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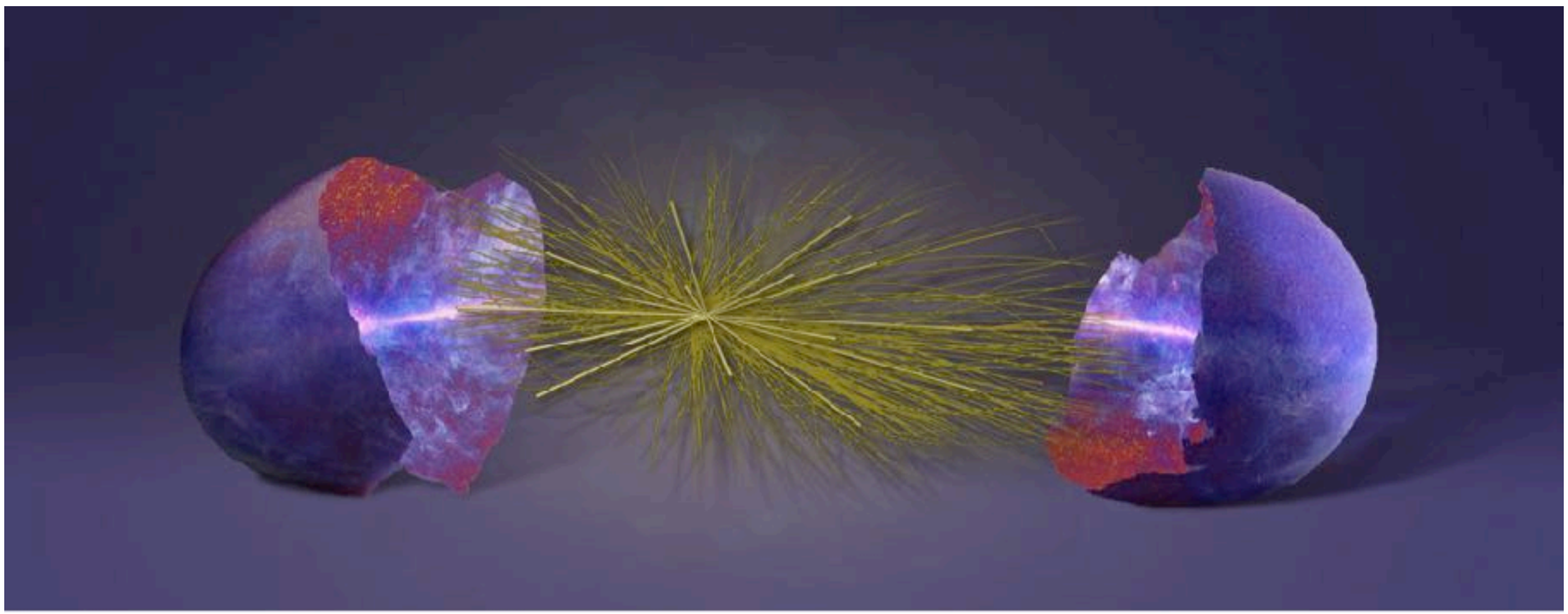
QUARKS 18, Valday

Spinning Cosmology



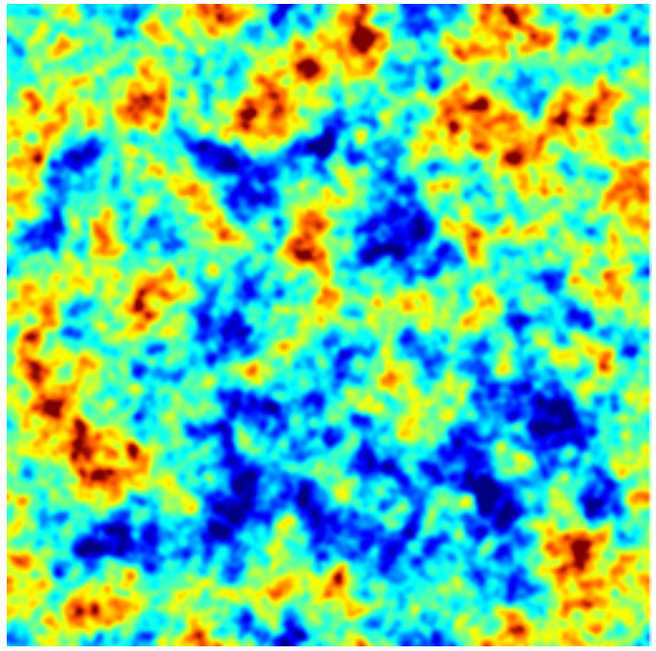
with L. Bordin, P. Creminelli, M. Mirbabayi, and L. Senatore

