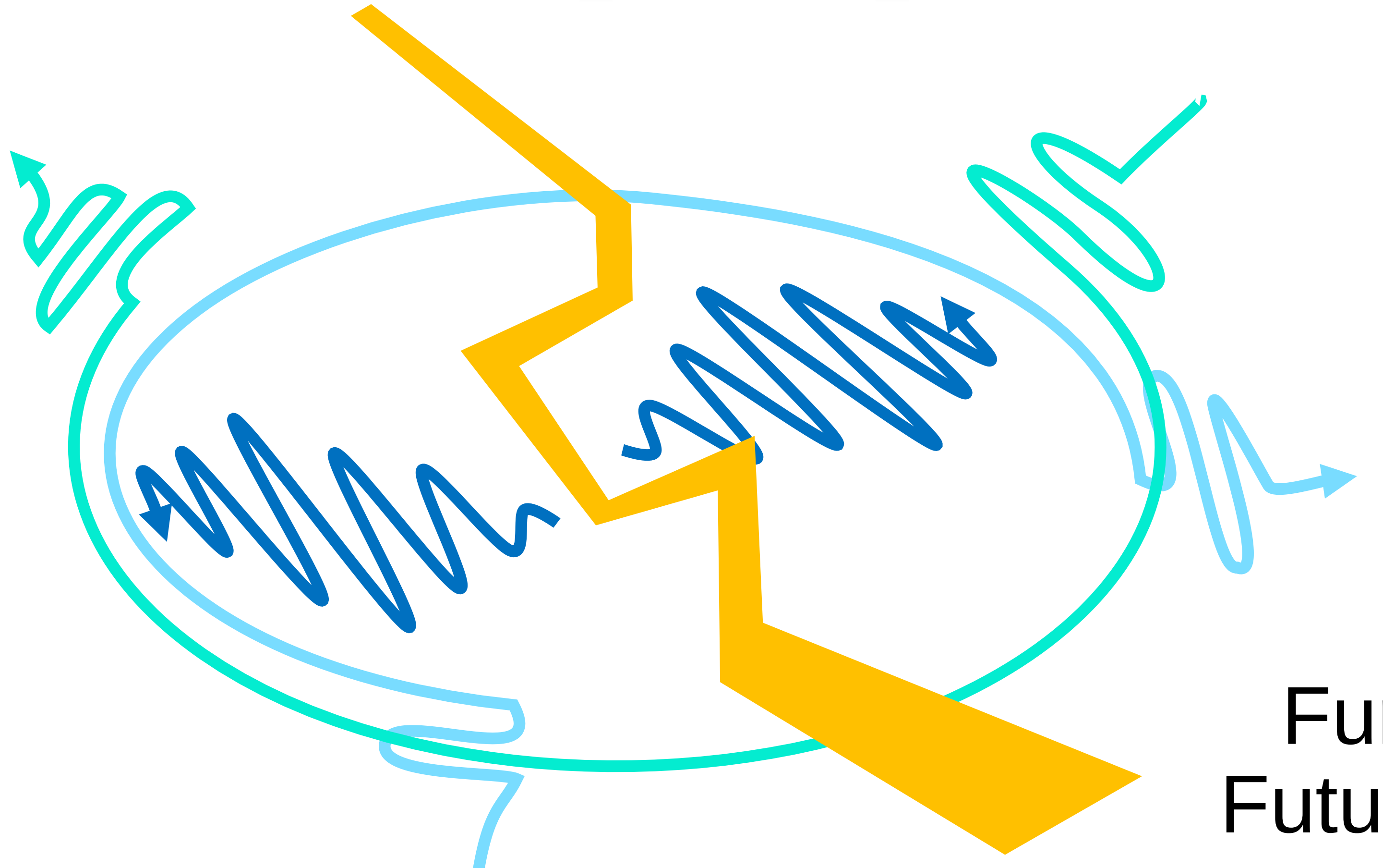
HYBRID COSMOLOGICAL COLLIDER OF (ISO)CURVATURE



arXiv: 2303.03406

with X. Chen & J. Fan

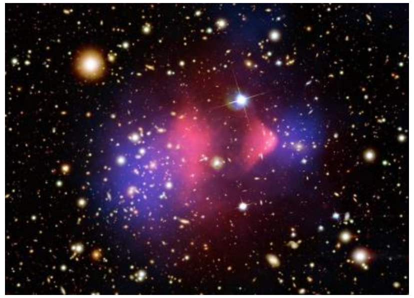
Lingfeng Li

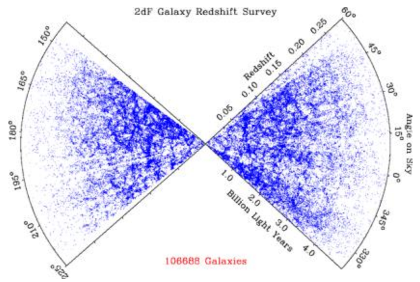
Brown University

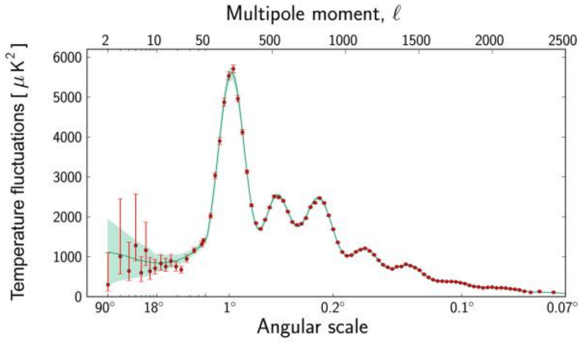
May 7, 2024, LBNL

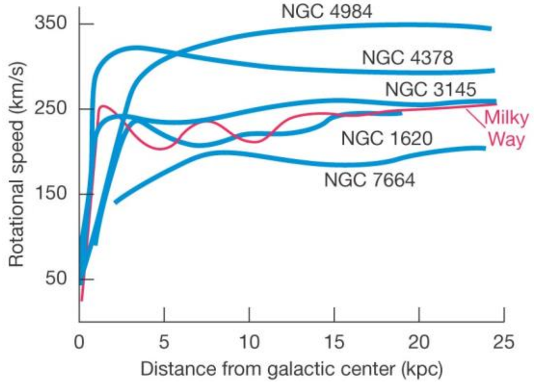
Fundamental Physics form Future Spectroscopic Surveys

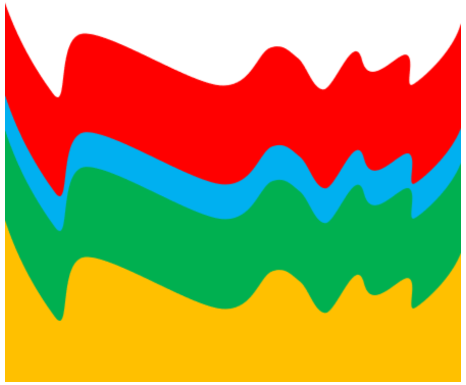
DM and DM Isocurvature











CURVA
TURE

Dark Matter Photon Neutrino Baryons

ISOCUR
VATURE

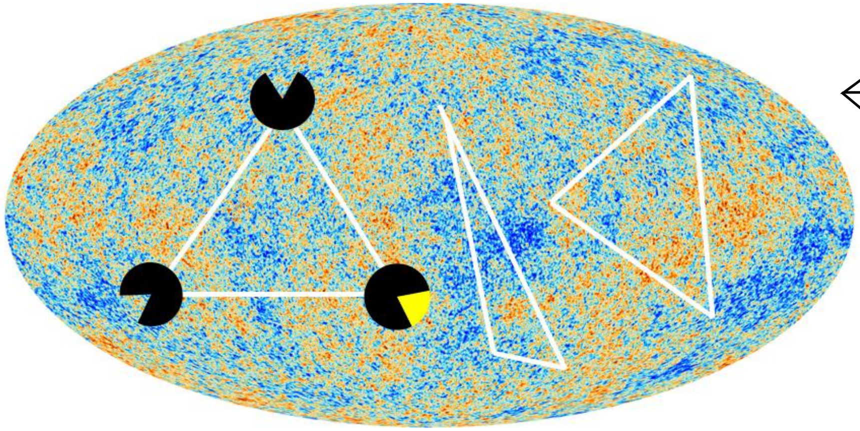
Strong constraints at large CMB scales (<4% of curvature), not as strong at smaller scales

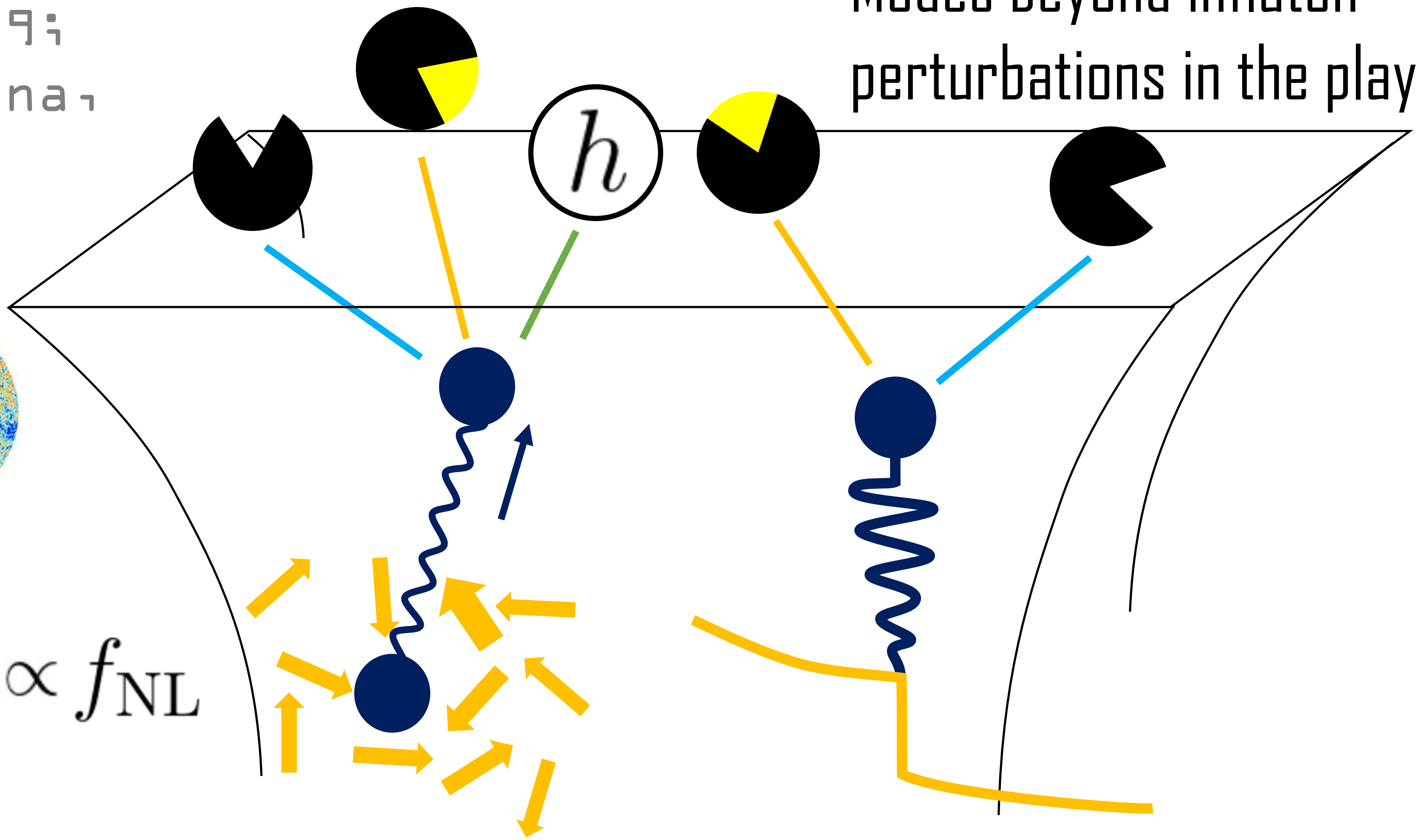
Planck collaboration, 2018
See P. Graham's talk

