第十七届TeV工作组会议

Non-Gaussianities in the PBH Formation

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Nanjing, Dec 17 2023

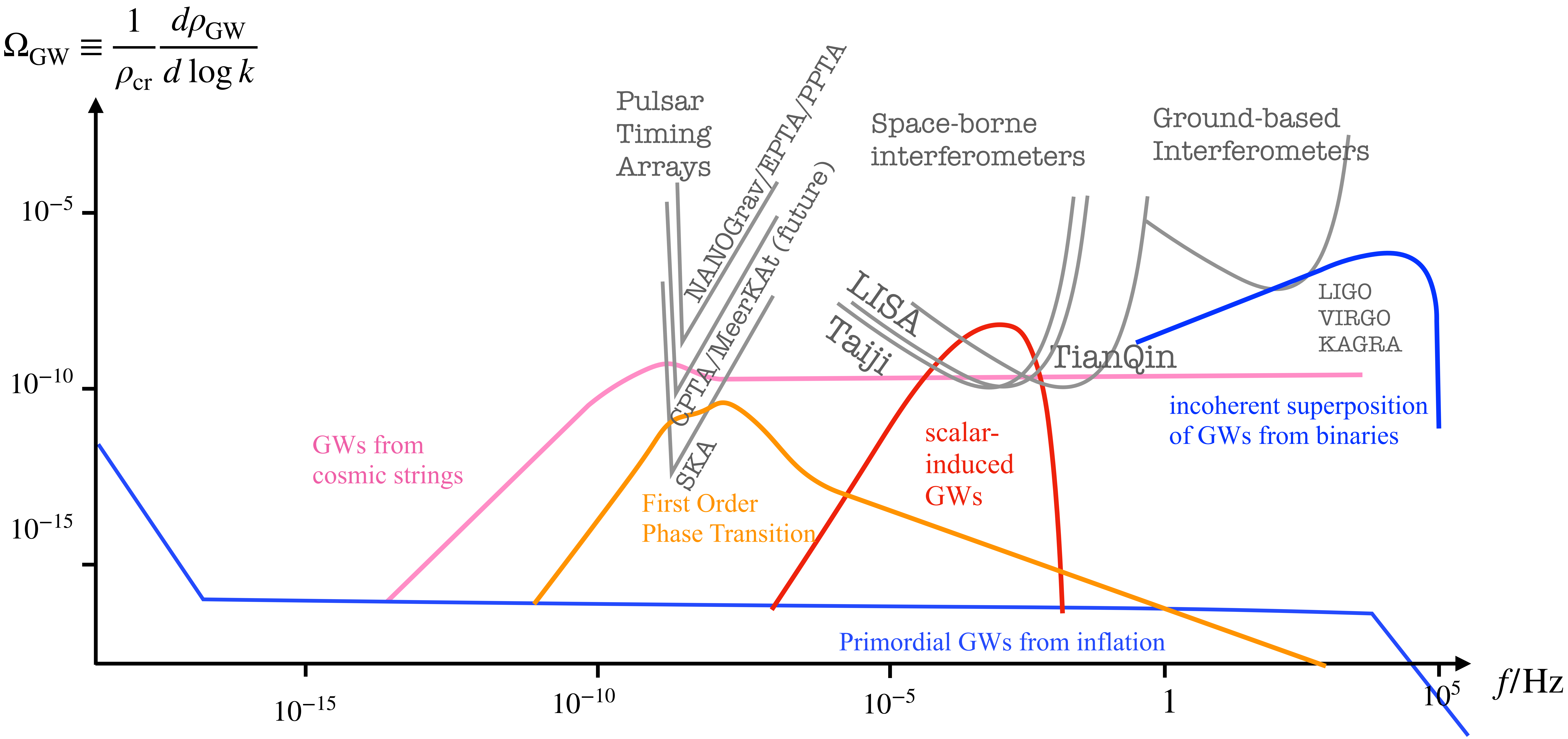
CONTENT

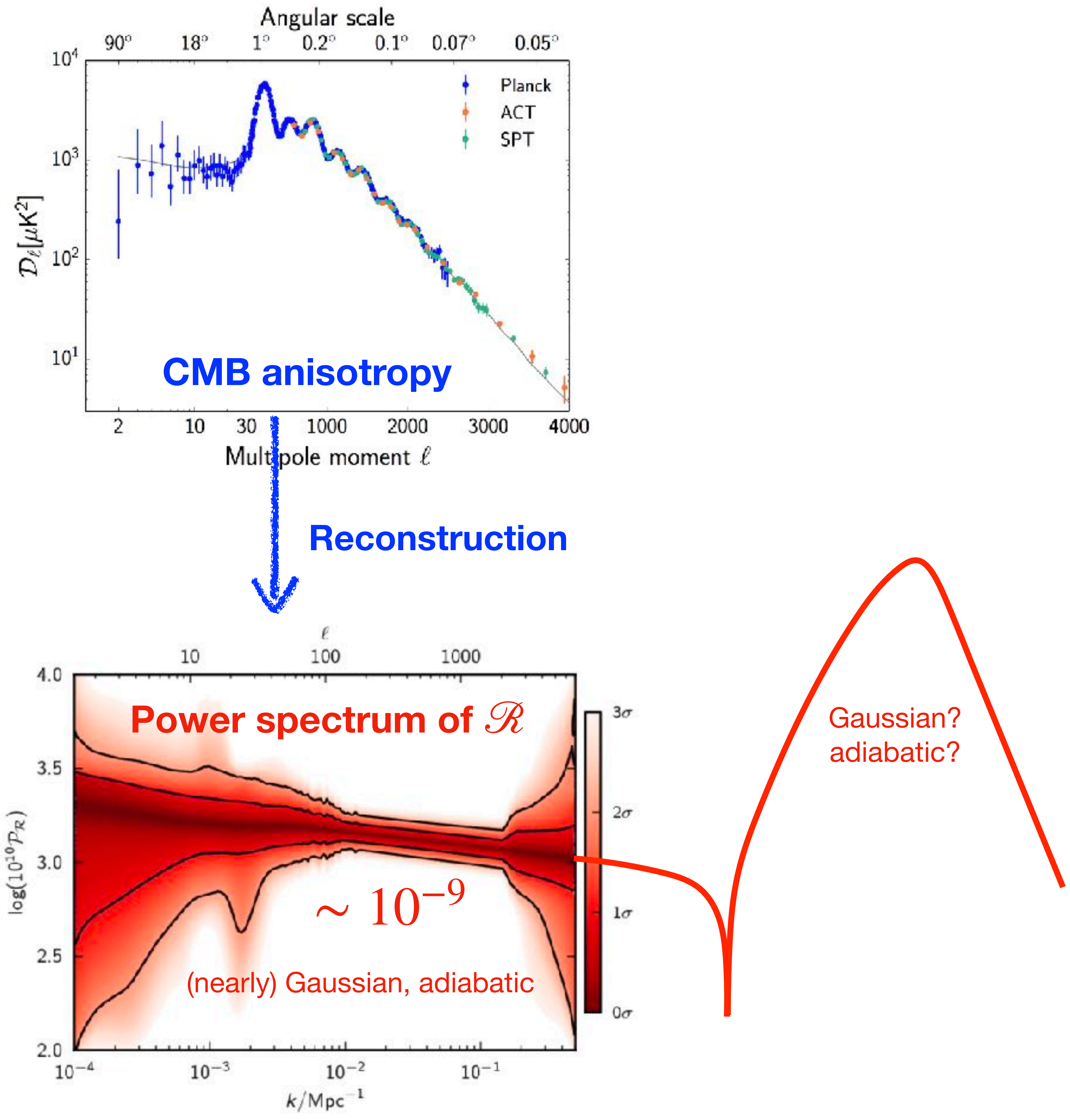
- Introduction: PBH and IGW
- Primordial NG of the curvature perturbation
- Application to ultra-slow-roll inflation
- Summary

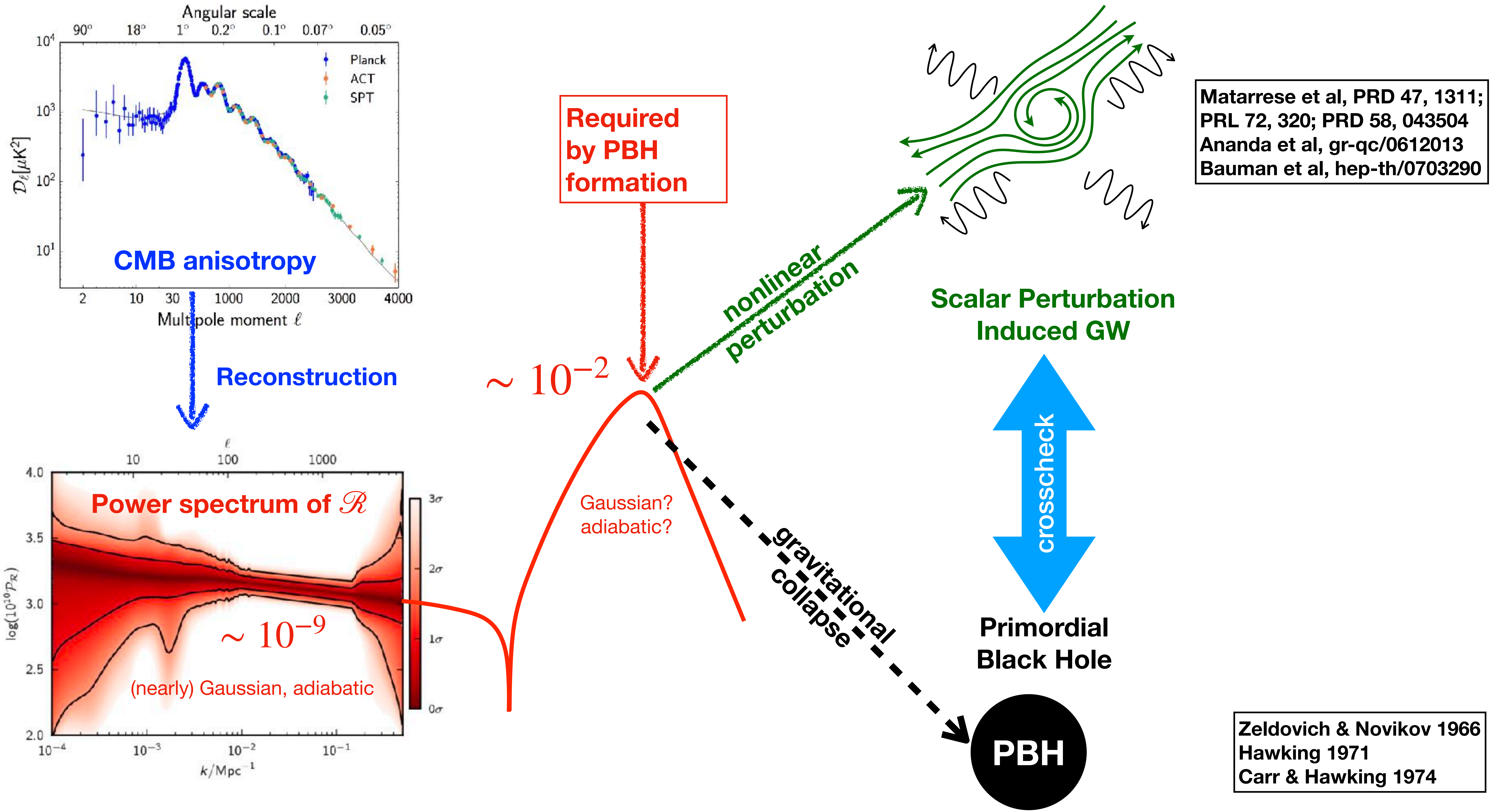
Introduction:

Primordial Black Hole and Scalar Induced Gravitational Waves

Possible SGWB Sources



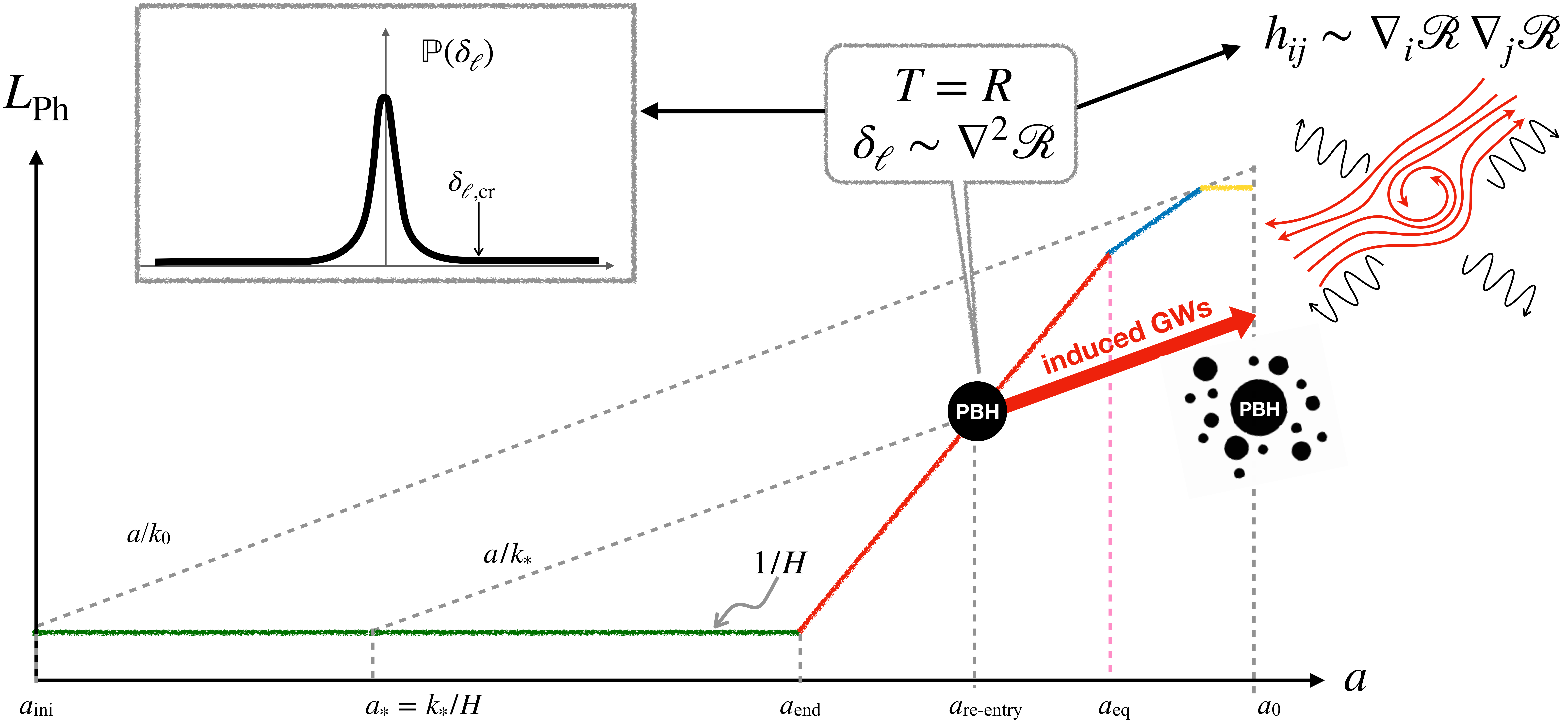

Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
0.05°
Planck
ACT
SPT
$\mathcal{D}_\ell [\mu K^2]$
CMB anisotropy
Multipole moment ℓ
Reconstruction
ℓ
Power spectrum of $\mathscr{R}$
$\log(10^{10}\mathcal{P}_\mathcal{R})$
$\sim 10^{-9}$
(nearly) Gaussian, adiabatic
k/Mpc^{-1}
Gaussian?
adiabatic?



Angular scale
90° 18° 1° 0.2° 0.1° 0.07° 0.05°
Planck
ACT
SPT
$\mathcal{D}_\ell [\mu K^2]$
CMB anisotropy
Multipole moment ℓ
Reconstruction
Power spectrum of $\mathscr{R}$
$\sim 10^{-9}$
(nearly) Gaussian, adiabatic
$\log(10^{10}\mathcal{P}_\mathcal{R})$
k/Mpc^{-1}
Required by PBH formation
$\sim 10^{-2}$
Gaussian? adiabatic?
nonlinear perturbation
gravitational collapse
Scalar Perturbation Induced GW
crosscheck
Primordial Black Hole
PBH
Matarrese et al, PRD 47, 1311; PRL 72, 320; PRD 58, 043504
Ananda et al, gr-qc/0612013
Bauman et al, hep-th/0703290
Zeldovich & Novikov 1966
Hawking 1971
Carr & Hawking 1974


PBH
Scalar induced GWs

PBH-IGW crosscheck



$M_{\rm PBH} \sim 5 \times 10^{26}{\rm g} \left(\frac{\rm TeV}{T}\right)^2$

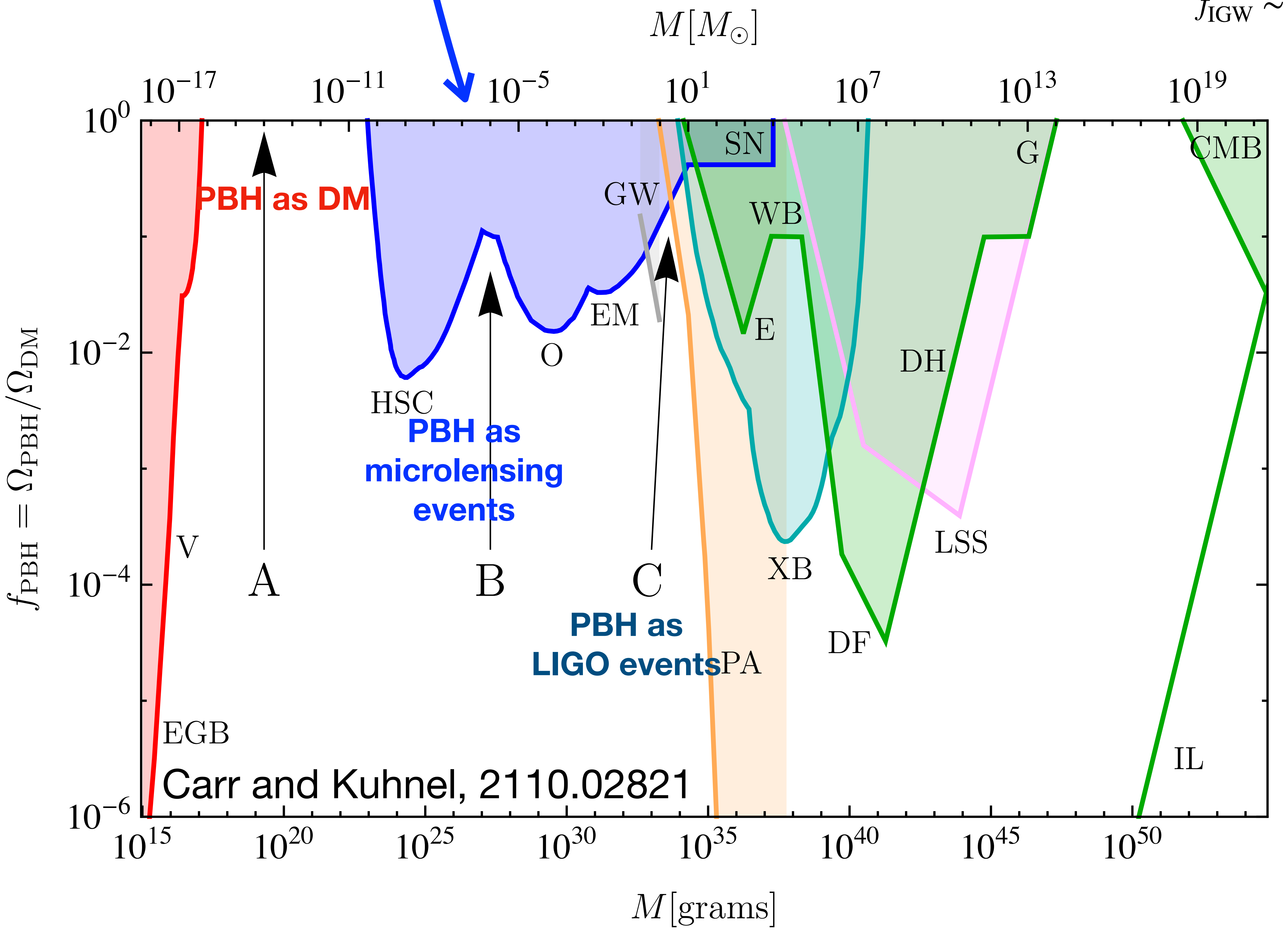
PBH-IGW crosscheck

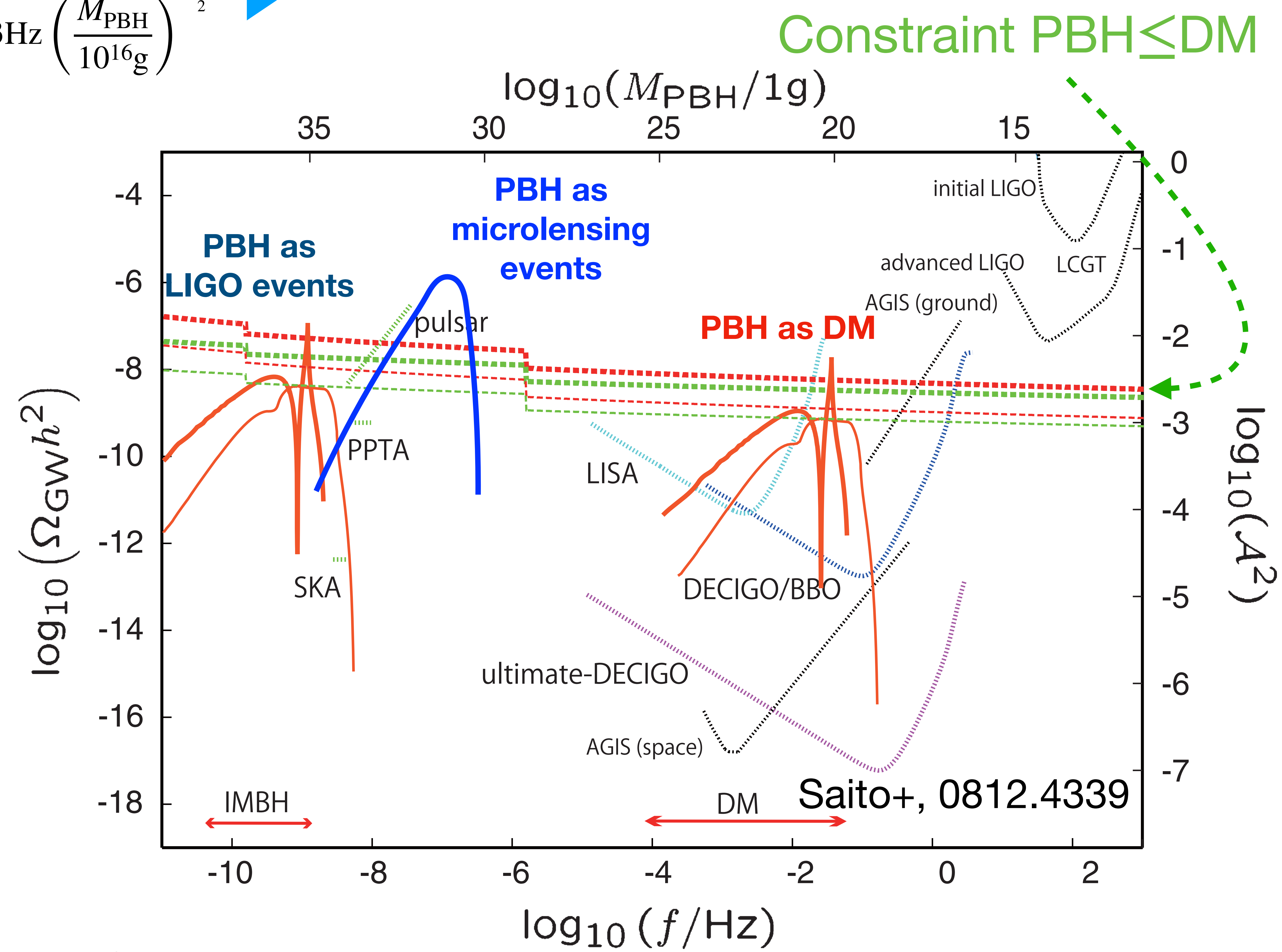
PBH constraints

crosscheck

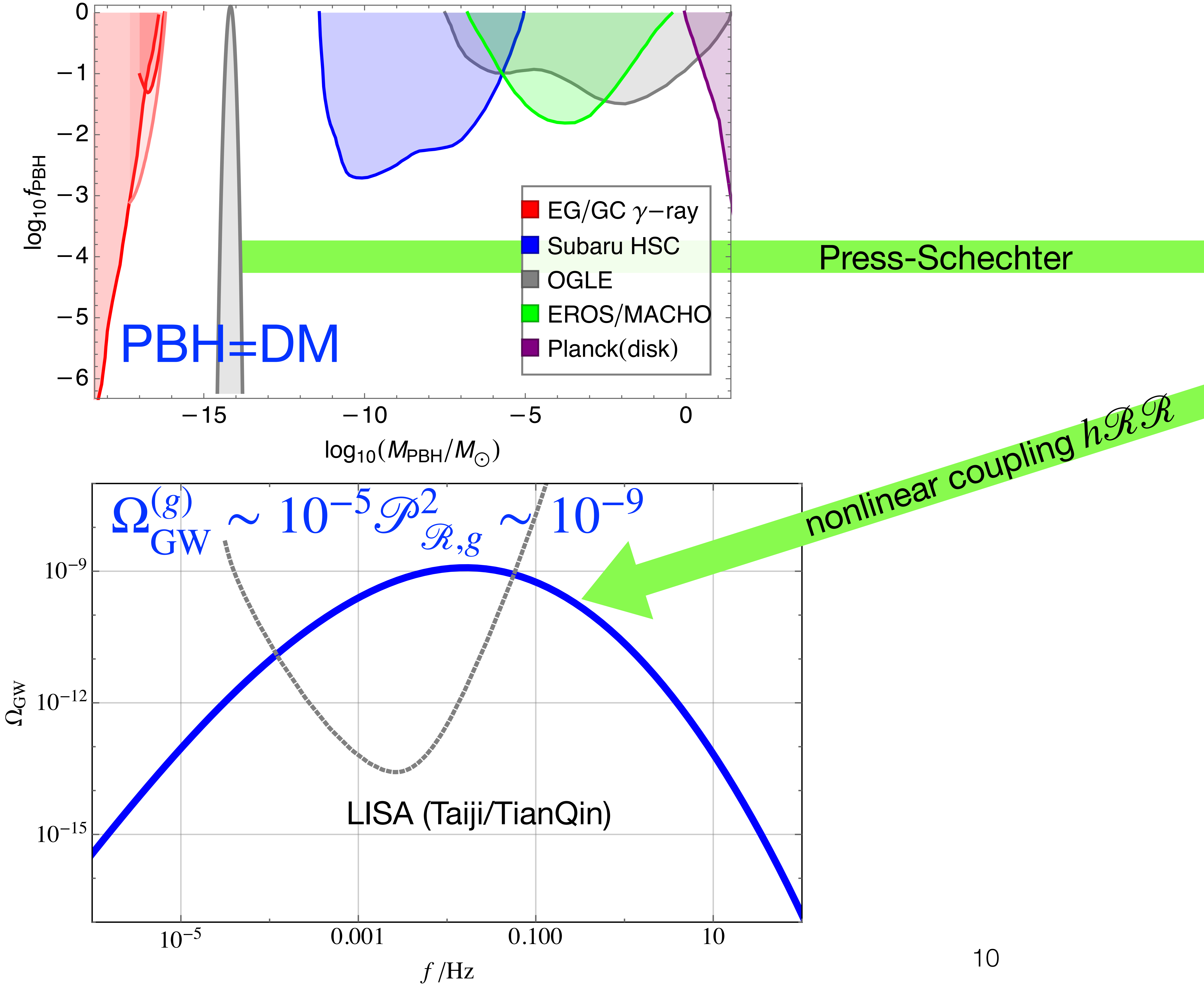
IGW constraints

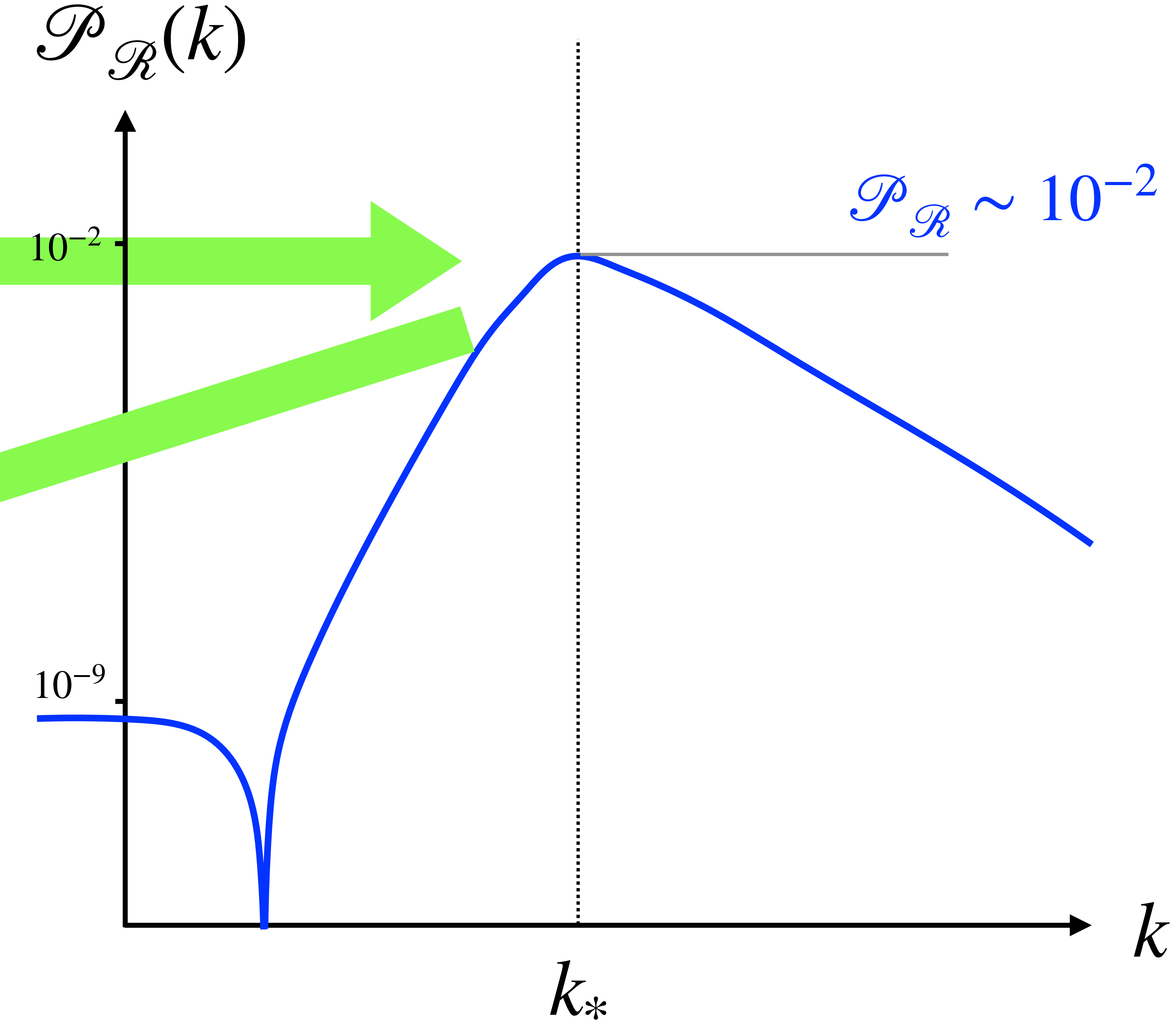
$f_{\rm IGW} \sim 3{\rm Hz} \left(\frac{M_{\rm PBH}}{10^{16}{\rm g}}\right)^{-\frac{1}{2}}$





