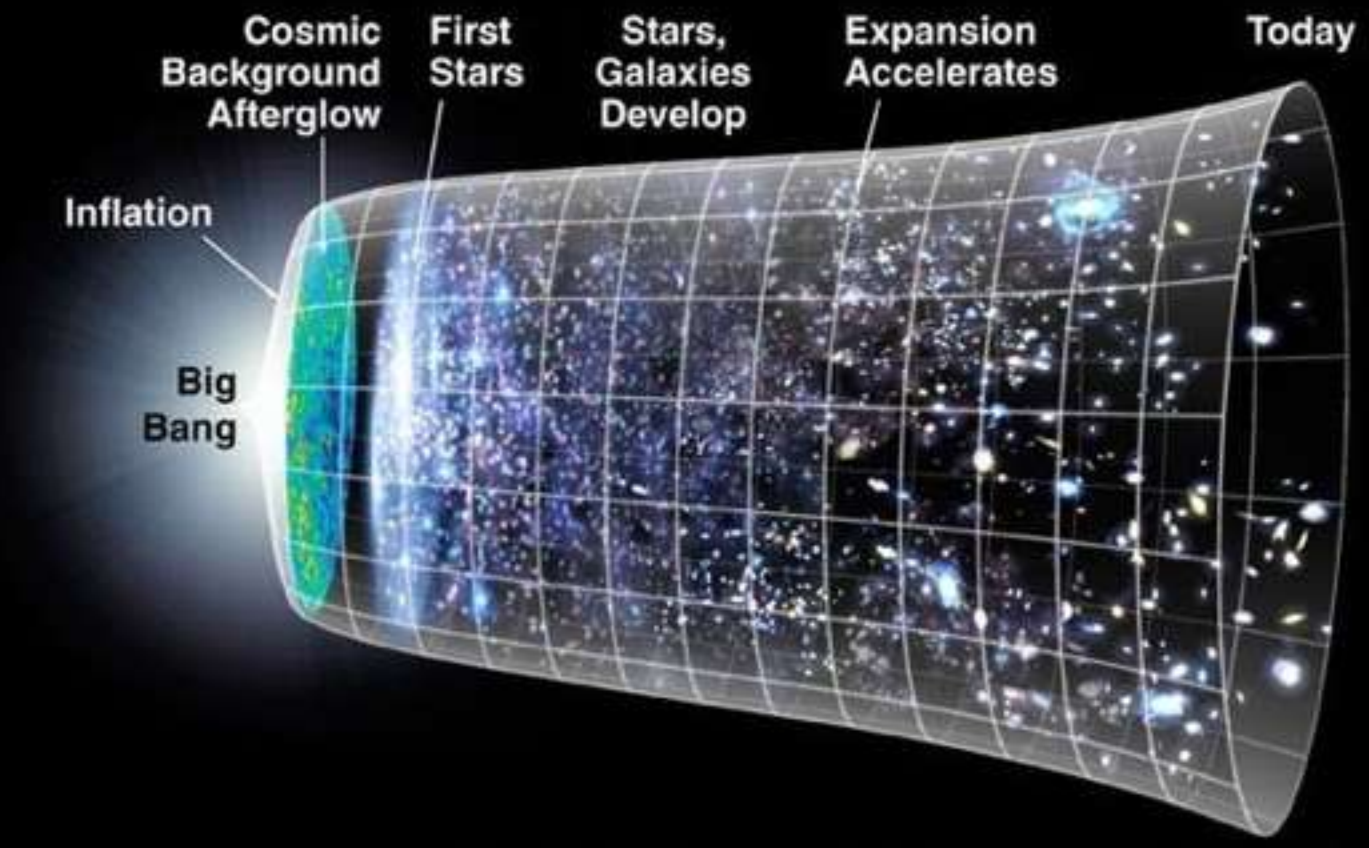
# Probing the Early Universe with Gravitational Waves



Matteo R. Fasiello
IFT Madrid

"Dawn of GW Cosmology and Theory of Gravity" Workshop
Tohoku, Japan, March 2nd 2022

# Inflation

- Inflation, the idea
- Single-field slow-roll scenario: successes and signatures
- The importance of upcoming GW observations
- Beyond the minimal scenario: axion inflation as a case study
- The “cosmological collider”
- Fossil fields ⏱
- EFT approach ⏱
- Conclusions

# Inflation, the minimal paradigm, SFSR

Simplest realization: single-scalar field in slow-roll

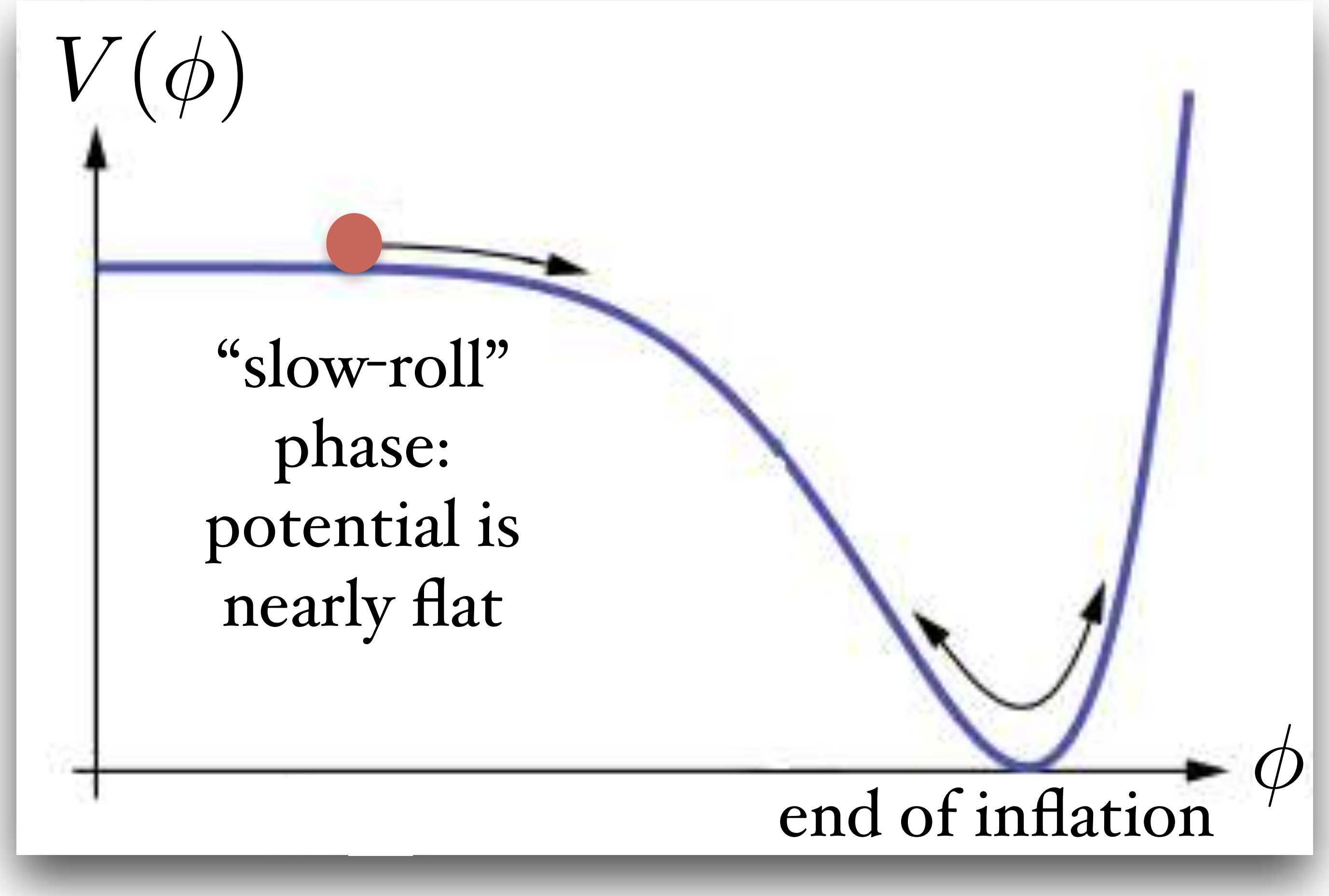
- Scalar field :

