ZOOLOGY OF GRAVITON NON-GAUSSIANITIES IN INFLATION

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OUTLINE

·) Motivations

·) "Zoology of condensed matter" review (Nicolis, Penco, Piazza, Rattazzi - 2015)

·) Coupling to gravity

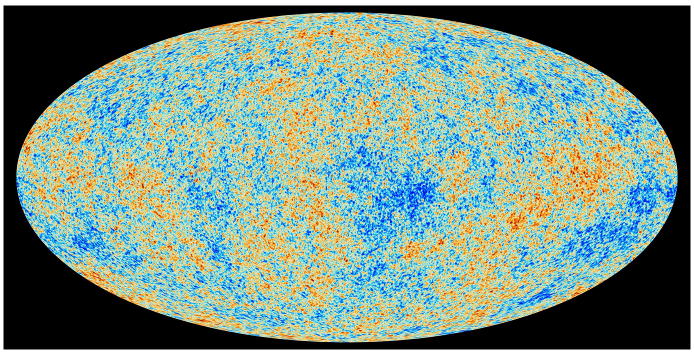
·) Graviton interactions and phenomenology

·) Conclusions

OVERVIEW & MOTIVATIONS

"Inflation seems to be the highest-energy observable natural process. The Hubble scale, H, during inflation could be as high as 10^{14} GeV. This is much larger than any energy we can achieve with particle accelerators in the foreseeable future."

(Arkani-Hamed, Maldacena - 2015)



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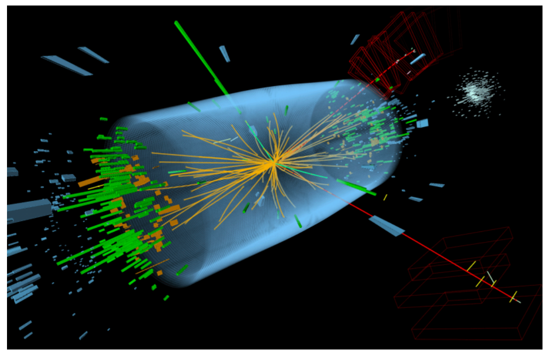
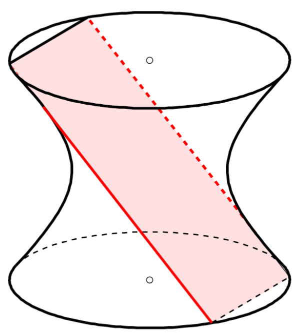


·) We can ask what are the signatures of new particles during inflation.

·) A difference with the collider case is that we are not in flat space: we are in de Sitter space.



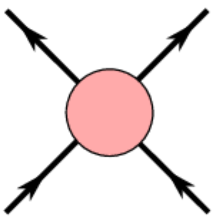
·) Lessons so far (from studies of Effective Field Theory of Inflation: large amount of literature!): phenomenologically-interesting cases involve breaking of de Sitter isometries (boosts, in particular).

Here I will not focus on new particles during inflation, but on the consequences of the different ways one can break these symmetries.

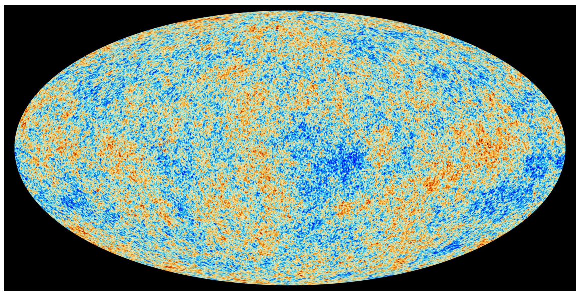
·) Spontaneous Symmetry Breaking: Goldstone modes are present! They can be many, so a complete analysis of all interactions (and resulting non-Gaussianities) is complicated. Focus on graviton self-interactions!

·) Recent developments in "Cosmological Bootstrap" program:

- ∘) set of rules to obtain correlation functions w/o referring to a Lagrangian (e.g.: Arkani-Hamed, Baumann, Lee, Pimentel - 2019)



$\longleftrightarrow$



- ∘) recently extended to "Boostless Bootstrap" (Pajer - 2020). Only the symmetry breaking pattern of single-clock inflation has been studied.

→ working at the level of the Lagrangian can help and guide the development of the bootstrap rules.

·) Of course, if primordial GWs are detected, having classified all the observational signatures would be useful!

ZOOLOGY OF CONDENSED MATTER

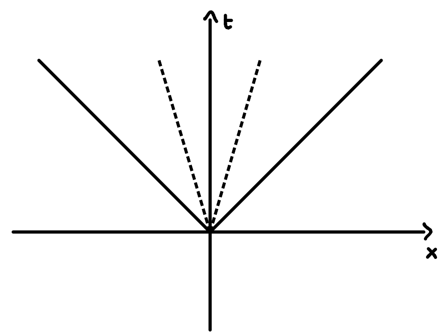
(Nicolis, Penco, Piazza, Rattazzi - 2015)

We want to look at different SB patterns. We can build intuition from working on sub-horizon scales ⇝ with Poincaré group.

