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LABORATOIRE DE PHYSIQUE
DE L'ÉCOLE NORMALE SUPÉRIEURE

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Open theoretical issues in Inflationary Cosmology

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Rencontres de Blois
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Credit: ESO/M. Kornmesser

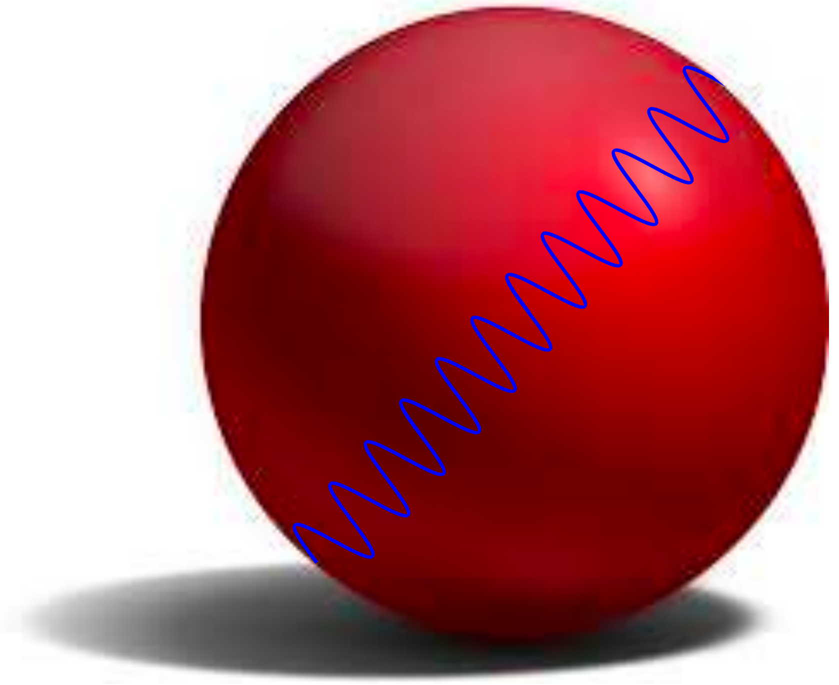
Cosmic Inflation: $\ddot{a} > 0$

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\,\mathrm{d}\vec{x}^2$$

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

↓

"unambiguous" vacuum state

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

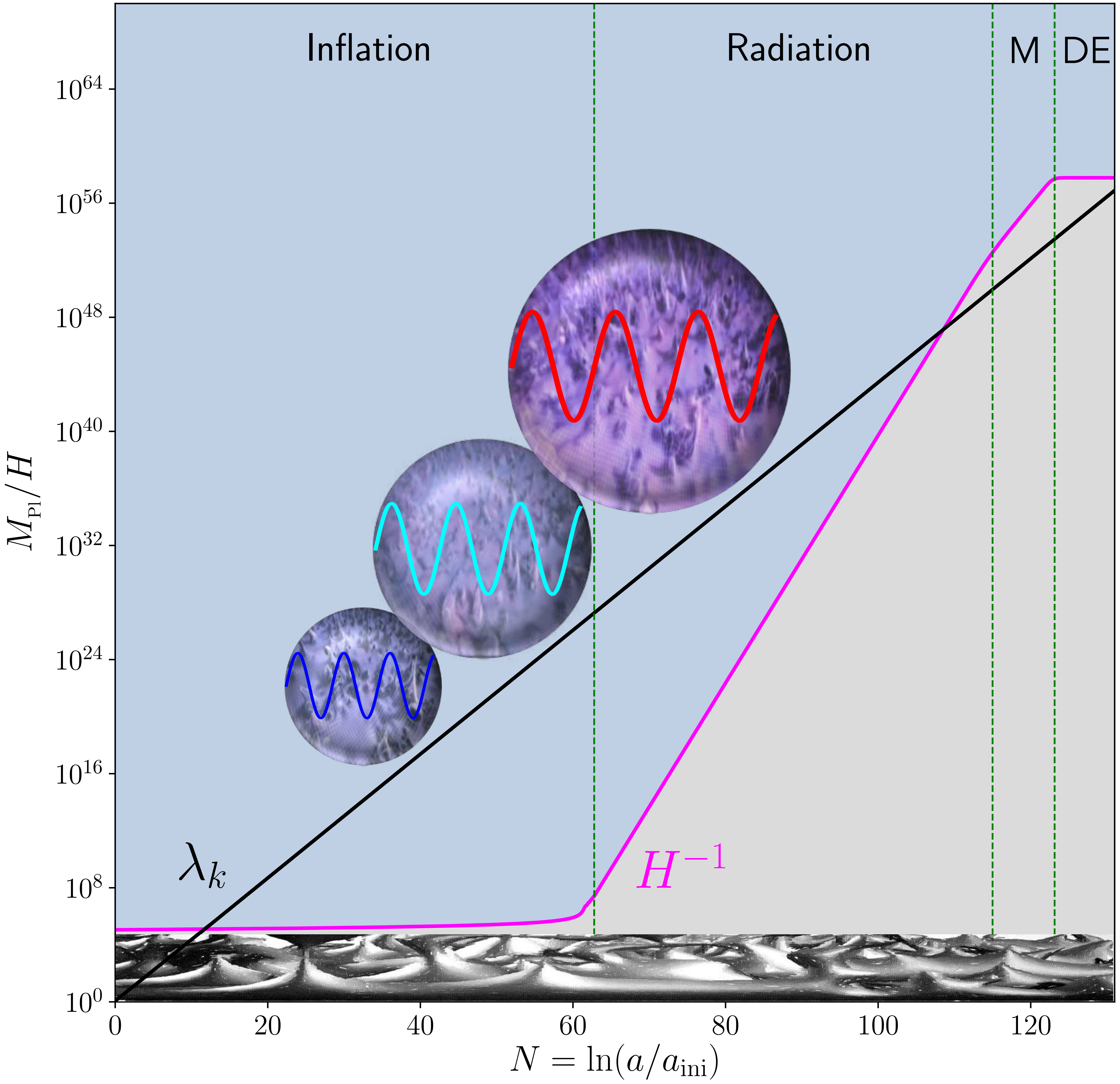
Feels space-time curvature

↓

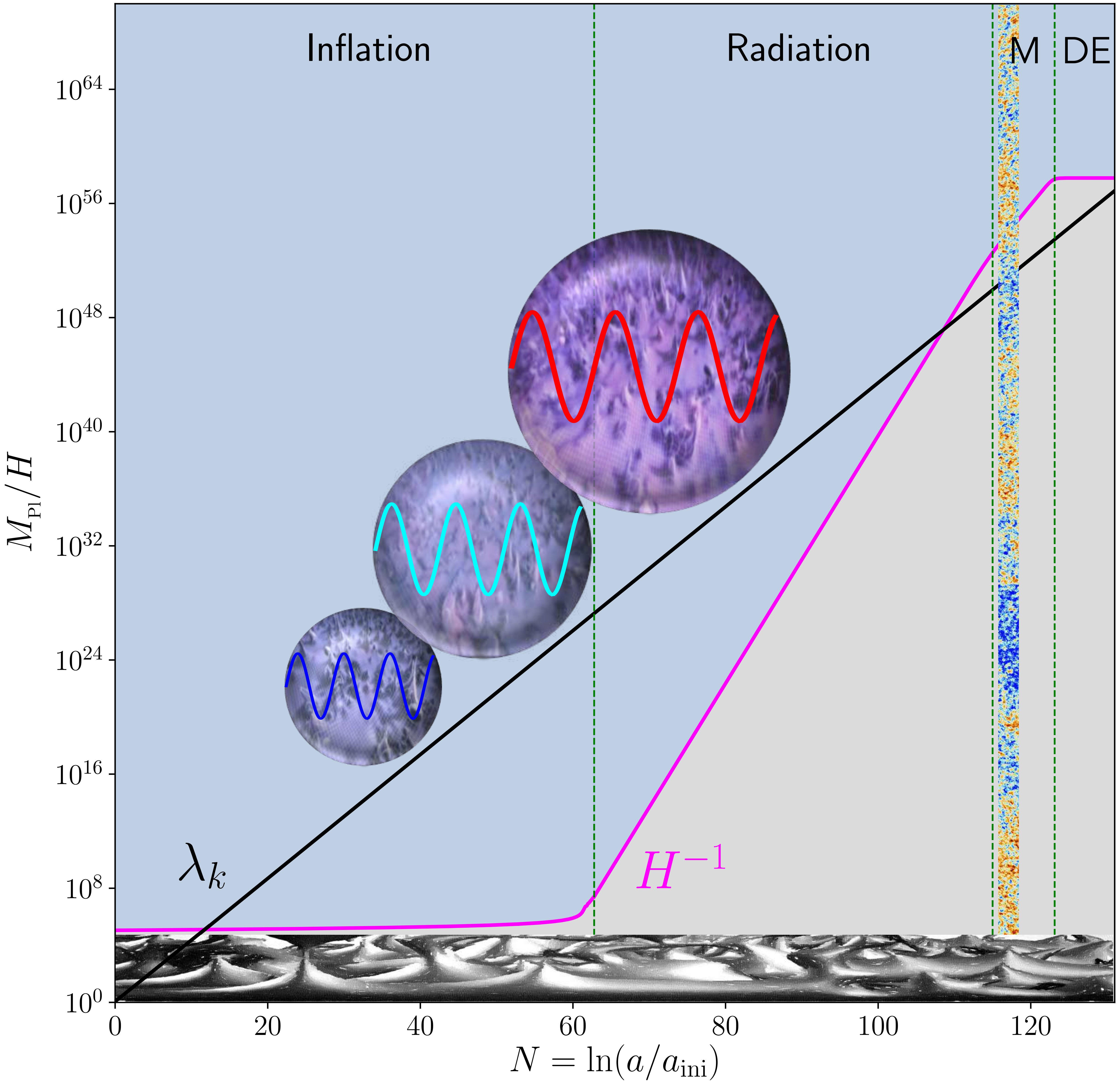
Quantum particule creation

(analogous to Schwinger effect, Hawking effect, etc)

