Stringy Axion Dark Energy

Francisco Gil Pedro

Based on:

2002.02695, 2007.11011 and 2206.10649
M. Brinkman, M. Cicoli and G. Dibitetto

2112.10783, 2112.10779, and 2407.03405
M. Cicoli, C. Cunillera and A. Padilla

Outline

- Introduction
- Dynamical alternatives to the cosmological constant
  - Multifield quintessence
  - Axionic quintessence
  - Embedding axionic quintessence

The CC problem

1998 SN Ia -> Universe in accelerated expansion

$$H_0 = 100\ h\ km/s/Mpc \approx 10^{-60} M_{pl}$$

$h = 0.675$ PLANCK 2018

$h = 0.73$ SH0ES

Explained by a fluid with $p = \omega\rho$ $\quad \omega \approx -0.99^{+0.15}_{-0.13}$ $\quad \Omega \sim 0.7$

Compatible with a cosmological constant $\Lambda \approx 10^{-120} M_P^4$

See however DESI: 2404.03002 $\quad \omega(a) = \omega_0 + (1-a)\omega_a$

$-0.55^{+0.39}_{-0.21}$ $\quad < -1.32$

The CC problem, theoretically

What if $\omega \neq -1$?

(Too) Many alternatives:

Quintessence: Single field $\lambda = -\frac{V_\phi}{V}$

$\lambda < 0.6$ [Agrawal et al. '18]
[Akrami et al. '18]

No dS conjecture? $\lambda \geq \mathcal{O}(1)$

How to explain the DE scale?

Radiative stability?

Fifth forces?

The CC problem, theoretically

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Alternatives:

-multifield dynamics [(Brinkman),Cicoli,Dibitetto,FGP ’20-22]

-axionic quintessence [Cicoli, Cunillera,Padilla,FGP ’21]

Stringy axions and moduli

Universal features of string theories: gravity

extra dimensions

higher form antisymmetric tensors

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Freund-Rubin compactification

$$S_{(D)} = \frac{M^{D-2}}{2} \int d^D x \sqrt{g_{(D)}} \left(R_{(D)} - |F_p|^2 \right)$$

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$$\Downarrow$$

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu + \sigma^2 g_{mn} dx^m dx^n$$

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$$S_{(D)} = \frac{M_P^2}{2} \int d^4 x \sqrt{g_{(4)}} \left(R_{(4)} - \frac{1}{2}(D-4)(D-2)(\partial \log \sigma)^2 + \frac{\chi}{2} M_P^2 \sigma^{2-D} - M_P^2 \sigma^{4-2p-D} f^2 \right)$$

where $M_P^2 = M^2 \sigma_0^{D-4}$ $\quad \int \mathrm{d}^{D-4} y \sqrt{g_{(D-4)}} R_{(D-4)} = \chi M^{6-D}$ $\quad \int \mathrm{d}^{D-4} y \sqrt{g_{(D-4)}} g^{m_1 n_1} \ldots g^{m_p n_p} F_{m_1 \ldots m_p} F_{n_1 \ldots n_p} \equiv M^{2-D} f^2$

Stringy axions and moduli

[Cicoli et al. '23]

Theory	Dimension	Supercharges	Massless Bosons
Heterotic $E_8 \times E_8$	10	16	g_{MN}, B_{MN}, ϕ A_M^{ij}
Heterotic $SO(32)$	10	16	g_{MN}, B_{MN}, ϕ A_M^{ij}
Type I $SO(32)$	10	16	g_{MN}, ϕ, A_M^{ij} C_{MN}
Type IIA	10	32	g_{MN}, B_{MN}, ϕ C_M, C_{MNP}
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M-Theory	11	32	g_{MN}, C_{MNP}

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Kahler moduli τ_i $h_{1,1}$

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(real) Kahler potential $K(\Phi, \bar{\Phi})$

(holomorphic) superpotential $W(\Phi)$

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$$\mathcal{L} = -K_{i\bar{j}}\partial_\mu T_i \partial^\mu \bar{T}_{\bar{j}} - V\,.$$

$$V = e^K \left[K^{i\bar{j}} D_i W D_{\bar{j}} \bar{W} - 3|W|^2\right]$$

Multifield Quintessence

[Spintessence, Boyle et al.'01]
[Sonner and Townsend '06]
[Achucarro and Palma '18]

Multifield modulus+axion

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{1}{2}\gamma_{ij}\partial_\mu\phi^i\partial^\mu\phi^j - V(\phi) \ ,$$

[(Brinkman),Cicoli,Dibitetto,FGP '20-22]

$$\gamma_{ij} = \begin{pmatrix} 1 & 0 \\ 0 & f^2(\phi_1) \end{pmatrix} \qquad f(\phi_1) = e^{-k_1\phi_1} \qquad V = V_0\, e^{-k_2\phi_1}$$

$$R_{fs} = -2k_1^2$$

Exploit difference between $\epsilon_V = \frac{1}{2}\left(\frac{V'}{V}\right)^2$ and $\epsilon_H = -\frac{\dot{H}}{H^2}$

accelerated expansion in steep potentials: $\frac{k_2^2}{2} \gtrsim \mathcal{O}(1)$

Multifield Quintessence

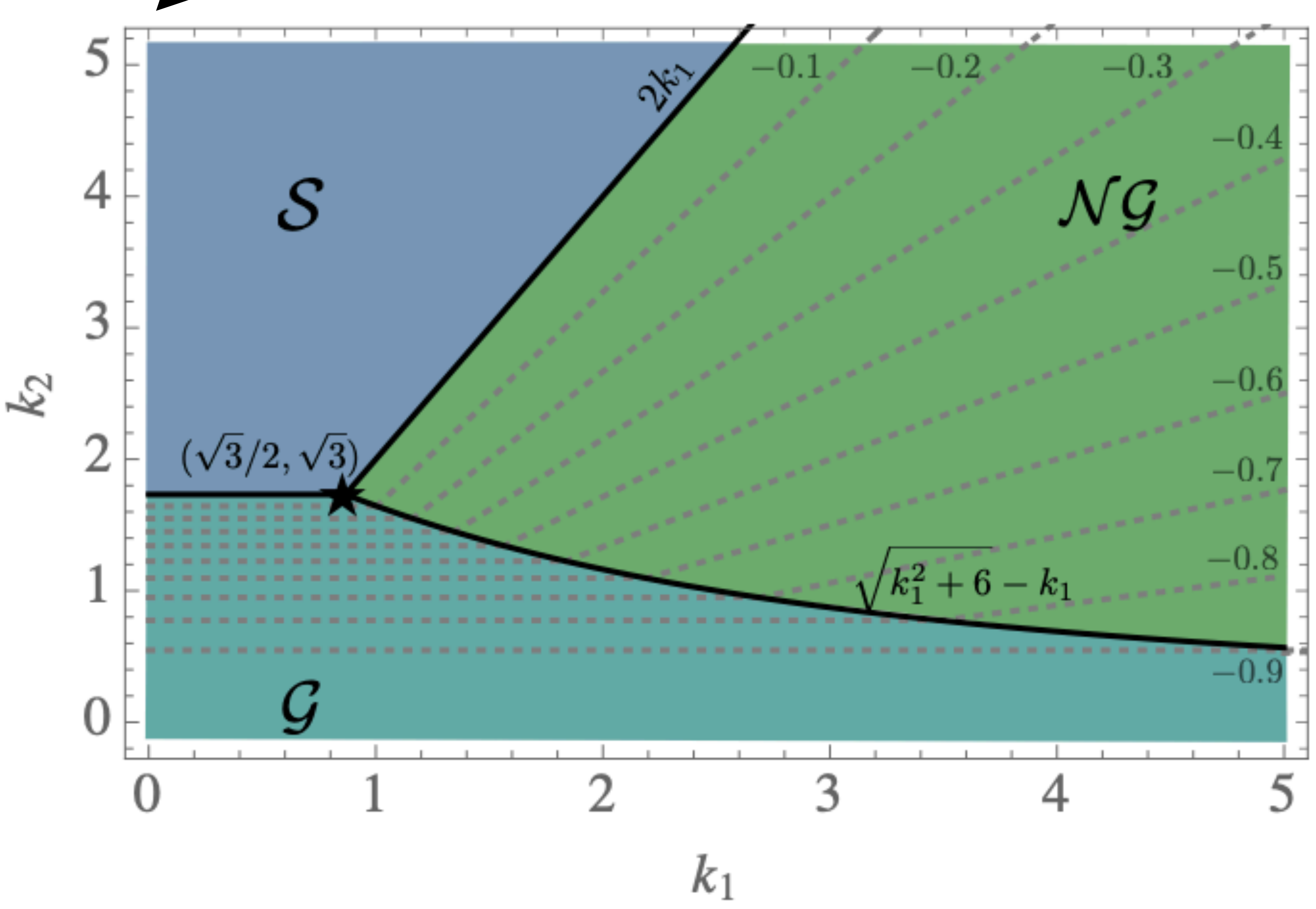
$$\begin{cases} \ddot{\phi}_1 + 3H\dot{\phi}_1 - f\, f_1 \dot{\phi}_2^2 + V_1 = 0 \ , \\ \ddot{\phi}_2 + 3H\dot{\phi}_2 + 2\frac{f_1}{f}\dot{\phi}_2\dot{\phi}_1 = 0 \ , \end{cases}$$

- Geodesic: $\dot{\phi}_2 = 0 \quad \dot{\phi}_1 = -\frac{V_1}{3H}$
- Non Geodesic: $\dot{\phi}_2 \neq 0 \quad \dot{\phi}_1 = -\frac{3Hf}{2f_1}$

	x_1	x_2	y_1	Ω_ϕ	ω_ϕ	existence
$\mathcal{K}_+$	1	0	0	1	1	all k_1, k_2, γ
$\mathcal{K}_-$	-1	0	0	1	1	all k_1, k_2, γ
$\mathcal{F}$	0	0	0	0	undefined	all k_1, k_2, γ
$\mathcal{S}$	$\frac{\sqrt{3/2}\gamma}{k_2}$	0	$\frac{\sqrt{3/2\gamma(2-\gamma)}}{k_2}$	$\frac{3\gamma}{k_2^2}$	$\gamma - 1$	$0 < \gamma < 2 \wedge k_2^2 \geq 3\gamma$
$\mathcal{G}$	$\frac{k_2}{\sqrt{6}}$	0	$\sqrt{1 - \frac{k_2^2}{6}}$	1	$-1 + \frac{k_2^2}{3}$	$k_2 < \sqrt{6}$
$\mathcal{NG}$	$\frac{\sqrt{6}}{(2k_1+k_2)}$	$\frac{\pm\sqrt{k_2^2+2k_2k_1-6}}{2k_1+k_2}$	$\sqrt{\frac{2k_1}{2k_1+k_2}}$	1	$\frac{k_2-2k_1}{k_2+2k_1}$	$k_2 \geq \sqrt{6+k_1^2} - k_1$

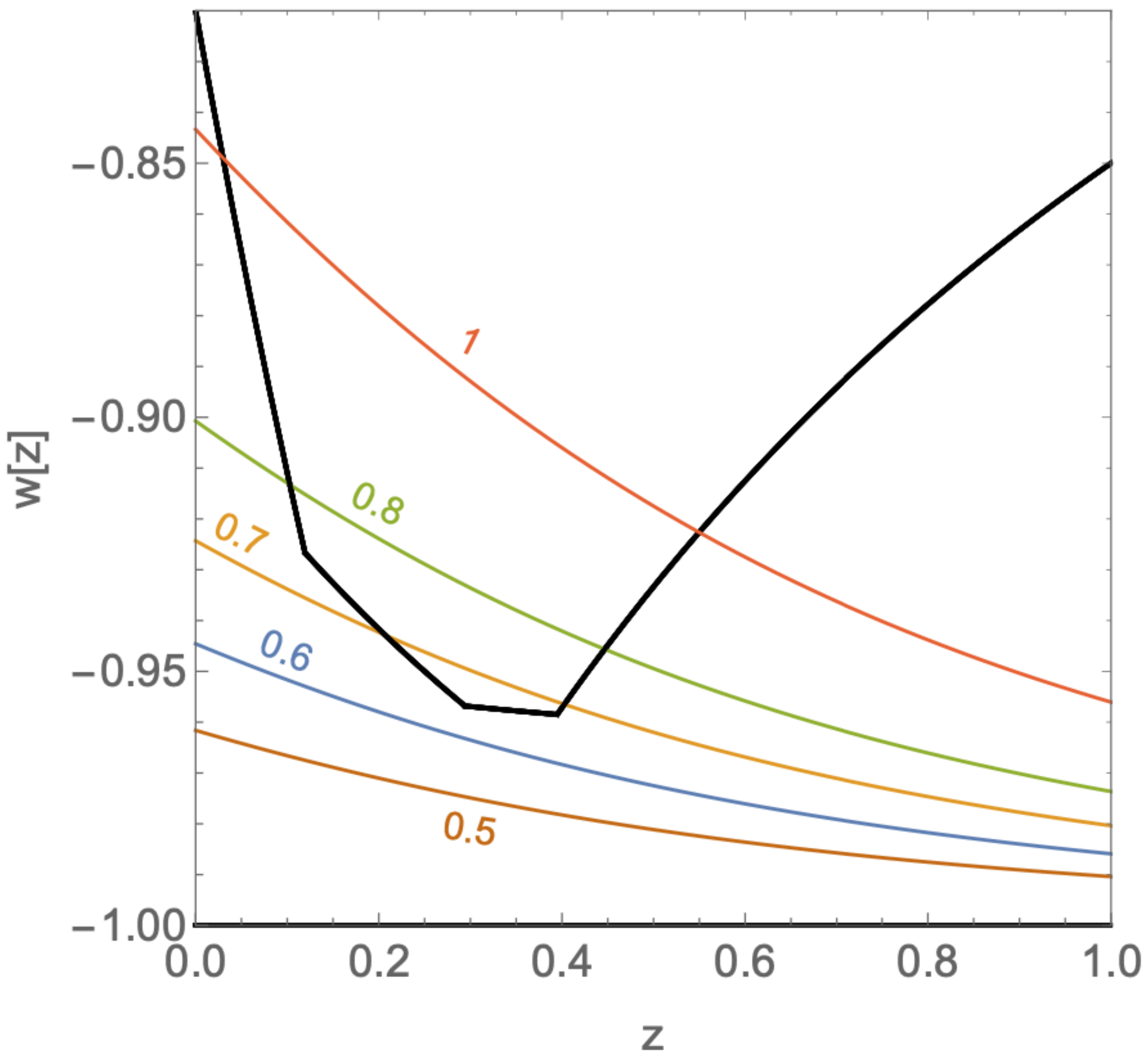
Multifield Quintessence

Single field regime $k_1 = 0$



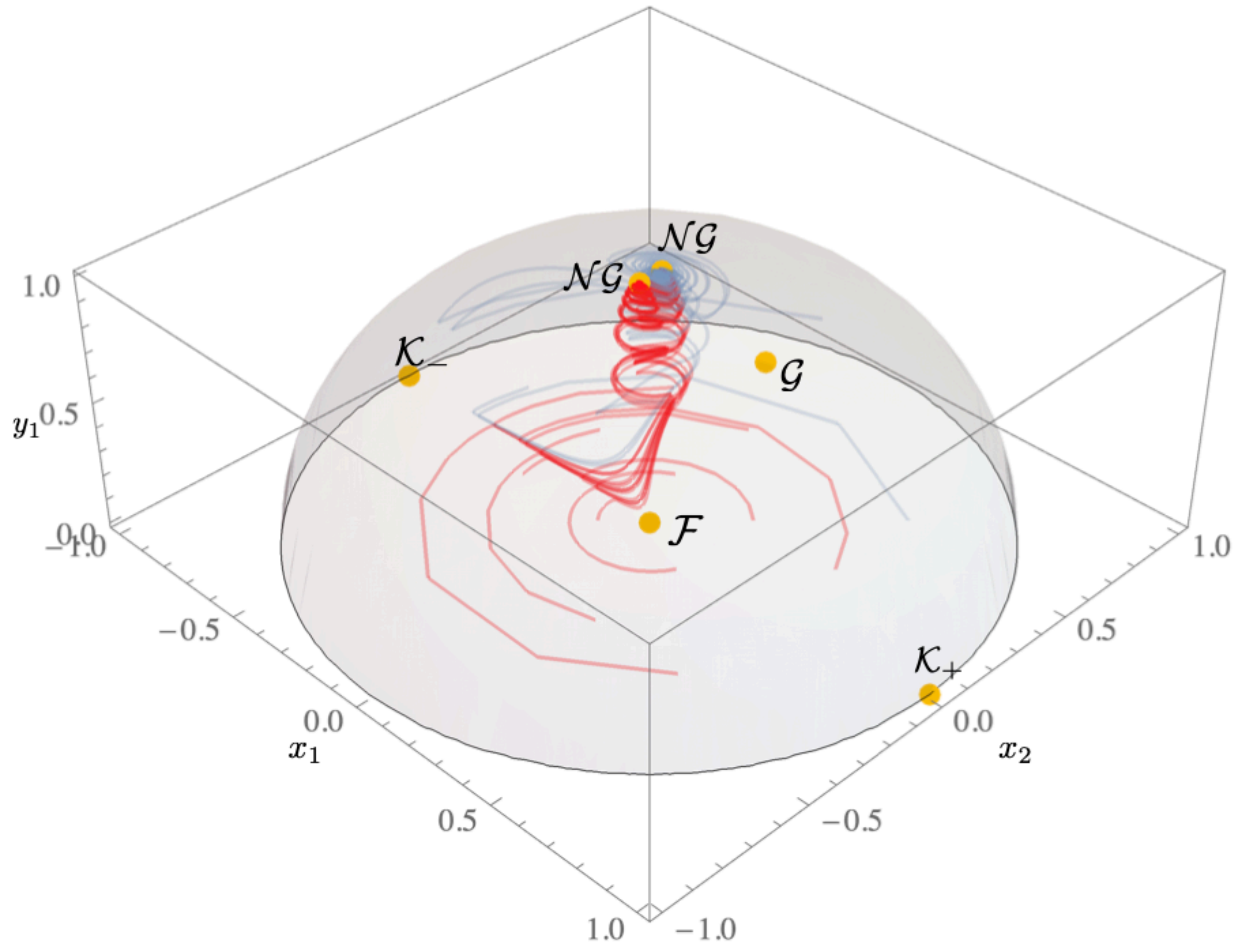
Look for observationally viable quintessence

