Tensor Non-Gaussianity from Axion-Gauge-Fields Dynamics

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MPA, Garching, 2018

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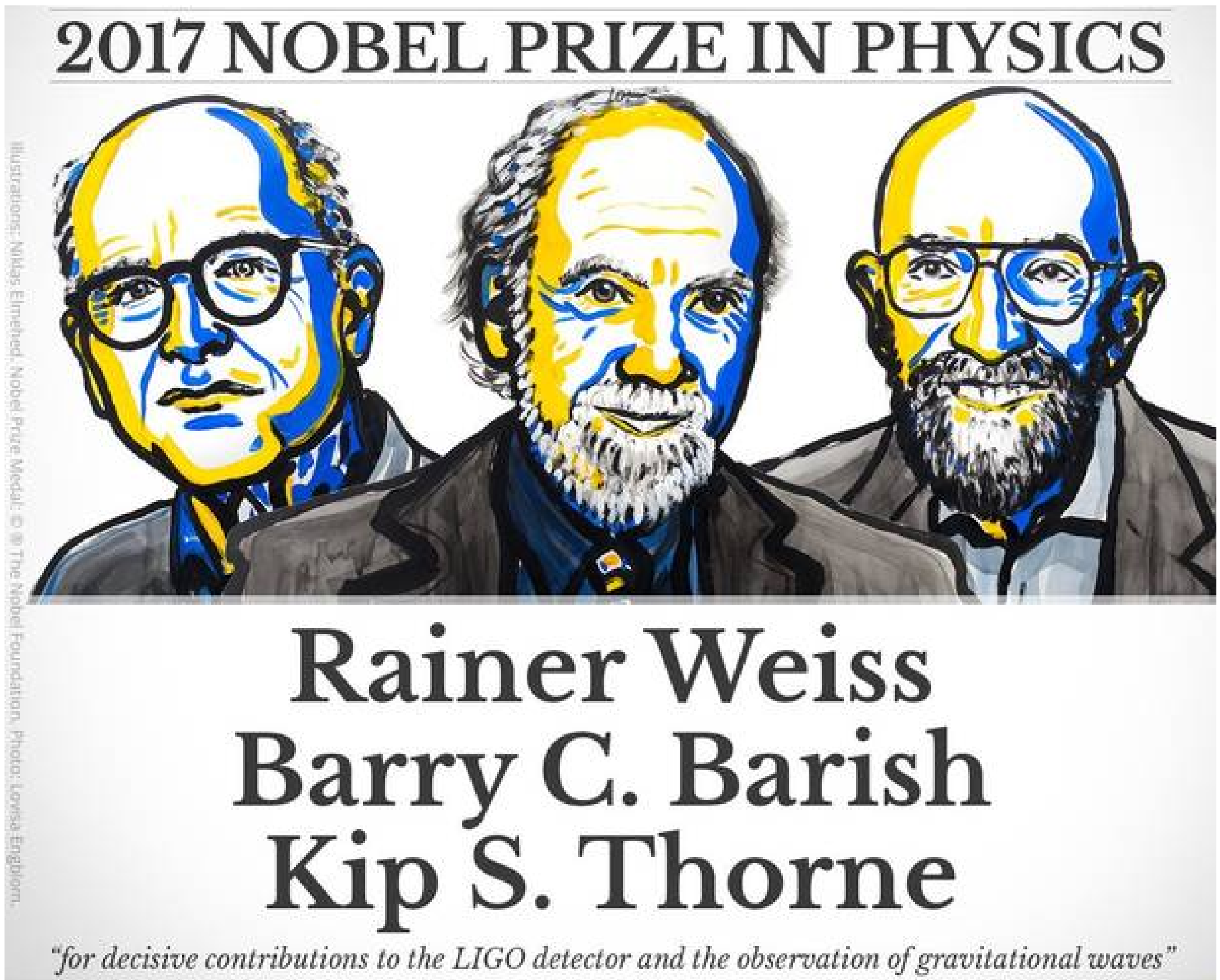
Gravitational Waves have been observed!!!



Gravitational Waves have been observed!!!

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [42] Brans-Dicke/$f(R)$ [43, 44] Kinetic Gravity Braiding [46]	quartic/quintic Galileons [13, 14] Fab Four [15, 16] de Sitter Horndeski [45] $G_{\mu\nu}\phi^{\mu}\phi^{\nu}$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18] Disformal Tuning (22) DHOST with $A_1 = 0$	quartic/quintic GLPV [19] DHOST [20, 48] with $A_1 \neq 0$
	Viable after GW170817	Non-viable after GW170817

arXiv.org > astro-ph > arXiv:1710.05835

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Astrophysics > Cosmology and Nongalactic Astrophysics

A gravitational-wave standard siren measurement of the Hubble constant

B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, C. Affeldt, M. Afrough, B. Agarwal, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain, P. Ajith, B. Allen, G. Allen, A. Allocca, P. A. Altin, A. Amato, A. Ananyeva, S. B. Anderson, W. G. Anderson, S. V. Angelova, S. Antier, S. Appert, K. Arai, M. C. Araya, J. S. Areeda, N. Arnaud, K. G. Arun, S. Ascenzi, G. Ashton, M. Ast, S. M. Aston, P. Astone, D. V. Atallah, P. Aufmuth, C. Aulbert, K. AultONeal, C. Austin, A. Avila-Alvarez, S. Babak, P. Bacon, M. K. M. Bader, S. Bae, P. T. Baker, F. Baldaccini, G. Ballardin, S. W. Ballmer, S. Banagiri, J. C. Barayoga, S. E. Barclay, B. C. Barish, D. Barker, K. Barkett, F. Barone, B. Barr, L. Barsotti, M. Barsuglia, et al. (1249 additional authors not shown)

(Submitted on 16 Oct 2017)

The detection of GW170817 in both gravitational waves and electromagnetic waves heralds the age of gravitational-wave multi-messenger astronomy. On 17 August 2017 the Advanced LIGO and Virgo detectors observed GW170817, a strong signal from the merger of a binary neutron-star system. Less than 2 seconds after the merger, a gamma-ray burst (GRB 170817A) was detected within a region of the sky consistent with the LIGO-Virgo-derived location of the gravitational-wave source. This sky region was subsequently observed by optical astronomy facilities, resulting in the identification of an optical transient signal within ~ 10 arcsec of the galaxy NGC 4993. These multi-messenger observations allow us to use GW170817 as a

arXiv.org > astro-ph > arXiv:1710.05901

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Dark Energy after GW170817

Jose María Ezquiaga (1 and 2), Miguel Zumalacárregui (2 and 3) ((1) Madrid IFT, (2) Nordita)

(Submitted on 16 Oct 2017)

Multi-messenger gravitational wave (GW) astronomy has commenced with the detection c neutron star merger GW170817 and its associated electromagnetic counterparts. The alm observation of the GW and the gamma ray burst GRB170817A constrain the speed of GWs $|c_g/c - 1| \leq 4.5 \cdot 10^{-16}$. We use this result to probe the nature of dark energy (DE), show tensor theories with derivative interactions with the curvature are highly disfavored. As ar consider the case of Galileons, a well motivated gravity theory with viable cosmology, whi variable GW speed at low redshift, and is hence strongly ruled out by GW170817. Our res eliminates any cosmological application of these DE models and, in general, of quartic an Horndeski and most beyond Horndeski theories. We identify the surviving scalar-tensor r particular, present specific beyond Horndeski theories avoiding this constraint. The viable either conformally equivalent to theories in which $c_g = c$ or rely on cancellations of the a speed that are valid on arbitrary backgrounds. Our conclusions can be extended to any o predicting an anomalous GW propagation speed such as Einstein-Aether, Ho\v{r}ava grav Proca, TeVeS and other MOND-like gravities.

arXiv.org > astro-ph > arXiv:1711.04825

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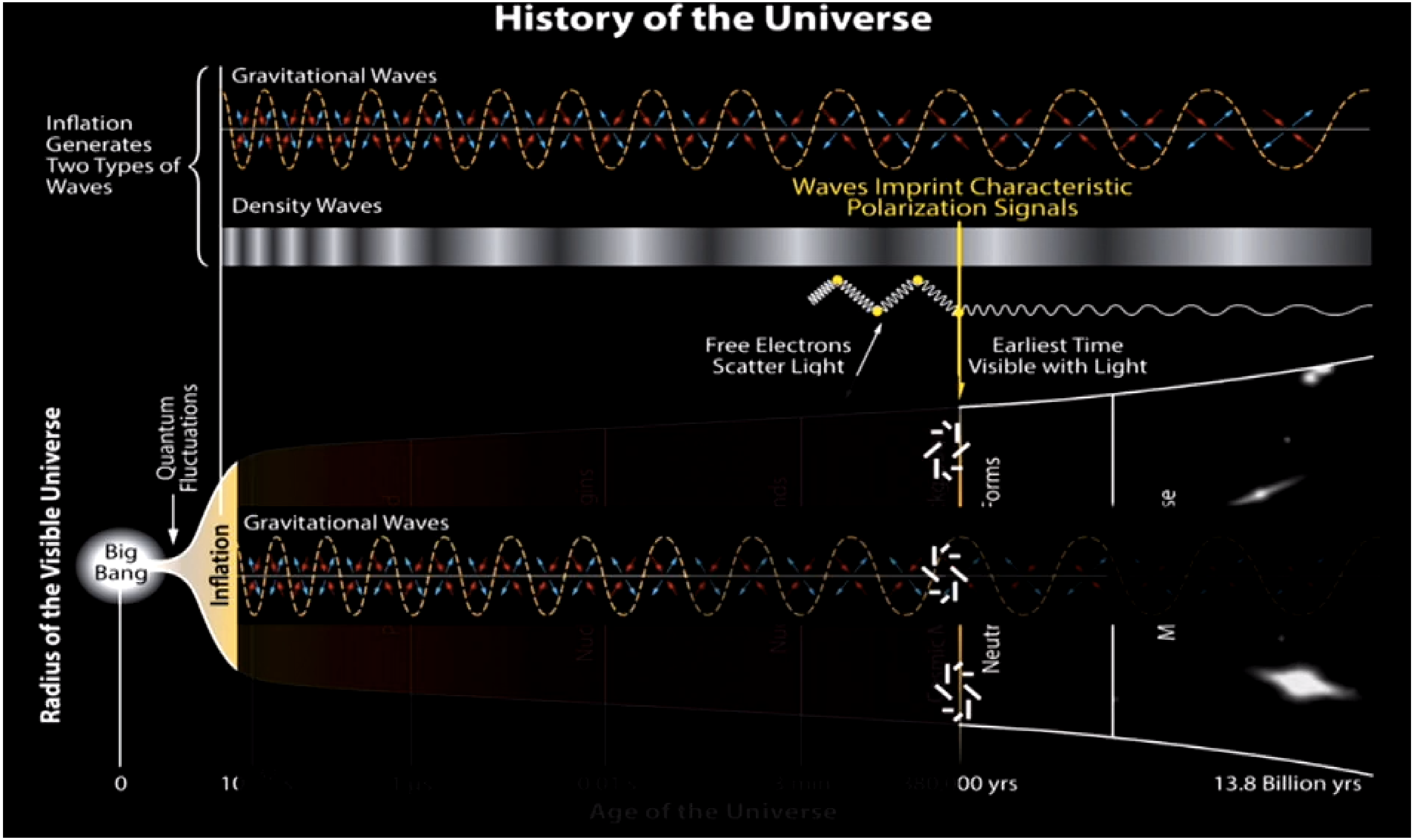
The fate of large-scale structure in modified gravity after GW170817 and GRB170817A

Luca Amendola (U. Heidelberg, ITP), Martin Kunz (Geneva U.), Ippocratis D. Saltas (Prague, Inst. Phys.), Ignacy Sawicki (Prague, Inst. Phys.)

