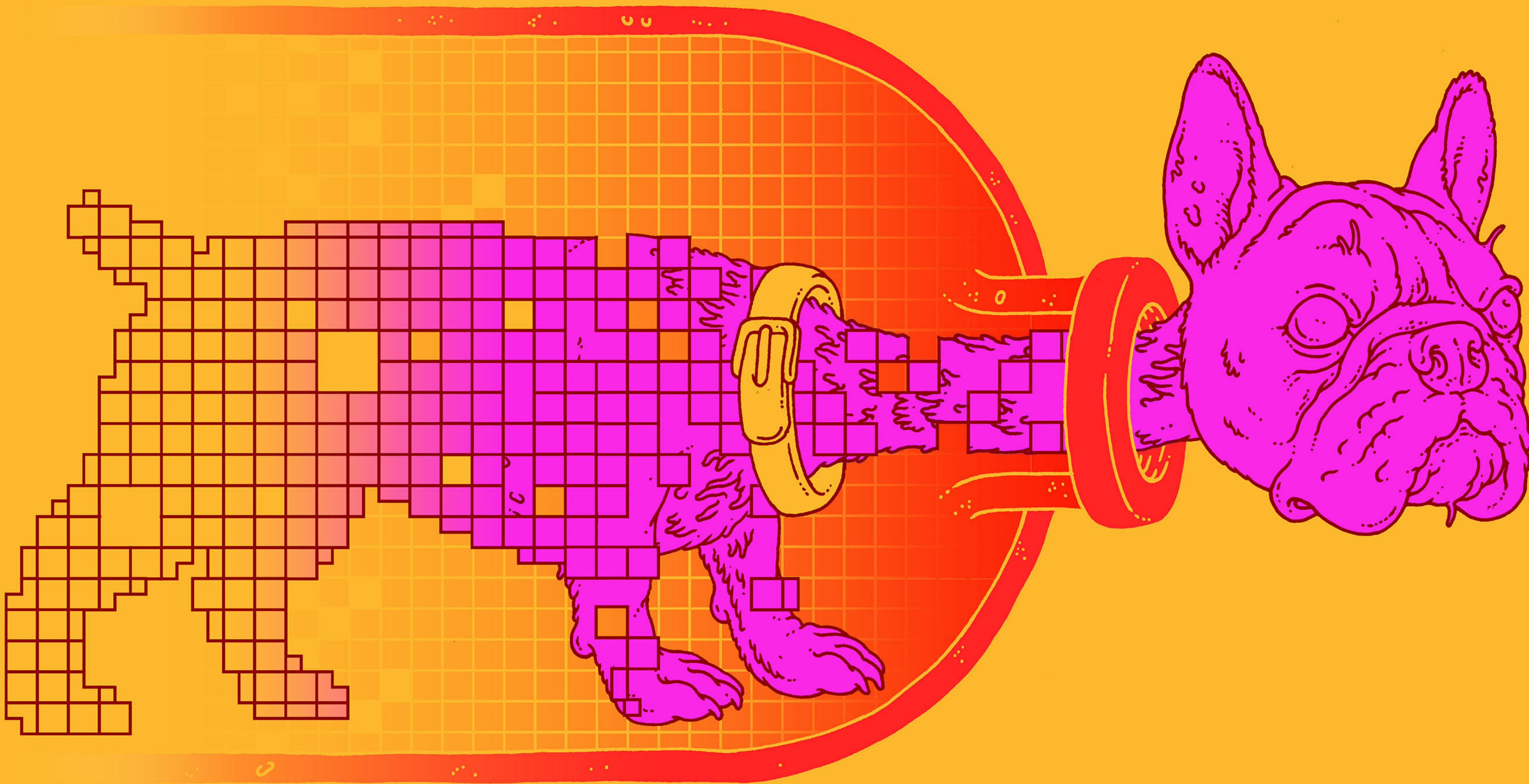
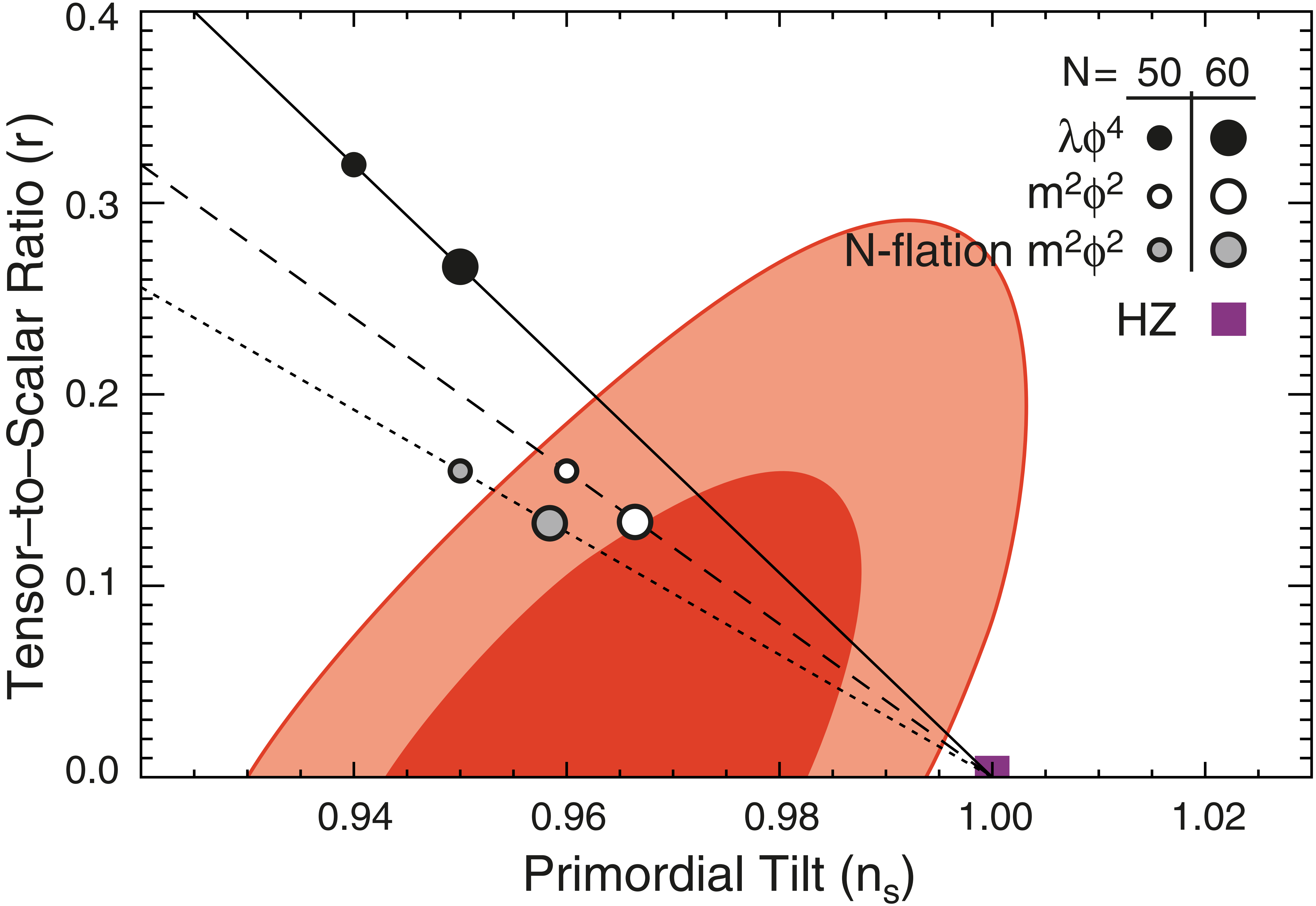