$$p_\phi = \frac{\dot{\phi}^2}{2} - V(\phi) \approx -V(\phi)$$

$$\rho_\phi = \frac{\dot{\phi}^2}{2} + V(\phi) \approx V(\phi)$$

$$\dot{\phi}^2 \ll V$$

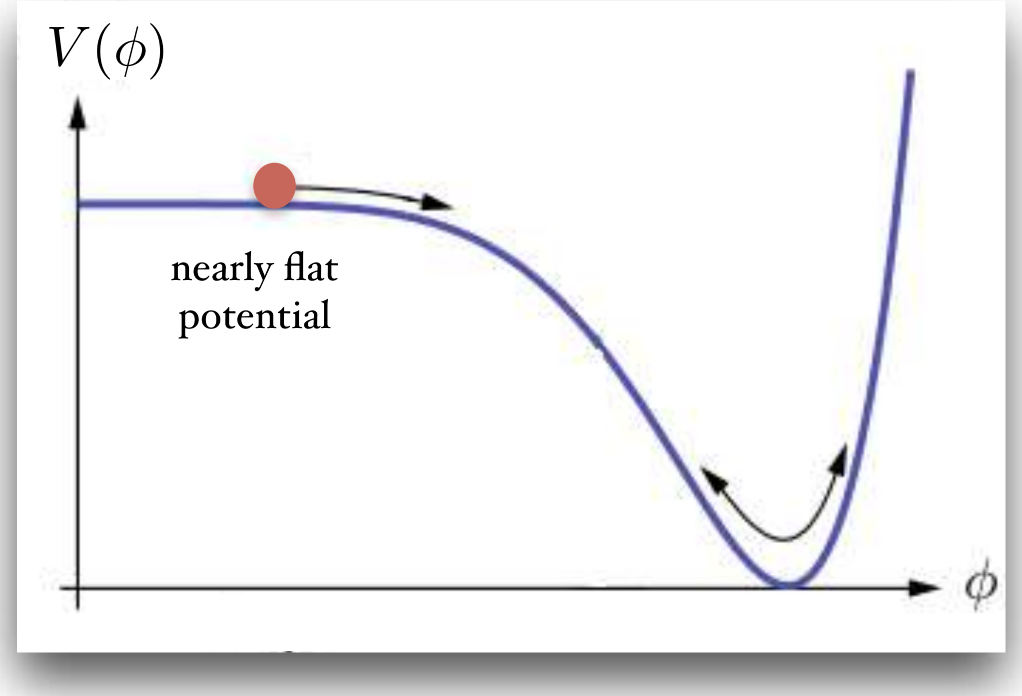
$$p_\phi \approx -\rho_\phi$$



# Slow-roll

**start flat**

$$\epsilon \equiv -\frac{\dot{H}}{H^2} \simeq \frac{M_{\mathrm{P}}^2}{2}\left(\frac{V^{'}}{V}\right)^2 \simeq \frac{3}{2}\frac{\dot{\phi}^2}{V} \ll 1$$



**stay flat**

$$|\eta| \equiv \frac{|\dot{\epsilon}|}{H\epsilon} \simeq -\frac{2}{3}\left(\frac{V^{''}}{H^2}\right) + 4\epsilon \ll 1$$

# Metric Fluctuations

$$ds^2 = (-dt^2 + a(t)^2[\underbrace{e^{2\zeta}}_{\text{scalar fluctuations}}\delta_{ij} + \underbrace{\gamma_{ij}}_{\text{tensor perturbations}}]dx^i dx^j)$$

# Primordial power spectra

(minimal scenario)

## scalar fluctuations

$$\mathcal{P}_\zeta(k) = \frac{1}{8\pi^2}\frac{1}{\epsilon}\frac{H^2}{M_{\rm pl}^2}\left(\frac{k}{k_*}\right)^{n_s-1}$$

$0.9649 \pm 0.0042$

$2.2 \times 10^{-9}$

$[k_* = 0.05\,\mathrm{Mpc}^{-1}, 68\%\mathrm{C.L.}]$

from Planck measurements
of CMB anisotropies

$$\boxed{n_s - 1 \simeq -2\epsilon - \eta}$$

# Primordial power spectra

(vacuum fluctuations)

## tensor fluctuations

energy scale of inflation

**red** tilt

$n_T \simeq -2\epsilon \simeq -r/8$

$$\mathcal{P}_\gamma^{\mathrm{vacuum}}(k) = \frac{2}{\pi^2}\frac{H^2}{M_{\mathrm{pl}}^2}\left(\frac{k}{k_*}\right)^{n_T}$$

$$r \equiv \frac{\mathcal{P}_\gamma}{\mathcal{P}_\zeta}$$

tensor-to-scalar ratio

bounds

current

~~$r < 0.056$ (95%CL, Planck$^+$)~~

$r < 0.035$ (BK$^+$)

future

$r < 0.01$ (CMB–S3)

$r < 0.001$ (CMB–S4)

also LiteBIRD!

# Crossing Qualitative Thresholds

agnostic/naive

$$n_s - 1 \simeq -2\epsilon - \eta$$

$\epsilon \sim \eta$ ==> $\boxed{r \gtrsim 10^{-2}}$

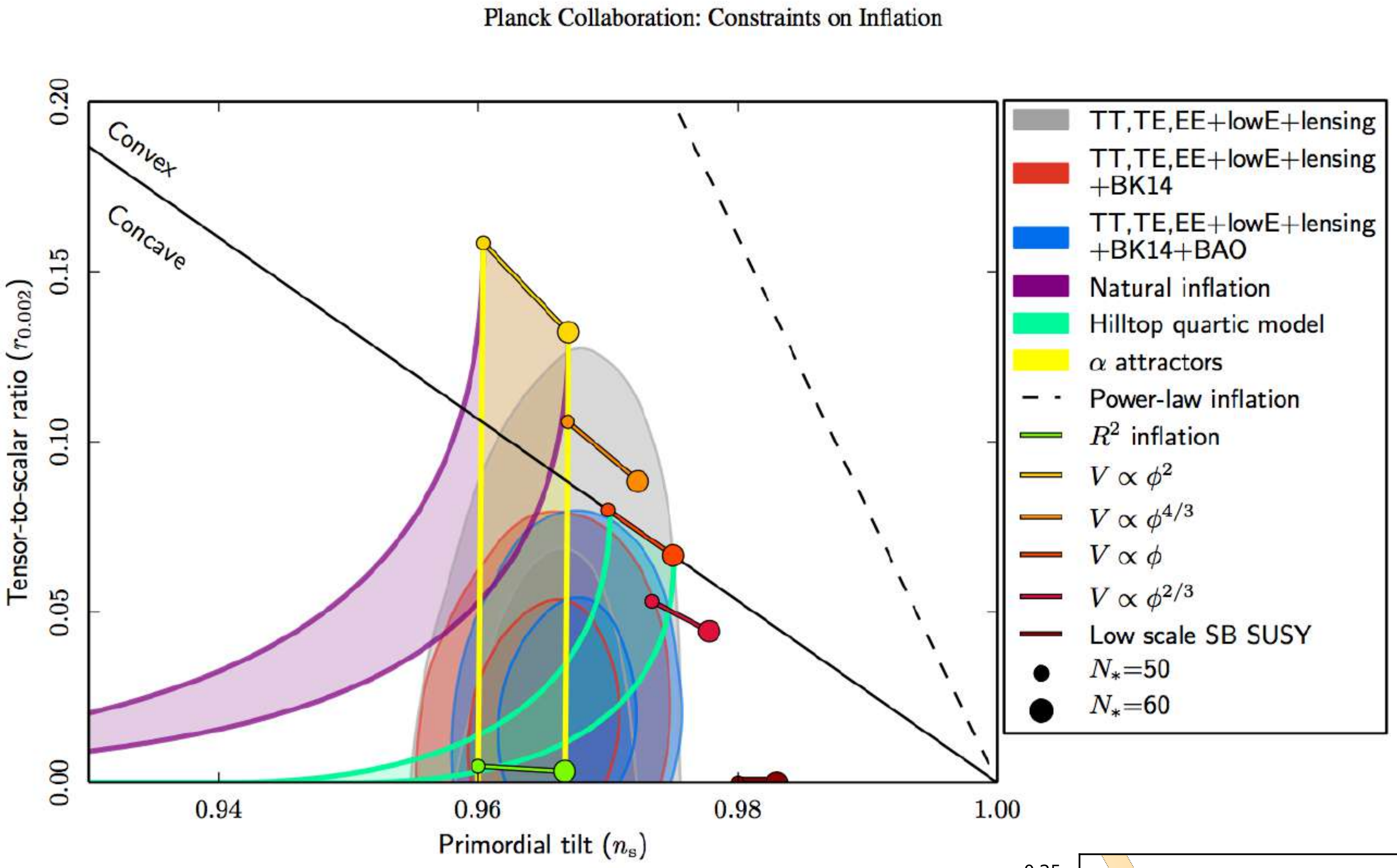
compelling
models
e.g. Starobinsky

$$1 - n_s \simeq \frac{2}{N} \quad , \quad r \simeq \frac{12}{N^2}$$

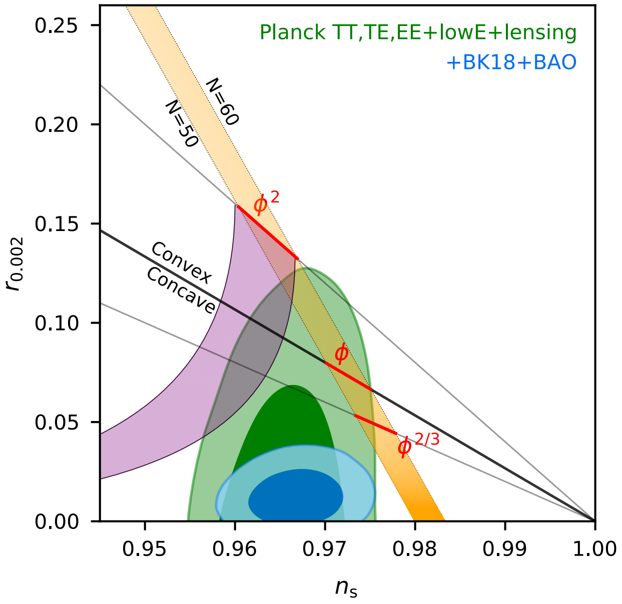
==>

$$\boxed{r \gtrsim 10^{-3}}$$

# Single-field Inflation is doing well



+BK update:



# Why go beyond the single-field scenario?

## interpreting observations

what to infer from GW detection?
e.g. r <—> H relation

## likely

string theory
|
flux compactifications
|
4D EFT with many moduli fields

## interesting

signatures of new content
on GW spectrum:
PS: scale-dependence, chirality,
n-G: (amplitude, shape, angular..)