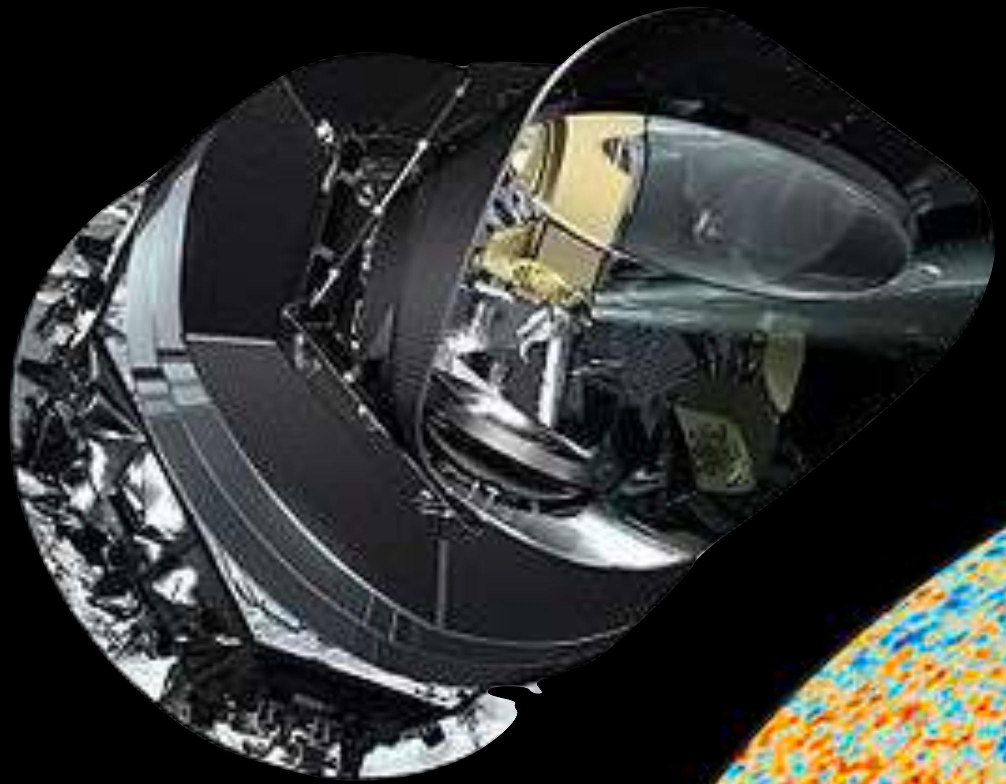
Cosmic Inflation

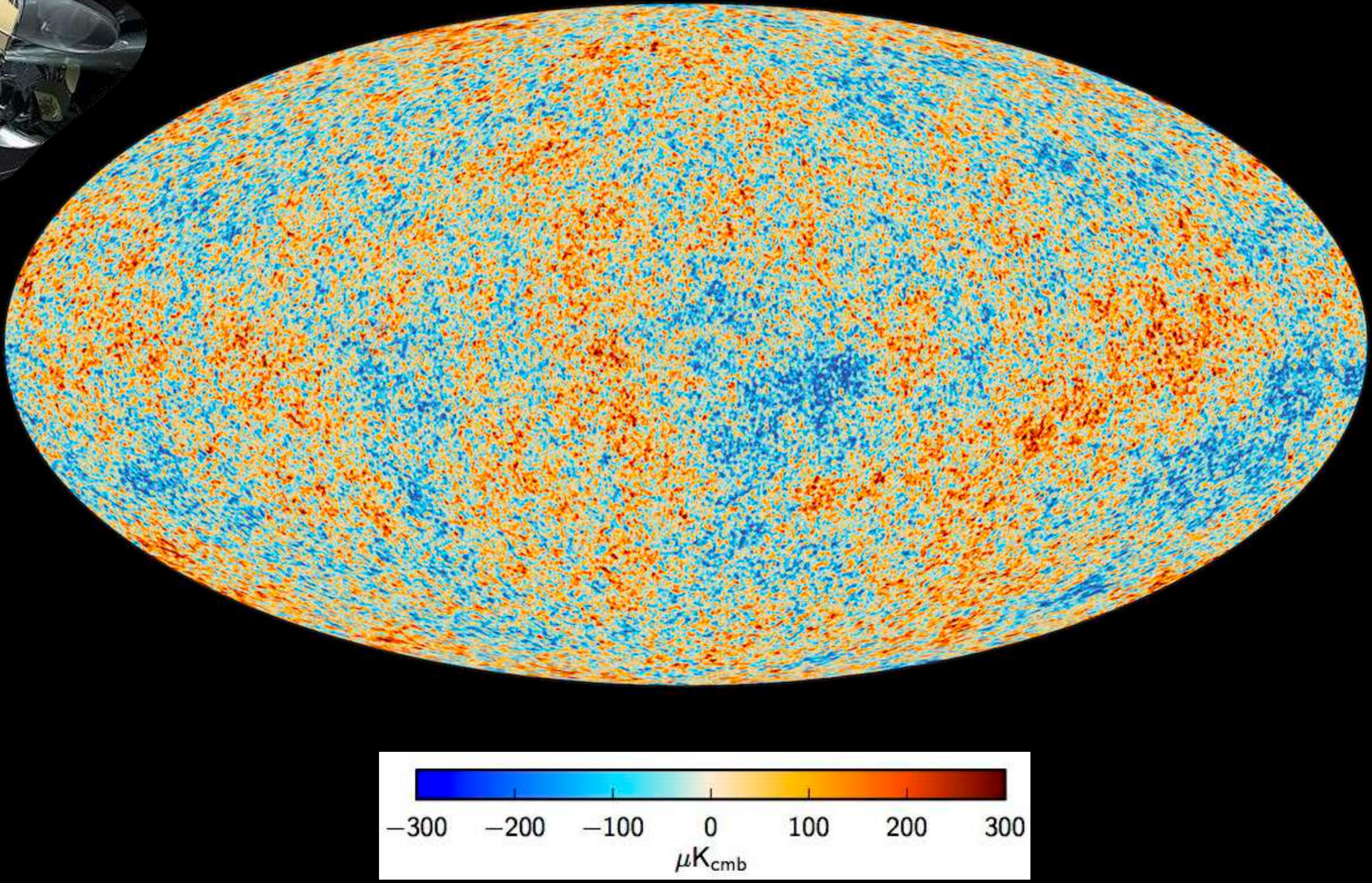


Cosmic Inflation



Planck satellite





Open issues

- How did inflation start?
- How to realise inflation in high-energy physics?
- Can we look for quantum properties of cosmological fluctuations?
- How to incorporate the backreaction of large fluctuations?
- How does inflation end, how doe the universe “reheat”?
- Can we apply (open)EFT/bootstrap approaches to inflationary fluctuations?
- Is inflationary physics linked with the dark sector?

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Initial conditions

Inflation is meant to explain why the universe is homogeneous at large scales…
but most of the time, homogeneous initial conditions are assumed!

Steigman, Turner 1983
Turner, Widow 1986
Anninos, Matzner, Rothman 1991

→ Inflation makes the universe isotropic $\rho_{\rm aniso} \propto a^{-6}$

Goldwirth, Piran 1990 & 1992

→ "Effective density approximation" $\rho_{\delta_\phi} \propto a^{-4}$

East, Kleban, Linde, Senatore 2016
Clough, Lim, DiNunno, Fischler, Fauger, Paban 2017
Bloomfield, Fitzpatrick, Hilbert, Kaiser 2019
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→ Numerical Relativity approaches

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super-Hubble, gradient initial conditions

super-Hubble, kinetic initial conditions

sub-Hubble, gradient initial conditions

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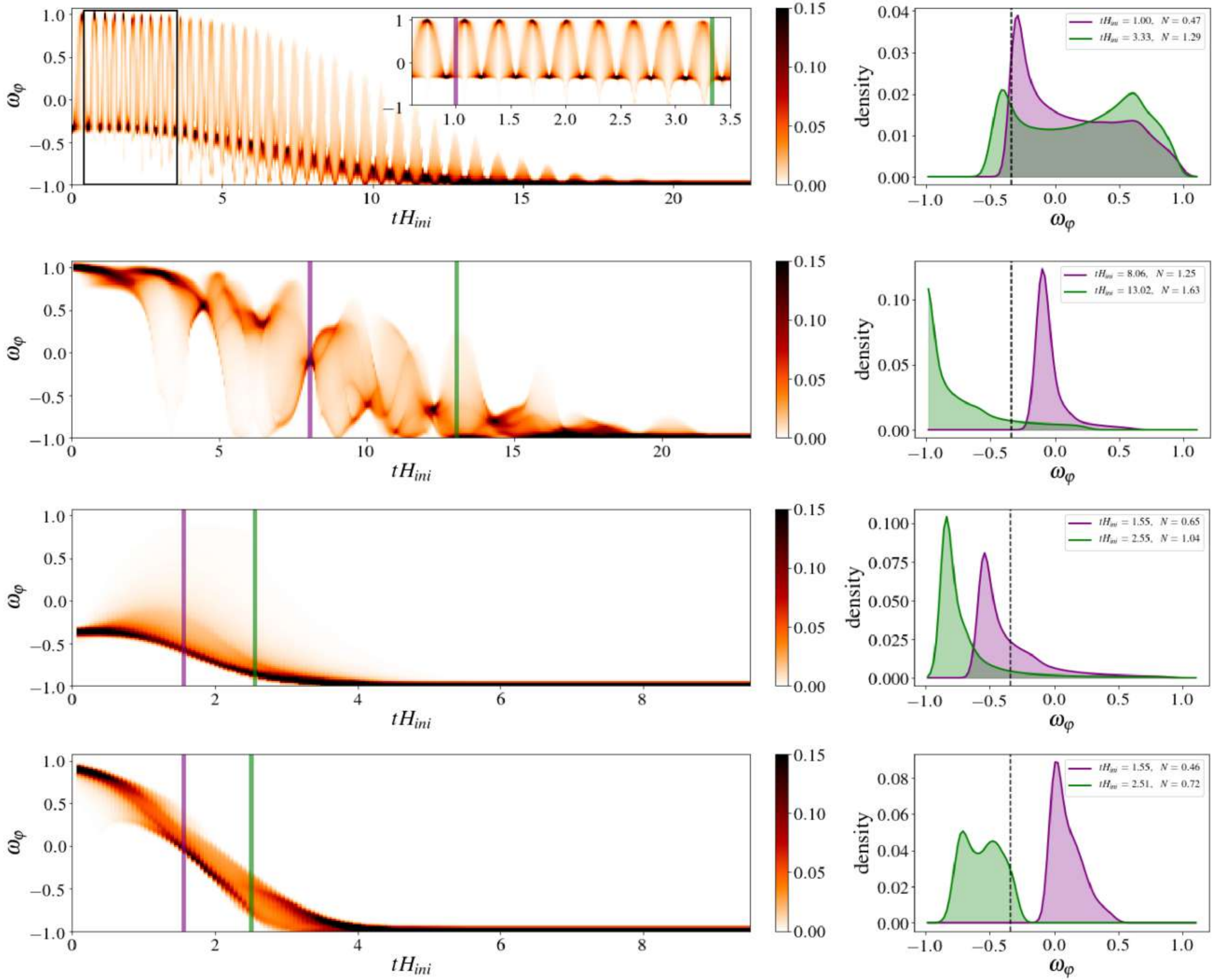