Motivations

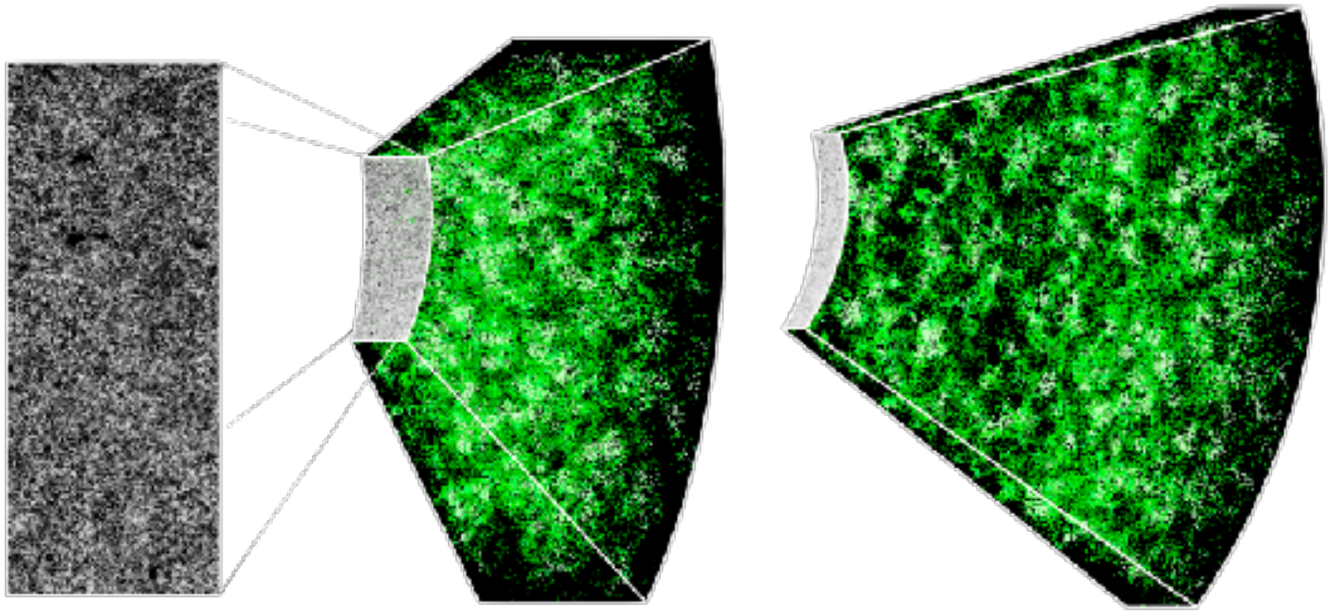
- Inflation: a period of accelerated expansion
  Resolves the horizon and the flatness problems

- Requires at least one dynamical field — a "clock" to end inflation
  Quantum fluctuations are generated:

CMB



LSS

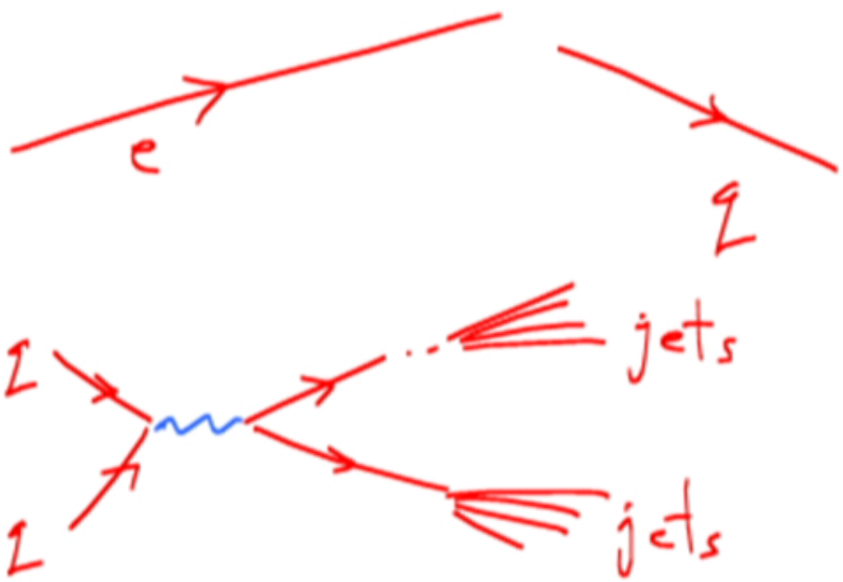


- Information about the Inflationary stage is encoded in the correlation functions of the primordial fluctuations

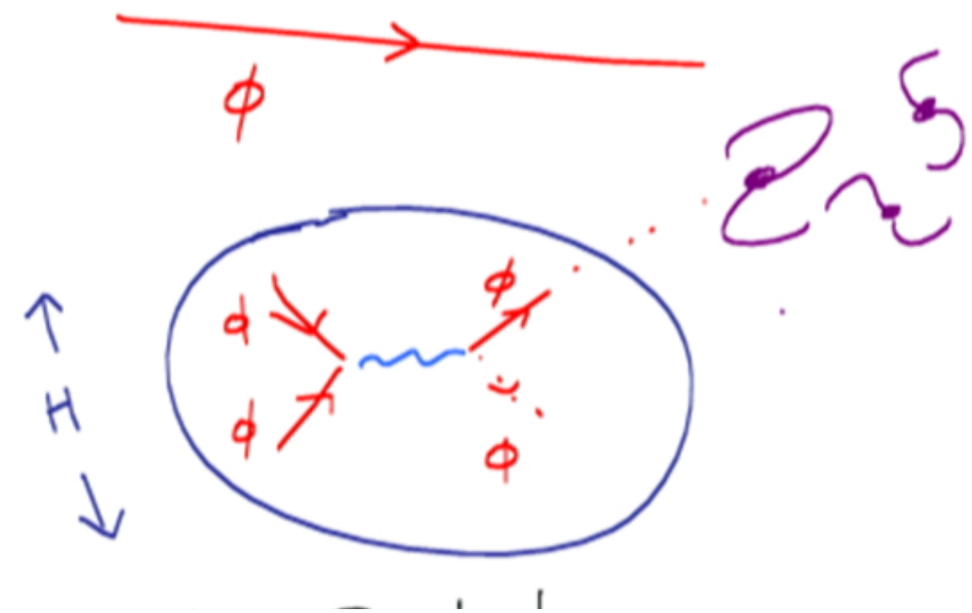
Cosmological Collider Physics

At least two light fields: the clock ζ and the graviton γ

We can use inflation as a ζ (and eventually γ) collider to search for new physics at energies up to $H_{inf} \lesssim 10^{14}$ GeV!



New particles at colliders from signals in scattering amplitudes



New particles from patterns in non-Gaussianities

Chen, Wang '09
Baumann, Green '11
Noumi, Yamaguchi, Yokoyama '12
Arkani-Hamed, Maldacena '15

