Corpuscular Considerations on Cosmological Observables and Eternal Inflation

Florian Kühnel

COSMO-15

Warsaw, 10th of September 2015

work in particular with

Roberto Casadio,
Alessio Orlandi,
Marit Sandstad,
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DG Framework: Classical vs. Quantum

★ Recall: The metric is a classical object

$$g_{\mu\nu}(x)$$

space-time coordinate

★ Now, in quantum theory there are operators acting on states (with certain occupation number N)

$$\hat{a}^{\dagger}\,|0\rangle = |1\rangle$$

DG Framework: Graviton Condensate

★ Key point (see Gia's talk):

> ★ Understand gravitational backgrounds, of characteristic wavelength R, as states on Minkowski space of a certain occupation number N of gravitons.

R being the $R_{\rm S}$ for black holes or $R_{\rm H}$ for cosmology.

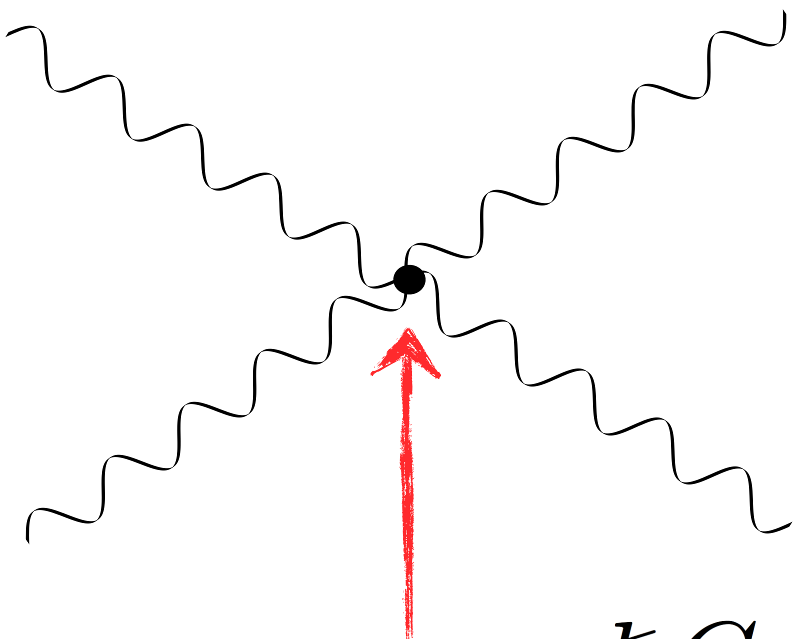
★ Occupation number:

$$N \sim \frac{R^2}{L_{\rm P}^2}$$

(… smells holographic…)

DG Framework: Self-Interaction

★ Gravitational quanta (of General Relativity), gravitons, have mass m = 0 and spin = 2, with momentum-dependent self-interactions.



★ Quantum entities:

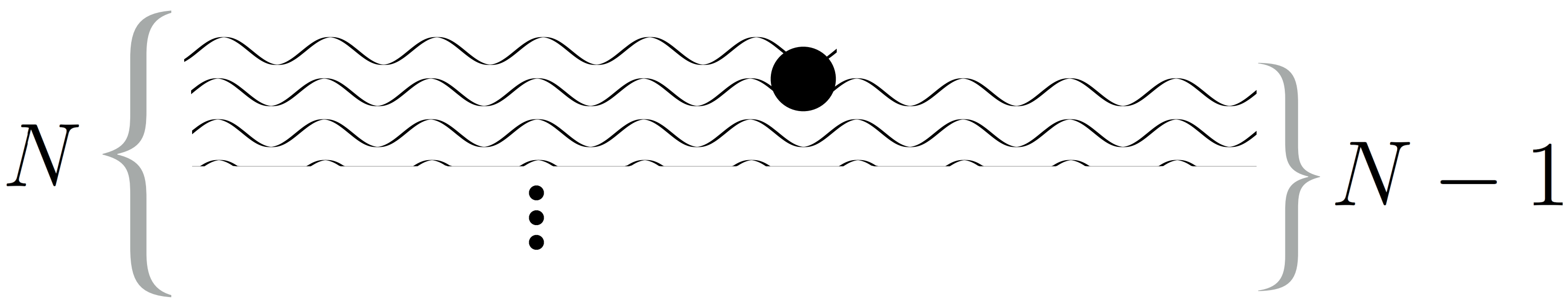
$$L_{\mathrm{P}} = \sqrt{\hbar G_N} \;, \qquad M_{\mathrm{P}} = \frac{\hbar}{L_{\mathrm{P}}}$$

$$\alpha \sim \frac{\hbar G_{\mathrm{N}}}{\lambda^2} \qquad \Rightarrow \qquad \alpha = \frac{L_{\mathrm{P}}^2}{\lambda^2}$$

