Recent progress in cosmological collider physics

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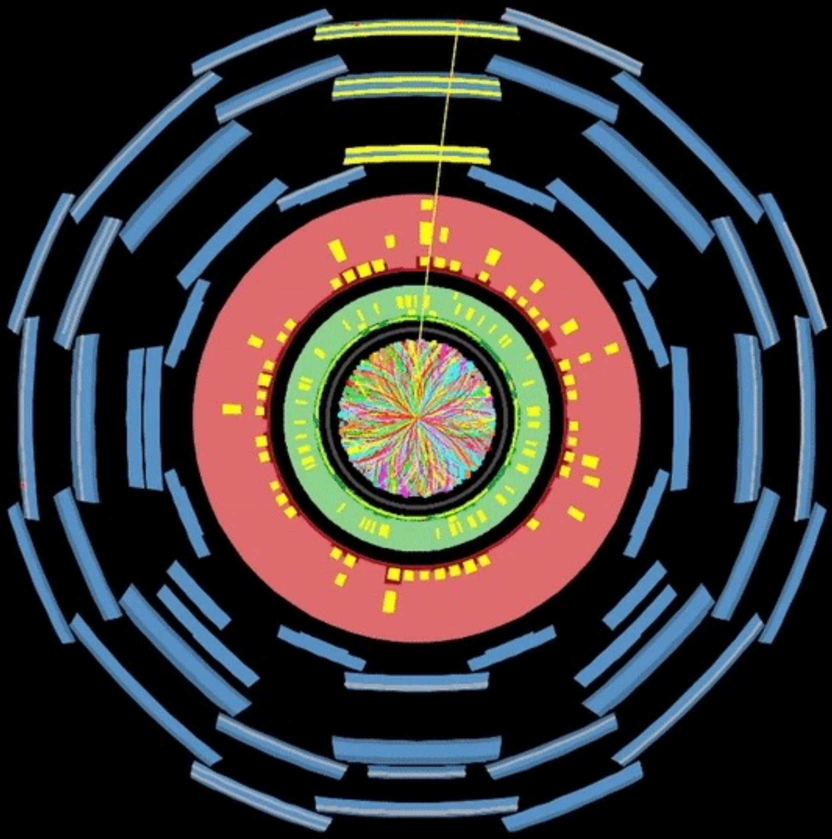
Dept. of Astronomy | April 22, 2021

w/ Xingang Chen, Tao Liu, Qianshu Lu, Shiyun Lu,
Matthew Reece, Xi Tong, Yi Wang, Liantao Wang, Yiming Zhong

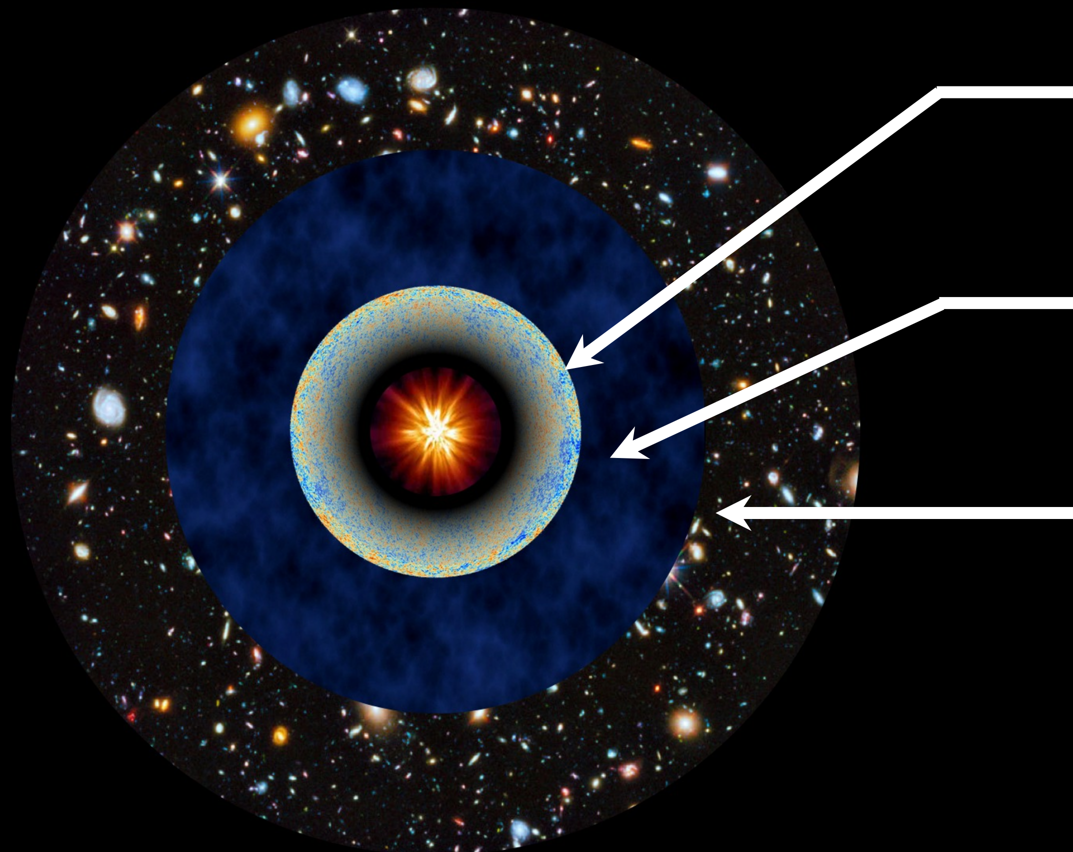
JHEP 08 (2016) 051; PRL 118 (2017) 261302; JHEP 04 (2017) 058;
JCAP 12 (2017) 006; JCAP 05 (2018) 049; JHEP 09 (2018) 022; JHEP 02 (2020) 011;
JHEP 02 (2020) 044; JHEP 04 (2020) 189; JHEP 11 (2020) 082; ongoing projects



Large Hadron Collider
ATLAS detector

Cosmological Collider

The universe



photon decoupling
CMB

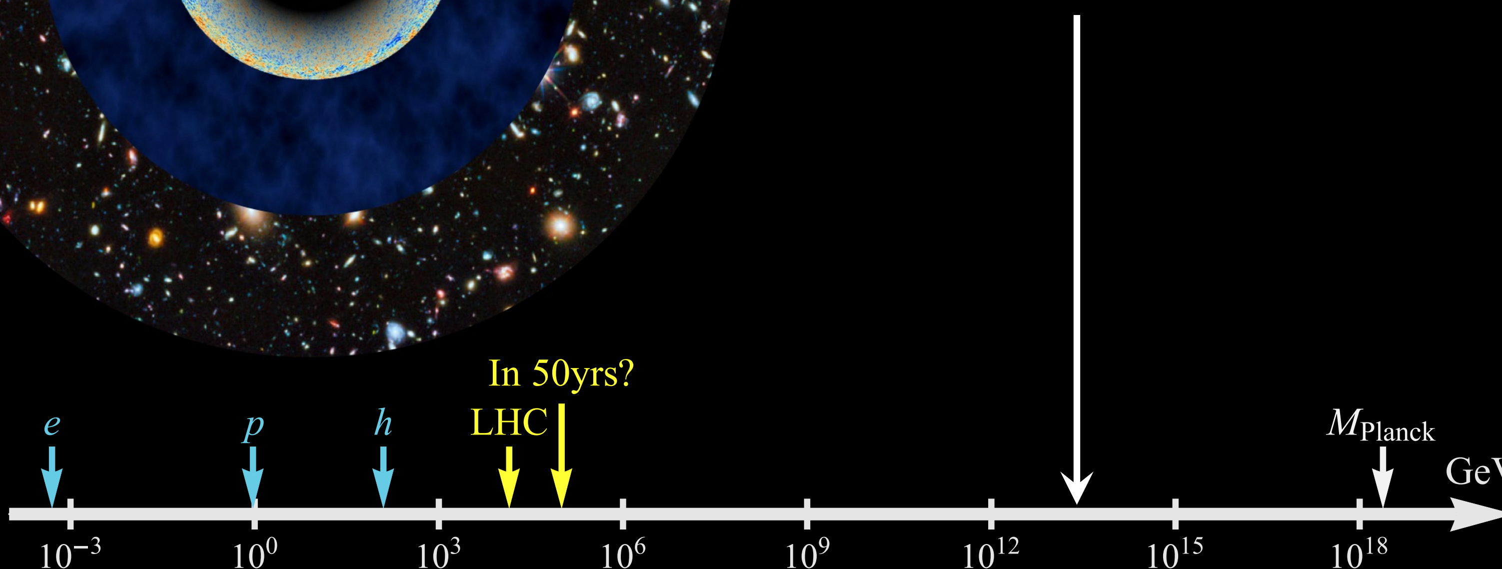
dark ages
21cm tomography

galaxies formed
LSS survey

Gravitational waves

Cosmological Collider

The universe



What is a cosmological collider?

How should we NOT use it?

Where are large signals from?

