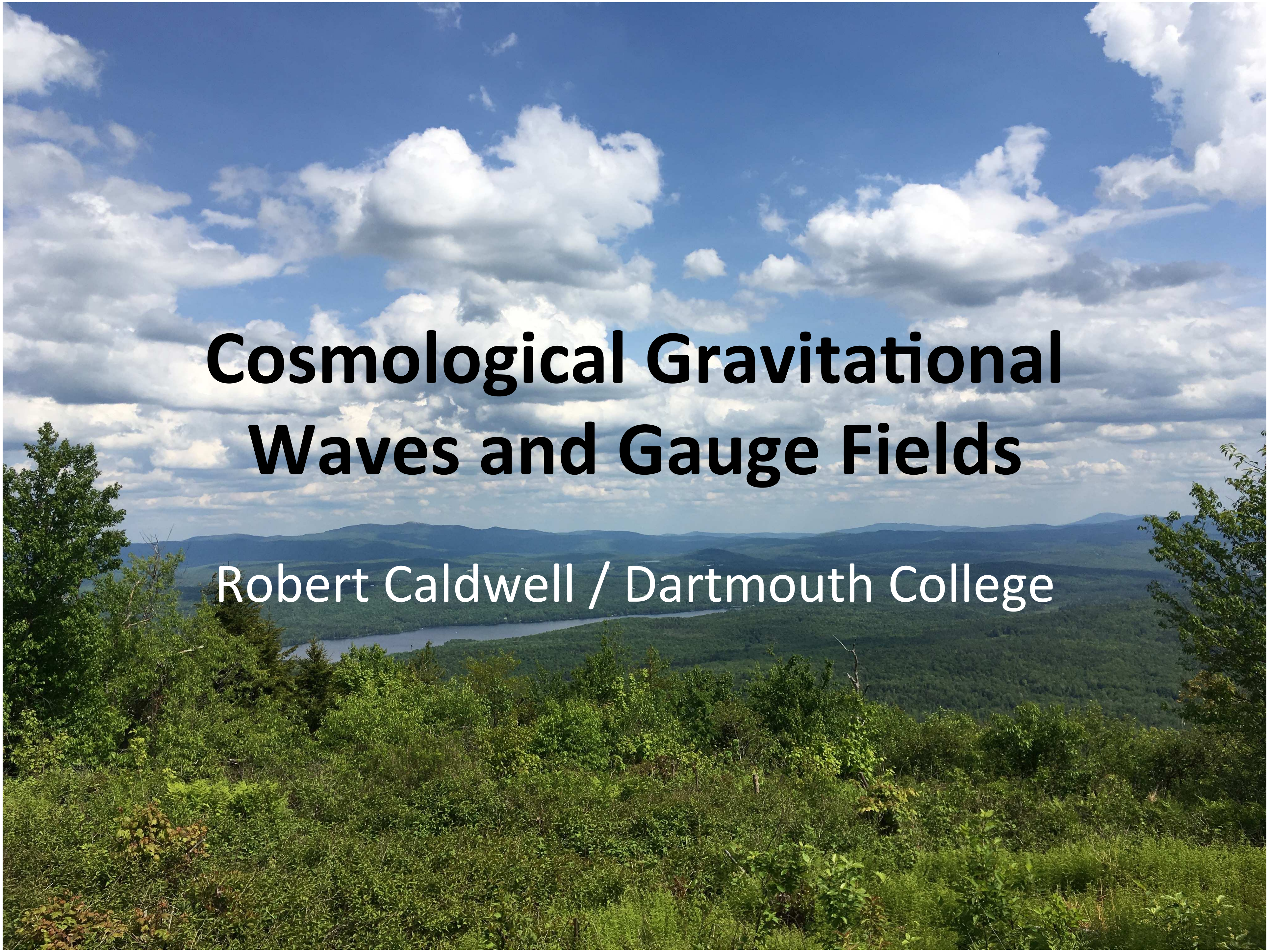
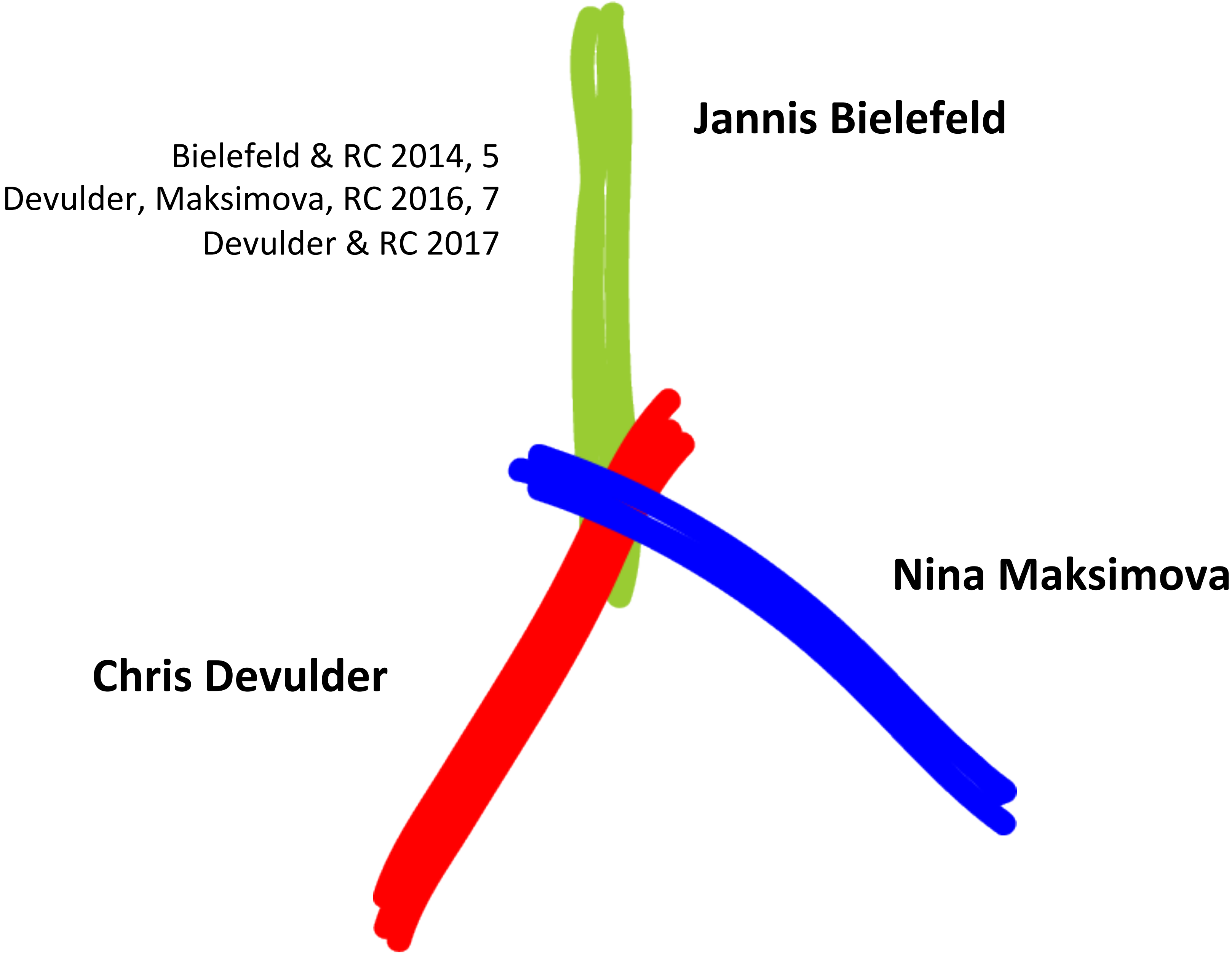


Cosmological Gravitational Waves and Gauge Fields

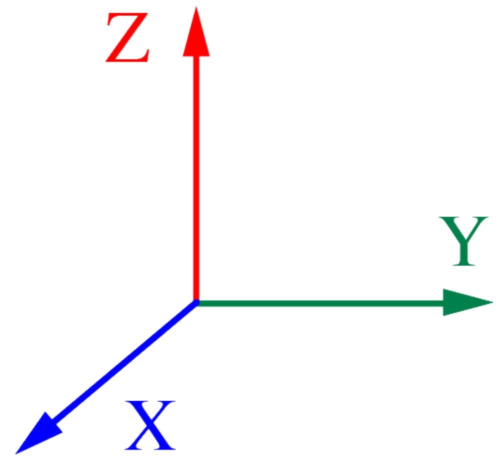
Robert Caldwell / Dartmouth College


Jannis Bielefeld
Bielefeld & RC 2014, 5
Devulder, Maksimova, RC 2016, 7
Devulder & RC 2017
Nina Maksimova
Chris Devulder

Flavor-Space Locked Field

$$\mathcal{L} = \frac{1}{2}M_P^2 R - \frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu}$$

$$\vec{F}_{\mu\nu} = \partial_\mu \vec{A}_\nu - \partial_\nu \vec{A}_\mu + g\vec{A}_\mu \times \vec{A}_\nu$$

