Testing axion-inflation with LISA

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IFT Madrid

"LISA Spain Meeting"
October 16th 2024, Barcelona

Based on works with Dimastrogiovanni, Fujita, Leedom, Michelotti, Ozsoy, Papageorgiou, Pinol, Putti, Wands, Westphal, Zenteno

Inflation, the minimal paradigm, SFSR

Simplest realization: single-scalar field in slow-roll

- Scalar field :

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

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

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

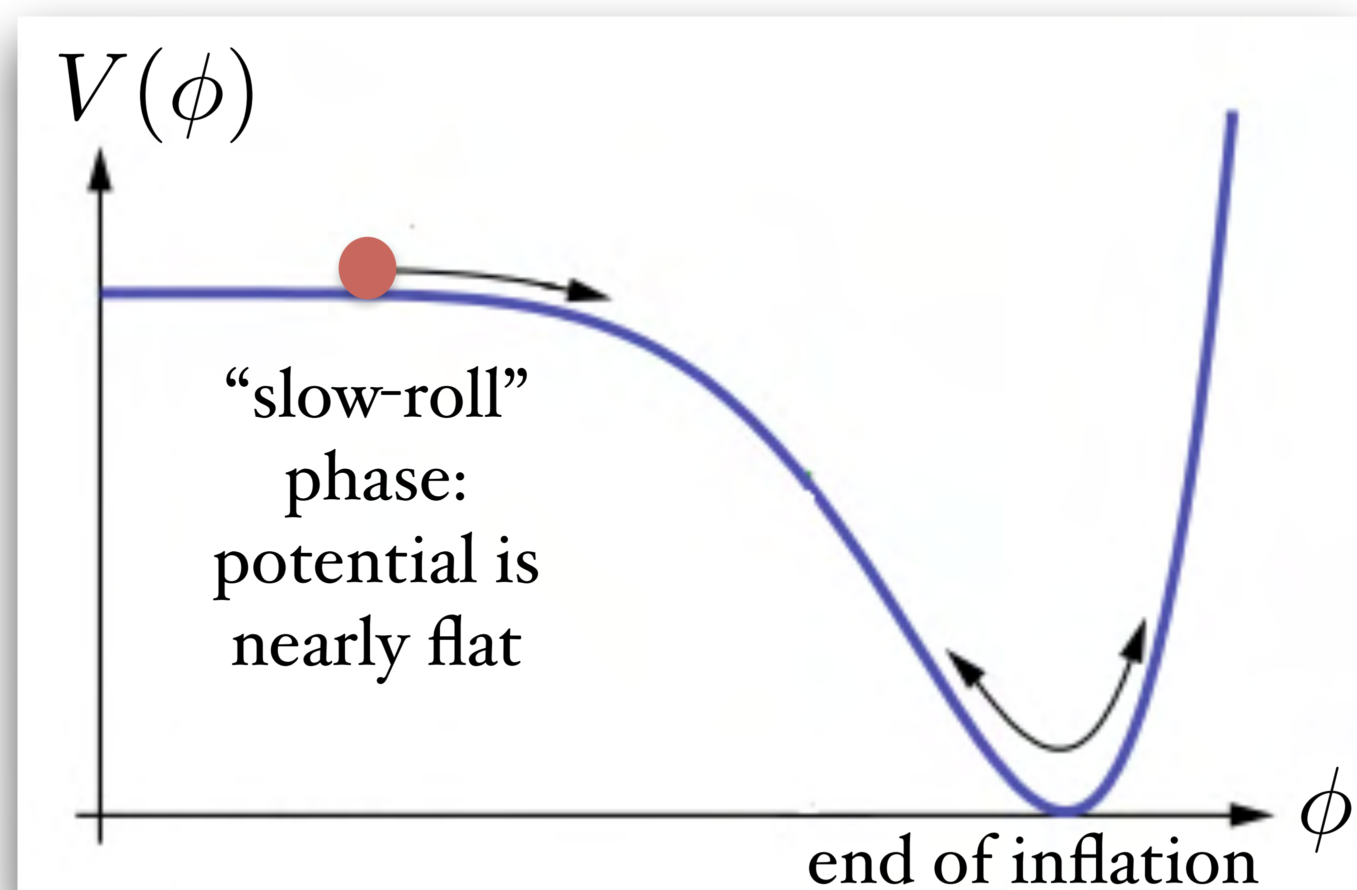
$$p_\phi \approx -\rho_\phi$$

start flat

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

stay flat

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



Primordial Fluctuations

(minimal scenario)

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

scalar fluctuations (2ζ)

tensor perturbations (γ_{ij})

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

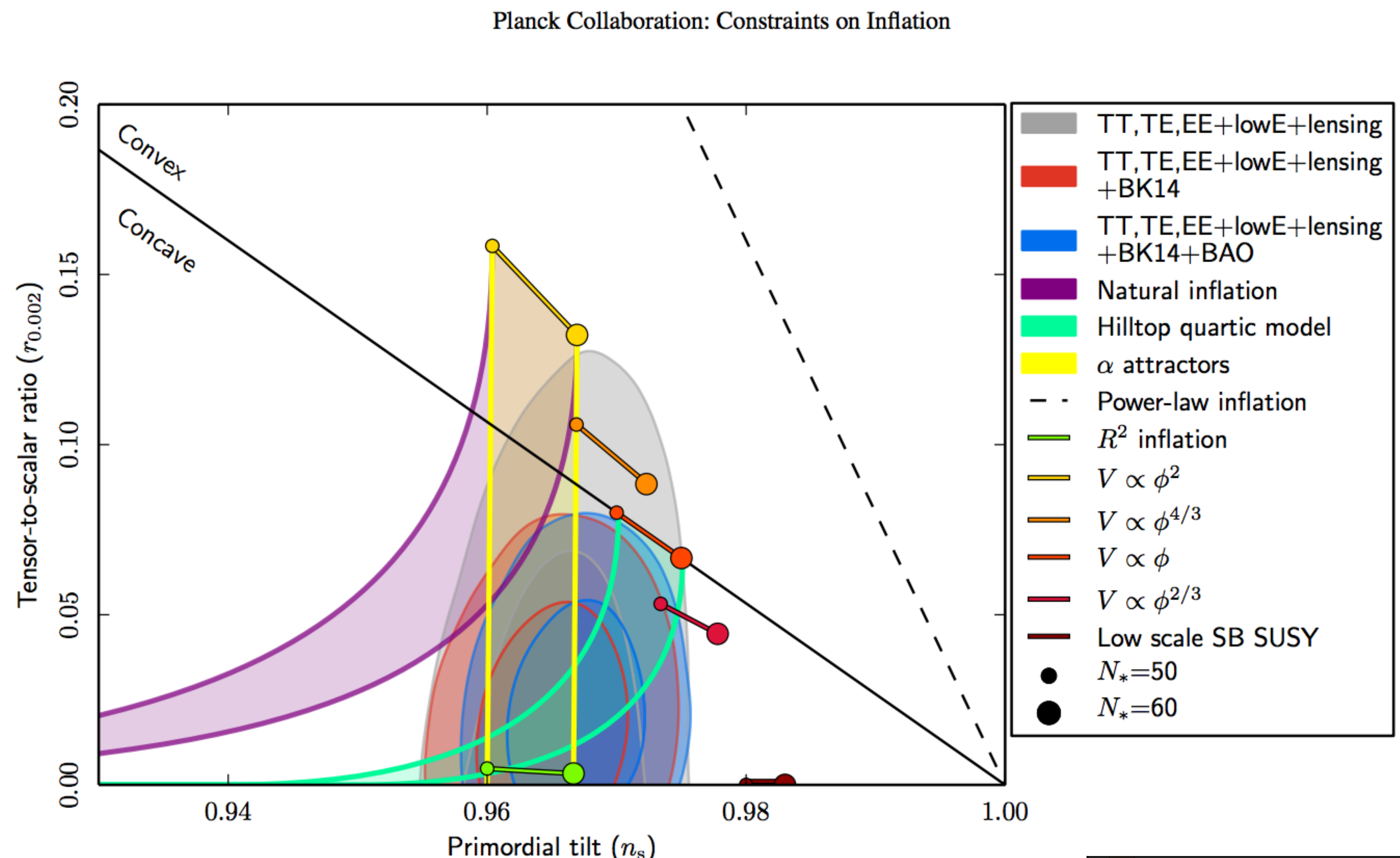
$r < 0.032\,(95\%\mathrm{CL}, \mathrm{Planck}^+)$

future

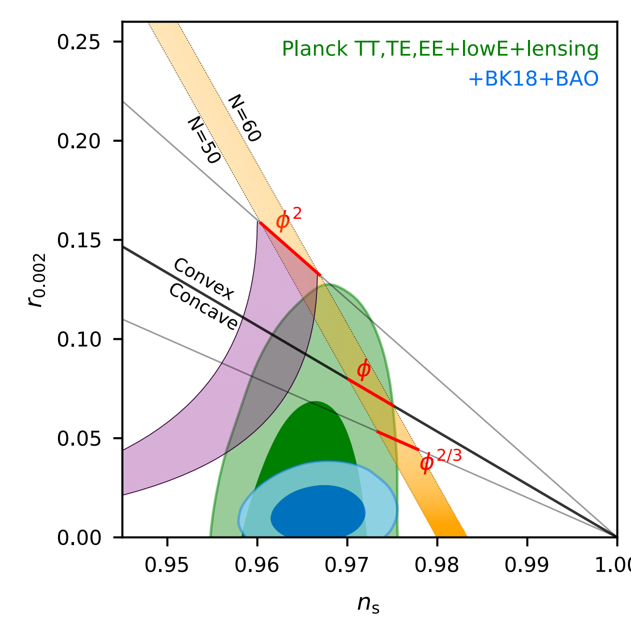
$r < 0.01$ (CMB-S3); $r < 0.001$ (-S4)

LiteBIRD

@ CMB scales



+BK update:



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
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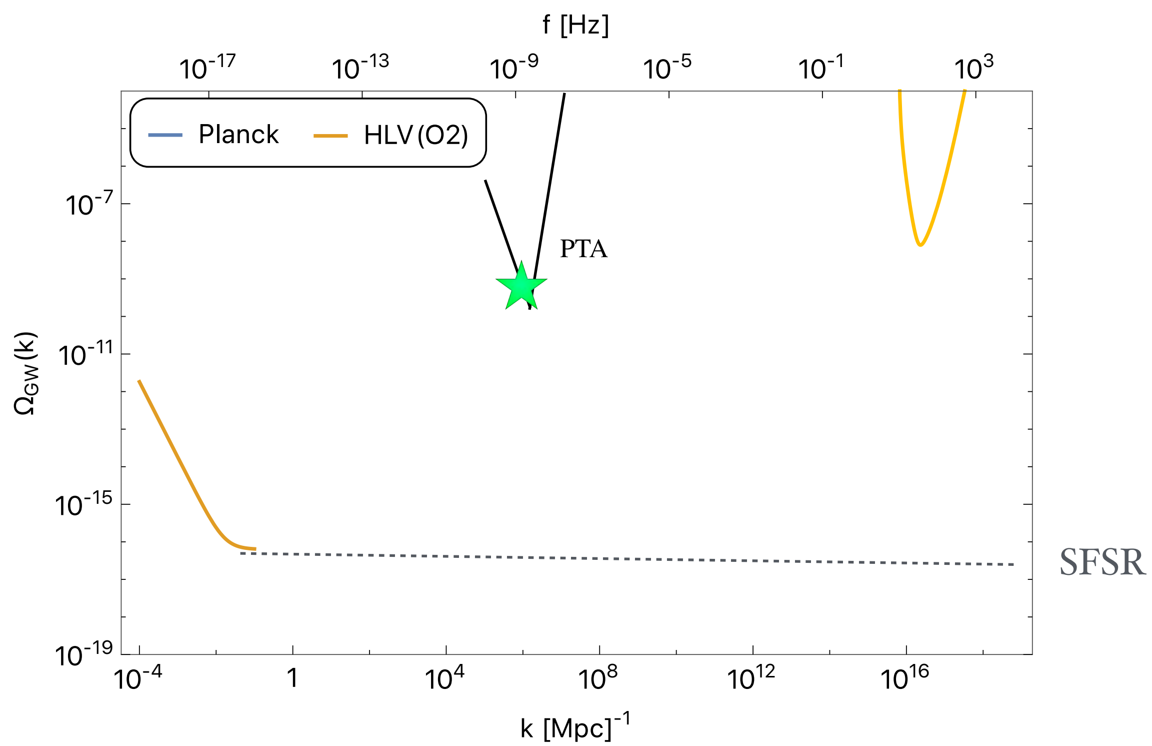
viable ones

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

Hope for a little more (GW)

now



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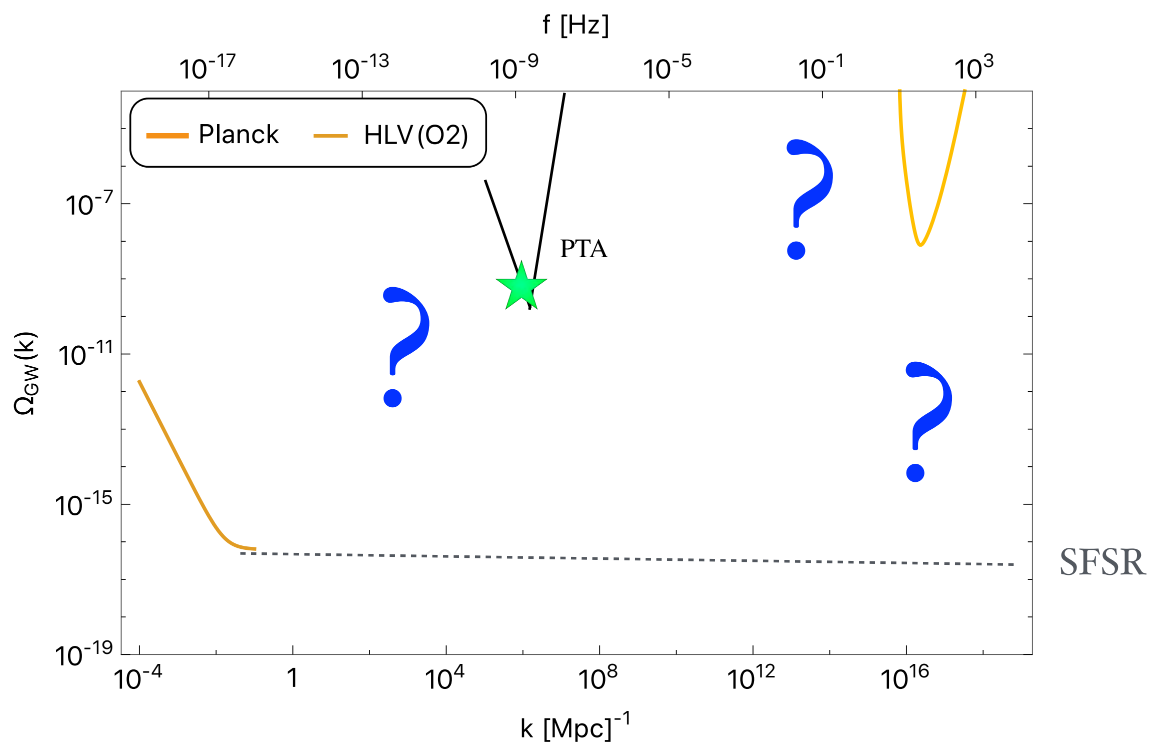