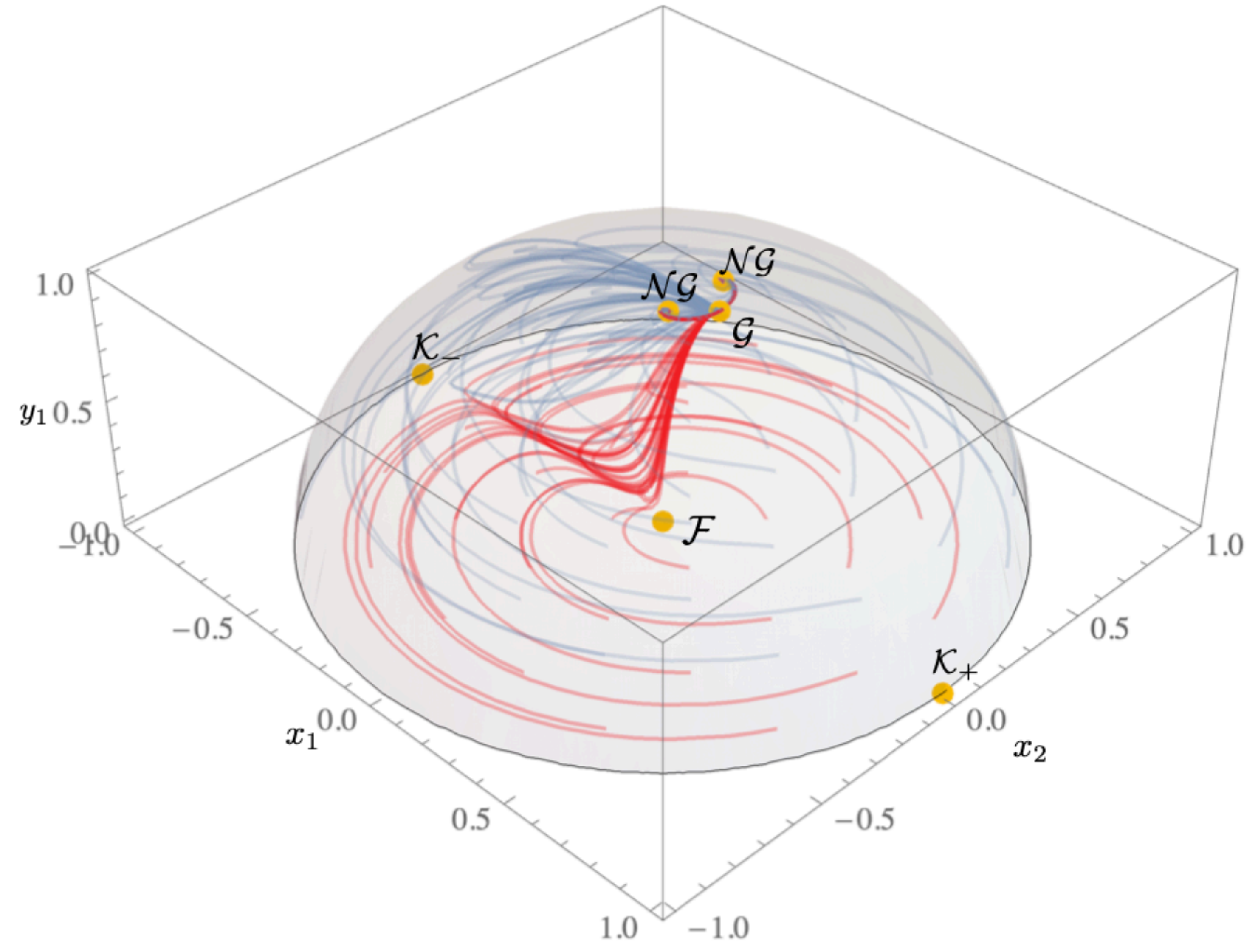
$$\omega_{DE} \sim -1 \qquad \Omega_{DE} = 0.7$$



[Agrawal et al. '18]

Multifield Quintessence





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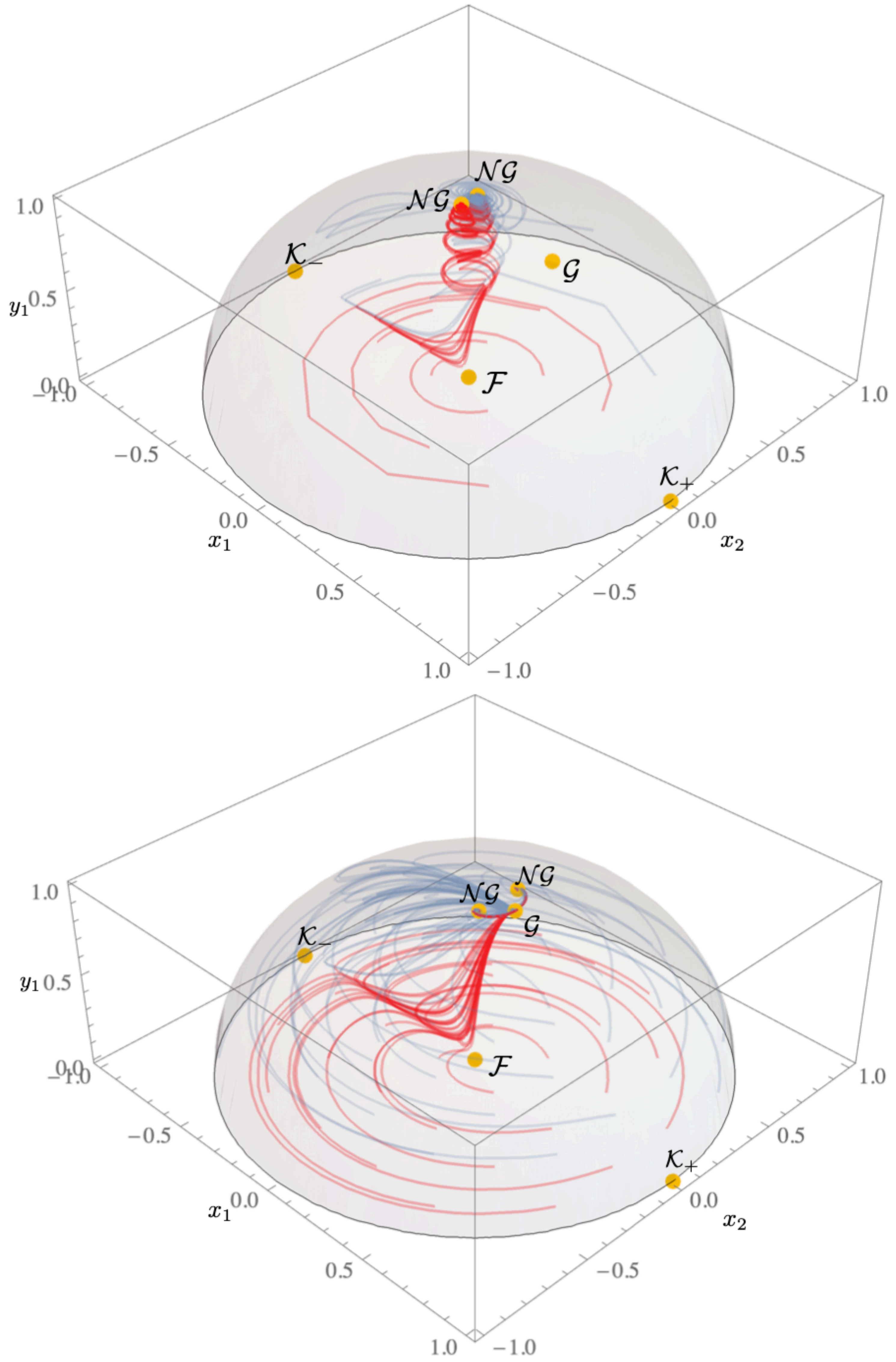
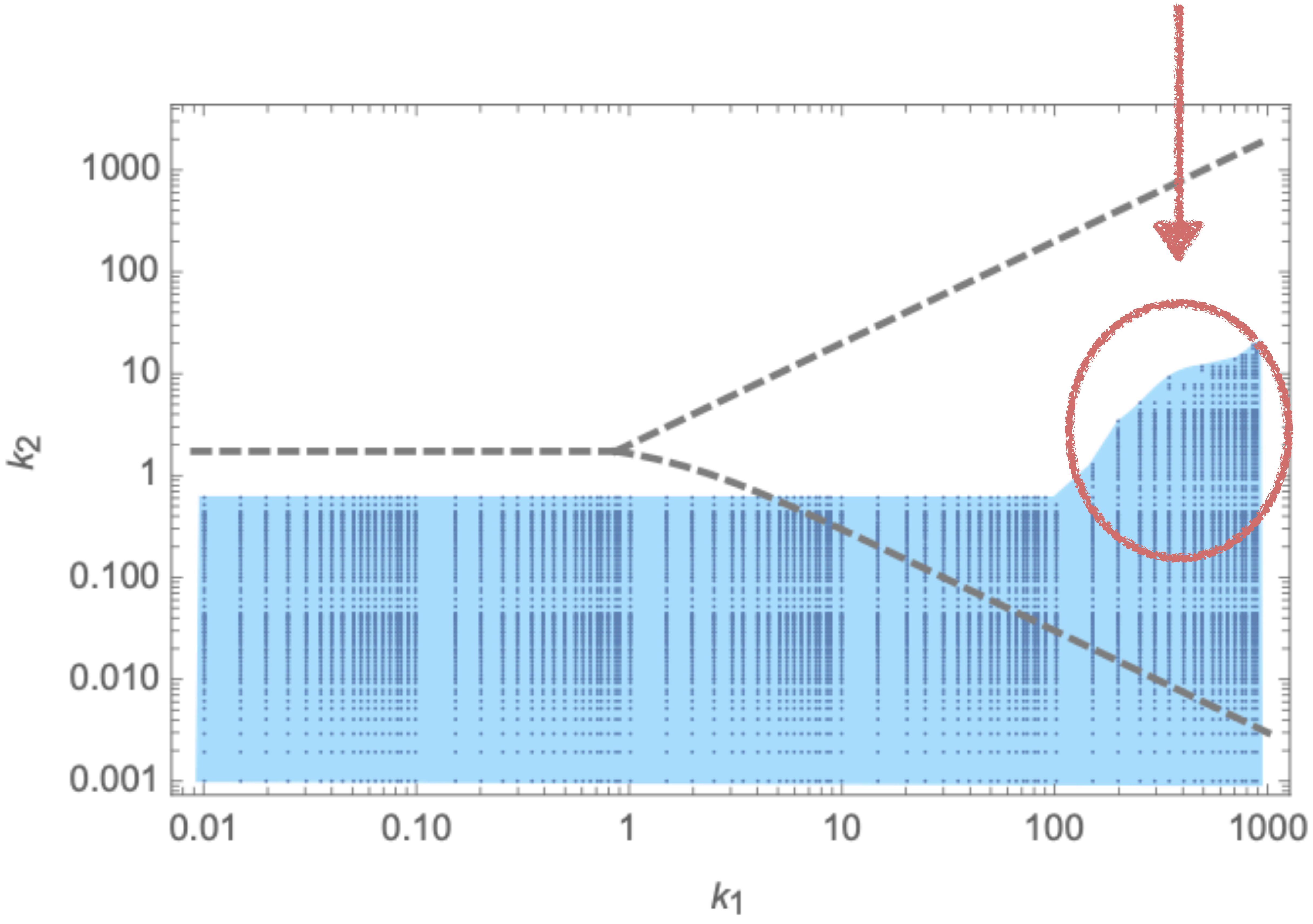


Steep potentials require LARGE field space curvatures



Multifield Quintessence

[Saltman,Silverstein, '04]
[(Brinkman),Cicoli,Dibitetto,FGP 2020-22]

?Embeddable into string theory?

$$K = -p \ln[X + \bar{X}] \qquad V_K \propto e^K = (X + \bar{X})^{-p}$$

$$k_1 = \sqrt{2/p} \qquad \text{and} \qquad k_2 = \sqrt{2p}\,.$$

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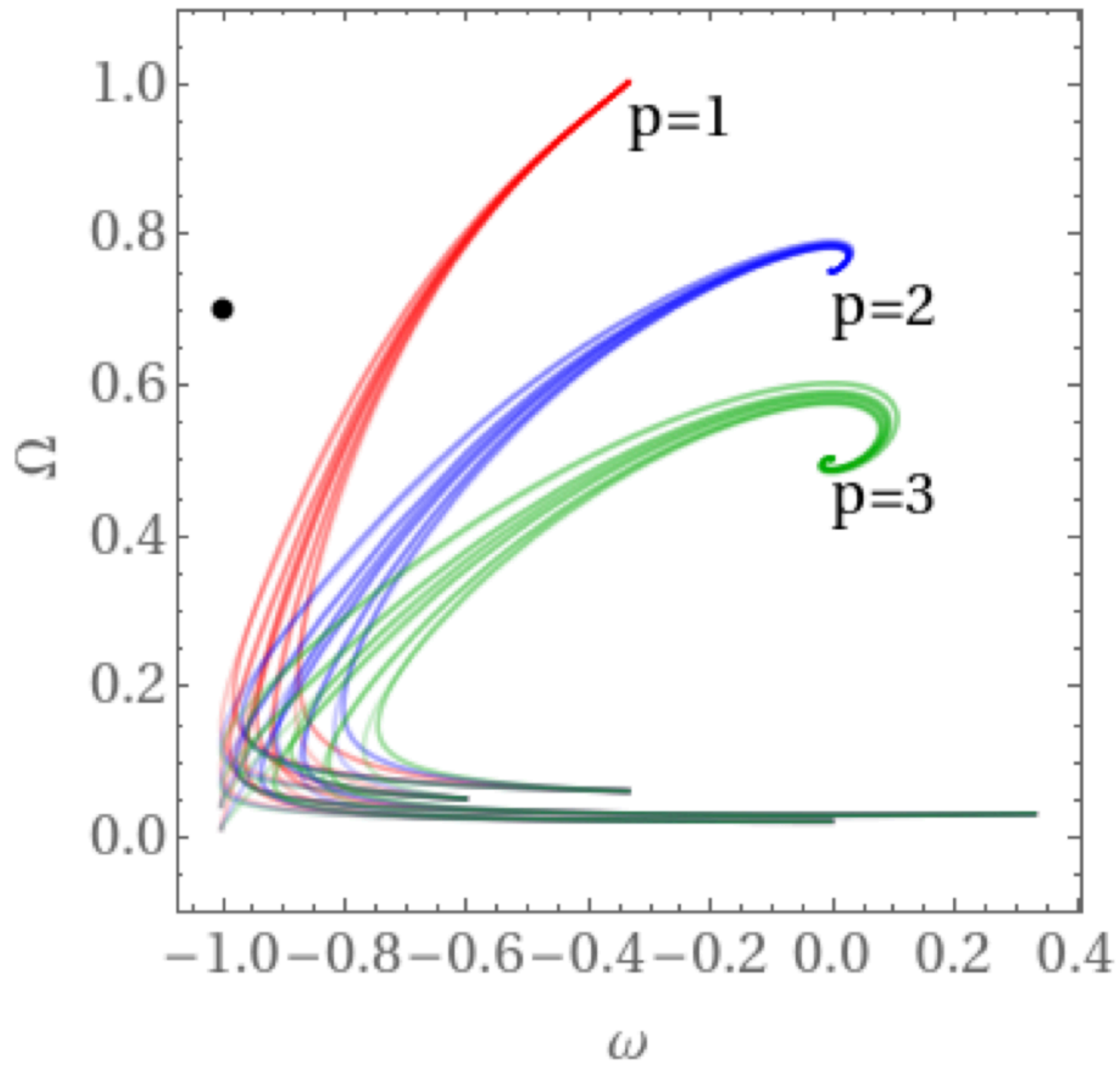

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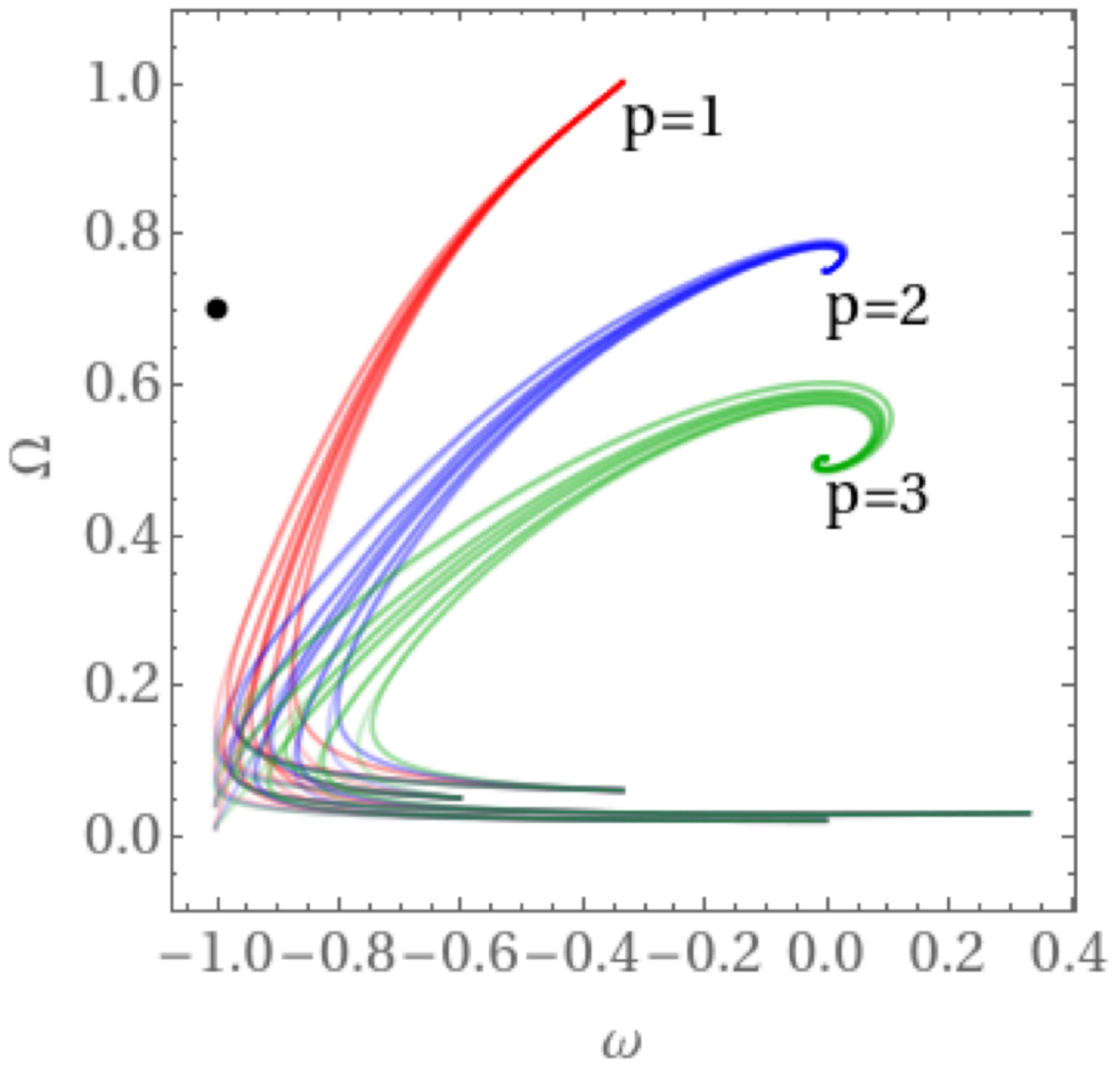
p	X	Theory	Sources	$\mathcal{M}_{\text{internal}}$
1	$S = e^{-\varphi} + \mathrm{i}\,a$	Heterotic	—	SU(3) str.
2	$T_2 = \mathrm{Vol}(\Sigma_4^{(2)}) + \mathrm{i}\int_{\Sigma_4^{(2)}} C_{(4)}$	Type IIB	D3/D7, O3/O7	K3-fibered CY_3
3	$T = \mathrm{Vol}(\Sigma_4) + \mathrm{i}\int_{\Sigma_4} C_{(4)}$	Type IIB	D3/O3	CY_3
7	$Z = \mathrm{Vol}(\Sigma_3) + \mathrm{i}\int_{\Sigma_3} A_{(3)}$	M-theory	KK6/KKO6	G_2 str.