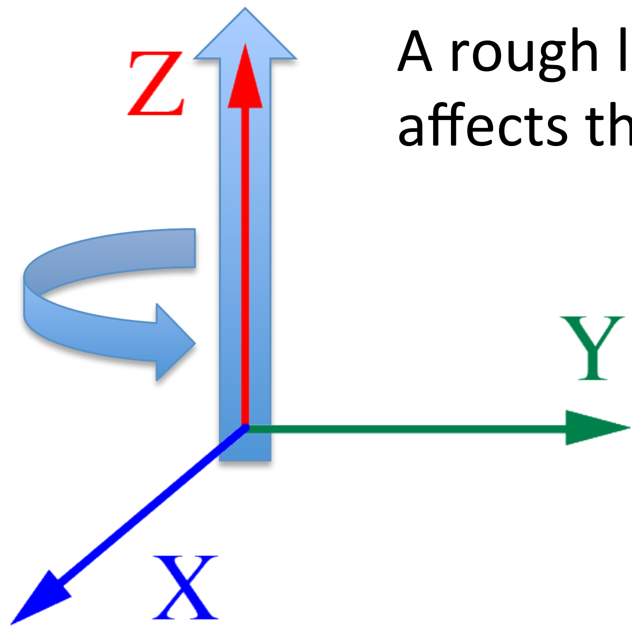


$$\vec{A}_\mu = \phi(\tau)\vec{e}_\mu$$ *"flavor-space locked"*

$$\delta g_{\mu\nu} = a^2(\tau)h_{\mu\nu}$$ gravitational wave

$$\delta \vec{A}_\mu \cdot \vec{e}_\nu = a(\tau)y_{\mu\nu}$$ gauge field wave

A rough look at how a gravitational wave affects the FSL field



$$E_2 = \phi_2',$$
$$B_2 = g\phi_3\phi_1$$

$$E_1 = \phi_1',$$
$$B_1 = g\phi_2\phi_3$$

A gravitational wave:

stretches X = enhances E1, B2

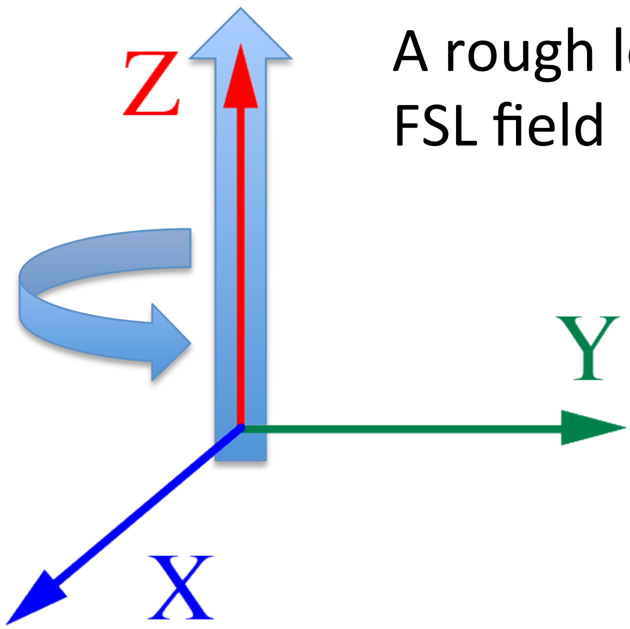
squeezes Y = diminishes B1, E2

E^2 energy is in phase with gravitational wave

B^2 energy is out of phase

suggest an effective mass: $m^2=B^2-E^2$

A rough look at transverse waves in the FSL field

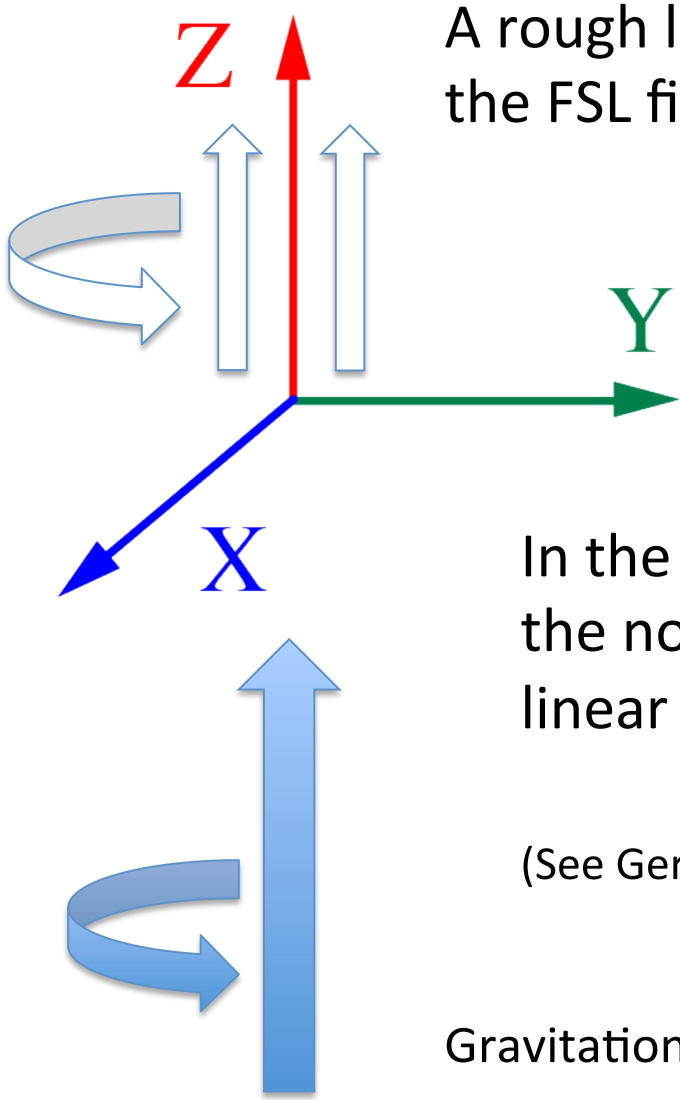


$$F^2_{13} = B_2 = g\phi_1\phi_3$$
$$\delta F^2_{13} = \delta B_2 - c_s^{-1}\delta E_1$$

$$F^1_{32} = B_1 = g\phi_3\phi_2$$
$$\delta F^1_{32} = \delta B_1 + c_s^{-1}\delta E_2$$

$$''\partial F = A \times F''$$

FSL wave introduces a (right) handedness
Enhanced by an instability in equation of motion



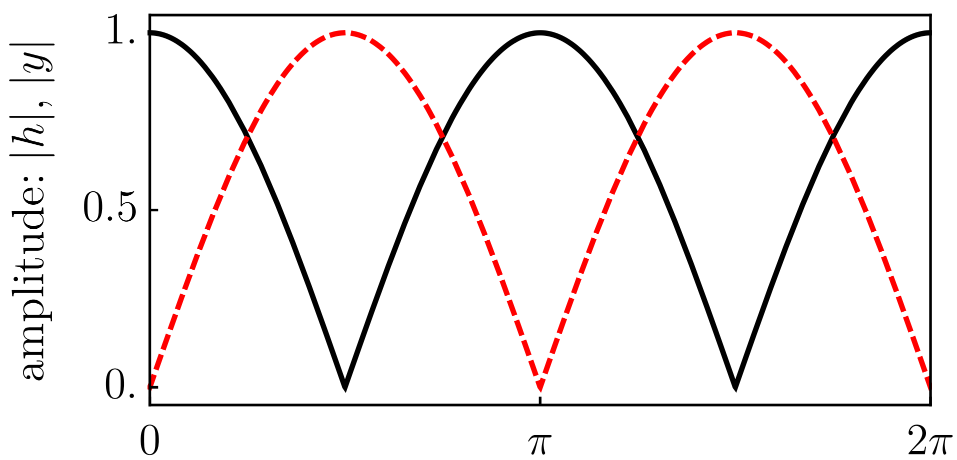
A rough look at high frequency waves in the FSL field

In the presence of the background FSL, the normal modes of propagation are linear combinations of h and δA

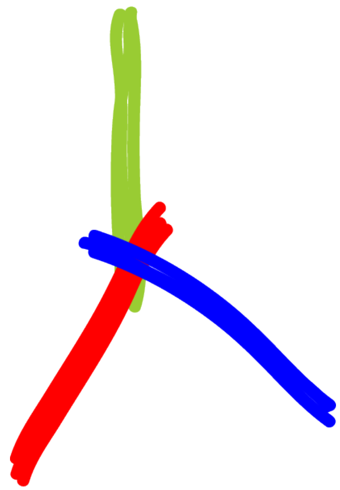
(See Gertsenshteyn 1961!)

