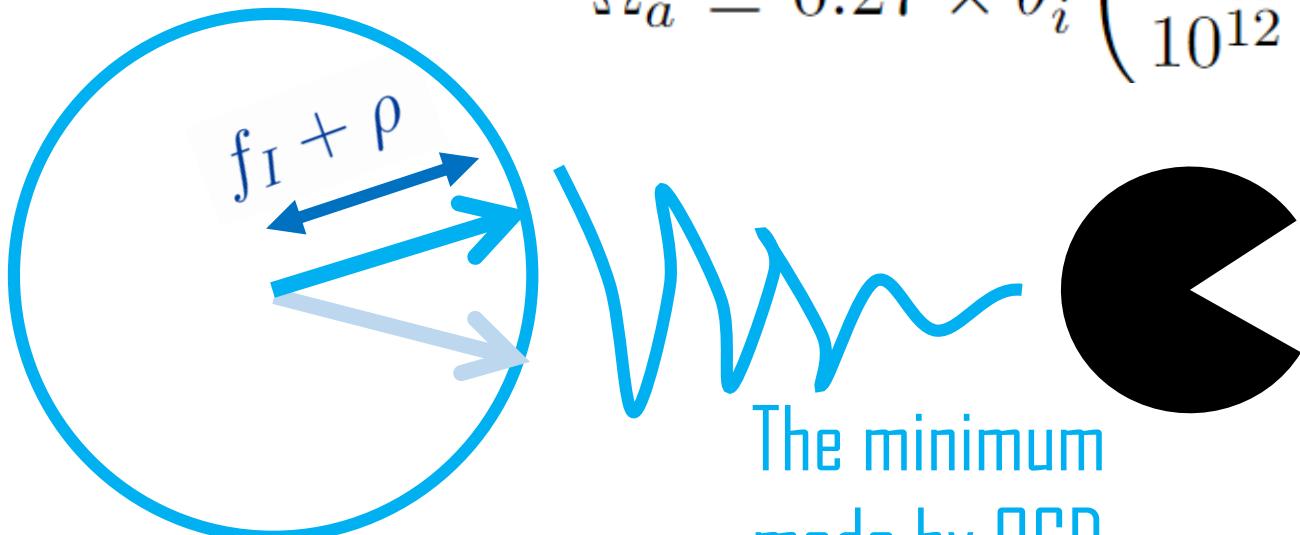


Axion CDM: Misalignment

Preskill, Wise, Wilczek; Dine, Fischler;
Abbott, Sikivie 1983

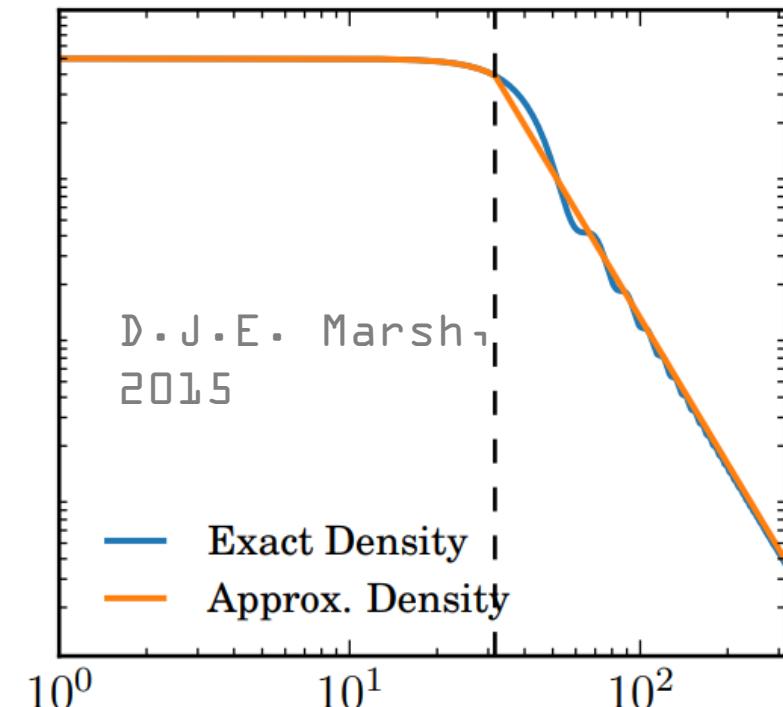
Axion oscillates when Hubble (universe lifetime inverse) is comparable to axion frequency m_a

$$\Omega_a \simeq 0.27 \times \theta_i^2 \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{\frac{7}{6}}$$

