Primordial Gravitational Waves from Axion-Gauge fields dynamics

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OUTLINE AND (SOME) REFERENCES

- GW from inflation
- Axion-gauge fields models: genesis and motivations
- Abelian vs non-Abelian case: inflaton as the axion
- Axion-gauge fields as spectators
- Conclusions and outlook

Anber - Sorbo 2009
Cook - Sorbo 2011
Barnaby - Peloso 2011
Barnaby - Namba - Peloso 2011
Adshead - Wyman 2011
Maleknejad - Sheikh-Jabbari, 2011
ED - Fasiello - Tolley 2012
ED - Peloso 2012
Namba - ED - Peloso 2013
Adshead - Martinec -Wyman 2013
Namba - Peloso - Shiraishi - Sorbo - Unal 2015
Obata - Miura - Soda 2016
Caldwell 2016
Smith - Caldwell 2016
Peloso - Sorbo - Unal 2016
ED - Fasiello - Fujita 2016
Adshead - Martinec - Sfakianakis - Wyman 2017
Adshead - Sfakianakis 2017
Agrawal - Fujita - Komatsu 2017
Thorne - Fujita - Hazumi - Katayama - Komatsu - Shiraishi ’17
Caldwell - Devulder 2017
… … …

GWs FROM INFLATION

Tensor fluctuations:

$$ds^2 = a^2(\tau)\left[-d\tau^2 + (\delta_{ij} + \gamma_{ij}(\tau, \vec{x}))dx^i dx^j\right]$$

transverse & traceless

$$\partial_i \gamma^i_j = 0 \qquad \gamma^i_i = 0$$

$6 - 4 = 2$
independent
degrees of
freedom

$$\gamma_{ij}(\vec{x}, t) = \int \frac{d^3k}{(2\pi)^{3/2}} \sum_{\lambda=\pm} \epsilon^\lambda_{ij}(\hat{k}) \gamma_\lambda(\vec{k}, t) e^{i\vec{k}\cdot\vec{x}}$$

Inflationary GWs : standard vacuum production

- Energy scale of inflation: $V_{\rm infl}^{1/4} \approx 10^{16} {\rm GeV}\,(r/0.01)^{1/4}$, $H \approx 2\times 10^{13}\sqrt{r/0.01}\,{\rm GeV}$
- Scalar field excursion (Lyth bound): $\Delta\phi/M_P \gtrsim (r/0.01)^{1/2}$
- Red tilt: $n_T \simeq -2\epsilon = -r/8$
- Non-chiral: $P_{\lambda+} = P_{\lambda-}$
- Gaussian

One or more of these predictions may be easily violated beyond the minimal set-up!

Beyond standard vacuum fluctuations

NEW SYMMETRIES

breaking of space-diff invariance
and non-zero graviton mass
[Endlich et al., 2013, Bartolo et al, 2015]

NEW FIELDS

additional GWs production next to
(irreducible) vacuum generation

$$\mathcal{L} = \mathcal{L}_{\text{inflaton}} + \mathcal{L}_{\text{spectator}}$$

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$$\mathcal{L} = \mathcal{L}_{\rm inflaton} + \mathcal{L}_{\rm spectator}$$

- Auxiliary scalars with time-varying masses :
  [Chung et al., 2000, Senatore et al, 2011, Pearce et al, 2016]
  $$\mathcal{L}_{\rm spectator} \supset \sum_i \chi_i^2 \left(\phi - \phi_i\right)^2$$
- Spectator fields with small sound speed
  [Biagetti, Fasiello, Riotto 2012,
  Biagetti, ED, Fasiello, Peloso 2014]
  $$\mathcal{L}_{\rm spectator} \supset P(X, \sigma)$$
- Axions and gauge fields
  [Sorbo 2011, Mukohyama et al. 2012-2014,
  ED-Fasiello-Fujita 2016, …]
  $$\mathcal{L}_{\rm spectator} \supset \chi F\tilde{F}$$