*We'll limit ourselves with ζ and γ correlation functions

Non-Gaussianity, f_{NL}, and Observations

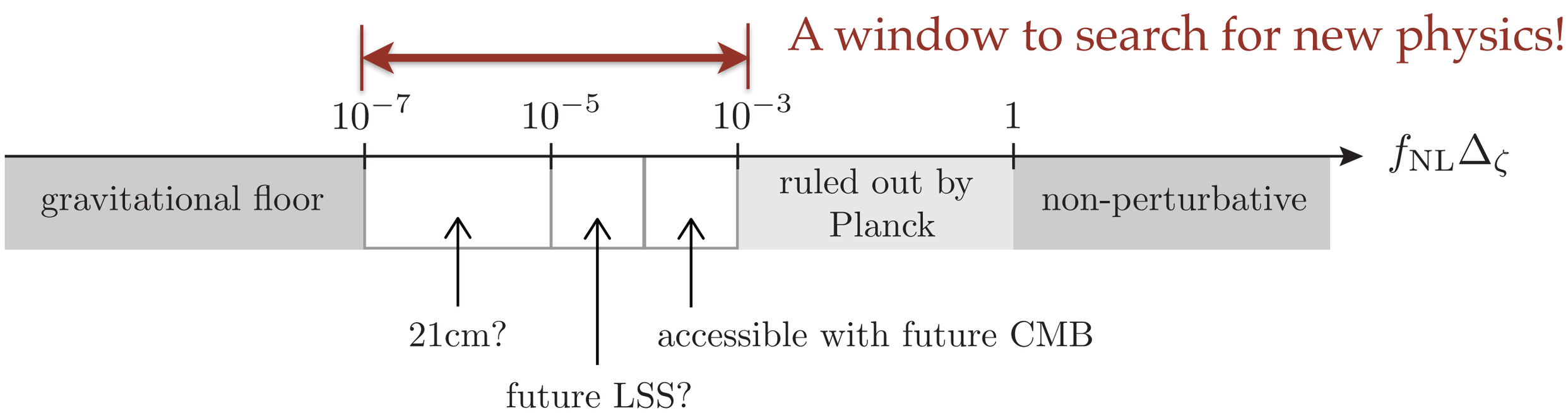
- Inflation predicts fluctuations to be Gaussian (free "clock") with almost scale-invariant power spectrum ($n_s - 1 \approx 0.04$)

$$\langle \zeta_{\vec{k}} \zeta_{\vec{k}'} \rangle = (2\pi)^3 \delta^3(\vec{k} + \vec{k}') \frac{\Delta_\zeta^2}{k^3} \left(\frac{k}{k_0} \right)^{n_s - 1}, \qquad \Delta_\zeta^2 \approx 2 \cdot 10^{-9}$$

- 3-point function is subdominant

$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle \sim \delta^3(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)\, f_{NL} P_{k_1} P_{k_3} \sim \mathcal{O}(f_{NL}\, \Delta_\zeta^4)$$

- Gravitational interactions alone produce $f_{NL} \sim (n_s - 1) \sim 10^{-2}$



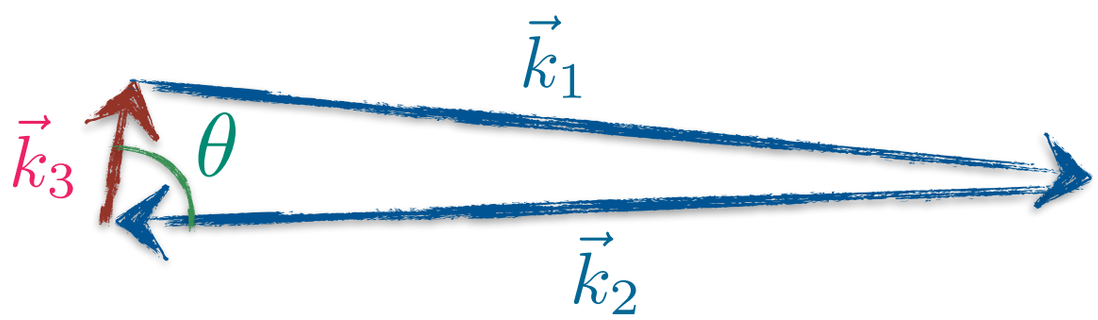
New Physics vs "Clock structure", Squeezed limit

Any non-trivial structure of the clock leads to the non-Gaussianities!

How to distinguish new particles from ζ self-interactions?

Local self-interaction produce analytic correlation functions.

Squeezed limit of $\langle\zeta\zeta\zeta\rangle$: $\quad k_3 \ll k_1 \simeq k_2$



Scale-invariance $\Rightarrow \dfrac{\langle\zeta\zeta\zeta\rangle'}{\langle\zeta\zeta\rangle'_{k_S}\,\langle\zeta\zeta\rangle'_{k_L}}$ is a function of $\dfrac{k_L}{k_S}$ and θ

