Primordial non-Gaussianities as a particle collider

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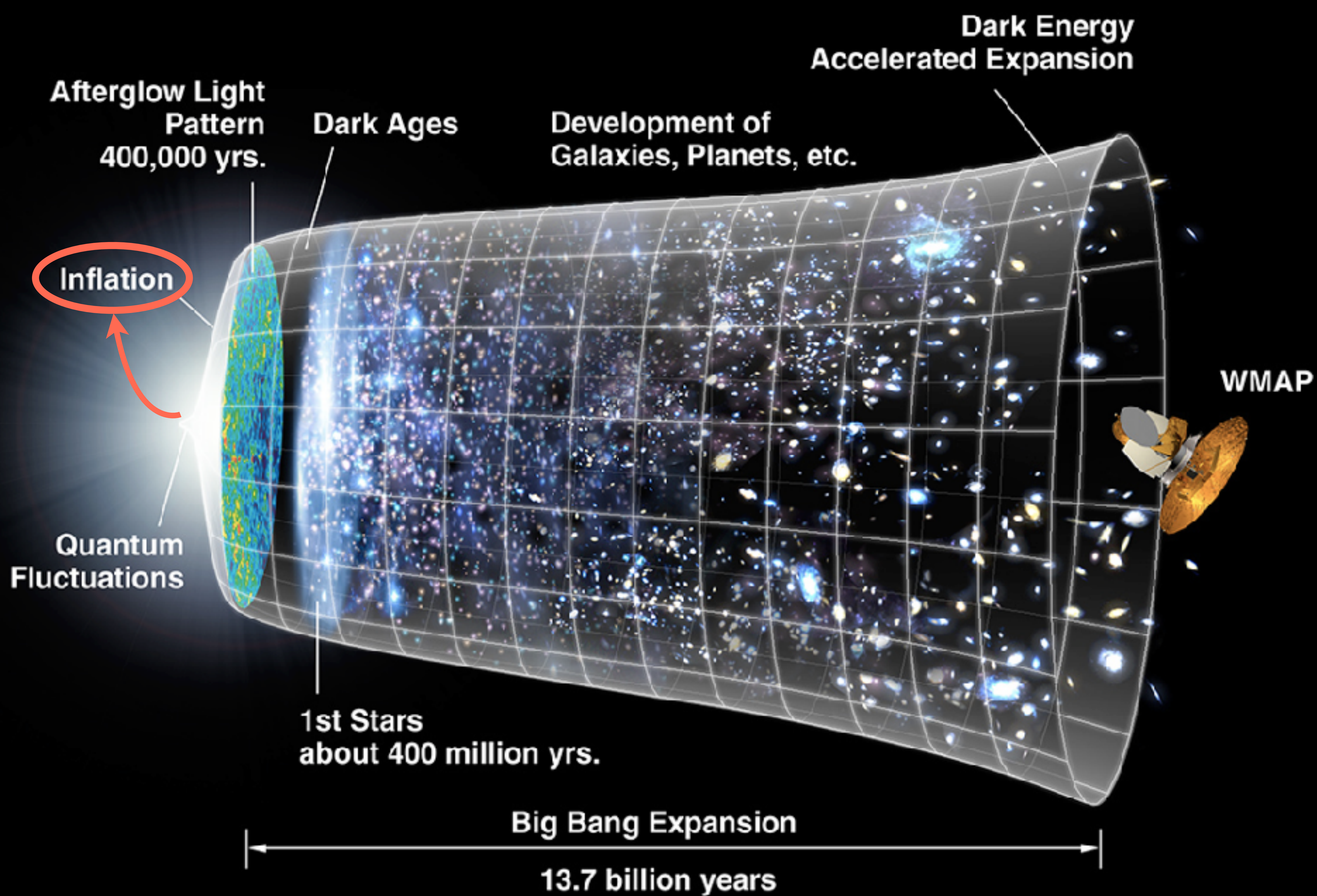
refs: to appear on Monday w/S.Kim, K.Takeuchi, S.Zhou

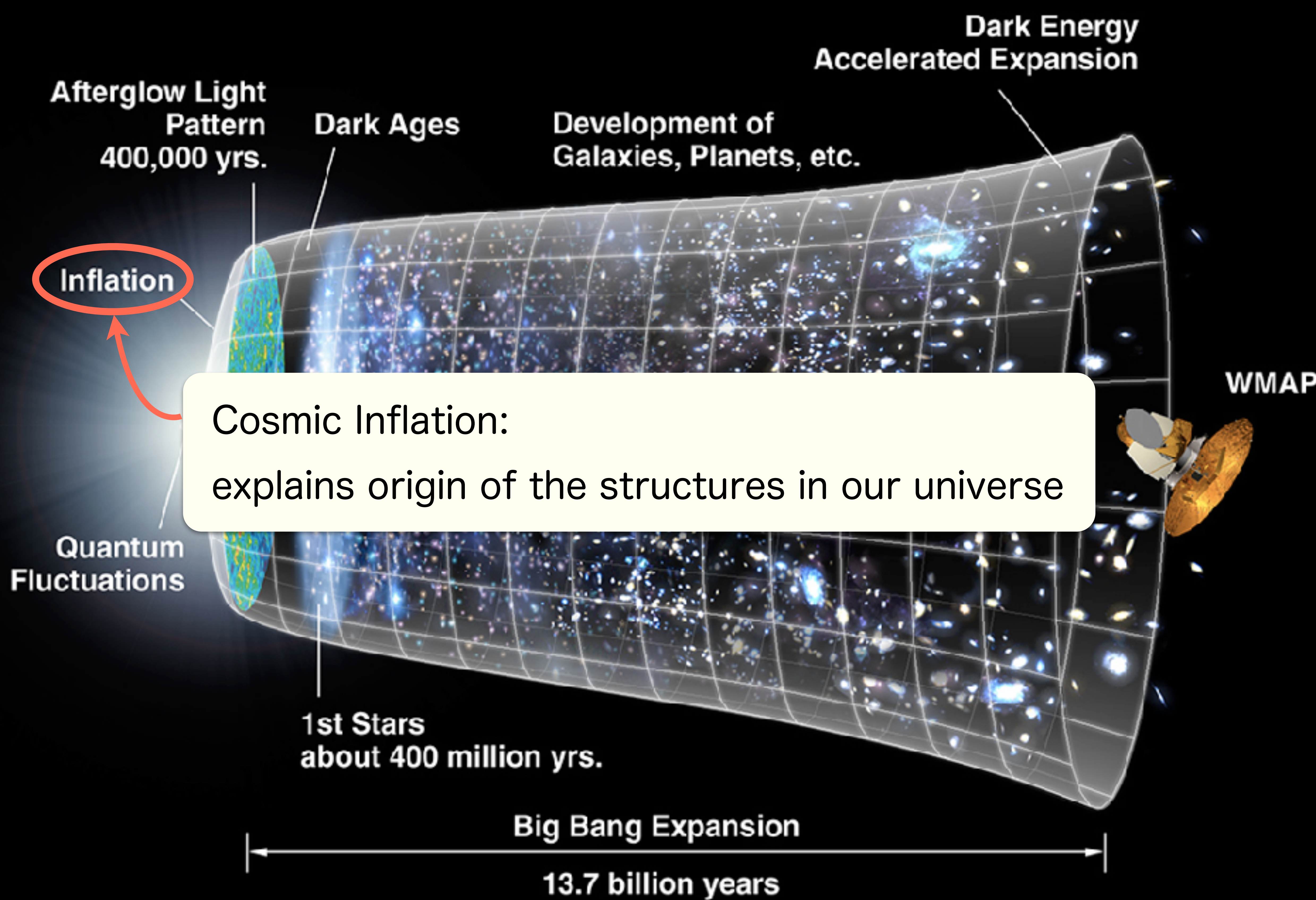
1211.1624 w/M. Yamaguchi, D. Yokoyama

28th June 2019 @ 名古屋E研

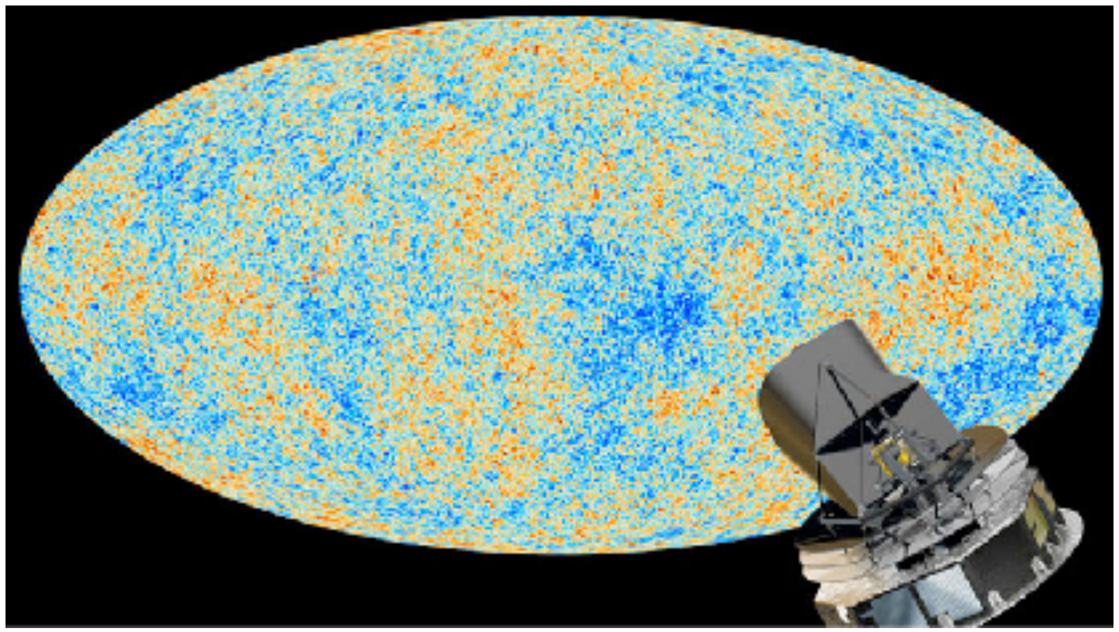

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Cosmic Inflation:

explains origin of the structures in our universe

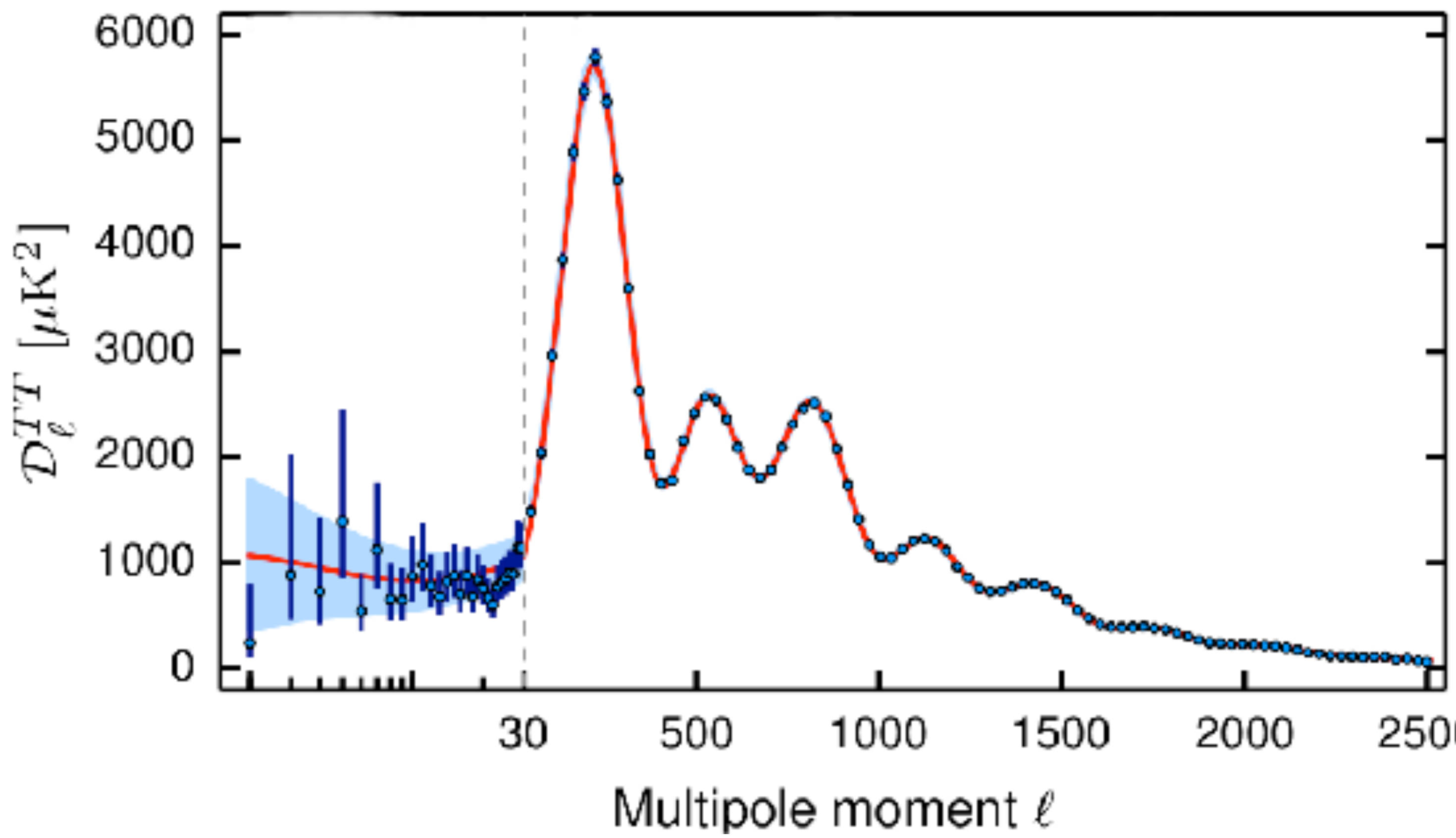


We are in the Era of Precision Cosmology!



