Primordial black holes as dark matter: the role of stochastic effects

Syksy Räsänen

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Daniel Figueroa, Sami Raatikainen and Eemeli Tomberg

University of Helsinki
Department of Physics and Helsinki Institute of Physics

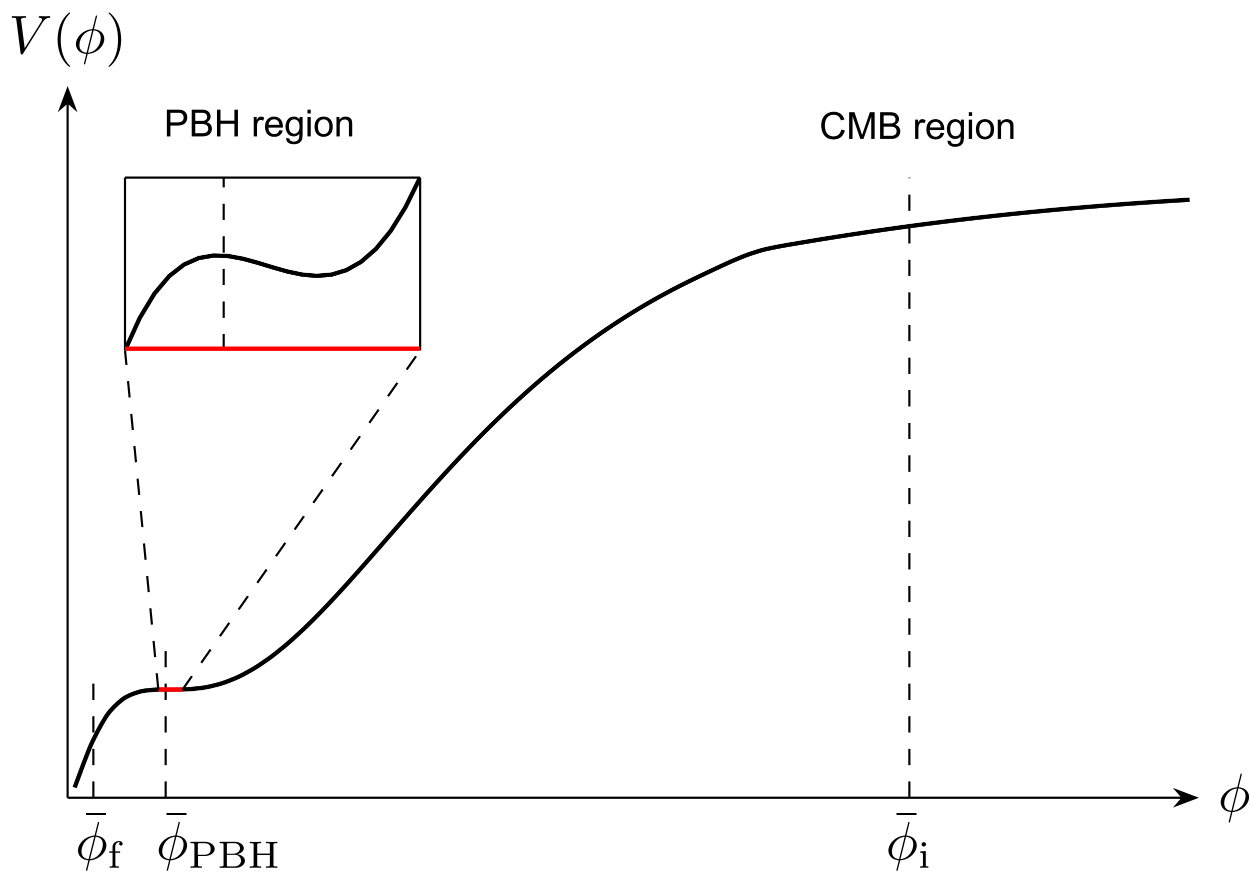
Dark matter without dark matter

- Primordial black holes (PBH) are a candidate for dark matter. (Hawking 1971)
- They could also seed supermassive black holes in centers of galaxies.
- Let's consider asteroid-mass PBHs as dark matter.