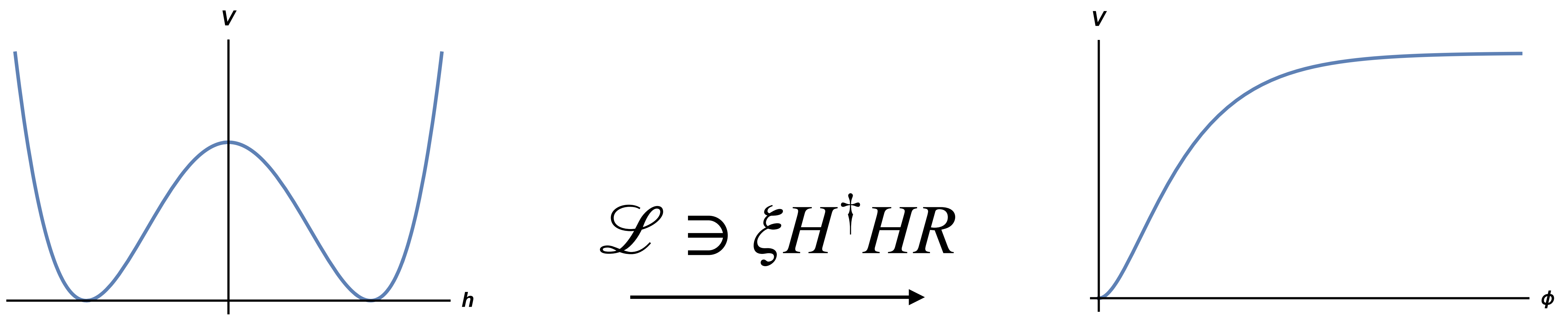
How to realise inflation?

General Relativity, homogeneous universe filled by a perfect fluid: $\frac{\ddot{a}}{a} = -\frac{\rho + 3p}{6M_{\rm Pl}^2}$

Inflation cannot be realised with matter in the form of Newtonian <u>fluids</u>.
In any case, it occurs at super-high energy where matter should rather be described in terms of <u>fields</u>.

In a cosmological background, a scalar field behaves “like” a perfect fluid with

$$\begin{cases} \rho = \frac{\dot{\phi}^2}{2} + V(\phi) \\ p = \frac{\dot{\phi}^2}{2} - V(\phi) \end{cases} \implies \text{inflation takes place if } V(\phi) > \dot{\phi}^2$$



- Within the standard model: Higgs inflation
- Beyond the standard model: SUSY, SUGRA, ST, etc
- Modified Gravity: $f(R)$, etc

Hundreds of models have been proposed…

Adverts

Encyclopædia Inflationaris

Jérôme Martin,[a] Christophe Ringeval[b] and Vincent Vennin[a]

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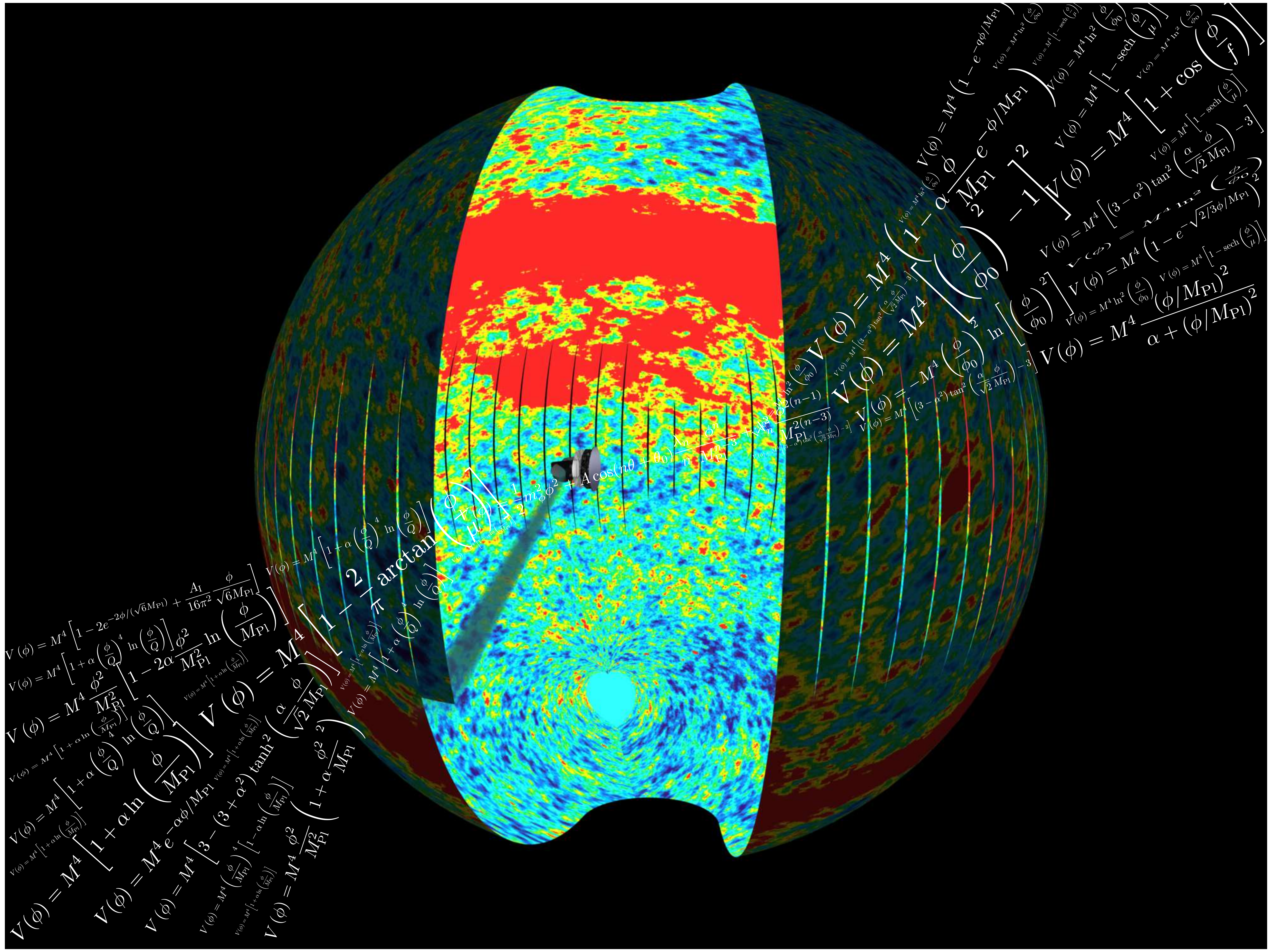
Abstract. The current flow of high accuracy astrophysical data, among which are the Cosmic Microwave Background (CMB) measurements by the Planck satellite, offers an unprecedented opportunity to constrain the inflationary theory. This is however a challenging project given the size of the inflationary landscape which contains hundreds of different scenarios. Given that there is currently no observational evidence for primordial non-Gaussianities, isocurvature perturbations or any other non-minimal extension of the inflationary paradigm, a reasonable approach is to consider the simplest models first, namely the slow-roll single field models with minimal kinetic terms. This still leaves us with a very populated landscape, the exploration of which requires new and efficient strategies. It has been customary to tackle this problem by means of approximate model independent methods while a more ambitious alternative is to study the inflationary scenarios one by one. We have developed the new publicly available runtime library `ASPIC`[1] to implement this last approach. The `ASPIC` code provides all routines needed to quickly derive reheating consistent observable predictions within this class of scenarios. `ASPIC` has been designed as an evolutive code which presently supports 74 different models, a number that may be compared with three or four representing the present state of the art. In this paper, for each of the `ASPIC` models, we present and collect new results in a systematic manner, thereby constituting the first *Encyclopædia Inflationaris*. Finally, we discuss how this procedure and `ASPIC` could be used to determine the best model of inflation by means of Bayesian inference.

Keywords: Cosmic Inflation, Slow-Roll, Reheating, Cosmic Microwave Background, Aspic

ArXiv ePrint: 1303.3787

[1]http://cp3.irmp.ucl.ac.be/~ringeval/aspic.html



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Edited in 2013:

- 74 single-field models
- Accurate calculation of predictions
- Comparison with Planck+2013 data
- Comes with a public library: ASPIC
- Bayesian model comparison
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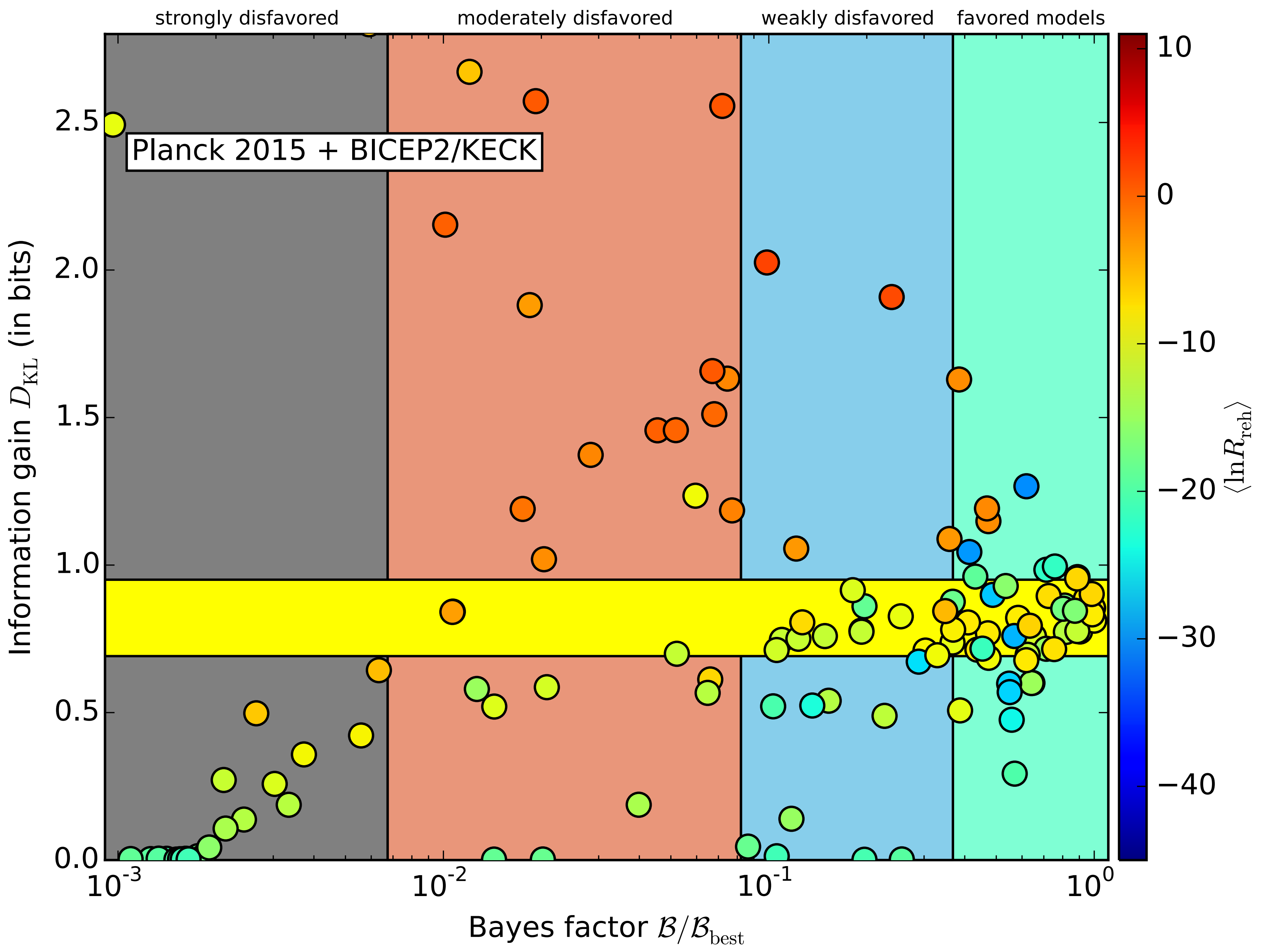
- Used in the PDG, etc.



