Cosmological Collider Signatures of Massive Gauge Bosons

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Outline

- **What is the cosmological collider?**
  - inflationary universe as a very high energy particle accelerator
- **Massive gauge field production during inflation**
  - chemical potential induced massive gauge modes, impacts both scalar and tensor perturbations
- **Cosmological collider signatures**
  - characteristic gravitational waves detectable at LISA, ALIGO, ...

Inflationary Universe as a Cosmological Collider

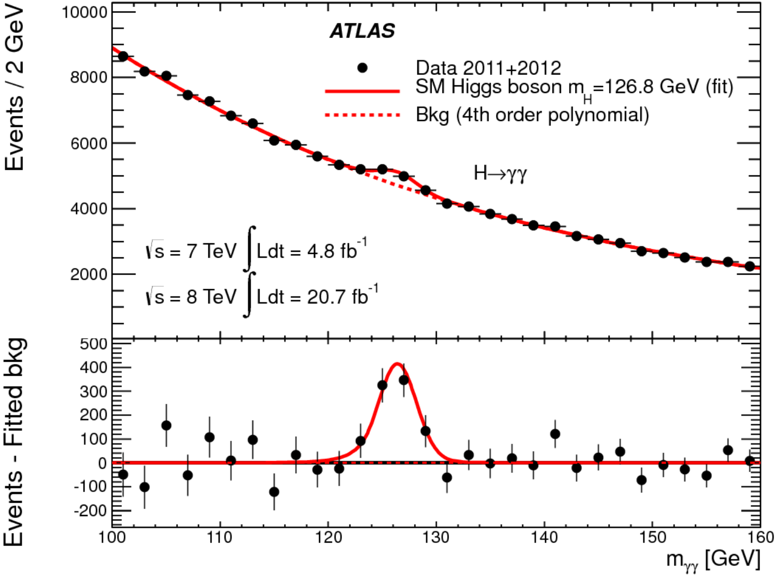
- Inflation theory: cosmological perturbations have a quantum mechanical origin, created during inflation
- Important parameter during inflation – Hubble scale, $H \lesssim 10^{14}$ GeV

$$3M_{\rm Pl}^2 H^2 = V$$

- Particle production during inflation: $m \sim H$
- Very high energy accelerator, opportunity to probe BSM physics!
- Interactions of particles with inflaton leave small imprint on the perturbations
- How to recognize new particles produced during inflation?

Arkani-Hamed, Maldacena 2015, ...

Observational Signature in Terrestrial Collider

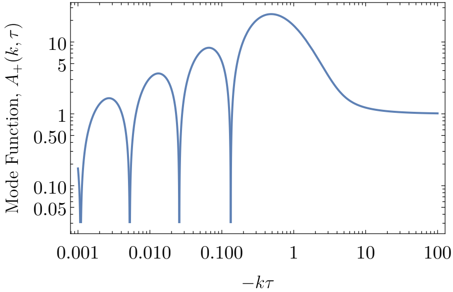


Observational Signatures in Cosmological Collider

- Correlation functions of primordial curvature perturbation
  - from CMB $\Delta T/T$, LSS, 21 cm $\delta\rho/\rho$
  - 2PCF: well-measured (COBE)
  - 3PCF, ... (nongaussianity): not yet observed, 10X sensitivity in SPHEREx
- Correlation functions of primordial tensor modes
  - GW: from CMB B-mode, not yet observed
  - might be sensitive to LIGO, LISA, PTA, ...
- Two point statistics for massive gauge boson production has not been looked at!

