Cosmological Signatures of the SM Higgs Vacuum Instability

Antonio Riotto

UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Center for Astroparticle Physics
GENEVA

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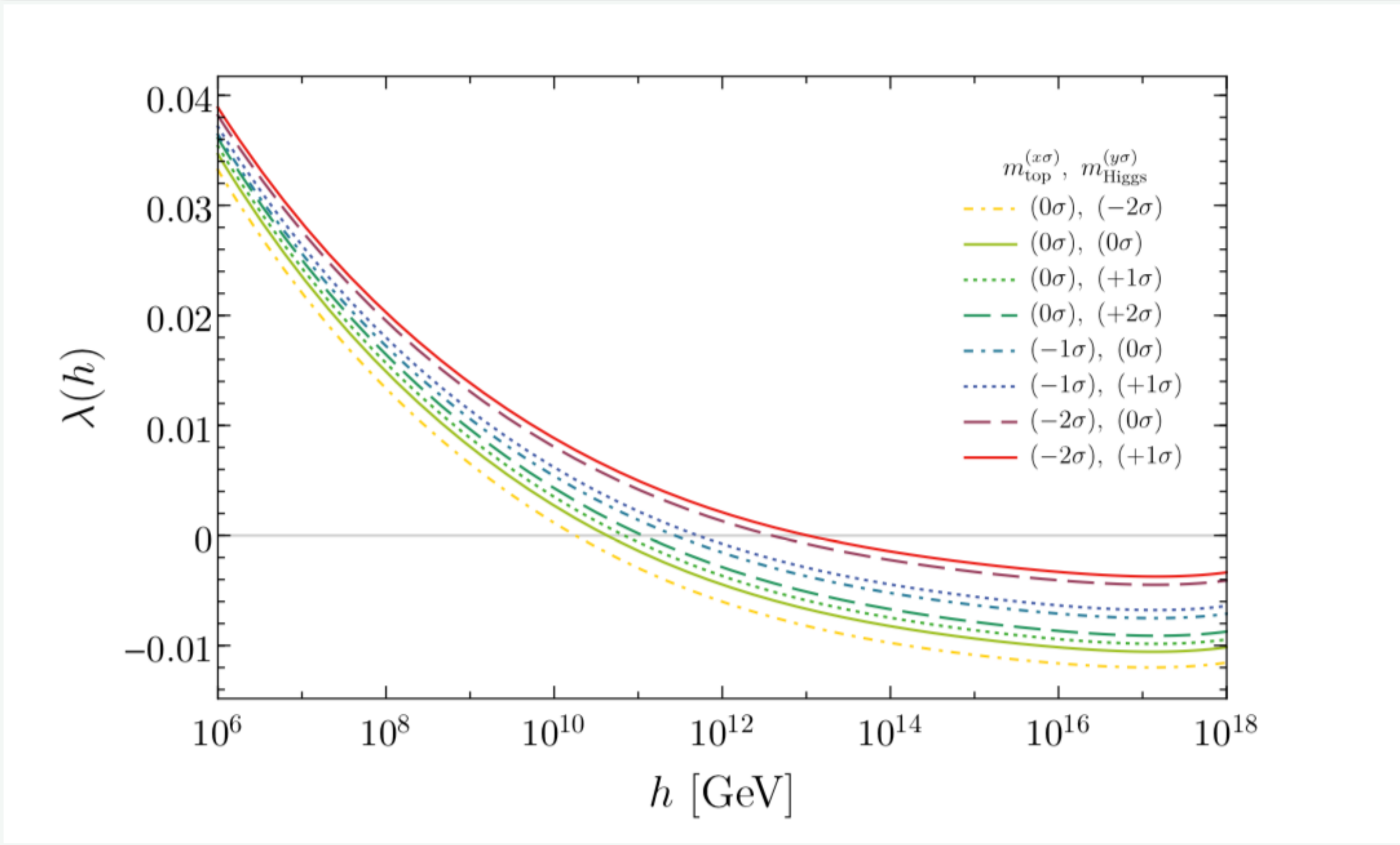
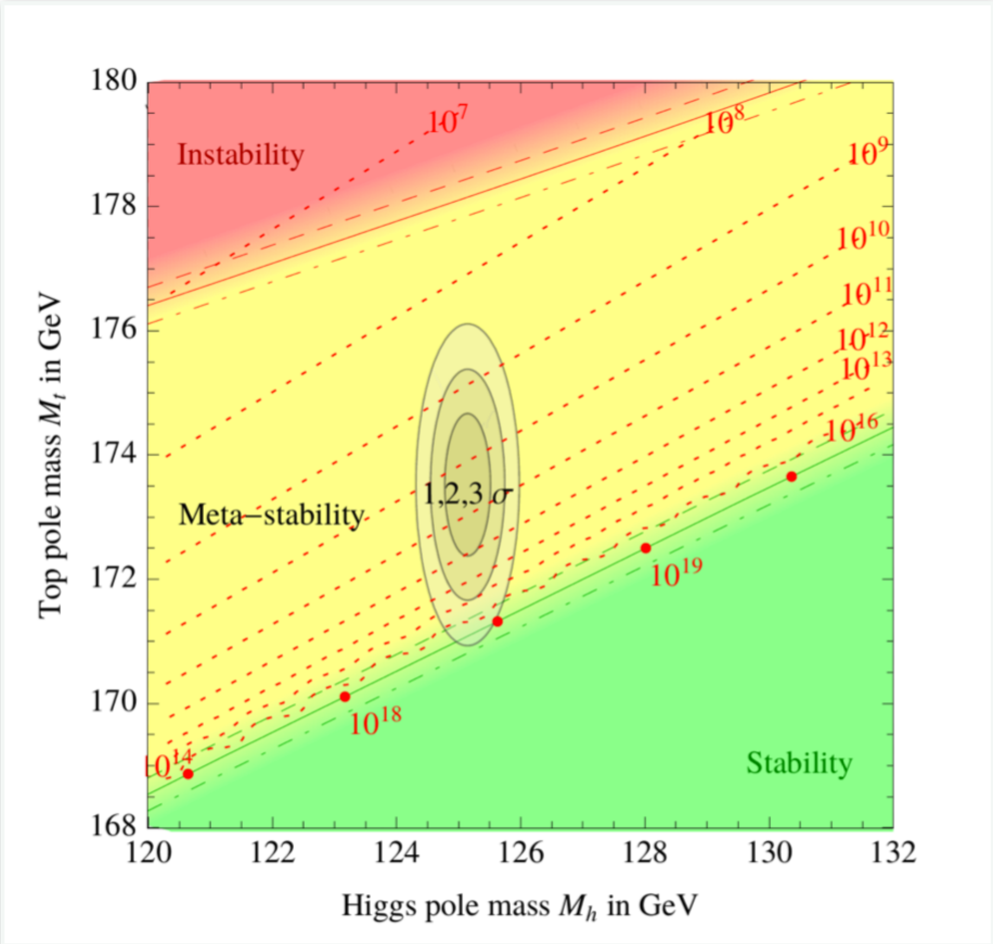
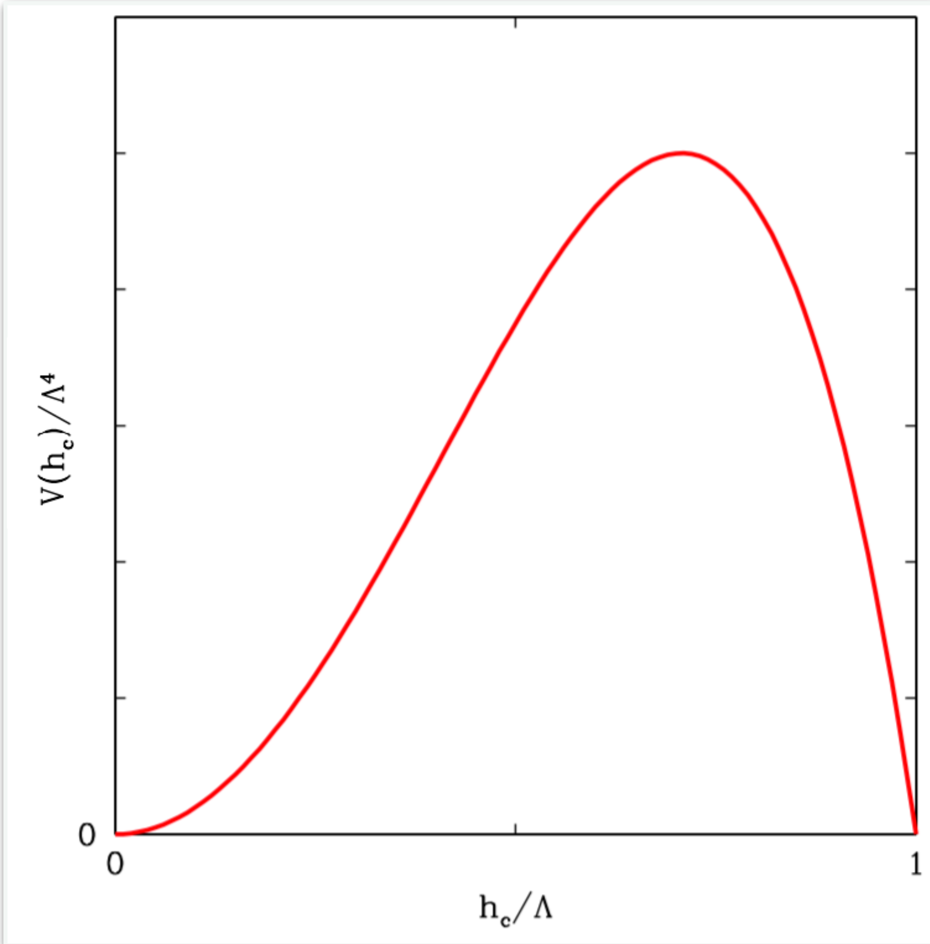
The SM Electroweak Instability



The EW SM vacuum is metastable





Buttazzo et al., 2013

How can we *probe* the EW SM instability?