# Focus

**1 (class of) model(s):** axion inflation

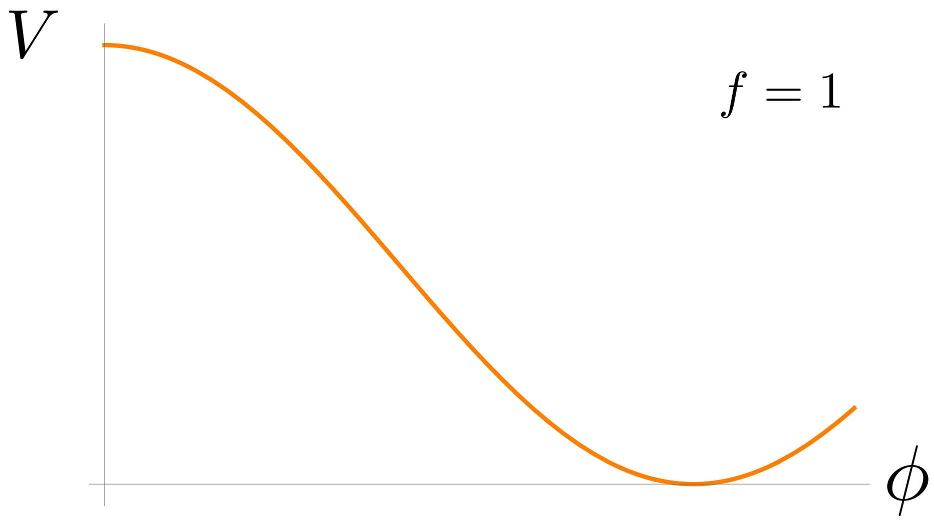
**1 probe:** primordial gravitational waves

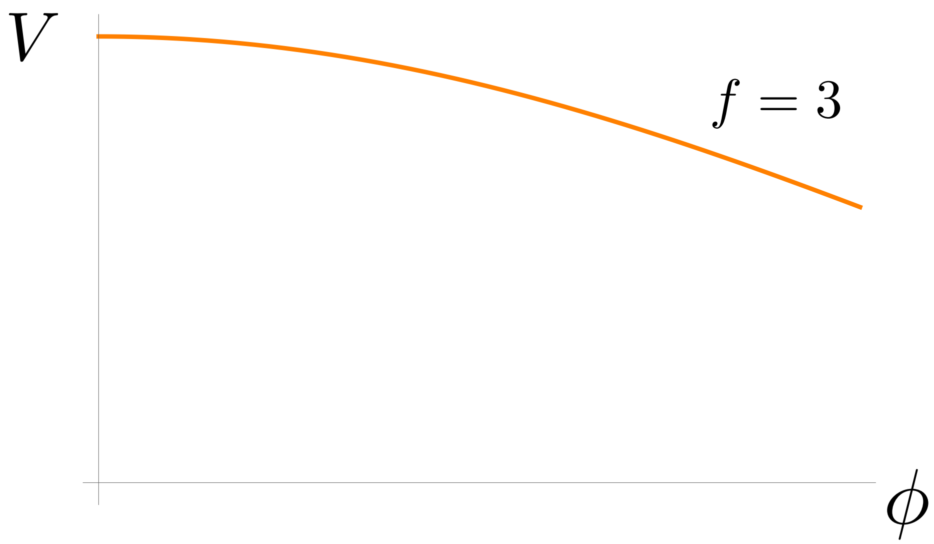
# Natural Inflation

$$\mathcal{L} = \sqrt{-g}\Big[R[g] - (\partial\phi)^2 - \mu^4\,(1 + \mathrm{Cos}[\phi/f])\Big]$$

{Freese, Frieman, Olinto}

axion-like potential





◆

- simple
- (technically) natural: shift symmetry
- viable for $f \gtrsim M_{\mathrm{P}}$

# Chromo Natural Inflation

[Adshead, Wyman]
[Dimastrogiovanni, **MF**, Tolley]
[...]

$$\mathcal{L} \supset -\frac{1}{4}F^2 + \frac{\lambda\phi}{4f}F\tilde{F} - (\partial\phi)^2 - U_{\rm axion}(\phi)$$

[Freese, Frieman, Olinto]
[...]

◆

- $f \ll M_{\rm P}$ realization
- very interesting GW signatures !

# Chromo Natural Inflation

SU(2) but could be U(1)

[Adshead, Wyman]
[Dimastrogiovanni, **MF**, Tolley]
[...]

$$\mathcal{L} \supset -\frac{1}{4}F^2 + \frac{\lambda\phi}{4f}F\tilde{F} - (\partial\phi)^2 - U_{\text{axion}}(\phi)$$

[Freese, Frieman, Olinto]
[...]

◆

$$\begin{cases} f \ll M_{\text{P}} \quad \text{realization} \\ \\ \text{very interesting GW signatures !} \end{cases}$$

# Extension of Chromo Natural Inflation

[Dimastrogiovanni, **MF**, Fujita]

$$\mathcal{L} \supset \mathcal{L}_{\text{inflaton}} - \frac{1}{4}F^2 + \frac{\lambda\chi}{4f}F\tilde{F} - (\partial\chi)^2 - U_{\text{axion}}(\chi)$$

◆

- $f \ll M_{\text{P}}$ realization
- same interesting GW spectrum
- observationally viable

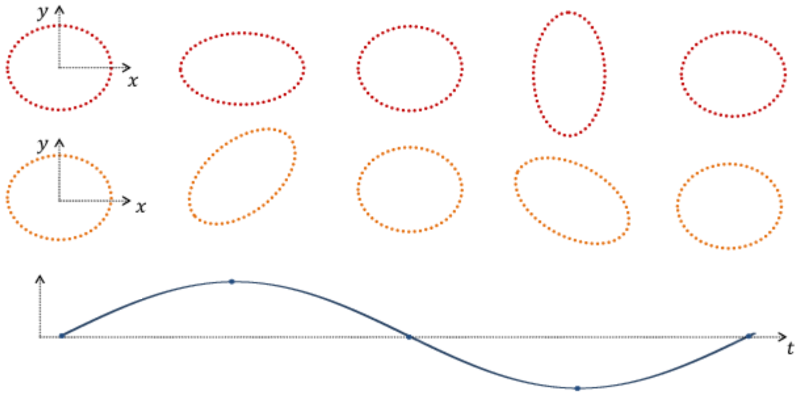
# (Primordial) Gravitational Waves

$$G_{\mu\nu} = 8\pi G \, T_{\mu\nu}$$

$$ds^2 = -dt^2 + a^2(t) \left(\delta_{ij} + \gamma_{ij}\right) dx^i dx^j$$

$$\gamma^i_i = \partial_i \gamma_{ij} = 0$$

**two polarization states**



$$\ddot{\gamma}_{ij} + 3H\dot{\gamma}_{ij} + k^2\gamma_{ij} = 16\pi G \, \Pi^{TT}_{ij}$$

anisotropic stress-energy tensor

# Primordial GW in our Model

$$\mathcal{L} \supset \mathcal{L}_{\text{inflaton}} - \frac{1}{4}F^2 + \frac{\lambda\chi}{4f}F\tilde{F} - (\partial\chi)^2 - U_{\text{axion}}(\chi)$$

$$\text{SU(2)} \begin{cases} A_0^a = 0 \\ A_i^a = aQ\delta_i^a \\ \delta A_i^a = t_{ai} + \ldots \end{cases}$$

$$\ddot{\gamma}_{ij}^{\lambda} + 3H\gamma_{ij}^{\lambda} + k^2\gamma_{ij}^{\lambda} \propto t_{ij}^{\lambda} + \cdots + \ldots$$

[Dimastrogiovanni, **MF**, Fujita]

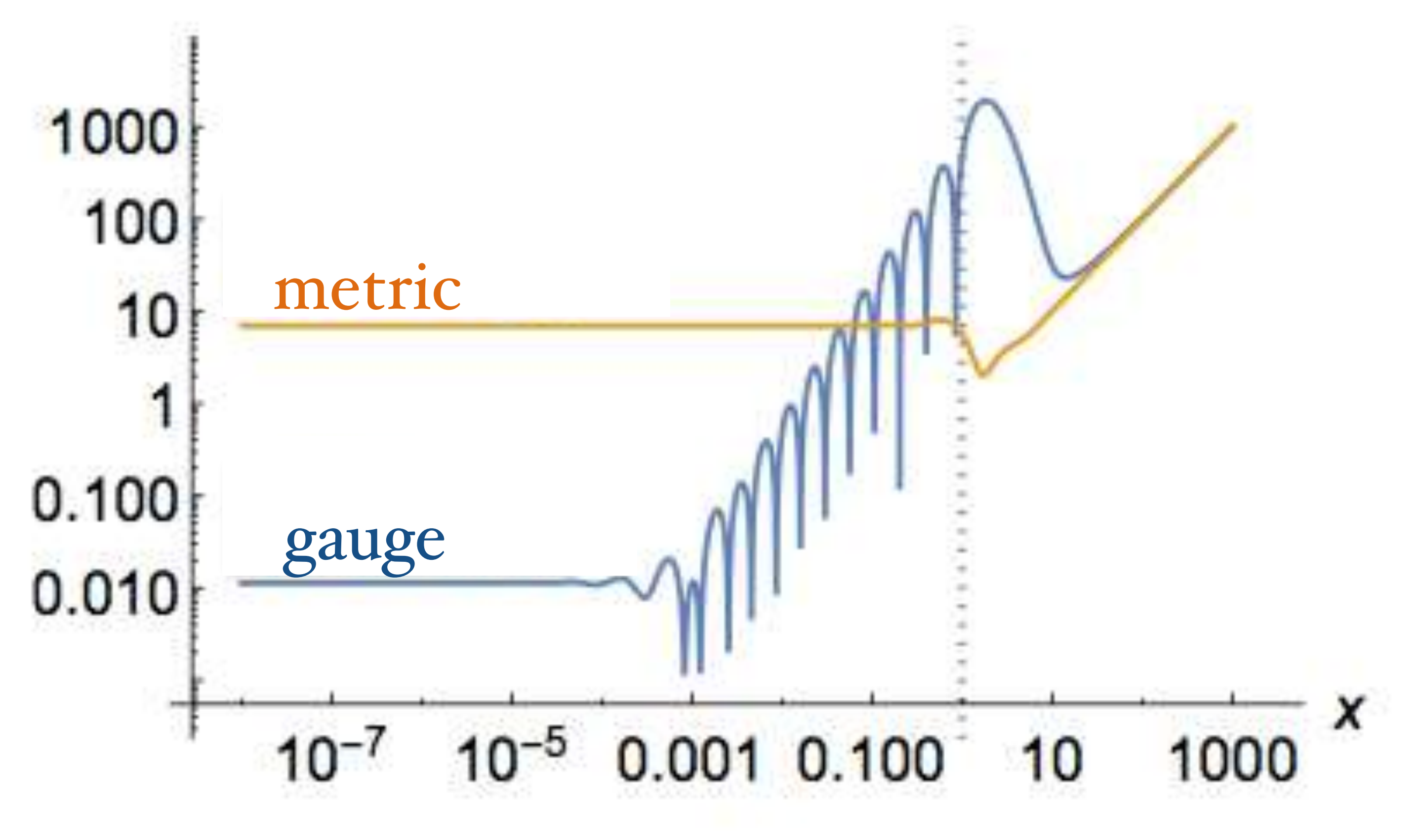
$$P_{\lambda}^{\text{sourced}} \gtrsim P_{\lambda}^{\text{vacuum}}$$