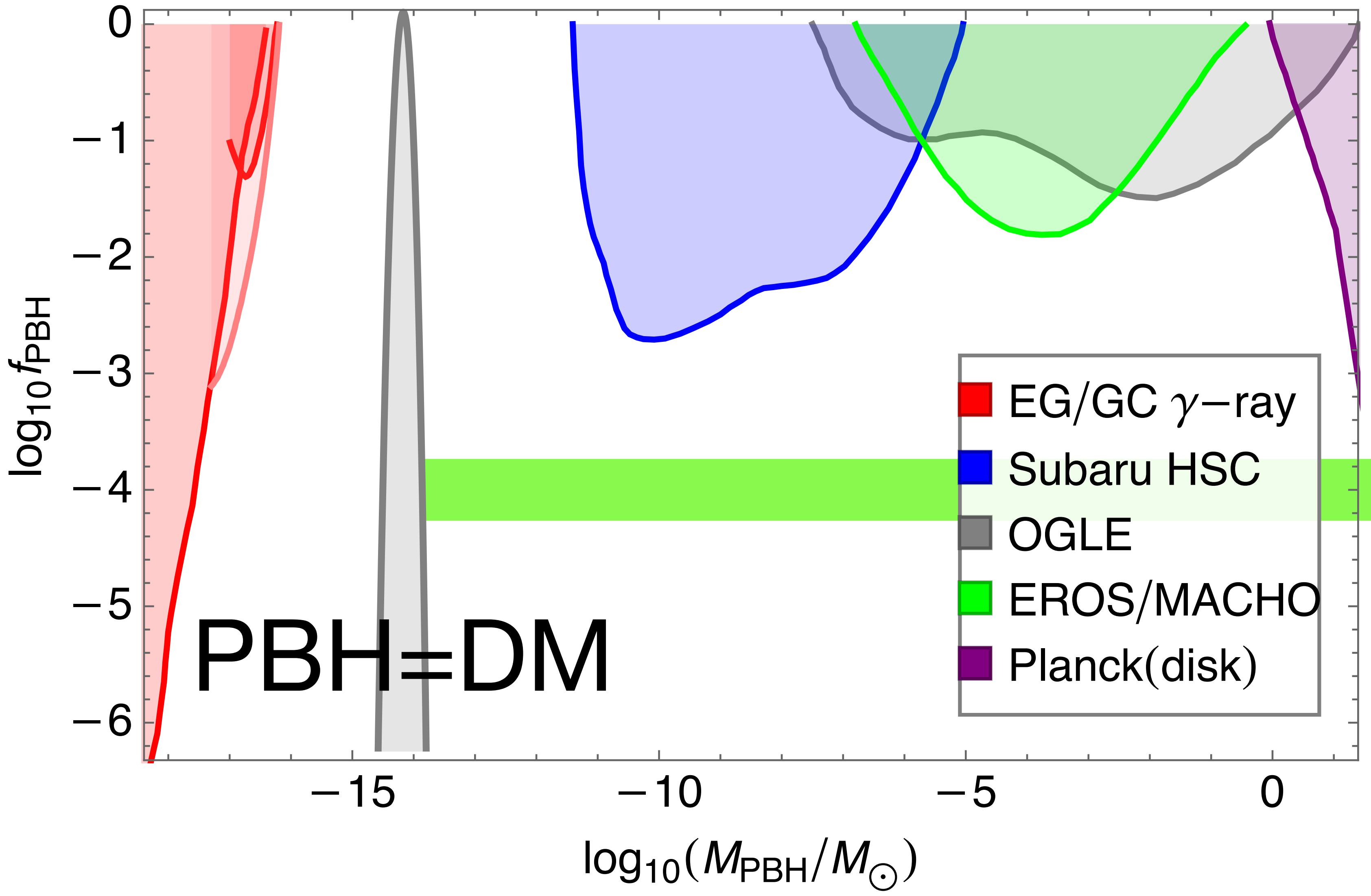
PBH-IGW crosscheck





Saito & Yokoyama 0812.4339; 0912.5317
Bugaev & Klimai 0908.0664; 1012.4697
Escriva et al, 2211.05767

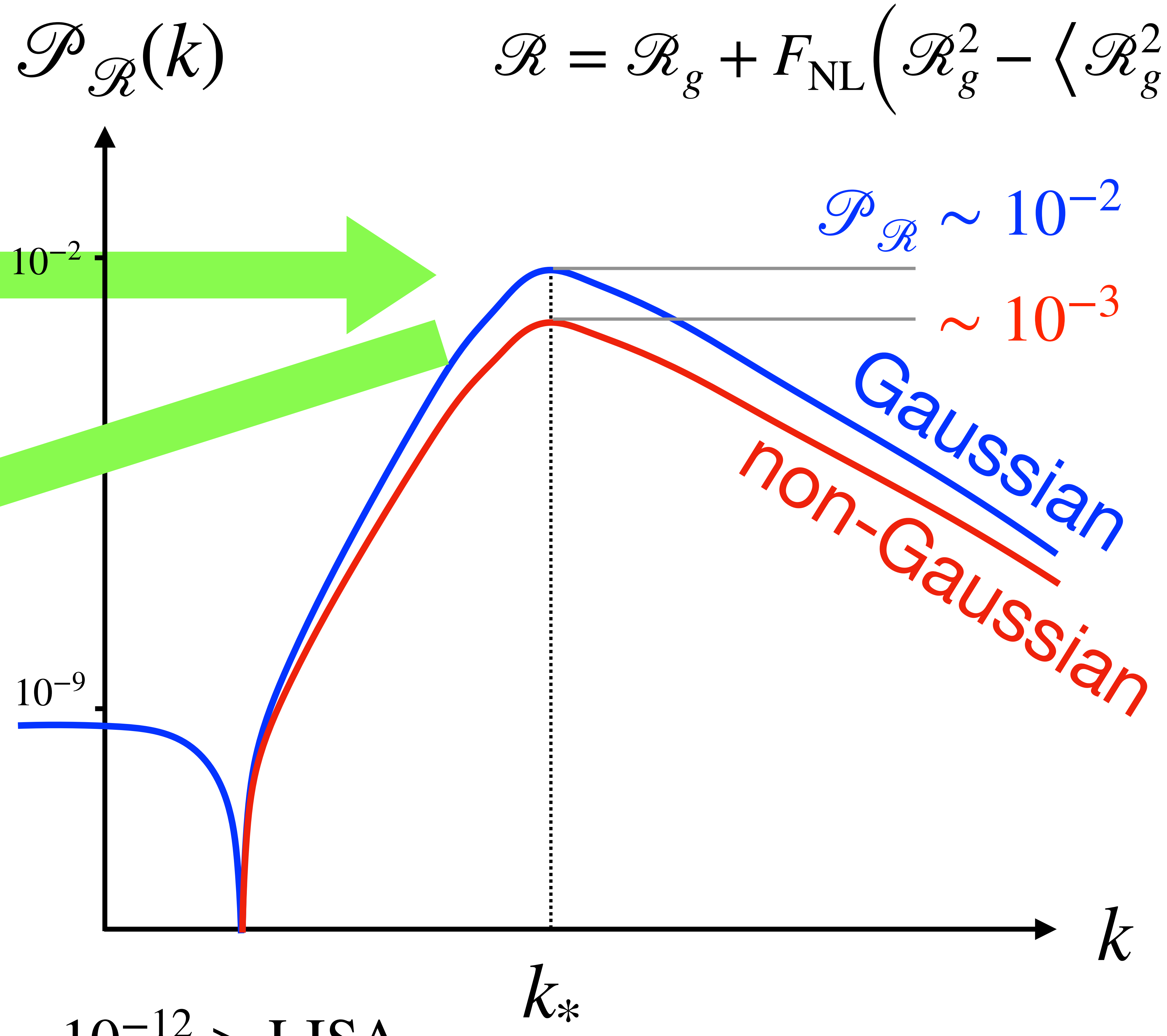
Including non-Gaussianity



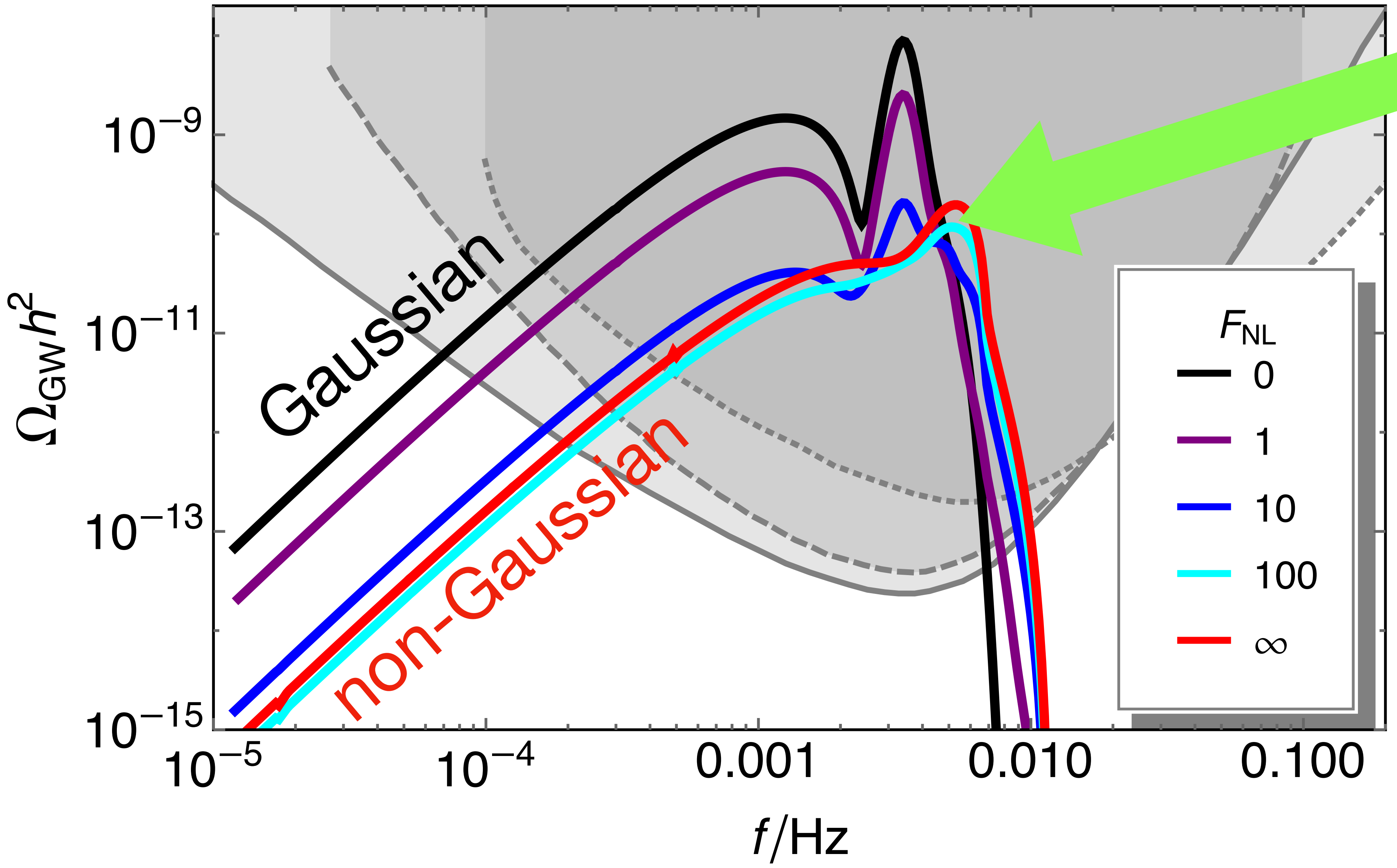
Press-Schechter

nonlinear coupling $h\mathcal{R}\mathcal{R}$

with $F_{\rm NL} > 0$



$$\mathcal{R} = \mathcal{R}_g + F_{\rm NL}\left(\mathcal{R}_g^2 - \langle \mathcal{R}_g^2 \rangle\right)$$



$F_{\rm NL}\mathcal{P}_\mathcal{R} \sim 10^{-2}$

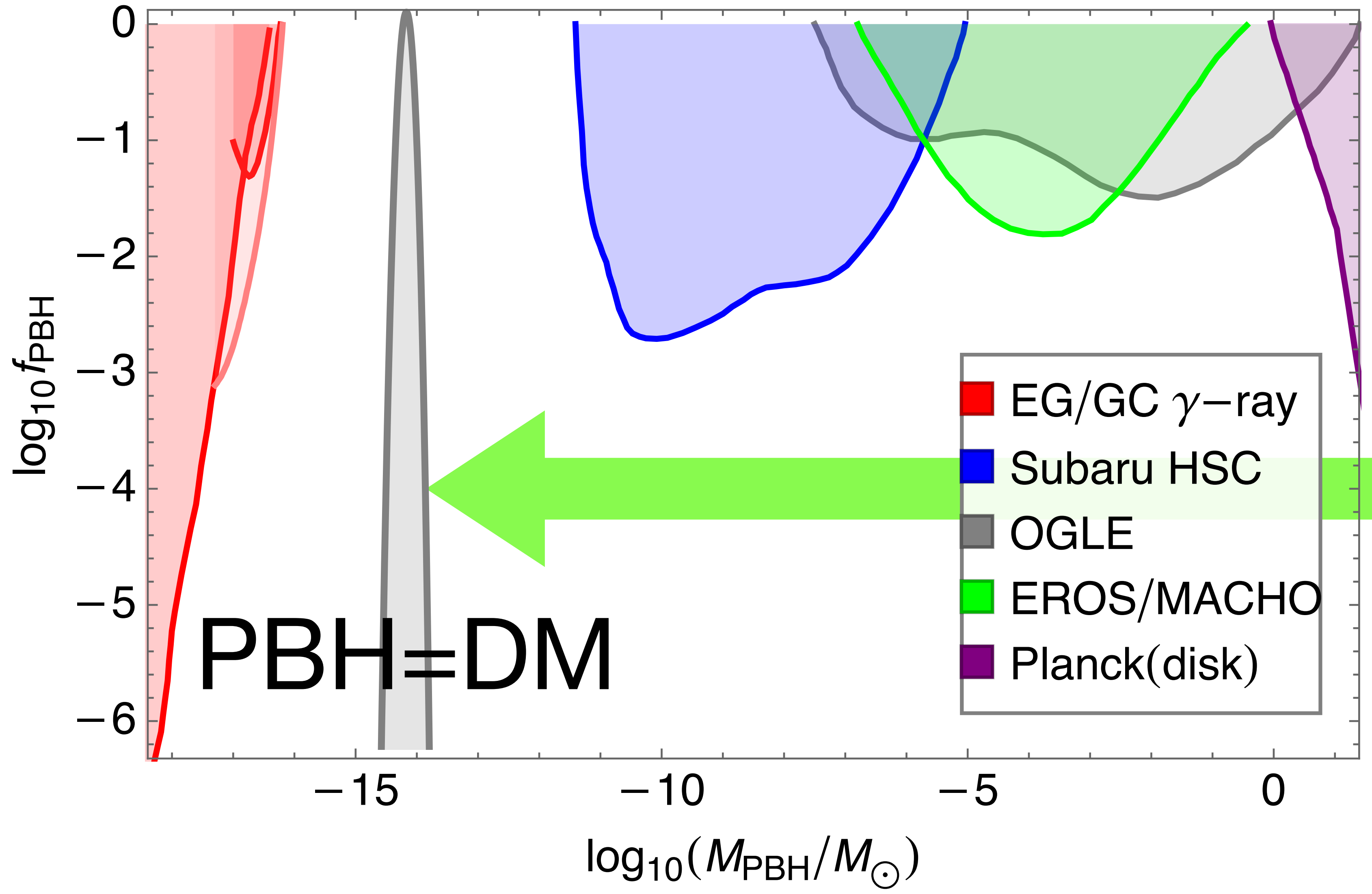
$\Omega_{\rm GW}^{\rm (NG)} \sim 10^{-5} F_{\rm NL}^4 \mathcal{P}_{\mathcal{R},g}^4 \sim 10^{-12} > \text{LISA}$

LISA/Taiji/TianQin can probe PBH-DM.

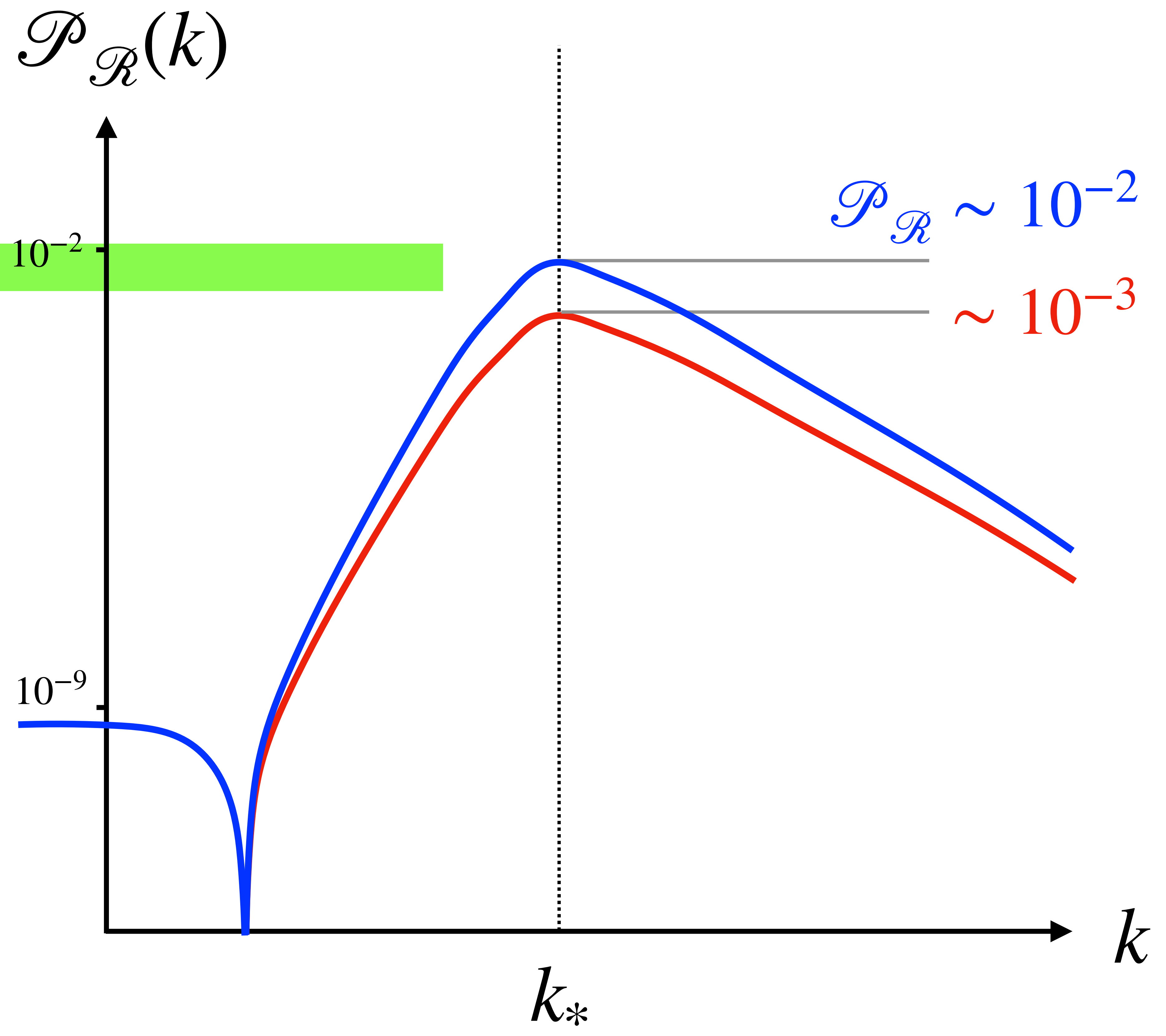
Cai, SP, Sasaki, 1810.11000

Bartolo et al., 1810.12218

More non-Gaussianities



extended PS/peak theory
ineludible non-Gaussianity
primordial non-Gaussianity

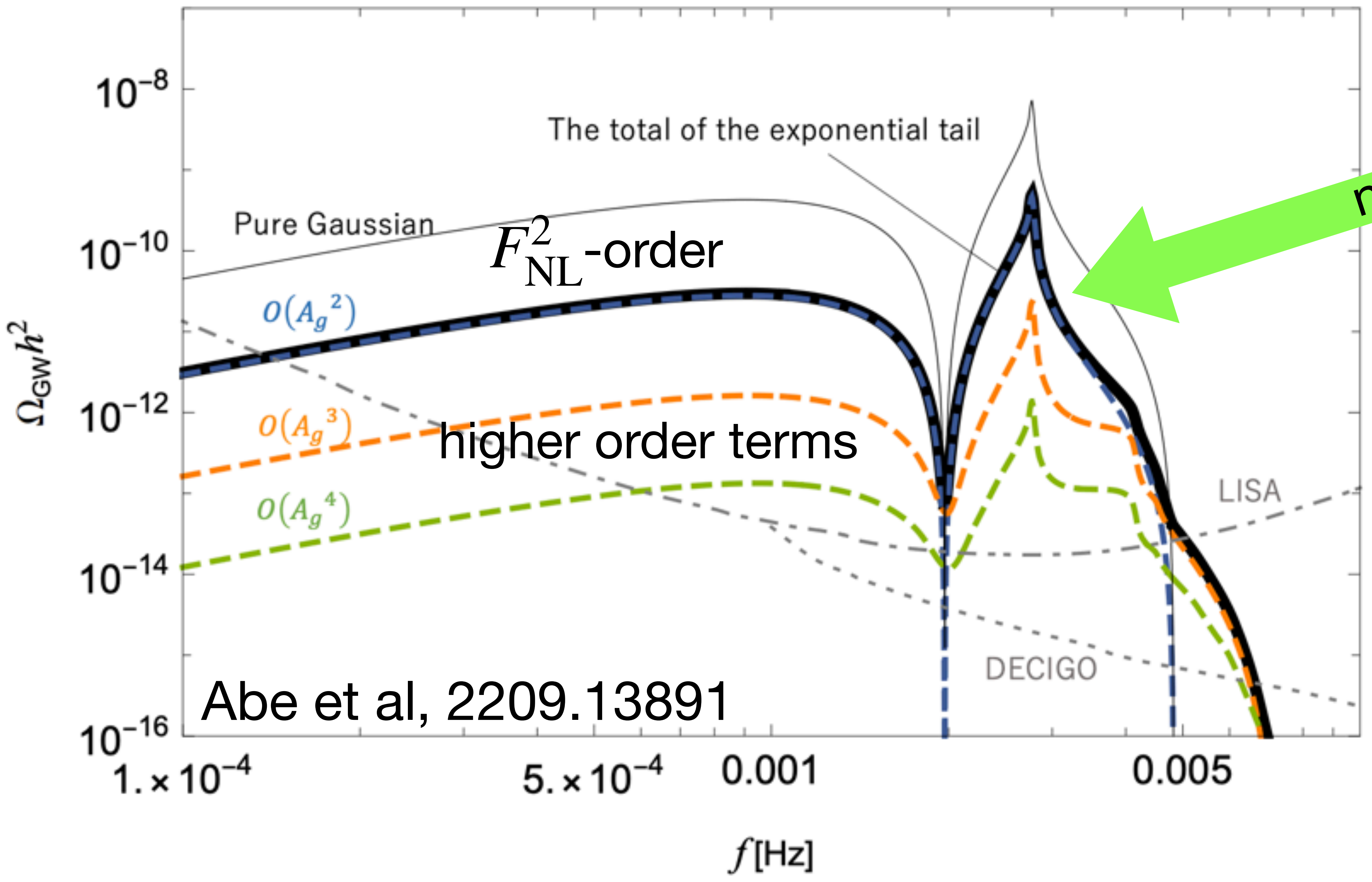


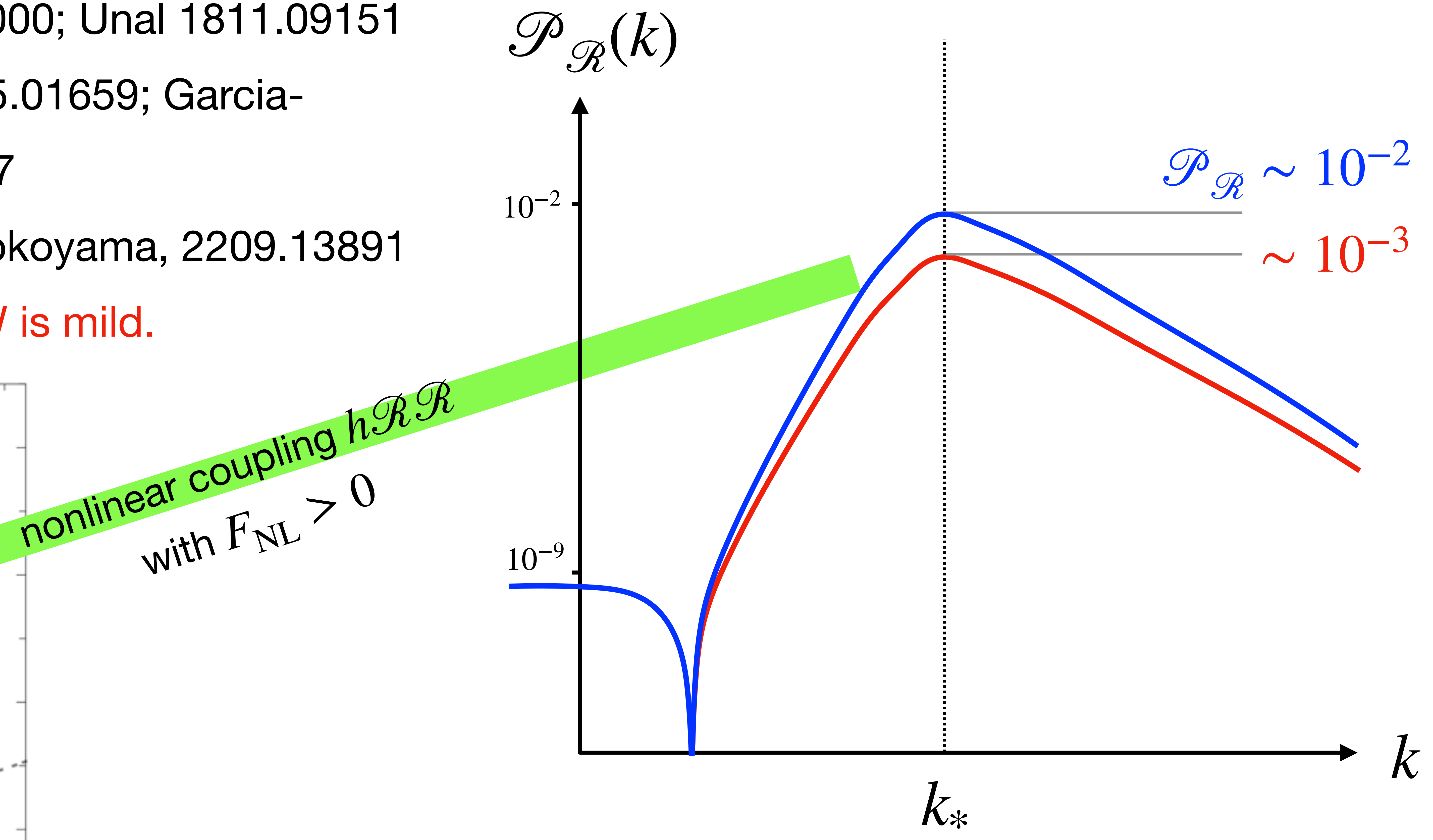
- Press-Schechter: Young & Byrnes 1307.4995; Young et al 1405.7023
- Extended Press-Schechter: Biagetti et al 2105.07810; Gow et al 2211.08348; Ferrante et al 2211.01728
- Peak theory: De Luca et al 1904.00970; Atal et al 1905.13202; Yoo et al 2008.02425; Kitajima et al 2109.00791; Escrivà et al 2202.01028; Germani & Sheth 1912.07072;
- Non-Gaussianity is important in calculating the PBH abundance.

