New Probes of Axions in the Sky

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Axions in Stockholm 2025, Nordita

Outline

— Pulsation in flux and polarization to probe axions from neutron stars

— New cosmic observables of pre-inflationary QCD axion dark matter

— Conclusion

Pulsation to probe axions from neutron stars (NSs)

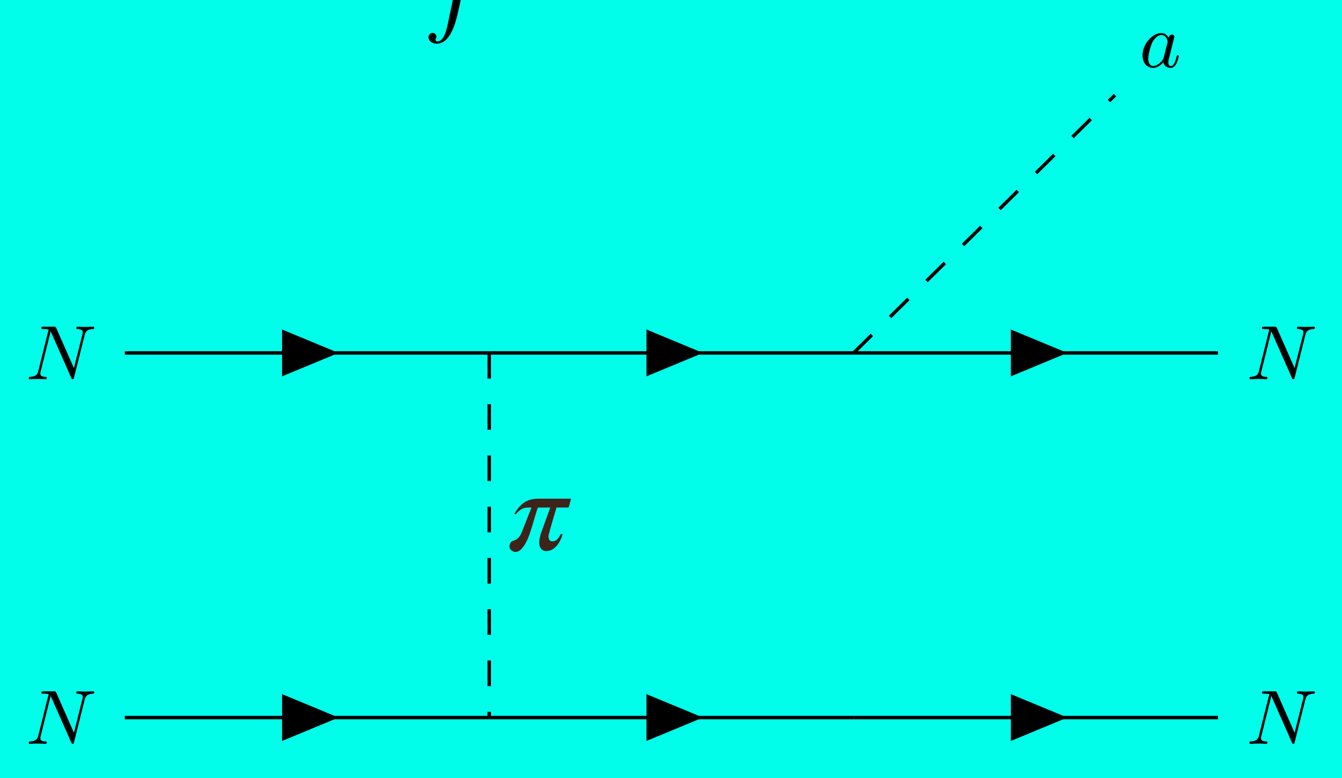
Axions here are general axion-like particles (ALPs); and may or may not be dark matter.

J. Fan, Lingfeng Li (to-be faculty at ICTP-AP), Chen Sun (postdoc at ICTP, to-be faculty at ICTP-AP), arXiv: 2501.12440 [hep-ph]

Production of axions in a neutron star

Nucleon bremsstrahlung

$$\frac{g_{af}}{2m_f}\partial_\mu a \bar{f}\gamma^\mu\gamma^5 f$$

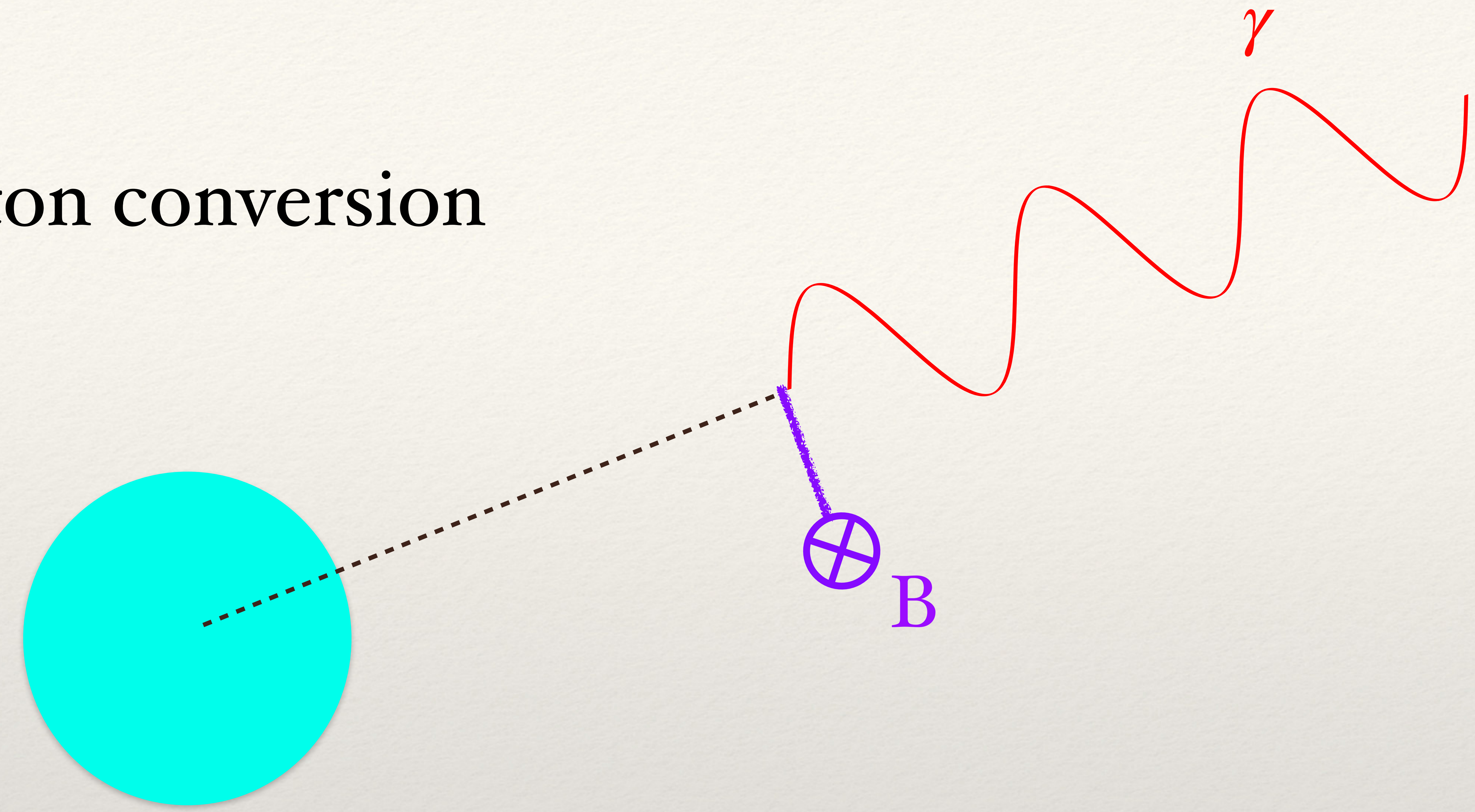


$T \sim \mathrm{keV}$

$$g_{af} = c_{af}\frac{m_f}{f_a}$$

Brinkmann, Turner 1988; Weber, 1999; ... Iwamoto 2001; ....

Axion-photon conversion



$E_\gamma \sim \mathrm{keV}$ X – ray

$\mathbf{E} \parallel \mathbf{B}$ O – mode

(energy independent)

$$-\frac{g_{a\gamma}}{4}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} \sim g_{a\gamma}\, a\, \mathbf{E}\cdot\mathbf{B} \qquad g_{a\gamma} = \frac{c_{a\gamma}}{f_a}$$

Axion-photon conversion: consider only the magnetic dipole

(Raffelt and Stodolsky, 1988)

photon energy

NS radius

$$\frac{r_{\rm con}}{r_0} = 85\left(\frac{\omega}{3\,\rm keV}\right)^{\frac{1}{5}}\left(\frac{B_0}{10^{13}\,\rm G}\right)^{\frac{2}{5}}\left(\frac{r_0}{12\,\rm km}\right)^{\frac{1}{5}}(\sin\theta)^{\frac{1}{5}}$$

conversion radius $r_{\rm con}$ (in unit of NS radius r_0)

B field at surface

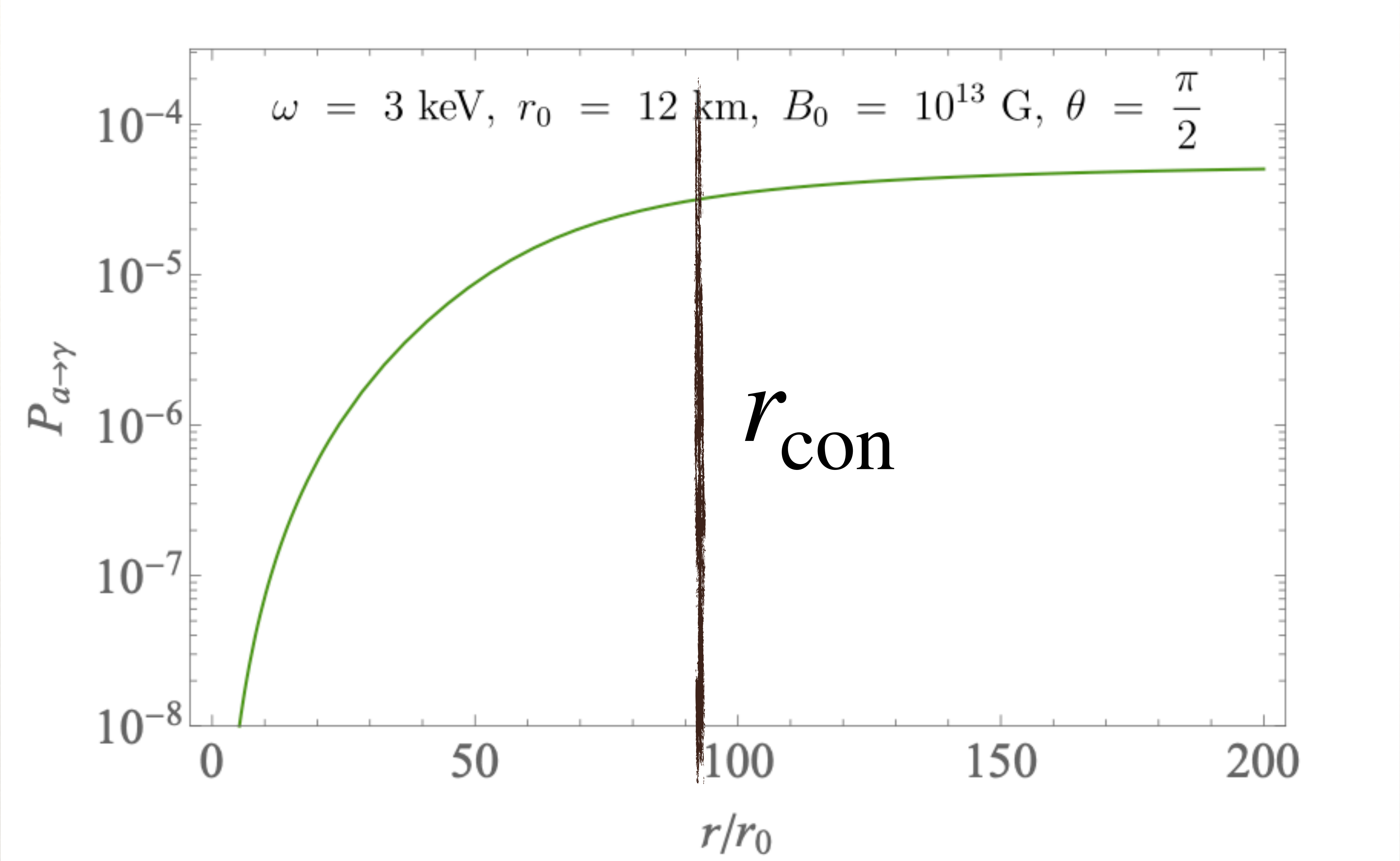
angle between photon propagation and local B field.
$\theta \ll 1$: magnetic polar region, conversion suppressed;

Conversions happen far away from NS !

