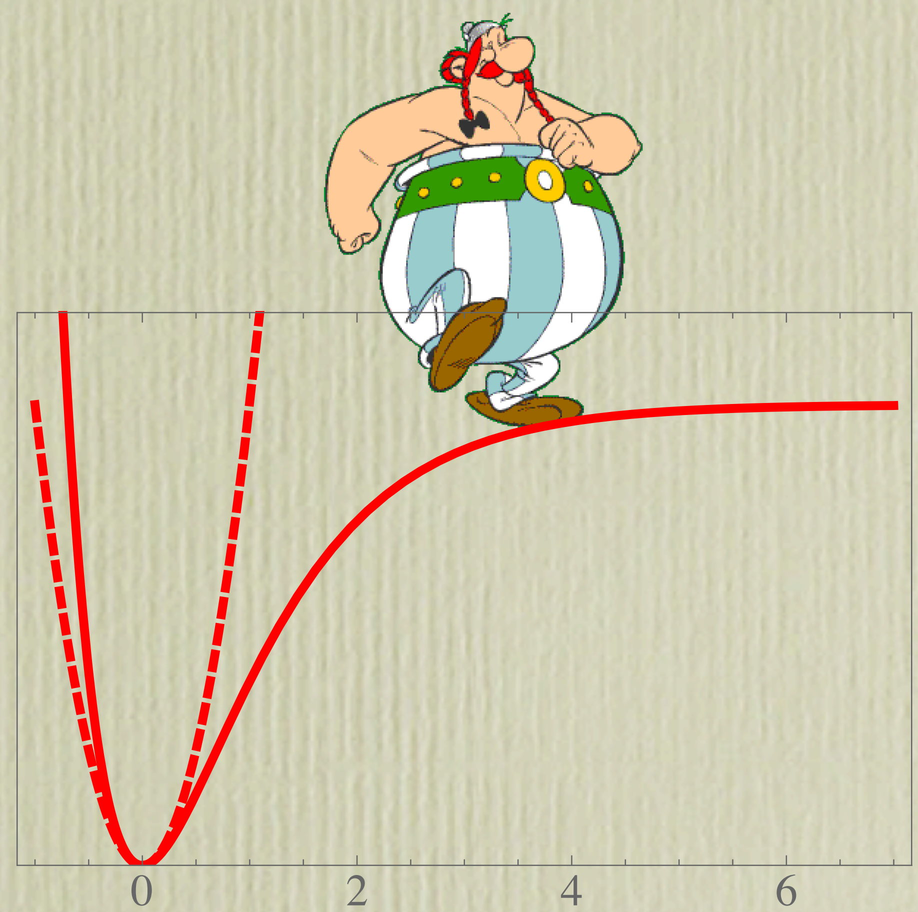
Flattened Axion Monodromy Beyond Two Derivatives

with F. Pedro [1909.08100]

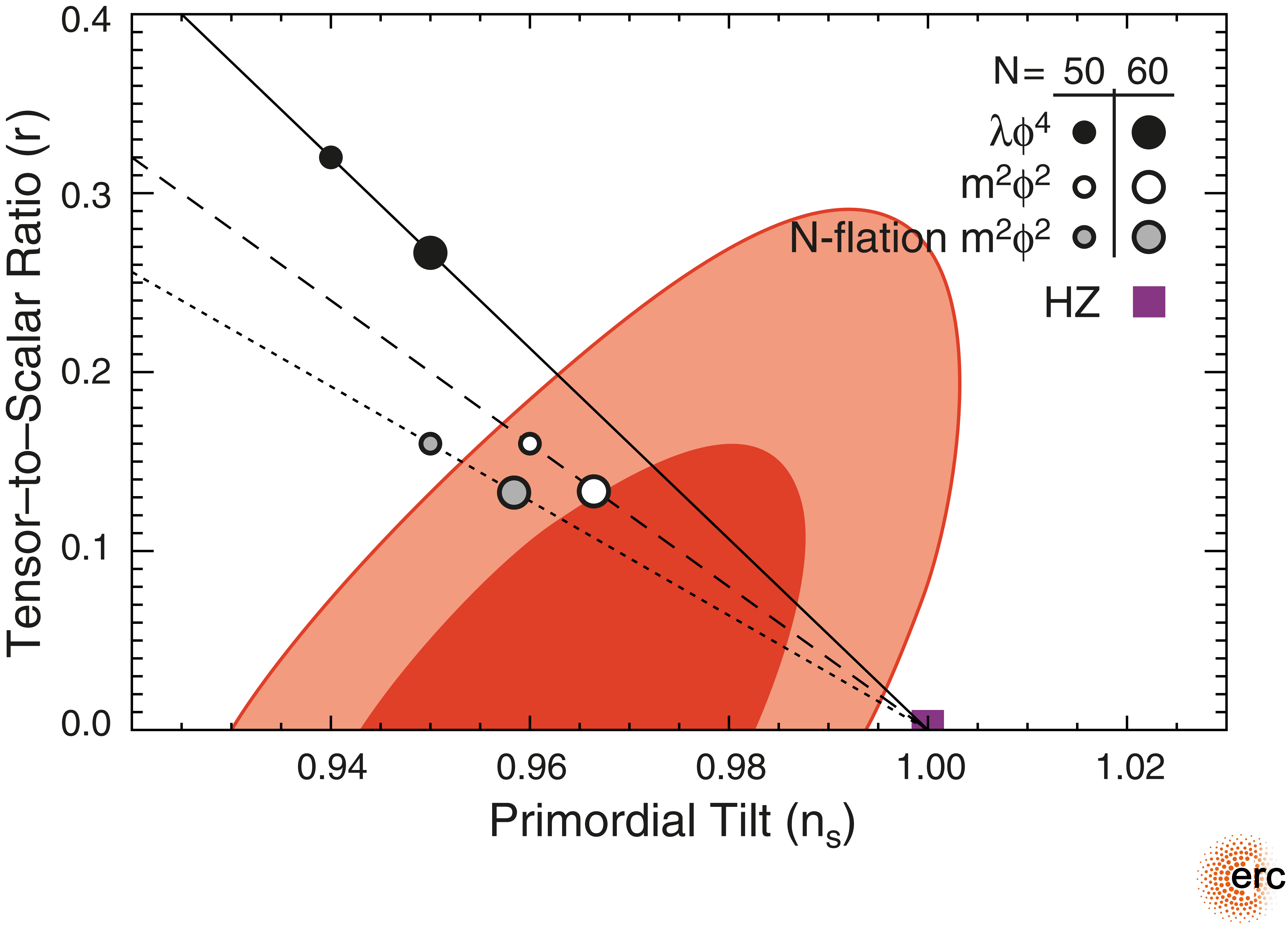


And work with: R. Flauger, E. Pajer, E. Silverstein, A. Uranga, T. Wrase, G. Xu

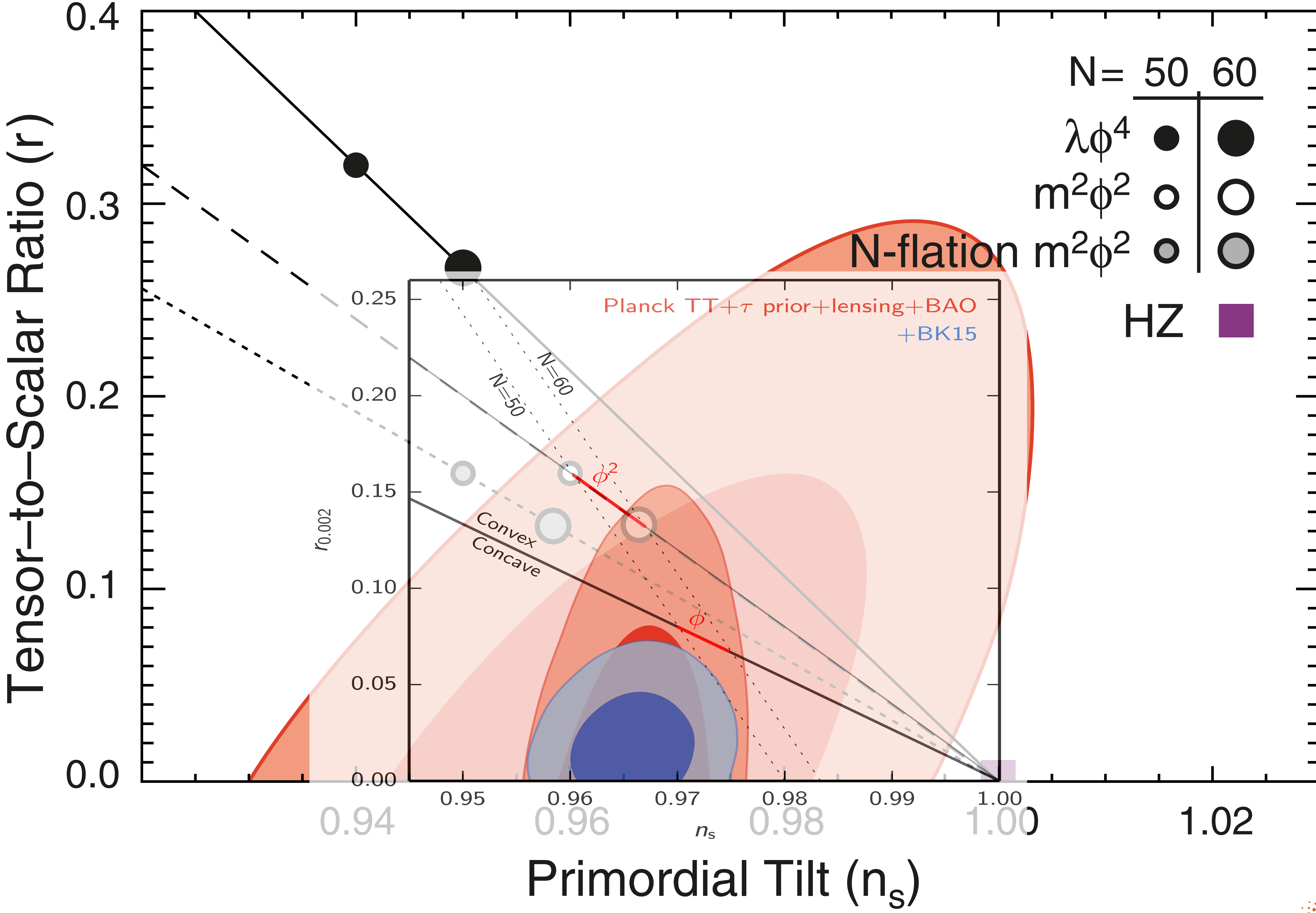
Alexander Westphal
(DESY)

