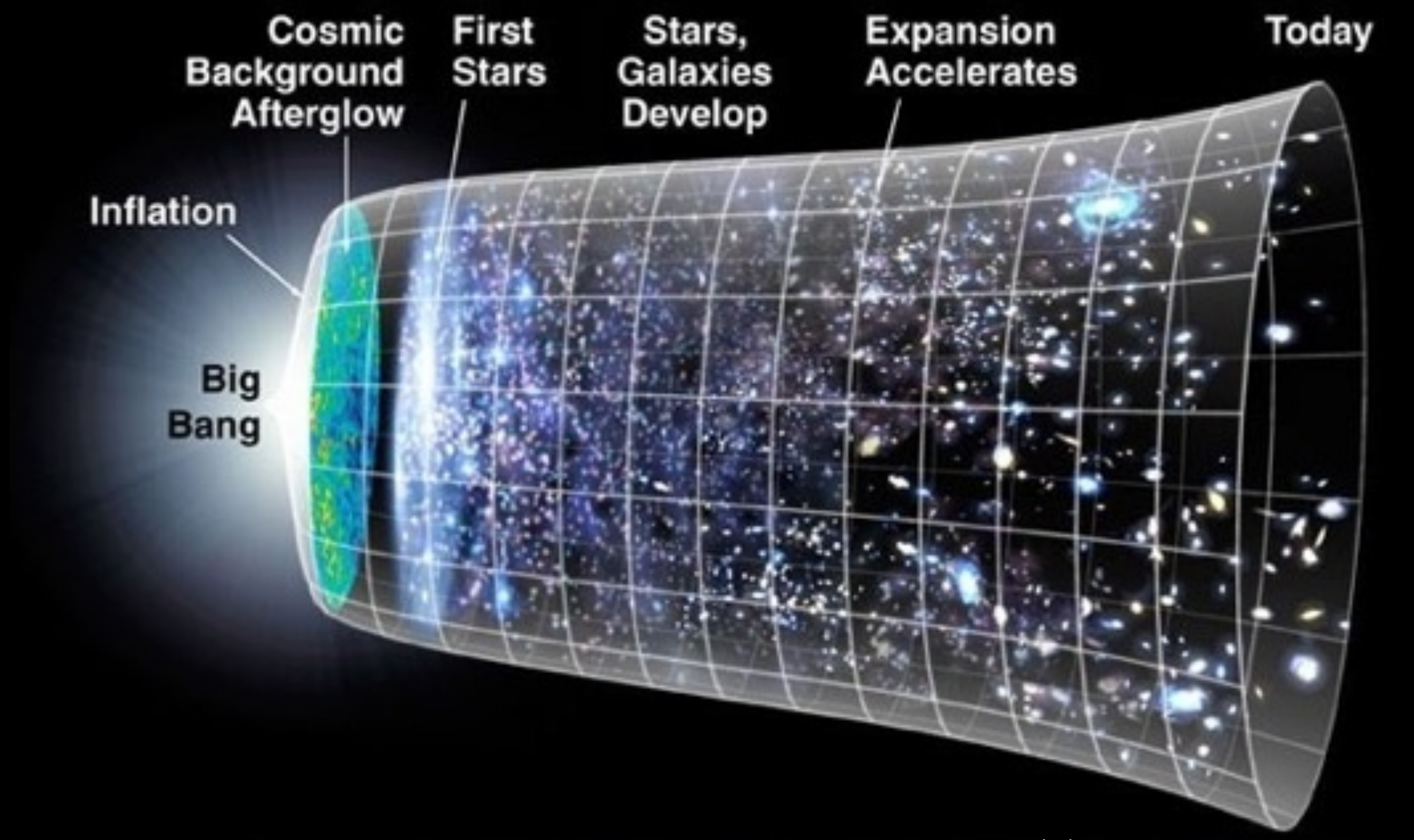
Probing the Early Universe Particle Content with Primordial Messengers



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“GW Primordial Cosmology”, May 17th 2021

based on work with Adshead, Afshordi, Assadullahi, Dimastrogiovanni, Iacconi, Jeong, Kamionkowski, Lim, Malhotra, Meerburg, Orlando, Shiraishi, Tasinato, Wands

