Large Spin-2 Signals at the Cosmological Collider (CC)

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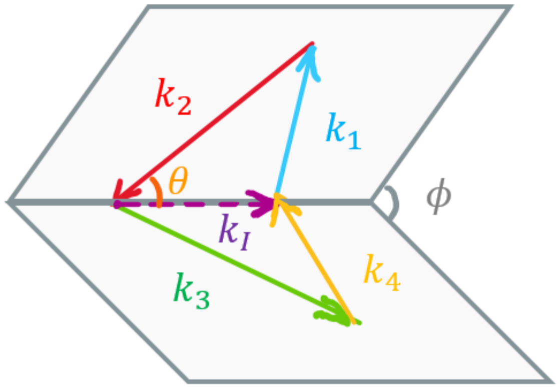
Cosmological collider physics: ideal vs challenge



coupling

mass　　decay width

$\sigma = \mu + i\delta$

$$\langle\zeta^4\rangle' \sim \lambda^2 \left(\frac{k_1+k_2}{k_I}\right)^{i\sigma} P_S(\cos\theta) f(\phi) \times e^{-\pi\, m/H}$$

spin　　P&CP

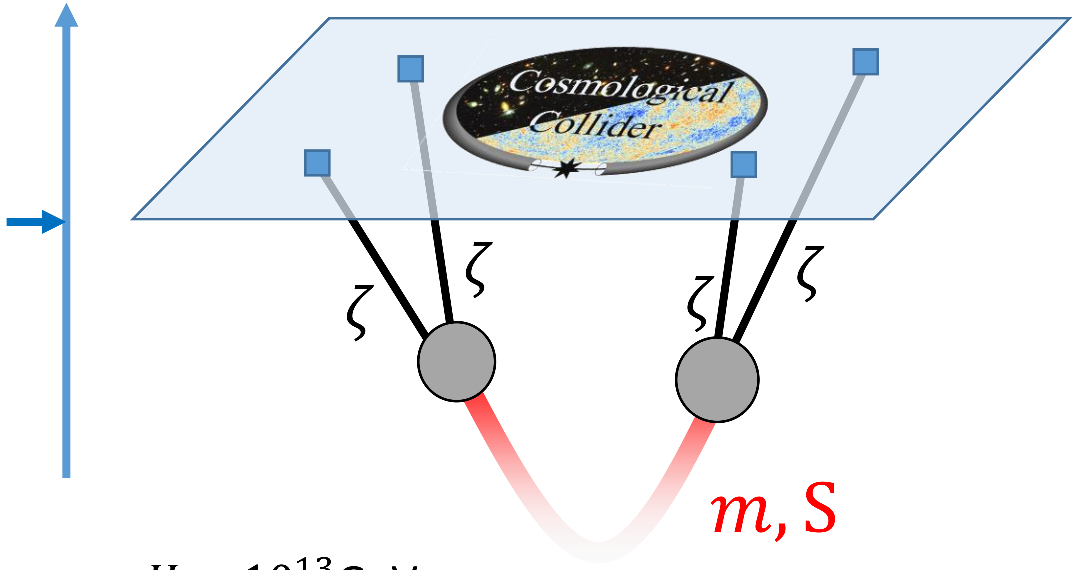
CC Signal strength:
Boltzmann suppression

Hard to observe heavy particles (e.g., $m > 5H$)

Amplification?

time

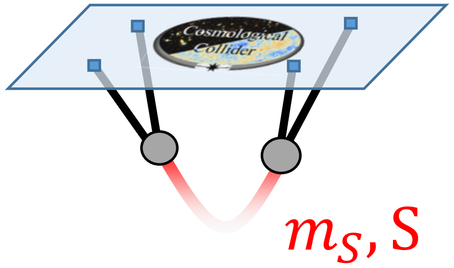
End of inflation



$H \sim 10^{13}$GeV

[Chen & Wang, 2009]
[Baumann & Green, 2011]
[Noumi, Yamaguchi & Yokoyama]
[Arkani-Hamed & Maldacena, 2015]

