Inflation in String Theory
-Landscape and Swampland-

Toshifumi Noumi

(Kobe University)

13th July 2017 @ Quy Nhon

Quy Nhon

La Thuile

I have been interested in this Vietnam conference

※ I really enjoyed the Moriond 2014 at La Thuile in Italy

Inflation in String Theory
-Landscape and Swampland-

Toshifumi Noumi
(Kobe University)

13th July 2017 @ Quy Nhon

we enjoyed many nice talks on

how to test/constrain physics models observationally my talk is about

how to test/constrain physics models theoretically "healthy" UV completion

↓

my talk is about

how to test/constrain physics models theoretically

↑

low energy effective theories

mostly a review of general ideas in the community,

but quite biased and related to my own works

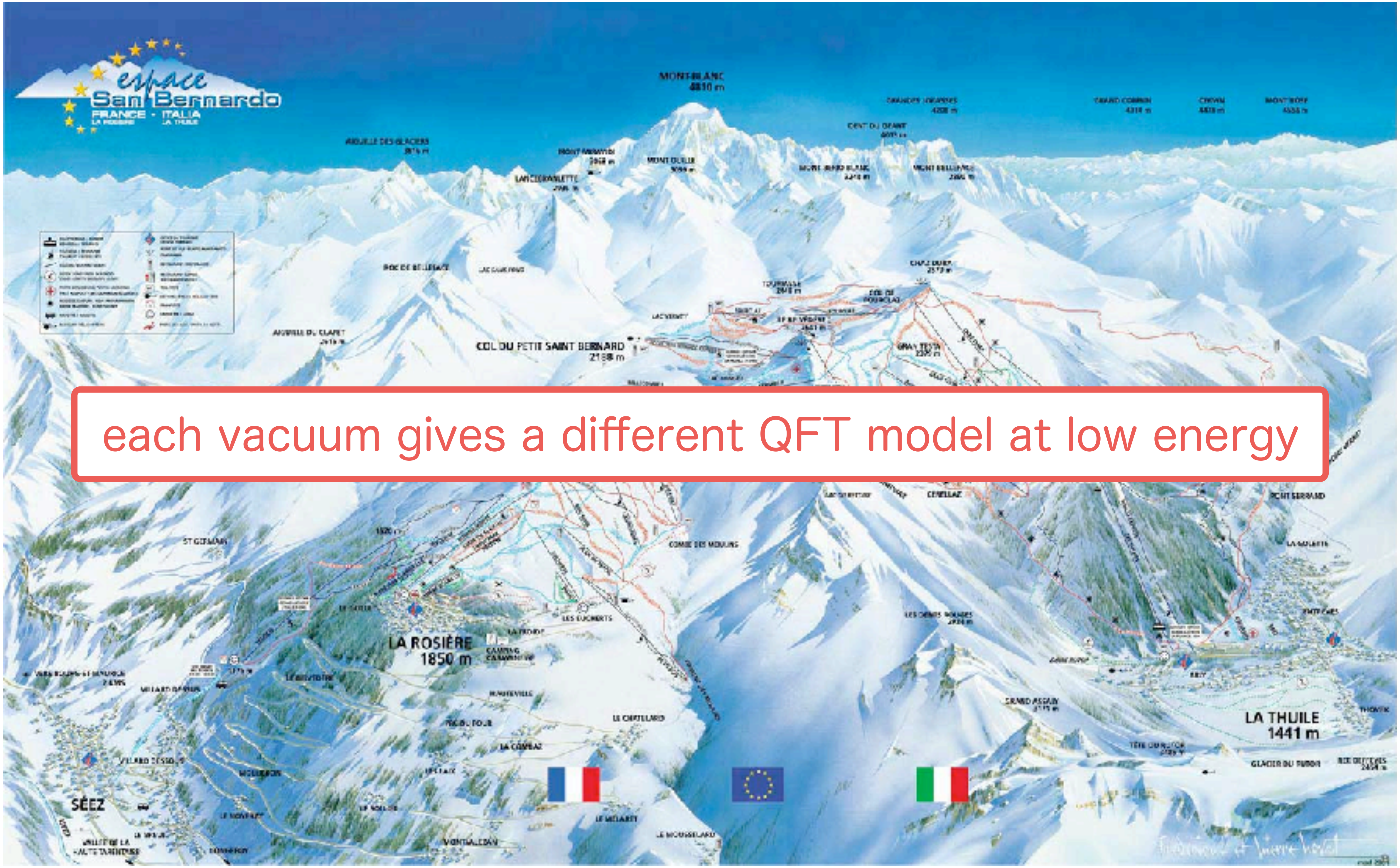
[Andriolo-Junghans-TN-Shiu to appear] [TN-Shiu in progress]

0. landscape vs swampland

probably, you have heard of “string landscape”

there seem to exist almost infinite vacua in string theory

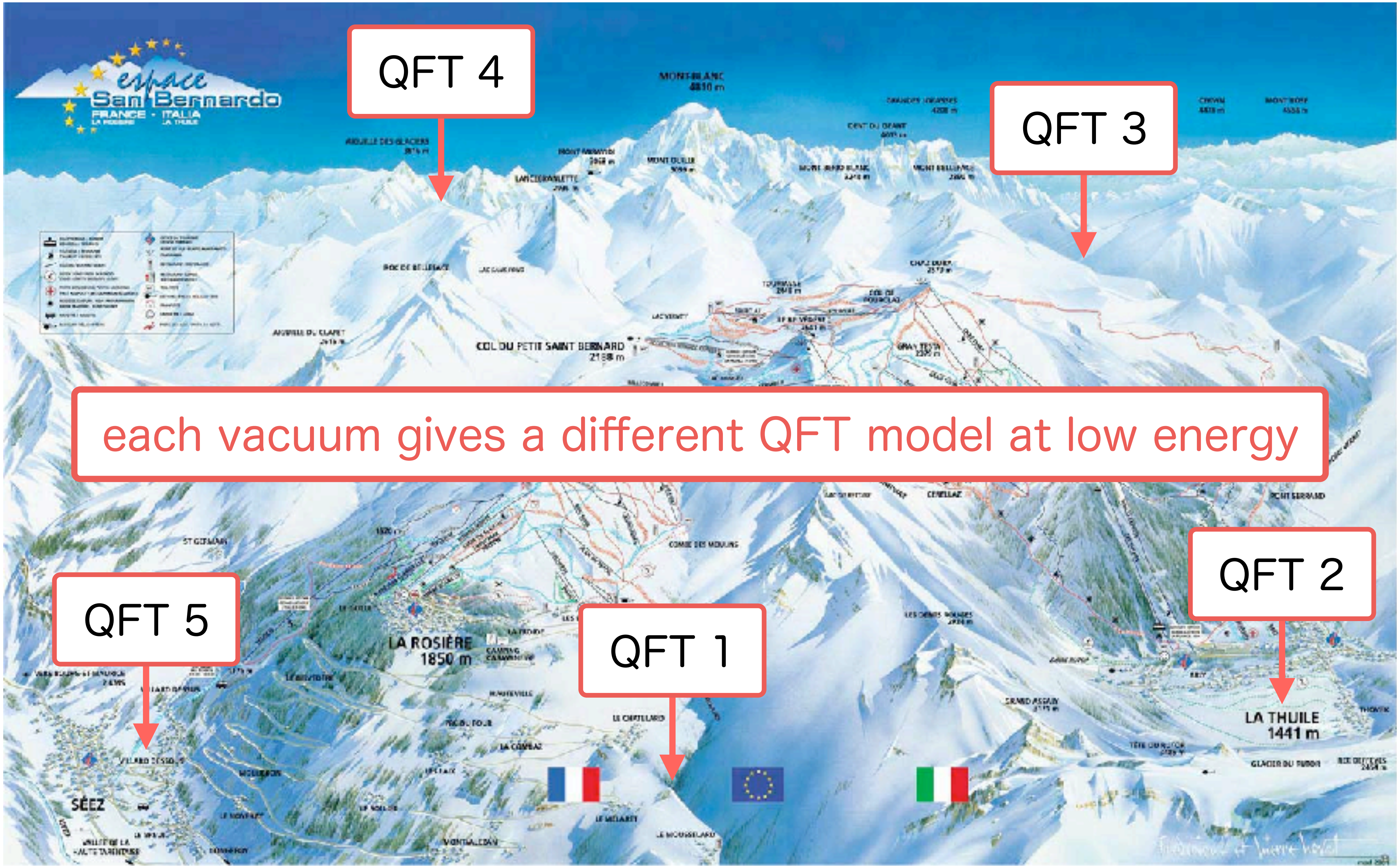
- how to compactify the extra dimensions
- how to put D-branes, ⋯



