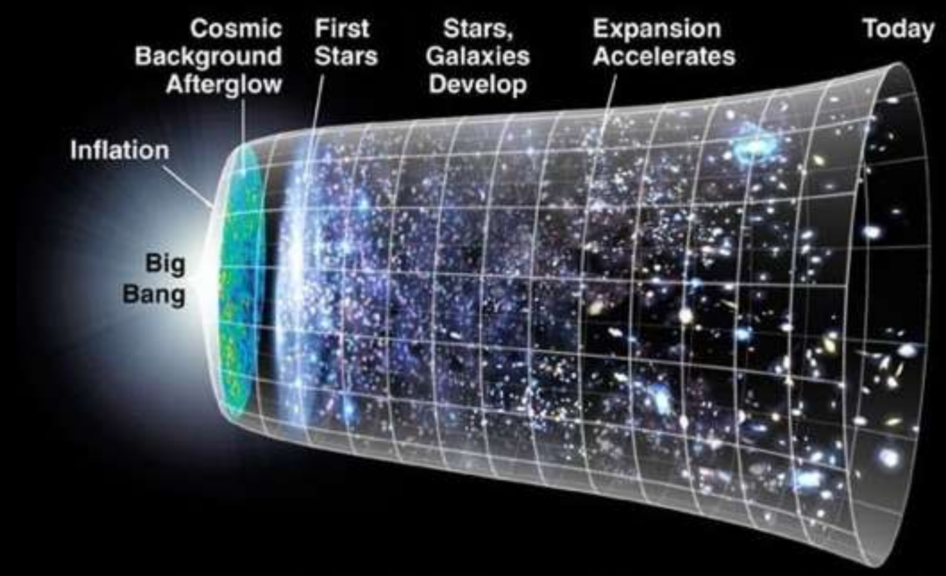
Inflating with Axions & Gauge Fields



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"Gravity and Cosmology 2024"
Yukawa Institute for Theoretical Physics, Kyoto

Collaborators

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Outline

- Inflation (SFSR & multifield, quickly)
- Axion inflation family
- Gauge fields via Chern-Simons, phenomenology
- Quickly on the Abelian case
- Focus on the non-Abelian case
  two examples
- Other key aspects and open questions
  perturbativity, backreaction & more

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Inflation, the minimal paradigm, SFSR

Simplest realization: single-scalar field in slow-roll

- Scalar field :

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

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

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

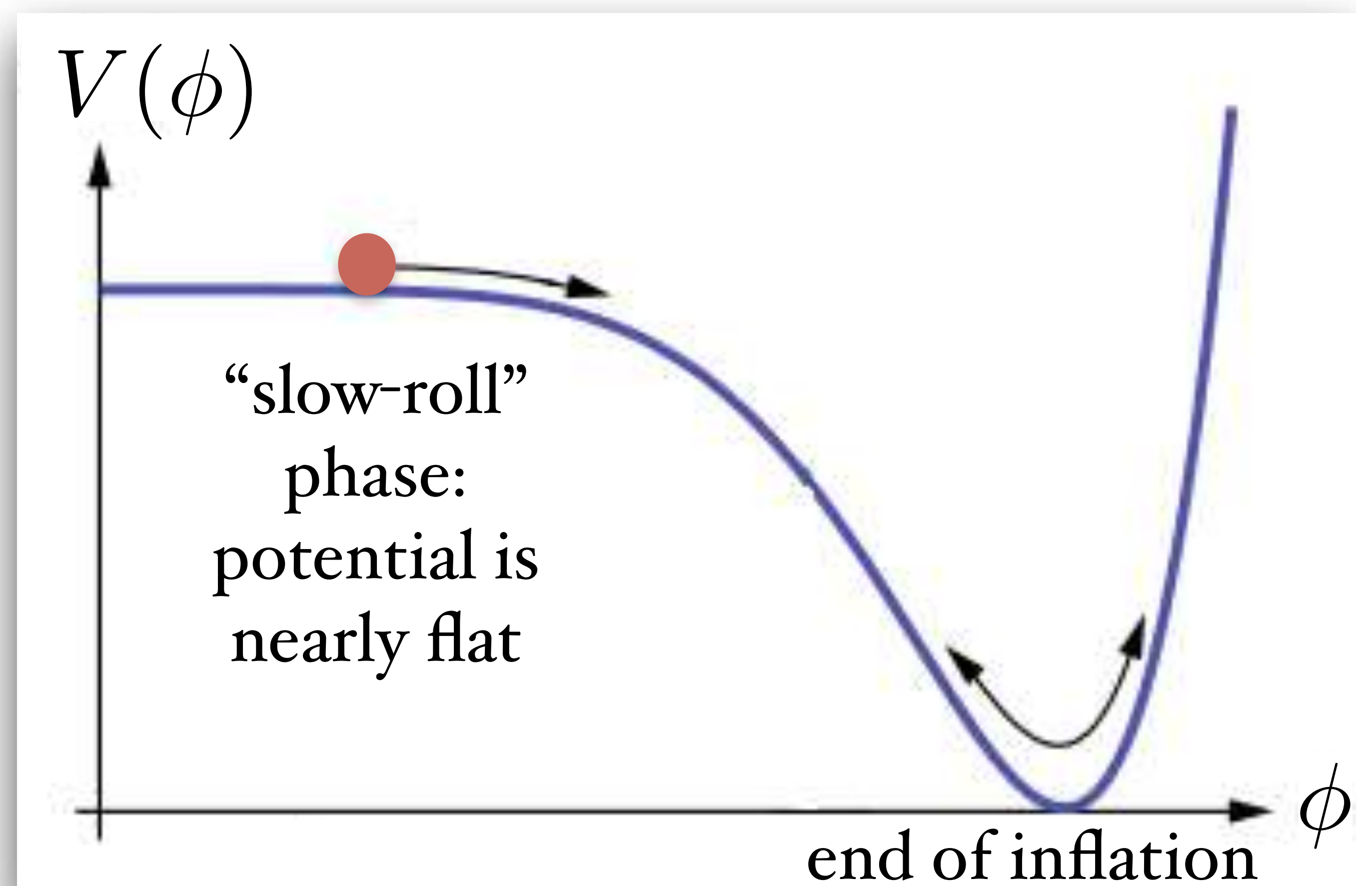
$$p_\phi \approx -\rho_\phi$$

start flat

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

stay flat

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



Primordial Fluctuations

(minimal scenario)

$$ds^2 = (-dt^2 + a(t)^2[e^{2\zeta}\delta_{ij} + \gamma_{ij}]dx^i dx^j)$$

scalar fluctuations

tensor perturbations

Primordial Fluctuations

(minimal scenario)

$$ds^2 = (-dt^2 + a(t)^2[e^{2\zeta}\delta_{ij} + \gamma_{ij}]dx^i dx^j)$$

scalar fluctuations

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

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

2.2×10^{-9}

0.9649 ± 0.0042

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

from Planck measurements of CMB anisotropies

tensor perturbations

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

energy scale of inflation

red tilt

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

tensor-to-scalar ratio $r \equiv \dfrac{\mathcal{P}_\gamma}{\mathcal{P}_\zeta}$

bounds

current

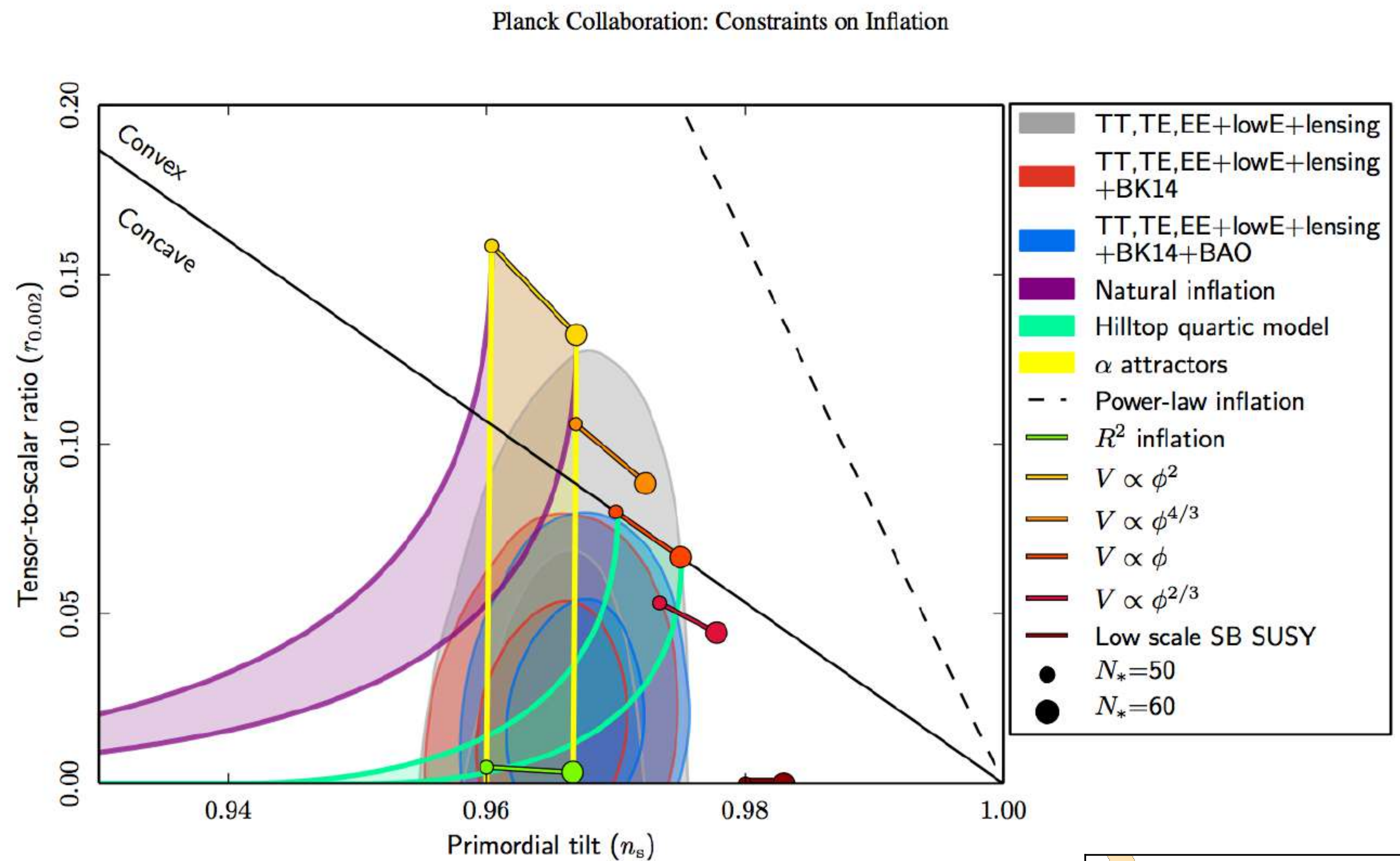
$r < 0.032\,(95\%\mathrm{CL}, \mathrm{Planck}^+)$

future

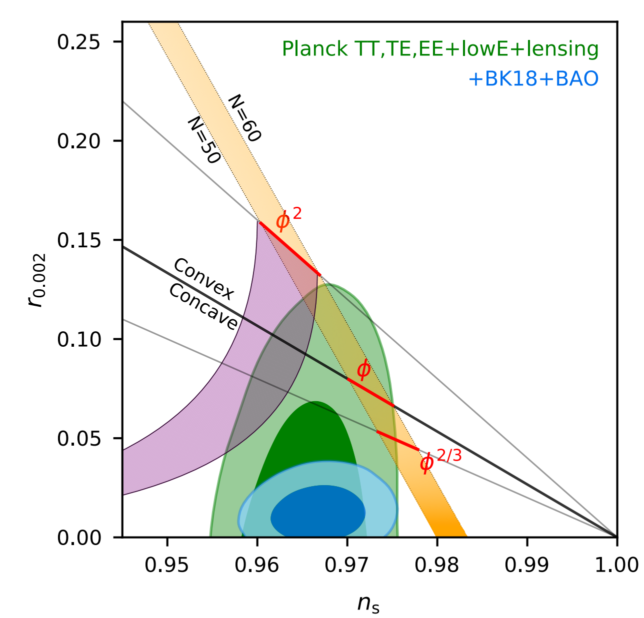
$r < 0.01$ (CMB-S3); $r < 0.001$ (-S4)

