Gravitational waves from Axion Monodromy

Fabrizio Rompineve

Institute for Theoretical Physics, Heidelberg

Ioannina, String Pheno 2016

In collaboration with A. Hebecker, J. Jäckel and L. Witkowski

Riding on (gravitational) waves, pt.1

→ **Inflationary tensor modes**: measured in the CMB.

→ Fundamental observable:

$$r = \frac{\Delta_T^2}{\Delta_S^2} \sim 16\epsilon \leq 0.08, \quad \text{where} \quad \epsilon \approx \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1.$$

- Very importantly:

$$\frac{\Delta\phi}{M_p} \gtrsim \left(\frac{r}{0.01}\right)^{1/2}.$$

⇒ Transplanckian field displacements may be required.

- Axions are ideal inflaton candidates because of their (discrete) shift symmetry.
- Axion monodromy is arguably the most promising mechanism to realise Large Field Inflation.

Riding on (gravitational) waves, pt. 2

2 **Radiation from post-inflationary sources**: e.g. phase transitions, preheating, topological defects, ...

- Standard example: first order EW phase transition in the SM, MSSM.
- Can be detected by future space- or ground-based gravitational wave interferometers (upgrades of aLIGO, eLISA, etc.).
- **Motivational question**: if inflation is Large Field, what are the peculiar signatures of axion monodromy?
  Peiris,Easther,Flauger'13/Kobayashi,Seto,Yamaguchi '13/
  Flauger,McAllister,Silverstein,Westphal '14/....
- **Focus of this talk**: post-inflationary gravitational radiation in models of axion monodromy inflation.

THE GRAVITATIONAL WAVE SPECTRUM

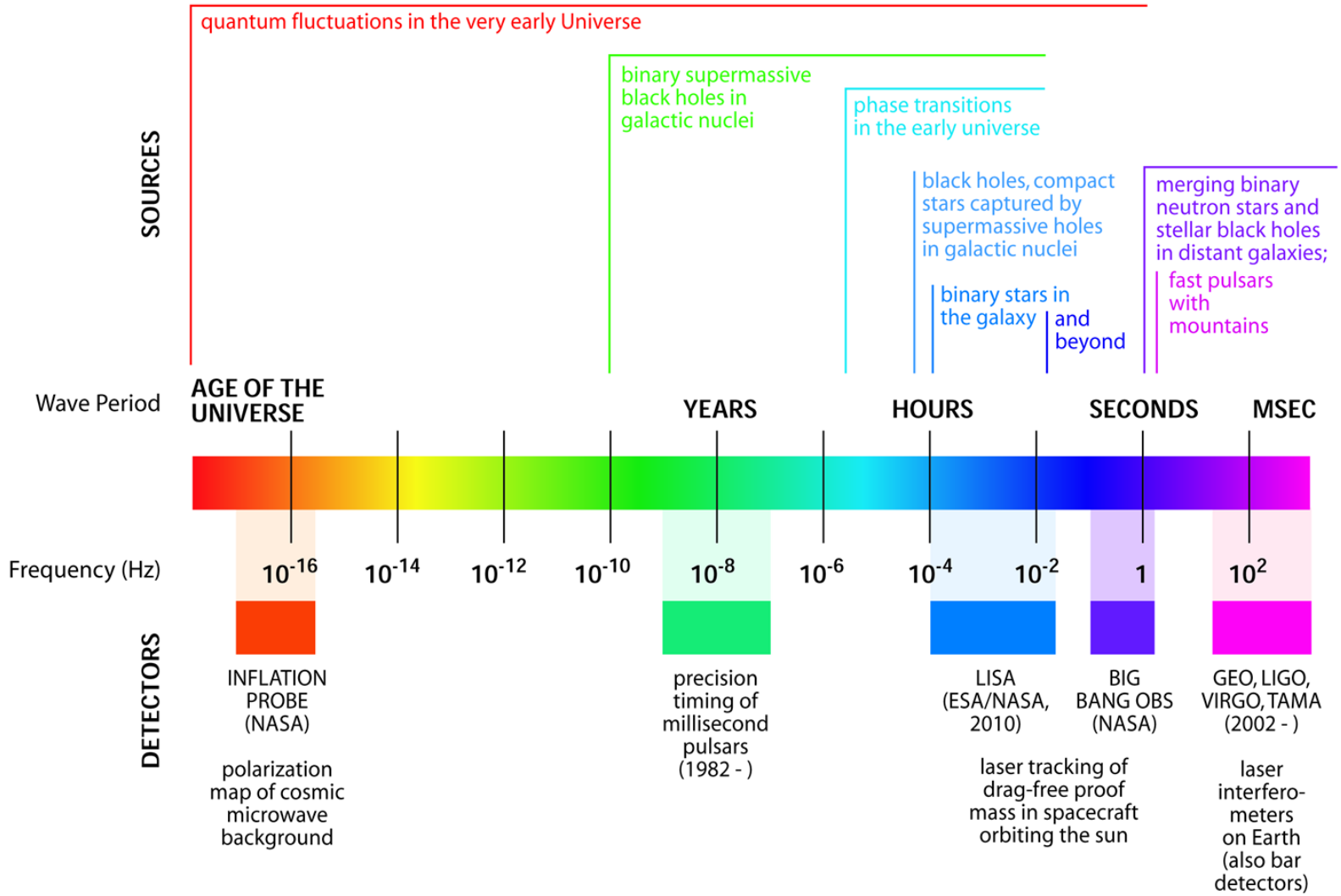


Figure: Taken from ligo.org.

