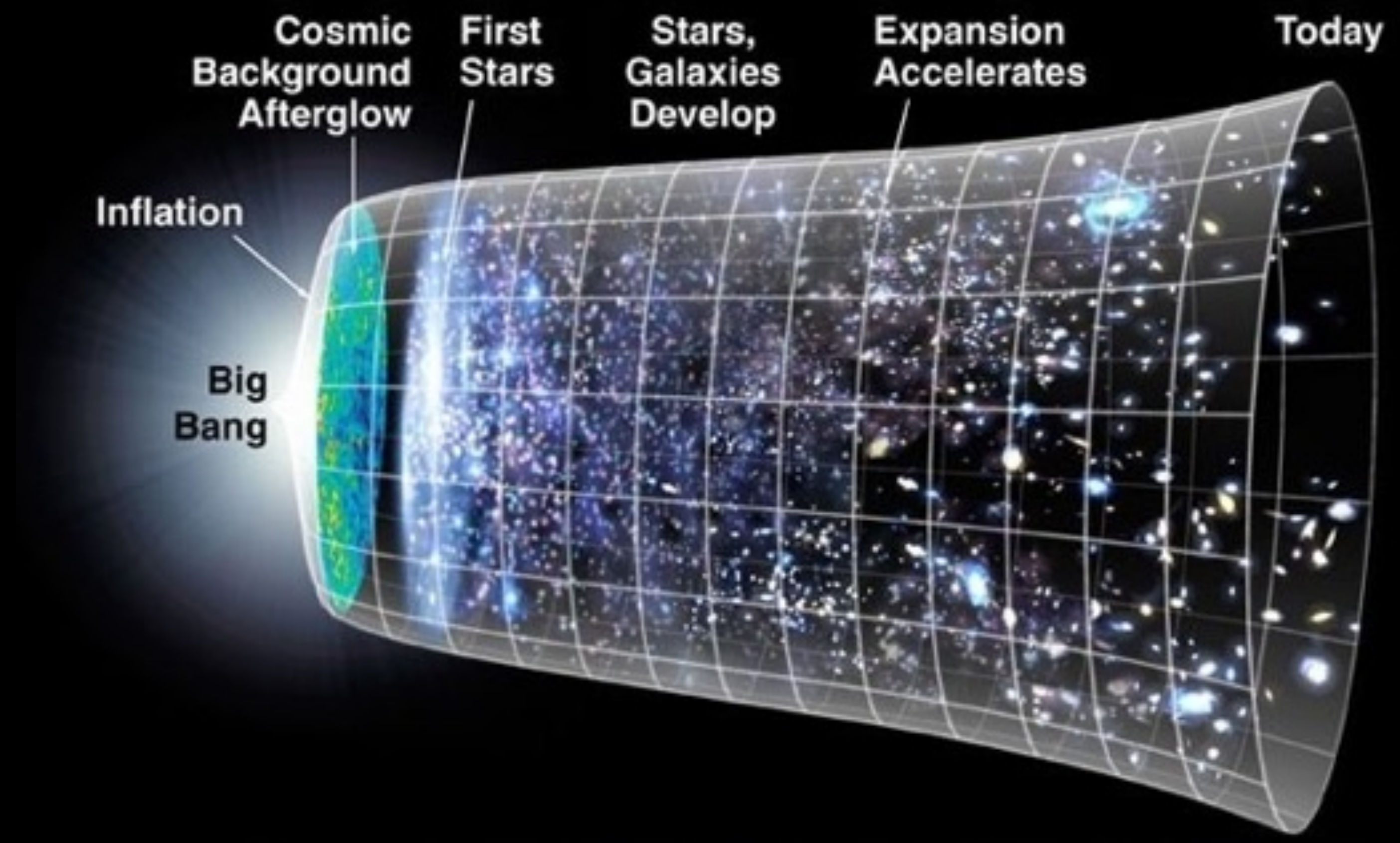
Probing Inflation with Primordial Messengers



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October 25th 2020, IAP

Inflation

- Inflation, the idea
- Single-field slow-roll scenario: successes and signatures
- The importance of upcoming-observations
- Axion inflation as a case study
- The “cosmological collider”
- Conclusions & Future work

Inflation

$$3M_{\rm P}^2 H^2 \simeq \rho_{\rm X}$$

must satisfy: $w_X \equiv p_X/\rho_X < -1/3$

What we learn

$$\frac{\ddot a}{a} = -\frac{1}{2M_P^2}(\rho + 3p)$$ acceleration!

$$\dot\rho + 3H(\rho + p) = 0$$ special case $p \simeq -\rho$

Inflation

Simplest realization: single-scalar field in slow-roll

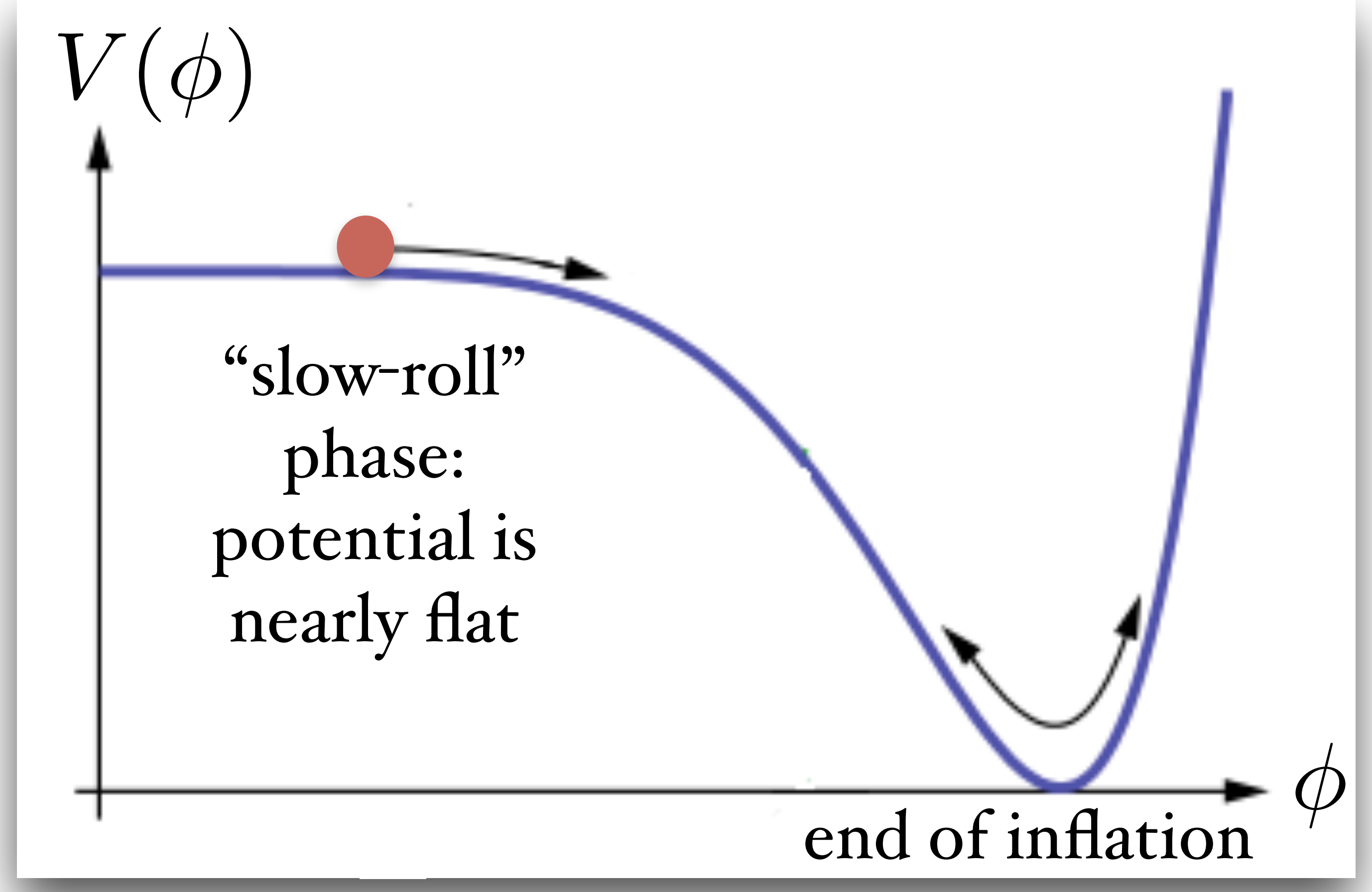
- Scalar field :

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

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

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

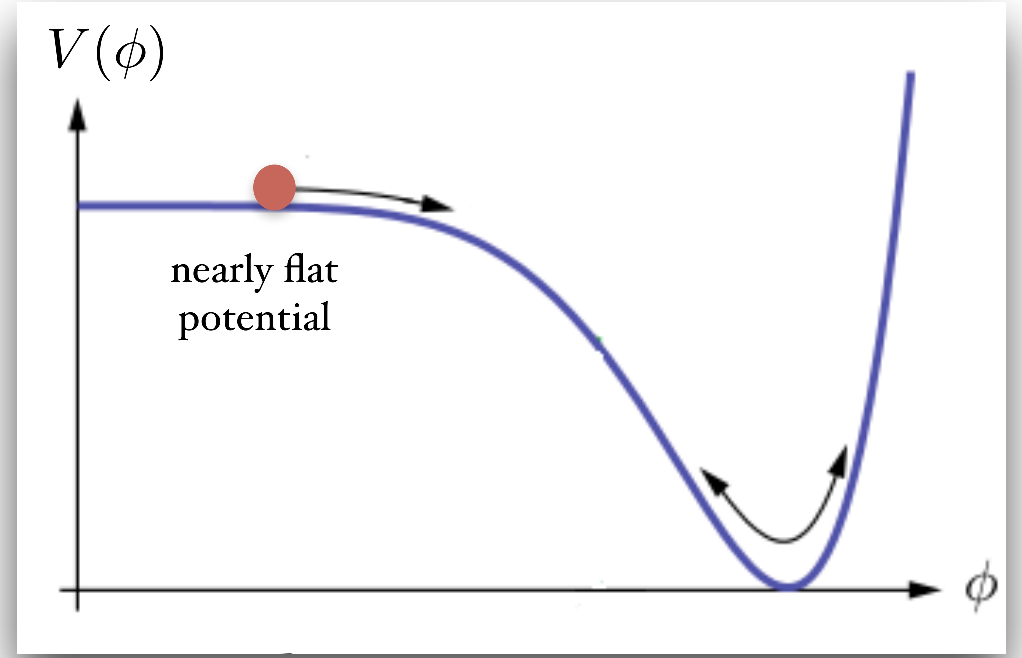
$$p_\phi \approx -\rho_\phi$$



Slow-roll

start flat

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



stay flat

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

Background + Fluctuations

$$\phi(\vec{x},t) = \bar{\phi}(t) + \delta\phi(\vec{x},t)$$

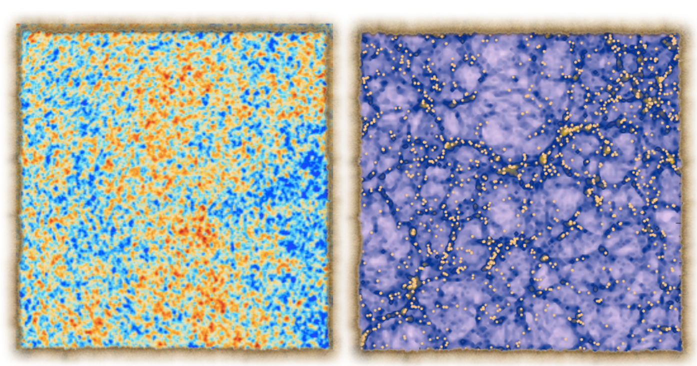
classical homogeneous background

quantum fluctuations

perturbation modes are stretched by the expansion, become super horizon and freeze out to their value at horizon exit

cosmological perturbations

ΔT $\delta\rho$



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 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 ± 0.0042