Facilitating collapse

- PBHs require large (~1) fluctuations on small scales.
- They could be generated by the same process as the small (~10^{-5}) fluctuations on large scales.
- Most successful scenario is inflation.
- The curvature perturbation (in single field slow-roll) is $\zeta = -H\delta\phi/\dot{\phi} \sim H^2/\dot{\phi}$.
- The slower the field, the larger the perturbations.

Potential for asteroid-mass PBHs



Making black holes

- During inflation, ***k***-modes stretch to super-Hubble scales and freeze.
- After inflation, they cross back inside the Hubble radius and start evolving.
- If a Hubble patch is overmassive enough, it collapses into a PBH.
  - PBH mass is close to the mass inside the Hubble patch.

Slow therefore stochastic

$$\ddot{\phi} + 3H\dot{\phi} = -V' + \xi$$

- Because the field moves slowly, stochastic effects are important. (Large kicks, small force.)

- Stochastic effects increase PBH production:
  1. Patches with large fluctuations are more likely: distribution tail is exponential, not Gaussian.
  2. Individual patches are choppy.

All inflation is stochastic inflation

- Inflaton evolution is stochastic when the coupling of small- and long-wavelength modes is taken into account. (Starobinsky 1986)

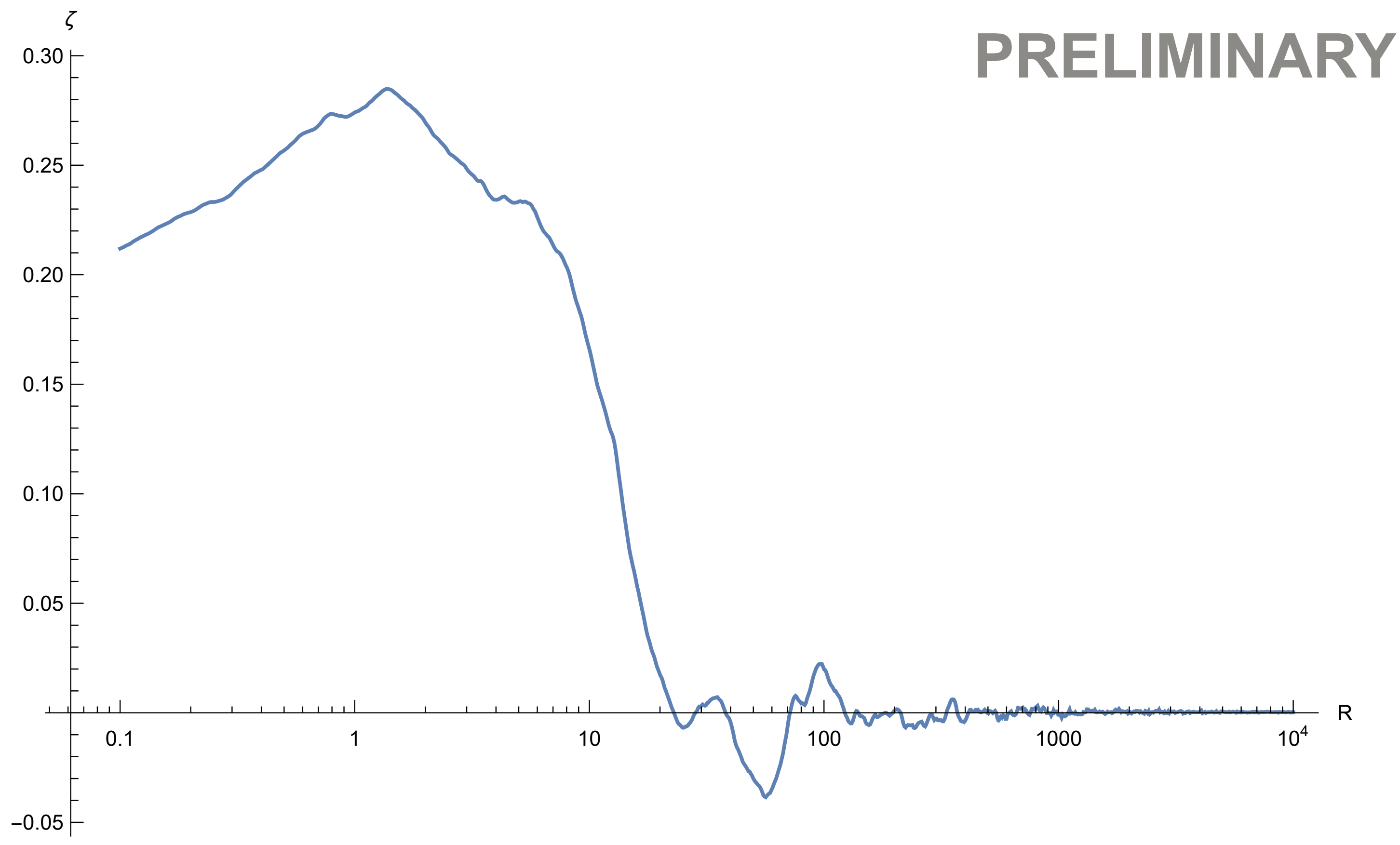
- As modes become super-Hubble and classicalise, they change the background in which shorter modes evolve.