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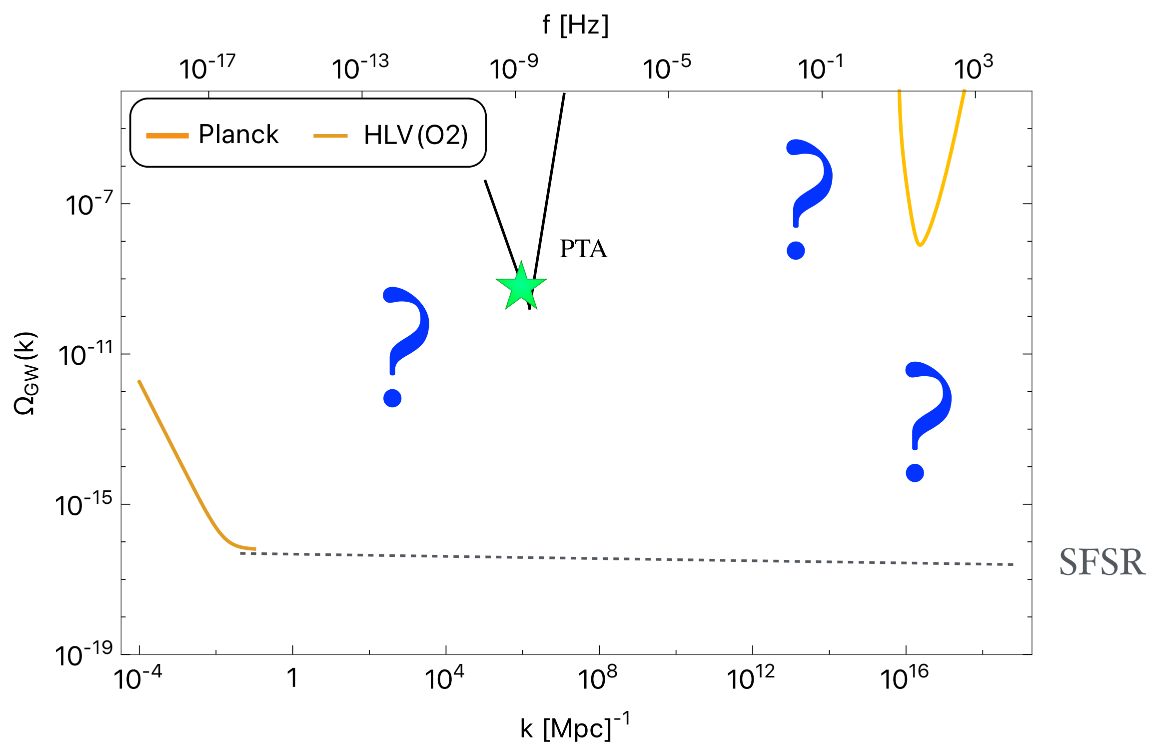
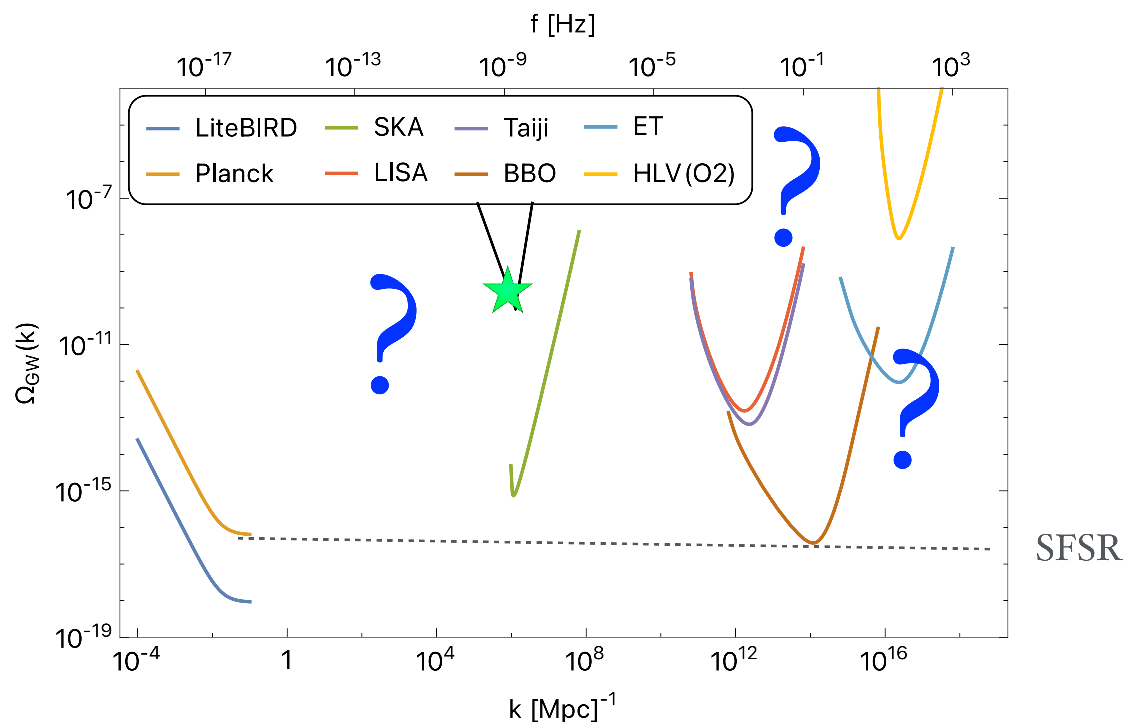


soon



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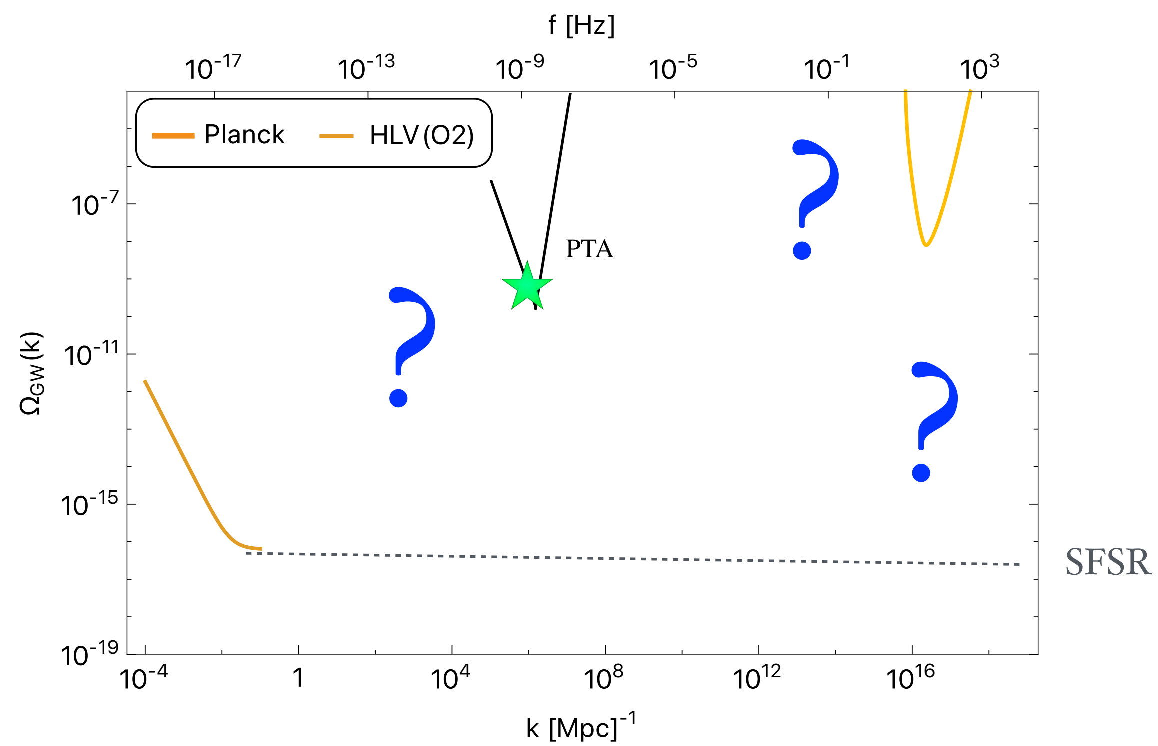
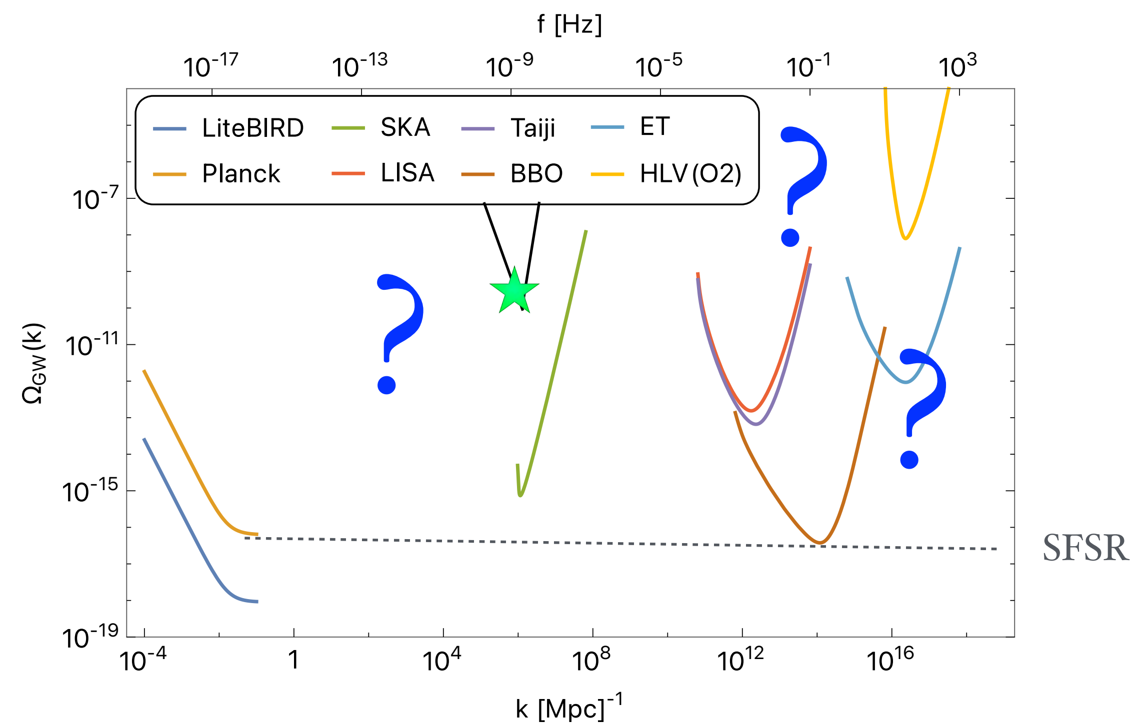