Large signal requires symmetry breaking



- Signal strength $\sim \sqrt{\langle n \rangle}$

~~dS symmetries~~

$f(m_S) = e^{-\pi \frac{m_S}{H}} \ll 1$ for heavy particles

- Secret: Symmetries

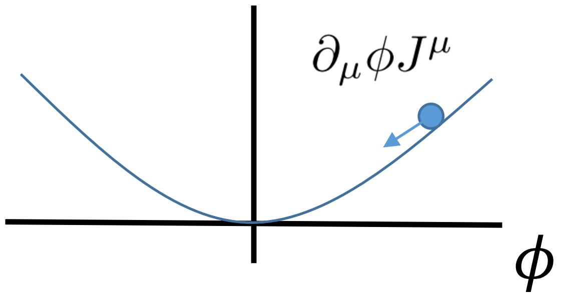
$$\text{dS: } SO(4,1) = \begin{cases} 3 \text{ translations } P_i \\ 3 \text{ rotations } J_i \\ 1 \text{ dilation } D \\ \cancel{3 \text{ dS boosts } K_i} \end{cases}$$

Broken by the rolling inflaton $\dot{\phi}_0$

Dictates dS-invariant particle production $\sim e^{-\pi\, \mu_S} \sim e^{-\pi\, m_S/H}$

$f(m_S, \dot{\phi}_0) \overset{?}{\to} e^{-\pi \frac{m_S - \dot{\phi}_0/H}{H}}$

Exponential amplification via a ***chemical potential***



Chemical potential: A brief review

Q : What do we mean by chemical potential?

Statistical mechanics

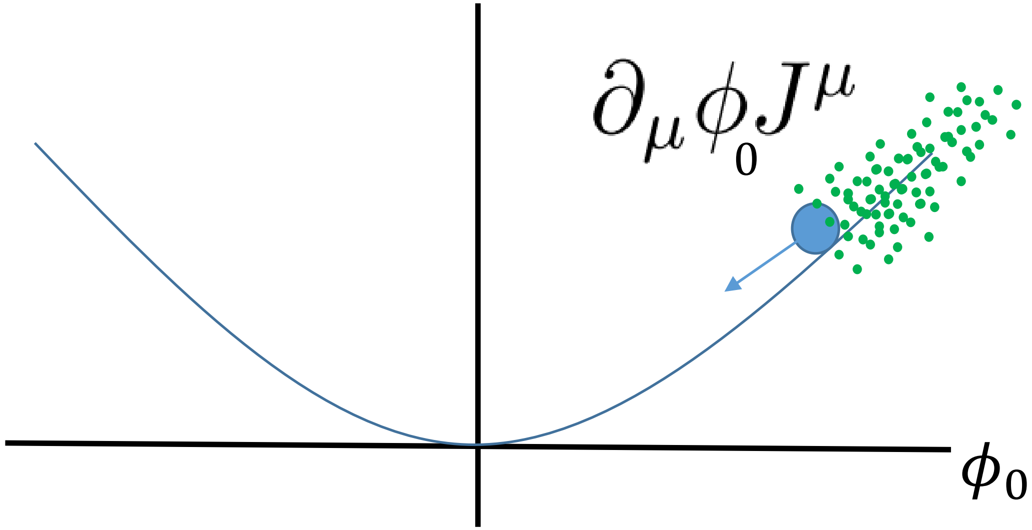
$$Z = e^{-(H-\kappa N)/T} \xrightarrow{\text{+ Locality \& Lorentz covariance}} \begin{cases} Z = \int \mathcal{D}\phi e^{i\int dt d^3x \sqrt{|g|}(\mathcal{L}(\phi,\partial\phi)+\Delta\mathcal{L}_{\text{chem}})} \\ \text{with } \boxed{\Delta\mathcal{L}_{\text{chem}} \equiv \kappa_\mu(x) J^\mu(x)} \end{cases}$$

[Wang & Xianyu, 2020]
[Sou, Tong & Wang, 2021]