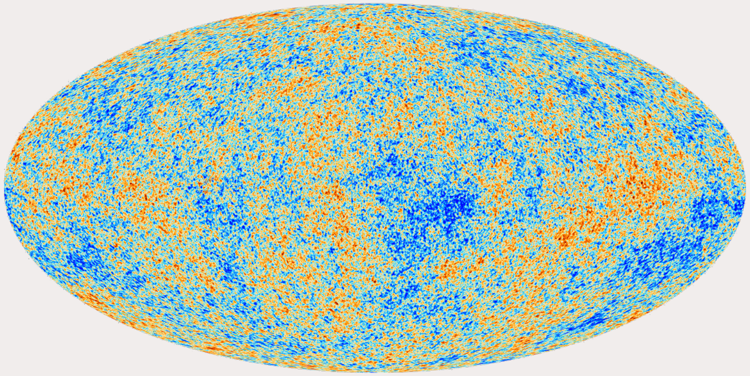
What if there are light fields?
A cosmological Higgs collider
Missing-energy signal

Basic picture

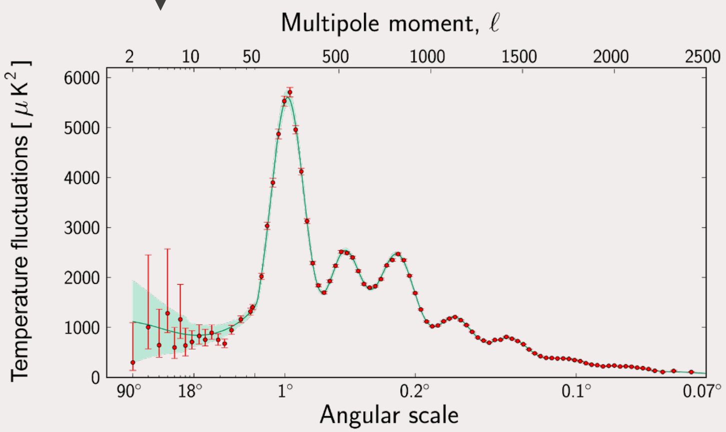
Two puzzles of big-bang cosmology:

1 - Why so uniform?

2 - Where were these fluctuations from?



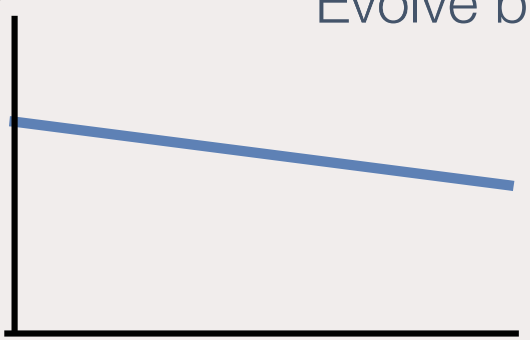
“Fourier transform”