Axion Monodromy Potential [Silverstein,Westphal/+McAllister'08]

→ Implementation in string compactification/SUGRA: **F-term axion monodromy**. Axions can be complex structure moduli, brane position moduli etc. Monodromies can be induced by fluxes.
[Marchesano,Shiu,Uranga/Blumenhagen,Plauschinn/Hebecker,Kraus,Witkowski '14]

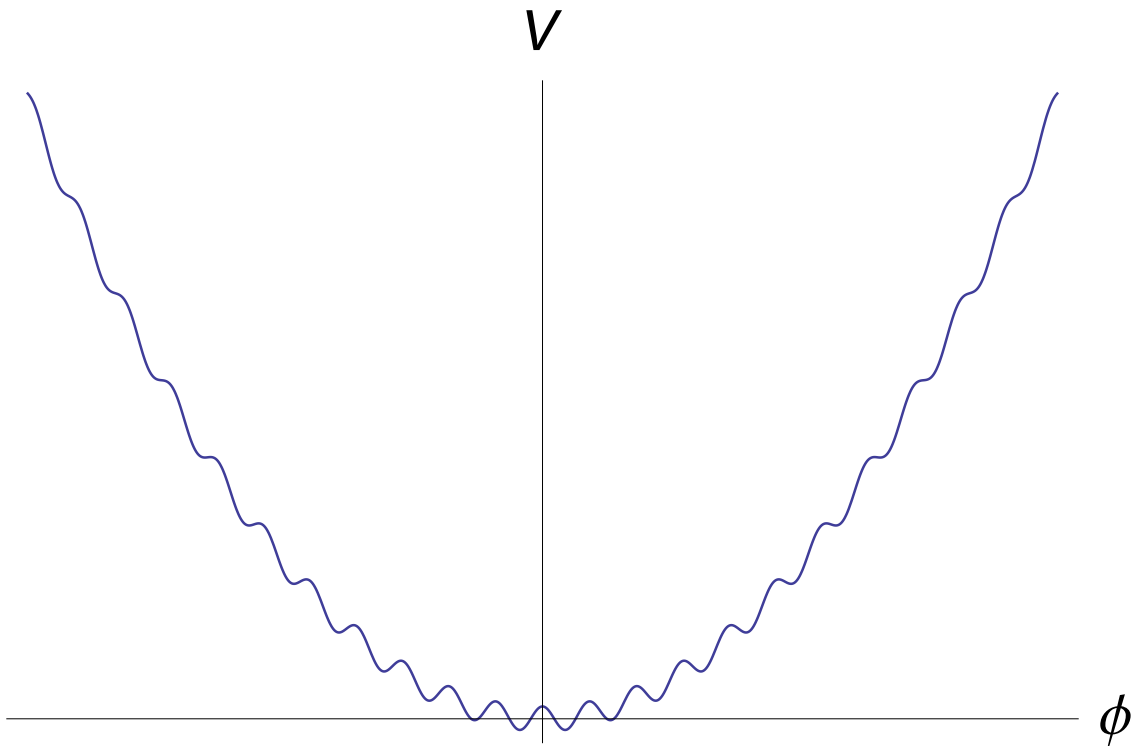
→ For the sake of this talk, low-energy phenomenological definition:

$$V = \underbrace{\frac{1}{2}m^2\phi^2}_{\text{monodromy breaking shift symmetry}} + \overbrace{\Lambda^4 \cos(\frac{\phi}{f}+\gamma)}^{\text{instanton-induced modulations}}$$

→ For

$$\kappa \equiv \frac{\Lambda^4}{m^2 f^2} > 1$$

the potential exhibits $\approx \kappa/\pi$ local minima.



→ Low energy wiggles provide a connection between Axion Monodromy and the Weak Gravity Conjecture. Hebecker, FR, Westphal '15/ see also Ibanez, Montero, Uranga,Valenzuela '15 for alternative perspective

→ Setup may also arise in **aligned** and **winding** models KNP '04/ Berg,Pajer,Sjors '09/Ben-Dayan,Pedro,Westphal '14.

→ In this case the WGC may actually force the presence of smaller modulations! Rudelius/Brown,Cotrell,Shiu,Soler '14.