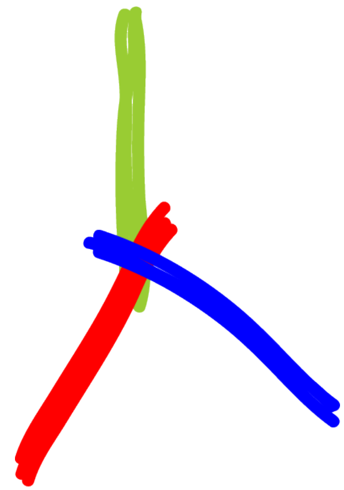
Gravitational and FSL waves propagate jointly

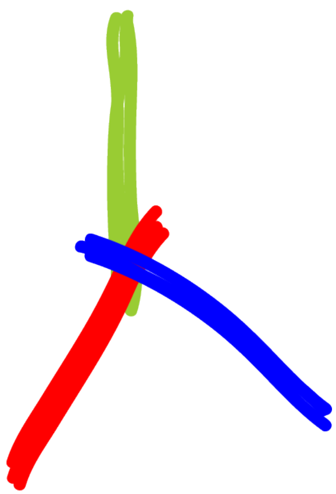
Gravitational Wave – Gauge Field Oscillations



$\mathcal{N} = 1$: gravitational wave, gauge field wave







Generalize to SU(N)

$\mathcal{N} \leq N/2$ disjoint SU(2) subgroups

or, direct product of $\mathcal{N}$ SU(2)'s

GW-GF Oscillations

$$\mathcal{L} = \tfrac{1}{2}H'^2 - \tfrac{1}{2}k^2H^2$$
$$+ \sum \tfrac{1}{2}Y_n'^2 - \tfrac{1}{2}k^2Y_n^2 + kg\phi Y_n^2 - \tfrac{2}{M_p}H(kg\phi^2 Y_n + \phi' Y_n')$$

$$\Psi = (H,\, Y_1,\, ...Y_{\mathcal{N}})$$
$$|\Psi|^2 = \text{constant}$$

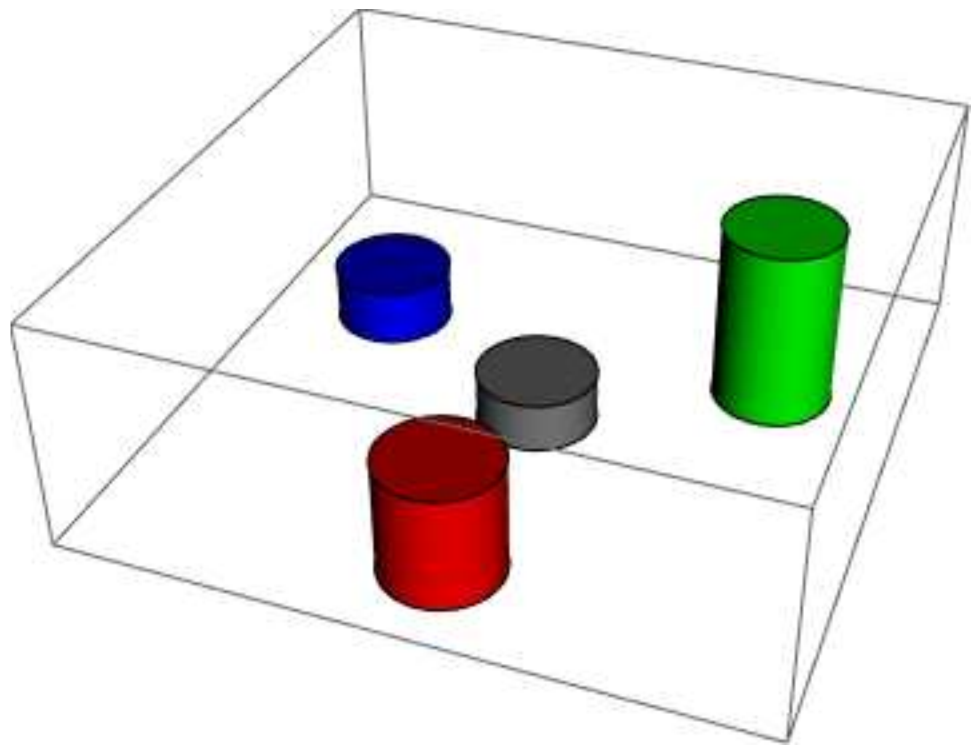
GW-GF oscillations

$$\Delta = (\Delta_0,\, \Delta_1,\, ...\Delta_{\mathcal{N}})$$
$$\propto e^{-i(k+\Omega)\tau}$$

normal modes

Devulder, Maksimova, RC 2016

GW-GF Oscillations



$\mathcal{N} = 3$: gravitational wave, gauge field wave

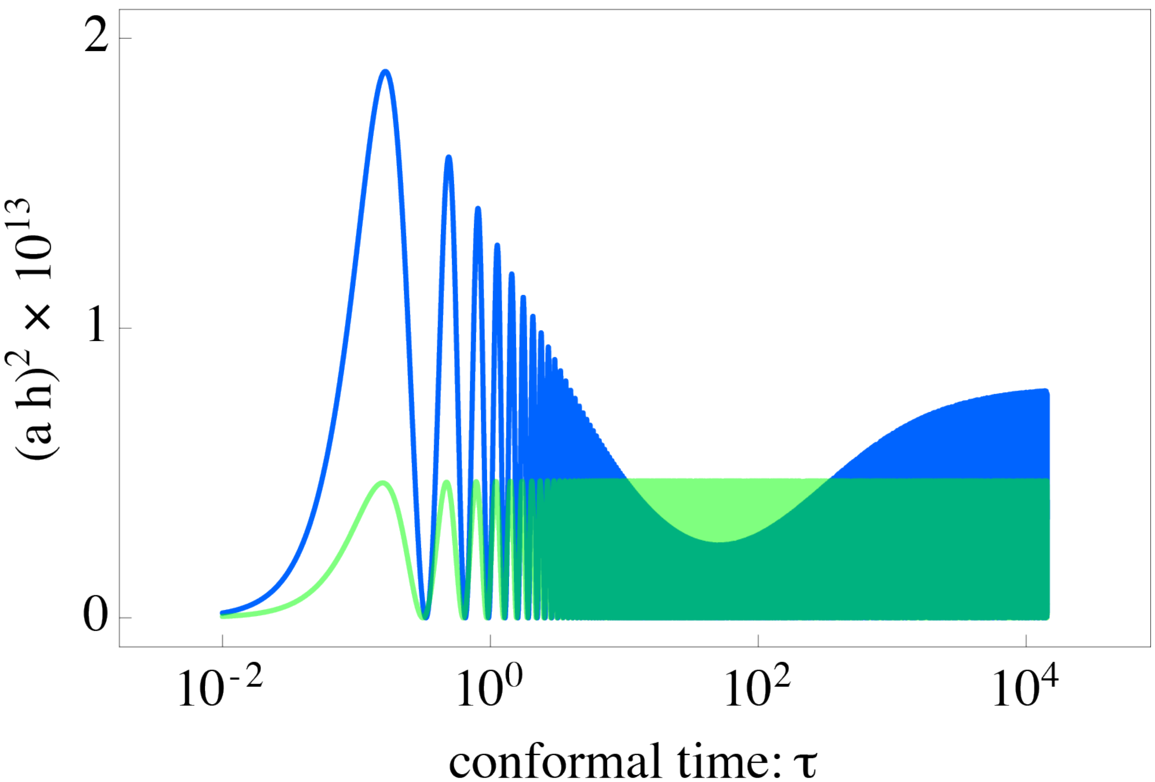
Scenario: Dark Radiation

- Dark Radiation

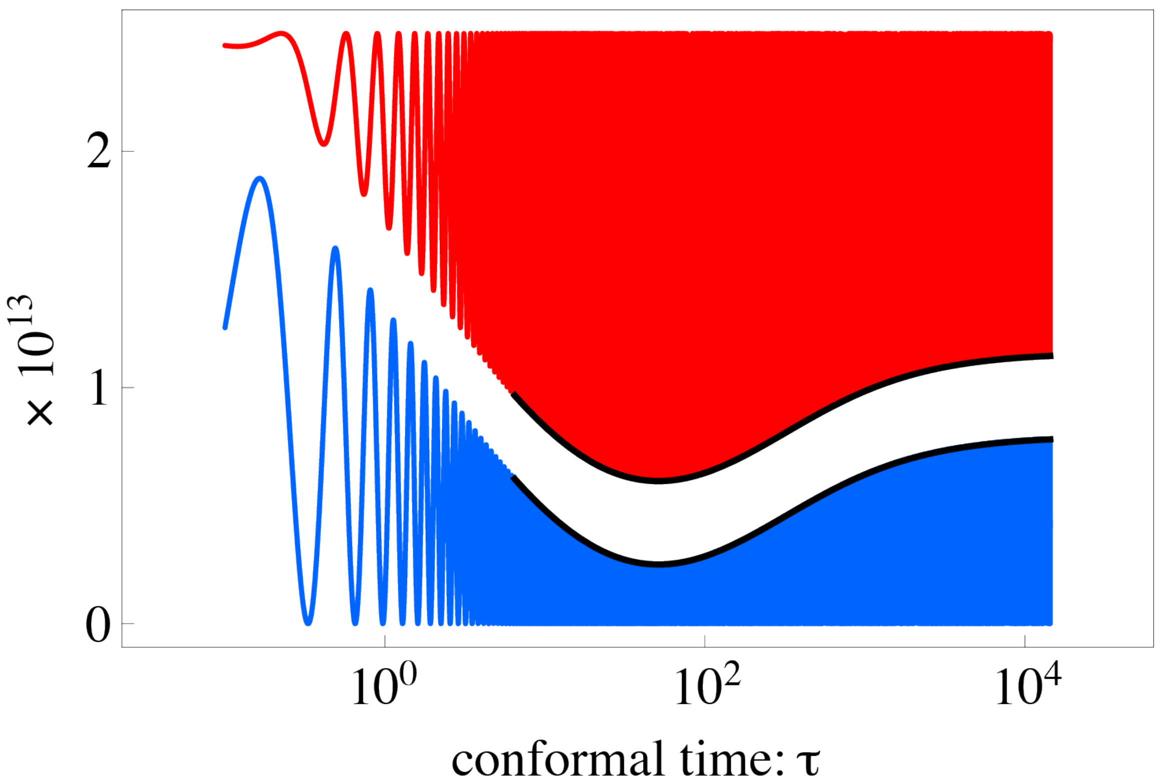
$$\mathcal{L} = \frac{1}{2} M_P^2 R - \frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu}$$