now possible!

$$\begin{array}{l} \textbf{metric} \\[4em] \textbf{gauge} \end{array} \left\{ \begin{array}{l} \Psi''_{R,L} + \left(1 - \frac{2}{x^2}\right) \Psi_{R,L} = \mathcal{O}^{(1)}(t_{R,L}) \\[4em] t''_{R,L} + \left[1 + \frac{2m_Q\xi}{x^2} \mp \frac{2}{x}\left(m_Q + \xi\right)\right] t_{R,L} = \tilde{\mathcal{O}}^{(1)}(\Psi_{R,L}) \end{array} \right.$$

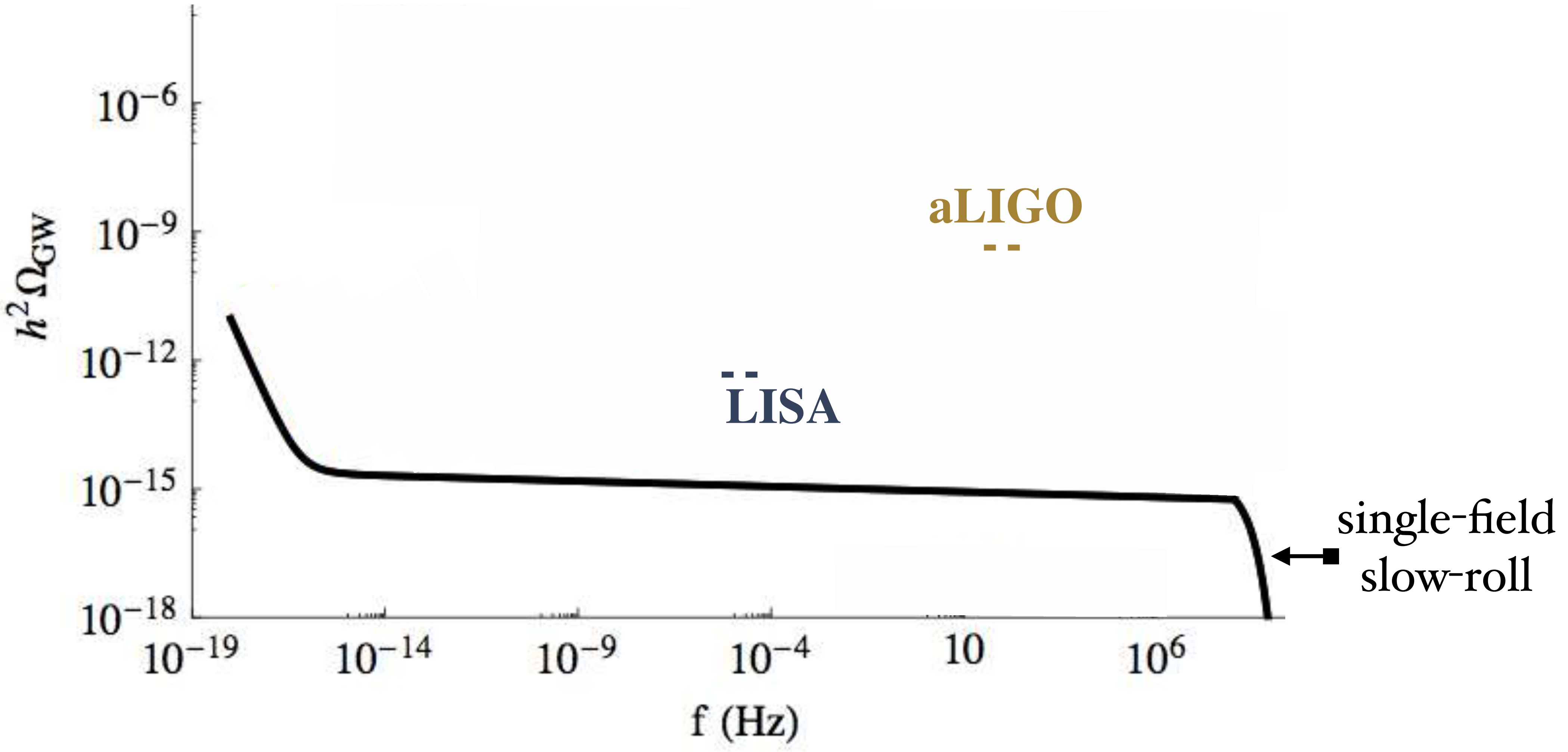
$$\xi = \frac{\lambda\dot{\chi}}{2fH}$$

$$x \sim -k\tau$$



Dimastrogiovanni, MF, Fujita 2016

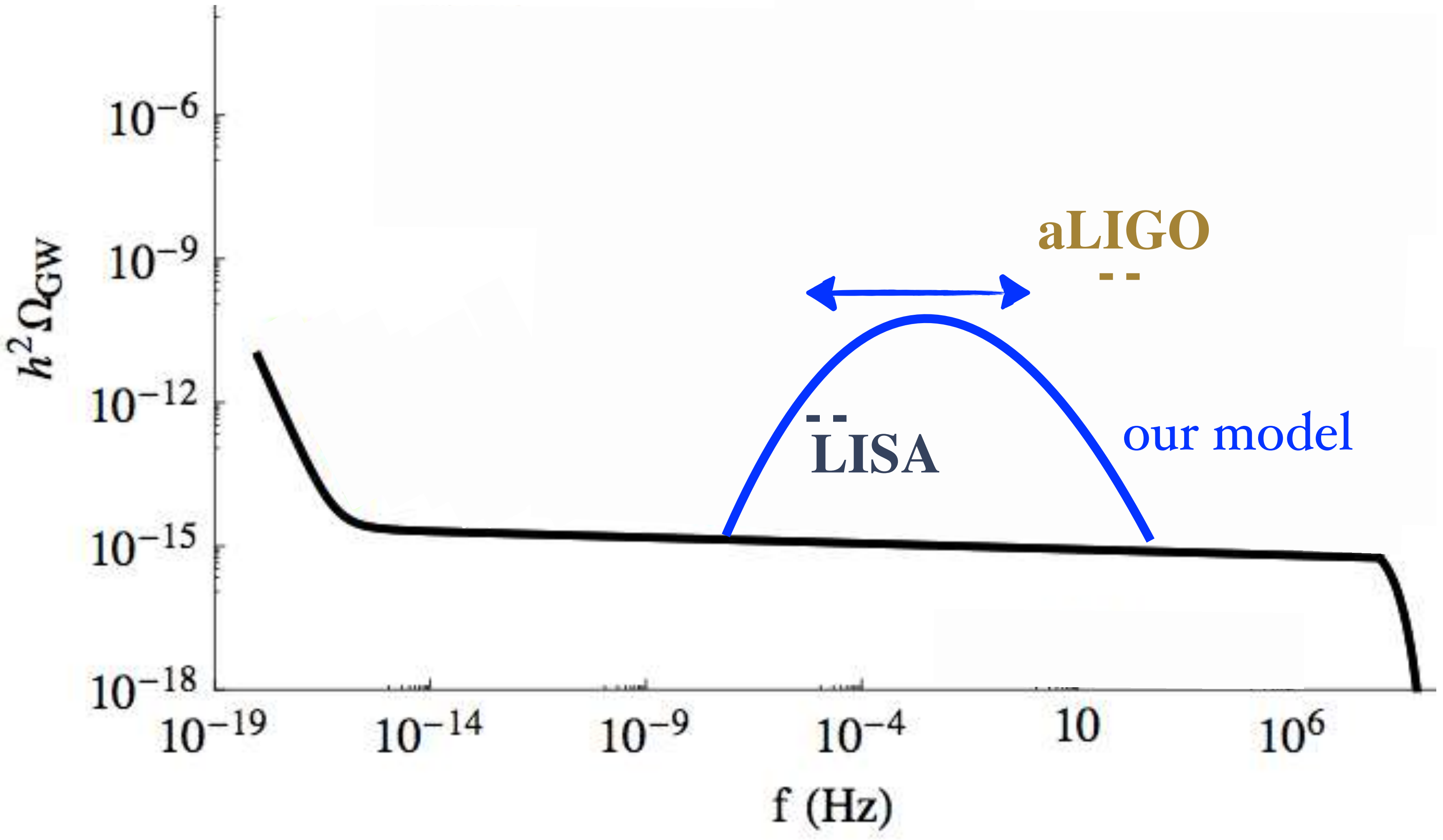
# Testing Amplitude & Scale Dependence



Laser Interferometers: new frontier to test primordial physics (GW) at small scales