2.2×10^{-9}

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

from Planck measurements of CMB anisotropies

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

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

$r < 0.056\,(95\%\mathrm{CL},\,\mathrm{Planck}^+)$

future

$r < 0.01\,(\mathrm{CMB\text{–}S3})$

$r < 0.001\,(\mathrm{CMB\text{–}S4})$

Crossing Qualitative Thresholds

agnostic/naive

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

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

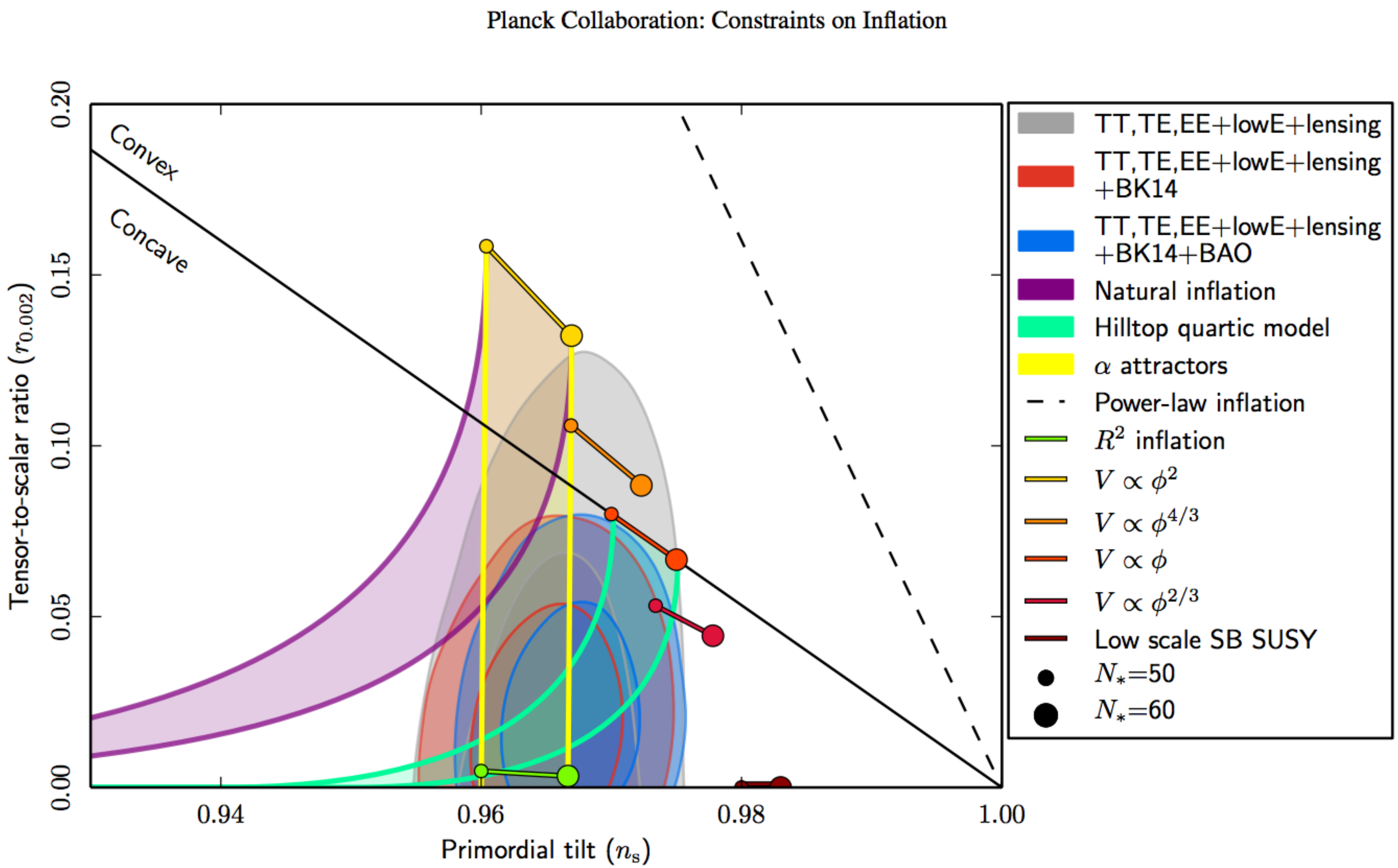
compelling models e.g. Starobinsky

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

==>

$r \gtrsim 10^{-3}$

Single-field Inflation is doing well



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

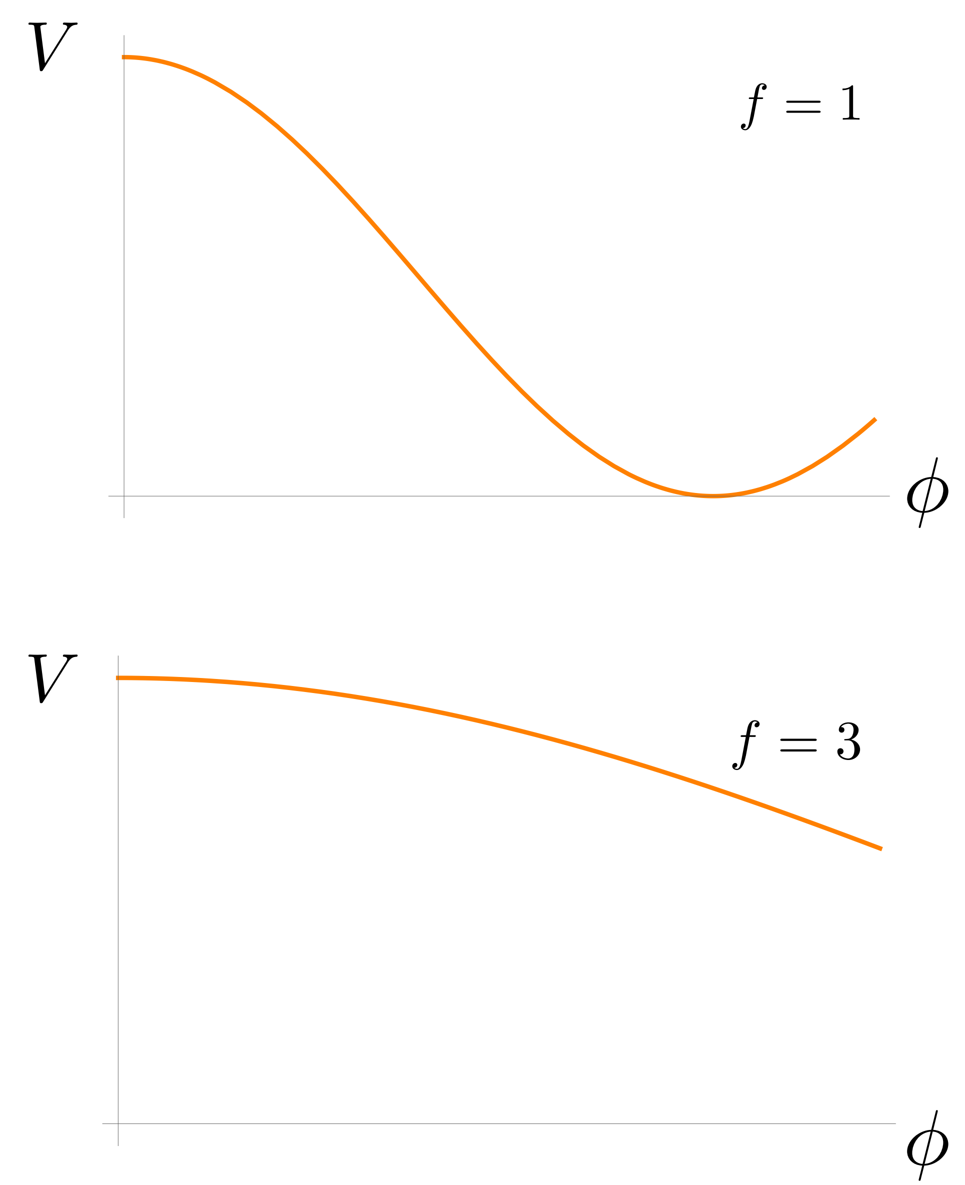
1 probe: primordial gravitational waves

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 $f \gtrsim M_{\rm P}$

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 !

