Primordial Black Holes

from the early universe

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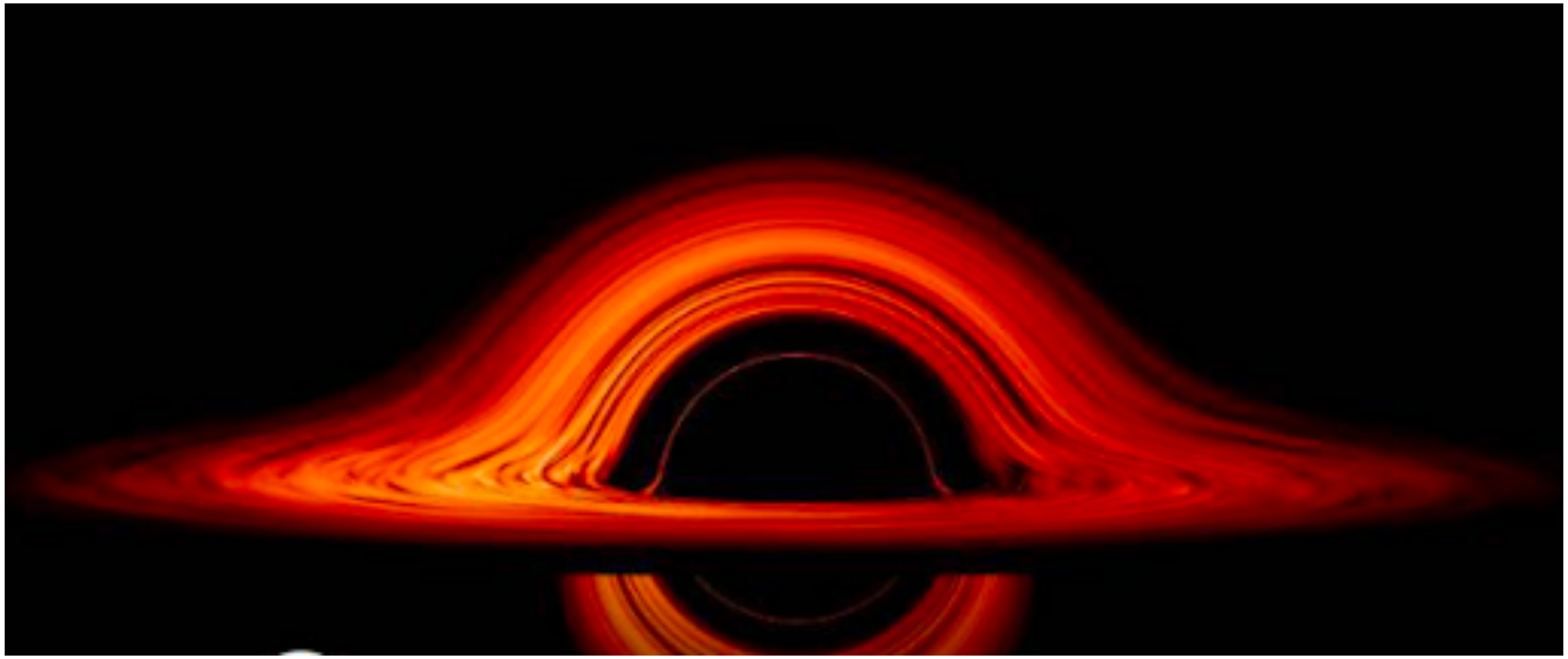
IRN TERASCALE MEETING

5 November 2020

Primordial black holes

Carr, Hawking 1974



Form from the collapse of large primordial fluctuations as they re-enter the Hubble radius

Roles in cosmology

- Could constitute part or all of dark matter Chapline 1975

  $M = 10^{16} - 10^{17}\text{g},\ 10^{20} - 10^{24}\text{g},\ 10 - 10^3 M_\odot$

- Could provide seeds for supermassive black holes in galactic nuclei

  $M > 10^3 M_\odot$ Carr, Rees 1984; Bean, Magueijo 2002

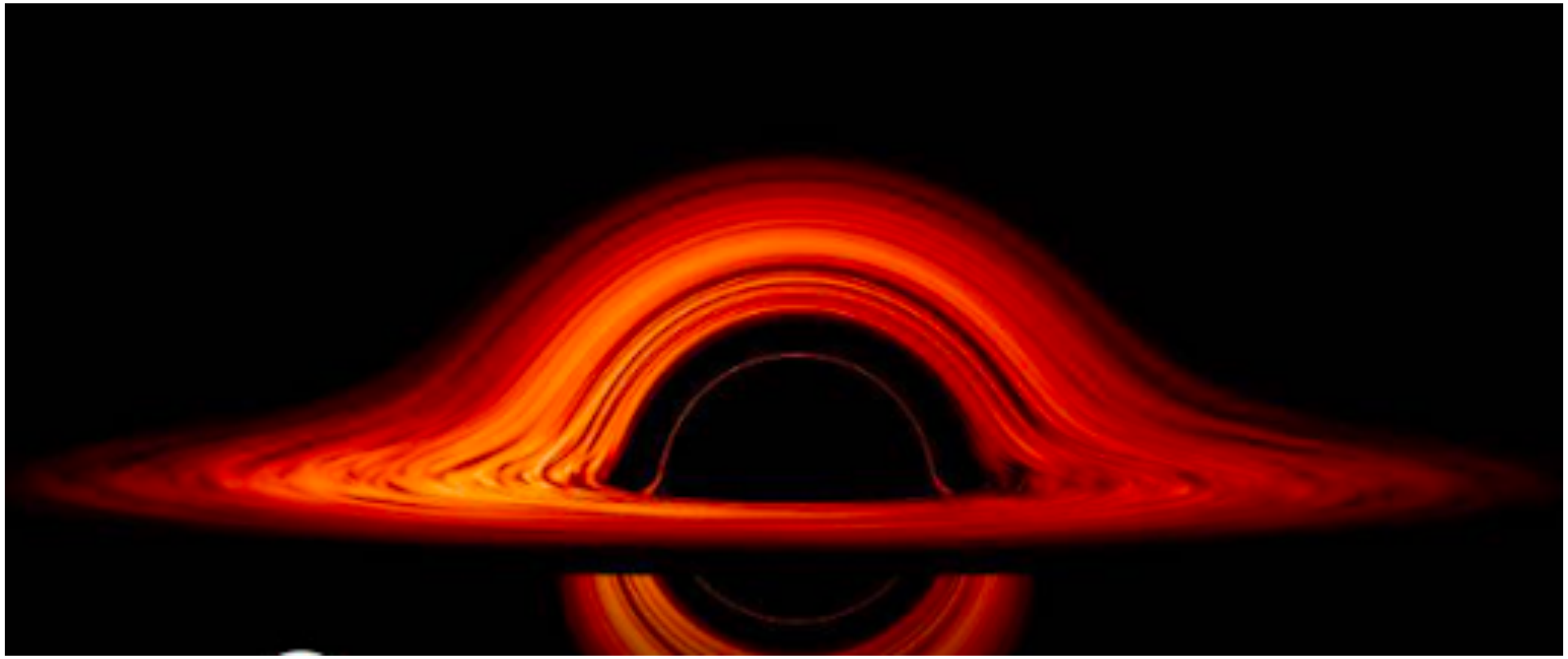
- Could provide seeds for cosmological structures

  $M > 10^3 M_\odot$ Mészáros 1975; Afshordi, McDonald, Spergel, 2003

- Could provide progenitors for the LIGO/VIRGO events

  $M = 10 - 100\ M_\odot$

For hints in favour of PBH existence, see *e.g.* García-Bellido and Clesse (1711.10458)



- How can those large primordial fluctuations can be seeded?

- Under what conditions do PBHs form? (How to compute their abundance?)

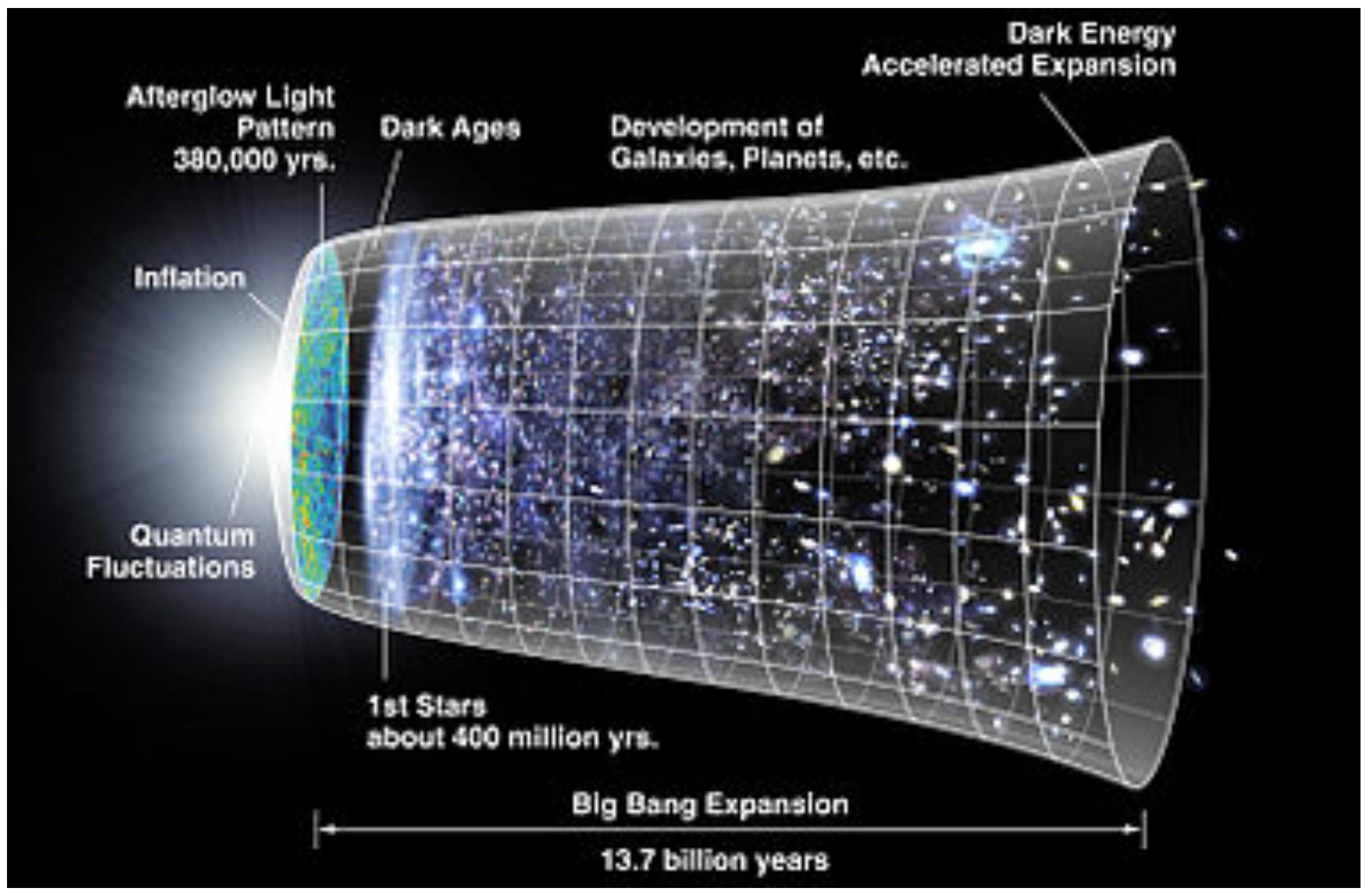
- How do they evolve?