Chemical potential by a background field

E.g., $\kappa_\mu \propto \partial_\mu \phi_0$

A : A *local operator* in the Lagrangian that *enhances particle production*



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$$Z = \int \mathcal{D}\phi e^{i\int dt d^3x \sqrt{|g|}(\mathcal{L}(\phi,\partial\phi)+\Delta\mathcal{L}_{\text{chem}})}$$

with $\Delta\mathcal{L}_{\text{chem}} \equiv \kappa_\mu(x) J^\mu(x)$

Chemical potential by a background field

E.g., $\kappa_\mu \propto \partial_\mu \phi_0$

- Chemical potential of (massive) lower spin particles are known:

$$\begin{cases} S=0 & \text{Schwinger effect} \\ S=\frac{1}{2} & \text{Axial current} \\ S=1 & \text{Chern-Simons} \end{cases}$$

$S=0$ Schwinger effect: [Kobayashi & Afshordi, 2014] [Chua, Ding, Wang, & Zhou, 2018]

$S=\frac{1}{2}$ Axial current: [Adshead & Sfakianakis, 2015] [Chen, Wang, & Xianyu, 2018]

$S=1$ Chern-Simons: [Barnaby & Peloso, 2011] [Liu et al., 2019] [Wang & Xianyu, 2020]

Huge amplification of CC signal

$$SNR \sim e^{-\pi m} \to e^{-\pi(m-\kappa)}$$

Reminder: Inflation may not be that far from the GUT/KK/string scale

How about higher spins? In particular, $S = 2$?

KK gravitons from GUT

[Kumar & Sundrum, 2019]

Open string spectrum

[Kim, Noumi, Takeuchi & Zhou, 2019]

[Noumi, Takeuchi & Zhou, 2020]

A spin-2 chemical potential?

- What do we need?

  1. An EFT operator with lowest possible dimension
  2. In the form $\Delta\mathcal{L}_{\rm chem} \equiv \kappa_\mu J^\mu(h)$
  3. Quadratic: $O(h_{\mu\nu}^2)$
  4. Break dS boosts but not rotations, translations and dilation
  5. Give rise to a consistent ghost-free theory

- The ***unique*** spin-2 chemical potential:

$$\Rightarrow \quad \boxed{S_c = \int d^4x\sqrt{-g}\left[\frac{\phi}{2\Lambda_c}\mathcal{E}^{\mu\nu\rho\sigma}\nabla_\mu h_{\nu\lambda}\nabla_\rho h_\sigma^{\ \lambda}\right]\ .}$$

The spin-2 chemical potential

- The linear theory

Einstein-Hilbert   Fierz-Pauli   Chemical potential

$$\boxed{\kappa = \frac{\dot{\phi}_0}{\Lambda_c}}$$

$$S = \int d^4x \sqrt{-g}\left[\frac{1}{4} h\,\partial^2 h + \frac{1}{4} m^2 h^2 + \frac{\phi}{2\Lambda_c}\epsilon\,\partial h\,\partial h\right]$$

$$\text{EoM:}\quad \left(\Box - (m^2 + 2H^2)\right) h_{\mu\nu} - \frac{\nabla_\alpha \phi}{\Lambda_c}\mathcal{E}^{\alpha\kappa\rho\sigma}\left(g_{\kappa\nu}\nabla_\rho h_{\mu\sigma} + g_{\kappa\mu}\nabla_\rho h_{\nu\sigma}\right) = 0\,,$$

$$\text{Constraints:}\quad \nabla^\mu h_{\mu\nu} = 0\,,\quad h = 0\,.$$

- Naïvely , DoF = 10 – 4 – 1 = 5?
- A non-local constraint kills the vector modes: $i\kappa a^2 h_{\pm 1} = 0\,.$ ⇒ DoF = 10 – 4 – 1 – 2 = 3
- Ghost-free √

$$\langle n_\lambda(\mathbf{k})\rangle' \xrightarrow{\mu \gg 1} \begin{cases} e^{-\pi\,(\mu+\tilde{\kappa})}, & \lambda = +2 \quad \text{(Suppressed)} \\ & \lambda = +1 \\ e^{-\pi\,\mu}, & \lambda = 0 \quad \text{(Unchanged)} \\ & \lambda = -1 \\ e^{-\pi\,(\mu-\tilde{\kappa})}, & \lambda = -2 \quad \text{(Enhanced)} \end{cases}$$

