Title: Productive interactions: heavy particles, gravitational waves and non-Gaussianity

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Abstract: I discuss the phenomenology of models of inflation with periodic particle production. Particle production occurs as the mass of heavy particles goes through non-adiabatic modulations as the inflaton field rolls. I show that this process can lead to significant emission of scalar and gravitational waves during inflation, with distinct observational signatures.

Productive Interactions: Heavy particles, non-Gaussianity, and gravitational waves

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How sensitive are inflationary predictions to microphysics at $E \gg H_{\rm inf}$?

Effective Field Theorist's standard response:

- Spectrum of light degrees of freedom
- Symmetries
- Construct the most general EFT. Microscopic details are encoded in the values coupling coefficients.

EFT

Successfully classifies the predictions of qualitatively different models (often in the form of consistency conditions):

- Einstein gravity – vacuum scalars – minimal slow-roll inflation:

$$\gamma \sim \frac{H}{M_{\rm pl}}, \qquad \zeta \sim \frac{H}{\sqrt{\epsilon} M_{\rm pl}} \quad \text{(notation)}$$

- Attractor single-field inflation (Maldacena's squeezed limit consistency)

$$f_{\rm NL,loc} = \frac{\langle \zeta(\mathbf{q}) \zeta_{\mathbf{k}} \zeta_{-\mathbf{k}} \rangle_{q \ll k}}{P_\zeta(q) P_\zeta(k)} = -\frac{5}{6}(n_s - 1)$$

There are EFTs of multifield, supersymmetric, solid, ... inflation.

Could the microphysics become relevant in a profoundly different way?

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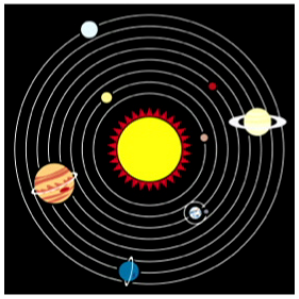
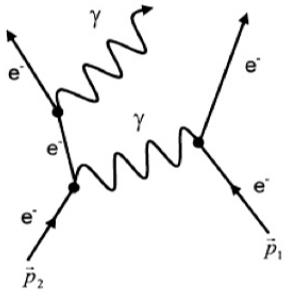
Gravitational Waves in Solar System

Jupiter?



Bremsstrahlung at the center of Sun (Weinberg '65).



The model: periodic particle production

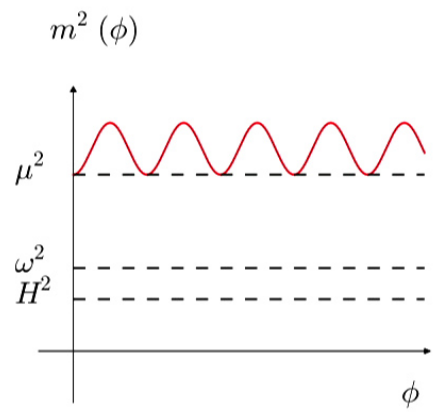
Suppose the mass of a heavy field is modulated by the inflaton ϕ:

$$M_X^2 = \mu^2 + g^2 f^2 \sin^2 \frac{\phi}{2f}$$

Whenever $\dot{M}_X / M_X^2$ becomes appreciable, X particles are produced with

$$n_X \sim \dot{M}_X^{3/2} e^{-\mu^2/\dot{M}_X}$$

(Traschen, Brandenberger '90, Chung, Kolb, Riotto, Tkachev '00)



- Non-adiabatic particle production

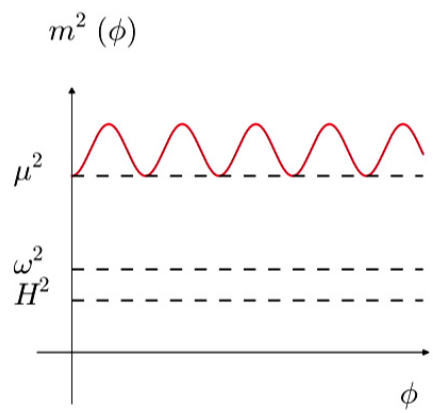
$$n_X \sim \dot{M}_X^{3/2} e^{-\mu^2/\dot{M}_X}$$