New Physics vs "Clock structure", Squeezed limit

Scale and rotation invariance also fixes the shape of a new particle contribution:

$$\frac{\langle\zeta\zeta\zeta\rangle'}{\langle\zeta\zeta\rangle'_{k_S}\,\langle\zeta\zeta\rangle'_{k_L}} = A_\zeta \left(\frac{k_L}{k_S}\right)^{3/2}\left[\left(\frac{k_L}{k_S}\right)^{i\mu} + c.c.\right] P_s(\cos\theta)$$

Arkani-Hamed, Maldacena '15

Non-analytic in k_L/k_S

Angular dependence

Exponent is given by the scaling dimension of a new field

$$\Delta = \frac{3}{2} \pm i\mu = \frac{3}{2} \pm i\sqrt{\frac{m^2}{H^2} - \left(s - \frac{1}{2}\right)^2}$$

A_ζ depends on the couplings and can be large, up to $\sim \Delta_\zeta^{-1}$

One can do a spectroscopy — obtain masses and spins!

NB Extensively studied for $s = 0$: Quasi-single field inflation

Chen, Wang '09
Baumann, Green '11
Noumi, Yamaguchi, Yokoyama '12

Fields with spin on de Sitter space-time

- In de Sitter space-time $ds^2 = (H\eta)^{-2}\left(-d\eta^2 + \delta_{ij}dx^i dx^j\right)$

the role of the mass is played by the scaling dimension Δ

$$\sigma_{i_1\ldots i_s} \propto \eta^{\Delta - s} \text{ when } \quad \eta \to 0$$

- Higuchi bound:

Helicity-zero component becomes a ghost unless $\Delta \geq 1$

$\Rightarrow$ $\sigma_{i_1\ldots i_s}\,\sigma^{i_1\ldots i_s} \propto \eta^{2\Delta}$ decays at late times and $\langle\zeta\zeta\zeta\rangle$ is suppressed at least as (k_L/k_S) in the squeezed limit

$\Delta \approx 0$ theory would have a clean squeezed limit signature!

- Different helicities are related by the special conformal transformation $\Rightarrow$ the bound is due to conformal symmetry

- NB The flat space version is: $m^2 \geq 0$ for any $s > 0$

(helicities are mixed by the boosts)

Inflation as a spontaneous symmetry breaking phase

- Existence of a "clock" means that there is a preferred time foliation by the $\phi = \text{const}$ slices

  $\Rightarrow$ conformal invariance of dS is broken

Not related to $\dot{H} \neq 0$! The clock makes all the difference.

- One can contract indices with $\partial_\mu \phi$ in addition to $g_{\mu\nu}$
- Unitary gauge: $\boxed{\phi = t}$

  $\Rightarrow$ Use ∂^0 and $\sigma^{0\ldots\mu_s}$ in the action — EFT of Inflation

- Much richer structure of quadratic actions. e.g., spin-one:

$$\mathcal{L}^{(2)} = \frac{1}{2}\alpha\, \nabla_\mu A^\mu \nabla_\nu A^\nu + \frac{1}{2}\beta\, \nabla_\mu A^\nu \nabla^\mu A_\nu$$
$$+ \frac{1}{2}\gamma\, g^{\mu\nu} \partial^0 A_\mu \partial^0 A_\nu + \frac{1}{2}\delta\, \partial_\mu A^0 \partial^\mu A^0 + \frac{1}{2}\eta\, \nabla_\mu A^\mu \partial^0 A^0 + \frac{1}{2}\epsilon\, \partial^0 A^0 \partial^0 A^0$$
$$- \mu\, A^\mu\, \partial_\mu A^0 - \frac{1}{2} m^2 A^\mu A_\mu - \frac{1}{2}(M^2 + m^2)\, A^0 A^0 \,.$$

- Too many possibilities — is there another approach?