⇒ CC signals ↑   ~~Parity~~

μ: mass
$\tilde{\kappa}$: chemical potential

Coupling to the visible sector

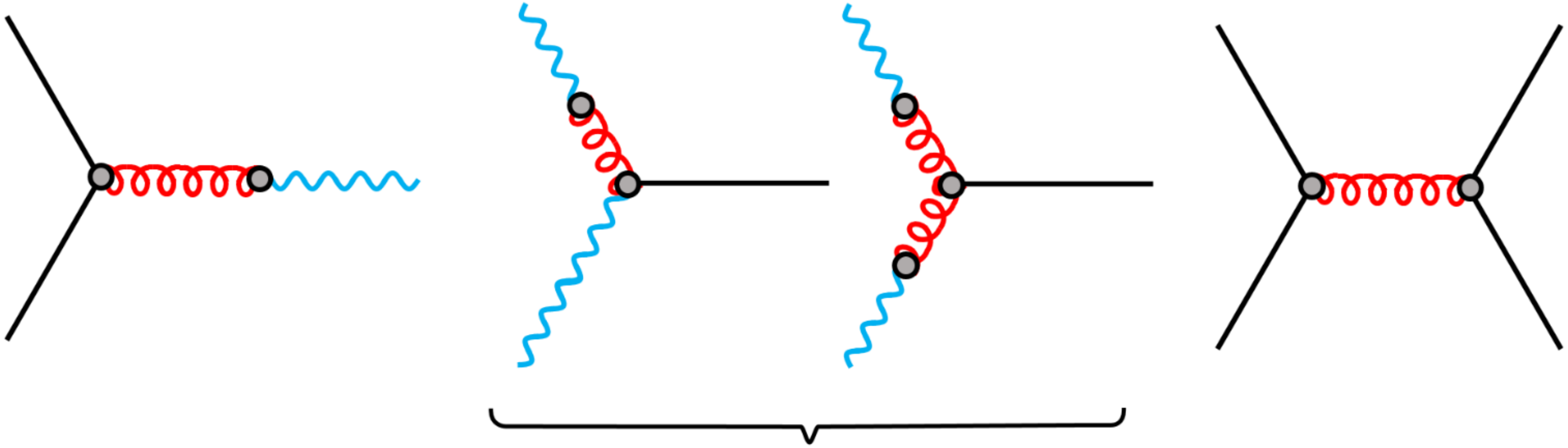
[Cheung et al., 2008]
[Lee, Baumann & Pimentel, 2016]

- Couple to inflatons and gravitons in the EFT of inflation

$$S_{h\gamma} = \int d\tau d^3x \rho \phi' \gamma'_{ij} h_{ij} \ ,$$
$$S_{h\phi^2} = -\int d\tau d^3x \frac{1}{M} h_{ij} \partial_i \phi \partial_j \phi \ .$$

- ➢ Dim-5
- ➢ Shift symmetric: $\phi \to \phi + C$
- ➢ ~~Spin-2 gauge~~ & ~~time diff~~

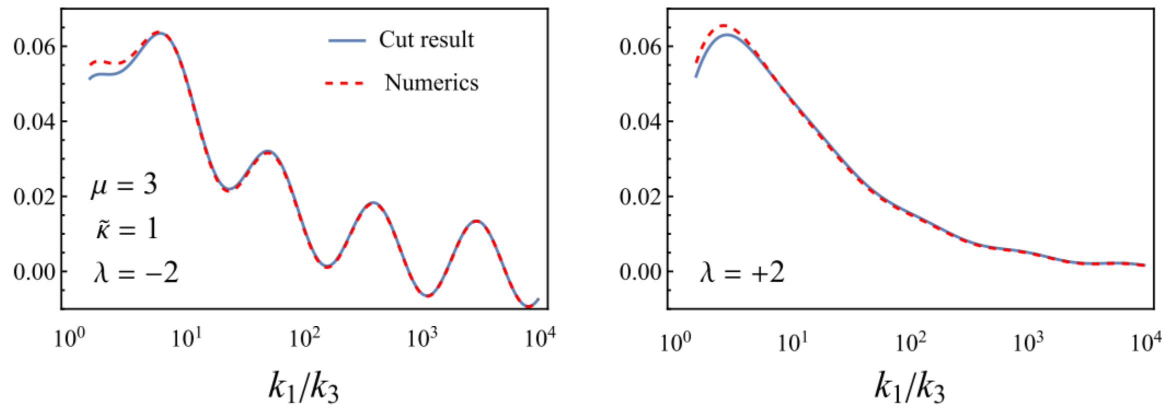
- Large non-Gaussianities from chemical potential



