JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Axion fragmentation

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Padova 13.04.2022

Cluster of Excellence
PRISMA+
Precision Physics, Fundamental Interactions and Structure of Matter

Mainz Institute for Theoretical Physics

References

- N. Fonseca, EM, R. Sato, G. Servant
  1911.08472, JHEP 04 (2020) 010
  1911.08473, JHEP 05 (2020) 080

- EM, W. Ratzinger, R. Sato, B. Stefanek
  2109.13823, JHEP 12 (2021) 037

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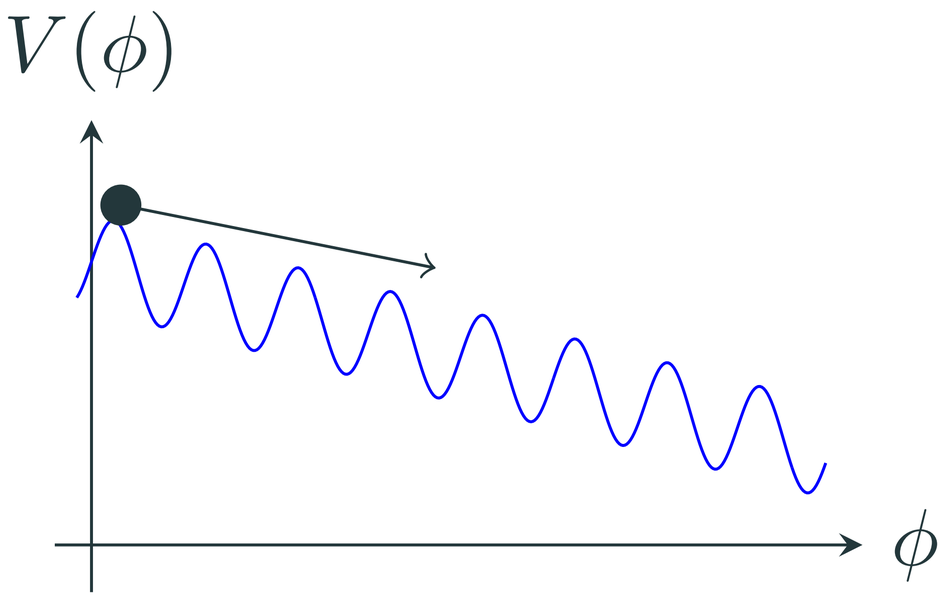
Axion fragmentation

Study the field evolution on a potential with periodic features

Include fluctuations: $\phi \to \phi_0(t) + \delta\phi(x,t)$



$$\ddot{\delta\phi}_k + \left[k^2 + V''(\phi_0)\right]\delta\phi_k = 0$$

- The oscillating potential induces a parametric resonance
- Fluctuations grow exponentially

$$\delta\phi_k \sim \exp\left[\sqrt{\delta k_{\rm cr}^2 - (k - k_{\rm cr})^2}\, t\right] \sin(\ldots)$$

- Kinetic energy transfer $\phi_0 \to \delta\phi$

Overview of models

Overview of models

Relaxion mechanism

The relaxion mechanism

Motivation

Cure the EW hierarchy problem without new physics at the EW scale, in cosmology

- ϕ an ALP with an almost flat potential
- Higgs — ϕ coupling (via a small breaking of the shift sym.)

$$\mu_h^2 |H|^2 = (\Lambda^2 - g\Lambda\phi)|H|^2$$

- Some mechanism to stop the evolution as

$$v_{\rm EW} \ll \Lambda$$

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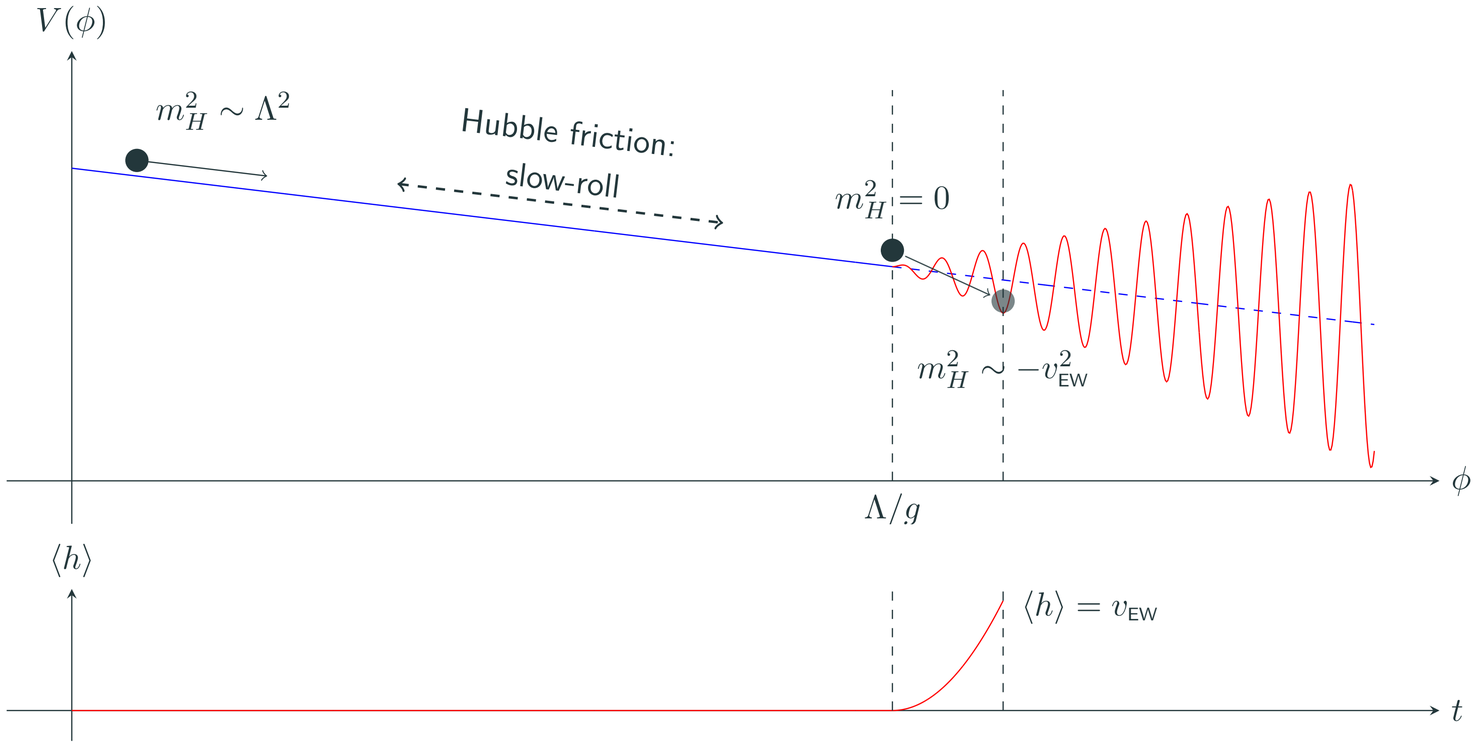
The relaxion mechanism

Graham, Kaplan, Rajendran, 1504.07551
Phys.Rev.Lett. 115 (2015) 22, 221801

$$V(\phi, H) = -g\Lambda^3\phi + \frac{1}{2}(\Lambda^2 - g\Lambda\phi)h^2 + \Lambda_c^{4-n}\langle h\rangle^n \cos\frac{\phi}{f} + \dots$$



Known issues:

- $H_I < \mathrm{GeV}$ (down to meV)
- $N_e \sim 10^5 - 10^{50}$
- super-Planckian field excursion
- CC

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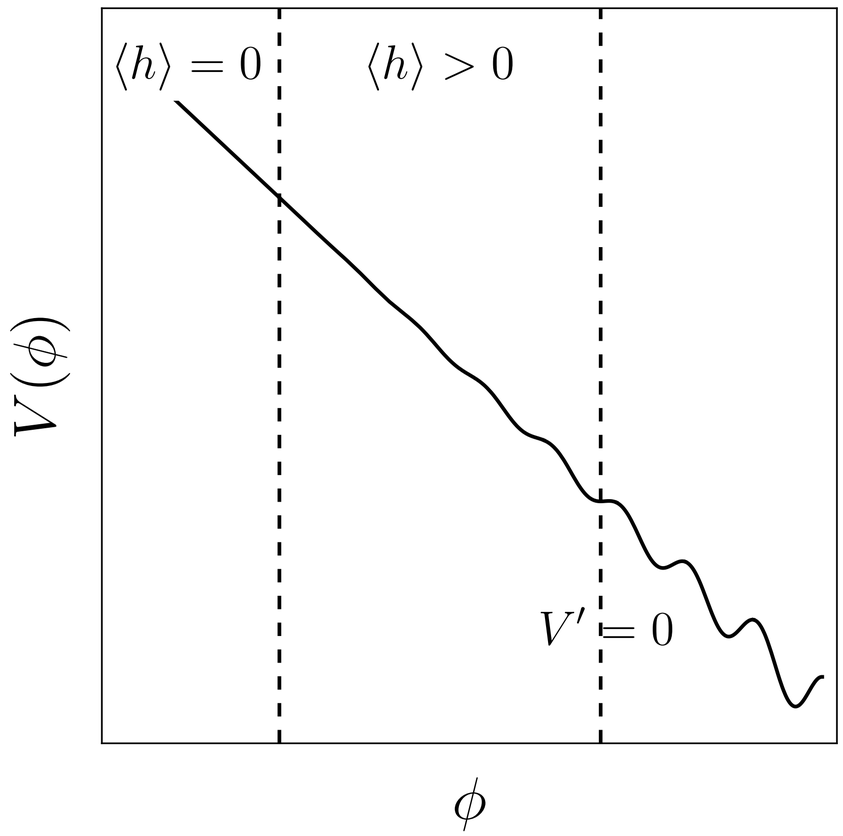
Energy dissipation

Hubble friction during inflation



- Assume slow-roll: $\dot{\phi} = V'/(3H_I)$
- Stop when $V' = 0$
- *Strong friction* regime

$$\Delta t_1 = \frac{2\pi f}{\dot{\phi}_{\rm SR}} > \frac{1}{H_I}$$

Overview of models

Kinetic misalignment

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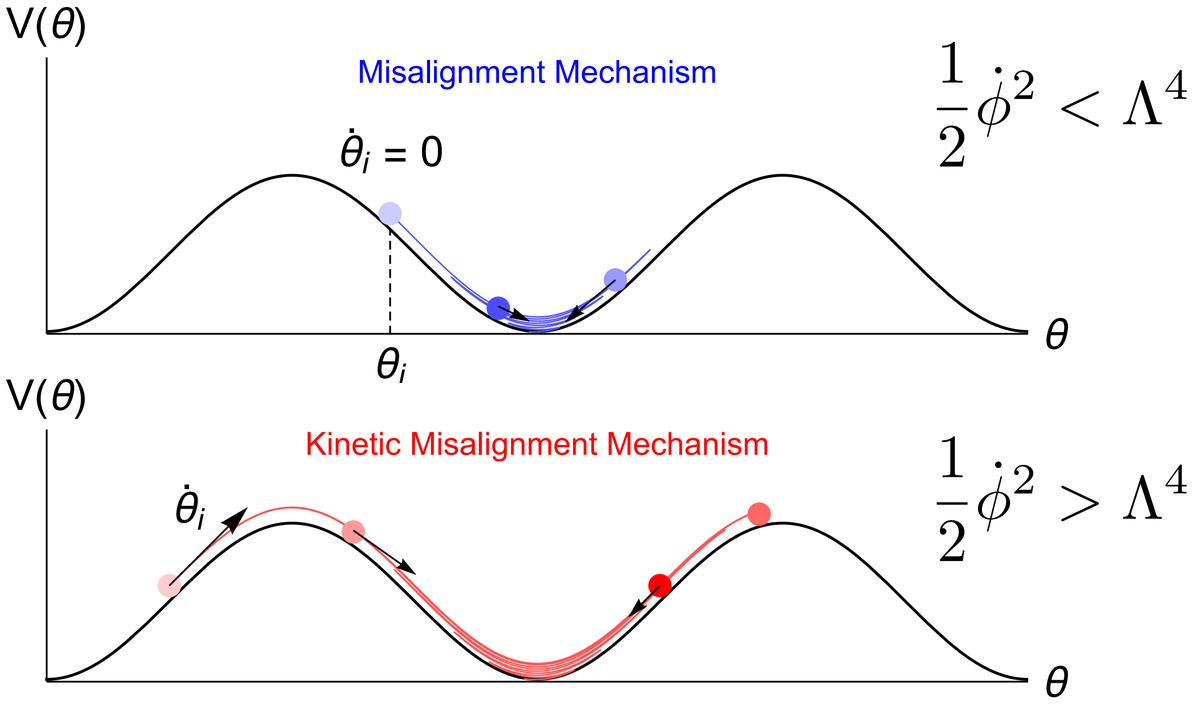
Kinetic misalignment

An axion with large kinetic energy can evolve over many fundamental periods



Co, Hall, Harigaya, 1910.14152, PRL

An inspiring idea:

- Delayed oscillations (axion DM with smaller f_a) [Co, Hall, Harigaya, 1910.14152, *PRL*, Chang, Cui, 1911.11885, *PRD*]
- Baryogenesis mechanism (axiogenesis) [Co, Harigaya, 1910.02080, *PRL*]
- Generate kination era, thus enhancing pre-existing GW signals [Co *et al*, 2108.09299, Gouttenoire, Servant, Simakachorn, 2108.10328, 2111.01150]
- Boost the GW signal from the axion — Dark photon coupling [Co, Harigaya, Pierce, 2104.02077, *JHEP*, Madge, Ratzinger, Schmitt, Schwaller, 2111.12730]
- Axion minicluster spectrum [Barman, Bernal, Ramberg, Visinelli, 2111.03677]