Axionic DE

[Kaloper,Sorbo '05]

Axionic DE: -Potential generated by non perturbative effects

-Derivative couplings to matter

-Radiative stability

scale suppression

fifth force suppression

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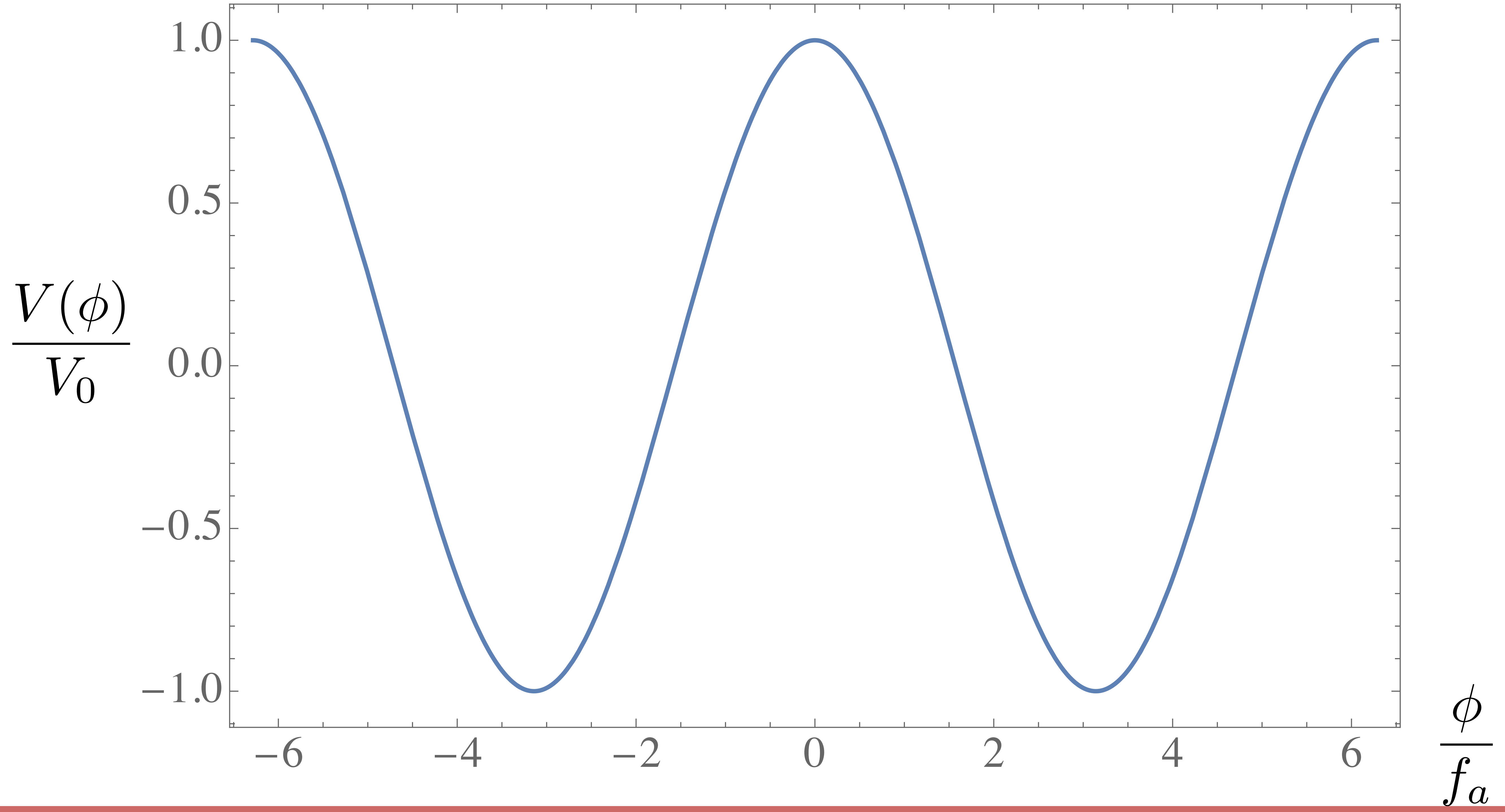

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$\phi < \phi_{ip}$

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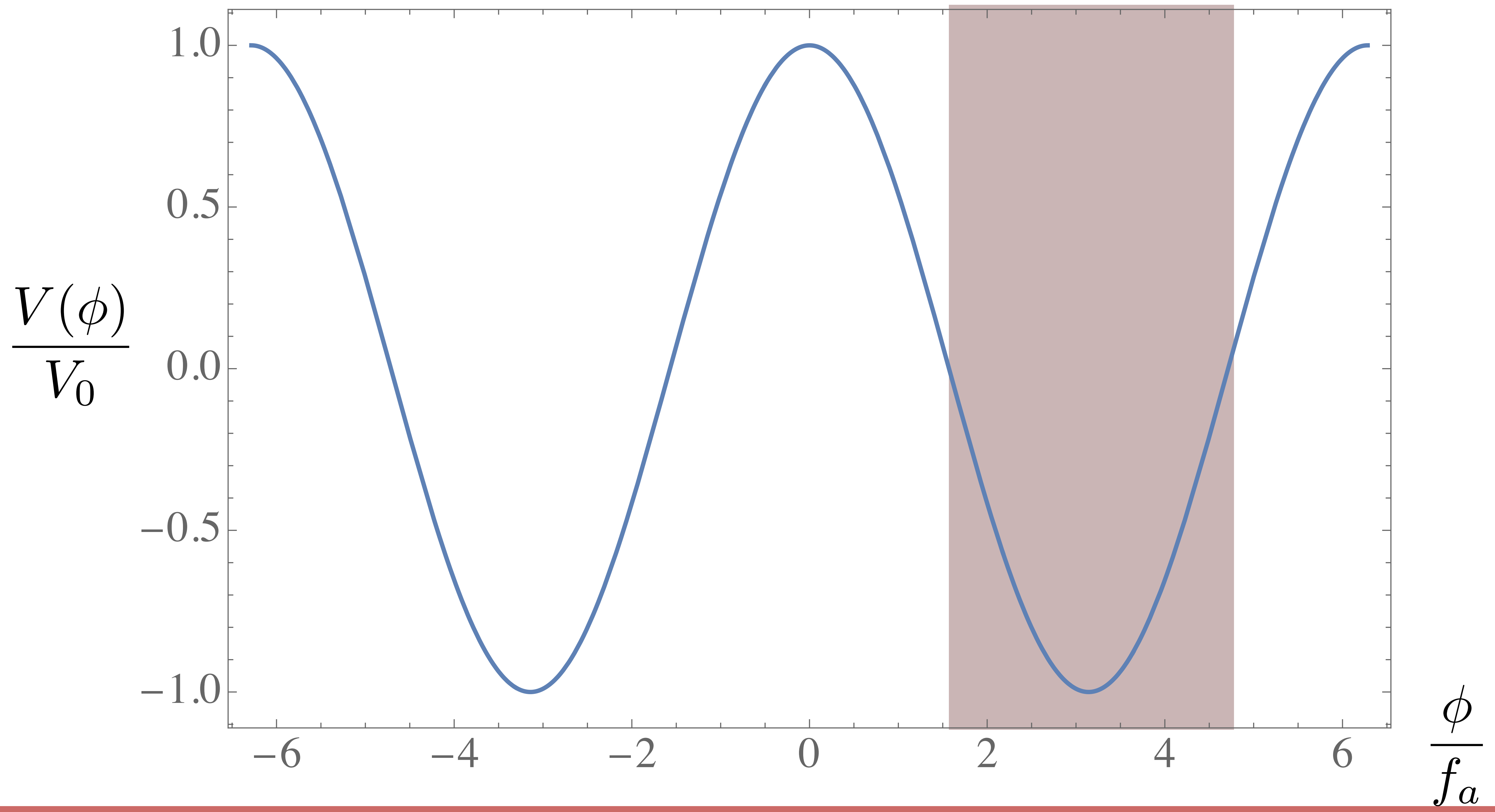

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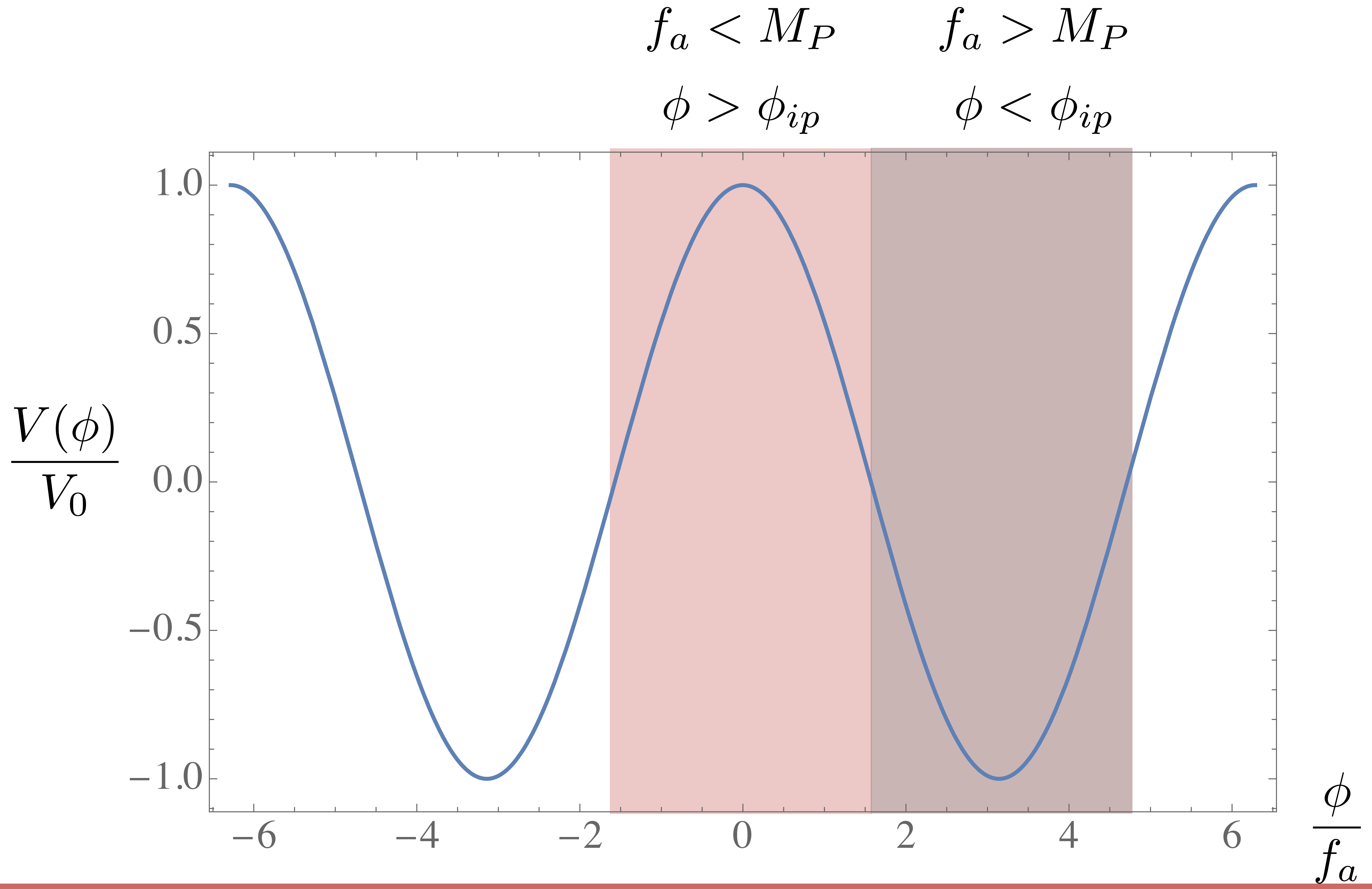

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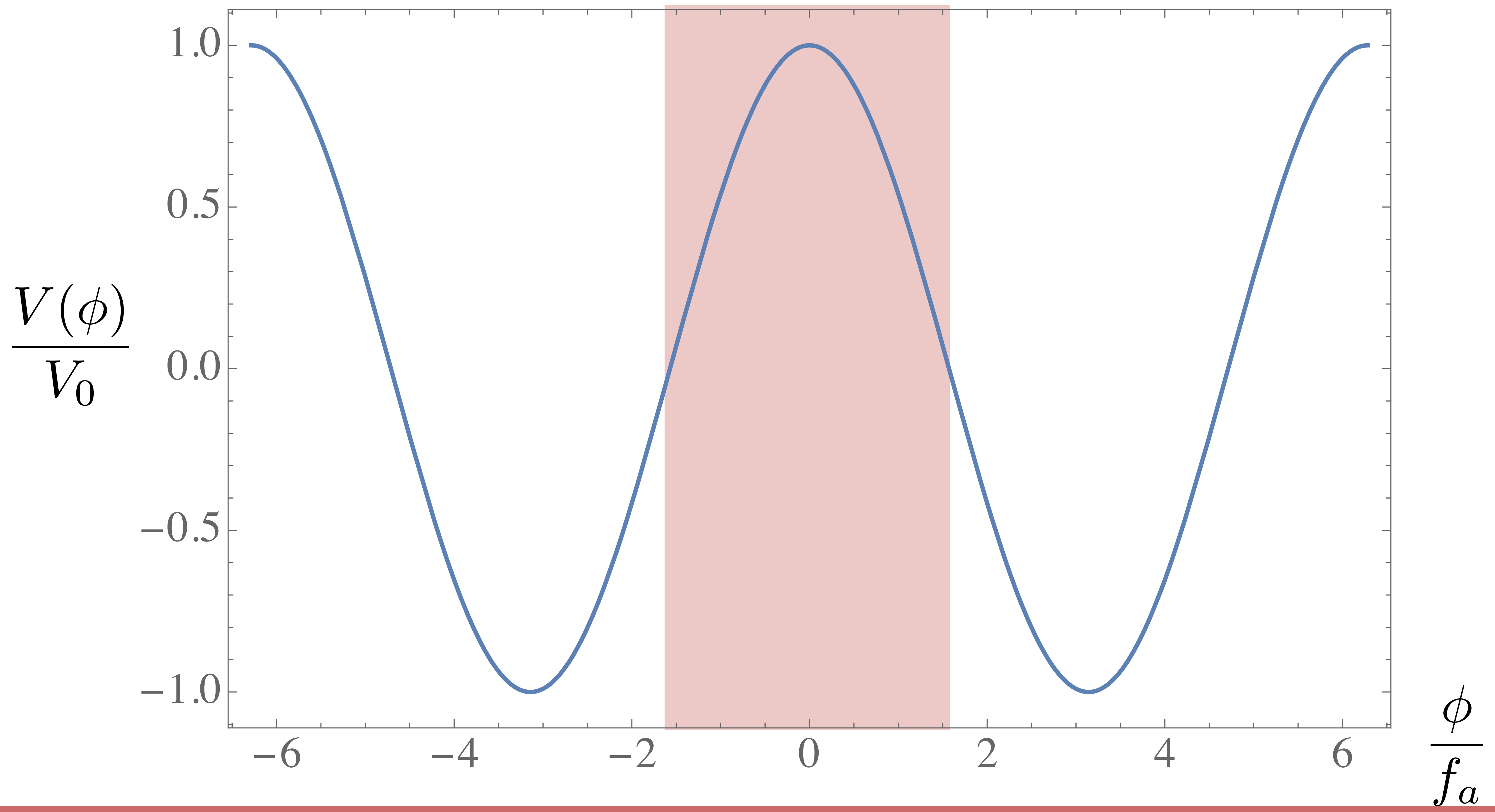

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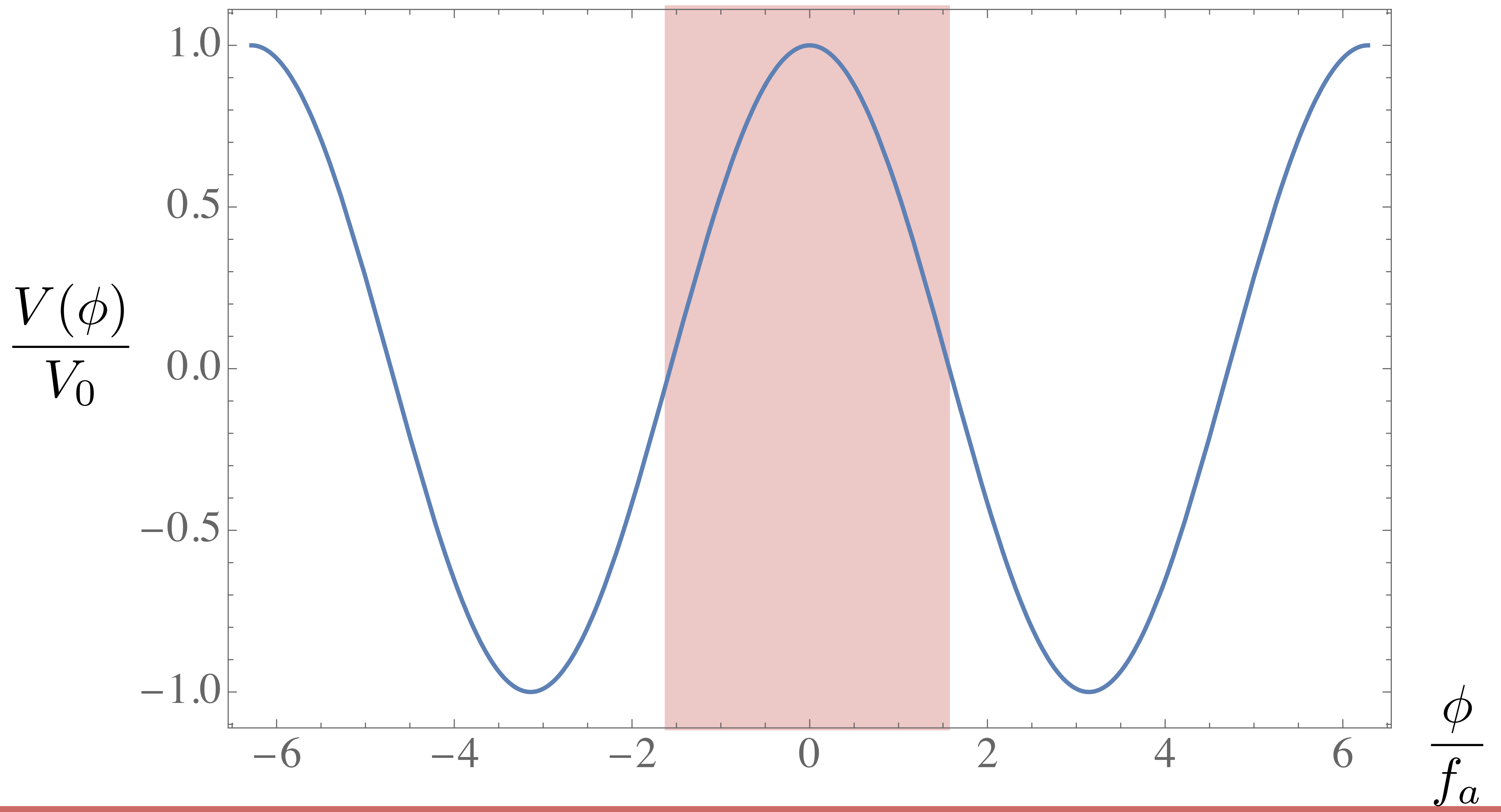
[Banks et al. '03] $\frac{f_a}{M_P} \sim \frac{(g_s)^p}{vol^q}$