DM as Primordial Black Holes (no need of BSM)

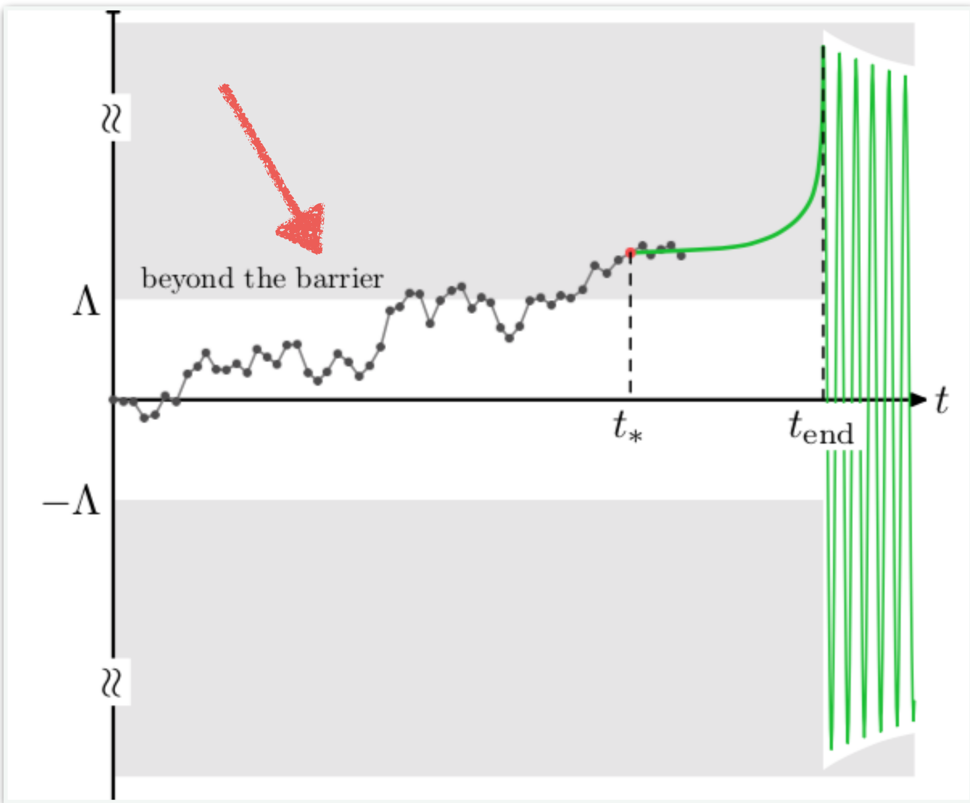
J.R. Espinosa, D. Racco and A.R., et al., hep-ph/1710.1196, PRL

Gravitational Waves

J.R. Espinosa, D. Racco and A.R., to appear

The idea

- During inflation, the SM Higgs is moved away from our current vacuum by quantum fluctuations and pushed over the barrier
- The SM Higgs rolls down along the unstable region
- Higgs fluctuations on super-Hubble scales are generated, they contribute to the curvature perturbation at small scales
- At the end of inflation thermal effects modify the SM Higgs potential and make the Higgs roll down back to our current EW vacuum
- The Higgs decays into radiation and the corresponding small scale curvature perturbation upon horizon re-entry generates PBHs and gravitational waves



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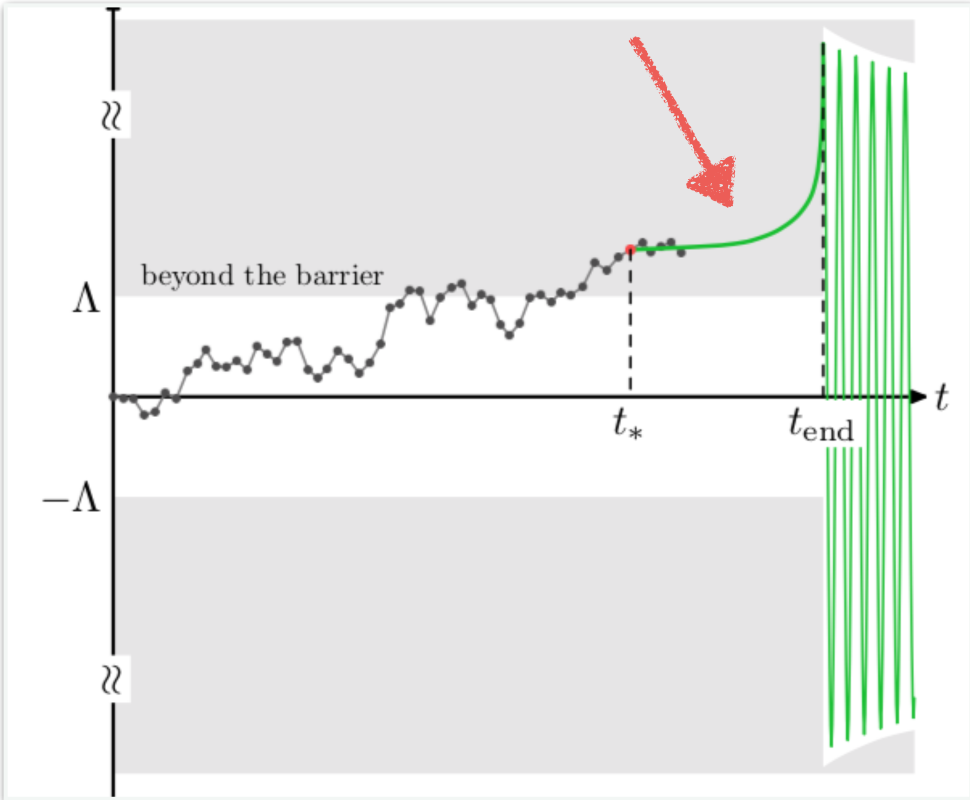

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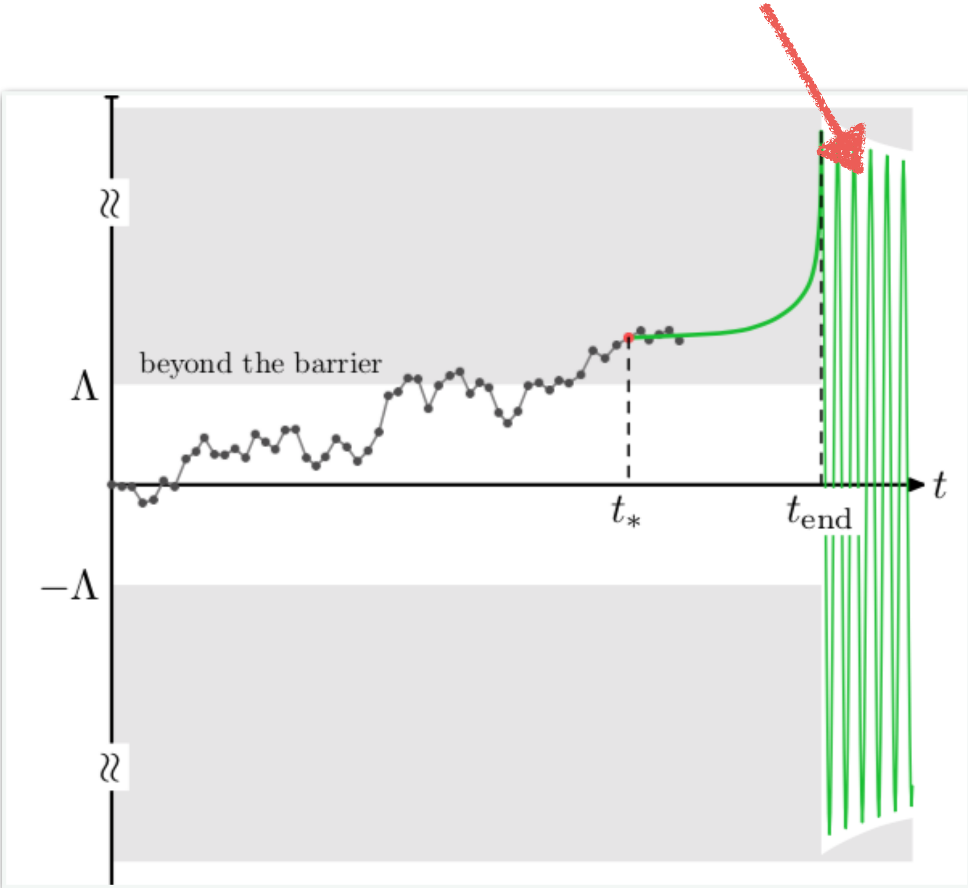

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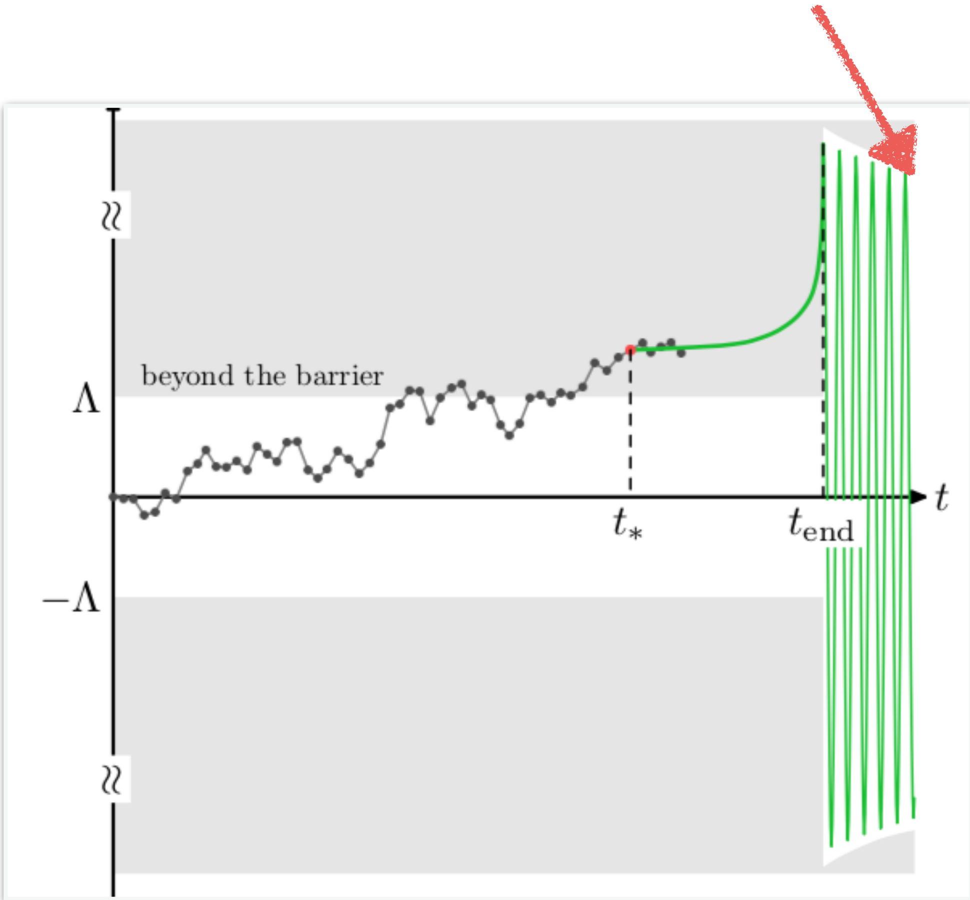