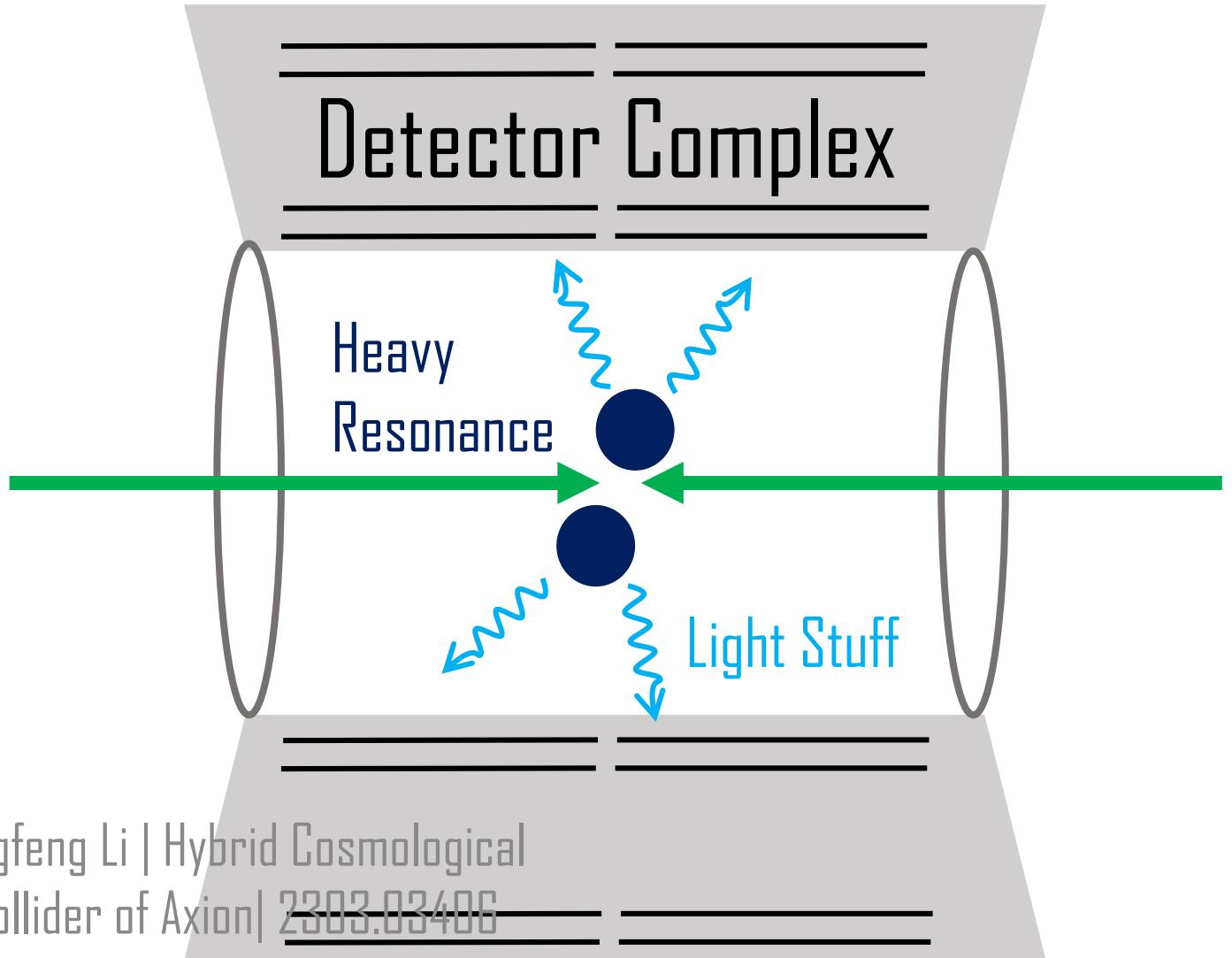


The minimum
made by QCD

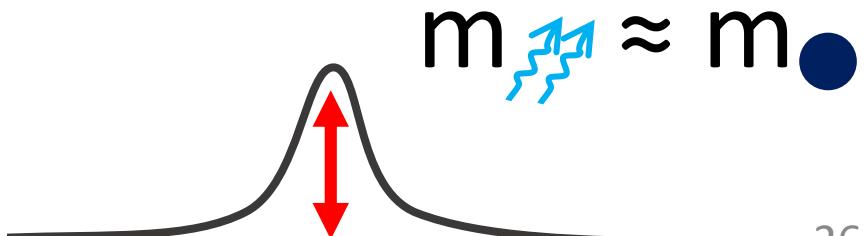
Oscillating field creates non-relativistic, coherent
axion particles

