Dynamical Phase Decomposition

and where to find it

Arthur Hebecker (Heidelberg)

based on work with J. Jaeckel F. Rompineve and L. Witkowski

Outline

- Dynamical Phase Decomposition
  and its gravitational wave signal
- A concrete case study:
  axion monodromy inflation
- Relation to other scenarios and further settings
  with Dynamical Phase Decomposition

Preliminary Remarks

- We are all used to the statement that
  'Inflation is the natural place to test string theory'.
- But this is only half-true:
  Indeed, already during inflation we expect to be deeply in the domain of low-energy EFT.
- Clearly, this does not get better after inflation.
- Thus, the topic of this conference
  is a very important but also very difficult one!
- Still, you gotta keep trying...

Preliminary Remarks (continued)

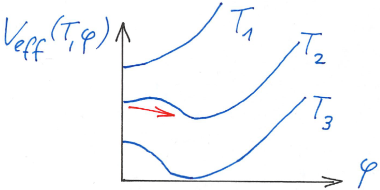
An incomlete list of options is...

- Dark matter from string theory
- Axions and other superlight fields
  (various, non-dark-matter effects thereof)
- Phase transitions, topological defects
  (e.g. gravitational wave effects thereof)
- Landscape considerations of various sorts
- etc. etc.

Introduction

- A classic source of (cosmological, post-inflationary) gravitational waves are thermal phase transitions.

  (such as the once so popular elctroweak phase transition)

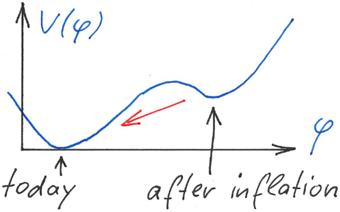


Temperatures: $T_1 > T_2 > T_3$ $\leftrightarrow$ Times: $t_1 < t_2 < t_3$.

Introduction (continued)

- Another classic source of of such gravitational waves are vacuum phase transitions ($T = 0$).

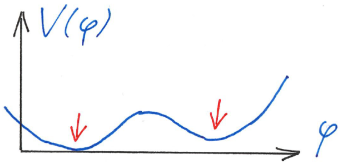
For a recent example in the context of Klebanov-Strassler-Throats / Randall-Sundrum models see Garcia Garcia/Krippendorf/March-Russell '16 .



- However, in either case one may feel that either very special models or very special parameters (e.g. barrier height) are needed.

Introduction (continued)

- Yet another option are domain wall networks:



$\Rightarrow$

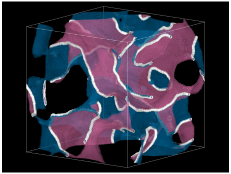


Figure from
Hiramatsu/Kawasaki/Saikawa/Sekiguchi '12

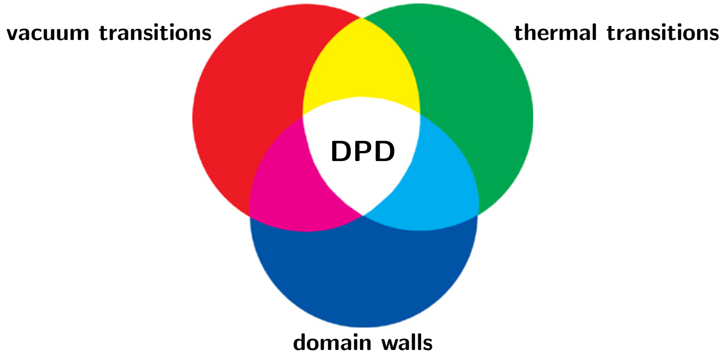
- Here, both minima are randomly occupied after inflation.
- Not to be ruled out, the network must collapse
  (either due to bias or due to boundary strings).
- The collapse leaves a gravitational wave signal.

Dynamical Phase Decomposition

- I would like to think of

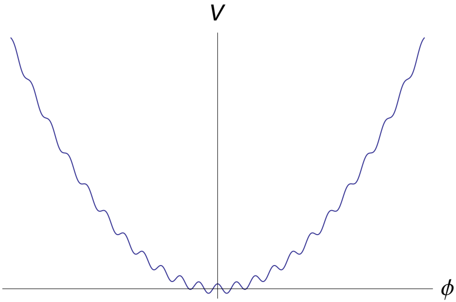
  Dynamical Phase Decomposition (**DPD**)

  as of lying somwhere in between the three ‘standard’ dynamical processes:



Dynamical Phase Decomposition (Motivation)

- Consider an axion-monodromy-type potential (recently popular in string-inflation and 'relaxiology').



