Primordial Black Holes from Modulations in Axion Monodromy Inflation

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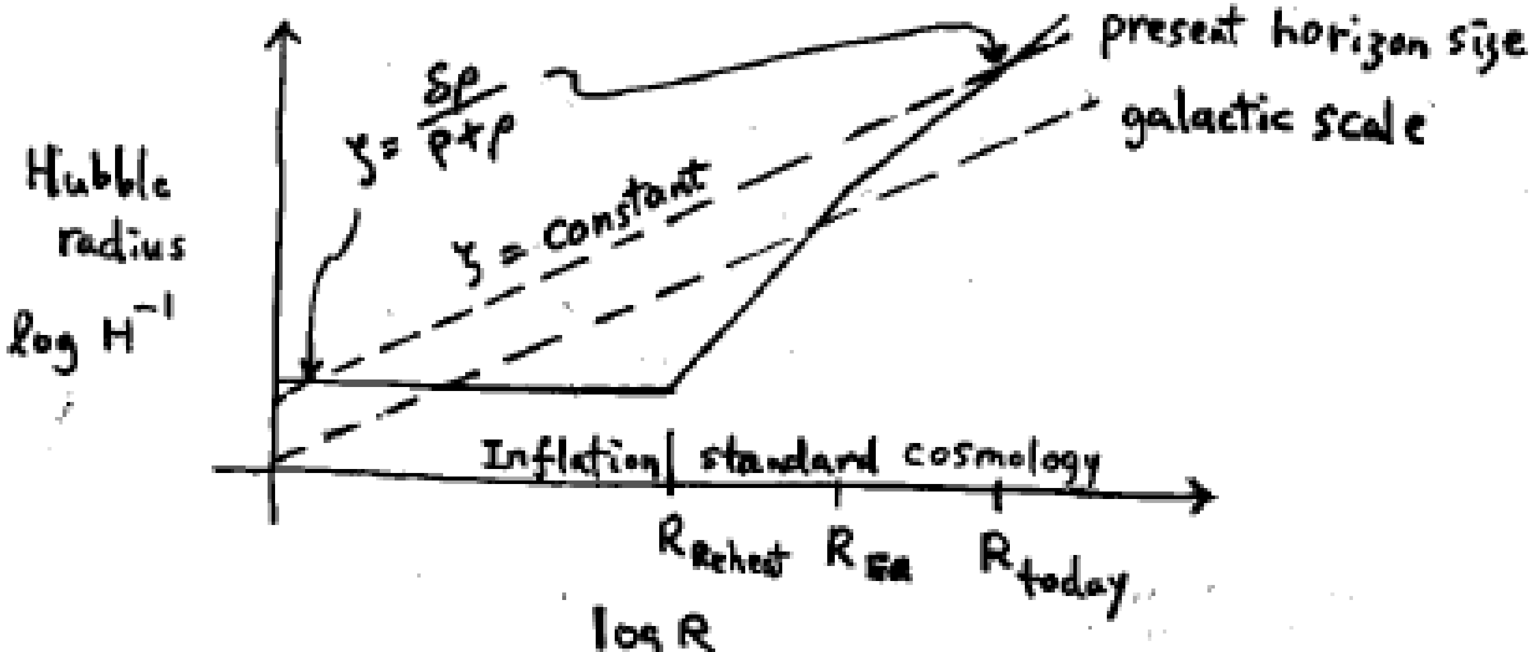
Introduction

- Axion monodromy realizes large-field inflation such as chaotic, power-law inflation models
- Monomial inflaton potential modulated by periodic corrections due to e.g. axion instanton effects
- Oscillations in matter power spectrum, imprinted on CMB anisotropies
- Axion couples to other quantum fields, leading to trapped inflation (successful inflation with a steep potential)
- Production of primordial black holes

Evolution of cosmological density perturbation



Evolution of gauge-invariant ζ Bardeen, Steinhardt & Turner 1983

- For super-horizon modes ζ = constant
- At horizon crossing ($\sim H^{-1}$) $\zeta = \dfrac{\delta\rho}{p+\rho}$

Scalar field equation of motion

$$\ddot{\phi} + 3\frac{\dot{R}}{R}\dot{\phi} + \frac{\partial V}{\partial \phi} = 0 \qquad \frac{\dot{R}}{R} = H$$

During inflation

$$\delta\rho = \delta\rho_\phi = \frac{\partial V}{\partial \phi}\delta\phi$$

$$P + \rho = P_\phi + \rho_\phi = \left(\tfrac{1}{2}\dot{\phi}^2 - V\right) + \left(\tfrac{1}{2}\dot{\phi}^2 + V\right) = \dot{\phi}^2$$

$$\therefore \left.\frac{\delta\rho}{\rho}\right|_{\substack{\text{horizon}\\ \text{cross-in}}} = \left.\frac{\delta\rho_\phi}{P_\phi + \rho_\phi}\right|_{\substack{\text{horizon}\\ \text{cross-out}}} = \left.\frac{\frac{\partial V}{\partial \phi}}{\dot{\phi}^2}\right|_{\substack{\text{horizon}\\ \text{cross-out}}} \times \delta\phi$$

$(P + \rho \simeq \rho)$

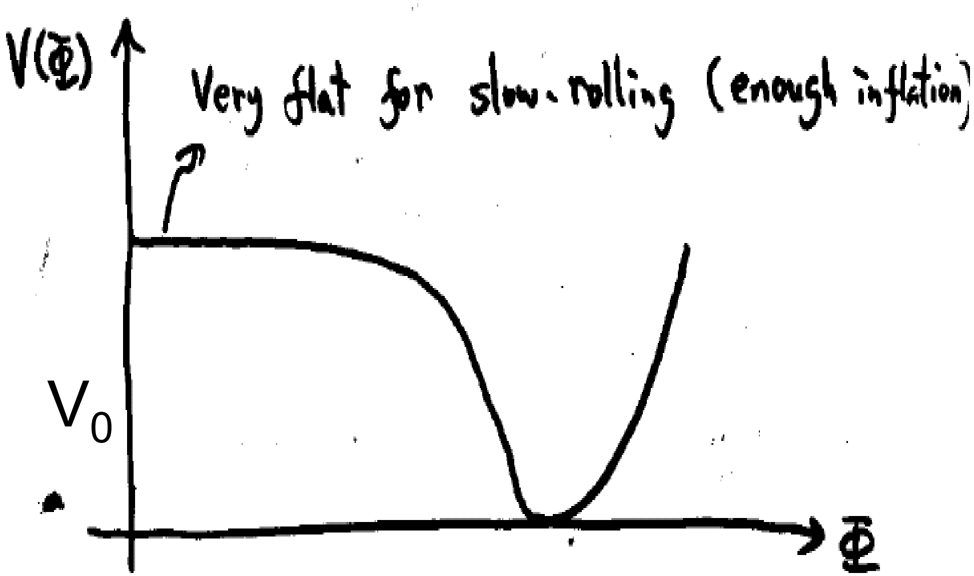
$\delta\phi \sim \frac{H}{2\pi}$ de Sitter quantum fluctuations