- Amplitude of every ***k***-mode is independently drawn from a Gaussian distribution, so the background is subject to Gaussian white noise.

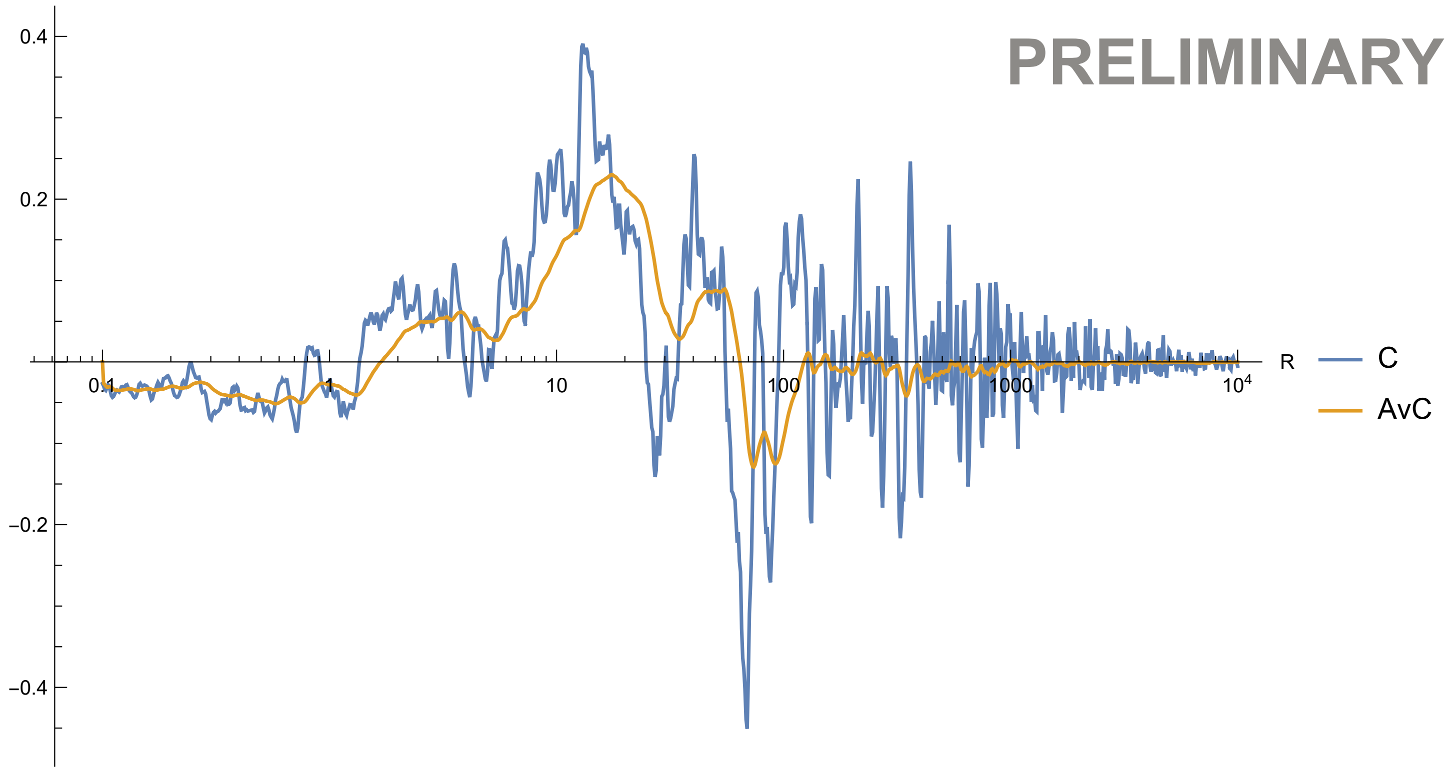
One step at a time

- We solve the full coupled background + perturbation evolution numerically:
  - Coarse-grain a mode, recalculate the background and perturbations at every timestep.
  - Continue until inflation ends, record the total number of e-folds *N.*
  - Repeat 10^{11} times to gather statistics.
  - Find distribution P(Δ*N*), where $\Delta N = N - \bar{N} = \zeta$.
- We also reconstruct the profile $\zeta(r)$ inside each patch, using a simplified treatment. (Tomberg: 2210.17441, 2304.10903)

