Hubble-induced phase transitions

Javier Rubio

Based on D.Bettoni, A. Lopez-Eiguren, JR, JCAP 01 (2022) 01, 002
G. Laverda, JR, JCAP 03 (2024) 033

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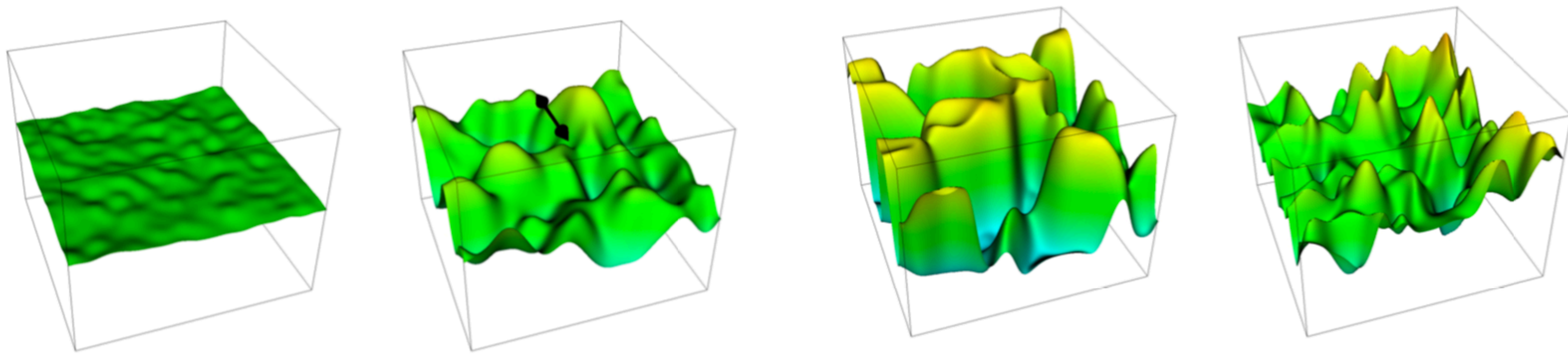
The general paradigm

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_P^2}{2} R - \frac{1}{2}(\partial\chi)^2 - f(R, R_{\mu\nu})\chi^2 - V(\chi)$$



- Natural triggering mechanism for phase transitions
- Non-thermal & non-perturbative
- Short-lived topological defects
- Specific gravitational waves signatures

A dedicated program

1. Quintessential Affleck-Dine baryogenesis with non-minimal couplings,
   D. Bettoni, J. Rubio Phys.Lett.B 784 (2018) 122-129

2. Gravitational waves from global cosmic strings in quintessential inflation,
   D. Bettoni, G. Domènech, J. Rubio, JCAP 02 (2019) 034

3. Hubble-induced phase transitions: Walls are not forever.
   D. Bettoni, J. Rubio, JCAP 01 (2020) 002

4. Hubble-induced phase transitions on the lattice with applications to Ricci reheating.
   D. Bettoni, J.Rubio, JCAP 01 (2022) 01, 002

5. Ricci reheating reloaded,
   G. Laverda, JCAP 03 (2024) 033

6. From Hubble to Bubble,
   M. Kierkla, G.Laverda, M. Lewicki, A. Mantziris, M.Piani, JHEP 11 (2023) 077

7. The rise and fall of the Standard-Model Higgs: electroweak vacuum stability during kination.
   G. Laverda, J. Rubio, JHEP 05 (2024) 339

For a review see D. Bettoni, JR, Galaxies 10 (2022) 1, 22

A worked-out example

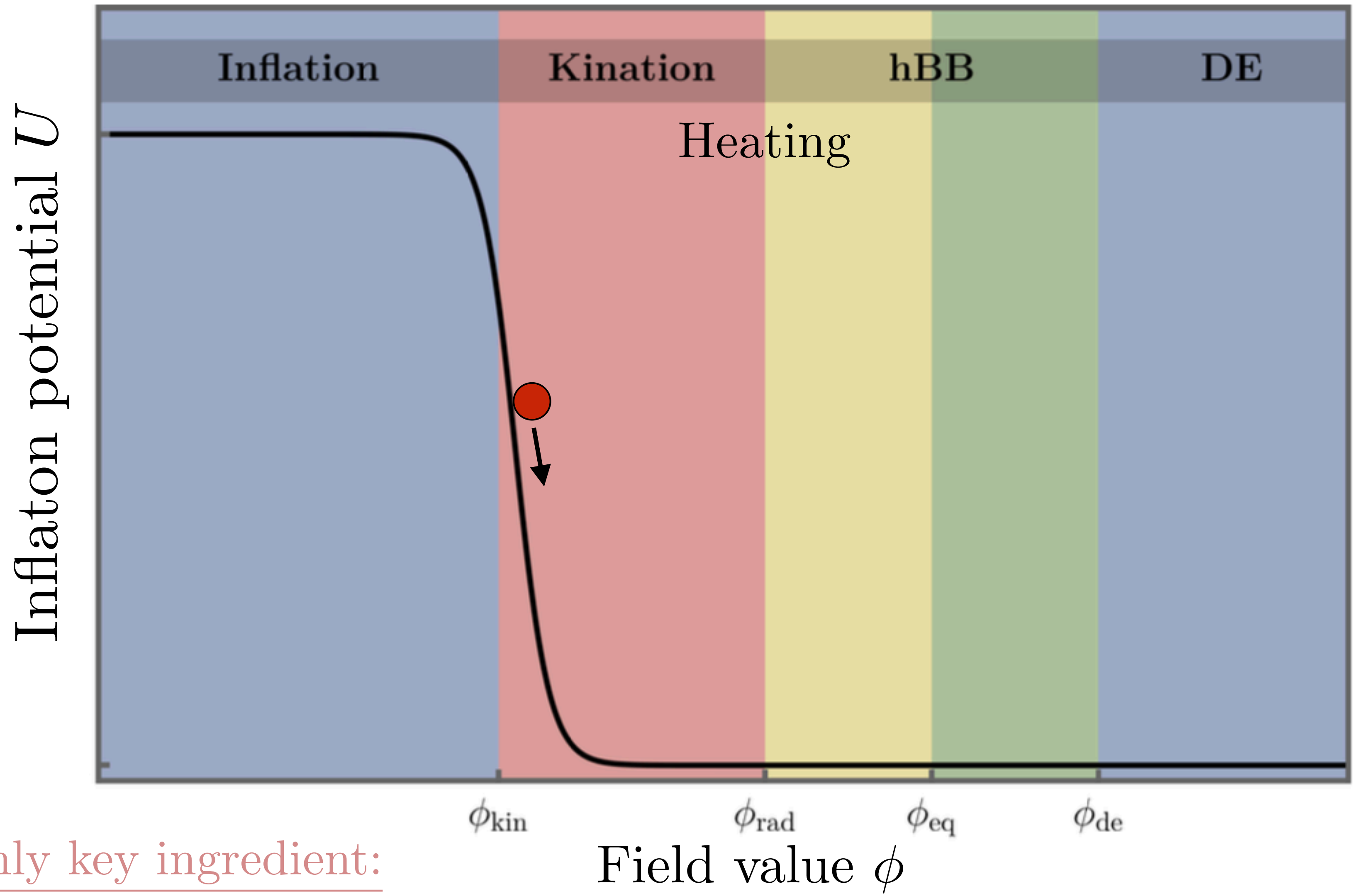
- A single scalar field ϕ for both inflation and dark energy
- A non-minimal coupling of a spectator field χ to gravity

