Probing Axion-U(1) Inflation: Gravitational Waves and Primordial Black Hole Formation

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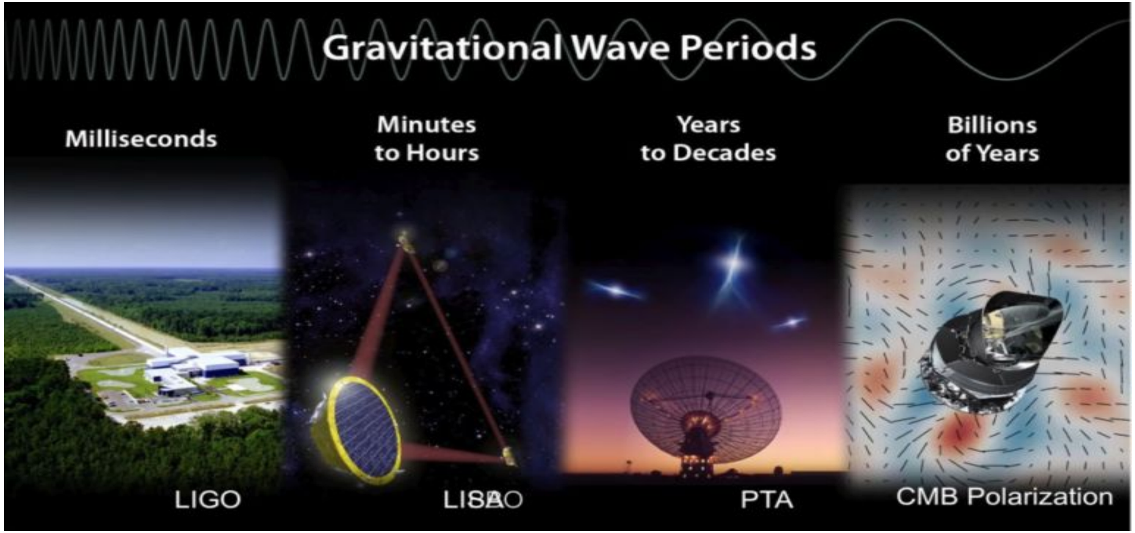
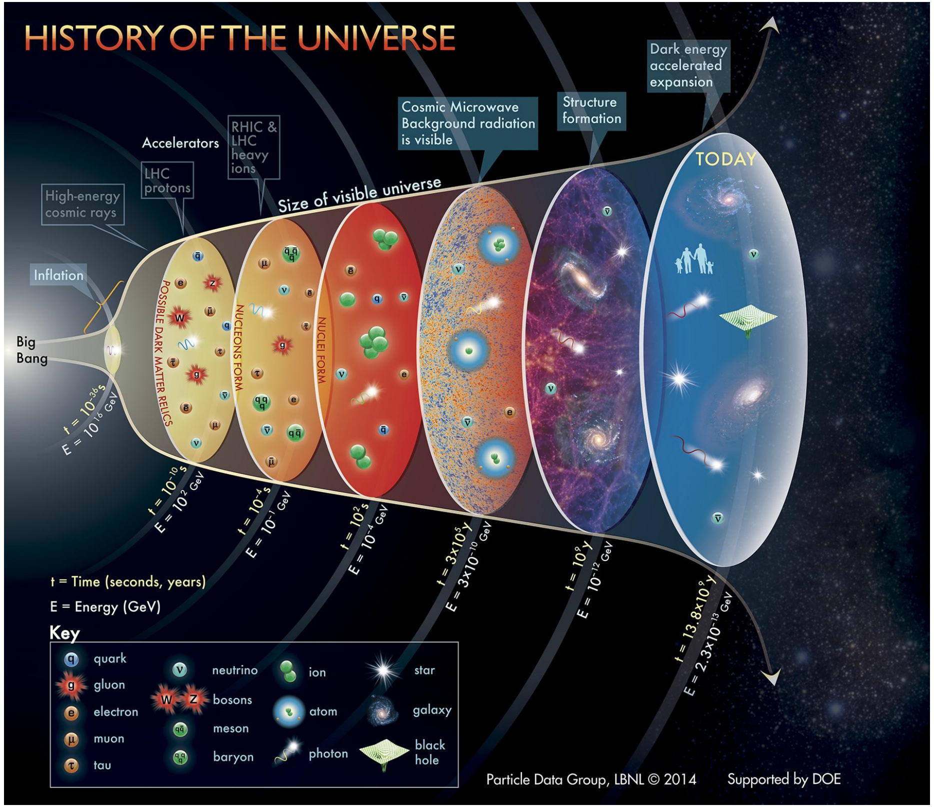


Outline

- Introduction to key epochs in the early Universe
- Observational status of axion inflation
- Axion-U(1) inflation and results from the previous studies
- Results from the lattice simulations
- Summary

A brief history of the Universe



LBNL Particle Data Group, 2014

Probes for Early Universe

- via photons
  - CMB anisotropies, spectral distortions
- via neutrinos
- via gravitational waves
  - by direct detections of GWs
  - by constraints on extra degrees of freedom from CMB