Fragmentation

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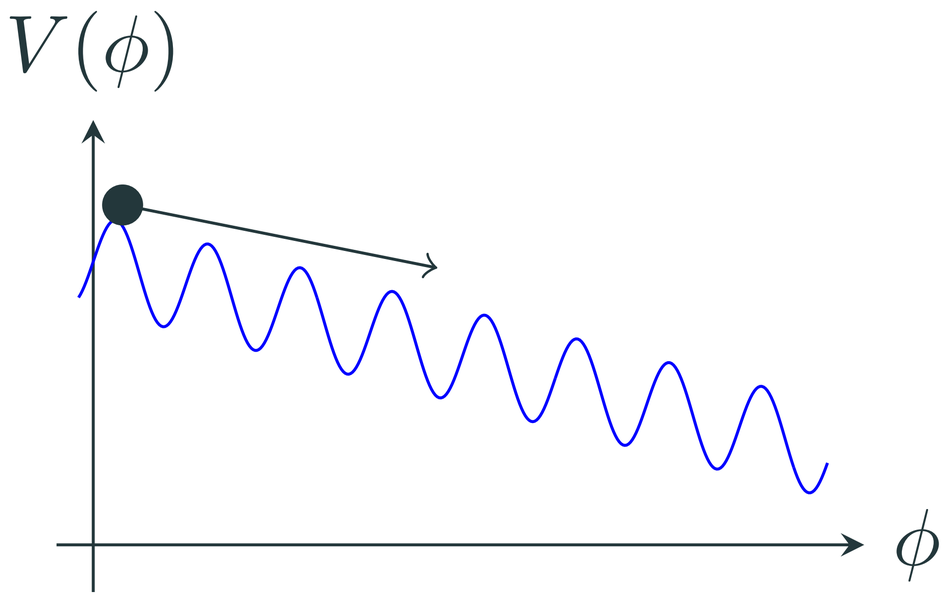
Setup

Scalar field evolving over a potential with periodic wiggles (and possibly a tilt)

$$V(\phi) = -\mu^3\phi + \Lambda_b^4 \cos\frac{\phi}{f} + \text{c.c.}$$



Define $m^2 = \Lambda_b^4/f^2$

Assumptions:

- "visible wiggles" $\Lambda_b^4/f > \mu^3$
- weak Hubble friction
- for simplicity $\mu = H = 0$

Relaxion: **neglect** growth of barriers

$$\cancel{\Lambda_b^4 \left(\frac{h}{v_{\rm EW}}\right)^n} \cos\frac{\phi}{f}$$

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Equations of motion

$$V(\phi) = -\mu^3\phi + \Lambda_b^4 \cos\frac{\phi}{f} + \text{c.c.}$$

$$\phi(\vec{x},t) \to \phi(t) + \delta\phi(\vec{x},t)$$

Eom in Fourier space

$$\ddot{\delta\phi}_k + \left[k^2 + V''(\phi)\right]\delta\phi_k = 0 \longrightarrow \ddot{\delta\phi}_k + \left[k^2 - \frac{\Lambda_b^4}{f^2}\cos\frac{\phi}{f}\right]\delta\phi_k = 0$$

$$\ddot{\phi}_0 + V'(\phi_0) = \frac{1}{2}V'''(\phi_0)\int\frac{d^3x}{\text{Vol}}\langle\delta\phi^2\rangle$$

Back-reaction: better studied using energy conservation

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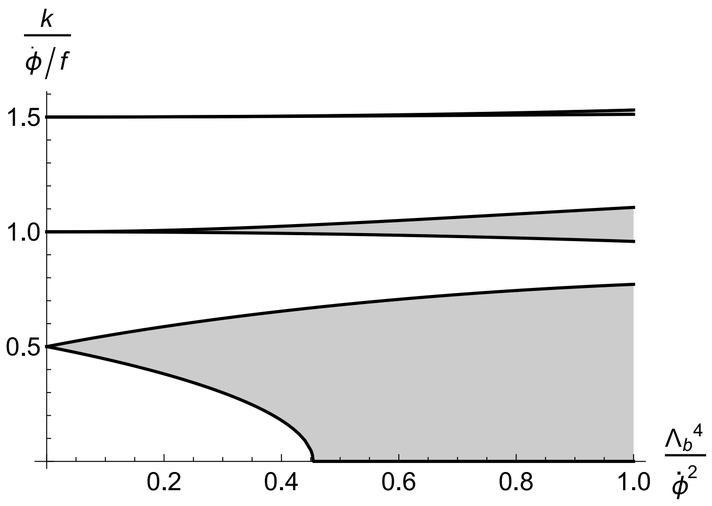
Growth of fluctuations

Neglecting back-reaction

For $\ddot{\phi} = 0$ the eom is a Mathieu equation

$$\delta\ddot{\phi}_k + \left[k^2 + \frac{\Lambda_b^2}{f}\cos\frac{\dot{\phi}_0 t}{f}\right]\delta\phi_k = 0 \longleftrightarrow y'' + (\delta + \epsilon\cos x)y = 0$$



First instability band:

$$|k - k_{\rm cr}| < \delta k_{\rm cr}$$

$$k_{\rm cr} = \frac{\dot{\phi}_0}{2f} \qquad \delta k_{\rm cr} = \frac{\Lambda_b^4}{2f\dot{\phi}_0}$$

Exponential growth

$$\delta\phi_k \sim \exp\left[\sqrt{\delta k_{\rm cr}^2 - (k - k_{\rm cr})^2}\, t\right]\sin(\ldots)$$

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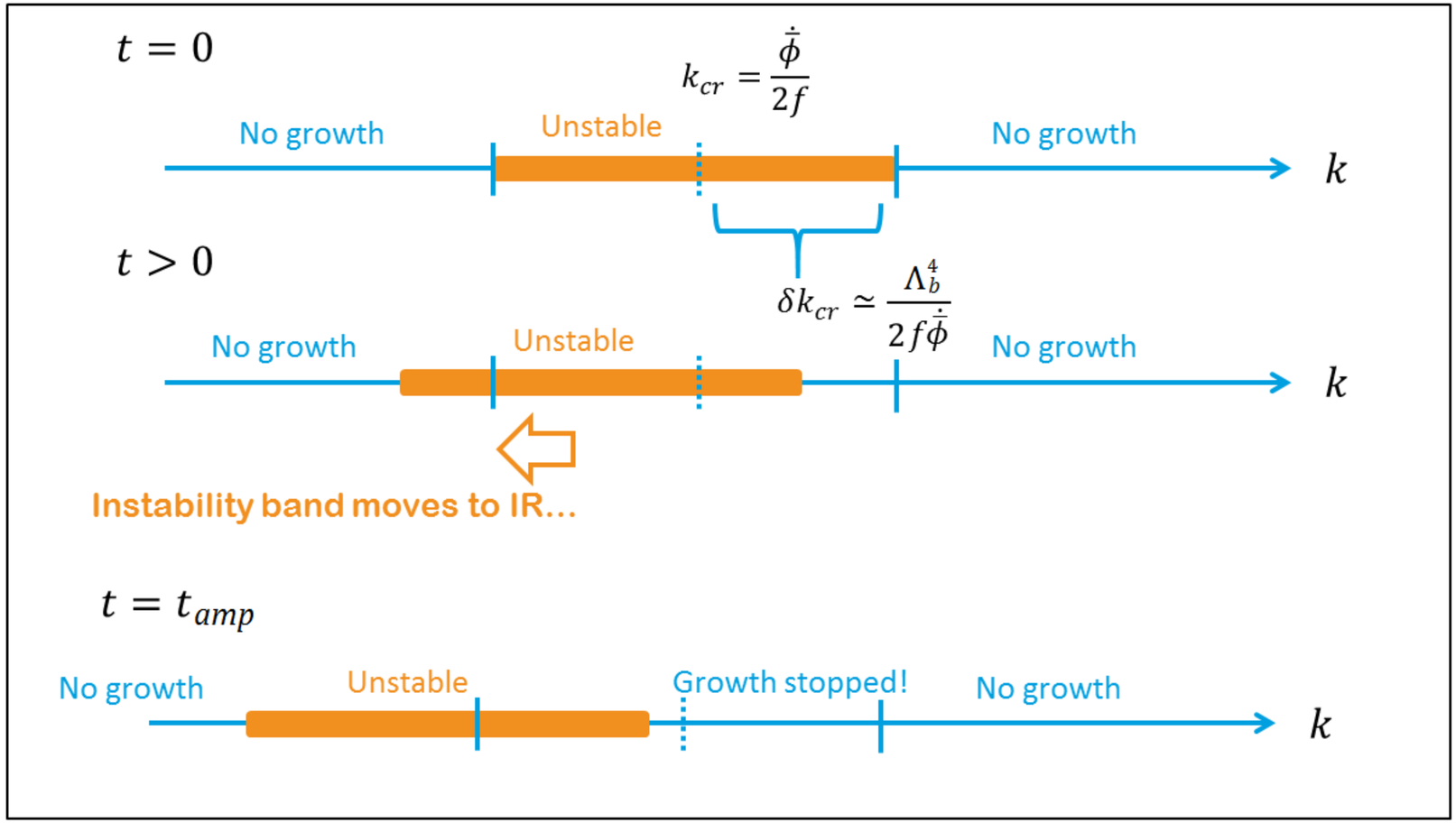
Back-reaction on the zero mode

$$\ddot{\phi}_0 + V'(\phi_0) = \frac{1}{2} V'''(\phi_0) \int \frac{d^3x}{\mathrm{Vol}} \langle \delta\phi^2 \rangle$$



Credit:
R. Sato

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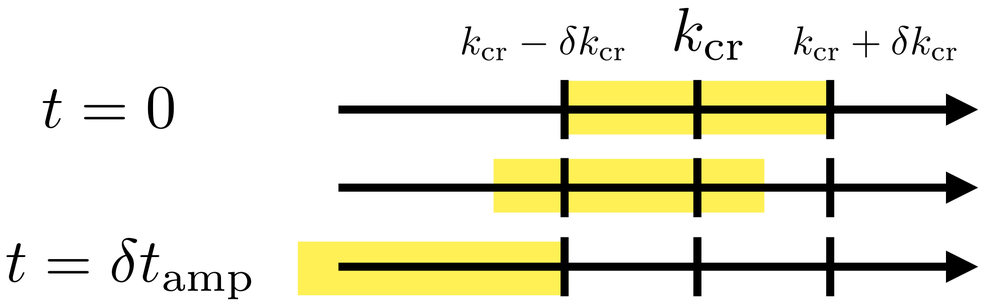
Estimate the back-reaction



Energy "inside" the instability band

$$\delta\rho = k_{\rm cr}^2 \delta k_{\rm cr} \times k_{\rm cr} \times \exp(2\delta k_{\rm cr} t)$$

volume of the instability band — typical energy — exponential growth

Growth stops when $k_{\rm cr}$ exits the inst. band

$$\dot\phi(t + \delta t_{\rm amp}) = \dot\phi(t)\left(1 - \frac{\delta k_{\rm cr}}{k_{\rm cr}}\right)$$

Energy in fluctuations grows (energy cons.)

$$\delta\rho = -\delta K \approx \dot\phi^2 \frac{\delta k_{\rm cr}}{k_{\rm cr}} \qquad K = \frac{1}{2}\dot\phi^2$$

Equate the two exprs. for $\delta\rho$

$$\delta t_{\rm amp} \approx \frac{1}{2\delta k_{\rm cr}} \log \frac{\dot\phi^2}{k_{\rm cr}^4}$$

Evolution of the zero-mode:

$$\frac{\rm d}{{\rm d}t}\frac{1}{2}\dot\phi^2 \approx \frac{\delta K}{\delta t_{\rm amp}} = -\frac{\Lambda_b^8}{f\dot\phi}\left(\log\frac{16 f^4}{\dot\phi^2}\right)^{-1}$$

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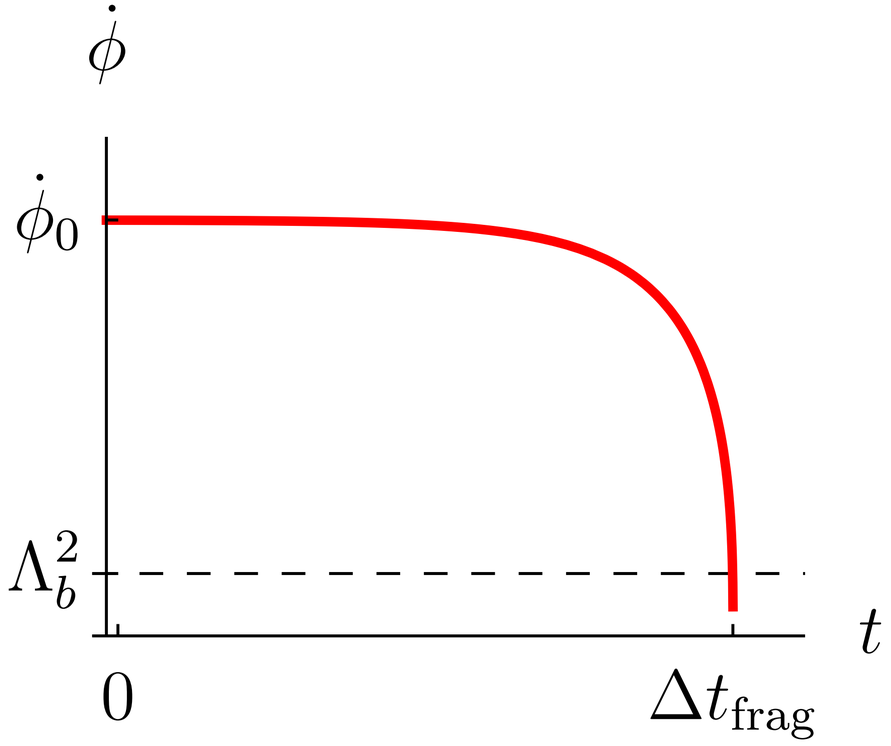
Back-reaction on the zero mode