- How can they be constrained?

Cosmic Inflation

Inflation is a **high-energy** phase of **accelerated expansion** in the early Universe

Starobinsky
Guth
Linde
Albrecht & Steinhardt
Mukhanov & Chibisov
Guth & Pi
Hawking
Bardeen, Steinhardt & Turner
(early 80's)



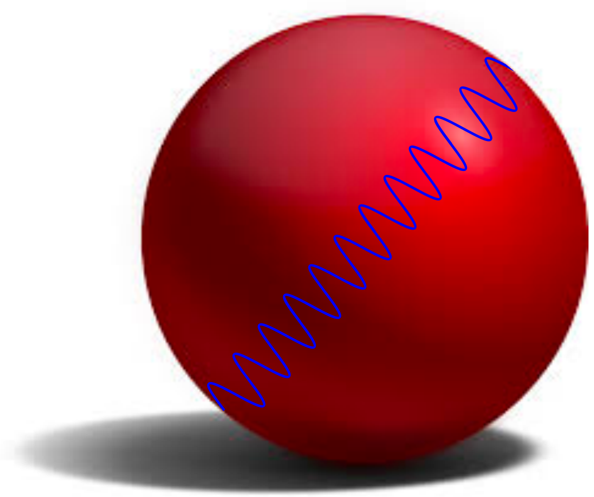
$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\,\mathrm{d}\vec{x}^2 \quad \text{with} \quad \ddot{a} > 0 \quad \text{and} \quad (10\,\mathrm{MeV})^4 < \rho < \left(10^{16}\,\mathrm{GeV}\right)^4$$

