Composite hybrid inflation

Seong chan Park (Yonsei & KIAS)

Jan 31 GC2024 @ YITP, Kyoto

image generated by ChatGPT


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composite hybrid inflation

G. Cacciapaglia, D. Y. Cheong, A. Deandrea, W. Isnard and SCP
JCAP 10 (2023) 063 [2307.01852]

Dhong Yeon

Wanda

Lagrangian of Universe

Standard Model

new physics

$$\mathscr{L}_{\text{universe}} = \sqrt{g}\left[\kappa R + \Lambda_{CC} + \mathscr{L}_{SM} + \Delta\mathscr{L}\right]$$

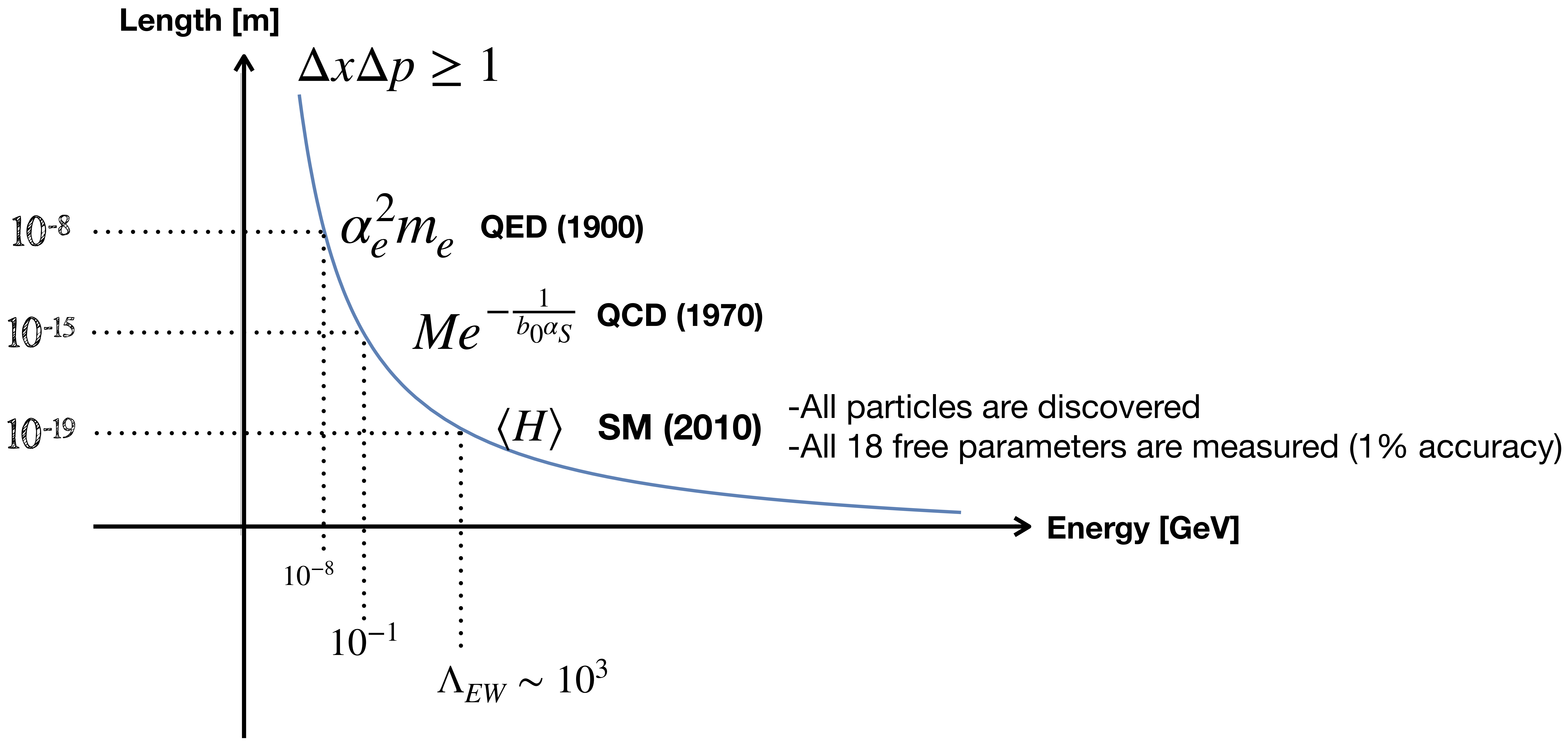
Dark energy

Gravity

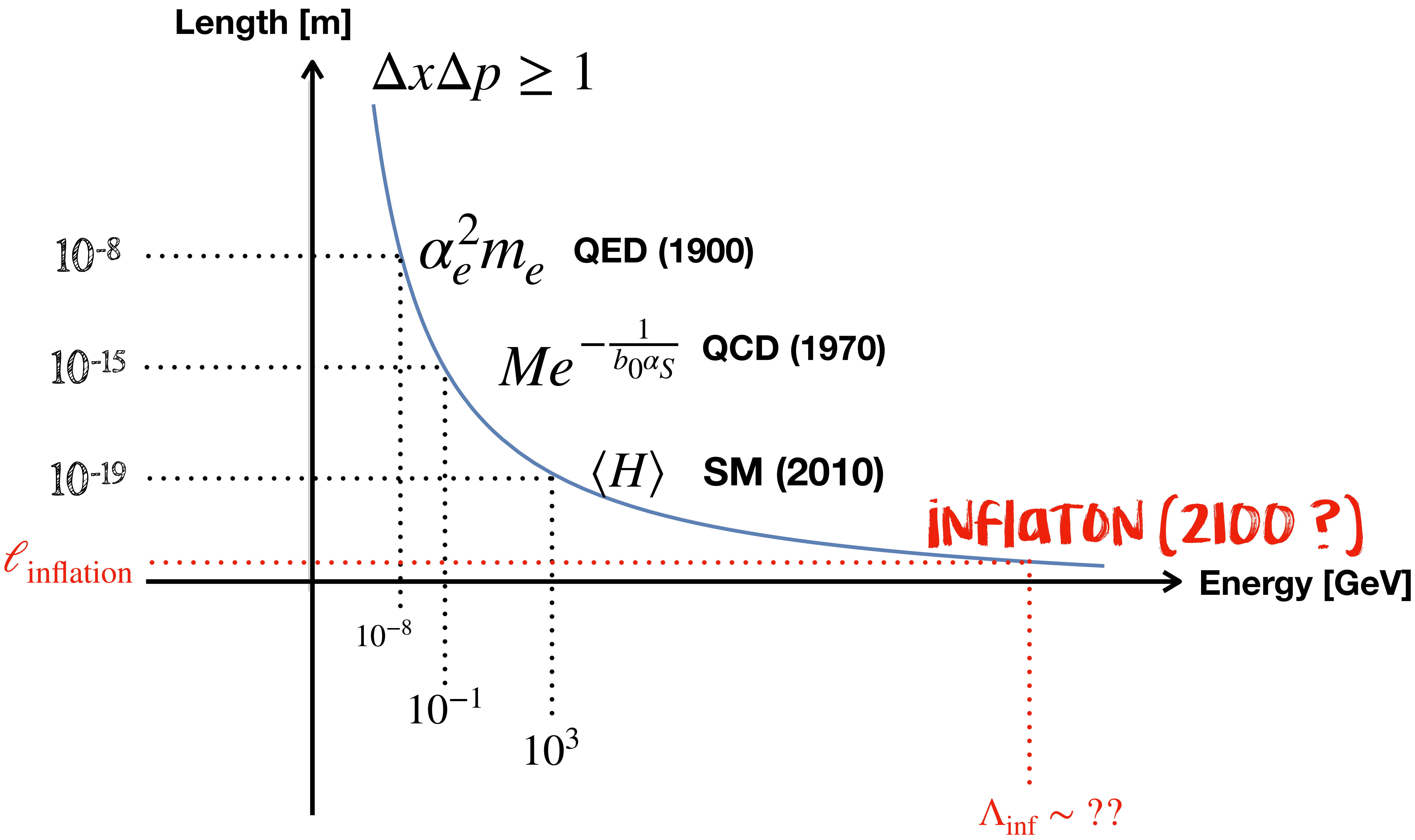
Team suit of Yonsei-HEP-COSMO group

http://hepcosmo.yonsei.ac.kr

Scales vs Physics



Scales vs Physics



Inflationary scale seems to be high

$$\Lambda_{inf} \gg \Lambda_{EW} \sim \mathrm{TeV}$$

because no inflaton was found at the LHC

But, what's the inflaton?