Planck 2018

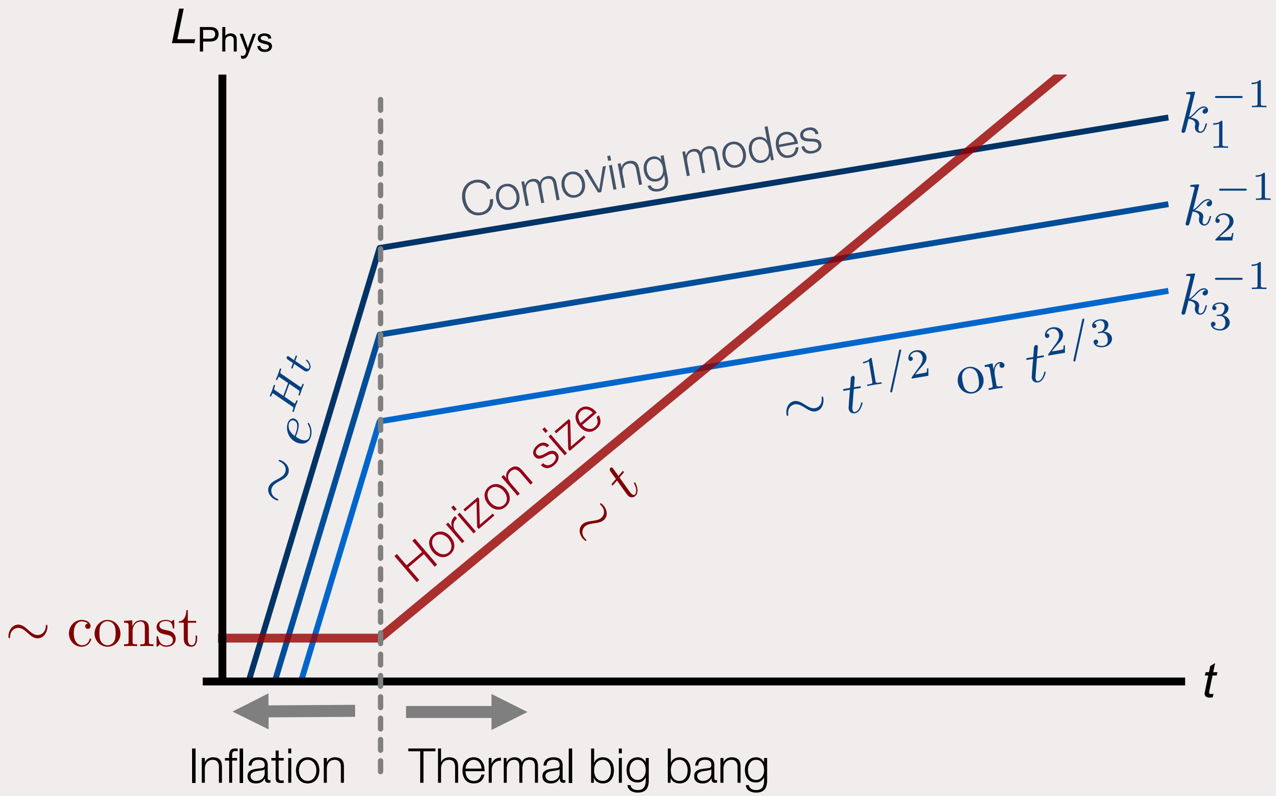
Evolve back in time

$P_\zeta(k)$

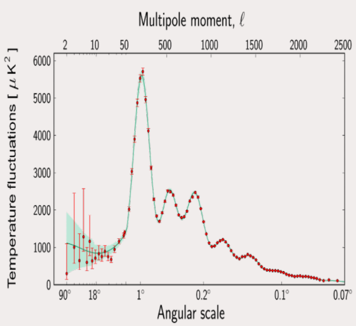


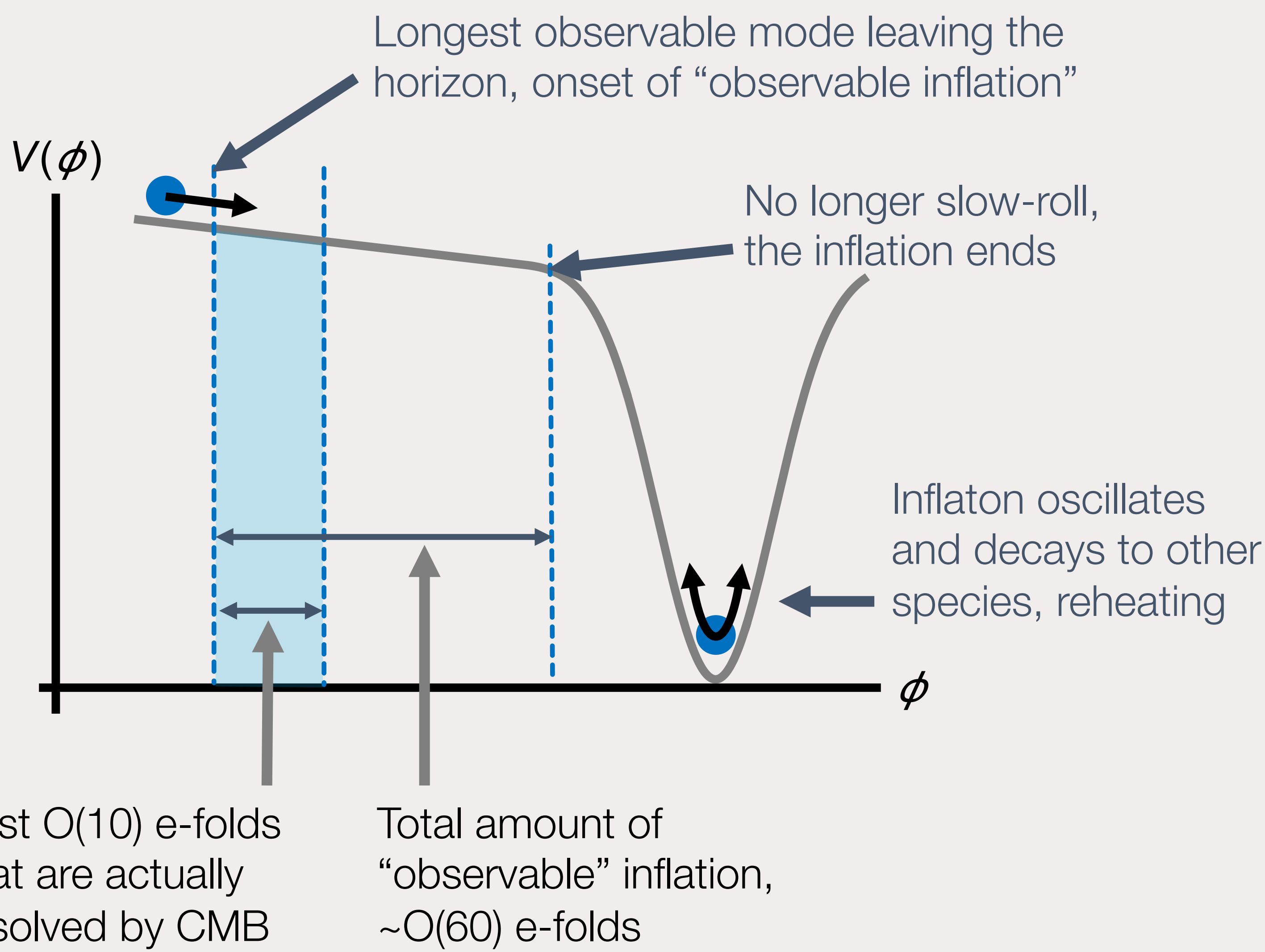
k

Basic picture

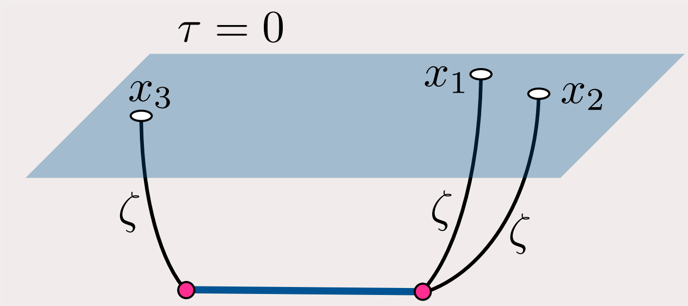


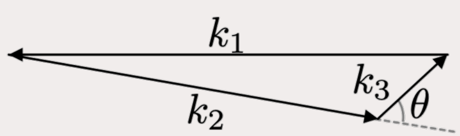
Basic picture





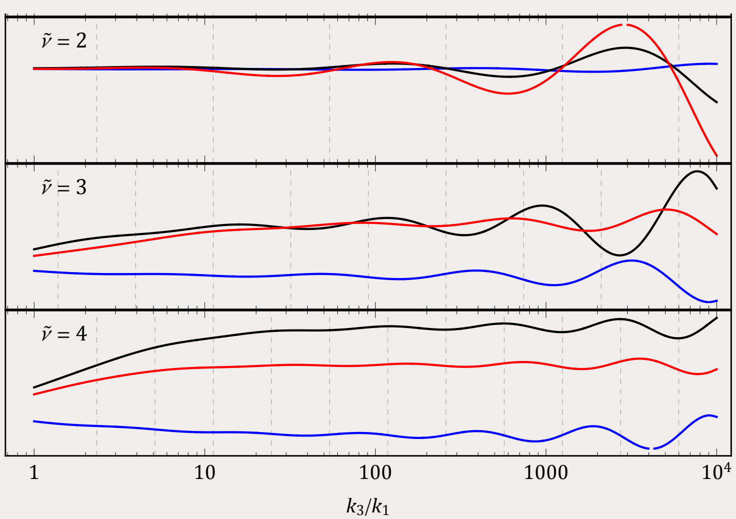
Basic picture



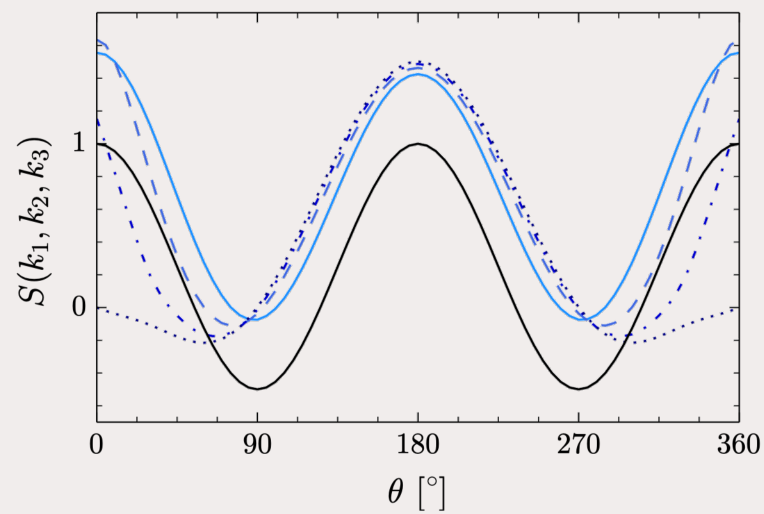


$$S(\mathbf{k}_1, \mathbf{k}_3) = A(\lambda, m) \left(\frac{k_3}{k_1} \right)^{1/2 \pm \nu} P_s(\cos\theta)$$

$$\nu = \begin{cases} \sqrt{\frac{9}{4} - \frac{m^2}{H^2}} & s = 0 \\ \sqrt{\left(s - \frac{1}{2}\right)^2 - \frac{m^2}{H^2}} & s \neq 0 \end{cases}$$



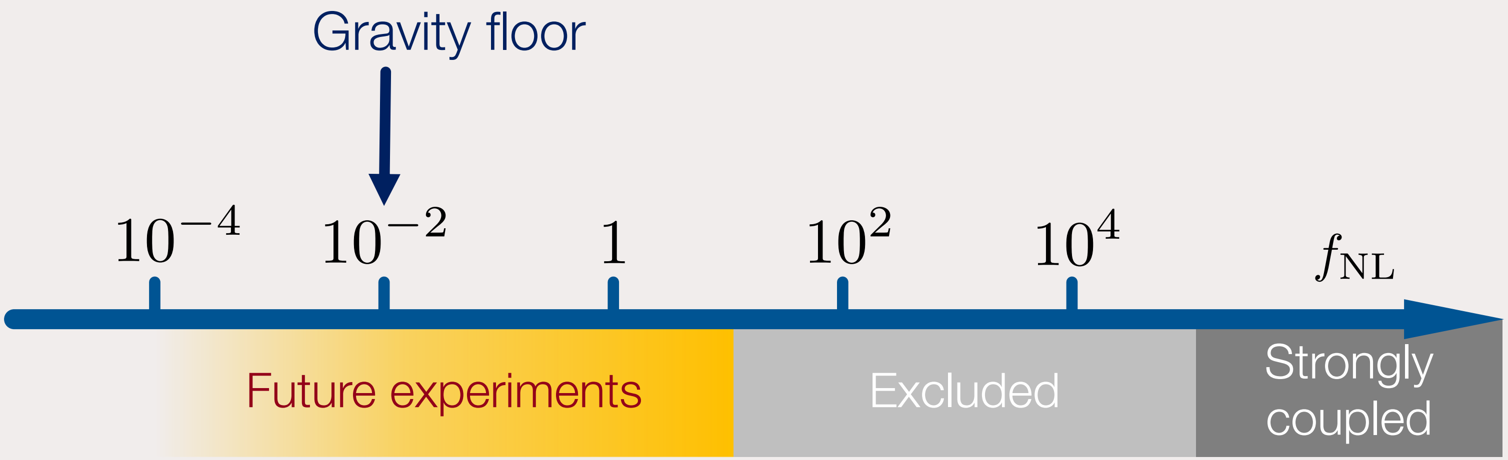
Chen, Chua, Guo, Wang, ZZX, Xie, 1803.04412



Lee, Baumann, Pimentel, 1607.03735

“non-Gaussianity”

$$f_{\rm NL} \simeq |S(\mathbf{k}_1, \mathbf{k}_3)|$$



Planck 2018

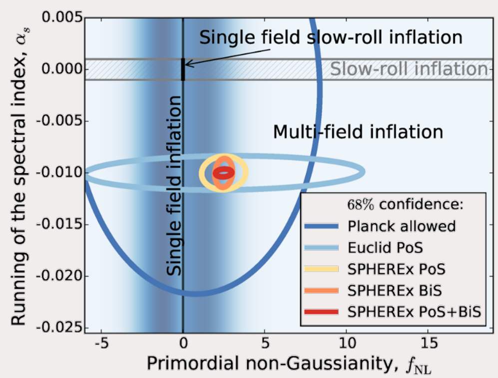
1905.05697

$$f_{\rm NL}^{\rm (local)} = -0.9 \pm 5.1$$

$$f_{\rm NL}^{\rm (equil)} = -26 \pm 47$$

$$f_{\rm NL}^{\rm (ortho)} = -38 \pm 24$$

O(1) in ~10yrs?