Extension of 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

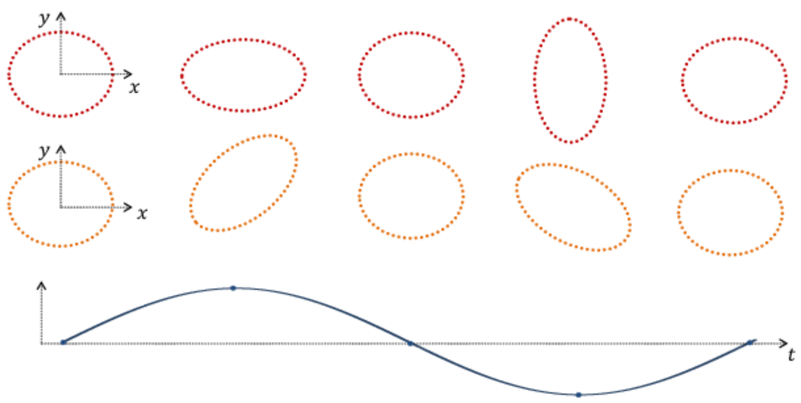
observationally viable

(Primordial) Gravitational Waves

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

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

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

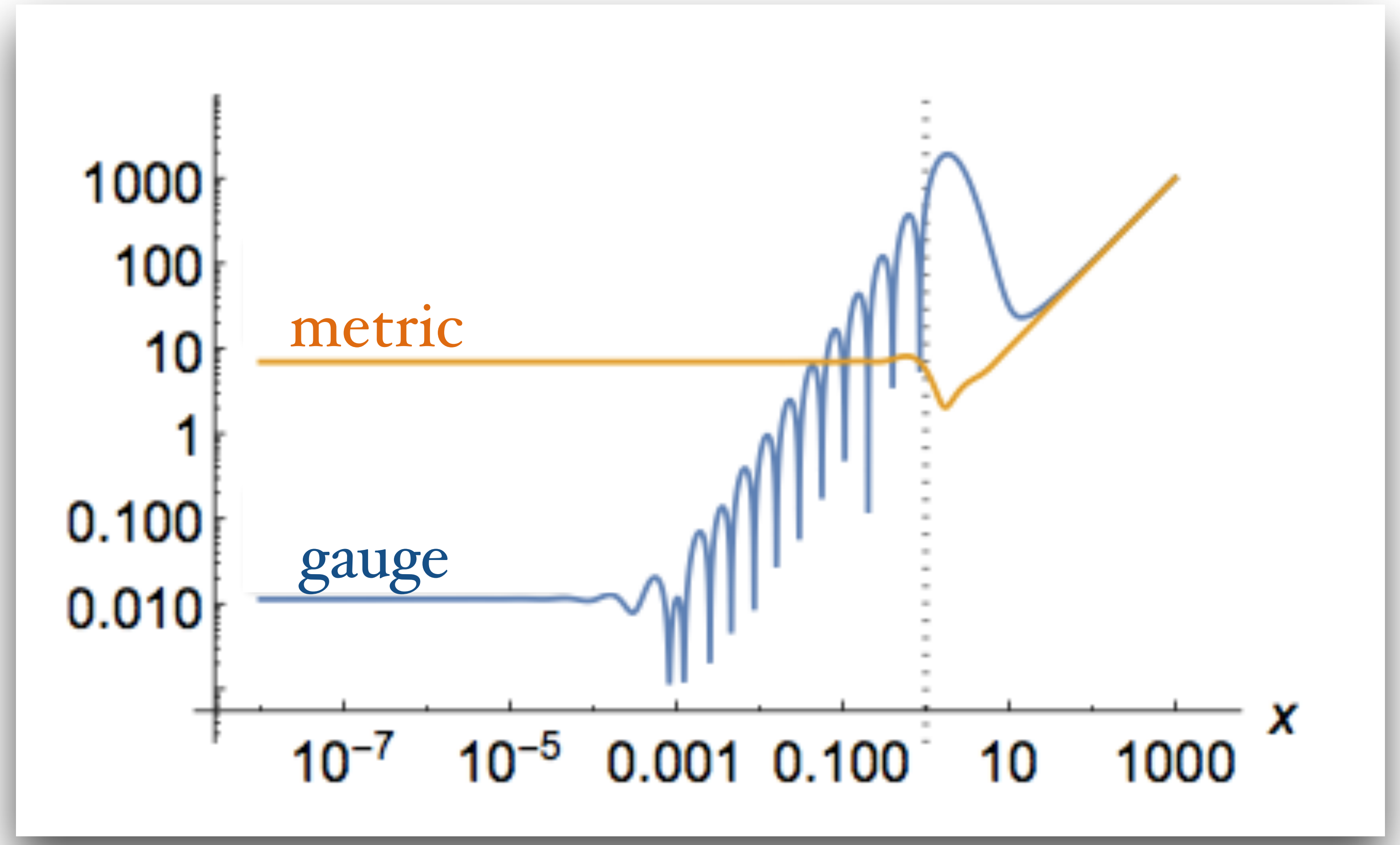
$$P_\lambda^{\text{sourced}} \gtrsim P_\lambda^{\text{vacuum}}$$

now possible!

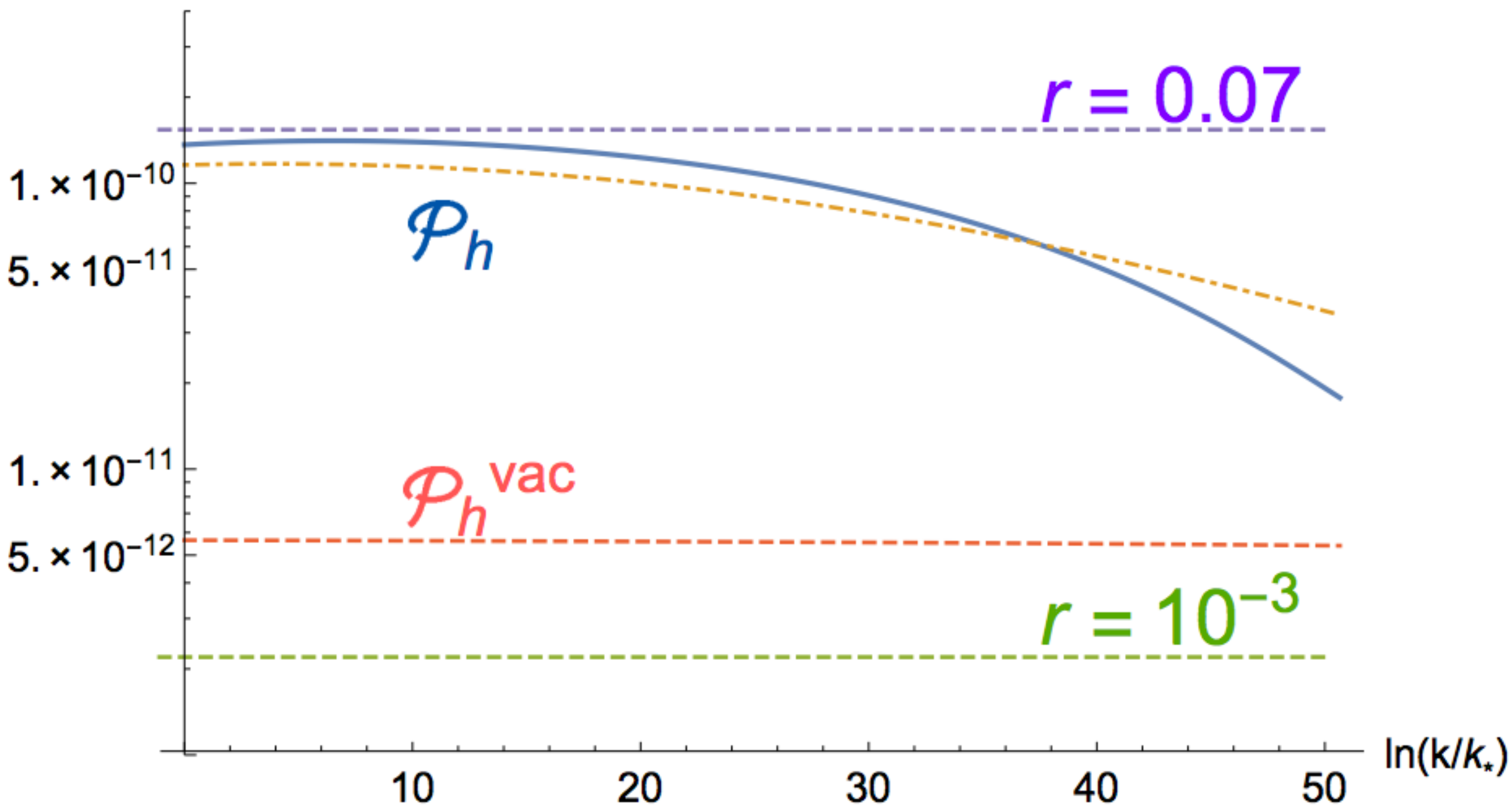
$$\text{metric} \begin{cases} \Psi''_{R,L} + \left(1 - \dfrac{2}{x^2}\right)\Psi_{R,L} = \mathcal{O}^{(1)}(t_{R,L}) \\ \text{gauge} \quad t''_{R,L} + \left[1 + \dfrac{2m_Q\xi}{x^2} \mp \dfrac{2}{x}(m_Q+\xi)\right] t_{R,L} = \tilde{\mathcal{O}}^{(1)}(\Psi_{R,L}) \end{cases}$$