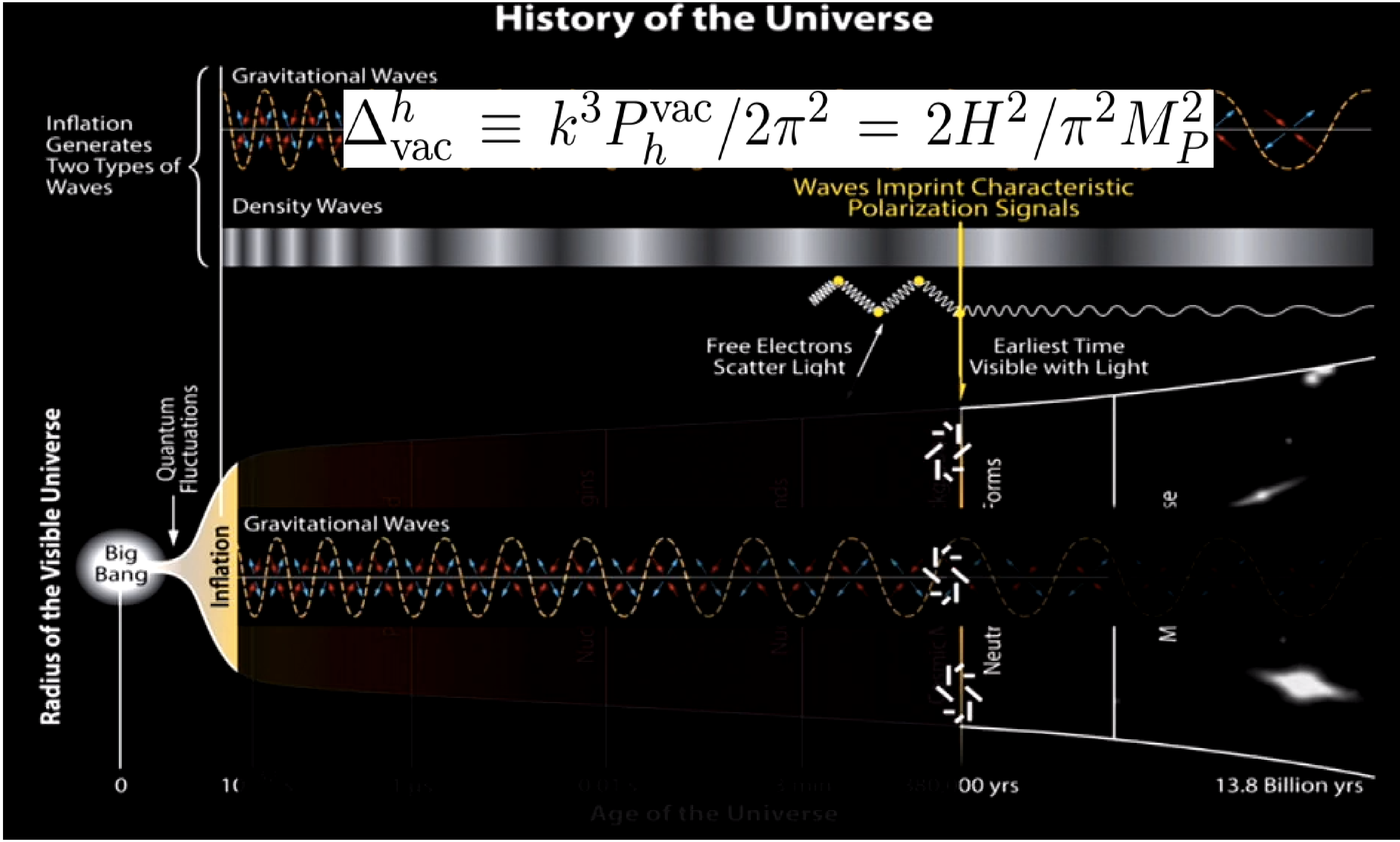
(Submitted on 13 Nov 2017)

The coincident detection of gravitational waves (GW) and a gamma-ray burst from a merger of neutron stars has placed an extremely stringent bound on the speed of GW. We showed previously that the presence of gravitational slip (η) in cosmology is intimately tied to modifications of GW propagation. This new constraint implies that the only remaining viable source of gravitational slip is a conformal coupling to gravity in scalar-tensor theories, while viable vector-tensor theories cannot now generate gravitational slip at all. We discuss structure formation in the remaining viable models, demonstrating that (i) the dark-matter growth rate must now be at least as fast as in GR, with the possible exception of the beyond Horndeski model. (ii) If there is any scale-dependence at all in the slip parameter, it is such that it takes the GR value at large scales. We show a consistency relation which must be violated if gravity is modified.

GWs from Inflation



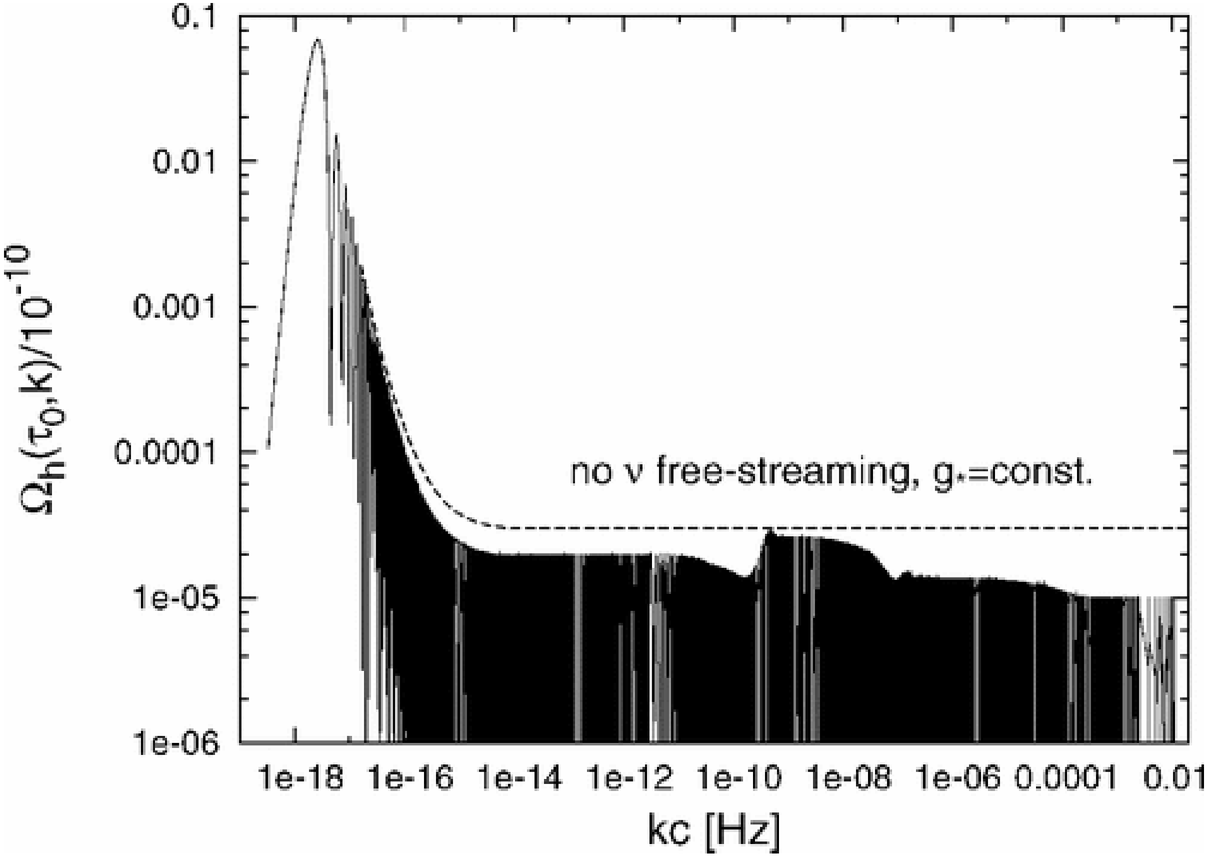
GWs from Inflation



$$\Delta_{\mathrm{vac}}^{h} \equiv k^3 P_h^{\mathrm{vac}}/2\pi^2 = 2H^2/\pi^2 M_P^2$$

GWs from Inflation

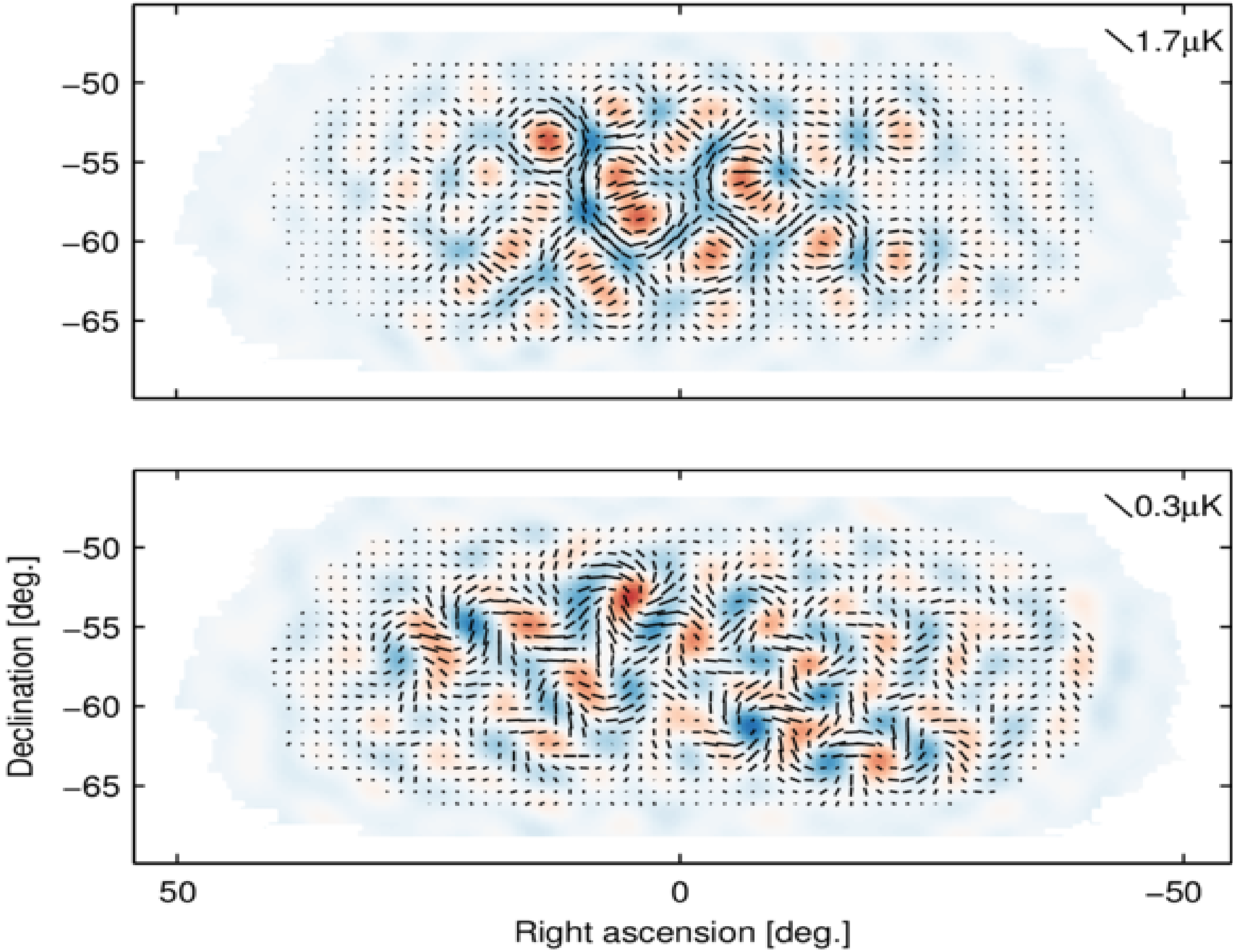
aLIGO



Time of horizon re-entry

Watanabe, Komatsu (2006)

