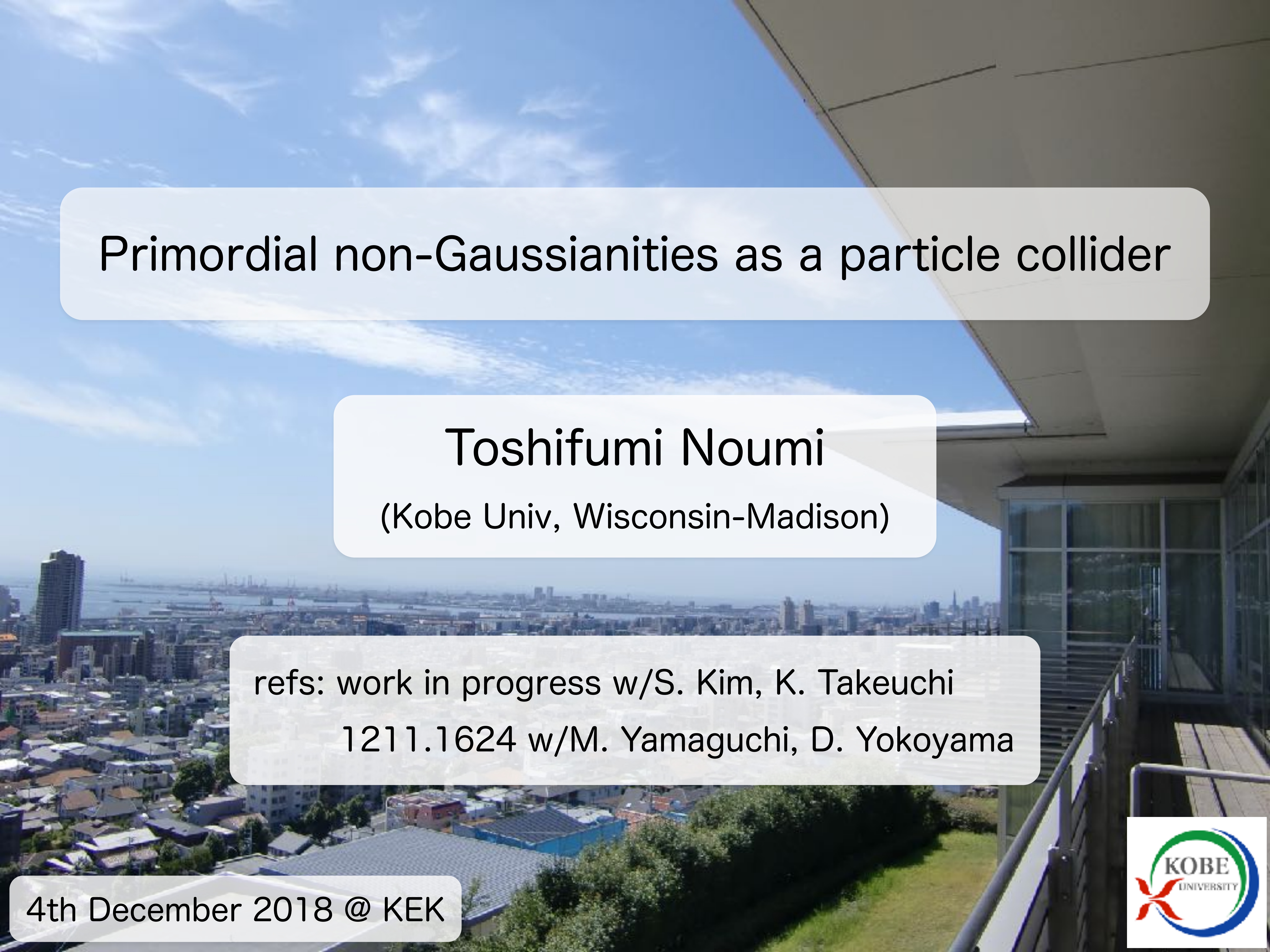


Primordial non-Gaussianities as a particle collider

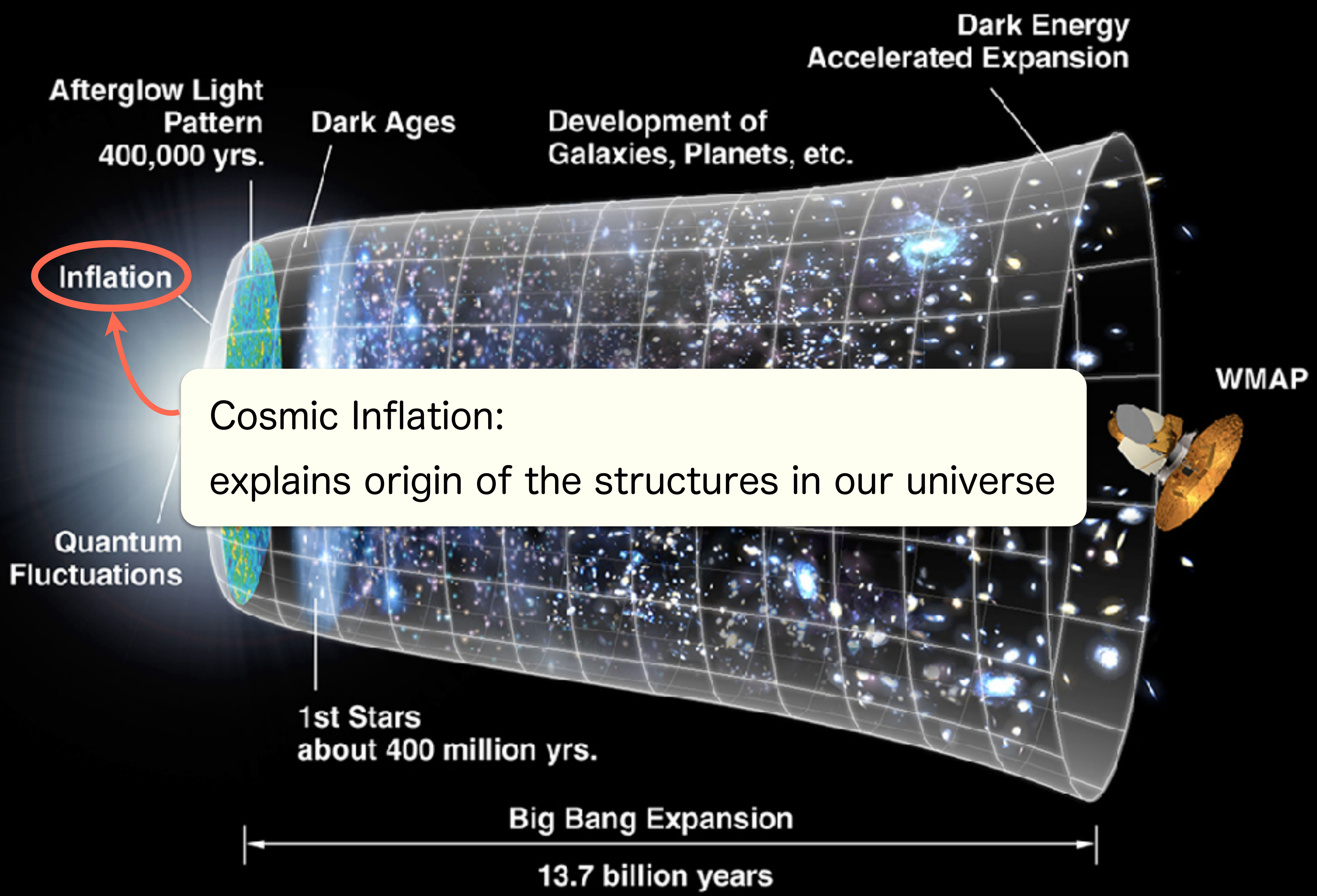
Toshifumi Noumi

(Kobe Univ, Wisconsin-Madison)

refs: work in progress w/S. Kim, K. Takeuchi

1211.1624 w/M. Yamaguchi, D. Yokoyama

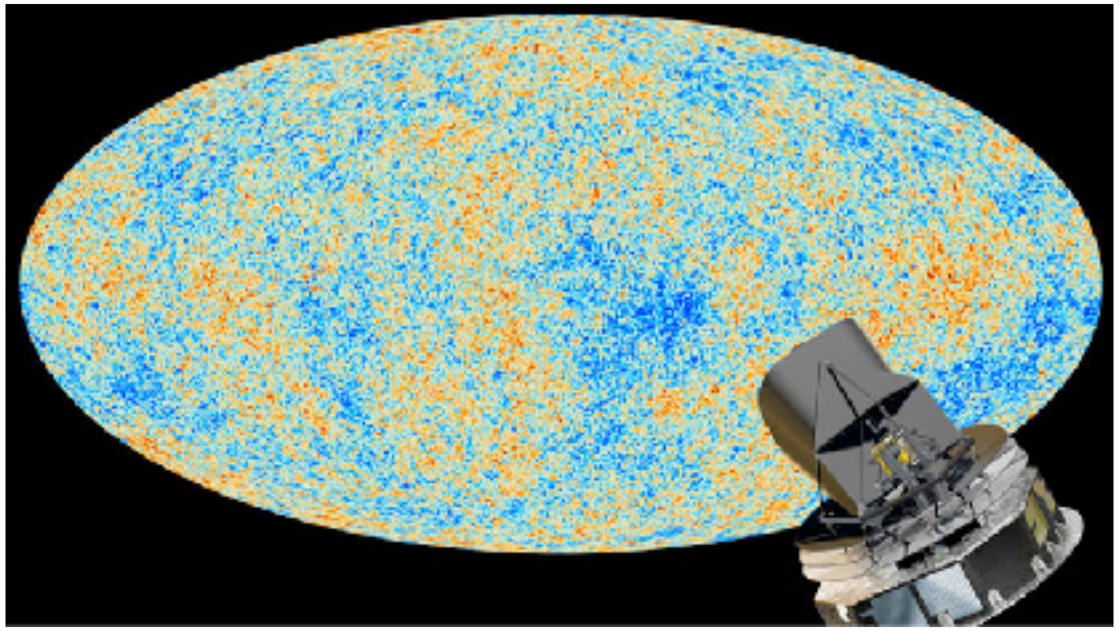
4th December 2018 @ KEK



Cosmic Inflation:

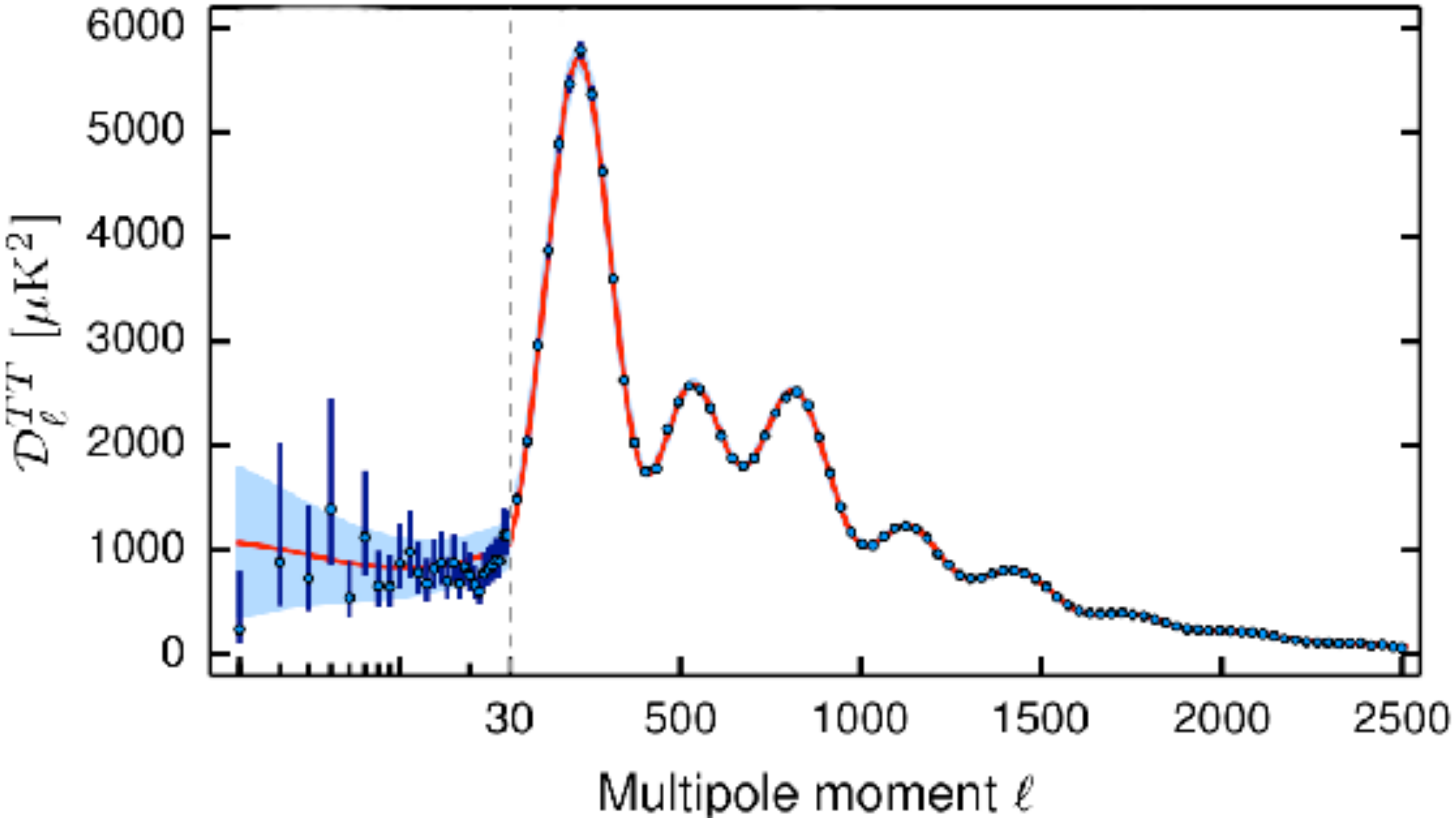
explains origin of the structures in our universe

We are in the Era of Precision Cosmology!