title page image by Eric Nyquist for Quanta Magazine

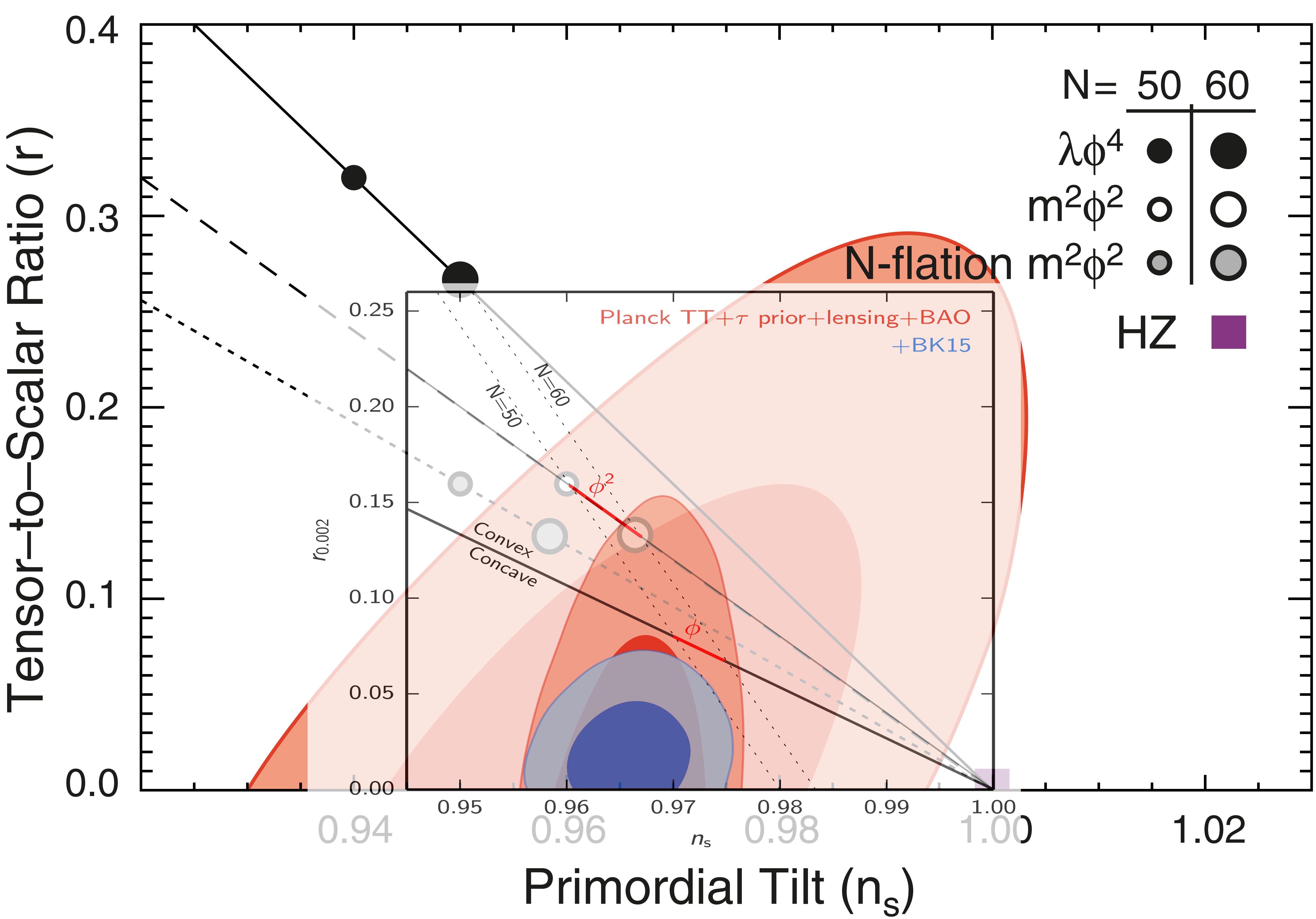
UV-IR Bottlenecks for Inflation and the Higgs

Alexander Westphal (DESY) with M. Dias, J. Frazer [1810.05199]
and N. Kaloper [1907.05837]

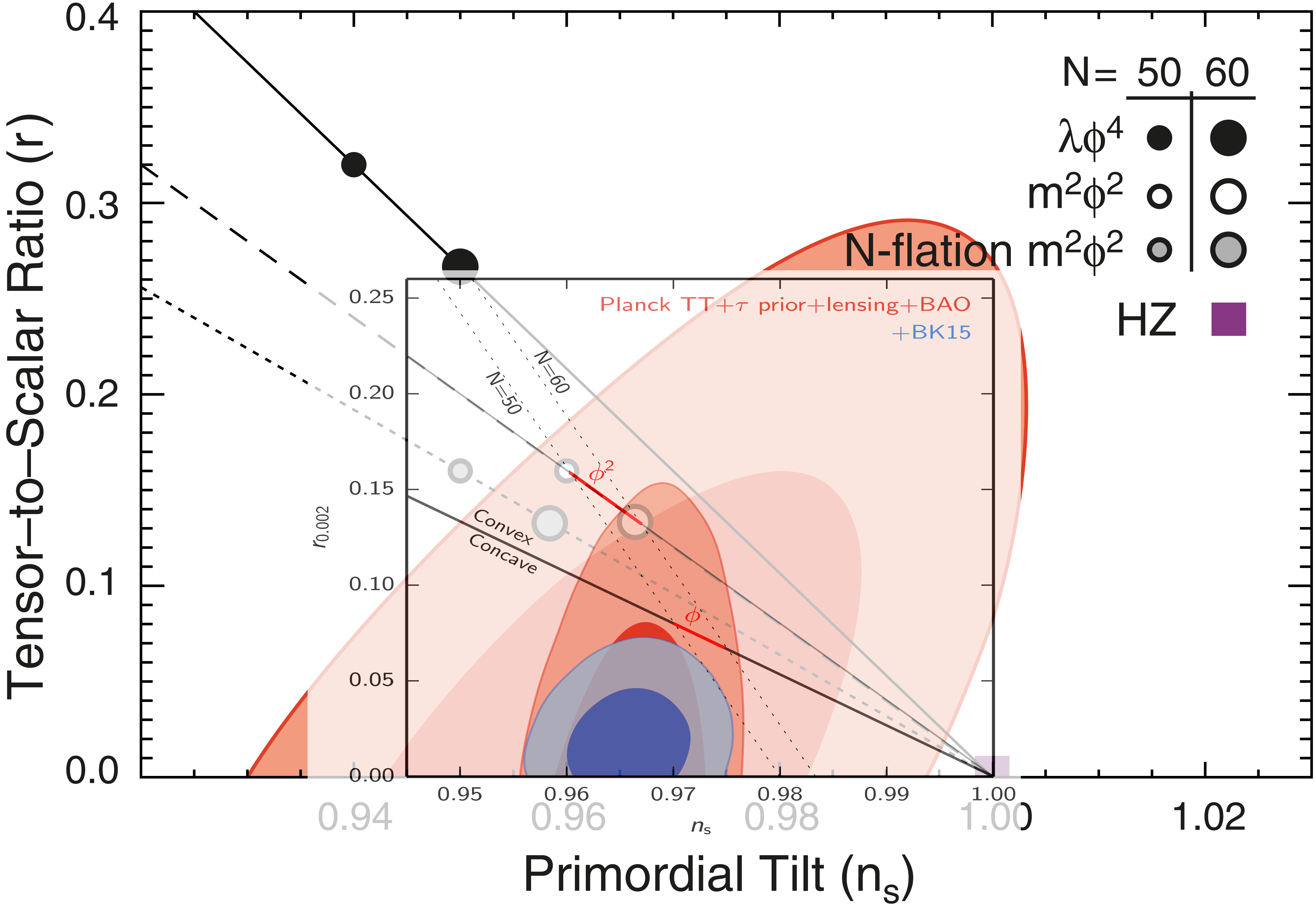
IPMU, Tokyo, Feb 18, 2020



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
$\lambda\phi^4$
$m^2\phi^2$
N-flation $m^2\phi^2$
HZ