Dynamics after inflation: the background

- Large wiggles during inflation may spoil slow-roll⇒ Focus on local minima **after** inflation.
- Consider first purely homogeneous inflaton, i.e. $\phi \equiv \phi(t)$.

→ After inflation: **fast roll** in approximately quadratic potential.

- Inflaton behaves approximately like matter:

$$\phi(t) \approx \phi_0(t)\cos(mt), \quad \text{with} \quad \phi_0 \sim a^{-3/2} \sim t^{-1}.$$

⇒ The energy density $\rho_\phi \sim m^2\phi^2$ decreases with each oscillation!

⇒ Eventually, the field is confined in a region where wiggles are not negligible.

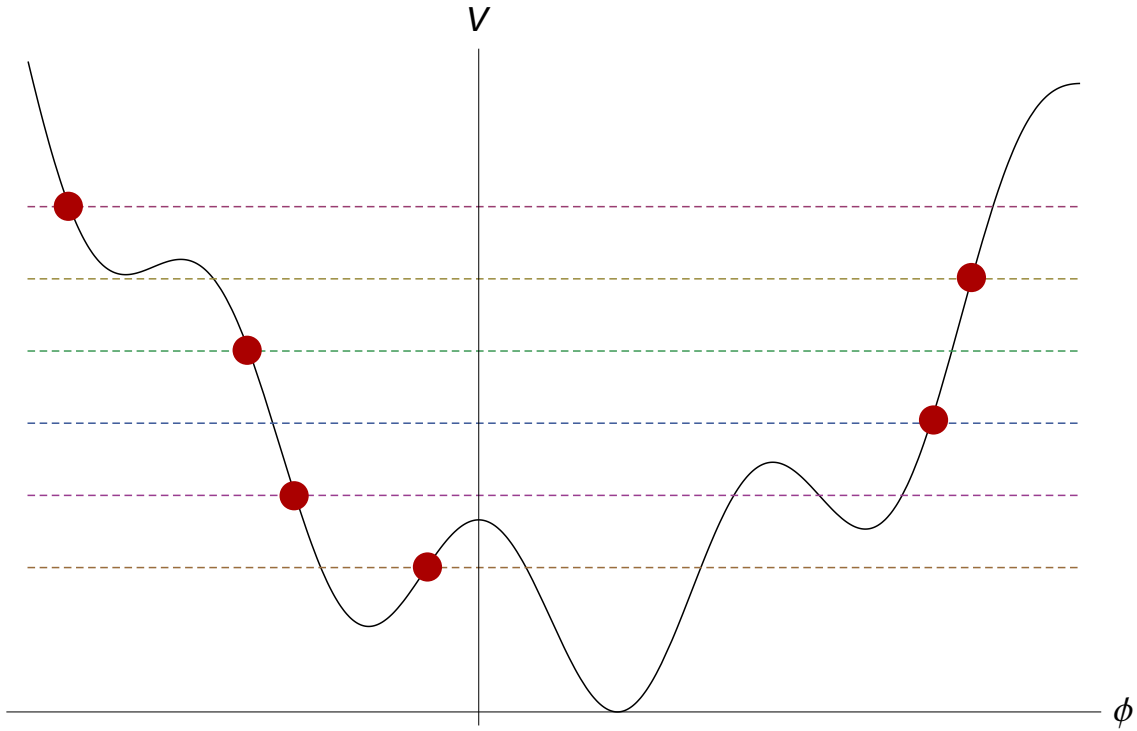


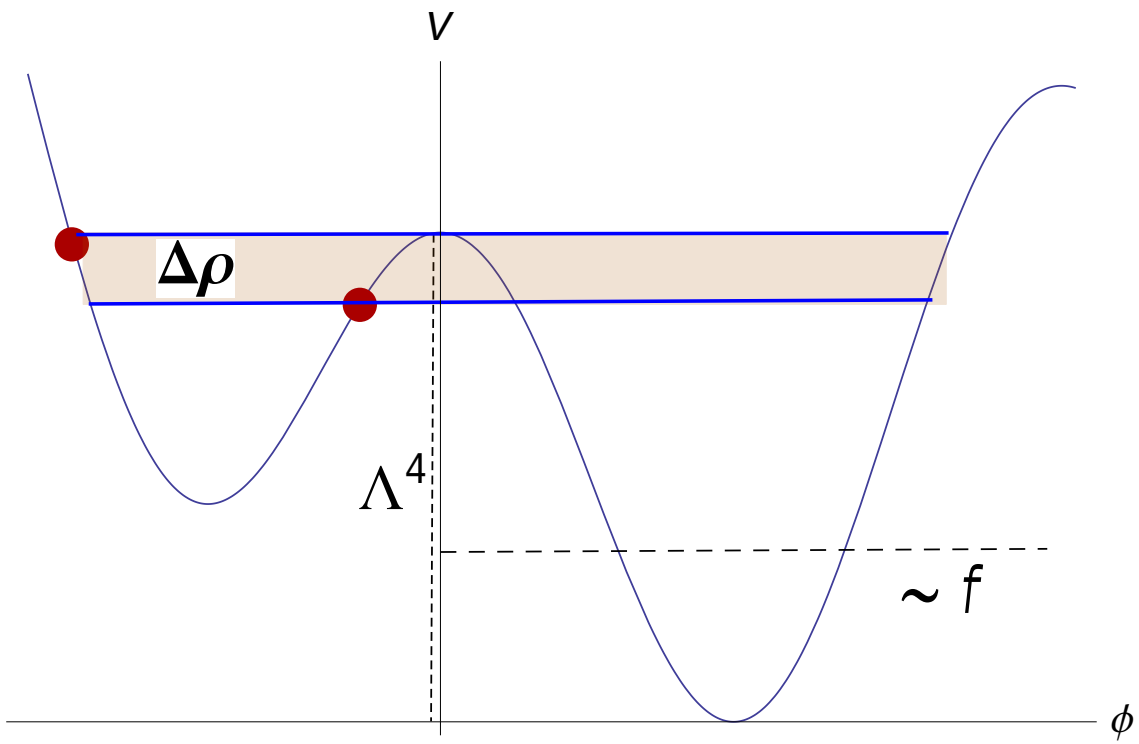
Figure: Dots show the turning points in the inflaton trajectory.