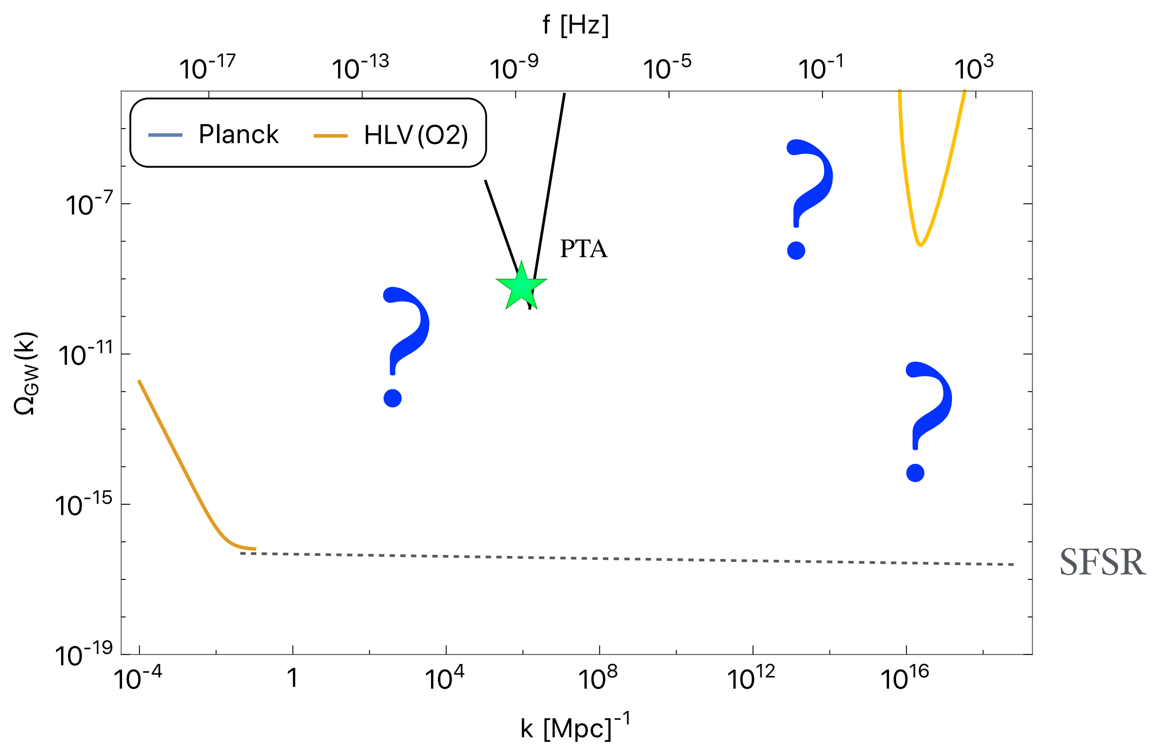
soon



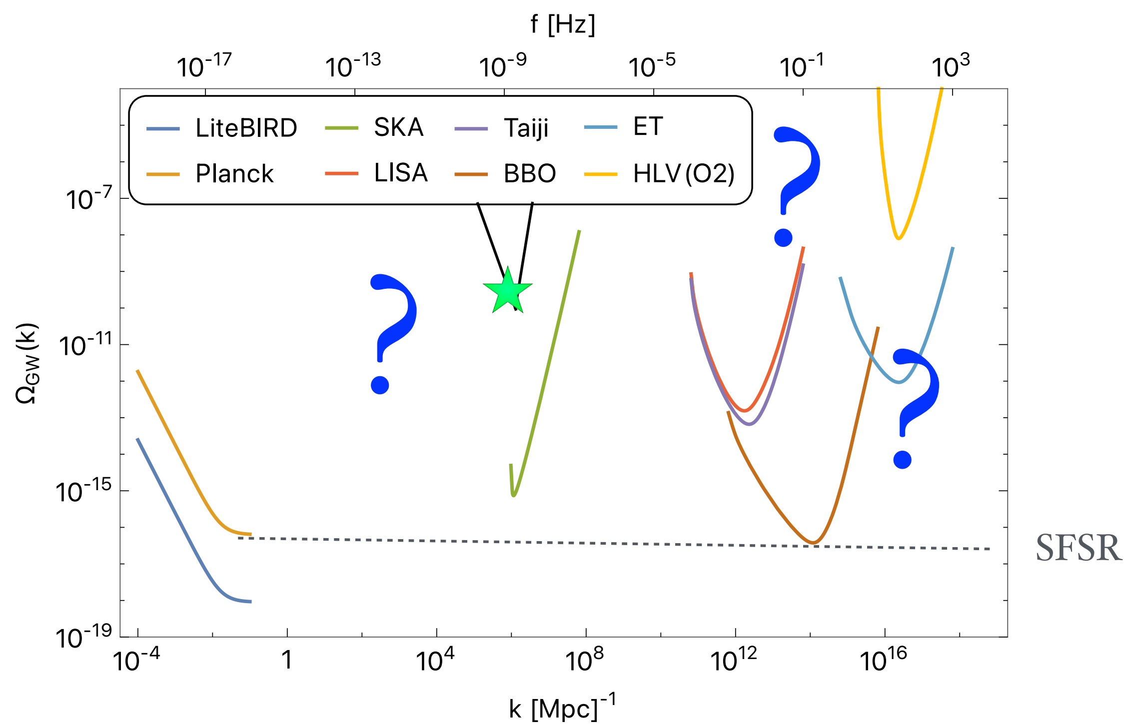
features

Hope for a little more (GW)

now



soon



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

Typically multiple fields required

why go beyond 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

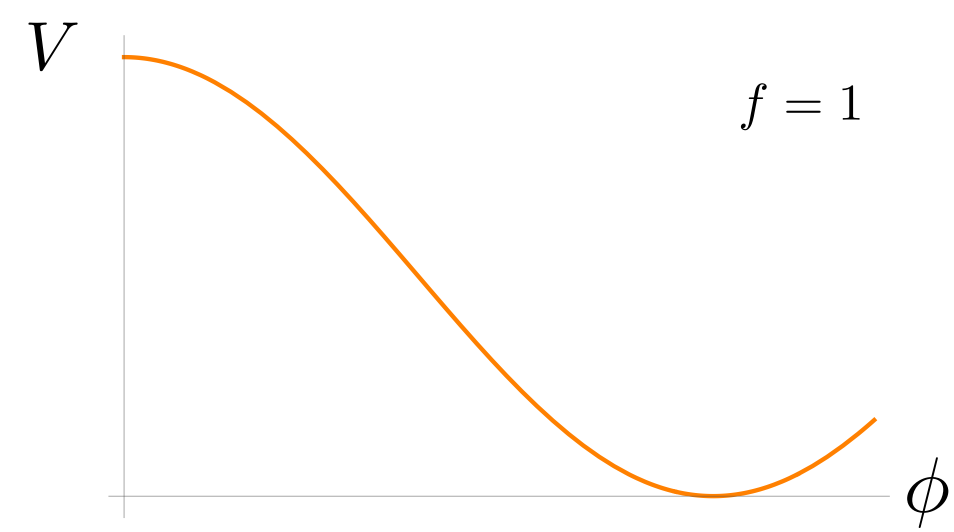
what to infer from
GW detection?
e.g. r <—> H relation

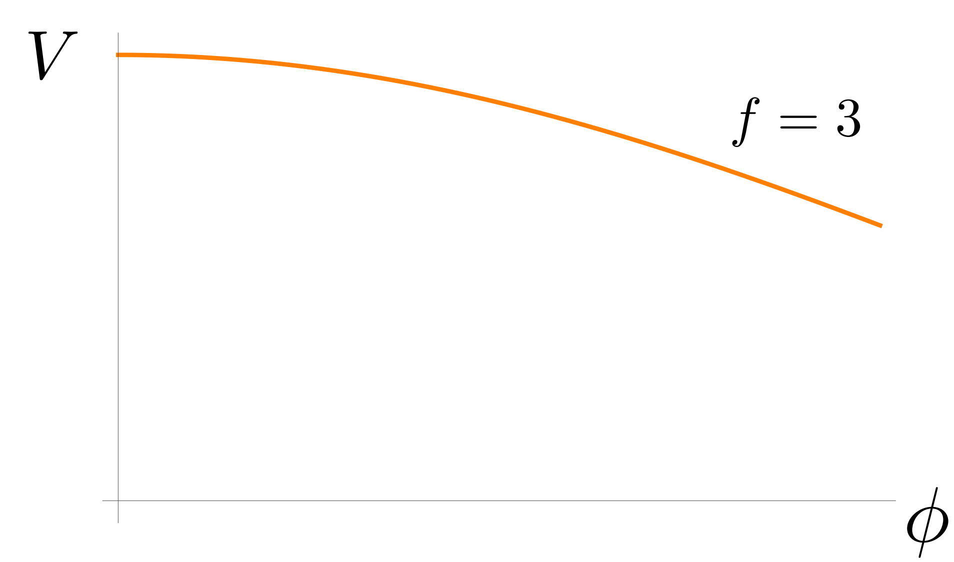
Natural Inflation

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

[Freese, Frieman, Olinto]

axion-like potential





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

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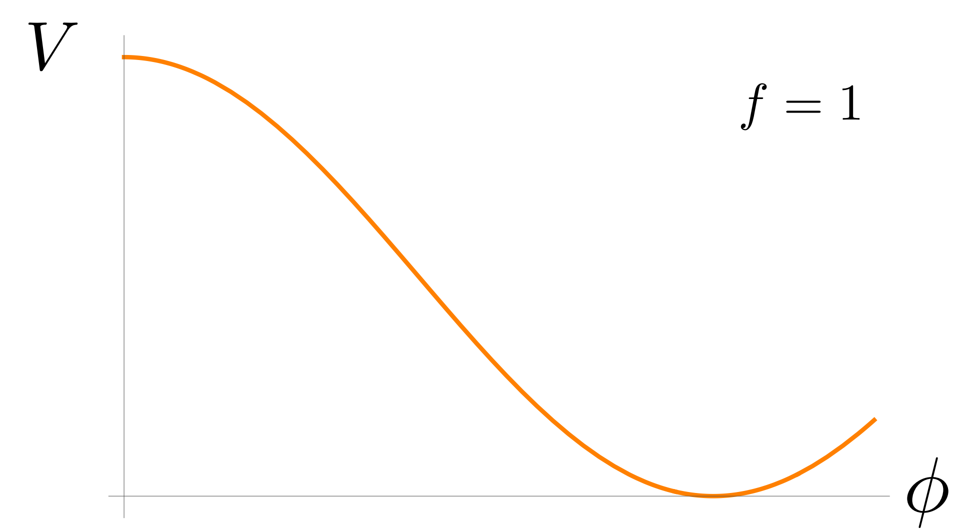

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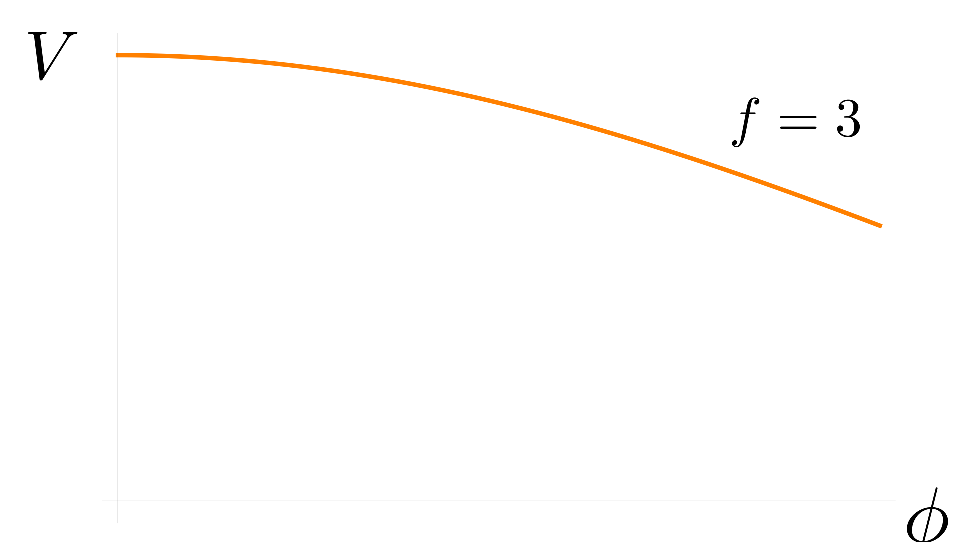
now ruled out



Natural Inflation + Gauge Sector

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

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

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

Natural Inflation + Gauge Sector

general properties

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

SU(2)

U(1)

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

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

Adshead & Wyman

Anber & Sorbo

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Gauge fields source GW, chiral signal if leading

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Adshead & Wyman

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Interferometer tests for chirality
- cross-correlation @ different locations [Smith, Caldwell 2017]
- kinematically induced dipole [Seto 2006, Domcke et al 2019]

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

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- ξ regulates the growth ==> possible blue spectrum