NEW FIELDS: overview of the approach

$$\mathcal{L} = \mathcal{L}_{\text{inflaton}} + \mathcal{L}_{\text{spectator}}$$

$$\rho_{\text{inflaton}} \gg \rho_{\text{spectator}}$$

$$P_{\gamma,\text{vacuum}} \lesssim P_{\gamma,\text{spectator}}$$

$$\ddot{\gamma}_{ij}(\vec{k},t) + 3H\dot{\gamma}_{ij}(\vec{k},t) + k^2\gamma_{ij}(\vec{k},t) = \frac{2}{M_P^2}\Pi_{ij}^{TT}(\vec{k},t)$$

$$a^2\Pi_{ij} = T_{ij} - a^2\,p\,(\delta_{ij} + \gamma_{ij})$$

(anisotropic stress)

* Main challenge:

sourcing tensors to observable level without badly affecting scalar sector!

AXION-GAUGE FIELDS MODELS: GENESIS/MOTIVATION

- Generic requirement for inflation: nearly flat potential: $\epsilon,\ |\eta| \ll 1$

$$\epsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2,\ \eta \equiv M_p^2 \frac{V''}{V}$$

… but flatness may be spoiled by radiative corrections!

- Flatness protected by a (nearly exact) axionic shift symmetry $\phi \to \phi + \mathrm{c}$

→ Spirit of Natural Inflation [Freese, Frieman, Olinto 1990]

$$V(\varphi) = \Lambda^4 \left[1 - \cos\left(\varphi/f\right)\right]$$

- Agreement with observations requires: $f \gtrsim M_P$

undesirable constraint on the theory

[Kallosh, Linde, Susskind, 1995, Banks et al, 2003]

AXION-GAUGE FIELDS MODELS: GENESIS/MOTIVATION

- If also gauge fields are around (why not?) we must include C-S coupling:

$$\mathcal{L}_{\text{inflaton}} = -\frac{1}{2}(\partial\varphi)^2 - V(\varphi) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{\alpha}{4f}\varphi F^{\mu\nu}\tilde{F}_{\mu\nu}$$

U(1) case:

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$
$$\tilde{F}^{\mu\nu} = -\frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$$

- Gauge field quanta are produced by the rolling axion:

$$\left[\partial_\tau^2 + k^2 \pm \frac{2k\xi}{\tau}\right] A_\pm(\tau, k) = 0$$

$$A_+(\tau, k) \propto e^{\pi\xi}$$

$$\xi \equiv \frac{\alpha\dot{\phi}}{2fH}$$

$$\vec{A}(\tau, \mathbf{x}) = \sum_{\lambda=\pm}\int \frac{d^3k}{(2\pi)^{3/2}}\left[\vec{\epsilon}_\lambda(\mathbf{k})a_\lambda(\mathbf{k})A_\lambda(\tau, \mathbf{k})e^{i\mathbf{k}\cdot\mathbf{x}} + \text{h.c.}\right]$$

[Anber, Sorbo 2009 - Barnaby, Peloso 2011, Barnaby, Namba, Peloso 2011]

AXION-GAUGE FIELDS MODELS: U(1)

- Gauge quanta in turn back-react on the background:

$$\ddot{\phi} + 3H\dot{\phi} + V^{'}(\phi) = \frac{\alpha}{f}\langle \vec{E}\cdot\vec{B}\rangle$$

$$3H^2 M_p^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi) + \frac{1}{2}\langle \vec{E}^2 + \vec{B}^2\rangle$$

