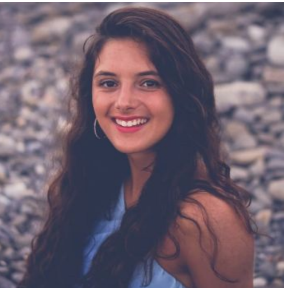
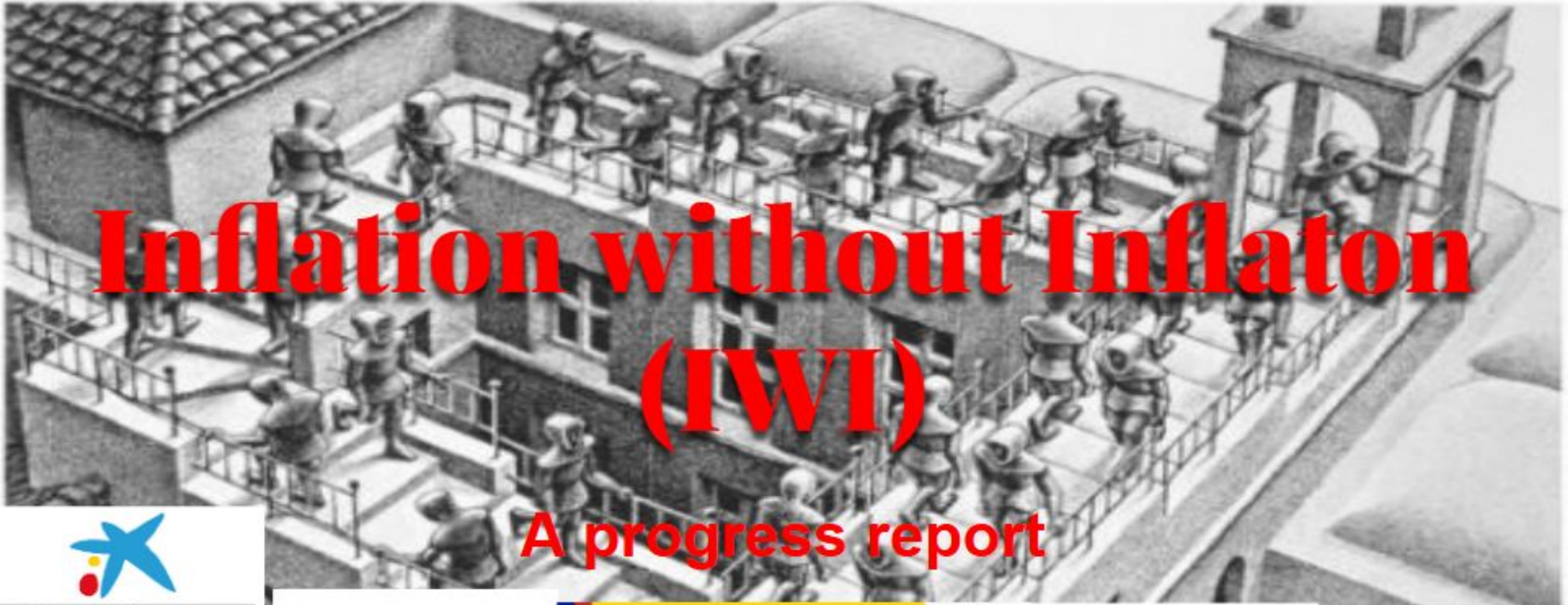
Inflation without Inflaton (IWI)

Raúl Jiménez – ICREA & ICCUB
Marisol Traforetti – PhD Student at ICCUB
Mariam Abdelaziz - Visiting PhD student at ICCUB



BIG Meeting, November 7th 2025



Inflation without Inflaton (IWI)

A progress report

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ΛCDM: The standard cosmological model

Just 7 numbers…..

describe the Universe composition and evolution

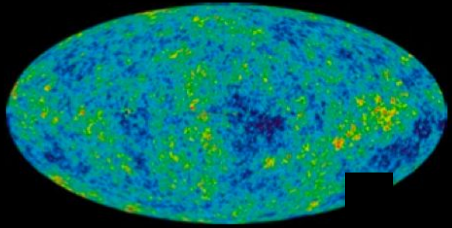
Homogenous background

$$\Omega_b, \Omega_c, \Omega_\Lambda, H_0, \tau$$

- atoms 4%
- cold dark matter 23%
- dark energy 73%

Λ? CDM?

Perturbations

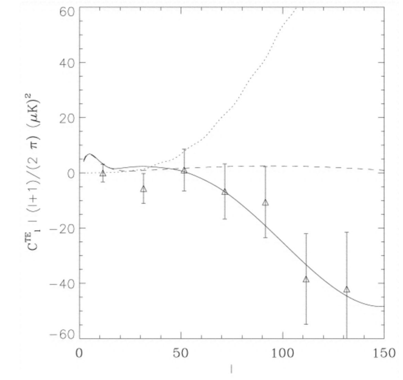


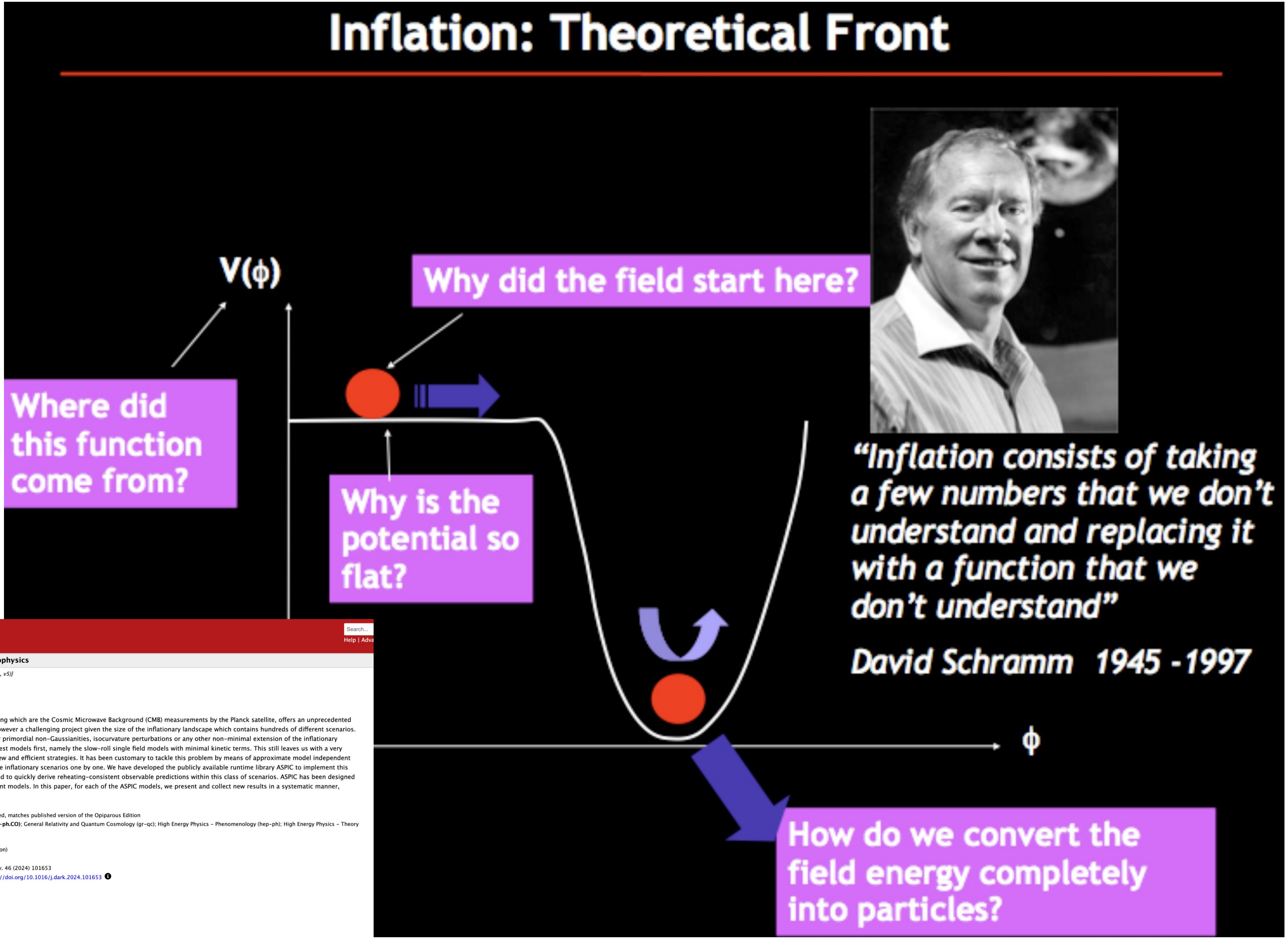
$$A_s, n_s, r$$

- nearly scale-invariant
- adiabatic
- Gaussian

ORIGIN??

