IRN Terascale @ Bonn

Induced gravitational waves from the cosmic coincidence

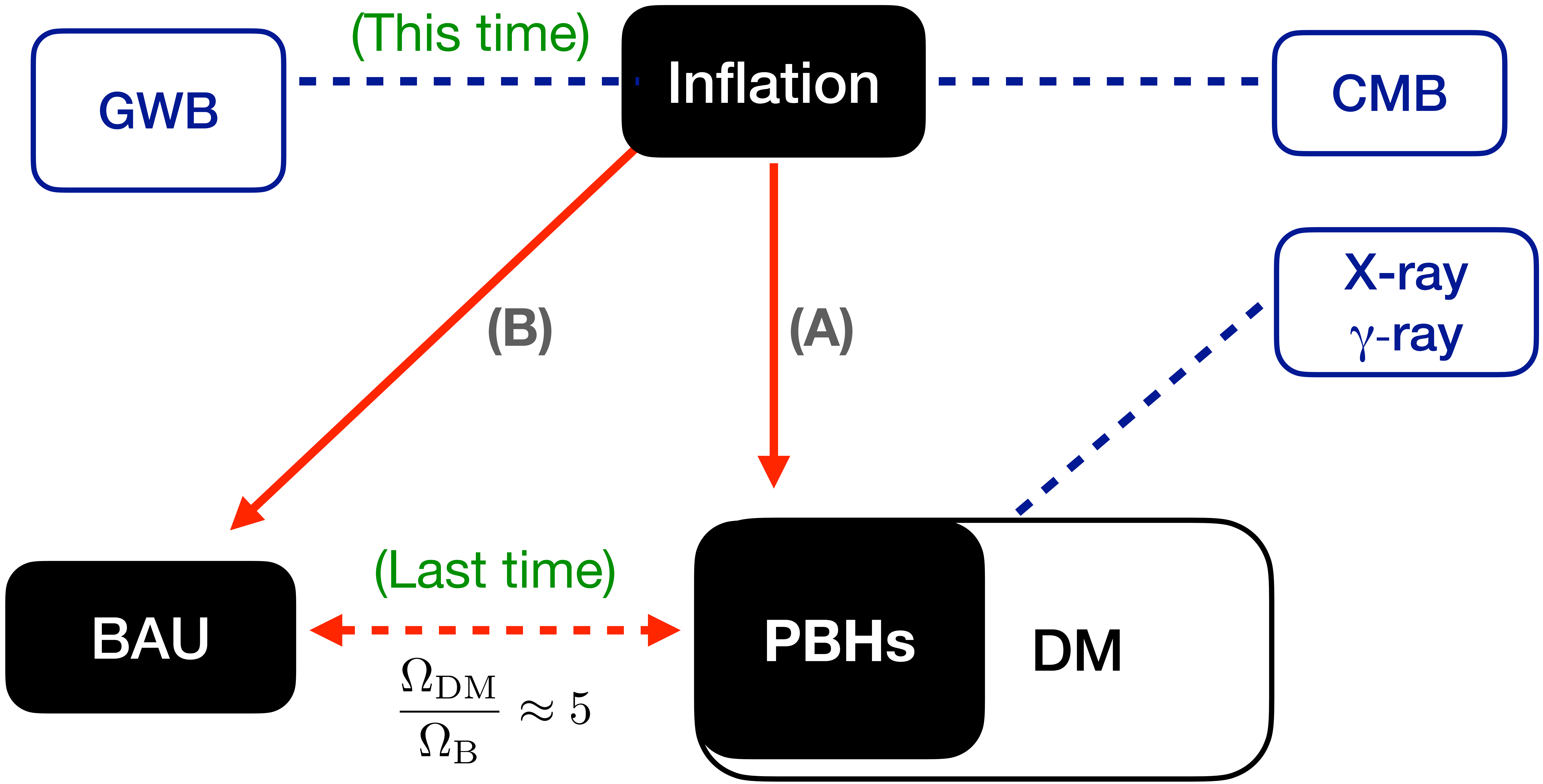
Based on [2202.00700] with Shyam Balaji (LPTHE & IAP), Joseph Silk (IAP & JHU & Oxford)

Yi-Peng Wu, LPTHE & Sorbonne Université, 29/03/2022

see also [2109.00118] & [2109.09875]

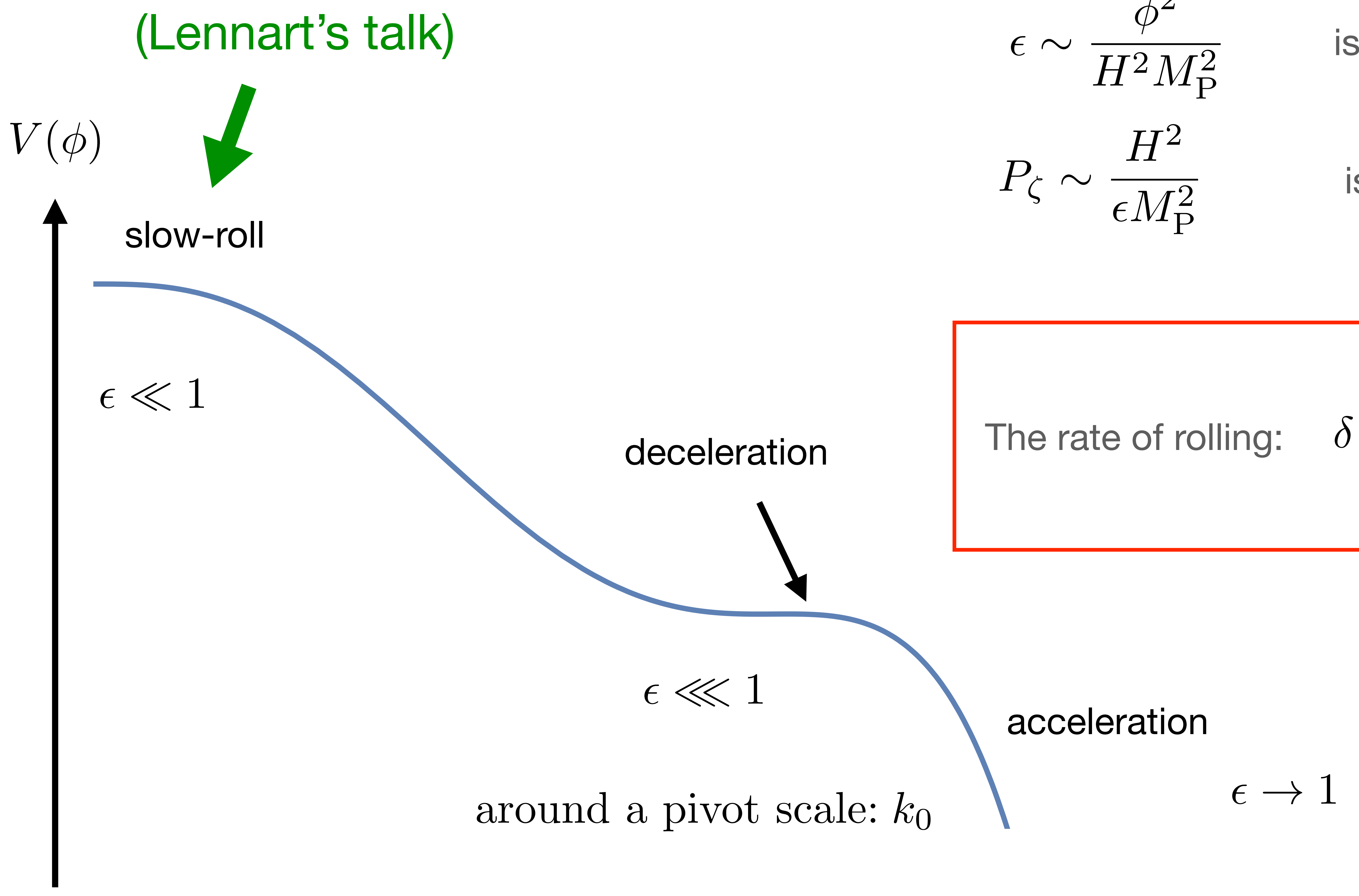
with Elena Pinetti (Fermi Lab), Kalliopi Petraki (LPTHE & Nikhef)

LPTHE
LABORATOIRE DE PHYSIQUE THEORIQUE ET HAUTES ENERGIES



GWB
(This time)
Inflation
CMB
X-ray
γ-ray
(B)
(A)
(Last time)
BAU
PBHs
DM
$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \approx 5$