Cosmic Microwave Backgrounds

by Planck



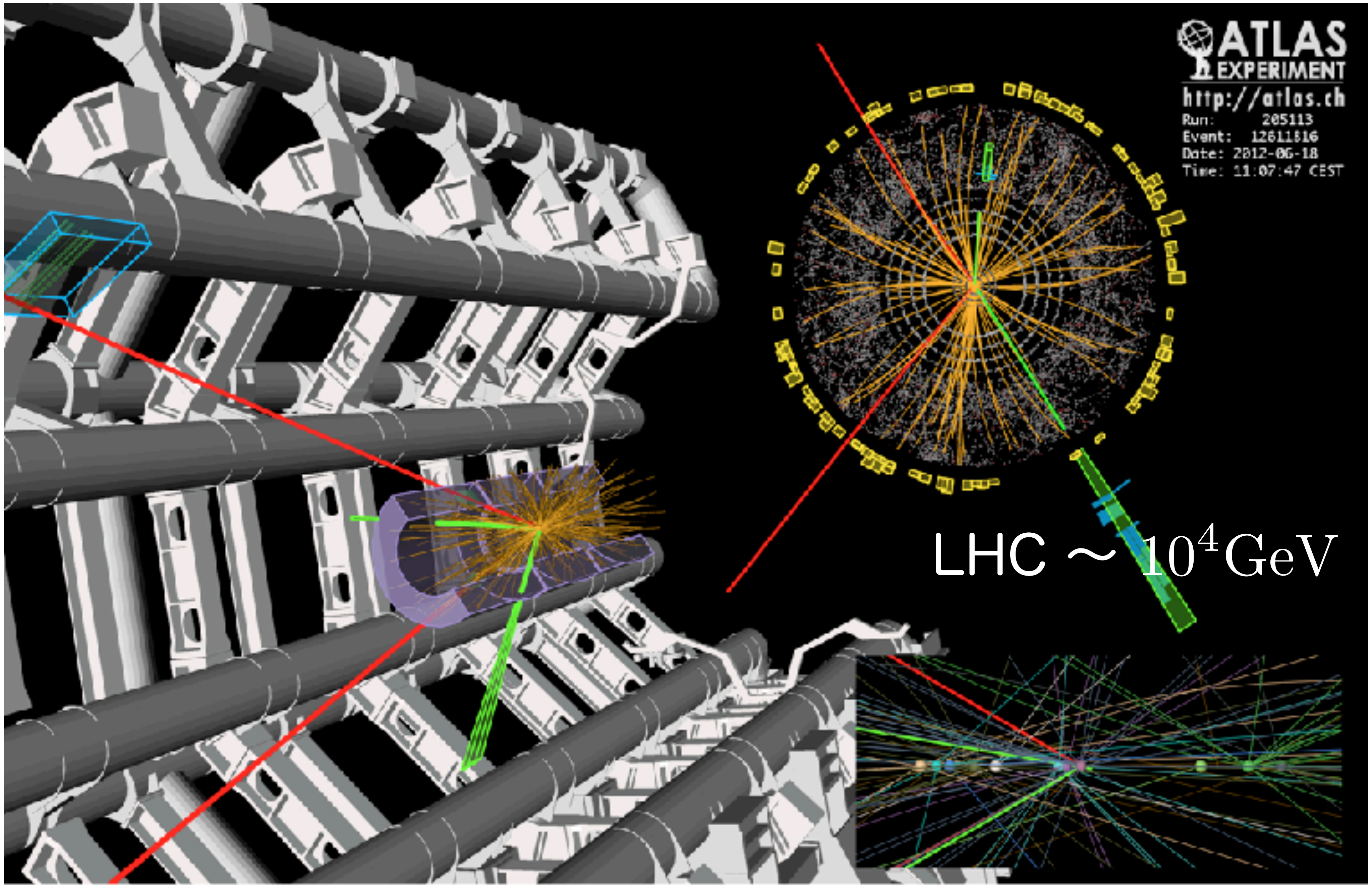
Standard Cosmology + Inflation as an initial condition:

strongly supported by observations such as CMB

→ precision test of inflationary models!

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

Inflation = 10^{14}GeV collider!



Inflation	GUT scale	String scale	Planck scale
$H \lesssim 10^{14}\mathrm{GeV}$	$\sim 10^{15}\mathrm{GeV}$	$\sim 10^{16}\mathrm{GeV}$	$\sim 10^{18}\mathrm{GeV}$

Q. How to probe new particles?

Main messages:

A. Inflationary scale $\sim 10^{14}$ GeV

※ to be tested by CMB B-mode observations in 2020's

B. non-Gaussianities = particle scattering

※ analogy w/particle collider, probable energy scale, …

Contents

1. Symmetry of Inflation

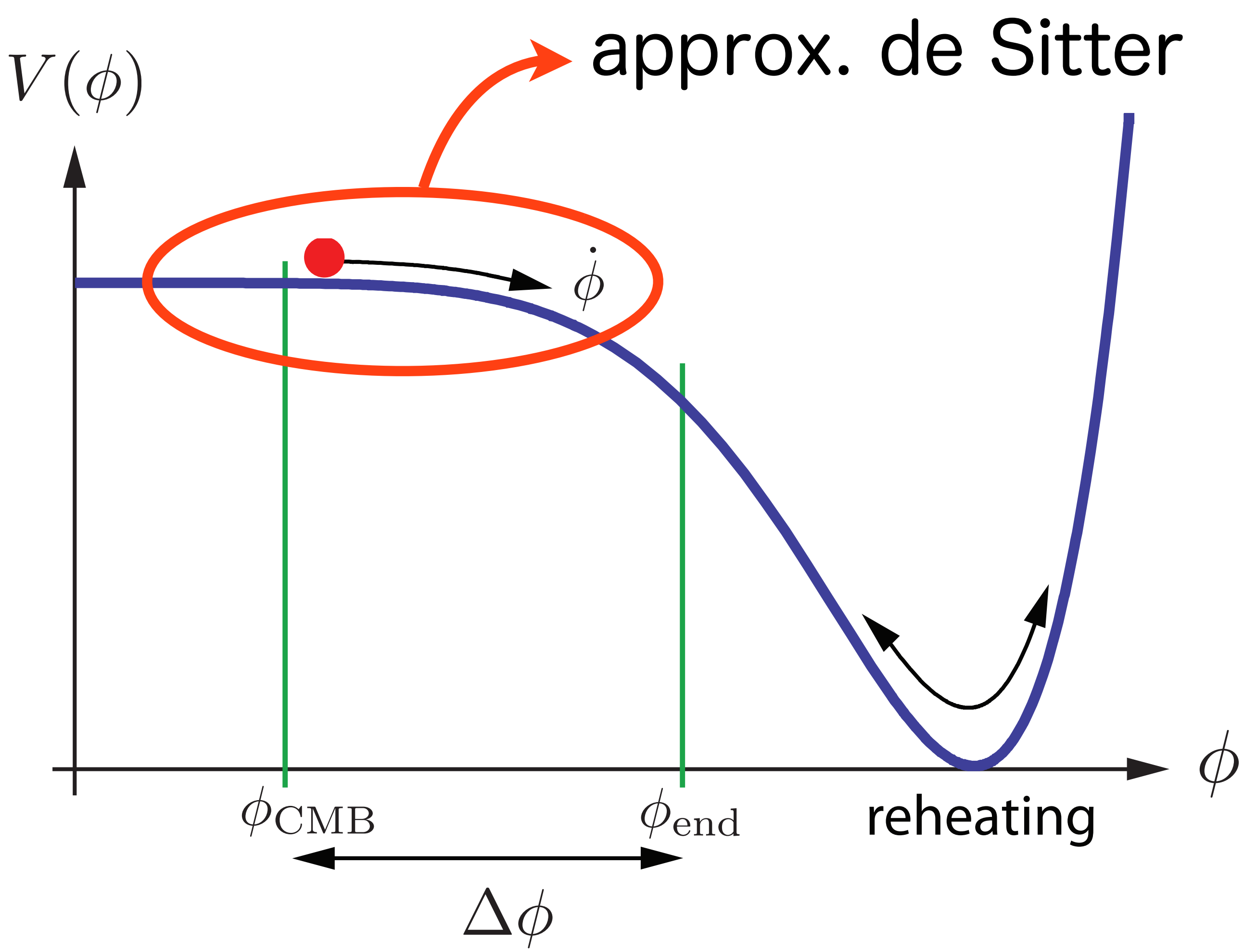
2. Energy Scale of Inflation

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

4. Summary and Prospects

1. Symmetry of Inflation

slow-roll inflation



- FRW spacetime

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

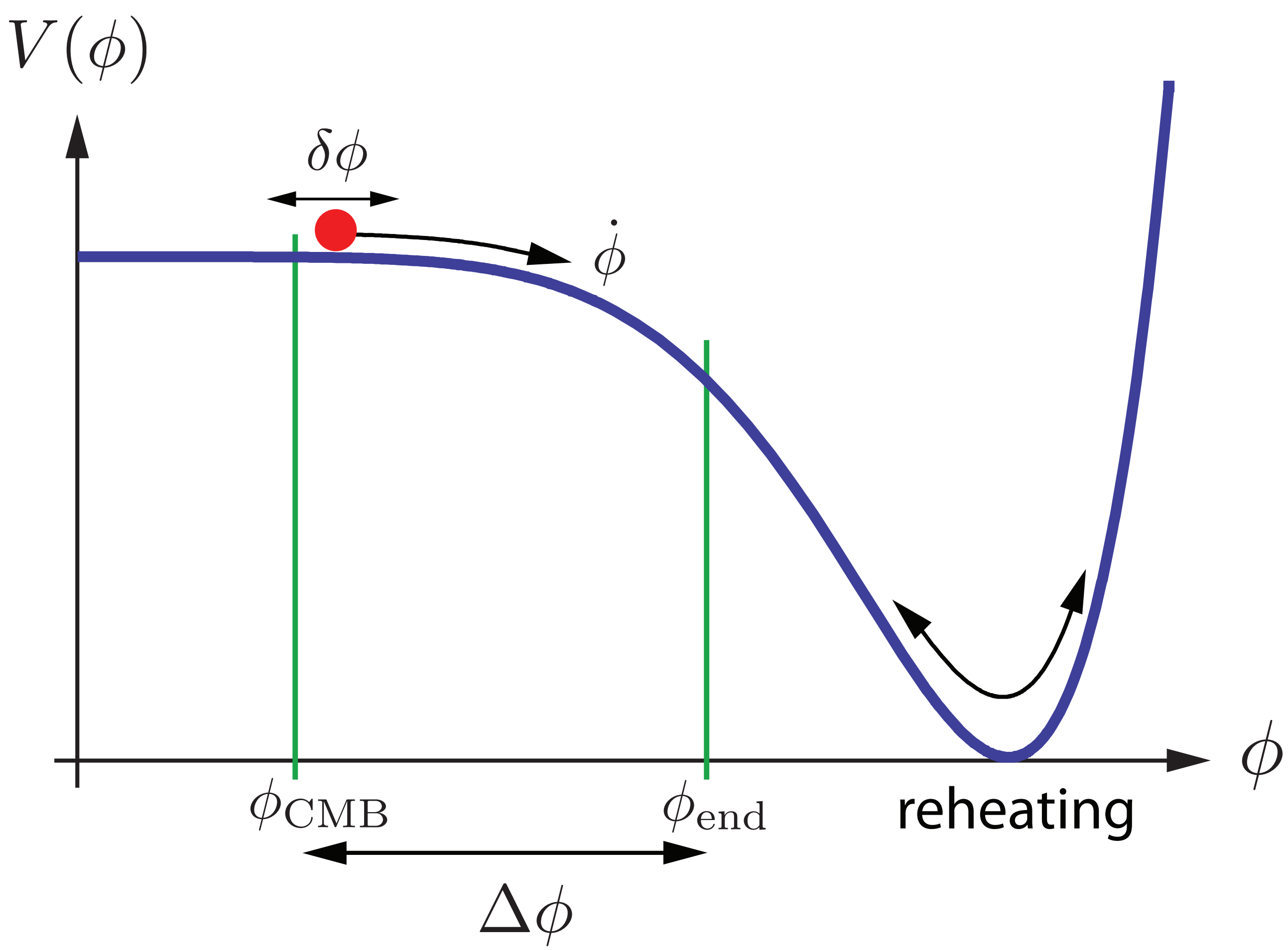
- Hubble parameter: $H(t) = \dfrac{\dot{a}}{a}$

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

as a consequence of symmetry

- order parameter vs size of fluctuations

- nonlinear rep. like chiral Lagrangian

Contents

2. Energy Scale of Inflation

Primordial 2pt functions

primordial 2pt functions

NG boson 2pt function

$$\langle\zeta\zeta\rangle \simeq H^2\langle\pi\pi\rangle \sim \frac{H^2}{M_{\rm Pl}^2\epsilon}$$