LISA: $10^{-4}\text{Hz} \lesssim f \lesssim 10^{-1}\text{Hz}$ ; LIGO+: $1\text{Hz} \lesssim f \lesssim 10^{3}\text{Hz}$

# Testing Amplitude & Scale Dependence



“ ⟷ ” freedom in parameter space

# Chirality

(background +) Chern-Simons coupling $\dfrac{\lambda\chi}{4f}F\tilde{F}$

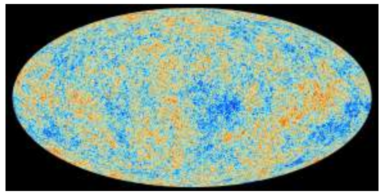
$$\ddot{t}_{ij}^{L/R} \pm \lambda(\ldots)t_{ij}^{L/R} + \cdots = 0$$

$$\gamma_{ij}^{L} \neq \gamma_{ij}^{R}$$

chiral spectrum

$$\mathcal{P}_{\gamma}^{L} \neq \mathcal{P}_{\gamma}^{R}$$

# Chirality



CMB tests

single-field
slow-roll inflation

no chirality

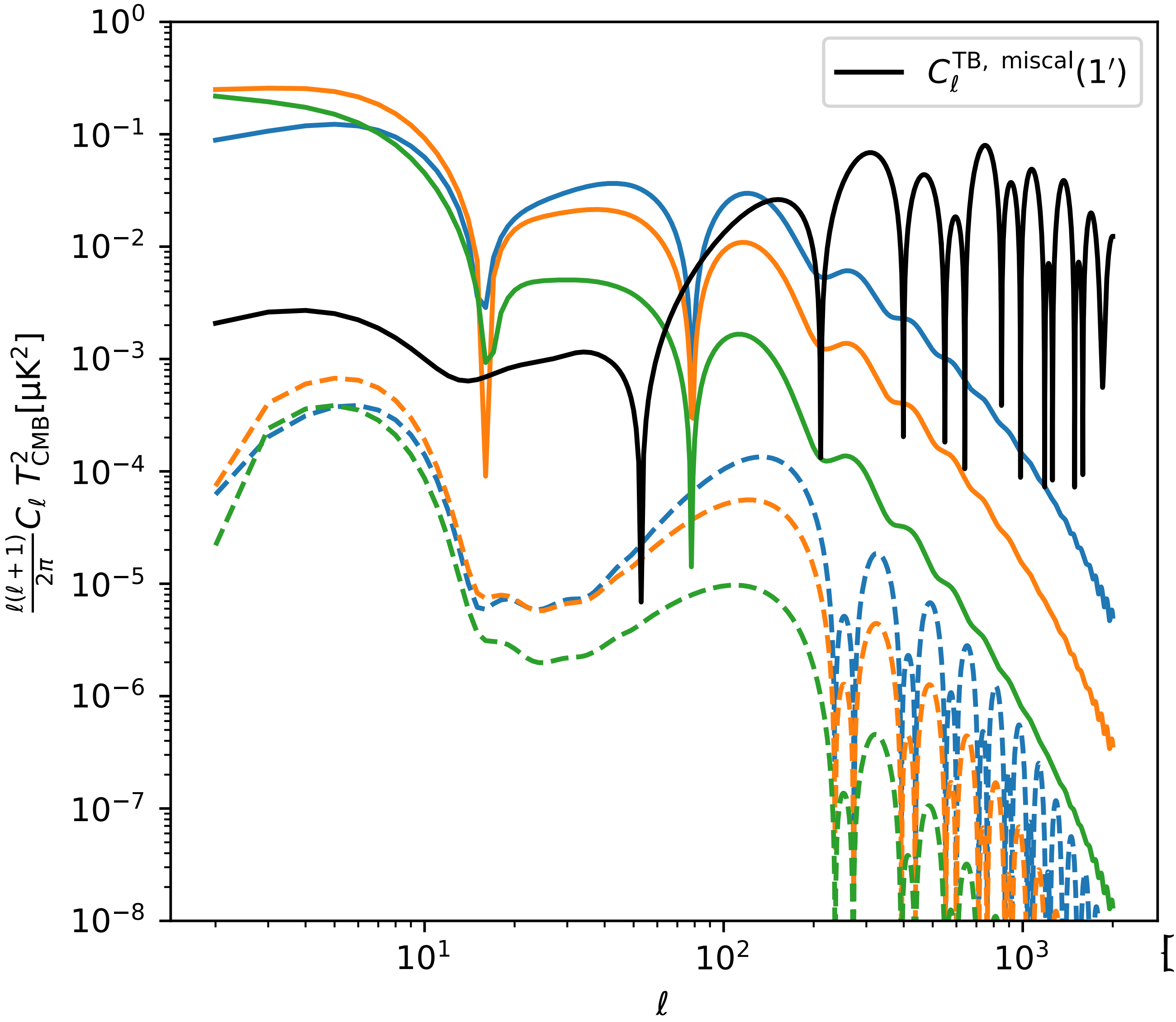
$$\langle BT \rangle = 0 = \langle EB \rangle$$

Chern-Simons
coupling

chirality

$$\langle BT \rangle \neq 0 \neq \langle EB \rangle$$

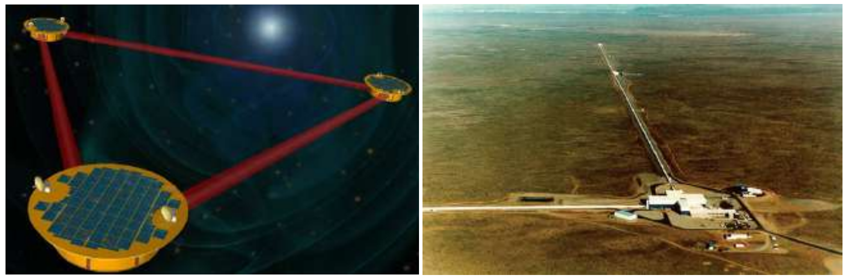
LiteBIRD



[Komatsu et al, 2017]

$$\mathcal{P}_h^{\mathrm{sourced}} = r_* \mathcal{P}_\zeta \, \mathrm{Exp}\Big[ -\frac{1}{2\sigma^2} \ln^2\left(\frac{k}{k_p}\right) \Big]$$

# Chirality



Interferometers tests

- cross-correlation between interferometers at different locations

[Smith, Caldwell 2017]

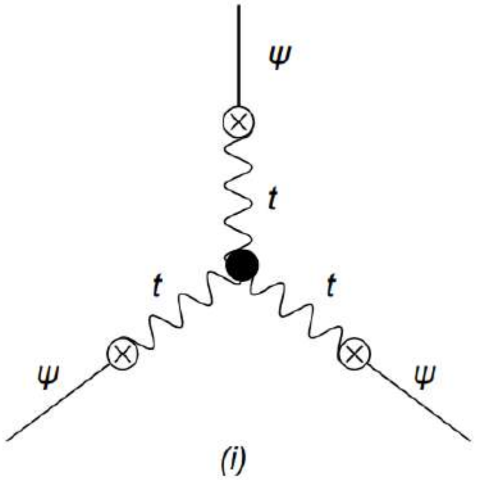
- recent work on LISA: use kinematically induced dipole

[Seto 2006]
[Domcke et al 2019]

# non-Gaussianity (TTT)

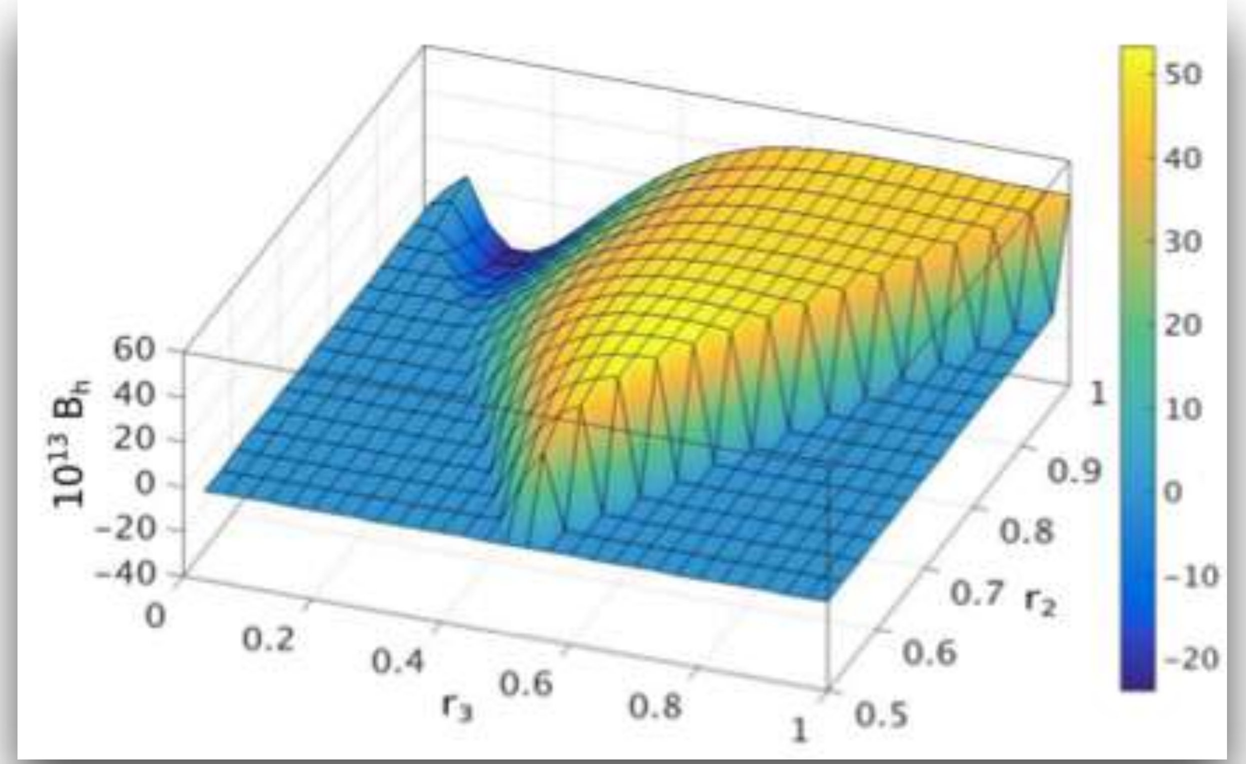
[Agrawal - Fujita - Komatsu 2017]