Hawking
Starobinsky 1982
Guth & Pi

Matter power spectrum $P_R(k) = (\delta\rho/\rho)^2$

Spectrum of the primordial curvature perturbation

A generic $V(\Phi)$ for inflation



scalar field equation of motion

$$\ddot{\phi} + 3\frac{\dot{R}}{R}\dot{\phi} + \frac{\partial V}{\partial \phi} = 0 \qquad \frac{\dot{R}}{R} = H$$

Φ Inflaton

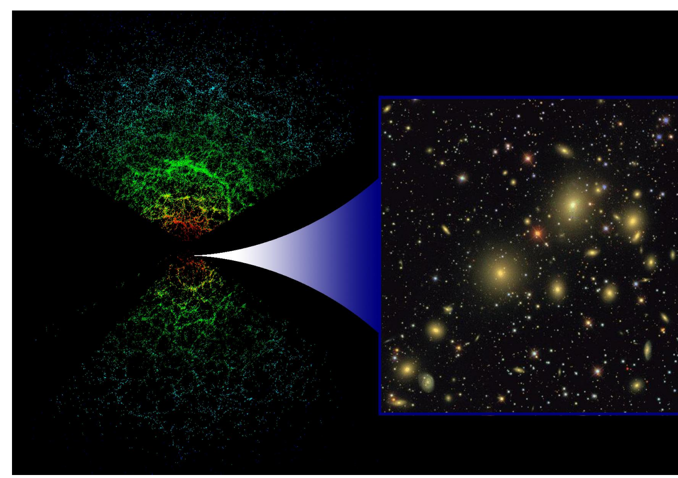
Slow-roll inflation

$$H^2 \simeq \frac{V(\phi)}{3M_{\rm Pl}^2},$$

$$3H\dot{\phi} \simeq -V'(\phi),$$

$$\mathcal{P}_{\mathcal{R}}(k) = \left(\frac{H}{\dot{\phi}}\right)^2 \left(\frac{H}{2\pi}\right)^2$$

$$\mathbf{P_R}(k) = (\delta\rho/\rho)^2$$



large scale structure of the Universe

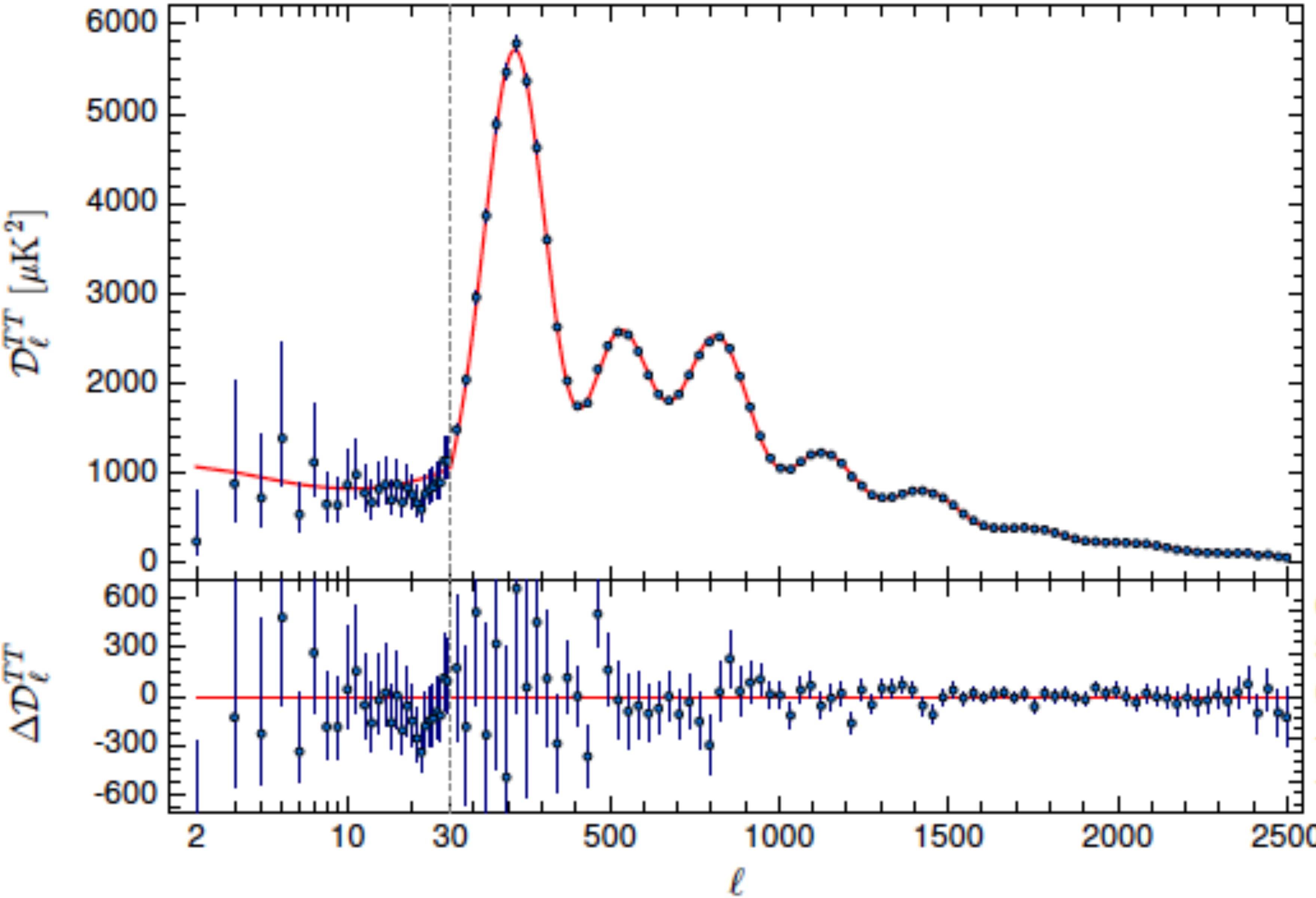
Planck Best-fit 6-parameter
ΛCDM model 2015

Density perturbation (scalar)

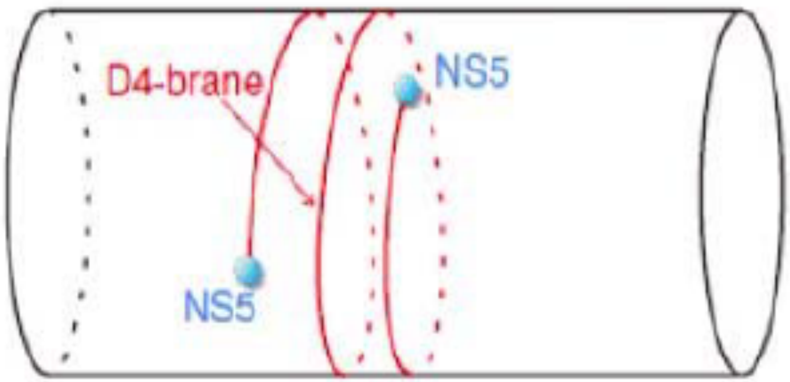
Spectral index $\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s-1}$