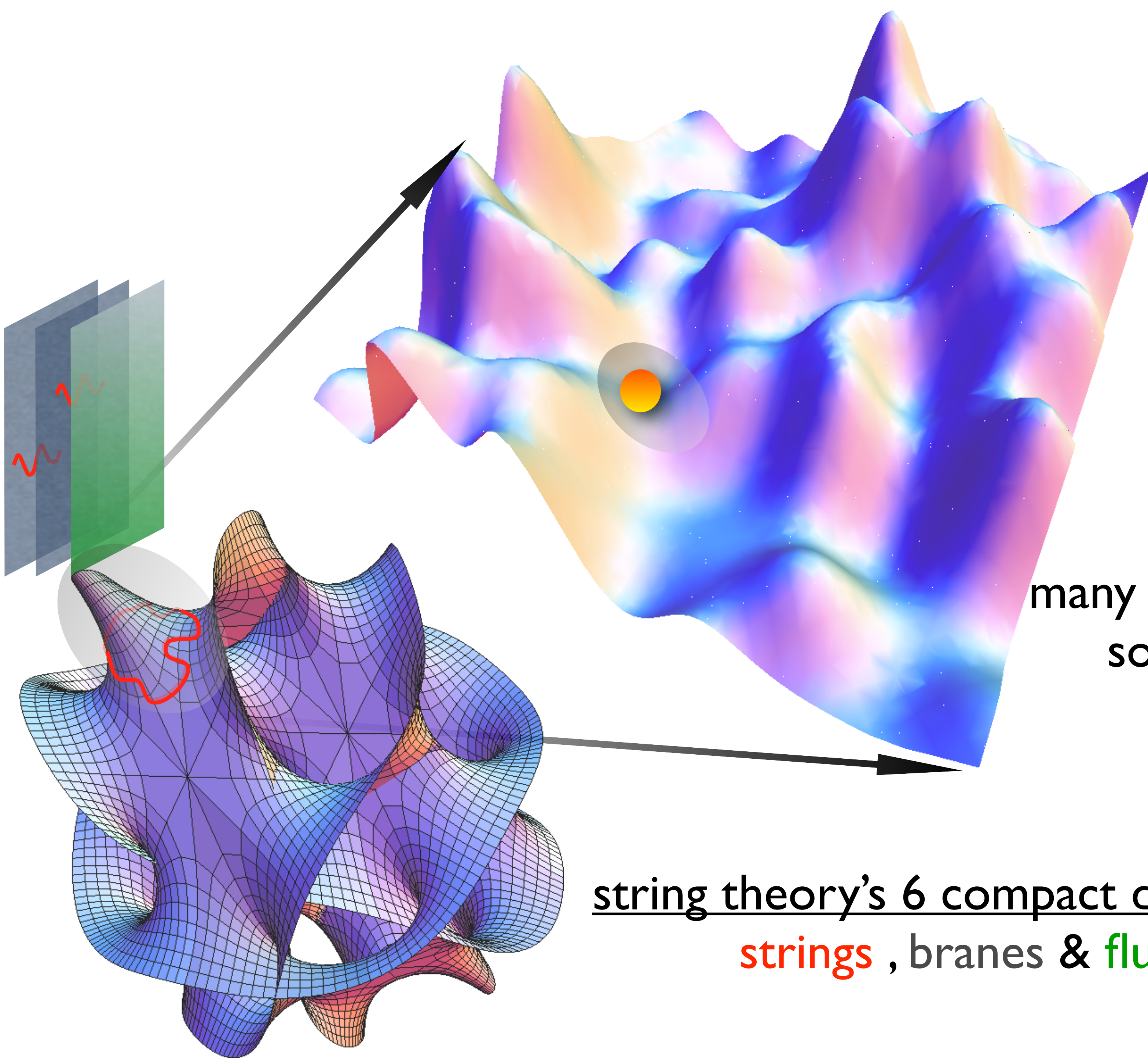


Tensor–to–Scalar Ratio (r)
Primordial Tilt (n_s)
N= 50 60
$\lambda\phi^4$
$m^2\phi^2$
N-flation $m^2\phi^2$
HZ
Planck TT+τ prior+lensing+BAO
+BK15
N=60
N=50
ϕ^2
ϕ
Convex
Concave
$r_{0.002}$
n_s
0.0
0.1
0.2
0.3
0.4
0.94
0.96
0.98
1.00
1.02
0.00
0.05
0.10
0.15
0.20
0.25
0.95
0.96
0.97
0.98
0.99
1.00



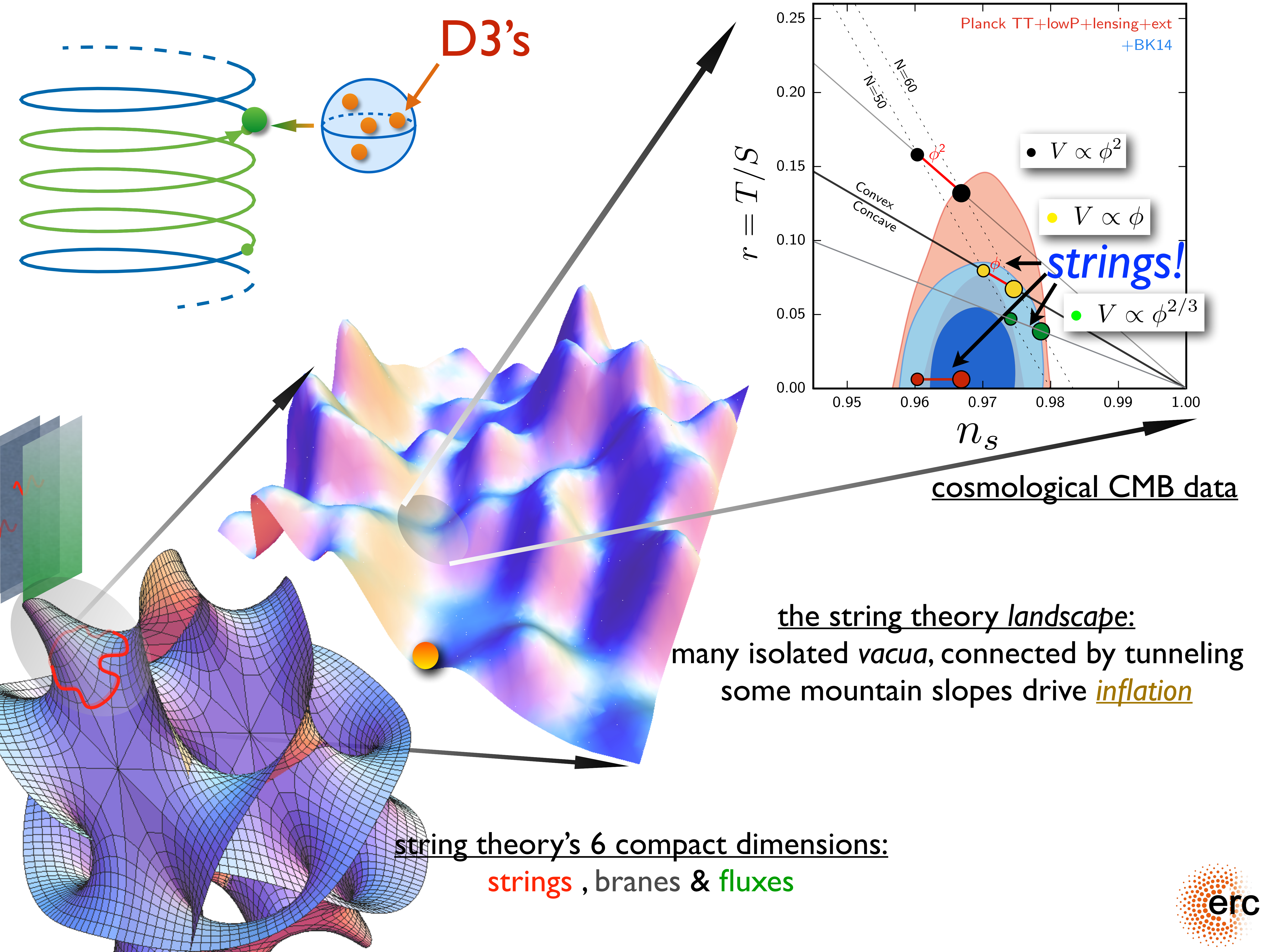
and future: Simons Array with σ(r) = 0.003 ; LiteBIRD with σ(r) = 6 x 10^{-4}

-> see talks yesterday afternoon!



