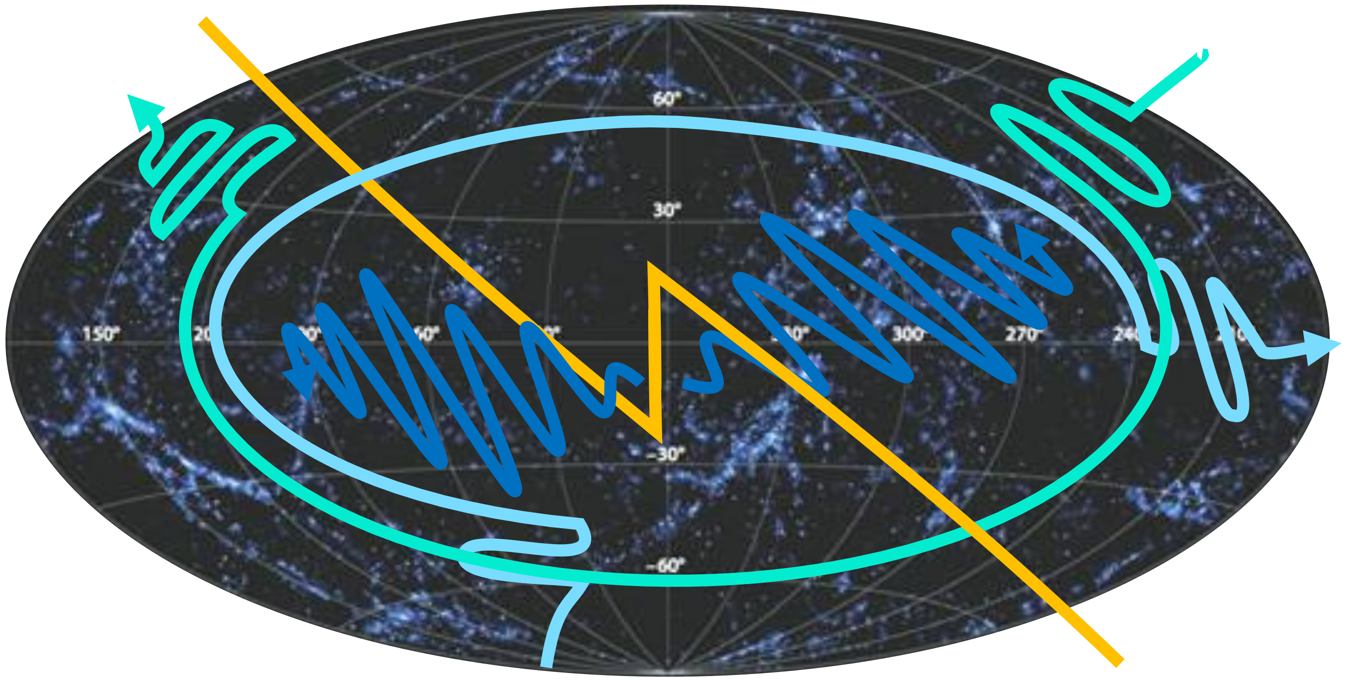
New Inflationary Probes of Axion Dark Matter



Lingfeng Li (Brown University)

Mar. 20, UC Davis

Hey, I am back!

Based on

2303.03406, With Xingang Chen & JiJi Fan

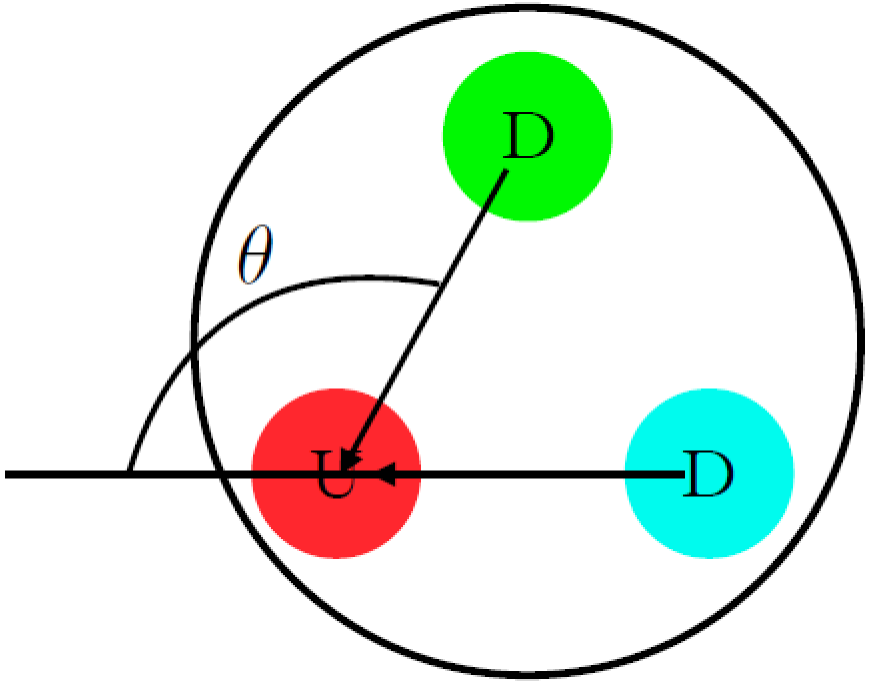
2209.09908, With Yunjia Bao & JiJi Fan

Outline

- Intro: Axions & cosmology
- Prelude: New mechanism and window for post-inflationary axion
- Development: Inflation as the cosmological collider
- Crescendo: Cosmological collider of axion
- Outro

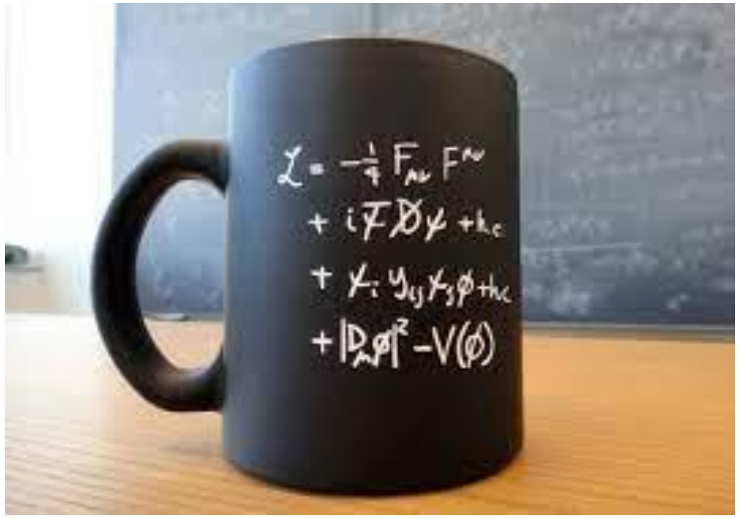
The Strong CP Problem

Allowed in SM, arises from SU(3) topology



A. Hook, 2018

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



Experimental hints: neutron EDM

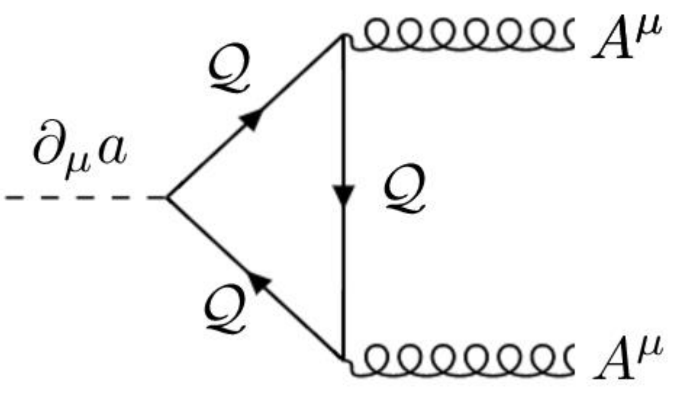
Natural expectation: O(Q × fm) ≈ 10^{-13} e cm

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

Small dimensionless parameters may not be natural: protected by some mechanism?

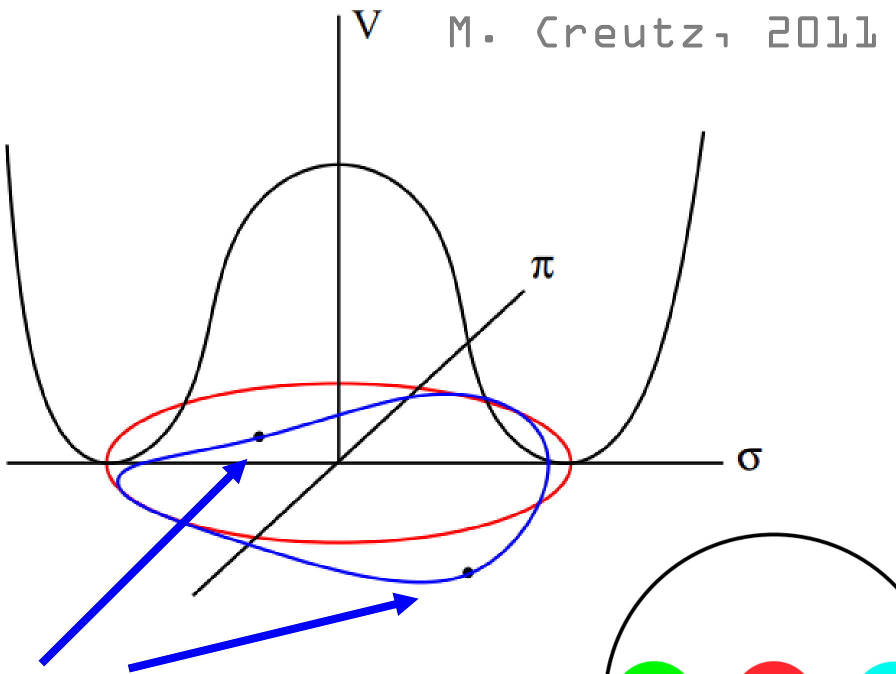
PQ Symmetry and QCD Axion

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

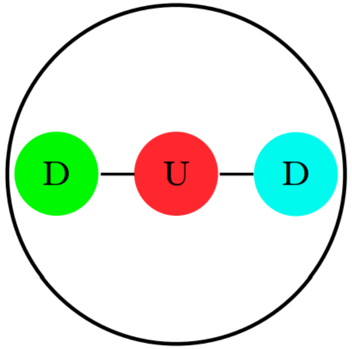


$$\mathcal{L} \supset \left(\frac{a}{f_a} + \theta\right) \frac{1}{32\pi^2} G\tilde{G}$$

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

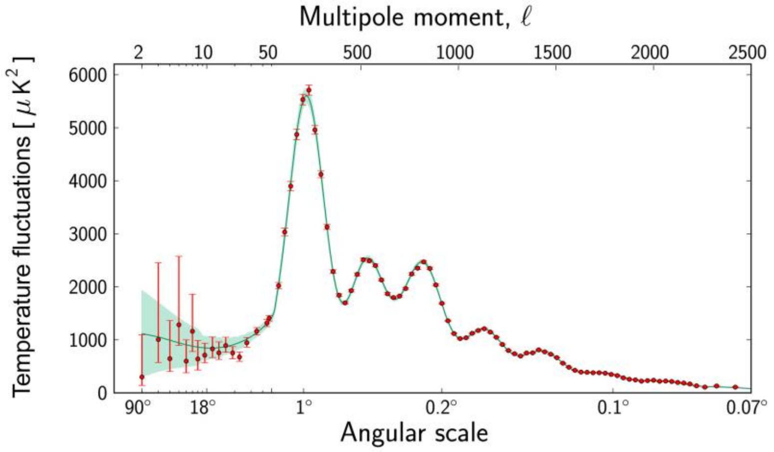


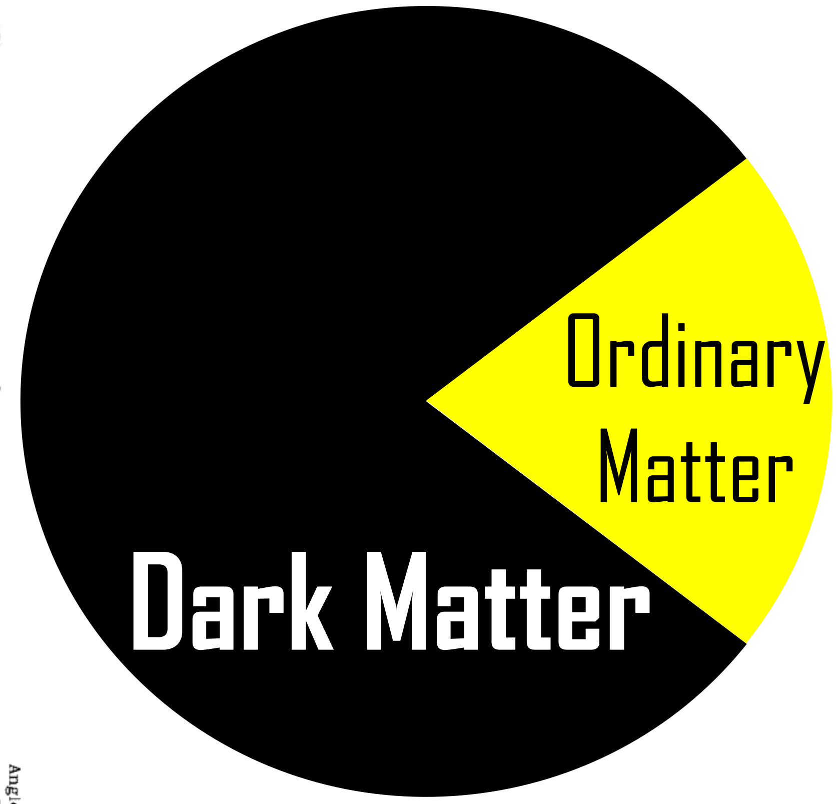
The strong CP θ angle are set to zero at the minima



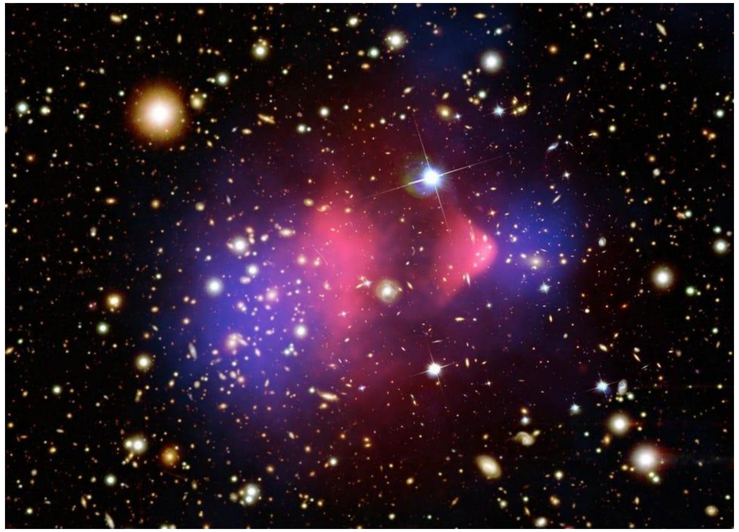
Peccei, Quinn; Weinberg; Wilczek; Kim; Shifman, Vainshtein, Zakharov; Zhitnitsky; Dine, Fischler, Srednicki, 1977-1981

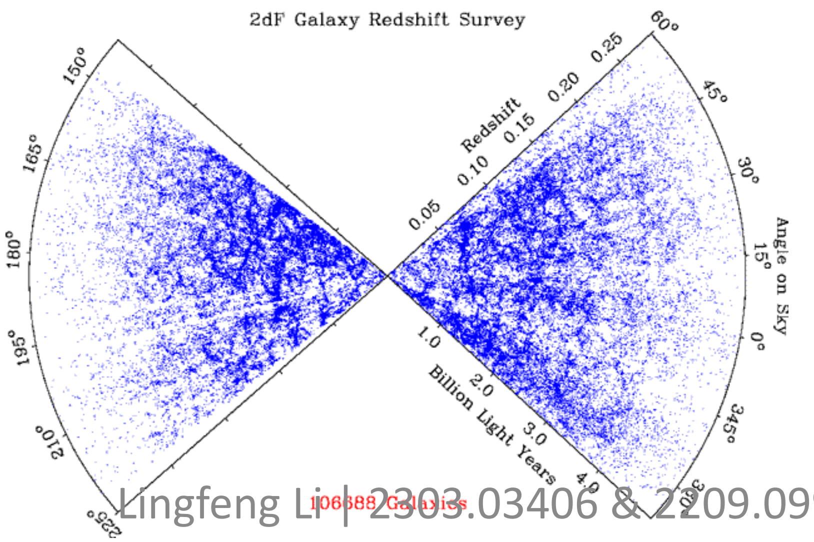
Dark Matter Exists

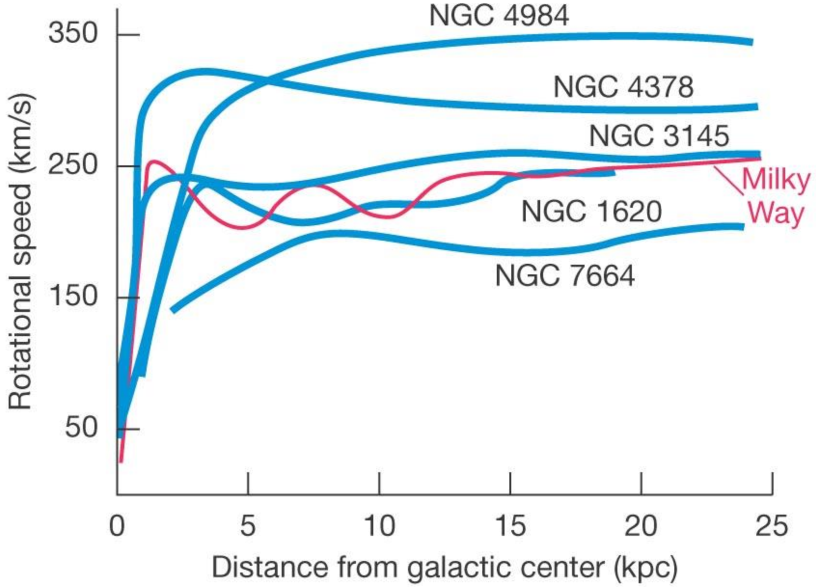




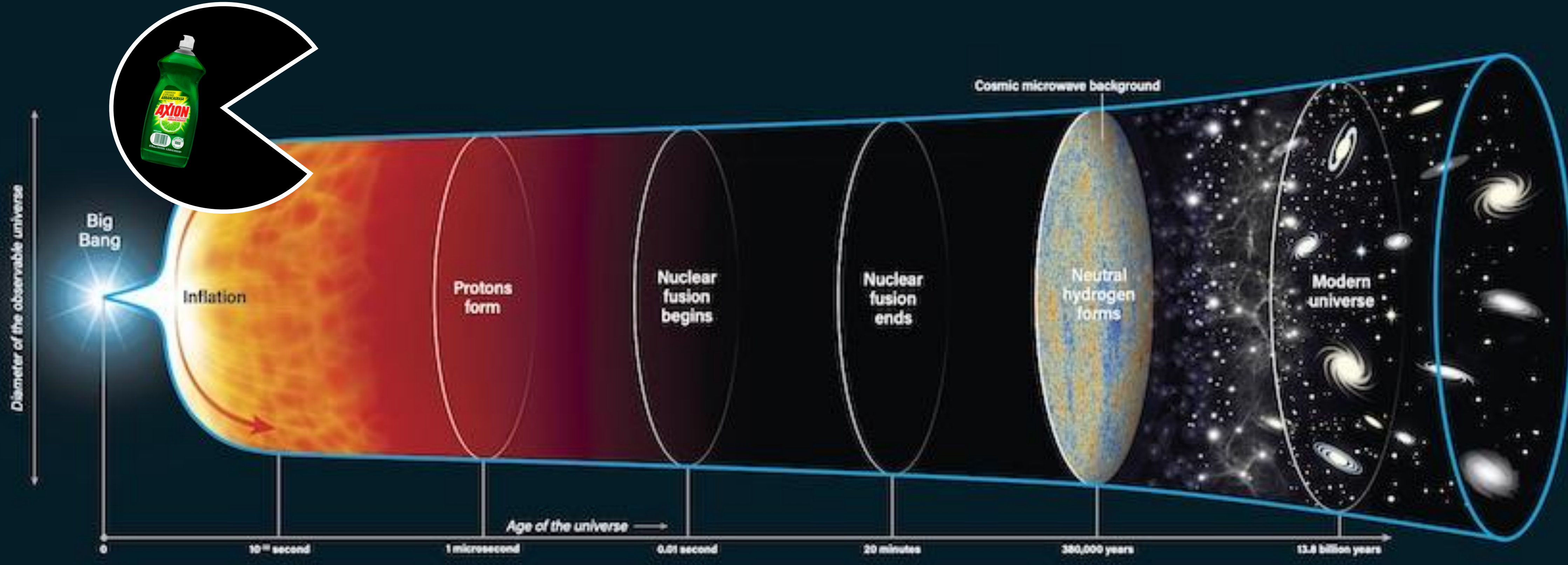
The matter budget of our universe







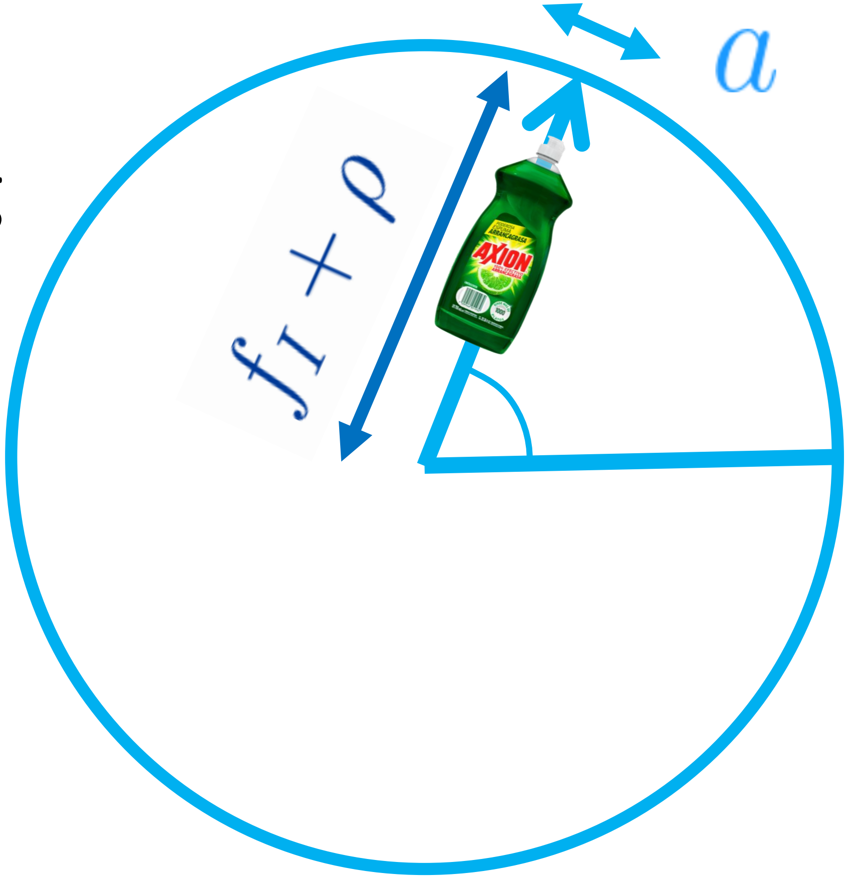
Inflationary Era of Axion DM



Most stories involves inflation non-trivially

Two Scenarios (I): Pre-Inflationary axion

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

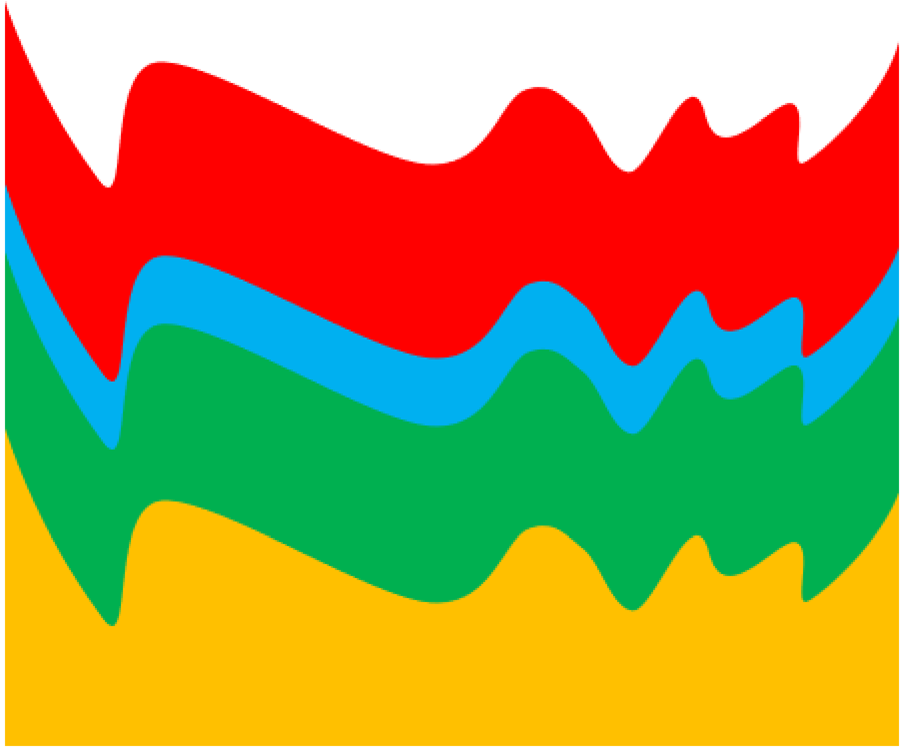


- $f_a > H_I / 2\pi$ with inflationary Hubble and PQ symmetry is not restored during (p)reheating
- PQ breaking during inflation: axion with similar phase
- Small perturbations of DM density: Axion isocurvature perturbation, **STRONG** Planck constraints

$$\beta \equiv \frac{A_i}{A_s} = \frac{1}{A_s}\left(\frac{\gamma H}{\pi f_I \theta_i}\right)^2 < 0.038$$

