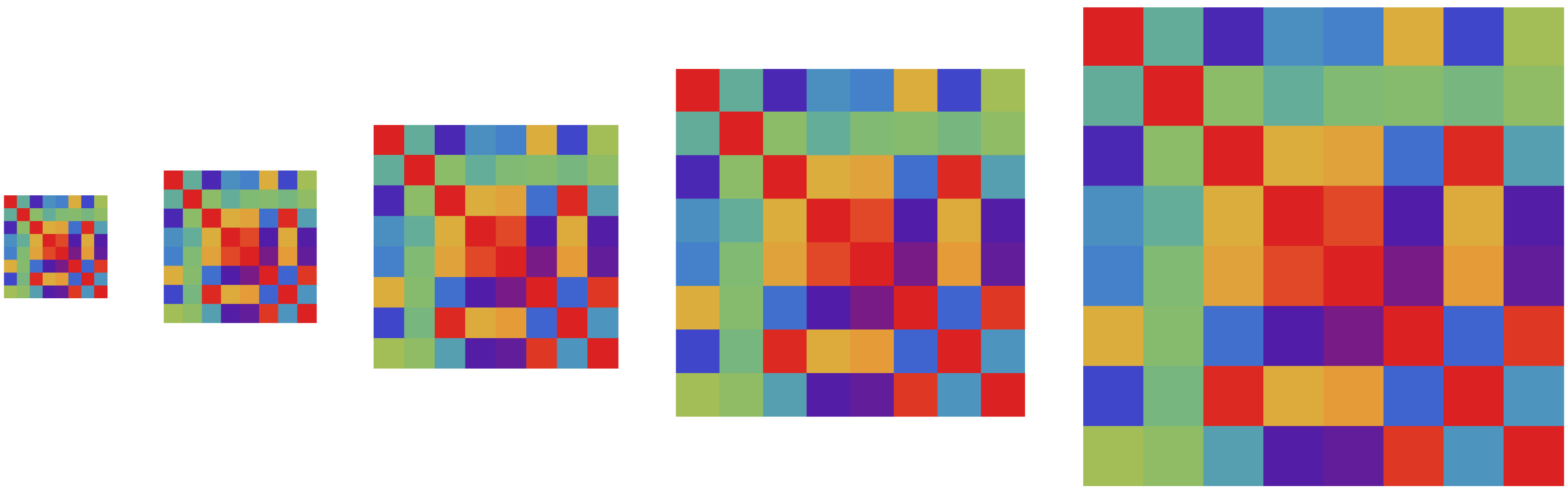
Scale symmetry, the Higgs and the Cosmos

Javier Rubio

based on Phys.Rev. D97 (2018) no.4, 043520 & Phys.Rev. D99 (2019) no.6, 063512



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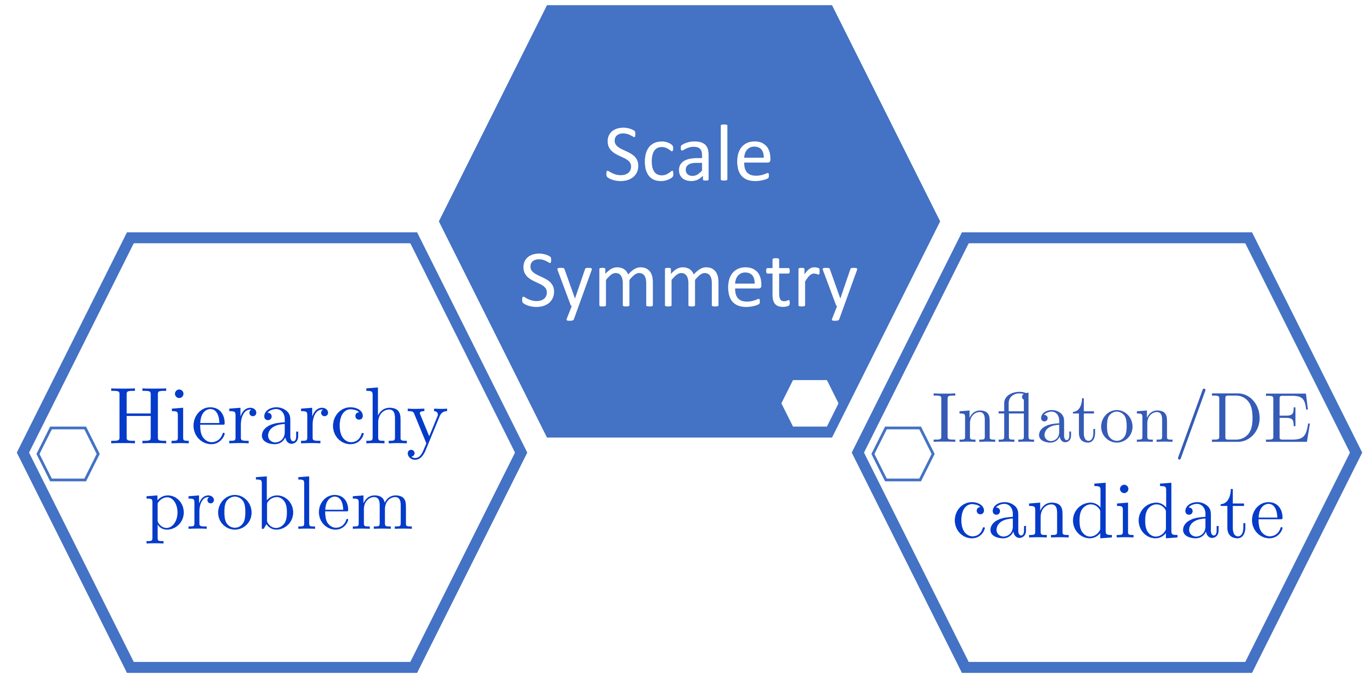
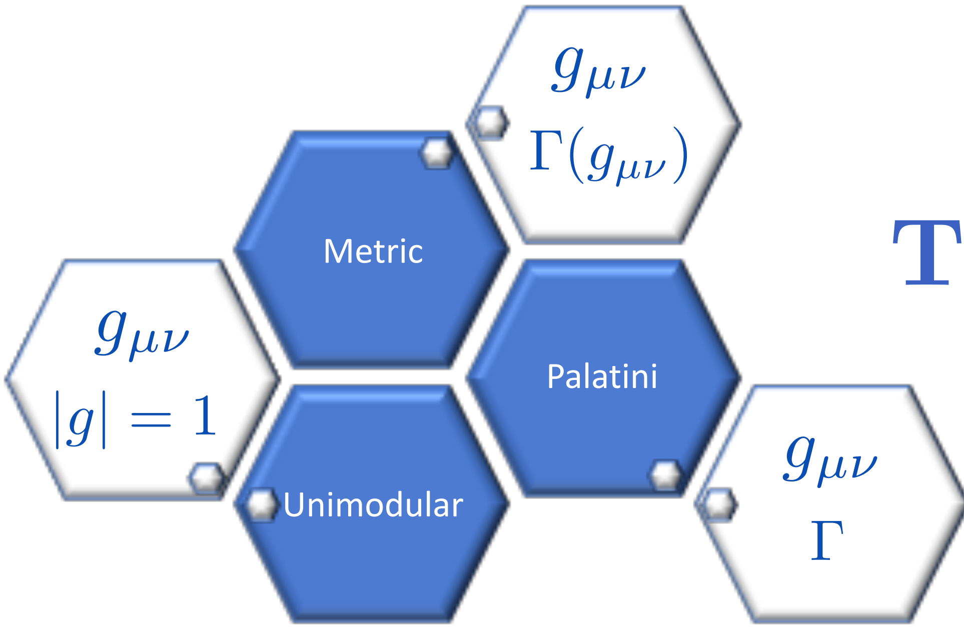
If the mass of the Higgs boson is put to zero in the SM, the Lagrangian has a larger symmetry

$$x^\mu \to \alpha^{-1} x^\mu \qquad \Phi_i(x) \to \alpha^{d_i} \Phi_i(\alpha^{-1} x)$$