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{1}{2}\dot{\phi}^2 \approx \frac{\delta K}{\delta t_{\mathrm{amp}}} = -\frac{\Lambda_b^8}{f\dot{\phi}}\left(\log\frac{16 f^4}{\dot{\phi}^2}\right)^{-1}$$

The axion is stopped in a finite time

$$\Delta t_{\mathrm{frag}} \sim \frac{f\dot{\phi}_0^3}{\Lambda_b^8}\log\frac{f^4}{\dot{\phi}_0^2}$$

$$\Delta\phi_{\mathrm{frag}} \sim \frac{f\dot{\phi}_0^4}{\Lambda_b^8}\log\frac{f^4}{\dot{\phi}_0^2}$$



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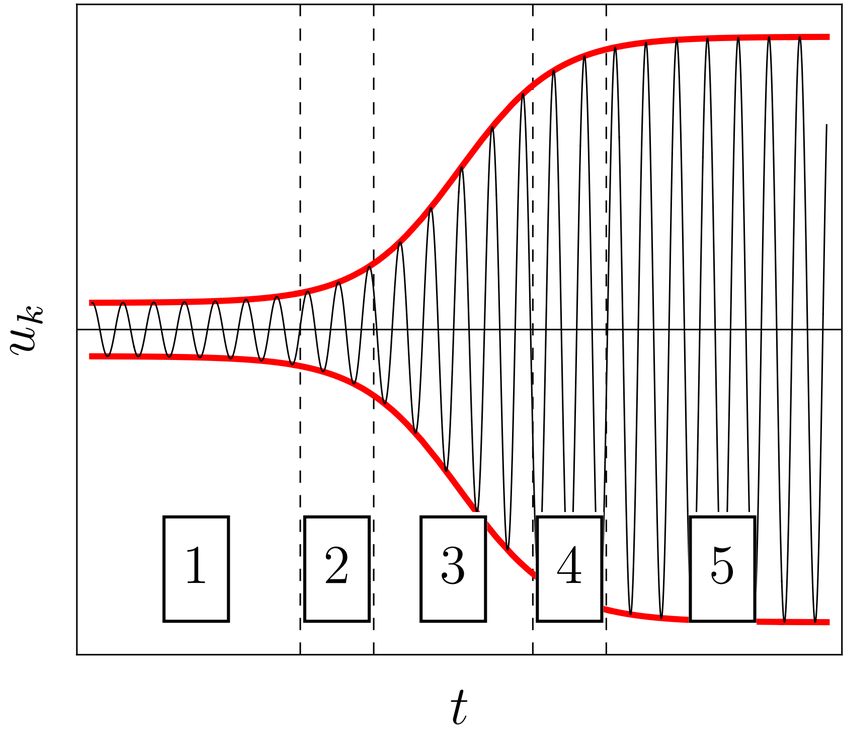
Back-reaction on the zero mode

Analytic calculation

Solve the eom in 5 distinct regions



1. oscillatory (WKB)
2. transition (Airy functions)
3. exp. growth (WKB)
4. transition (Airy functions)
5. oscillatory (WKB)

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Zero-mode evolution

$$\ddot{\phi} = -3H\dot{\phi} + \mu^3 - \frac{1}{32\pi^2 f^4}\dot{\phi}^2|\ddot{\phi} + H\dot{\phi}| \exp\left(\frac{\pi\Lambda_b^8}{2f\dot{\phi}^2|\ddot{\phi} + H\dot{\phi}|}\right)$$

Neglecting H and μ^3

$$\ddot{\phi} = -\frac{\pi\Lambda_b^8}{2f\dot{\phi}^2}\left(\log\frac{32\pi^2 f^4}{\dot{\phi}^2}\right)^{-1}$$

Finite field excursion

$$\Delta t_{\rm frag} = \frac{2f\dot{\phi}_0^3}{3\pi\Lambda_b^8}\log\frac{32\pi^2 f^4}{\dot{\phi}_0^2}$$

$$\Delta\phi_{\rm frag} = \frac{f\dot{\phi}_0^4}{2\pi\Lambda_b^8}\log\frac{32\pi^2 f^4}{\dot{\phi}_0^2}$$

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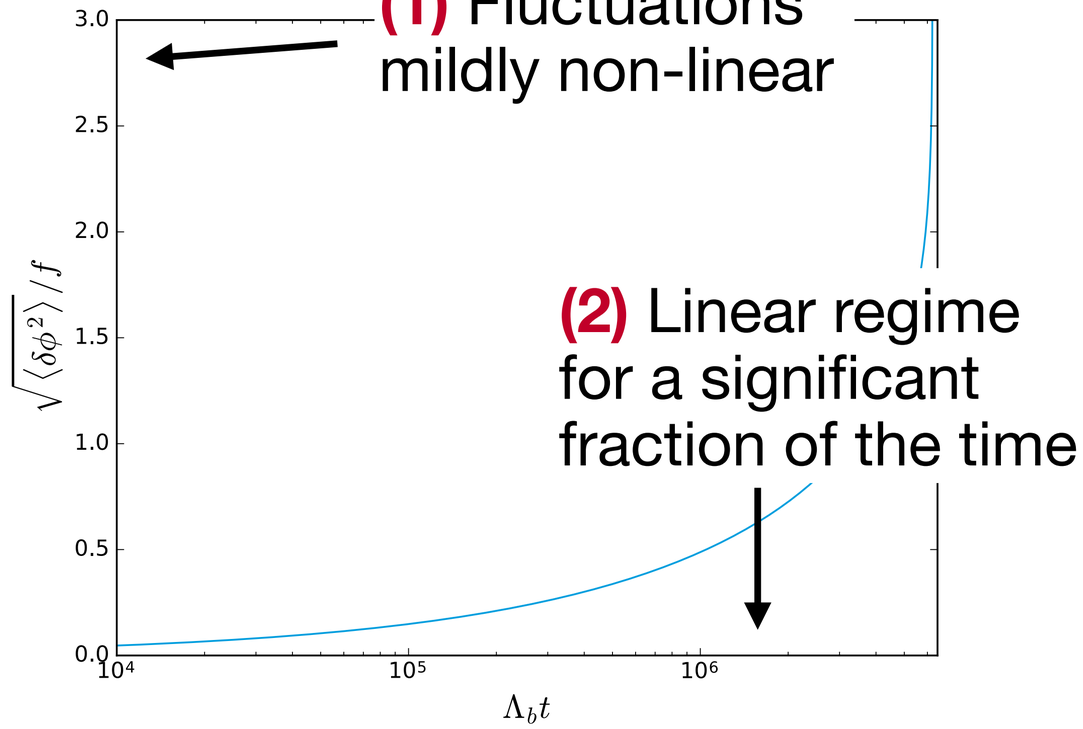
NLO analysis

Are the linear results robust?

Yes.



Periodic potential

$$\ddot{\delta\phi}_k + \left[k^2 + \frac{\Lambda_b^2}{f}\cos\frac{\phi_0}{f}\right]\delta\phi_k = 0$$

(3) No effective mass term

$$(\langle \delta\phi^2 \rangle + \langle \chi^2 \rangle)\chi^2$$

(4) The oscillating term has a constant amplitude

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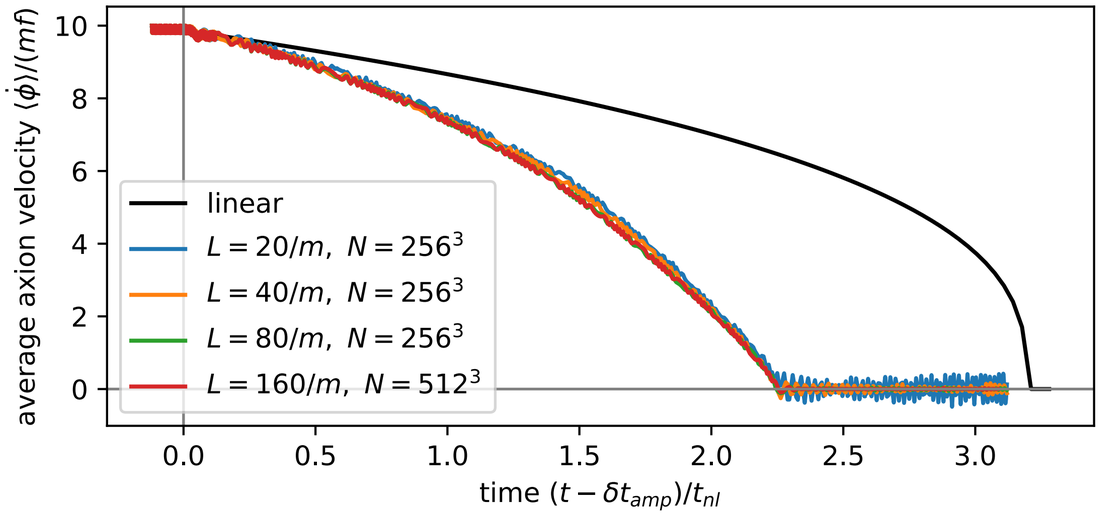
Lattice results

Zero mode evolution



Morgante, Ratzinger, Sato, Stefanek, 2109.13823, *JHEP*

- O(1) agreement
- Non-linear effects make fragmentation more efficient (2 —> 1 scattering)

2nd order perturb. $\delta\phi_{\vec{k}} = \delta\phi^{(1)}_{\vec{k}} + \delta\phi^{(2)}_{\vec{k}}$

$$\ddot{\delta\phi}^{(2)}_{\vec{k}} + k^2\,\delta\phi^{(2)}_{\vec{k}} = \frac{1}{2}V_0''' \int \frac{d^3p}{(2\pi)^3}\delta\phi^{(1)}_{\vec{p}}\,\delta\phi^{(1)}_{\vec{k}-\vec{p}}$$

Reproduces the spectrum of fluctuations

Consequences

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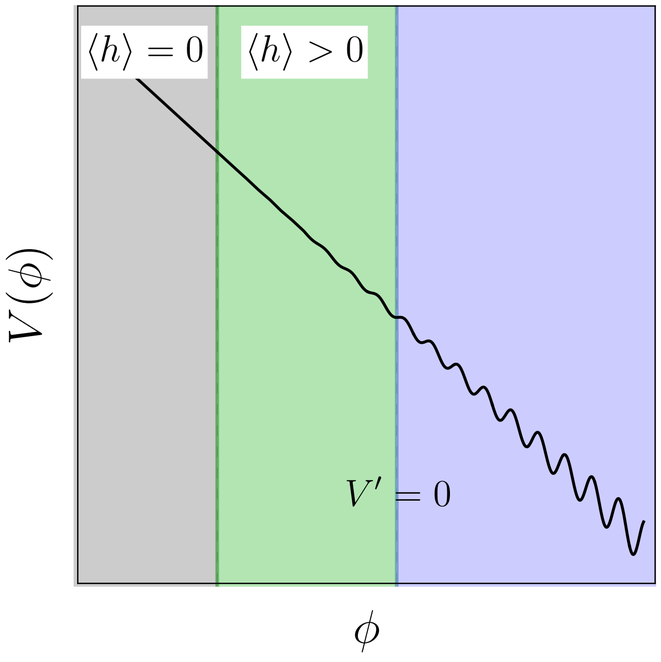
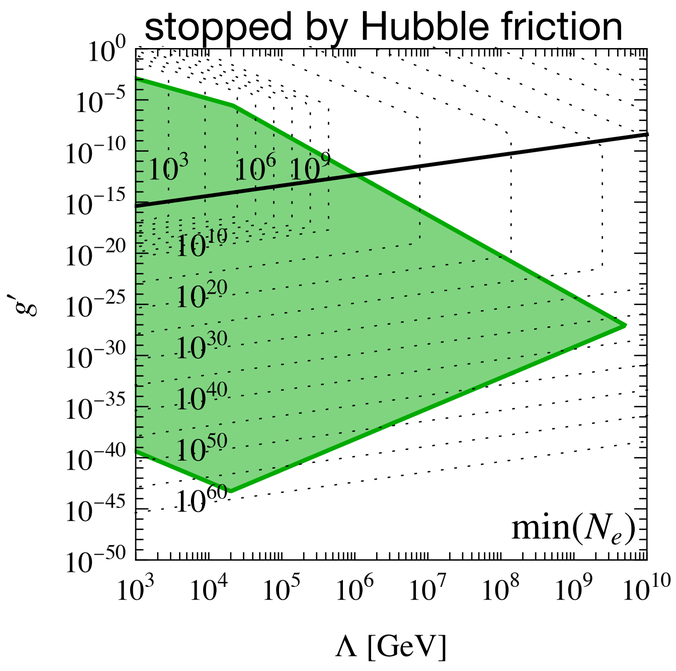
GKR relaxion