LiteBIRD

@ CMB scales



+BK update:



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We may additionally ask for

technically natural light inflaton

give the theory a chance
at solving the eta
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“embeddable” scenarios

a + if e.g. string theory
constructions can realise
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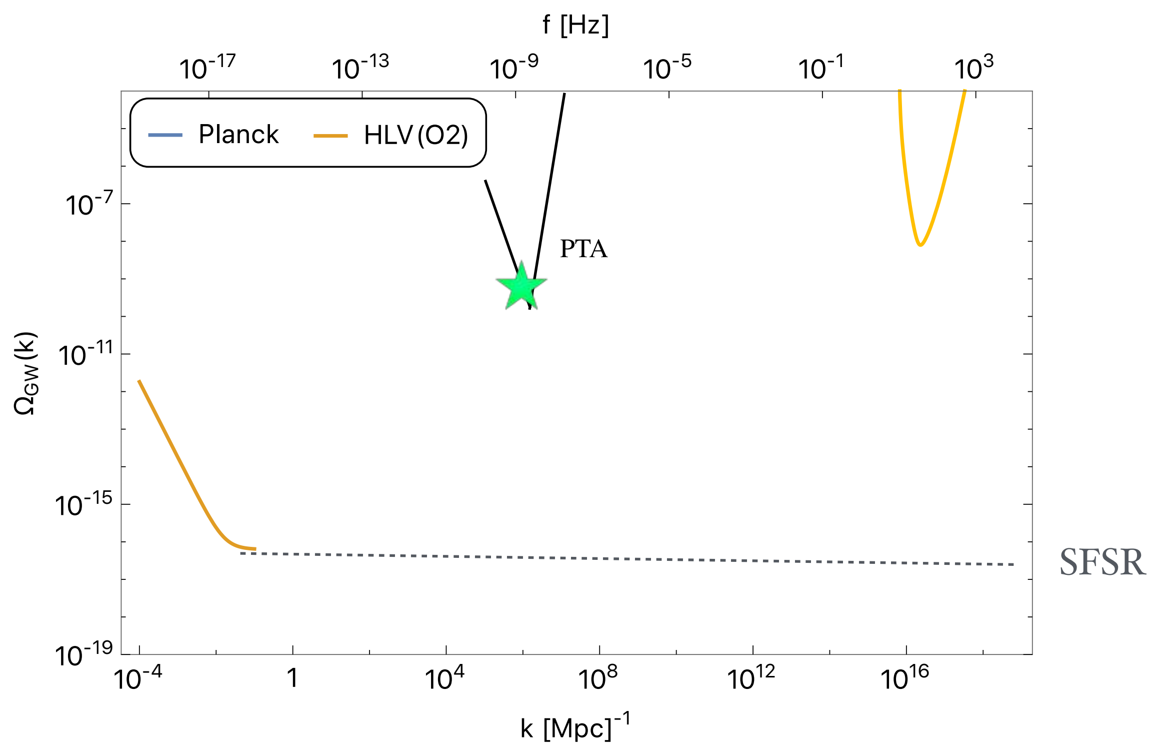
viable ones

CMB quite constraining,
many more bounds
coming
(20 decades in frequency)

Hope for a little more (GW)

now



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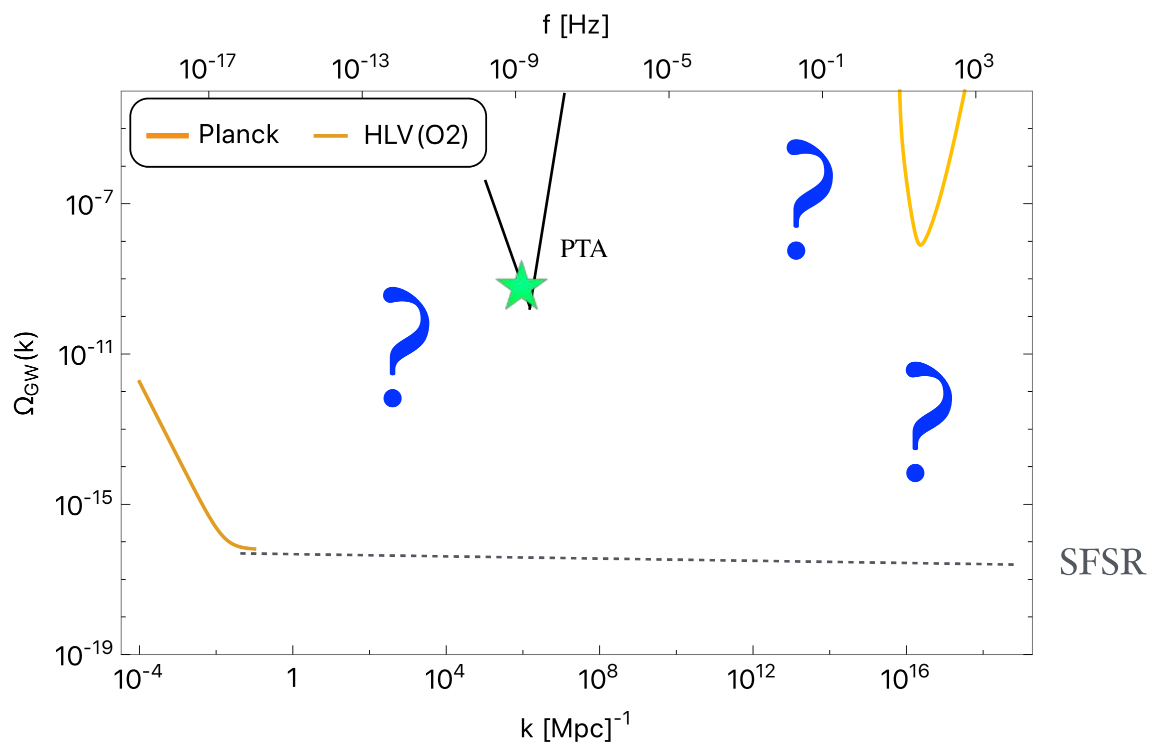

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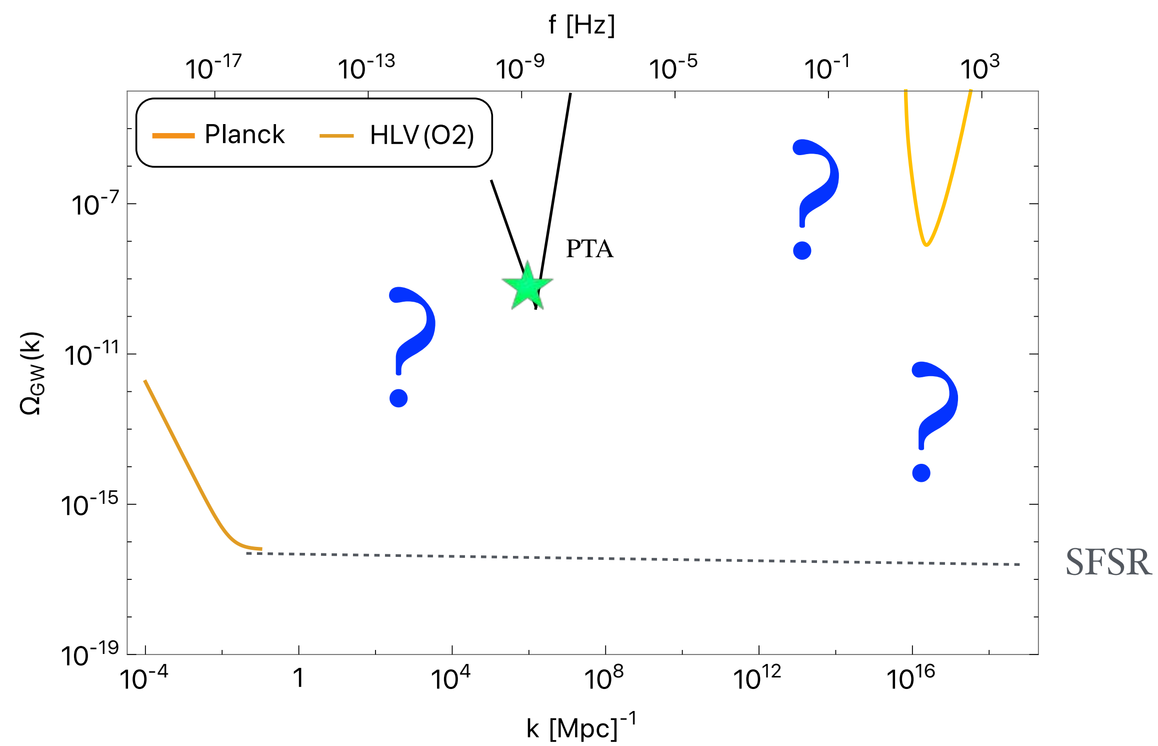

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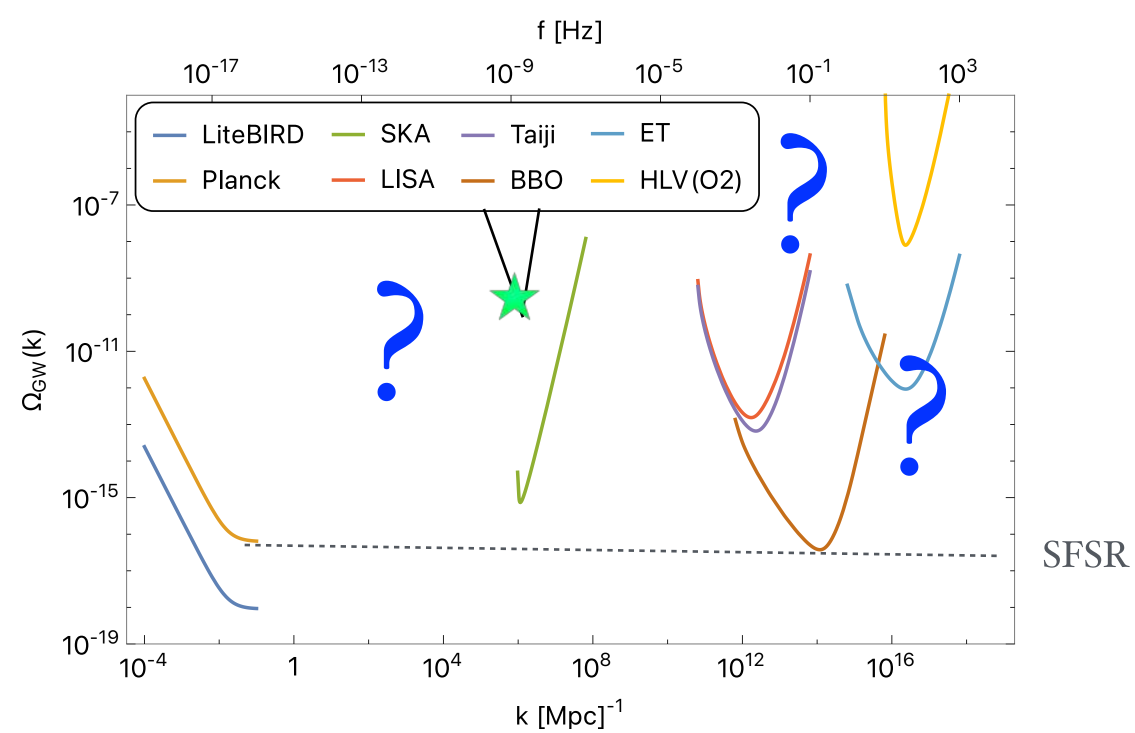