axionic WGC: $S_a \; f_a < 1$

$f_a < M_P$

$\phi > \phi_{ip}$

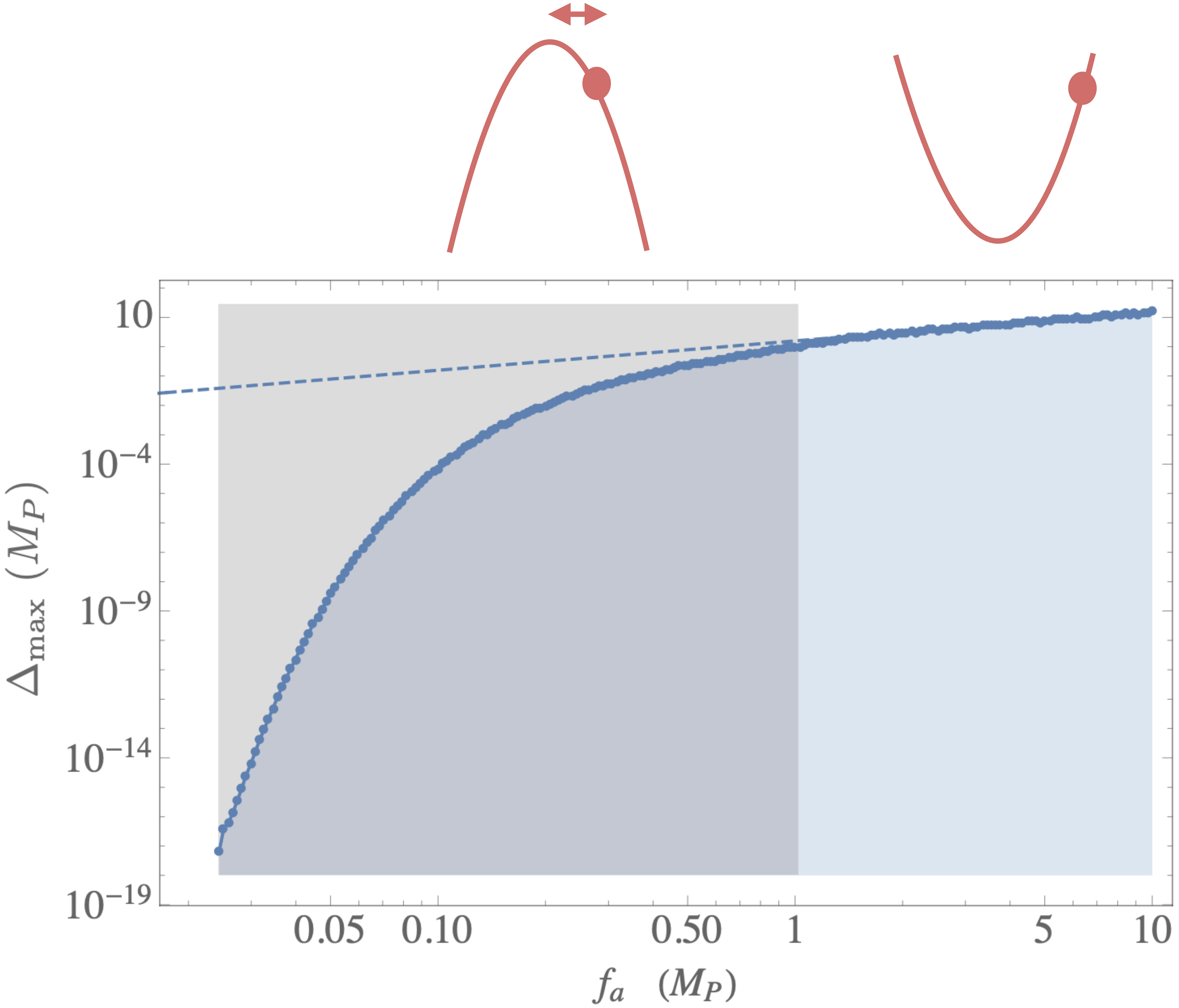


Axionic DE

$$\Delta_{max} = |\phi_i - \phi_{max}|$$

[Dutta and Scherrer ‘08]

[Cicoli, Cunillera,Padilla,FGP ’21]



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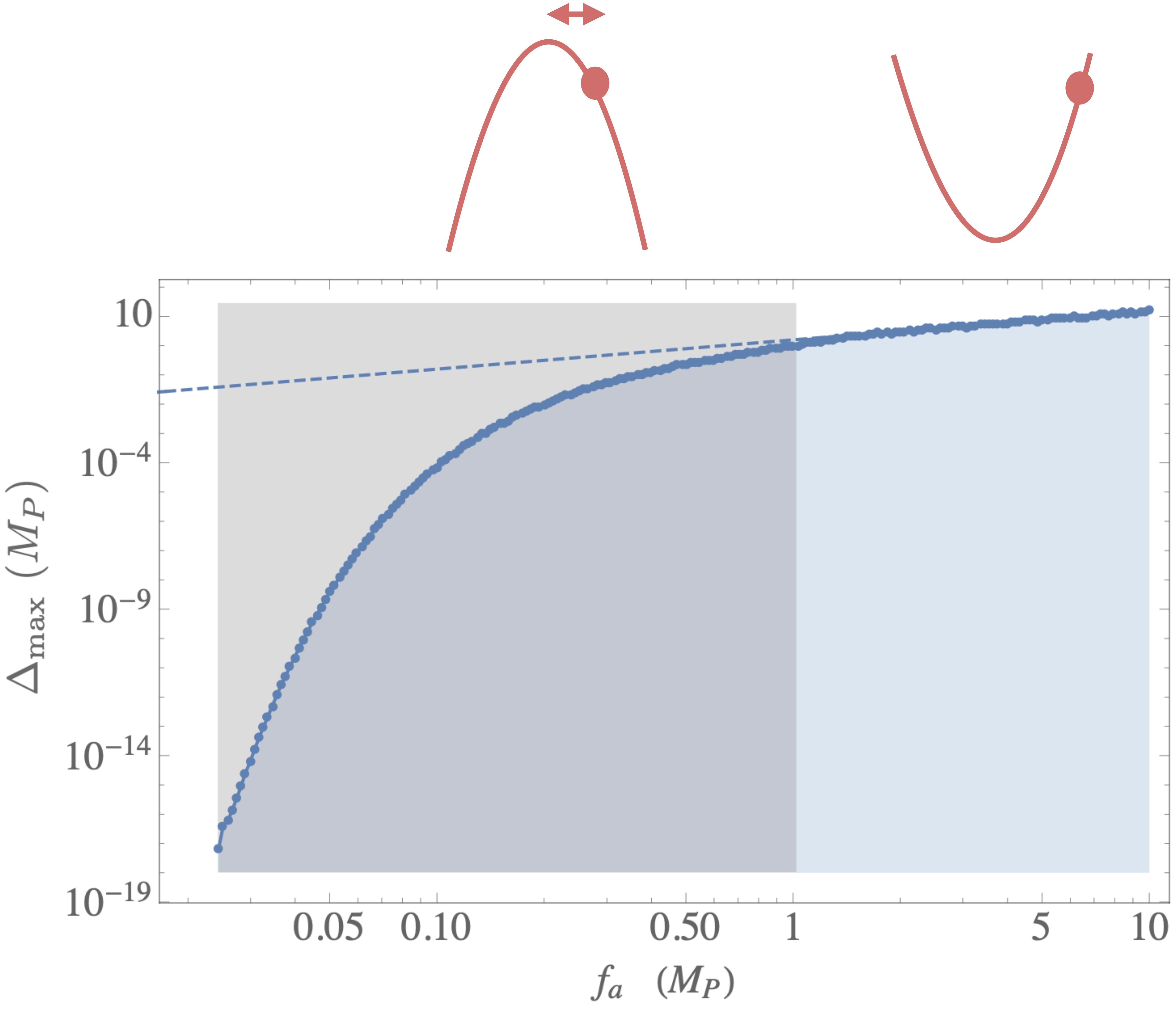

Small decay constant

Start very close to top of the hill

tuning of initial conditions

Axionic DE

[Cicoli, Cunillera,Padilla,FGP '21]

Axion is classically frozen until today

$$\frac{\partial \phi}{\partial N} = -\frac{V_\phi}{3H_{\text{inf}}^2}$$

$$V_\phi \ll H_{inf}^2 \qquad \frac{\partial \phi}{\partial N} = 0$$

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Quantum diffusion during inflation

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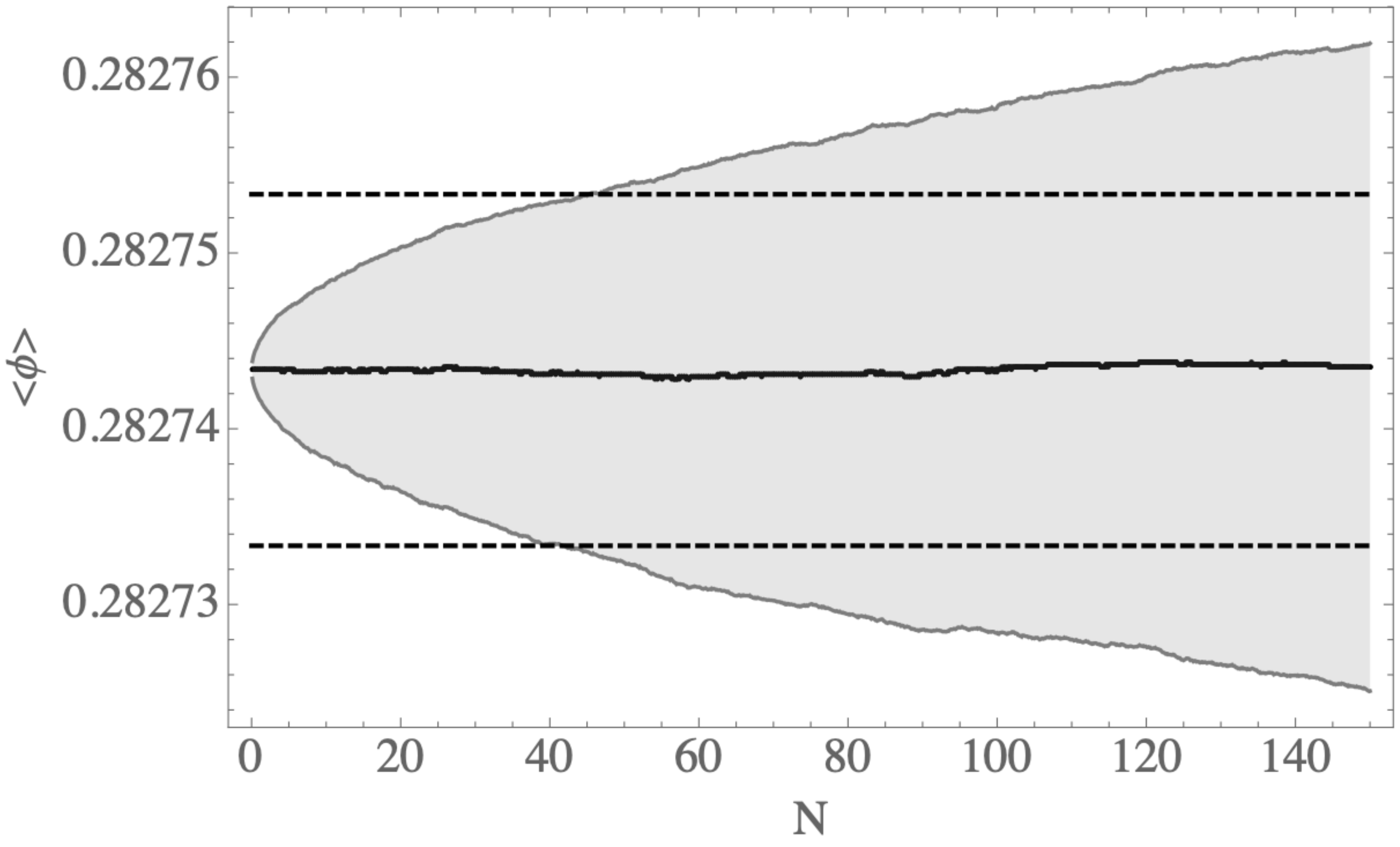


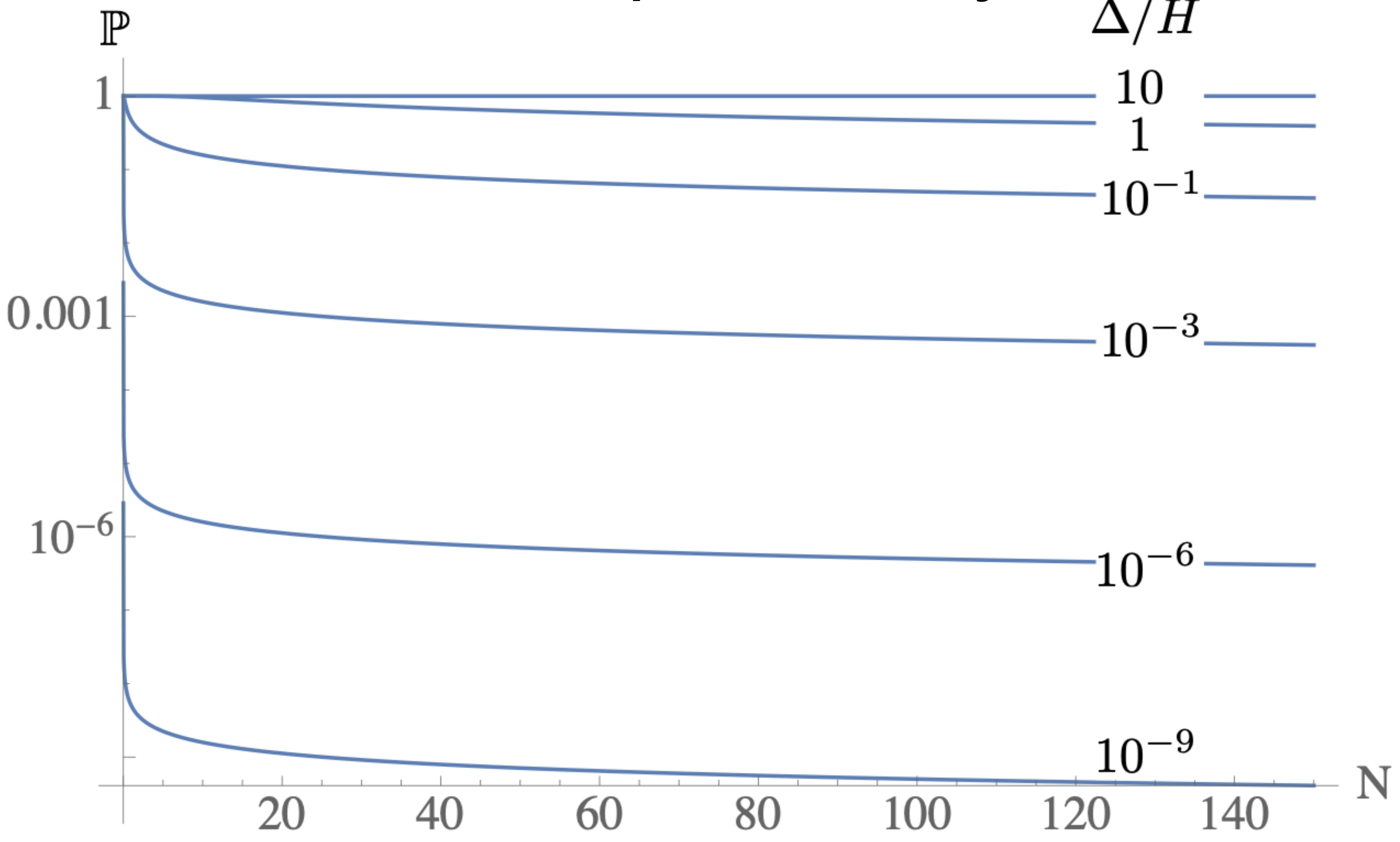
Quantum diffusion during inflation

Choice of ics gets blurred during inflation

Axionic DE

[Cicoli, Cunillera,Padilla,FGP '21]

Survival probability



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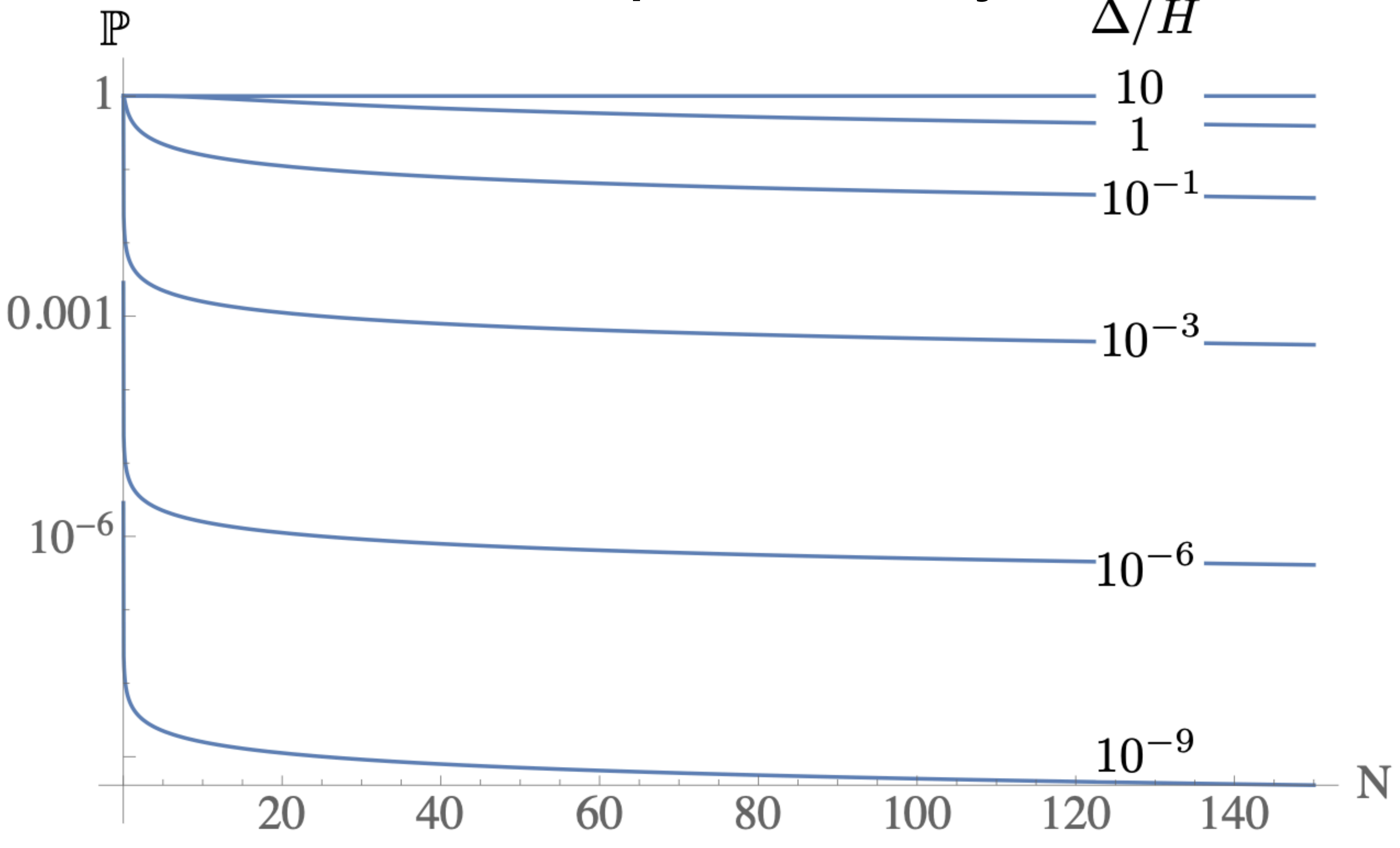