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

$$x \sim -k\tau$$

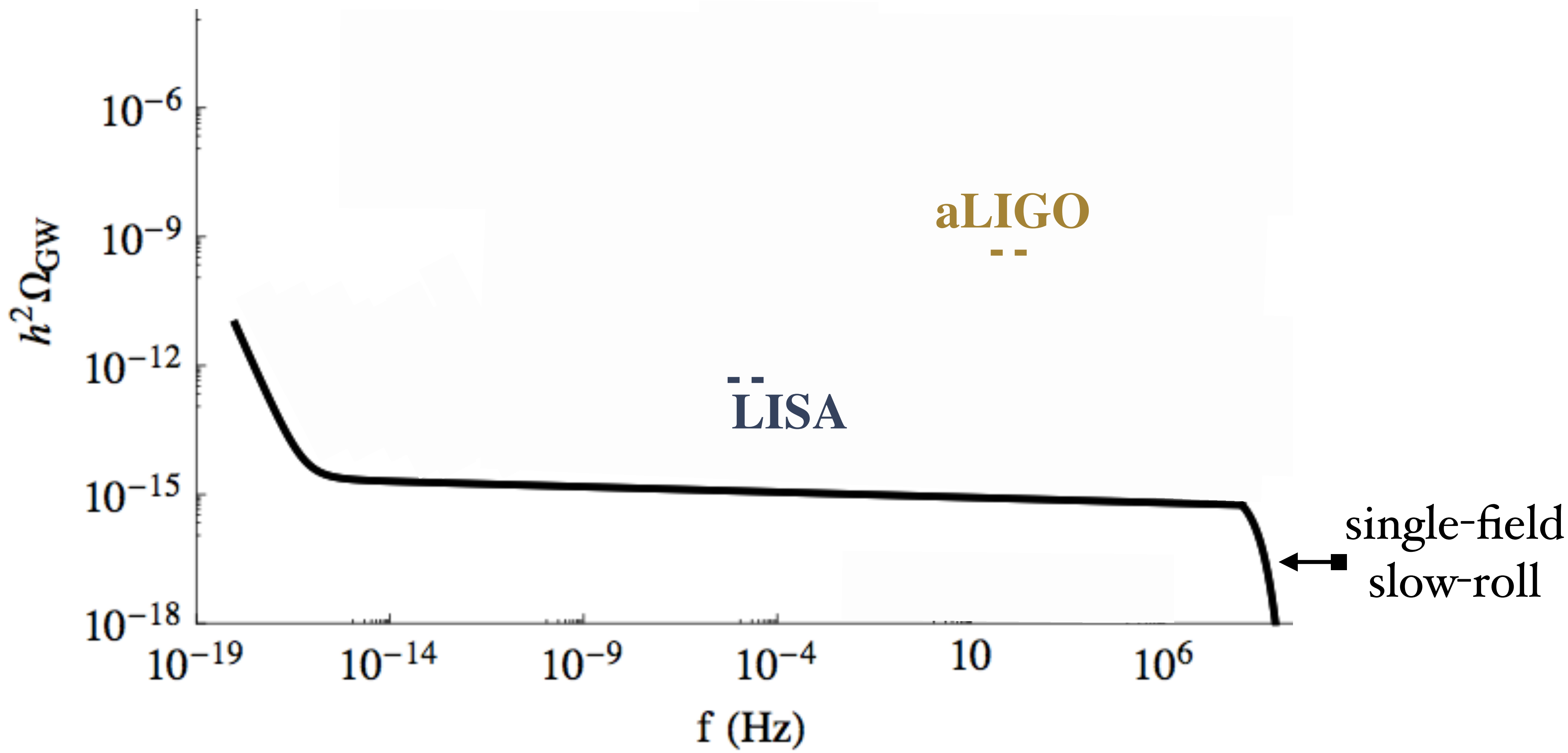


Dimastrogiovanni, MF, Fujita 2016



Dimastrogiovanni, MF, Fujita 2016

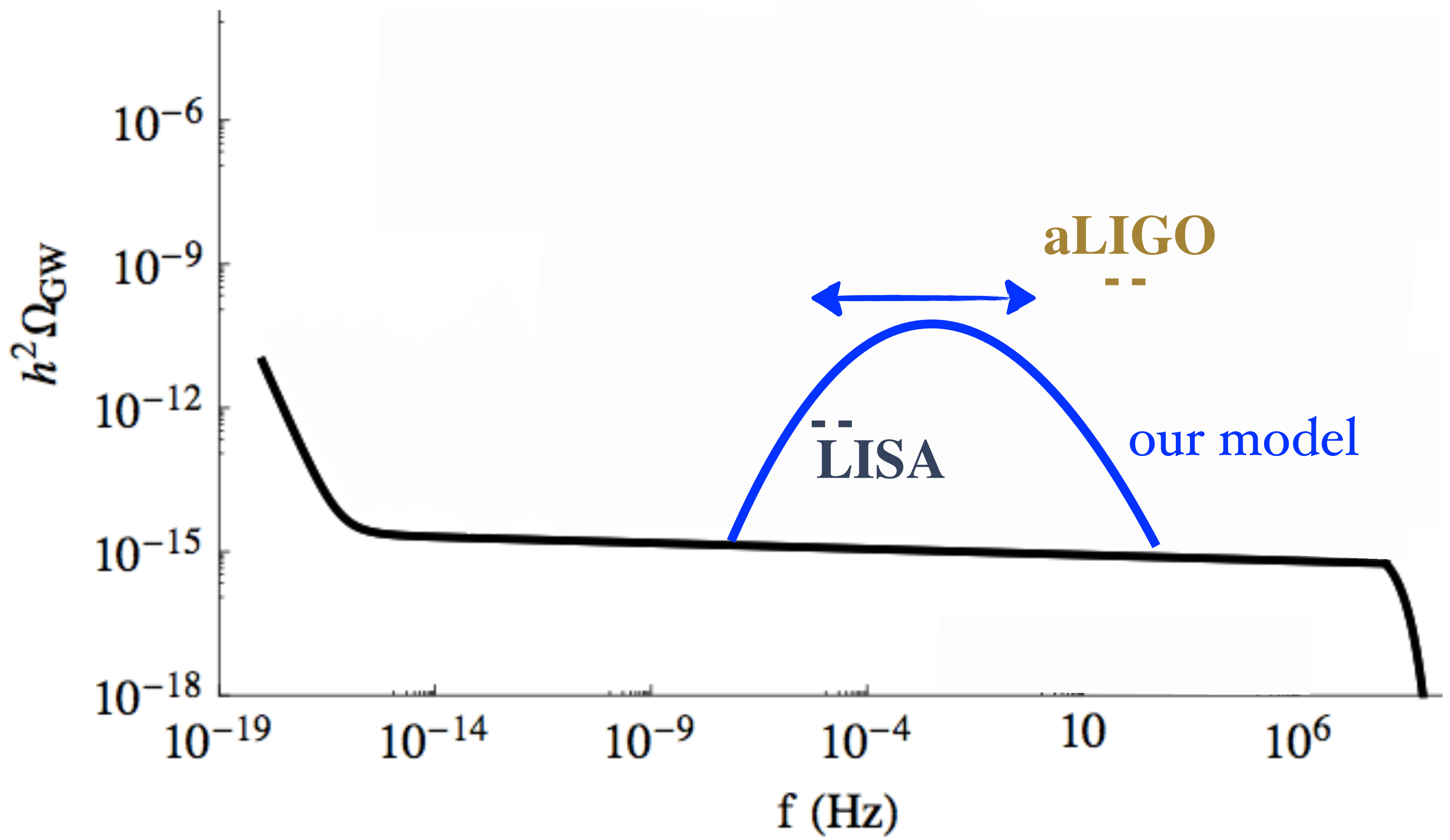
Testing Amplitude & Scale Dependence



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 $\frac{\lambda\chi}{4f}F\tilde{F}$

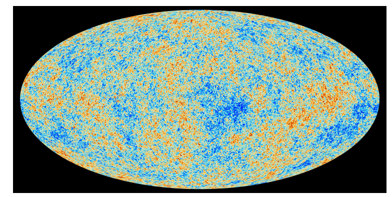
$$\ddot{t}_{ij}^{L/R} \pm \lambda(\dots)t_{ij}^{L/R} + \cdots = 0$$

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

chiral spectrum

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

Chirality



CMB tests

single-field
slow-roll inflation

no chirality

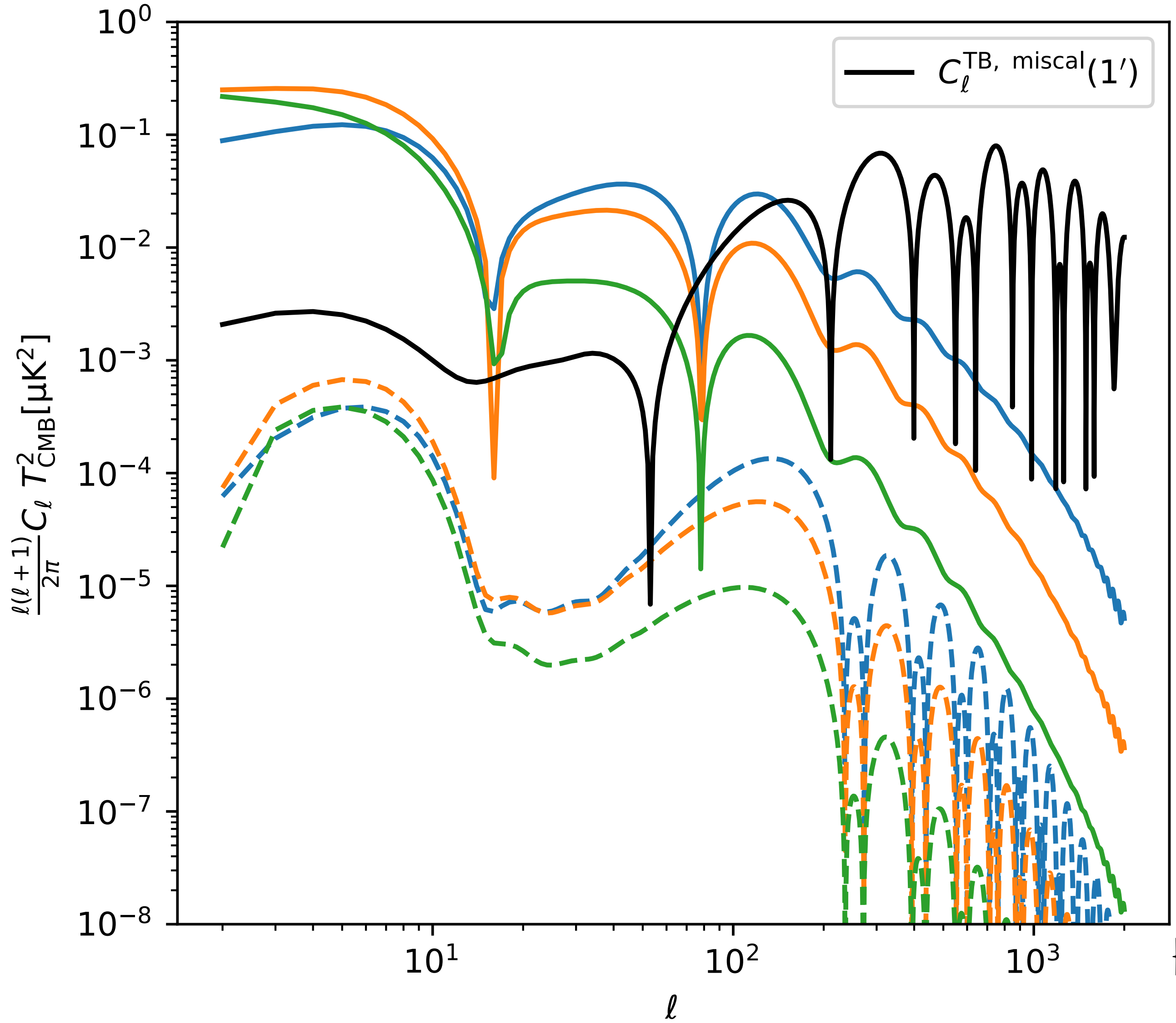
$$\langle BT \rangle = 0 = \langle EB \rangle$$

Chern-Simons
coupling

chirality

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

LiteBIRD



[Komatsu et al, 2017]

