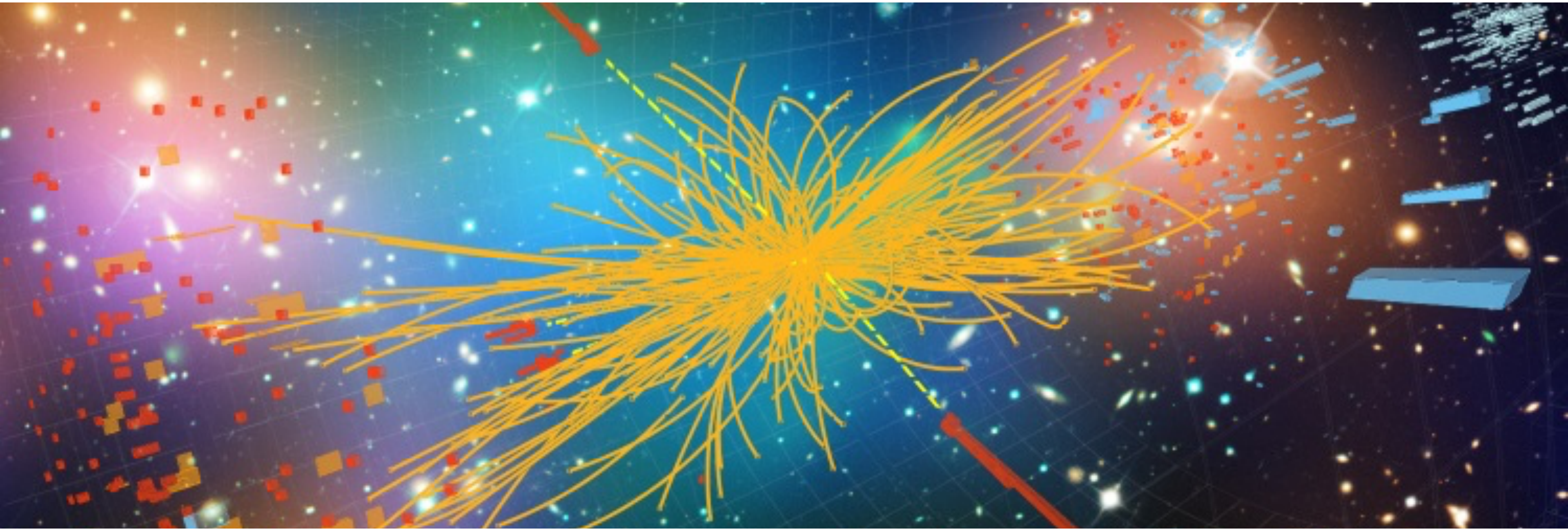
The Higgs field and the Nature of Gravity

Javier Rubio

Based on M. Piani and JR 2304.13056 [hep-ph] & JR, Front.Astron.Space Sci. 5 (2019) 50.



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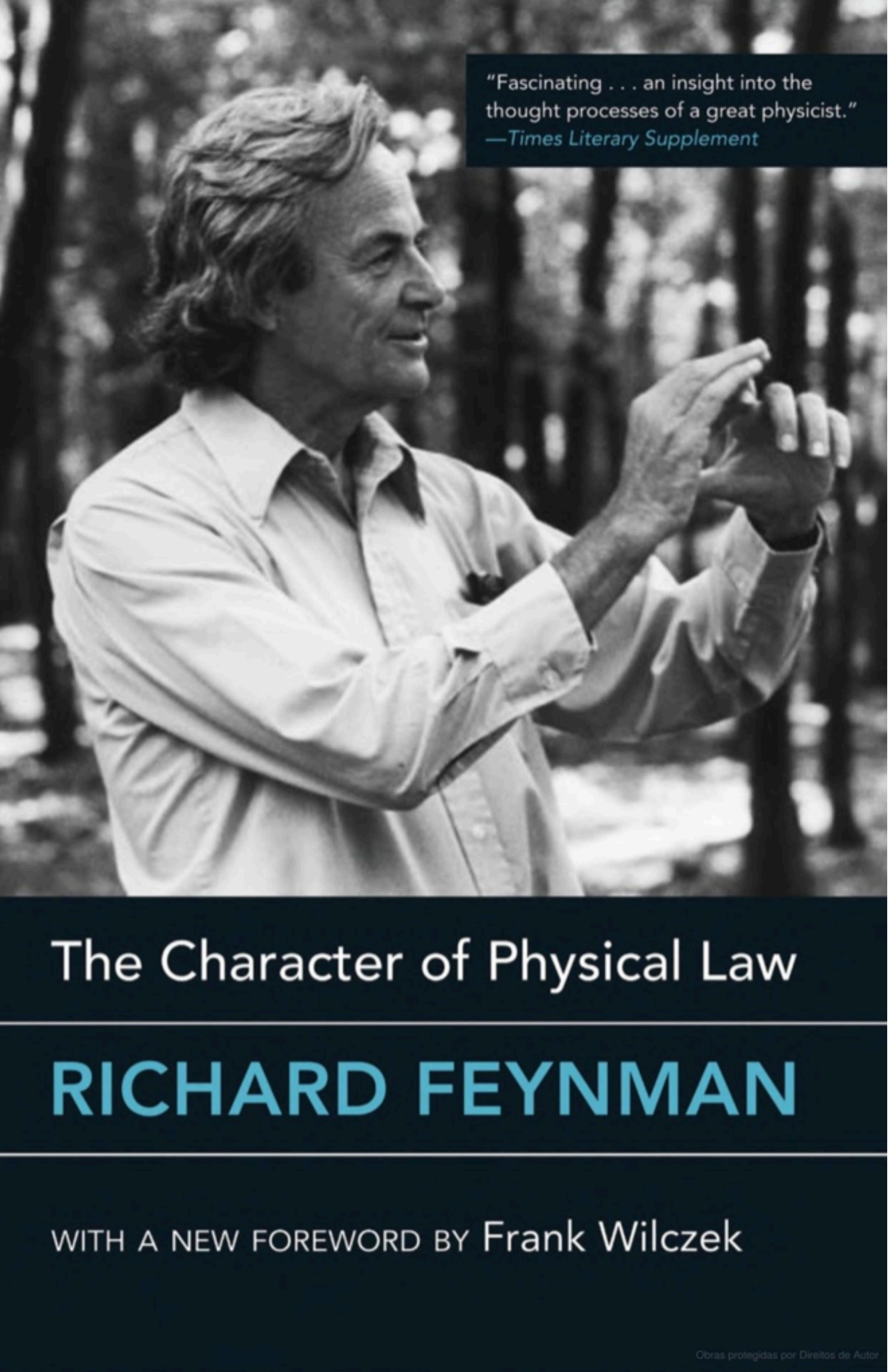
Outline

- Introduction
- Higgs inflation in alternative theories of gravity
- Universality classes
- The onset of the hot Big Bang: Impact on inflationary observables
- Conclusions



"Every theoretical physicist who is any good knows six or seven different theoretical representations for exactly the same physics.

He* knows that they are all equivalent, [...] but he* keeps them in his head, hoping that they will give him different ideas for guessing"

*This is a 1965 quote, so please read also "she", "they"

The Einstein's route

In 1915, the only geometrical field was the metric

Physical requirements

Equivalence principle   Metric/affine geodesics

$$\Gamma^{\sigma}{}_{\mu\nu} = \frac{1}{2} g^{\sigma\rho} \left(\partial_\mu g_{\nu\rho} + \partial_\nu g_{\rho\mu} - \partial_\rho g_{\mu\nu} \right)$$

is a founding issue

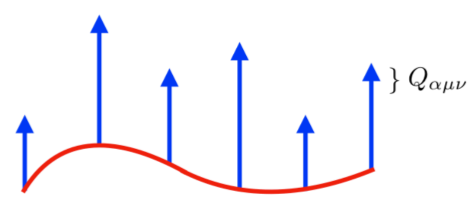
Connections

Levi-Civita introduced connections in 1919

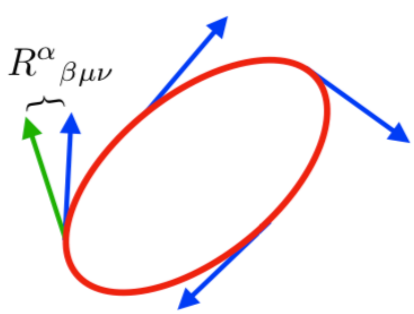
$$\Gamma^{\rho}_{\mu\nu}(p) = \left\{ {\rho \atop \mu\nu} \right\} + S^{\rho}_{\mu\nu} + T^{\rho}_{\mu\nu}$$

Levi-Civita | Disformation tensor | Contortion tensor

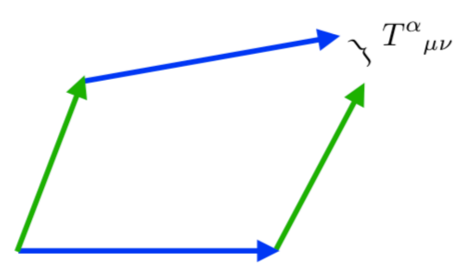
These pieces induce:



Non-metricity

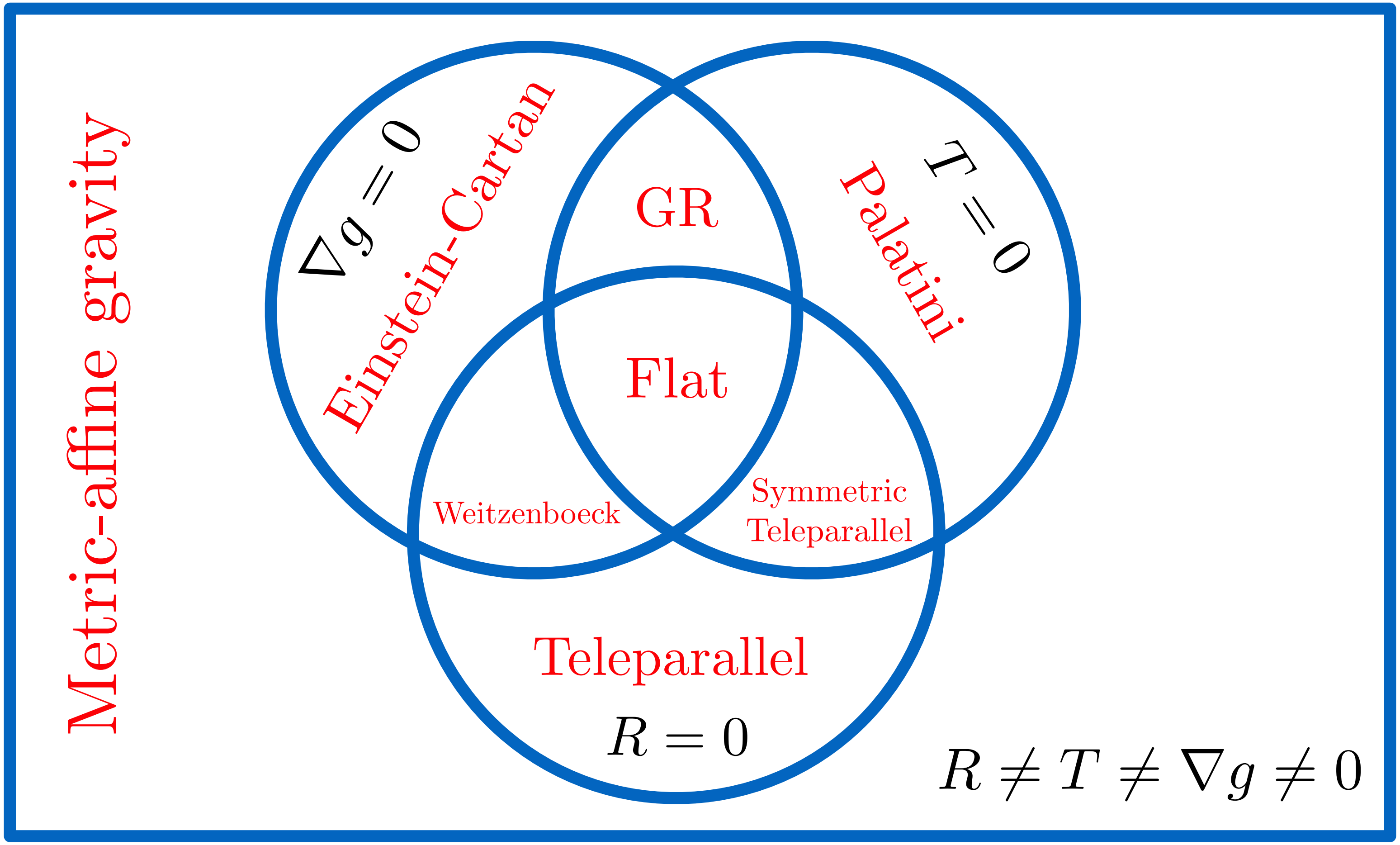


Curvature



Torsion

Ambiguities in GR



Pure gravity versions equivalent to General Relativity

7 equivalent theories

$$\mathcal{L}_{\text{affine}} \sim \mathring{R} + c_{TT}T^2 + c_{QQ}Q^2 + c_{TQ}TQ$$

Formulation of gravity	$R_{\alpha\beta\gamma\delta}$	$T_{\alpha\beta\gamma}$	$Q_{\alpha\beta\gamma}$	Equivalent to metric GR for arbitrary coefficients of T^2, QT, Q^2
Metric-affine				Yes
Einstein-Cartan			$=0$	Yes
Weyl		$=0$		Yes
Metric		$=0$	$=0$	(not applicable)
Generic teleparallel	$=0$			No
Metric teleparallel	$=0$		$=0$	No
Symmetric teleparallel	$=0$	$=0$		No

Adapted from 2204.03003

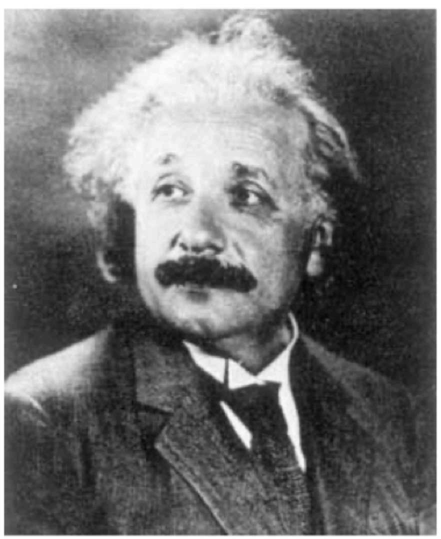
Particle spectra are identical, only massless graviton.

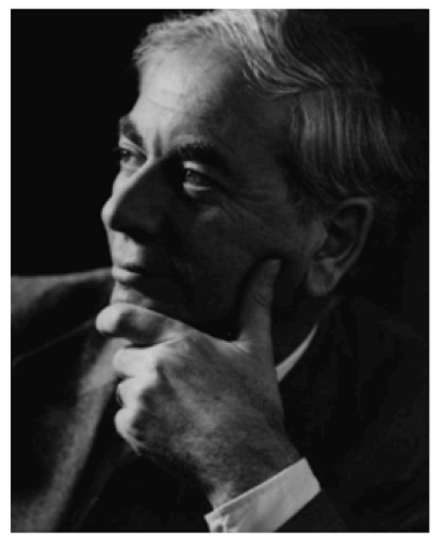
Not modified gravities, just different representations of the same theory

Complementary / Advantages

- No GHY term for a well-defined variational principle
- Potential implication for BH entropy and topological problems
- Theories such as LQG or SUGRA need torsion
- Einstein-Cartan gravity follows from gauging the Poincaré group ☆

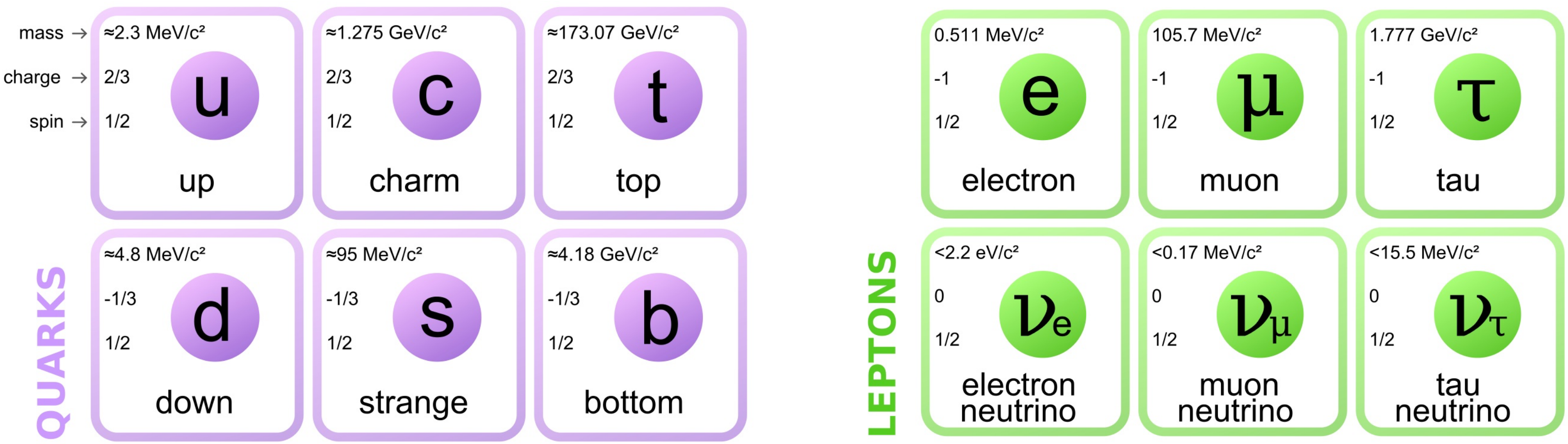
This talk






M. Blagojevic, B. Cvetkovic JHEP 10 (2006) 005
Utiyama, Phys. Rev. 101, 1597 (1956) T. Kible, J. Math. Phys. 2, 212 (1961)

SM fermions source torsion



$$i\gamma^\mu \nabla_\mu \psi + \boxed{\frac{3}{8M_P}\left(\bar{\psi}\gamma_\mu\gamma^5\psi\right)\gamma^\mu\gamma^5\psi} - m\psi = 0$$

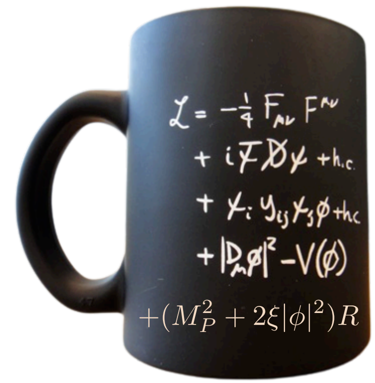
- Changes maximum star compactness (Buchdahl limit).
- Formation of singularities may be avoided

P. Luz and S. Carloni, PRD 100, 084037 (2019)

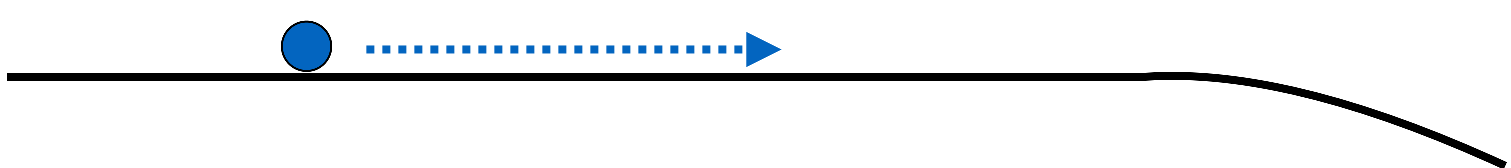
P. Luz, F. C. Mena and A.H. Ziaie, CQG. 36, 015003 (2019)
S. Hensh, S. Liberati, Phys.Rev.D 104 (2021) 8

An unavoidable gravity proxy

$$\frac{\Delta\mathcal{L}_{\text{SM+G}}}{\sqrt{-g}} = \frac{M_P^2 + \xi h^2}{2} g^{\mu\nu} R_{\mu\nu}(\Gamma)$$



- Not suppressed by any scale
- Not a choice, required by the self-consistency of the theory
- Higgs EXISTS, so NATURE is indeed described by a scalar-tensor theory
- Emergent scale symmetry at large field values $h \gg M_P/\sqrt{\xi}$
- There must exist variables where the Higgs behaves as a massless scalar