→ At a certain point, the inflaton does not have enough energy to overcome one of the cosine bumps.

⇒ **Conclusion**: homogeneous field is trapped inside one of the wells!

→ From now on: focus on last **two** wells, generically **non-degenerate** (field is more likely to get caught at the bottom of V).

Shaded band=energy lost in half oscillation



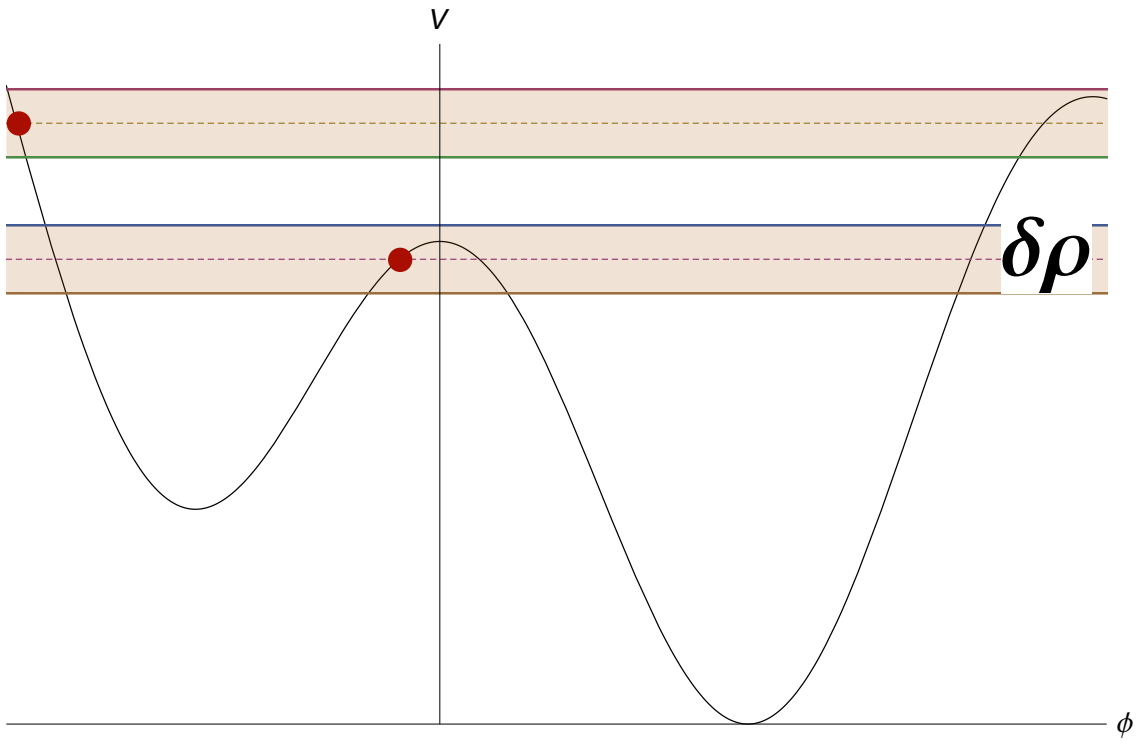
$$\frac{\Delta\rho}{\rho} \sim \frac{H}{m_\phi}, \quad \text{with} \quad H \sim \frac{\rho^{1/2}}{M_p} \sim \frac{\Lambda^2}{M_p}, \quad m_\phi = V''|_{min} \sim \frac{\Lambda^2}{f}$$