Planck collaboration, 2018

Curvature vs. Isocurvature



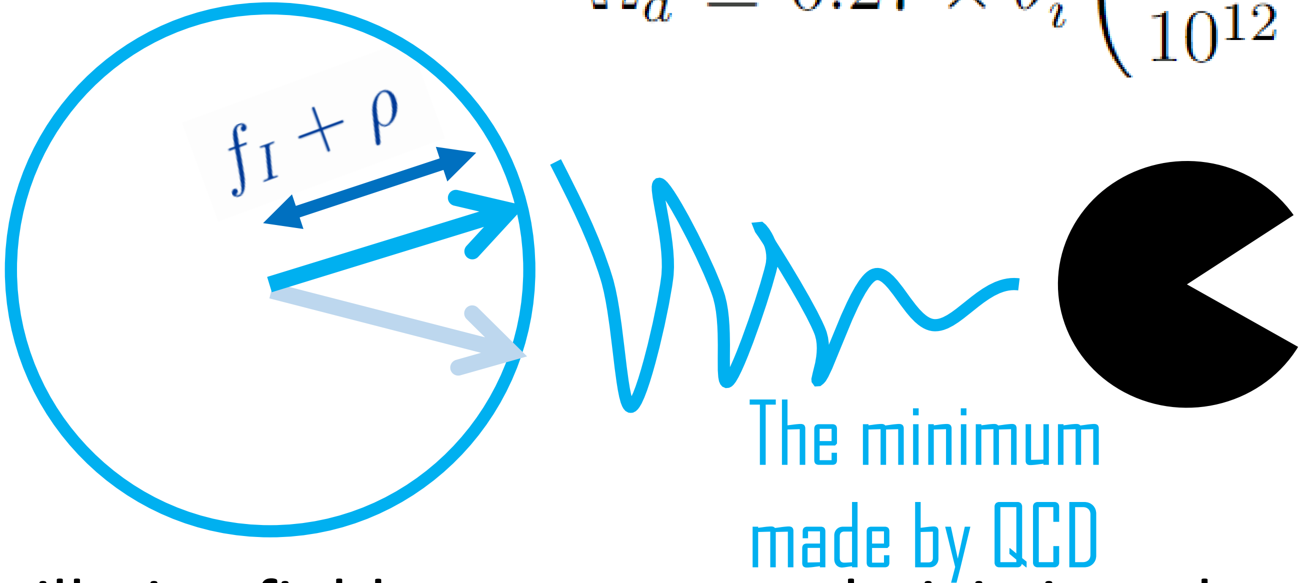
Dark Matter
Photon
Neutrino
Baryons

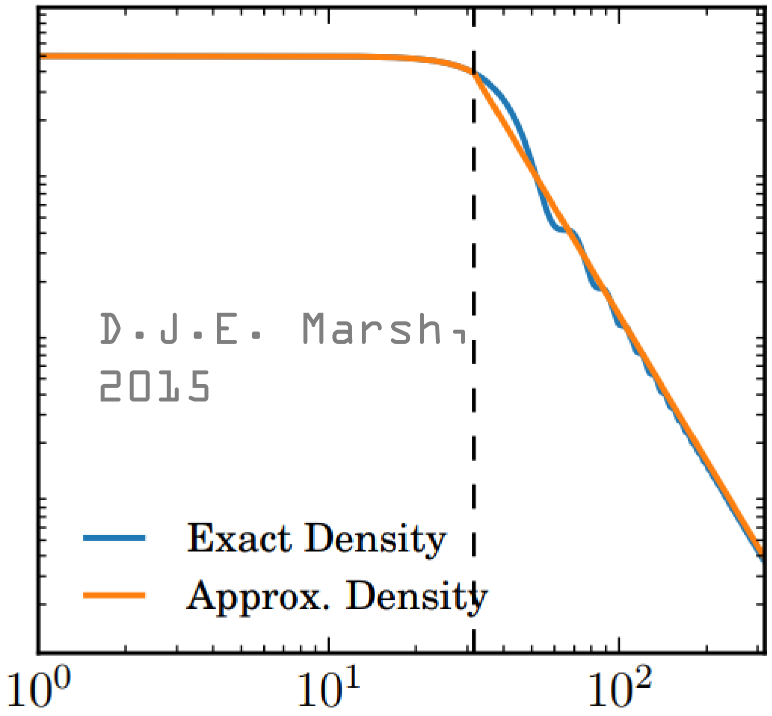
Axion CDM: Misalignment

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

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

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

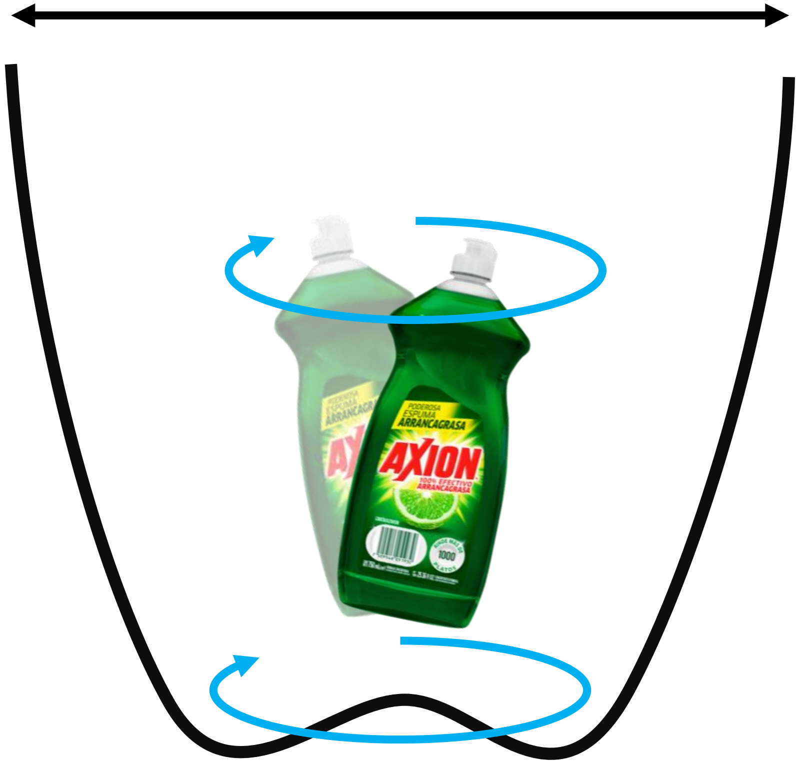




Oscillating field creates non-relativistic, coherent axion particles

Two Scenarios (II): Post-Inflationary axion (PIA)

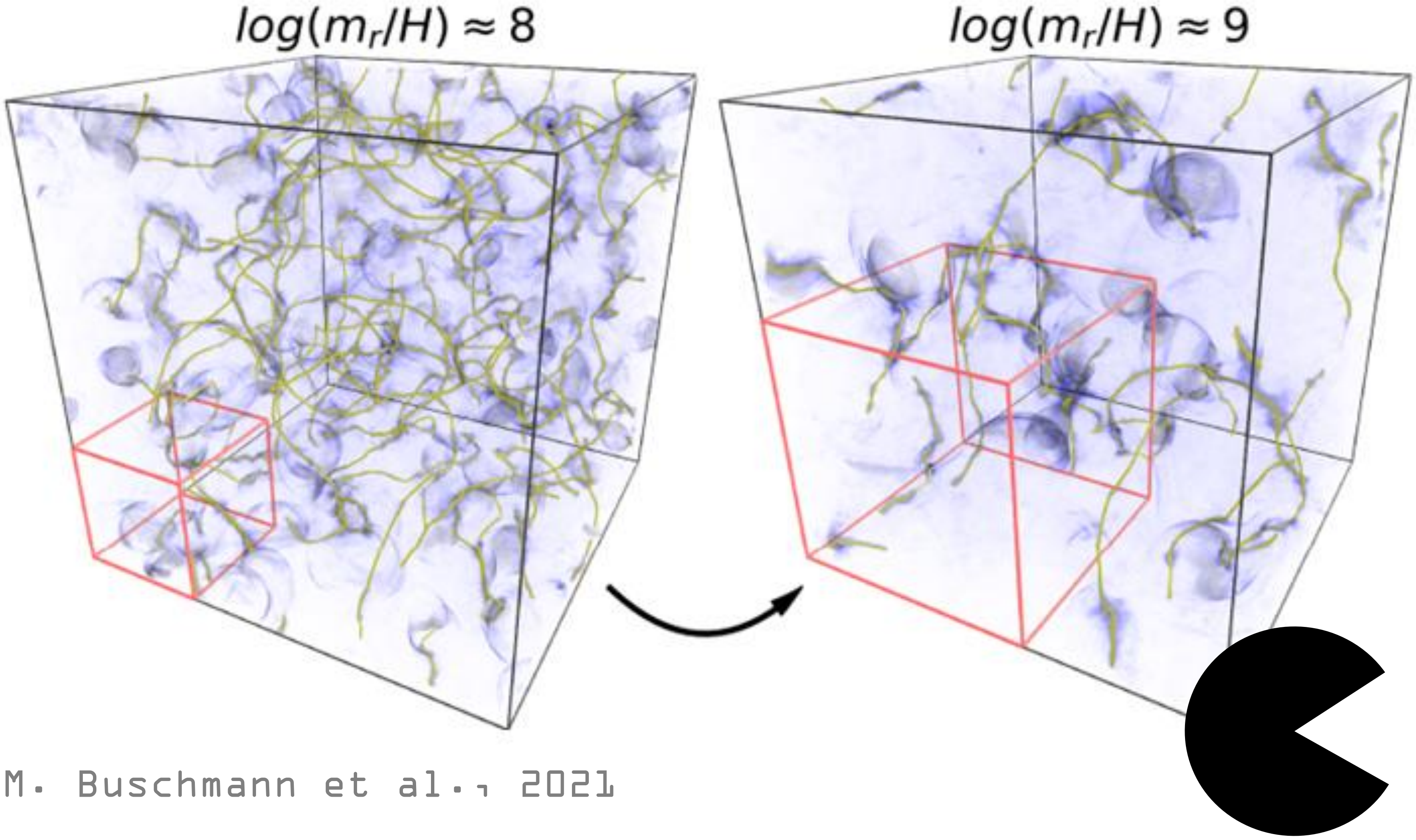
$$\delta\chi \simeq H/2\pi \gtrsim f_a$$



- ❑$f_a < H_I/(2\pi)$; symmetry unbroken during inflation.
- ❑No preferred phase, **NO** isocurvature at large scales
- ❑Topological defects after inflation (assuming no domain wall problem by setting $N_{\mathrm{DW}} = 1$)

Davis 1986; Vilenkin and Vachaspati 1987;…
Gorghetto, et.al 2020; Buschmann et.al 2021.

QCD Axion DM Density



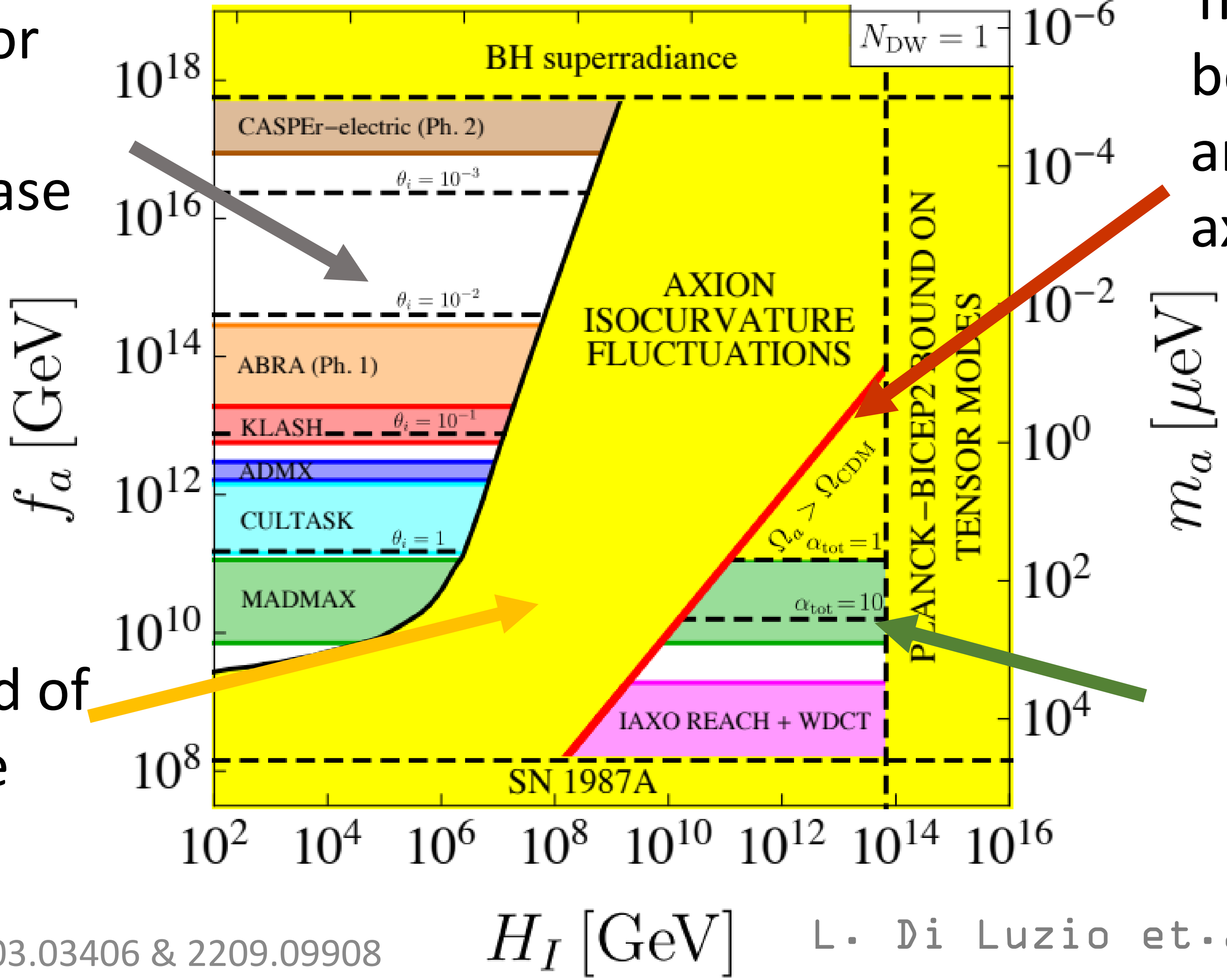
M. Buschmann et al., 2021

- Axion string network with tension ~ f_a^2 is formed, evaporating follow the scaling law
- The network decay dominates the DM relic density
- $f_a \sim 10^{10\text{-}11}$ GeV for full axion DM

Map of QCD Axion DM

H $\lesssim 10^9$ GeV for the pre-inflationary case

The bad land of isocurvature



Traditional boundary between inflationary and post-inflationary axions

The little "delta oasis" for PIA free from many issues

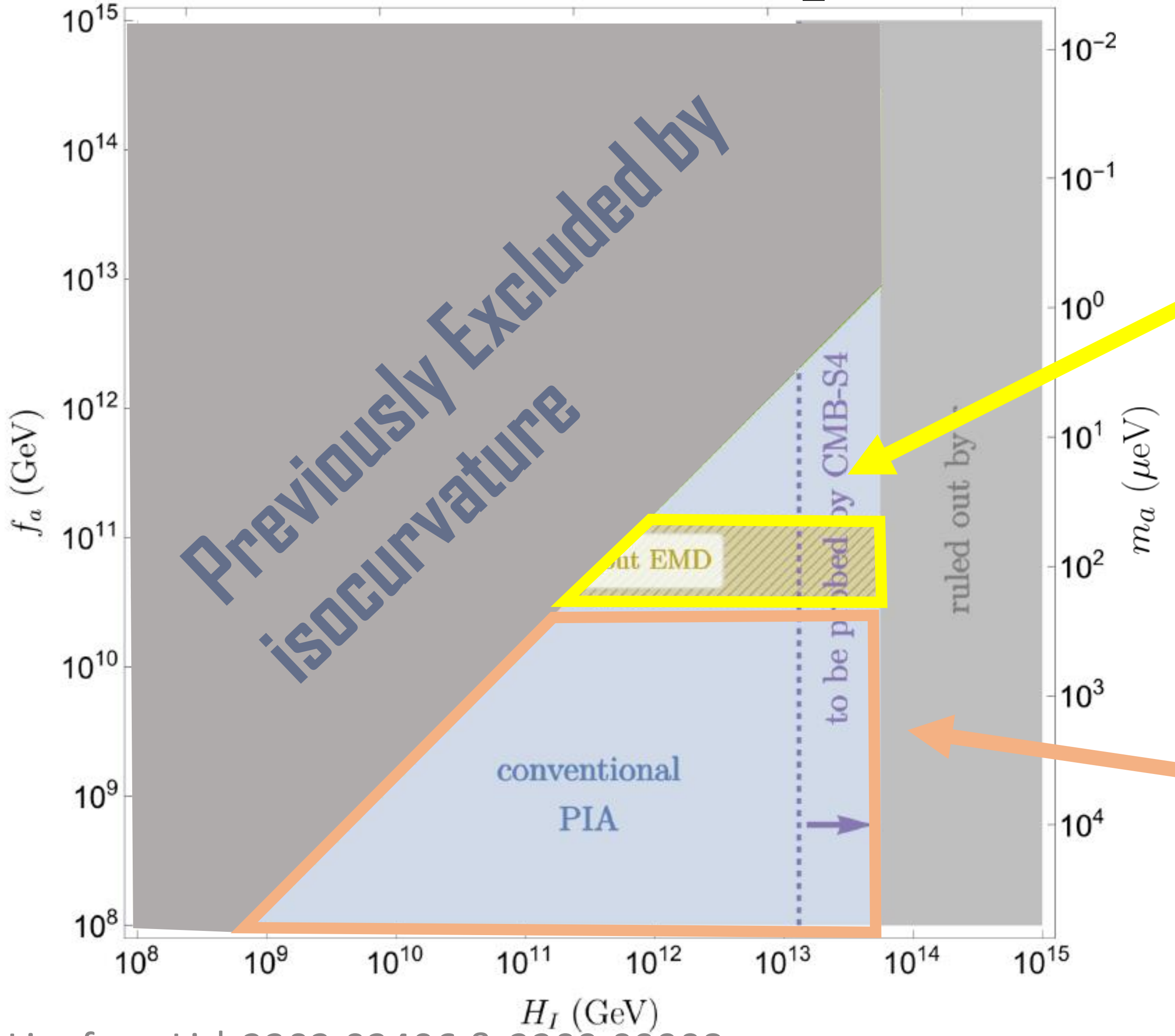
L. Di Luzio et.al, 2020

Question 1:

How can we expand the parameter space of the post inflationary axion case since it has such nice features?