One realisation of the curvature perturbation $\zeta(r)$



One realisation of the compaction function $\mathcal{C}(r)=2G_N\Delta M(r)$



Tail and spikes

- Taking into account the stochastic tail for the patch distribution enhances PBH abundance by $\sim 10^5$.

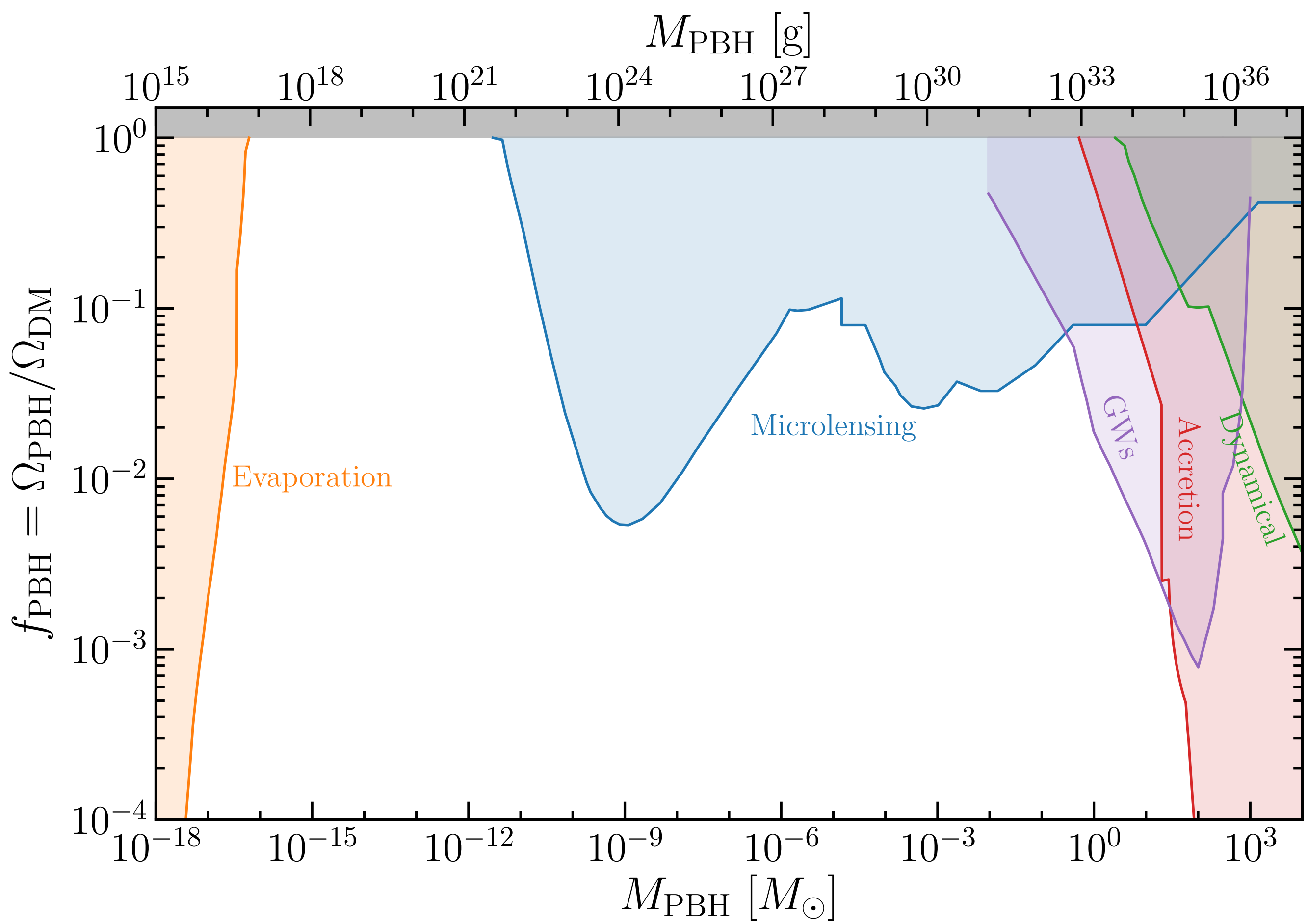
- Taking into account the stochastic nature of individual patches naively enhances PBH abundance by an extra factor of $\sim 10^2$-10^8. (Numbers preliminary.)
  - Caveat: once inside Hubble radius, spikes lead to large pressure gradients that smoothen the profile.
  - PBH formation simulations have to be redone.