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New edition in 2023:

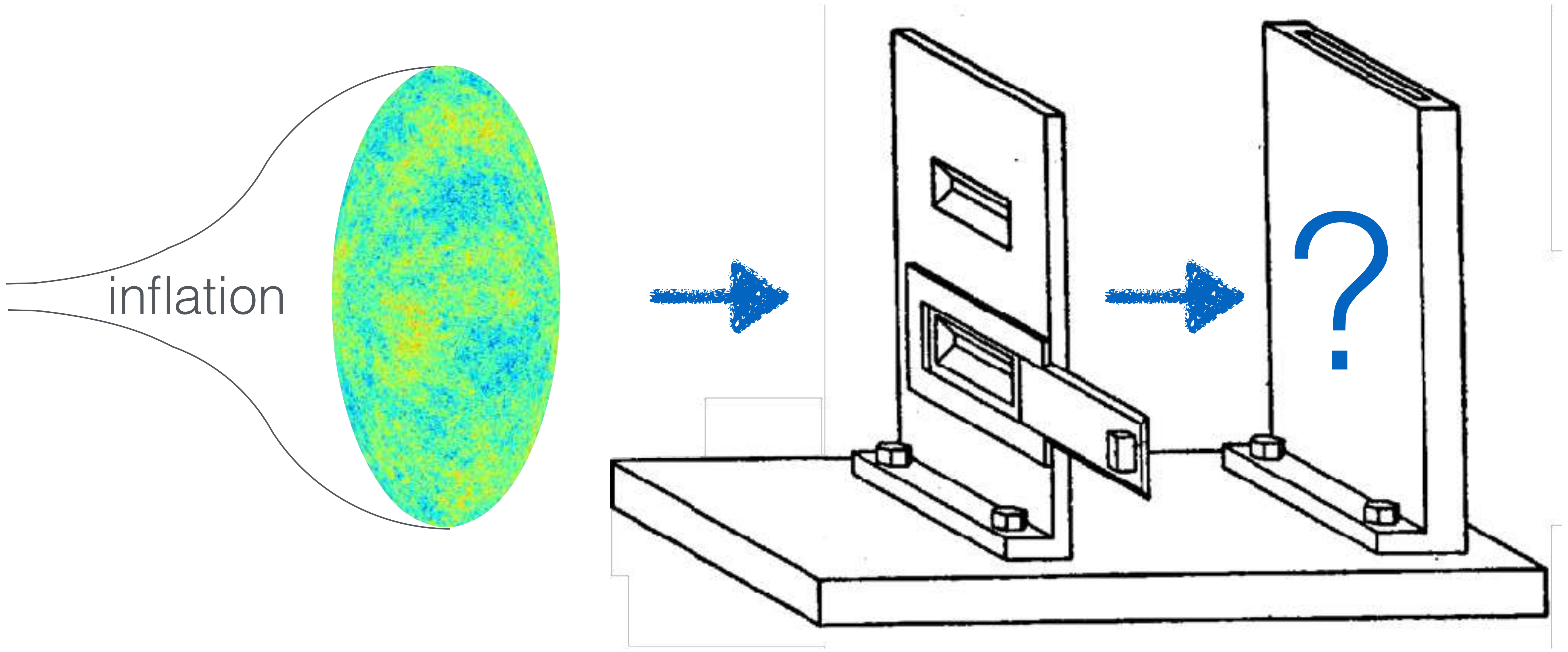
- 46 new models
- Addition of 400 pages
- Comparison with Planck+2018 data
- Updated ASPIC
- Bayesian and reheating analyses: incoming

Quantum aspects of inflationary fluctuations

According to inflation (and most alternatives): cosmic inhomogeneities arise from the gravitational amplification of vacuum quantum fluctuations

- Can we trust QM at cosmological scales?
- Is it legit to quantise metric fluctuations?
- What about the quantum measurement problem?

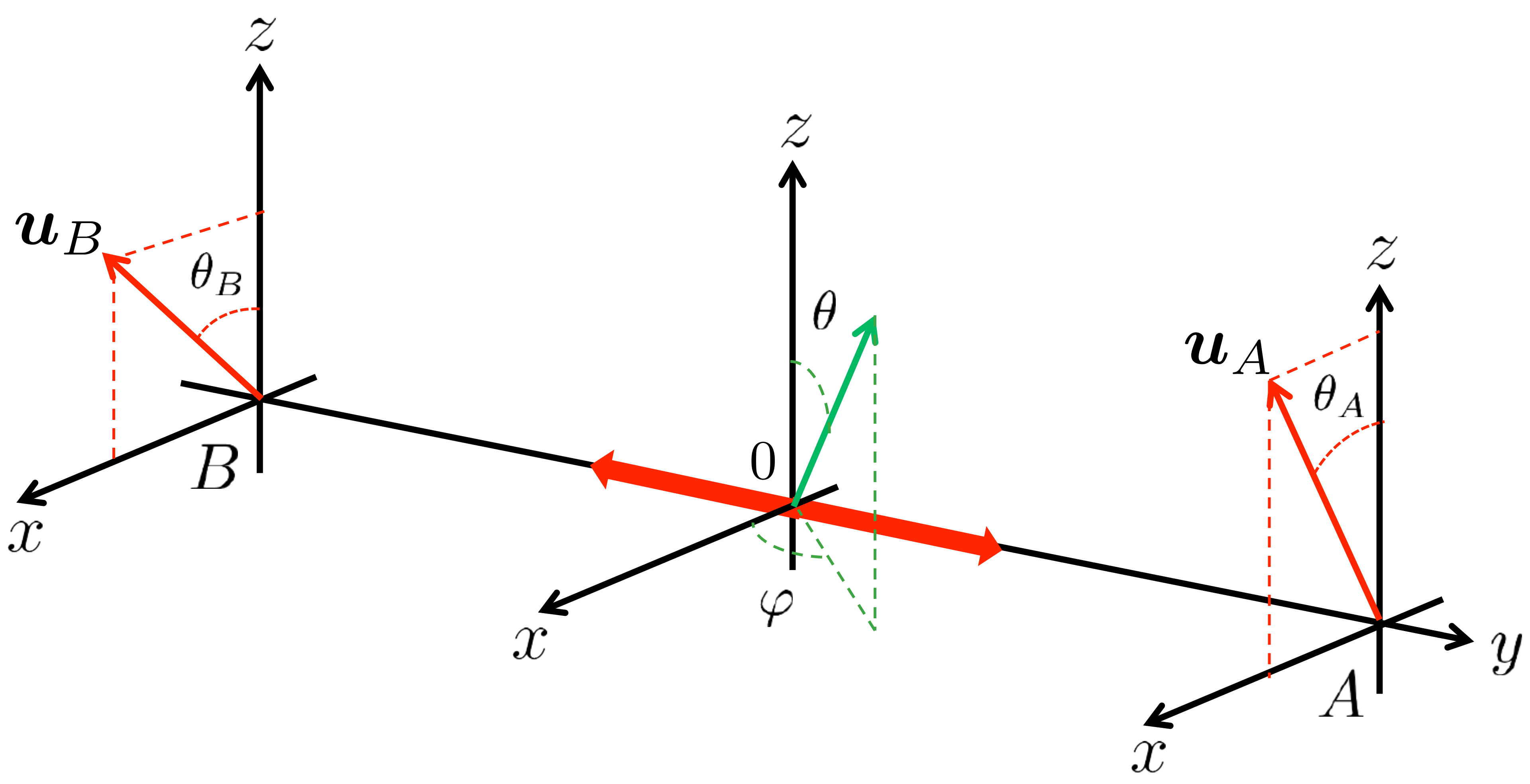
Can we prove that cosmic structures are of quantum mechanical origin?