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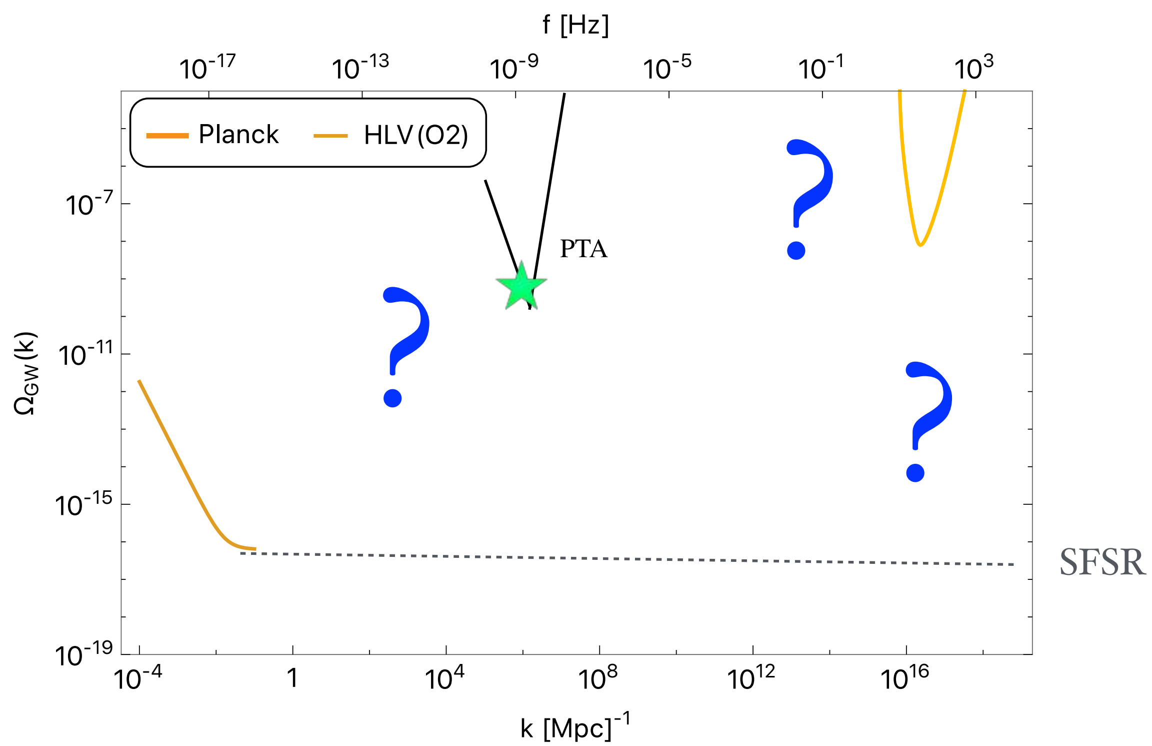

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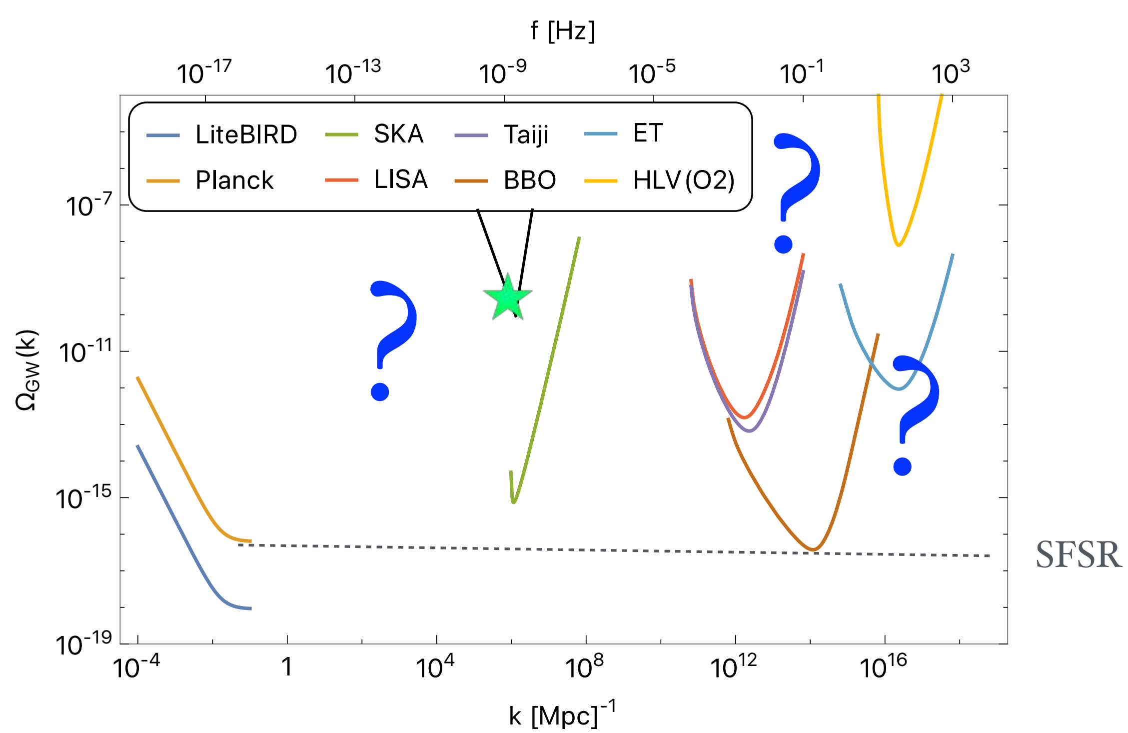
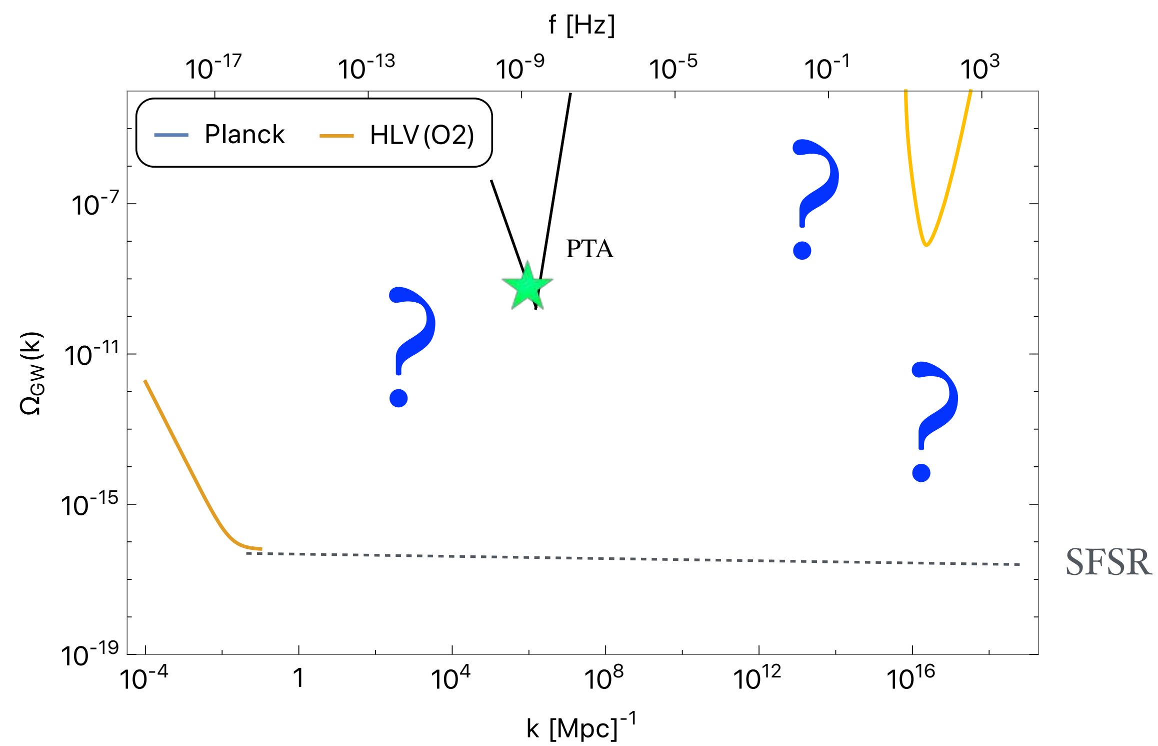


features!

Hope for a little more (GW)

now



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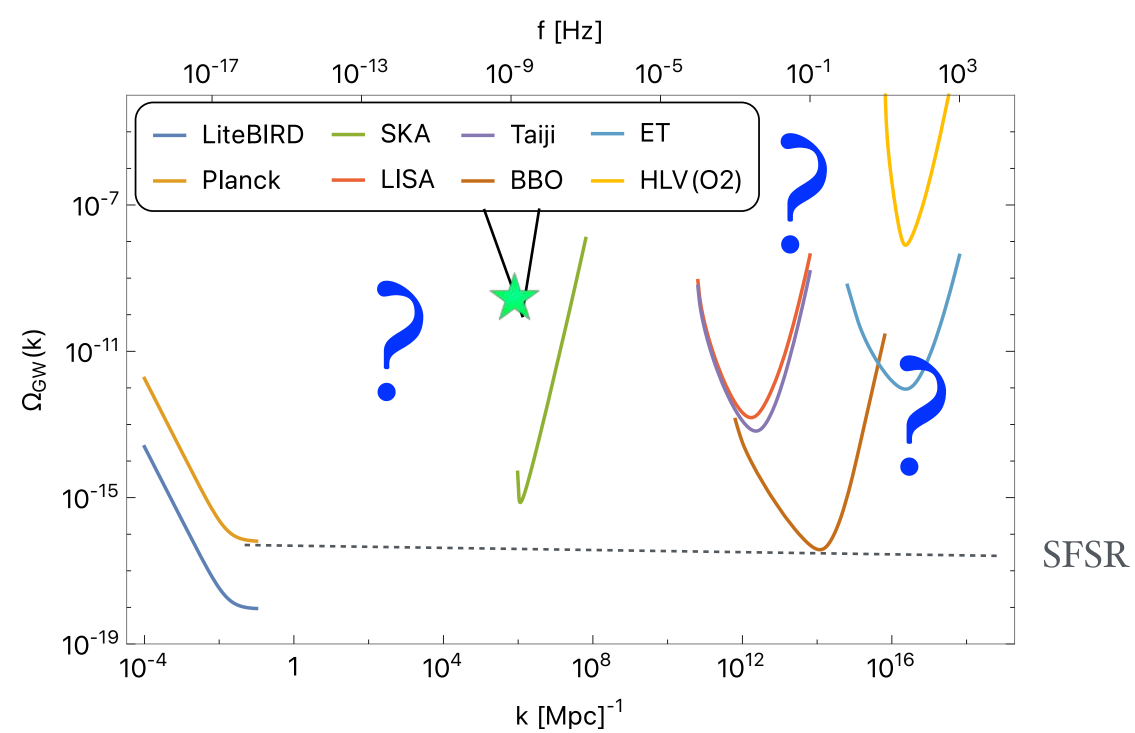


blue or bump-like GW spectrum testable @ PTA or via laser interferometers

Typically multiple fields required

why go beyond the single-field?