Turns the primordial universe into an ultra-high energy laboratory

Cosmic Inflation

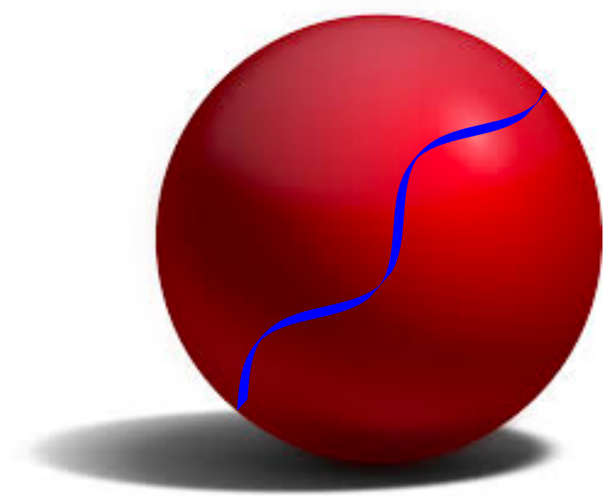
Hubble parameter $H = \dot{a}/a$

H^{-1} : characteristic time scale, or length scale ($c = 1$), of the expansion



$\lambda \ll H^{-1}$

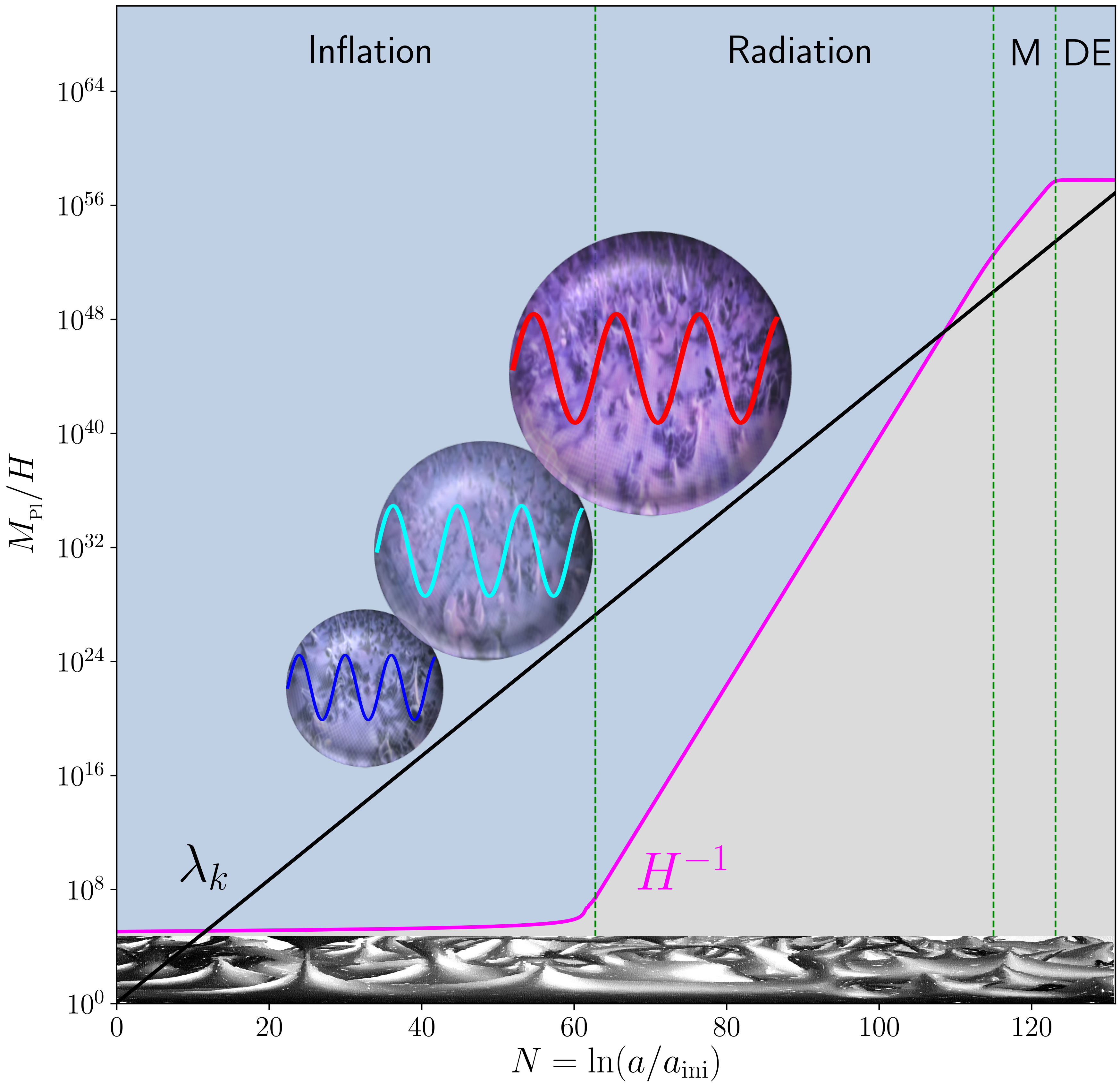
Insensitive to space-time curvature



$\lambda \gtrsim H^{-1}$

Feels space-time curvature

Cosmic Inflation



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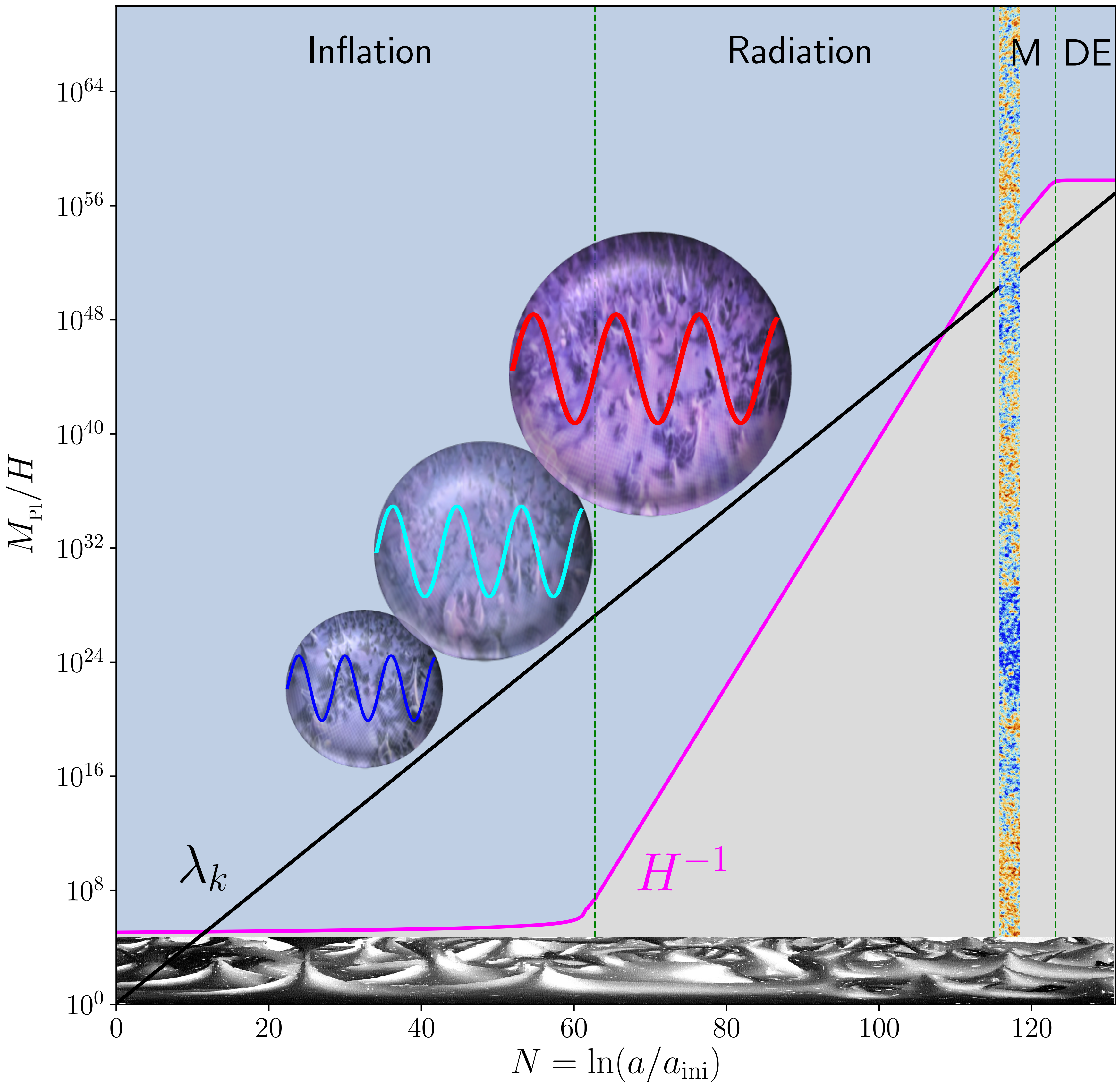
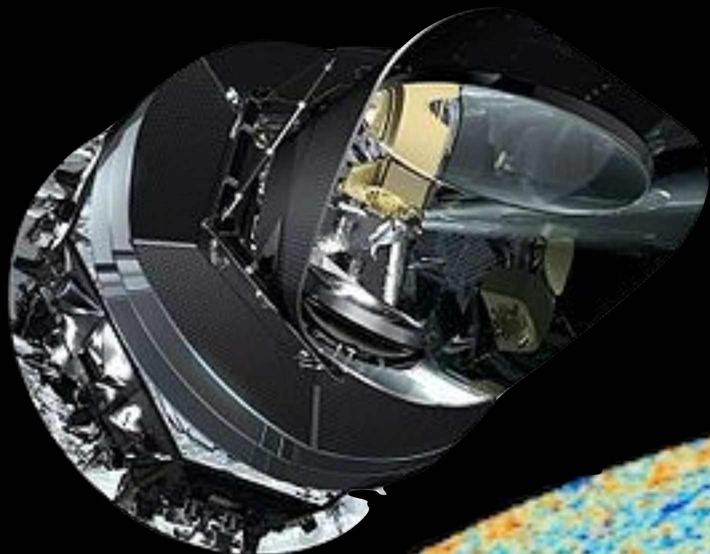
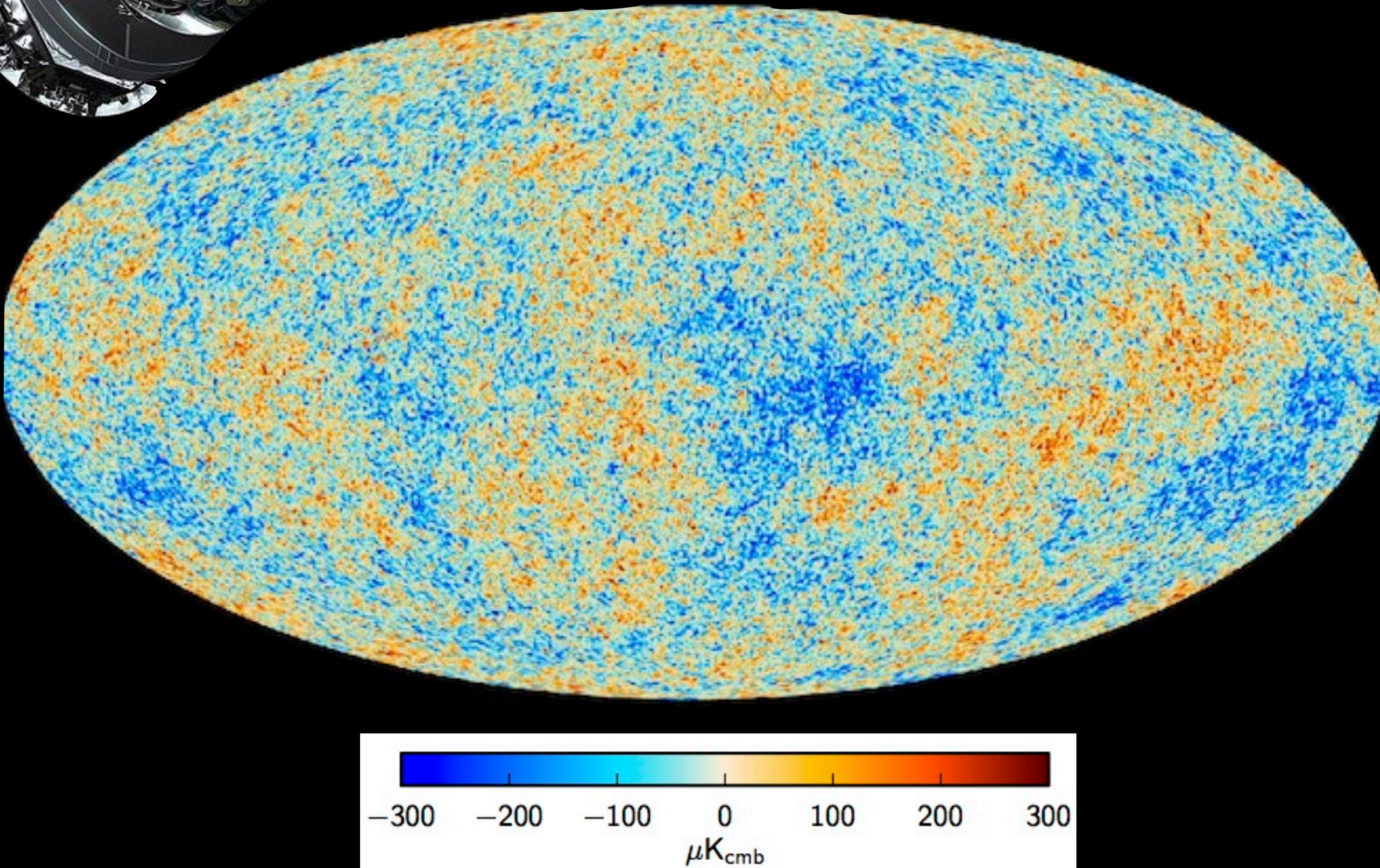
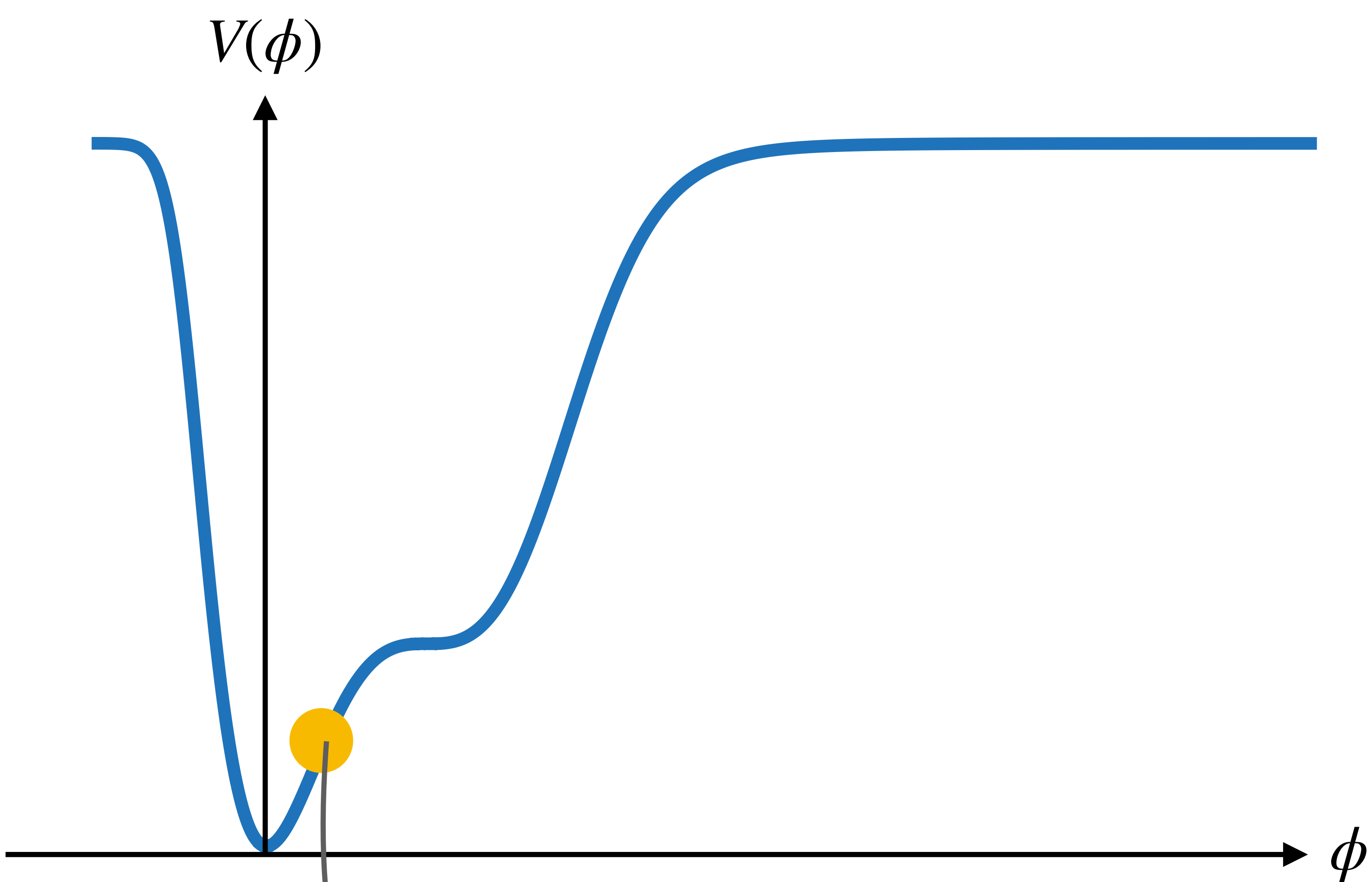


