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Monodromy Dark Matter

New Ideas in String Pheno
DESY, Hamburg
17th February 2017

Joerg Jaeckel, Lukas T. Witkowski,
Viraf M. Mehta

arXiv:1605.01367[hep-th] . . .

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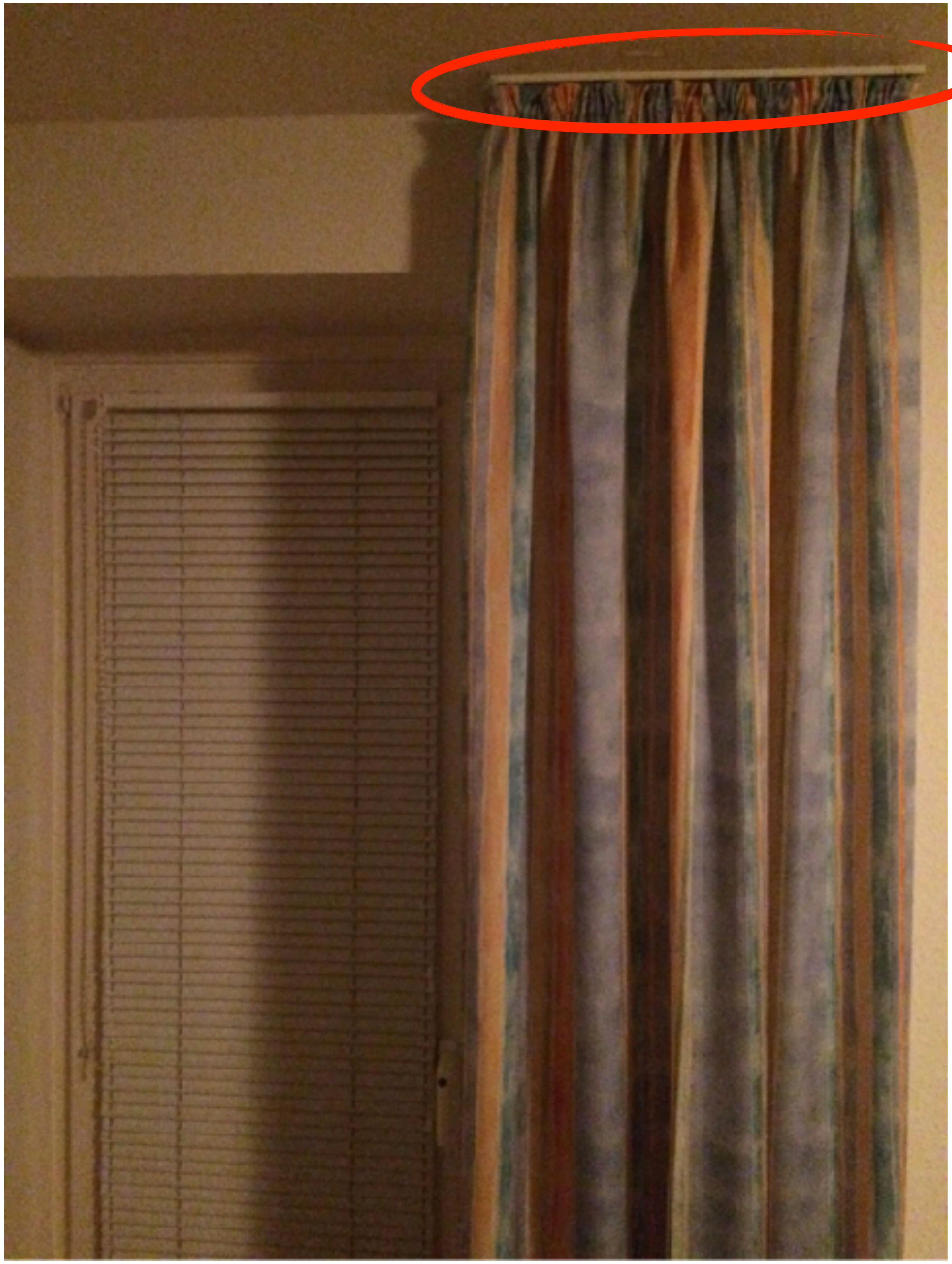
Light shining through walls?



??!

Monodromy Dark Matter

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INTRODUCTION

Dark Matter Candidates

- >80 years since Zwicky "postulated" DM

  Zwicky 1933

- $10^{-22}\mathrm{eV} \lesssim m_{\mathrm{DM}} \lesssim 10^{59}\mathrm{eV}$

  e.g. ULAs e.g. PBHs

- Main proposals - two classes:
  - Particles: LSP, WIMPs, Sterile Neutrinos, KK states, ...
  - Field oscillations ALPs, familons, flavons, ...

pNGBs

Introduction

Axions as Dark Matter

- pNGBs of spontaneously broken approximate global symmetries
- ubiquitous in string models
- bottom-up ADM models employ *misalignment mechanism*
- field has random initial displacement set by inflation and then relaxes to minimum
- process is *non-thermal*

Introduction

Misalignment Mechanism

Abbott, Sikivie;
Preskill, Wise, Wilczek;
Dine, Fischler; 1983

Random ϕ_i, after inflation

$\mathcal{L}_{\text{int}} \to m \equiv m(t)$

e.g. $\mathcal{L} \supset m^2\phi^2$

EoM: $\boxed{\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0}$

2 regimes:

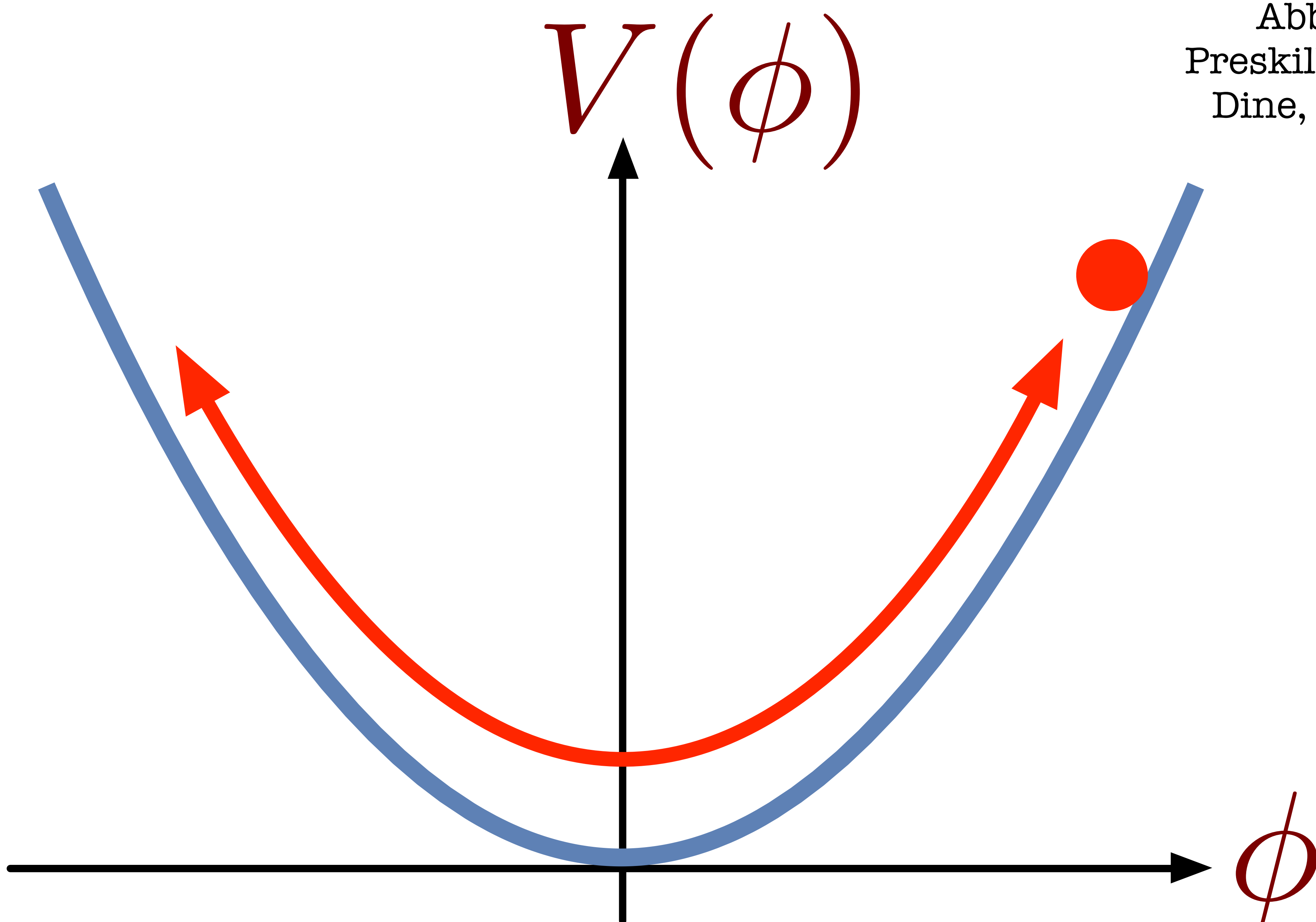
ϕ frozen until t_1

$3H \gg m$ $\quad$ $3H \ll m$

Introduction

Misalignment Mechanism

Abbott, Sikivie;
Preskill, Wise, Wilczek;
Dine, Fischler; 1983



Fast oscillations, slow amplitude decay

Introduction

Using pNGBs

$$\boxed{V(\phi) = \Lambda^4 \left(1 - \cos\left(\frac{\phi}{f}\right)\right)}$$

limited by

quantifies small explicit breaking

shift symmetry breaking scale

$$\boxed{\begin{gathered} m^2 = \frac{\Lambda^4}{f^2} \\ |\phi| \lesssim \pi f \end{gathered}}$$

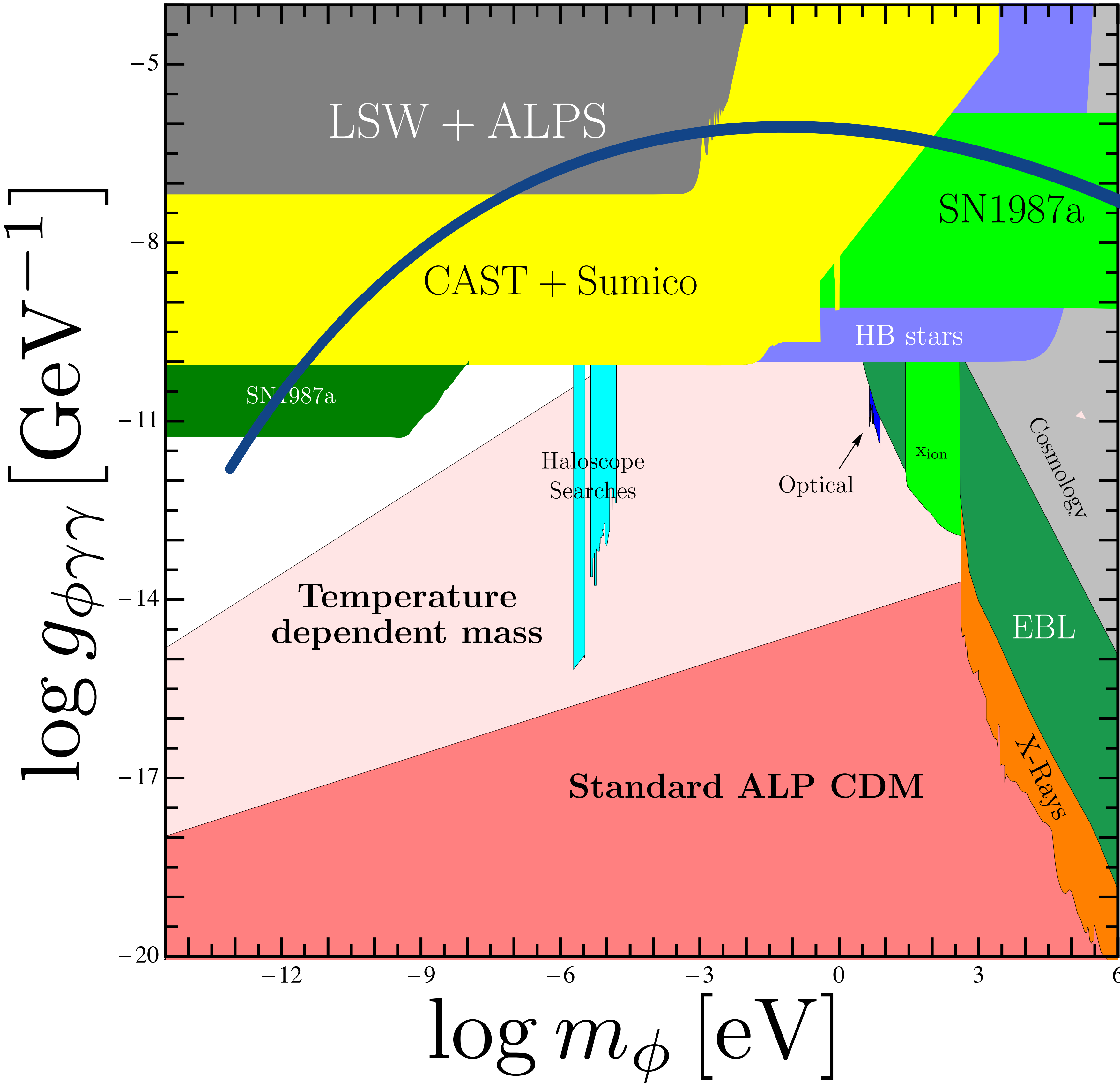
enters couplings to matter, e.g. $g_{\phi\gamma\gamma}$

$$\mathcal{L} \supset \frac{\phi}{f} F\tilde{F}, \frac{\partial_\mu \phi}{f} \overline{\psi}\gamma^\mu\gamma^5\psi$$

thus, limits coupling!!