How does she look like?

PDG Book V 2023

Citation: R.L. Workman *et al.* (Particle Data Group), Prog.Theor.Exp.Phys. **2022**, 083C01 (2022) and 2023 update

LEPTONS

e

$$J = \tfrac{1}{2}$$

Mass $m = (548.579909065 \pm 0.000000016) \times 10^{-6}$ u

Mass $m = 0.51099895000 \pm 0.00000000015$ MeV

$\left|m_{e^+} - m_{e^-}\right|/m < 8 \times 10^{-9}$, CL = 90%

$\left|q_{e^+} + q_{e^-}\right|/e < 4 \times 10^{-8}$

Magnetic moment anomaly

$(g-2)/2 = (1159.65218062 \pm 0.00000012) \times 10^{-6}$

$(g_{e^+} - g_{e^-}) \,/\, g_{\text{average}} = (-0.5 \pm 2.1) \times 10^{-12}$

Electric dipole moment $d < 0.11 \times 10^{-28}$ e cm, CL = 90%

Mean life $\tau > 6.6 \times 10^{28}$ yr, CL = 90% [a]

Non-colored

Lorentz Symmetry

Zero thanks to CPT Symmetry

Zero if Chiral Symmetry

Zero if CP Symmetry

Absolute Stable by Gauge Symmetry

1/12 of ^{12}C = 1 u = 931.49410242(28) MeV/c^2 (CODATA 2018)

PDG Book V. 2100

Citation : SC Park et. al. Particle Data Group (2100 update)

INFLATON

ϕ_{inf}

Spin=0 ??
Mass =??
Charge= 0 ??
Lifetime =??
Elementary??

Lorentz Symmetry

Non-colored ?

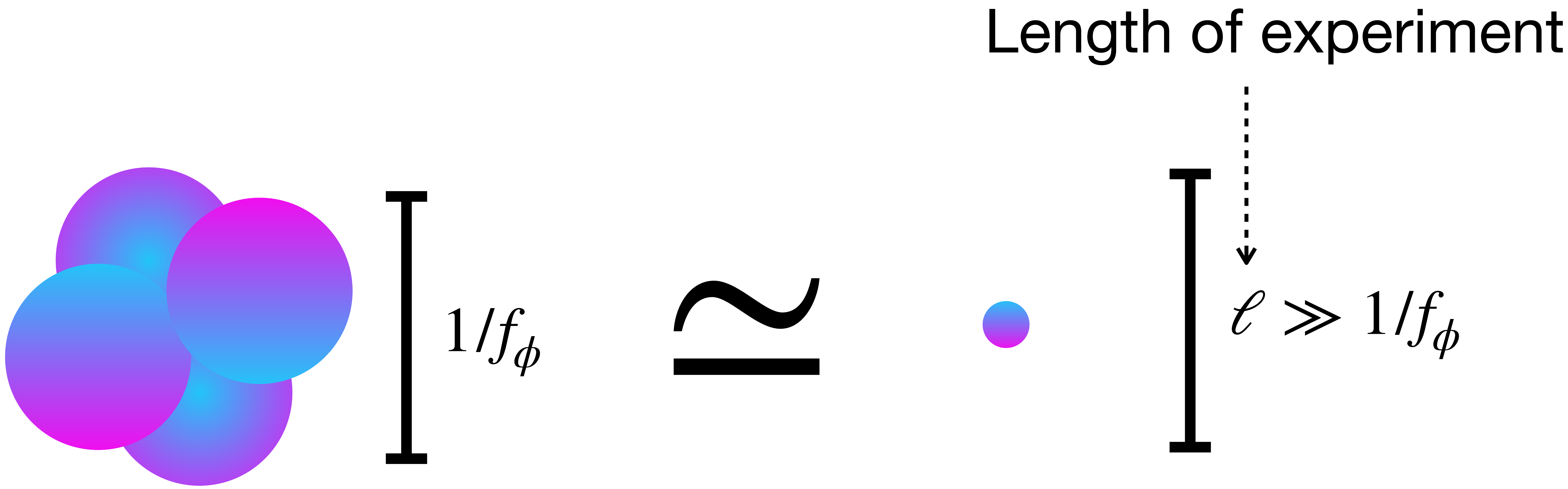
Not Stable for Reheating

Spin of inflaton

- Scalar (s=0) is favored due to isotropy
  - s=1/2 condensate $\langle \psi \rangle$ generates Lorentz violation
  - s=1 models tried [Golovnev, Mukhanov, Vanchurin (08)], [Natuko, Eiichiro, Yamaguchi (14)], but disfavored because of anisotropy. $\langle V^i \rangle$ breaks Lorentz.
  - maybe in extra dimensions $A^M = (A^\mu, A^5)$ [Arkani-Hamed, Cheng, Creminelli, Randall (03)]

Composite or elementary?

- It is not certain whether inflaton is composite or elementary.
- Situation is similar to the SM Higgs: The Higgs could be a composite state. Technicolor in 4D (or RS in 5D) is regarded natural as $m^2_{scalar} \sim \Lambda^2_{composite} \ll \Lambda^2_{cut}$
- Strong dynamics ==> organizing principle for multiple “composite states”
- (ex) pions, dilatons…+other mesons



$$f_\phi = \frac{\Lambda_{composite}}{2\pi}$$

Looks elementary

This work

[G. Cacciapaglia, D. Y. Cheong, A. Deandrea, W. Isnard and SCP [2307.01852] *JCAP* 10 (2023) 063].

- We propose a composite inflaton model based on $SU(N_c)$ gauge theory coupled to N_f Dirac fields of fundamental representation.
- But, $SO(N), SP(N), G_2$ also work
- For a certain set of (N_c, N_f), the theory will flow to an IR fixed point, hence generates a phase of nearly scale invariant dynamics (Walking regime) e.g. [Dietrich and F. Sannino (06)], [F. Sannino (07)]

walking = slow-rolling

This work

[G. Cacciapaglia, D. Y. Cheong, A. Deandrea, W. Isnard and S. C. Park [2307.01852] *JCAP* 10 (2023) 063].

✓Condensation $\langle \psi \bar{\psi} \rangle$ or $\langle GG \rangle$ generates spontaneous breaking for chiral and scale symmetry

✓ PNGBs (they are light!) are the pions $\phi(x) = \phi^a(x) T^a$ (chiral symmetry breaking) and dilaton $\chi(x)$ (scale symmetry breaking)

✓Technically, it is convenient to use non-linear realization of pion by $U(x) = e^{i\phi^a T^a / f_\phi}$.

