The Physics of the Cosmological Collider

-- Non-Gaussianity in the Post-Planck Era

Yi Wang 王一, 2017.01.11

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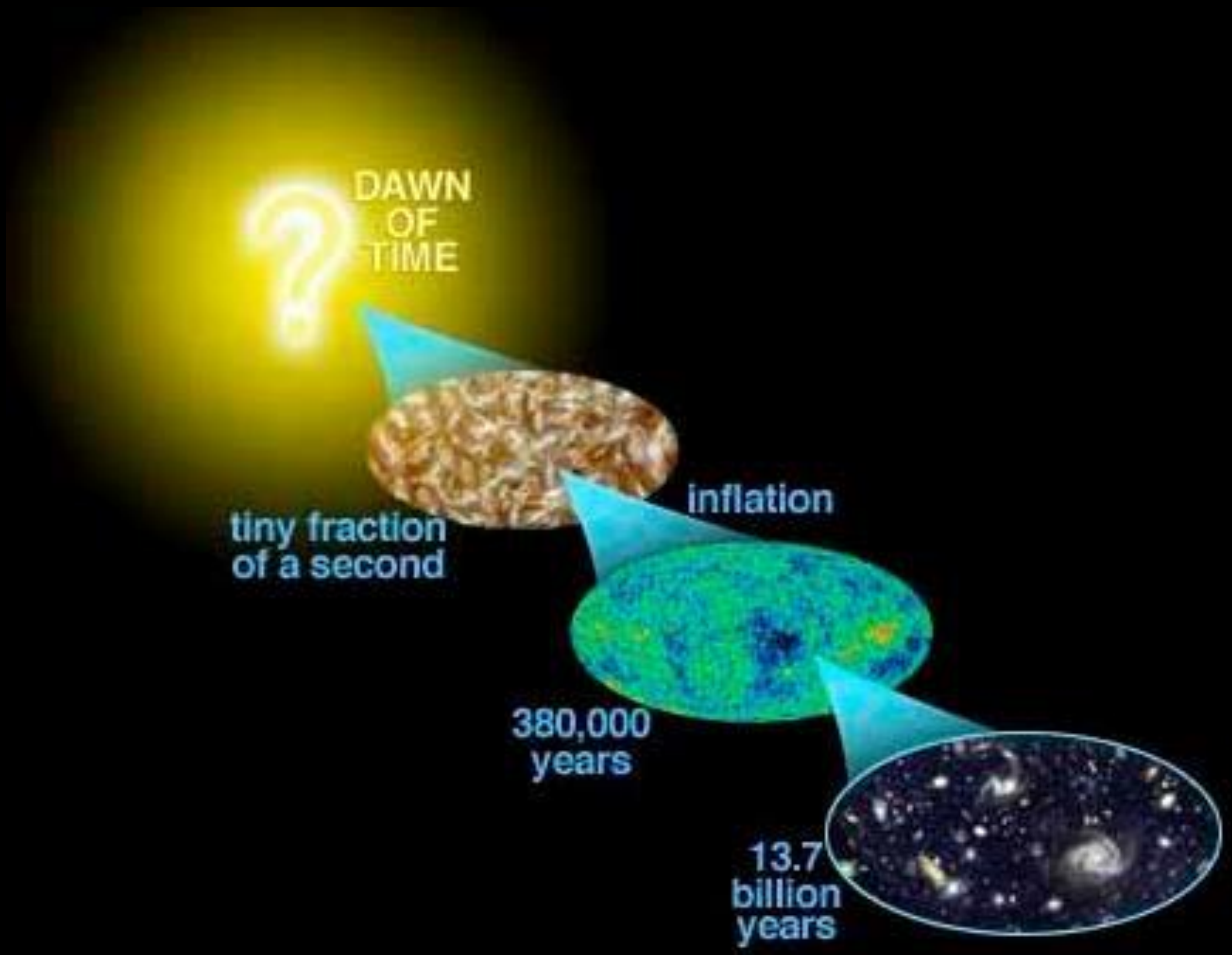
Collaboration with

X. Chen 0909.0496, 0911.3380, 1205.0160

X. Chen & Z. Z. Xianyu 1604.07841, 1610.06597, 1612.08122

X. Chen & M. H. Namjoo 1509.03930, 1601.06228, 1608.01299


DAWN
OF
TIME
inflation
tiny fraction
of a second
380,000
years
13.7
billion
years

Review of Non-G before Planck

Inflationary ($a \sim e^{Ht}$) correlation functions

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \ldots \zeta_{\mathbf{k}_n} \rangle$$

ζ: curvature fluctuation on uniform density slices

$$\zeta \Leftrightarrow \frac{\delta T}{T} \text{ (CMB)}, \qquad \zeta \Leftrightarrow \frac{\delta \rho}{\rho} \text{ (LSS)}$$

How to calculate $\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \ldots \zeta_{\mathbf{k}_n} \rangle$?

in-in formalism

$$\langle\Omega|Q(\tau)|\Omega\rangle = \langle 0| \left[\bar{T} e^{i\int_{\tau_0}^{\tau} H_I(\tau')d\tau'}\right] Q^I(\tau) \left[T e^{-i\int_{\tau_0}^{\tau} H_I(\tau')d\tau'}\right]|0\rangle$$

expansion order by order ~ “Feynman” diagrams

Inflationary ($a \sim e^{Ht}$) correlation functions

$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \ldots \zeta_{\mathbf{k}_n} \rangle$$

ζ: curvature fluctuation on uniform density slices

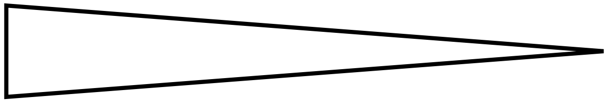
$$\zeta \Leftrightarrow \frac{\delta T}{T} \text{ (CMB)}, \qquad \zeta \Leftrightarrow \frac{\delta \rho}{\rho} \text{ (LSS)}$$

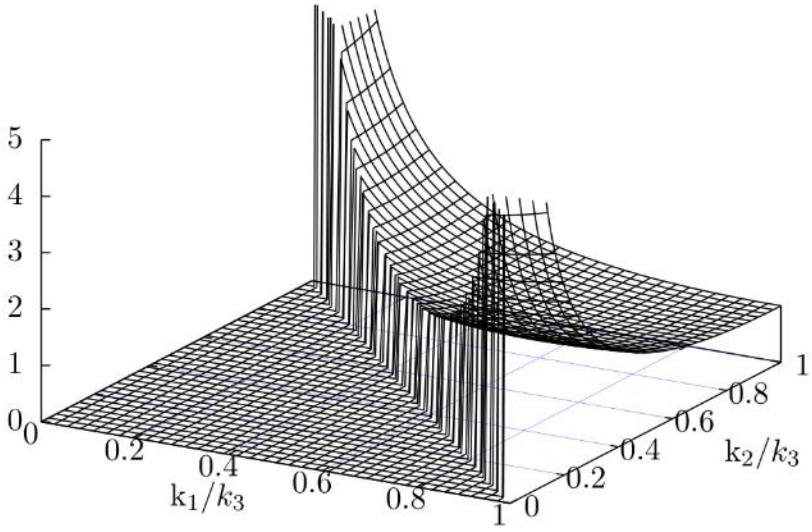
$$\langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle = (2\pi)^7 \delta^3(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3) \frac{P_\zeta^2}{k_1^2 k_2^2 k_3^2} \mathcal{F}(k_1/k_3, k_2/k_3)$$

$P_\zeta \sim$ 2pt

$\mathcal{F}$ {
- size of non-G: $\sim f_{NL}$
- shape: shape of non-G

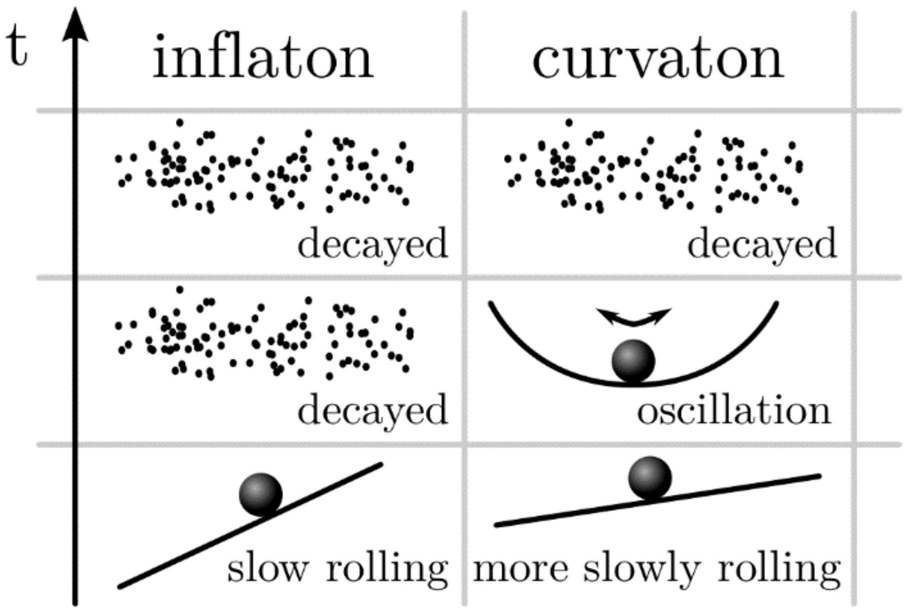
Local shape non-G:





Example of local non-G: the curvaton scenario:

Sasaki, Valiviita, Wands 2006



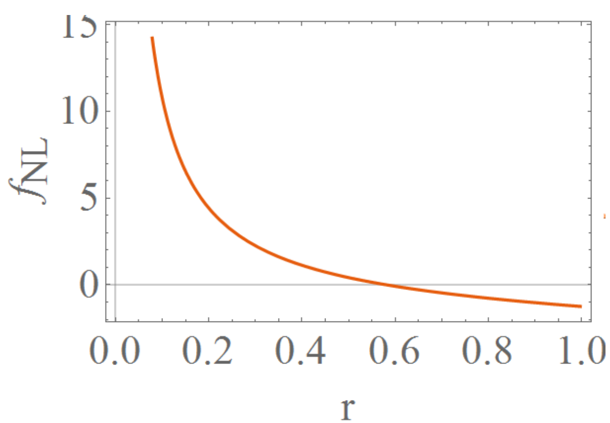
assuming same decay product
entropy perturbation becomes adiabatic

curvaton density catches up
perturbation starts to gravitate

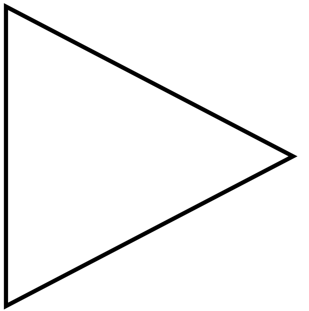
curvaton has entropy perturbation
inflaton perturbation assumed small

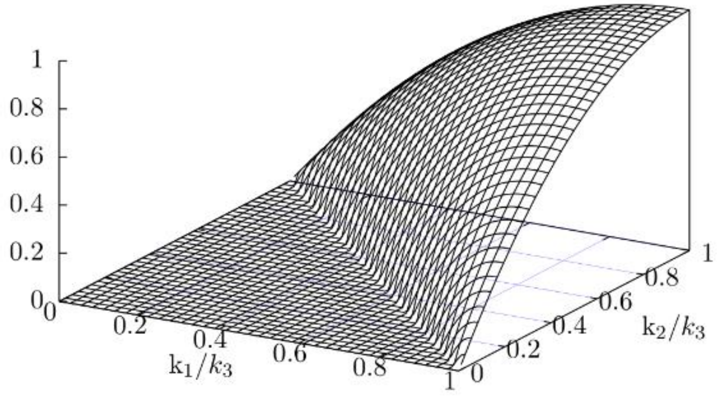
$$f_{NL} = \frac{5}{4r}\left(1 + \frac{gg''}{g'^2}\right) - \frac{5}{3} - \frac{5r}{6}$$

