DESY Theory Workshop 2017

Primordial Black Holes from Critical Higgs Inflation

Jose María EZQUIAGA

Based on:

arXiv **1705.04861** by **JME**, J. GARCÍA-BELLIDO and E. RUIZ MORALES

UAM UNIVERSIDAD AUTONOMA DE MADRID
ift Instituto de Física Teórica UAM-CSIC
GOBIERNO DE ESPAÑA MINISTERIO DE EDUCACIÓN, CULTURA Y DEPORTE
THE UNIVERSITY OF CALIFORNIA BERKELEY 1868 LET THERE BE LIGHT

HIGGS $\longrightarrow$ INFLATION

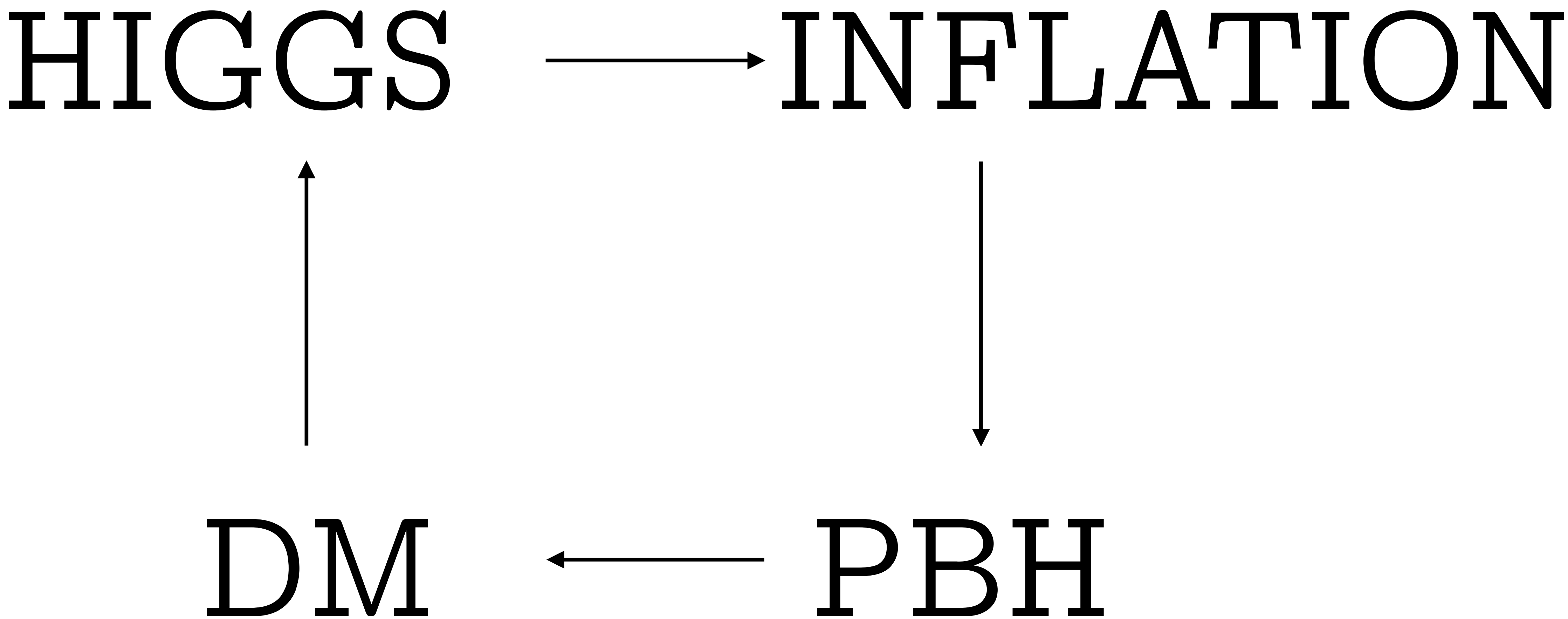
HIGGS ⟶ INFLATION

DM ⟵ PBH

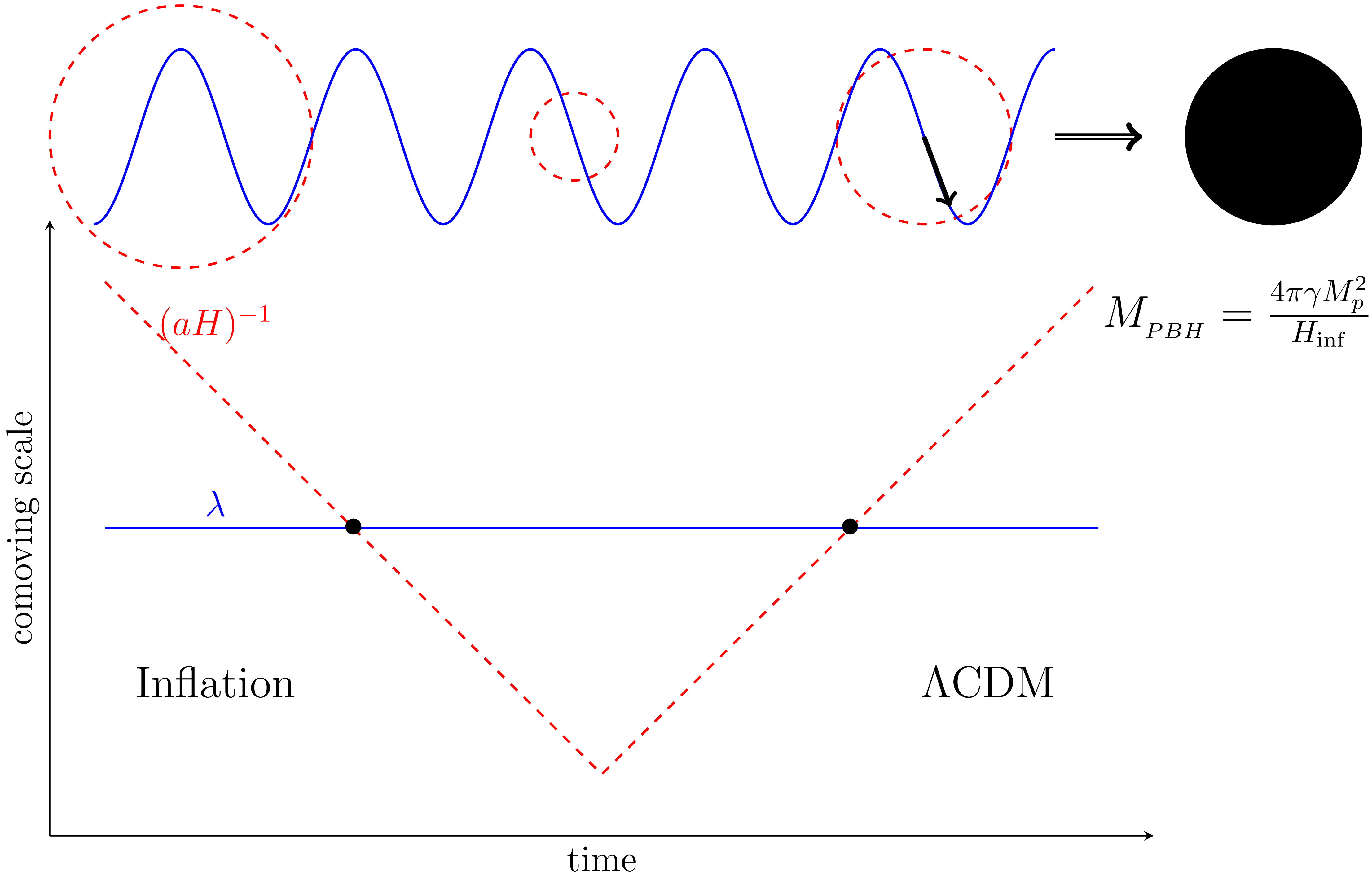
HIGGS → INFLATION

↓

DM ← PBH

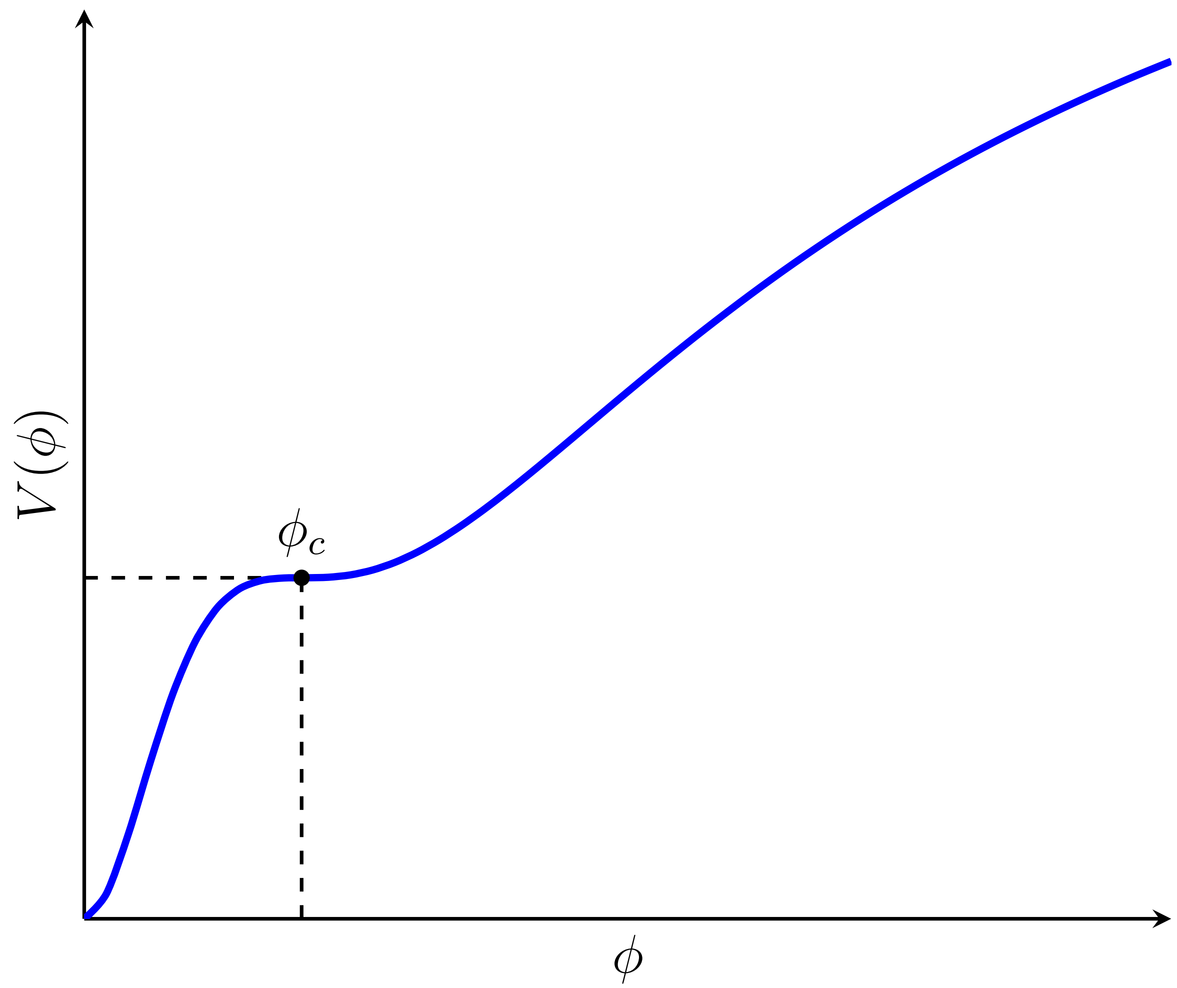

HIGGS
INFLATION
PBH
DM

- PBHs form when large fluctuations reenter horizon



$$M_{PBH} = \frac{4\pi\gamma M_p^2}{H_{\rm inf}}\, e^{2N}$$

- PBH from Single-field Inflation [García-Bellido and Ruiz Morales 2017]



- Large fluctuations are produced if there is a second plateau

$$\mathcal{P}_{\mathcal{R}}(N) \simeq \frac{\kappa^2}{2\epsilon}\left(\frac{H}{2\pi}\right)^2 \xrightarrow[\epsilon\to 0]{} \frac{1}{\epsilon}$$

- This must be a near-inflection point

$$V' \simeq V'' \simeq 0$$

- The difficulty here is to have consistent CMB observable at the same time that a copious production of PBH

Could the SM Higgs produce PBHs?

Higgs Inflation

[Bezrukov and Shaposhnikov 2008]

- The Higgs has a non-minimal coupling to gravity

$$S=\int d^4x\sqrt{-g}\left(\left(\frac{1}{2\kappa^2}+\frac{\xi}{2}\phi^2\right)R-\frac{1}{2}(\partial\phi)^2-\frac{1}{4}\lambda\phi^4\right)$$

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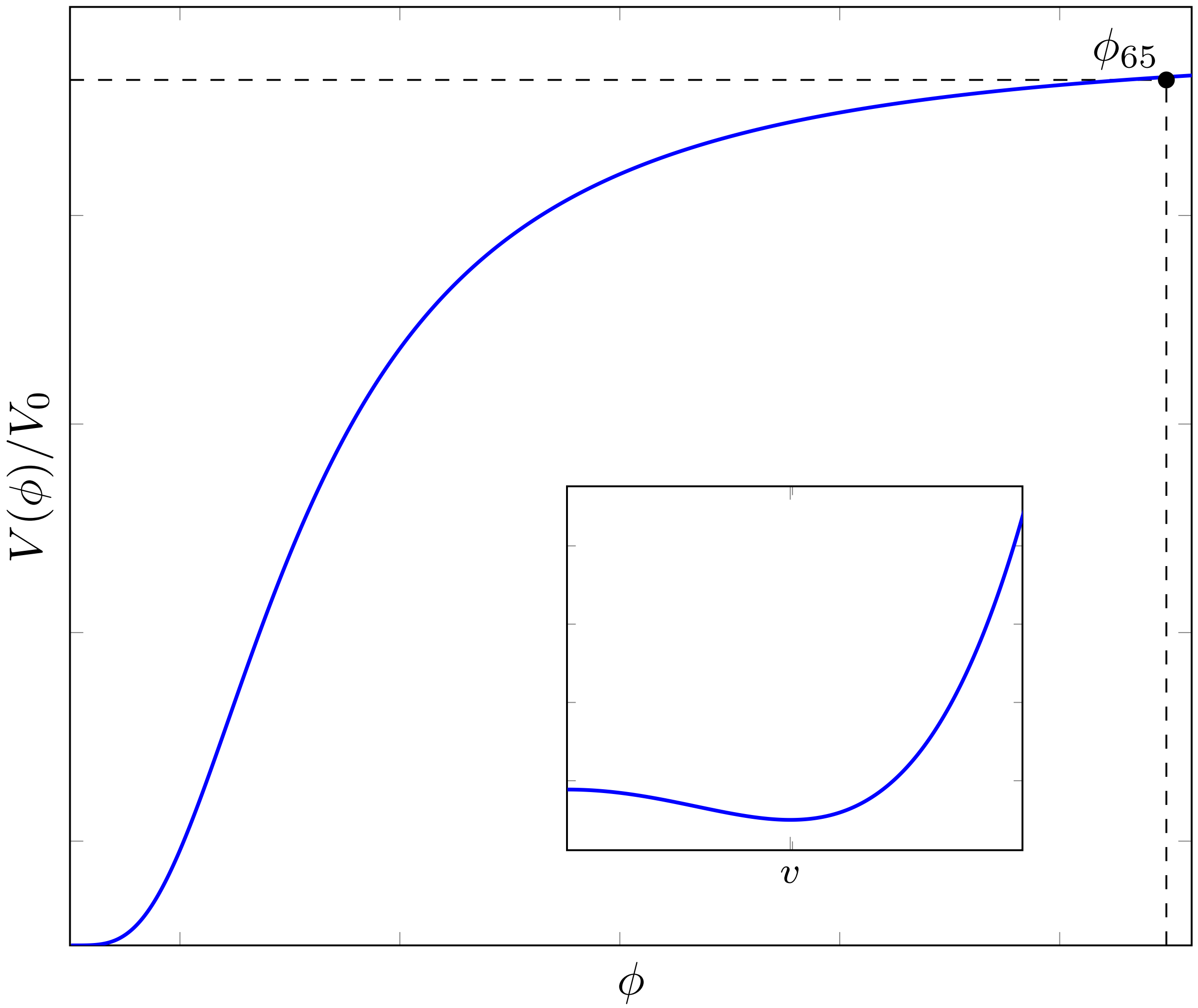
- After a field redefinition