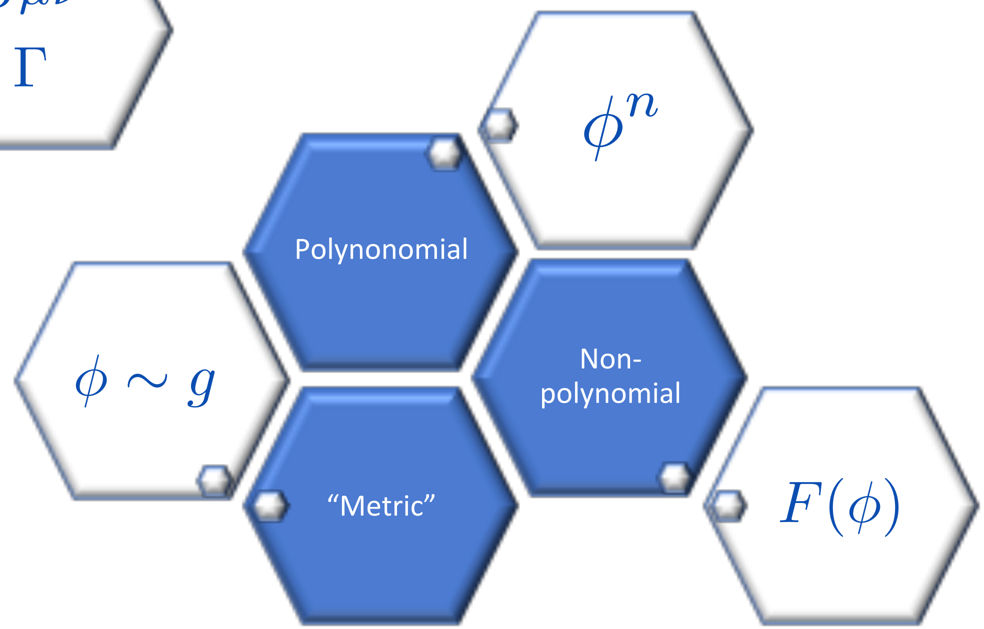
It is tempting to use this symmetry for something



The players



Theory of gravity



Scalar sector

The simplest possibility

J-frame

$$\frac{\mathcal{L}}{\sqrt{g}} = \frac{\xi_h h^2}{2} R - \frac{1}{2}(\partial h)^2 - \frac{\lambda}{4} h^4 - y h \bar{\psi}\psi$$

E-frame

$$\frac{\mathcal{L}}{\sqrt{g}} = \frac{M_P^2}{2} R - \frac{1}{2}(\partial \phi)^2 - \frac{\lambda M_P^4}{4\xi_h^2} - y \frac{M_P}{\xi_h} \bar{\psi}\psi$$

with $\phi = -\frac{M_P}{2\sqrt{|\kappa_c|}} \log \frac{M_P^2}{\xi_h h^2}$ $\qquad \kappa_c \equiv -\frac{\xi_h}{1 + 6y\xi_h}$

$y = 1$ for metric case $\qquad y = 0$ for Palatini case

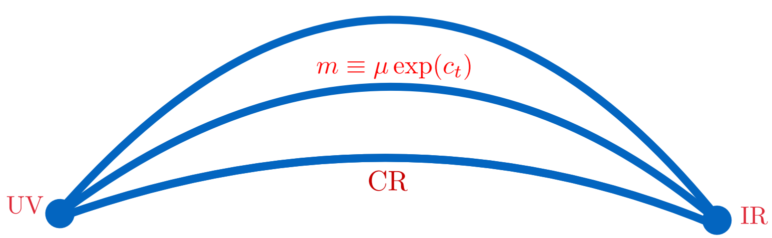
Scale symmetry must be broken in one way or another

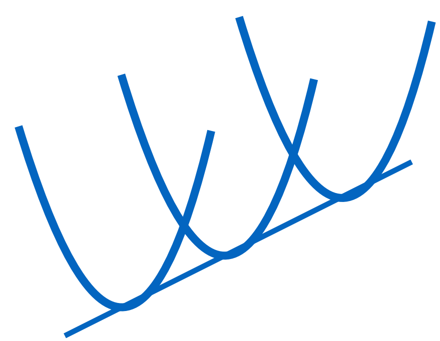
2 different perspectives

Classical
but not
Quantum

Classical
and
Quantum (SSB)

EFT





The Higgs-Dilaton model

$$\frac{\mathcal{L}}{\sqrt{g}} = \frac{1}{2}\left(\xi_\chi \chi^2 + \xi_h h^2\right) R - \frac{1}{2}(\partial h)^2 - \frac{1}{2}(\partial \chi)^2 - U(h,\chi)$$

with $U(h,\chi) = \frac{\lambda}{4}\left(h^2 - \alpha \chi^2\right)^2$

A singlet under the Standard Model gauge group

All scales generated by SSB of global scale invariance

Hierarchy of scales not addressed

M. Shaposhnikov, D. Zenhausern, Phys.Lett. B671 (2009) 187-192

J. García-Bellido, JR, M. Shaposhnikov, D. Zenhausern, Phys.Rev. D84 (2011) 123504

A recent revival: P. G: Ferreira, C. T. Hill, G. G. Ross Phys.Lett. B763 (2016) 174-178, Phys.Rev. D95 (2017) no.4, 043507

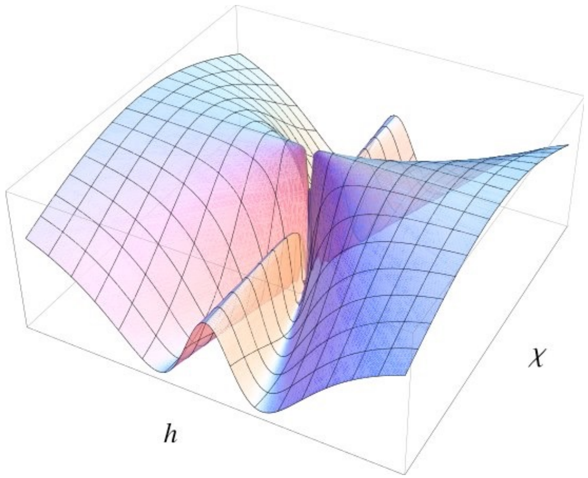
Einstein-frame formulation

$$\frac{\tilde{\mathcal{L}}}{\sqrt{-\tilde{g}}} = \frac{M_P^2}{2}\tilde{R} - \frac{1}{2}\gamma_{ab}(\Omega)\tilde{g}^{\mu\nu}\partial_\mu\varphi^a\partial_\nu\varphi^b - V(\varphi)$$

Asymptotically flat

Vacuum is infinitely degenerate

Physics independent of dilaton value

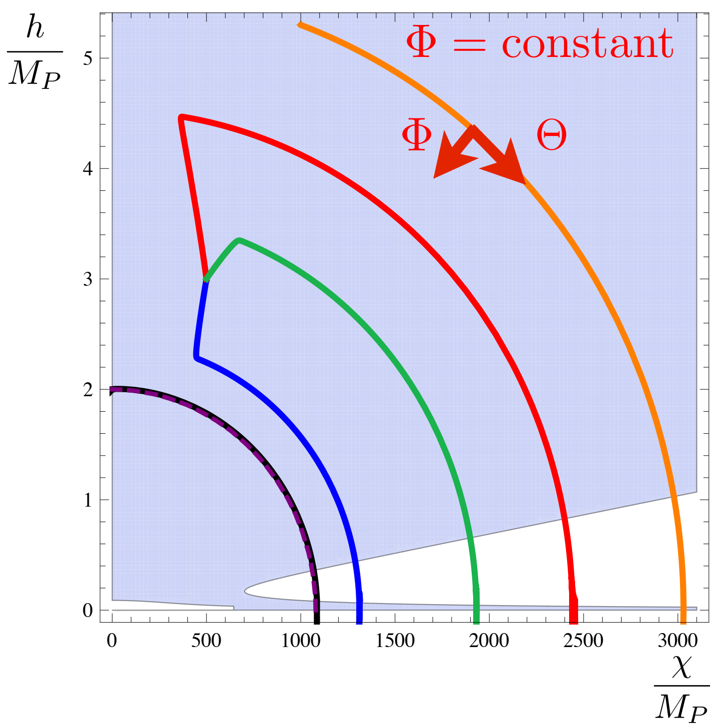


$$\gamma_{ab}(\Omega) = \frac{1}{\Omega^2}\left(\delta_{ab} + y \times \frac{3}{2}M_{\mathrm{P}}^2\frac{\partial_a\Omega^2\partial_b\Omega^2}{\Omega^2}\right)$$

$$R_{\gamma_{ab}} \neq 0 \quad \text{unless} \quad \xi_h \neq \xi_\chi$$

Isocurvature fluctuations
and
non-gaussianities?