$(\sigma, k_p\ [\mathrm{Mpc}^{-1}])$

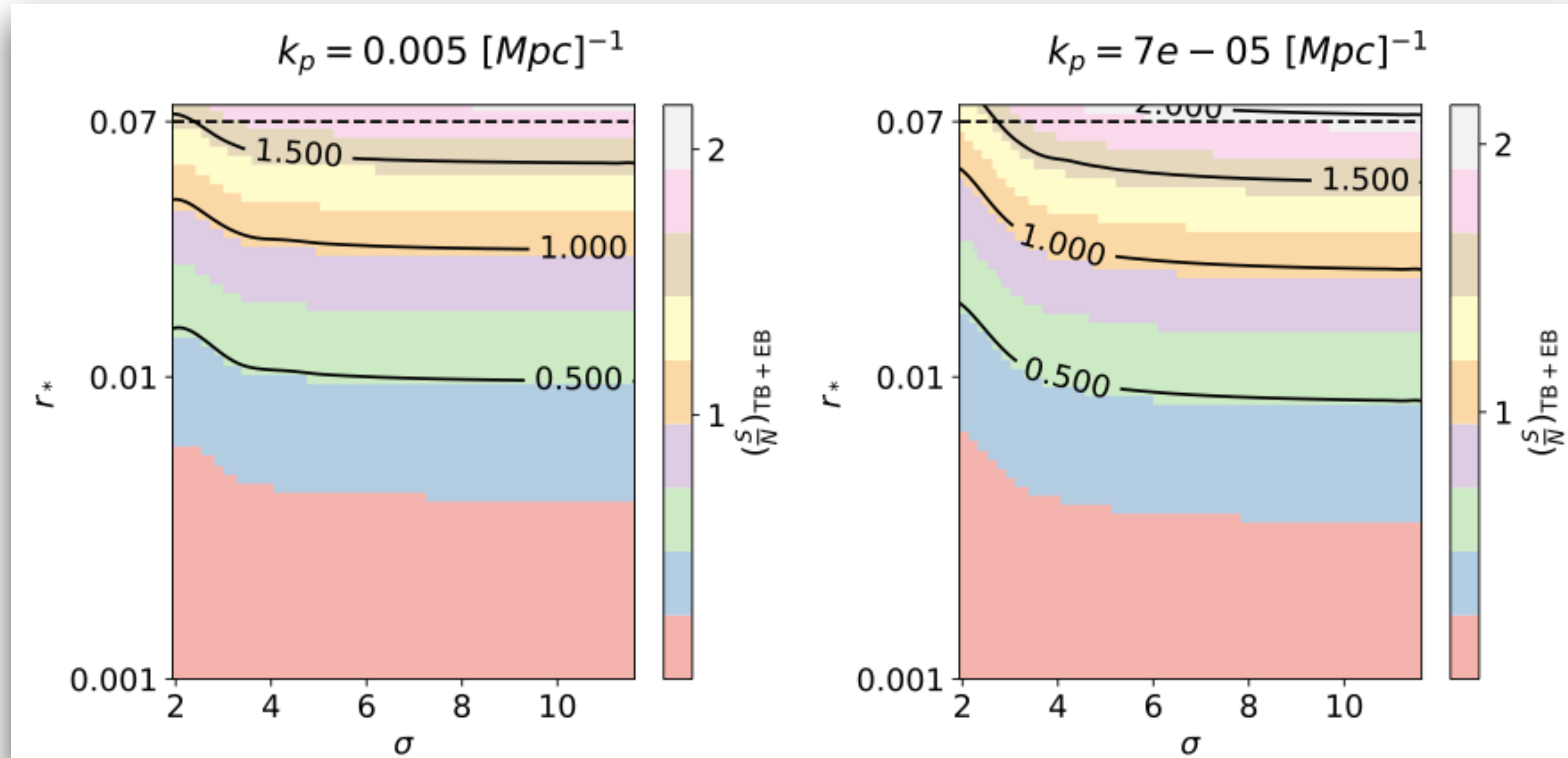
$(2, 0.005)$ $(4, 7\times10^{-5})$ $(2, 7\times10^{-5})$

$(4, 0.0005))$ $(4, 0.005)$ $(2, 0.0005)$

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

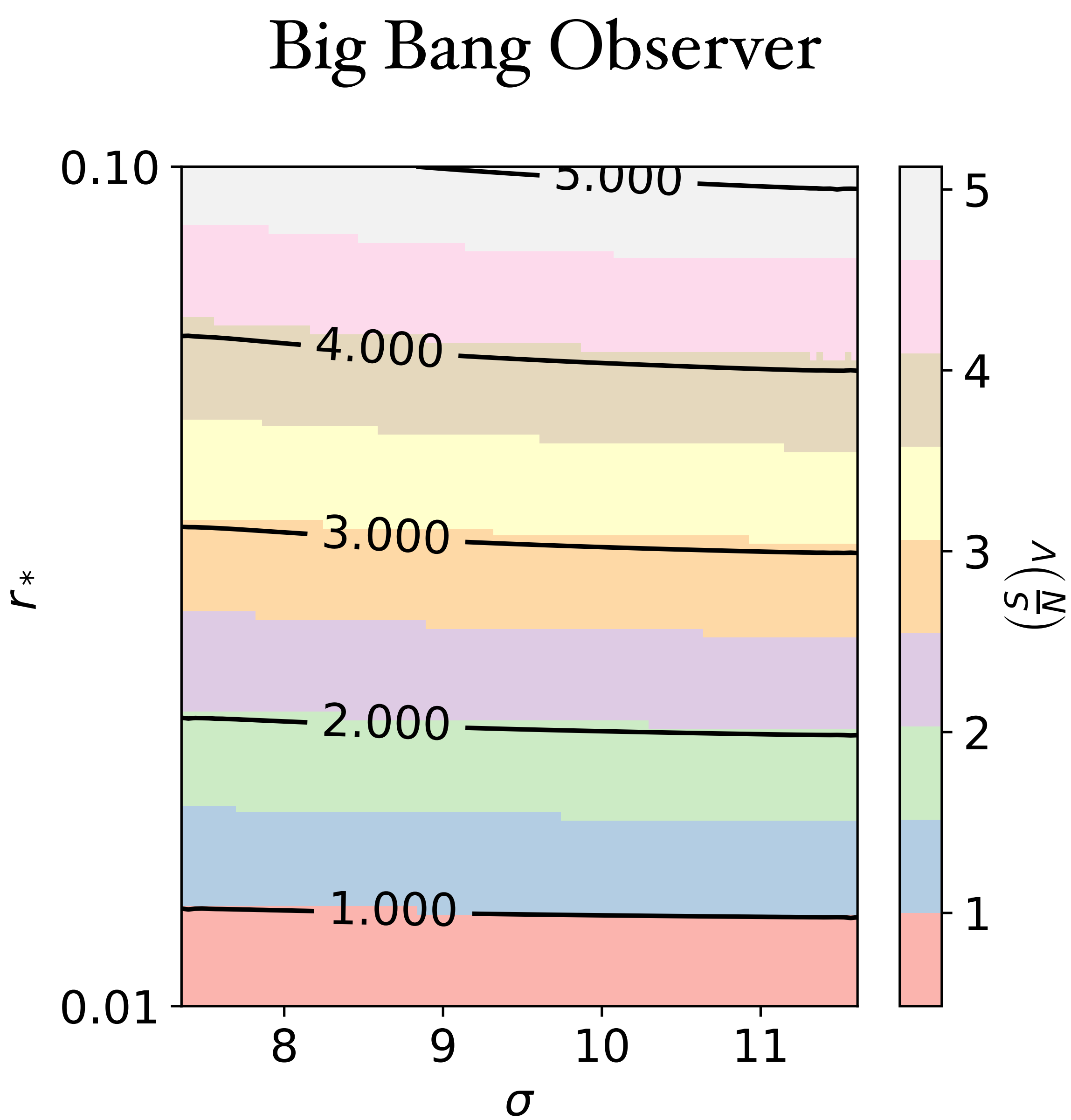
Extended Chromo-Natural

gravitational waves forecast: LiteBIRD



Komatsu et al 2017

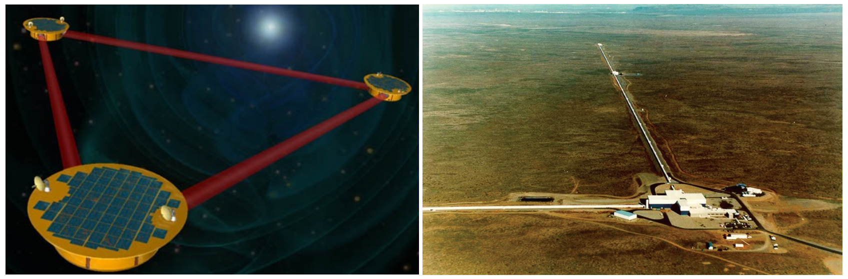
Extended Chromo-Natural



$k_p \sim 10^{13}\,\mathrm{Mpc}^{-1}$

Komatsu et al 2017

Chirality



Interferometers tests

- cross-correlation between interferometers at different locations

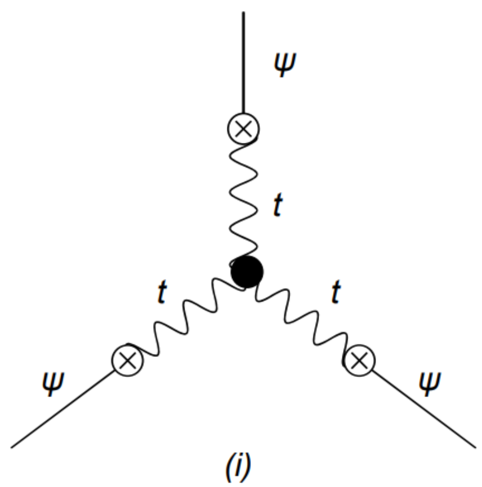
[Smith, Caldwell 2017]