Loss of energy

$$\Rightarrow \Delta\rho \sim \kappa \cdot \frac{m^2 f^3}{M_p}$$

Situation with field fluctuations

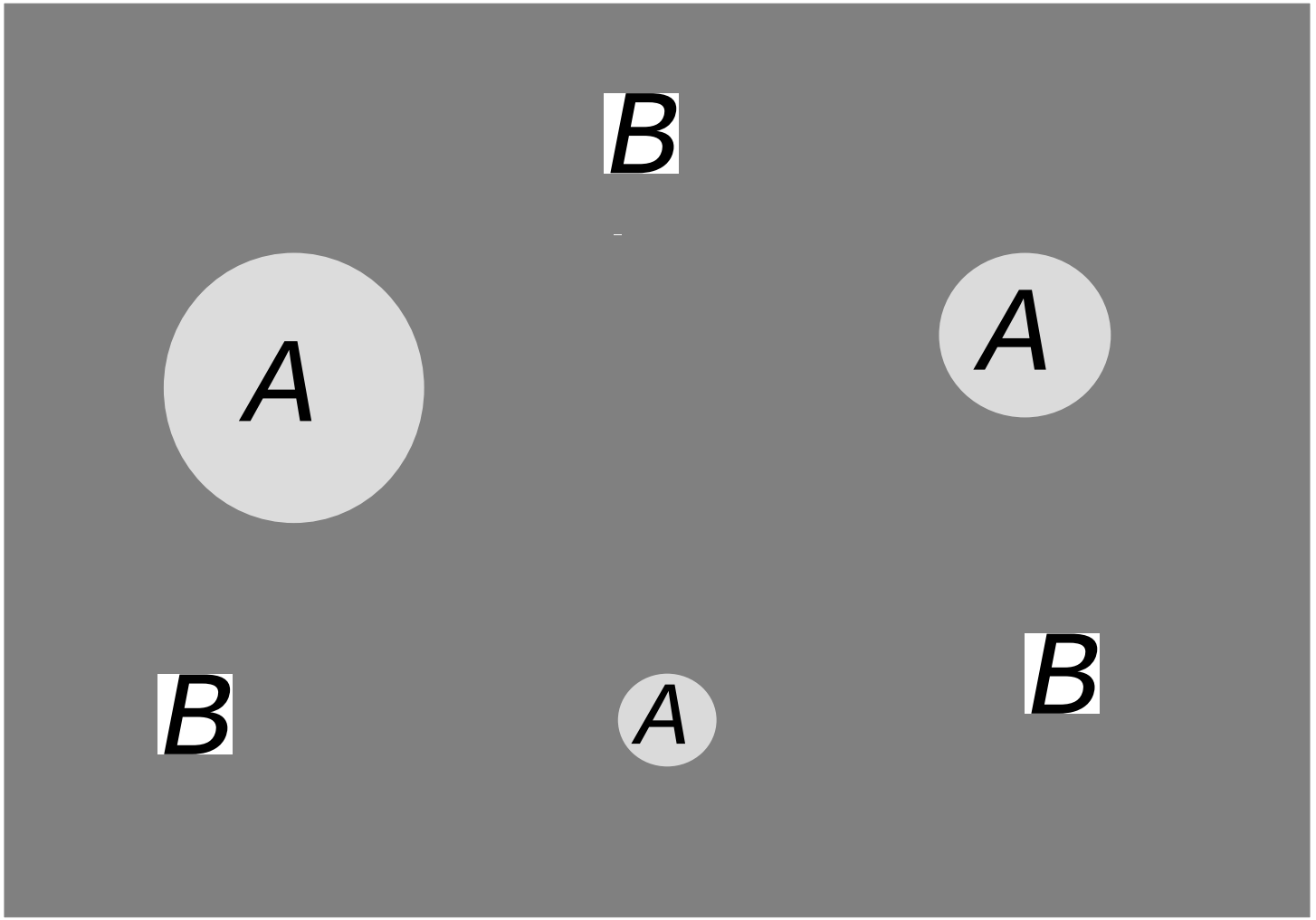
→ Now consider the real world: $\phi(\mathbf{x}, t) = \phi(t) + \delta\phi(\mathbf{x}, t)$.



→ Fluctuations induce an uncertainty in the energy density, represented as shaded bands in the picture.

⇒ Field populates other minimum with non-vanishing probability!

Phase decomposition



→ Energy density is different in different regions of the same Hubble patch!

→ Eventually bubbles of true vacuum expands and collide⇒ Emission of gravitational waves!

- **How likely is this situation?**

→ Probability of phase decomposition can be estimated as

$$\mathcal{P} \sim \frac{\delta\rho}{\Delta\rho}$$

- There are two possible sources for $\delta\rho$:

$\rightarrow$ Eventually bubbles of true vacuum expands and collide$\Rightarrow$ Emission of gravitational waves!