Introduction

Using pNGBs



theoretically inaccessible region

$$g \equiv \frac{\alpha}{2\pi}\frac{1}{f}\mathcal{N}$$

Introduction

Choose your favourite description

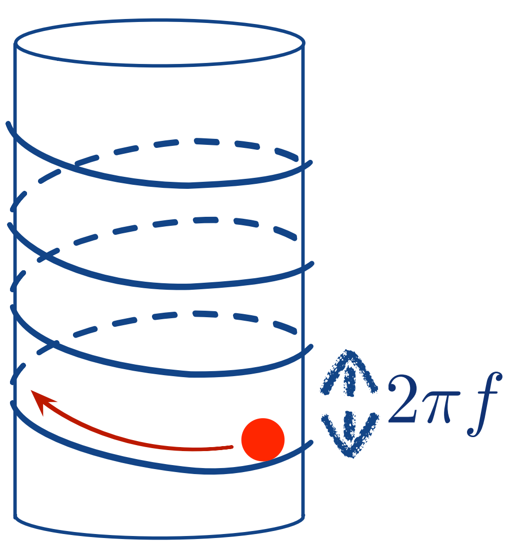
$$V(\phi) = \frac{1}{2} m^2 \phi^2 + \Lambda^4 \left(1 - \cos\left(\frac{\phi}{f} \right) \right)$$

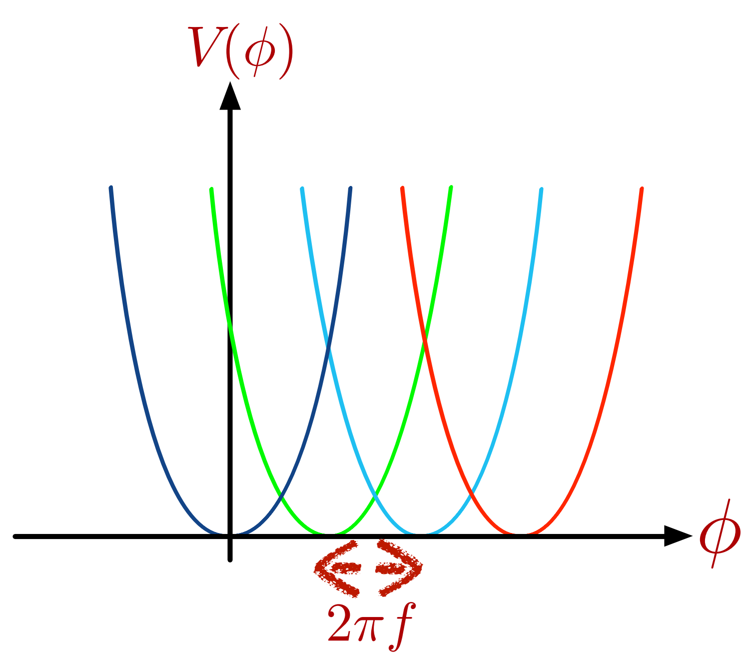
Monodromy $\Leftrightarrow$ **Multi-branched** **Aligned**

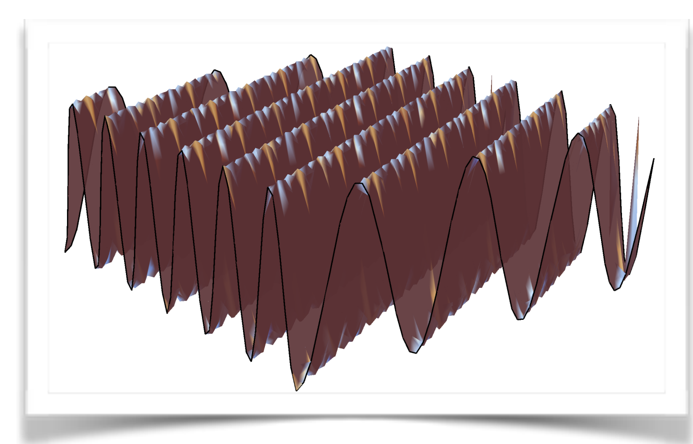
Monodromy: Silverstein, Westphal; McAllister, Silverstein, Westphal 2008

Multi-branched: Kaloper, Sorbo 2008

Aligned: Kim, Nilles, Peloso 2004

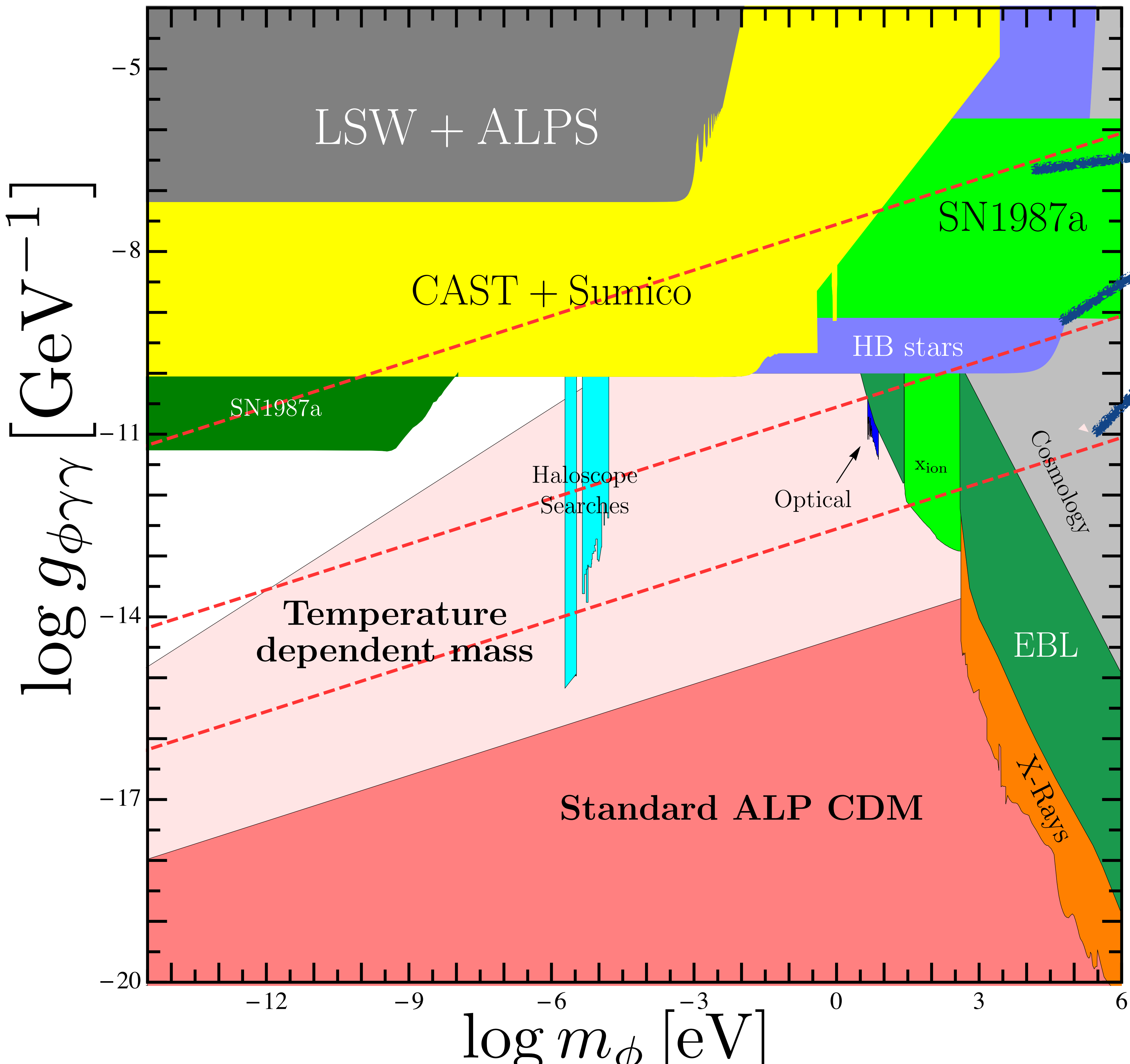






...