- recent work on LISA: use kinematically induced dipole

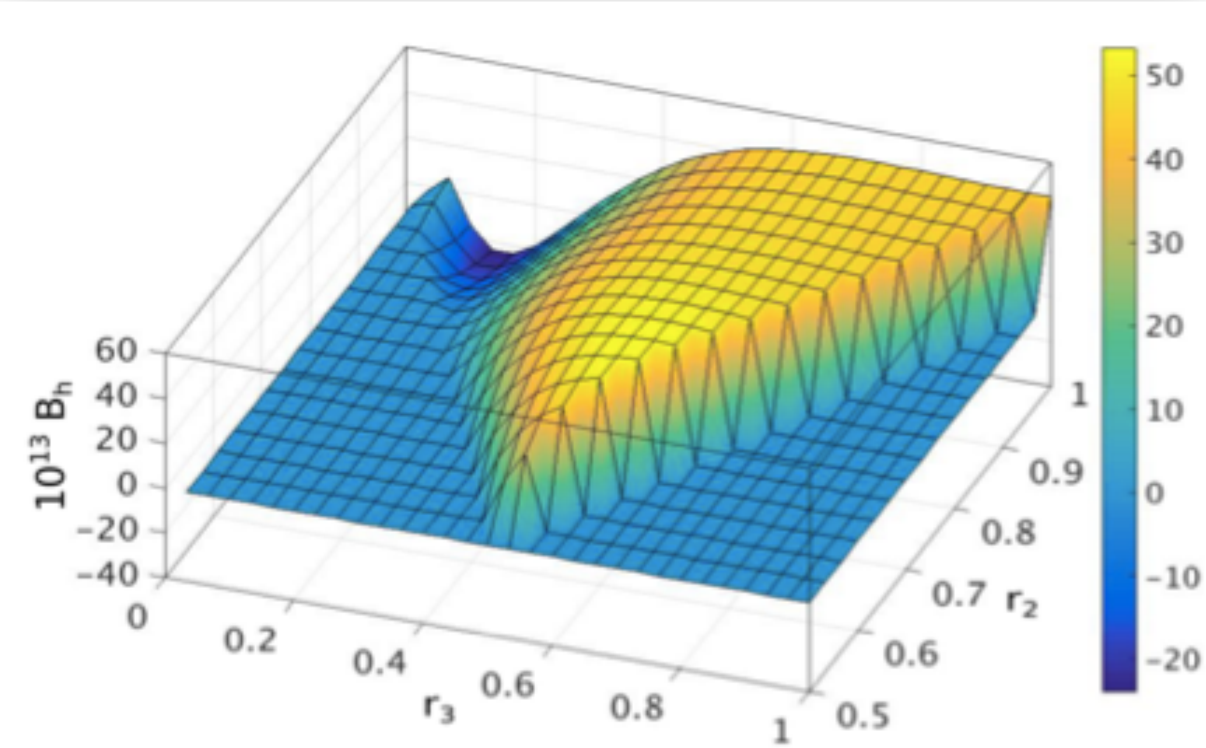
[Seto 2006]
[Domcke et al 2019]

n-G in Axion-Gauge Field Model

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
much larger than in SFSR

[Agrawal - Fujita - Komatsu 2017]

Primordial GW to test inflationary particle content

more later

scale-dependence

…non-Gaussianity

chirality

Axion-gauge field models

general approach: inflationary particle content

Organizing Principles for extra particle content: the mass

(effective) mass range

$$m \gg H$$

fields integrated out, some remnants

Achucarro et al 2012
Burgess et al 2013
MF et al 2013
Silverstein 2017

$$m \lesssim H$$

immediate and detectable effects

Organizing Principles for particle content: the spin

consequences on the mass range

Particles as unitary irr. rep of spacetime isometry group, dS

[Wigner]

principal series

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

complementary

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

discrete series

$$\frac{m^2}{H^2} = s(s-1) - t(t-1)$$

$s \geq t \; ; \; s, t, = 0, 1, 2, \ldots$

Mass & Spin

spin-2 example

can source tensors linearly!

$$m^2 = 0 \checkmark \quad m^2 \geq 2H^2$$

+

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

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

Extra spin-2 field is a massive graviton

know how to write it non-linearly

$$S_{\rm tot} = S_\phi + \int d^4x \Big[\sqrt{-g}\, M_P^2\, R[g] + \underline{\sqrt{-f}\, M_f^2\, R[f]} - \underline{m^2 M^2 \sqrt{-g}\, \beta_n\, \mathcal{E}_n(\sqrt{g^{-1} f})} \Big]$$

[de Rham, Gabadadze, Tolley (2011)]

[Hassan, Rosen (2011)]

ghost-free

+

well-known use for late-time acceleration, m~H_0

check the unitarity bound

&

use in inflationary context

Unitarity bound

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

[MF, Tolley (2012&2013)]

somewhat weakened constraint but

$$m \sim H$$

extra spin-2 fields tend to decay quickly

not the end of the story!

[Biagetti, Dimastrogiovanni, MF (2017)]
[Dimastrogiovanni, MF, Tasinato (2018)]
partially massless: [Goon, Hinterbichler, Joyce, Trodden (2018)]

but see also

[Lin, Sasaki (2015)]
[Fujita, Kuroyanagi, Mizuno, Mukohyama (2018)]

How can we probe info on Mass & Spin?

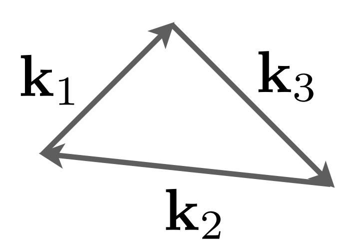
non-Gaussianities

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

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



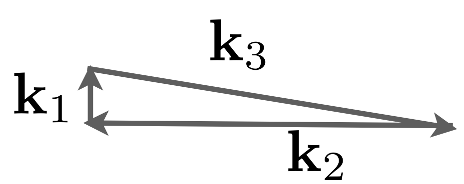
Amplitude

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

Squeezed Bispectrum: single-field inflation

$$\lim_{\mathbf{k}_1 \to 0} \frac{1}{P_\zeta(k_1)} \langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle = -\mathbf{k}_2 \cdot \frac{\partial}{\partial \mathbf{k}_2} \langle \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle$$

[Maldacena, 2003]



standard consistency relation
for single-field inflation

$$\langle \zeta_{k_1} \zeta_{k_2} \zeta_{k_3} \rangle \Big|_{k_1 \ll k_3} \propto \frac{1}{k_1^3 k_3^3} \underbrace{\sum_{n=0} b_n \left(\frac{k_1}{k_3} \right)^n}_{\propto f_{\rm NL}}$$

physical information from n=2

qualitative threshold for LSS surveys $f_{\rm NL} \sim 1$

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

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

$\Big|_{m \geq \frac{3}{2}H}$

direct mass suppression

non-analytical scaling

crucial fact for s ≥ 2 spinning fields

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

Tensor-scalar-scalar Bispectrum

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

non-analytical scaling, CRs breakimg

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

extra angular dependence

Connections with "tensor fossils" as diagnostic of new physics

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

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

Crucial for non-Gaussianity at small scales (e.g. LISA)

$$P_\gamma^{\rm tot}(\mathbf{k}, \mathbf{x}_c)\Big|_{\gamma_L} = P_\gamma(k)\left(1 + \mathcal{Q}_{lm}(\mathbf{x}_c, \mathbf{k})\hat{k}_l \hat{k}_m\right)$$

[Dimastrogiovanni, MF, Tasinato, PRL 2020]

$$\mathcal{Q}_{lm}(\mathbf{x}_c, \mathbf{k}) \equiv \int \frac{d^3 q}{(2\pi)^3}\, e^{i\mathbf{q}\cdot\mathbf{x}_c} \sum_\lambda \left[\frac{\tilde{B}^{\,\rm sq}(\mathbf{k}, \mathbf{q})}{2\, P_\gamma(k) P_\gamma^\lambda(q)}\right] \epsilon_{lm}^\lambda(-\hat{q})\gamma_{-\mathbf{q}}^{*\lambda}$$

Caveat: only squeezed non-G

- propagation effects typically de-correlate primordial non-Gaussianities

[Bartolo, De Luca, Franciolini, Lewis, Peloso, Riotto, 2019]

- an important exception is the ultra-squeezed regime (e.g. long mode horizon-size)

[Dimastrogiovanni, MF, Tasinato]

◆ application: correlate STT-sourced GW anisotropies with CMB anis. to test primordial origin

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

$$\delta F_{NL}^{\rm sq} \simeq \frac{2.8 \times 10^3}{\rm SNR_{SGWB}}$$

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

non-minimal coupling to the inflaton!

Effective Field Theory Approach

[Iacconi, **MF** et al, 2019] *GW at interferometers*

[Dimastrogiovanni, **MF**, Tasinato, Wands 2018] *large non-Gaussianity*

[Bordin, Creminelli, Khmelnitsky , Senatore 2018] ***spinning fields***

Examples

quasi-single-field

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

[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 at LISA scales

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

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

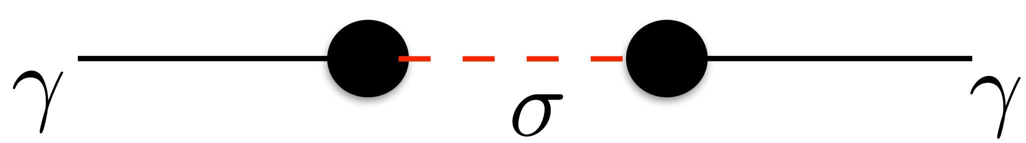
[Bordin et al 2018]

Power Spectrum

Extra spin-2 case

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

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



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

[Bordin et al 2018]

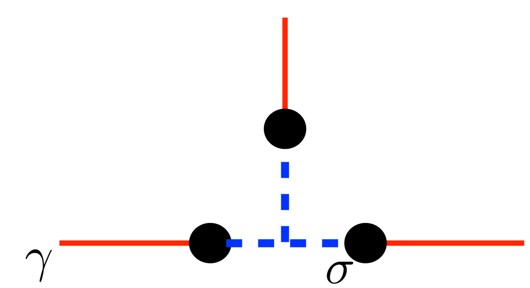
$\frac{\rho}{H} \ll 1$ perturbative treatment of quadratic mixing

$\frac{\mu}{H} \ll 1$ 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]

Small scales signatures?

time-dependent sound speeds $\{c_0, c_1, c_2\}$, $s_i = \frac{\dot{c}_i}{Hc_i}$

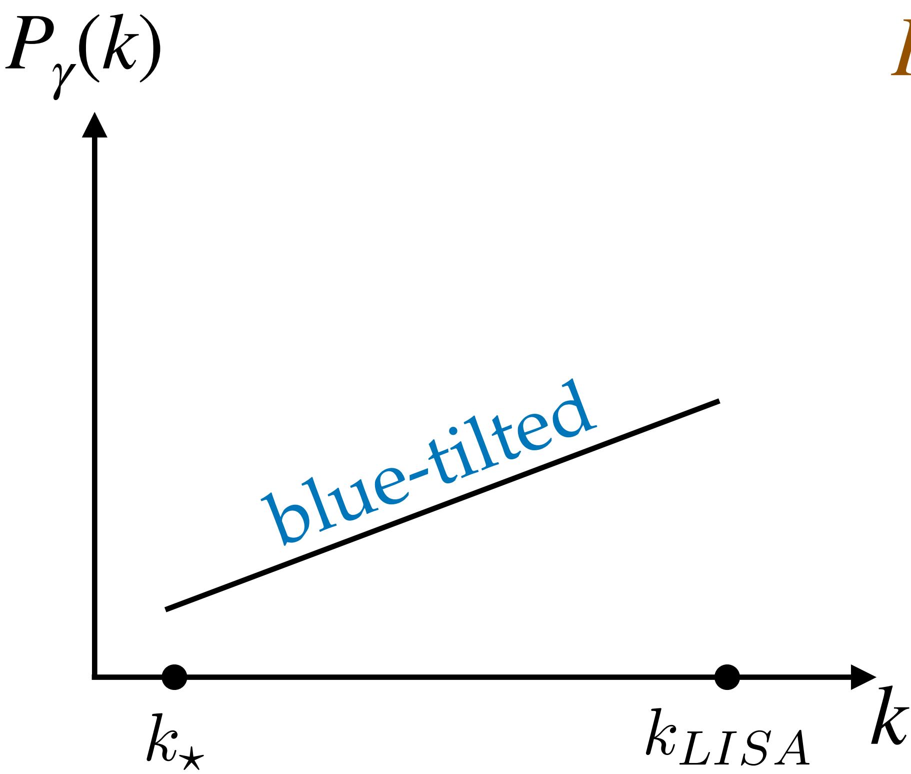
[Iacconi et al 2019]