SP, Sasaki, Takhistov, Jianing Wang, in prep.

Non-Gaussianities in IGW

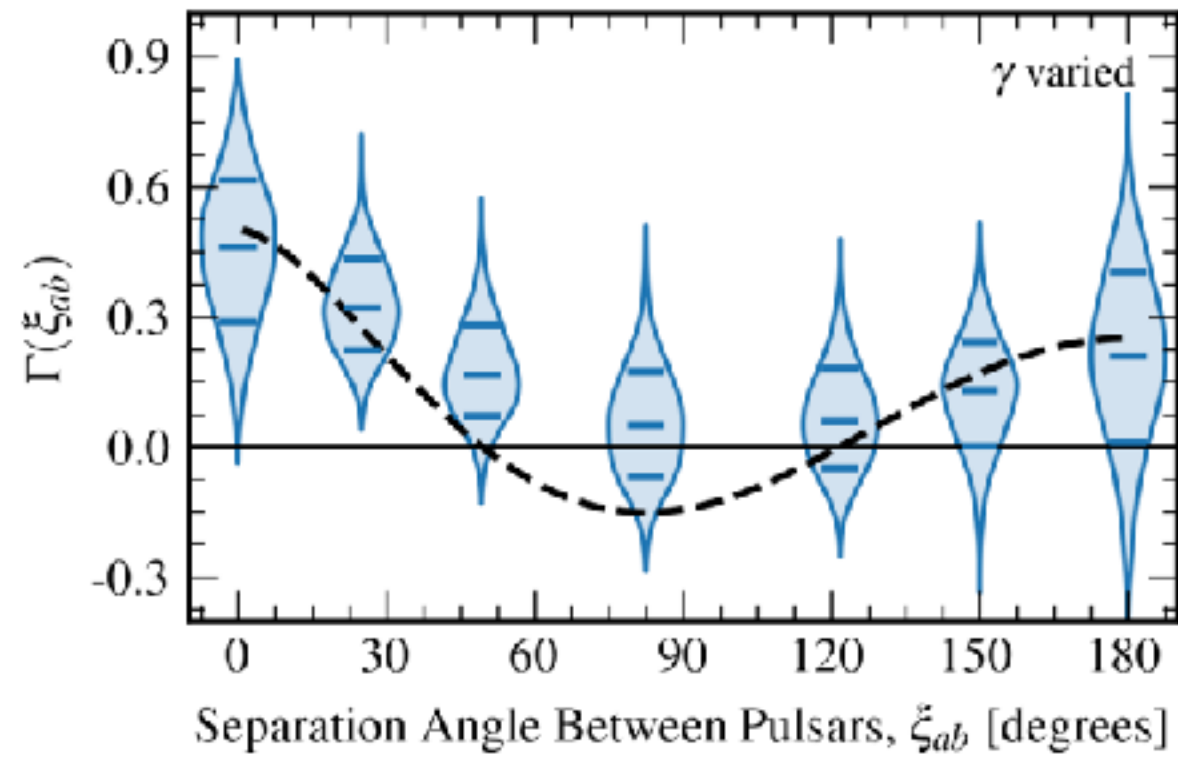
- Quadratic expansion: Cai, SP, Sasaki 1810.11000; Unal 1811.09151
- Higher orders: Adshead, Lozanov, Weiner 2105.01659; Garcia-Saenz, Pinol, Renaux-Petel, Werth, 2207.14267
- For exponential-tail of USR: Abe, Inui, Tada, Yokoyama, 2209.13891
- The impact of non-Gaussianity on induced GW is mild.