Spiking the conclusions

- PBHs can constitute all dark matter.
- Generating PBHs requires slowing down the inflaton, in single-field models.
- Stochastic effects can change PBH abundance by many orders of magnitude.

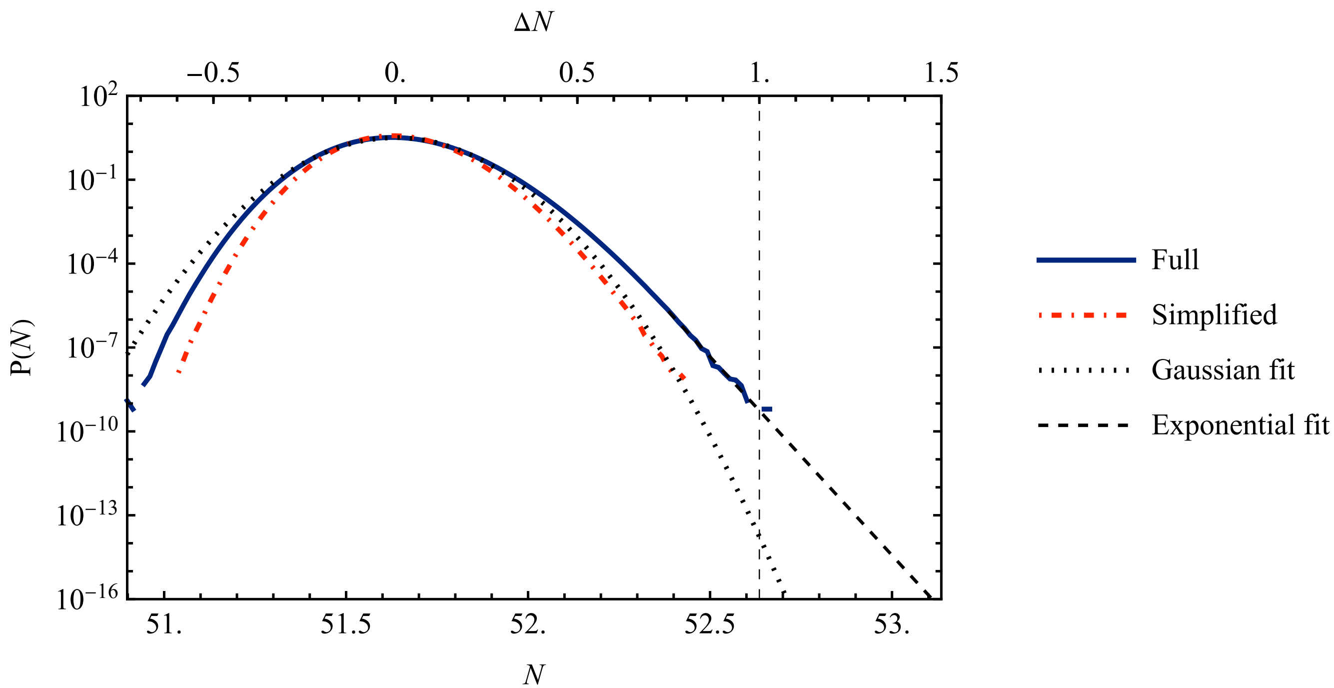
Backup slides

Asteroid-mass or Planck scale



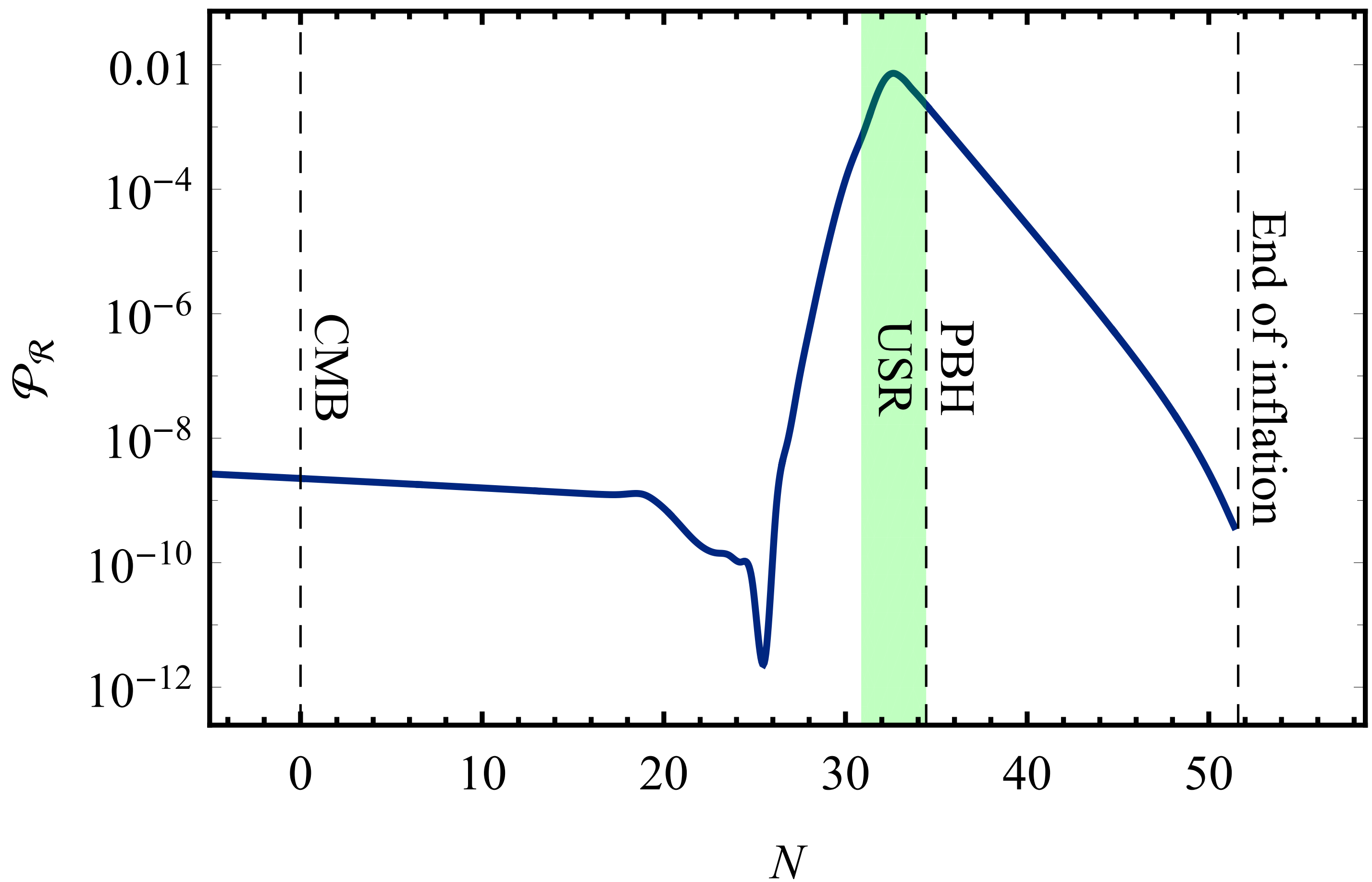
Green and Kavanagh: 2007.10722

P(ΔN=ζ)