$$\Omega^2 = 1 + \xi\kappa^2\phi^2$$

$$\frac{d\varphi}{d\phi} = \frac{\sqrt{1+\xi(1+6\xi)\phi^2}}{1+\xi\phi^2}$$

$$V(\phi) = \frac{\lambda\phi^4}{4(1+\xi\phi^2)^2}$$



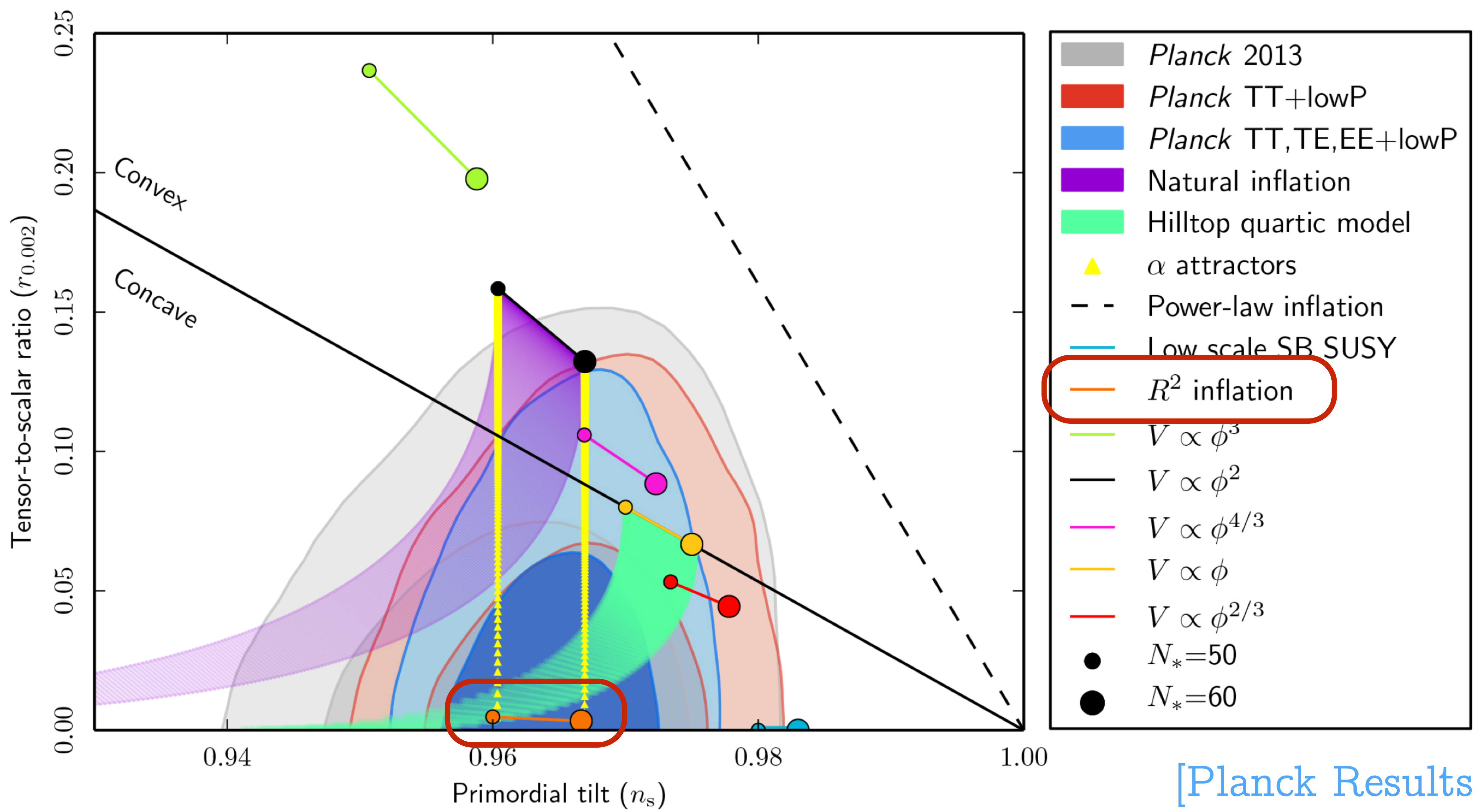
i) CMB determined by plateau

ii) Amplitude fixed by $\lambda \simeq 0.13, \ \xi \sim 10^5$

$$n_s = 1 - \frac{2}{N}$$

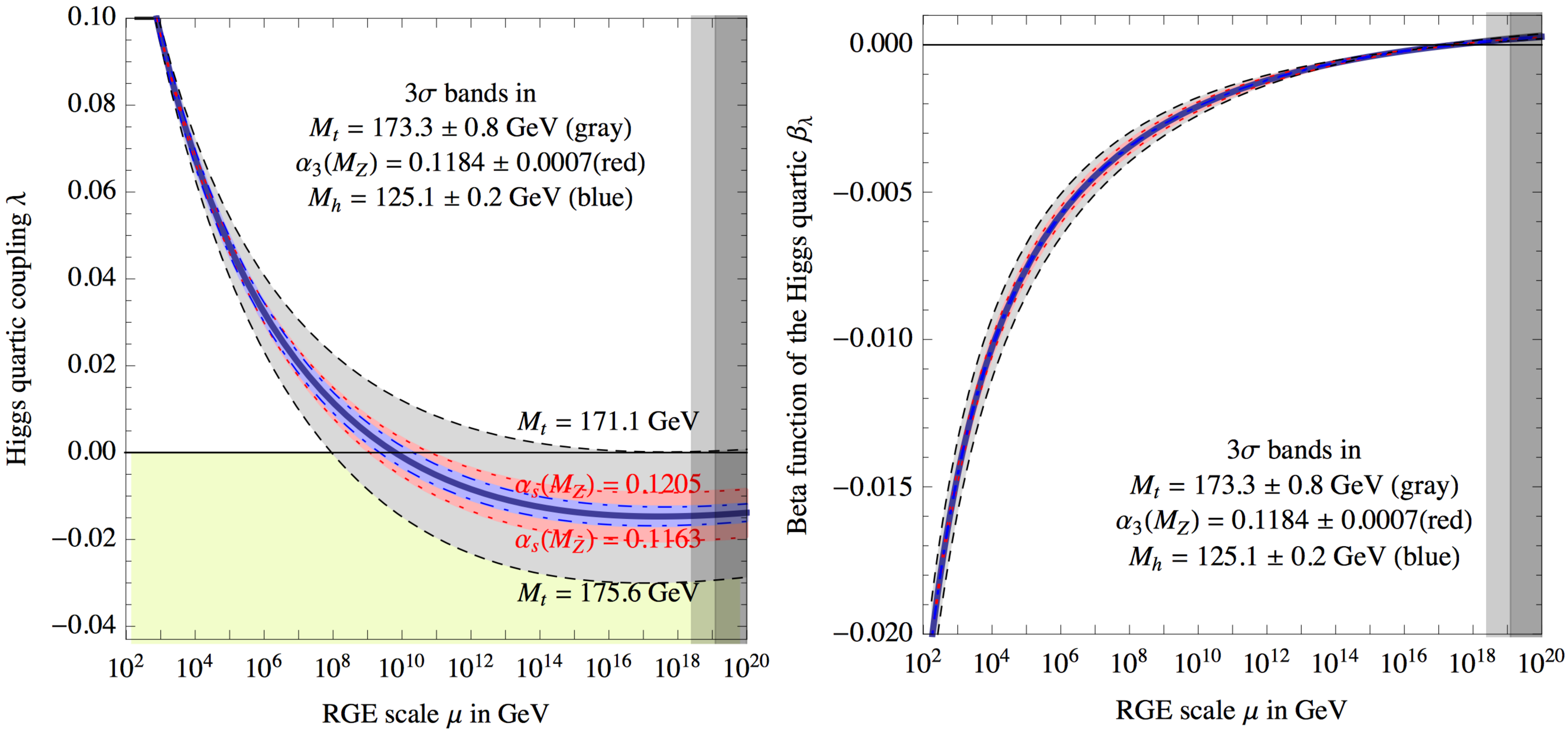
$$r = \frac{12}{N^2}$$

$$V(\phi) \to \lambda/\xi^2$$



[Planck Results 2015]

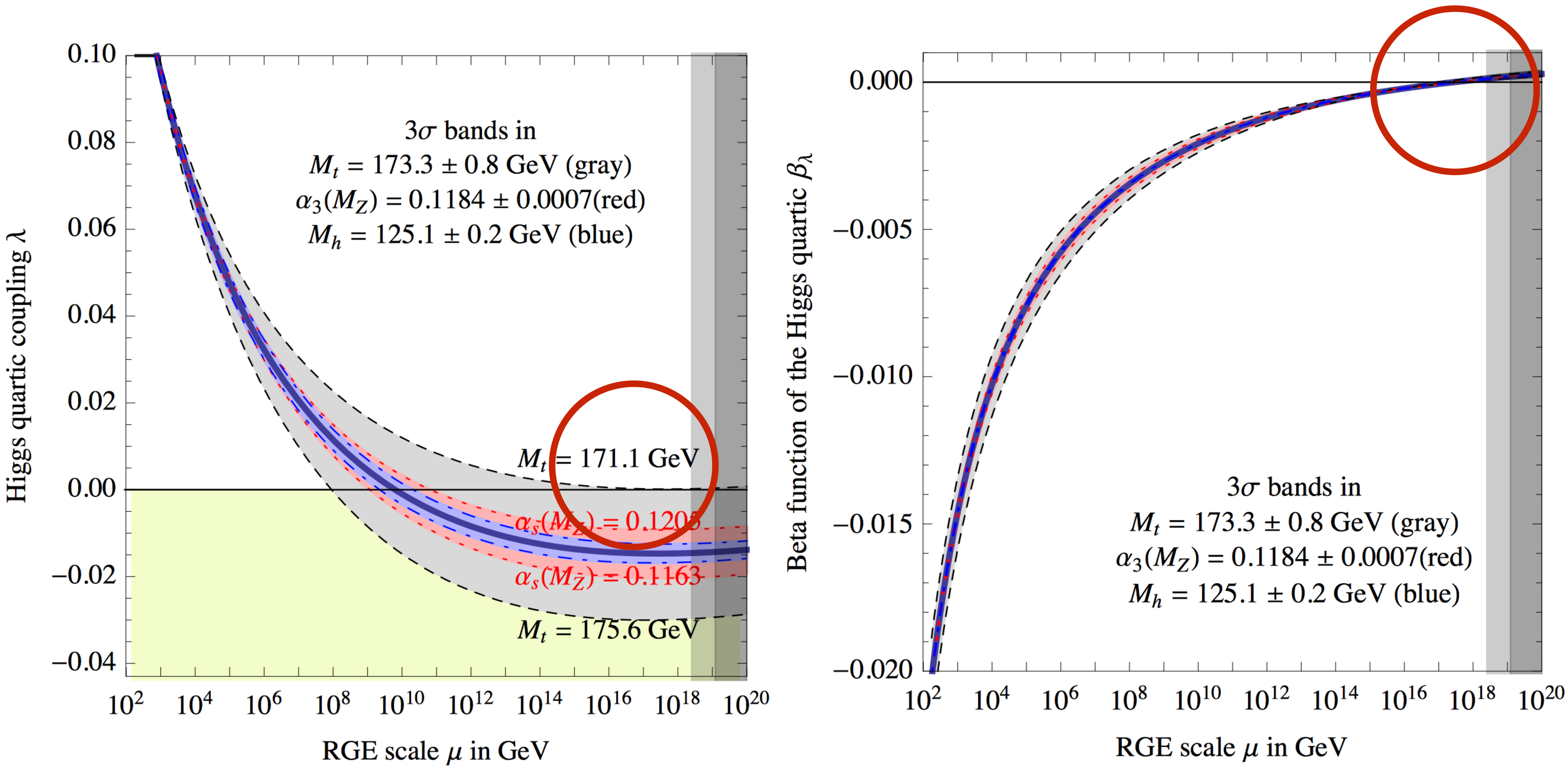
What if we include the RG flow?



[Buttazzo *et al.* 2013]

Critical-point near Planck scale

$$\lambda(\mu_c) \ll 1$$
$$\beta_\lambda(\mu_c) \simeq 0$$



[Buttazzo *et al.* 2013]

[Ezquiaga *et al.* 2017]

Critical Higgs Inflation

- We consider both the running of $\lambda(\phi)$ and $\xi(\phi)$

$$S = \int d^4x\sqrt{-g}\left(\left(\frac{1}{2\kappa^2} + \frac{\xi(\phi)}{2}\phi^2\right)R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{4}\lambda(\phi)\phi^4\right)$$

where

$$\lambda(\phi) = \lambda_0 + b_\lambda \ln^2(\phi/\mu)$$
$$\xi(\phi) = \xi_0 + b_\xi \ln(\phi/\mu)$$

[Ezquiaga *et al.* 2017]

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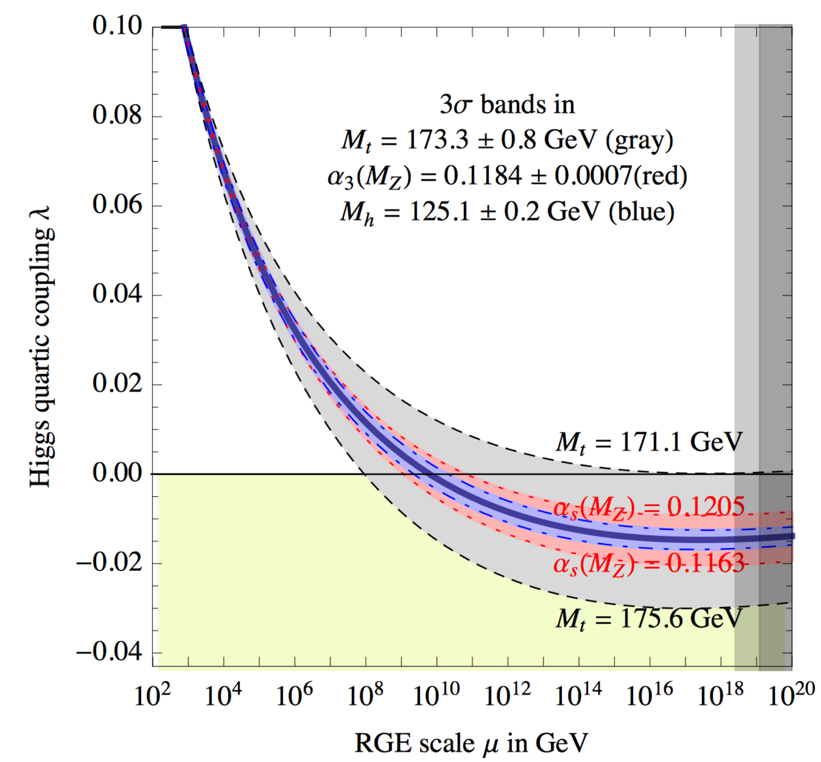


- We are expanding the couplings around the near-critical point of the Higgs self-coupling

- We perform a standard metric and field redefinition

$$\Omega^2 = 1 + \xi\kappa^2\phi^2 \qquad \frac{d\varphi}{d\phi} = \frac{\sqrt{1+\phi^2(\xi(\phi)+6(\xi(\phi)+\phi\xi(\phi)'/2)^2)}}{1+\xi(\phi)\phi^2}$$