Hubble Horizon at key epochs

Scales that can have a signature of this period
10^{-18}pc to ~10^4 Mpc

$d + n \longrightarrow H^3 + \gamma$
$H^3 + p \longrightarrow He^4 + \gamma$
$d + p \longrightarrow He^3 + \gamma$
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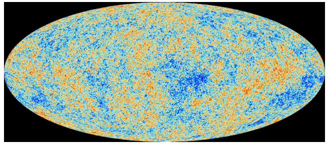
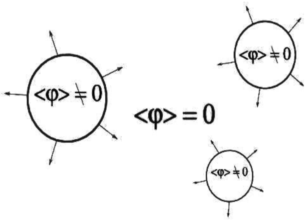


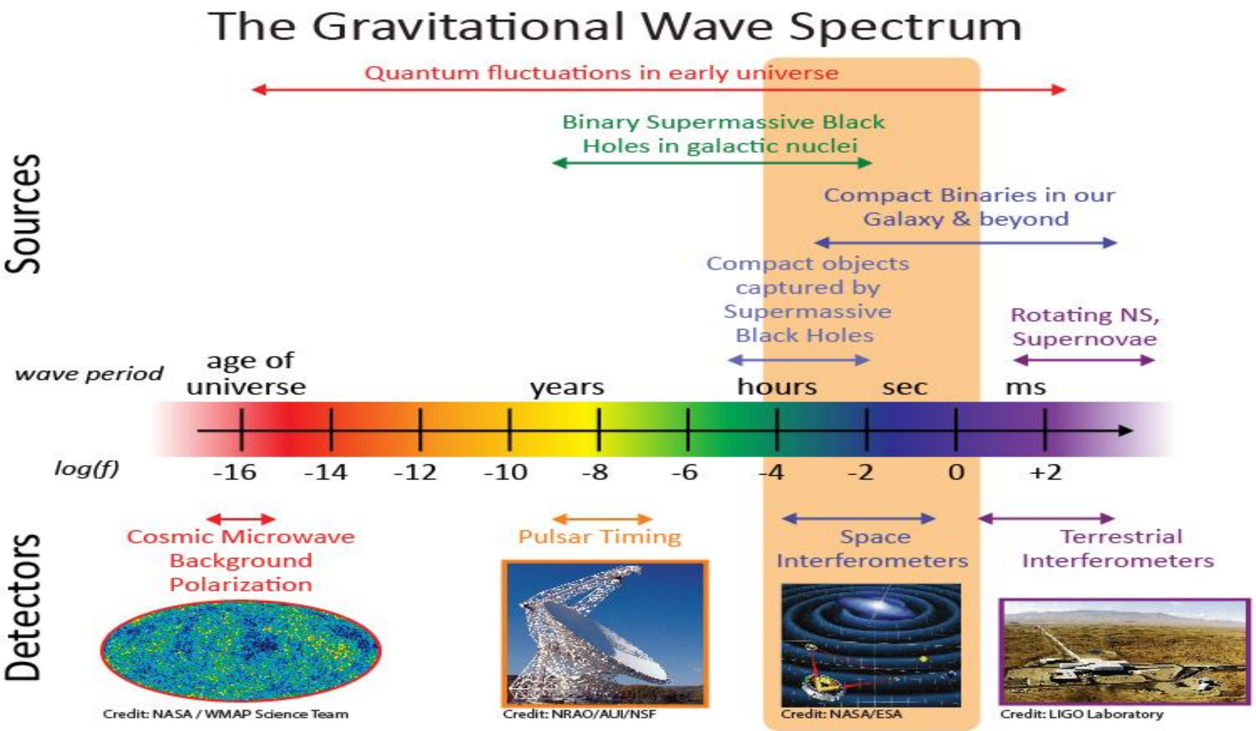
Inflation | T=100 GeV | 150 MeV | 1 MeV | 0.3 eV | Time

~ $5*10^{-18}$pc | ~$5*10^{-4}$pc | ~ 1 pc | ~ 100 pc | ~100 Mpc | 4 Gpc



T= 1 eV, radiation-matter equality

Gravitational waves



https://lisa.nasa.gov/

Gravitational waves from Binary mass system

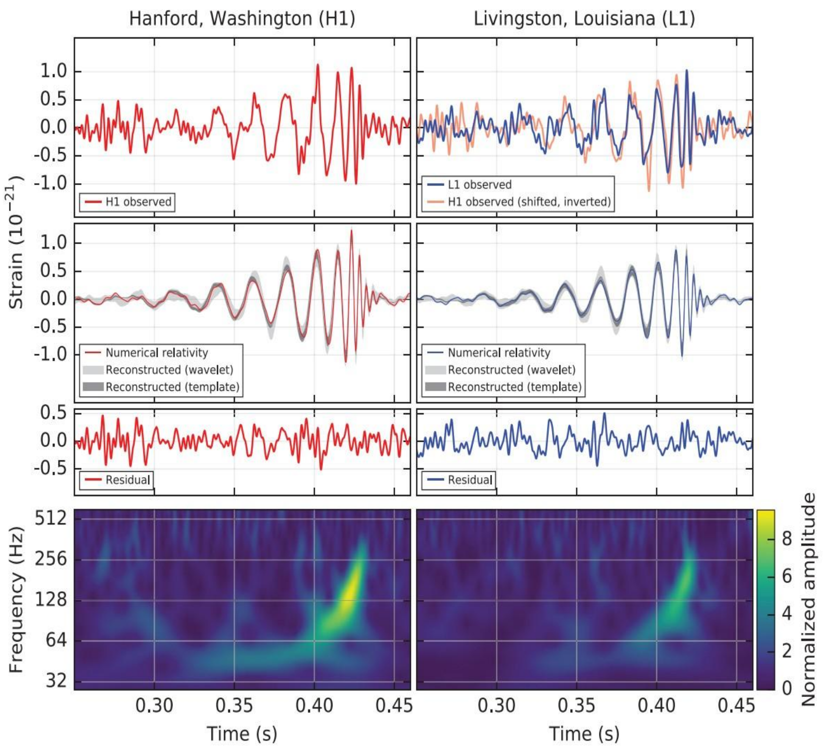
$$\Box \bar{h}_{ij} = 16\pi G \bar{T}_{ij}$$