※ slow-roll parameter ϵ is order parameter of ~~symmetry~~

graviton 2pt function

$$\langle\gamma\gamma\rangle \sim \frac{H^2}{M_{\rm Pl}^2}$$

※ graviton directly probes the scale of inflation!

primordial 2pt functions

NG boson 2pt function

$$\langle\zeta\zeta\rangle \simeq H^2\langle\pi\pi\rangle \sim \frac{H^2}{M_{\rm Pl}^2\epsilon}$$

※ slow-roll parameter ϵ is order parameter of ~~symmetry~~

graviton 2pt function

$$\langle\gamma\gamma\rangle \sim \frac{H^2}{M_{\rm Pl}^2}$$

※ graviton directly probes the scale of inflation!

graviton (primordial GW) has not been detected yet

- bound on tensor-to-scalar ratio $r \sim \dfrac{\langle\gamma\gamma\rangle}{\langle\zeta\zeta\rangle}$

$$r \simeq 16\epsilon < 0.07\,(95\%\,\mathrm{CL})$$ by Planck + BICEP2/KECK

- bound on inflation scale : $H = 3\times 10^{13}\times\left(\dfrac{r}{0.01}\right)^{1/2}\,[\mathrm{GeV}]$

primordial 2pt functions

scale dependence of NG boson 2pt function

spectral index: $n_s - 1 = \dfrac{d \ln \langle \zeta\zeta \rangle}{d \ln k}$

$$n_s - 1 \simeq -2\epsilon - \eta = -0.0333 \pm 0.0040\,(68\%\,\mathrm{CL})$$

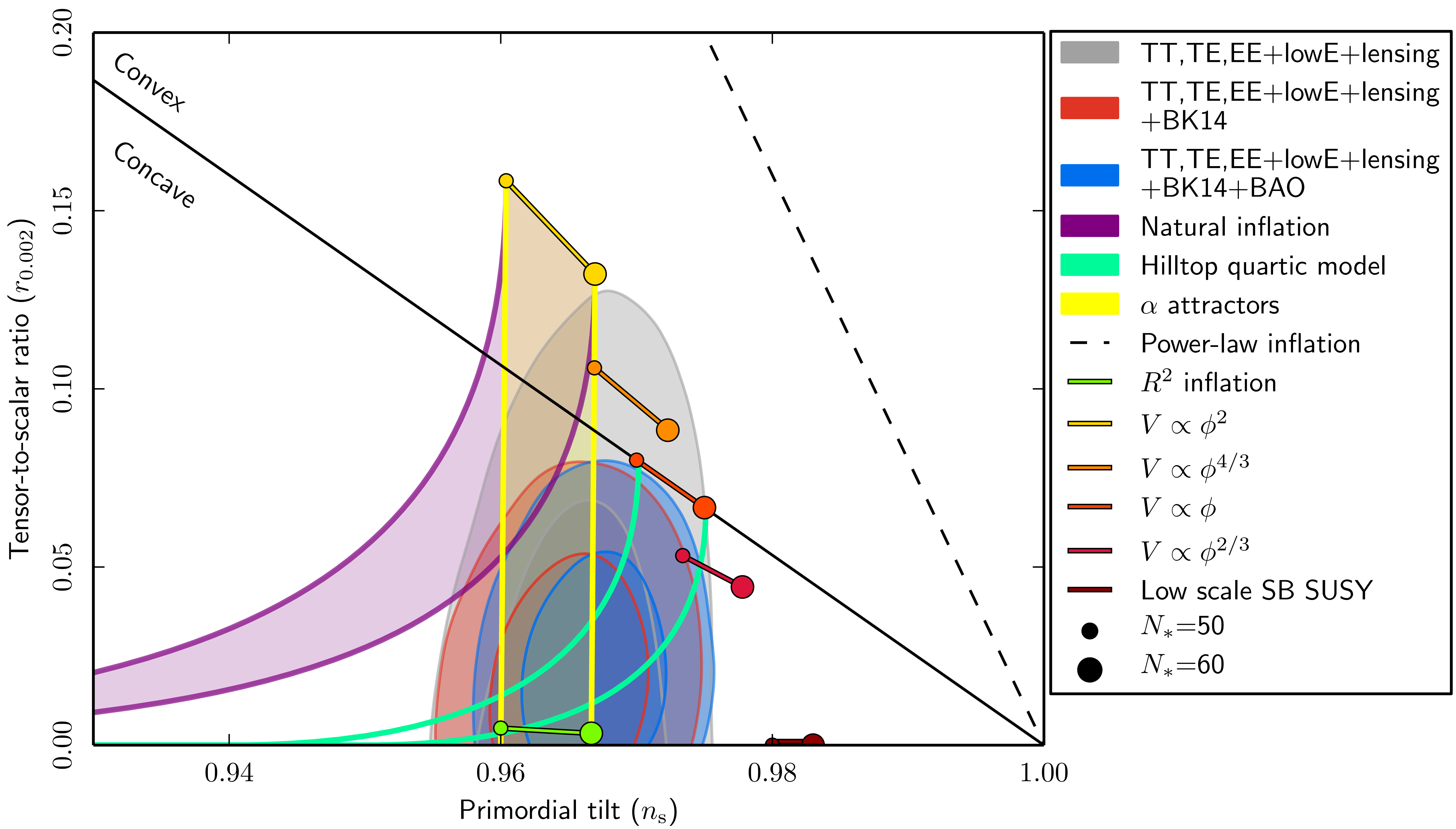
by Planck + BICEP2/KECK + $\cdots$

- 8 σ detection of deviation from de Sitter
- slow-roll parameters are $\mathcal{O}(0.01)$
- if $\epsilon \sim \eta \sim \mathcal{O}(0.01)$,

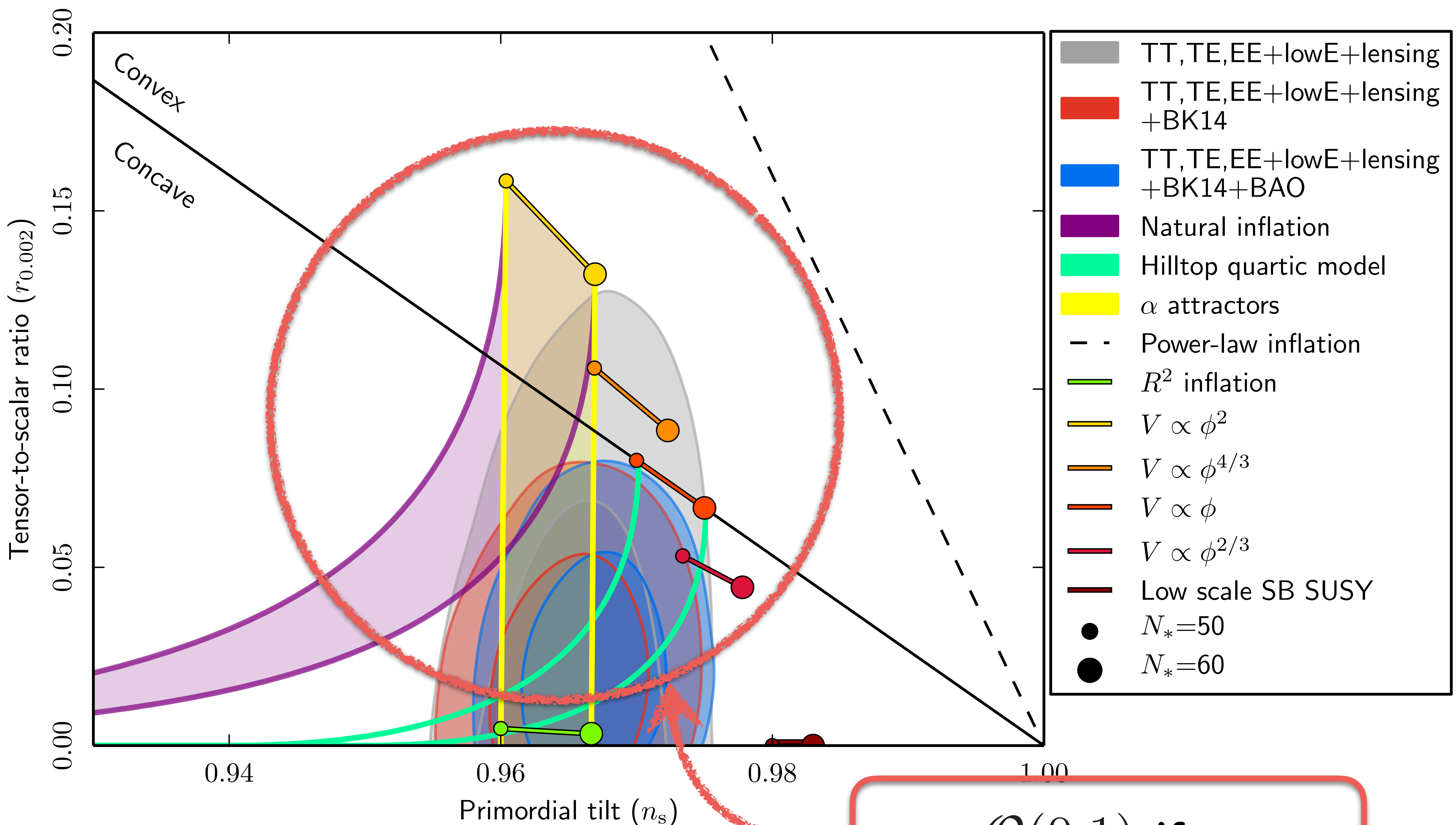
  $r \simeq 16\epsilon \sim \mathcal{O}(0.1)$, $H \sim 10^{14}\mathrm{GeV}$

  cf. current obs. bound $r < 0.07\,(95\%\,\mathrm{CL})$

typical tensor-to-scalar ratios

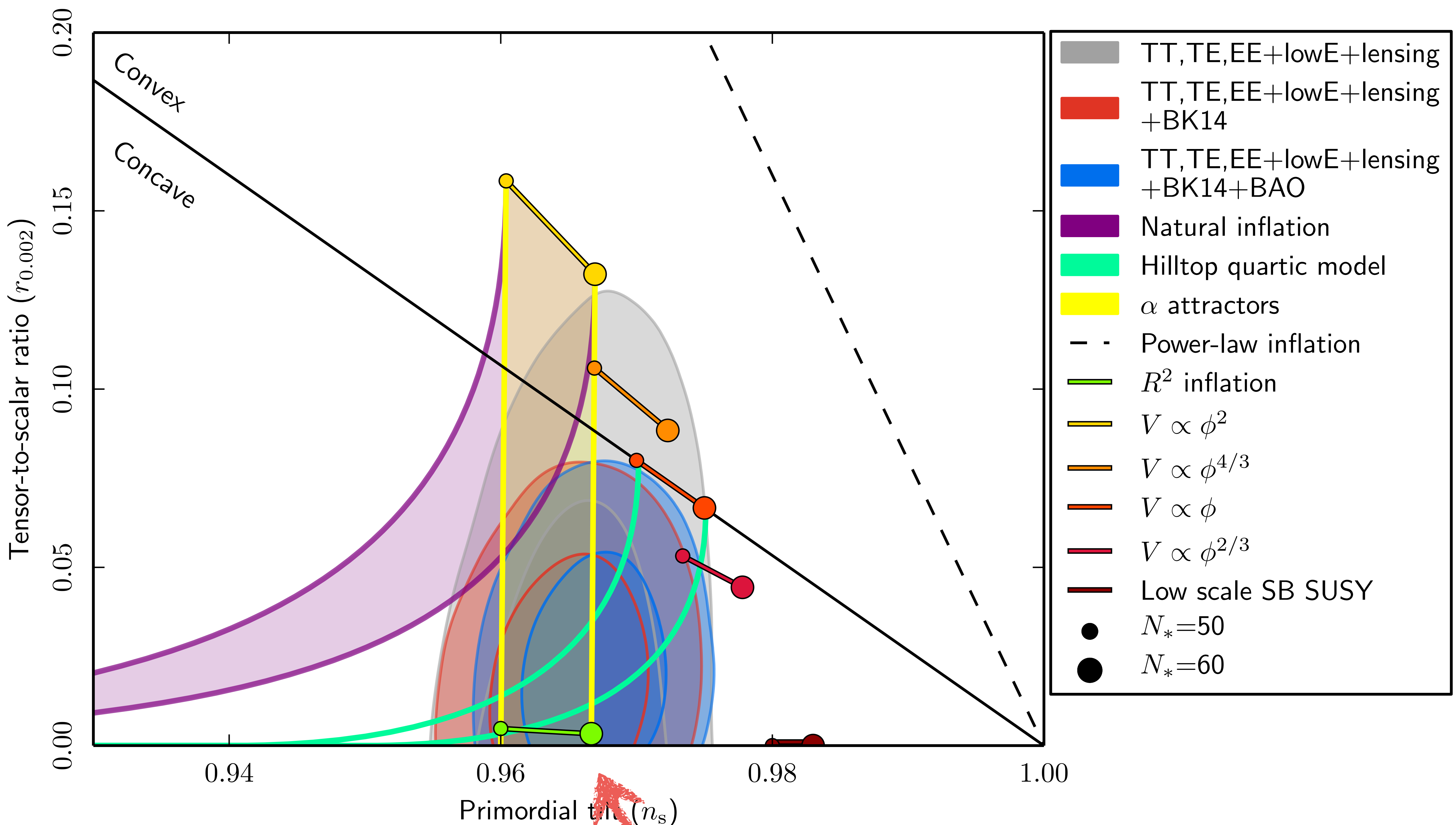


typical tensor-to-scalar ratios



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

typical tensor-to-scalar ratios



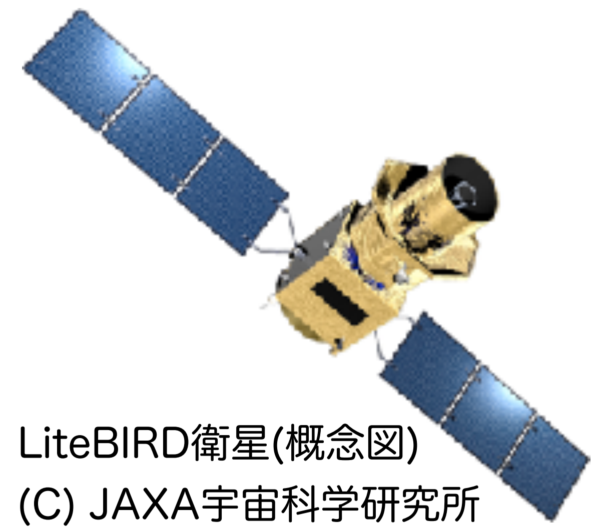
$r \simeq 0.003$

future of primordial GW observation

LiteBIRD satellite

all-sky CMB polarization survey

- primordial GW sources CMB B-mode
- target sensitivity: $\Delta r \lesssim 0.001$
- planned schedule: late 2020's