Likely

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

Testable

soon to cross key thresholds
$r < 0.001$ (CMB)
$f_{NL} < 1$ (LSS, 21cm)

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

Necessary

extraordinary claims
require extraordinary evidence

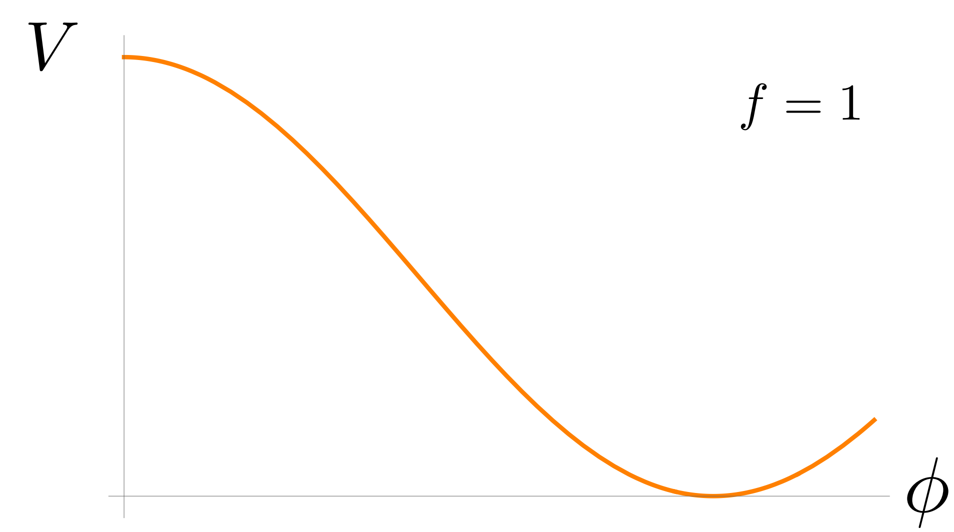
what to infer from
GW detection?
e.g. r <—> H relation

Natural Inflation

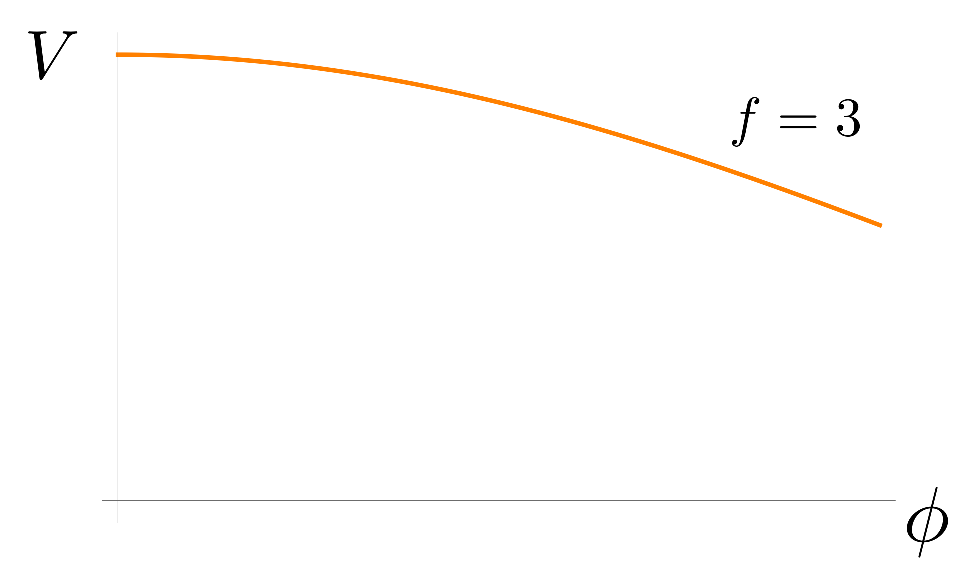
$$\mathcal{L} = \sqrt{-g}\left[R[g] - (\partial\phi)^2 - \mu^4\left(1 + \mathrm{Cos}[\phi/f]\right)\right]$$

[Freese, Frieman, Olinto]

axion-like potential



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



now ruled out

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Natural Inflation + Gauge Sector

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

$\hookrightarrow U(\chi) \sim \mu^4[1+\cos(\chi/f)]$

- friction/dissipation slows the roll
- $f \ll M_{\rm P}$ realization
- very interesting GW signatures !

Natural Inflation + Gauge Sector

general properties

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

SU(2)

U(1)

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

Adshead & Wyman

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

Anber & Sorbo

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U(1) SU(2)

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Gauge fields source GW, chiral signal if leading

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- Gauge fields source GW, chiral signal if leading
- ξ regulates the growth ==> possible blue spectrum

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

Natural Inflation + Gauge Sector

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

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

- chiral GW spectrum
- blue or bump-like features
- large scalar, GW & mixed non-Gaussianity

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Natural Inflation + Gauge Sector

briefly on U(1)

$$\Phi'' + 2\,a\,H\,\Phi' - \nabla^2\Phi + a^2\frac{dV(\Phi)}{d\Phi} = \frac{\alpha}{f}a^2\vec{E}\cdot\vec{B}$$

E_{kin} in production of gauge quanta

[Anber, Sorbo]

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

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

CS ==> parity breaking ==> different sols for polarisations

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

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

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

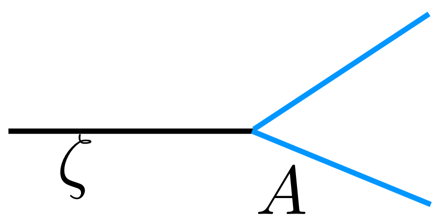
[Barnaby, Peloso 2011, Barnaby, Namba, Peloso 2011, Bartolo et al 2014+...]

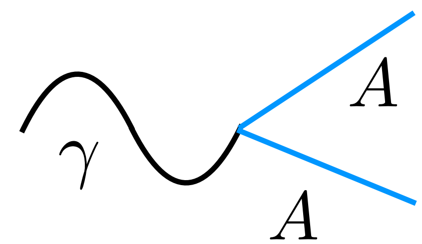
[Pajer, Peloso (2013)]

Natural Inflation + Gauge Sector

briefly on U(1)

non-linear sourcing w/ enhanced field





- observed scalar spectrum @ CMB & chiral GW

  inflaton coupled to $\mathcal{N} \sim \mathcal{O}(10^5)$ gauge fields

  - or for a different potential

    - or introducing spectator axions

[Mukohyama, Namba, Peloso, Shiu 2014]

blue or bump-like, chiral, GW spectrum
possibly large GW non-Gaussianities

U(1) many many applications, e.g. in PBH context

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Chromo Natural Inflation

SU(2)

[Adshead, Wyman]

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

[Dimastrogiovanni, MF, Tolley]
[Dimastrogiovanni, Peloso],
[Domcke, Mares, Muia, Pieroni],
[...]

◆
- $f \ll M_{\text{P}}$ realization
- very interesting GW signatures !
- in tension with the data..

Spectator Chromo Natural Inflation

[Dimastrogiovanni, MF, Fujita]
[Obata, Soda]

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

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

Primordial GW in SCNI

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

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

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

[Dimastrogiovanni, MF, Fujita]

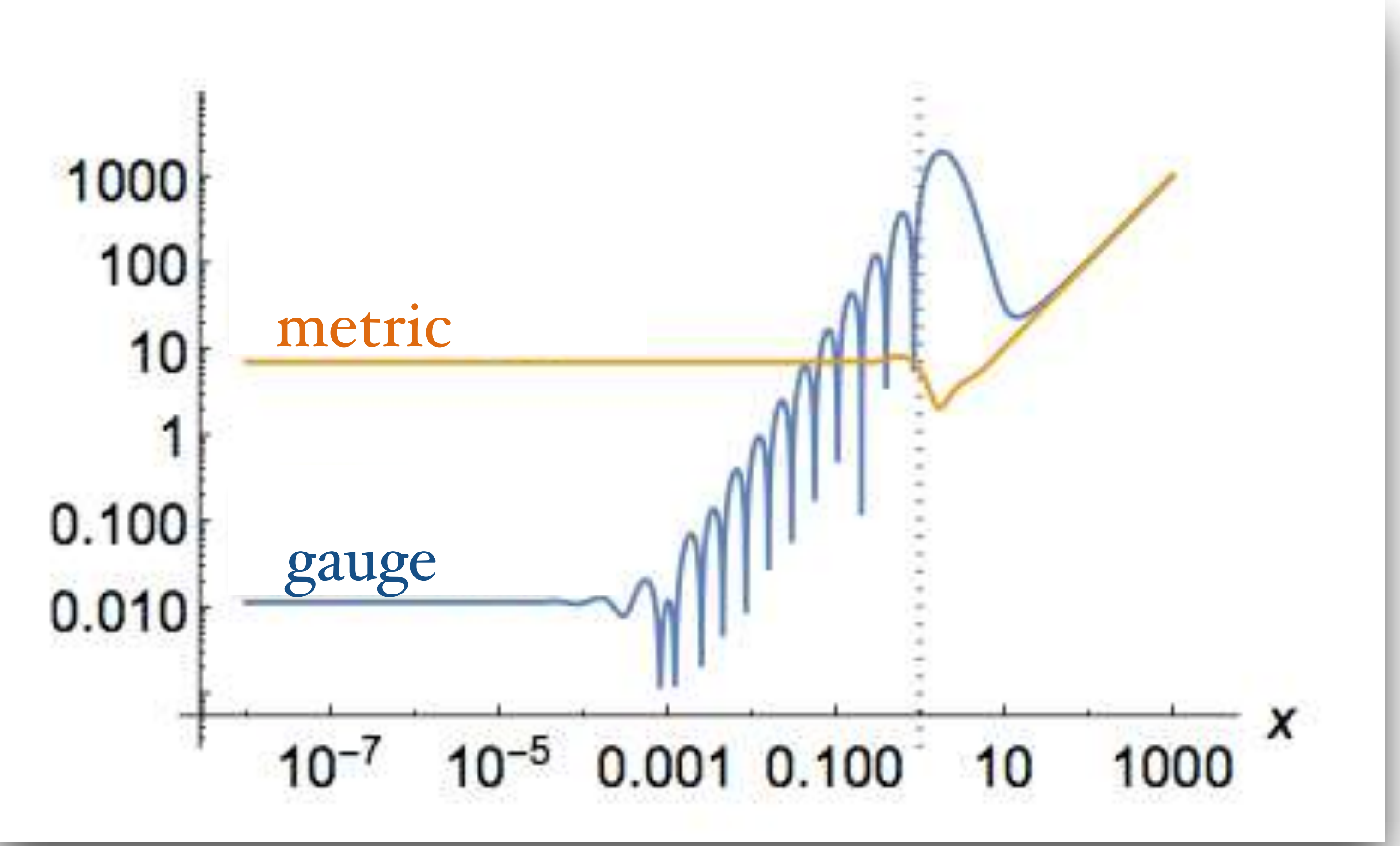
$$P_{\lambda}^{\text{sourced}} \gtrsim P_{\lambda}^{\text{vacuum}}$$

now possible!