Inflation, the minimal paradigm, SFSR

Simplest realization: single-scalar field in slow-roll

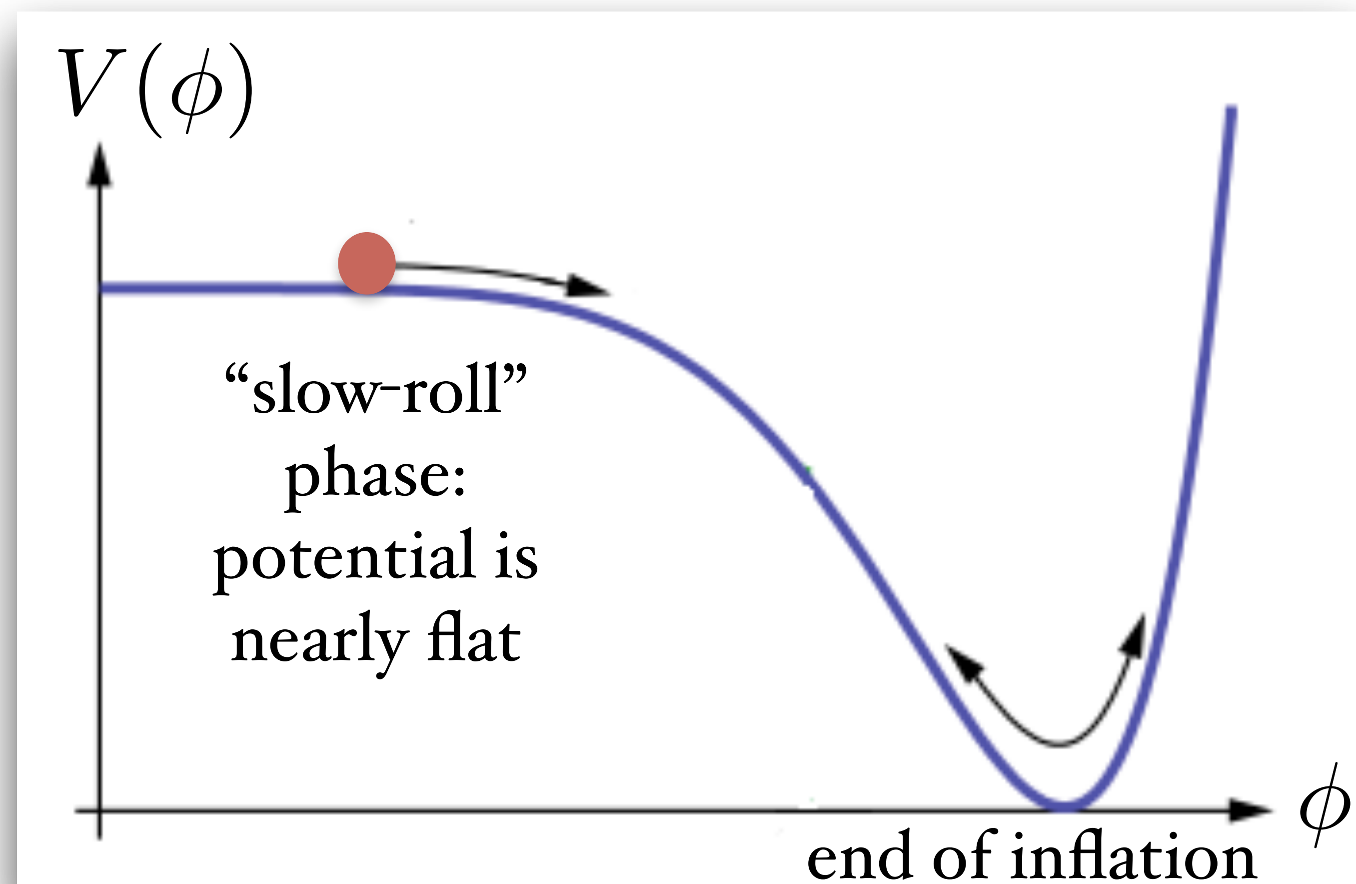
- Scalar field :