Introduction



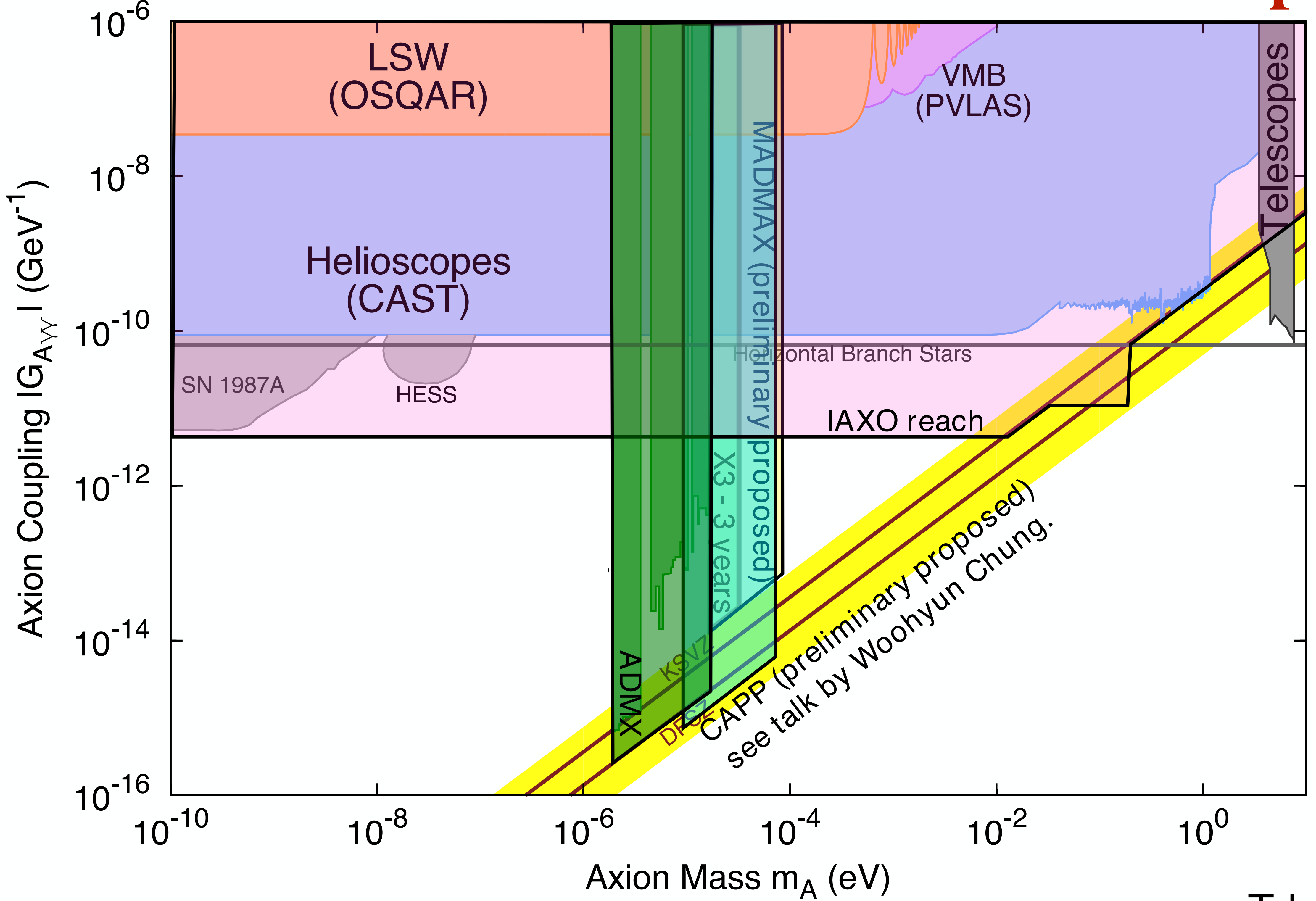
Different ϕ_{initial} in units of $2\pi f$

Increased parameter space!