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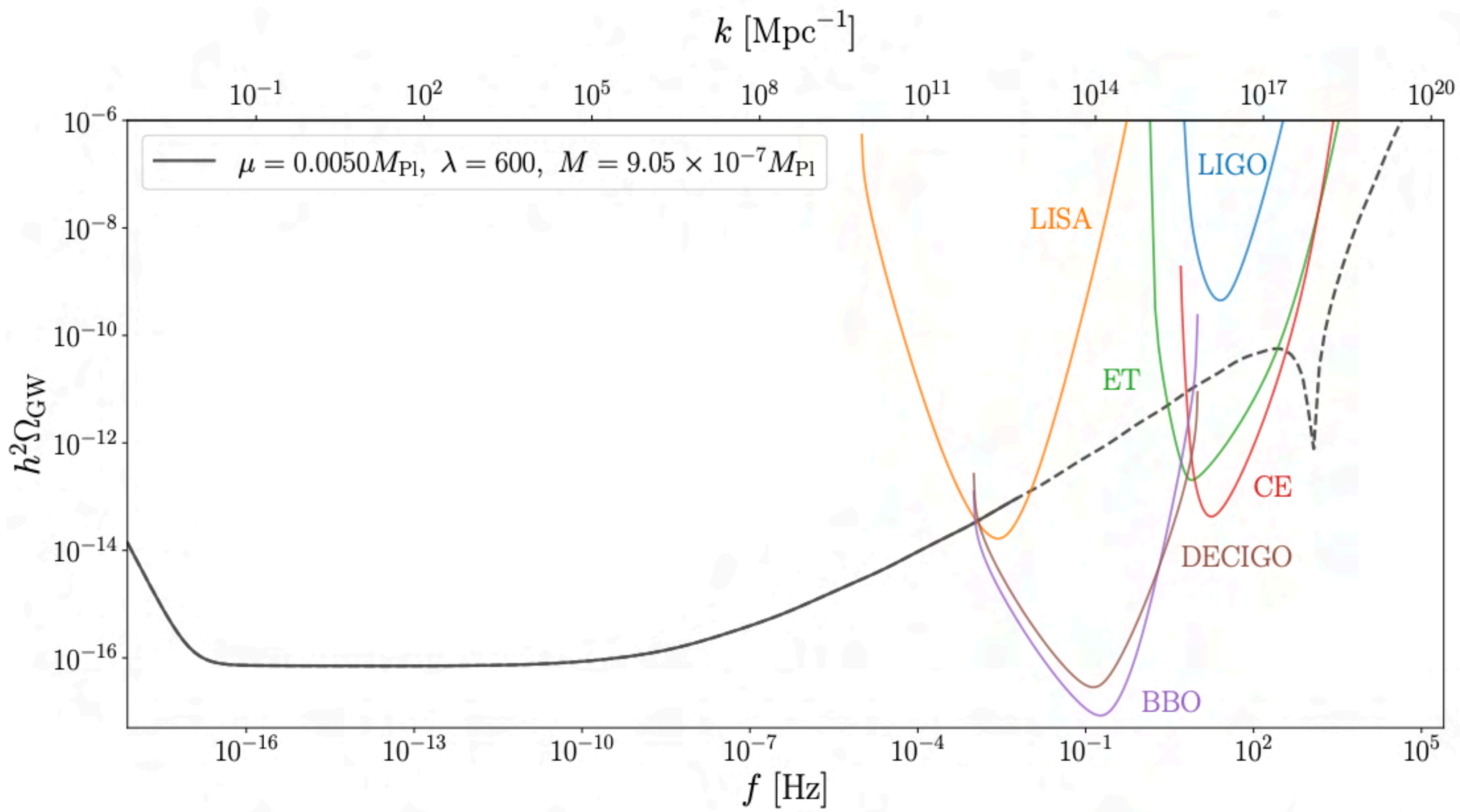
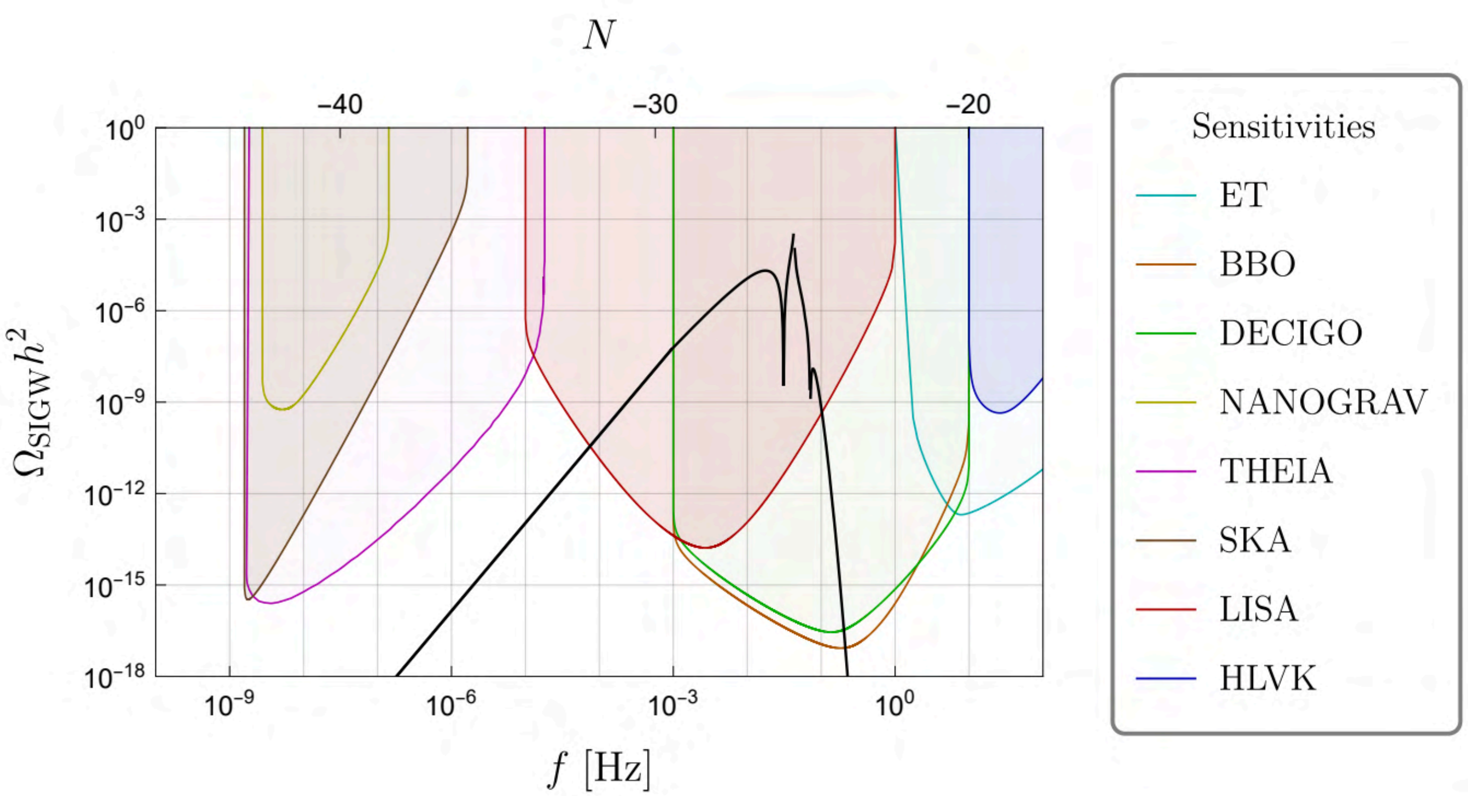
i.e. LISA tests !

e.g.

blue



peaked



Not easy to keep things minimal/simple

Chromo Natural Inflation

SU(2)

[Adshead, Wyman]

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

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

◆ $f \ll M_{\rm P}$ realization

very interesting GW signatures !

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[...]

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

~~Chromo~~ Natural Inflation

U(1)

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◆ $f \ll M_{\text{P}}$ realization

very interesting GW signatures !

$\mathcal{N} \sim 10^5$ gauge fields

U(1)

Spectator Chromo Natural Inflation

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

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

SU(2)

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

Spectator Chromo Natural Inflation

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

[Garcia-Bellido, Peloso, Unal]

U(1)

Primordial GW in SCNI

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

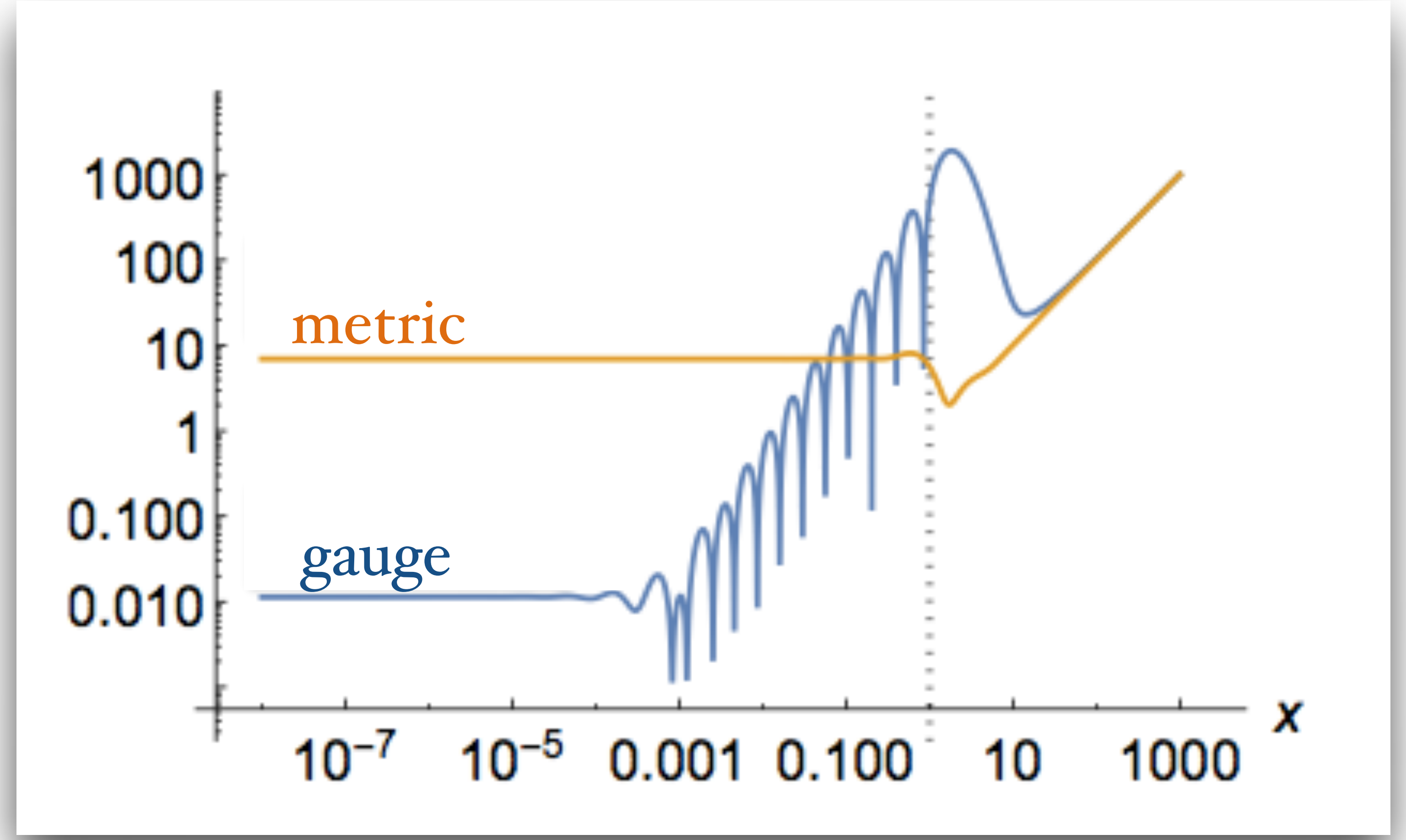
$$\text{SU(2)} \begin{cases} A_0^a = 0 \\ A_i^a = aQ\delta_i^a \\ \delta A_i^a = t_{ai} + \dots \end{cases}$$

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

[Dimastrogiovanni, MF, Fujita]

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

now possible!



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

SCNI

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

agnostic
on the potential

==> SC~~N~~I?

Chromo + non-Minimal Coupling

- Mechanisms to slow the rolling without abandoning naturalness

Einstein tensor

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

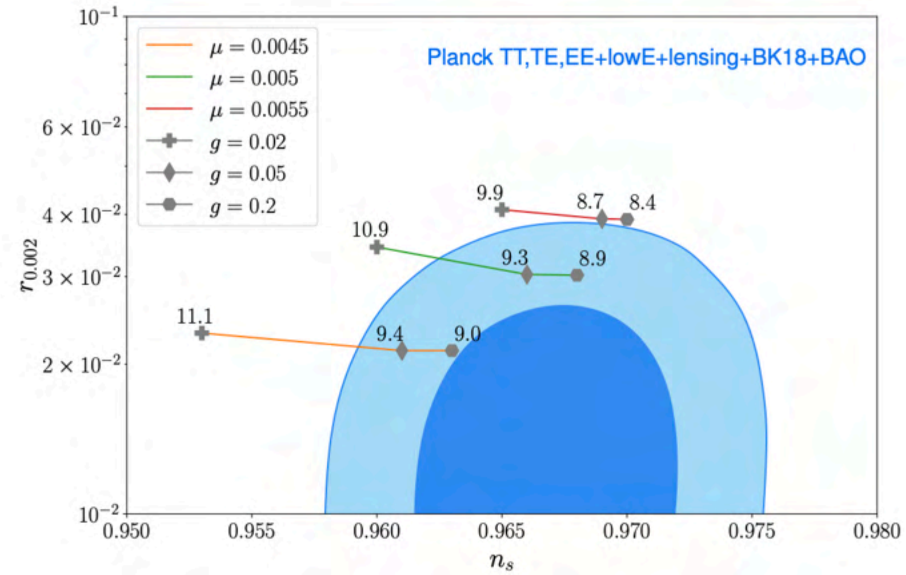
[Dimastrogiovanni, MF, Michelotti, Pinol 2023]



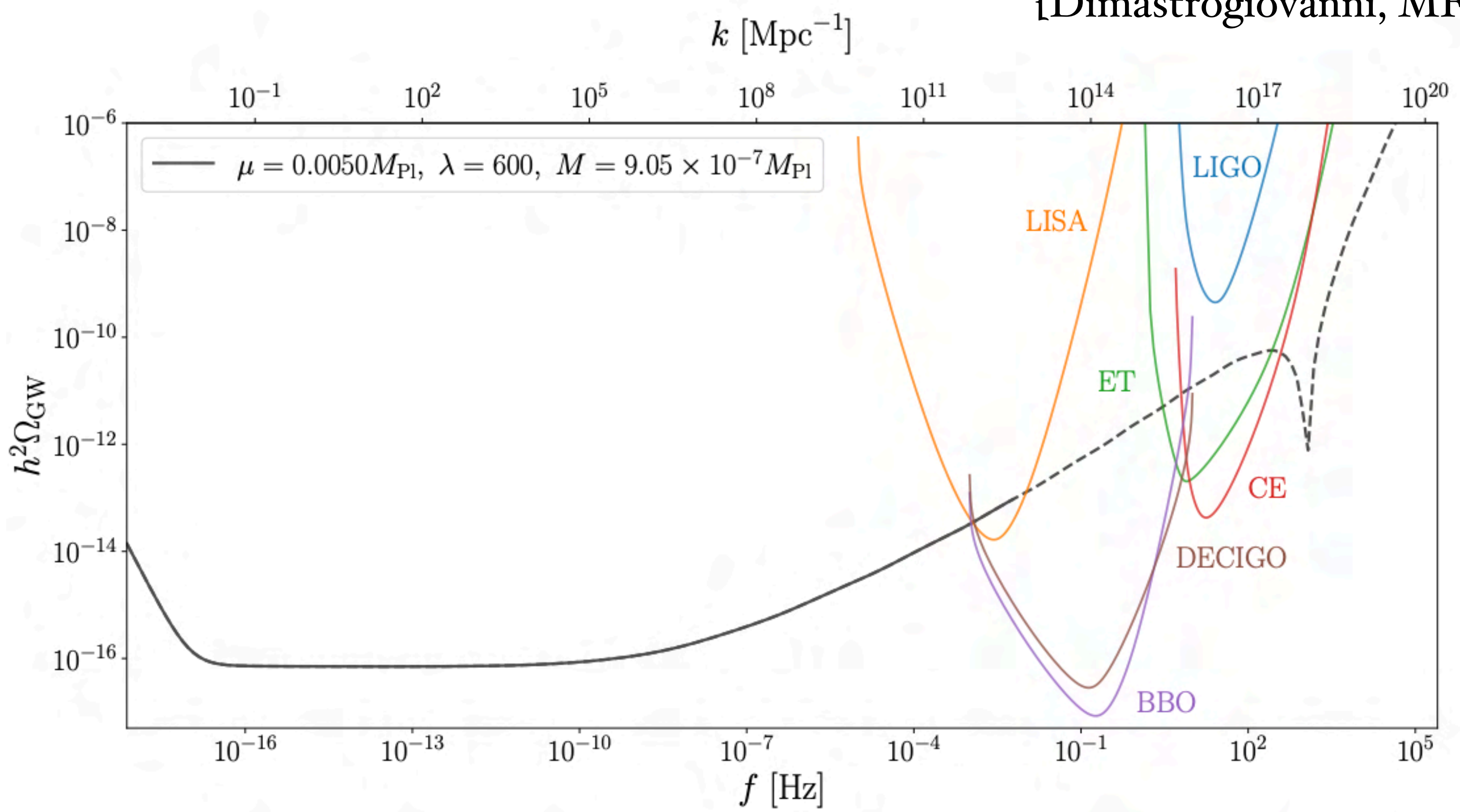
[see also Komatsu and Watanabe 2020]

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

Chromo + non-Minimal Coupling



[Dimastrogiovanni, MF, Michelotti, Pinol 2023]



Other <u>natural</u> axion-inflaton potentials

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

Appeal of axion-gauge field models

Model Building

“simple” ingredients

eta problem

UV complet-able

scale-dependence

non-Gaussianity

chirality

PBHs too!