Projective symmetry

$$R \sim \mathring{R} + c_{TT}T^2 + c_{QQ}Q^2 + c_{TQ}TQ \quad + d_T \mathring{\nabla} T^\mu + d_q \mathring{\nabla} Q^\mu$$

Invariant under most general transformation that changes the auto-parallel curves by a reparametrization of the affine parameter

$$\Gamma^\rho{}_{\mu\nu} \to \Gamma^\rho{}_{\mu\nu} + \delta^\rho_\nu A_\mu$$

The connection $\Gamma^\gamma{}_{\mu\nu}$ cannot be uniquely determined by its equations of motion

Non-minimal couplings

$$R \sim \mathring{R} + \xi h^2 \mathring{R} + c_{TT}T^2 + c_{QQ}Q^2 + c_{TQ}TQ + \xi_T h^2 \mathring{\nabla} T + \xi_Q h^2 \mathring{\nabla} Q$$

The equations of motion for T and Q yield a non-trivial result

$$T \sim \partial h^2 \,, \qquad Q \sim \partial h^2$$

Standard Model in Palatini

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2 + \xi h^2}{2} g^{\mu\nu} R_{\mu\nu}(\Gamma) - \frac{1}{2} g^{\mu\nu}\partial_\mu h \partial_\nu h - V(h)\right]$$

$$\frac{\delta S}{\delta \Gamma} = 0 \quad \Rightarrow \quad \nabla_\rho\left[(M_P^2 + \xi h^2)\sqrt{-g}g^{\mu\nu}\right] = 0$$

with admits a solution

$$\Gamma^\rho_{\mu\nu} = \left\{ {\rho \atop \mu\nu} \right\} + \delta^\rho_\mu \partial_\nu \omega(h) + \delta^\rho_\nu \partial_\mu \omega(h) - g_{\mu\nu}\partial^\rho \omega(h)$$

$$\omega = \ln\Omega = \ln\sqrt{1 + \frac{\xi h^2}{M_P^2}}$$

Standard Model in EC

1. No gravitational operators with mass dimension greater than 2
2. No extra degrees of freedom in the gravitational sector
3. Renormalizable Lagrangian in flat space-time limit

Decomposing torsion into vector, axial and tensor irreducible components

$$T_{\mu\nu\rho} = \frac{2}{3} v_{[\nu} g_{\rho]\mu} - \frac{1}{6} a^{\sigma} \epsilon_{\mu\nu\rho\sigma} + \tau_{\mu\nu\rho}$$

we get

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{1+\xi h^2}{2} g^{\mu\nu} R_{\mu\nu}(\Gamma) - \frac{1}{2} g^{\mu\nu} \partial_\mu h \partial_\nu h - \frac{\lambda}{4}(h^2 - v^2)^2 + \zeta_h^v v^\mu \partial_\mu h^2 + \zeta_h^a a^\mu \partial_\mu h^2$$
$$+ \frac{1}{2}\Big(G_{vv} v_\mu v^\mu + 2 G_{va} v_\mu a^\mu + G_{aa} a_\mu a^\mu + G_{\tau\tau} \tau_{\alpha\beta\gamma} \tau^{\alpha\beta\gamma} + \tilde{G}_{\tau\tau} \epsilon^{\mu\nu\rho\sigma} \tau_{\lambda\mu\nu} \tau^{\lambda}{}_{\rho\sigma} \Big)$$

with $G_{ij} = c_{ij}\left(1 + \xi_{ij} h^2\right)$

Karananas, Shaposhnikov, Shkerin, Zell Phys.Rev.D 104 (2021) 6, 064036
M. Piani and JR 2304.13056 [hep-ph]

Einstein frame formulation

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{2} - \frac{1}{2}\frac{1+c\,h^2}{(1+\xi h^2)^2}(\partial h)^2 - \frac{\lambda}{4}\frac{h^4}{(1+\xi h^2)^2}\right]$$

$$c(h) = \xi + 6\xi^2 + 4(1+\xi h^2)\frac{G_{aa}(\zeta_h^v)^2 + G_{vv}(\zeta_h^a)^2 - G_{va}\zeta_h^v\zeta_h^a}{G_{vv}G_{aa} - G_{va}^2}$$

M. Piani and JR 2304.13056 [hep-ph]

A case of study: The Nieh-Yan term

Covers several equivalence classes

$$c_{va} = \xi_{va} = 0\,, \qquad c_{vv} = -16c_{aa} = -\frac{2}{3}\,, \qquad \xi_{vv} = \xi_{aa} = -\zeta_h^v = \xi\,, \qquad \zeta_h^a = \frac{1}{4}\xi_\eta$$

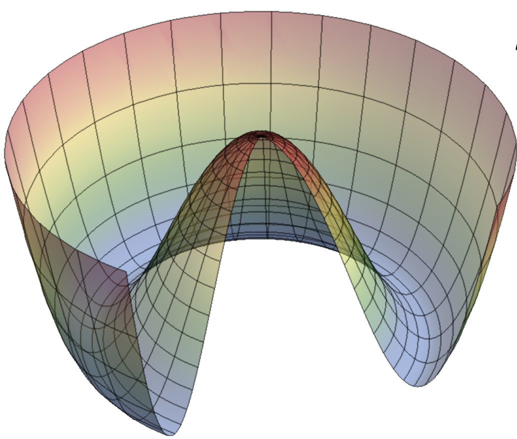
$$\frac{\mathcal{L}}{\sqrt{-g}} = -\frac{1}{4}\int d^4x\,\xi_\eta h^2\partial_\mu\left(\sqrt{-g}\epsilon^{\mu\nu\rho\sigma}T_{\nu\rho\sigma}\right) \qquad c = \xi + 6\xi_\eta^2$$

Smooth parametric interpolation between
metric ($\xi_\eta = \xi$) and Palatini formulations ($\xi_\eta = 0$)

Higgs Inflation

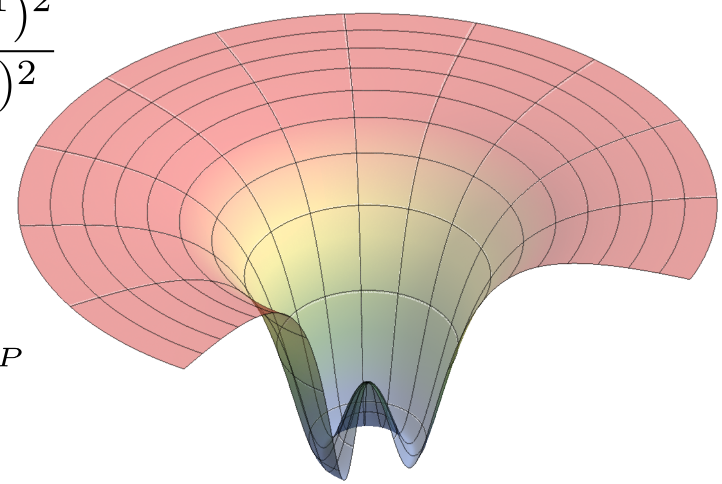
$$S = \int d^4x\sqrt{-g}\left[\frac{R}{2} - \frac{1}{2}\frac{1+c\,h^2}{(1+\xi h^2)^2}(\partial h)^2 - \frac{\lambda}{4}\frac{h^4}{(1+\xi h^2)^2}\right]$$

Non-linear realisation of scale-symmetry $=$ Shift symmetry in canonical variables



$$h \to h^{-1} \qquad K \sim \frac{(\partial h^{-1})^2}{(h^{-1})^2}$$

$$h \approx \frac{M_P}{\sqrt{\xi}} e^{\sqrt{|\kappa_c|}\,\chi/M_P}$$

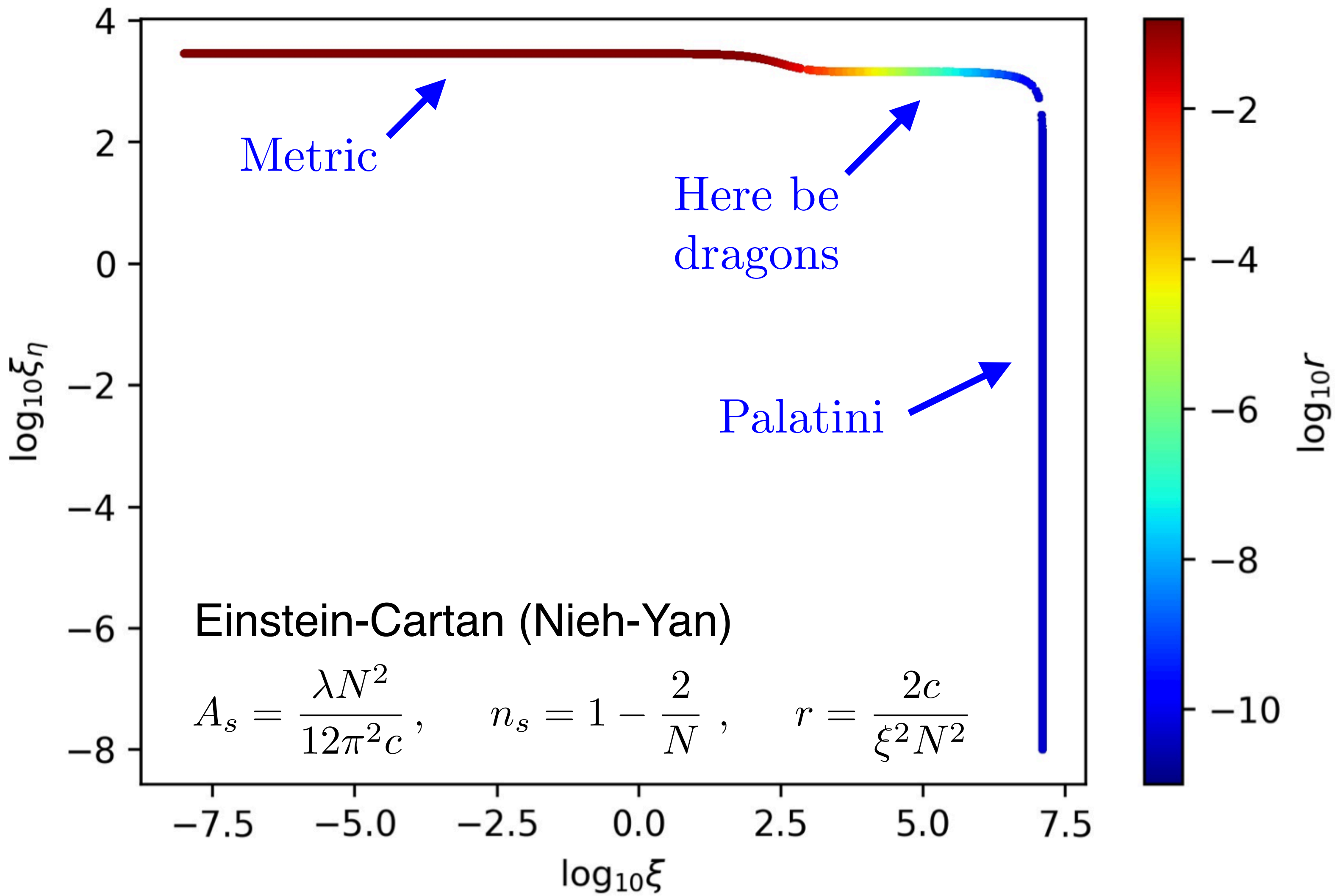


Predictions depend on the residue $\kappa_c = c/\xi^2$ of quadratic pole

For a review see JR, Front.Astron.Space Sci. 5 (2019) 50.