OVERVIEW

1. Recap on flattening in axion monodromy inflation
2. Flattening beyond 2 derivatives



Tensor–to–Scalar Ratio (r)
0.4
0.3
0.2
0.1
0.0
0.94
0.96
0.98
1.00
1.02
Primordial Tilt (n_s)
N= 50 60
λφ⁴
m²φ²
N-flation m²φ²
HZ
erc



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Planck TT+τ prior+lensing+BAO
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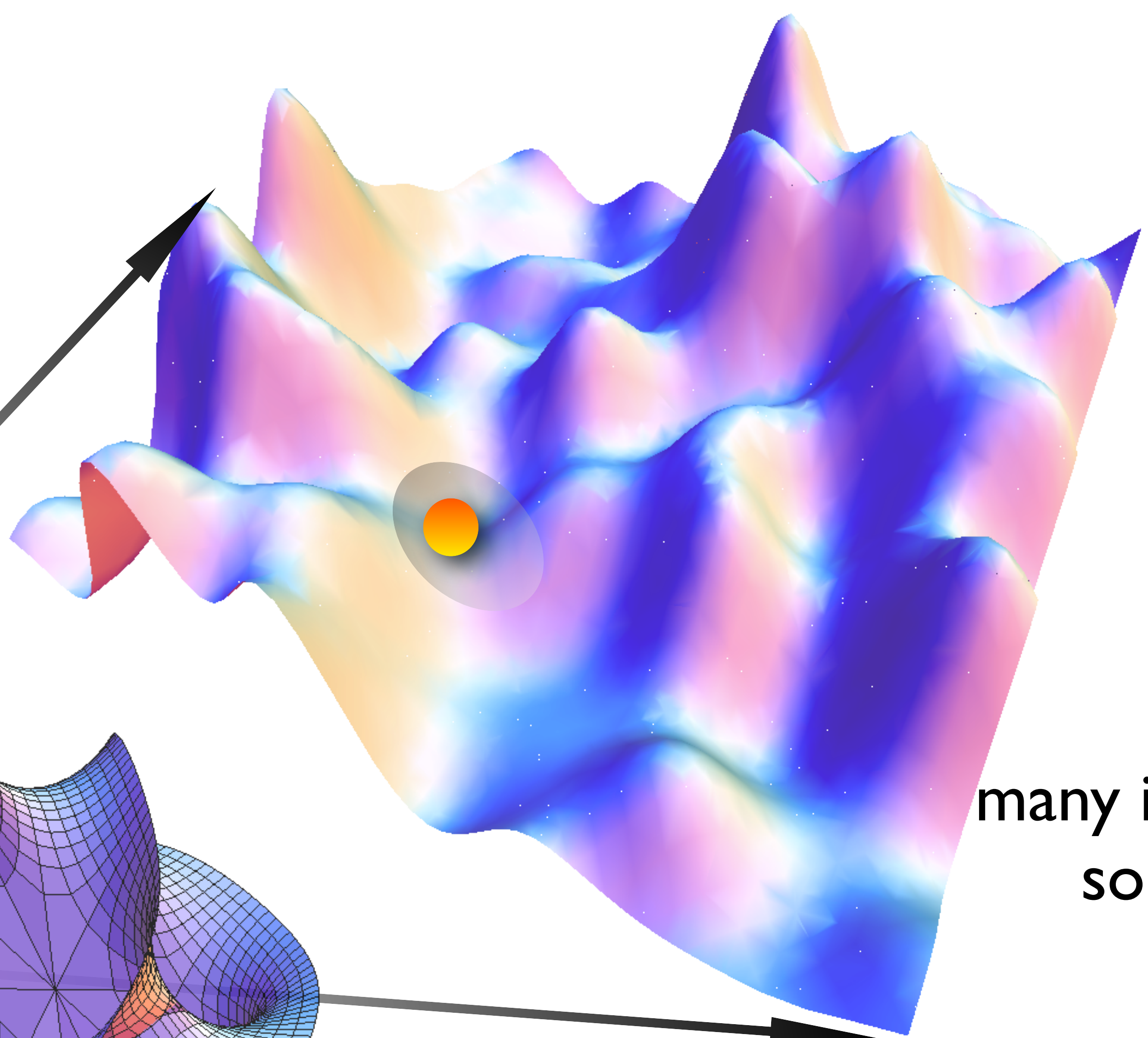
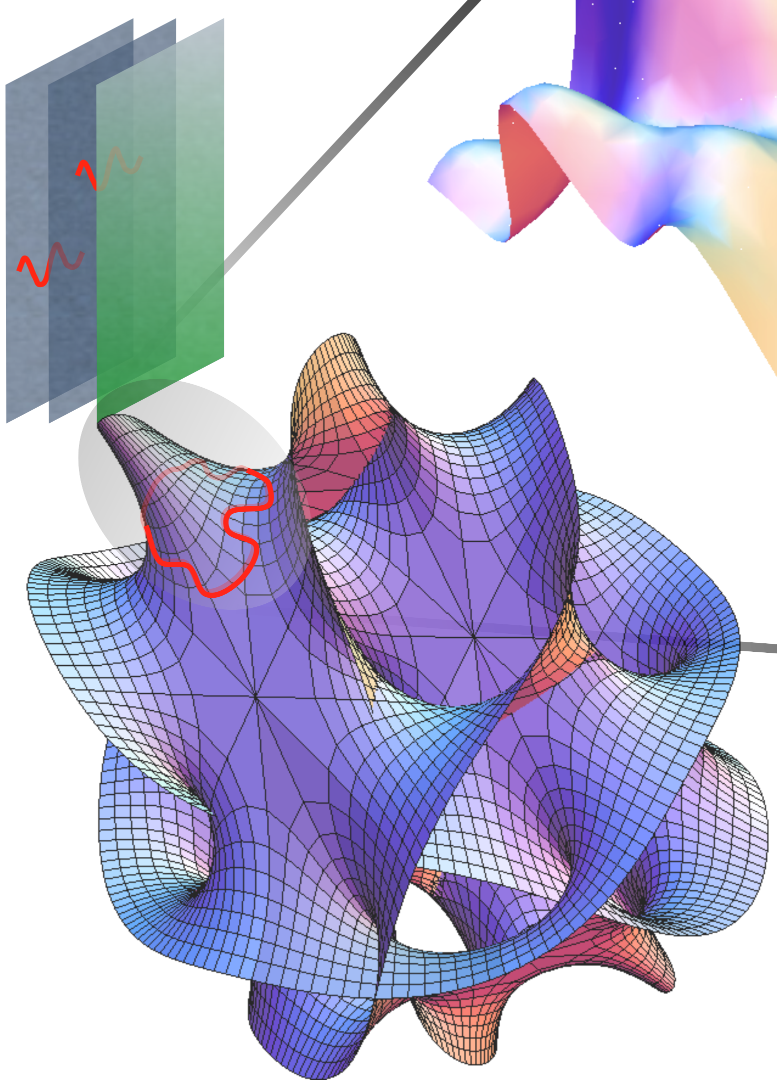