each vacuum gives a different QFT model at low energy

there seem to exist almost infinite vacua in string theory

- how to compactify the extra dimensions
- how to put D-branes, ⋯



there seem to exist almost infinite vacua in string theory

- how to compactify the extra dimensions
- how to put D-branes, ⋯

in traditional string phenomenology,

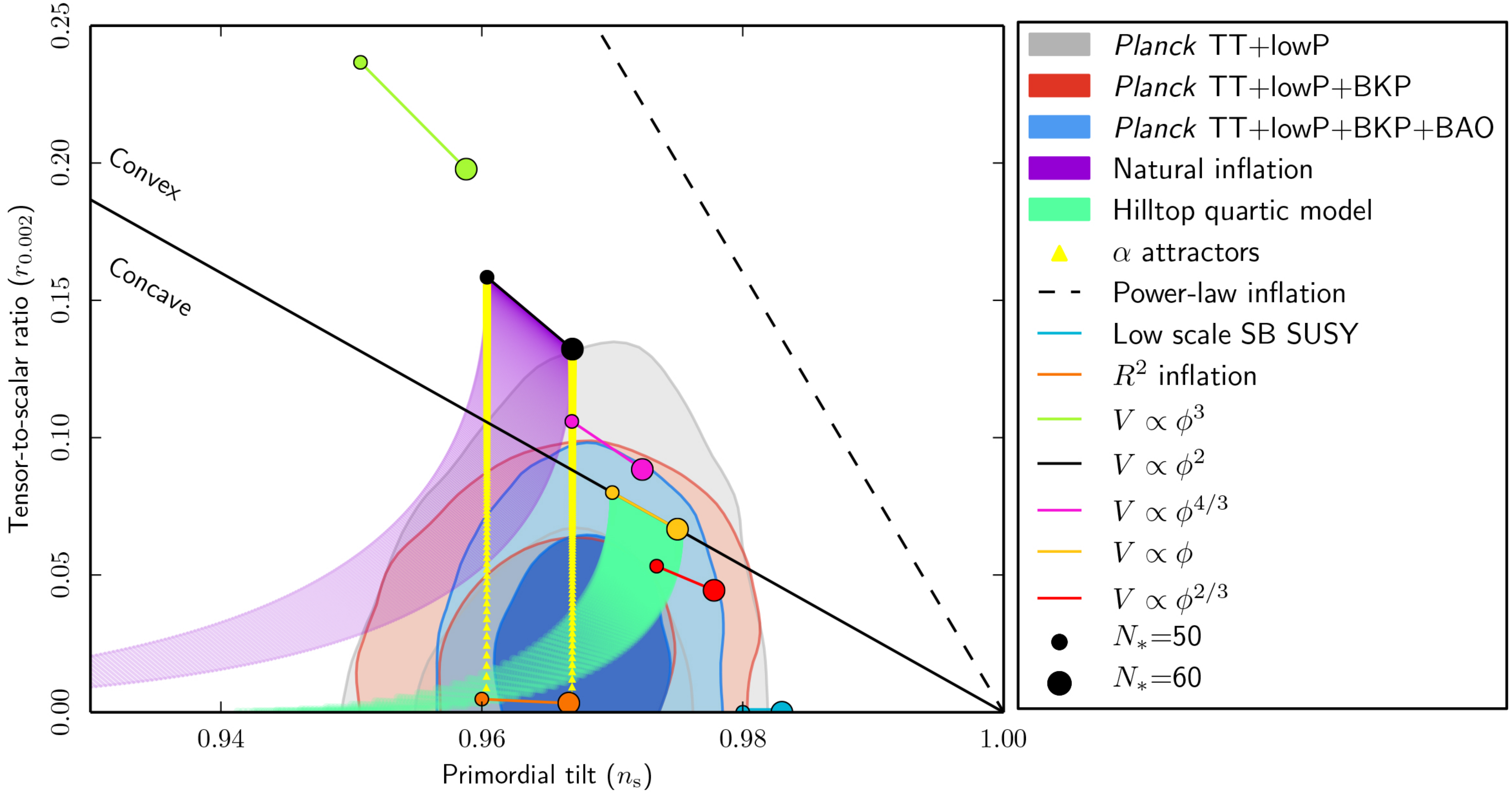
people look for vacua in the landscape ($\sim$ QFT models)

- describing Standard Model of particle physics
- realizing good models of inflation, dark matter, etc

in the case of inflation...