The composite inflation model

$\eta = (-1, +1, +1, +1), M_P = 1/\sqrt{8\pi G} = 1$ $\quad U(x) = e^{i\phi^a T^a/f_\phi}$

$(f_\phi, \lambda_\chi, f_\chi, \delta_1, \delta_2)$

Order param. of Scale anomaly

dilaton kinetic term

pion kinetic term

$A \sim 1/4$ for $\langle \chi \rangle = f_\chi$

$$\frac{\mathcal{L}}{\sqrt{-g}} \supset \frac{1}{2}R - \frac{1}{2}\partial_\mu \chi \partial^\mu \chi - \frac{f_\phi^2}{2}\left(\frac{\chi}{f_\chi}\right)^2 \mathrm{Tr}\left[\partial_\mu U^\dagger \partial^\mu U\right] - \frac{\lambda_\chi}{4}\chi^4\left(\log\frac{\chi}{f_\chi} - A\right)$$
$$+ \frac{\lambda_\chi \delta_1 f_\chi^4}{2}\left(\frac{\chi}{f_\chi}\right)^{3-\gamma_m} \mathrm{Tr}\left[U + U^\dagger\right] + \frac{\lambda_\chi \delta_2 f_\chi^4}{4}\left(\frac{\chi}{f_\chi}\right)^{2(3-\gamma_{4f})} \mathrm{Tr}\left[(U - U^\dagger)^2\right]$$
$$- V_0 \,,$$

C.C.

scaling dimensions

$0 < \gamma_m, \gamma_{4f} \lesssim 1$

Effective potential of pions from chiral symmetry breaking

δ_1: from bare mass term of confining fermion

δ_2: from four-fermi interactions

Parameters

- Along $\phi/f_\phi = 0$, 4 Free parameters $(\lambda_\chi, f_\chi, \delta_1, \delta_2)$ describes the composite dynamics of dilaton
- $0 < \gamma_m, \gamma_{4f} \lesssim 1$: scaling dimensions of the induced operators suggested by lattice calculations [DeGrand (15)]
- $\mathrm{Max}[\lambda_\chi \delta_1 f_\chi^4, \lambda_\chi \delta_2 f_\chi^4] \lesssim f_\phi^4$ such that the theory stays in a perturbative regime ==> We request $\mathrm{Max}(\delta_1, \delta_2) \lesssim \dfrac{f_\phi^4}{\lambda_\chi f_\chi^4}$

J. von Neumann's elephant

John von Neumann

Enrico Fermi

Freeman Dyson in 2005

I remember my friend Johnny von Neumann used to say,
"With four parameters I can fit an elephant,
and with five I can make him wiggle his trunk."

E. Fermi to F. Dyson in response to his calculation of meson-proton scattering (1951)

F. Dyson (2005) https://www.nature.com/articles/427297a

Four parameter fit to an elephant

Elephant Drawing

created by scp

Ref) http://aapt.scitation.org/doi/abs/10.1119/1.3254017?journalCode=ajp

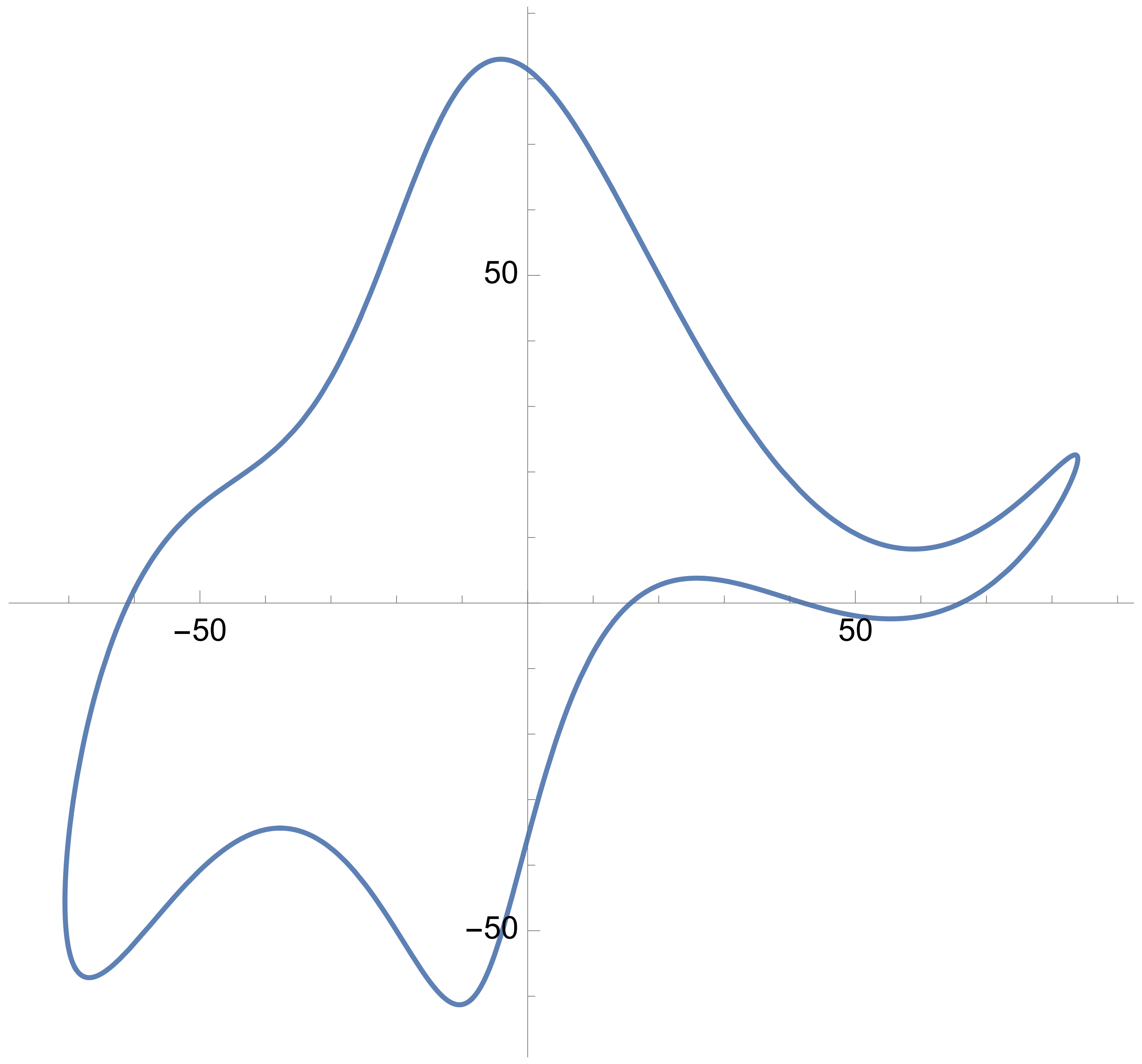
```
In[•]:= p1 = 50. - 30. I; p2 = 18. + 8. I; p3 = 12. - 10. I; p4 = -14. - 60. I;

In[•]:= cx[1] = Re[p1] * I;
        cx[2] = Re[p2] * I;
        cx[3] = Re[p3];
        cx[4] = 0;
        cx[5] = Re[p4];
        cy[1] = Im[p4] + I * Im[p1];
        cy[2] = Im[p2] * I;
        cy[3] = Im[p3] * I;
        cy[4] = 0;
        cy[5] = 0;

In[•]:= Do[ax[k] = Re[cx[k]], {k, 1, 5}];
        Do[bx[k] = Im[cx[k]], {k, 1, 5}];
        Do[ay[k] = Re[cy[k]], {k, 1, 5}];
        Do[by[k] = Im[cy[k]], {k, 1, 5}];

In[•]:=
        myx = Sum[ax[k] * Cos[k * t] + bx[k] * Sin[k * t], {k, 1, 5}];
        myy = Sum[ay[k] * Cos[k * t] + by[k] * Sin[k * t], {k, 1, 5}];
        ParametricPlot[{myy, -myx}, {t, 0, 2 Pi}]
```

