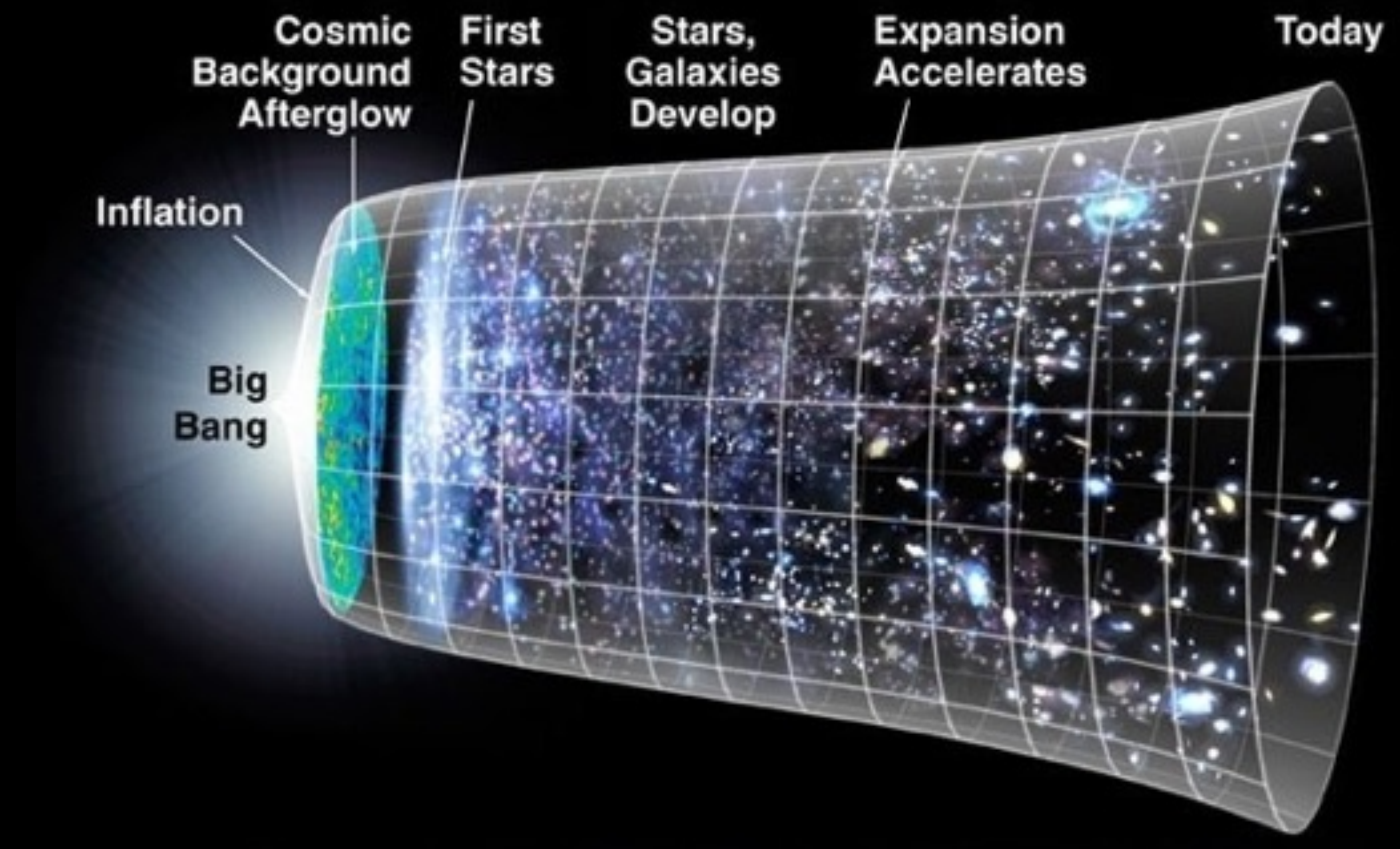
Primordial GW from Axion-Gauge Fields Dynamics



Matteo R. Fasiello
IFT Madrid

June 8th 2023
10th LISA CosWG meeting, Stavanger, Norway

Instituto de Física Teórica UAM-CSIC
CSIC Consejo Superior de Investigaciones Científicas

Inflation, the minimal paradigm, SFSR

Simplest realization: single-scalar field in slow-roll

- Scalar field :

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

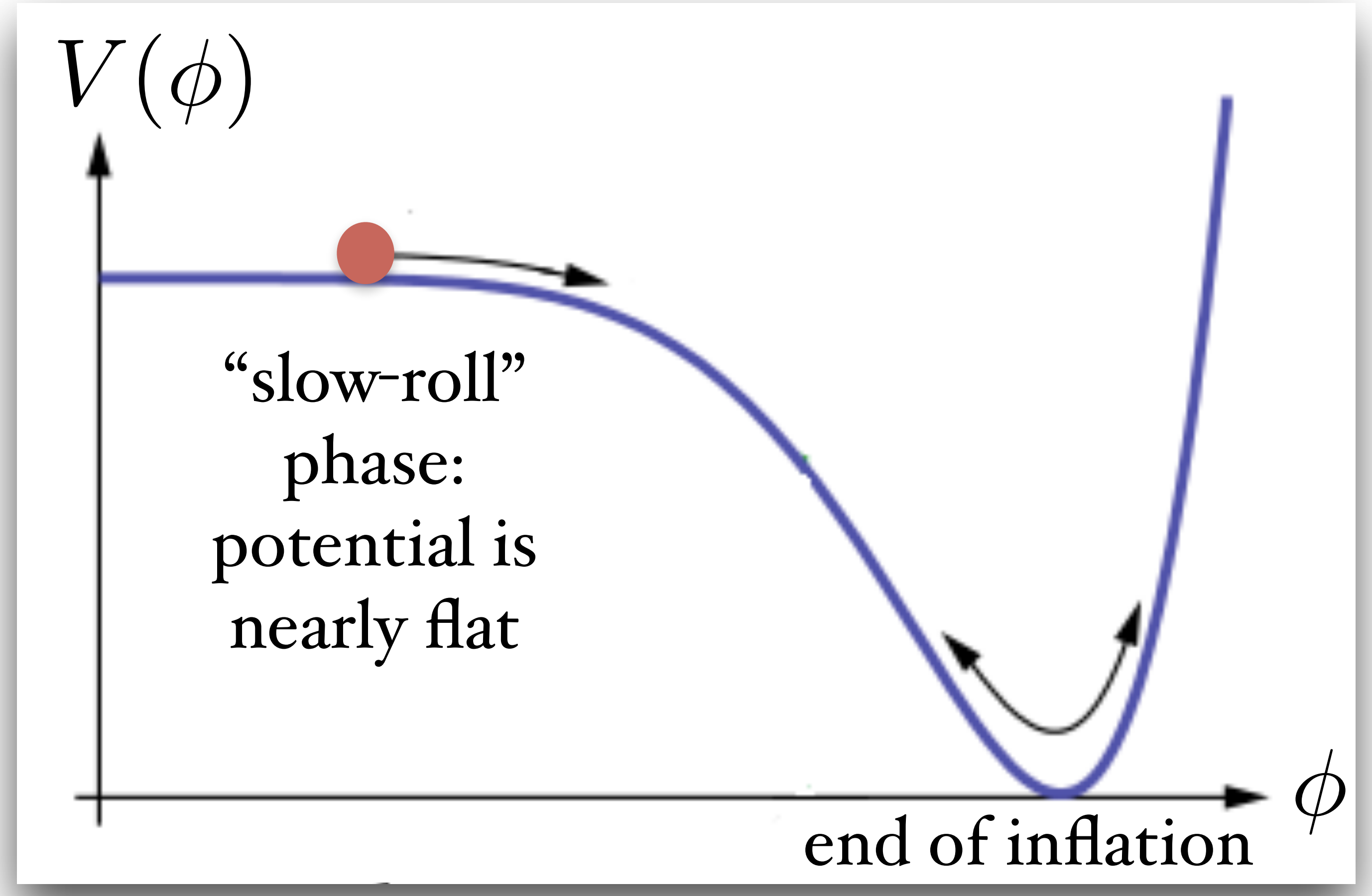
$$\dot\phi^2 \ll V$$
$$p_\phi \approx -\rho_\phi$$

