Opening up window of post-inflationary QCD axion

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Oct. 26, 2022

SYSU-PKU Collider Physics Forum for Young Scientists

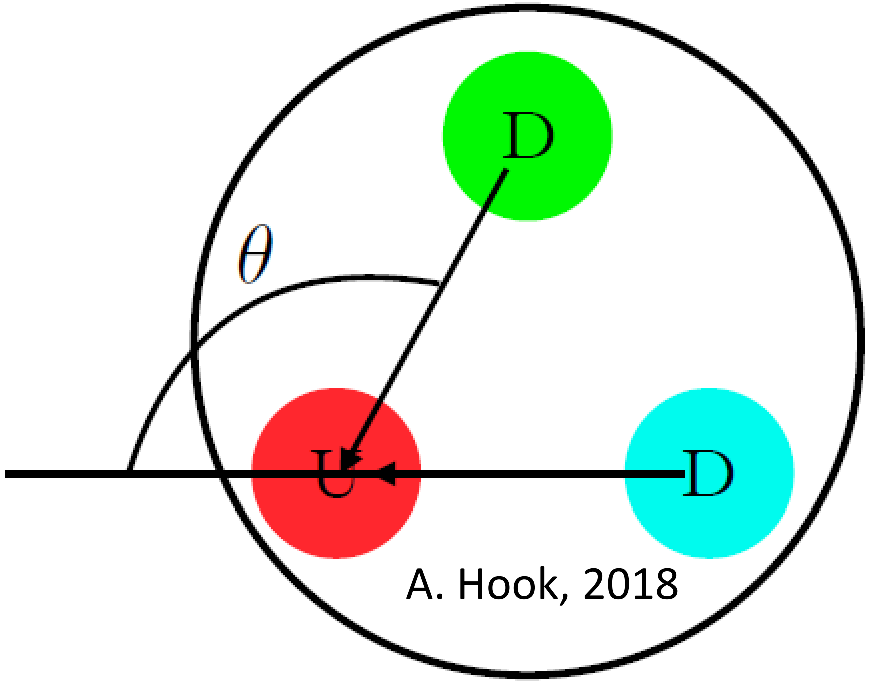
Based on 2209.09908

With Yunjia Bao and JiJi Fan

Outline

- ❑Brief overview of QCD Axion
- ❑Axion Cosmology: QCD Axion Dark Matter
- ❑New Mechanisms for Post-Inflationary Axion
- ❑Early Matter Domination to Make Things Better
- ❑Conclusion

The Strong CP Problem



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

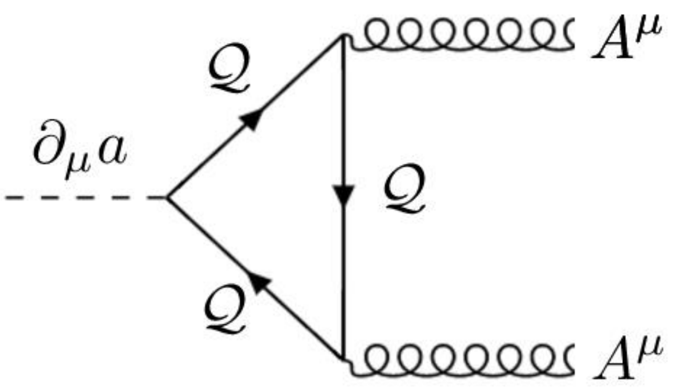
Allowed in SM Lagrangian, arises at quantum level

Experimental hints: neutron EDM
Natural expectation: O(Q × fm) ≈ 10^{-13} e cm
Experimental result $\lesssim 10^{-26}$ e cm, $\theta \lesssim 10^{-13}$

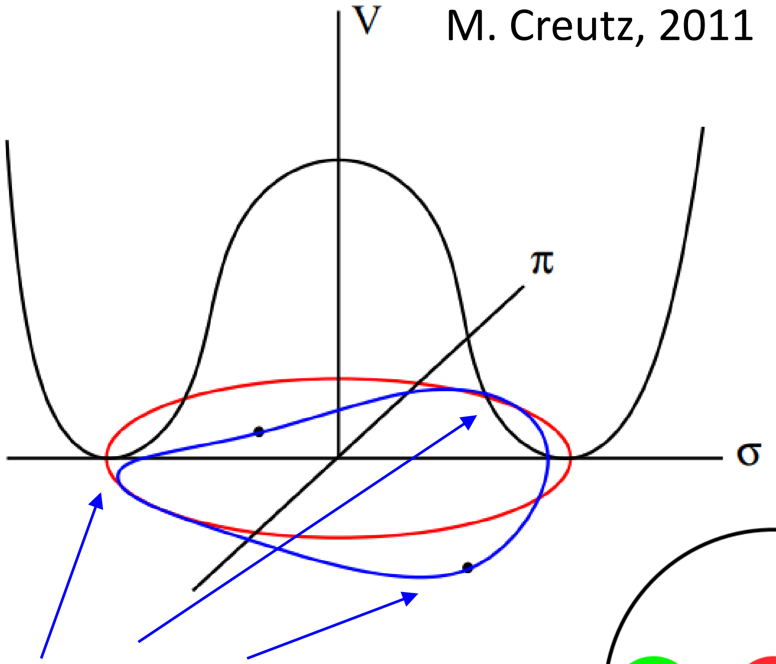
Small dimensionless parameters may not be natural: protected by a symmetry?

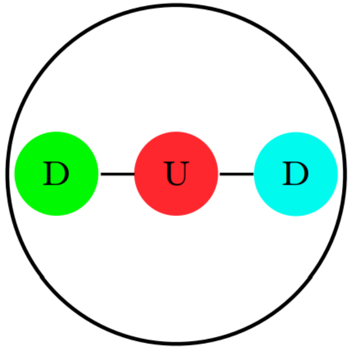
PQ Symmetry and QCD Axion

QCD axion: A pseudo Nambu-Goldstone Boson (pNGB) of a broken U(1) global symmetry (the Peccei-Quinn symmetry)