$$h_{ij} = 2\frac{G}{d}\Lambda_{ij}^{kl}\ddot{I}_{kl}, \quad I_{kl} = \int d^3y(y_k y_l - \frac{1}{3}y^2\delta_{kl})T_{00}$$

Parameters
(1) Distance from the observer (d)
(2) Masses(M_1 and M_2)
(3) Orbital frequency (ω)
(4) Distance between the sources (r)

$$h_{ij} \sim \frac{G}{d}\mu r^2\omega^2\cos(2\omega t)$$

$$h_{ij} \sim 10^{-21}\left(\frac{M}{10M_\odot}\right)^{5/3}\left(\frac{\omega}{100Hz}\right)^{2/3}\frac{10\text{Mpc}}{d}$$



LIGO Scientific Collaboration and Virgo Collaboration Phys. Rev. Lett. 116, 061102

Gravitational waves in cosmology

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Stochastic GW background

- Sourced by anisotropic stress

$$h''_{ij} + \frac{2a'}{a}h'_{ij} + k^2 h_{ij} = 16\pi G a^2\bar{T}_{ij}$$

$$\Omega_{GW} \equiv \frac{\rho_{GW}}{\rho_c} = \frac{1}{32\pi G\rho_c}\frac{\langle h'_{ij}h'^{ij}\rangle}{a^2} = \frac{\Omega_r}{12H^2}\frac{\langle h'_{ij}h'^{ij}\rangle}{a^2}$$

- Relevant Parameters
  - energy budget of the source
  - peak of the source
  - Hubble scale

$$\Omega_{GW} \propto \Omega_r\left(\frac{\rho_s}{\rho_r}\right)^2\left(\frac{H}{k_p}\right)^2$$

$$f \sim \frac{H}{k_p}\frac{T}{10^5GeV}\mathrm{mHz}, \; h \sim \frac{10^{-21}}{f\mathrm{inmHz}}\sqrt{\Omega_{GW}}$$

Axion-U(1) Inflation

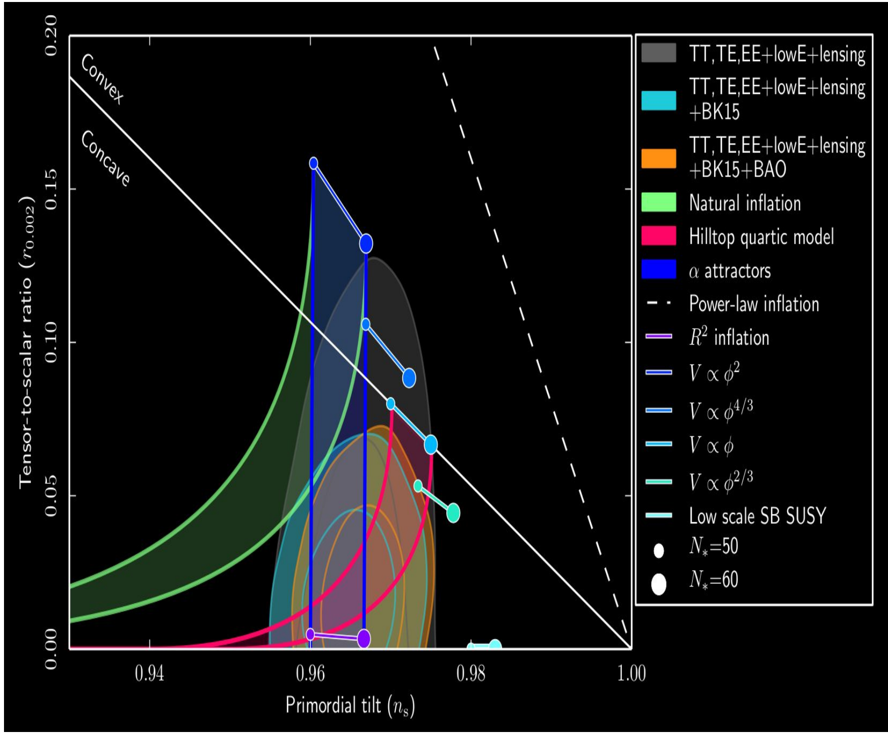
- Flatness of the potential is protected due to shift symmetry

- First model suggested by the name Natural Inflation

  K. Freese, J. A. Frieman and A. V. Olinto, PRL 1990

$$V(\phi) = \Lambda^4 \left(1 + \cos\left(\frac{\phi}{f}\right)\right)$$

- Various scenarios has been suggested to make it compatible with the CMB observations



Planck results 2018

$$S = \int d^4x \sqrt{-g}\left[\frac{m_{\rm pl}^2}{16\pi} R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha}{4f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}\right]$$