<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


D3's
Planck TT+lowP+lensing+ext
+BK14
N=60
N=50
Convex
Concave
$V \propto \phi^2$
$V \propto \phi$
$V \propto \phi^{2/3}$
strings!
$r = T/S$
n_s
0.25
0.20
0.15
0.10
0.05
0.00
0.95
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0.98
0.99
1.00
cosmological CMB data
the string theory *landscape*:
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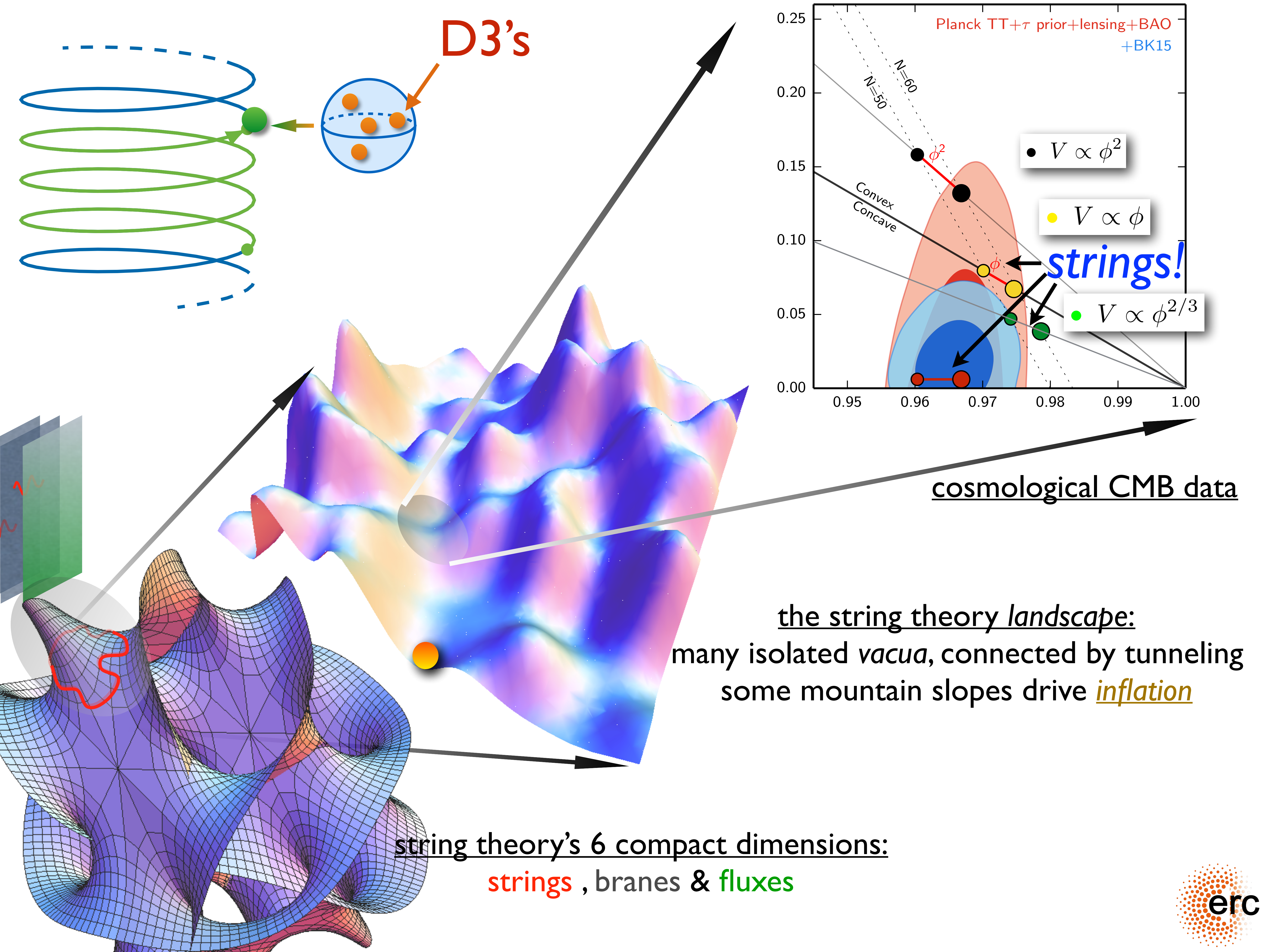
some mountain slopes drive *inflation*
string theory's 6 compact dimensions:
strings , branes & fluxes
erc