SPHEREx, 1412.4872

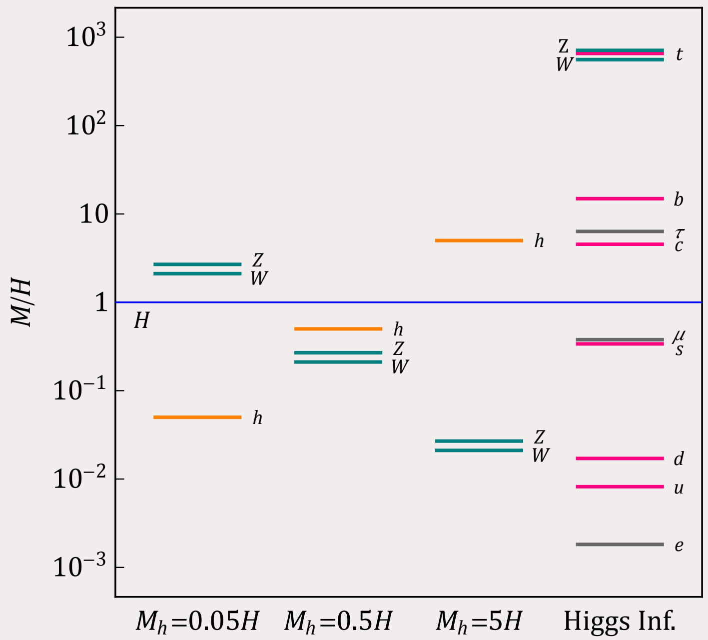
O(0.01) ultimately

21cm tomography

Meerburg, Muñoz, Ali-Haïmoud, Kamionkowski, 1506.04152; Münchmeyer, Muñoz, Chen, 1610.06559; Dizgah, Lee, Muñoz, Dvorkin 1801.07265;

How NOT to use the cosmological collider

$$S(\mathbf{k}_1, \mathbf{k}_3) = A(\lambda, m)\left(\frac{k_3}{k_1}\right)^{1/2\pm\nu} P_s(\cos\theta)$$



Example: "SM background"

"Thermal" mass ~ Hubble

All in loops: spin info lost

Signal size: tiny unless tuned

Xingang Chen, Yi Wang, ZZX, JHEP 1608 (2016) 051;
PRL 118 (2017) 261302; JHEP 1704 (2017) 058

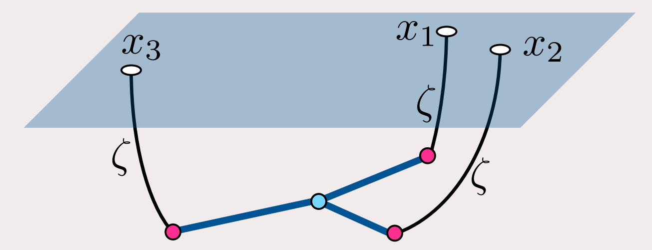
Signal size

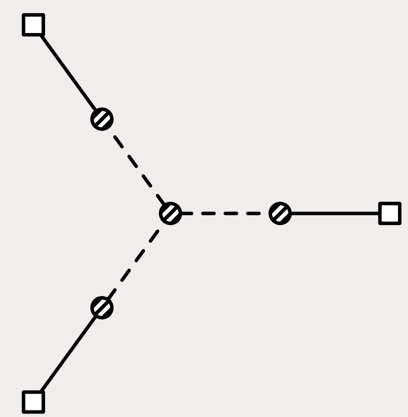
$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle' \equiv (2\pi)^4 P_\zeta^2 \frac{1}{(k_1 k_2 k_3)^2} S(\mathbf{k}_1, \mathbf{k}_2, \mathbf{k}_3)$$

In the unit of Hubble: $\zeta = -\dfrac{H}{\dot{\phi}_0} \delta\phi = -2\pi P_\zeta^{1/2} \delta\phi$

$$f_{\rm NL} \sim (2\pi P_\zeta^{1/2})^{-1} \langle \delta\phi^3 \rangle$$

$$\sim 3.6 \times 10^3 \cdot \text{(vertices)} \cdot \text{(propagators)}$$





Signal size

Challenging to get visible signals in “minimal” scenario

1. Standard slow-roll inflation

2. Scale invariance (up to slow-roll correction)

3. No further spacetime symmetry breaking

4. Dimensionless parameter being O(1)

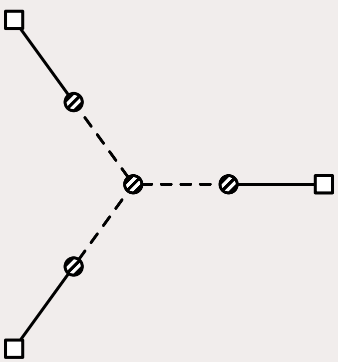
5. No tree-level tuning

Signal size

$$\frac{1}{\Lambda^2}(\partial_\mu\phi)^2\sigma^2 \longrightarrow \frac{\dot\phi_0^2}{\Lambda^2} \sim H^2 \longrightarrow \Lambda \simeq 3600H$$

No Boltzmann supression $\qquad \dot\phi_0 \simeq (60H)^2$

$$\mathscr{L} = \frac{1}{2}(\partial_\mu\sigma)^2 - \frac{1}{2}m^2\sigma^2 - \lambda\sigma^4 + \frac{1}{\Lambda^2}(\partial_\mu\phi)^2\sigma^2$$



$$f_{\mathrm{NL}} \sim 3600 \cdot \left(\frac{\dot\phi_0}{\Lambda^2}\langle\sigma\rangle\right)^3 \cdot \lambda\langle\sigma\rangle \sim 10^{-7} \cdot \lambda\langle\sigma\rangle^4$$

QSFI: a very shallow potential is needed

$$\langle\sigma\rangle^2 \sim H^2/\lambda \longrightarrow \lambda\langle\sigma\rangle^4 \sim 1/\lambda \longrightarrow \lambda \lesssim 10^{-7}$$

$f_{\mathrm{NL}} \gtrsim 1$

Where are large signals from?

$$\frac{1}{\Lambda}(\partial_\mu\phi)\mathcal{J}^\mu \longrightarrow \frac{1}{\Lambda}\dot{\phi}_0\mathcal{N}$$