(A) PBHs from (ultra-slow-roll) inflation

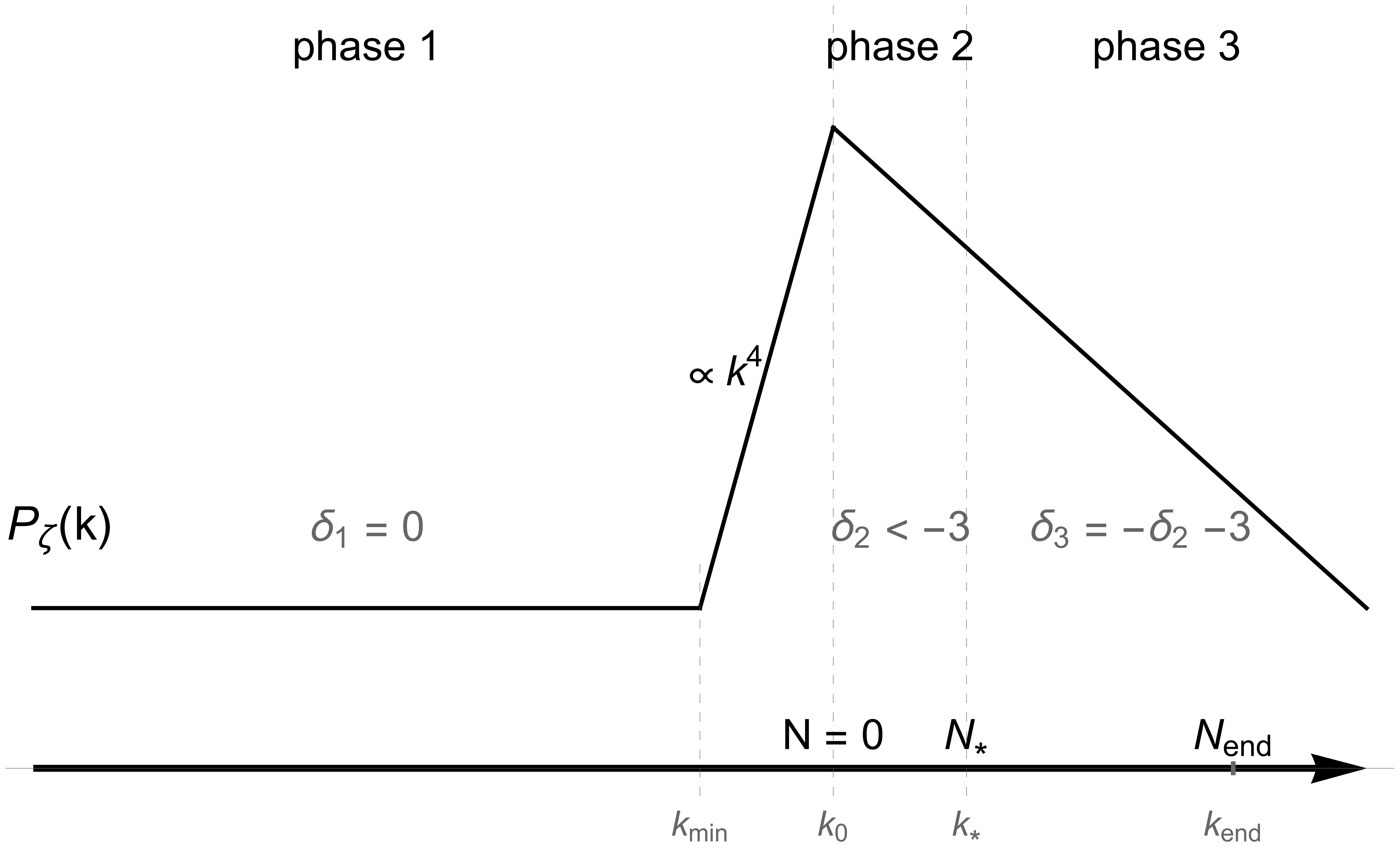


$$\epsilon \sim \frac{\dot{\phi}^2}{H^2 M_{\rm P}^2}$$ is the first slow-roll parameter

$$P_\zeta \sim \frac{H^2}{\epsilon M_{\rm P}^2}$$ is the power spectrum of curvature perturbation

The rate of rolling: $$\delta = \frac{\ddot{\phi}}{H\dot{\phi}} \approx \begin{cases} 0, & \text{slow-roll}, \\ \delta_{\rm USR} \leq -3, & \text{ultra-slow-roll}, \\ \delta \geq 0, & \text{fast-roll}, \end{cases}$$

Ultra-slow-roll inflation



k_0 is the pivot scale for the peak of the power spectrum

Key parameters:

$$\delta \equiv \frac{\ddot{\phi}}{H\dot{\phi}}, \qquad \Delta N \equiv N_* - N_0, \qquad N_{\rm end},$$

N_0 is the onset of the USR phase

N_* is the end of the USR phase

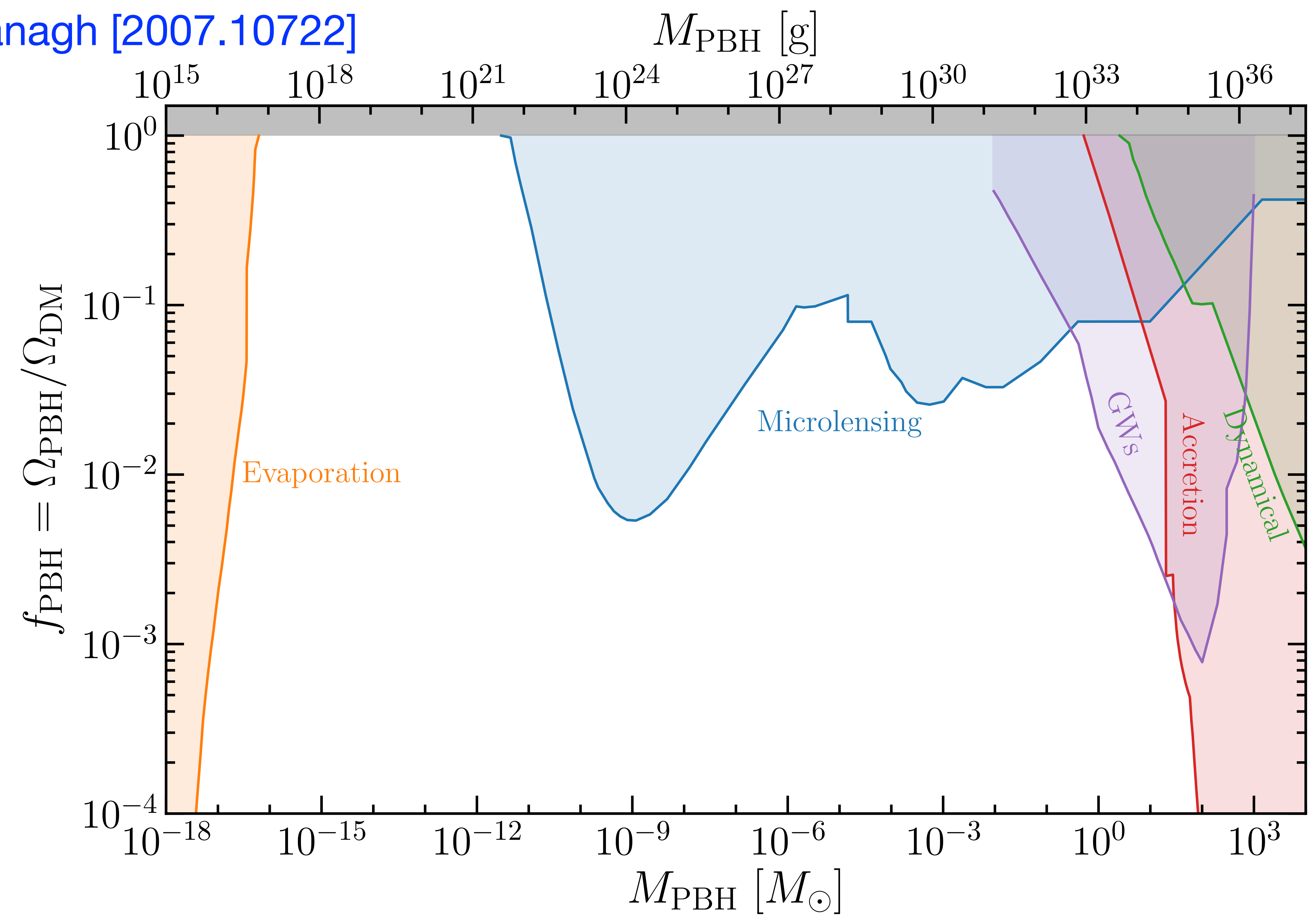
$N_{\rm end}$ is the end of inflation

(A) PBHs from (ultra-slow-roll) inflation

Enhanced curvature perturbation → large density contrast → collapse to PBHs

(inflation) (reheating) (radiation domination)

Green & Kavanagh [2007.10722]



The pivot scale:

$$k_0 \sim 10^{12} - 10^{15}\mathrm{Mpc}^{-1}$$

Schwarschild radius:

$$10^{-9} - 10^{-13}\mathrm{m}$$

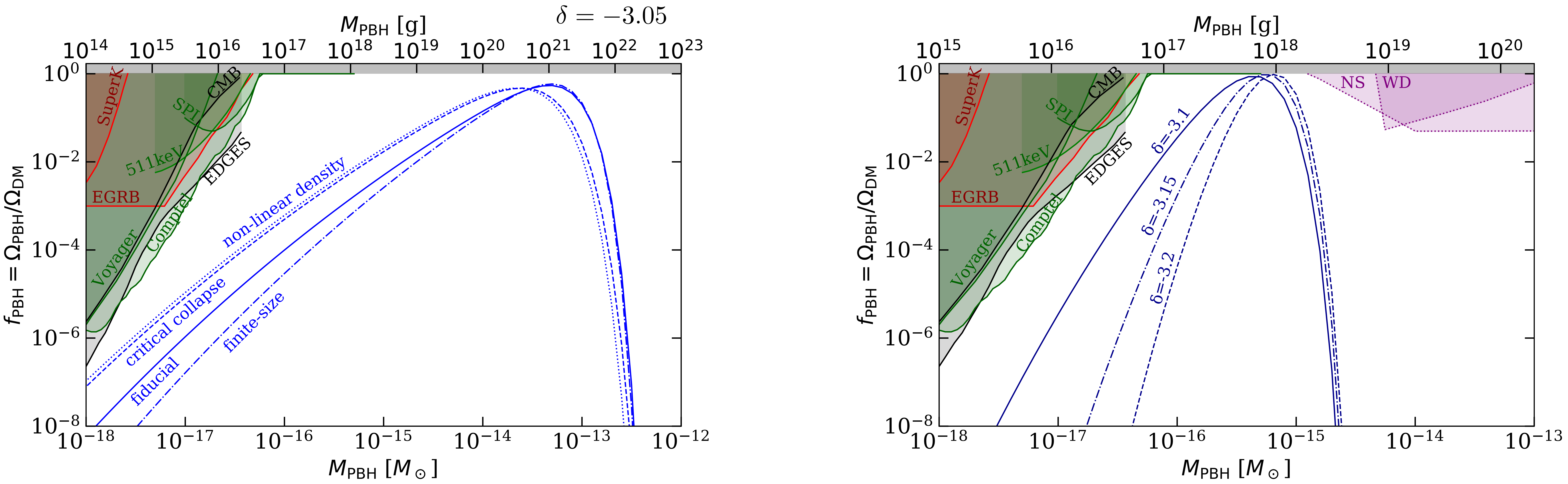
(A) PBHs from (ultra-slow-roll) inflation …as all dark matter

$$f_{\rm PBH} = f_{\rm PBH}(\delta, N_*) = 1$$

USR parameters

YPW, Pinetti, Petraki & Silk [2109.00118]

YPW, Pinetti, & Silk [2109.09875]