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_P^2}{2} R - \frac{1}{2}(\partial\chi)^2 - \xi R \chi^2 - V(\chi) + \mathcal{L}_\phi$$

Interesting outputs

- No isocurvature perturbations even if χ is light
- Highly efficient heating mechanism
- Onset of radiation domination rather independent of $V(\chi)$

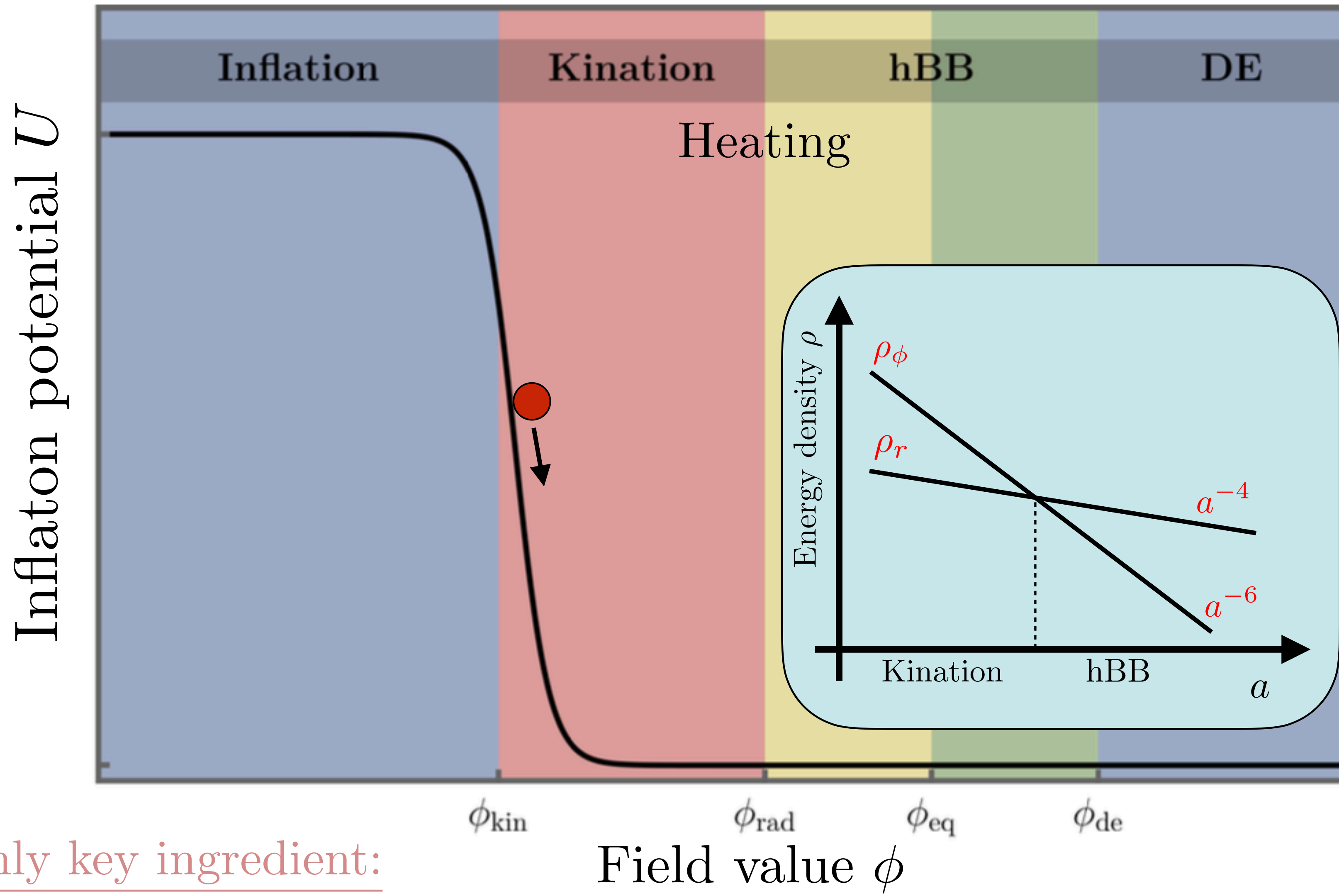
Quintessential inflation



Only key ingredient:
Period of kination

For a review see e.g. D. Bettoni, JR, Galaxies 10 (2022) 1, 22

Quintessential inflation



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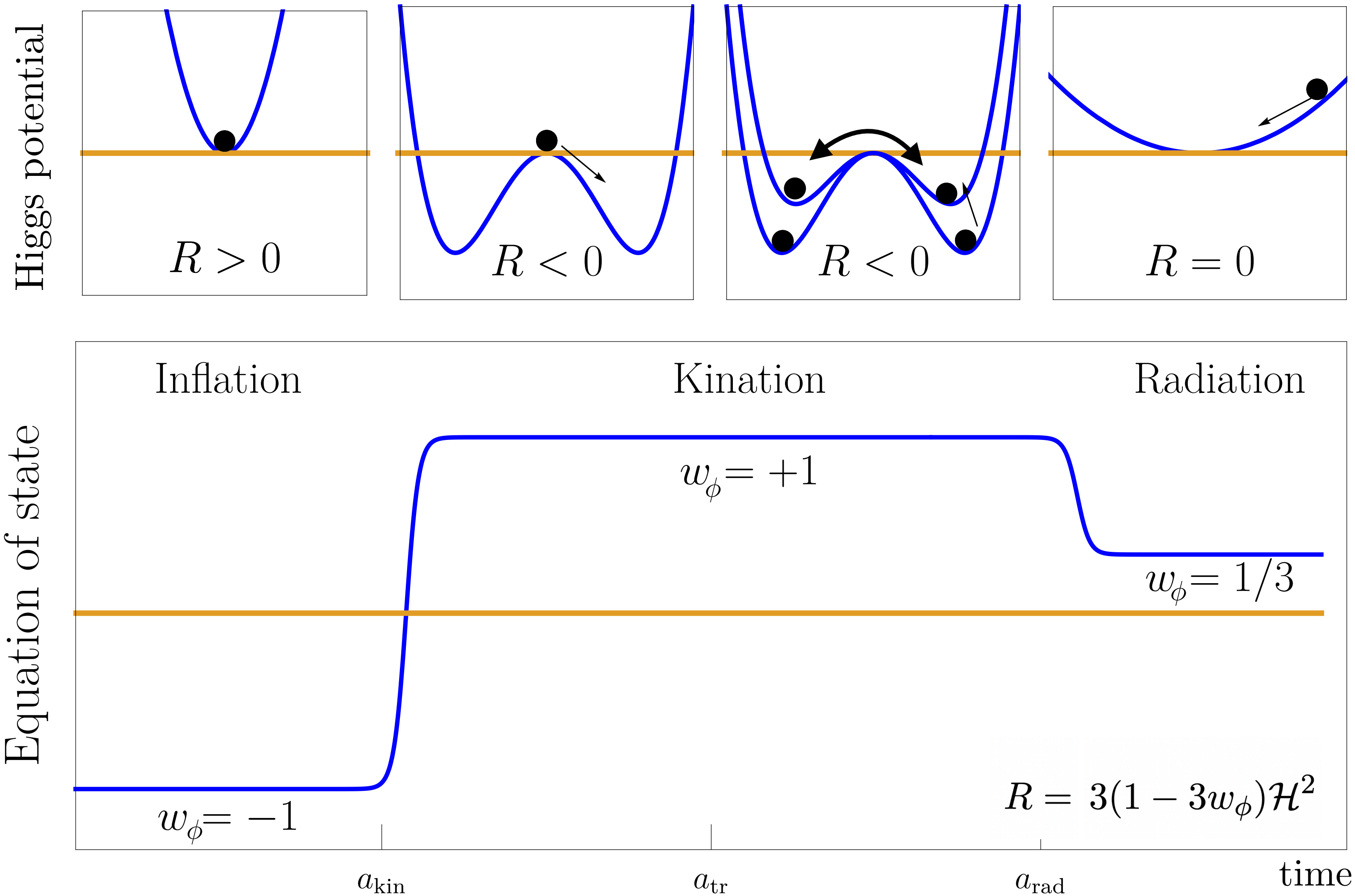
Equation of state as order parameter



D. Bettoni, JR, Phys.Lett.B 784 (2018) 122-129; D. Bettoni, G. Domènech, JR, JCAP 02 (2019) 034, D. Bettoni, JR, JCAP 01 (2020) 002, D. Bettoni, A. López-Eiguren, JR, JCAP 01 (2022) 01, 002

See also Figueroa & Byrnes 1604.03905, Dimopoulos, Markkanen 1803.07399, Opferkuch, Schwaller, Stefanek 1905.06823 (homogeneous approx. only)

Linear dynamics

$$Y \equiv \frac{a}{a_{\rm kin}} \frac{\chi}{\chi_*}, \qquad \vec{y} \equiv a_{\rm kin}\chi_*\, \vec{x}, \quad z \equiv a_{\rm kin}\chi_*\, \tau, \qquad \chi_* \equiv \sqrt{6\xi} H_{\rm kin}$$

Spinodal/Tachyonic instability

$$S_\chi = \int d^3\vec{y}\, dz \left[\frac{1}{2}(Y')^2 - \frac{1}{2}|\nabla Y|^2 + \frac{1}{2}M^2(z)Y^2 - V(Y)\right]$$