observational constraints on inflaton potential

primordial gravitational waves



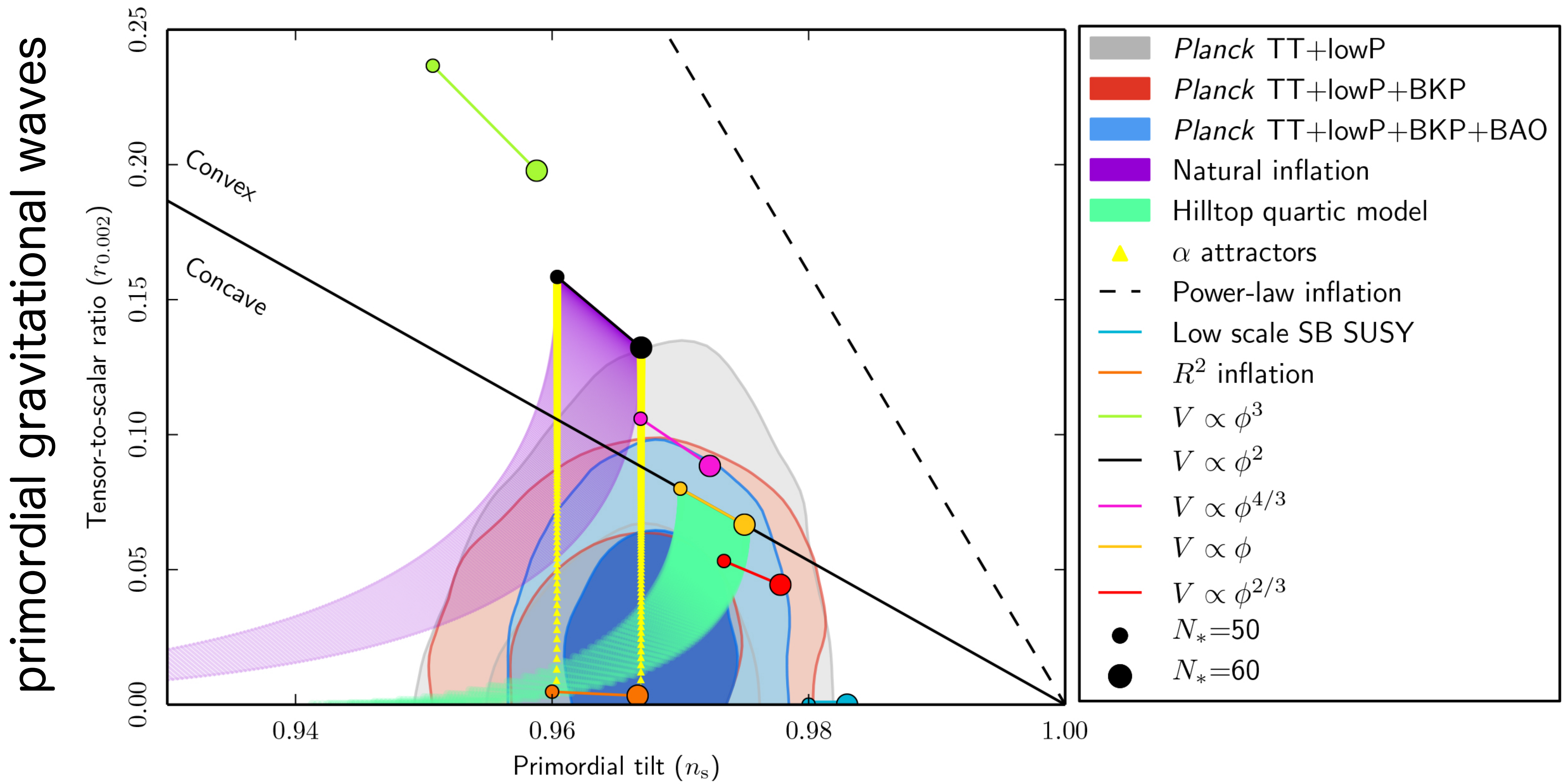
deviation from scale invariance

find a stringy setup reproducing correct inflaton potential!

it is known that there are a class of QFT models

which are “difficult” to realize in string theory a typical example is the so-called natural inflation

observational constraints on inflaton potential

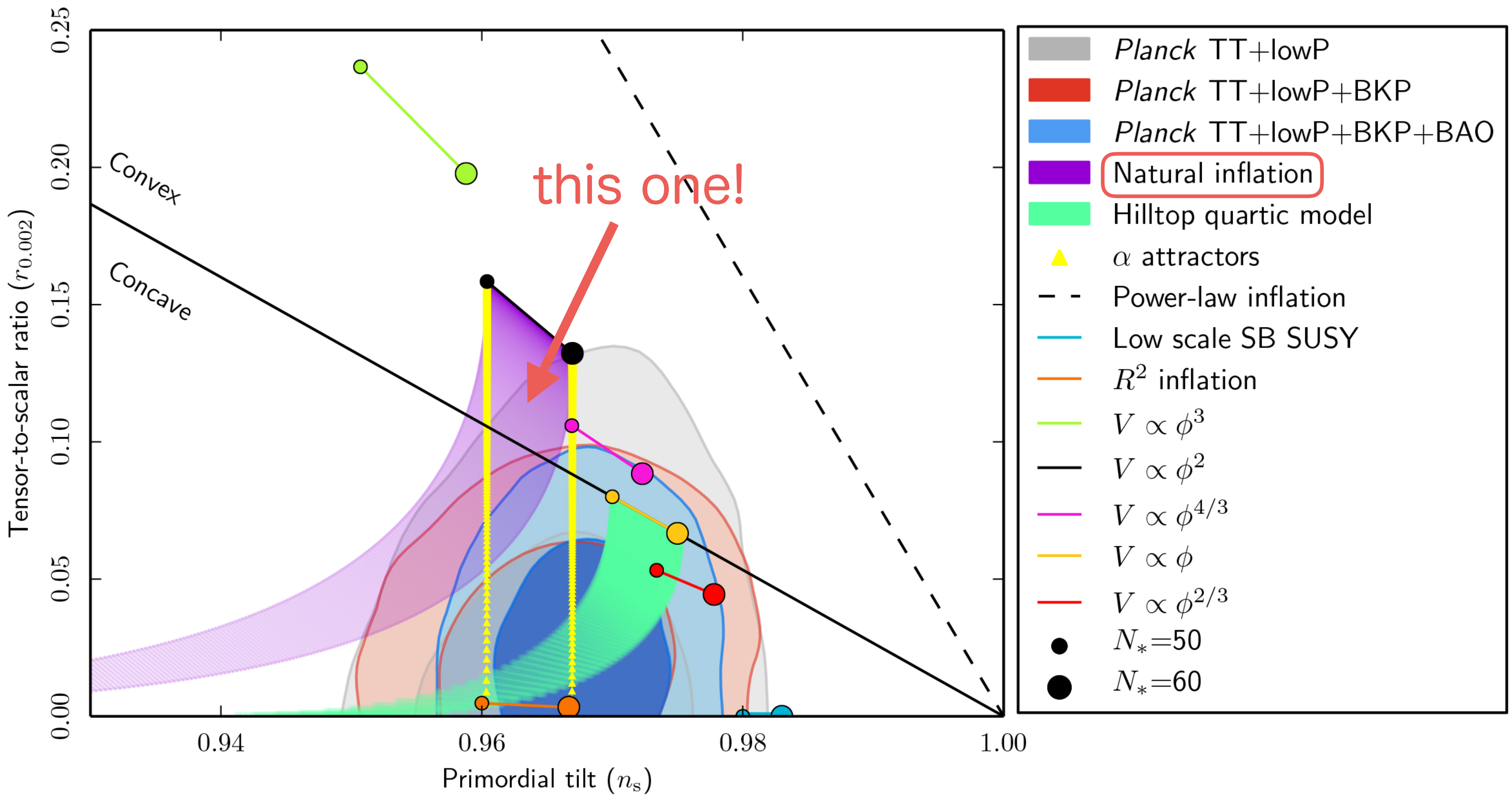


deviation from scale invariance

find a stringy setup reproducing correct inflaton potential!

observational constraints on inflaton potential

primordial gravitational waves



deviation from scale invariance

find a stringy setup reproducing correct inflaton potential!

natural inflation: axion = inflaton

natural inflation [Freese-Frieman-Olinto '90]

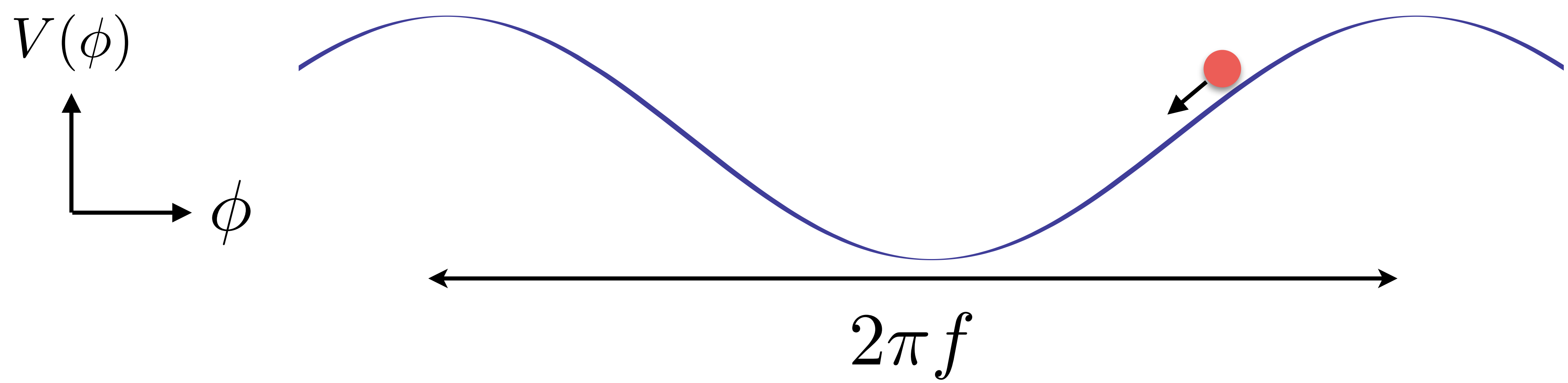
inflaton is an axion with the Lagrangian