- Consider effect on primordial spectrum of gravitational waves
- Extreme parameter regime: $g = H_0/M_P$

Bielefeld & RC 2014, 5

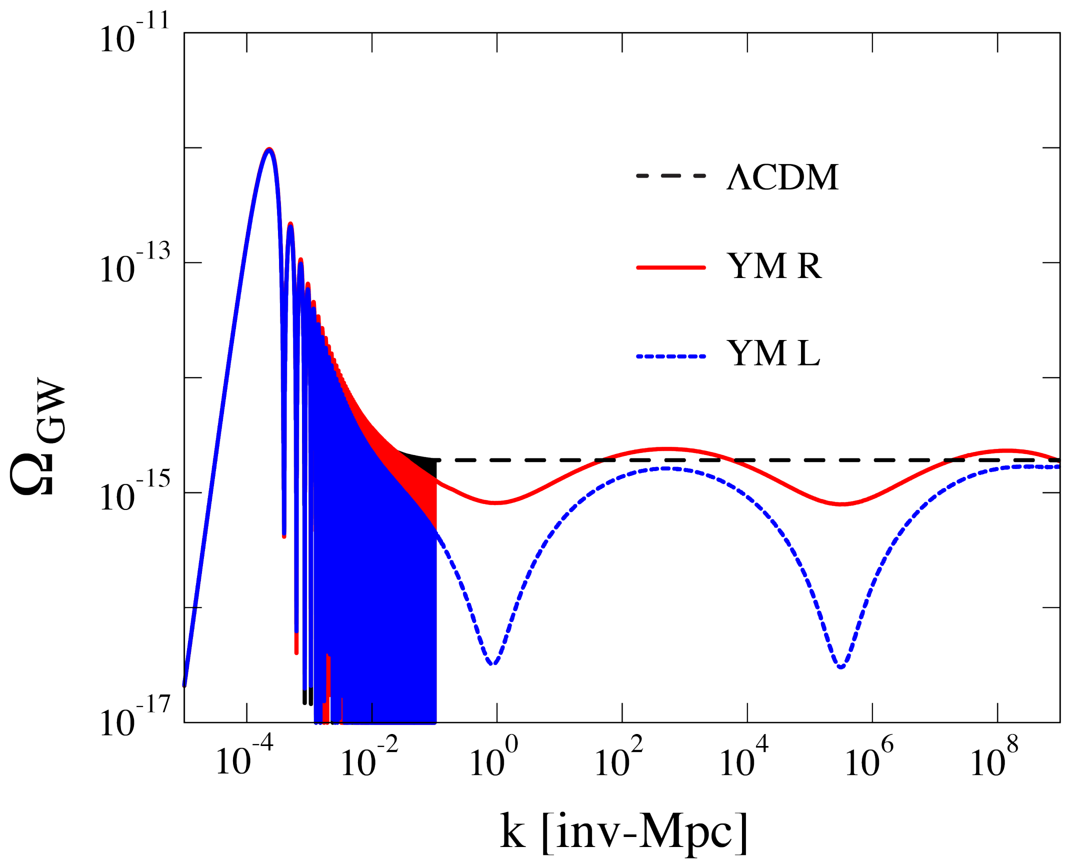


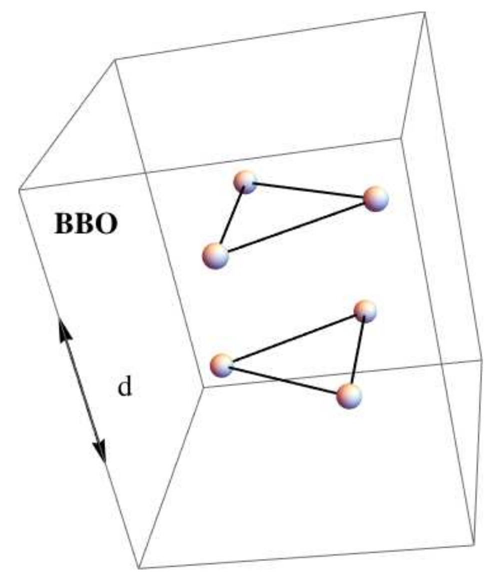
2
1
0
(a h)^2 × 10^{13}
10^{-2}
10^0
10^2
10^4
conformal time: τ



2
1
0
× 10^13
10^0
10^2
10^4
conformal time: τ

Gravitational Wave Spectrum





Seto 2006
Seto & Taruya 2007
Crowder et al 2013
Smith & RC 2016

Scenario: Dark Energy

- "Gauge Quintessence"

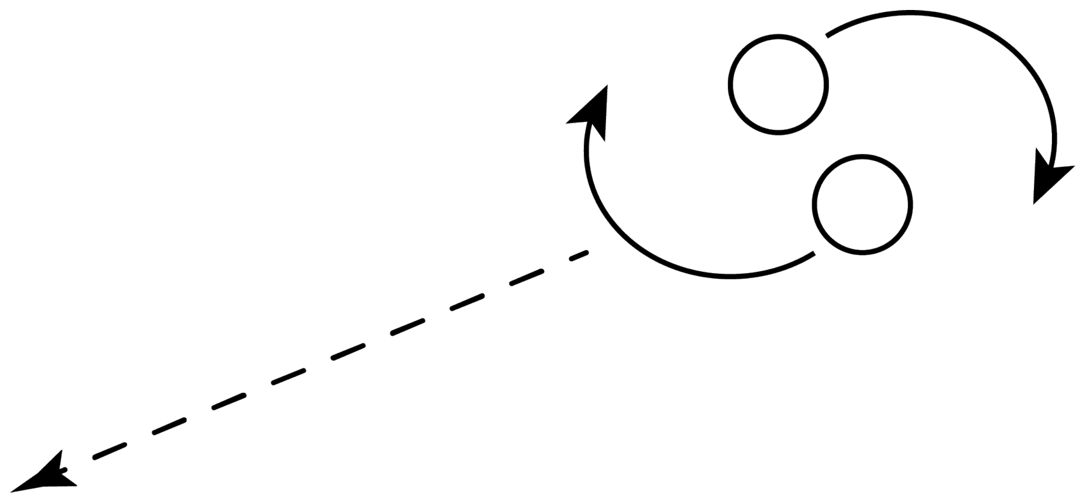
$$\mathcal{L} = \frac{1}{2}M_P^2 R - \frac{1}{2}(\partial\chi)^2 - V(\chi) - \frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} + \frac{\chi}{M}F^a_{\mu\nu}\widetilde{F}_a^{\mu\nu}$$

$$V = \mu^4(1-\cos\chi/f) \to \frac{1}{2}m^2\chi^2$$

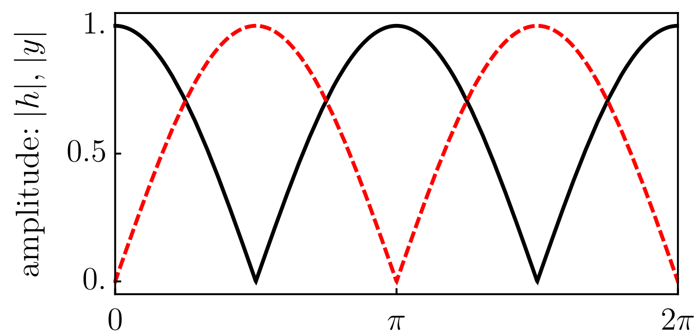
$$\mathcal{L} = \frac{1}{2}M_P^2 R - \frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} + \kappa(F^a_{\mu\nu}\widetilde{F}_a^{\mu\nu})^2$$

- Consider effect on primordial spectrum of gravitational waves
- Extreme parameter regime: $g = H_0/M_P$