Accessible to experiments

INTRODUCTION

Current and future experiments



Taken from E. Daw
IDM 2016

Monodromy Dark Matter

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

Monodromy Dark Matter

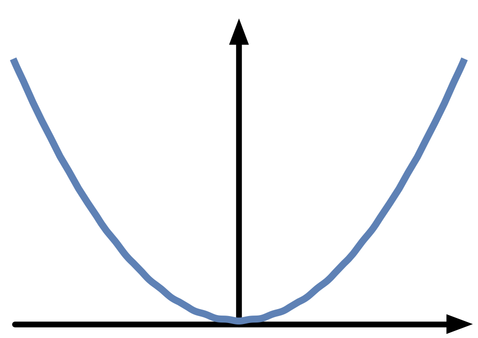
Note on notation

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

$$\kappa^2 \sim \frac{\Lambda^4}{f^2}$$

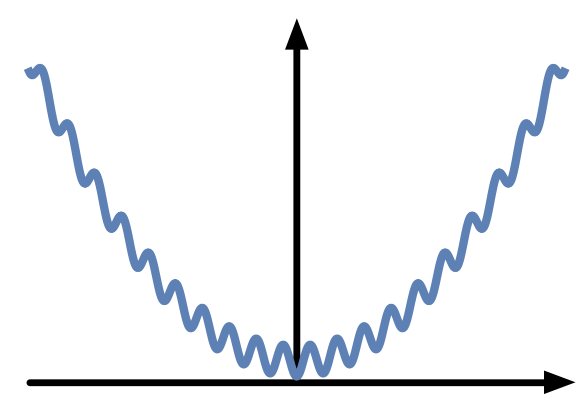
$$\kappa \ll 1$$

$$\left(\text{or } \frac{\phi_{\text{initial}}}{2\pi f} \gg 1\right)$$



$$\kappa \gtrsim 1$$

$$\left(\text{or } \frac{\phi_{\text{initial}}}{2\pi f} \sim 1\right)$$



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Monodromy Dark Matter