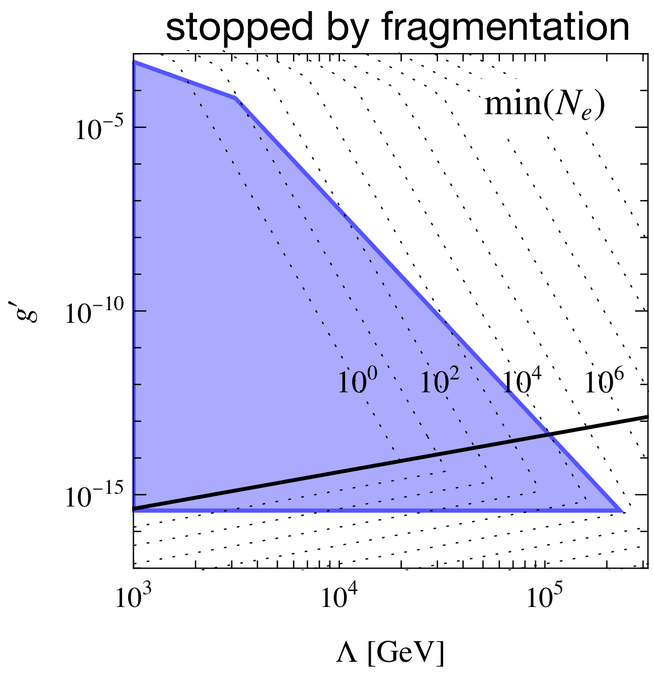
Consequences I

- Strong Hubble friction —> ϕ stops as soon as $V' = 0$
- Weak friction —> fragmentation stops the relaxion





$m_\phi \in [10^{-25}, 1]\,\mathrm{GeV}$



$m_\phi \in [10^{-9}, 10^{2}]\,\mathrm{GeV}$

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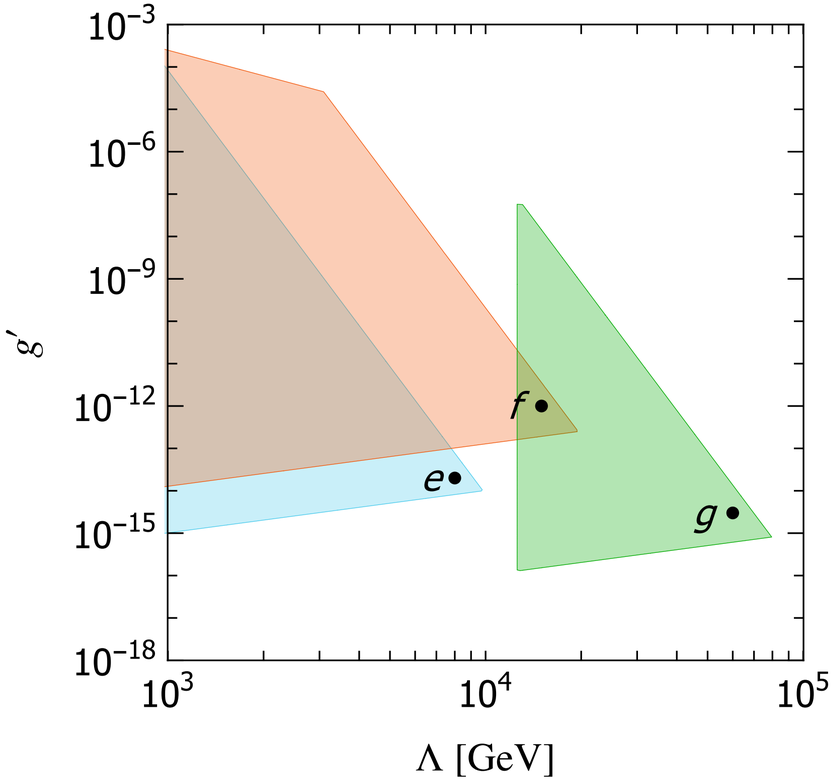
Stopping without inflation

"self-stopping relaxion"

No need for a strong Hubble friction $\Longrightarrow$ relaxation after inflation



Main difference: $\dot{\phi} \sim \Lambda^2 < \dot{\phi}_{\rm SR}$

- $\dot{\phi} = \sqrt{2g/g'}\Lambda^2\,,\ \ g/g' = 1$
- $\dot{\phi} = \sqrt{2g/g'}\Lambda^2\,,\ \ g/g' = 1/(4\pi)^2$
- $\dot{\phi} = 10^{-2}\sqrt{2}\Lambda^2\,,\ \ g/g' = 1$

e: $m_\phi \in [139{,}169\,\text{GeV}]$

f: $m_\phi \in [14{,}37\,\text{GeV}]$

g: $m_\phi \in [3{,}9\,\text{GeV}]$

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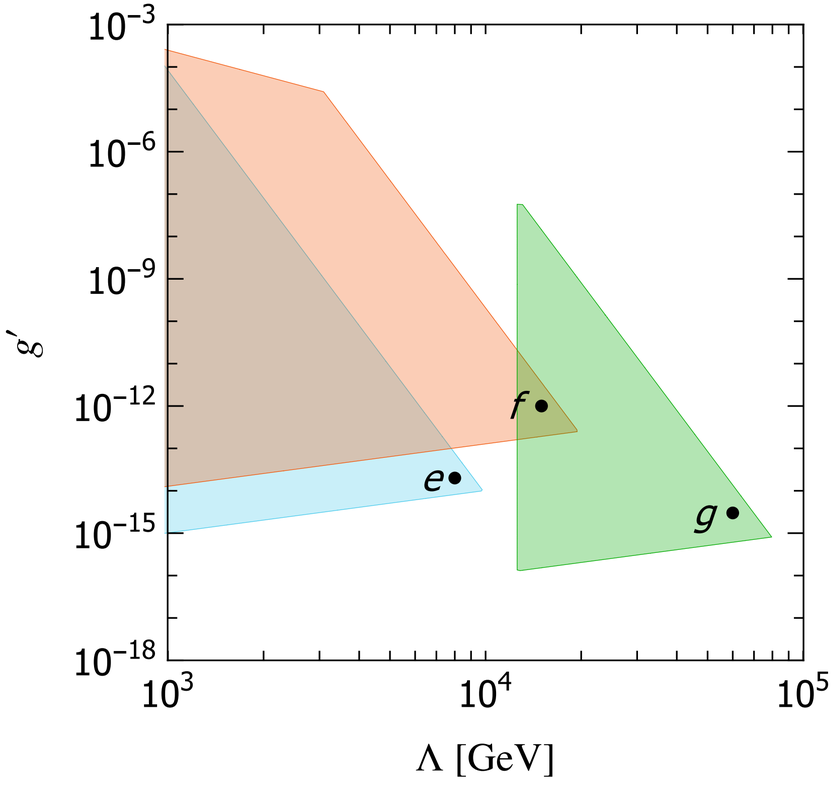

Initial conditions require some care + extra assumptions:

- Thermal history? V(T)? $T < \mathcal{O}(100)\,\mathrm{GeV}$ (*)
- Abundance? Over-abundant if it dominates the energy budget (but it decays before BBN)

(*) see papers by A. Banerjee, G. Perez, *et al*

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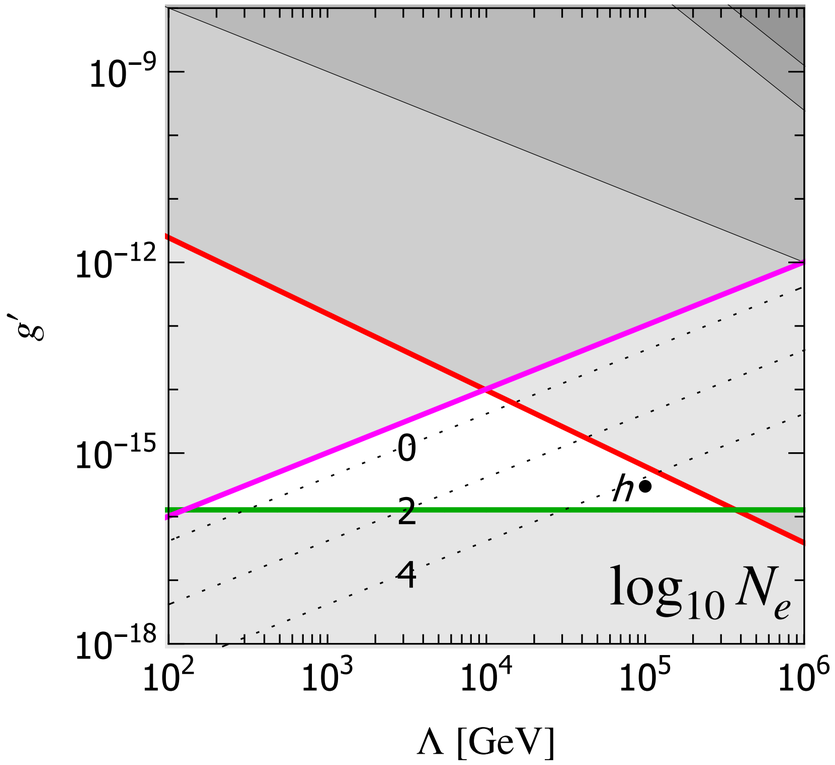
Relaxion driving inflation?

ϕ can drive a period of inflation



- Needs super-Planckian field excursions
- How to generate sufficient amount of perturbations?
- reheating $\longleftrightarrow$ fragmentation?

h: $m_\phi \in [0.2, 3\,\mathrm{GeV}]$

Relaxion bubbles?

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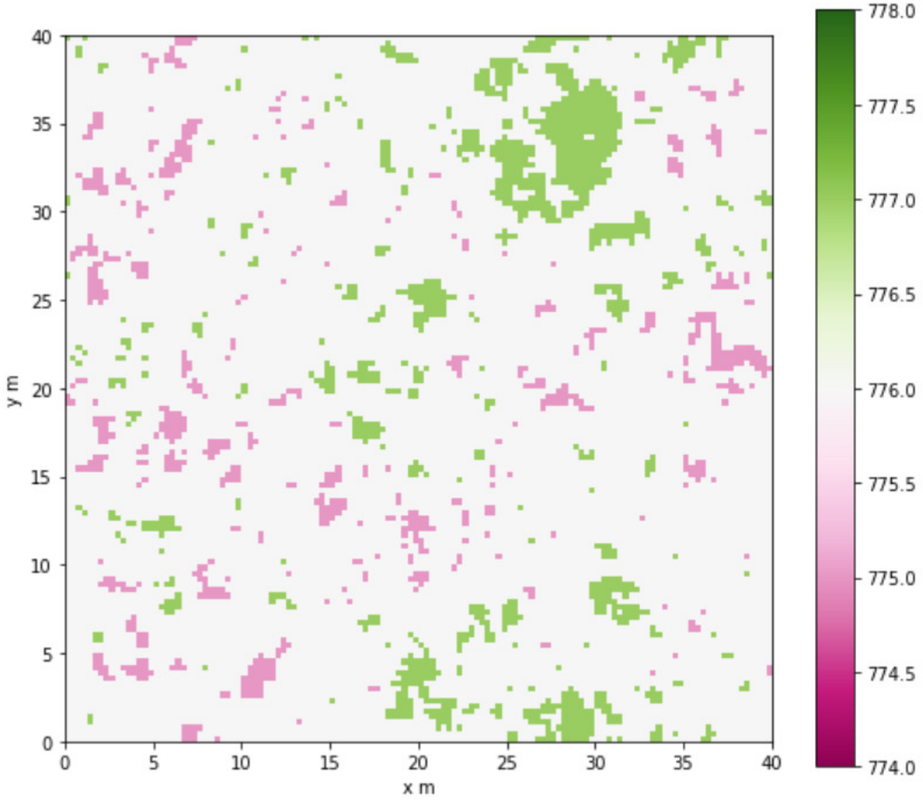
Large fluctuations

$$\delta\phi \gtrsim 2\pi f$$



Large fluctuations can populate multiple minima

Bubbles/walls dynamics?