WMAP2003





arXiv > astro-ph > arXiv:1303.3787

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Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 15 Mar 2013 (v1), last revised 17 Dec 2024 (this version, v5)]

Encyclopaedia Inflationaris

Jerome Martin, Christophe Ringeval, Vincent Vennin

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 publicly available runtime library ASPIC 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 118 different models. In this paper, for each of the ASPIC models, we present and collect new results in a systematic manner, thereby constituting the first Encyclopaedia Inflationaris.

Comments:	781 pages, 513 figures, uses jcappub. Preface added, matches published version of the Opiparous Edition
Subjects:	**Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc); High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Theory (hep-th)
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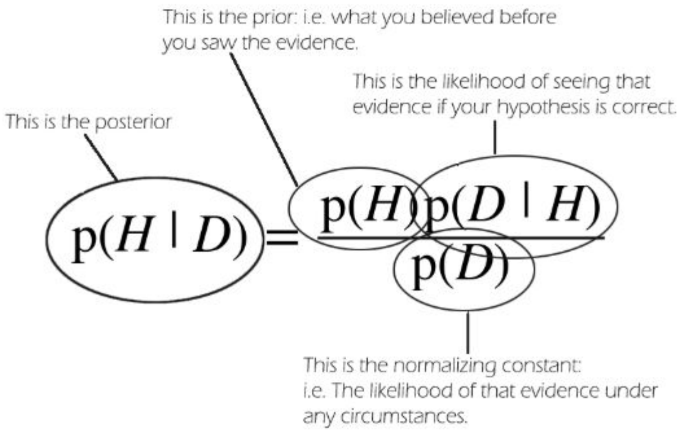
challenges

Big data; Cosmology is special we only observe one sky; we only fit models



$$p(D|\mathcal{H}) = \int p(D|\alpha, \mathcal{H})p(\alpha|\mathcal{H})d\alpha$$

Evidence Likelihood prior

What is a prior? What to use?

Exp(accuracy-complexity)

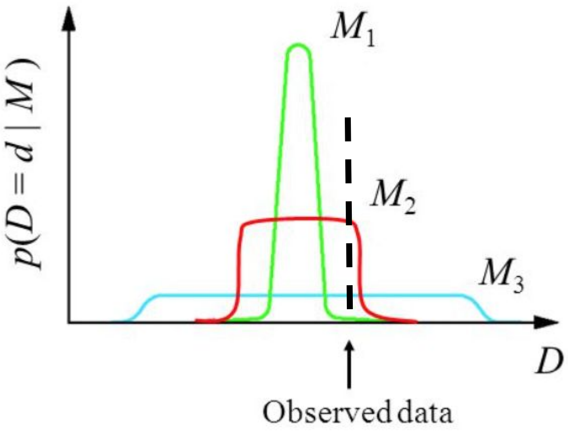
Model selection question: Bayesian Evidence

When comparing two models or hypotheses use
the Bayesian evidence and the Bayes factor

$$p(D|\mathcal{H}) = \int p(D|\alpha, \mathcal{H}) p(\alpha|\mathcal{H}) d\alpha$$

Evidence Likelihood prior

Exp(accuracy-complexity)



Heavy dependence on prior choice

Goldilocks 1 D example

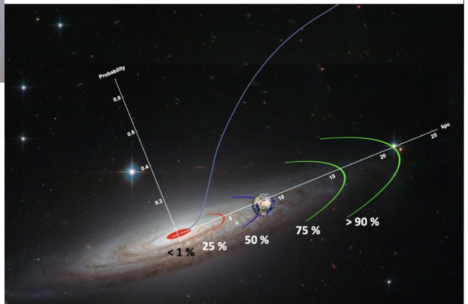
M1: too simple,
unlikely to generate the data

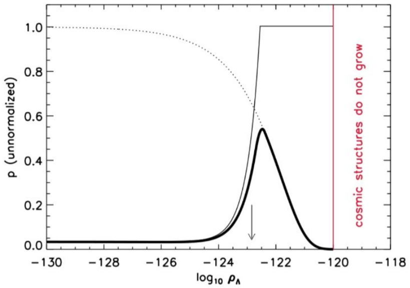
M3: too complex,
can generate many other cases,
why this one?

M2: just right

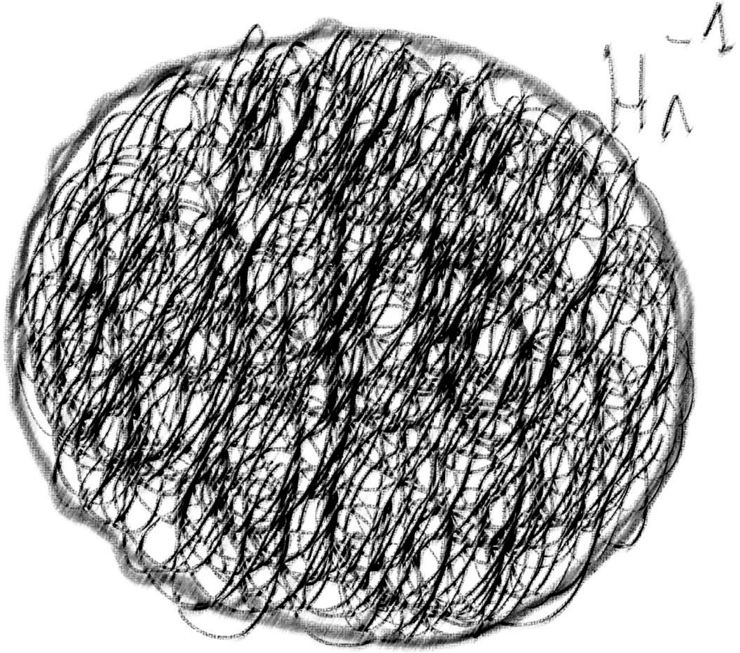
Coincidences

PRL Jimenez et al. 2014, 2016





The Essence of IWI

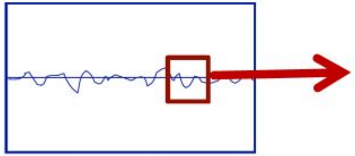


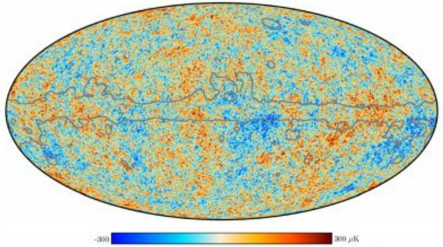
Motivations

- The inflationary paradigm refers to a sufficiently long period of accelerated expansion in the early Universe

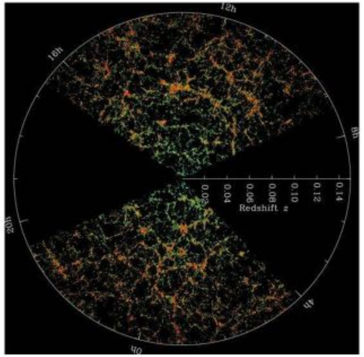
Solves the hot Big Bang shortcomings

Generates the seeds necessary for the formation of cosmic structures





[Planck satellite (2018)]