Y. Bao, J. Fan, LL, 2209.09908

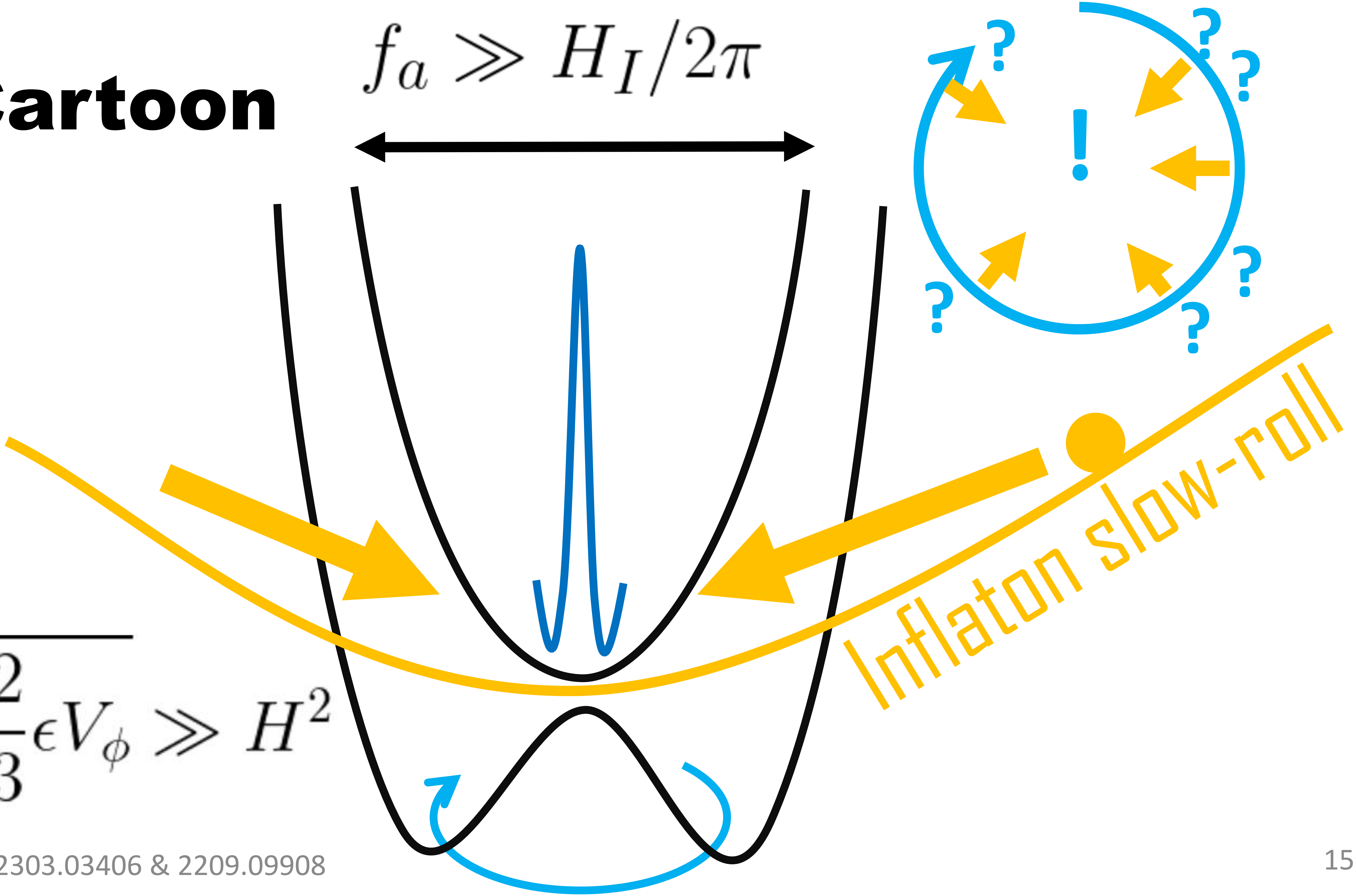
Parameter Space



Correct DM relic abundance

Also fine but need other DM

A Cartoon



$$\dot{\phi} \simeq \sqrt{\frac{2}{3}\epsilon V_\phi} \gg H^2$$

*: only inflaton shift-breaking (ϕ^2) coupling has been considered before, e.g. Shafi, Vilenkin, 1984

Heavy-Lifting Mechanism

$$\mathcal{L} = (\partial_\mu \phi)^2/2 + |\partial_\mu \chi|^2 - V(\phi, \chi) \ ,$$

$$V(\phi, \chi) = V(\phi) + \frac{\lambda}{2}\left(|\chi|^2 - \frac{f_a^2}{2}\right)^2 + \frac{c\,(\partial\phi)^2}{\Lambda^2}|\chi|^2 ,$$

In single field inflation, $\dot{\phi}$ is related to primordial power spectrum by

$$A_s \approx H_I^4/(4\pi^2\dot{\phi}_0^2)$$

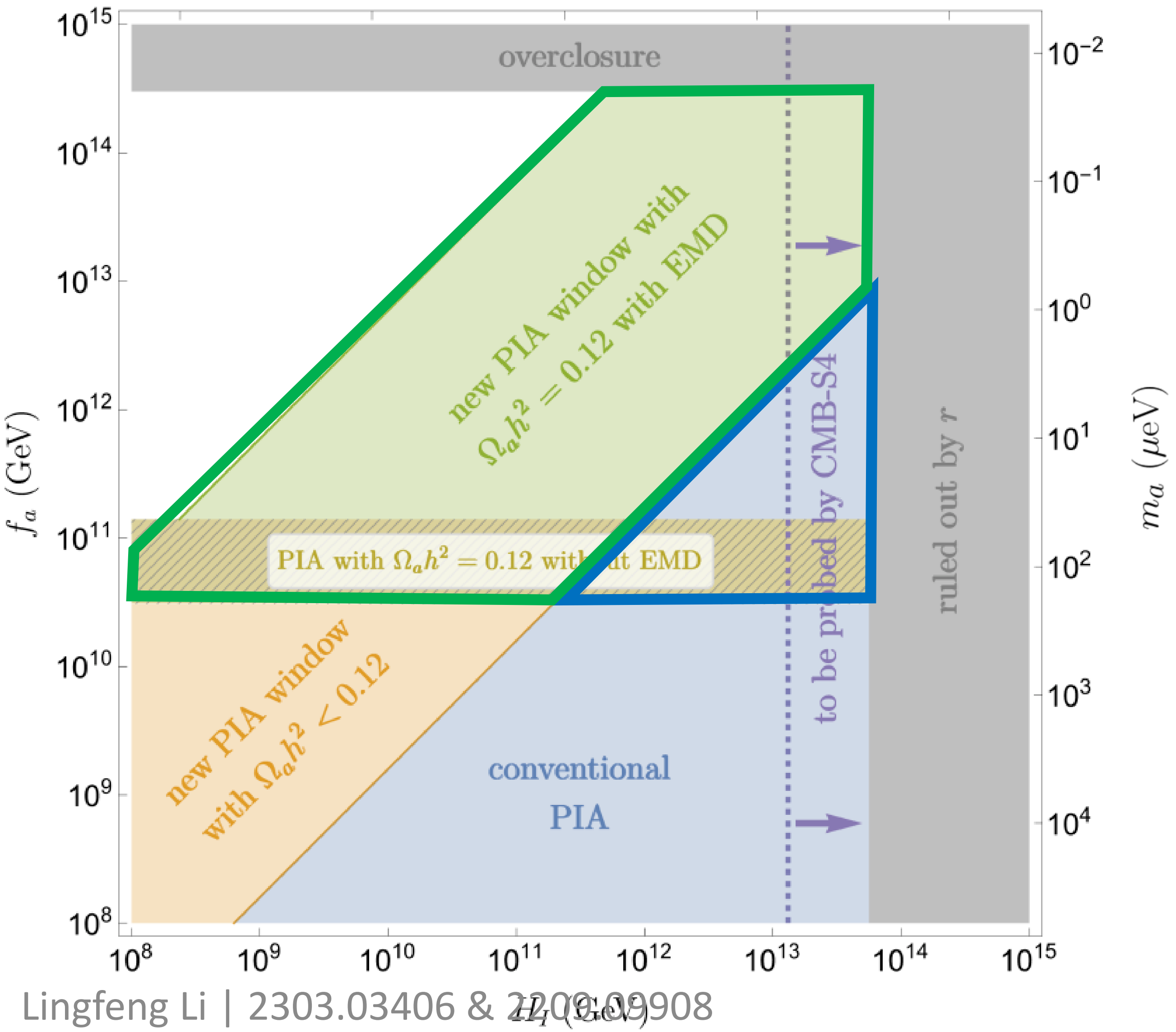
$$A_s \approx 2.1 \times 10^{-9} \Rightarrow \sqrt{\dot{\phi}_0} \approx 60 H_I$$

PQ symmetry is safely unbroken as the effective mass is heavy-lifted

$$m_{\mathrm{PQ,eff}}^2 \approx \frac{c\,\dot{\phi}_0^2}{\Lambda^2} - \frac{\lambda}{2} f_a^2 \gtrsim (1.5 H_I)^2$$

For EW symmetry breaking examples, see: S. Kumar, R. Sundrum, 2017

More opened space



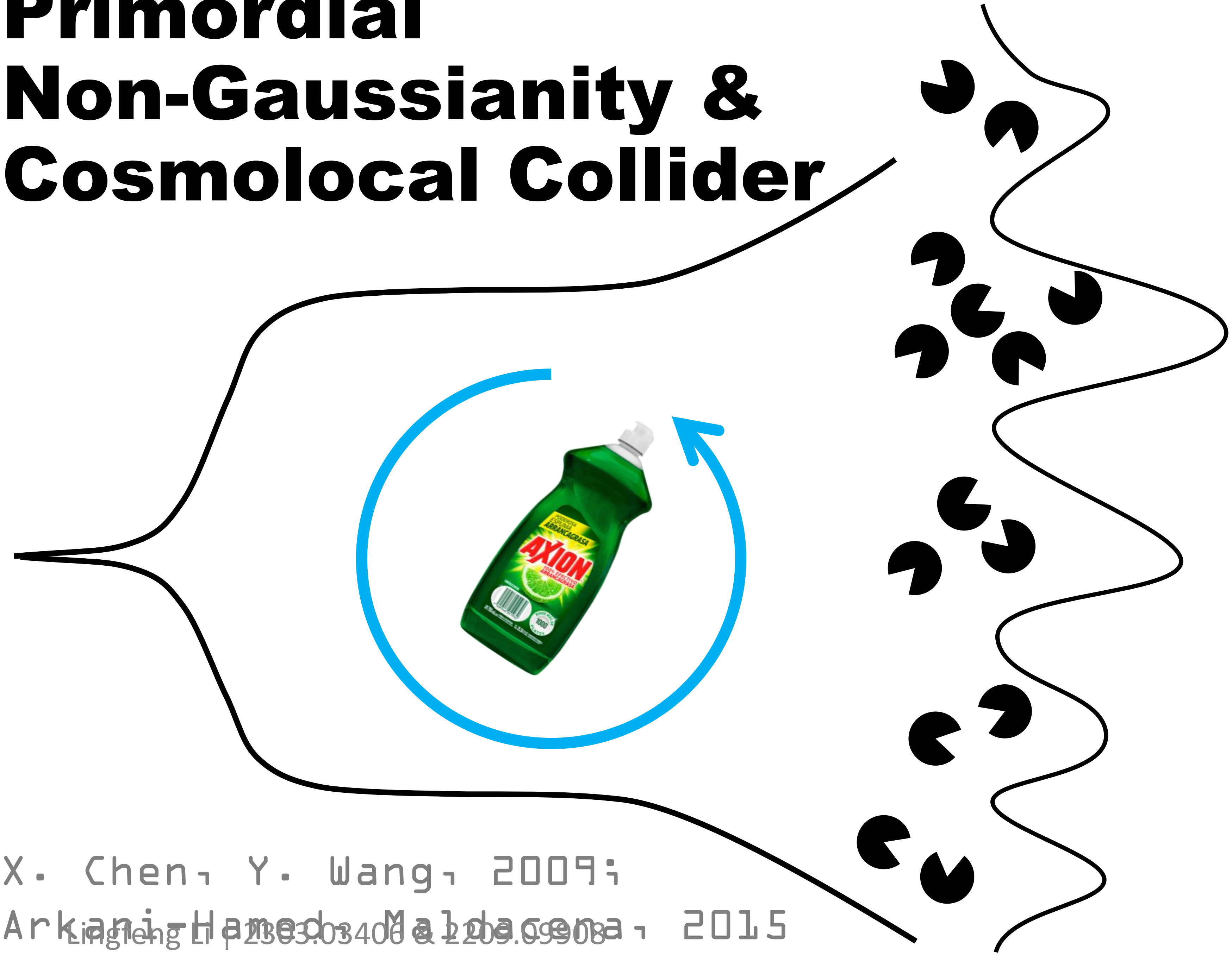
- ❑New window free from isocurvature problem
- ❑Better with early matter domination and curvaton
- ❑Large inflationary scale: closer to GUT & higher observability

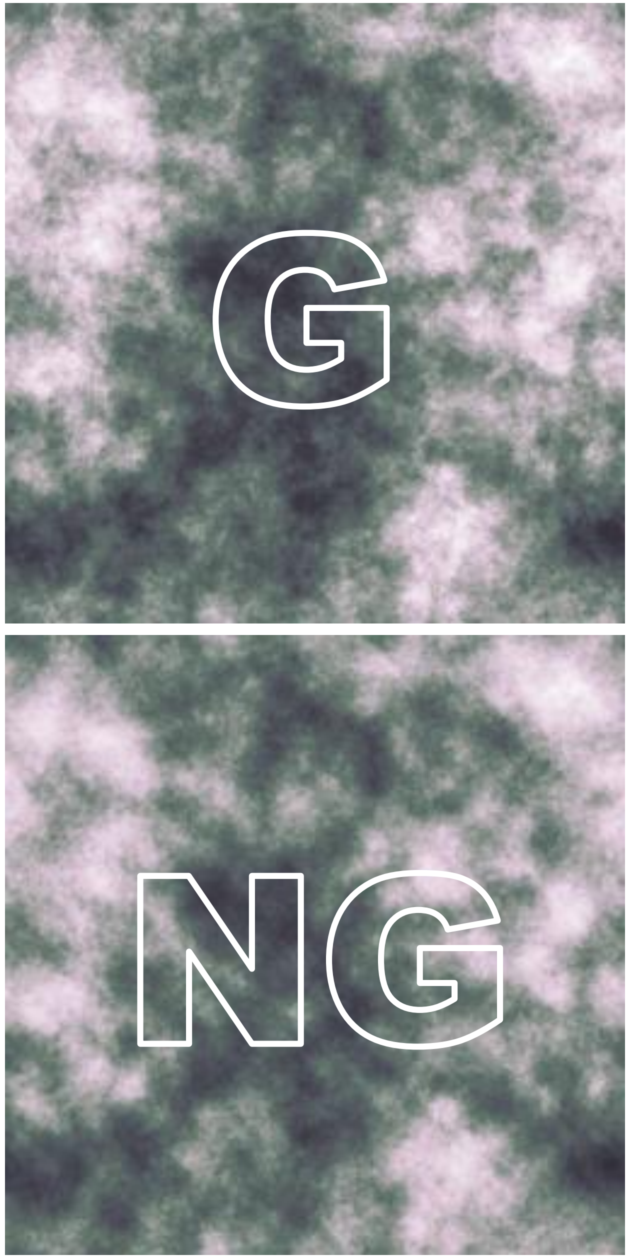
Question 2:

What if the same mechanism applies to the pre-inflationary axion case (f_a>>H)?

X. Chen, J. Fan, LL, 2203.03406

Primordial Non-Gaussianity & Cosmolocal Collider

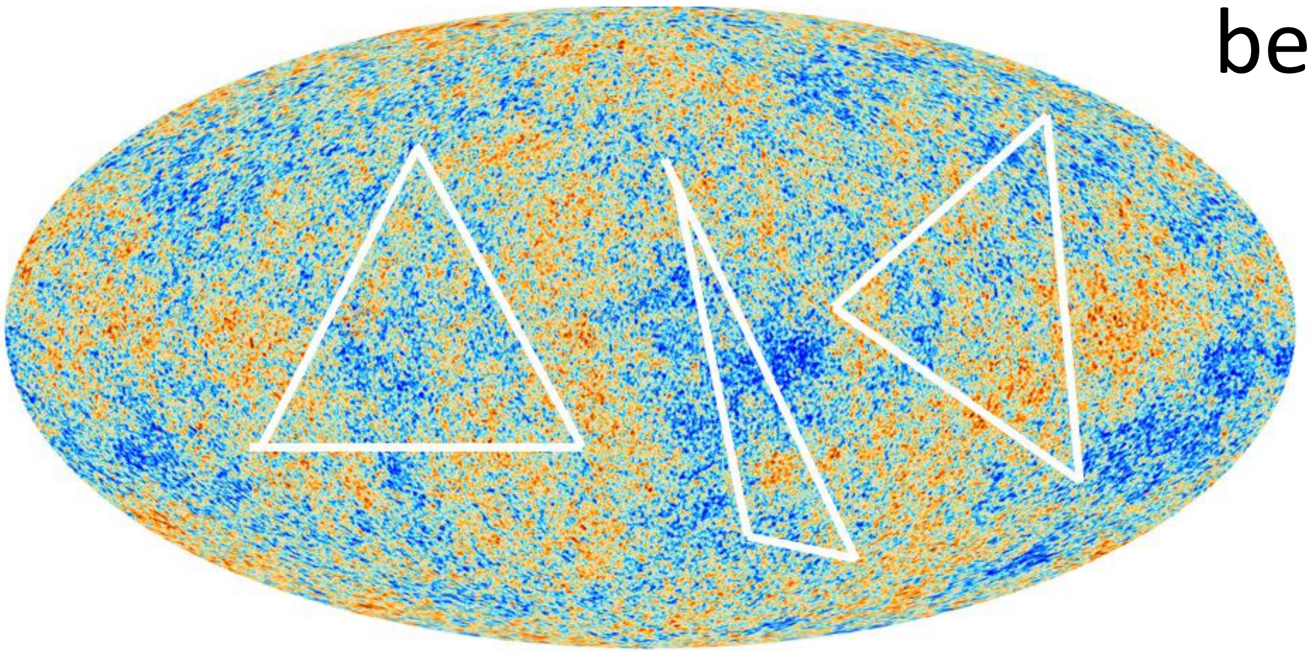




X. Chen, Y. Wang, 2009;
Arkani-Hamed, Maldacena, 2015

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

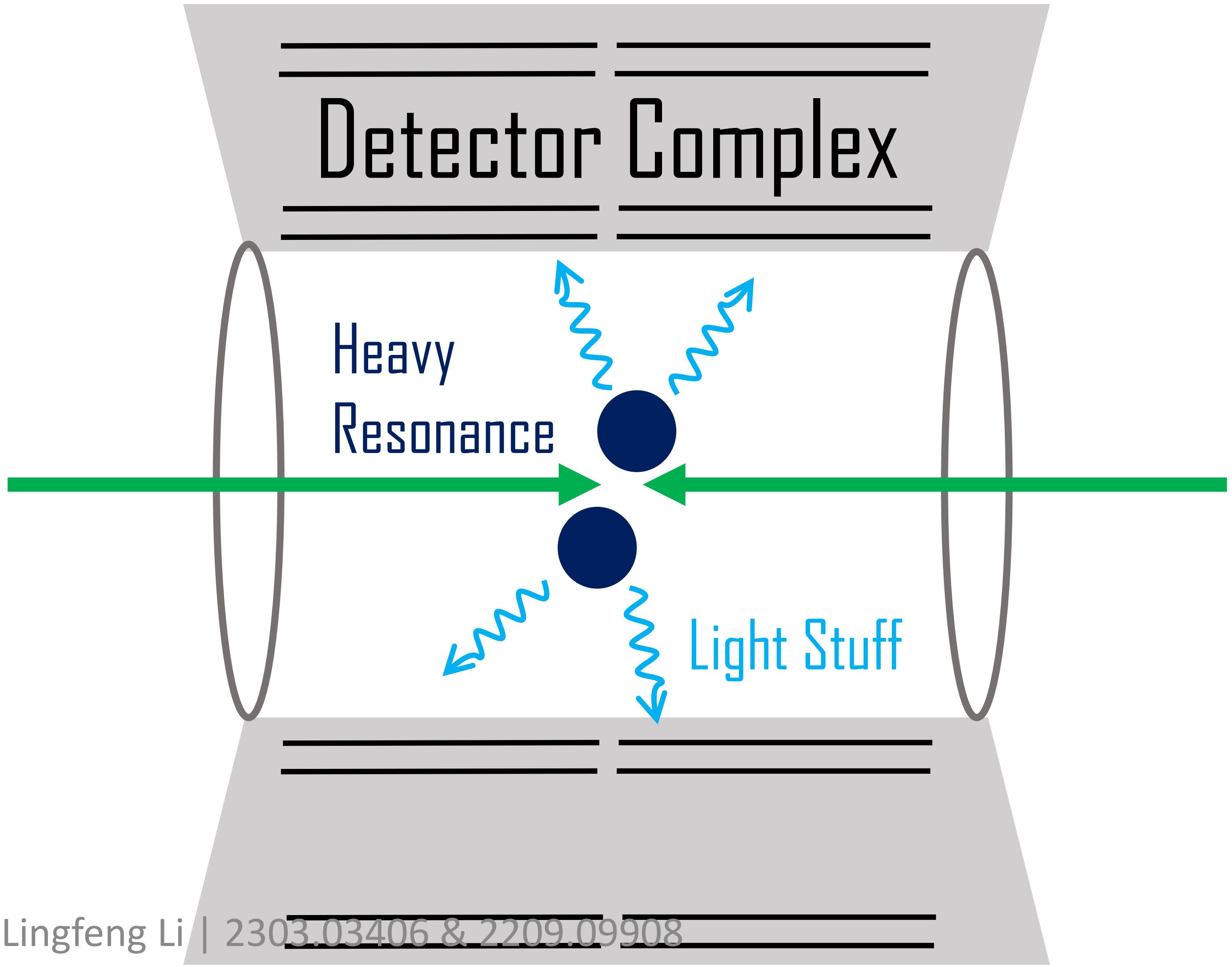
Wouldn’t happen if everything behave as free fields!



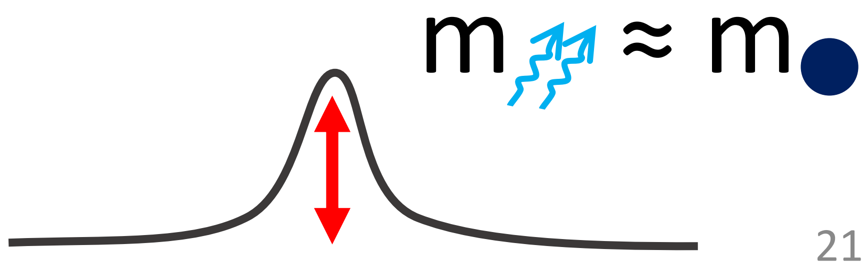
Planck limit on f_{NL}: O(10) for pure curvature.