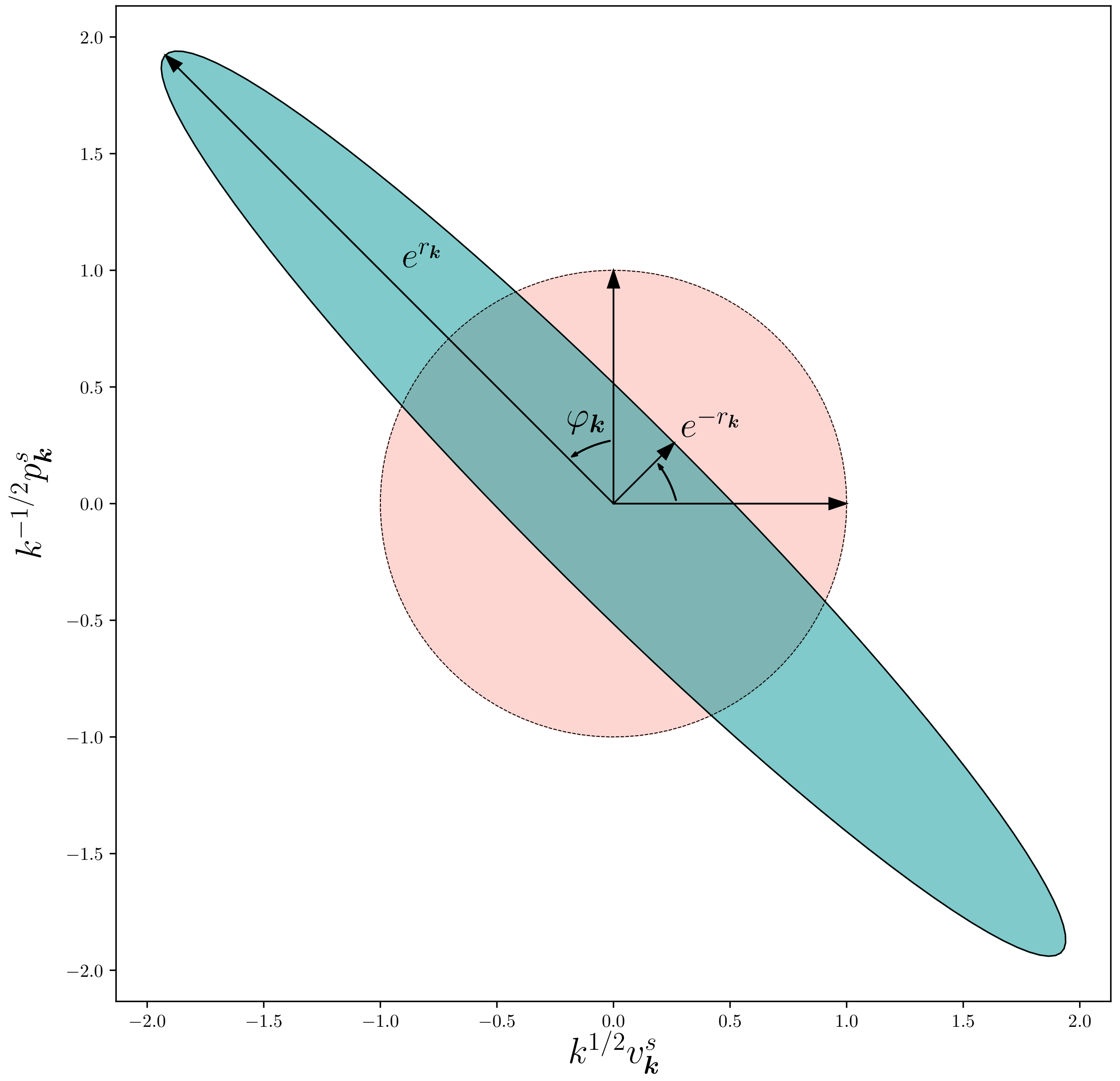
Quantum aspects of inflationary fluctuations

Bell inequalities

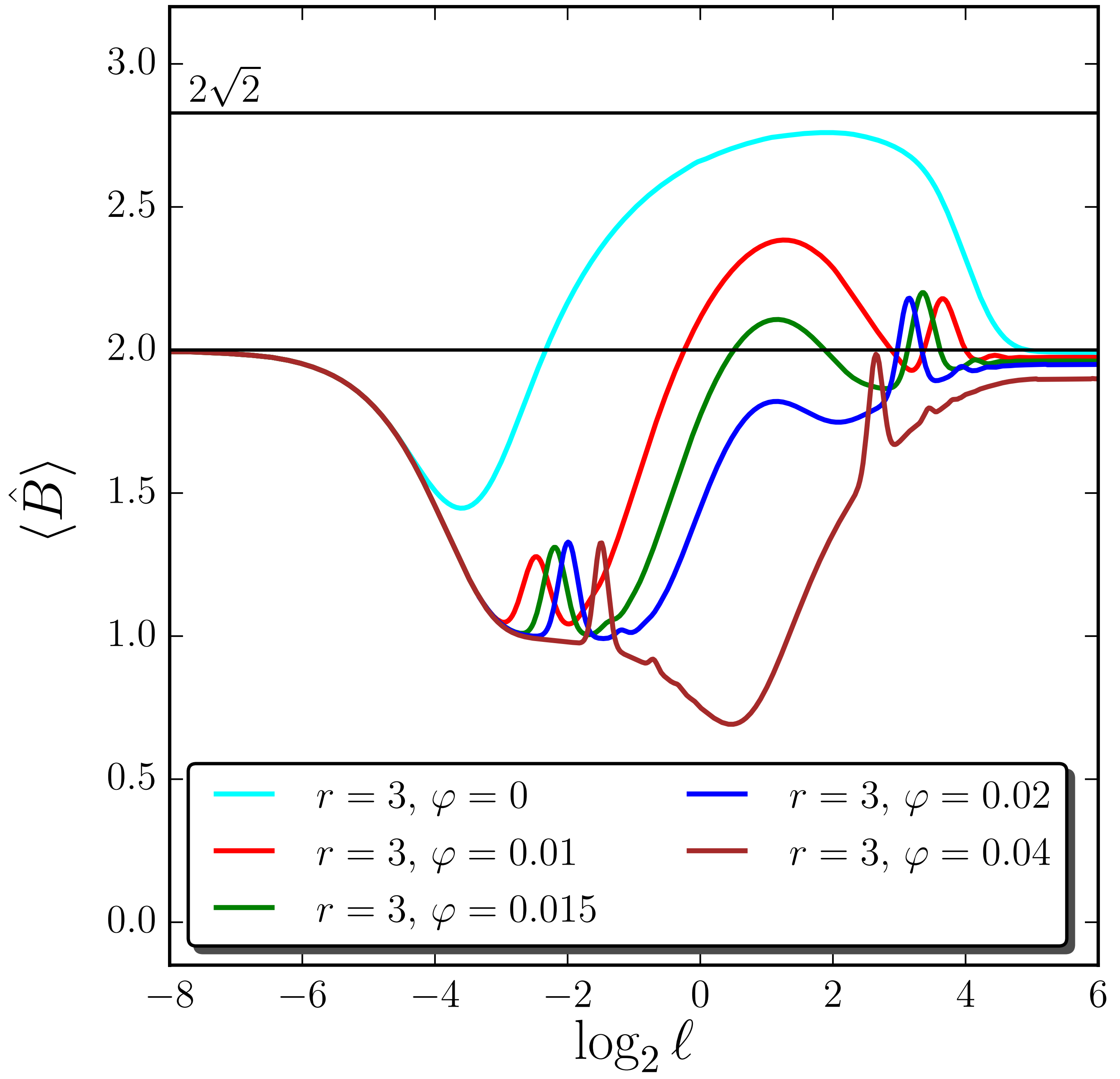
$$\langle \hat{S}_{\theta_a}\hat{S}_{\theta_b}\rangle + \langle \hat{S}_{\theta'_a}\hat{S}_{\theta_b}\rangle + \langle \hat{S}_{\theta_a}\hat{S}_{\theta'_b}\rangle - \langle \hat{S}_{\theta'_a}\hat{S}_{\theta'_b}\rangle \leq 2$$



During inflation, cosmological perturbations are placed in a two-mode squeezed state



J. Martin & VV 2016



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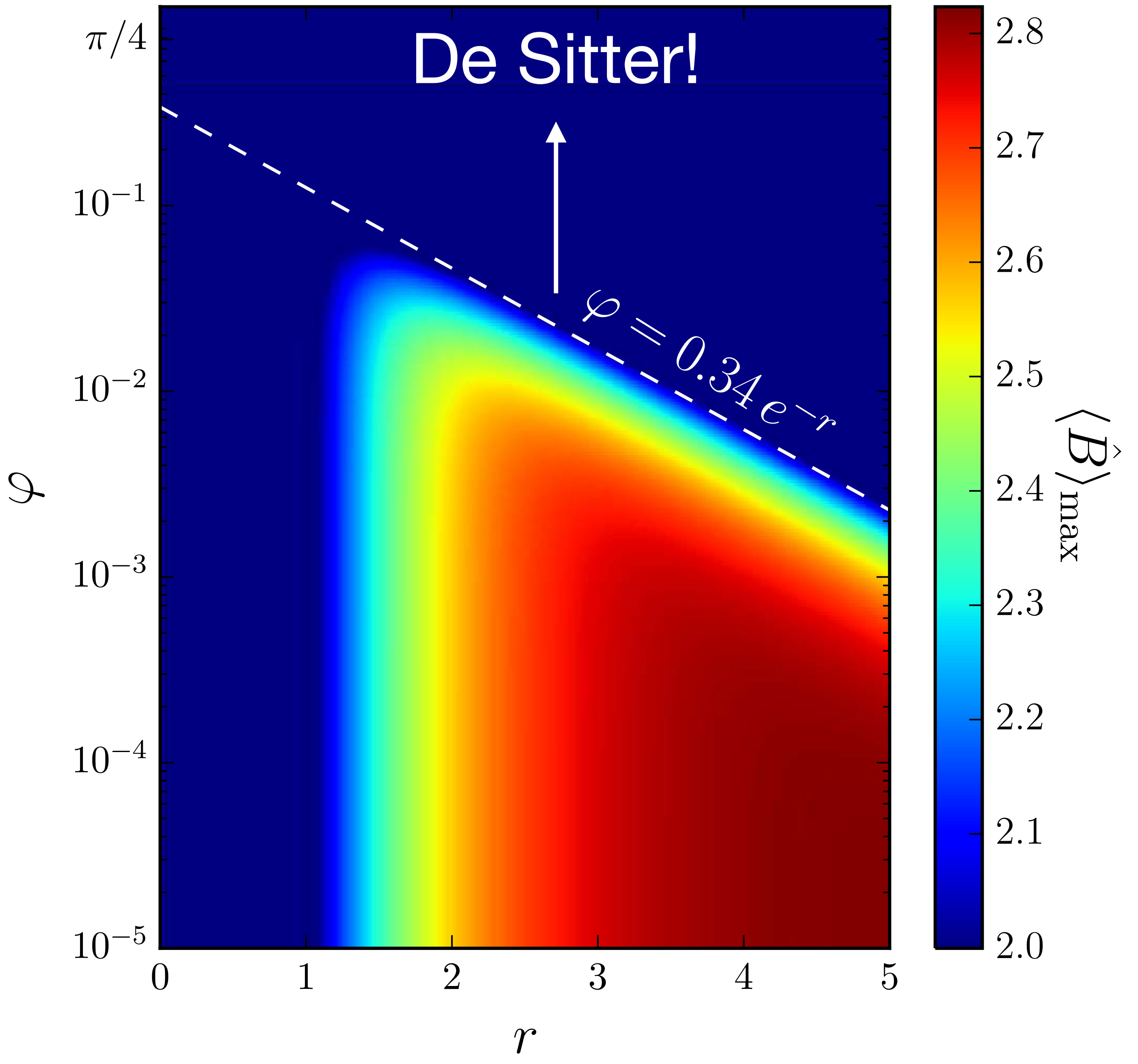