Inertial symmetry breaking



$$D_\mu J^\mu = 0 \longrightarrow \Box\Phi^2 = 0$$

Independent of slow-roll

Insensitive to IR form of the potential

Easily applicable to other scenarios

$$\exp\left[\frac{2\gamma\Phi}{M_{\rm P}}\right] \equiv \frac{\kappa_c}{\kappa}\frac{(1+6\,y\,\xi_h)h^2+(1+6\,y\,\xi_\chi)\chi^2}{M_{\rm P}^2} \qquad \gamma^{-2}\Theta \equiv \frac{(1+6\,y\,\xi_h)h^2+(1+6\,y\,\xi_\chi)\chi^2}{\xi_h h^2+\xi_\chi\chi^2}$$

$$\kappa_c \equiv -\frac{\xi_h}{1+6y\xi_h} \qquad \kappa \equiv \kappa_c\left(1-\frac{\xi_\chi}{\xi_h}\right) \qquad \gamma \equiv \sqrt{\frac{\xi_\chi}{1+6y\xi_\chi}}$$

The pole structure

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_P^2}{2}R - \frac{K(\Theta)}{2}(\partial\Theta)^2 - \frac{\Theta}{2}(\partial\Phi)^2 - U$$

No 5th force

$$K(\Theta) = -\frac{M_P^2}{4\,\Theta}\left(\frac{1}{\kappa\Theta + c} + \frac{a}{1-\Theta}\right) \qquad U(\Theta) = U_0(1-\Theta)^2$$

$c \sim \xi_\chi$ — Minkowski pole — Single field

$$\Theta > 0 \qquad \kappa\Theta + c < 0$$

A geometrical interpretation

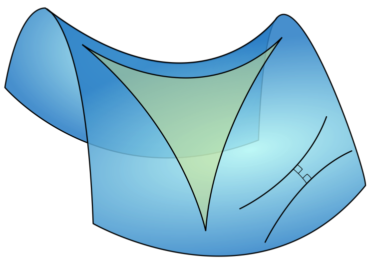
κ is the Gaussian curvature (in units of M_P) of the manifold spanned by $\varphi_1 = \Theta$ and $\varphi_2 = \Phi$

$$\frac{\mathcal{L}}{\sqrt{g}} = \frac{M_P^2}{2} R - \frac{1}{2} \gamma_{ab}(\varphi_1) g^{\mu\nu} \partial_\mu \varphi^a \partial_\nu \varphi^b - V(\varphi_1)$$

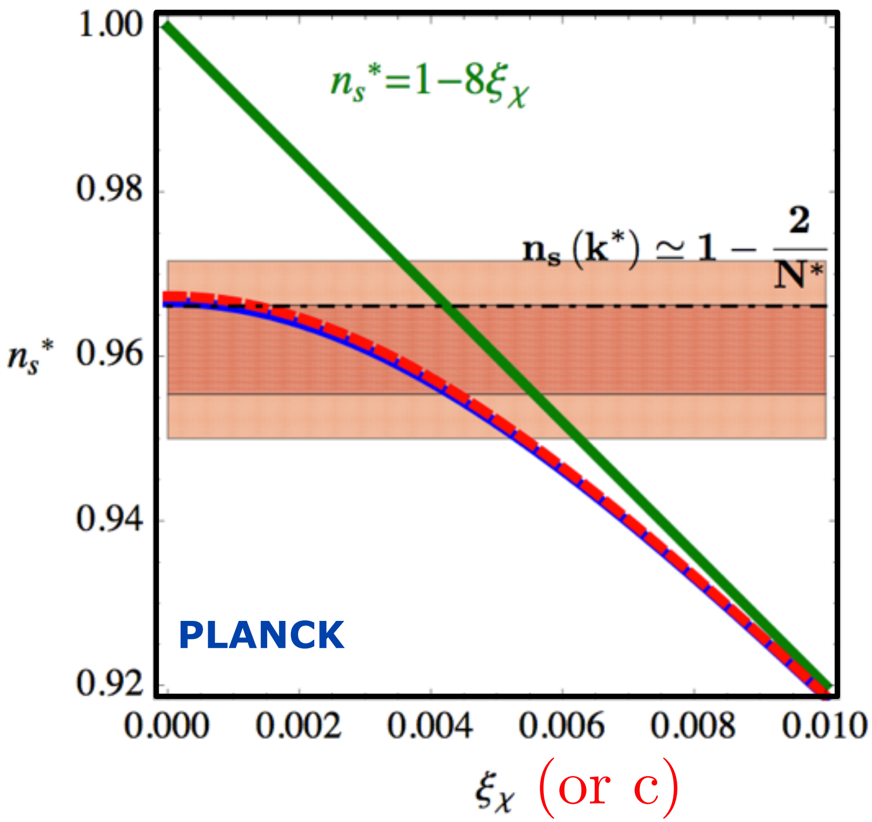
For large field values, the field space of the Higgs-Dilaton model is

MAXIMALLY SYMMETRIC

$$\kappa \equiv \kappa_c \left(1 - \frac{\xi_\chi}{\xi_h}\right)$$



Inflationary observables



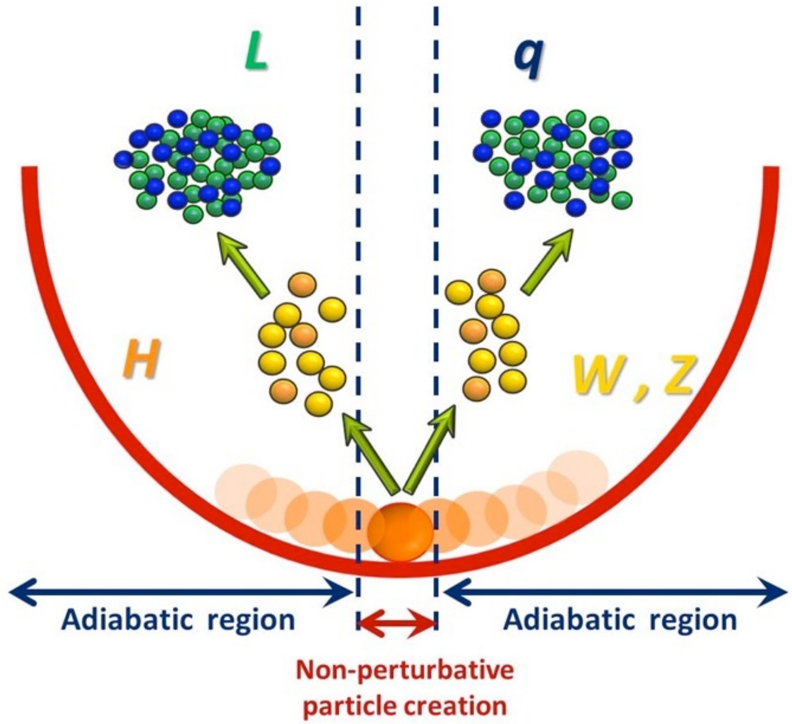
$$A_s = \frac{\lambda \sinh^2(4cN_*)}{1152\pi^2 \xi_h^2 \, c^2}$$

$$n_s = 1 - 8\,c\coth(4cN_*)$$

$$r = \frac{32\,c^2}{|\kappa_c|}\sinh^{-2}(4cN_*)$$

No free parameters left

Onset of hot big bang



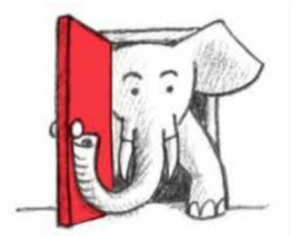
$$\color{red}{\Delta N_{\rm eff}} \equiv \frac{g_0}{g_\nu}\left(\frac{g_f}{g_0}\right)^{4/3} \color{red}{C} \approx 2.85\ \color{red}{C} \qquad \text{with} \qquad \color{red}{C} \equiv \frac{\rho_D}{\rho_{SM}} \ll 1$$

No extra relativistic degrees of freedom

A bunch of nice properties

1. 2-field but single field dynamics
2. Maximally symmetric E-frame kin. sector
3. No isocurvature perturbations
4. Excellent agreement with observations
5. No fifth-force effects
6. Massless field without massless d.o.f.

Late-time acceleration ?



SI and Unimodular gravity

General Relativity

CC at the level of the action

$$S = \int d^4x \left(\mathcal{L}\left(g_{\mu\nu}, \partial g_{\mu\nu}, \Phi, \partial\Phi\right) + \Lambda_0\right)$$

Unrestricted metric determinant

$$|g|$$

Unimodular Gravity

No CC at the level of the action

$$S = \int d^4x \mathcal{L}\left(g_{\mu\nu}, \partial g_{\mu\nu}, \Phi, \partial\Phi\right)$$

Restricted metric determinant

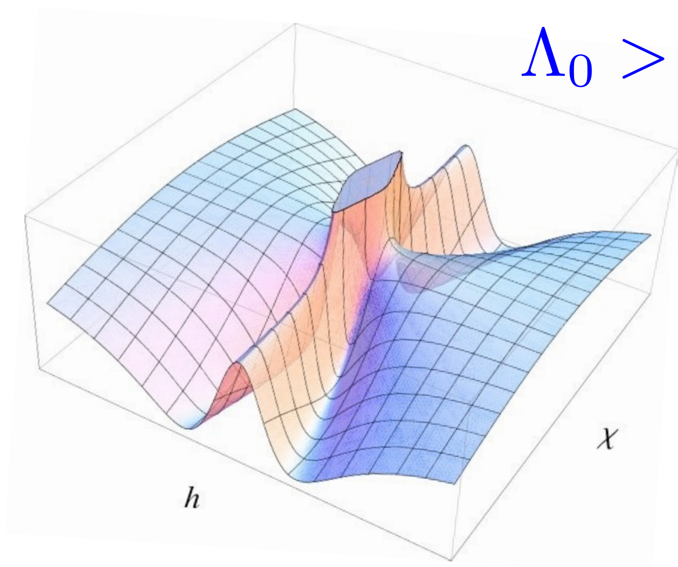
$$|g| = 1 \qquad \partial_\mu \lambda(x) = 0$$