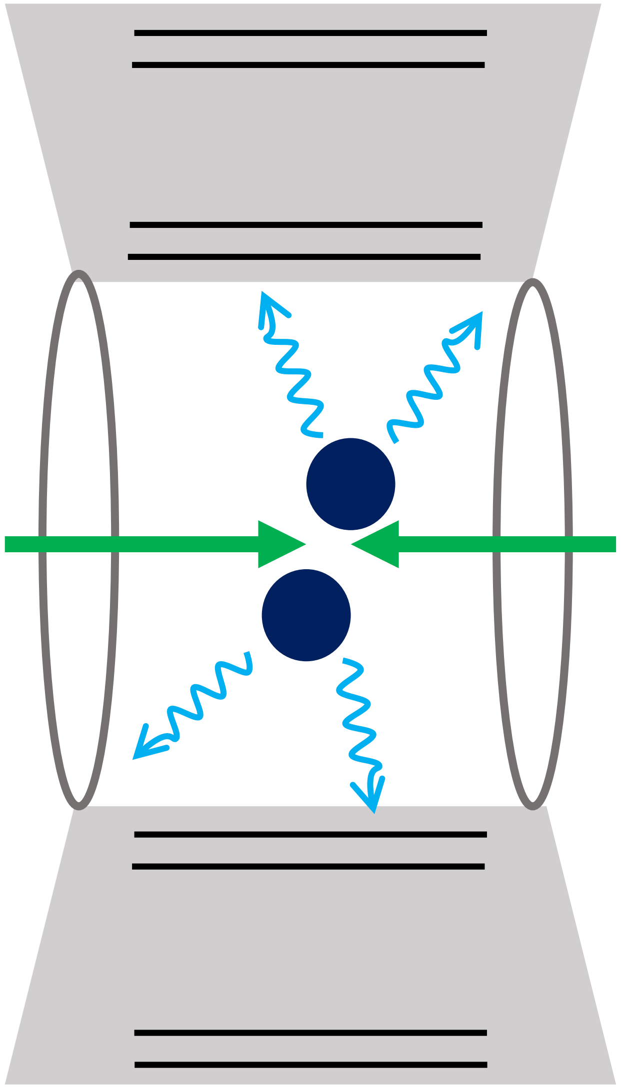
Planck collaboration, 2018

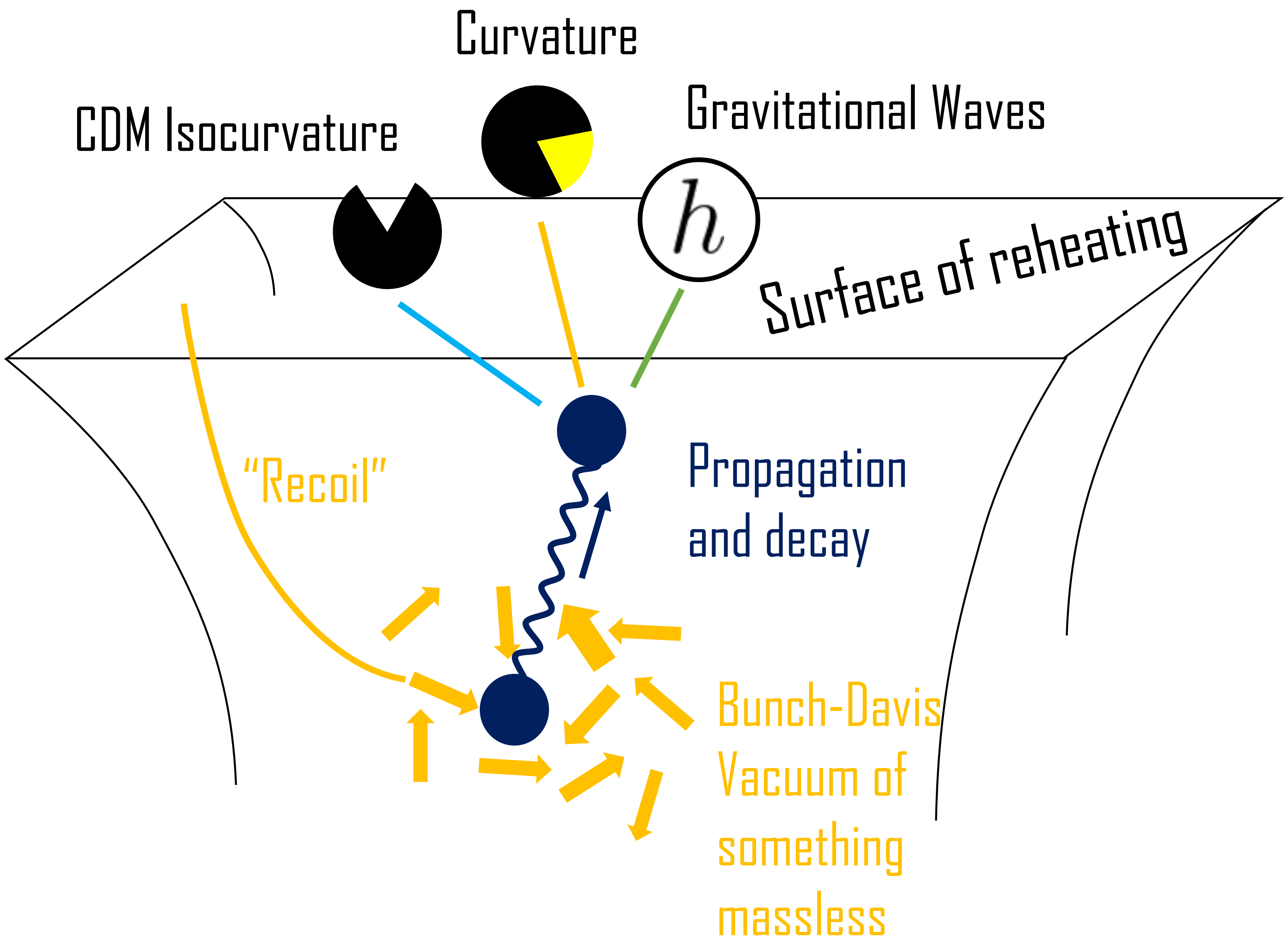
Cosmological Collider: Start from an Actual Collider



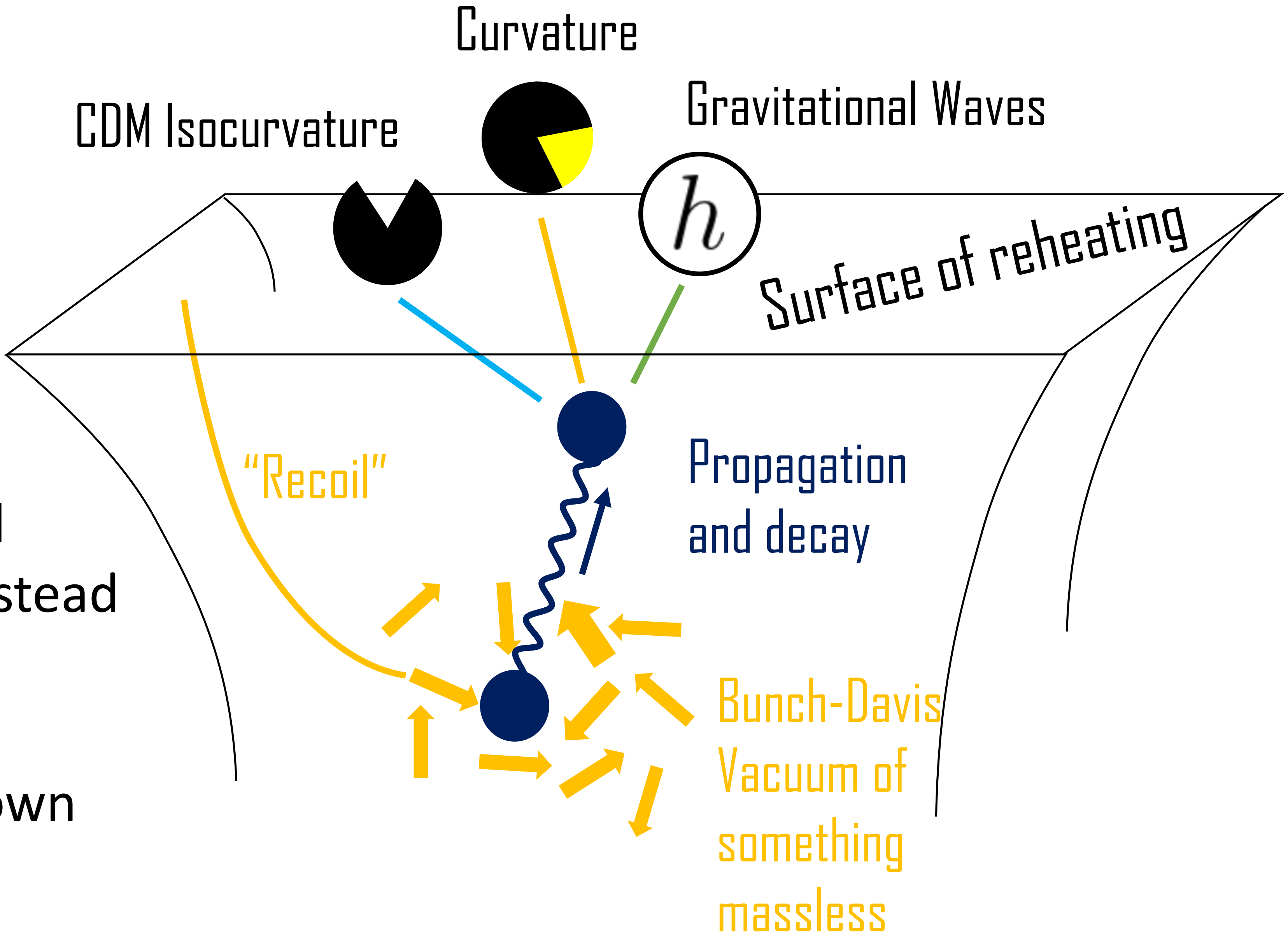
- ❑ Precisely prepared initial state: fixed Ecm, luminosity, direction…
- ❑ Short-lived resonances: the detector surfaces are too far compared to m●$^{-1}$
- ❑ Multi-species: γ, $e^{\pm}$, $\pi^{\pm}$, $K^{\pm}$ …
- ❑ Flat space time: invariant mass



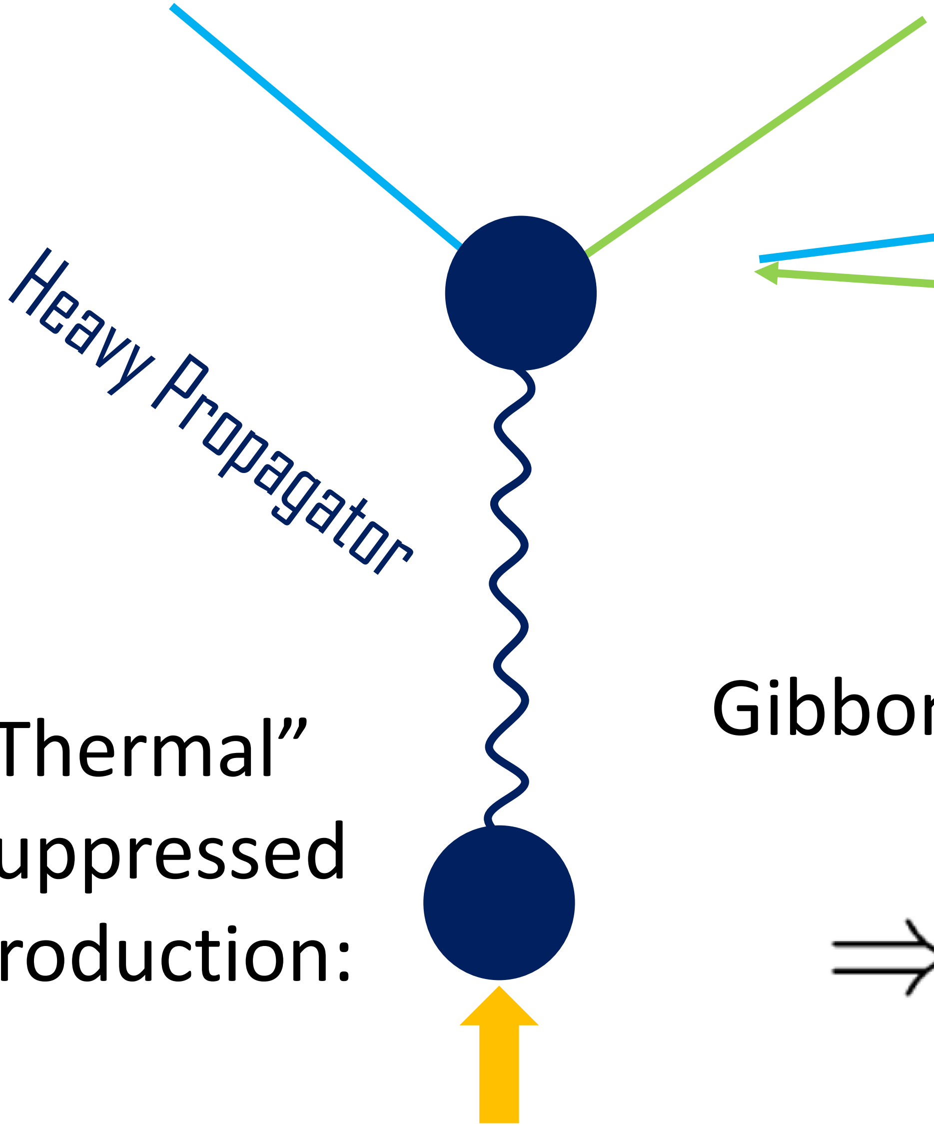


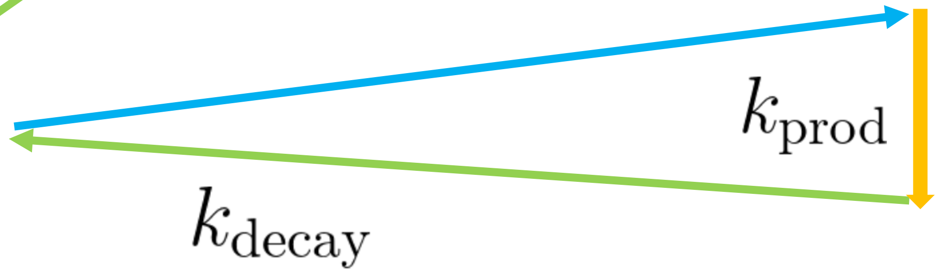

Curvature
CDM Isocurvature
Gravitational Waves
h
Surface of reheating
"Recoil"
Propagation
and decay
Bunch-Davis
Vacuum of
something
massless

- Chaotic initial state, heavy field created in quantum fluctuations
- The "detector surface" is "closer" to the location of decay
- Interfere with background fluctuations, amplitude instead of its square
- Time invariance breaks down by inflation: No invariant masses



Sketch of a Cosmological Collider





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

Momentum Conservation

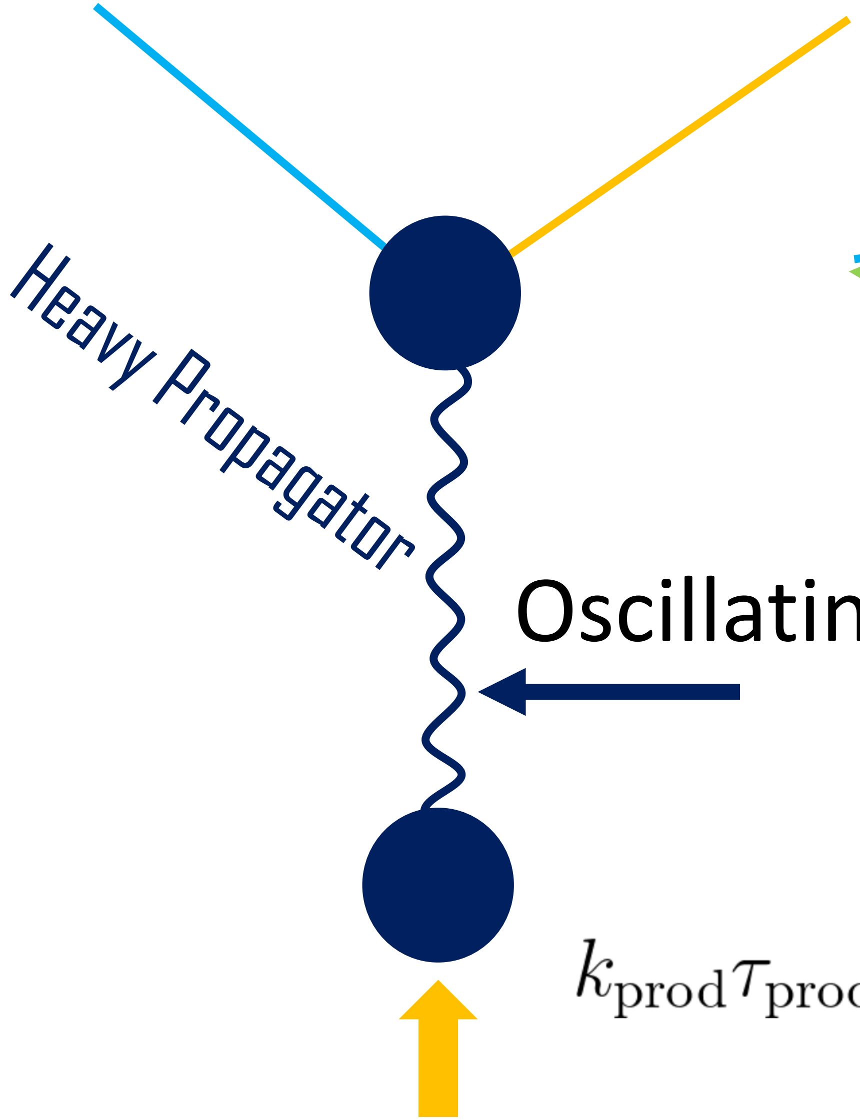
"Thermal" Suppressed production:

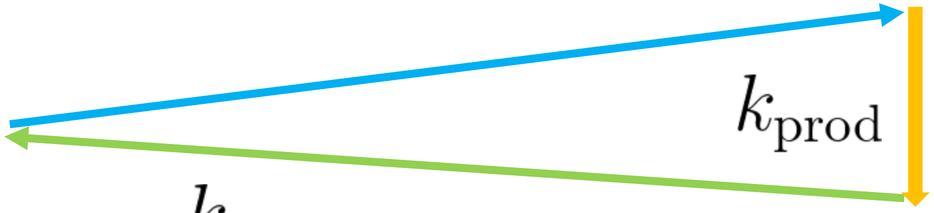
Gibbons-Hawking temperature: $T \sim \frac{H}{2\pi}$

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

Sketch of a Cosmological Collider

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





Oscillating as： e^{imt}

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

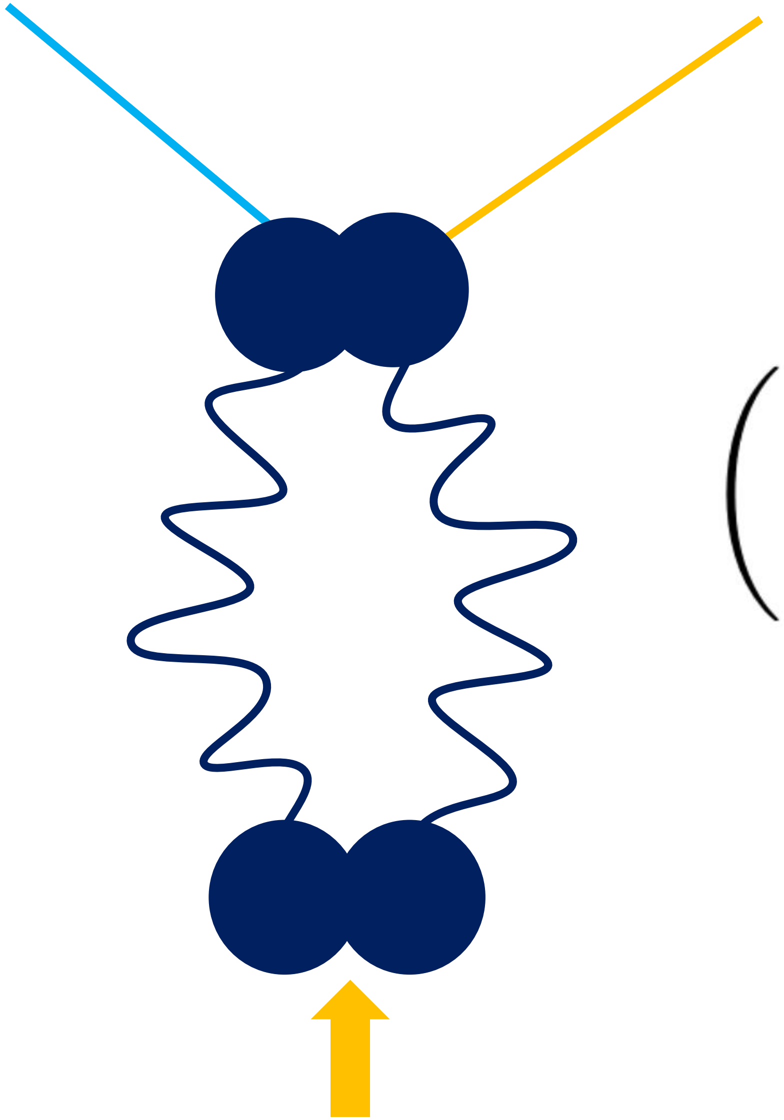
Mass observed through phases：

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

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

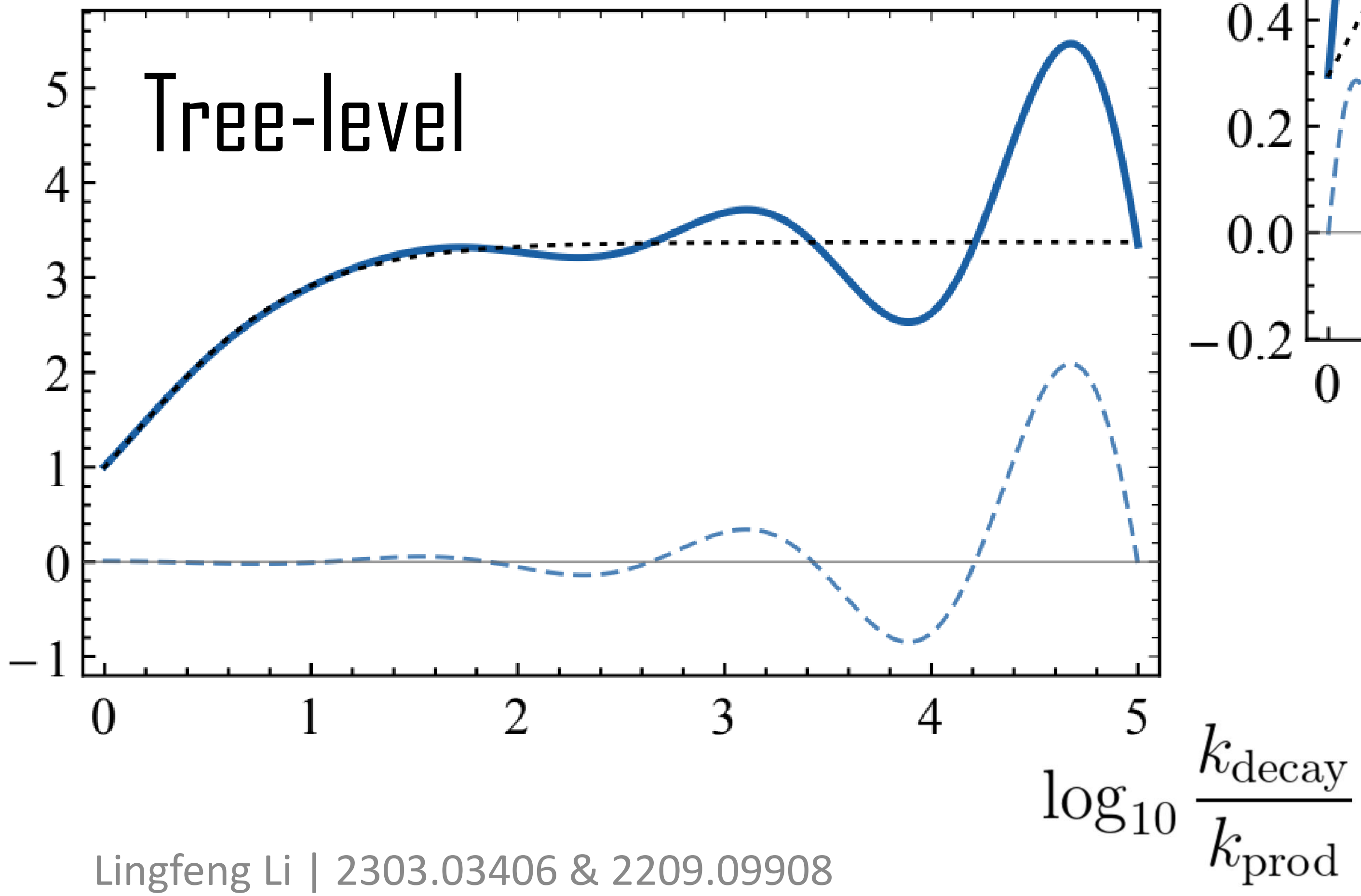
$$e^{im\Delta t} \sim \left(\frac{k_{\text{decay}}}{k_{\text{prod}}}\right)^{im/H}$$