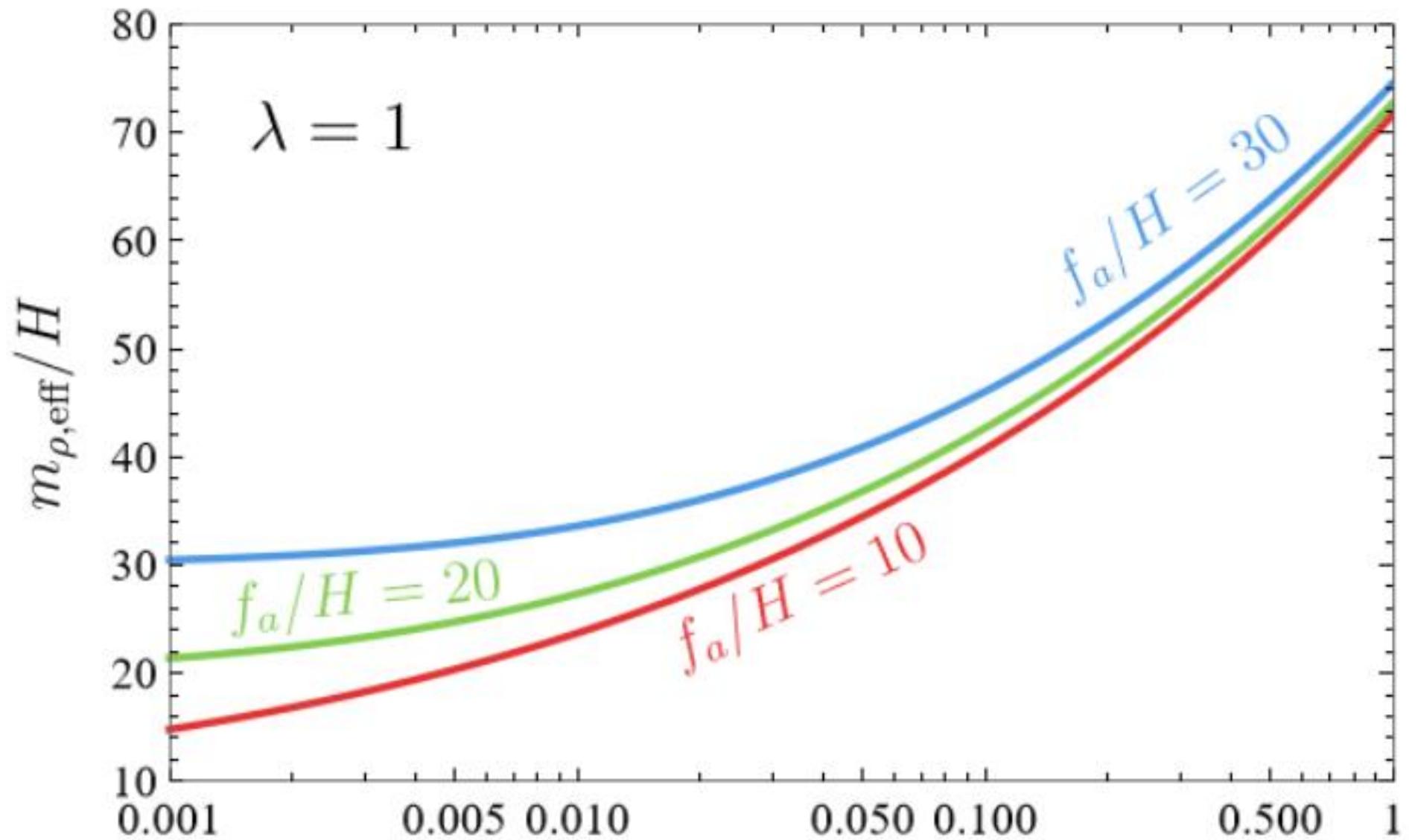


Cosmological Collider: Start from an Actual Collider



- Precisely prepared initial state: fixed E_{cm} , luminosity, direction...
- Short-lived resonances: the detector surfaces are too far compared to m^{-1}
- Multi-species: $\gamma, e^\pm, \pi^\pm, K^\pm \dots$
- Flat space time: invariant mass