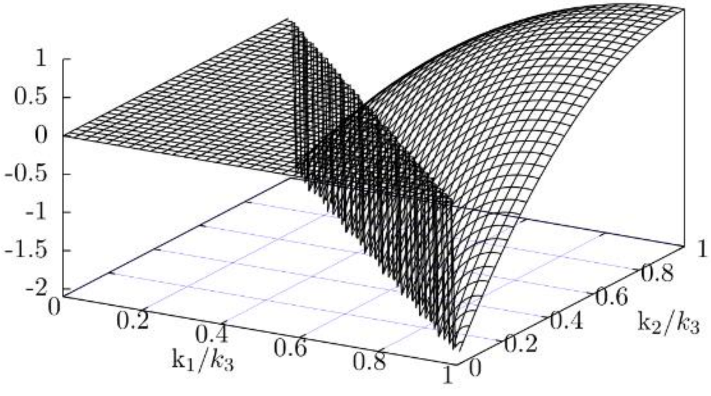
$$r = \frac{3\Omega_{\chi,\rm dec}}{4 - \Omega_{\chi,\rm dec}} = \frac{3\bar{\rho}_\chi}{3\bar{\rho}_\chi + 4\bar{\rho}_r}\bigg|_{t_{\rm dec}}$$



Equilateral and orthogonal shapes of non-G:







Example of equilateral non-G: modified sound speed

$$\mathcal{L} = P(\phi, X) \qquad S_2 = \int dt d^3x \left[a^3 \frac{\epsilon}{c_s^2} \dot{\zeta}^2 - a\epsilon (\partial\zeta)^2 \right]$$

$$c_s^2 = \frac{P_{,X}}{P_{,X} + 2XP_{,XX}}$$

$$\mathcal{F} = \left(\frac{1}{c_s^2} - 1 - \frac{2\lambda}{\Sigma} \right) \frac{3k_1k_2k_3}{2(k_1+k_2+k_3)^3} + \left(\frac{1}{c_s^2} - 1 \right) \left[-\frac{k_1^2k_2^2 + k_1^2k_3^2 + k_2^2k_3^2}{k_1k_2k_3(k_1+k_2+k_3)} + \frac{k_1^2k_2^3 + k_1^2k_3^3 + k_2^2k_3^3 + k_2^2k_1^3 + k_3^2k_1^3 + k_3^2k_2^3}{2k_1k_2k_3(k_1+k_2+k_3)^2} + \frac{k_1^3+k_2^3+k_3^3}{8k_1k_2k_3} \right]$$

Of order f_{NL}

Chen, Huang, Kachru, Shiu 2006

Many many many similar stories 2000s – 2013.

Planck 2013 results. XXIV. Constraints on primordial non-Gaussianity

Planck Collaboration

P. A. R. Ade[87], N. Aghanim[60], C. Armitage-Caplan[93], M. Arnaud[73], M. Ashdown[70,6], F. Atrio-Barandela[18], J. Aumont[60], C. Baccigalupi[86], A. J. Banday[96,9], R. B. Barreiro[67], J. G. Bartlett[1,68], N. Bartolo[34*], E. Battaner[97], K. Benabed[61,95], A. Benoît[58], A. Benoit-Lévy[25,61,95], J.-P. Bernard[96,9], M. Bersanelli[37,51], P. Bielewicz[96,9,86], J. Bobin[73], J. J. Bock[68,10], A.

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Abstract

The *Planck* nominal mission cosmic microwave background (CMB) maps yield unprecedented constraints on primordial non-Gaussianity (NG). Using three optimal bispe estimators, separable template-fitting (KSW), binned, and modal, we obtain consistent values for the primordial local, equilateral, and orthogonal bispectrum ampli quoting as our final result $f_{\rm NL}^{\rm local} = 2.7 \pm 5.8$, $f_{\rm NL}^{\rm equil} = -42 \pm 75$, and $f_{\rm NL}^{\rm orth} = -25 \pm 39$ (68% CL statistical). Non-Gaussianity is detected in the data; using skew-C_ℓ sta we find a nonzero bispectrum from residual point sources, and the integrated-Sachs-Wolfe-lensing bispectrum at a level expected in the ΛCDM scenario. The results are on comprehensive cross-validation of these estimators on Gaussian and non-Gaussian simulations, are stable across component separation techniques, pass an ext suite of tests, and are confirmed by skew-C_ℓ, wavelet bispectrum and Minkowski functional estimators. Beyond estimates of individual shape amplitudes, we present r independent, three-dimensional reconstructions of the *Planck* CMB bispectrum and thus derive constraints on early-Universe scenarios that generate primordial NG, inc general single-field models of inflation, excited initial states (non-Bunch-Davies vacua), and directionally-dependent vector models. We provide an initial survey of dependent feature and resonance models. These results bound both general single-field and multi-field model parameter ranges, such as the speed of sound, $c_{\rm s} \geq 0.02$ CL), in an effective field theory parametrization, and the curvaton decay fraction $r_{\rm D} \geq 0.15$ (95% CL). The *Planck* data significantly limit the viable parameter space ekpyrotic/cyclic scenarios. The amplitude of the four-point function in the local model $\tau_{\rm NL} < 2800$ (95% CL). Taken together, these constraints represent the highest pre tests to date of physical mechanisms for the origin of cosmic structure.

$f_{\rm NL}^{\rm local} = 2.7 \pm 5.8$, $f_{\rm NL}^{\rm equil} = -42 \pm 75$, and $f_{\rm NL}^{\rm orth} = -25 \pm 39$ (68% CL statistical)

Planck 2015 results
XVII. Constraints on primordial non-Gaussianity

Planck Collaboration

P. A. R. Ade[97], N. Aghanim[63], M. Arnaud[79], F. Arroja[71,85], M. Ashdown[75,6], J. Aumont[63], C. Baccigalupi[95], M. Ballardini[51,53,34], A. J. Banday[109,10], R. B. Barreiro[70], N. Bartolo[33,71]*, S. Basak[95], E. Battaner[110,111], K. Benabed[64,108], A. Benoît[61], A. Benoit-Lévy[26,64,108], J.-P. Bernard[109,10], M. Bersanelli[37,52], P. Bielewicz[89,10,95], J. J. Bock[72,12], A.

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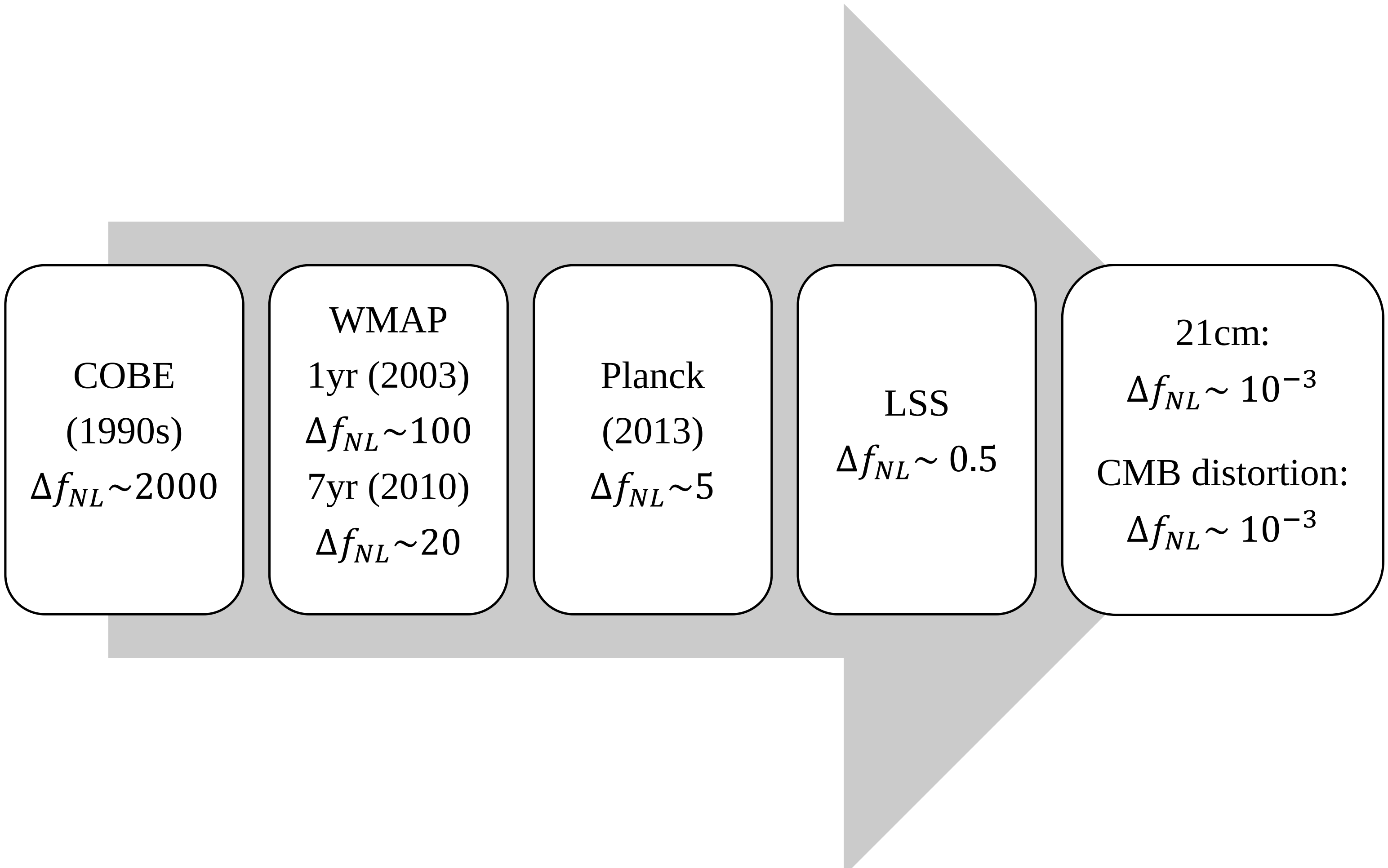
Abstract

The *Planck* full mission cosmic microwave background (CMB) temperature and *E*-mode polarization maps are analysed to obtain constraints on primordial non-Gauss (NG). Using three classes of optimal bispectrum estimators – separable template-fitting (KSW), binned, and modal – we obtain consistent values for the primordial equilateral, and orthogonal bispectrum amplitudes, quoting as our final result from temperature alone $f^{\text{local}}_{\text{NL}} = 2.5 \pm 5.7$, $f^{\text{equil}}_{\text{NL}} = -16 \pm 70$, , and $f^{\text{ortho}}_{\text{NL}} = -34 \pm 32$ CL, statistical). Combining temperature and polarization data we obtain $f^{\text{local}}_{\text{NL}} = 0.8 \pm 5.0$, $f^{\text{equil}}_{\text{NL}} = -4 \pm 43$, and $f^{\text{ortho}}_{\text{NL}} = -26 \pm 21$ (68% CL, statistical). The resul based on comprehensive cross-validation of these estimators on Gaussian and non-Gaussian simulations, are stable across component separation techniques, pa extensive suite of tests, and are consistent with estimators based on measuring the Minkowski functionals of the CMB. The effect of time-domain de-glitching systemat the bispectrum is negligible. In spite of these test outcomes we conservatively label the results including polarization data as preliminary, owing to a known mismatch noise model in simulations and the data. Beyond estimates of individual shape amplitudes, we present model-independent, three-dimensional reconstructions of the CMB bispectrum and derive constraints on early universe scenarios that generate primordial NG, including general single-field models of inflation, axion inflation, initia modifications, models producing parity-violating tensor bispectra, and directionally dependent vector models. We present a wide survey of scale-dependent featur resonance models, accounting for the "look elsewhere" effect in estimating the statistical significance of features. We also look for isocurvature NG, and find no signal, b obtain constraints that improve significantly with the inclusion of polarization. The primordial trispectrum amplitude in the local model is constrained to be $g^{\text{local}}_{\text{NL}}$ = (- 7.7) X 10^4(68% CL statistical), and we perform an analysis of trispectrum shapes beyond the local case. The global picture that emerges is one of consistency wi premises of the ΛCDM cosmology, namely that the structure we observe today was sourced by adiabatic, passive, Gaussian, and primordial seed perturbations.