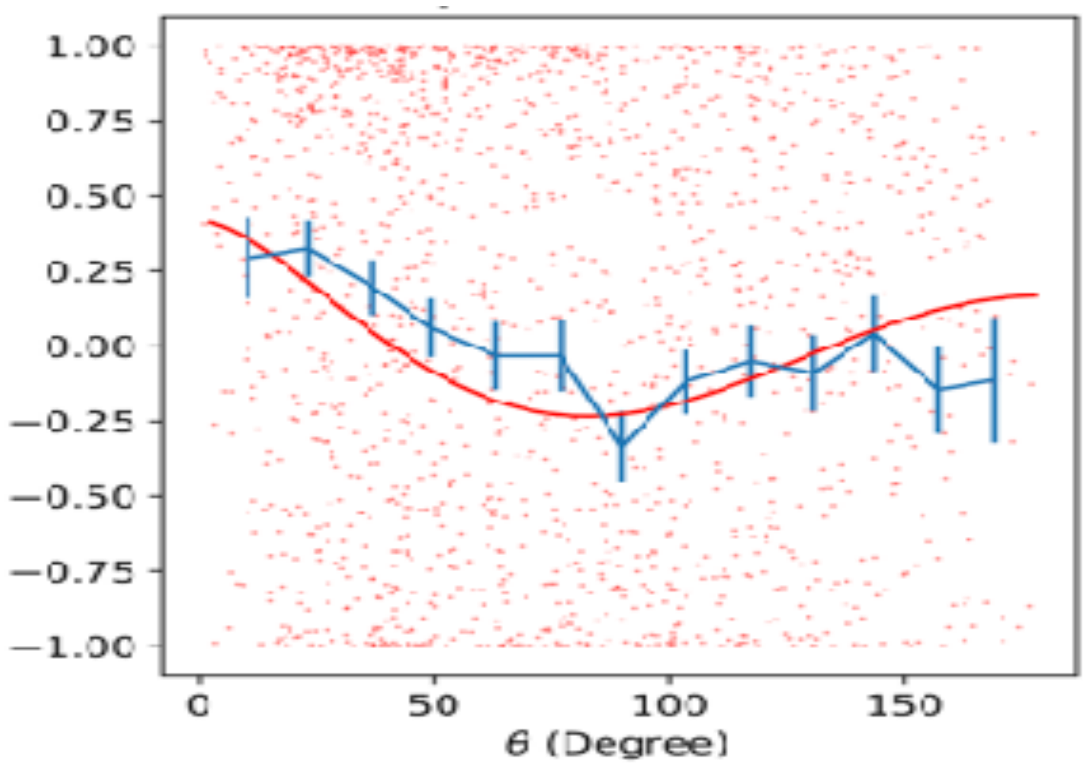


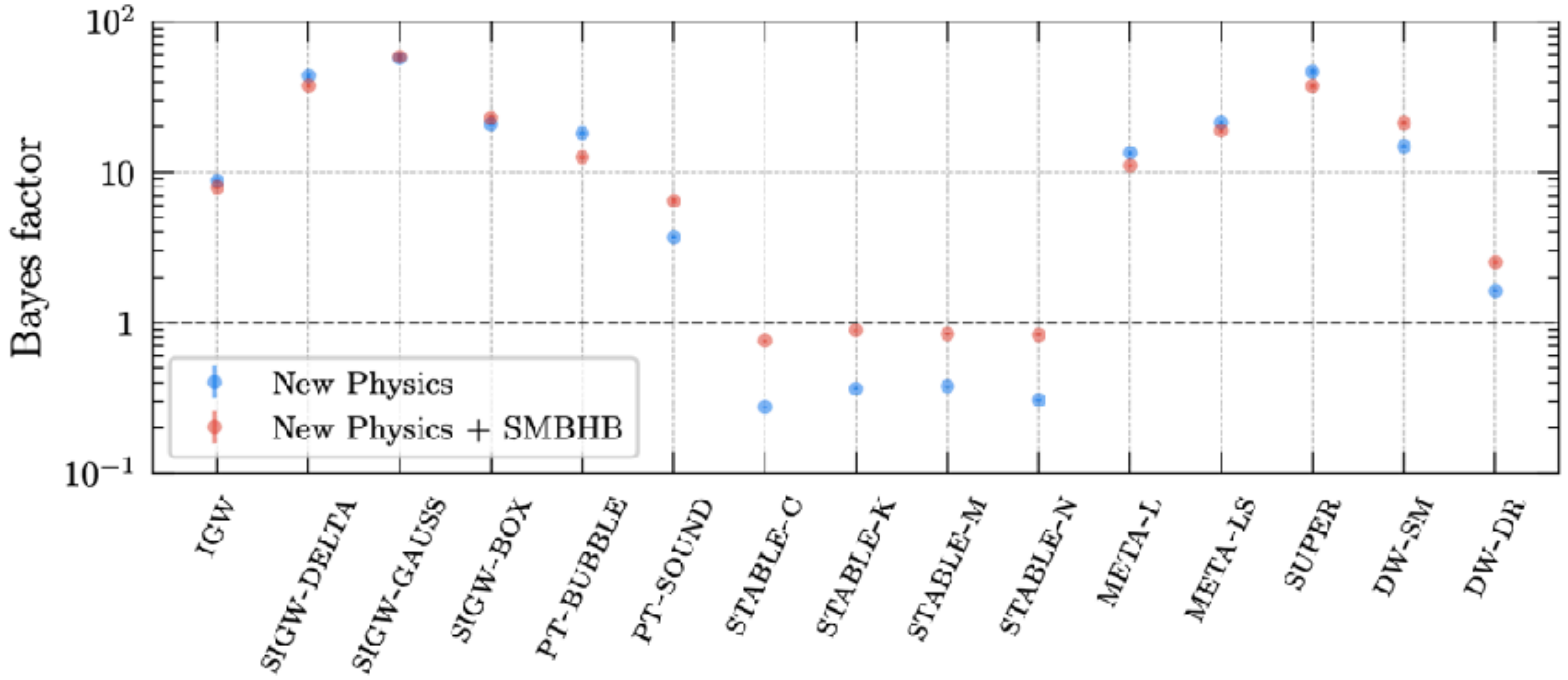
Application: nHz SGWB

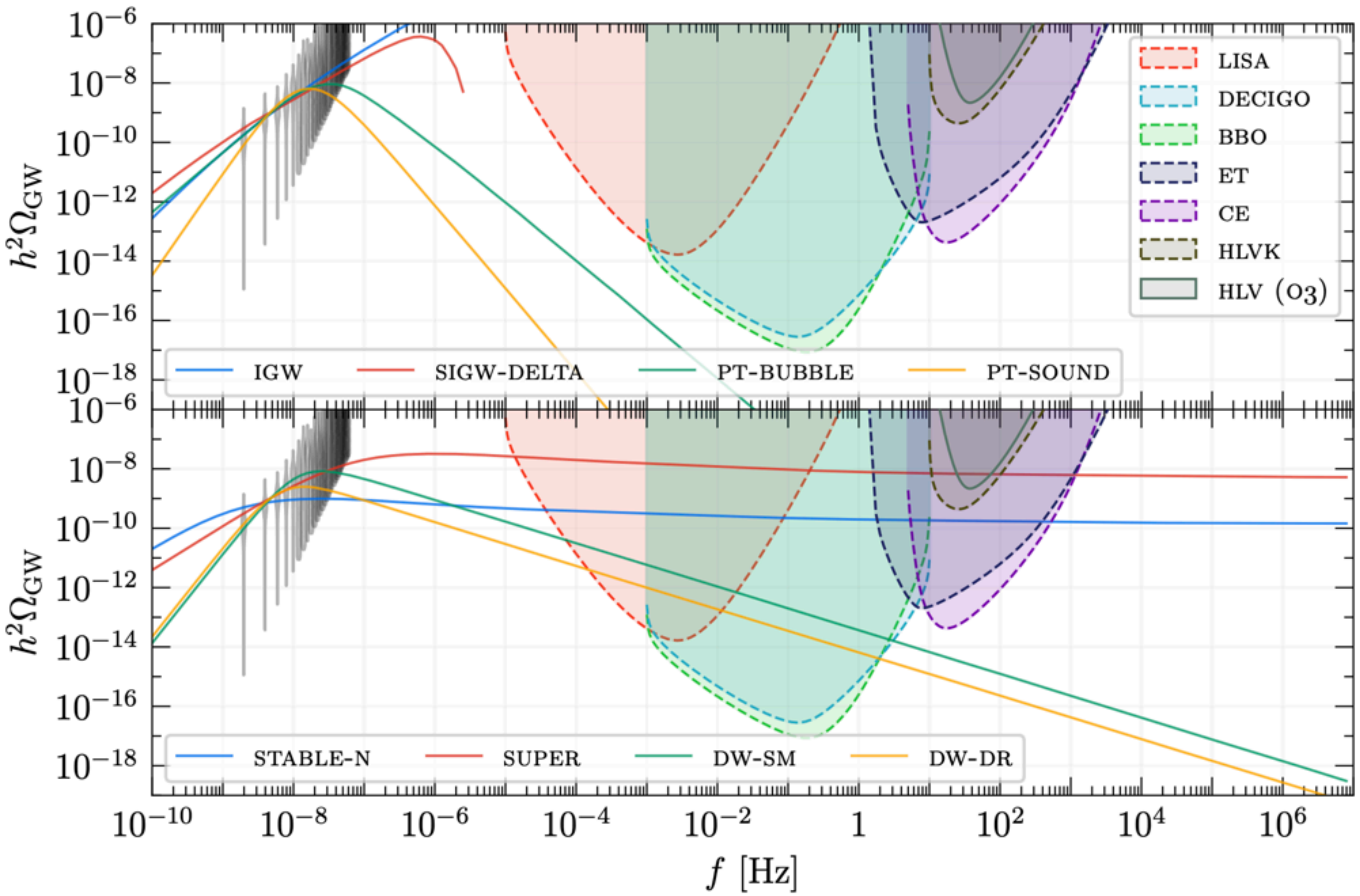
NANOGrav, 2306.16213



CPTA, 2306.16216



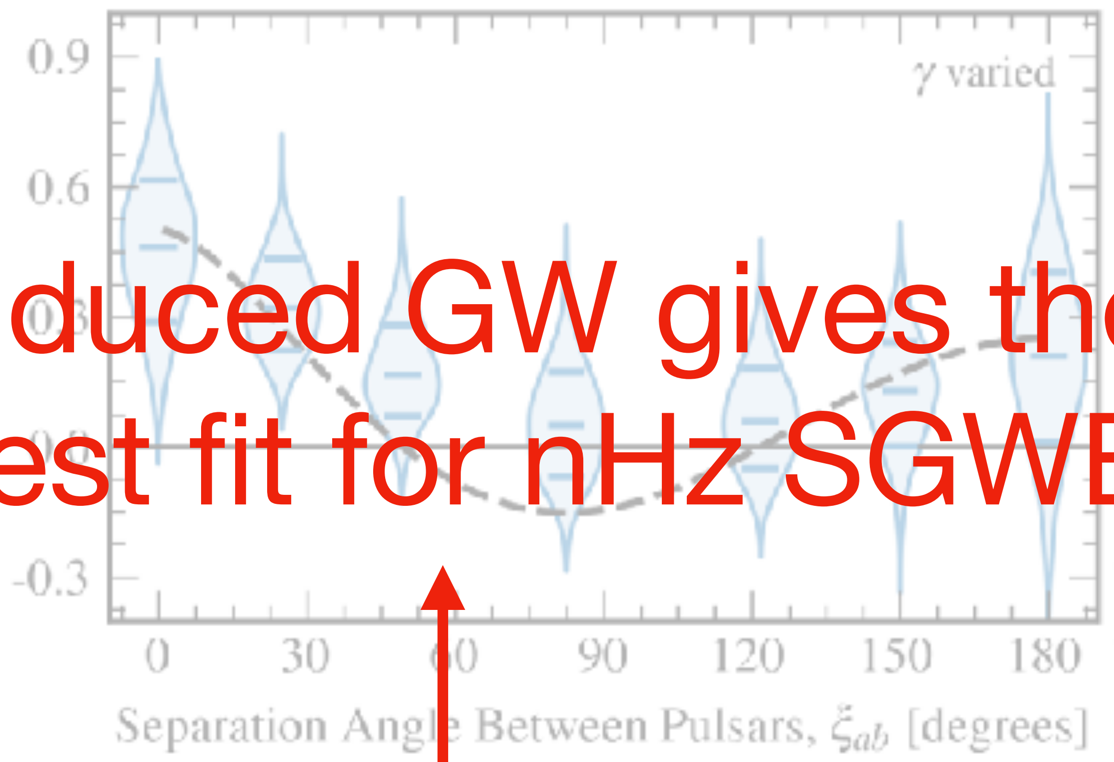




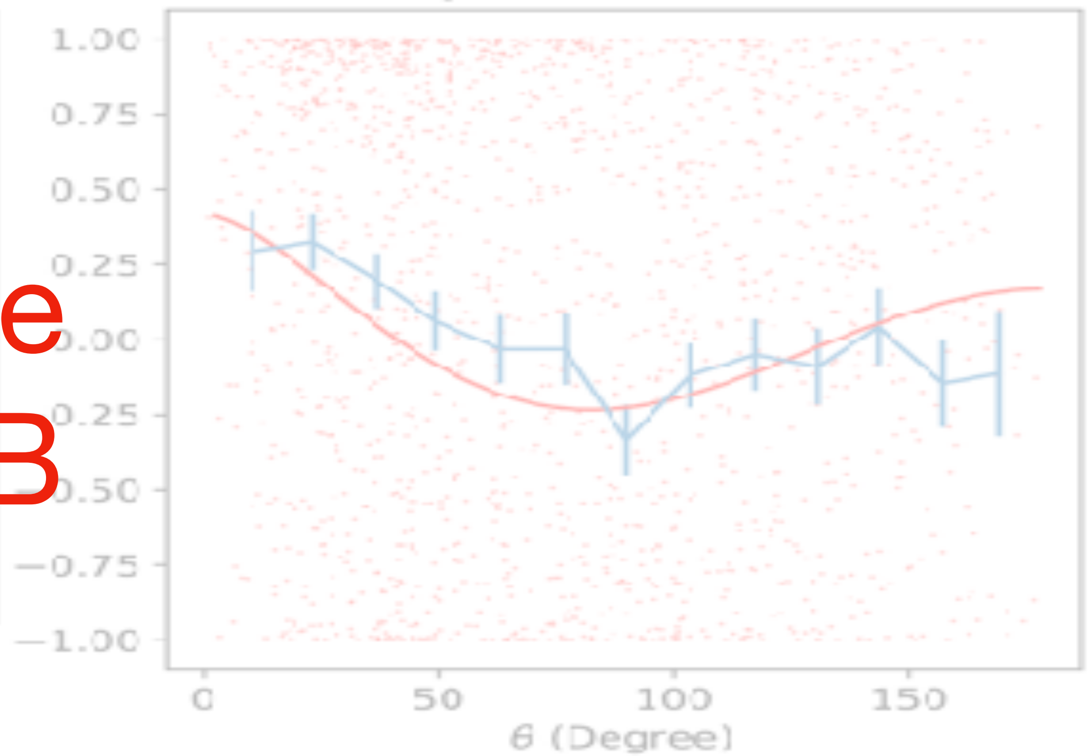
NANOGrav, 2306.16219

Application: nHz SGWB

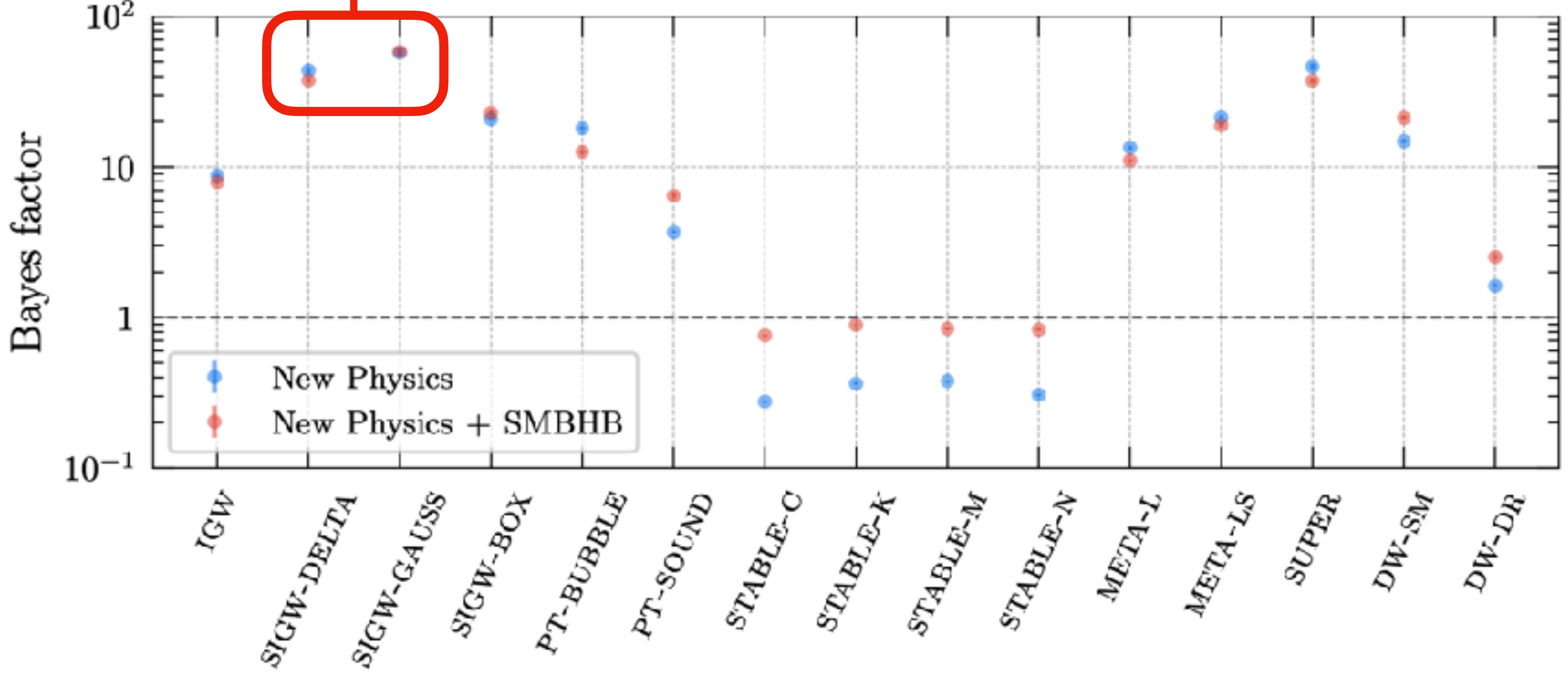
NANOGrav, 2306.16213



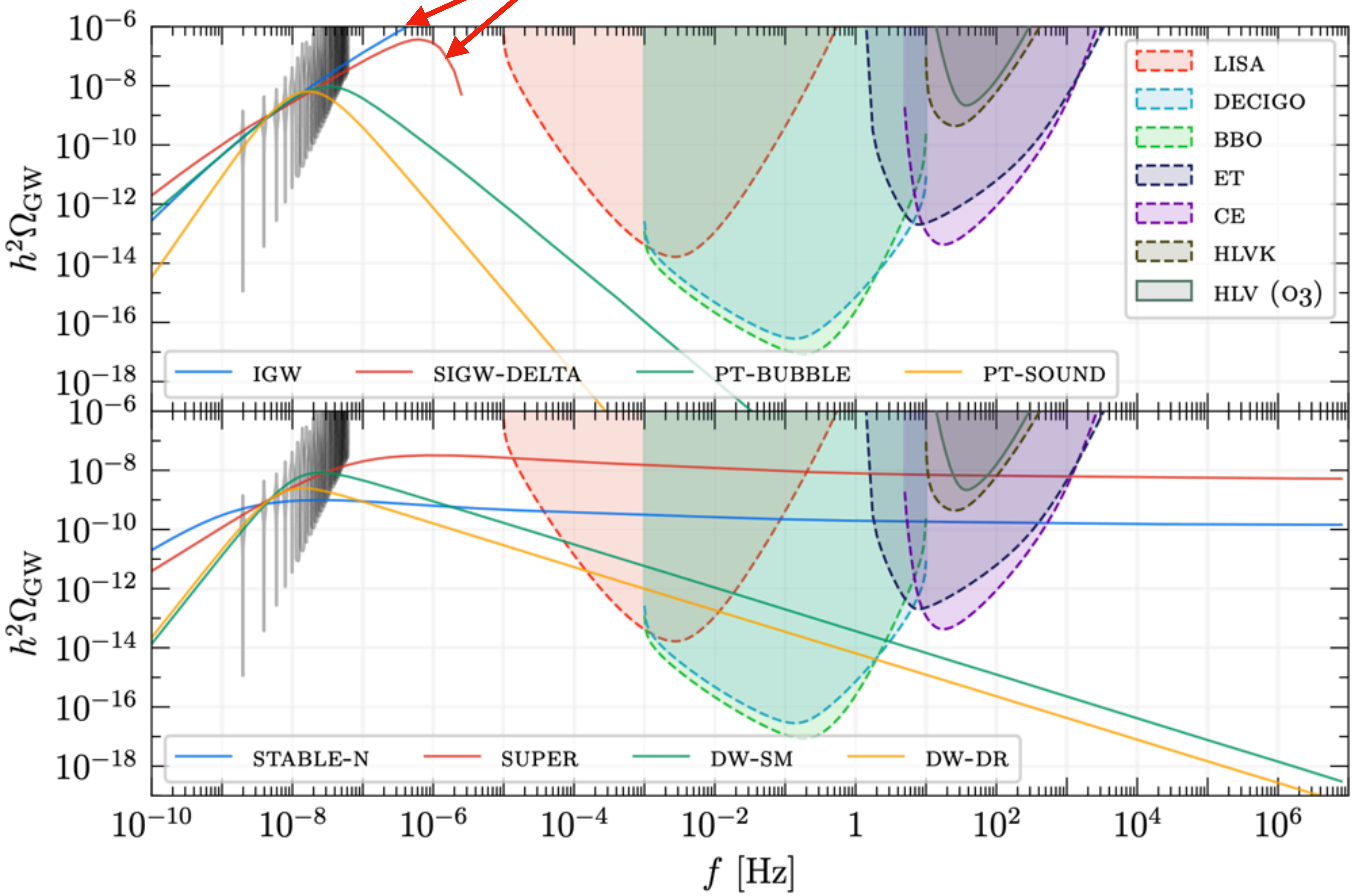
CPTA, 2306.16216



Induced GW gives the best fit for nHz SGWB

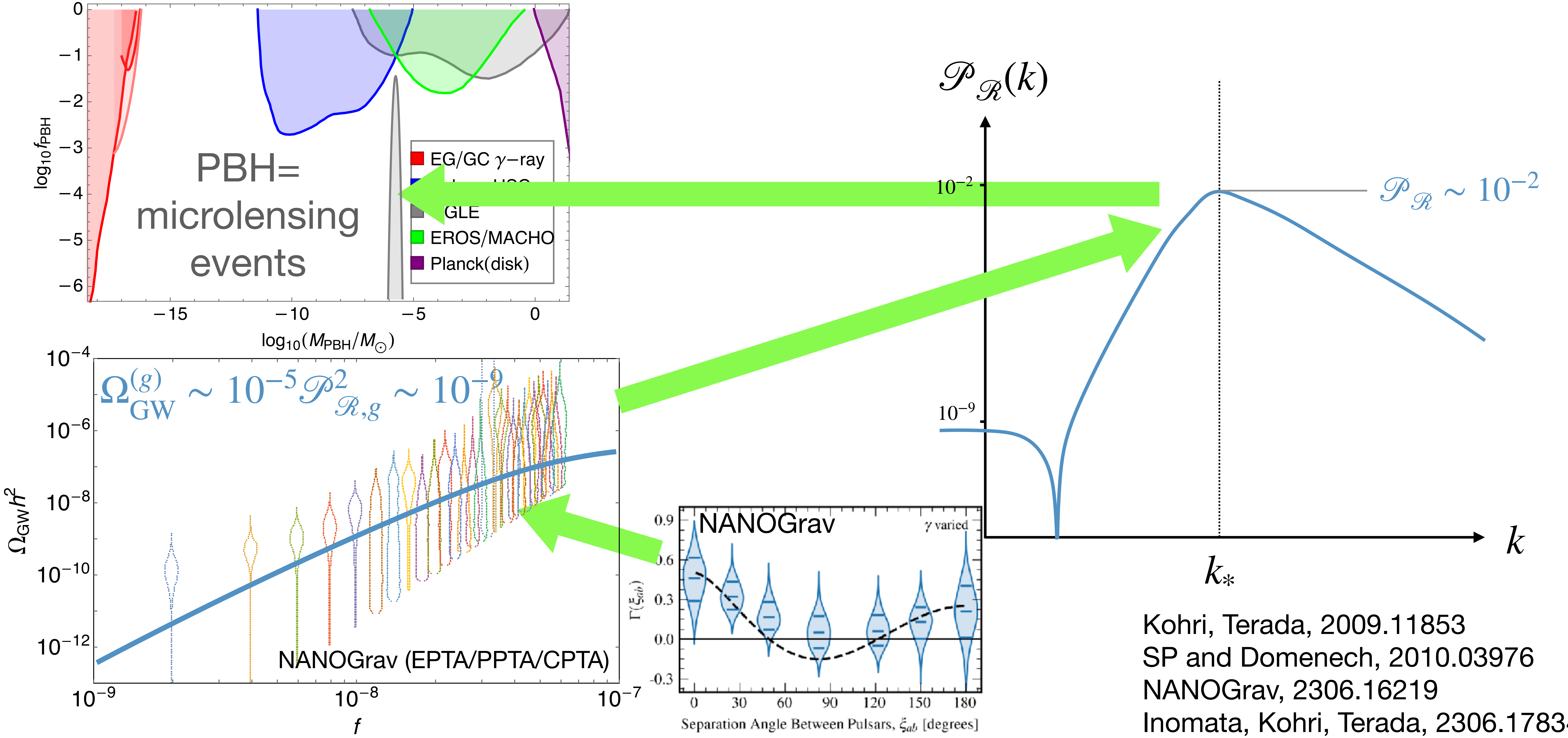


Induced GW



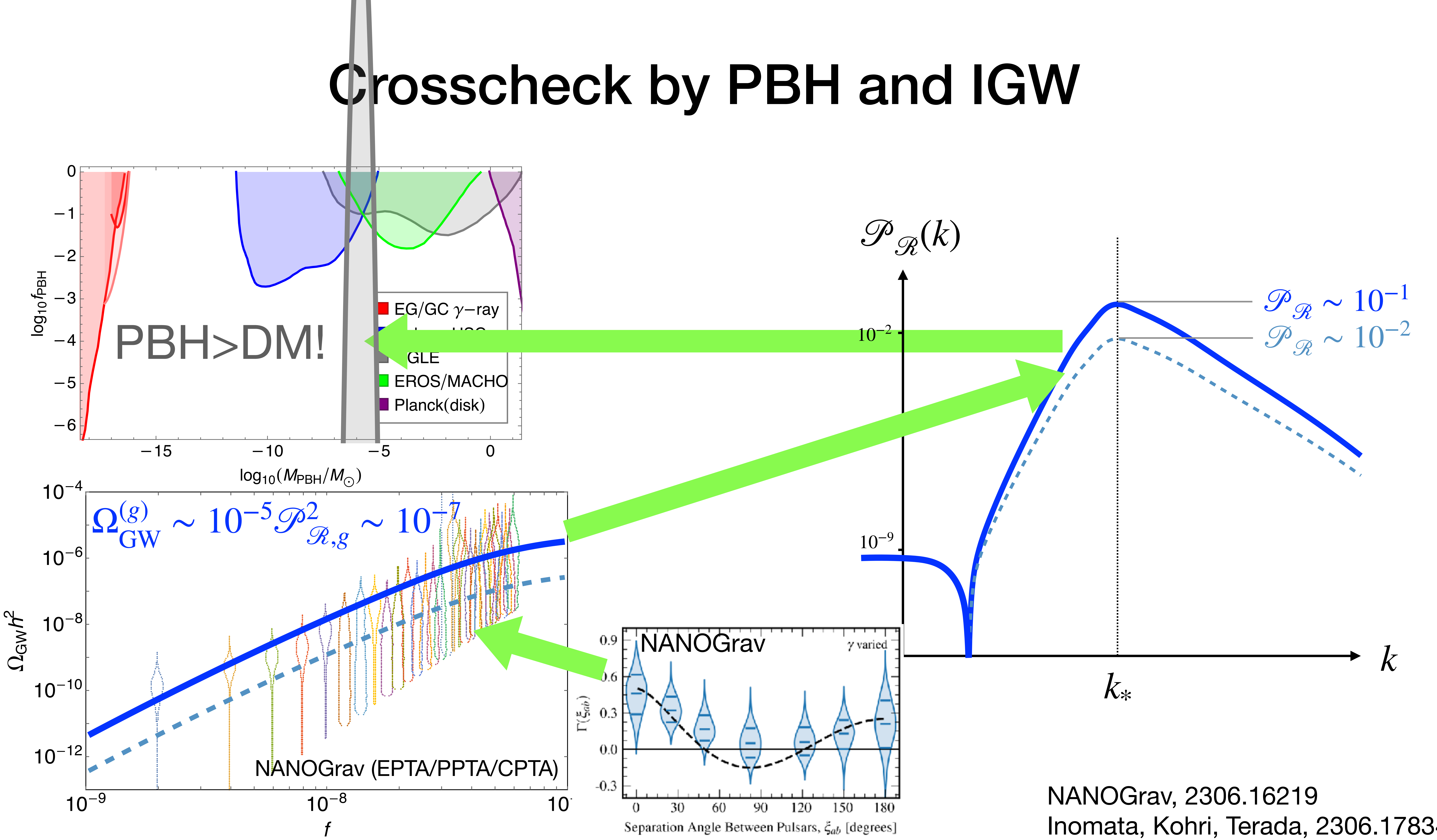
NANOGrav, 2306.16219

Crosscheck by PBH and IGW



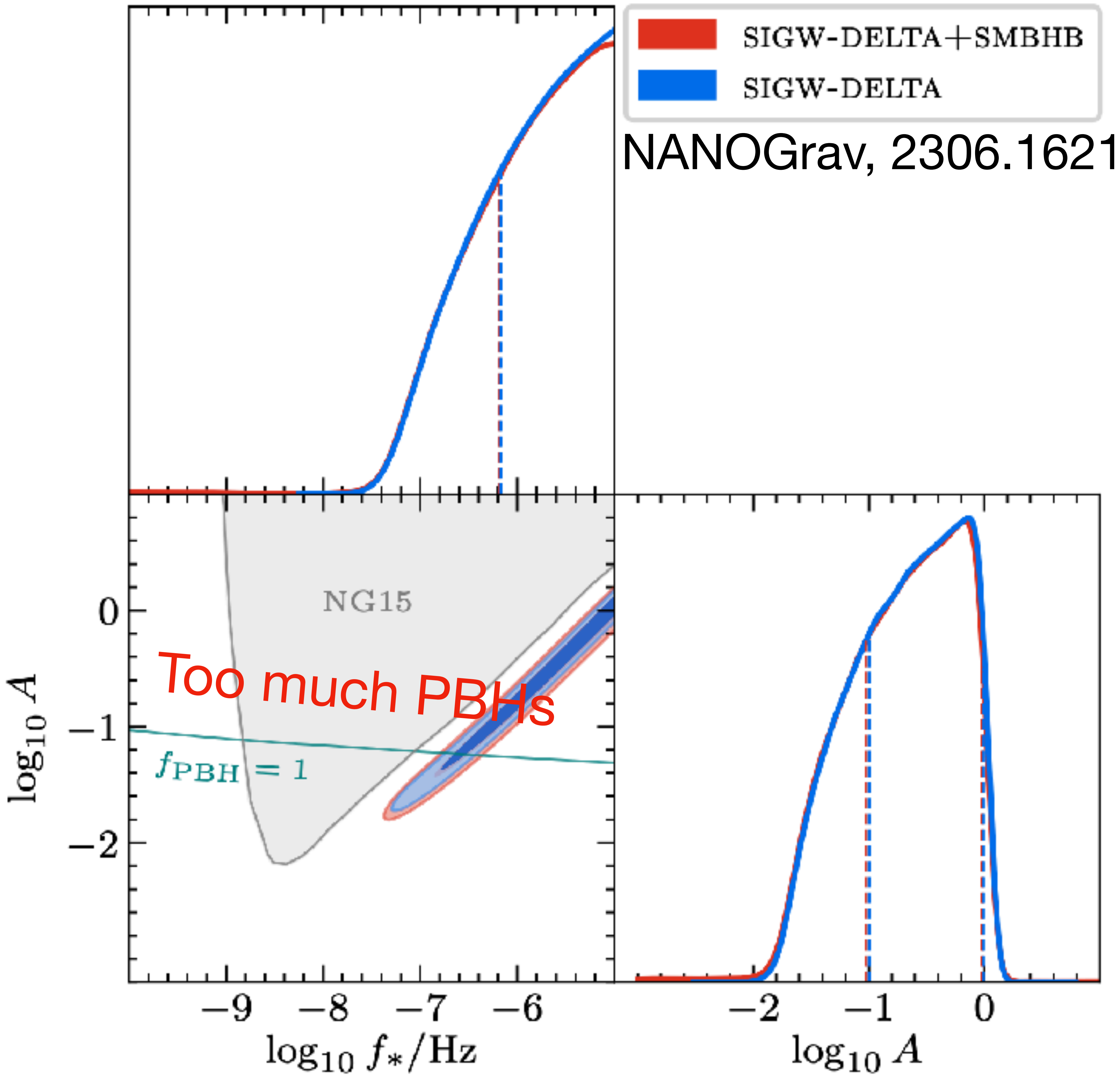
Kohri, Terada, 2009.11853
SP and Domenech, 2010.03976
NANOGrav, 2306.16219
Inomata, Kohri, Terada, 2306.17834

Crosscheck by PBH and IGW



NANOGrav, 2306.16219
Inomata, Kohri, Terada, 2306.17834

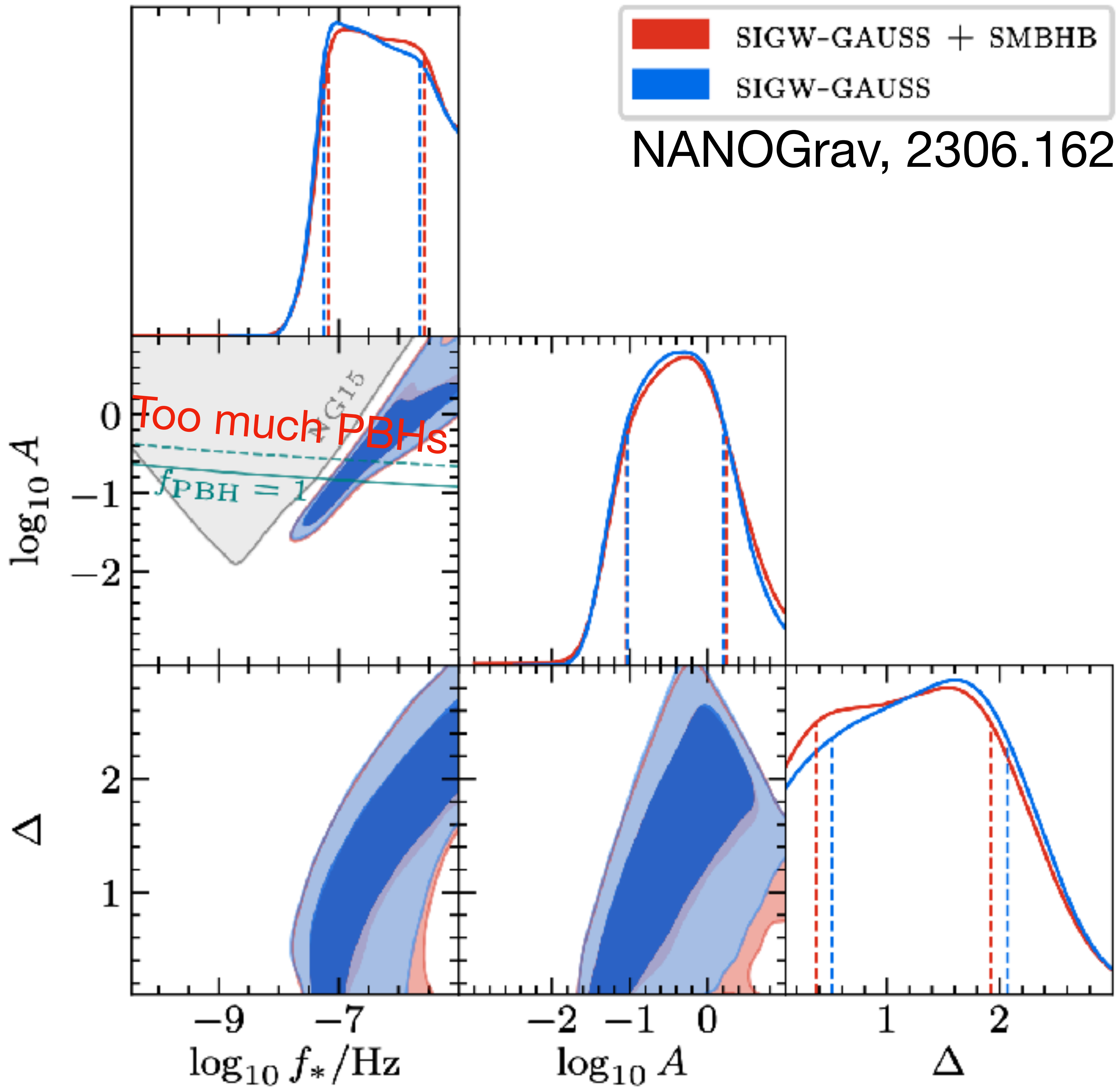
IGW as nHz SGWB



NANOGrav, 2306.16219

$$\mathscr{P}_{\mathscr{R}} = A\delta(\ln k - \ln k_*)$$

monochromatic



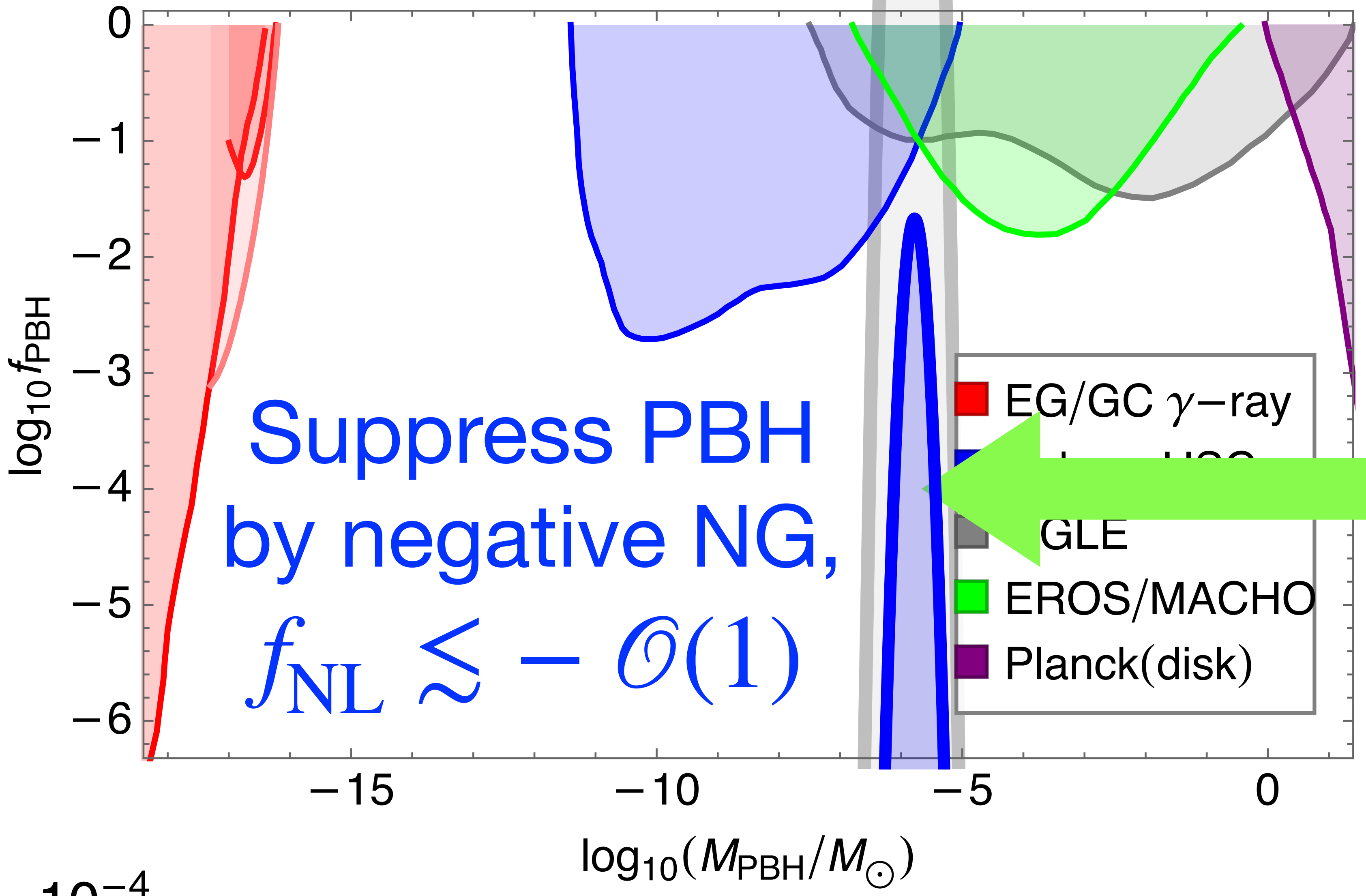
NANOGrav, 2306.16219

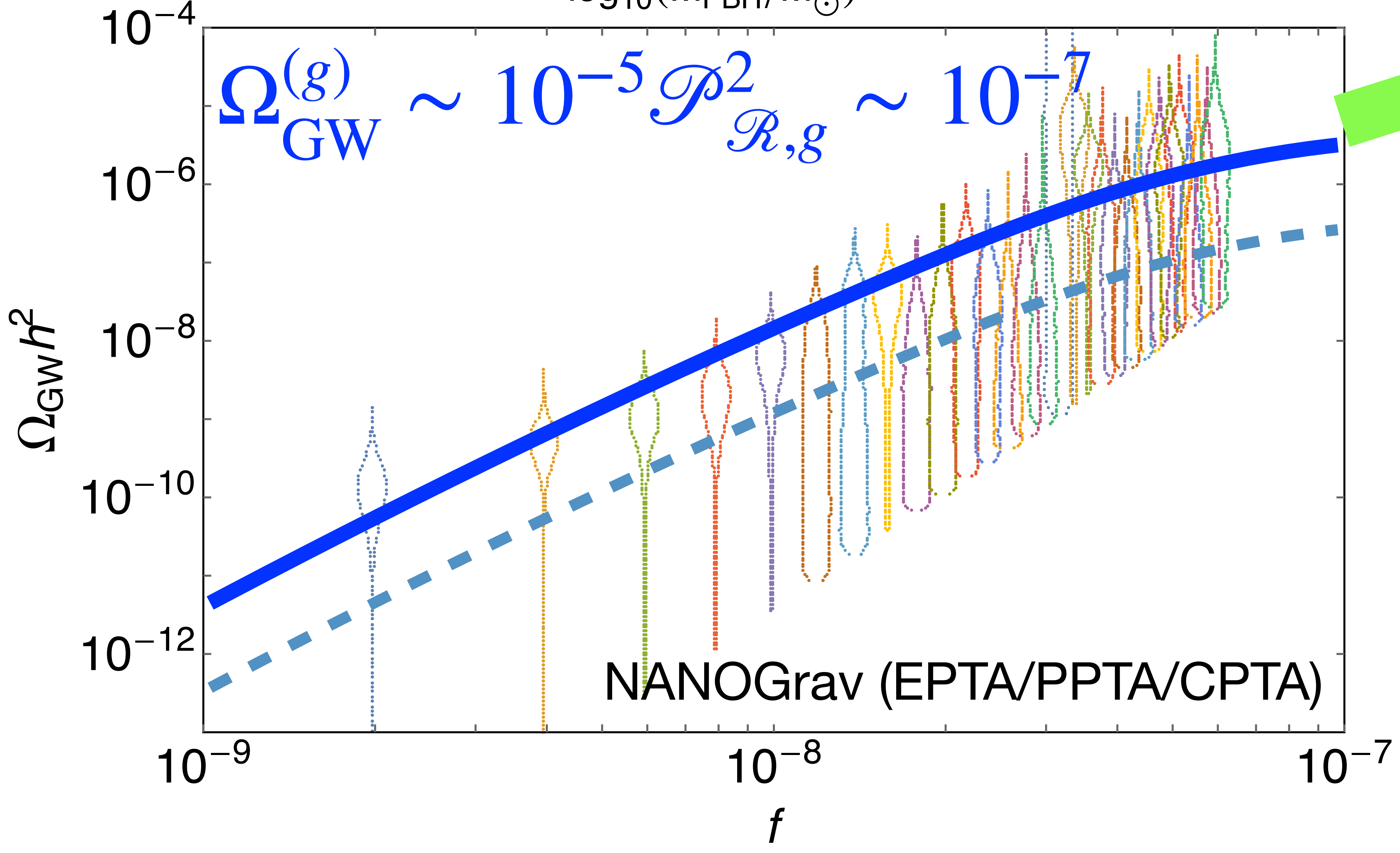
$$\mathscr{P}_{\mathscr{R}} = \frac{A}{\sqrt{2\pi}\Delta} \exp\left(-\frac{(\ln k - \ln k_*)^2}{2\Delta^2}\right)$$

lognormal [SP and Sasaki 2005.12306]

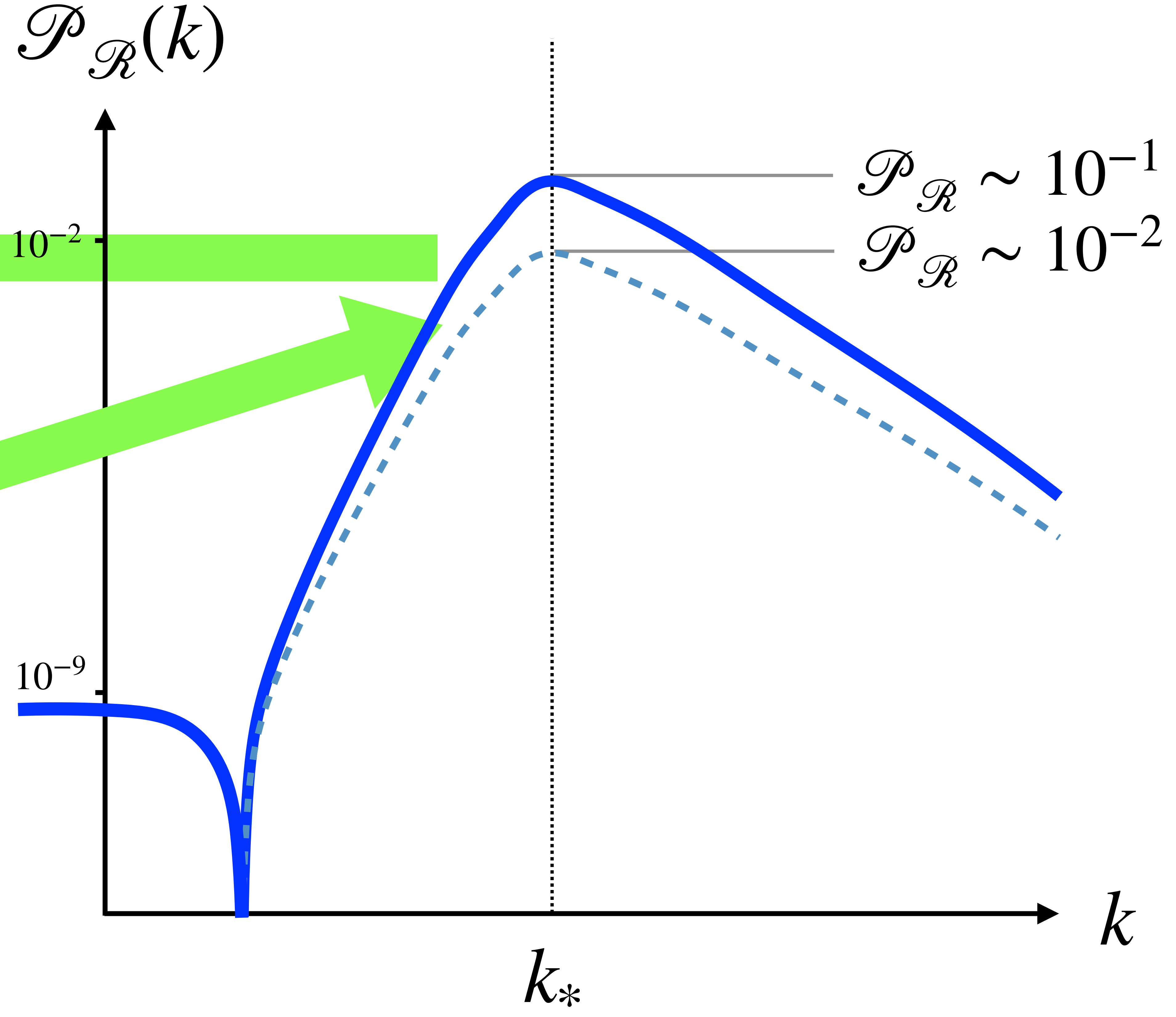
Crosscheck by PBH and IGW

Gaussian case,
PBH>DM!