Cosmic Microwave Backgrounds

by Planck

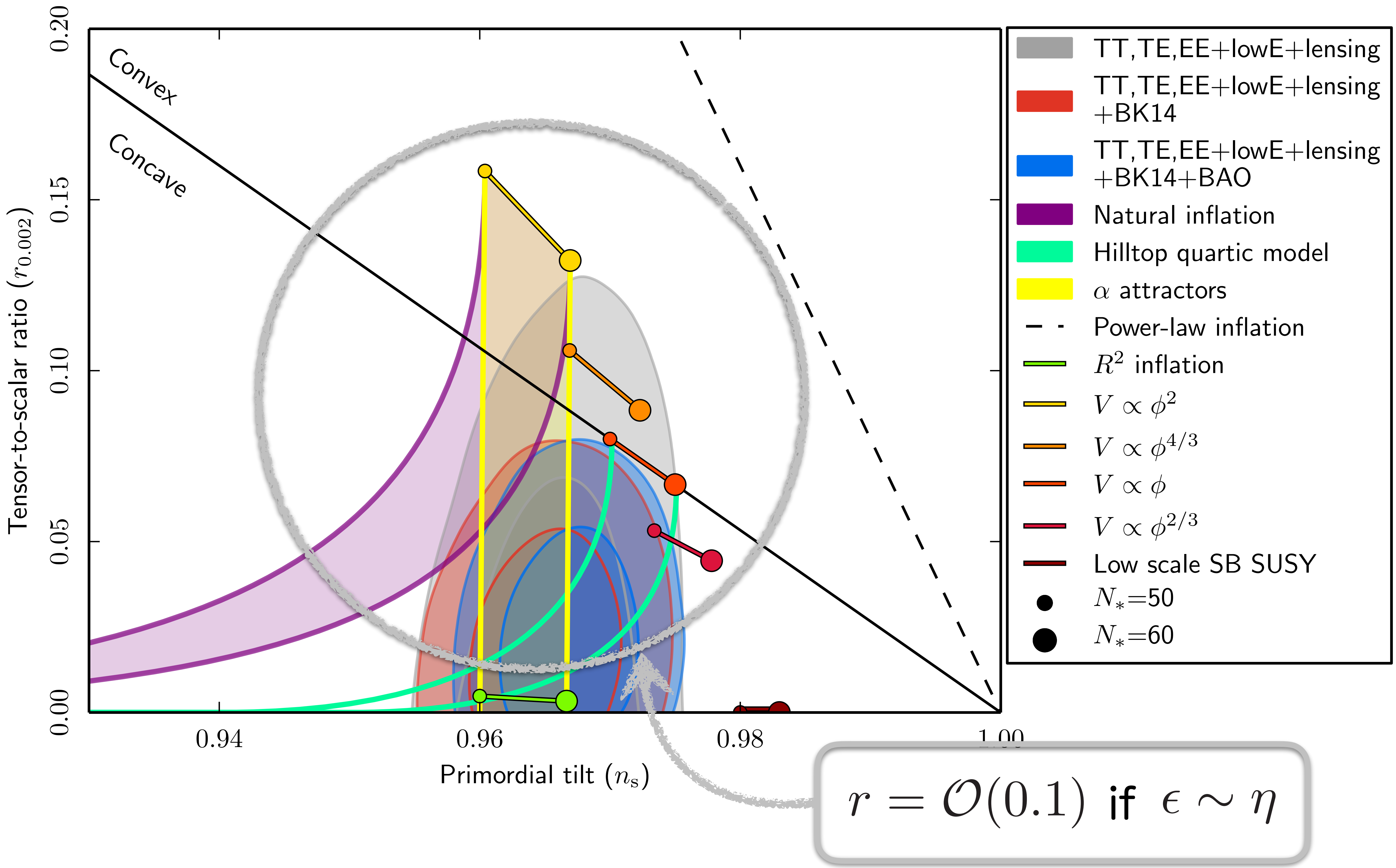


Standard Cosmology + Inflation as an initial condition:

strongly supported by observations such as CMB

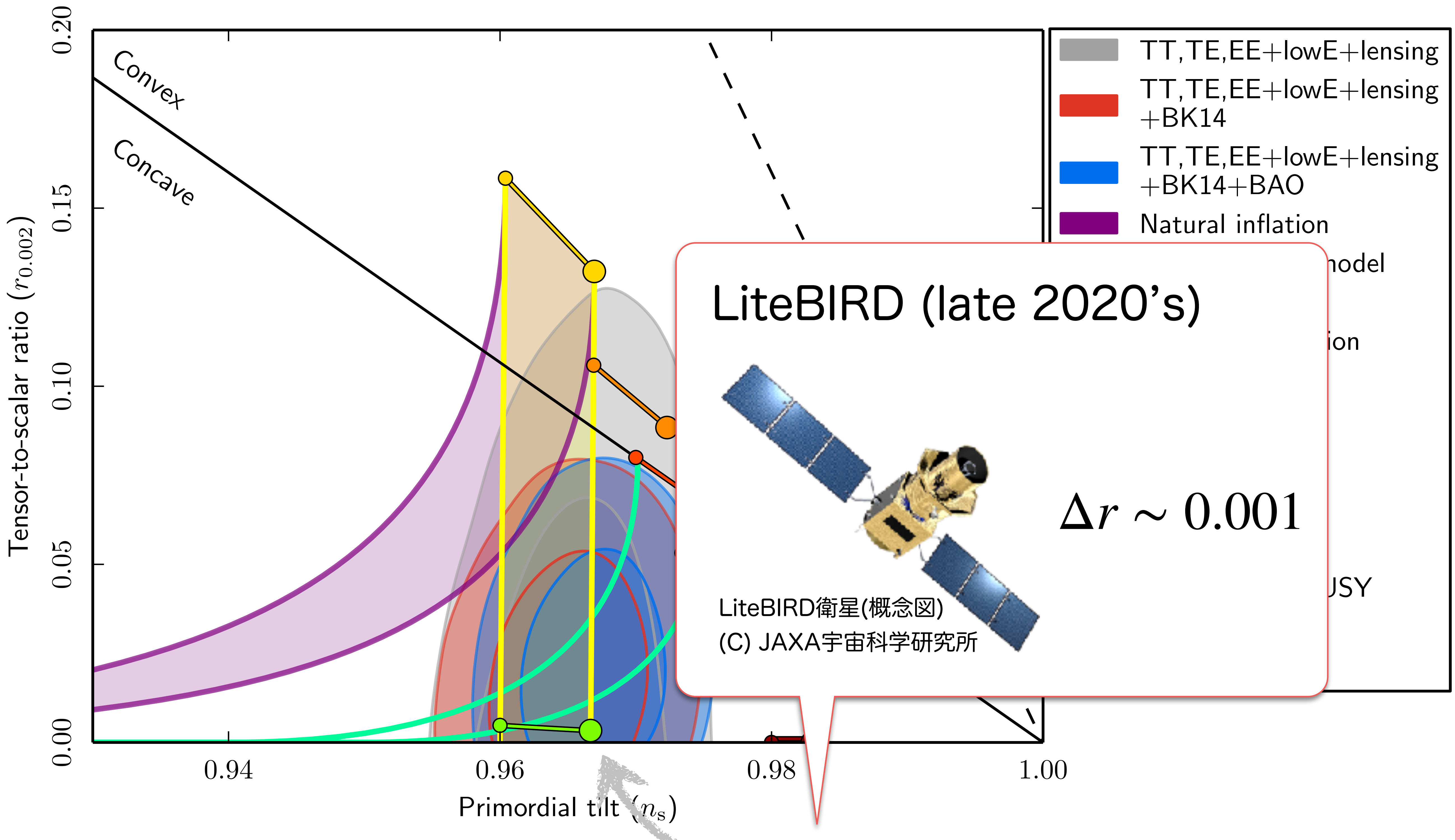
→ precision test of inflationary models!

typical tensor-to-scalar ratios



$r = \mathcal{O}(0.1)$ if $\epsilon \sim \eta$

typical tensor-to-scalar ratios



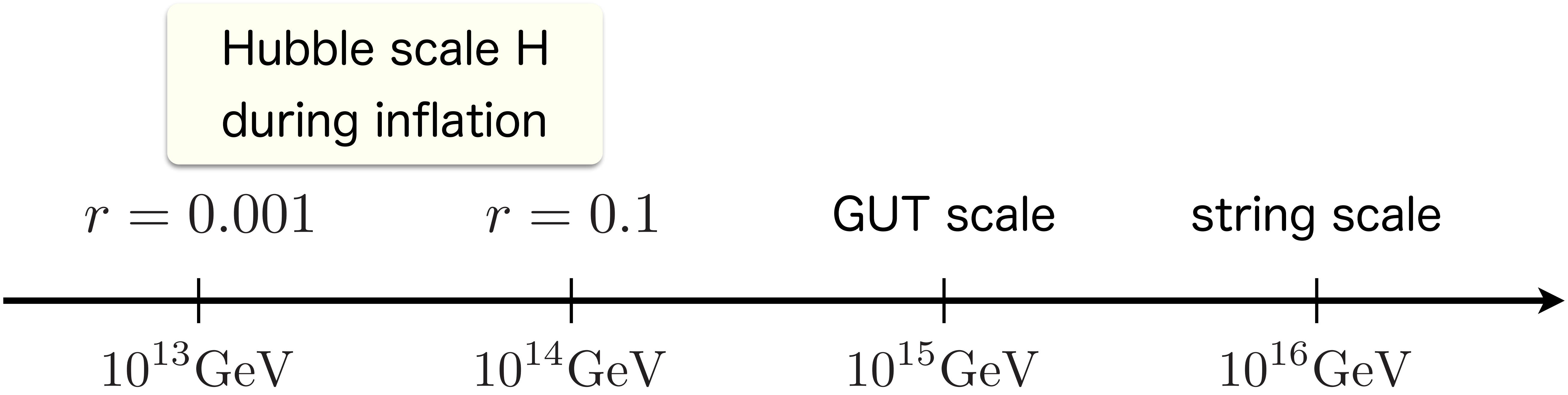
LiteBIRD (late 2020's)