- **How likely is this situation?**

$\rightarrow$ Probability of phase decomposition can be estimated as

$$\mathcal{P} \sim \frac{\delta\rho}{\Delta\rho}$$

- There are two possible sources for $\delta\rho$:

  1 Our focus in this talk: **Classical** fluctuations $\delta\phi_k^{inf}$, naturally inherited from inflation.

  $\rightarrow$ Start as quantum, then stretched to superhorizon scales during inflation $\rightarrow$ classicalised $\rightarrow$ re-enter the horizon at $H \sim k$.

$\rightarrow$ Eventually bubbles of true vacuum expands and collide$\Rightarrow$ Emission of gravitational waves!

- **How likely is this situation?**

$\rightarrow$ Probability of phase decomposition can be estimated as

$$\mathcal{P} \sim \frac{\delta\rho}{\Delta\rho}$$

- There are two possible sources for $\delta\rho$:

1. Our focus in this talk: **Classical** fluctuations $\delta\phi_k^{inf}$, naturally inherited from inflation.

$\rightarrow$ Start as quantum, then stretched to superhorizon scales during inflation $\rightarrow$ classicalised $\rightarrow$ re-enter the horizon at $H \sim k$.

2. **Quantum** modes uncertainties which characterize any quantum field at any given time, $\delta\phi_k^q \sim k$.

$\rightarrow$ Inflationary modes with $k \gtrsim m$ are also quantum and may be exponentially enhanced see Viraf's talk.

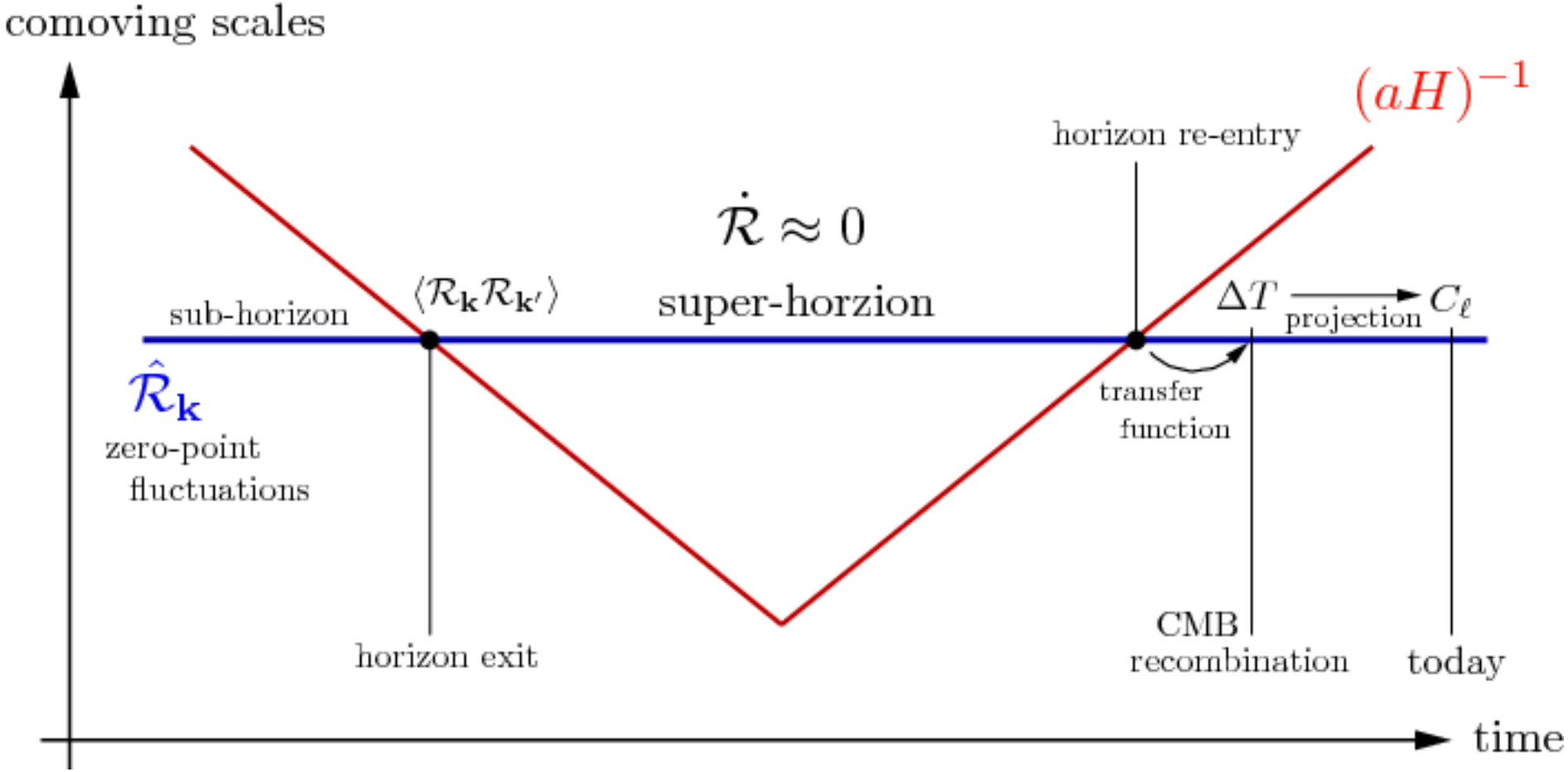


Figure: Taken from Baumann *TASI 09 Lecture Notes*

$\rightarrow$ Modes that exit later re-enter earlier!