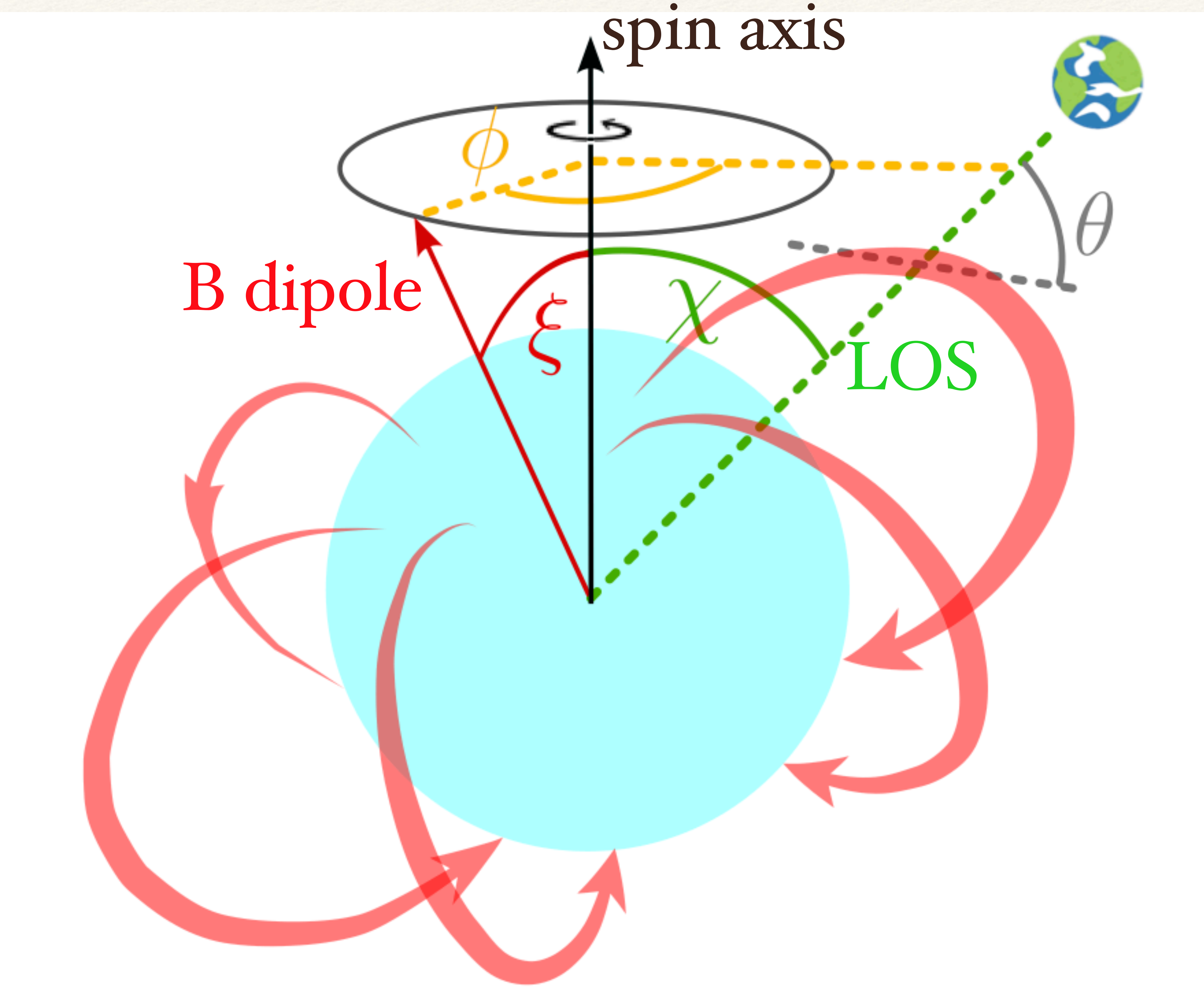
Not subject to complications near NS: NS atmosphere (cm thick), strong GR correction (Schwarzschild radius ~ km), high multipoles of B field.

Astrophysical sources of hard X-rays could be subject to all of these, leading to energy-dependent mixtures of O- and X- modes!

A large literature on using X-rays from neutron stars to probe/constrain axions. Morris 1986; Raffelt, Stodolsky 1988; … Fortin and Sinha 2018; Buschmann et.al 2019.



Pulsation in flux



Intensity of the B field along the line of sight (LOS) is ***phase-dependent.***
Converted photon flux from axions, *I*, is also ***phase-dependent.***

$$I = I_{\max} \times \left(1 - \cos^2\chi\cos^2\xi - \sin^2\chi\sin^2\xi\cos^2\phi + \frac{1}{2}\sin 2\chi\sin 2\xi\cos\phi\right)^{\frac{1}{5}}, \quad \text{(III.1)}$$

ϕ: rotational angle (phase)

Pulse fraction (PF):

$$\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

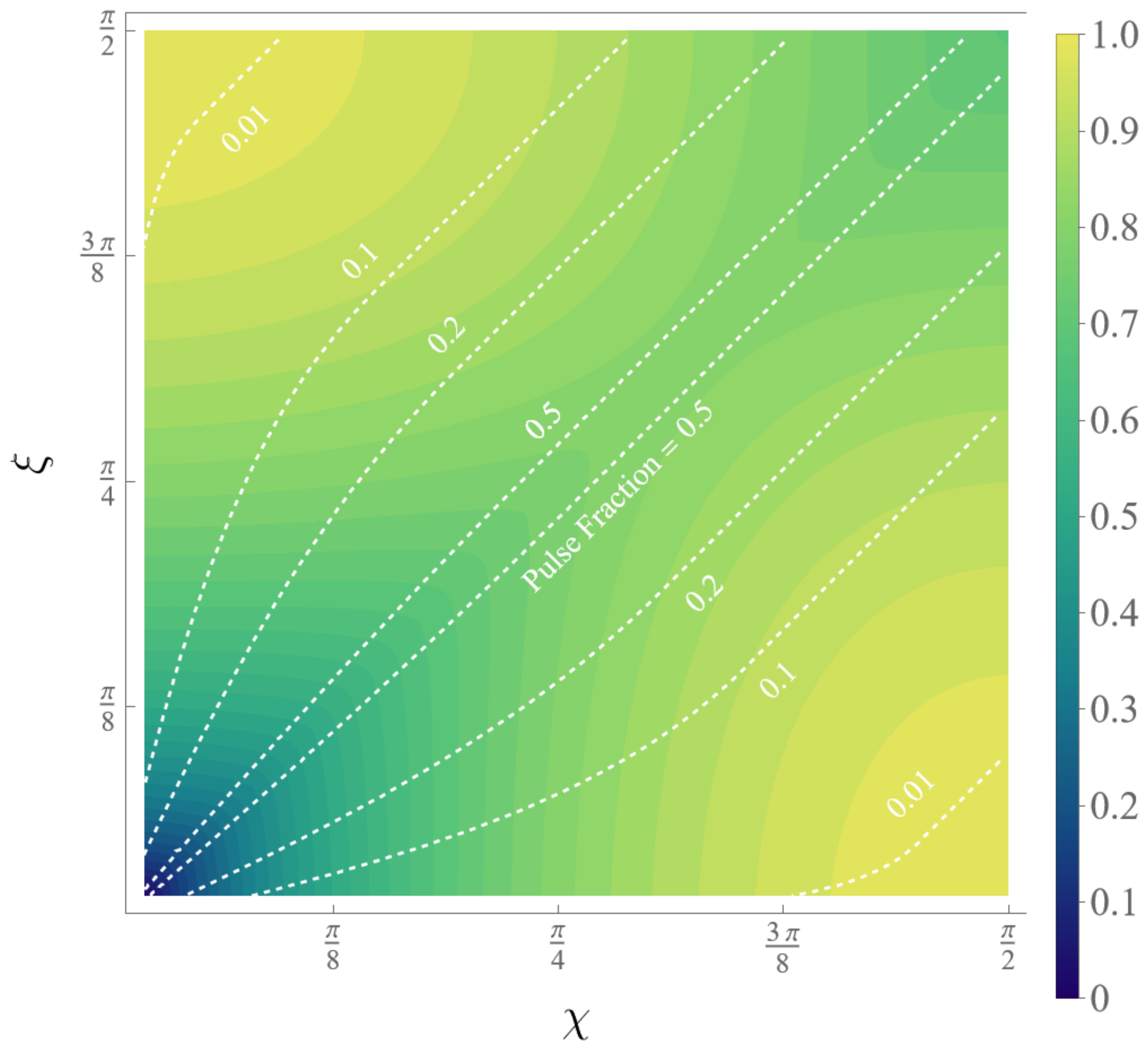
$$\mathrm{PF} = \begin{cases} \frac{\sin^{2/5}(\xi+\chi) - \sin^{2/5}(|\xi-\chi|)}{\sin^{2/5}(\xi+\chi) + \sin^{2/5}(|\xi-\chi|)}, & \chi + \xi \leq \pi/2\,, \\ \frac{1-\sin^{2/5}(\xi-\chi)}{1+\sin^{2/5}(\xi-\chi)}, & \chi + \xi > \pi/2\,. \end{cases}$$

Pulse fraction of axion-induced X-ray is ***energy independent !***

(Mild) attenuation of the flux.

Degenerate in χ and ξ.

phase-averaged attenuation factor of the flux



Pulsation in polarization

Axion-induced X-rays: 100% polarized along with the local B field instantaneously (***energy-independent***).

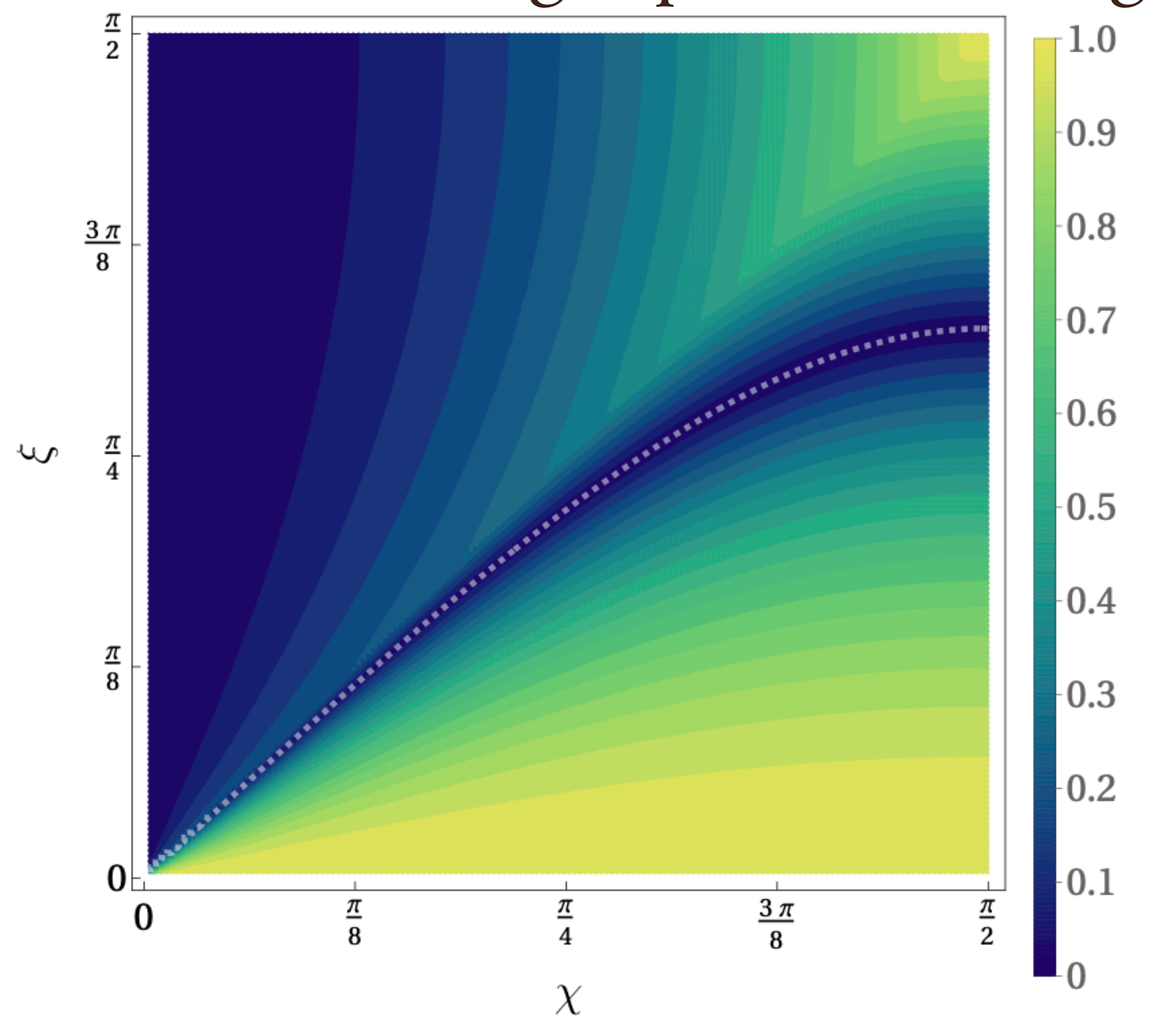
Direction of the B field is phase-dependent and polarization is ***phase-dependent (energy-independent).***

Time-averaged polarization degree is reduced.

