Observing primordial GWs from excited states

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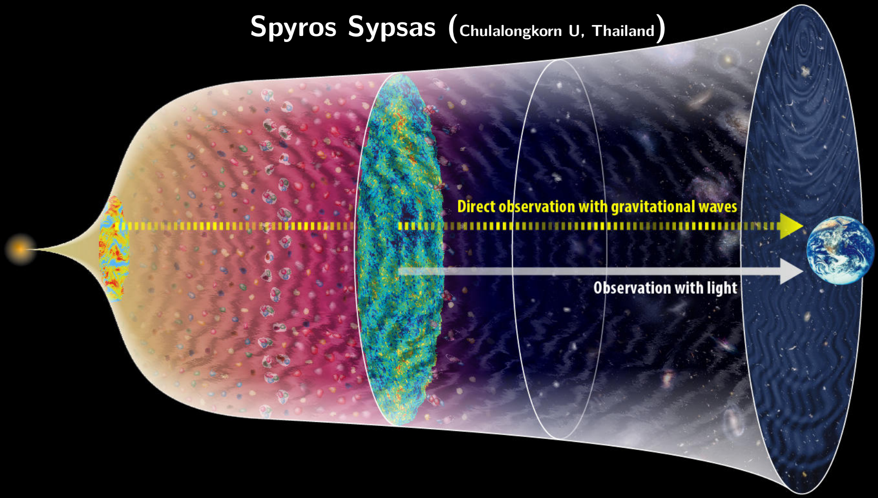


COSMO-22 @ cidade maravilhosa

Based on

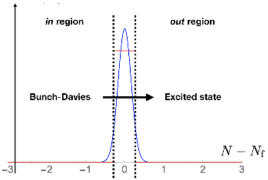
2111.14664, 2209.xxxxx

in collaboration with:

Jacopo Fumagalli, Gonzalo Palma, Nicolás Parra, Sébastien Renaux-Petel, Lukas Witkowski, Cristobal Zenteno

EFT perspective: sharp feature

preferred scale $\Rightarrow$ excited state



$$\hat{\zeta}_{\rm BD}(\tau < \tau_{\rm out}) = \zeta_{\rm dS}(k\tau)\hat{a}_\zeta + \zeta^*_{\rm dS}(k\tau)\hat{a}^\dagger_\zeta$$

$$\zeta^*_{\rm dS}(k\tau) = \zeta_{\rm dS}(-k\tau)$$

$$\hat{\zeta}(\tau > \tau_{\rm out}) = \left[\alpha_k\zeta_{\rm dS}(k\tau) + \beta_k\zeta^*_{\rm dS}(k\tau)\right]\hat{a}_\zeta + [\,]^*\hat{a}^\dagger_\zeta$$

UV completions

- ⋆ turn in 2-field inflation: $\mathcal{L} \supset \eta_\perp(\tau - \tau_{\rm out})\dot{\zeta}\psi$

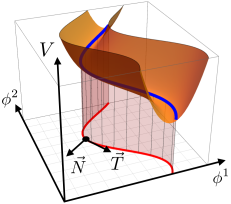
  Achúcarro et al '10; Palma, SS, Zenteno; Fumagalli et al.; Braglia et al. '20
- ⋆ multi-stage inflation: $\epsilon(\tau - \tau_{\rm out})$ Pi et al '17; D'Amico, Kaloper '20
- ⋆ time dependent $c_s(\tau - \tau_{\rm out})$ Ballesteros, Jimenez, Pieroni '18
- ⋆ particle production: $m_\chi(\tau - \tau_{\rm out})$ Cook, Sorbo '11
- ⋆ PTs during inflation: $T(\tau - \tau_{\rm out})$ An et al '20

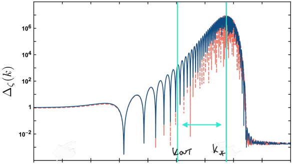
General characteristics: Bump and oscillations in P_ζ