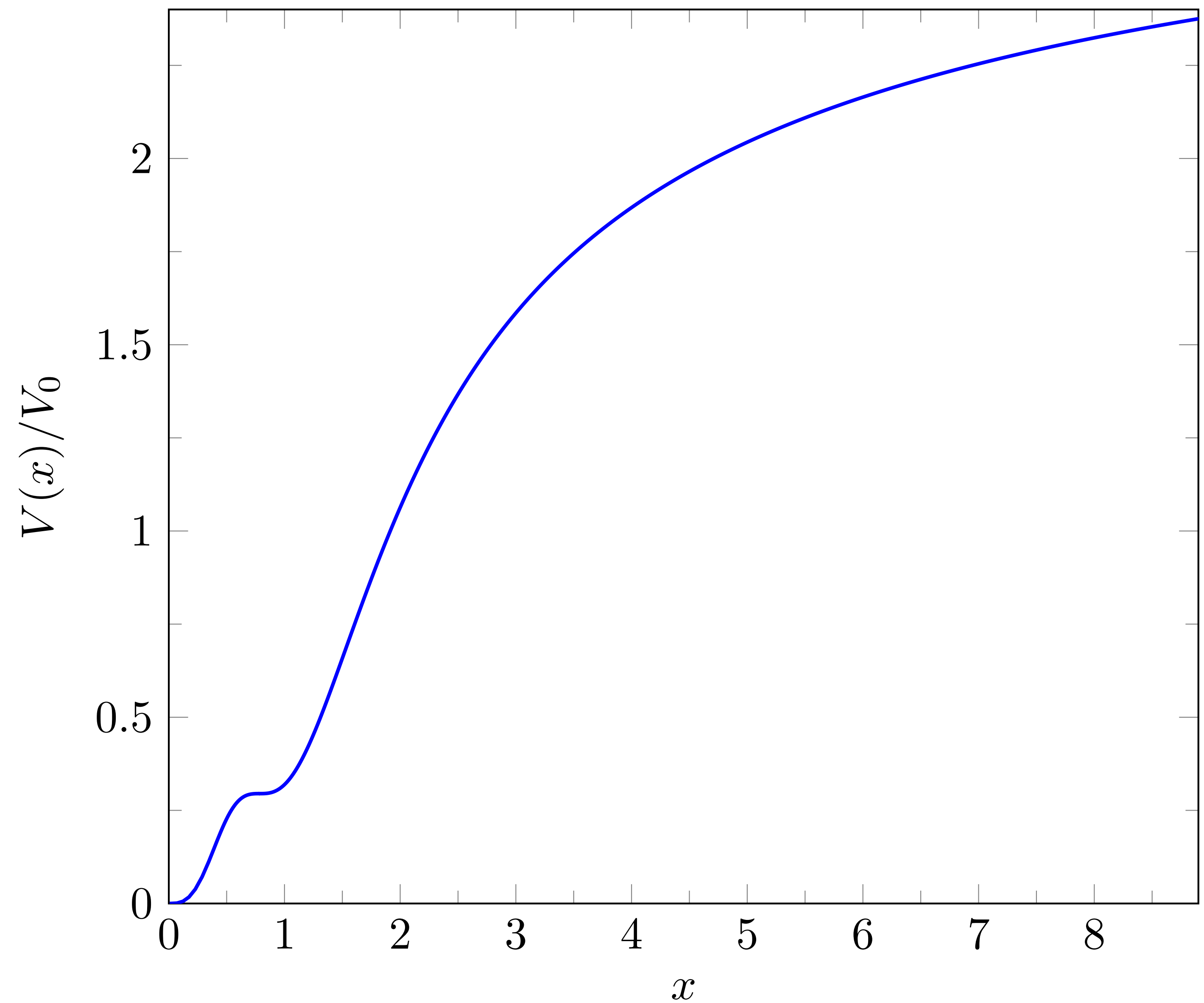
- The potential:

$$V(x) = \frac{V_0\,(1+a\,\ln^2 x)\,x^4}{(1+c\,(1+b\,\ln x)\,x^2)^2}$$

$$V_0 = \lambda_0\mu^4/4$$

$$a = b_\lambda/\lambda_0 \qquad b = b_\xi/\xi_0$$

$$c = \xi_0\,\kappa^2\mu^2 \qquad x = \phi/\mu$$



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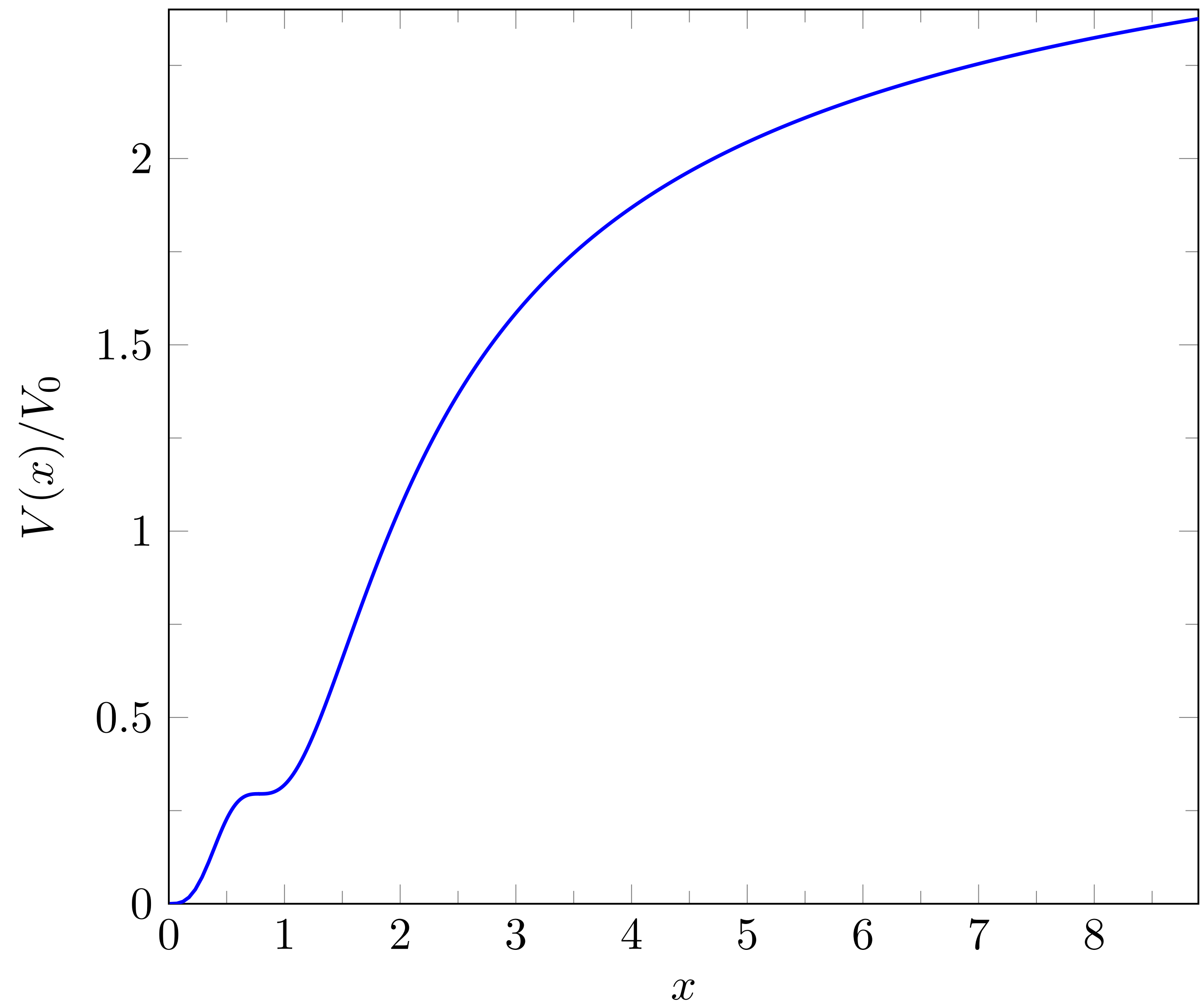
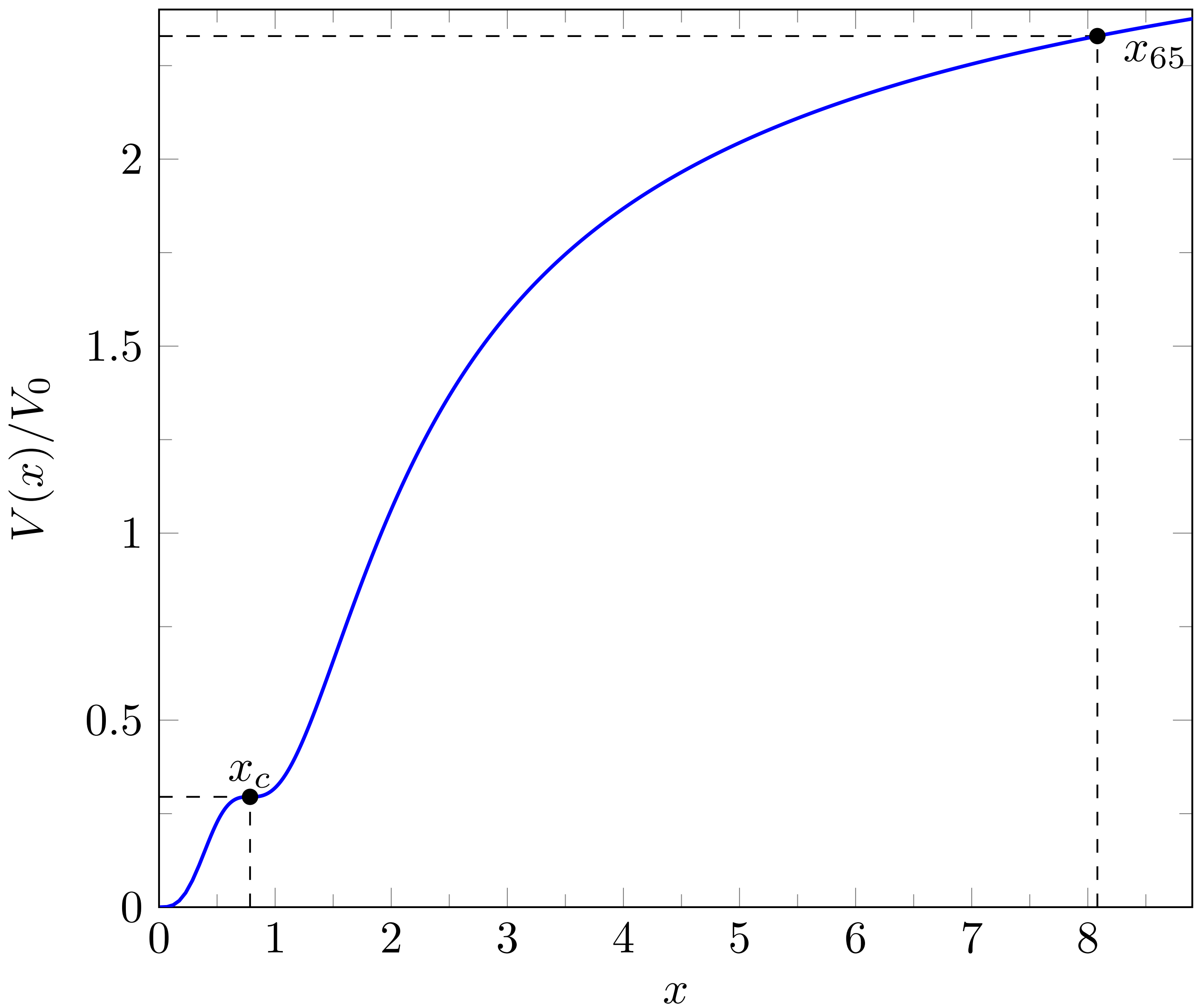
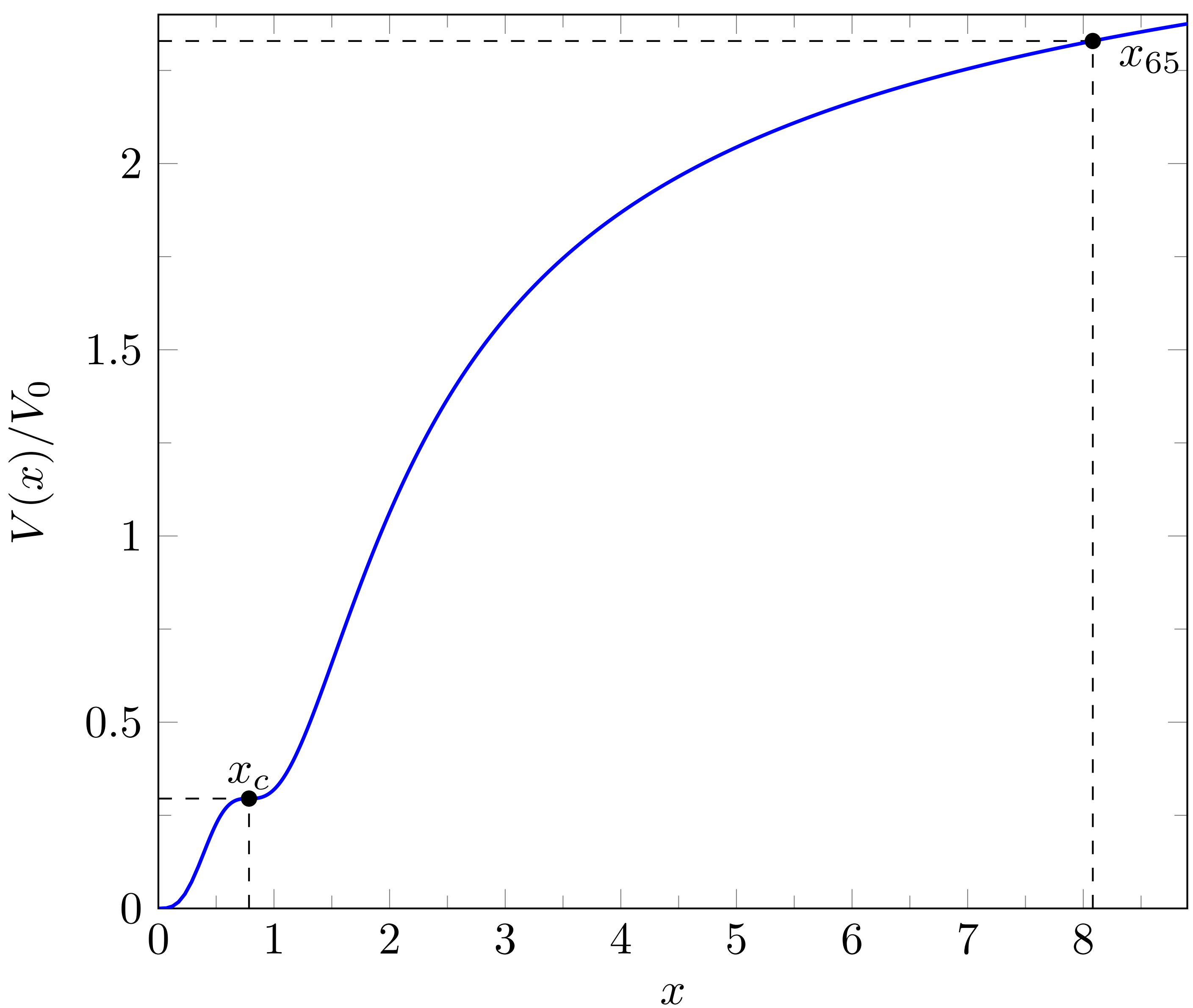


[Ezquiaga *et al.* 2017]



- Large field values of the potential are dominated by the running

$$V(x \gg x_c) \simeq V_0\, a/(b\, c)^2 \sim b_\lambda / b_\xi^2 \ll M_{pl}^4$$



[Ezquiaga *et al.* 2017]