LiteBIRD衛星(概念図)
(C) JAXA宇宙科学研究所

Hubble scale H
during inflation

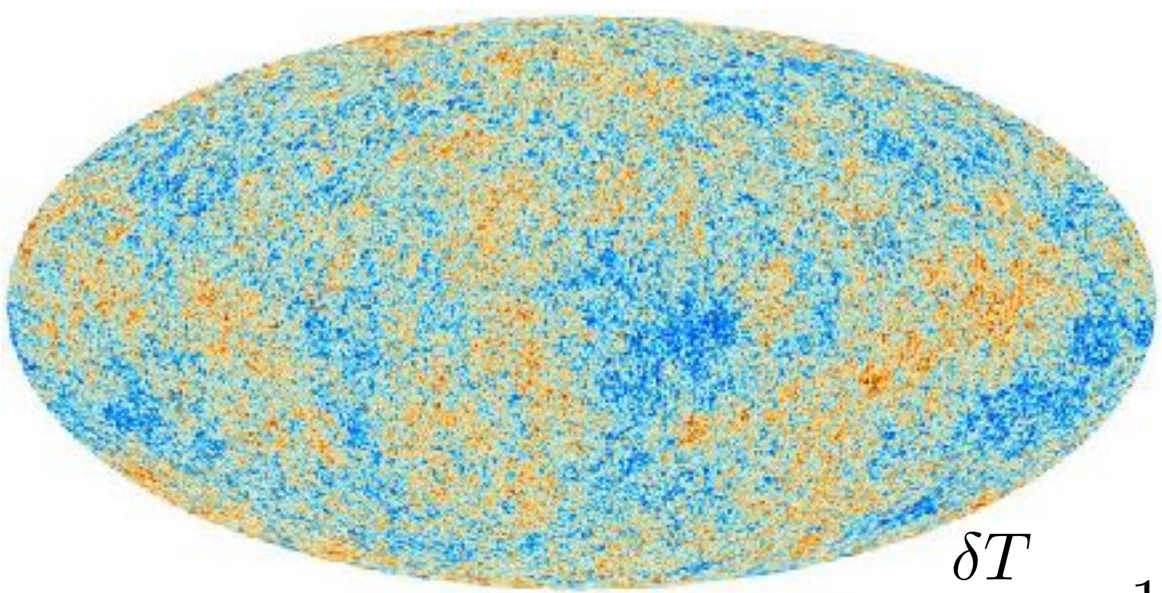
$r = 0.001$	$r = 0.1$	GUT scale	string scale
$10^{13}\mathrm{GeV}$	$10^{14}\mathrm{GeV}$	$10^{15}\mathrm{GeV}$	$10^{16}\mathrm{GeV}$

Contents

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

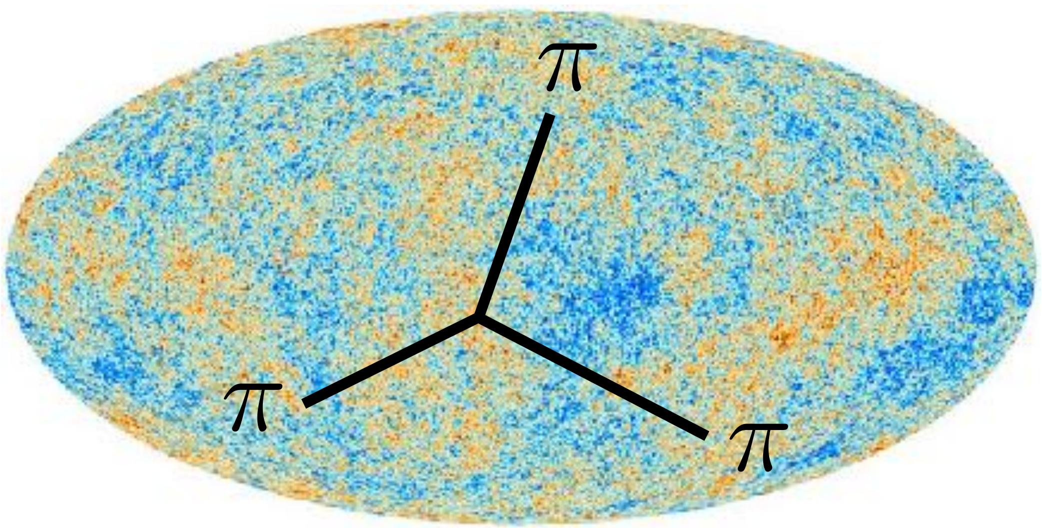
CMB temperature fluctuations are Gaussian

$\rightarrow$ 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

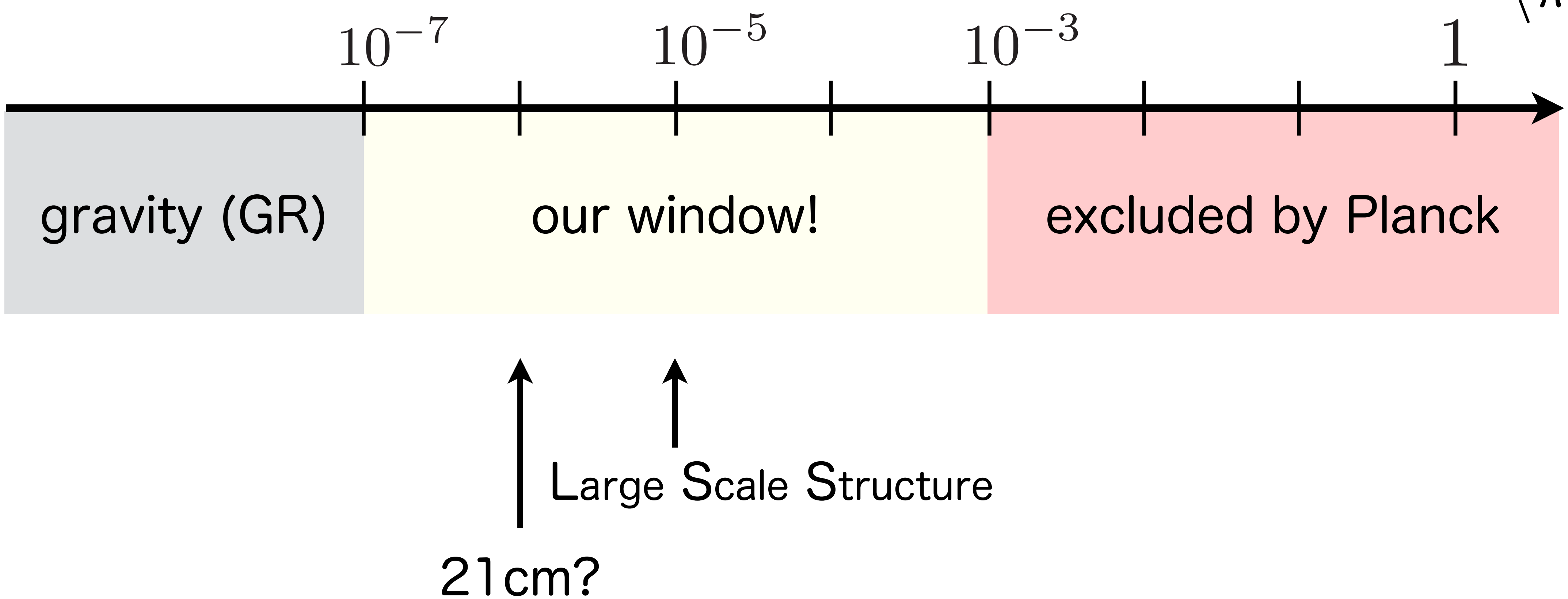
→ probe of new particles at a very high energy scale!!

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

Primordial non-Gaussianities

bounds on NG boson 3pt functions

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

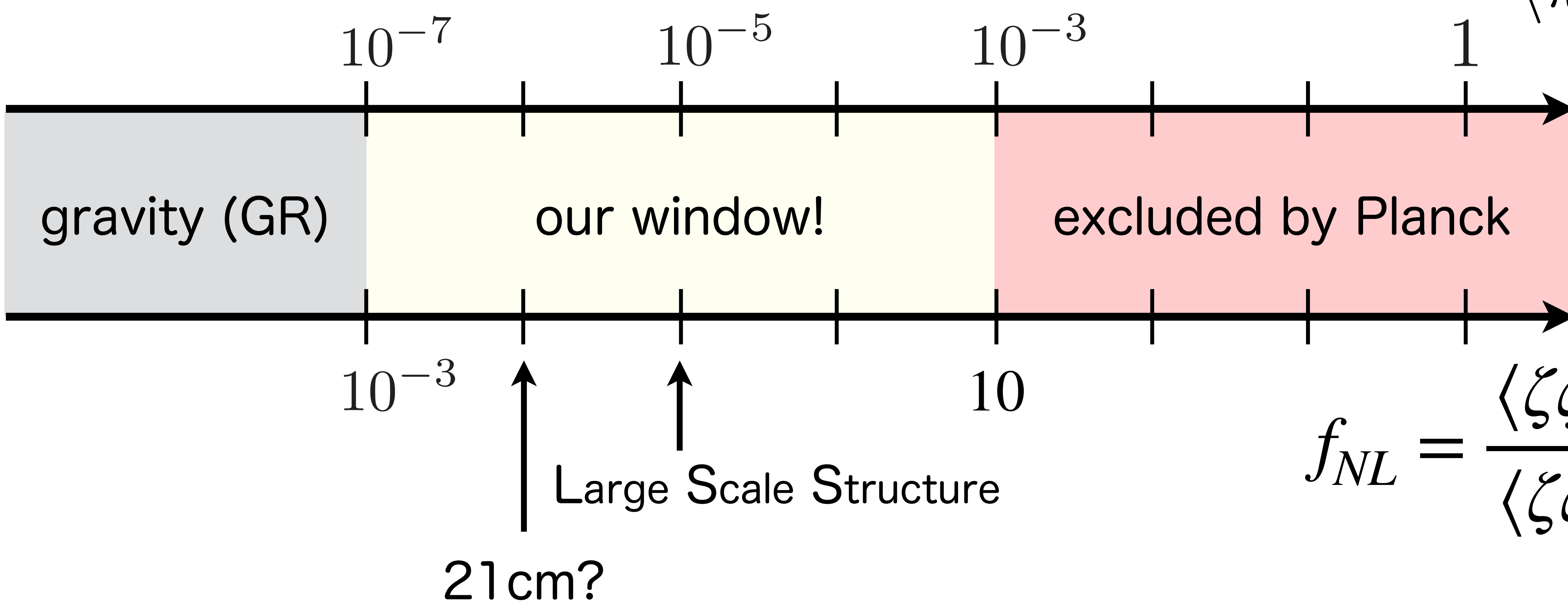


- we already know that they are weakly coupled
- at least we have gravitational interactions
- improvements by 2~3 order are expected

Primordial non-Gaussianities

\# bounds on NG boson 3pt functions

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



$$f_{NL} = \frac{\langle \zeta\zeta\zeta \rangle}{\langle \zeta\zeta \rangle^{2}}$$

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

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

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

※ 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

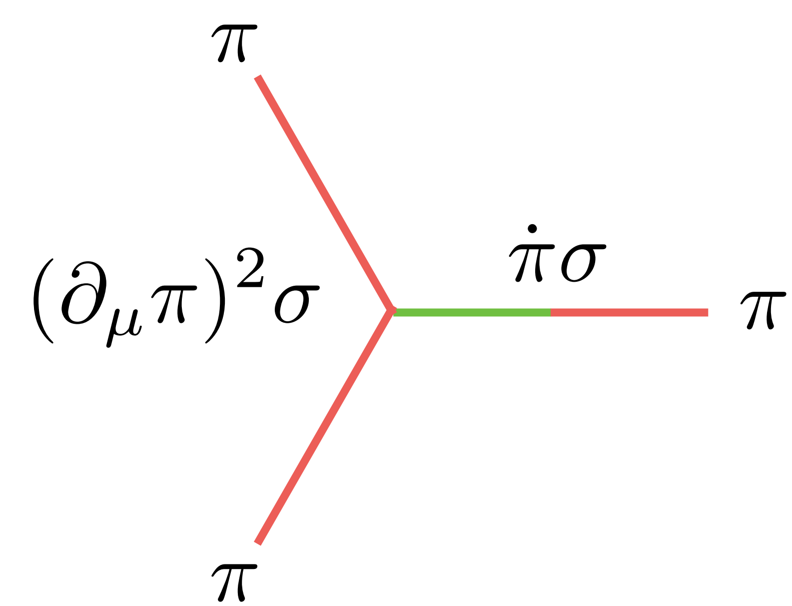
$$\mathcal{L}_\pi = M_{\rm Pl}^2 \dot{H} (\partial_\mu \pi)^2$$