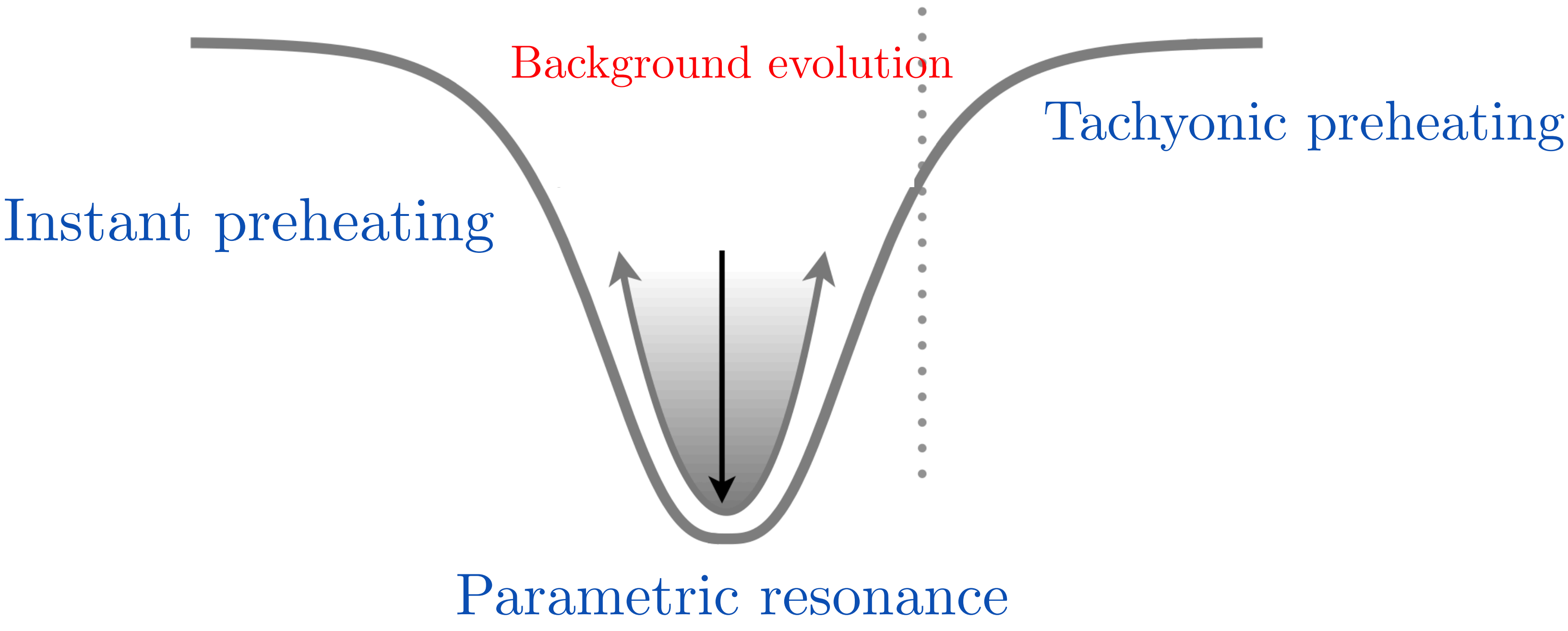
Different inflation predictions

Consistent with observations for most parameter choices



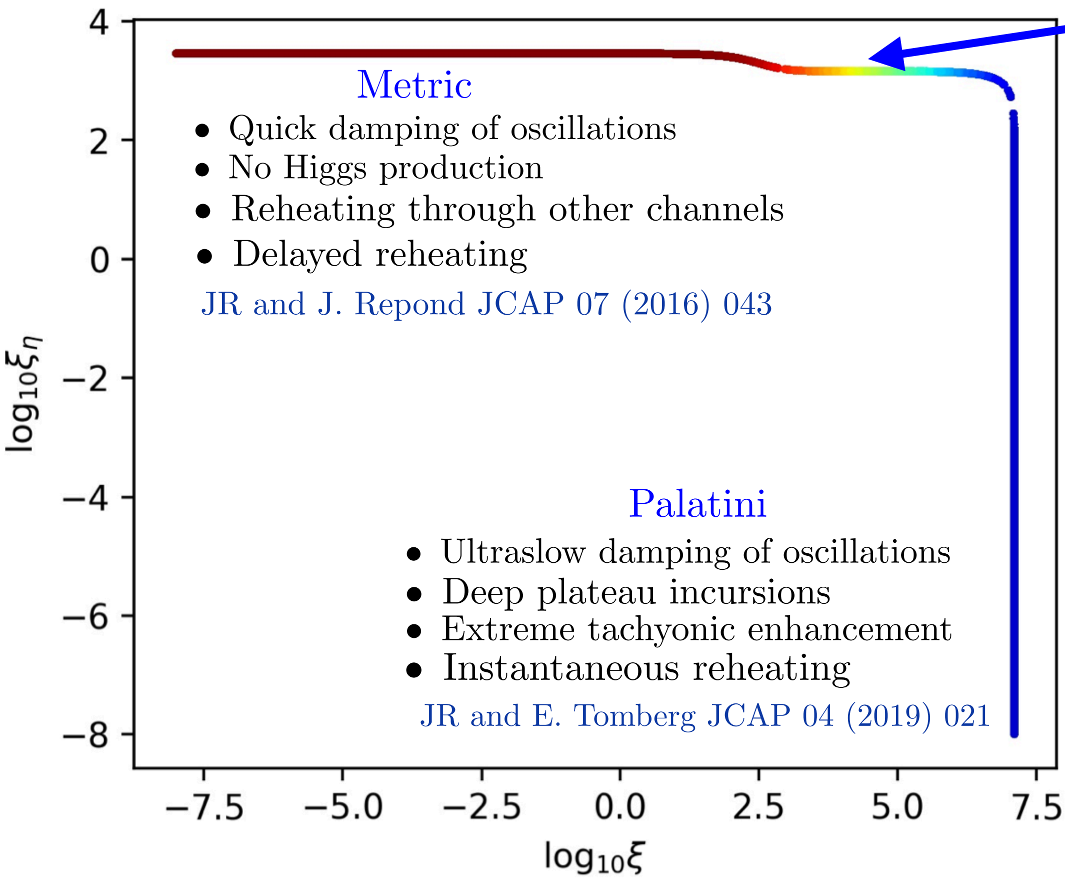
Onset of hot Big Bang

- Potentially computable, all couplings are known
- Perturbative decays suppressed immediately after inflation
- Non-perturbative particle production, preheating



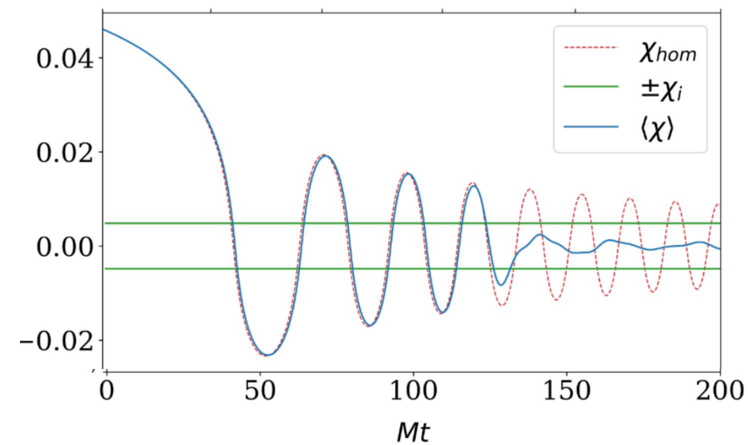
Different preheating stages

$$M_P^2 \frac{dH}{dh} = -\frac{1}{2}\sqrt{6H^2M_P^2 - 2U[\chi(h)]}\,\frac{d\chi}{dh} \qquad \frac{d\chi}{dh} = \sqrt{\frac{1 + c\,h^2}{(1+\xi h^2)^2}}$$