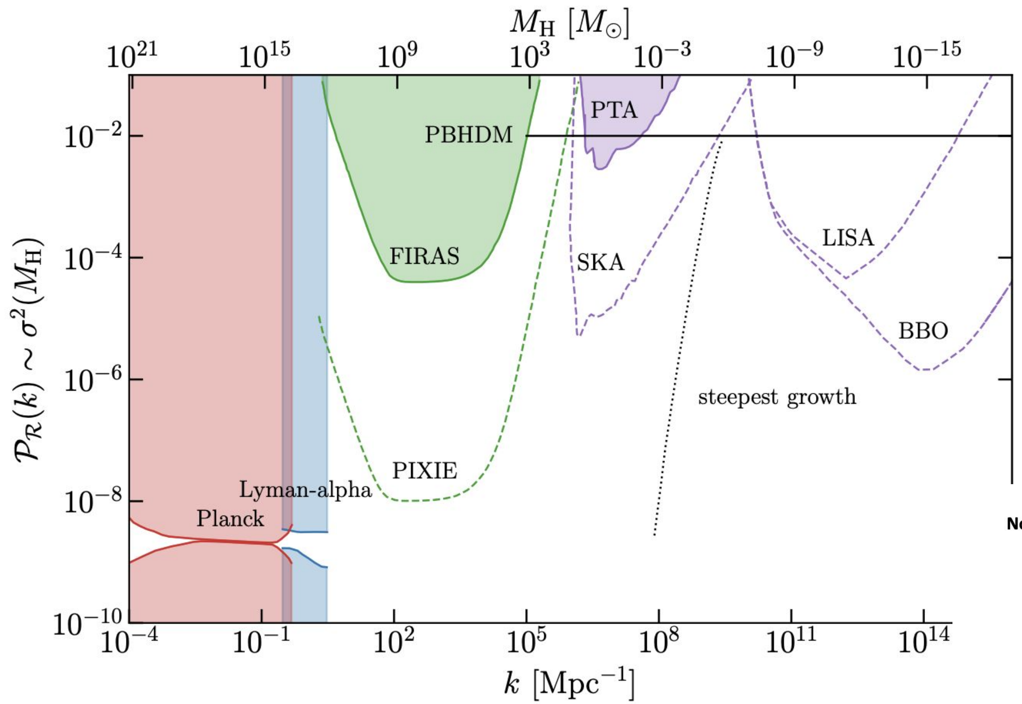


[Sloan Digital Sky Survey (SDSS)]

- In the simplest models, we assume the existence of a scalar field: the *inflaton*

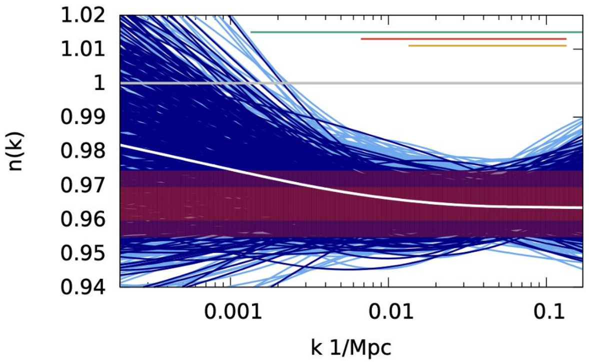
- However…many inflationary models can fit current observations!

Can we search for scenarios that are fully model-independent?



From Verde et al.

Now, be as more model independent as possible and take an almost free form for P(k) a spline



Now, much looser constraints. The choice of what to fit to data is a (theoretical) prior

…inflation without the inflaton?

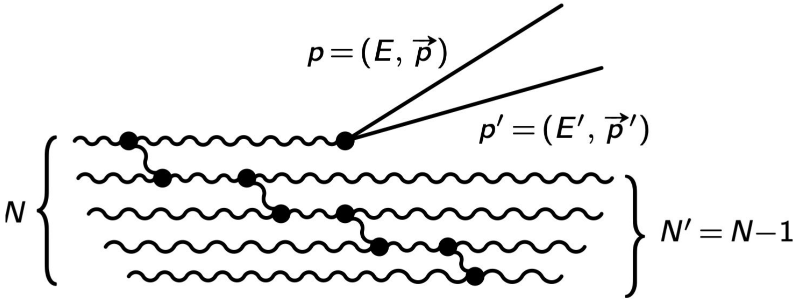
- In 2412.14265, we focus on how scalar perturbations are generated in a model-independent fashion, within a purely quantum physics framework.
- We propose a novel scenario in which scalar perturbations, that seed the large-scale structure of the Universe, are generated without relying on a scalar field (the inflaton).
- In this framework, inflation is driven by a de Sitter space-time (dS), where tensor metric fluctuations (i.e., gravitational waves) naturally arise from quantum vacuum oscillations, and scalar fluctuations are generated via second-order tensor effects
- We show that scalar perturbations arise as a second-order effect from tensor perturbations and can become significantly enhanced, allowing them to dominate over the linear tensor modes, which are inherently present in dS.

Generation of second-order scalar modes from tensor perturbations

- The generation of these tensor perturbations was first studied in Tomita (1971, 1972) and Matarrese, S. Mollerach and M. Bruni (1998).
- Recently, a quantitative analysis of such tensor-induced scalar perturbations was done in Bari+(2022, 2023) for post-inflationary epochs. Our scenario relies on a similar mechanism to generate the scalar perturbations.
- In addition, the instability of dS space [see, e.g., Mottola (1985), Antoniadis+ (2007), Polyakov (1982, 2007, 2012), Dvali+ (2007, 2014, 2017), Alicki+ (2023a, b)] provides both a natural way for a graceful exit from inflation and also the means to end into a radiation dominated epoch.

If dS metric as process of scattering and decay of the gravitons: Dvali et al. point of view

- If one describes dS as a quantum coherent state composite of gravitons, then the self-coupling of gravitons— as well as their coupling to other relativistic particle species, such as those in the Standard Model (SM), which must always be present—leads to quantum scattering and decay of the constituent gravitons of dS.
- In this case, the final quantum state cannot be described as a coherent state, and there will no longer be the dispersion relations of the free quanta propagating on a classical dS background.



Higher order process of particle production, in which the produced particles recoil against all remaining gravitons. In particular, this allows for produced particles of low energies E, $E_{'} \ll m/2$.

About perturbations?

- In 2412.14265 we introduce a novel mechanism where we derive the exact expressions for the second-order scalar potentials and the scalar power spectrum resulting from second-order tensor perturbations.
- We demonstrate that the latter agrees with the expected nearly scale-invariance from observations, opening the way for numerous potential follow-up studies and extensions.

Note that here the considered fluid unavoidably arises from the vacuum expectation value of the second-order contribution to the Einstein's tensor from gravitational waves (GW), which on sub-horizon scales leads to non-vanishing energy, pressure and anisotropic stress (this point is raised also in Dvali + 2013!!).

SCALAR PERTURBATIONS FROM TENSOR MODES

- We consider pure dS metric, which is in Cartesian coordinates, $ds^2 = -dt^2 + e^{2t/\alpha}(dx^2 + dy^2 + dz^2)$,

where $\alpha \equiv (3/\Lambda)^{1/2}$ and $\Lambda/8\pi G$ is the vacuum energy.

- We assume Einstein gravity and the following perturbed second order metric

$$g_{00} = -a^2(1+\psi_2),$$
$$g_{0i} = \frac{a^2}{2}\omega_{2i},$$
$$g_{ij} = a^2\left[(1-\phi_2)\delta_{ij} + \chi_{1ij} + \frac{1}{2}\chi_{2ij}\right],$$

Now a first question that we can make…

- Unless the "background" vacuum energy (by Mottola et al.) or coherent states (by Dvali et al.) $\Lambda/8\pi G$ and if we exclude any (perturbative) contributions on the right-hand side of Einstein's equations, is it possible to obtain solutions for, e.g., ψ_2 and ϕ_2, which depend only on χ_{1ij}?

No, we can't…

Indeed, if we try to solve the Einstein Equations for ψ_2 and ϕ_2 we get as inconsistence on the solution for ϕ_2 (and, at the same time ψ_2=0).

SCALAR PERTURBATIONS FROM TENSOR MODES

For generality, on the RHS of Einstein's equations, we allow for the presence of a stress-energy tensor which accounts for the sum of the cosmological constant driving our dS expansion plus a generic fluid, with energy density ρ, isotropic pressure p, four-velocity u^μ and anisotropic stress tensor π^μ_ν, namely

$$T^\mu_\nu = -\frac{\Lambda}{8\pi G}\delta^\mu_\nu + (\rho + p)u^\mu u_\nu + p\delta^\mu_\nu + \pi^\mu_\nu \,.$$

NOTE: by using the idea by Dvali et al 2013 and 2017 this seemingly-classical system quantum mechanically as the mixture of the two "Bose-gases":

1) the quantum coherent state that describes Λ;
2) a cosmological fluid that plays the role of a cosmic clock! Precisely, this compositeness acts as a quantum clock (that becomes classical at scales larger than horizon) that imprints measurable effects into cosmological observables.