Note on notation

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

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

$$h = \frac{H}{m}$$

$$\phi \to \varphi \equiv \frac{\phi}{f}$$

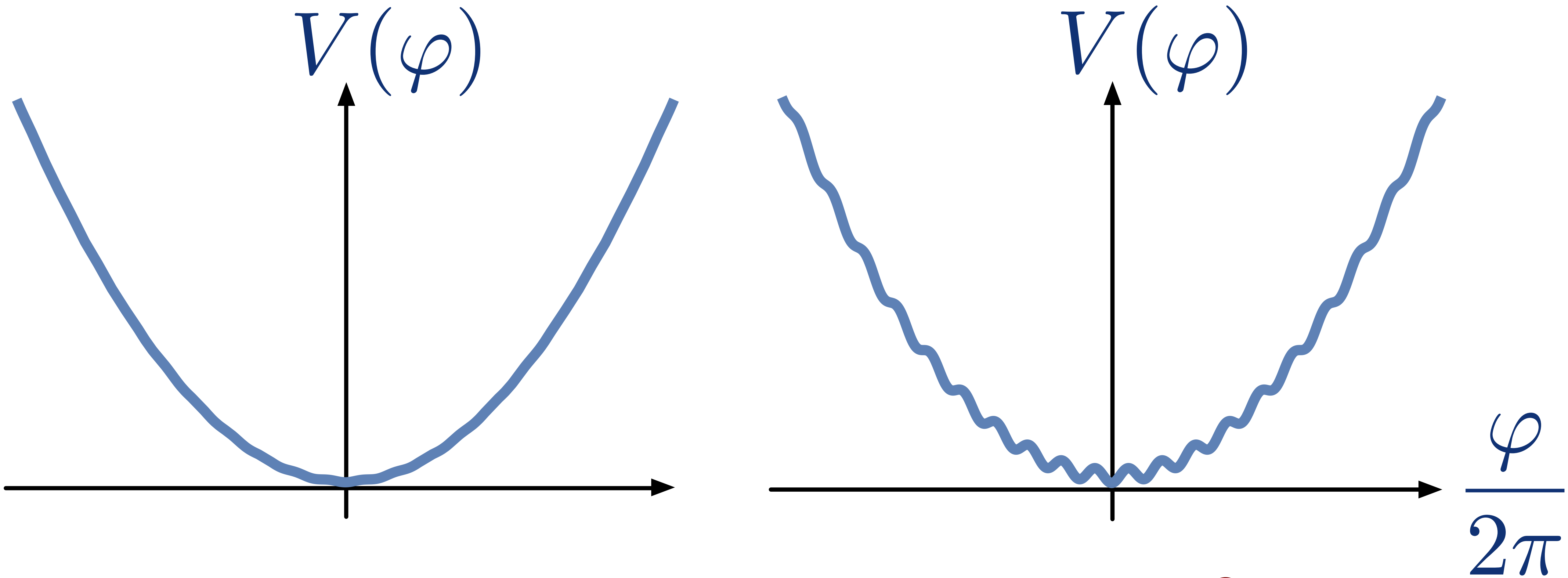
$$t \to \tau \equiv mt$$

$$\mathbf{x} \to \varkappa \equiv m\mathbf{x}$$

$$V(\varphi) \sim \frac{1}{2}\varphi^2 + \kappa^2(1 - \cos\varphi)$$

Monodromy Dark Matter

Classical evolution



$\kappa = 2$ $\kappa = 6$

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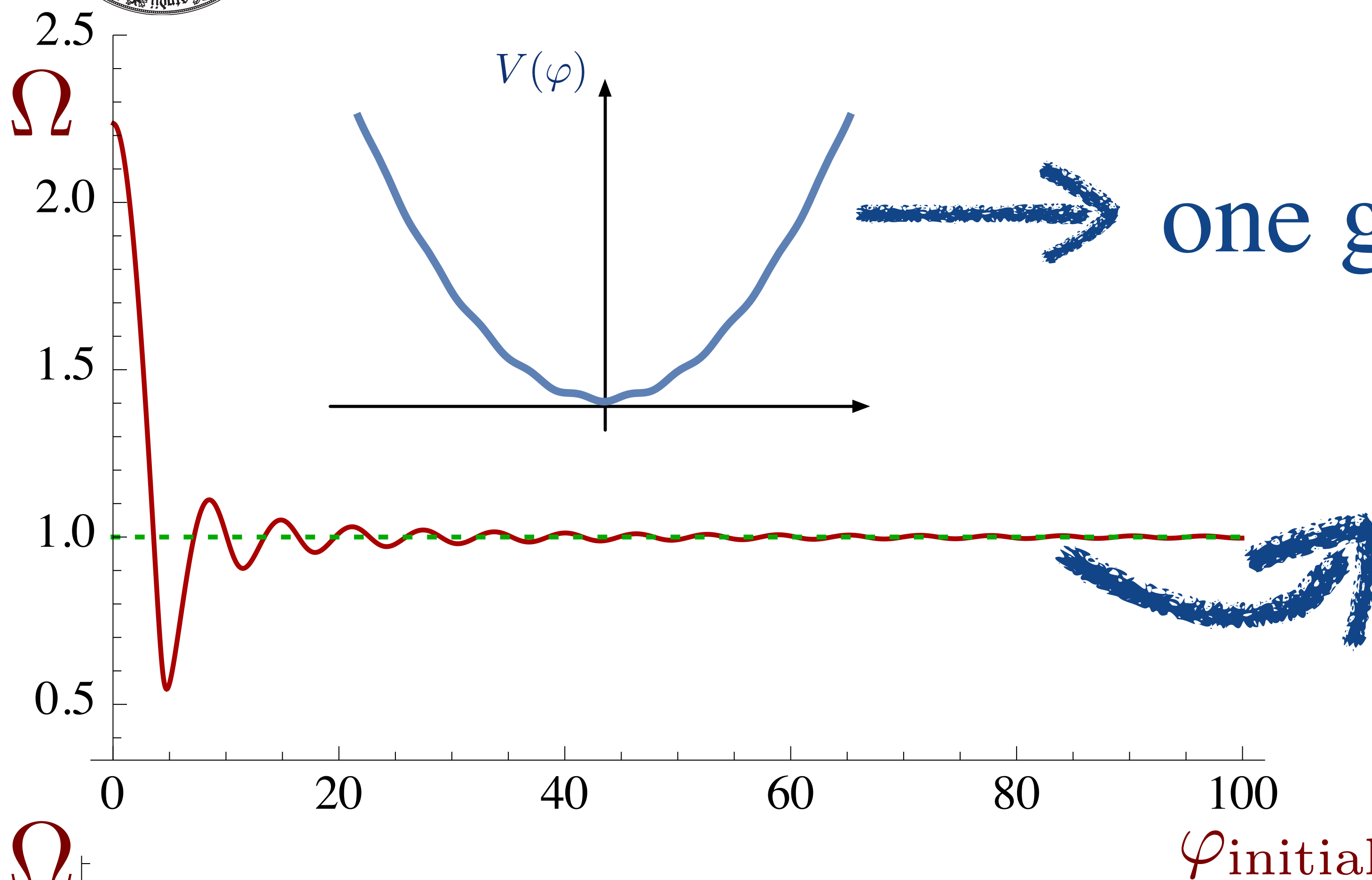
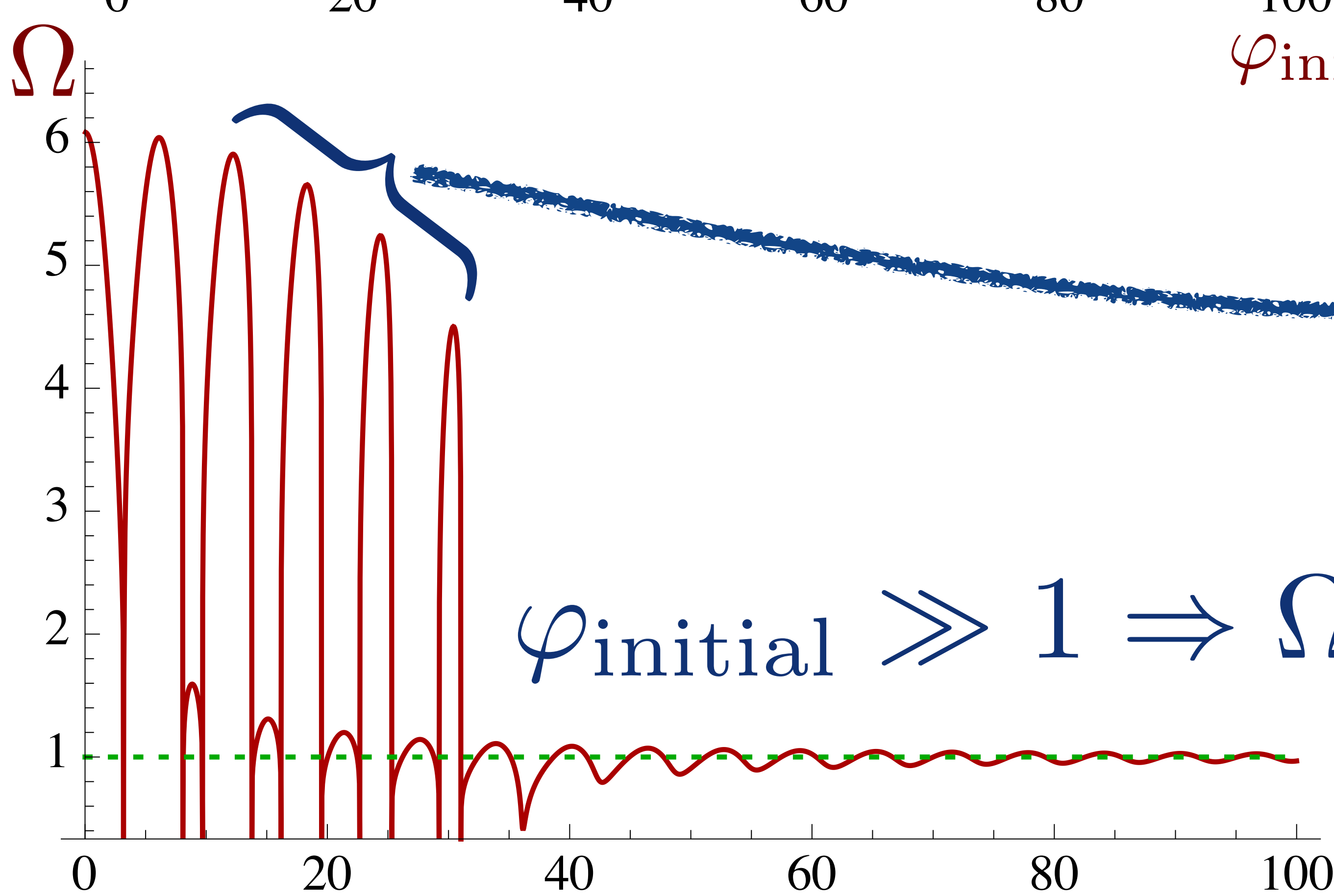
Monodromy Dark Matter