Safe from diffusion if $\Delta_{max} > H_{inf}$

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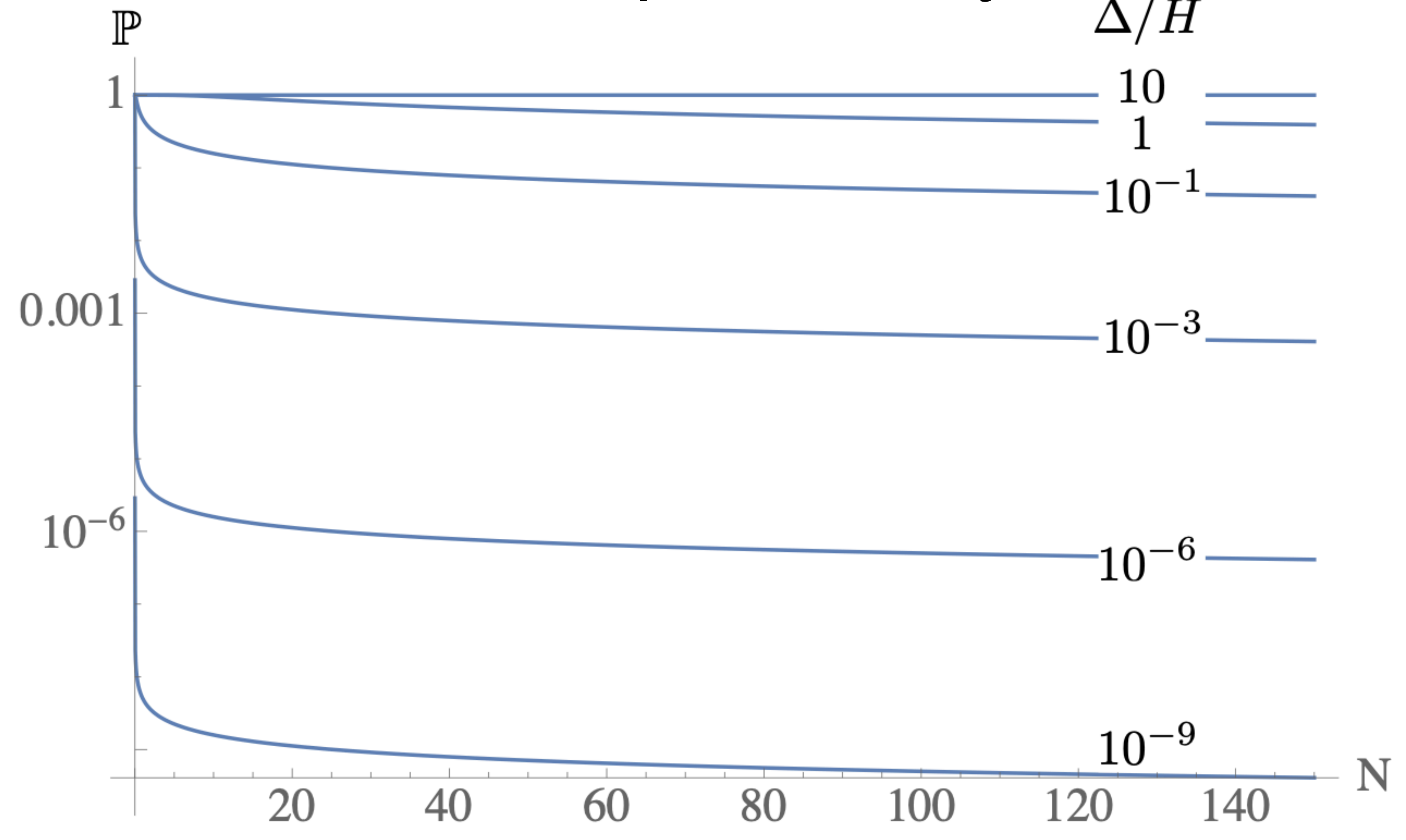

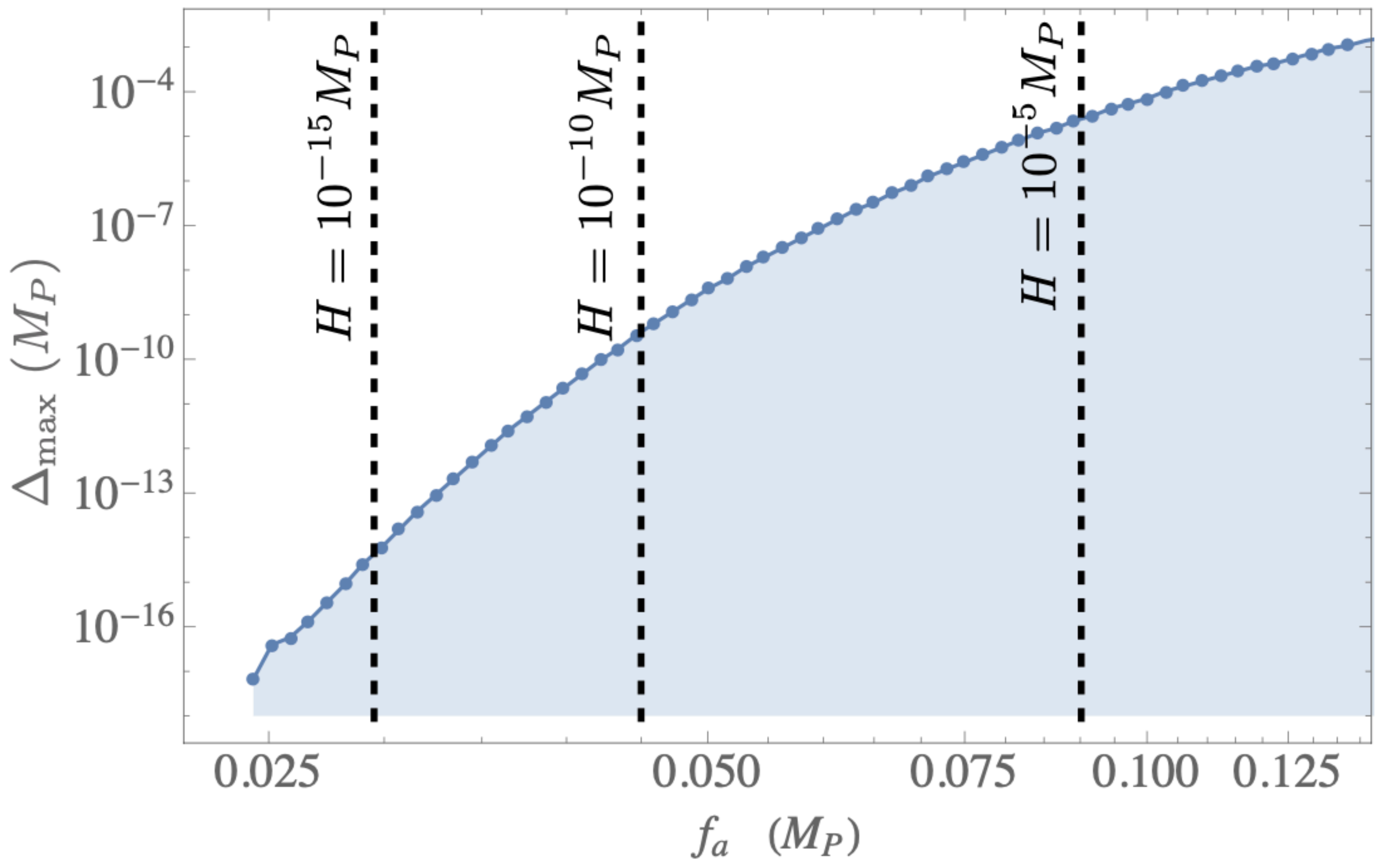

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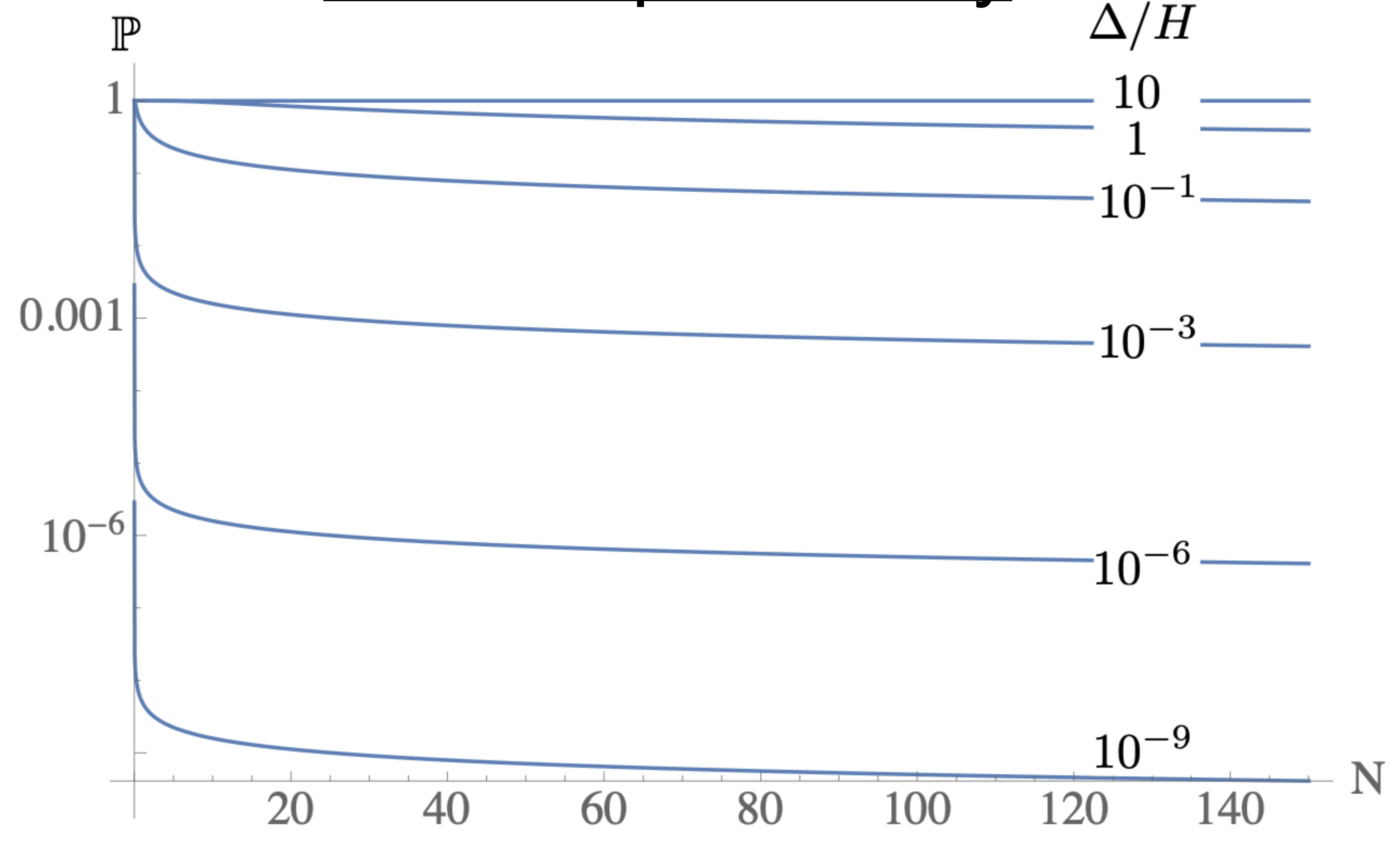
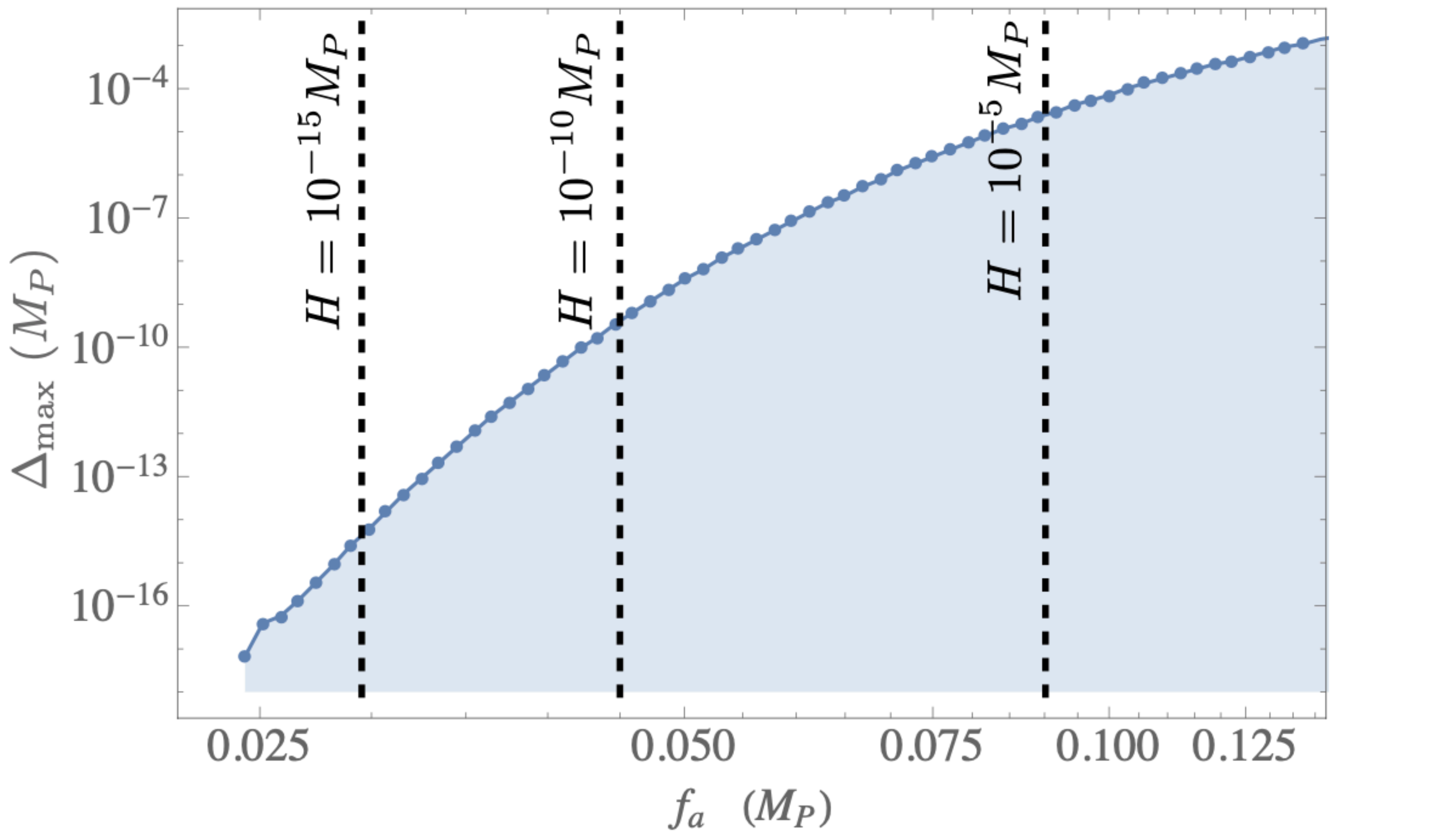
[Cicoli, Cunillera,Padilla,FGP ’21]

Survival probability





Safe from diffusion if $\Delta_{max} > H_{inf}$

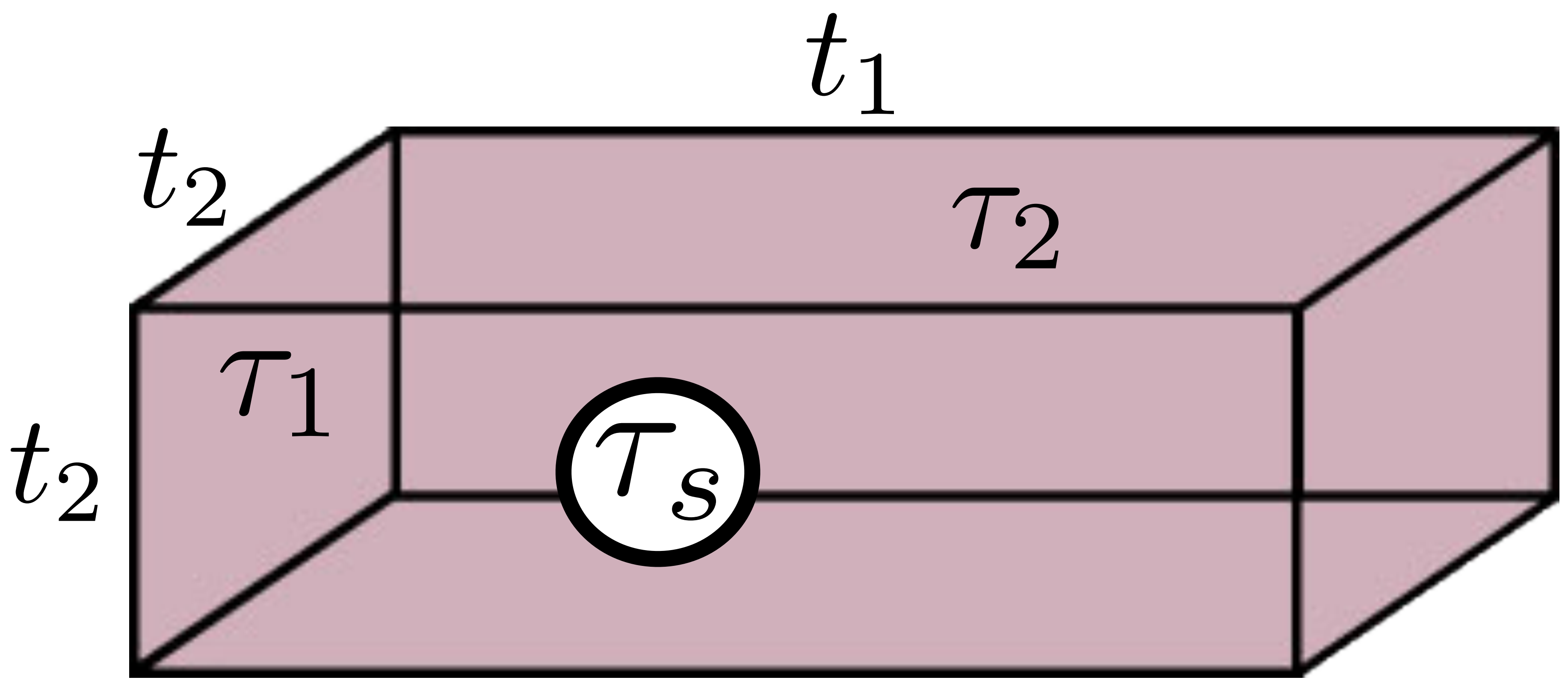
example: $H_{inf} \sim 10^{-5} M_P \rightarrow f_a > 0.08 M_P$