$\Delta r \sim 0.001$

LiteBIRD衛星(概念図)
(C) JAXA宇宙科学研究所

$r \simeq 0.003$

energy scale of inflation: $H \lesssim 10^{14}$ GeV



Hubble scale H during inflation

$r = 0.001$ — $10^{13}\mathrm{GeV}$

$r = 0.1$ — $10^{14}\mathrm{GeV}$

GUT scale — $10^{15}\mathrm{GeV}$

string scale — $10^{16}\mathrm{GeV}$

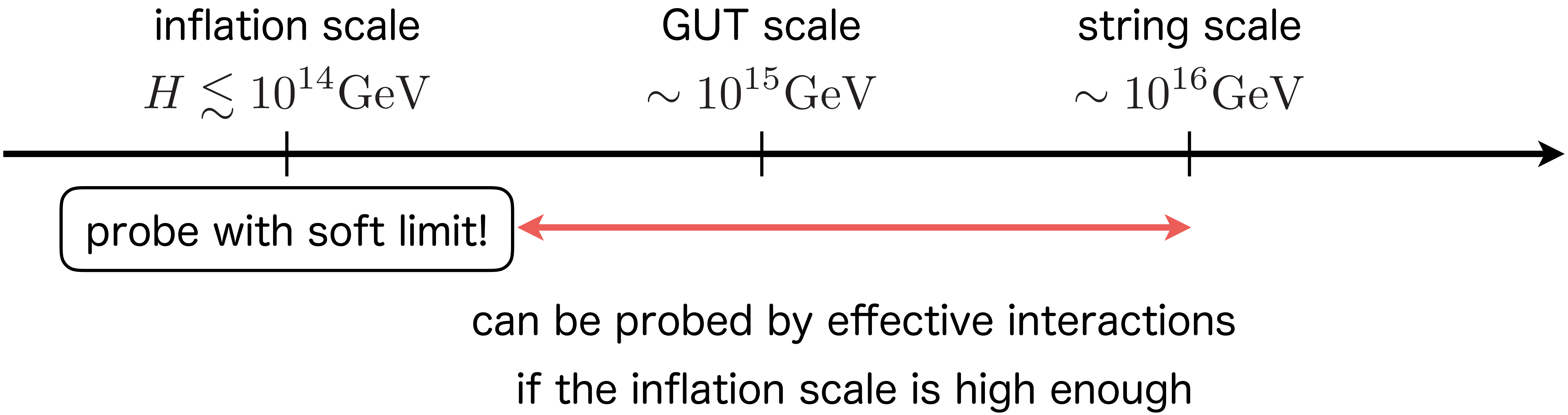
The highest energy scale we may explore!

Q. Can we probe new particles?

A. Yes, just like particle colliders!

Main message:

primordial non-Gaussianities = 10^{14} GeV collider



inflation scale

$H \lesssim 10^{14}\mathrm{GeV}$

GUT scale

$\sim 10^{15}\mathrm{GeV}$

string scale

$\sim 10^{16}\mathrm{GeV}$

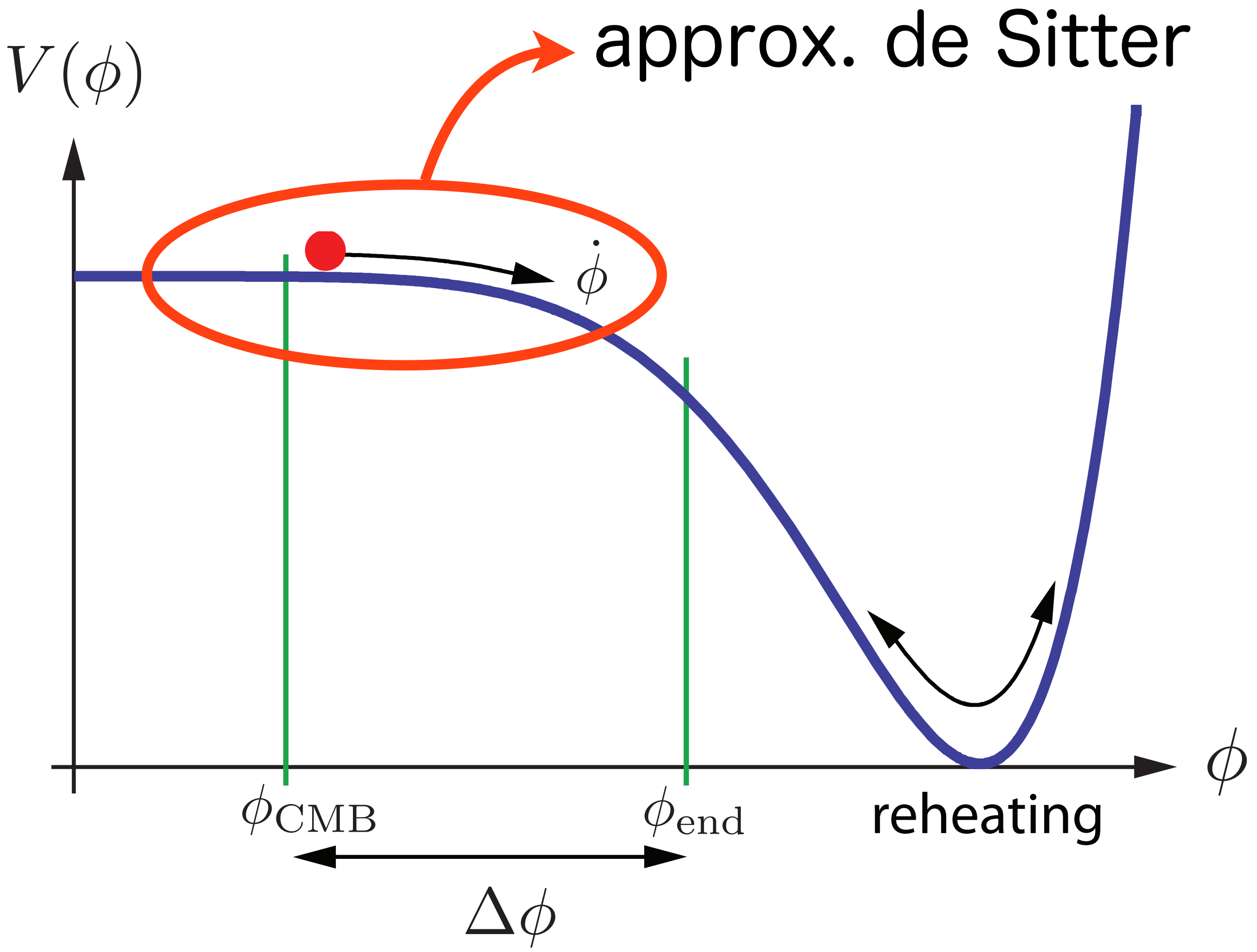
probe with soft limit!

can be probed by effective interactions

if the inflation scale is high enough

1. Inflation fluctuations = NG boson

slow-roll inflation



- FRW spacetime

$$ds^2 = -dt^2 + a(t)^2 d\vec{x}^2$$

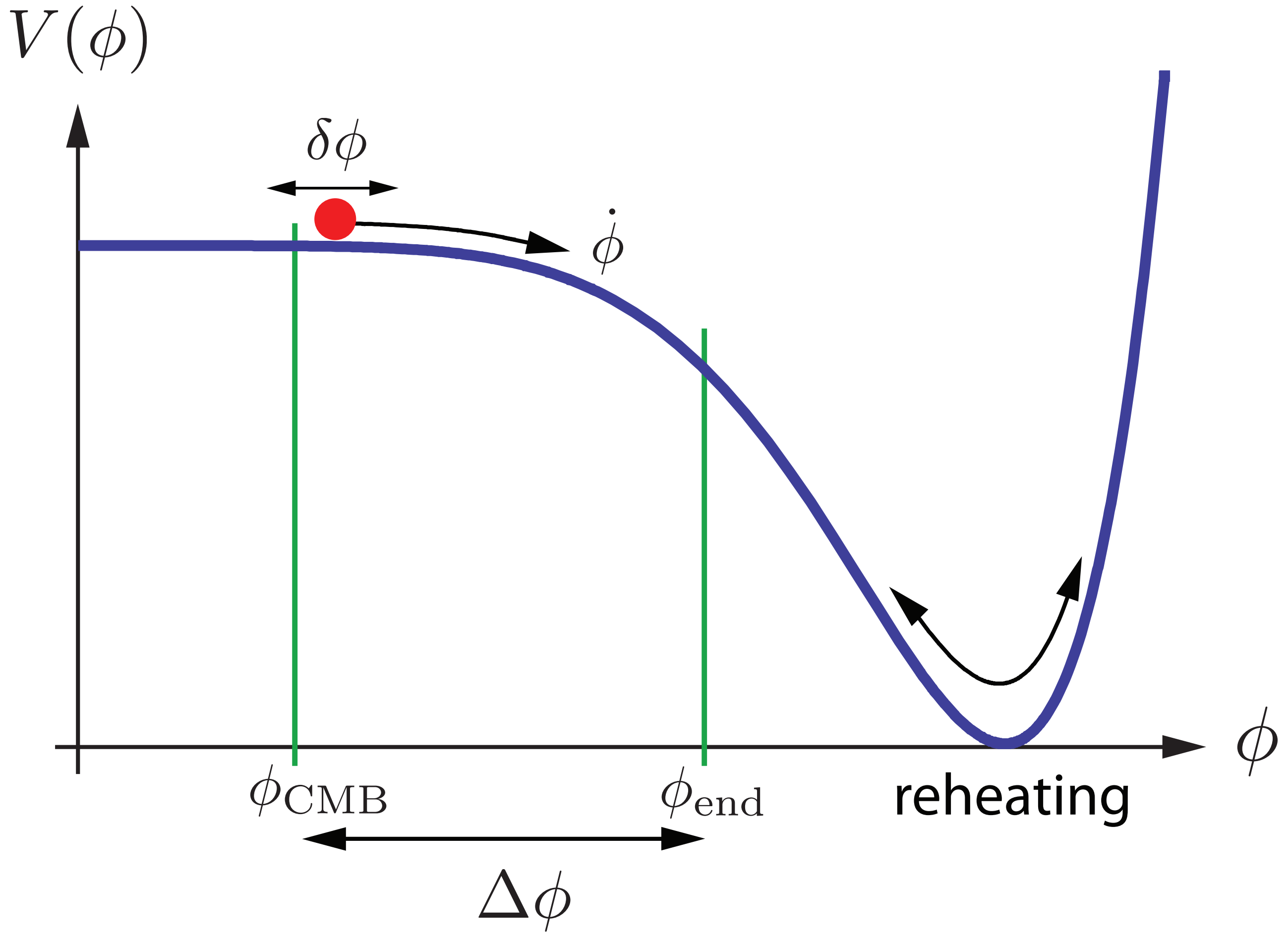
- Hubble parameter: $H(t) = \dfrac{\dot{a}}{a}$

introduce an inflaton field ϕ with $\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$

※ approx. de Sitter is realized by the potential $V(\phi)$

slow-roll condition: $\epsilon = -\dfrac{\dot{H}}{H^2} \ll 1 \quad \eta = \dfrac{\dot{\epsilon}}{\epsilon H} \ll 1$

slow-roll inflation



inflaton fluctuations

॥

fluctuations of cosmic history

$\delta\phi > 0$: more time evolved

$\delta\phi < 0$: less time evolved

introduce an inflaton field ϕ with $\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi)$

※ approx. de Sitter is realized by the potential $V(\phi)$

slow-roll condition: $\epsilon = -\frac{\dot{H}}{H^2} \ll 1 \quad \eta = \frac{\dot{\epsilon}}{\epsilon H} \ll 1$

inflaton fluctuations = time fluctuations

※ look like Nambu-Goldstone bosons

in fact

- inflaton vev $\langle\phi(t,\vec{x})\rangle=\bar{\phi}(t)$ spontaneously breaks

time translational (diffs.) symmetry

- NG boson π may be introduced as

$$\phi(t,\vec{x})=\bar{\phi}(t+\pi(t,\vec{x}))\,, \quad \delta\phi\simeq\dot{\bar{\phi}}(t)\pi(t,\vec{x})$$

quantum fluctuations during inflation

gravitational system w/~~time translation~~

π NG boson

γ_{ij} graviton

these two always exist as light dof

※ origin of structure (ex. CMB temp. fluctuations)