Concrete example: sharp turn in multifield inflation

$$S[\zeta,\psi] = \int d^3x\, dt\, a^3 \left[\epsilon \left(\dot{\zeta} - \lambda(\tau)\psi \right)^2 - \frac{\epsilon}{a^2}(\nabla\zeta)^2 + \frac{1}{2}\dot{\psi}^2 - \frac{1}{2a^2}(\nabla\psi)^2 - \frac{1}{2}\mu^2\psi^2 \right],$$

$$\begin{aligned}\hat{\zeta}(\tau) &= \left[\alpha_k(\tau)\zeta_{\rm dS}(\tau) + \beta_k(\tau)\zeta^*_{\rm dS}(\tau)\right]\hat{a}_1 + \left[\gamma_k(\tau)\zeta_{\rm dS}(\tau) + \delta_k(\tau)\zeta^*_{\rm dS}(\tau)\right]\hat{a}_2 \\ &+ \text{c.c.}\end{aligned}$$





Palma, SS, Zenteno; Fumagalli et al. '20

Scope: how do these affect $\Omega_{\rm GW}^{\rm inf}$? ($\Omega_{\rm GW}^{\rm rad}$: Fumagalli, Renaux-Petel, Witkowski '20)

2^{nd} order source for tensors

$$h = h_0 + h_S$$

$$h_{\boldsymbol{k}}^{\lambda\,\prime\prime}(\tau) + 2\mathcal{H} h_{\boldsymbol{k}}^{\lambda\,\prime}(\tau) + k^2 h_{\boldsymbol{k}}^{\lambda}(\tau) = S_{\boldsymbol{k}}^{\lambda}(\tau)$$

$$\hat{S}_{\boldsymbol{k}}^{\lambda}(\tau) = \int \frac{\mathrm{d}^3\boldsymbol{p}}{(2\pi)^3} \varepsilon^{\lambda}(\boldsymbol{k},\boldsymbol{p}) \left(2\epsilon \hat{\zeta}_{\boldsymbol{p}}(\tau)\hat{\zeta}_{|\boldsymbol{k}-\boldsymbol{p}|}(\tau) + \underbrace{\hat{\psi}_{\boldsymbol{p}}(\tau)\hat{\psi}_{|\boldsymbol{k}-\boldsymbol{p}|}(\tau)}_{2-\text{field generalisation}} \right)$$

$$\left\langle \hat{h}_{\boldsymbol{k}}^{\lambda} \hat{h}_{\boldsymbol{k}'}^{\sigma} \right\rangle(\tau) = \int_{\tau_{\text{out}}}^{\tau} \mathrm{d}\tau' \, G_{\boldsymbol{k}}(\tau,\tau') \int_{\tau_{\text{out}}}^{\tau} \mathrm{d}\tau'' \, G_{\boldsymbol{k}'}(\tau,\tau'') \left\langle \hat{S}_{\boldsymbol{k}}^{\lambda}(\tau')\hat{S}_{\boldsymbol{k}'}^{\sigma}(\tau'') \right\rangle_{\beta}$$

Can also proceed via *in-in* formalism.

$$P_h(k) = \frac{H^4}{16\pi^4} \int_1^\infty \mathrm{d}y \int_{|1-y|}^{1+y} \mathrm{d}x \, \mathcal{T}(x,y) \; \times$$

$$\sum_{ij} \left| \sum_{X\pm} A^{\pm}_{Xi}(xk) A^{\pm}_{Xj}(yk) \mathcal{G}(\pm x, \pm y; k\tau_{\rm out}) \right|^2$$

$$\underbrace{A^{+} \equiv \alpha, \; A^{-} \equiv \beta}_{\text{model dependence}}; \; \zeta^*_{\rm dS}(k\tau) = \zeta_{\rm dS}(-k\tau)$$

$$\boxed{\mathcal{G}(x, y; k\tau_{\rm out}) \equiv \int_{\tau_{\rm out}}^{0} \mathrm{d}\tau \, \zeta_{\rm dS}(xk\tau)\zeta_{\rm dS}(yk\tau) \, \mathrm{Im}\, \zeta_{\rm dS}(k\tau)}$$

Universal kernel for excited states and $\mathcal{N}$-fields.