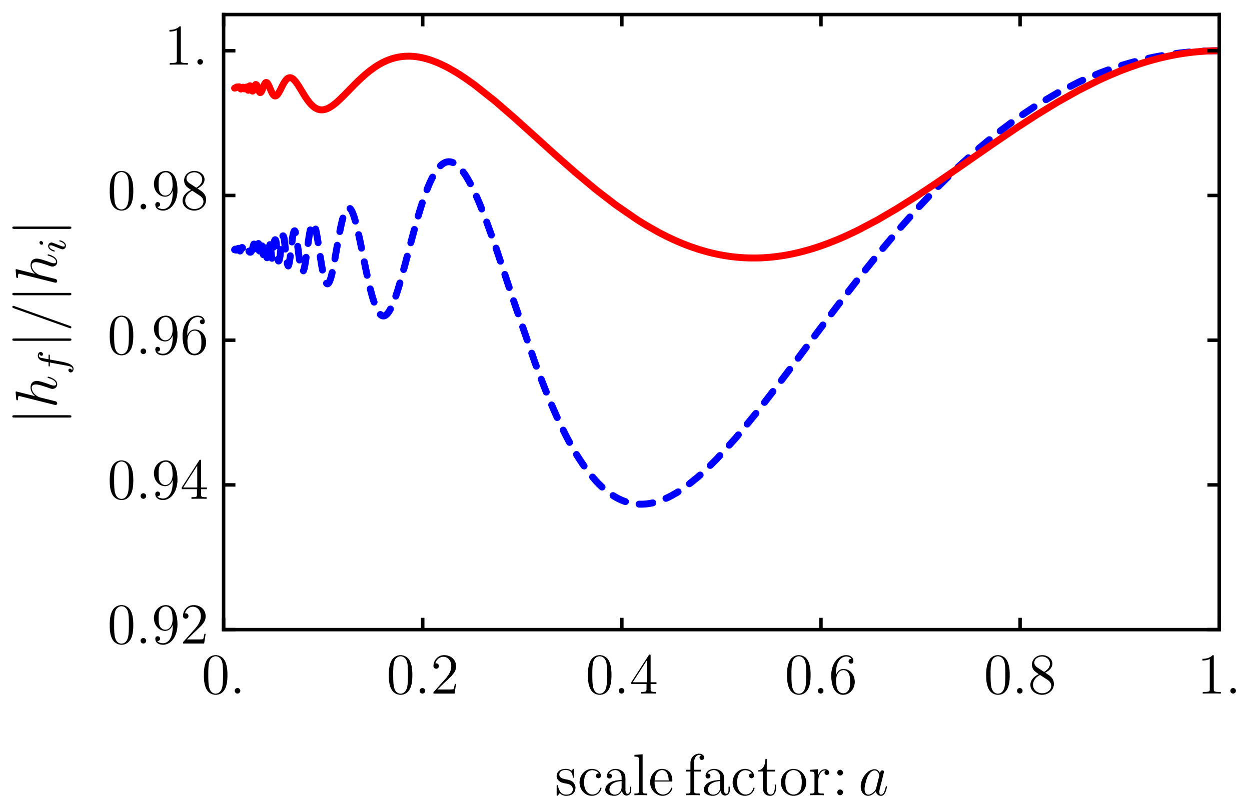
GW “Optical Depth”



A portion of high frequency GWs oscillate into GFs



GW “Optical Depth”



High frequency GWs oscillate into GF dark energy

Models of Inflation

Chromo-Natural Inflation, Gauge-Flation

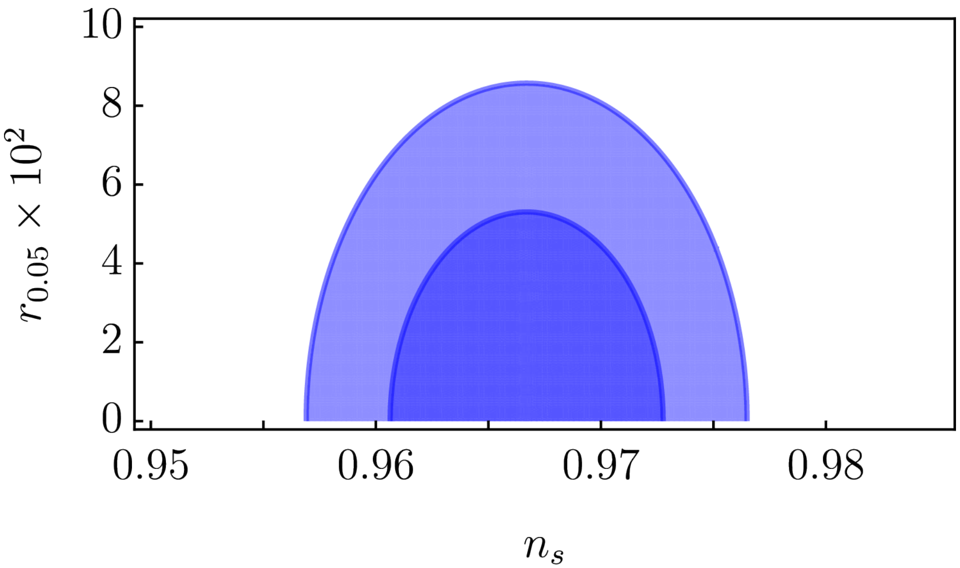
$$\mathcal{L} = \frac{1}{2}M_P^2 R - \frac{1}{2}(\partial\chi)^2 - V(\chi) - \frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} + \frac{\chi}{M}F^a_{\mu\nu}\widetilde{F}_a^{\mu\nu}$$

$$V = \mu^4(1 - \cos\chi/f) \rightarrow \frac{1}{2}m^2\chi^2$$

$$\mathcal{L} = \frac{1}{2}M_P^2 R - \frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} + \kappa(F^a_{\mu\nu}\widetilde{F}_a^{\mu\nu})^2$$

Adshead & Wyman 2012;
Maleknejad & Sheikh-Jabbari 2011;
Dimastrogiovanni & Peloso 2013

Models of Inflation



$n_s = 0.9667 \pm 0.0040\,(1\sigma)$ Planck 2016

$r < 0.07\,(95\%\,C.L.)$ BKP 2016

New: Toy Model of Inflation

$$\mathcal{L} = \frac{1}{2} M_P^2 R - \frac{1}{2}(\partial\chi)^2 - V(\chi) - \frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} + \frac{\chi}{M} F^a_{\mu\nu} \widetilde{F}_a^{\mu\nu}$$

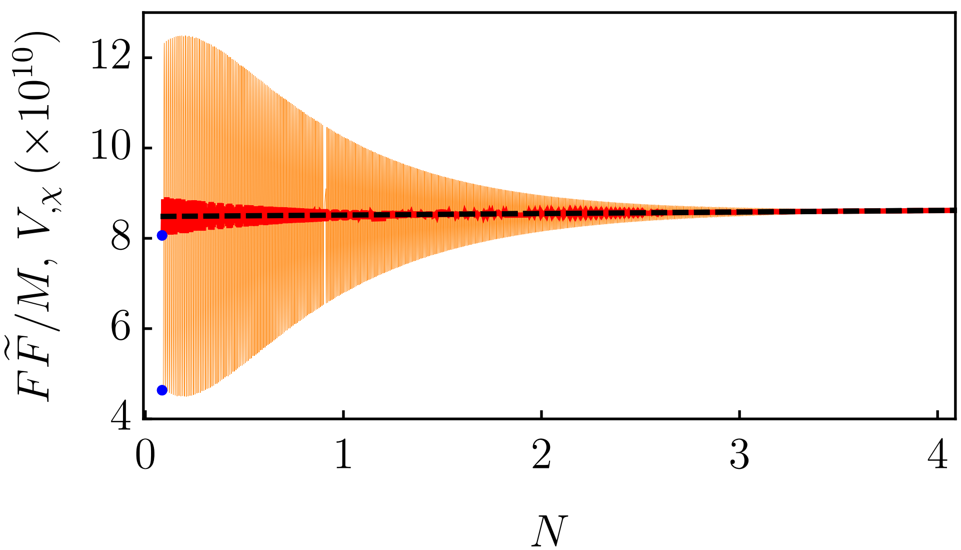
$$V = \frac{1}{n} m^4 (\chi/m)^n$$

Devulder & RC 2017

New: Toy Model of Inflation

V is too steep to inflate ($\varepsilon_V \gg 1$), but… $V_{\rm eff} = V - \frac{\chi}{M} F\widetilde{F}$