- μ can be larger than H at all times

$$\dot{M}_X \sim g\dot{\phi} \quad \text{(for typical } g \sim 1) \quad \gg H^2$$

- The frequency of production events is

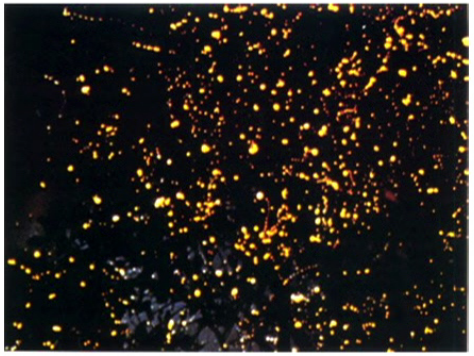
$$\omega = \frac{\dot{\phi}}{f} \quad \text{(for a range of } f) \quad \gg H.$$



The auxiliary sector X absorbs energy from the background.
Scalars are emitted in a universal fashion during energy transfer:

$$\frac{1}{2}\dot{\phi}^2 \to \rho_X \Longrightarrow \delta\phi_X.$$

Gravitational waves can be emitted using ρ_X.



Universal scalar emission

Exponential Expansion

Suppose emission is at a physical frequency $k/a \sim \omega_{\rm phys}$.

1. Then due to redshift each mode can be excited in a period

$$\Delta t \sim H^{-1}$$

2. The excitation number at horizon crossing, $k/a \sim H$, redshifts compared to that at the emission time

$$N_\zeta \sim \frac{dE}{d\omega_{\rm phys}} \frac{H^3}{\omega_{\rm phys}^3}.$$

Most efficient emission is at $\omega_{\rm phys} \sim H$

Scalar Emission from Energy Conservation

- Scalar fluctuations $\delta\phi_X$ lead to: $\delta\rho_\phi = \dot{\phi}\delta\dot{\phi}_X$.
- Energy conservation: $\int d^3x\delta\rho_\phi = M_X \Longrightarrow \delta\phi_X \propto \frac{M_X}{\dot{\phi}}$
- This is a coherent emission from each individual event.
- Adiabatic fluctuations are related to $\delta\phi$ as $\zeta \simeq -H\delta\phi/\dot{\phi}$.
- There are $N_X \sim n_X H^{-3}$ independent events in a Hubble patch:

$$\left\langle \zeta_X^N \right\rangle \sim N_X \left(\frac{M_X}{\sqrt{\epsilon}M_{\rm pl}}\right)^N \left(\frac{H^2}{\epsilon M_{\rm pl}^2}\right)^{N/2}$$

Factorized non-Gaussianity

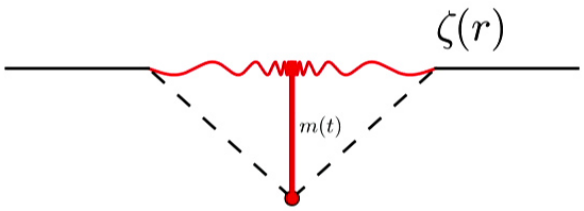
$$\langle \zeta^N \rangle'_X \sim \left(\frac{1}{\epsilon M_{\rm pl}^2} \right)^N \frac{n_X}{H^3} \sum_{n^{th}\text{event}} \eta_n^{-3} \prod_{i=1}^{N} \frac{h(-k_i \eta_n)}{k_i^3}$$

where

$$h(-k\eta_n) = \int_{\eta_n}^{0} \frac{d\eta'}{\eta'} \frac{dm(t')}{dt'} \, g(k\eta')$$