$+$

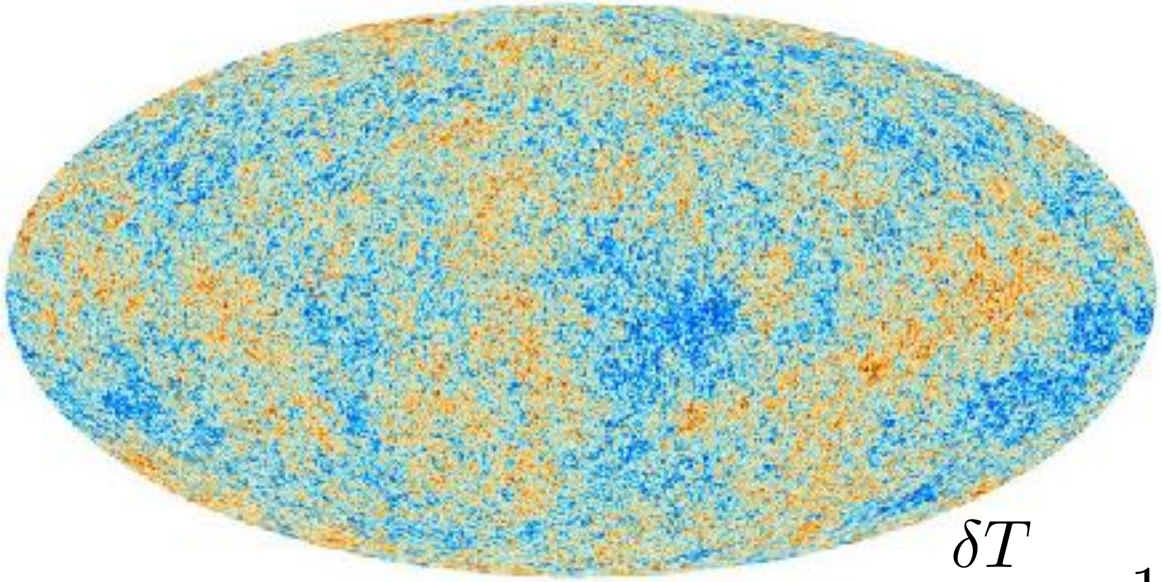
model-dep. (generically heavy) dof

ex. SUSY, extra dim, GUT, string

what we know about this NG boson?

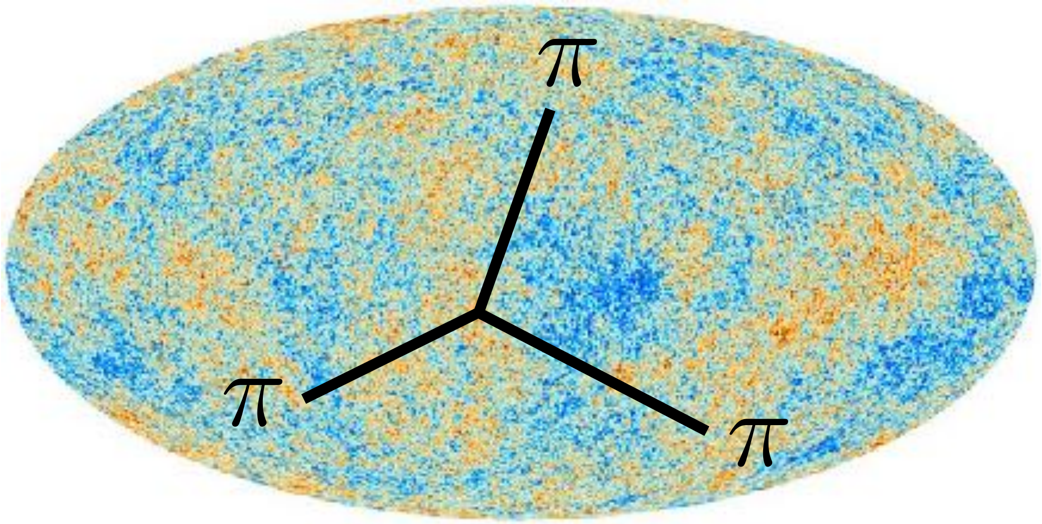
CMB temperature fluctuations are Gaussian

→ NG fluctuations are Gaussian (weakly coupled)



$$\frac{\delta T}{T} \sim 10^{-5}$$

Primordial non-Gaussianities



non-Gaussianities:

3pt and higher point correlations

inflation = 10^{14} GeV collider (Cosmological Collider)

non-Gaussianities directly prove interactions during inflation

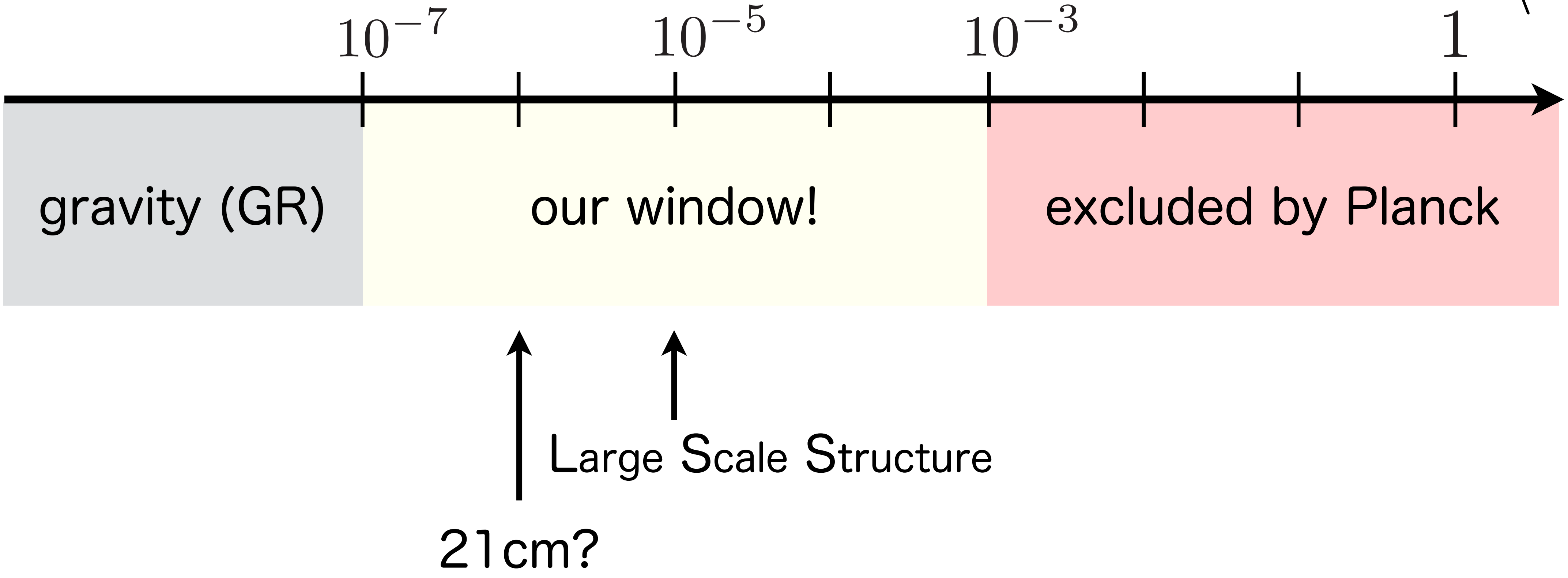
→ probe of new particles at a very high energy scale!!

[Chen-Wang ’10, Baumann-Green ’12, TN-Yamaguchi-Yokoyama ’13, ArkaniHamed-Maldacena ’15, ⋯]

Primordial non-Gaussianities

bounds on NG boson 3pt functions

$$F_{\mathrm{NL}} = \frac{\langle \pi\pi\pi \rangle}{\langle \pi\pi \rangle^{3/2}}$$



gravity (GR)

our window!

excluded by Planck

Large Scale Structure

21cm?

- we already know that they are weakly coupled
- at least we have gravitational interactions
- improvements by 2~3 order are expected

Contents

1. Inflaton fluctuations = NG boson ✓
2. non-Gaussianities = 10^{14} GeV collider
3. Summary and Prospects

2. non-Gaussianities = 10^{14} GeV collider

non-Gaussianities & particle spectrum

(neglect graviton effects in the following)

non-Gaussianities & particle spectrum

Lagrangian of NG boson

$$\mathcal{L}_\pi = M_{\rm Pl}^2 \dot{H} (\partial_\mu \pi)^2$$

↑

order parameter

cf. chiral Lagrangian

$$\mathcal{L} = -\frac{f_\pi^2}{2} \mathrm{tr}\left[\partial_\mu U \partial^\mu U^\dagger\right] \quad \left(U = e^{i\pi_a T^a}\right)$$

※ no self-interaction at the leading order in derivatives

※ observable non-Gaussianities are only though

- interactions with other sectors
- higher derivative terms

→ clean channel to probe new particles!

non-Gaussianities & particle spectrum

ex. interactions with a massive scalar [TN-Yamaguchi-Yokoyama ’13]

NG boson π

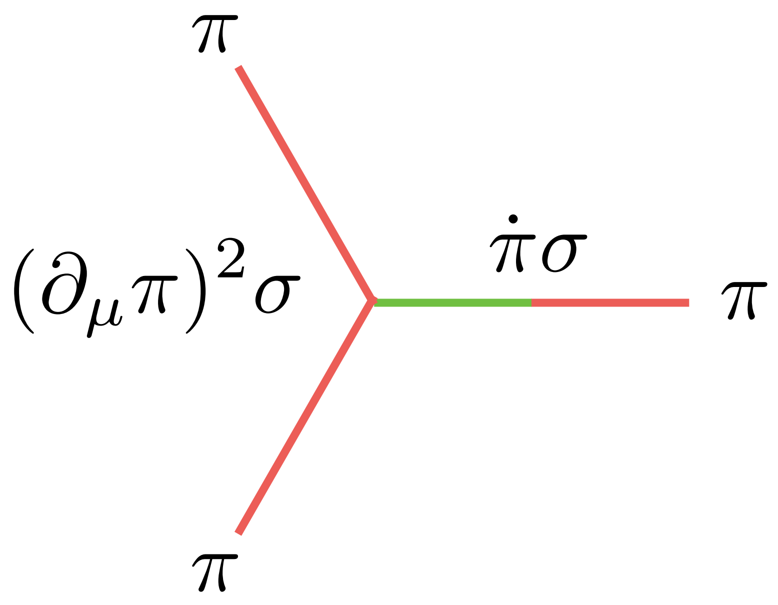
$$\mathcal{L}_\pi = M_{\rm Pl}^2 \dot{H} (\partial_\mu \pi)^2$$

$$\mathcal{L}_{\rm mix} = g_{\rm mix}\, \sigma\, \underline{\left[-2\dot{\pi} + (\partial_\mu \pi)^2\right]}$$

nonlinear realization

massive scalar σ

$$\mathcal{L}_\sigma = -\frac{1}{2}(\partial_\mu \sigma)^2 - \frac{m^2}{2}\sigma^2 - V(\sigma)$$