GWs from Inflation

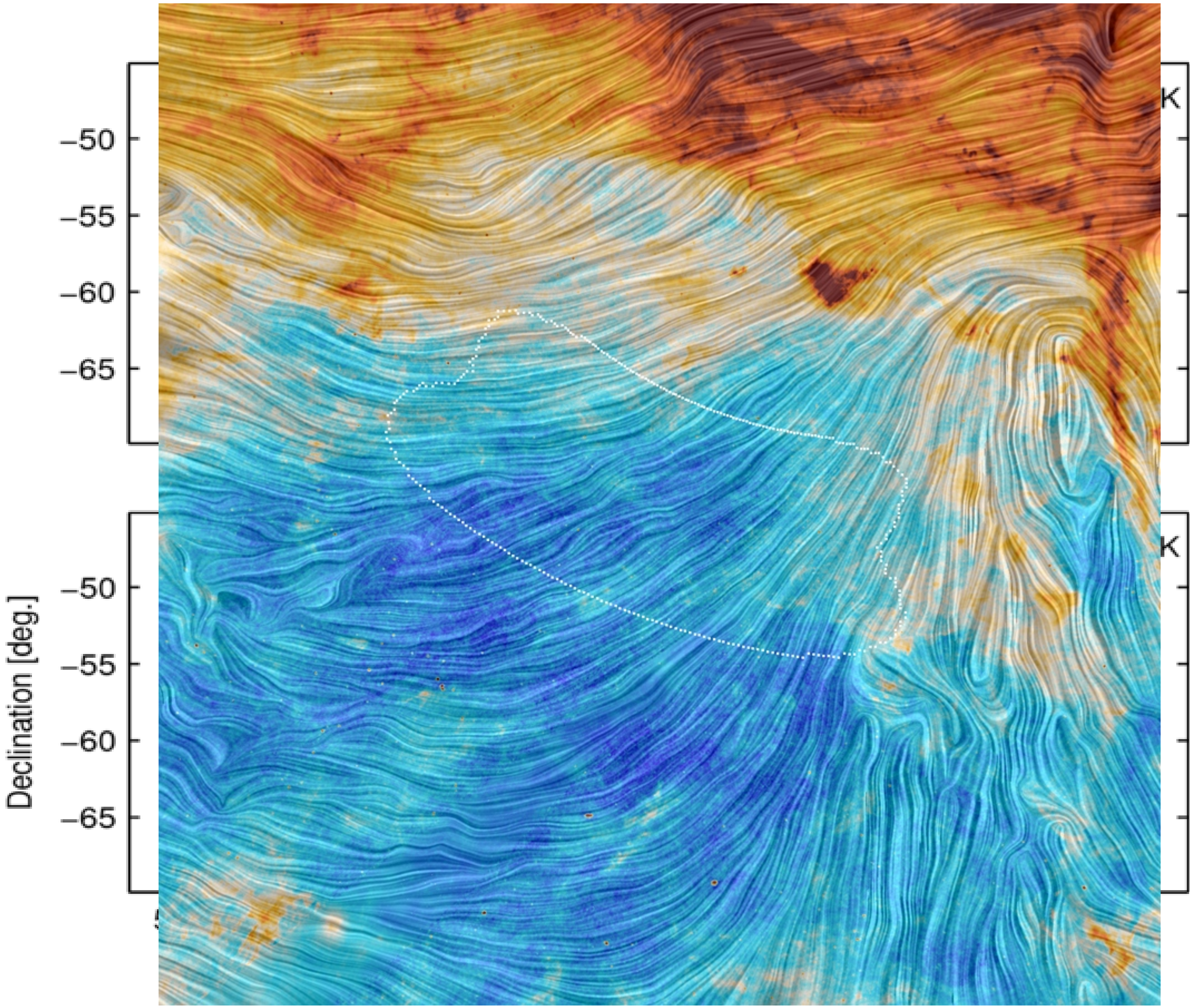


E Modes

B Modes

BICEP Collaboration (2014)

GWs from Inflation



E Modes

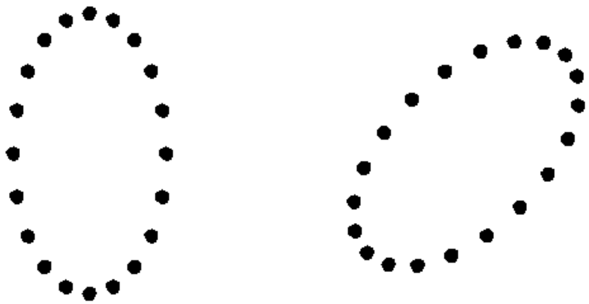
B Modes

BICEP/Planck Collaboration (2015)

Characterising GWs from Inflation

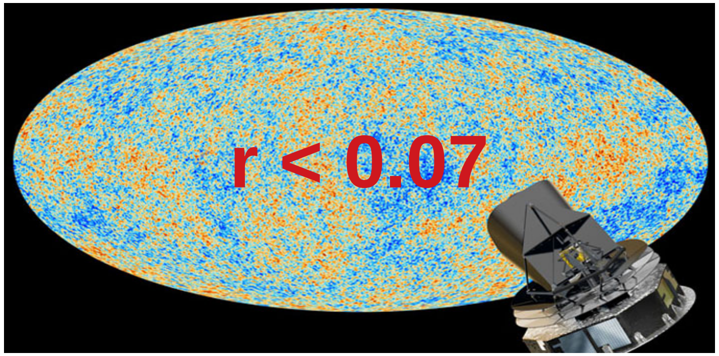
- Almost scale-independent with $n_T < 0$
  - Non-zero B-mode power in different frequencies

- Parity invariant
  - TB/EB correlations = 0



- Almost Gaussian
  - Non-Gaussianity ~ 1

Why do we care about these GWs?



- Fluctuations of the CMB are
  - Super-horizon
  - Adiabatic
  - Gaussian
  - Almost scale-independent with $n_s < 1$
  - $r = \mathcal{P}_h / \mathcal{P}_\zeta \neq 0$ with $n_T < 0$
- Definitive evidence for inflation!
- Detection of non-zero r
  - Energy scale of inflation → $\rho_{\rm inf} \sim H^2 \sim r$
  - Evidence for quantum gravity → $\Box h_{ij} = 0$

BICEP/Planck Collaboration (2015)

(Some) Open Questions

- Scale independence of tensor modes, n_T
  - $n_T < 0$ → quantum fluctuations?
  - $n_T > 0$ → ??
- If we detect $r \neq 0$, $r >= 0.001$, super-Planckian field excursions? (**Lyth Bound**)

$$\Delta\phi/M_P \gtrsim (r/0.01)^{1/2} \approx 0.3$$

- What about spectator fields?

Lyth (1996)

Axion-Gauge-Fields Dynamics : Background

$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{\phi} + \mathcal{L}_{\chi} - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \frac{\lambda\,\chi}{4f} F^a_{\mu\nu} \tilde{F}^{a\mu\nu}$$

- Φ -> scalar inflaton
- χ -> pseudo-scalar axion. Spectator field (negligible contribution to homogeneous energy density)
- A^a_ν: SU(2) gauge field, with field strength tensor

$$F^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g\epsilon^{abc} A^b_\mu A^c_\nu$$

Dimastrogiovanni, Fasiello, Fujita (2016)

Axion-Gauge-Fields Dynamics : Background

$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{\phi} + \mathcal{L}_{\chi} - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \frac{\lambda\,\chi}{4f} F^a_{\mu\nu} \tilde{F}^{a\mu\nu}$$

- Φ -> slow roll, generate scalar perturbations
- χ -> slow roll, generate tensor perturbations
- As the axion rolls down its potential, it excites perturbations (scalar+vector+tensor) of the SU(2) gauge field
- By choosing the strength of the coupling (m_Q) appropriately, the scalar perturbations of the gauge field can be suppressed

Dimastrogiovanni, Fasiello, Fujita (2016)

Axion-Gauge-Fields Dynamics : Perturbations

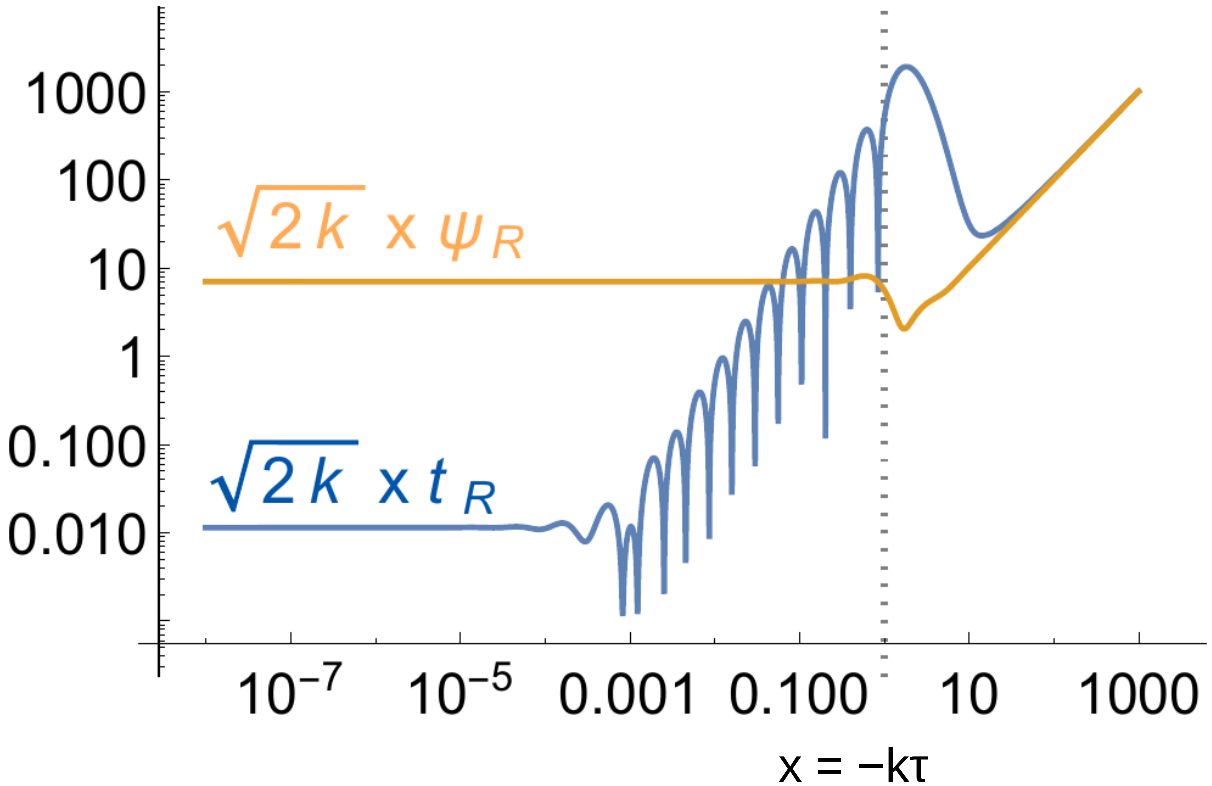
- Tensor sector of these perturbations then sources gravitational waves

$$\Box h_{ij}(t,\boldsymbol{x}) = \Pi_{ij}(t,\boldsymbol{x})$$

- Two parameters characterise tensor perturbations
  - What is the energy density in gauge fields? ~ ϵ_B
  - How strongly gauge fields couple to the axion? ~ m_Q

Dimastrogiovanni, Fasiello, Fujita (2016)

Amplification of Tensor Modes



- Tensor fluctuations of SU(2) gauge field
  - Are amplified exponentially,
  - to peak before horizon crossing....
- sourcing metric perturbations which remain constant on super-horizon scales

Dimastrogiovanni, Fasiello, Fujita (2016)

Characterising GWs from Inflation

- Almost scale-independent with $n_T < 0$
  - Non-zero B-mode power in different frequencies
- Parity invariant
  - TB/EB correlations = 0

