Scale invariance: connecting inflation & dark energy

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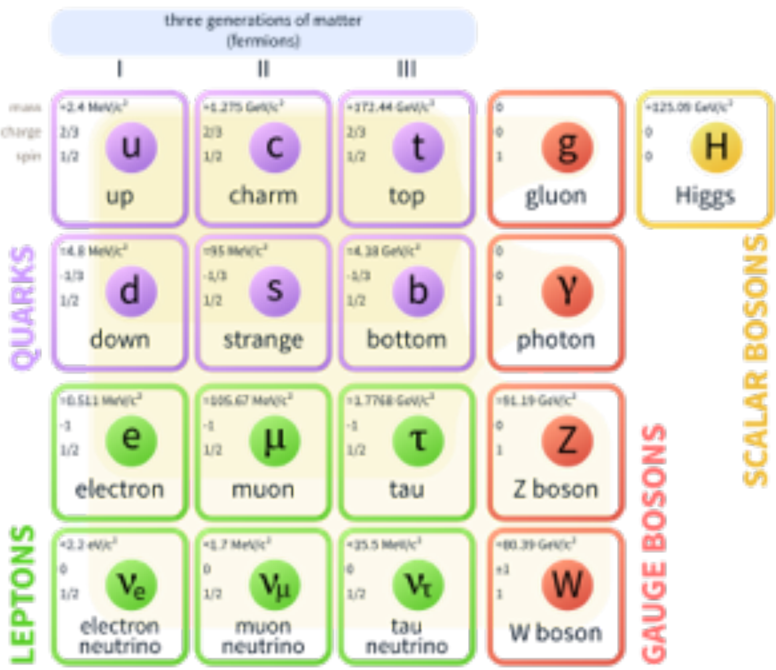
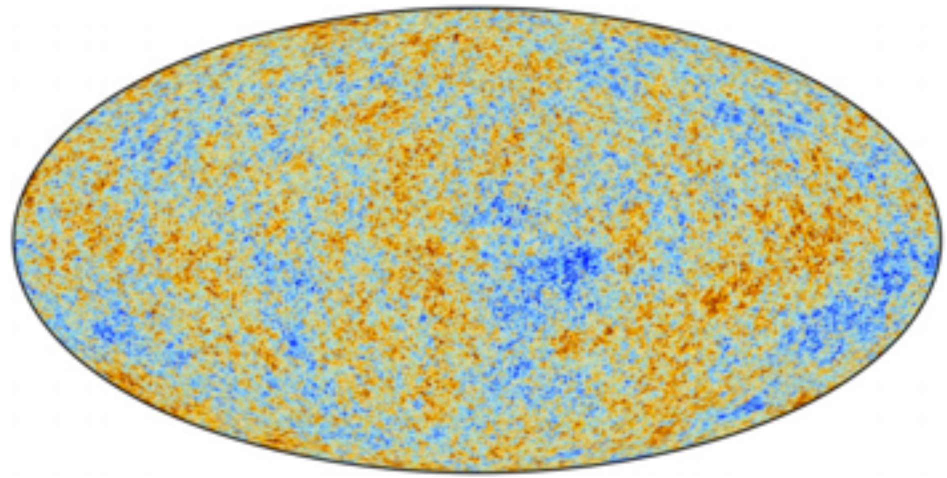
“SMs” are nicely compatible with Nature





Our overall conclusion is that the *Planck* data are remarkably consistent with the predictions of the base ΛCDM cosmology.

... and they want to remain

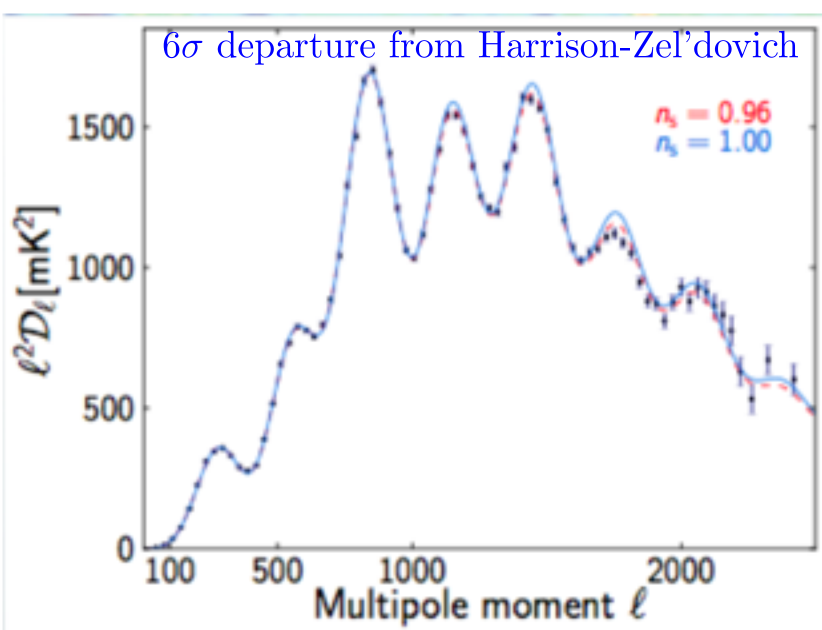
“SIMPLE”

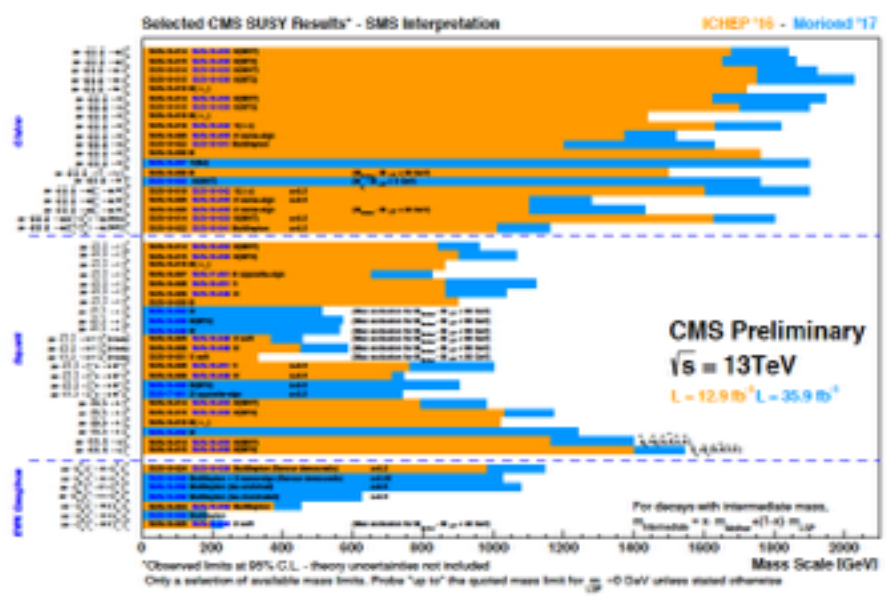
PLANCK

- "Single field SR inflation has survived its most stringent
- "Small isocurvature contribution"
- "No evidence for primordial NG"
- "No evidence for additional relativistic particles"

LHC

- "Clear evidence for a neutral boson with a mass of 126 GeV"
  6 years ago already !
- "Extensive search without any significant deviations from the SM so far"



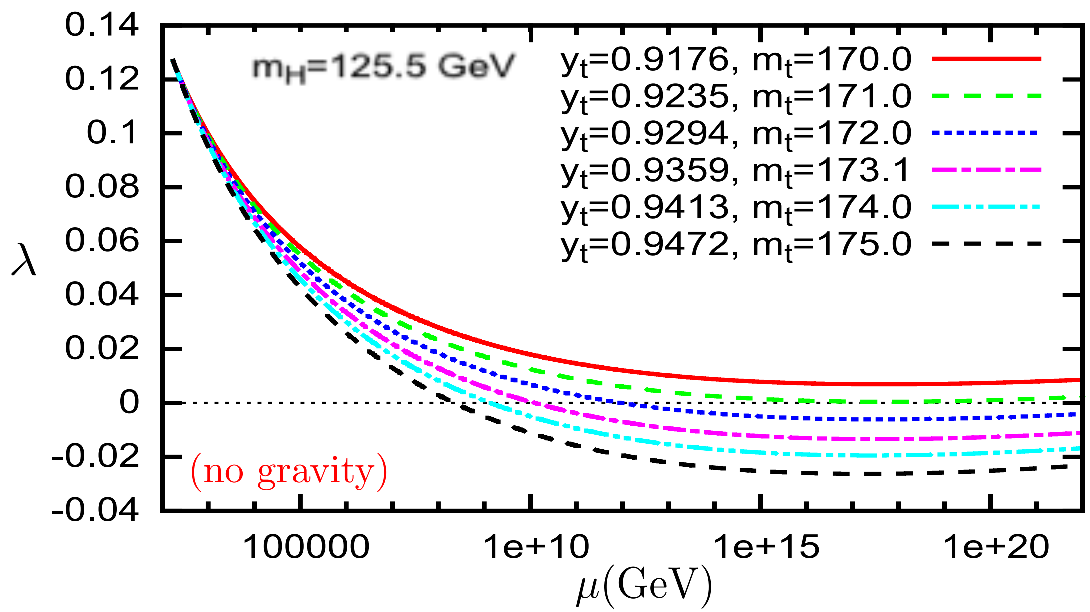


On the edge of stability

- ***SM remains perturbative all the way up till the inflat./Planck scale***
- ***Does the SM vacuum remains stable till those scales?***

$$\mu \frac{d\lambda(\mu)}{d\log(\mu)} = +\#\lambda^2 + \ldots - \#y_t^4$$

Non trivial interplay between Higgs self-coupling and top quark Yukawa coupling

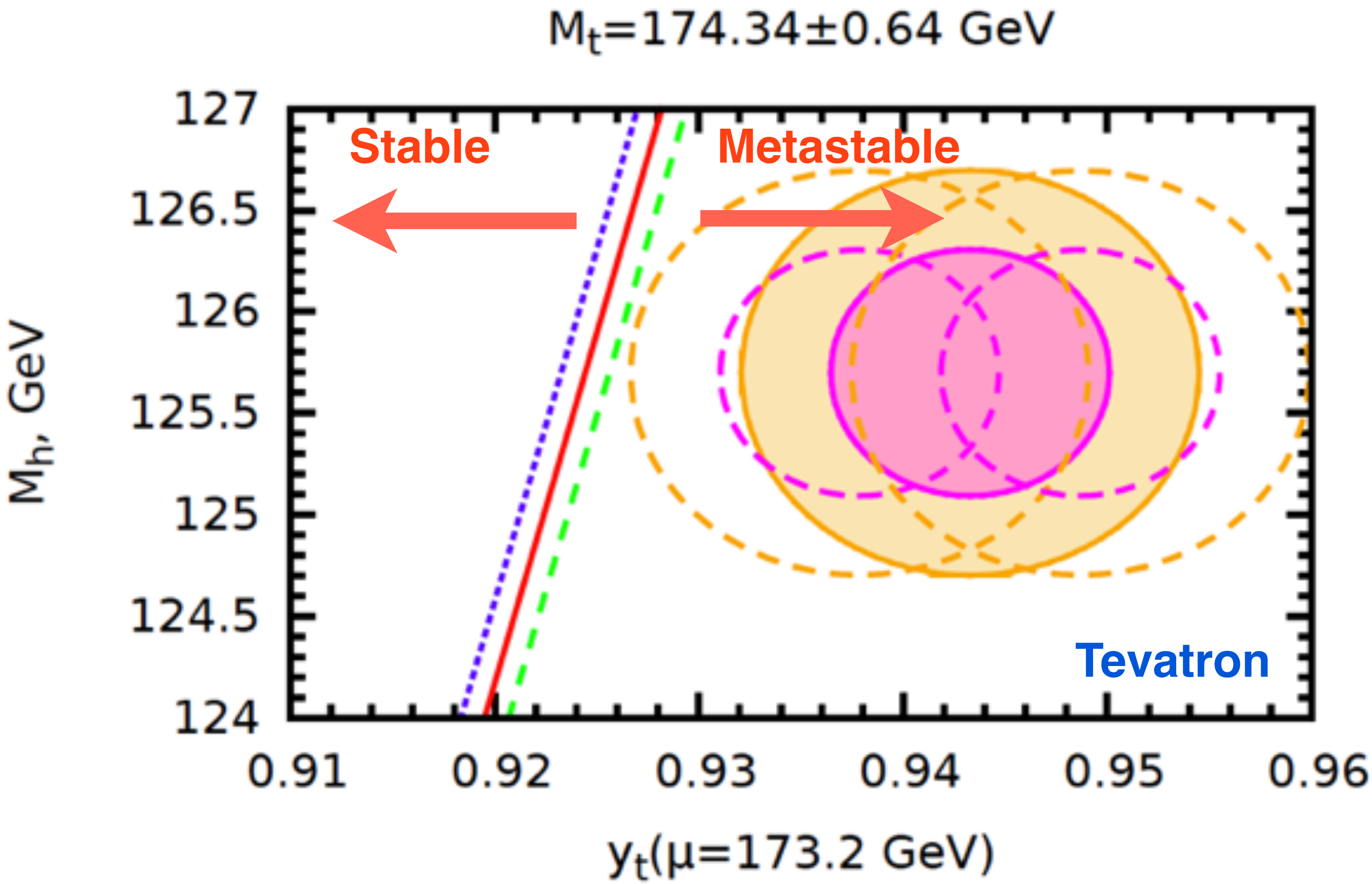


Is there a reason for that? M. Lindner, M. Sher, and H. W. Zaglauer, Phys.Lett., B228, 139 (1989), C. Froggatt and H. B. Nielsen, Phys.Lett., B368,96 (1996), M. Shaposhnikov and C. Wetterich, Phys.Lett., B683, 196 (2010), M. Veltman, Acta Phys.Polon., B12, 437 (1981), B683, 196 (2010), M. Holthausen, K.S.Lim, M.Lindner and references therein....

Gravitational corrections? Lalak,Lewicki, Olszewki arXiv 14.02.3826, Branchina, Massina Phys.Rev.Lett. 111 (2013) 241801 etc...