χ and ξ degeneracy is broken.

New formulas of pulsation derived for both flux and polarization apply to a wide range of isolated NSs (magnetars and pulsars).

Phase-averaged polarization degree



An excess ?

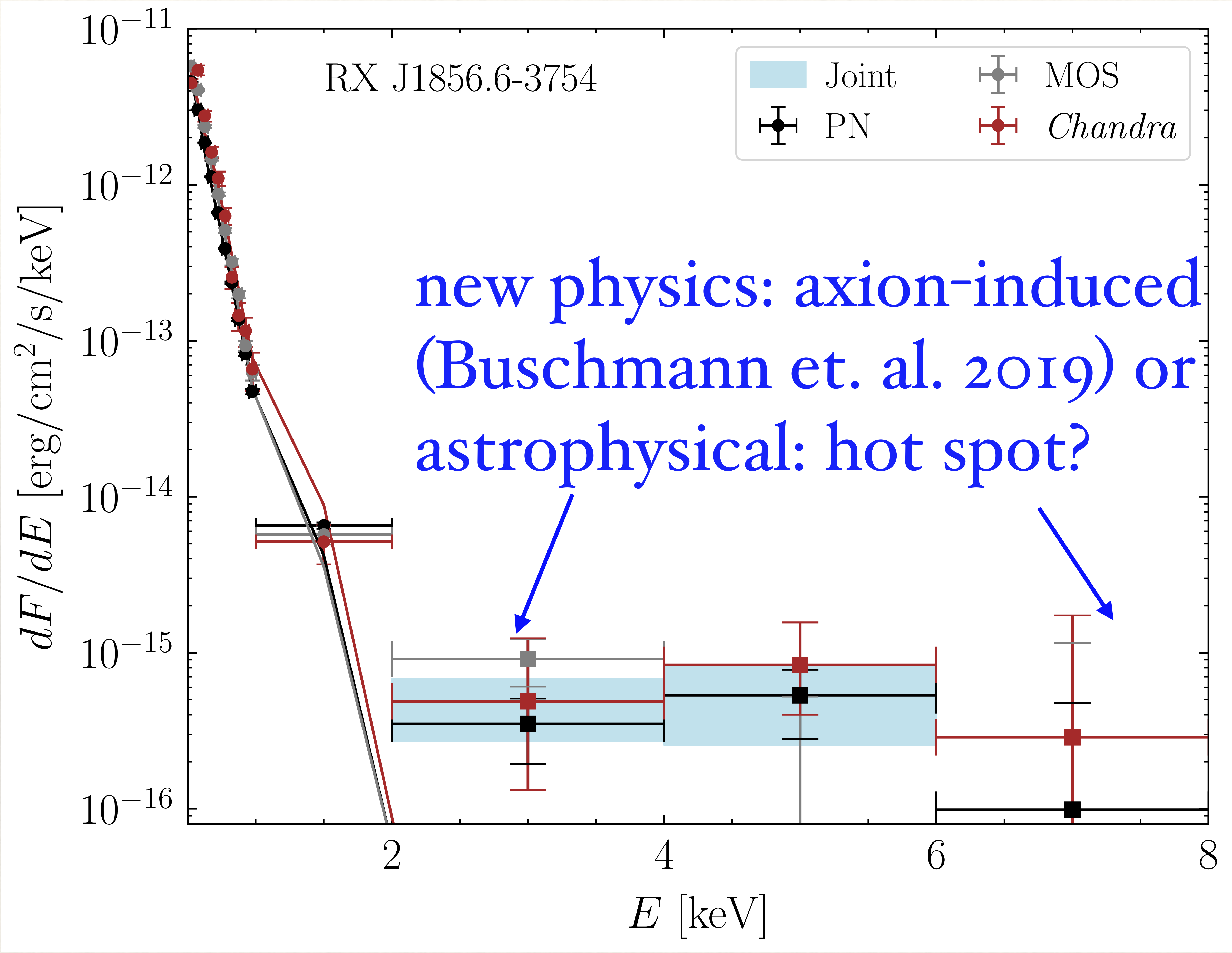
XMM-Newton (X-ray multi-mirror mission) space telescope. Credits: D.Ducros; ESA/ XMM-Newton, CC BY-SA 3.0 IGO

X-ray Dim Isolated Neutron Stars (XDINSs) or “Magnificent seven”

Seven isolated NSs includes the NS closest to us discovered so far: J1856.

Soft thermal X-ray emission (E < keV) very well characterized by blackbody emission with $T_{\rm SBB} \sim (50 - 100)$ eV.

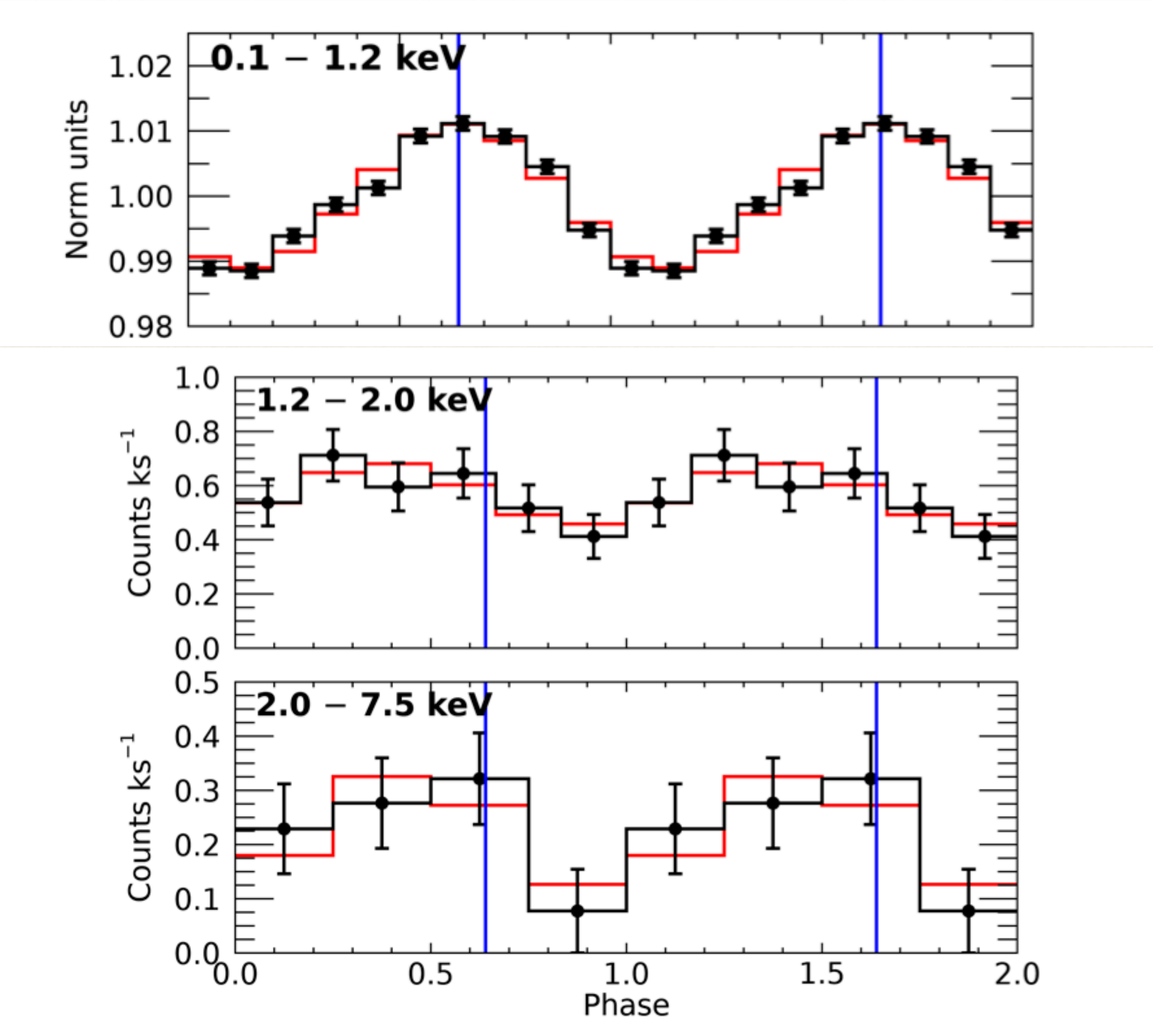
Unexpected hard X-ray emission above ~keV!



Yoneyama et. al 2017; 2018; Dessert et. al 2019

Pulse fraction (PF):

$$\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$



$\sim 1\,\%$

$\sim 30\,\%$

$\sim 50\,\%$

De Grandis et.al. 2022

A case study: J1856

A new fit to all the high-energy X-ray data available for J1856:

1. flux data up to 8 keV;
2. pulsation data in (1.2- 2.0) keV and (2.0 - 7.5) keV bins.