$f^{\text{local}}_{\text{NL}} = 0.8 \pm 5.0$, $f^{\text{equil}}_{\text{NL}} = -4 \pm 43$, and $f^{\text{ortho}}_{\text{NL}} = -26 \pm 21$ (68% CL, statistical)



COBE
(1990s)
Δf_{NL}~2000
WMAP
1yr (2003)
Δf_{NL}~100
7yr (2010)
Δf_{NL}~20
Planck
(2013)
Δf_{NL}~5
LSS
Δf_{NL}~ 0.5
21cm:
Δf_{NL}~ 10^{-3}
CMB distortion:
Δf_{NL}~ 10^{-3}

In ~ 5-10 years $\Delta f_{NL} \sim 0.5$ (e.g. SPHEREx)

(And $\Delta f_{NL} \sim 10^{-3}$ in the very distant future.)

What is the implication if $|f_{NL}| < 1$?

In ~ 5-10 years $\Delta f_{NL} \sim 0.5$ (e.g. SPHEREx)

What is the implication if $|f_{NL}| < 1$?

- Local: Curvaton will be very unlikely.
- Equilateral: $c_s \sim 1$, up to small corrections.

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What is the implication if $|f_{NL}| < 1$?

- Local: Curvaton will be very unlikely.
- Equilateral: $c_s \sim 1$, up to small corrections.

What is the motivation for future study?

(Before addressing motivation of $|f_{NL}| < 1$ …)

History of particle physics experiments:

- Early stage: studying external particle
  - α particle scattering
  - μ from cosmic rays
  - deep inelastic scattering
  - …
- Nowadays: study internal particle
  - Higgs - BSM - …

(Before addressing motivation of $|f_{NL}| < 1$ …)

external particle $\rightarrow$ internal particle

Cosmological non-G: is there a similarity?

Curvaton, c_s, … : external particle (ζ)

If seen: pin down inflation model.

What about internal particles?

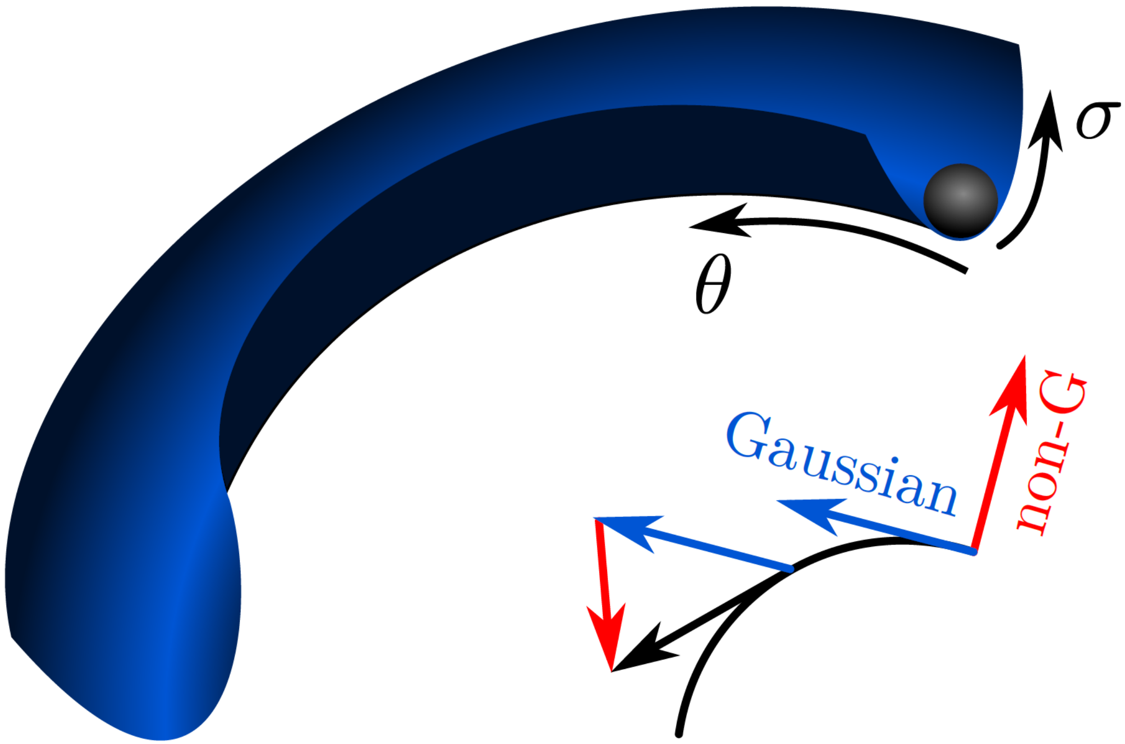
Internal particles:

Quasi-single field inflation

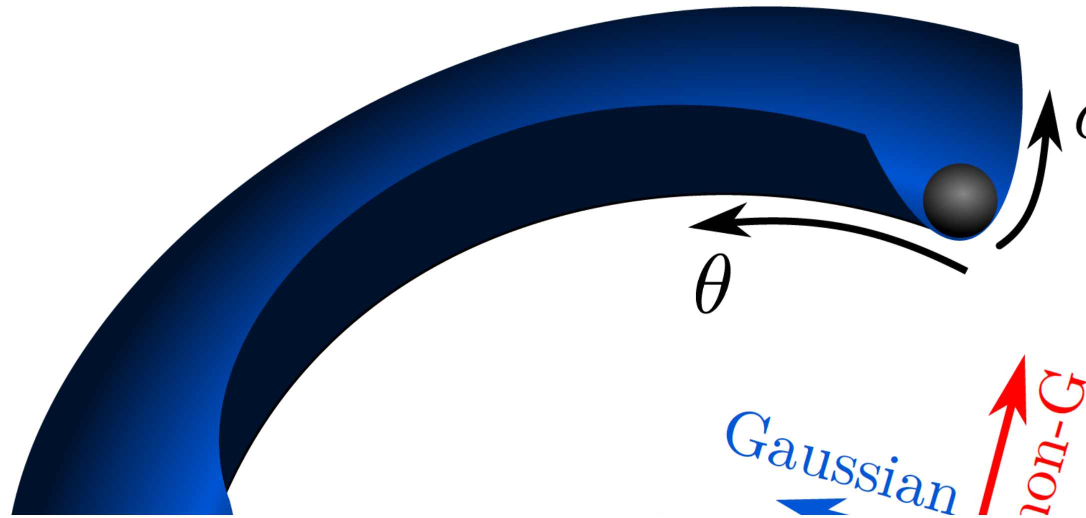
Xingang Chen & YW 2009

m ~ H fields

Example: quasi-single field inflation

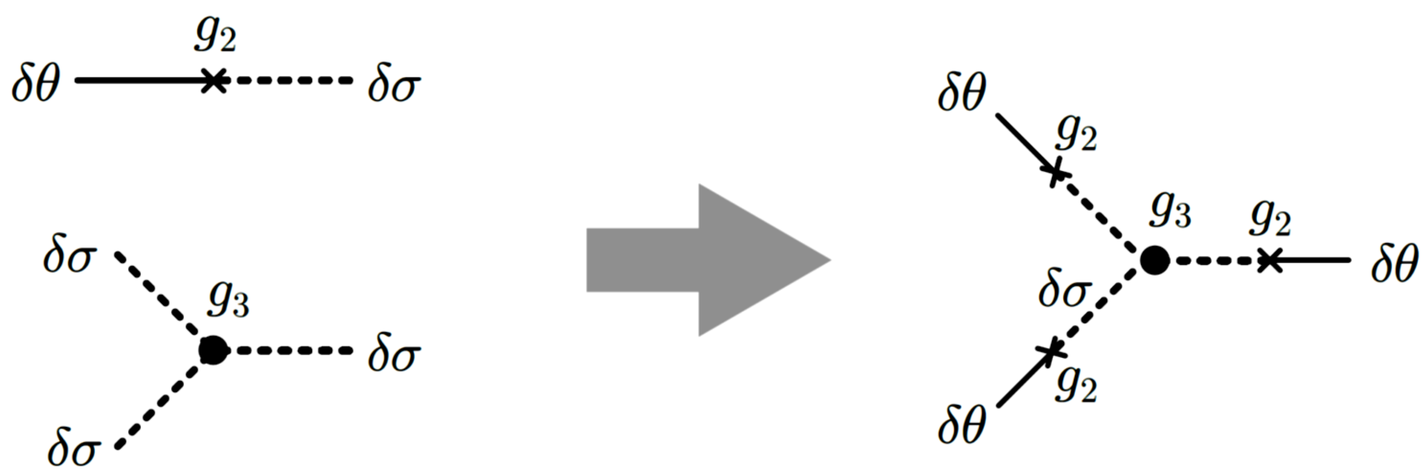


X. Chen, YW 2009



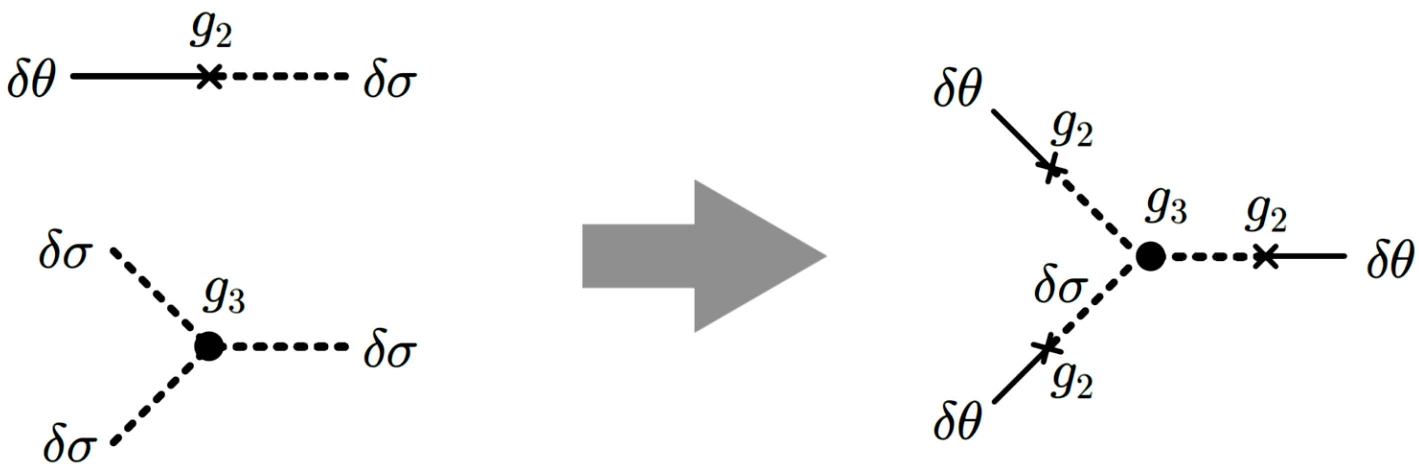
$$S_m = \int d^4x\sqrt{-g}\left[-\frac{1}{2}(\tilde{R}+\sigma)^2 g^{\mu\nu}\partial_\mu\theta\partial_\nu\theta - \frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - V_{\rm sr}(\theta) - V(\sigma)\right]$$

$$\delta\mathcal{L}_2 \;=\; 2a^3R\dot{\theta}_0\,\delta\sigma\dot{\delta\theta}\;, \qquad\qquad \mathcal{L}_3 \;=\; -\frac{1}{6}a^3V'''\delta\sigma^3$$