A Hybrid Cosmological Collider

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

Modes beyond inflaton perturbations in the play





$$\langle \delta\phi(\mathbf{k}_1)\delta\phi(\mathbf{k}_2)\delta\phi(\mathbf{k}_3)\rangle \propto f_{\rm NL}$$

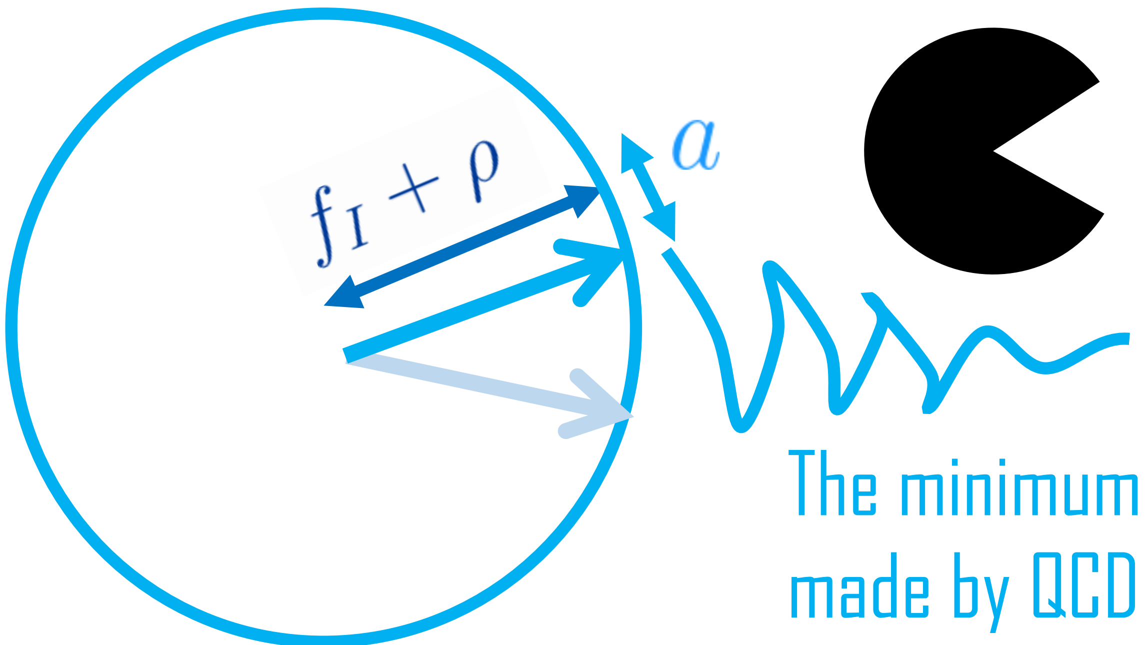
$$f_{\rm NL} \sim \left(\frac{k_{\rm decay}}{k_{\rm prod}}\right)^{im/H}$$

See A. Joyce's talk

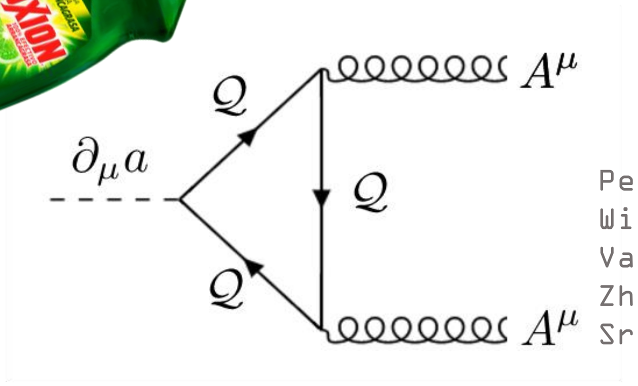
Testing physics principles/symmetries during inflation

Isocurvature from Axion(like) DM

- ❑ Spontaneous symmetry breaking during inflation: massless goldstone boson & the unbroke global symmetry
- ❑ Global symmetry broken only in the late universe, creating non-relativistic particle in coherent oscillations (misalignment mechanism)
- ❑ CDM isocurvature from the goldstone mode fluctuations.