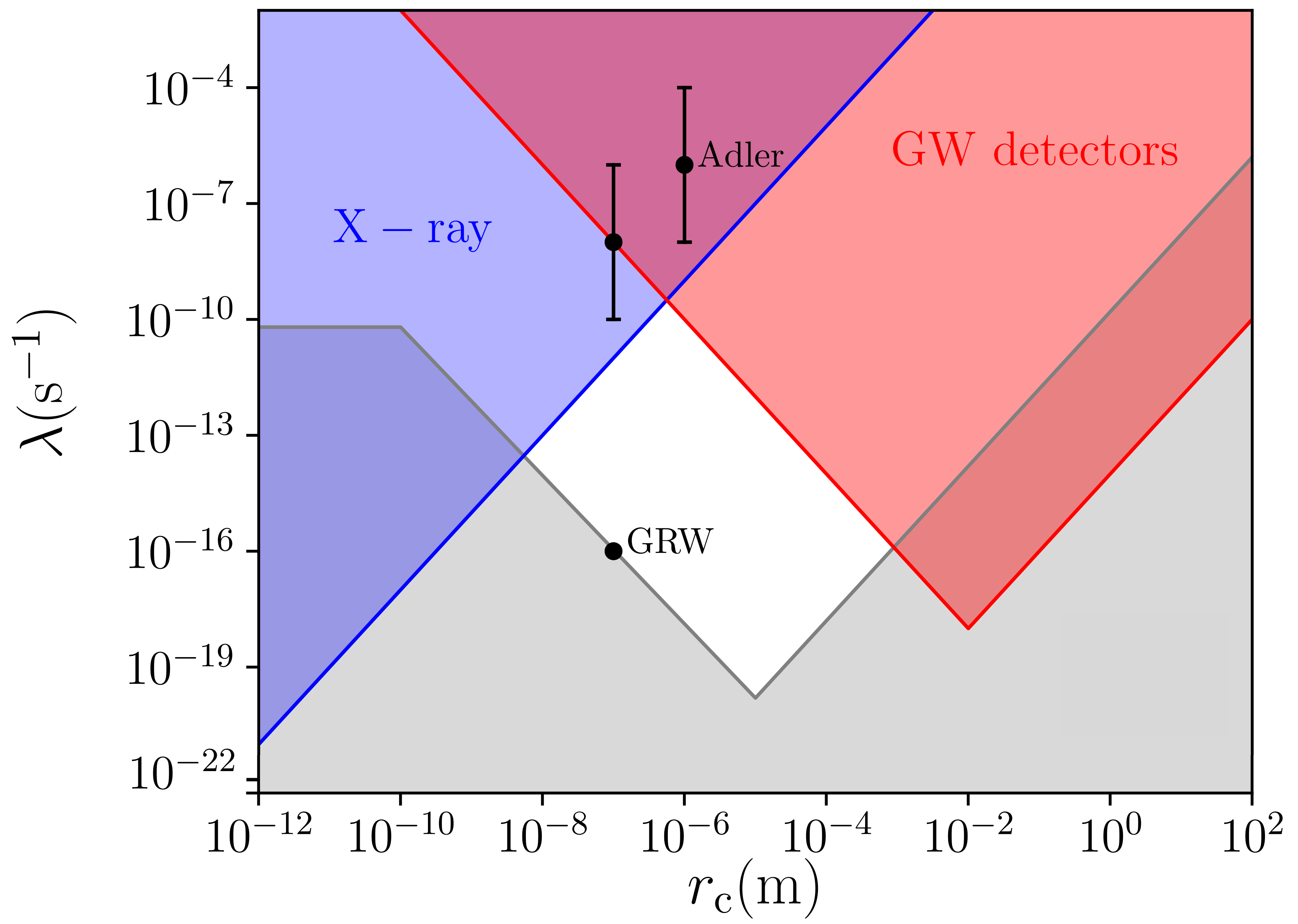
Quantum aspects of inflationary fluctuations

Can we test quantum mechanics itself?

Dynamical collapse models: $\frac{\mathrm{d}|\psi\rangle}{\mathrm{d}t} = -i\hat{H}|\psi\rangle + \gamma\left(\hat{C} - \langle\hat{C}\rangle\right)\xi(t)|\psi\rangle$

- Induces the collapse of the wavefunction
- Leads to the Born rule
- Is endowed with an amplification mechanism
- Has been extensively tested in the lab

Bassi & Ghirardi 2003



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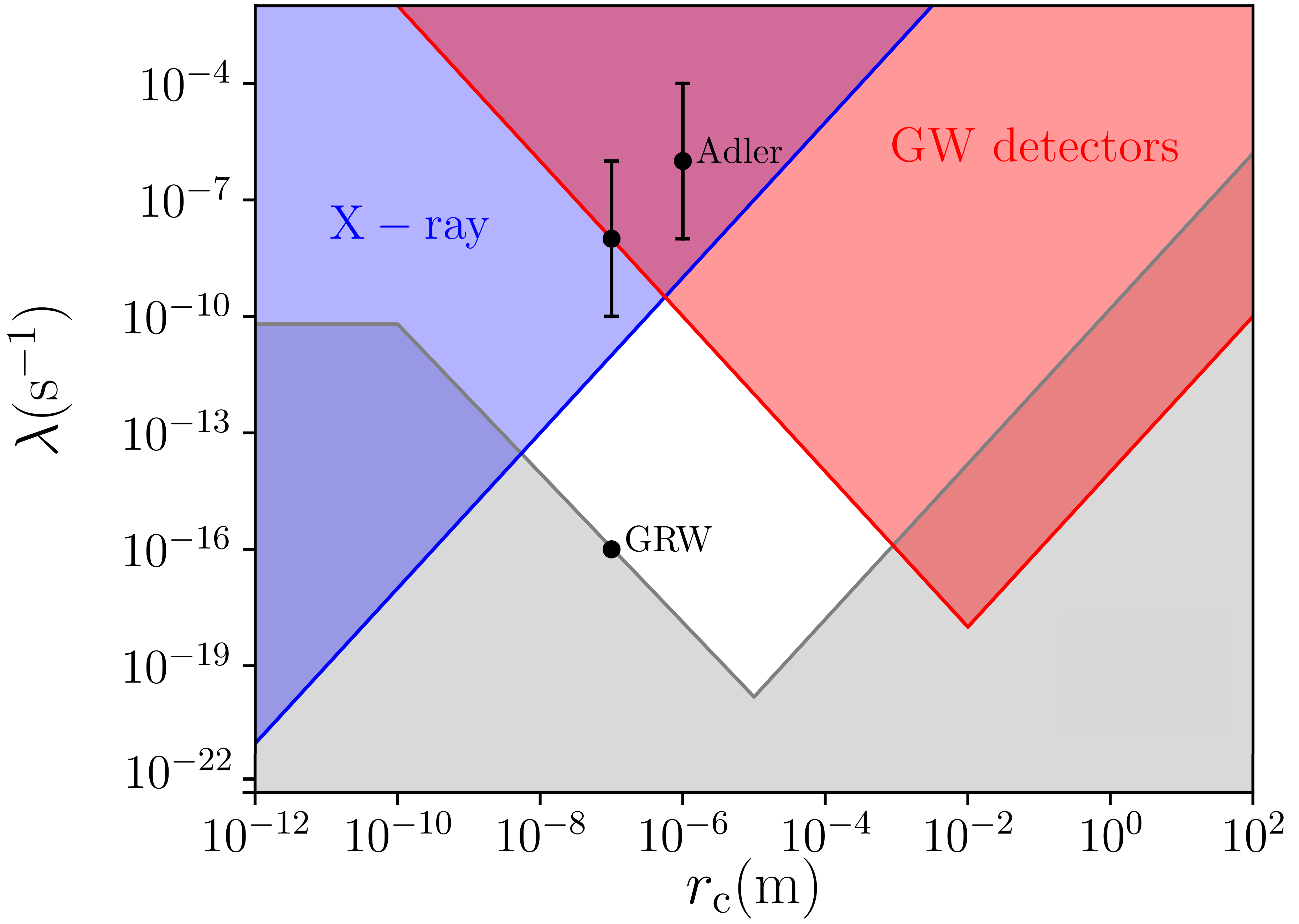
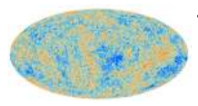


Can this explain how we obtain a single outcome in the early universe?

$|\Psi_{2\,\mathrm{sq}}\rangle = \sum$  $c($  $)|$  $\rangle \rightarrow |$  $\rangle_{\mathrm{Planck}}$