D3's
Planck TT+τ prior+lensing+BAO
+BK15
N=60
N=50
Convex
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$V \propto \phi^2$
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strings!
$V \propto \phi^{2/3}$
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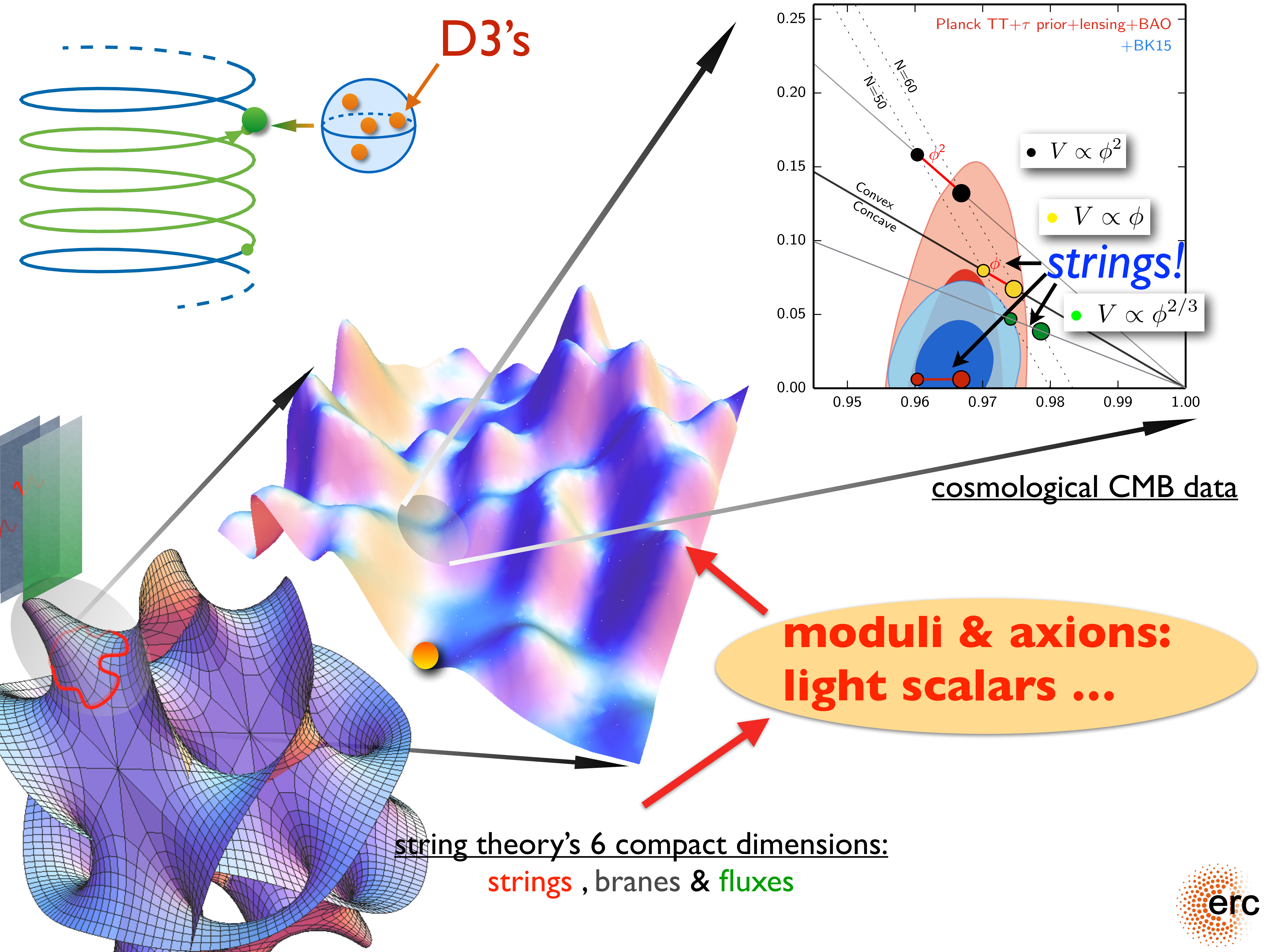
D3's
Planck TT+τ prior+lensing+BAO
+BK15
0.25
0.20
0.15
0.10
0.05
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0.95
0.96
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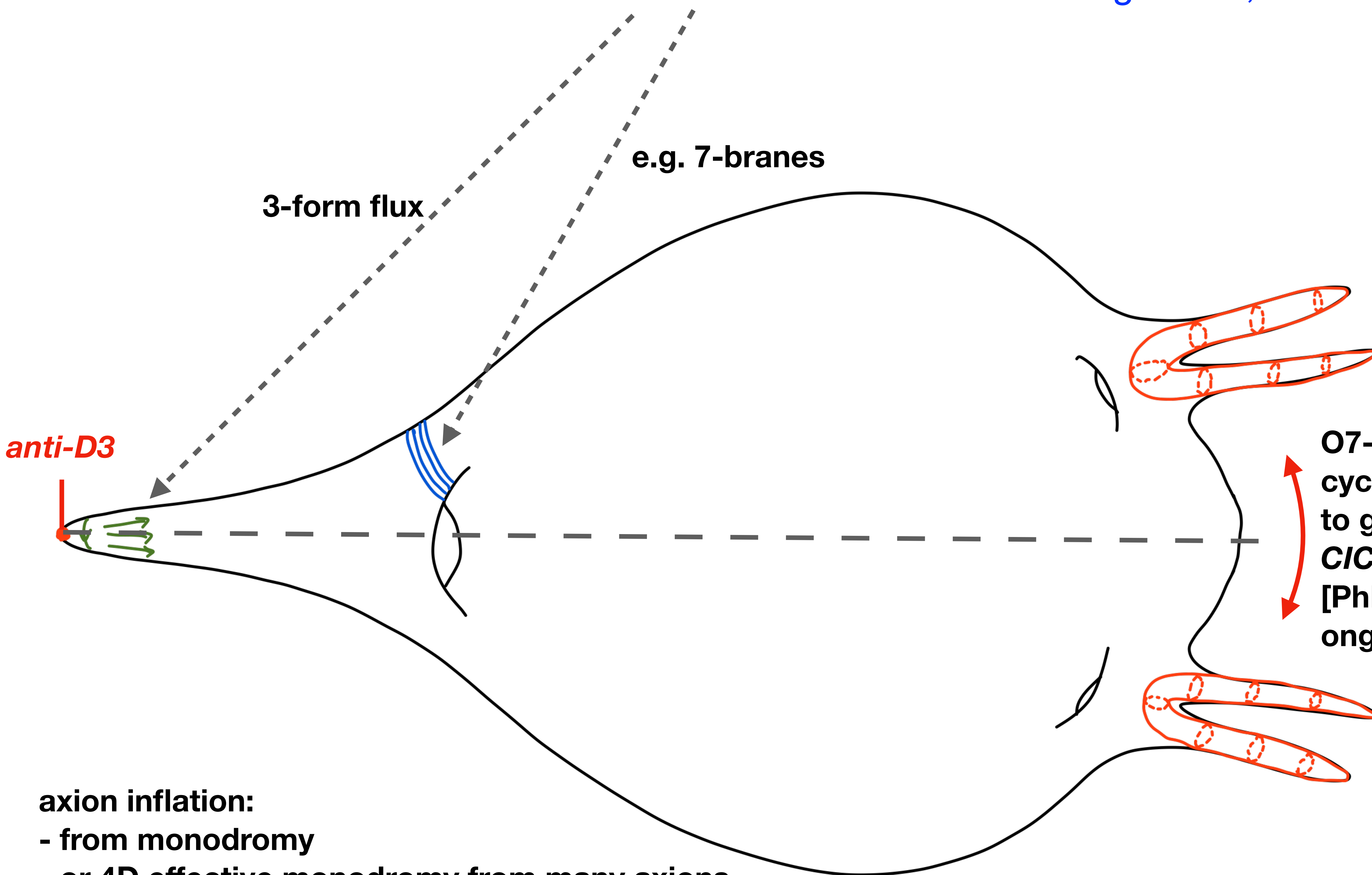
0.98
0.99
1.00
N=60
N=50
Convex
Concave
ϕ^2
ϕ
$V \propto \phi^2$
$V \propto \phi$
strings!
$V \propto \phi^{2/3}$
cosmological CMB data
moduli & axions:
light scalars ...
string theory's 6 compact dimensions:
strings , branes & fluxes

inflation in string theory …

must-haves … controlled moduli stabilization & inflation - e.g. KKLT, LVS …



O7-Z_2: swap 2-cycle bananas to get C_2 axions - *CICY scan* [PhD R. Altman & ongoing work]

axion inflation:
- from monodromy
- or 4D effective monodromy from many axions
e.g. [Kim, Nilles & Peloso '04; Higaki & Takahashi '14; Choi, Kim & Yun '14]

inflation

axion monodromy - a summary

[Silverstein & AW; McAllister,
Silverstein & AW; Kaloper & Sorbo '08]
[Kaloper, Lawrence & Sorbo '11]

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

- example - B_2 - axion monodromy from flux:

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

axion
mass term

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

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

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

Flattening 1: moduli backreact in axion monodromy

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

$$V = \frac{C_1}{\phi} + C_2\phi^2(\mu^2 + b^2) \longrightarrow \langle\phi\rangle = \langle\phi\rangle_0(1 + b^2/\mu^2)^{-1/3}$$

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

$$V_{eff.}(b) = V|_{\langle\phi\rangle} \sim \langle\phi\rangle_0^2 \frac{b^2}{(1+b^2/\mu^2)^{2/3}} \sim \begin{cases} b^2 - \frac{2}{3}\frac{b^4}{\mu^2} \quad , & \mu \gg 1 \\ b^{2/3} \quad , & \mu \ll 1 \end{cases}$$

- other powers as well: ϕ, $\phi^{4/3}$, ϕ^2

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

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

4D effective axion monodromy inflation

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

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

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

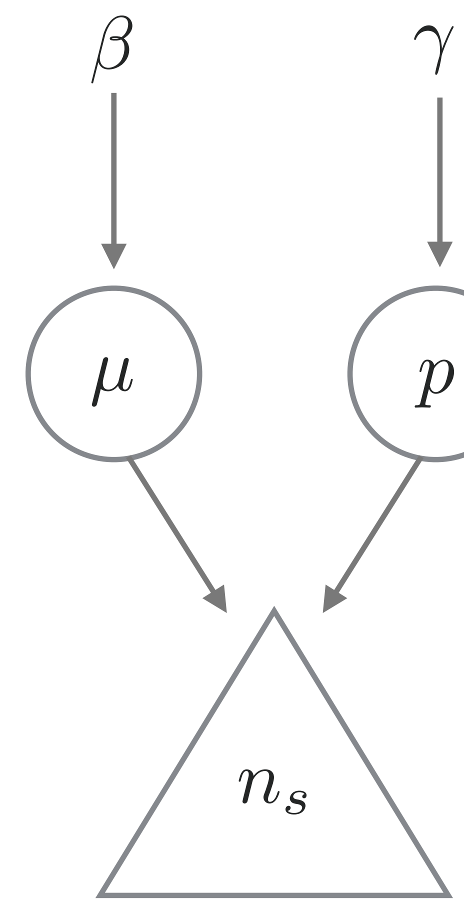
$$S = \mathcal{C}\,\mathcal{V}^k \qquad \Lambda_{UV}^4 \sim \frac{1}{\mathcal{V}^2} \qquad \chi_n C_n^{\text{eff.}} \equiv C_n^{\text{tree}} + \chi_n C_n$$