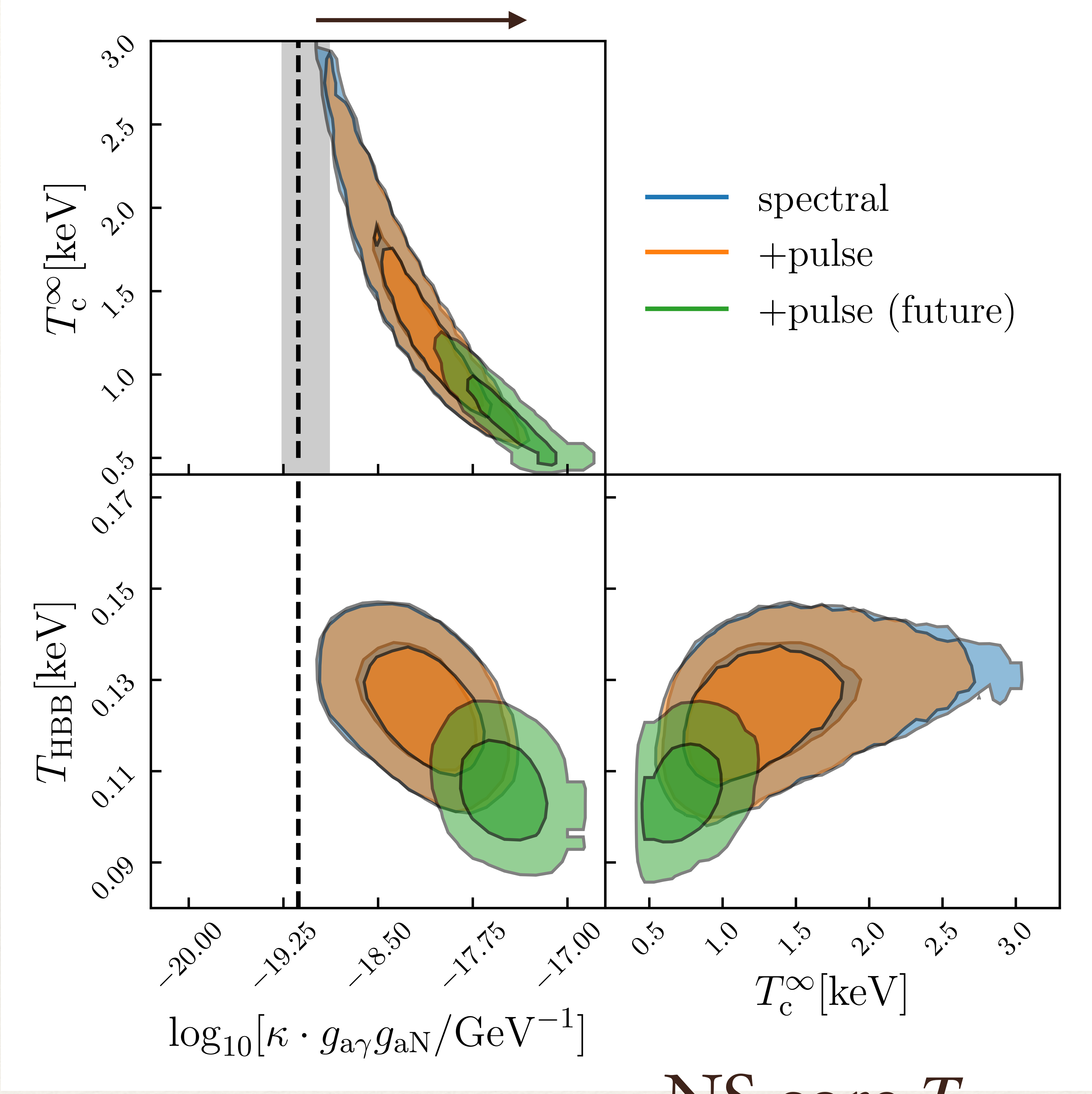
Fitting Model:

1. Soft blackbody (entirely determined by the spectrum below keV);
2. Hard blackbody (for the intermediate energy between 1 and 2 keV);
3. Axion-induced X-rays (for the flat excess $\gtrsim$ 2 keV).

Ruled out by other bounds

NS core T (axion production)

Hard BB T



product of axion couplings

NS core T (axion production)

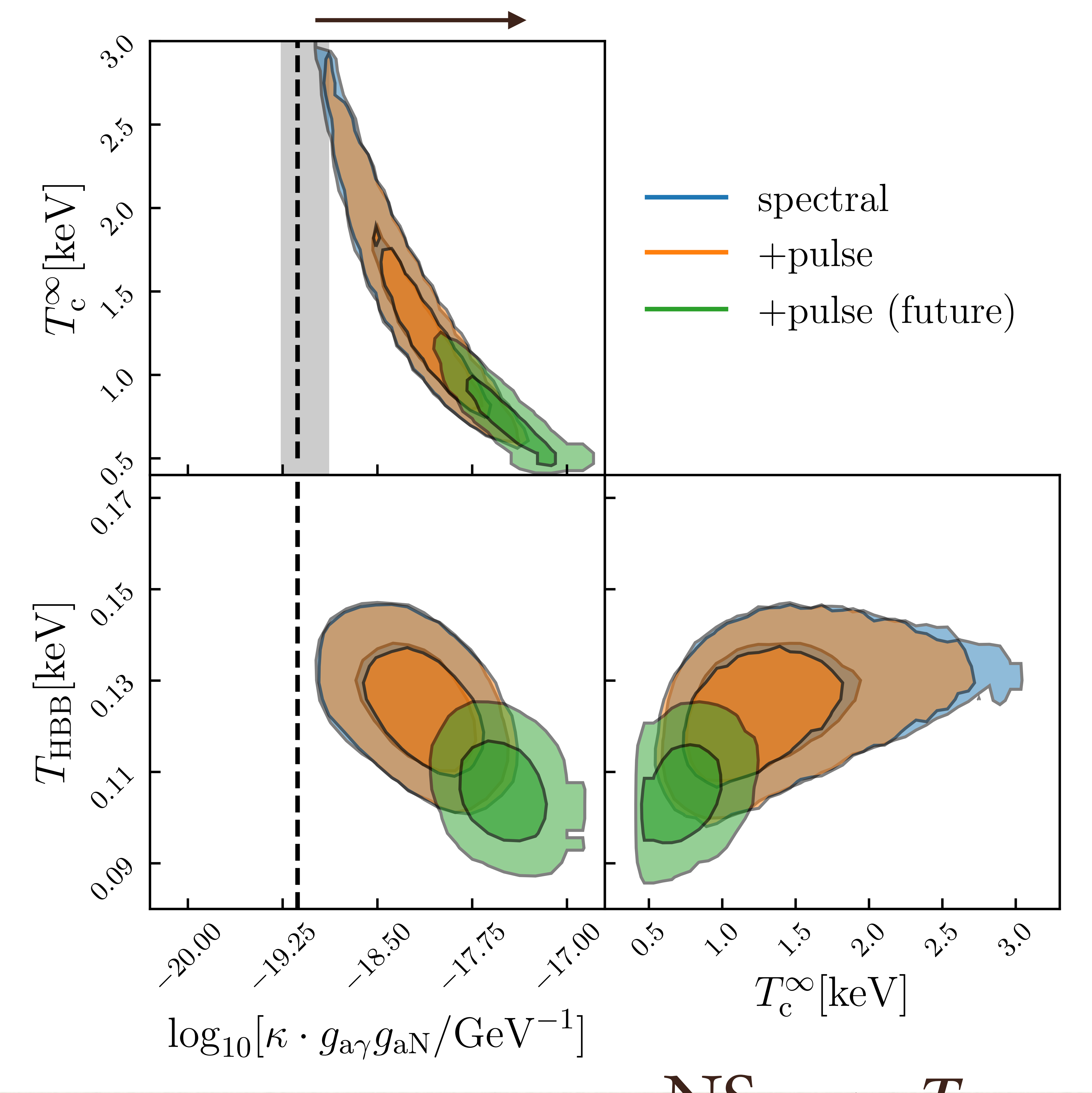
Need large axion coupling (at best marginally consistent with the other axion bounds) and high NS core temperature to explain the excess!

The current pulse data is not precise and its impact is not obvious.

Ruled out by other bounds

NS core T (axion production)

Hard BB T



product of axion couplings

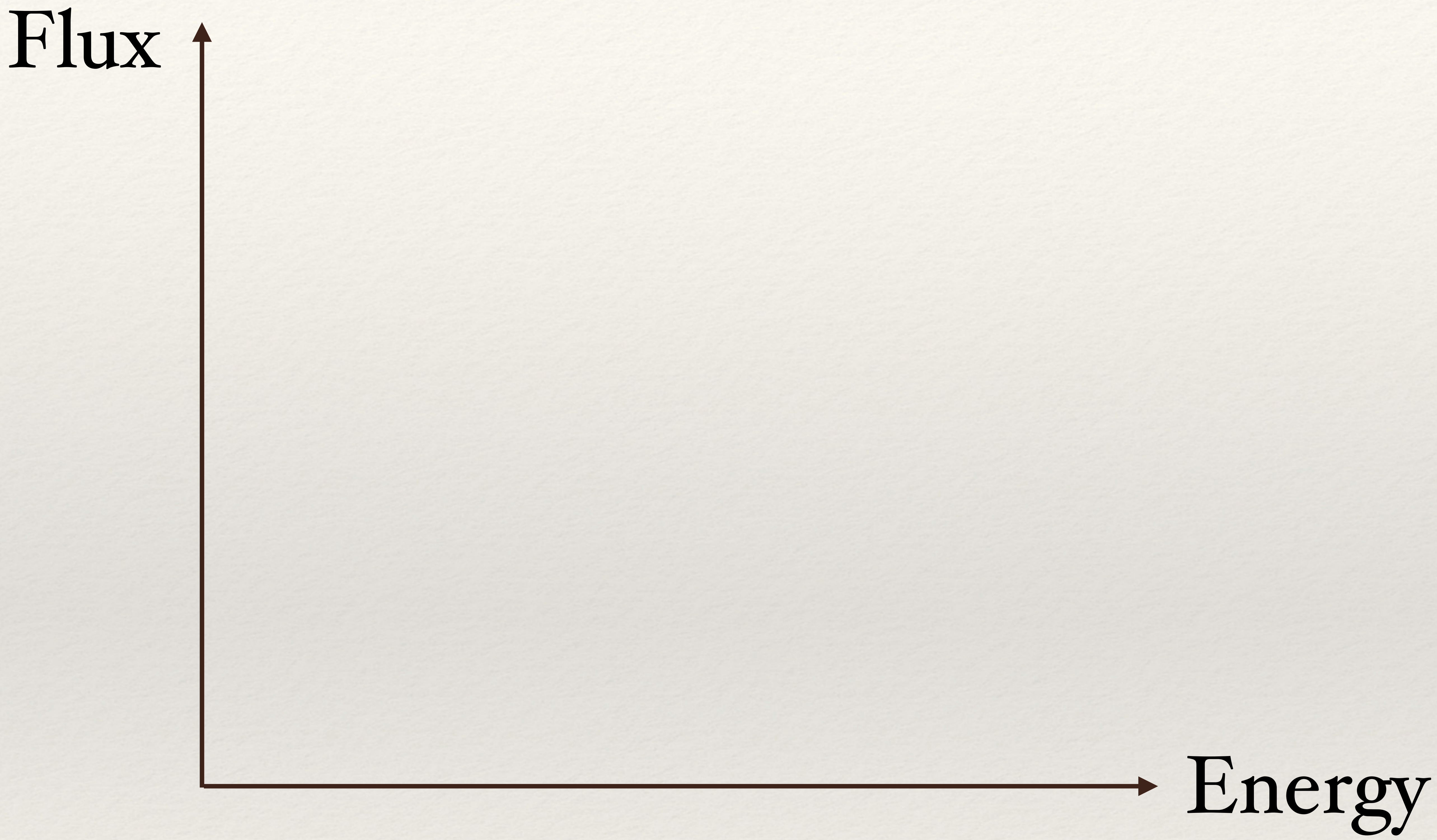
NS core T (axion production)

Reduce the uncertainties of the pulse data by a factor of 4 (assuming unchanged central values).

Axion-induced X-ray prefers an energy-independent pulse fraction while data doesn't.