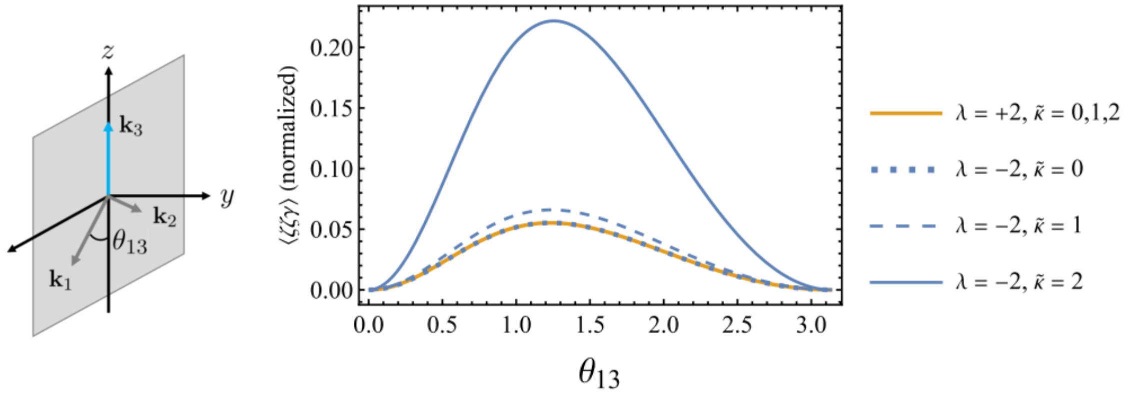
$\langle \zeta\zeta\gamma \rangle$ $\langle \gamma\gamma\zeta \rangle$ $\langle \zeta^4 \rangle$

Summary of features in observables

- Helicity-dependent CC signals

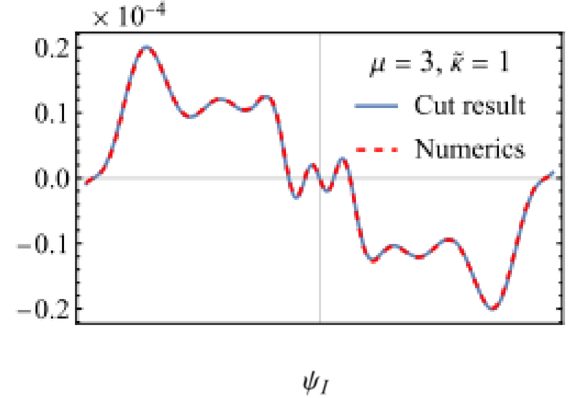


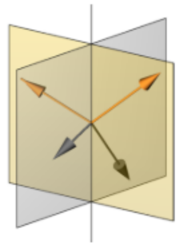
- Characteristic angular dependence



- Imaginary "decay plane" correlation

[Liu, Tong, Wang & Xianyu, 2019]





Non-perturbative ***imaginary*** part:

$$\mathrm{Im}\,\langle\zeta^4\rangle \propto e^{-\pi\mu}\sinh \pi\tilde{\kappa}\,\sin\psi_I$$