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

$$V(\phi) \propto e^{-S_{\rm inst}}\left(1 - \cos\frac{\phi}{f}\right) + \sum_{n\geq 2} e^{-nS_{\rm inst}}\left(1 - \cos\frac{n\phi}{f}\right)$$

- f is the axion decay constant $\sim$ (coupling)$^{-1}$
- enjoys a periodic shift symmetry $\phi \to \phi + 2\pi f$
- $S_{\rm inst}$ is the instanton action $\sim$ energy

slow-roll axion potential



for a successful inflation,

inflaton potential has to be flat enough (slow-roll condition)

$$V(\phi) \propto e^{-S_{\rm inst}} \left(1 - \cos\frac{\phi}{f}\right) + \sum_{n\geq 2} e^{-nS_{\rm inst}} \left(1 - \cos\frac{n\phi}{f}\right)$$

- negligible higher harmonics ($n \geq 2$) $\to S_{\rm inst} > 1$
- long enough periodicity $\to f > M_{\rm Pl}$

string theory has so many axions,

but seems no axion satisfying these two conditions

[Banks-Dine-Fox-Gorbaatov ‘03]

Q. Is there any reason behind?

A. Not all the EFTs are UV completable
in a consistent way

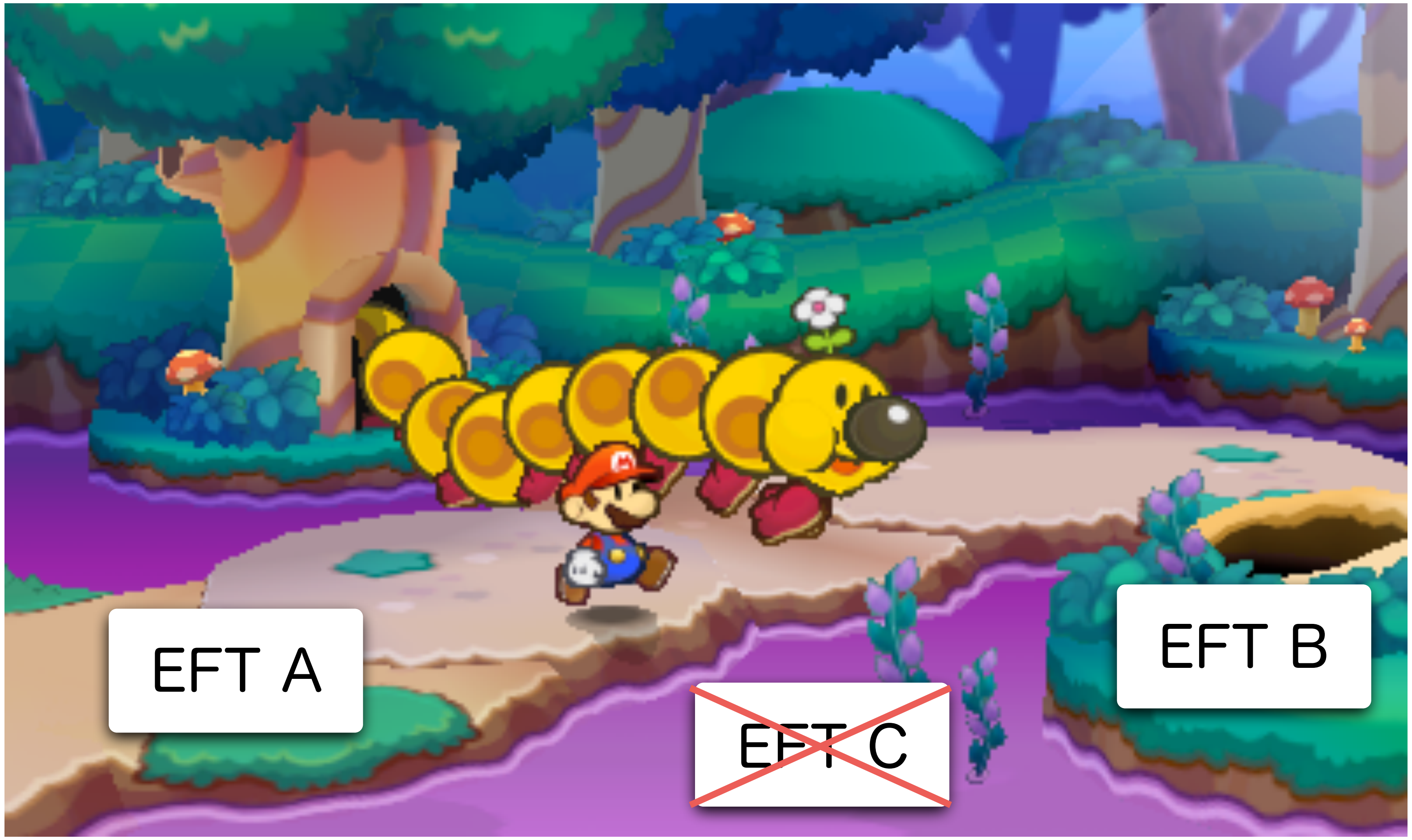
in string theory community,

such an idea is dubbed swampland

[Vafa ‘05]

landscape :

EFT with healthy UV completion



swampland :

apparently consistent, but problematic

clarifying boundaries of landscape and swampland

is important for both the theory and phenomenology in the rest of my talk,

I introduce 2 types of swampland arguments

1. weak gravity conjecture
2. positivity bounds

1. Weak Gravity Conjecture

the claim is very simple

“gravity is the weakest force”

Weak Gravity Conjecture

[ArkaniHamed-Motl-Nicolis-Vafa 06']

ex. electromagnetic force vs gravity

electric force $\sim g^2 q^2$ (g: gauge coupling, q: charge)

gravitational force $\sim G_N m^2 \sim \dfrac{m^2}{M_{\rm Pl}^2}$ (m: mass)

electric force > gravitational force $\rightarrow gq \geq \dfrac{m}{M_{\rm Pl}}$

roughly speaking, “coupling > energy”

WGC vs axion inflation

generalization to axion

$$V(\phi) \propto e^{-S_{\rm inst}}\left(1-\cos\frac{\phi}{f}\right)+\sum_{n\geq 2} e^{-nS_{\rm inst}}\left(1-\cos\frac{n\phi}{f}\right)$$

$S_{\rm inst} \sim$ energy of instanton, $f \sim$ (coupling) $^{-1}$

"coupling > energy" $\leftrightarrows \quad \frac{1}{f} > \frac{S_{\rm inst}}{M_{\rm Pl}} \quad \leftrightarrows \quad \frac{f}{M_{\rm Pl}} \cdot S_{\rm inst} < 1$