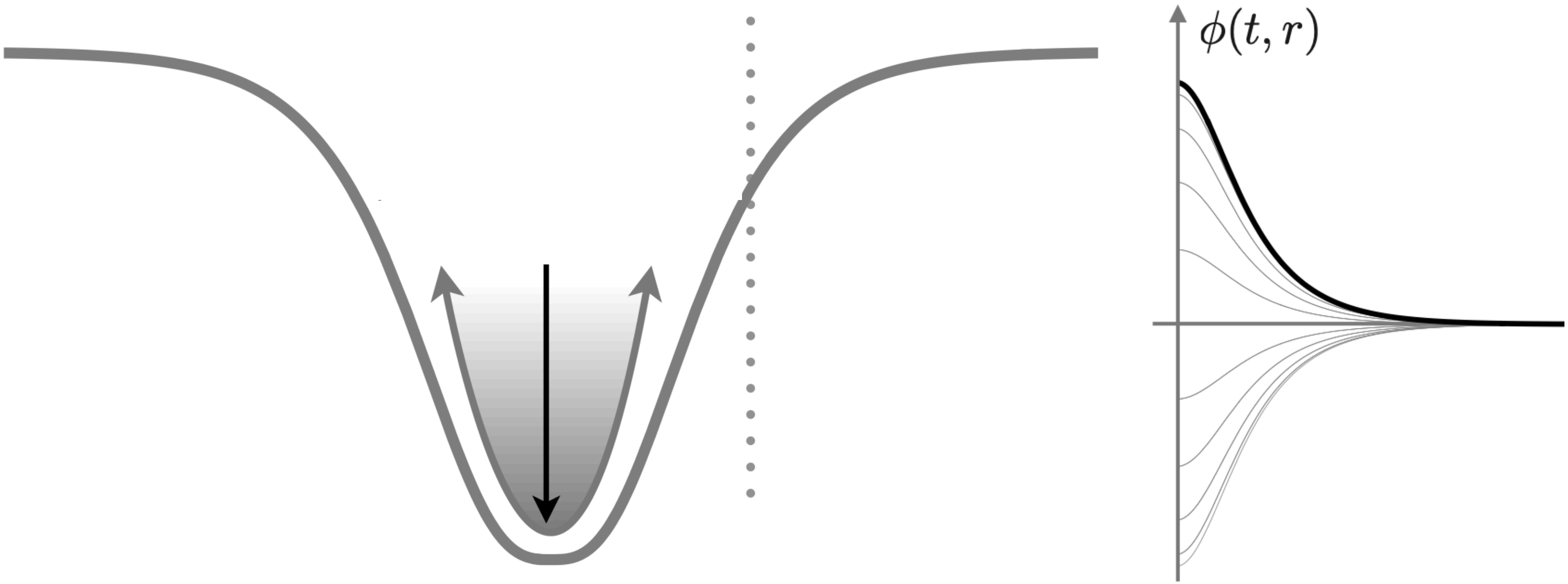
Here be dragons

- Slow damping of oscillations
- Small plateau incursions
- Inflaton condensate fragmentation



$$\delta\ddot{\chi}_{\mathbf{k}} + 3H\delta\dot{\chi}_{\mathbf{k}} + \left(\mathbf{k}^2/a^2 + V_{,\chi\chi}\right)\delta\chi_{\mathbf{k}} = 0$$

Here be dragons: Oscillons



- They may appear in potentials shallower than quadratic
- Similar to Q-balls but without conserved charged
- Still, amazingly long-lived

Adapted from JCAP 07 (2020) 055

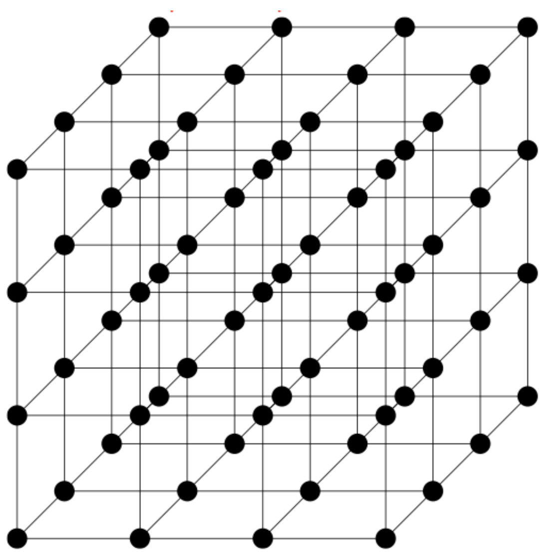
Lattice simulations

Hamiltonian scheme: coupled first-order differential equations

$$\frac{d^2\chi}{dt^2} - \frac{1}{a^2}\nabla^2\chi + \frac{3}{a}\frac{da}{dt}\frac{d\chi}{dt} = -\frac{dV}{d\chi} \qquad \begin{cases} (\pi_\chi)' = -a^{3+\alpha}\frac{dV}{d\chi} + a^{1+\alpha}\nabla^2\chi \\ \chi' \equiv \pi_\chi a^{\alpha-3} \end{cases}$$

Second Friedmann equation use to evolve the scale factor

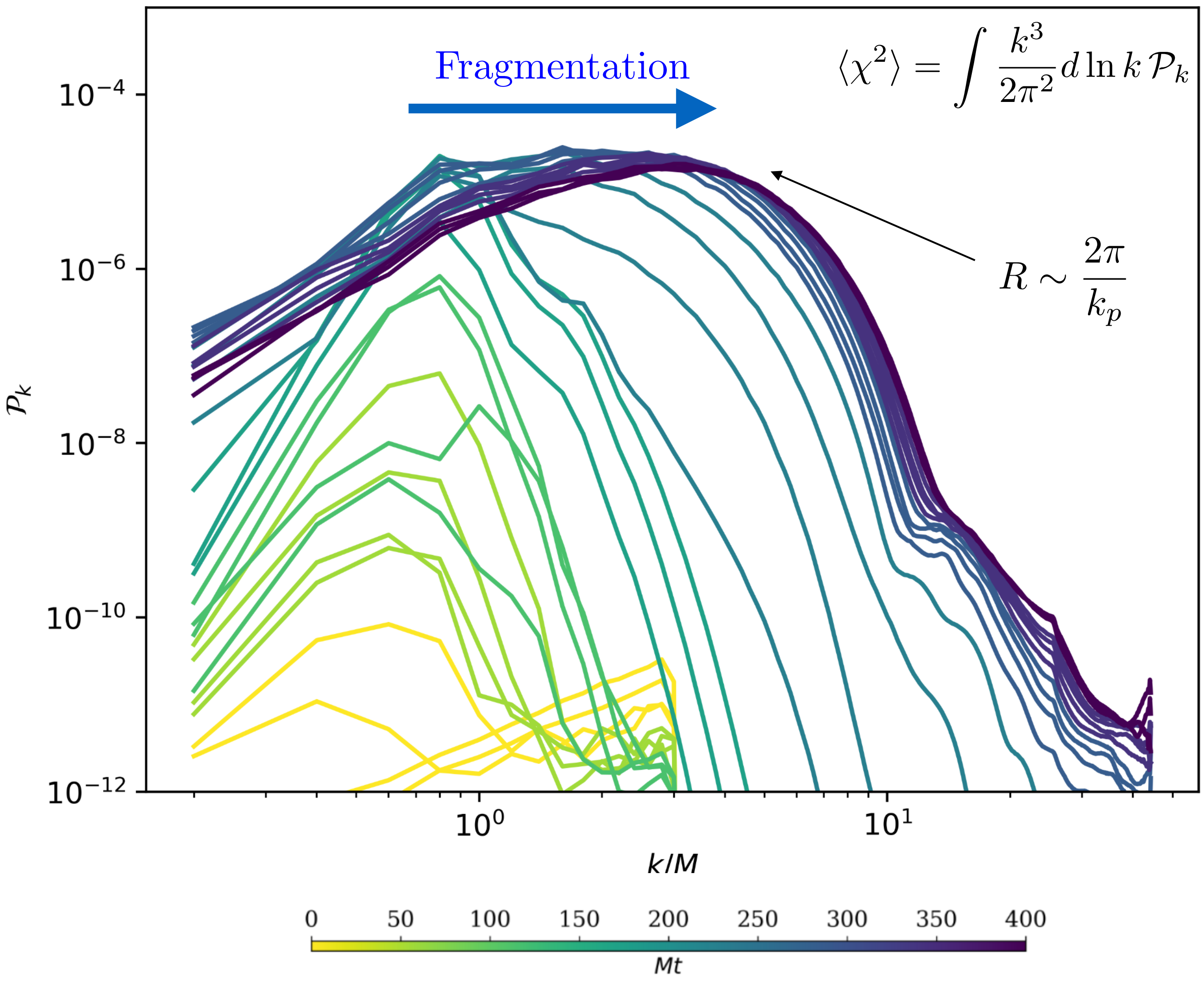
First Friedmann equation used to check energy conservation



- Periodic Boundary Conditions
- Limited resolution

$$k_{\rm min} = \frac{2\pi}{L} \qquad k_{\rm max} = \frac{\sqrt{3}}{2} N k_{\rm min}$$