Relaxion: problematic

- Effect on v_{EW} negligible
- Issue with c.c.: $\delta V \gg \Lambda_{\rm cc}^4$ (on very small scale)
- Domain walls would over-close the Universe
  - During inflation, diluted away
  - After inflation is more tricky

Large fluctuations

$$\delta\phi \gtrsim 2\pi f$$

- Relevant scales: $R_{\rm crit} = \Lambda_b^2/\mu^3$, $c\,\delta t_{\rm amp}$, H^{-1}
- Unfortunately, on the lattice, $L \ll R_{\rm crit} \ll c\,\delta t_{\rm amp} \ll H$
- Need to extrapolate and/or use analytic arguments
- Actually avoided: on large scale fluctuations $\ll 2\pi f$
- Caveat: on separated Hubble patches inflation can lead to different initial conditions

EM, W. Ratzinger, R. Sato, B. Stefanek
2109.13823, JHEP 12 (2021) 037

Fragmented ALP DM

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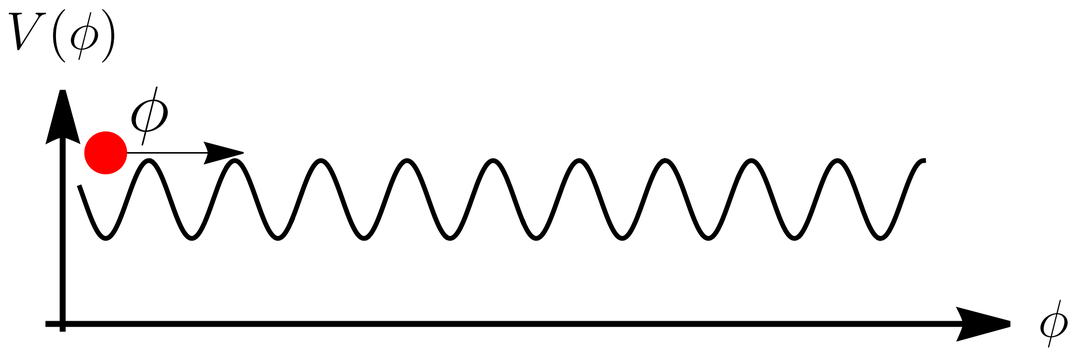
Kinetic misalignment



Co, Hall, Harigaya, 1910.14152, PRL

Kinetic misalignment: the axion rolls over many wiggles before getting trapped

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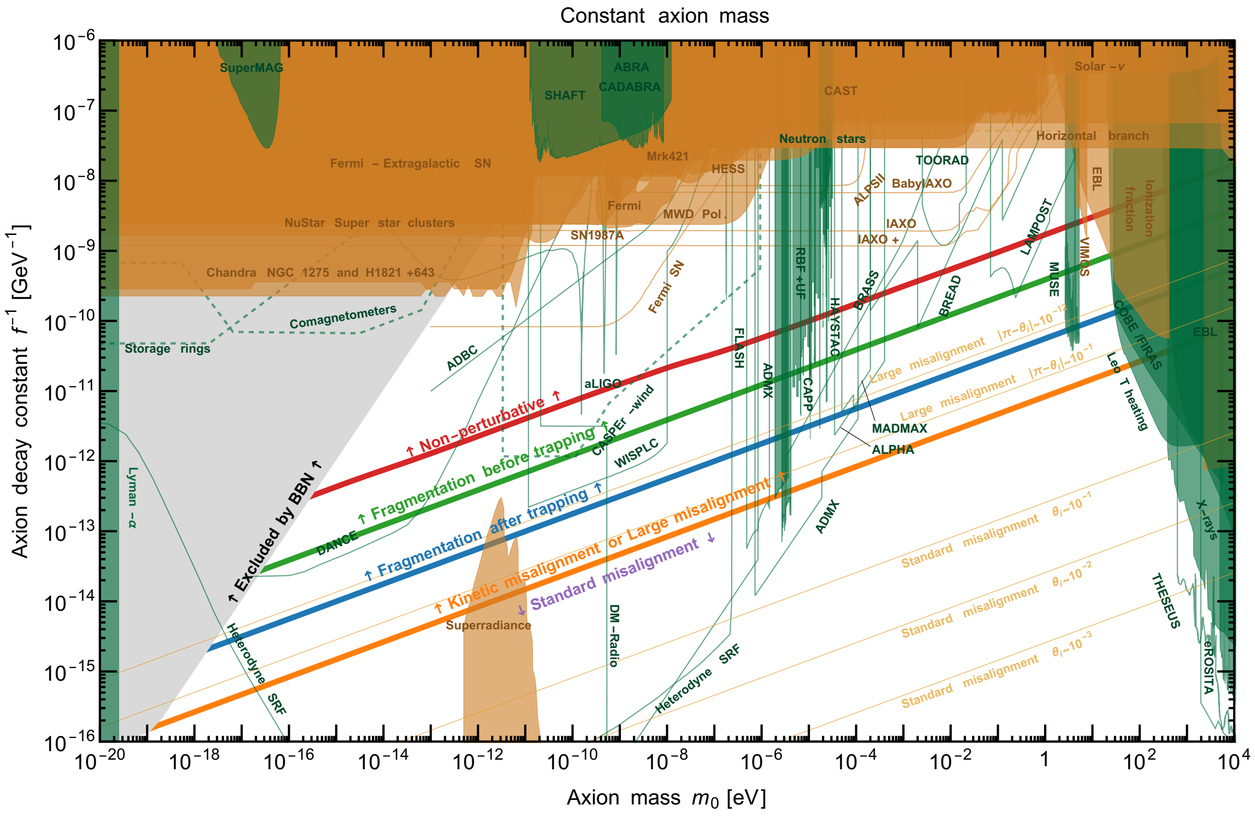
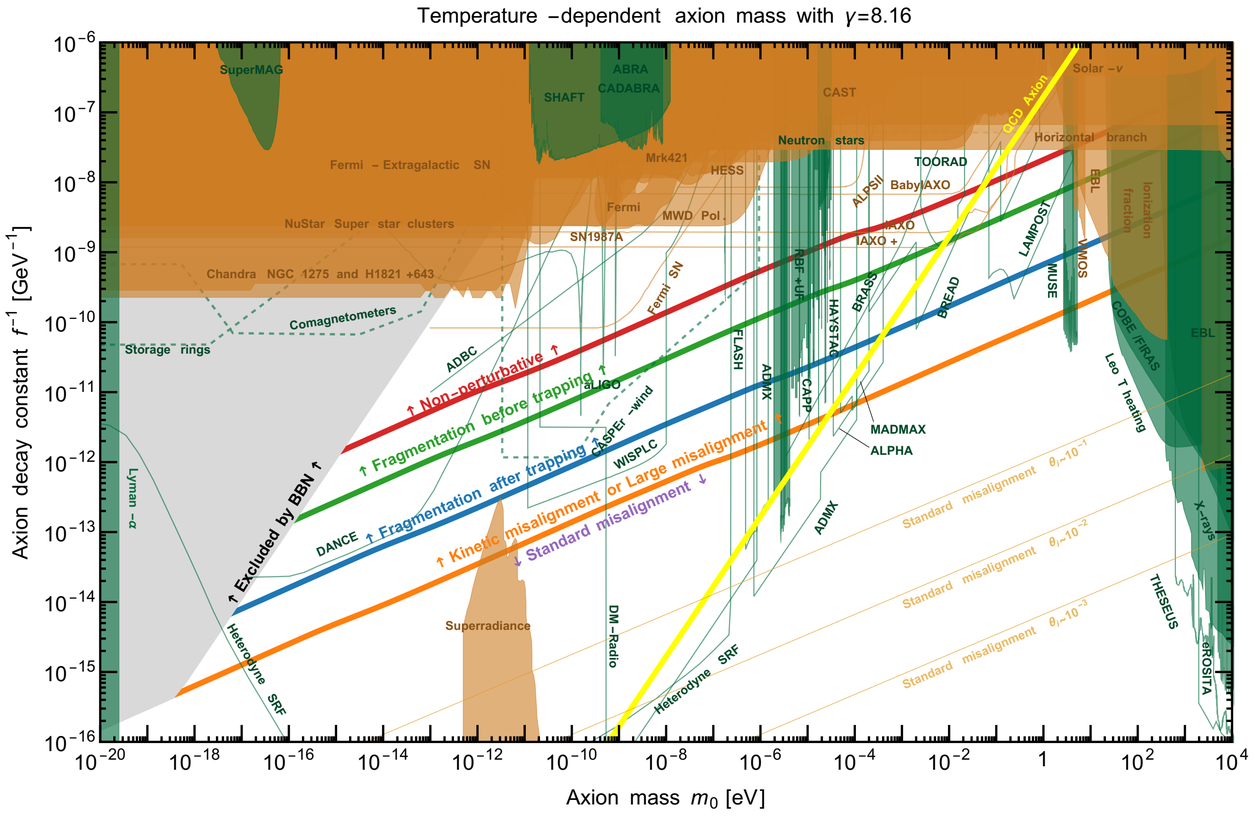
Kinetic misalignment

Eröncel, Sato, Servant, Sørensen 2206.14259

[see also Eröncel & Servant 2207.10111 —> axion miniclusters]





Conclusion

Summary

Fragmentation: a built-in effect with important consequences

Relaxion

- Provides additional friction
- New parameter space with a viable inflationary scenario
- Relaxion after inflation **[Self-stopping relaxion]**

Axion-like particles

- Can be relevant in other constructions such as kinetic misalignment

Thank you

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Examples: QCD *relaxion*

$$V(\phi, H) = -g\Lambda^3\phi + \frac{1}{2}(\Lambda^2 - g\Lambda\phi)h^2 + \Lambda_c^{4-n}\langle h\rangle^n \cos\frac{\phi}{f} + \dots$$

Chiral Lagrangian:

$$V(\phi) = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2}\sin^2\left(\frac{\phi}{2f_a}\right)}$$

with

$$m_\pi^2 f_\pi^2 = 2\langle\bar{q}q\rangle m_q \approx \Lambda_{\rm QCD}^3\, y_u \langle h\rangle$$

Tilts the potential and moves the minimum to

$$\theta_{\rm QCD} \sim \mathcal{O}(1)$$

Slope must disappear after inflation

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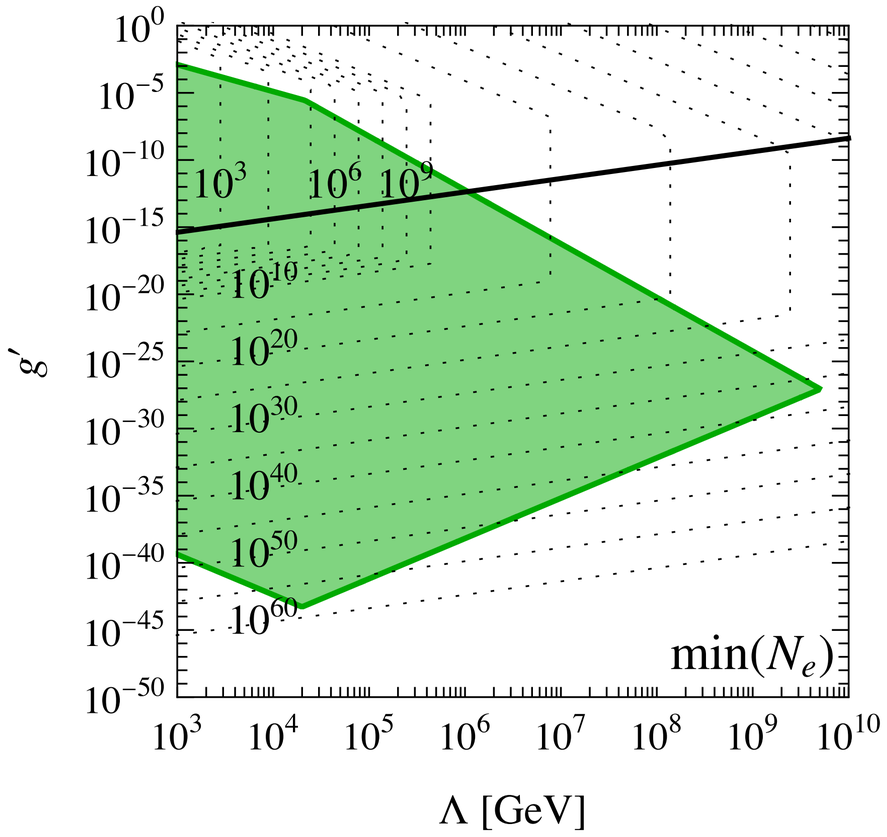
Parameter space



$$m_\phi \in [10^{-25}, 1]\,\mathrm{GeV}$$

Free parameters: $g, g', \Lambda, \Lambda_b, f, H_I, \dot{\phi}_0$

- Precision of the mass scanning: $g\Lambda(2\pi f) < m_h^2$
- UV construction $\Lambda_b < \sqrt{4\pi} v_{\mathrm{EW}}$
- Higgs tracks the minimum of the potential $|\dot{v}/v^2| < 1$
- Strong Hubble friction $H > (2\pi f)/\dot{\phi}$
- “Visible barriers” ==> stop: $f = \Lambda_b^4/(g\Lambda^3)$
- Inefficient fragmentation
- $\Lambda < f < M_P$

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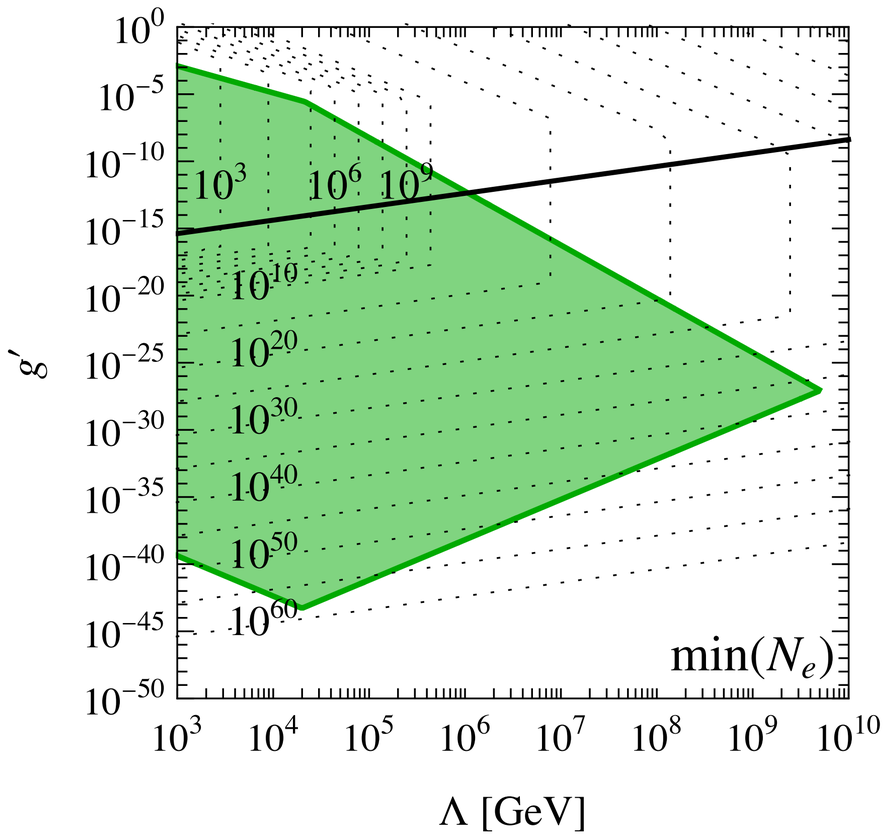
Parameter space