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040

Planck CMB Anisotropy $D^{TT}_l = l(l+1)\ C^T_l$ 2015



Axion Monodromy Inflation



Silverstein 2016 TASI Lectures;
McAllister, Westphal 2008; ….

$$V(\phi) = V_0 + \mu^{4-p}\phi^p + \Lambda(\phi)^4 \cos\Big(\gamma_0 + \phi/f(\phi)\Big)$$

Large-field inflation
p=3,2,4/3,1,2/3

Modulations

Oscillations in matter power spectrum $P_R(k)$, imprinted in CMB anisotropies

Primordial Black Holes

- Formed at high-density contrasts over a wide range of scales or masses in the radiation-dominated Universe
- There have been stringent astrophysical and cosmological constraints on M_{PBH}
- A window $10M_{\odot}<M_{BH}<100M_{\odot}$ is still allowed
- These PBHs could be the binary BHs observed by aLIGO gravity-wave detectors

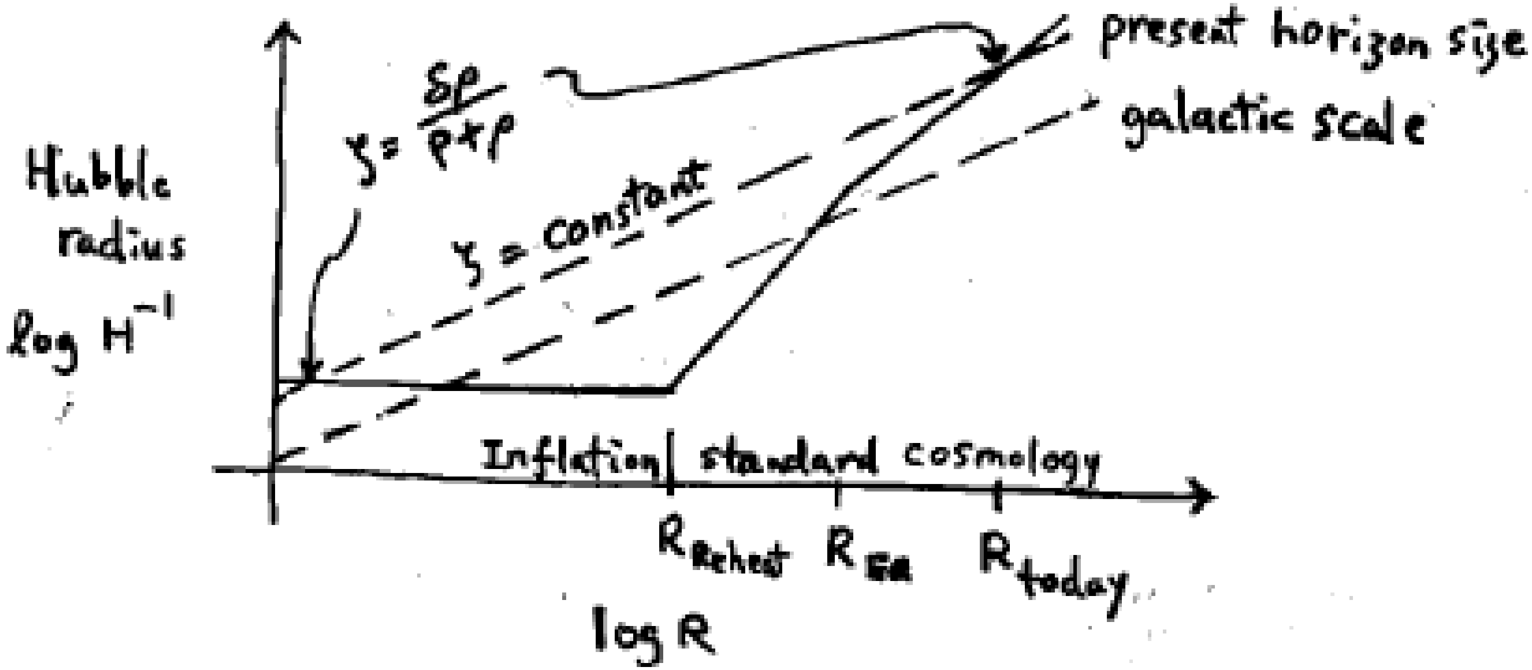
Bird et al. 16. Sasaki et al. 16

- These PBHs behave like cold dark matter
- They, although being of baryonic origin, do not participate in big-bang nucleosynthesis

PBH Formation

- spontaneously formed in phase transitions, e.g., quark-hadron phase transition $M_{BH} \sim M_{\odot}$
- arisen from the collapse of horizon-sized large matter inhomogeneities seeded by quantum fluctuations during inflation that re-enter the horizon in the subsequent radiation-dominated Universe, with M_{BH} spans a wide range of mass

Evolution of cosmological density perturbation



Evolution of gauge-invariant ζ Bardeen, Steinhardt & Turner 1983

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How to determine PBH mass

as follows. The energy contained within the comoving seed volume that leaves the horizon N e-foldings before the end of inflation is governed by

$$\frac{4}{3}\pi H^{-3}\rho\, e^{3N} \quad \text{with} \quad \rho = 3H^2 M_p^2, \tag{1}$$

where H is the Hubble constant during inflation and M_p the reduced Planck mass. After the inflation has ended,

The comoving volume re-enters the horizon when

$$M_{\rm BH} = \frac{4\pi M_p^2}{H}\, e^{2N} = 2.74 \times 10^{-38} e^{2N} \left(\frac{M_p}{H}\right) M_\odot. \tag{2}$$

PBH Production in Inflation

- Single-field slow-roll inflation models, matter density perturbation (*$\delta\rho/\rho \sim 10^{-5}$*) too small
- Modified inflation potential to achieve blue-tilted matter power spectra or running spectral indices, leading to large density perturbation at the end of inflation, but mostly $M_{PBH} << M_\odot$
- To boost M_{PBH} , hybrid inflation, double inflation, curvaton models by inflating small-scale density perturbation to the size of a stellar-mass to supermassive PBH.