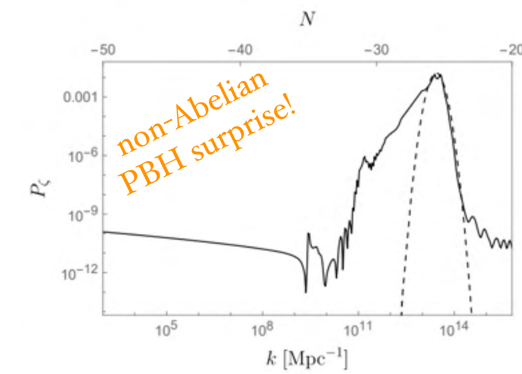
Testable

Challenges & Opportunities

(I) Gauge fields **backreaction** on the background

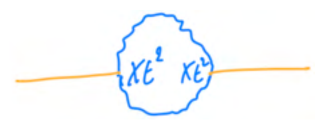
Tackled numerically under homogeneous assumption

[Iarygina, Sfakianakis, Sharma, Brandenburg 2023]
[Dimastrogiovanni, MF, Papageorgiou 2024]
[Garcia-Bellido, Papageorgiou, Peloso, Sorbo 2023]
but see [Domcke, Ema, Sandner 2023]



Lattice the ultimate test [Figueroa, Lizarraga, Urio, Urrestilla 2023], [Caravano, Komatsu, Lozanov, Weller 2022]

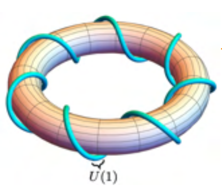
(II) **Perturbativity** bounds



Explored, can be competitive with backreaction, need better numerical studies

[Ferreira, Ganc, Noreña, Sloth 2015]
[Papageorgiou, Peloso, Unal 2018]
[Dimastrogiovanni, MF, Michelotti, Ozsoy 2024]

(III) **UV** completion



Abelian sector ok, non-Abelian ok but signatures only upon fine-tuning

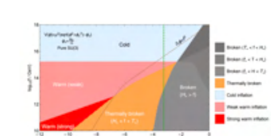
...
[Dall'Agata 2018]
[Agrawal, Fan, Reece 2018]
[Holland, Zavala, Tasinato 2020]
[Bagherian, Reece, Xu 2022]
[Cicoli et al 2023]
[Dimastrogiovanni, MF, Leedom, Putti, Westphal 2023]...

(IV) **Re-heating** with (dark) sectors

Lots of interesting work, past & future

...
[Dufaux, Figueroa, Garcia-Bellido 2010]
[Lozanov, Amin 2016]
[Adshead, Giblin, Weiner 2018]
[Adshead, Giblin, Pieroni, Weiner 2019]...

(VI) **Thermalization?**



...
[Ferreira, Notari 2017 x 2]
[Berghaus, Graham, Kaplan 2019]
[DeRocco, Graham, Kalia 2021]
[Mukuno, Soda 2024]...

(V) **Magneto-genesis, baryogenesis**

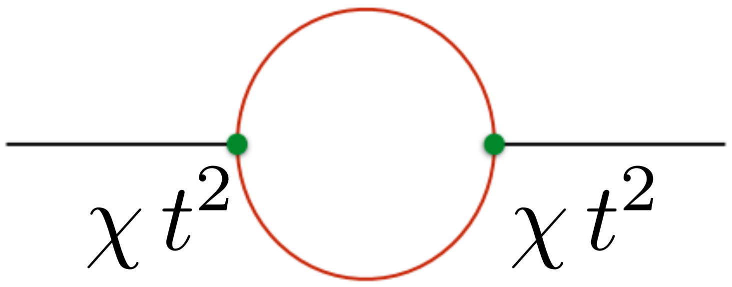
Not easy, but very intriguing

...
[Fujita, Yokoyama 2014)]
[Adshead, Giblin, Scully, Sfakianakis 2016]
[Caldwell, Devulder 2017]
[Cado, Quirós 2022]...

Thank you!

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]

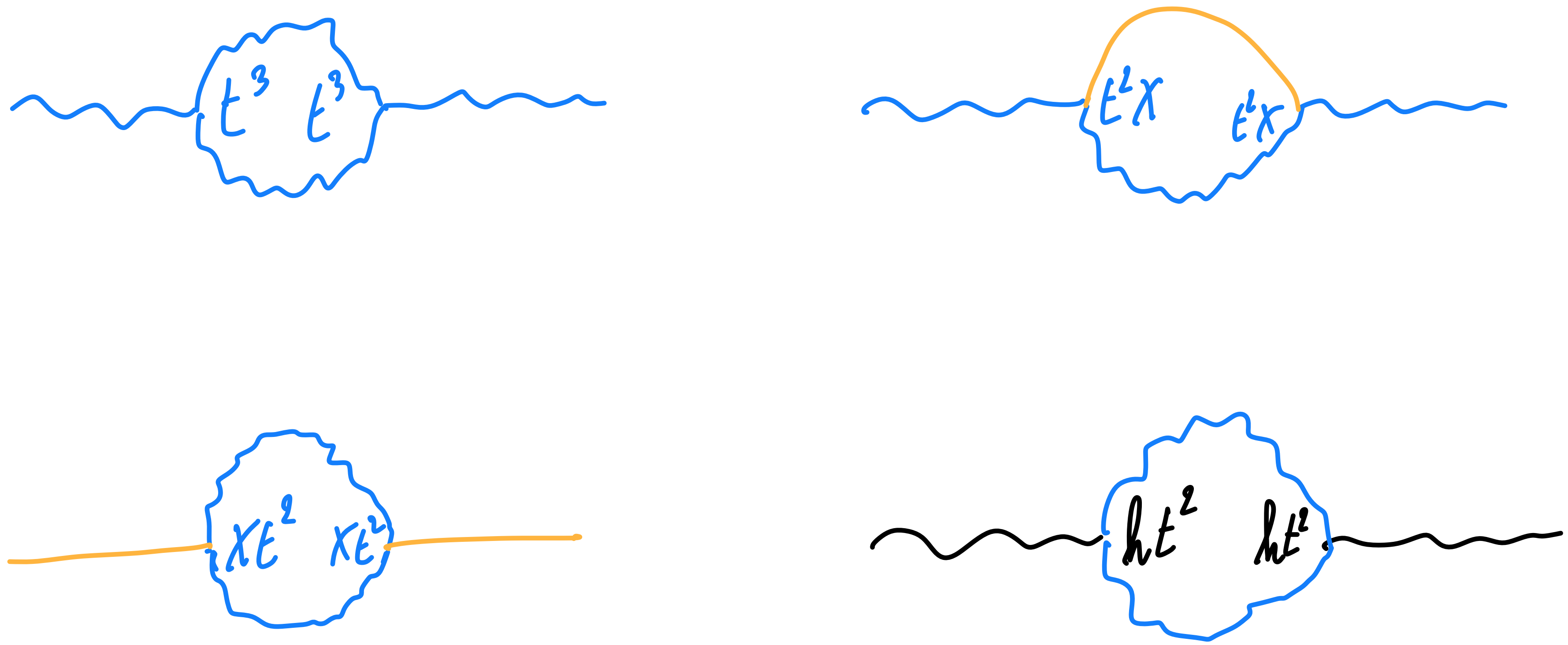
in similar context see also [Ferreira, Ganc, Noreña, Sloth 2015]

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

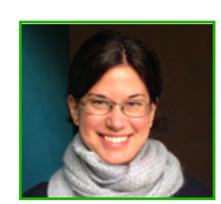
Challenge I: Perturbativity

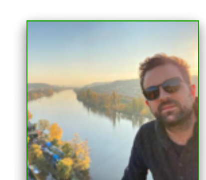
(non-minimal CNI case)

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



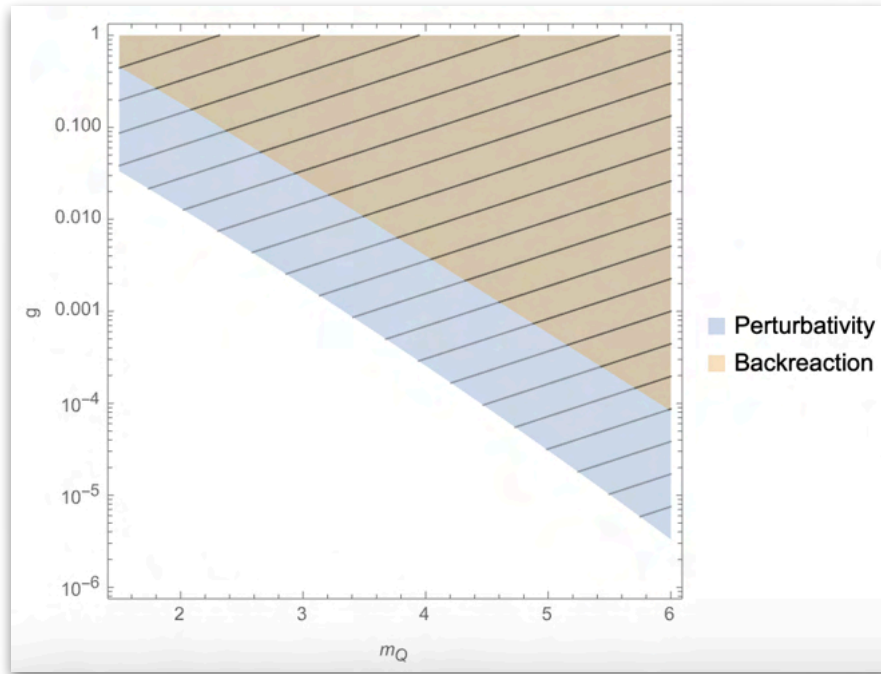
[Dimastrogiovanni, MF, Michelotti, Ozsoy, **to appear**]





Challenge I: Perturbativity

(non-Abelian case)

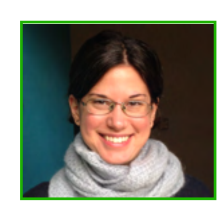


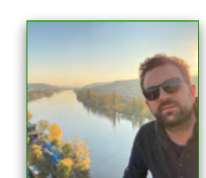
backreaction via
rough analytical estimate

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)

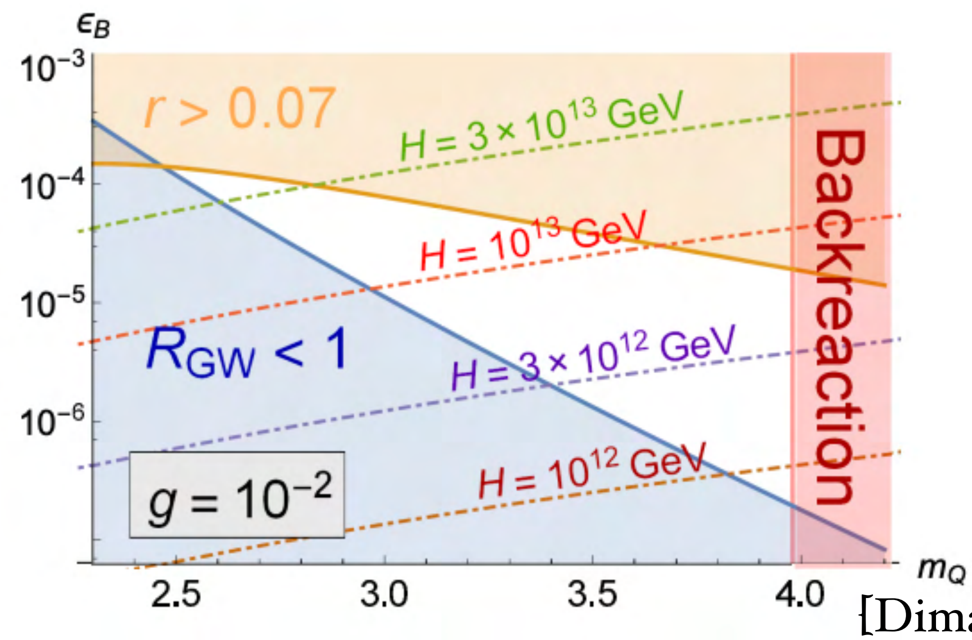
eom for the gauge field background

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

(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]

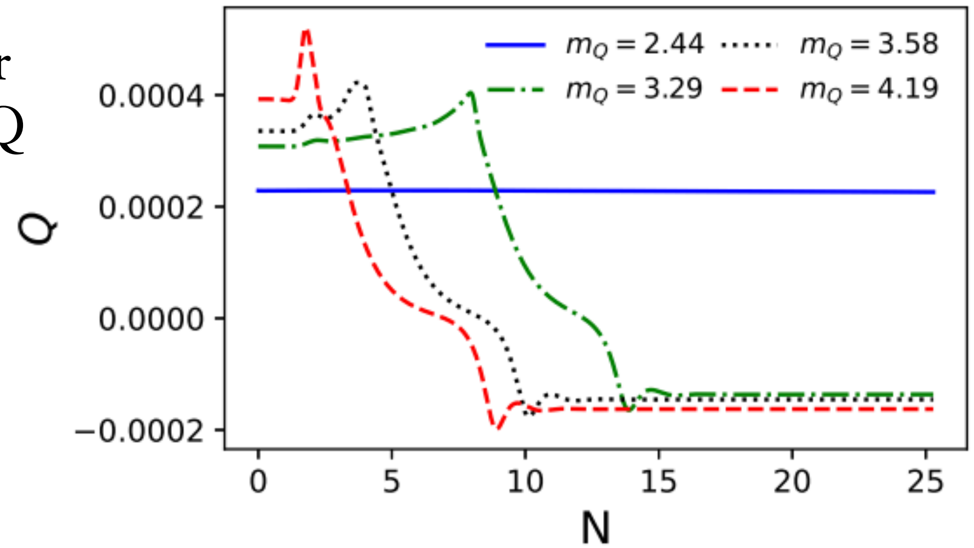
[Maleknejad, Komatsu 2018]