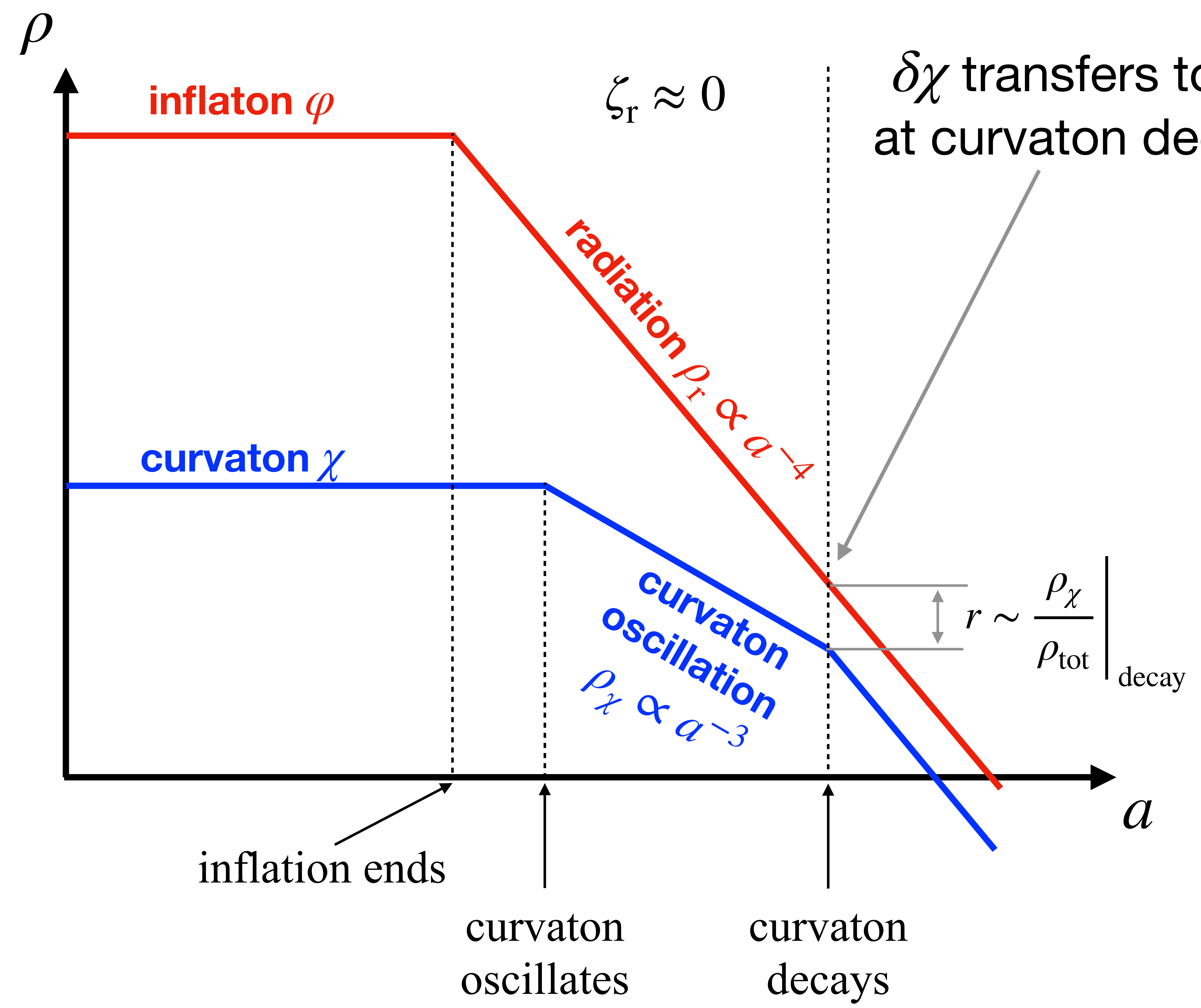
$f_{\rm NL} < 0$



Franciolini et al, 2306.17149
Liu et al, 2307.01102

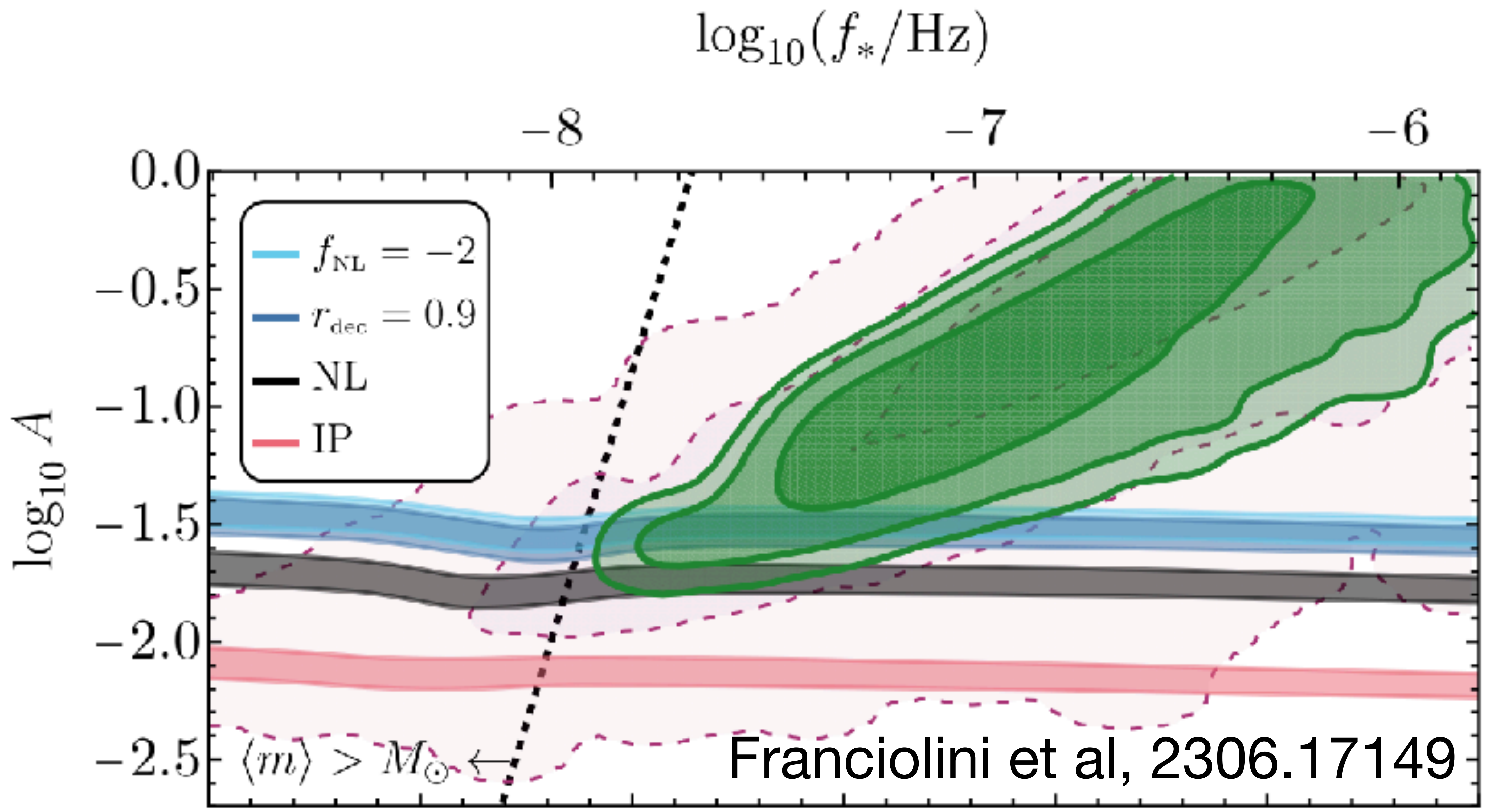
Curvaton Scenario

SP and Sasaki, 2112.12680
Ferrante et al, 2211.01728



$$\zeta = \zeta(\delta\chi/\chi) \longrightarrow \begin{cases} \frac{r}{3}\left[2\frac{\delta\chi}{\chi} + \left(\frac{\delta\chi}{\chi}\right)^2\right] & \text{when } r \ll 1 \\ \frac{2}{3}\ln\left|1 + \frac{\delta\chi}{\chi}\right| & \text{when } r \sim 1 \end{cases}$$

- $\zeta(\delta\chi)$ degenerates to a logarithmic relation ($f_{\rm NL} = -5/4$) when the curvaton dominates.



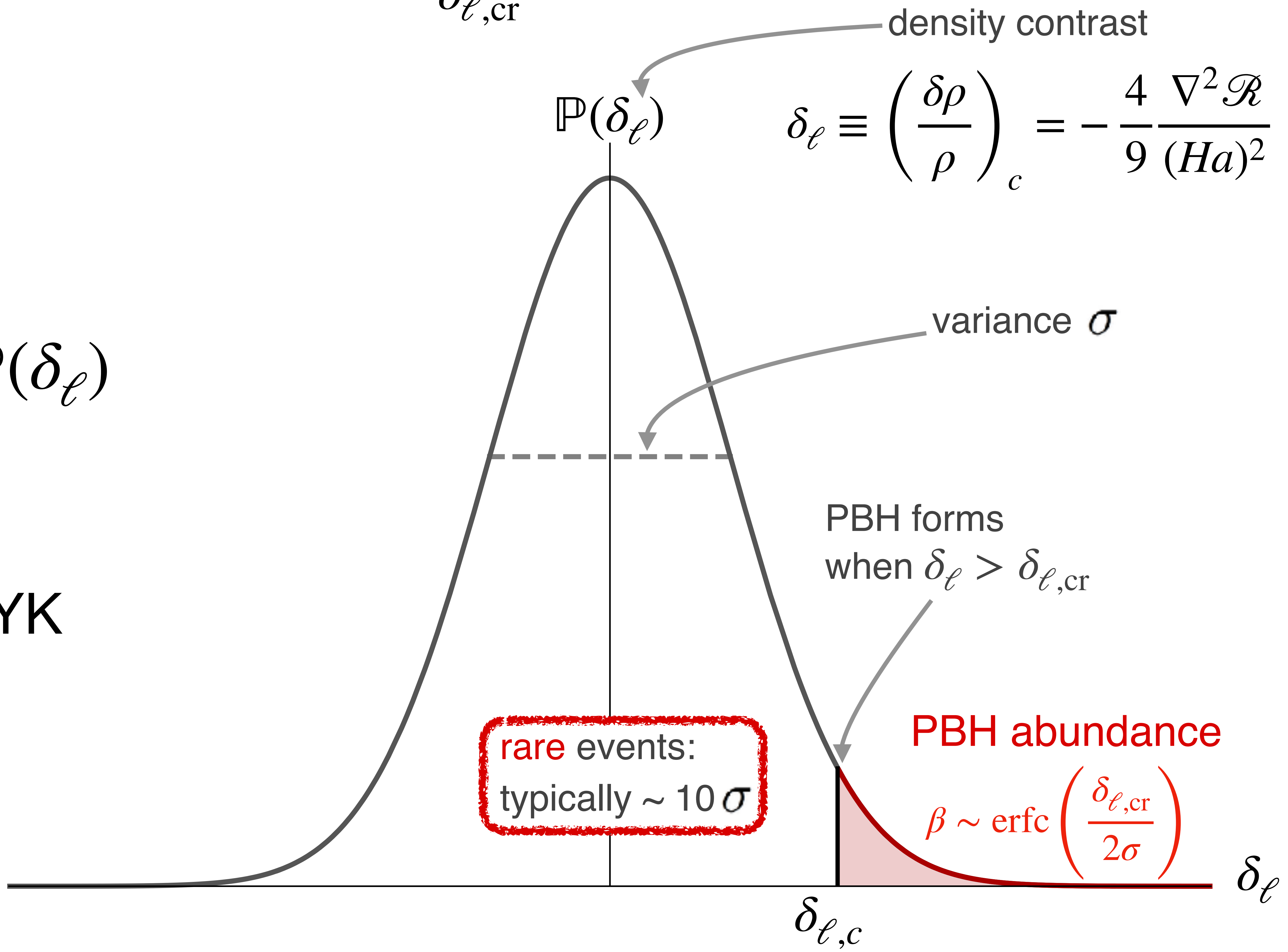
Franciolini et al, 2306.17149

How to calculate: Press-Schechter

$$\left.\begin{array}{l} \mathscr{R} \xrightarrow{(1)} \delta_\ell \\ \mathbb{P}(\mathscr{R}) \xrightarrow{(2)} \mathbb{P}(\delta_\ell) \end{array}\right\} \xrightarrow[\text{(4) Window function}]{\text{(3) given } \delta_{\ell,\text{cr}}} \beta = \int_{\delta_{\ell,\text{cr}}} \mathbb{P}(\delta_\ell) M(\delta_\ell) d\delta_\ell$$

Every step is linear/Gaussian.

- (1) Linear Poisson equation.
- (2) Gaussian PDF $\mathbb{P}(\mathscr{R})$ goes to Gaussian PDF $\mathbb{P}(\delta_\ell)$ by $\mathbb{P}(\mathscr{R})d\mathscr{R} = \mathbb{P}(\delta_\ell)d\delta_\ell$
- (3) Critical density contrast $\delta_{\ell,\text{cr}}$ is given by the HYK limit (Harada, Yoo, Kohri, 1309.4201).
- (4) Window function matters for broad peaks.



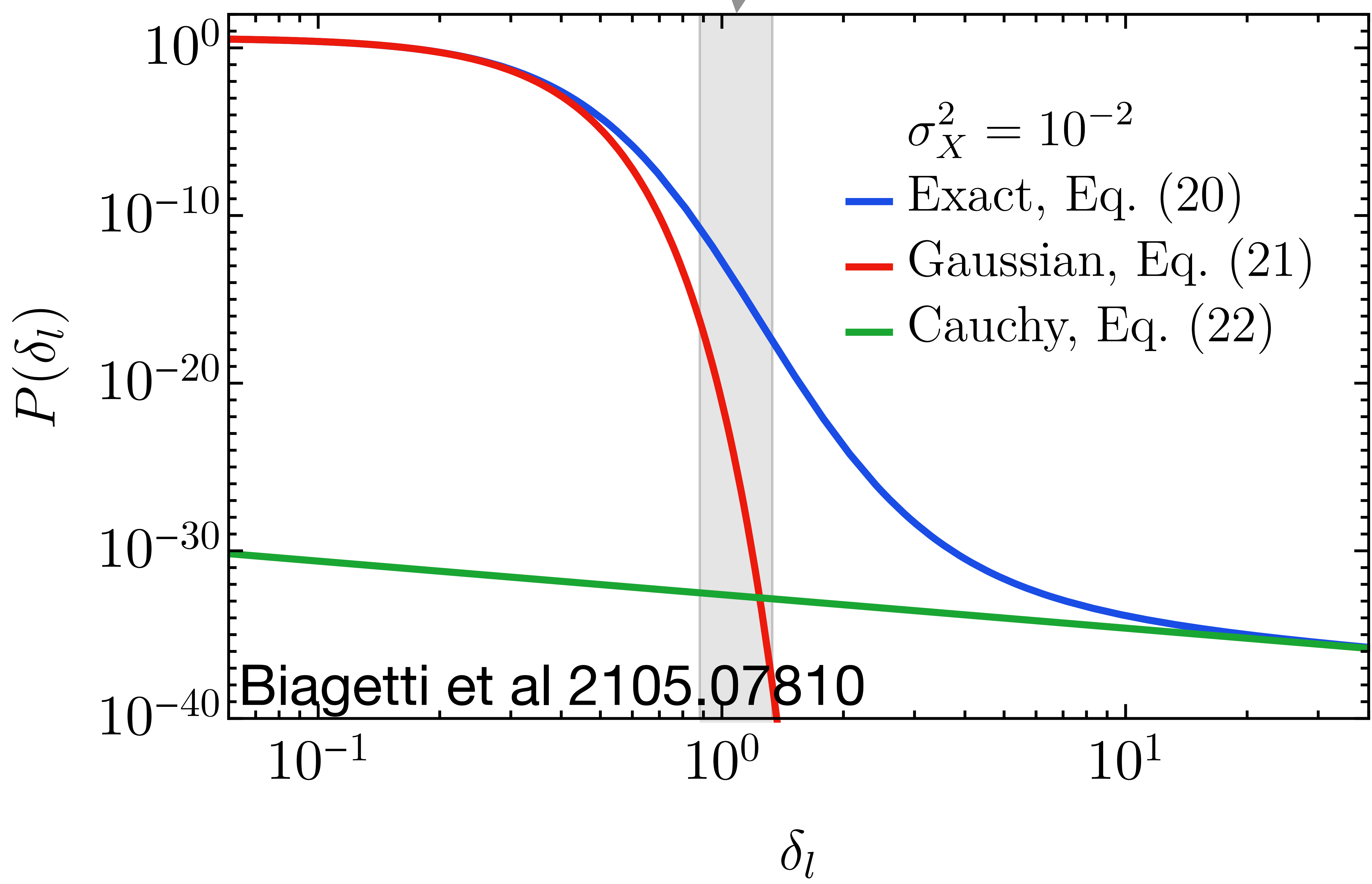
Why non-Gaussianity?

$$\begin{array}{ccc} \mathscr{R} & \xrightarrow{(1)} & \mathscr{C} \\ \mathbb{P}(\mathscr{R}) & \xrightarrow{(2)} & \mathbb{P}(\mathscr{C}) \end{array} \Bigg\} \xrightarrow[\text{(4) Window function}]{\text{(3) given } \mathscr{C}_{\rm cr}} \beta = \int_{\mathscr{C}_{\rm cr}} \mathbb{P}(\mathscr{C}) M(\mathscr{C}) d\mathscr{C}$$

Non-Gaussianity enters in different processes

- (1) Use the compaction $\mathscr{C}$ function to calculate, which is connected to $\mathscr{R}$ by nonlinear Poisson equation. (Harada et al 1503.03934; De Luca et al 1904.00970.)
- (2) PDF $\mathbb{P}(\mathscr{R})$ could be non-Gaussian, which goes to non-Gaussian PDF $\mathbb{P}(\mathscr{C})$. (Main topic of this talk)
- (3) Critical density contrast $\mathscr{C}_{\rm cr}$ given by numerical simulations. (Musco 1809.02127; Escrivà et al 1907.13311)

PBH formation regime

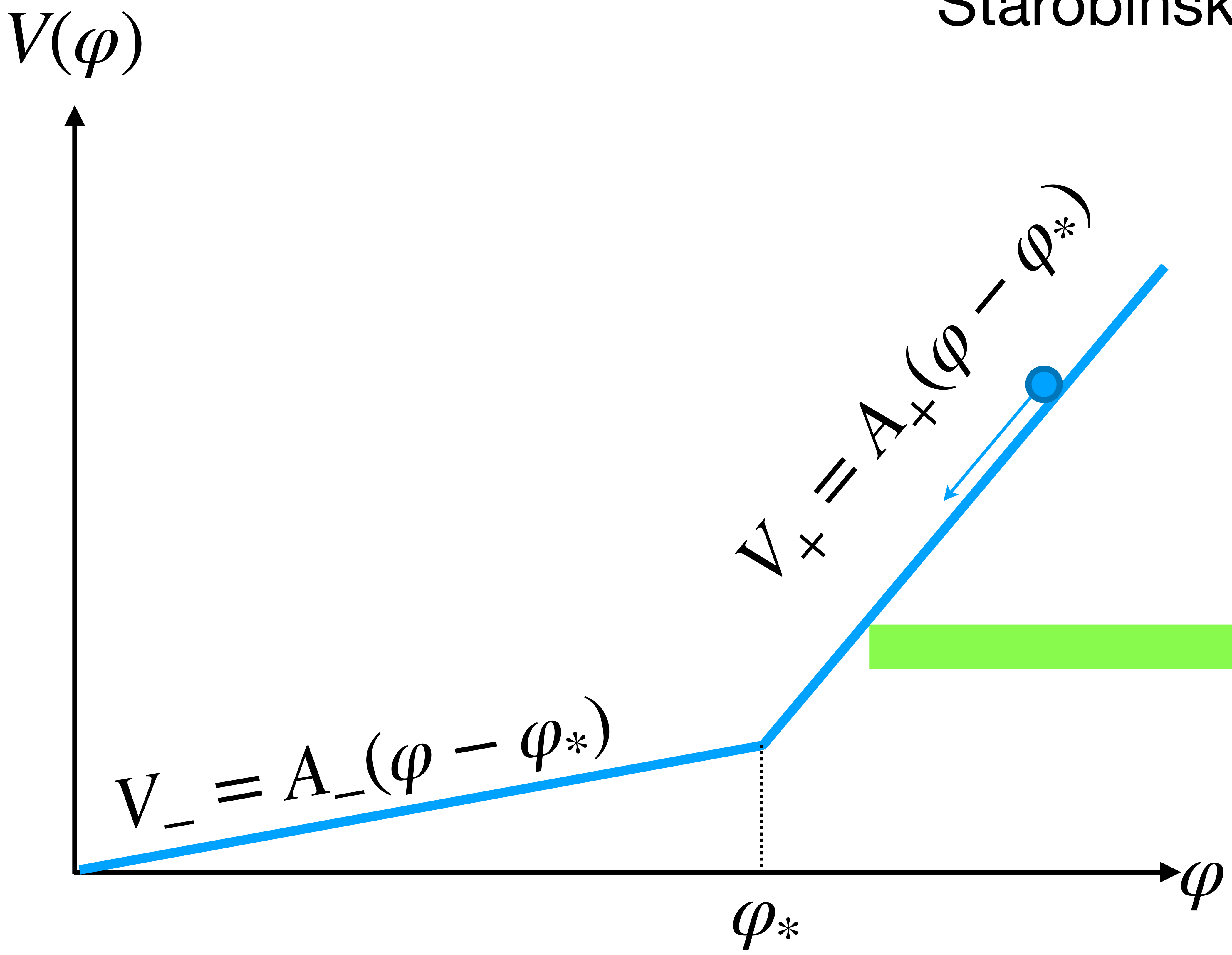


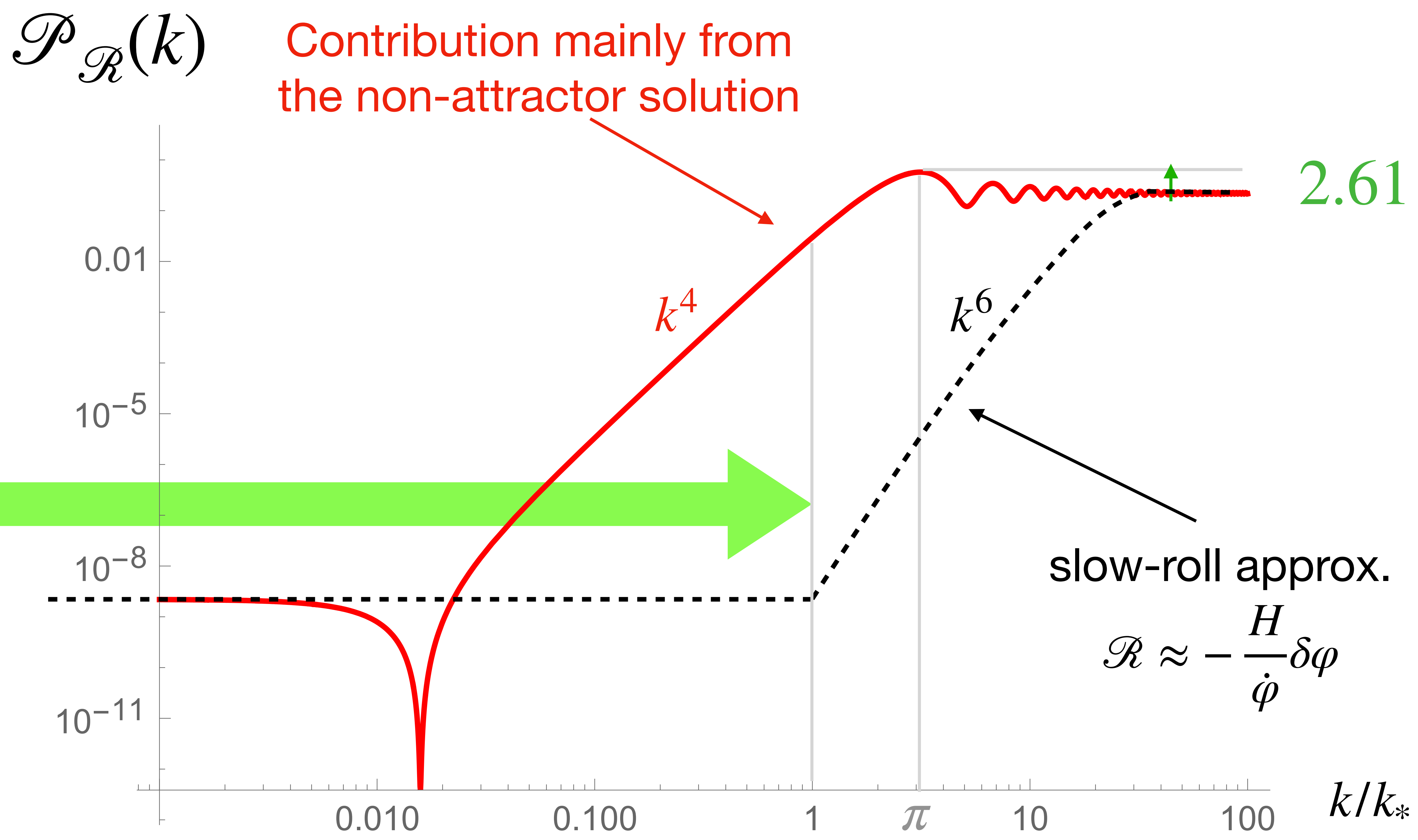
Nonlinearity of the curvature perturbation

A general relation between $\mathscr{R}$ and $\delta\varphi$

Ultra-slow-roll Inflation

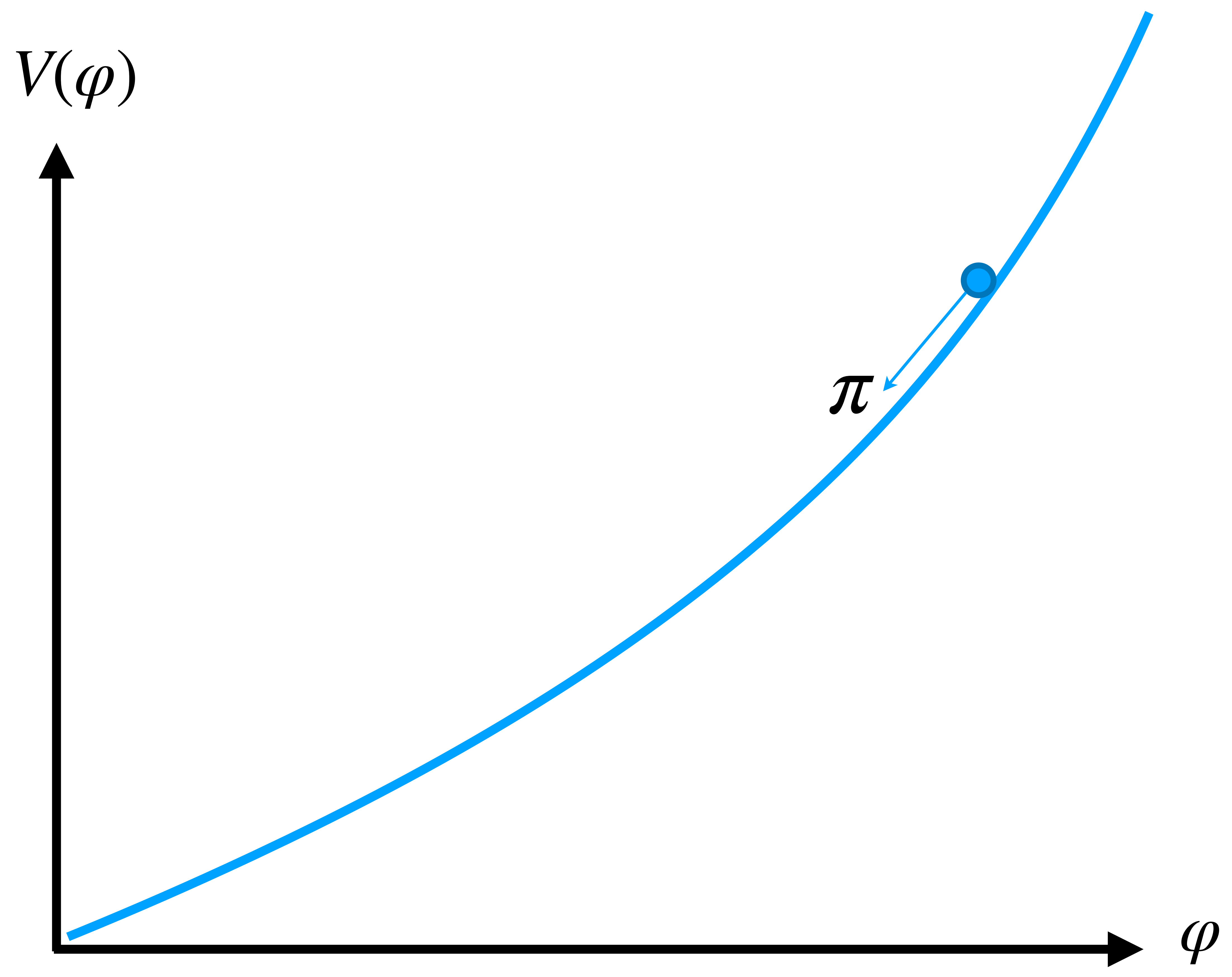
Starobinsky's linear potential model





Starobinski, JETP Lett. 55, 489
Byrnes, Cole, Patil, 1811.11158
Cole, Gow, Byrnes, Patil, 2204.07573
SP, Jianing Wang, 2209.14183
Domenech, Vargas, Vargas, 2309.05750