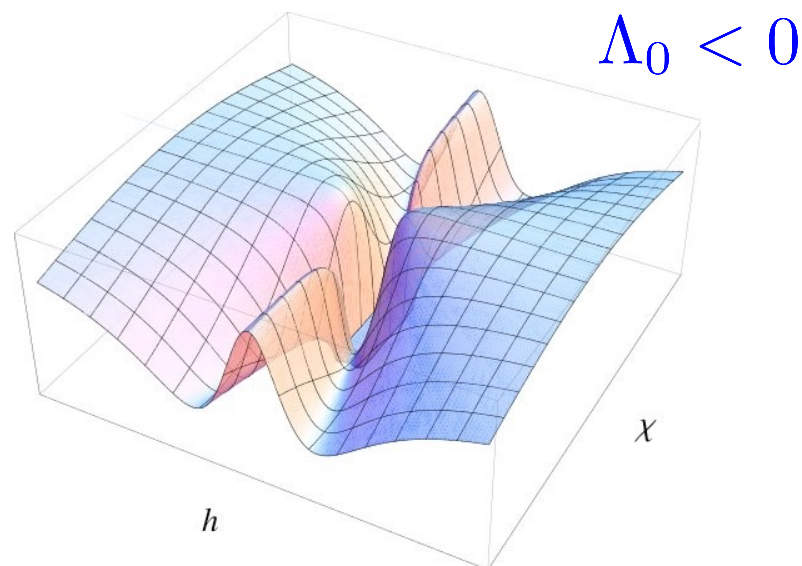
The Cosmological Constant reappears ...

... with a very different interpretation: the strength of a potential

$$U_\Lambda(\Phi) = \frac{\Lambda_0}{c^2} e^{-\frac{4\gamma\Phi}{M_P}}$$

Back to the 80's!
C. Wetterich 1988





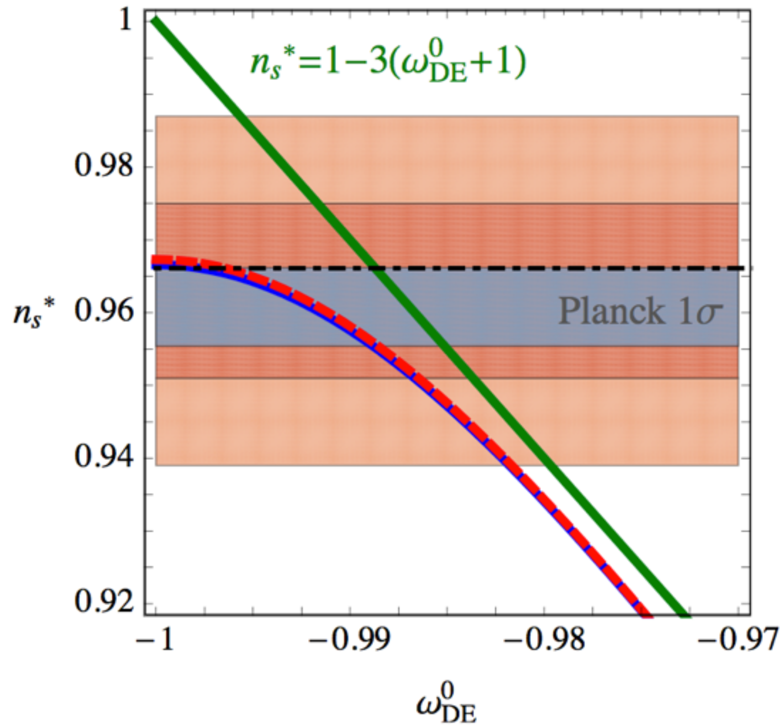
All the new parameters determined by inflation

Consistency relations

$$n_s = 1 - \frac{2}{N_*} X \coth X$$

$$r = \frac{2}{|\kappa_c| N_*^2} X^2 \sinh^{-2} X$$

$$X \equiv 4cN_* = \frac{3N_*(1+w)}{4F(\Omega_{\rm DE})}$$



with

$$F(\Omega_{\rm DE}) = \left[\frac{1}{\sqrt{\Omega_{\rm DE}}} - \Delta \tanh^{-1}\sqrt{\Omega_{\rm DE}}\right]^2 \qquad \Delta \equiv \frac{1-\Omega_{\rm DE}}{\Omega_{\rm DE}}$$

Present data constraints

MCMC analysis

Planck TT+pol, Keck/BICEP2, JLA,

6dF, SDSS, BOSS.