Tachyonic amplification

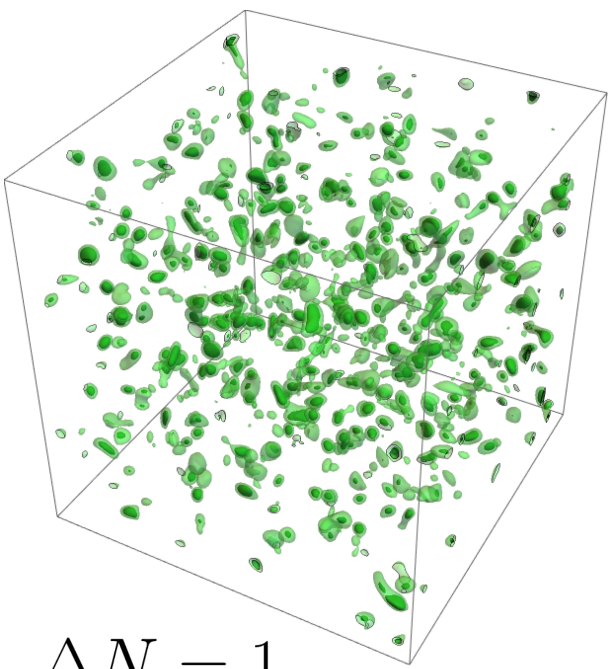


M. Piani and JR 2304.13056 [hep-ph]

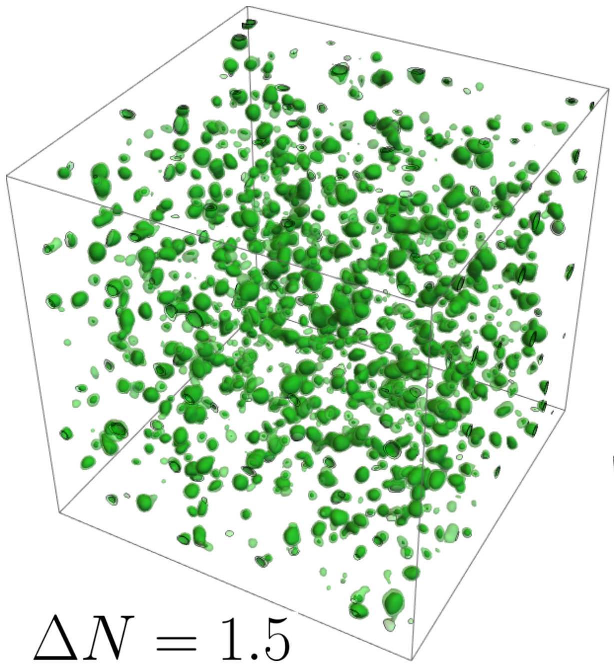
Oscillons in EC

Long-lived quasi-spherical pseudo-solitonic configurations

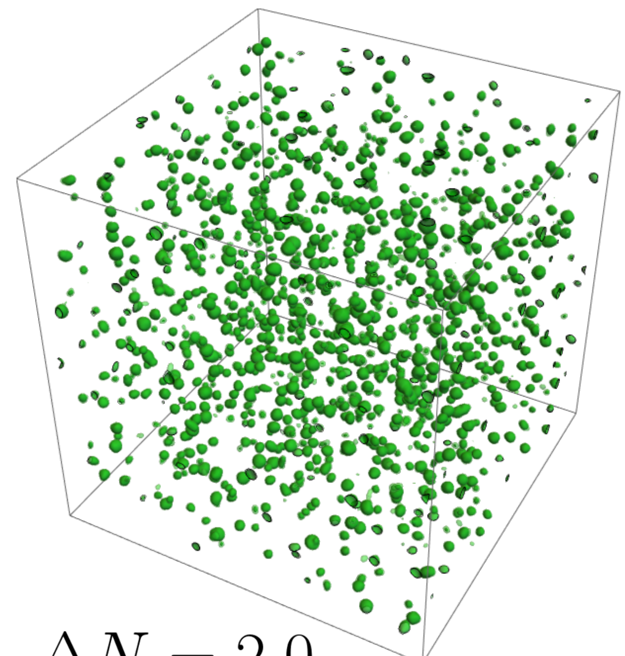
$$|\Phi| \sim \frac{\mathcal{M}}{R} \ll 1$$