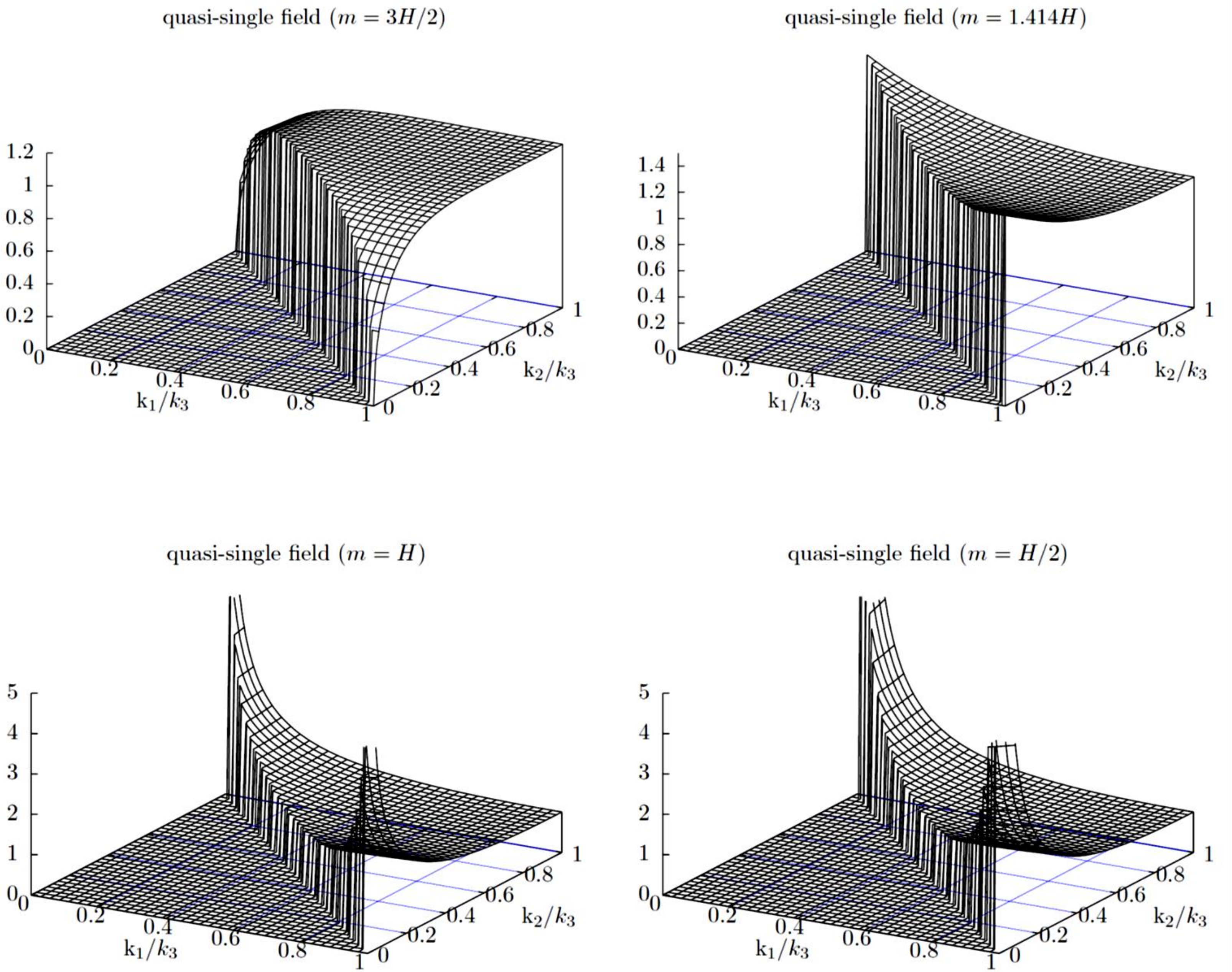


$$S_m = \int d^4x \sqrt{-g} \left[-\frac{1}{2}(\tilde{R}+\sigma)^2 g^{\mu\nu}\partial_\mu\theta\partial_\nu\theta - \frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - V_{\rm sr}(\theta) - V(\sigma) \right]$$

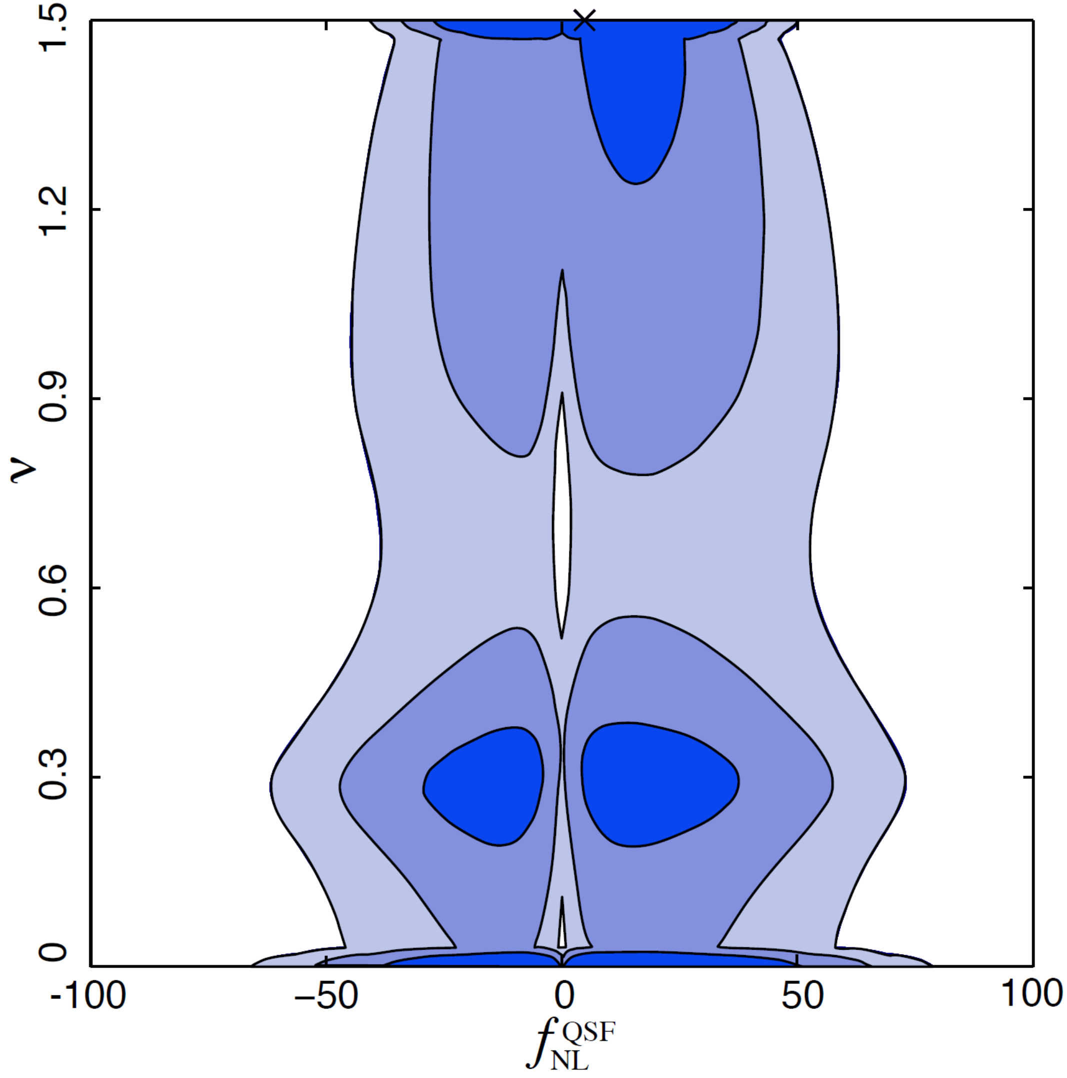
$$\delta\mathcal{L}_2 \;\; = \;\; 2a^3 R\dot{\theta}_0 \; \delta\sigma\dot{\delta\theta} \; , \qquad\qquad \mathcal{L}_3 \;\; = \;\; -\frac{1}{6}a^3 V'''\delta\sigma^3$$



$$
\begin{aligned}
- & \quad 12 c_2^3 c_3 u_{p_1}^*(0) u_{p_2}(0) u_{p_3}(0) \\
\times & \quad \mathrm{Re}\left[\int_{-\infty}^{0} d\tilde{\tau}_1 \ a^3(\tilde{\tau}_1) v_{p_1}^*(\tilde{\tau}_1) u_{p_1}'(\tilde{\tau}_1) \int_{-\infty}^{\tilde{\tau}_1} d\tilde{\tau}_2 \ a^4(\tilde{\tau}_2) v_{p_1}(\tilde{\tau}_2) v_{p_2}(\tilde{\tau}_2) v_{p_3}(\tilde{\tau}_2) \right. \\
\times & \quad \left. \int_{-\infty}^{0} d\tau_1 \ a^3(\tau_1) v_{p_2}^*(\tau_1) u_{p_2}'^*(\tau_1) \int_{-\infty}^{\tau_1} d\tau_2 \ a^3(\tau_2) v_{p_3}^*(\tau_2) u_{p_3}'^*(\tau_2) \right] \\
\times & \quad (2\pi)^3 \delta^3\Big(\sum_i \mathbf{p}_i\Big) + 9 \text{ other similar terms} \\
+ & \quad 5 \text{ permutations of } \mathbf{p}_i \ .
\end{aligned}
$$