Planck satellite





How can large fluctuations be seeded?



end of inflation $\frac{\lambda_{\rm end}}{\rm m} \simeq \frac{10^{16}\,\mathrm{GeV}}{\rho_{\rm end}^{1/4}}\, R_{\rm rad}^{-1}$

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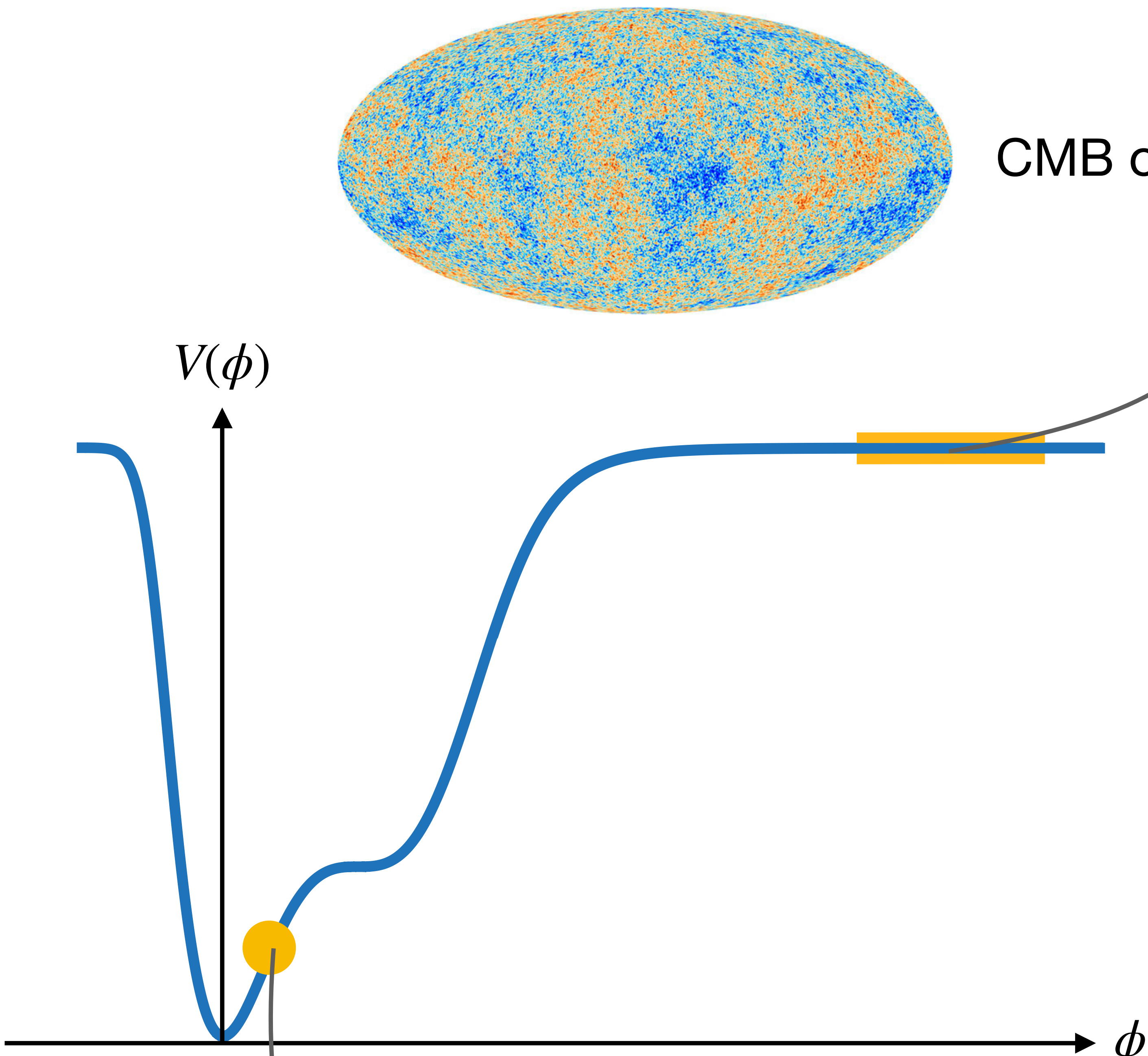

CMB observed scales

$\lambda \simeq \mathrm{Mpc}$

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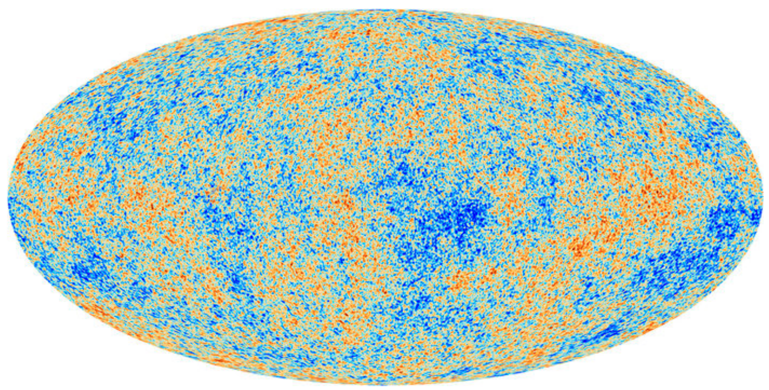