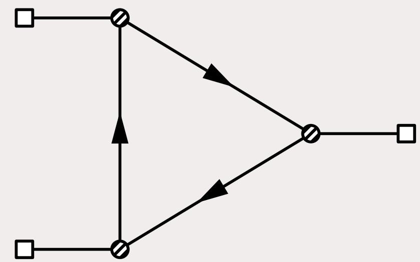
A new source of particle production

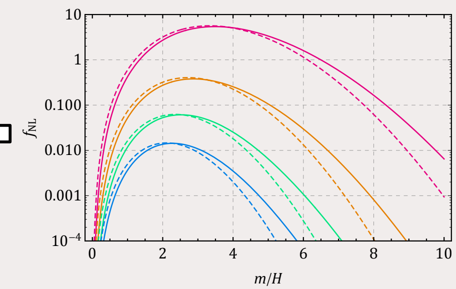
L. Wang, ZZX, 1910.12876

Fermion $(\partial_\mu\phi)\overline{\Psi}\gamma^\mu\gamma^5\Psi$

Probing heavy neutrinos

Chen, Wang, ZZX, 1805.02656



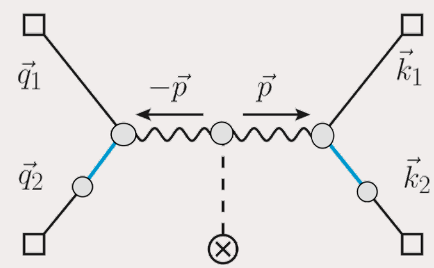


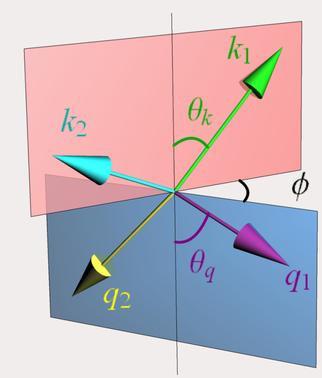
Gauge boson $\phi F\widetilde{F}$

Liantao Wang, ZZX, 2004.02887

CP-breaking in trispectrum

Liu, Tong, Wang, ZZX, 1909.01819

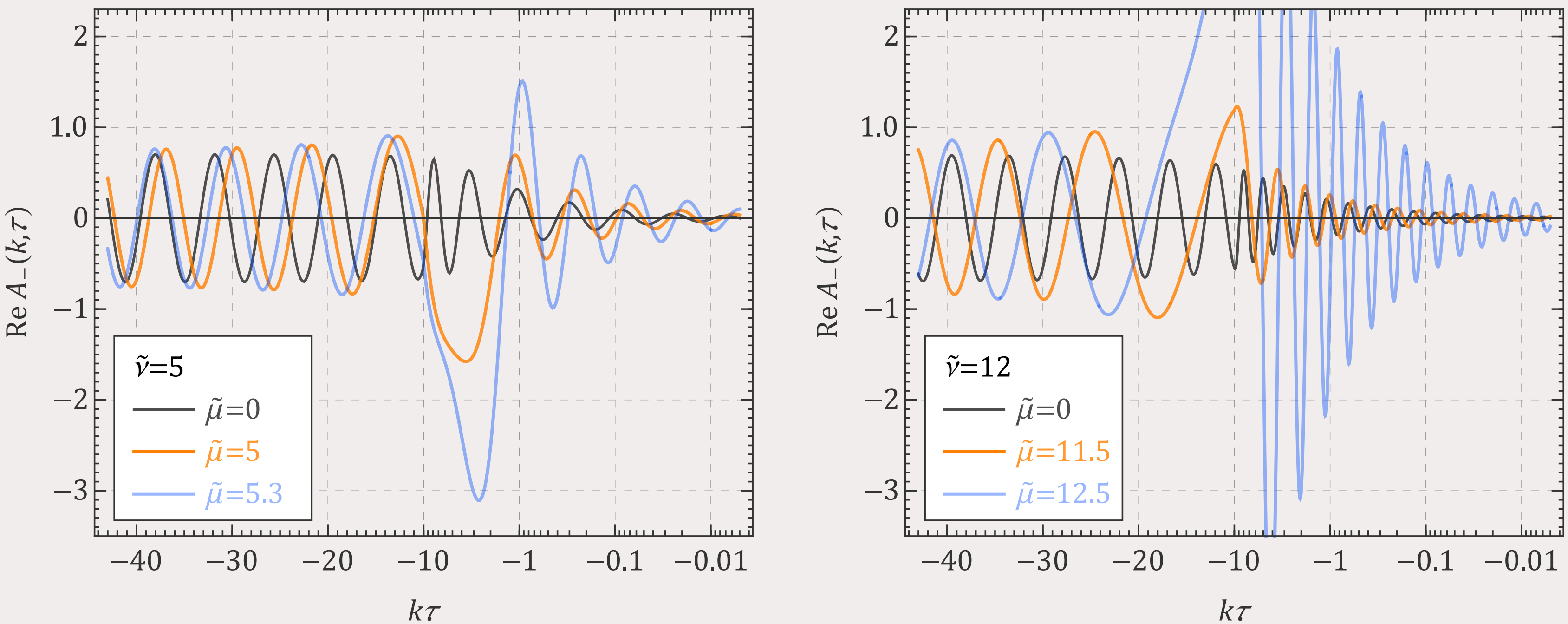




Helical GWs $\phi R\widetilde{R}$

Lue, Wang, Kamionkowski, astro-ph/9812088

dim-5 operators: chemical potential



Liantao Wang, ZZX, 2004.02887

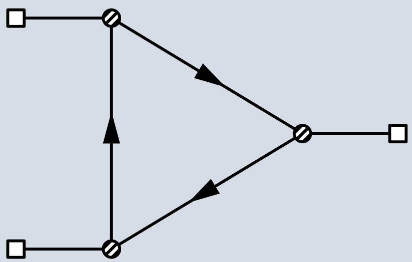
Probing heavy neutrinos

A rare chance to see right-handed neutrinos

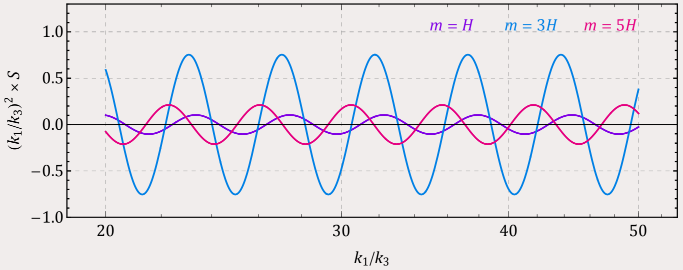
$$m \sim 10^{13}\mathrm{GeV} \sim H$$

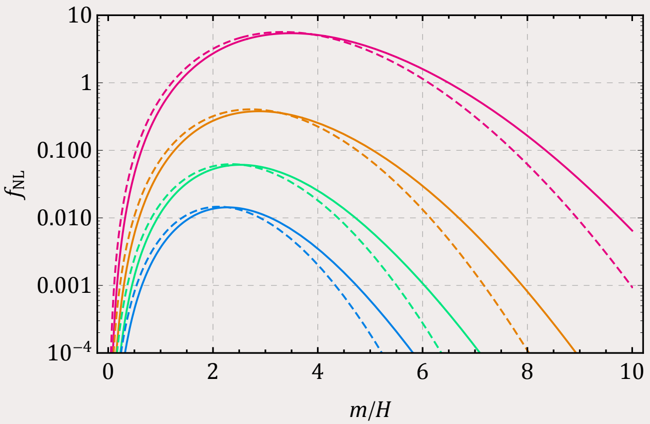
Inflaton background as a neutrino source

$$\frac{1}{\Lambda}(\partial_\mu \phi) N^\dagger \bar{\sigma}^\mu N \rightarrow \frac{\dot{\phi}}{\Lambda} N^\dagger \bar{\sigma}^0 N$$



$$\lambda = \frac{\dot{\phi}_0}{\Lambda} \qquad \mu = \sqrt{m^2 + \lambda^2}$$





$$f_{NL}(\text{clock}) \simeq \frac{3\pi^2}{2} P_\zeta \tilde{\lambda}^5 \tilde{m}^3 e^{-5\pi \tilde{m}^2/(4\tilde{\lambda})}$$

Chen, Wang, ZZX, JHEP **1809** (2018) 022

CP violation

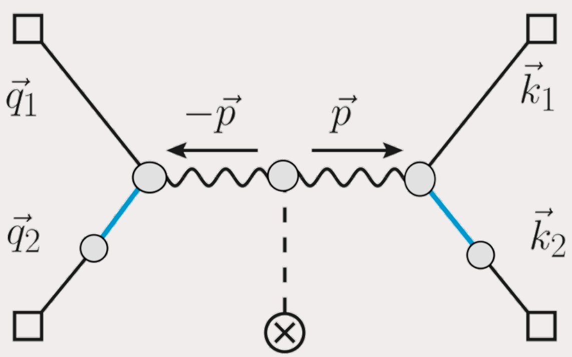
$$\Delta\mathscr{L} = \frac{c_1}{\Lambda}\partial_\mu\phi(\mathcal{H}^\dagger D^\mu\mathcal{H}) + \frac{c_2}{\Lambda^2}(\partial\phi)^2\mathcal{H}^\dagger\mathcal{H} - \frac{c_0}{4}\theta(t)Z_{\mu\nu}Z_{\rho\sigma}\mathcal{E}^{\mu\nu\rho\sigma}$$