Anber and Sorbo 2009

Axion-U(1) Inflation : dynamics

By neglecting the inhomogeneity of axion

$$\left(\partial_\eta^2 + k^2 \mp 2\xi(\mathcal{H}\eta)\frac{k}{\eta}\right) A_k^\pm = 0\,, \qquad \text{where} \qquad \xi = -\frac{\alpha}{2f}\,\frac{\phi'}{\mathcal{H}}$$

$$A_k^+ \simeq \frac{1}{\sqrt{2\,k}}\left(\frac{k}{2\,\xi\,a\,H}\right)^{1/4} e^{\pi\xi - 2\sqrt{2\xi k/(aH)}},$$

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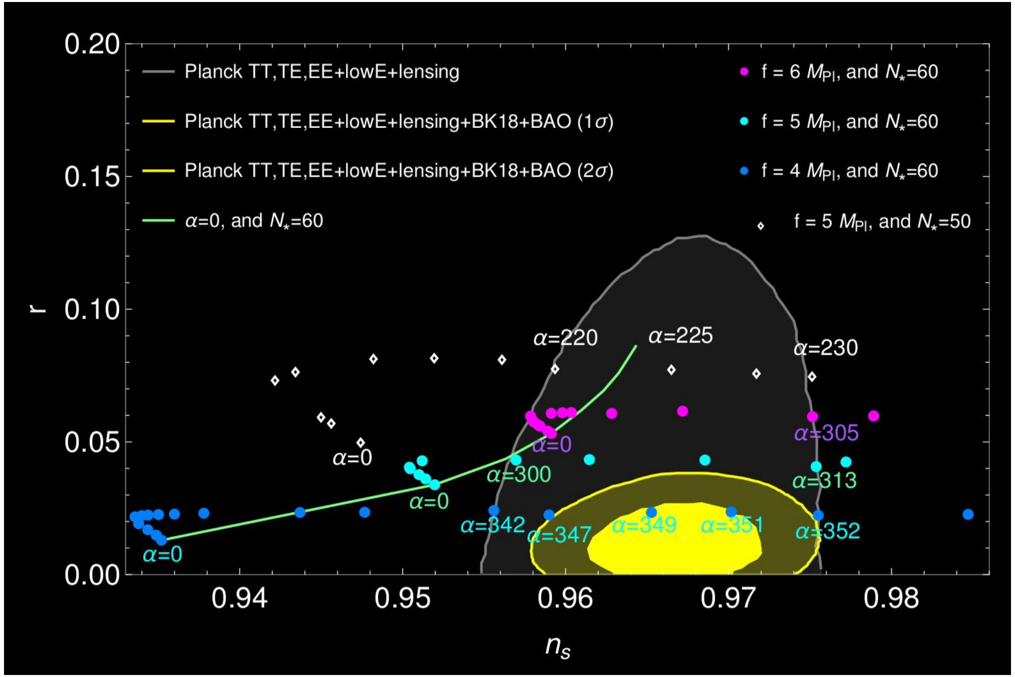
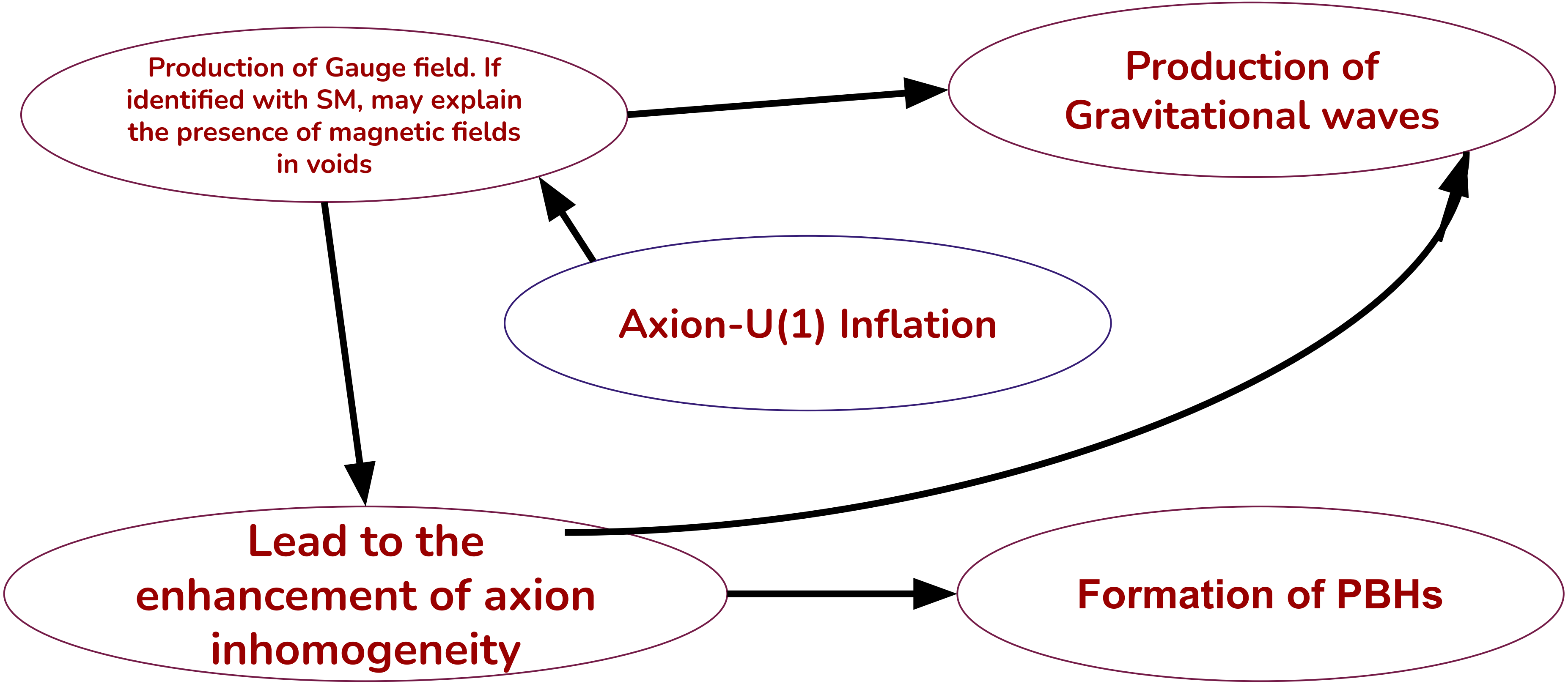
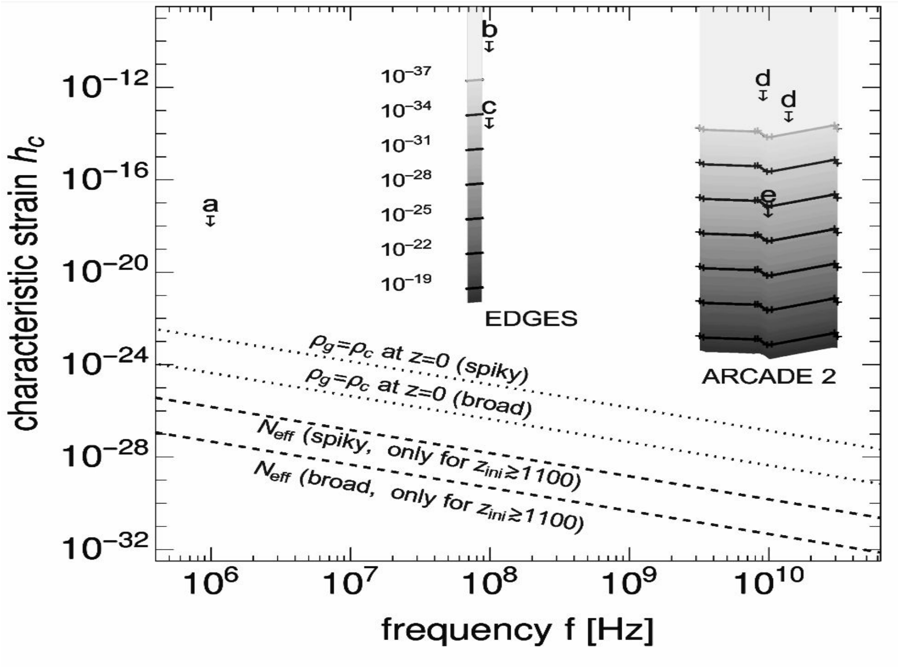