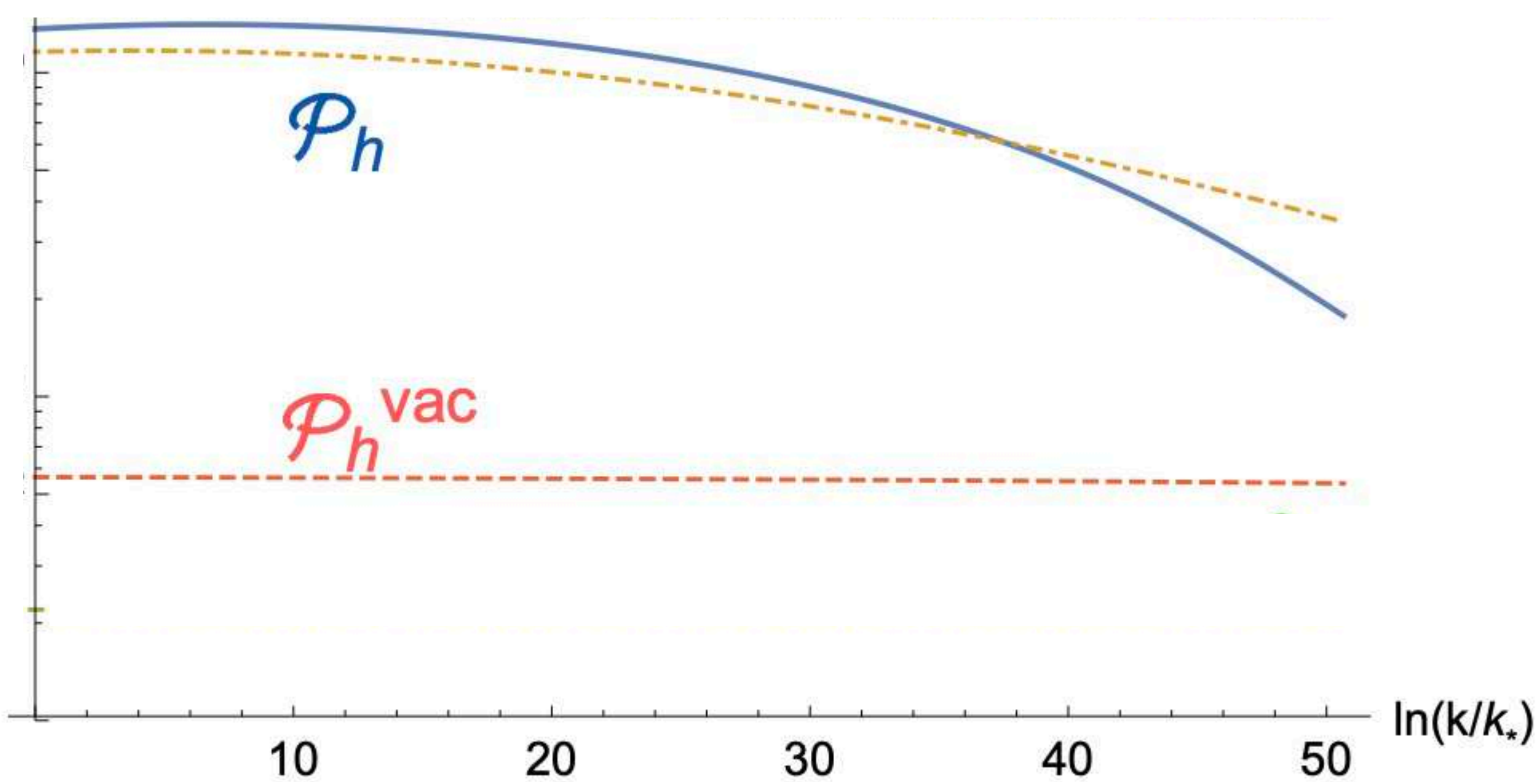
$$\begin{cases} \Psi''_{R,L} + \left(1 - \dfrac{2}{x^2}\right)\Psi_{R,L} = \mathcal{O}^{(1)}(t_{R,L}) & \textbf{metric} \\ t''_{R,L} + \left[1 + \dfrac{2m_Q\xi}{x^2} \mp \dfrac{2}{x}\left(m_Q + \xi\right)\right] t_{R,L} = \tilde{\mathcal{O}}^{(1)}(\Psi_{R,L}) & \textbf{gauge} \end{cases}$$

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

$$x \sim -k\tau$$


metric
gauge
1000
100
10
1
0.100
0.010
10^-7
10^-5
0.001
0.100
10
1000
x

Slightly Bump-like GW Power Spectrum



Chirality

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

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

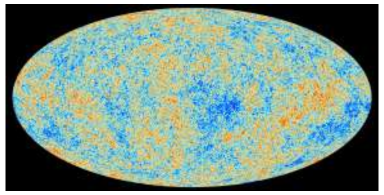
$$\gamma_{ij}^{L} \neq \gamma_{ij}^{R}$$

chiral spectrum

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

Testable at small scales via interferometers
- cross-correlation @ different locations [Smith, Caldwell 2017]
- kinematically induced dipole [Seto 2006, Domcke et al 2019]

Chirality



CMB tests

single-field
slow-roll inflation

Chern-Simons
coupling

no chirality

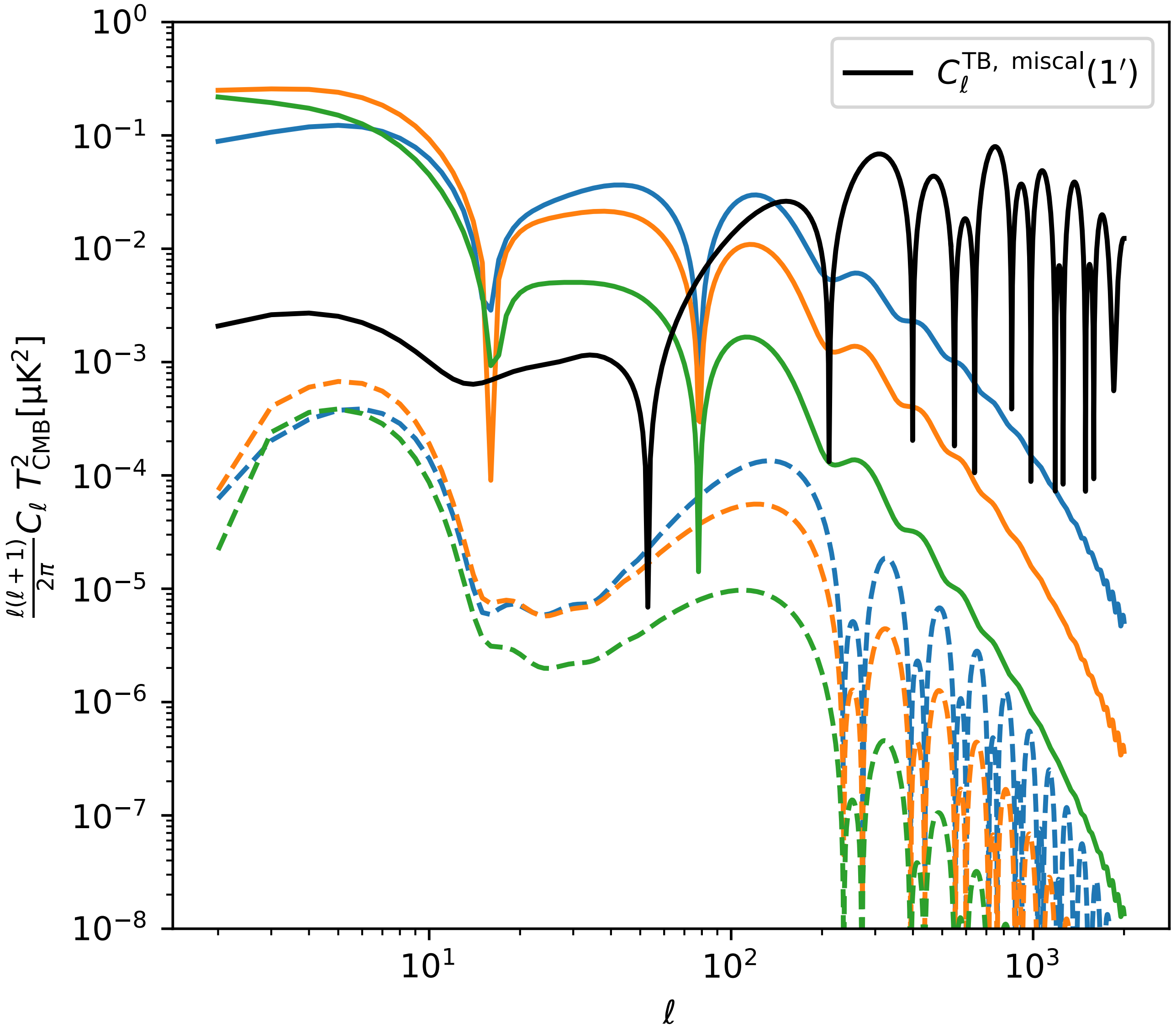
chirality

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

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

Chirality

LiteBIRD



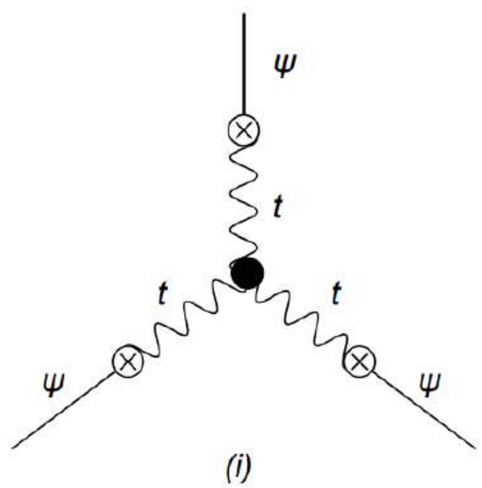
[Thorne, Fujita, Hazumi, Katayama, Komatsu, Shiraishi, 2017]

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

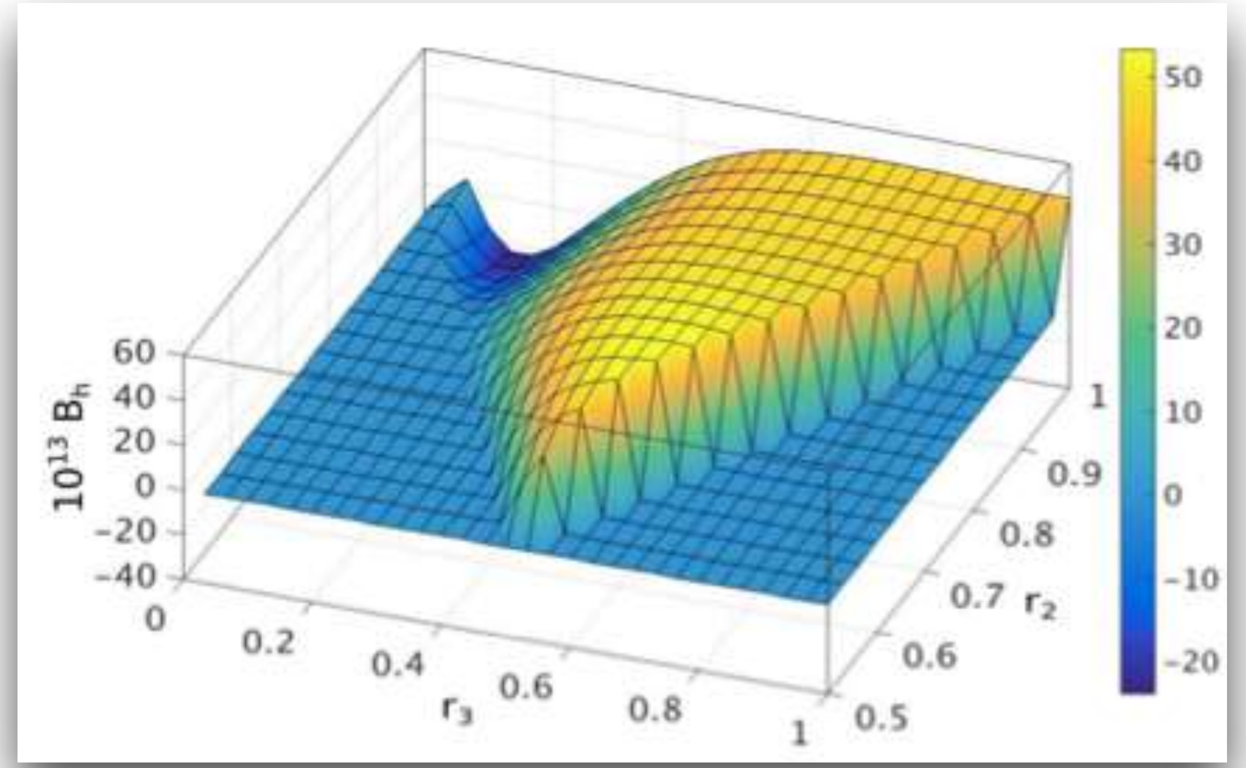
non-Gaussianity (TTT)

[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)



$m_Q = 3.45$
$\epsilon_B \simeq 10^{-5}$
$H \simeq 10^{13}$ 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

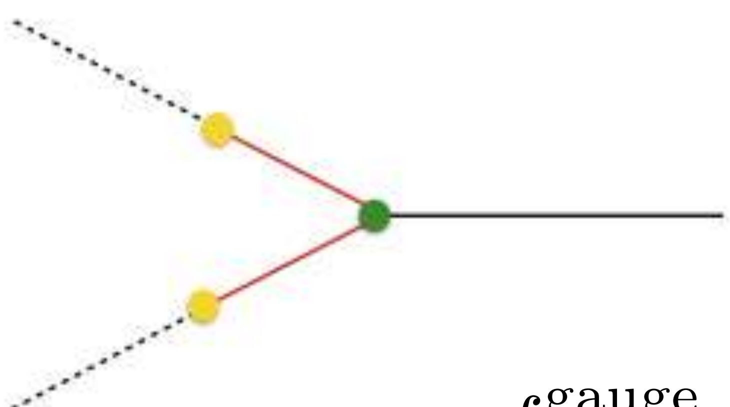
non-Gaussianity (STT)

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

[Dimastrogiovanni, MF, Hardwick, Koyama, Wands]

[Fujita, Namba, Obata]

several channels (e.g. mixing terms between scalars) contribute to STT



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

SCNI

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

completely agnostic
on the potential

==>

SC~~N~~I?