**n-G** $$\langle h_R(\vec{k}_1) h_R(\vec{k}_2) h_R(\vec{k}_3)\rangle = (2\pi)^3 \delta^{(3)}\left(\sum_{i=1}^{3} \vec{k}_i\right) B_h(k_1, k_2, k_3)$$



$\Psi =$ GW

$t =$ tensor SU(2)



$m_Q = 3.45$

$\epsilon_B \simeq 10^{-5}$

$H \simeq 10^{13}\,\mathrm{GeV}$

$r_{\rm vac} \simeq 0.002$

$r_{\rm sourced} \simeq 0.04$

$$\frac{B_h}{P_\zeta^2} \lesssim r^2 10^6$$

sourced nG tensors
larger than in minimal SFSR

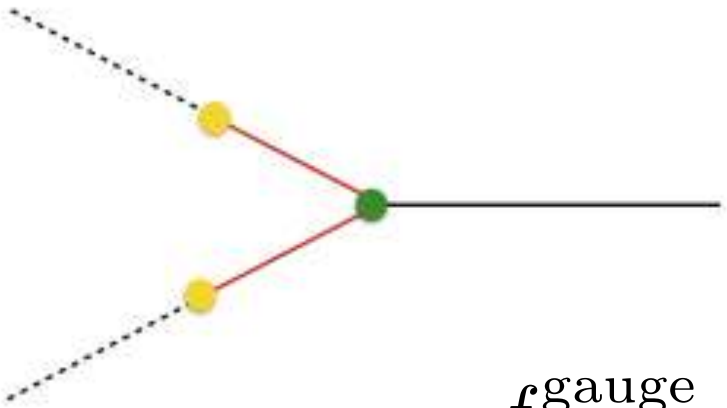
# non-Gaussianity (STT)

$$\langle \zeta \gamma \gamma \rangle$$

[Fujita, Namba, Obata]

[Dimastrogiovanni, MF, Hardwick, Koyama, Wands]

several channels (e.g. mixing terms between scalars)
contribute to STT ==> folded shape



$$f_{\rm NL}^{\rm gauge} \sim 10^3 r$$

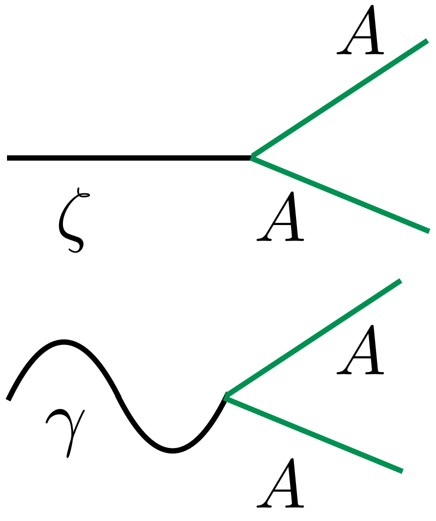
# Abelian case (intriguing phenomenology)

$$\mathcal{L} = \mathcal{L}_{\mathrm{EH}} - (\partial_\mu \phi)^2 - V(\phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{\lambda}{4f} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

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 produced by the rolling axion

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

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

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

[Anber, Sorbo 2009 - Barnaby, Peloso 2011, Barnaby, Namba, Peloso 2011, Bartolo et al 2014+…]

[Pajer, Peloso (2013)]

# Primordial GW to test inflationary particle content

scale-dependence

chirality

non-Gaussianity

Axion-gauge field models

# By now a rich literature on the subject

…Anber - Sorbo 2009; Cook - Sorbo 2011; Barnaby - Peloso 2011; Adshead- Wyman 2011; Maleknejad - Sheikh-Jabbari, 2011; Dimastrogiovanni - MF - Tolley 2012; Dimastrogiovanni - Peloso 2012; Adshead - Martinec -Wyman 2013; Garcia-Bellido - Peloso - Unal 2016; Agrawal - Fujita - Komatsu 2017; Fujita - Namba - Obata 2018; Domcke - Mukaida 2018; Iarygina - Sfakianakis 2021; …

Supergravity embedding

[Dall'Agata]

Lots of research in this direction

+ gravitational Chern-Simons term
+ fermions production
+ back-reaction

[Komatsu et al, x 3]

+ gravitational leptogenesis

[Caldwell, Devulder]

+ SCNI in string theory

[Holland, Zavala, Tasinato]

+ perturbativity bounds

[Papageorgiou, Peloso, Unal]

general approach: inflationary particle content

# How can we probe info on Mass & Spin?

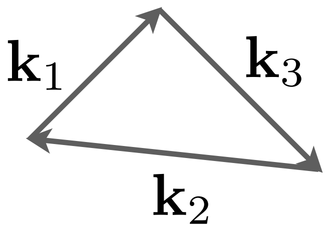
# non-Gaussianities

so far

$$\langle \zeta_{k_1} \zeta_{k_2} \rangle \equiv \frac{2\pi}{k^3} \mathcal{P}(k) \delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2)$$

n>2-point functions probe interactions

$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle \equiv (2\pi)^3 \delta^{(3)}(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) B(k_1, k_2, k_3)$$



Amplitude

$$f_{\rm NL} \sim B/P^2$$

# Squeezed Bispectrum: new physics

extra particle content ==> non-analytical scaling ==> directly probe new physics

$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle \Big|_{k_1 \ll k_3} \propto \underbrace{\frac{1}{k_1^3 k_3^3}}_{\text{standard}} \left( \frac{k_1}{k_3} \right)^{3/2 - \nu_s} P_s(\hat{k}_1 \cdot \hat{k}_3)$$

non-analytical scaling

extra angular dependence

[Noumi et al 2012]

[Arkani-Hamed, Maldacena 2015]

[Kehagias, Riotto 2015]

$$i\,\nu_s = \mu_s = \sqrt{\frac{m^2}{H^2} - \left(s - \frac{1}{2}\right)^2}$$

info on mass & spin!

# Squeezed Bispectrum: new physics

(heavier mediating masses)

$$\langle \zeta_{k_1}\zeta_{k_2}\zeta_{k_3}\rangle\Big|_{k_1 \ll k_3} \propto \underbrace{\frac{1}{k_1^3 k_3^3}}_{\text{standard}} \; e^{-\pi\mu_s}\left(\frac{k_1}{k_3}\right)^{3/2} P_s(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_3)\cos\Bigg|_{m\geq\frac{3}{2}H}\left[\mu_s \ln\left(\frac{k_1}{k_3}\right)\right]$$

non-analytical scaling

direct mass suppression

extra periodic spin-dependent feature

# Tensor-scalar-scalar Bispectrum

(generically true for squeezed non-Gaussianities)

$$\langle \gamma_{k_L} \zeta_{k_S} \zeta_{k_S} \rangle \Big|_{k_L \ll k_S} \propto \frac{1}{k_L^3 k_S^3} \left( \frac{k_L}{k_S} \right)^{3/2 - \nu_s} \mathcal{E}_2^{\lambda}(\hat{\mathbf{k}}_L \cdot \hat{\mathbf{k}}_S) \, P_s^{\lambda}(\hat{\mathbf{k}}_L \cdot \hat{\mathbf{k}}_S)$$

non-analytical scaling, CRs breakimg

extra angular dependence

$$\nu_s = \sqrt{\left( s - \frac{1}{2} \right)^2 - \frac{m^2}{H^2}}$$

standard polarization tensor

# Connections with "tensor fossils"

## as a diagnostic of new physics

$$P_\zeta(\mathbf{k},\mathbf{x}_c)|_{\gamma_L} = P_\zeta(k)\Big(1+\mathcal{Q}^{\gamma\zeta\zeta}_{\ell m}(\mathbf{x}_c,\mathbf{k})\hat{k}_\ell\hat{k}_m\Big)$$