K. Alam, K. Dutta and N. Jamana 2024

Axion-U(1) Inflation : Phenomenology



Constraints on High frequency GWs from radio telescopes

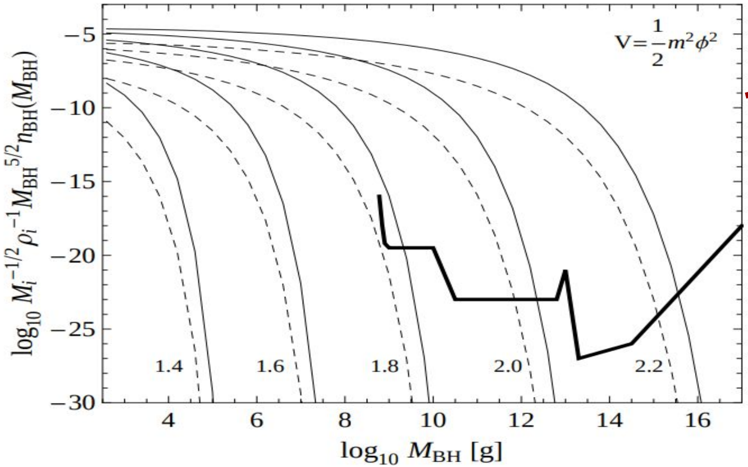


$$\Omega_{GW} = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\Delta N_{eff}\Omega_\gamma$$