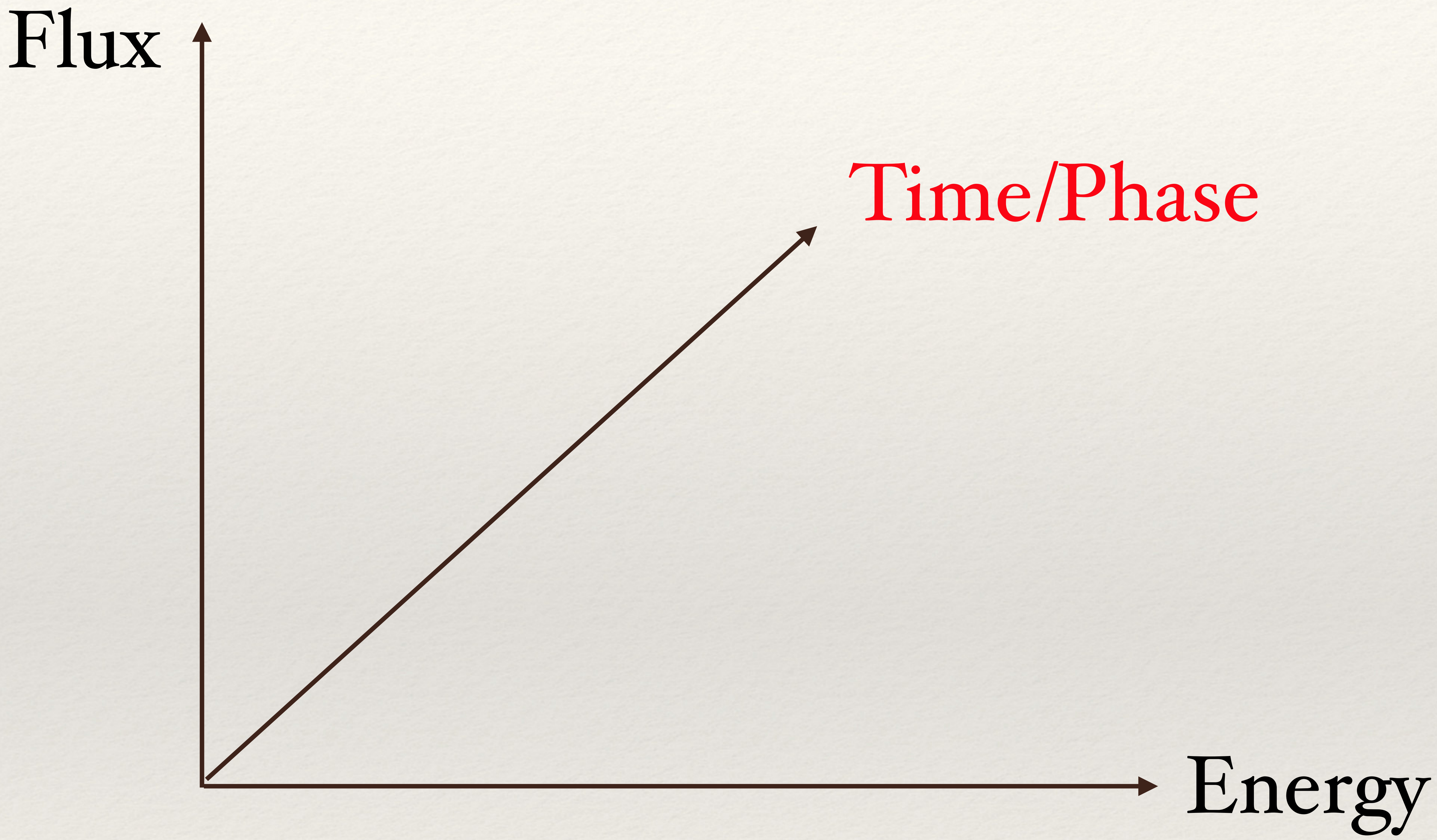
Summary

So far, using the X-rays from NSs to probe axions focuses on the spectrum only



Summary

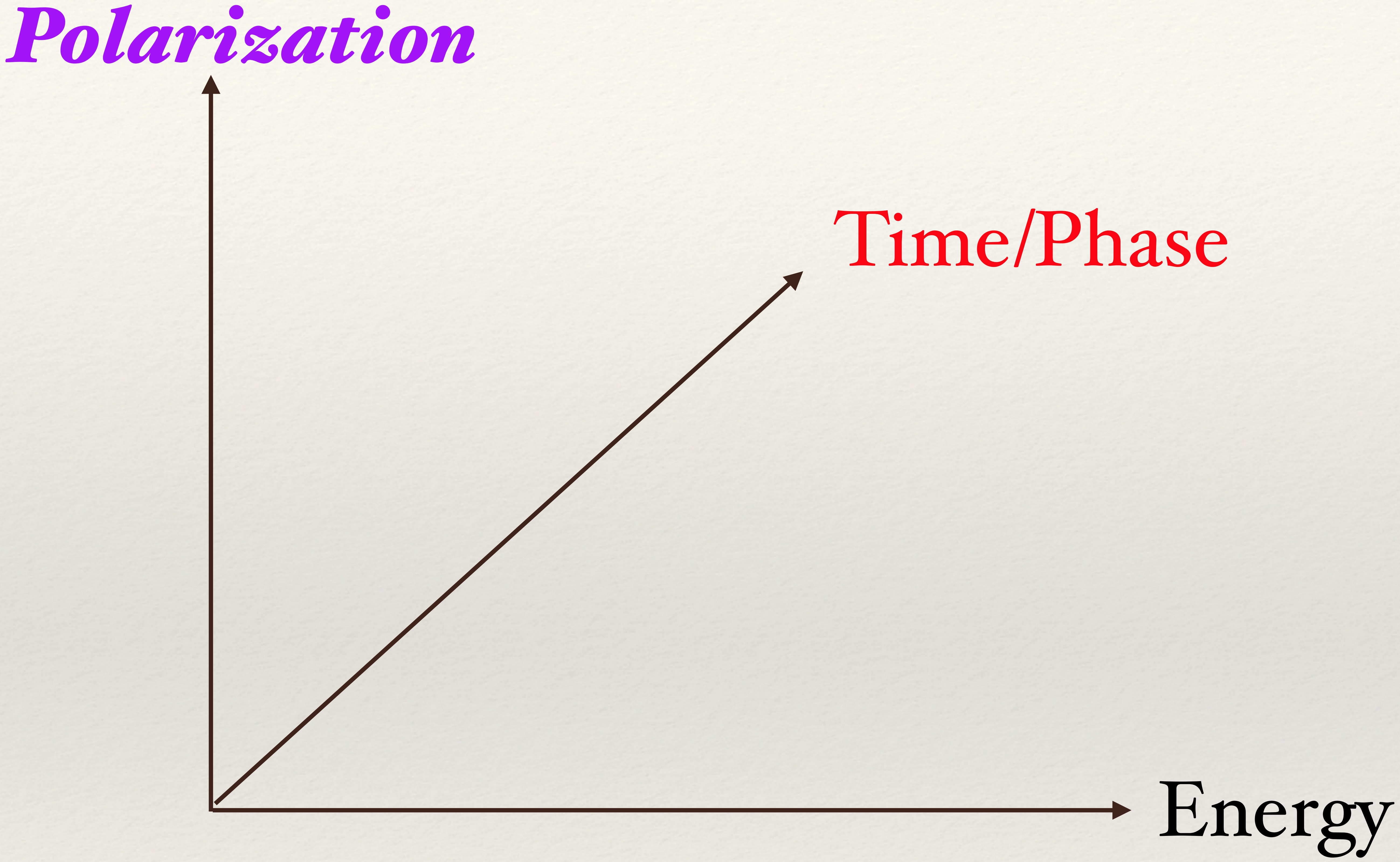
More information:



Precise timing data could potentially help us rule out/in axion-induced X-rays.

Summary

Even more information:



Currently one X-ray polarimetry, IXPE, only publishes data for magnetars so far.

New inflationary probes of pre-inflationary QCD axion dark matter

Xingang Chen (faculty at Harvard CFA), J. Fan, Lingfeng Li, JHEP 12 (2023) 197, arXiv: 2303.03406 [hep-ph];

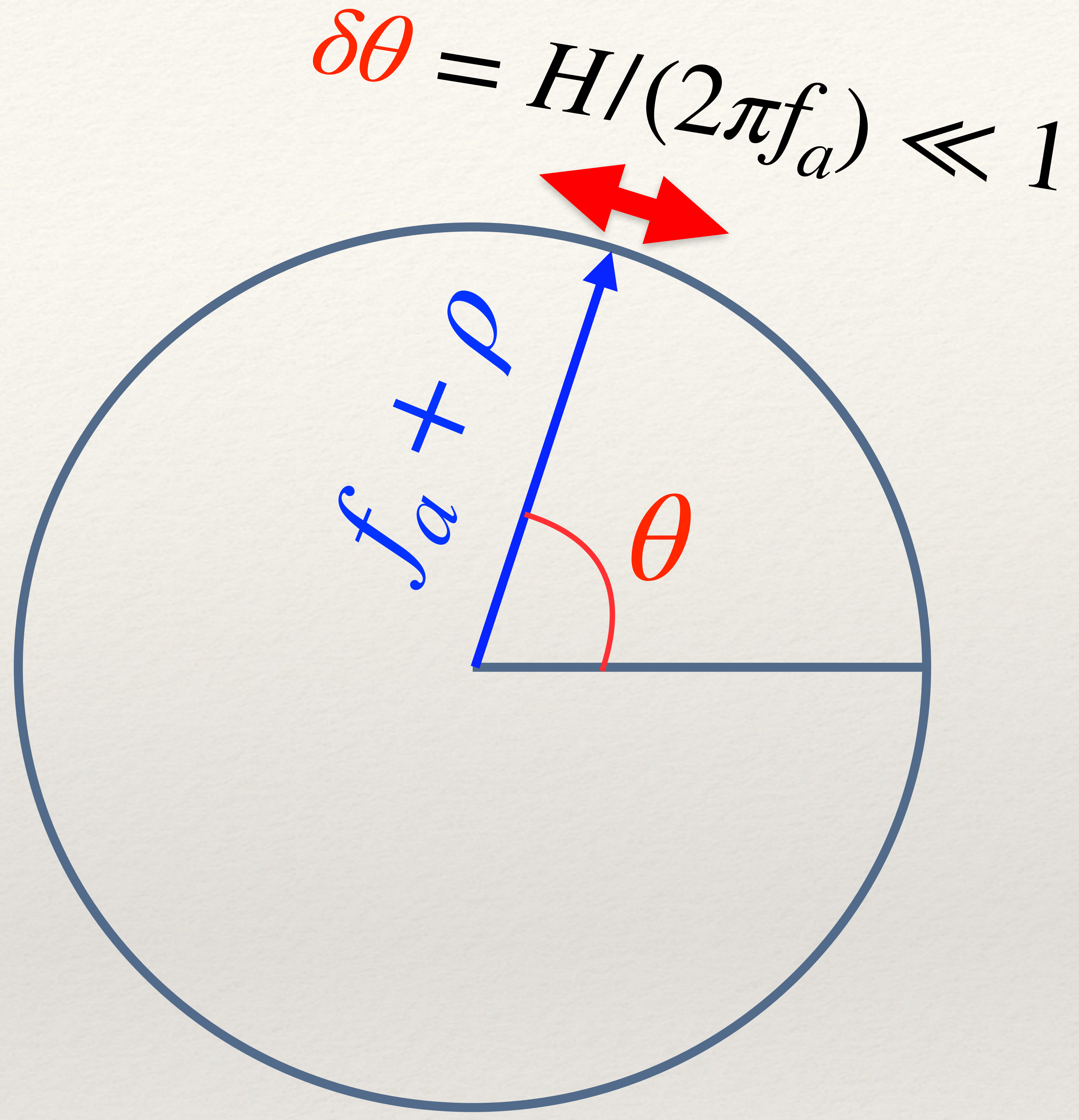
Matteo Braglia (postdoc at NYU), Catherine Petretti (PhD at Harvard), Praniti Singh (PhD at Brown), Xingang Chen, J. Fan, Lingfeng Li, work in progress;

Pre-inflationary QCD axion

Review: D.J.Marsh, 2015; Di Luzio et.al 2020

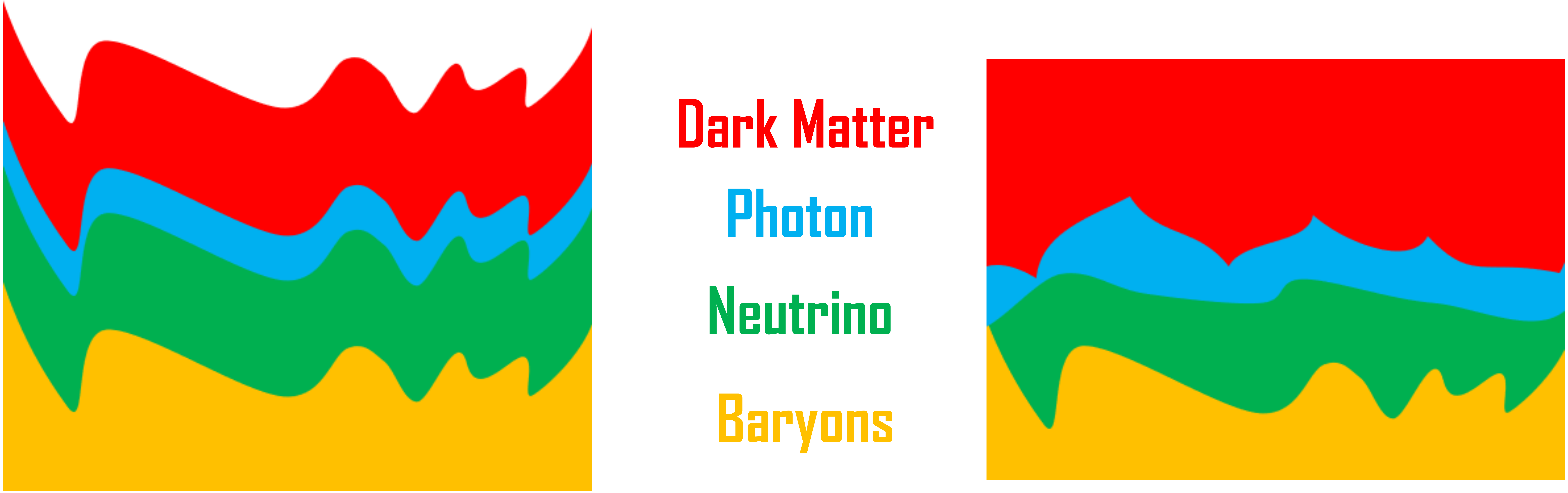
- PQ symmetry is broken during inflation. In addition, PQ symmetry is not restored during (p)reheating;
- Massless axion is present during inflation;