Interacting inflaton

Quantum environment Wu et al. JCAP 07

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \, \partial_\nu \phi + \frac{1}{2} g^{\mu\nu} \partial_\mu \sigma \, \partial_\nu \sigma - V(\phi) - \frac{m_\sigma^2}{2} \sigma^2 - \frac{g^2}{2} \phi^2 \sigma^2$$

Trapped Inflation Green et al. PRD 09

Inflaton coupled to instantaneously massless fields

$$\mathcal{L} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) + \frac{1}{2} \sum_i (\partial_\mu \chi_i \partial^\mu \chi_i - g^2 (\phi - \phi_i)^2 \chi_i^2) + \cdots,$$

Natural Inflation with axion-like couplings

$$\mathcal{S} = \int d^4 x \sqrt{-g} \left[\frac{M_p^2}{2} R - \frac{1}{2} \partial_\mu \varphi \partial^\mu \varphi - V(\varphi) - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{\alpha}{4f} \varphi \tilde{F}^{\mu\nu} F_{\mu\nu} \right]$$

Trapped Inflation

We consider a version of the trapped inflation driven by a pseudoscalar φ that couples to a $U(1)$ gauge field A_μ:

$$\mathcal{S} = \int d^4x\sqrt{-g}\left[\frac{M_p^2}{2}R - \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{\alpha}{4f}\varphi\tilde{F}^{\mu\nu}F_{\mu\nu}\right], \quad (3)$$

$$\varphi = \phi(\eta) + \delta\varphi(\eta, \vec{x})$$

Under the temporal gauge, $A_\mu = (0, \vec{A})$, we decompose $\vec{A}(\eta, \vec{x})$ into its right and left circularly polarized Fourier modes, $A_\pm(\eta, \vec{k})$, whose equation of motion is then given by

$k/(aH) < 2|\xi|$

Spinoidal instability

$$\left[\frac{d^2}{d\eta^2} + k^2 \mp 2aHk\xi\right]A_\pm(\eta, k) = 0, \quad \xi \equiv \frac{\alpha}{2fH}\frac{d\phi}{dt}. \quad (5)$$

Background

$$\frac{d^2\phi}{dt^2} + 3H\frac{d\phi}{dt} + \frac{dV}{d\phi} = \frac{\alpha}{f}\langle \vec{E}\cdot\vec{B}\rangle,$$

$$3H^2 = \frac{1}{M_p^2}\left[\frac{1}{2}\left(\frac{d\phi}{dt}\right)^2 + V(\phi) + \frac{1}{2}\langle \vec{E}^2 + \vec{B}^2\rangle\right]$$

$$\frac{1}{2}\langle \vec{E}^2 + \vec{B}^2\rangle = \int \frac{dk\, k^2}{4\pi^2 a^4}\sum_{\lambda=\pm}\left(\left|\frac{dA_\lambda}{d\eta}\right|^2 + k^2|A_\lambda|^2\right),$$

$$\langle \vec{E}\cdot\vec{B}\rangle \;=\; -\int \frac{dk\, k^3}{4\pi^2 a^4}\frac{d}{d\eta}\left(|A_+|^2 - |A_-|^2\right).$$

Perturbation

$$\left[\frac{\partial^2}{\partial t^2} + 3\beta H\frac{\partial}{\partial t} - \frac{\vec{\nabla}^2}{a^2} + \frac{d^2V}{d\phi^2}\right]\delta\varphi(t,\vec{x}) = \frac{\alpha}{f}\left(\vec{E}\cdot\vec{B} - \langle \vec{E}\cdot\vec{B}\rangle\right)$$

$$\beta \equiv 1 - 2\pi\xi\frac{\alpha}{f}\frac{\langle \vec{E}\cdot\vec{B}\rangle}{3H(d\phi/dt)}$$

$$\delta\varphi = \frac{\alpha}{3\beta f H^2}\left(\vec{E}\cdot\vec{B} - \langle \vec{E}\cdot\vec{B}\rangle\right) \qquad \Delta_\zeta^2(k) = \langle \zeta(x)^2\rangle = \frac{H^2\langle \delta\varphi^2\rangle}{(d\phi/dt)^2} = \left[\frac{\alpha\langle \vec{E}\cdot\vec{B}\rangle}{3\beta f H(d\phi/dt)}\right]^2$$