- Simplest analysis: **first** modes to re-enter the horizon, i.e. with $k \sim m$.
- Initial amplitude set by inflationary power spectrum:

$$\frac{\delta\rho^{inf}}{\rho}(t_{re-entry}) \sim \sqrt{\Delta^2_\phi} \sim \frac{1}{M_p}\frac{H}{\epsilon^{1/2}}|_{exit} \sim \frac{m}{M_p} \sim 10^{-5}.$$

$\rightarrow$ Then they decay like dark matter fluctuations until $H \sim \Lambda^2/M_p$:

$$\frac{\delta\rho^{inf}}{\rho} \sim a, \quad \text{with} \quad \rho \sim a^{-3} \quad \Rightarrow \quad \delta\rho^{inf} \sim a^{-2}$$

Probability of phase decomposition

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

$\rightarrow$ For $\kappa \sim 10$, phase decomposition is likely for $f \lesssim 0.3 \cdot 10^{-2} M_p$.

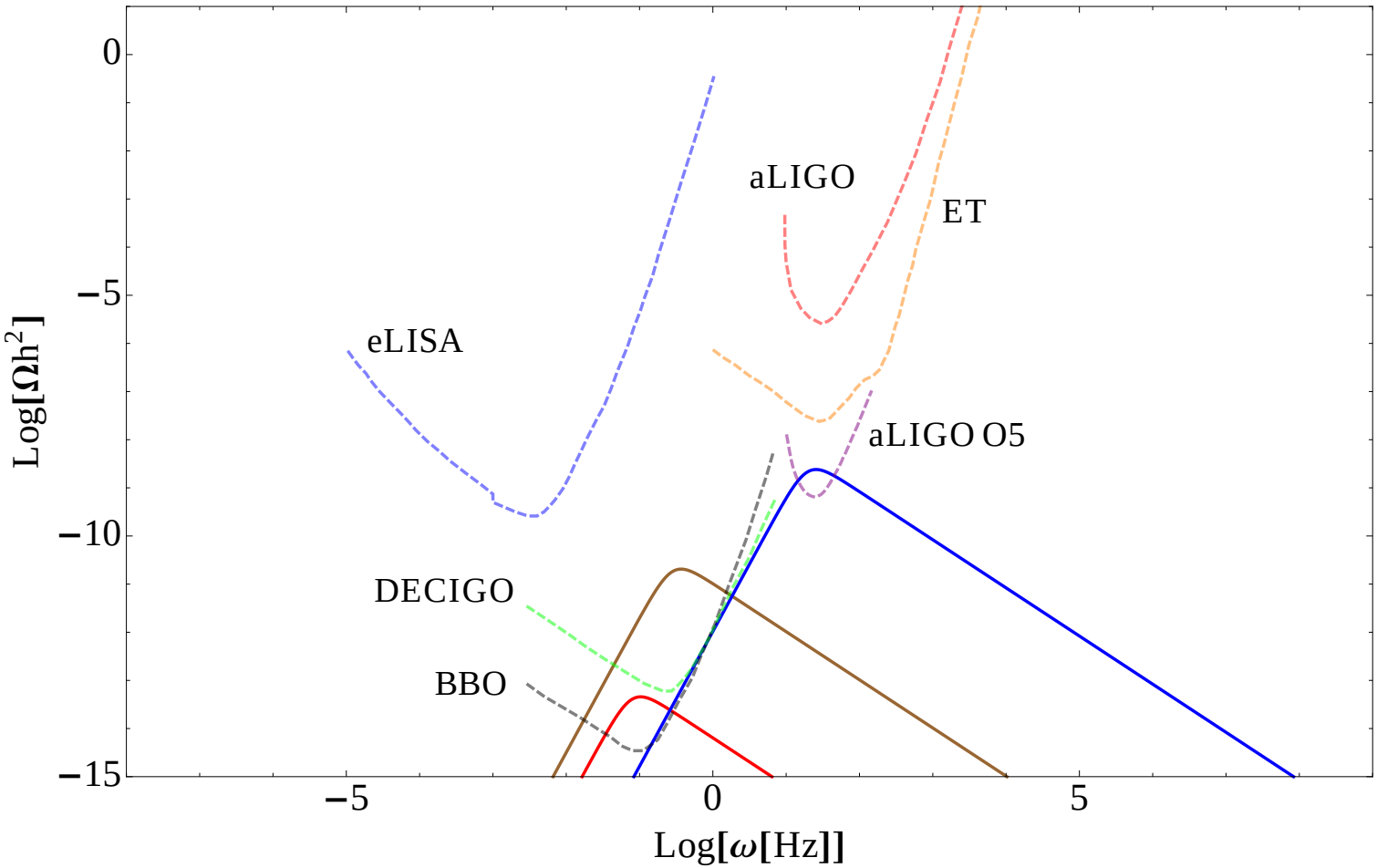
Take-home messages

1. **Axion Monodromy models with local minima and $f \lesssim 0.5 \cdot 10^{-2} M_p$ are likely to be characterised by a "dynamical" phase decomposition after inflation!**