$$\Omega_{GW}h^2 < 1.2\times10^{-6}$$

V. Domcke, C. G. Cely, PRL 2021

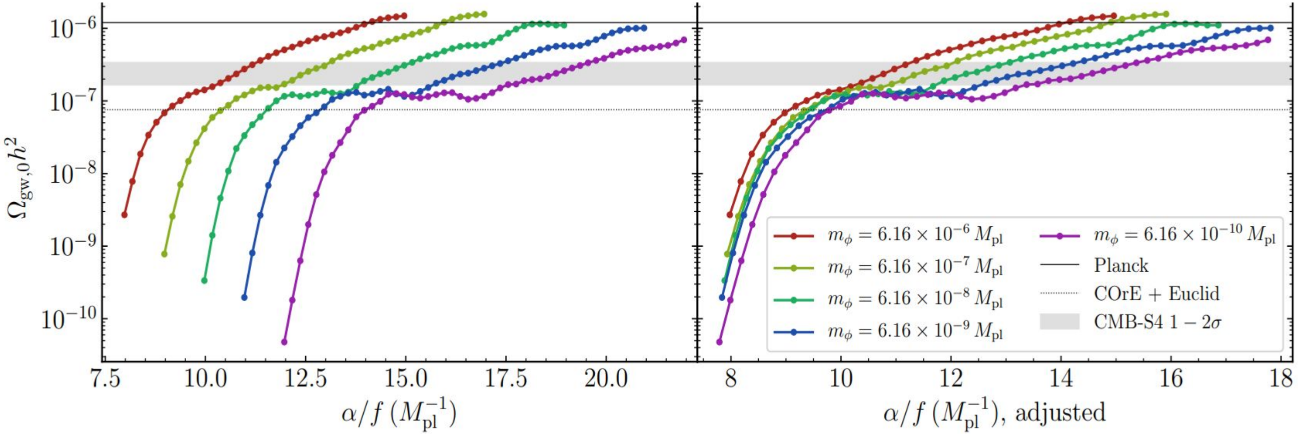
Constraints on the coupling between axion and gauge field



Assume chi square PDF

$$\frac{\alpha}{f} < 130/m_{pl}$$

E. Bugaev and P. Klimai, PRD 2014



Adshead et al, PRD 2020
Adshead el al, PRL 2020

$$\frac{\alpha}{f} < 70/m_{pl}$$

for $m_\phi = 6.16 \times 10^{-6} M_{pl}$

Lattice simulations of Axion-U(1) Inflation

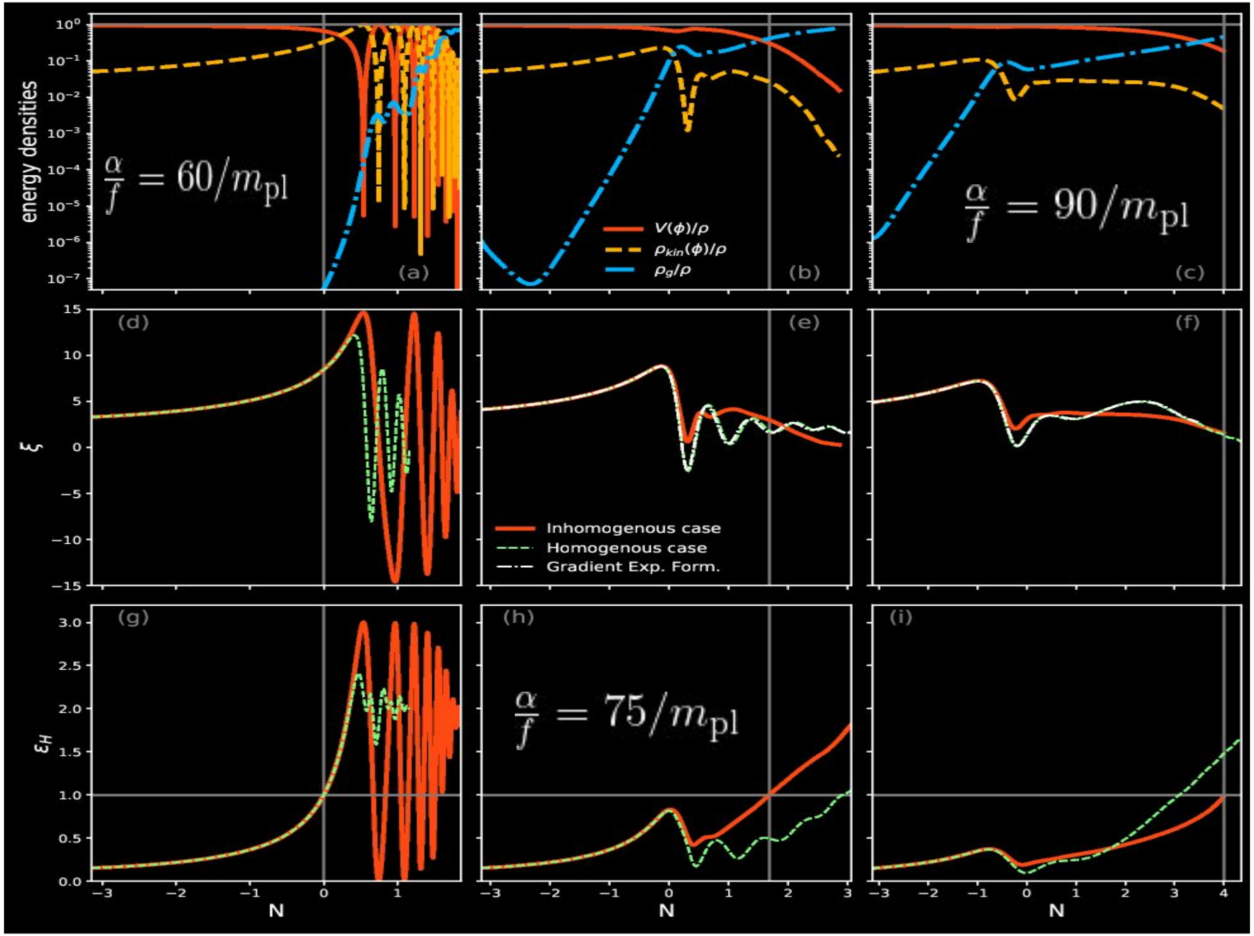
- We use pencil code to solve the axion-U(1) setup.
  Equations are begin solved

$$\phi'' + 2\mathcal{H}\phi' - \nabla^2\phi + a^2\frac{dV}{d\phi} = \frac{\alpha}{f}\frac{1}{a^2}\mathbf{E}\cdot\mathbf{B}\,,$$

$$\mathbf{A}'' - \boldsymbol{\nabla} A_0' - \nabla^2\mathbf{A} + \boldsymbol{\nabla}(\boldsymbol{\nabla}\cdot\mathbf{A}) - \frac{\alpha}{f}\left(\phi'\mathbf{B} + \boldsymbol{\nabla}\phi\times\mathbf{E}\right) = 0\,,$$

Along with the FLRW background.