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

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

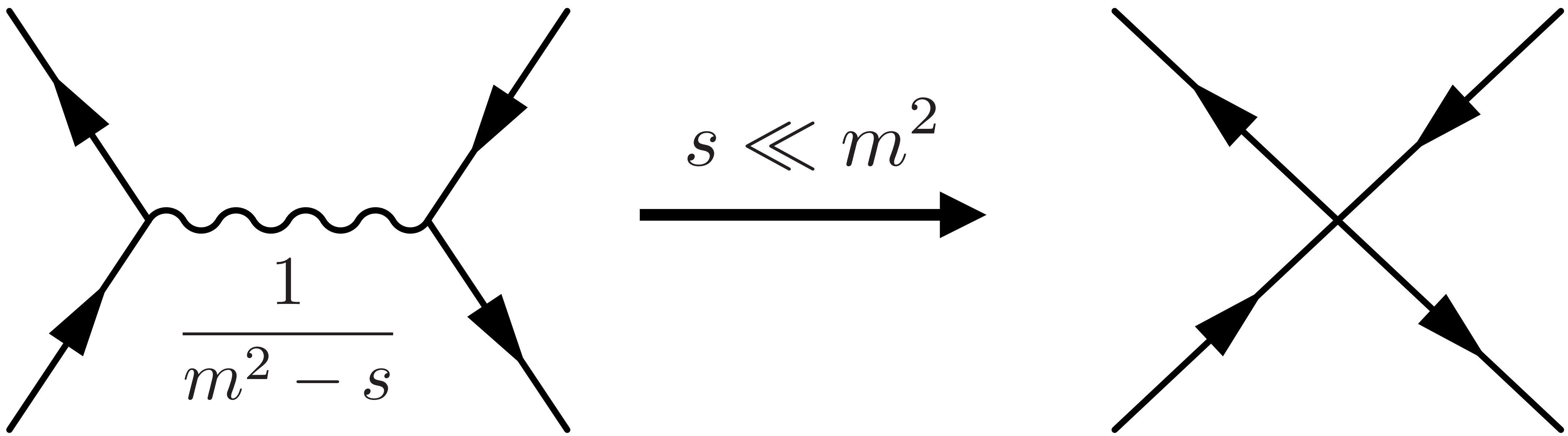
in the rest of my talk …

- how to detect new particles w/non-G

- up to which scale we may explore

new particles @ collider

new particles @ collider



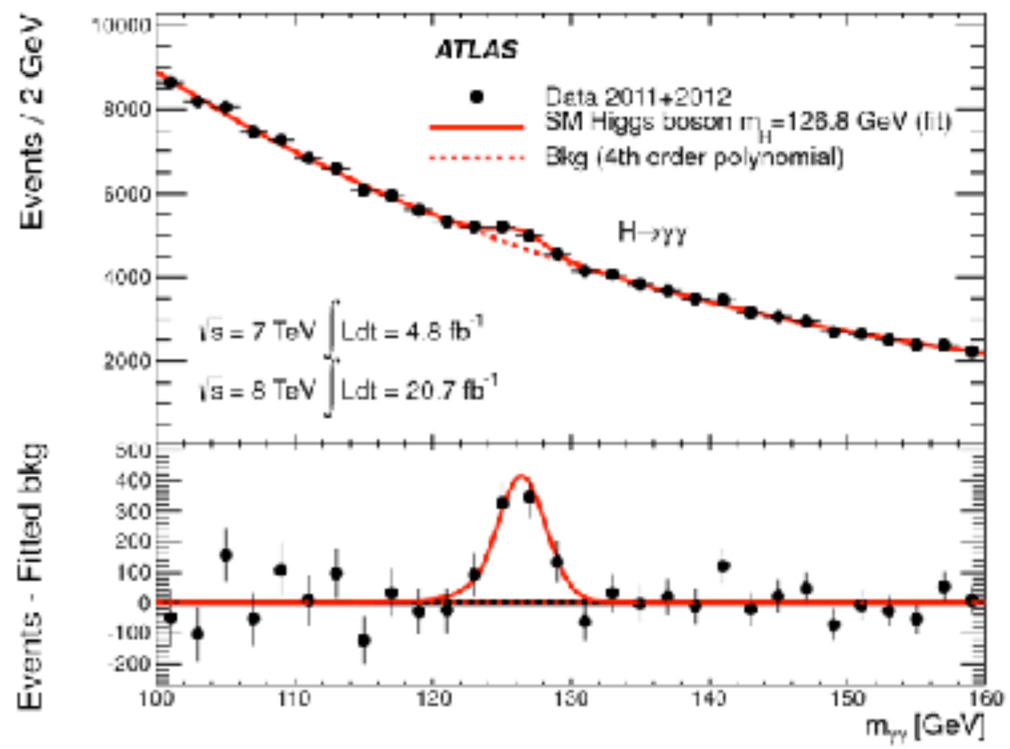
light particles $\rightarrow$ resonance

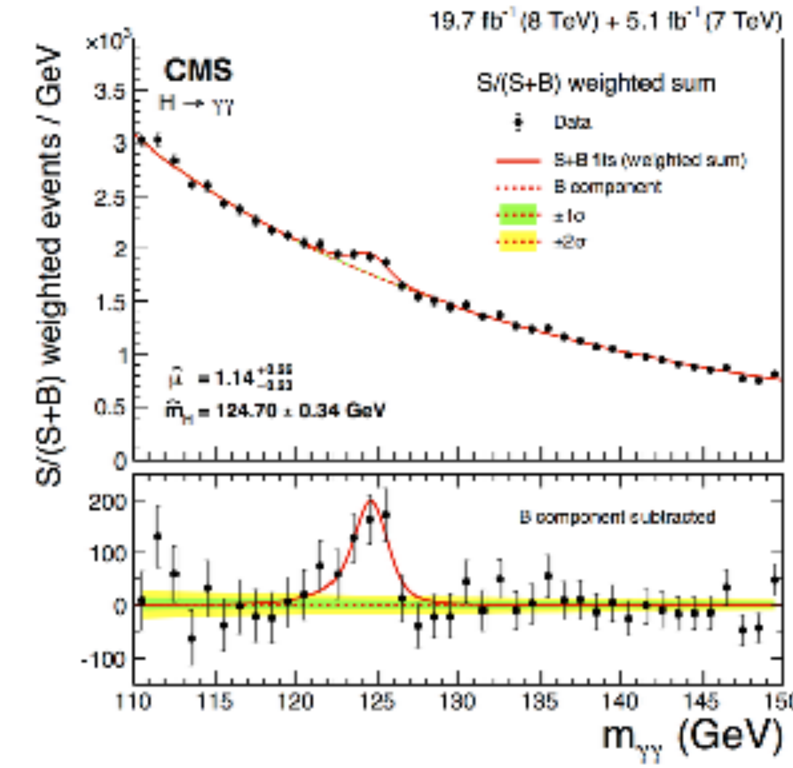
- non-analyticity @ $s \sim m^2$
- factorization of amplitudes

heavy particles $\rightarrow$ effective int.

ex. W boson was predicted

from Fermi interaction





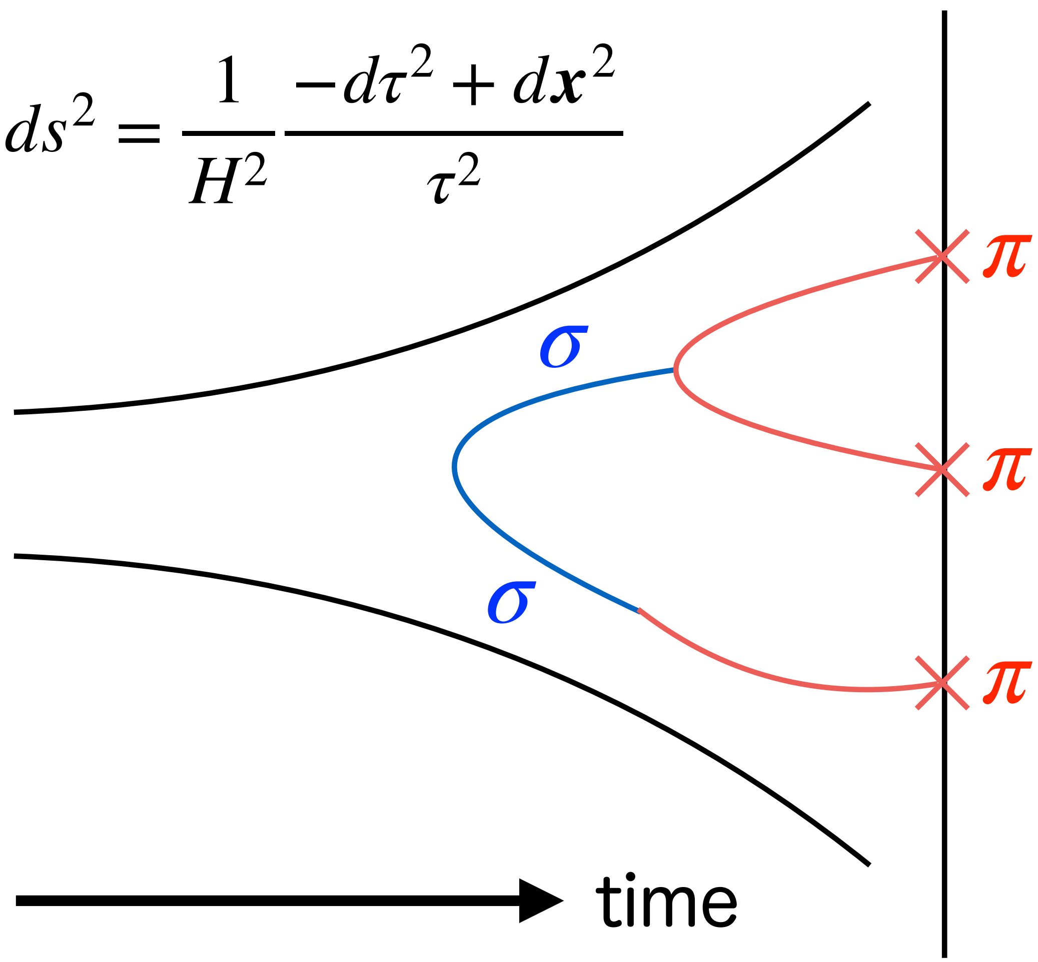
analogy with resonance?

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

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



time

$\tau = 0$

future boundary

(end of inflation)

inflationary correlation functions

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

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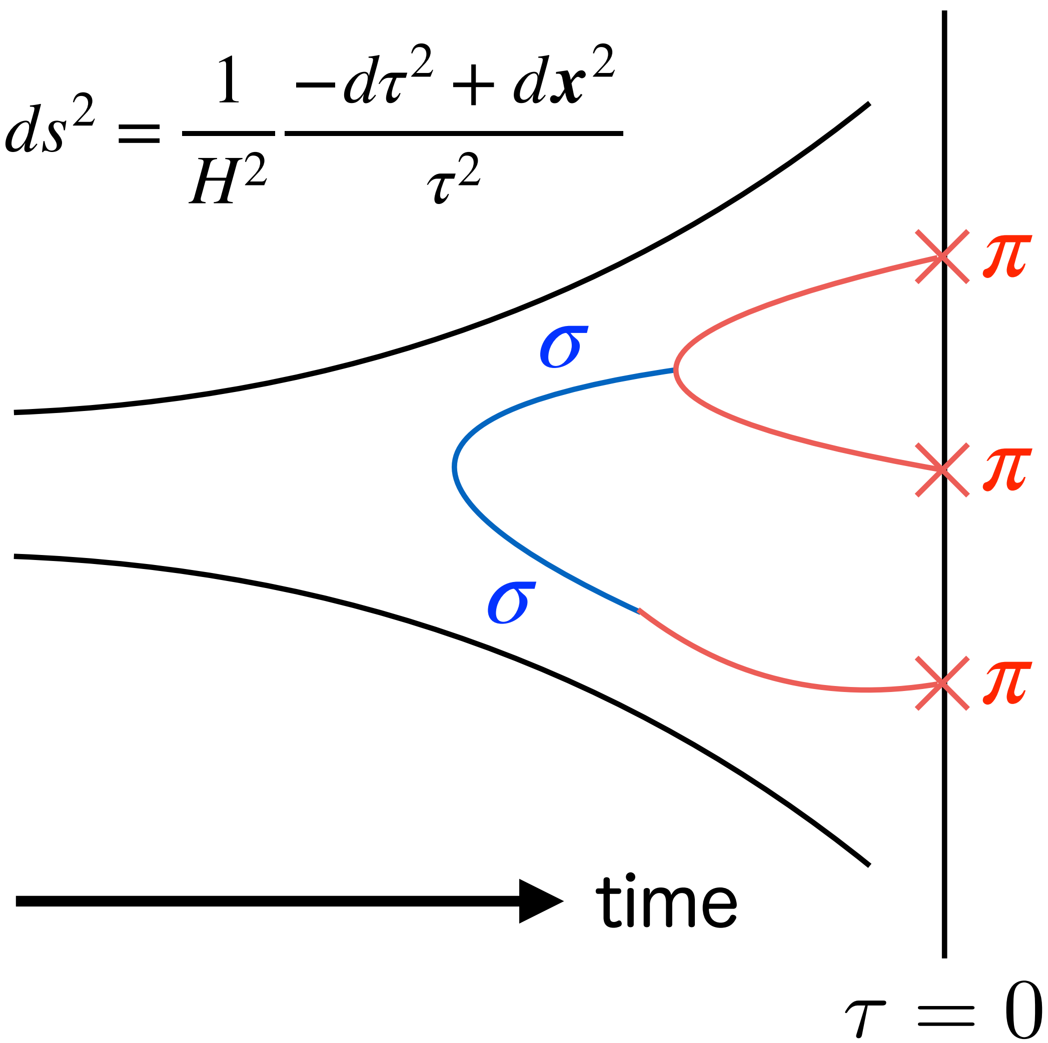