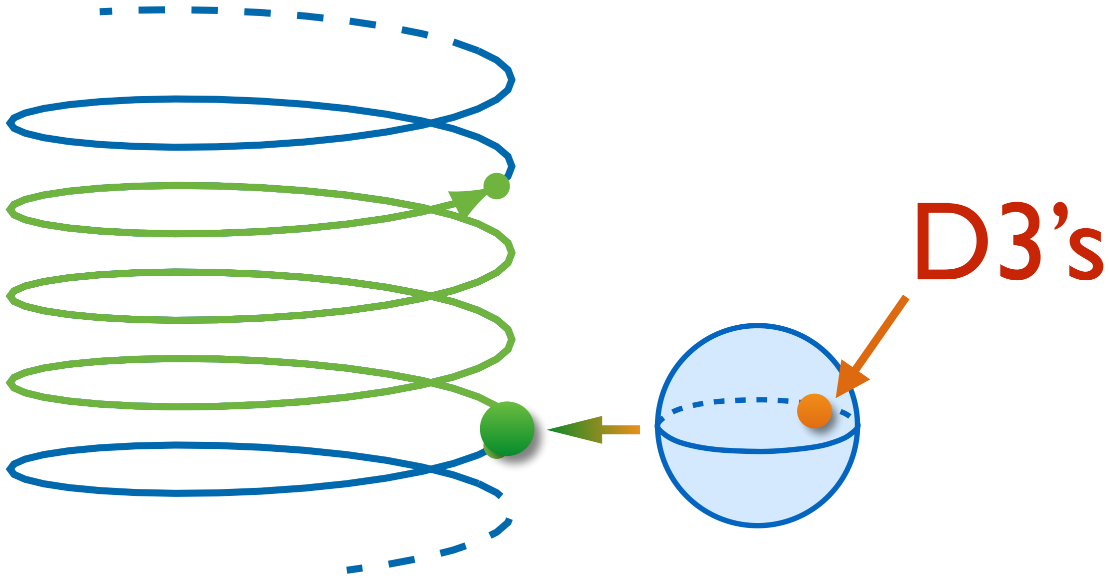
<u>the string theory *landscape*:</u>

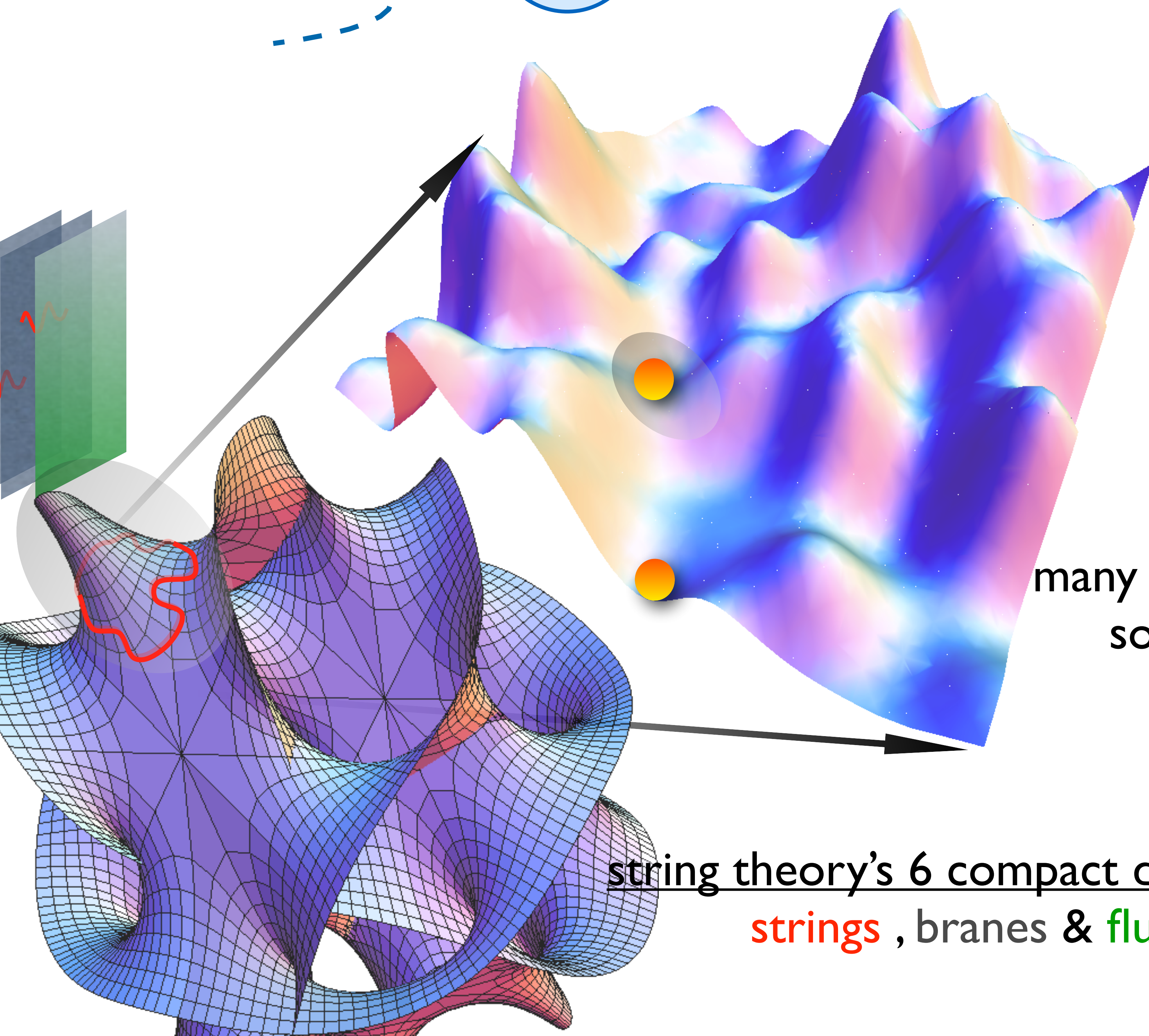
many isolated *vacua*, connected by tunneling