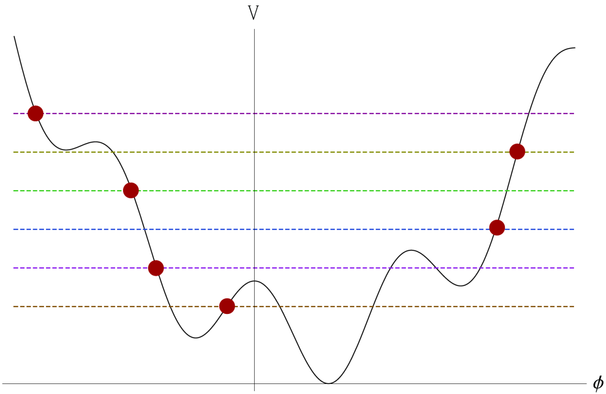
- How does Rehating in this potential work?

for related considerations see papers by
Daido/Kitajima/Takahashi '15, Higaki et al. '16;
Kaloper/Padilla '16; Jaeckel/Mehta/Witkowski '16

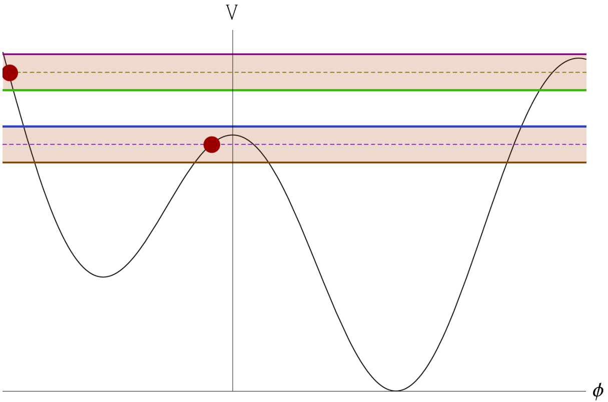
for preheating in this context see Brandenberger et al. '16
(see also talks of Amin, Muia, Krippendorf, Kang, ...)

- The field oscillates and eventually 'gets stuck' in one of the local minima

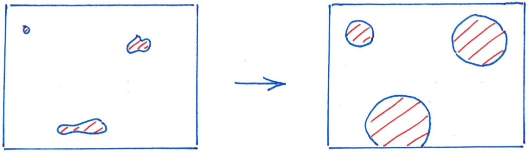
- It then continues to oscillate in that minimum (where it later decays to light particles, i.e. reheats)



- Crucially, at each ‘turning point’, an uncertainty due to field fluctuations exists
- Hence, with a certain probability, two different minima are populated inside one Hubble patch



- Consider the situation where, in most of the universe, the field gets caught in a metastable minimum.
- As described, there may also exist some patches where it ends up in the stable minimum.



- Those small patches will evolve into bubbles, grow and eventually collide and produce gravitational waves.

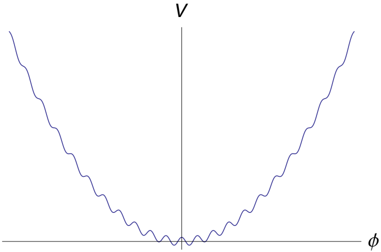
Gravitational wave analysis
(highly simplified)

- In analogy to thermal phase transitions:

$$\frac{\rho_{GW}}{\rho_{tot}} \simeq \theta \left(\frac{H_*}{\delta} \right)^2 \frac{\eta^2}{(1+\eta)^2} \, .$$

- H_*/δ – Hubble scale and bubble separation at time of transition
- $\eta \equiv \epsilon/\rho^*_{rad}$ – relative strength of transiton (in our case: $\rho^*_{rad} \; \to \; \rho^*_{osc}$)
- $\theta \sim 0.01$ from detailed dynamics.

- To relate this to model parameters (e.g. of axion monodromy inflation), recall the basic potential

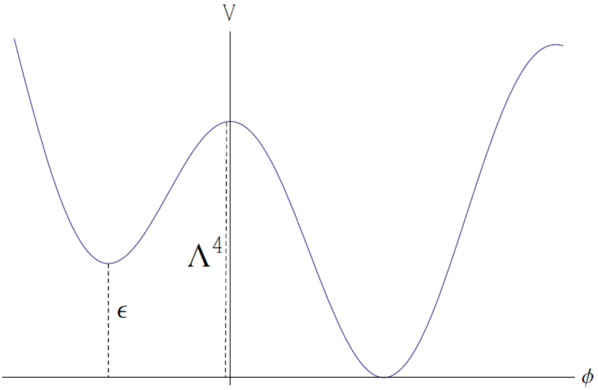


$$V(\phi) = \frac{1}{2} m^2 \phi^2 + \Lambda^4 \cos\left(\frac{\phi}{f} + \gamma\right)$$

- Here $m \sim 10^{-5}$ from CMB perturbations;
  $\Lambda^4 \ll m^2$ from non-observation of oscillations;
  $f \ll 1$ to have any metastable minima

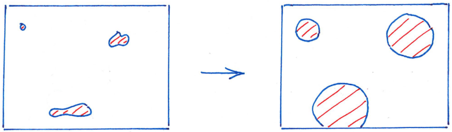
- The number of minima is estimated by $\kappa \equiv \dfrac{\Lambda^4}{f^2 m^2}$.