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

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

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

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



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

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

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

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

bounds

current

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

future

$r < 0.01\,({\rm CMB{-}S3})$

$r < 0.001\,({\rm CMB{-}S4})$

Crossing Qualitative Thresholds

compelling
models
e.g. Starobinsky

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

==>

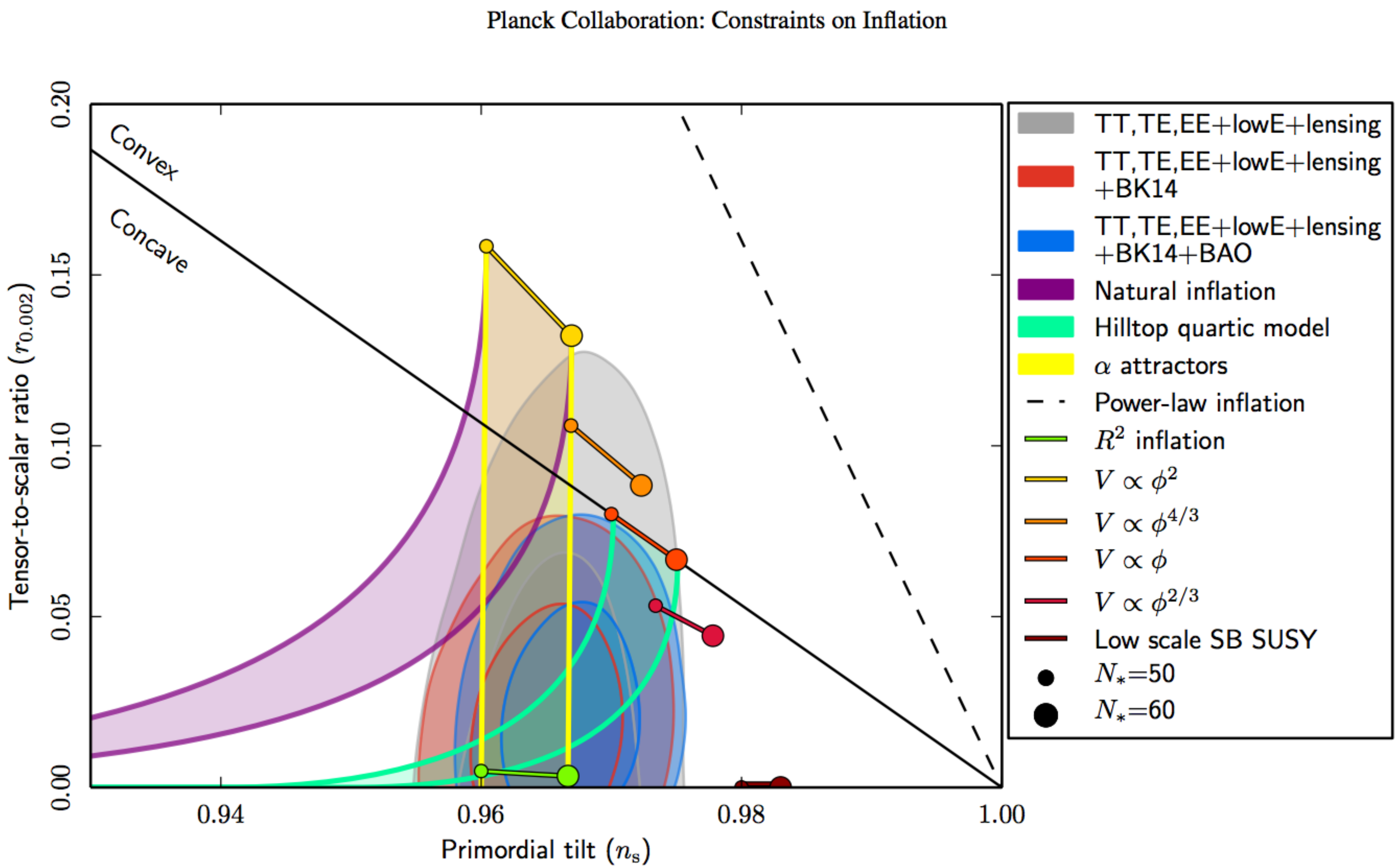
$$r \gtrsim 10^{-3}$$

single
vs
multi-field

$$f_{\rm NL} \sim 1$$

maybe possible with Euclid LSST, SKA
&
later w/ 21cm

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..)