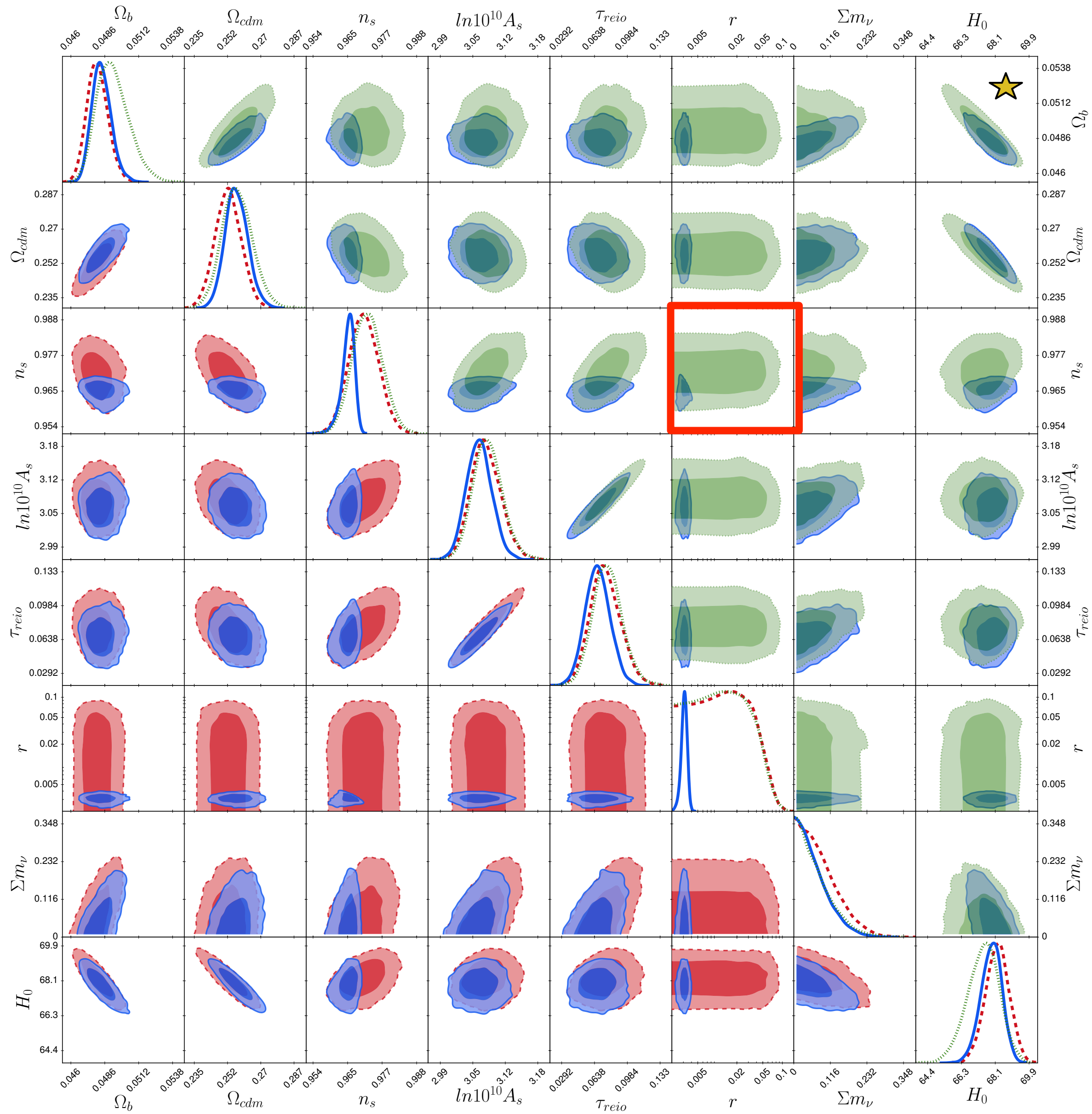
ΛCDM

wCDM

HD

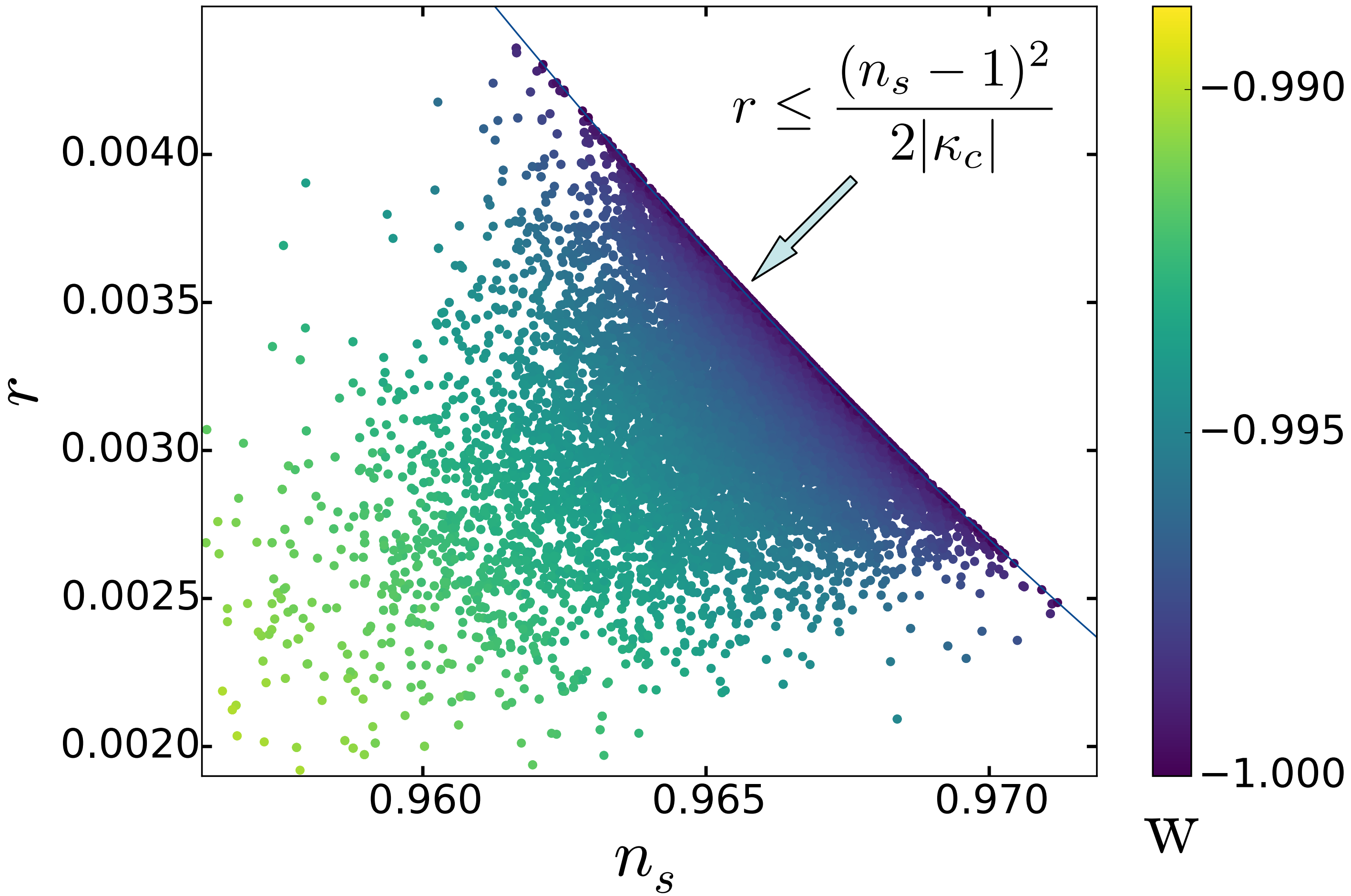
$$B(M) = \frac{p(\mathbf{x}|M)}{p(\mathbf{x}|M_{\Lambda\mathrm{CDM}})}$$

Model	ΛCDM	HD	wCDM
$\ln B$	0.00	0.88	−2.63



S. Casas, M. Pauly, JR, Phys.Rev. D97 (2018) 043520

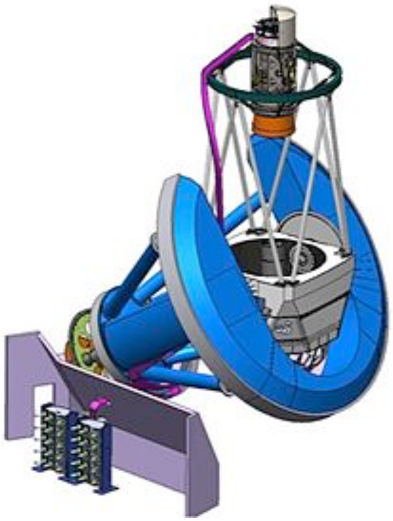
Consistency relations



$$n_s = 1 - \frac{2}{N_*} X \coth X \qquad r = \frac{2}{|\kappa_c| N_*^2} X^2 \sinh^{-2} X \qquad X \equiv 4cN_* = \frac{3N_*(1+w)}{4F(\Omega_{\rm DE})}$$

Future surveys

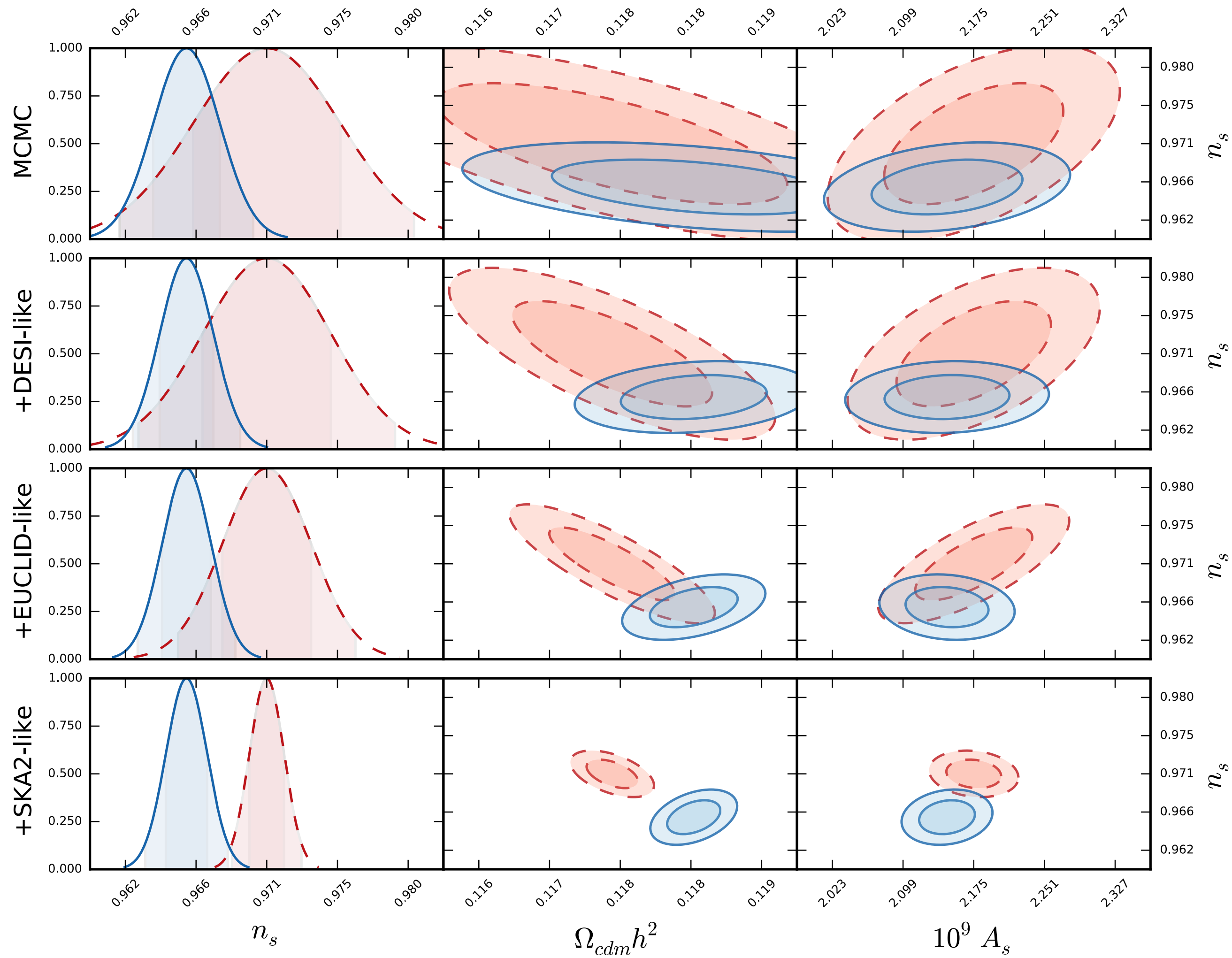
✴ Dark Energy Spectroscopic Instrument (DESI)
ground-based experiment (Arizona)
30 million spectroscopic redshifts
2018



✴ Euclid
satellite
100 million spectroscopic redshifts
2019 –-> 2020 —> 2021—> ?