Top quark & vac. instability

$$y_t^{\rm crit} = 0.9223 + 0.00118\left(\frac{\alpha_s - 0.1184}{0.0007}\right) + 0.00085\left(\frac{M_h - 125.03}{0.3}\right)$$



See F. Bezrukov, M. Shaposhnikov J.Exp.Theor.Phys. 120 (2015) 335-343 and references therein

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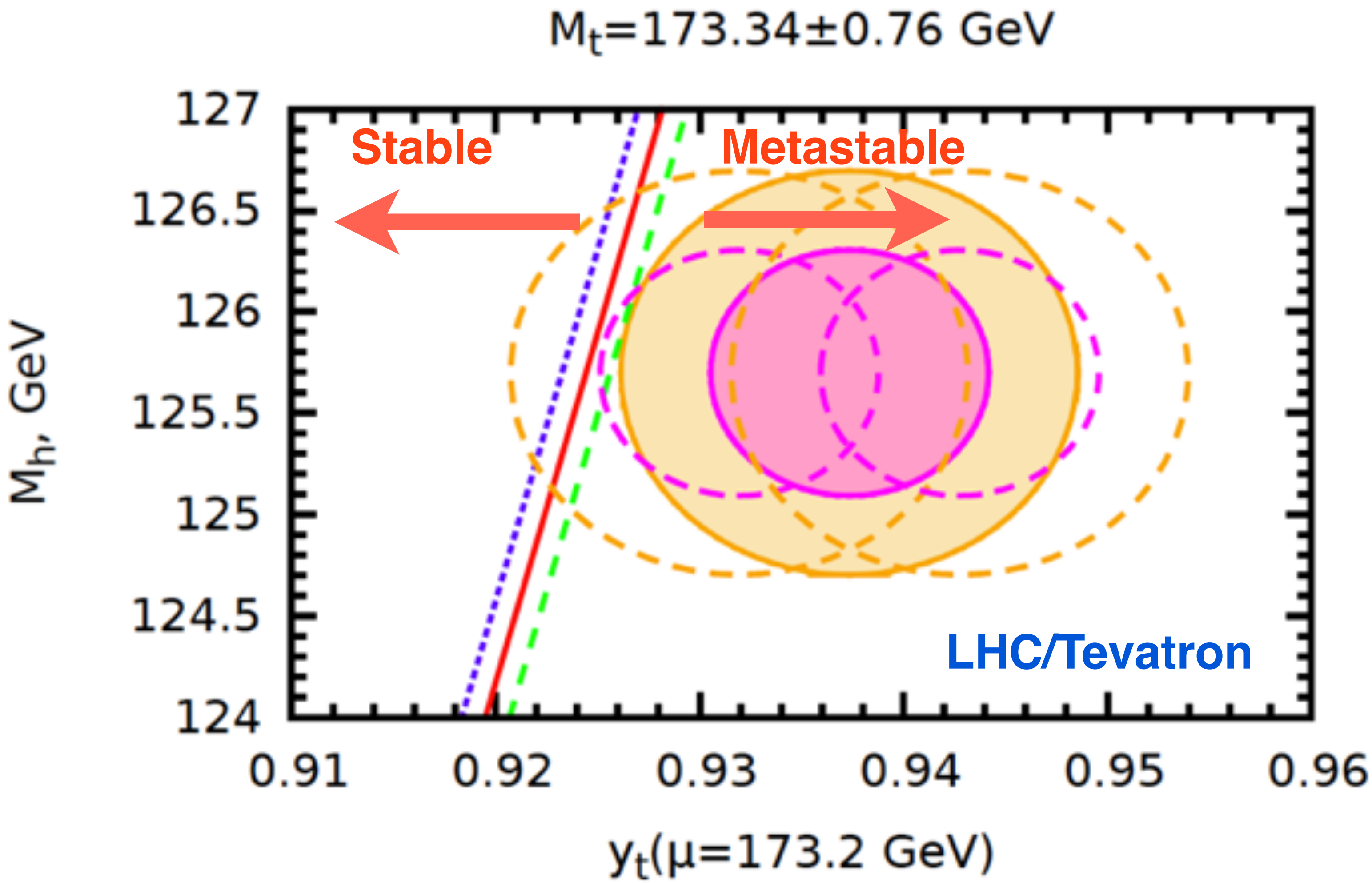

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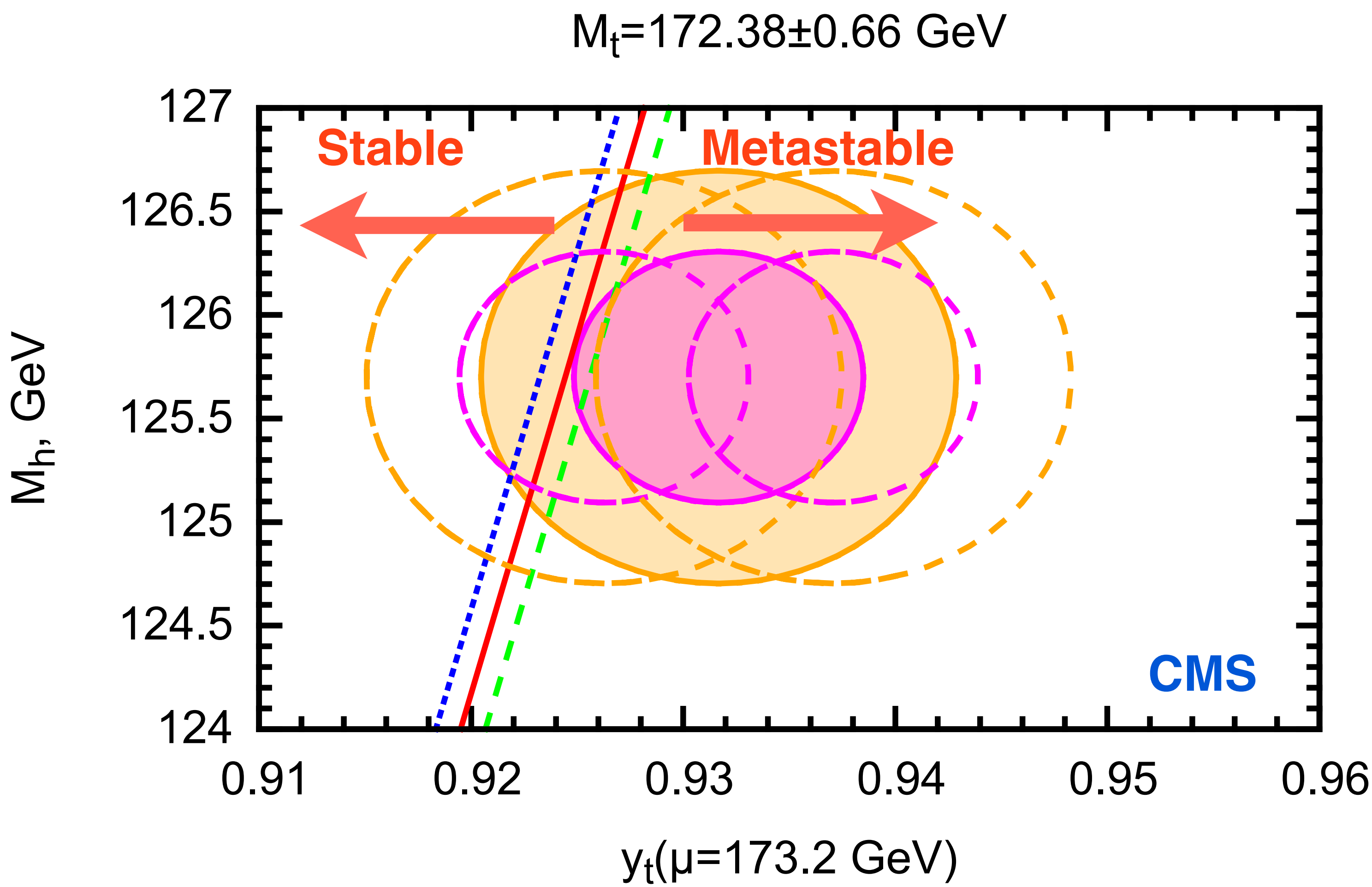
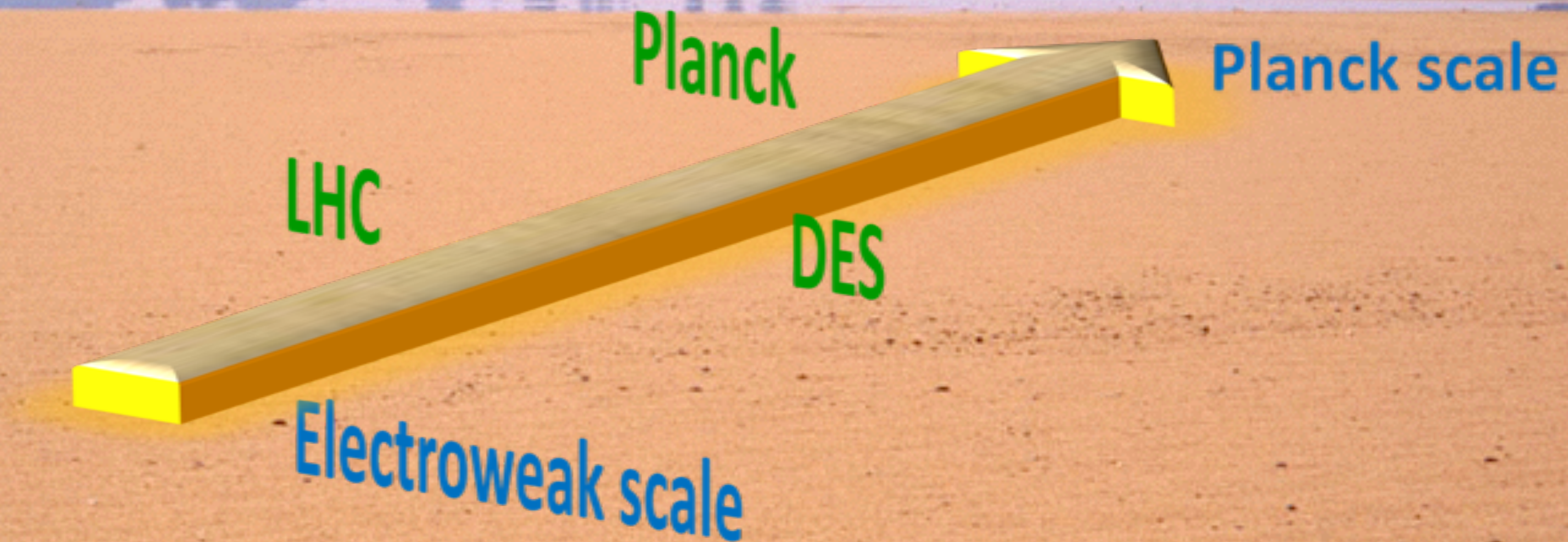


See F. Bezrukov, M. Shaposhnikov J.Exp.Theor.Phys. 120 (2015) 335-343 and references therein

Fantastic BSM Beasts and Where to Find Them

1. Neutrino Oscillations
2. Dark Matter
3. Baryogenesis
4. Inflation
5. Dark energy
6. Naturalness …



The quest for flatness

Inflation/DE: accelerated expansion sourced by:

a negative pressure

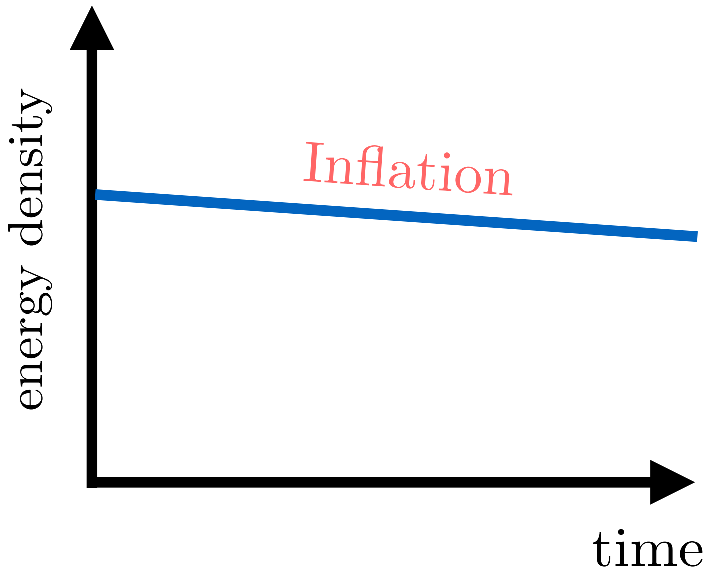
$$\frac{\ddot{a}}{a} = -\frac{\rho}{6}(1+3w) > 0$$

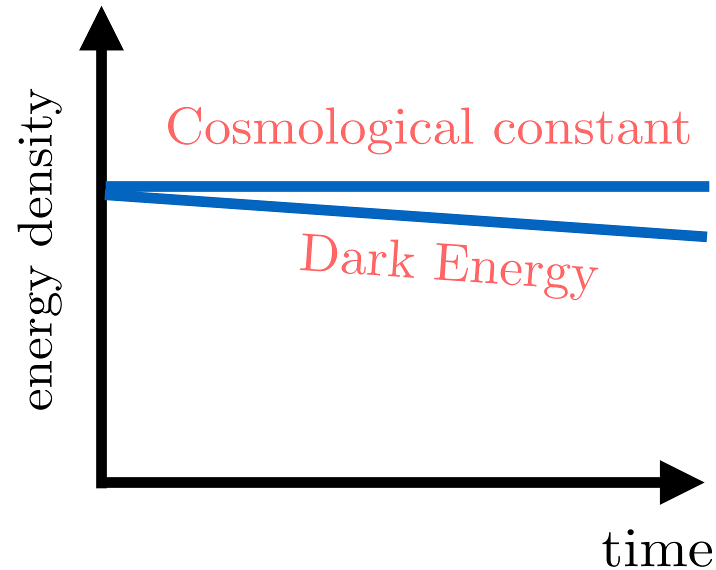
$$w < -\frac{1}{3}$$

and a nearly constant energy density

$$\frac{\ddot{a}}{a} = (H^2 + \dot{H}) > 0$$

$$H = \sqrt{\frac{\rho}{3}} \approx const.$$



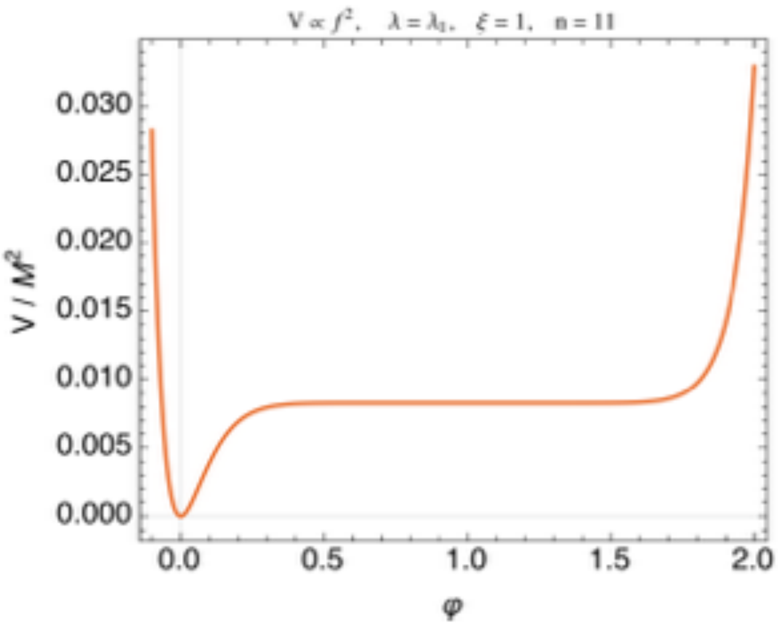


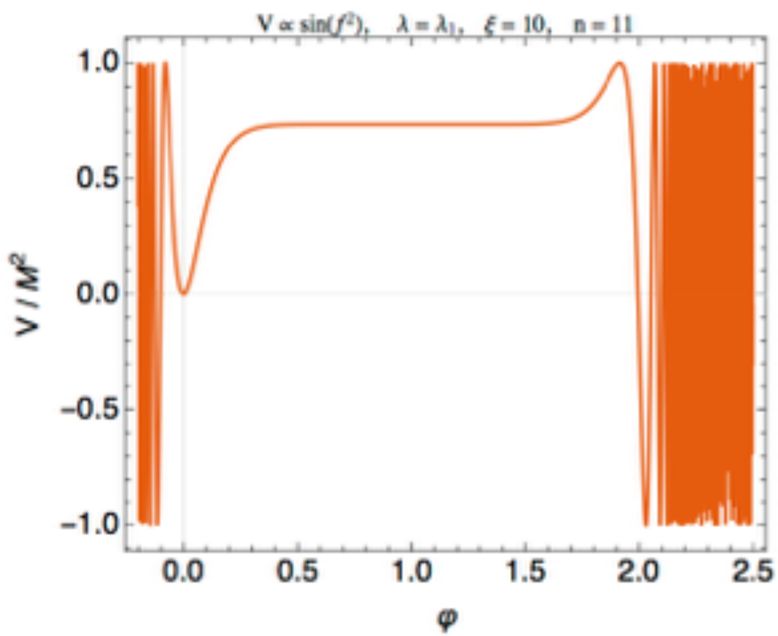
Flatness from stationary points

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{1}{2}R + \frac{1}{2}(\partial\varphi)^2 - V(f(\varphi)) \quad \text{with} \quad f(\varphi) = \xi \sum_{k=1}^{n} \lambda_k\, \varphi^k$$