M. Creutz, 2011





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

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

As the pNGB settles at the minima, the strong CP θ angle are set to zero

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

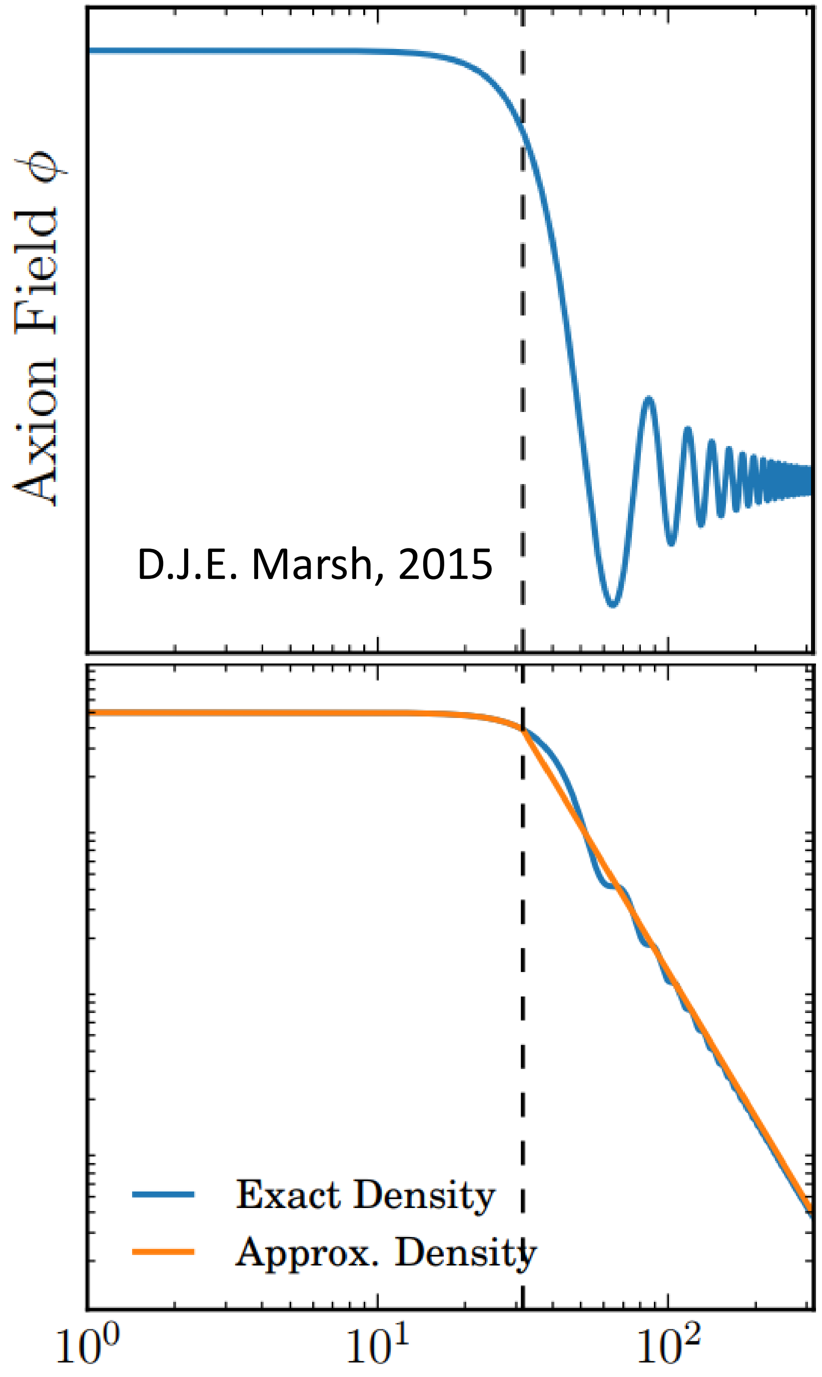
Axion CDM: Misalignment

Axion oscillates at T* when H is comparable to its own frequency (thus m_a)

Behaves as dark matter and scale as a^{-3} afterwards Preskill, Wise, Wilczek; Dine, Fischler; Abbott, Sikivie 1983

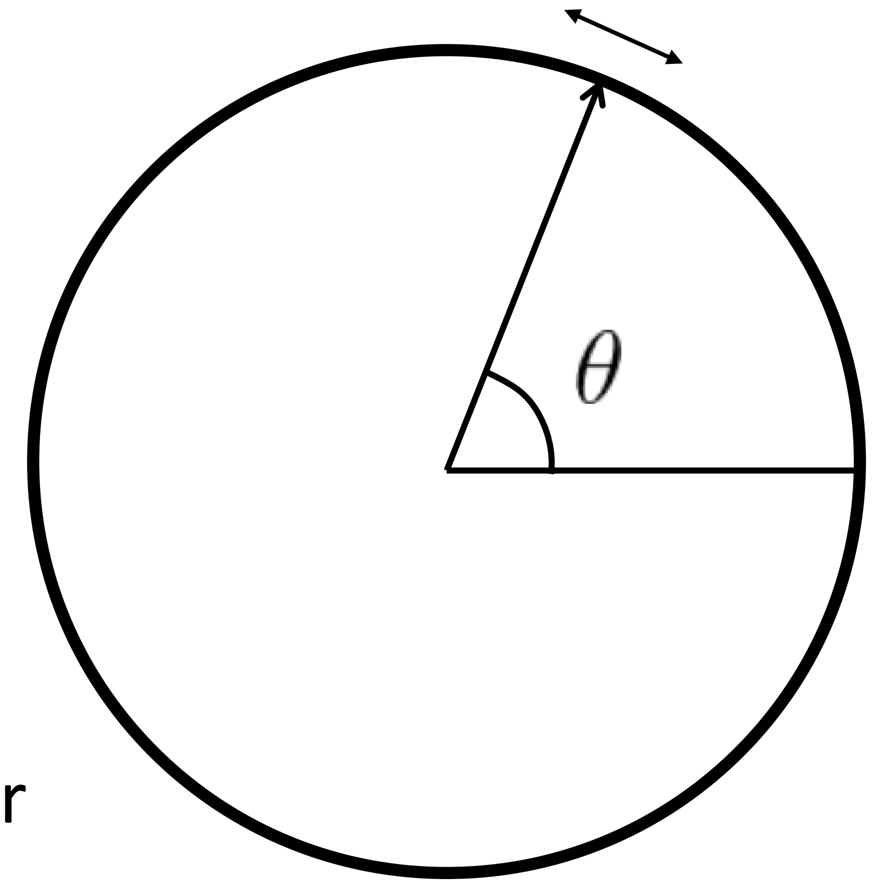
$$\rho_a(T_*) \approx \frac{1}{2} m_a(T_*)^2 a_i^2 = \frac{1}{2} m_a(T_*)^2 f_a^2 \theta_i^2$$

$$R(T)^3 n_a(T) \approx R(T)^3 \frac{\rho_a(T)}{m_a(T)} \approx \frac{R(T_*)^3}{2} m_a(T_*) f_a^2 \theta_i^2$$



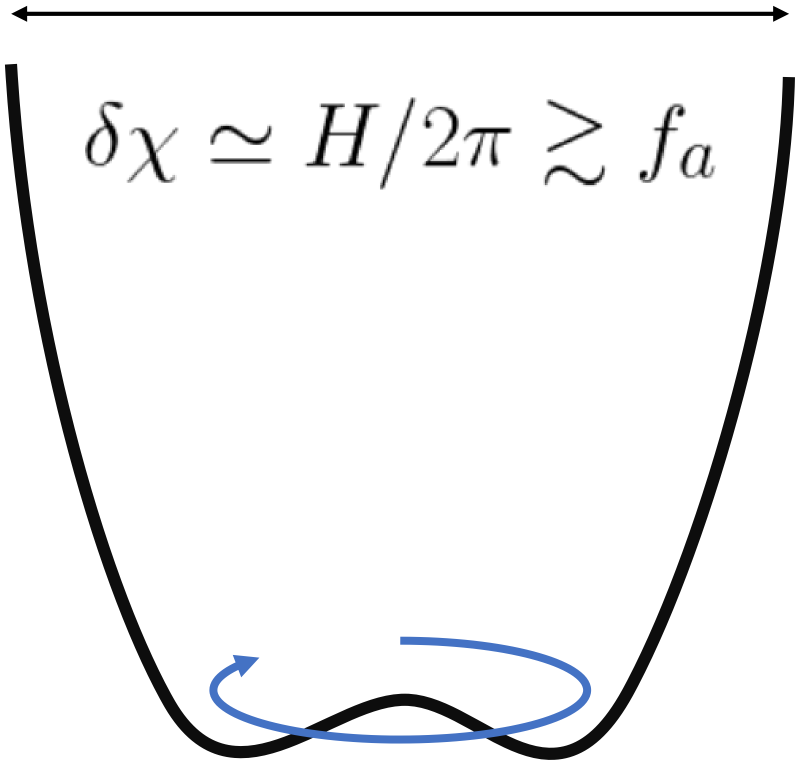
Two Scenarios (I): Pre-Inflationary axion