$$V(\varphi) = \frac{m^2}{2}\varphi^2$$

$$m = 1.8 \times 10^{13}\ \text{GeV}$$

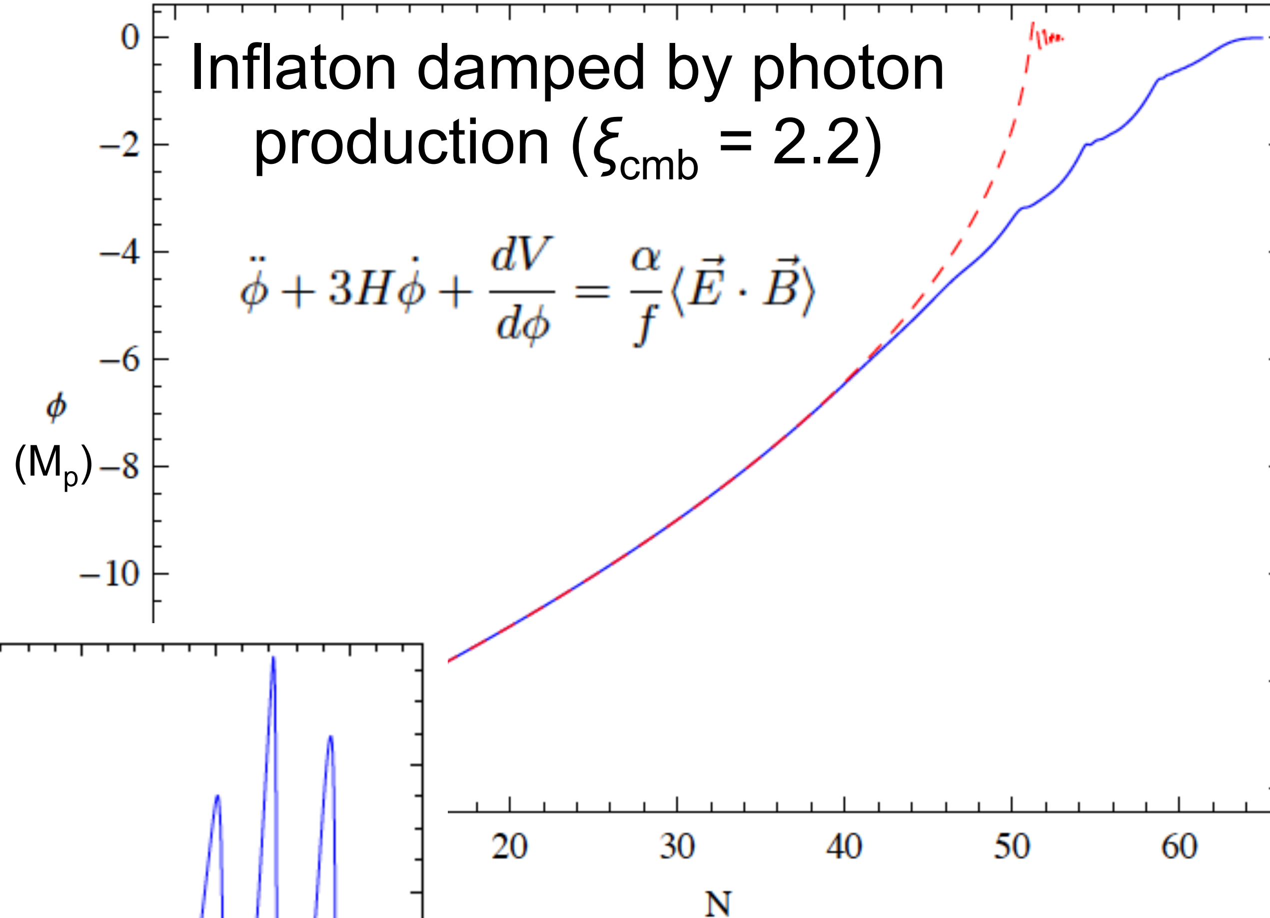
$$\alpha = 32 \qquad f = M_p$$

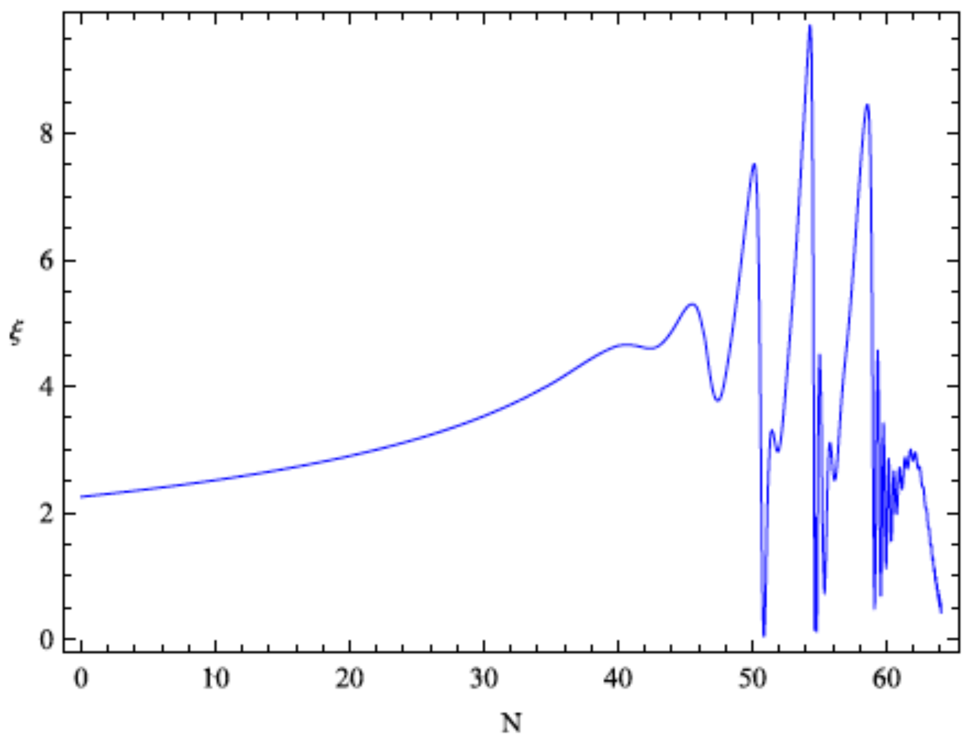
$$\phi_0 = -14.15\ M_p$$

$$\dot{\phi}_0 = 6 \times 10^{-6}\ M_p^2$$

Inflaton damped by photon production (ξ_{cmb} = 2.2)

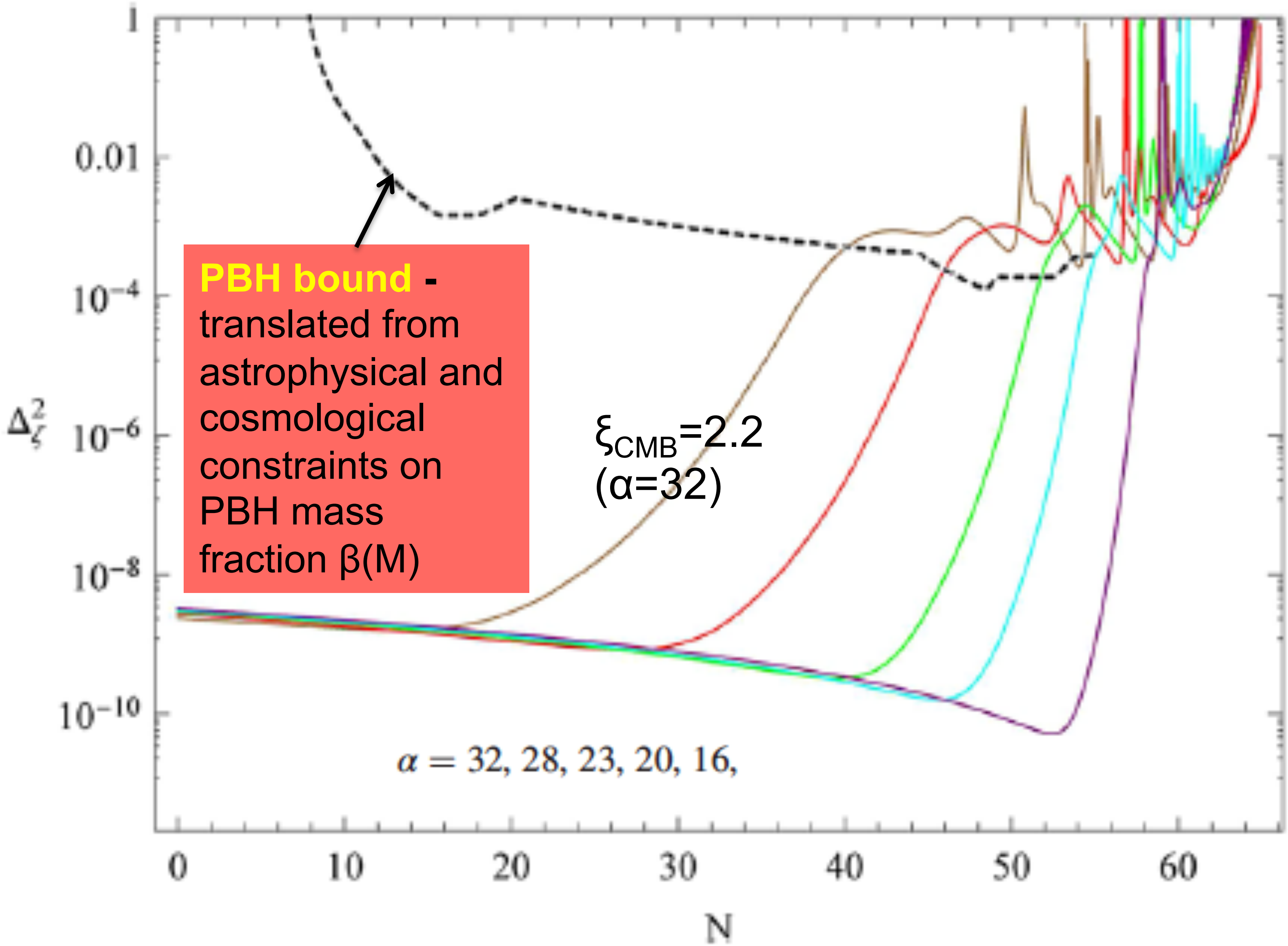
$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = \frac{\alpha}{f}\langle \vec{E} \cdot \vec{B} \rangle$$