Stationary point of order m $\quad \dfrac{d^m V}{d\varphi^m} = 0$

$$f(\varphi) = \frac{\xi}{n}(n\,\lambda)^{\frac{-1}{n-1}}\left(1 - \left(1 - (n\,\lambda)^{\frac{1}{n-1}}\,\varphi\right)^n\right) \quad \text{with} \quad \lambda \equiv \lambda_n$$





M. Artymowski, JR, Phys.Lett. B761 (2016) 111-114

Flatness from scale invariance

J-frame

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

with $\xi_h > 0$ and $\lambda > 0$

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

No graceful inflationary exit

Two different perspectives

Classical
but not
Quantum

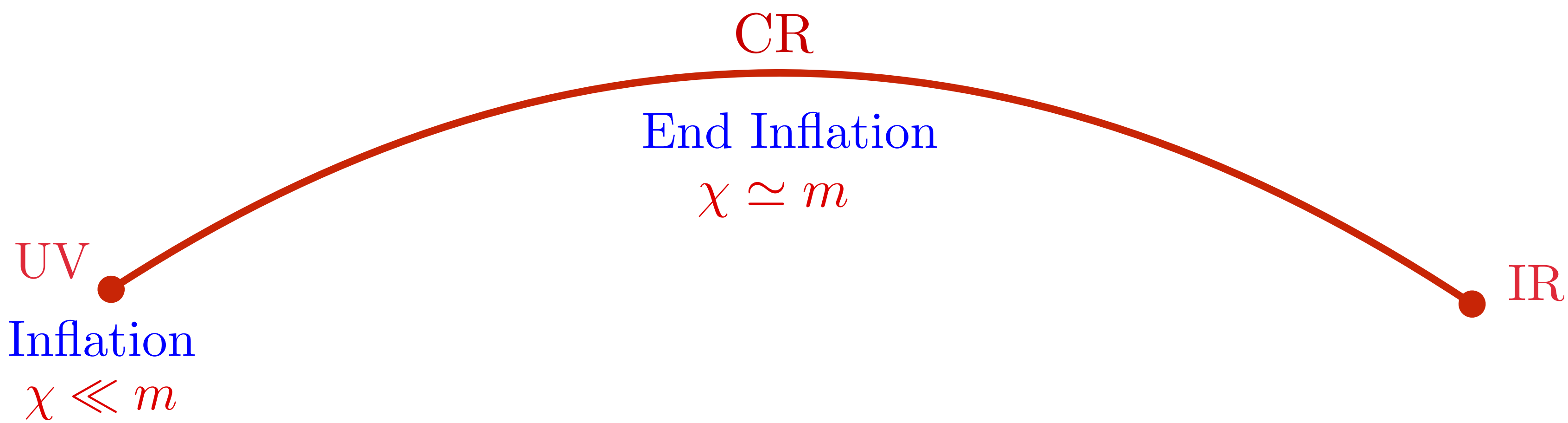
Classical
and
Quantum
(with SSB)

Wetterich, Meissner, Nicolai
Iso, Okada, Orikasa
Boyle, Farnsworth, Fitzgerald, Schade
Salvio, Strumia, Rubio ….

W.A.Bardeen,
Englert, Truffin, Gastmans, 1976
Zenhäusern, Shaposhnikov, Rubio
Armillis, Monin, Shaposhnikov
Gretsch, Monin
Herrero-Balea
D.M. Ghilencea, Z. Lalak, P. Olszewski …

Classical but not Quantum

Scale symmetry reappears in the vicinity of fixed points, as in QCD



The approximate scale symmetry emerging at the UV fixed point is the origin of the almost flat primordial fluctuation spectrum.

The scale m is an integration constant of an almost logarithmic flow. The small amplitude of scalar perturbations arises naturally.

$$\mathcal{A} = \frac{1}{32}\left[2(\sigma N + 1)\right]^{1+\frac{2}{\sigma}} \frac{\mu^2}{m^2} \propto \exp(-2c_t)$$

JR, C. Wetterich , Phys.Rev. D96 (2017) no. 6, 063509

Classical and Quantum

All the scales are generated by SSB of global scale invariance

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

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

The dilaton is the new mass donor
It gives mass to the Higgs and defines the Planck scale.

A singlet under the SM group
No couplings with SM particles

We *won't try to be UV complete*
We treat *this as a low-energy effective theory*

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 rediscovery of our old idea: P. G: Ferreira, C. T. Hill, G. G. Ross Phys.Lett. B763 (2016) 174-178, Phys.Rev. D95 (2017) no.4, 043507

For similar ideas see for instance Lindner Z.Phys. C31 (1986) 29, T. Asaka, S. Blanchet, M. Shaposhnikov, Phys.Lett. B631 (2005) 151, K.A. Meissner, H. Nicolai, Phys.Lett. B648 (2007) 312, M. Holthausen, K.S.Lim, M.Lindner and references therein.

SI inflationary models are non-renormalizable

Quantum corrections should be introduced by interpreting the theory as an EFT in which a particular set of higher dim. operators are included but.....

Which set of operators?

Cutoffs in a background

1. Compute the quadratic lagrangian (Jordan F.)

$$\mathscr{K}_2^{\mathrm{G+S}} = \frac{\xi_\chi \bar{\chi}^2 + \xi_h \bar{h}^2}{8}\left(\delta g^{\mu\nu}\Box\delta g_{\mu\nu} + 2\partial_\nu \delta g^{\mu\nu}\partial^\rho \delta g_{\mu\rho} - 2\partial_\nu \delta g^{\mu\nu}\partial_\mu \delta g + \delta g \Box \delta g\right)$$
$$-\frac{1}{2}(\partial\delta\chi)^2 - \frac{1}{2}(\partial\delta h)^2 + (\xi_\chi\bar{\chi}\delta\chi + \xi_h \bar{h}\delta h)(\partial_\lambda\partial_\rho\delta g^{\lambda\rho} - \Box\delta g)\ .$$

$$\Phi(\mathbf{x},t) = \bar{\Phi}(t) + \delta\Phi(\mathbf{x},t) \rightarrow c_n \frac{\mathcal{O}_n(\delta\Phi)}{[\Lambda(\bar{\Phi})]^{n-4}}$$

Background dependent!

2. Get rid of the mixings in the quadratic action

Non-canonical kinetic terms for perturbations

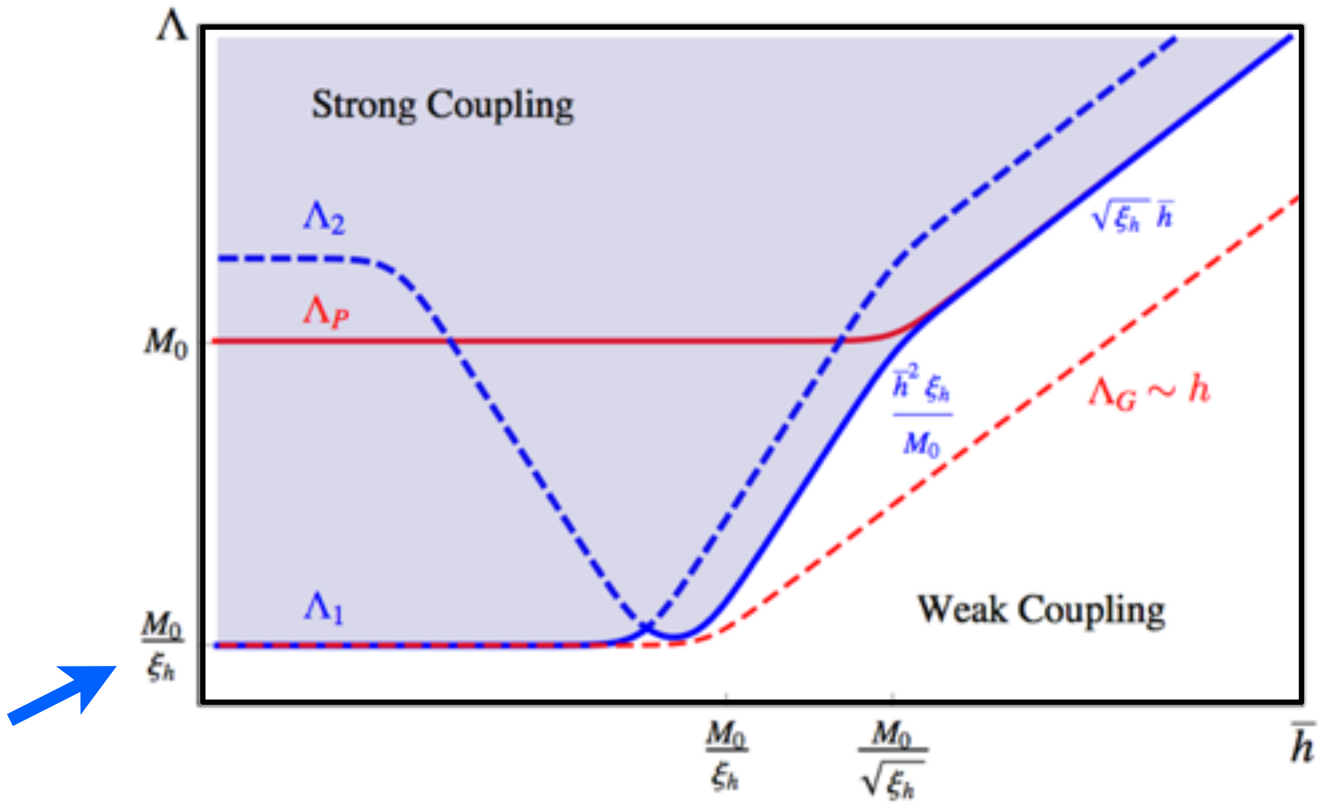
$$\delta\hat{h} = \frac{1}{\sqrt{\xi_\chi^2\bar{\chi}^2 + \xi_h^2\bar{h}^2}}\left(-\xi_h\bar{h}\delta\chi + \xi_\chi\bar{\chi}\delta h\right)$$

$$\delta\hat{\chi} = \sqrt{\frac{\xi_\chi\bar{\chi}^2(1+6\xi_\chi) + \xi_h\bar{h}^2(1+6\xi_h)}{(\xi_\chi^2\bar{\chi}^2 + \xi_h^2\bar{h}^2)(\xi_\chi\bar{\chi}^2 + \xi_h\bar{h}^2)}}\left(\xi_\chi\bar{\chi}\delta\chi + \xi_h\bar{h}\delta h\right)$$

$$\delta\hat{g}_{\mu\nu} = \frac{1}{\sqrt{\xi_\chi\bar{\chi}^2 + \xi_h\bar{h}^2}}\left[(\xi_\chi\bar{\chi}^2 + \xi_h\bar{h}^2)\delta g_{\mu\nu} + 2\bar{g}_{\mu\nu}(\xi_\chi\bar{\chi}\delta\chi + \xi_h\bar{h}\delta h)\right]$$

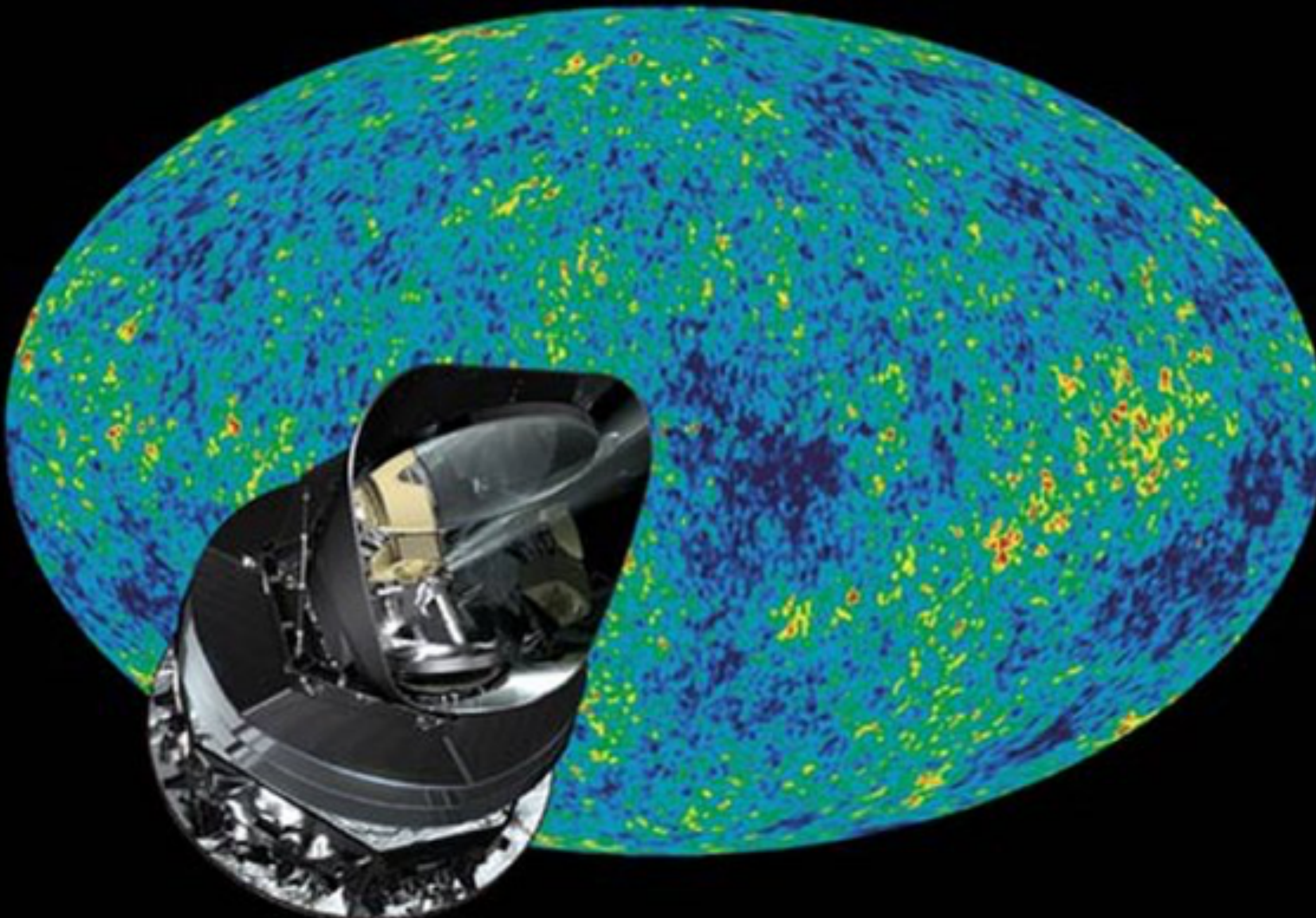
3. Read out the cutoff from higher order operators