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$$V(x \gg x_c) \simeq V_0\, a/(b\, c)^2 \sim b_\lambda/b_\xi^2 \ll M_{pl}^4$$

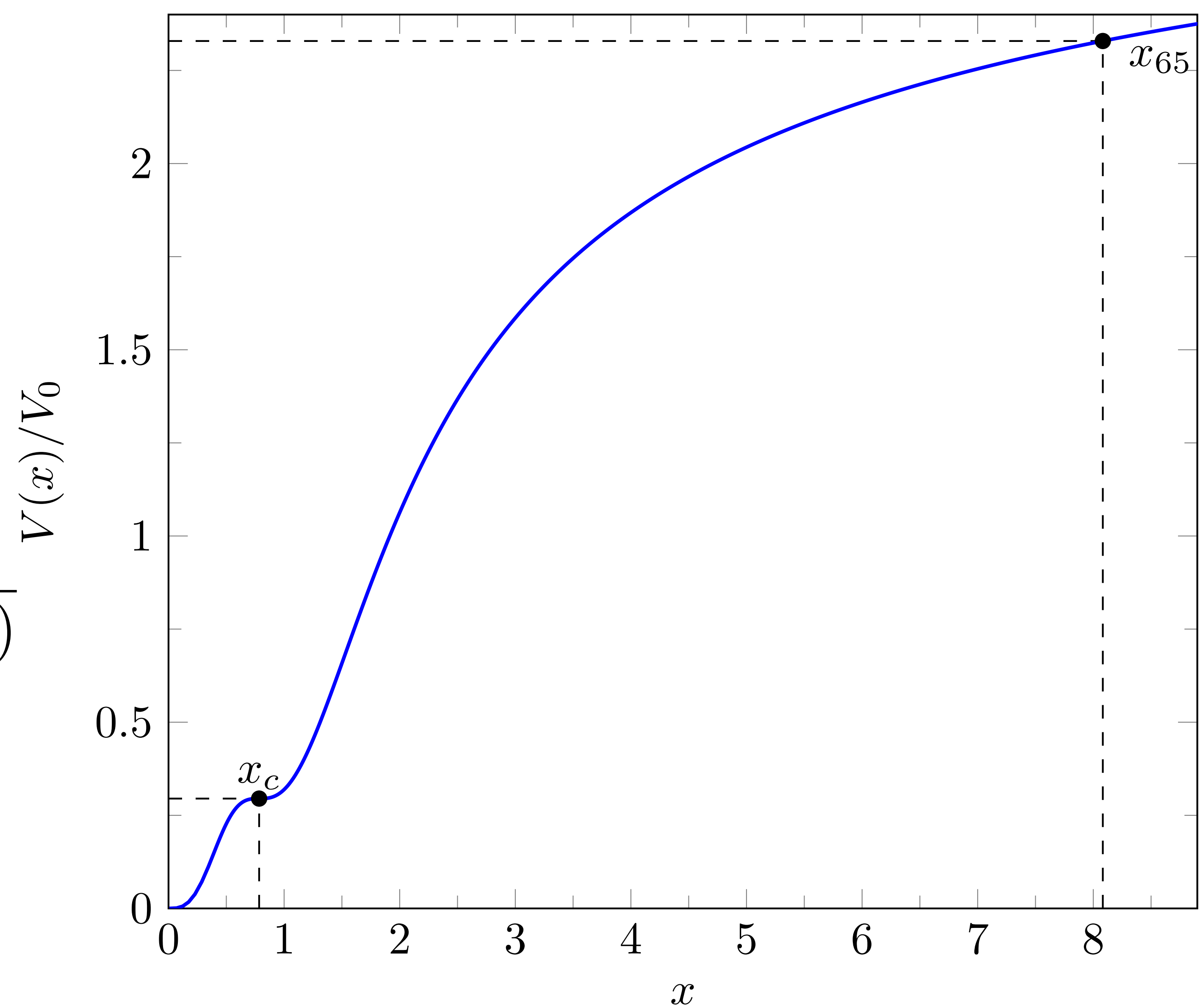
- The inflection point fixed by

$$V'(x_c) = V''(x_c) = 0$$

$$a(c, x_c) = \frac{4}{1 + c \cdot x_c^2 + 2z - 4z^2}$$

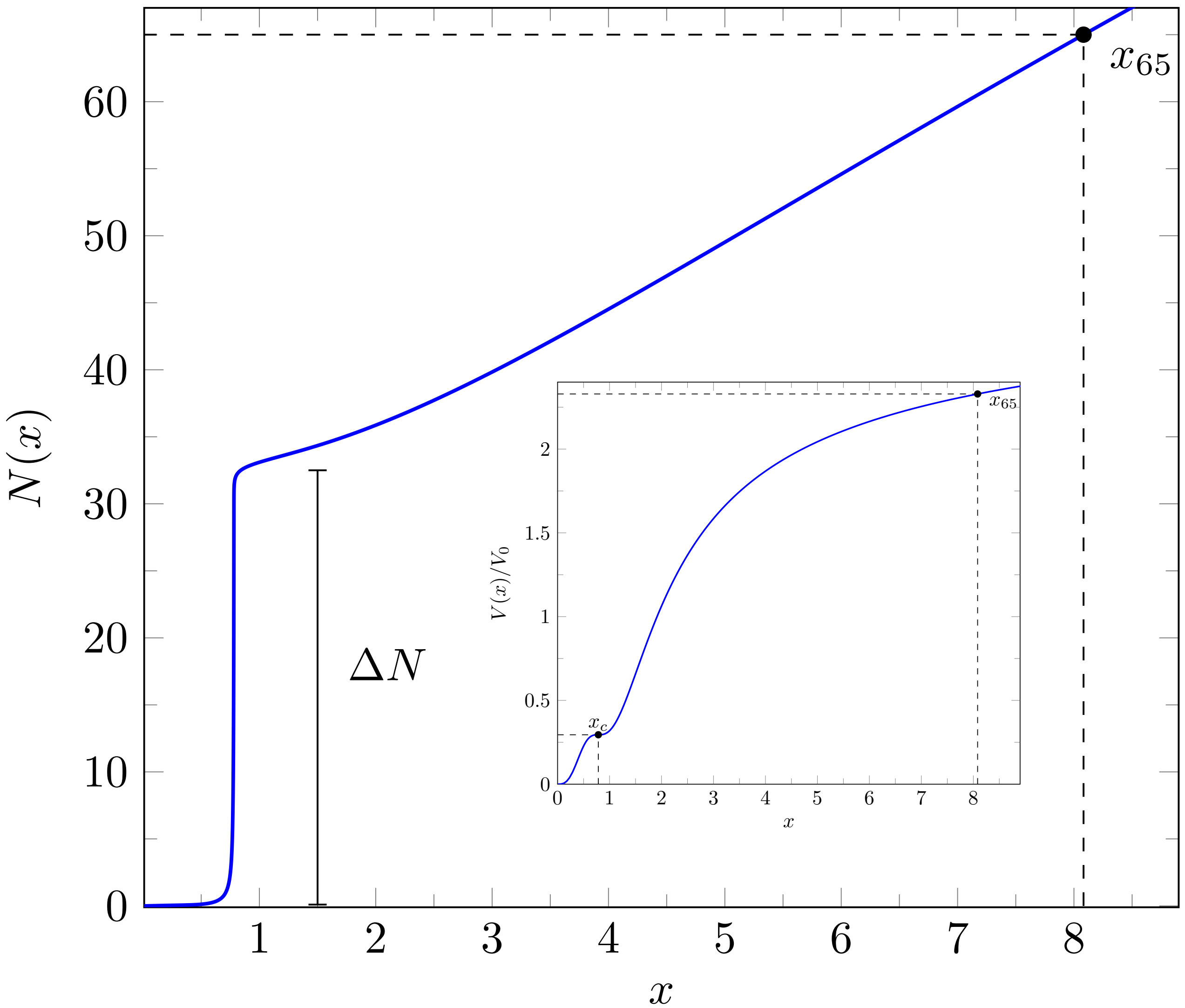
$$b(c, x_c) = \frac{2(1 + c \cdot x_c^2 + 4z - 4z^2)}{c \cdot x_c^2(1 + c \cdot x_c^2 + 2z - 4z^2)}$$

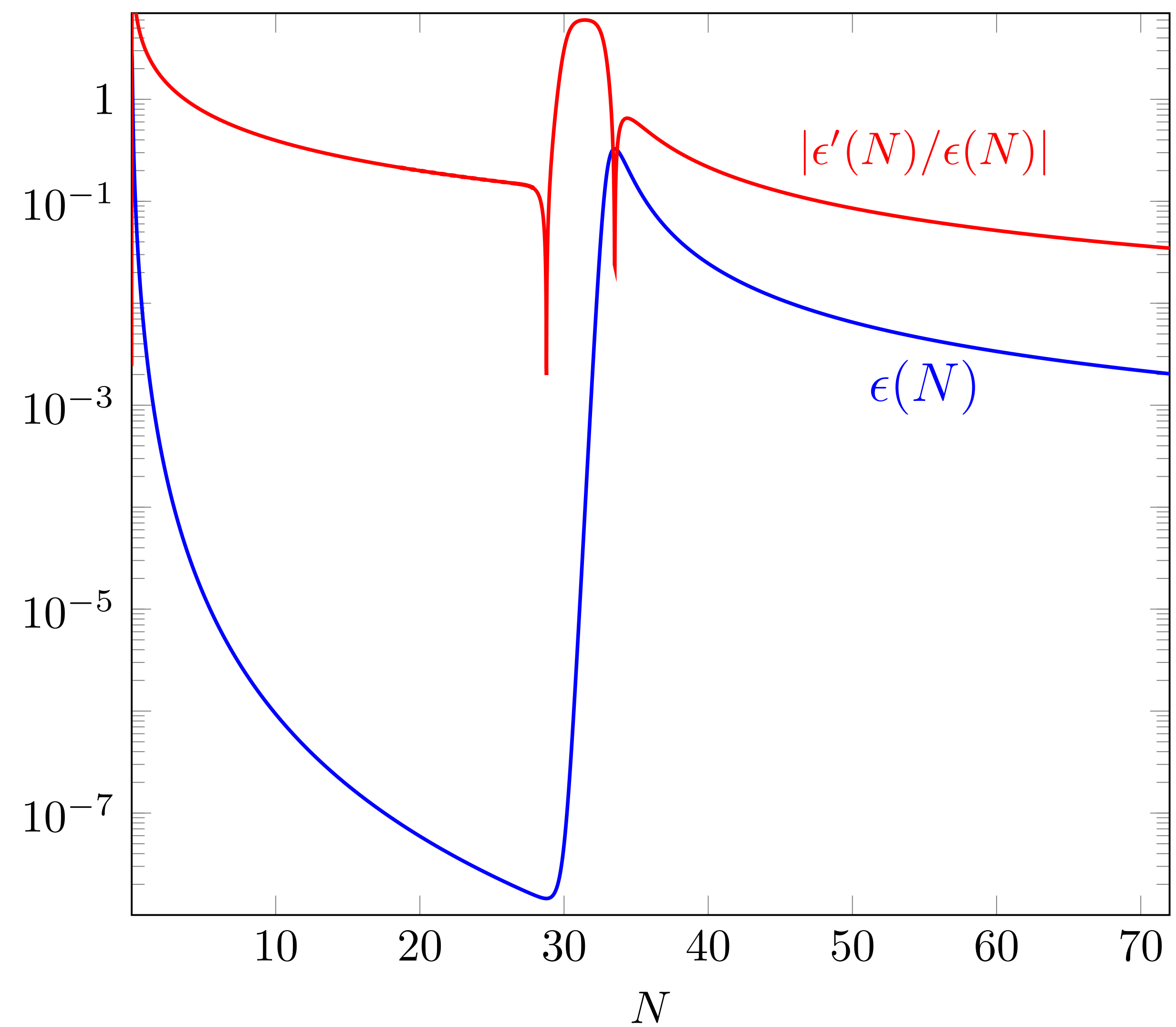
where $z \equiv \log x_c$



[Ezquiaga *et al.* 2017]

- The model can be characterized by the **width** and **peak** of the spectrum





- Near-inflection point condition:

$$a \to a(c, x_c)$$
$$b \to b(c, x_c)(1-\beta)$$

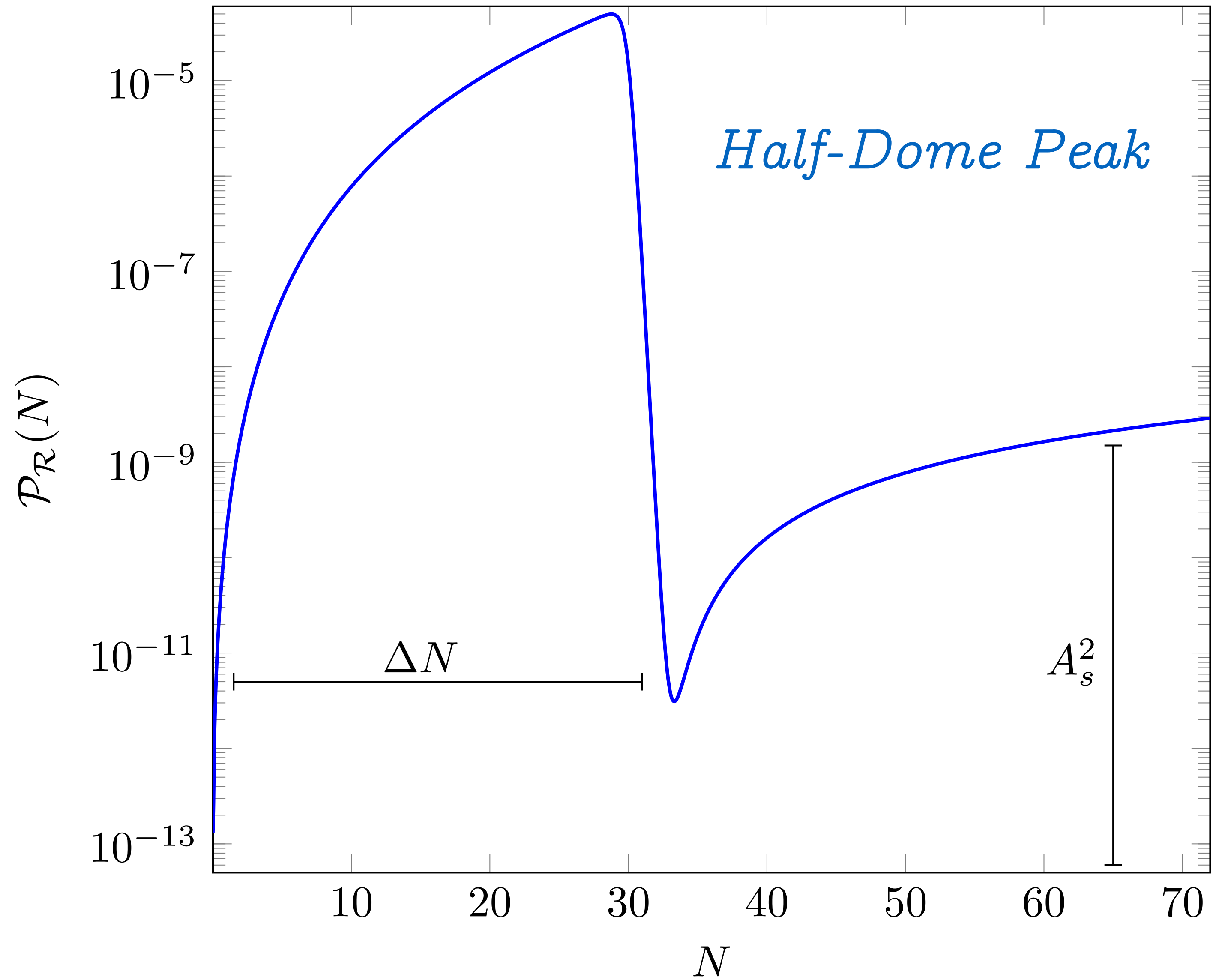
PBH from CHI

[Ezquiaga *et al.* 2017]