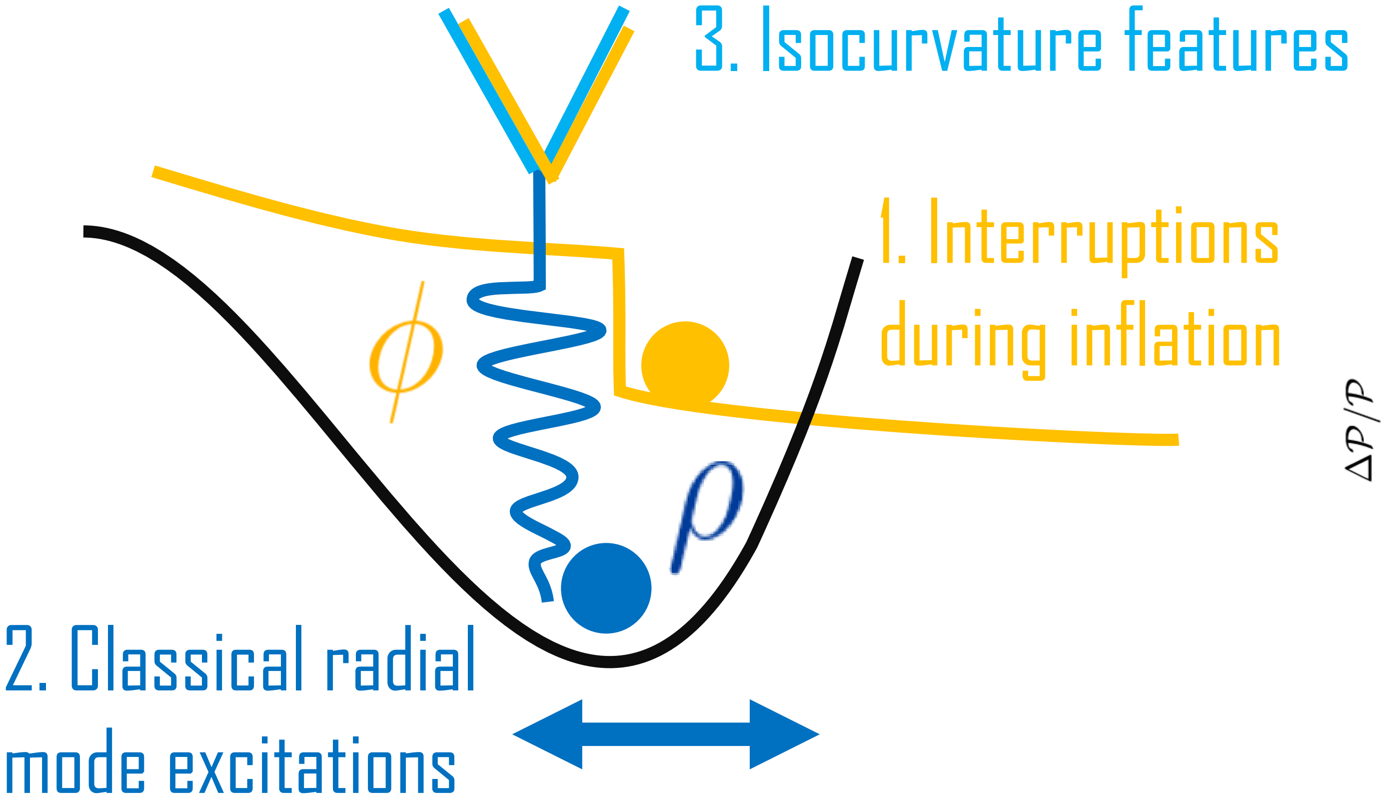
The U(1) example: axion and ALP

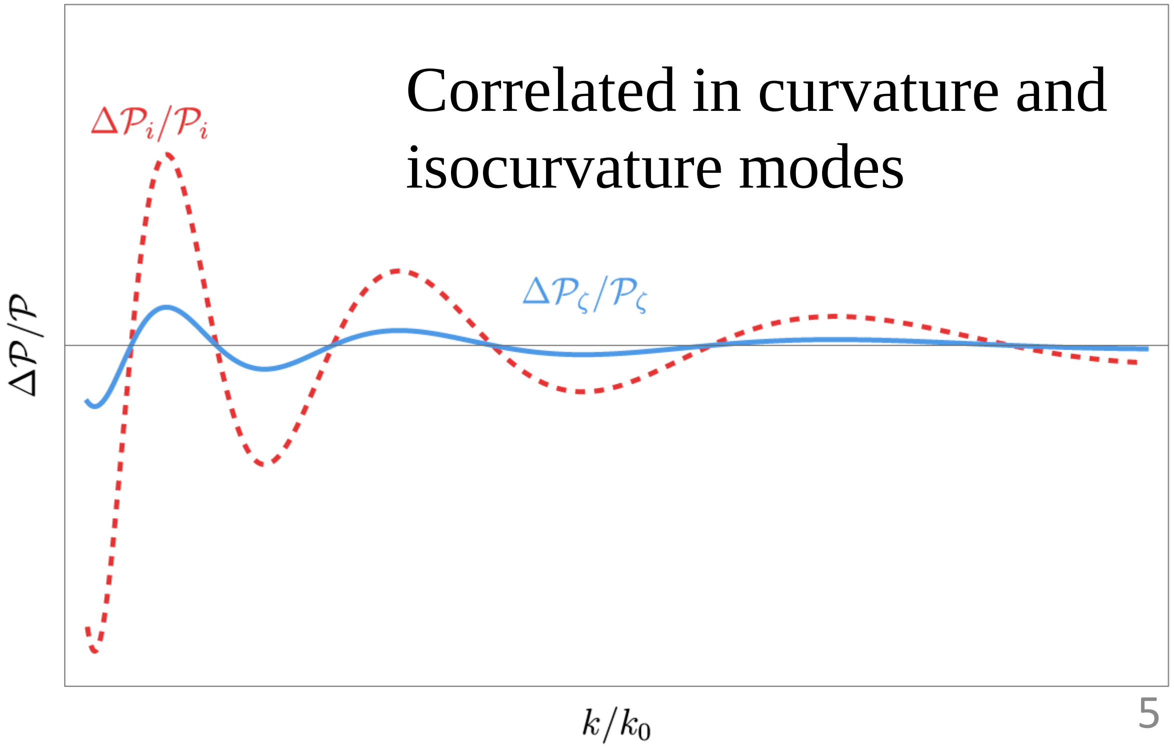


Peccei, Quinn; Weinberg; Wilczek; Kim; Shifman, Vainshtein, Zakharov; Zhitnitsky; Dine, Fischler, Srednicki, 1977-1981

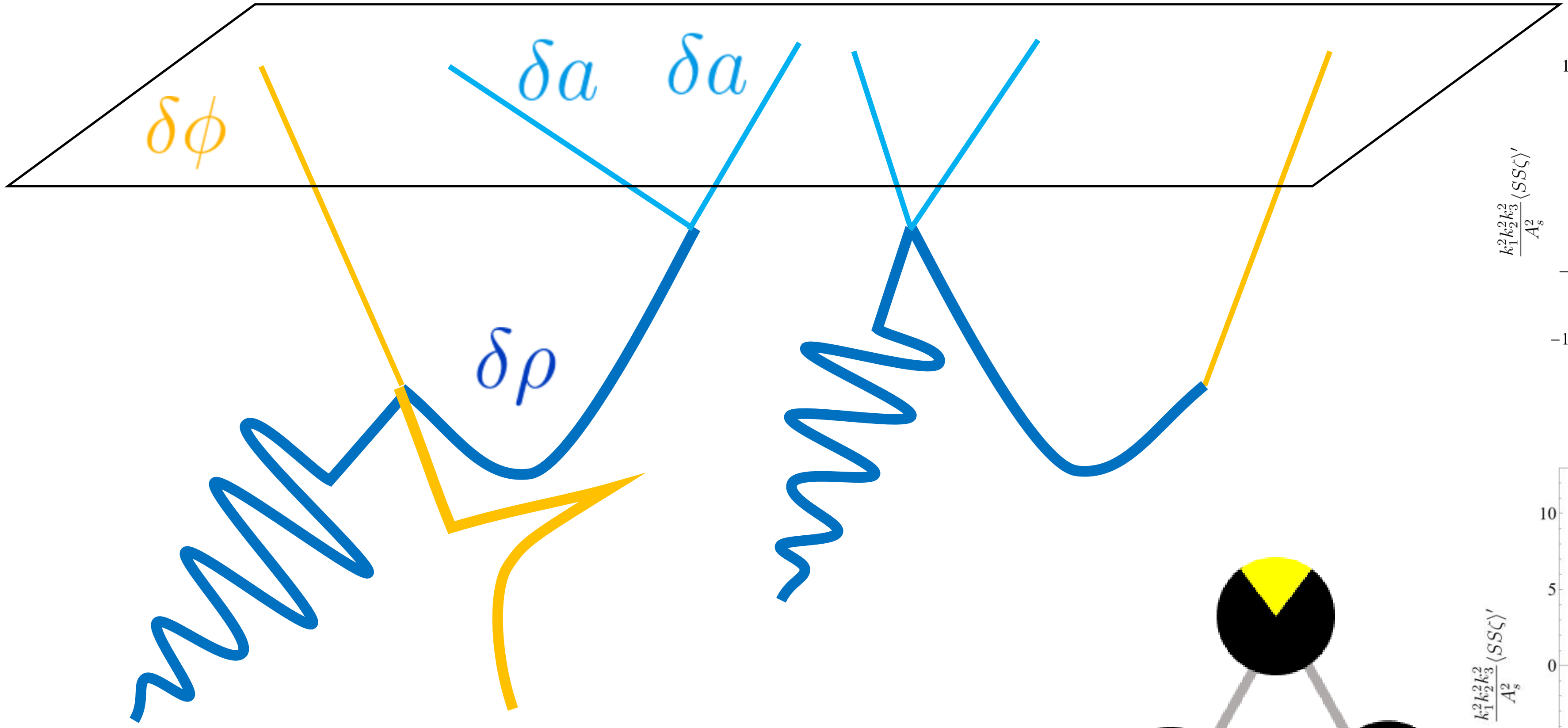
Scenario 1: Primordial Feature

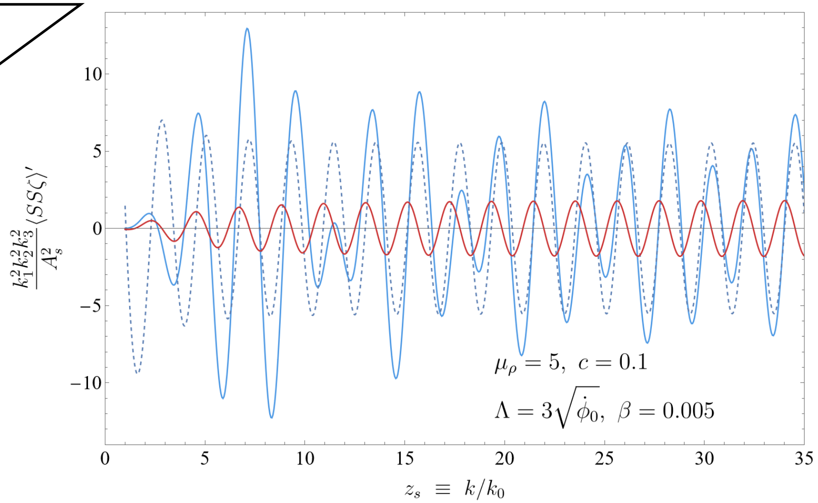
Inflaton - PQ interaction $\frac{c}{\Lambda^2}(\partial\phi)^2|\chi|^2 \Rightarrow \mathcal{L}_1^{(2)} \supset \frac{cf_I^2}{\Lambda^2}\frac{\rho_{\rm bkg}}{f_I}\left((\delta\dot{\phi})^2 - \frac{1}{R^2}(\partial_i\delta\phi)^2\right) + \frac{\rho_{\rm bkg}}{f_I}\left((\delta\dot{a})^2 - \frac{1}{R^2}(\partial_i\delta a)^2\right)$