Axionic DE embedding

[Cicoli, Cunillera,Padilla,FGP ’24]

Embedding into type IIB compactifications

$$\mathcal{V} = t_1 t_2^2 - t_s^3 = \sqrt{\tau_1}\tau_2 - \tau_s^{3/2}$$



$T_j = \tau_j + i\theta_j$ 3 moduli + 3 axions

Theory defined by $$K = -2\ln\left(\mathcal{V} + \frac{\xi}{2g_s^{3/2}}\right) + K_{g_s}$$

$$W_{\rm np} = A_s\, e^{-a_s T_s} + A_2\, e^{-a_2 T_2} + A_1\, e^{-a_1 T_1}$$

Axionic DE embedding

Hierarchical structure

$$V = V_{LVS}(\mathcal{V}, \tau_s, \theta_s) + V_{inf}(\tau_1/\tau_2) + V_{late}(\theta_1, \theta_2)$$

→ smaller →

LVS stabilisation α'^3 corrections + n.p. effects [Conlon et al. '05]

$$V_{\rm vol} = \frac{\kappa}{\mathcal{V}^n} + \frac{3\xi|W_0|^2}{4g_s^{3/2}\mathcal{V}^3} - 4|W_0|A_s a_s \tau_s \frac{e^{-a_s\tau_s}}{\mathcal{V}^2} + 4\sqrt{2\hat{k}}\, A_s^2 a_s^2 \sqrt{\tau_s}\, \frac{e^{-2a_s\tau_s}}{\mathcal{V}}\,.$$

Axionic DE embedding

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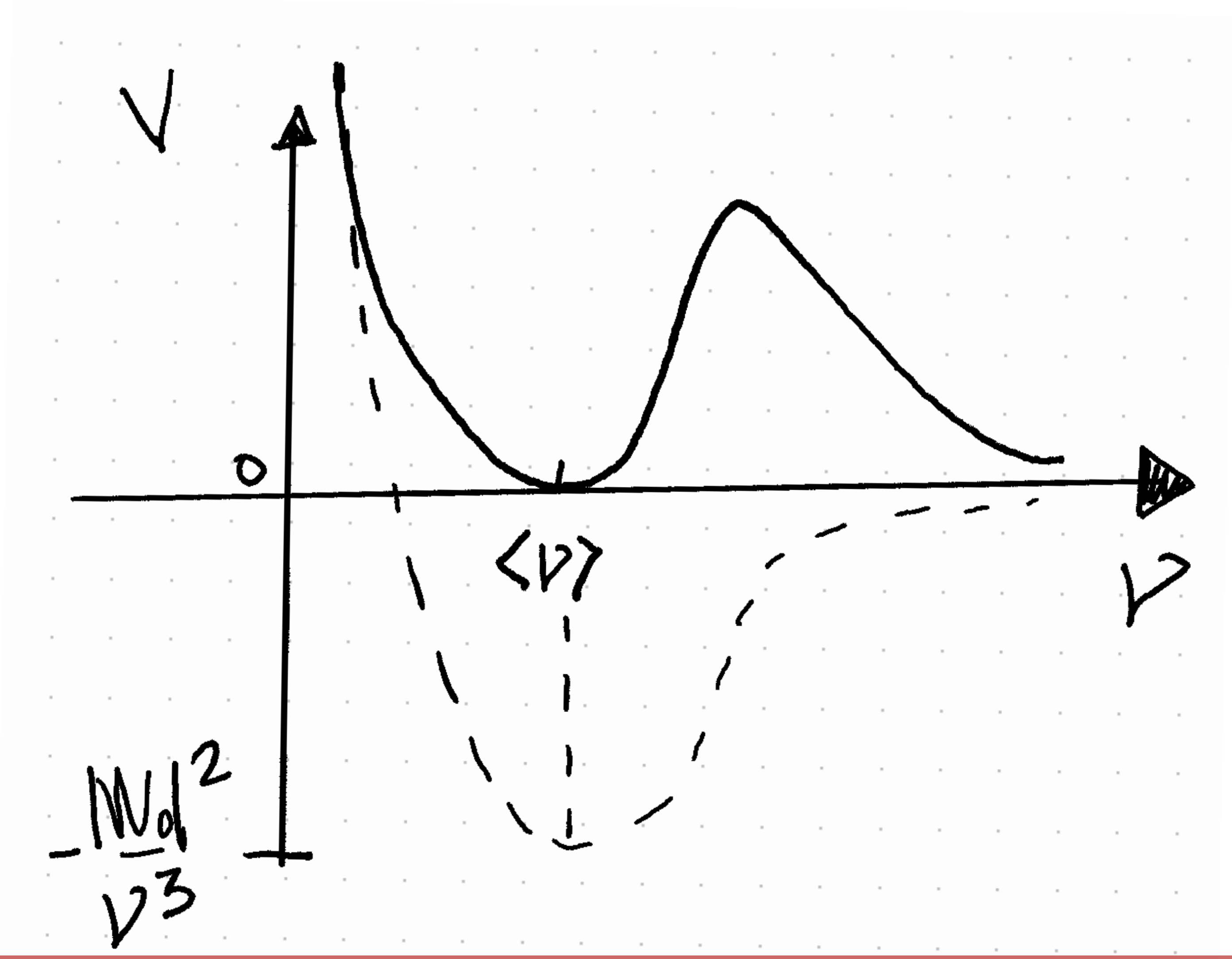
uplift

non SUSY AdS

$$\langle V \rangle \sim -\frac{|W_0|^2}{\mathcal{V}^3}$$

$$\langle \tau_s \rangle \propto 1/g_s$$

$$\langle \mathcal{V} \rangle \propto e^{1/g_s}$$



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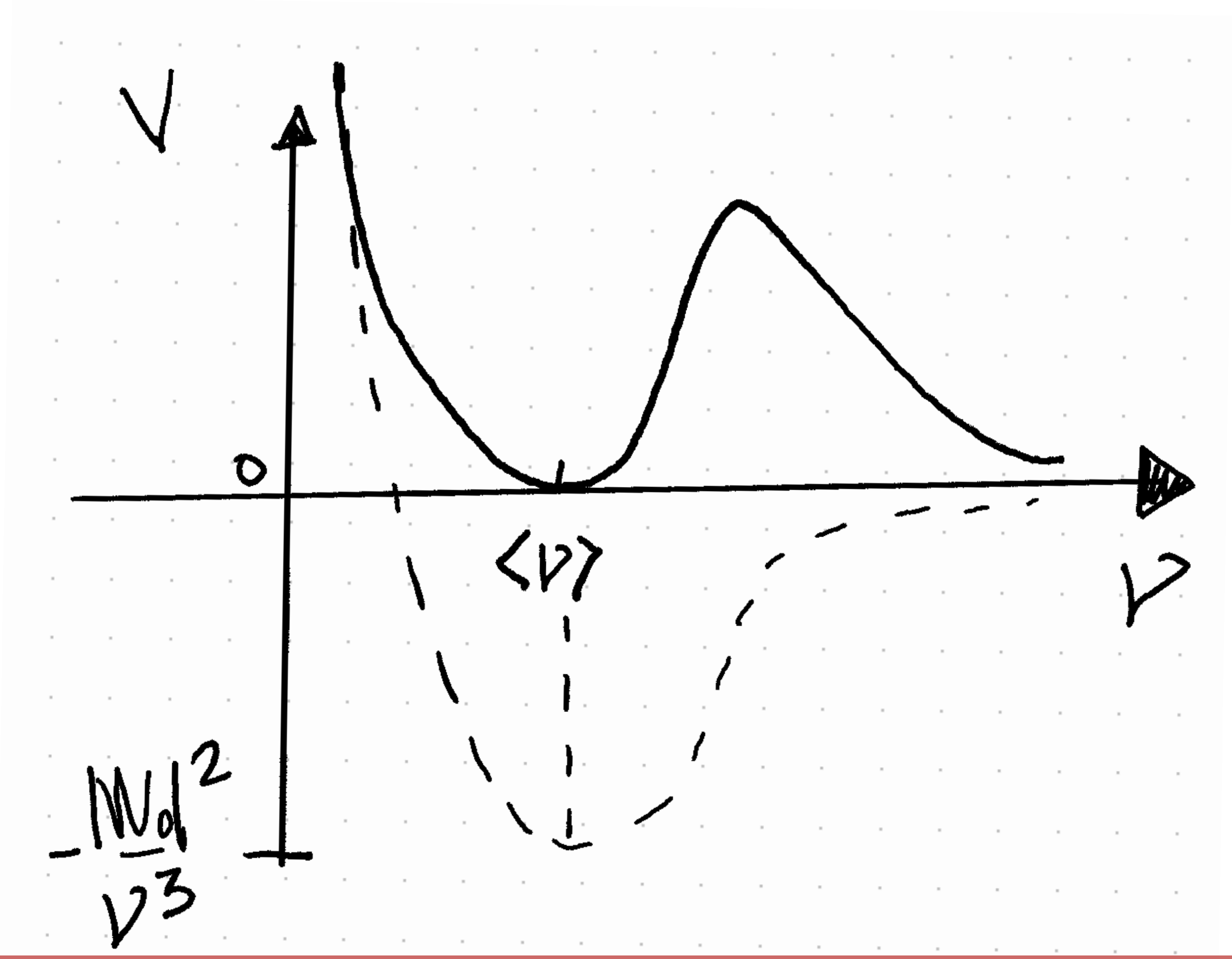


Mass hierarchy

$$m_{\tau_s} \sim m_{\theta_s} \sim \frac{M_P}{\mathcal{V}} >> m_{\mathcal{V}} \sim \frac{M_P}{\mathcal{V}^{3/2}}$$

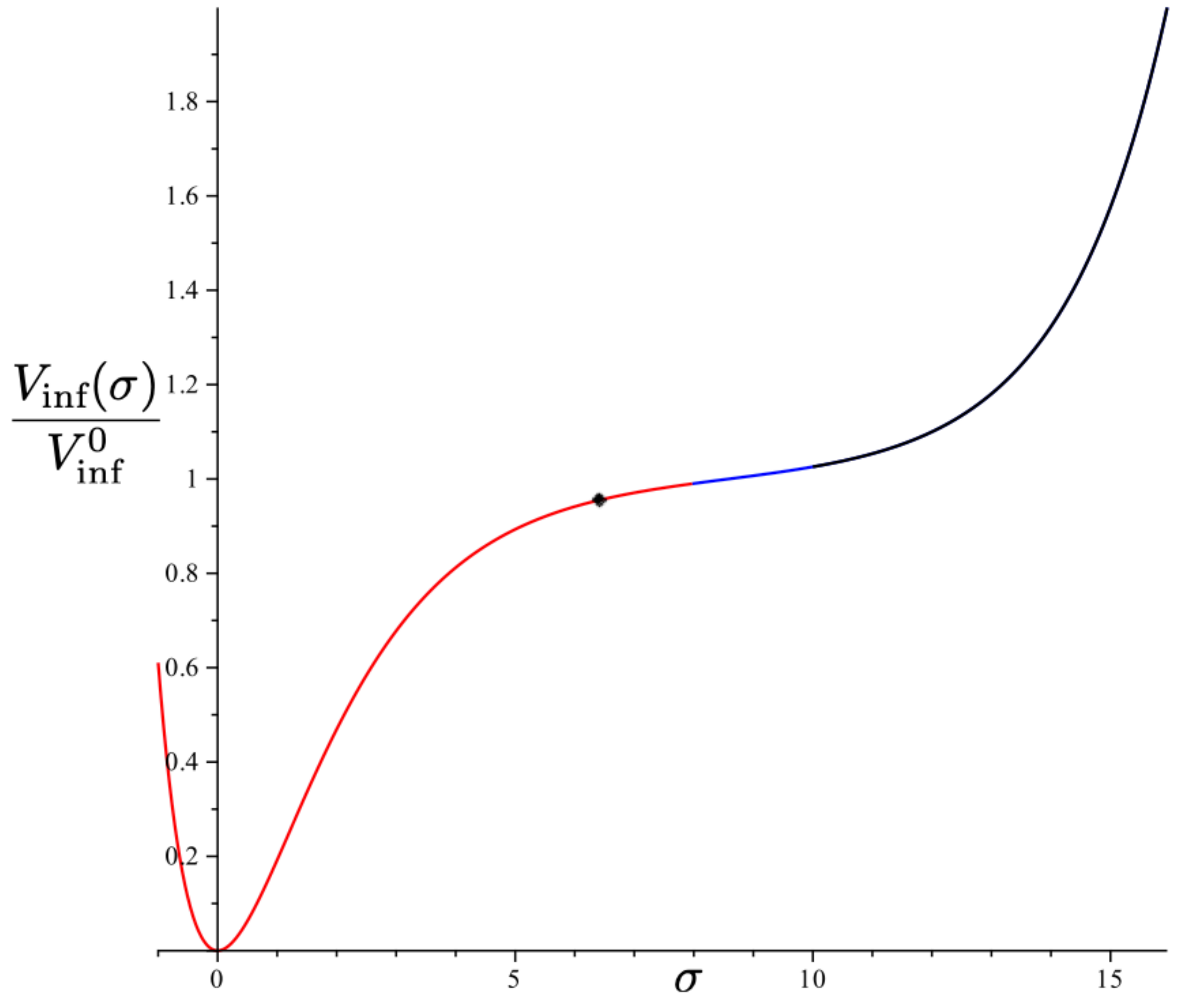
Axionic DE embedding

Fibre inflation: string loops (W) + HD [Cicoli et al. '08]

$$K_{g_s} = \sum_i g_s \frac{C_i(U,\bar{U})\, t_i^{\perp}}{\mathcal{V}} + \sum_i \frac{\tilde{C}_i(U,\bar{U})}{t_i^{\cap}\mathcal{V}} \,. \qquad V_{\rm hd} = -\frac{\lambda}{g_s^{3/2}} \frac{|W_0|^4}{\mathcal{V}^4} \Pi_i t_i \qquad \sigma \sim \log(\tau_1/\tau_2)/\sqrt{3}$$

$$V_{\rm inf}(\sigma) = V_0 \left[\left(1 - e^{-\frac{\sigma}{\sqrt{3}}}\right)^2 - 2\mathcal{R}\left(1 - \cosh\left(\frac{\sigma}{\sqrt{3}}\right)\right)\right] \qquad V_0 \propto \frac{|W_0|^4}{\mathcal{V}^{11/3}}$$

plateau steepening



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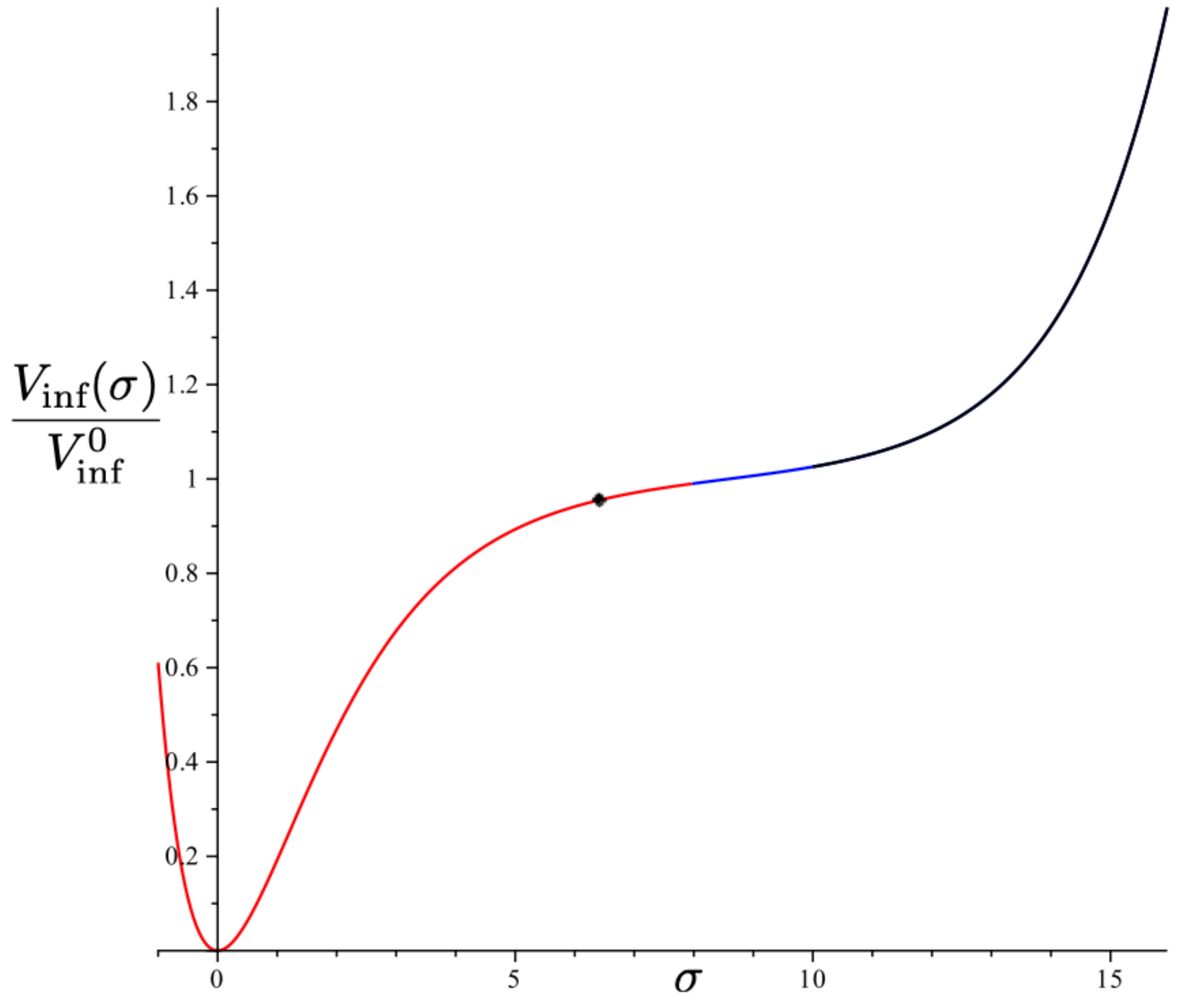
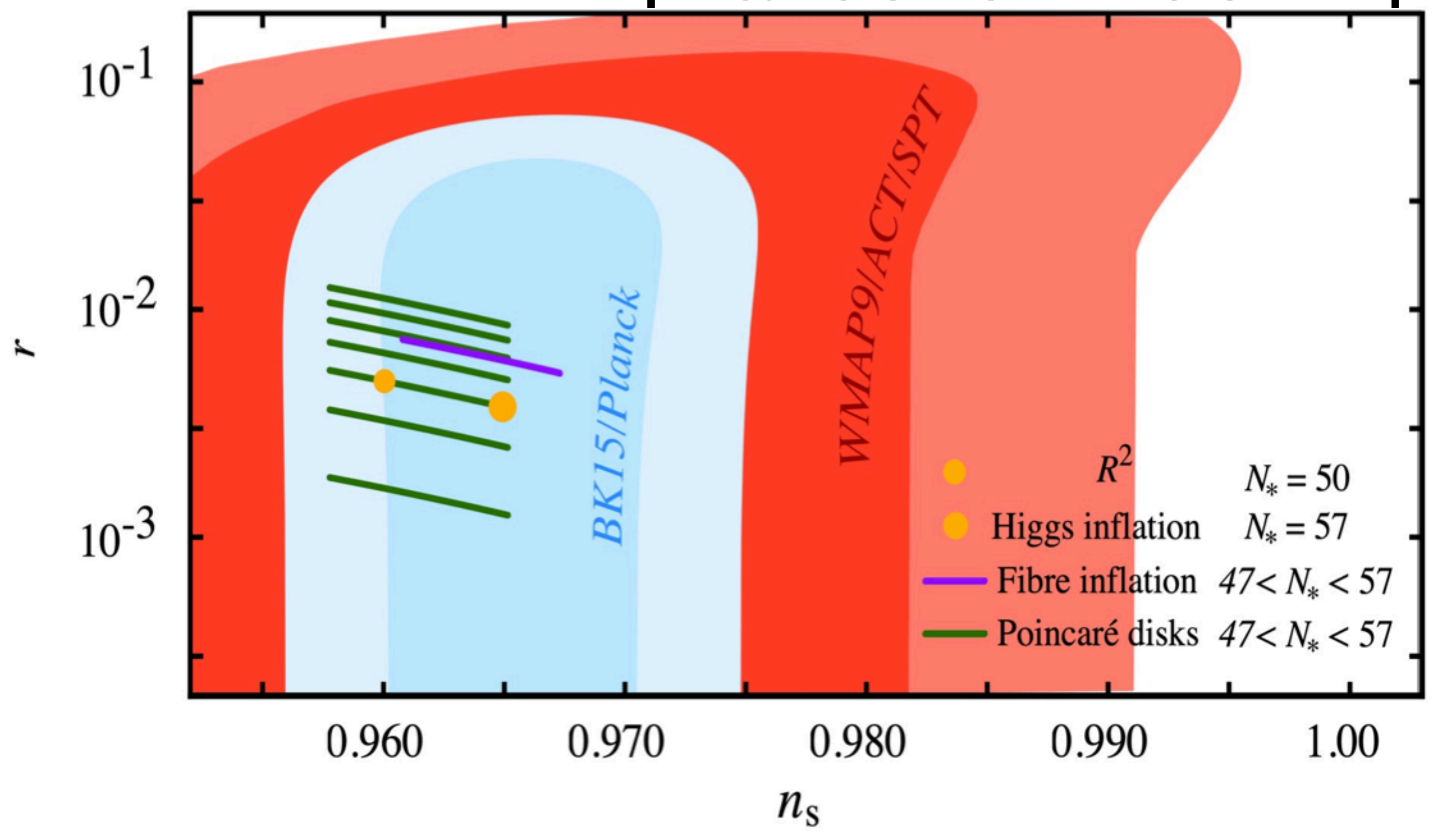
plateau steepening

