Inflation

Mehrdad Mirbabayi

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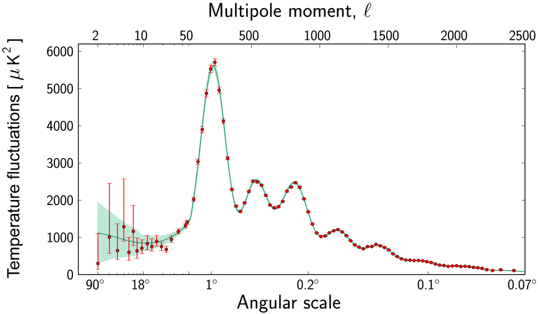
Inflationary paradigm

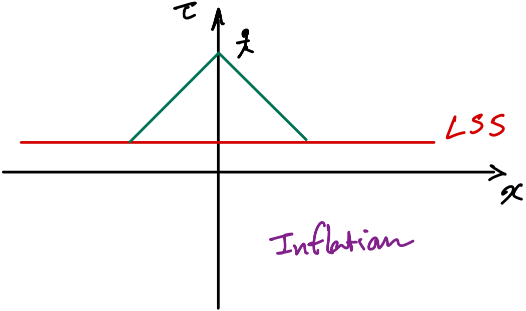
Guth,Hawking,Linde,Mukhanov,Starobinsky,. . .

Inflation is a remarkably simple theory of initial condition. It is a mechanism that promotes sub-horizon quantum fluctuations into super-horizon cosmological perturbations that we observe.



Inflationary paradigm

Inflation can also be thought of as a semi-classical resolution of the initial singularity in the hot big-bang cosmology.



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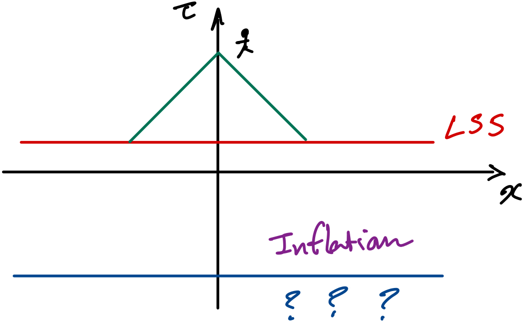


But by Penrose signularity theorem it cannot be eternal to the past.

Active areas of research I. Conceptual

- The origin of inflation, the wavefunction of the universe,
  Hartle-Hawking wavefunction; Uptunneling; Bracket wormholes;. . .
- Search for alternatives,
  Bounce; Galilean genesis; . . .
- The measure problem and eternal inflation,
- Consequences of symmetries on the correlation functions,
  Cosmological collider; Bootstrap; Holography
- Embedding in quantum gravity,
  String construction; Swampland conjecture;. . .
- . . .

Active areas of research II. Phenomenology

Goal is to identify the explicit model that drives inflation:

- Inflaton potential $V(\phi)$
- Interactions and non-Gaussianity $\frac{(\partial\phi)^4}{\Lambda^4}$
- Single-field vs. multi-field, $V(\phi, \sigma)$
- Inflation driven by exotic phases of matter, elastic/solid inflation
- Particle and gravitational wave production,
- Origin of fluctuations, thermal, stochastic, or quantum
- Primordial magnetic fields,
- . . .

Scalar perturbations

So far only two inflationary parameters have been "detected"

$$P_s(k) \approx A_s k^{n_s - 4},$$

$$A_s = 4.1 \times 10^{-8}, \qquad n_s = 0.97 \qquad \textit{Planck}$$

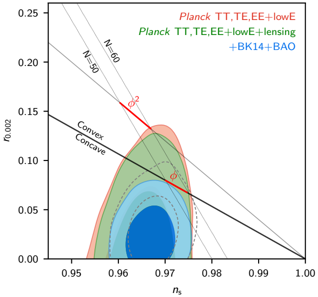
There are several other parameters that we would like (and hope) to detect, e.g.

- Running (deviation from power-law)
- Tensor modes,
- non-Gaussianity.