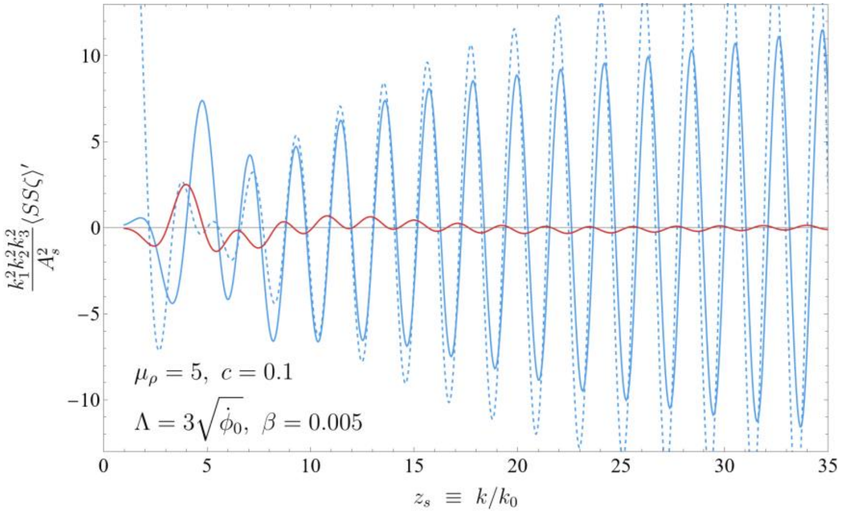




Hybrid Three Point Correlator





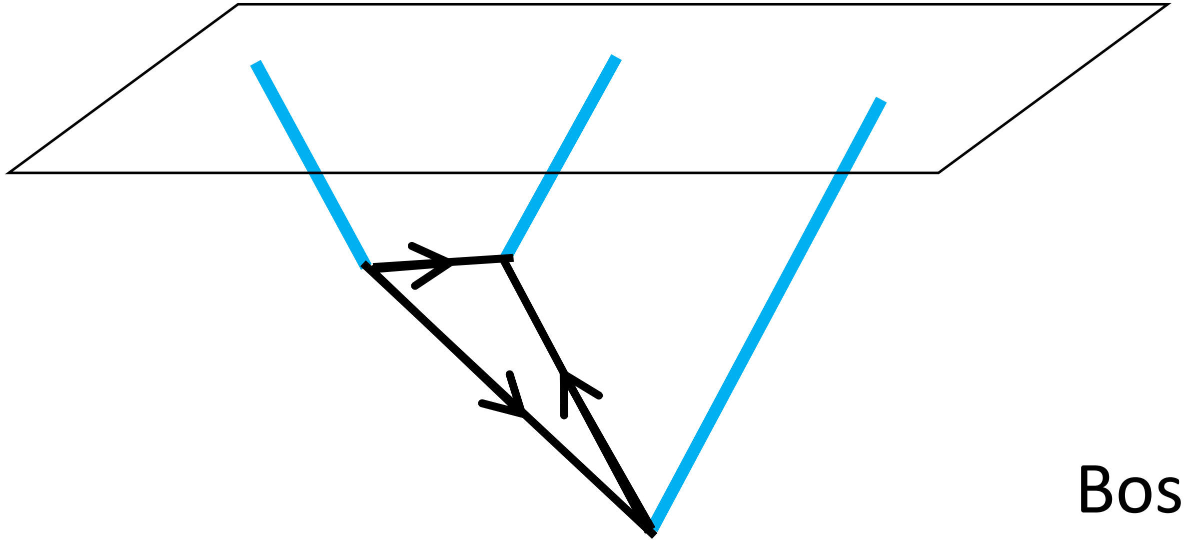


Double-isocurvature hybrid pattern
due to the unbroken Z_2 symmetry

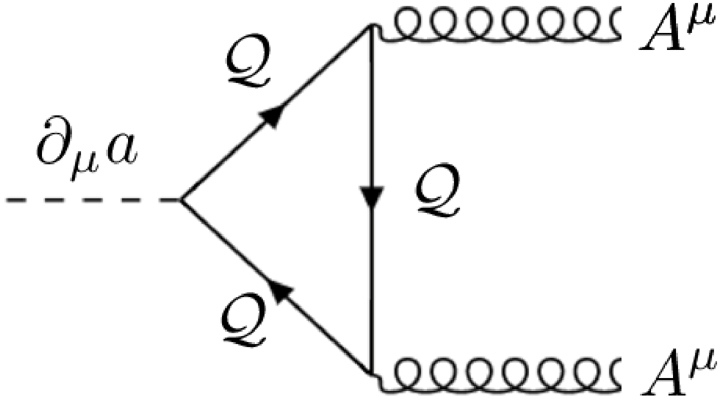
Scenario 2: Fermion Loops

Heavy fermions are common in axion theories, e.g. KSVZ axion

$$\frac{\partial_\mu a}{2 f_I}\bar{\psi}\gamma^\mu\gamma_5\psi$$



Introduces non-trivial isocurvature bispectrum



Boson loop is also an option:

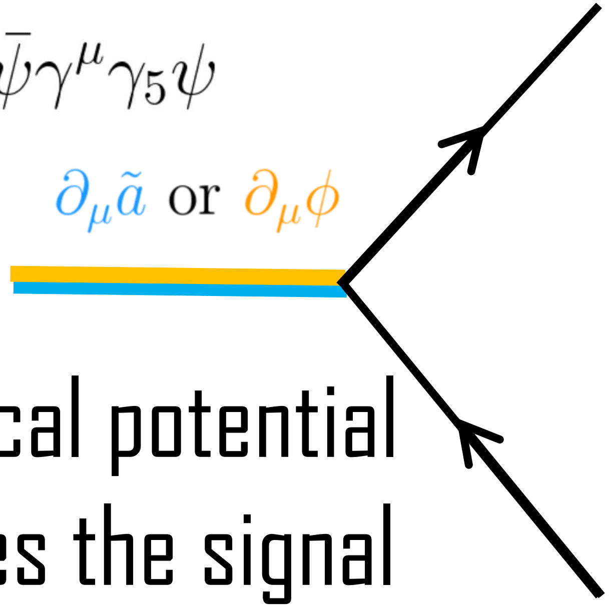
S. Lu, 2021; X. Niu, M. H. Rahat, K. Sirinvasan, W. Xue 2022

Mixture and Chemical Potential

Inflaton - J_{PQ} interaction $\quad i\frac{\kappa\partial_\mu\phi}{\Lambda}(\chi^\dagger\partial^\mu\chi - \chi\partial^\mu\chi^\dagger)$ $\Rightarrow$ Axion & inflaton kinetic mixing

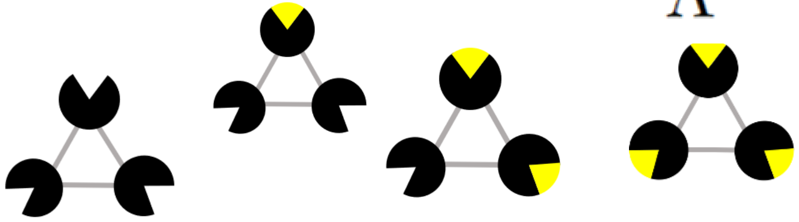
$$\tilde{\rho} = \rho\ , \quad \tilde{a} = a - z\phi\ , \quad z \equiv \frac{\kappa f_I}{\Lambda}$$

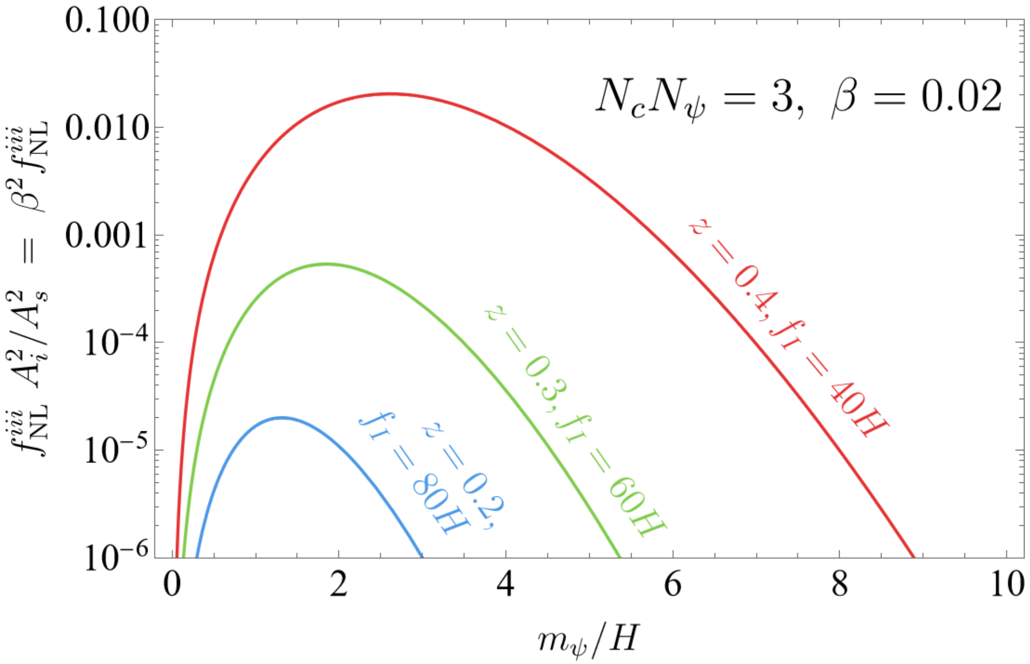
$$\frac{\partial_\mu\tilde{a} + z\partial_\mu\phi}{2f_I}\bar{\psi}\gamma^\mu\gamma_5\psi$$



Large chemical potential also enhances the signal

Getting all kinds of hybrid correlators





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

What's Next?

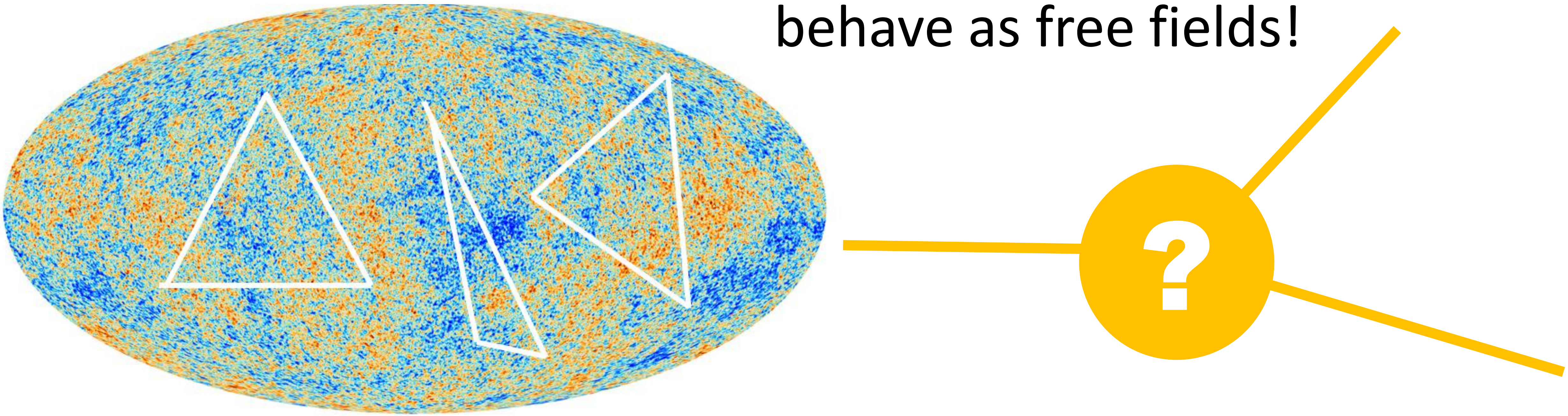
M. Braglia, X. Chen, J. Fan, LL,
L. Pinol, P. Singh, Y. Wu, in progress

- Extends the discussion to other types of isocurvature
  - Not limited to DM production
- C.C. / feature with explicit symmetry breaking
  - Only massive modes in the isocurvature sector
- CMB implications
  - What about LSS?

BAKCUPS &
EXTRA THOUGHTS

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

Wouldn't happen if everything behave as free fields!