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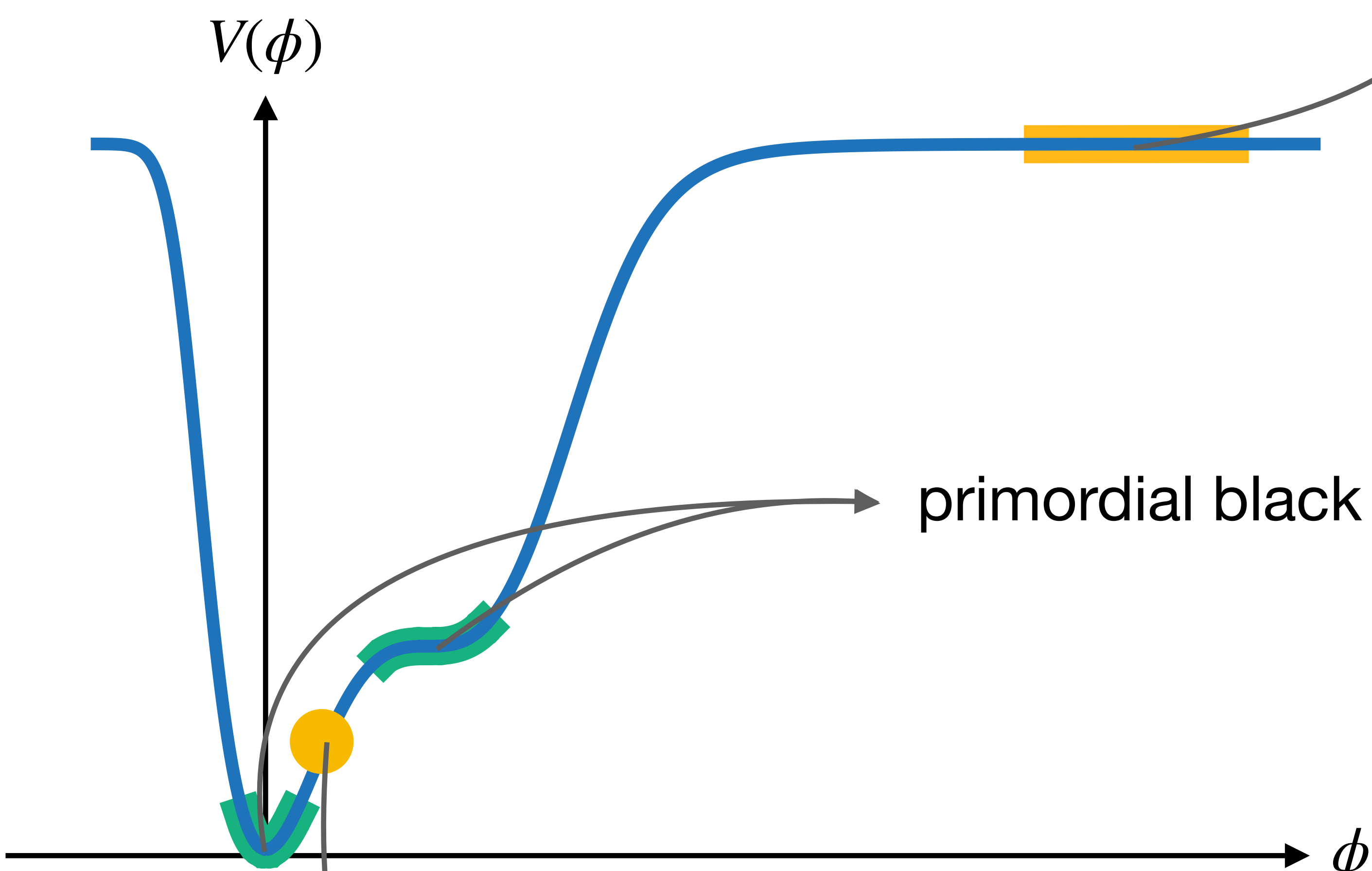
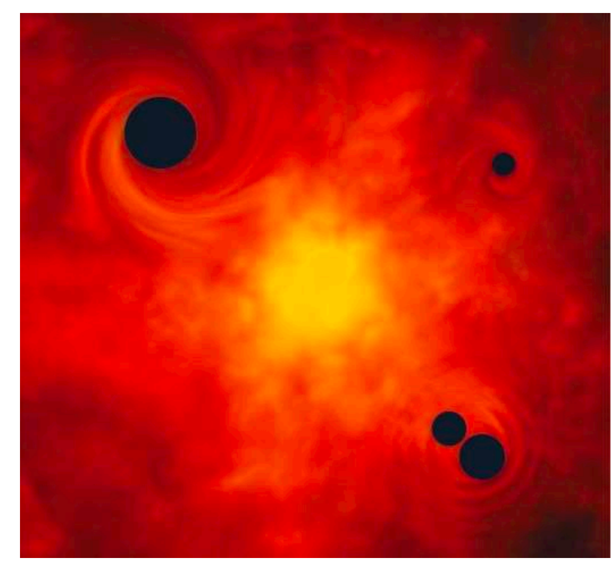


primordial black holes?



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Case study 1: inflationary enhancement

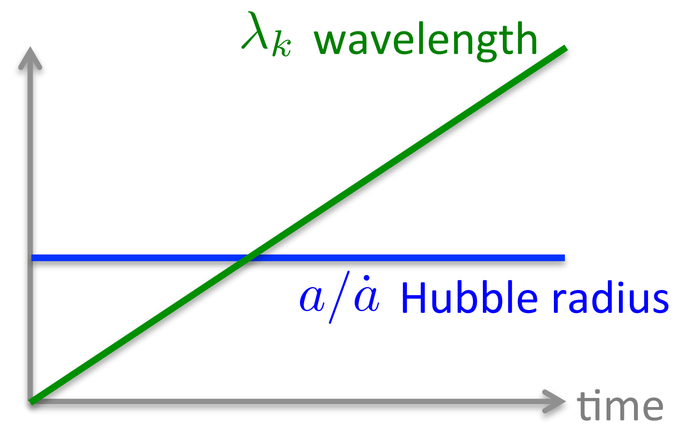
Dynamics of a scalar field in FLRW cosmology:

$$\dot{\phi} = \pi + \xi_\phi$$

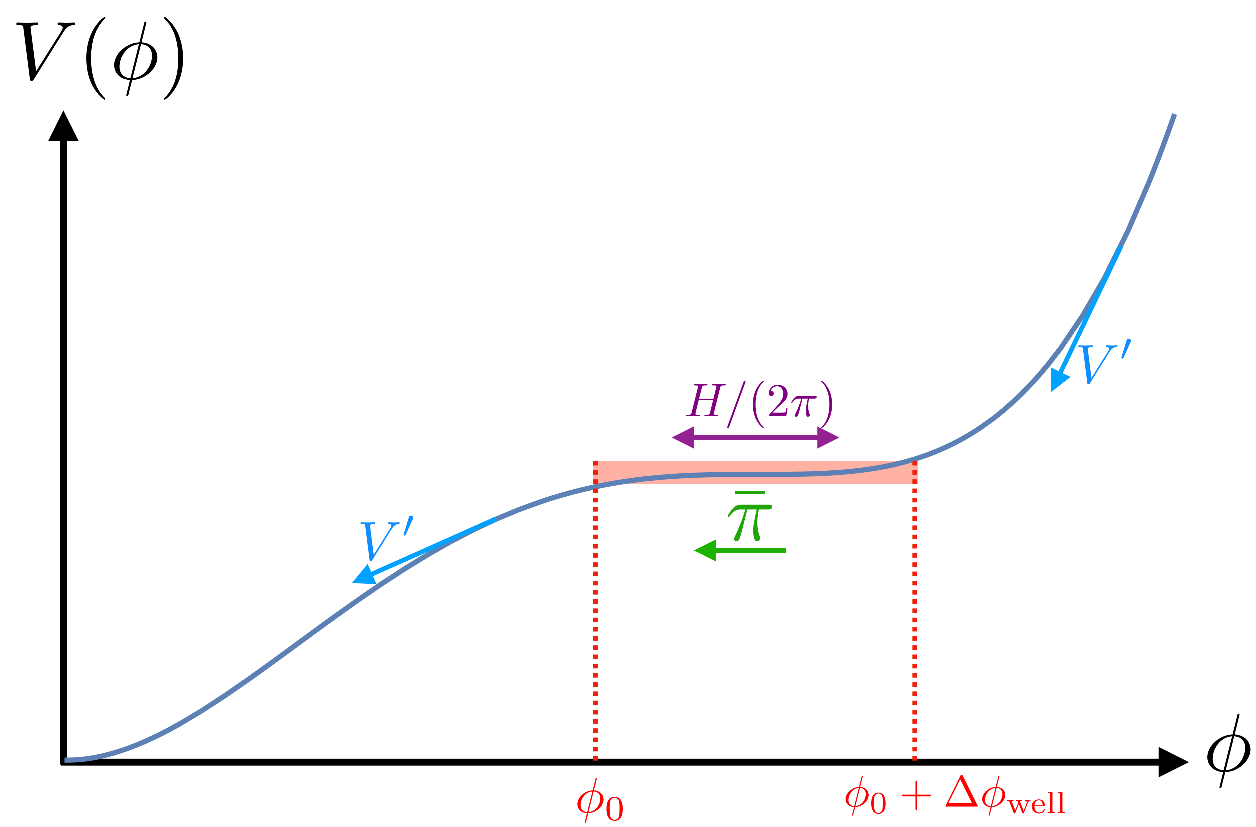
$$\dot{\pi} = -3H\pi - \frac{\mathrm{d}V}{\mathrm{d}\phi} + \xi_\pi$$

friction term $H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{V(\phi) + \frac{\pi^2}{2}}{3M_{\mathrm{Pl}}}$

potential gradient



Quantum fluctuations as they cross out the Hubble radius and source the large-scale dynamics



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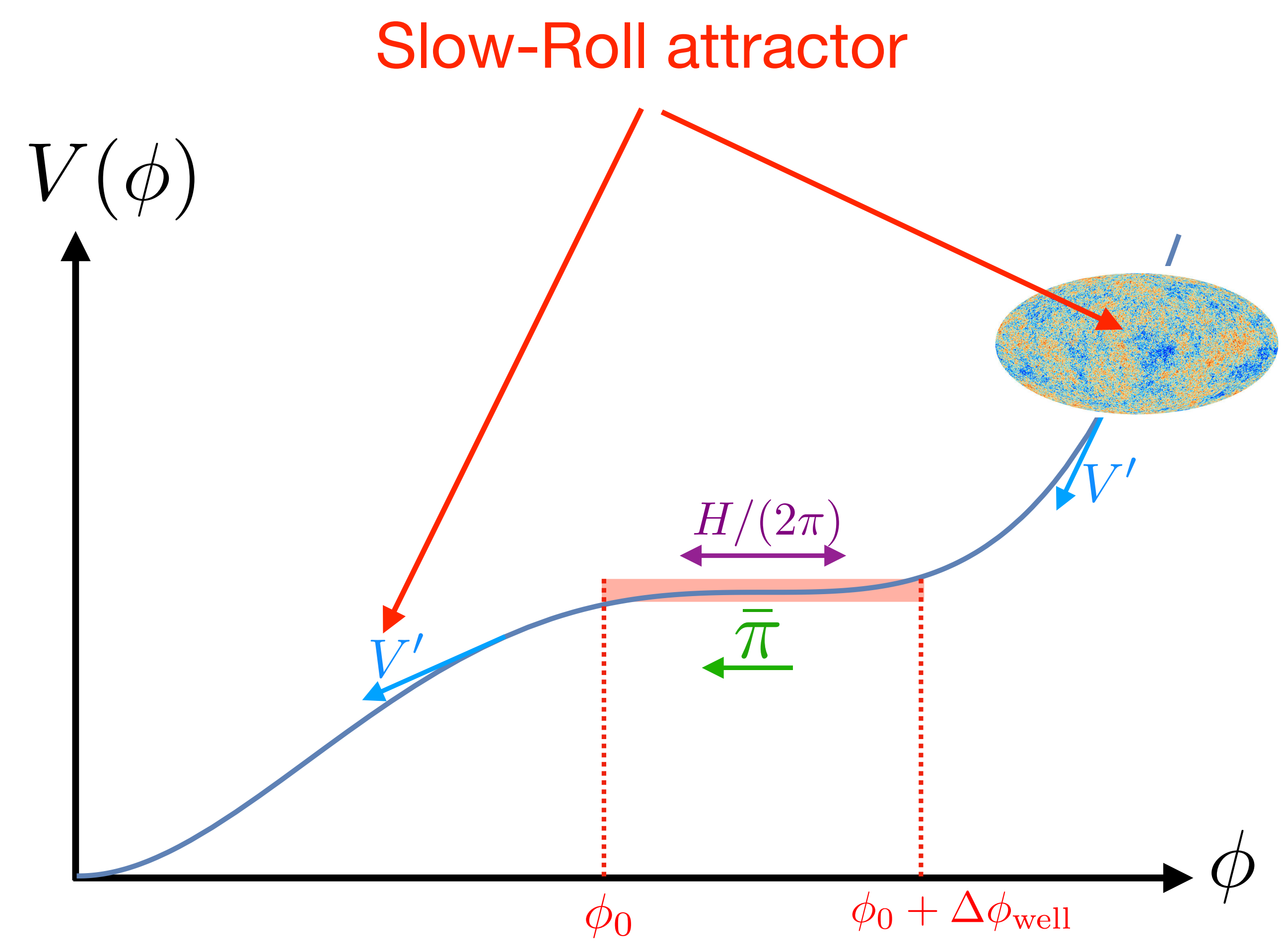