implications to axion inflation

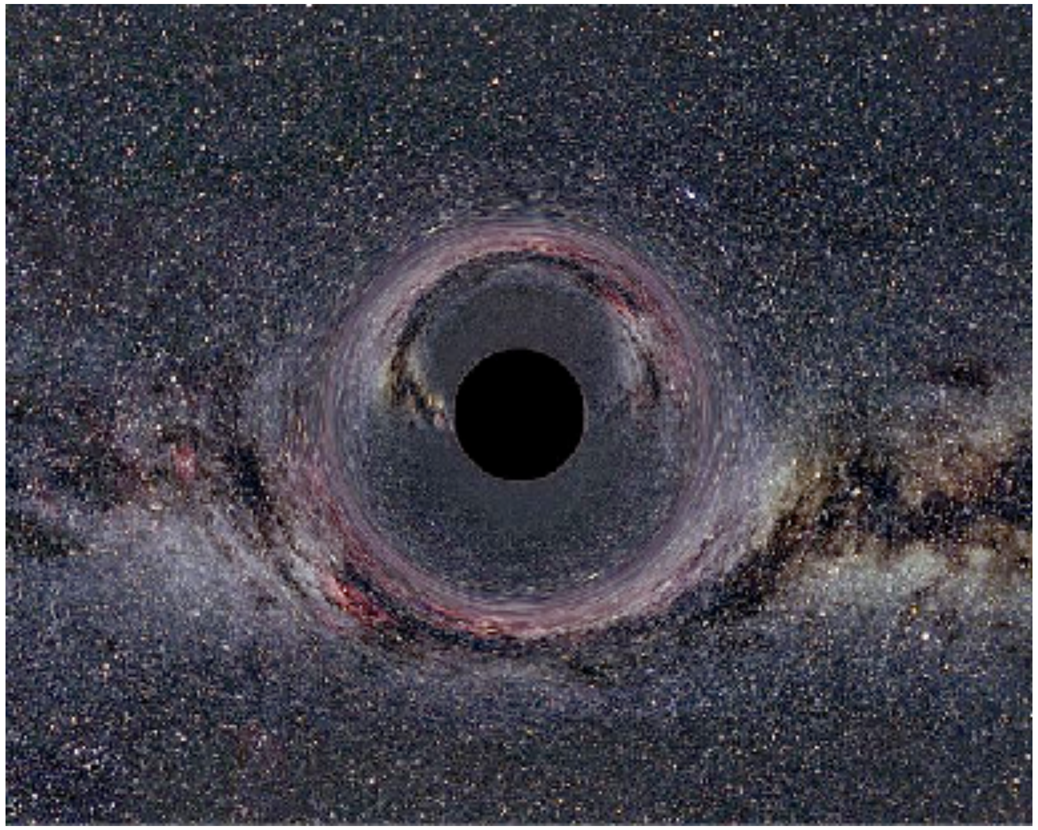
we need $S_{\rm inst} > 1$ and $f > M_{\rm Pl}$ for a successful inflation,

but WGC prohibits these two satisfied at the same time

Q. what is behind the conjecture?

A. black hole dynamics

black hole entropy



BH enjoys thermodynamic properties

[Bekenstein, Hawking,...]

in particular, its entropy S is

$$S = \frac{A}{4} \quad (A : \text{horizon area})$$

in quantum gravity (= microscopic description of gravity)

we expect that BH entropy is statistical entropy $S = -\mathrm{tr}(\rho \ln \rho)$

indeed, string theory explicitly showed that it is the case

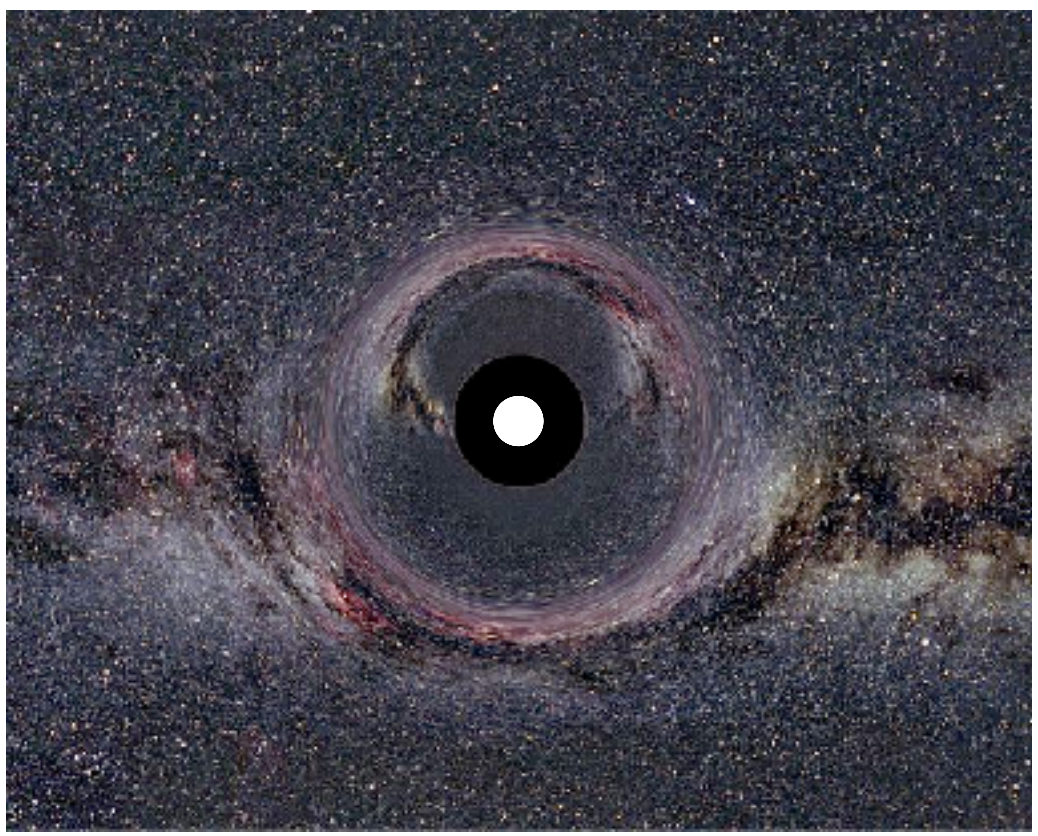
at least for certain black holes [Strominger-Vafa '96]

no global symmetry in quantum gravity

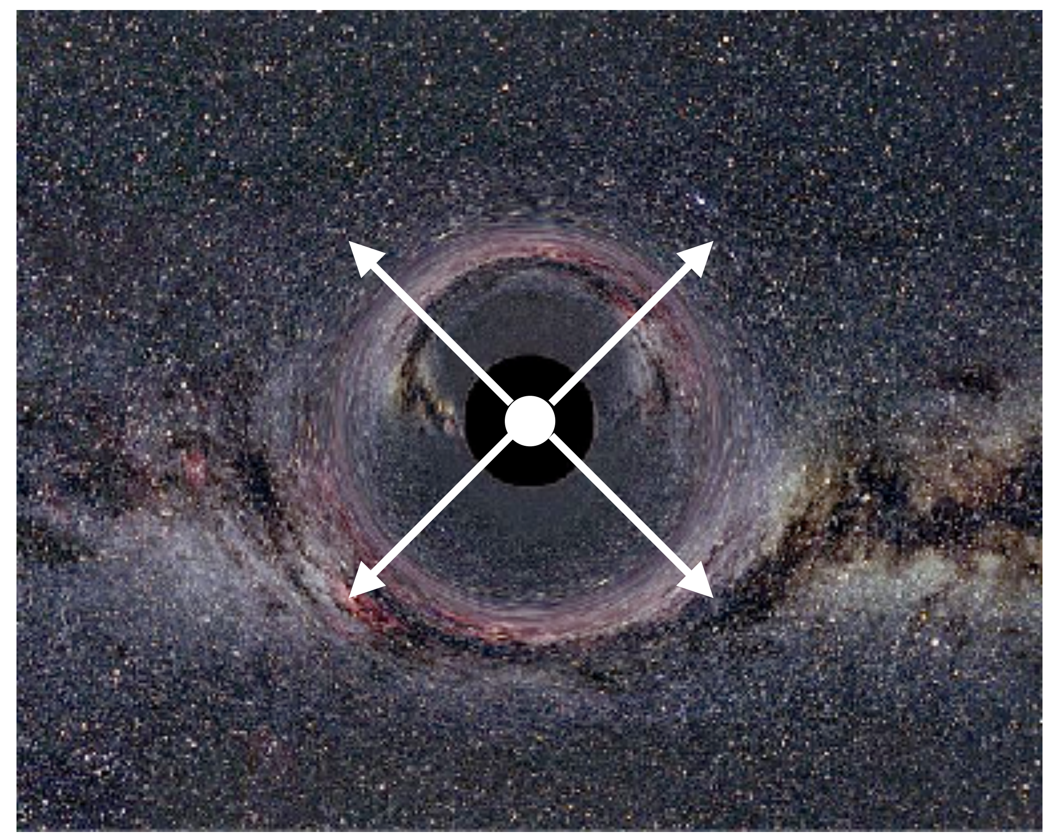
no-hair theorem:

event horizon → global symmetry charge cannot be observed

cf. elemag charge is observable via background gauge field



global symmetry



gauge symmetry

no global symmetry in quantum gravity

no-hair theorem:

event horizon → global symmetry charge cannot be observed

cf. elemag charge is observable via background gauge field

statistical BH entropy in theories with global symmetries

require ensemble of states wth ∀ global charge

→ generically large degeneracy & divergent entropy

→ no global symmetry in quantum gravity!?