Axion-U(1) Inflation : dynamics from lattice simulations

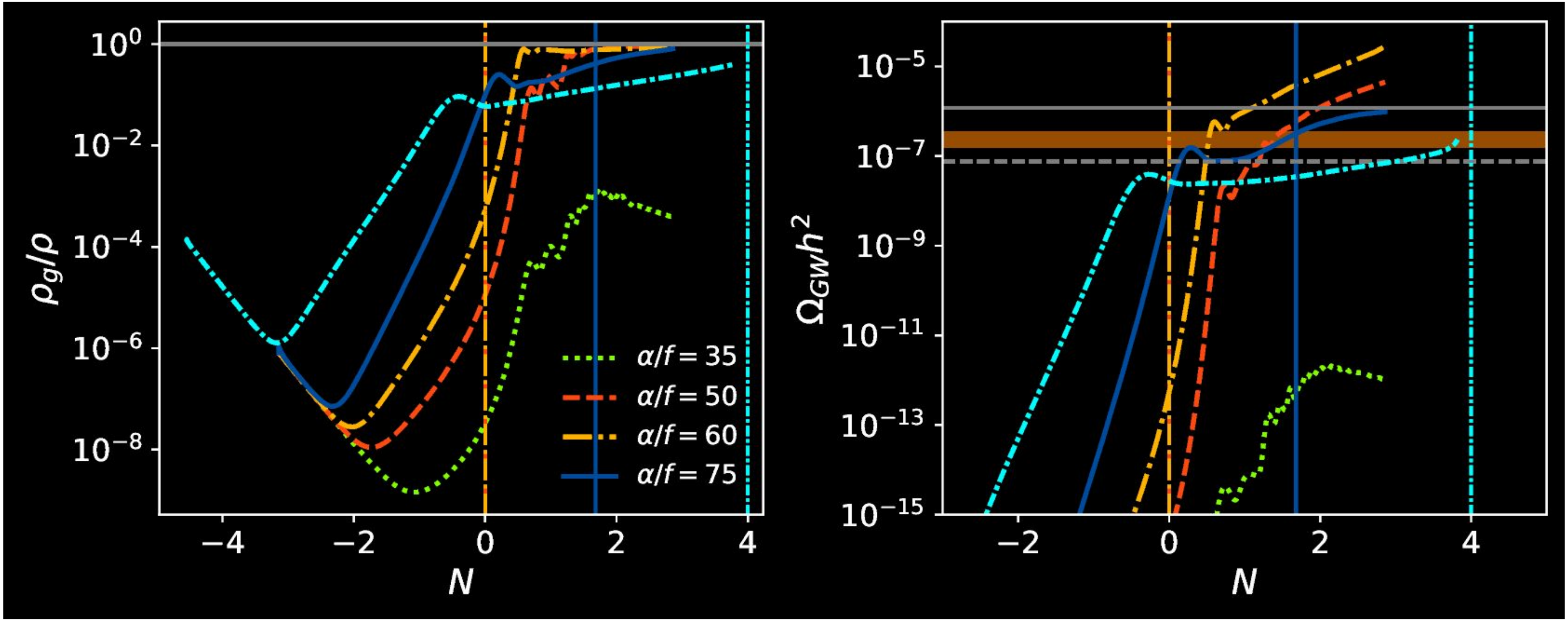


RS, AB, KS, AV, Arxiv 2411.04854

AB - Axel Brandenburg
KS – Kandaswamy Subramanian
AV - Alex Vikman

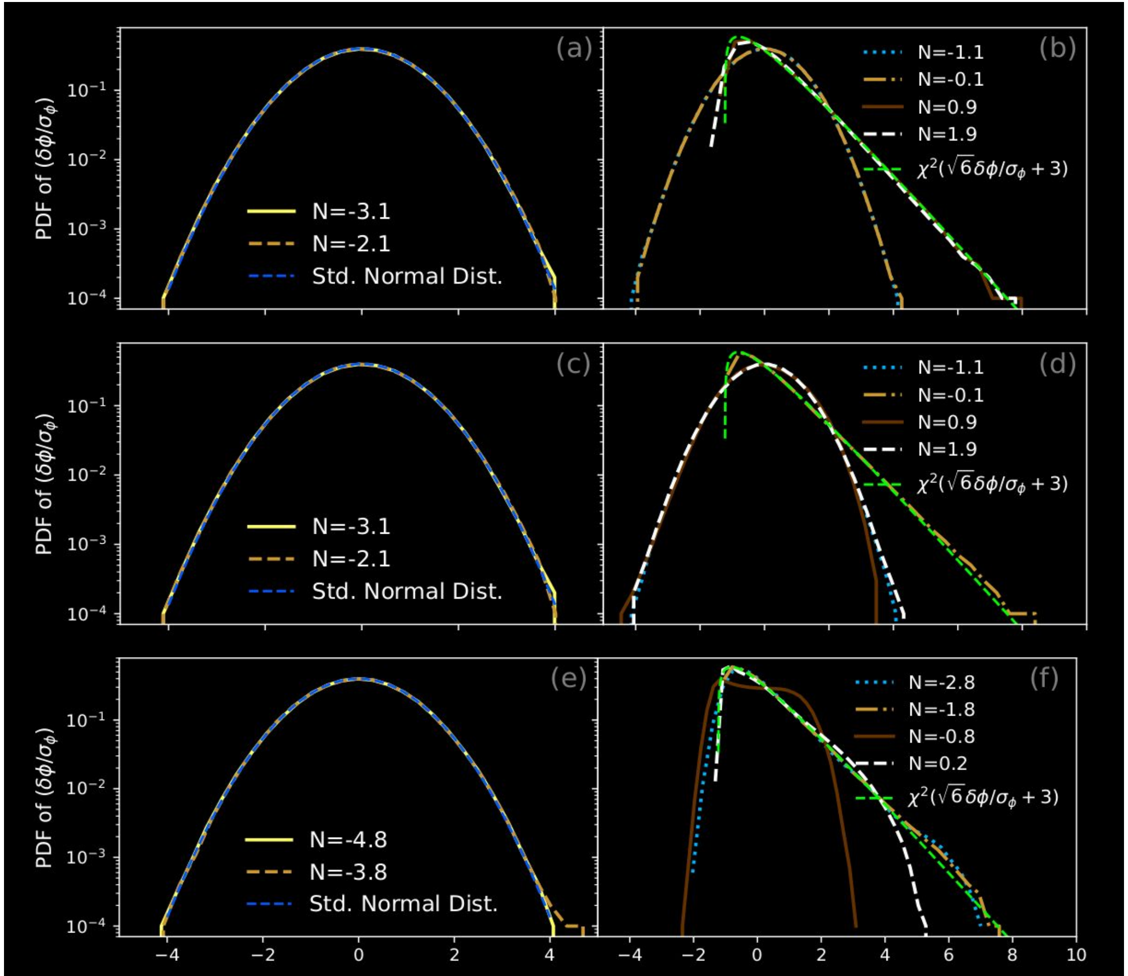
D. G. Figueroa, J. Lizarraga, A. Urio and J. Urrestilla, PRL 2023

Energy budget of gauge field and produced GWs



RS, AB, KS, AV, Arxiv 2411.04854

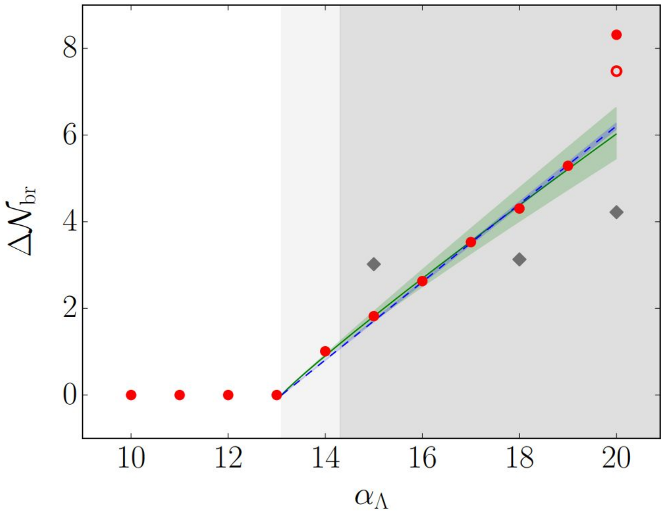
PDF of the axion fluctuations



RS, AB, KS, AV, Arxiv 2411.04854

A. Caravano, E. Komatsu, K. D. Lozanov and J. Weller, PRD 2022

Extended duration of inflation due to backreaction



α_Λ	$\Delta\mathcal{N}_{\rm br}$			
	linear (77)	power-law (78)	linear (79)	power-law (80)
20	6.21 ± 0.07	$6.03^{+0.61}_{-0.57}$	5.9 ± 0.1	$5.85^{+0.45}_{-0.45}$
22.5	8.46 ± 0.09	$8.04^{+0.90}_{-0.83}$	7.9 ± 0.2	$8.88^{+0.81}_{-0.77}$
25	10.7 ± 0.1	$10.0^{+1.21}_{-1.08}$	9.9 ± 0.2	$12.06^{+1.20}_{-1.12}$
30	15.2 ± 0.2	$13.9^{+1.80}_{-1.67}$	13.8 ± 0.3	$18.75^{+2.11}_{-1.94}$
35	19.7 ± 0.2	$17.6^{+2.53}_{-2.16}$	17.8 ± 0.4	$25.76^{+3.15}_{-2.84}$

D. G. Figueroa, J. Lizarraga, Nicolas Loayza,
A. Urio and J. Urrestilla, Arxiv: 2411.16368

Summary

- Axion-U(1) inflation exhibits rich phenomenology and this can be used to constrain the coupling between axion and gauge field.
- In the backreaction dominated regime, the PDF of axion fluctuations have less tails compared to the one considered in the analytical study. Hence the bounds obtained from PBH evaporation will be relaxed.
- The bounds obtained from constraints High frequency gravitational may also be relaxed.
- Need to Address: the effect of charged fields

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Thank you