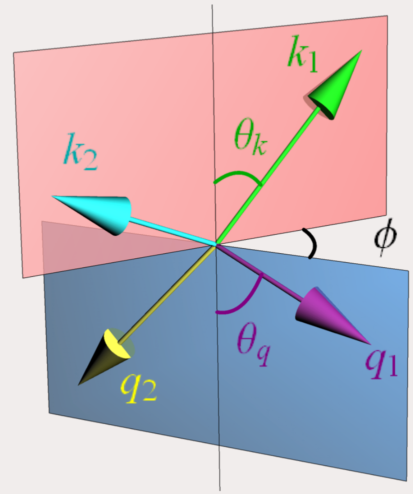
Two types of external legs needed

Odd-angular dependence in imaginary part

No local CP-odd correlations in dS limit

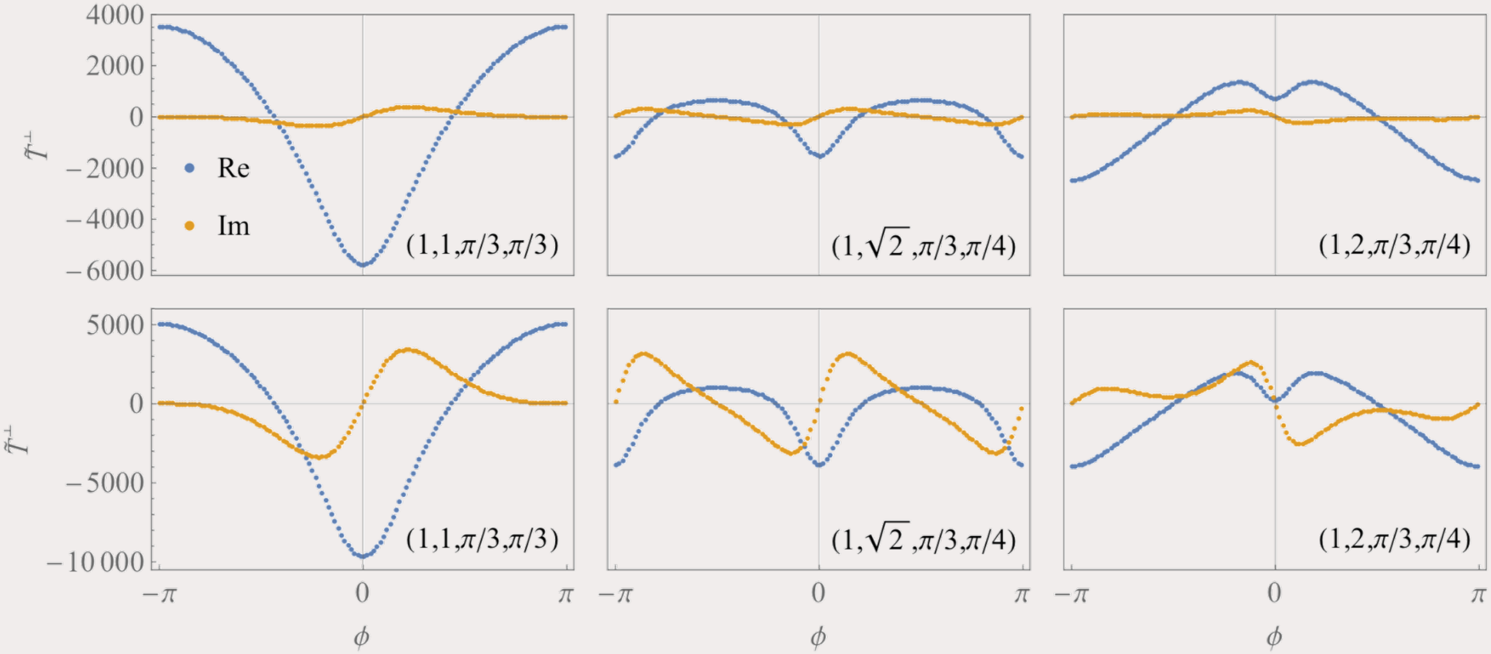
Chemical potential helps

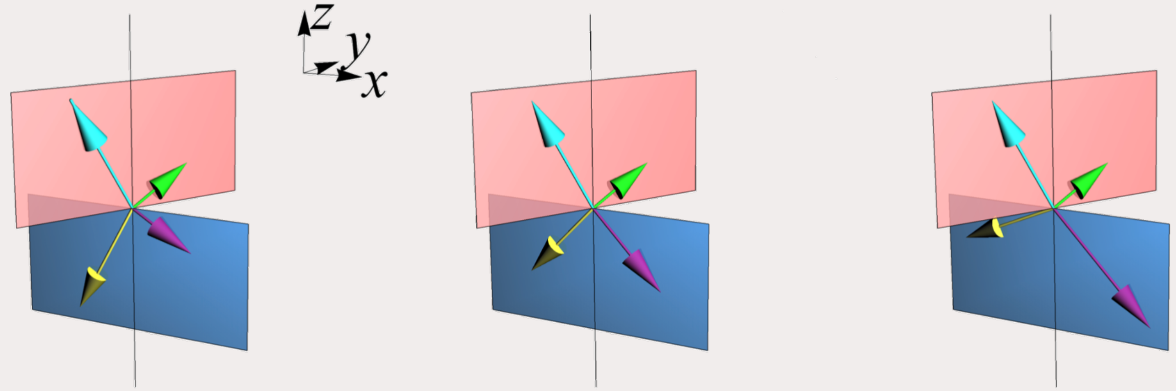




Liu, Tong, Wang, ZZX, 1909.01819

CP violation





Liu, Tong, Wang, ZZX, 1909.01819

Signal size

Beyond the “minimal” scenario

1. Standard slow-roll inflation

2. Scale invariance (up to slow-roll correction)

3. No further spacetime symmetry breaking

4. Dimensionless parameter being O(1)

5. No (tree-level) tuning

Signal size

Beyond the “minimal” scenario

~~1. Standard slow-roll inflation~~

Providing vacuum energy to expand; Generating inhomogeneities

Can separate

Vacuum energy from inflaton / fluctuations from a different source

Modulated reheating (Dvali, Gruzinov, Zaldarriaga, astro-ph/0303591)

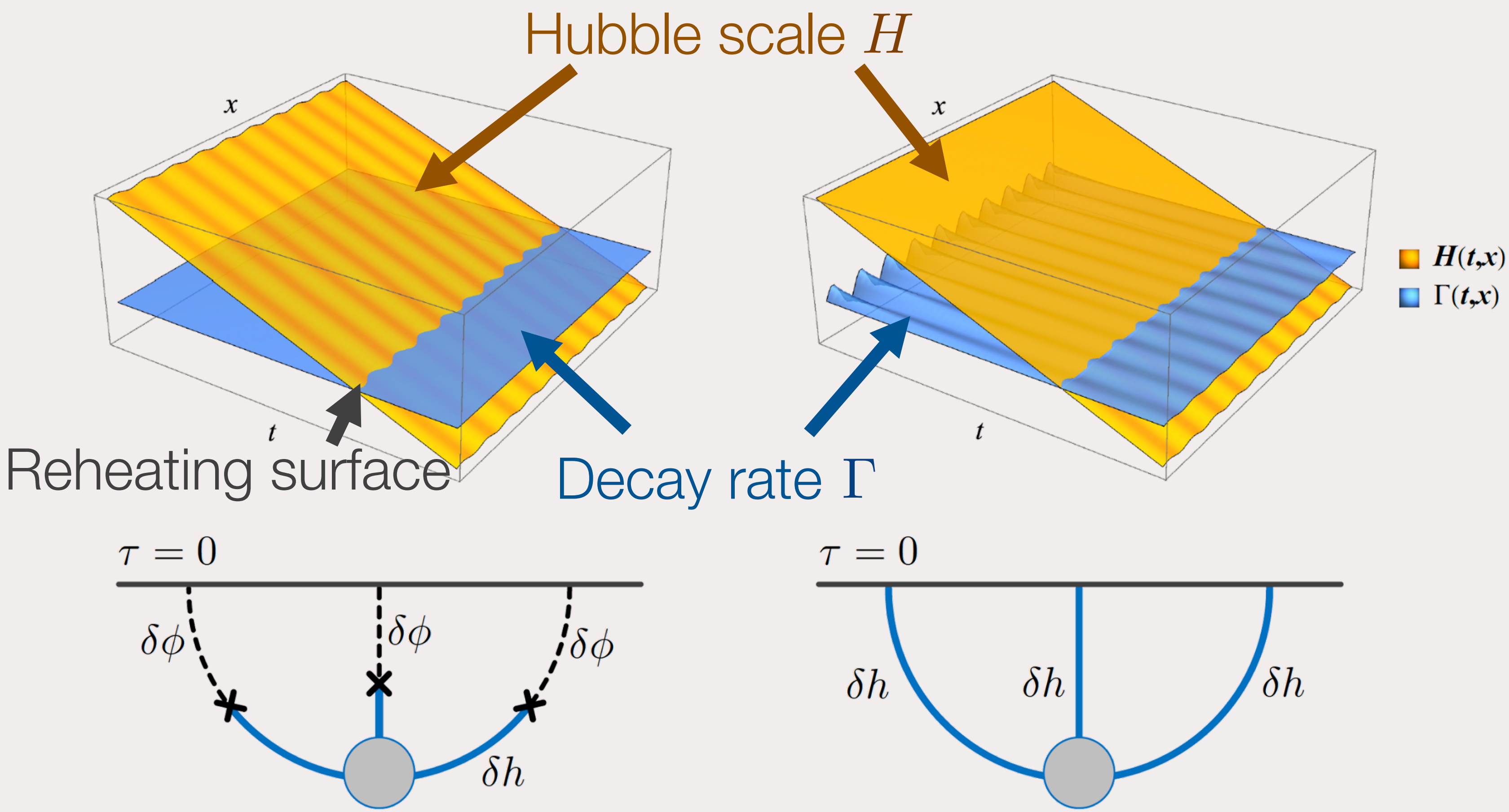
CHC: A cosmological Higgs collider Lu, Wang, ZZX, 1907.07390

Curvaton Kumar, Sundrum, 1908.11378

Modulated reheating

Shiyun Lu, Yi Wang, ZZX, JHEP 02 (2020) 011

Standard inflation | Modulated reheating



Modulated reheating

Shiyun Lu, Yi Wang, ZZX, JHEP 02 (2020) 011

$$\zeta(t_2, \mathbf{x}) = \zeta(t_1, \mathbf{x}) + \delta N(t_1, t_2, \mathbf{x})$$

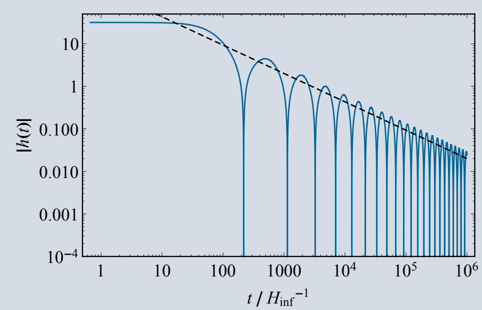
Standard inflation — Modulated reheating

$$\delta N = \frac{1}{6}\frac{\delta t_{\rm reh}}{t_{\rm reh}} = -\frac{1}{6}\frac{\delta\Gamma}{\Gamma}$$

$$\mathcal{O} = \phi h \cdot \text{something}$$

$$\rho_h \sim \lambda h^4 \sim a^{-4} \sim t^{-8/3}$$

$$\Rightarrow \Gamma(\phi \to \text{somthing}) \propto h^2 \propto t^{-4/3}$$



$$\Delta\mathscr{L} = -\frac{1}{2}(\partial_\mu S_i)^2 - \frac{1}{2}m_{S0}^2 S_i^2 - \alpha S_i^2|\mathbf{H}|^2 + \frac{1}{\Lambda_S}(\partial_\mu\phi)S_i\partial^\mu S_i$$

$$\Gamma(\phi \to SS) = \frac{m_\phi^3}{16\pi\Lambda_S^2}\left(1 - \frac{4m_S^2}{m_\phi^2}\right)^{1/2} \qquad m_S^2(h_0) = m_{S0}^2 + \alpha h_0^2$$