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



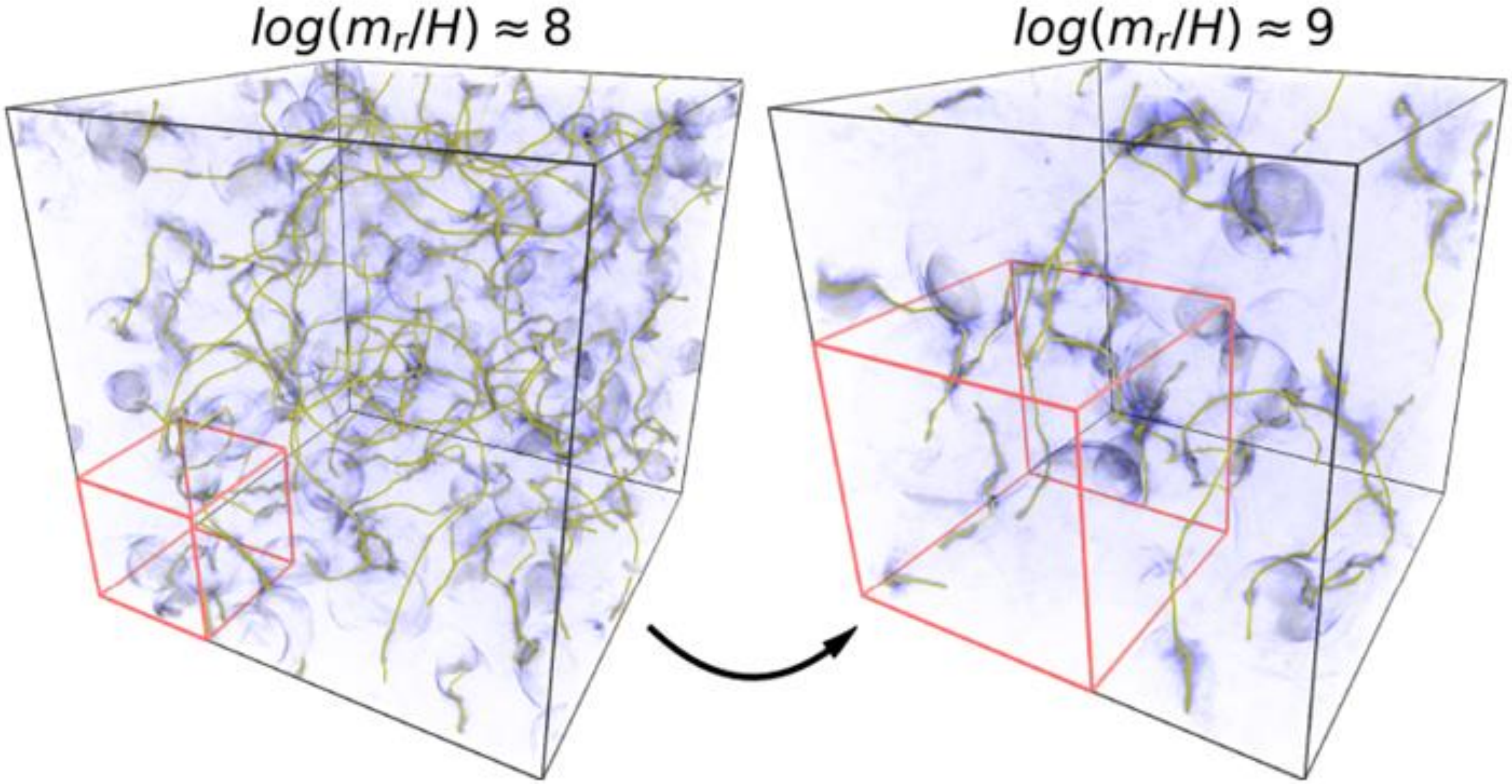
- $f_a > H_I / 2\pi$ with inflationary Hubble and PQ symmetry is not restored during (p)reheating;
- PQ is broken and QCD axion is present during inflation, same phase allover the universe
- Small perturbations of DM density: Axion isocurvature mode
- Incompatibility with the high-scale inflation: for $f_a \approx 10^{11}$ GeV, $H_I < 10^7$ GeV

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



- $f_a < H_I / (2\pi)$; symmetry unbroken during inflation.
- Symmetry breaking and axion appears after inflation ends.
- No preferred phase, no isocurvature at large scale.
- Topological defects: axion strings and domain walls (assuming no domain wall problem by setting $N_{\rm DW} = 1$). Ongoing study and simulations Davis 1986; Vilenkin and Vachaspati 1987;… Gorghetto, et.al 2020; Buschmann et.al 2021.
- Late-time universe: ultra-dense compact minihalos Hogan and Rees 1988; Kolb and Tkachev 1993, 1994.

QCD Axion DM Density



M. Buschmann et al., 2021

- No uniform phase of PQ field after inflation.
- Axion string network with tension ~ f_a^2 is formed, evaporating follow the scaling law
- The network decay dominates the DM relic density, fixing f_a as $10^{10\text{-}11}$ GeV