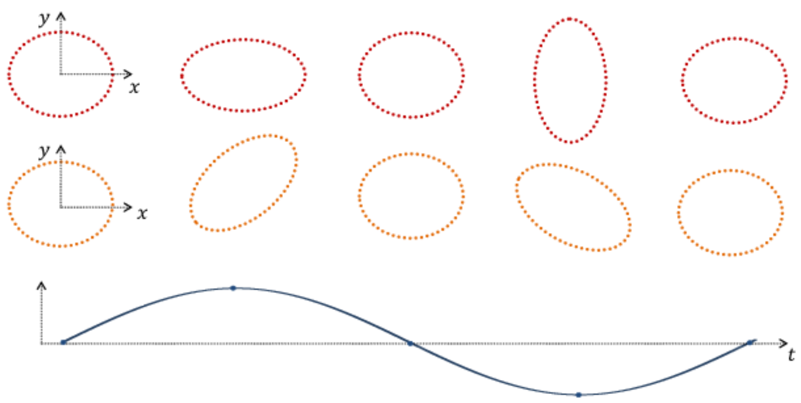
(Primordial) Gravitational Waves

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

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

$$\gamma_i^i = \partial_i \gamma_{ij} = 0$$

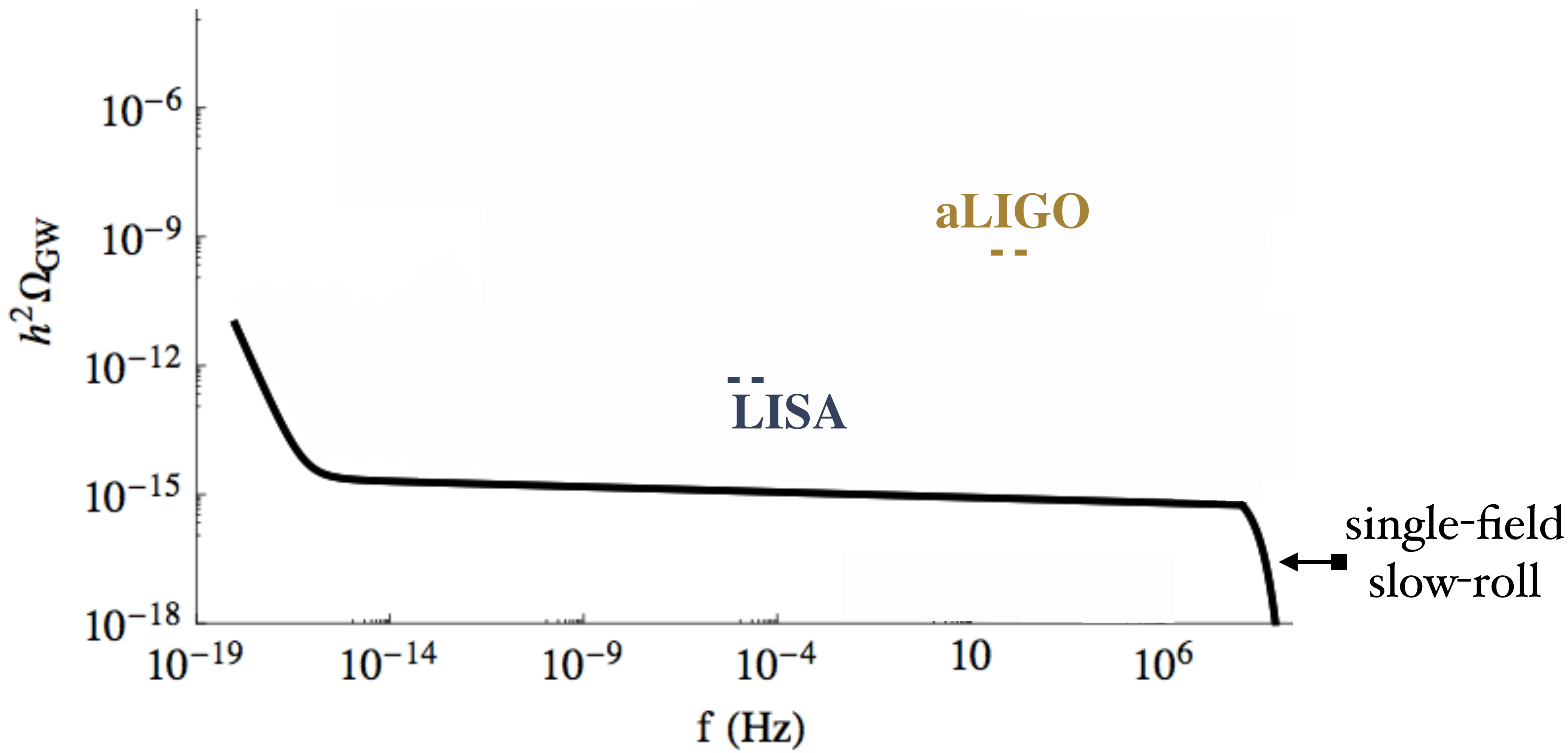
two polarization states



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

anisotropic stress-energy tensor

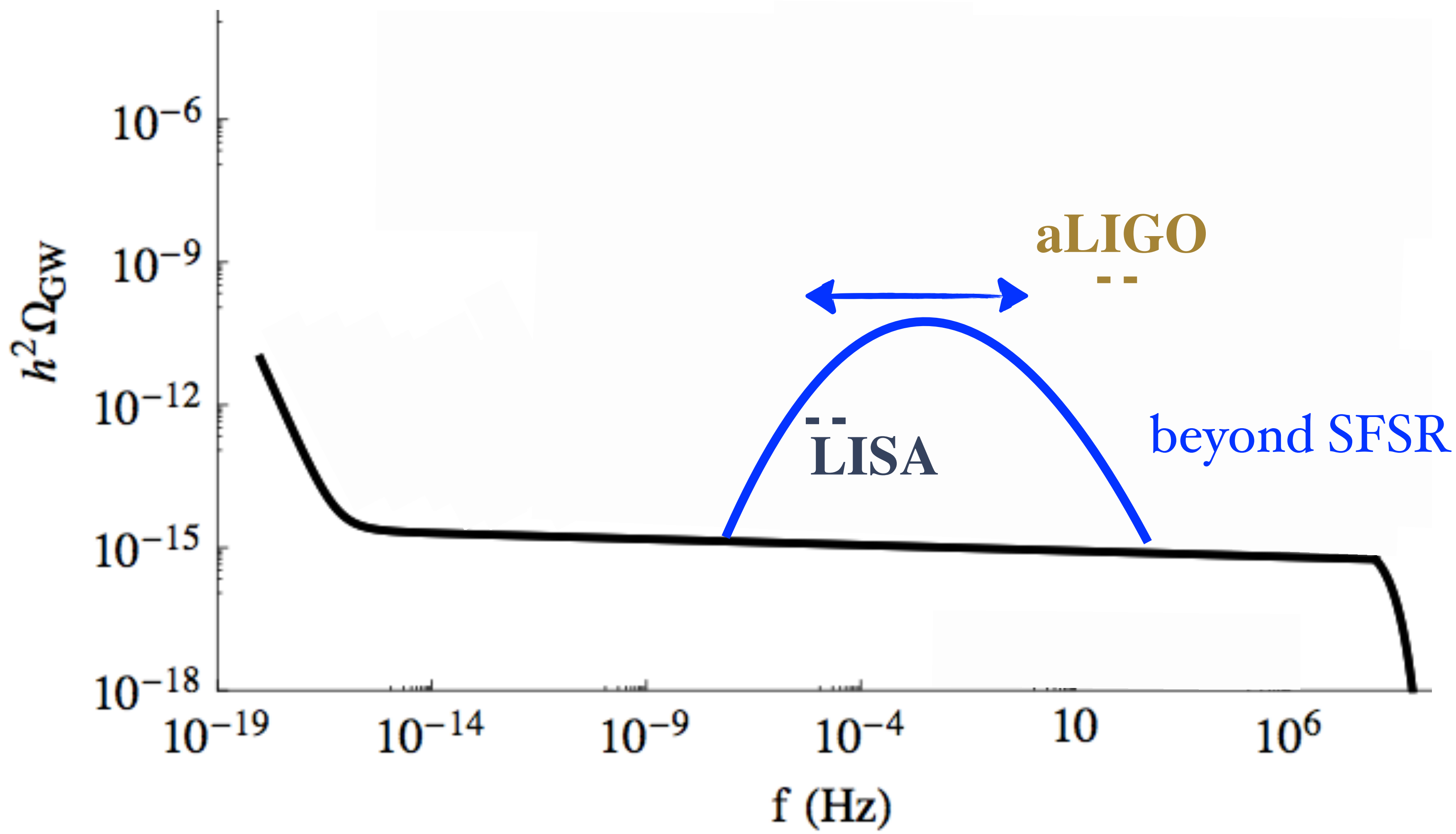
Testing Amplitude & Scale Dependence



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



GW Tests of inflationary content

power spectrum

scale-dependence

chirality

non-Gaussianity

e.g. Axion-gauge field models

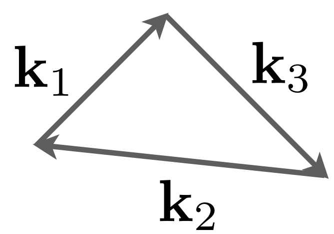
$$\begin{cases} \chi F\tilde{F} \\ \chi R\tilde{R} \end{cases}$$

see next talk by Ema & also Azadeh's and Lorenzo's talks

non-Gaussianities

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

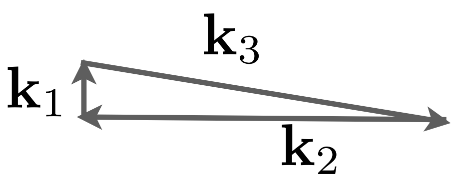
$$f_{\rm NL} \sim B/P^2$$

we can probe info on Mass & Spin of the field content

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

(heavier mediating masses)

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