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



A consistent EFT : **Cutoffs are parametrically larger than all the energy scales involved in the history of the Universe**

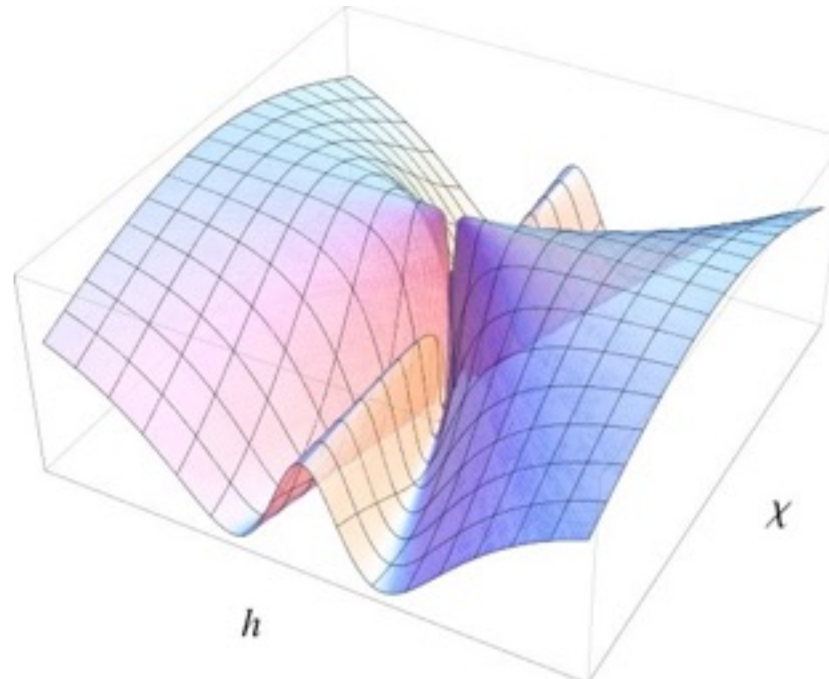
Inflation



Einstein frame

Conformal transformation

$$\tilde{g}_{\mu\nu} = M_P^{-2}(\xi_\chi \chi^2 + \xi_h h^2) g_{\mu\nu}$$



Vacuum is infinitely degenerate

Physics does not depend on the particular value of the dilaton

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

$$\gamma_{ab}(\Omega) = \frac{1}{\Omega^2}\left(\delta_{ab} + \frac{3}{2}M_P^2\frac{\Omega^2_{,a}\Omega^2_{,b}}{\Omega^2}\right)$$

Canonical fields?

$R_{\gamma_{ab}} \neq 0$ ***unless*** $\xi_h = \xi_\chi$

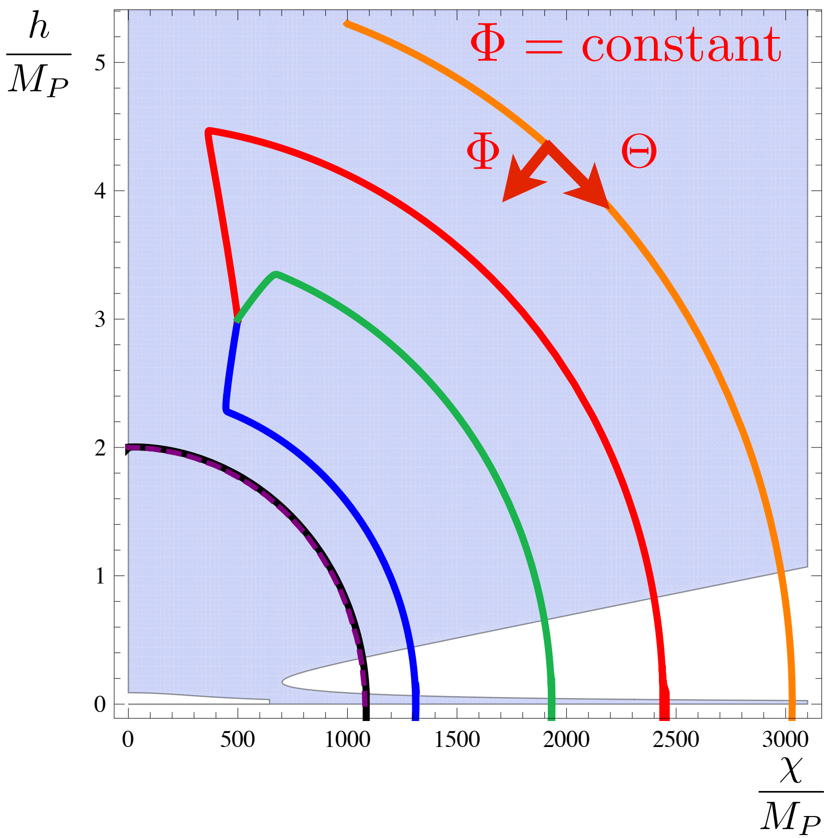
J. García-Bellido, JR, M. Shaposhnikov, D. Zenhausern, Phys.Rev. D84 (2011) 123504


Blah, blah, blah …
Multifield inflation generates
isocurvature fluctuations and non-gaussianities!!!
MORE
FAKE
NEWS

Exploiting scale-invariance

A dynamical constraint between Higgs and Dilaton

J. Garcia-Bellido, J. Rubio, M. Shaposhnikov, D. Zenhäusern



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

$$\exp\left[\frac{2\gamma\Phi}{M_P}\right] \equiv \frac{\kappa_c}{\kappa}\frac{(1+6\xi_h)h^2 + (1+6\xi_\chi)\chi^2}{M_P^2}$$

$$\gamma^{-2}\Theta \equiv \frac{(1+6\xi_h)h^2 + (1+6\xi_\chi)\chi^2}{\xi_h h^2 + \xi_\chi \chi^2}$$

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

The pole structure

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

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

$c \equiv \frac{\kappa}{\kappa_c}\gamma^2$ "Minkowski" pole Single field

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

G. Karananas, JR, Phys.Lett. B761 (2016) 223-228

The meaning of κ

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

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

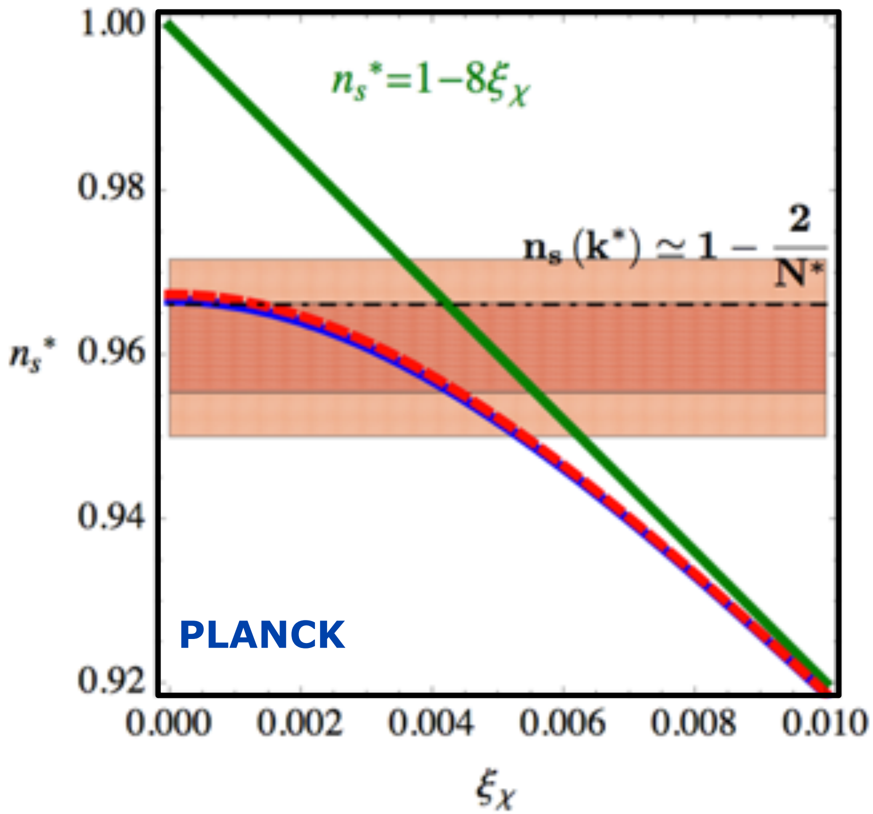
For large field values, the field space of the Higgs-Dilaton model is

MAXIMALLY SYMMETRIC

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

G. Karananas, JR, Phys.Lett. B761 (2016) 223-228

Inflationary Observables



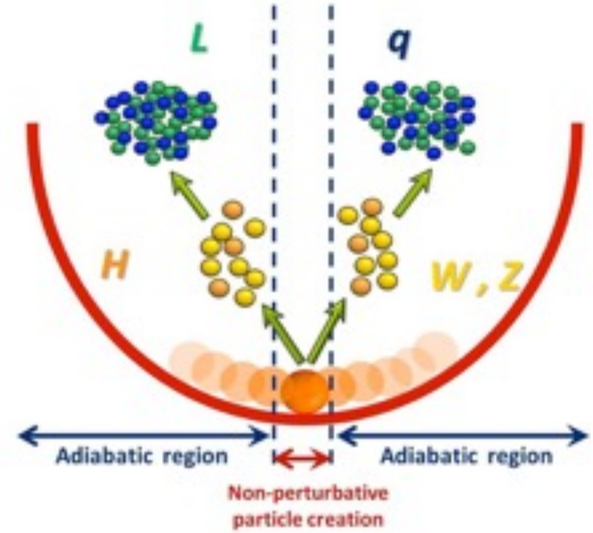
$$A_s = \frac{\lambda \sinh^2(4cN_*)}{1152\pi^2 \xi_h^2 c^2}$$

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

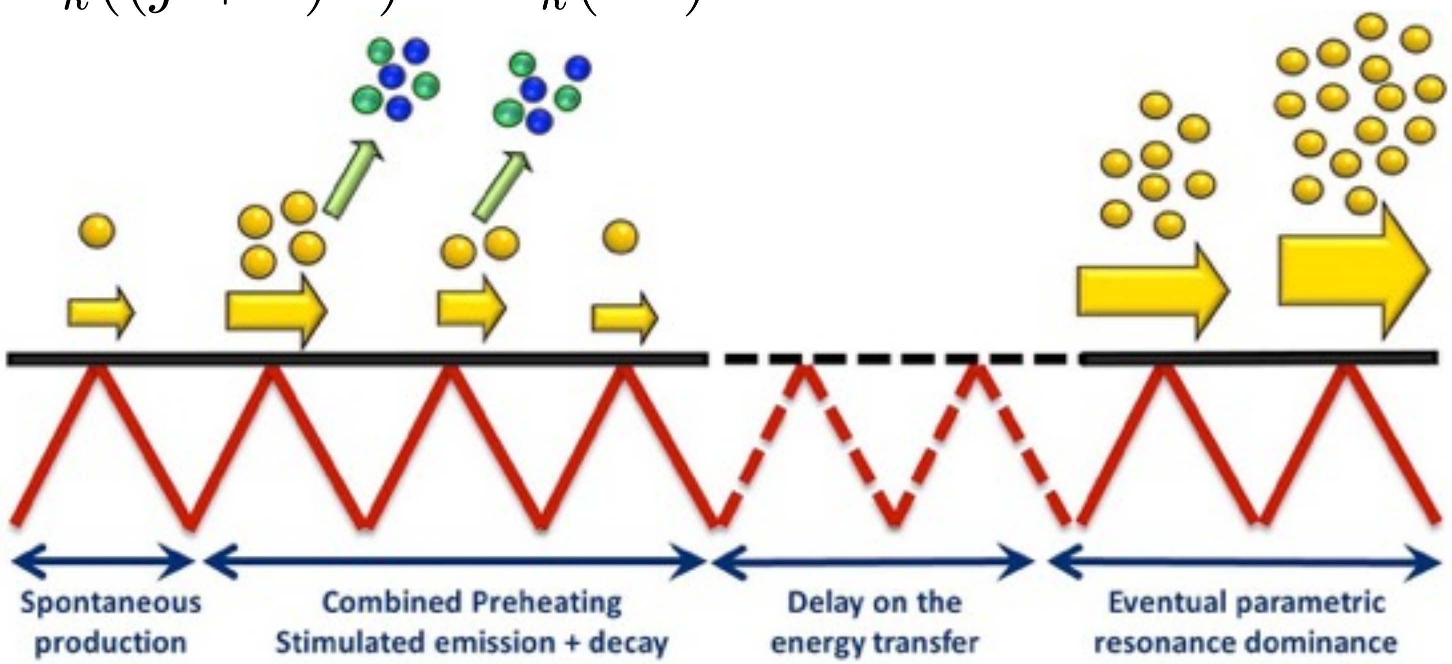
$$r = \frac{32\,c^2}{|\kappa_c|} \sinh^{-2}(4cN_*)$$