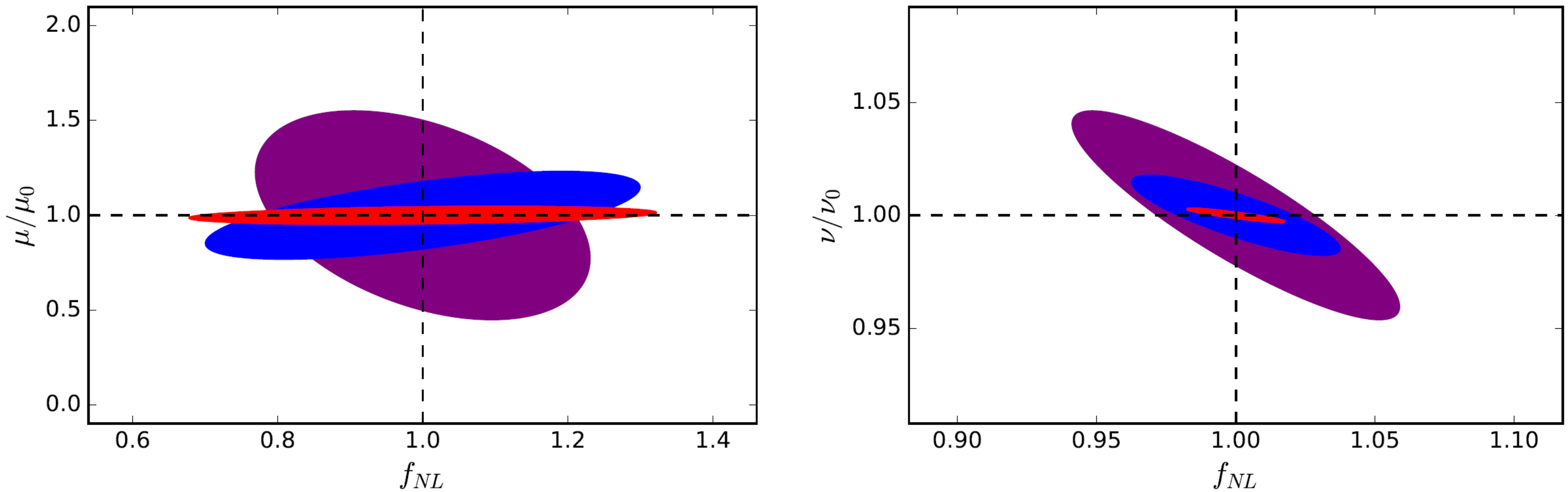
quasi-single field ($m = 3H/2$)
quasi-single field ($m = 1.414H$)
quasi-single field ($m = H$)
quasi-single field ($m = H/2$)
k_1/k_3
k_2/k_3



$$\nu = \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$

Planck collaboration 2013

Distant future 21cm forecast



$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

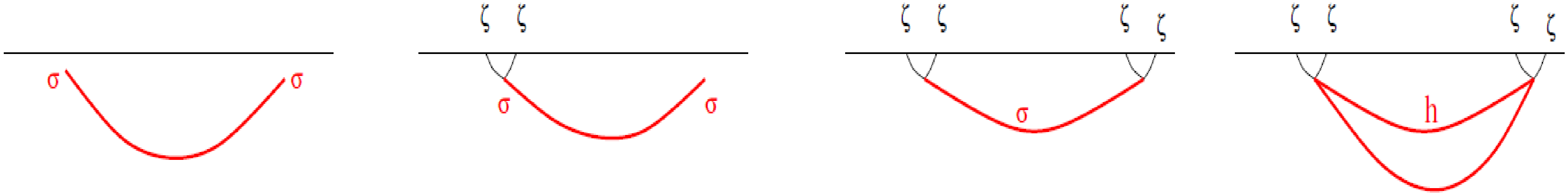
$$\nu = \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$

μ = 0.7 (purple), μ = 1.0 (blue), μ = 3.0 (red)

ν = 0.8 (purple), ν = 1.0 (blue), ν = 1.4 (red)

Meerburg, Munchmeyer, Munoz, Chen 2016

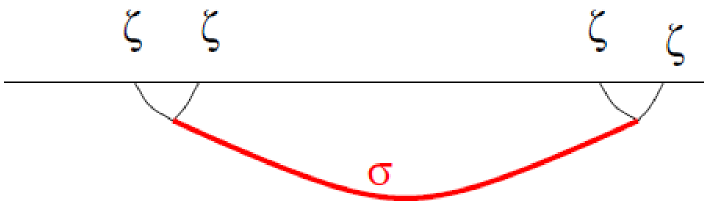
Cosmological double slit experiment



Arkani-Hamed, Maldacena 2015

X. Chen, YW 09, 12, Pi, Sasaki 12, Gong, Pi, Sasaki 13

Arkani-Hamed, Maldacena 15



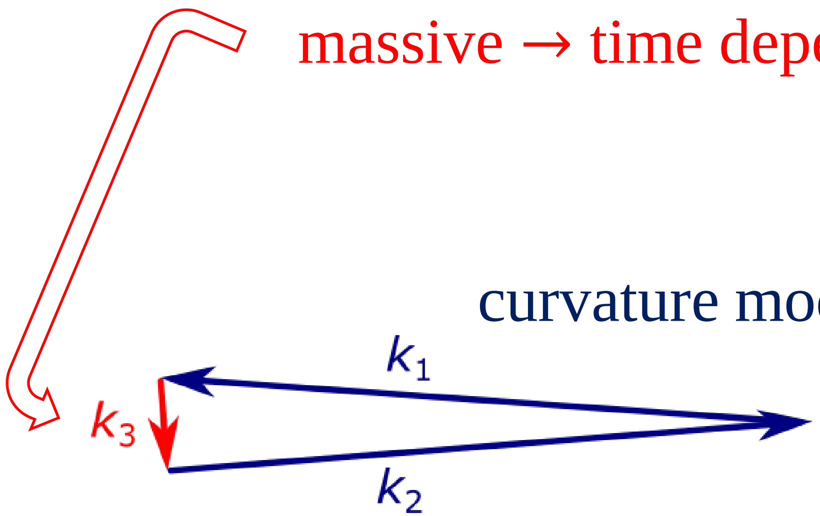
Contributions to correlation functions:

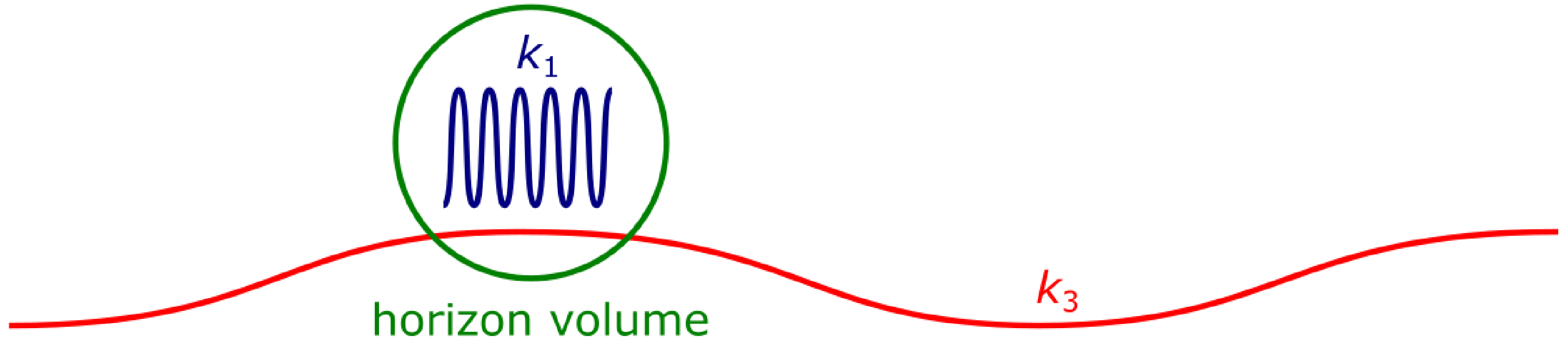
type	meaning	analytic in k?	integrate out?	suppression at large μ	suppression at large x
local	vacuum correlation	Yes	Yes	$1/\mu^2$	vanish outside lightcone
non-local	thermal particle production	No	No	$e^{-\pi\mu}$	non-vanishing

$\langle \zeta^3 \rangle$

massive → time dependent phase $e^{imt} \sim (-\tau)^{im/H}$

curvature mode $\sim e^{ik\tau}$, at resonance record the phase

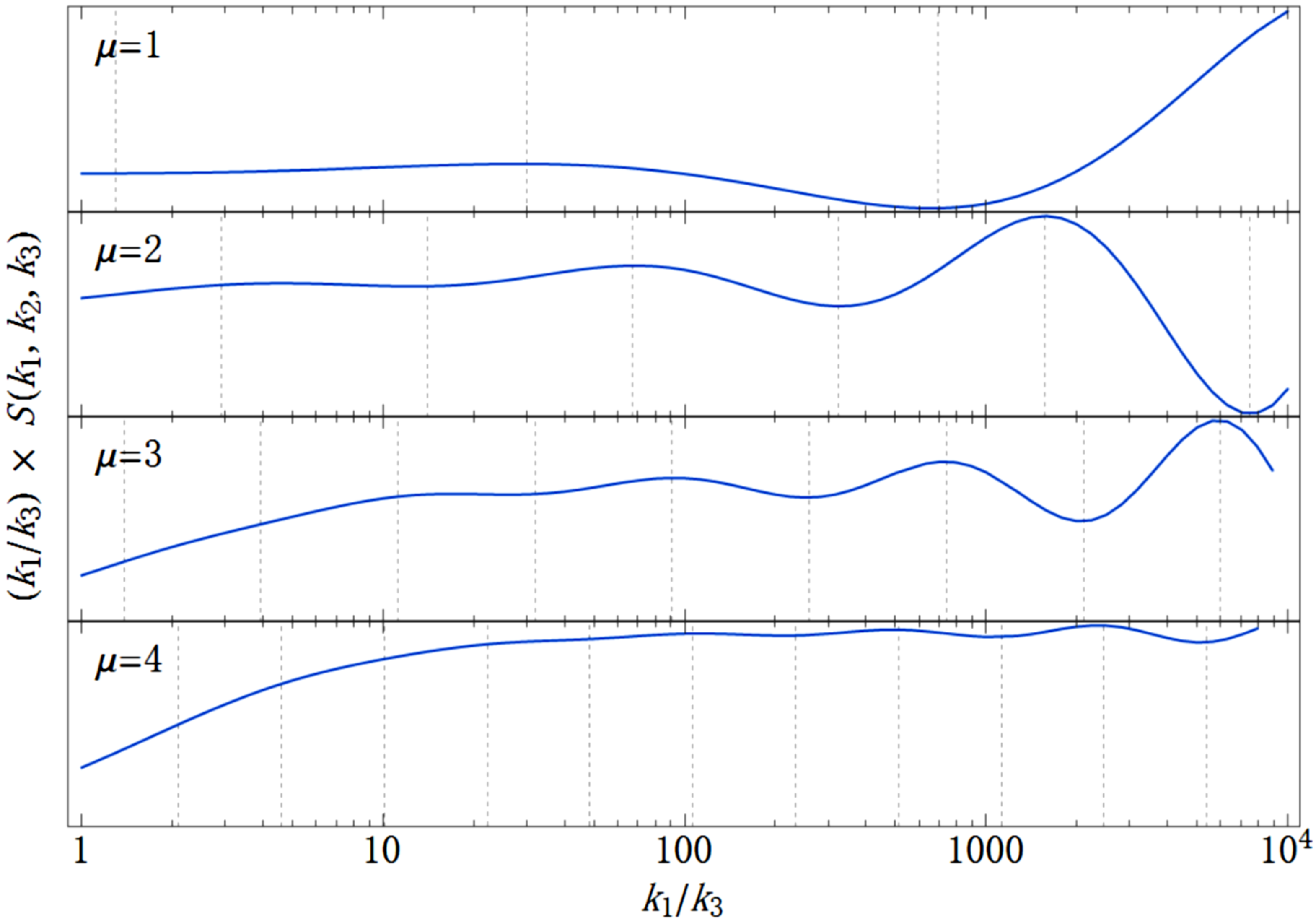




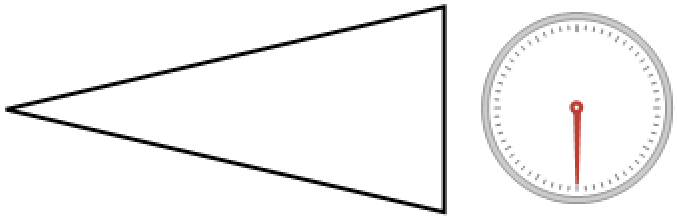
$$\mu = \sqrt{\frac{m^2}{H^2} - \frac{9}{4}}$$

$$\frac{\langle\zeta\zeta\zeta\rangle}{\langle\zeta\zeta\rangle_{\rm short}\langle\zeta\zeta\rangle_{\rm long}} \sim \epsilon e^{-\pi\mu}|c(\mu)| \left[e^{i\delta(\mu)} \left(\frac{k_{\rm long}}{k_{\rm short}}\right)^{\frac{3}{2}+i\mu} + e^{-i\delta(\mu)} \left(\frac{k_{\rm long}}{k_{\rm short}}\right)^{\frac{3}{2}-i\mu} \right] P_s(\cos\theta)$$