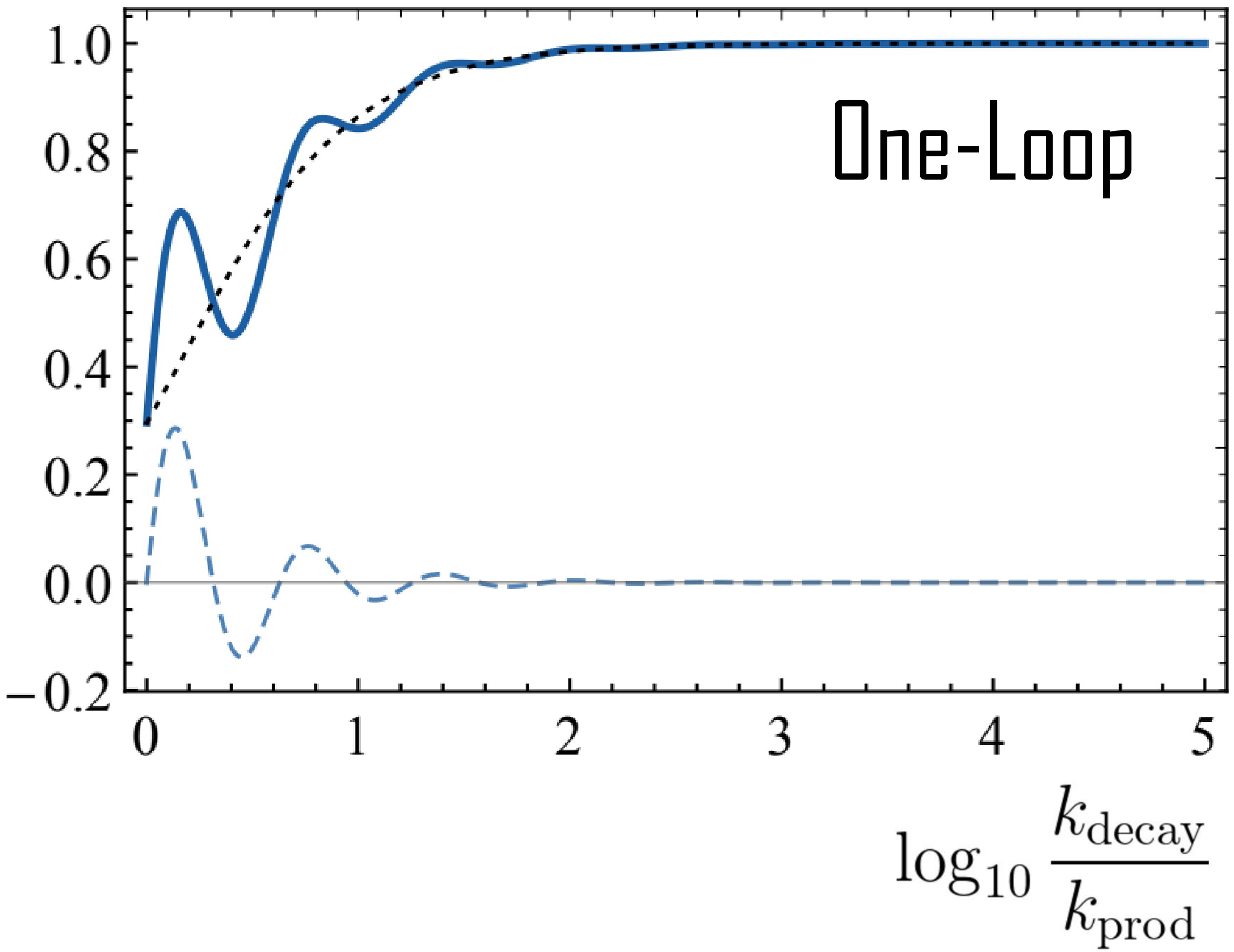
At One Loop



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

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



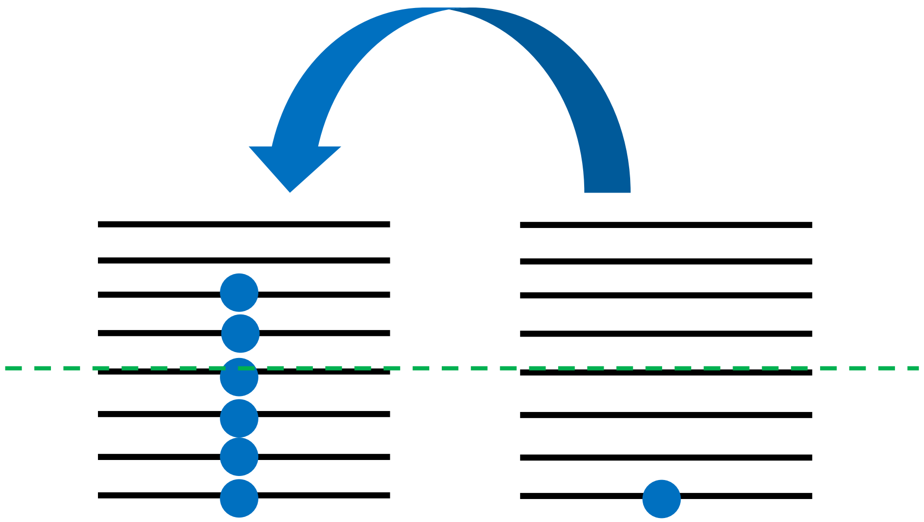


L.T. Wang, Z.Z Xianyu, Y. Zhong, 2021

Beyond Boltzmann Suppression

❑Chemical potential

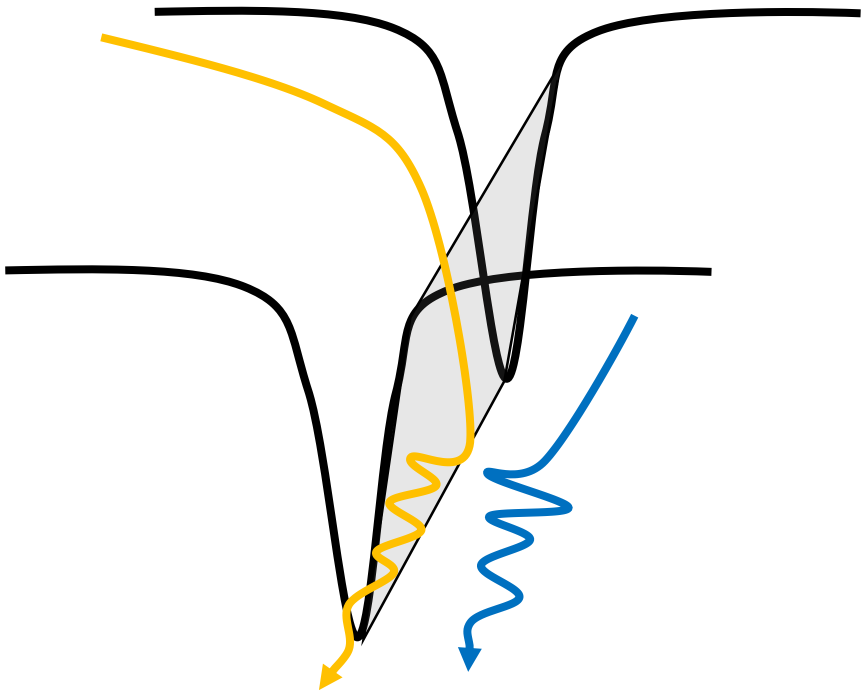
A rolling field creates uneven chemical potential in a sector, greatly enhancing occupation number



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

❑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 …

❑Slow Motion

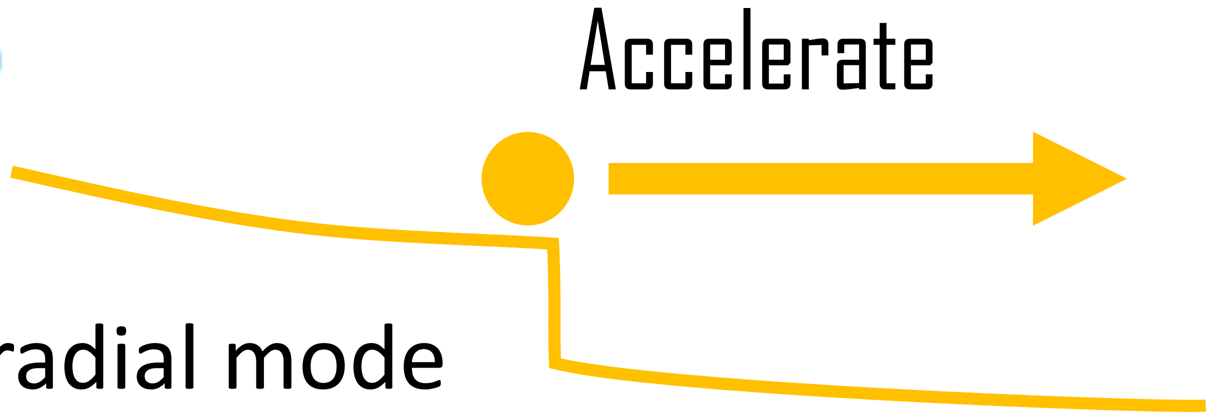
S. Jazayeri, S. Renaux-Petel 2022

Scenario 1: Classical Feature

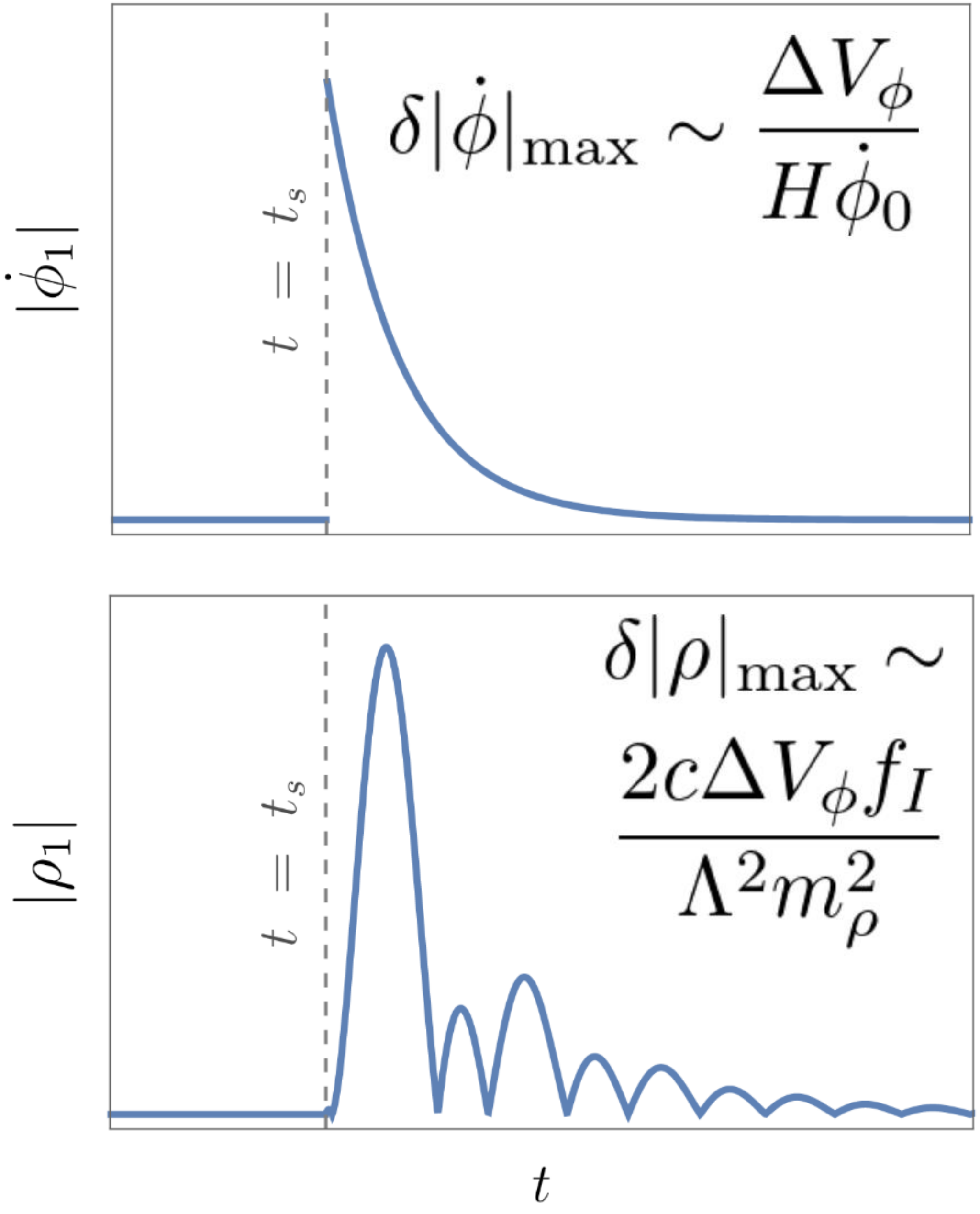
$$\mathcal{L}_1 = -\frac{(\partial_\mu \phi)^2}{2} - |\partial_\mu \chi|^2 - V_\phi(\phi) - V_\chi(\chi) - \frac{c}{\Lambda^2}(\partial\phi)^2|\chi|^2$$

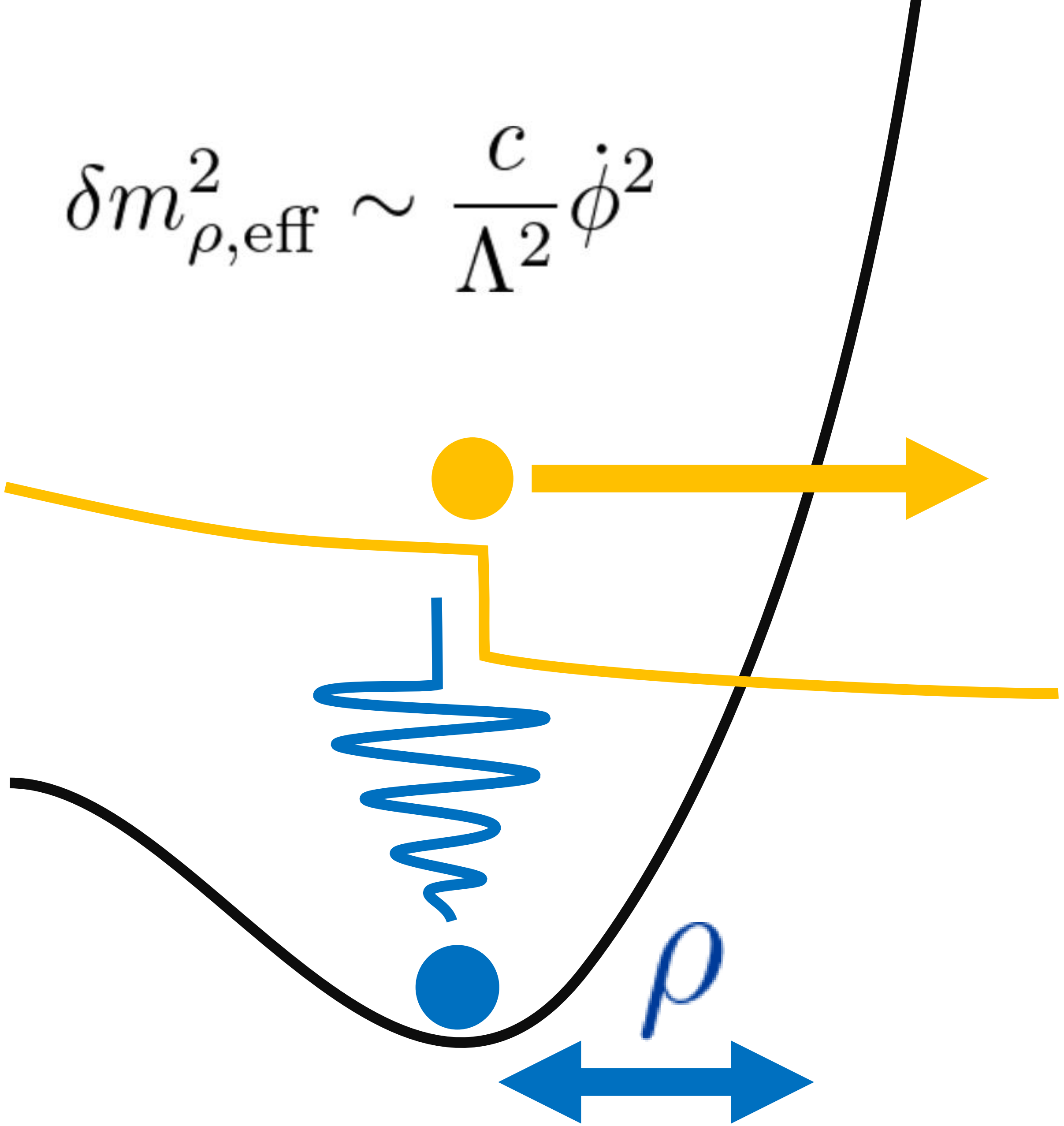
+ Toy feature: a step in potential

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

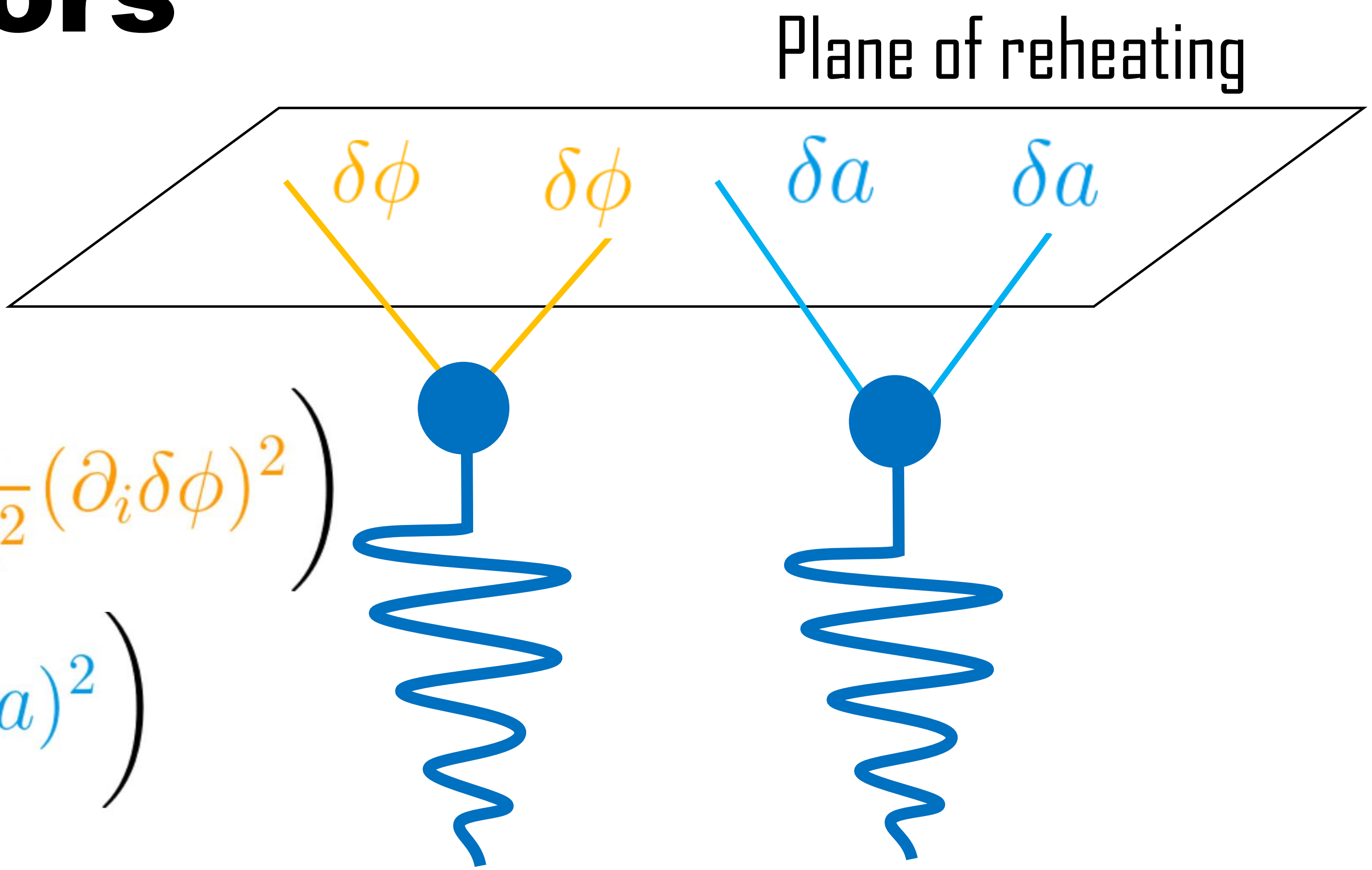


Mediator excited: ρ the radial mode


$|\dot{\phi}_1|$
$t = t_s$
$\delta|\dot{\phi}|_{\max} \sim \frac{\Delta V_\phi}{H\dot{\phi}_0}$
$|\rho_1|$
$t = t_s$
$\delta|\rho|_{\max} \sim \frac{2c\Delta V_\phi f_I}{\Lambda^2 m_\rho^2}$
t


$\delta m^2_{\rho,\mathrm{eff}} \sim \frac{c}{\Lambda^2}\dot{\phi}^2$
ρ

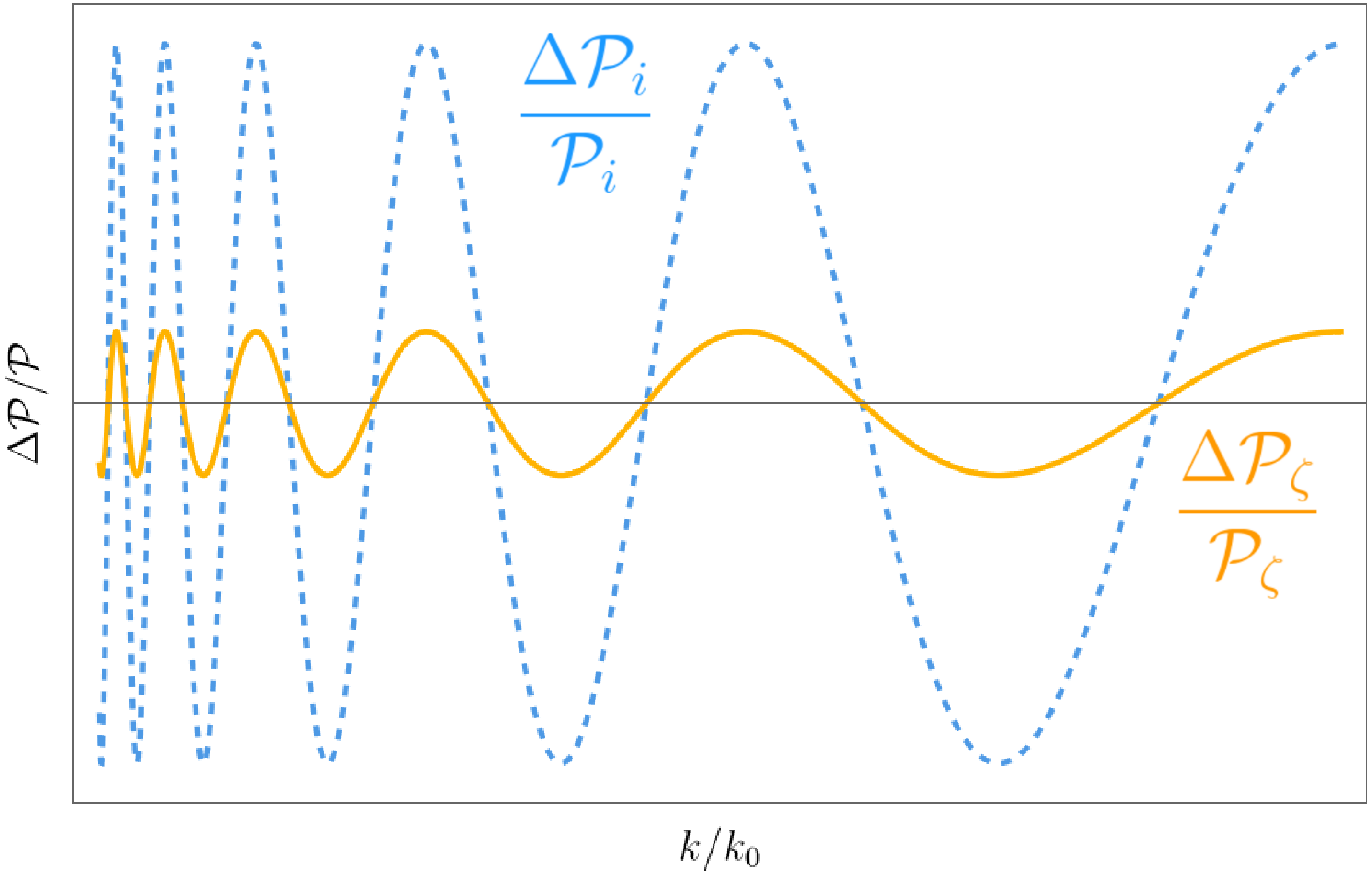
2-PT Correlators



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

Scale dependence (the scale of the feature injected) in 2-pt **LARGER** in isocurvature