Classical evolution

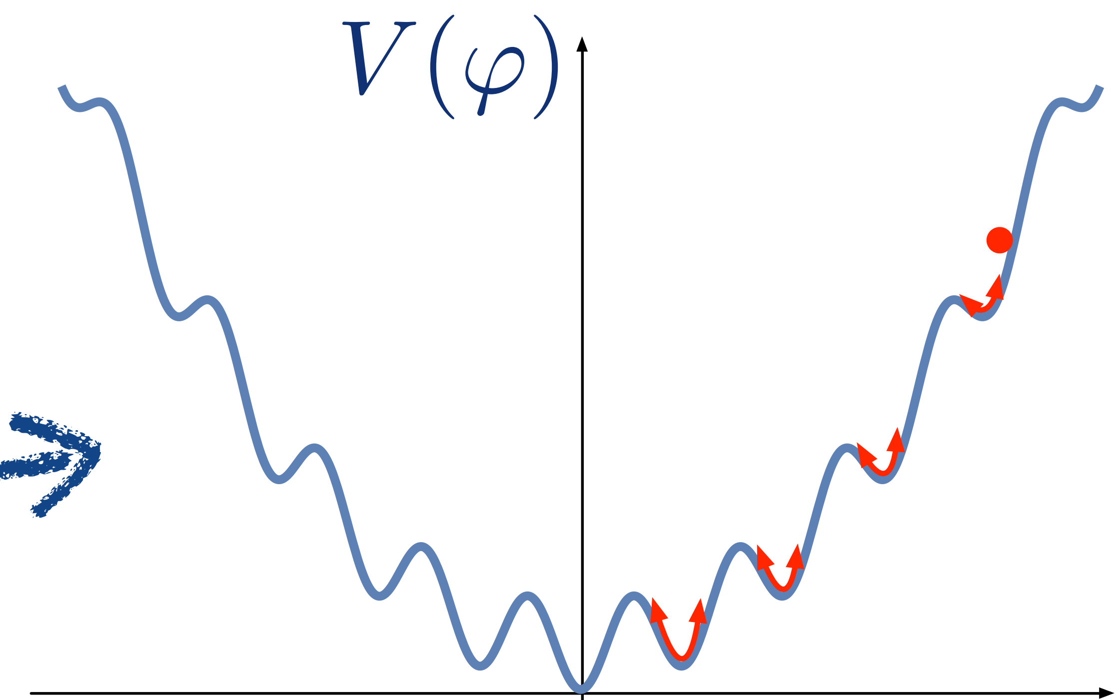


one global minimum

$$\Omega\big|_{\kappa=0} = 1$$



$$\varphi_{\text{initial}} \gg 1 \Rightarrow \Omega \to \Omega_0$$



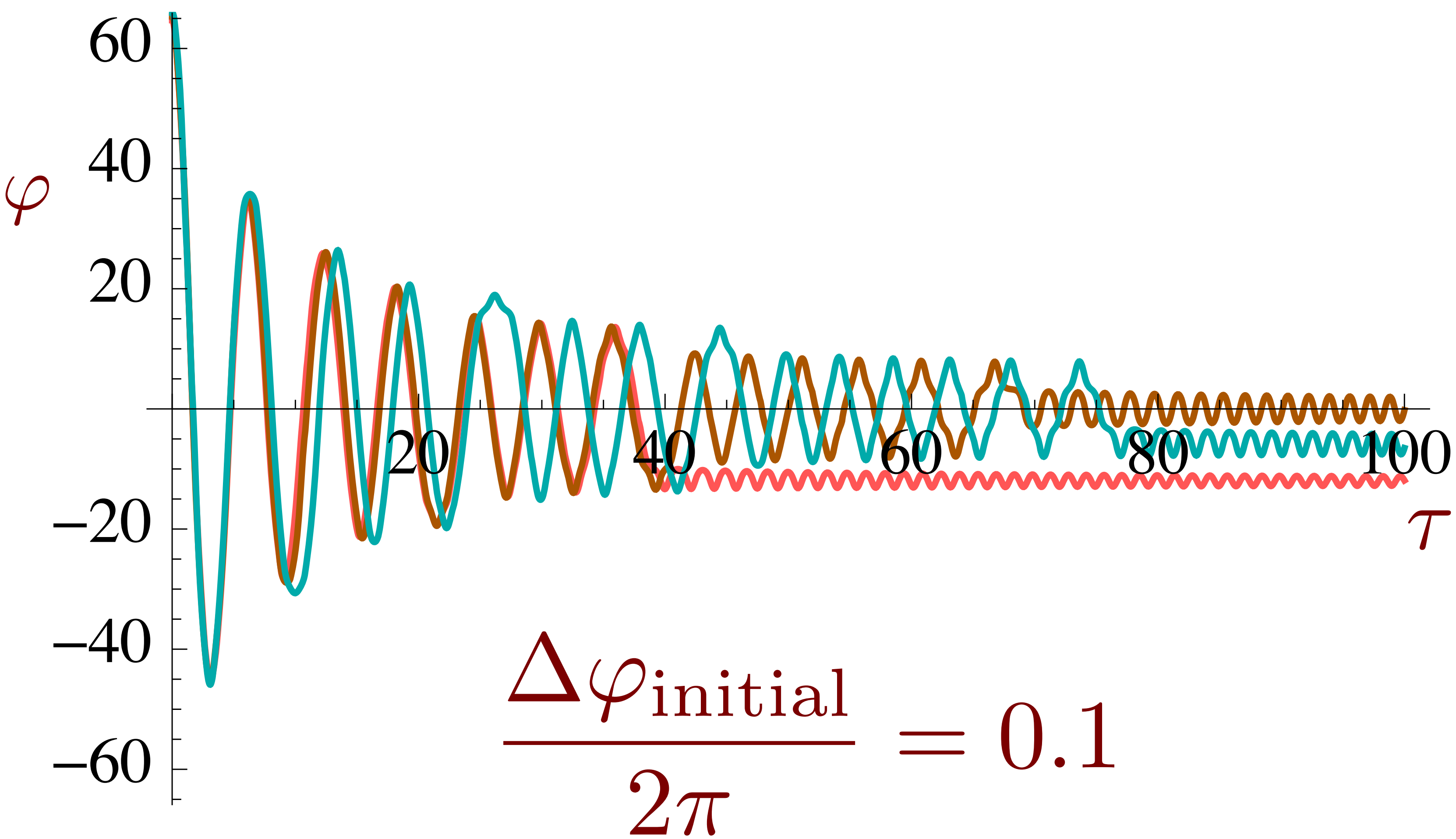
multiple minima

effects on cosmological evolution?

Monodromy Dark Matter

Classical evolution

$$\boxed{\ddot{\varphi} + 3h\dot{\varphi} + \varphi + \kappa^2 \sin(\varphi) = 0}$$



field stuck in different minima

only requires small change in φ_{initial}

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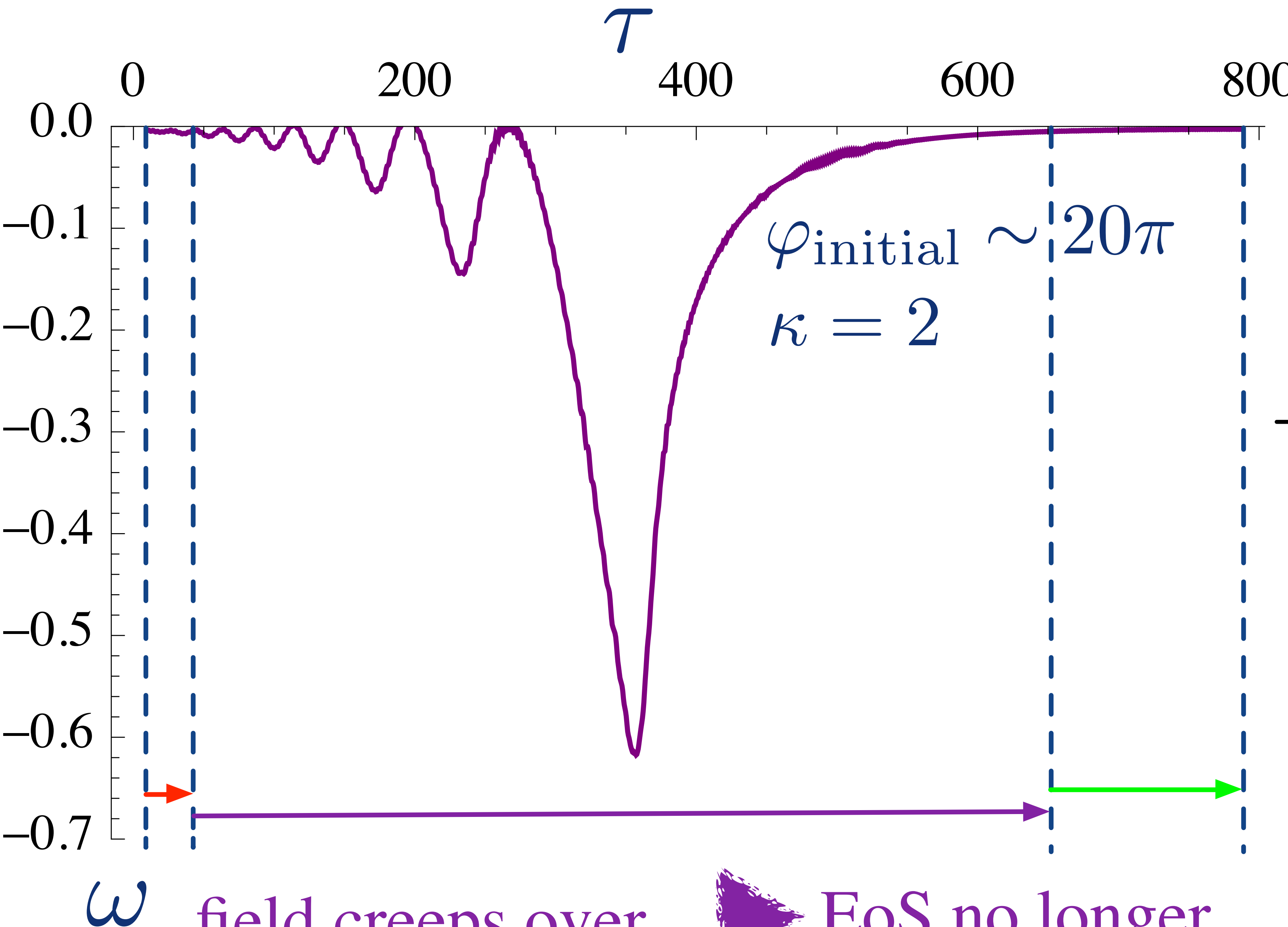
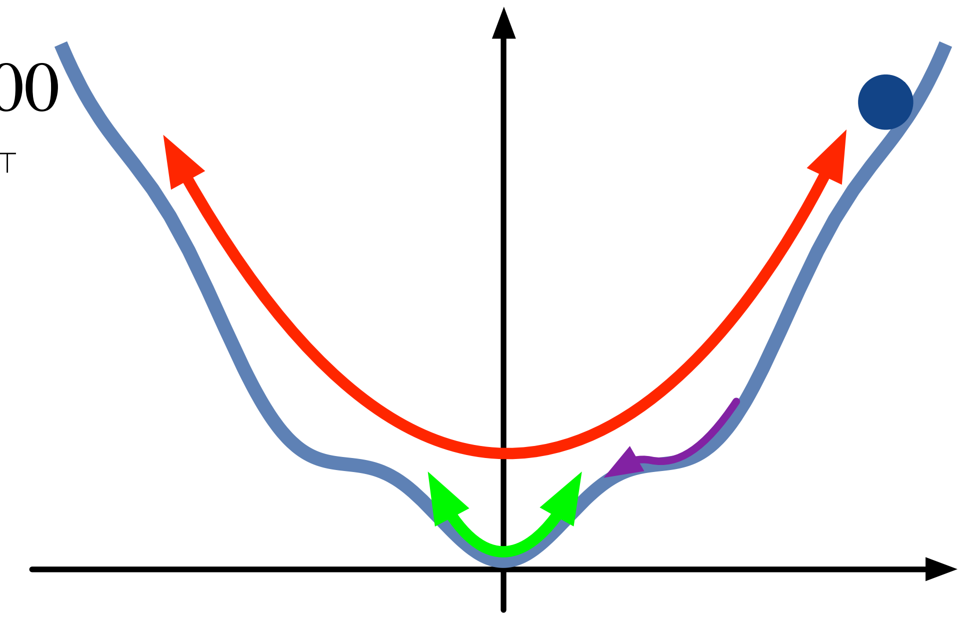
Monodromy Dark Matter