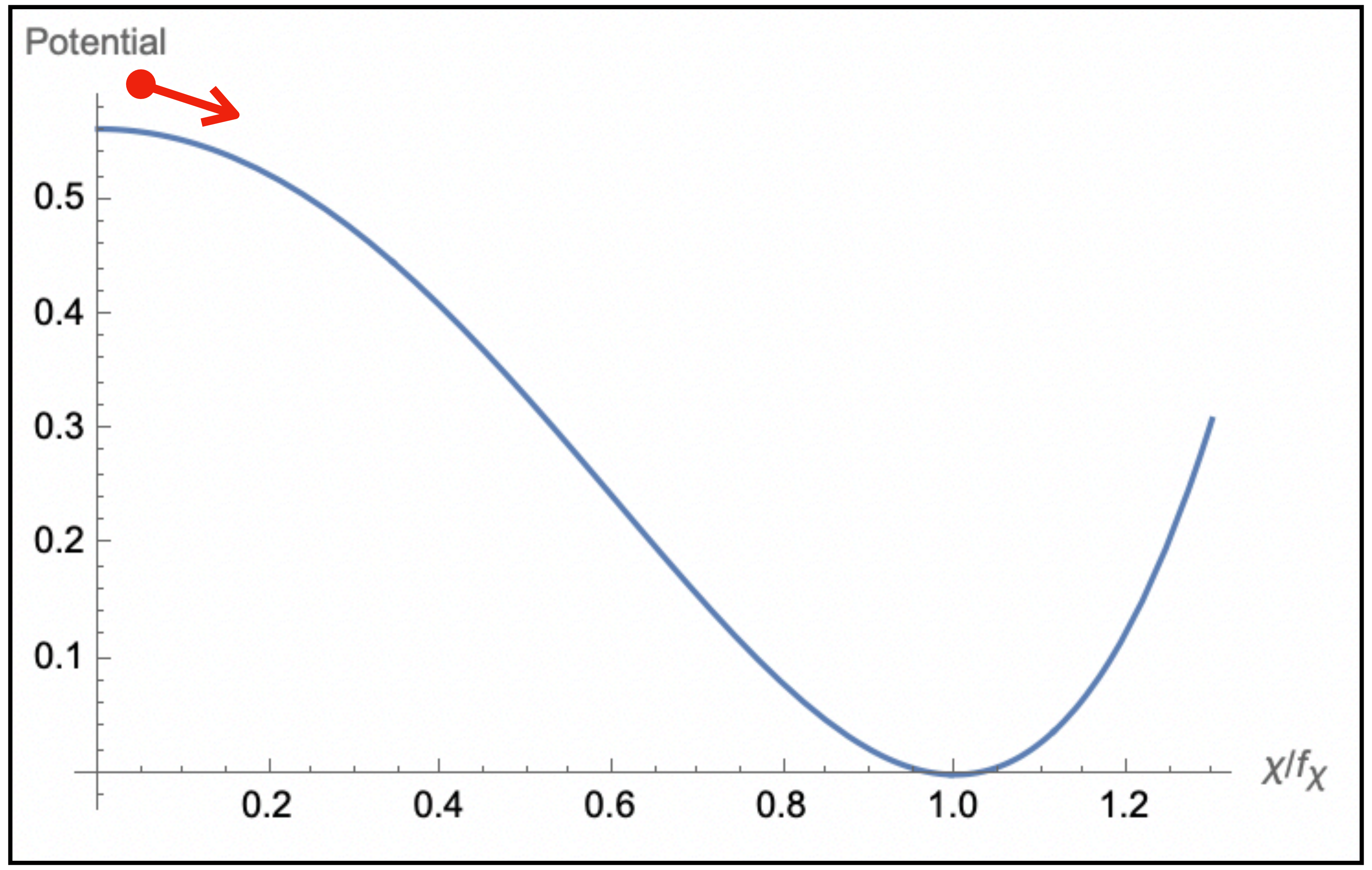
Out[•]=



Dilaton as inflaton

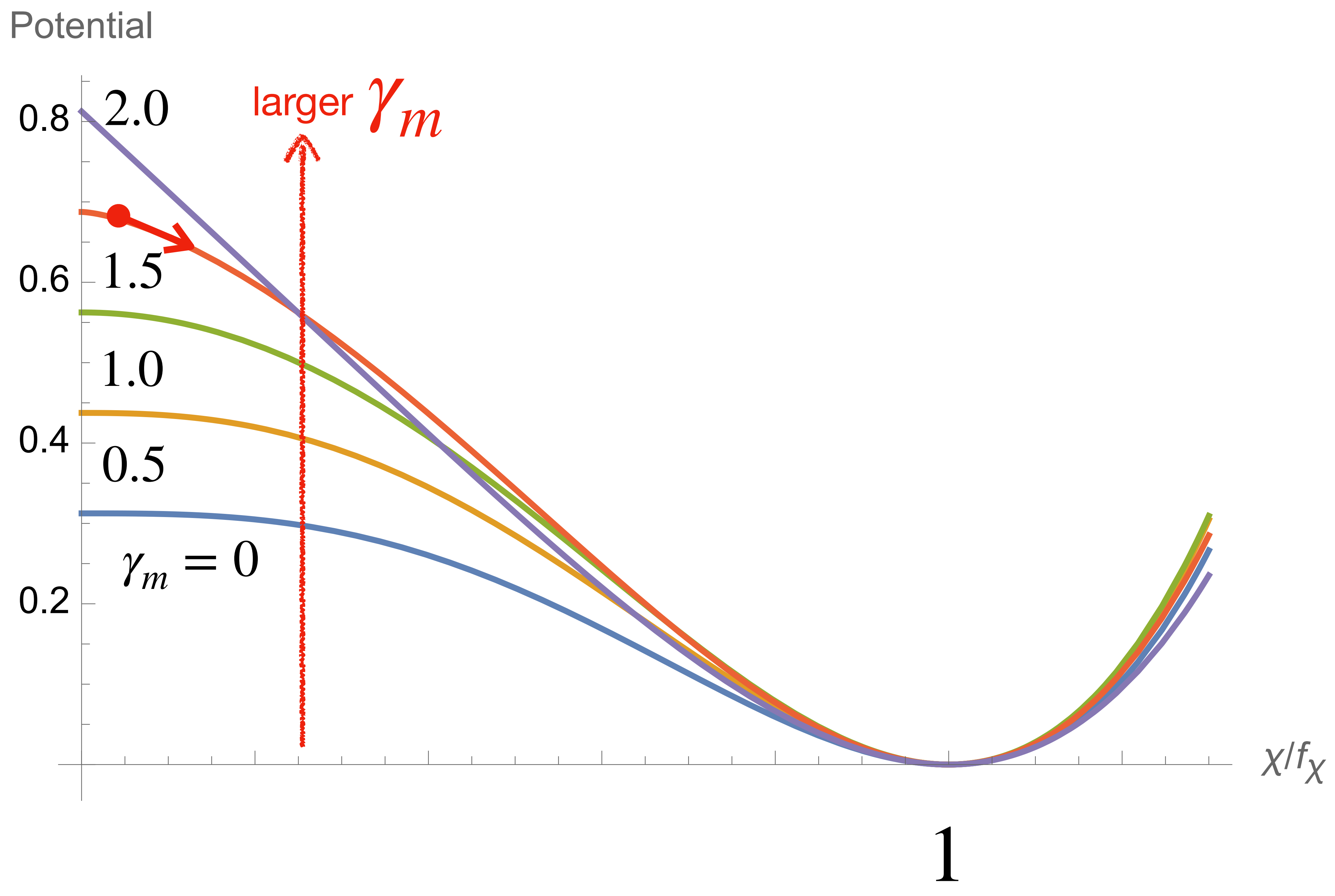
- The dilaton potential along $\phi/f_\phi = 0$