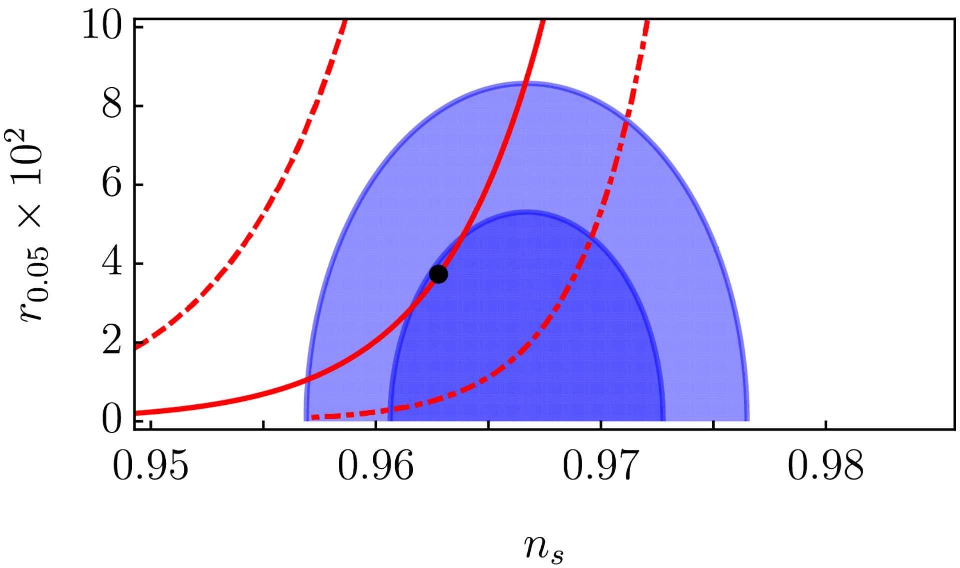
Accelerating Track: coupling flattens potential



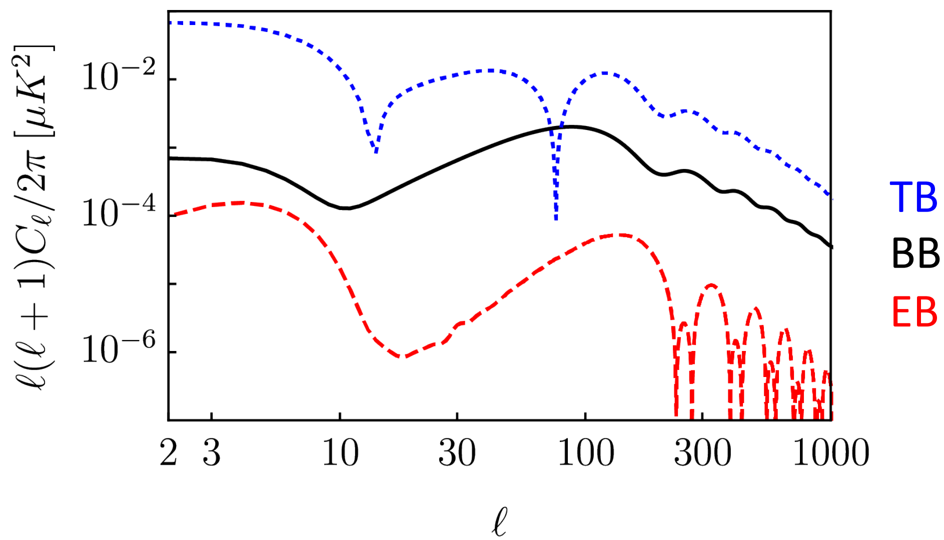
Parameters: n, m, M, g

Constraints: Δ_ζ^2, r(n_s)