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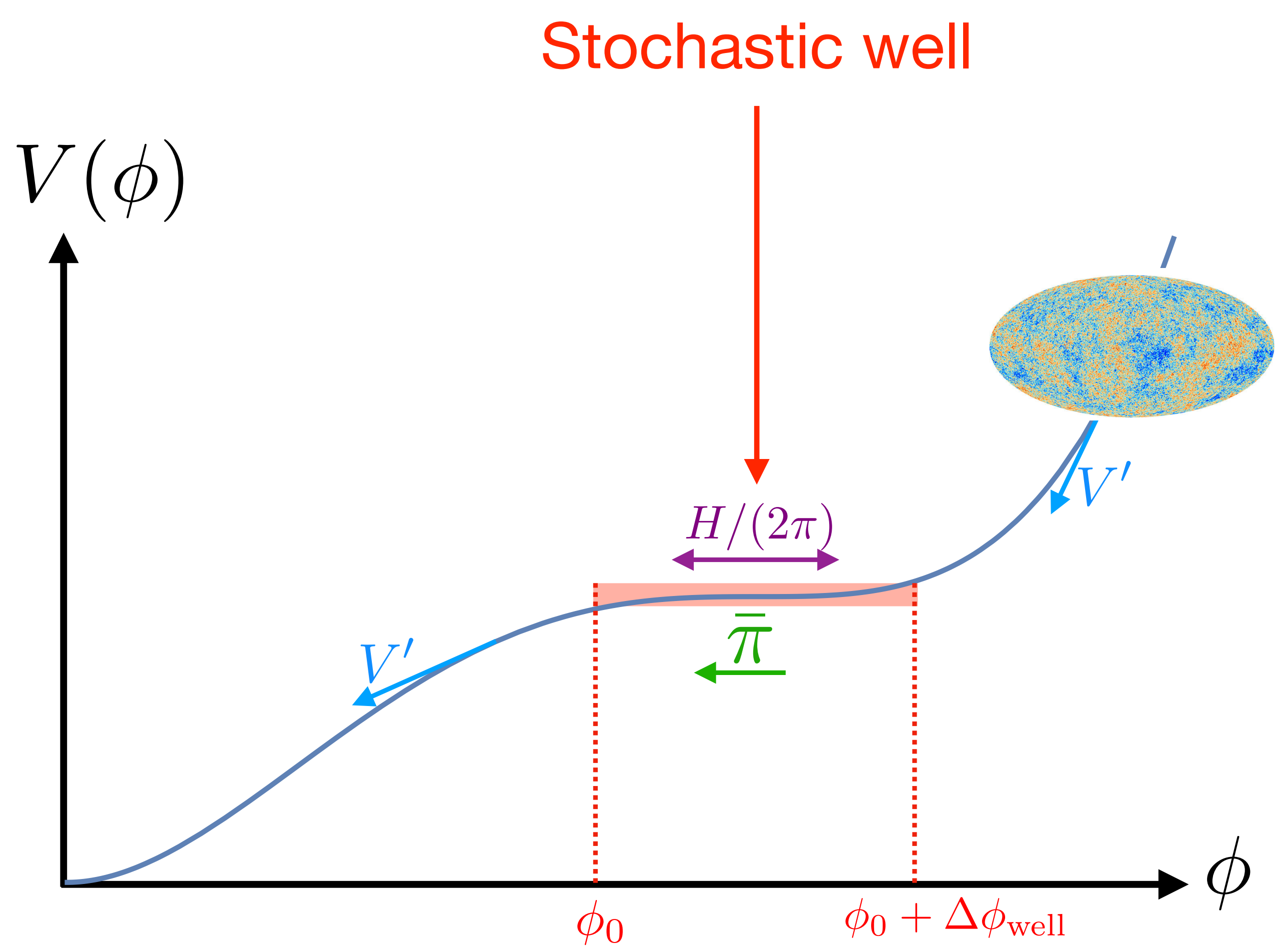

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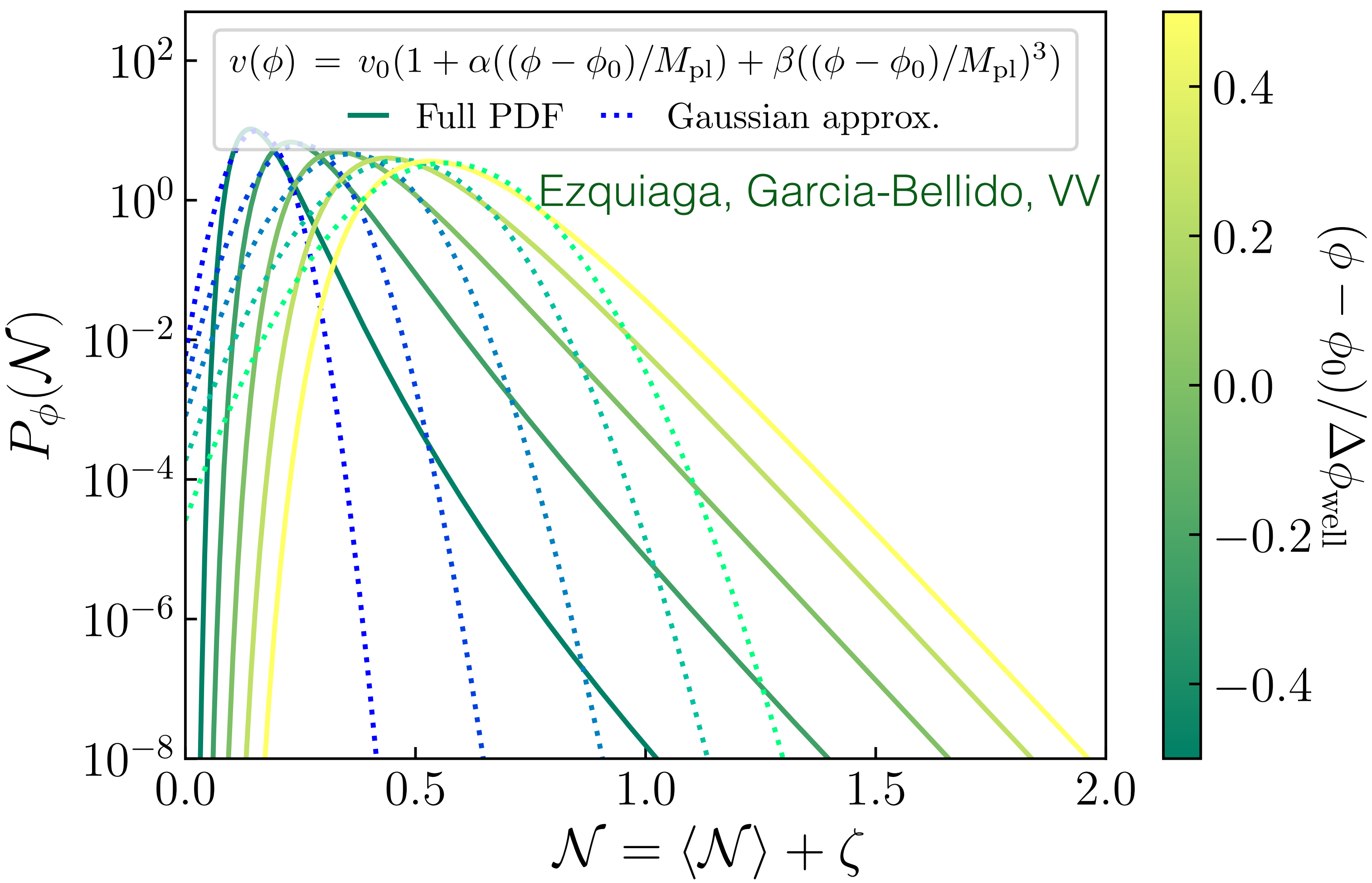
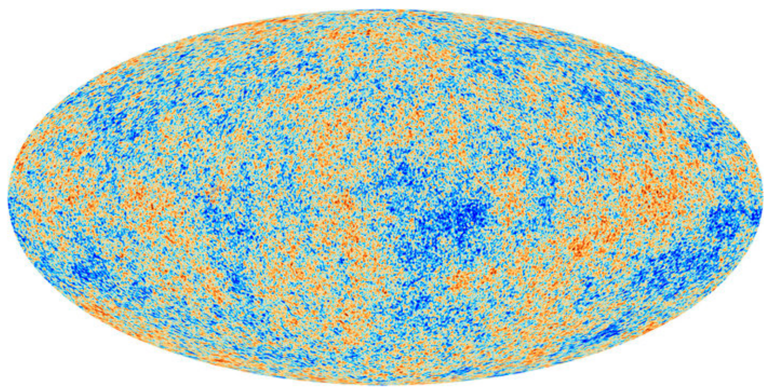
Need to compute statistics of cosmological perturbations in the presence of non-perturbative stochastic effects



Stochastic δN formalism

VV, Starobinsky (2015)
Pattison, Assadullahi, VV, Wands (2017)

How can large fluctuations be seeded?