✴ Square Kilometer Array (SKA1 and SKA2)
array of radio telescopes (S. Africa & Australia)
1000 million spectroscopic redshifts
2030

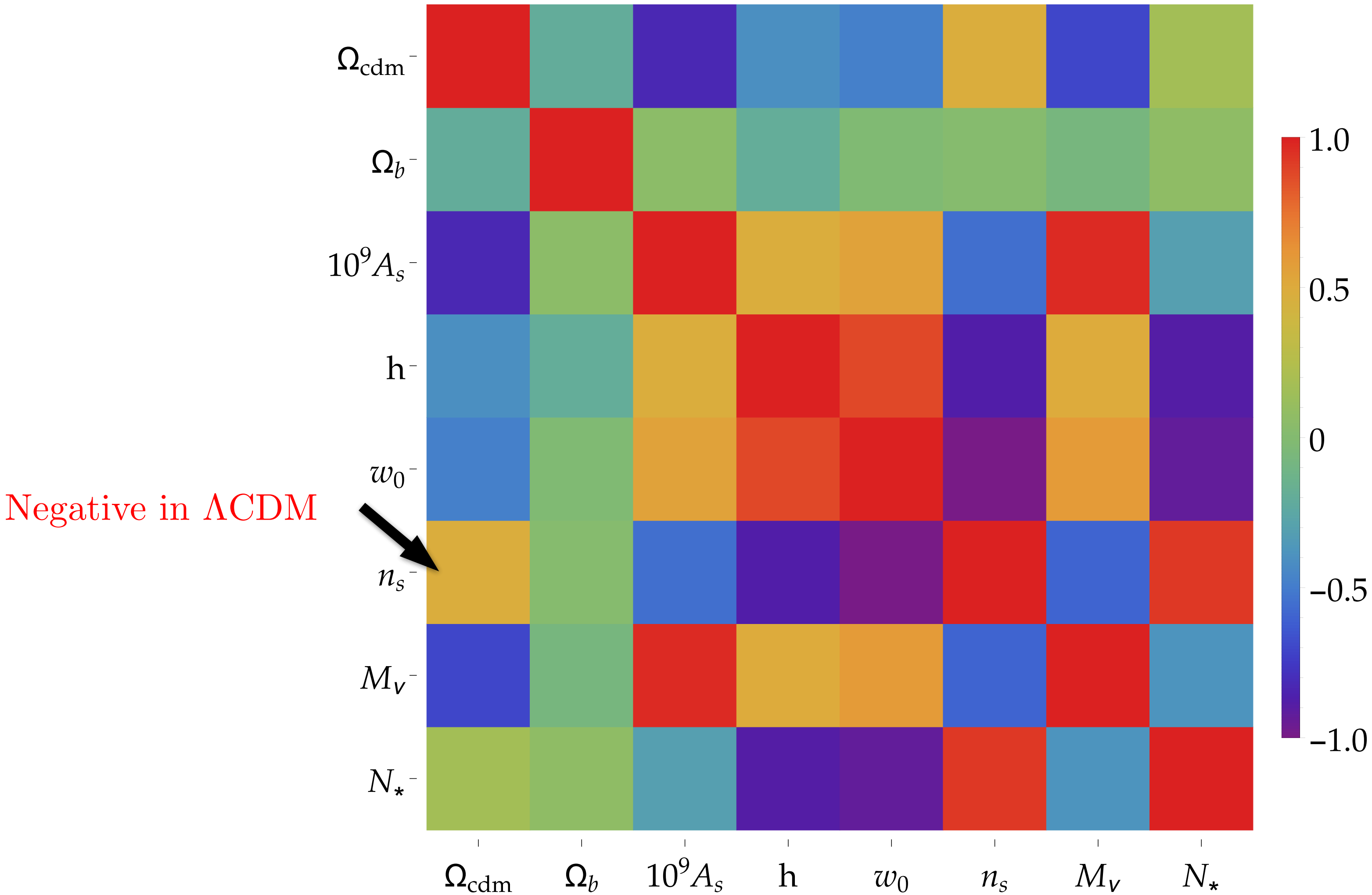
Fisher forecast



Models centered on the fiducial values obtained from its own MCMC run
Rotated ellipses indicate changes in correlations

S. Casas, M. Pauly, JR, Phys.Rev. D97 (2018) 043520

Correlation matrices



This breaks degeneracies in param.space/ helps to constrain other

S. Casas, M. Pauly, JR, Phys.Rev. D97 (2018) 043520

GENERALIZATIONS

Dilaton as part of the metric

TDiff: minimal gauge group including spin-2 polarizations

$$x^\mu \mapsto \tilde{x}^\mu(x), \text{ with } J \equiv \left|\frac{\partial \tilde{x}^\mu}{\partial x^\nu}\right| = 1 \qquad \textit{with} \qquad \begin{array}{c} \delta x^\mu = \xi^\mu \\ \partial_\mu \xi^\mu = 0 \end{array}$$

TDiff action contains arbitrary functions of g

$$\frac{\mathcal{L}_{\text{TDiff}}}{\sqrt{g}} = \frac{\rho^2 f(g)}{2} R - \frac{1}{2}\rho^2 G_{gg}(g)(\partial g)^2 - \frac{1}{2} G_{\rho\rho}(g)(\partial\rho)^2 - G_{\rho g}(g)\rho\, \partial g \cdot \partial\rho - \rho^4 v(g)$$

invariant under $\quad g_{\mu\nu}(x) \to g_{\mu\nu}(\lambda x) \qquad \rho(x) \mapsto \lambda \rho(\lambda x)$

TDiff as Diff

TDiff action describes 3 propagating degrees of freedom

A equivalent Diff version can be obtained using the Stückelberg trick

$$a = J^{-2} \qquad \theta = g/a$$

J-frame

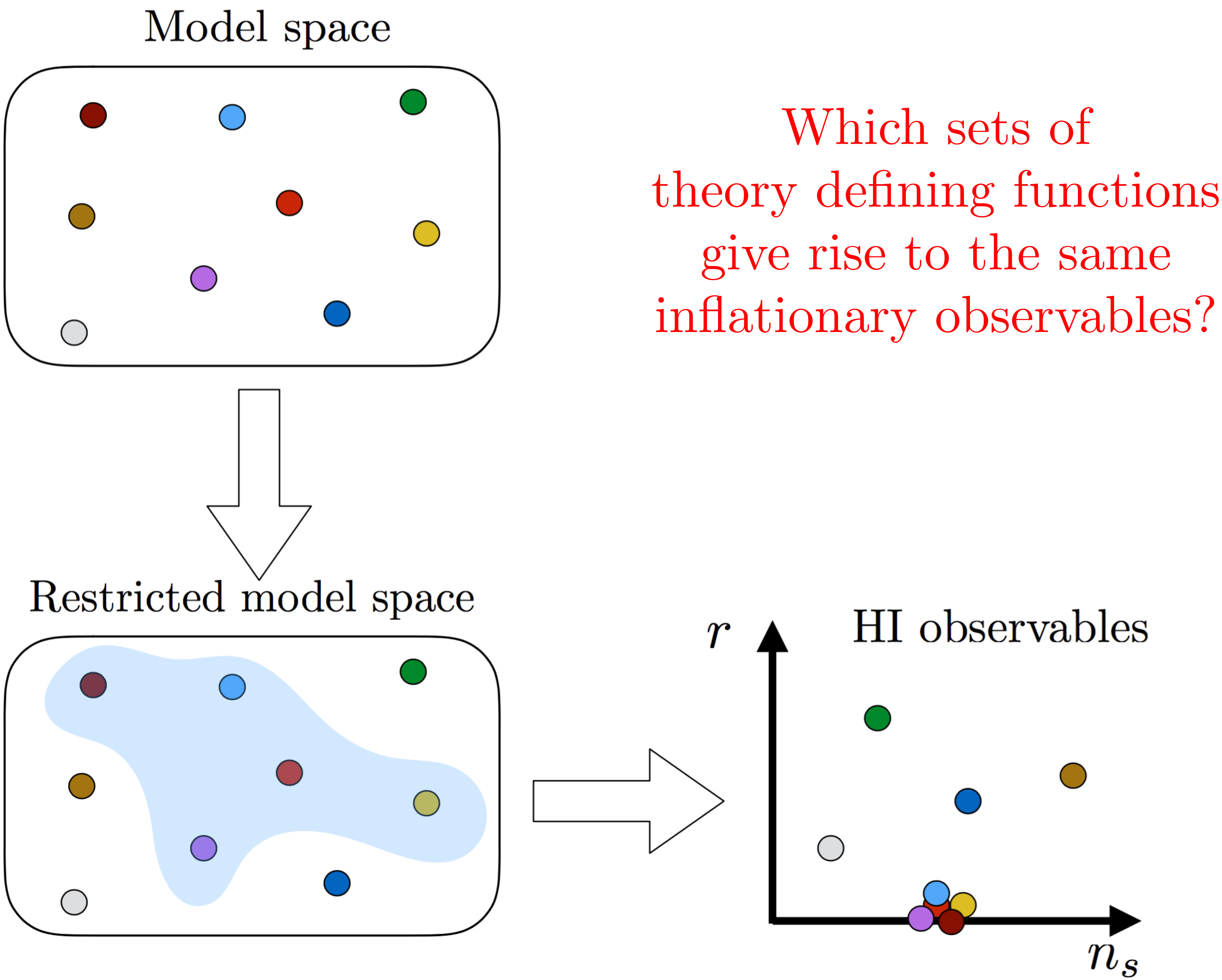
$$\frac{\mathcal{L}_{\mathrm{Diff}}}{\sqrt{g}} = \frac{\rho^2 f(\theta)}{2} R - \frac{1}{2}\rho^2 G_{gg}(\theta)(\partial\theta)^2 - \frac{1}{2} G_{\rho\rho}(\theta)(\partial\rho)^2 - G_{\rho g}(\theta)\rho\,\partial\theta\cdot\partial\rho - \rho^4 v(\theta)$$

invariant under $g_{\mu\nu}(x) \to g_{\mu\nu}(\lambda x)$ $\quad \rho(x) \mapsto \lambda\rho(\lambda x)$ $\quad \theta(x) \mapsto \theta(\lambda x)$