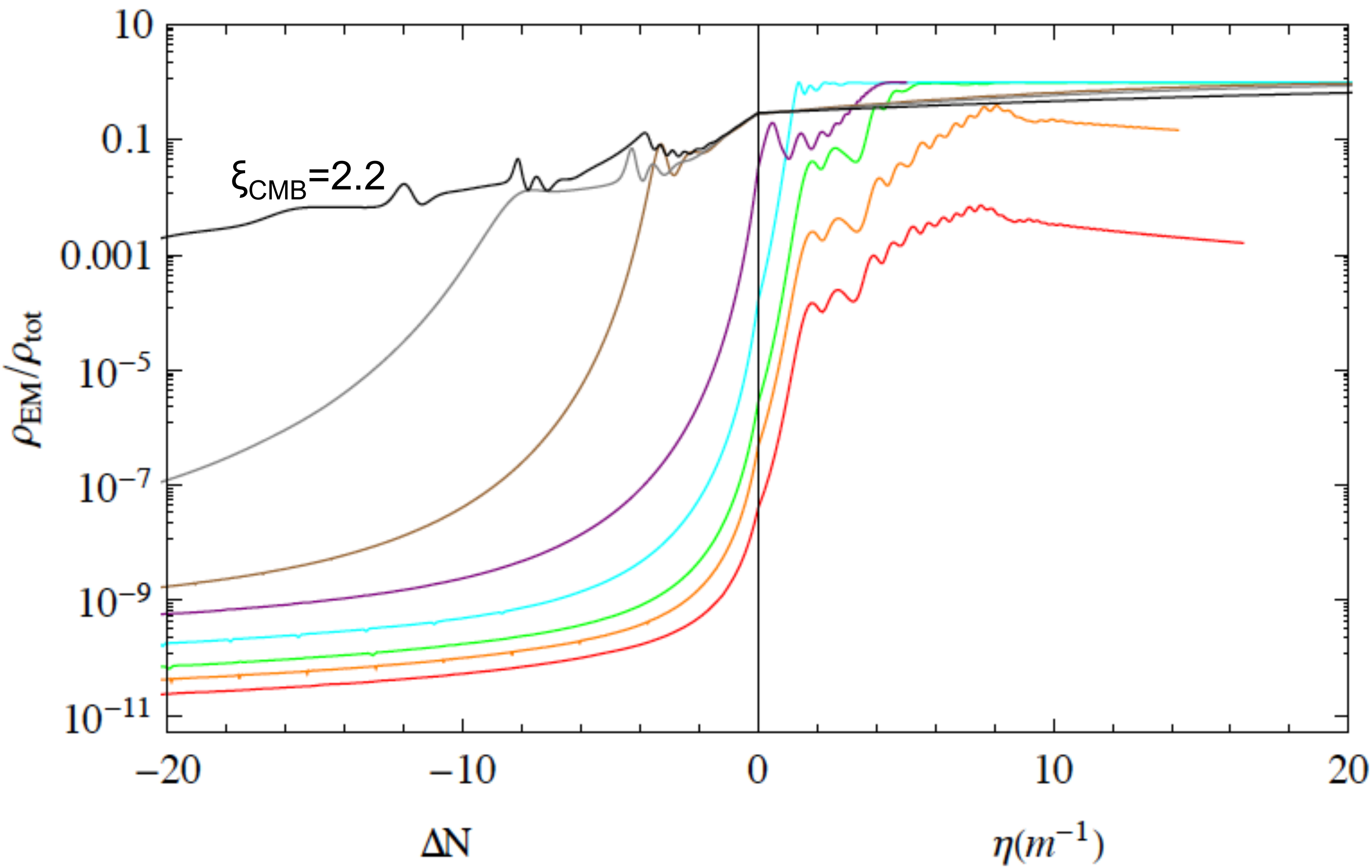


Cheng, Ng, Lee 16

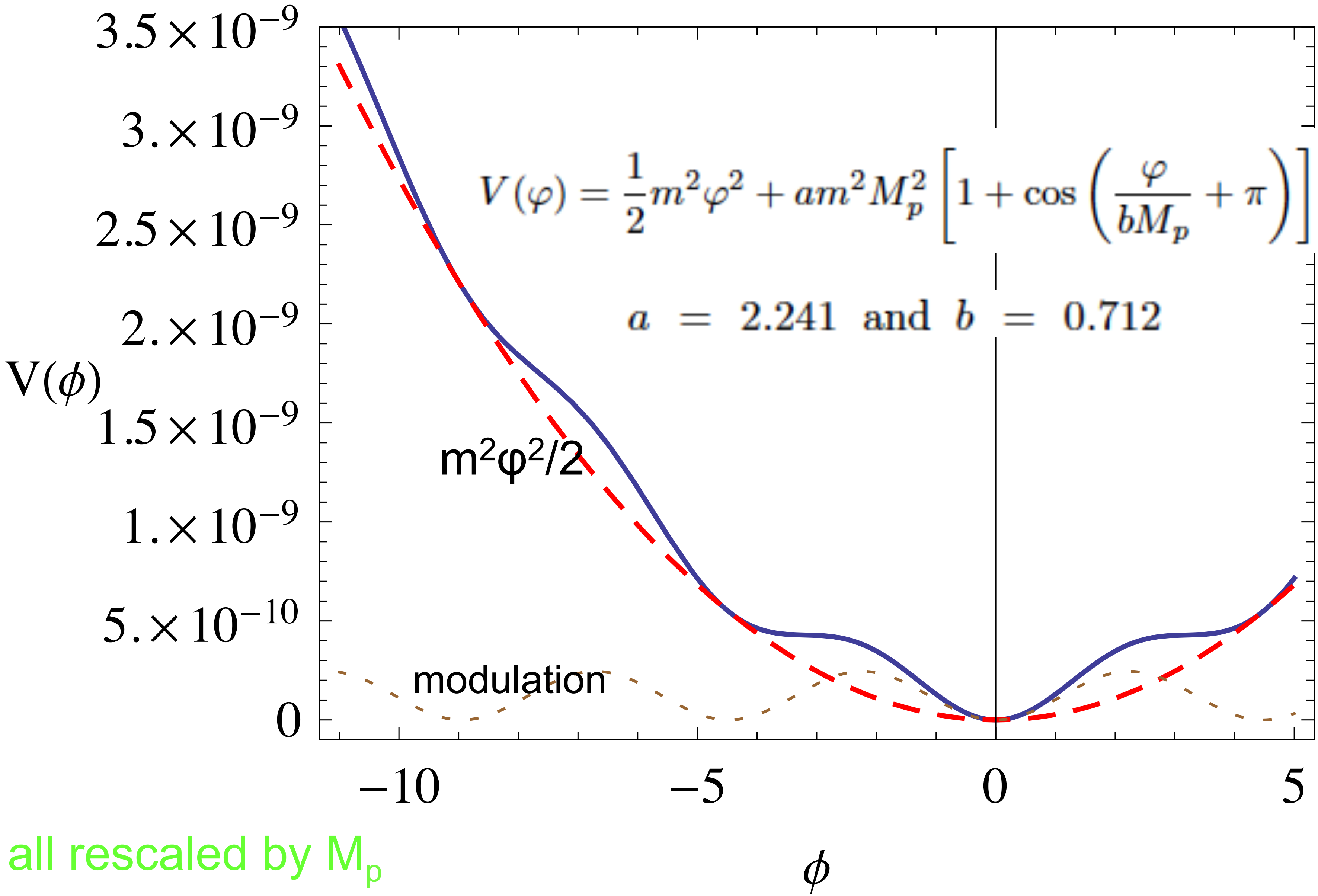
Density perturbation and PBH production



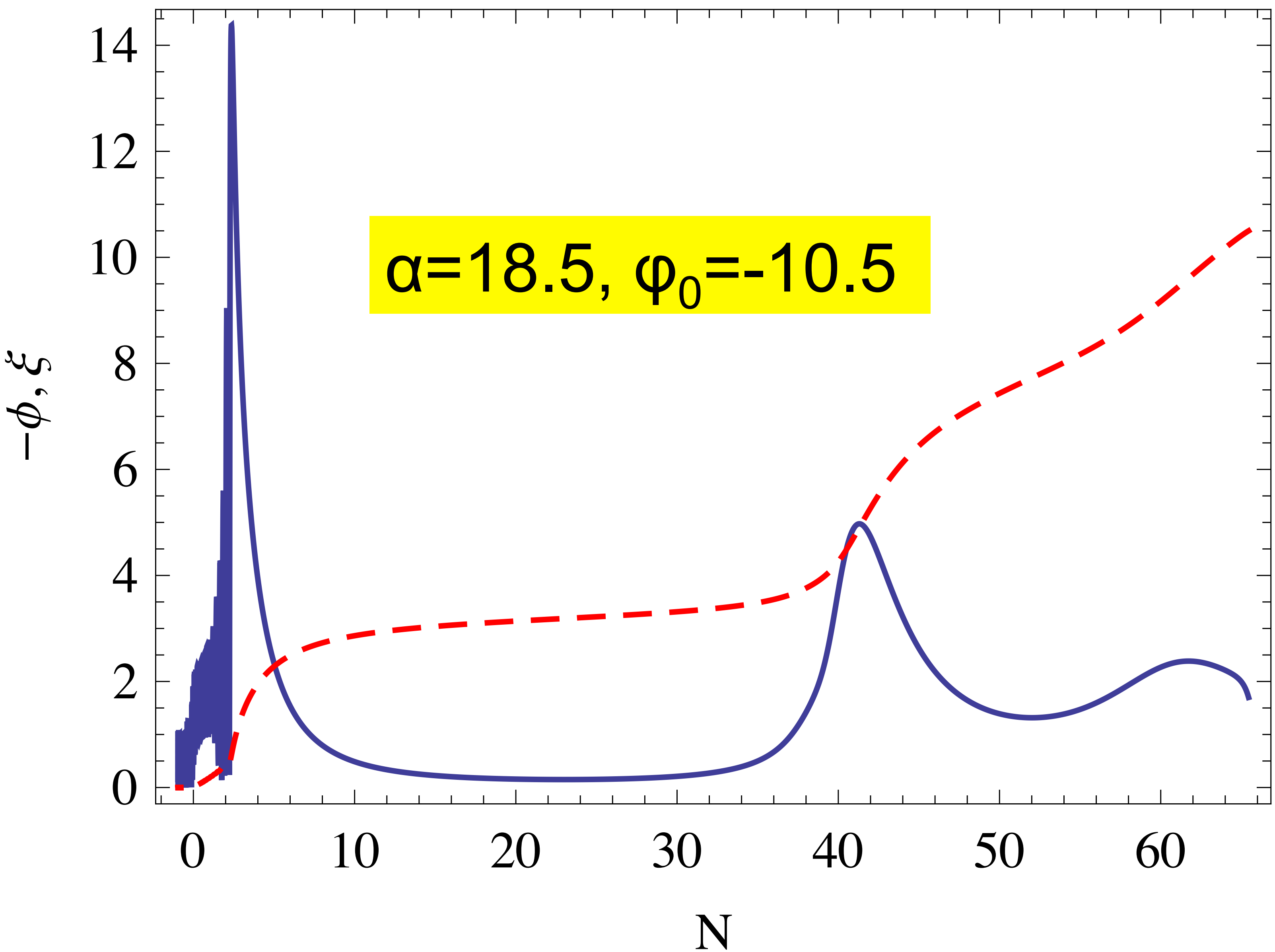
Leading to a warm inflation



Axion monochromy inflation with modulations



all rescaled by M_p



Note that inflation starts at N=61

Production of 10-100$M_\odot$ PBHs

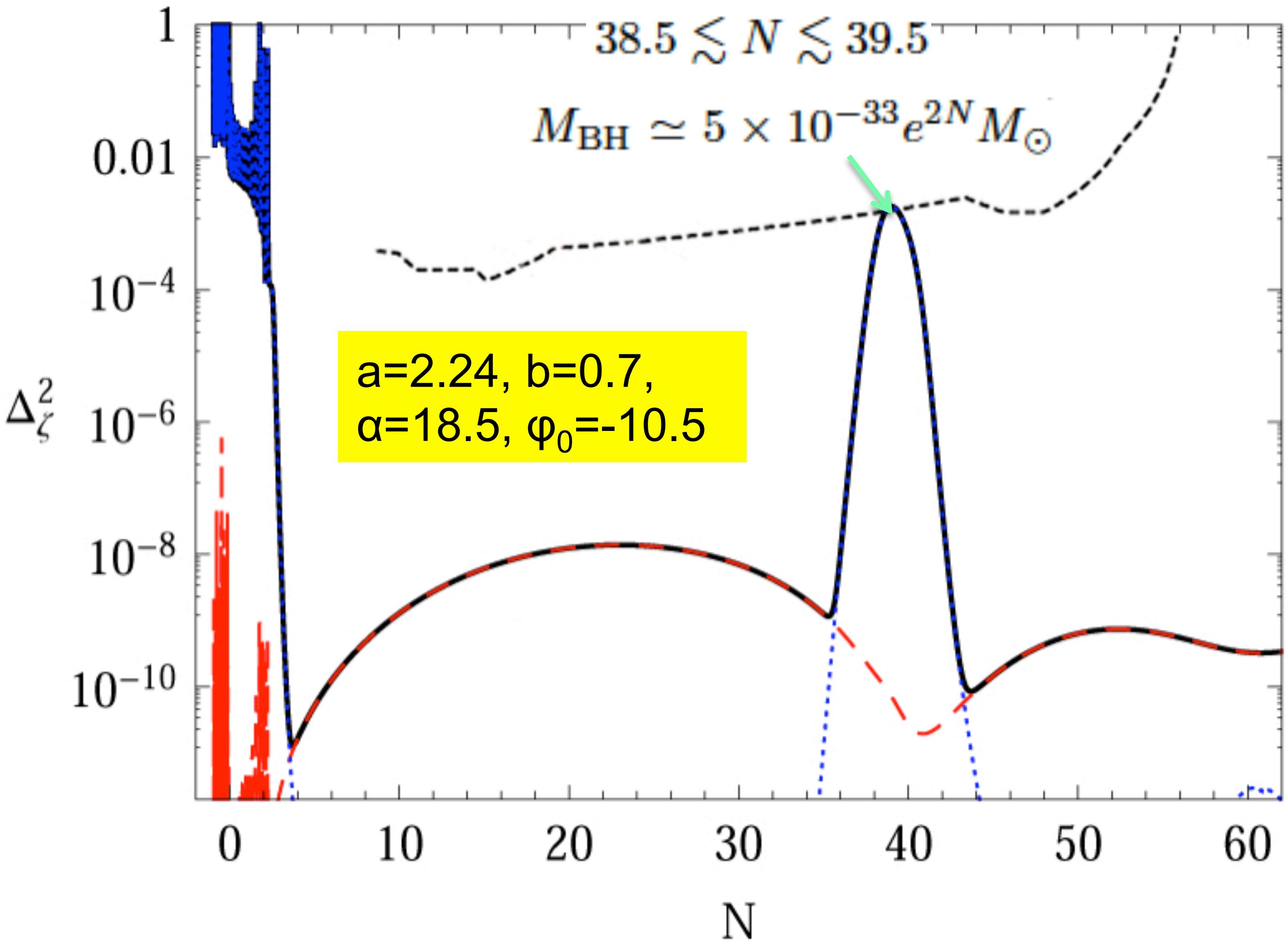