- Primordial Spectrum

$$\mathcal{P}_{\mathcal{R}}(N) \simeq \frac{\kappa^2}{2\epsilon}\left(\frac{H}{2\pi}\right)^2$$

$$H^2 = \kappa^2 \frac{V(\phi(N))}{3-\epsilon(N)}$$



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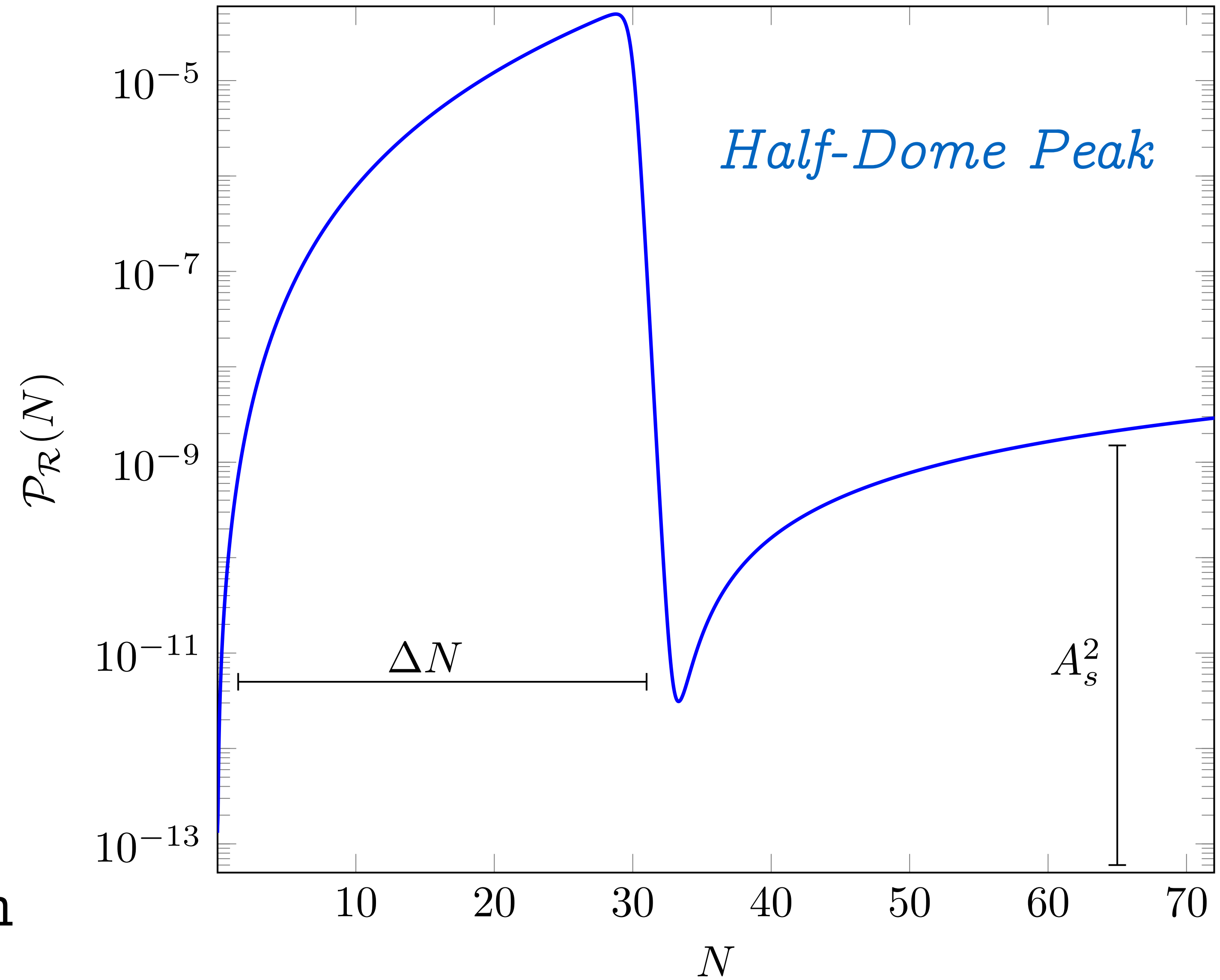

- Press-Schechter formalism

$$\beta^{form}(M) \equiv \left.\frac{\rho_{PBH}(M)}{\rho_T}\right|_{t=t_M} = 2\int_{\zeta_c}^{\infty} \frac{d\zeta}{\sqrt{2\pi}\sigma} e^{-\frac{\zeta^2}{2\sigma^2}} = \mathrm{erfc}\left(\frac{\zeta_c}{\sqrt{2}\sigma}\right)$$

$$\sigma^2 = \mathcal{P}_{\mathcal{R}}(N)$$

[Ezquiaga *et al.* 2017]

- Evolution until matter-radiation equality:
    - Density of PBH grow faster than radiation

$$\beta^{eq}(M) = \frac{a_{eq}}{a(t_M)}\beta^{form}(M) \qquad \Omega_{PBH}^{eq} = \int_{M_{ev}}^{M_{eq}} \beta^{eq}(M) d\ln M$$

[Ezquiaga *et al.* 2017]

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- Evolution after matter-radiation equality:

  - Clustered PBHs: non-linear evolution+merging+accretion

[Chisholm 2006]

[Ezquiaga *et al.* 2017]

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[Chisholm 2006]

- Final distribution: approximately LogNormal

$$P(M) = \frac{A\,\mu_{\rm PBH}}{M\,\sqrt{2\pi\sigma^2_{\rm PBH}}}\exp\left(-\frac{\ln^2(M/\mu_{\rm PBH})}{2\sigma^2_{\rm PBH}}\right)$$

Results

[Ezquiaga *et al.* 2017]

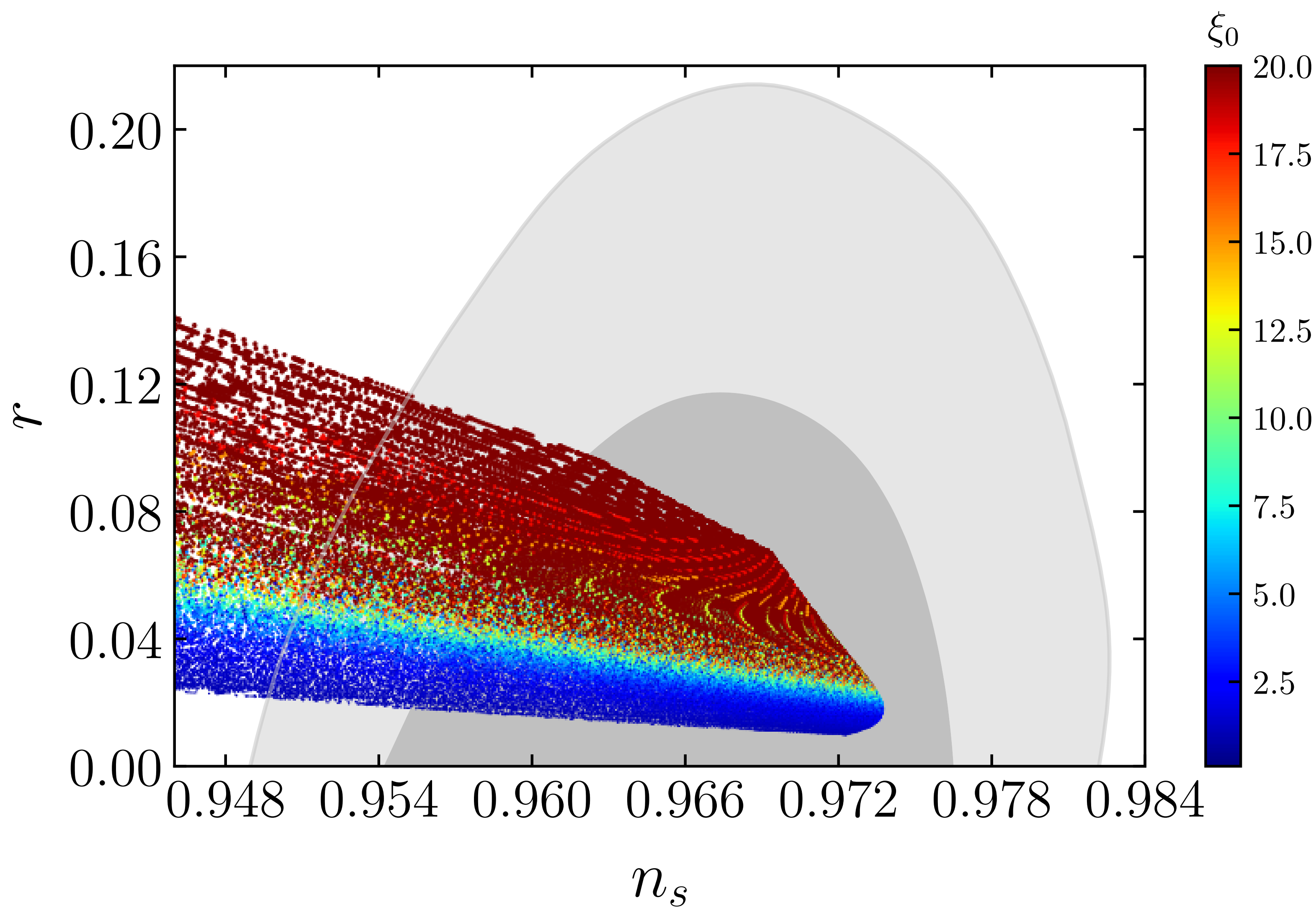
Results

[Ezquiaga *et al.* 2017]

$\beta \in (0.1 - 9) \times 10^{-4}$

$\Delta N \in (10 - 45)$

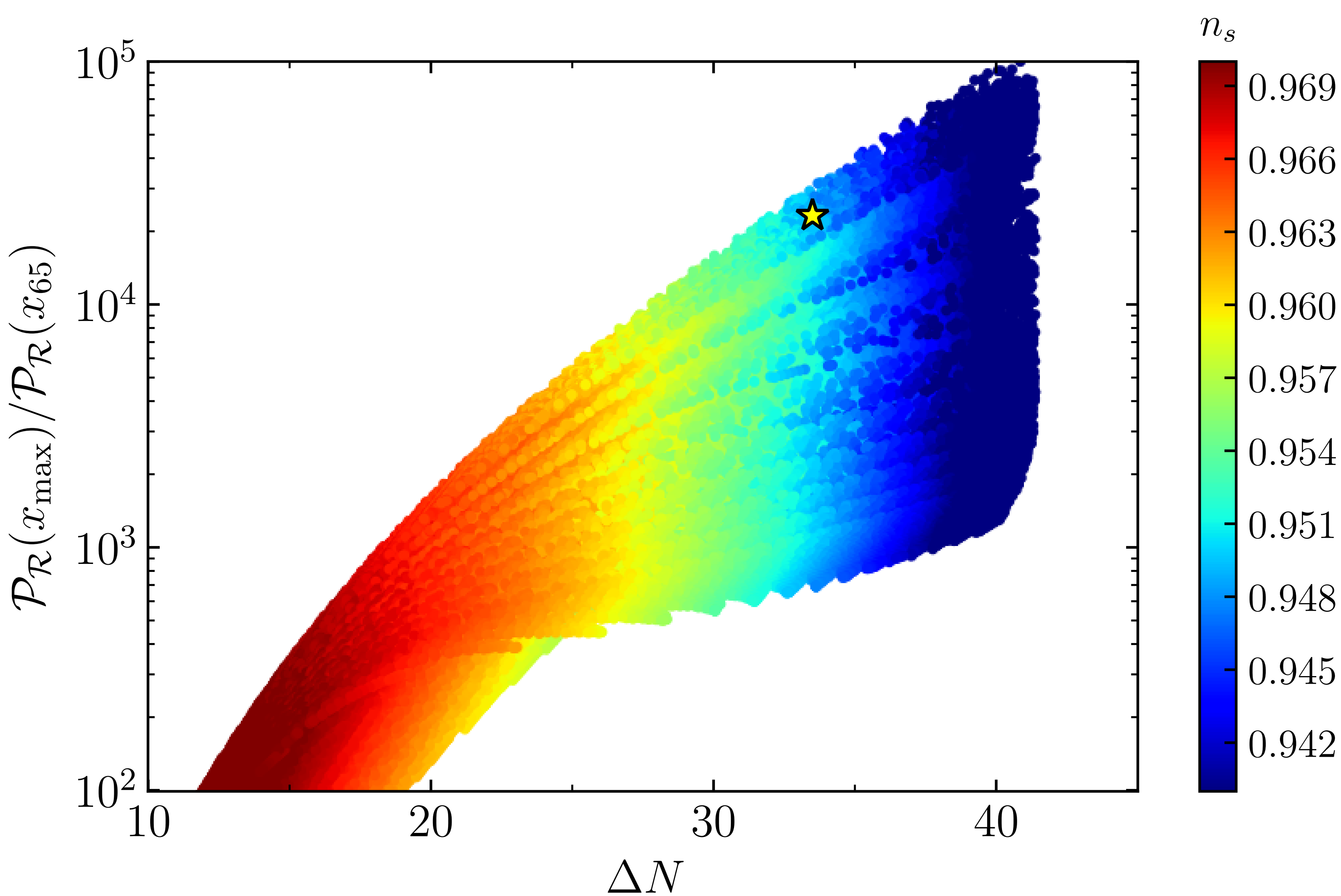
- Large parameter space compatible with Planck 2015

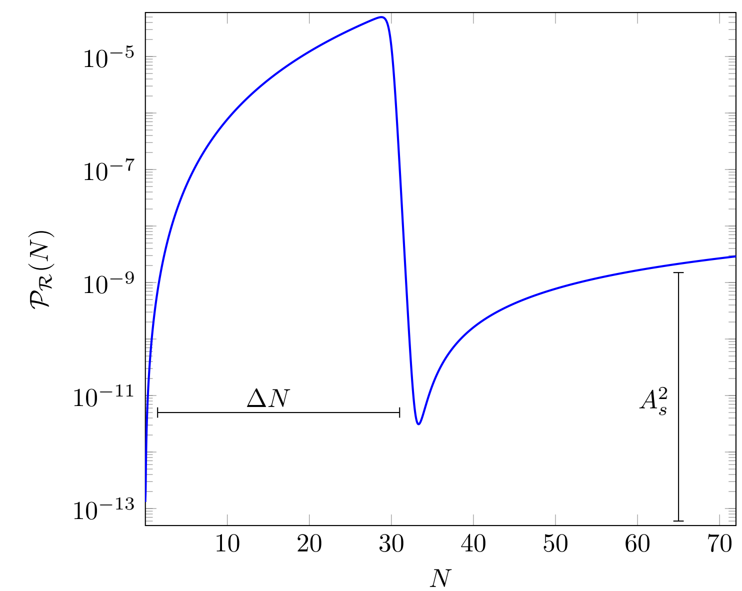


- CMB observables are sensitive to the width (ΔN) of the peak

[Ezquiaga *et al.* 2017]