★ Classical limit: $\left(L_{\mathrm{P}},\ M_{\mathrm{P}},\ \alpha\right) \xrightarrow{\hbar \to 0} 0$

DG Framework: Hawking Radiation

★ Quantum depletion:



$$\rightarrow \quad \frac{\mathrm{d}N}{\mathrm{d}t} \sim -\frac{1}{\sqrt{N}} + \mathcal{O}\left(N^{3/2}\right)$$

(in Planck units) or, with $M \sim \sqrt{N}$

$$\rightarrow \quad \boxed{\frac{\mathrm{d}M}{\mathrm{d}t} \sim -M^{-2}} \quad \rightarrow$$

Hawking's result at leading order in $1/N$!

★ Note that particle creation is not a vacuum process!

DG Framework: N-Portrait

★ States are characterised by a single number

$$\boxed{N}$$

DG Framework: N-Portrait

★ States are characterised by a single number

$$\boxed{N}$$

★ Mass: $$M = \sqrt{N}$$

★ Wavelength: $$\lambda = \sqrt{N}$$

★ Coupling: $$\alpha = \frac{1}{N}$$

DG Framework: From Classical to Quantum

★ Overview:

1. Classical: $\hbar = 0$, $\dfrac{1}{N} = 0$

DG Framework: From Classical to Quantum

Oskar Klein centre

★ Overview:

1. Classical: $\hbar = 0 \ , \ \dfrac{1}{N} = 0$

2. Semi-Classical: $\hbar \neq 0 \ , \quad \dfrac{1}{N} = 0$

   (Background cannot be resolved)

DG Framework: From Classical to Quantum

★ Overview:

1. Classical: $\hbar = 0 \ , \ \frac{1}{N} = 0$

2. Semi-Classical: $\hbar \neq 0 \ , \ \frac{1}{N} = 0$

   (Background cannot be resolved)

3. Quantum: $\hbar \neq 0 \ , \ \frac{1}{N} \neq 0$

   (Background can be resolved)

   a) $\alpha N \neq 1$ (non-critical systems)

   b) $\alpha N = 1$ (critical systems)

DG Framework: From Classical to Quantum

★ Overview:

1. Classical: $\hbar = 0 \ , \ \dfrac{1}{N} = 0$

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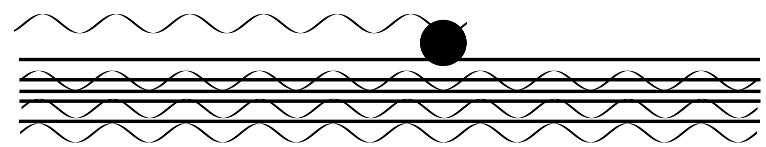
DG Framework: Inflatons

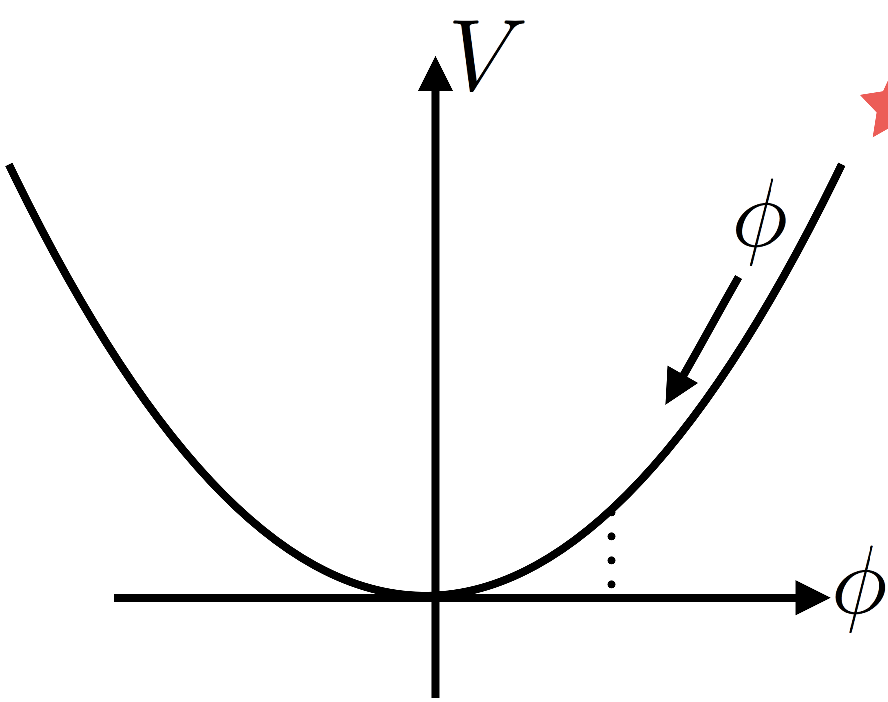
★ What does adding extra species, e.g. inflatons, do?