- A single uniform central value of initial misalignment angle θ_i ;
- Axion fluctuates and has an ***isocurvature*** perturbation $\langle \delta\theta_i^2 \rangle = \left(H/(2\pi f_a)\right)^2$;
- Axion becomes dark matter through ***misalignment*** mechanism after inflation and leads to ***cold dark matter isocurvature***;



PQ field $\quad \chi = \dfrac{f_I + \rho}{\sqrt{2}} e^{ia/f_I} = \dfrac{f_I + \rho}{\sqrt{2}} e^{i\theta},$

Curvature vs. Isocurvature



Side note: QCD axion perturbation at large scales

Well-known fact: at superhorizon scale, QCD axion dark matter perturbation is ***adiabatic perturbation*** + ***primordial isocurvature (pre-inflationary)***. How is the adiabatic part generated? Will the ***temperature-dependent non-quadratic*** QCD axion potential affect the conclusion [a lot of perturbation studies for ALP just takes a temperature-independent quadratic potential]?

background θ_0: $\ddot{\theta}_0 + 3H\dot{\theta}_0 = -\frac{1}{f_a^2}\frac{\partial V_a}{\partial \theta_0}$

Evolution of θ_0 and resulting relic abundance depends on the details of axion potential V_a . The temperature dependence and anharmonic effects are important!

Side note: QCD axion perturbation at large scales

Itamar Allali, Prish Chakraborty, J. Fan, Matt Reece, a note to appear

perturbation $\delta\theta$ at superhorizon scale (conformal Newtonian gauge):

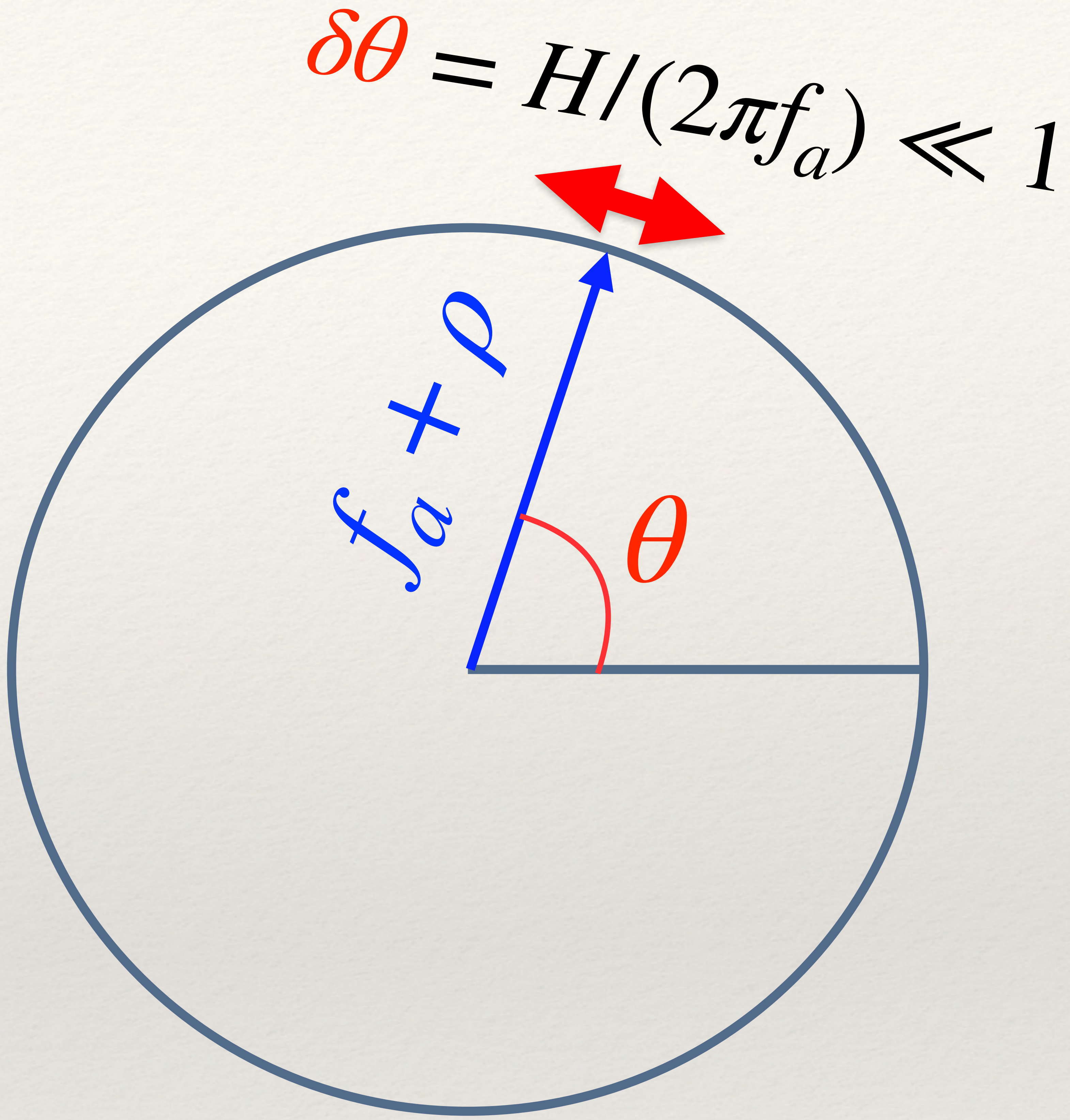
$$\delta\ddot{\theta} + 3H\delta\dot{\theta} + \frac{1}{f_a^2}\frac{\partial^2 V_a}{\partial\theta_0^2}\delta\theta = -2\frac{1}{f_a^2}\frac{\partial V_a}{\partial\theta_0}\underbrace{\Phi}_{\text{Gravitational potential}} - \frac{1}{f_a^2}\frac{\partial^2 V_a}{\partial\theta_0 \partial T_0}\delta T \longrightarrow \text{temperature fluctuation}$$

Simple exact solution (for any V_a and $a(t) \propto t^p$ with any p): $\delta\theta = \underbrace{\delta\theta_i}_{\text{primordial isocurvature}} + c \times \underbrace{t\Phi\dot{\theta}_0}_{\text{adiabatic}}$

Consistent with Weinberg's general theorem (2003): scalar perturbations in conformal Newtonian gauge always have an adiabatic solution.

- **Disadvantage:** Incompatibility between QCD axion DM with the high-scale inflation, assuming a ***flat*** isocurvature spectrum:

$$H < 0.9 \times 10^7\,\mathrm{GeV}\left(\frac{f_a}{10^{11}\,\mathrm{GeV}}\right)^{0.408} \quad \text{Planck 2018;}$$



On-going work to constrain QCD axion DM isocurvature (i.e., *blue-tilted* spectrum) using Planck + ACT, Braglia et.al.

- **Advantage**: leading solution to QCD axion quality problem such as extra-dimensional axion (Witten 1984) is pre-inflationary.

Q: Taking into the isocurvature constraint, could there be any interesting new ***observational*** signatures in isocurvature?

Yes! When we consider **PQ field - inflaton interaction**.

Xingang Chen, J. Fan, Lingfeng Li, JHEP 12 (2023) 197, arXiv: 2303.03406 [hep-ph]

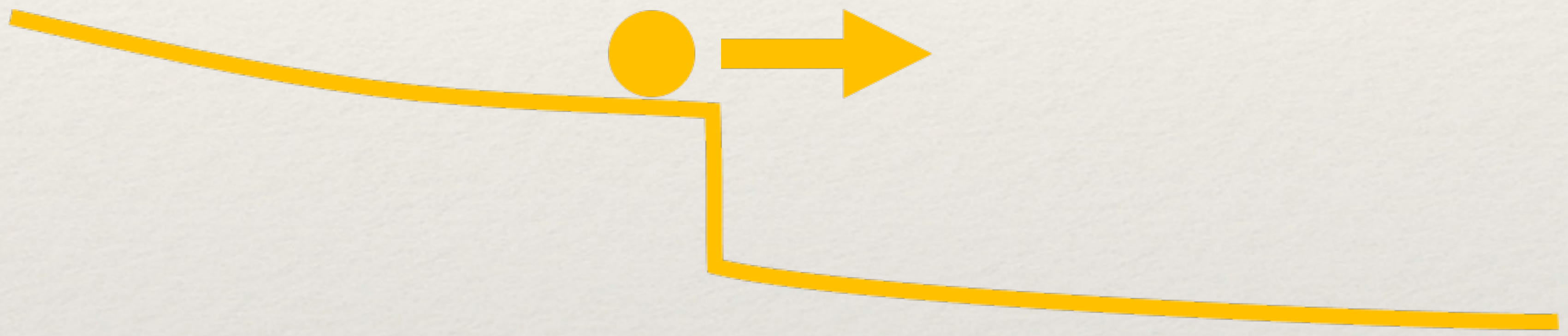
One example: classical features

PQ field

$\mathscr{L} \supset -\frac{c}{\Lambda}(\partial\phi)^2|\chi|^2$ + a toy feature: a step in the inflaton potential