Fields with spin on the foliation in EFT of Inflation

- Why to use 4-tensors once there is a foliation?
- Fields are tensors under 3-diffs on the slices: $\sigma^{i_1 \dots i_s}(t; \vec{x})$
- An action invariant under non-linearly realised 4-diffs?
- $\phi(t)$ gives a frame: normal vector $n^\mu = -\dfrac{\partial^\mu \phi}{\sqrt{-(\partial\phi)^2}}$

push forward a 3-frame on the slices $\left.\dfrac{\partial x^\mu}{\partial x^j}\right|_\phi \equiv \left\{ -\dfrac{\partial_j \phi}{\dot{\phi}};\ \delta^\mu_j \right\}$

- Use $\left.\dfrac{\partial x^\mu}{\partial x^j}\right|_\phi$ to construct a 4-tensor

$$\Sigma^{\mu_1 \dots \mu_s} \equiv \left.\frac{\partial x^{\mu_1}}{\partial x^{i_1}}\right|_\phi \cdots \left.\frac{\partial x^{\mu_s}}{\partial x^{i_s}}\right|_\phi \cdot \sigma^{i_1 \dots i_s}$$

and write any covariant action using $\Sigma^{\mu_1 \dots \mu_s}$ and n^μ

NB CCWZ gives the same set of the EFT building blocks

Minimal spin-two theory

- NB Odd-spin contributions to $\langle \zeta_{k_S} \zeta_{-k_S} \zeta_{k_L} \rangle$ are odd in k_L

  $\Rightarrow$ an extra (k_L/k_S) suppression. We skip the spin-one!

- Minimal action for a spin-two field

$$S[\Sigma] = \frac{1}{4}\int d^4x\,\sqrt{-g}\Big((1-c_2^2)n^\mu n^\nu \nabla_\mu \Sigma^{\alpha\beta}\,\nabla_\nu \Sigma_{\alpha\beta} - c_2^2 \nabla_\mu \Sigma^{\alpha\beta}\,\nabla^\mu \Sigma_{\alpha\beta}$$
$$-\frac{3}{2}(c_0^2 - c_2^2)\,\nabla_\mu \Sigma^{\mu\alpha}\,\nabla^\nu \Sigma_{\nu\alpha} - (m^2 + 2c_2^2 H^2)\,\Sigma^{\alpha\beta}\Sigma_{\alpha\beta}\Big)$$

- Expanding in the Goldstone field $\pi \equiv \phi - t$ we get a quadratic action for σ :

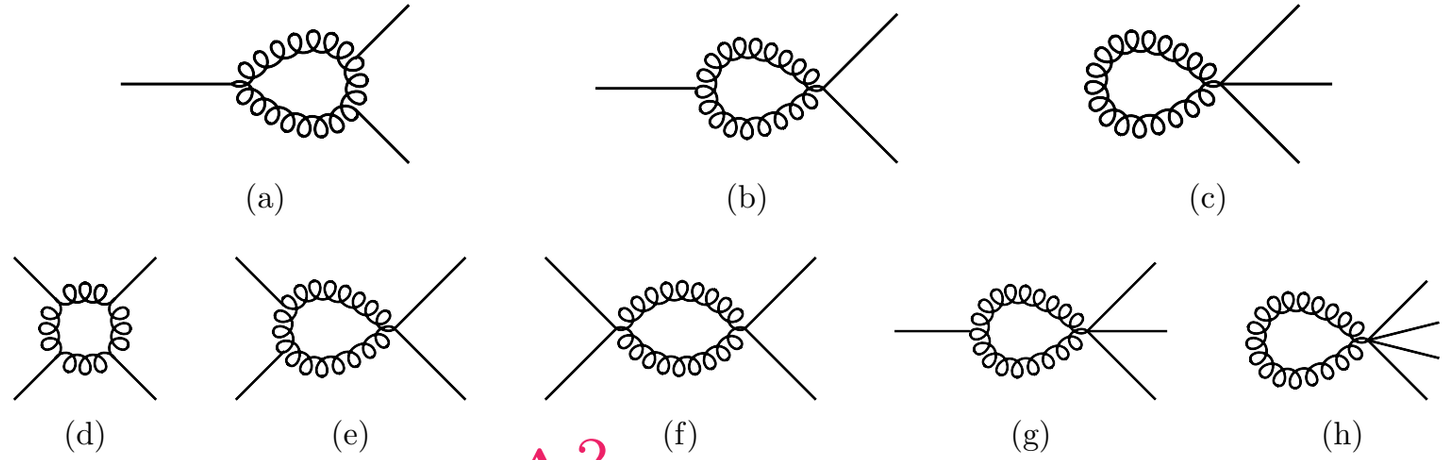
$$\frac{1}{4}\int dt\, d^3x\, a^3\Big((\dot\sigma^{ij})^2 - c_2^2\, a^{-2}\,(\partial_i \sigma^{jk})^2 - \frac{3}{2}(c_0^2 - c_2^2)\, a^{-2}\,(\partial_i \sigma^{ij})^2 - m^2\,(\sigma^{ij})^2\Big)$$