[Dimastrogiovanni, **MF**, Jeong, Kamionkowski 2014]
[Dimastrogiovanni, **MF**, Kamionkowski 2016]

$$\mathcal{Q}^{\gamma\zeta\zeta}_{lm}(\mathbf{x},\mathbf{k}) = \int \frac{d^3q}{(2\pi)^3}\, e^{i\mathbf{q}\cdot\mathbf{x}}\, f_{\rm nl}^{\gamma\zeta\zeta}(\mathbf{q},\mathbf{k}) \sum_\lambda \epsilon^\lambda_{lm}(-\hat{q})\, \gamma^{*\lambda}_{-\mathbf{q}}$$

# “Tensor Fossils”, a crucial handle on GW non-Gaussianity

$$P_\gamma(\mathbf{k}',\mathbf{x})|_{\gamma_L} = P_\gamma(k')\Big[1+\mathcal{Q}^{\gamma\gamma\gamma}_{lm}(\mathbf{x},\mathbf{k}')\hat{k}'_l\hat{k}'_m\Big]$$

{Dimastrogiovanni, MF, Tasinato PRL 2020}

PS anisotropies not key test of n-G <u>if</u> the bispectrum is accessible, but

propagations effects through structure wash away GW n-G initial conditions

(in most bispectrum configurations)

{Bartolo, De Luca, Franciolini, Lewis, Peloso, Riotto (2019)}

GW anisotropies probe the ultra-squeezed configuration ==> handle on n-G

$$\mathcal{Q}^{\gamma\gamma\gamma}_{lm}(\mathbf{x},\mathbf{k}) = \int \frac{d^3q}{(2\pi)^3}\, e^{i\mathbf{q}\cdot\mathbf{x}}\, f_{\rm nl}^{\gamma\gamma\gamma}(\mathbf{q},\mathbf{k})\sum_\lambda \epsilon^\lambda_{lm}(-\hat{q})\,\gamma^{*\lambda}_{-\mathbf{q}}$$

# Testing “Fossils Fields” with cross-correlations: SGWB x CMB

squeezed 3-point function (scalar/tensor/mixed) leads to anisotropies, take STT

$$P_\gamma(\mathbf{k},\mathbf{x})|_{\zeta_L} \sim P_\gamma(k)\left[1+\int \frac{d^3q}{(2\pi)^3}\, e^{i\mathbf{q}_L\mathbf{x}}\, \frac{\langle\zeta_L\gamma_S\gamma_S\rangle}{\langle\zeta_L\zeta_L\rangle\langle\gamma_S\gamma_S\rangle}\zeta(q_L)\right]$$

can define anisotropies $\delta_{\rm GW} \propto \zeta_L$ of GW energy density $\Omega_{\rm GW}$

and correlate it with CMB temperature anisotropies $\delta_T \propto \zeta$

[Adshead, Afshordi, Dimastrogiovanni, MF, LIM, Tasinato, PRD 2021]

(i) to constrain $f_{\rm NL}^{\zeta\gamma\gamma}$ at small scales

(ii) test primordial nature of $\delta_{\rm GW}$

# Testing “Fossils Fields” with cross-correlations: SGWB x CMB

[Adshead, Afshordi, Dimastrogiovanni, **MF**, Lim, Tasinato 2020]

$$P_\gamma(\mathbf{k},\mathbf{x})|_{\zeta_L} \sim P_\gamma(k)\left[1+\int \frac{d^3q}{(2\pi)^3}\, e^{i\mathbf{q}_L\mathbf{x}} \frac{\langle \zeta_L \gamma_S \gamma_S\rangle}{\langle \zeta_L\zeta_L\rangle\langle\gamma_S\gamma_S\rangle}\zeta(q_L)\right]$$

$$\boxed{\delta_{\rm GW}(k,\hat{n}) = \mathcal{Q}_{\ell m}(\mathbf{k},\mathbf{d})\,\hat{n}_\ell \hat{n}_m}$$

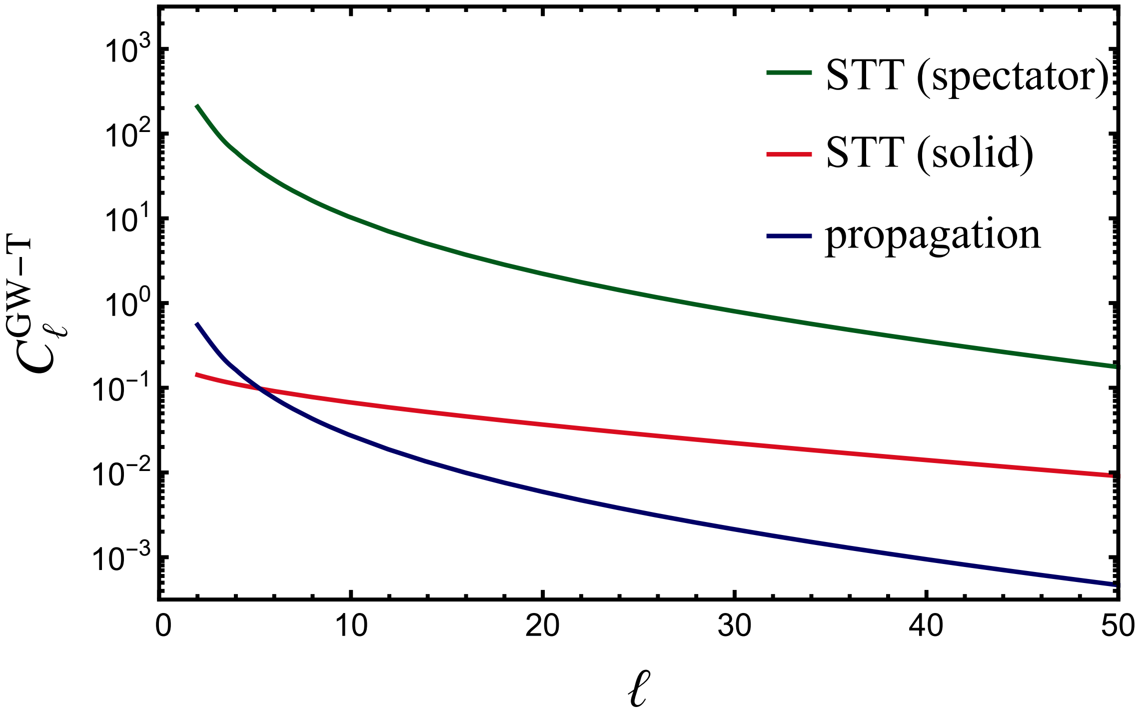
$$\Omega_{\rm GW}(k) = \bar{\Omega}_{\rm GW}(k)\left[1+\frac{1}{4\pi}\int d^2\hat{n}\,\delta_{\rm GW}(k,\hat{n})\right]$$

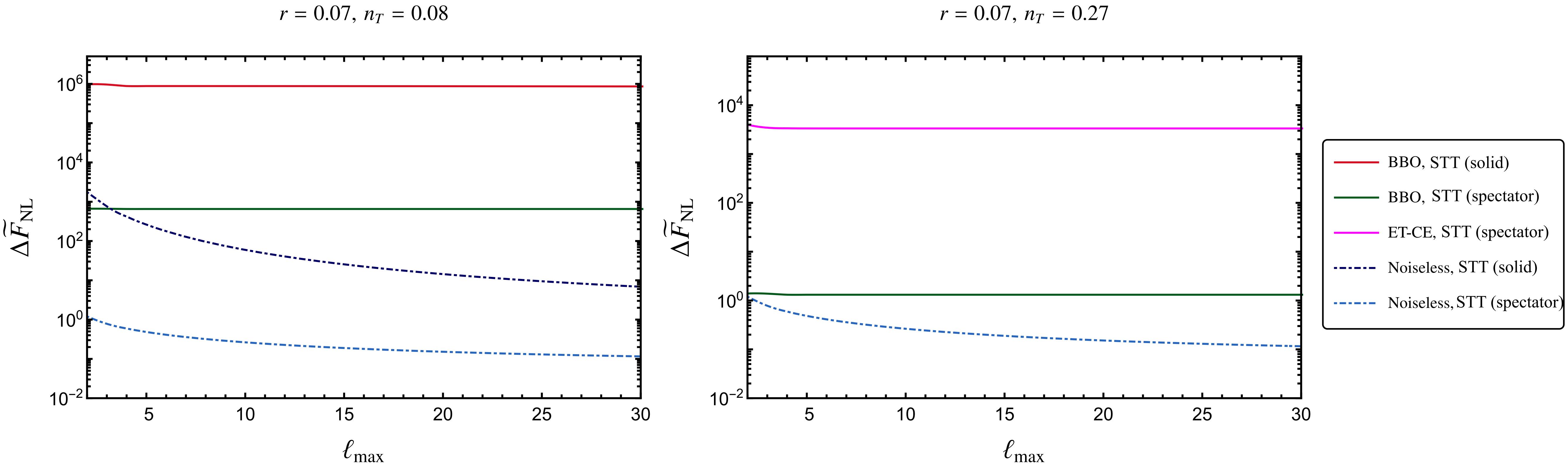
$$\mathbf{d} = -(\eta_0-\eta_{\rm in})\hat{n}$$

$$\left.\begin{aligned} &\delta^{\rm stt}_{\rm GW} \sim F^{\rm stt}_{\rm NL}\cdot\zeta_L \\ &\frac{\Delta T}{T} \sim \zeta_L \end{aligned}\right\} \quad C_\ell^{\text{GW-T}} \sim F^{\rm stt}_{\rm NL}\cdot C_\ell^{TT}$$

# Testing "Fossils Fields" with cross-correlations: SGWB x CMB

[Malhotra, Dimastrogiovanni, **MF**, Shiraishi 2020]





# Squeezed Bispectrum: new physics

$$\langle \zeta_{k_1}\zeta_{k_2}\zeta_{k_3}\rangle\Big|_{k_1 \ll k_3} \propto \underbrace{\frac{1}{k_1^3 k_3^3}}_{\text{standard}} \; e^{-\pi\mu_s}\left(\frac{k_1}{k_3}\right)^{3/2} P_s(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_3)\cos\left[\mu_s \ln\left(\frac{k_1}{k_3}\right)\right]$$

$m \geq \frac{3}{2}H$

non-analytical scaling

direct mass suppression

crucial fact for s ≥ 2 spinning fields

$$\boxed{m \gtrsim H}$$

[**MF**, Tolley 2012]
[**MF**, Tolley 2013]

# Mass & Spin

spinning fields ==> more signatures

spin-2 example can source tensors linearly!

unitary reps in dS ==> $m^2 = 0 \checkmark$ $m^2 \geq 2H^2$

+

interactive spin-2 fields ==> at most 1 is massless

[Boulanger, Damour, Gualtieri, Hennaux (2000)]

extra spin-2 field is a massive graviton!