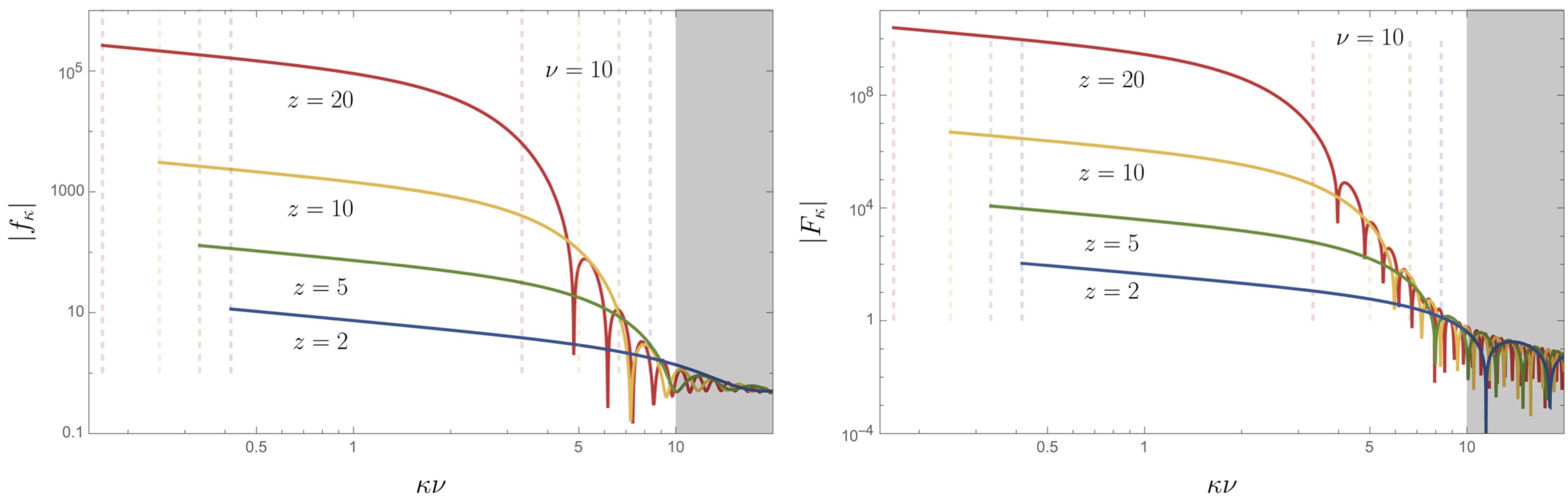
$$M^2(z) \equiv (4\nu^2 - 1)\mathcal{H}^2 \qquad \nu \equiv \sqrt{\frac{3\xi}{2}}$$

- The Z_2 symmetry of the action is preserved by the dynamics.
- The field is *not* classical but rather quantum.
- A homogeneous component description is *completely inaccurate*.

D. Bettoni, JR, JCAP 01 (2020) 002

Classicalization

$$f_\kappa'' + (\kappa^2 - M^2(z)) f_\kappa = 0 \qquad F_\kappa(z) = \mathrm{Re}(f_\kappa^* f_\kappa')$$



$$\Delta Y_\kappa^2 \, \Delta \Pi_\kappa^2 = |F_\kappa(z)|^2 + \frac{1}{4} \geq \frac{1}{4} \left| \langle [Y_\kappa(z), \; \Pi_\kappa^\dagger(z)] \rangle \right|^2$$

- Following dynamics needs non-analytical techniques.
- High occupation numbers $\rightarrow$ Classical Lattice Simulations

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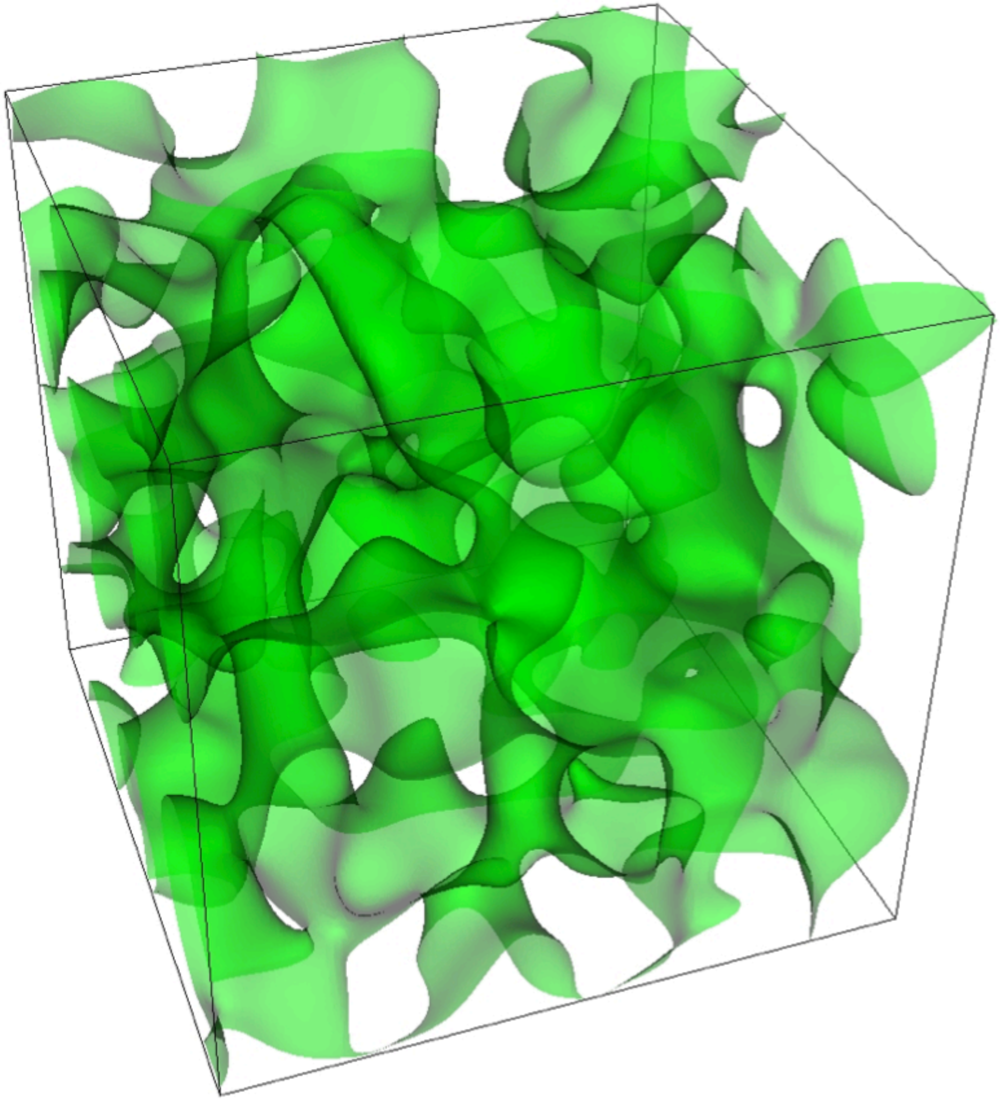
Beating Domain Walls