Goldstone

E-frame

$$\frac{\mathcal{L}}{\sqrt{g}} = \frac{M_P^2}{2} R - \frac{M_P^2}{2}\left[K_{\theta\theta}(\theta)(\partial\theta)^2 + 2K_{\theta\rho}(\theta)(\partial\theta)(\partial\log\rho/M_P) + K_{\rho\rho}(Z)(\partial\log\rho/M_P)^2\right] - V(\theta)$$

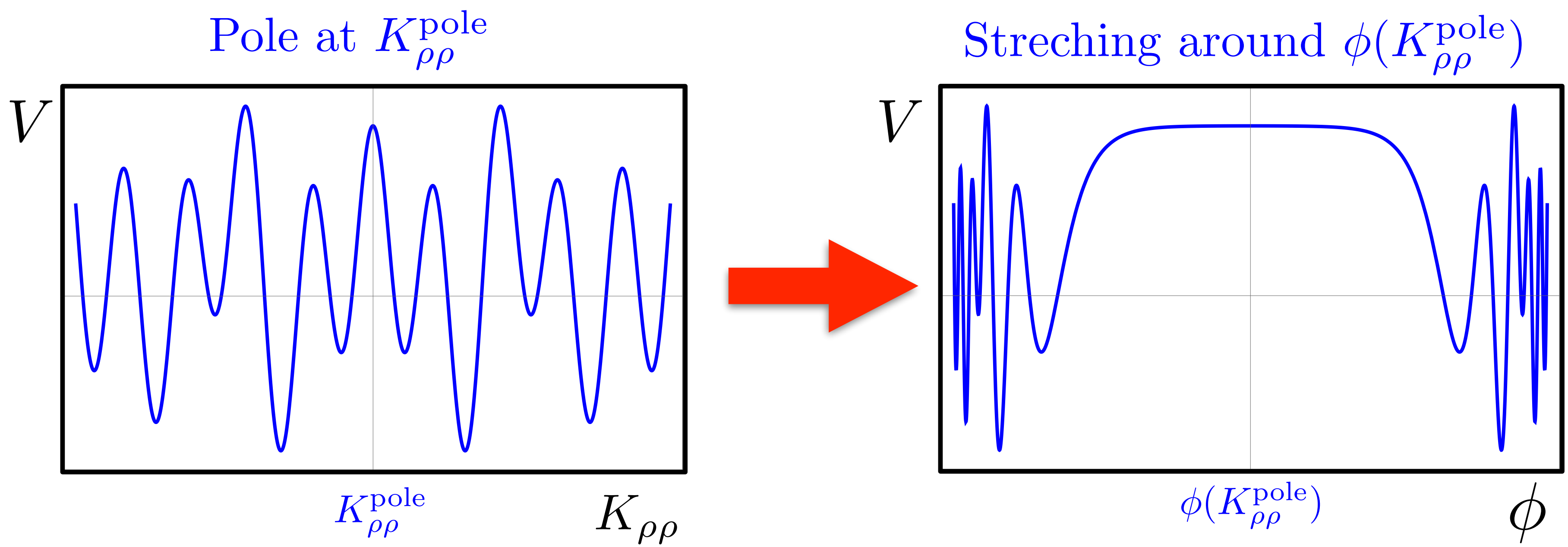

Model space
Which sets of theory defining functions give rise to the same inflationary observables?
Restricted model space
HI observables
r
n_s

Canonical field stretching

$$\frac{\mathcal{L}}{\sqrt{g}} = \frac{M_P^2}{2} R - \frac{M_P^2}{2}\left[-\frac{(\partial K_{\rho\rho})^2}{4\,K_{\rho\rho}(\kappa_0 K_{\rho\rho} + c)} + K_{\rho\rho}(\partial\rho)^2 \right] - V(K_{\rho\rho})$$

Canonically normalized field

$$\phi = \int \frac{dK_{\rho\rho}}{\sqrt{4\;K_{\rho\rho}(|\kappa_0| K_{\rho\rho} - c)}}$$



The pole structure

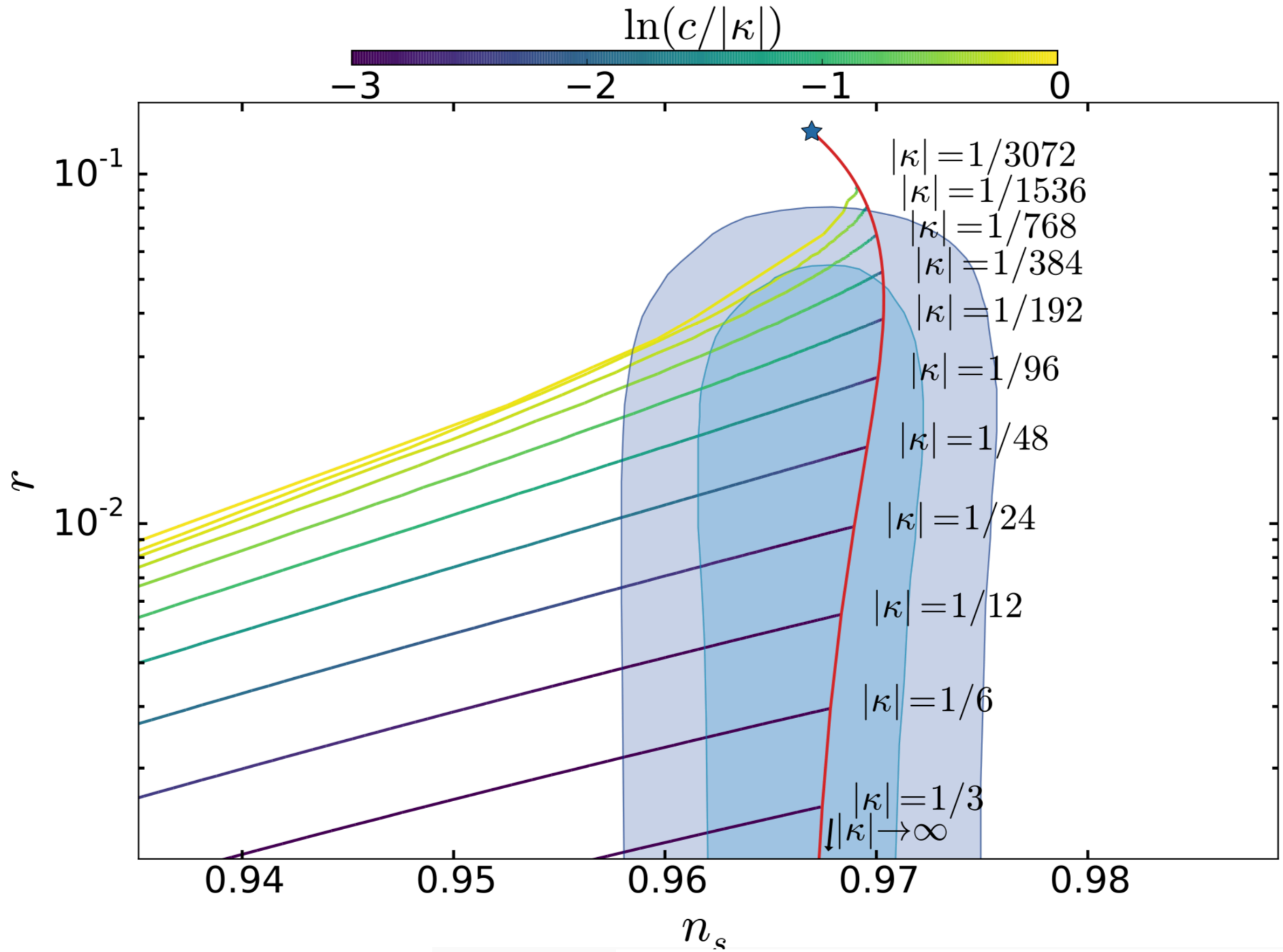
$$\frac{\mathcal{L}}{\sqrt{g}} = \frac{M_P^2}{2} R - \frac{M_P^2}{2} \left[-\frac{(\partial K_{\rho\rho})^2}{4\,K_{\rho\rho}(\kappa_0 K_{\rho\rho} + c)} + K_{\rho\rho}(\partial\rho)^2 \right] - V(K_{\rho\rho})$$