- Super-Planckian field excursion (mostly)
- Small Hubble rate
  - $\Delta\phi_{\rm class} > \Delta\phi_{\rm quant} \Rightarrow H_I^3 < V' = g\Lambda^3$
- Huge number of efolds $N_e \gtrsim 10^5 - 10^{60}$
  - Large field excursion: $\Delta\phi \gtrsim \Lambda/g$
  - Long enough inflation stage: $N_e > H_I^2/(g\Lambda)^2$
  - Relaxion subdominant: $H_I > \Lambda^2/M_P$
- **Fine tuning in the inflationary sector?**

Examples: new TeV fermions

Add new fermions and a confining gauge group

$$\mathcal{L} = -m_N N N^c - m_L L L^c + y H L N^c + \widetilde{y} H^\dagger L^c N + \frac{\phi}{f} G\widetilde{G} + \text{h.c.}$$

- $L(L^c)$ ~ left- (right-) handed leptons
- N, N^c singlets
- G confining at a scale $f_{\pi'}$
- $m_N \ll 4\pi f \ll m_L$

Integrating out L and with $\langle N N^c \rangle = 4\pi f_{\pi'}^3$ one gets

$$\frac{y\widetilde{y}}{m_L}(4\pi f_{\pi'}^3)\,\langle h^2 \rangle \cos\phi/f$$

…but $f_{\pi'}, m_L \lesssim$ few TeV. “Coincidence” problem?

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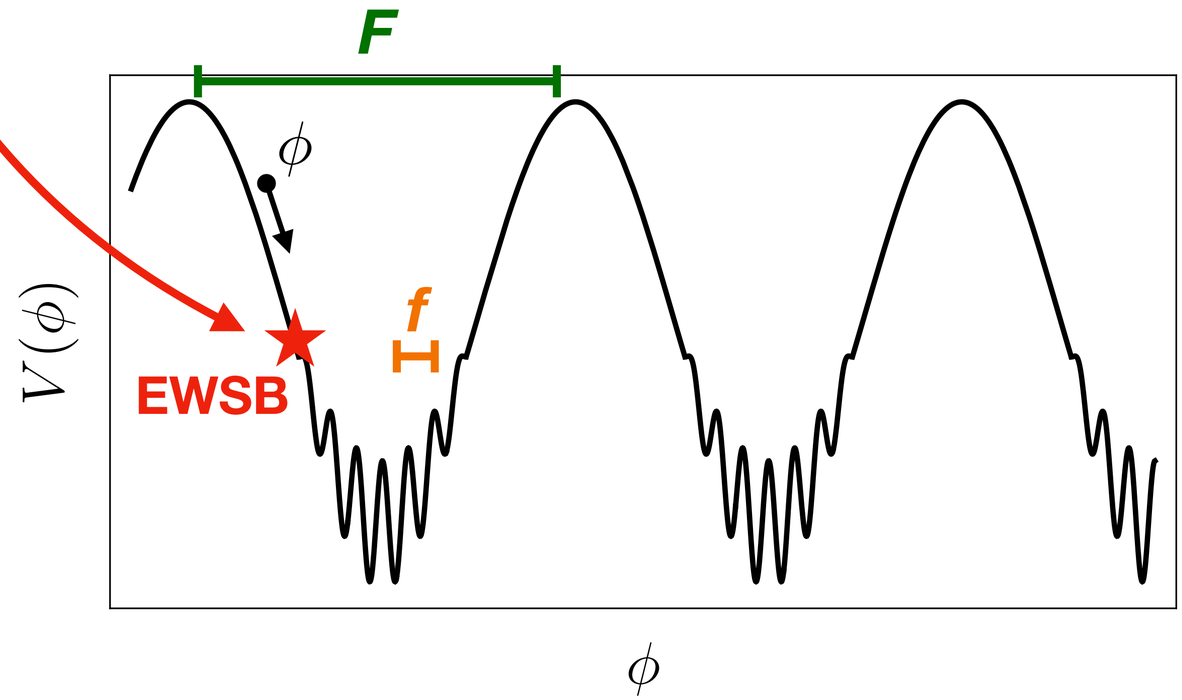
Hierarchy of scales

$$V(\phi, H) = \boxed{-g\Lambda^3\phi} + \frac{1}{2}(\Lambda^2 - g\Lambda\phi)h^2 + \Lambda_c^{4-n}\langle h\rangle^n \boxed{\cos\frac{\phi}{f}} + \dots$$

Relaxion as a pNGB:

$$V \sim \Lambda^4 \boxed{\cos\frac{\phi}{F}} + M_f^4 \boxed{\cos\frac{\phi}{f}}$$

A “clockwork” construction generates $F \gg f$



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Exponential scale separation

Assume spontaneously broken $U(1)^{N+1}$. Lagrangian for the Goldstones:

$$\mathcal{L} = -\frac{f}{2}\sum_{j=0}^{N}\partial_\mu U_j^\dagger \partial^\mu U_j + \frac{m^2 f^2}{2}\sum_{j=0}^{N-1}\left(U_j^\dagger U_{j+1}^q + \text{h.c.}\right)$$

$$U_j = e^{i\pi_j/f}$$

$$m^2 \ll f^2$$

Choi, Im, 1511.00132, *JHEP*
Kaplan, Rattazzi, 1511.01827, *PRD*
...
Kim, Nilles, Peloso, hep-ph/0409138, *JCAP*

$$= -\frac{1}{2}\sum_{j=0}^{N}\partial_\mu \pi_j \partial^\mu \pi_j + \frac{m^2}{2}\sum_{j=0}^{N-1}\left(\pi_j - q\pi_{j+1}\right)^2 + \mathcal{O}(\pi^4)$$

$$M_\pi^2 = m^2 \begin{pmatrix} 1 & -q & 0 & \dots & & 0 \\ -q & 1+q^2 & -q & \dots & & 0 \\ 0 & -q & 1+q^2 & \dots & & 0 \\ \vdots & \vdots & \vdots & \ddots & & \vdots \\ & & & & 1+q^2 & -q \\ 0 & 0 & 0 & \dots & -q & 1 \end{pmatrix}$$

Exactly 1 massless-eigenvector

$$a_0 = \frac{\mathcal{N}_0}{q^j}\pi_j$$

identify a_0 with the relaxion ϕ

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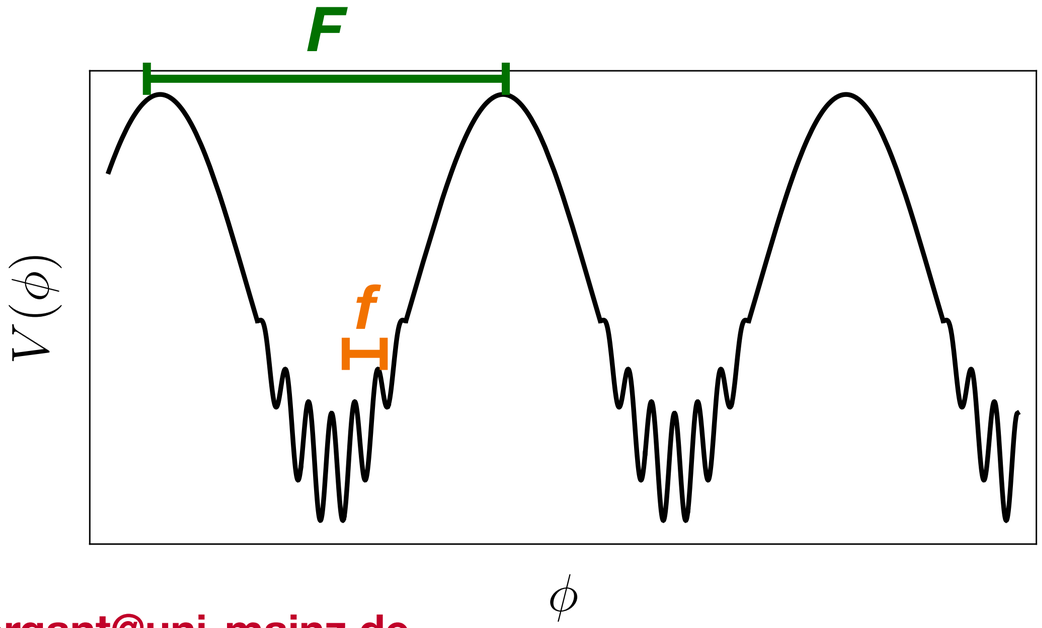
Exponential scale separation

Couple the first and last sites to Chern-Simons terms of a confining gauge group

$$\mathcal{L} \supset \frac{\pi_0}{16\pi^2 f} G_{\mu\nu}\widetilde{G}^{\mu\nu} + \frac{\pi_N}{16\pi^2 f} G'_{\mu\nu}\widetilde{G}'^{\mu\nu}$$

Potential for the zero-mode: $V(a_0) = \Lambda_F^4 \cos\frac{a_0}{F} + \Lambda_f^4 \cos\frac{a_0}{f}$ where $F = q^N f$



Choi, Im, 1511.00132, JHEP
Kaplan, Rattazzi, 1511.01827, PRD
Giudice, McCullough, 1610.07962, JHEP
Craig, Garcia Garcia, Sutherland, 1704.07831, JHEP
Giudice, McCullough, 1705.10162

Fonseca, Lima, Machado, Matheus, 1601.07183, PRD
Fonseca, von Harling, Lima, Machado, 1712.07635 JHEP
[non-abelian symmetry, continuous limit straightforward (warped extra-dimension)]

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Gauge bosons production

Hook & Marques-Tavares, 1607.01786, JHEP
Fonseca, EM, Servant, 1805.04543, JHEP
Fonseca, EM, 1809.04534, PRD

Idea: dissipate kinetic energy with production of SM gauge bosons

$$\mathcal{L} = \frac{1}{2}(\partial\phi)^2 + \frac{1}{2}(\partial h)^2 - \frac{1}{4}(W_{\mu\nu})^2 - V(\phi, h) - \frac{\phi}{4f} W_{\mu\nu}\widetilde{W}^{\mu\nu} + \frac{\pi\alpha}{2} h^2 W_\mu W^\mu$$

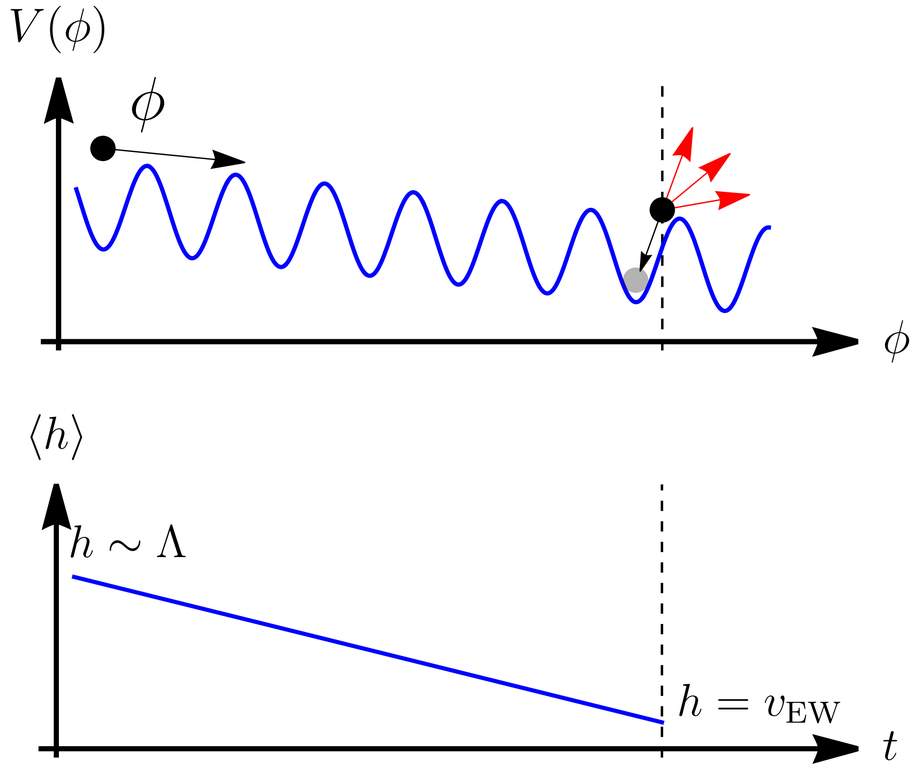
When W is light there is a tachyonic instability

$$\ddot{W}_\pm + (k^2 + m_W^2 \pm k\frac{\dot{\phi}}{f})W_\pm = 0$$

The growth of $W\tilde{W}$ slows down ϕ

$$\ddot{\phi} + \partial_\phi V + \frac{1}{4f}\langle W\widetilde{W}\rangle = 0$$

$$\langle W\widetilde{W}\rangle = \frac{1}{4\pi^2}\int \mathrm{d}k k^3 \frac{\mathrm{d}}{\mathrm{d}t}(|A_+|^2 - |A_-|^2)$$