WATCH NOW
AND RELAX

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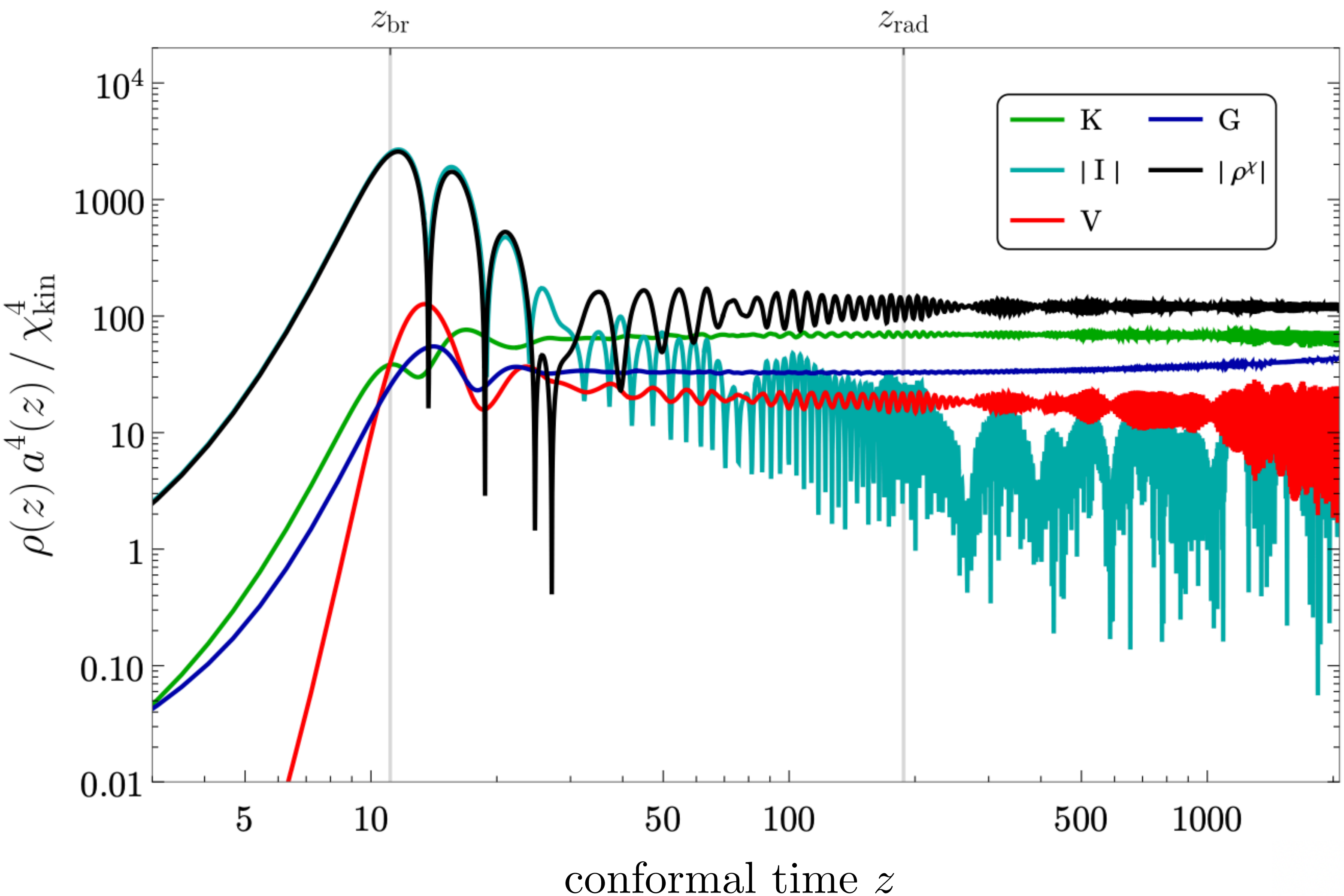
Energy distribution



$$\nu = \sqrt{\frac{3\xi}{2}}$$

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Gradients are crucial

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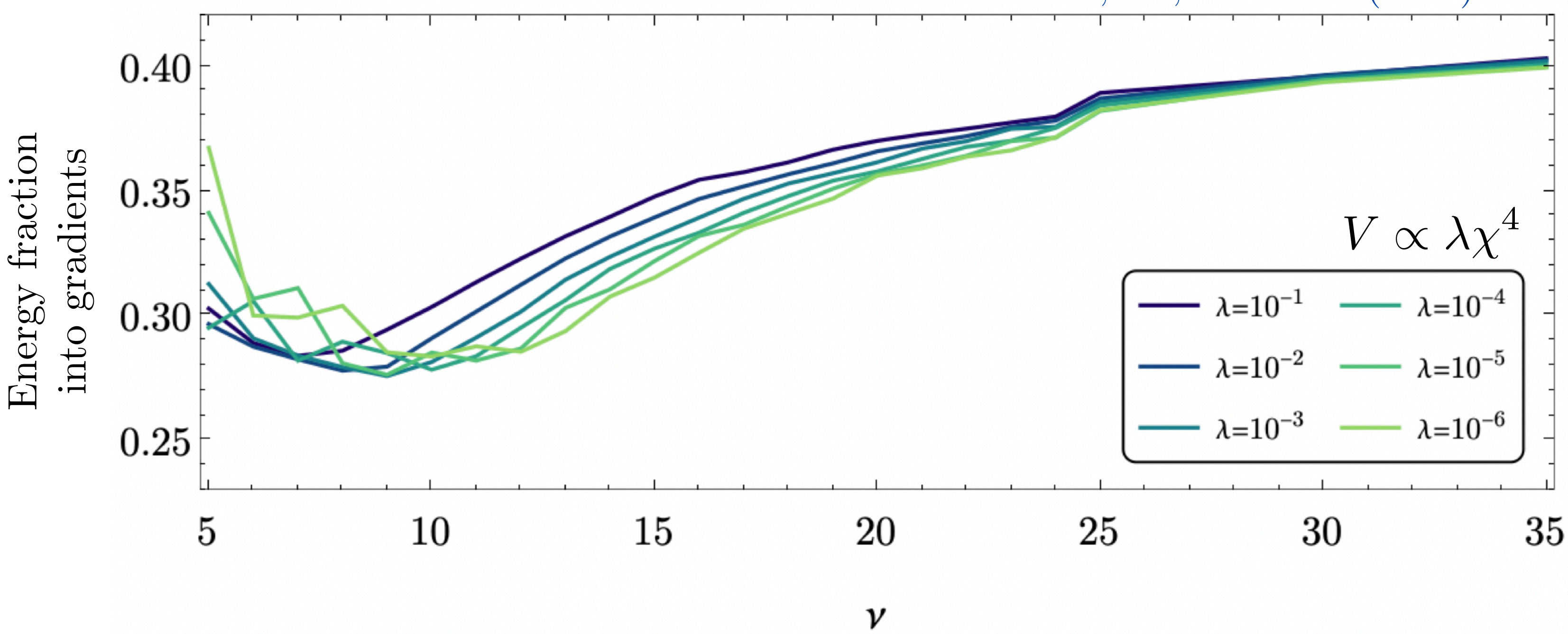

