# New Inflationary Probes of Axion Dark Matter 

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## Outline

- Brief overview of basic axion physics
- New ideas on the interplay between inflation and axion dark matter
* Opening up a new window of post-inflationary QCD axion
* New cosmic observables of pre-inflationary axion
- Conclusion


## What is an axion?

a periodic compact pseudo-scalar field: realized as a Goldstone boson of a spontaneously breaking $U(1)$ symmetry, the Peccei-Quinn (PQ) symmetry.


$$
V_{\chi}=\frac{\lambda}{2}\left(|\chi|^{2}-\frac{f_{a}^{2}}{2}\right)^{2} \quad \chi: \text { Peccei-Quinn }(\mathrm{PQ}) \text { scalar field }
$$

$$
\begin{gathered}
\chi=\frac{\left(f_{a}+\rho\right)}{\sqrt{2}} e^{i a l f_{a}}=\frac{\left(f_{a}+\rho\right)}{\sqrt{2}} e^{i \theta} \\
m_{\rho}=\sqrt{\lambda} f_{a}, \quad m_{a}=0
\end{gathered}
$$

## Strong CP problem: QCD axion



Neutron electric dipole moment (EDM): $\vec{d}=\sum q \vec{r} \Rightarrow\left|d_{n}\right| \approx 10^{-13} \sqrt{1-\cos \theta} \mathrm{ecm}$

Experimental result: $\left|d_{n}\right| \lesssim 10^{-26} \mathrm{ecm} \Rightarrow \theta \lesssim 10^{-13}$

## Strong CP problem: QCD axion




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

## Other Applications

## Natural inflation



Terrestrial Experiments:
light axion: ADMX, CAST-CAPP, DM radio, Casper,
heavy axion: LHC and future colliders....
Theory and
Model
Building: go

## Axion (QCD axion and ALP)

beyond vanilla
scenarios


Astrophysical/Cosmic Signals and Probes: CMB, gravitational waves, stars, galaxies....

Terrestrial Experiments: light axion: ADMX, CAST-CAPP, DM radio, Casper, ABRACADABRA... heavy axion: LHC and future colliders....

Theory and Model Building: go

## Axion (QCD axion and ALP)

# Astrophysical/Cosmic Signals: 

 and Probes: CMB, gravitational waves, stars, galaxies....Inflation and axion: new models and cosmic signals

## Two types of axion cosmologies

Review: Marsh, 2015

- (Pre-)inflationary axion

稳 $f_{a}>H_{I} /(2 \pi)$ with $H_{I}$ inflationary Hubble scale, PQ symmetry is broken during inflation. In addition, PQ symmetry is not restored during (p)reheating;

糕 Massless axion is present during inflation;

## Two types of axion cosmologies

## －（Pre－）inflationary axion

$$
\delta \theta=H_{I} /\left(2 \pi f_{a}\right) \ll 1
$$

閻 A single uniform central value of initial misalignment angle $\theta_{i}$ ；

缕 Axion fluctuates and has an isocurvature perturbation $\left\langle\delta \theta_{i}^{2}\right\rangle=\left(H_{I} /\left(2 \pi f_{a}\right)\right)^{2} ;$

綦 Axion becomes dark matter after inflation；
業 Incompatibility between QCD axion DM with the high－scale inflation：
$H_{I}<0.9 \times 10^{7} \mathrm{GeV}\left(\frac{f_{a}}{10^{11} \mathrm{GeV}}\right)^{0.408}$

## Curvature

vS.

## Isocurvature



Dark Matter
Photon
Neutrino
Baryons


## Axion dark matter

Misalignment mechanism: Preskill, Wise, Wilczek; Dine, Fischler; Abbott, Sikivie 1983


䊣 $f_{a}<H_{I} /(2 \pi)$ ，no symmetry breaking during inflation or PQ symmetry is restored during（p）reheating；

恶 No axion isocurvature problem；
糕 uniform distribution of $\theta_{i}$ with $\left\langle\theta_{i}^{2}\right\rangle=\pi^{2} / 3$ ；
粎 topological defects：axion strings and domain walls．Decays of topological defects also contribute to the abundance of axion dark matter，in addition to misalignment mechanism．Ongoing study and simulations Davis 1986； Vilenkin and Vachaspati 1987；．．．Gorghetto，et．al 2020；Hindmarsh et．al 2021；Buschmann et．al 2O2I．

Tensor-to-scalar ratio $r$


Review by Di Luzio et.al, 2003.01100

# QI: could we increase the parameter space for post-inflationary axion? 

## Opening up window of post-inflationary QCD axion



Yunjia Bao (former master student at Brown, PhD student at Chicago)