Higgsed Chromo

another way to rescue the model

[Adshead, Martinec, Sfakianakis, Wyman]

spontaneous breaking of the SU(2) gauge symmetry

Goldstones modes provide additional d.o.f.s

these contribute more to scalars, decrease r

Chromo + non-Minimal Coupling

- Mechanisms to slow the rolling without abandoning naturalness

Einstein tensor

$$S = \int \mathrm{d}^4 x \sqrt{-g} \left[\frac{M_{\mathrm{Pl}}^2}{2} R - \frac{1}{2} \left(g^{\mu\nu} - \frac{G^{\mu\nu}}{M^2} \right) \partial_\mu \chi \partial_\nu \chi - V(\chi) - \frac{1}{4} F^{a\mu\nu} F^a_{\mu\nu} + \frac{\lambda \chi}{8 f \sqrt{-g}} \epsilon^{\mu\nu\rho\sigma} F^a_{\mu\nu} F^a_{\rho\sigma} \right]$$

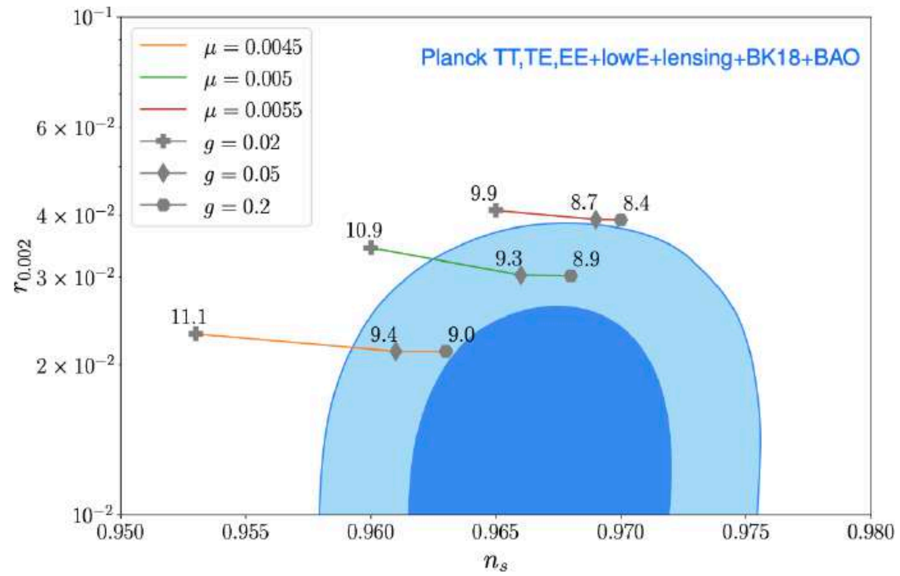
[Dimastrogiovanni, MF, Michelotti, Pinol 2023]



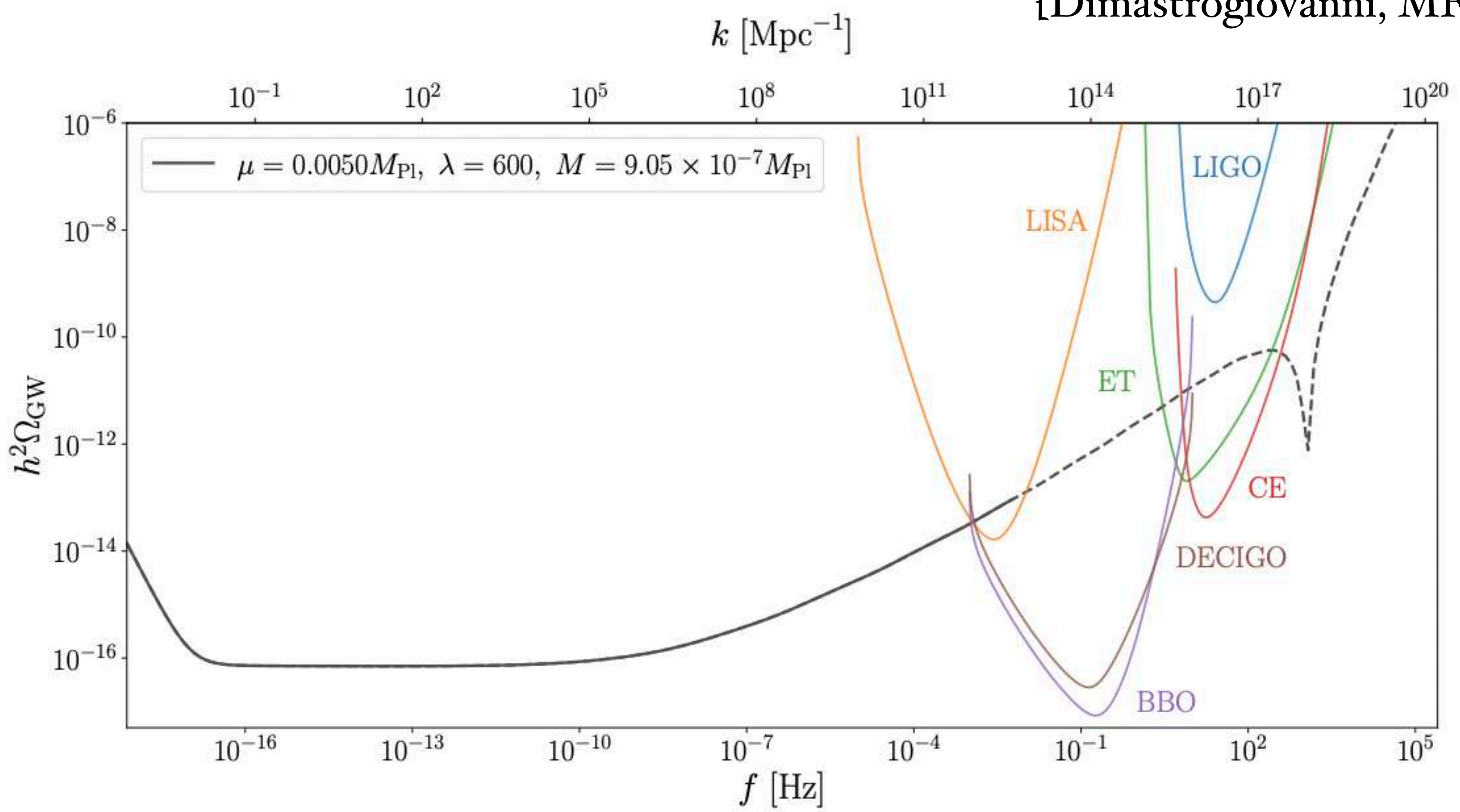
[see also Komatsu and Watanabe 2020]

more general coupling but w/o potential (kinetically driven)

Chromo + non-Minimal Coupling



[Dimastrogiovanni, MF, Michelotti, Pinol 2023]



* Optimistic with backreaction

Appeal of axion-gauge field models

Model Building

"simple" ingredients

eta problem

UV complet-able

scale-dependence

non-Gaussianity

chirality

PBHs for U(1)!

Testing

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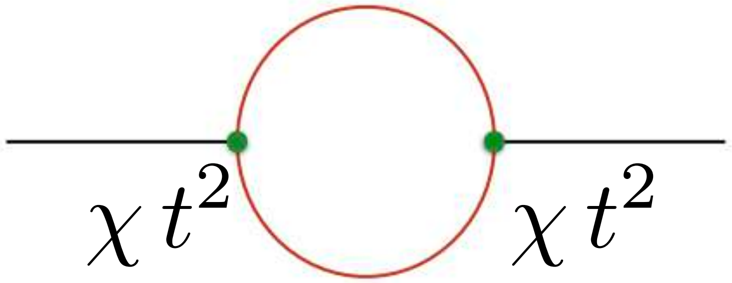
Challenge I: Perturbativity

(SCNI case)



the same interaction enhancing sourced GW affects the 1-loop scalar PS

From $P_\zeta^{\rm tree} \gg P_\zeta^{\rm 1-loop}$ or at least $P_\zeta^{\rm n} \gg P_\zeta^{\rm n+1}$ from a given *n* onwards

strong constraints on parameter space

====>

in SCNI sourced GW signal can be > vacuum but no more than 1 order of magnitude

[Dimastrogiovanni, MF, Hardwick, Assadullahi, Koyama, Wands 2018]

[Papageorgiou, Peloso, Unal 2018 & 2019]

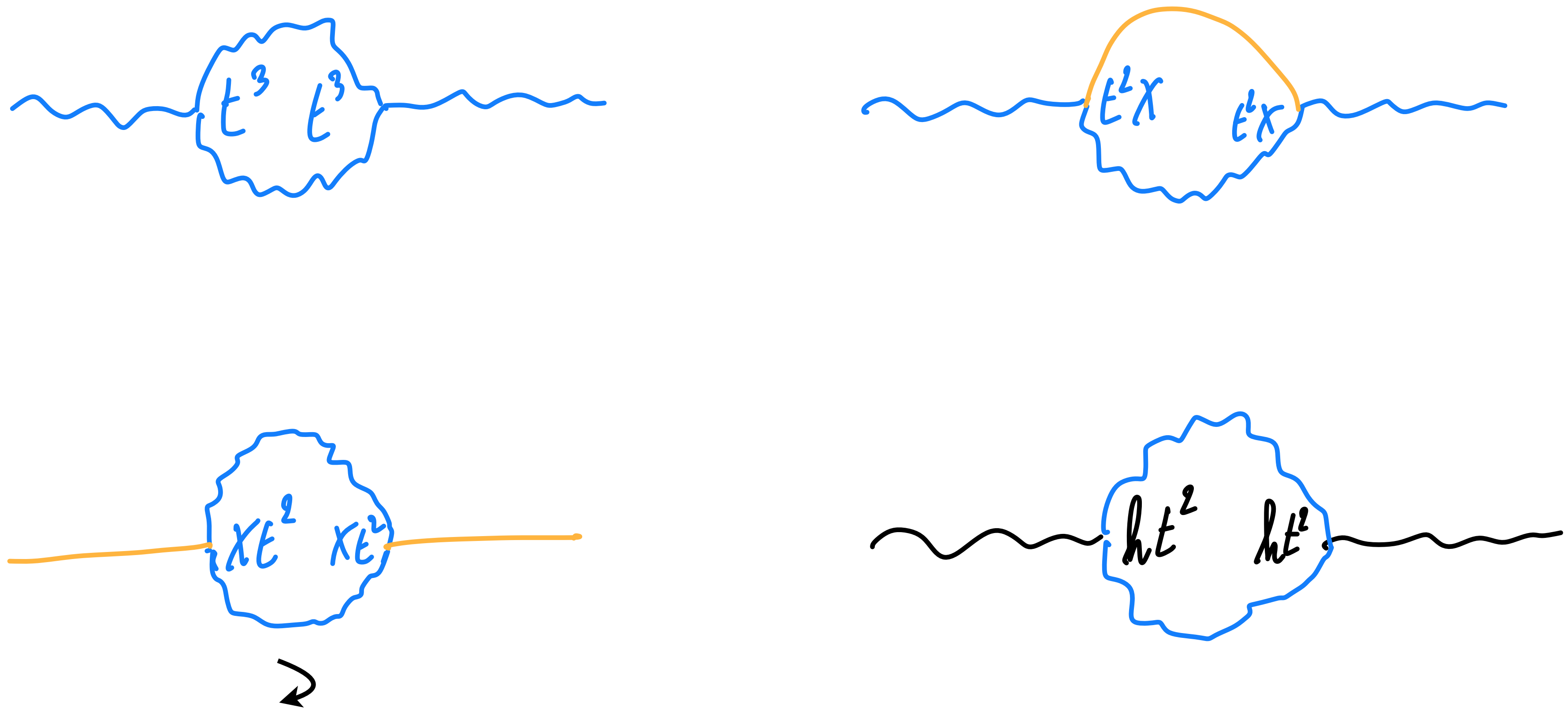
in similar context see also [Ferreira, Ganc, Noreña, Sloth 2015]