Why? Integrating out heavy fields may result into $c_s < 1$ for the remaining light field(s)

{1201.6342 - Achucarro et al., …}

- $c_1{}^2 = \frac{1}{4}c_2{}^2 + \frac{3}{4}c_0{}^2$
- $s_0 = \frac{4}{3}\frac{c_1^2}{c_0^2}s_1 - \frac{1}{3}\frac{c_2^2}{c_0^2}s_2$
- perturbativity bound: $c_2 > 10^{-4}$, sets a bound on $s_2 = \frac{\dot{c}_2}{Hc_2}$

Consequence: scale dependent P_ζ &/or P_γ



$$P_\gamma(k) \propto \frac{1}{{c_2}^{2\nu}} \left(\frac{k}{k_\star} \right)^{-2\nu s_2}$$

if $s_2 < 0$ the sourced contribution is blue-tilted:

can this signal be detected ?

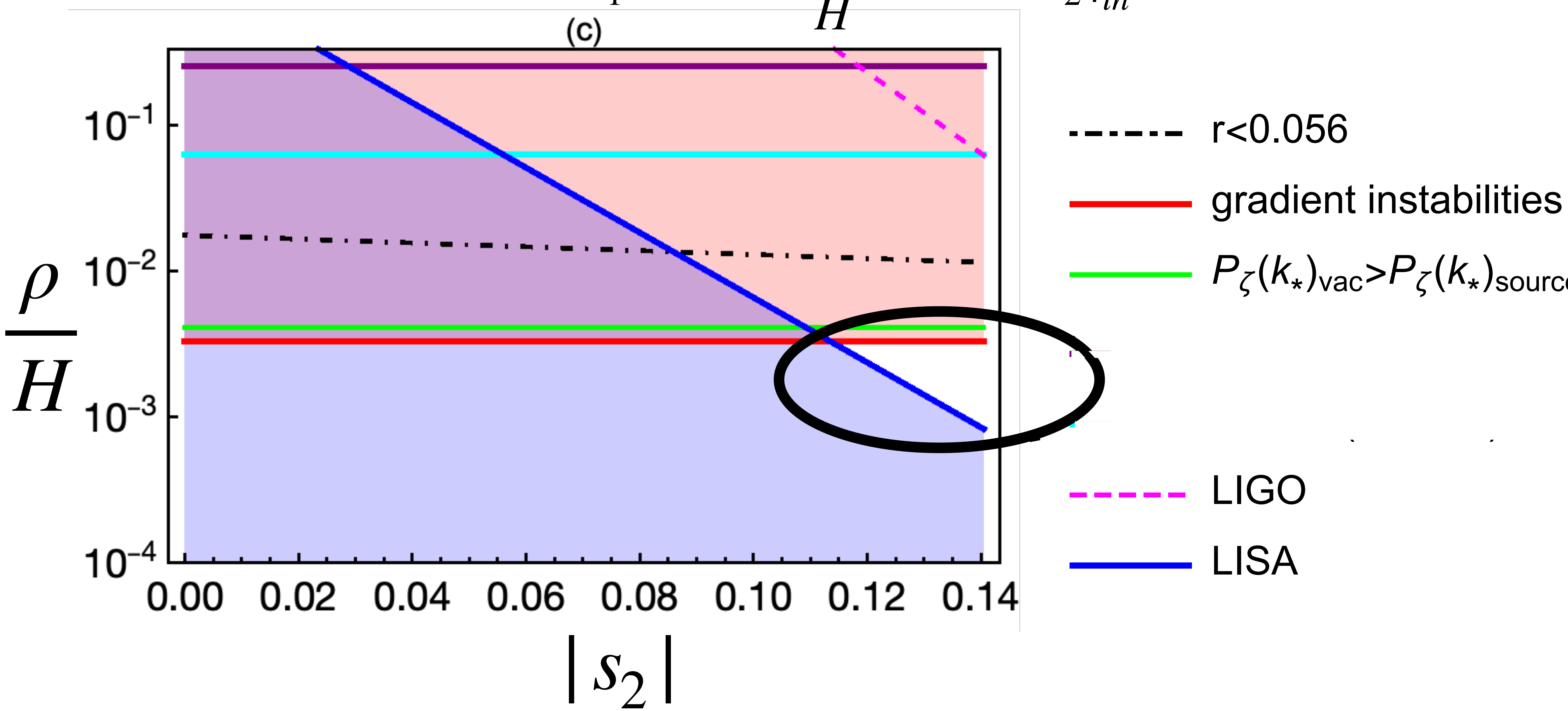
Example: $\{s_2 < 0,\ s_1 = 0,\ s_0 > 0\}$

$$\begin{cases} c_2(k) = c_2|_{in} \left(\dfrac{k}{a_0 H_0} \right)^{s_2} \\ c_0(k) = \sqrt{\dfrac{4}{3} c_1^2 - \dfrac{1}{3} c_2(k)^2} \end{cases}$$

parameters: $\{H, c_2|_{in}, c_1, \frac{m}{H}\}$

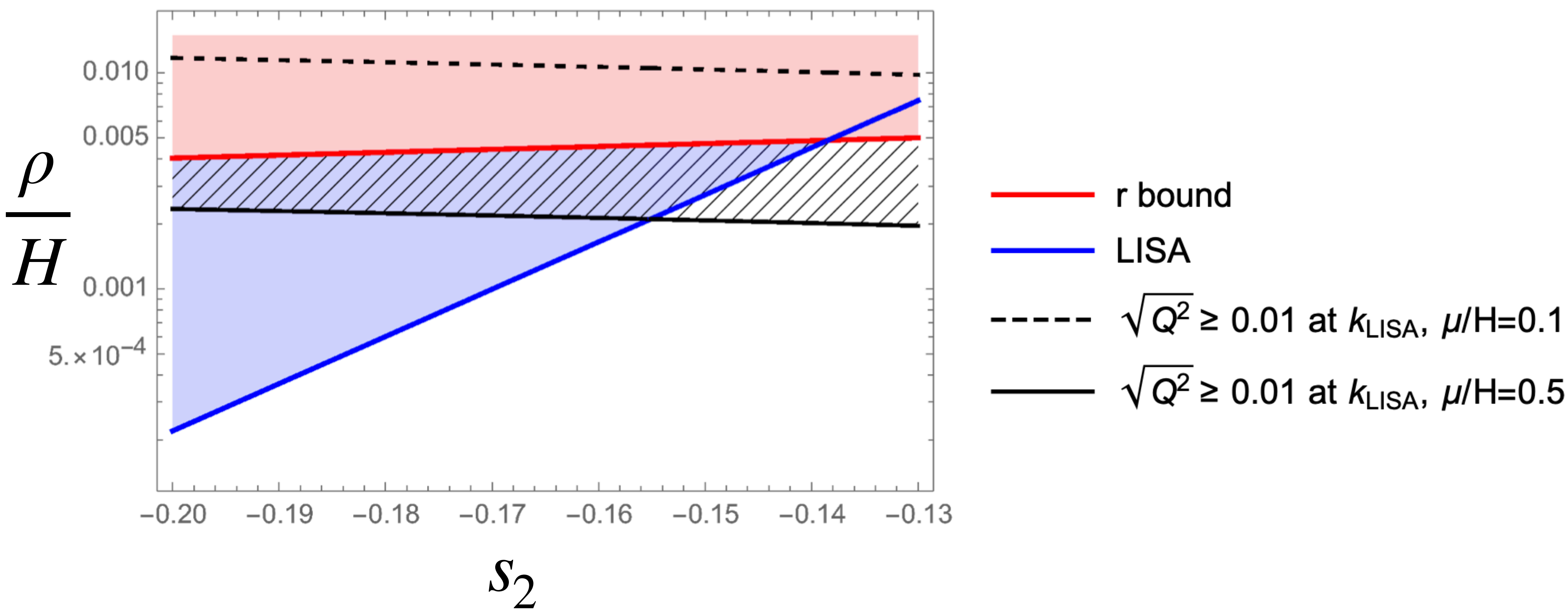
Example of parameter space analysis

$$H = 10^{13}\ \mathrm{Gev}\ ,\ c_1 = 0.85\ ,\ \frac{m}{H} = 0.54\ ,\ c_2|_{in} = 10^{-1}$$

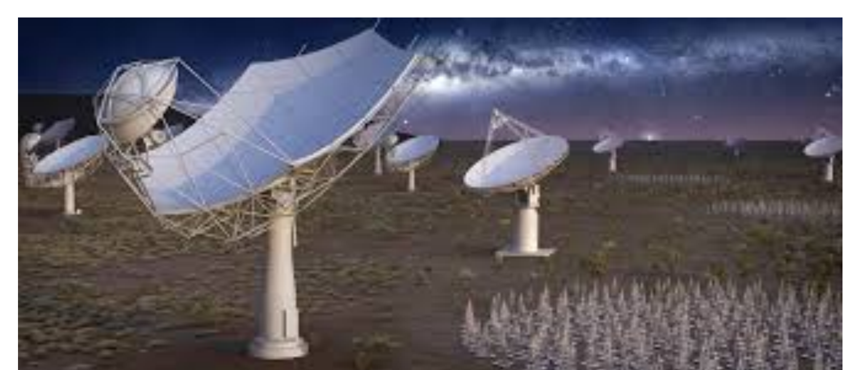


L. Iacconi's slide!

$\mathcal{Q}_{lm}$ standard deviation: $\sqrt{\bar{Q}^2} = 16 \int_0^{k_{L\,max}} \frac{dk_L}{k_L} f_{NL}^2(k_L, k_S)\, \mathcal{P}_\gamma(k_L)$