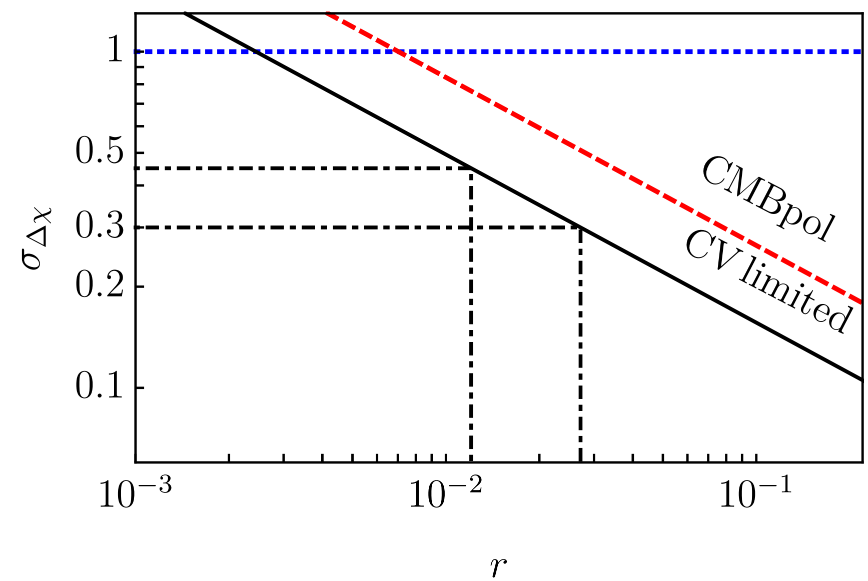
New: Toy Model of Inflation



Chiral Gravitational Waves

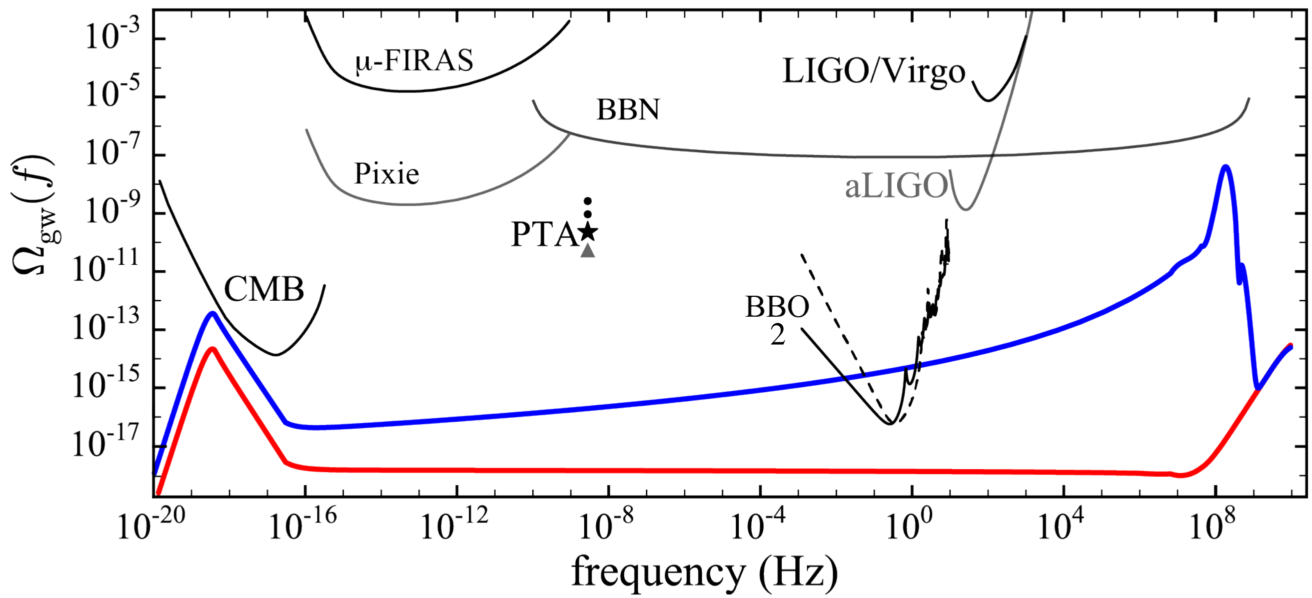


This model predicts
$\Delta\chi \simeq 0.9$



Gluscevic
& Kamionkowski 2010

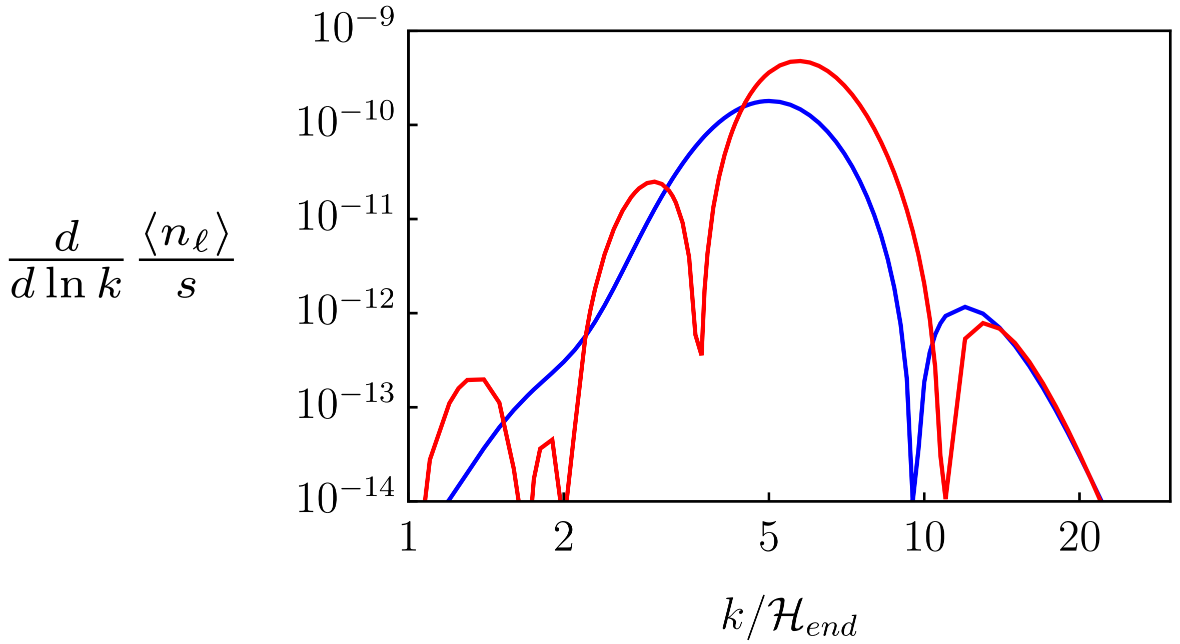
Chiral Gravitational Waves



Lasky et al 2016;
Smith & RC 2017;
Chluba et al 2014

Leptogenesis

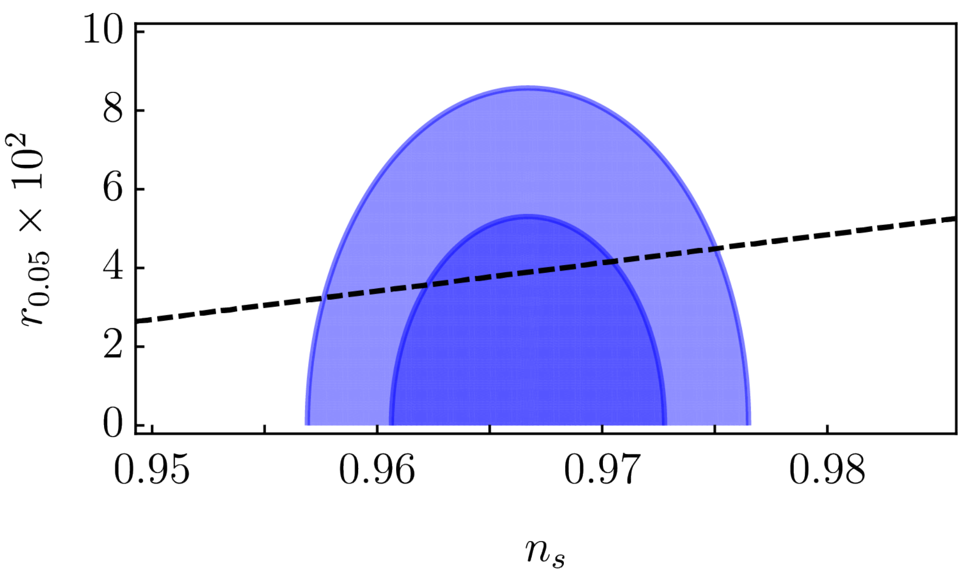
$$N_R - N_L = \frac{1}{24(16\pi^2)} \int d^4x \sqrt{-g} R\widetilde{R}$$



Eguchi, Gilkey, Hanson (1980)

Leptogenesis

$$\eta \equiv \frac{n_B}{n_\gamma}$$
$$\simeq \frac{1}{7} \times \frac{28}{79} \times \frac{\langle n_\ell \rangle}{s}$$