Only two independent sound speeds: $c_1^2 = \frac{1}{4}(3c_0^2 + c_2^2)$

No ghosts for any $\Delta = \frac{3}{2} \pm \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$

Minimal spin-two theory

- Higher order terms give $\sigma^2\pi^n$ interactions
- Without $\sigma\pi$ mixing the non-Gaussianities at loop level:



- The one-loop $f_{\rm NL} \sim \dfrac{\Delta_\zeta^2}{c_s^5}$ can be large for small c_s
- UV dominated: equivalent to local π self-interactions
- Absence of NG puts an observational bound

$$c_s \gtrsim 10^{-2}$$

- Minimal theory can produce sizeable non-Gaussianities but no characteristic features. Let's add the mixing!

Phenomenology of a light spin-two field

- In the spirit of EFT one has to add all allowed operators
- At the leading order in π and derivatives there are $\sigma\pi$ mixing, $\pi^2\sigma$ and σ^3 interactions:

$$S_{int} = \int d^4x \sqrt{-g}\Big(M_{\rm Pl}\rho\, \delta K_{\alpha\beta}\Sigma^{\alpha\beta} + M_{\rm Pl}\tilde{\rho}\, \delta g^{00}\delta K_{\alpha\beta}\Sigma^{\alpha\beta} - \mu\, \Sigma^{\alpha\beta}\Sigma_\alpha{}^\gamma\Sigma_{\gamma\alpha}\Big)\ ,$$

- In terms of the canonically normalised $\pi_c \equiv (2\epsilon H^2 M_{\rm Pl}^2)^{1/2}\pi$

$$S_{int} = \int d^4x \sqrt{-g}\left[-\frac{\rho}{\sqrt{2\epsilon}\, H}\, a^{-2}\, \partial_i\partial_j\pi_c\, \sigma^{ij} + \frac{1}{2}\,\rho\, \dot{\gamma}^{(c)}_{ij}\sigma^{ij} \right.$$

$$\left. -\frac{\rho}{2\epsilon H^2 M_{\rm Pl}}\, a^{-2}\, \left(\partial_i\pi_c\partial_j\pi_c\, \dot{\sigma}^{ij} + 2H\, \partial_i\pi_c\partial_j\pi_c\, \sigma^{ij}\right) + \frac{\tilde{\rho}}{\epsilon H^2 M_{\rm Pl}}\, a^{-2}\, \dot{\pi}_c\partial_i\partial_j\pi_c\sigma^{ij} - \mu(\sigma^{ij})^3 \right]$$

- NB spin-two σ mixes with the graviton!
- No large radiative corrections to $m^2 \ll H^2$:

  $\rho,\ \tilde{\rho} \lesssim \sqrt{\epsilon}H$ and $\mu \lesssim H$ — not hard to arrange

Main signatures of a light spin-two field

- Mixing with π and γ affects the power spectra

$$\delta P_\zeta \sim \frac{H^2}{\epsilon M_{\rm Pl}^2}\frac{1}{k^3}\left(\frac{\rho}{\sqrt{\epsilon}H}\right)^2\frac{1}{c_0^3} \qquad \delta P_\gamma \sim \frac{H^2}{M_{\rm Pl}^2}\frac{1}{k^3}\left(\frac{\rho}{H}\right)^2\frac{N^2}{c_2^3}$$

- GW spectrum can be dominated by the mixing with σ if

$$c_2^3 \lesssim \epsilon\, N^2\left(\frac{\rho}{\sqrt{\epsilon}H}\right)^2$$

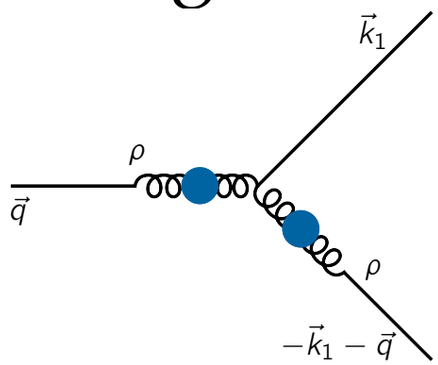
- Even without affecting the scalar modes if $c_2 \lesssim c_0$
- P_γ is time dependent — extra tilt: $n_T - 1 \simeq -2\epsilon - \frac{2}{N}$
- In strong mixing regime γ can be completely non-Gaussian if $\langle\sigma\sigma\sigma\rangle$ is large