some mountain slopes drive <u>*inflation*</u>

<u>string theory's 6 compact dimensions:</u>

strings , branes & fluxes





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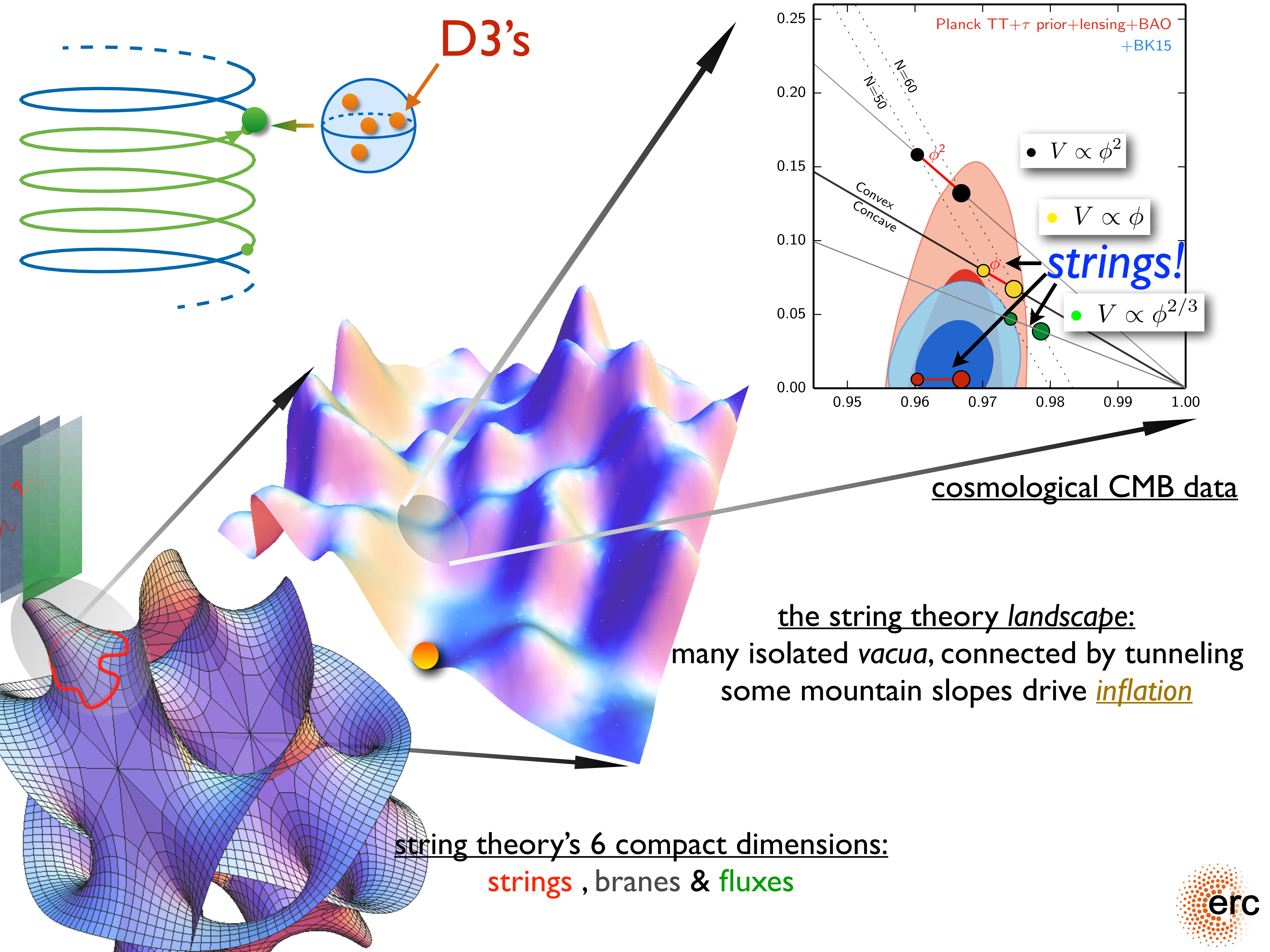
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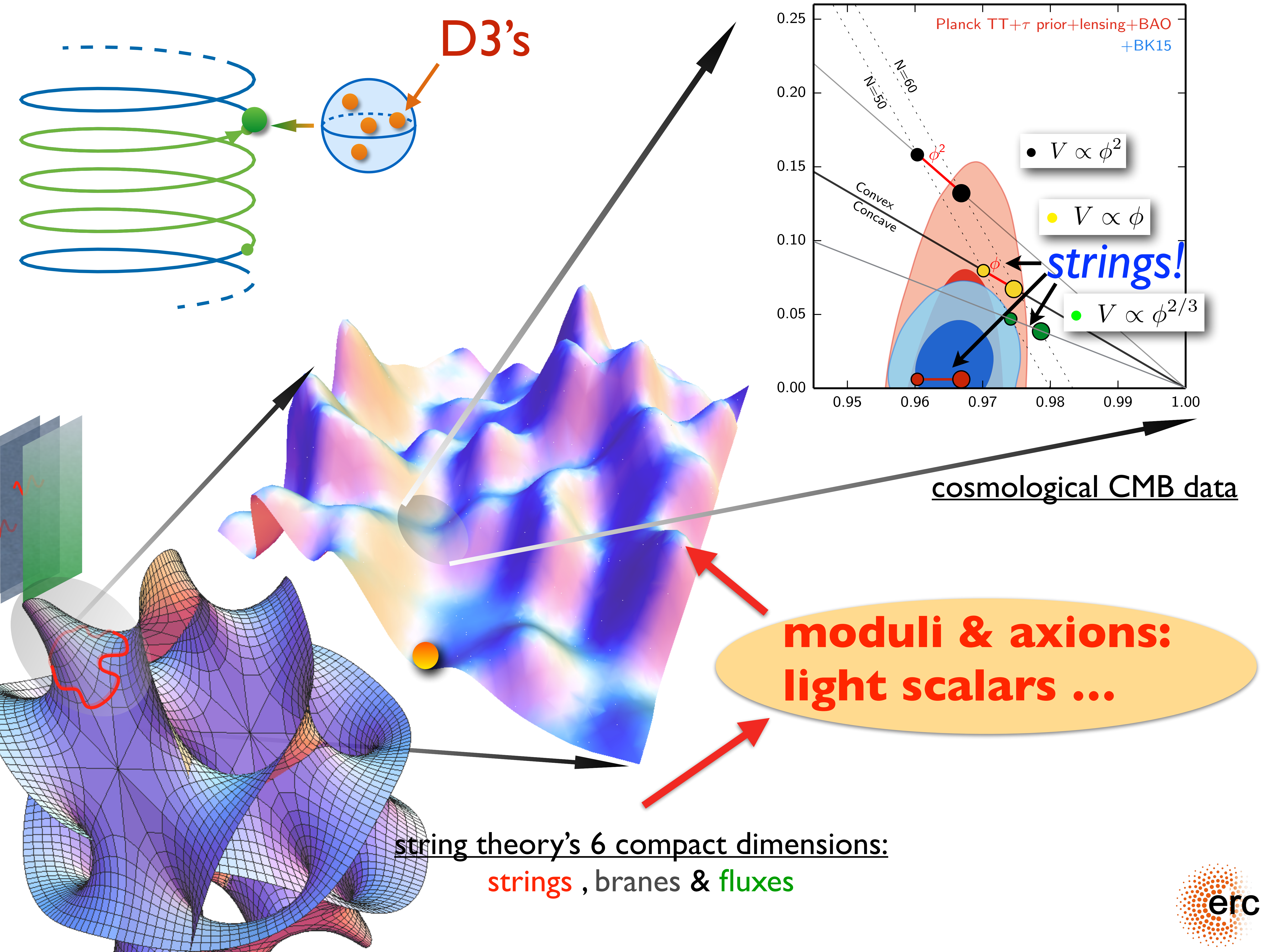
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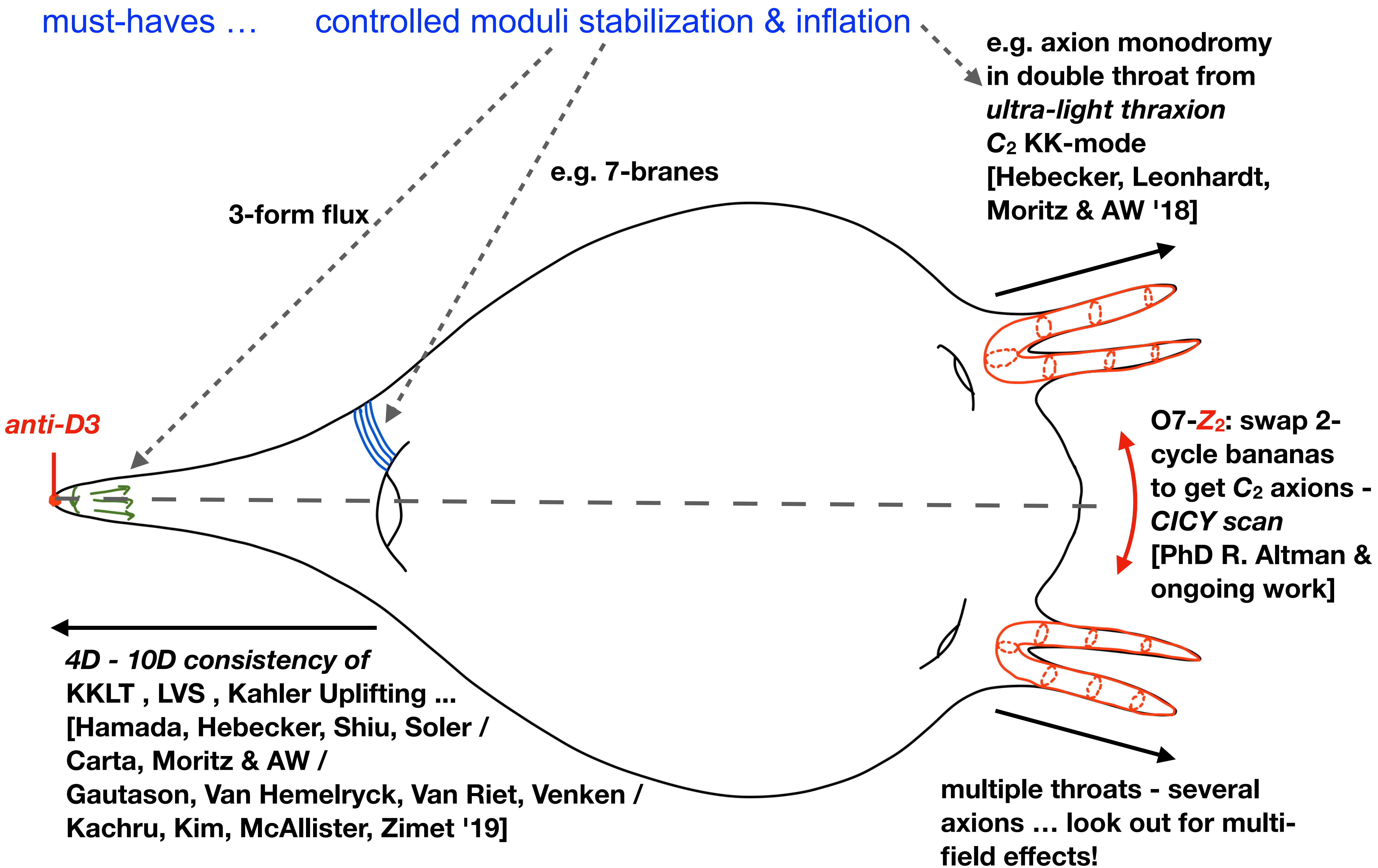
cosmological CMB data
moduli & axions:
light scalars ...
string theory's 6 compact dimensions:
strings , branes & fluxes
erc

inflation in string theory …



axion monodromy inflation from 10D

$$\int \mathrm{d}^{10}x \left(\frac{|dB|^2}{g_s^2} + |F_1|^2 + |F_3|^2 + \left|\tilde{F}_5\right|^2 \right)$$

- example - B_2 - axion monodromy from flux:

$$|\tilde{F}_p|^2 = |dC_{p-1} + B_2 \wedge F_{p-2}|^2$$

$$flux \;\; F_{p-2} = N f_{p-2} \;, \quad \int_{\Sigma_{p-2}} f_{p-2} = 1$$

$$B_2 \to B_2 + d\Lambda_1 \quad \Rightarrow \quad C_{p-1} \to C_{p-1} - N\Lambda_1 \wedge f_{p-2}$$

many models in ’10-’18: Stanford/Cornell/Hamburg, Madrid, Madison, Heidelberg, …

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axion mass term

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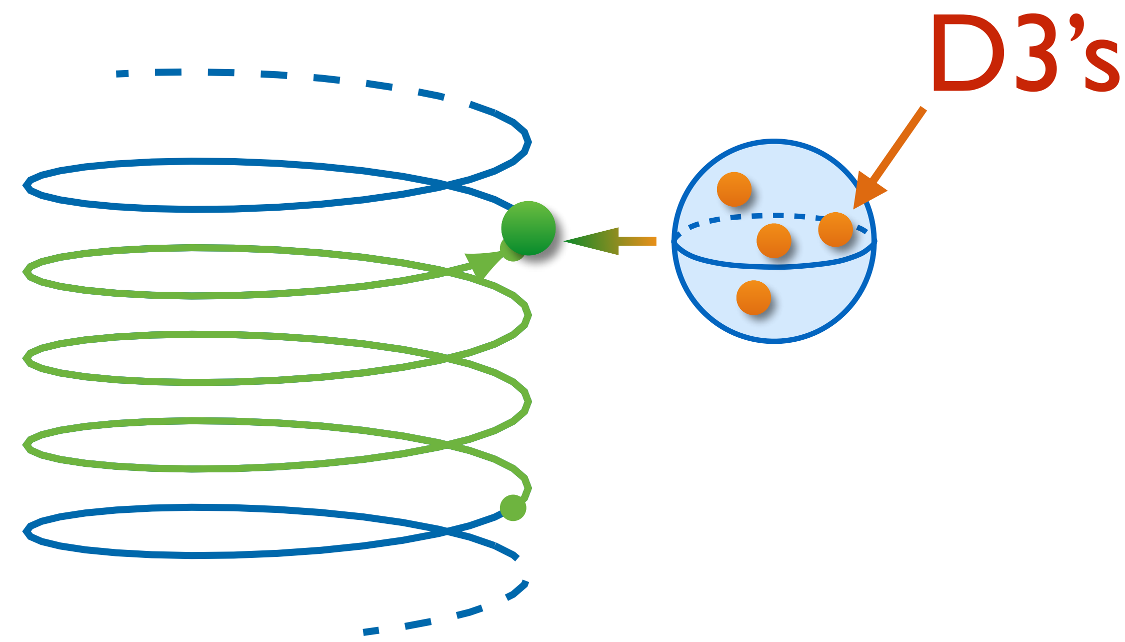
axion monodromy inflation