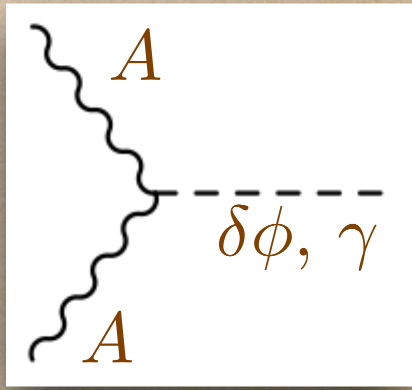
$$\vec{B} = \frac{1}{a^2}\vec{\nabla}\times\vec{A}$$

$$\vec{E} = -\frac{1}{a^2}\vec{A}'$$

- … as well as source scalar fluctuations:

$$\left[\partial_\tau^2 + 2\mathcal{H}\partial_\tau - \nabla^2 + a^2 m^2\right]\delta\varphi(\tau,\mathbf{x}) = a^2\frac{\alpha}{f}\left(\vec{E}\cdot\vec{B} - \langle\vec{E}\cdot\vec{B}\rangle\right)$$

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



- … and tensor fluctuations:

$$\left[\partial_\tau^2 + 2\mathcal{H}\partial_\tau - \nabla^2\right] h_{ij} = -\frac{2a^2}{M_p^2}\left(E_i E_j + B_i B_j\right)^{TT}$$

[Anber, Sorbo 2009 - Barnaby, Peloso 2011, Barnaby, Namba, Peloso 2011]

AXION-GAUGE FIELDS MODELS: U(1)

- Power spectra:

$$P_\zeta(k) = \mathcal{P}\left(\frac{k}{k_0}\right)^{n_s-1}\left[1+\mathcal{P}f_2(\xi)e^{4\pi\xi}\right]$$

$$P_\gamma = P_{\gamma,L} + P_{\gamma,R} \simeq \frac{2H^2}{\pi^2 M_p^2}\left(\frac{k}{k_0}\right)^{n_T}\left[1+\frac{H^2}{M_p^2}f_{\gamma,L}(\xi)e^{4\pi\xi}\right]$$

- Scalar bispectrum: the sourced scalar fluctuation is a convolution of two gauge field fluctuations → non-Gaussian field!

In the regime where sourced GWs dominate over vacuum GWs, non-Gaussianity becomes too large

[Anber, Sorbo 2009 - Barnaby, Peloso 2011, Barnaby, Namba, Peloso 2011]

AXION-GAUGE FIELDS MODELS: non-Abelian case

[Adshead, Wyman 2011]

$$\mathcal{L}_{\text{inflaton}} = -\frac{1}{2}\left(\partial\chi\right)^2 - U(\chi) - \frac{1}{4}FF + \frac{\lambda\chi}{4f}F\tilde{F}$$

$$\begin{cases} \chi \longrightarrow \text{Inflaton} \\ A^a_\mu \longrightarrow \text{SU(2) gauge field} \end{cases}$$

isotropic background:

$A^a_0 = 0$

$A^a_i = \delta^a_i a(t) Q(t)$

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

$$U(\chi) = \mu^4\left[1 + \cos(\chi/f)\right]$$

BACKGROUND EVOLUTION :

- Equations of motion for inflaton and gauge field are coupled
- Gauge field provides a damping term in the equation of motion of the axion, which effectively flattens its potential

AXION-GAUGE FIELDS MODELS: non-Abelian case

[Adshead - Wyman 2011, ED - Fasiello - Tolley 2012, ED - Peloso 2012]

- Scalar perturbations:

$$\{\delta\chi, \delta Q, \delta M\}$$

inflaton ($\delta\chi$) gauge-field ($\delta Q, \delta M$)

$$\partial_x^2 \Delta_i - 2K_{ij}\partial_x \Delta_j + \left(\Omega_{ij}^2 - \partial_x K_{ij}\right)\Delta_j = 0$$

$x \approx -k\tau$

- scalar fluctuations undergo tachyonic growth for

  $m_Q \equiv gQ/H < \sqrt{2}$

- power spectrum amplitude for curvature pert. dominated by $\delta\chi$

AXION-GAUGE FIELDS MODELS: non-Abelian case

[Adshead - Wyman 2011, ED - Fasiello - Tolley 2012, ED - Peloso 2012]