- PBH production controlled by the **height** and **width** of the *half-dome*





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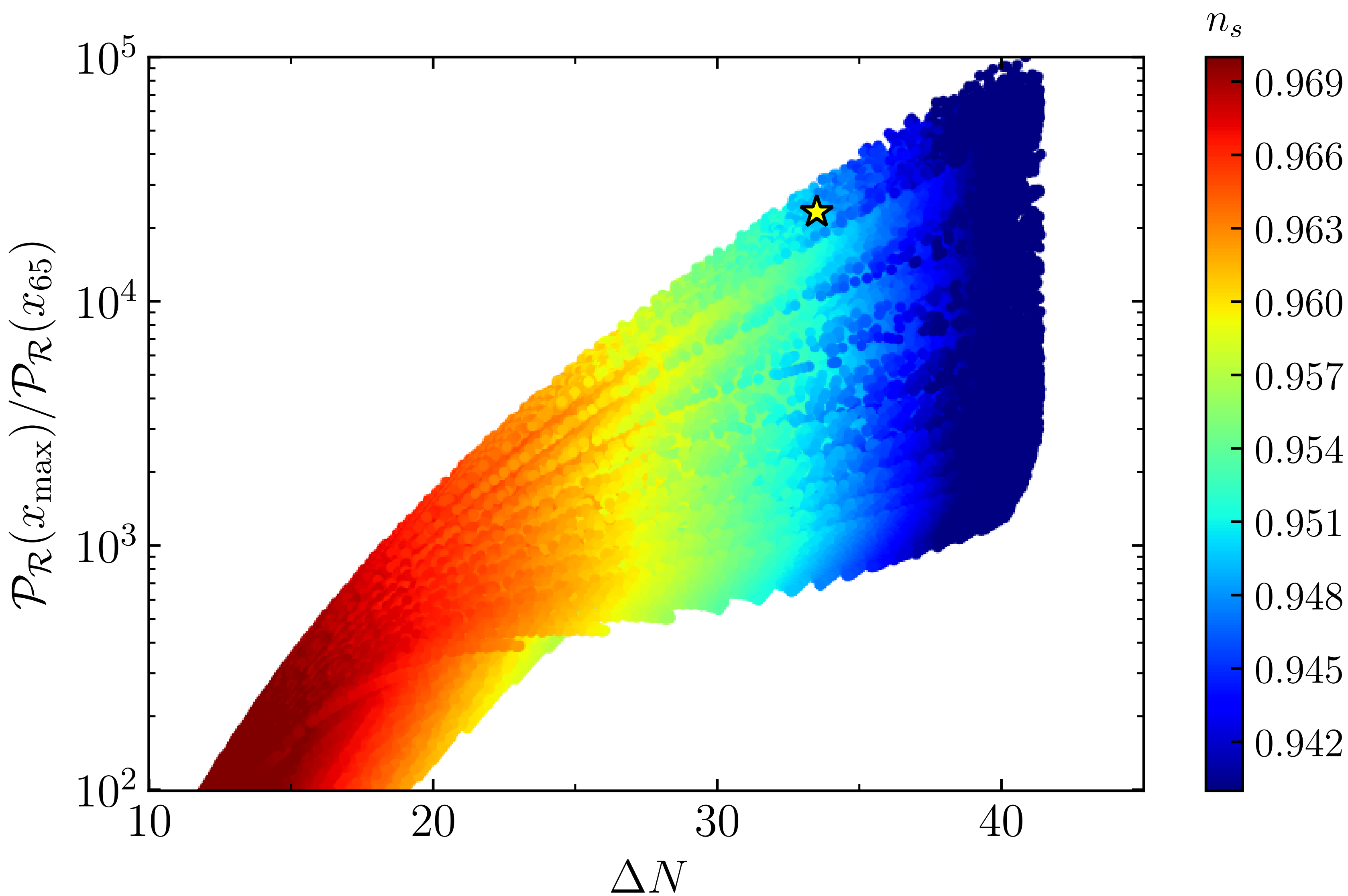
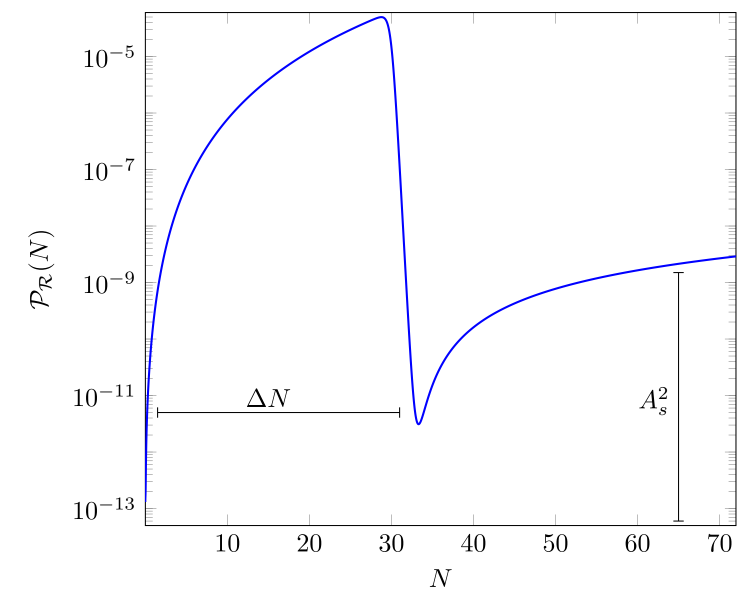




- Mean value of PBH distribution depends on the location of maximum

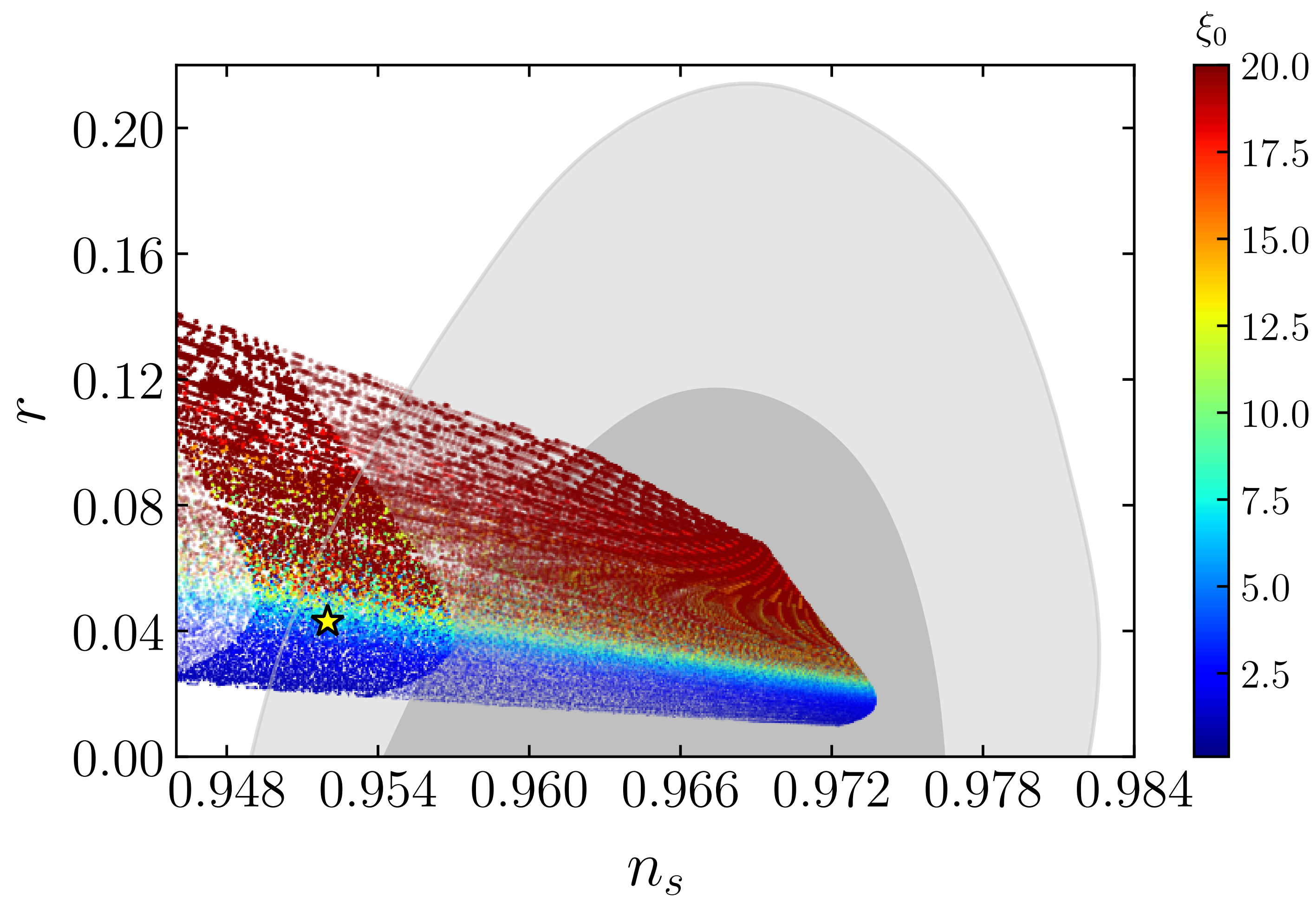
$$\mu_{\rm PBH} \sim 10\, M_\odot \cdot e^{2(N_{\rm peak}-28.8)}$$

★ $\mu_{\rm PBH} \sim 11\, M_\odot$

[Ezquiaga *et al.* 2017]

- CMB observables for reference case:

$$\star \quad n_s = 0.952\,,\ r = 0.043\,,\ \alpha_s = -0.0017$$
$$\lambda_0 = 2.23 \times 10^{-7}\,,\ \xi_0 = 7.55\,,\ \kappa^2\mu^2 = 0.102\,,\ b_\lambda = 1.2 \times 10^{-6}\,,\ b_\xi = 11.5$$



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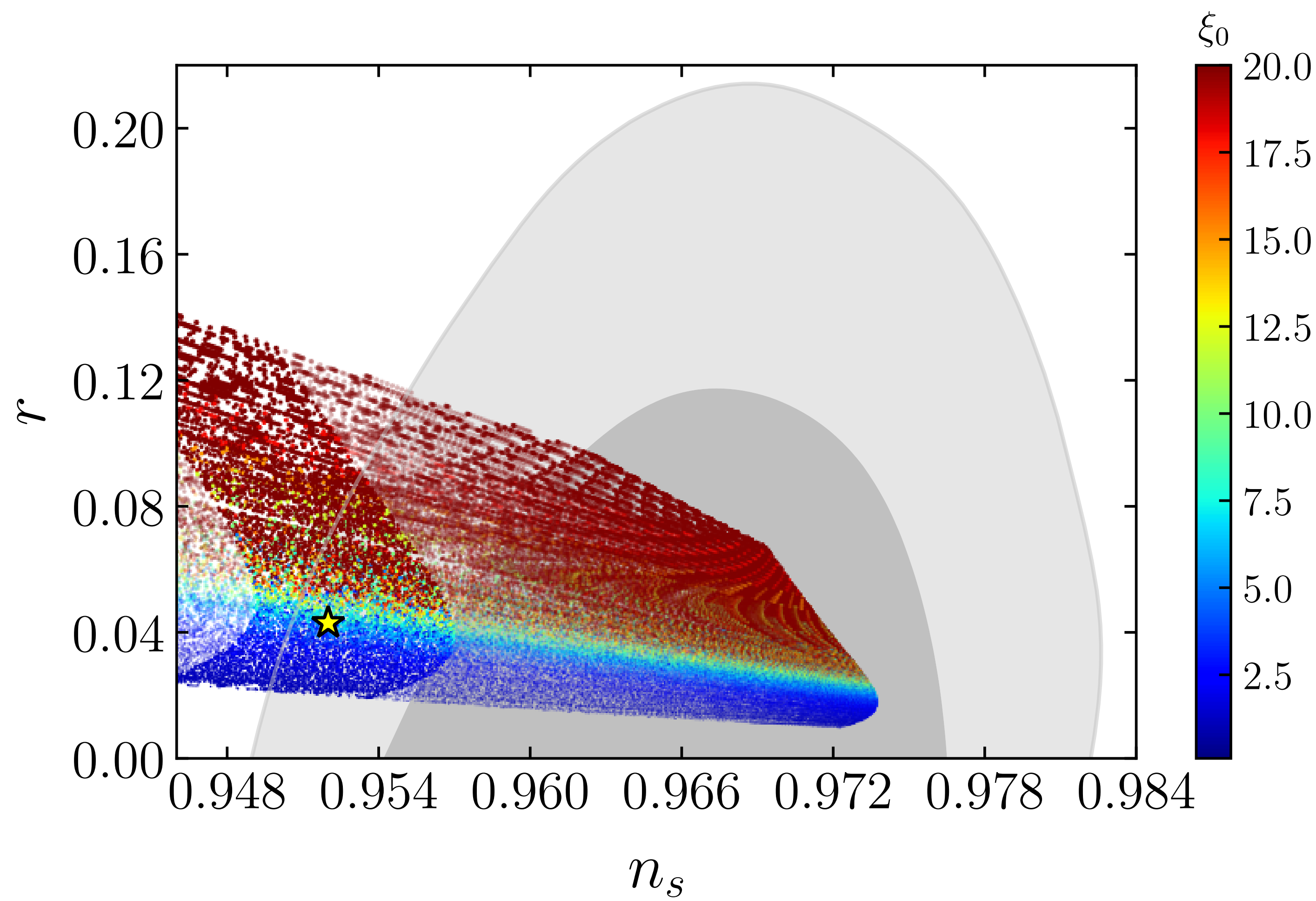
- Region $\Delta N \in (30-35)$:

$$\lambda_0 \sim (0.01-8)\cdot10^{-7}$$
$$\xi_0 \sim (0.5-15)$$
$$\kappa^2\mu^2 \sim (0.05-1.2)$$
$$b_\lambda \sim (0.008-4)\cdot10^{-6}$$
$$b_\xi \sim (1-18)$$



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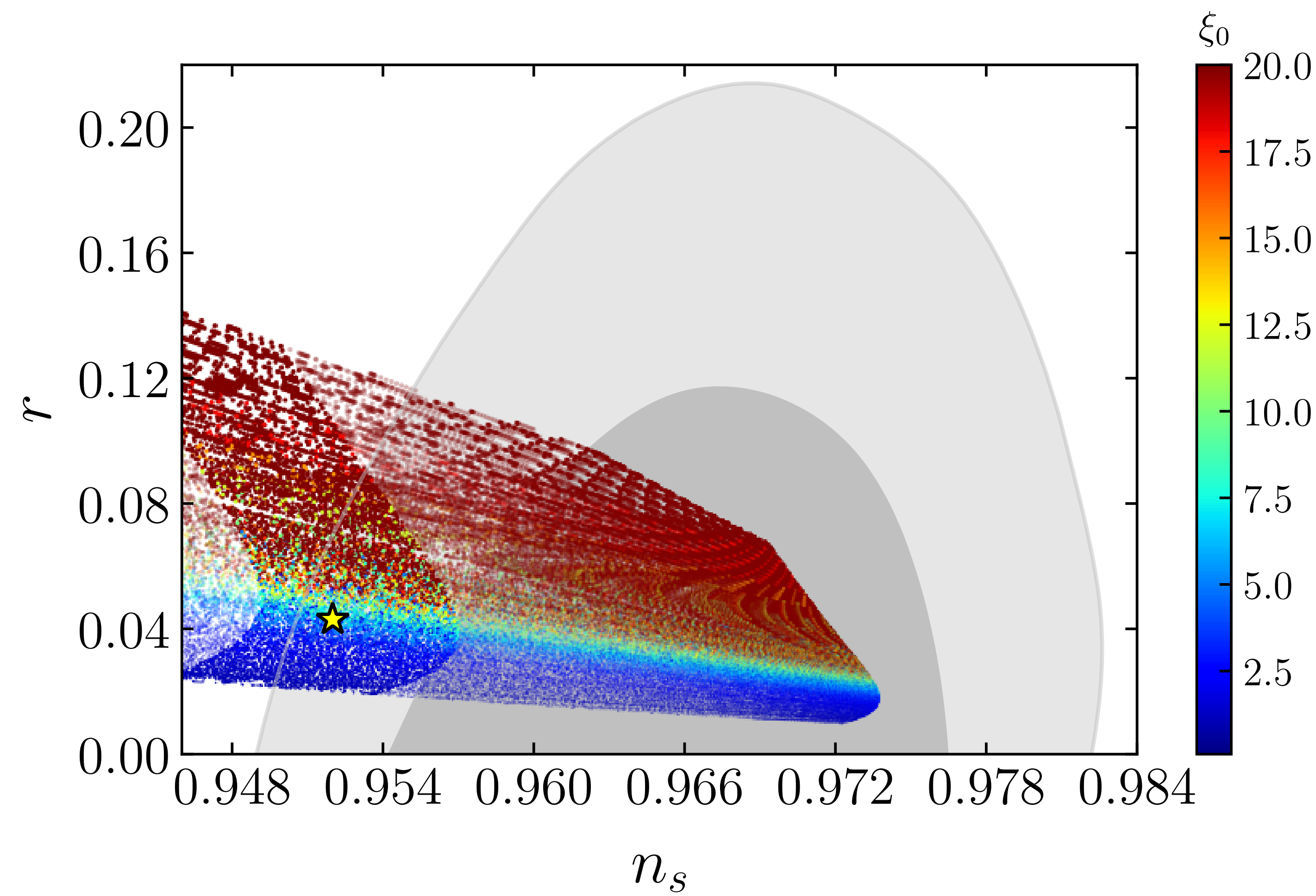