$$\mathcal{L}_Q \sim q \int A_1$$



$$\mathcal{L}_Q^{NS5} \sim \int C_2 \wedge C_4 \sim \underbrace{\int_{S^2} C_2}_{q=N_w} \times \int_{\mathcal{M}_4} C_4 \sim N_w \underbrace{\int_{\mathcal{M}_4} C_4}_{\mathcal{L}_Q^{D3}}$$

charge *backreacts* on geometry

— charged vs neutral BH !

[McAllister, Silverstein & AW '08; McAllister, Pedro, Servant, Stout & AW '16; Kim & McAllister '18]

axion monodromy inflation

- bare bones monodromy:

$$\int \mathrm{d}^{10}x \left(\frac{|dB|^2}{g_s^2} + |F_1|^2 + |F_3|^2 + \left|\tilde{F}_5\right|^2 \right)$$

[McAllister, Silverstein, AW & Wrase '14]
[Hebecker et al. '14]
[Buchmüller, Dudas, Heurtier, AW, Wieck & Winkler '15]

axion monodromy inflation

- bare bones monodromy:

$$\int \mathrm{d}^{10}x \left(\frac{|dB|^2}{g_s^2} + |F_1|^2 + |F_3|^2 + \left|\tilde{F}_5\right|^2 \right)$$

$$\downarrow$$

$$V = \frac{C_1}{\phi} + C_2\phi^2(\mu^2 + b^2)$$

$$\partial_\phi V = 0$$

$$\langle\phi\rangle = \langle\phi\rangle_0(1 + b^2/\mu^2)^{-1/3}$$

[McAllister, Silverstein, AW & Wrase '14]
[Hebecker et al. '14]
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axion monodromy inflation

- 2 types of flattening — **additive** & **multiplicative**:

$$V_{eff.}(b) = V|_{\langle\phi\rangle} \sim \langle\phi\rangle_0^2 \frac{b^2}{(1+b^2/\mu^2)^{2/3}}$$

$$\sim \begin{cases} b^2 - \frac{2}{3}\frac{b^4}{\mu^2} \ , & \mu \gg 1 \\ b^{2/3} \ , & \mu \ll 1 \end{cases}$$

- other powers as well: b, $b^{4/3}$, b^2

[McAllister, Silverstein, AW & Wrase '14]
[Hebecker et al. '14]
[Buchmüller, Dudas, Heurtier, AW, Wieck & Winkler '15]

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4D effective axion monodromy inflation

b now called φ

[Kaloper & Sorbo '08]
[Kaloper, Lawrence & Sorbo '11; Kaloper & Lawrence ...]

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \frac{1}{48}F_{(4)}^2 - \frac{\mu}{24}\phi \star F_{(4)} - \sum_{n\geq 2} \chi_n C_n^{\text{eff.}} \frac{(F_{(4)}^2)^n}{M_{\text{P}}^{4n-4}} - V_{\text{np}}$$

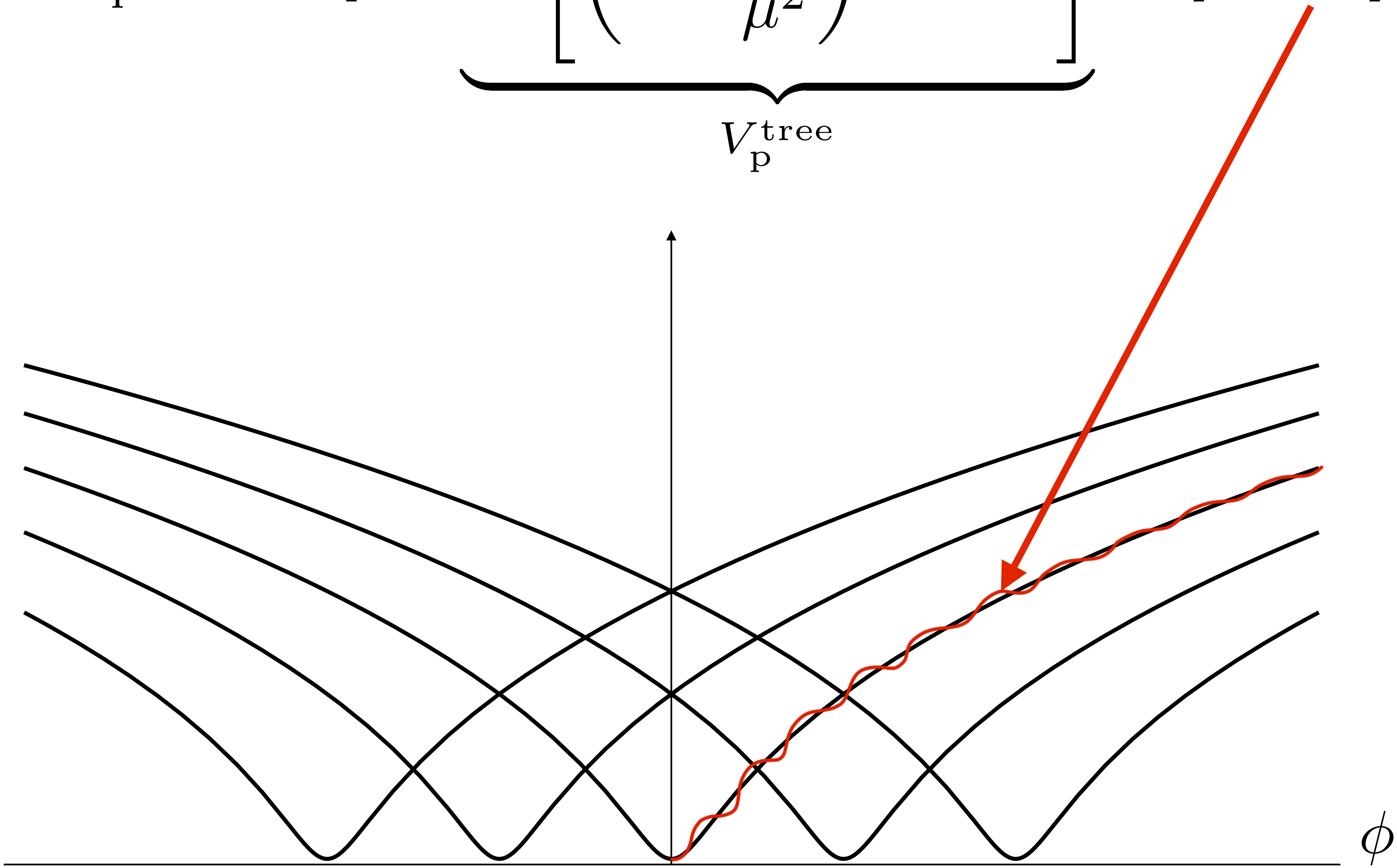
$$V_{\text{p}}^{\text{eff.}} = \sum_{n\geqslant 2}^{N} \chi_n \, C_n^{\text{eff.}} \frac{\left(V^{(0)}(\phi)\right)^n}{M_{\text{p}}^{4n-4}} \quad , \quad V_{\text{np}} = \Lambda_{\text{UV}}^4 \sum_{m\geqslant 1}^{M} D_m e^{-mS} \cos\left(\frac{m\phi}{f_\phi}\right)$$

$$S = \mathcal{C}\,\mathcal{V}^k \qquad \Lambda_{UV}^4 \sim \frac{1}{\mathcal{V}^2} \qquad \chi_n C_n^{\text{eff.}} \equiv C_n^{\text{tree}} + \chi_n C_n$$

$$V_{\text{p}}^{\text{tree}} = \sum_{n\geqslant 2}^{N} C_n^{\text{tree}} \frac{\left(V^{(0)}(\phi)\right)^n}{M_{\text{p}}^{4n-4}} = V_0\left[\left(1+\frac{\phi^2}{\mu^2}\right)^{p/2} - 1\right] \quad , \quad V_{\text{p}} = \sum_{n\geqslant 2}^{N} \chi_n C_n \frac{\left(V^{(0)}(\phi)\right)^n}{M_{\text{p}}^{4n-4}}$$

axion monodromy inflation

$$V = V_{\rm p}^{\rm eff.} + V_{\rm np} = \underbrace{V_0 \left[\left(1 + \frac{\phi^2}{\mu^2} \right)^{p/2} - 1 \right]}_{V_{\rm p}^{\rm tree}} + V_{\rm p} + V_{\rm np}$$



flattening from modulus backreaction

[Dong, Horn, Silverstein & AW '10]

2-field system: $$V(\phi, \chi) = g\,\phi^2\chi^2 + M^2(\chi - \chi_0)^2$$

$$m_\phi^2 = g\,\chi_0^2 \sim \chi_0^2 \ll M^2 \quad (g \lesssim 1)$$

effective potential: $$V_{eff.}(\phi) = M^2\chi_0^2\,\frac{g\,\phi^2}{M^2 + g\,\phi^2}$$

$$= \frac{m_\phi^2\phi^2}{1 + \frac{m_\phi^2}{M^2}\cdot\frac{\phi^2}{\chi_0^2}} \simeq \frac{m_\phi^2\phi^2}{1 + \frac{\phi^2}{M^2}}$$

axion monodromy inflation with full mixing ...