→ Enhancement $$\frac{\mathrm{d}N_{\mathrm{grav},\,\phi}}{\mathrm{d}t} \sim \frac{\mathrm{d}N_{\mathrm{grav}}}{\mathrm{d}t}\,\boxed{\frac{N_\phi}{N_{\mathrm{grav}}}}$$

★ While for gravitons $N_{\mathrm{grav}} \sim R_{\mathrm{H}}^2$, we have far more inflatons during inflation:

$$\frac{N_\phi}{N_{\mathrm{grav}}} \sim \frac{1}{\sqrt{\varepsilon}}$$



$$\ddot{\phi} + 3\,H\,\dot{\phi} + V' = 0$$

$$\eta = \frac{V''}{V}$$

$$\varepsilon = \left(\frac{V'}{V}\right)^2$$

DG Framework: Time Evolution

- Time evolution:

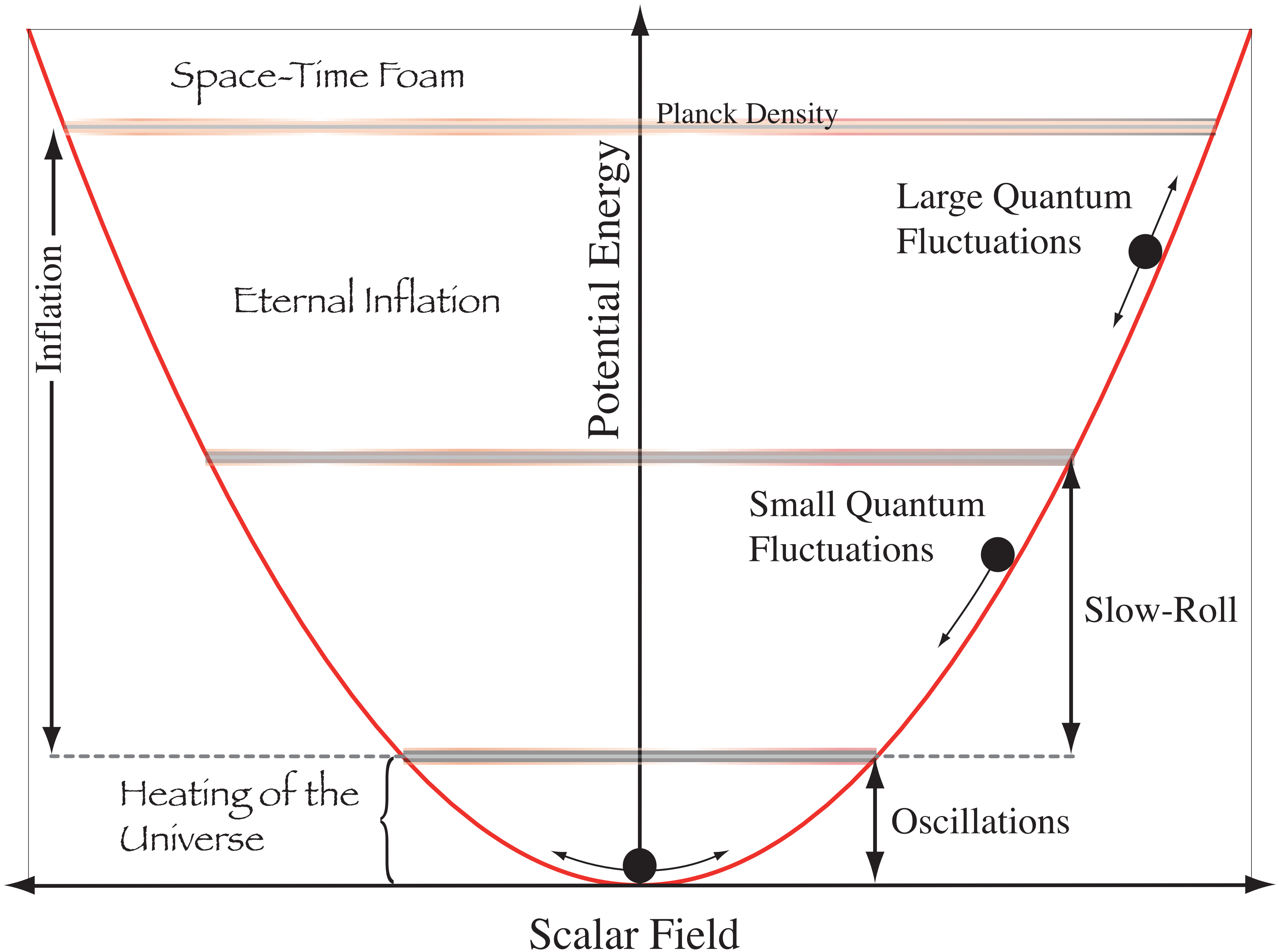
$$\frac{\dot{N}}{N} \sim \varepsilon H - \frac{1}{\sqrt{N}}$$

- Two clocks: classical and quantum

(refilling the reservoir) (emptying the reservoir)

→ Limit on the total number of e-foldings!