No free parameters left

Combined Preheating

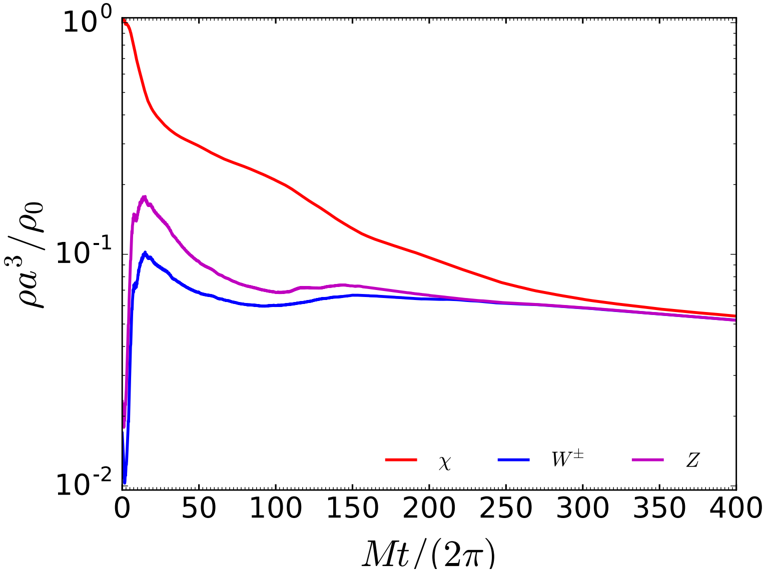


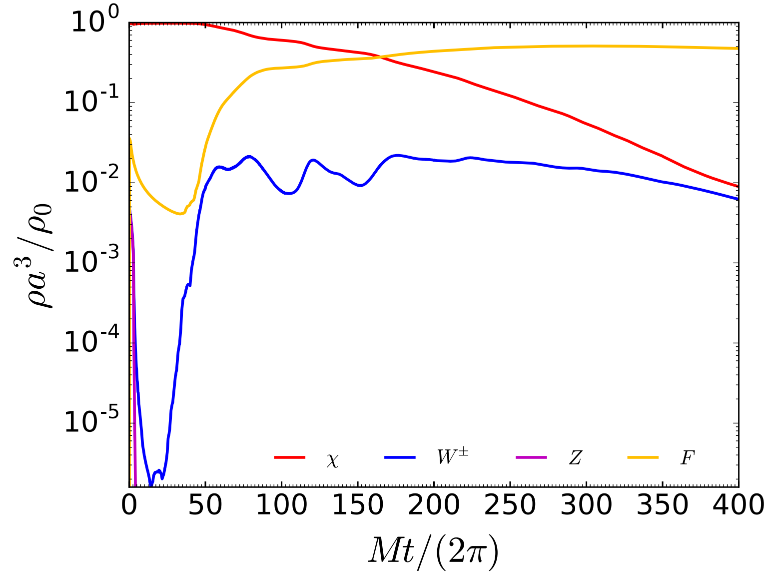
$$n_k((j+1)^+) = n_k(1^+)\, e^{-\gamma F_\Sigma(j)}\, e^{2\pi \sum_{i=1}^{j} \mu_k(i+1)}$$

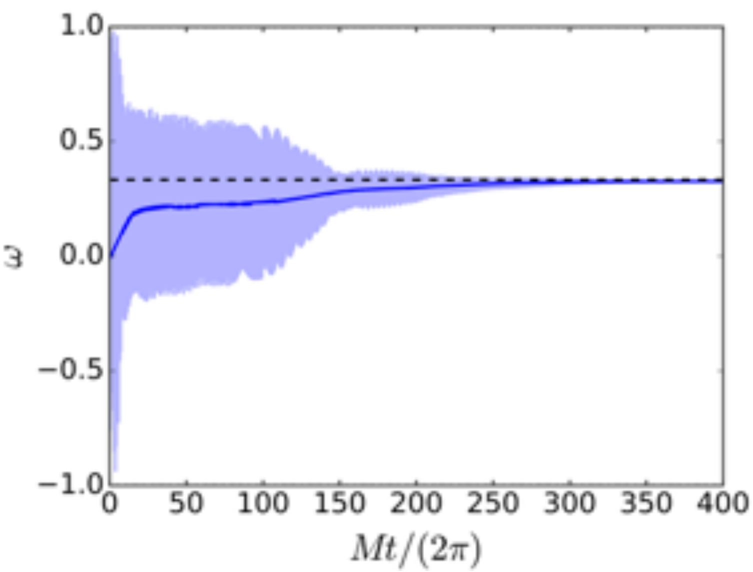


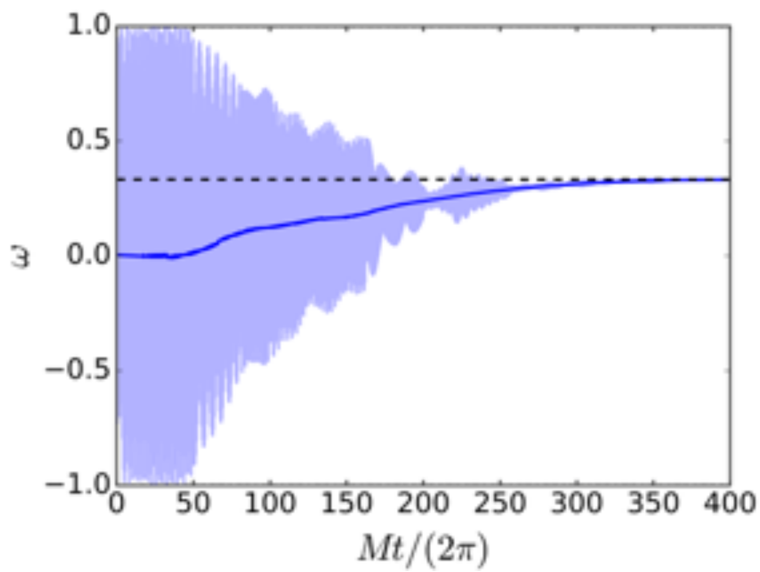
J. Garcia-Bellido, D. G. Figueroa, JR, Phys.Rev. D79 (2009) 063531

Lattice results without/with decays









J. Repond, JR, JCAP 1607 (2016) no.07, 043

An extra relativistic d.o.f ?

Dilaton is a Goldstone boson

Unique coupling: kinetic term

$$\frac{\mathcal{L}}{\sqrt{-g}} \supset -\frac{\Theta}{2}(\partial\rho)^2$$

$$\Delta N_{\rm eff} \equiv \frac{g_0}{g_\nu}\left(\frac{g_f}{g_0}\right)^{4/3} C \approx 2.85\, C$$ **with** $$C \equiv \left.\frac{\rho_D}{\rho_{SM}}\right|_{t=t_{RH}}$$

$C \sim 10\%$ **in order to have a contribution within the reach of Planck**

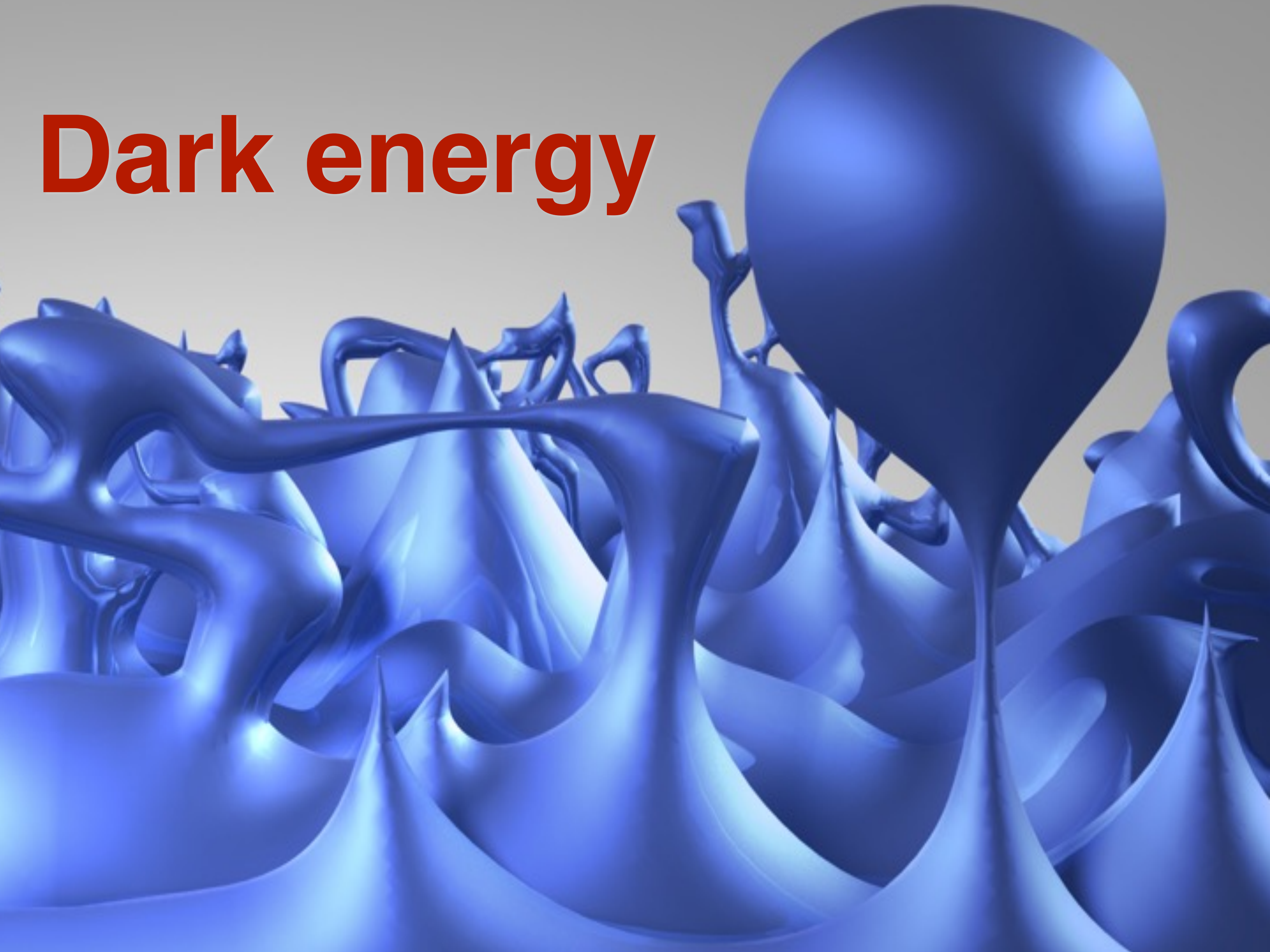
Direct production $C_1 \sim 10^{-7}$

Secondary product $C_2 \ll C_1$

No extra degrees of freedom

J- Garcia-Bellido, M. Shaposhnikov, JR Phys. Lett. B718 (2012) 507

Dark energy



SI and Unimodular Gravity

General Relativity	Unimodular Gravity
CC at the level of the action	No CC at the level of the action
$S = \int d^4x \left(\mathcal{L}\left(g_{\mu\nu}, \partial g_{\mu\nu}, \Phi, \partial\Phi\right) + \Lambda_0 \right)$	$S = \int d^4x \mathcal{L}\left(g_{\mu\nu}, \partial g_{\mu\nu}, \Phi, \partial\Phi\right)$
Unrestricted metric determinant	Restricted metric determinant
$\lvert g \rvert$	$\lvert g \rvert = 1$
Variation of the action	Variation of the action with a lagrange multiplier
	$\partial_\mu \lambda(x) = 0 \Longleftrightarrow \lambda(x) = \Lambda_0$

Same equations of motion

The Cosmological Constant reappears ...

Thawing Quintessence

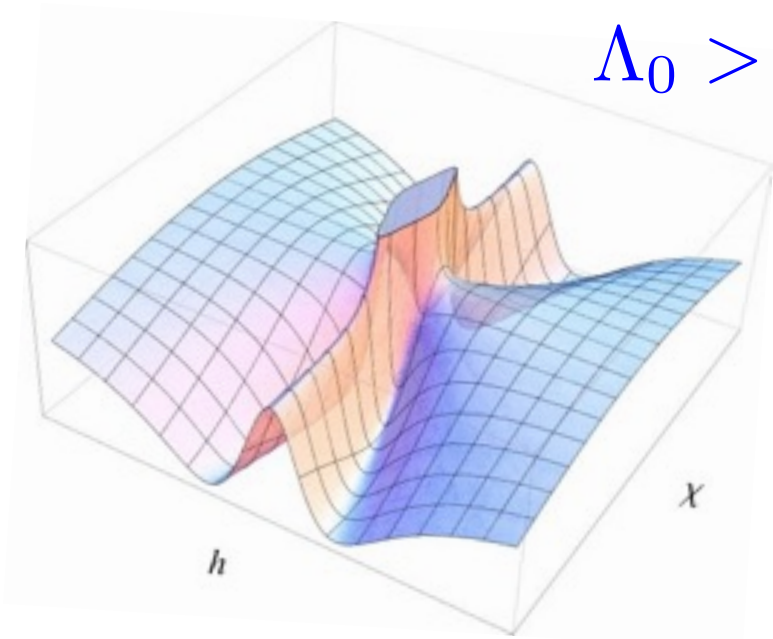
… with a very different interpretation

the strength of a potential

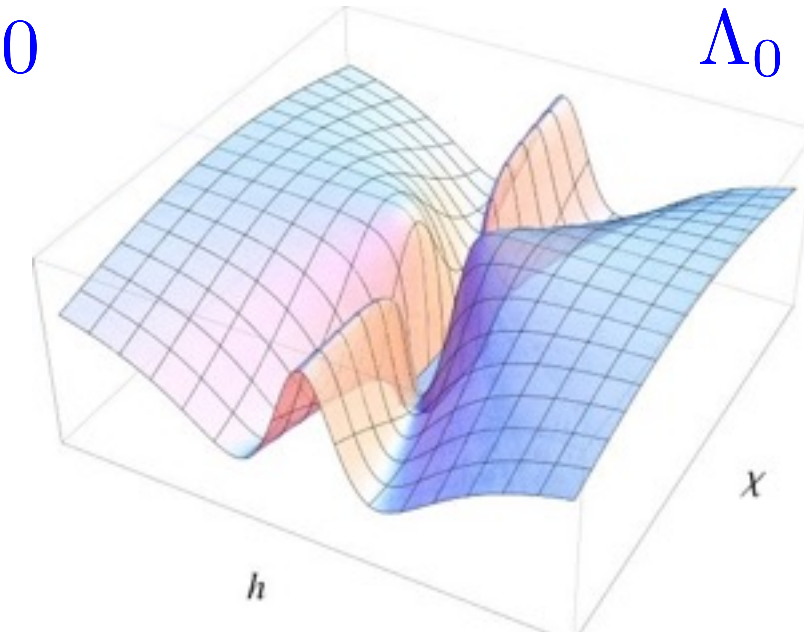
$$U_\Lambda(\Phi) = \frac{\Lambda_0}{c^2} e^{-\frac{4\gamma\Phi}{M_P}}$$