- Neglected so far here - kinetic coupling:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \chi)^2 + \frac{f^2(\chi/\Lambda)}{2}(\partial_\mu \phi)^2 - V$$

$$V = \frac{M^2}{2}(\chi - \chi_0)^2 + \frac{m^2}{2}\phi^2 + \frac{g}{2}\chi^2\phi^2 \quad , \quad M^2 \gg H^2 > m^2$$

- 2 limits:

(I) rigid mass: g = 0
(II) field-dependent mass: m = 0

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[Pedro & AW '19]

String compactification - UV input

- Kinetic coupling - use string input:

(B) bulk moduli:

$$\mathcal{L} = \frac{\Lambda^2}{2} \frac{(\partial\tilde{\chi})^2 + (\partial\phi)^2}{\tilde{\chi}^2} \to \frac{1}{2}(\partial\chi)^2 + \frac{f^2}{2}(\partial\phi)^2 \quad , \quad f = \exp(\chi/\Lambda)$$

(L) small/local 'blow-up' moduli:

$$\mathcal{L} = \left(\frac{\tilde{\chi}}{\Lambda}\right)^{\tilde{p}} \left[(\partial\tilde{\chi})^2 + (\partial\phi)^2\right] \to \ f = \left(\frac{\chi}{\Lambda}\right)^p$$

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[Pedro & AW '19]

A Tale of 2 EFTs ...

- Full system is 2-field

See also e.g.: [Achucarro, Atal, Cespedes, Gong, Palma & Patil '12]

- Just integrating out heavy field χ at 2-derivative level too naive, if turn-rate large

- 2 EFTs of light field:

(HD) integrate out heavy field χ correctly:
-- higher-deriv. action for φ

(2F) 2-field perturbation theory, then correctly integrate out orthogonal perturbation

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[Pedro & AW '19]

A Tale of 2 EFTs ...

- Method (HD):

$$\chi = \chi_0(1+\delta) \quad , \quad \delta = \sum_n a_{2n}\dot{\phi}^{2n}$$

↓

$$\mathcal{L} = \frac{f_\alpha^2}{2}\dot{\phi}^2 - V(\phi) + \frac{f_\alpha^2 f_\alpha'^2}{2\Lambda^2 V_\alpha''}\dot{\phi}^4 + \frac{f_\alpha^2 f_\alpha'^2}{2\Lambda^2 V_\alpha''}\frac{3f_\alpha'^2 V_\alpha'' + 3 f_\alpha f_\alpha'' V_\alpha'' - \Lambda f_\alpha f_\alpha' V_\alpha'''}{V_\alpha''^2\Lambda^2}\dot{\phi}^6 + \dots$$

$$x_\alpha^{(n)} \equiv x^{(n)}(\chi_0(1+a_0)) \quad , \quad x \in f, V$$

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[Pedro & AW '19]

A Tale of 2 EFTs ...

- Method (2F):

$$\frac{d^2 v_\alpha^T}{d\tau^2} + 2aH\eta_\perp \frac{dv_\alpha^N}{d\tau} - a^2H^2\eta_\perp^2 v_\alpha^T + \frac{d(aH\eta_\perp)}{d\tau} v_\alpha^N + \Omega_{TN} v_\alpha^N + (\Omega_{TT} + k^2) v_\alpha^T = 0$$

$$\frac{d^2 v_\alpha^N}{d\tau^2} - 2aH\eta_\perp \frac{dv_\alpha^T}{d\tau} - a^2H^2\eta_\perp^2 v_\alpha^N - \frac{d(aH\eta_\perp)}{d\tau} v_\alpha^T + \Omega_{TN} v_\alpha^T + (\Omega_{NN} + k^2) v_\alpha^N = 0$$

$$\begin{aligned}
\Omega_{TT} &= -a^2H^2(2 + 2\epsilon - 3\eta_\parallel + \eta_\parallel\xi_\parallel - 4\epsilon\eta_\parallel + 2\epsilon^2 - \eta_\perp^2) \ , \\
\Omega_{NN} &= -a^2H^2(2 - \epsilon) + a^2 V_{NN} + a^2H^2\epsilon R \ , \\
\Omega_{TN} &= a^2H^2\eta_\perp(3 + \epsilon - 2\eta_\parallel - \xi_\perp) \ .
\end{aligned}$$

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[Pedro & AW '19]

A Tale of 2 EFTs ...

- Resulting speed of sound for curvature perturbation:

$$|\Omega_{NN} \gg |\Omega_{TN}| \;,\; |\Omega_{TT}|$$

$$c_s^{-2} = 1 + 4\frac{f_\alpha'^2}{2\Lambda^2 V_\alpha''}\dot{\phi}^2 + 4\frac{f_\alpha'^2}{\Lambda^2 V_\alpha''}\frac{f_\alpha'^2 V_\alpha'' + 3 f_\alpha f_\alpha'' V_\alpha'' - \Lambda f_\alpha f_\alpha' V_\alpha'''}{V_\alpha''^2 \Lambda^2}\dot{\phi}^4 + \ldots$$

- Same as for method (HD) -- the 2 EFTs agree order by order!

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[Pedro & AW ’19]

Flattening at Tower of 2nd derivatives …

- cross-over from regime (I) to (II) controlled by ratio:

	(I) : $\frac{g\chi_0^2}{m^2} \ll 1$	(II) : $1 \ll \frac{g\chi_0^2}{m^2}$
(L) :	$\frac{g\phi^2}{M^2} \ll 1$	$\textit{no constraint}$
(B) :	$\frac{g\phi^2}{M^2} \lessgtr 1$	$\frac{g\phi^2}{M^2} \lessgtr 1$

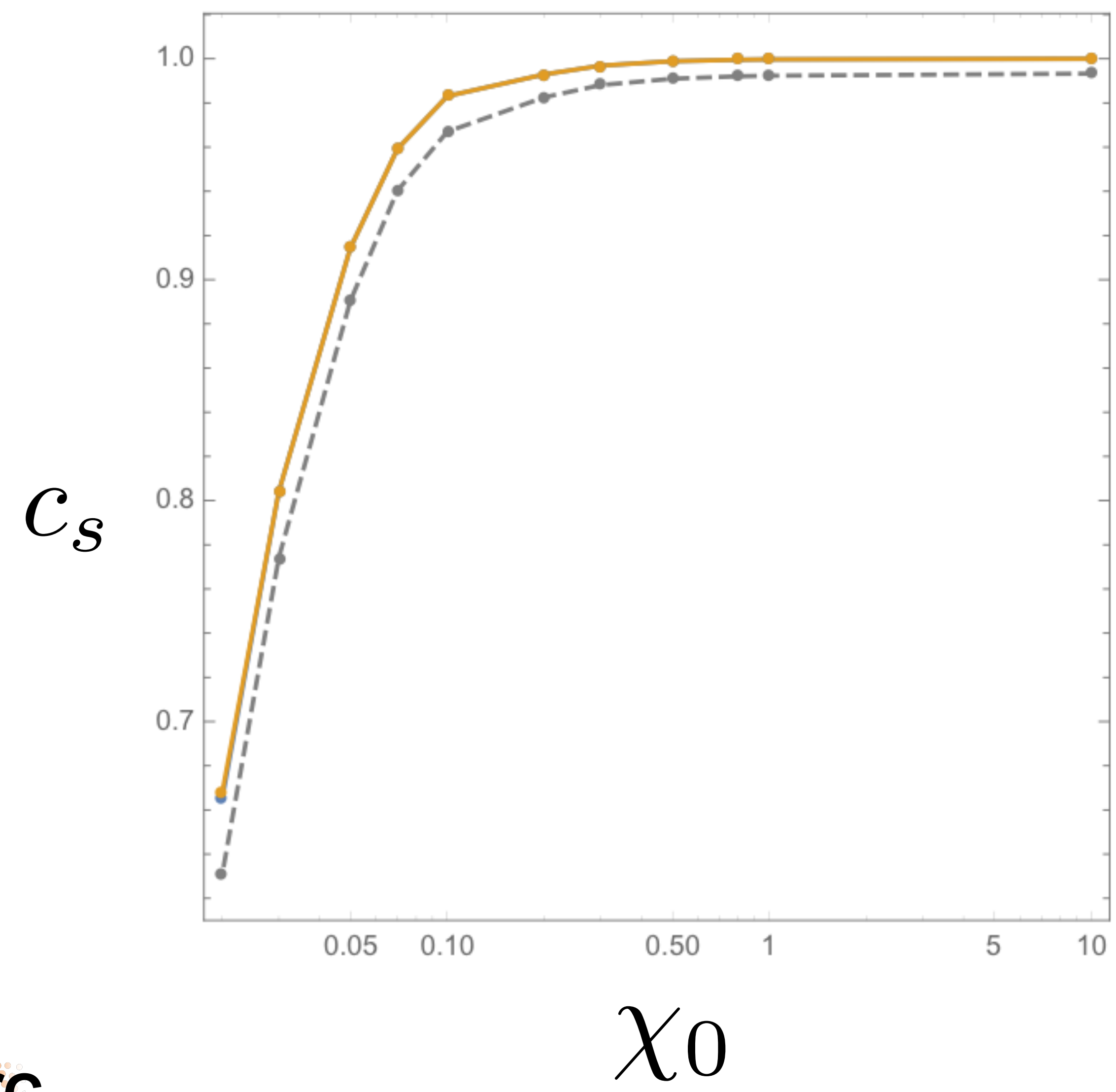
[Pedro & AW '19]