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Gauge bosons production

Hook & Marques-Tavares, 1607.01786, JHEP
Fonseca, EM, Servant, 1805.04543, JHEP
Fonseca, EM, 1809.04534, PRD

$$\ddot{W}_\pm + (k^2 + m_W^2 \pm k\frac{\dot{\phi}}{f})W_\pm = 0$$

EW scale

- tachyonic growth starts when $\dot{\phi} \gtrsim m_W f$
- Impose this happens at $h \sim v_{\rm EW}$
- Field velocity $\dot{\phi} = \min(\Lambda^2, V'/H_I)$

$$v_{\rm EW} \sim \frac{\Lambda^2}{f} \quad \text{or} \quad v_{\rm EW} \sim \frac{g\Lambda^3}{H_I f}$$

Two key points (but not enough time)

- $W\tilde{W}$ should not contain $F_\gamma \tilde{F}_\gamma$

$$\frac{\phi}{4f}(g_2^2 W^a_{\mu\nu}\tilde{W}^{a\,\mu\nu} - g_1^2 B_{\mu\nu}\tilde{B}^{\mu\nu})$$

- Thermalisation reduces the efficiency of the mechanism

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Gauge bosons production

Hook & Marques-Tavares, 1607.01786, JHEP
Fonseca, EM, Servant, 1805.04543, JHEP
Fonseca, EM, 1809.04534, PRD

Main advantage: no need for strong Hubble friction. Works as well **after inflation**

- No worries for the inflationary sector
- (In principle) some observable features? GW? —> actually not, but…

Disclaimer:

- Backreaction not under control (more complicate than eg axion inflation)
- Recent claim: Schwinger pair production of SM fermions kills the model

Domcke, Schmitz, You, 2108.11295

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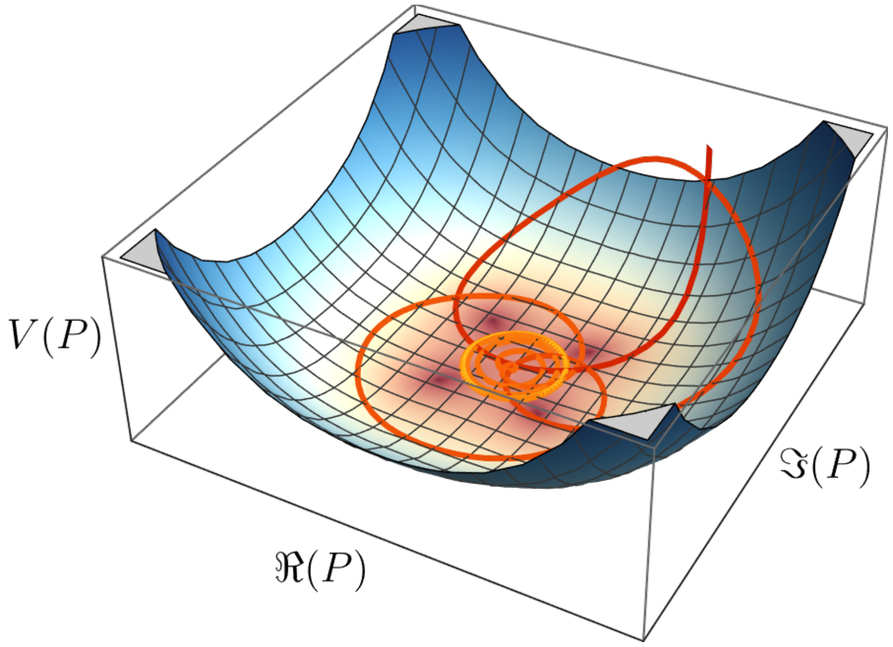
Kinetic misalignment

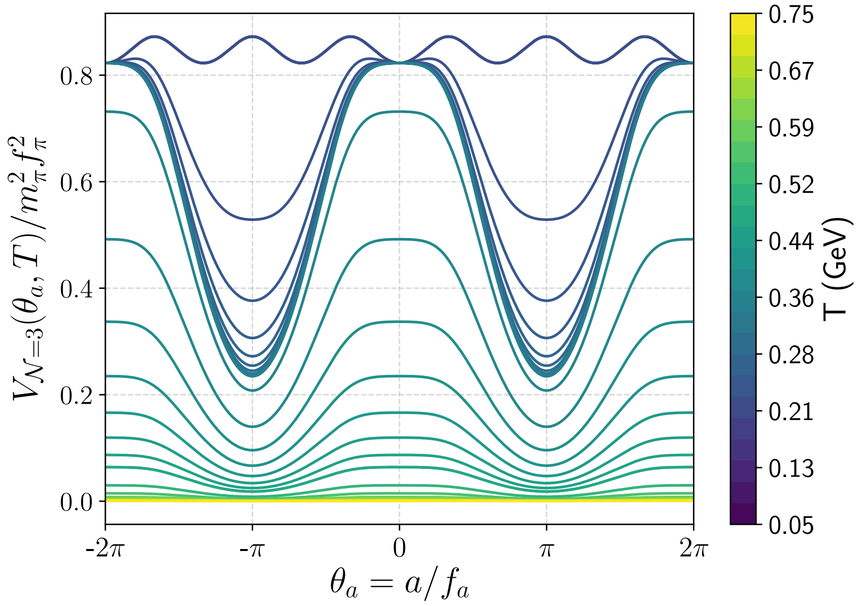
Sources: PQ violation, trapped misalignment

$$V(P) = \lambda(|P|^2 - f^2)^2 + \left(\frac{P^n}{M^{n-4}} + \text{hc}\right)$$

$$P = \rho\, e^{i\phi/f}$$



Non-trivial evolution of V(T), in a Z_N symmetric world



Di Luzio, Gavela, Quilez, Ringwald
2102.00012 *JHEP*, 2102.01082, *JHEP*

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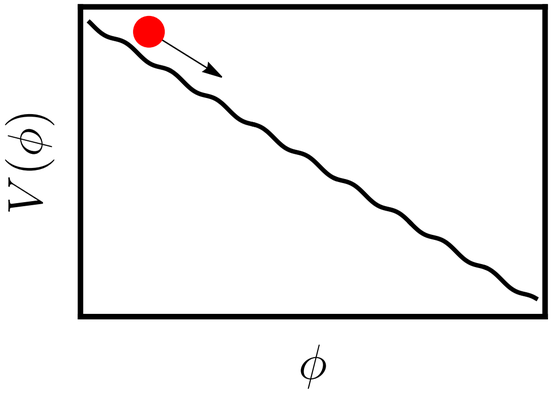
Monodromy inflation

A lot of work has been done in monodromy inflation

$$V(\phi) = V_{\rm smooth} + \Lambda^4 \cos\frac{\phi}{f}$$

$$\hookrightarrow \frac{1}{2}m^2\phi^2\,,\ \mu^3\phi\,,\ldots$$

Small wiggles regime: $V' > 0$

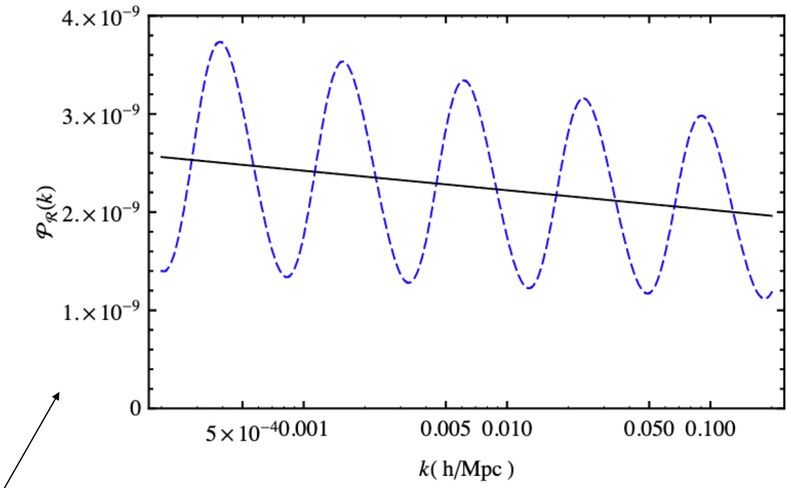


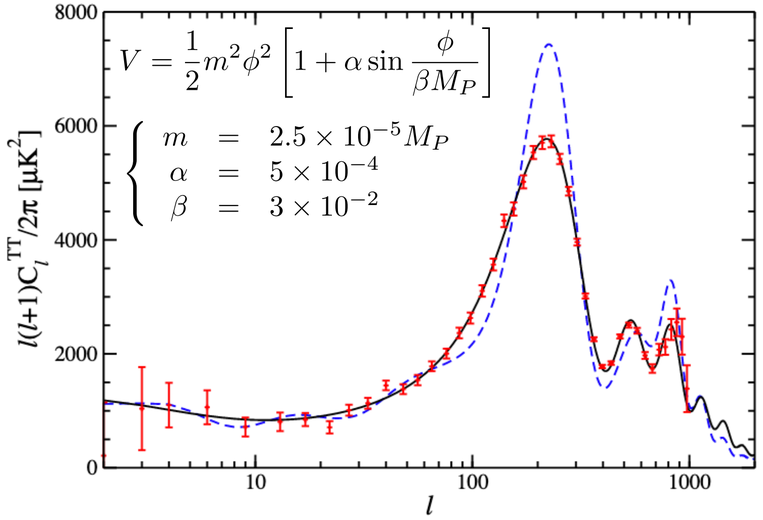
Small (perturbative) influence on the zero-mode evolution

See *e.g.*

- Flauger, McAllister, Pajer, Westphal, Xu 0907.2916, JCAP
- Pahud, Kamionkowski, Liddle, 0807.0322, PRD

+ others (before/after Planck)





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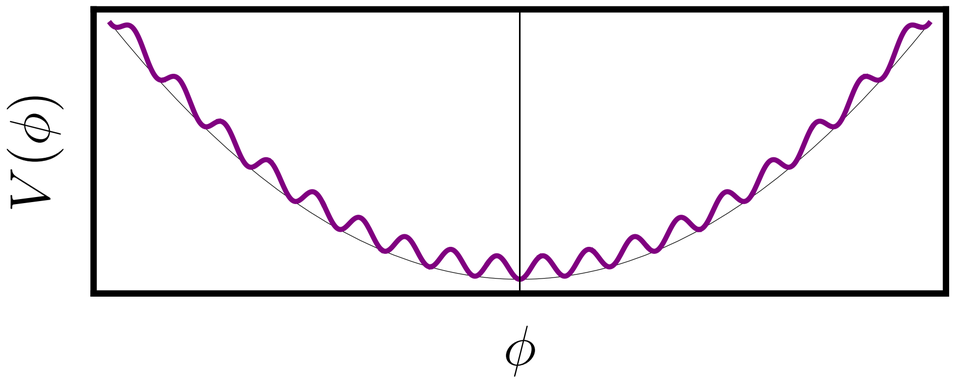
Monodromy and misalignment



$$V(\phi) = \frac{1}{2}m^2\phi^2 + \Lambda^4 \cos\frac{\phi}{f}$$

Presence of the wiggles can induce ϕ particle production

Can act as a ‘warm’ DM component

Berges, Chatrchyan, Jaeckel, 1903.03116, *JCAP*

Chatrchyan, Jaeckel, 2004.07844, *JCAP*

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Amplification

$$u_k(t) = \frac{e^{-ik\tau}}{a\sqrt{2k}} \longrightarrow u_{k_{\rm cr}}(t) \simeq \sqrt{\frac{2}{k_{\rm cr}}} \exp\left(\boxed{\frac{\pi\Lambda_b^8}{4f\dot{\phi}^2\,|\ddot{\phi}+H\dot{\phi}|}}\right) \sin\left(k_{\rm cr}t+\delta\right)$$

$\gg 1$ for efficient fragmentation

$$\frac{{\rm d}^3\rho}{{\rm d}k^3} = \frac{1}{(2\pi)^3}\frac{1}{2a^2}k_{\rm cr}^2|u_{k_{\rm cr}}|^2 \approx \frac{1}{(2\pi)^3}\frac{k_{\rm cr}^4}{a^4}\exp\left(\frac{\pi\Lambda_b^8}{2f\dot{\phi}^2\,|\ddot{\phi}+H\dot{\phi}|}\right)$$

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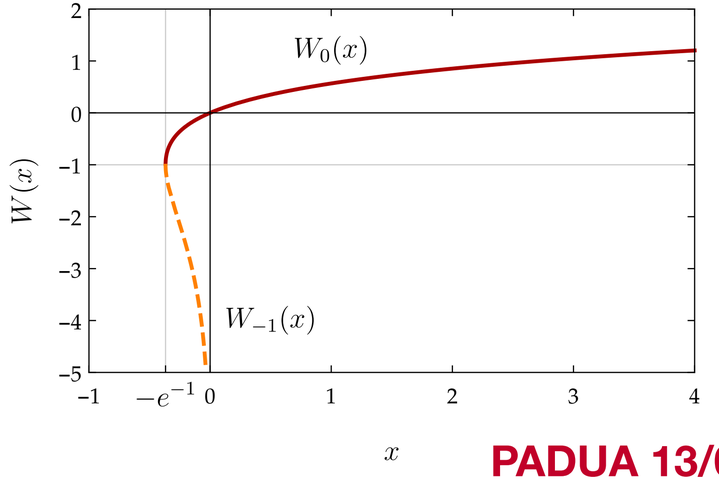
Hubble friction and slope