future boundary

(end of inflation)

dS boundary

- conformal symmetry on future b.d.
- analytic property is similar to CFT
- inflation breaks dS symmetry

special conf. is spontaneously broken

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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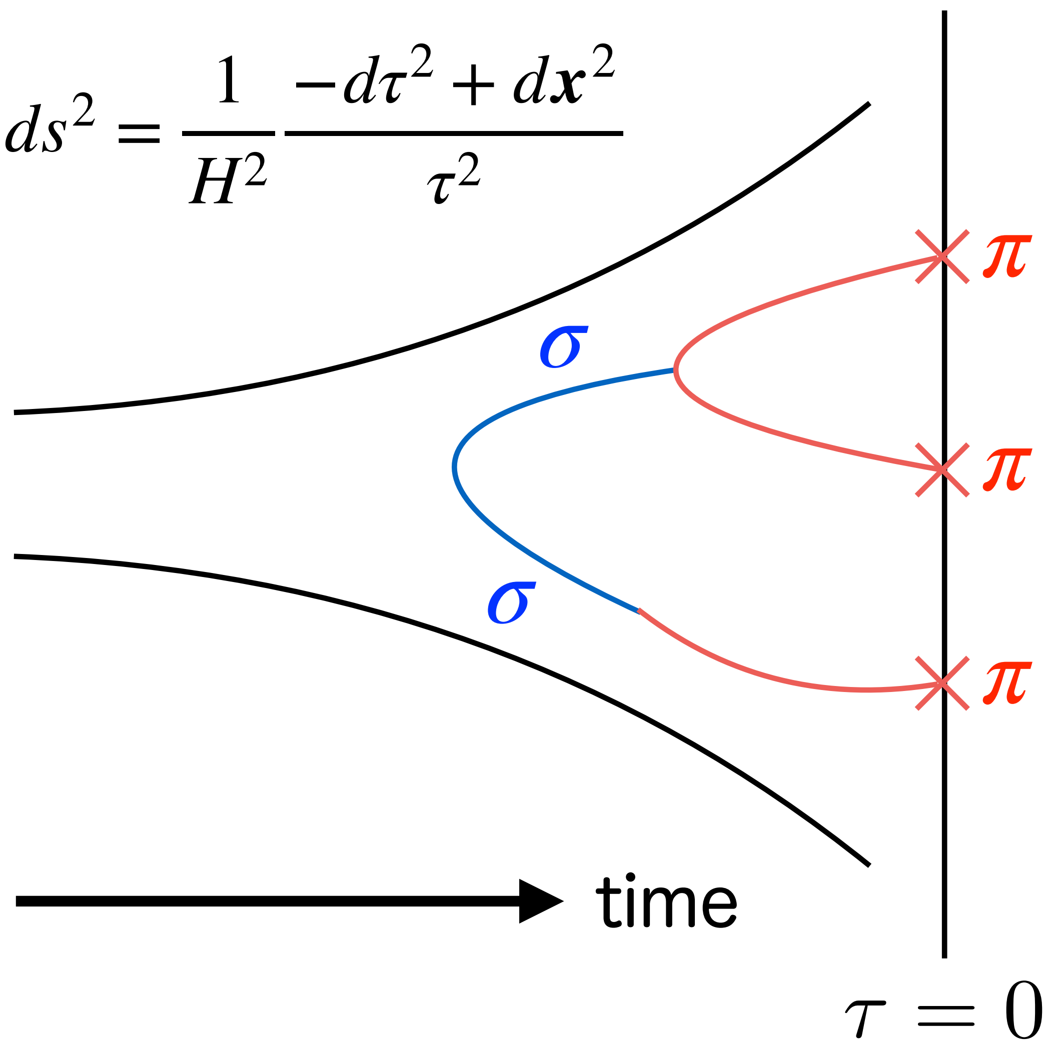

future boundary

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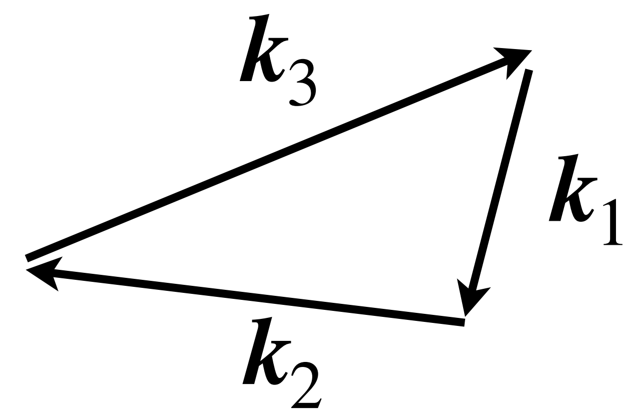
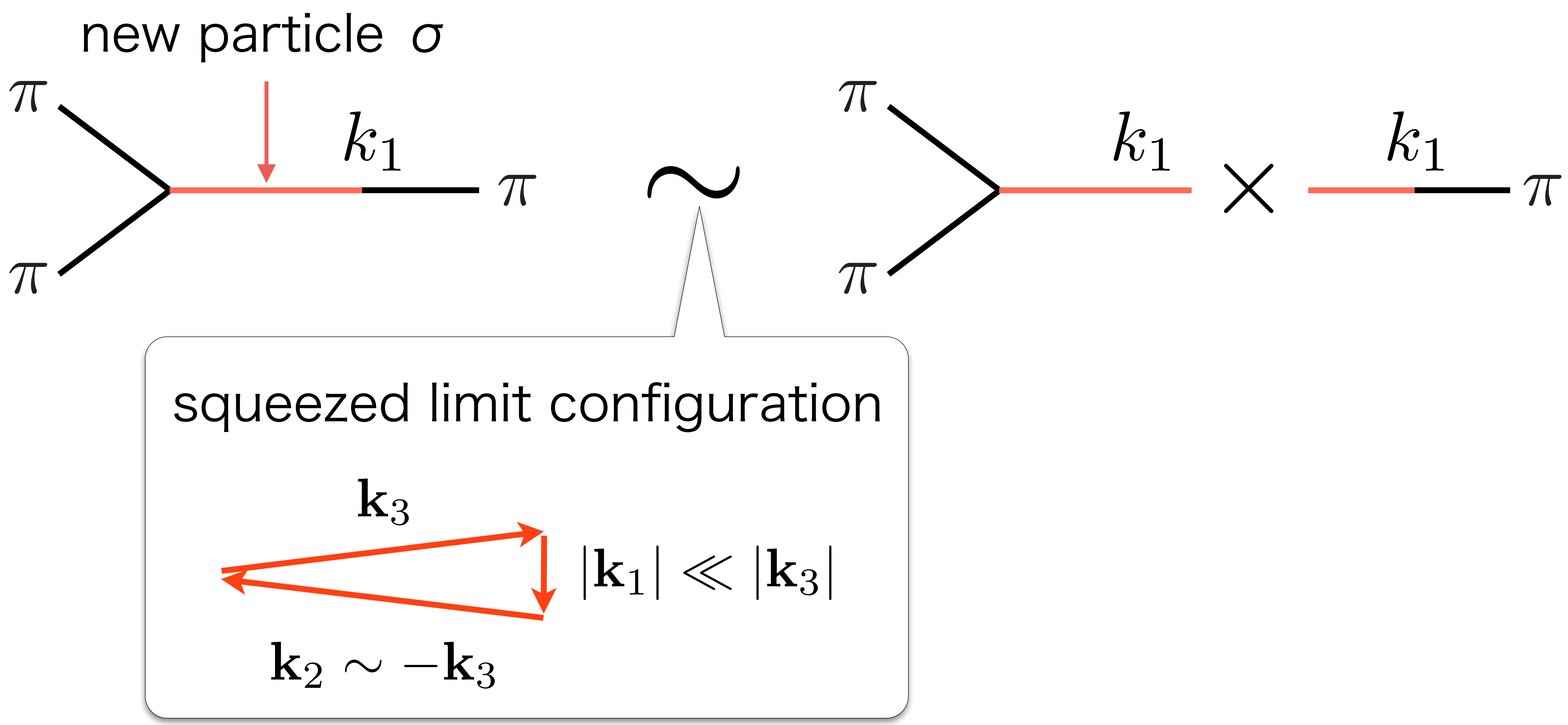


- functions of 3D spatial momenta
- approximate scale invariance

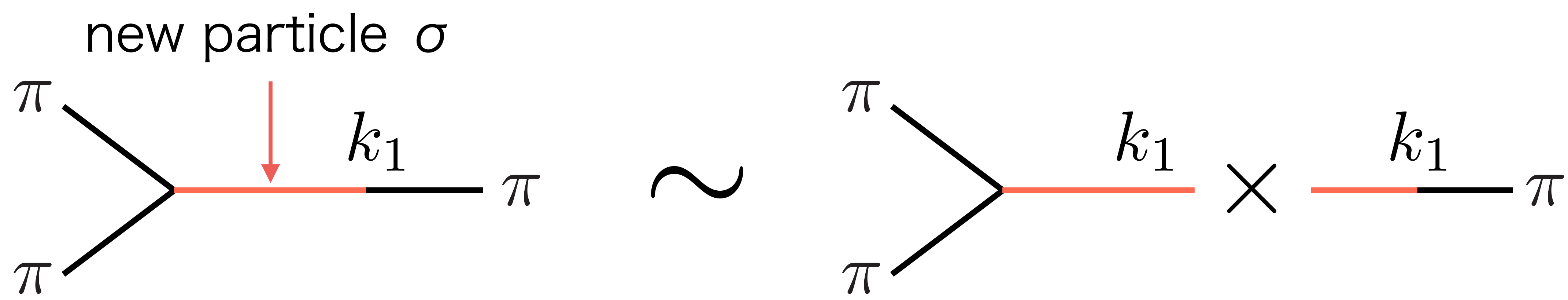
  → functions of triangle shape

A. analogue of resonance = soft limit

NG boson 3pt functions factorize in the squeezed limit



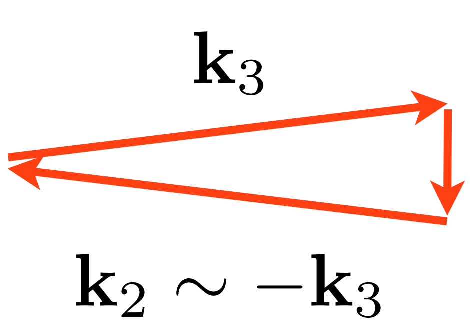
NG boson 3pt functions factorize in the squeezed limit



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

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

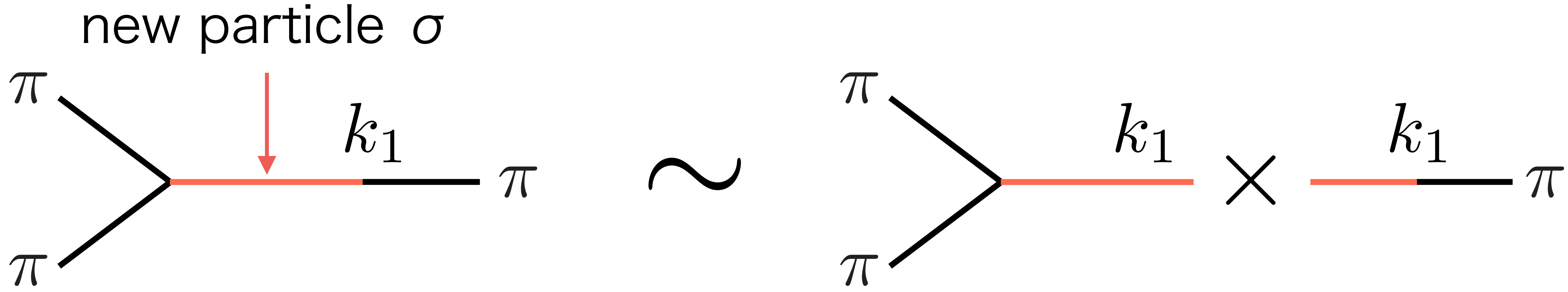
squeezed limit config.



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

mass of the new particle!