※ consistent with string theory, AdS/CFT etc

[ex. Susskind 95', Banks-Seiberg 10']

global symmetry = gauge symmetry at $g = 0$

$\rightarrow$ natural to expect a lower bound on the gauge coupling weak gravity conjecture provides a quantitative bound by requiring finiteness of the # of stable states

※ to make extremal BH (no hawking radiation) unstable,

require existence of a particle satisfying $gq \geq \dfrac{m}{M_{\mathrm{Pl}}}$

[ArkaniHamed-Motl-Nicolis-Vafa 06']

recent directions:

1. how to evade WGC and realize axion inflation models

[De la Fuente et al ’14, Bachlechner et al ’15, Choi-Kim ‘15, Conlon-Krippendorf ’16, …]

2. better understanding & towards a proof of WGC

- lessons from string theory examples

[Brown et al ’15, Heidenreich et al ’15, Hebecker-Soler ’17, Montero et al ’17]

- use of AdS/CFT (holography)

[Nakayama-Nomura ’15, Harlow ’15, Benjamin et al ’16, Montero et al ’16]

- relation to positivity bounds

[Cheung-Remmen ’14, Andriolo-Junghans-TN-Shiu to appear]

2. positivity bound

consistency such as unitarity, analyticity and causality

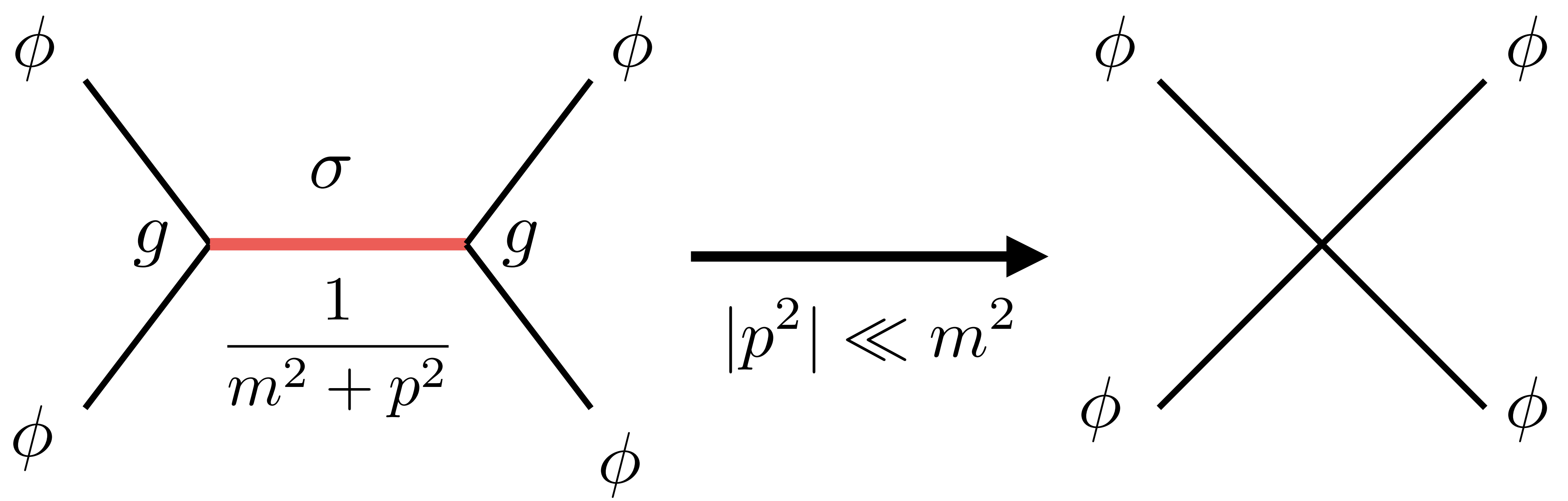
$\rightarrow$ generically constrain signs of effective interactions

an illustrative example for positivity

a scalar EFT with a shift symmetry $\phi \to \phi + \mathrm{const}$

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

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



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

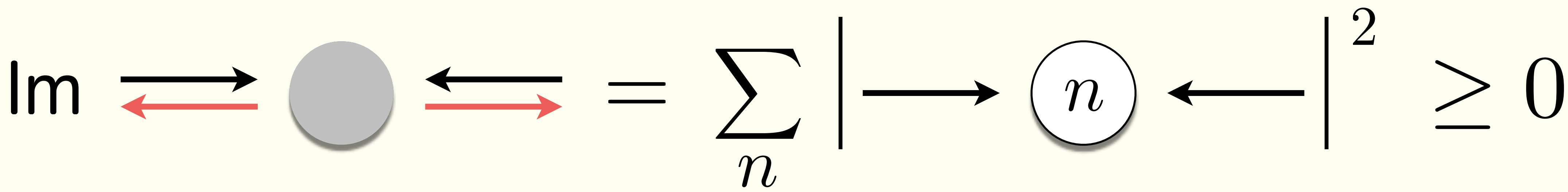
more generally, positivity of α follows only from

- unitarity of UV completion
- analyticity of scattering amplitudes

[Adams-Arkani Hamed-Dubovsky-Nicolis-Rattazzi '06]