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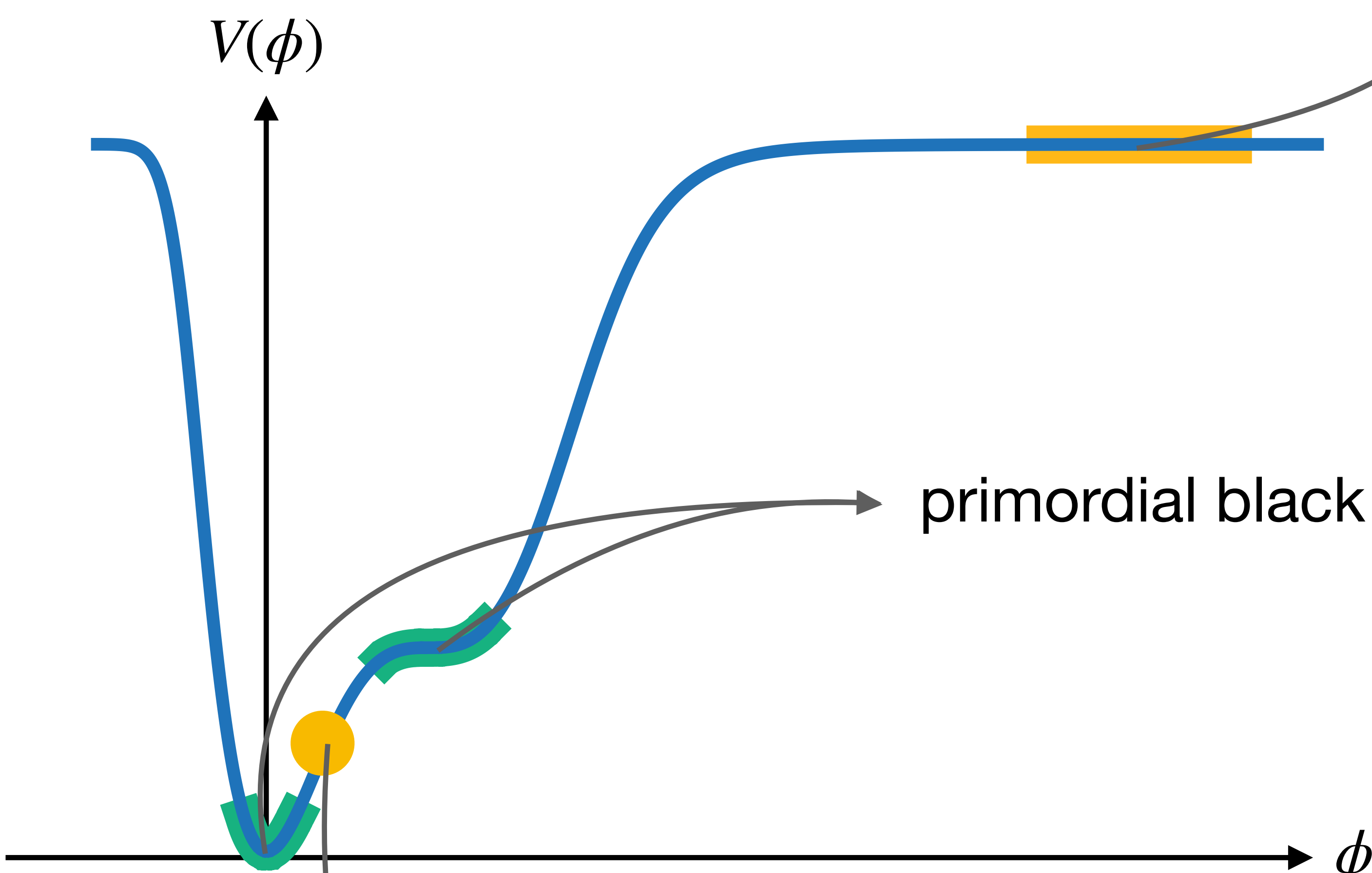

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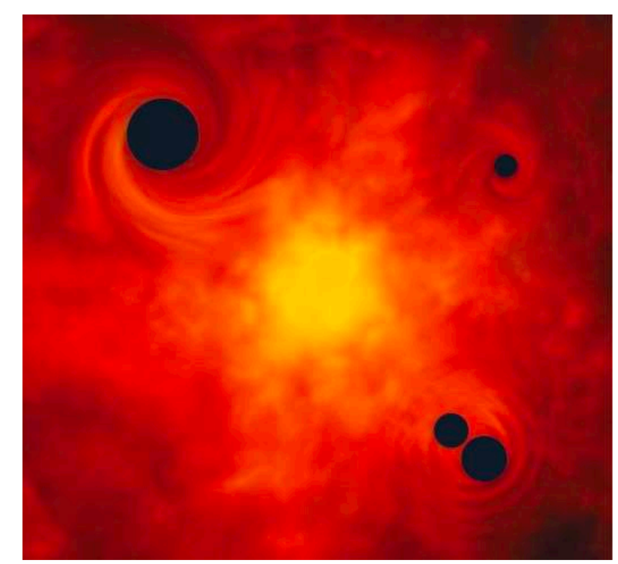

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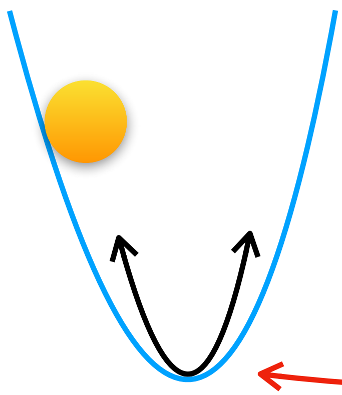
Case study 2: post-inflationary enhancement

Parametric resonance



$$v_k'' + \left[k^2 - \frac{(a\sqrt{\epsilon_1})''}{a\sqrt{\epsilon_1}}\right] v_k = 0$$

with $\epsilon_1 = -\dot{H}/H^2$

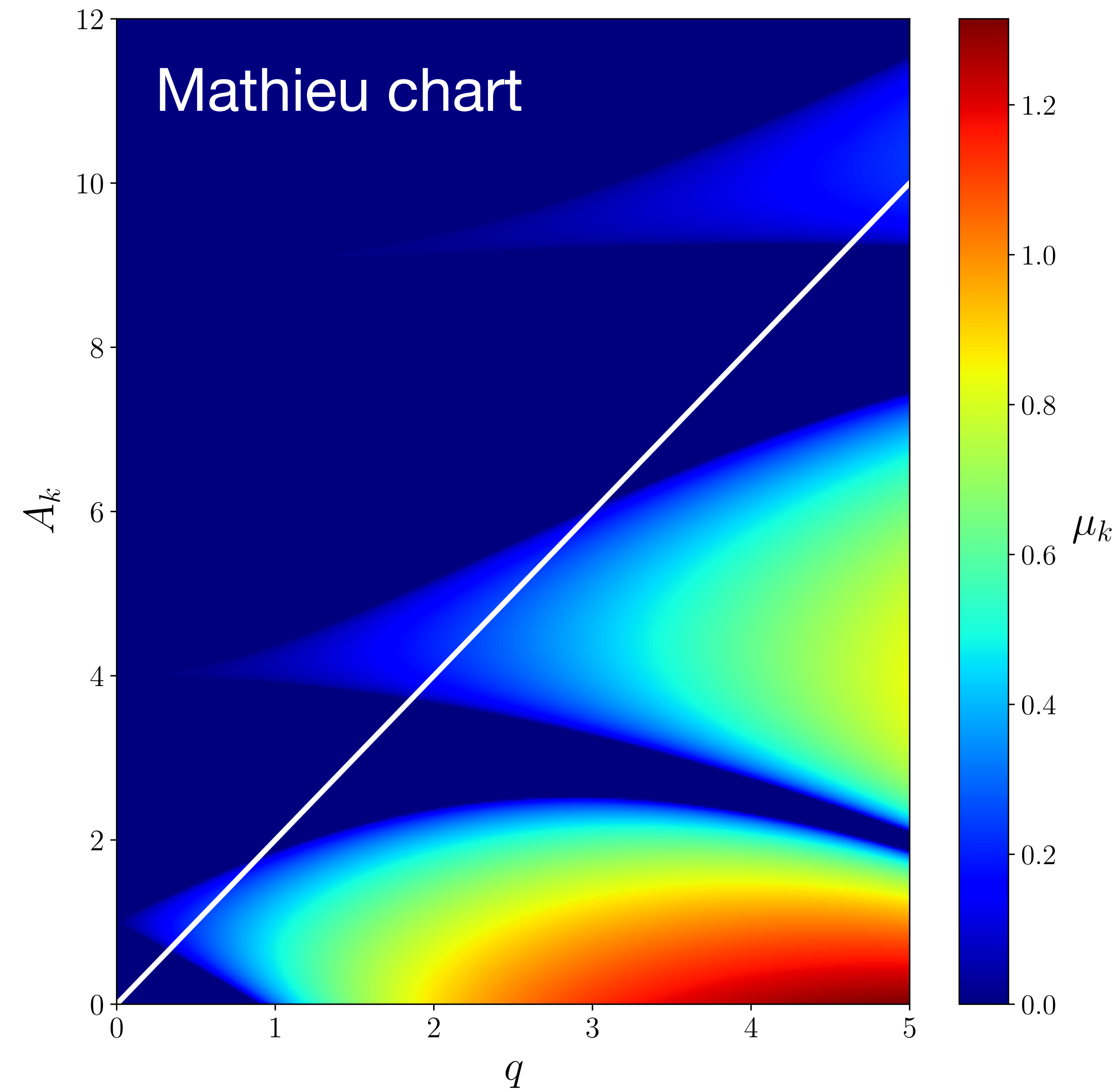
$$\frac{\mathrm{d}^2}{\mathrm{d}z^2}\left(\sqrt{a}v_k\right) + \left[A_k - 2q\cos(2z)\right]\left(\sqrt{a}v_k\right) = 0$$