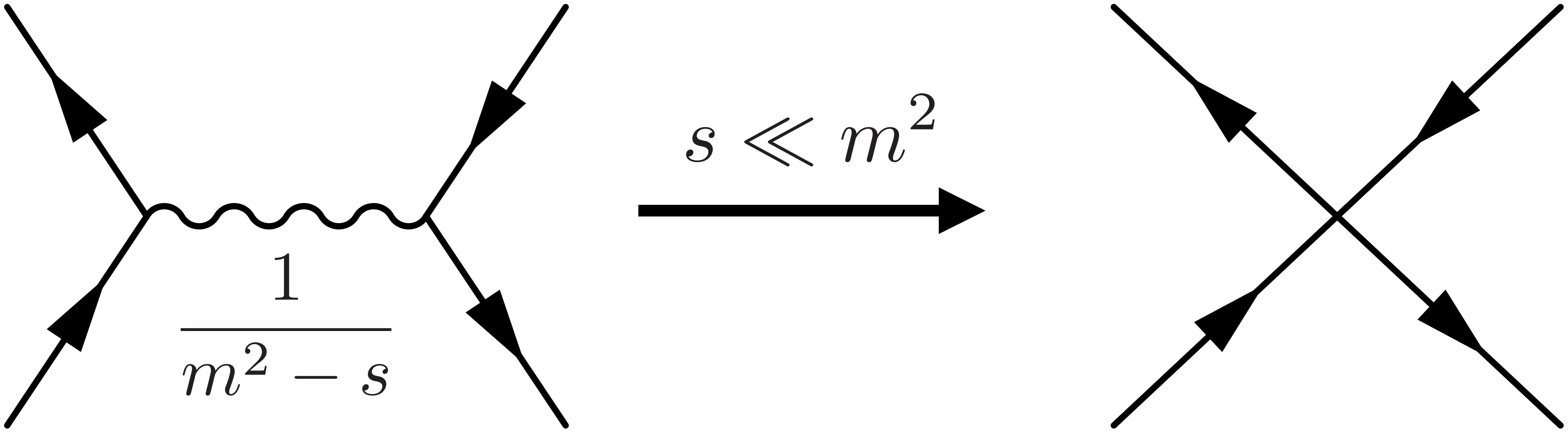
NG boson 3pt function

in the rest of my talk …

- how to detect new particles w/non-G
- up to which scale we may explore

new particles @ collider

new particles @ collider

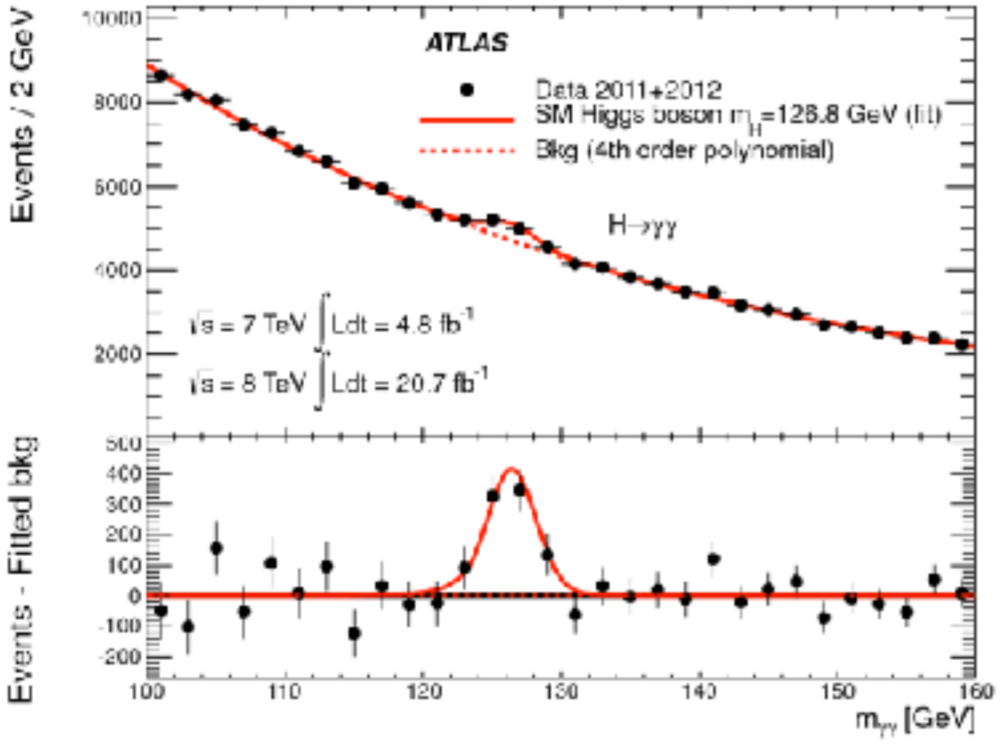


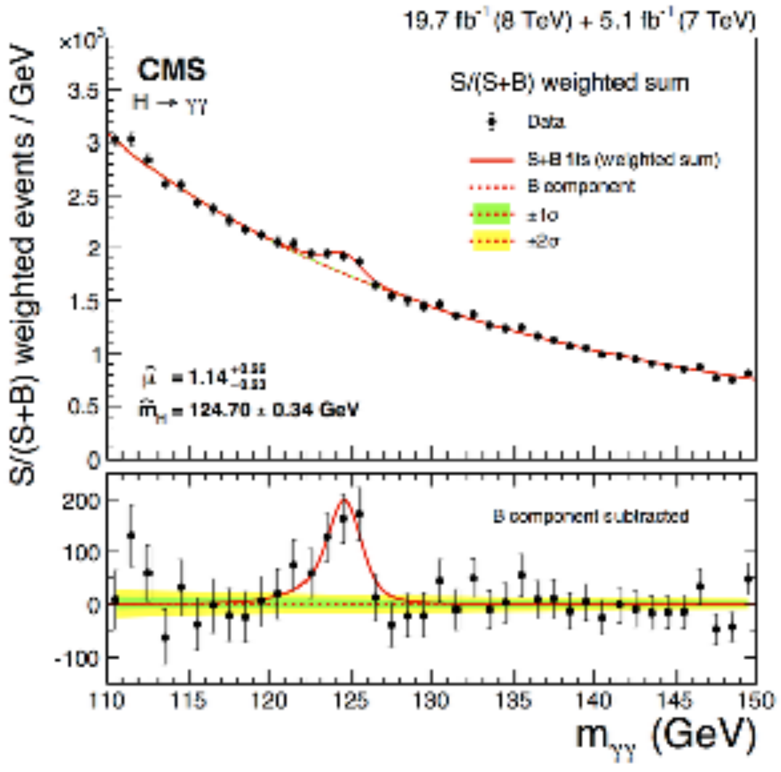
light particles → resonance

- non-analyticity @ $s \sim m^2$
- factorization of amplitudes

heavy particles → effective int.

ex. W boson was predicted
from Fermi interaction



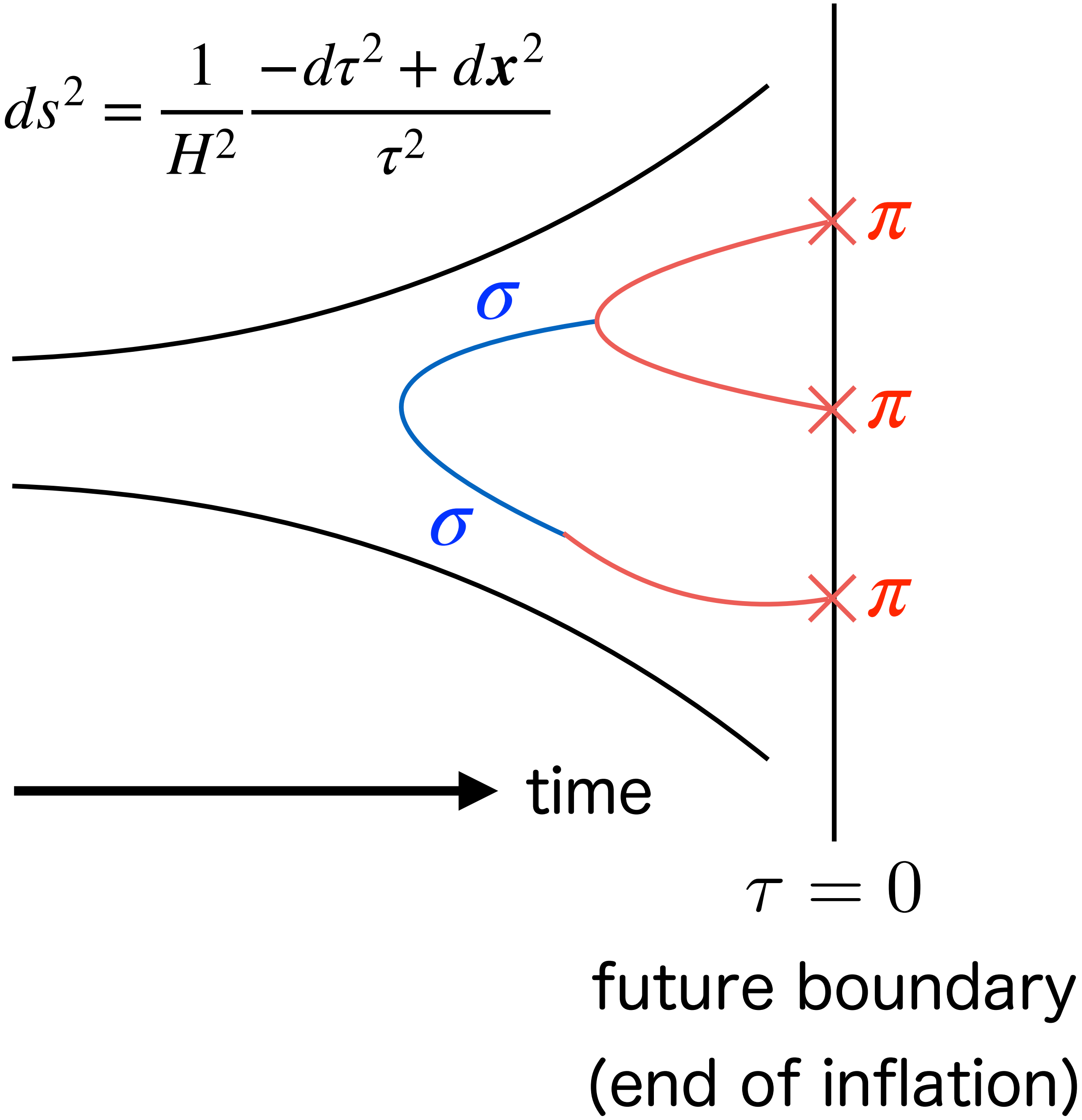


analogy with resonance?

inflationary correlation functions

late time correlators $\left\langle \pi_{\boldsymbol{k}_1}(\tau)\pi_{\boldsymbol{k}_2}(\tau)\pi_{\boldsymbol{k}_3}(\tau) \right\rangle_{\tau\to 0}$

= initial conditions of standard cosmology


$$ds^2 = \frac{1}{H^2}\frac{-d\tau^2 + d\boldsymbol{x}^2}{\tau^2}$$

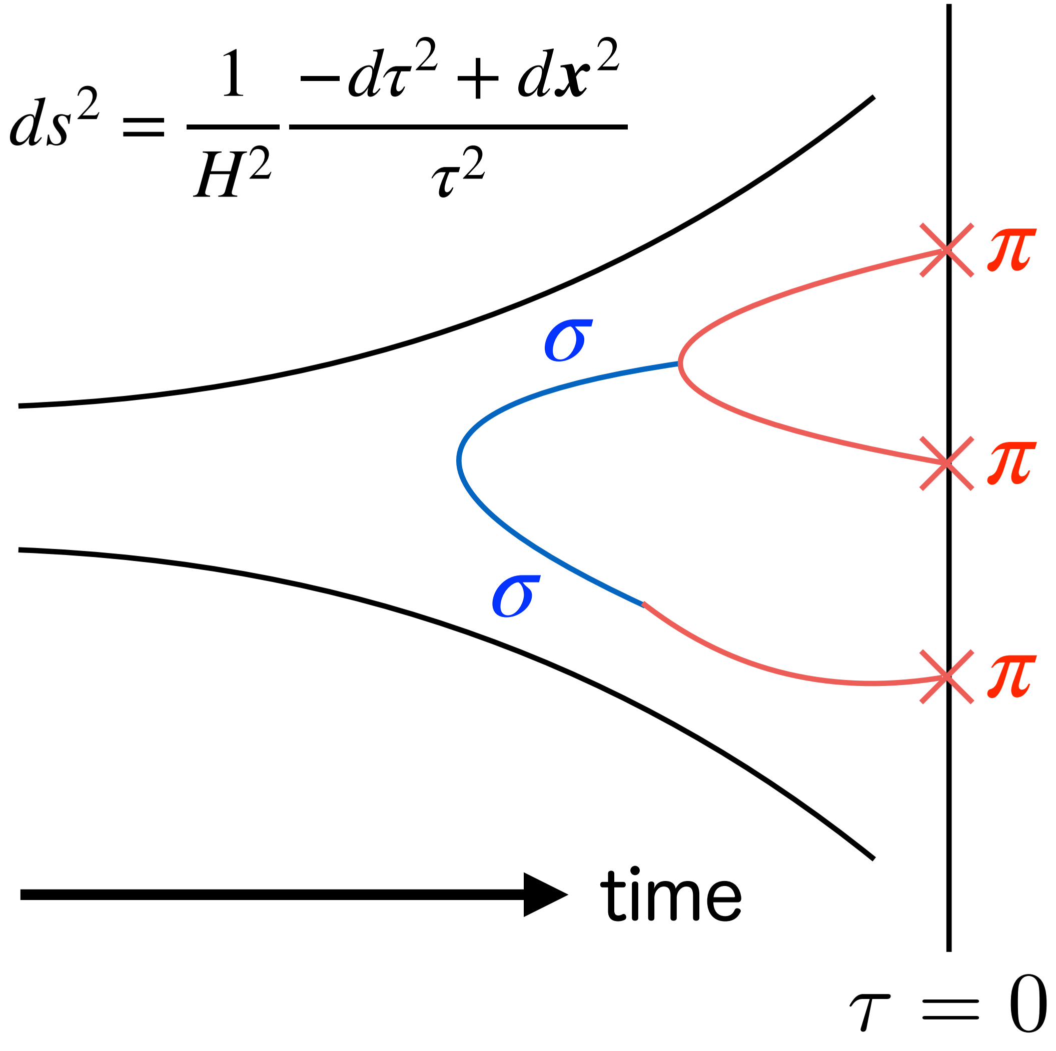
future boundary

(end of inflation)

inflationary correlation functions

late time correlators $\left\langle \pi_{\boldsymbol{k}_1}(\tau)\pi_{\boldsymbol{k}_2}(\tau)\pi_{\boldsymbol{k}_3}(\tau)\right\rangle_{\tau\to 0}$