Arkani-Hamed, Maldacena 15

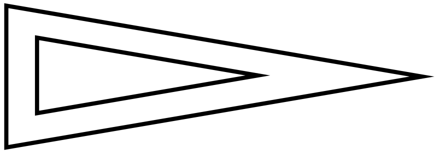


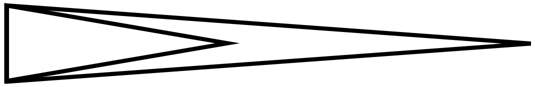
μ=1
μ=2
μ=3
μ=4
$(k_1/k_3) \times S(k_1, k_2, k_3)$
1
10
100
1000
10^4
k_1/k_3



Correlation between the density fluctuation and a clock

Observational consequence:

scale-independent 

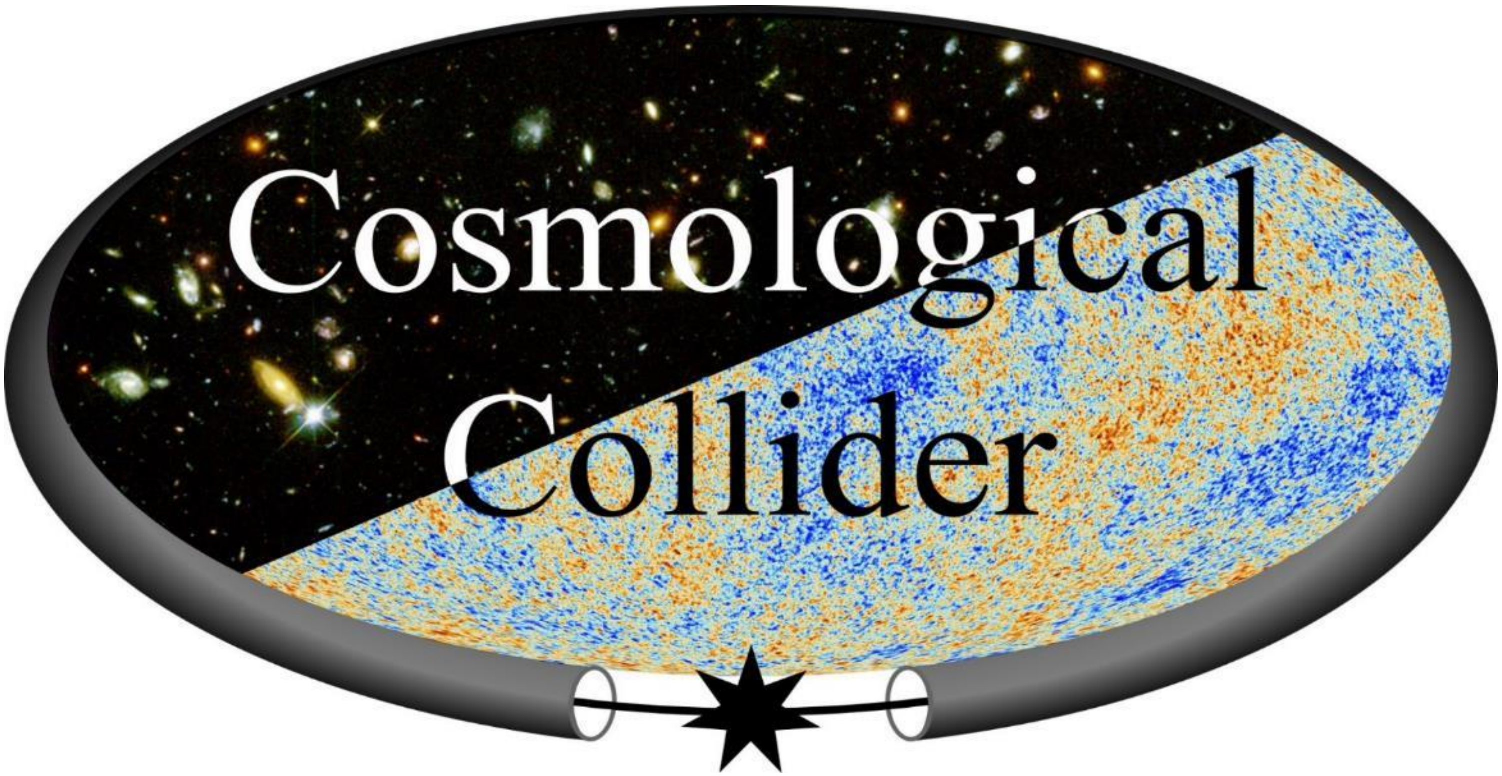
shape-dependent 

oscillations on shape of non-Gaussianities

The Precision Era of Non-Gaussianity

Era	Pre-Planck	Post-Planck
Observable	CMB	LSS
NonG size	$f_{NL} > \mathrm{O}(1)$	$f_{NL} < \mathrm{O}(1)$
Physics	Curvaton, EFT, …	Massive states
Interest	External particles	Internal particles
Toolkit	In-in formalism	+ EdS, O_{12}, nEFT, …

Standard Model background of the



X. Chen, YW, Z. Z. Xianyu

SM background contains two questions:

1. Mass spectrum of the SM particles
2. Their contributions to $\langle\, \zeta_{\mathbf{k}_1}\, \zeta_{\mathbf{k}_2} \ldots \zeta_{\mathbf{k}_n} \,\rangle$

How to extract mass of SM particles?

Aren't they known already?

For example, $M_h = 125\mathrm{GeV}$?

During inflation, roughly:

$h \sim T \sim H, \qquad \lambda h^4 \supset \lambda\langle h^2\rangle h^2, \qquad m_{\rm eff}^2 \sim \lambda\langle h^2\rangle$

Similarly for W, Z. However,

(curvature radius) $\sim T \sim H$,

thus flat space thermal field theory is not enough.

How to extract mass of SM particles?

We extract the SM mass spectrum

from cosmological correlation functions,

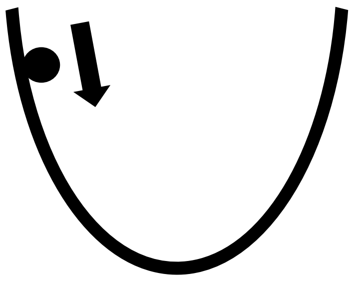
calculated using in-in formalism.

How to extract mass of SM particles?

Method 1:

calculate IR growth

+ DRG resummation



rolling speed

time dependence in the IR

2pt ~ $(-\tau)^s$

$s = \frac{2m^2}{3H^2}$ (from tree level)

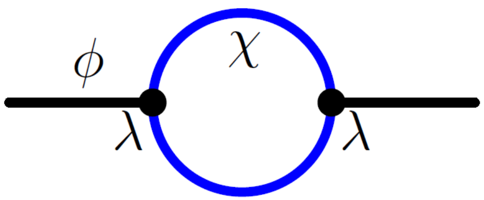
s calculable for loop (and DRG)

Then mass obtained.

How to extract mass of SM particles?

Method 2: mass renormalization on a sphere

Example:



on a sphere (EdS)

$$S_{\rm toy} = -\frac{1}{2}\int \mathrm{d}^D x\,\sqrt{-g}\Big[(\partial_\mu\phi)^2 + (\partial_\mu\chi)^2 + M_\phi^2\phi^2 + M_\chi^2\chi^2 + \lambda\phi\chi^2\Big]$$

mass renormalization ~ $\frac{\lambda^2\mu_R^{4-D}}{2}\int \mathrm{d}\Omega\mathrm{d}\Omega'\phi(x)\phi(x')G_\chi(x,x')^2$

can set $\phi =$ constant

$$\frac{\lambda^2 \mu_R^{4-D}}{2} \int \mathrm{d}\Omega \mathrm{d}\Omega' \phi(x)\phi(x') G_\chi(x,x')^2$$

$$= \frac{\lambda^2 \mu_R^{4-D} H^{2D-4}}{2} \int \mathrm{d}\Omega \mathrm{d}\Omega' \sum_{\vec{L},\vec{M}} \frac{1}{\lambda_L \lambda_M} Y_{\vec{L}}(x) Y^*_{\vec{L}}(x') Y^*_{\vec{M}}(x) Y_{\vec{M}}(x')$$

$$= \frac{\lambda^2 \mu_R^{4-D} H^{D-4}}{2} \int \mathrm{d}\Omega \sum_{\vec{L}} \frac{1}{\lambda_L^2} Y_{\vec{L}}(x) Y^*_{\vec{L}}(x)$$

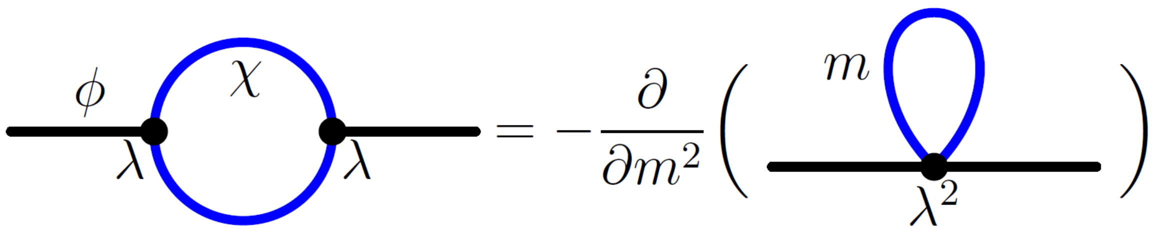
$$= -\frac{\lambda^2 \mu_R^{4-D} H^{D-2}}{2} \frac{\partial}{\partial m^2} \int \mathrm{d}\Omega \sum_{\vec{L}} \frac{1}{\lambda_L} Y_{\vec{L}}(x) Y^*_{\vec{L}}(x)$$

$$= -\frac{\lambda^2 \mu_R^{4-D}}{2} \left[\partial_{m^2} G(x,x)\right]_{m^2 = M_\chi^2} \int \mathrm{d}\Omega,$$

$$\lambda_L = (L + d/2 + \mu)(L + d/2 - \mu)$$

$$\mu = \sqrt{(d/2)^2 - (m/H)^2}$$

Thus



$$\delta M_\phi^2 = \frac{3\lambda^2 H^4}{8\pi^2 M_\chi^2} + \mathcal{O}(M_\chi^0)$$

How to extract mass of SM particles?