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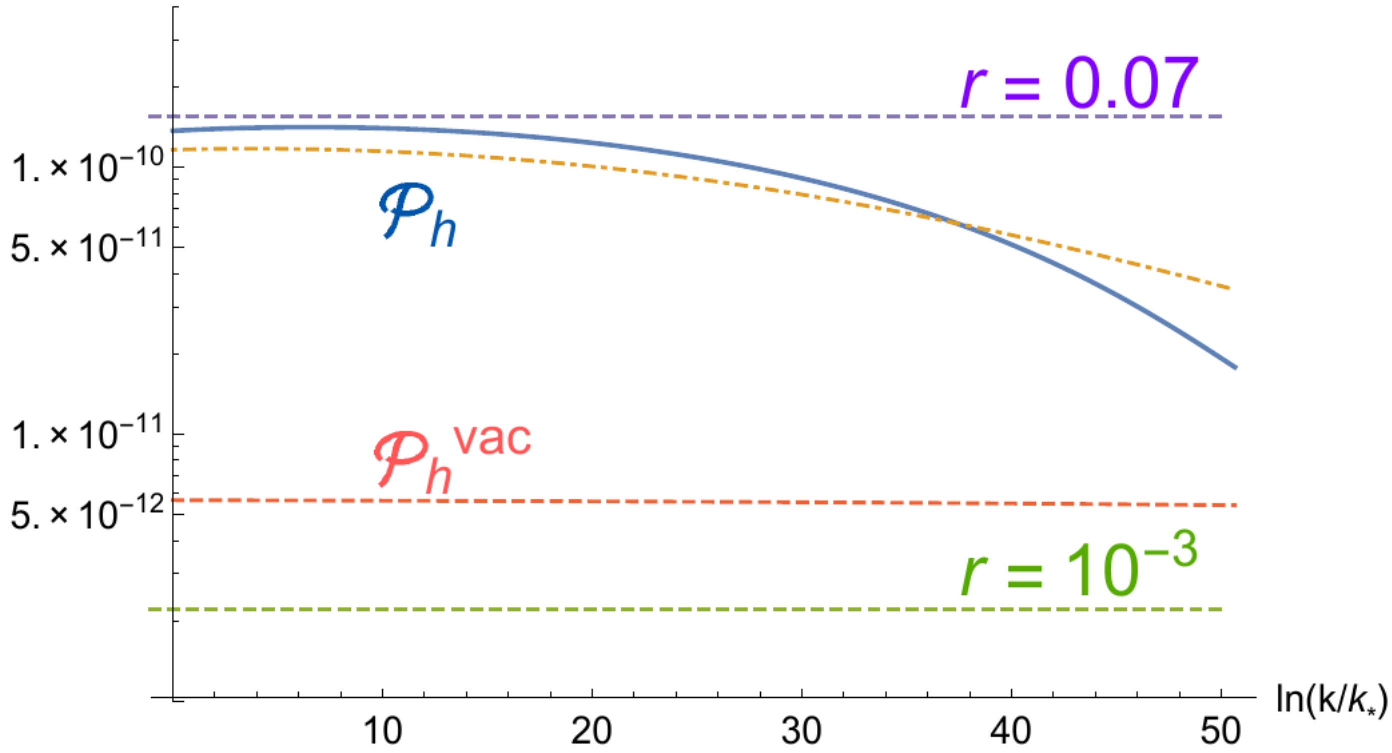
Sourced Tensor Modes



These GWs

- Can be scale-independent, red tilted or blue tilted

Dimastrogiovanni, Fasiello, Fujita (2016)

Characterising GWs from Inflation

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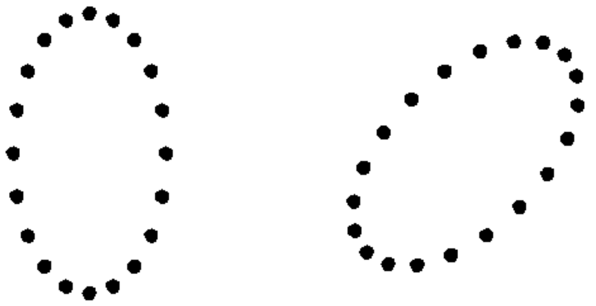
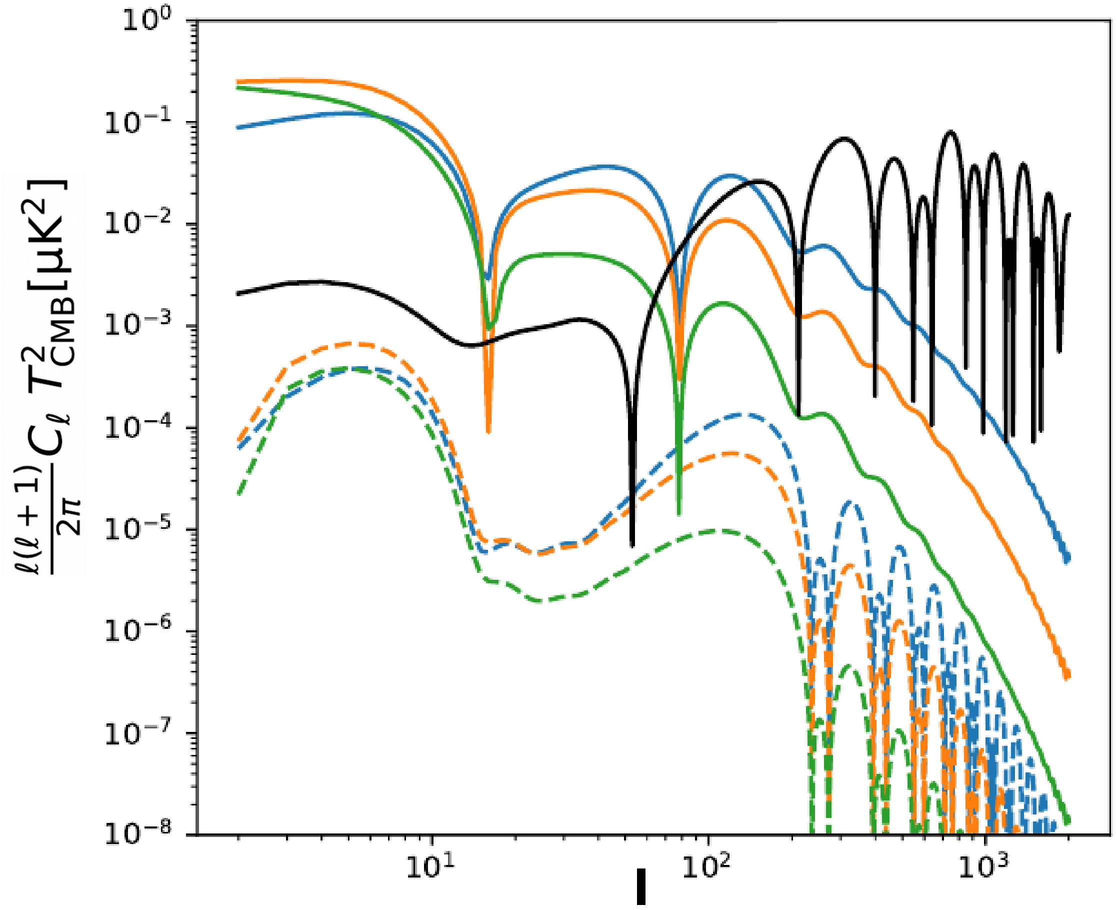


- Almost Gaussian
  - Non-Gaussianity ~ 1

Sourced Chiral Tensor Modes



Solid : TB Spectra

Dashed : EB Spectra

These GWs

- Can be scale-independent, red tilted or blue tilted
- Are chiral (pseudo-scalar axion violates parity)

Saito et. al. (2007), Thorne, Fujita, Komatsu et. al. (2017)

Characterising GWs from Inflation

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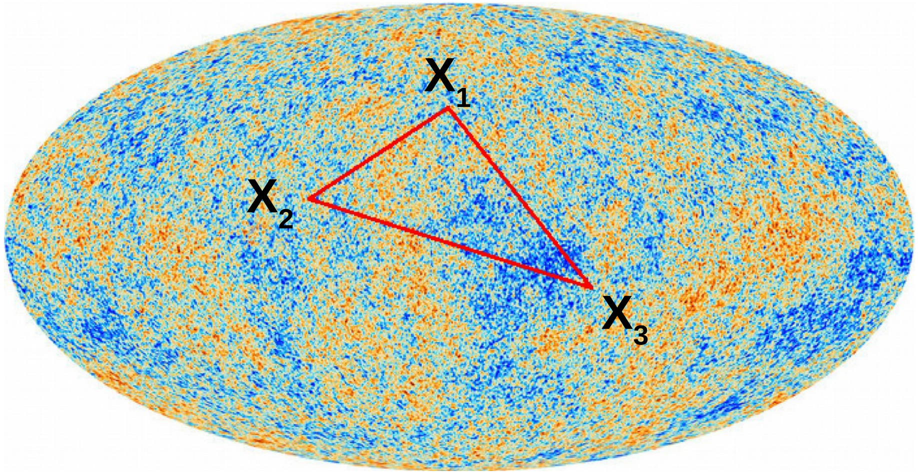
Non-Gaussianity

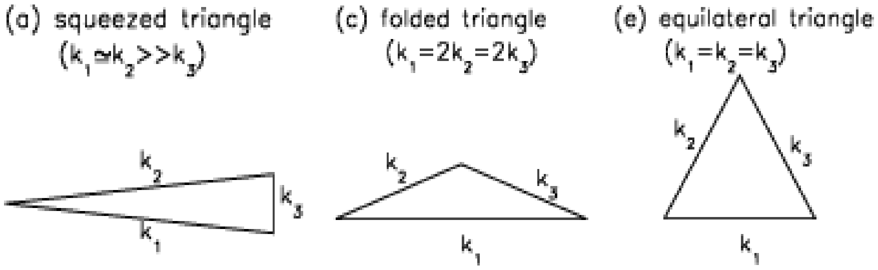
- Gaussian distribution -> P(k)/ξ(r)
- Non-Gaussian distribution? Bispectrum +Trispectrum+....



$$\zeta(\boldsymbol{x}_1, \boldsymbol{x}_2, \boldsymbol{x}_3) = \langle X_1 X_2 X_3 \rangle$$

$$(2\pi)^3 \delta_D(\boldsymbol{k}_1 + \boldsymbol{k}_2 + \boldsymbol{k}_3) \mathcal{B}(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3)$$

$$= \prod_{j=1}^{3} \int d^3 x_j \, e^{i\boldsymbol{k}_j \cdot \boldsymbol{x}_j} \zeta(\boldsymbol{x}_1, \boldsymbol{x}_2, \boldsymbol{x}_3)$$



Bispectrum

- Non-Gaussian distribution? Bispectrum
- Triangle condition -> 3 variables, k1 > k2 > k3
- For scale-invariant P(k) -> k1 = 1

$$\zeta(\boldsymbol{x}_1, \boldsymbol{x}_2, \boldsymbol{x}_3) = \langle X_1 X_2 X_3 \rangle$$