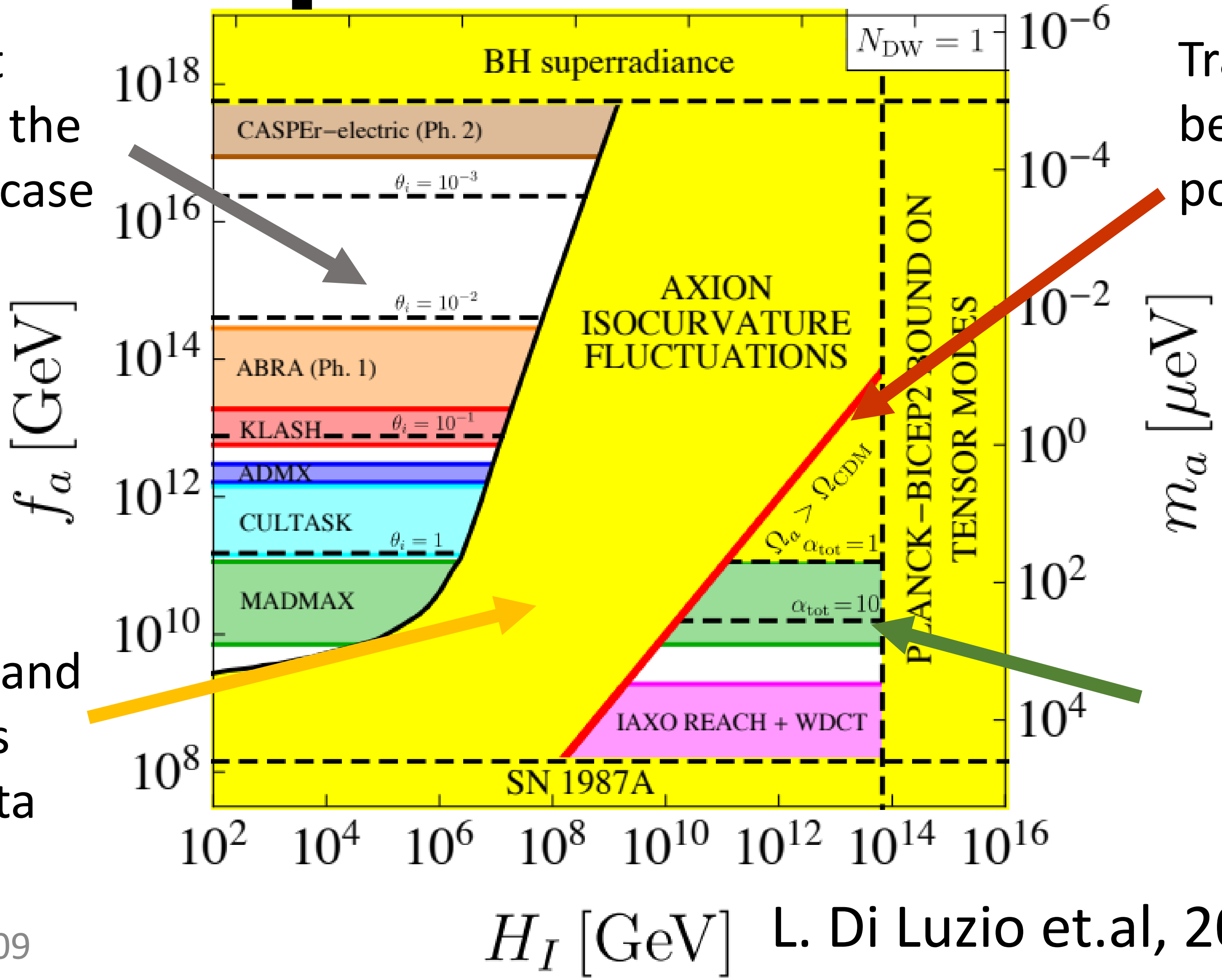
Limited Space for PIA

Inflation scale at most 10^9 GeV in the pre-inflationary case

Inhabitable badland
Nothing survives cosmological data

Traditional boundary between inflationary and post-inflationary axions

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



L. Di Luzio et.al, 2020

Heavy-Lifting Mechanism (I)

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

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

Arbitrary inflaton potential

PQ field potential

Interaction term

During inflation, the slow-rolling inflaton field yields:

$$\langle \partial_\mu \phi \rangle = \dot{\phi}_0 \delta_{\mu 0}$$

Effective mass during inflation

$$V(\phi,\chi) \supset \left(\frac{c\,\dot{\phi}_0^2}{\Lambda^2} - \frac{\lambda}{2} f_a^2\right)|\chi|^2$$

*: only inflaton shift-breaking (ϕ^2) coupling has been considered before, e.g. Shafi and 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, the size of $\dot{\phi}$ is related to primordial power spectrum by

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

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

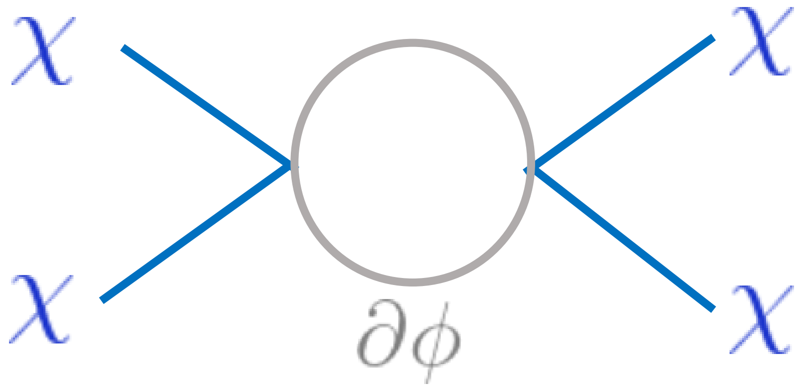
PQ symmetry is safely unbroken as the effective mass

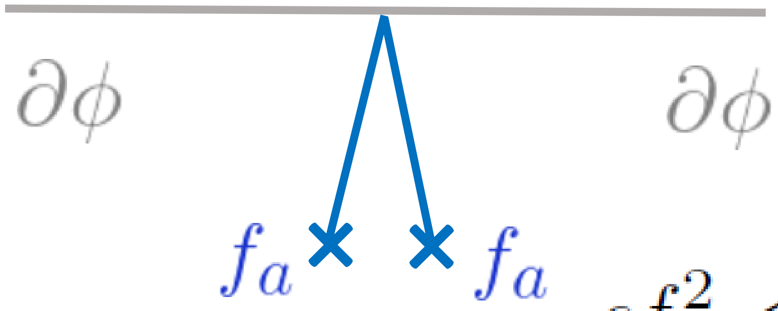
$$m^2_{\rm PQ,eff} \approx \frac{c\,\dot{\phi}_0^2}{\Lambda^2} - \frac{\lambda}{2} f_a^2 \gtrsim (1.5 H_I)^2$$

Such an operator has been used in non-axion scenarios to generate new observable signals in inflaton spectrum (Fan, Reece, Yi 2019) or bi-spectrum (Kumar, Sundrum 2017)

EFT Validity

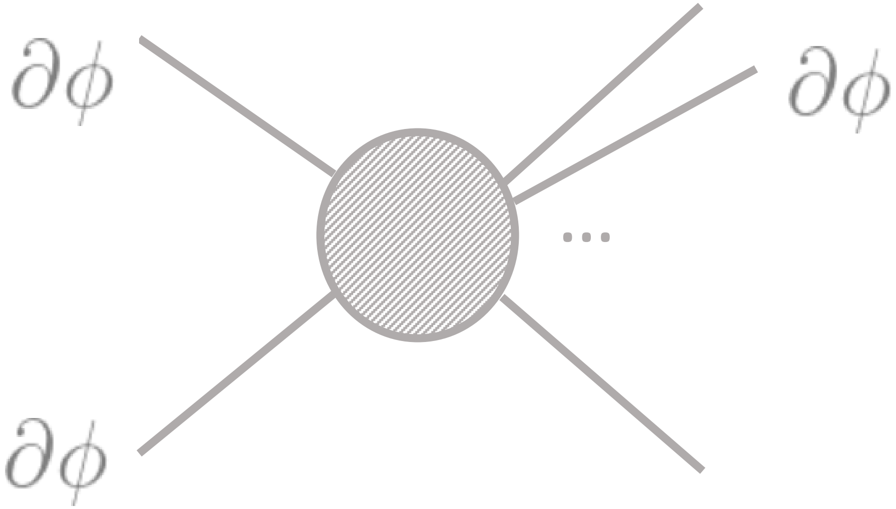
$$\delta\lambda \sim \frac{c^2}{16\pi^2} \lesssim \lambda \implies c \lesssim 4\pi\sqrt{\lambda}$$