Primordial gravitational waves

A direct probe of the energy scale of inflation $h \sim \frac{H_{\rm inf}}{M_{\rm pl}}$. Conventionally, it is normalized by the scalar power

$$r = \frac{2P_t}{P_s} < 0.04 \qquad \textit{Planck} + \textit{BK}$$



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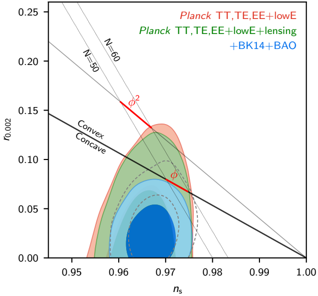


$$T_{\rm reheat} \sim 10^{16}{\rm GeV} \times r^{1/4}.$$

Non-Gaussianity

- The observations are consistent with a fully Gaussian spectrum of primordial fluctuations.
- But even the most minimal model of inflation has gravitational interactions. Hence, there is a nonzero $\left\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \right\rangle$.
- We use a bank of templates to search for NG,

$$\left\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \right\rangle = \sum_a f_{NL}^a F_a(k_1, k_2, k_3)$$

- In single-field inflation

$$\min(f_{NL}) \sim 1 - n_s \sim 10^{-2}, \qquad \text{(Maldacena '03)}$$

f_{NL} constraints

The best existing constrains come from Planck:

- **Equilateral template,** characterizes self-interactions of inflaton (challenging to improve by LSS)

$$|f_{NL}^{\mathrm{eq}}| < 50, \qquad (\text{Planck})$$

- **Local template,** characterizes multi-field models (likely to improve by LSS)

$$|f_{NL}^{\mathrm{loc}}| < 5, \qquad (\text{Planck})$$

It is nice to identify models with a floor on non-Gaussianity.

Example: Warm inflation

Fang 80', Moss 85', Yokoyama, Maede 86', Berera,Fang 95',. . .

Conceptual novelties:

- There is a small but non-decaying radiation component ($T \gg H$) because of continuous particle production and thermalization.
- The origin of cosmic fluctuations are thermal.

Phenomenological signatures:

- Different n_s and r for a given potential.
- New shapes of non-Gaussianity.

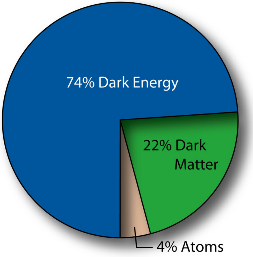
Hot radiation during inflation?

Inflation is a period of accelerated expansion

$$ds^2 = -dt^2 + a(t)^2 dx^2, \qquad \frac{\dot{a}}{a} = H.$$

Radiation density, if not replenished, decays exponentially

$$\rho_r \propto \frac{1}{a^4}.$$



Energy budget

Warm inflation needs a continuous energy transfer

$$\phi \to X \quad \text{(another sector)}$$

such that

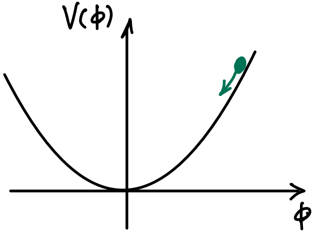
$$\frac{\rho_X}{\rho_{\rm tot}} \sim \epsilon \qquad \text{small but approximately fixed.}$$

Assuming thermalization, the temperature can be much greater than H:

$$T \gg H \qquad \text{is compatible with} \qquad T^4 \ll M_{\rm pl}^2 H^2.$$

because $M_{\rm pl} \gg H$.

Background evolution



Simplest realization of cold inflation

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

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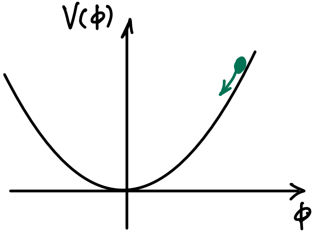


Particle production back-reacts on the inflaton evolution

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

$$\dot{\rho}_X + 4H\rho_X = \gamma\dot{\phi}^2.$$

This can have a warm slow-roll attractor. But for a given $V(\phi)$, the predictions are different.