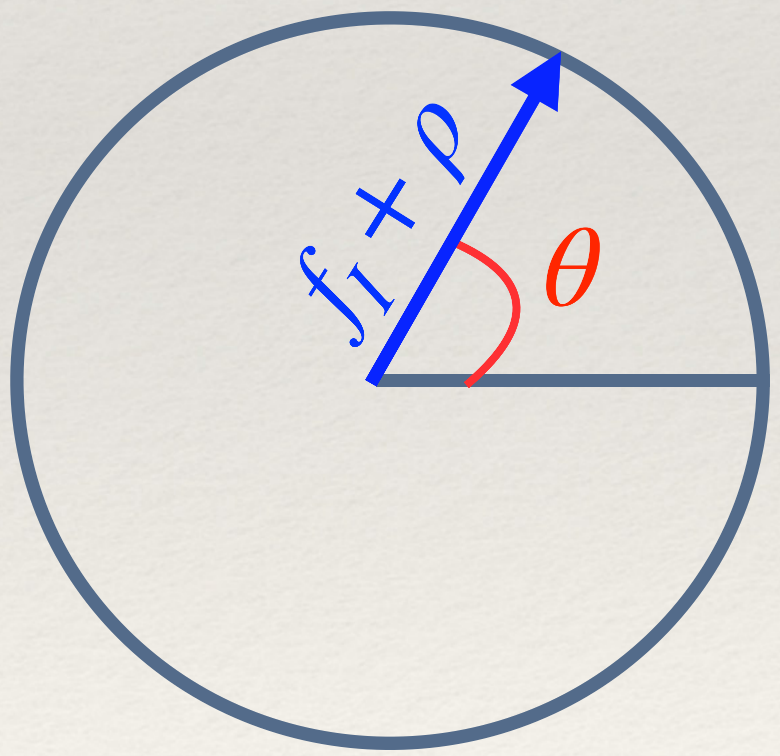
Inflaton ϕ

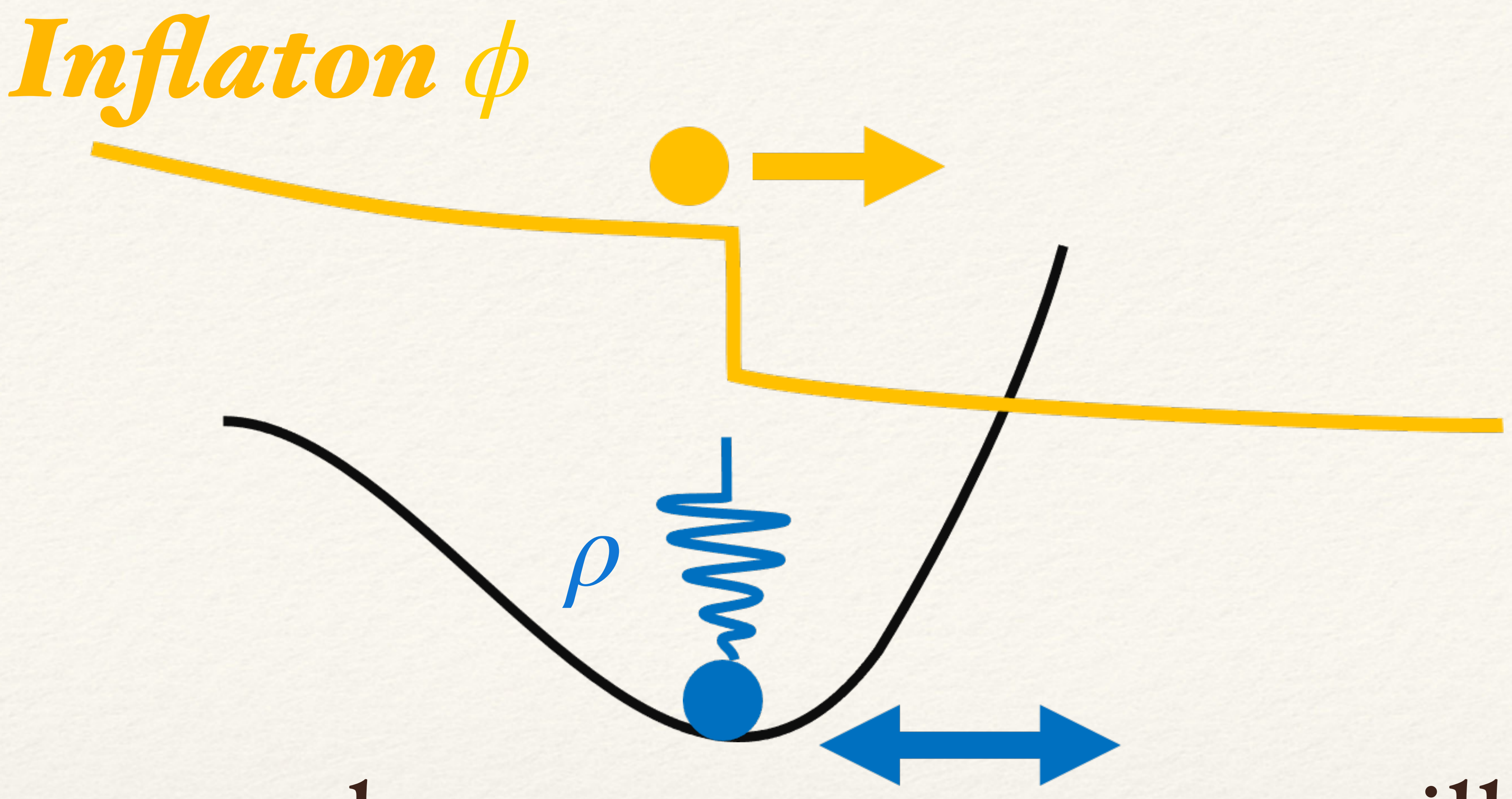
$$V_{\phi 1}(\phi) = -bV_{\phi 0}\,\theta(\phi - \phi_s)$$



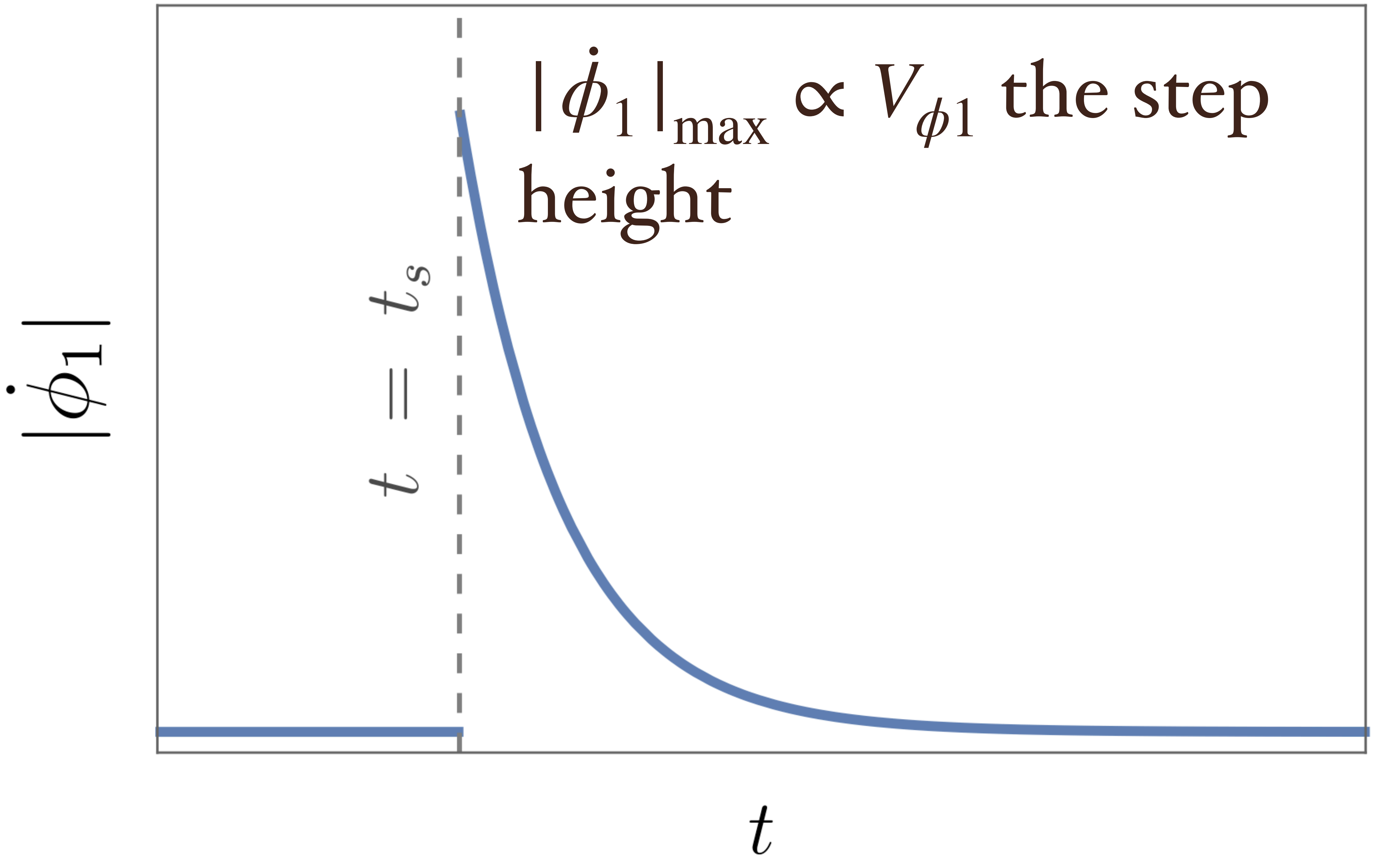
Excite the radial mode of the PQ field, ρ

$$\chi = \frac{f_I + \rho}{\sqrt{2}} e^{ia/f_I} = \frac{f_I + \rho}{\sqrt{2}} e^{i\theta}, \quad m_\rho = \sqrt{\lambda} f_a, \quad m_a = 0$$