- $\mu^3 \neq 0$: the slope accelerates the field, contrasting the effect of fragmentation
- $H \neq 0$: Hubble suppresses the growth of fluctuations if $H\,\delta t_{\rm amp} > 1$
  (but it contrasts $\mu^3 \neq 0$)

$$\mu^3 < 2H\dot{\phi}_0 + \frac{\pi\Lambda_b^8}{2f\dot{\phi}_0^2}\left(W_0\left(\frac{32\pi^2 f^4}{e\dot{\phi}_0^2}\right)\right)^{-1}$$

W_0: product logarithm or Lambert-W function

$$We^W = x$$



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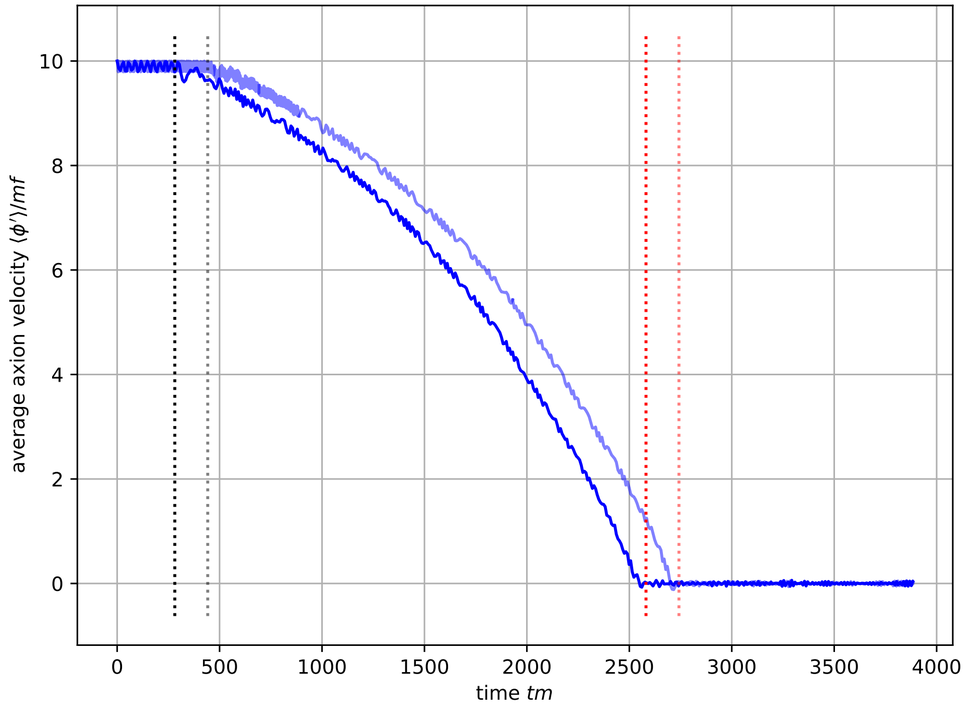
Lattice results

Dependence on the initial spectrum

- Analytic results obtained for a Bunch-Davies vacuum
- Exponential amplification —> Log dependence of the amplitude of the *initial* instability band

$$\left(\frac{\mathrm{d}\rho}{\mathrm{d}\log k}\right)_{k^0_{\rm cr}} \to x\left(\frac{\mathrm{d}\rho}{\mathrm{d}\log k}\right)_{k^0_{\rm cr}} \qquad \delta t_{\rm amp} = \frac{f\dot\phi}{\Lambda_b^4}\log\left(x\frac{16 f^4}{\dot\phi^2}\right)$$

- Subsequent evolution dominated by the spectrum induced by 2->1 processes



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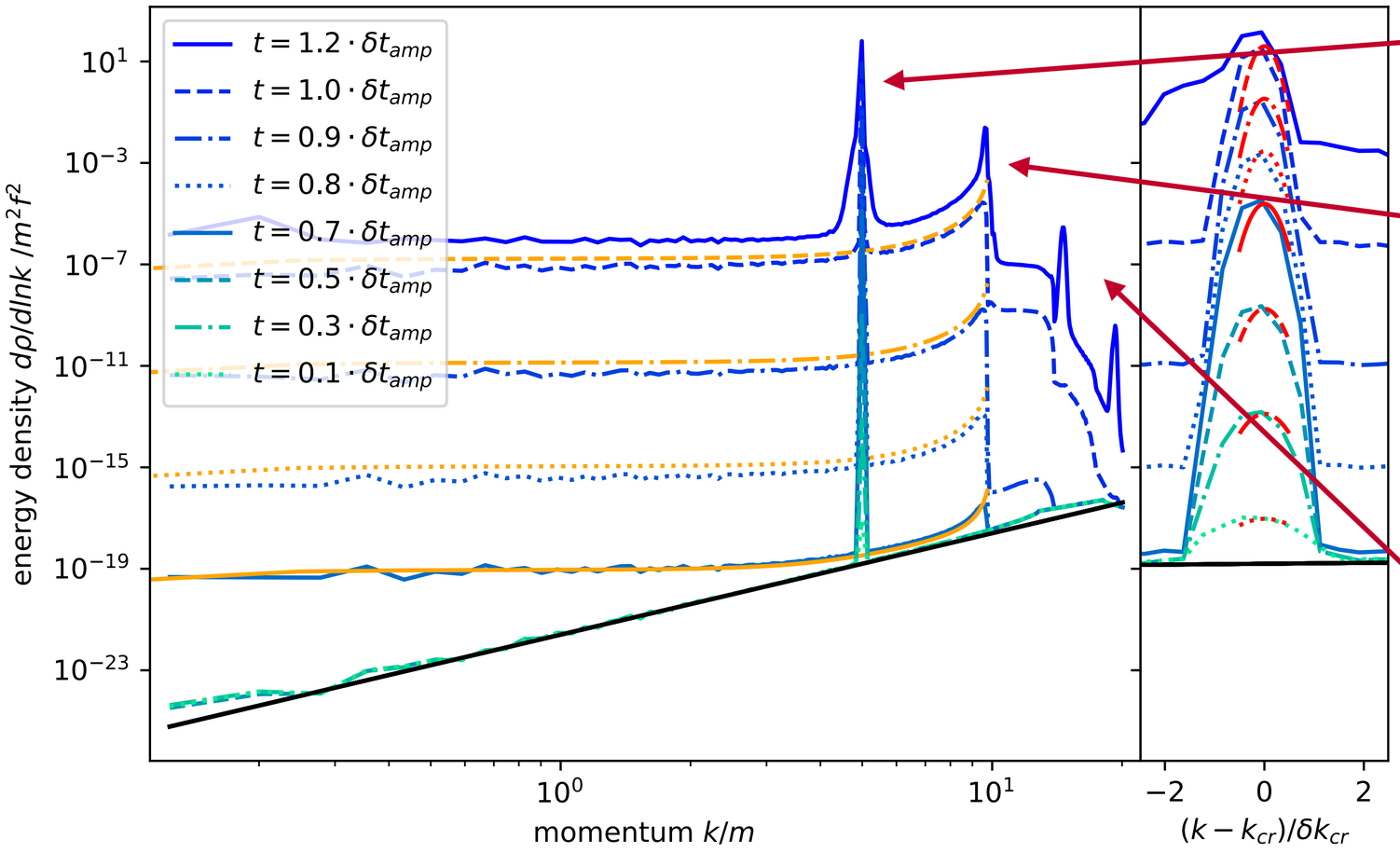
Lattice results

Particle spectrum



Instability band k~k_{cr}

2—>1 scattering k~2k_{cr}

$$\frac{d\rho^{(2)}}{d\log k} \approx \frac{k^2 \delta k_{cr}}{2^9 \pi^3} \frac{\Lambda_b^8}{f^6} \frac{1}{t} \exp\left(4\delta k_{cr} t\right) \times \left[\frac{1}{k^2 + 4\delta k_{cr}^2} + \frac{1}{(k - 2k_{cr})^2 + 4\delta k_{cr}^2} + \dots\right]$$

Higher peaks (non-perturbative)

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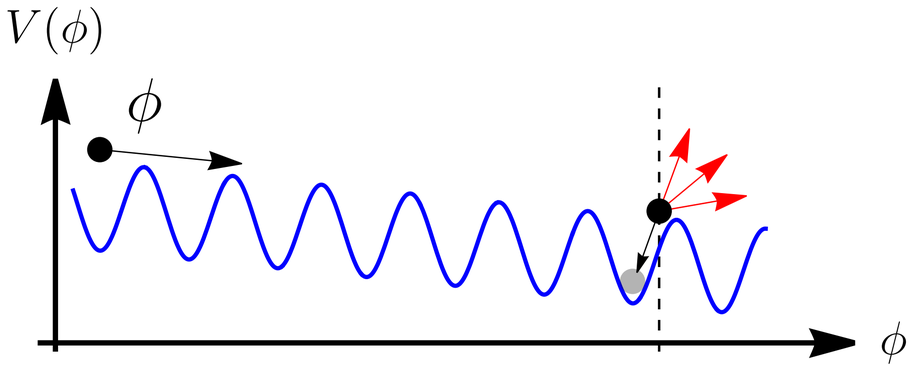
Hook & Marques-Tavares, 1607.01786, JHEP
Fonseca, EM, Servant, 1805.04543, JHEP
Fonseca, EM, 1809.04534, PRD

Gauge bosons production

Consequences II

Idea: dissipate kinetic energy with production of SM gauge bosons



$$\frac{\phi}{4f} W\widetilde{W} \longrightarrow \ddot{W}_\pm + (k^2 + m_W^2 \pm k\frac{\dot{\phi}}{f})W_\pm = 0$$

Constant barriers ⇒ fragmentation always active: ϕ stops when $\langle h \rangle$ is still large

After inflation: *dead*

During inflation: still OK

Arguments against bubbles

on small scales (lattice)

1. On the lattice, exponential suppression of large bubbles

$$n(V) \sim \exp(-\Gamma V)$$

extrapolate to $V \to R_{\rm crit}^3$

2. On small scales $\Delta x \lesssim m^{-1}$ (where most of the energy is)

$$\sqrt{\langle \delta\phi^2 \rangle} \approx (0.1 - 1) \times 2\pi f$$

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Arguments against bubbles

$\Delta x \gtrsim c\,\delta t_{\rm amp}$

3. On scales larger than $c\,\delta t_{\rm amp}$, fragmentation proceeds independently
   - multiple instances of the same quantum experiment
   - each time one samples the quantum (stochastic) initial condition
   - finite size of the box ⇒ finite variance

$$\frac{\sigma(\dot\phi_0 \delta t_{\rm amp})}{2\pi f} \approx \frac{1}{2}\left(\log\frac{8\pi f^2}{\dot\phi_0}\right)^{-3/2} \times \mathcal{O}(10) \approx 0.01 - 0.1$$

$\mathcal{O}(1)$ fluctuation is $(10-100)\sigma$ away (but we don't know the distribution)

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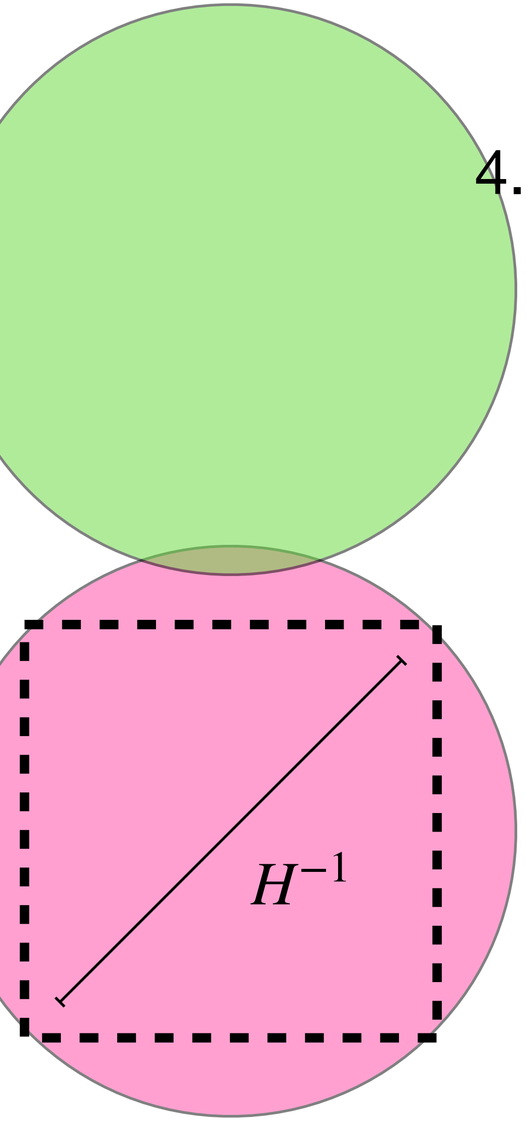
Arguments against bubbles

on super-Hubble scales



4. Different Hubble patches during inflation have different initial conditions

- Induced inflationary fluctuations $\delta\phi \sim H_I/(2\pi)$
- Variation in $\Delta\phi_{\rm frag}$ controlled by H_I
- Expect 1 DW of area H^{-2} at any time $\Rightarrow$ overclosure, CC
- Avoided imposing $\delta(\Delta\phi_{\rm frag}) \ll 2\pi f$

(sub-GeV in original relaxion construction)

$$H_I < \frac{\pi^2}{z_\phi}\frac{\Lambda_b^8}{\dot{\phi}_0^4}\frac{\Lambda}{g'} \sim 10^{10-16}\,\text{GeV}$$