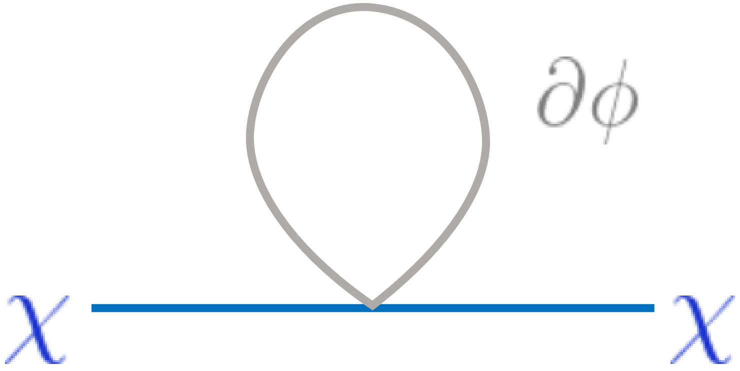


$$c f_a^2 \ll \Lambda^2$$

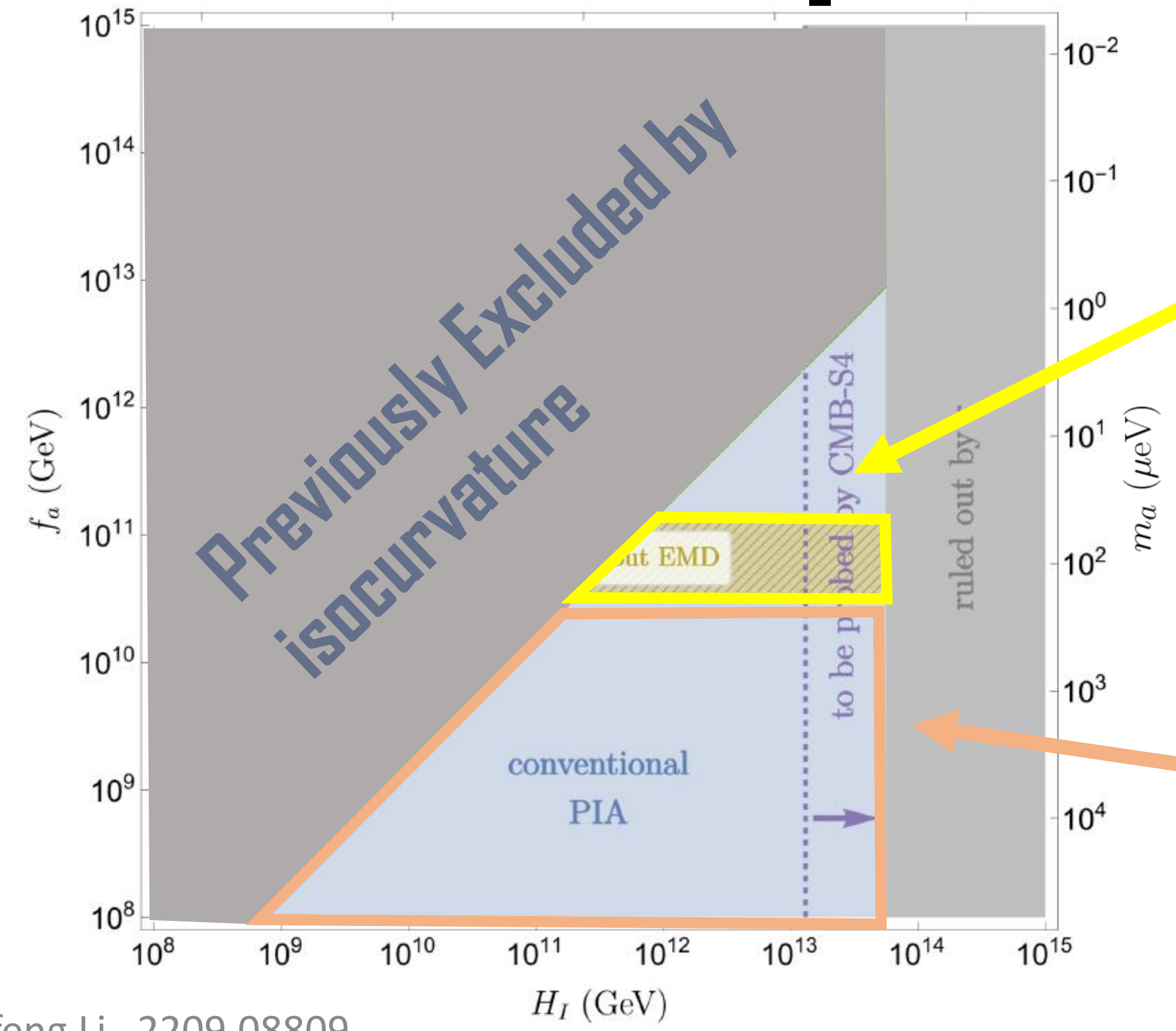
$$\left(\frac{\partial\phi}{\Lambda^2}\right)^n \lesssim 1 \Rightarrow \Lambda \gtrsim \dot{\phi}_0^{1/2}$$