Nicolis, Penco, Piazza, Rattazzi - 2015 : classify all symmetry breaking patterns associated with a static, homogeneous and isotropic medium.

Why static? An example :

t_0:

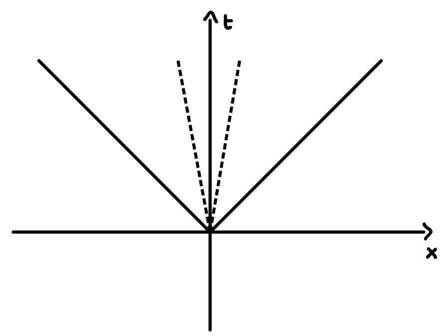


$$S = \frac{g_\pi^2}{2} \int d^4x \left(\dot{\pi}^2 - c_s^2 \vec{\nabla}\pi \cdot \vec{\nabla}\pi \right)$$

Boosts strongly broken

$$\rightarrow \quad \frac{1 - c_s^2}{c_s^2} \gg 1$$

t_1:



Staticity : $\dfrac{\dot{c}_s}{H c_s} \ll 1$

GENERATORS

P_0	(time traslations)
P_i	(spatial traslations)
J_i	(rotations)
K_i	(boosts)

spacetime

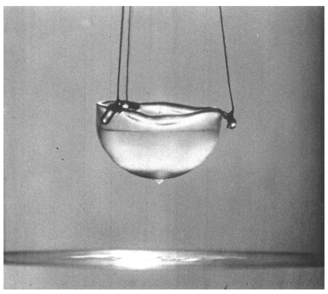
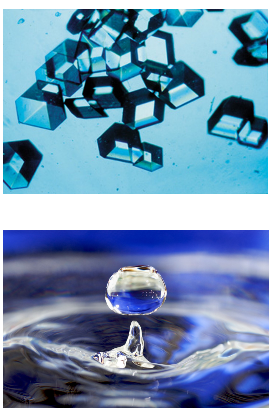
\+ $\bar{P}_0$, $\bar{P}_i$, $\bar{J}_i$ (unbroken)

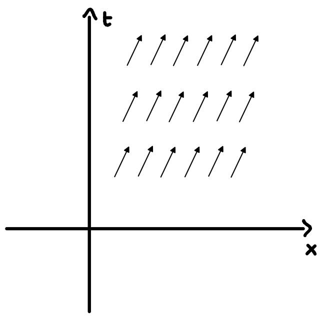
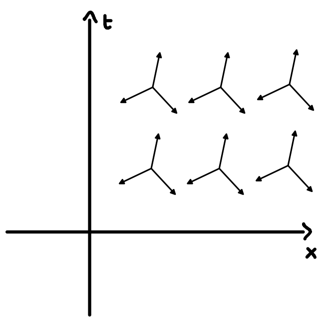
generators that govern collective excitations of the system

Unbroken generators : $\bar{P}_0 = P_0 + Q$, $\bar{P}_i = P_i + Q_i$, $\bar{J}_i = J_i + \tilde{Q}_i$

→ different cases depending on whether generators of internal symmetries Q, Q_i, $\tilde{Q}_i$ are non zero !

Focus on the case where Q, Q_i, $\tilde{Q}_i$ commute with spacetime symmetries : otherwise we have "galileids" which are difficult to couple to gravity.

SYSTEM	GENERATORS	ORDER PARAMETER + GOLDSTONE MODES
 type - I superfluid	$\bar{P}_0 = P_0 + Q, \quad \bar{P}_i = P_i, \quad \bar{J}_i = J_i$	$\langle \psi(x) \rangle = t$ $\psi(x) = t + \pi(x)$
 solids (absence of preferred axes : jellies) & fluids	$\bar{P}_0 = P_0, \quad \bar{P}_i = P_i + Q_i, \quad \bar{J}_i = J_i + \tilde{Q}_i$	$\langle \phi^I(x) \rangle = x^I$ $\phi^I(x) = x^I + \pi^I(x)$ FLUIDS: require symmetry $\phi^a \to \xi^a(\phi) \, , \qquad \det \frac{\partial \xi^a}{\partial \phi^b} = 1$ (only compression matters)