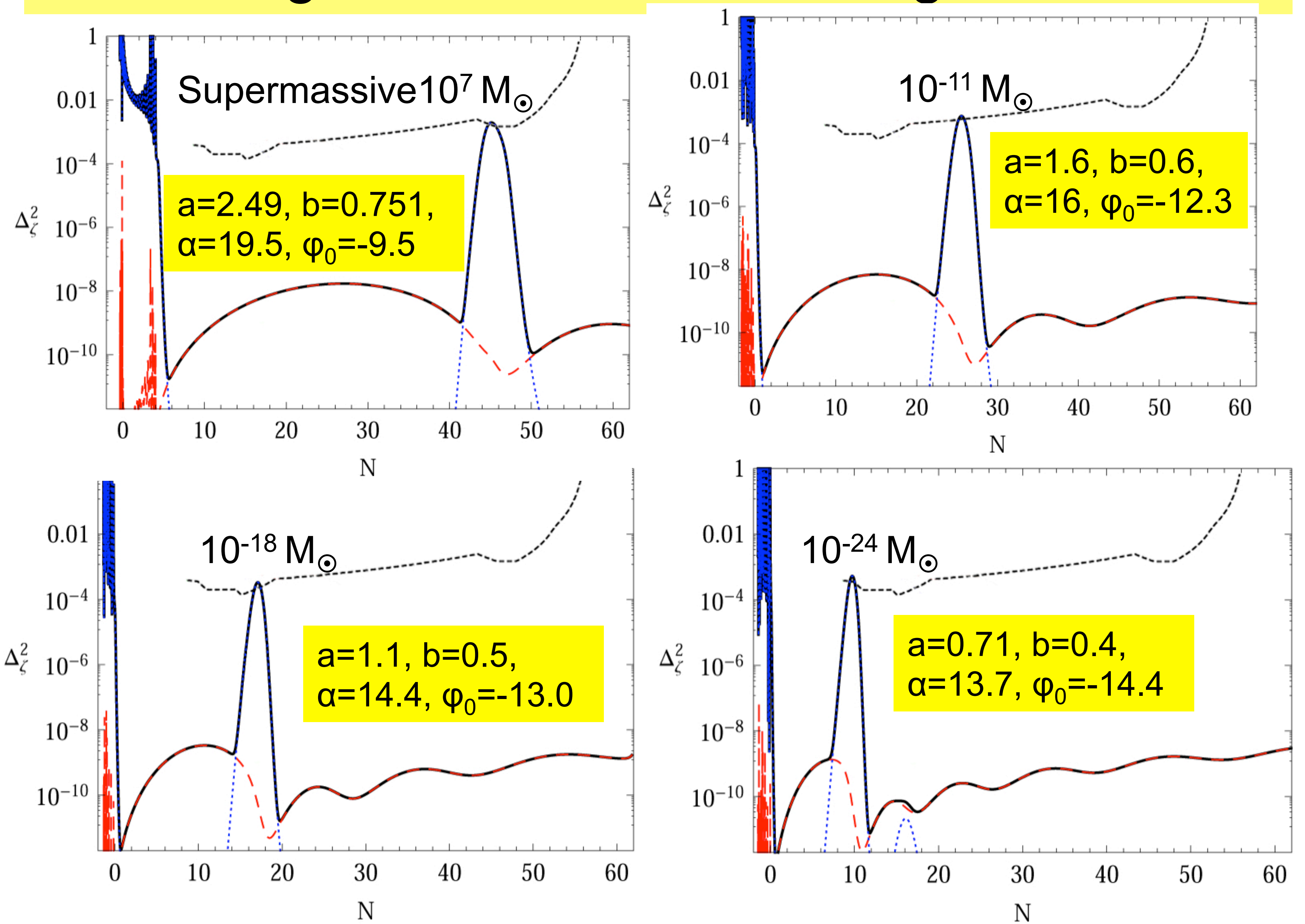


FIG. 3: Solid line is the total power spectrum of the curvature perturbation. The contribution induced by photon production is denoted by the dotted line and the vacuum contribution by the dashed line. The e-folding N denotes the time when the k-mode leaves the horizon. The primordial black hole bound is the short-dashed line.

Producing PBHs with a wide range of masses



Conclusion

- The binary BHs observed by aLIGO gravity-wave detectors may be primordial BHs
- 10-100 $M_{\odot}$ PBHs could be dark matter
- Production of PBHs in axion monodromy inflation
- Modulation can produce 10-100 $M_{\odot}$ PBHs
- Also can produce a wide range of PBH masses
- How to distinguish PBHs from astrophysical BHs?
- CMB non-Gaussianty