$$\frac{\langle\gamma\gamma\gamma\rangle}{P_\gamma^{3/2}} \gg \frac{\langle\gamma\zeta\zeta\rangle}{P_\gamma^{1/2}P_\zeta} \gg \frac{\langle\zeta\zeta\zeta\rangle}{P_\zeta^{3/2}}$$

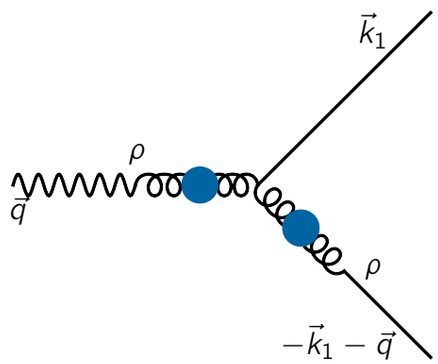
Light spin-two strongly affects primordial GW

Main signatures of a light spin-two field

- Mixing with π and γ generates squeezed limit NG

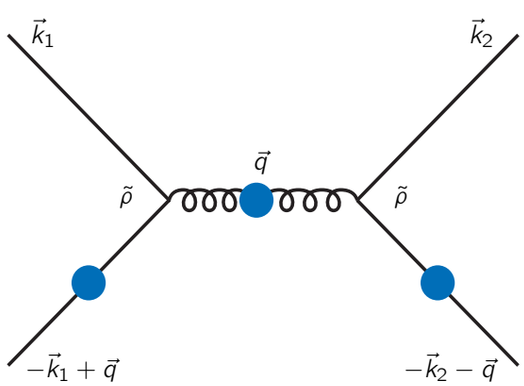


$$\frac{\langle \zeta_{\vec{q}\to 0}\zeta_{\vec{k}}\zeta_{-\vec{k}}\rangle'}{P_\zeta(q)\,P_\zeta(k)} = \frac{1}{c_0^6}\left(\frac{\rho}{H\sqrt{\epsilon}}\right)^2\left((\hat{q}\cdot\hat{k})^2 - \frac{1}{3}\right)$$



$$\frac{\langle \gamma_{\vec{q}\to 0}\zeta_{\vec{k}}\zeta_{-\vec{k}}\rangle'}{P_\gamma(q)\,P_\zeta(k)} = \frac{1}{c_0^3 c_2^3}\left(\frac{\rho}{H\sqrt{\epsilon}}\right)^2 \epsilon_{ij}^{(s)}(\vec{q})\hat{k}_i\hat{k}_j$$

- No suppression and characteristic angular dependence
- Sizeable trispectrum even without mixing



$$\frac{\langle \zeta_{\vec{k}_1-\vec{q}}\zeta_{-\vec{k}_1}\zeta_{\vec{k}_2+\vec{q}}\zeta_{-\vec{k}_2}\rangle'}{P_\zeta(q)\,P_\zeta(k_1)\,P_\zeta(k_2)} = \frac{1}{c_s^3}\left(\frac{\tilde{\rho}}{H\sqrt{\epsilon}}\right)^2 \epsilon_{ij}^{(s)}(\hat{q})\,\hat{k}_i\hat{k}_j$$

Conclusions

- Inflation provides us with a window to new physics at the energy scales up to 10^{14} GeV.
- Correlation functions of primordial fluctuations carry the signatures of the new particles and information about their mass and spin.
- With the CMB IV, LSS, and 21 cm data coming within the next decades it's the right time to think about it.

- It is possible to have a light spin-two field which amplitude does not decay on super-horizon scales during inflation
- Mixing with γ changes the properties of the primordial GW's:
- One can change the spectrum of GW and make them completely non-Gaussian
- It is possible to generate sizeable 3- and 4-point functions with distinct angular dependence if the new field has small c_s