Back to the 80's!
C. Wetterich 1988

$\Lambda_0 > 0$



$\Lambda_0 < 0$



All the new parameters determined by inflation

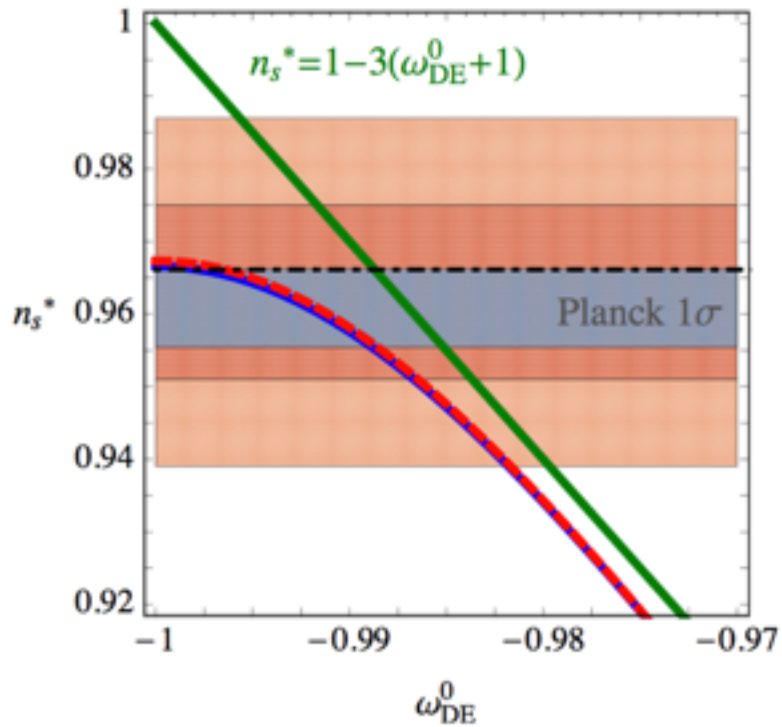
J. García-Bellido, JR, M. Shaposhnikov, D. Zenhausern, Phys.Rev. D84 (2011) 123504

Consistency conditions

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

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

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



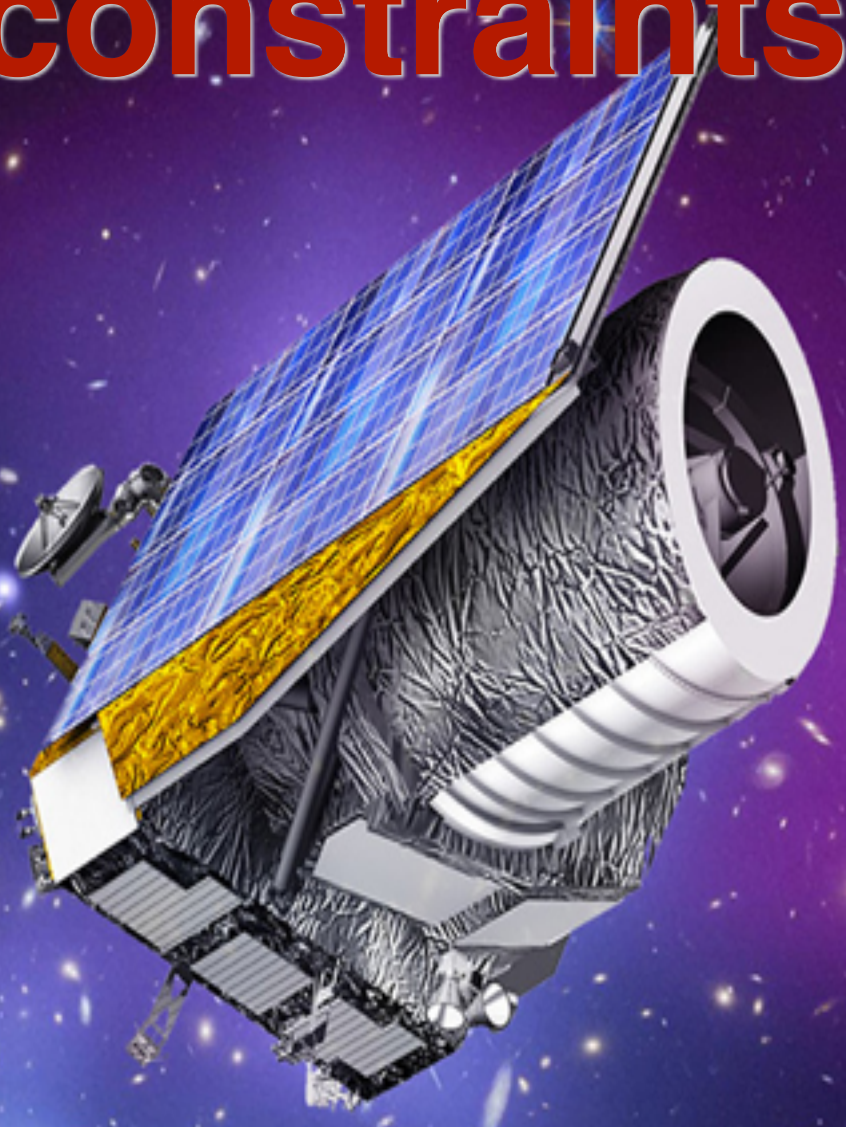
with

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

"it directly links early and late universe physics [...] This is a nice model."

Dark energy in light of the discovery of the Higgs, Annalen Phys. 528 (2016) 62-67, Edmund J. Copeland

Present and future constraints



Present data

MCMC analysis

Planck TT+pol, Keck/BICEP2, JLA, 6dF, SDSS, BOSS.

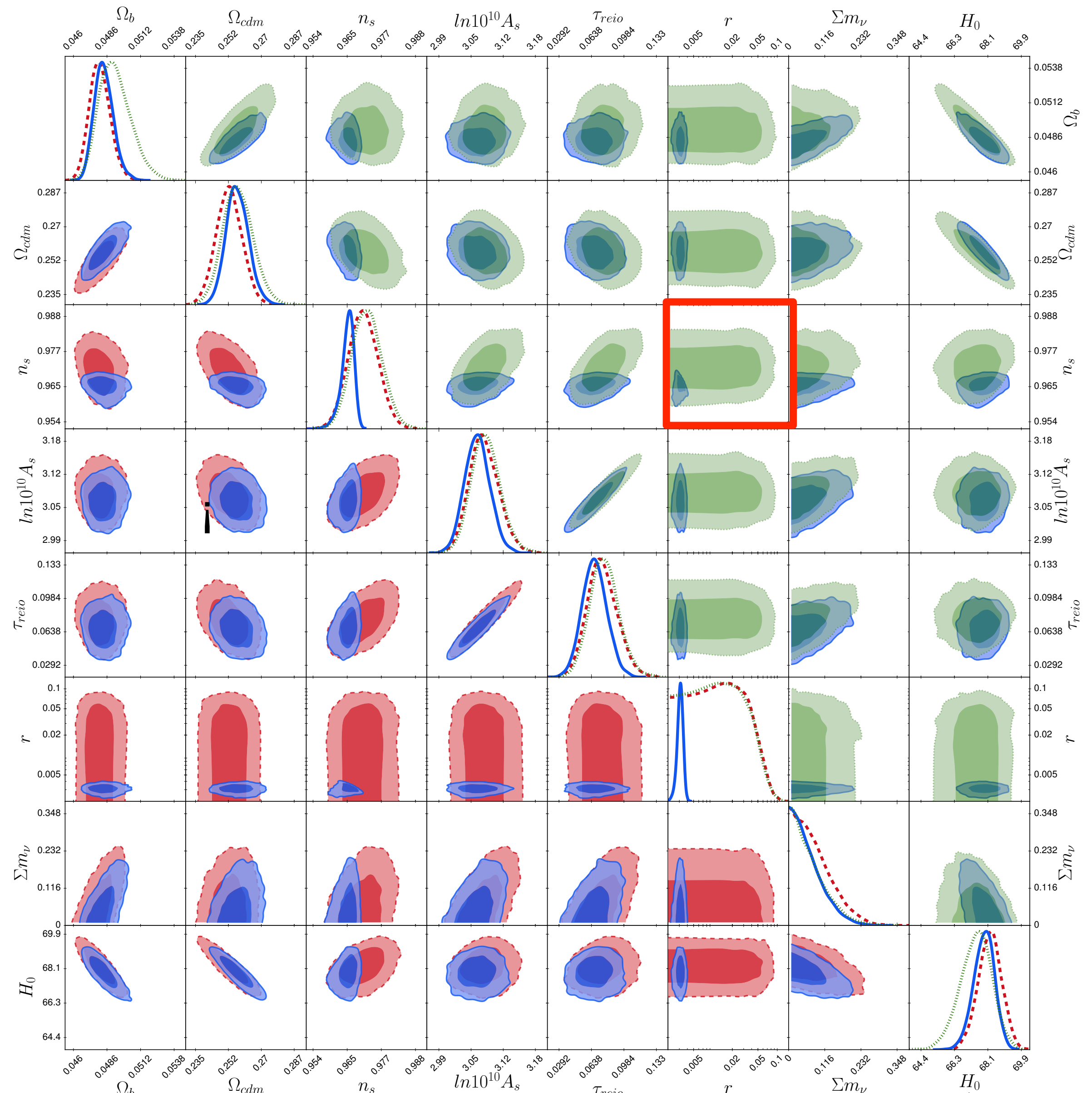
ΛCDM

wCDM

HD

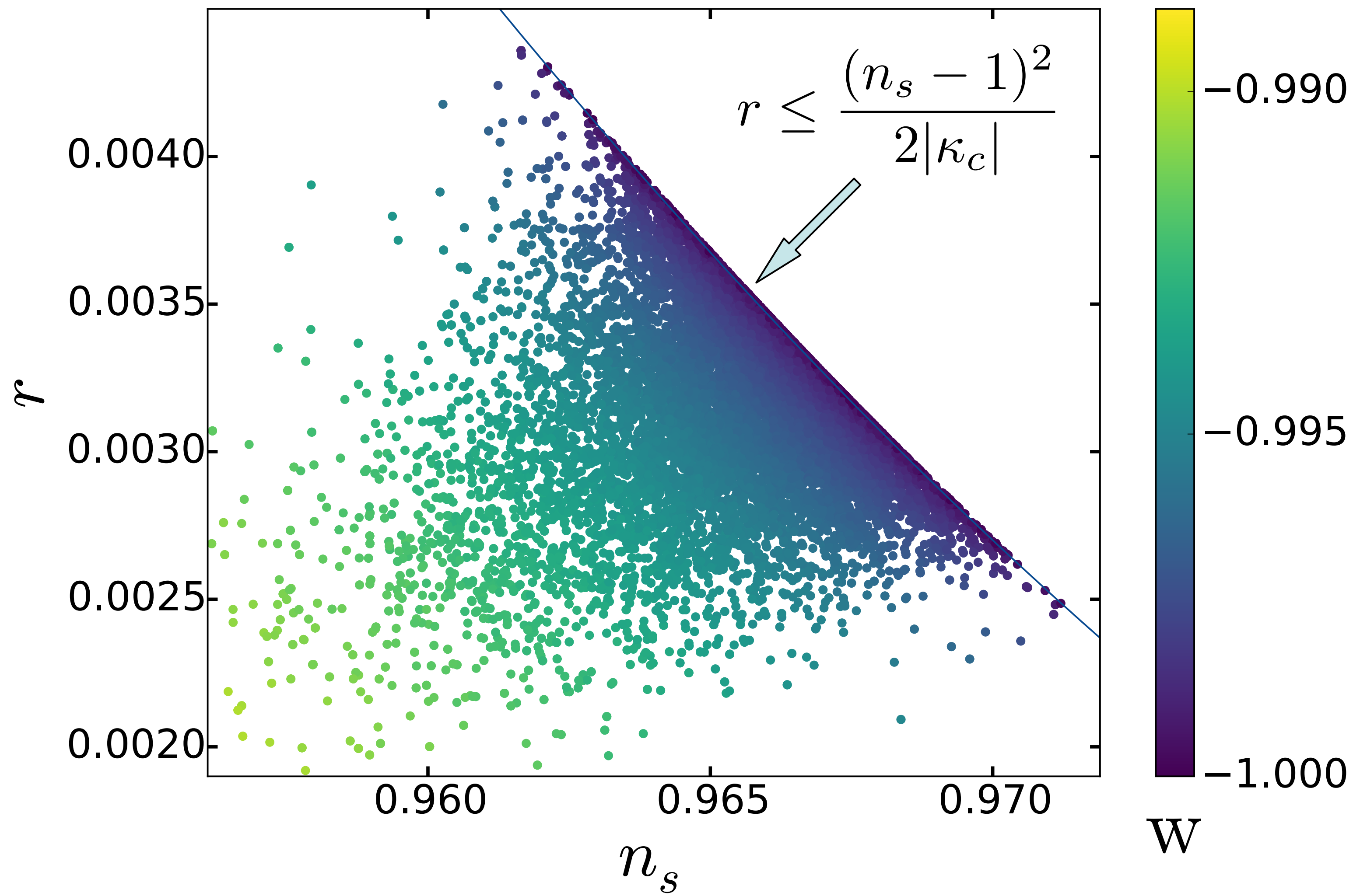
$$B(M) = \frac{p(\mathbf{x}|M)}{p(\mathbf{x}|M_{\Lambda\mathrm{CDM}})}$$

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



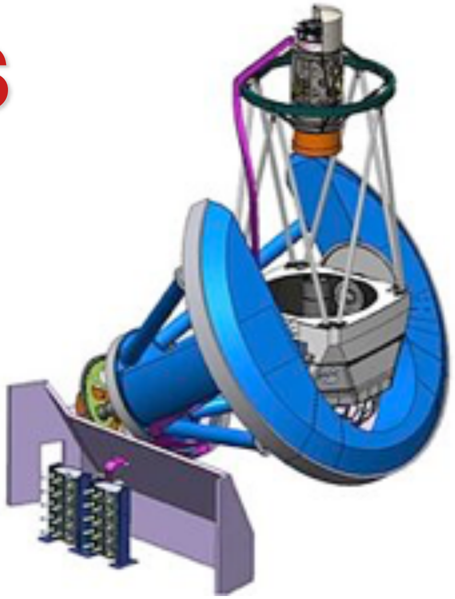
S. Casas, M. Pauly, JR, Phys.Rev. D97 (2018) 043520