= initial conditions of standard cosmology



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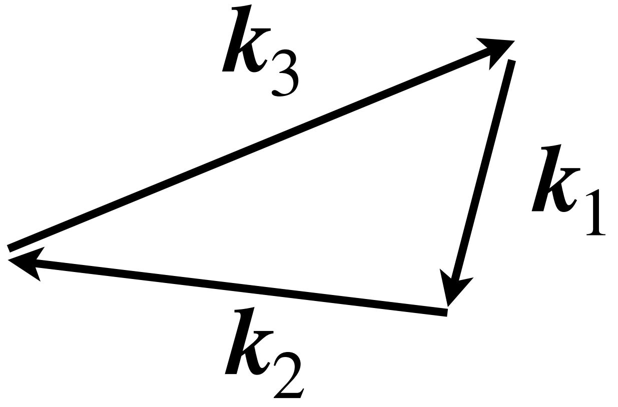
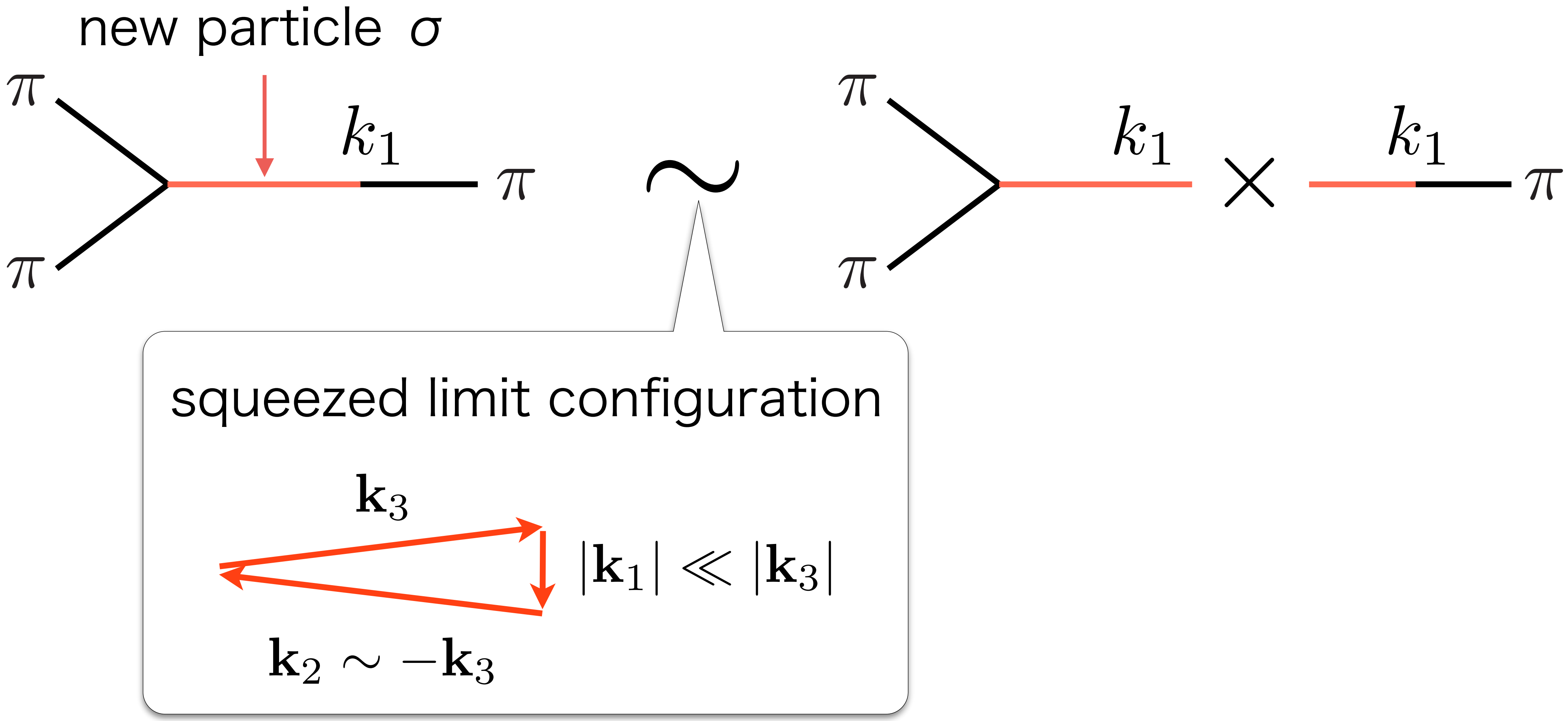


- functions of 3D spatial momenta
- approximate scale invariance

  → functions of triangle shape

A. analogue of resonance = soft limit

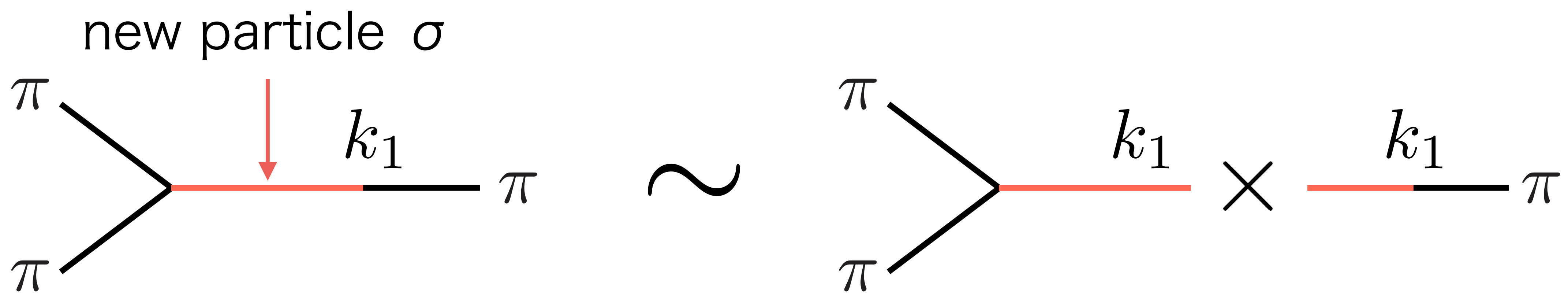
NG boson 3pt functions factorize in the squeezed limit



squeezed limit configuration

$|\mathbf{k}_1| \ll |\mathbf{k}_3|$

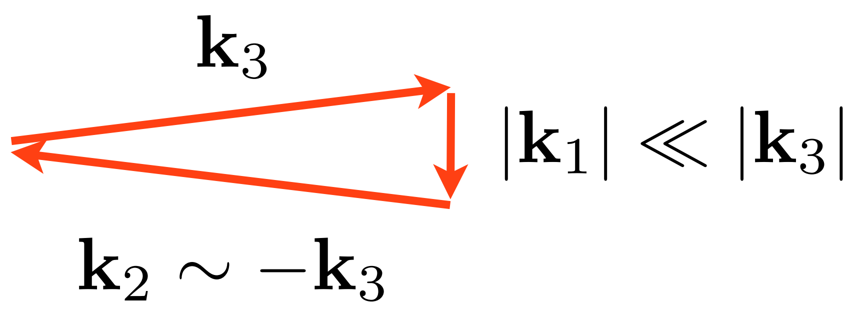
NG boson 3pt functions factorize in the squeezed limit



generically of the following form [TN-Yamaguchi-Yokoyama ’13]

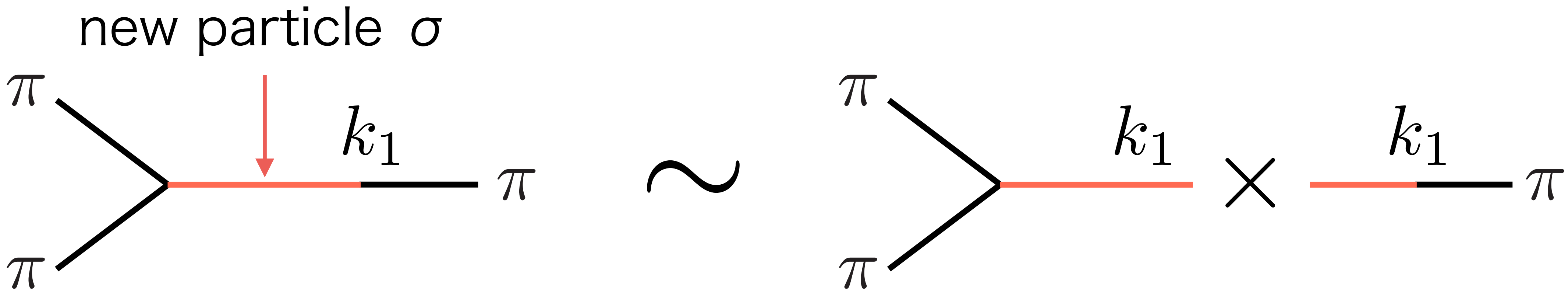
$$\frac{\langle\zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle}{\langle\zeta_{\mathbf{k}_1}\zeta_{-\mathbf{k}_1}\rangle\langle\zeta_{\mathbf{k}_3}\zeta_{-\mathbf{k}_3}\rangle} \propto (k_1/k_3)^{3/2}\ \mathrm{Im}\left[(k_1/k_3)^{i\sqrt{\frac{m^2}{H^2}-\frac{9}{4}}}e^{i\,\mathrm{phase}}\right]$$

squeezed limit config.



mass of the new particle!

NG boson 3pt functions factorize in the squeezed limit



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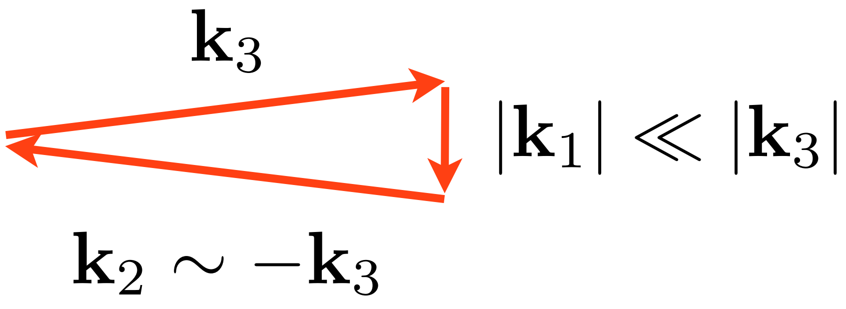
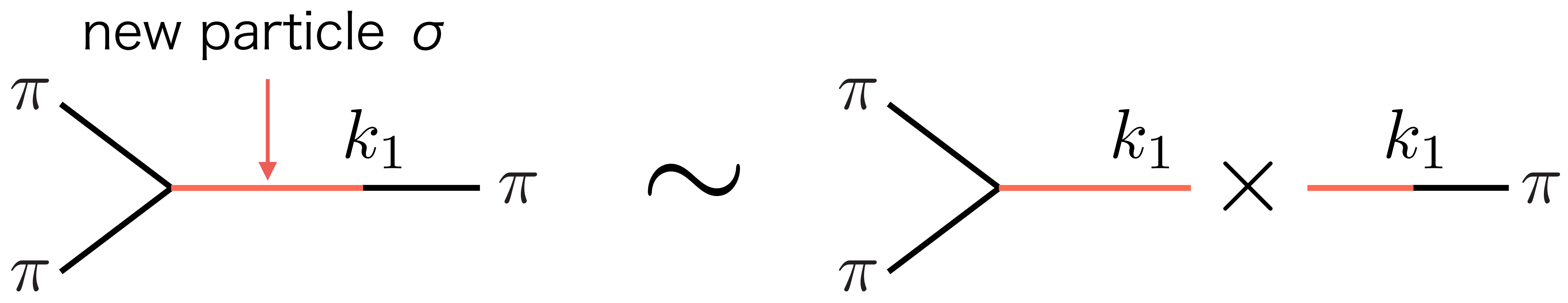
squeezed limit config.



mass of the new particle!