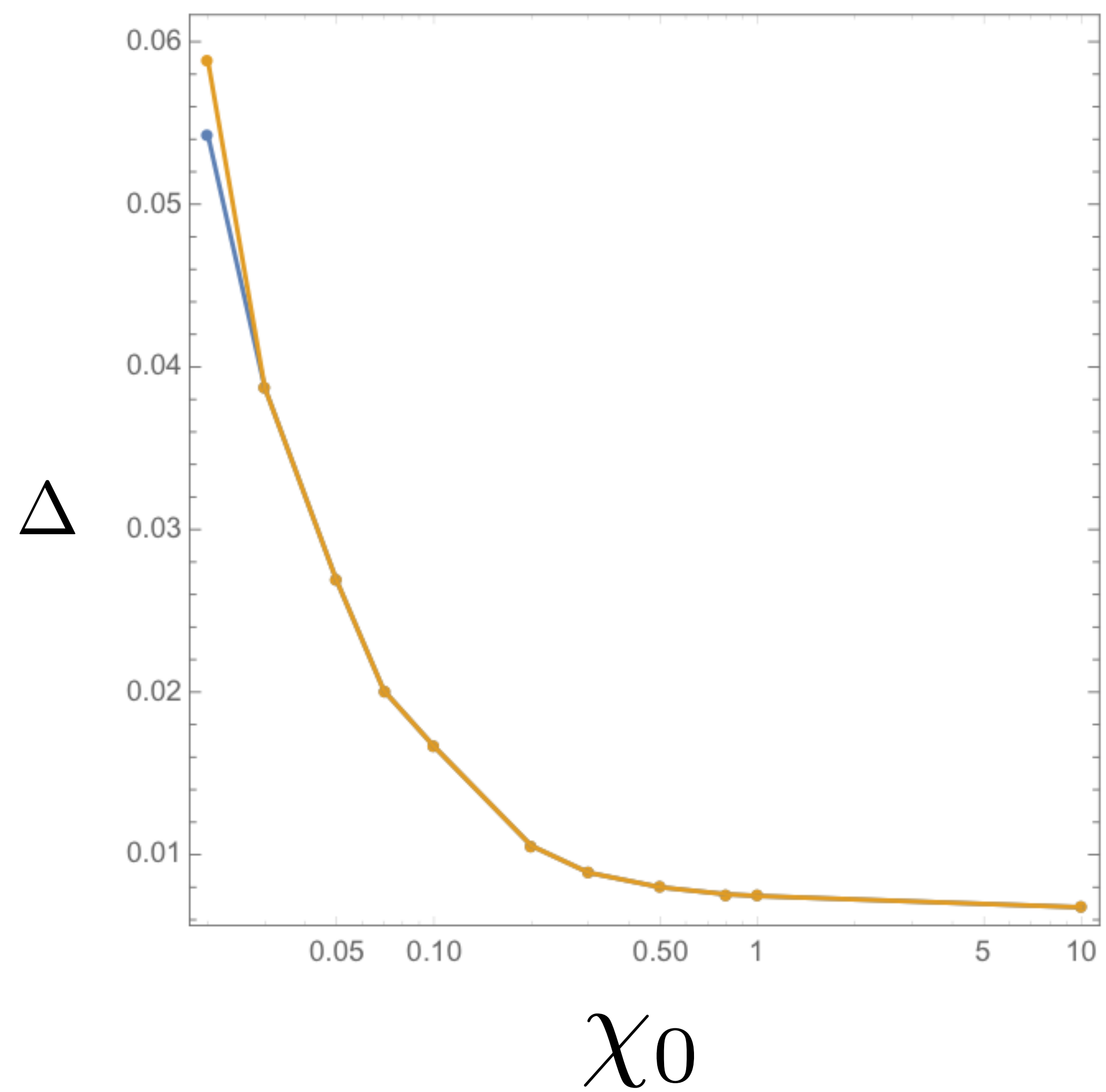
Flattening at more than 2 derivatives ...

- Can now check various examples of the 4 regimes ...

See also e.g.: [Achucarro, Atal & Welling '15]

- The g = 0 limit of (I)-(L) has been extensively studied & we agree & use it to check EFT accuracy; g = 0 limit of (I)-(B) similar

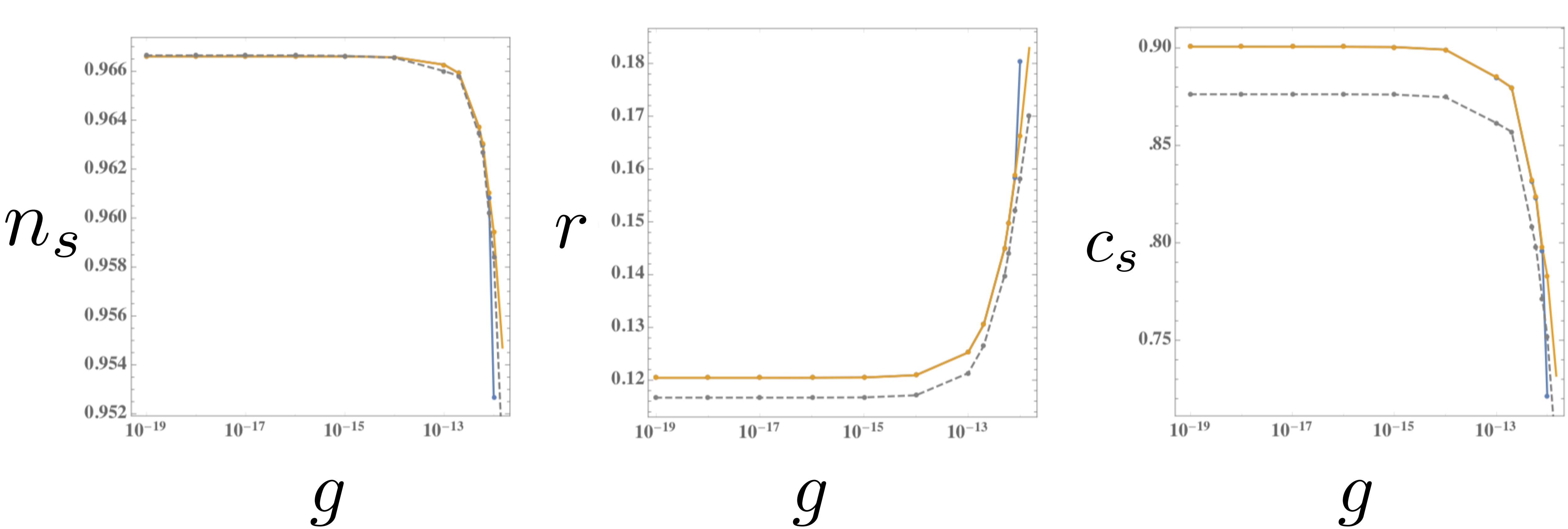




[Pedro & AW '19]

Flattening at more than 2 derivatives ...

- Case (I)-(L) at finite g -- kinetic steepening !