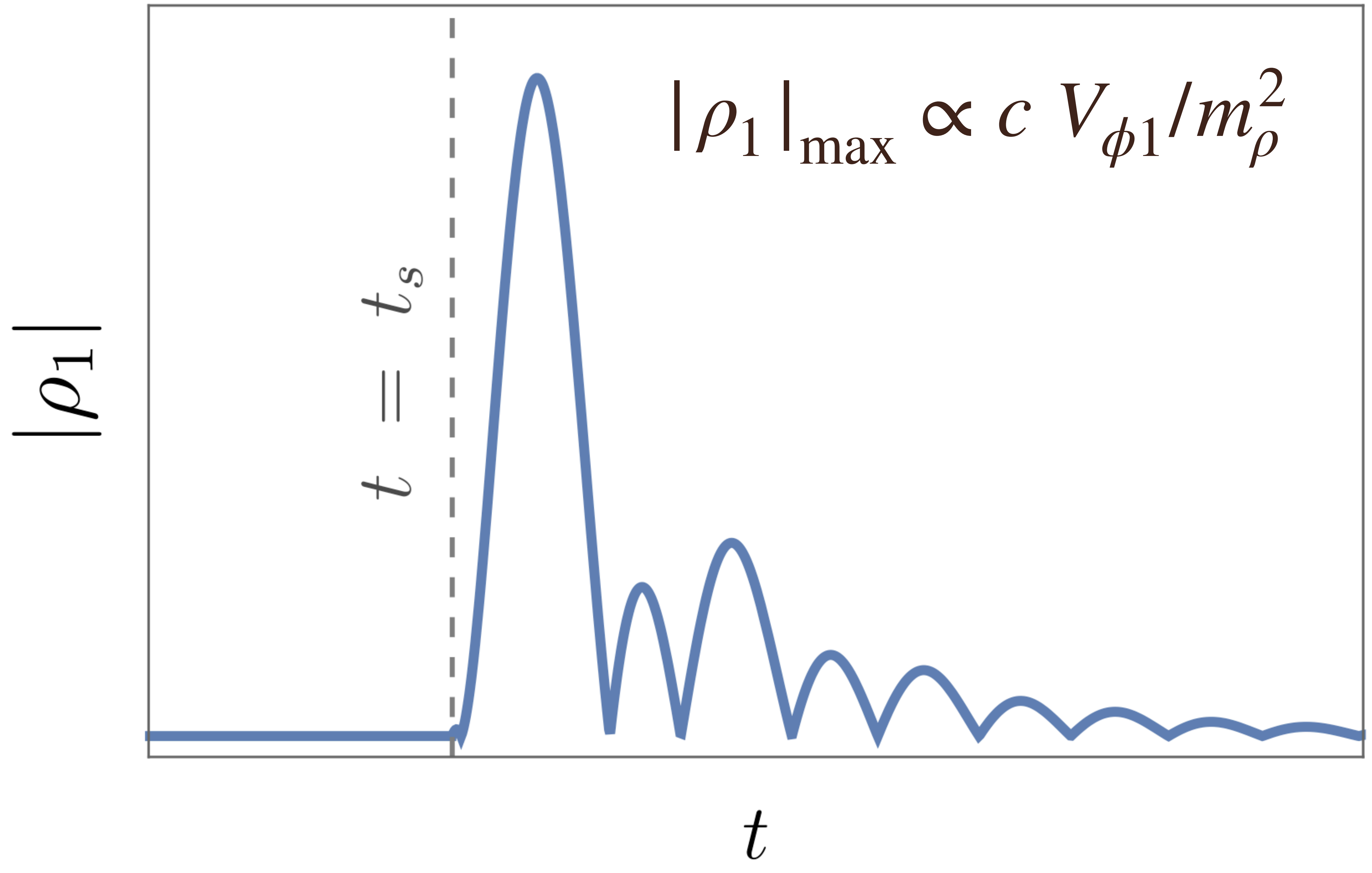




additional inflaton speed



oscillation of the radial mode

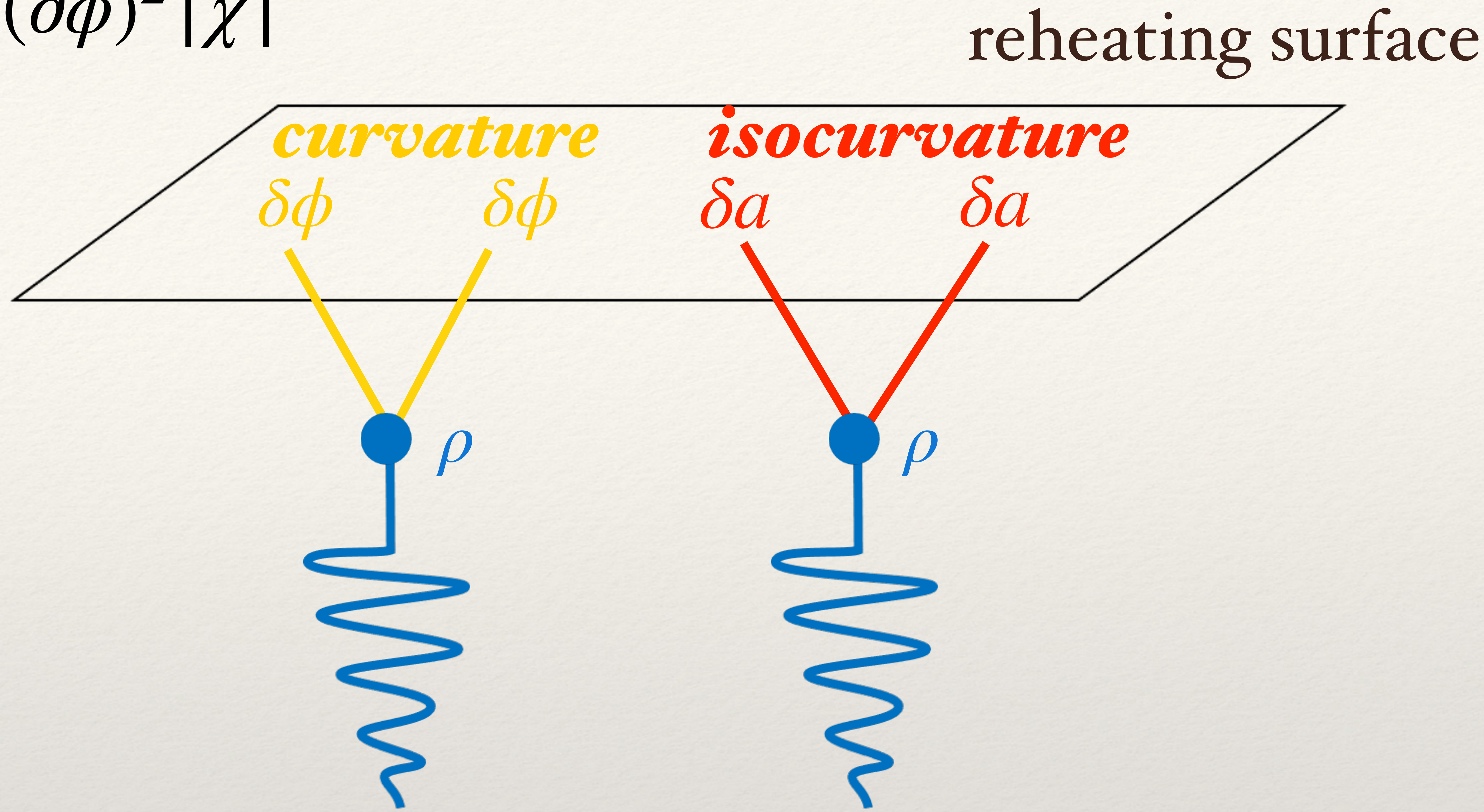


high-dim op: $\frac{c}{\Lambda}(\partial\phi)^2|\chi|^2$

$$\mathscr{L} \supset c\frac{f_I}{\Lambda^2}\rho\left((\delta\dot{\phi})^2 - \cdots\right)$$

$$+\frac{\rho}{f_I}\left((\delta\dot{a})^2 - \cdots\right)$$

kinetic term: $|\partial\chi|^2$



Resonances between ρ oscillation and ϕ/a quantum fluctuation result in **scale-dependent** oscillations (***clock signals***) in two-point correlation functions: curvature and isocurvature spectra;

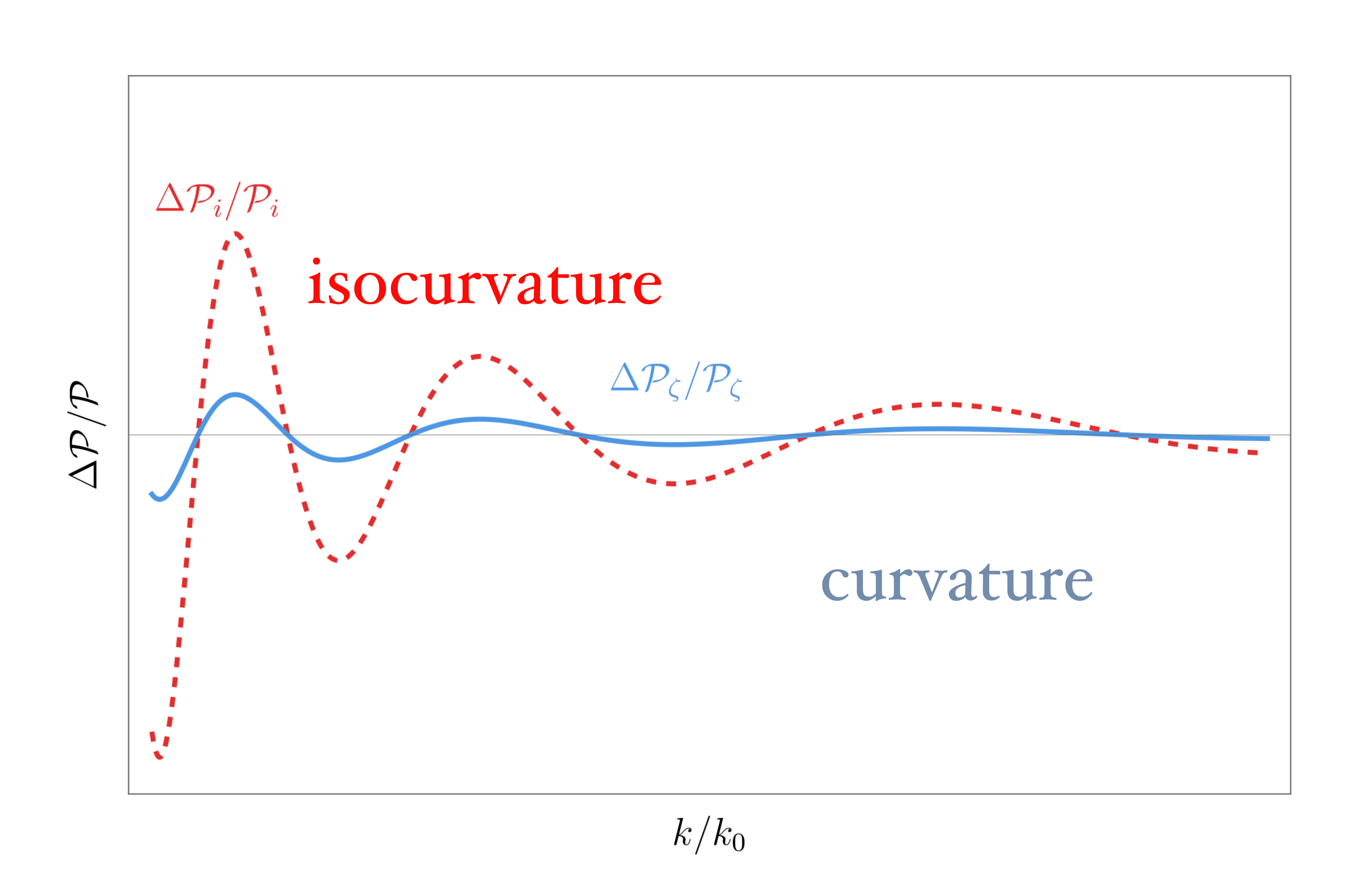
Stronger clock signal in isocurvature spectrum!

Clock signals in spectra

ΔP: correction to the power spectrum P

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

mass of radial mode: $m_\rho \sim f_a$

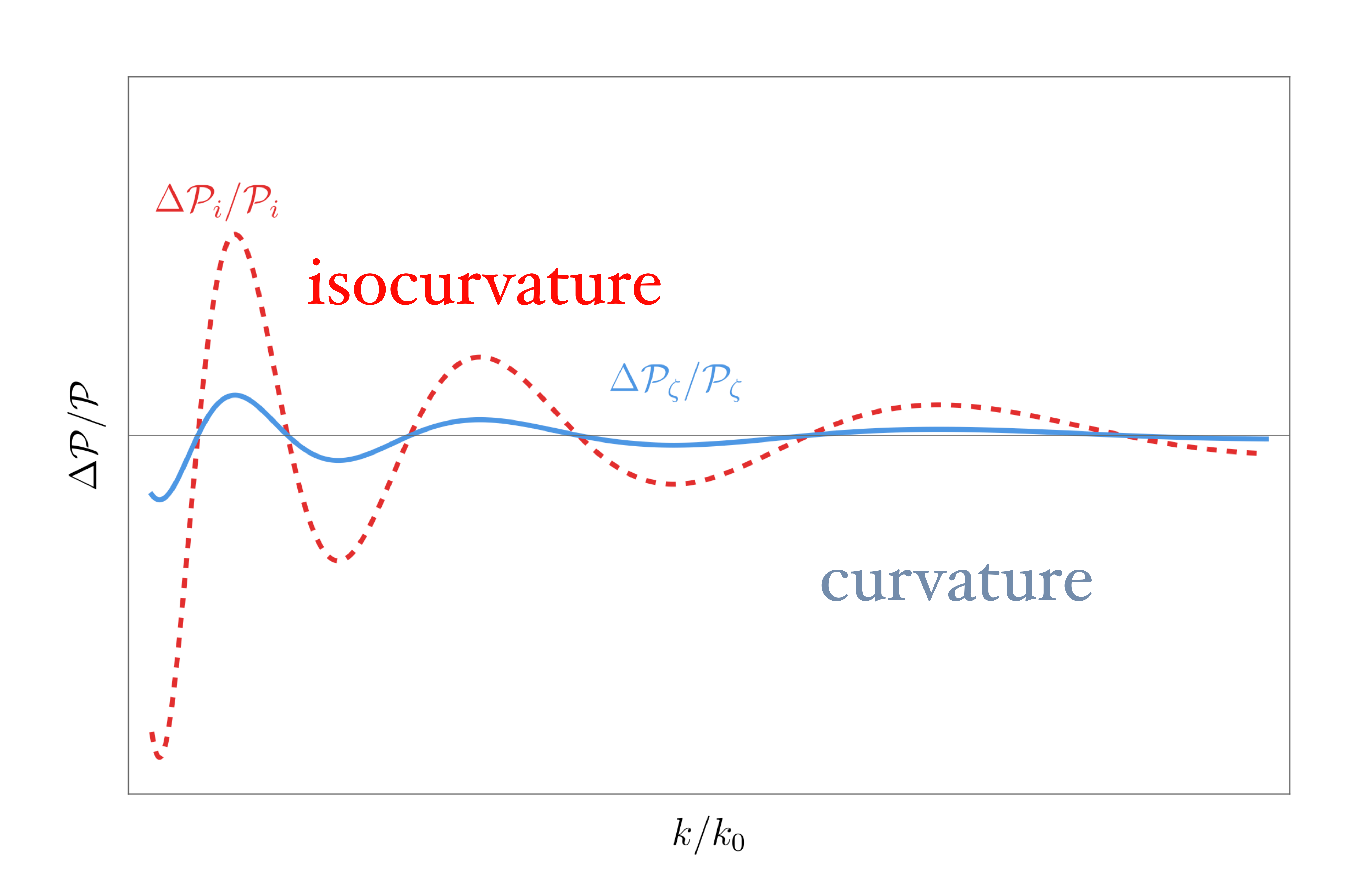


same phase, ***different*** amplitudes

Even considering QCD axion DM is 10^{-3} of the entire DM, $\Delta P_i/P_i \sim 1$!

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

Similar oscillations in three-point functions (***cosmological collider*** signals in isocurvature or isocurvature-curvature mixed three-point functions).

Conclusions and Outlook

Axion is old (QCD axion proposed 40 years ago; many studies over the years).

But it is also new (new ideas of models, experiments, and observables).

Two new possible probes in the sky:
1. Neutron star probes: pulsation profiles of both the flux and polarization;
2. Cosmological correlators: features and non-Gaussianities in isocurvature correlators or isocurvature-curvature mixed correlates.

Thank you!