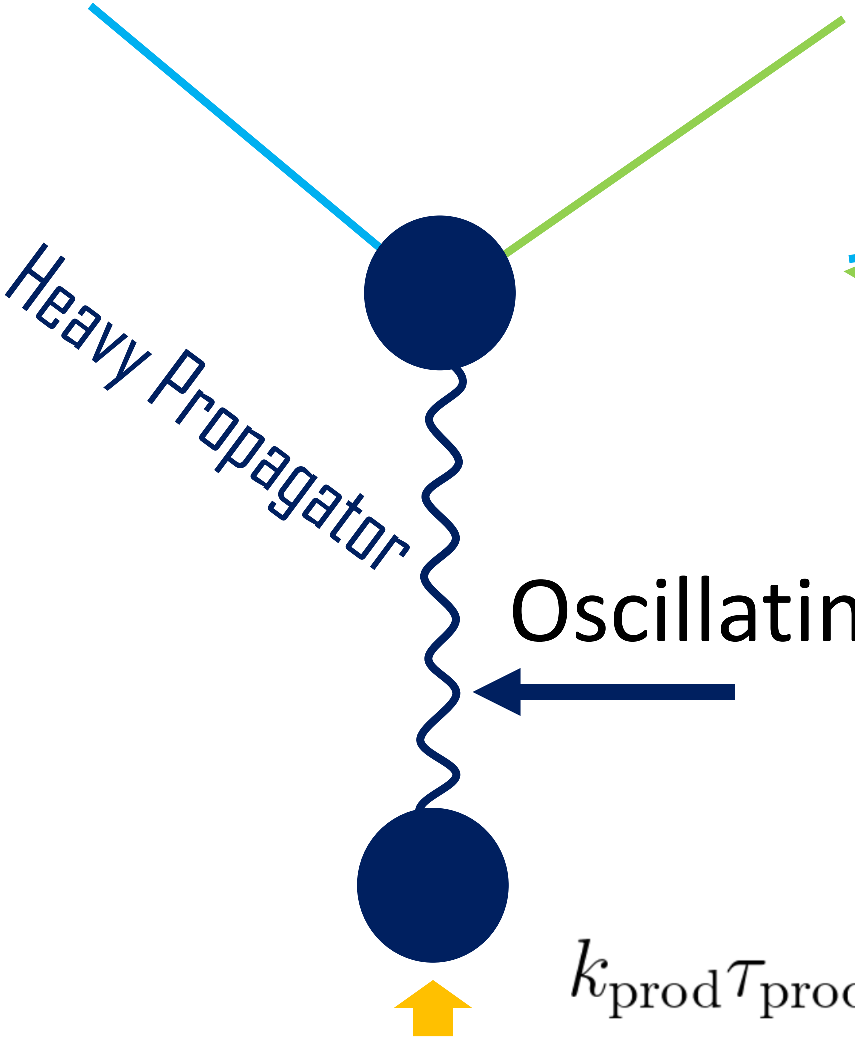


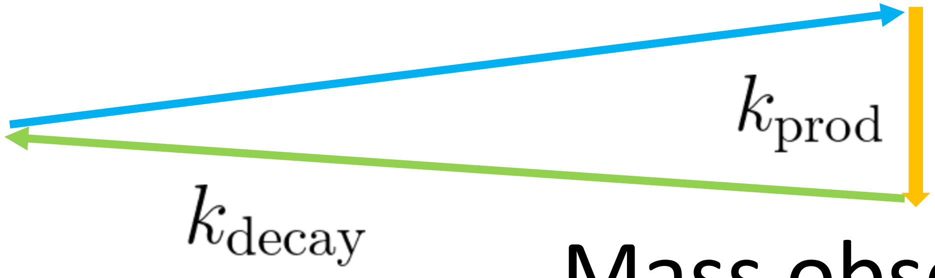
Planck limit on f_{NL}: O(10) for pure curvature.

Planck collaboration, 2018

Sketch of a Cosmological Collider

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





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

Oscillating as: e^{imt}

Mass observed through phases:

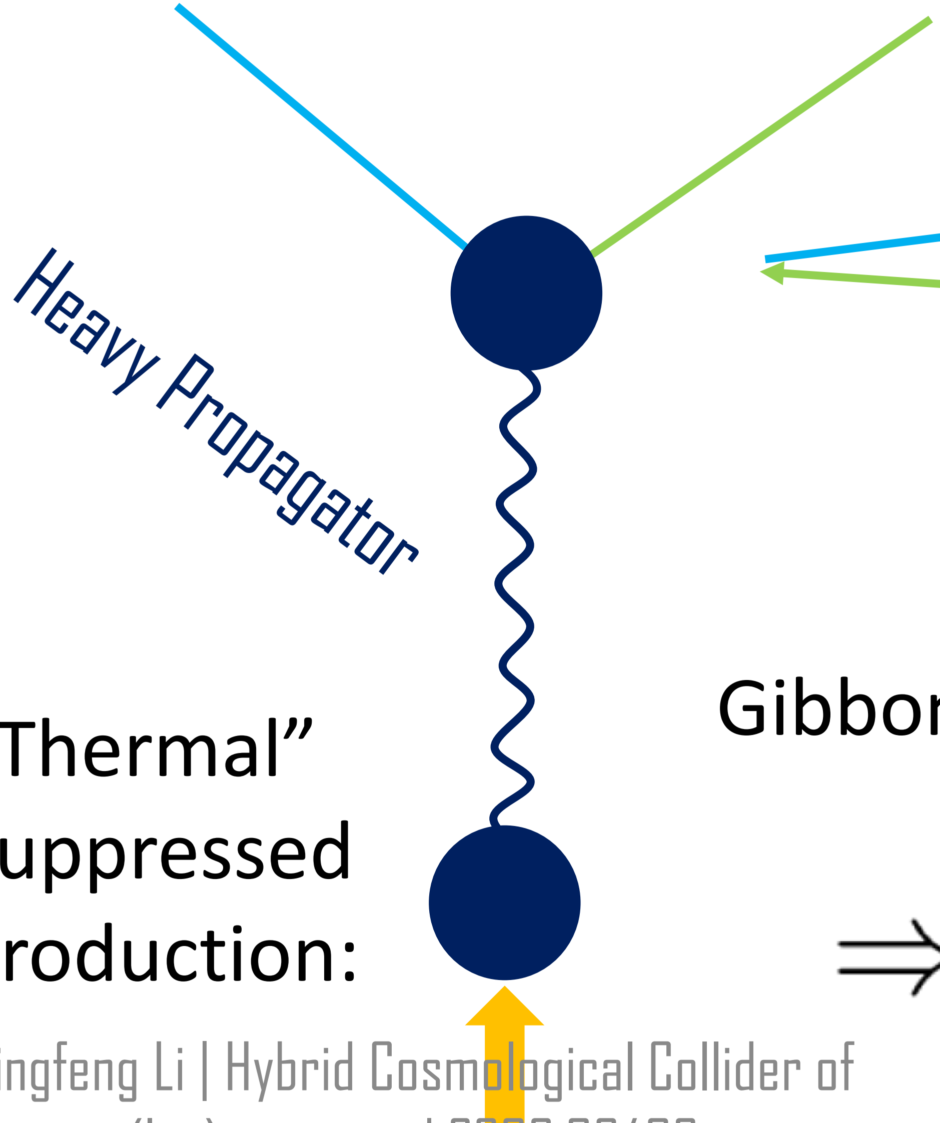
$$|\tau| \sim H^{-1} e^{-Ht} \Rightarrow$$

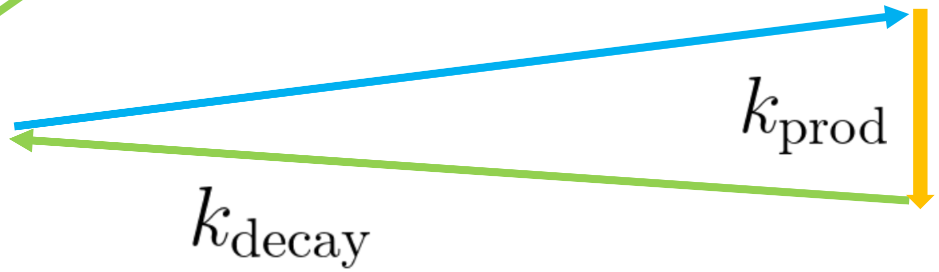
$$t_{\rm decay} - t_{\rm prod} \simeq H^{-1} \log\left|\frac{\tau_{\rm prod}}{\tau_{\rm decay}}\right|$$

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

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

Sketch of a Cosmological Collider



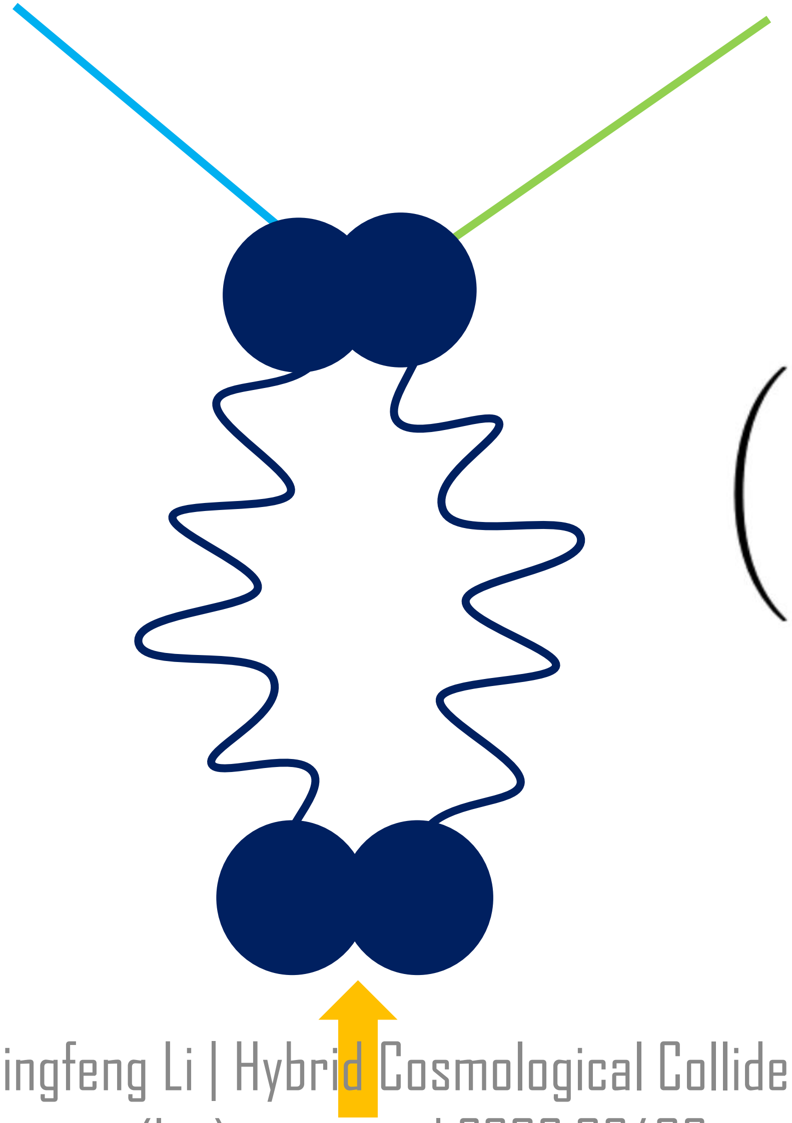


Momentum Conservation

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

"Thermal" Suppressed production: $\Rightarrow A \propto \sqrt{e^{-\frac{m}{T}}} \sim e^{-\frac{\pi m}{H}}$