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



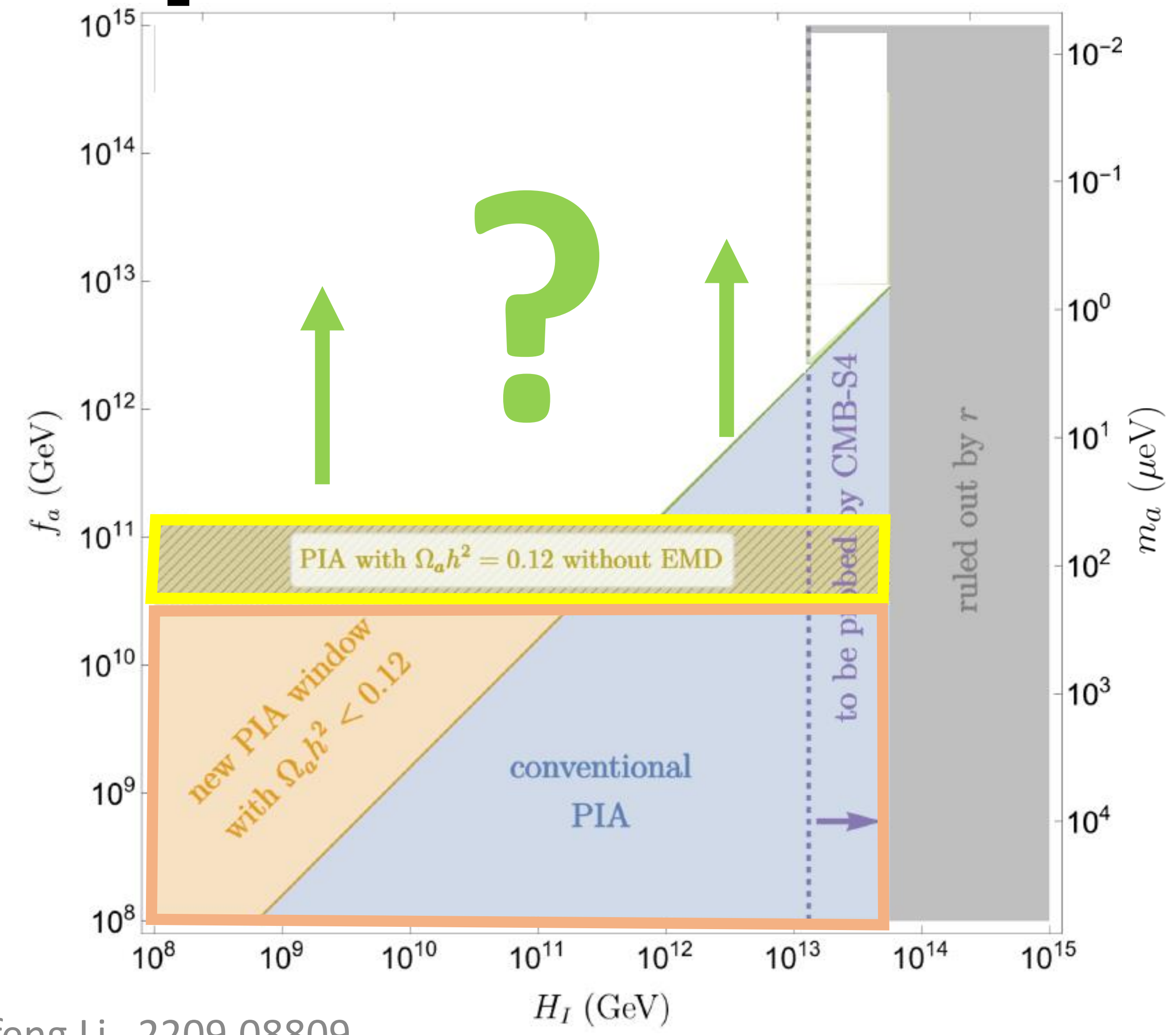
Parameter Space



Correct DM relic abundance

Also fine but need other DM

Opened Parameter Space



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

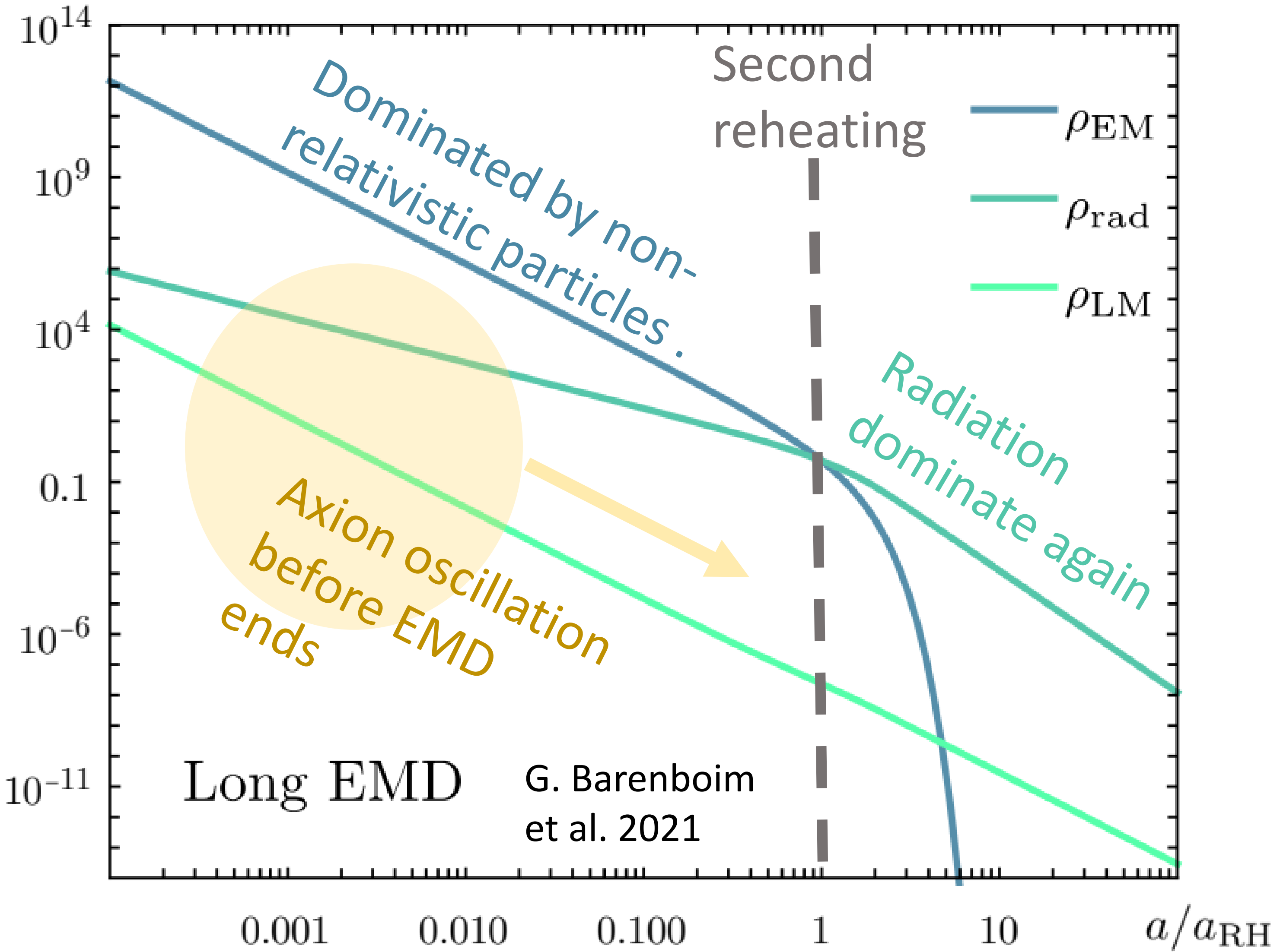
Opens up quite some parameter space, but mostly $H_I < 10^{11}$ GeV. Bounded by Ω_{DM}

Question: can we ask for even more?

More Parameter Space from Early Matter Domination (EMD)