with $z = mt + \pi/4$

$$A_k = 1 + \frac{k^2}{m^2a^2} \quad , \quad q = \frac{\sqrt{6}}{2}\frac{\phi_{\mathrm{end}}}{M_{\mathrm{Pl}}}\left(\frac{a_{\mathrm{end}}}{a}\right)^{3/2}$$

Floquet index: $\sqrt{a}v_k \propto \exp(\mu_k z)$

Jedamzik, Lemoine, Martin (2010)
Easther, Flauger, Gilmore (2011)



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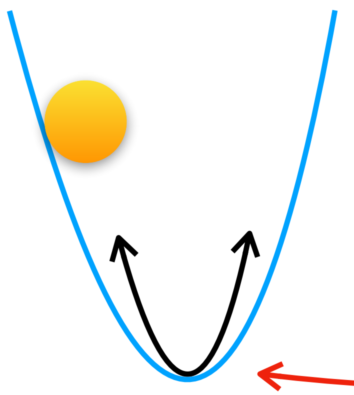

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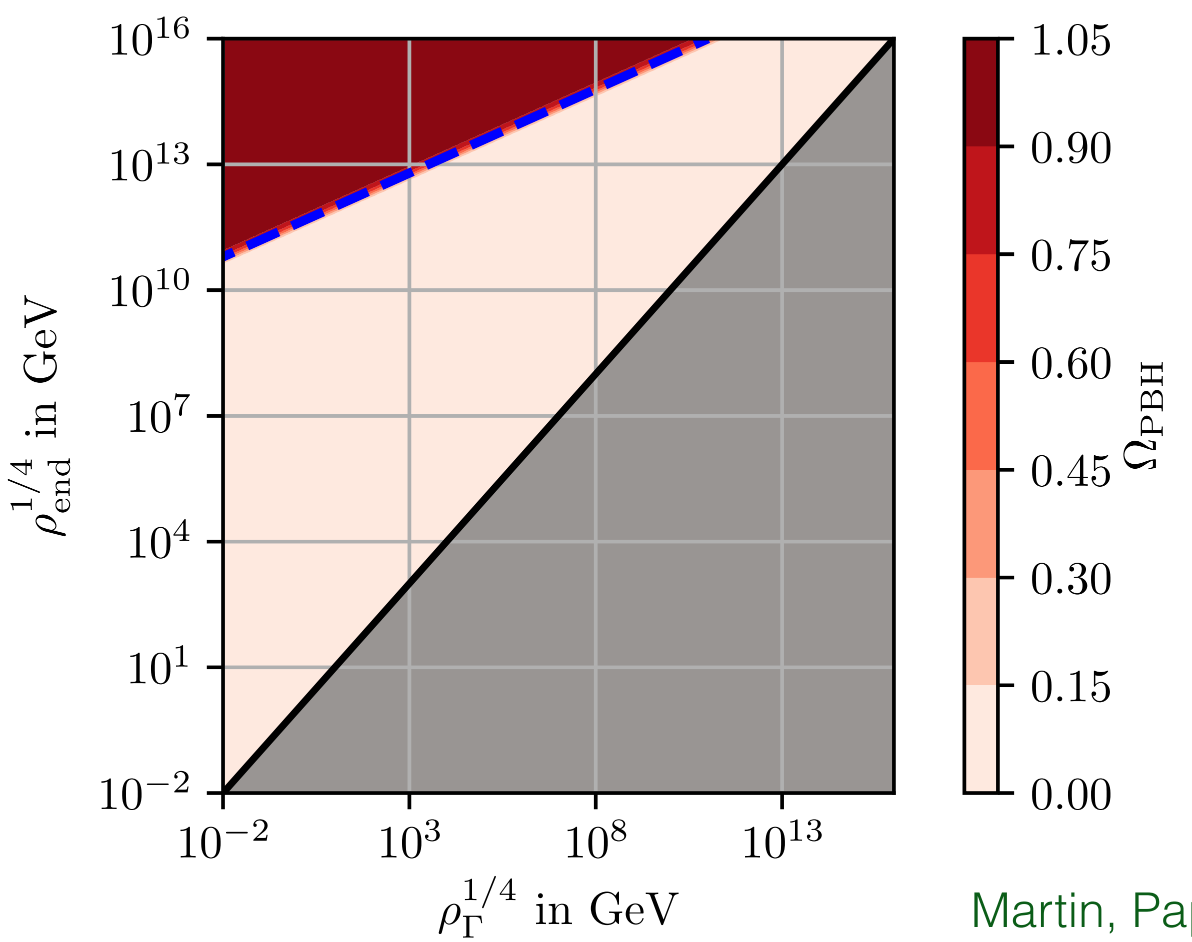

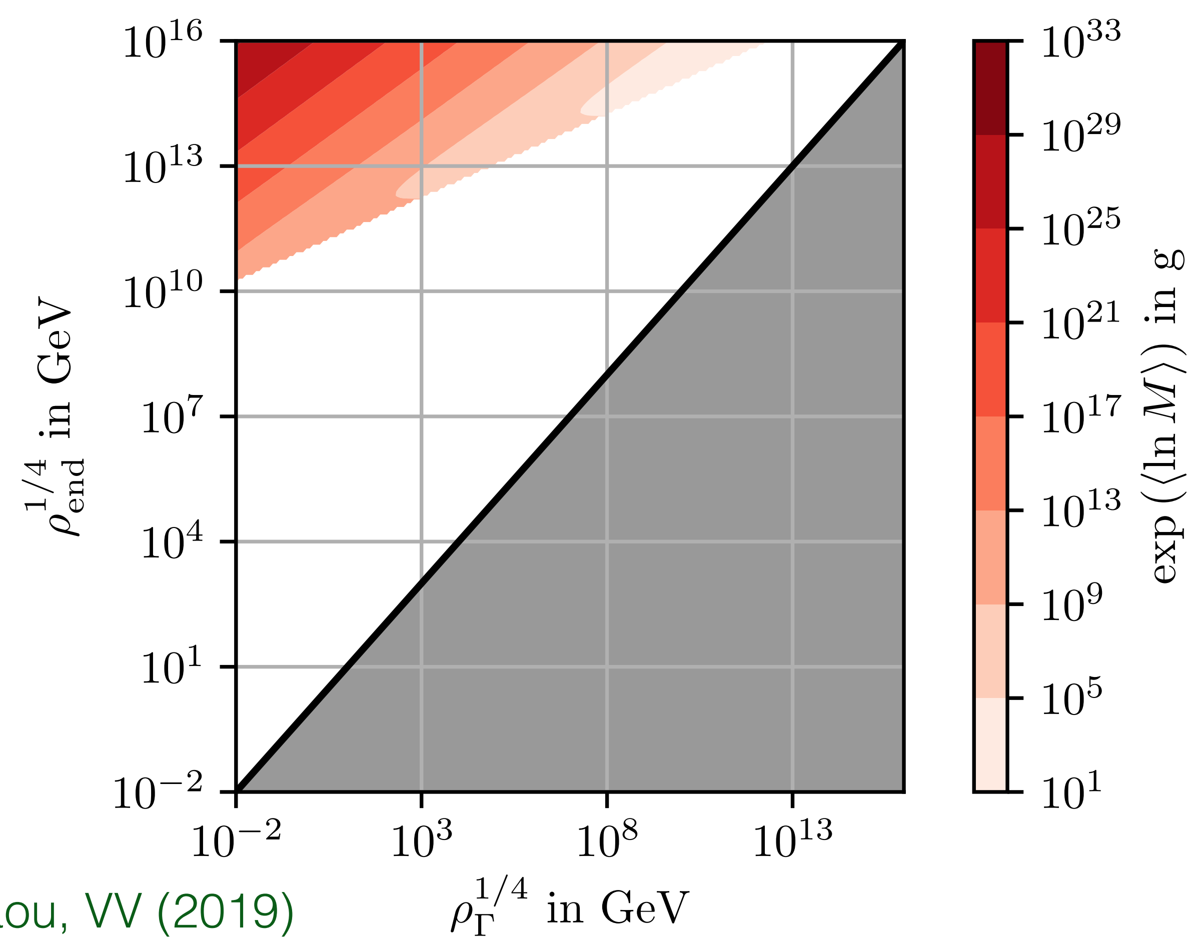

Martin, Papanikolaou, VV (2019)
Martin, Papanikolaou, Pinol, Vennin (2020)
Auclair, VV (in prep)

Thank you for your attention!