Corpuscular Eternal Inflation?



Corpuscular Eternal Inflation?

- ★ Three contributions for $\mathrm{V} = \lambda_n \, \phi^n$
  - ★ typical quantum jumps:

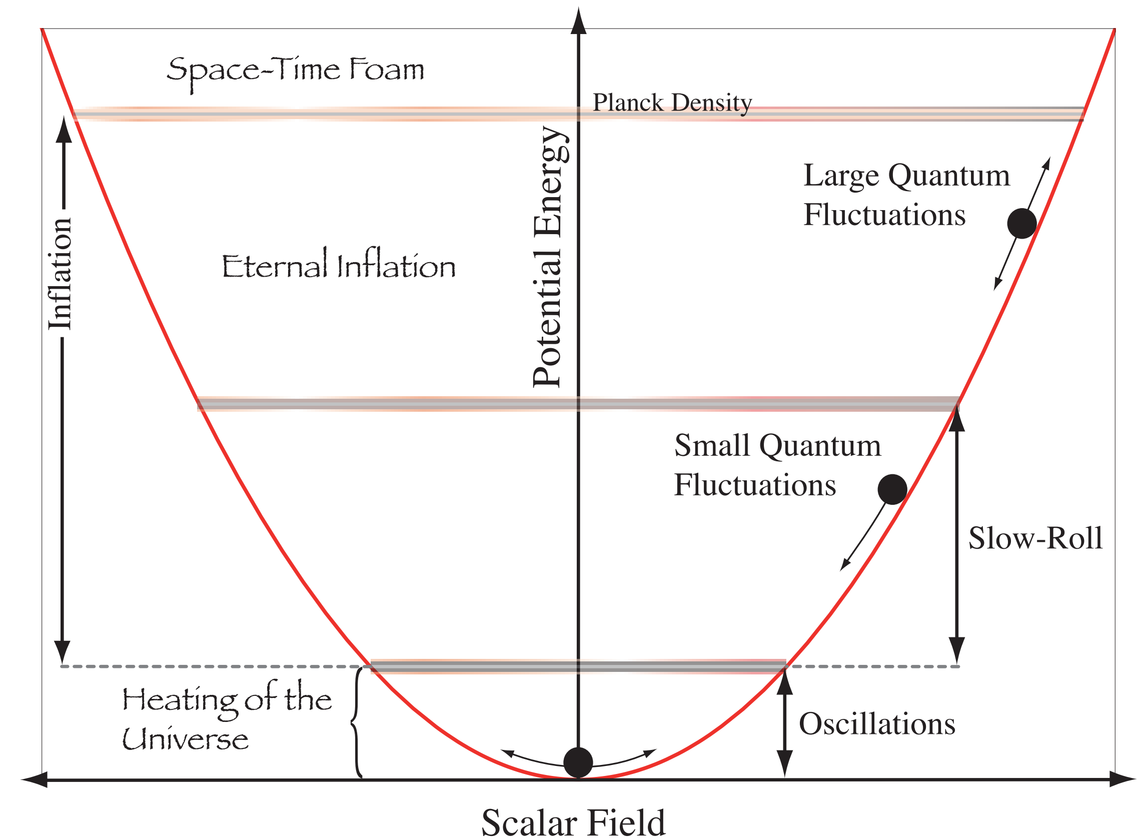
$$\dot{N}_{\rm qf} \simeq \frac{n}{2\pi} \sqrt[n]{\frac{\lambda_n}{3\,n!}}\, N^{\frac{1}{n}}$$