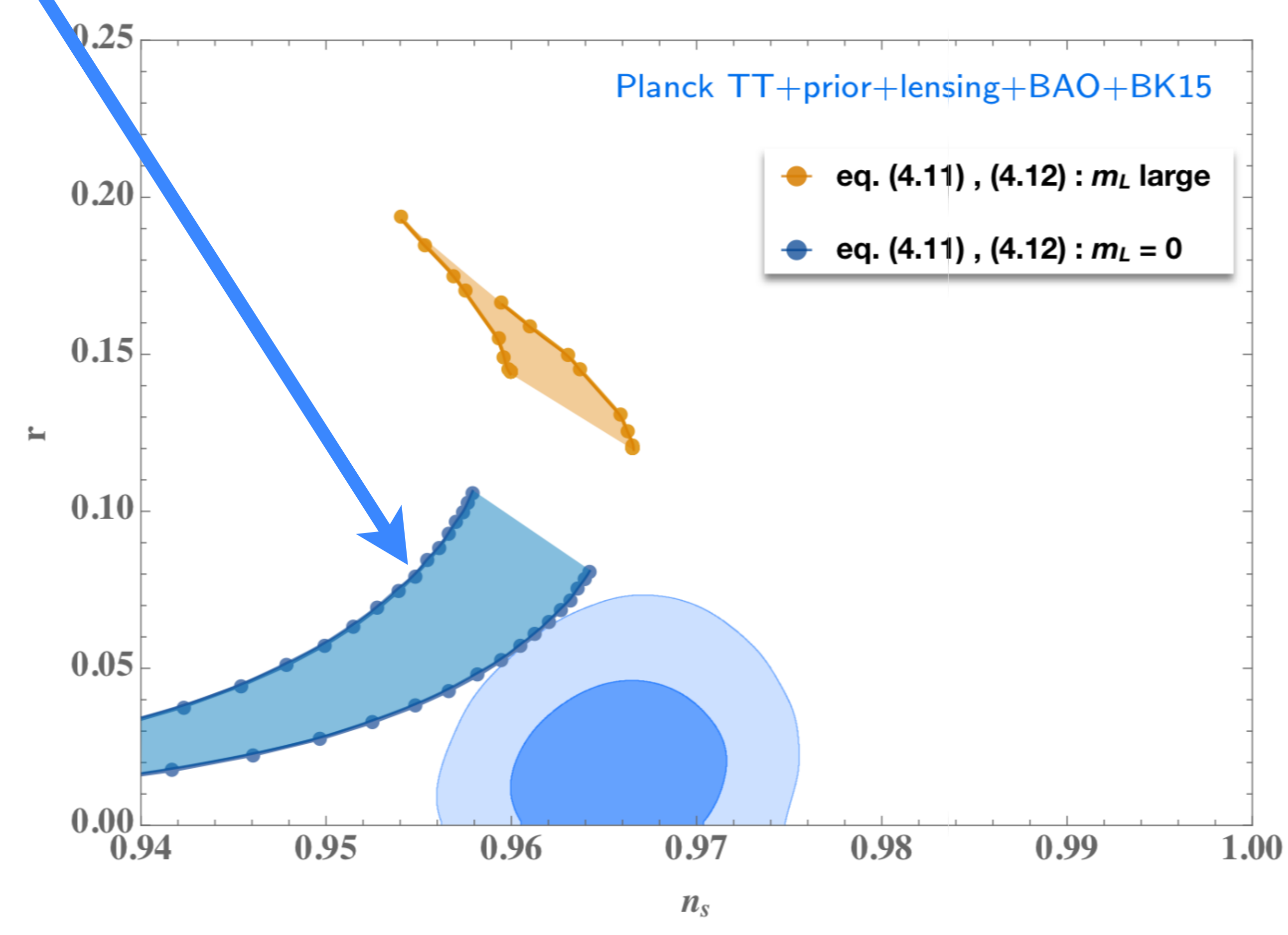
[Pedro & AW '19]

Flattening at more than 2 derivatives ...

- The m = 0 limit of (II)-(L) for an f with p = 1:

$$V_{eff}(\Phi) = \mu^4 \left[1 - \cos^2\left(\frac{\Phi}{f_a}\right)\right]$$

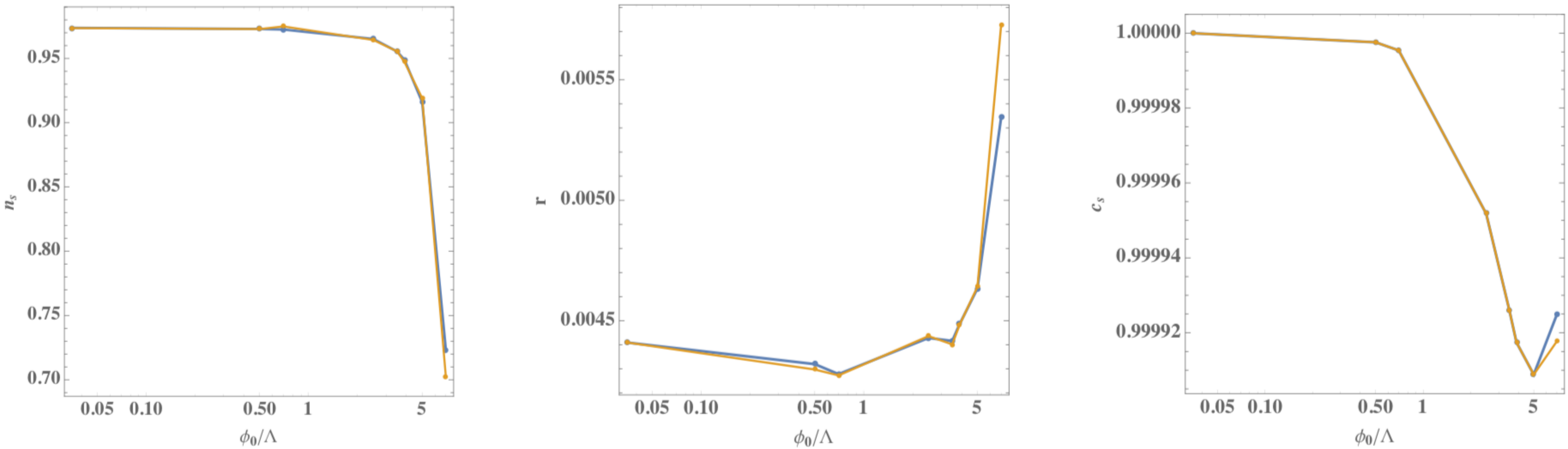
$$c_s^{-2} - 1 \approx \sum_n \frac{\epsilon^n}{\cos^{2n}(\Phi/f_a)}$$



[Pedro & AW '19]

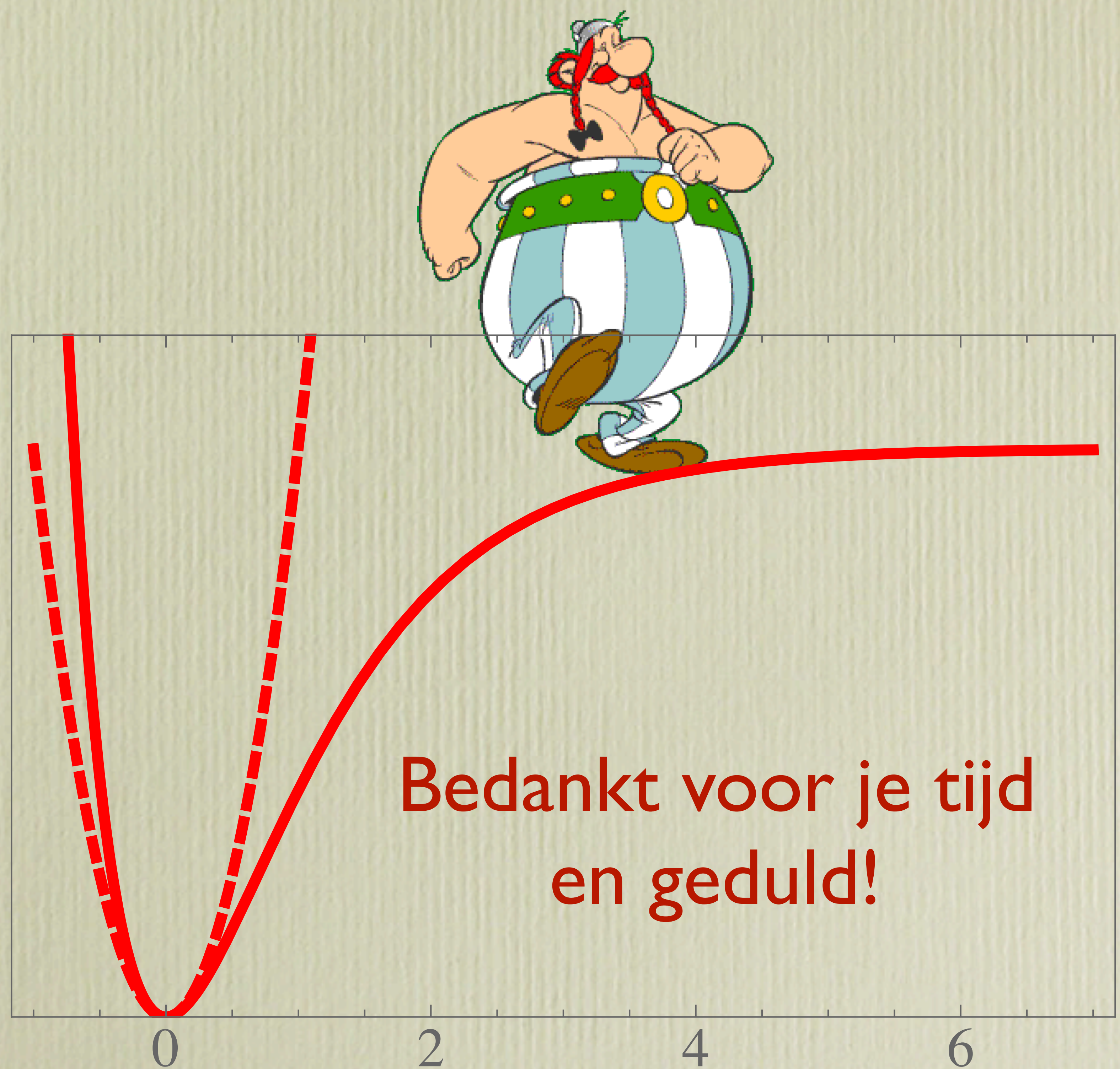
Flattening at more than 2 derivatives ...

- The m = 0 limit of (II)-(B) for an exponential f :



Observables for $f = e^{\chi/\Lambda}$ in the regime $m^2 \ll g\chi_0^2$ and $\frac{g\phi^2}{M^2} \gg 1$.

- kinetic mixing drives sizable 3pt-CMB correlations
- efficient description with single-field Higher-Deriv. EFT
- even for strong potential backreaction, 2-deriv. EFT not enough



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