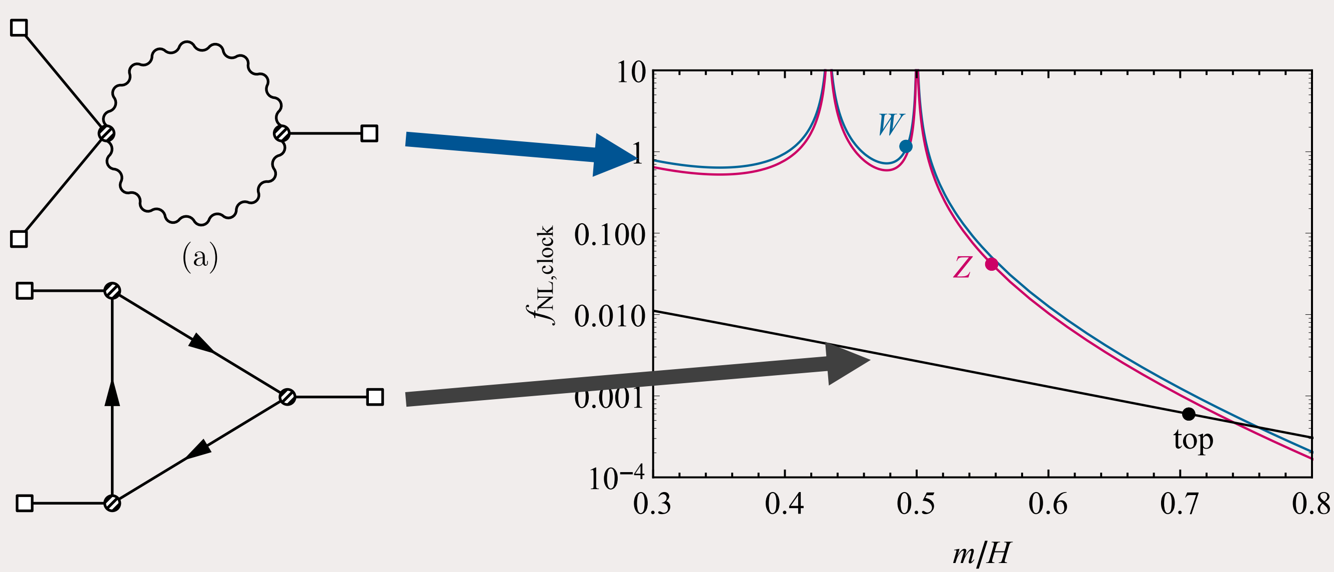
A Cosmological Higgs Collider

Shiyun Lu, Yi Wang, ZZX, JHEP 02 (2020) 011

Constraint from local non-G

$$f_{\rm NL}(\text{local}) \sim -\mathcal{O}(1)\frac{R_h^3}{2\pi P_\zeta^{1/2}}\lambda N_e + \mathcal{O}(1)\frac{R_h^3}{(2\pi)^6 P_\zeta}\frac{2\alpha N}{(m_\phi/H_{\rm inf})^2}$$

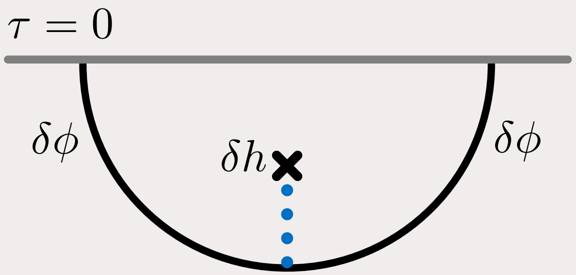
$$R_h \lesssim 0.14\left(\frac{\lambda}{0.01}\right)^{-1/3}\left(\frac{N_e}{50}\right)^{-1/3}$$

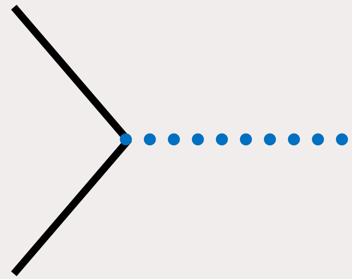


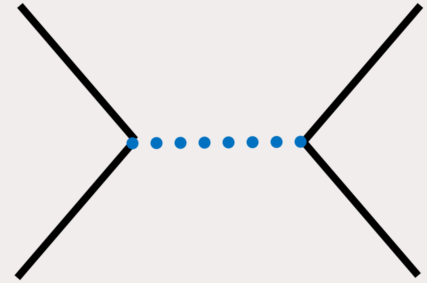
Missing energy

Qianshu Lu, Matt Reece, ZZX, 210X.XXXXX

What if a light scalar does not modulate the reheating?





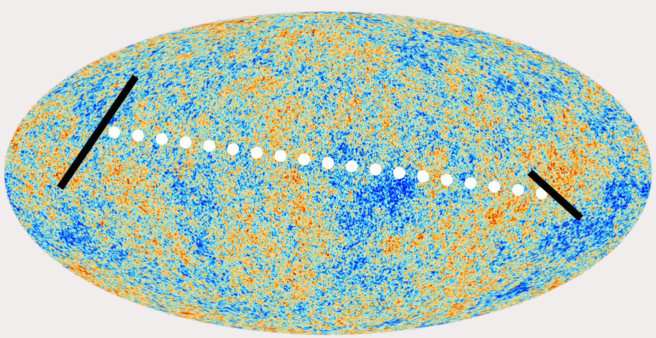


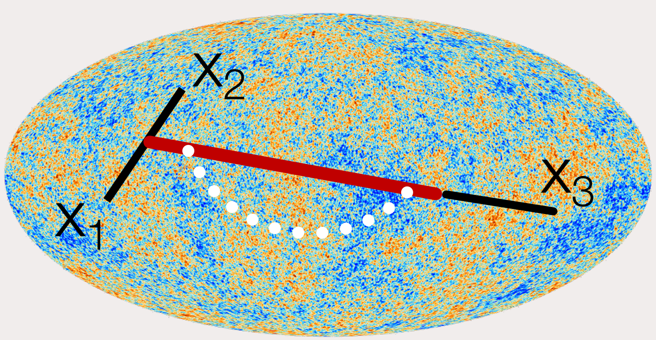
Missing energy. How to probe it?

momentum non-conservation doesn't work

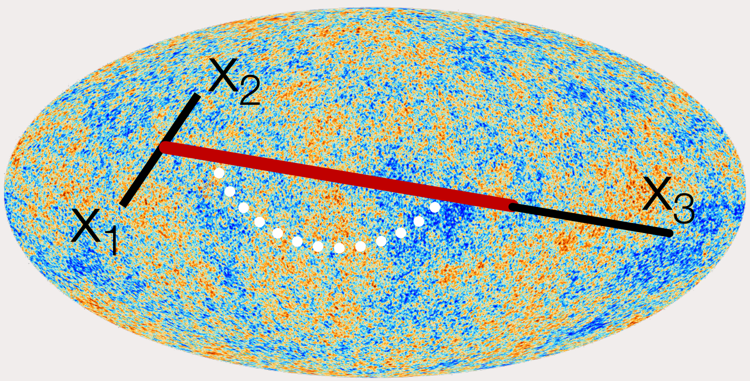
"Cosmic fossils," but only in trispectrum