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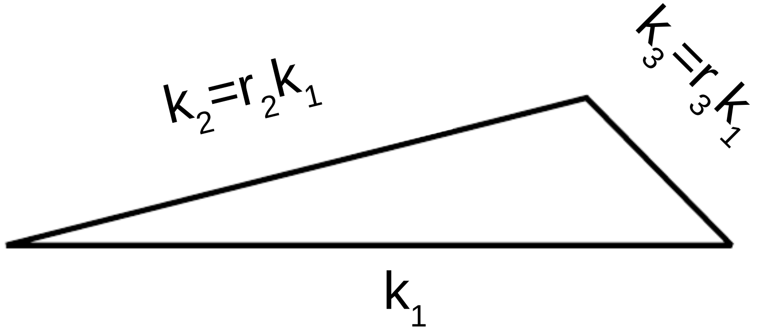
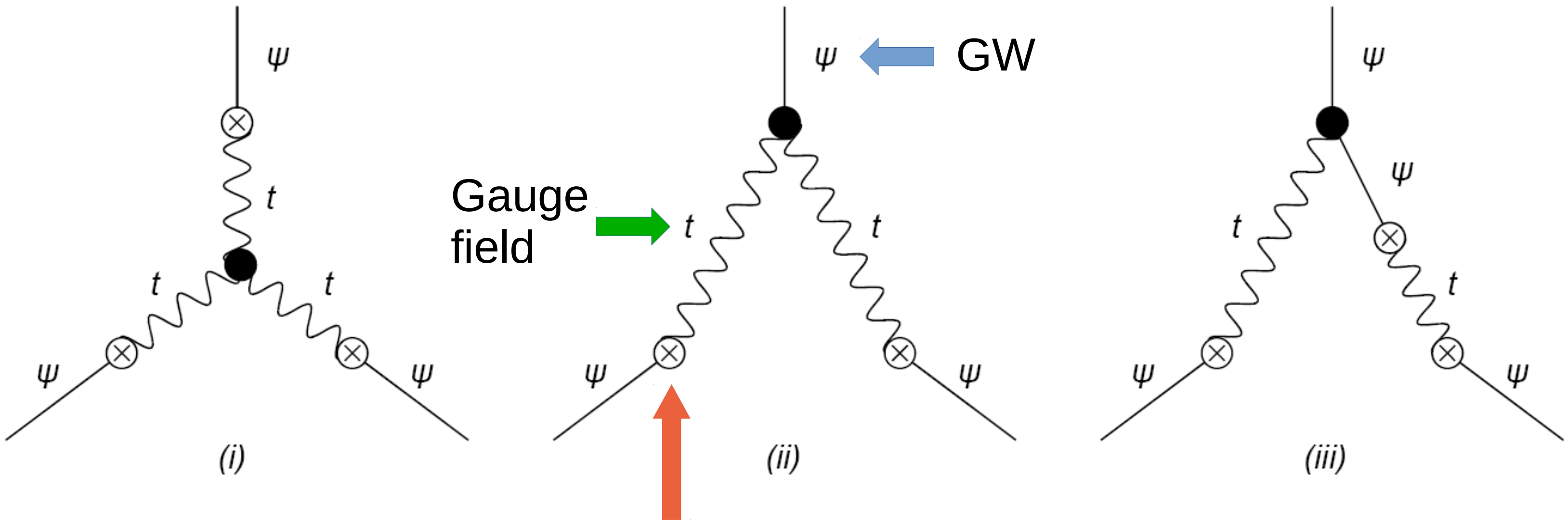


Generating tensor bispectrum

- Second order interactions of the gauge fields generate tensor bispectrum at tree-level



$$\Box h_{ij}(t, \boldsymbol{x}) = \Pi_{ij}(t, \boldsymbol{x})$$

AA, Fujita, Komatsu (2017)

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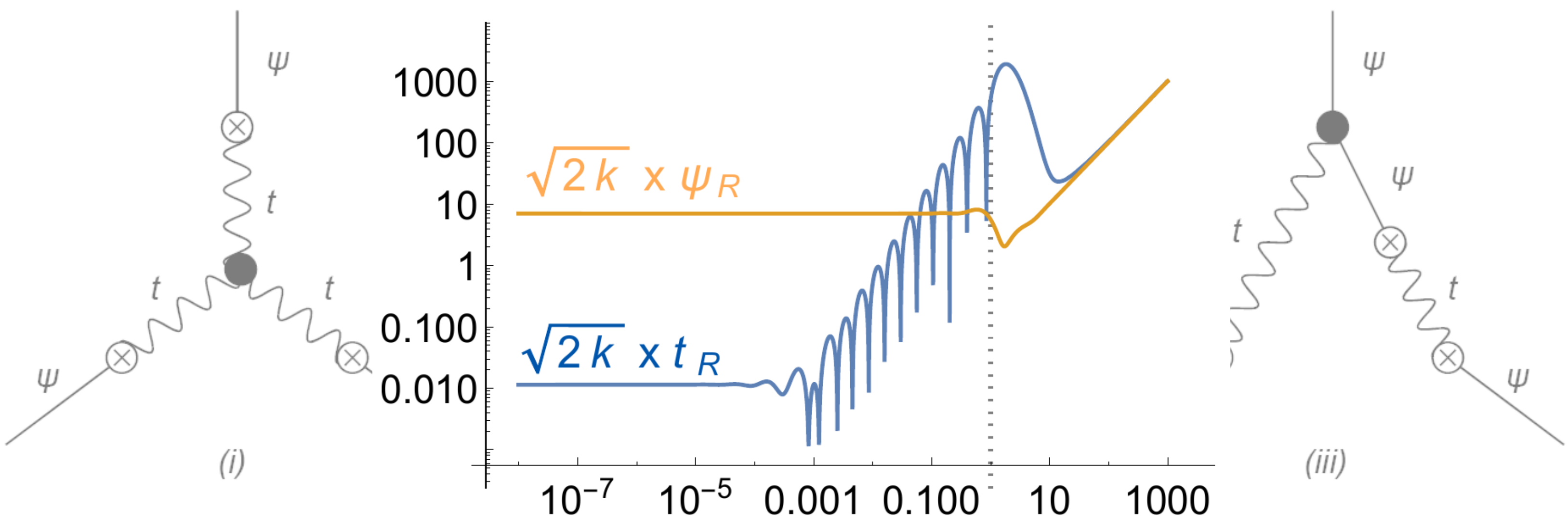

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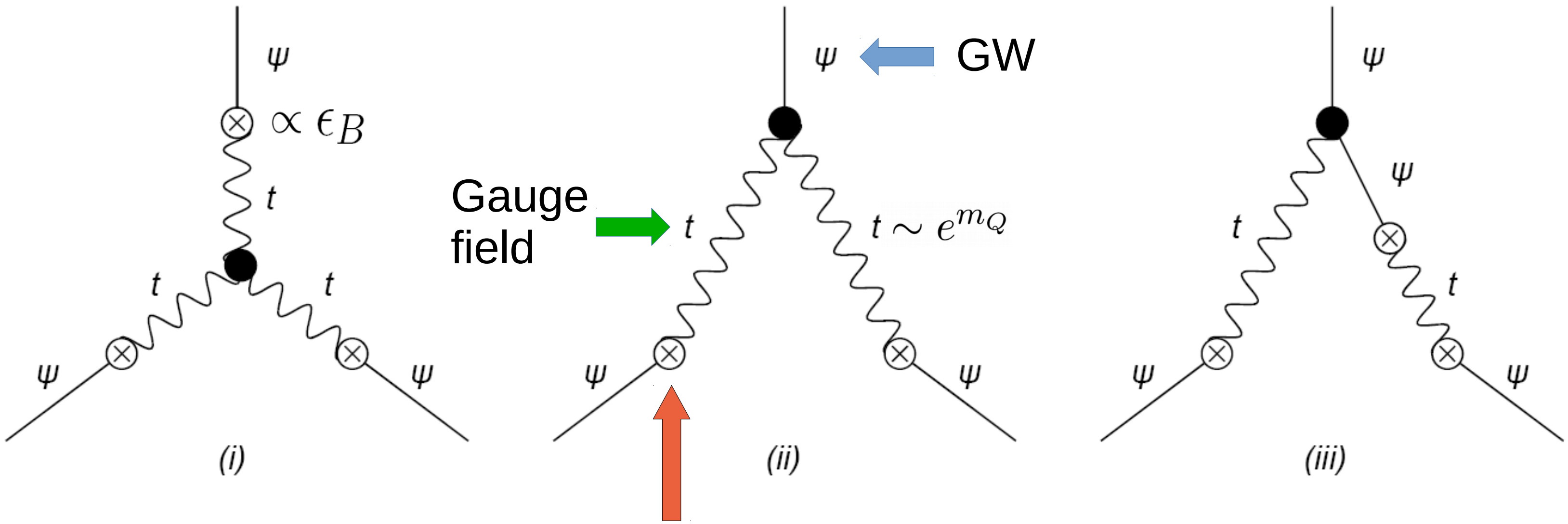
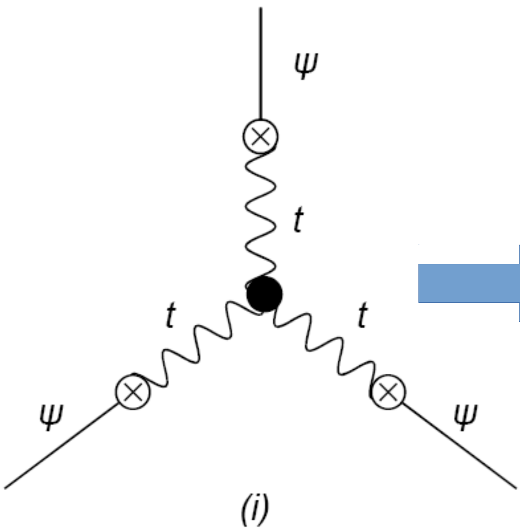
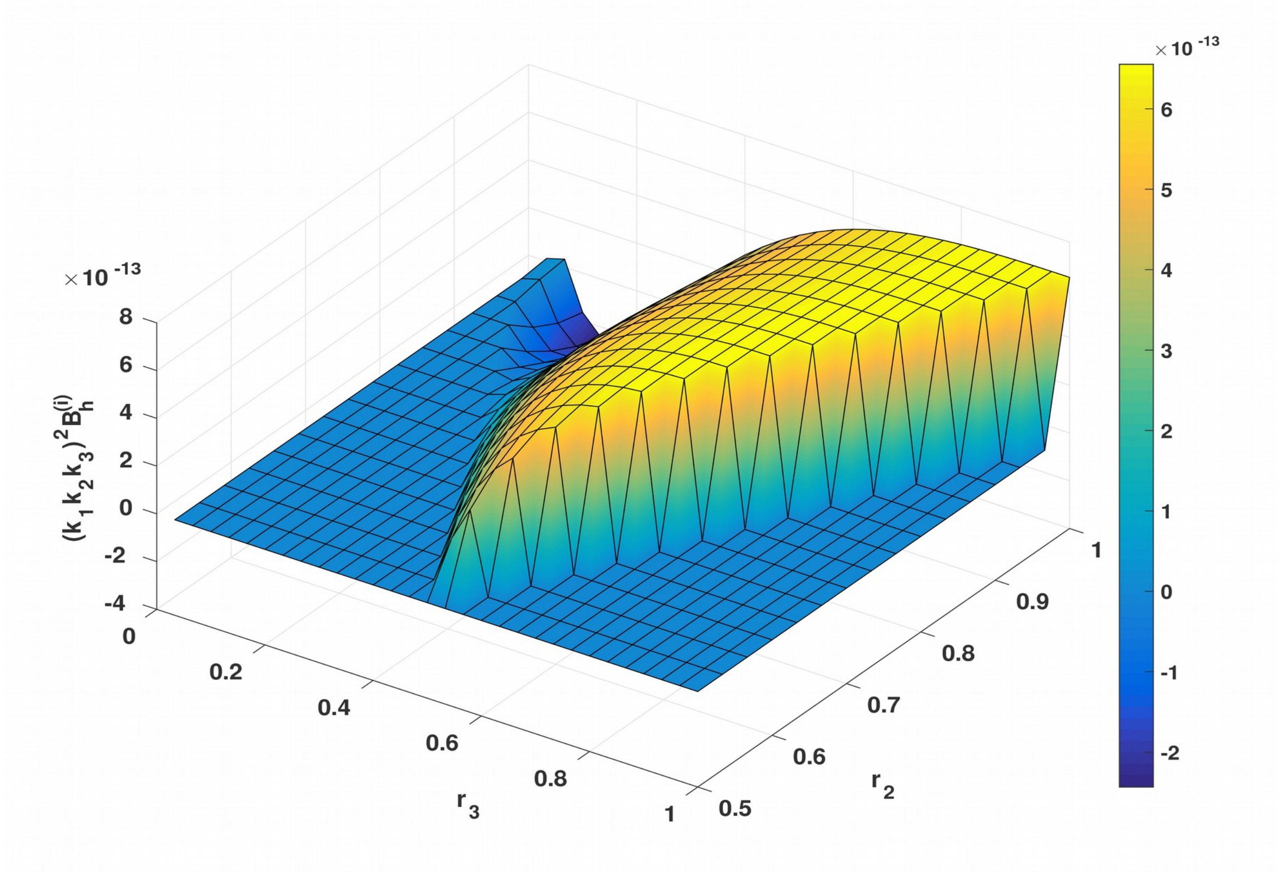


$$\Box h_{ij}(t, \boldsymbol{x}) = \Pi_{ij}(t, \boldsymbol{x})$$

AA, Fujita, Komatsu (2017)