In-in Formalism

$$\langle W(t) \rangle = \left\langle \left(T e^{-i \int_{-\infty}^t H_{\text{int}}(t') dt'} \right)^\dagger W(t) \left(T e^{-i \int_{-\infty}^t H_{\text{int}}(t'') dt''} \right) \right\rangle$$

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

Numerical Benchmark

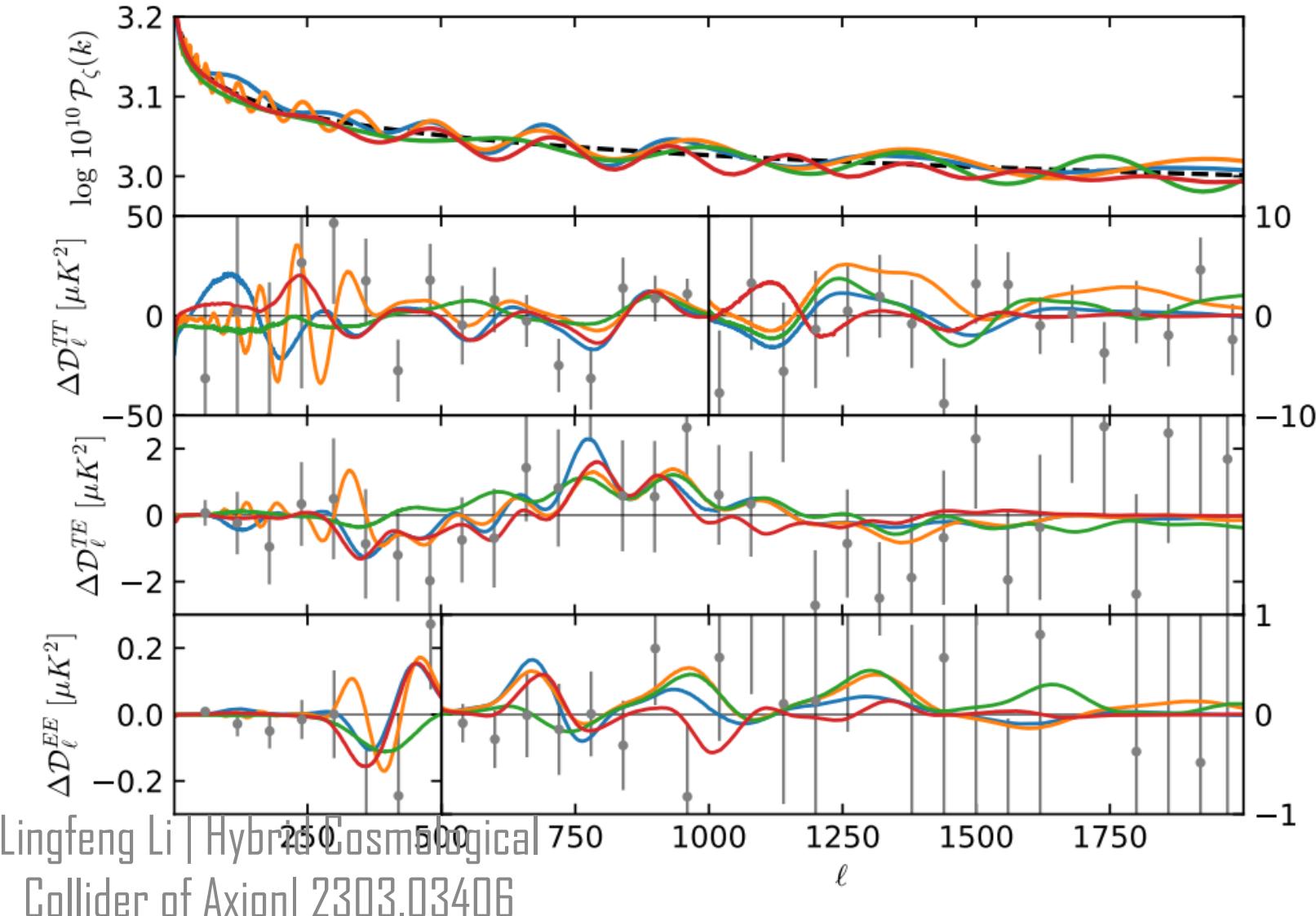
$$\left| \frac{\Delta P_\zeta}{P_\zeta} \right|_{\text{clock;amp}} = \frac{2c^2 b V_{\phi 0} f_I^2}{\Lambda^4 H^2} \sqrt{\frac{2\pi}{\mu_\rho^3}}$$