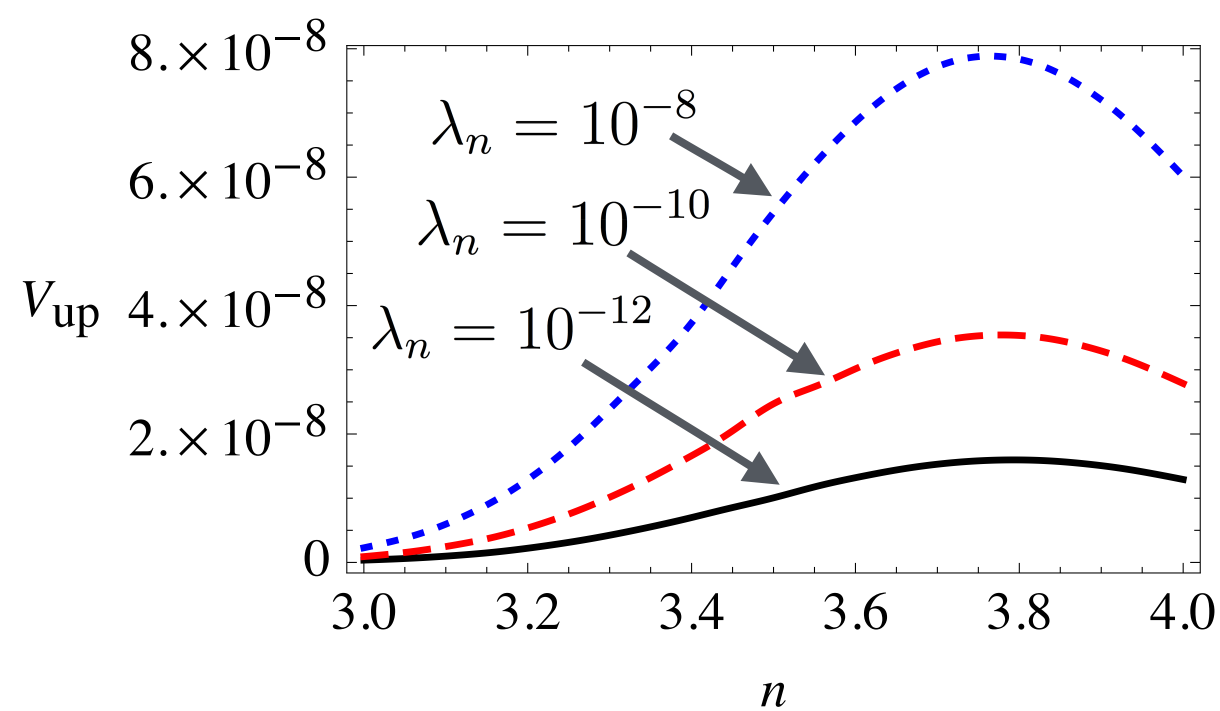
  - ★ quantum depletion:

$$\dot{N}_{\rm dep} \simeq \sqrt{\frac{3}{n|n-1|}}\, \sqrt[n]{\frac{3\,n!}{\lambda_n}}\, N^{-\frac{2+n}{2n}}$$

  - ★ classical drift:

$$\dot{N}_{\rm cl} \simeq n^2 \left(\frac{\lambda_n}{3\,n!}\right)^{\frac{2}{n}} N^{\frac{4+n}{2n}}$$