The same analysis can be performed also considering SKA

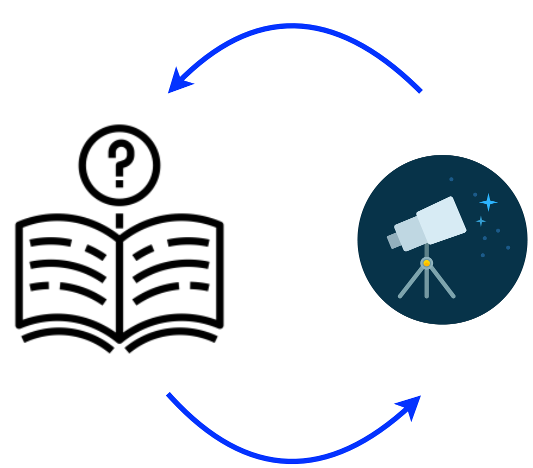


Conclusions

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

Lots we can learn on inflationary field content, strong connection with particle physics

Prepare theory to meet experiments

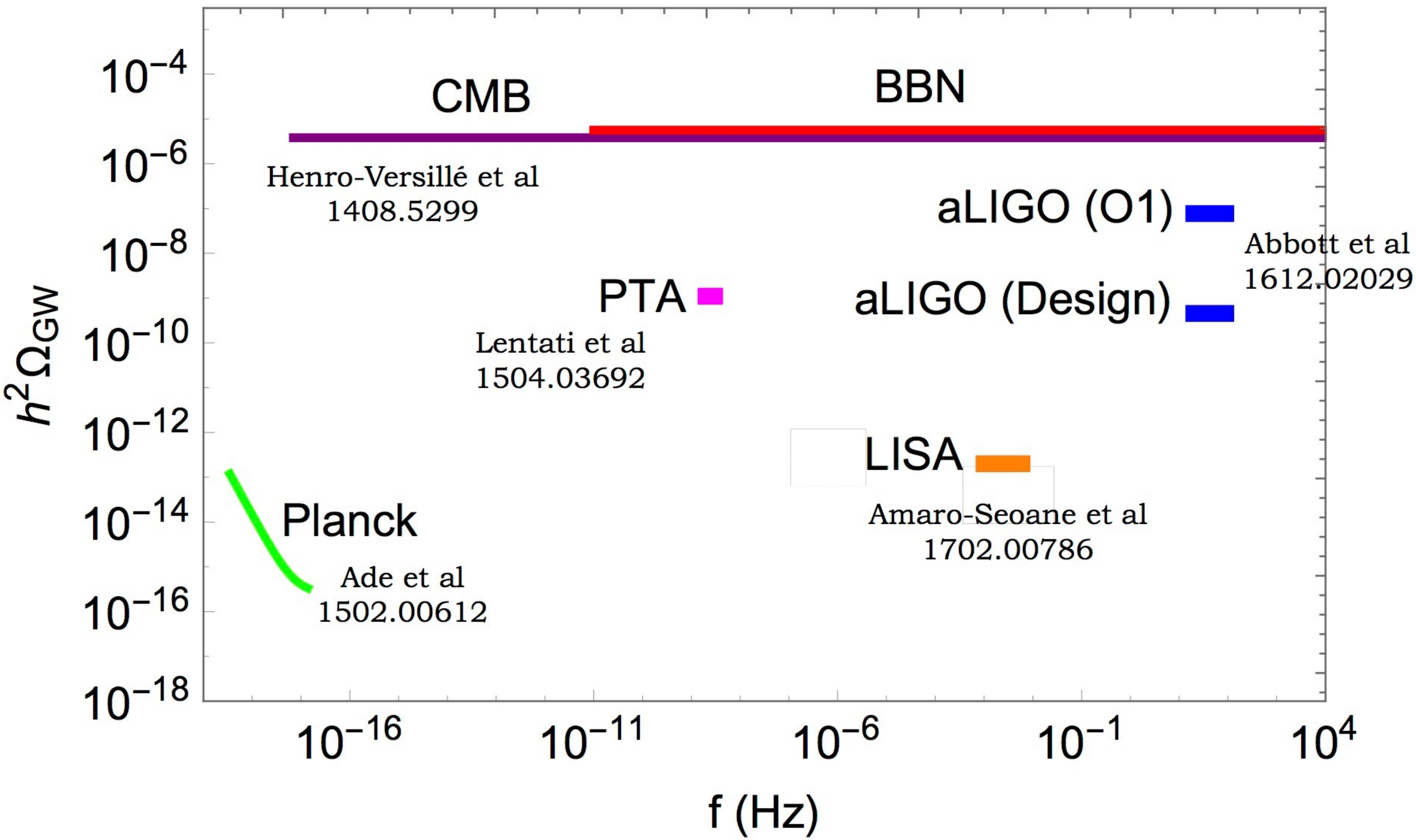


What is Compelling & Testable?

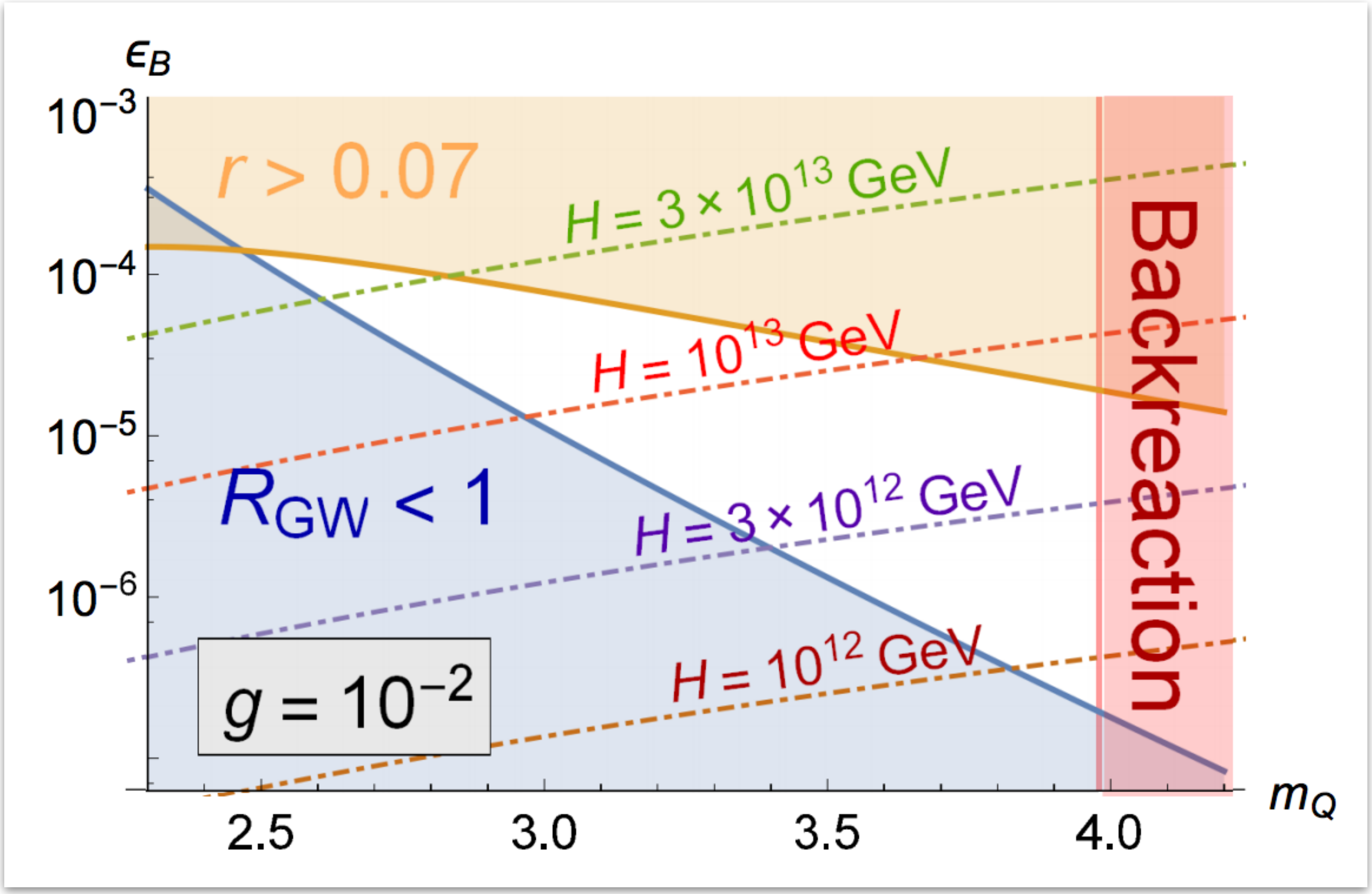
Thank You!

Back-up Slides

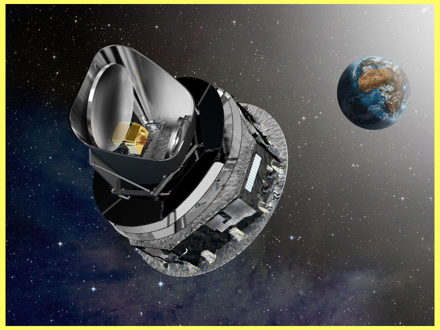
Observational bounds/sensitivities for SGWB



Backreaction Under Control



Scalar bispectrum: current bounds



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

[68 % CL]

Scalar bispectrum: future bounds

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

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

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

[Munoz, Ali-Haımoud, Kamionkowski]

Tensor bispectrum

- **Planck**

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

[68 % CL]

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

(parity violating models / roughly equilateral)

- **LiteBIRD**

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

(possibly also with **PICO**)

Tensor-Scalar-Scalar bispectrum

$$f_{\rm NL}^{\gamma\zeta\zeta} \equiv \frac{B_{\gamma\zeta\zeta}}{P_\zeta^2}$$

$$f_{\rm NL}^{\gamma\zeta\zeta} = -48 \pm 28 \qquad [68\,\%\ \mathrm{CL}]$$

Local shape — temperature data [Shiraishi, Liguori, Fergusson]

$$f_{\rm NL}^{\gamma\zeta\zeta} \longleftrightarrow \sqrt{r} f_{\rm NL}$$

Improvement expected from Planck to CMB-S4 (from BTT):

	CMB-S4	Relative improvement
Local ($r = 0.01$)	$\sigma(\sqrt{r} f_{\rm NL}) = 0.7$	25.3
Equilateral ($r = 0.01$)	$\sigma(\sqrt{r} f_{\rm NL}) = 14.7$	13.7

[CMB-S4 Science Book]