NG boson 3pt functions factorize in the squeezed limit



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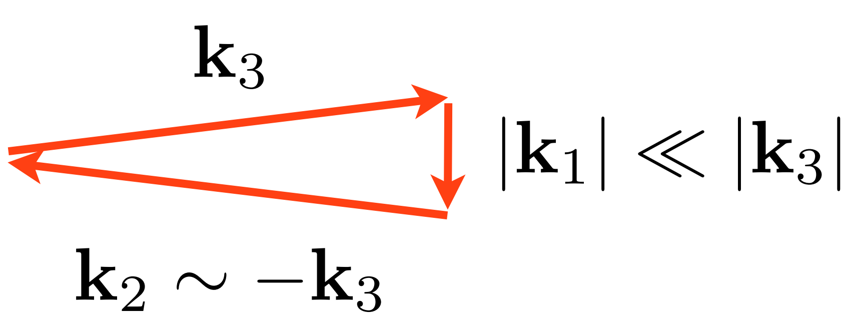
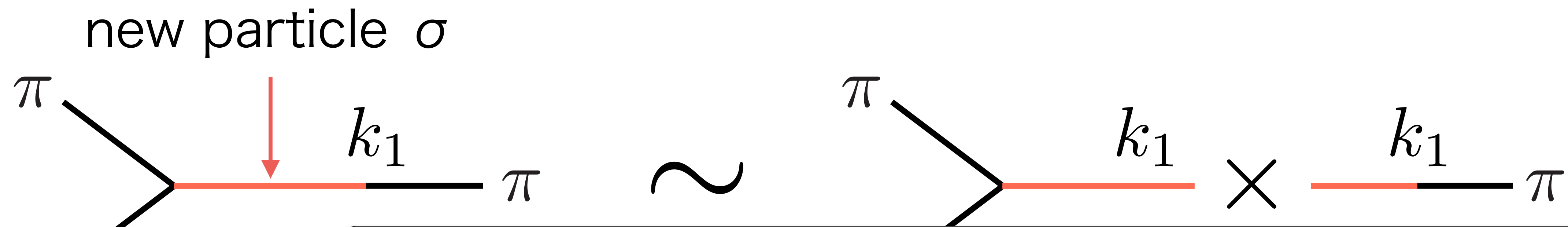
squeezed limit config.



mass of the new particle!

NG boson 3pt functions factorize in the squeezed limit



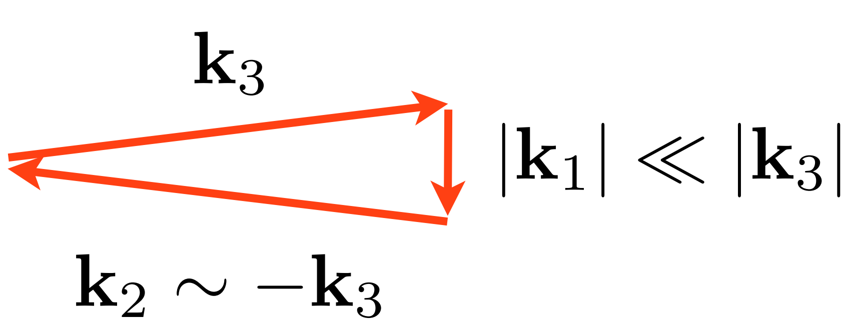
generically of t

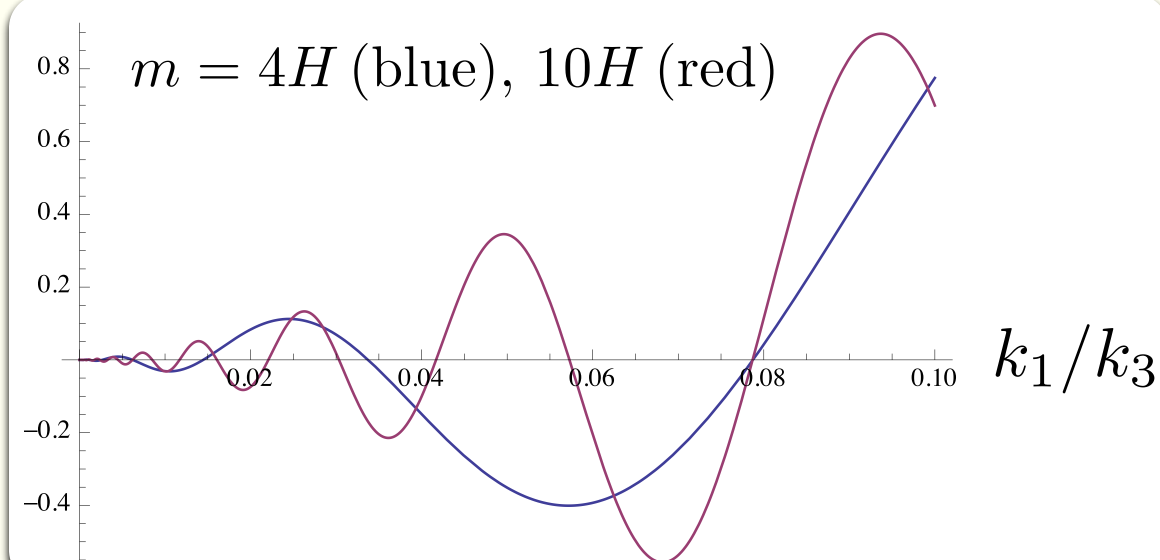
Boltzmann suppression:

non-analytic signal is highly suppressed for $m \gg H$

$$\frac{\langle \zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle'}{\langle \zeta_{\mathbf{k}_1}\zeta_{-\mathbf{k}_1}\rangle'\langle \zeta_{\mathbf{k}_3}\zeta_{-\mathbf{k}_3}\rangle'} \propto e^{-\pi\mu}(k_1/k_3)^{3/2}\sin\left[\mu\ \ln(k_1/k_3)+\ \text{phase}\right]$$

squeezed limit config.



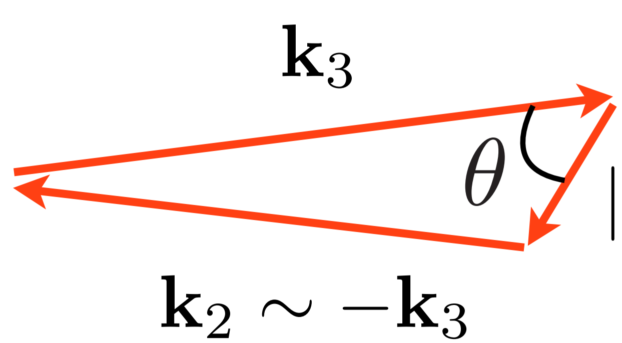


more generally,

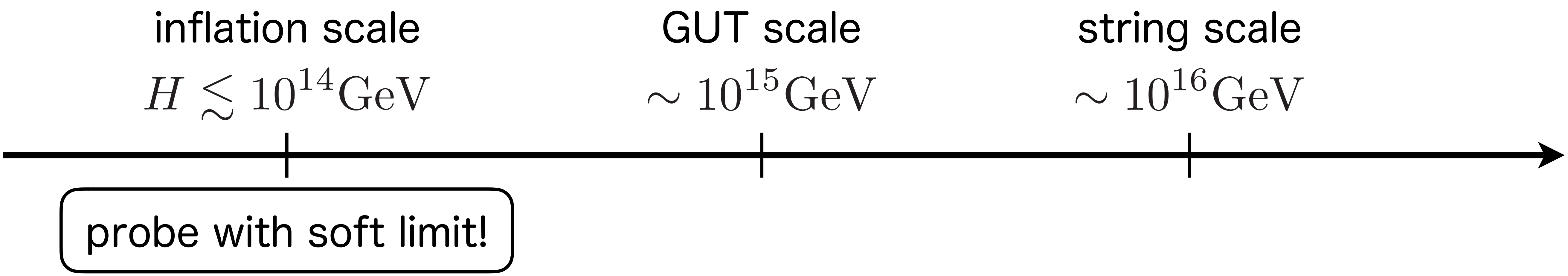
spin of new particle can be read off from angular dependence

[Arkani Hamed-Maldacena ’15]

squeezed limit configuration



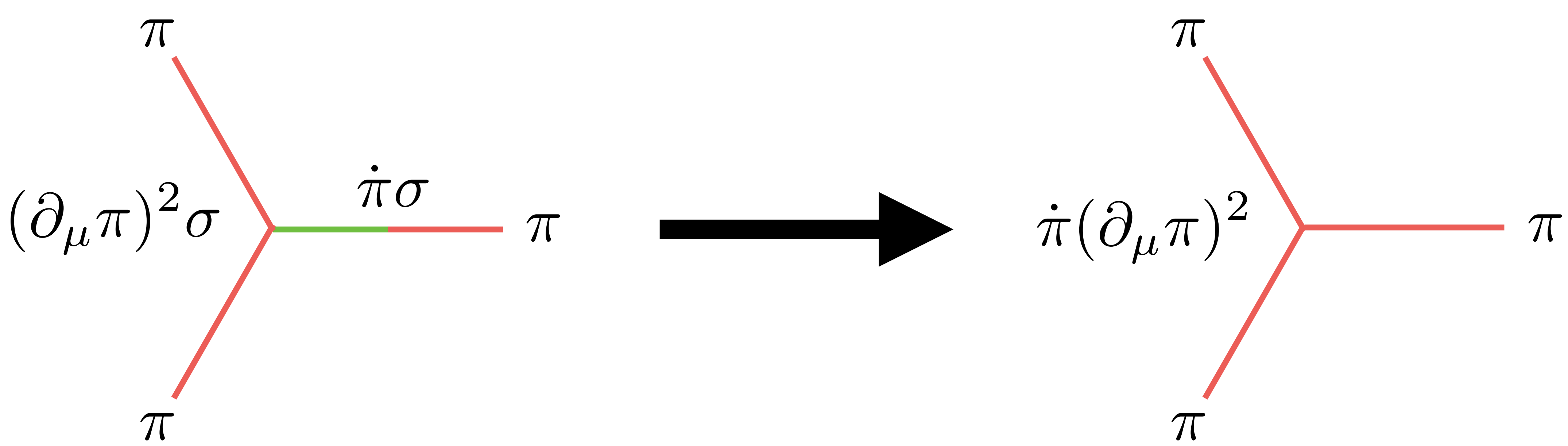
$|\mathbf{k}_1| \ll |\mathbf{k}_3| \quad \propto P_s(\cos\theta)$ (s: spin of new particle)



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 are captured by effective interactions

※ 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

$$\mathscr{L}_\phi = -\frac{1}{2}(\partial_\mu \phi)^2 + \frac{\alpha}{\Lambda^4}(\partial_\mu \phi \partial^\mu \phi)^2 + \cdots$$

- can be used to probe small non-G (generically $f_{NL} < \mathcal{O}(1)$)
- NG boson vs inflaton: $\phi(t,\vec{x}) = \bar{\phi}(t + \pi(t,\vec{x}))$

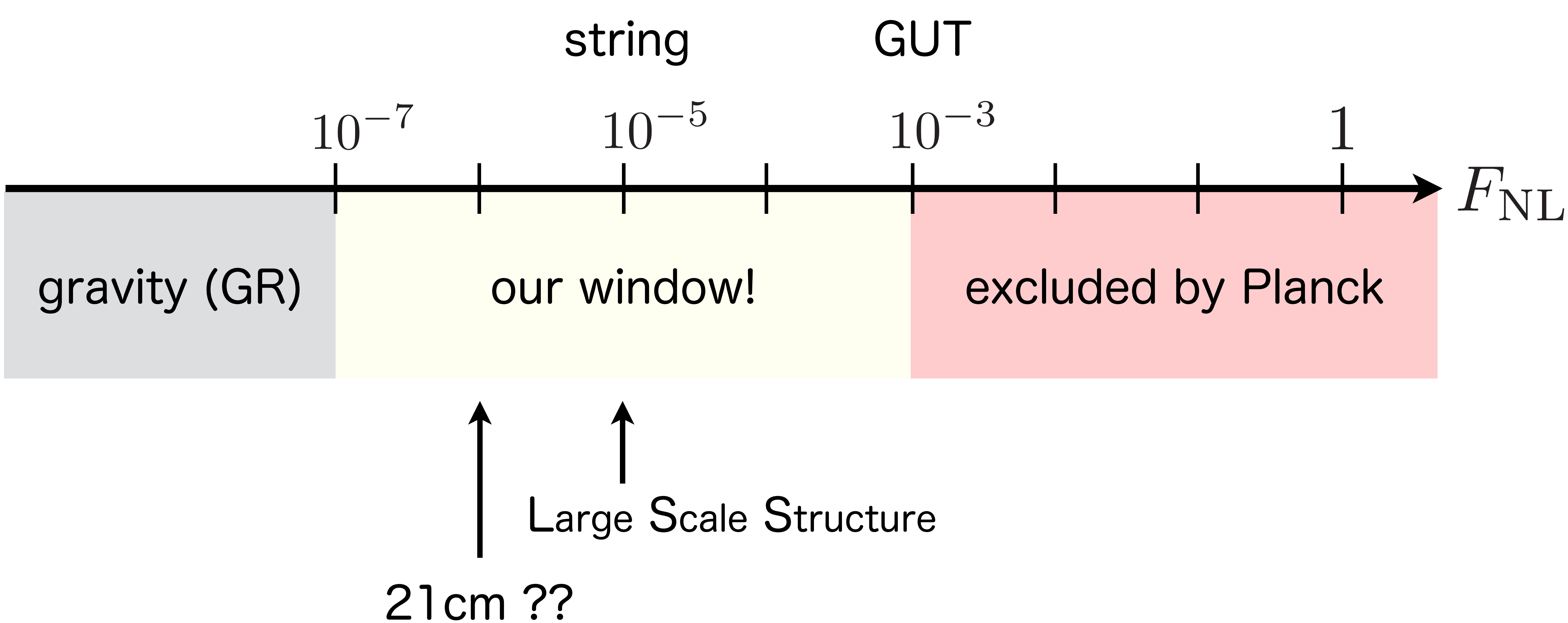
ex. $(\partial_\mu \phi)^2 = \dot{\bar{\phi}}^2 \partial_\mu (t+\pi) \partial^\mu (t+\pi) = \dot{\bar{\phi}}^2 \left[-1 - 2\dot{\pi} + (\partial_\mu \pi)^2 \right]$