- Tensor perturbations:

$$\{ \Psi_{R,L} \, , \, t_{R,L} \}$$

metric gauge field

$$\begin{cases} \Psi''_{R,L} + \left(1 - \frac{2}{x^2}\right) \Psi_{R,L} = \mathcal{O}^{(1)} \left(t_{R,L}\right) \\ t''_{R,L} + \left[1 + \frac{2 m_Q \xi}{x^2} \mp \frac{2}{x}(m_Q + \xi)\right] t_{R,L} = \tilde{\mathcal{O}}^{(1)} \left(\Psi_{R,L}\right) \end{cases}$$

linear mixing
(unlike Abelian case!)

$$FF \supset g \epsilon^{ijk} A_i A_j \partial A_k$$
$$\chi F \tilde{F} \supset \epsilon^{ijk} \dot{\chi} A_i \partial_j A_k$$

$$\xi = \frac{\lambda \dot{\chi}}{2 f H}$$
$$x \approx -k\tau$$

one of the two polarization of the gauge field undergoes transient growth, hence the corresponding polarization of the metric is amplified!

AXION-GAUGE FIELDS MODELS: non-Abelian case

[Adshead - Martinec -Wyman 2013]

- Comparison with observations:

Tensors are overproduced in the region of parameter space
where the spectral index for scalar fluctuations
is within experimental bounds

GAUGE-FLATION [Maleknejad, Sheikh-Jabbari, 2011]

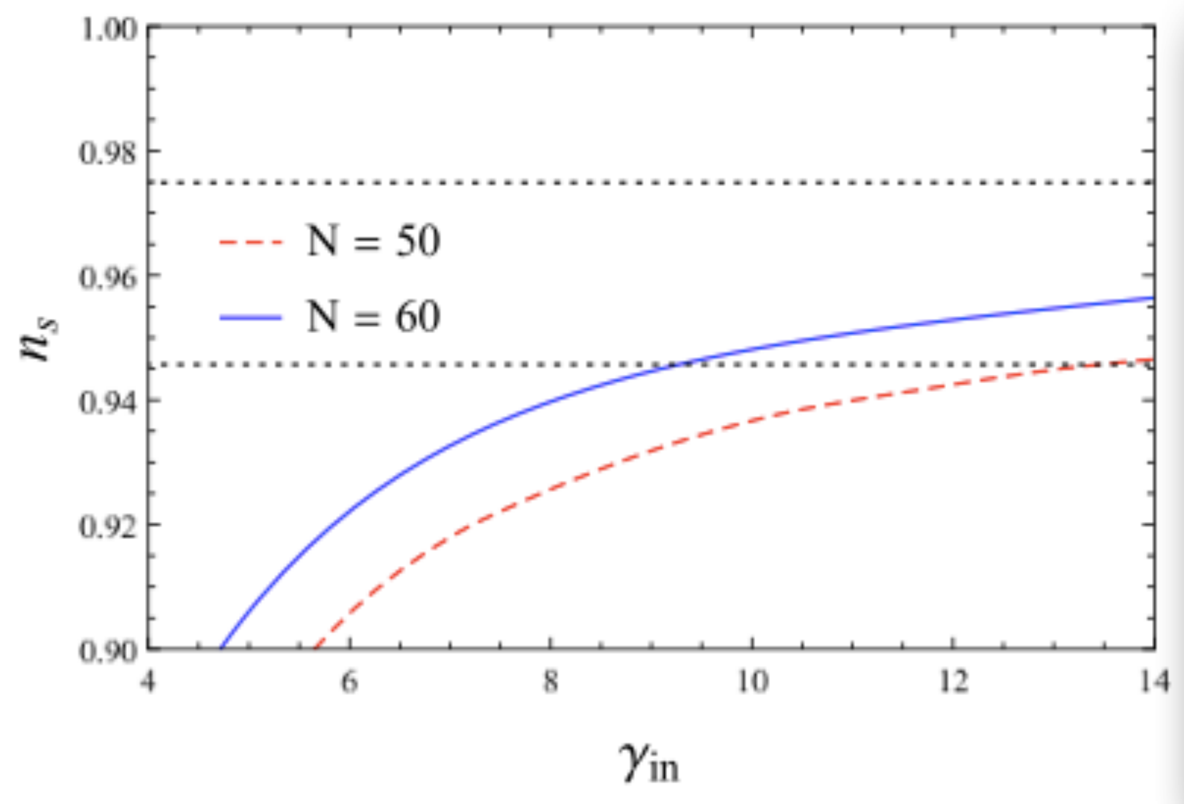
$$\mathcal{L}_{\text{inflaton}} = \underbrace{-\frac{1}{4}FF}_{\mathcal{L}_{\text{YM}}} + \underbrace{\frac{\kappa}{96}\left(F\tilde{F}\right)^2}_{\mathcal{L}_\kappa}$$