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

EXAMPLE: AXION MONODROMY

Steps:

1. Identify relevant scales (class of models)
2. Learn the mapping from parameters to observables
3. Study how predictions change according to prior choice



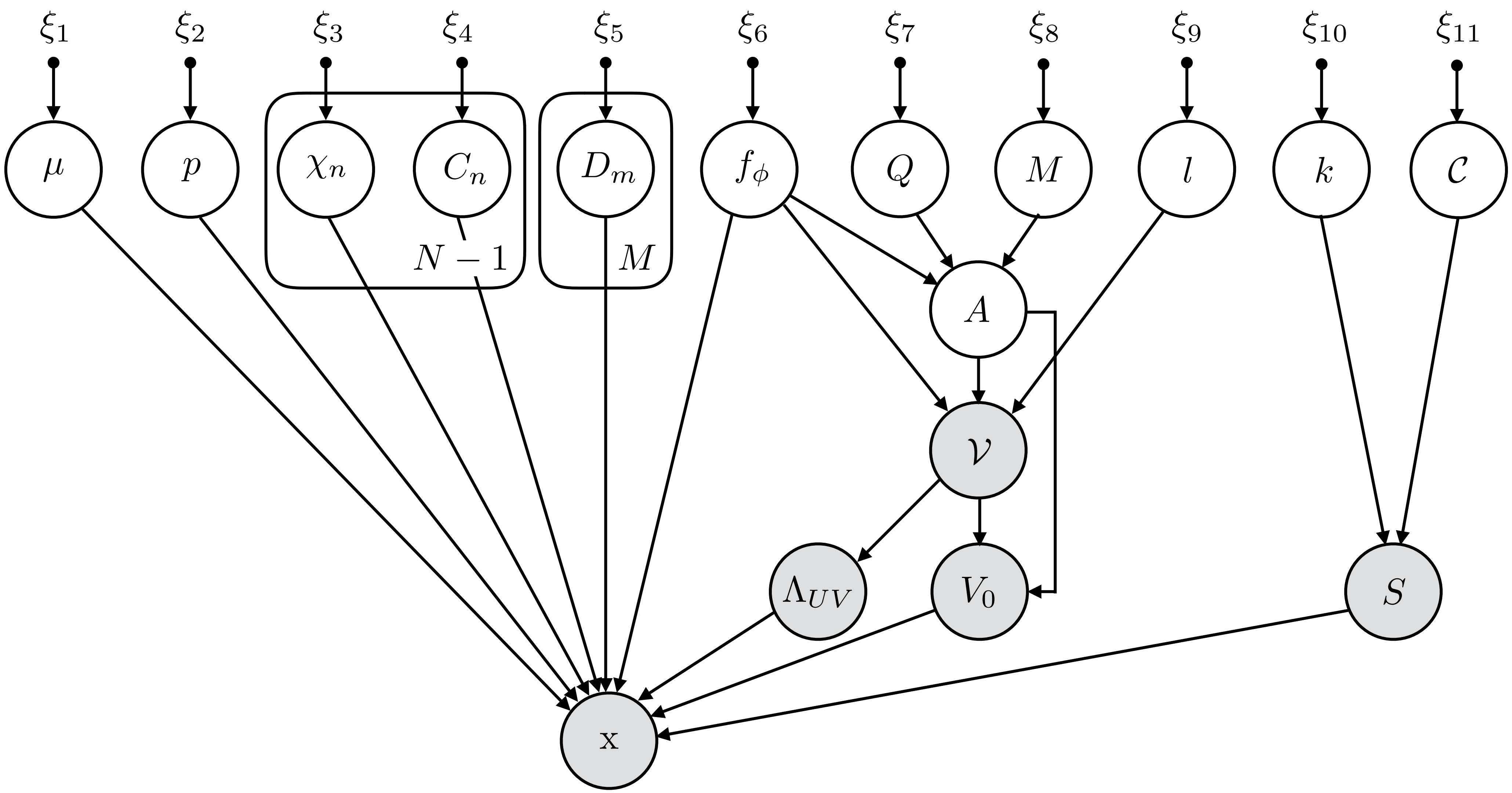
Use numerical methods developed in previous work to generate a large sample assuming

$$\mu \sim \mathcal{U}(0.1, 1) \quad p \sim \mathcal{U}(0.1, 2)$$

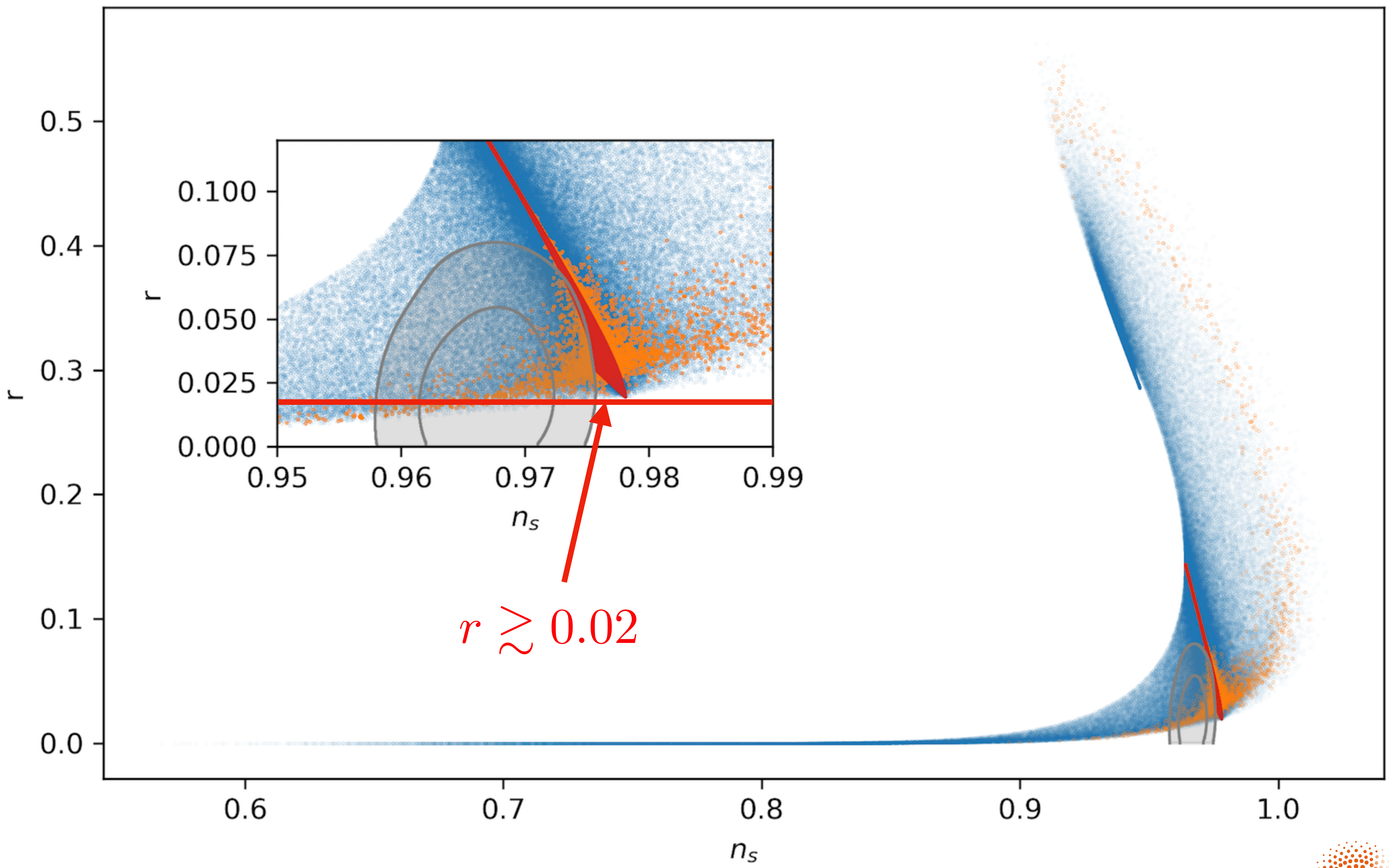
- Take a random draw of μ and p
- Solve background equations of motion to get total number of e-folds
- Solve equations of motion for the perturbations and compute n_s at pivot scale
- Repeat many times
- Use machine learning to get $n_s(\mu, p)$