At One Loop



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

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

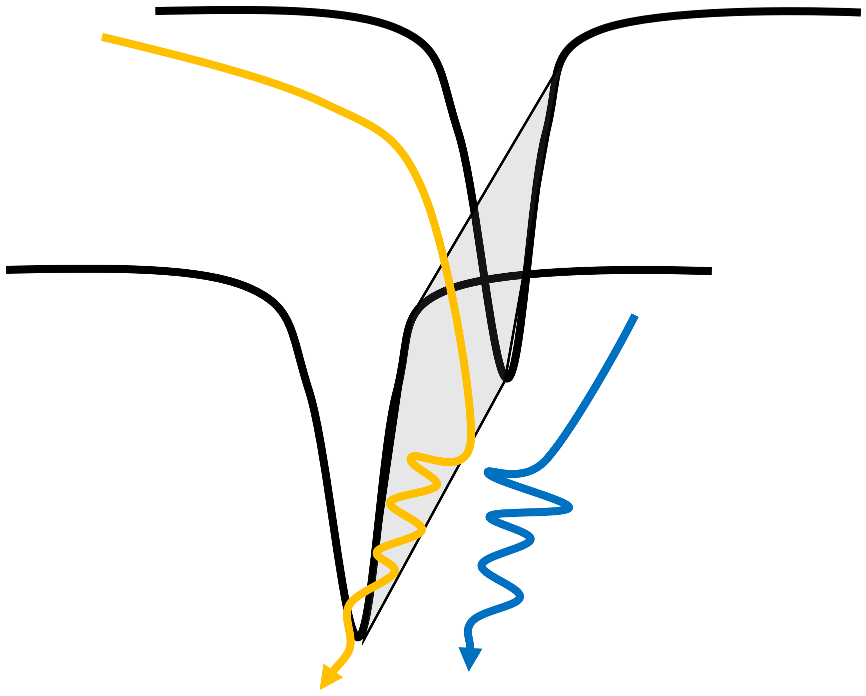
and loop factors

Beyond Boltzmann Suppression

❑Classical Feature

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

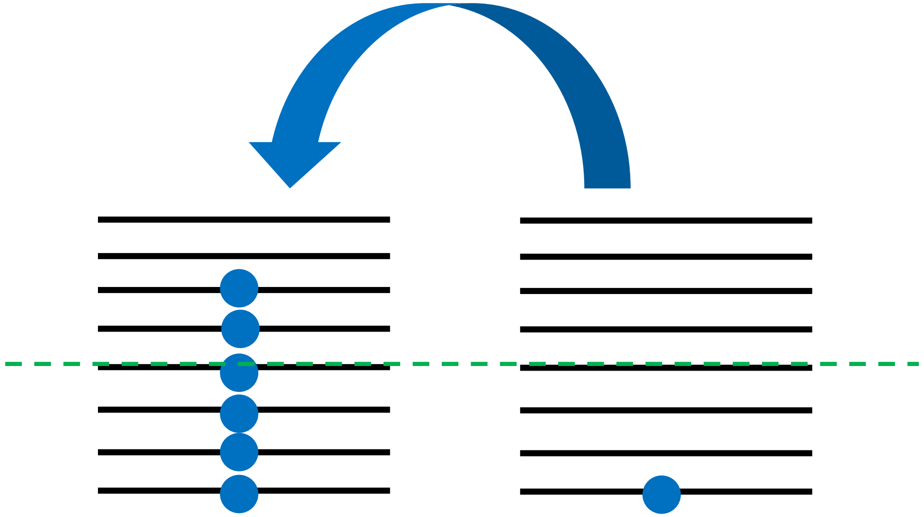
X. Chen, 2011; X. Chen, R. Ebadi, S. Kumar, 2022; A. Bodas, R. Sundrum, 2022 …