Lingfeng Li (postdoc at Brown)

Phys. Rev. Lett. 130 (2023) 24, arXiv: 2209.09908 [hep-ph]

## A new angle from interaction with inflaton

$$
\begin{gathered}
\text { inflaton } \mathscr{L}=\left(\partial_{\mu} \phi\right)^{2} / 2+\left|\partial_{\mu} \chi\right|^{2}-V(\phi, \chi) \\
V(\phi, \chi)=V(\phi)+\frac{\lambda}{2}\left(|\chi|^{2}-\frac{f_{a}^{2}}{2}\right)^{2}+\left(\frac{c(\partial \phi)^{2}}{\Lambda^{2}}|\chi|^{2}\right) \\
\text { respect the (approximate) shift } \\
\text { symmetry of inflaton }
\end{gathered}
$$

Note: only $\phi^{2}|\chi|^{2}$ coupling has been considered before and it is subject to constraints from large quantum corrections, Shafi and Vilenkin 1984...

During inflation, $\left\langle\partial_{\mu} \phi\right\rangle=\dot{\phi}_{0} \delta_{\mu 0}$,

$$
\begin{gathered}
V(\phi, \chi) \supset\left(\frac{\left.\left(\frac{c \dot{\phi}_{0}{ }^{2}}{\Lambda^{2}}\right)-\frac{\lambda}{2} f_{a}^{2}\right)|\chi|^{2}}{\frac{c(\partial \phi)^{2}}{\Lambda^{2}}|\chi|^{2}}\right.
\end{gathered}
$$

$\dot{\phi}_{0}$ could be $\gg H_{I}^{2} \Rightarrow \mathrm{PQ}$ symmetry might remain unbroken during inflation even when $f_{a}>H_{I}$.

Such type of derivative operators has been used in non-axion scenarios (e.g. $(\partial \phi)^{2} h^{\dagger} h$ ) to generate new observable signals in inflaton spectrum Fan, Reece, Yi 2019, or bi-spectrum Kumar, Sundrum 2017


## New window for post-inflationary axion (PIA)

single field inflation


New window for post-inflationary axion


## New window for post-inflationary axion (PIA)

Early matter domination (EMD) to dilute the axion abundance: universe's energy density dominated by some nonrelativistic particles (e.g., moduli or dark glueballs) after inflationary reheating. Lazarides, et.al 1990; Kawaski et.al I995...


## New window for post-inflationary axion (PIA)

Early matter domination (EMD) to dilute the axion abundance: reheating at the end of EMD and before BBN produces a lot of entropy to dilute $\Omega_{a} h^{2}$ $f_{a} \lesssim 3 \times 10^{14} \mathrm{GeV}$


## Recap

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 $2 C D$ axion could be opened up; parameter space suffering from the QCD axion isocurvature problem shrinks correspondingly.

# Q2: what if the similar mechanism applies to the pre-inflationary axion scenario? 

## New inflationary probes of axion dark matter



Lingfeng Li (postdoc at Brown)

$$
\text { arXiv: } 2303.03406 \text { [hep-ph] }
$$

## Cosmological Collider in a nutshell



O Prepared initial state: fixed $E_{\mathrm{cm}}$, luminosity, beam directions;

O Short-lived heavy resonances: away from the detector;

O Decay to light stuff: $\gamma, e^{ \pm}, \cdots$
O Flat space-time: invariant
$\operatorname{mass}\left(\sum p_{i \text {,decay }}\right)^{2}$

cold dark matter
curvature
(CDM) isocurvature graviton


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

O Chaotic initial state: heavy field created in quantum fluctuations;

O Interfere with background fluctuations, amplitude instead of its square;

O Time invariance breaks down in the inflationary background: no invariant masses;


Bunch-Davis vacuum
of something massless
$k_{\text {decay }} \tau_{\text {decay }} \sim m / H$
Mass observed through phase:

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

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

$$
e^{i m \Delta t} \sim\left(\frac{k_{\mathrm{decay}}}{k_{\mathrm{prod}}}\right)^{i m / H}
$$

Gibbons-Hawking temperature:

$$
\begin{aligned}
& T \sim \frac{H}{2 \pi} \Rightarrow \\
& \mathscr{A} \propto \sqrt{e^{-m / T}} \propto e^{-\pi m / H}
\end{aligned}
$$

"Thermal" suppressed production

To overcome the Boltzmann suppression:
糕 Classical feature Chen, 2oir; ...Chen, Ebadi, Kumar, 2022;
橉 Chemical potential Chen, Wang, and Xianyu 2or8; ...