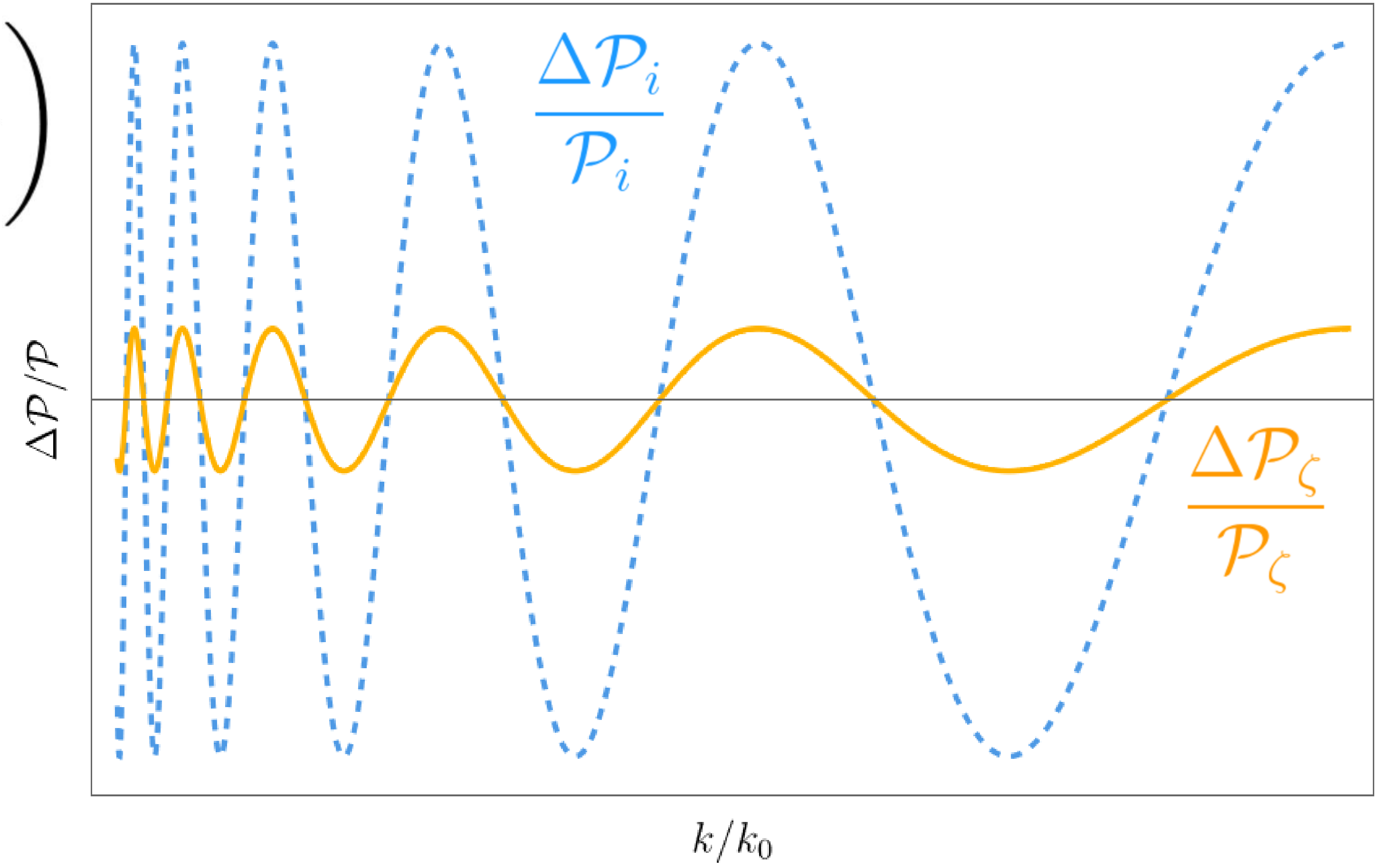
“Music” of Dark Matter



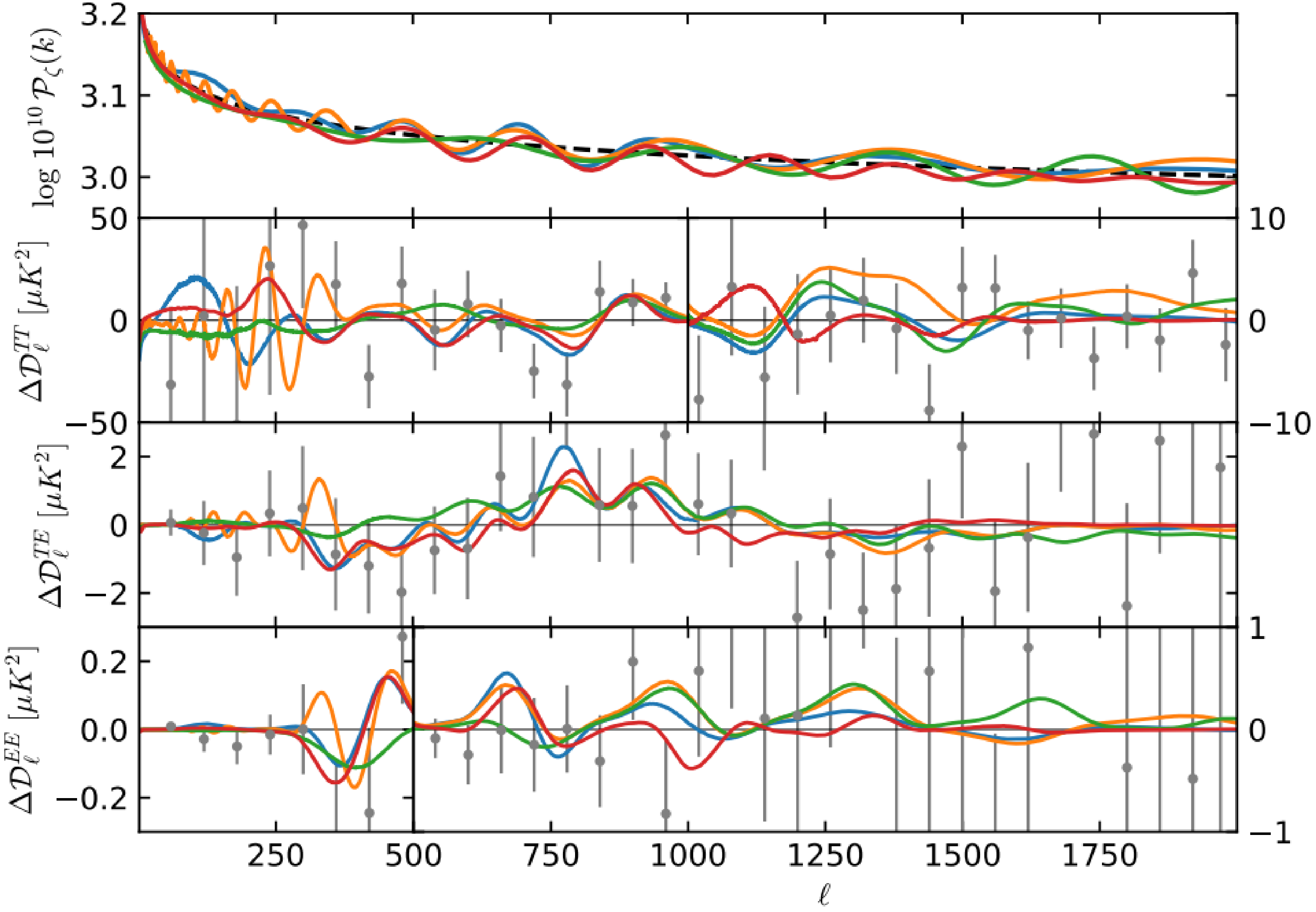
2-PT Clock Signal Reveals m_ρ

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

"Standard clock" to probe the radial mode of the PQ field

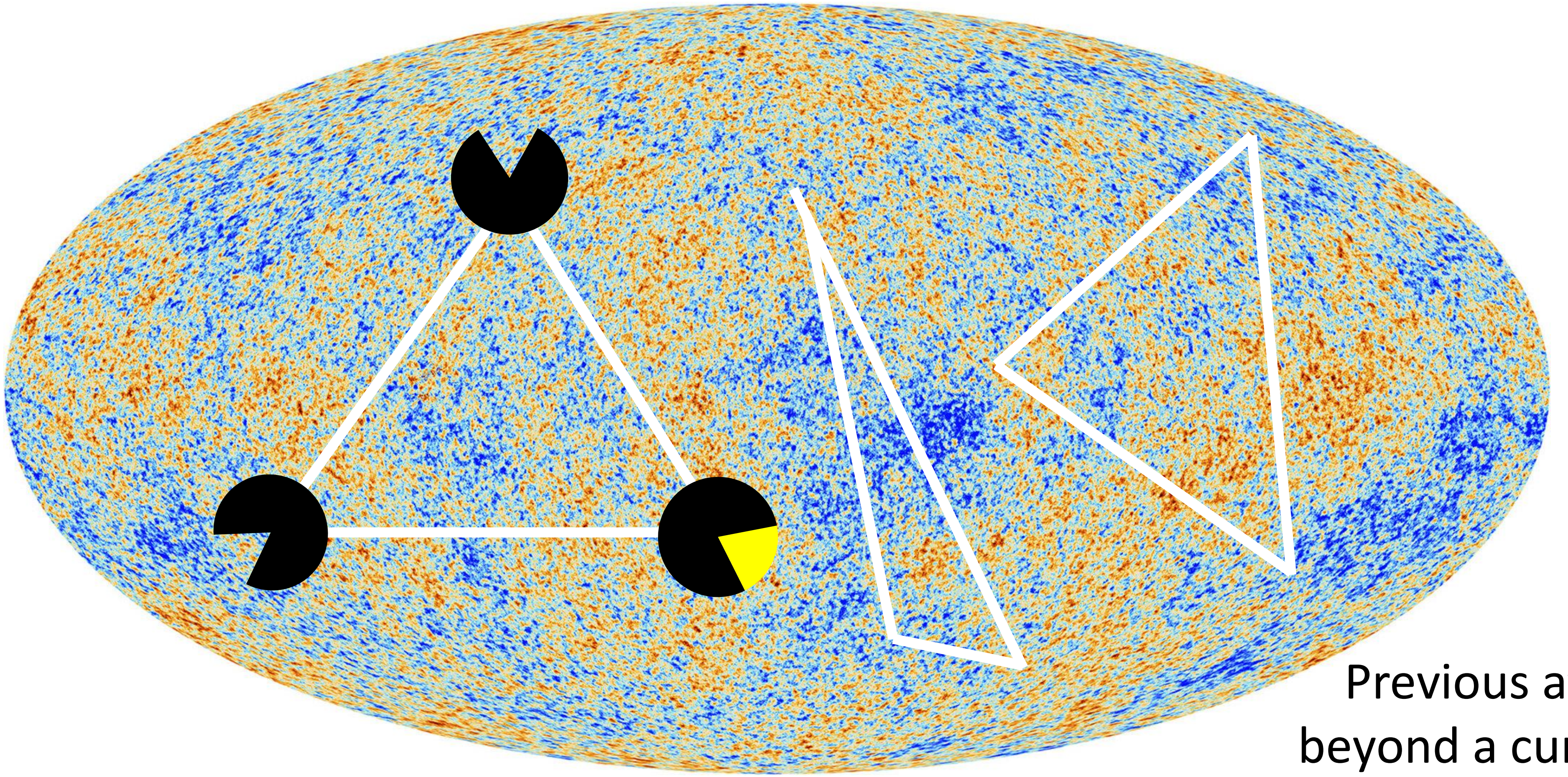


Observational Hints



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

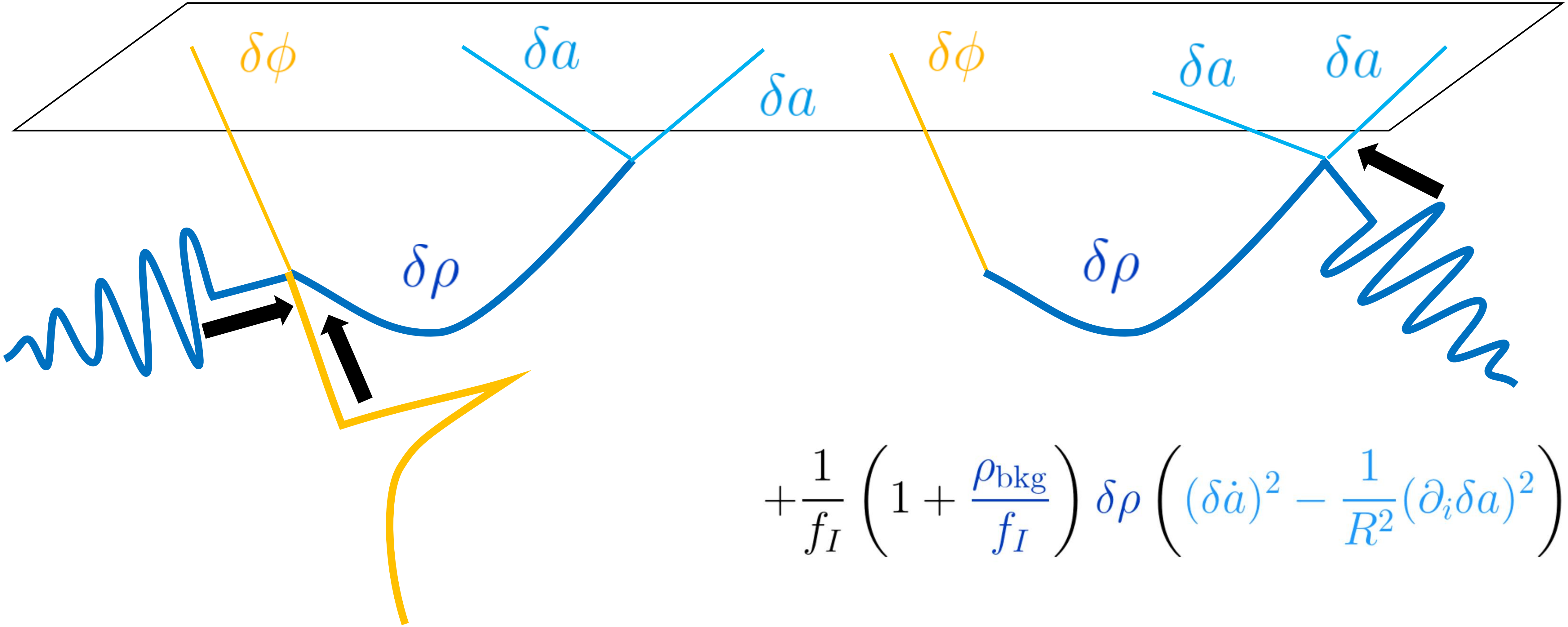
Cosmological Collider Signals of Hybrid Modes



Previous attempts to go beyond a curvature collider:

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

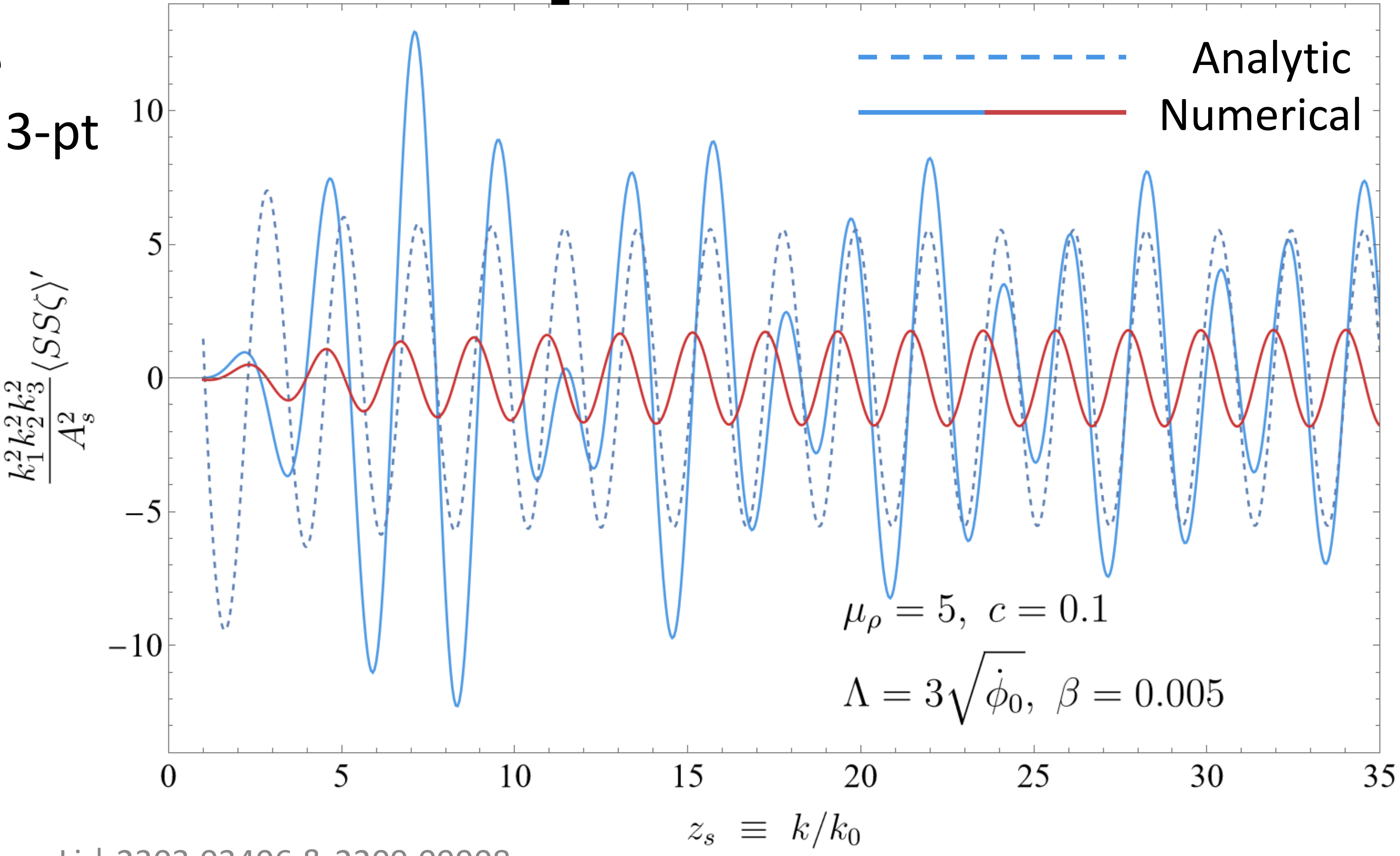
$$\frac{2cf_I\dot{\phi}_0}{\Lambda^2}\left(1+\frac{\dot{\phi}_1}{\dot{\phi}_0}+\frac{\rho_{\rm bkg}}{f_I}\right)\delta\dot{\phi}\delta\rho$$