Gaussian Curvature Perturbation

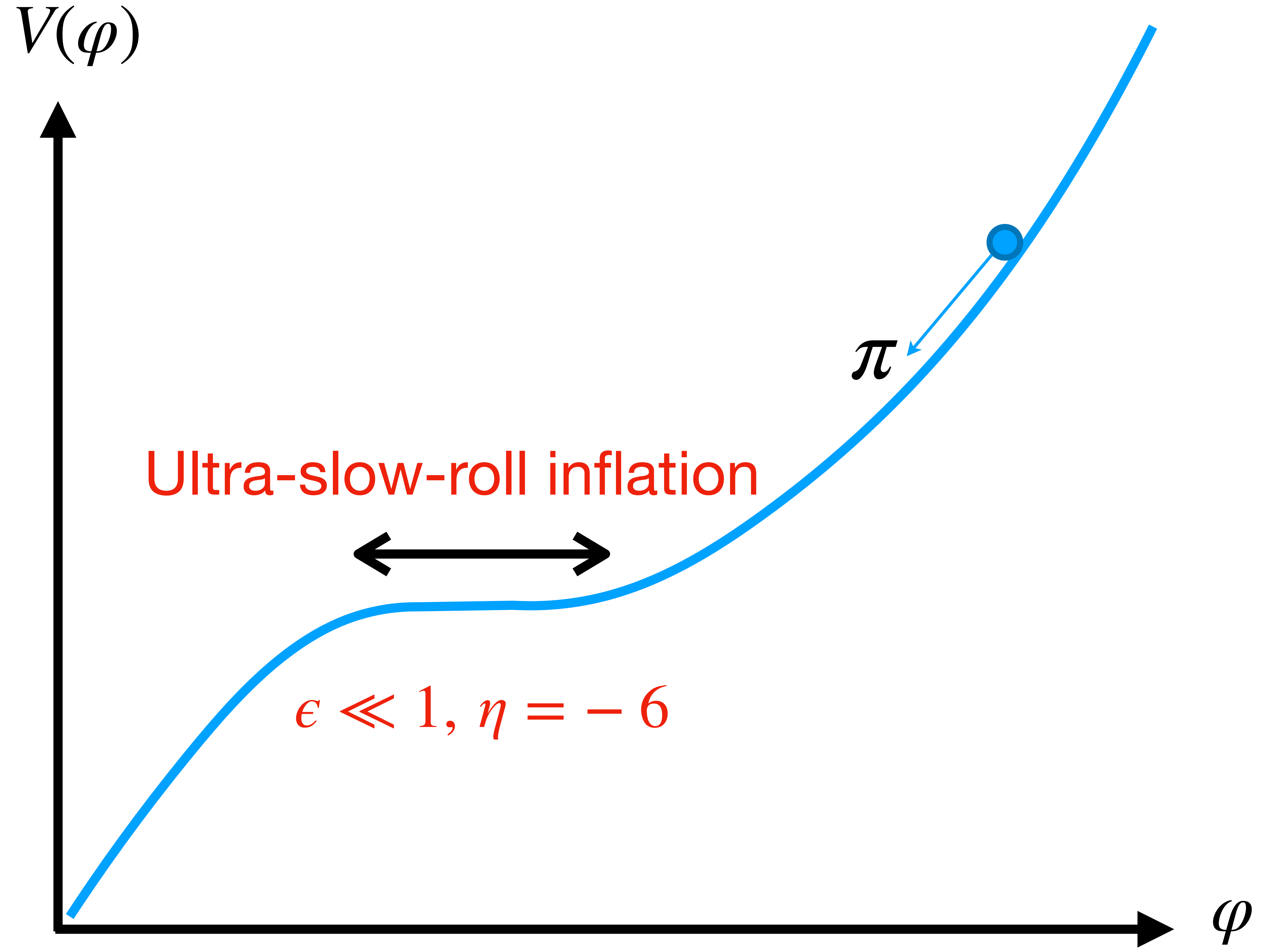


$$\mathcal{R} = \delta N \approx N_{,\varphi}\delta\varphi + \frac{1}{2}N_{,\varphi\varphi}\delta\varphi^2 + \cdots$$
$$= -H\frac{\delta\varphi}{\dot\varphi} + \frac{3}{5}\boxed{f_{\rm NL}}\left(-H\frac{\delta\varphi}{\dot\varphi}\right)^2\cdots$$

$f_{\rm NL} \rightarrow \mathcal{O}(\epsilon, \eta)$

Stewart and Sasaki, astro-ph/9507001
Lyth and Roquigez, astro-ph/0504045
Maldacena, astro-ph/0210603

Logarithmic Relation in the USR inflation



$\mathcal{O}(\epsilon, \eta) \sim \mathcal{O}(1)$

$$\mathcal{R} = \delta N = N_{,\varphi}\delta\varphi + \frac{1}{2}N_{,\varphi\varphi}\delta\varphi^2 + \cdots$$

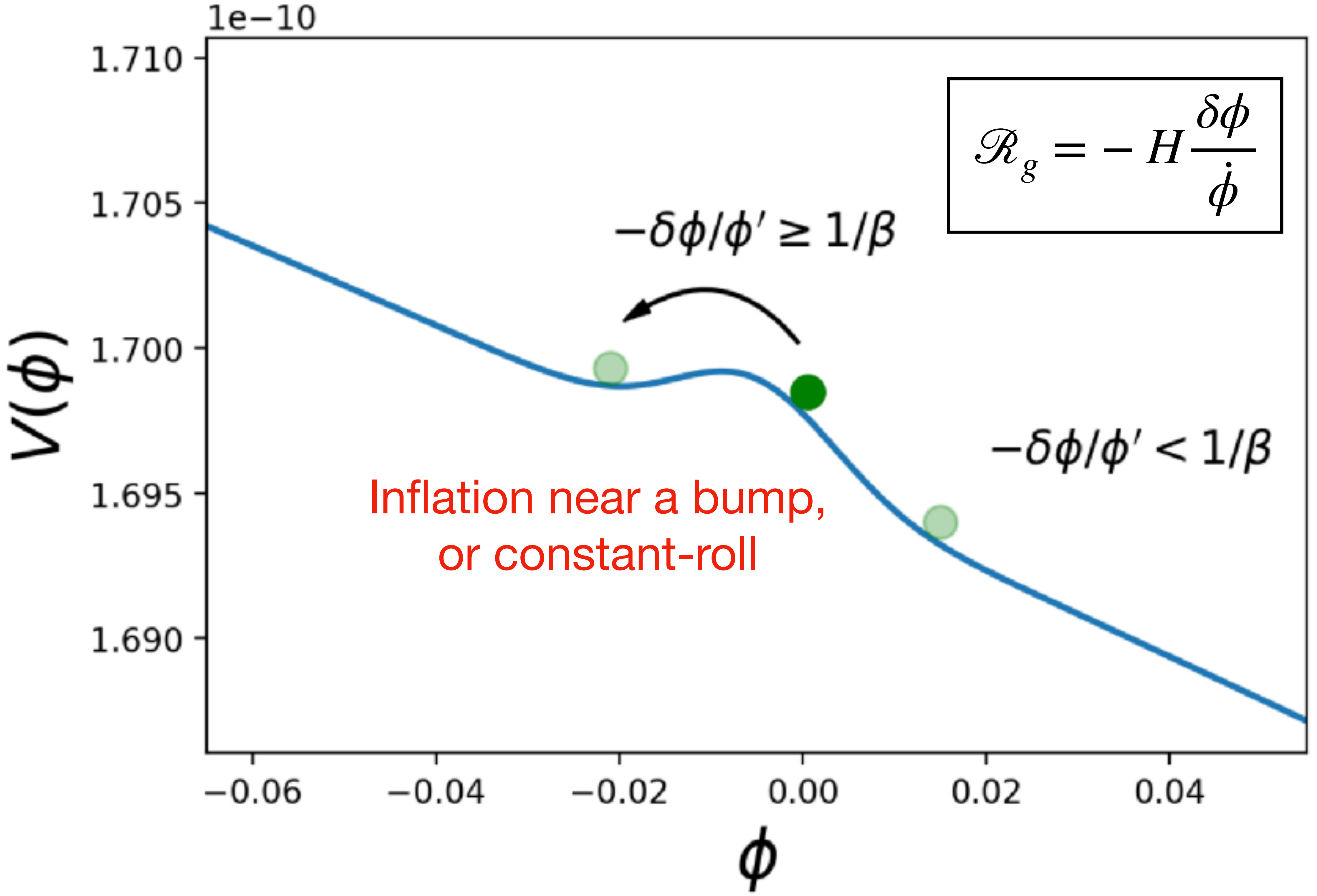
$$+N_{,\pi}\delta\pi + \frac{1}{2}N_{,\pi\pi}\delta\pi^2 + \cdots$$

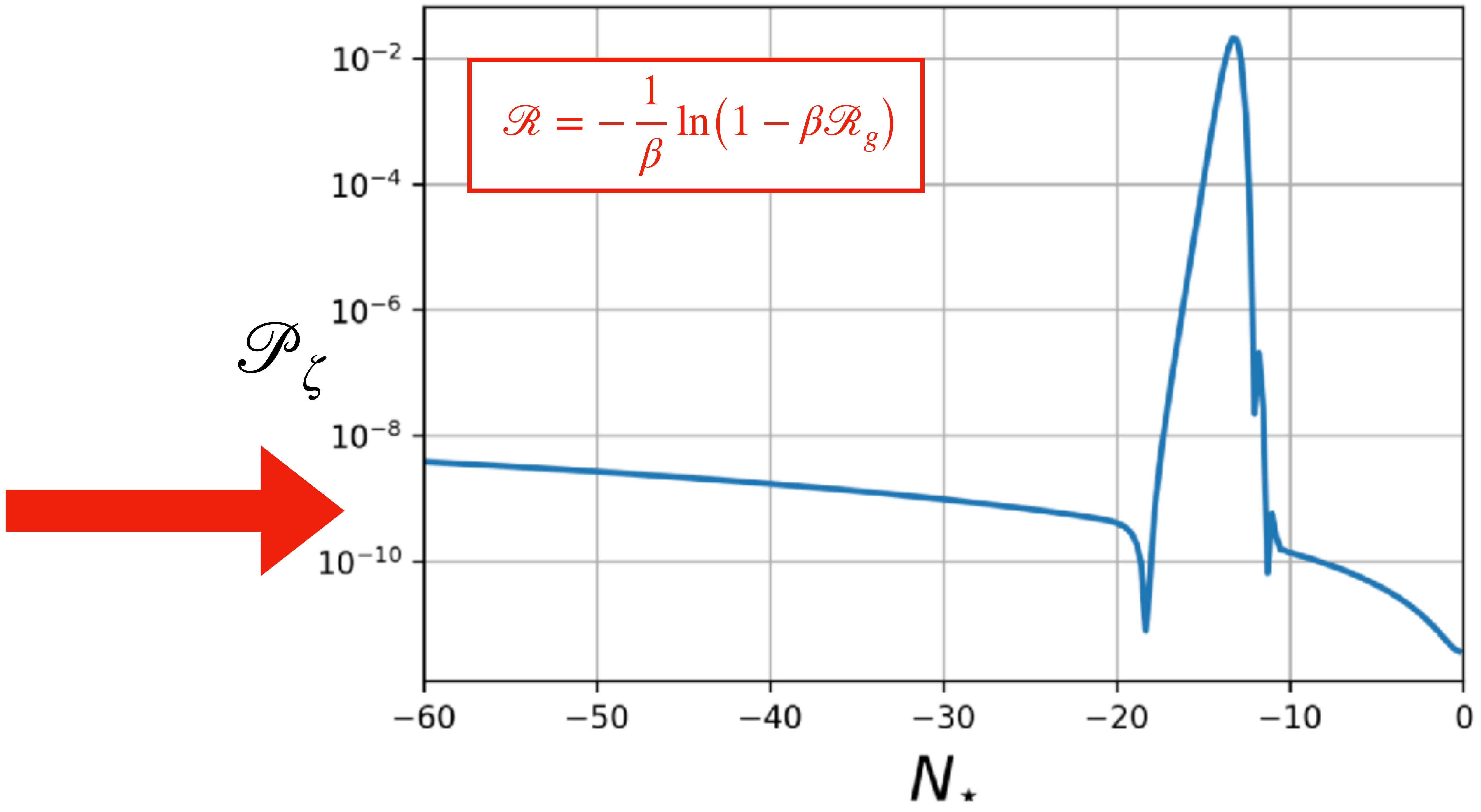
(For USR) $$= -\frac{1}{3}\ln\left(1 + \frac{3\delta\varphi}{\pi_*}\right).$$

$$\left(f_{\rm NL} = \frac{5}{2}, \quad g_{\rm NL} = -\frac{25}{3}, \quad \cdots\right)$$

Namjoo, Firouzjahi, Sasaki, 1210.3692
Chen, Firouzjahi, Komatsu, Namjoo, Sasaki, 1308.5341
Cai, Chen, Namjoo, Sasaki, Wang, Wang, 1712.09998
Biagetti, Franciolini, Kehagias, Riotto, 1804.07124
Passaglia, Hu, Motohashi, 1812.08243
Also verified by stochastic approach, see e.g.
Pattison et al 2101.05741

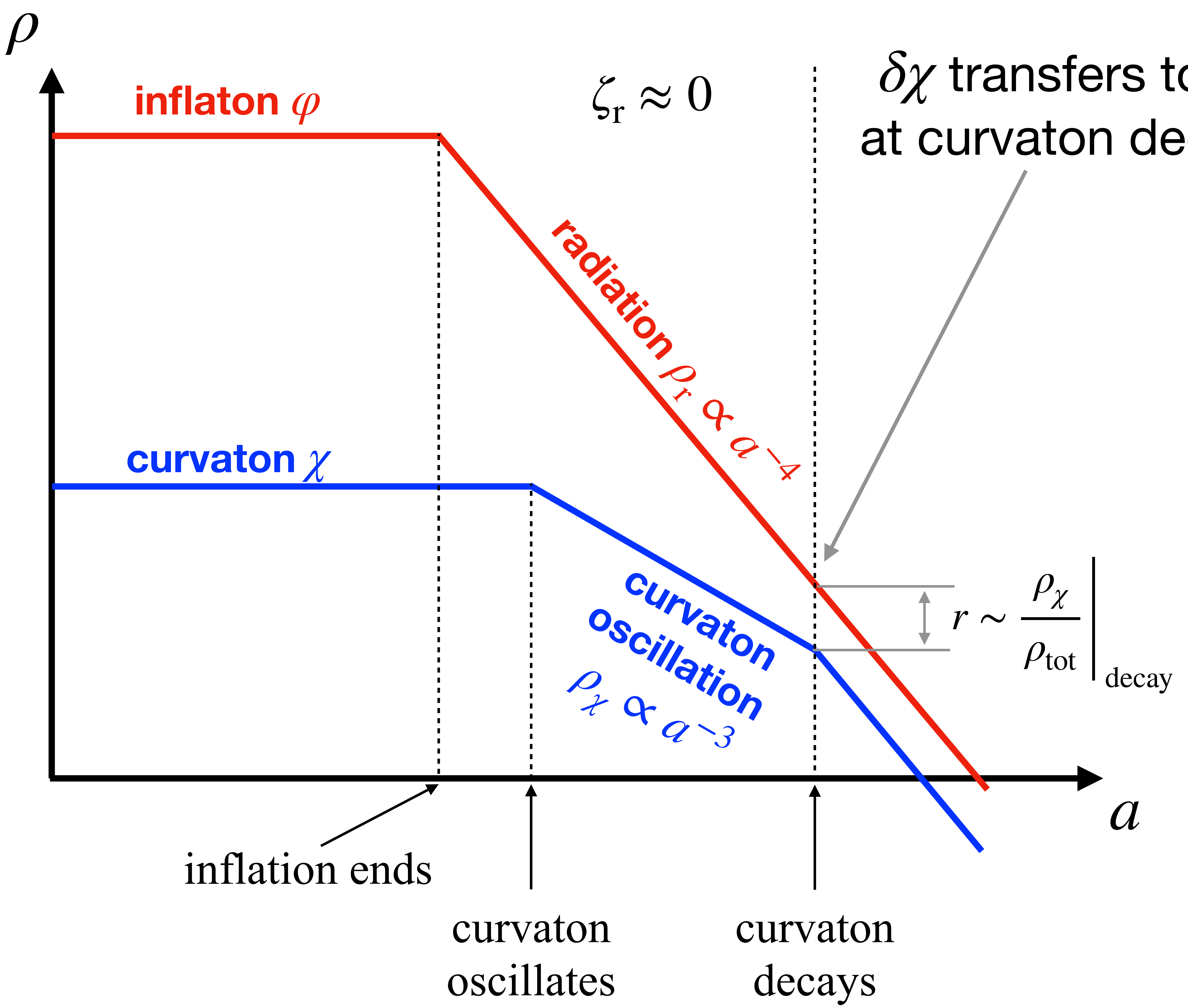
Logarithmic Relation in Constant-Roll Inflation





Atal, Garriga, Marcos-Caballero, 1905.13202
Atal, Cid, Escrivà, Garriga, 1908.11357
Escrivà, Atal, Garriga, 2306.09990

Curvaton Scenario



$$\Longrightarrow \quad e^{4\zeta} - \frac{4r}{3+r}\left(1 + \frac{\delta\chi}{\chi}\right)^2 e^{\zeta} + \frac{3r-3}{3+r} = 0$$

$$\zeta = \zeta(\delta\chi/\chi) \longrightarrow \begin{cases} \frac{r}{3}\left[2\frac{\delta\chi}{\chi} + \left(\frac{\delta\chi}{\chi}\right)^2\right] & \text{when } r \ll 1 \\ \frac{2}{3}\ln\left|1 + \frac{\delta\chi}{\chi}\right| & \text{when } r \sim 1 \end{cases}$$

- $\zeta(\delta\chi)$ is strictly quadratic when the curvaton is negligible, $f_{NL} = 5/(4r) \gg 1$.
- $\zeta(\delta\chi)$ degenerates to a logarithmic relation ($f_{NL} = -5/4$) when the curvaton dominates.

SP and Sasaki, 2112.12680
Ferrante et al, 2211.01728

$$\mathscr{R}(\delta\varphi)$$

$$\mathscr{R} = \frac{1}{\lambda}\ln\left(1+\lambda\mathscr{R}_g\right)$$

$\lambda \ll 1$

$\left(f_{NL} = -\frac{5}{6}\lambda\right)$

$$\mathscr{R} = -H\frac{\delta\varphi}{\dot\varphi} + \frac{3}{5}f_{\rm NL}\left(-H\frac{\delta\varphi}{\dot\varphi}\right)^2$$

Stewart and Sasaki, 1995
Lyth and Roquigez, 2005

$\lambda \to 0$ (?)

$\lambda = -3$

$$\mathscr{R} = -\frac{1}{3}\ln\left(1+\frac{\delta\pi_*}{\pi_*}\right)$$

Cai et al 1712.09998
Biagetti et al 1804.07124
Passaglia et al 1812.08243

$\lambda = 3/2$

$$\mathscr{R} = \frac{2}{3}\ln(1+\delta)$$

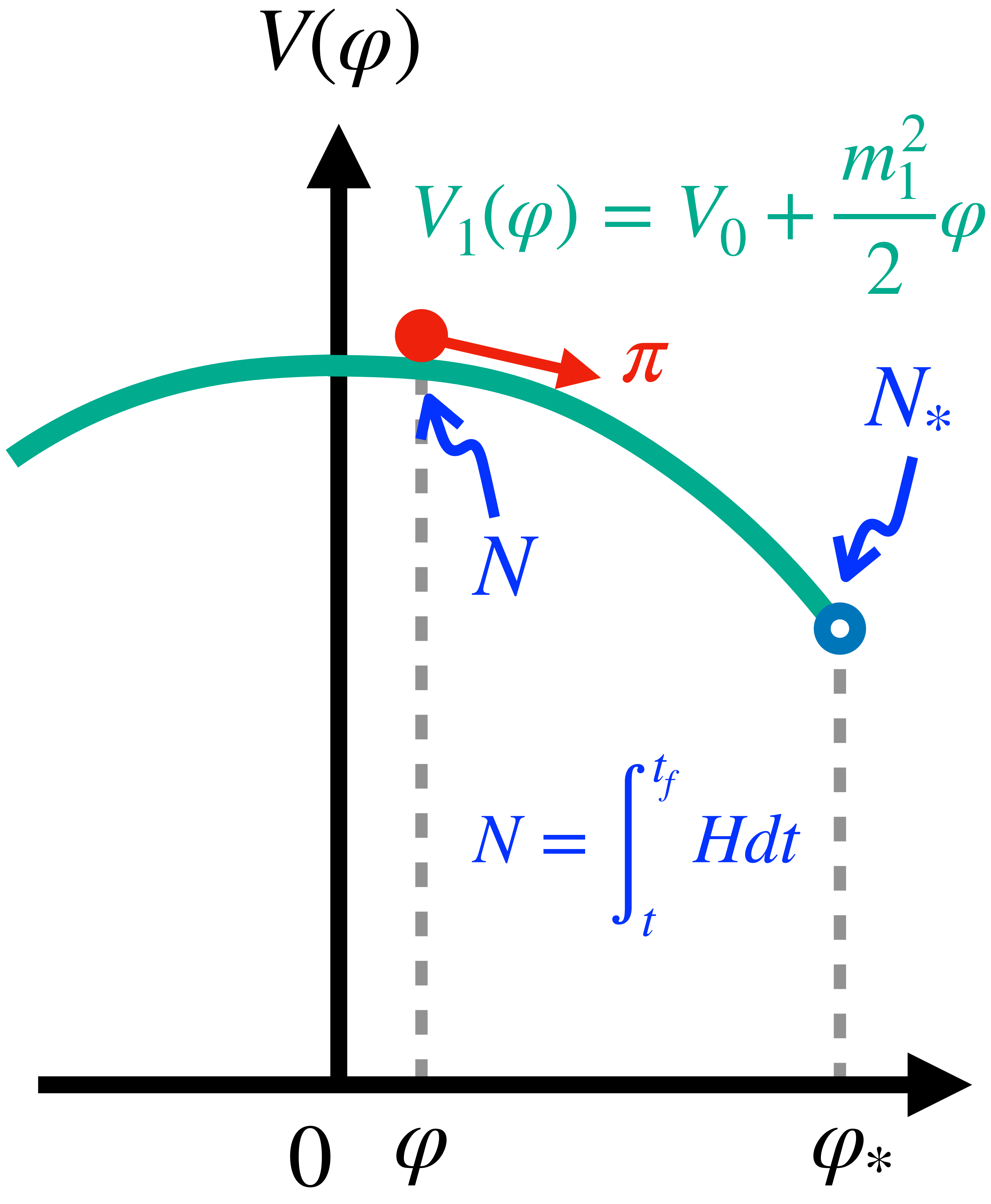
Curvaton scenario,
SP and Sasaki, 2112.12680
Ferrante et al, 2211.01728

$\lambda = -6$

$$\mathscr{R} = -\frac{1}{6}\ln\left(1-6\mathscr{R}_{\rm G}\right)$$

Modulated reheating,
Shuichiro Yokoyama, in prep.

Logarithmic Duality



$$\frac{\partial^2\varphi}{\partial^2 N} - 3\frac{\partial\varphi}{\partial N} + 3\eta_V\varphi = 0$$

$$\Longrightarrow \quad \varphi = c_+ e^{\lambda_+ N} + c_- e^{\lambda_- N}$$

$$\lambda_\pm = \frac{3 \pm \sqrt{9 - 12\eta_V}}{2} \qquad \eta_V = \frac{m_1^2}{3H^2}$$

We show that $\mathscr{R}$ can be expressed by two equivalent expressions:

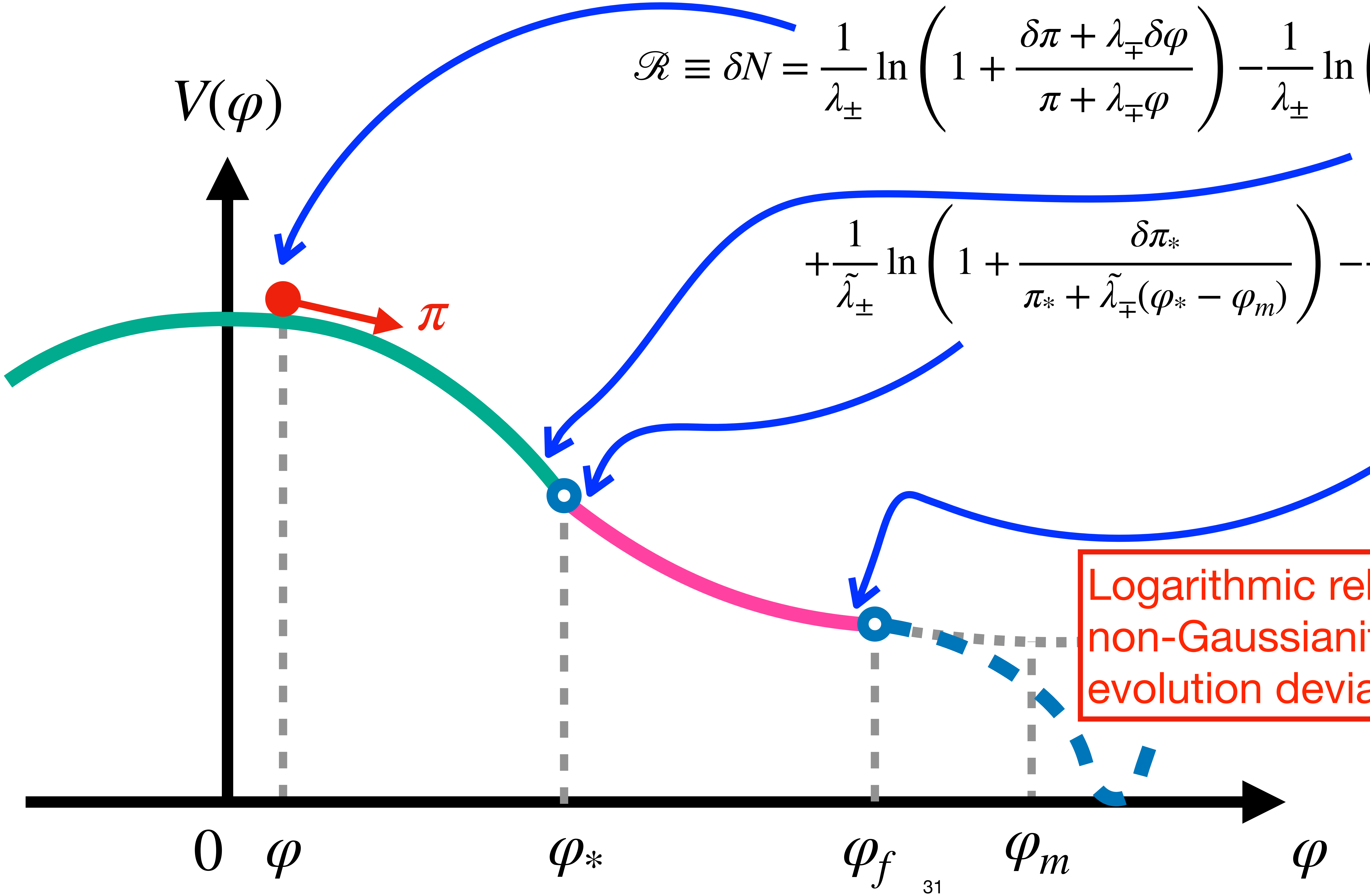
$$\mathscr{R} = \frac{1}{\lambda_\pm}\ln\left(1 + \frac{\delta\pi + \lambda_\mp\delta\varphi}{\pi + \lambda_\mp\varphi}\right) - \frac{1}{\lambda_\pm}\ln\left(1 + \frac{\delta\pi_*}{\pi_* + \lambda_\mp\varphi_*}\right)$$

SP and Sasaki, 2211.13932

Logarithmic Duality

$$\mathscr{R} \equiv \delta N = \frac{1}{\lambda_\pm} \ln\left(1 + \frac{\delta\pi + \lambda_\mp \delta\varphi}{\pi + \lambda_\mp \varphi}\right) - \frac{1}{\lambda_\pm} \ln\left(1 + \frac{\delta\pi_*}{\pi_* + \lambda_\mp \varphi_*}\right)$$

$$+ \frac{1}{\tilde{\lambda}_\pm} \ln\left(1 + \frac{\delta\pi_*}{\pi_* + \tilde{\lambda}_\mp(\varphi_* - \varphi_m)}\right) - \frac{1}{\tilde{\lambda}_\pm} \ln\left(1 + \frac{\delta\pi_f}{\pi_f + \tilde{\lambda}_\mp(\varphi_f - \varphi_m)}\right)$$



Logarithmic relation, which leads to large non-Gaussianity, is generated when the evolution deviates from attractor solution.