- (mostly CMB) bounds on non-Gaussianity play a similar role

Challenge I: Perturbativity

(non-minimal CNI case)

Perturbativity and primordial non-Gaussianity bounds on all axion-gauge field models

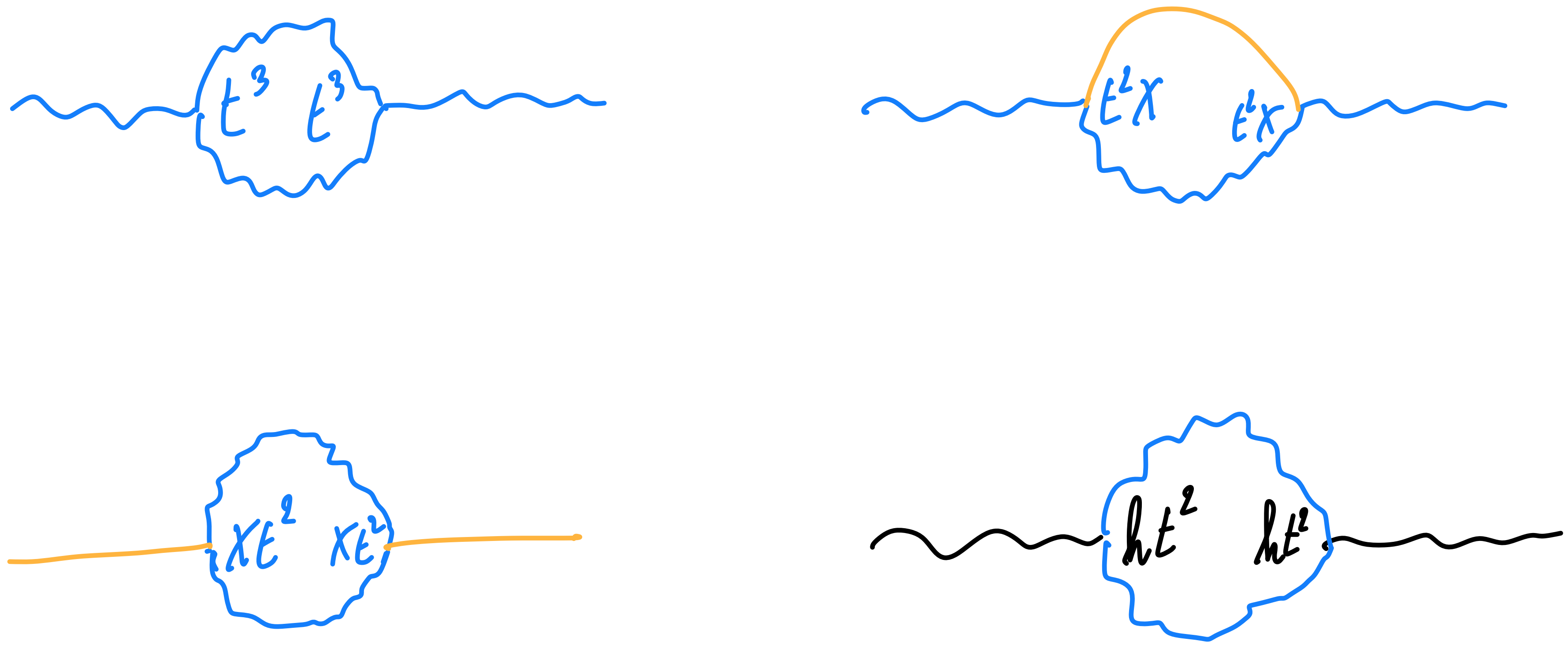


[Dimastrogiovanni, MF, Michelotti, Ozsoy, **to appear**]

Challenge I: Perturbativity

Perturbativity and primordial non-Gaussianity bounds on all axion-gauge field models



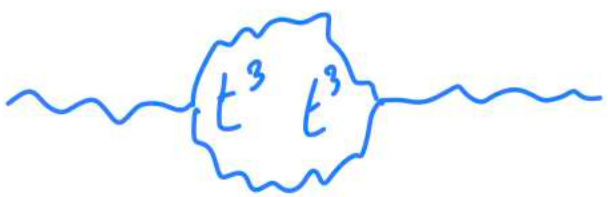
[Dimastrogiovanni, MF, Michelotti, Ozsoy, **to appear**]

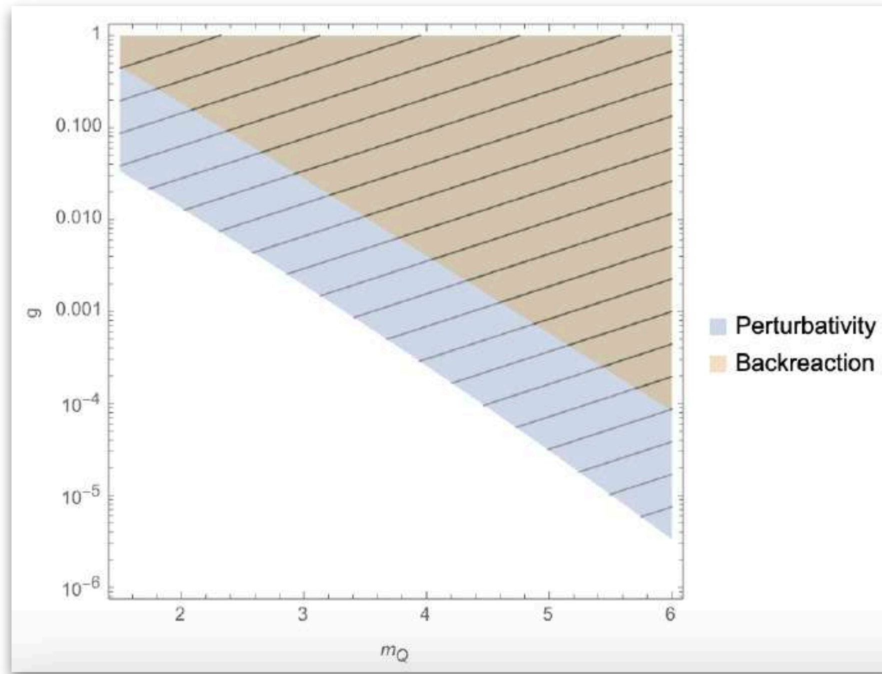


analogous diagram, just $t_{ij} \leftrightarrow A_\mu$ to go from non-Abelian to Abelian

Challenge I: Perturbativity

(non-Abelian case)





backreaction via
rough analytical estimate

most stringent bound,
largely insensitive to potential,
indirectly dependent on λ

universal behaviour in the non-Abelian case

[Dimastrogiovanni, MF, Michelotti, Ozsoy, **to appear**]

Challenge II: Backreaction

(SCNI case)

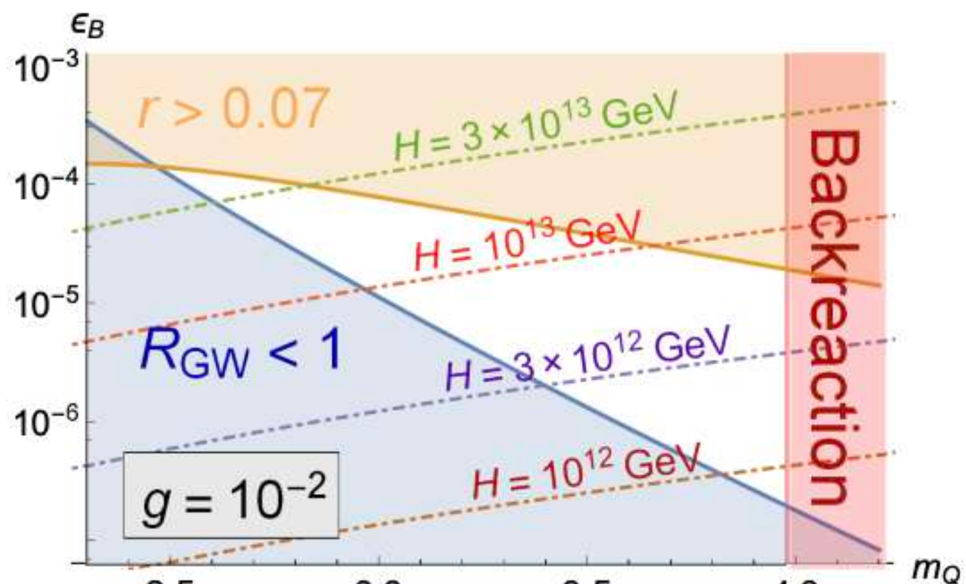
eom for the gauge field background

$$\ddot{Q} + 3H\dot{Q} + \left(\dot{H} + 2H^2\right)Q + 2g^2Q^3 = \frac{g\lambda}{f}\dot{\chi}Q^2 + \ldots$$

(same goes for χ e.o.m.)

fluctuations backreact on background ==> reduced regime of validity

$$\mathcal{T}^{Q}_{BR} \equiv \frac{g\xi}{3a^2}H\int\frac{\mathrm{d}^3k}{(2\pi)^3}|t_R|^2 + \frac{g}{3a^2}\int\frac{\mathrm{d}^3k}{(2\pi)^3}\frac{k}{a}|t_R|^2$$



[Dimastrogiovanni, MF, Fujita]

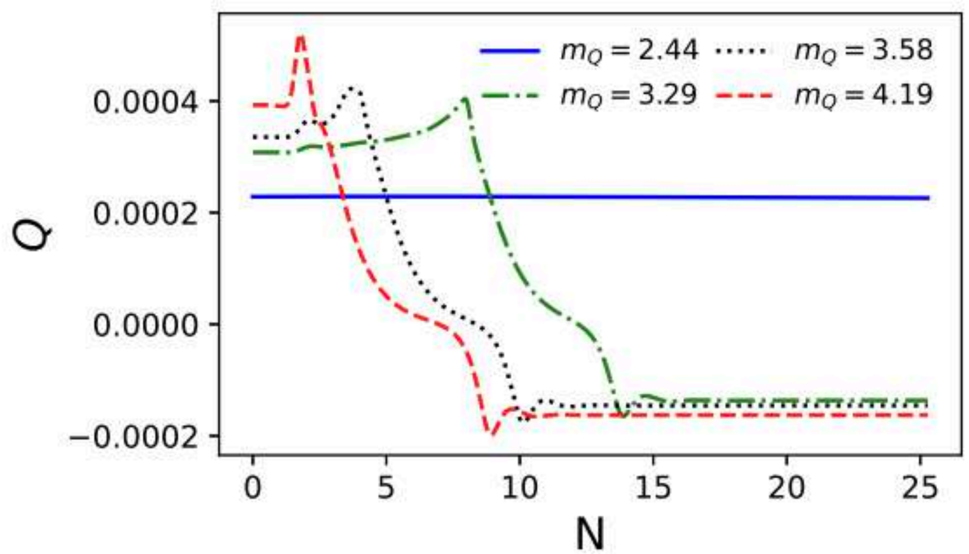
[Mirzagholi, Maleknejad, Lozanov 2020]

[Maleknejad, Komatsu 2018]