Gauge Boson Production during Inflation

- Massive particle production during inflation: Boltzmann suppression $\sim e^{-\pi m/H}$
- Inflaton coupled to a $U(1)$ gauge field



$$\mathcal{L} \supset \frac{1}{4\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + m_A^2 A_\mu A^\mu$$

- Three modes, longitudinal mode unaffected, transverse modes enhanced/suppressed

$$A_\pm(\tau,k) = \frac{1}{\sqrt{2k}} e^{\pm\pi\xi/2} W\left(\mp i\xi, i\sqrt{\left(\frac{m_A}{H}\right)^2 - \frac{1}{4}}, 2ik\tau\right)$$

- Exponentially enhanced chemical potential $e^{\pi\xi}$, where $\xi \equiv \dot{\phi}/(2\Lambda H)$

L. Sorbo et al. (2011), N. Barnaby, M. Peloso (2011) ...

Constraints

- Production of the gauge field at the expense of the energy of inflaton should not affect the slow-roll potential of the inflaton:

$$3H|\dot{\phi}| \simeq |-dV/d\phi| \gg |\frac{1}{\Lambda}\langle\vec{E}\cdot\vec{B}\rangle|$$

where

$$\vec{B} = \frac{1}{a^2}\vec{\nabla}\times\vec{A}, \qquad \vec{E} = -\frac{1}{a^2}\frac{\partial\vec{A}}{\partial\tau}$$

Not very stringent, can be evaded by modifying the inflaton potential

- Energy density of the gauge field should not be dominant: 00 component of the Einstein eq. yields

$$3M_{Pl}^2H^2 \simeq V \gg \langle\vec{E}^2 + \vec{B}^2 + \frac{1}{a^2}m^2\vec{A}^2\rangle$$

Scalar Perturbations

- Inflaton fluctuations can be expressed as

$$\delta\varphi(\tau,\mathbf{x}) = \underbrace{\delta\varphi_{\rm vac}(\tau,\mathbf{x})}_{\rm homogeneous} + \underbrace{\delta\varphi_{\rm inv.decay}(\tau,\mathbf{x})}_{\rm particular}$$

- Homogeneous part corresponds to usual vacuum fluctuations from inflaton, particular part arise due to the inverse decay $\delta A + \delta A \to \delta\varphi$

- Observable curvature perturbation $\zeta_{\mathbf{k}} \sim -\frac{H}{\dot{\phi}}\delta\varphi$, can be expressed using the 'source function' formalism

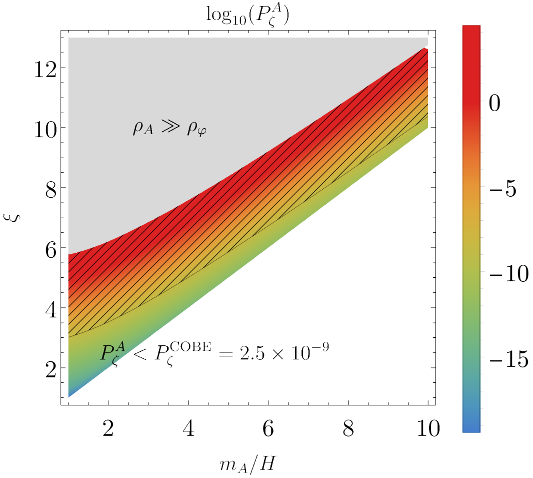
$$\left[\partial_\tau^2 + k^2 + \frac{m^2}{H^2\tau^2} + a^2 V''^2 - \frac{a''}{a}\right](a\delta\varphi_{\mathbf{k}}) = \frac{a^3}{\Lambda}\mathcal{F}[\vec{E}\cdot\vec{B}]$$

Scalar Power Spectrum

- Scalar power spectrum has two parts

$$P_\zeta = P_\zeta^{\text{inf.}} + P_\zeta^A$$
$$P_\zeta^{\text{inf.}} = \frac{H^2}{\dot{\phi}^2}\frac{H^2}{(2\pi)^2}$$

- COBE measurement $P_\zeta \simeq 2.5 \times 10^{-9}$
- Gauge field contribution can be dominant by orders of magnitude for $\xi \gg m_A/H$.
- P_ζ^{COBE} excludes a large parameter space.