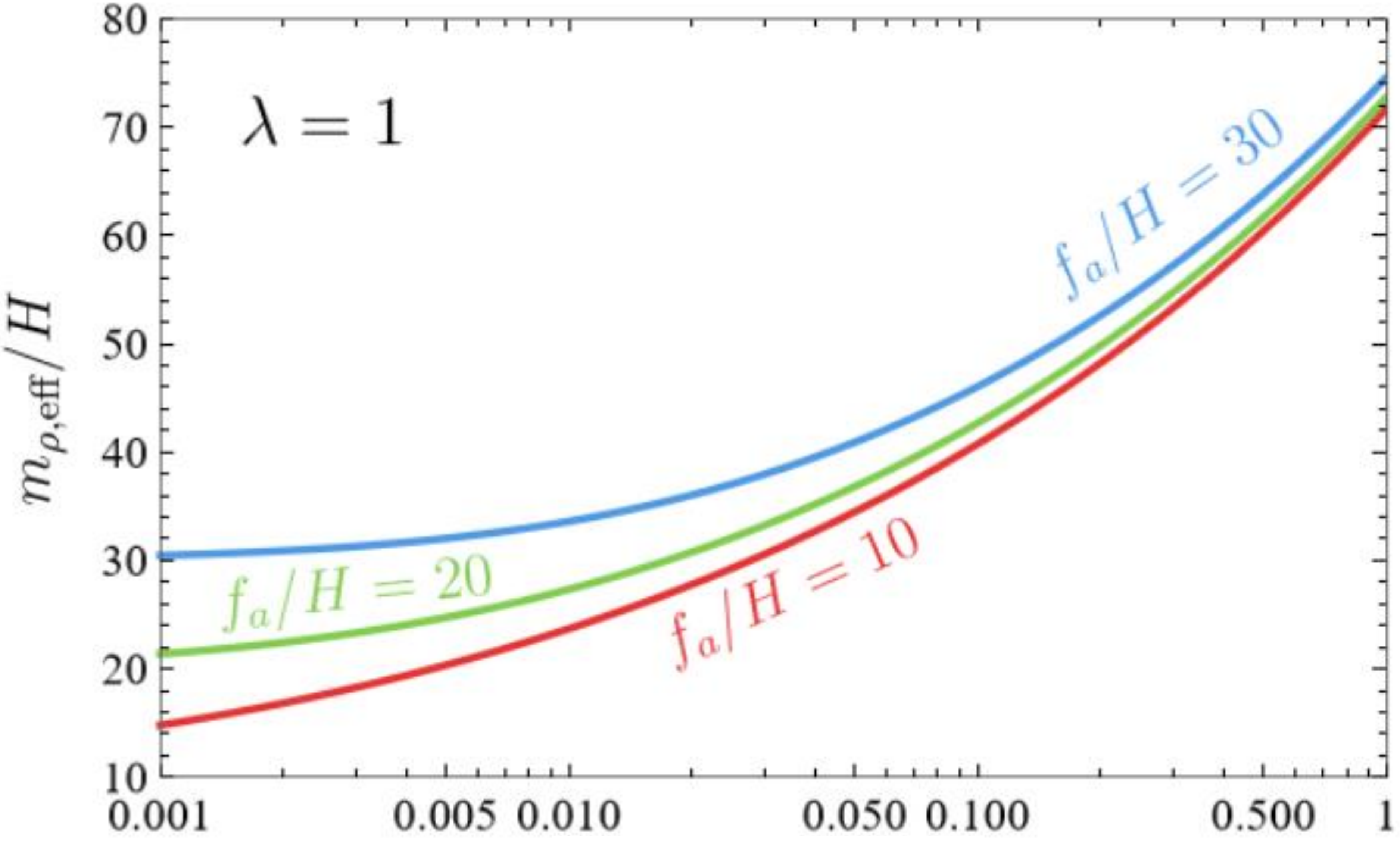


❑Chemical potential

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 …





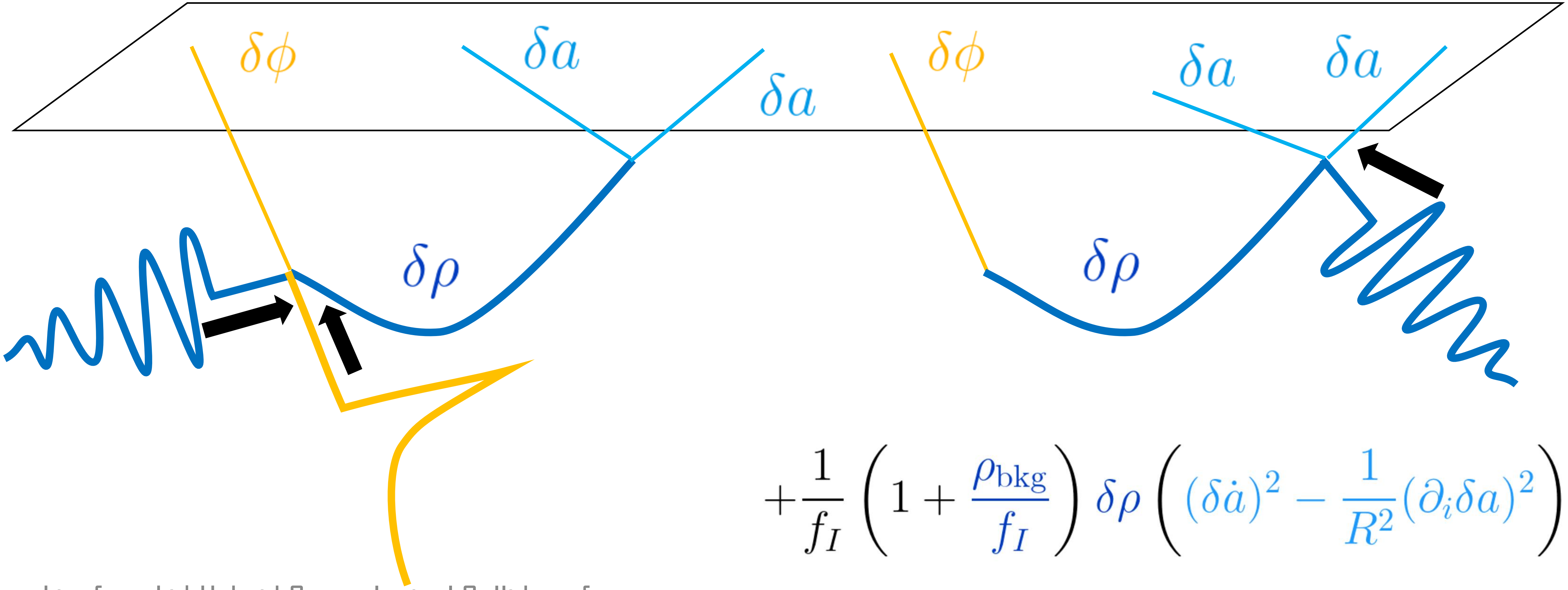
$$q \equiv c f_I^2/\Lambda^2 \ll 1$$

In-in Formalism

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

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

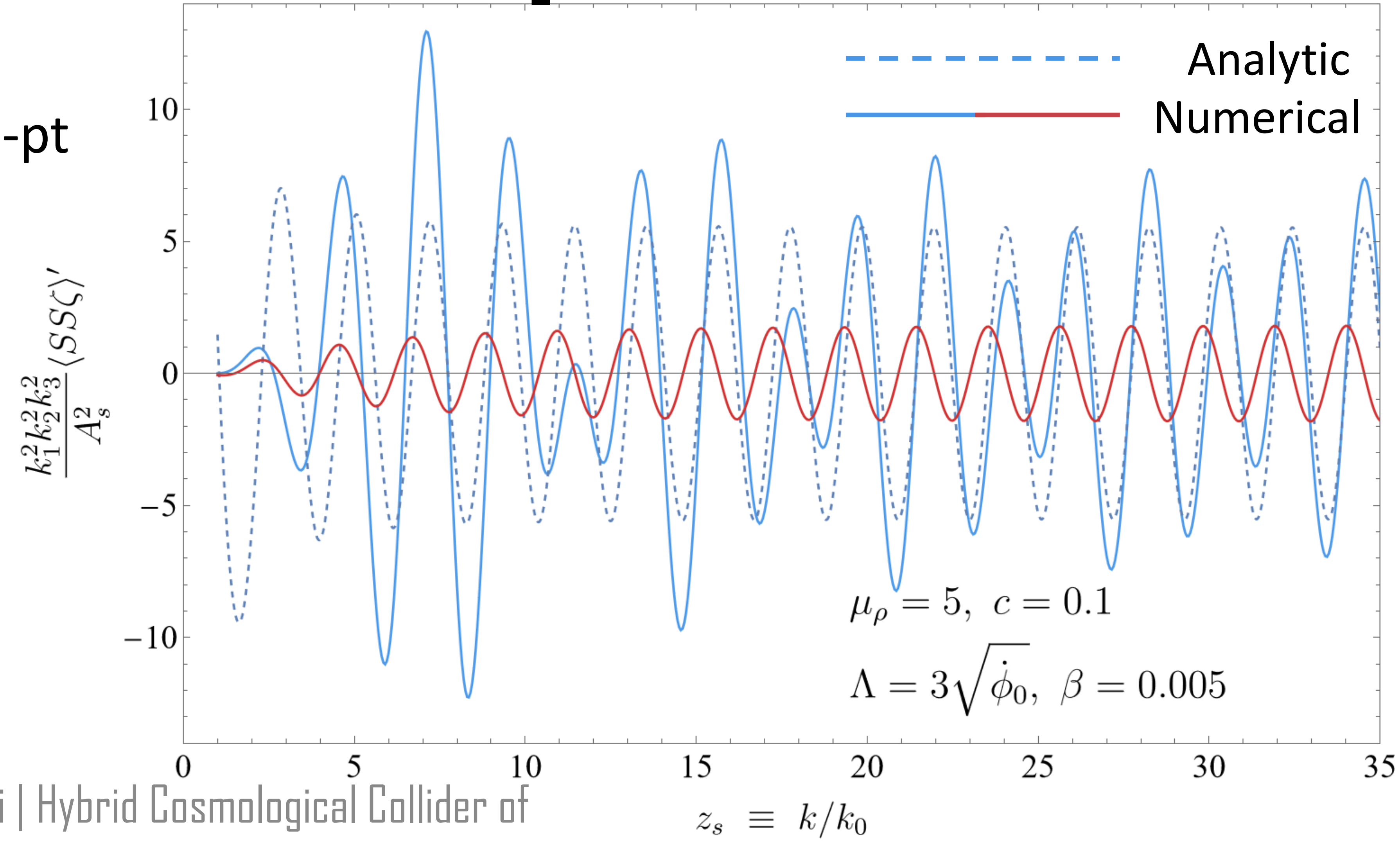
$$\frac{2cf_I\dot{\phi}_0}{\Lambda^2}\left(1+\frac{\dot{\phi}_1}{\dot{\phi}_0}+\frac{\rho_{\rm bkg}}{f_I}\right)\delta\dot{\phi}\delta\rho$$



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

NG in the Equilateral limit

Sizable hybrid 3-pt signal



Numerical Benchmark

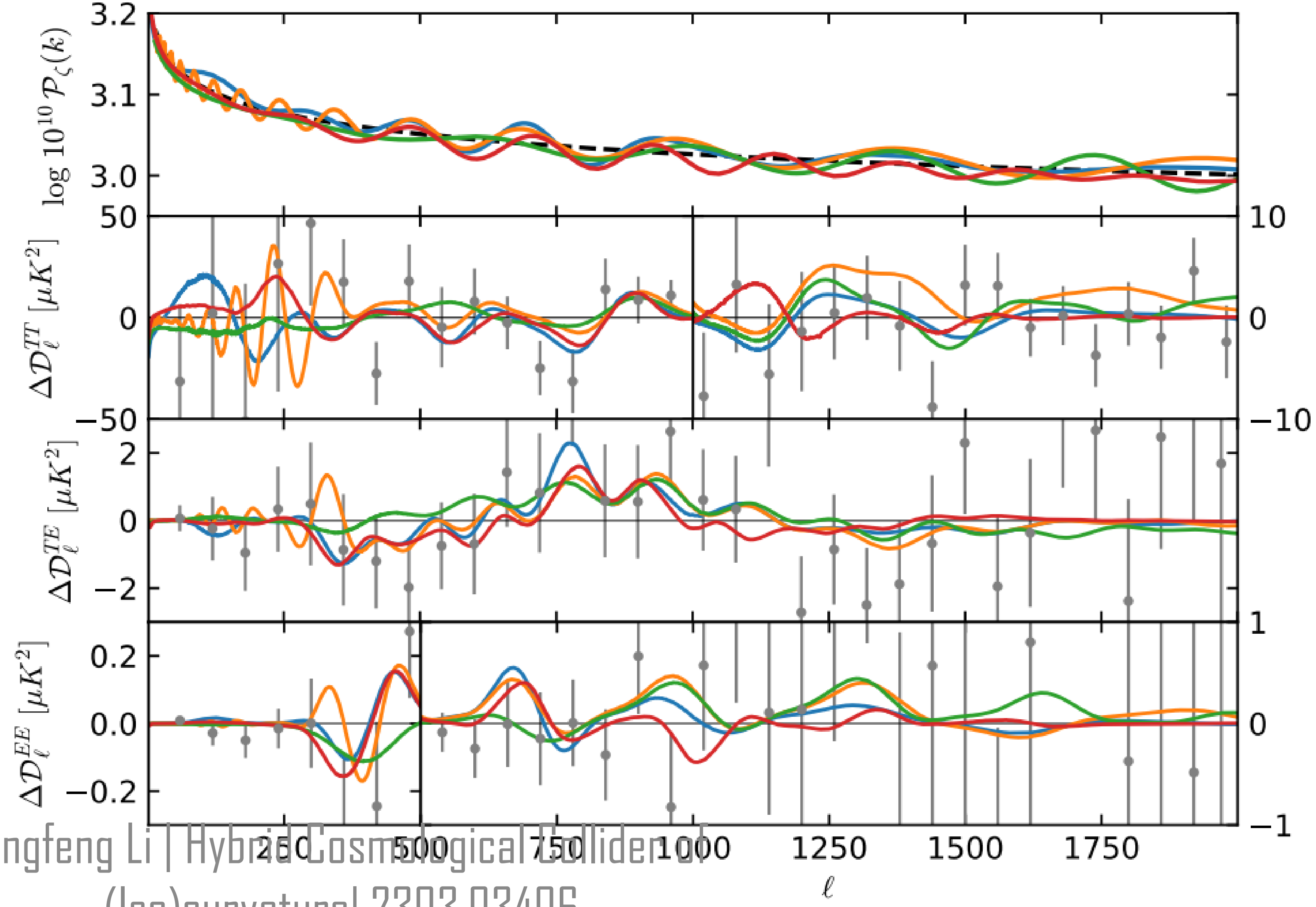
$$\left|\frac{\Delta P_\zeta}{P_\zeta}\right|_{\rm clock;amp} = \frac{2c^2 b V_{\phi 0} f_I^2}{\Lambda^4 H^2}\sqrt{\frac{2\pi}{\mu_\rho^3}}$$

$$\approx \; 0.019\left(\frac{q}{0.02}\right)^2\left(\frac{bV_{\phi 0}}{0.3\dot\phi_0^2}\right)\left(\frac{\dot\phi_0}{(60H)^2}\right)^2\left(\frac{40H}{f_I}\right)^{7/2}\left(\frac{1}{\lambda}\right)^{3/4}$$