Dai, Jeong, Kamionkowski 1302.1868

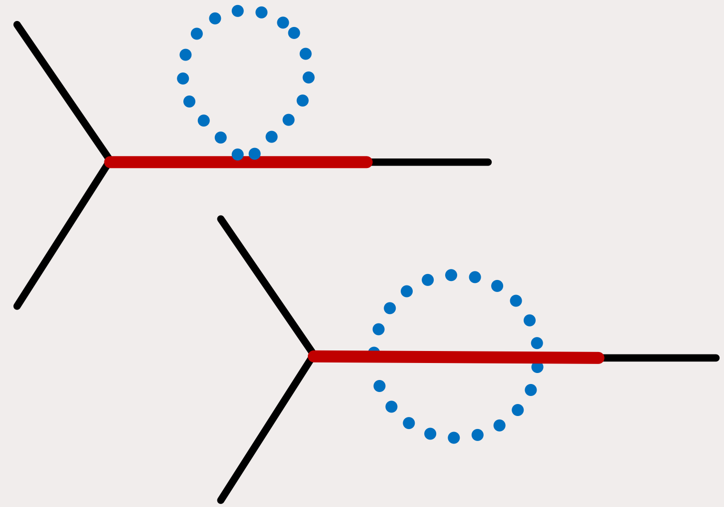




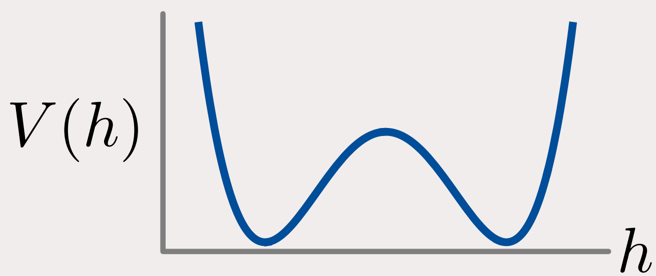
Missing energy



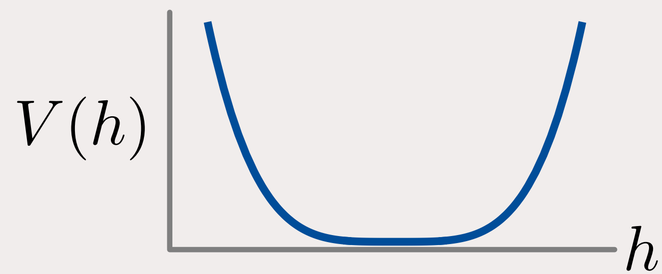
Qianshu Lu, Matt Reece, ZZX, 210X.XXXXX



Telling thermal mass from symmetry-breaking mass

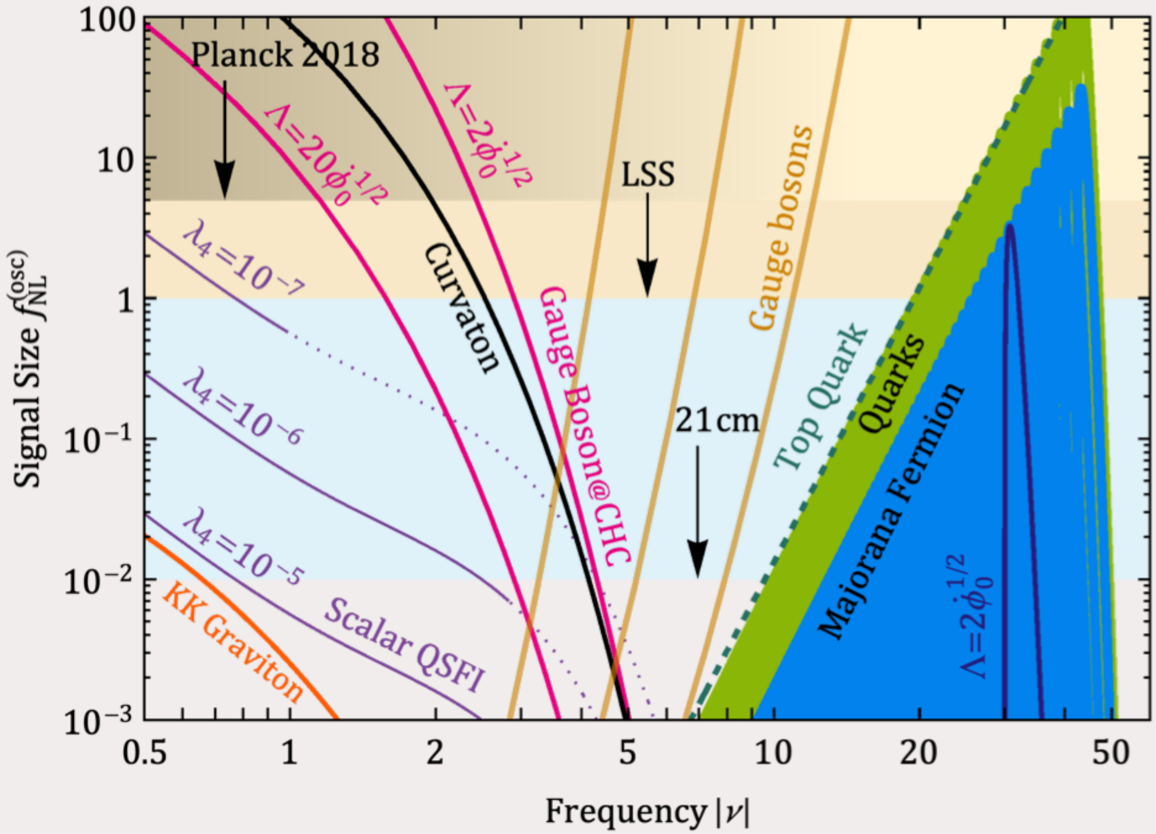


$$m^2 \sim m_0^2 + g^2 \langle h \rangle^2$$



$$m^2 \sim m_0^2 + g^2 \langle h^2 \rangle$$

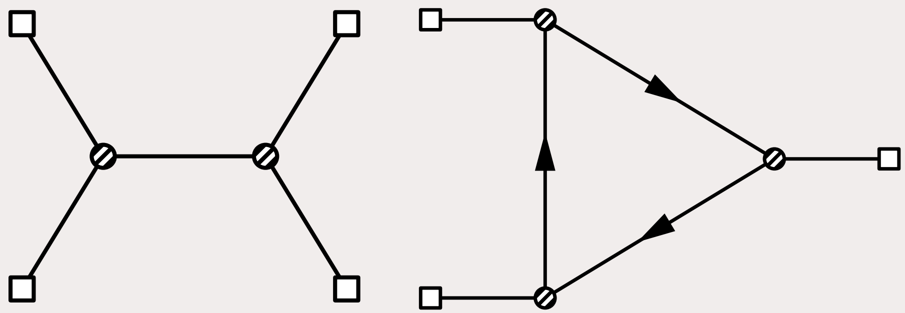
A status summary

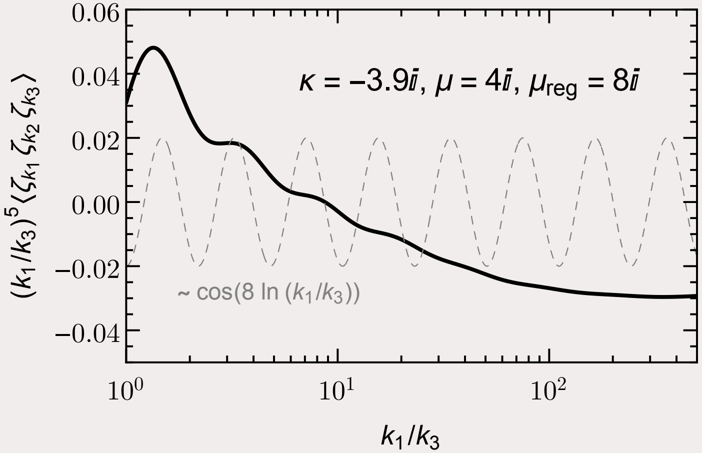


L. Wang, ZZX, 1910.12876, 2004.02887

Theory challenges

Calculating Feynman graphs in dS is difficult





Recent development in formal techniques

Conformal Bootstrap

Arkani-Hamed, Baumann, Joyce, Lee, Pimentel, 1811.00024, 1910.14051, 2005.04234

Mellin-Barnes representation

Sleight, Taronna, 1906.12302, 1907.01143

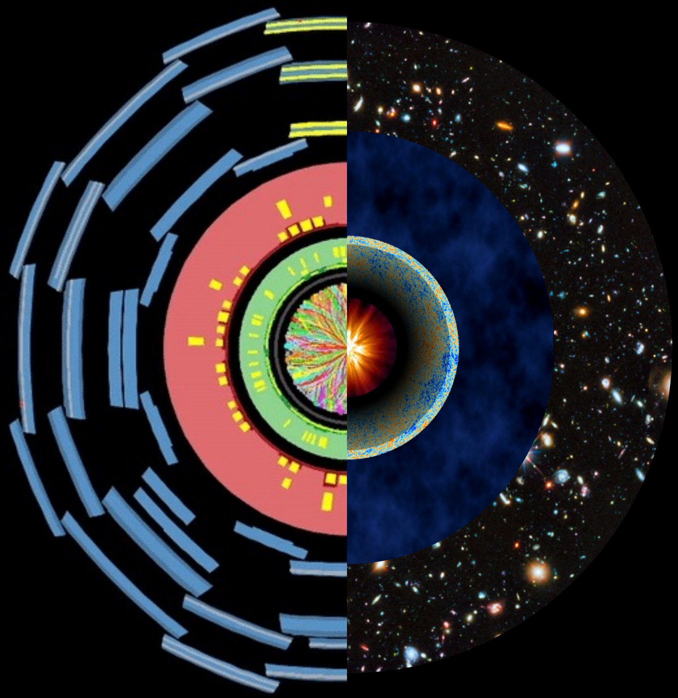
More pragmatic approaches

Schwinger-Keldysh diagrammatics

Chen, Wang, ZZX, 1703.10166

“brute force” computation

Wang, ZZX, Zhong, in progress



Take-home

Observational progress ahead

1 order of magnitude improvement in next decade / Can already test some interesting scenarios / another 1-2 orders ultimately, can reach gravity floor

Chance to do some real particle physics

More theoretical efforts called for / Not the sort of “1000 inflation models to fit 2 parameters n_s and r” thing