$$V(\phi = 0, \chi) = -\lambda_\chi \delta_1 f_\chi^4 \left(\frac{\chi}{f_\chi}\right)^{3-\gamma_m} + \frac{\lambda_\chi}{4}\chi^4 \left(\log\frac{\chi}{f_\chi} - A^{\text{single}}\right) + V_0^{\text{single}}$$



$$V(\phi = 0, \chi) = -\lambda_\chi \delta_1 f_\chi^4 \left(\frac{\chi}{f_\chi}\right)^{3-\gamma_m} + \frac{\lambda_\chi}{4}\chi^4 \left(\log \frac{\chi}{f_\chi} - A^{\text{single}}\right) + V_0^{\text{single}}$$

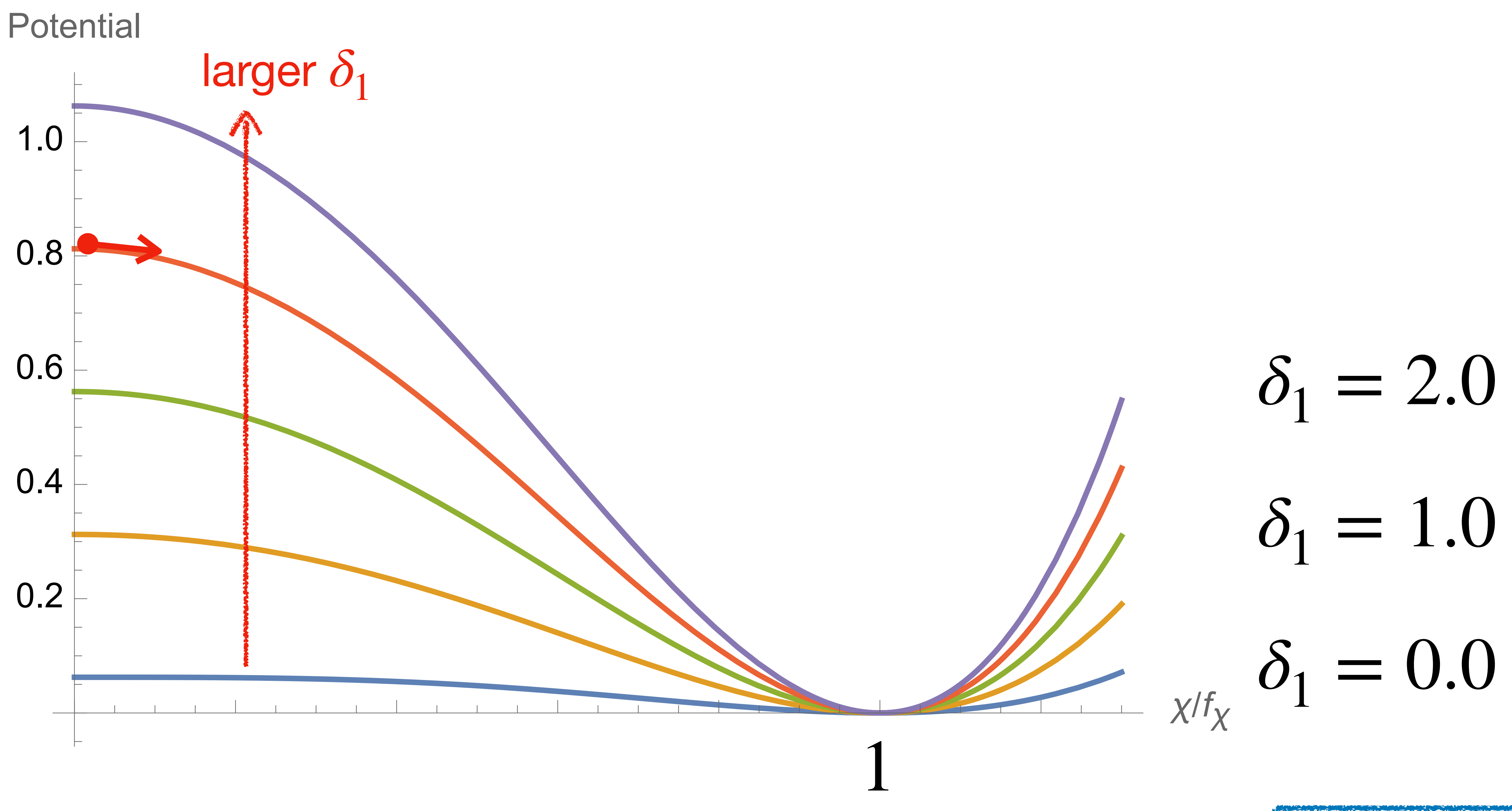
$\delta_1 = 1.0$ fixed



- $A^{\text{single}} = \frac{1}{4} + \delta_1(3 - \gamma_m)$ for $V_{,\chi} = 0$ at $\chi = f_\chi$,
- $V_0 = \frac{\lambda_\chi f_\chi^4}{16}\left[1 + 4\delta_1(1 + \gamma_m)\right]$ for $V = 0$ at $\chi = f_\chi$

$$V(\phi=0,\chi) = -\lambda_\chi \delta_1 f_\chi^4 \left(\frac{\chi}{f_\chi}\right)^{3-\gamma_m} + \frac{\lambda_\chi}{4}\chi^4 \left(\log\frac{\chi}{f_\chi} - A^{\text{single}}\right) + V_0^{\text{single}}$$

$\gamma_m = 1.0$ fixed



- $A^{\text{single}} = \frac{1}{4} + \delta_1(3-\gamma_m)$ for $V_{,\chi} = 0$ at $\chi = f_\chi$,
- $V_0 = \frac{\lambda_\chi f_\chi^4}{16}\left[1 + 4\delta_1(1+\gamma_m)\right]$ for $V = 0$ at $\chi = f_\chi$