unitarity is the origin of the bound

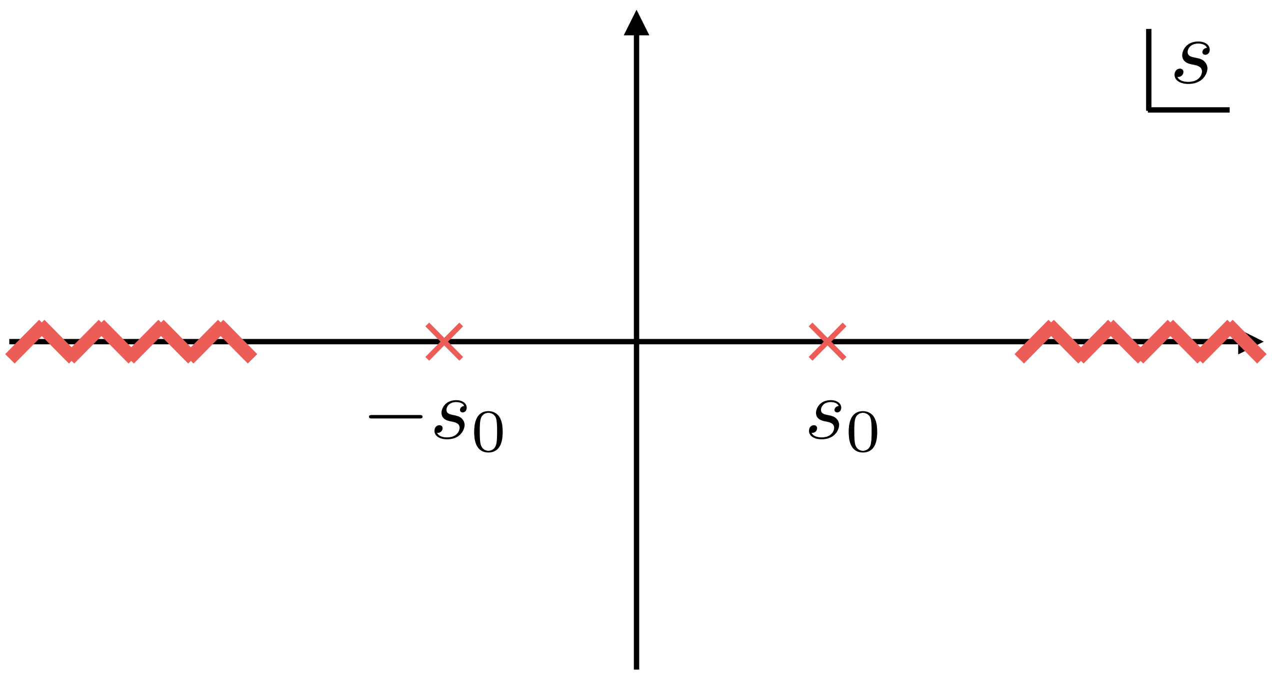
optical theorem → positivity of Im [forward scattering]



what we assume are

- existence of complete set of physical states
- absence of negative norm states (unitarity)

analyticity relates IR and UV

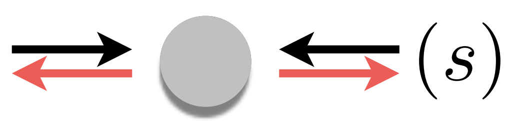


assumptions:

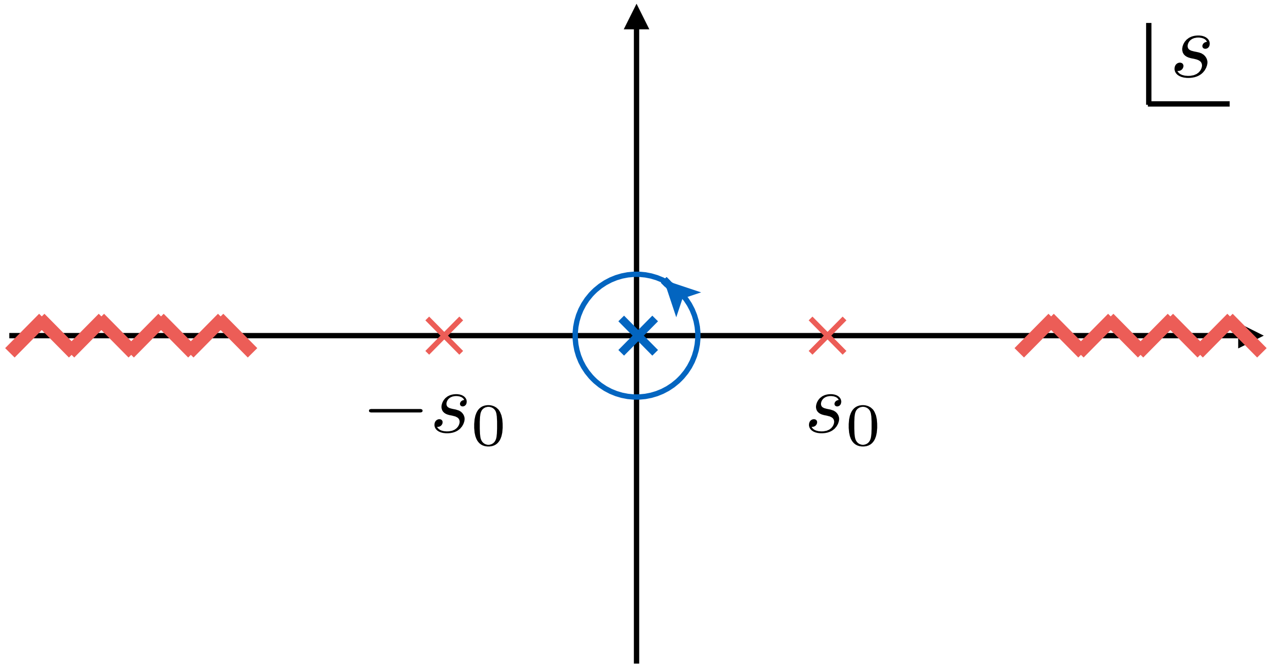
- poles & branch cuts on the shell
- analytic on the other points

analytic structure of 4pt amplitudes

in the forward limit

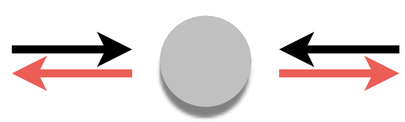


analyticity relates IR and UV

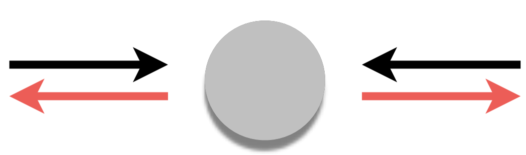


assumptions:
- poles & branch cuts on the shell
- analytic on the other points

analytic structure of 4pt amplitudes

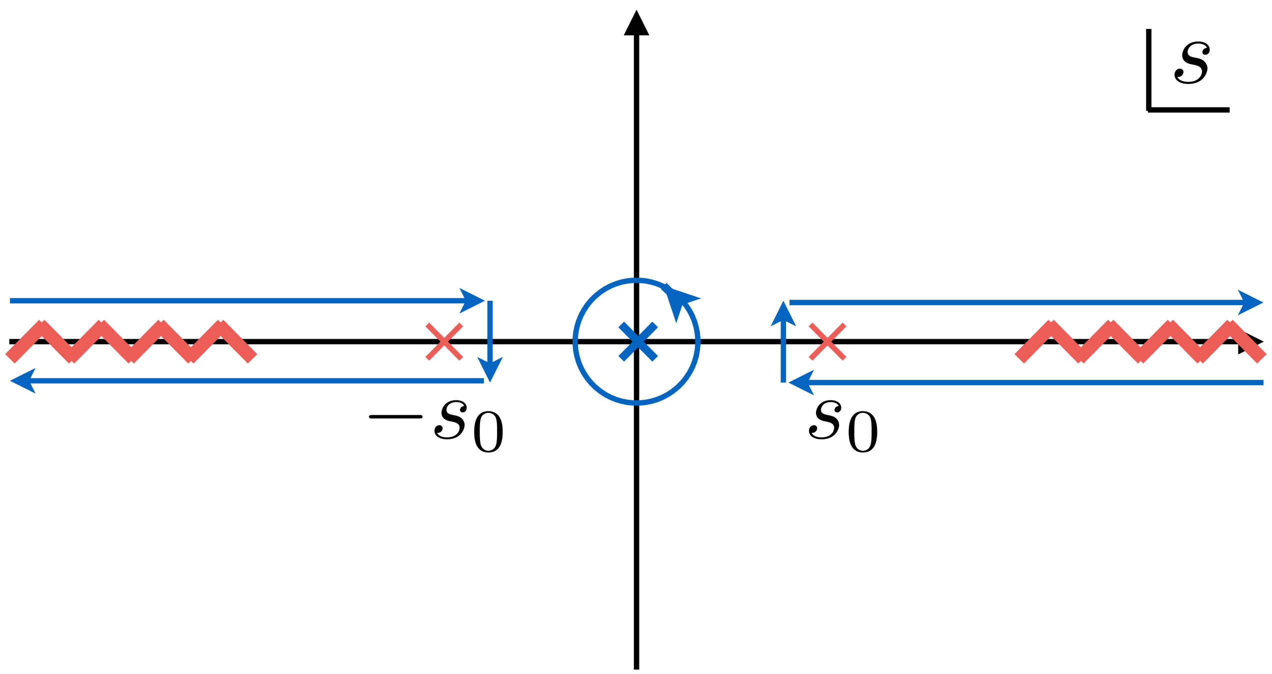
in the forward limit  $(s) \times s^{-3}$