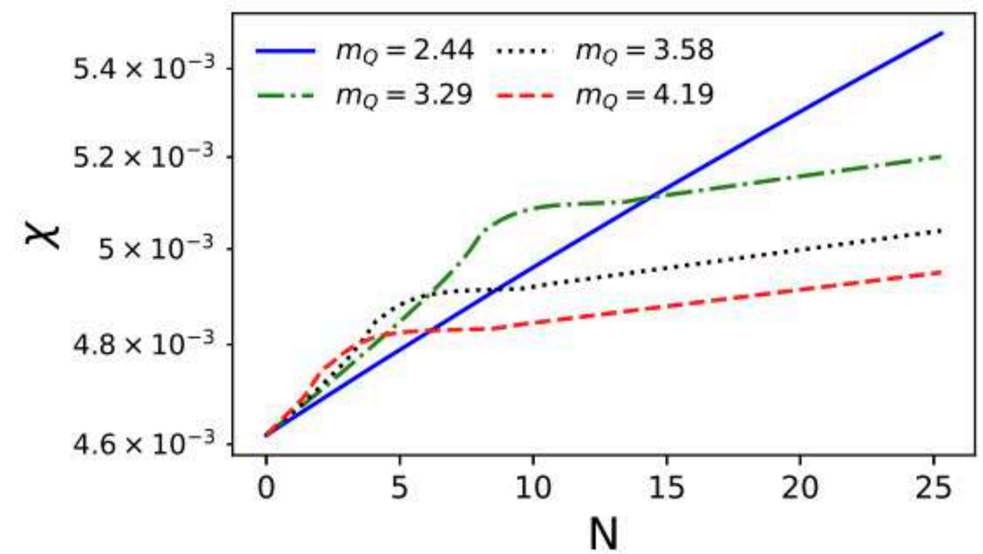
[Ishiwata, Komatsu, Obata 2021]

Challenge II: Backreaction

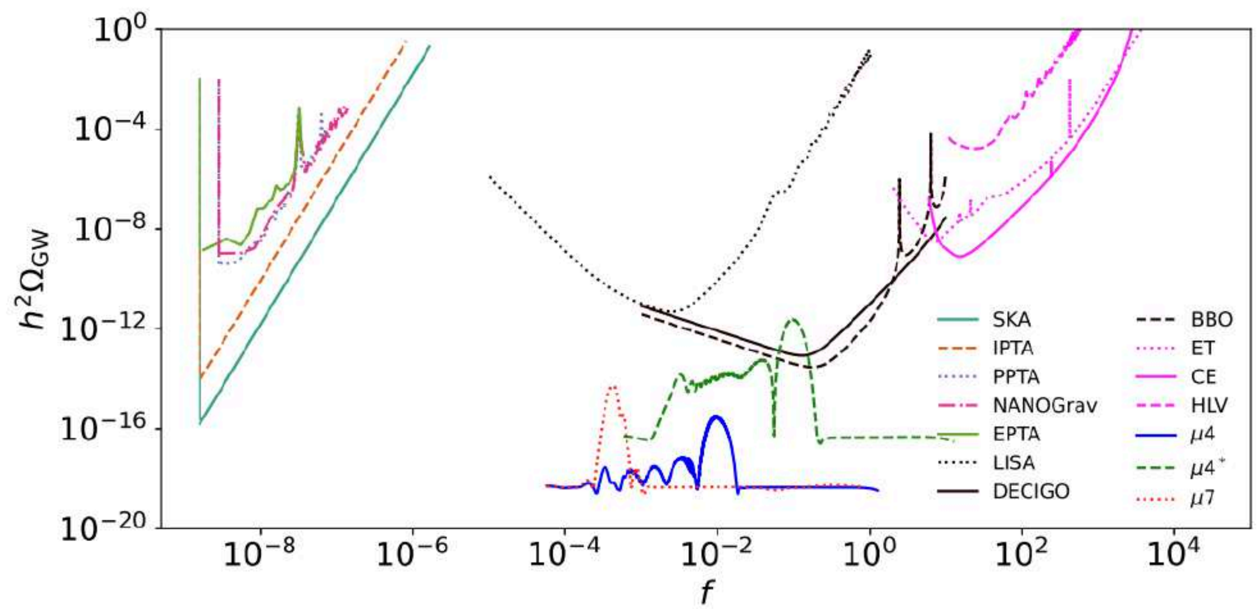
SCNI case, very interesting recent numerical* work



new attractor solution for Q



[Iarygina, Sfakianakis, Sharma, Brandenburg 2023]



GW signatures

[Iarygina, Sfakianakis, Sharma, Brandenburg 2023]

* $\mathcal{T}_Q$ and $\mathcal{T}_\chi$ and their interplay considered now, homogeneous inflaton background remains an assumption

see also [Ishiwata, Komatsu,Obata 2022]

full U(1) studied on the lattice
- [Caravano, Komatsu, Lozanov, Weller x 3]
- [Figueroa, Lizarraga, Urio, Urrestilla 2023]

Challenge III: UV Completion

(SCNI case)

field content easily obtained, key is strength of CS interaction, i.e. λ

interesting GW phenomenology requires $\lambda > 100$

very hard to obtain in clockwork mechanisms
[Agrawal, Fan, Reece 2018]
[Kim, Nilles, Peloso 2004]

(less yet non-trivially) constrained on more general unitarity grounds
[Agrawal, Fan, Reece 2018]
[Bagherian, Reece, Xu 2022]

nevertheless possible in string theory
[Holland, Zavala, Tasinato 2020]

Multiple Abelian Spectator Sectors

[Dimastrogiovanni, MF, Leedom, Putti, Westphal 2023]

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crucial caveat

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how well my collaborators understand the string theory part

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Multiple Abelian Spectator Sectors

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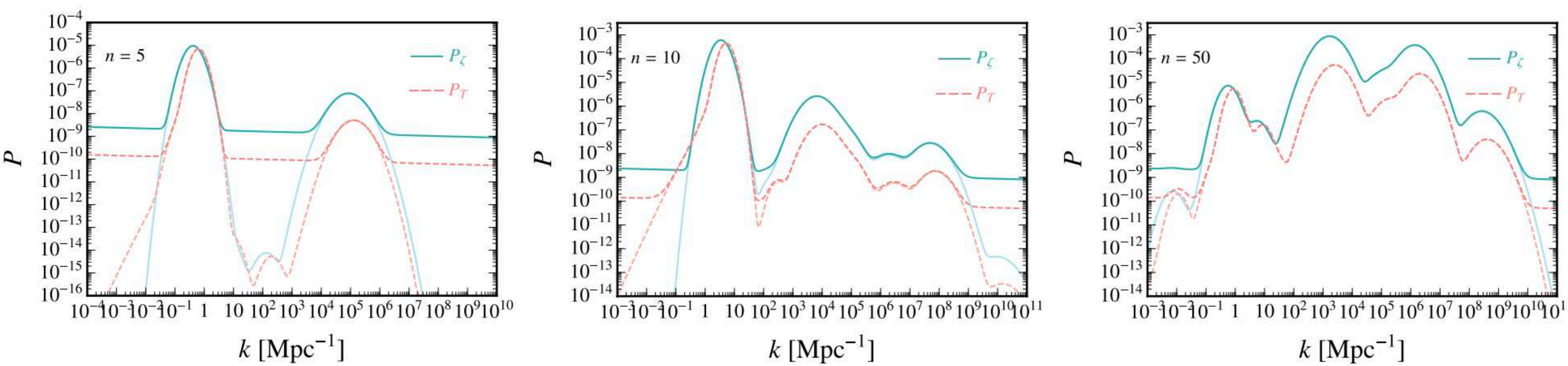
crucial caveat

my level

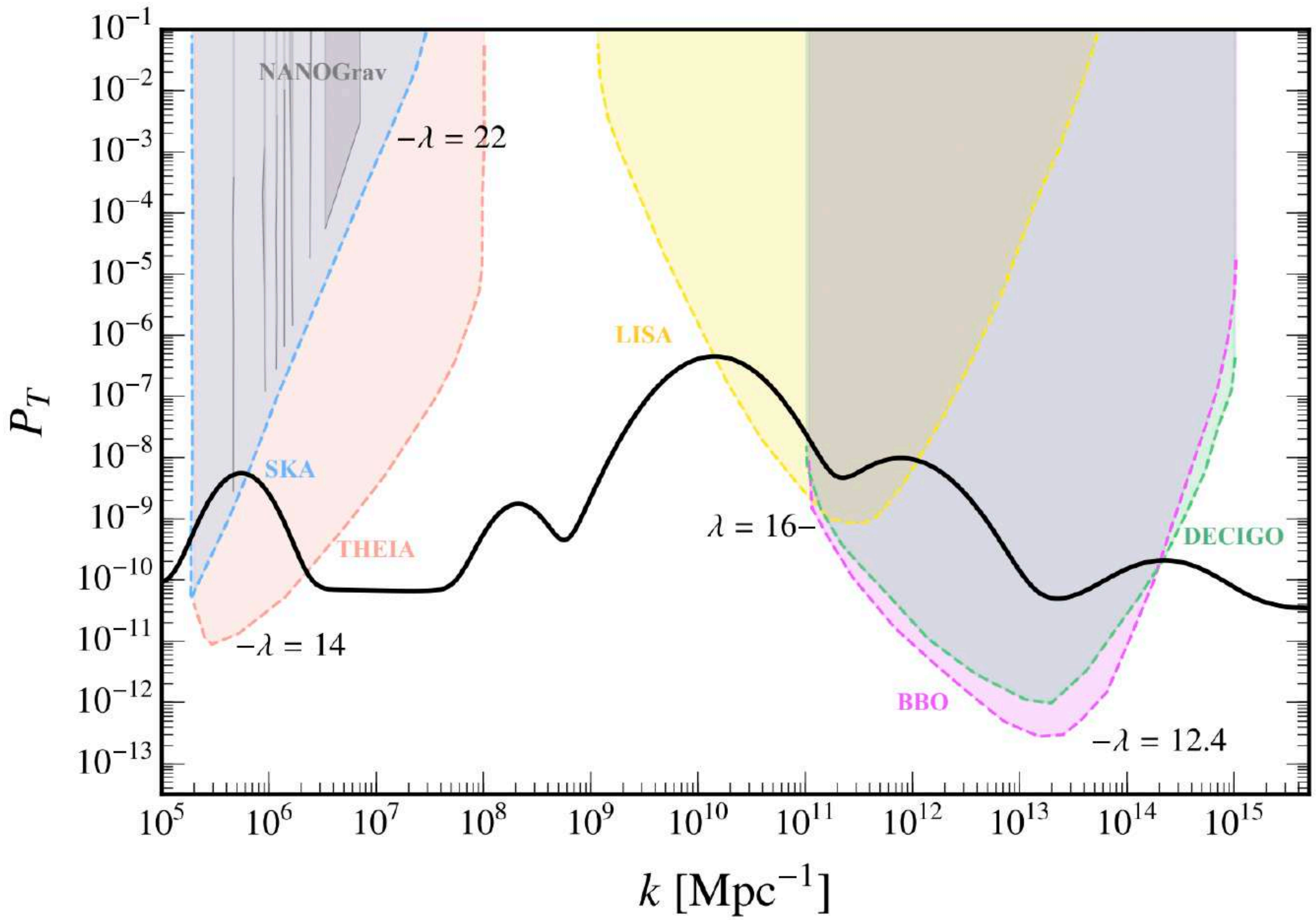
Multiple Abelian Spectator Sectors

$$-\frac{1}{2}(\partial\varphi)^2 - V_{inf}(\varphi) - \frac{1}{4}F_{ia\mu\nu}F_i^{a\mu\nu} - \frac{1}{2}(\partial\chi_i)^2 - V_{S_i}(\chi_i) - \frac{\lambda_i}{4f_i}\chi_i\, F_{ia\mu\nu}\tilde{F}_i^{a\mu\nu}$$

scalar (blue) & tensor (red) fluctuations



Multiple Abelian Spectator Sectors



10 fields, ad hoc initial conditions, Abelian case

Naturalness of CS couplings is MASA models

phenomenological "needs"
(*caveat from backreaction!)

Abelian: $\lambda \sim 20$

non-Ab: $\lambda \sim \text{a few} \times \mathcal{O}(100)$

Abelian case

detectable GW from
orientifold-odd 2-form axion spectators

[Dimastrogiovanni, MF, Leedom, Putti, Westphal 2023]

non-Ab case

N ~ 10^5 D7-branes (i.e. fine tuning)

[Holland, Zavala, Tasinato 2020]

Thank you!