[Ishiwata, Komatsu, Obata 2021]

Challenge II: Backreaction

SCNI case, very interesting recent numerical* work

new attractor solution for Q



[Iarygina, Sfakianakis, Sharma, Brandenburg 2023]

* $\mathcal{T}_Q$ and $\mathcal{T}_\chi$ & interplay considered, homogeneous inflaton bckg remains 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]

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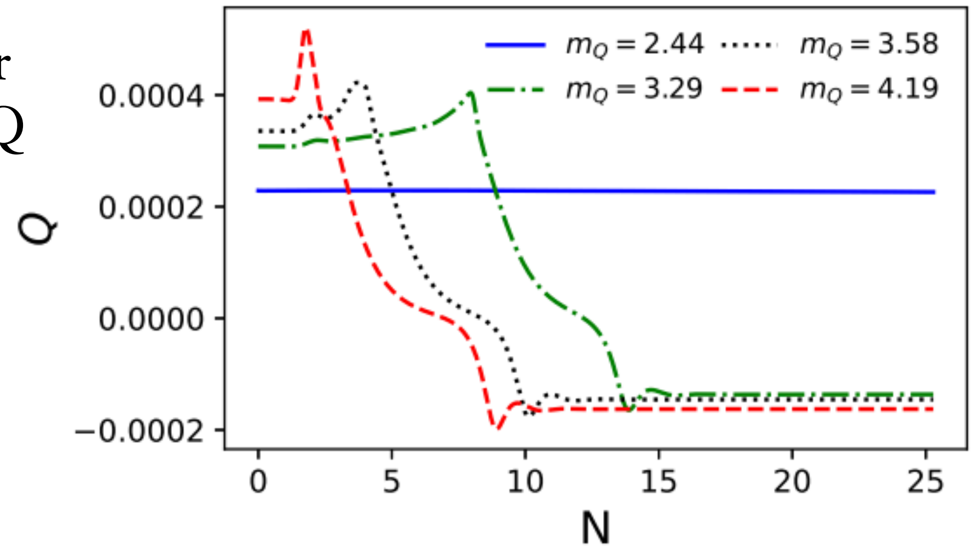

[Iarygina, Sfakianakis, Sharma, Brandenburg 2023]

! **but** [Dimastrogiovanni, Peloso 2012]

small |Q| values ==> scalar instability

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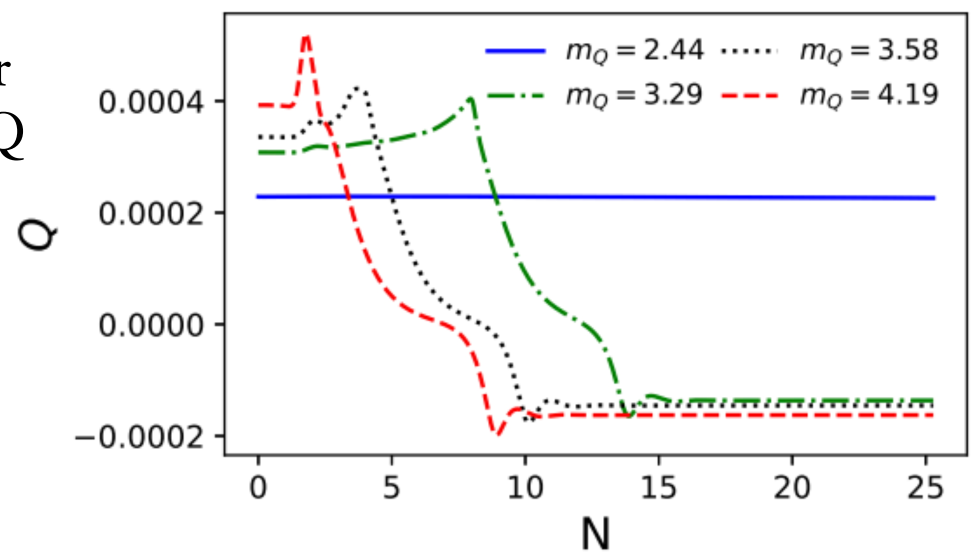


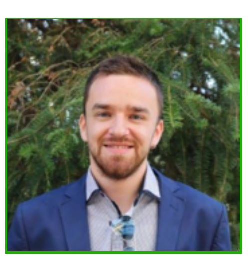
[Iarygina, Sfakianakis, Sharma, Brandenburg 2023]

but [Dimastrogiovanni, Peloso 2012]

small |Q| values ==> scalar instability

harness it towards PBH & SIGW

see talk by Alex!



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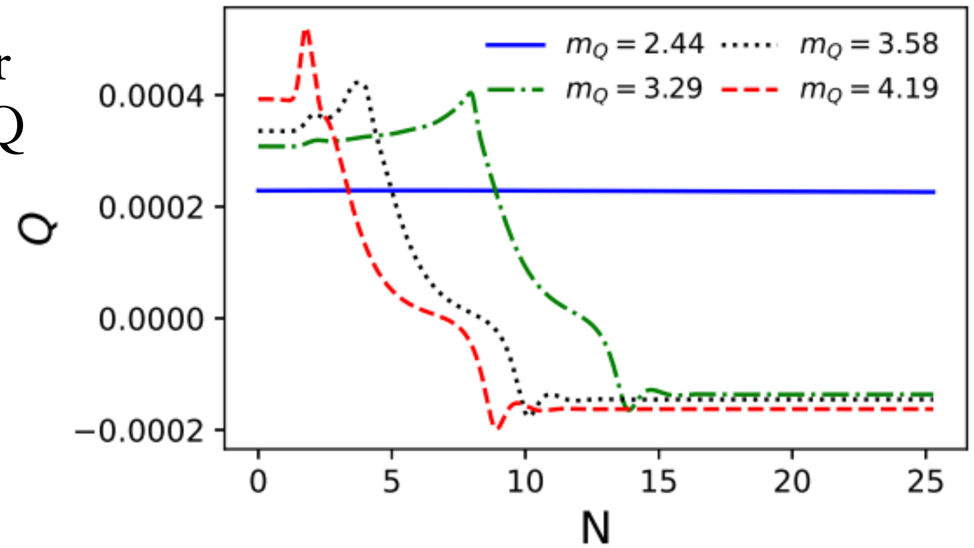

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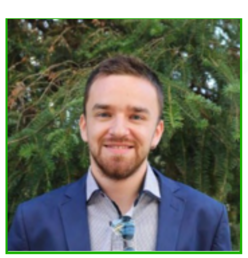

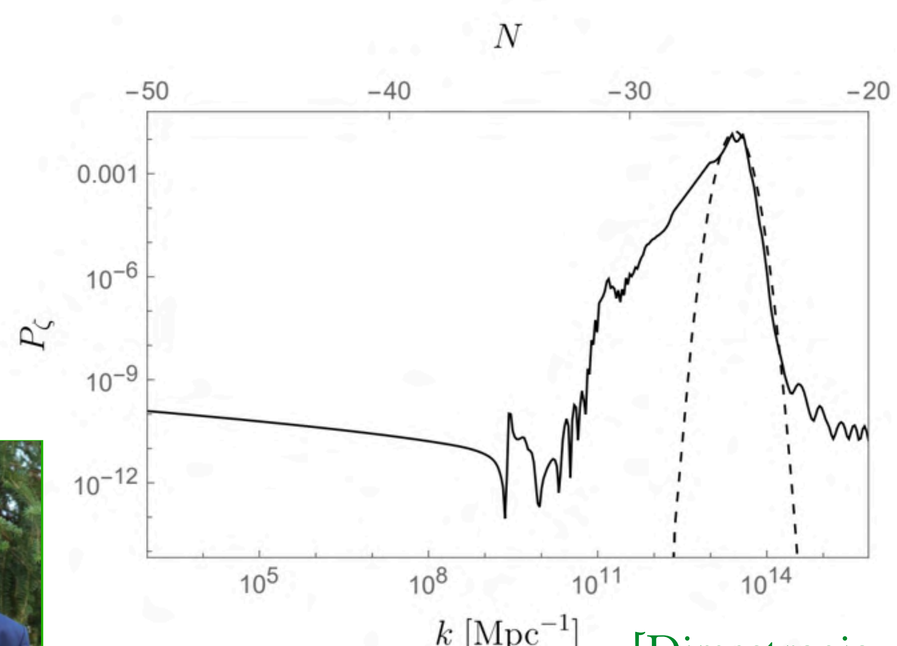

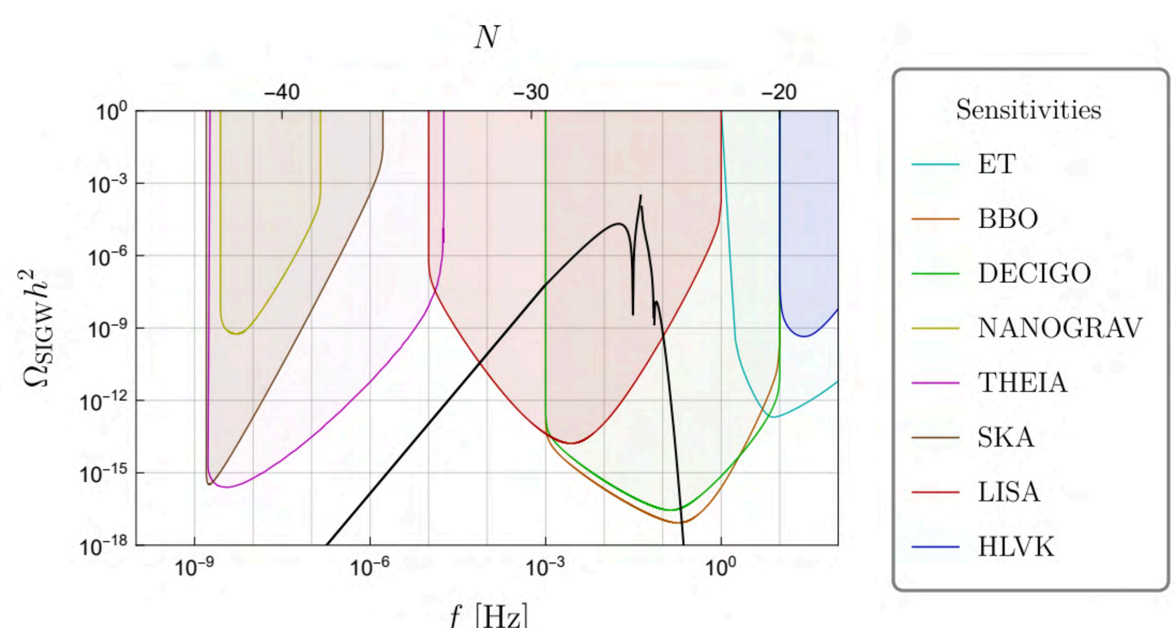

[Dimastrogiovanni, MF, Papageorgiou 2024]

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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

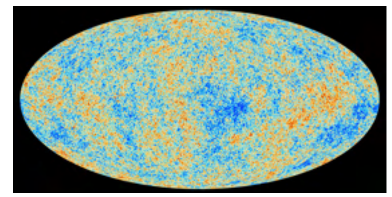
interesting GW phenomenology requires $\lambda > 100$

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]

Chirality



CMB tests

single-field
slow-roll inflation

no chirality

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

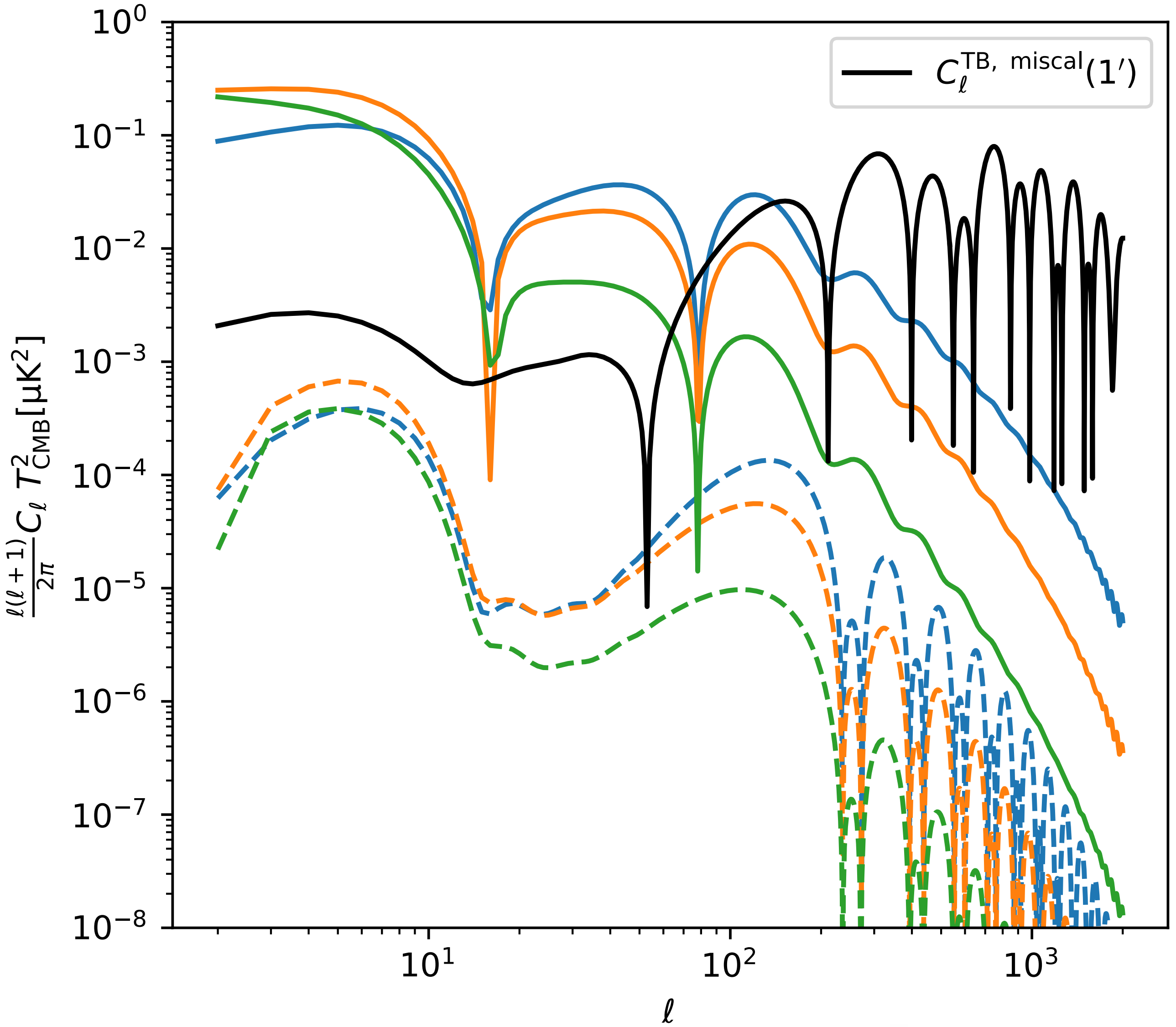
Chern-Simons
coupling

chirality

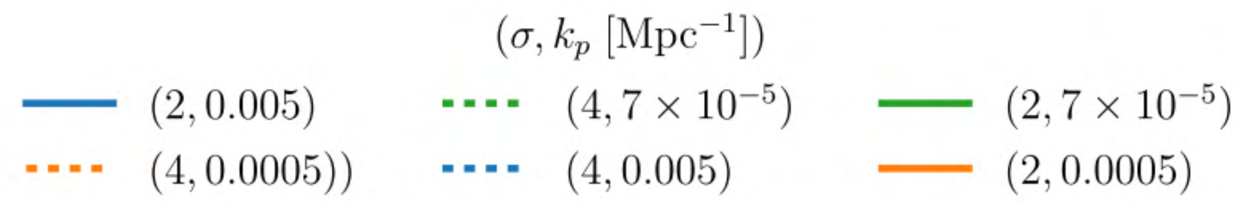
$$\langle BT \rangle \neq 0 \neq \langle EB \rangle$$