consider a contour integral

$$\oint \frac{ds}{2\pi i}\frac{1}{s^3}$$  $$= 4\alpha$$

IR: $s \sim 0$ $\quad 4\alpha s^2 + \mathcal{O}(s^3)$

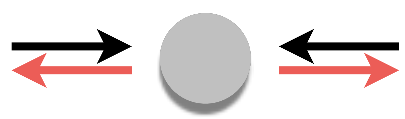
analyticity relates IR and UV



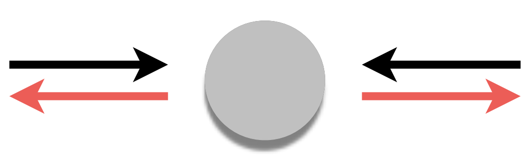
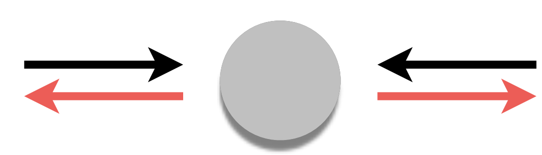
assumptions:

- poles & branch cuts on the shell
- analytic on the other points

analytic structure of 4pt amplitudes

in the forward limit  $(s) \times s^{-3}$

consider a contour integral and deform the contour

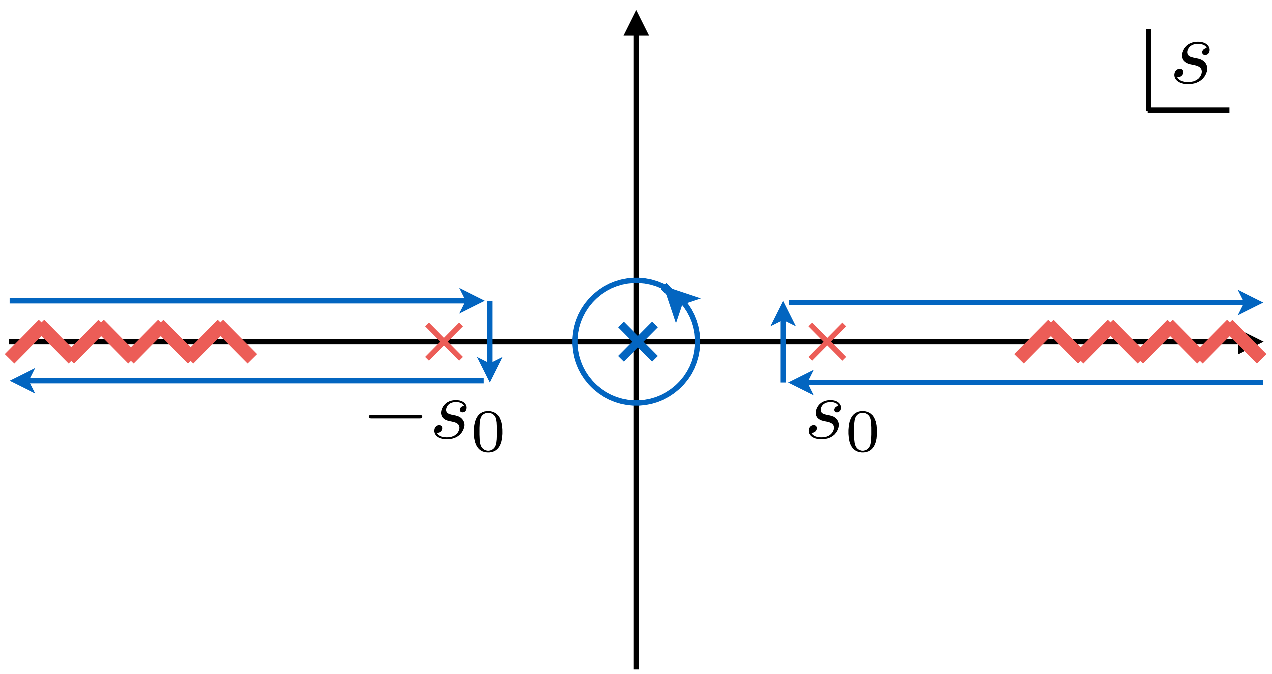
$\oint \frac{ds}{2\pi i} \frac{1}{s^3}$  $= \frac{2}{\pi} \int_{s_0}^{\infty} \frac{ds}{s^3}$ Im  ≥ 0

IR: $s \sim 0$

UV: $s_0 \leq s \leq \infty$

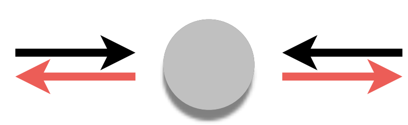
※ $(\text{l.h.s.}) = 4\alpha$

analyticity relates IR and UV

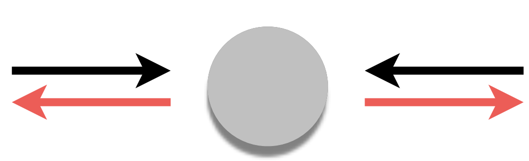
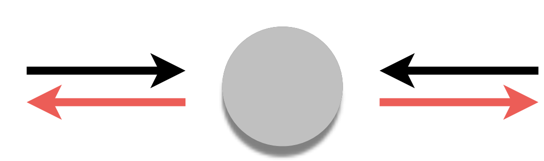


assumptions:

- poles & branch cuts on the shell
- analytic on the other points

analytic structure of 4pt amplitudes in the forward limit  $(s) \times s^{-3}$

consider a contour integral and deform the contour

$\oint \frac{ds}{2\pi i} \frac{1}{s^3}$  $= \frac{2}{\pi} \int_{s_0}^{\infty} \frac{ds}{s^3}$ Im  ≥ 0

IR: $s \sim 0$ UV: $s_0 \leq s \leq \infty$

※ $(\text{l.h.s.}) = 4\alpha$, so that positivity $\alpha \geq 0$ follows in this way,

principles such as unitarity, analyticity and causality

generically imply positivity of effective interactions

※ if this bound is violated, we should give up some of them

applications of positivity bound

Weak Gravity Conjecture from positivity bounds

- positivity of corrections to Einstein-Maxwell theory
  after integrating out massive charged particles

[Cheung-Remmen '14, Andriolo-Junghans-TN-Shiu to appear]

positivity in EFT of inflation

- positivity of primordial scalar 4pt functions [Baumann et al '15]

- positivity of primordial scalar 3pt functions [TN-Shiu in progress]

positivity in modified gravity such as massive gravity

[Cheung-Remmen '16, Bonifacio et al '16, de Rham et al '17]

summary messages

Landscape vs Swampland

- apparently consistent EFT can be problematic
  if we take into account the healthiness of UV completion
- better to check if your model is in landscape or swampland
- if experiments prefer what we think swampland,
  we need to drastically change our approach to UV theory

summary messages

Weak Gravity Conjecture

- compatibility with BH dynamics constrains IR physics
- upper bound on axion decay constant

  → relevant to axion inflation, string axion DM, ...

positivity bound

- signs of effective interactions are generically constrained by unitarity, analyticity and causality
- ex. sign of primordial non-Gaussianity can be useful to check these QFT principles at inflationary scale!

cảm ơn!