The dynamics of the classical Higgs

$$\ddot{h}_c + 3H\dot{h}_c + V'(h_c) = \xi$$

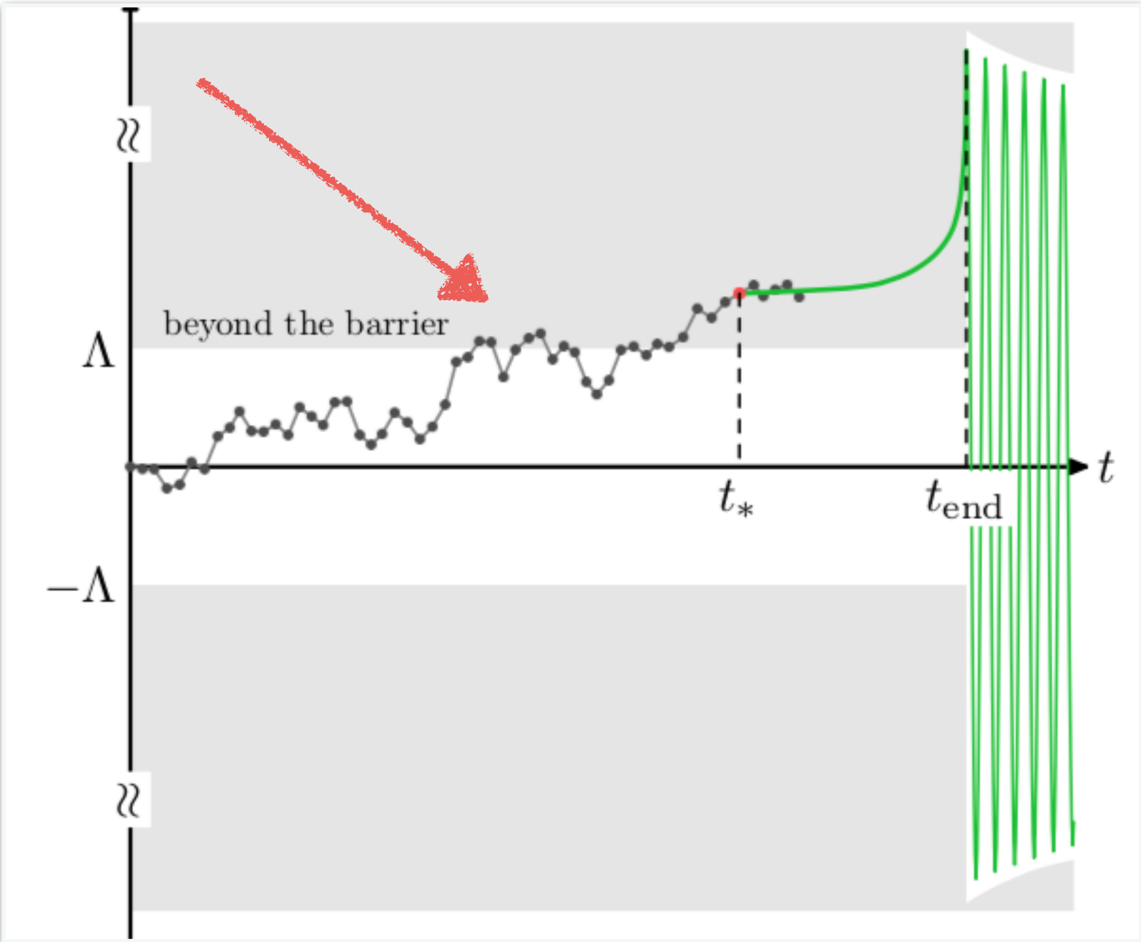
$$\langle \xi(t)\xi(t') \rangle = \frac{H^3}{4\pi^2}\delta(t-t')$$

Gaussian random white noise induced by Higgs perturbations whose wavelength leaves the Hubble radius

J.R. Espinosa, G.F. Giudice, and A.R., 2007

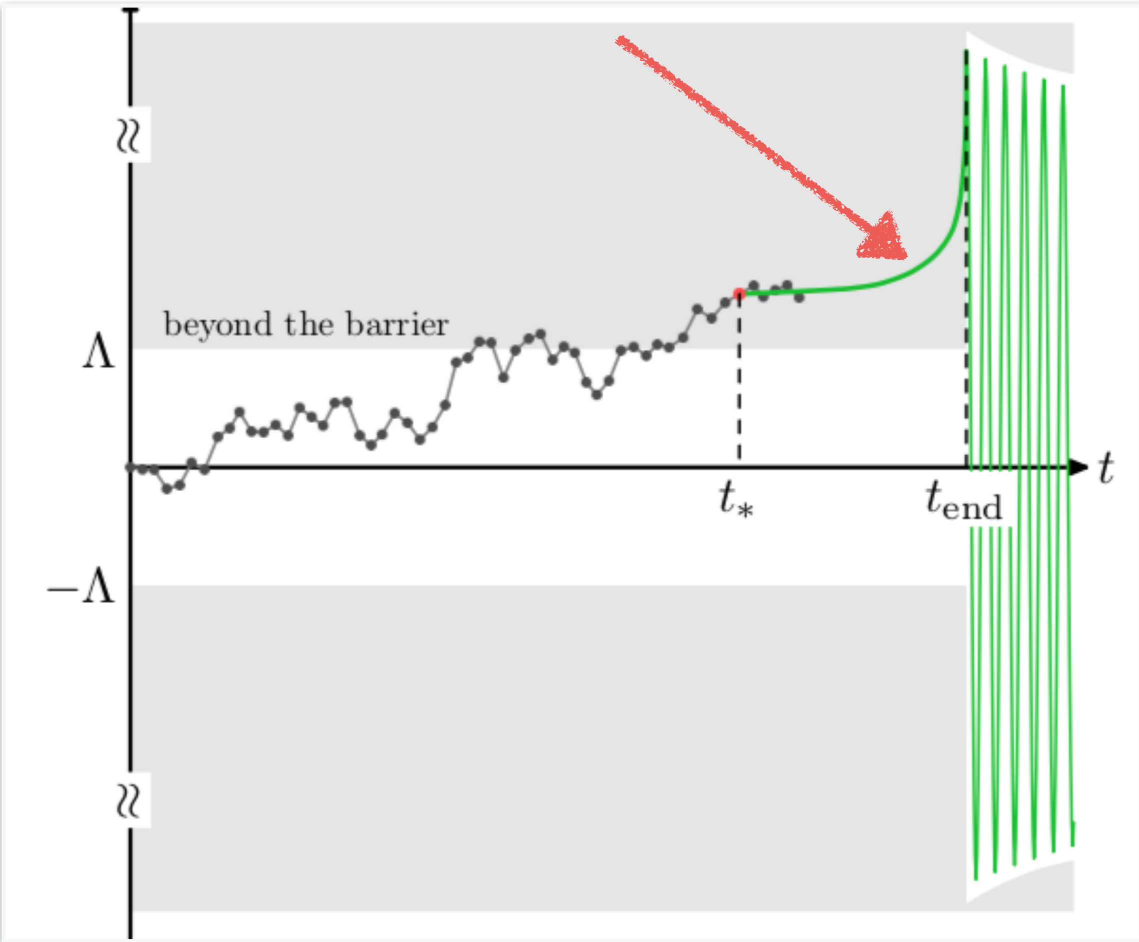
First phase: quantum beats classical

$$\Delta h_{\mathrm{q}} = \frac{H}{2\pi} \gg \Delta h_{\mathrm{c}} \simeq \left| \frac{V'(h_{\mathrm{c}})}{3H^2} \right|$$



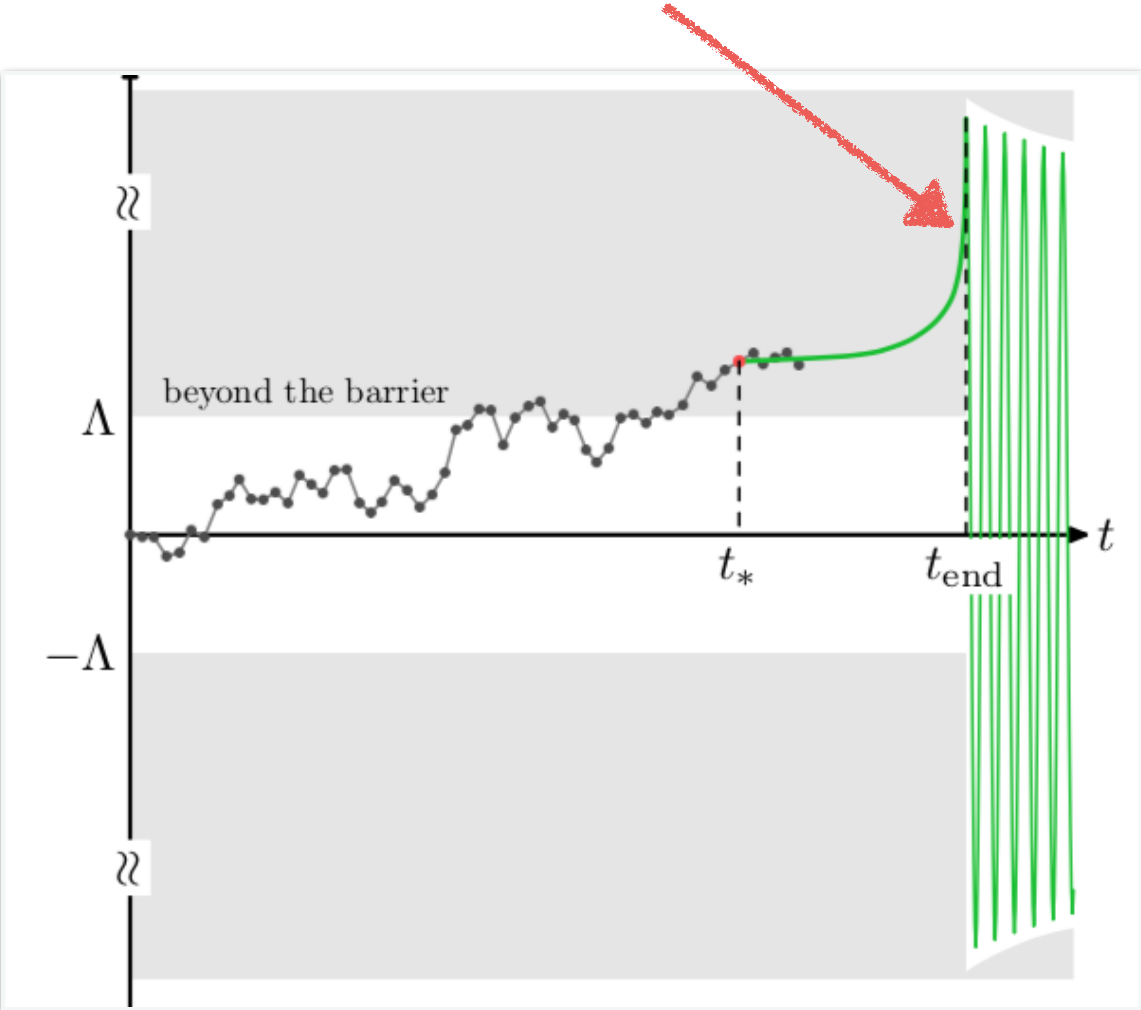
Second phase: classical beats quantum slow-roll

$$\Delta h_{\mathrm{q}} = \frac{H}{2\pi} \lesssim \Delta h_{\mathrm{c}} \simeq \left| \frac{V'(h_{\mathrm{c}})}{3H^2} \right| \quad \text{or} \quad h_{\mathrm{c}}^3 \gtrsim \frac{3H^3}{2\pi\lambda}$$