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

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

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

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

Chemical Potential

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

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

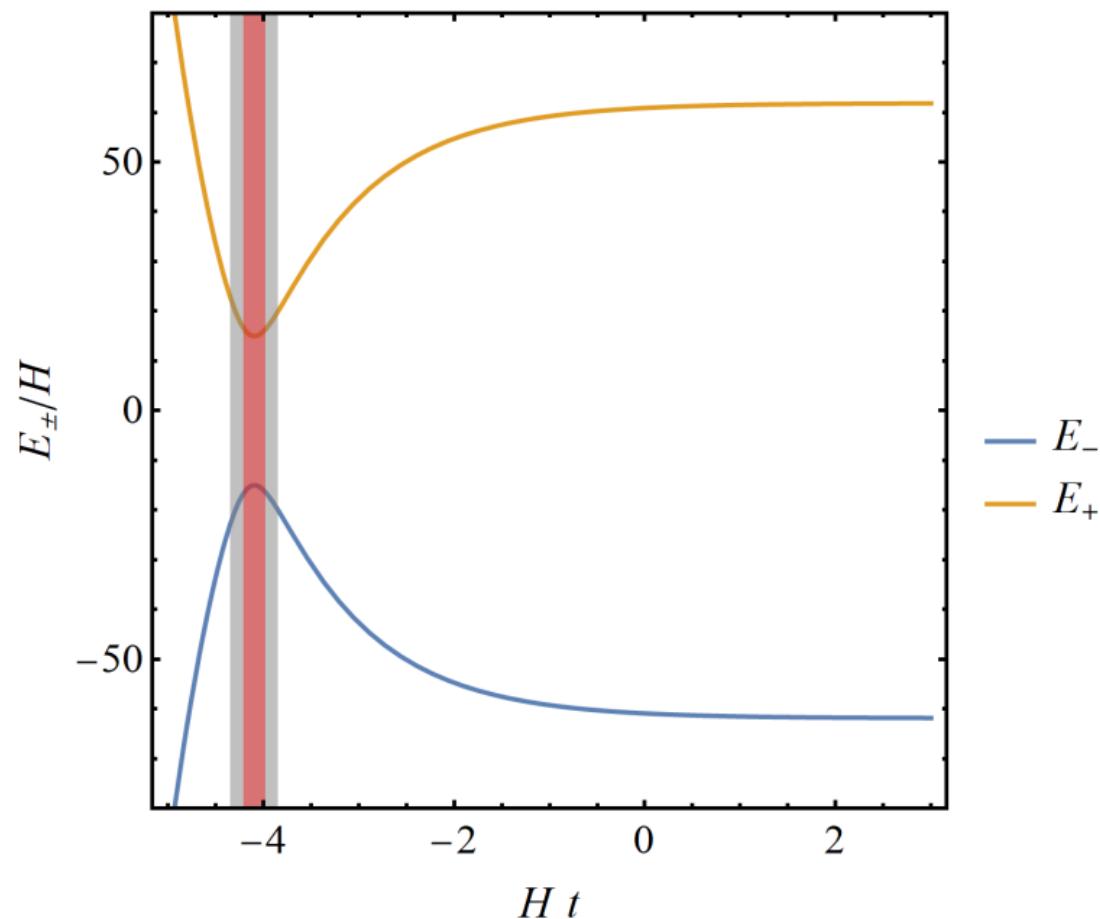
The chemical potential

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

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

Lingfeng Li | Hybrid Cosmological
Collider of Axion | 2303.03406

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



Numerical Approximation

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

γ^3 if QCD

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