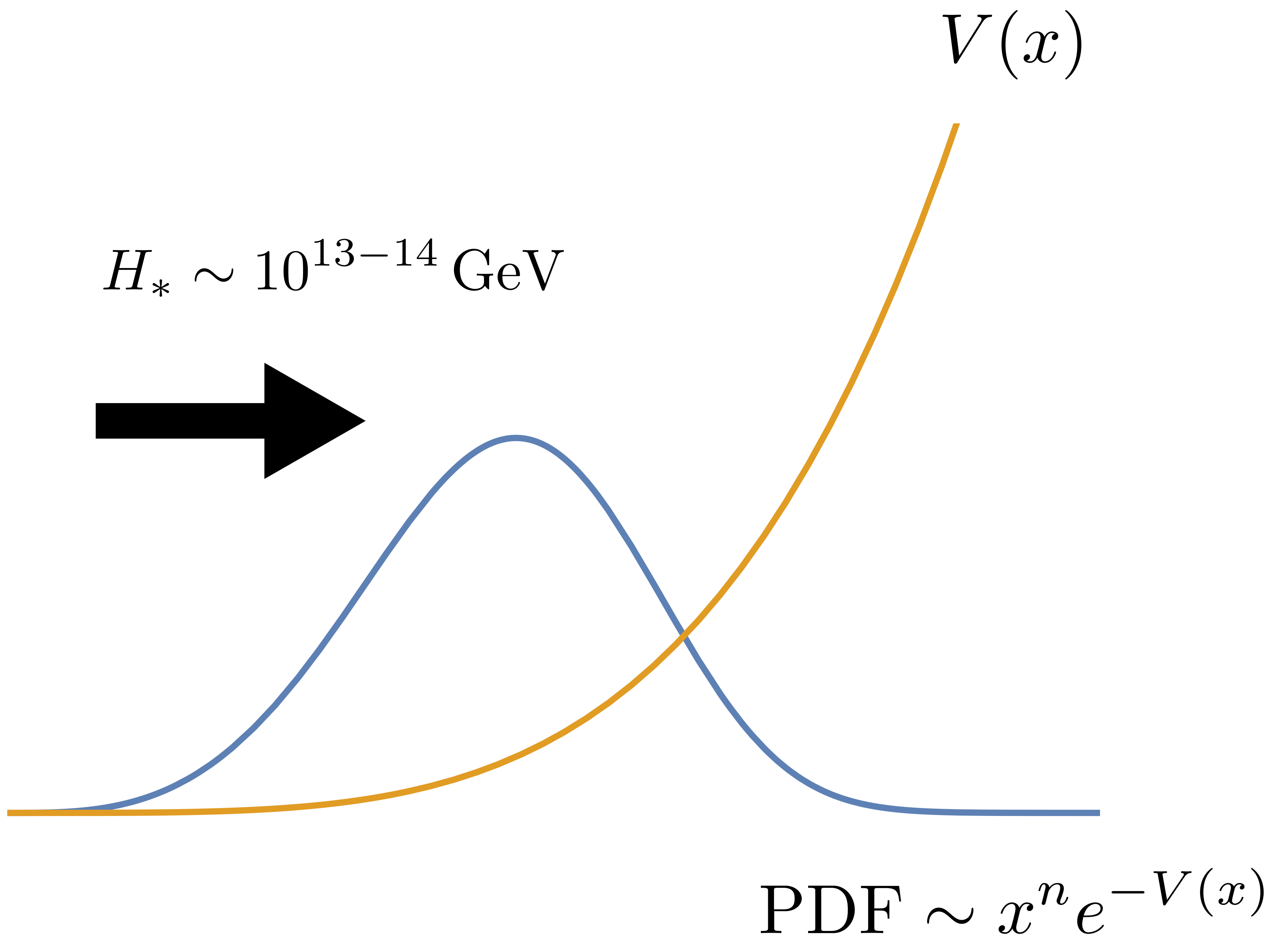


Fiducial: the Press-Schechter method (Carr 1975)

(B) Baryogenesis from USR inflation

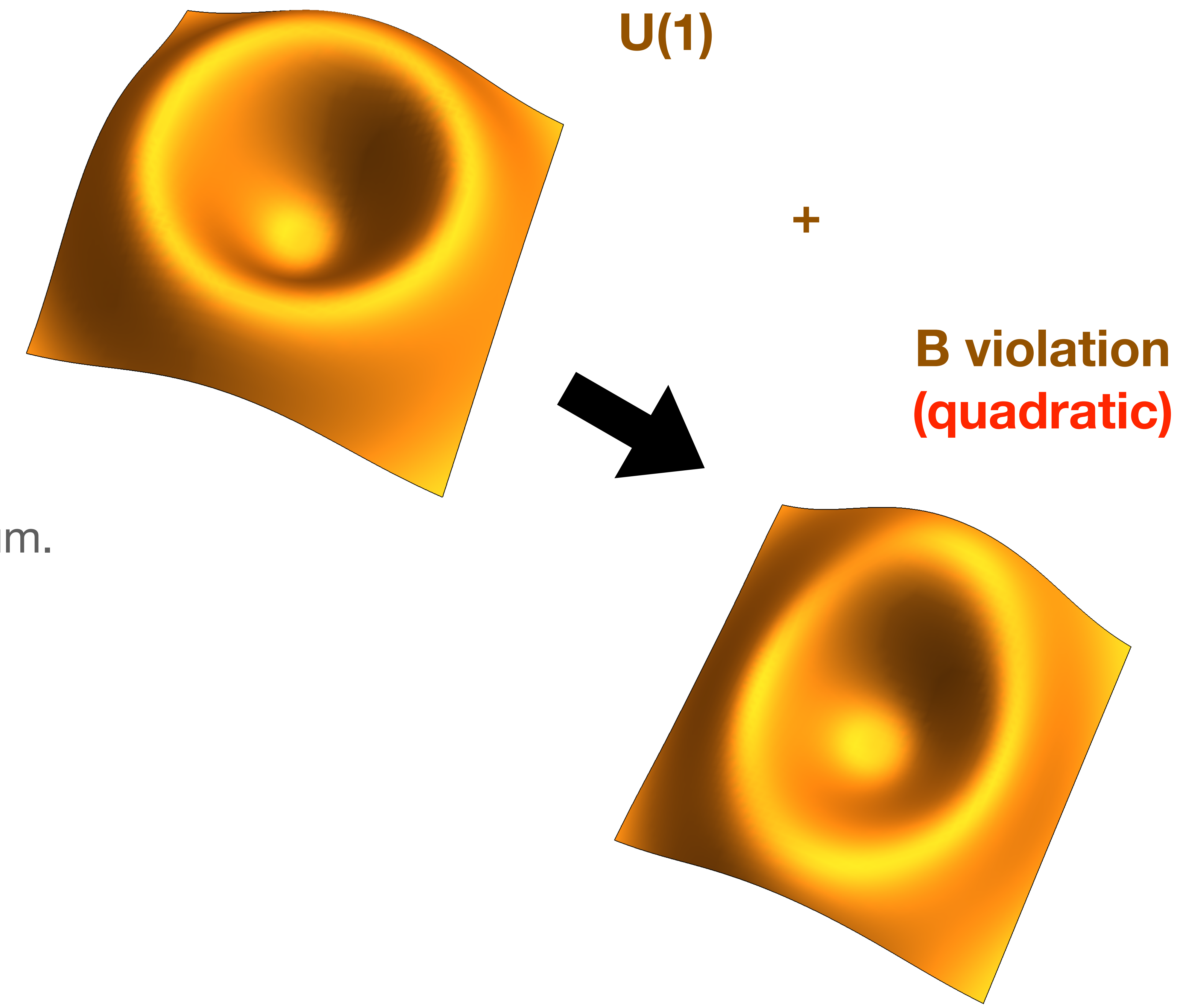
The Affleck-Dine mechanism:

1. Scalar fields develop large VEVs during inflation.
2. The relaxation of scalar VEVs after inflation end is out-of-equilibrium.



(B) Baryogenesis from USR inflation

The Affleck-Dine mechanism:



1. Scalar fields develop large VEVs during inflation.
2. The relaxation of scalar VEVs after inflation end is out-of-equilibrium.
3. The presence of B / L / B-L number violating interactions.
4. Spontaneous CP violation at the beginning of relaxation!

Dine, Randall & Thomas [9507453]

YPW & Petraki [2008.08549]

(B) Baryogenesis from USR inflation

If the USR transition runs into the effective mass of the AD field:

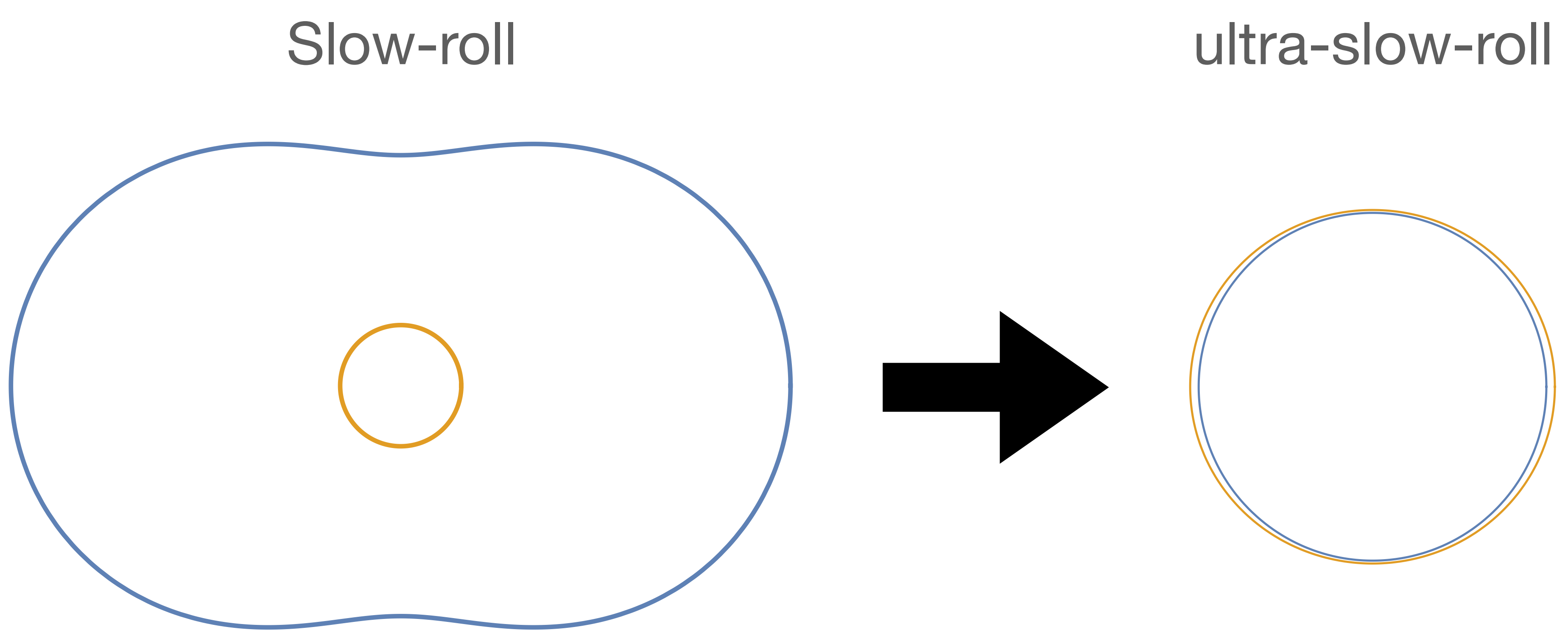
YPW, Pinetti, Petraki & Silk [2109.00118]