SYSTEM	GENERATORS	ORDER PARAMETER + GOLDSTONE MODES
supersolids & finite-temperature superfluids	$\bar{P}_0 = P_0 + Q, \quad \bar{P}_i = P_i + Q_i, \quad \bar{J}_i = J_i + \tilde{Q}_i$	$\langle \phi^\mu(x) \rangle = x^\mu$ $\phi^\mu(x) = x^\mu + \pi^\mu(x)$
type-I framid 	$\bar{P}_0 = P_0, \quad \bar{P}_i = P_i, \quad \bar{J}_i = J_i$	$\langle A^\mu \rangle = \delta^\mu_0$ Goldstones: rapidity $\vec{\eta}(x)$ of broken Lorentz boosts acting on the vacuum
type-II framid 	$\bar{P}_0 = P_0, \quad \bar{P}_i = P_i, \quad \bar{J}_i = J_i + \tilde{Q}_i$	$\langle A^\mu_I \rangle = \delta^\mu_I$ Goldstones: rapidity $\vec{\eta}(x)$ and Euler angles $\vec{\theta}(x)$ of of broken Lorentz boosts and rotations acting on the vacuum

Finally, type-II superfluids : $\bar{P}_0 = P_0 + Q, \quad \bar{P}_i = P_i, \quad \bar{J}_i = J_i + \tilde{Q}_i$ $\rightsquigarrow$ superfluid + type-II framid (plays role of spin in NR limit).

COUPLING TO GRAVITY

Either gauge Poincaré group within Callan, Coleman, Wess, Zumino construction (see e.g. Delacrétaz, Endlich, Monin, Penco, Riva - 2014), OR realize that we either have a preferred coordinate system (superfluids and solids) or a preferred frame (framids).

Intuition bolstered by explicit constructions of

·) Delacrétaz, Endlich, Monin, Penco, Riva - 2014 + Bordin, Creminelli, Khmelnitsky, Senatore - 2018 → superfluids

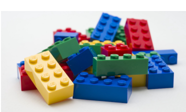
·) Delacrétaz, Nicolis, Senatore - 2015 → type-I framids

We can eat the additional degrees of freedom from breaking of diffeomorphisms and local Lorentz transformations with the metric: unitary gauge!

GRAVITON INTERACTIONS

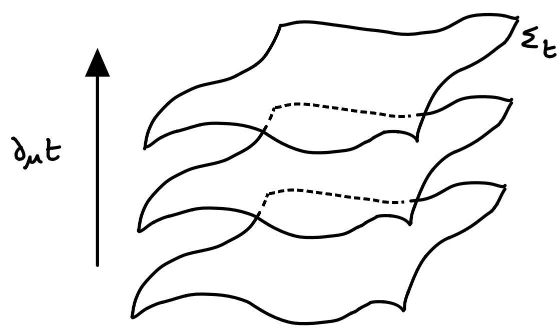
·) Enough to consider $ds^2 = -dt^2 + a^2 (e^{\gamma})_{ij}\, dx^i dx^j$, w/ $\gamma_{ii} = 0 = \partial_i \gamma_{ij}$.

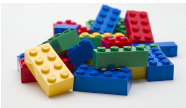
·) Let's see how we can just focus on Solid Inflation first, then we will look at a few interactions.



of EFT I: ~) at lowest order in fluctuations, γ must enter w/ derivatives

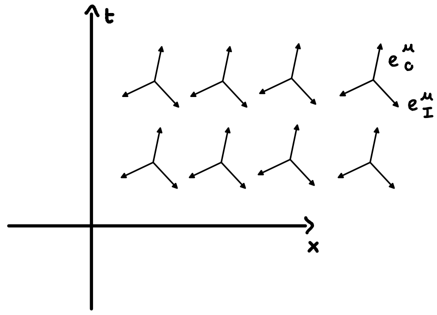
~) these can be either $\dot{\gamma}_{ij} \sim \nabla_\mu \partial_\nu t$ or $\partial_k \partial_l \gamma_{ij} \sim$ curvature of Σ_t





of type - II framid : ~) we still cannot have γ w/o derivatives, since all lowest-order operators give a cosmological constant

~)

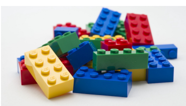


~) $e^\mu_0 = -\frac{g^{\mu\nu}}{6}\, \varepsilon_{IJK}\, e_{\nu\alpha\beta\gamma}\, e^\alpha_I\, e^\beta_J\, e^\gamma_K$ (framid type - I) allows to write γ_{ij} as before.