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

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



Metric Fluctuations

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

scalar fluctuations

tensor perturbations

Primordial Fluctuations

(in the 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 $\quad r \equiv \dfrac{\mathcal{P}_\gamma}{\mathcal{P}_\zeta}$

bounds

current

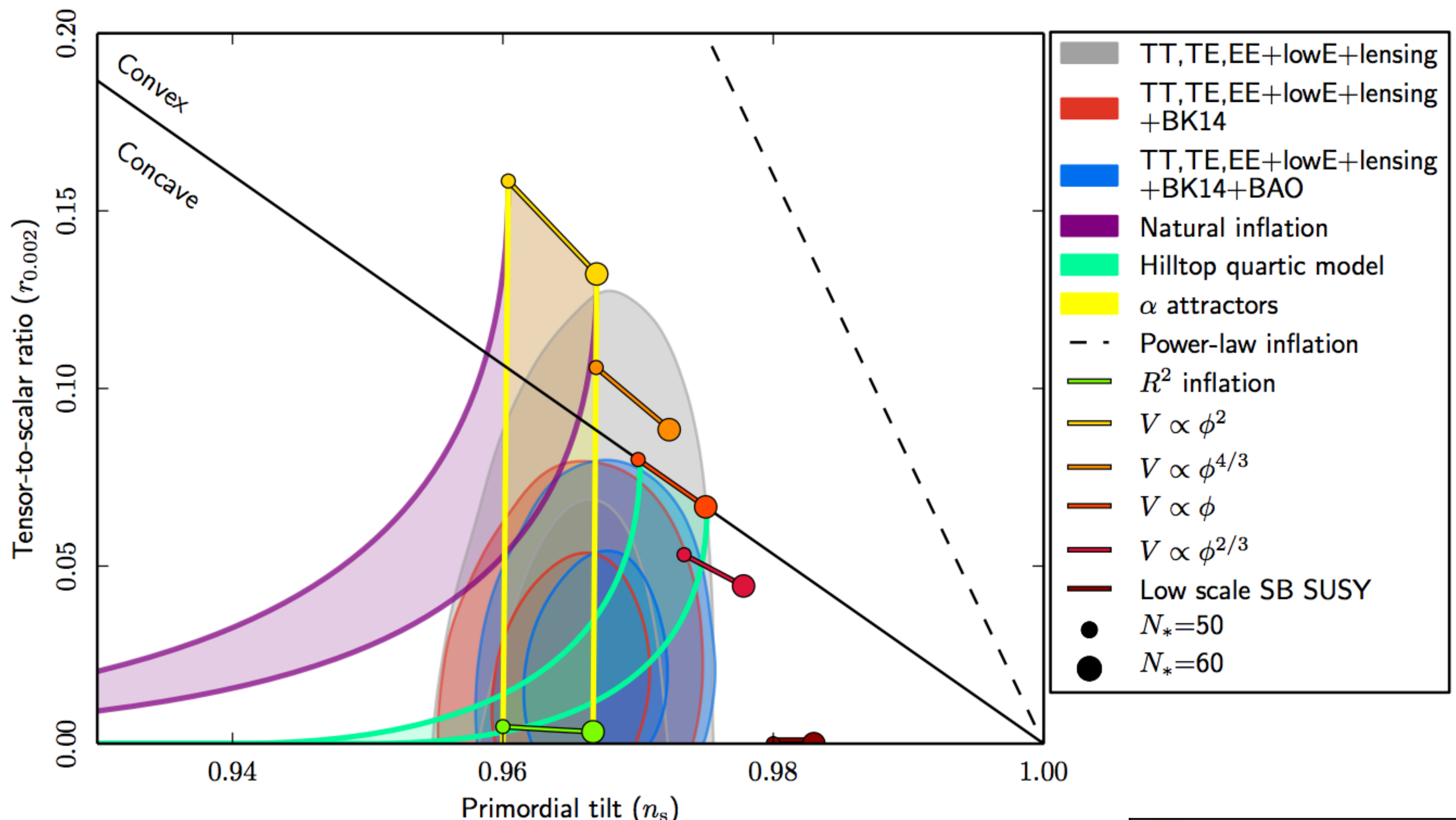
$r < 0.032$ (95%CL, Planck$^+$)

future

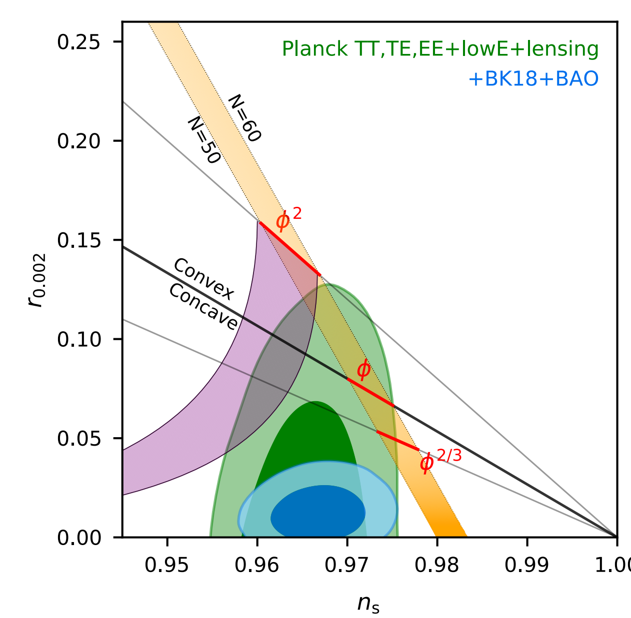
$r < 0.01$ (CMB-S3); $\quad r < 0.001$ (-S4)