$\Delta N = 1$



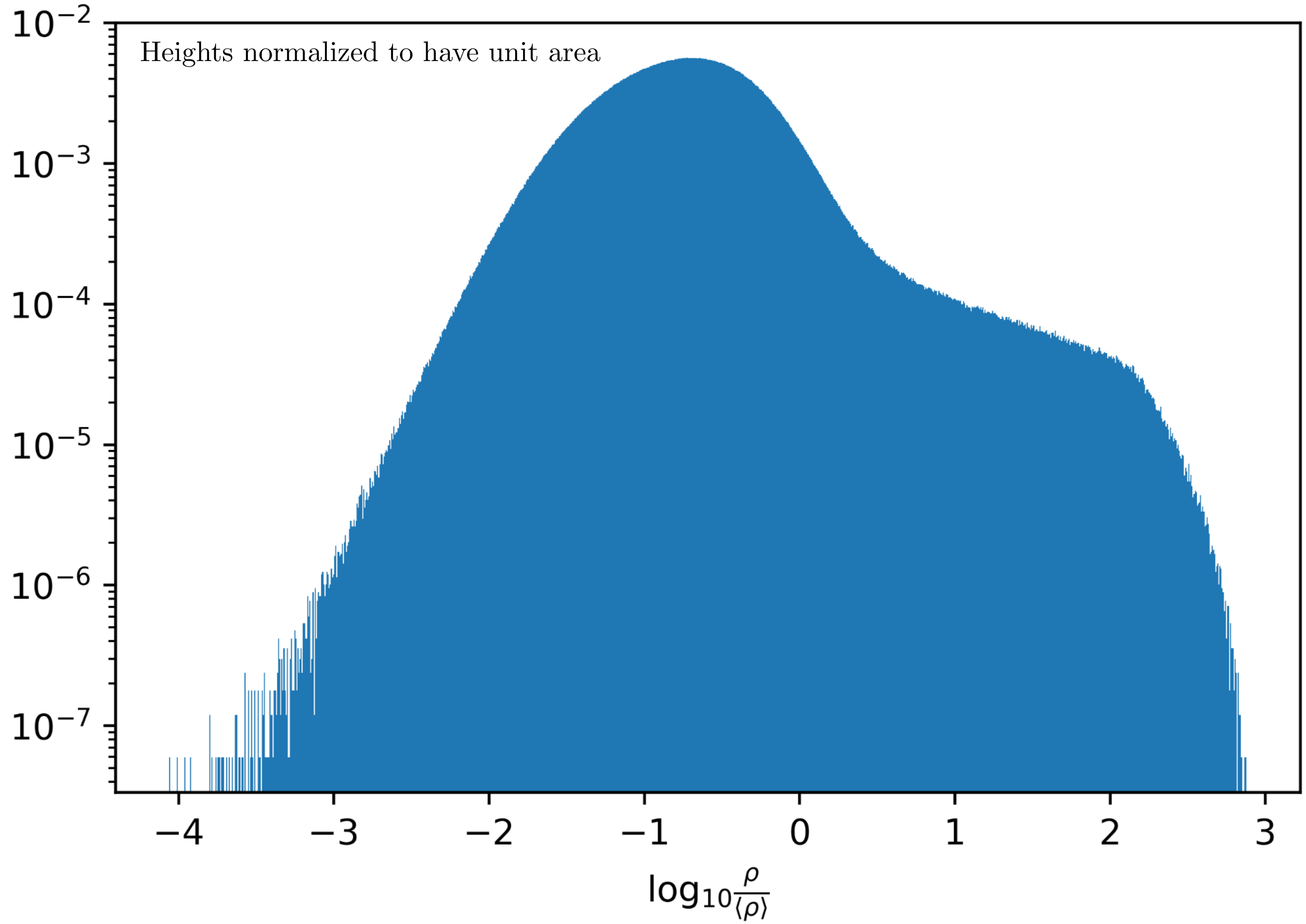
$\Delta N = 1.5$



$\Delta N = 2.0$

M. Piani and JR 2304.13056 [hep-ph]

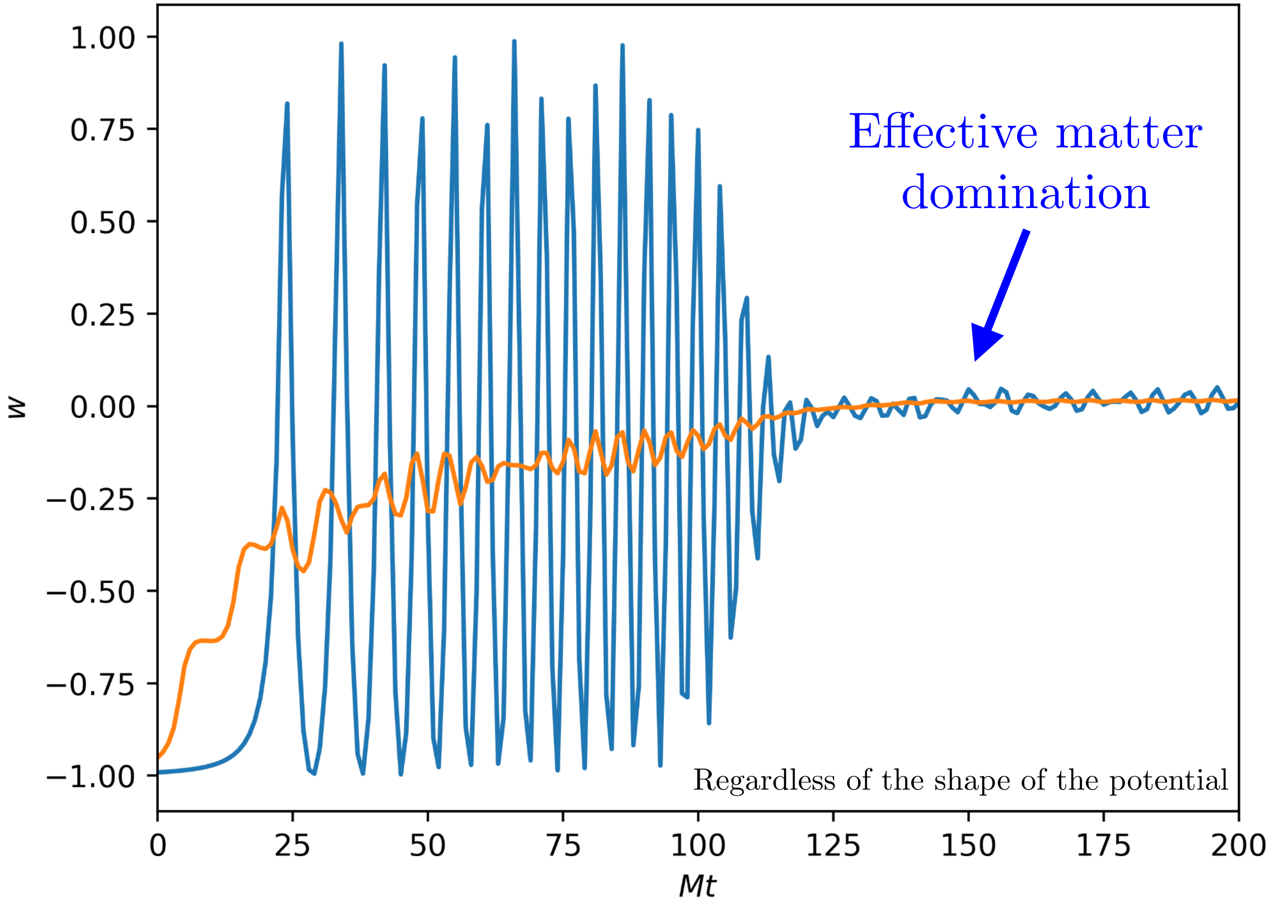
Energy density histograms



Subdominant in volume, but dominate the energy, with about 66% of the total

M. Piani and JR 2304.13056 [hep-ph]

Extended Matter Domination

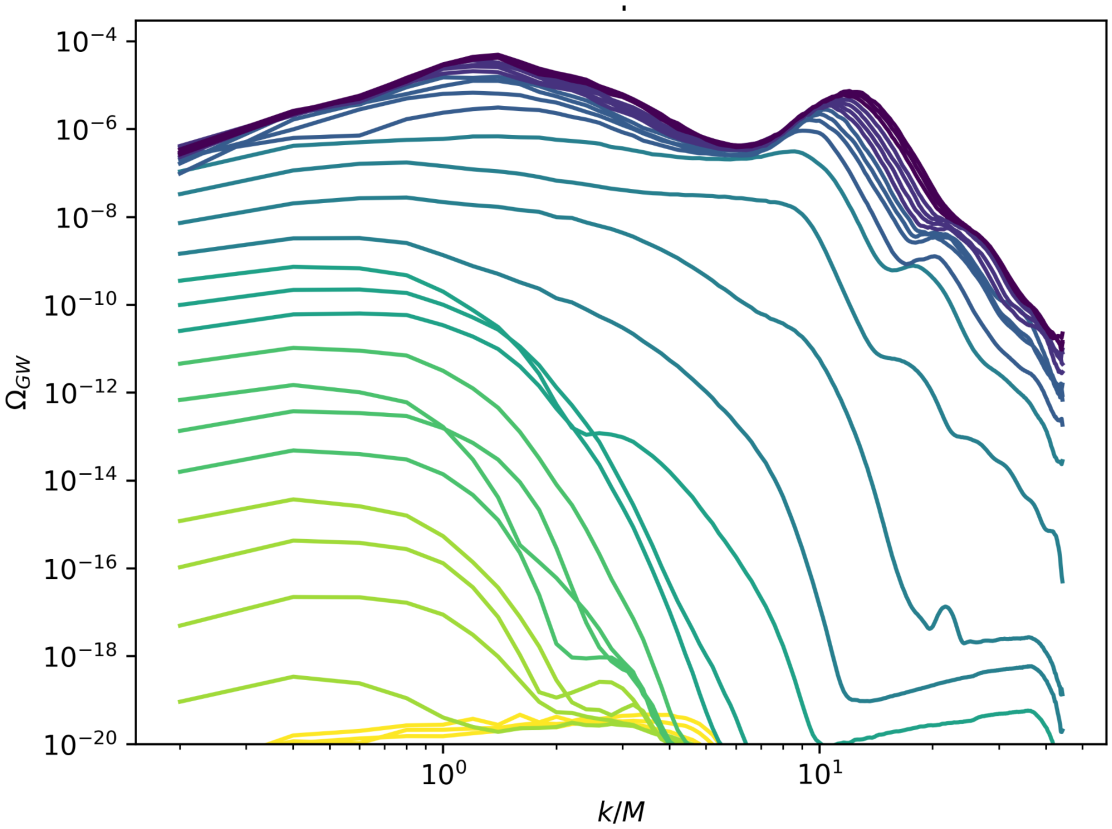


This modifies the minimal number of e-folds of inflation needed to solve the flatness and horizon problems, as compared to metric and Palatini formulations

M. Piani and JR 2304.13056 [hep-ph]

Gravitational waves in EC

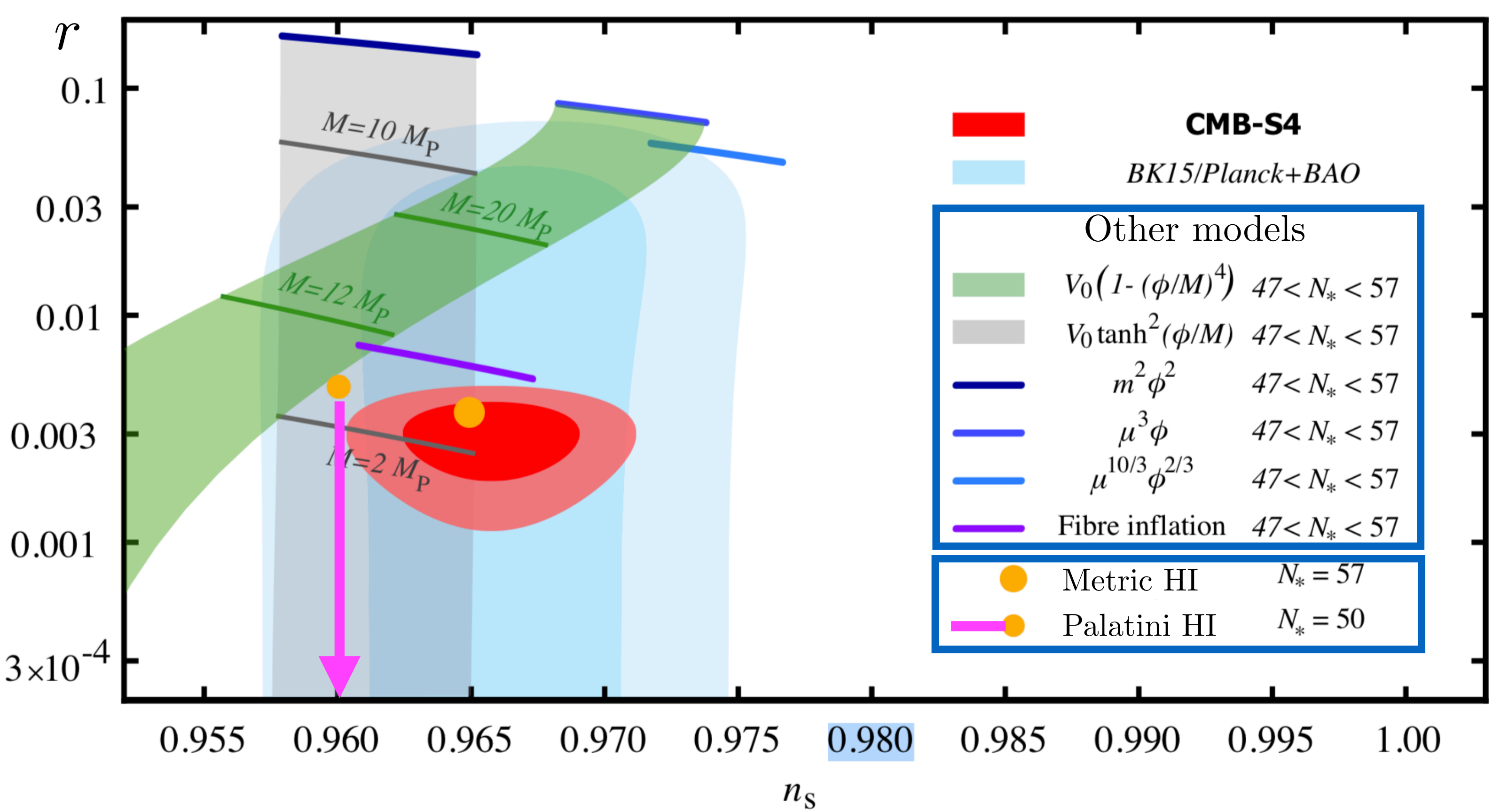
$$\ddot{h}_{ij} + 2H\dot{h}_{ij} - \nabla^2 h_{ij} = 2\Pi_{ij}^{TT}$$



The signal is commensurable with the sensitivity of current GWs experiments, but the peak frequency turns out to be $\mathcal{O}(\text{GHz})$, lying therefore far away from the available observational window.

M. Piani and JR 2304.13056 [hep-ph]

Distinctive predictions



Some gravity incarnations are 2σ distinguishable

JR and Eemeli Tomberg, JCAP 04 (2019) 021

Conclusions

Different formulations of gravity become inequivalent in the presence of non-minimal couplings to the SM Higgs

Cosmological consequences

- The tensor-to-scalar ratio in some formulations is highly suppressed as compared to the metric case.
- Different preheating dynamics translate also into different spectral tilt values, potentially distinguishable by future CMB-S4 experiments.

All this is controlled by the inverse residue in the E-frame

Future directions

- Include full Standard Model structure
- Particle production in oscillon backgrounds (Quantum oscillons)
- Gravitational waves from oscillon decay

Backup Slides

Minimal set of operators

$$= \frac{1}{2}\,\mathrm{Tr}\ln\left[\Box - \left(\frac{\lambda}{4}(F^4)''\right)^2\right]$$

$$U(\chi) = \frac{\lambda}{4}F(\chi) \quad + \text{ counterterms to cancel divergencies}$$

$$\delta\mathcal{L}_{\rm ct} = \left(-\frac{2}{\bar\epsilon}\frac{9\lambda^2}{64\pi^2} + \delta\lambda_a\right)\left(F'^2 + \frac{1}{3}F''F\right)^2 F^4 \qquad \text{new}$$