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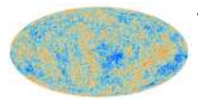
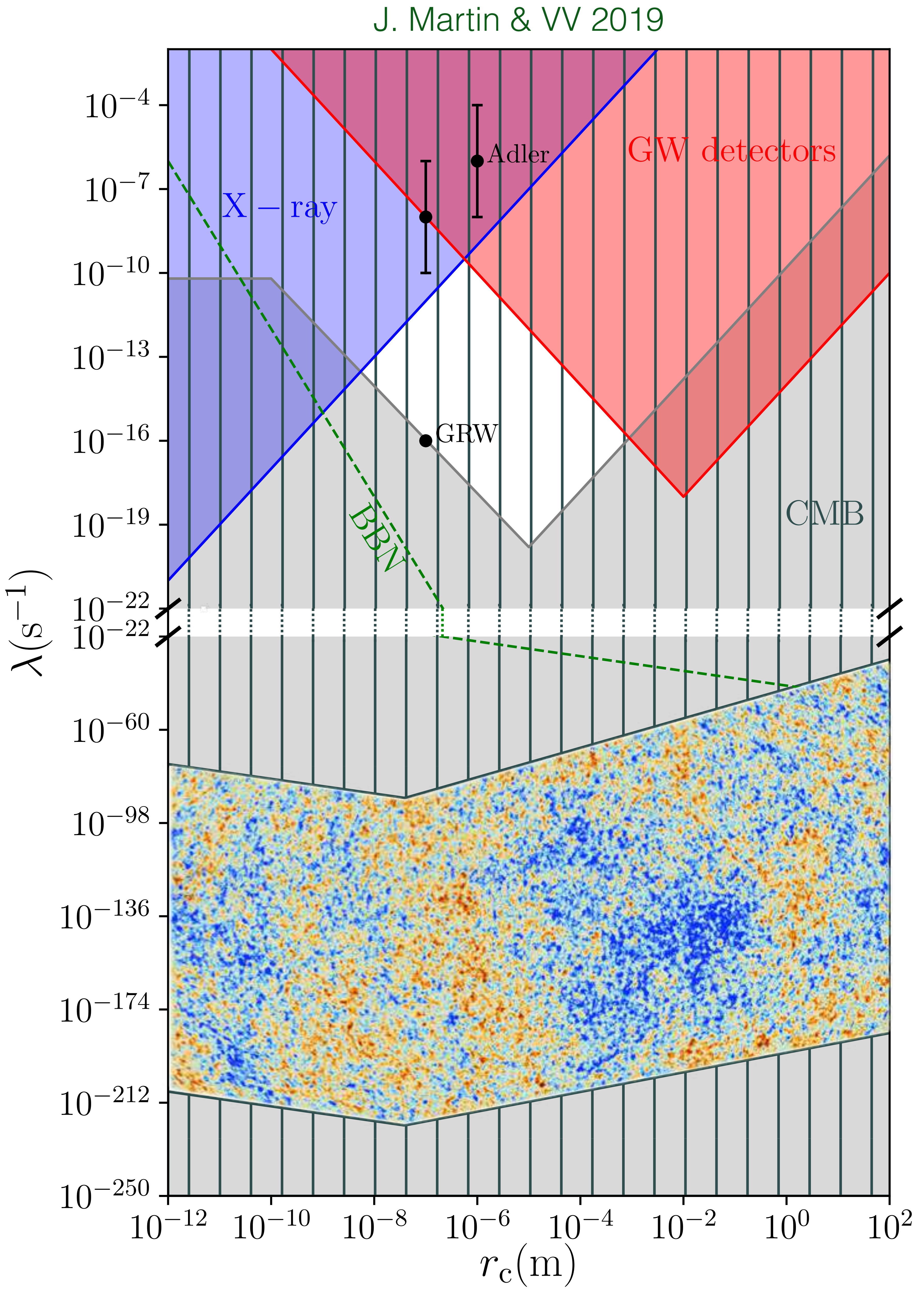
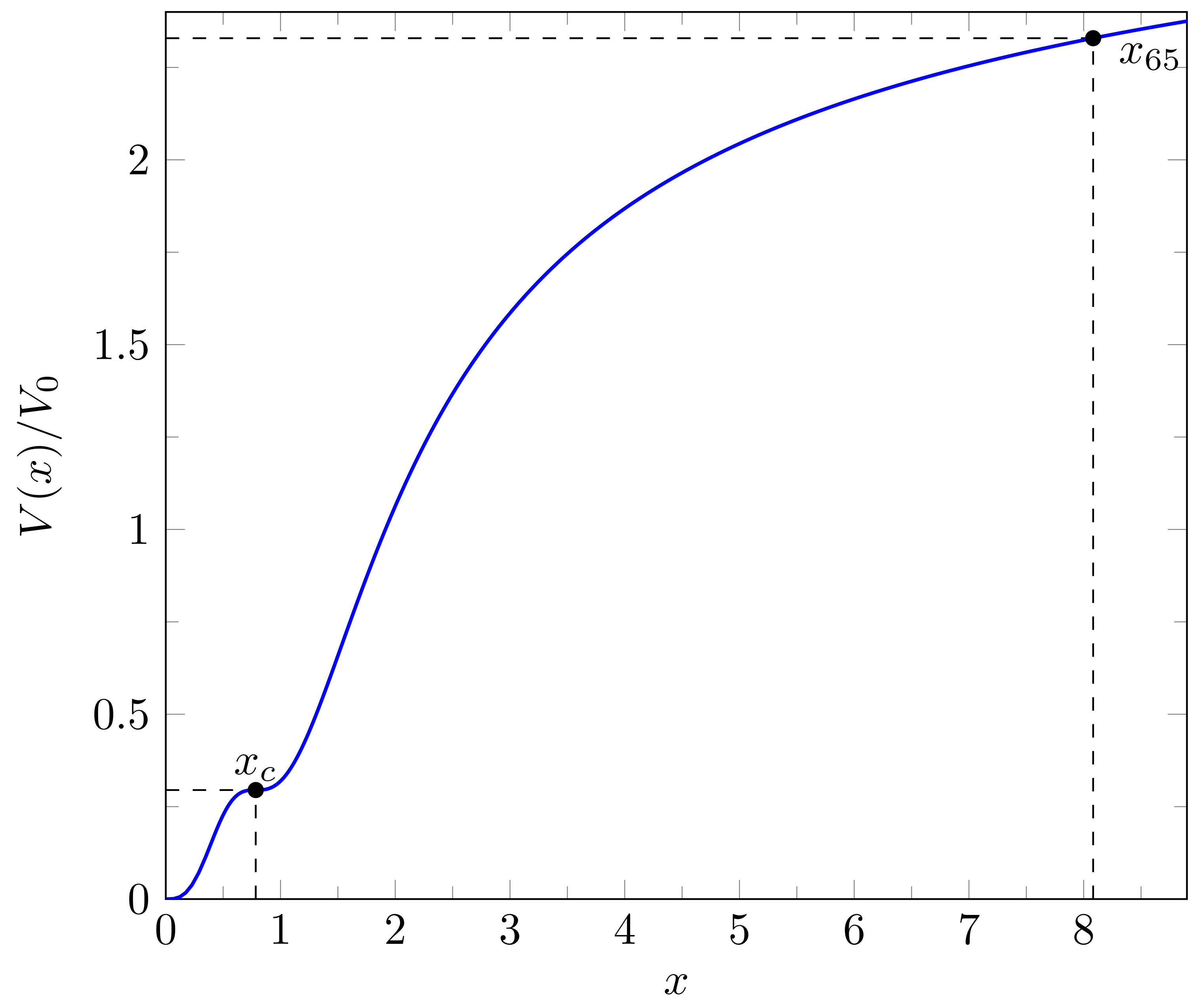
$|\Psi_{2\,\mathrm{sq}}\rangle = \sum$  $c($  $)|$  $\rangle \rightarrow |$  $\rangle_{\mathrm{Planck}}$

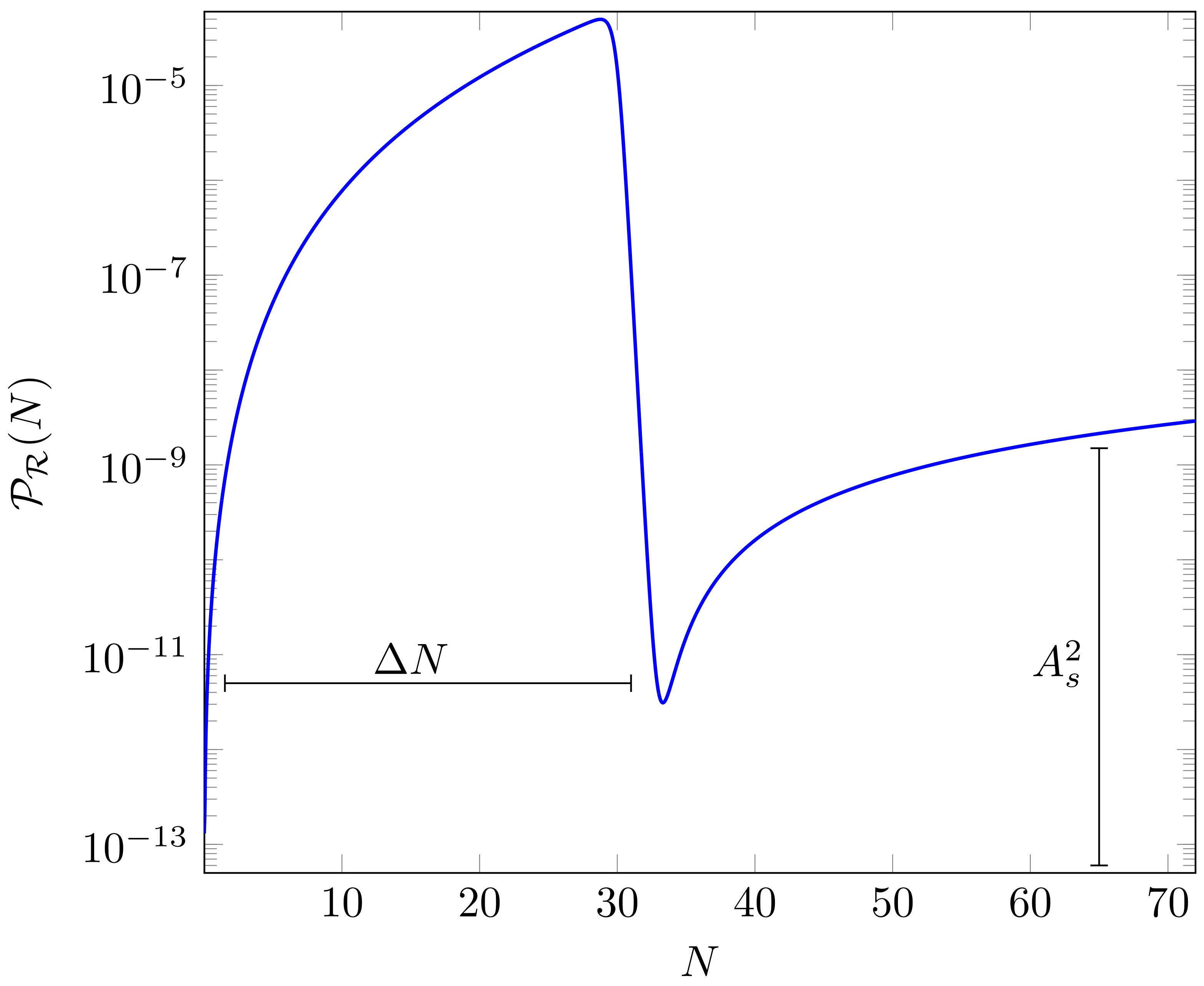


Producing large fluctuations

Example: critical Higgs inflation $\xi(\phi) = \xi_0 + b\ln(\phi/\mu)$

Garcia-Bellido & Ezquiaga 2017



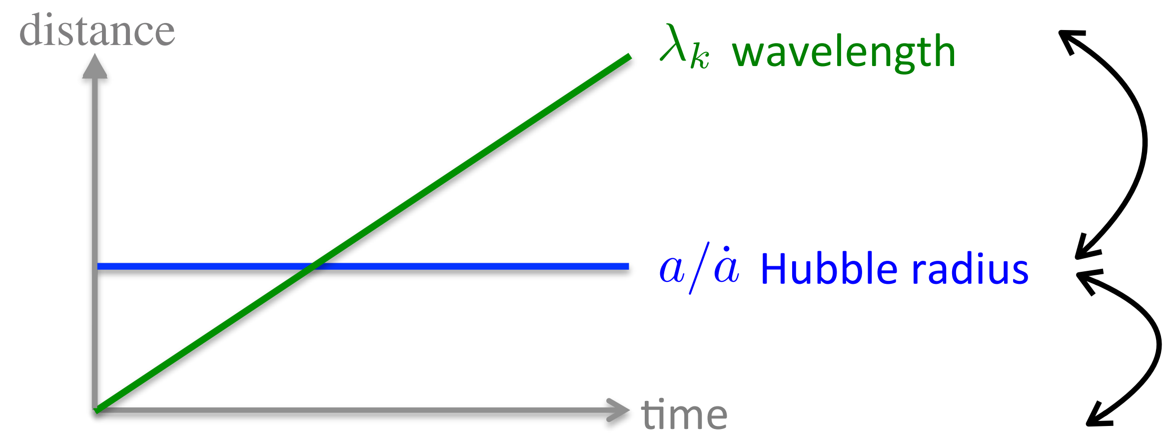


Large fluctuations produced towards the end of inflation might collapse into primordial black holes →