Single-field Inflation is doing well

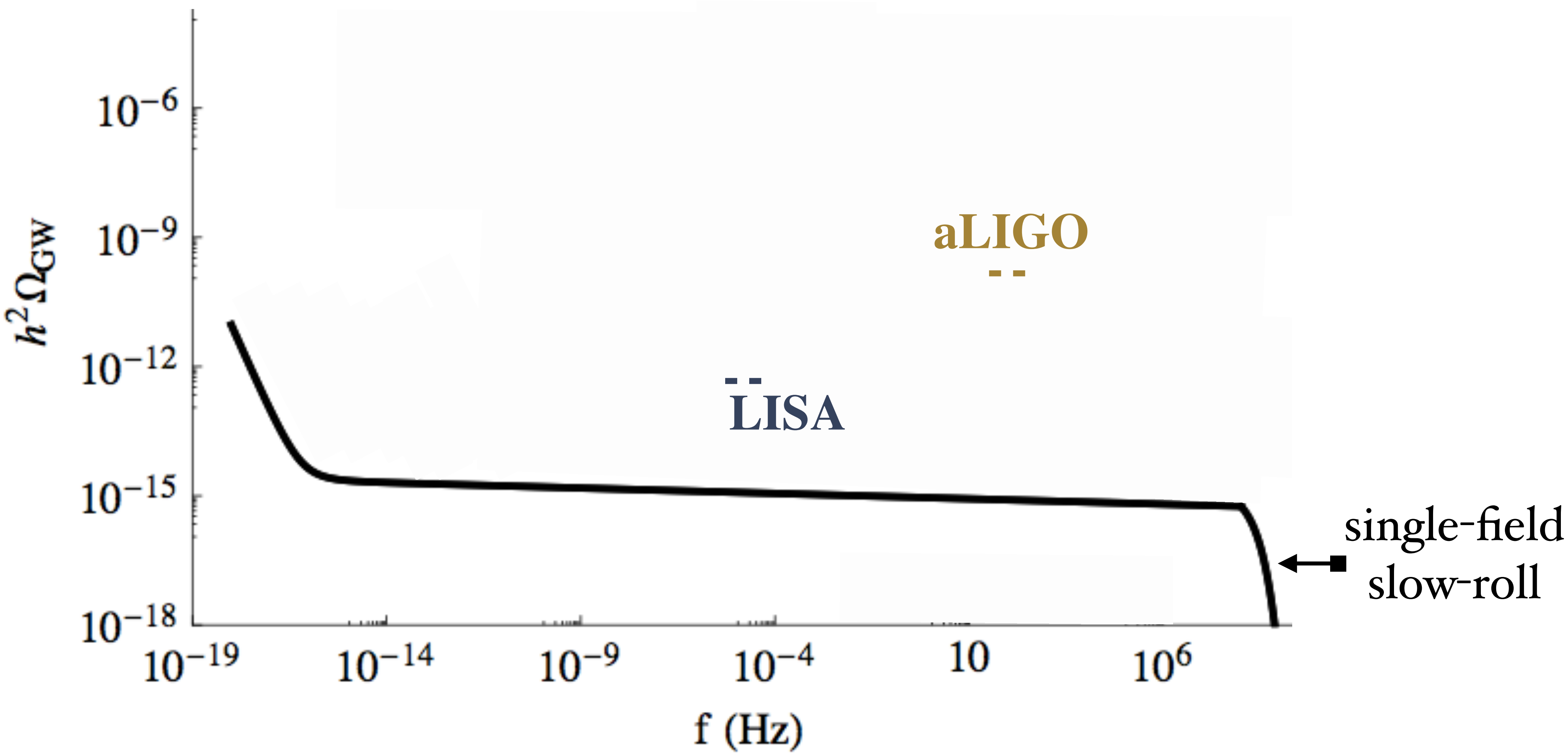
Planck Collaboration: Constraints on Inflation



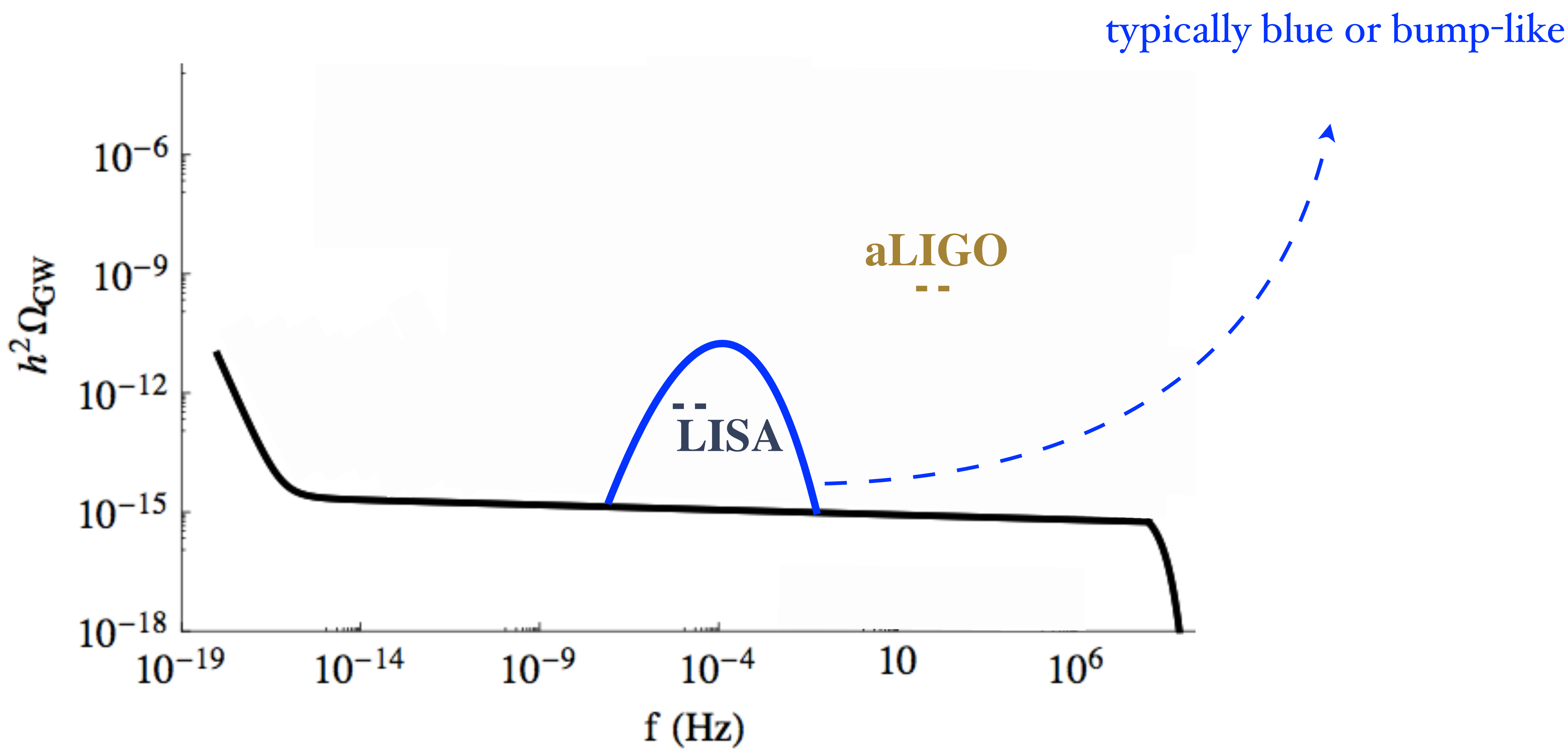
+BK update:



Amplitude & Scale Dependence in SFSR



Axion-Gauge Field Models



Laser Interferometers a new frontier to test primordial physics at small scales

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

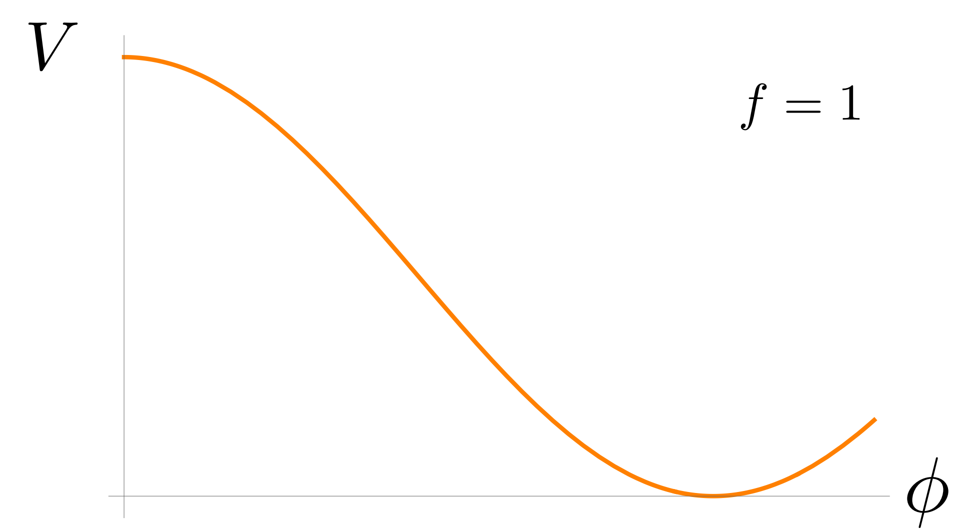
signatures of new content
on GW spectrum:
PS: scale-dependence, chirality,
n-G: (amplitude, shape, angular..)

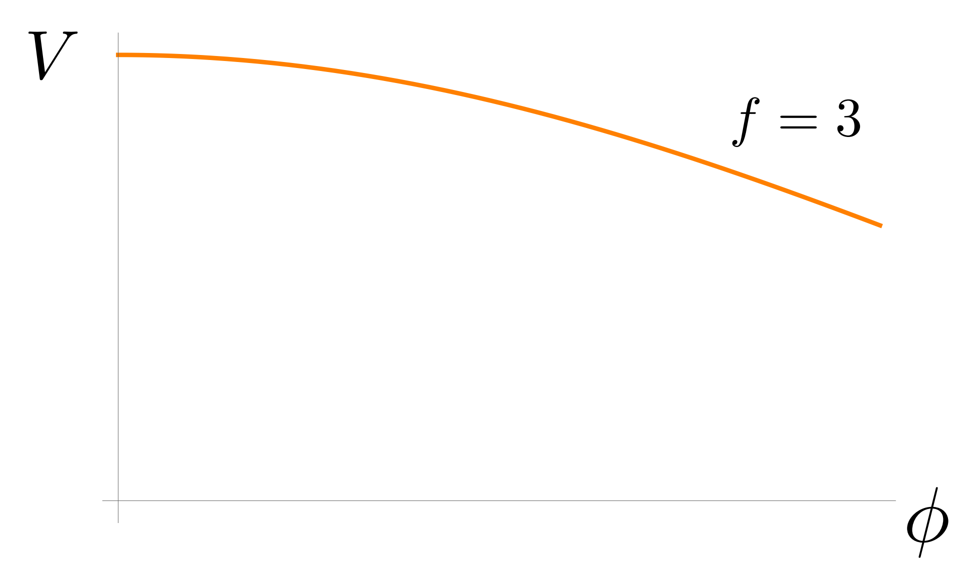
Natural Inflation

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

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

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

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

Chromo Natural Inflation

SU(2) but could be U(1) !

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

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

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

Spectator Chromo Natural Inflation

[Dimastrogiovanni, MF, Fujita]

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

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

Spectator Chromo Natural Inflation

[Dimastrogiovanni, MF, Fujita]

SU(2) but could be U(1) !
e.g. Juan's talk on Tuesday

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

◆
- $f \ll M_{\rm P}$ 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]