At low energies

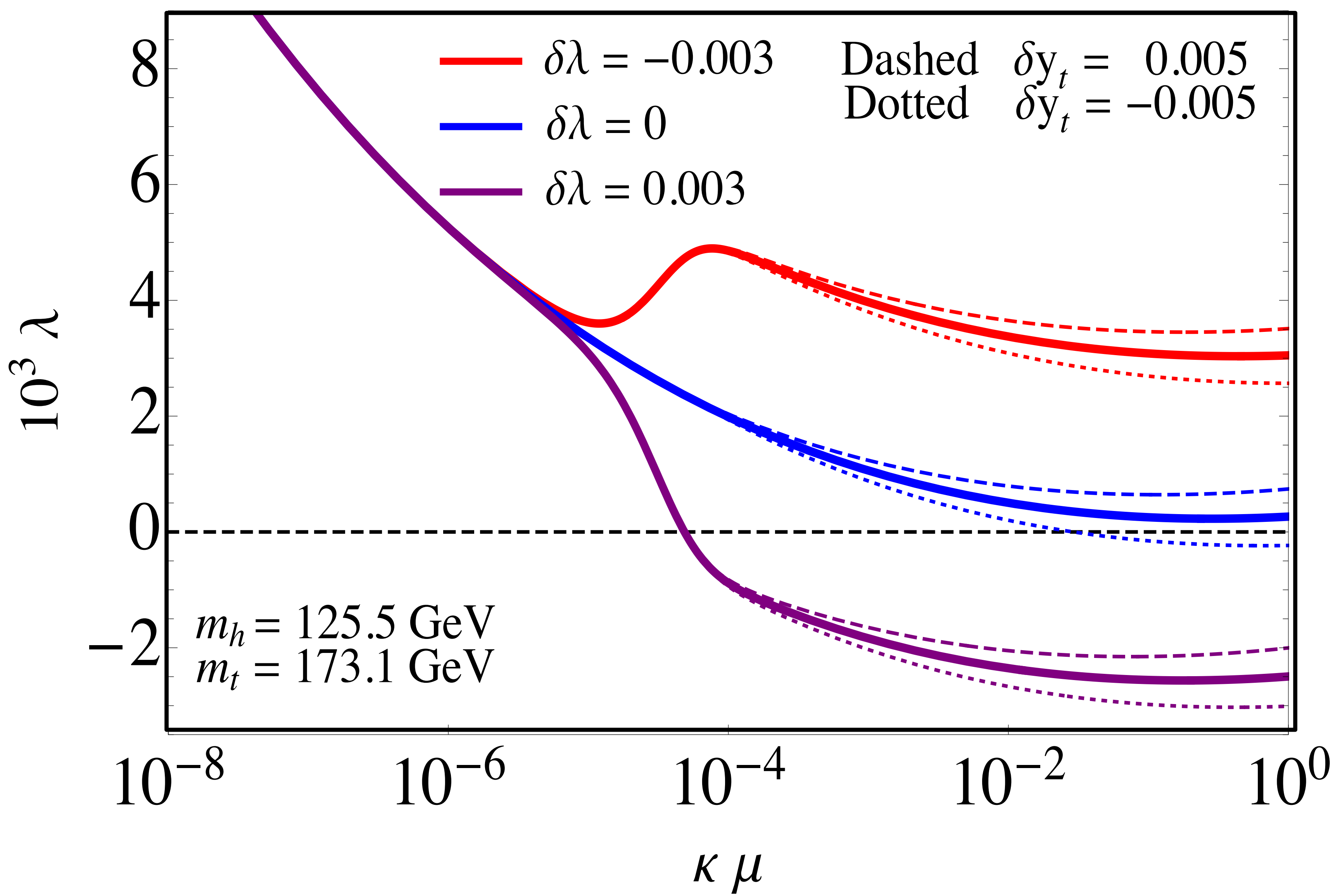
$F = \chi \quad F'(0) = 1$

At high energies

$F = const. \quad F'(\phi_0) = 0$

F. L. Bezrukov, J. Rubio, M. Shaposhnikov Phys.Rev. D92 (2015) no.8, 083512

Threshold corrections



IR-UV connection

Metric formulation

$$\Lambda < \mu_{\text{inf}} \sim \frac{y_t M_P}{\sqrt{\xi}}$$

$$\delta\beta = \frac{g^2}{16\pi^2}$$

$$\delta\lambda = \frac{g^2 \ln \xi}{32\pi^2} \approx 2 \times 10^{-2}$$

Palatini formulation

$$\Lambda > \mu_{\text{inf}} \sim \frac{y_t M_P}{\sqrt{\xi}}$$

$$\delta\beta = \frac{g^2}{16\pi^2} \frac{\mu_{\text{inf}}^2}{\Lambda^2}$$

$$\delta\lambda = \frac{g^2 y_t^2}{32\pi^2} \sim 6 \times 10^{-4}$$

IR-UV connection lost in metric Higgs inflation
IR-UV connection not lost in Palatini Higgs inflation

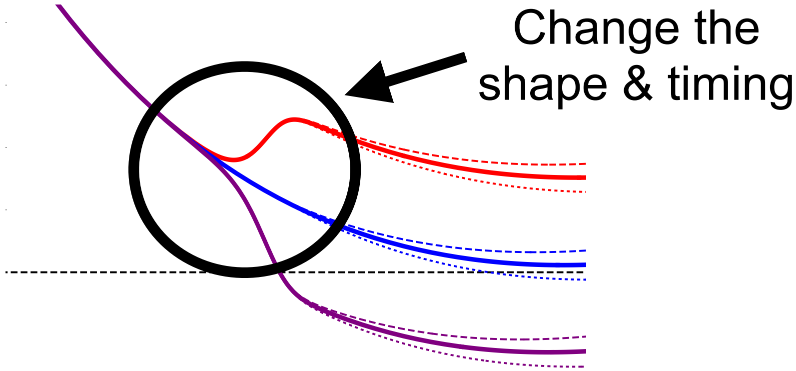
M. Shaposhnikov, A. Shkerin, S. Zell, e-Print: 2002.07105

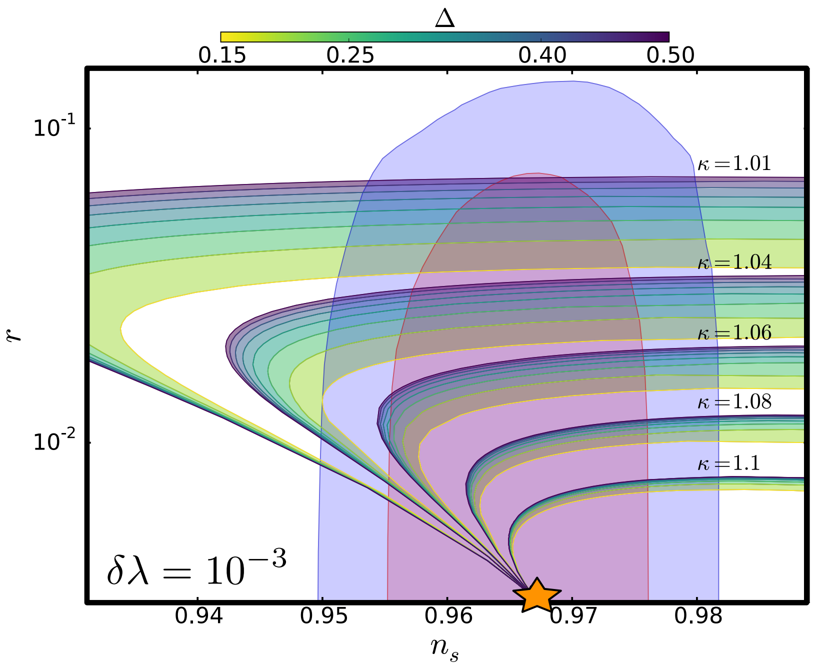
OBSERVABLES' ROBUSTNESS

- Running of finite parts?

$$\delta\Lambda(\phi) = \delta\lambda \frac{\left(1 - F^2/F_\infty^2\right)^4}{\left(1 + \Delta \cdot 6\,\xi\, F^2/F_\infty^2\right)^2}$$

- Higher order operators?





✓ **HI preditions are "fireproof"**

The spectral tilt in both metric and Palatini Higgs inflation is insensitive to the model parameters

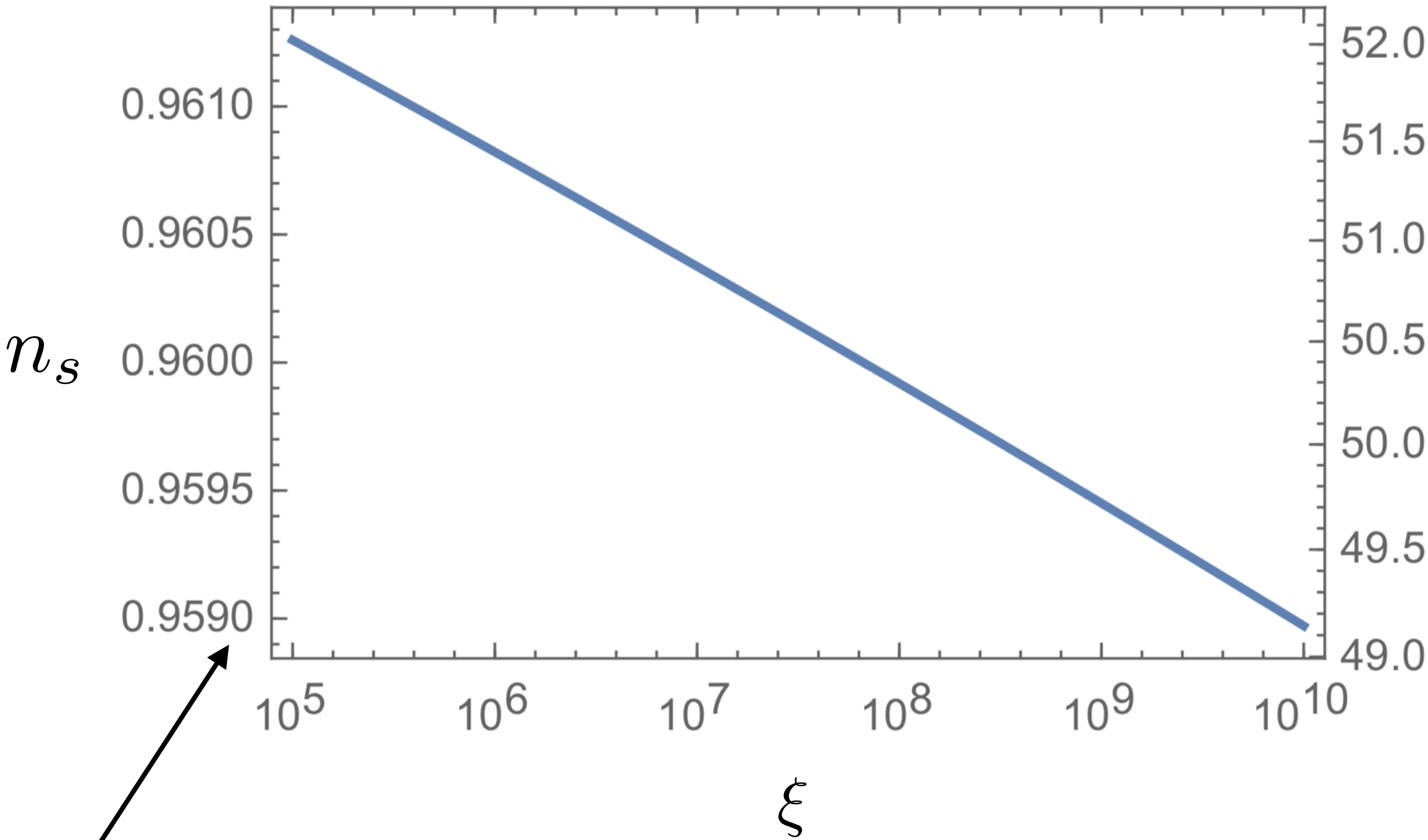
$$n_s \simeq 1 - \frac{2}{N}$$

Instantaneous reheating

ξ	$n_{\rm osc}$	Peak ΔN
10^5	1.75	0.10
10^6	1.25	0.04
10^7	1.25	0.02
10^8	0.75	0.007
10^9	0.75	0.004

Result applicable to T-attractor scenarios

Required number of e-folds



$\mathcal{O}(1/N^2)$