$$H_{inf} \sim 10^{-5} M_P$$

$$\mathcal{V} \sim \mathcal{O}(10^3)$$



[Kallosh&Linde'21]



Axionic DE embedding

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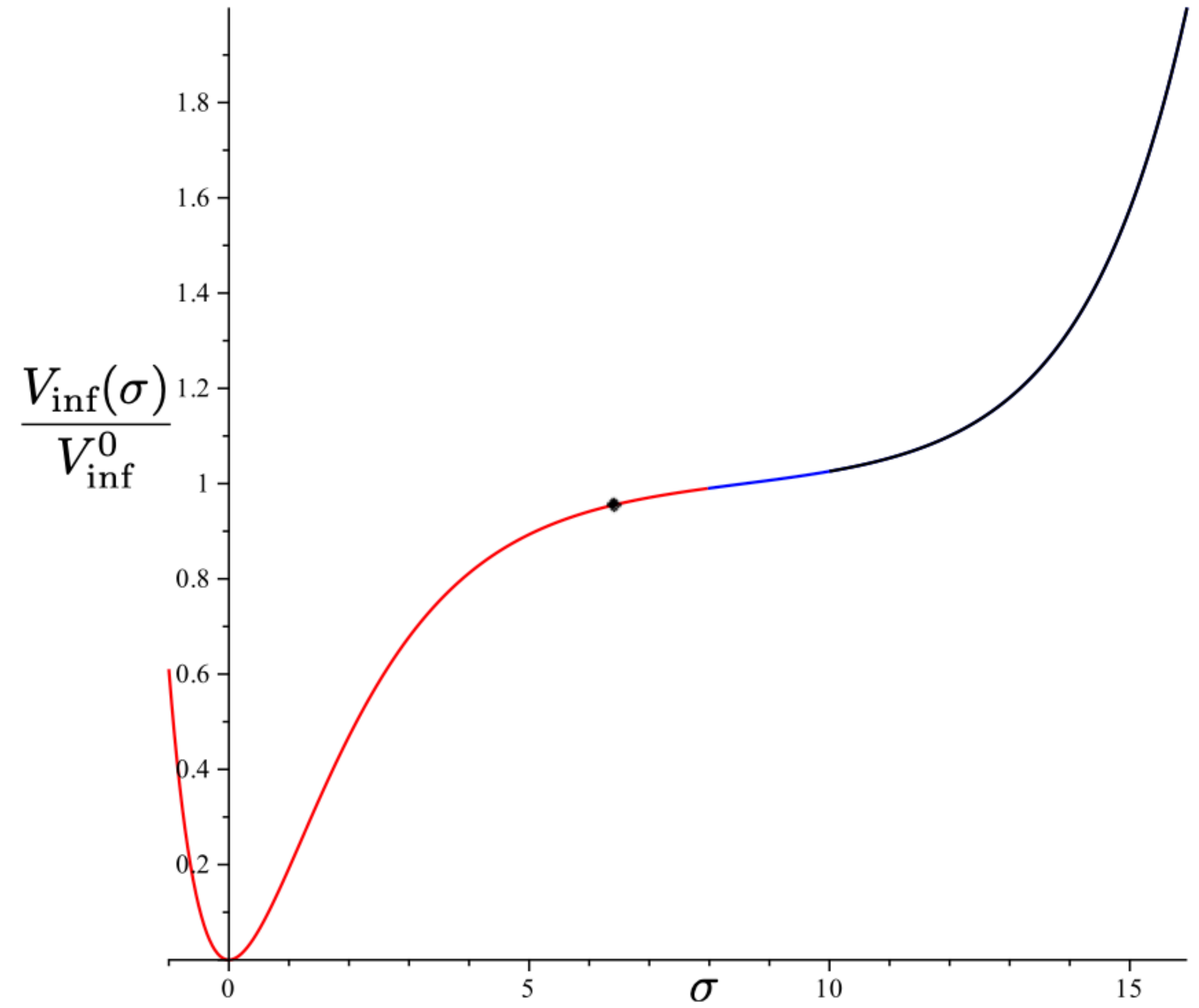
plateau steepening

$$H_{inf} \sim 10^{-5} M_P$$

$$\mathcal{V} \sim \mathcal{O}(10^3)$$

single field inflation

$$m_{\theta_s} \sim m_{\tau_s} \sim m_{3/2} \gg m_{\mathcal{V}} > m_\sigma \sim H_{\rm inf}$$



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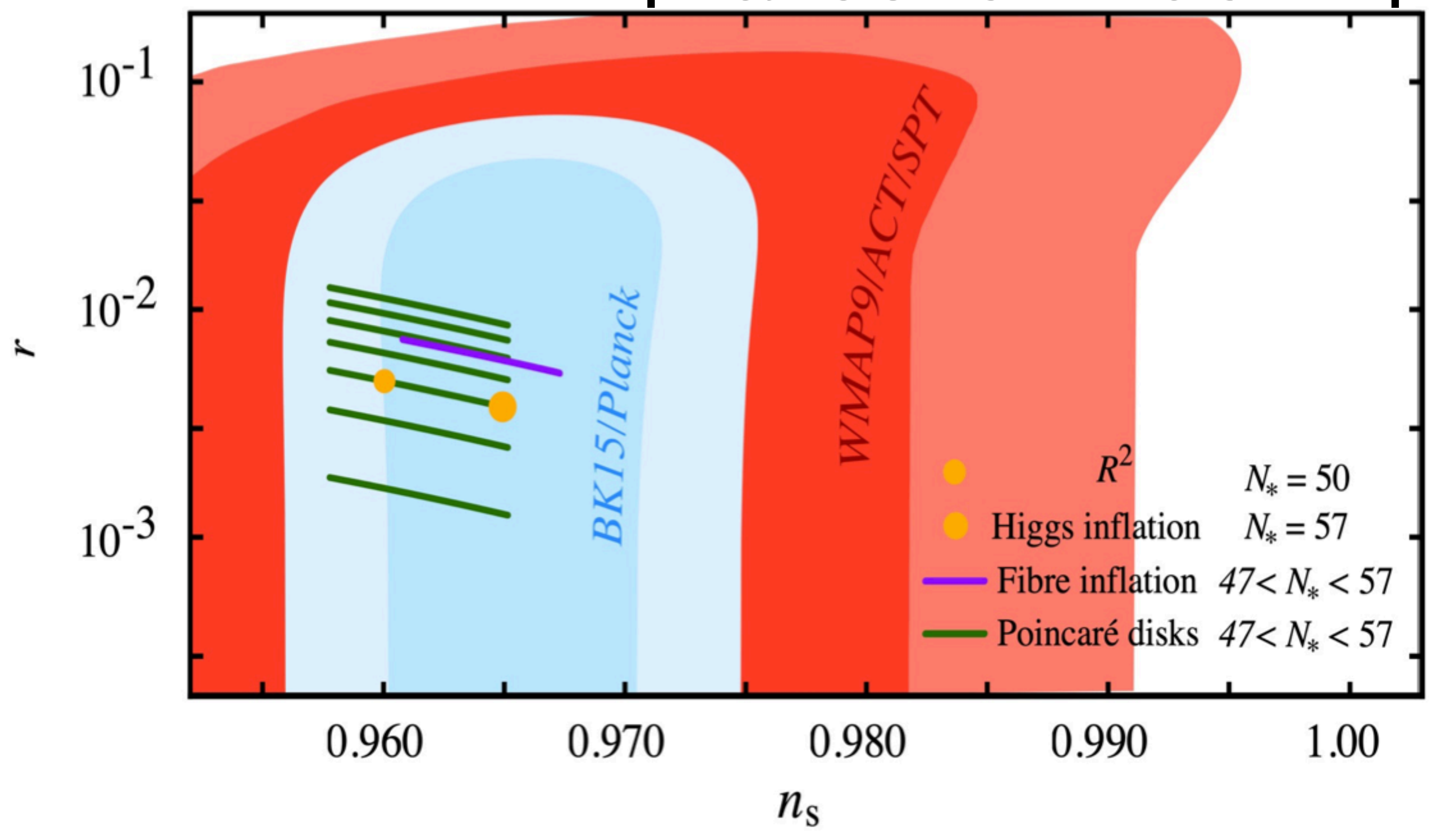

Axionic DE embedding I

Late time potential generated by poly-instanton

$$W_{\rm np} = A_s\, e^{-a_s T_s} + A_2\, e^{-a_2 T_2 + A_1\, e^{-a_1 T_1}}$$
$$= A_s\, e^{-a_s T_s} + A_2\, e^{-a_2 T_2} + A_2 A_1\, e^{-(a_2 T_2 + a_1 T_1)} + \ldots$$

[Blumenhagen et al. '08-'12]
[Lüst, Zhang.'13]

$$V_{\rm late} = \Lambda_2^4\,[1 - \cos(a_2\theta_2)] + \Lambda_1^4\,[1 - \cos(a_2\theta_2 + a_1\theta_1)]$$

$$\Lambda_2^4 = \frac{4W_0 A_2}{\mathcal{V}^2}(a_2\langle\tau_2\rangle)e^{-a_2\langle\tau_2\rangle} \qquad \Lambda_1^4 = \frac{4W_0 A_1 A_2}{\mathcal{V}^2}(a_1\langle\tau_1\rangle + a_2\langle\tau_2\rangle)e^{-a_1\langle\tau_1\rangle - a_2\langle\tau_2\rangle}$$

Hierarchy: $a_i\tau_i > 1$ $\qquad \Lambda_1^4 \ll \Lambda_2^4$

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Hierarchy: $a_i \tau_i > 1$ $\quad \Lambda_1^4 \ll \Lambda_2^4$ $\quad f_1 = \frac{1}{\sqrt{2} a_1 \langle \tau_1 \rangle}$ $\quad f_2 = \frac{1}{a_2 \langle \tau_2 \rangle}$

$$\boxed{V_{DE} = \Lambda_1^4 \left(1 - \cos\frac{\phi_1}{f_1}\right)}$$

$$f_1, f_2 \ll 1$$

Axionic DE embedding I

Model's structure: $\Lambda_2^4 = \Lambda_2^4(f_2) \qquad \Lambda_1^4 = \Lambda_1^4(f_1, f_2)$

Example: safe ics ⟷ $f_1 = 0.085$ DE scale $\Lambda_1^4 \sim 10^{-120}$ ⟷ $f_2 = 0.0038$

↓

$\Lambda_2^4 \sim 10^{-117}$

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axionic mass hierarchy

$$m_2 \sim 10^{-56} = 10^{-29} eV \qquad m_1 \sim 10^{-59} = 10^{-32} eV$$

$$< H_{eq} \sim 10^{-27} eV$$

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$$a_i = \frac{2\pi}{N_i}$$

$N_1 = 1$	$\langle\tau_1\rangle = 1.3$	$N_2 = 27$	$\langle\tau_2\rangle \sim 10^3$
$N_1 = 5$	$\langle\tau_1\rangle \sim 5$	$N_2 = 10$	$\langle\tau_2\rangle \sim 500$

Summary

- From a bottom up perspective dynamical DE is no easier than dS
- But if observationally $\omega \neq -1$ or theoretically no dS in QG
- Two alternatives: multifield quintessence
  - acceleration in steep potentials
  - string embedding?

  axionic quintessence
  - radiative stability (shift symmetry)
  - scale suppression
  - evades fifth force
  - $f_a < M_P$ hilltop

Thank you

Backup slides

Axionic DE

Simplest models

$$V = e^{-S}\cos\left(\frac{\phi}{f}\right) \qquad \text{where} \qquad S = \frac{M_P}{f}$$

DE constrains $V \sim 10^{-120} M_P^4$ $\quad S \sim 276$ $\quad f \sim 3 \times 10^{-3} M_P$

Requires VERY low scale inflation

Need to be more sophisticated: break the link between V_0 and f

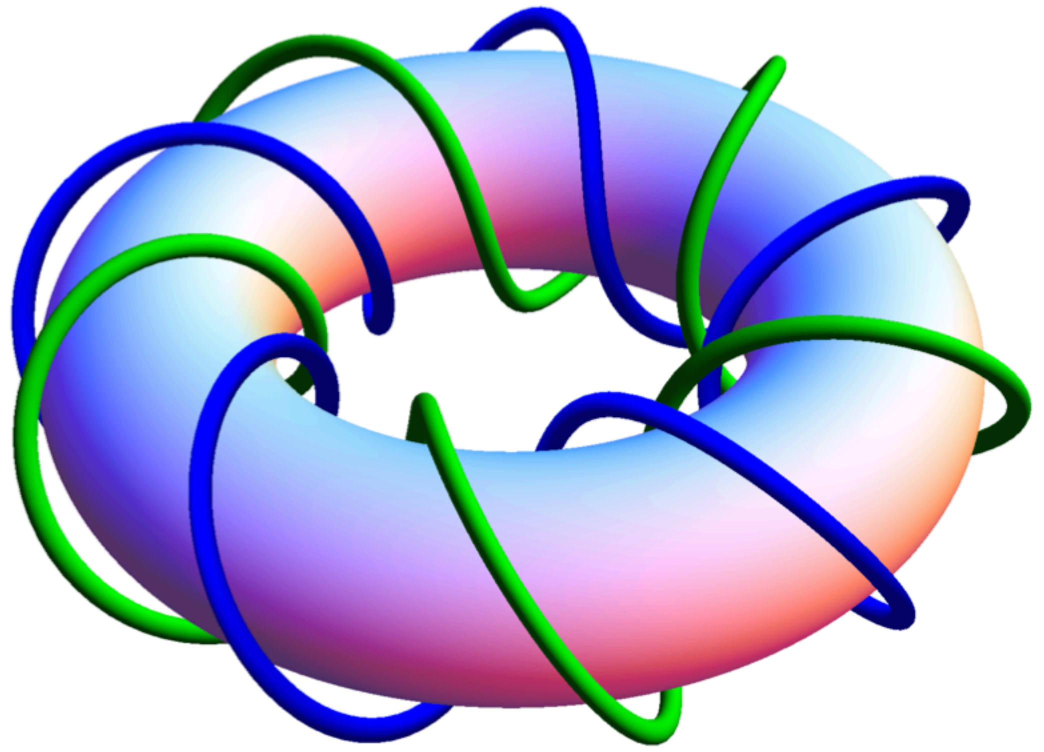
Alignment
Poly-instantons

Axionic DE embedding II

Late time potential generated by KNP alignment

q_{ij} winding numbers

$$W_{\rm np} = A_s\, e^{-a_s T_s} + \sum_{i=1}^{3} A_i\, e^{-a_i (q_{i1}\, T_1 + q_{i2}\, T_2)}$$



[Long et al, 2014]

$$V_{\rm late} \simeq \hat{\Lambda}_1^4 \left[1 - \cos\left(\frac{q_{11}}{N_1}\frac{\phi_1}{\mathfrak{f}_1} + \frac{q_{12}}{N_1}\frac{\phi_2}{\mathfrak{f}_2}\right)\right] + \hat{\Lambda}_2^4 \left[1 - \cos\left(\frac{q_{21}}{N_2}\frac{\phi_1}{\mathfrak{f}_1} + \frac{q_{22}}{N_2}\frac{\phi_2}{\mathfrak{f}_2}\right)\right]$$

$$\hat{\Lambda}_i^4 \equiv \frac{4|W_0|A_i}{\mathcal{V}^2}\, a_i\, (q_{i1}\,\tau_1 + q_{i2}\,\tau_2)\; e^{-a_i (q_{i1}\,\tau_1 + q_{i2}\,\tau_2)}$$