direct mass suppression

non-analytical scaling

extra periodic spin-dependent feature

Tensor-scalar-scalar Bispectrum

(generically true for squeezed non-Gaussianities)

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

non-analytical scaling, CRs breakimg

extra angular dependence

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

standard polarization tensor

Connections with "tensor fossils"

as a diagnostic of new physics

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

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

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

more on this in Ema's talk!

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

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

[Dimastrogiovanni, MF, Tasinato PRL 2020]
[Ricciardone, Tasinato 2018]

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

propagations effects through structure wash away GW n-G initial conditions
(in most bispectrum configurations)

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

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

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

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

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

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

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

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

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

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

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

much more on this in Ema's talk!

Squeezed Bispectrum: new physics

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

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

non-analytical scaling

direct mass suppression

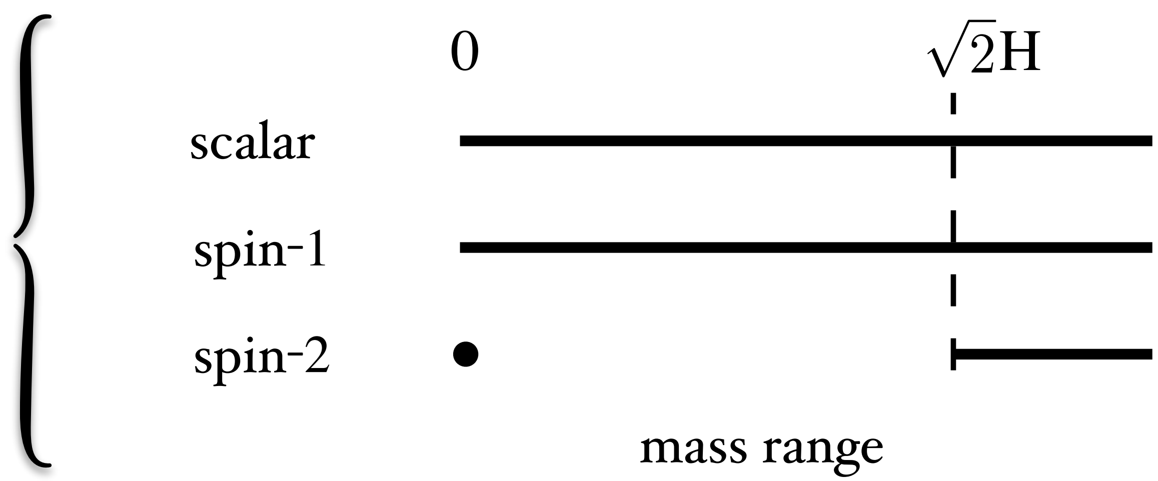
crucial fact for s $\geq$ 2 spinning fields

$$m \gtrsim H$$

Mass & Spin

spinning fields ==> more signatures, but

unitary reps in dS



spin-2: $m^2 = 0$ ✓ $m^2 \geq 2H^2$ → similar in FRW & non-linear mGR

[MF, Tolley (2012 + 2013)]

[Crisostomi, Comelli, Pilo (2012)]

+

interactive spin-2 fields ==> at most 1 is massless ==> extra spin-2 is a (quite) massive graviton!