These effects are cumulative and gather the information throughout the entire duration of inflation.

For ϕ_2 is const., is it possible to have $\psi_2 \neq 0$?

At super-horizon scales, still assuming ϕ_2 is const. , where we left w and c_s generic

$$\bar{\rho}(\eta) = \bar{\rho}_{\rm in} \left(\frac{\eta}{\eta_{\rm in}} \right)^{3(1+w)} = \bar{\rho}_{\rm in} \left(c_s k |\eta| \right)^{3(1+w)}$$

for ζ_2 we find

$$\tilde{\zeta}_2 - \tilde{\phi}_2 = -\frac{H_\Lambda^2}{4\pi G(1+w)\bar{\rho}} \tilde{\psi}_2 = -\frac{H_\Lambda^2}{4\pi G(1+w)\bar{\rho}_{\rm in}} \left[-\frac{8\pi G}{H_\Lambda^2} c_s^2 k^2 \tilde{\Pi}_{2\rm in} + \left(\tilde{\phi}_2 - \frac{1}{4} \tilde{\mathcal{F}}_\chi \right) \right] (c_s k |\eta|)^{3\left(c_s^2 - w\right)}$$

Now we need to know the value of c_s and $\bar{\rho}_{\rm in}$ at a given mode k.
It is transparent that

$$w - c_s^2 > 0$$

for the scalar fluctuations to be larger than the tensor ones. This can be achieved by the same gravitons produced during de Sitter phase. For this particle (fluid) radiation, the scalar perturbations will no longer grow [Dvali + 2013, 2017].

This provides a natural route to end inflation!

Cosmological perturbation theory

- ➢ Inflation is driven by de Sitter (dS) space-time
- ➢ We use the following perturbed line element

$$ds^2 = a^2(\eta)\left\{ -\left(1+\psi^{(2)}\right) d\eta^2 + \left[\left(1-\phi^{(2)}\right)\delta_{ij} + \chi_{ij}^{(1)}\right] dx^i dx^j \right\}$$

- Linear order ⟶ Perturbations are dynamically decoupled
- Second order ⟶ Perturbations can be sourced by the coupling of first-order perturbations

[Malik K. A., Wands D. [0809.4944]
Kodama H., Sasaki M. (1984),
Matarrese S. et al. (1998)]

Second-order Einstein equations

➢ Assume Einstein gravity $$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

➢ Energy-momentum tensor $$T^{\mu}_{\nu} = -\frac{\Lambda}{8\pi G}\delta^{\mu}_{\nu} + (\rho + p)u^{\mu}u_{\nu} + p\delta^{\mu}_{\nu} + \pi^{\mu}_{\nu}$$

➢ Equation of motion for the potential at second-order

$$\phi_2'' + 3\left(1 + c_s^2\right)\mathcal{H}\phi_2' + \left[2\mathcal{H}' + \left(1 + 3c_s^2\right)\mathcal{H}^2\right]\phi_2 - c_s^2\nabla^2\phi_2 = O(\underline{\chi_{1\,ij}\chi_1^{ij}}\ ;\ \chi'_{1\,ij}\chi_1^{ij\prime})$$

$$\boxed{\text{Primordial tensor power spectrum}} \longrightarrow \boxed{\text{Scalar power spectrum}}$$

[Tomita (1971, 1972),
Matarrese et al. (1998),
Bari et al. (2022), Bari et al. (2023)]

Scalar power spectrum

- Large scale limit $\phi_2 = \frac{\mathcal{F}_\chi}{4} = (A) + (B)$

- Primordial power spectrum of scalar fluctuations

$$\langle \phi(\mathbf{k})\phi(\mathbf{k}')\rangle = \frac{1}{4}\langle \phi_2(\mathbf{k})\phi_2(\mathbf{k}')\rangle = (2\pi)^3 \delta^{(3)}(\mathbf{k}+\mathbf{k}')\mathcal{P}_\phi(k)$$

$$\mathcal{P}_\phi(k) = \mathcal{P}_\phi^{(AA)}(k) + \mathcal{P}_\phi^{(BB)}(k) + 2\mathcal{P}_\phi^{(AB)}(k)$$

- Tensor power spectrum in de Sitter $\mathcal{P}_h(k) = \frac{2\pi^2}{k^3}\Delta_h^2(k) = \frac{2\pi^2}{k^3}\left[\frac{16}{\pi}\left(\frac{H_{\rm inf}}{m_{\rm pl}}\right)^2\right]$

where $H_{\rm inf}$ is the Hubble constant during inflation

Observational constraints

$$\Delta_\phi^2(k) = \Delta_\phi^2(k_*)\left(\frac{k}{k_*}\right)^{n_S-1} \qquad \Delta_h^2(k) = \Delta_h^2(k_*)\left(\frac{k}{k_*}\right)^{n_T}$$

At CMB scales:

- ➢ Amplitude of scalar perturbations $\Delta_\phi^2(k_*) \simeq 2.1 \times 10^{-9}$
- ➢ Tensor-to-scalar ratio $r(k_*) = \dfrac{\Delta_h^2(k_*)}{\Delta_\phi^2(k_*)} \longrightarrow r_{0.01} < 0.066$ at 95% CL
- ➢ Spectral tilts $n_s = 0.9649 \pm 0.0042$ at 68% confidence level (CL)

  $-0.76 < n_t < 0.52$ at 95% CL

[*Planck* 2018 results,
Tristram et al. (2021),
Galloni et al. (2022)]

Scale-invariance ?

- ➢ Let us take only the first contribution

$$\mathcal{P}_{\phi}^{(AA)}(k) \propto \frac{1}{k^4} \int d^3k_1 d^3k_2\, \delta^{(3)}(\mathbf{k} - (\mathbf{k}_1 + \mathbf{k}_2))\, \mathcal{K}_h^{(AA)}(\mathbf{k}_1, \mathbf{k}_2, k^2) \left[\frac{1}{k_1^3}\Delta_h^2(k_1)\right] \left[\frac{1}{k_2^3}\Delta_h^2(k_2)\right]$$

$$\begin{aligned} \mathcal{K}_h^{(AA)}(\mathbf{k}_1, \mathbf{k}_2, k^2) = \frac{1}{4} \Big\{ & (k_1^2 + k_2^2 + 3\mathbf{k}_1 \cdot \mathbf{k}_2)^2 \left[(1 - \hat{\mathbf{k}}_1 \cdot \hat{\mathbf{k}}_2)^4 + (1 + \hat{\mathbf{k}}_1 \cdot \hat{\mathbf{k}}_2)^4\right] + \\ & +8k_1^2 k_2^2 (\hat{\mathbf{k}}_1 \times \hat{\mathbf{k}}_2)^4 \left[1 + (\hat{\mathbf{k}}_1 \cdot \hat{\mathbf{k}}_2)^2\right] \\ & +8(\mathbf{k}_1 \cdot \mathbf{k}_2)(k_1^2 + k_2^2 + 3\mathbf{k}_1 \cdot \mathbf{k}_2)(\hat{\mathbf{k}}_1 \times \hat{\mathbf{k}}_2)^2 \left[3 + (\hat{\mathbf{k}}_1 \cdot \hat{\mathbf{k}}_2)^2\right] \Big\} \end{aligned}$$

- ➢ Rescaling of the momenta
  - ➔ Every term in the kernel is homogeneous of degree 4

[Bertacca et al. (2024)]

Scale-invariance ?

$$\mathcal{P}_\phi^{(AA)}(k) \propto k^{-3}$$

- Dimensionless scalar power spectrum $\Delta_\phi^2(k) = \frac{k^3}{2\pi^2}\mathcal{P}_\phi(k)$

- Putting everything together …

$$\Delta_\phi^2(k) = \int_0^\infty dx \int_{|x-1|}^{x+1} dy \frac{1}{x^2y^2}\mathcal{K}_h(x,y)\left(\frac{H_{\rm inf}}{m_{pl}}\right)^4$$

Change of variables

$$x = \frac{k_1}{k} \quad \text{and} \quad y = \frac{k_2}{k} = \frac{|\mathbf{k}-\mathbf{k}_1|}{k}$$

- It is exactly scale-invariant !