Bispectrum - I

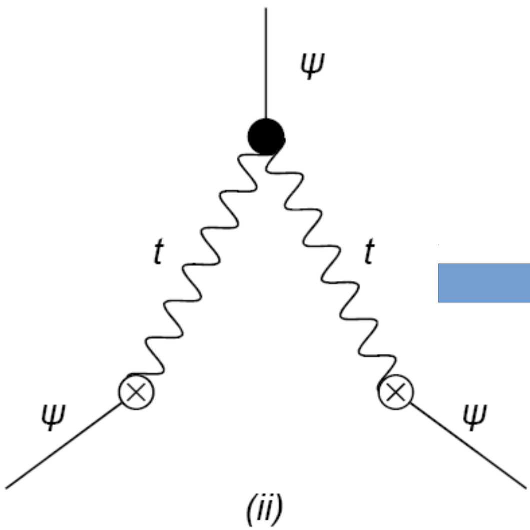


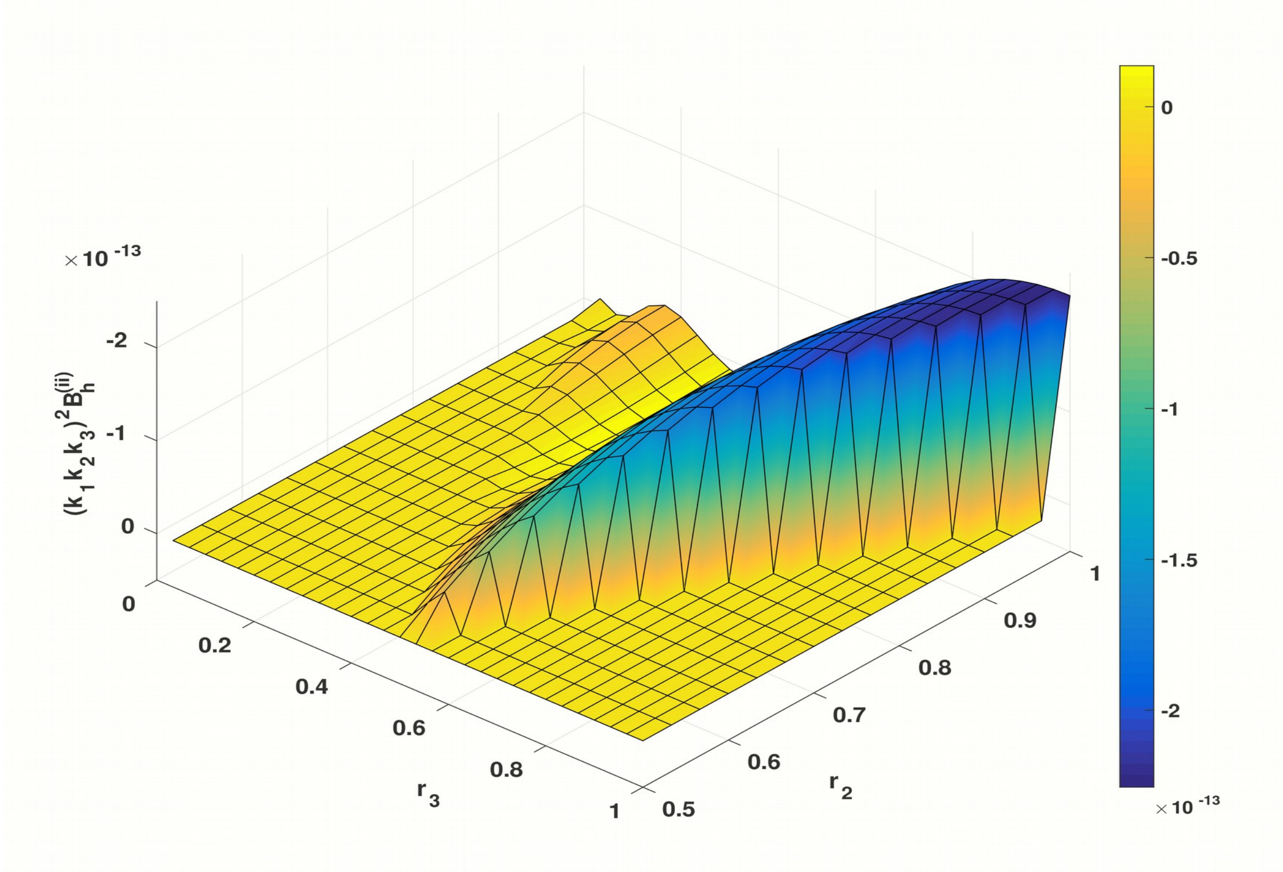


- Self interaction of gauge fields
- Peak at r2 = r3 ~ 0.6
- Equilateral shape
- 0 for r2+r3 = 1

AA, Fujita, Komatsu (in prep)

Bispectrum - II

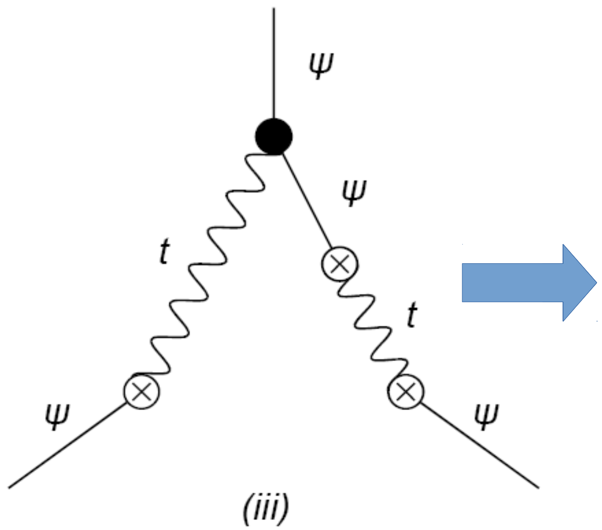


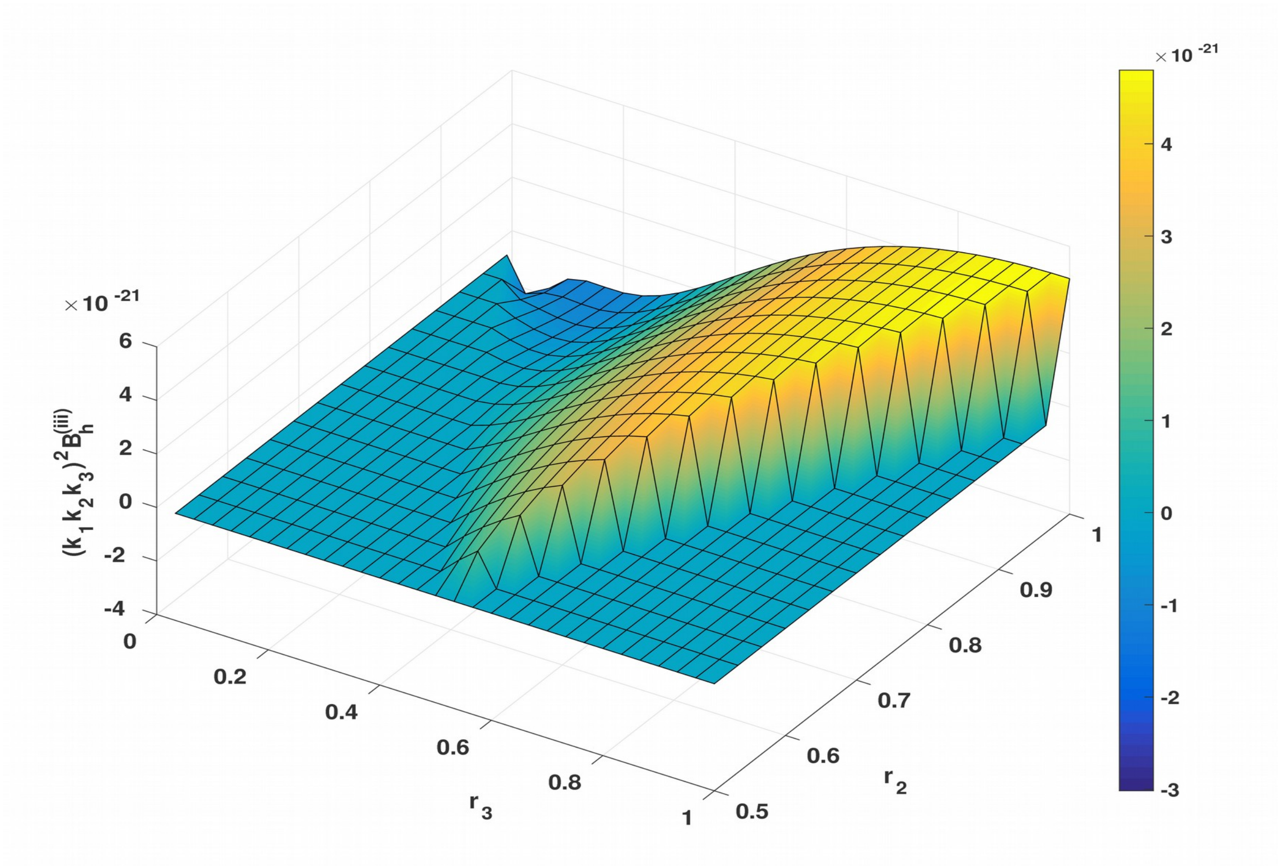


- Non-linear sourcing by gauge fields
- Peak at r2 = r3 = 1
- Equilateral shape
- 0 for r2+r3 = 1

AA, Fujita, Komatsu (in prep)

Bispectrum - III

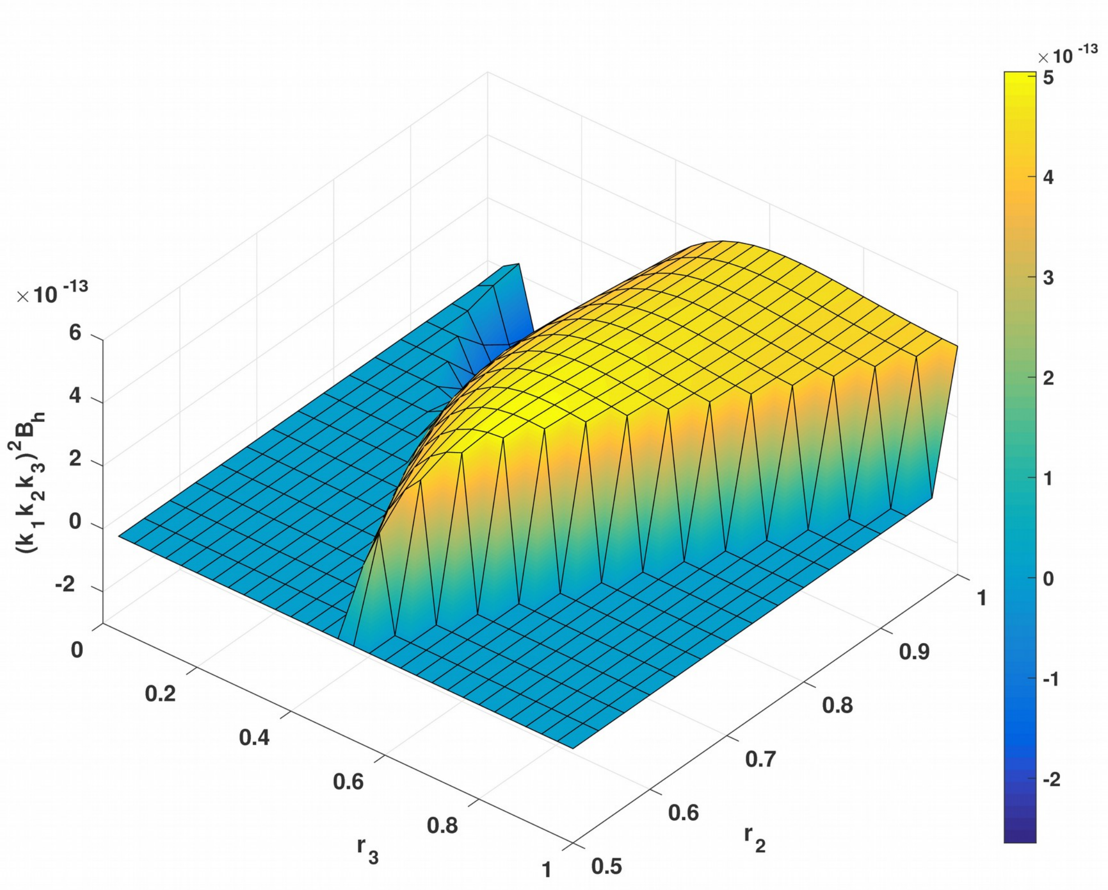




- Non-linear sourcing by gauge field + metric
- Peak at r2 = r3 = 1
- Equilateral shape
- 0 for r2+r3 = 1