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

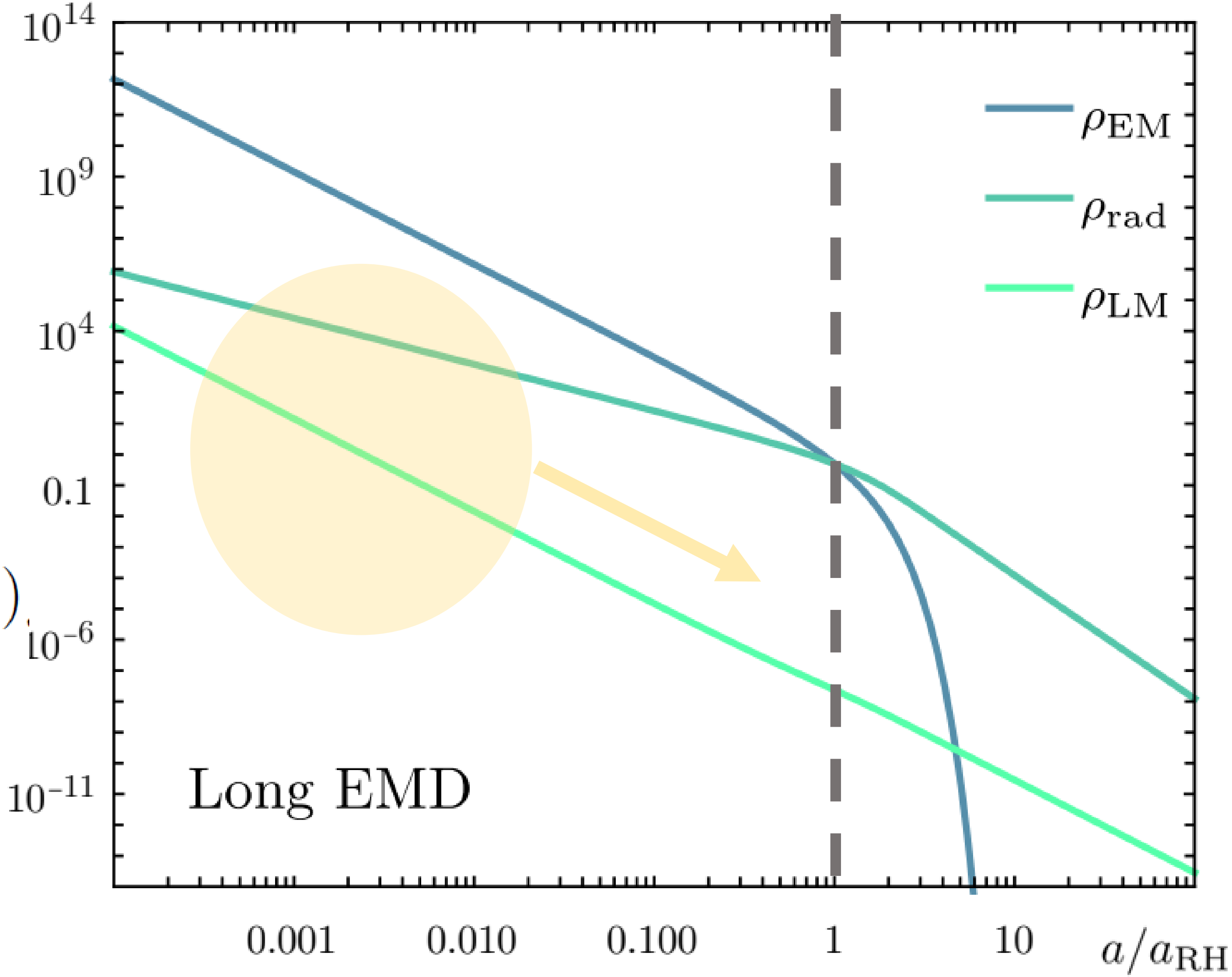
- Axion comoving abundance diluted by the entropy produced during EMD reheating
- Various candidates from heavy moduli to dark glueballs



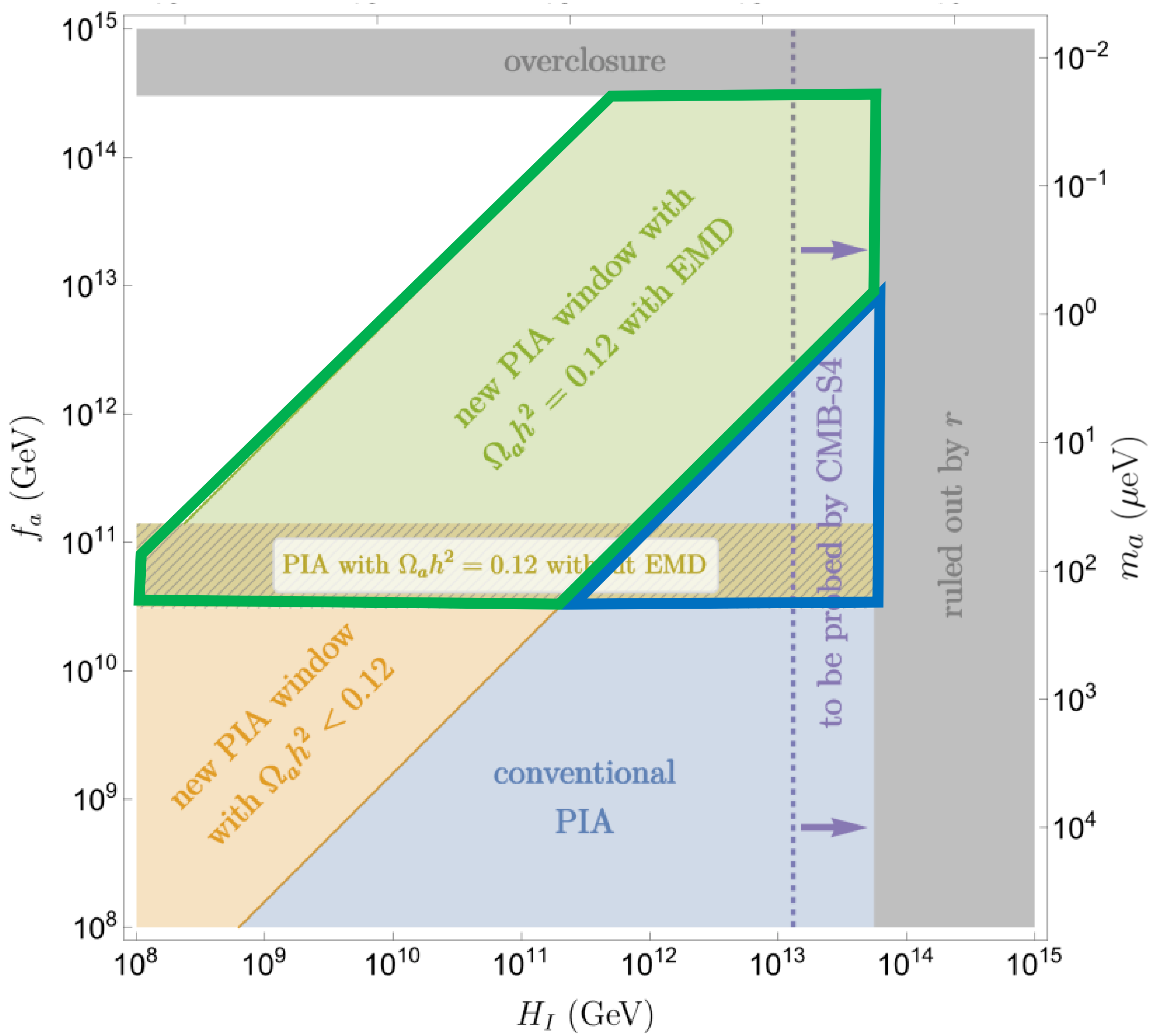
More Parameter Space from Early Matter Domination (II)

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

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



More opened space



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Extra EMD Scenario: Curvaton