Axionic DE embedding II

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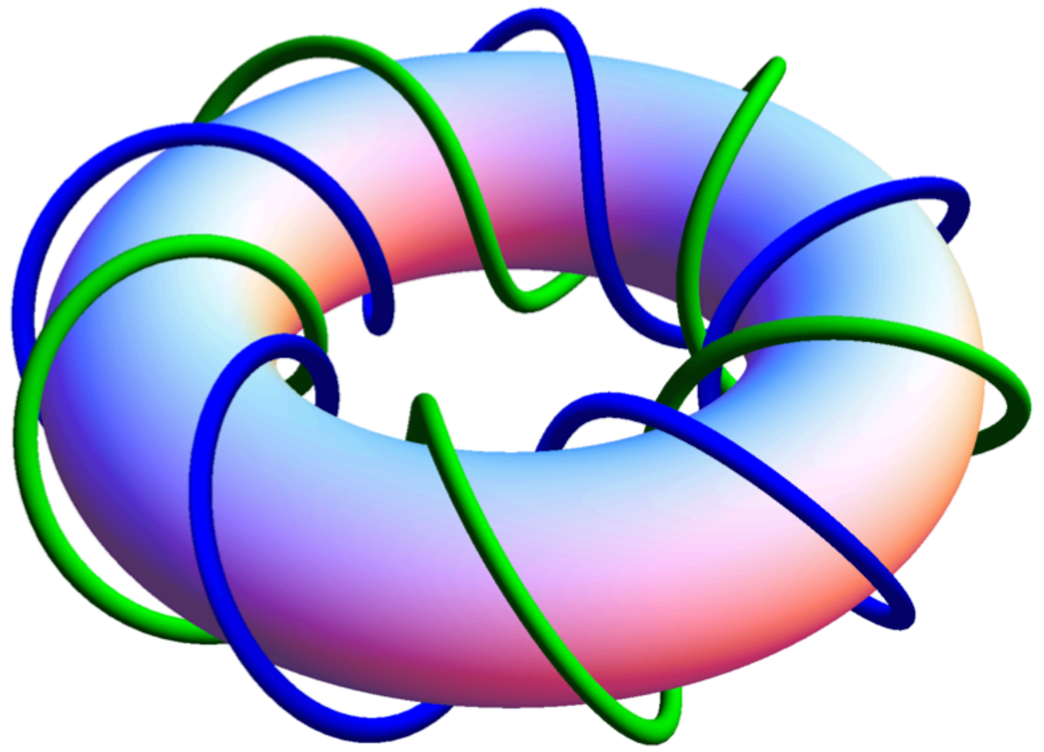

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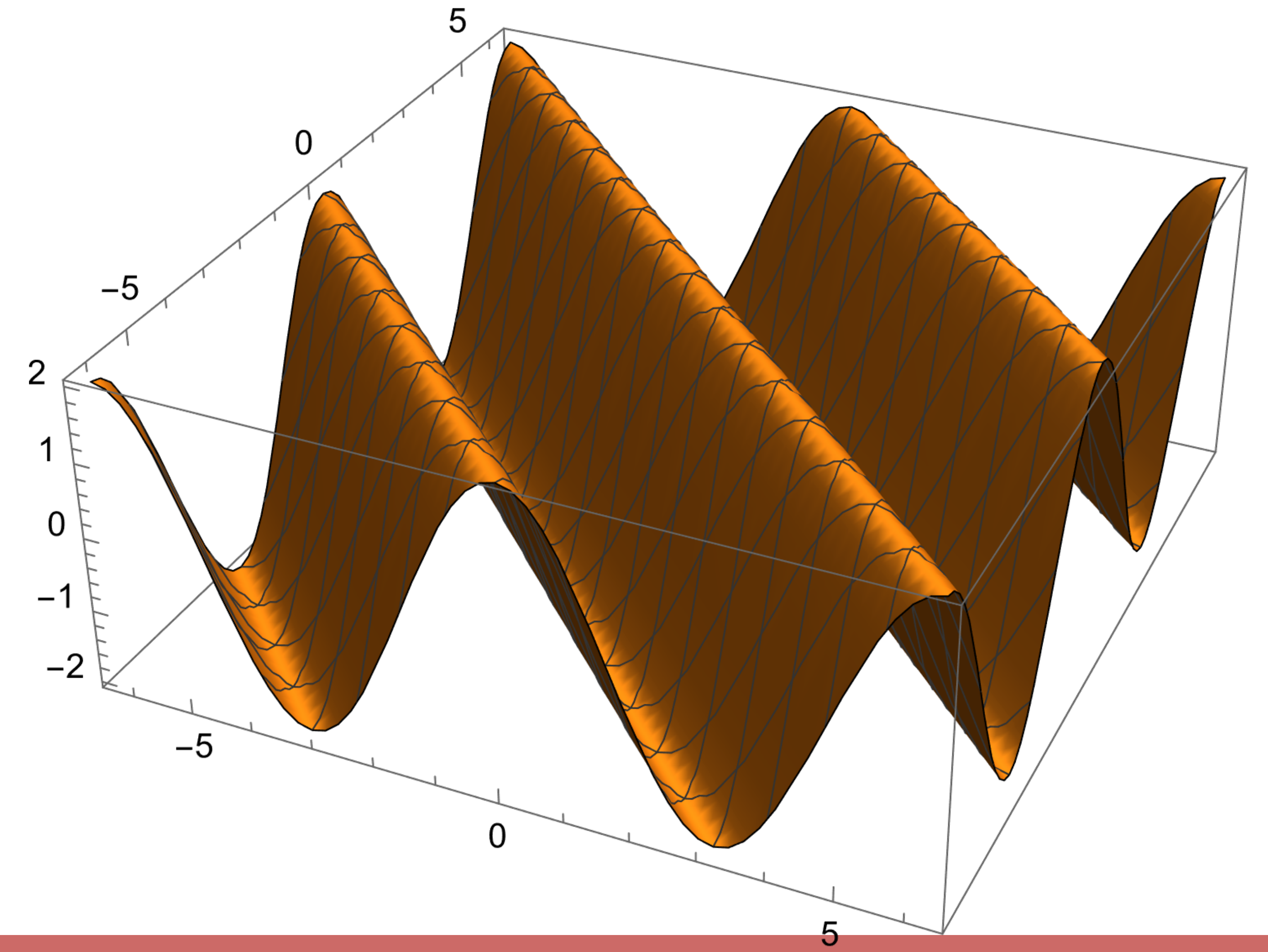

one massless axion if $q_{11}q_{22} = q_{12}q_{21}$

Axionic DE embedding II

Late time potential generated by KNP alignment

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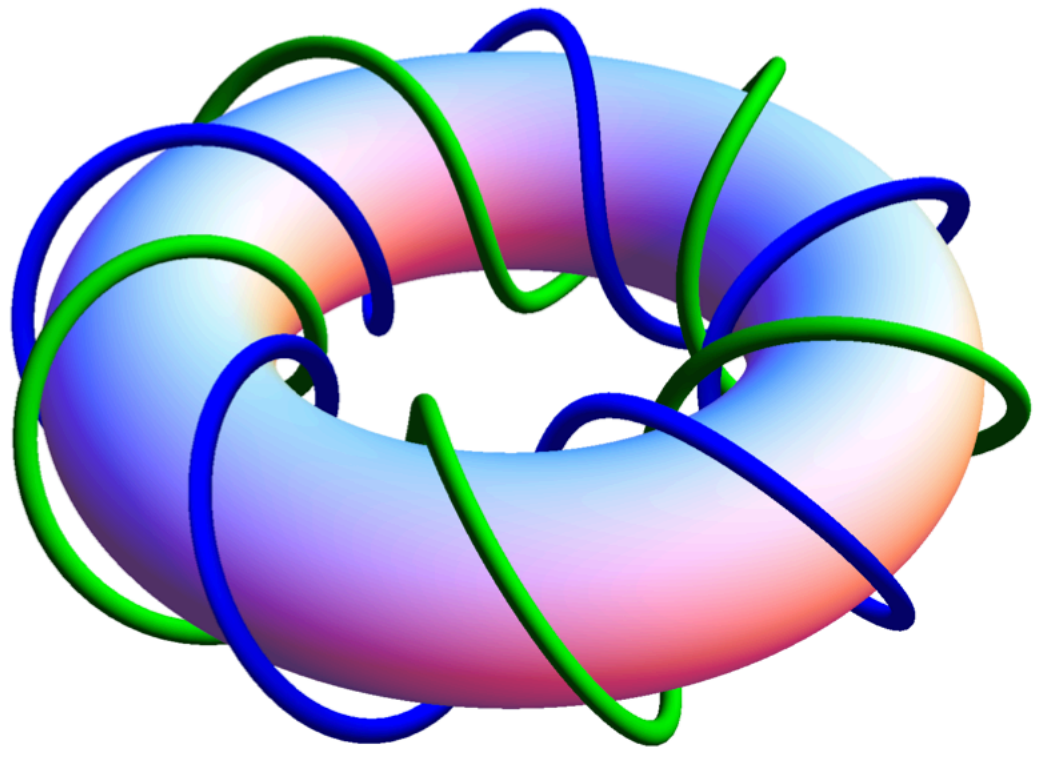

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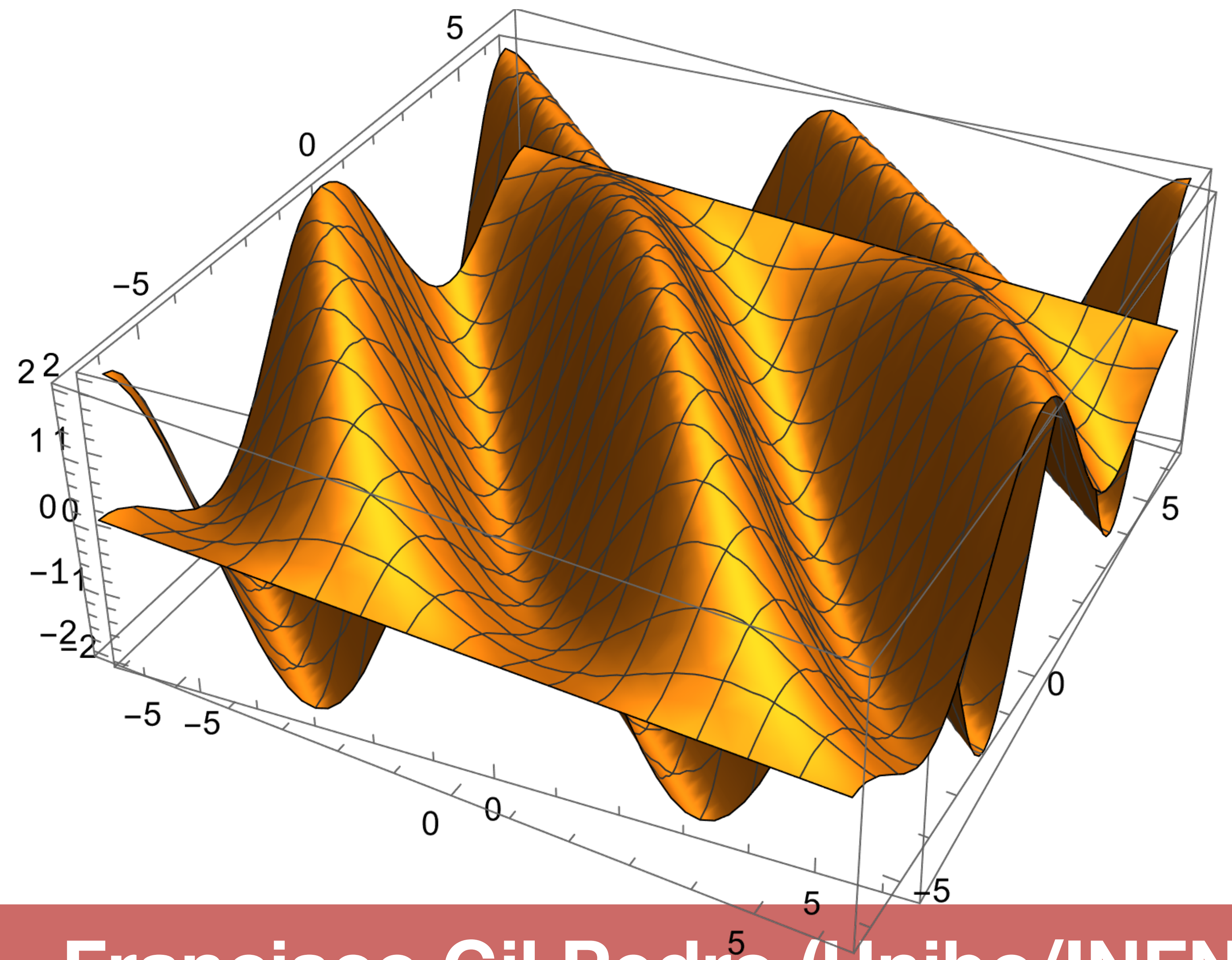


one massless axion if $q_{11} q_{22} = q_{12} q_{21}$

mass hierarchy if $q_{11} q_{22} = (1+\delta) q_{12} q_{21}$ $\delta \ll 1$

Axionic DE embedding II

In terms of mass eigenstates
$$V_{\rm late} \simeq \hat\Lambda_2^4\left[1-\cos\left(q_{2H}\frac{\phi_H}{\mathfrak{f}_H}\right)\right]+\hat\Lambda_1^4\left[1-\cos\left(q_{1H}\frac{\phi_H}{\mathfrak{f}_H}+q_L\frac{\phi_L}{\mathfrak{f}_L}\right)\right]$$

$$\mathfrak{f}_H \equiv \sqrt{\frac{q_{21}^2+q_{22}^2}{q_{21}^2/\mathfrak{f}_1^2+q_{22}^2/\mathfrak{f}_2^2}} \qquad \mathfrak{f}_L \equiv \frac{\mathfrak{f}_1\mathfrak{f}_2}{\mathfrak{f}_H}$$

$$m_H \simeq q_{2H}\frac{\hat\Lambda_2^2}{\mathfrak{f}_H} \gg |m_L| \simeq q_L\frac{\hat\Lambda_1^2}{\mathfrak{f}_L}$$

$$V(\phi_L) \simeq \hat\Lambda_1^4\left[1-\cos\left(\frac{\phi_L}{f_L}\right)\right]$$

$$f_L \equiv \frac{\mathfrak{f}_L}{q_L} = \frac{N_1\mathfrak{f}_1\mathfrak{f}_2}{|\det q|}\sqrt{q_{21}^2/\mathfrak{f}_1^2+q_{22}^2/\mathfrak{f}_2^2}$$

More freedom: DE sector does not fix mass of heavy axion ▶ DM

Axionic DE embedding II

assuming $m_H > H_{eq} = 10^{-27} eV$

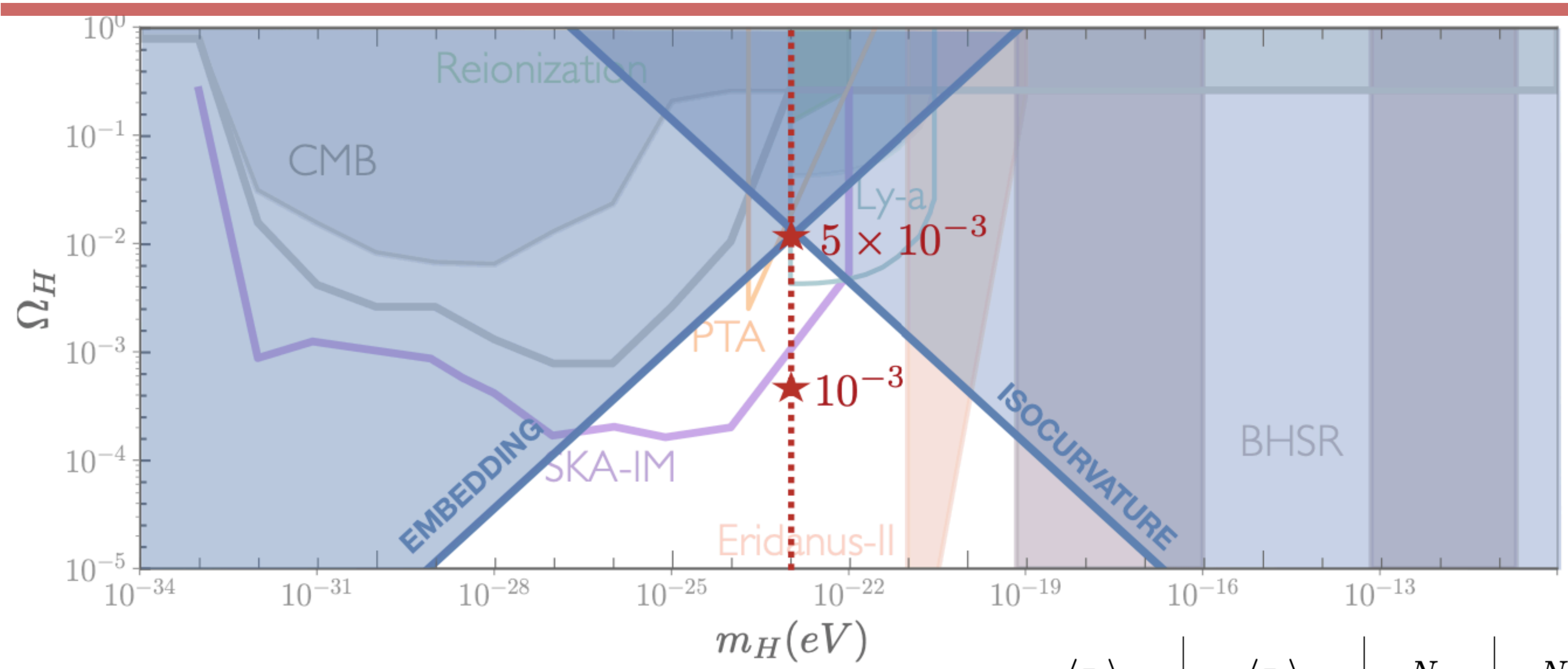
[Marsh.'15]

$$\Omega_H = \frac{1}{6}(9\Omega_r)^{3/4}\sqrt{\frac{m_H}{10^{-60}M_p}}\left(\frac{\delta\phi_H}{M_p}\right)^2$$

<u>isocurvature constraint:</u> $\mathcal{A}_I = \left(\frac{\Omega_H}{\Omega_m}\right)^2\left(\frac{H_{\rm inf}}{\pi\delta\phi_H}\right)^2 < 0.038\mathcal{A}_s$ $\qquad \frac{\Omega_H}{\Omega_m} \lesssim 3395\sqrt{\frac{10^{-60}M_p}{m_H}}\left(\frac{0.0005}{\epsilon}\right)$

<u>embedding constraint:</u> $f_H < 0.005 M_P$ $\qquad \frac{\Omega_H}{\Omega_m} \lesssim 6.95\times 10^{-7}\sqrt{\frac{m_H}{10^{-60}\,M_p}}$

Axionic DE embedding II



$$m_H \sim 10^{-23} eV$$

$$\frac{\Omega_H}{\Omega_M} < 0.045$$

$\langle\tau_1\rangle$	$\langle\tau_2\rangle$	N_1	N_2	q_{ij}	f_L	f_H	Ω_H^{max}/Ω_m
106.13	97.07	23	42	$\begin{pmatrix} 2 & 8 \\ 3 & 13 \end{pmatrix}$	0.17	0.005	0.045
95.08	102.56	20	16	$\begin{pmatrix} -19 & 26 \\ -13 & 18 \end{pmatrix}$	0.15	0.001	0.002
94.13	103.07	11	24	$\begin{pmatrix} -122 & 116 \\ -231 & 220 \end{pmatrix}$	0.11	0.0001	2×10^{-5}