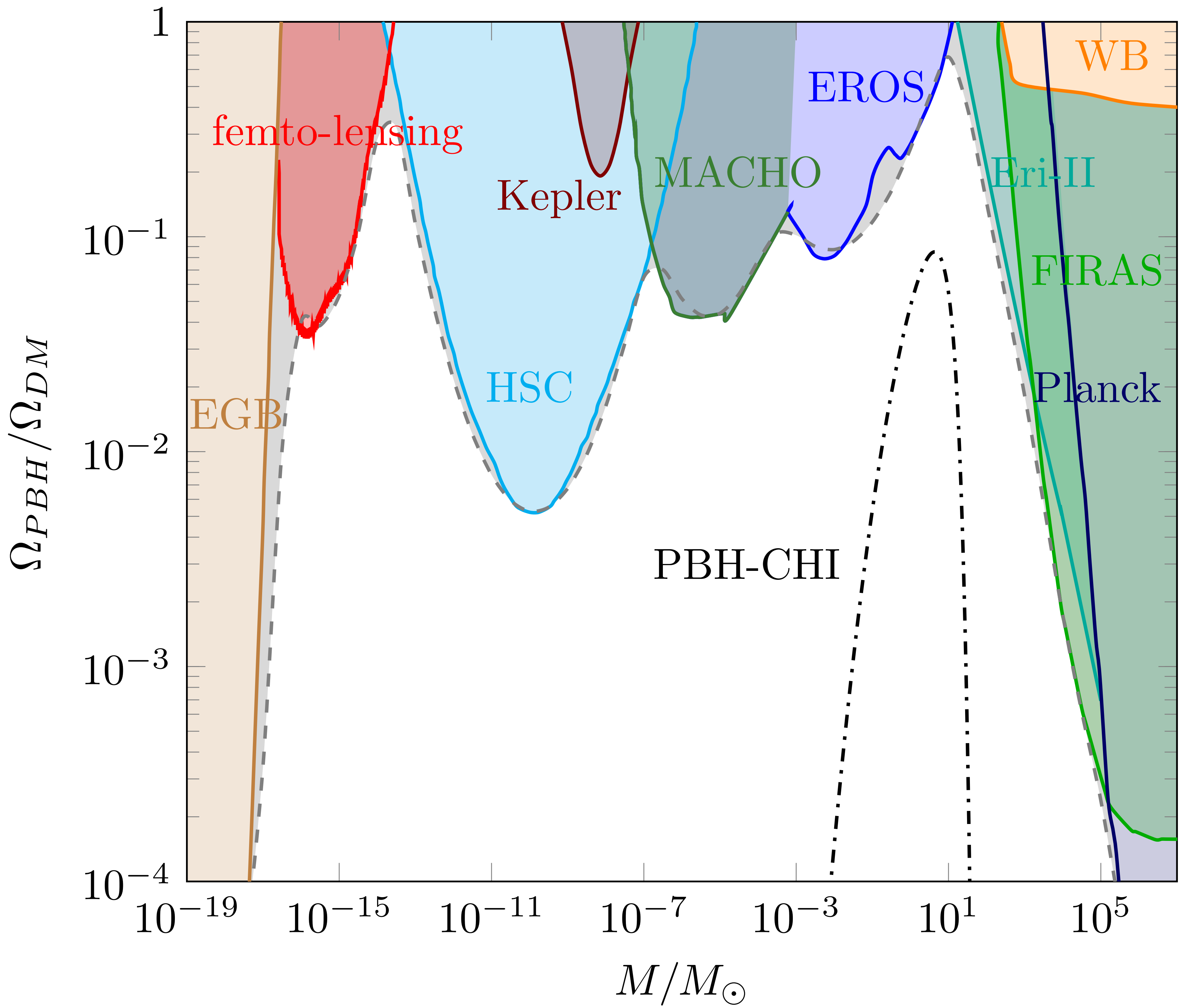
- PBH spectrum:

$$N_{\rm peak} \sim (25-30)$$

$$\mu_{\rm PBH} \sim (0.01-100)\,M_\odot$$
$$\sigma_{\rm PBH} \sim (0.6-1)$$

[Ezquiaga *et al.* 2017]

- Constraints on the fraction of PBH (extended mass function)



$\mu_{\rm PBH} \sim 11\, M_\odot$
$\sigma_{\rm PBH} \sim 0.8$

[Ezquiaga *et al.* 2017]

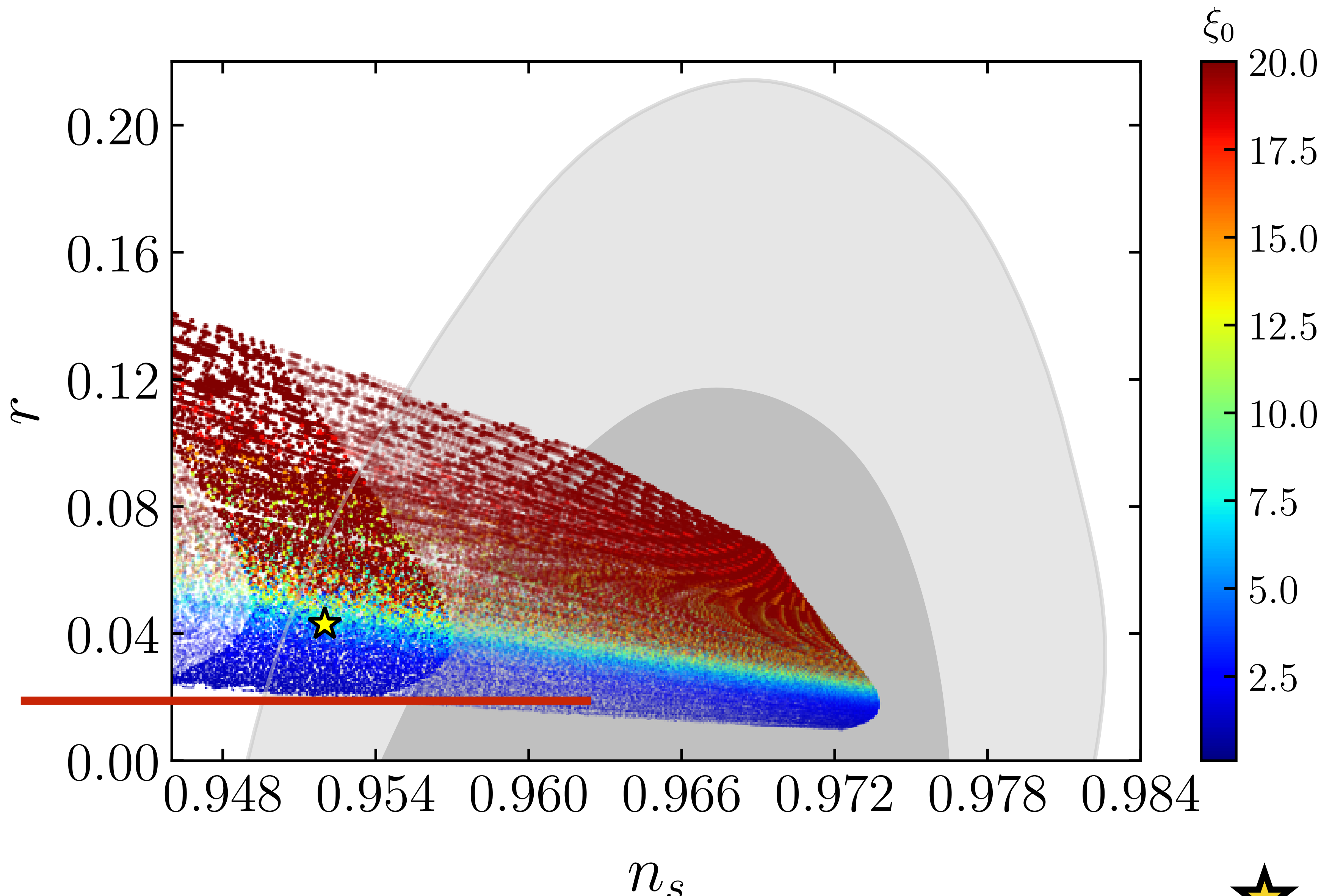
Signatures of PBH-CHI

[Ezquiaga *et al.* 2017]

Signatures of PBH-CHI

[Early Universe]

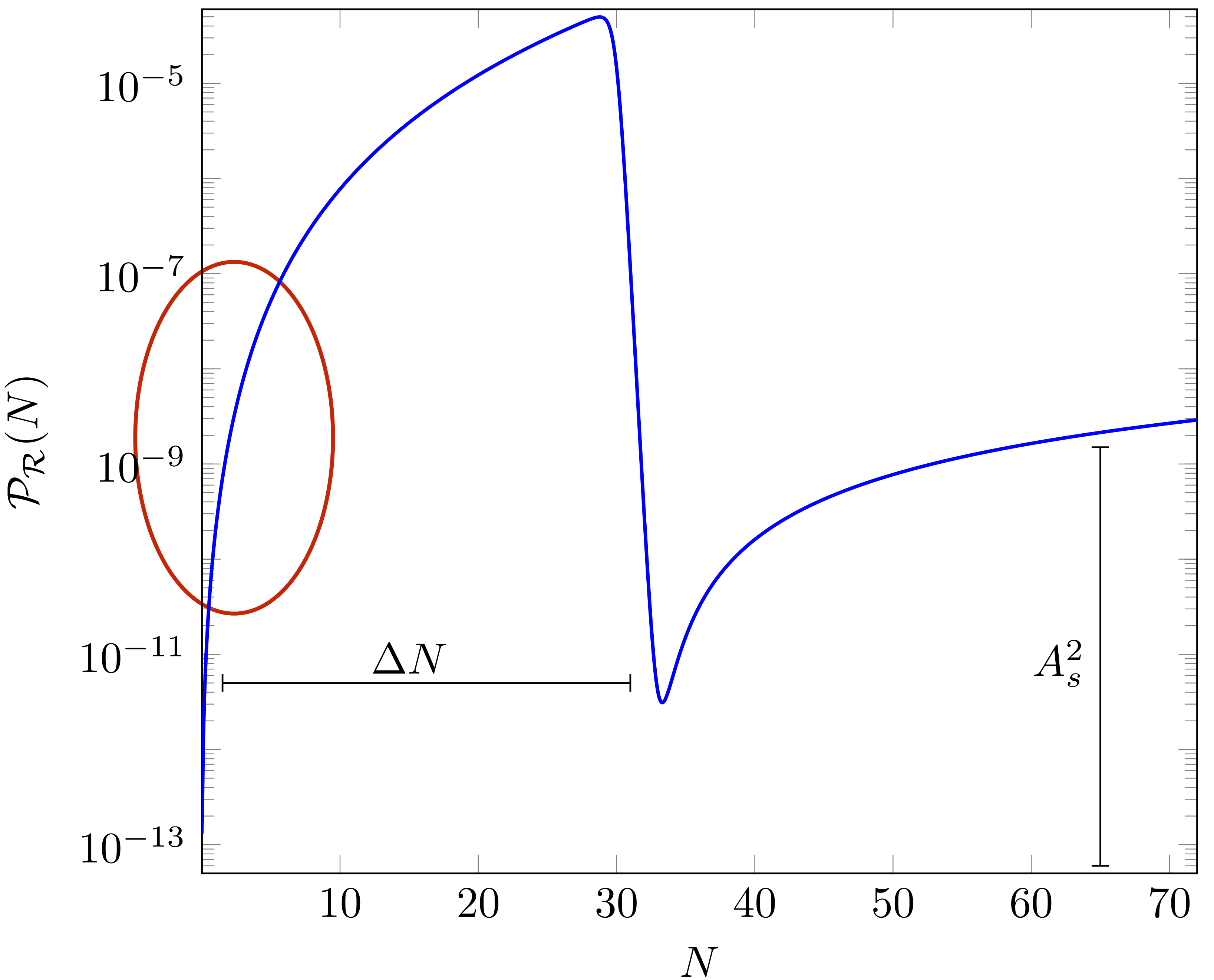
- Relatively large tensor modes: $r > 0.019$ in $\Delta N \in (30 - 35)$



★ $r = 0.043$

[Ezquiaga *et al.* 2017]

- Large fluctuations at the end of inflation: *inhomogeneous reheating*



$\rho_{\rm end} = 4 \times 10^{63}\ \mathrm{GeV}^4$

$T_{\rm rh} = 3.2 \times 10^{15}\ \mathrm{GeV}$

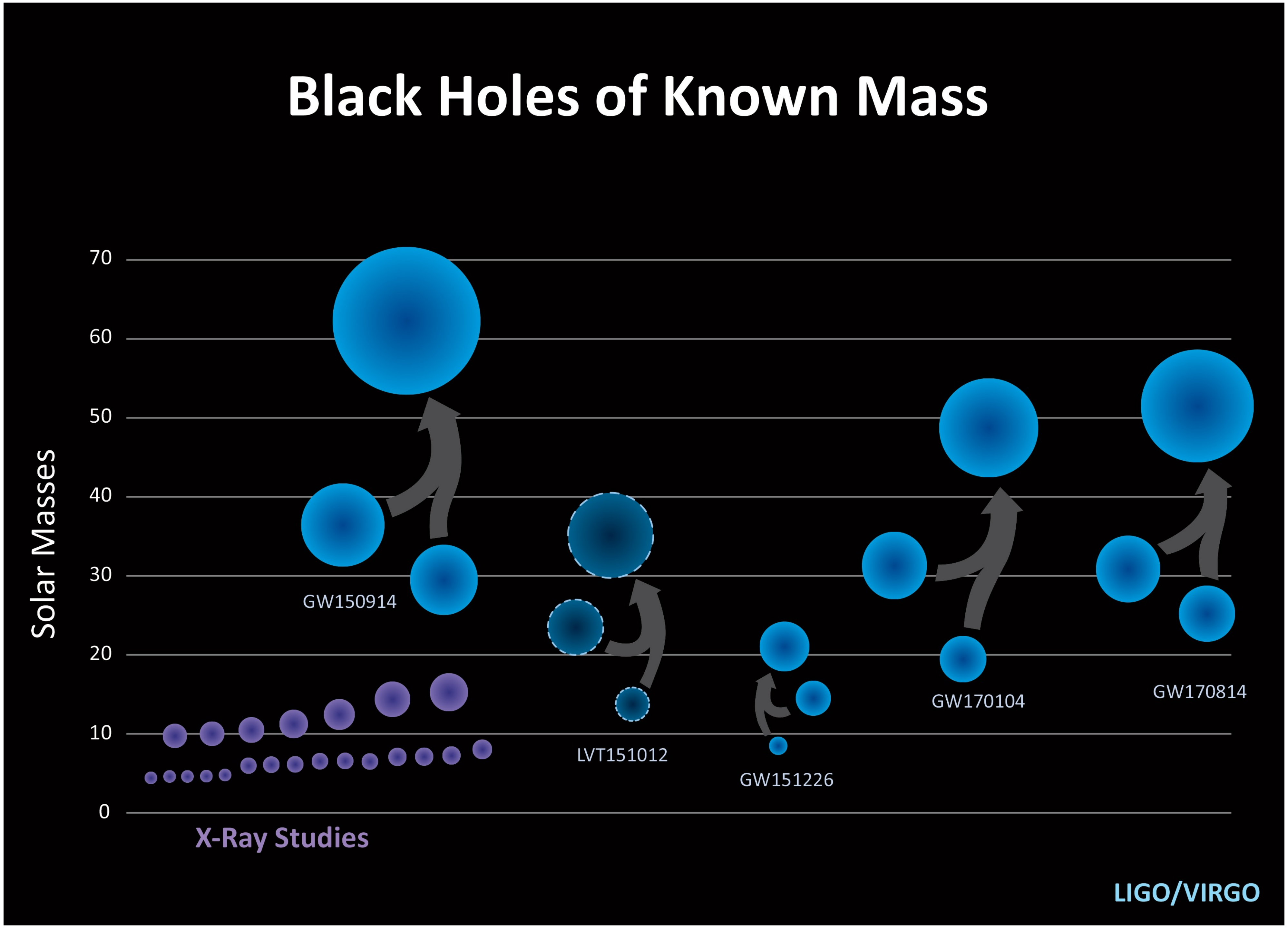
(for $g_* = 106.75$)