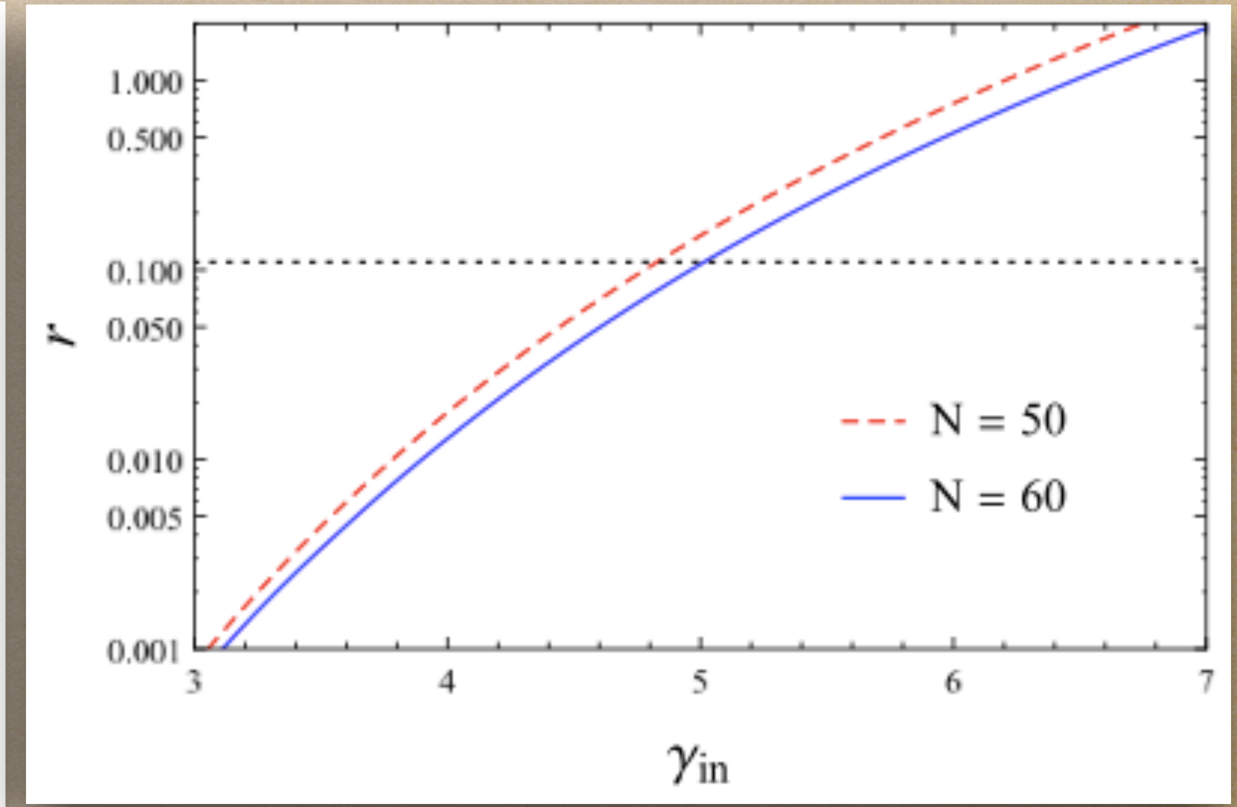
$$A_i^a = \delta_i^a a(t) Q(t)$$

$$\gamma \equiv \frac{g^2 Q^2}{H^2}$$

$$p_{\text{YM}} = \frac{\rho_{YM}}{3}$$

$$p_\kappa = -\rho_\kappa$$





ruled out!

$$P_\zeta = \frac{\mathcal{A}_\zeta}{k^{3+(1-n_s)}}$$

$$r = \frac{\sum_{\lambda=\pm} P_\lambda}{P_\zeta}$$

[Namba, ED, Peloso, 2013]

WHERE WE ARE AT SO FAR:

- Axion+gauge field models are theoretically compelling and have an interesting phenomenology but difficult to reconcile with observations
- But do we want to give them up? Predictions are very distinctive:
  — alternative gravitational waves production
  — chiral signal
  — non-Gaussianity …

Possible way forward :

Eliminating direct coupling between inflaton and axion-gauge fields, making the latter a **spectator sector**

Proven to work both for Abelian and non-Abelian case, while introducing one more distinctive signature: non-conventional **spectral index**

Inflaton+[axion+U(1)]

$$\mathcal{L}_{\text{inflaton}} = -\frac{1}{2}(\partial\varphi)^2 - V(\varphi) - \frac{1}{2}(\partial\chi)^2 - W(\chi) - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{\alpha}{4f}\chi F^{\mu\nu}\tilde{F}_{\mu\nu}$$

$\mathcal{L}_{\text{spectator}}$

$$W(\chi) = \frac{\Lambda^4}{2}\left[1 + \cos(\chi/f)\right]$$