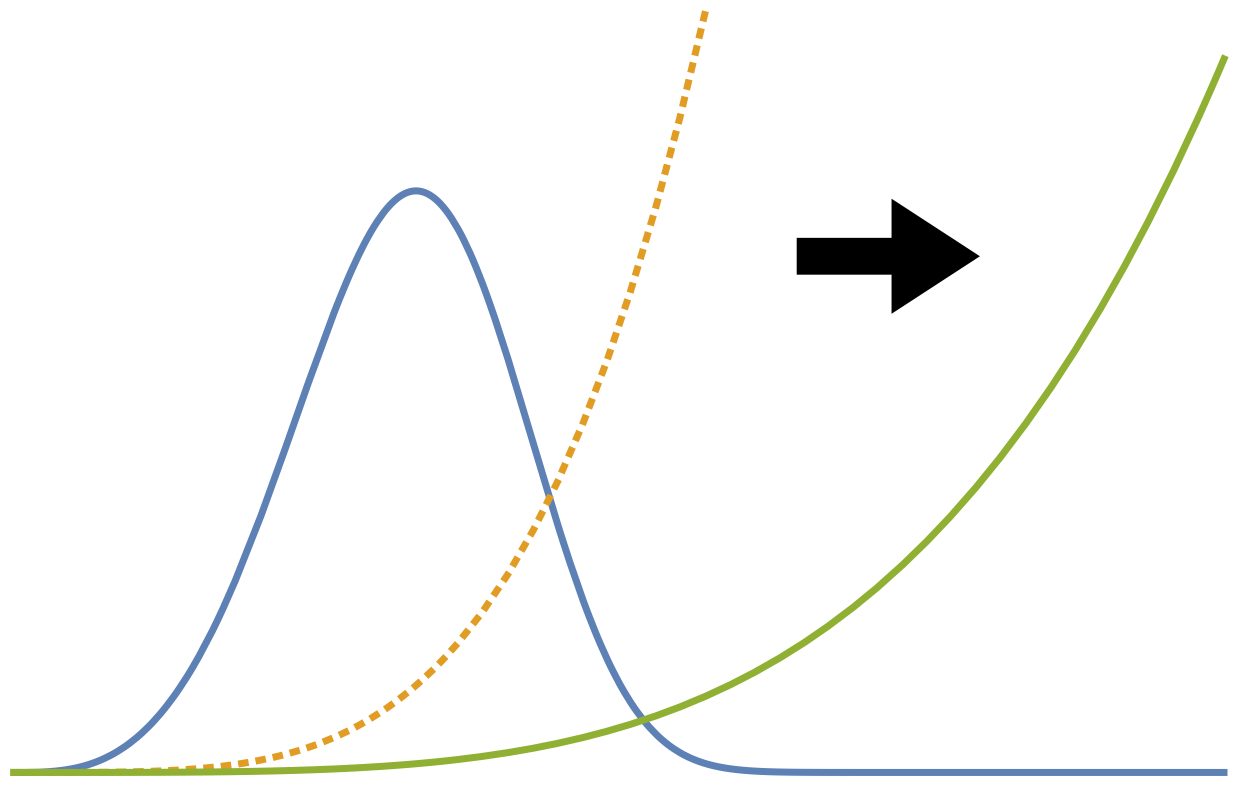
YPW, Pinetti, & Silk [2109.09875]

$$m^2_{\rm AD} \sim \Box\phi/\Lambda$$

$$\Box\phi = -\ddot{\phi} - 3H\dot{\phi} = -(\delta + 3)$$

δ : rate of rolling





(B) Baryogenesis from USR inflation

If the USR transition runs into the effective mass of the AD field:

$$m_{\rm AD}^2 \sim \Box\phi/\Lambda$$

YPW, Pinetti, Petraki & Silk [2109.00118]

YPW, Pinetti, & Silk [2109.09875]

$$\Box\phi = -\ddot{\phi} - 3H\dot{\phi} = -(\delta+3)$$

δ : rate of rolling

$$Y_B = \frac{n_B}{s} = \frac{i(\sigma^*\dot{\sigma} - \sigma\,\dot{\sigma}^*)}{s}$$

$$\sigma(t_0) = \sigma(t_0;\ \delta, N_*, N_{\rm end})$$

➡

$$Y_{\rm B} = Y_{\rm B}(\delta, N_*, N_{\rm end})$$

USR parameters

The cosmic coincidence **from inflation**

YPW, Pinetti, Petraki & Silk [2109.00118]