Second phase: rapid evolution

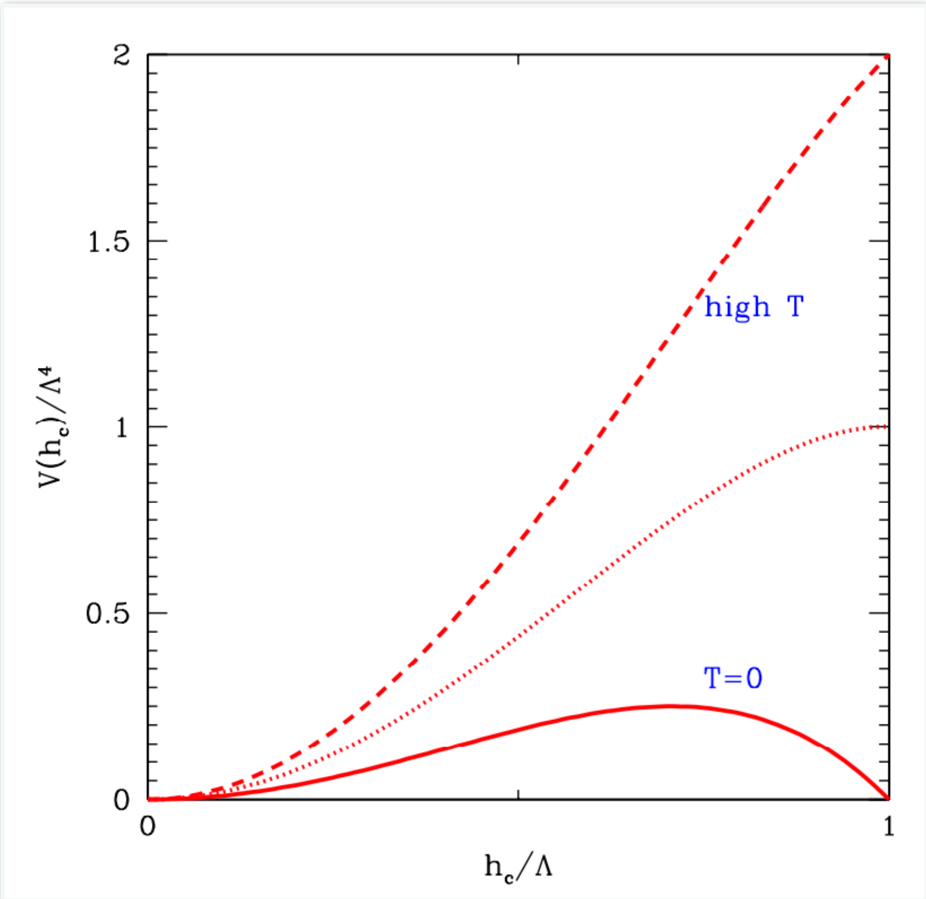
$$h_{\mathrm{c}} \simeq \sqrt{\frac{2}{\lambda}}\frac{1}{t_{\mathrm{p}} - t}$$

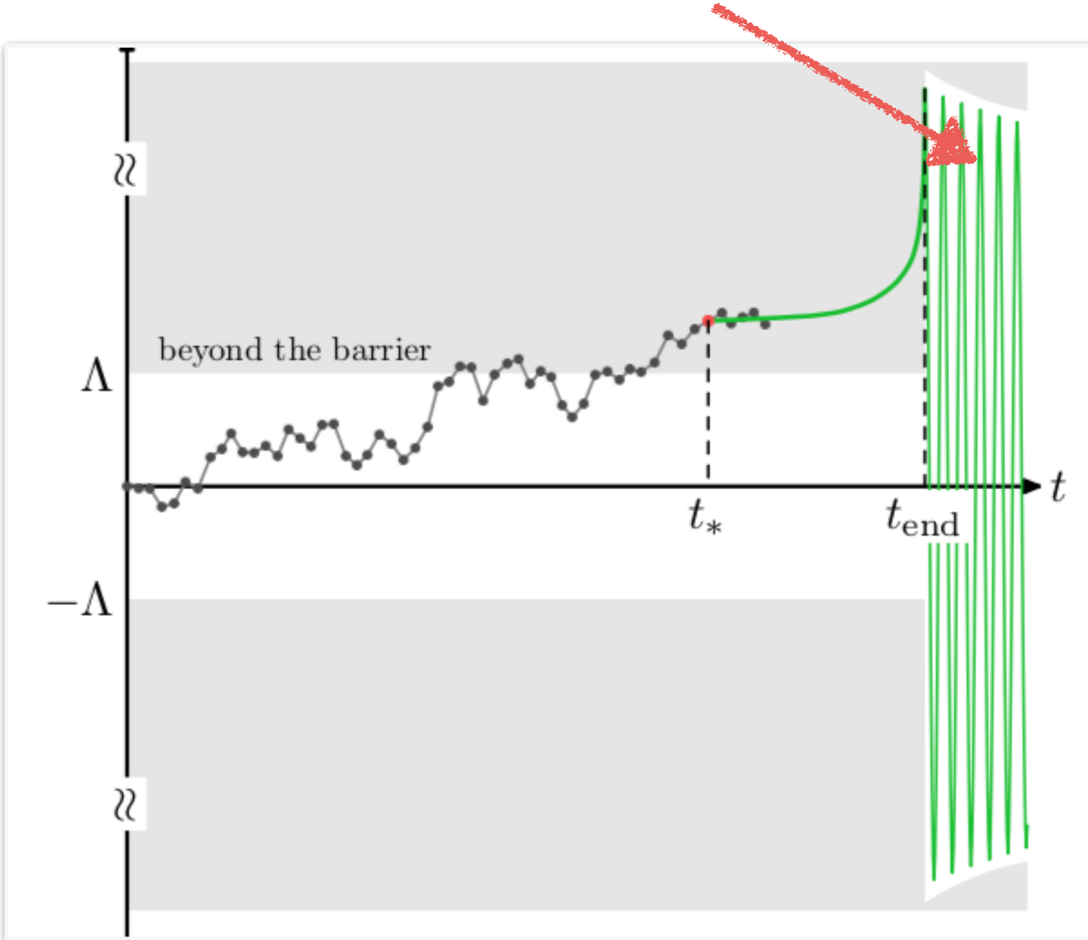


Third phase: end of inflation and reheating

$$V_T \simeq \frac{1}{2} m_T^2 h_c^2, \;\; m_T^2 \simeq 0.12\, T^2\, e^{-h_c/(2\pi T)}$$

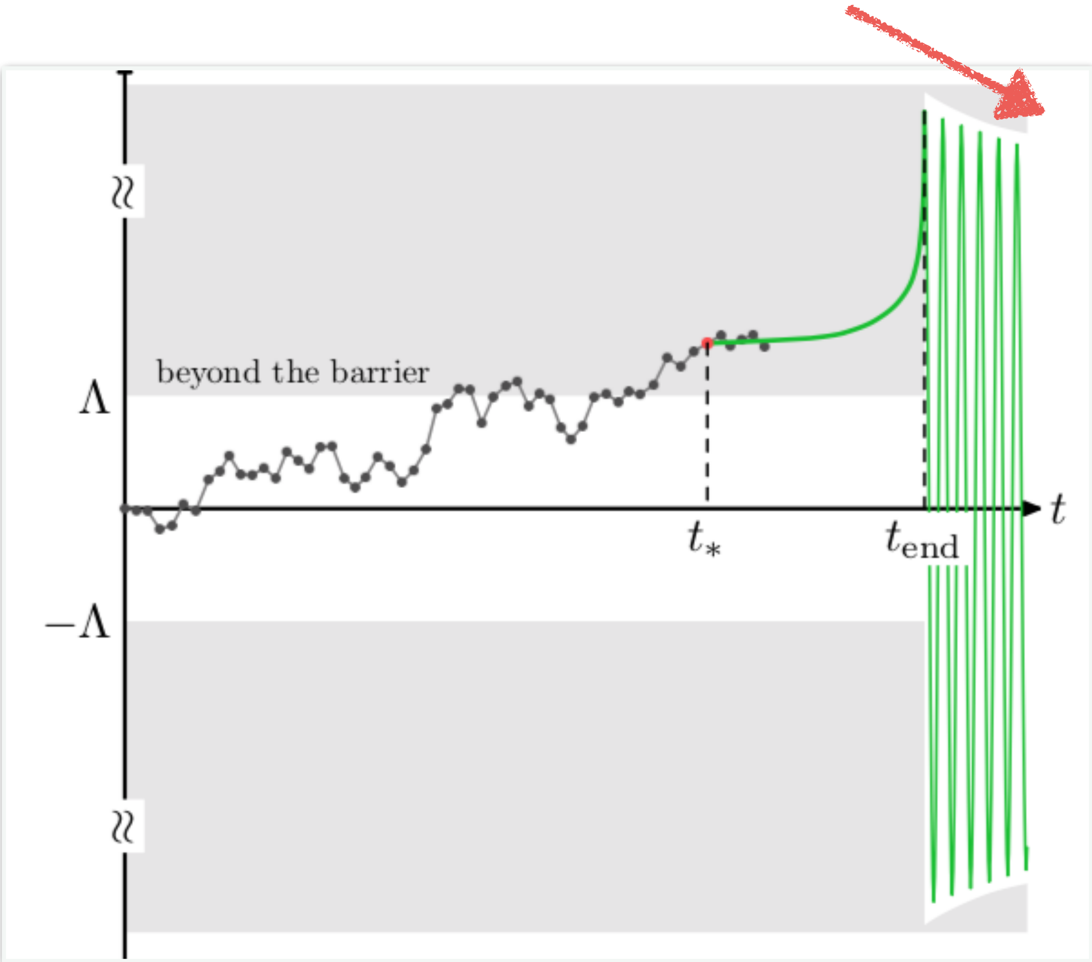
The Higgs oscillates around our current vacuum with EoS of radiation