## Scenario I: classical features

pre-inflationary axion, PQ symmetry breaking
$\mathscr{L} \supset-\left.\frac{c}{\Lambda}(\partial \phi)^{2}|\chi|\right|^{2}+$ a toy feature: a step in inflaton potential Inflation $\phi$

$$
V_{\phi 1}(\phi)=-b V_{\phi 0} \theta\left(\phi-\phi_{s}\right)
$$

Excite the radial mode of the PQ field, $\rho$

$$
\chi=\frac{f_{l}+\rho}{\sqrt{2}} e^{i a l f_{l}}=\frac{f_{l}+\rho}{\sqrt{2}} e^{i \theta}, \quad m_{\rho}=\sqrt{\lambda} f_{a}, \quad m_{a}=0
$$



## Inflaton $\phi$






Resonance between $\rho$ oscillation and $\phi / a$ quantum fluctuation results in scale-dependent oscillations (clock signal) in two-point correlation functions: curvature and isocurvature spectra;

Stronger clock signal in isocurvature spectrum!

## Clock signals in spectra

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


same phase, different amplitudes

https://cajohare.github.io/AxionLimits

Narrow down the inflation scale
$f_{a}$ inferred from axion measurement;

- axion isocurvature amplitude $\theta_{i}^{2} H^{2} f^{1 / 3}$;
- clock frequency $\sqrt{\lambda} f / H$
$\theta_{i}, \lambda$ order one parameters


## Hybrid Cosmological Collider signals



Earlier work: Lu, 202I; Li, Lu, Wang, Zhou 2O2I



Non-Gaussianity in the equilateral limit

Sizable hybrid bi-spectrum signal


## Scenario 2: chemical potential

pre-inflationary axion, PQ symmetry breaking

$$
\mathscr{L}_{\text {chem }} \supset-\underset{\Lambda_{\text {Inflaton } \phi}^{i \partial_{\mu} \phi}}{\Lambda_{\text {PQ field }}}\left(\chi^{\dagger} \partial^{\mu}(\chi)-\chi \partial^{\mu} \chi^{\dagger}\right)
$$

kinetic mixing between the massless axion and the massive inflaton;
$\left(\chi=\frac{f_{l}+\rho}{\sqrt{2}} e^{i a f_{l}}=\frac{f_{l}+\rho}{\sqrt{2}} e^{i \theta}\right)$
Diagonalize the kinetic terms by
$\tilde{\rho}=\rho, \tilde{a}=a-z \phi, \quad z \equiv \frac{\kappa f_{I}}{\Lambda}$
$\tilde{a}$ does not roll during inflation ( $\dot{\tilde{a}}=0$ ) and will turn into CDM with isocurvature after inflation;

## Axion-fermion coupling

Natural in KSVZ-type axion models (Kim, 1979; Shifman, Vainshtein and Zakharov 1980): PQ field couples to heavy fermions

$$
\frac{\partial_{\mu} a}{2 f_{I}} \bar{\psi} \gamma^{\mu} \gamma^{5} \psi \xrightarrow{\tilde{a}=a-z \phi} \frac{\partial_{\mu}(z \phi+\tilde{a})}{2 f_{I}} \bar{\psi} \gamma^{\mu} \gamma^{5} \psi
$$

Chemical potential: $\mu_{c}=\frac{z \dot{\phi}}{2 f_{I}}$
fermion dispersion: $\omega^{2}=k^{2}+\left(m_{\psi}^{2} \pm 2 \mu_{c} k+\cdots\right)$
enhancement in particle production


Chen, Wang and Xianyu 2oı8; Hook, Huang, Racco 2019; Wang, Xianyu 2019, 2O20; Bodas, Kumar, and Sundrum 2020; Sou, Tong and Wang
$e^{-2 \pi\left(\sqrt{m_{\psi}^{2}+\mu_{c}^{2}} / H-\mu_{c} / H\right)} \approx e^{-\pi m_{\psi}^{2} /\left(\mu_{c} H\right)}$ 2O2I


## Conclusions and Outlook

Interactions between inflaton and the axion sector lead to new pheno:

- change the standard boundary of axion cosmologies drastically;
- a whole new suite of cosmological observables: isocurvature clock signals, hybrid cosmological collider signals.

More studies are needed...
Axion and inflation are both old businesses, but there is a lot of new fun to be explored!

## Thank you!

Backup


## Observational hints for features



Braglia, Chen and Hazra 202I; Antony, Finelli, Hazra and Shafieloo 2022; Braglia, Chen, Hazra and Pinol 2022