Tensor Perturbations

- Transverse and traceless tensor perturbation h_{ij}, metric given by

$$ds^2 = a^2(\tau)\left(d\tau^2 - (\delta_{ij} + h_{ij})dx^i dx^j\right)$$

  ignoring scalar and vector perturbations

- EOM of tensor perturbation

$$\left[\partial_\tau^2 + k^2 + 2\partial_\tau\right] h_{\mathbf{k}} = \underbrace{\frac{2}{M_{Pl}^2}\tilde{T}_{ij}^{TT}}_{\text{source}},$$

  where $\tilde{T}_{ij} \approx -\frac{1}{a^2}\mathcal{F}(E_i E_j)$

Tensor Power Spectrum

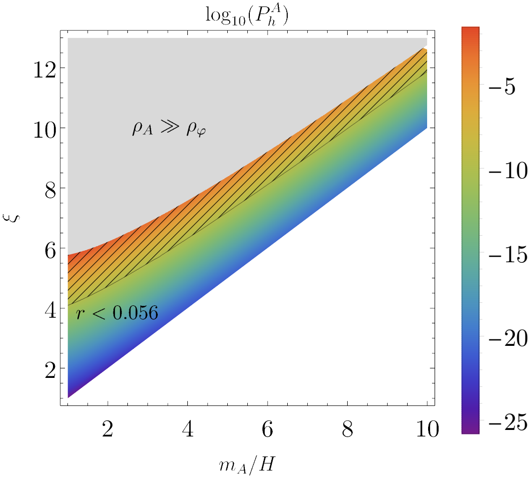
- Tensor power spectrum has two parts

$$P_h = P_h^{\text{inf.}} + P_h^A$$

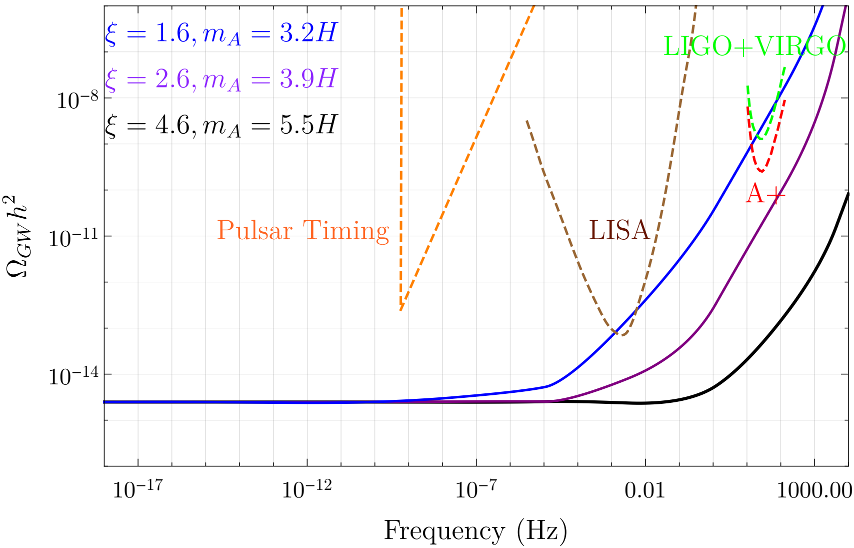
$$P_h^{\text{inf.}} = \frac{2H^2}{\pi^2 M_{\text{Pl}}^2} \sim 2 \times 10^{-11}$$

- Tensor to scalar ratio, $r < 0.056$ excludes a smaller parameter space Planck 2018

- Gauge field contribution is dominant for larger $\xi - m_A/H$ compared to scalar case



Gravitational Wave Signatures



Summary and Outlook

- Chemical potential induced massive gauge field production during inflation can be efficient
- Parameter space is tightly constrained by scalar power spectrum measurements
- $m \sim \mathcal{O}(H)$ gauge modes leave characteristic GW signatures, detectable at LISA and Advanced LIGO
- Future directions: nongaussianity in scalar three point correlation function (f_{NL}), parity violation ...