# Unitarity bound

$$\boxed{\tilde{m}^2\left[1+\left(\frac{H_f/M_f}{H/M_P}\right)^2\right] \geq 2H^2}$$

[MF, Tolley (2012)]
[MF, Tolley (2013)]

weakened constraint but

$$m \sim H$$

extra spin-2 fields tend to decay quickly!

[Biagetti, Dimastrogiovanni, MF (2017)]
[Dimastrogiovanni, MF, Tasinato (2018)]

extra spin-2 field is a massive graviton!

# Recap

extra fields can be probed via squeezed bispectrum
because they break consistency relations

&

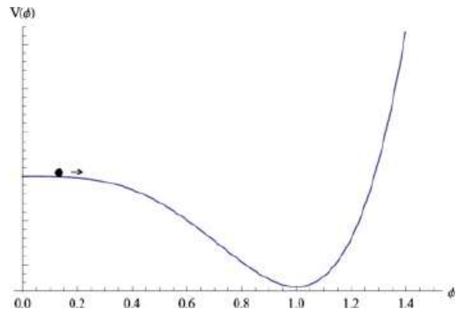
spinning ==> richer set of signatures
but, typically
spinning ==> mass bounds ==> suppression

[Biagetti, Dimastrogiovanni, **MF** 2017]

# One crucial ingredient

the mass, the spin... the coupling

∃ 1 field that doesn't decay: the inflaton



in case of sizable i.e. non-minimal coupling to the inflaton:

(i) exchange between different sectors

(ii) can keep massive spin-2 and HS fields afloat for longer

(iii) can help with Higuchi bound

HS

[Bumann et al 2016]
[Kehagias & Riotto (2017+..)]
[Bartolo et al 2017]

[Bordin, Creminelli, Khmelnitsky , Senatore 2018]
[Dimastrogiovanni, MF, Tasinato, Wands 2018]

# Examples

## quasi-single-field

$$S_m = \int d^4x\sqrt{-g}\left[-\frac{1}{2}(R+\sigma)^2(\partial_\mu\theta)^2 - \frac{1}{2}(\partial_\mu\sigma)^2 - V_{\mathrm{sr}}(\theta) - V(\sigma)\right]$$

[Chen, Wang 2009]+...

scalar sector

inflaton

extra

## (gauge) vector field

U(1), SU(2)...

$$I(\phi)F^2 \quad \text{or} \quad I(\phi)F\tilde{F}$$

strongly affects tensor sector, chiral GW etc

# The EFT approach

## philosophy and cooking instructions

● unitarity bounds on spinning particles masses are dictated by dS isometries ●

● inflation needs to end <—> dS iso are broken by inflaton ●

[Cheung et al 2007]

● couple directly to the inflaton any otherwise massive field ●
that you want to make effectively lighter

● non-linearly realized symmetries prescribe ●
inflaton <—> extra field(s) coupling(s)

# The EFT approach

can be implemented for generic extra spin

it is an EFT of fluctuations around FLRW

.....

$$S[\sigma] = \frac{1}{4}\int d^4x a^3 \left[ (\dot{\sigma}^{ij})^2 - c_2^2(\partial_i \sigma^{jk})^2/a^2 - \frac{3}{2}(c_0^2 - c_2^2)(\partial_i \sigma^{ij})^2/a^2 - m^2(\sigma^{ij})^2 \right]$$

spin-2

$$S_{\rm int} = \int d^4x \sqrt{-g} \quad \Big[ \quad -\frac{\rho}{2\epsilon H a^2}\partial_i\partial_j\pi_c\sigma^{ij} + \underline{\frac{1}{2}\rho\,\dot{\gamma}_{c\,ij}\sigma^{ij}}$$

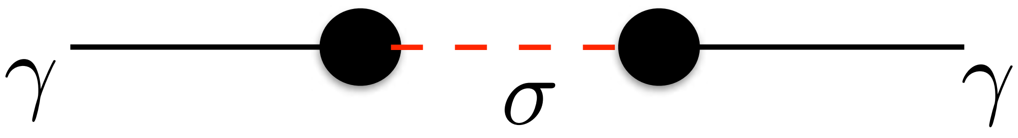
$$-\frac{\rho}{2\epsilon H^2 M_P\, a^2}(\partial_i\pi_c\partial_j\pi_c\dot{\sigma}^{ij} + 2H\,\partial_i\pi_c\partial_j\pi_c\sigma^{ij}) + \frac{\tilde{\rho}}{\epsilon H^2 M_P\, a^2}\dot{\pi}_c\partial_i\partial_j\pi_c\sigma^{ij} - \underline{\mu(\sigma^{ij})^3} \Big]$$

[Bordin et al 2018]

# Power Spectrum

Extra spin-2 case

$$S_{\rm int} = \int d^4x\sqrt{-g}\left[ -\frac{\rho}{2\epsilon H a^2}\partial_i\partial_j\pi_c\sigma^{ij} + \underline{\frac{1}{2}\rho\,\dot{\gamma}_{c\,ij}\sigma^{ij}} - \frac{\rho}{2\epsilon H^2 M_P\,a^2}\left(\partial_i\pi_c\partial_j\pi_c\dot{\sigma}^{ij} + 2H\,\partial_i\pi_c\partial_j\pi_c\sigma^{ij}\right) + \frac{\tilde{\rho}}{\epsilon H^2 M_P\,a^2}\dot{\pi}_c\partial_i\partial_j\pi_c\sigma^{ij} - \mu(\sigma^{ij})^3\right]$$

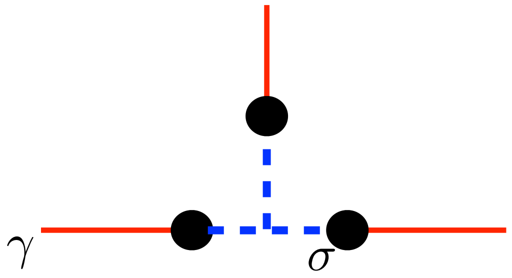


$$P_\gamma(k) = \frac{4H^2}{M_p^2\,k^3}\left[1 + \frac{\mathcal{C}_\gamma(\nu)}{c_\sigma^{2\nu}}\left(\frac{\rho}{H}\right)^2\right]$$

[Bordin et al 2018]

| | |
|---|---|
| $\frac{\rho}{H} \ll 1$ | perturbative treatment of quadratic mixing |
| $\frac{\mu}{H} \ll 1$ | L_3 < L_2 |
| $\frac{\rho}{\sqrt{\epsilon} H} \ll 1$ | small radiative corrections to sigma mass |
| $c_\sigma \gtrsim 10^{-2}$ | tensor nG limits as well |

# Bispectrum



$$f_{\rm nl}^{\rm eq} \simeq \begin{cases} \frac{77782}{\sqrt{r}}\, r^2 \simeq 1143 & \text{for } c_\sigma = 0.1 \\ \frac{155563}{\sqrt{r}}\, r^2 \simeq 2286, & \text{for } c_\sigma = 0.05 \\ \frac{777817}{\sqrt{r}}\, r^2 \simeq 11431 & \text{for } c_\sigma = 0.01 \end{cases}$$

[Dimastrogiovanni, MF, Tasinato, Wands 2018]

# The Inflationary Field Content

most dramatic signatures correspond to a non-minimal coupling of extra (spinning) fields to the inflaton

the EFT route delivers the richest phenomenology

**signatures** ✓

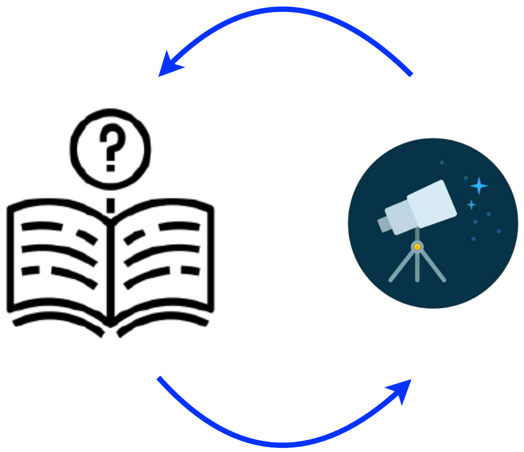
a lot (if not all) of what is possible will be captured by EFT framework

# Conclusions

Cosmological probes will soon cross qualitative thresholds e.g. on $r$, $f_{\mathrm{NL}}$

Lots to do on the theory side:
explore (& put forward new) compelling models
build a theory-to-data pipeline to test inflationary particle content

At reach
(I) deeper understanding of early universe
(II) connection with very high energy particle physics



Compelling & Testable Scenarios

Thank You!