Scalars bigger than tensors?

$$\Delta^2_\phi(k) = \int_0^\infty dx \int_{|x-1|}^{x+1} dy \frac{1}{x^2y^2} \mathcal{K}_h(x,y) \left(\frac{H_{\text{inf}}}{m_{pl}}\right)^4$$

From observations

Free parameter

➔ Simple testable framework

➢ Naively we would expect $\Delta^2_\phi \sim \Delta^2_h \Delta^2_h$

➔ tensor-to-scalar ratio $r > 1$?

Scalars bigger than tensors?

$$\Delta_\phi^2(k) = \int_0^\infty dx \int_{|x-1|}^{x+1} dy \frac{1}{x^2 y^2} \mathcal{K}_h(x,y) \left(\frac{H_{\text{inf}}}{m_{pl}}\right)^4$$

$$x = \frac{k_1}{k} \quad \text{and} \quad y = \frac{k_2}{k} = \frac{|\mathbf{k} - \mathbf{k}_1|}{k}$$

➢ Caveat

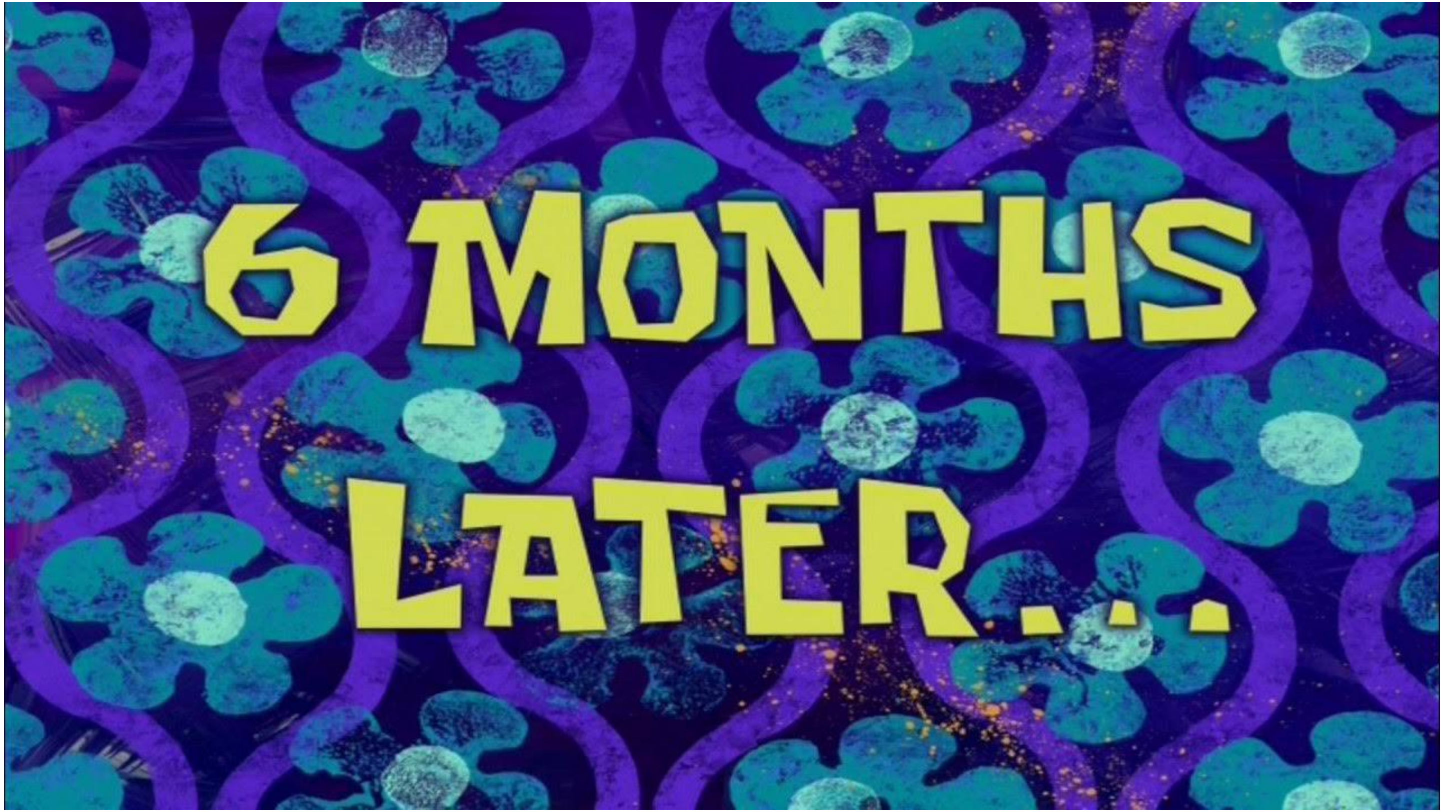
$k_1, k_2 < k_{end}$ ⟶ outside the horizon

$k_1, k_2 > k_{end}$ ⟶ inside the horizon

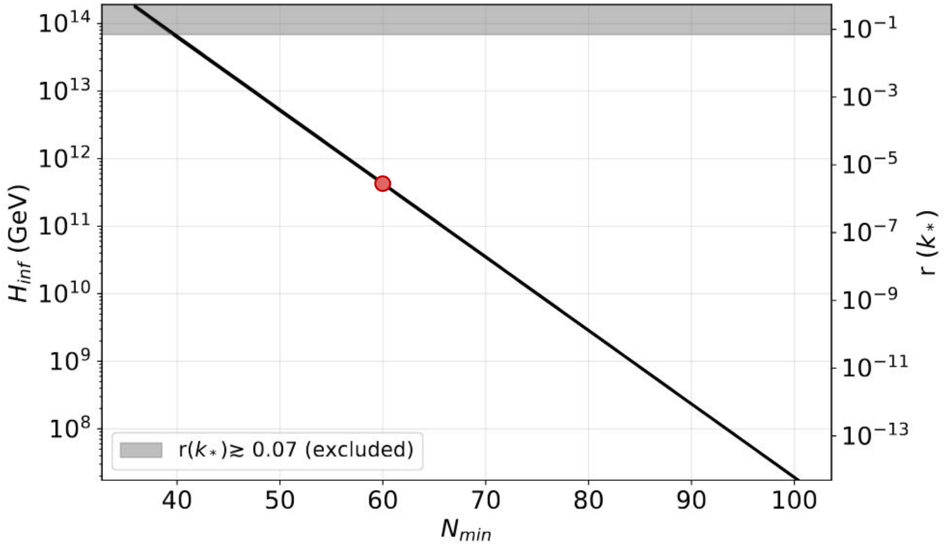
- number of e-folds $N_{\text{end}} \equiv \ln\left(\frac{a_{\text{end}}}{a_{\text{in}}}\right)$ ⟶ N_{min}

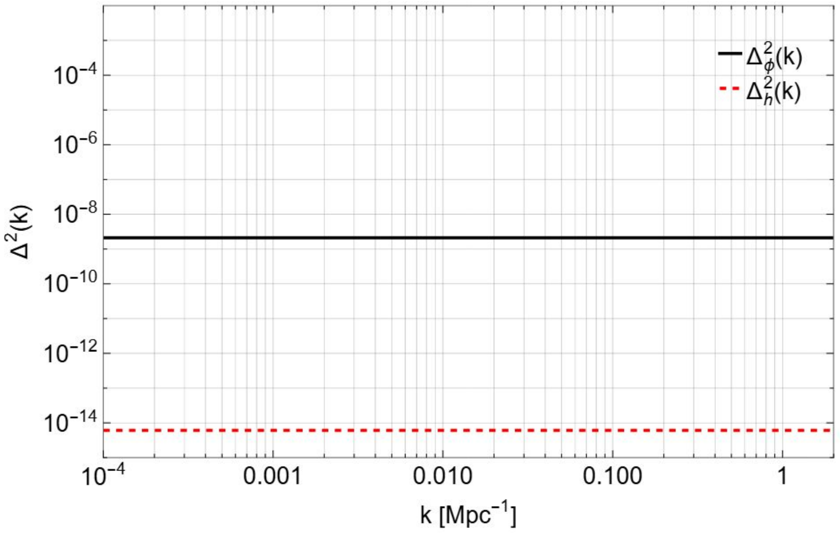
Free parameter

Power spectrum



Preliminary Results





- For example $N_{\rm min} = 60$ $H_{\rm inf} \simeq 4 \times 10^{11}\,{\rm GeV}$ $r(k_*) \simeq 10^{-6}$

Quantum break-time

$$t_q = \frac{1}{\mathcal{N}_{\rm sp}} \frac{m_{\rm pl}^2}{H^3}$$

number of species

- This imposes a consistency condition

  For example: If $\sqrt{\Lambda} = 10^{-42}\,\text{GeV}$ and $\mathcal{N}_{\rm sp} \sim 10^{32}$,
  saturate the bound only if the Universe were 10^{100} years old.