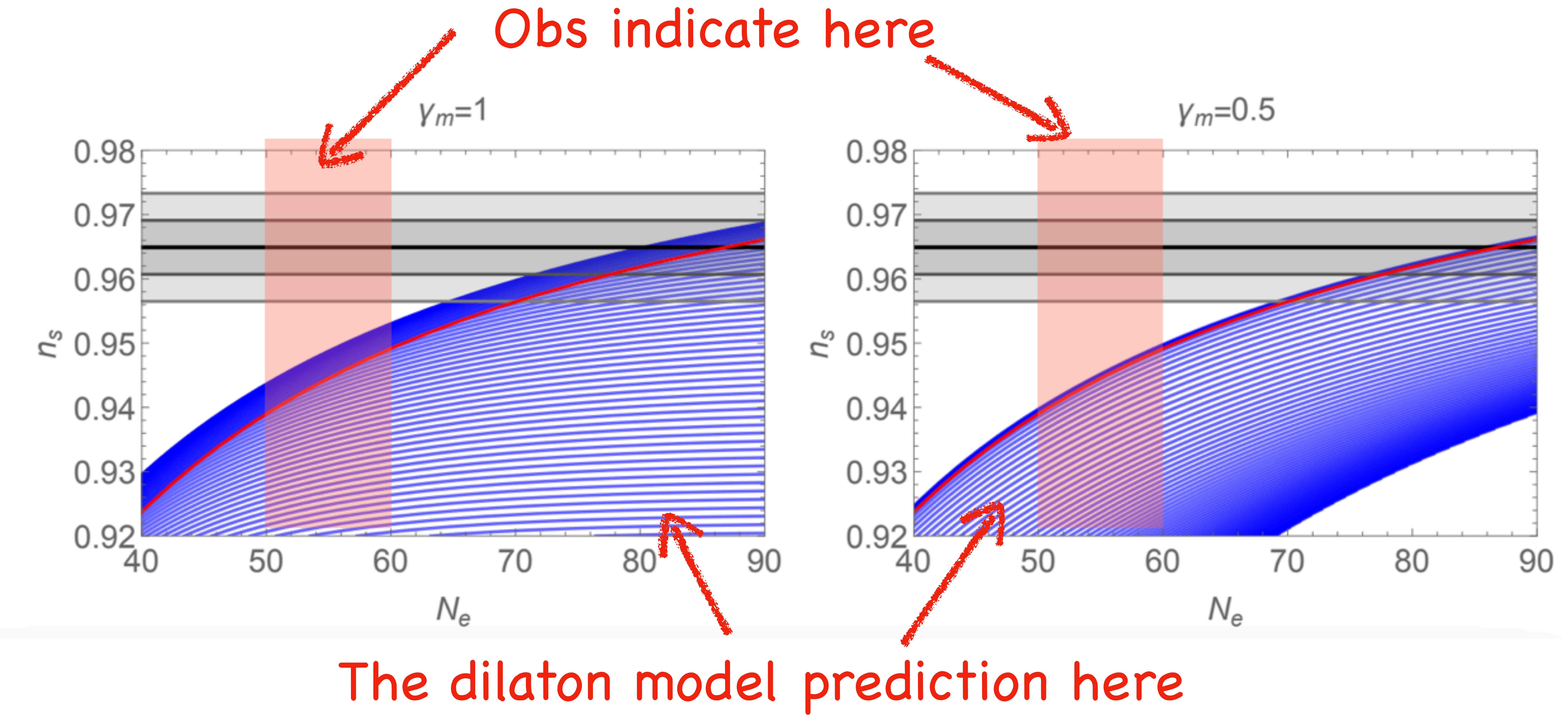
Precision test

- PLANCK [Planck 1807.06277]

$$\begin{aligned} n_s &= 0.9649 \pm 0.0042, \\ r &< 0.036\,, \\ \ln(10^{10}\mathcal{P}_\zeta(k_*)) &= 3.040 \pm 0.0016\,, \\ \frac{\mathrm{d}n_s}{\mathrm{d}\ln k} &= -0.0045 \pm 0.0067\,. \end{aligned}$$

- Many representative models were already ruled out
- We can test our composite model

Dilaton inflaton (n_s, N_e) $r \ll 1$ all the cases



Wait! Pions

$$m_\phi^2 = \lambda_\chi \frac{f_\chi^4}{f_\phi^2} \times \begin{cases} \delta_1 f_\chi^{\gamma_m - 3} \chi^{3-\gamma_m} - 2\delta_2 f_\chi^{2(\gamma_{4f}-3)} \chi^{2(3-\gamma_{4f})} & \text{if } \phi = 0\,,\ \chi < \chi_c\,, \\ \left(2\delta_2 - \frac{\delta_1^2}{2\delta_2}\right) & \text{if } \phi = \phi_0\,,\ \chi = f_\chi\,. \end{cases}$$

along dilaton direction

at the minimum

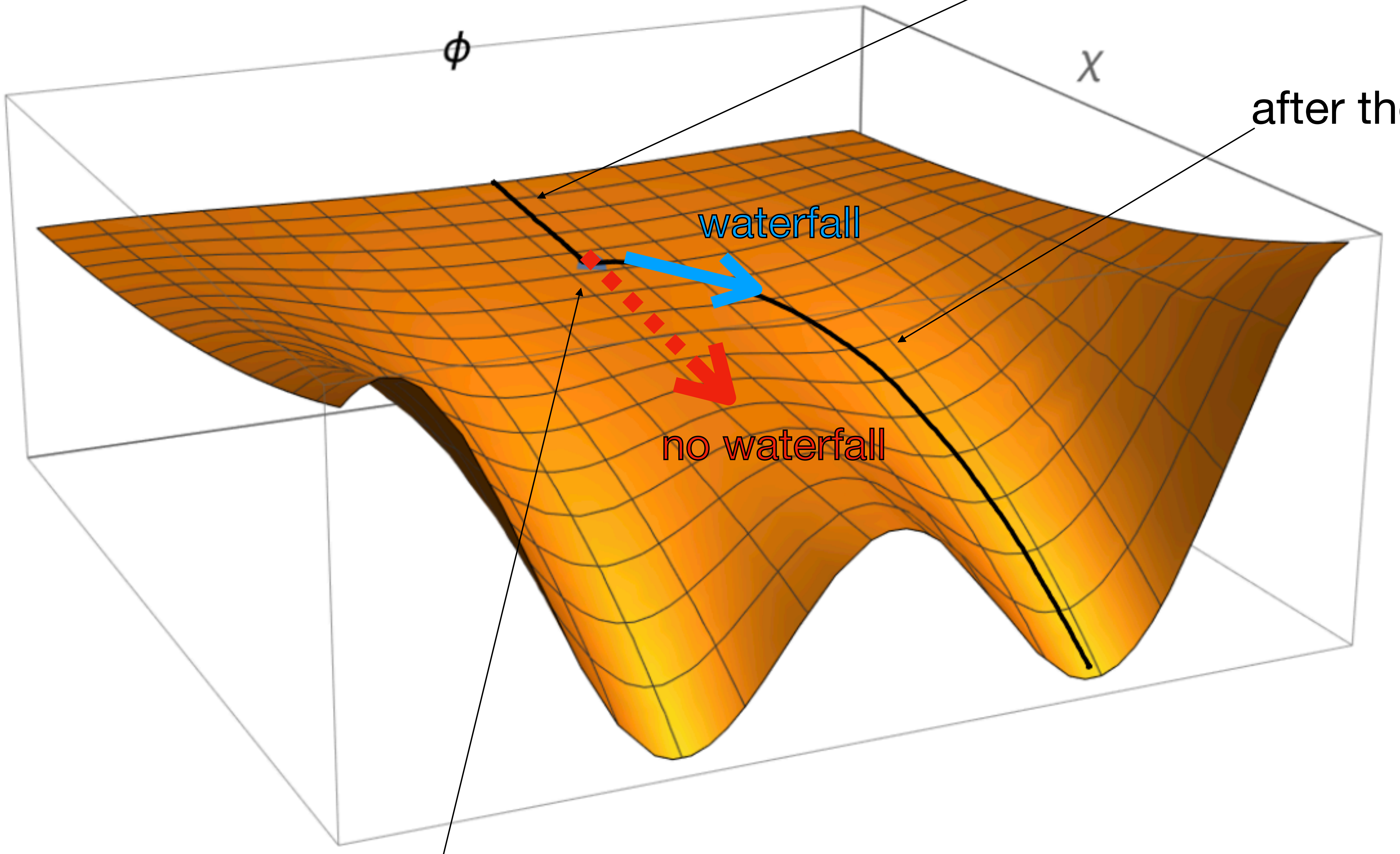
- At the turning point, $\chi = \chi_c$, m_ϕ^2 changes its sign then rapidly turns into the waterfall direction $\phi \to \phi_0$ then terminates the inflation
- Pions play the role of waterfall field!