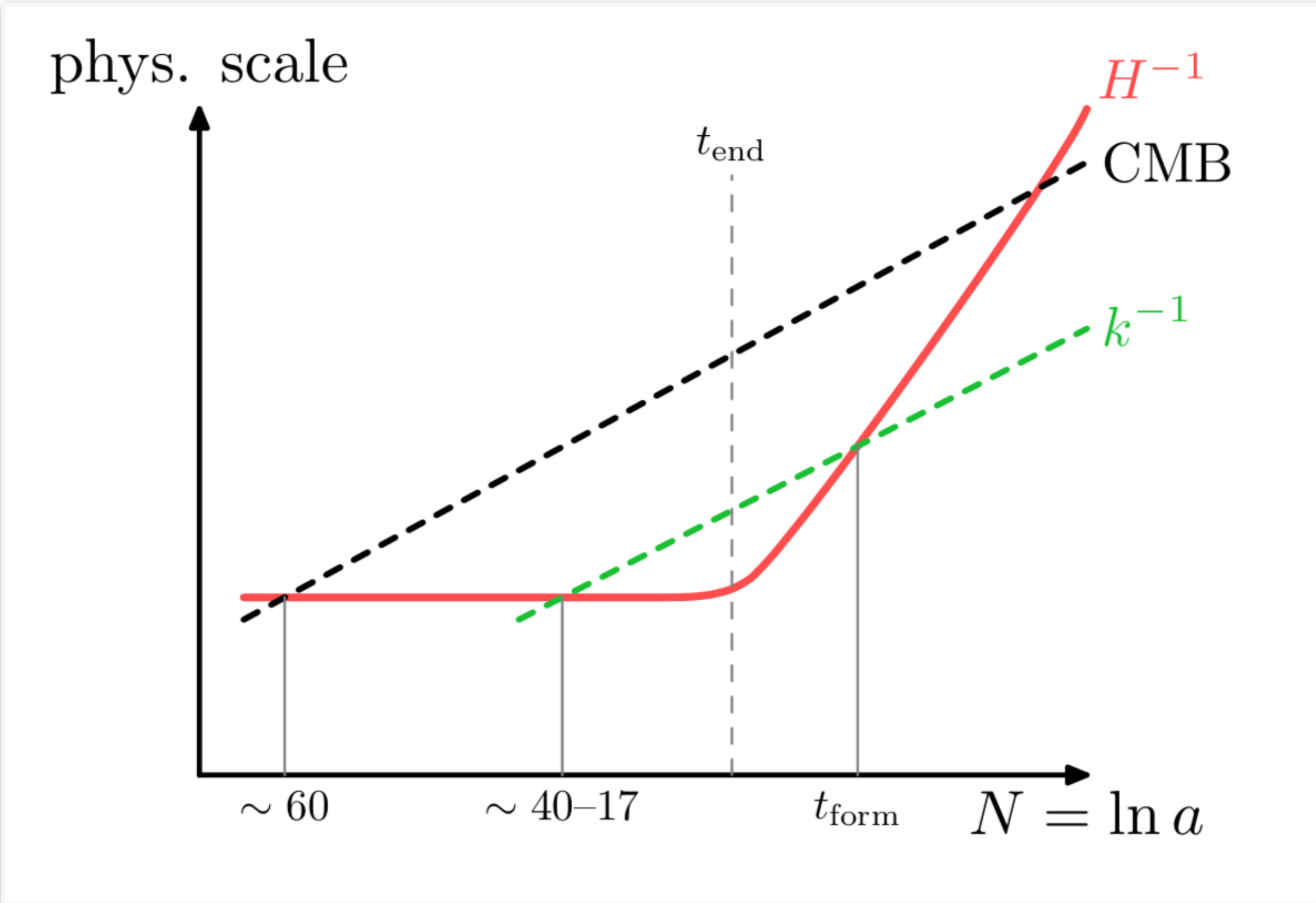
Last phase: the Higgs decays

$$\gamma_h \sim 3g_2^2 T^2/(256\pi m_T) \sim 10^{-3}T$$



The dynamics of the Higgs perturbations

$$\delta\ddot{h}_k + 3H\delta\dot{h}_k + \frac{k^2}{a^2}\delta h_k + V''(h_c)\delta h_k = \frac{\delta h_k}{a^3 m_P^2}\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{a^3}{H}\dot{h}_c^2\right)$$



flat gauge

During inflation

$$\delta h_k(t) = C(k)\dot{h}_{\rm c}(t) \qquad C(k) = \frac{H}{\dot{h}_{\rm c}(t_k)\sqrt{2k^3}}$$

Gauge-invariant comoving curvature perturbation

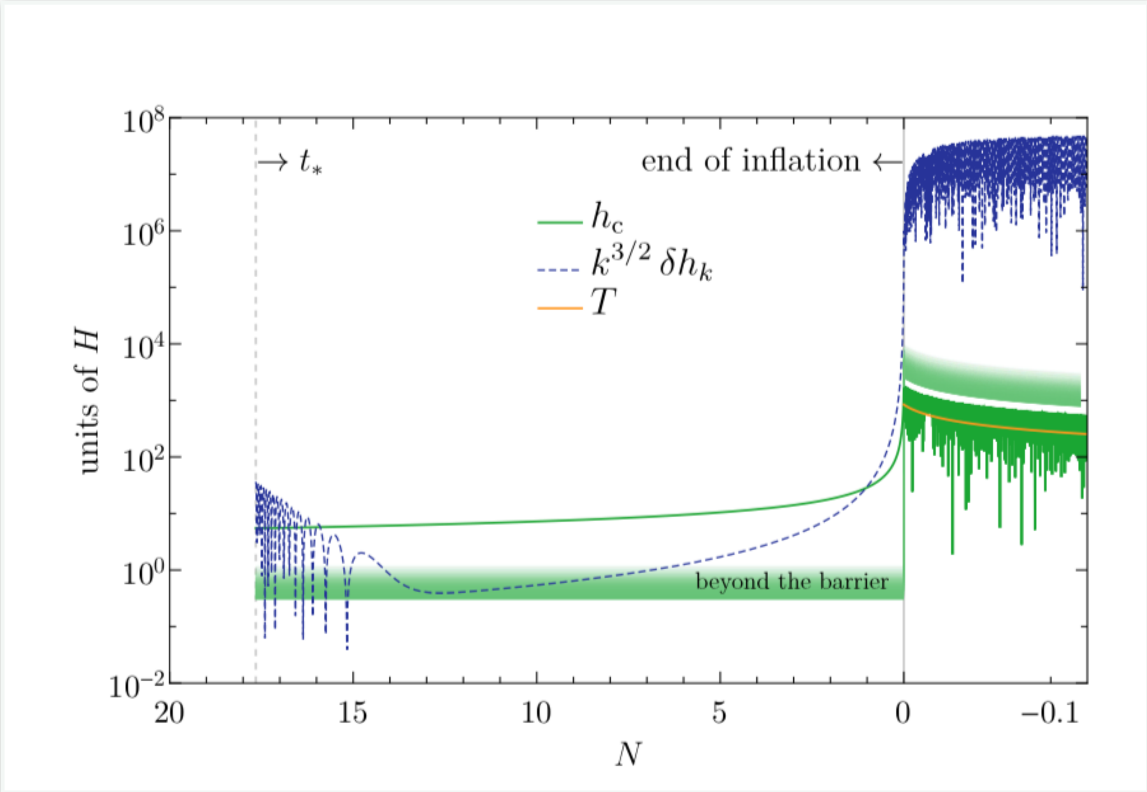
$$\zeta = \psi + H\frac{\delta\rho}{\dot{\rho}} = \frac{\dot{\rho}_{\rm st}}{\dot{\rho}}\zeta_{\rm st} + \frac{\dot{\rho}_h}{\dot{\rho}}\zeta_h$$

$$\zeta_h = \psi + H\frac{\delta\rho_h}{\dot{\rho}_h} = HC(k)$$

A constant curvature perturbation is generated on small scales

Radiation phase after inflation

The Higgs perturbations oscillate like its the classical value and upon decay the get transferred to curvature perturbation



$$\mathcal{P}_\zeta^{1/2}(t_{\rm dec}) = \frac{\dot\rho_h(t_{\rm dec})}{2\dot\rho(t_{\rm dec})}\left(\frac{H}{2\pi}\right)\left(\frac{\dot h_c(t_e)}{h_c(t_e)\dot h_c(t_k)}\right)$$