- When applied to the inflationary stage:

  - Maximum number of e-foldings $N_{\rm end} < \frac{1}{\mathcal{N}_{sp}} \frac{m_{\rm pl}^2}{H_{\rm inf}^2}$

[Dvali et al. (2017)]

Quantum break-time

- In our framework: $N_{min} \longrightarrow H_{\rm inf}$

fixed to match CMB constraint

$$\Delta^2_\phi(k_*) \simeq 2.1 \times 10^{-9}$$

- Maximum number of allowed species

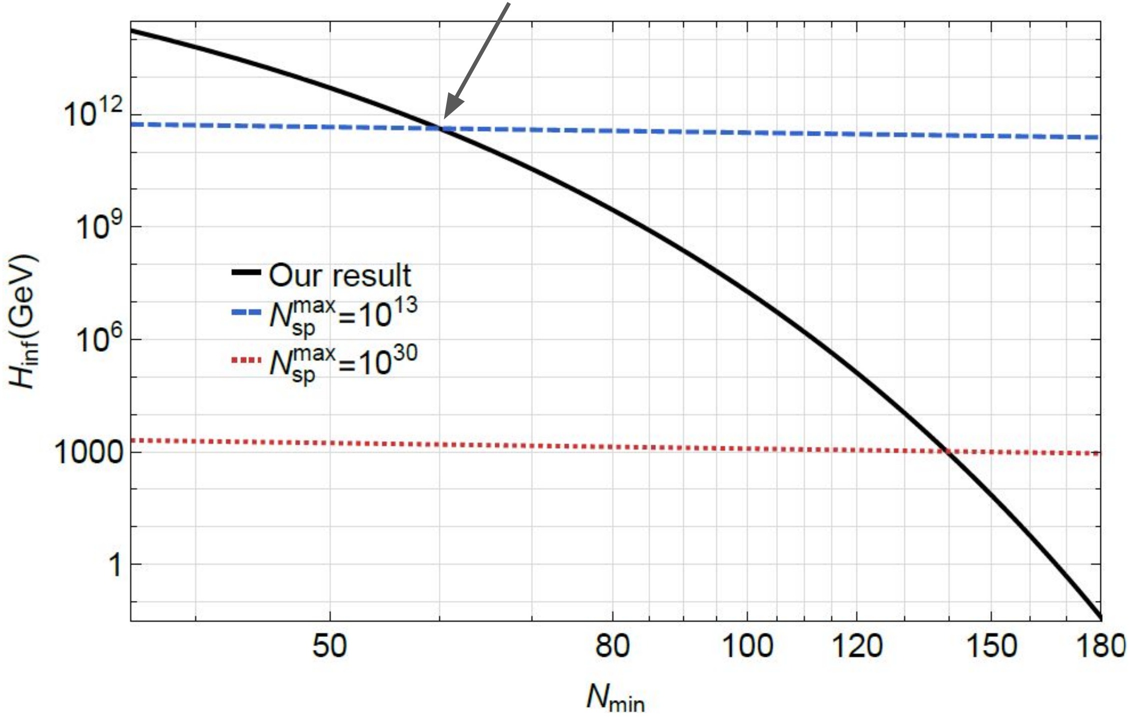
$$\mathcal{N}_{\rm sp} < \frac{1}{N_{\rm min}} \frac{m_{\rm pl}^2}{H_{\rm inf}^2} \equiv \mathcal{N}_{\rm sp}^{\rm max}$$

➔ The longer inflation lasts,
the lower the bound on the energy scale
and the more species it houses

[Dvali et al. (2017)]

Preliminary Results

Reference value $N_{\rm min} = 60$



Non-Gaussianity

Motivation

Starting from the solution when $\psi_2 = 0$ and $\phi_2 = \mathcal{F}_\chi/4$

$$\phi_2 = \nabla^{-2}\left(\frac{3}{4}\chi_1^{lk,m}\chi_{1kl,m} + \frac{1}{2}\chi_1^{kl}\nabla^2\chi_{1lk} - \frac{1}{2}\chi_{1,l}^{km}\chi_{1m,k}^{l}\right)$$

The Second order Scalar modes are sourced by quadratic Linear tensor modes, Because of that (If GW are Gaussian) our potential is chi-squared distributed, hence intrinsically NG.

In *Abdelaziz et. al Phys.Rev.D 112 (2025) 2, 023505,* It was shown that tensor-induced density perturbations arising from quadratic modes of G indeed have a large NG signal.

Bispectrum

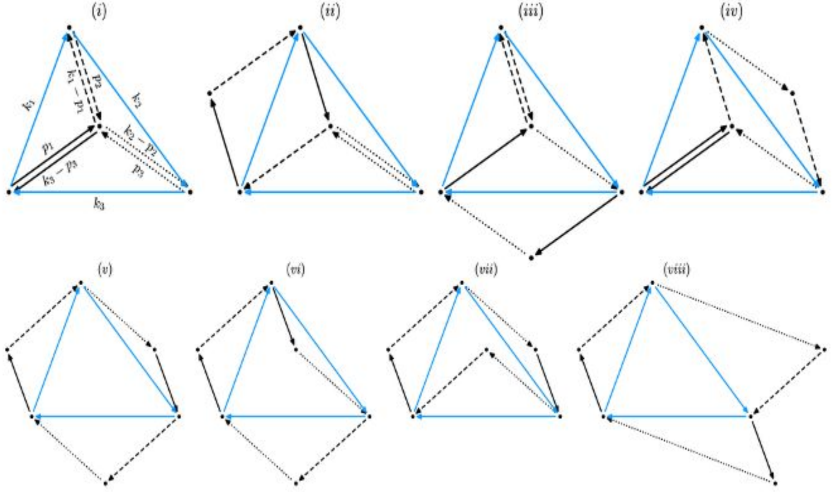
We define the bispectrum by

$$\langle \phi_2(\boldsymbol{k}_1)\, \phi_2(\boldsymbol{k}_2)\, \phi_2(\boldsymbol{k}_3) \rangle = (2\pi)^3\, \delta^{(3)}(\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3)\, B_{\phi_2}(k_1, k_2, k_3).$$

$$\langle \phi_2(\boldsymbol{k}_1)\phi_2(\boldsymbol{k}_2)\phi_2(\boldsymbol{k}_3) \rangle = \frac{1}{k_1^2 k_2^2 k_3^2} \int \prod_{i=1}^{3} \frac{d^3 p_i}{(2\pi)^3} \sum_{s_i, t_i} \left[\prod_{i=1}^{3} K_i^{s_i t_i}(\boldsymbol{p}_i, \boldsymbol{q}_i) \right] \times \langle \chi^{s_1}(p_1)\, \chi^{t_1}(q_1)\, \chi^{s_2}(p_2)\, \chi^{t_2}(q_2)\, \chi^{s_3}(p_3)\, \chi^{t_3}(q_3) \rangle.$$

$$\Downarrow$$

$$\langle \phi_2(\boldsymbol{k}_1)\phi_2(\boldsymbol{k}_2)\phi_2(\boldsymbol{k}_3) \rangle = \frac{8}{k_1^2 k_2^2 k_3^2} \int d^3 p_1 \sum_{s_i, t_i} \left[\prod_{i=1}^{3} K_i^{s_i t_i}(\boldsymbol{p}_i, \boldsymbol{q}_i) \right] \times \delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3)\, (2\pi)^3\, \pi^3 \frac{\Delta_\chi^2(p_1)}{p_1^3} \frac{\Delta_\chi^2(p_2)}{p_2^3} \frac{\Delta_\chi^2(p_3)}{p_3^3}$$



Plot from: "A Cosmological Signature of the SM Higgs Instability: Gravitational Waves"