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

NG in the Equilateral limit

Sizable hybrid 3-pt signal



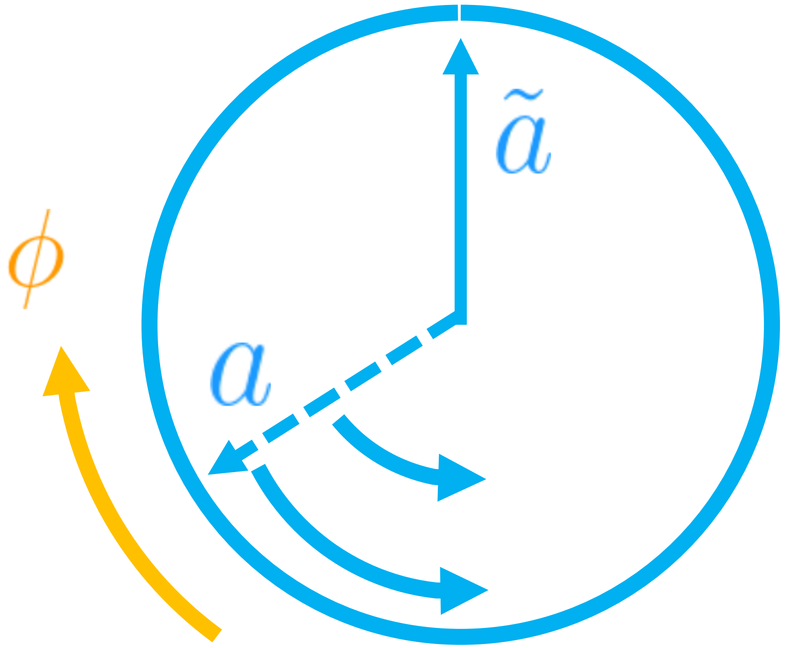
Scenario 2: Chemical Potential

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

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

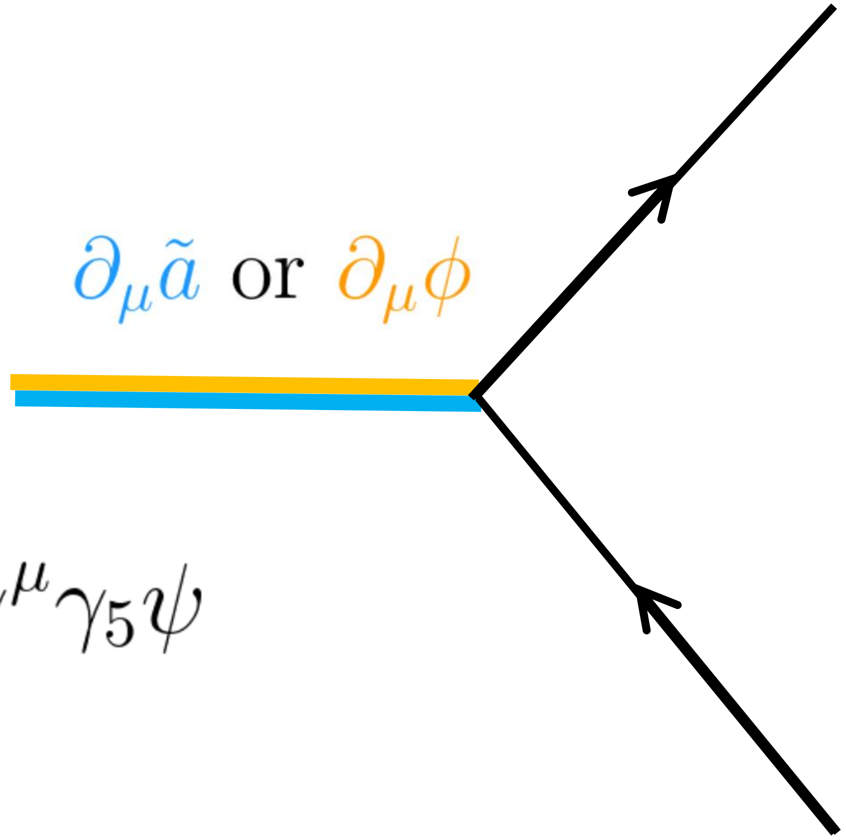


Axion-Fermion Coupling

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



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

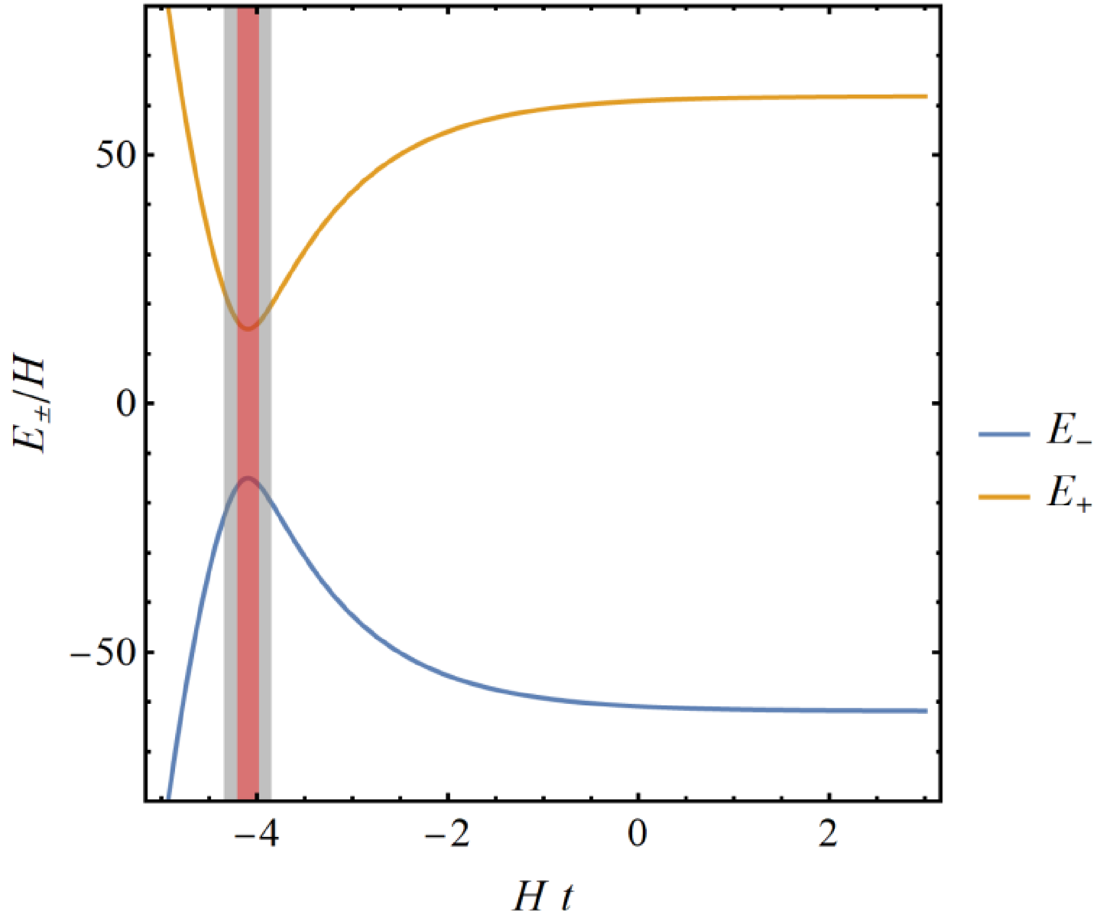
Chemical Potential

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

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

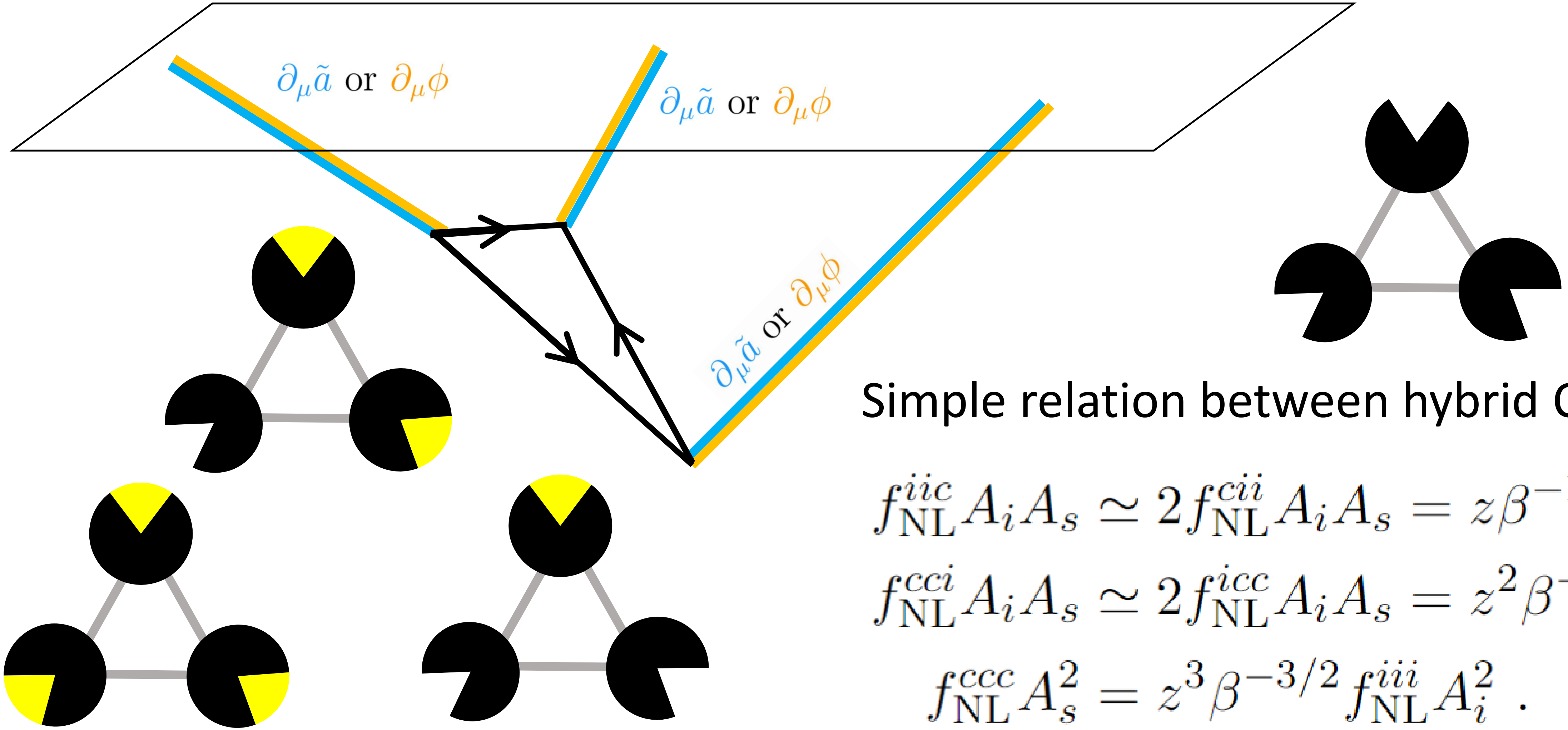
The chemical potential



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



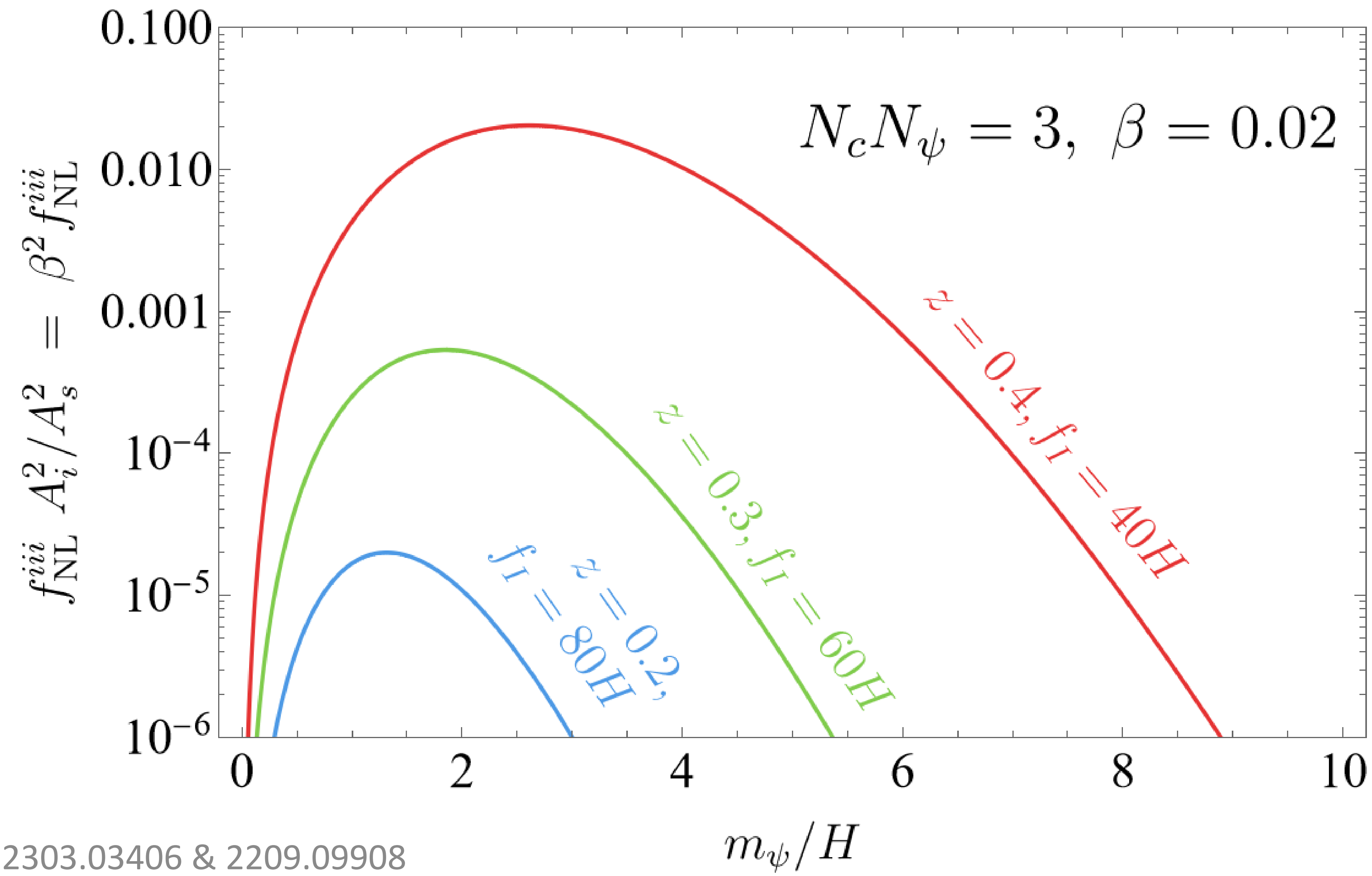
Simple relation between hybrid CC signals:

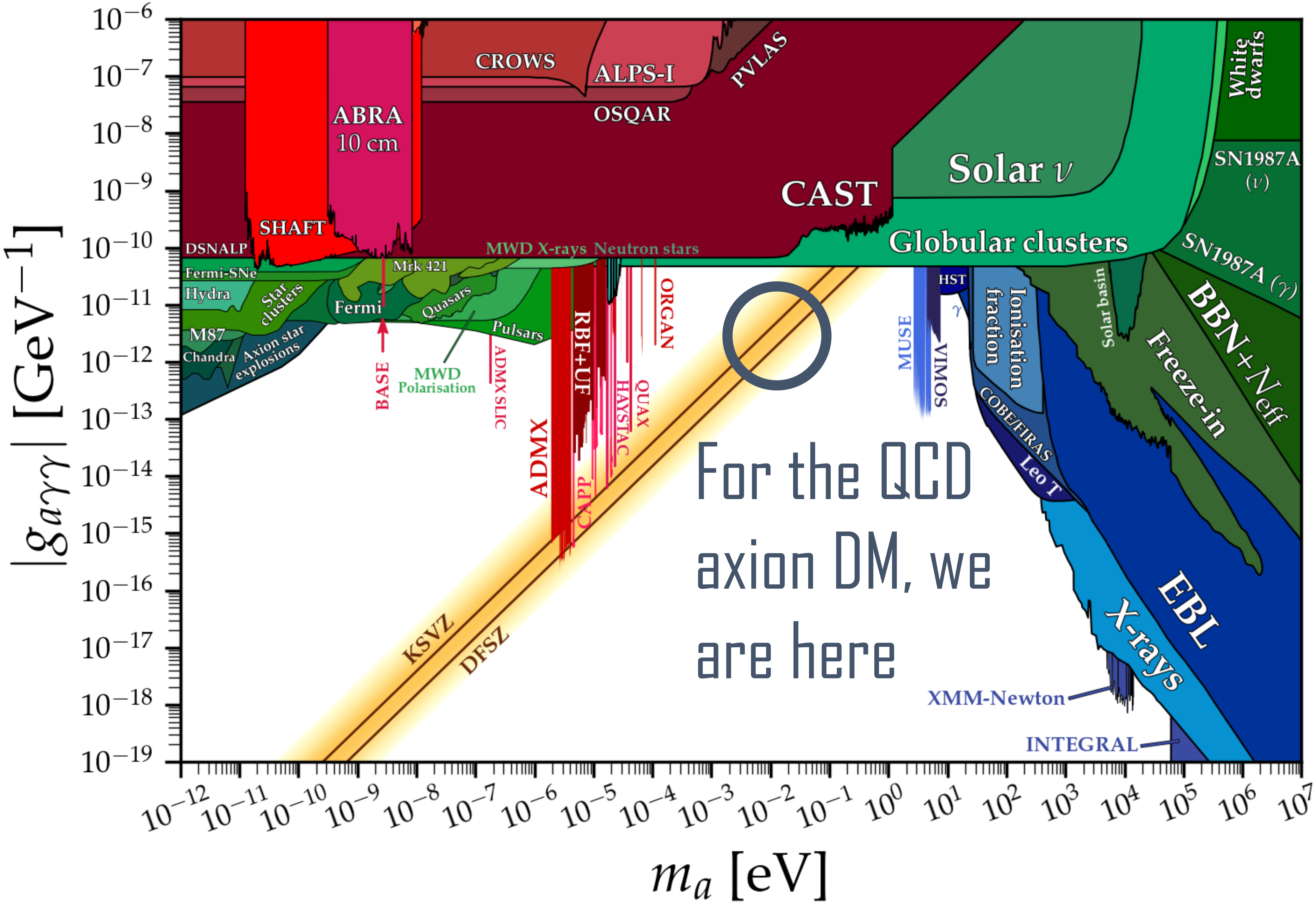
$$f_{\rm NL}^{iic} A_i A_s \simeq 2 f_{\rm NL}^{cii} A_i A_s = z\beta^{-1/2} f_{\rm NL}^{iii} A_i^2$$

$$f_{\rm NL}^{cci} A_i A_s \simeq 2 f_{\rm NL}^{icc} A_i A_s = z^2\beta^{-1} f_{\rm NL}^{iii} A_i^2$$

$$f_{\rm NL}^{ccc} A_s^2 = z^3\beta^{-3/2} f_{\rm NL}^{iii} A_i^2 \,.$$

Sizable Signals

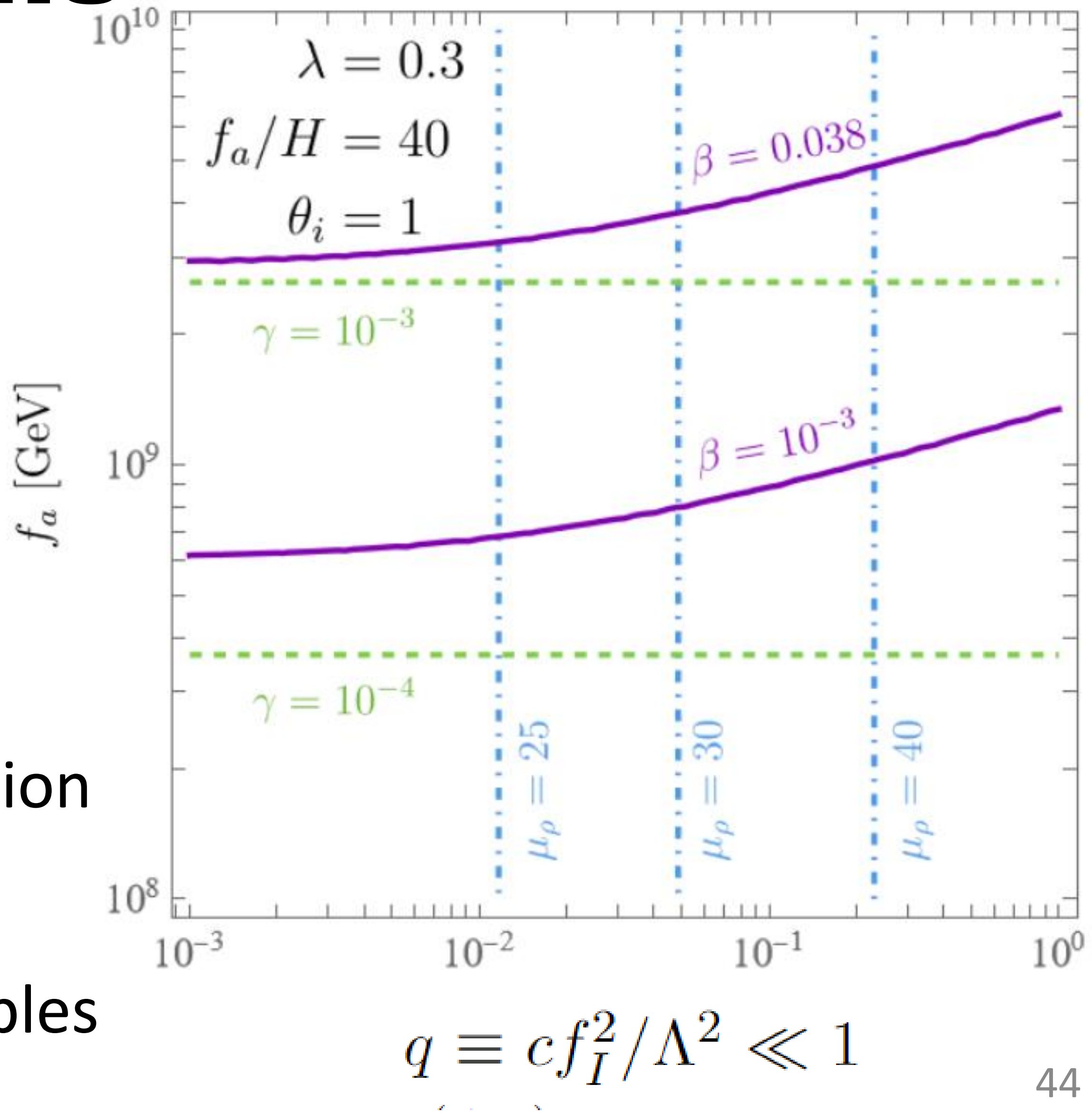




For the QCD axion DM, we are here

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



Summary & Outlook

- ❑Inflaton-PQ interaction could lead to big differences
- ❑Opens a new window of post-inflationary axion
- ❑Rich cosmological signal in both curvature and isocurvature modes
- ❑Applies to axion-like-particles
- ❑Reveals the PQ radial mode and the inflationary scale


Thank you!

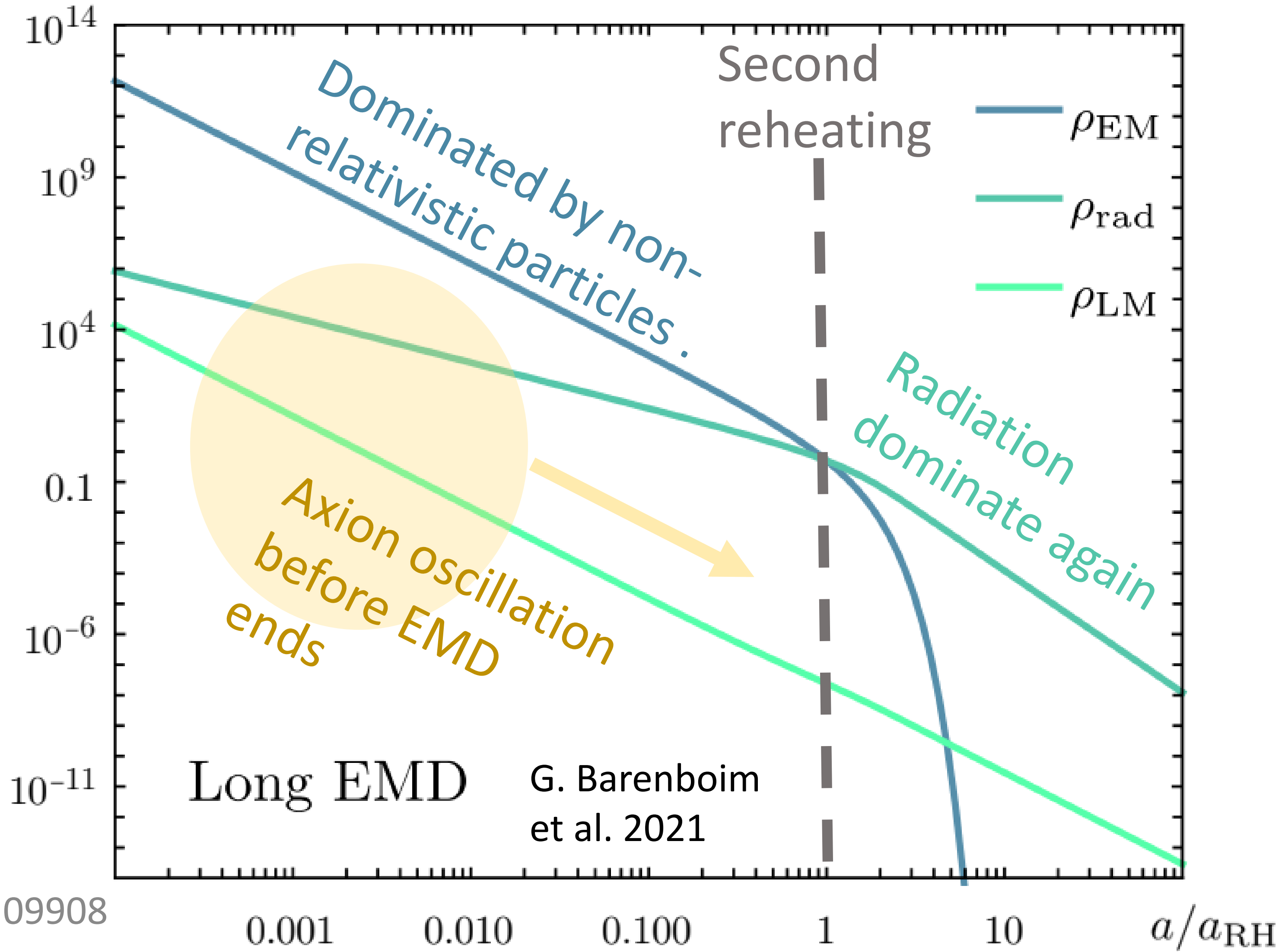
BAKCUPS &
EXTRA THOUGHTS

More Parameter Space from Early Matter Domination (EMD)

Lazarides, et.al 1990;
Kawaski et.al 1995…

- ❑ Axion comoving abundance diluted by the entropy produced during EMD reheating