Dilaton + pion potential

Inflation is driven by dilaton

$\chi_* = \chi_{0.05\mathrm{Mpc}^{-1}}$

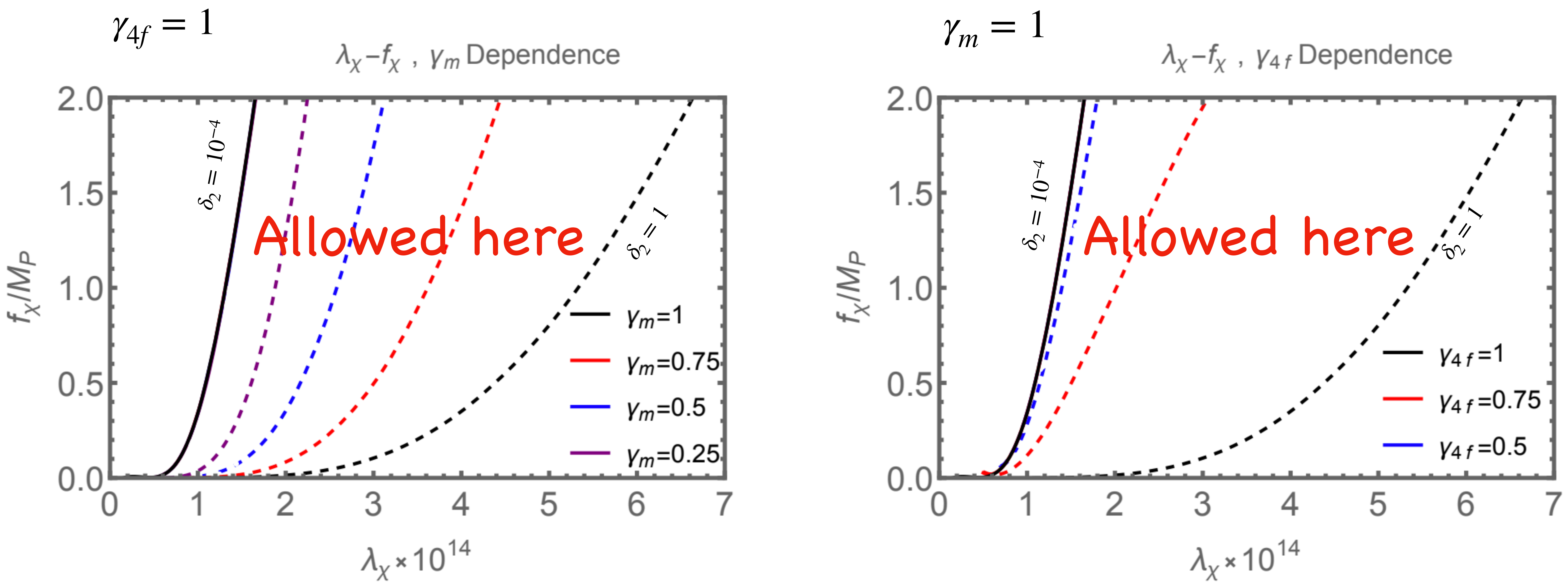
after the turning into the waterfall



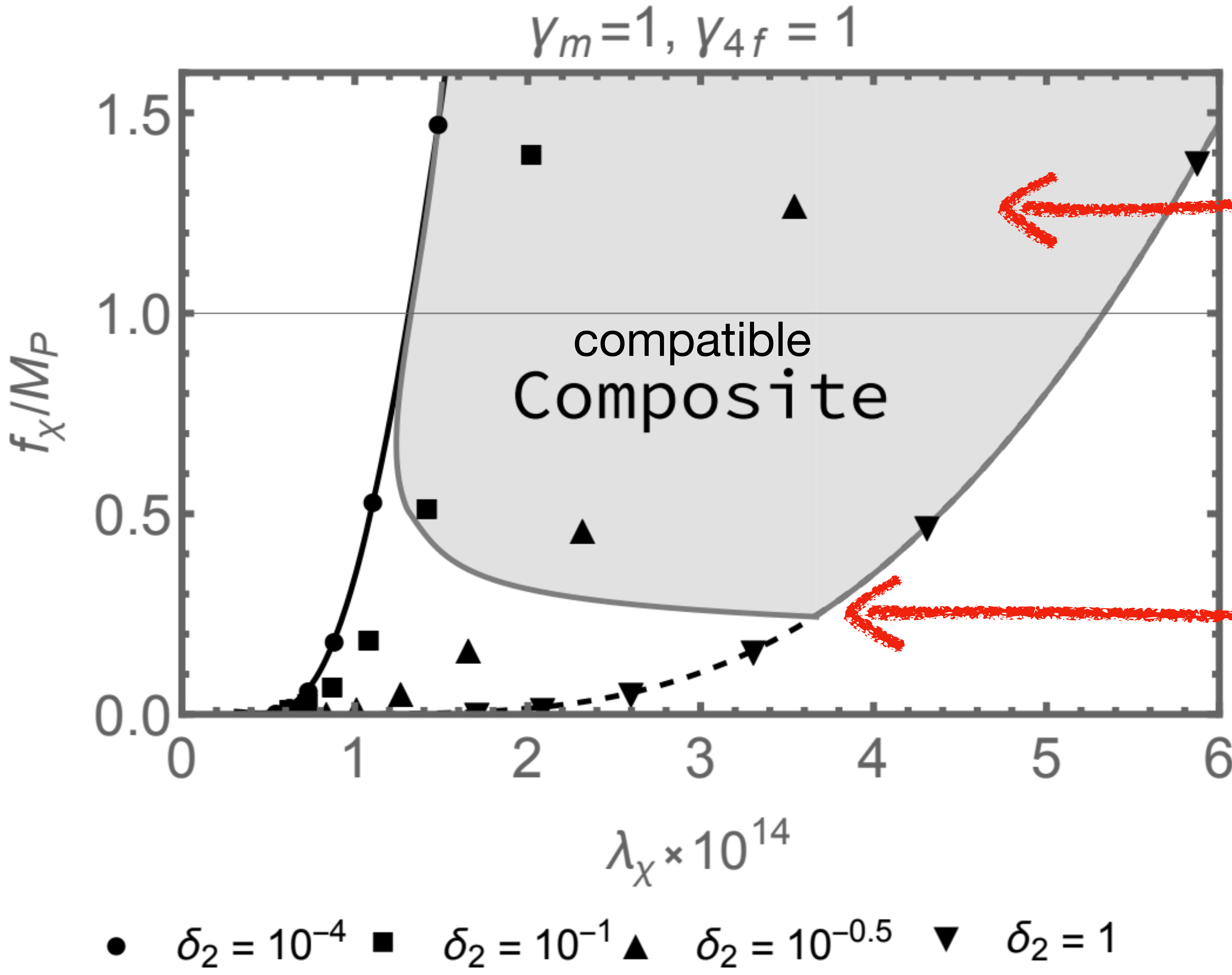
$V_{\phi\phi}$ changes the sign and 'Turn' made at $\chi = \chi_c \equiv \left(\frac{\delta_1}{2\delta_2}\right)^{\frac{1}{3+\gamma_m-2\gamma_{4f}}} f_\chi$