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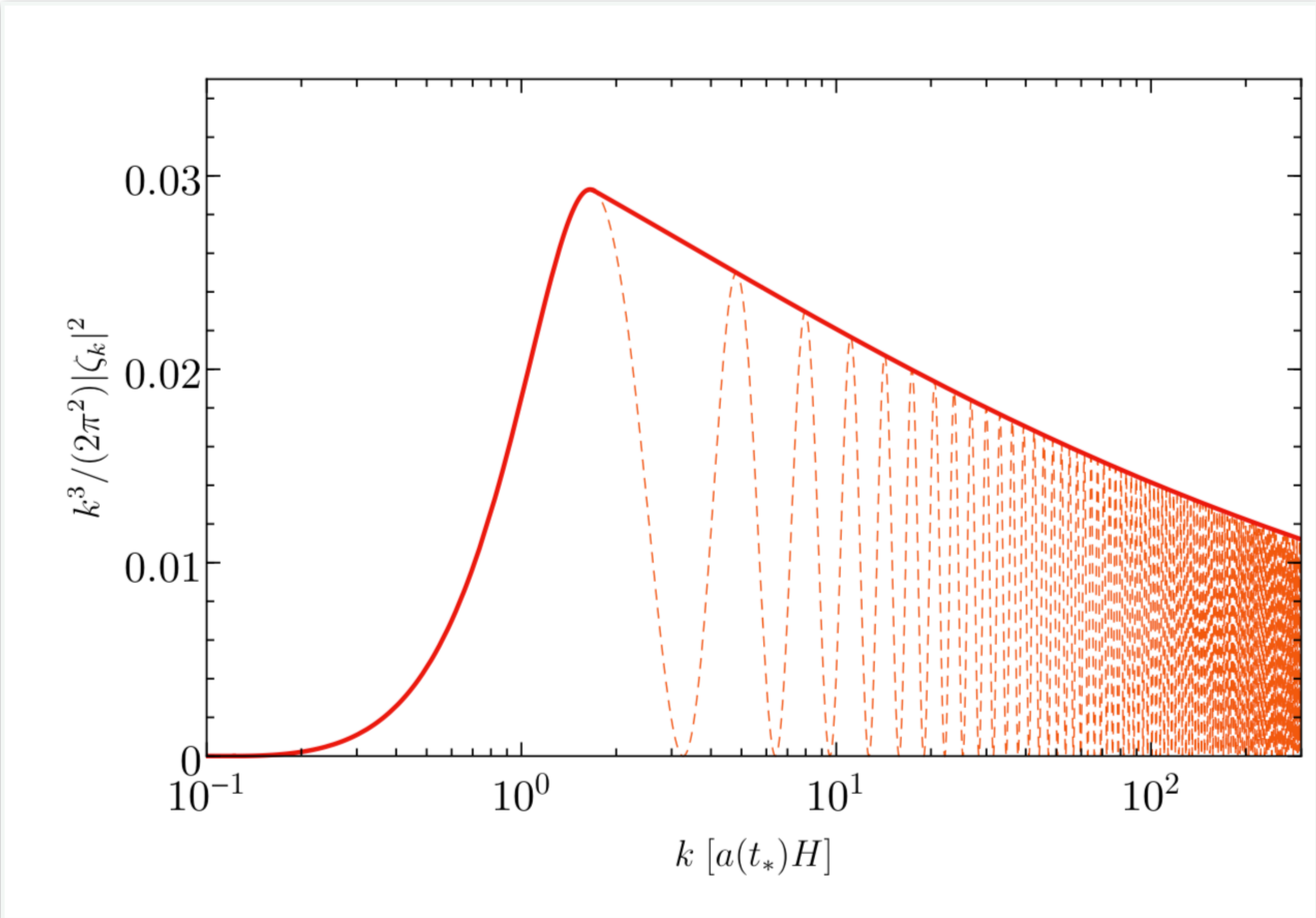
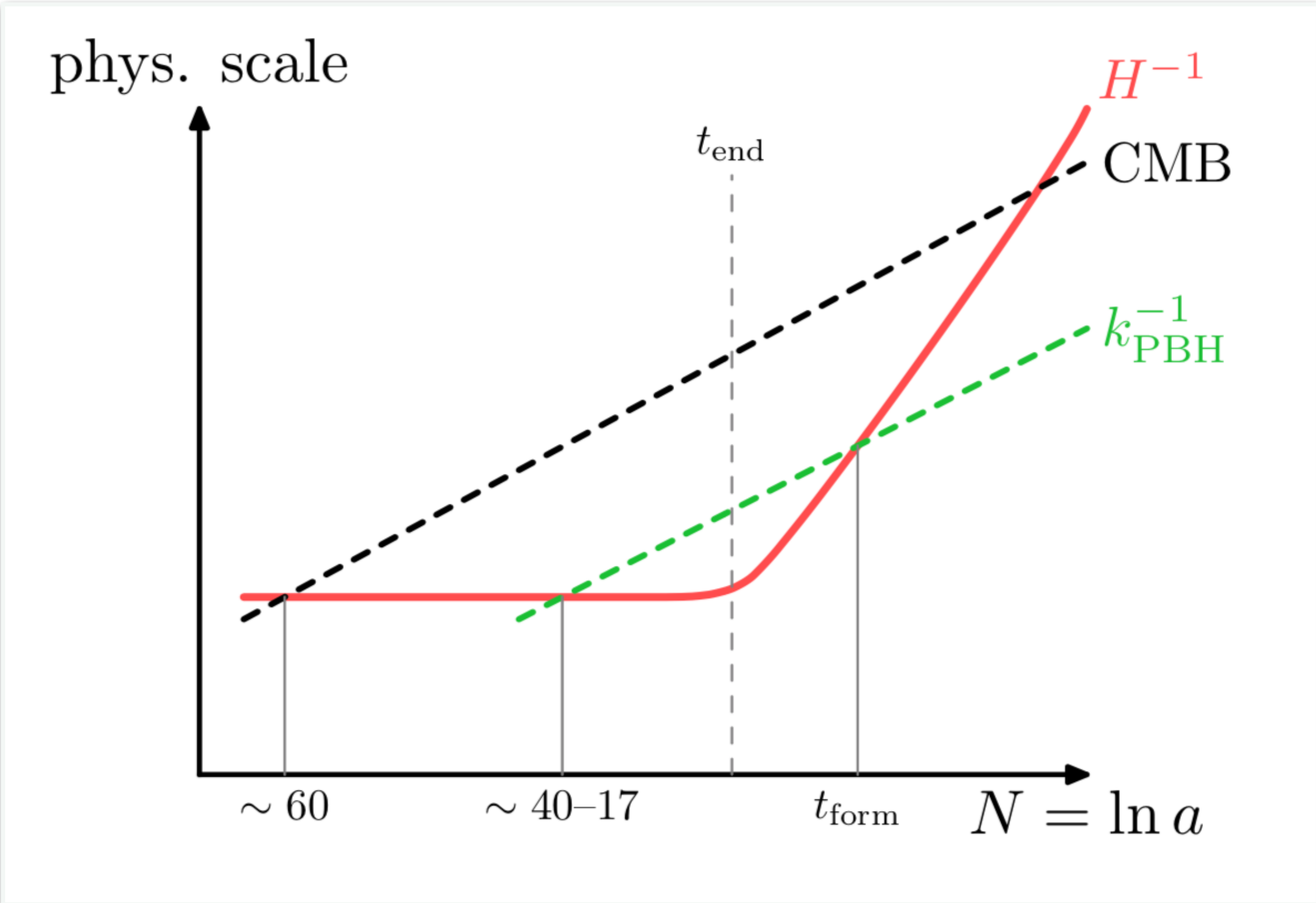


DM as PBHs from the SM



Upon horizon re-entry, the small-scale curvature perturbations induced by the Higgs can form PBHs if they are sizeable enough

This happens if the density contrast is above a critical value

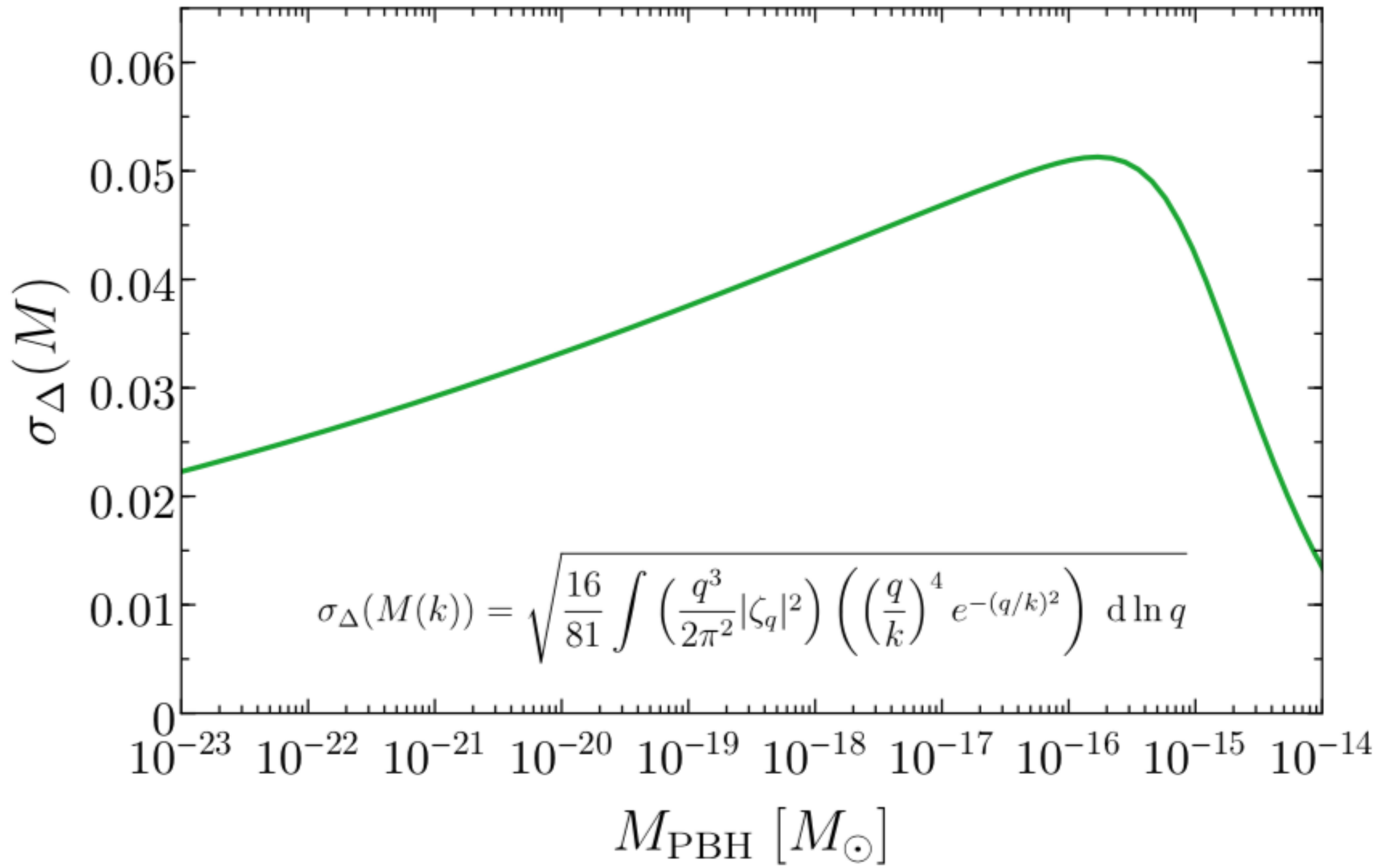
$$\Delta(\vec{x}) = \frac{4}{9a^2H^2}\nabla^2\zeta(\vec{x}) \gtrsim \Delta_{\rm c} \simeq 0.45$$

The mass of the PBH is roughly the mass contained inside the Hubble volume and the mass fraction at formation time is

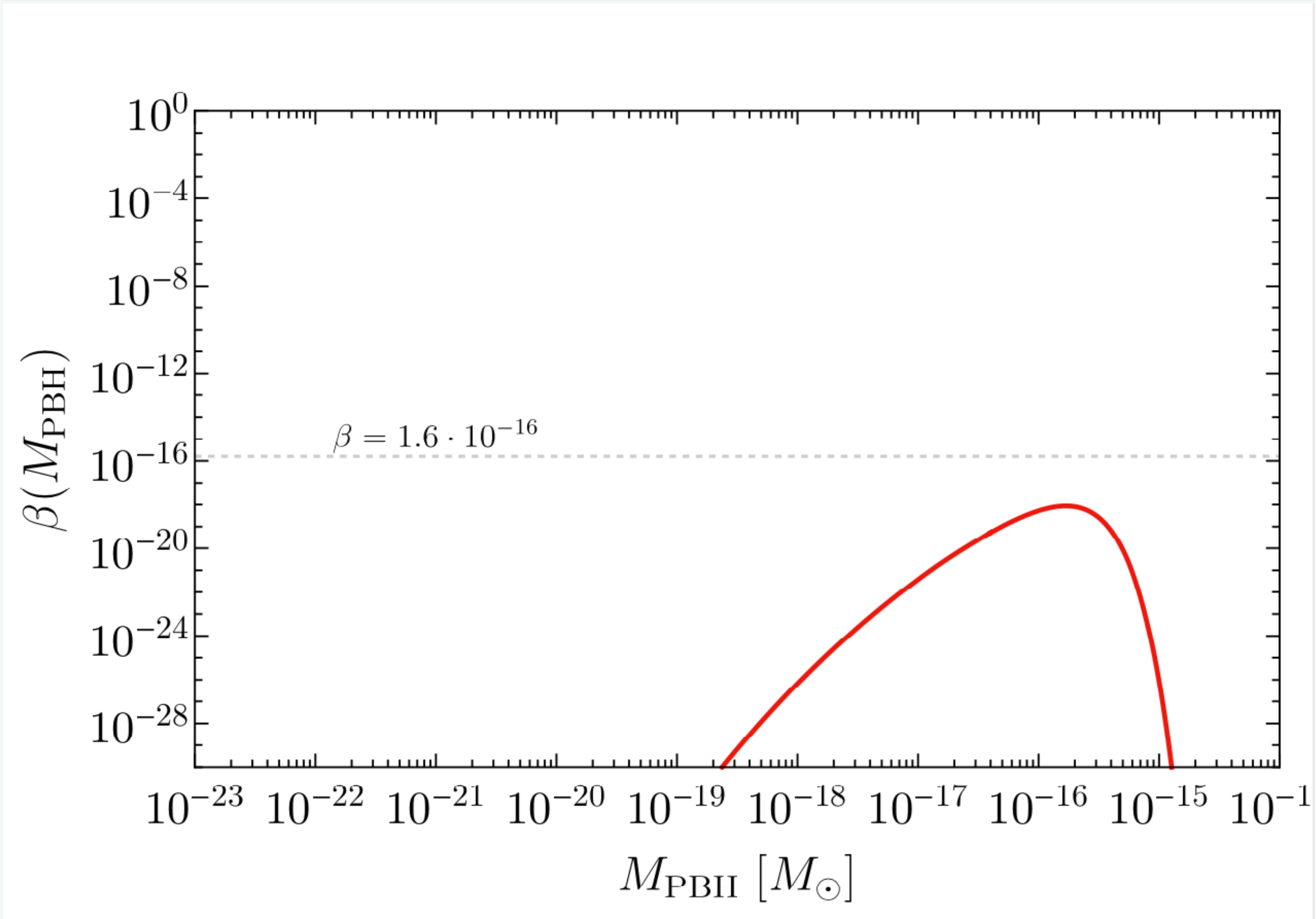
$$\beta(M) = \int_{\Delta_{\rm c}}^{\infty} \frac{{\rm d}\Delta}{\sqrt{2\pi}\,\sigma_\Delta} e^{-\Delta^2/2\sigma_\Delta^2}$$