Method 3: for Higgs only – non-perturbative PI

$$S \supset -\int \mathrm{d}^4x\sqrt{-g}\Big[f_H(X,\phi)\mathbf{H}^\dagger\mathbf{H} + f_{DH}(X,\phi)|\mathrm{D}_\nu\mathbf{H}|^2 - \int \mathrm{d}^4x\sqrt{-g}\xi R\mathbf{H}^\dagger\mathbf{H}$$

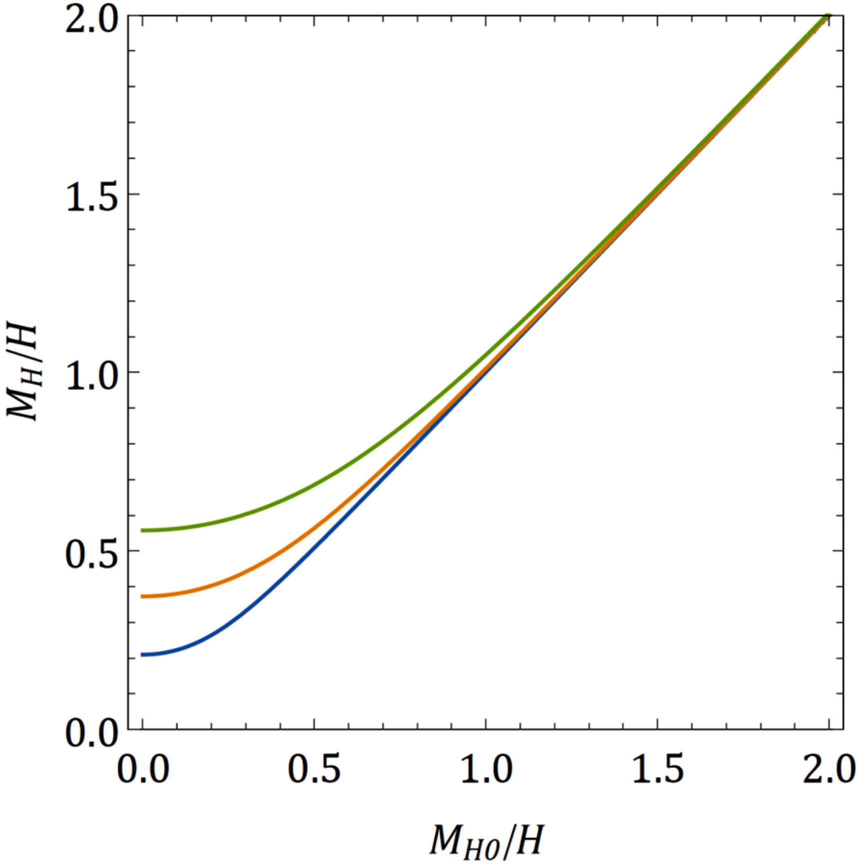
$$M_{H0}^2 = \frac{12\xi H^2 + f_H(X_0,\phi_0)}{1 + f_{DH}(X_0,\phi_0)}$$

$$\langle h^2\rangle \equiv \frac{\int \mathrm{d}^{\mathcal{N}}h\, h^2 \exp[-V_D(m_0^2h^2/2 + \lambda h^4/4)]}{\int \mathrm{d}^{\mathcal{N}}h\, \exp[-V_D(m_0^2h^2/2 + \lambda h^4/4)]}$$
$$= \frac{2}{\sqrt{V_D\lambda}}\frac{{}_1\widetilde{F}_1\left(\frac{\mathcal{N}+2}{4};\frac{1}{2};z^2\right) - z\,{}_1\widetilde{F}_1\left(\frac{\mathcal{N}+4}{4};\frac{3}{2};z^2\right)}{{}_1\widetilde{F}_1\left(\frac{\mathcal{N}}{4};\frac{1}{2};z^2\right) - z\,{}_1\widetilde{F}_1\left(\frac{\mathcal{N}+2}{4};\frac{3}{2};z^2\right)}$$

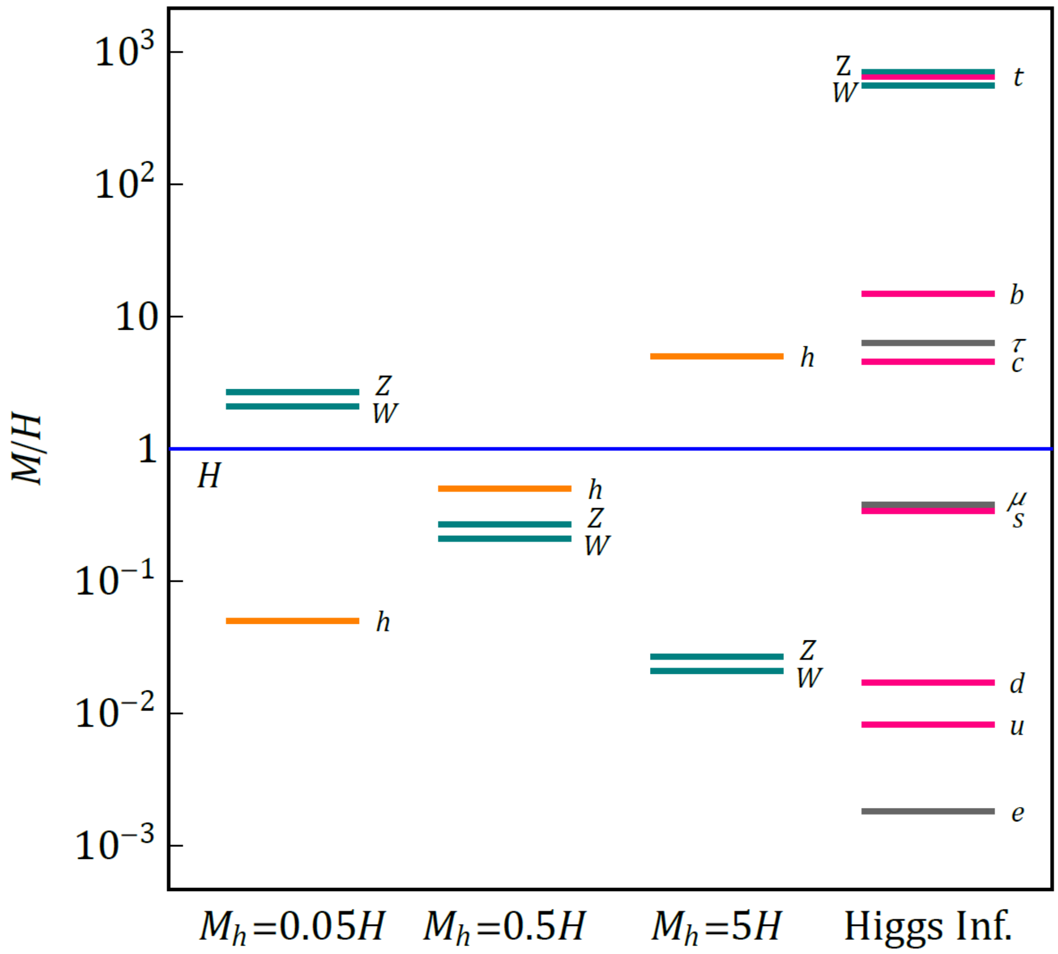
$$M_H^2 = \sqrt{\frac{\lambda}{V_D}}\frac{4\left[1-\sqrt{\pi}ze^{z^2}\mathrm{Erfc}(z)\right]}{-2z+\sqrt{\pi}(1+2z^2)e^{z^2}\mathrm{Erfc}(z)} \qquad z \equiv \tfrac{1}{2}m_0^2\sqrt{V_D/\lambda}$$

For $z = 0$: $M_H^2 = \sqrt{\frac{6\lambda}{\pi^3}}H^2$

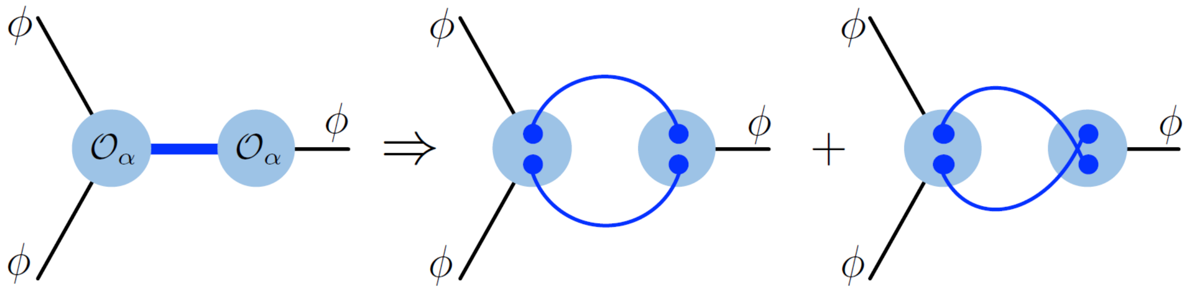
The Higgs mass: tree vs quantum-corrected



The full SM spectrum depending on inflation models



3pt based on the SM mass spectrum



$$
\begin{aligned}
&\left\langle \delta\phi(\mathbf{k}_1)\delta\phi(\mathbf{k}_2)\delta\phi(\mathbf{k}_3)\right\rangle'_\alpha \\
&= 4 f_\alpha'^2(X_0) \sum_{a,b=\pm} ab \int_{-\infty}^{0} \frac{\mathrm{d}\tau'}{(H\tau')^2} \int_{-\infty}^{0} \frac{\mathrm{d}\tau''}{(H\tau'')^2} \Big[-\partial_{\tau''} G_{+b}(\mathbf{k}_3,\tau,\tau'')\partial_{\tau''}\phi_0 \Big] \\
&\quad \times \Big[-\partial_{\tau'} G_{+a}(\mathbf{k}_1,\tau,\tau')\partial_{\tau'} G_{+a}(\mathbf{k}_2,\tau,\tau') - \mathbf{k}_1\cdot\mathbf{k}_2 G_{+a}(\mathbf{k}_1,\tau,\tau') G_{+a}(\mathbf{k}_2,\tau,\tau') \Big] \\
&\quad \times \int \mathrm{d}^3 X\, e^{-\mathrm{i}\mathbf{k}_I\cdot\mathbf{X}} \Big\langle \mathcal{O}_\alpha(\tau',\mathbf{x}')\mathcal{O}_\alpha(\tau'',\mathbf{x}'') \Big\rangle_{ab}
\end{aligned}
$$

No UV divergence in the non-local part of loop.

$$S_H = \frac{f_H'^2(X_0)\dot{\phi}_0^2}{\pi^4}\left[C_H(\mu_h)\left(\frac{k_L}{2k_S}\right)^{2-2\mu_h} + (\mu_h \to -\mu_h)\right],$$

$$S_{DH} = \frac{f_{DH}'^2(X_0)H^4\dot{\phi}_0^2}{4\pi^4}\left[C_{H4}(\mu_h)\left(\frac{k_L}{2k_S}\right)^{2-2\mu_h} + (\mu_h \to -\mu_h)\right],$$

$$S_\Psi = \frac{f_\Psi'^2(X_0)H^4\dot{\phi}_0^2\mu_{1/2}^6}{2\pi^4}\left[C_\Phi(\mu_{1/2})\left(\frac{k_L}{k_S}\right)^{1+2\mathrm{i}\mu_{1/2}} + \text{c.c.}\right],$$

$$S_A = \frac{27f_A'^2(X_0)H^8\dot{\phi}_0^2}{16\pi^4M_A^4}\left[C_A(\mu_1)\left(\frac{k_L}{2k_S}\right)^{2-2\mu_1} + (\mu_1 \to -\mu_1)\right].$$

SM spectra is affected by coupling to inflaton.

e.g. gauge sector is affected by the following:

$$S \supset -\int \mathrm{d}^4x\sqrt{-g}\left[f_{DH}(X,\phi)|\mathrm{D}_\mu \mathbf{H}|^2 + \frac{1}{4}f_W(X,\phi)W^a_{\mu\nu}W^{\mu\nu a} + \frac{1}{4}f_B(X,\phi)B_{\mu\nu}B^{\mu\nu} + \cdots\right].$$

$$g^2 = \frac{g^2_{\mathrm{SM}}}{1+f_W(X_0,\phi_0)},$$

$$g'^2 = \frac{g'^2_{\mathrm{SM}}}{1+f_B(X_0,\phi_0)}.$$

$$M_W^2 = \frac{3g^2H^4}{8\pi^2 M_H^2}, \quad M_Z^2 = \frac{3g^2H^4}{8\pi^2 M_H^2\cos^2\theta_W}$$

SM spectra is affected by coupling to inflaton.