José Ramón Espinosa, Davide Racco, Antonio Riotto

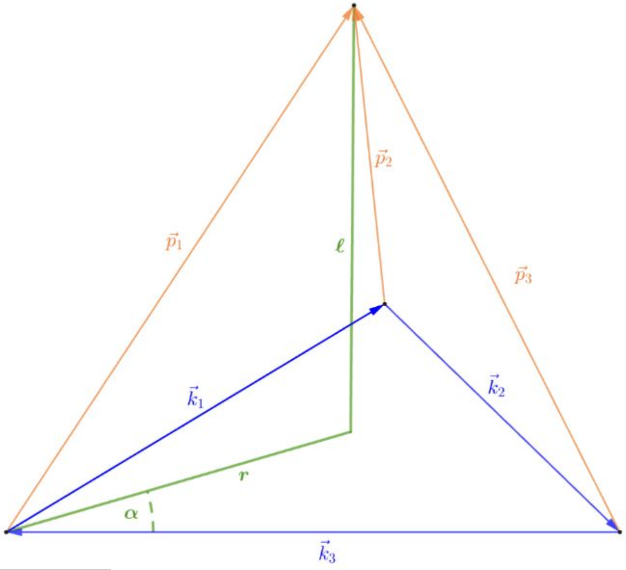
Bispectrum

$$B_{\phi_2}(k_1,k_2,k_3)=\frac{8^4}{k_1^2k_2^2k_3^2}\left(\frac{H_{\rm inf}}{m_{\rm pl}}\right)^6\int d^3p_1\mathcal{K}\frac{1}{p_1^3p_2^3p_3^3}$$

Choosing to work in Cylindrical coordinates

$$\int \mathrm{d}^3p_1 \longrightarrow \int_{-\infty}^{+\infty}\mathrm{d}\ell\int_0^{+\infty} r\,\mathrm{d}r\int_0^{2\pi}\mathrm{d}\alpha\,.$$

$$\mathbf{k}_1=(k_{1x},k_{1y},0)\,,\quad \mathbf{k}_2=(k_{2x},k_{2y},0)\,,\quad \mathbf{k}_3=(-k_3,0,0)\,.$$



Consequently, the momenta $\boldsymbol{p_i}$ can be expressed as

$$\mathbf{p}_1=(r\cos\alpha,r\sin\alpha,\ell)\,,\quad \mathbf{p}_2=(-k_{1x}+r\cos\alpha,-k_{1y}+r\sin\alpha,\ell)\,,\quad \mathbf{p}_3=(-k_3+r\cos\alpha,r\sin\alpha,\ell)\,.$$

Bispectrum

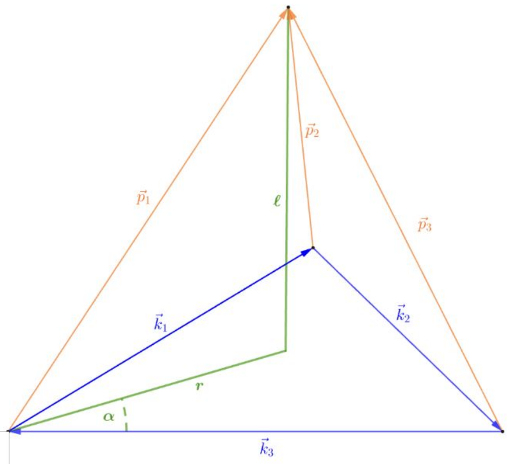
$$\boxed{B_{\phi_2}(k_1,k_2,k_3) = \frac{8^4}{k_1^2k_2^2k_3^2}\left(\frac{H_{\rm inf}}{m_{\rm pl}}\right)^6 \int d^3p_1 \mathcal{K}\frac{1}{p_1^3p_2^3p_3^3}}$$

$$\begin{aligned}\mathcal{K} = &\left[\frac{3}{4}\mathbf{p_1}\cdot\mathbf{p_2}\,\epsilon^{s_1,lk}(\hat{\mathbf{p}}_1)\,\epsilon^{s_2}_{kl}(-\hat{\mathbf{p}}_2) + \frac{1}{4}(p_1^2+p_2^2)\,\epsilon^{s_1,kl}(\hat{\mathbf{p}}_1)\,\epsilon^{s_2}_{lk}(-\hat{\mathbf{p}}_2) - \frac{1}{2}p_{1l}\,p_{2k}\,\epsilon^{s_1,km}(\hat{\mathbf{p}}_1)\,\epsilon^{s_2,l}{}_{m}(-\hat{\mathbf{p}}_2)\right]\\
&\times\left[\frac{3}{4}\mathbf{p_2}\cdot\mathbf{p_3}\,\epsilon^{s_2,uv}(\hat{\mathbf{p}}_2)\,\epsilon^{s_3}_{vu}(-\hat{\mathbf{p}}_3) + \frac{1}{4}(p_2^2+p_3^2)\,\epsilon^{s_2,vu}(\hat{\mathbf{p}}_2)\,\epsilon^{s_3}_{uv}(-\hat{\mathbf{p}}_3) - \frac{1}{2}p_{2u}\,p_{3v}\,\epsilon^{s_2,vr}(\hat{\mathbf{p}}_2)\,\epsilon^{s_3,u}{}_{r}(-\hat{\mathbf{p}}_3)\right]\\
&\times\left[\frac{3}{4}\mathbf{p_3}\cdot\mathbf{p_1}\,\epsilon^{s_3,ij}(\hat{\mathbf{p}}_3)\,\epsilon^{s_1}_{ji}(-\hat{\mathbf{p}}_1) + \frac{1}{4}(p_3^2+p_1^2)\,\epsilon^{s_3,ji}(\hat{\mathbf{p}}_3)\,\epsilon^{s_1}_{ij}(-\hat{\mathbf{p}}_1) - \frac{1}{2}p_{3i}\,p_{1j}\,\epsilon^{s_3,jz}(\hat{\mathbf{p}}_3)\,\epsilon^{s_1,i}{}_{z}(-\hat{\mathbf{p}}_1)\right]\end{aligned}$$

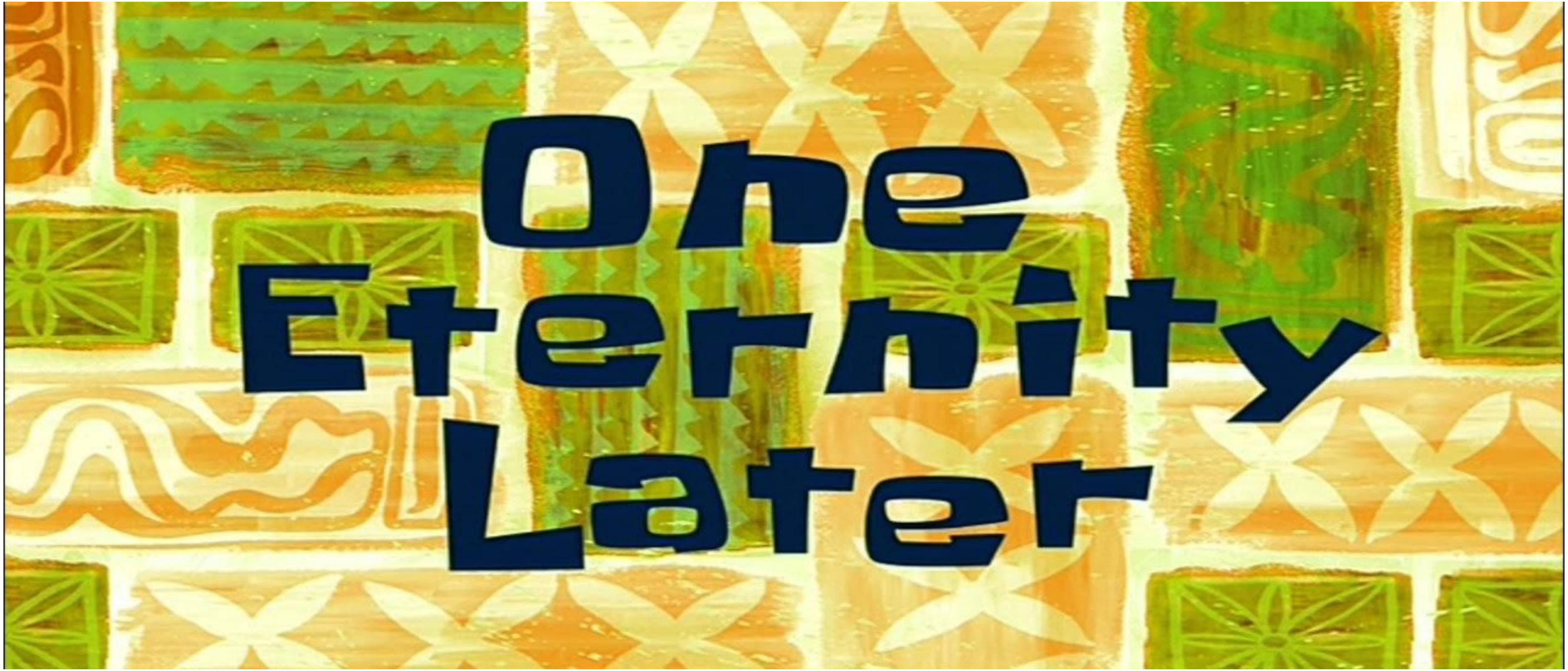
Using the following properties of the polarization tensors