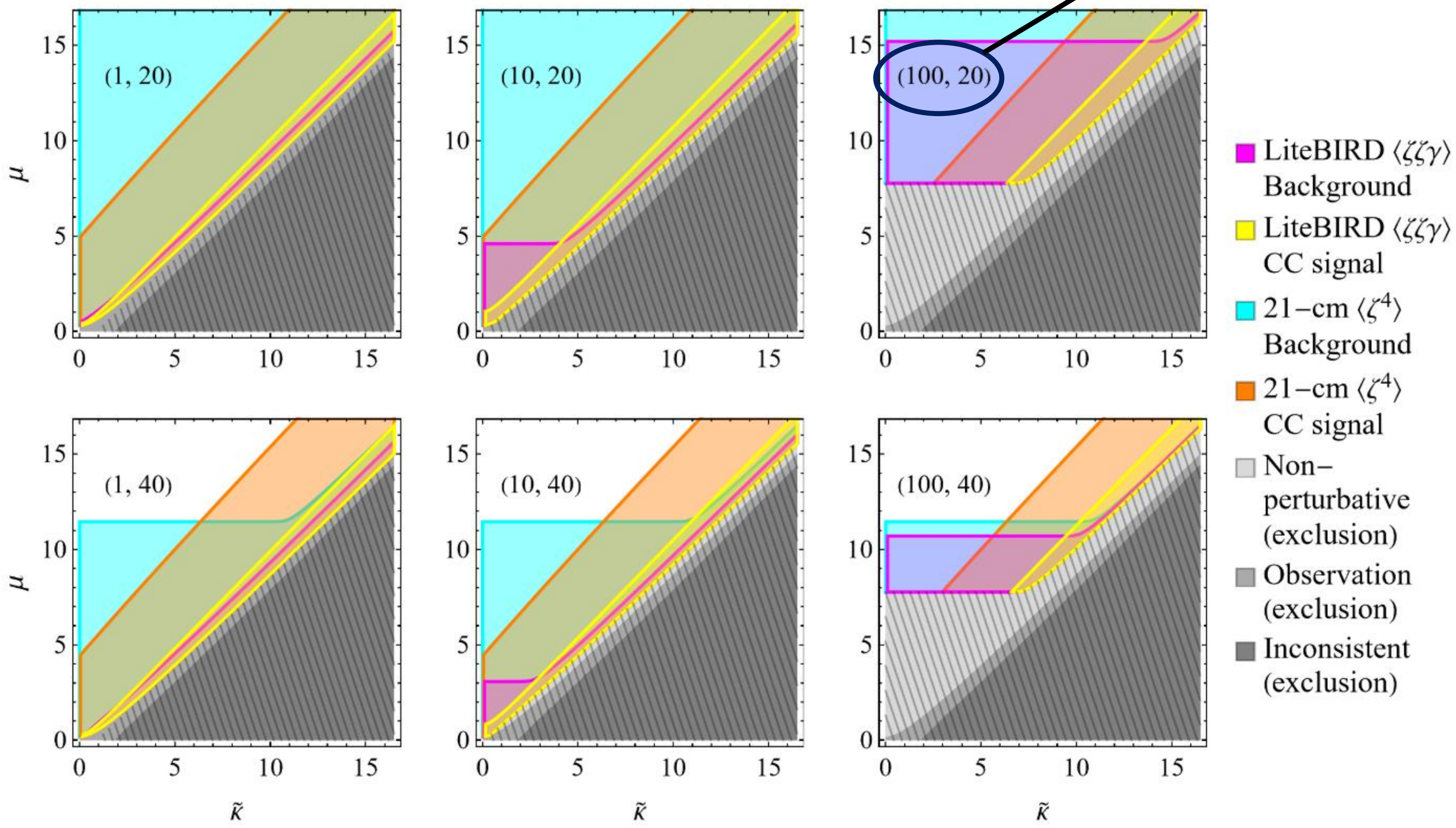
Can we see them?

Magic of the chemical potential:

Heavy spin-2 particles

- Parameter space for future CMB & 21-cm observations

$(\rho, M/H)$



[Shiraishi, 2019]
[Flöss, Wild, Meerburg & Koopmans, 2021]

Summary and outlooks

- ✓ CC physics
- ✓ Symmetry suppresses signal
- ✓ Amplification via chemical potential
- ✓ Generalization to spin-2
- ✓ Features observable in future experiments

- ☐ Non-perturbative mixing between graviton and the spin-2 particle?
- ☐ Apparent discontinuity in the DoF count?
- ☐ UV completions?
- ☐ Going beyond spin-2?
- ☐ Probing the Regge trajectory?

Thanks for listening!

Backup pages