(Generalisation of Biagetti, Fasiello, Riotto '13)

Dominant contribution:

$$P_h(k) \supset \int_1^\infty \mathrm{d}y \int_{|1-y|}^{1+y} \mathrm{d}x \, \mathcal{T}(x,y) \, P_\zeta(xk) P_\zeta(yk) |\mathcal{G}(x, -y; k_\star)|^2$$

We can compute this explicitly and derive a template for $\Omega_{\rm inf}$:

$$\Omega_{\rm GW}^{\rm inf}(k) \propto \underbrace{\mathcal{N}^4 \frac{k_\star^2}{k_{\rm out}^2} \frac{k_\star^3}{k^3} \left(1 - \frac{k^2}{4k_\star^2}\right)^2}_{\text{Bump}} \cdot \underbrace{\left(\sin(k/k_{out}) - 2\frac{(1-\cos(k/k_{out}))}{k/k_{out}}\right)^2}_{\text{Oscillation}}$$

Three characteristics (analytical predictions):

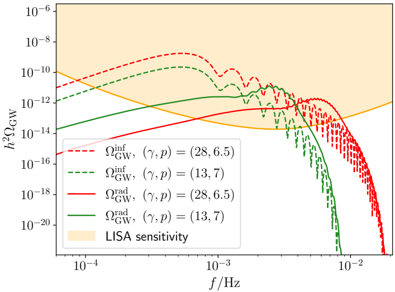
- ⋆ Max: $k_{\mathrm{max}}^{\mathrm{inf}} \sim k_{\mathrm{out}}$
- ⋆ Spectral frequency: $\omega^{\mathrm{inf}} = 2/k_{\mathrm{out}}$

and comparing to

$$\Omega_{\mathrm{GW}}^{\mathrm{rad}}(k) = \underbrace{F(k, k_\star)}_{\text{peak at } k_\star} \left[1 + \cos\left(\frac{2\sqrt{3}k}{k_{\mathrm{out}}} + \phi\right)\right]$$

Fumagalli, Renaux-Petel, Witkowski '20

- ⋆ Enhancement: $\frac{\Omega^{\mathrm{inf}}|_{\mathrm{max}}}{\Omega^{\mathrm{rad}}|_{\mathrm{max}}} \sim 10^{-2}\mathcal{N}^2\epsilon^2\frac{k_\star^5}{k_{\mathrm{out}}^5} \sim 10 - 100$

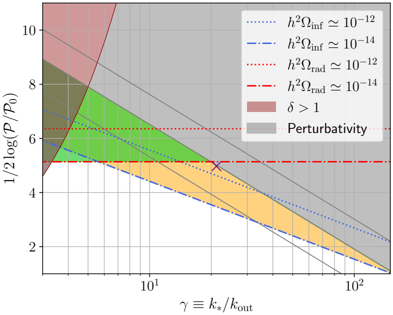


Identifiers: spectral frequency vs max position

Inf: $\omega_{\rm inf} \cdot k^{\rm inf}_{\rm max} \sim 5$ | Rad: $\omega_{\rm rad} \cdot k^{\rm rad}_{\rm max} = 4k_\star / k_{\rm out} \gg 1$

If both peaks observable: $\omega_{\rm rad} \sim \omega_{\rm inf}$ & $k^{\rm inf}_{\rm max} = 10/\omega_{\rm rad}$

"Realistic" examples with perturbativity and backreaction under control:



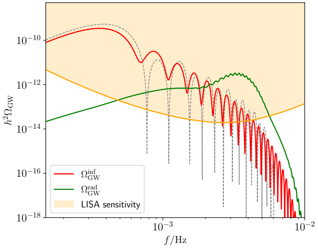
LISA forecasts: Fumagalli, Pieroni, Renaux-Petel, Witkowski '21

Message: 2111.14664

smoking gun for excited states:

bump at low f vs bump/oscillations at high f

- ⋆ Analytical templates
- ⋆ single/double peak diagnostics
- ⋆ Best case scenario: observing both peaks



Obrigado!