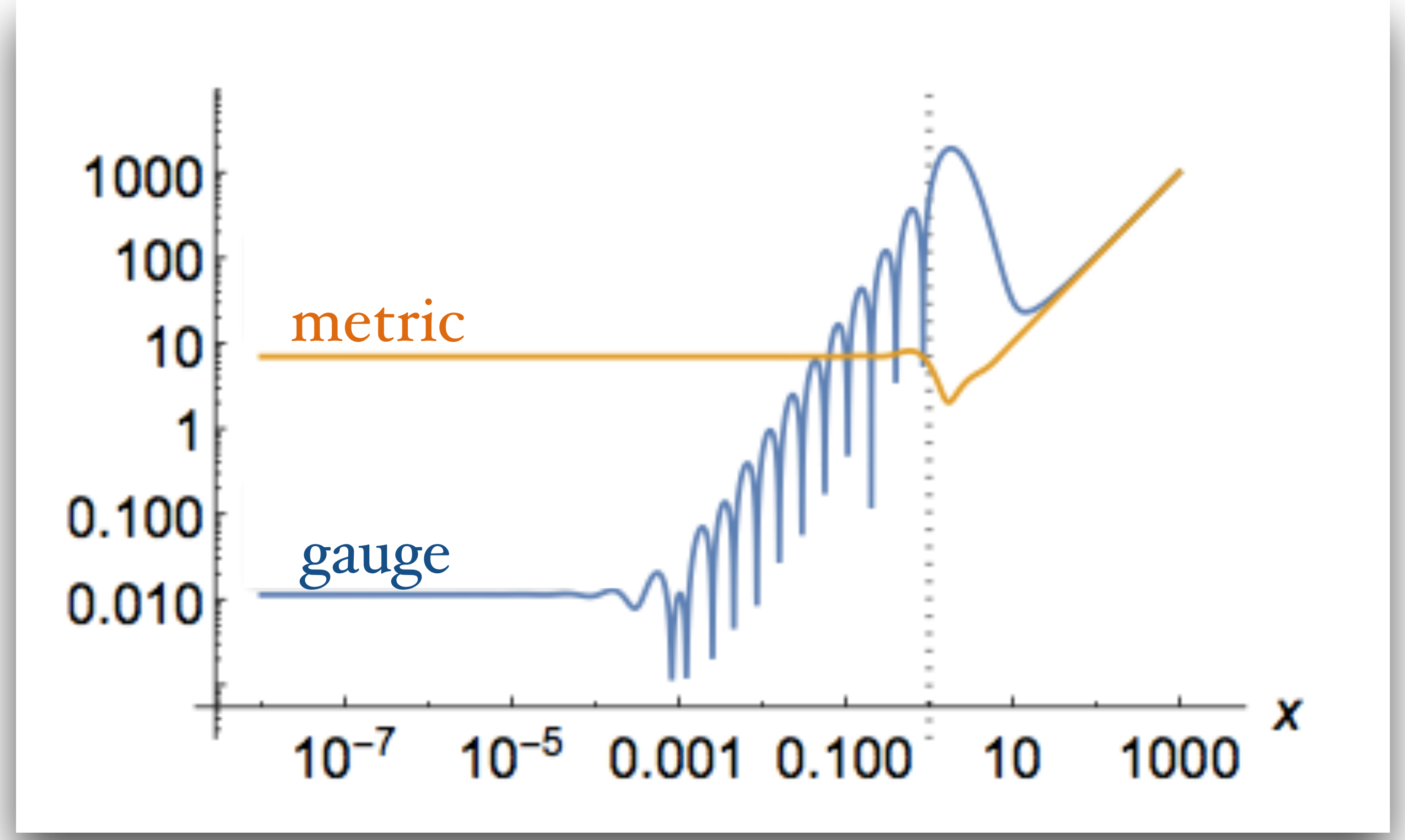
$$P_\lambda^{\text{sourced}} \gtrsim P_\lambda^{\text{vacuum}}$$

now possible!

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

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

$$
x \sim -k\tau
$$



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

Chirality

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

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

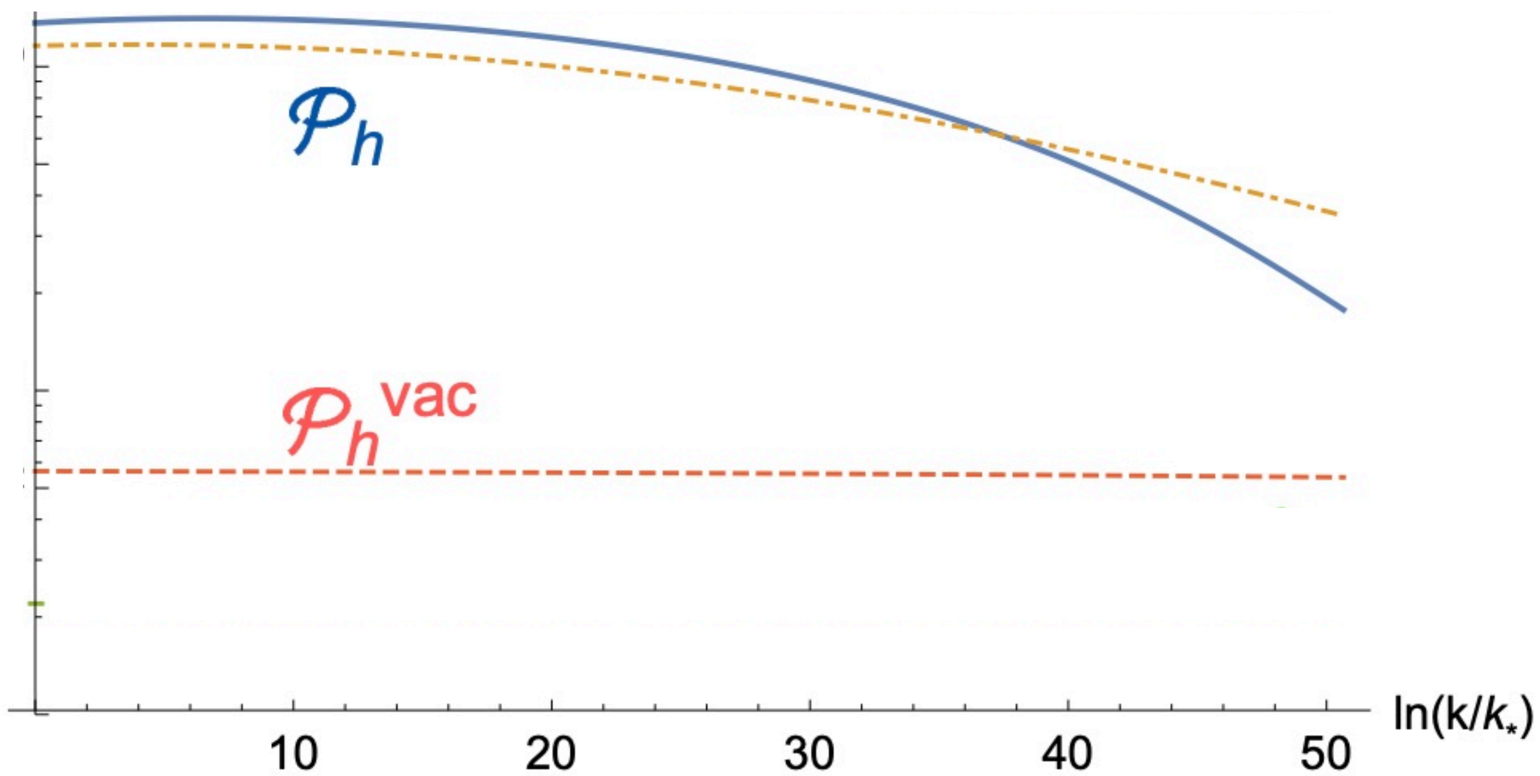
$$\gamma_{ij}^{L} \neq \gamma_{ij}^{R}$$