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V_0\left[\left(1 + \left(\frac{\phi}{\mu}\right)^2\right)^{p/2} - 1\right]$$

Dias, JF, Mulryne, Seery: Implementations in C++, Python and Mathematica publicly available at https://transportmethod.com



ξ_1
ξ_2
ξ_3
ξ_4
ξ_5
ξ_6
ξ_7
ξ_8
ξ_9
ξ_{10}
ξ_{11}
μ
p
χ_n
C_n
$N-1$
D_m
M
f_ϕ
Q
M
l
k
$\mathcal{C}$
A
$\mathcal{V}$
Λ_{UV}
V_0
S
x



0.5
0.4
0.3
0.2
0.1
0.0
r
0.6
0.7
0.8
0.9
1.0
n_s
0.100
0.075
0.050
0.025
0.000
r
0.95
0.96
0.97
0.98
0.99
n_s
$r \gtrsim 0.02$

From 4-forms to Goldilocks ...

- string dS construction have many dS vacua from fluxes — *accommodate* small CC a la Bousso-Polchinski:

[Bousso & Polchinski '00]

$$S=\int d^4x\sqrt{-g}\left(\frac{M_{\rm P}^2}{2}R-\Lambda_0-\sum_i\left(F_{(4)}^{(i)}\right)^2\right)+S_{bound.}$$

$$F_{(4)}^{(i)}=F_{\mu\nu\rho\sigma}^{(i)}=\partial_{[\mu}A_{\nu\rho\sigma]}^{(i)}\qquad,\qquad S_{membr.}=q_i\int A_{(3)}^{(i)}$$

- string dS construction have many dS vacua from fluxes — <u>*accommodate*</u> small CC a la Bousso-Polchinski:

[Bousso & Polchinski '00]

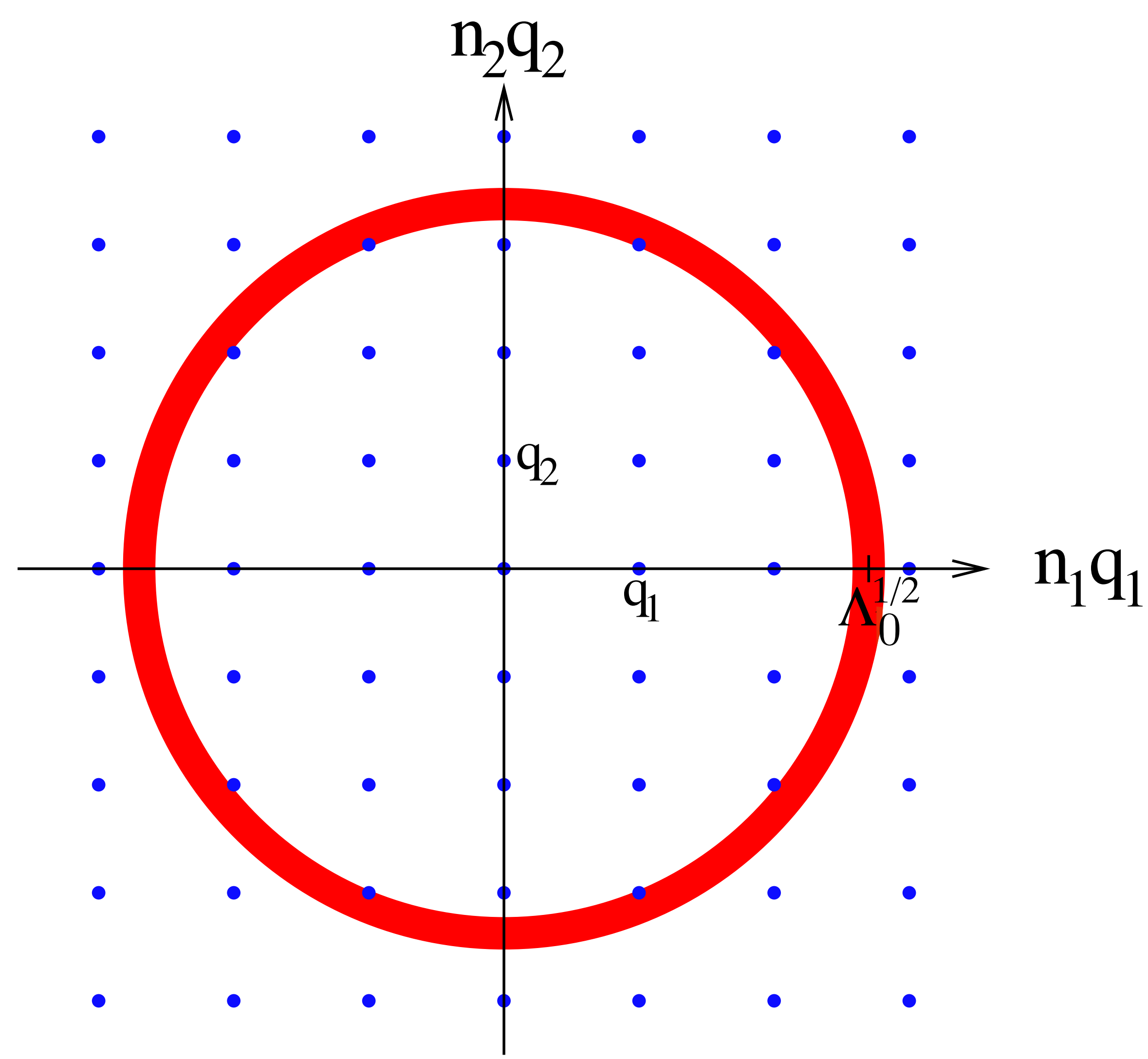
flux quantization:

$$\int_X F^{(i)}_{(4)} = \frac{2\pi n_i}{q_i} \quad , \quad n_i \in \mathbb{Z}$$

plug-in quantized $F_{(4)}$

$$\Lambda = \Lambda_0 + \frac{1}{2}\sum_i n_i^2 q_i^2$$

anthropic selection of CC
via Weinberg argument ['87]



- extend this to Higgs VEV, using coupling structure of axion monodromy:

[Kaloper & AW '19]
[Giudice, Kehagias & Riotto '19]

for simplicity, U(1) Higgs:

$$V_0 = \frac{\lambda}{4}|\phi|^4 - \frac{v^2}{2}|\phi|^2 + \Lambda$$

couple one $F_{(4)}$ to Higgs

$$\Delta V = \frac{c}{24}\epsilon_{\mu\nu\lambda\sigma}F^{\mu\nu\lambda\sigma}|\phi|^2 - \frac{1}{48}F^2_{\mu\nu\lambda\sigma}$$

- extend this to Higgs VEV, using coupling structure of axion monodromy:

[Kaloper & AW '19]
[Giudice, Kehagias & Riotto '19]

solve e.o.m of $F_{(4)}$ & plug in

$$V = \frac{\bar{\lambda}}{4}|\phi|^4 - \frac{\bar{v}^2}{2}|\phi|^2 + \frac{1}{2}Q^2 + \Lambda$$

extract

$$\begin{aligned}\bar{\lambda} &= \lambda + 2c^2 \\ \bar{v}^2 &= v^2 - 2cQ\end{aligned}$$

erc

- extend this to Higgs VEV, using coupling structure of axion monodromy:

[Kaloper & AW '19]
[Giudice, Kehagias & Riotto '19]

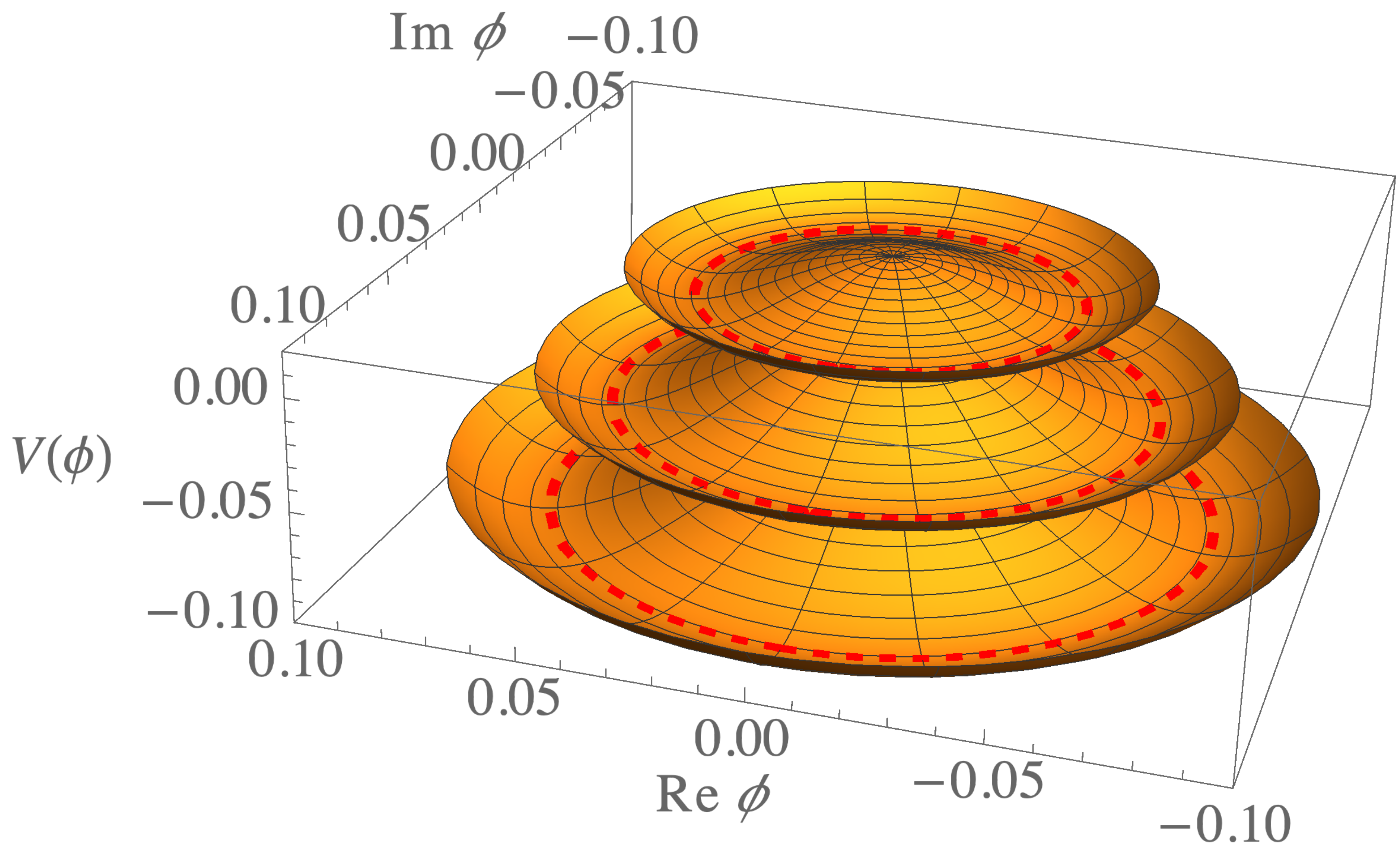
$$cq \lesssim \mathrm{TeV}^2 \quad \longrightarrow \quad N_* = \left[\frac{v^2}{cq}\right]$$

$$\Delta\Lambda = \Lambda_{N_*} - \Lambda_{N_*-1} \simeq \frac{qv^2}{c}$$

$$= \tfrac{1}{c^2} cq\, v^2 \sim \mathrm{TeV}^2 v^2$$

- extend this to Higgs VEV, using coupling structure of axion monodromy:

[Kaloper & AW '19]
[Giudice, Kehagias & Riotto '19]



The Goal

- energy scale of inflation – 10^{13} x LHC – close to **Planck Scale** !

  ➜ unique window to **quantum gravity** !

- **proposal:**

  test string theory with inflation & CMB, or EW SSB!

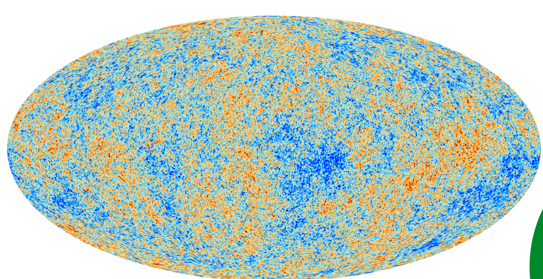
erc

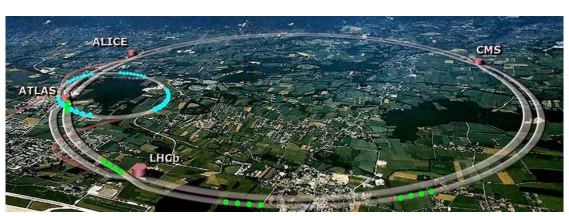
A Roadmap into the Post -Naturalness Era (?) ...

[Giudice '17]

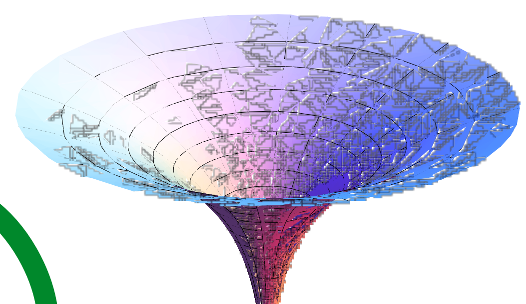
EW symmetry breaking

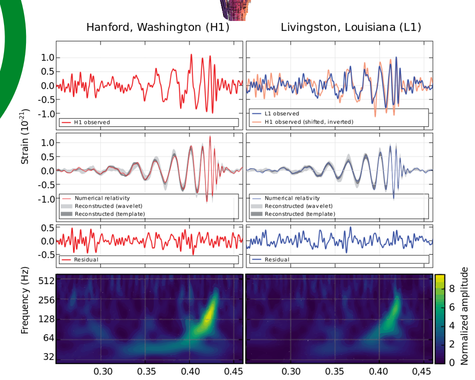
cosmological & terrestrial colliders





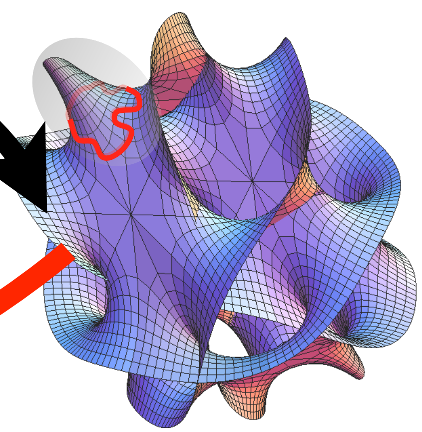
inflation & GWs





compare models

strings



systematic study !

dark energy

Funding acknowledgement:

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