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

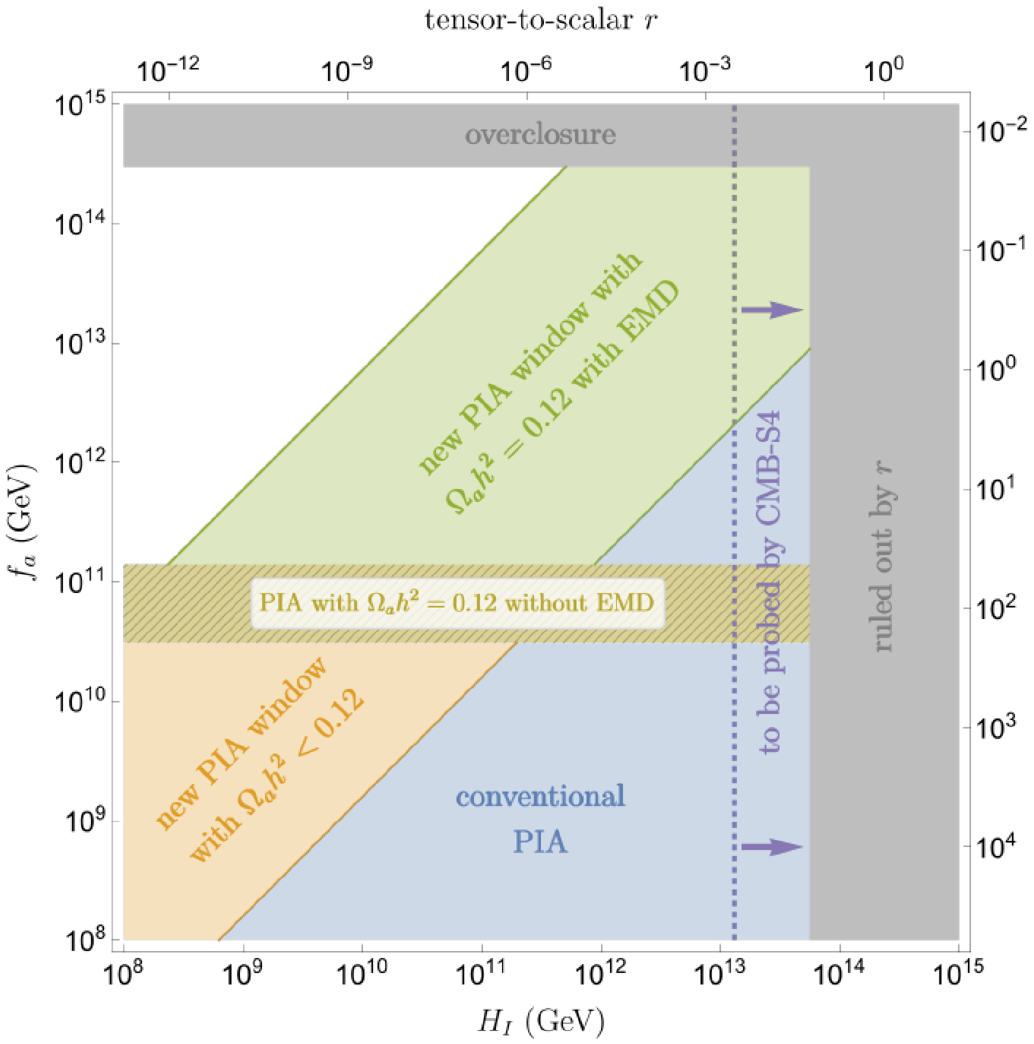
$$P_\sigma = \frac{H_I^2}{9\pi^2\langle\sigma\rangle^2} \gg P_\phi = \frac{H_I^2}{4\pi^2\dot{\phi}^2}$$

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

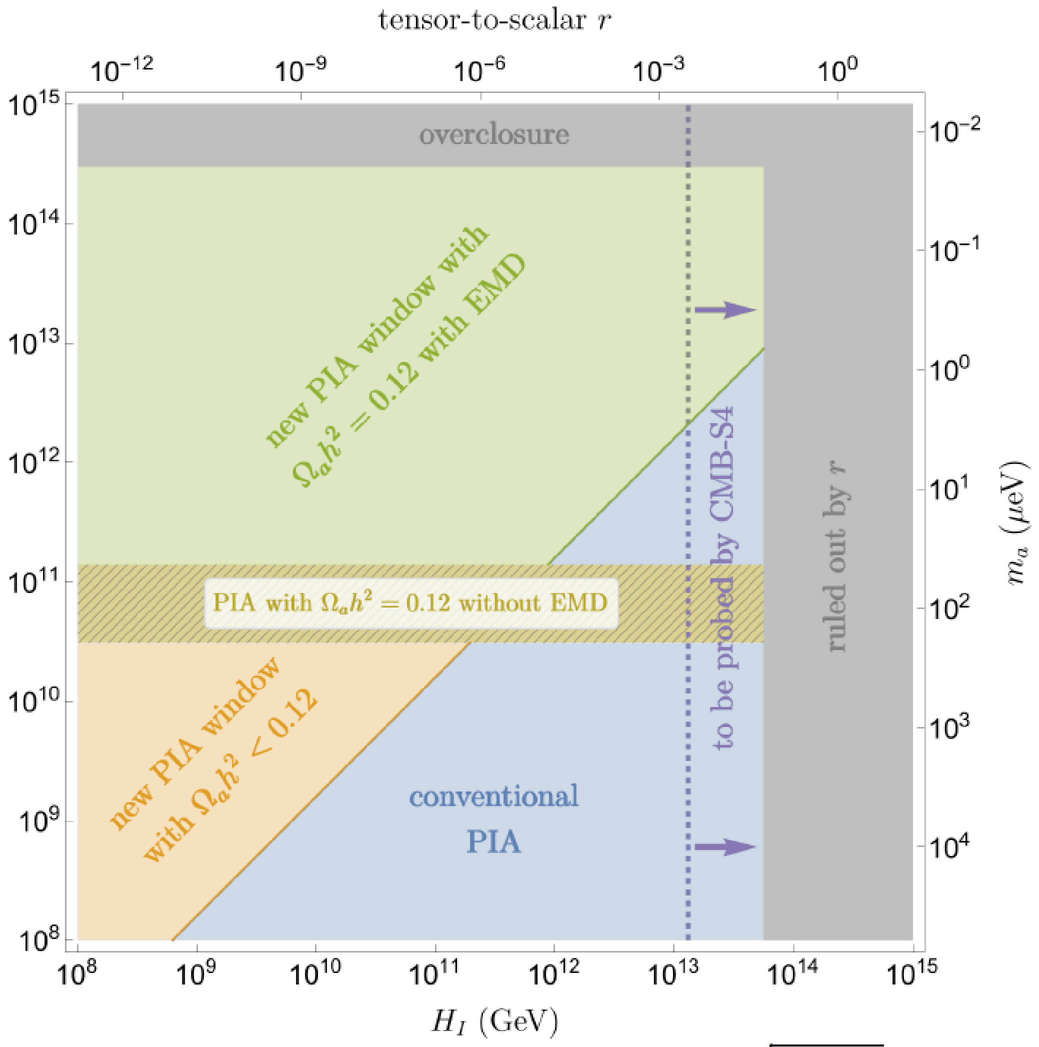
Free $\dot{\phi}$ partially from observation, fixed by $\epsilon \approx \dot{\phi}_0^2/(2H_I^2 M_{\rm Pl}^2)$ instead, could be much larger than $(60\ H_I)^2$

*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.

Results and Constraints



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



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

Outlook: Possible Signatures

- ❑Interaction between inflaton and the PQ field (without modifying the inflation dynamics) could lead to *big changes in axion cosmologies*.

- ❑In particular, a *new window of post-inflationary axion* could be opened up; parameter space suffering from axion isocurvature problem shrinks correspondingly.