Radiation-like products for arbitrary potential

$$w_\chi = \frac{1}{3} + \frac{2}{3}\frac{(n-2)}{(n+1) + \langle(\nabla\chi/a)^2\rangle/\langle V\rangle} \qquad V \propto \chi^{2n}$$

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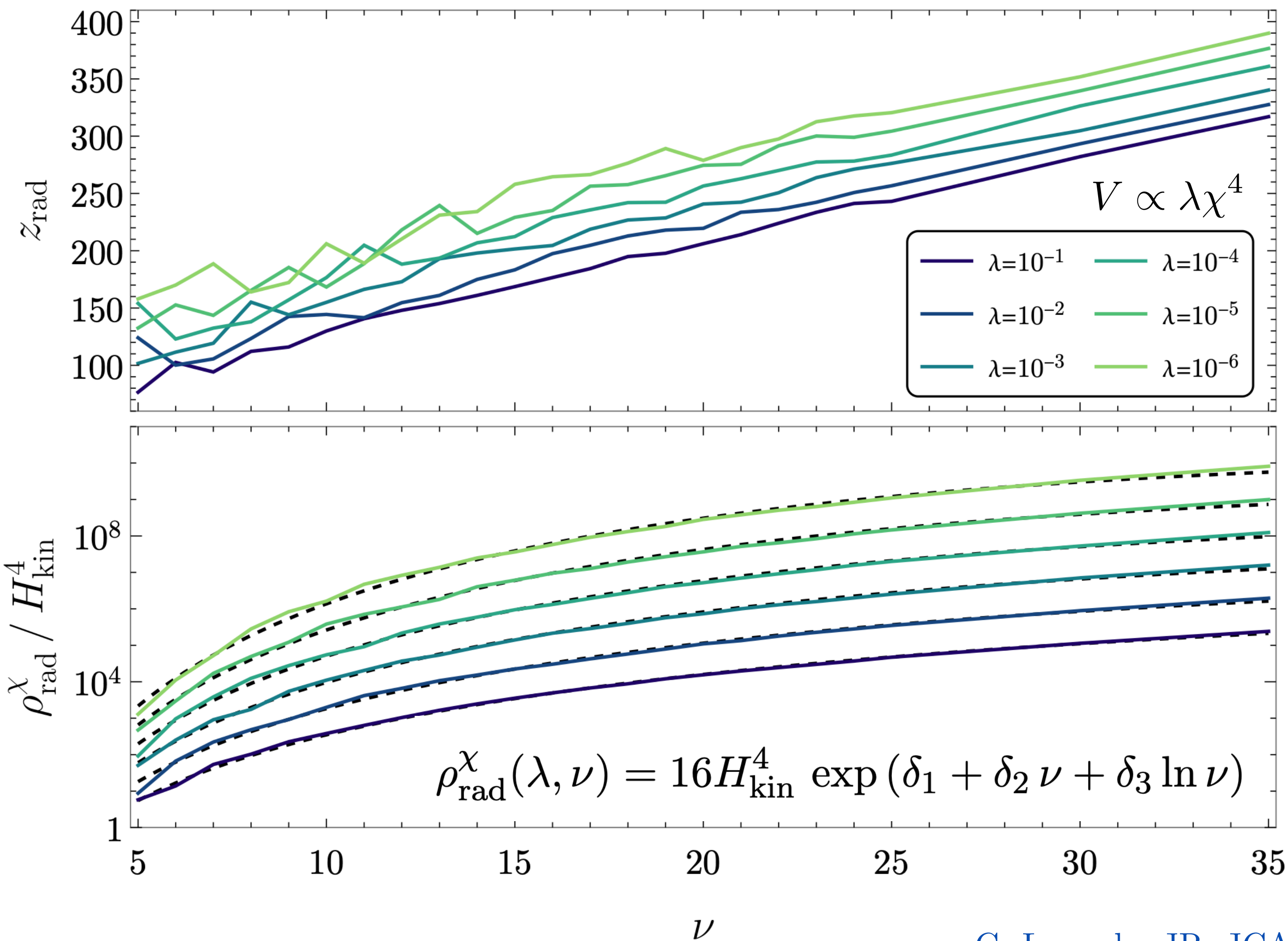
Onset of radiation domination