chiral spectrum

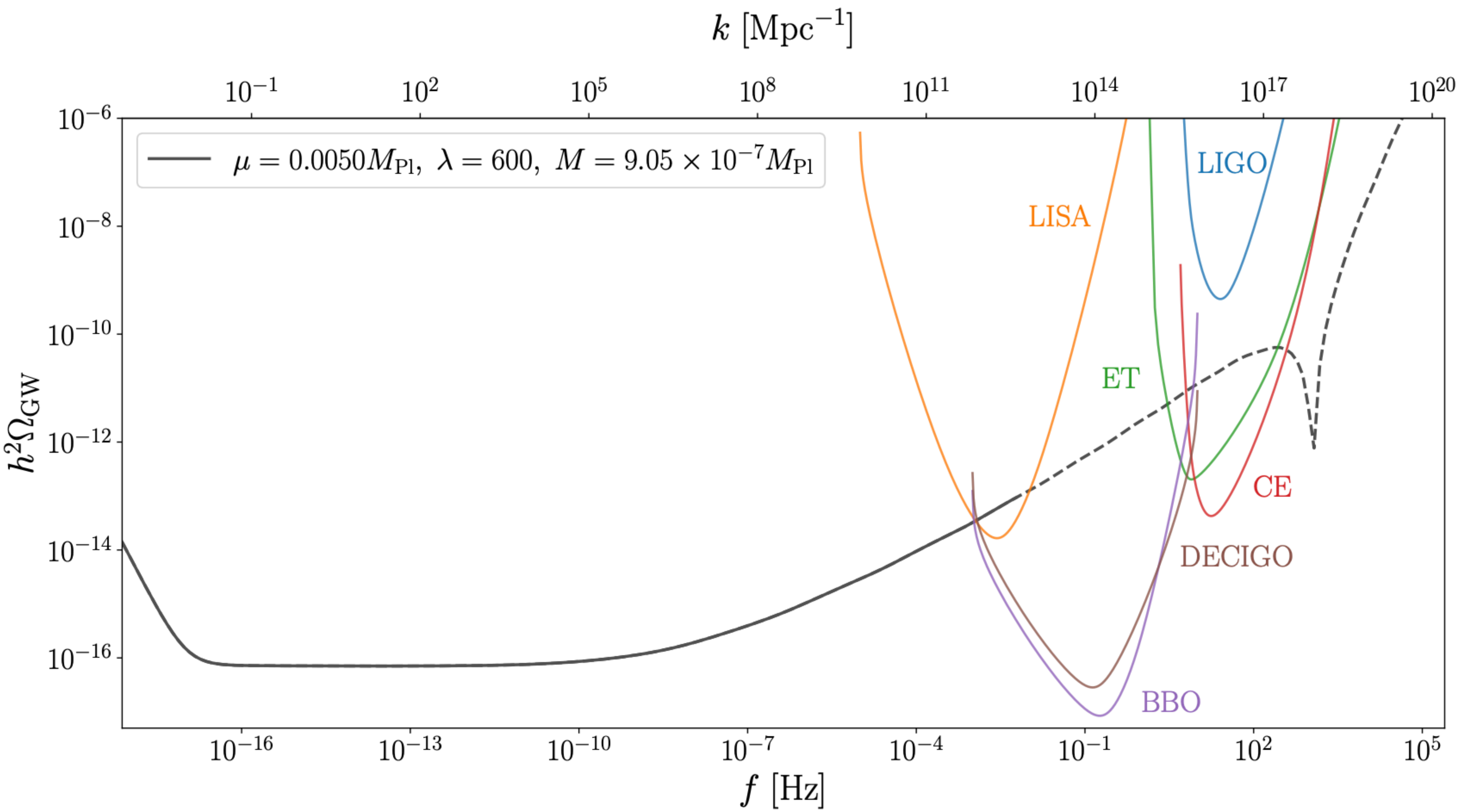
$$\mathcal{P}_{\gamma}^{L} \neq \mathcal{P}_{\gamma}^{R}$$

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

Slightly Bump-like GW Power Spectrum



Related models can be blue



[Dimastrogiovanni, MF, Michelotti, Pinol 2023]

Appeal of axion-gauge field models

Model Building

"simple" ingredients

eta problem

UV complet-able

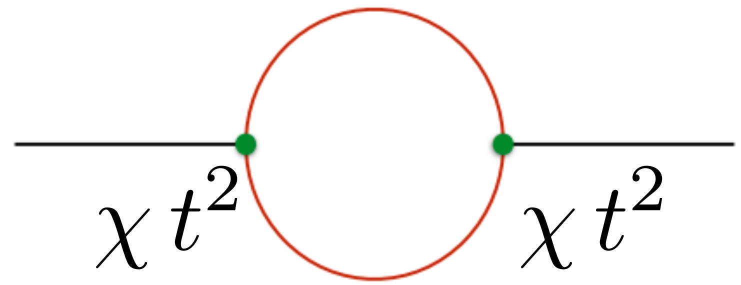
scale-dependence

non-Gaussianity

chirality

Tests

Challenge I: Perturbativity



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

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

stem strong constraints on the theory parameter space

====>

in SCNI the sourced GW signal can be larger than the vacuum but within same order of magnitude

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

[Papageorgiou, Peloso, Unal 2018 & 2019]

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

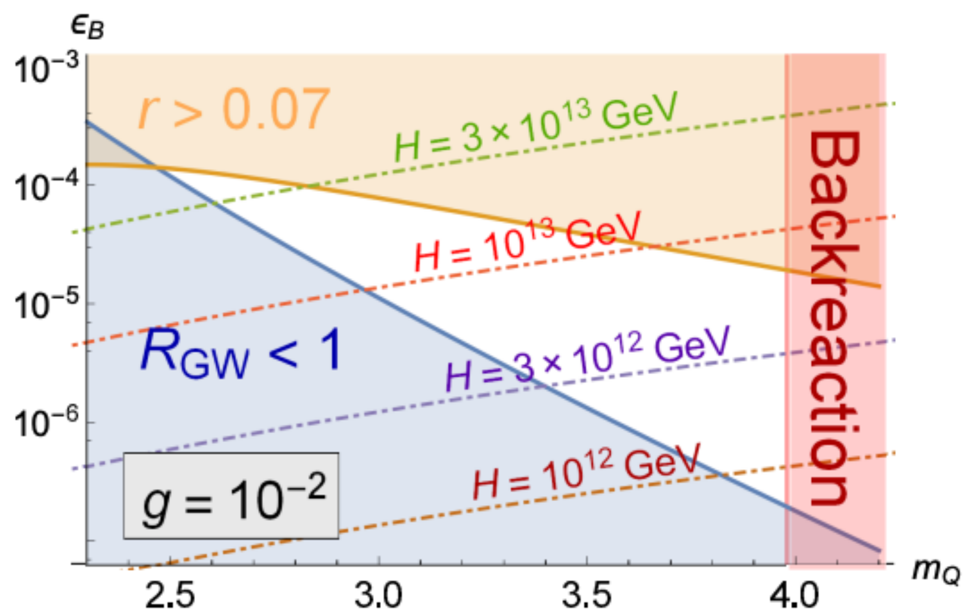
Challenge II: Backreaction

eom for the gauge field background

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

fluctuations backreact on background ==> reduced regime of validity

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



SCNI further restricted, small window still viable. For non-Abelian need strong-backreaction regime, numerical & eventually lattice