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

in inflationary context such fields tend to decay quickly (a few e-folds)

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

for different setups (e.g. Lorentz breaking) see [Lin, Sasaki (2015)], [Fujita, Kuroyanagi, Mizuno, Mukohyama (2018)]

Recap

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

&

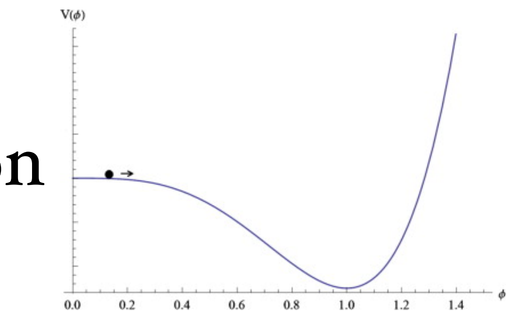
spinning ==> richer set of signatures
but, typically
spinning ==> mass bounds ==> suppression

{Biagetti, Dimastrogiovanni, MF 2017]

One crucial ingredient

the mass, the spin... the coupling

∃ 1 field that doesn't decay: the inflaton



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

(i) exchange between different sectors

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

(iii) can help with Higuchi bound

HS

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

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

Examples

quasi-single-field

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

[Chen, Wang 2009]+...

scalar sector

inflaton

extra

(gauge) vector field

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

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

strongly affects tensor sector, chiral GW etc

[.....Anber - Sorbo 2009, Cook - Sorbo 2011, Barnaby - Peloso 2011, Adshead - Wyman 2011, Maleknejad - Sheikh-Jabbari, 2011, Dimastrogiovanni - MF - Tolley 2012, Namba - Dimastrogiovanni - Peloso 2013, Adshead - Martinec -Wyman 2013, Dimastrogiovanni - MF - Fujita 2016, Garcia-Bellido - Peloso - Unal 2016, Agrawal - Fujita - Komatsu 2017, Fujita - Namba -Obata 2018, Domcke - Mukaida 2018], [Gorji, Mansoori, Firouzjahi 2020] +......

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

.....

Spin-2

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

L2 & L3 interactions

$$S_{\rm int} = \int d^4x\sqrt{-g} \left[-\frac{\rho}{2\epsilon H a^2}\partial_i\partial_j\pi_c\sigma^{ij} + \frac{1}{2}\rho\,\dot\gamma_{c\,ij}\sigma^{ij} \right.$$

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

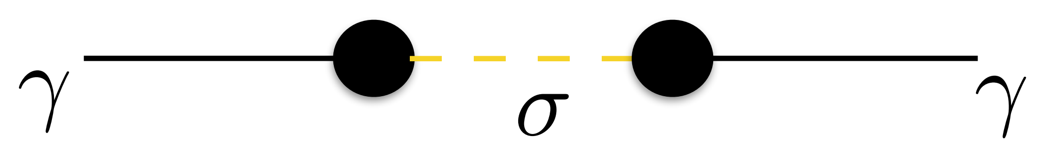
[Bordin et al 2018]

Power Spectrum

Extra spin-2 case

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

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



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

[Bordin et al 2018]

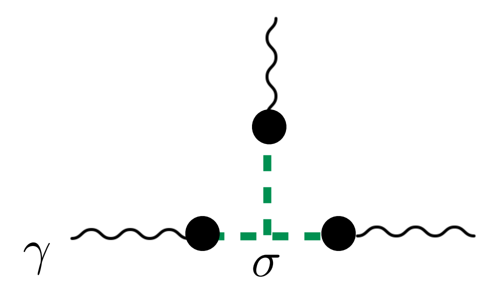
$$\frac{\rho}{H} \ll 1$$ perturbative treatment of quadratic mixing