AA, Fujita, Komatsu (in prep)

Bispectrum - I+II



These GWs

- Can be scale-independent, red tilted or blue tilted
- Are chiral (pseudo-scalar axion violates parity)
- Are non-Gaussian

AA, Fujita, Komatsu (2017)

Constraining SU(2)

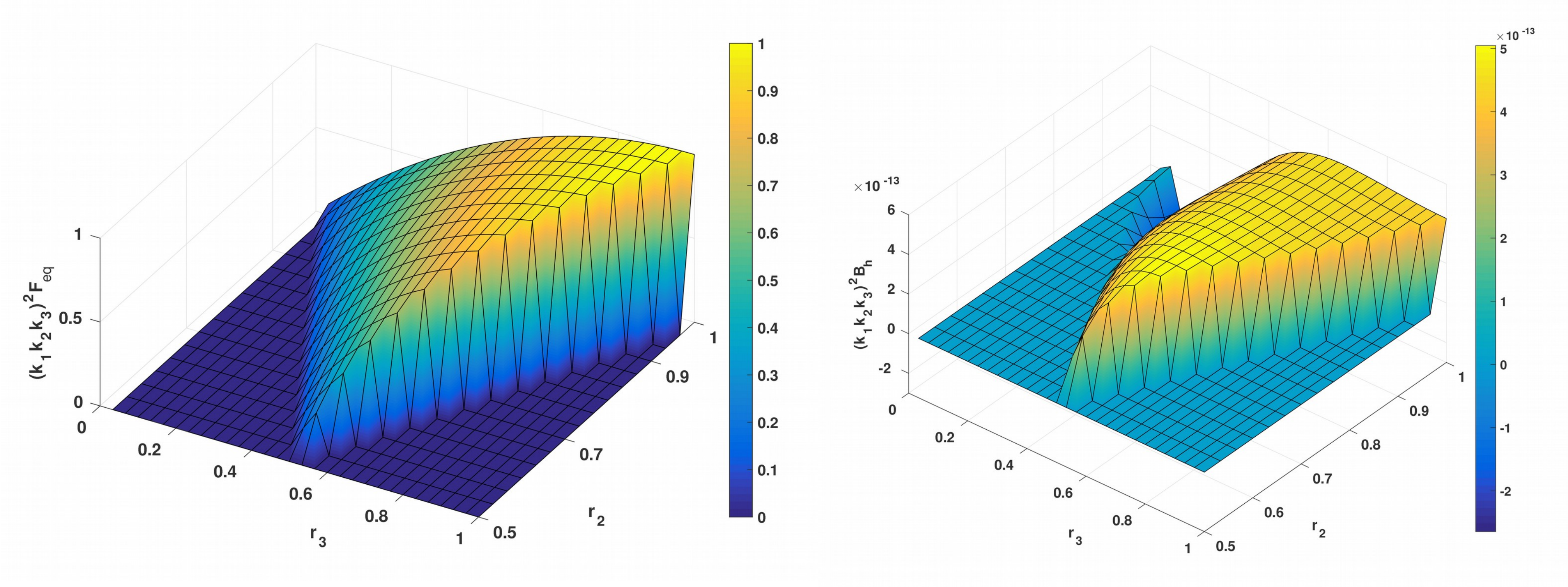
- GWs => Temperature+Polarisation
- Tensor NG is constrained by Planck, using the odd-parity temperature bispectrum to constrain

$$f_{\rm NL}^{\rm tens} \equiv \frac{B_h^{RRR}(k,k,k)}{2\sqrt{2}F_\zeta^{\rm eq}(k)}\,,\; F_\zeta^{\rm eq}(k) \equiv (18/5)P_\zeta^2(k)$$

- Planck measures $f_{\rm NL}^{\rm tens} = 400 \pm 1500$
- using the equilateral template

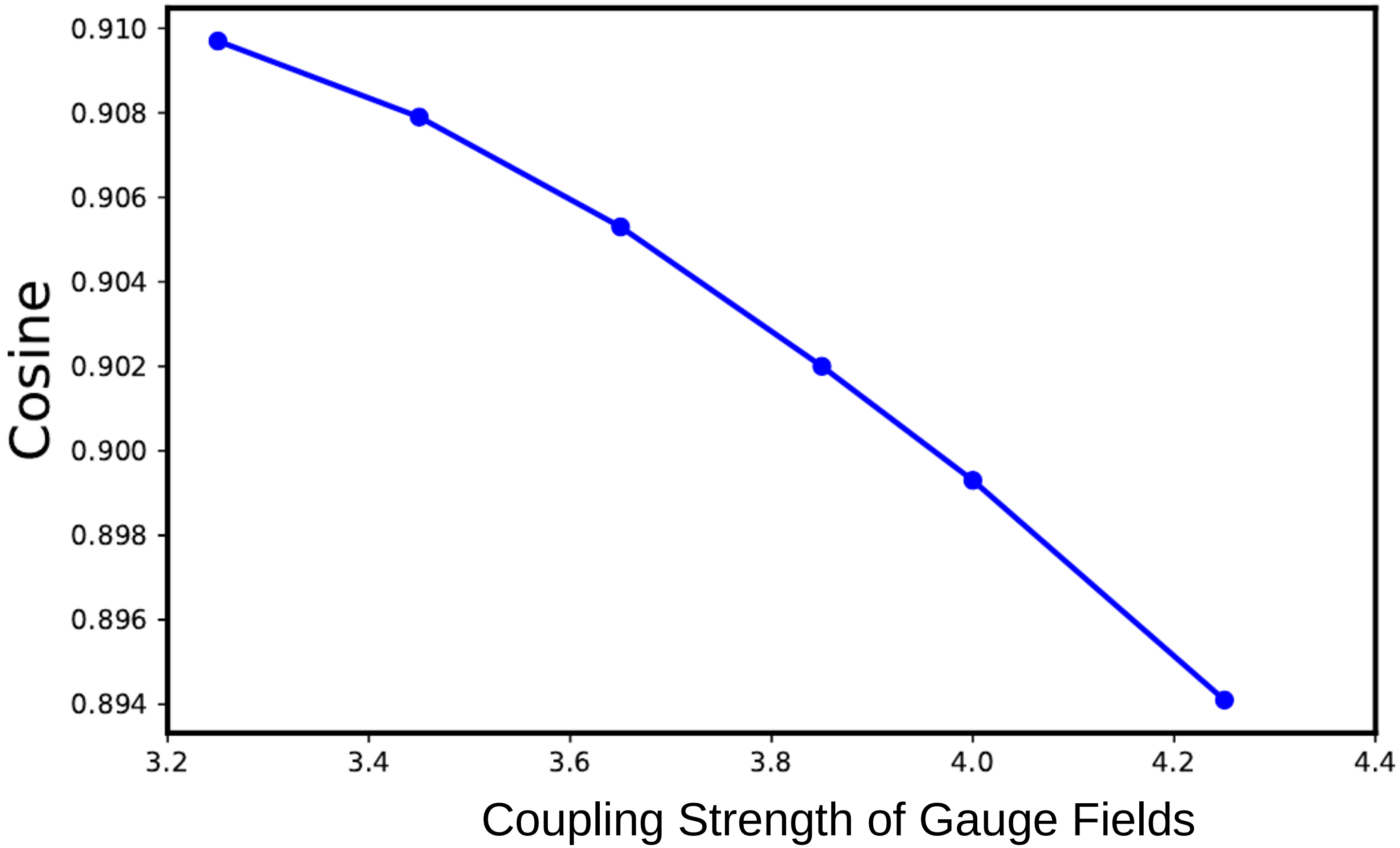
Planck (2015), **AA**, Fujita, Komatsu (2017)

Equilateral Template



Planck (2015), **AA**, Fujita, Komatsu (2017)

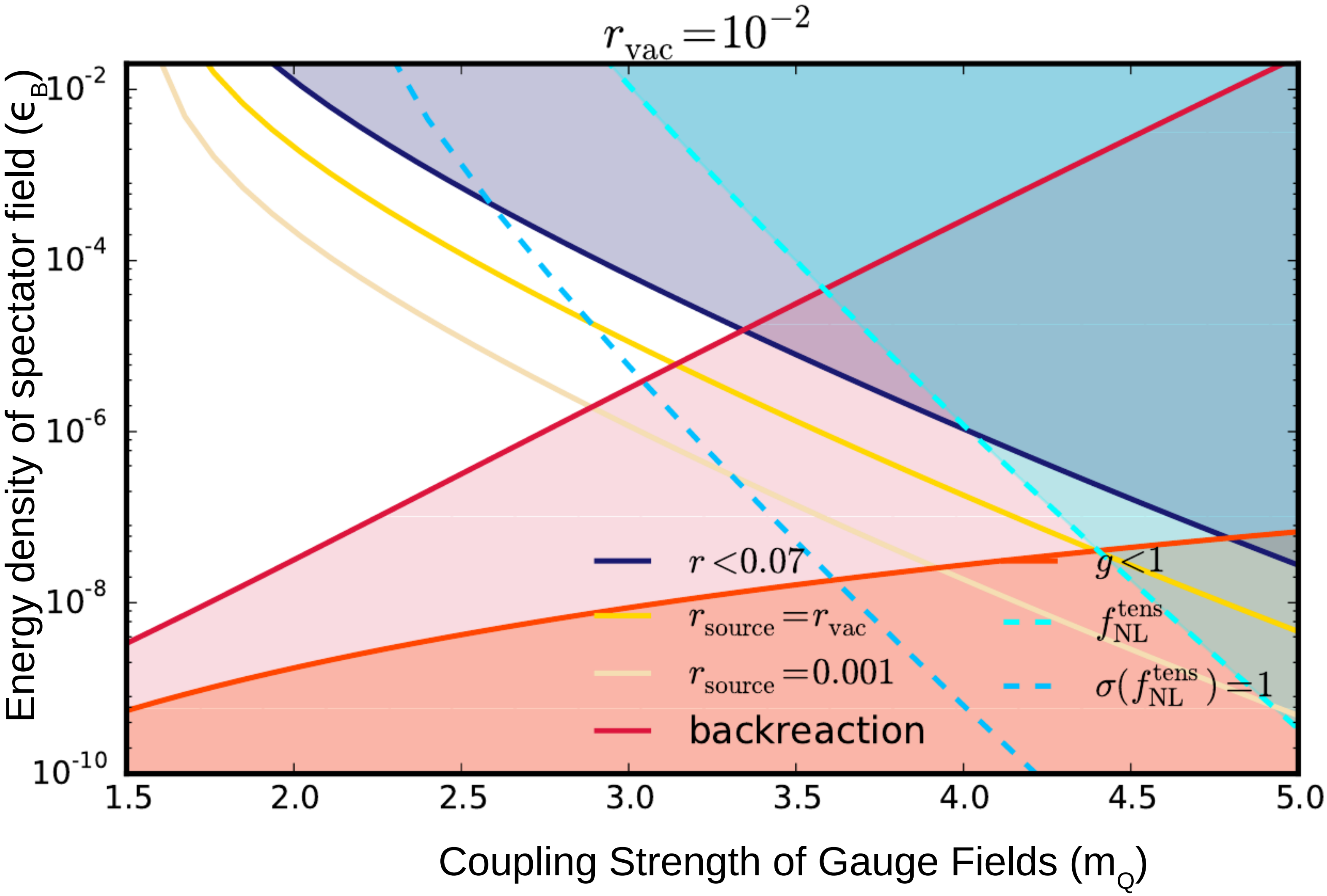
Constraining SU(2)



- For our model, $f_{\rm NL}^{\rm tens} \propto \epsilon_B$
- Already constrains the **energy density ϵ_B of gauge fields!**