e^μ_I allows to write $\partial_K \gamma_{IJ}$, essentially via

$g_{\nu\rho}\, e^\mu_I\, e^\rho_K\, \nabla_\mu e^\nu_J \sim \Gamma^K_{IJ}$

~) via e^μ_0 we can also construct all the operators of the EFTI

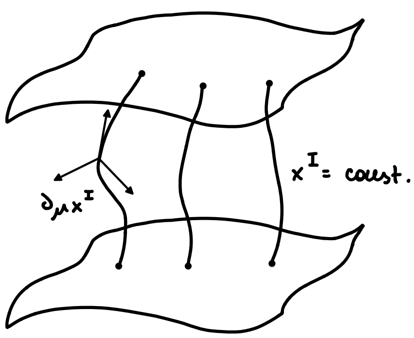


of Solid Inflation : ~) we can have γ_{ij} appearing w/o derivatives. Indeed it appears already in the leading action :

$$S = \int d^4x \sqrt{-g}\left[\frac{M_{Pl}^2}{2} R + F(X, Y, Z)\right]$$

$X \to g^{II}$, $\quad Y \to \dfrac{g^{IJ} g^{JI}}{X^2}$, $\quad Z \to \dfrac{g^{IJ} g^{JK} g^{KI}}{X^3}$

~)



TANGENT VECTOR TO THREADING : $\sigma^\mu = \dfrac{e^{\mu\nu\rho\sigma}\, \varepsilon_{IJK}\, \partial_\nu x^I\, \partial_\rho x^J\, \partial_\sigma x^K}{6\sqrt{\det g^{IJ}}}$,

$\sigma_\mu \sigma^\mu = -1$

~) $\dot{\gamma}_{ij}$ → use o) $h_{\mu\nu} = g_{\mu\nu} + O_\mu O_\nu$

o) $\delta K_{\mu\nu} = h_{(\mu}{}^{\rho} \nabla_\rho O_{\nu)} - \frac{\nabla_\rho O^\rho h_{\mu\nu}}{3}$

Further time derivatives can be taken via $O^\mu \nabla_\mu [\ldots]$

~) Spatial derivatives : similar to type - II framid

(only be careful about $x^I \to \lambda \cdot x^I$ symmetry)

⇒ take the quantity $\Gamma^{KIJ} = \frac{g^{\mu I} g^{\nu J} \nabla_\mu x^K_\nu}{Tr(g)^{5/2}}$

$\partial_K \gamma_{IJ} \sim \Gamma^{IJK} + \Gamma^{JIK}$

~) we can contract indices of $\partial_K \gamma_{IJ}$ or $\dot{\gamma}_{IJ}$ either with δ_{IJ} or with γ_{IJ} itself, using $\frac{g^{IJ}}{g^{KK}} - \delta^{IJ}$.

PHENOMENOLOGY

Essentially we can write "whatever we want" : I will discuss some particular cases.

Expansion in perturbations and derivatives → will stop at $O(2)$ in ∂ and $O(3)$ in perturbations (tree - level graviton bispectrum)

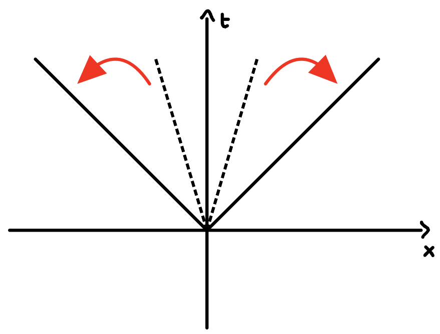
·) From $F(X, Y, Z)$ we get a graviton mass and a cubic interaction without derivatives : $S_{\gamma\gamma} \sim \gamma^2_{ij} \cdot M_P^2 \cdot \varepsilon \cdot H^2$ (slow - roll - suppressed)

$S_{\gamma\gamma\gamma} \sim \gamma^3_{ij} \cdot M_P^2 \cdot \frac{F_{Y,Z}}{F}$

→ purely <u>local</u> interaction which gives rise to non-Gaussianity whose size depends on $N_{e\text{-folds}}$ (Endlich, Horn, Nicolis, Wang - 2013).

·) New interactions at $\mathcal{O}(\delta^2)$: can change c_T^2 via many operators.

·) $c_T^2 \ll 1$ not tied to large interactions univocally.



redefining lightcone doesn't remove the interactions!

·) Cubic interactions: $\gamma_{kl}\,\partial_k \gamma_{ij}\,\partial_l \gamma_{ij} \subset {}^{(4)}R$

$\gamma_{ij}\,\dot\gamma_{jk}\,\dot\gamma_{ki} \not\subset {}^{(4)}R$

break soft graviton consistency relation

CONCLUSIONS

▷ Solid Inflation captures all possible interactions for the graviton.

▷ The freedom we have could allow to find regions of parameter space where I can modify tensor non-Gaussianities w/o strongly affecting the scalar sector.

▷ This is difficult to do in single-clock inflation! Can only be done at $\mathcal{O}(\delta^4)$ (Bordin, Cabass - 2020)

▷ The main shortcoming of the current implementation of the Boostless Bootstrap is clear here: we can recover the correct bispectrum in terms of five free parameters, but we don't yet have a rule to tell us which of these parameters may be large and which must be small.

(Pajer - 2020) ⇝ working @ the level of the Lagrangian can help!

Thanks!