→ Possible production of GWs and more PBHs

[Late Universe]

[Ezquiaga *et al.* 2017]

- LIGO-VIRGO events: $\mu_{\rm PBH} \sim (0.01 - 100)\, M_\odot$

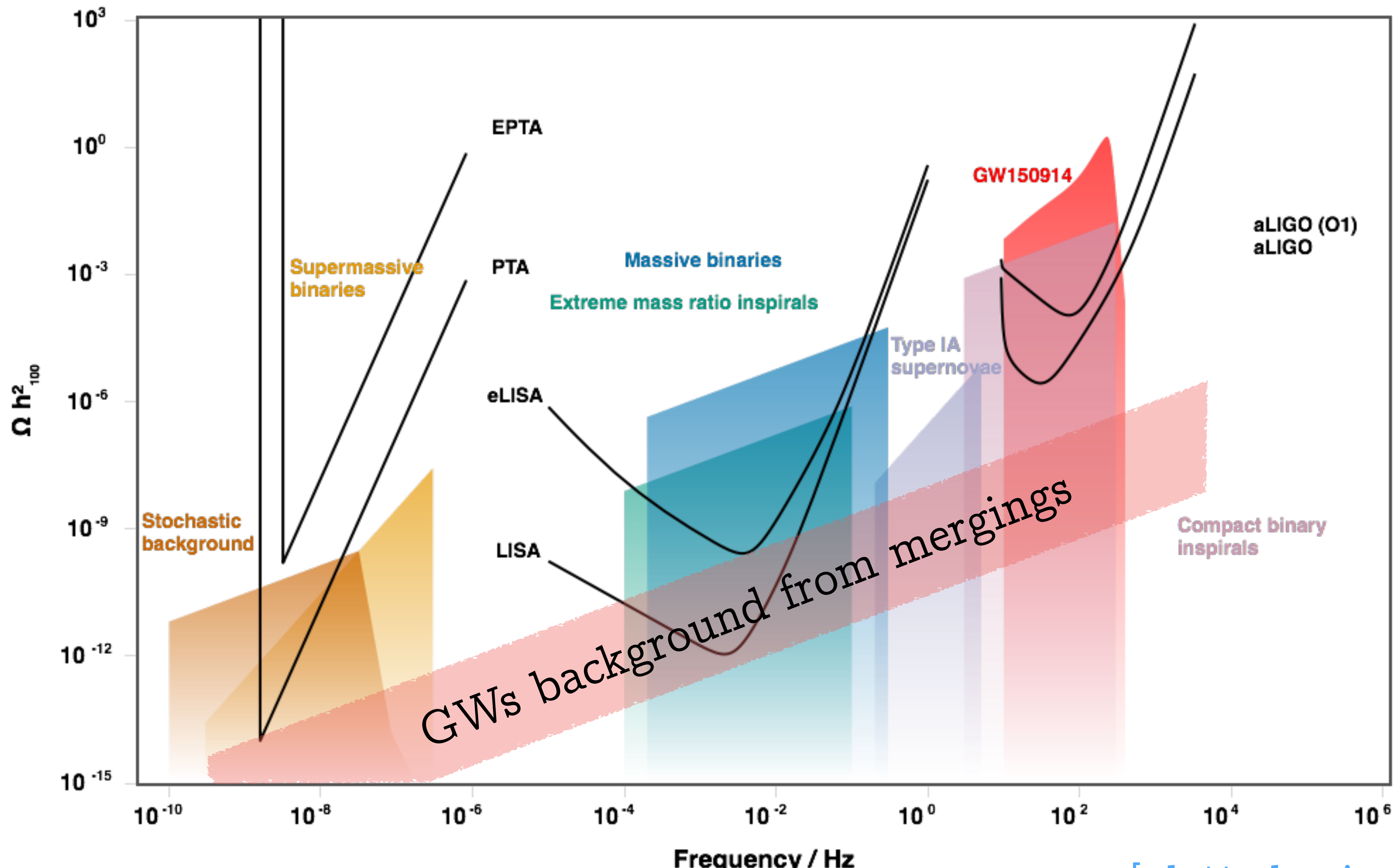


[yesterday's announcement!]

[Late Universe] [Ezquiaga *et al.* 2017]

- Broad peak: clustering of PBH enhance GWs background

$$h^2\,\Omega_{\rm GW}(f) = 8\times 10^{-15}\;\tau_m\, f^{2/3}({\rm Hz})\,\mu^{5/3}(M_\odot)\,R(\sigma)$$



[plotted using GWplotter]

6 Discussion

[Ezquiaga *et al.* 2017]

- The PBH Critical Higgs Inflation is a successful inflationary model with distinctive signatures

  i) $V(x \gg x_c) \sim b_\lambda / b_\xi^2 \ll M_{pl}^4$

  ii) Large tensor modes $r \sim 0.04$

  iii) Preheating with large fluctuations

- The production of PBH is associated to the near-criticality of the Higgs self-coupling

  * PBH from CHI lie in the LIGO band

- This scenario could be tested by different means, such as CMB polarization, stochastic GWs backgrounds or microlensing

6 Future Prospects

- Further developments (in progress) are needed to test the model at the level of precision of the SM parameters

  i) Theoretical: full RGE evolution of SM non-minimally coupled to gravity from EW scales to inflationary scales.
  Quantum diffusion effects may increase PBH production.

  ii) Computational: N-body simulations are required to determine the non-linear evolution of the mass spectrum in this clustered PBH scenario

- Constraints on PBHs should be carefully reexamined in the context of broad mass spectrum with clustered PBH

Find more details at

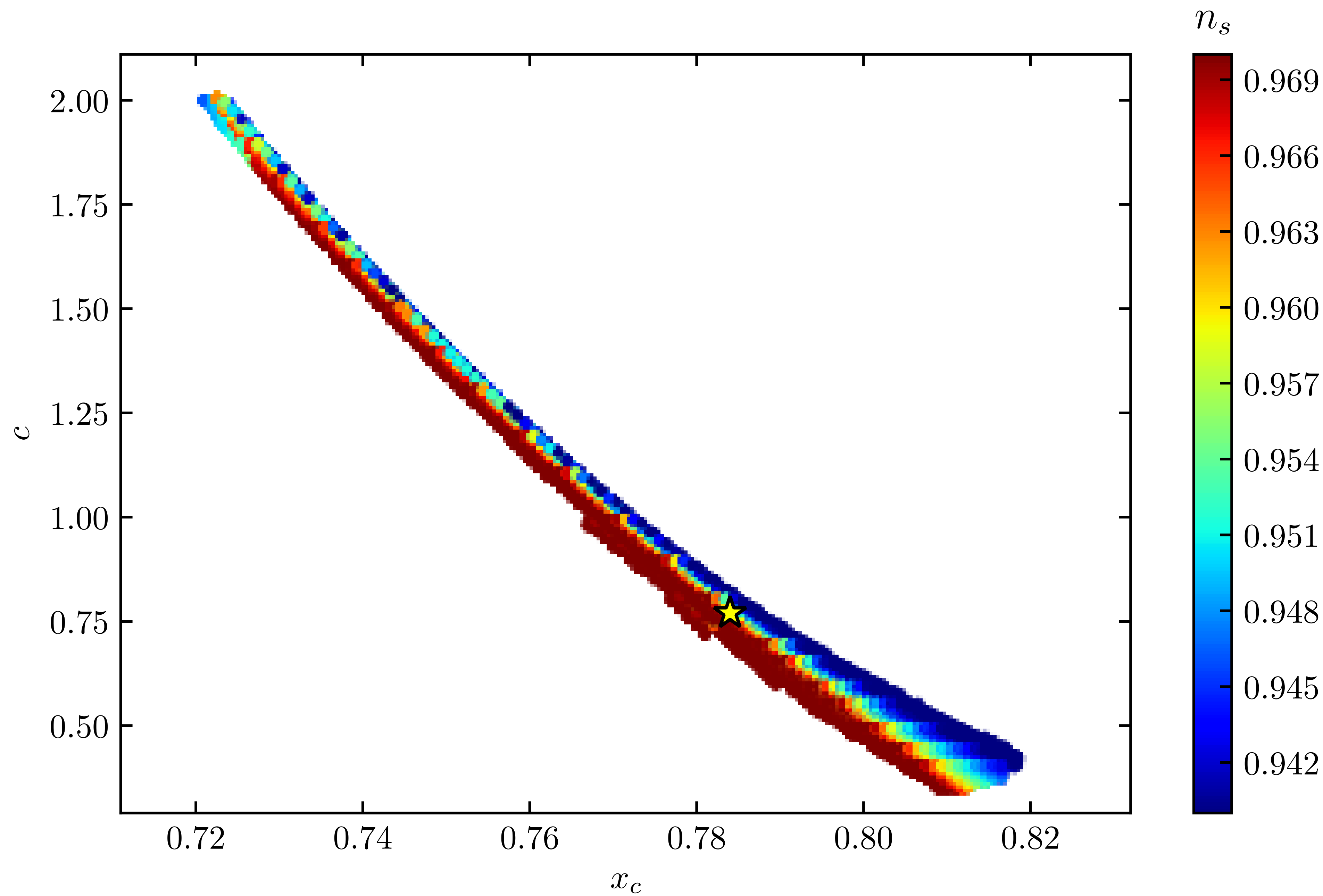
arXiv 1705.04861 by JME, J. GARCÍA-BELLIDO, E. RUIZ MORALES

or by e-mail

jose.ezquiaga@uam.es

Back-up slides

- Parameter space:

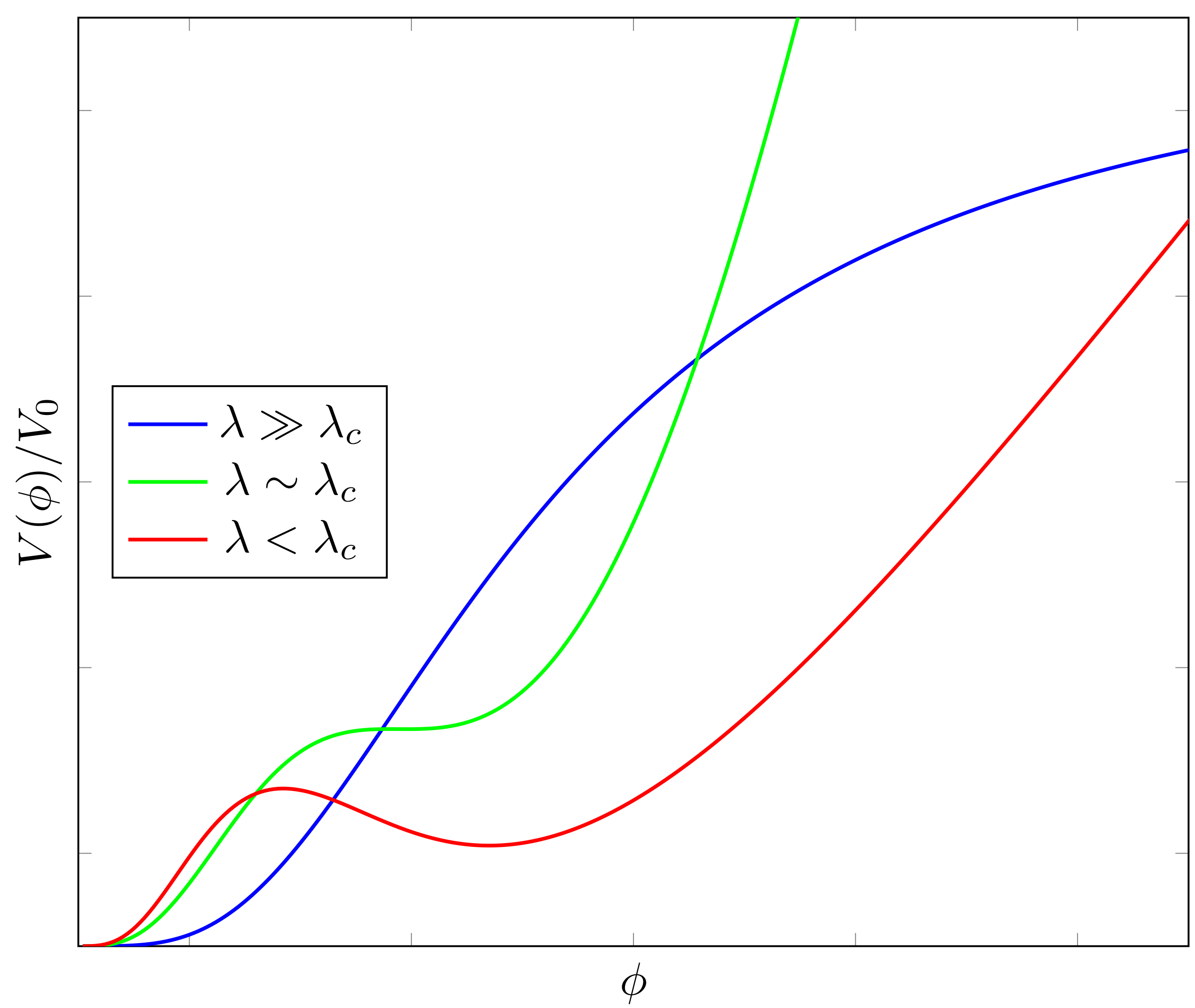


★ $(\beta = 10^{-5},\ \Delta N = 33.5,\ x_c = 0.784,\ c = 0.77)$

[Bezrukov *et al.*, Hamada *et al.* 2014]

- Inflation near the critical point: $\lambda(\phi) = \lambda_0 + b_\lambda \ln^2(\phi/\mu)$

$$S = \int d^4x\sqrt{-g}\left(\left(\frac{1}{2\kappa^2} + \frac{\xi}{2}\phi^2\right)R - \frac{1}{2}(\partial\phi)^2 - \frac{1}{4}\lambda(\phi)\phi^4\right)$$



- Potential can develop an inflection point

$$V(\varphi) = \frac{\lambda(\phi)\phi^4}{4(1+\xi\phi^2)^2}$$

and it is very sensitive to the Higgs self-coupling w.r.t. its critical value

- Some remarks:

i) Most e-folds spent near the inflection point. r can be large

$$\boxed{r = 16\epsilon}$$

ii) Amplitude fixed by couplings at critical point

$$\boxed{V(\phi) \to \lambda_c/\xi^2}$$

with SM RGE giving $\lambda_c \sim 10^{-6}$ and thus $\xi \sim 10$

iii) SM parameters (mainly top mass) play crucial roll in determining λ and b_λ