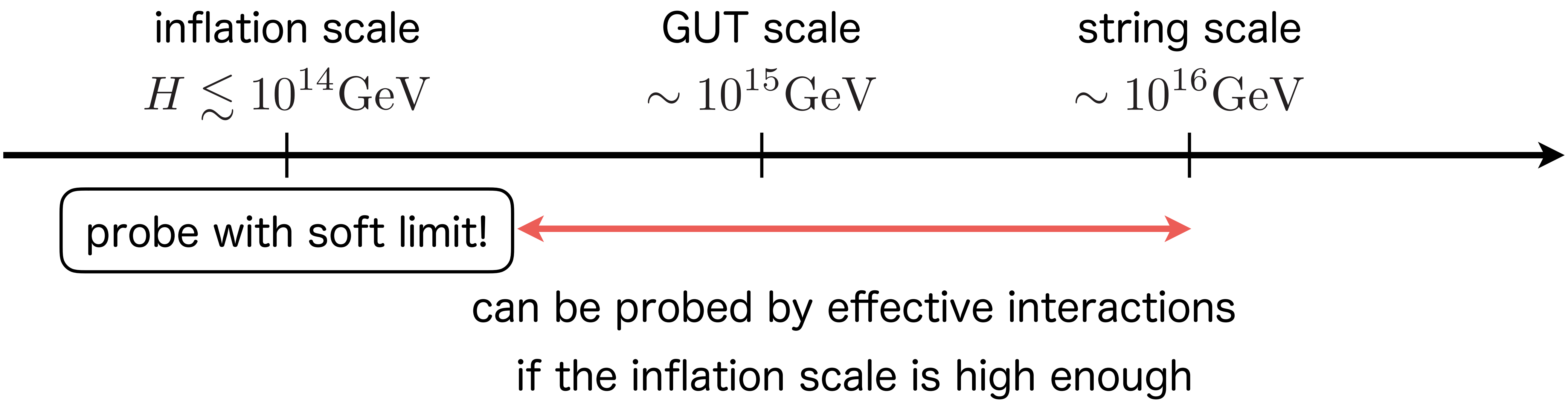
up to which scale we can probe?

$$H^2 \propto r$$

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

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





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

Q. how to identify spin from effective interactions?

A. Let's go beyond the positivity bound!

[Kim-TN-Takeuchi-Zhou to appear on Monday]

Heavy Spinning Particles from Signs of Primordial Non-Gaussianities: Beyond the Positivity Bounds

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Abstract: Within the so-called cosmological collider program, imprints of new particles on primordial non-Gaussianities have been studied intensively. In particular, their non-analytic features in the soft limit provide a smoking gun for new particles at the inflation scale. While this approach is very powerful to probe particles of the mass near the Hubble scale, the signal is exponentially suppressed for heavy particles. In this paper, to enlarge the scope of the cosmological collider, we explore a new approach to probing spins of heavy particles from signs of Wilson coefficients of the inflaton effective action and the corresponding primordial non-Gaussianities. As a first step, we focus on the regime where the de Sitter conformal symmetry is weakly broken. It is well known that the leading order effective operator $(\partial_\mu\phi\partial^\mu\phi)^2$ is universally positive as a consequence of unitarity. In contrast, we find that the sign of the six derivative operator $(\nabla_\mu\partial_\nu\phi)^2(\partial_\rho\phi)^2$ is positive for intermediate heavy scalars, whereas it is negative for intermediate heavy spinning particles, hence the sign can be used to probe spins of heavy states generating the effective operator. We also study phenomenology of primordial non-Gaussianities thereof.

in [Kim-TN-Takeuchi-Zhou to appear]

as a first step, we focused on the small non-G regime

and studied spin vs sign in the EFT of the inflaton

Positivity of the inflaton effective interaction

EFT of the inflaton ϕ (approximately shift symmetric)

$$\mathscr{L} = -\frac{1}{2}(\partial_\mu \phi)^2 + \frac{\alpha}{\Lambda^4}(\partial_\mu \phi \partial^\mu \phi)^2 + \cdots$$

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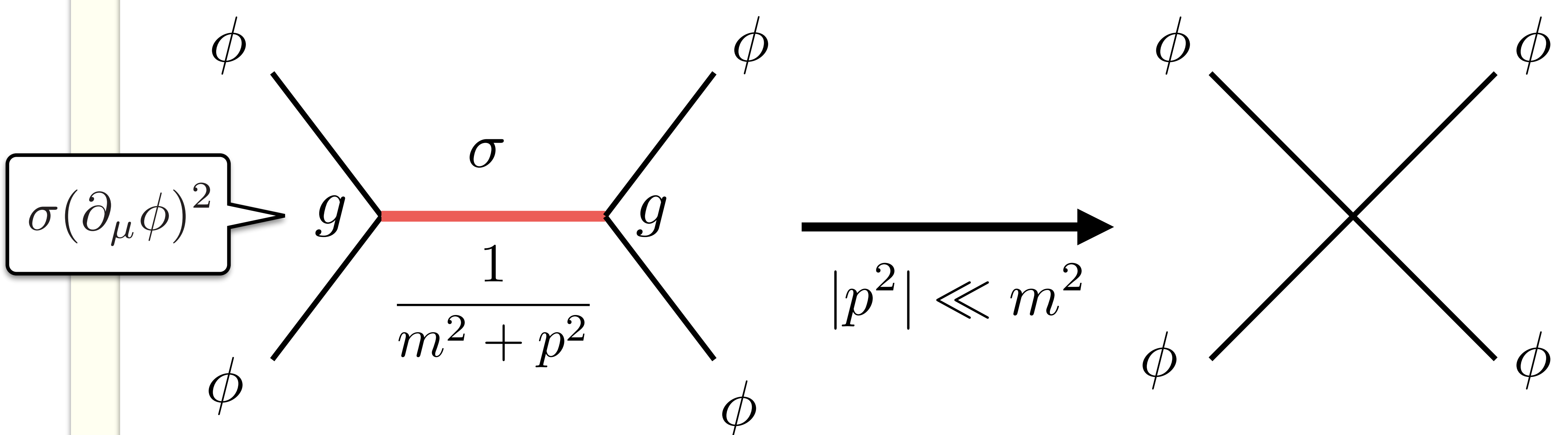
※ α shows up, e.g., after integrating out a heavy field σ



the effective coupling is $\dfrac{\alpha}{\Lambda^4} = \dfrac{g^2}{2m^2} \geq 0$

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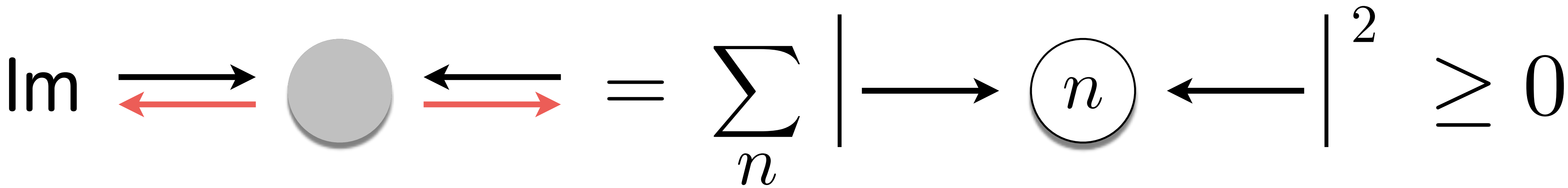
more generally, positivity of α follows only from

- unitarity of UV completion



- analyticity & locality of forward amplitudes

[Adams-Arkani Hamed-Dubovsky-Nicolis-Rattazzi '06] positivity bounds are

- universal & elegant consistency cond.!
- detailed info (ex. spin) of UV particles is obscured at the cost of universality

our main massage:

signs of interactions not constrained by positivity

are useful to probe spins of heavy particles!

Beyond the positivity bounds

EFT of the inflaton ϕ (approximately shift symmetric)

$$\mathscr{L} = -\frac{1}{2}(\partial_\mu \phi)^2 + \frac{\alpha}{\Lambda^4}(\partial_\mu \phi \partial^\mu \phi)^2 + \frac{\beta}{\Lambda^6}(\partial_\mu \phi)^2 \Box (\partial_\mu \phi)^2 + \cdots$$

① IR expansion of 4pt scattering amplitudes

$$M_4(s,t) = \frac{4\alpha}{\Lambda^4}\left(s^2 + st + t^2\right) - \frac{6\beta}{\Lambda^6}\left(s^2 t + st^2\right) + \cdots$$

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② analyticity & unitarity imply

$$M_4(s,t) = \sum_n g_n^2 P_{l_n}\left(1 + \frac{2t}{m_n^2}\right)\left[\frac{1}{m_n^2 - s} + \frac{1}{m_n^2 + s + t}\right] + \alpha_0(t) + \alpha_1(t)s$$

- m_n and l_n are mass and spin of UV state n
- assumed $|M_4(s,t)| < s^2$ for large s and tiny negative t (fixed)

Beyond the positivity bounds

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$$\mathscr{L} = -\frac{1}{2}(\partial_\mu\phi)^2 + \frac{\alpha}{\Lambda^4}(\partial_\mu\phi\partial^\mu\phi)^2 + \frac{\beta}{\Lambda^6}(\partial_\mu\phi)^2\Box(\partial_\mu\phi)^2 + \cdots$$

① IR expansion of 4pt scattering amplitudes

$$M_4(s,t) = \frac{4\alpha}{\Lambda^4} \cdots$$

responsible for correct factorization
on the complex s plane

② analyticity & unitarity imply

$$M_4(s,t) = \boxed{\sum_n g_n^2 P_{l_n}\left(1+\frac{2t}{m_n^2}\right)\left[\frac{1}{m_n^2 - s} + \frac{1}{m_n^2+s+t}\right]} + \alpha_0(t) + \alpha_1(t)s$$

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① IR expansion of 4pt scattering amplitudes

$$M_4(s,t) = \frac{4\alpha}{\Lambda^4}\left(s^2+st+t^2\right) - \frac{6\beta}{\cdots}\cdots$$

$\mathcal{O}(s^0)$ and $\mathcal{O}(s^1)$ cannot be determined

② analyticity & unitarity imply

$$M_4(s,t) = \sum_n g_n^2 P_{l_n}\!\left(1+\frac{2t}{m_n^2}\right)\left[\frac{1}{m_n^2-s}+\frac{1}{m_n^2+s+t}\right] + \boxed{\alpha_0(t)+\alpha_1(t)s}$$

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matching IR and UV expressions gives

$$\frac{\alpha}{\Lambda^4} = \sum_n \frac{g_n^2}{2m_n^6} > 0 \leftarrow$$ universal positivity bound (spin indep)

$$\frac{\beta}{\Lambda^6} = \sum_n \frac{g_n^2}{6m_n^8}(3 - 2\ell_n - 2\ell_n^2) \leftarrow$$ positive for scalars
negative for nonzero spins

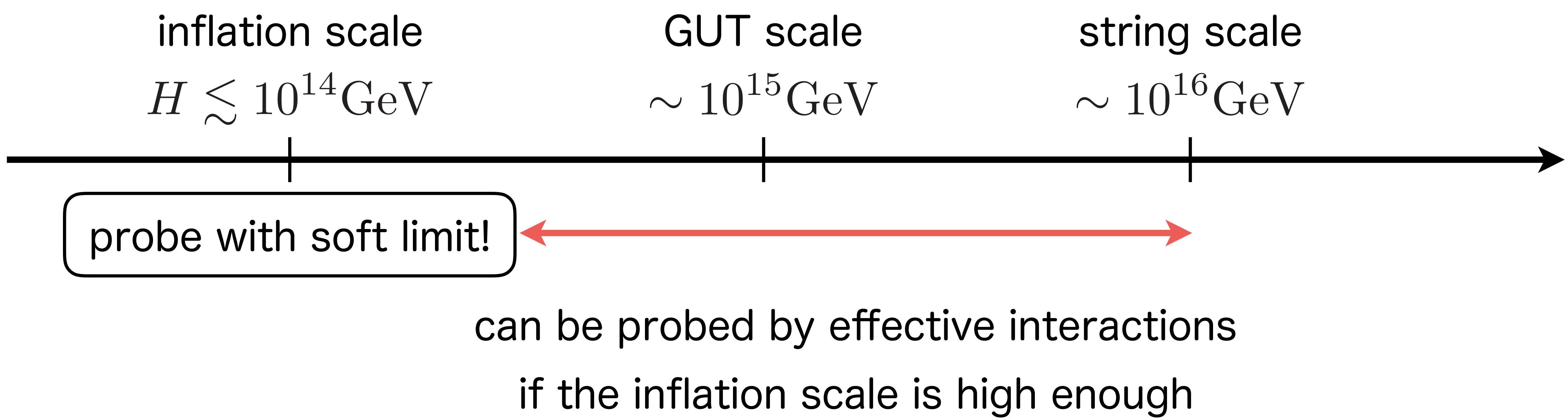
sign of β can be used to probe spin of heavy particles!

Summary and Prospects

A. energy scale of inflation $\sim 10^{14}$ GeV if $\epsilon \sim \eta$

※ near future experiments will clarify it!

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



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Thank you!