But still we can make predictions:

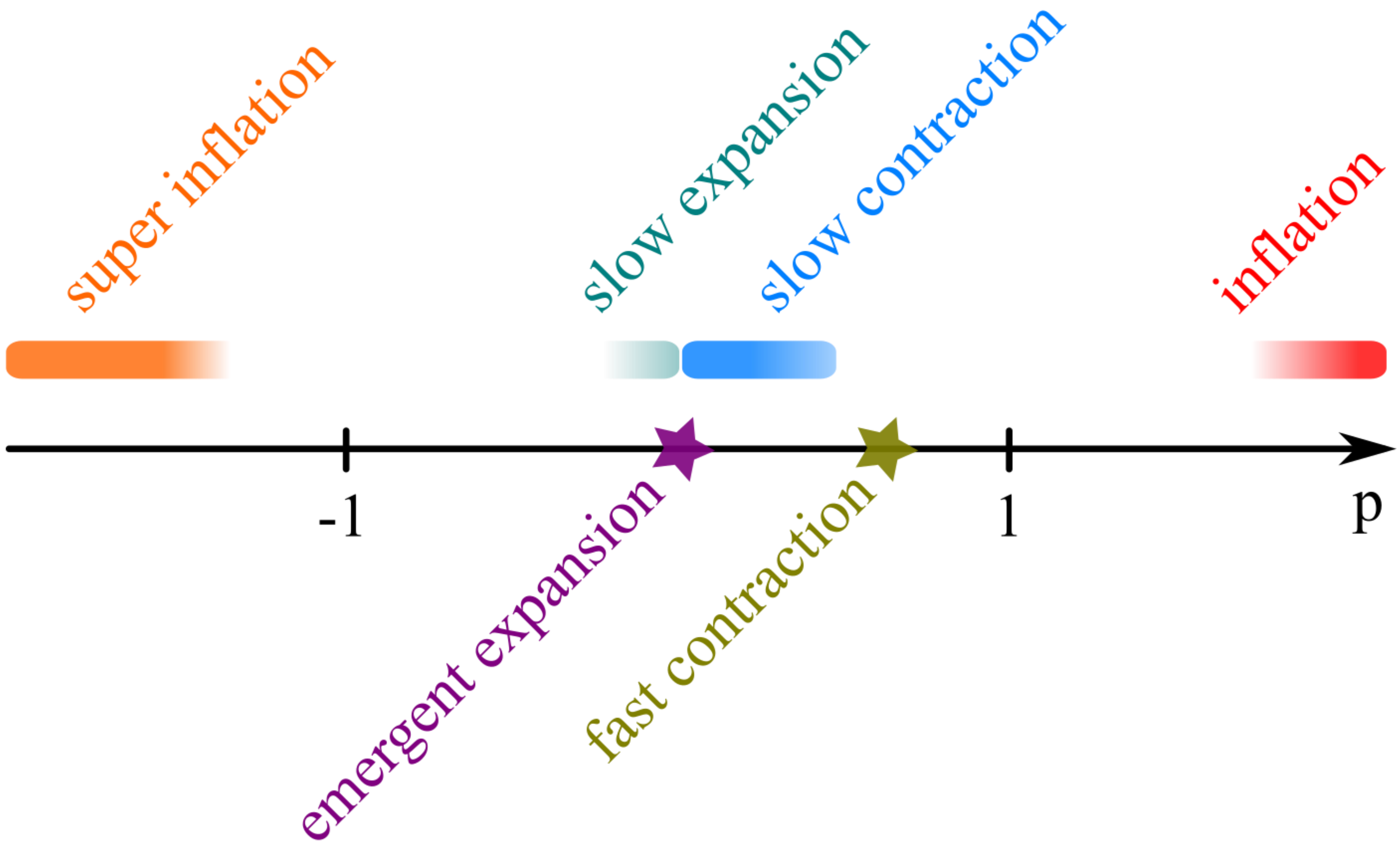
$$\frac{d\ln\tan^2\theta_W}{d\ln k} = \frac{\pi(\eta - 2\epsilon)}{3\sqrt{3P_\zeta}\sin^2\theta_W}\left[\frac{M_W^2}{H^2}\sqrt{\frac{f_{NL}^W}{N_W|C_A(\mu_W)|}} - \frac{M_Z^2}{H^2}\sqrt{\frac{f_{NL}^Z}{N_Z|C_A(\mu_Z)|}}\right]$$

Predictions for BSM physics on the cosmological collider?

Expansion History of the Primordial Universe

X. Chen, M. H. Namjoo, YW 2015/16

Possibilities: $a = t^p$



Inflation is the most natural paradigm.

But alternative scenarios are also being studied.

Nice to distinguish those scenarios observationally.

The question is equivalent to --

How to measure the evolution history of the primordial universe?

It is a difficult job.

There is no structure in the primordial universe.

Only 10^{-5} fluctuations, quantum to classical.

How to measure the evolution history of the primordial universe?

1. Primordial gravitational waves (GWs)

2. Quantum Primordial Standard Clocks (massive fields)

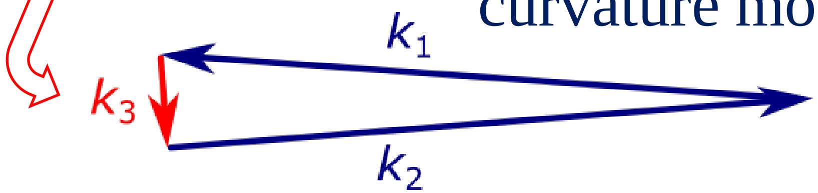
Quantum Primordial Standard Clock

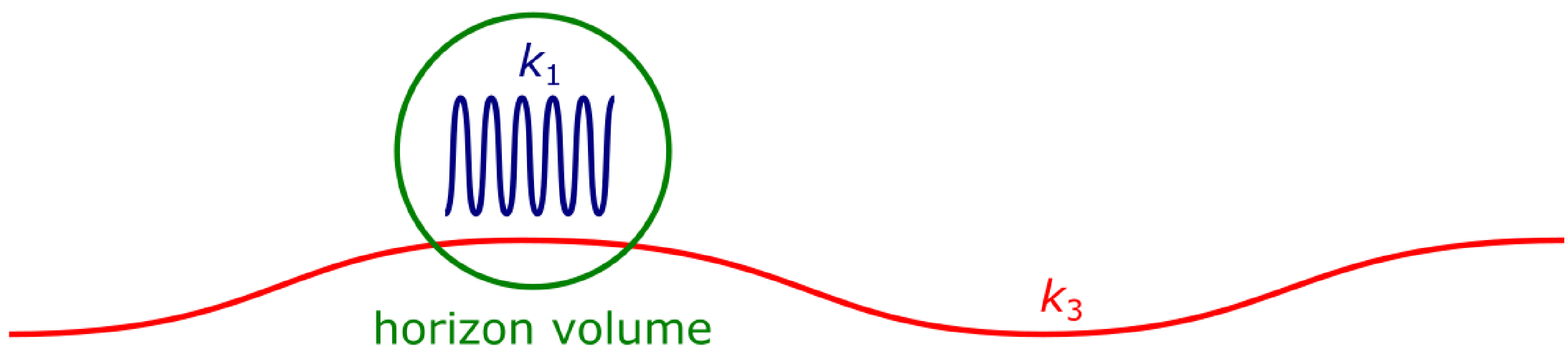
$\langle \zeta^3 \rangle$

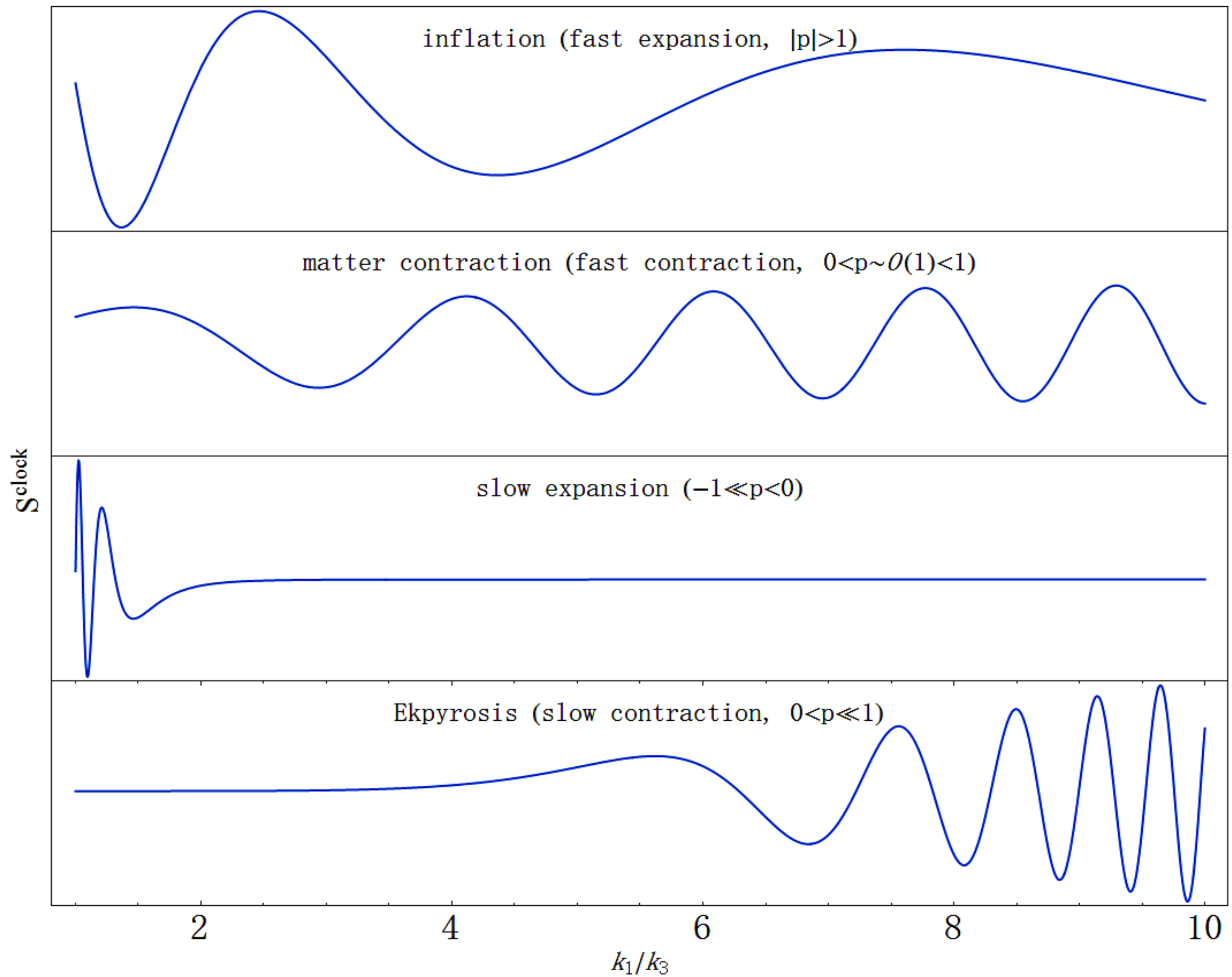
$$a(t) = a_0 \left(\frac{t}{t_0} \right)^p$$

massive → curvature, tells physical time

curvature mode, tells conformal time at $k\tau = \frac{M}{H}$







inflation (fast expansion, |p|>1)
matter contraction (fast contraction, 0<p~O(1)<1)
slow expansion (−1≪p<0)
Ekpyrosis (slow contraction, 0<p≪1)
S^clock
2
4
6
8
10
k1/k3

Summary: massive fields during inflation

Cosmological collider:

SM studied

BSM? Strings? Black holes?

Quantum primordial standard clock

Probing the expansion history

Thank you!