NG boson 3pt functions factorize in the squeezed limit



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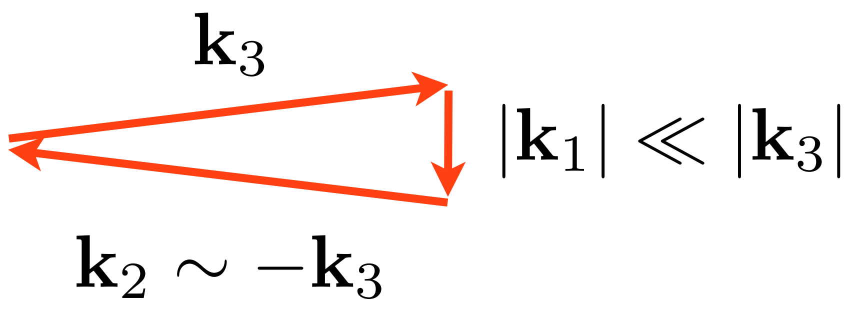
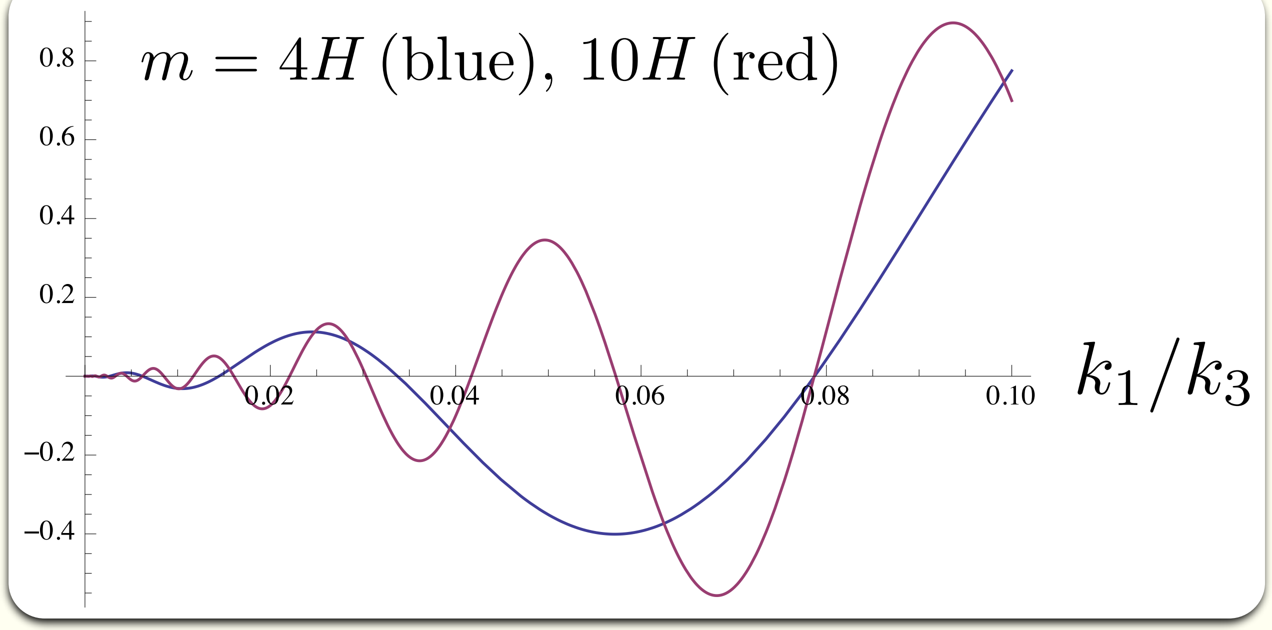
squeezed limit config.



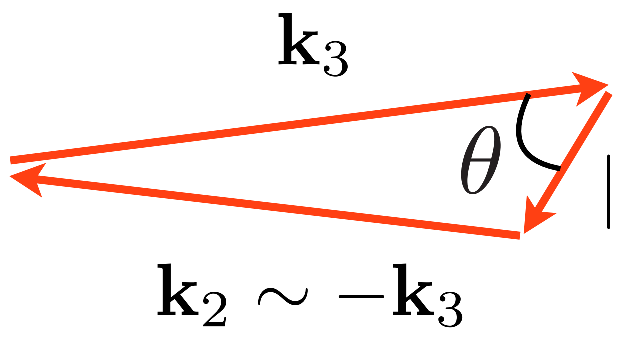


more generally,

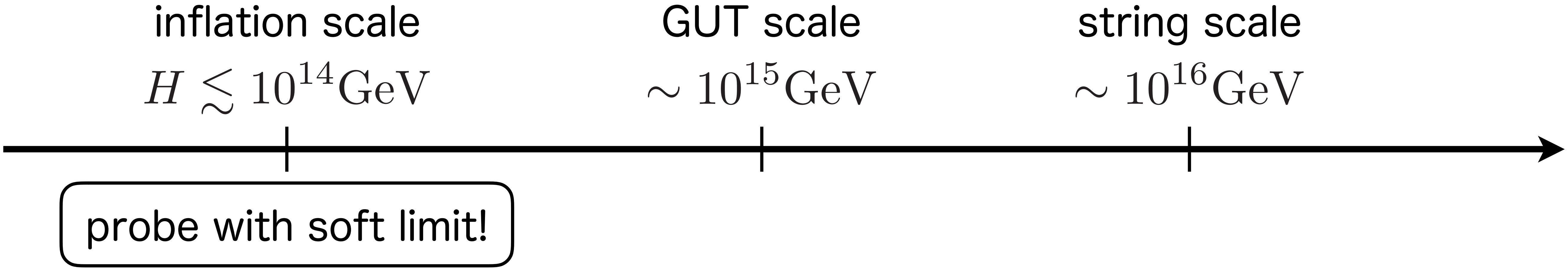
spin of new particle can be read off from angular dependence

[Arkani Hamed-Maldacena ’15]

squeezed limit configuration

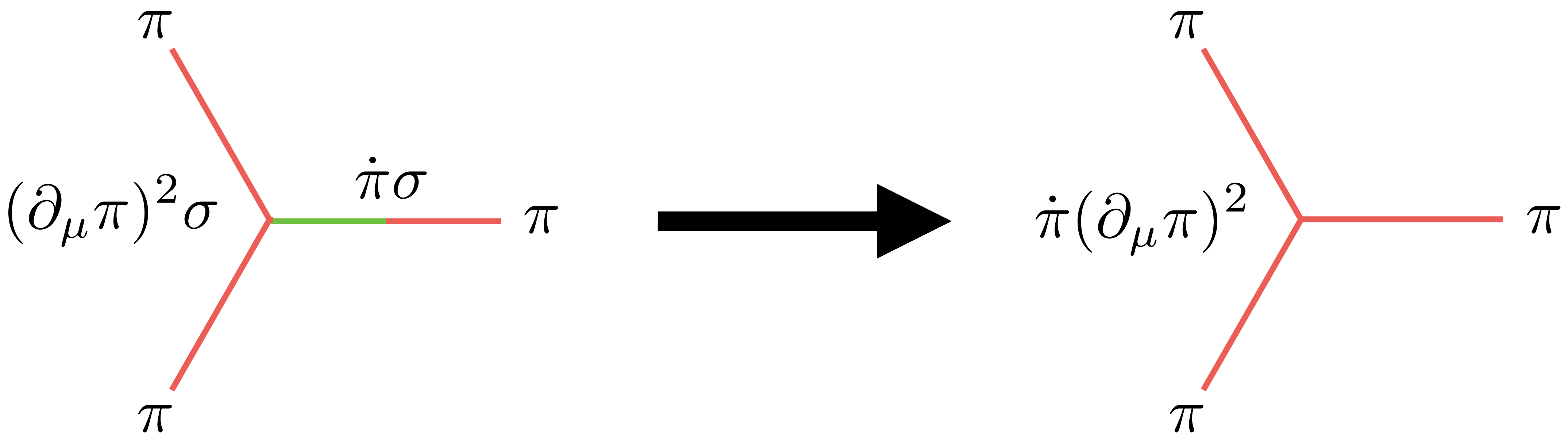


$|\mathbf{k}_1| \ll |\mathbf{k}_3| \quad \propto P_s(\cos\theta)$ (s: spin of new particle)


inflation scale
$H \lesssim 10^{14}\mathrm{GeV}$
GUT scale
$\sim 10^{15}\mathrm{GeV}$
string scale
$\sim 10^{16}\mathrm{GeV}$
probe with soft limit!

effective interactions

non-Gaussianities from heavy fields



if the intermediate particle σ is heavy $m \gg H$,

its effects is reduced to an effective interaction

※ typically, the coupling is $\sim \dfrac{H^2}{m^2}$

we can use nonlinear representation

to construct the effective theory

(cf. chiral Lagrangian)

EFT of inflation [Cheung et al '08]

effective Lagrangian of NG boson (~~time translation~~)

$$\mathcal{L}_\pi = M_{\rm Pl}^2 \dot{H} (\partial_\mu \pi)^2 + \sum_{n=2}^{\infty} \frac{M_n^4}{n!} \left[-2\dot{\pi} + (\partial_\mu \pi)^2 \right]^n + \dots$$

order parameter

nonlinear realization

cf. inflaton Lagrangian

$$\mathcal{L}_\phi = -\frac{1}{2}(\partial_\mu \phi)^2 + \frac{(\partial_\mu \phi)^4}{\Lambda^4} + \dots$$

- NG boson vs inflaton: $\phi(t, \vec{x}) = \bar{\phi}(t + \pi(t, \vec{x}))$

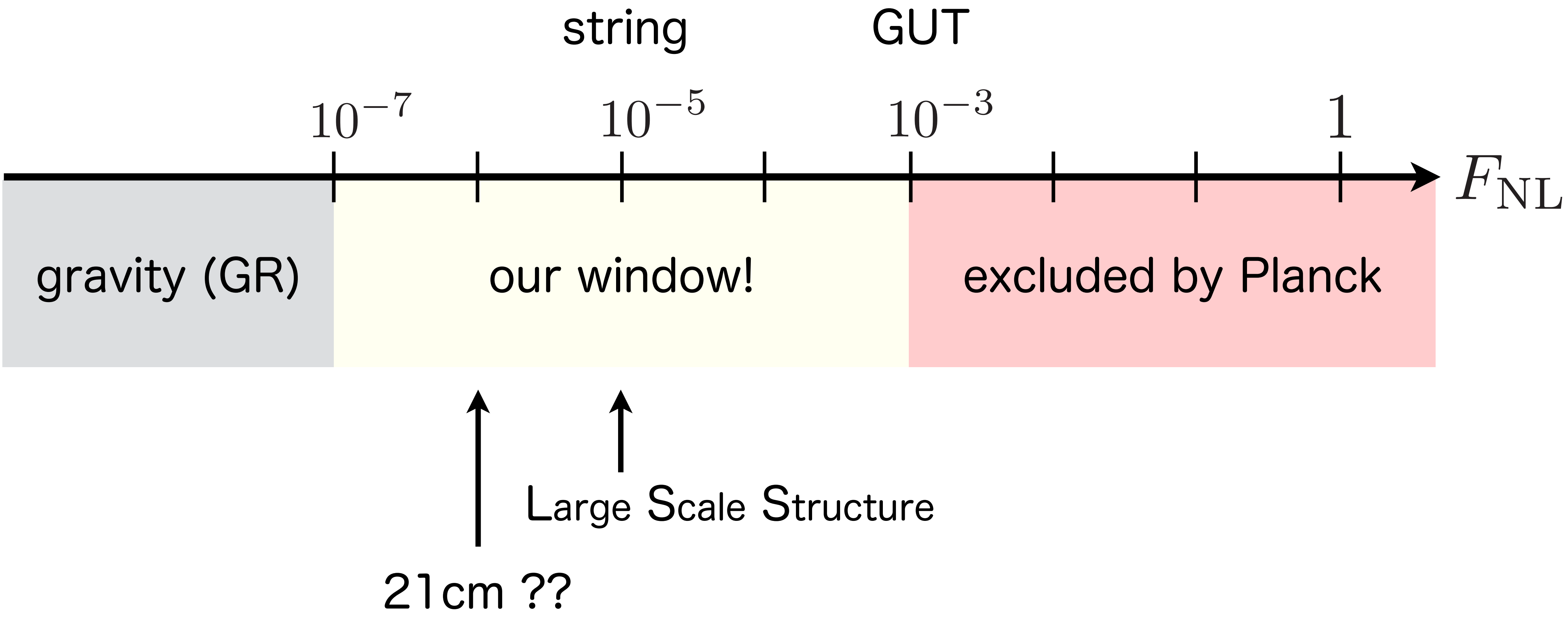
ex. $(\partial_\mu \phi)^2 = \dot{\bar{\phi}}^2 \partial_\mu (t+\pi) \partial^\mu (t+\pi) = \dot{\bar{\phi}}^2 \left[-1 - 2\dot{\pi} + (\partial_\mu \pi)^2 \right]$