$\delta A + \delta A \to \delta\phi$ ← weaker (gravitational strength)!!!

$\delta A + \delta A \to \delta\chi$ ← from direct coupling, but W<<V by assumption

$\delta A + \delta A \to \gamma$ →

- feature in the spectrum (relevant scale depends on slow-roll evolution of the axion) $\xi \equiv \frac{\alpha\dot{\chi}}{2fH}$
- chirality
- interestingly large tensor nG

[Barnaby et al, 2012 - Namba et al, 2015 - Peloso et al 2016]

Inflaton+[axion+SU(2)] [ED-Fasiello-Fujita 2016]

$$\mathcal{L} = \mathcal{L}_{\rm inflaton} - \frac{1}{2}(\partial\chi)^2 - U(\chi) - \frac{1}{4}FF + \frac{\lambda\chi}{4f}F\tilde{F}$$

$\mathcal{L}_{\rm inflaton} \rightarrow P_{\gamma,\rm vacuum}$

$\mathcal{L}_{\rm spectator} \rightarrow P_{\gamma,\rm sourced}$

- Inflaton field dominates energy density of the universe
- Spectator sector contribution to curvature fluctuations negligible

Inflaton+[axion+SU(2)] [ED-Fasiello-Fujita 2016]

$$\Psi''_{R,L} + \left(1 - \frac{2}{x^2}\right)\Psi_{R,L} = \mathcal{O}^{(1)}\left(t_{R,L}\right)$$

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$FF \supset g\epsilon^{ijk}A_iA_j\partial A_k$

$\chi F\tilde{F} \supset \epsilon^{ijk}\dot{\chi}A_i\partial_j A_k$

Ψ = GW

t = tensor SU(2)