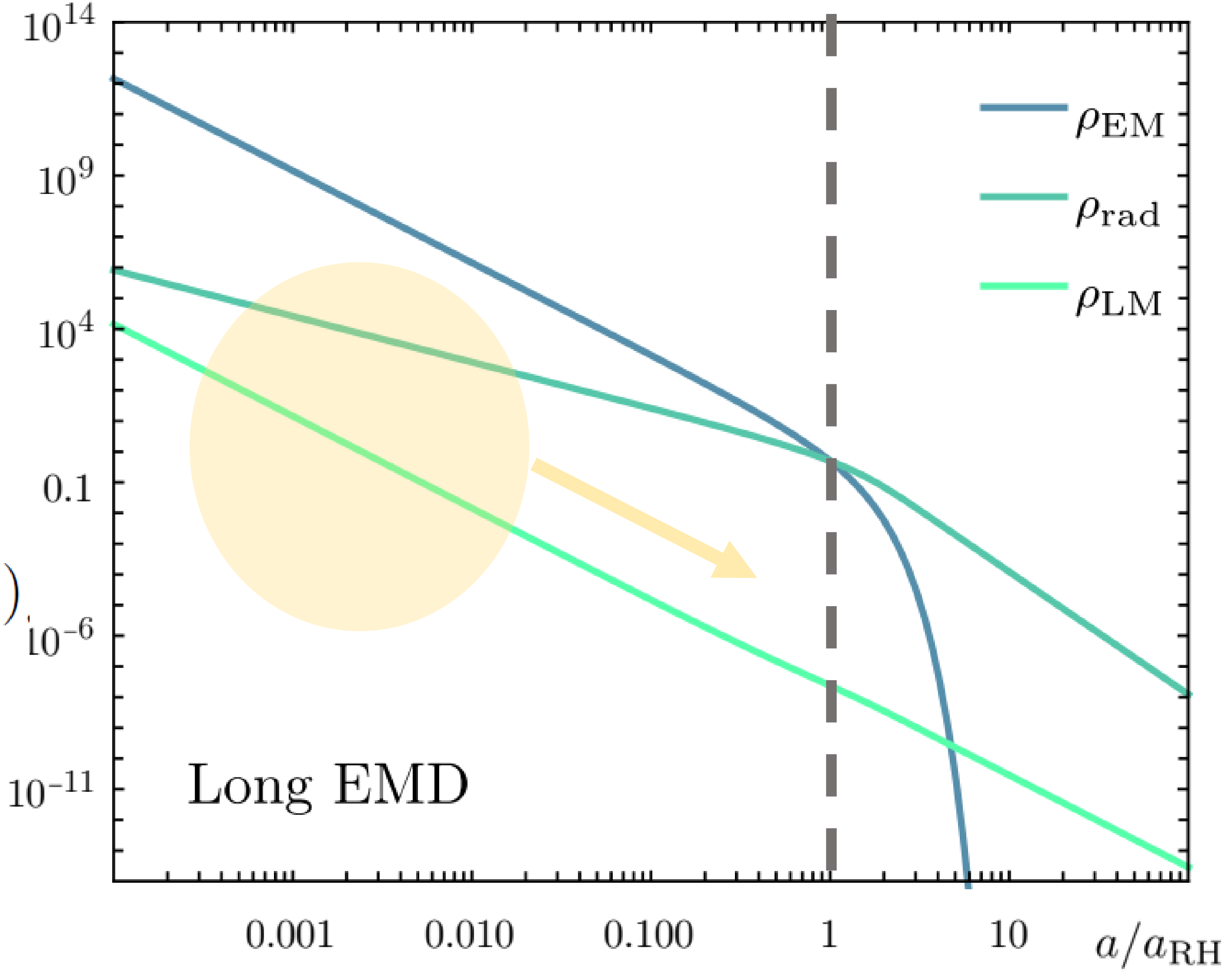
- ❑ Various candidates from heavy moduli to dark glueballs



More Parameter Space from Early Matter Domination (II)

- Reheating temperature needs to be greater than 1 MeV (or lifetime < 1 sec) to be fine with BBN

$$\Omega_a^{\rm mis} h^2 = \frac{h^2}{2\rho_{\rm crit}} m_a(T_*) m_a(T_0) \times f_a^2 \theta_i^2 \frac{h_*(T_0)}{h_*(T_R)} \frac{T_0^3 T_R^5}{T_*^8}$$



Extra EMD Scenario: Curvaton

A light spectator field σ during, power spectrum larger than that of inflaton

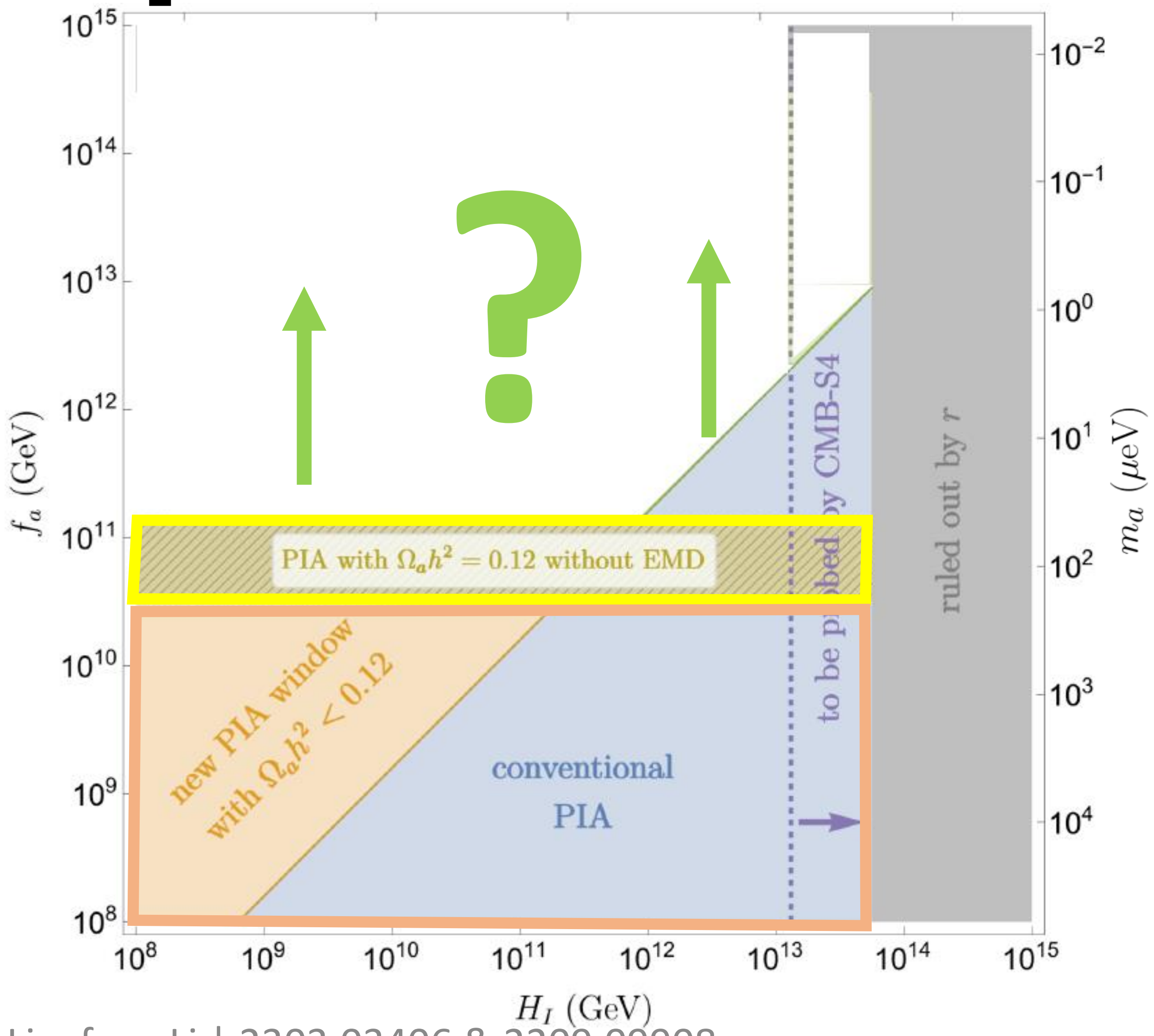
$$P_\sigma = \frac{H_I^2}{9\pi^2 \langle\sigma\rangle^2} \gg P_\phi = \frac{H_I^2}{4\pi^2 \dot{\phi}^2}$$

Becomes massive after reheating, dominate the cosmoic evolution: exactly needed for EMD!

Free $\dot{\phi}$ partially from observation, fixed by $\epsilon \approx \dot{\phi}_0^2/(2H_I^2 M_{\rm Pl}^2)$ instead, could be much larger than $(60\ H_I)^2$

*The potential isocurvature problem if axion DM from string decays inherit inflaton perturbations. Yet even though axion string network is created much before EMD, it follows the attractive solution of the scaling law, insensitive to the initial conditions. The correlation carried by the axion string network in the early universe could be washed out during the long EMD era.

Opened Parameter Space

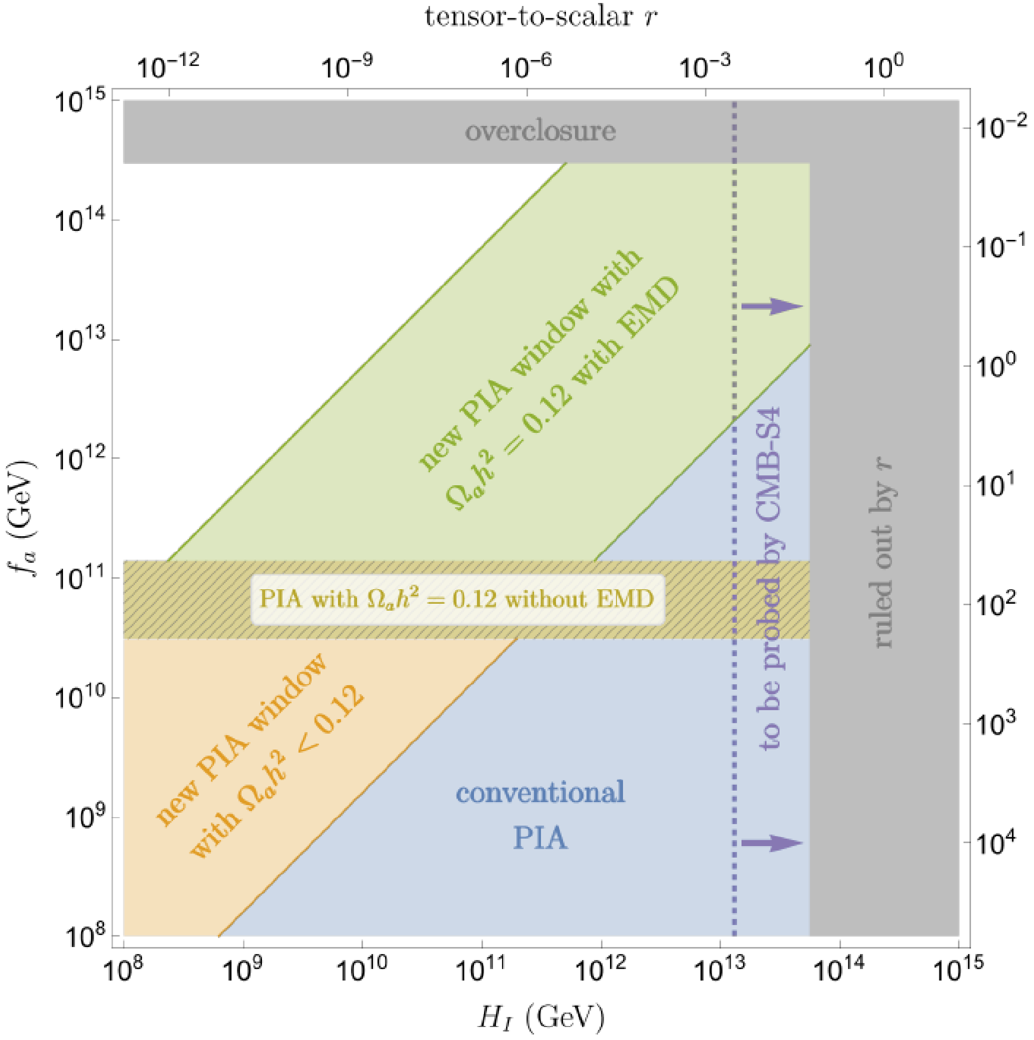


$$f_a \lesssim \frac{\sqrt{2}\pi}{27}\frac{\dot{\phi}_0}{H_I} \gg H_I$$

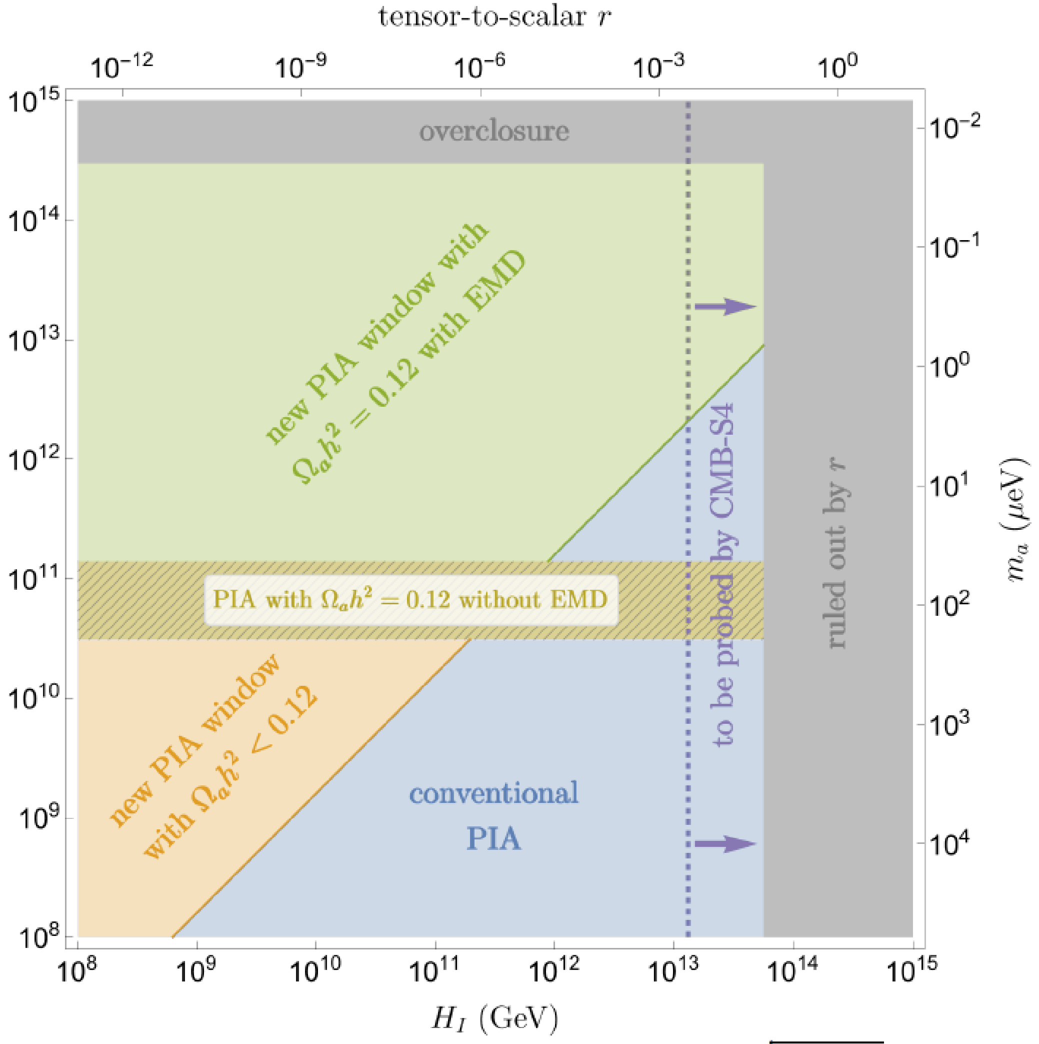
Opens up quite some parameter space, but mostly $H_I < 10^{11}$ GeV. Bounded by Ω_{DM}

Question: can we ask for even more?

Results and Constraints



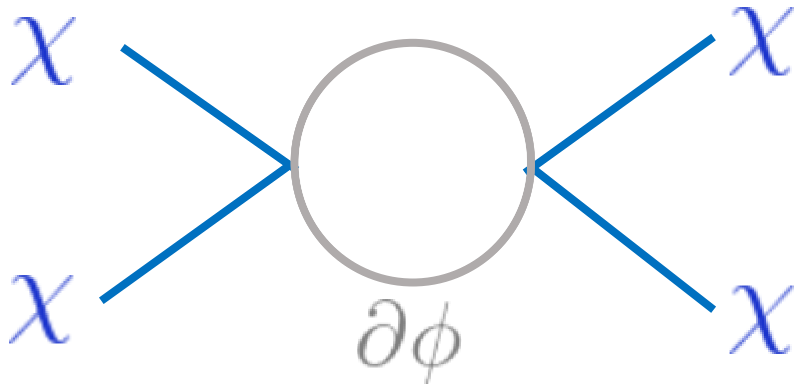
$$\text{case 1} : f_a \lesssim 600 H_I$$

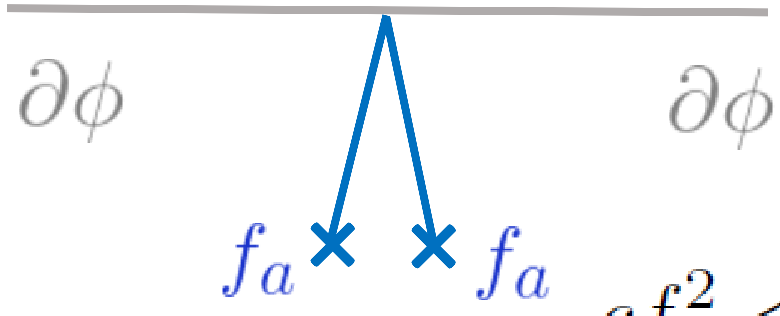


$$\text{case 2} : f_a \lesssim 8 \times 10^{16}\ \text{GeV} \sqrt{\frac{\epsilon}{0.02}}$$

EFT Validity

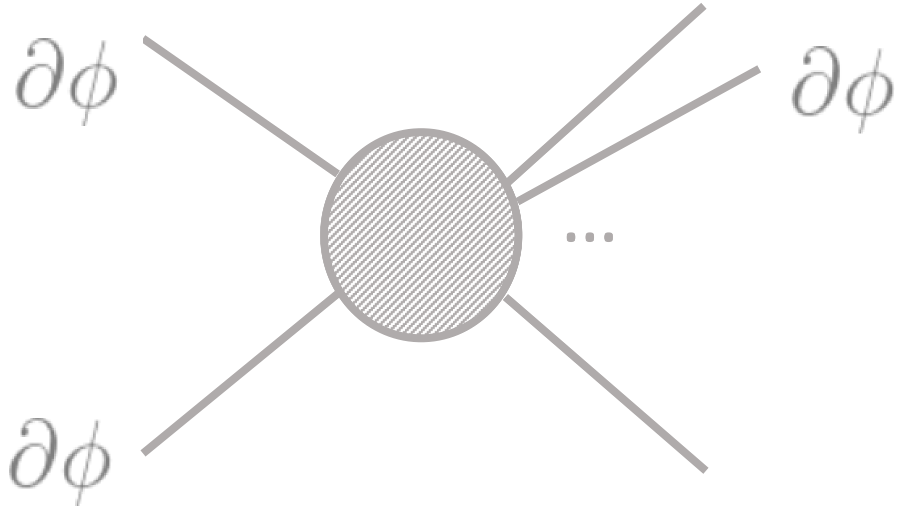
$$\delta\lambda \sim \frac{c^2}{16\pi^2} \lesssim \lambda \implies c \lesssim 4\pi\sqrt{\lambda}$$



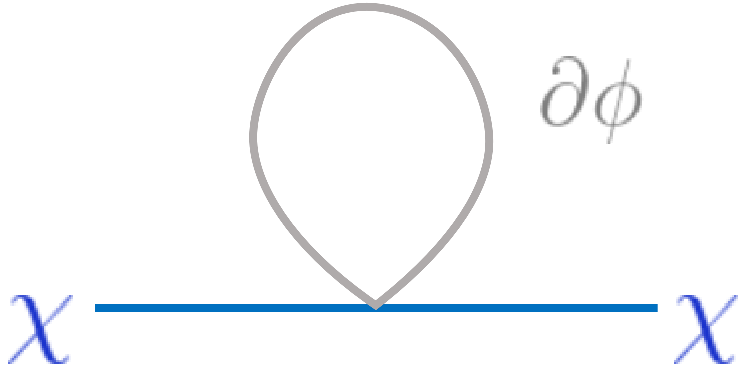


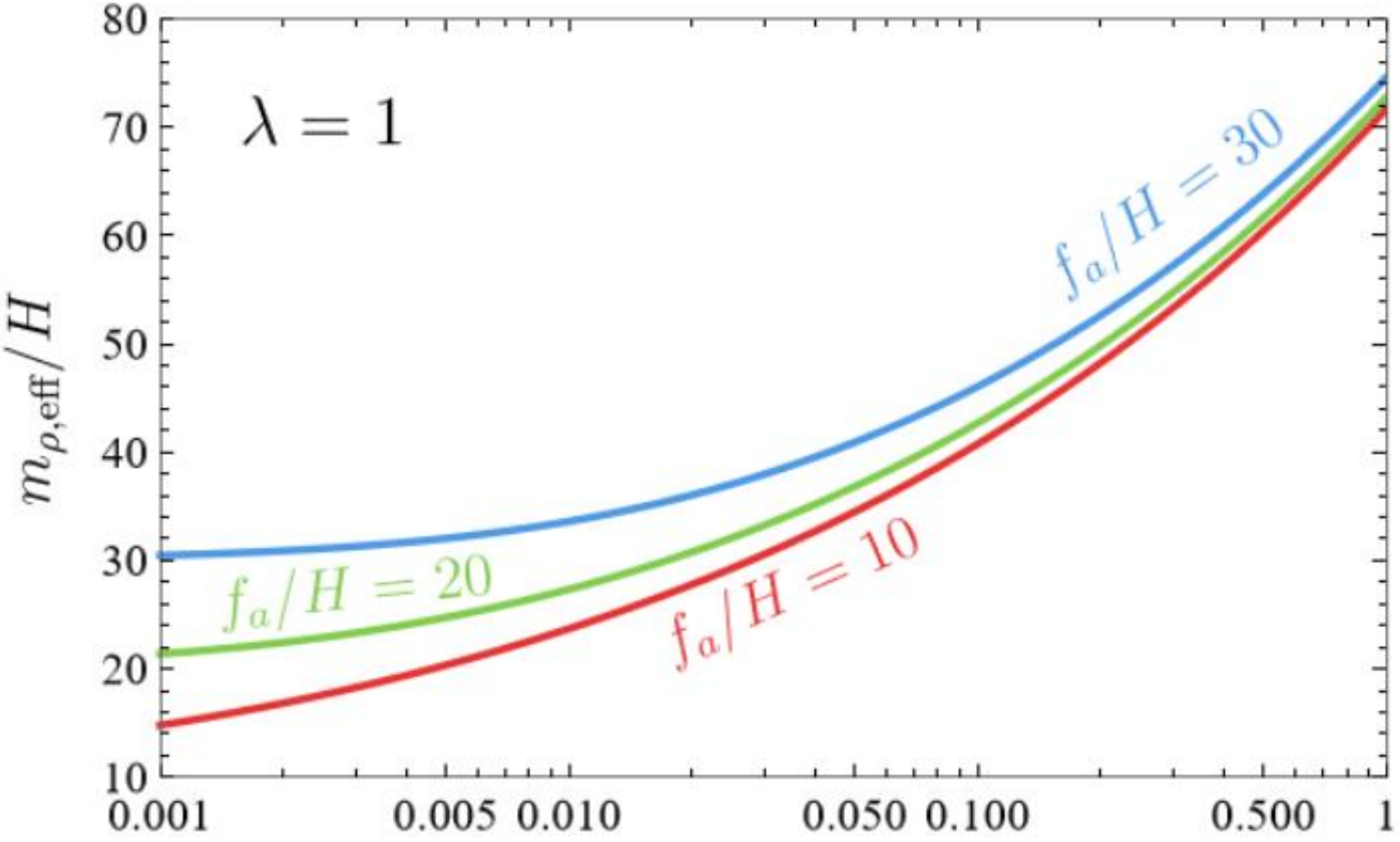
$$cf_a^2 \ll \Lambda^2$$

$$\left(\frac{\partial\phi}{\Lambda^2}\right)^n \lesssim 1 \Rightarrow \Lambda \gtrsim \dot{\phi}_0^{1/2}$$



$$\delta m_{\rm PQ}^2 \sim \frac{c}{16\pi^2}\Lambda^2 \lesssim \lambda f_a^2$$





$q \equiv cf_I^2/\Lambda^2 \ll 1$

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

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

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

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

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

Numerical Approximation

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

≥3 if QCD

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

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