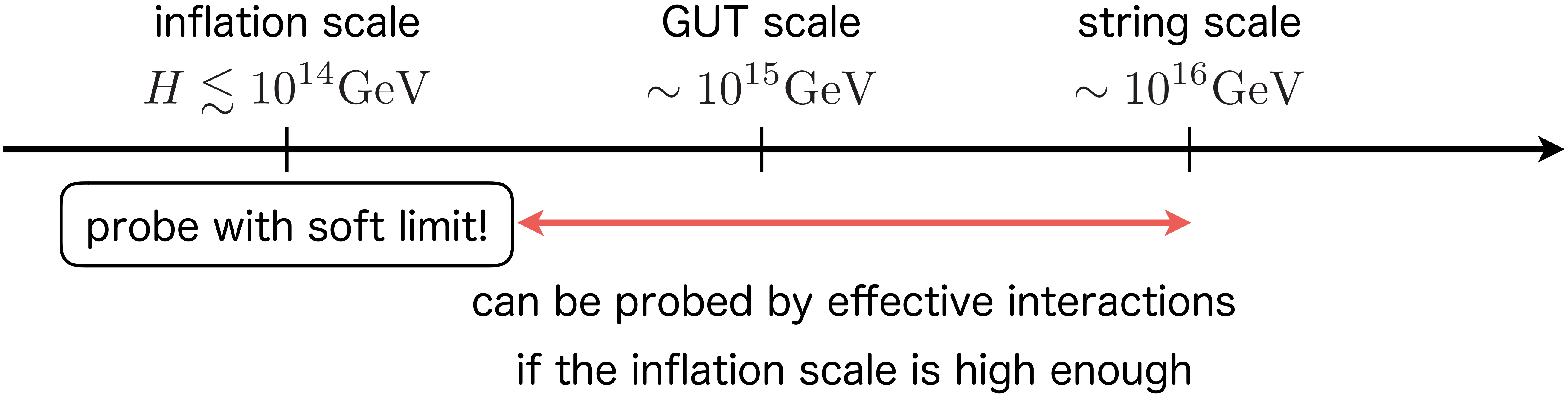
up to which scale we can probe?

$$H^2 \propto r$$

3pt functions from heavy fields $F_{\rm NL} = \frac{\langle \pi\pi\pi \rangle}{\langle \pi\pi \rangle^{3/2}} \sim \frac{H^2}{m^2}$

if we assume $H = 3 \times 10^{13}{\rm GeV}\ (r = 0.01)$,





inflation scale

$H \lesssim 10^{14}\mathrm{GeV}$

GUT scale

$\sim 10^{15}\mathrm{GeV}$

string scale

$\sim 10^{16}\mathrm{GeV}$

probe with soft limit!

can be probed by effective interactions

if the inflation scale is high enough

how to identify spin from effective interactions?

in progress w/S. Kim, K. Takeuchi

cubic effective interactions

general effective Lagrangian up to cubic order [Bordin et al '17]

$$\mathscr{L} = \frac{M_{\rm Pl}^2 |\dot{H}|}{c_s^2}\Big[\dot{\pi}^2 - c_s^2(\partial_i\pi)^2 \\ -\left(1-c_s^{-2}\right)\dot{\pi}\,(\partial_\mu\pi)^2 + \alpha\dot{\pi}^3 \\ +\beta_1(\partial_\mu\pi)^2\partial_i^2\dot{\pi} + \beta_2\,\dot{\pi}^2\,\partial_i^2\dot{\pi} + \beta_3\,\dot{\pi}\,(\partial_i^2\pi)^2 + \dots\Big]$$

- used field redefinition to resolve operator degeneracy
- 2 indep. operators c_s and α at the leading order in derivatives
- 3 indep. operators β_i at the next leading order

Wilson coefficients contain information of heavy particles!

→ can we read off spin etc from these coefficients?

as a first step,

we determined the parameter set for a UV scalar

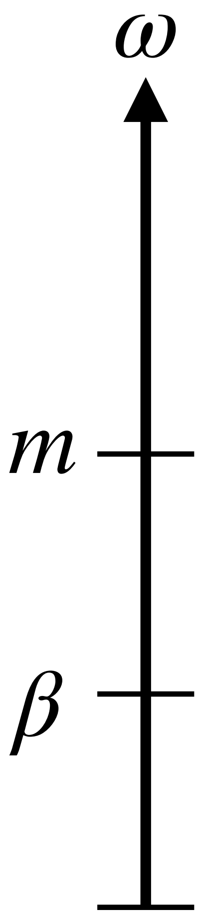
by assuming that Lorentz invariance is restored @UV

UV π - σ theory

\# general π - σ UV Lagrangian up to second order

$$\mathscr{L}_2 = -\frac{1}{2}(\partial_\mu \pi_c)^2 - \frac{1}{2}(\partial_\mu \sigma)^2 - \frac{1}{2}m^2\sigma^2 + \beta\dot{\pi}_c\sigma$$

- π is canonically normalized here for simplicity
- dispersion relation: $\det\begin{pmatrix} \omega^2 - k^2 & -i\beta\omega \\ i\beta\omega & \omega^2 - k^2 - m^2 \end{pmatrix} = 0$



$\omega^2 = k^2,\ \omega^2 = m^2 + k^2$ → Lorentz invariance restored!

$\omega^2 = c_s^2 k^2$ w/sound speed $c_s^2 = \left(1 + \frac{\beta^2}{m^2}\right)^{-1}$

$\omega^2 = \frac{k^4}{\beta^2}$ → non-relativistic dispersions

UV π - σ theory

general π - σ UV Lagrangian up to second order

$$\mathscr{L}_2 = -\frac{1}{2}(\partial_\mu \pi_c)^2 - \frac{1}{2}(\partial_\mu \sigma)^2 - \frac{1}{2}m^2\sigma^2 + \beta\dot{\pi}_c\sigma$$

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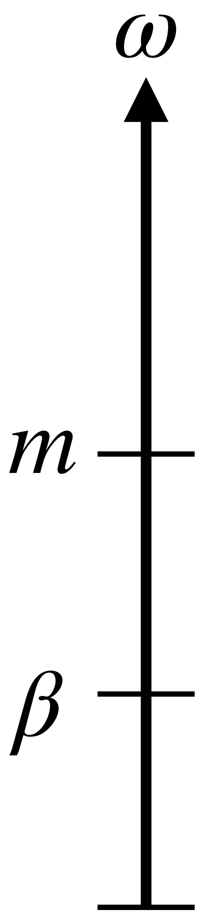

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→ non-relativistic dispersions

$\omega^2 = \frac{k^4}{\beta^2}$

$\partial_i\pi\partial_i\sigma$ is not UV complete

UV π - σ theory

general π - σ UV Lagrangian up to cubic order

- 3 UV parameters (m, g, λ) characterizing heavy scalar σ

$$\mathscr{L}_\pi = -M_{\rm Pl}^2 |\dot{H}| (\partial_\mu \pi)^2$$

$$\mathscr{L}_\sigma = -\frac{1}{2}(\partial_\mu \sigma)^2 - \frac{1}{2}m^2 + \lambda \sigma^3$$

$$\mathscr{L}_{\rm mix} = g\,\sigma\,(-2\dot{\pi} + \partial_\mu \pi \partial^\mu \pi) - \frac{g^2}{2}\sigma^2(-2\dot{\pi} + \partial_\mu \pi \partial^\mu \pi)$$

UV Lorentz invariance of 3pt amplitudes

cf. nonlinear sigma model

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

effective action

$$\mathscr{L}_3 = -\left(1 - c_s^{-2}\right)\dot{\pi}\,(\partial_\mu \pi)^2 + \alpha \dot{\pi}^3$$

$$+\beta_1 (\partial_\mu \pi)^2 \partial_i^2 \dot{\pi} + \beta_2\, \dot{\pi}^2\, \partial_i^2 \dot{\pi} + \beta_3\, \dot{\pi}\,(\partial_i^2 \pi)^2 + \dots$$

after integrating out σ, we find

$$c_s^2 = \left(1 + \frac{g^2}{2m^2}\right)^{-2}, \quad \alpha = -\frac{g^4}{2m^4} + \lambda \frac{g^6}{m^6}$$

$$\beta_1 = -(1 - c_s^2)\frac{2g^2}{m^4}, \;\; \beta_2 = (1 - c_s^2)\left[-\frac{g^4}{2m^6} + 3\lambda \frac{g^6}{m^8}\right], \;\; \beta_3 = 0$$

if we consider a single UV scalar

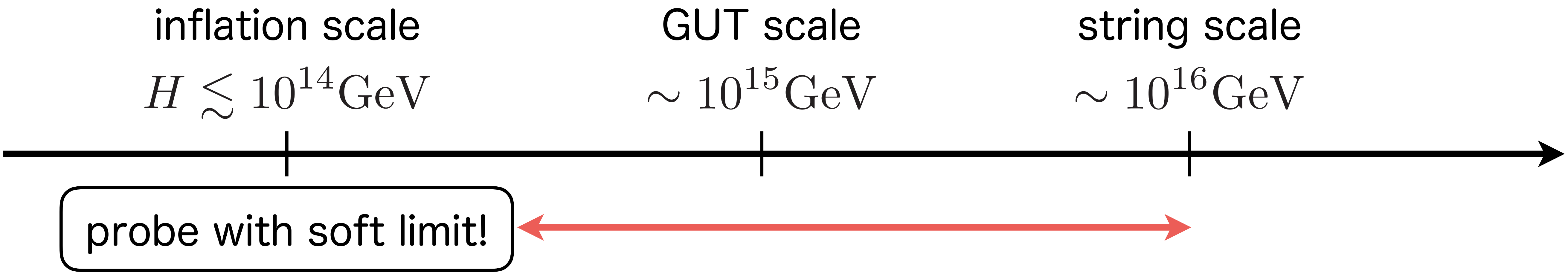
- β_3 can never show up → β_3 is a sign of nonzero spin
- $\beta_{1,2}$ are further suppressed by a factor $(1 - c_s^2)$

the same conclusion applies for multiple scalars

Summary and Prospects

Main message:

primordial non-Gaussianities = 10^{14} GeV collider



inflation scale

$H \lesssim 10^{14}\mathrm{GeV}$

GUT scale

$\sim 10^{15}\mathrm{GeV}$

string scale

$\sim 10^{16}\mathrm{GeV}$

probe with soft limit!

can be probed by effective interactions

if the inflation scale is high enough

bootstrapping EFT of inflation

illustrated how to bootstrap EFToI for a single UV scalar

- extension to heavy particles with general spins
- bounds on Wilson coefficients (cf. ArkaniHamed-Huang-Huang)
- observational aspects (shape of non-Gaussianities)
- non-Gaussianities with tensor modes

→ probe spins of heavy particles through effective coupling

Thank you!