$A_i^a = \delta_i^a a(t)Q(t)$

$m_Q = \dfrac{gQ}{H}$

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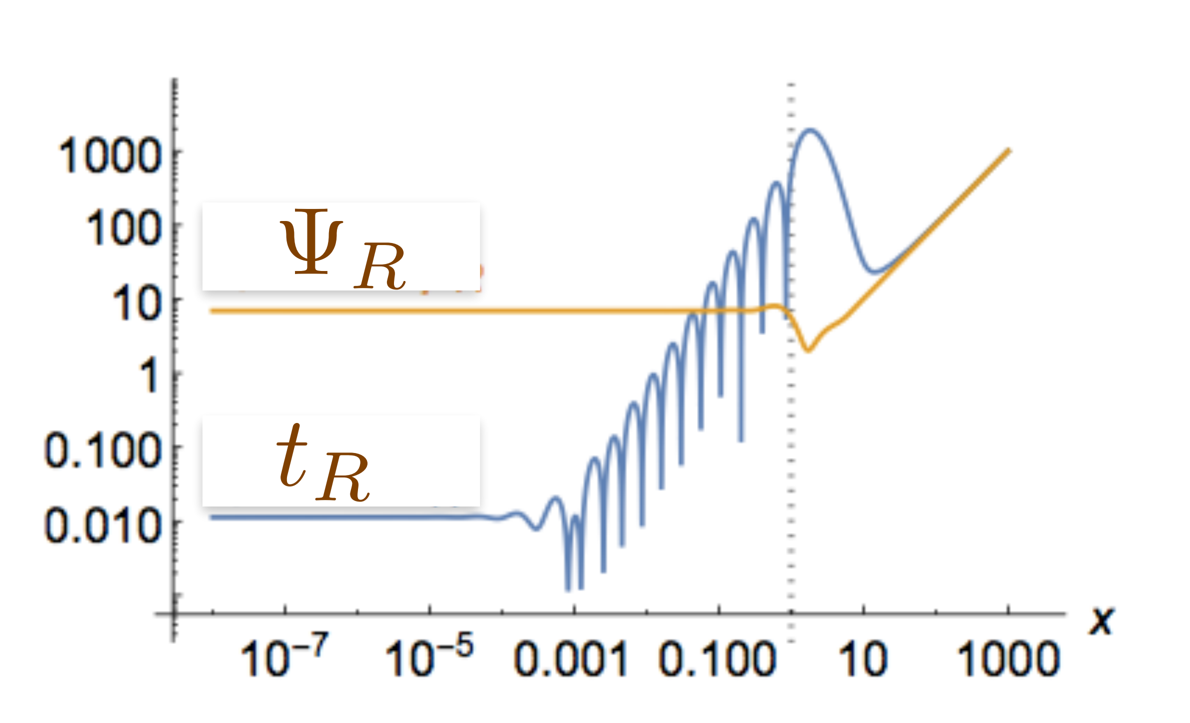
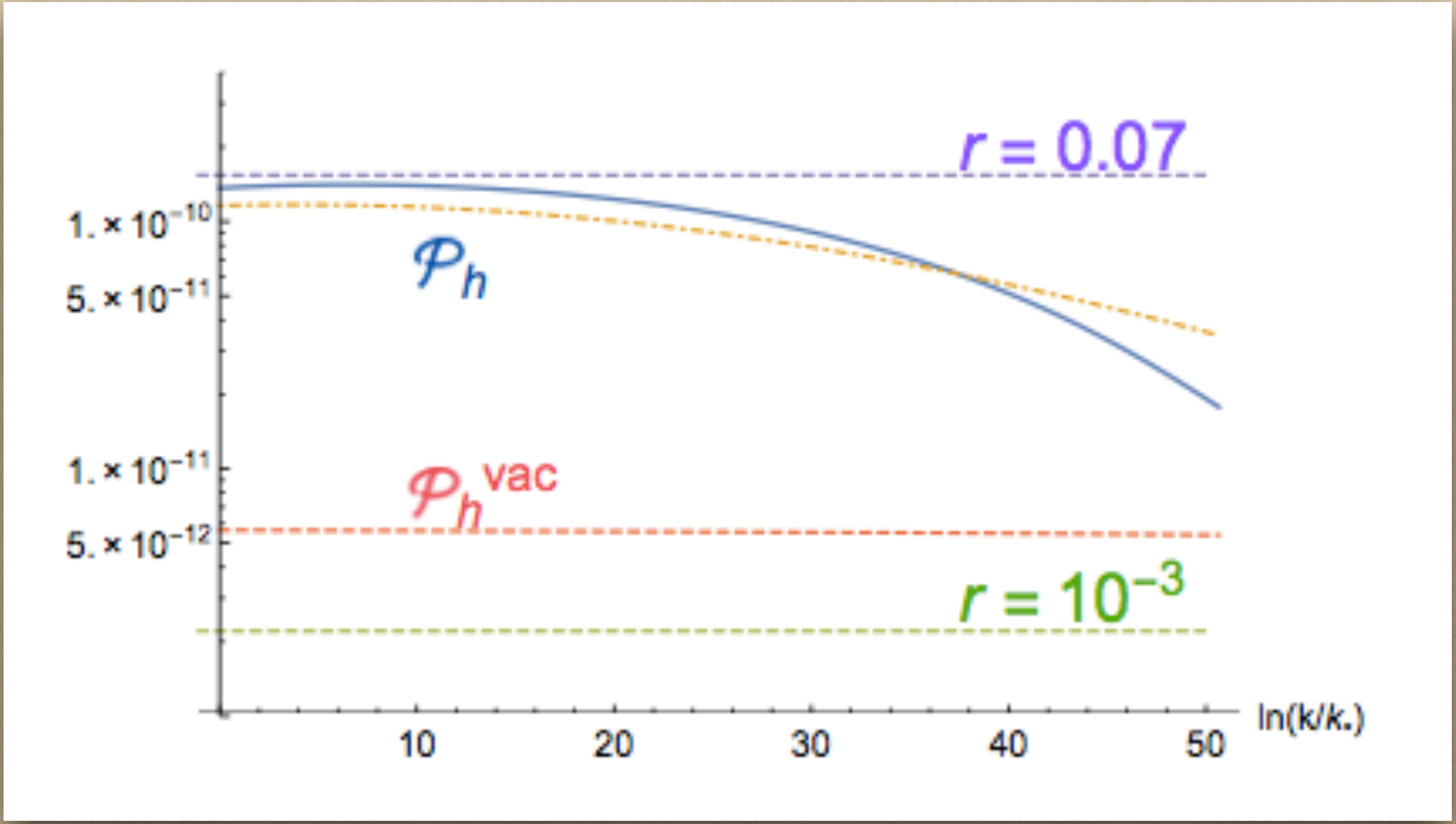


Inflaton+[axion+SU(2)] [ED-Fasiello-Fujita 2016]

Sourced GWs :

- can be easily **larger** than vacuum contributions
- are **chiral** and spectrum can be **blue/bumpy**



example for $\left\{g,\, \chi_*,\, f,\, H_*,\, \mu,\, \lambda\right\}$

Inflaton+[axion+SU(2)]

[Thorne - Fujita - Hazumi - Katayama - Komatsu - Shiraishi 2017, Agrawal - Fujita - Komatsu 2017]

- Forecasts for our ability to constrain r, scale dependence, chirality, tensor non-Gaussianity in this model (CMB, interferometers…)

See Ben's and Eiichiro's talks!!!

CONCLUSIONS AND OUTLOOK

Axion-gauge field models:
rich phenomenology and potentially testable predictions

- Breaking standard r—H relation and Lyth bound
- Blue spectrum: interesting also for interferometers GWs search
- Chiral signal: expect non-zero TB, EB correlations
- Non-Gaussianity

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Experiments should be on the lookout for . . .

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Thank you!