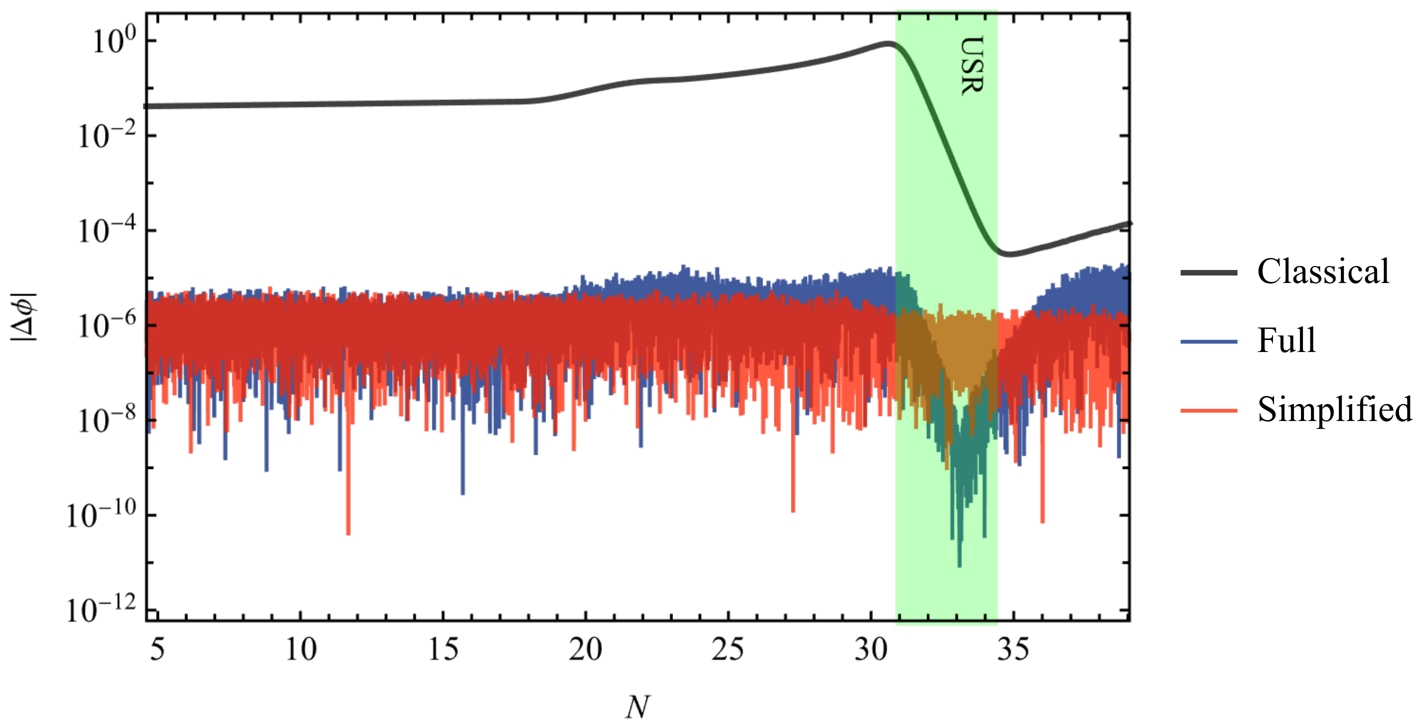


- Stochastic kicks generate exponential tail.
  (Pattison, Vennin, Assadullahi, Wands: 1707.00537; Ezquiaga, Garcia-Bellido, Vennin: 1912.05399)
- This enhances PBH abundance by $\sim 10^5$.

Curvature power spectrum



Classical force vs quantum kicks



Correlation of max(ζ) and max($\bar{\mathcal{C}}$)