$g(-k\eta)$ is the retarded Green's function from $-\eta$ to 0. In real space $h(x)$ is just the memory of the paticle mass:

$$\zeta(\mathbf{r}) \simeq -\frac{H}{8\pi\epsilon M_{\rm pl}^2} m(t_r).$$



Observability of non-Gaussianity, $\zeta_X < \zeta_{\rm vac} \sim \frac{H}{\sqrt{\epsilon} M_{\rm pl}}$

$$\frac{S}{N} \propto \frac{\langle \zeta_X^n \rangle}{\langle \zeta^2 \rangle_{\rm vac}^{n/2}} \sim N_X \left(\frac{M_X}{\sqrt{\epsilon} M_{\rm pl}} \right)^n \sim N_X \left(\frac{gH}{\omega} \right)^n$$

- This typically decreases with n.
- Thus the periodic corrections to the 2-point correlation function is the best observable signature.
- However, there is a regime in which resonant emission at $k/a \sim \omega$ dominates and the emission is strongly non-Gaussian.

Gravitational emission, in weak Gravity

- Exponential expansion makes emission most efficient at $k/a \sim H$
- Emission from symmetric, non-relativistic and short distance processes are suppressed by $v/c \sim x/\lambda$.
- At large distances one can use linearized gravity

$$G_{\mu\nu}^{\text{lin.}} \simeq \frac{1}{M_{\text{pl}}^2} T_{\mu\nu} \Rightarrow \partial^2 \gamma \sim \frac{\rho x}{M_{\text{pl}}^2}$$

For each event $\rho_X \propto M_X$.

Gravitational emission, in weak Gravity

- Bremsstrahlung emission from relativistic scattering agrees with this bound $\partial^2 \gamma_X \sim \frac{\rho_X}{M_{\rm pl}^2}$.

- There are N_X incoherent localized events of mass M_X per Hubble volume:

$$\langle \gamma_X^2 \rangle \sim N_X \frac{M_X^2}{M_{\rm pl}^2} \frac{H^2}{M_{\rm pl}^2} \qquad \left(\text{recall} \quad \langle \zeta_X^2 \rangle \sim N_X \frac{M_X^2}{\epsilon M_{\rm pl}^2} \frac{H^2}{\epsilon M_{\rm pl}^2} \right)$$

- One can have $\gamma_X > \gamma_{\rm vac}$. However, it implies $\zeta_X \gg \zeta_{\rm vac}$

$$r \sim \epsilon^2$$

- These scenarios can dominate vacuum tensor fluctuations and break the relation between r and $H_{\rm inf}$.
- But then they dominate vacuum scalar fluctuations.
- ϵ must be relatively large for observable values of r.
- However, scalar and tensor tilts are less sensitive to ϵ:

$$n_s - 1 = -\frac{1}{2}\epsilon - \frac{5}{4}\frac{\dot{\epsilon}}{H\epsilon}$$

$$n_t = -\frac{1}{2}\epsilon - \frac{3}{4}\frac{\dot{\epsilon}}{H\epsilon}$$

Non-Gaussianity, $\zeta_X \gg \zeta_{\rm vac}$

If there are N_X incoherent emission events per H^{-4}:

$$\frac{S}{N} \propto \frac{\langle \zeta_X^3 \rangle}{\langle \zeta^2 \rangle_X^{3/2}} \equiv f_{NL}\zeta_X \sim \frac{1}{N_X^{1/2}}$$

f_{NL} can be made small by increasing N_X. But there is an upper bound

$$\rho_X = N_X H^3 M_X \ll M_{\rm pl}^2 H^2 \epsilon$$

Combined with ζ_X gives

$$f_{NL} \gg 1$$

Conclusions

1. Microphysics can significantly affect predictions of Inflation.
2. Time-dependent background allows heavy particles with $M_X \gg H$ to be produced.
3. Cosmological observations have a chance of identifying the distinct imprints of such a possibility.
4. It is hard to change predictions for γ without significantly modifying ζ spectrum.

Thank you!