Allowed Parameter spaces

$$n_s = 0.9649 \pm 0.0042,$$
$$r < 0.036\,,$$
$$\ln(10^{10}\mathcal{P}_\zeta(k_*)) = 3.040 \pm 0.0016\,,$$
$$\frac{\mathrm{d}n_s}{\mathrm{d}\ln k} = -0.0045 \pm 0.0067\,.$$

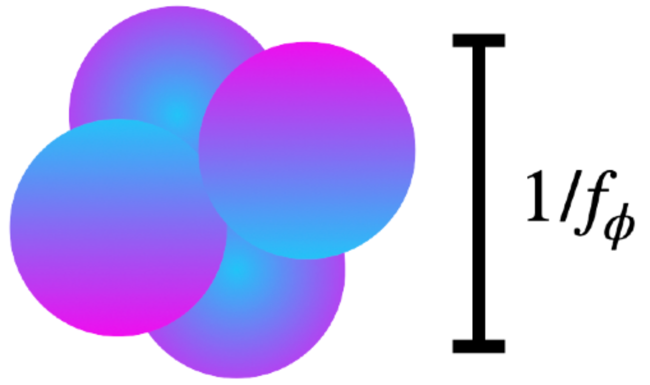


CMB compatible space



In here, we realize successful composite inflation

$$\mathrm{Max}(\delta_1, \delta_2) \lesssim \frac{f_\phi^4}{\lambda_\chi f_\chi^4}$$



Conclusion & Outlook

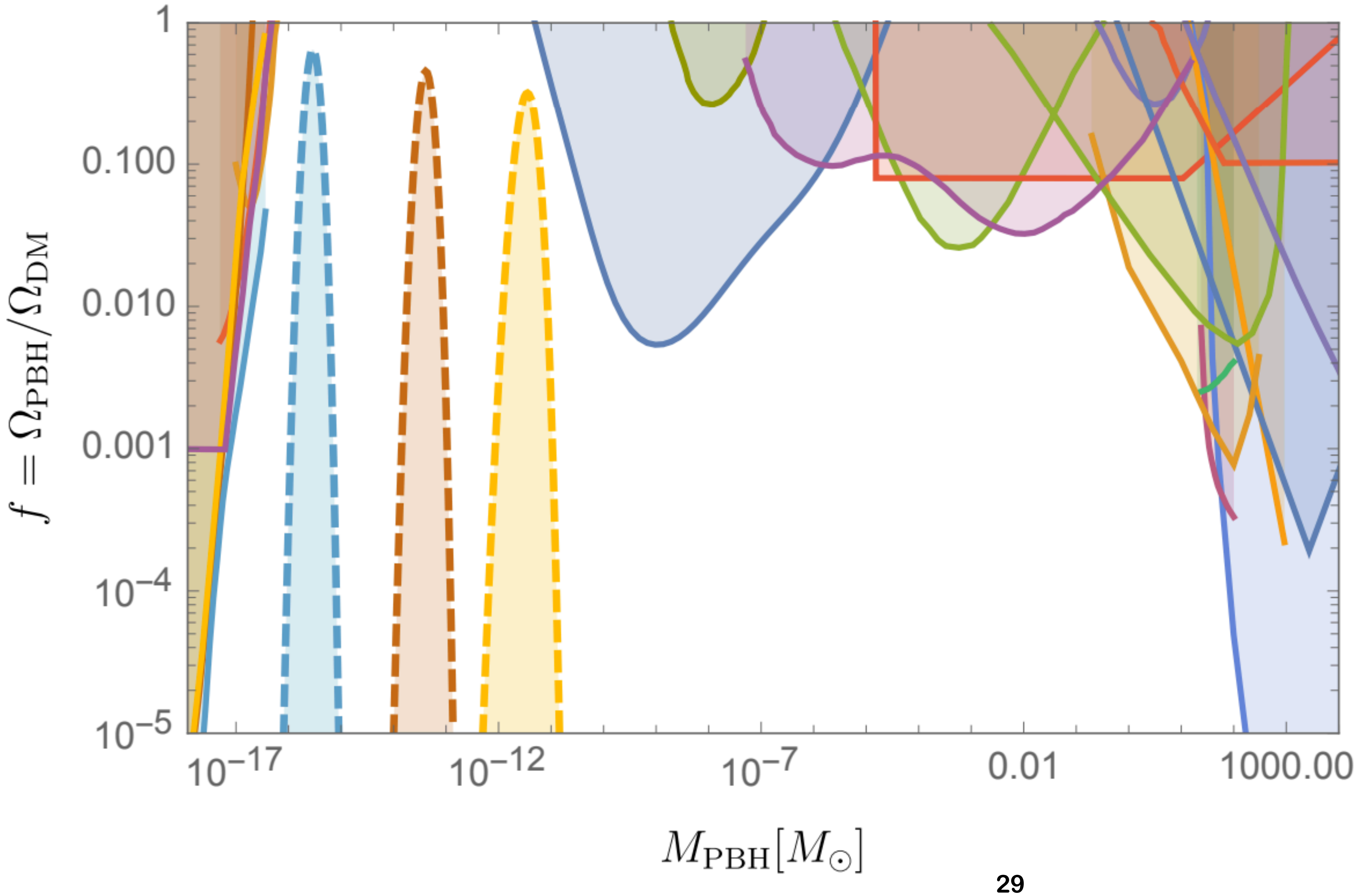
- Composite inflation model is suggested based on a $SU(N_c)$ gauge symmetry
- The suggested Composite model is compatible with the Planck 18+ BK18 + BAO observation when dilation plays the role of inflaton and pion plays the role of waterfall.
- Inflation scale $H_{inf} \sim 10^{10}$ GeV, Composite (pion) scale $m_\phi \sim f_\phi \sim 10^{14}$ GeV : everything is below Planck scale ~ good EFT description
- More details of reheating is specified only after (pion-standard model) and (dilaton~standard model) interactions are are given.
- Some of the pions could be stable and **WIMPZILLA** Dark matter (work in progress)
- Tachyonic instability generates **PBH & GWs** etc. (work in progress)

PBH from Higgs-R^2

D.Y.Cheong, S.M.Lee, SCP JCAP01 (2021) 032 [1912.12032]

$$S_J = \int d^4x\sqrt{-g_J}\left[F(h,R_J) - \frac{1}{2}g^{\mu\nu}\nabla_\mu h\nabla_\nu h - \frac{\lambda}{4}h^4\right],$$

$$F(h,R_J) = \frac{M_P^2}{2}\left(R_J + \frac{\xi h^2}{M_P^2}R_J + \frac{R_J^2}{6M^2}\right)$$



+RG running effect

$$\beta_\alpha = -\frac{1}{16\pi^2}\frac{(1+6\xi)^2}{18},$$

$$\beta_\xi = -\frac{1}{16\pi^2}\left(\xi+\frac{1}{6}\right)\left(12\lambda + 6y_t^2 - \frac{3}{2}g'^2 - \frac{9}{2}g^2\right),$$

$$\beta_\lambda \beta_{\rm SM} + \frac{1}{16\pi^2}\frac{2\xi^2(1+6\xi)^2 M^4}{M_P^4},$$

+ R^3

D.Y.Cheong, H.M.Lee, SCP
PLB 805 (2020) 135453 2002.07981

Tachyonic instability

D.Y.Cheong, K. Kohri, SCP
JCAP 10 (2022) 015 2205.14813