Lattice-based fitting formulas: O(100) 3+1 classical lattice simulations



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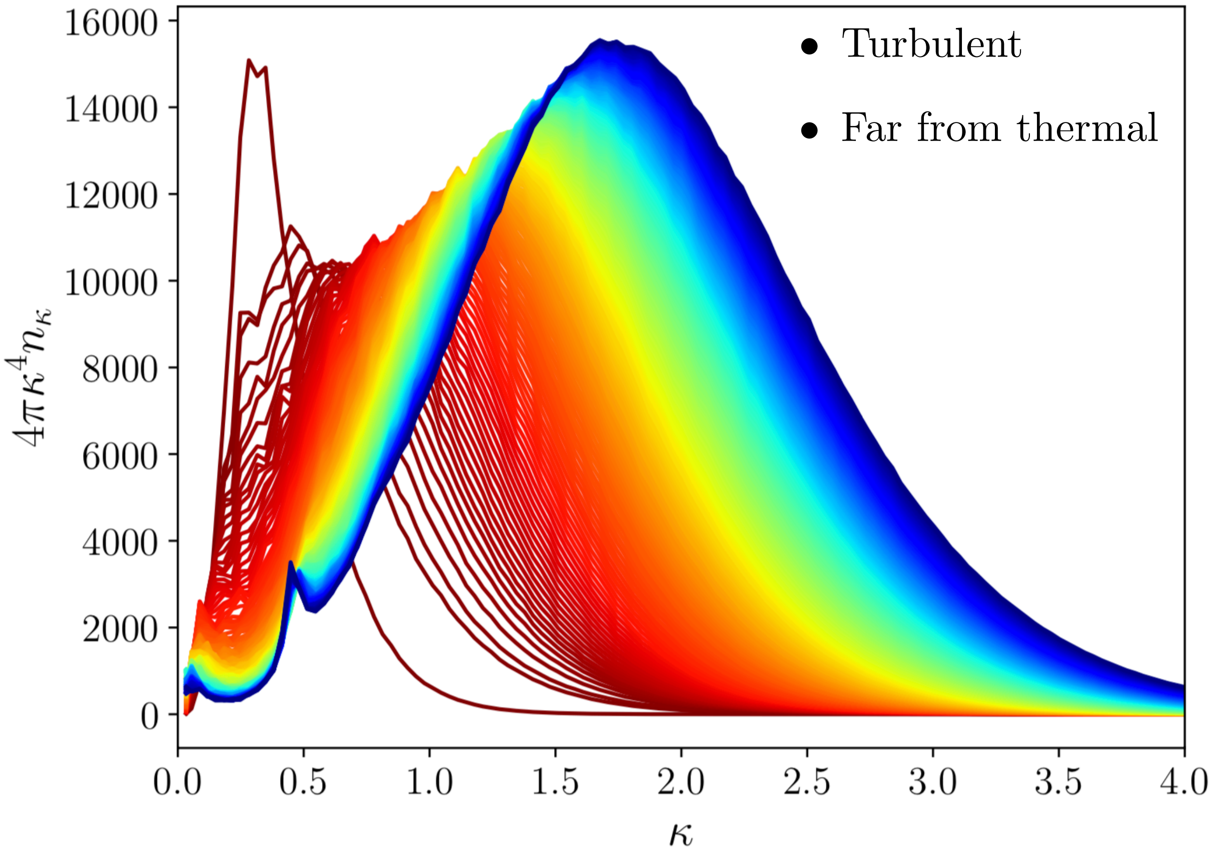
Heating "temperature"

By-product
First lattice characterisation of Ricci reheating



$$T_{\rm ht} \simeq 2.7 \times 10^8\,\text{GeV}\left(1+\frac{z_{\rm rad}}{\nu}\right)^{-3/4}\left(\frac{\rho^{\chi}_{\rm rad}/\rho^{\phi}_{\rm rad}}{10^{-8}}\right)^{3/4}\left(\frac{H_{\rm kin}}{10^{11}\,\text{GeV}}\right)^{1/2}$$

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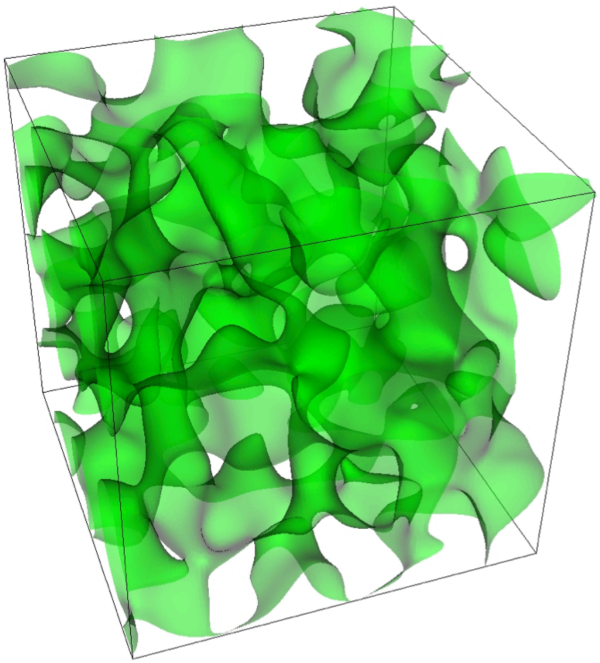
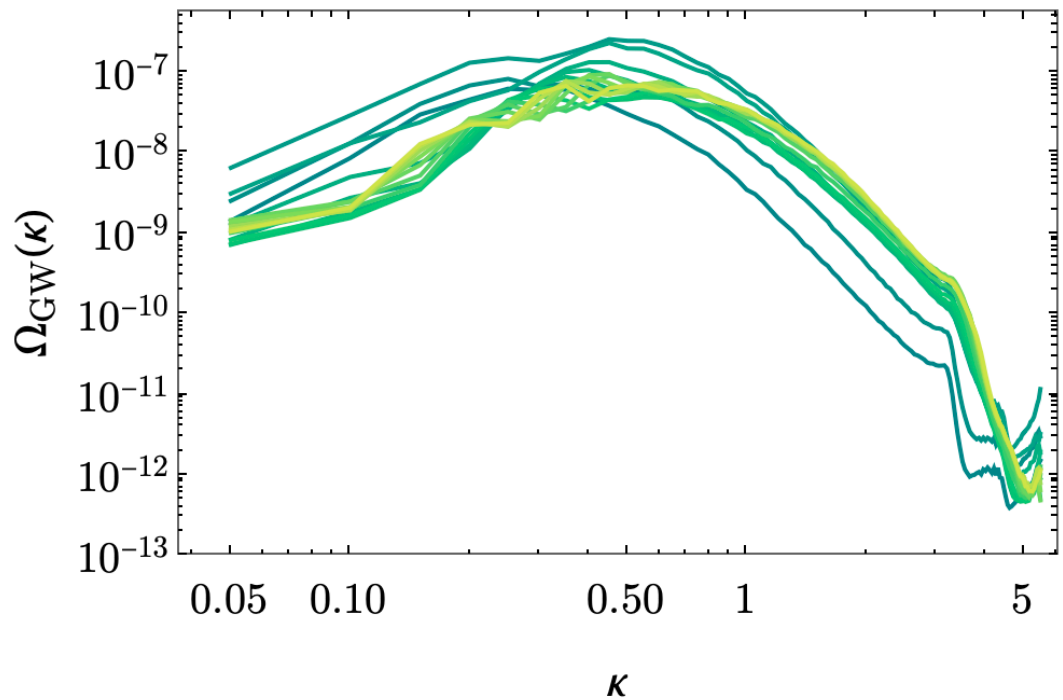
Gravitational waves

