Primordial GW and the Inflationary Field Content

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ICG Portsmouth

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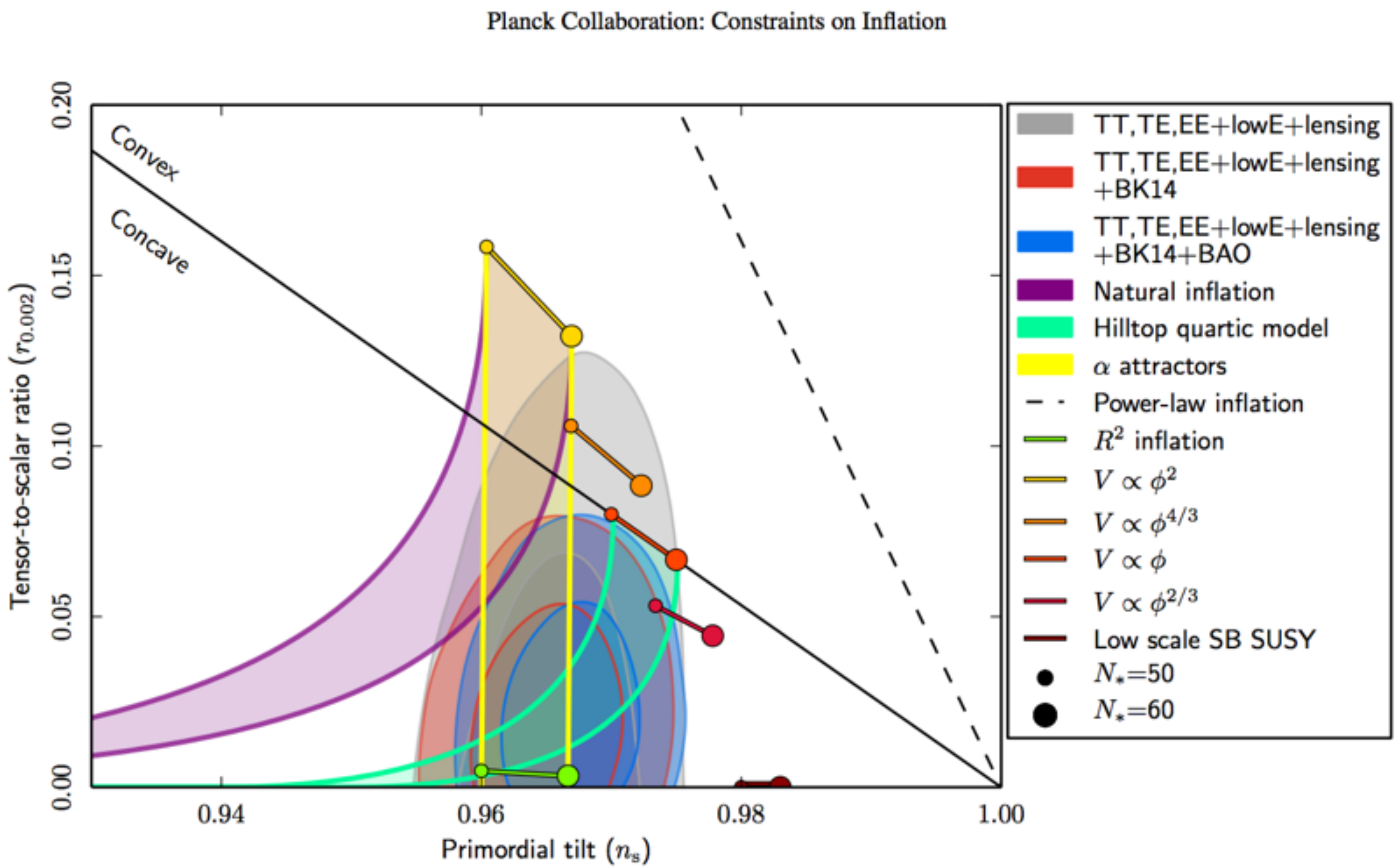
Single-field Inflation is doing well



Why go further?

possible

O(100)

Marsh et al 2013
Paban, Rosati 2018

likely

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

necessary/useful

robustness of
H <—> r
as
1-to-1 map

interesting

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

Organizing Principle I: 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 Principle II: the spin

consequences on the mass range

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

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, Guatieri, 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~H0

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

[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)]

Observables

extra (spinning) fields probed via scalar/GW power spectrum

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

scalar fluctuations

tensor perturbations

$$\Box\gamma_{ij} = 16\pi G \Pi_{ij}^{TT}$$

homogeneous solution: GWs from vacuum fluctuations

inhomogeneous: GWs from sources (e.g. extra field content)

Squeezed scalar/mixed/tensor bispectrum

spinning ==> extra angular dependence in 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

[Arkani-Hamed, Maldacena (2015)]

but, again

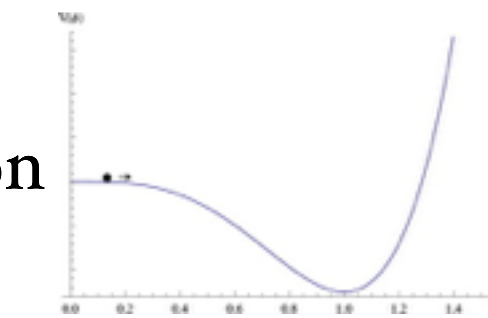
$$\langle \gamma_{k_L} \zeta_{k_S} \zeta_{k_S} \rangle \Big|_{k_L \ll k_S} \propto e^{-\pi \mu_s} \frac{1}{k_L^3 k_S^3} \left(\frac{k_L}{k_S} \right)^{3/2} \mathcal{E}_2^\lambda (\hat{\mathbf{k}}_L \cdot \hat{\mathbf{k}}_S) P_s^\lambda (\hat{\mathbf{k}}_L \cdot \hat{\mathbf{k}}_S) \cos \left[i \nu_s \ln \left(\frac{k_L}{k_S} \right) + \phi \right] \Bigg|_{m \geq \frac{3}{2} H}$$

spinning ==> mass bounds ==> suppression (mass + power of k_L/k_S)