Minimal warm inflation

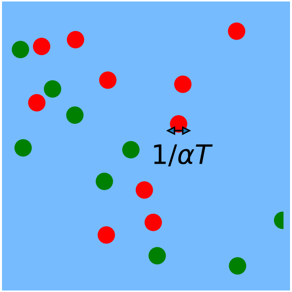
Berghaus,Graham,Kaplan '19

Suppose inflaton is an axion coupled to a Yang-Mills plasma at $T > T_c$,

$$\Delta\mathcal{L} = \frac{\phi}{f}\alpha \mathrm{Tr}(G_{\mu\nu}\tilde{G}^{\mu\nu}).$$

Then a process called *Sphaleron heating* leads to

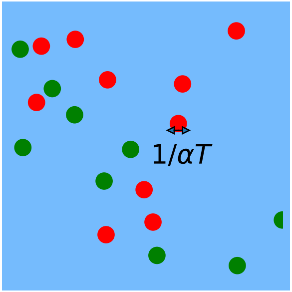
$$\gamma \sim \frac{\alpha^5 T^3}{f^2}.$$



Grigoriev,Rubakov,Shaposhnikov '89,
Arnold,Son,Yaffe '96,
Moore,Tassler '10,
MM,Gruzinov '22

Origin of perturbations

The transfer of energy $\phi \to$ YM is not uniform. It is a random microscopic process.



- This induces large (effectively classical) fluctuations already inside the horizon

$$\delta\phi \gg \delta\phi_{\rm vac}.$$

- Computing them in the microscopic theory is challenging.

Effective field theory for cosmological perturbations

- At wavelengths $\gg 1/\alpha T$ the effective description is hydrodynamics:

  $$T^{YM}_{\mu\nu} = \frac{4}{3}\rho u_\mu u_\nu + \frac{1}{3}\rho g_{\mu\nu},$$

  up to small corrections to the equation of state, and $\mathcal{O}(H/T)$ dissipative corrections.
- However, there is one dissipative term that is essential

  $$-\nabla^2\phi + V'(\phi) = \frac{\alpha}{f}\mathrm{Tr}G\tilde{G} = \underbrace{-\gamma(\rho)u^\mu\partial_\mu\phi}_{\langle\rangle\text{on long-}\lambda\text{ bgr}} + \underbrace{\xi}_{\text{noise}}.$$

  This couples ϕ to the fluid:

  $$\nabla^\nu T^{YM}_{\mu\nu} = \partial_\mu\phi(\gamma u^\nu\partial_\nu\phi - \xi).$$

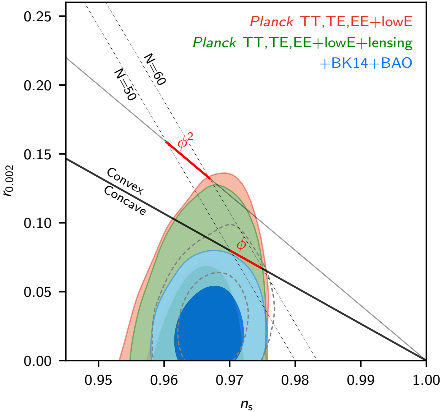
Bastero-Gil, Berera, Moss, Ramos '14

Warm ϕ^4 inflation (ϕ^2 can't be saved) MM,Gruzinov '22

$$N_e = 55, \qquad \phi \approx 11.6 M_{\rm pl}, \qquad 1 - n_s \approx 0.0337, \qquad \gamma \approx 5.34 H.$$

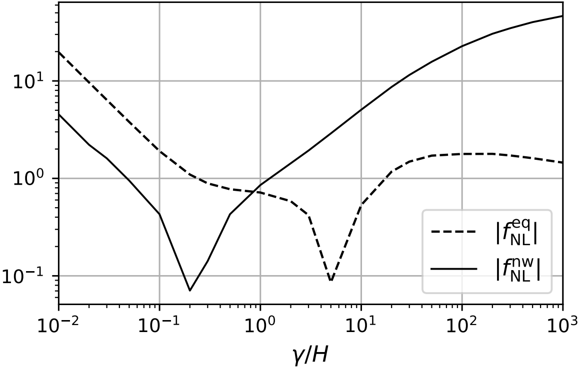
For $\phi + SU(2)$Yang-Mills

$$\frac{T}{H} \approx 1200, \qquad r \approx 4.7 \times 10^{-7}.$$



$\mathcal{O}(1)$ lower bound on non-Gaussianity

MM,Gruzinov '22



Planck constraint on $f_{\rm NL}^{\rm eq}$ is about 50.

Conclusions

- There is much to learn about inflation.
- It can be a promising window into the BSM physics, and quantum gravity.
- Warm inflation is a qualitatively distinct model of inflation that provides a realistic target for non-Gaussianity searches.

Thank you!