- The strength of the transition, $\eta = \dfrac{\epsilon}{\rho^*_{osc}} = \dfrac{\epsilon}{\Lambda^4}$, can be as large as $\mathcal{O}(1)$.



- Finally, the crucial parameter H_*/δ can vary widely.
- δ can be as large as the mass scale near the bottom of the potential: $\delta \sim M$ with $M \equiv \Lambda^2/f$. Then $H_*/\delta \ll 1$.
- However, if the phase decomposition is unlikely, very few bubbles may form.

  Then H_*/δ can easily be a large as $\mathcal{O}(1)$ (or even beyond!)



Gravitational wave analysis – Peak frequency

- Peak frequency at phase transition decomposition:

$$\omega_{peak} \simeq 0.1\,\delta\,.$$

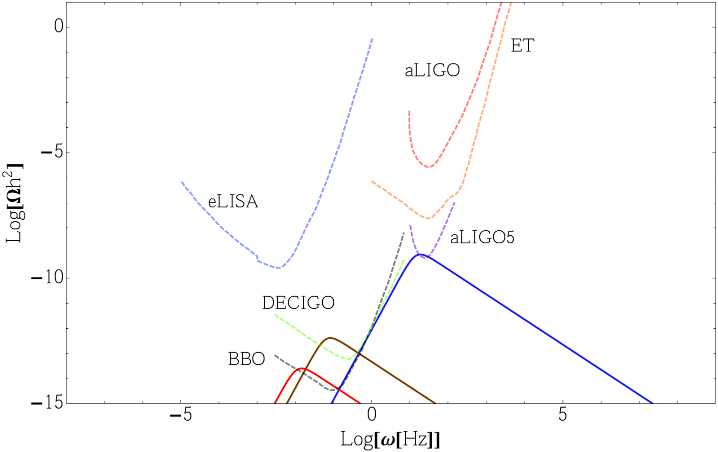
- Peak frequancy today:

$$\omega_0 \simeq 10^7\text{Hz} \cdot \left[\frac{T_{RH}}{10^{15}\text{GeV}}\right] \cdot \left(\frac{\delta}{H_*}\right) \cdot \nu_w \cdot \nu_{nr}\ .$$

- The factors $\nu_w = \left(\frac{\rho_{NR}}{\rho_*}\right)^{1/(3+3w)}$ and $\nu_{nr} = \left(\frac{\rho_{RH}}{\rho_{NR}}\right)^{1/3}$

  are peculiar to our setting; they describe
  a highly inhomogeneous period after the transition
  and a subsequent matter domination period.

- Combining the above, we can give some example signals at the margin of expected observability:

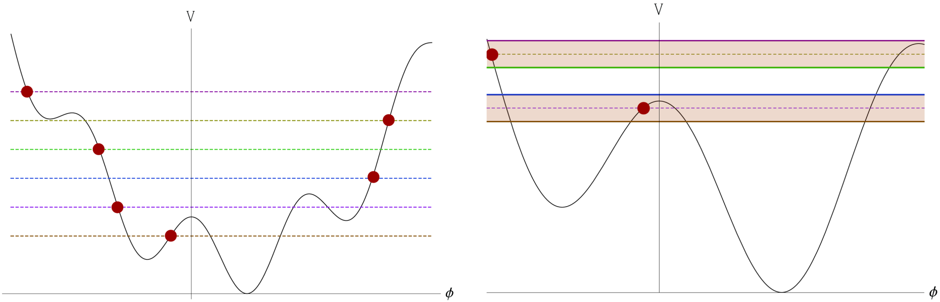


- Values used: $\kappa = 5,\ f = 0.1 M_P,\ T_{RH} = 10^{12}\mathrm{GeV}$
  $\kappa = 10,\ f = 0.01 M_P,\ T_{RH} = 10^{11}\mathrm{GeV}$
  $\kappa = 70,\ f = 0.001 M_P,\ T_{RH} = 10^{11}\mathrm{GeV}$

Problem of the likelihood of phase decomposition

- Unfortunately, we can not choose our parameters $(\kappa, f, \cdots)$ at will and expect to see a graviational wave signal.