Consistency conditions



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

Future surveys

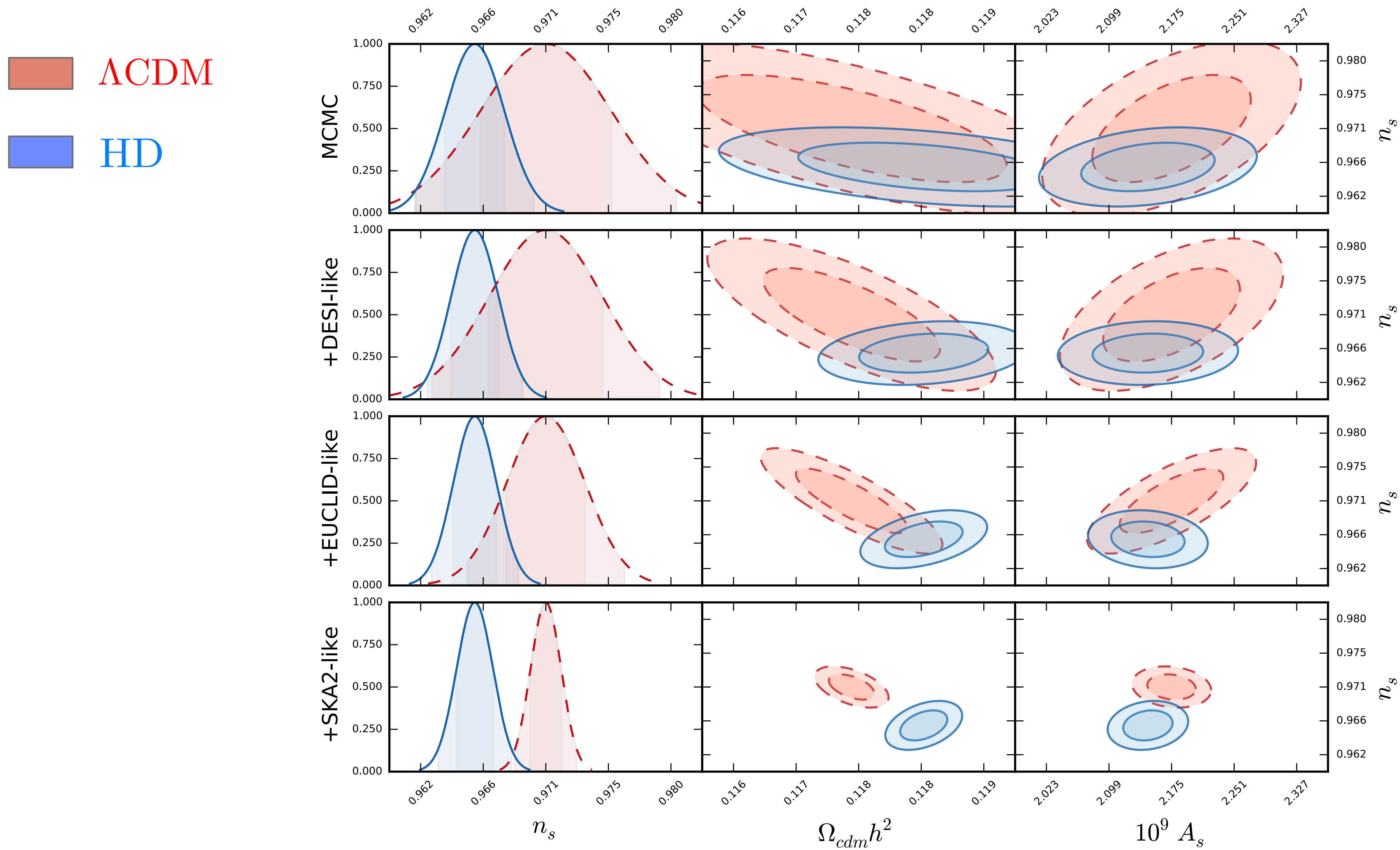


✳ Dark Energy Spectroscopic Instrument (DESI)
ground-based experiment (Arizona)
30 million spectroscopic redshifts
2018.

✳ 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

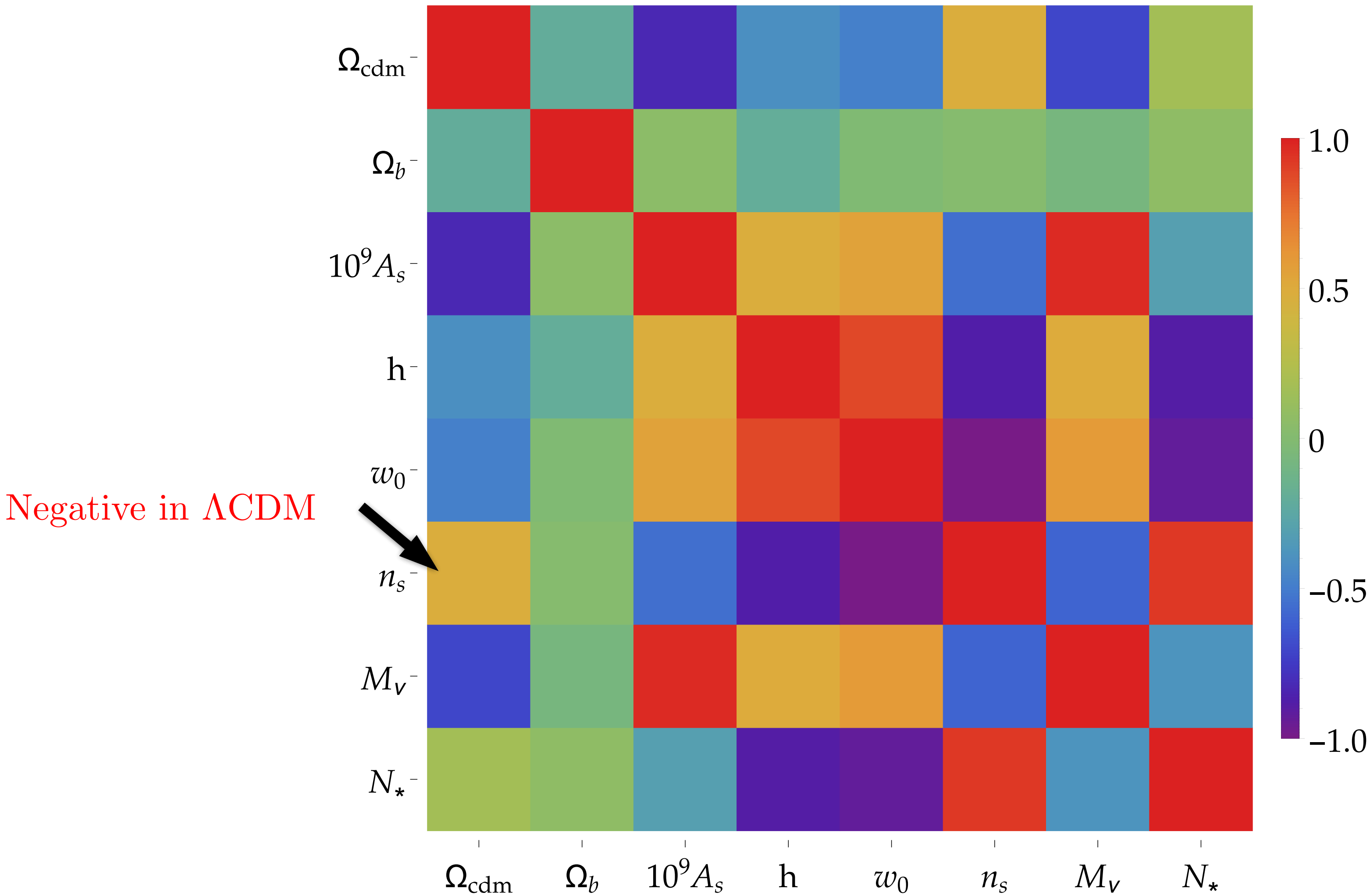
Future surveys (Fisher forecast)



Each model is centered on the fiducial values obtained from its own MCMC run

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

Future surveys (Fisher forecast)



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

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

The dilaton is introduced ad hoc

Can it appear “naturally”?

Dilaton as part of the metric

- **The minimal gauge group required to construct a metric theory including spin-2 polarizations is transverse diffeomorphisms**

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

- **The TDiff action contains arbitrary (theory-defining) 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

- **The TDiff action describes in general three propagating degrees of freedom, the graviton plus a new scalar (exceptions: GR & UG).**
- **A equivalent Diff version can be obtained using the Stückelberg trick**

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

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

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

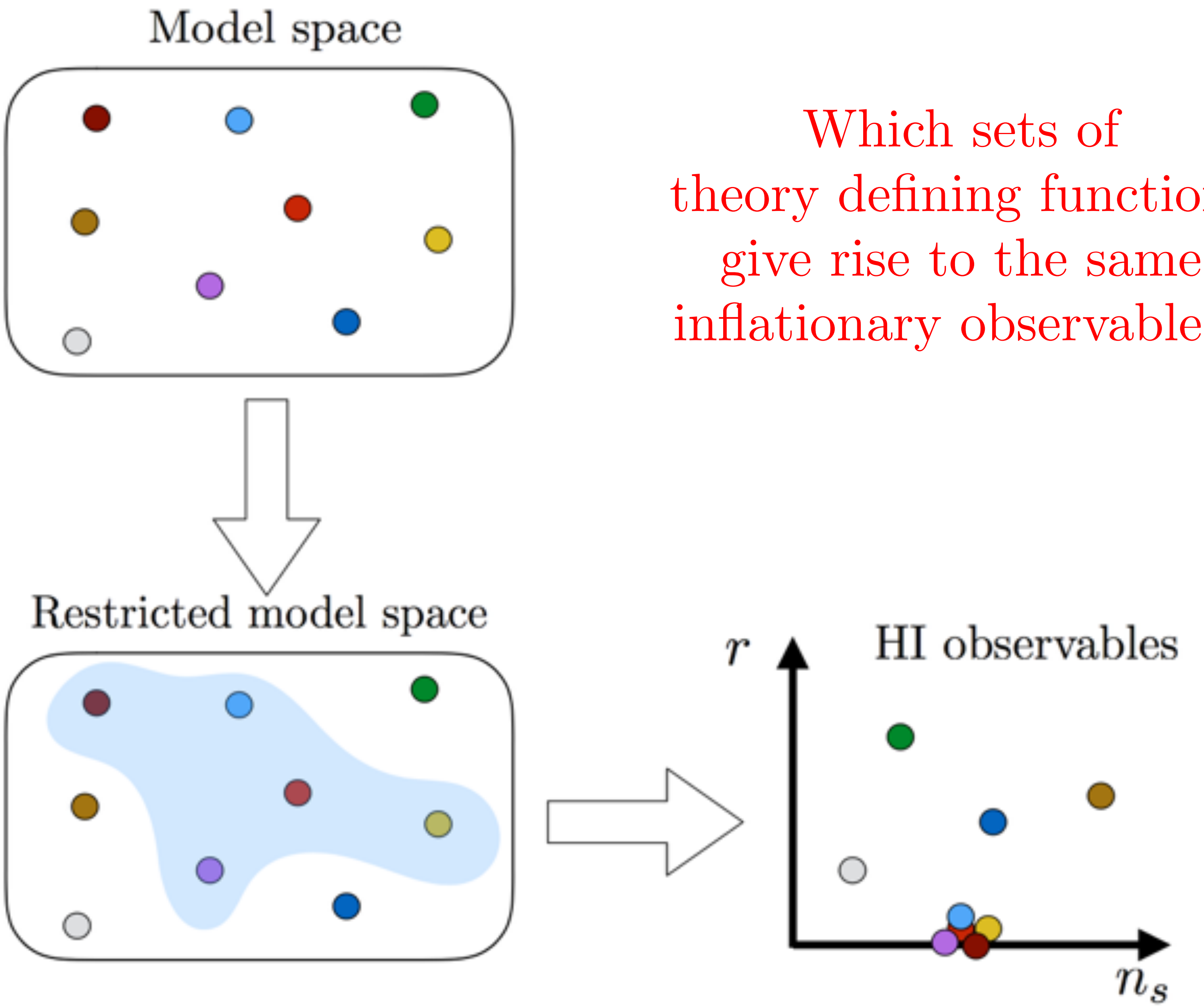
Goldstone

- **In Einstein frame**

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

D. Blas, M. Shaposhnikov, D. Zenhausern Phys.Rev. D84 (2011) 044001
G. Karananas, JR, Phys.Lett. B761 (2016) 223-228

SI TDiff theory contains a massless dilaton.



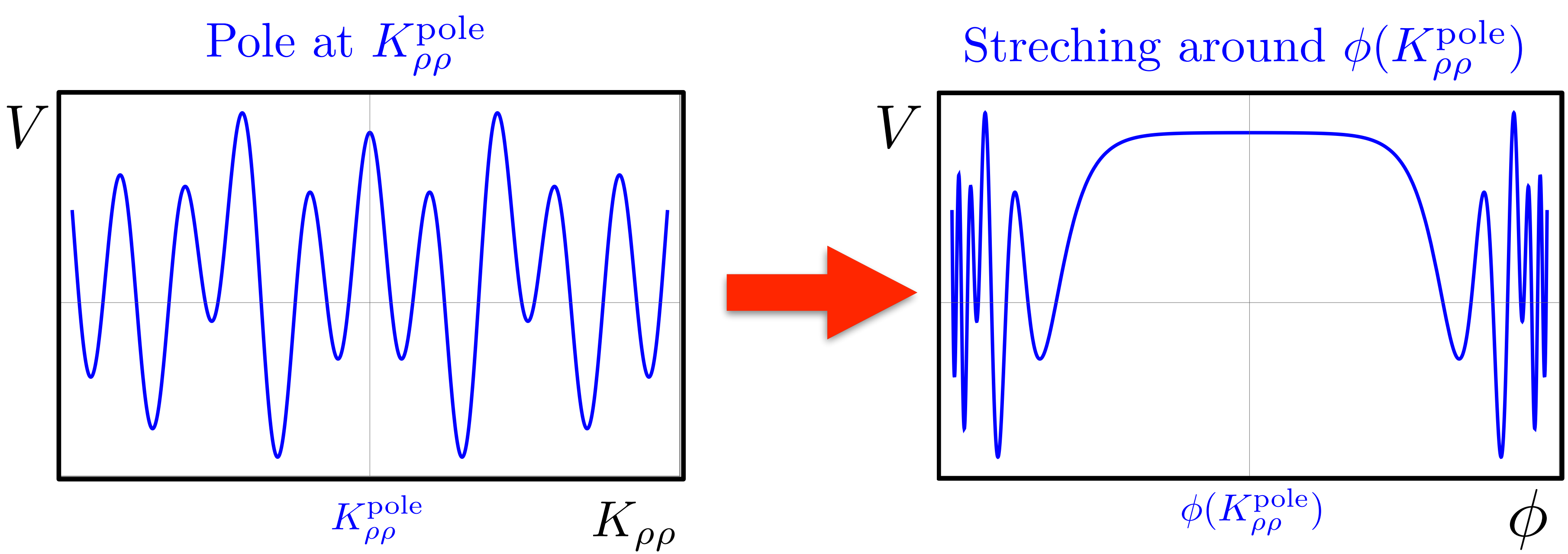
Which sets of theory defining functions give rise to the same inflationary observables?