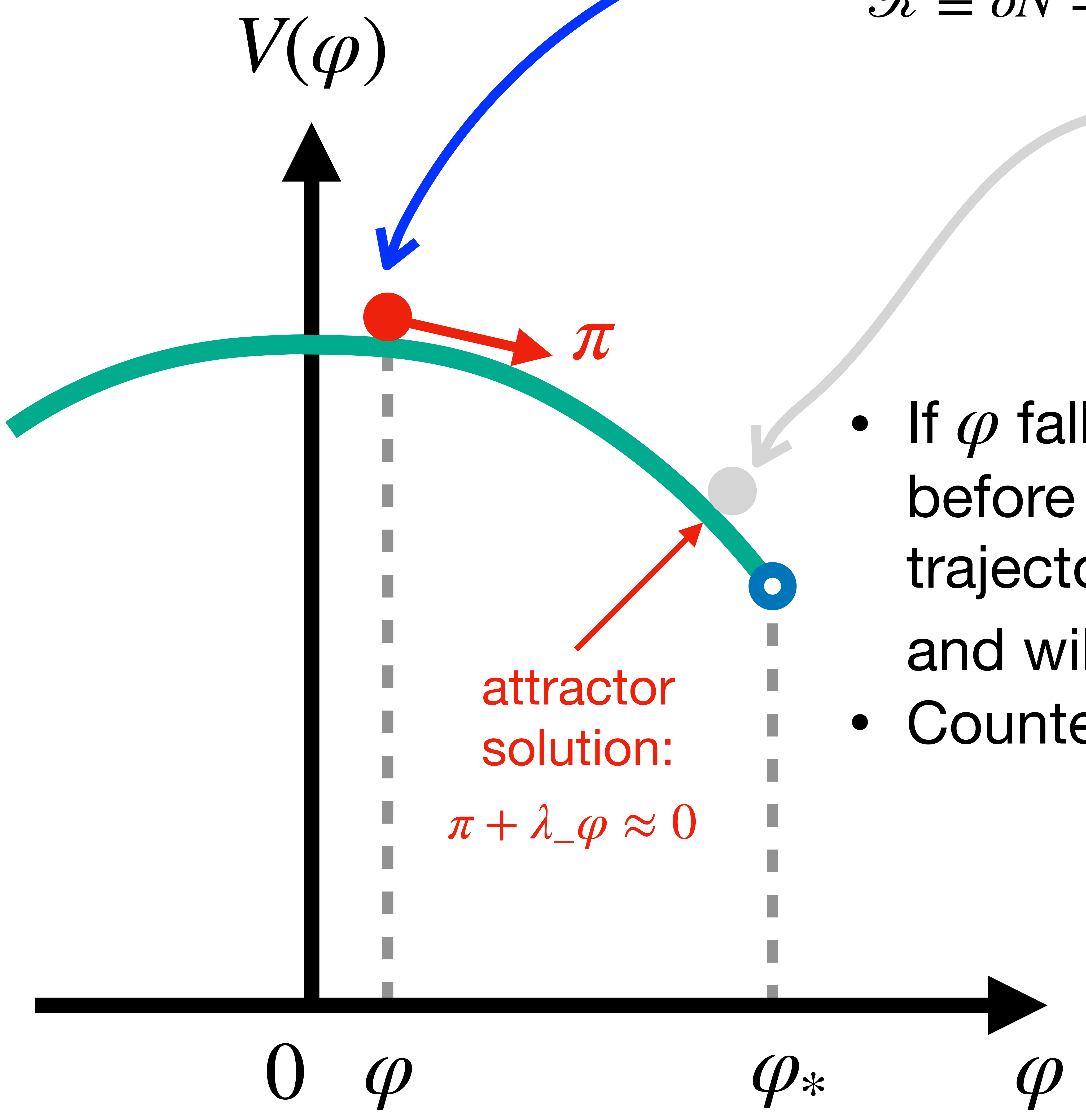
SP and Sasaki, 2211.13932

Application:

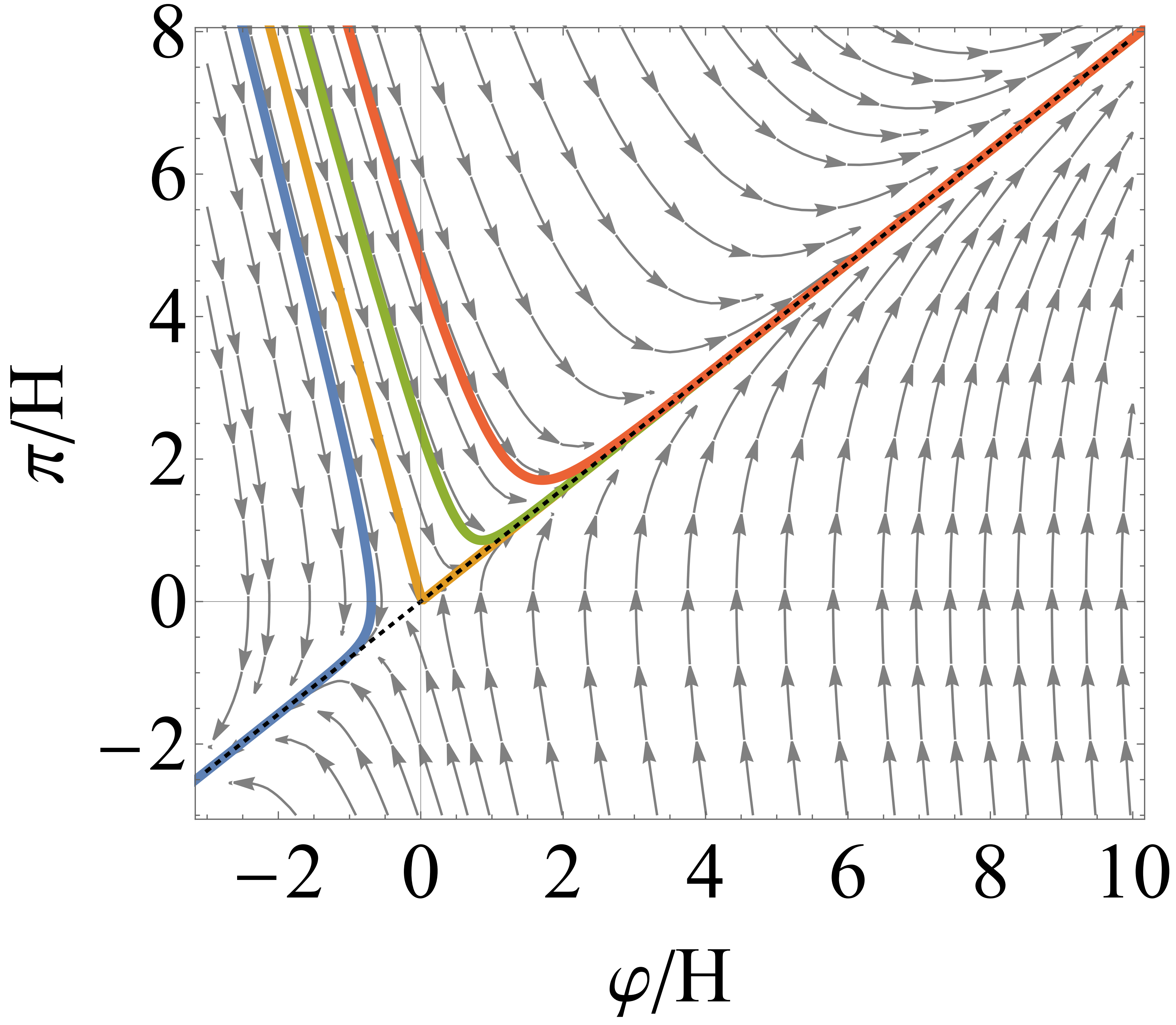
Ultra-slow-roll inflation

Constant-roll

$$\mathscr{R} \equiv \delta N = \frac{1}{\lambda_-}\ln\left(1+\frac{\delta\pi+\lambda_+\delta\varphi}{\pi+\lambda_+\varphi}\right) - \frac{1}{\lambda_-}\ln\left(1+\frac{\delta\pi_*}{\pi_*+\lambda_+\varphi_*}\right)$$



- If φ falls into the attractor before the boundary, its trajectory becomes unique and will not contribute to δN.
- Counterexample: USR

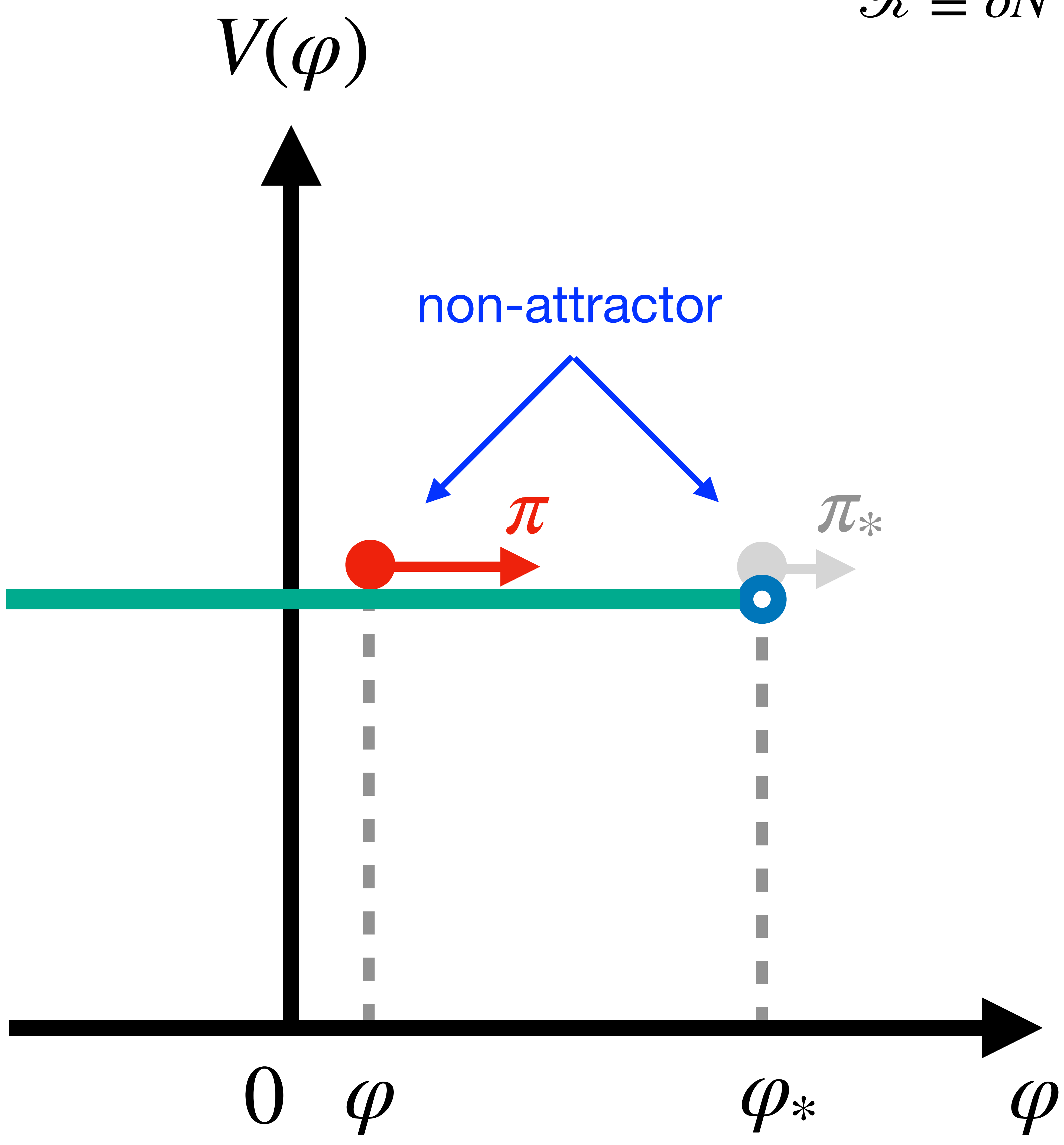


See also Atal et al, 1908.11357, 1905.13202

USR

$(\lambda_- = 0, \quad \lambda_+ = 3)$

$$\mathcal{R} \equiv \delta N = \frac{1}{3} \ln\left(1 + \frac{\cancel{\delta\pi} + \cancel{\lambda_\pm}\delta\varphi}{\pi + \lambda_\mp \varphi}\right) - \frac{1}{3} \ln\left(1 + \frac{\delta\pi_*}{\pi_* + \cancel{\lambda_\pm}\varphi_*}\right)$$



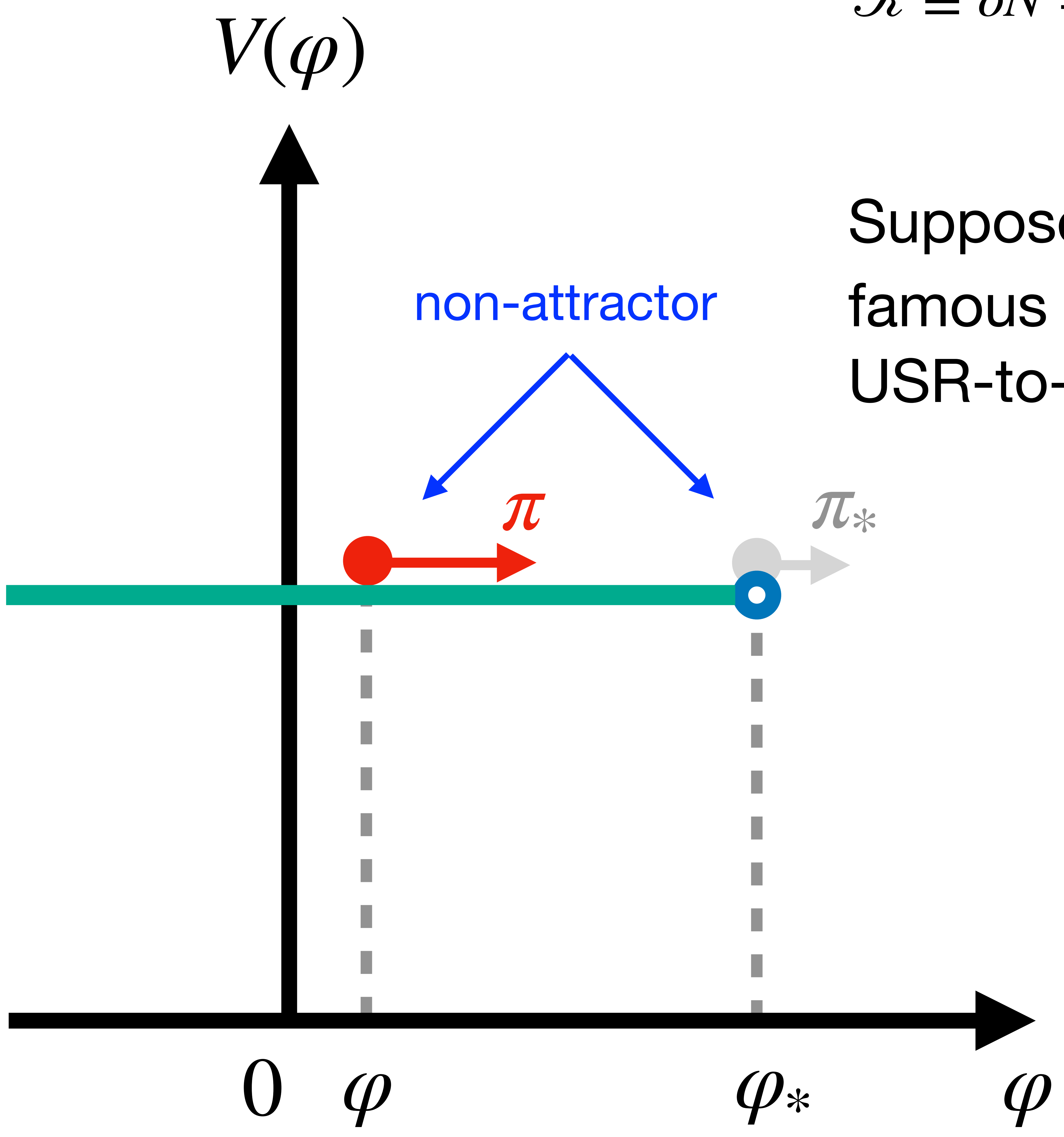
- If φ reaches the attractor solution before the boundary, it got stuck (classically), and quantum diffusion dominates. We must use stochastic approach to inflation.

Figueroa et al, 2012.06551
Pattison et al, 2101.05741
Rigopoulos & Wilkins, 2107.05317
Cruces & Germani, 2107.12735
Tada & Vennin, 2111.15280

USR

$(\lambda_- = 0, \quad \lambda_+ = 3)$

$$\mathcal{R} \equiv \delta N = -\frac{1}{3}\ln\left(1 + \frac{\delta\pi_*}{\pi_*}\right)$$



Suppose inflation ends as the USR ends, it gives a famous result of $\mathbb{P}(\mathcal{R}) \propto \exp(-3\mathcal{R})$. However, the USR-to-SR transition should be considered.

Namjoo et al., 1210.3692
Chen et al., 1308.5341

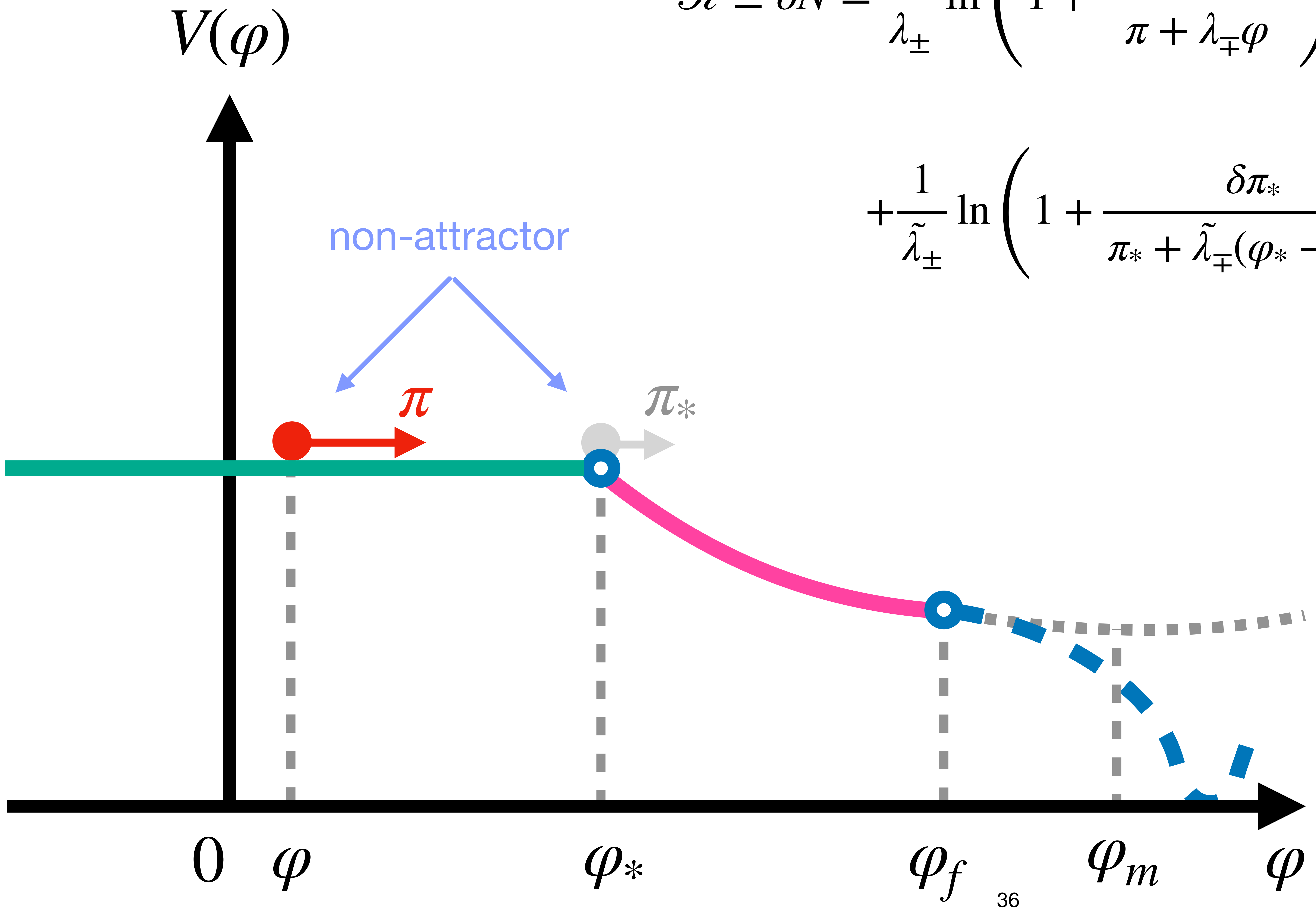
USR

$(\lambda_- = 0, \quad \lambda_+ = 3)$

$(\tilde{\lambda}_- = \tilde{\eta}, \quad \tilde{\lambda}_+ = 3 - \tilde{\eta})$

$$\mathscr{R} \equiv \delta N = \frac{1}{\lambda_\pm} \ln\left(1 + \frac{\delta\pi + \lambda_\mp \delta\varphi}{\pi + \lambda_\mp \varphi}\right) - \frac{1}{\lambda_\pm} \ln\left(1 + \frac{\delta\pi_*}{\pi_* + \lambda_\pm \varphi_*}\right)$$

$$+ \frac{1}{\tilde{\lambda}_\pm} \ln\left(1 + \frac{\delta\pi_*}{\pi_* + \tilde{\lambda}_\mp(\varphi_* - \varphi_m)}\right) - \frac{1}{\tilde{\lambda}_\pm} \ln\left(1 + \frac{\delta\pi_f}{\pi_f + \tilde{\lambda}_\pm(\varphi_f - \varphi_m)}\right)$$

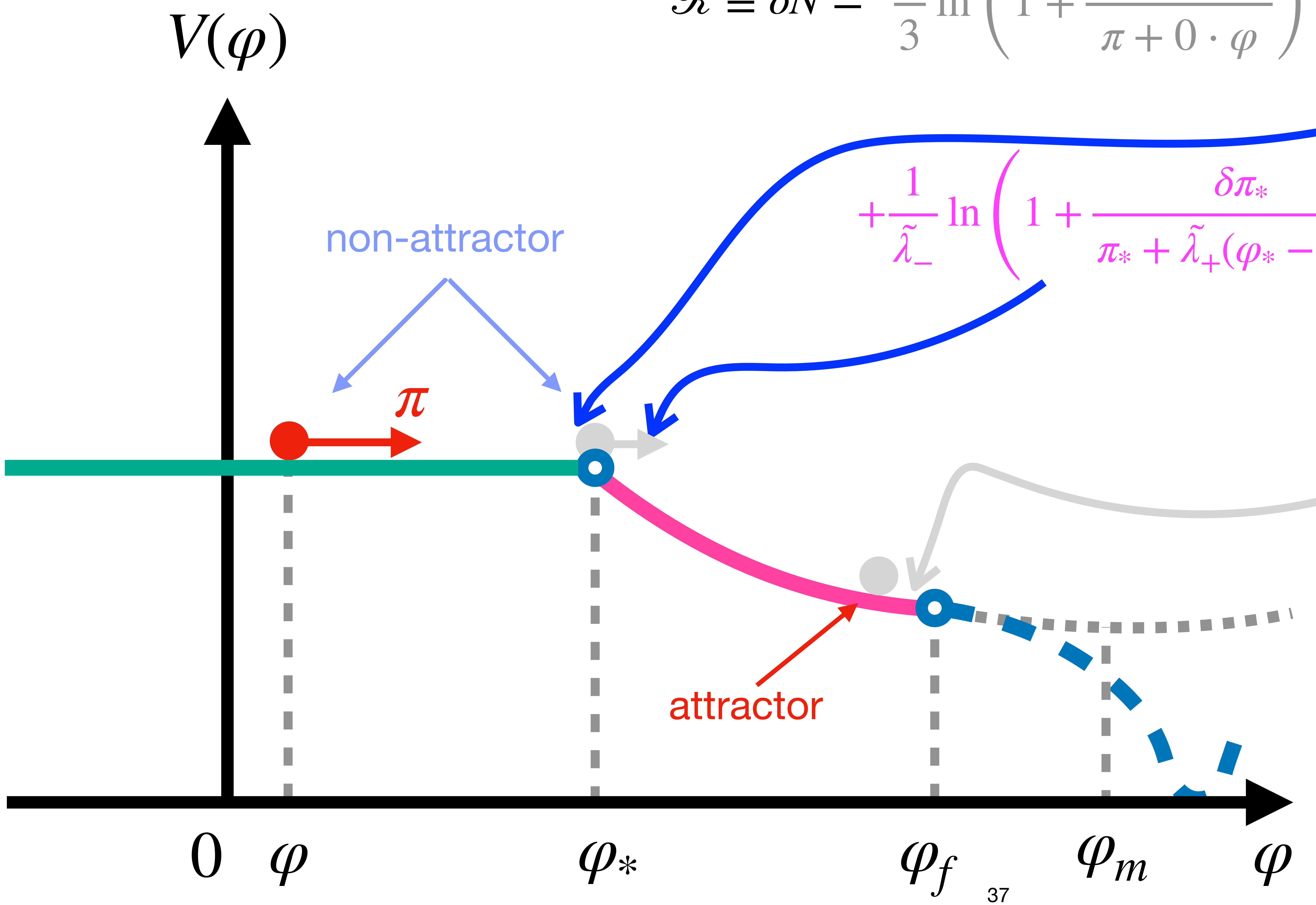


USR

$$(\lambda_- = 0, \quad \lambda_+ = 3)$$
$$(\tilde\lambda_- = \tilde\eta, \quad \tilde\lambda_+ = 3 - \tilde\eta)$$

$$\mathscr{R} \equiv \delta N = \frac{1}{3}\ln\left(1+\frac{0+0\cdot\delta\varphi}{\pi+0\cdot\varphi}\right) - \frac{1}{3}\ln\left(1+\frac{\delta\pi_*}{\pi_*}\right)$$

$$+\frac{1}{\tilde\lambda_-}\ln\left(1+\frac{\delta\pi_*}{\pi_*+\tilde\lambda_+(\varphi_*-\varphi_m)}\right) - \frac{1}{\tilde\lambda_-}\ln\left(1+\frac{\delta\pi_f}{\pi_f+\tilde\lambda_+(\varphi_f-\varphi_m)}\right)$$



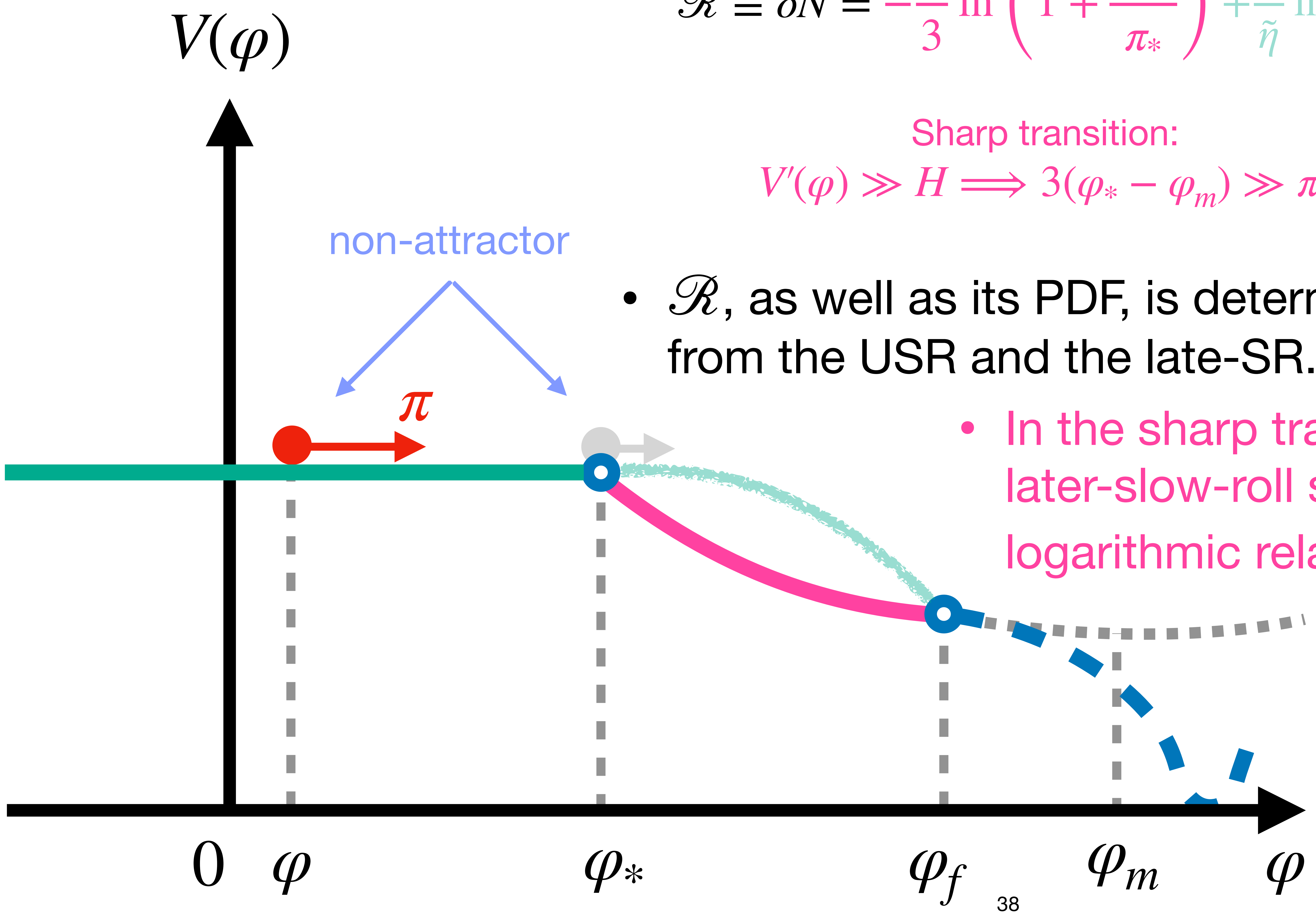
USR

$(\lambda_- = 0, \quad \lambda_+ = 3)$
$(\tilde\lambda_- = \tilde\eta, \quad \tilde\lambda_+ = 3 - \tilde\eta)$

$$\mathscr{R} \equiv \delta N = -\frac{1}{3}\ln\left(1+\frac{\delta\pi_*}{\pi_*}\right) + \frac{1}{\tilde\eta}\ln\left(1+\frac{\delta\pi_*}{\pi_* + (3-\tilde\eta)(\varphi_* - \varphi_m)}\right)$$

Sharp transition:
$V'(\varphi) \gg H \Longrightarrow 3(\varphi_* - \varphi_m) \gg \pi_*$

Smooth transition
$V'(\varphi) \ll H \Longrightarrow 3(\varphi_* - \varphi_m) \ll \pi_*$



- $\mathscr{R}$, as well as its PDF, is determined by the larger contribution from the USR and the late-SR.
  - In the sharp transition case, the contribution from later-slow-roll stage is negligible, thus the logarithmic relation of $\mathscr{R}(\delta\varphi)$ is preserved.