Chirality

LiteBIRD



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

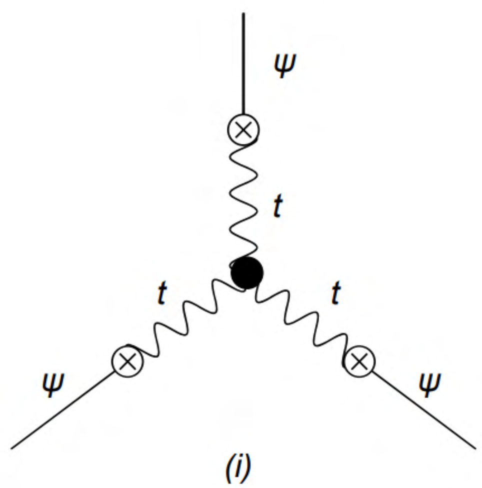


$$\mathcal{P}_h^{\rm sourced} = r_* \mathcal{P}_\zeta\, {\rm Exp}\Big[-\frac{1}{2\sigma^2} \ln^2\left(\frac{k}{k_p}\right)\Big]$$

non-Gaussianity (TTT)

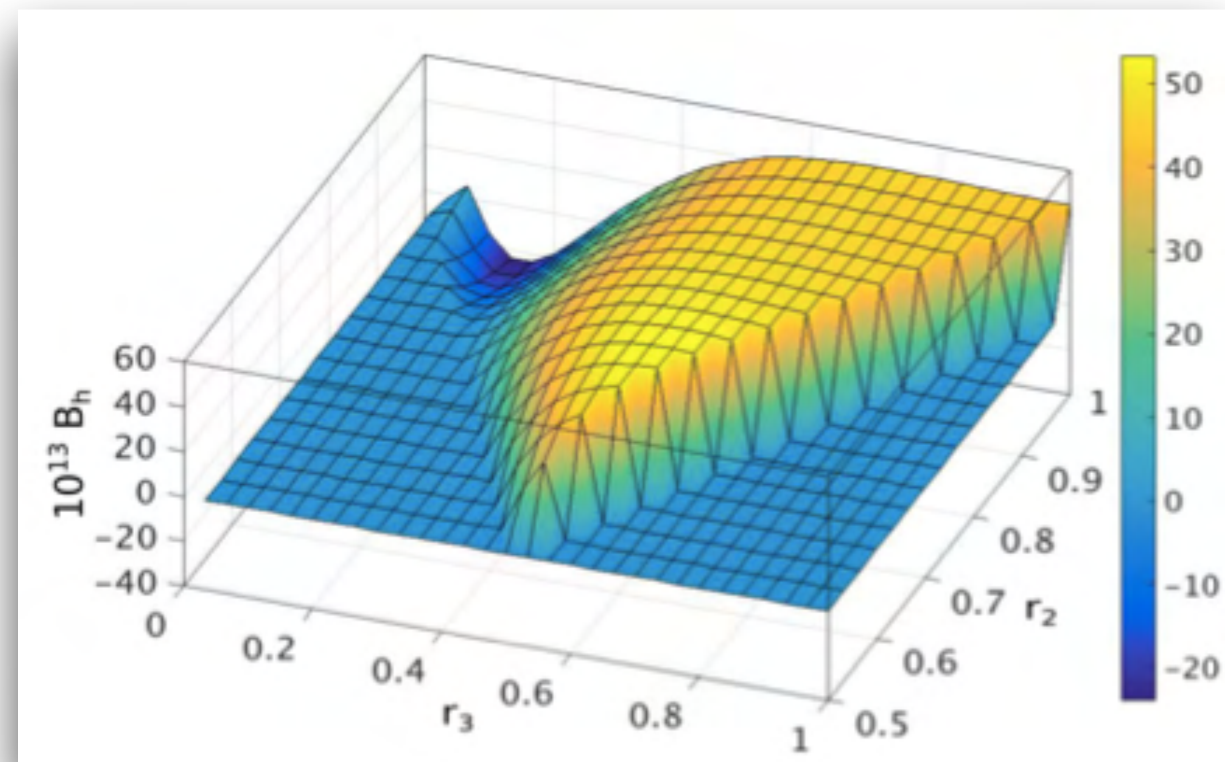
[Agrawal - Fujita - Komatsu 2017]

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

Natural Inflation + Gauge Sector

briefly on U(1)

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

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

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

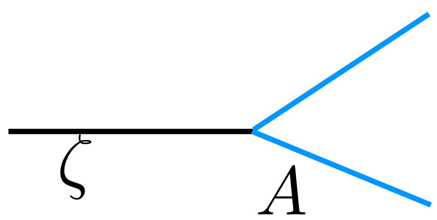
[Barnaby, Peloso 2011, Barnaby, Namba, Peloso 2011, Bartolo et al 2014+...]

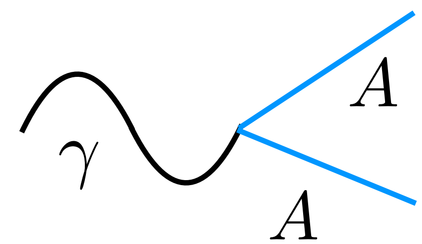
[Pajer, Peloso (2013)]

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

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]

$$\epsilon_B \equiv g^2 Q^4/(H M_{\rm Pl})^2$$

Multiple Abelian Spectator Sectors

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

Multiple Abelian Spectator Sectors

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

crucial caveat

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crucial caveat

how well my collaborators understand the string theory part

Multiple Abelian Spectator Sectors

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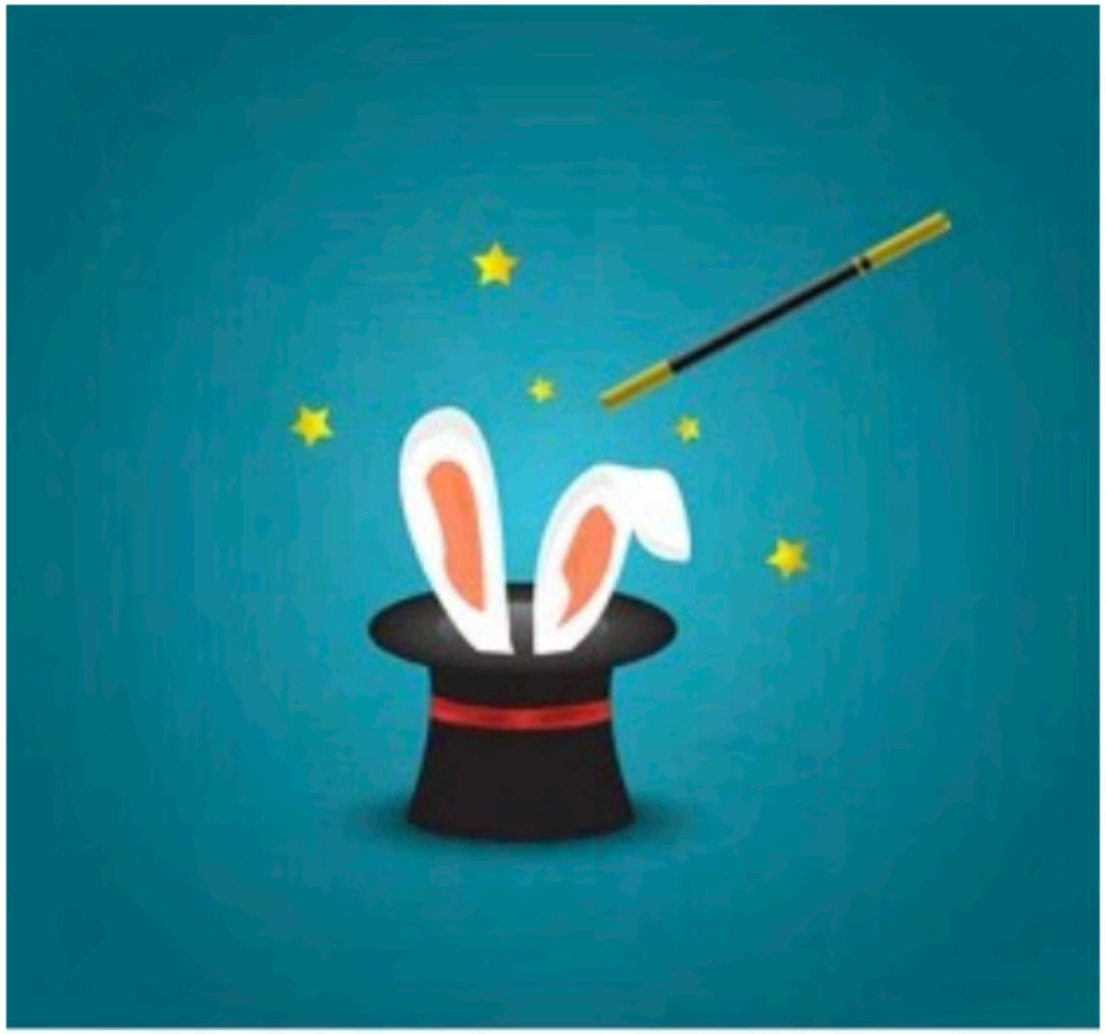
Multiple Abelian Spectator Sectors