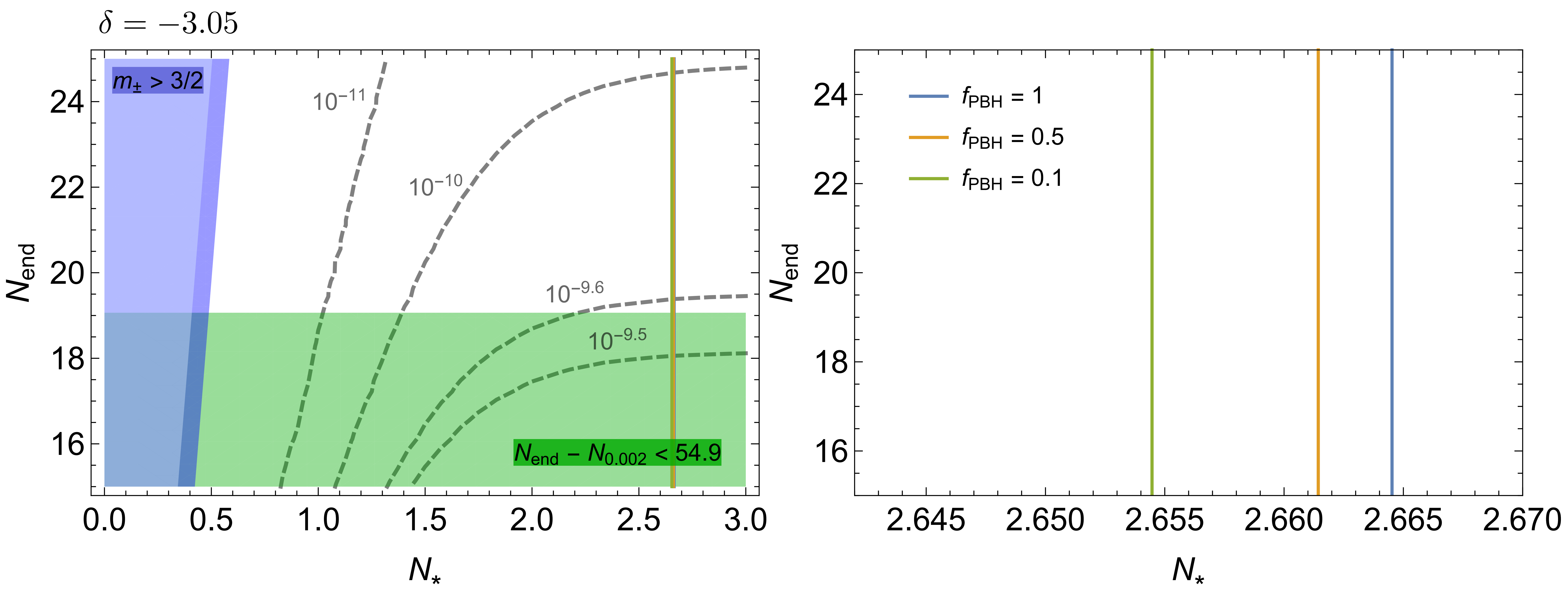
δ : rate of rolling

$\Delta N_{\rm USR} = N_* - N_0 = N_*$

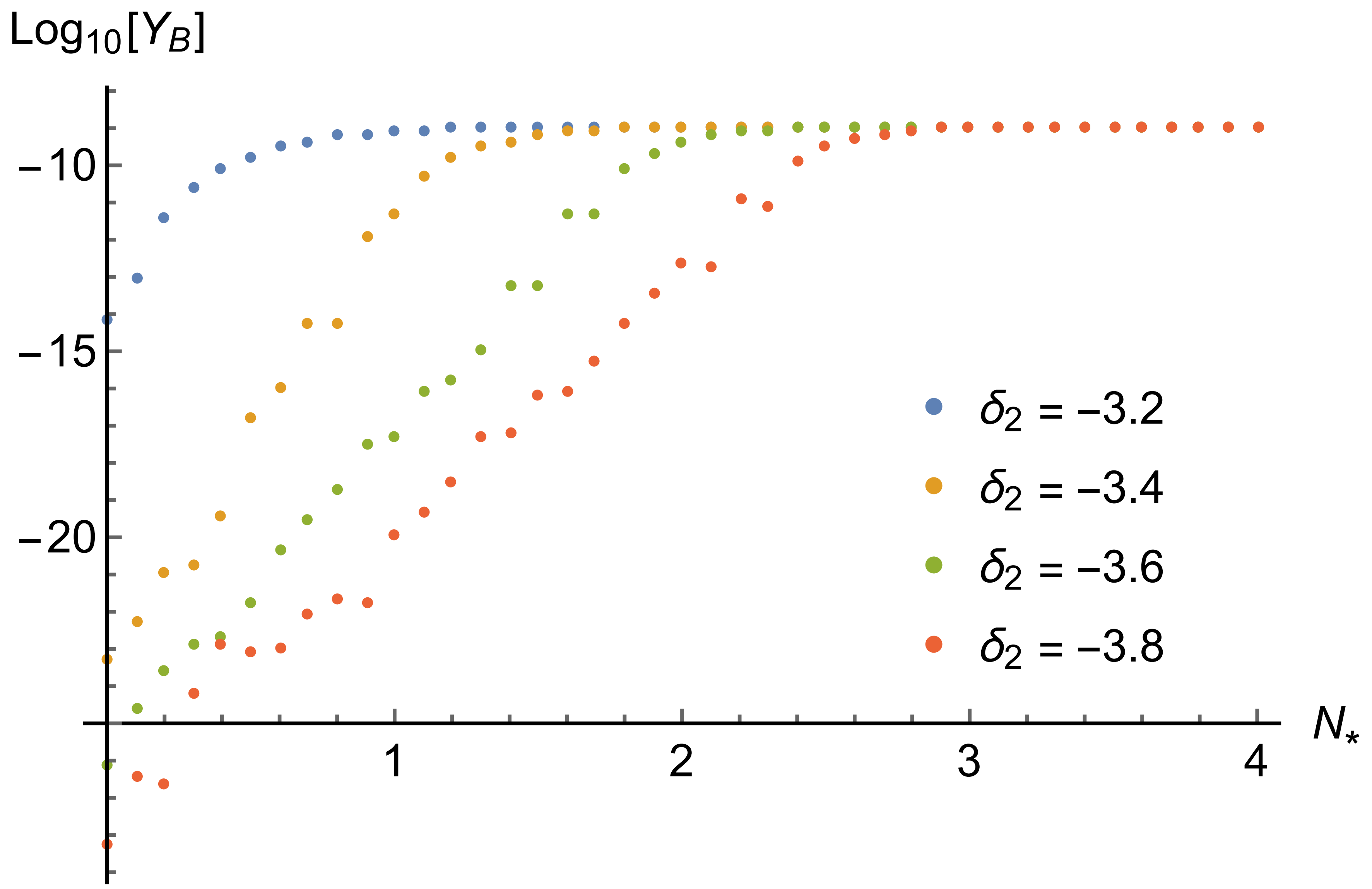
$N_{\rm end}$: end of inflation

A. PBHs from USR inflation: $f_{\rm PBH} = f_{\rm PBH}(\delta, N_*)$

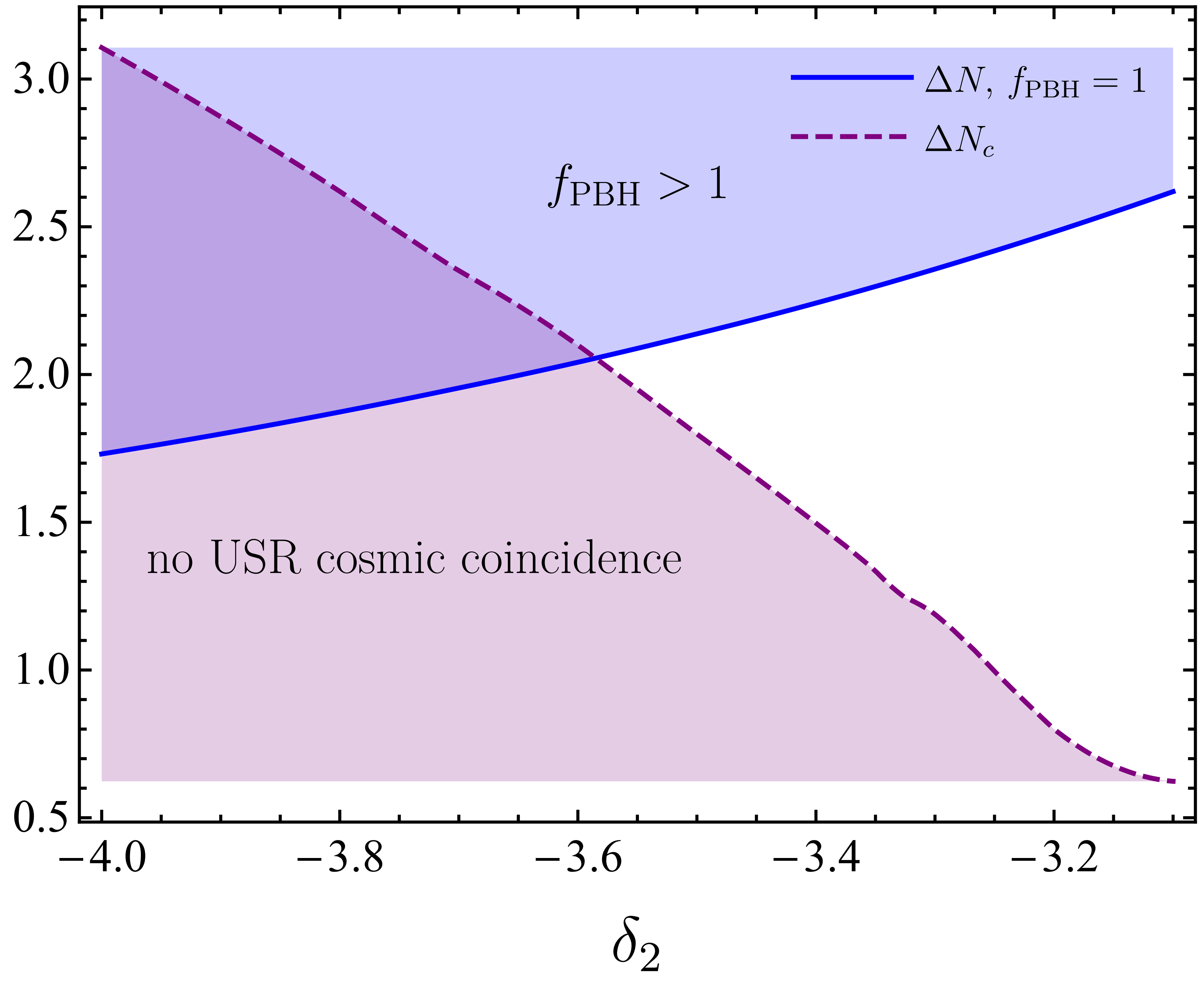
B. Baryons from USR inflation: $Y_{\rm B} = Y_{\rm B}(\delta, N_*, N_{\rm end})$



The cosmic coincidence **from inflation**



Balaji, Silk & YPW [2202.00700]



Induced gravitational waves from USR inflation

Large scalar perturbations are sources of tensor modes at second order (induced GWs).

Tomita, PTP 37 (05, 1967)

$$h_{ij}^{(2)} \sim \partial_i \Phi \partial_j \Phi$$

Observationally relevant for PBH from inflation.

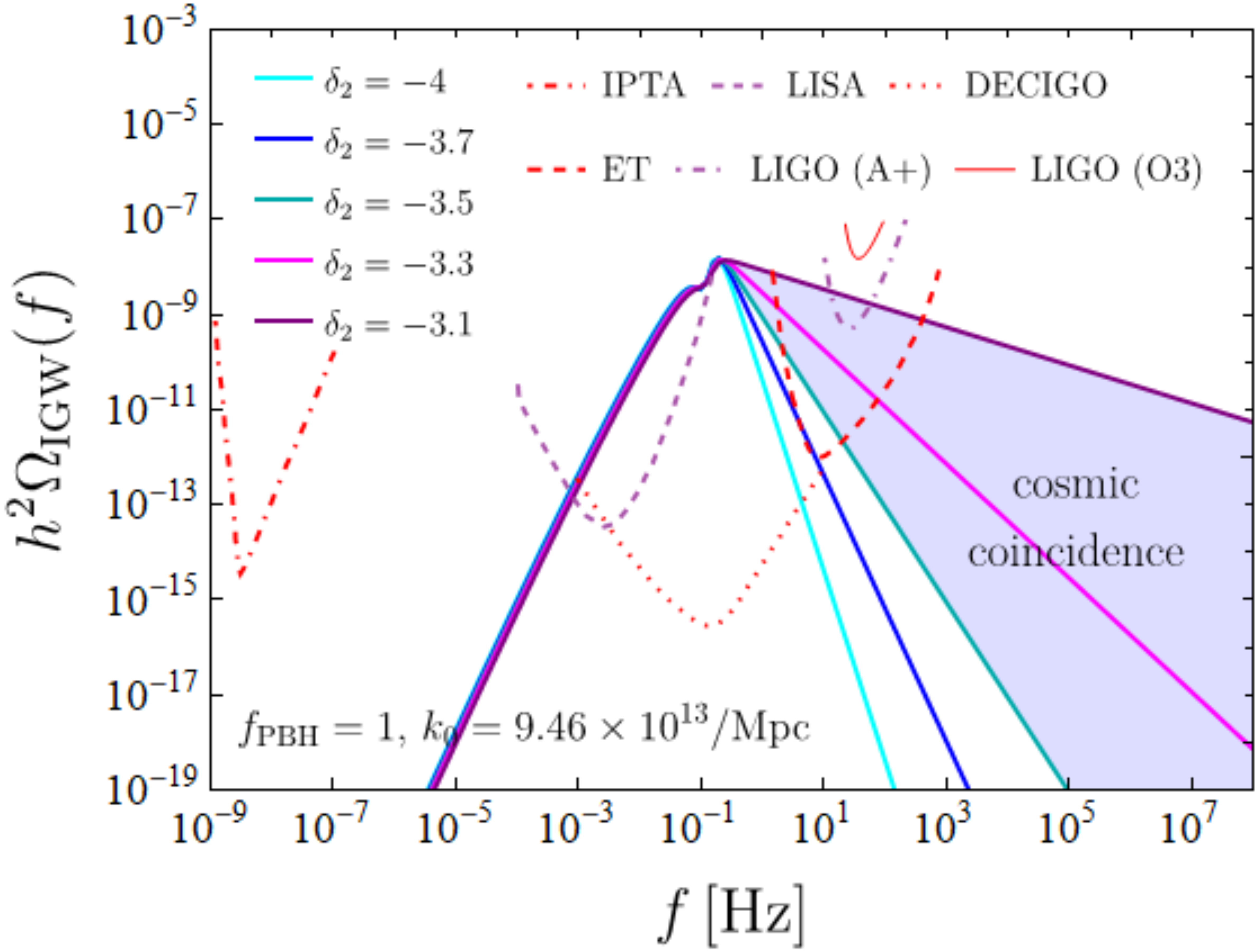
Saito & Yokoyama [0812.4339]