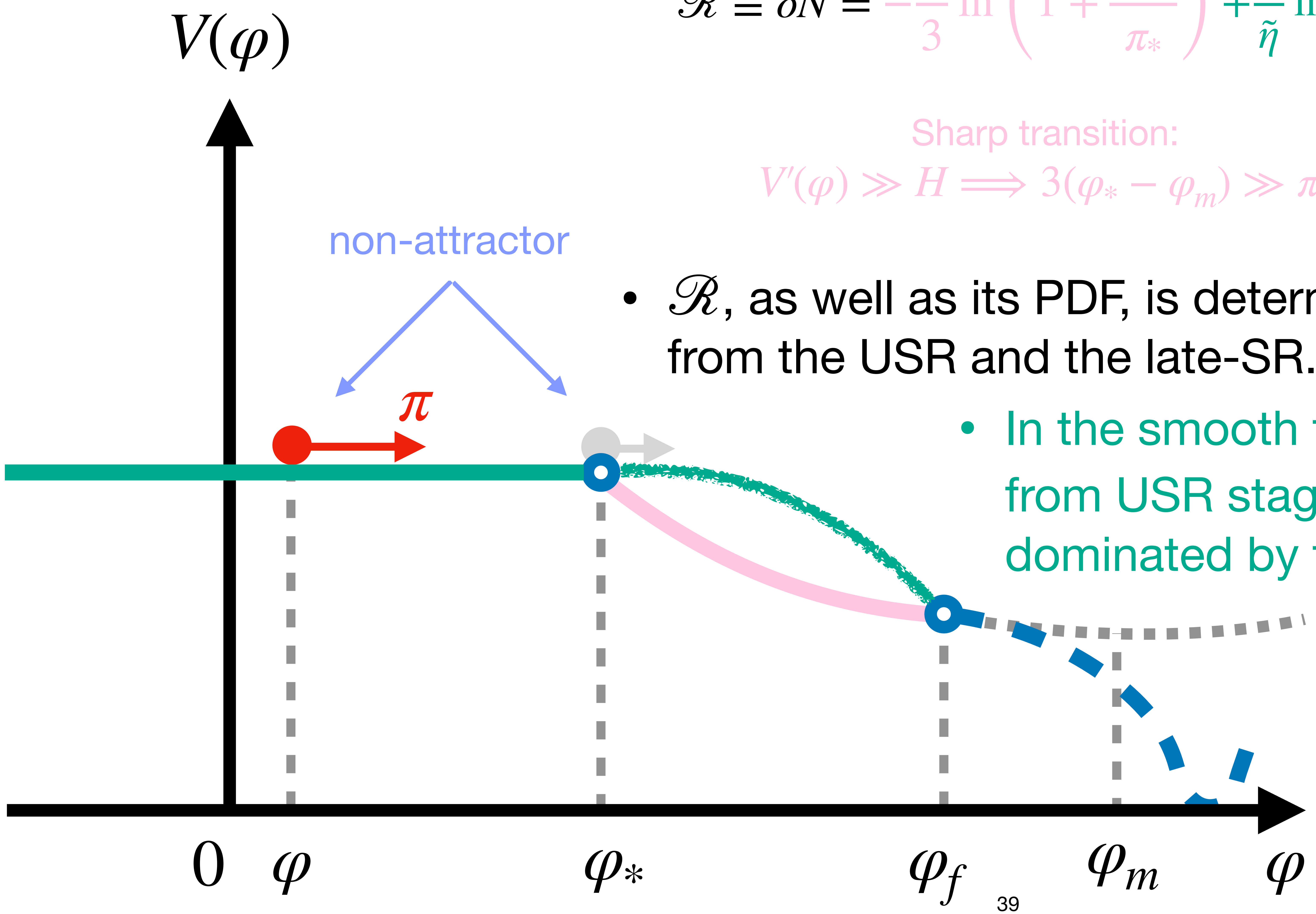
USR

$(\lambda_- = 0, \quad \lambda_+ = 3)$
$(\tilde{\lambda}_- = \tilde{\eta}, \quad \tilde{\lambda}_+ = 3 - \tilde{\eta})$

$$\mathscr{R} \equiv \delta N = -\frac{1}{3}\ln\left(1 + \frac{\delta\pi_*}{\pi_*}\right) + \frac{1}{\tilde{\eta}}\ln\left(1 + \frac{\delta\pi_*}{\pi_* + (3-\tilde{\eta})(\varphi_* - \varphi_m)}\right)$$

Sharp transition:
$V'(\varphi) \gg H \Longrightarrow 3(\varphi_* - \varphi_m) \gg \pi_*$

Smooth transition
$V'(\varphi) \ll H \Longrightarrow 3(\varphi_* - \varphi_m) \ll \pi_*$



- $\mathscr{R}$, as well as its PDF, is determined by the larger contribution from the USR and the late-SR.
    - In the smooth transition case, the contribution from USR stage is negligible, and $\mathscr{R}(\delta\varphi)$ is dominated by the slow-roll part.

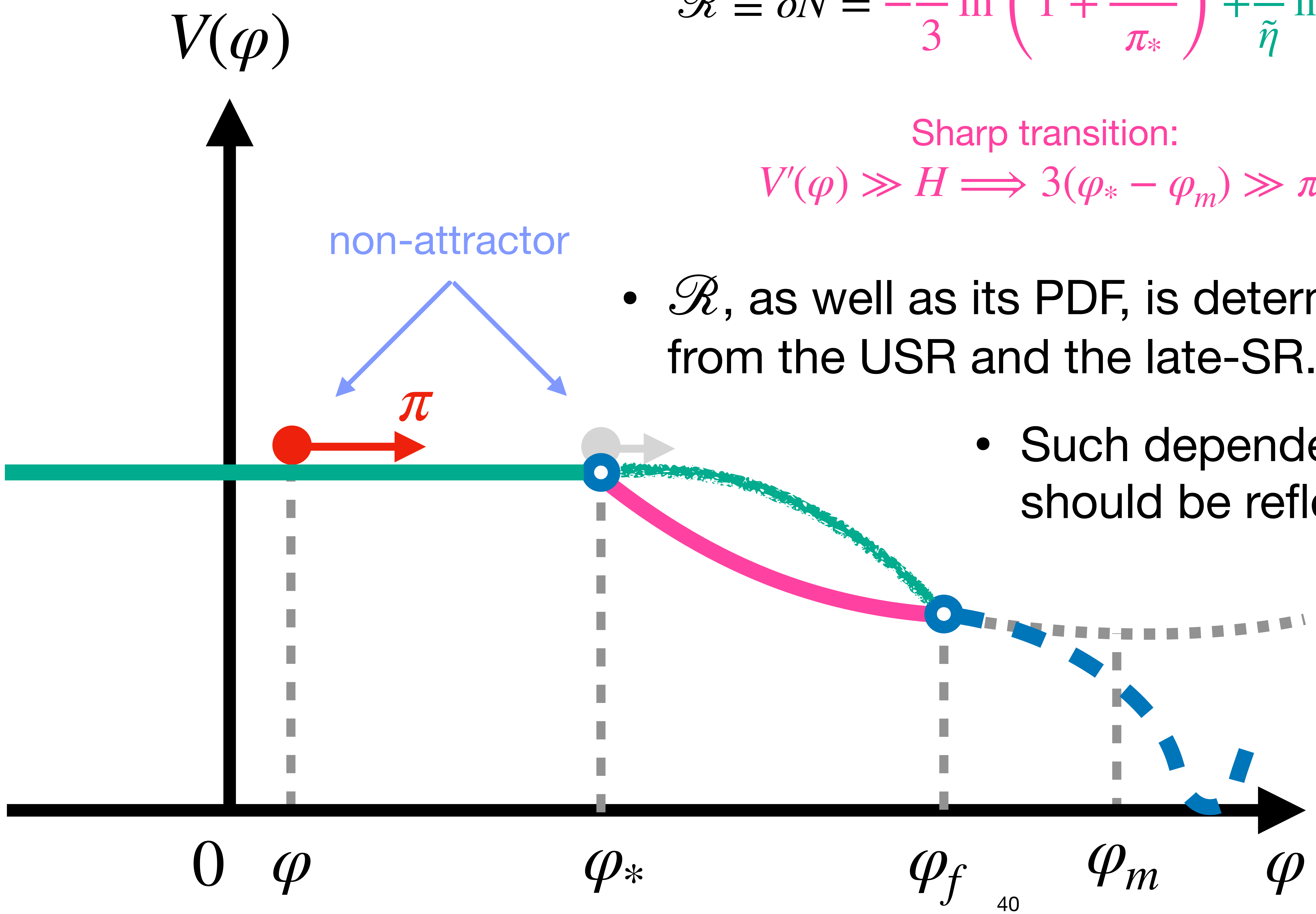
USR

$(\lambda_- = 0, \quad \lambda_+ = 3)$
$(\tilde{\lambda}_- = \tilde{\eta}, \quad \tilde{\lambda}_+ = 3 - \tilde{\eta})$

$$\mathscr{R} \equiv \delta N = -\frac{1}{3}\ln\left(1 + \frac{\delta\pi_*}{\pi_*}\right) + \frac{1}{\tilde{\eta}}\ln\left(1 + \frac{\delta\pi_*}{\pi_* + (3-\tilde{\eta})(\varphi_* - \varphi_m)}\right)$$

Sharp transition:
$V'(\varphi) \gg H \Longrightarrow 3(\varphi_* - \varphi_m) \gg \pi_*$

Smooth transition
$V'(\varphi) \ll H \Longrightarrow 3(\varphi_* - \varphi_m) \ll \pi_*$



- $\mathscr{R}$, as well as its PDF, is determined by the larger contribution from the USR and the late-SR.
- Such dependence on the boundary condition should be reflected in the stochastic approach.

Pattison et al., 2101.05741
Cruces, SP, Sasaki, in prep.

- Sharp transition will make the separate universe approach (thus δN formalism) invalid transiently.

Domenech et al., 2309.05750
Jackson et al., 2311.03281

Probability Distribution Function

For the USR case we use the dual relation: $$\mathscr{R} \equiv \delta N = -\frac{1}{3}\ln\left(1 + \frac{3\delta\varphi}{\pi_*}\right)$$

$$\Downarrow \quad \mathbb{P}(\mathscr{R})d\mathscr{R} = \boxed{\mathbb{P}(\delta\varphi)}d\delta\varphi$$

→ Gaussian PDF with variance $\sigma^2_{\delta\varphi}$

$$\mathbb{P}(\mathscr{R}) = \frac{e^{-3\mathscr{R}}}{\sqrt{2\pi}\sigma_{\delta\varphi}}\pi_* \exp\left[-\frac{\pi_*^2}{18\sigma^2_{\delta\varphi}}\left(e^{-3\mathscr{R}} - 1\right)^2\right]$$

$$\downarrow \quad \mathscr{R} \sim \mathcal{O}(1)$$

$$\mathbb{P}(\mathscr{R}) \sim e^{-3\mathscr{R}}$$

exponential tail

Biagetti et al, 2105.07810
Pattison ett al, 2101.05741
SP and Sasaki, 2211.13932

Probability Distribution Function

For the simplest single-logarithm case: $$\mathscr{R} \equiv \delta N = \frac{1}{\lambda_-} \ln\left(1 + \frac{\delta\pi + \lambda_+ \delta\varphi}{\pi + \lambda_+ \varphi}\right)$$

$$\Downarrow \quad \mathbb{P}(\mathscr{R})d\mathscr{R} = \mathbb{P}(\delta\varphi)d\delta\varphi$$

$\mathbb{P}(\delta\varphi)$ → Gaussian PDF with variance $\sigma_{\delta\varphi}^2$

$$\mathbb{P}(\mathscr{R}) = \frac{e^{\lambda_- \mathscr{R}}}{\sqrt{2\pi}\sigma_{\delta\varphi}} \left|\lambda_-\right| \varphi \exp\left[-\frac{\varphi^2}{2\sigma_{\delta\varphi}^2}\left(e^{\lambda_- \mathscr{R}} - 1\right)^2\right]$$

$\lambda_- < 0$, $\mathscr{R} \sim \mathcal{O}(1)$:

$$\mathbb{P}(\mathscr{R}) \sim e^{\lambda_- \mathscr{R}}$$

exponential tail

$\lambda_- > 0$, $\mathscr{R} \sim \mathcal{O}(1)$:

$$\mathbb{P}(\mathscr{R}) \sim \exp\left(-c^2 e^{2\lambda_- \mathscr{R}}\right)$$

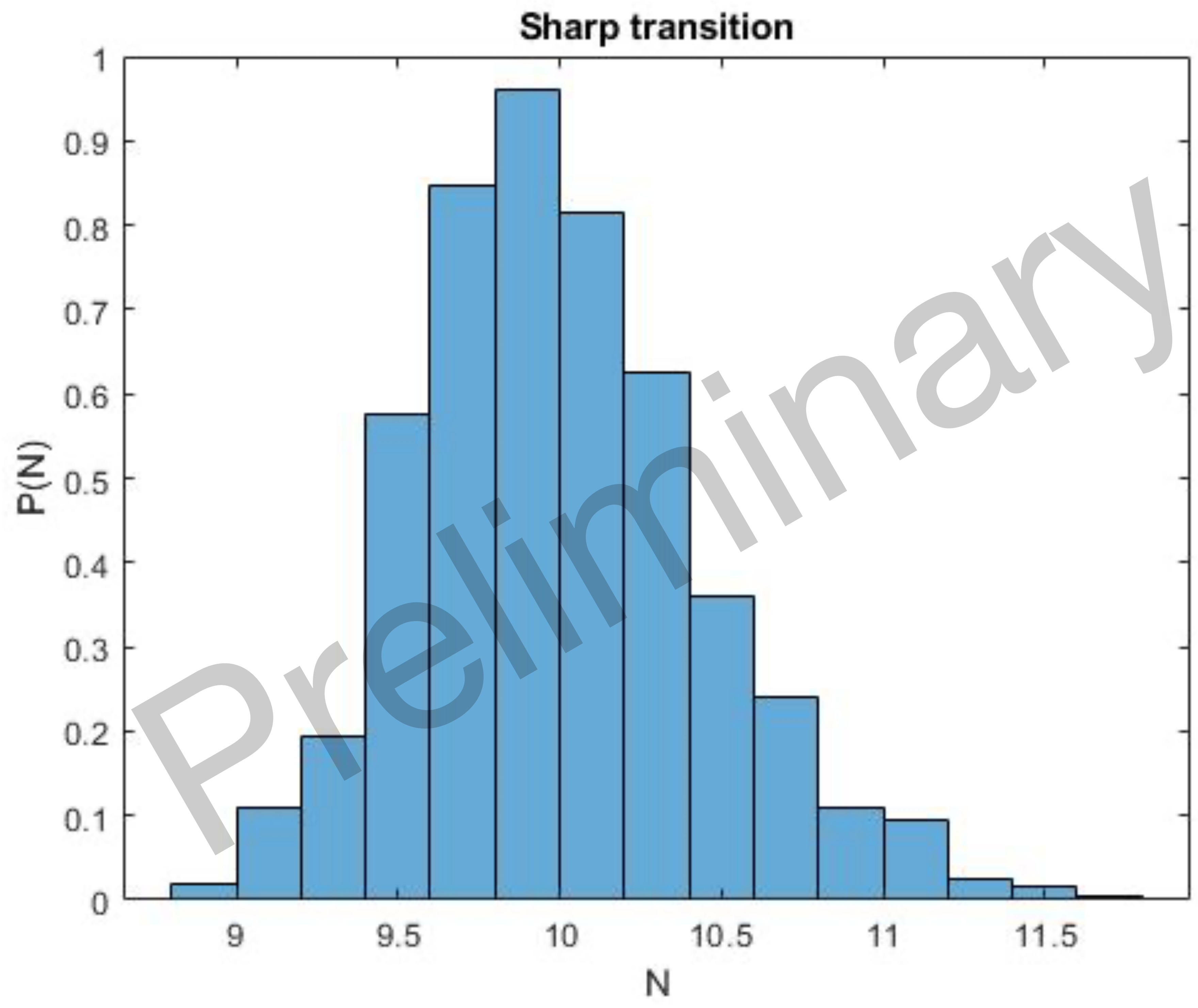
Gumbel-distribution-like tail

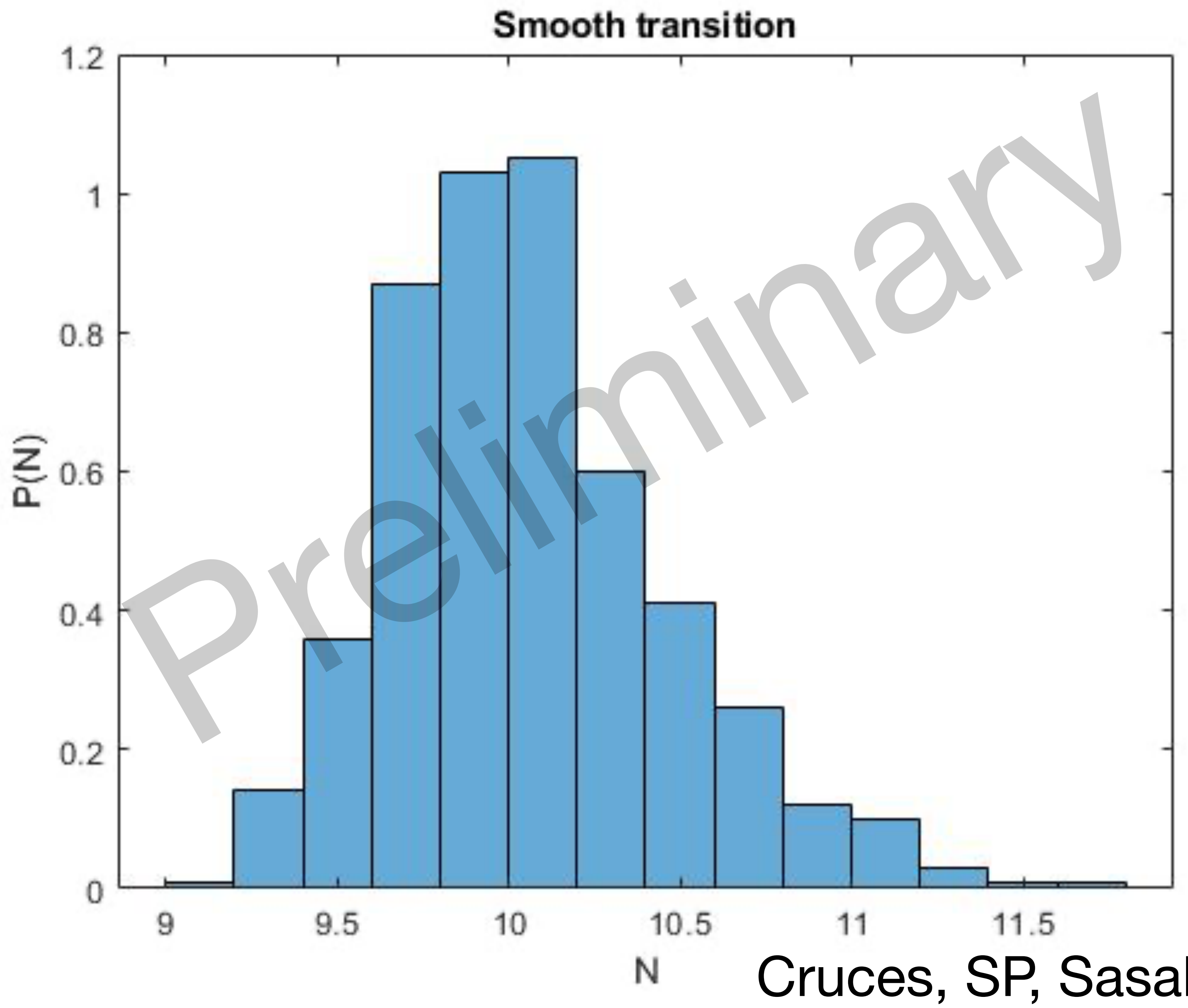
SP and Sasaki, 2211.13932

Probability Distribution Function

For a general case: $$\mathscr{R} = -\frac{1}{3}\ln\left(1+\frac{\delta\pi_*}{\pi_*}\right) + \frac{1}{\tilde{\lambda}_-}\ln\left(1+\frac{\delta\pi_*}{\pi_* + \tilde{\lambda}_+(\varphi_* - \varphi_m)}\right) \qquad \left(\tilde{\lambda}_- = -\frac{1}{2}, \quad \tilde{\lambda}_+ = \frac{7}{2}\right)$$

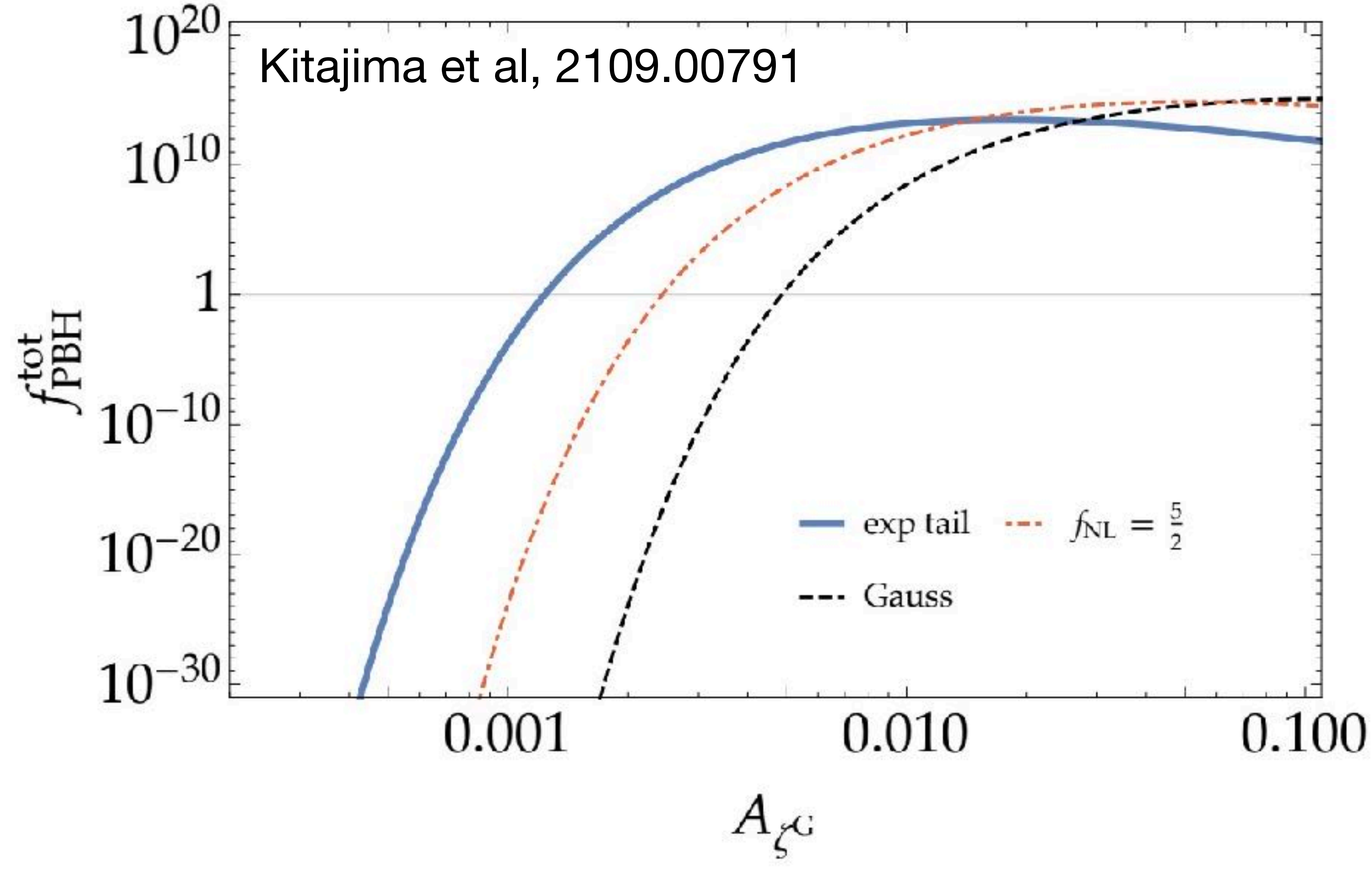
- It shows that smooth transition could be even "more non-Gaussian", depending on the value of $\tilde{\lambda}_-$.

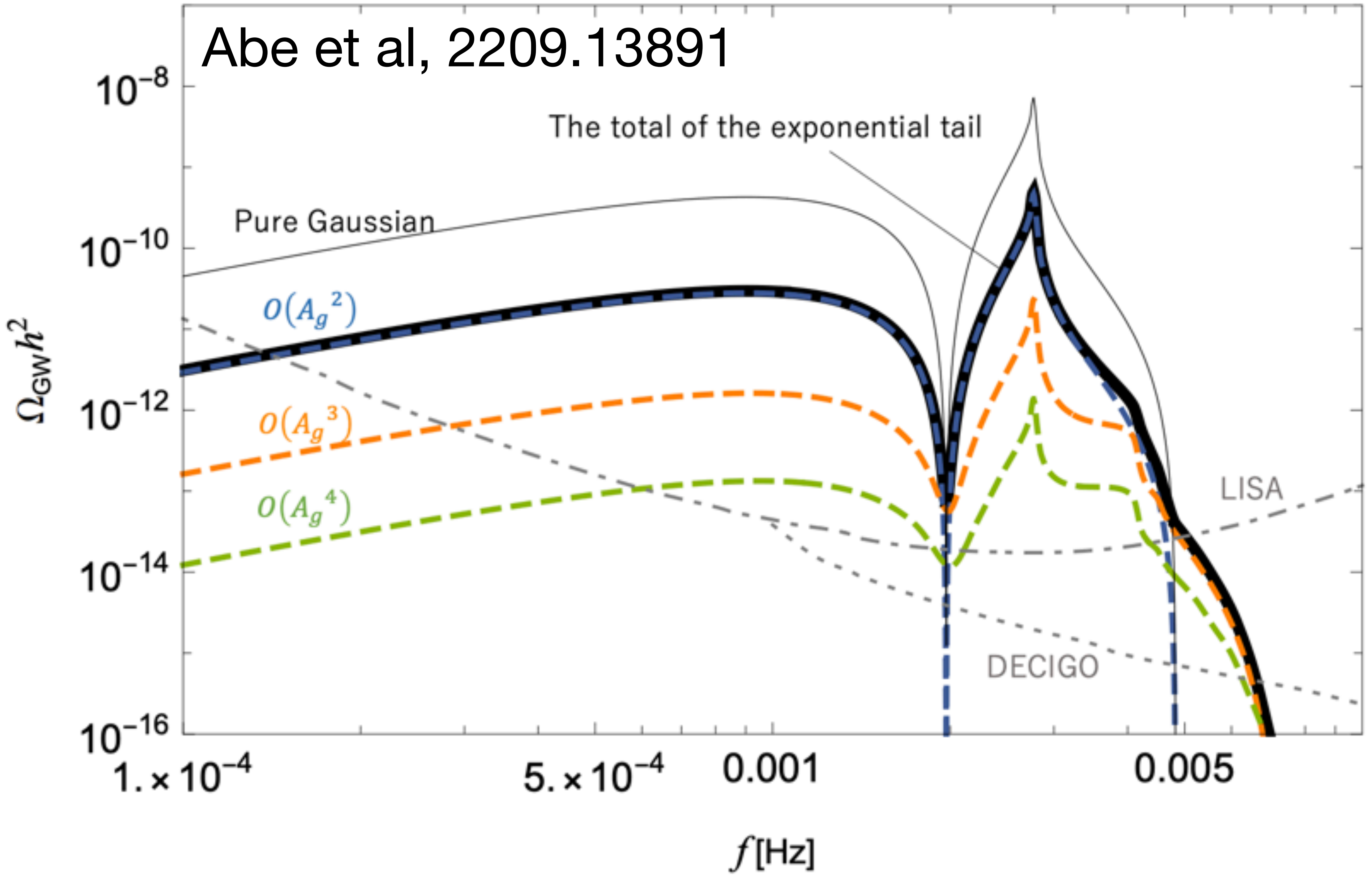




Cruces, SP, Sasaki, in prep.

PBH and IGW with NG





SP, Sasaki, Takhistov, Jianing Wang, in prep.

Summary

- The simplest Press-Schechter ignores non-Gaussianities of different origins, which greatly(mildly) enhance/suppress the PBH abundance (IGW spectrum) when NG is positive/negative.

- Primordial non-Gaussianity in $\mathscr{R}(\delta\varphi)$ originates from the non-attractor evolution. The final $\mathscr{R}(\delta\varphi)$ is a sum of contributions from all the stages.

- If $\mathscr{R}(\delta\varphi)$ is dominated by one stage, $\mathbb{P}(\mathscr{R})$ displays an exponential tail or a Gumbel-like (double exponential suppression) tail, depending on the signature of $V''(\varphi)$.

- When $|f_{\rm NL}| \sim \mathcal{O}(1)$, all the NG effect must be taken appropriately to calculate the PBH abundance. This is necessary when interpreting nHz GW as the IGW.