$$\sigma_\Delta^2(M) = \int_0^\infty {\rm d}\ln k\, W^2(k,R)\mathcal{P}_\Delta(k)$$

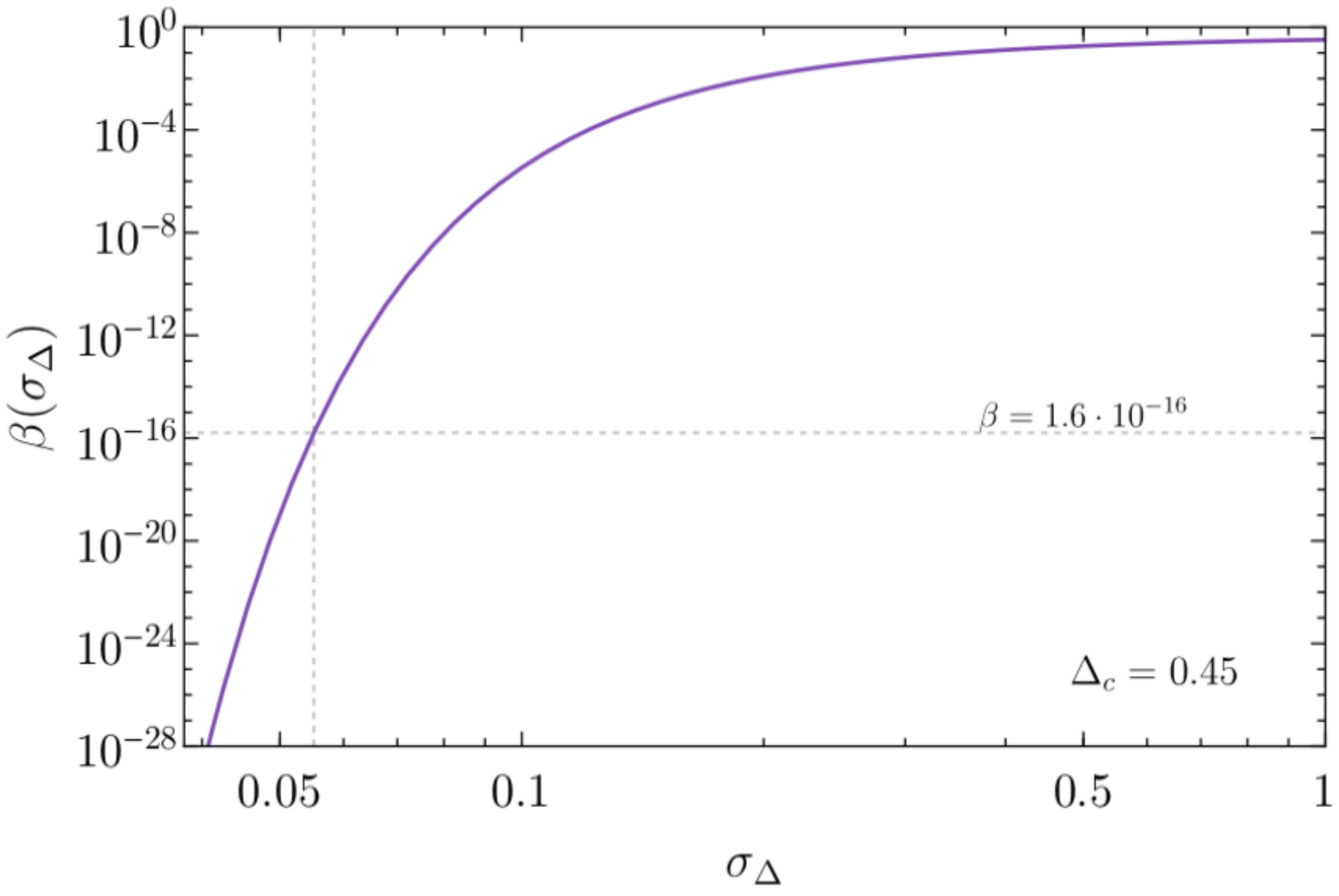
The variance

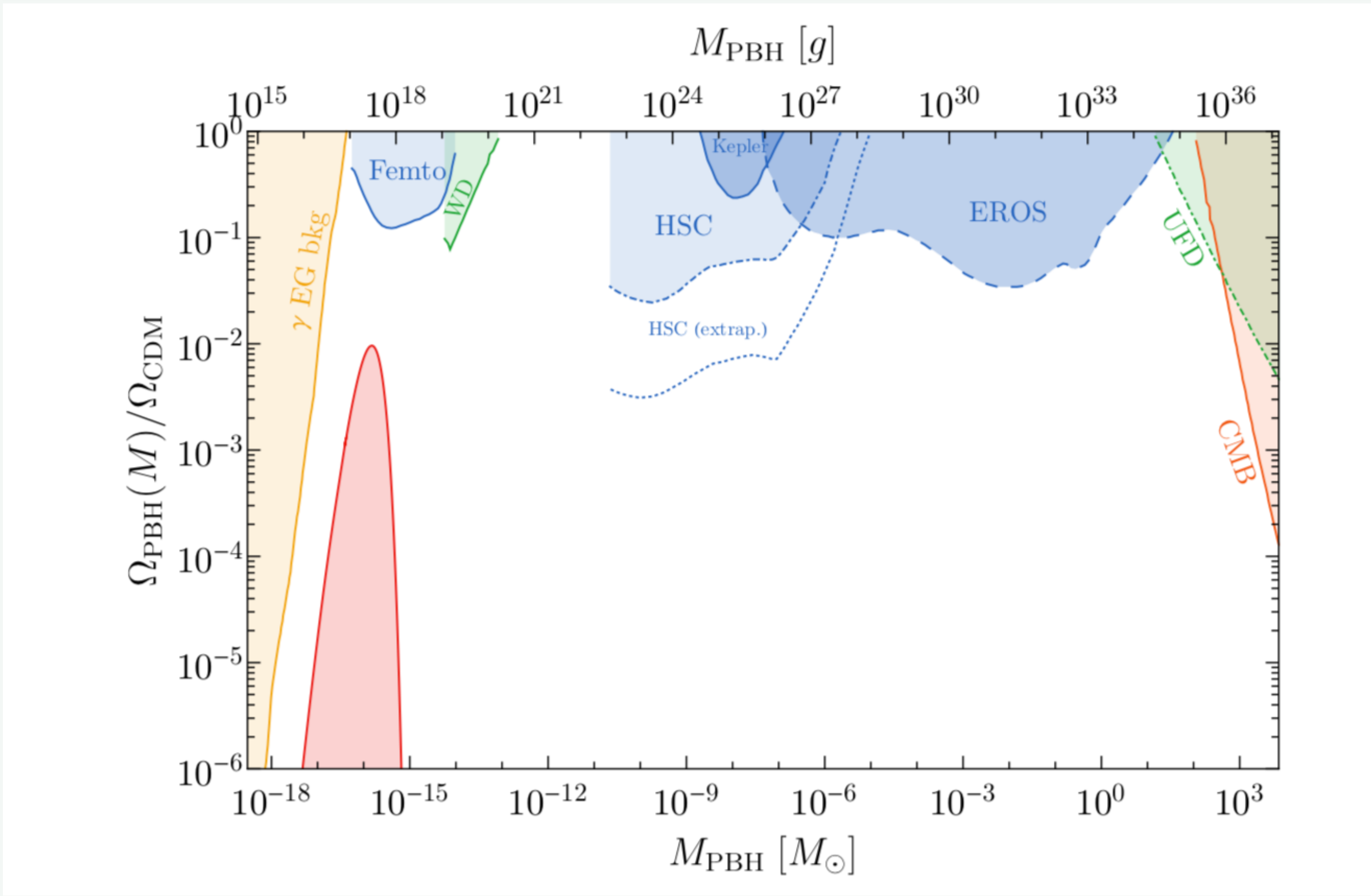


The mass fraction



The mass fraction vs the variance
Fine-tuning

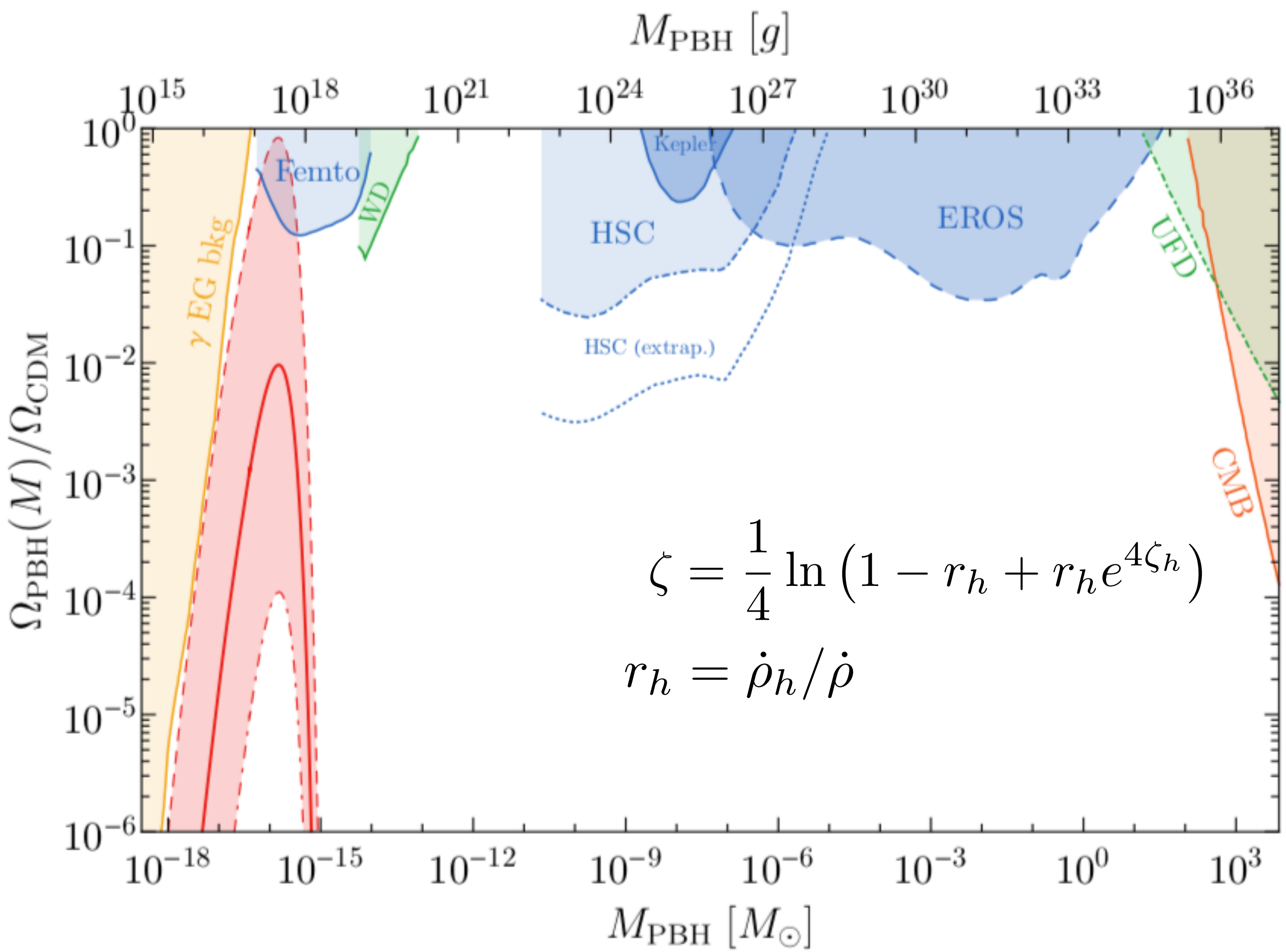




$$\frac{\Omega_{\rm PBH}(M)}{\Omega_{\rm CDM}} = \frac{\beta(M)}{1.6\cdot 10^{-16}}\left(\frac{\gamma}{0.2}\right)^{3/2}\left(\frac{g_*(T_f)}{106.75}\right)^{-1/4}\left(\frac{M}{10^{-15}M_\odot}\right)^{-1/2}$$

The non-Gaussianity

$$\beta(M) = \frac{1}{\sqrt{2\pi}\,\nu} \exp\left[-\frac{1}{2}\nu^2 \left(1 - S_3 \frac{\sigma_\Delta}{3}\left(\nu - 2 - \frac{1}{\nu^2}\right)\right)\right]$$



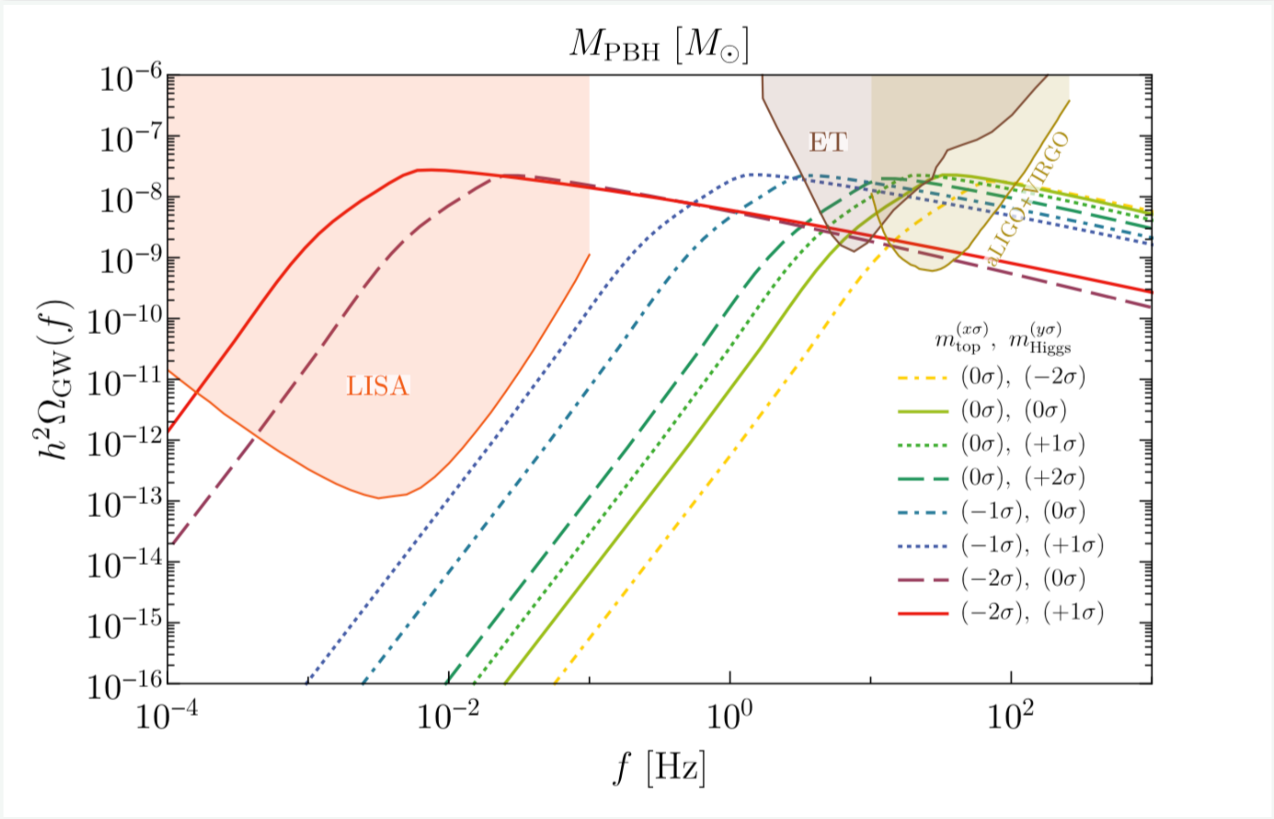
$$\zeta = \frac{1}{4}\ln\left(1 - r_h + r_h e^{4\zeta_h}\right)$$

$$r_h = \dot{\rho}_h/\dot{\rho}$$

Gravitational waves from the SM instability

Meanwhile, the same small-scale curvature perturbation induced by the Higgs can source, at second-order, gravitational waves

$$\Box h^s_{ij} = S_{ij} \qquad S_{ij} = \mathcal{O}(\partial_i\zeta\partial_j\zeta)$$



$$\Omega_{\rm GW}(f) \simeq 3\cdot 10^{-8}\left(\frac{f}{f_*}\right)^{n_T}$$

$$n_T = \begin{cases} 3 & \text{for } f < f_*, \\ -0.6 & \text{for } f > f_*. \end{cases}$$

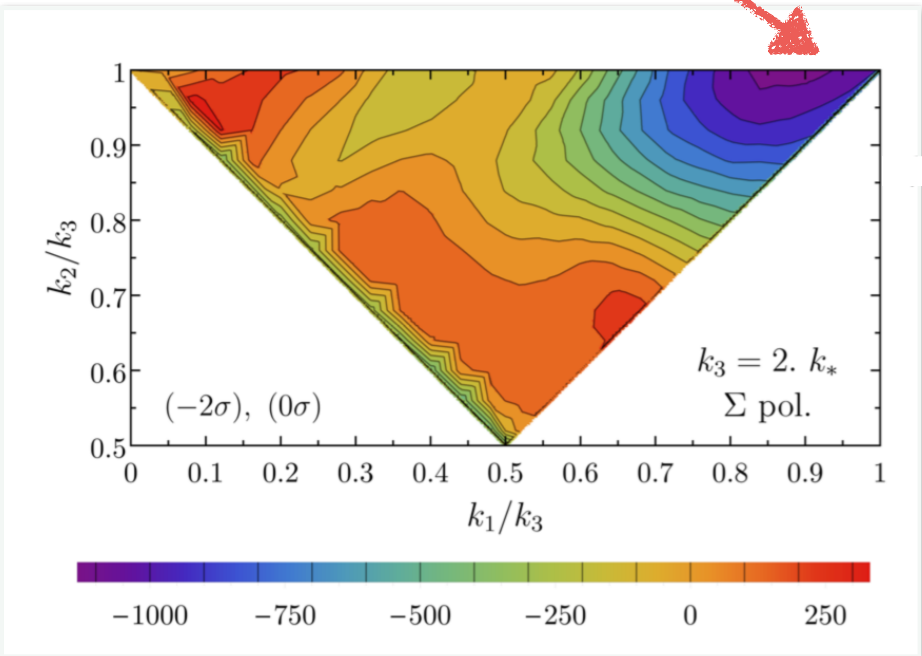
Consistency relation

Three-point corralator

$$\langle h^r(\mathbf{k}_1)h^s(\mathbf{k}_2)h^t(\mathbf{k}_3)\rangle \equiv (2\pi)^3\delta(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)\, B_h^{rst}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