$$(h_{ij}^{TT})'' + 2H(h_{ij}^{TT})' - \frac{\nabla^2 h_{ij}^{TT}}{a^2} \simeq \frac{2a^2}{M_P^2}\Pi_{ij}^{TT}$$





Frecuencies typically out of range of current experiments

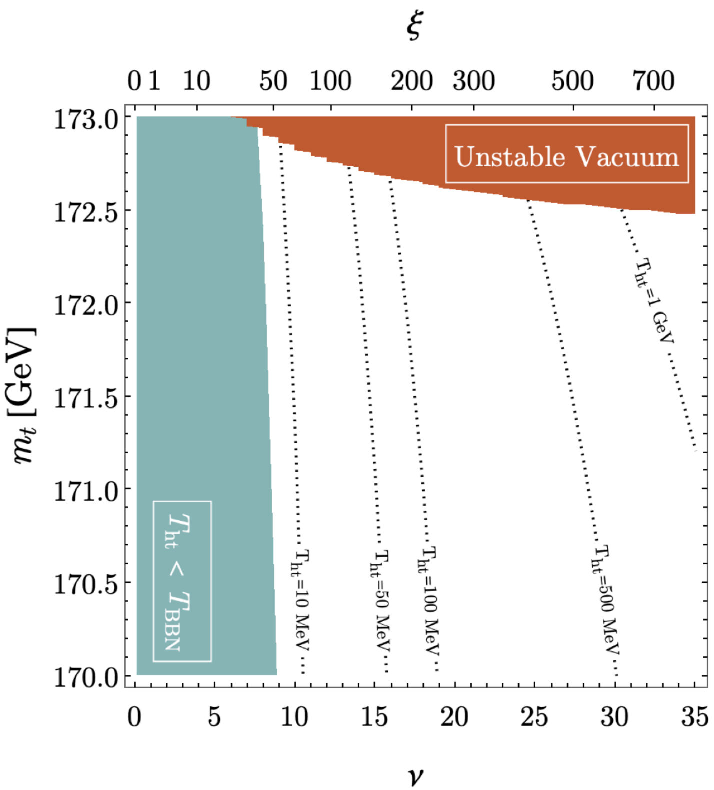
D. Bettoni, G. Domènech, J. Rubio, JCAP 02 (2019) 034

Further applications & generalizations

- The SM Higgs can be responsible for heating the Universe

See G. Laverda's talk on Tuesday

- Coupling to other species can lead to stabilization of defects
- Possible extensions to radiation/matter domination in an EFT framework
- Easily generalizable to other symmetry groups, defects and FOPT



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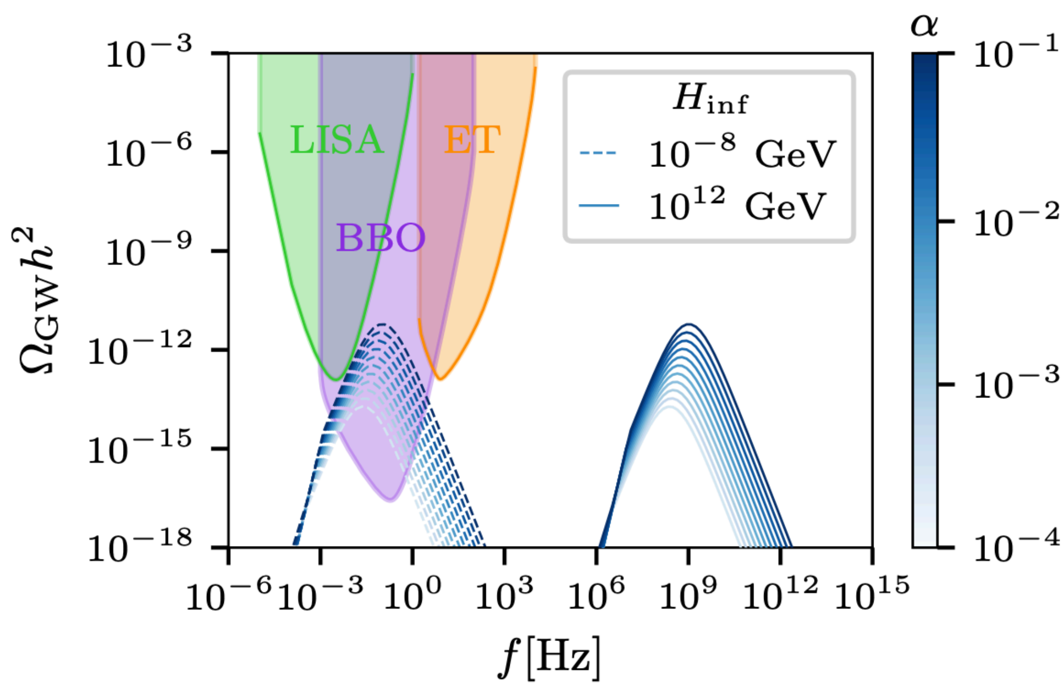

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Conclusions

- Non-minimal couplings to gravity may lead to the spontaneous symmetry breaking of internal symmetries.
- These interactions act as a natural cosmic clock, triggering the formation of short-topological defects and potentially detectable gravitational wave backgrounds
- The eventual fragmentation of these objects allows heating the Universe after inflation.
- Easily generalizable to other groups and topological defects.