One missing 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

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

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

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

...+[Anber, Sorbo 2006]...[Adshead, Wyman, 2012], [Dimastrogiovanni, MF, Tolley 2013],...+ [Dimastrogiovanni, MF, Fujita 2017],...+...[Agrawal, Fujita, Komatsu], [Domcke at al 2018...], [Dimastrogiovanni, MF, Hardwick, Assadullahi, Koyama Wands 2018]...

Extension of Chromo Natural Inflation

[Freese, Frieman, Olinto, 1990]

$$\mathcal{L} = \mathcal{L}_{\text{inflation}} - \frac{1}{2}(\partial\chi)^2 - U(\chi) - \frac{1}{4}FF + \frac{\lambda\chi}{4f}F\tilde{F}$$

[Dimastrogiovanni, MF, Fujita 2017]
[Obata, Soda 2016]

[Adshead, Wyman, 2012]

Chiral GW spectrum, testable at widely different scales from CMB to Interferometers

for more on this see
Ema's talk on Friday

EFT approach

(1) So far: pick specific models

(2) EFT of fluctuations approach to coupling

[Bordin et al 2018]

.....

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

spin-2

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

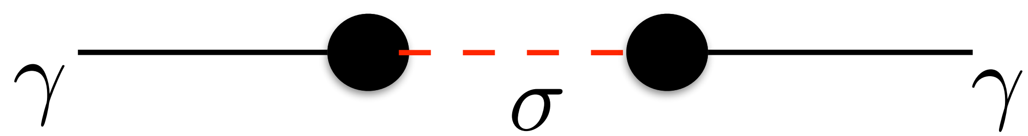
$$\left. -\frac{\rho}{2\epsilon H^2 M_P\, a^2}(\partial_i\pi_c\partial_j\pi_c\dot{\sigma}^{ij} + 2H\,\partial_i\pi_c\partial_j\pi_c\sigma^{ij}) + \frac{\tilde{\rho}}{\epsilon H^2 M_P\, a^2}\dot{\pi}_c\partial_i\partial_j\pi_c\sigma^{ij} - \mu(\sigma^{ij})^3 \right]$$

EFT route: power spectrum

Extra spin-2 case

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

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



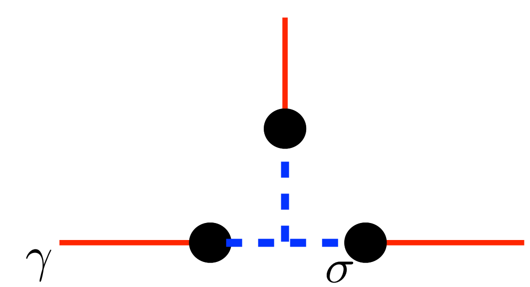
$$P_\gamma(k) = \frac{4H^2}{M_p^2\,k^3}\left[1 + \frac{\mathcal{C}_\gamma(\nu)}{c_\sigma^{2\nu}}\left(\frac{\rho}{H}\right)^2\right]$$

[Bordin et al 2018]

PS at interferometer scales: see Laura Iacconi's poster

$$\left\{ \begin{array}{ll} \frac{\rho}{H} \ll 1 & \text{perturbative treatment of quadratic mixing} \\ \frac{\mu}{H} \ll 1 & \text{L\_3 < L\_2} \\ \frac{\rho}{\sqrt{\epsilon} H} \ll 1 & \text{small radiative corrections to sigma mass} \\ c_\sigma \gtrsim 10^{-2} & \text{tensor nG limits as well} \end{array} \right.$$

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]

The Inflationary Field Content

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

↓

the EFT route delivers the richest phenomenology

signatures ✓

a lot (if not all) of what is possible will be captured by EFT framework

model building !

important to reverse engineer to identify full model

Thank you!

And one more slide…

30th Texas Symposium on Relativistic Astrophysics

15th - 20th December 2019

Portsmouth, UK

Invited speakers:

Antony Lewis (University of Sussex, UK)
Astrid Eichorn (University of Southern Denmark & Heidelberg University (Germany)
Chris Reynolds (University of Cambridge, UK)
Claudia De Rham (Imperial College London, UK)
Dany Page (National Autonomous University, Mexico)
Elena Gallo (University of Michigan, USA)
Elena Rossi (Leiden University, Netherlands)
Elisa Resconi (Technical University Munich, Germany)
Elisabeth Krause [TBC] (University of Arizona, USA)
Giovanni Losurdo (INFN Pisa, Italy)
Juan Garcia-Bellido (University of Madrid, Spain)
Luciano Rezzolla (University of Frankfurt, Germany)
Martin Lemoine (IAP, France)
Rennan Barkana (Tel Aviv University, Israel)
Takahiro Tanaka (Kyoto University, Japan)
Tanja Hinderer (University of Amsterdam, Netherlands)
Tom Giblin (Kenyon College Ohio, USA)
Ulisses Barres de Almeida (CBPF, Brazil)

texas2019.org

Generically

extra (spinning) fields probed via scalar/GW power spectrum

and squeezed scalar/mixed/tensor bispectrum

&

spinning ==> extra angular dependence in bispectrum

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but

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