- Dark-matter candidate
- Seed of supermassive black holes
- Catalyst of structure formation
- etc

Producing large fluctuations

How do large fluctuations backreact?



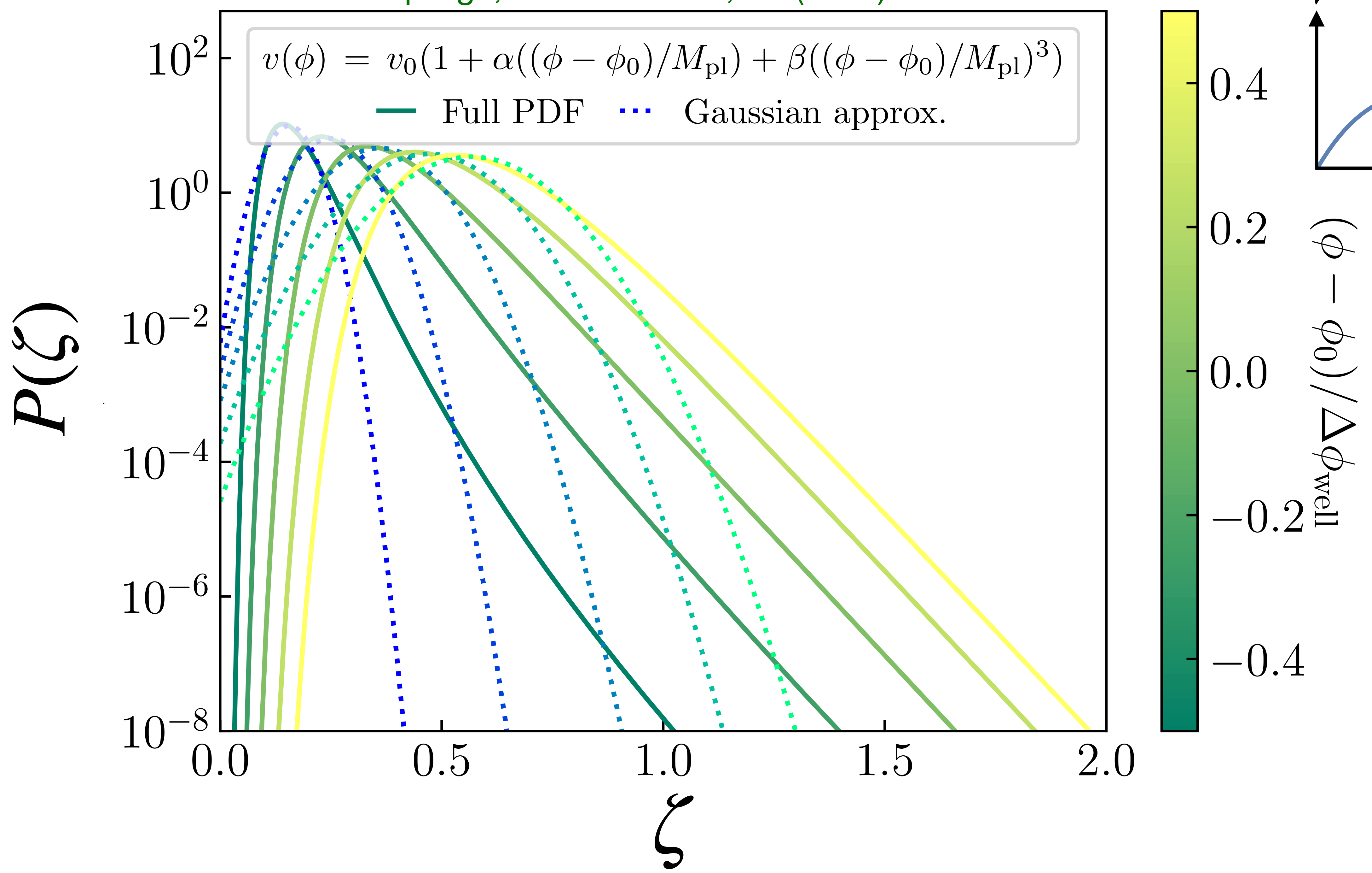
super-Hubble scales —> Stochastic Inflation

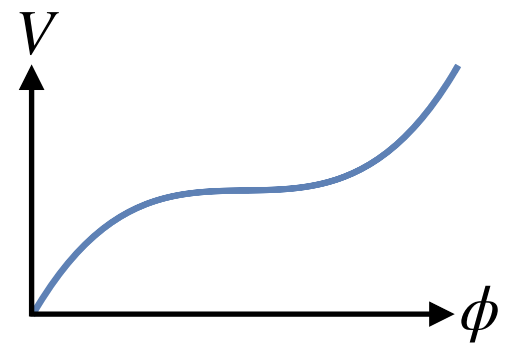
sub-Hubble scales —> Cosmological Perturbation Theory

$$\frac{\mathrm{d}}{\mathrm{d}N}\mathbf{\Phi}_{\mathrm{cg}} = \mathscr{D}_{\mathrm{background}}(\mathbf{\Phi}_{\mathrm{cg}}) + \xi$$

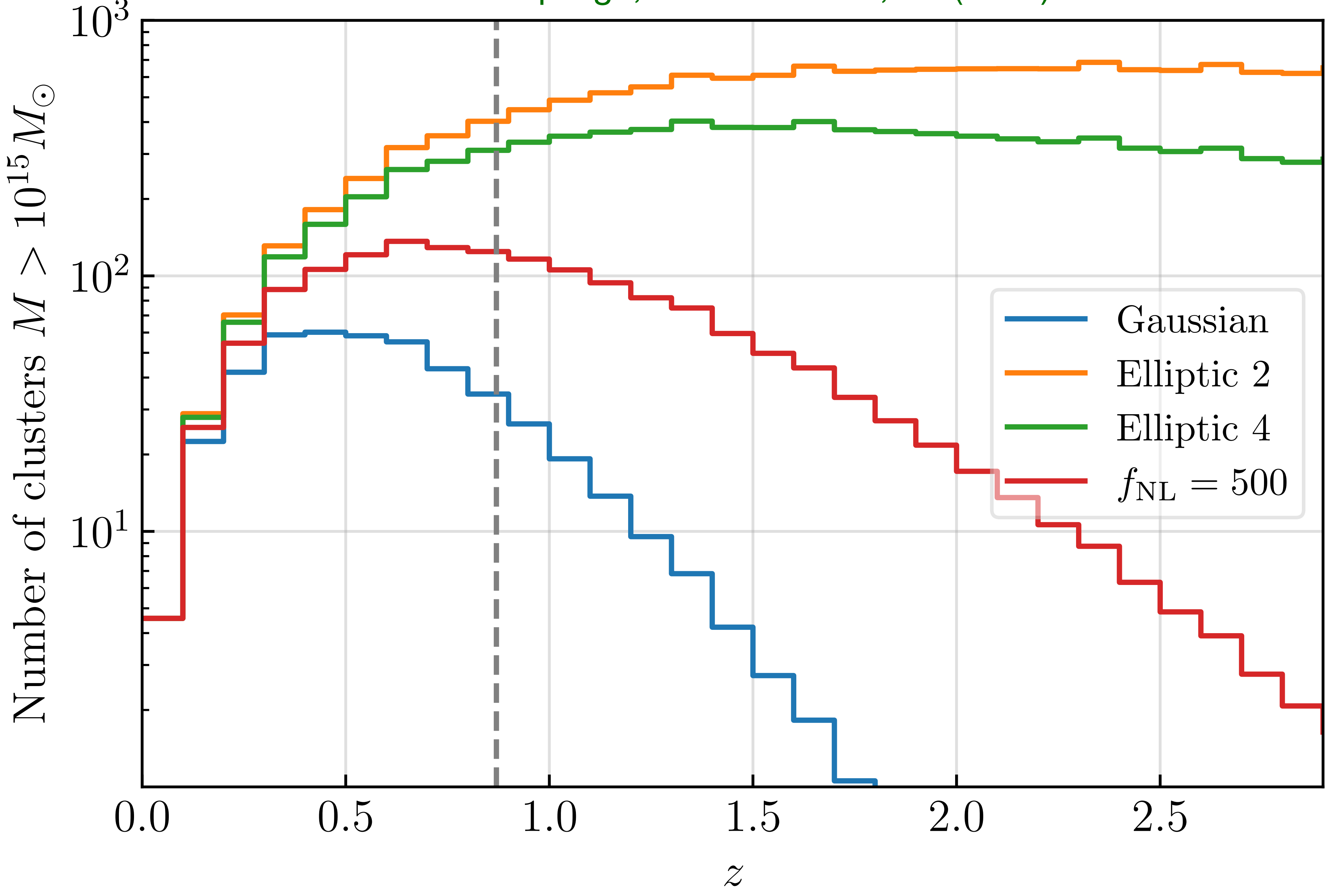
Starobinsky 1986

Pattison, VV, Assadullahi, Wands (2017)
Ezquiaga, Garcia-Bellido, VV (2020)





Ezquiaga, Garcia-Bellido, VV (2022)



Various theoretical challenges…

But exciting observational prospects ahead!

See Josquin Errard’s talk next