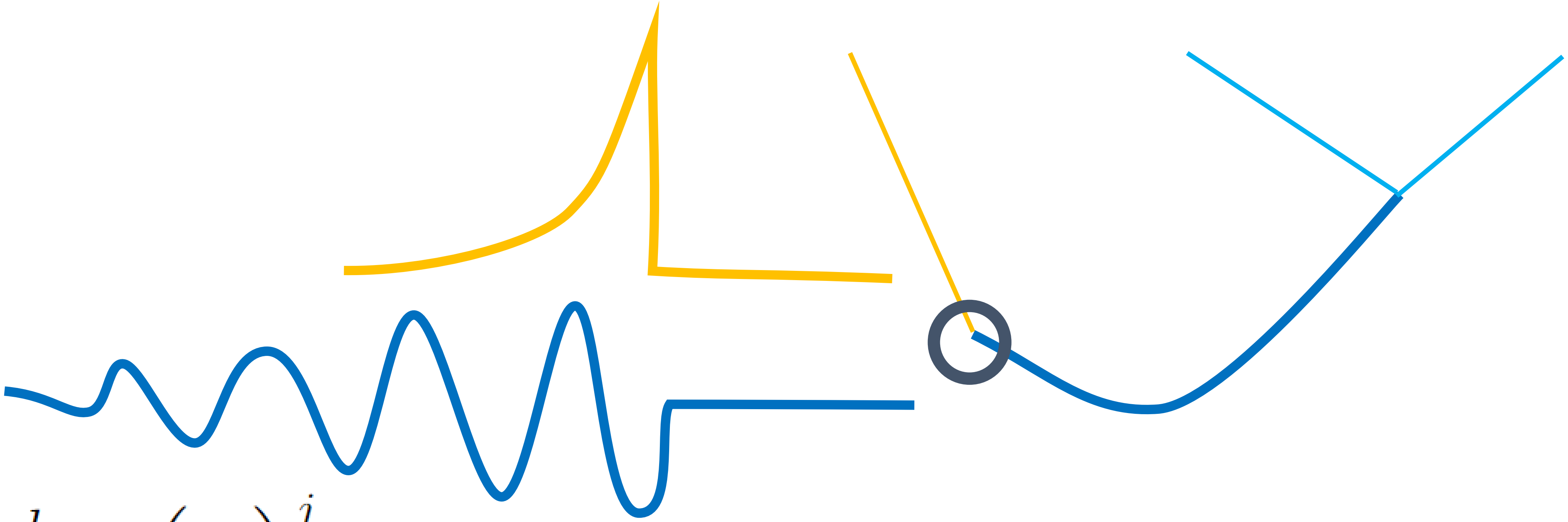
$$\left|\frac{\Delta P_i}{P_i}\right|_{\rm clock;amp} \approx \frac{2cbV_{\phi 0}}{\Lambda^2 H^2}\sqrt{\frac{2\pi}{\mu_\rho^3}}$$

$$\approx \; 0.96\left(\frac{q}{0.02}\right)\left(\frac{bV_{\phi 0}}{0.3\dot\phi_0^2}\right)\left(\frac{\dot\phi_0}{(60H)^2}\right)^2\left(\frac{40H}{f_I}\right)^{7/2}\left(\frac{1}{\lambda}\right)^{3/4}$$

Observational Hints



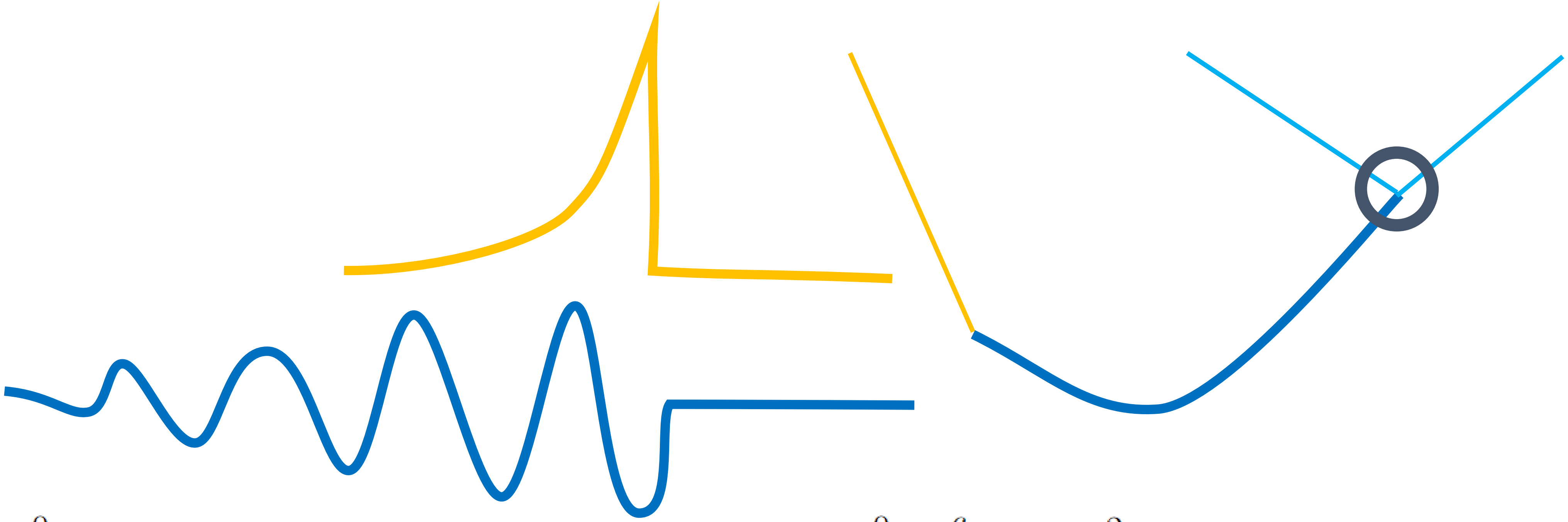
M. Braglia, X. Chen and D. K. Hazra 2021; A. Antony, F. Finelli, D. K. Hazra and A. Shafieloo, 2022; M. Braglia, X. Chen, D. K. Hazra and L. Pinol, 2022



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

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

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



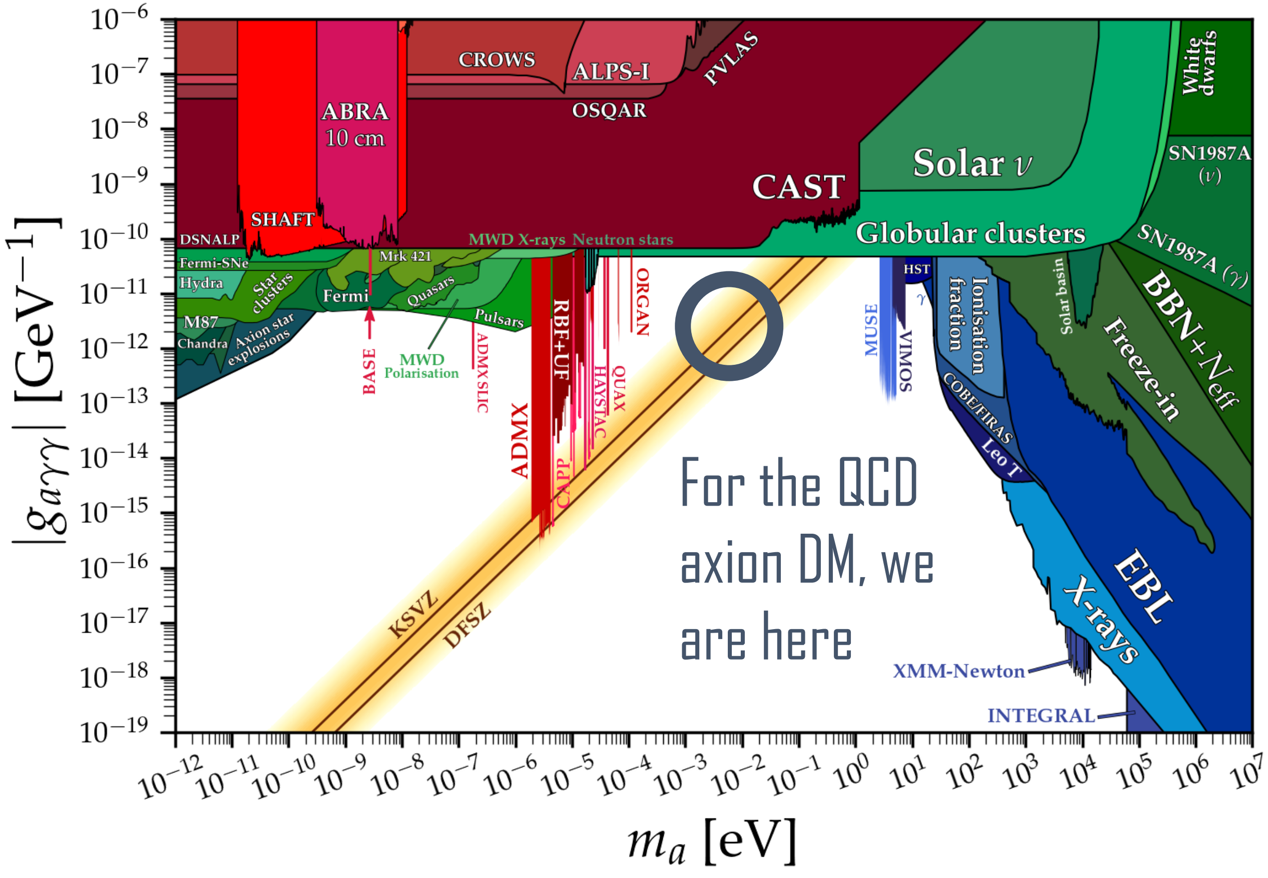
$$u_{k_1}u_{k_2}(\tau_{\mathrm{end}})\int_{-\infty}^{0}\frac{d\tau_1}{(H\tau_1)^4}\partial_\mu u^*_{k_1}\partial^\mu u^*_{k_2}v_{k_3}(\tau_1)\theta(\tau_1-\tau_s)=\int_{\tau_s}^{0}\frac{H^6 d\tau_1}{(H\tau_1)^4}\frac{\tau_1^2}{4k_1^3k_2^3}v_{k_3}(\tau_1)\mathcal{D}e^{ik_{12}\tau_1}$$

$$=\frac{(-1)^{\frac{3}{4}}e^{-\pi\mu_\rho/2}H^3\sqrt{\pi}}{8k_1^3k_2^3k_3^{5/2}}\int_0^{z_s}dz_1 e^{-ik_{12}z_1/k_3}\left[(k_1^2k_2^2-\mathbf{k}_1\cdot\mathbf{k}_2k_1k_2)z_1^{\frac{3}{2}}+i\mathbf{k}_1\cdot\mathbf{k}_2k_{12}k_3z_1^{\frac{1}{2}}+\mathbf{k}_1\cdot\mathbf{k}_2k_3^2/z_1^{\frac{1}{2}}\right]$$

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

$$=\frac{(-1)^{\frac{1}{4}}e^{-\pi\mu_\rho/2}H^3\sqrt{\pi}}{16k_3^{9/2}}\int_0^{z_s}\frac{dz_1}{\sqrt{z_1}}e^{-2iz_1}(3iz_1^2+2z_1-i)H^{(1)}_{i\mu_\rho}(z_1),$$

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