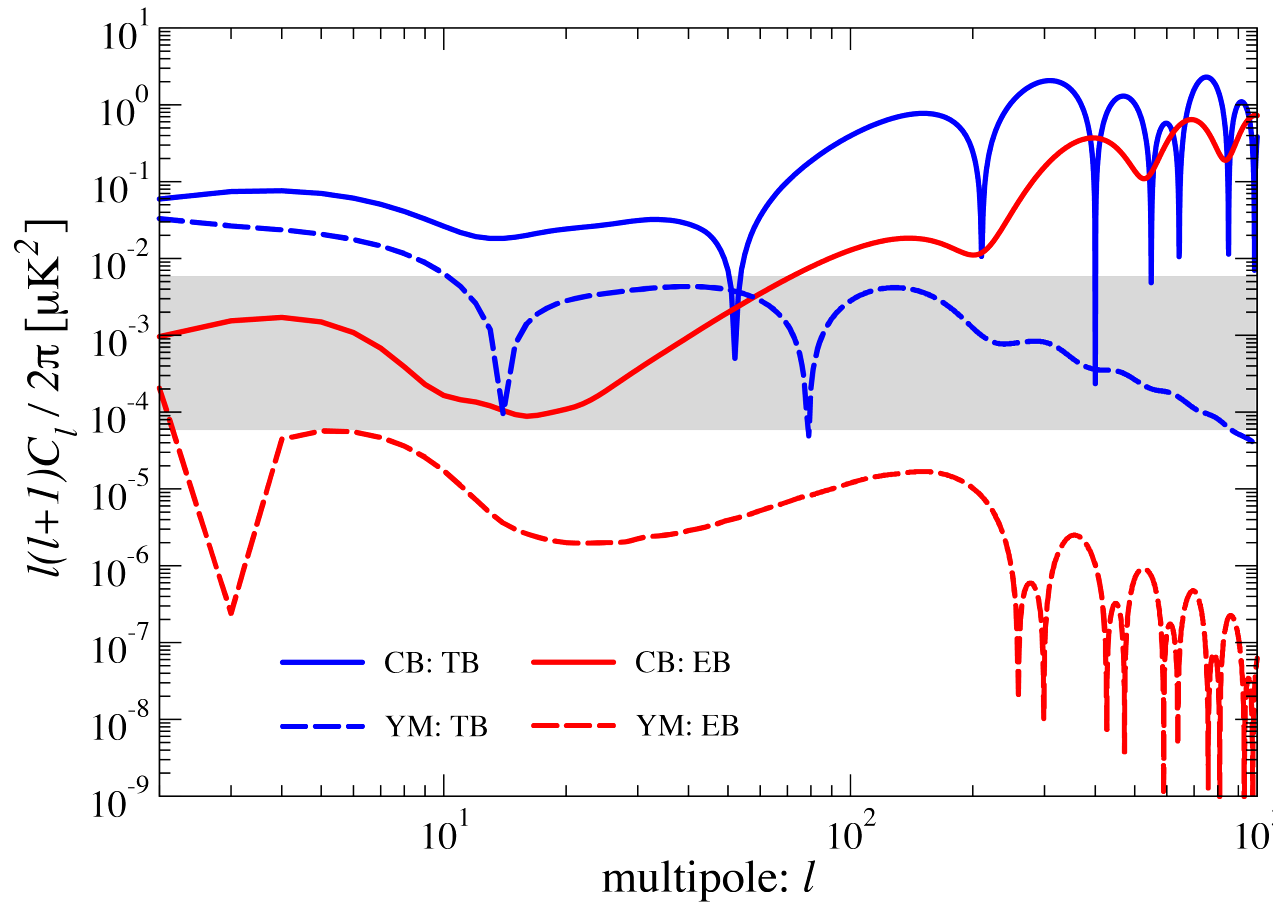


$$\eta \simeq 6.1(\pm 0.04) \times 10^{-10}$$

Planck 2016

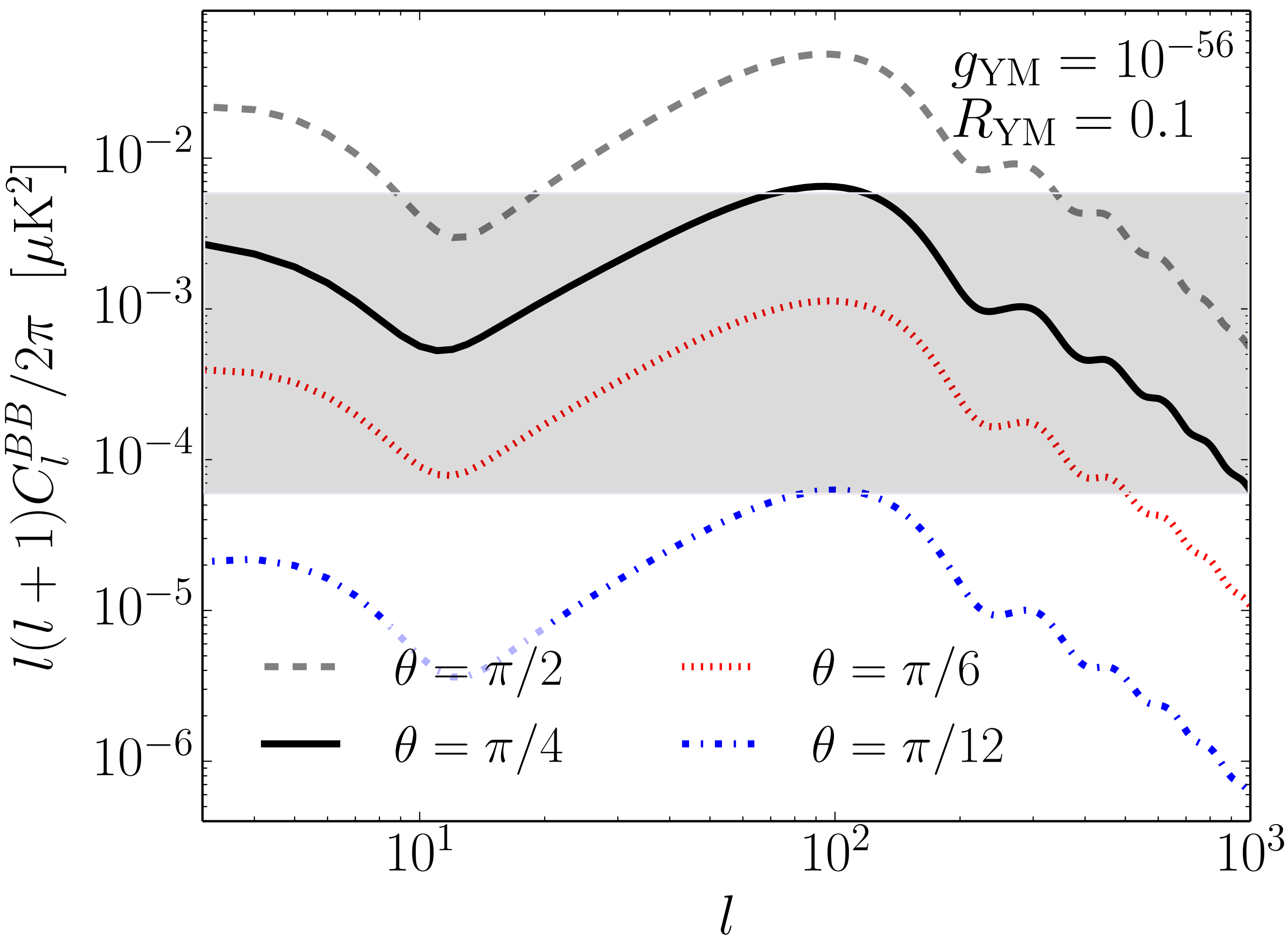

Axion-Gauge Field Inflation
Viable scalar, tensor spectra
Unique imprint: chiral asymmetric SGWB
Leptogenesis: lower bound for B modes

CMB Signature*



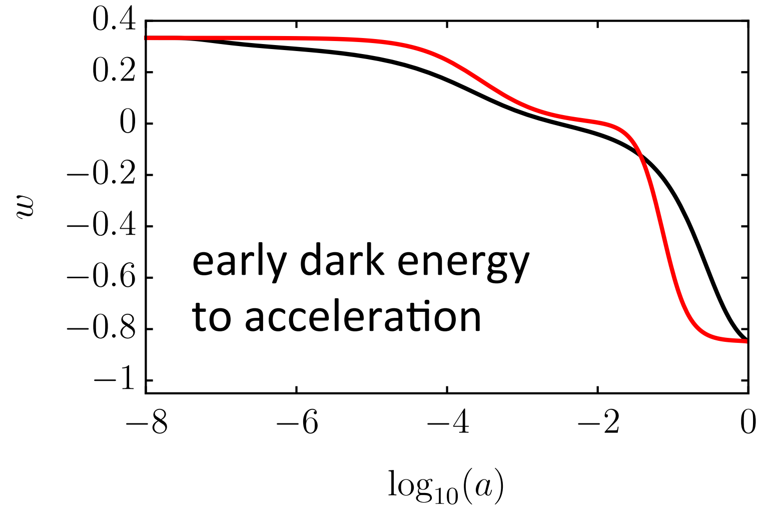
* $10^{-3}<r<10^{-1}$, absolute polarization calibration below 1°

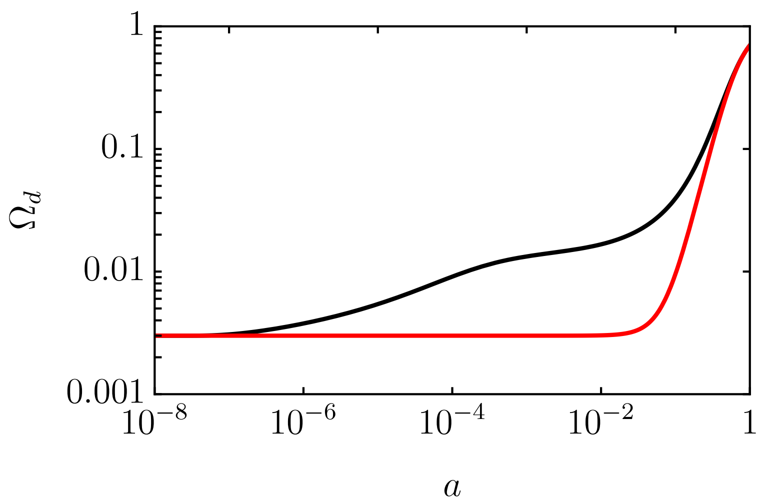
CMB Signature*



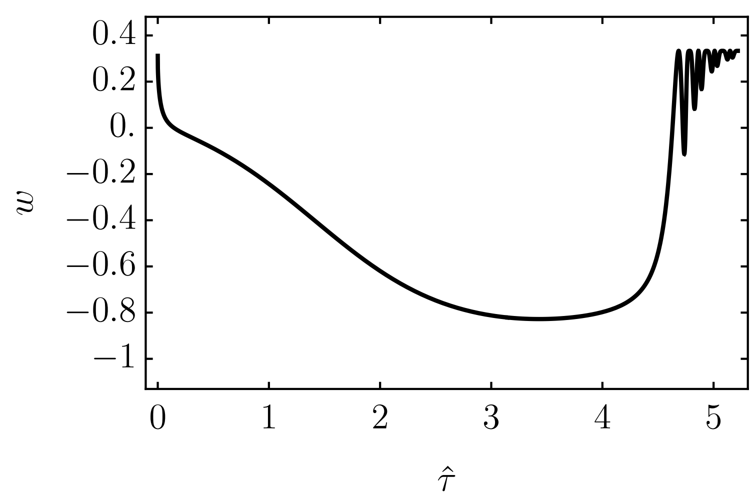
* Amplify, Suppress, or Modulate the B-mode spectrum

Gauge Quintessence evolution: compare to standard EDE



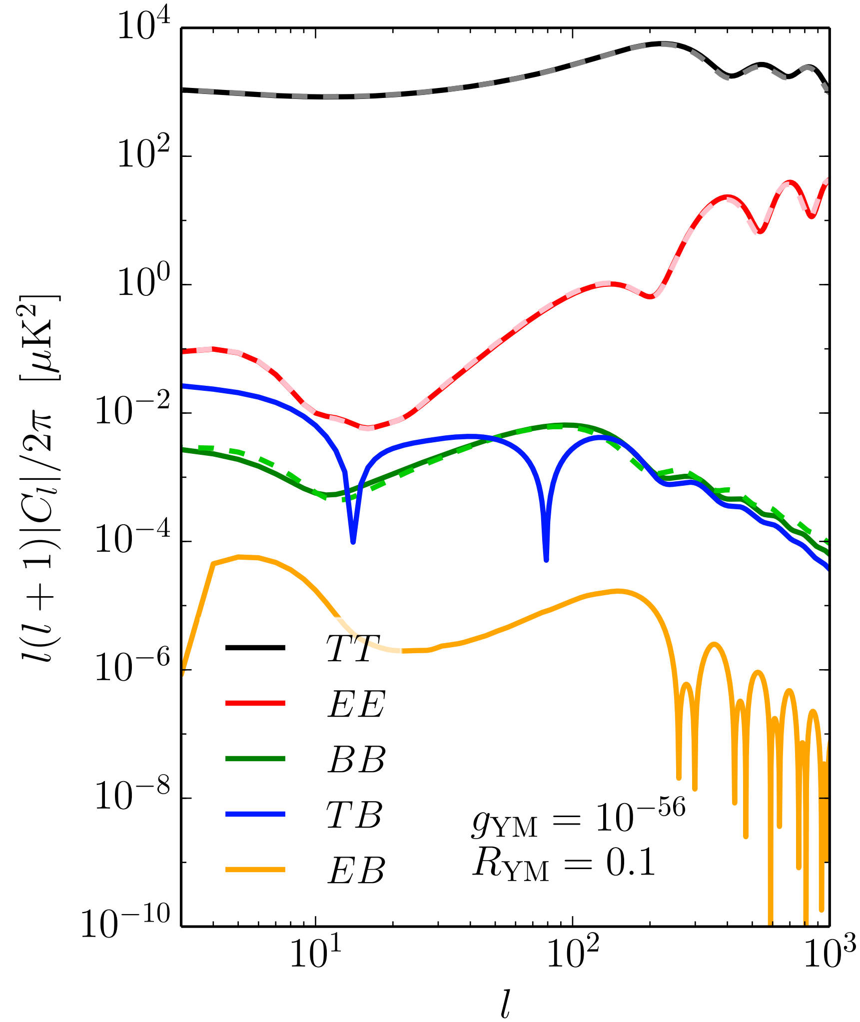


CMB-era growth



past, future radiation

CMB Spectrum



Gravitational Birefringence

A polarization sensitive medium
for gravitational waves

J Bielefeld & RC 2015