AA, Fujita, Komatsu (2017, in prep)

Parameter Search



AA, Fujita, Komatsu (in prep)

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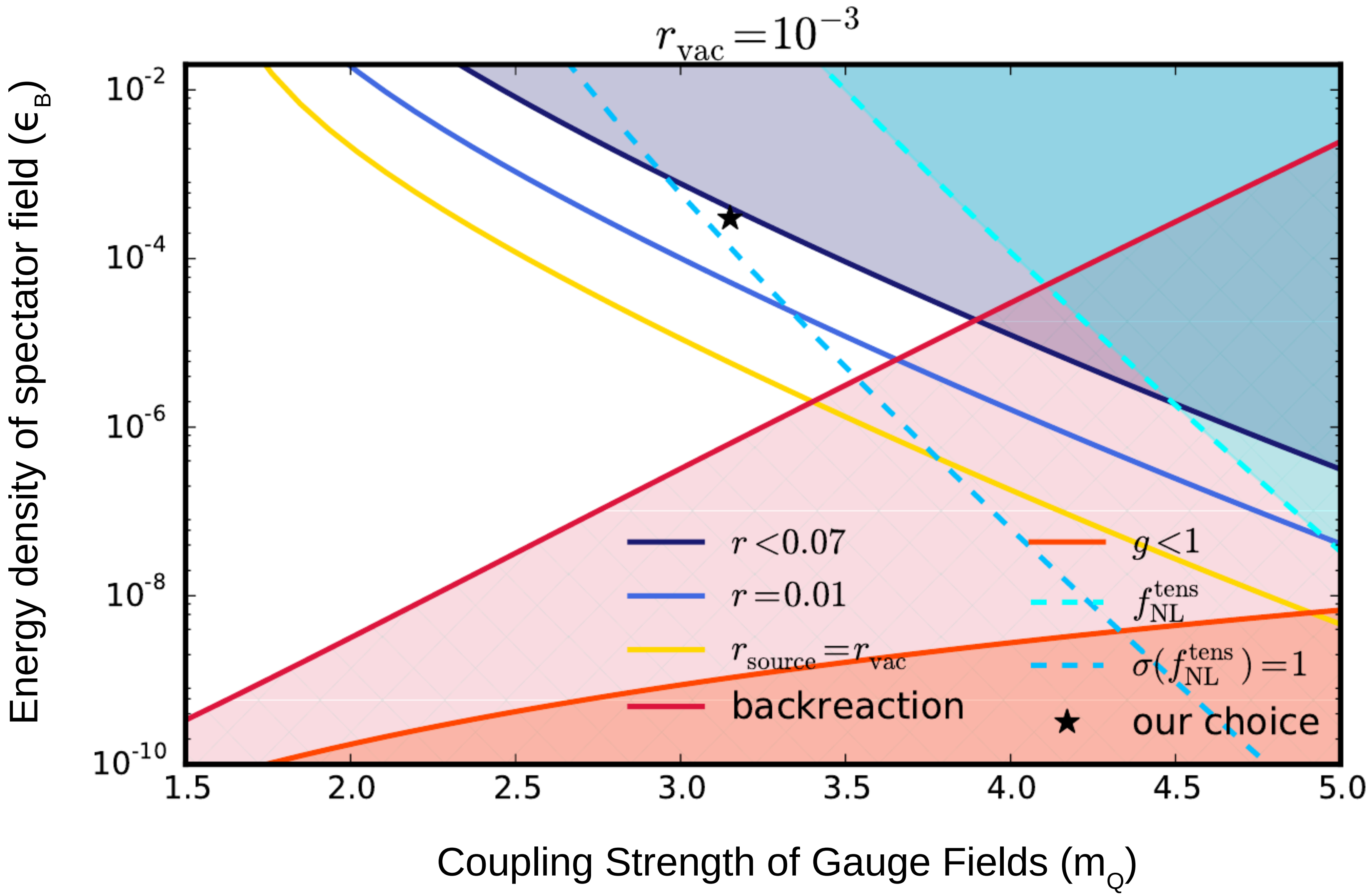

AA, Fujita, Komatsu (in prep)

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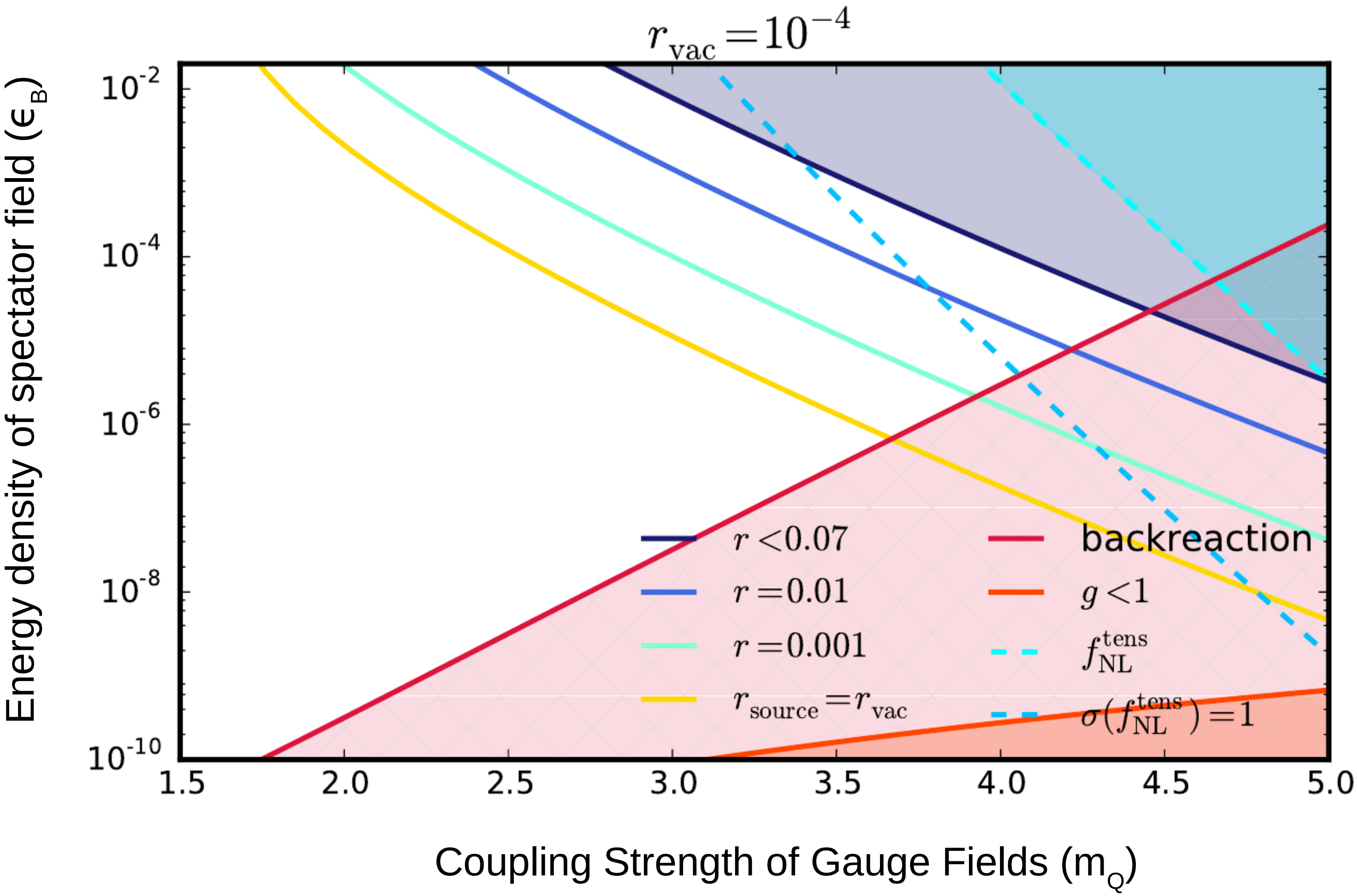
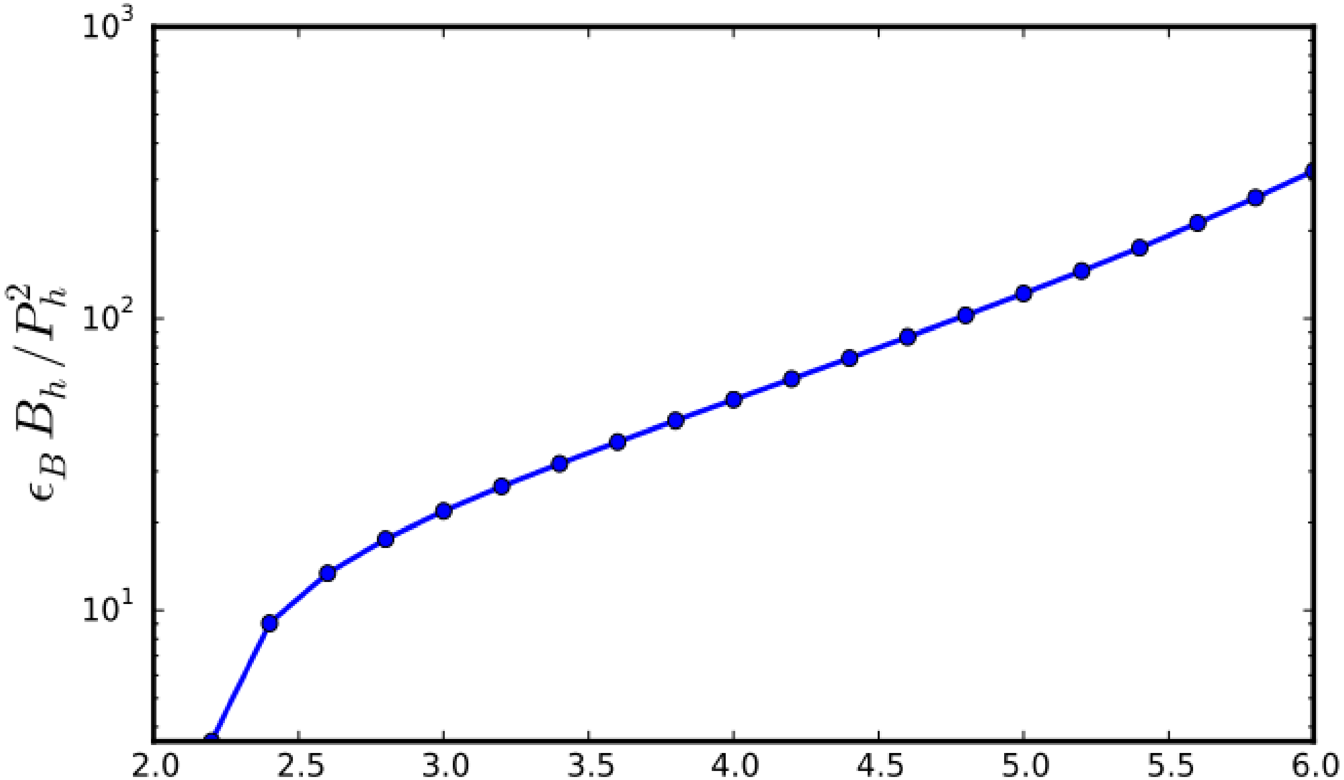


AA, Fujita, Komatsu (in prep)

Non-Gaussianity - Vacuum Fluctuations vs. Sources



Coupling Strength of Gauge Fields (m_Q)

- For vacuum fluctuations

$$\frac{B_h^{RRR}}{P_h^2} \approx 1$$

- For our model

$$\frac{B_h^{RRR}}{P_h^2} \approx \frac{50}{\epsilon_B}$$

- This can be much greater than 1 – highly non-Gaussian!!

Maldacena (2003), Maldacena, Pimentel (2011), **AA**, Fujita, Komatsu (2017, in prep)

Conclusion

- Spectator fields can generate observable tensor fluctuations, without violating constraints on the scalar sector
- For future detections of B modes we need to check for
  - Scale independence
  - Parity invariance
  - Gaussianity
- Only after all these are consistent with the quantum origin should we claim to have discovered quantum gravity
- If not, they can be used to constrain the energy density of spectator fields