The peak frequency for ultralight asteroid mass window:

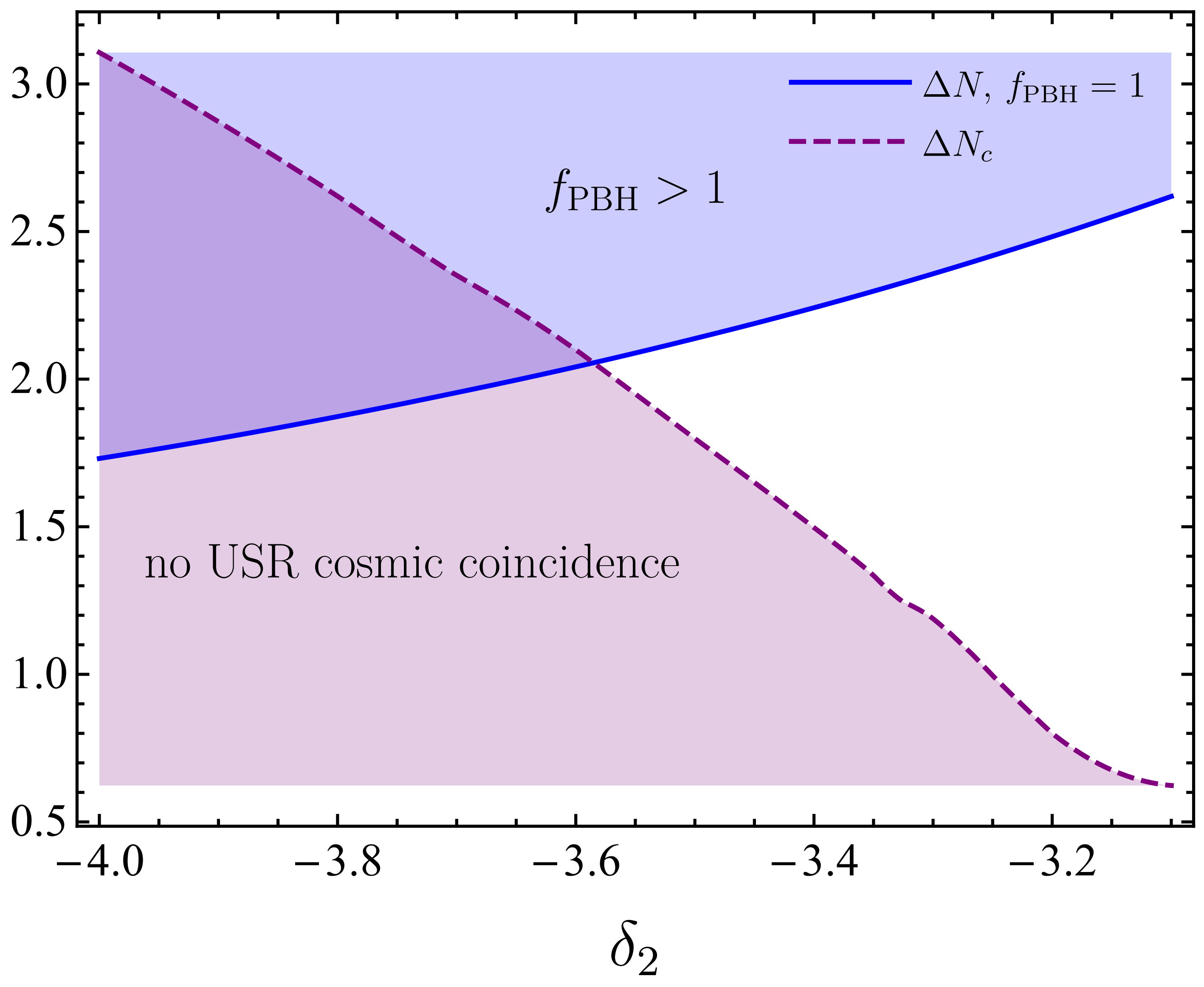
Ragavendra, Saha, Sriramkumar & Silk [2008.12202]

$$f_{\rm peak} \sim 10^{-3} - 1\ {\rm Hz}$$

Induced gravitational waves from USR inflation



Balaji, Silk & YPW [2202.00700]



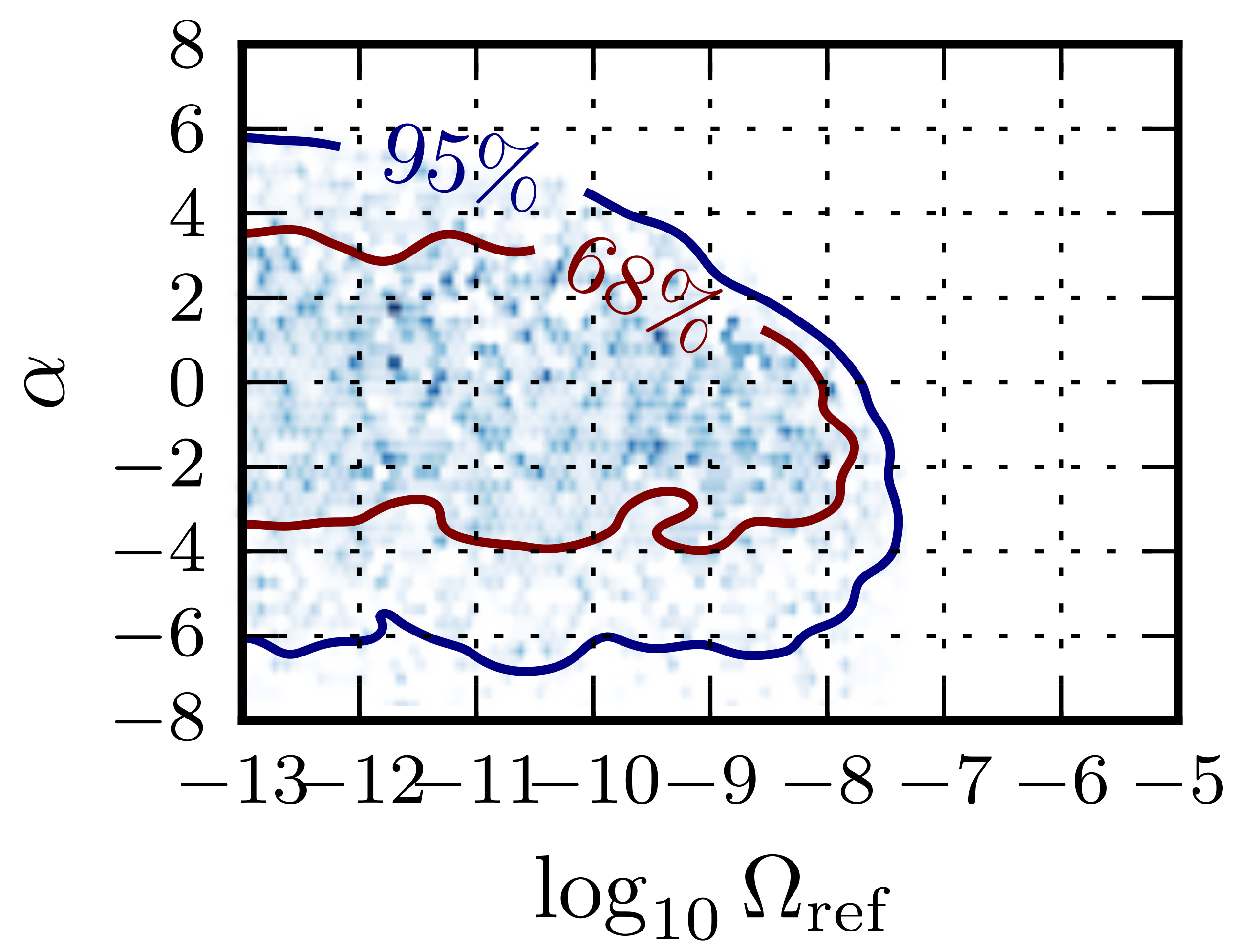
k_0 is the pivot scale for the peak of the power spectrum

$$k_0 = 10^{14}\mathrm{Mpc}^{-1} \to M_{\mathrm{PBH}} \approx 10^{-15} M_\odot$$

Induced gravitational waves from USR inflation

Stochastic GWB in LIGO & Virgo: $\Omega_{\rm GW}(f) = \Omega_{\rm ref}\left(\frac{f}{f_{\rm ref}}\right)^{\alpha}$

aLIGO & aVirgo O3 [2101.12130]



$f_{\rm ref} = 25\,{\rm Hz}$

$\alpha = 0;$ GWB from slow-roll inflation or cosmic string

$\alpha = 2/3;$ GWB from compact binary coalescence

$\alpha = 3;$ GWB from astrophysical sources (supernovae...)

$-2 < \alpha < 0$ for the cosmic coincidence from USR inflation

Balaji, Silk & YPW [2202.00700]

Take home messages

- If "PBHs from USR inflation" contribute more than 10% of the DM density, then "Baryogenesis from USR inflation" admits the cosmic coincidence.

- "Baryogenesis from USR inflation" does not rely on the presence of PBHs.

- As long as PBHs are found to be important DM (i.e. $f_{PBH} > 0.1$) in the ultralight asteroid-mass window, LISA can test the IR tail of the induced GWB from USR inflation.

- The UV tail of the induced GWB from USR cosmic coincidence has distinctive negative power law: $-2 < \alpha < 0$

Thank you very much!