$$\begin{aligned}&\epsilon^{+/\times}_{ab}(\hat{\boldsymbol{k}}) = \epsilon^{+/\times *}_{ab}(\hat{\boldsymbol{k}}), \quad \epsilon^{+}_{ab}(\hat{\boldsymbol{k}}) = \epsilon^{+}_{ab}(-\hat{\boldsymbol{k}}), \quad \epsilon^{\times}_{ab}(-\hat{\boldsymbol{k}}) = -\epsilon^{\times}_{ab}(\hat{\boldsymbol{k}}),\\
&\epsilon^{+}_{ab}(\hat{\boldsymbol{k}})\epsilon^{+}_{ab}(\hat{\boldsymbol{k}}) = 1, \qquad \epsilon^{\times}_{ab}(\hat{\boldsymbol{k}})\epsilon^{\times}_{ab}(\hat{\boldsymbol{k}}) = 1, \quad \epsilon^{+}_{ab}(\hat{\boldsymbol{k}})\epsilon^{\times}_{ab}(\hat{\boldsymbol{k}}) = 0.\end{aligned}$$

$$\begin{aligned}2\sum_\lambda \epsilon_{ij,\lambda}(\hat{\boldsymbol{k}})\epsilon^*_{ab,\lambda}(\hat{\boldsymbol{k}}) = &\left(\delta_{ia} - \hat{\boldsymbol{k}}_i\hat{\boldsymbol{k}}_a\right)\left(\delta_{jb} - \hat{\boldsymbol{k}}_j\hat{\boldsymbol{k}}_b\right) + \left(\delta_{ib} - \hat{\boldsymbol{k}}_i\hat{\boldsymbol{k}}_b\right)\left(\delta_{ja} - \hat{\boldsymbol{k}}_j\hat{\boldsymbol{k}}_a\right)\\
&- \left(\delta_{ij} - \hat{\boldsymbol{k}}_i\hat{\boldsymbol{k}}_j\right)\left(\delta_{ab} - \hat{\boldsymbol{k}}_a\hat{\boldsymbol{k}}_b\right),\end{aligned}$$



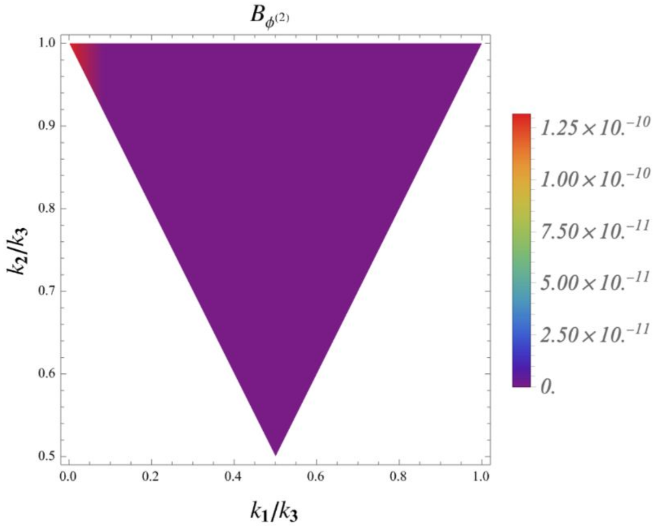
Bispectrum



Preliminary Results

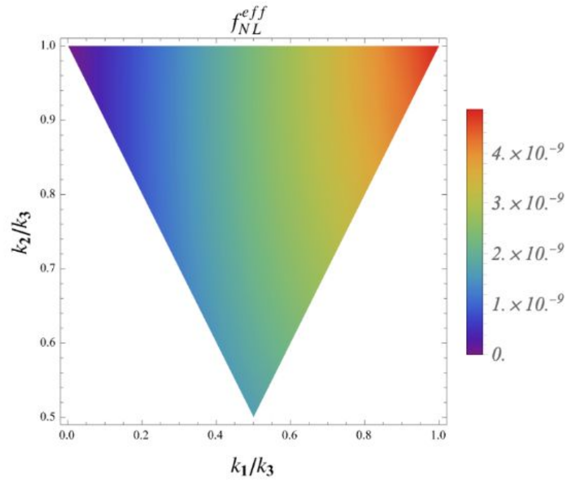
$$B_{\phi_2}(k_1, k_2, k_3) = \frac{8^4}{k_1^2 k_2^2 k_3^2} \left(\frac{H_{\text{inf}}}{m_{\text{pl}}}\right)^6 \int d^3p_1 \mathcal{K} \frac{1}{p_1^3 p_2^3 p_3^3}$$

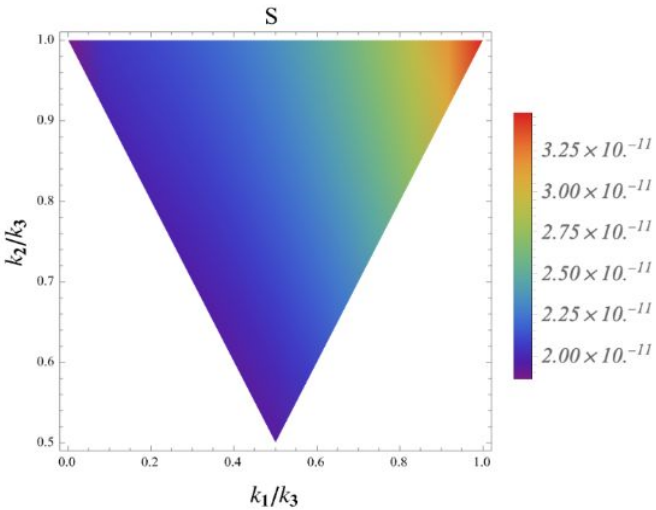
- We present the numerical results for the bispectrum on a plane of $(k_1/k_3, k_2/k_3)$, keeping k_3 fixed and ordering the momenta as $k_1 \leq k_2 \leq k_3$.
- The Bispectrum peaks in squeezed configurations naturally due to the k^6 factor in front of the integral.



For: $k_3 = 0.05\ \text{Mpc}^{-1}$, $\mathcal{H}_{\text{inf}} = 2.7 \times 10^{13}$ GeV

Preliminary Results





$$f_{NL}^{eff} \approx \frac{B_{\phi^{(2)}}}{2[P_{\phi^{(2)}}(k_1)P_{\phi^{(2)}}(k_2) + P_{\phi^{(2)}}(k_2)P_{\phi^{(2)}}(k_3) + P_{\phi^{(2)}}(k_3)P_{\phi^{(2)}}(k_1)]}$$

$$\mathcal{S}(k_1, k_2, k_3) = k_1^2 k_2^2 k_3^2 \frac{B_{\phi^{(2)}}}{\sqrt{\Delta_{\phi^{(2)}}(k_1)\Delta_{\phi^{(2)}}(k_2)\Delta_{\phi^{(2)}}(k_3)}}$$

The NG signal is peaking in the equilateral configuration as sourcing occurs primarily around horizon crossing, and the bispectrum peaks when the sourcing momenta are equal in magnitude.

Conclusions and future prospects

- Model-independent picture of inflation with a simple framework.
- Scalar perturbations reproduce the characteristics that we expect from observations.
- We have shown how to connect our analysis to the concept of quantum break-time of de Sitter and the number of particle species.
- Intrinsic non-Gaussianity of the tensor-induced scalar potential is expected and could be a powerful observable.
- We have shown that the signal is peaking in the equilateral configuration as GWs are frozen outside the horizon and start the sourcing at horizon-entry.

- Solve the problem in a more complete way accounting for the time dependence.
- Account for the observed scalar spectral tilt.

Thank you

“The sky swirls with waves, and from their dance, stars are born”