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

crucial caveat

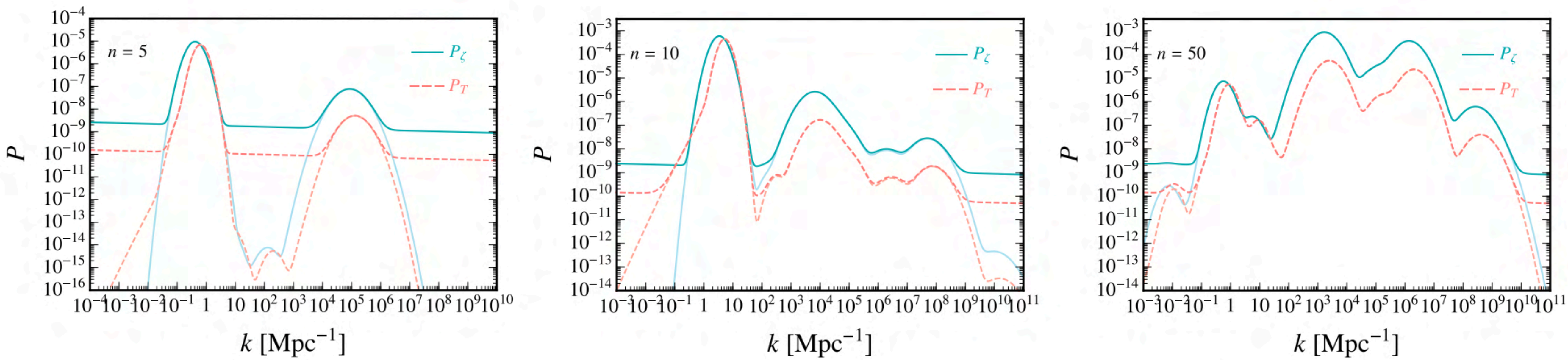
my level



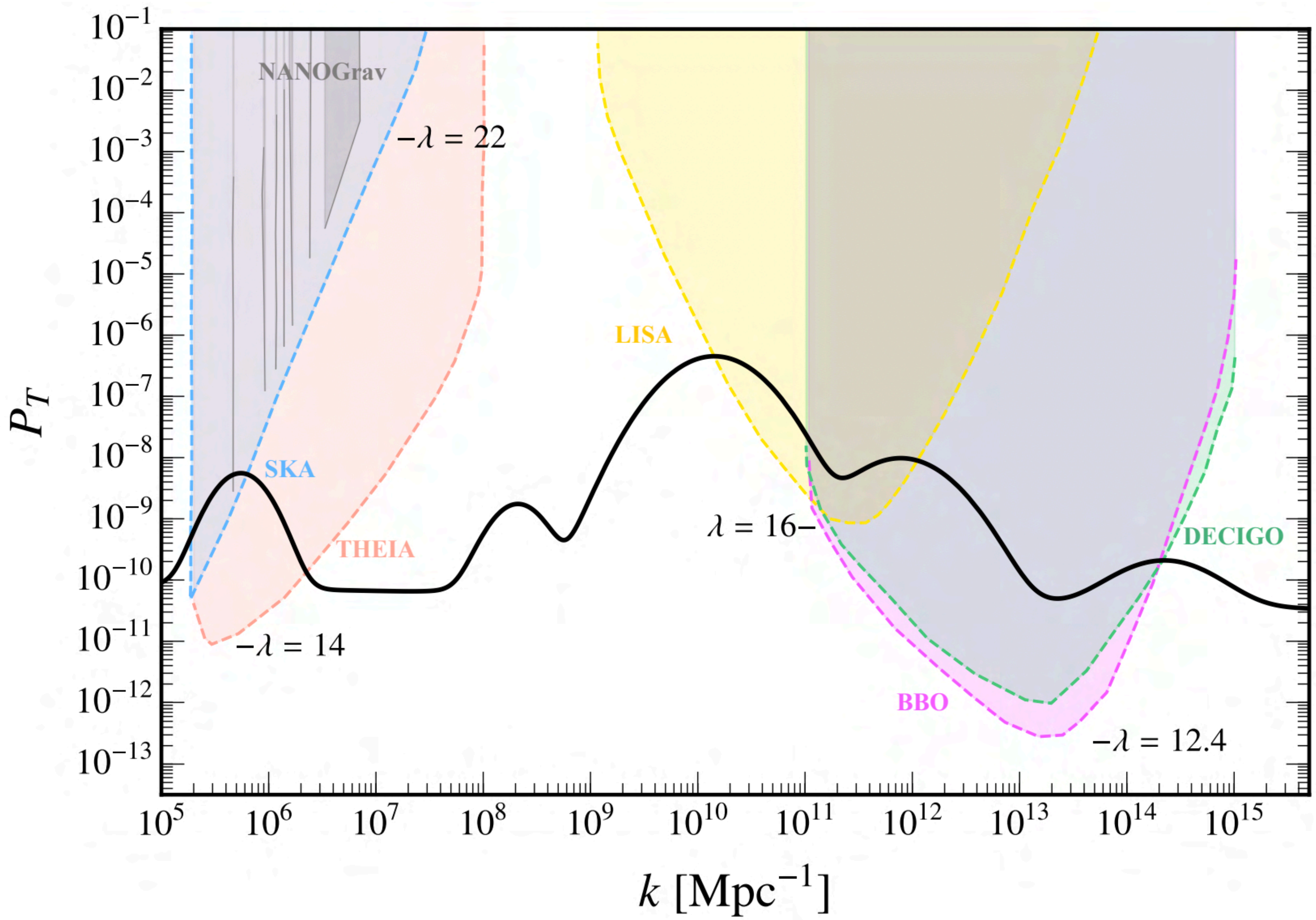
Multiple Abelian Spectator Sectors

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

scalar (blue) & tensor (red) fluctuations



Multiple Abelian Spectator Sectors



10 fields, <u>ad hoc</u> 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]

Why not clockwork in a Nutshell

[Agrawal, Fan, Reece 2018]
[Bagherian, Reece, Xu 2022]

From periodicity of axion field follows

$$\lambda = \frac{j \cdot k \cdot g^2}{8\pi^2}$$

Integer k from integrating out fermions carrying SU(2) gauge charge with χ-dependent masses

Validity of such EFT of fermions (and gauge) fields needs k < 4π/g^2

act on "j" instead via clockwork

$$\sum_{i=1}^{n-1} \mu_{i+1}^4 \cos\left[\frac{m_i \chi_i}{f_i} + \frac{\chi_{i+1}}{f_{i+1}}\right] + \mu_1^4 \cos\frac{\chi_1}{f_1}$$

Integrating out heaviest modes ==> parametrically light χ with effective potential having j = Π m_i

each cosine mediates axion scattering ==> perturbative unitarity bound —> upper bound on μ

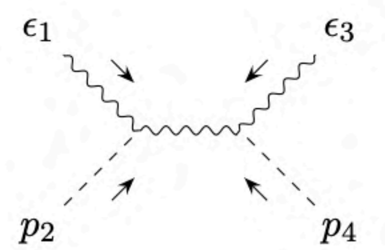
$\lambda \leq \frac{f}{2\pi\mu}$

==>

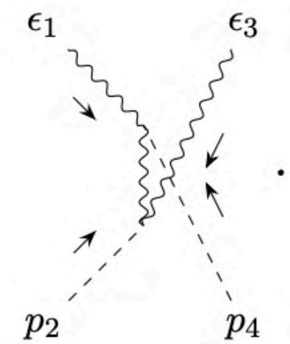
paired up with phenomenological constraints implies this mechanism does not work for the model

Unitarity Bounds [Bagherian, Reece, Xu 2022]

a: 2—> 2 axion gauge scattering amplitudes



, and

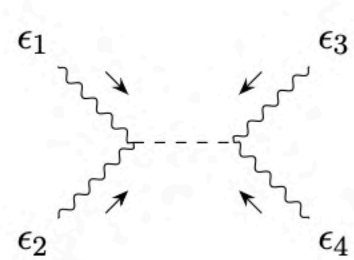


.

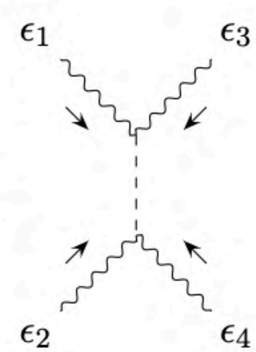
$$\mathcal{M}^{A\chi}_{+-} = \delta^{ab}\frac{u+s}{su}\left(\frac{\lambda}{2f}\right)^2 \langle 14\rangle^2[34]^2 \propto \delta^{ac}\left(\frac{\lambda}{4f}\right)^2 2s(1-\cos\theta),$$

$$\mathcal{M}^{A\chi}_{++} = -2\delta^{ac}\left(\frac{\lambda}{2f}\right)^2 \langle 13\rangle^2 \propto \delta^{ab}\left(\frac{\lambda}{4f}\right)^2 4s(1-\cos\theta).$$

b: gauge scattering mediated by axion



,



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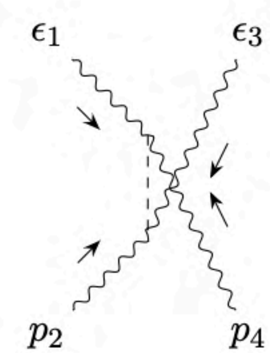


.

$$\mathcal{M}^{AA}_{++++} = -\left(\frac{\lambda}{4f}\right)^2\left[\frac{\delta^{ab}\delta^{cd}}{s-m_\chi^2}[12]^2[34]^2 + \frac{\delta^{ac}\delta^{bd}}{t-m_\chi^2}[34]^2[13]^2 + \frac{\delta^{ad}\delta^{bc}}{u-m_\chi^2}[14]^2[23]^2\right]$$

a & b much weaker (than cw) bound $\mu \lesssim 8\sqrt{\pi}\frac{f}{\lambda}$ small SCNI region still viable

String Theory Embedding

[Holland, Zavala, Tasinato 2020]

Framework

Kahler inflation in type IIB large volume string compactifications

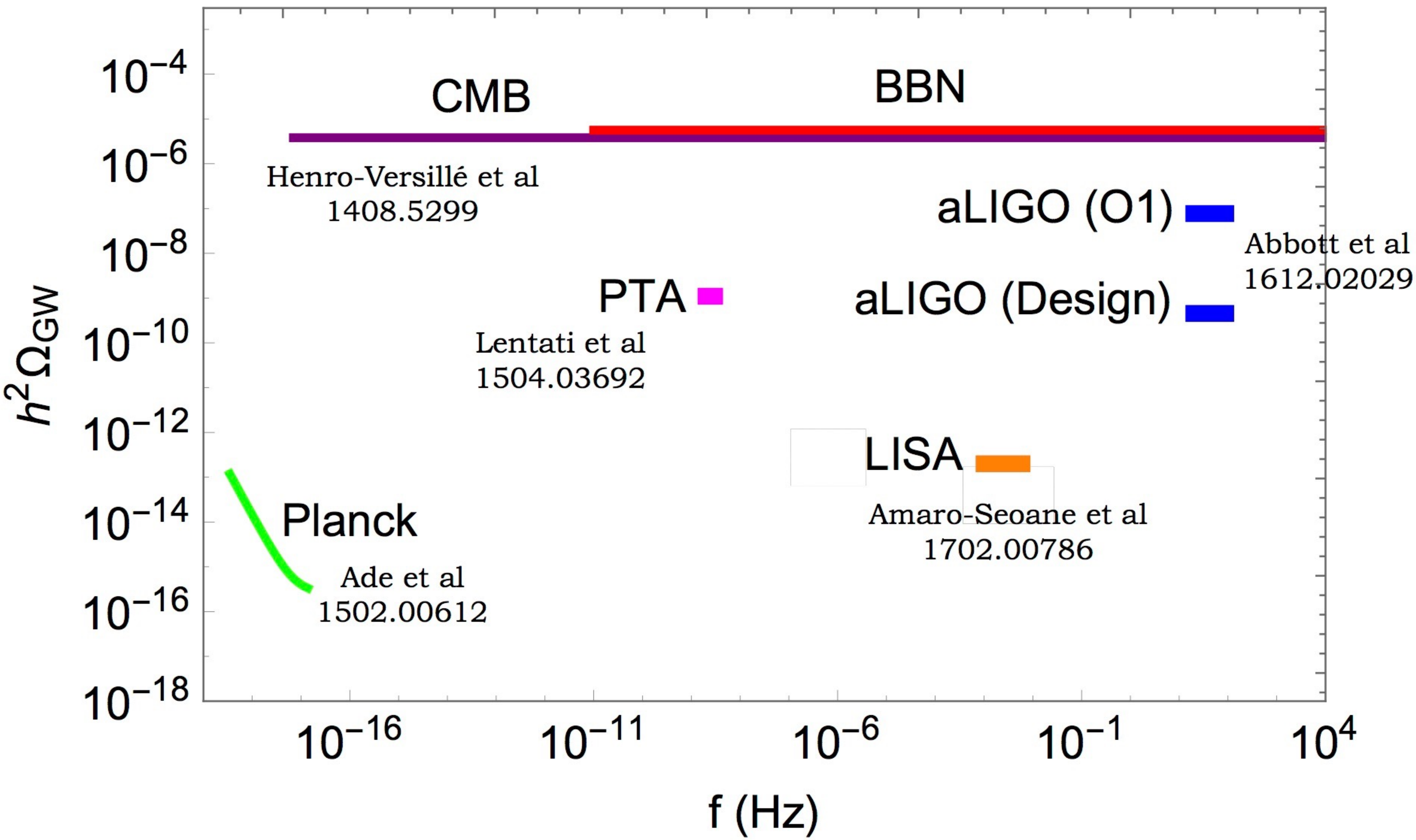
need spectator sector associated with gaugino condensation on multiply magnetised D7-branes

Successful inflation (+large GW enhancement) hinges on suitable values of three parameters:

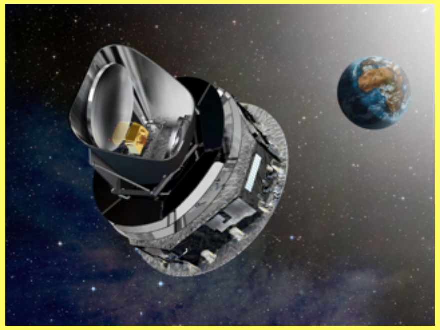
- magnetic flux
- degree of the condensing gauge group
- wrapping number of the D7-brane

gauge group degree (~ number of D7s) N ~ 10^5 not easy to realise, yet necessary for phenomenology!

Observational bounds/sensitivities for SGWB



Scalar bispectrum: current bounds



$f_{\rm NL}^{\rm local} = -0.9 \pm 5.1 \quad f_{\rm NL}^{\rm equil} = -26 \pm 47 \quad f_{\rm NL}^{\rm ortho} = -38 \pm 24$

$[68\,\%\ \rm CL]$

Scalar bispectrum: future bounds

- **LSST**
- **SKA**
- **SPHEREx**

$\sigma\left(f_{\rm NL}^{\rm local}\right) \simeq 1$

- **21-cm** $\sigma\left(f_{\rm NL}^{\rm local}\right) \lesssim 10^{-1}$

[Munoz, Ali-Haımoud, Kamionkowski]

Tensor bispectrum

- **Planck**

$f_{\rm NL}^{\rm tens} = (8 \pm 11) \times 10^2$

$[68\,\%\ \rm CL]$

$$f_{\rm NL}^{\rm tens} \equiv \frac{B_\gamma^{+++}(k,k,k)}{(18/5)P_\zeta^2(k)}$$

(parity violating models / roughly equilateral)

- **LiteBIRD**

$\sigma\left(f_{\rm NL}^{\rm tens}\right) = \text{a few}$

(possibly also with **PICO**)

The axionic portion of the spectator sector can arise from dimensional reduction of p-forms in the 10d string theories.

Gauge sector of spectator models depends greatly on which corner of the string landscape one works in. Largely focus on type IIB string theory compactified on orientifolded Calabi-Yau (CY) manifolds with quantized 3-form fluxes, D7-branes and O7-orientifold planes.

4d axions arise as KK zero modes of the 4-form C4 and 2-form C2 gauge fields.
The number of axions is governed by the number of compact n-dimensional sub-manifolds (n-cycles) of the 6d CY manifold chosen, as well as the structure of the orientifold projection: some number of 4-form axions are always present, while 2-form axions arise from a non-trivial 'projection-odd' sector of the orientifold action.

Gauge sectors are realized by the worldvolume theory of D7-branes wrapping 4-cycle submanifolds of the CY and permeating our 4d spacetime.

The two types of closed string axions differ in the way they couple to the D7-brane worldvolume gauge fields via Chern-Simons terms: the 4-form axions intrinsically couple to the worldvolume theory, while 2-form axions only acquire such a coupling in the presence of a particular type of quantized magnetic flux on the D7-brane. The "intrinsic" size of these CS couplings turns out to be too small to generate GW signals detectable with current or planned experiments.

Both CS couplings increase linearly with the number of times the D7-brane "wraps" a 4-cycle, and the 2-form axion CS coupling in addition increases with the amount of magnetic flux used on the D7- brane to generate it.

better definition of gauge invariant quantities

$$\sum_a (E_i^a)^2 \propto Q^2$$

$$\sum_a (B_i^a)^2 \propto Q^4$$