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

GW at small scales

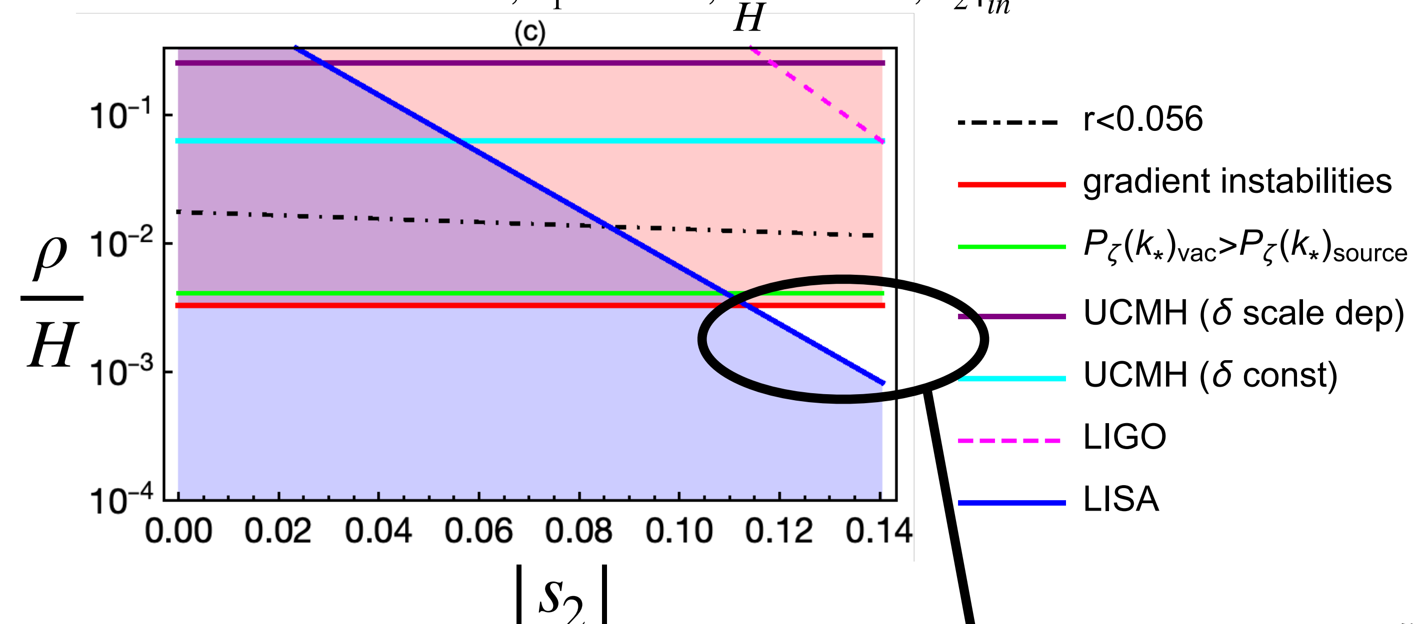
$$P_\gamma(k) = \frac{4H^2}{M_p^2\, k^3}\left[1 + \frac{\mathcal{C}_\gamma(\nu)}{c_\sigma^{2\nu}}\left(\frac{\rho}{H}\right)^2\right]$$

consider time-dep.

consider time-dep.

Example of parameter space analysis:

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



region above red line: excluded by bounds

LISA can be an efficient probe in constraining the inflationary field content

[Iacconi, MF, Assadullahi, Dimastrogiovanni, Wands, 2020]

small-scales primordial GW anisotropies from squeezed bispectra

$\langle \gamma_L \gamma_S \gamma_S \rangle$

[Iacconi, MF, Assadullahi, Wands, 2020]

$\langle \zeta_L \gamma_S \gamma_S \rangle$

[Dimastrogiovanni, MF, Malhotra, Orlando, Meerburg, *in progress*]

The Inflationary Field Content

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

power spectrum: GW spectral shape (CMB,...,Interferometers), chirality (e.g. <BT> @ CMB, cross interferometers..) ↓
bispectrum: k-scaling, angular dependence, periodic features, anisotropies

the EFT route delivers the richest phenomenology

signatures ✓

model-building

Thank You!