$\lvert c\rvert \to 0$ $K_{\rho\rho} \to \lvert c/\kappa_0\rvert \to 0$	Quadratic pole Asymptotic flatness $K_{\rho\rho} = e^{-2\sqrt{\lvert\kappa_0\rvert}\frac{\phi}{M_P}}$
$\lvert c\rvert \neq 0$ $K_{\rho\rho} = 0$ unreachable	Linear pole Restricted flatness $K_{\rho\rho} = \frac{c}{-\kappa_0}\cosh^2\left(\frac{\sqrt{-\kappa_0}\phi}{M_P}\right)$ $\frac{M_P}{\sqrt{-\kappa_0}}$ non-compact analog of axion decay constant

Inflationary observables

$$\frac{\mathcal{L}}{\sqrt{g}} = \frac{M_P^2}{2} R - \frac{M_P^2}{2} \left[- \frac{(\partial K_{\rho\rho})^2}{4\, K_{\rho\rho}(\kappa_0 K_{\rho\rho} + c)} + K_{\rho\rho}(\partial \rho)^2 \right] - V(K_{\rho\rho})$$

$\lvert c\rvert \to 0$ $K_{\rho\rho} \to \lvert c/\kappa_0\rvert \to 0$	Quadratic pole $n_s \simeq 1 - \frac{2}{N}$ $\qquad r \simeq \frac{2}{\lvert\kappa_0\rvert N^2}$
$\lvert c\rvert \neq 0$ $K_{\rho\rho} = 0$ unreachable	Linear pole $\mathcal{O}\left(c^2/\kappa_0\right)$ $n_s \approx 1 - 4\lvert c\rvert$ $\qquad r \approx 32\lvert c\rvert^2\, e^{-4\,\lvert c\rvert\, N}$

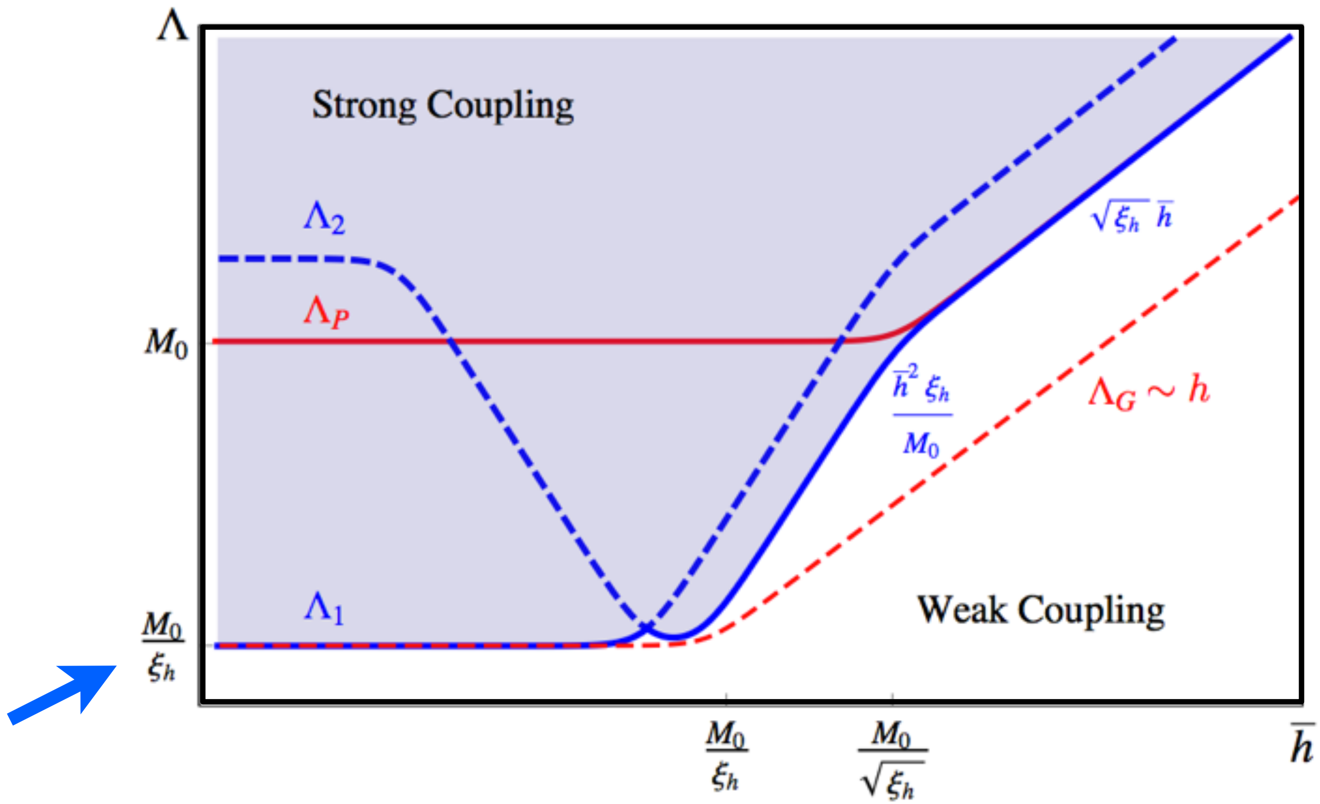


$$r = \frac{128\,|\kappa|}{(1+\mathcal{W}_{-1})^2} \,,\qquad n_s = 1 - 16|\kappa|\frac{1-\mathcal{W}_{-1}}{(1+\mathcal{W}_{-1})^2}$$

OPEN ISSUES

We deal with an EFT

$$\frac{1}{\Lambda_1(h,\chi)}(\delta\hat{h})^2\Box\delta\hat{g} \quad , \quad \frac{1}{\Lambda_2(h,\chi)}(\delta\hat{\chi})^2\Box\delta\hat{g} \quad , \quad \frac{1}{\Lambda_3(h,\chi)}(\delta\hat{h})(\delta\hat{\chi})\Box\delta\hat{g} \quad , \text{ etc ...}$$



Cutoffs are parametrically larger than all the energy scales involved in the history of the Universe

Beyond EFT?

1. Self-healing mechanism? Borel summation?
2. Introducing new degrees of freedom?
    - additional scalar fields?
    - higher order curvature corrections?
3. Asymptotic safety?

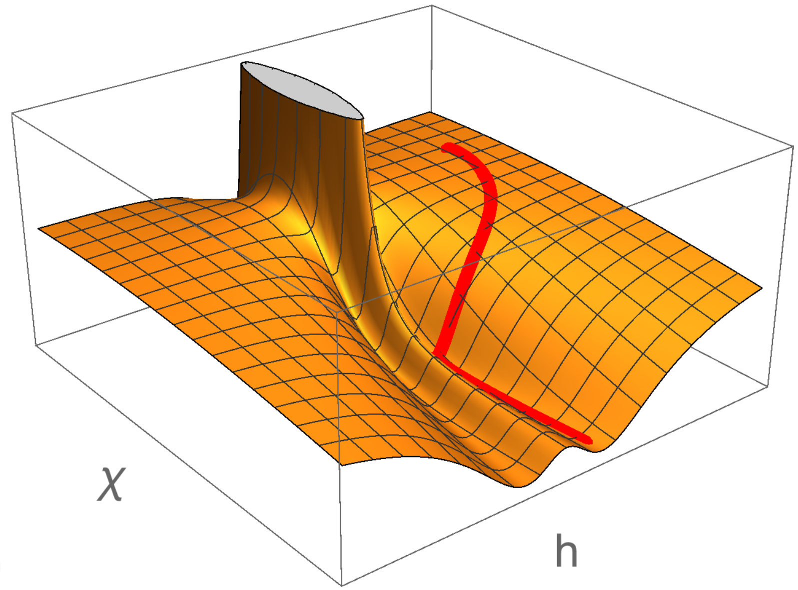
Conclusions

Higgs-Dilaton Cosmology: A SI + UG EFT extension of the SM

✓ Inflation with a graceful exit

✓ Dark energy without CC

✓ Appealing:



- No fifth forces
- No non-gaussianities
- No isocurvature perturbations.
- No extra relativistic degrees of freedom at BBN.
- Non-trivial relations between inflationary and DE observables

✓ Massless dilaton: unique source for masses / scales.

✓ Natural embedding in a TDiff framework: dilaton as a metric d.o.f