U(1) more well-studied, strong backreaction from the start + recent works including lattice qualitatively agreeing on main effects

Challenge III: UV Completion

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]

strongly constrained on more general unitarity grounds
[Agrawal, Fan, Reece 2018]
[Bagherian, Reece, Xu 2022]

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

For the latest on inflation & GW with non-Abelian fields

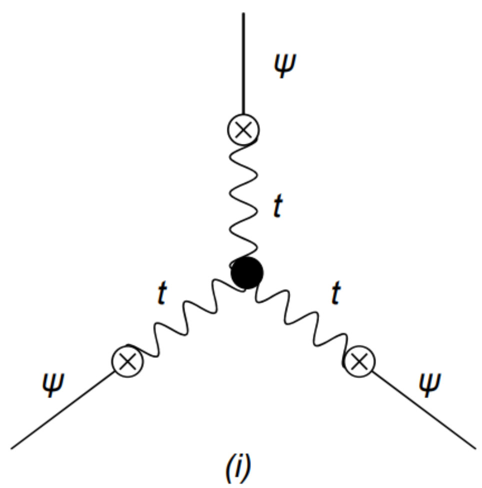
tune in for Martino's talk this afternoon!

Thank you!

non-Gaussianity (TTT)

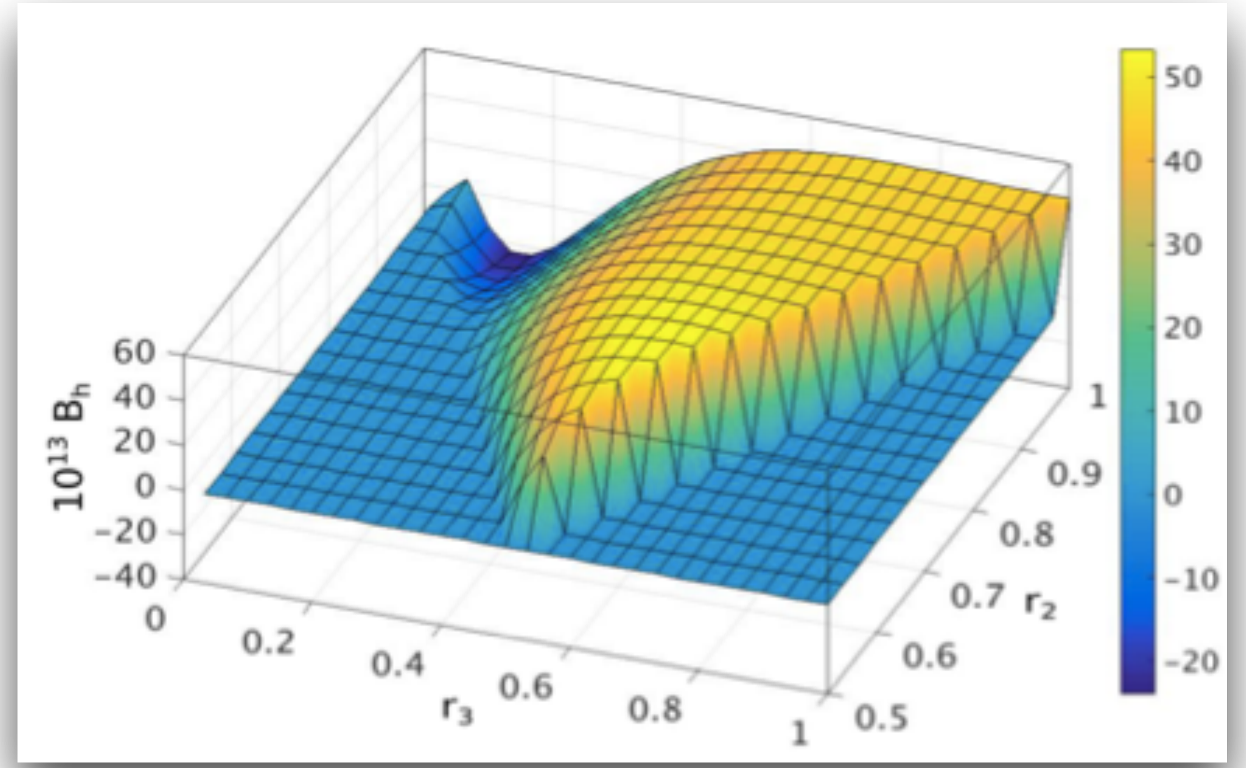
[Agrawal - Fujita - Komatsu 2017]

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

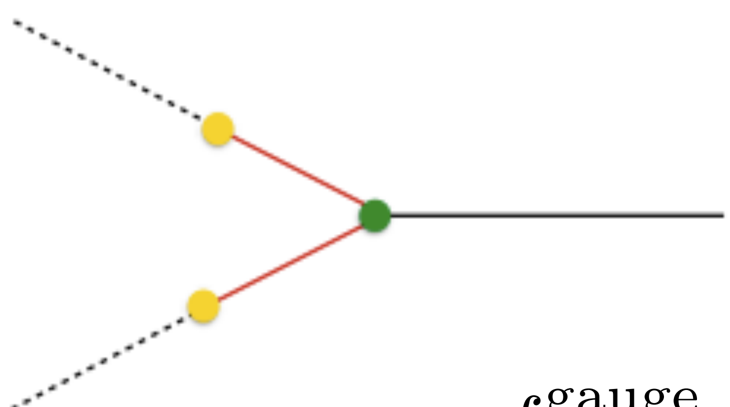
non-Gaussianity (STT)

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

[Fujita, Namba, Obata]

[Dimastrogiovanni, MF, Hardwick, Koyama, Wands]

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



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

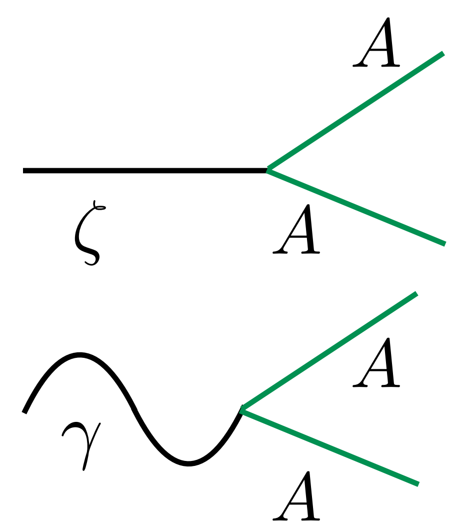
Abelian case (intriguing phenomenology)

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

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

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

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

$$\xi \equiv \frac{\lambda \dot{\phi}}{2 f H}$$

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

[Pajer, Peloso (2013)]