Shape (peaked at equilateral configurations)

$$S_h^{rst}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = k_1^2k_2^2k_3^2\frac{B_h^{rst}(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)}{\sqrt{\mathcal{P}_h(k_1)\mathcal{P}_h(k_2)\mathcal{P}_h(k_3)}}$$



$$\sum_{\text{pol}} S_h = \mathcal{O}(1500)$$

Conclusions

1. The SM Higgs may be responsible of the dark matter we see in the Universe as the result of the EW instability

2. Future interferometers may detect gravitational waves ascribable to the presence of the EW instability: measuring the spectral index as well as the three-point correlator may assess the origin of the signal

Remarks on hep-ph/1803.10242 by C. Gross et al.

Argument: the mechanism needs a fine tuning of one per mille on the initial value of the Higgs, not compatible with dS fluctuations leading to a an exponentially small probability

1. Anthropic principle in action, have to count how many universes, number much larger than small probability

2. The small probability does not apply to PBH abundance

3. AdS bubbles may shrink

4. Increase the initial value of the Higgs, increase number of e-folds plus merging and accretion (PBHs are extremely exponentially clustered)

5. Can avoid AdS by having the quartic positive at large field values, this already relaxes the fine-tuning by ten

6. Relax the fine-tuning by account for the velocities (KM equation not FP equation)