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

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



G. Karananas, JR, Phys.Lett. B761 (2016) 223-228

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

G. Karananas, JR, Phys.Lett. B761 (2016) 223-228

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

G. Karananas, JR, Phys.Lett. B761 (2016) 223-228

A universality class

Any TDiff embedding of the Higgs-Dilaton idea

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

constructed out of a sufficiently well-behaved potential and (arbitrary) functions $K_{\theta\theta}$, $K_{\theta\rho}$, $K_{\rho\rho}$ giving rise to an approximately constant field-space curvature

$$\kappa(\theta) = \frac{K'_{\rho\rho}(\theta)F'(\theta) - 2F(\theta)K''_{\rho\rho}(\theta)}{4F^2(\theta)} \qquad F(\theta) \equiv K(\theta)K_{\rho\rho}(\theta)$$

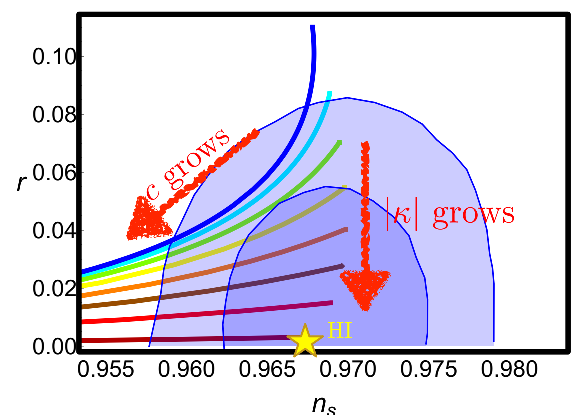
can be written as

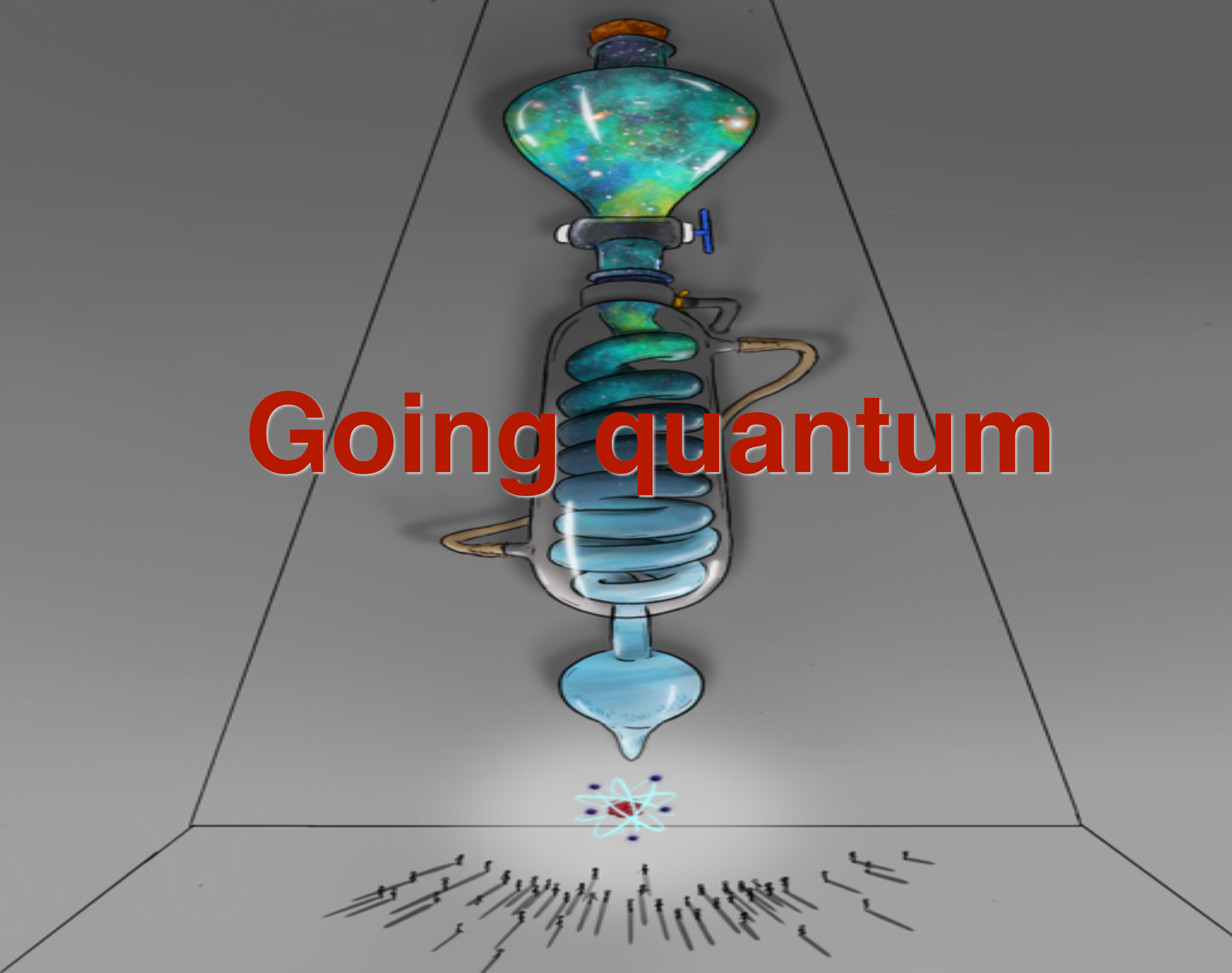
$$\frac{\mathcal{L}}{\sqrt{g}} = \frac{M_P^2}{2}R - \frac{M_P^2}{2}\left[-\frac{(\partial K_{\rho\rho})^2}{4\,K_{\rho\rho}(\kappa K_{\rho\rho}+c)} + K_{\rho\rho}(\partial\rho)^2\right] - V(K_{\rho\rho})$$

The inflationary observables of this class of models approach

$$n_s \simeq 1 - \frac{2}{N} \qquad r \simeq \frac{2}{|\kappa|N^2}$$

in the large curvature/ large number of e-folds limit




Going quantum

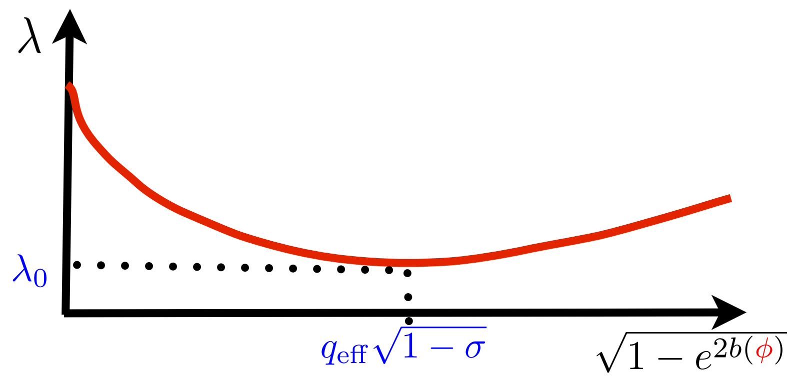
3 possibilities

$$\lambda(\mu(\phi)) = \lambda_0 + b\log^2\left(\frac{\sqrt{1-e^{2b(\phi)}}}{q_{\rm eff}\sqrt{1-\sigma}}\right)$$

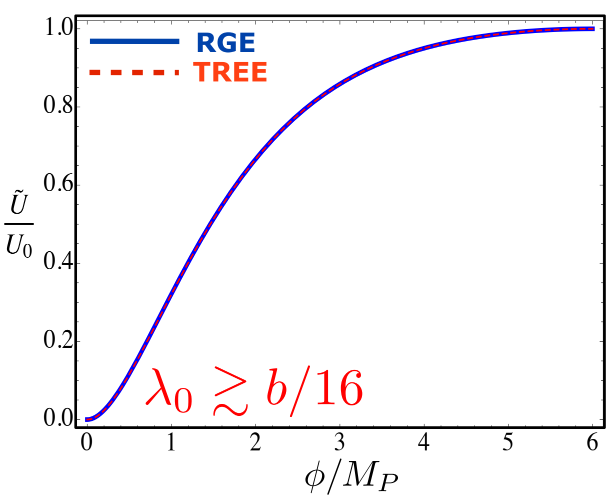
$$\sigma \sim \xi_\chi \qquad b \simeq 2.3\times 10^{-5}$$

$$\lambda_0 = \lambda_0(m_h^*, m_t^*) \ll 1$$

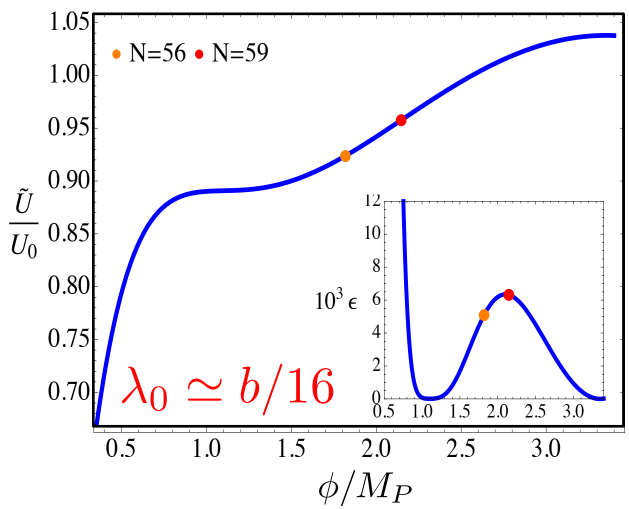
$$q_{\rm eff} = q_{\rm eff}(m_h^*, m_t^*) \sim \mathcal{O}(1)$$



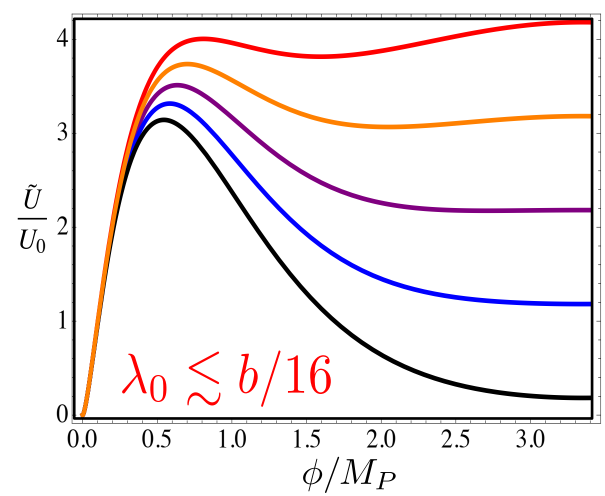
UNIVERSALITY

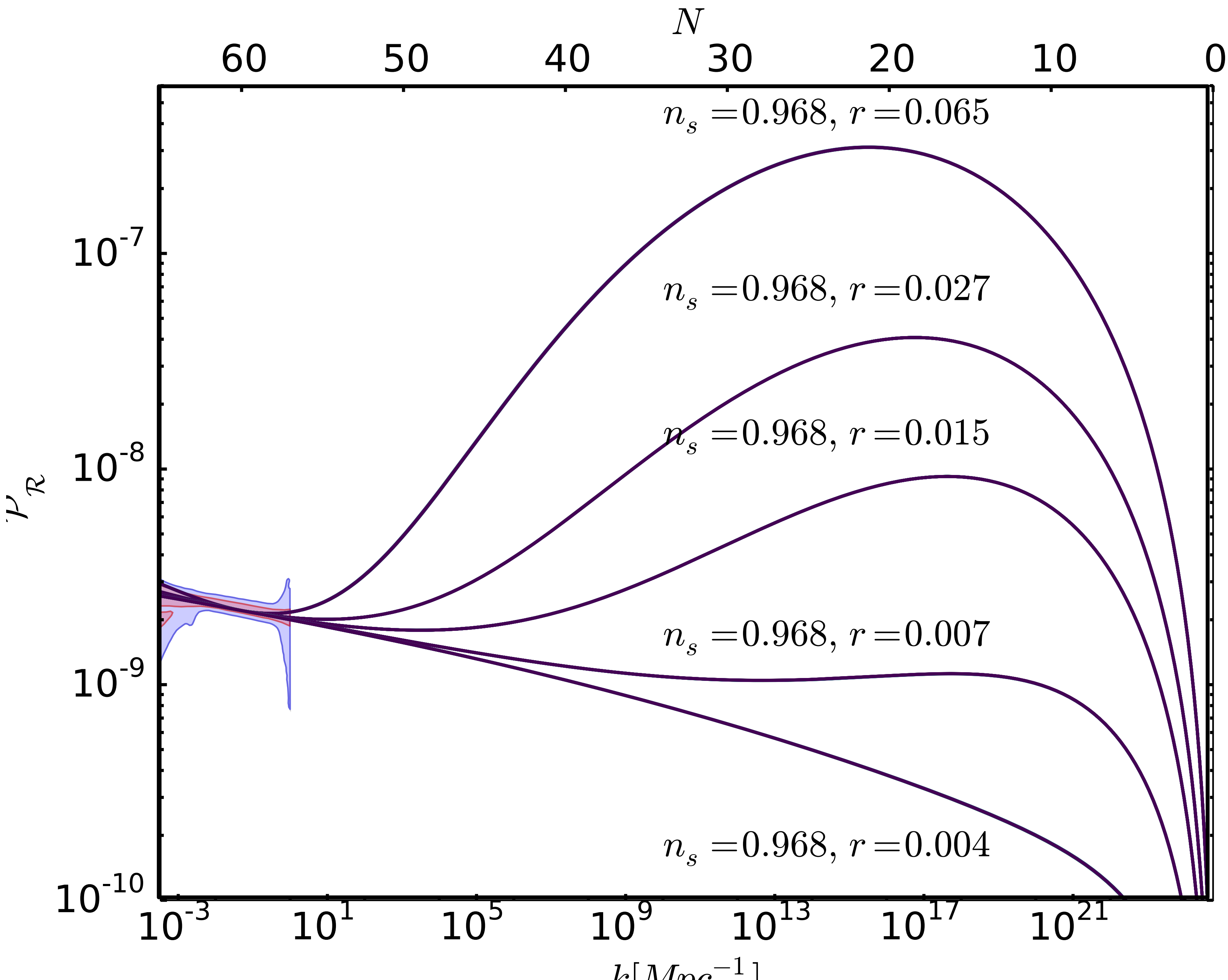


CRITICALITY



NO INFLATION

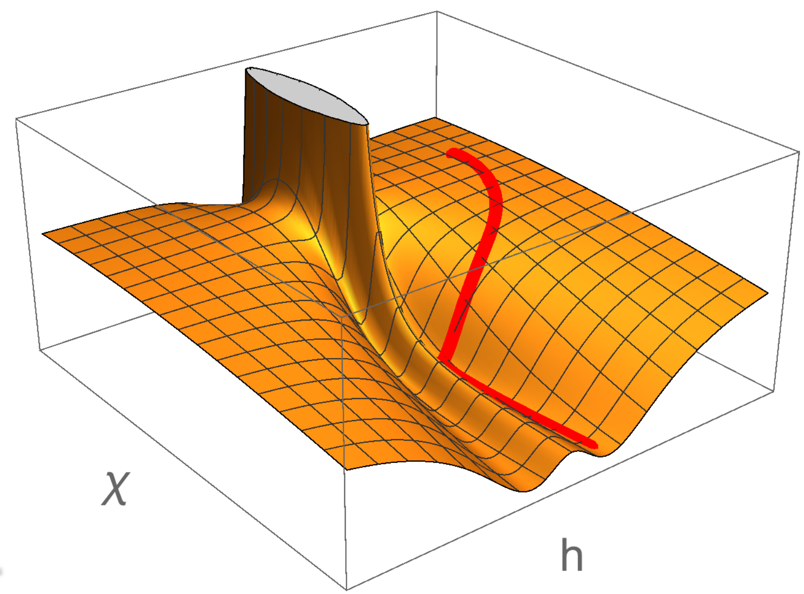




F. Bezrukov, M. Pauly, JR JCAP 1802 (2018) no.02, 040

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


Thanks!