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]

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

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 big "j" instead via clockwork

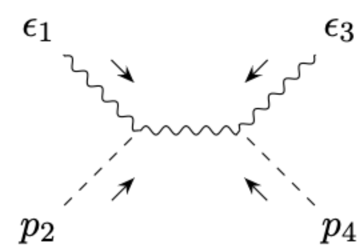
$$\sum_{i=1}^{n-1} \mu_{i+1}^4 \cos\left[\frac{m_i \chi_i}{f_i} + \frac{\chi_{i+1}}{f_{i+1}}\right] + \mu_1^4 \cos\frac{\chi_1}{f_1}$$

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

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



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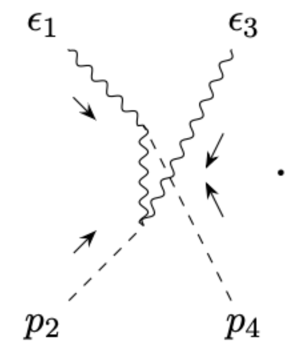
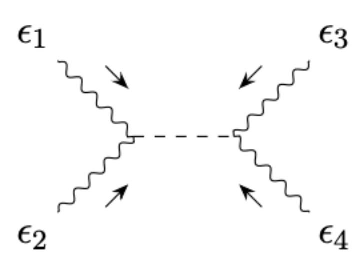


.

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

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

b: gauge scattering mediated by axion



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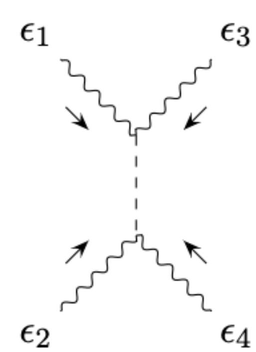

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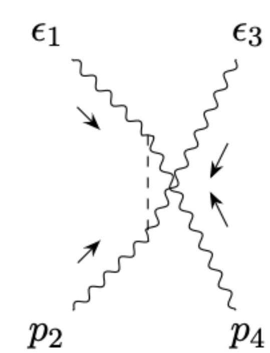


.

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

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

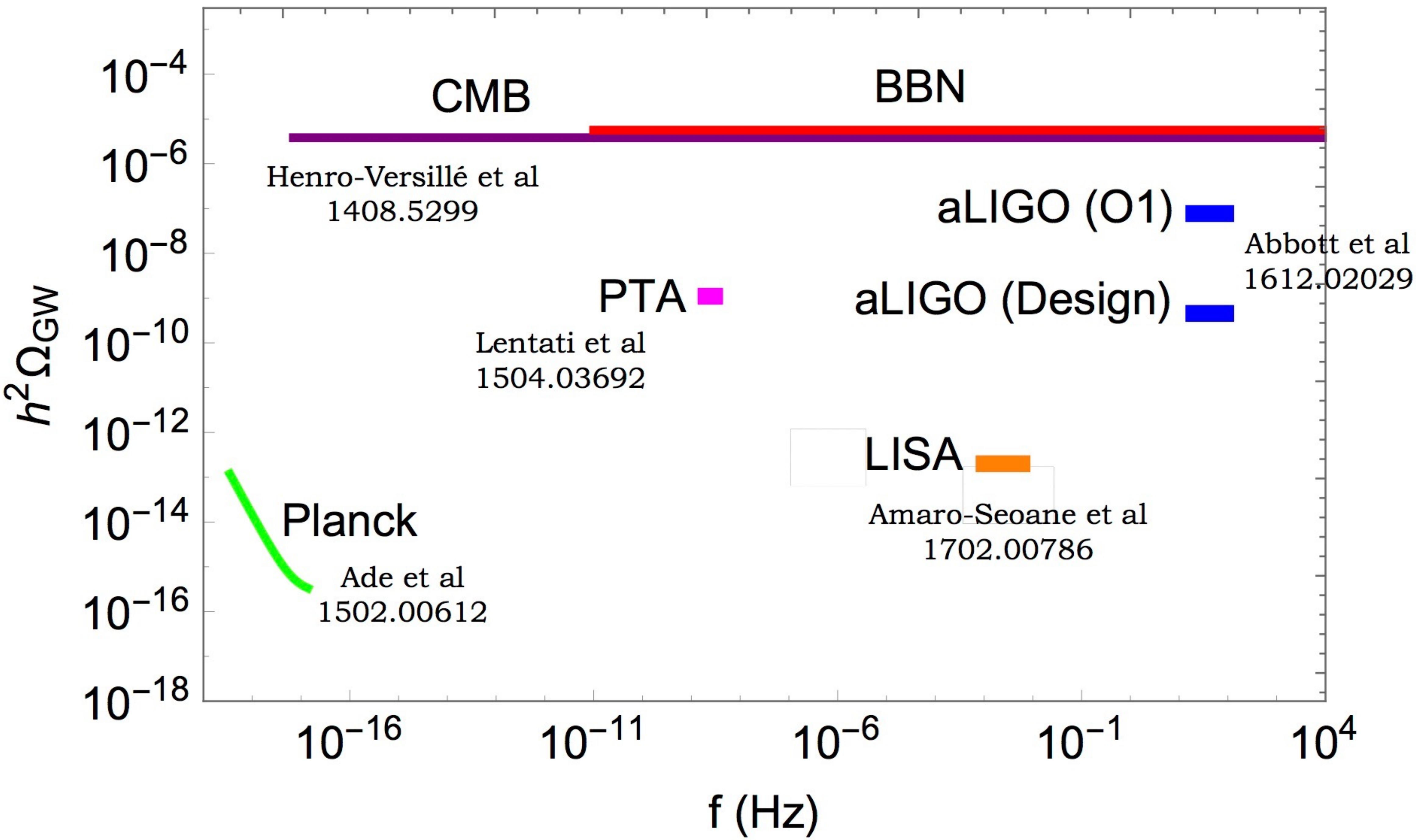
<u>need</u> spectator sector associated with gaugino condensation on multiply magnetised D7-branes

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

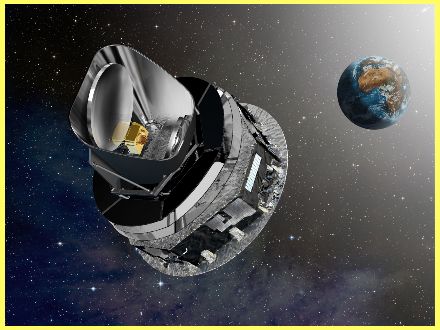
- magnetic flux
- degree of the condensing gauge group
- wrapping number of the D7-brane

gauge group degree N ~ 10^5 not easy to realise, yet necessary for phenomenology!

Observational bounds/sensitivities for SGWB



Scalar bispectrum: current bounds



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

[68 % 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 % 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**)

Backreaction Under Control