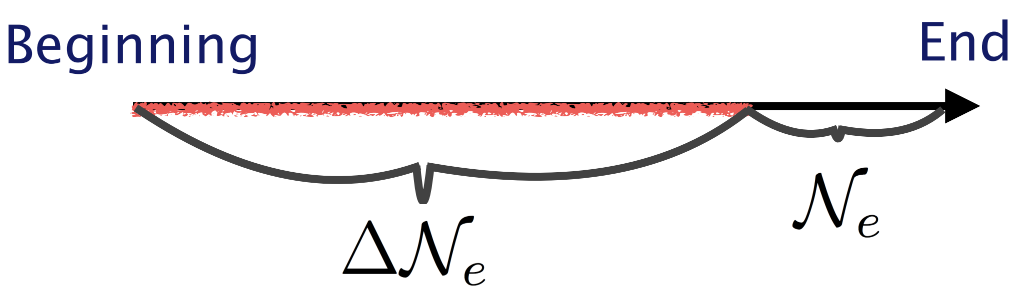


Corrections to Cosmological Observables

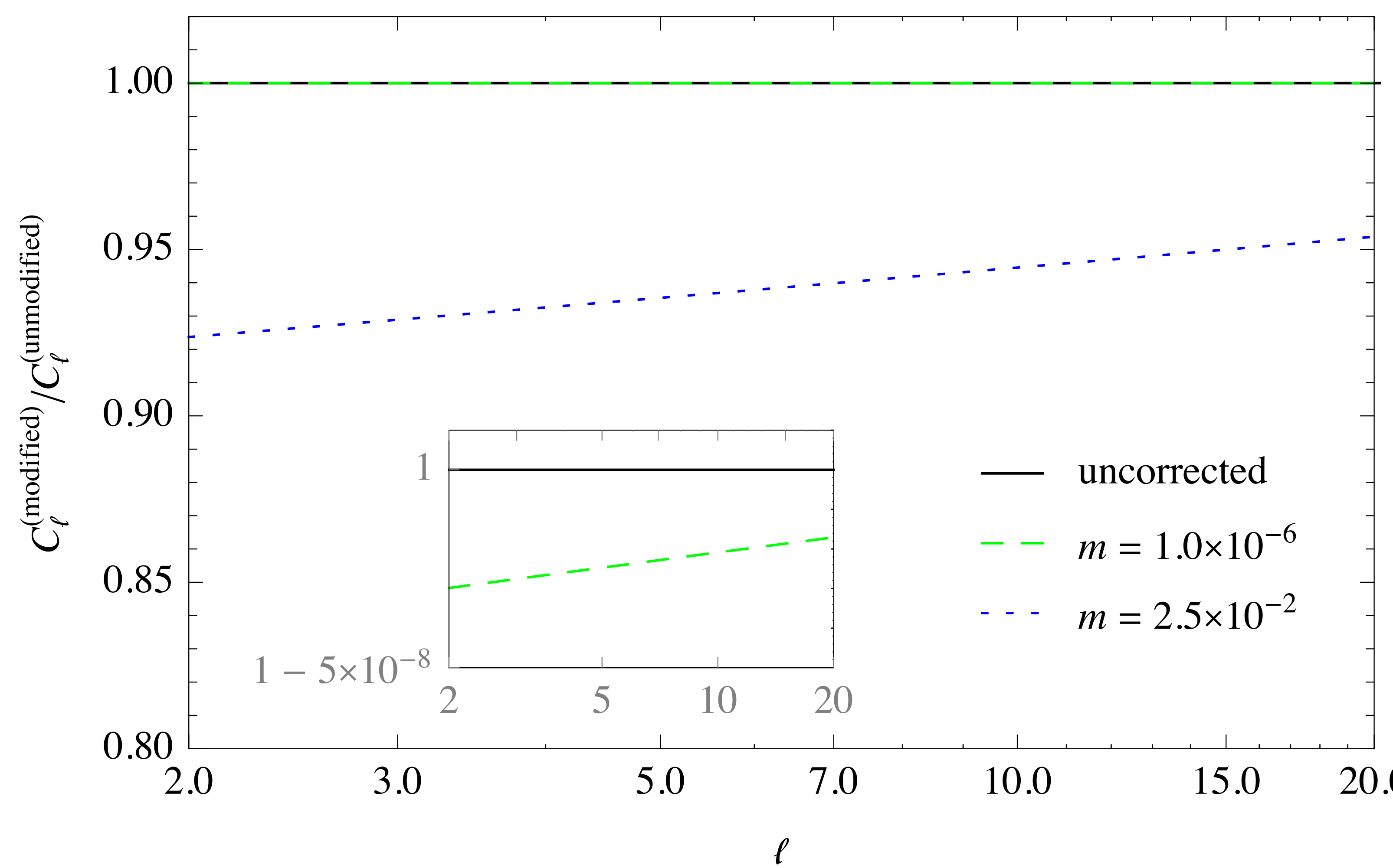
★ Quantum depletion can have strong impacts on observables:

[Dvali-Gomez '14]

$$r \simeq \frac{N}{N_\phi}\left[1 - \boxed{\frac{\Delta\mathcal{N}_e}{N}}\right] \qquad\qquad (1 - n_s) \simeq \frac{3}{2}\varepsilon - \eta - \boxed{\frac{1}{\sqrt{\varepsilon}\, N}}$$



★ … and also on CMB multipole moments:



Tensor-to-Scalar ratio

Oskar Klein centre

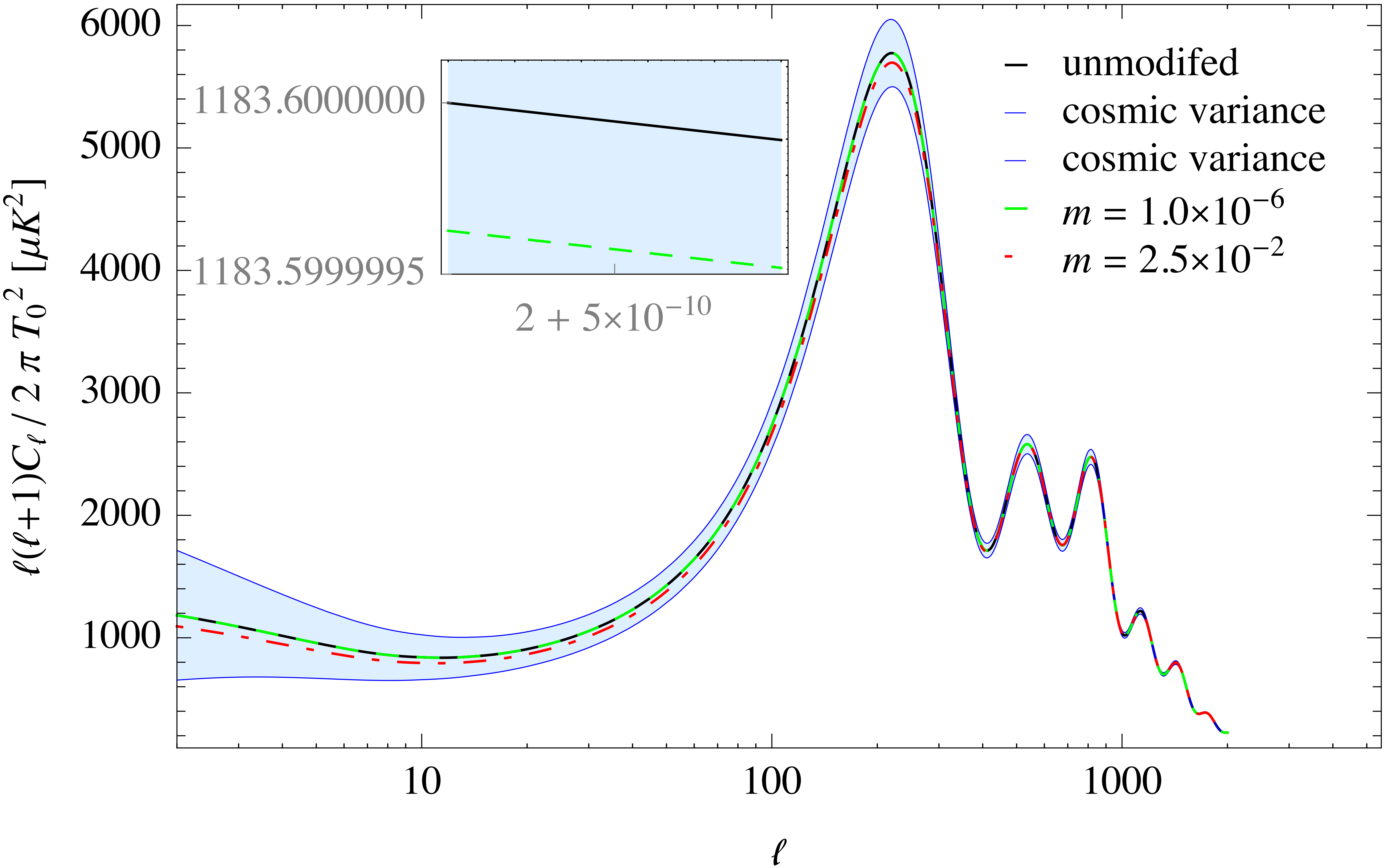
★ The inflatons increase the number of depletion channels

→ Leads to a faster depletion rate and naturally explains a small tensor-to-scalar ratio…

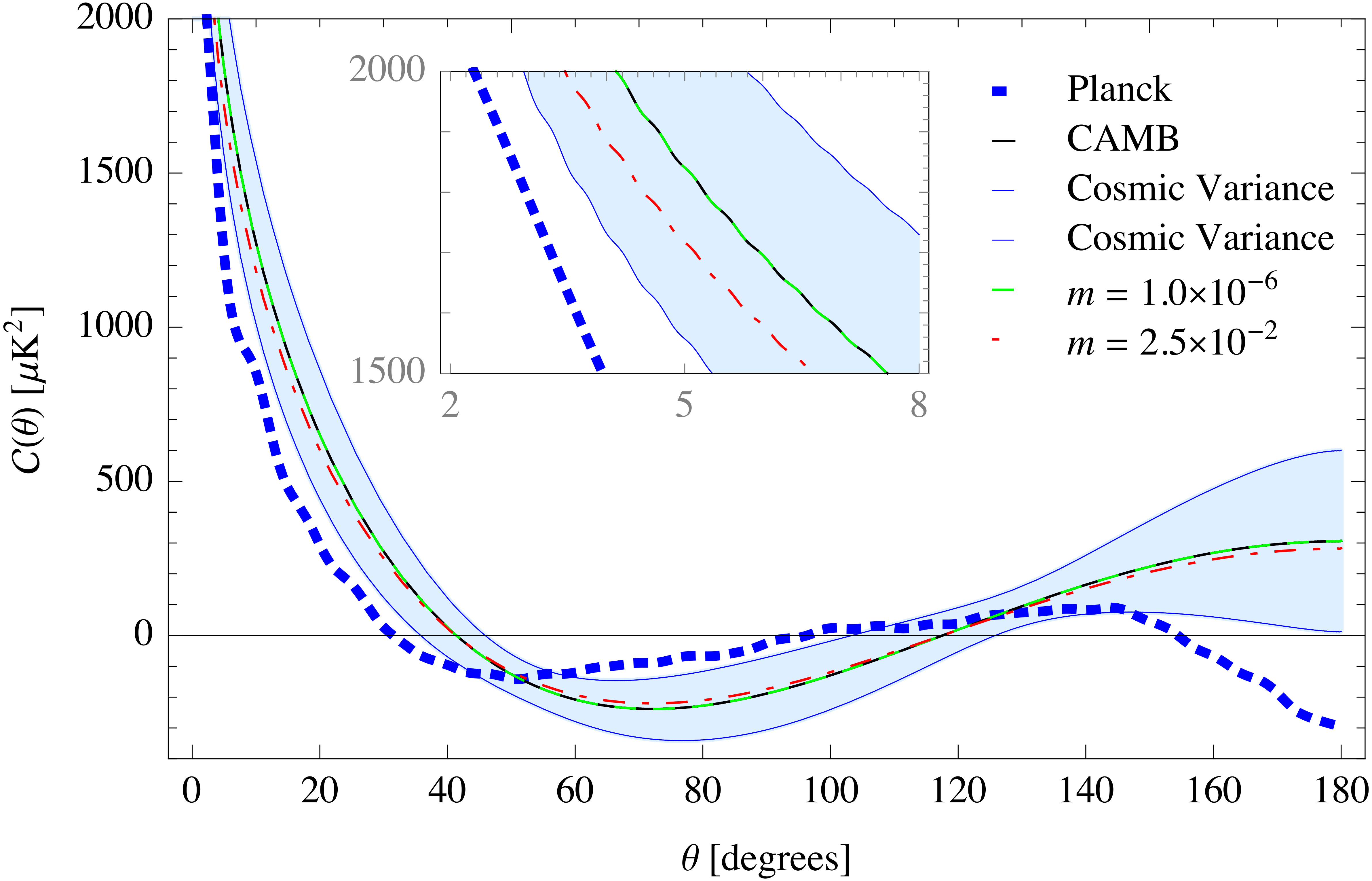
★ … which is furthermore suppressed with the mass scale:

$m[m_{\rm p}]$ / ratio	10^{-6}	10^{-5}	10^{-4}	10^{-3}	$5\cdot 10^{-3}$	10^{-2}	$1.5\cdot 10^{-2}$	2×10^{-2}
corrected / uncorrected	1	1	1	0.93	0.43	0.25	0.18	0.14

Power Spectrum



Angular Temperature Auto-Correlation



Primordial Black Holes (PHBs)

★ PBHs are black holes formed in the (very) early Universe.

★ Possibly formed by: inhomogeneity, bubble collisions, cosmic strings, domain walls, ...

★ Probe a huge range of scales:

$M \sim 10^{-5}$g: Quantum gravity (Planck relics, Brane cosmology, TeV QG, ...)
$M \lesssim 10^{15}$g : Early Universe (Baryogenesis, Nucleosynthesis, Reionisation, ...)
$M \sim 10^{15}$g : High-energy physics (Ultra-high cosmic rays, ...)
$M \gtrsim 10^{15}$g : Gravity (CDM, gravitational waves, LSS, BH in galactic nuclei, ...)

★ Connection to critical phenomena [Choptuik '93]:

density contrast

$$\frac{M_{BH}}{M_H} = K(\delta - \delta_c)^\gamma$$

horizon mass

★ Now add baryons and consider the master equations:

[Dvali–Gomez '13]

$$\dot{N} \simeq -\frac{1}{L_{\mathrm{P}}\sqrt{N}} \qquad \text{gravitons}$$

$$\dot{N}_{\mathrm{B}} \simeq -\frac{1}{L_{\mathrm{P}}\sqrt{N}}\frac{N_{\mathrm{B}}}{N} \qquad \text{baryons}$$

→ For $N_{\mathrm{B}} \ll N$ the graviton depletion rate will be much larger than that of the baryons.

→ Baryon density increases till a critical value is reached.

→ Formation of a new state!

Corpuscular Primordial Black Holes

Oskar Klein centre

- Predictions (for $n_c \equiv 1\,\text{baryon}/\text{fm}^3$):
  - Mass: $M \simeq 3 \cdot 10^{23}\,\text{kg}$
  - Formation time: $t_{\text{form}} \sim 10^{-12}\text{s}$

- Applied to astrophysical black-hole formation, using the same critical baryon density, and estimating $N_{B,\text{initial}} \sim M_{\text{Star}}/M_{\text{Proton}}$

→ Lowest possible mass of the bound state

$$M \geq \frac{c^3}{4}\sqrt{\frac{3 \cdot 10^{57}}{2\pi\, M_\odot\, n_c}}\; G_{\text{N}}^{-3/2} \approx 3\, M_\odot$$

which roughly reproduces the Chandrasekhar limit!