- In some regimes, one has to be lucky with model parameters.



- Indeed, the uncertainty band has to hit one of the local maxima to realize phase decomposition.

Problem of the likelihood of phase decomposition (continued)

- Note that the 'randomness' of the vertical positions of the bands is not due to unknon initial conditions.

  It comes from fine details of the inflationary potential.

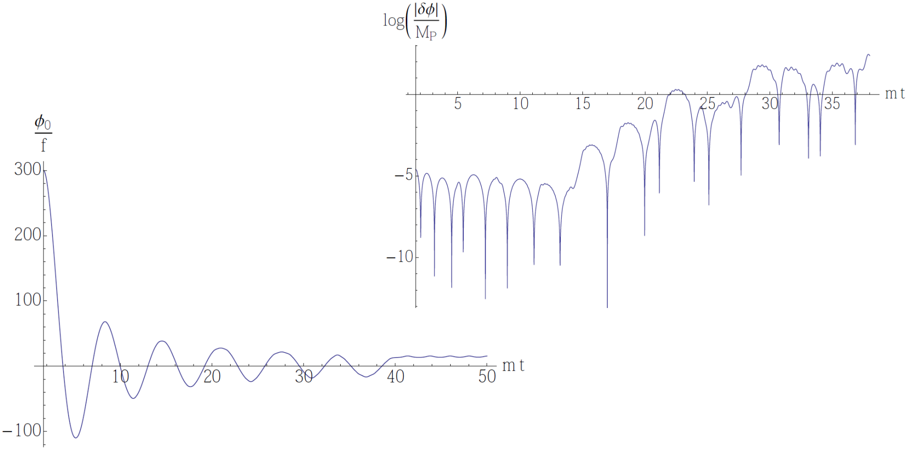
- Relying solely on primordial fluctuations, the quantity which needs to be $\mathcal{O}(1)$ to get a very likely phase decomposition is

$$\frac{\delta\rho^{inf}}{\Delta\rho} \sim \kappa^{-1/3}\left(\frac{m}{M_p}\right)\left(\frac{M_p}{f}\right)^{5/3} .$$

- We clearly see that fairly small f is needed to overcome the suppression by $m/M_p \sim 10^{-5}$.

- But, as an axion monodromy model builder, why would one start with $f = 10^{-3}$ when $f = 0.1$ is also available?

- Fortunately, resonant enhancement of both primordial and late-time quantum fluctuations of ϕ generically occurs.



- It is driven by the continued oscillations of the field in its 'washboard potential'.

- The dynamics is governed by the Hill differential equation,

$$\delta\phi_k'' + \frac{2}{t'}\delta\phi_k' + \left[1 + \frac{k^2}{m^2 a^2(t')} - \kappa \cos\left(\varphi_0\left(t'\right)\right)\right]\delta\phi_k\left(t'\right) = 0,$$

  supplemented by cosmic friction effects.

- While a full analytic understanding of the resonance is difficult, we roughly observe two regimes:

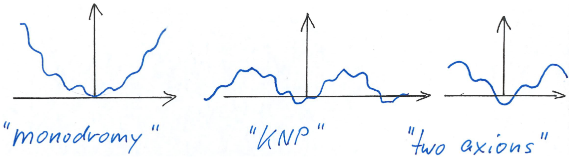
- $f \gg 0.01 M_P$ – no resonance, no dynamical phase decomposition.
- $f \ll 0.01 M_P$ – resonance leads to non-linearities on many scales, dynamical phase decomposition occurs (but may be much more complicated than described above).

- What we described before is just the simple 'borderline regime'.

Summary and Conclusions

- In potentials with several minima, ‘dynamical phase decomposition’ can arise and produce a strong gravitational wave signal.

- The details can be very diverse

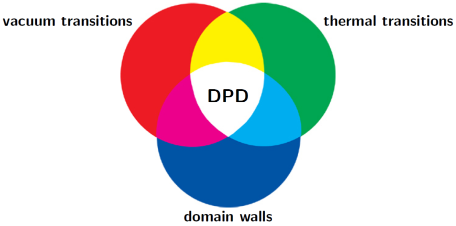


and we only analysed one particular, ‘monodromy-inflation -motivated’ case.

- While our findings are encouraging, they also rely on a (possibly unnatural) small value of f/M_P.

Summary and Conclusions (continued)

- But many more parametric regimes remain to be analysed....



- In between the 'monodromy-inflation' case discussed here and the related 'domain-wall-type' (axion-roulette) scenarios of

  Daido/Kitajima/Takahashi ,

  further interesting options certainly exist.

- Interesting questions are whether some of them are completely 'natural' and whether the gravitational-wave-signal is specific enough to teach us about the dynamics.