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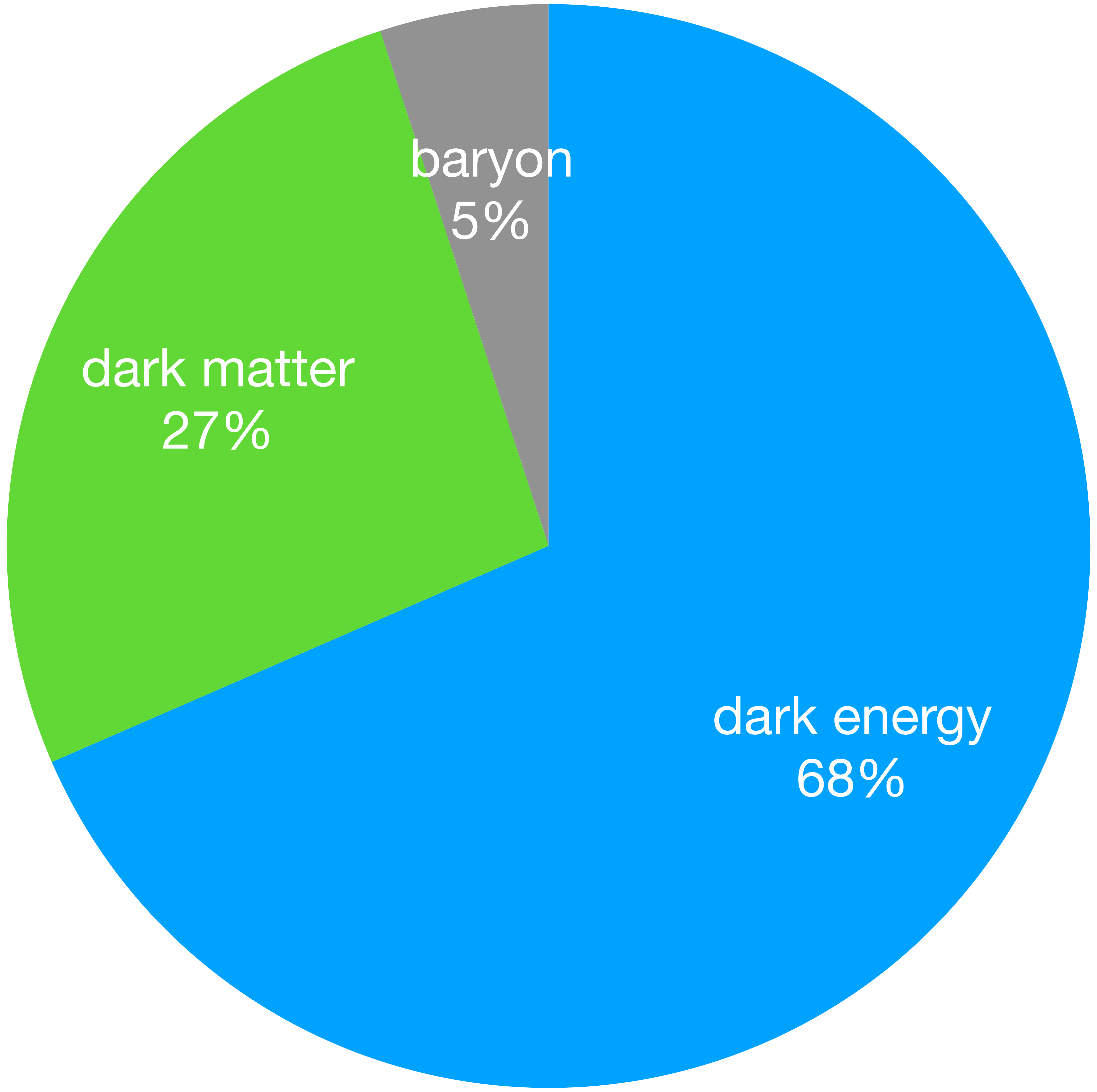
Supplement

The cosmic coincidence **(in this talk)**



$$\frac{\Omega_{\mathrm{DM}}}{\Omega_{\mathrm{B}}} \approx 5$$

An answer from particle physics: asymmetry dark matter

Bell, Petraki, Shoemaker & Volkas [1105.3730]

von Harling, Petraki & Volkas [1201.2200]

Petraki & Volkas [1305.4939]

A. PBHs from (ultra-slow-roll) inflation

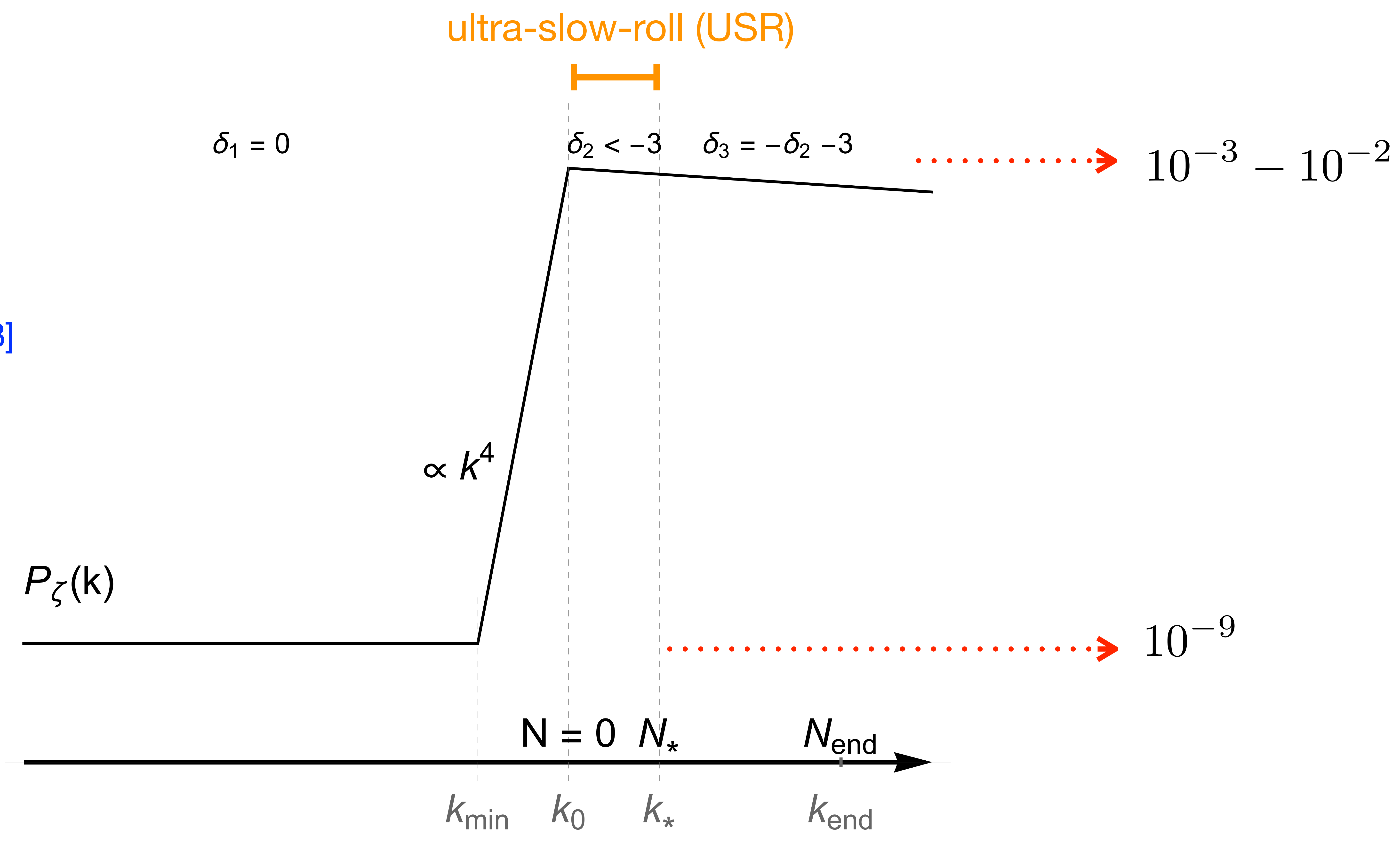
Analytic templates:

Liu, Guo & Cai [2003.02075]

Ng & YPW [2102.05620]

YPW, Pinetti, Petraki & Silk [2109.00118]

ζ : curvature perturbation



A. PBHs from (ultra-slow-roll) inflation

adiabatic condition (conformal weight continuity)

Ng & YPW [2102.05620]

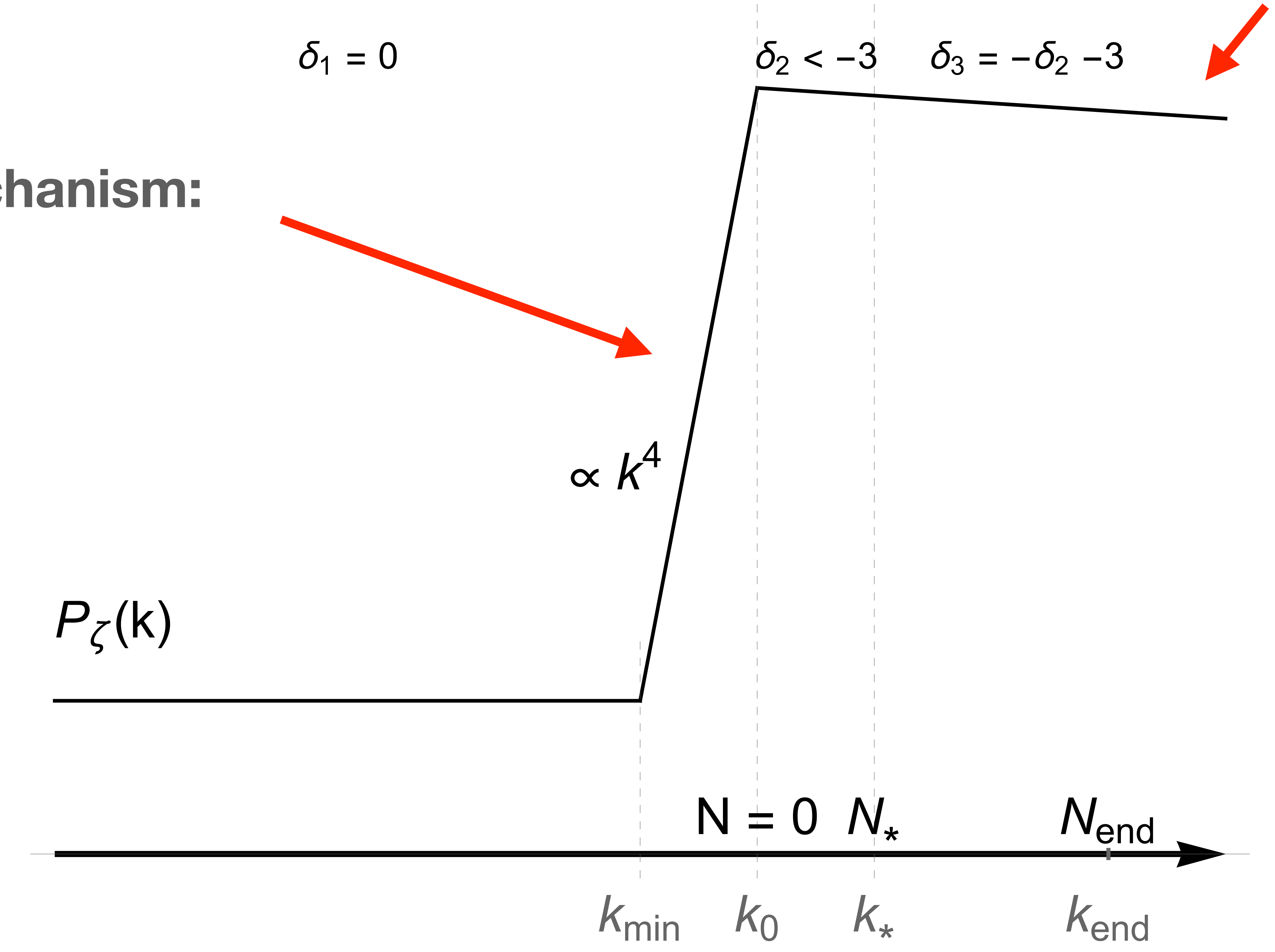
The Leach-Sasaki-Wands-Liddle mechanism:

Leach et al [astro-ph/0101406]

(also called the steepest growth)

Byrnes, Cole & Patil [1811.11158]

Carrilho, Malik & Mulryne [1907.05237]



The correlation length problem:

Baryogenesis from flat directions

Dine, Randall & Thomas [9507453]

$$V(\sigma) = -\xi H^2 |\sigma|^2 + \left(\frac{\lambda H \sigma^n}{n M^{n-3}} + h.c \right) + |\lambda|^2 \frac{|\sigma|^{2n-2}}{M^{2n-6}}$$

$$\sigma = R e^{i\theta}/\sqrt{2}$$

$$n_B = R^2 \dot{\theta}$$

$$\theta \to \text{(anti)matter}$$

The correlation length problem:

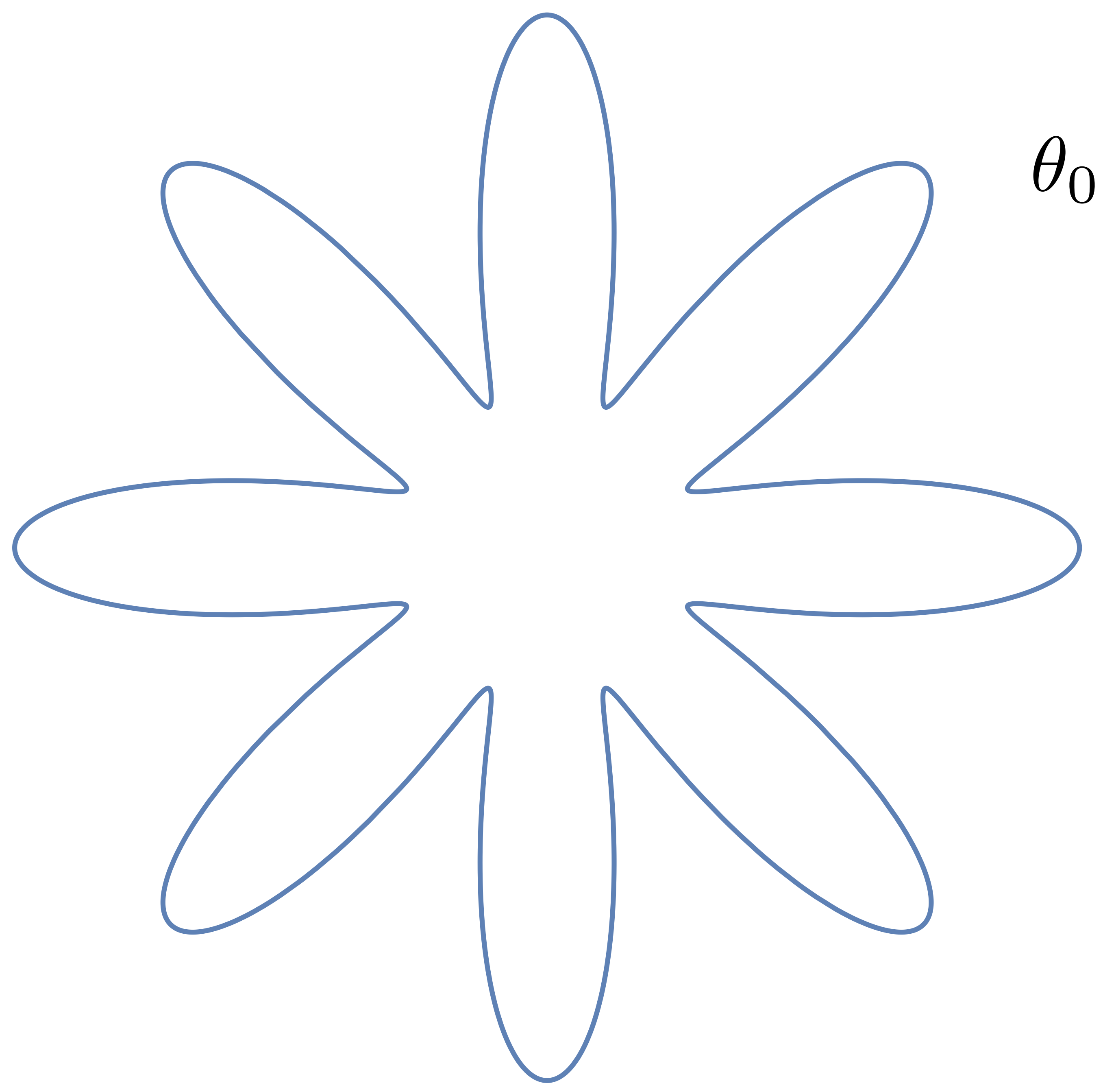
Baryogenesis from flat directions

Dine, Randall & Thomas [9507453]

n = 8

$$\theta_0 + \delta\theta \approx \theta_0$$

$$V(R, \theta) =$$



$$m_\theta^2 \gg H^2$$

The correlation length problem:

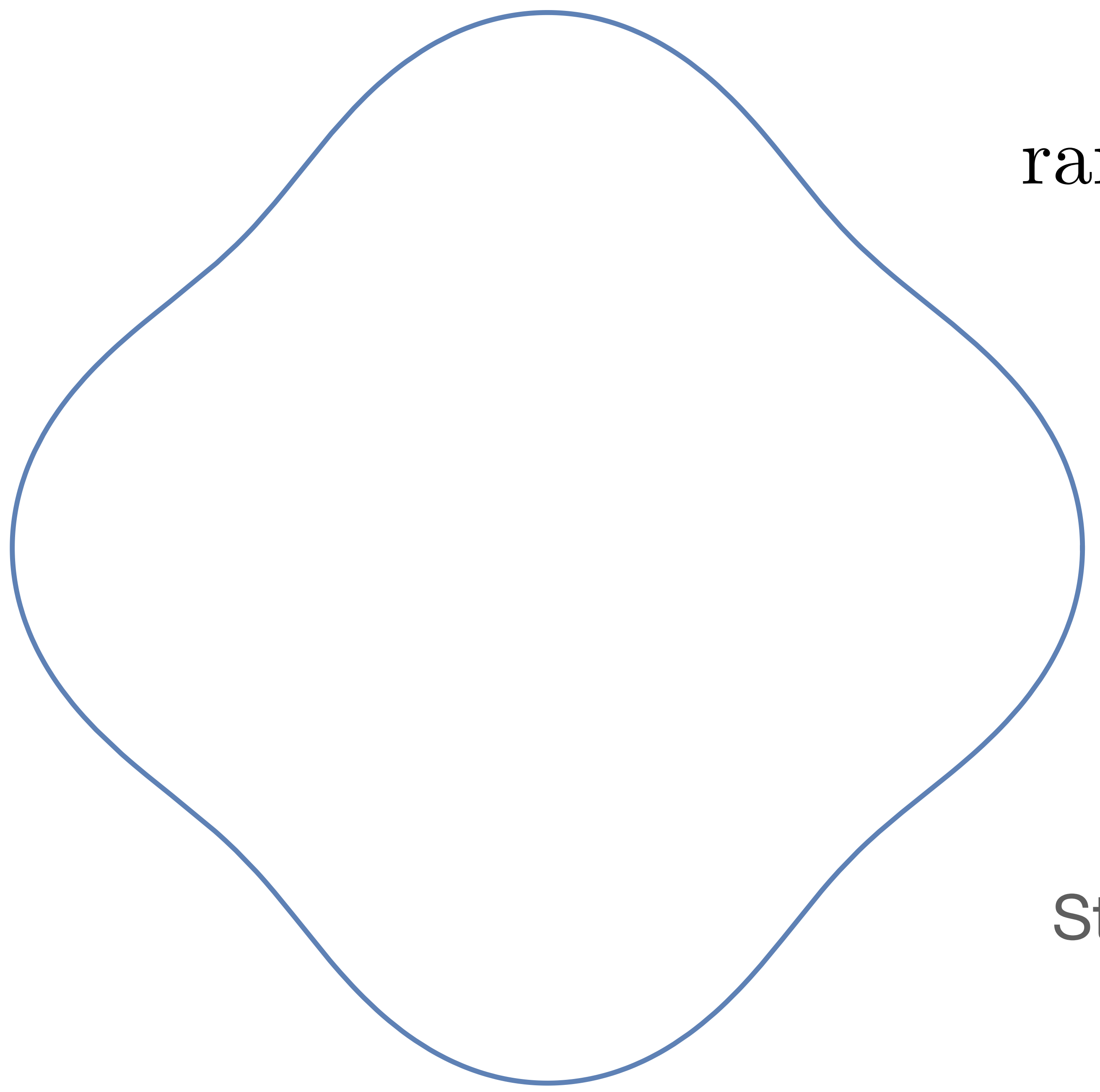
Baryogenesis from flat directions

Dine, Randall & Thomas [9507453]

n = 4

random θ_0

$V(R,\theta) =$



Stochastic initial conditions from small B-violation

YPW & Petraki [2008.08549]

$m_\theta^2 \ll H^2$