Take-home messages

1. **Axion Monodromy models with local minima and $f \lesssim 0.5 \cdot 10^{-2} M_p$ are likely to be characterised by a "dynamical" phase decomposition after inflation!**

2. **If this occurs, the collision of bubbles of true vacuum sources gravitational radiation!**



→ Blue: $f \sim 0.1 M_p, \kappa = 5, T_{RH} \sim 10^{12}$ GeV.

→ Brown: $f \sim 0.01 M_p, \kappa = 10, T_{RH} \sim 10^{11}$ GeV.

→ Red: $f \sim 0.001 M_p, \kappa = 70, T_{RH} \sim 10^{11}$ GeV.

Summary

→ Future progress in Primordial Cosmology/Particle Physics is very possibly tied to **gravitational waves**.

→ If **large** r is measured, gravitational wave astronomy can help in selecting particular model.

→ Axion Monodromy (possibly also aligned, winding) potentials can exhibit **local minima** in their **post-inflationary** region.

→ **Dynamical phase decomposition** can be induced by classical or quantum inflaton fluctuations. In particular

Summary

→ Future progress in Primordial Cosmology/Particle Physics is very possibly tied to **gravitational waves**.

→ If **large** r is measured, gravitational wave astronomy can help in selecting particular model.

→ Axion Monodromy (possibly also aligned, winding) potentials can exhibit **local minima** in their **post-inflationary** region.

→ **Dynamical phase decomposition** can be induced by classical or quantum inflaton fluctuations. In particular

2 For $f \gtrsim 10^{-2} M_p$: phase decomposition is **rare**, gravitational wave signal is **stronger**!

Summary

→ Future progress in Primordial Cosmology/Particle Physics is very possibly tied to **gravitational waves**.

→ If **large** r is measured, gravitational wave astronomy can help in selecting particular model.

→ Axion Monodromy (possibly also aligned, winding) potentials can exhibit **local minima** in their **post-inflationary** region.

→ **Dynamical phase decomposition** can be induced by classical or quantum inflaton fluctuations. In particular

2. For $f \gtrsim 10^{-2} M_p$: phase decomposition is **rare**, gravitational wave signal is **stronger**!

3. For $f \lesssim 10^{-2} M_p$: phase decomposition is **likely**, signal is **weaker**.

Summary

→ Future progress in Primordial Cosmology/Particle Physics is very possibly tied to **gravitational waves**.

→ If **large** r is measured, gravitational wave astronomy can help in selecting particular model.

→ Axion Monodromy (possibly also aligned, winding) potentials can exhibit **local minima** in their **post-inflationary** region.

→ **Dynamical phase decomposition** can be induced by classical or quantum inflaton fluctuations. In particular

2. For $f \gtrsim 10^{-2} M_p$: phase decomposition is **rare**, gravitational wave signal is **stronger**!

3. For $f \lesssim 10^{-2} M_p$: phase decomposition is **likely**, signal is **weaker**.

→ Post-inflationary gravitational waves from monodromy may be in the reach of future detectors!

Thanks for your attention!

Enhanced quantum modes (see also Viraf's talk!)

$\rightarrow$ Inflationary modes with $k \gtrsim m$ never exited the horizon$\rightarrow$ they were not classicalised!

- KG equation for any mode is of the *parametric resonant* type:

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

  where $t' = mt$.

- **Assumption**: classical equations of motion still capture resonance effects.

- Modes with $k \gtrsim m$ at horizon re-entry are generically exponentially enhanced for $f \lesssim 10^{-2} M_p$!

Take-home message

Axion Monodromy models with local minima and $f \lesssim 10^{-2} M_p$ are likely to lead to a phase decomposition after inflation.

Gravitational wave spectrum

→ Collision of bubble walls sources gravitational radiation (varying quadrupole moment)!

- Relic density and frequency from such transitions

$$\Omega_{GW} \propto \left[\frac{H}{\delta}\right]^2 \cdot \frac{\eta^2}{(1+\eta)^2}$$

$$\omega_{peak} \propto \left(\frac{\delta}{H}\right) \left[\frac{T_{RH}}{10^{15}\text{GeV}}\right]$$

- δ is the rate of the phase transition and η is the relative energy difference between the two minima.

→ Largest signal is obtained when transition is less likely, only few bubbles per Hubble patch nucleate and $\delta \sim H$.