Classical evolution





field rolls through large parabola at early times

➤ EoS that of DM

field creeps over plateau-like regions

➤ EoS no longer consistent with matter!

field oscillates about minimum

➤ EoS still that of DM

effects only felt if this occurs post matter-radiation equality

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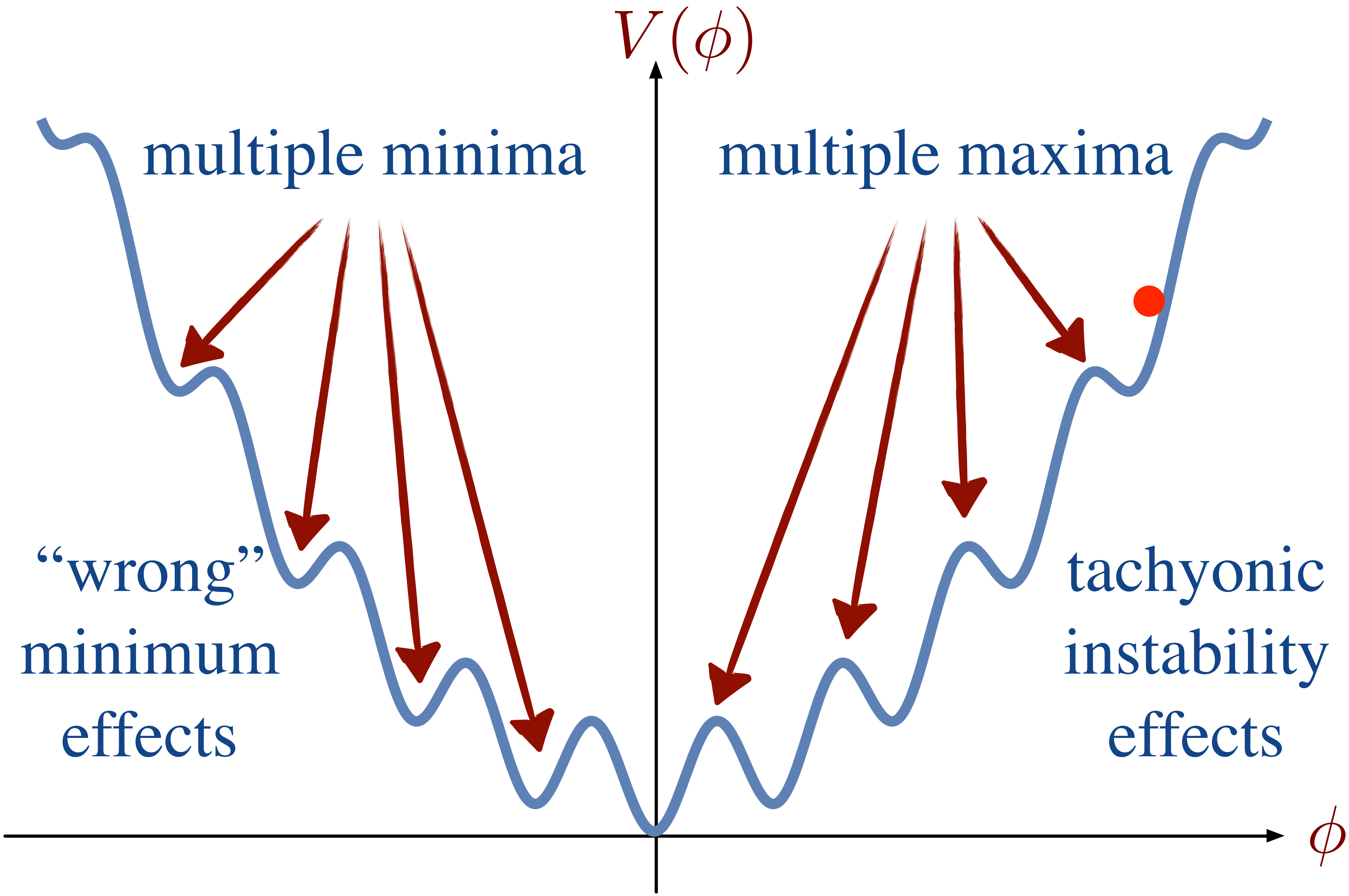
Quantum Fluctuations



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Linearized EoMs

$$\boxed{\varphi(\tau,\varkappa) = \varphi_0(\tau) + \delta\varphi(\tau,\varkappa)}$$

homogenous background solution

$$\int \frac{d^3k}{(2\pi)^{3/2}}\, c_{\mathbf{k}}(\tau)\exp(i\mathbf{k}\cdot\varkappa)$$

problematic dependence

$$\boxed{\ddot{c}_{\mathbf{k}} + \left(1 + |\mathbf{k}|^2 - \kappa^2\cos(\varphi_0)\right)c_{\mathbf{k}} = 0}$$

Hill equation: $\ddot{c} + p(\tau)c = 0$

Monodromy Dark Matter

Linearized EoMs

$$\boxed{\text{Hill equation: } \ddot{c} + p(\tau)c = 0}$$

$$e^{\eta\tau}F(\tau) \qquad\qquad e^{-\eta\tau}F(-\tau)$$

periodic function

real, complex or imaginary

certain values of $|\mathbf{k}|$

$$\boxed{\ddot{c}_{\mathbf{k}} + \left(1 + |\mathbf{k}|^2 - \kappa^2\cos(\varphi_0)\right)c_{\mathbf{k}} = 0}$$

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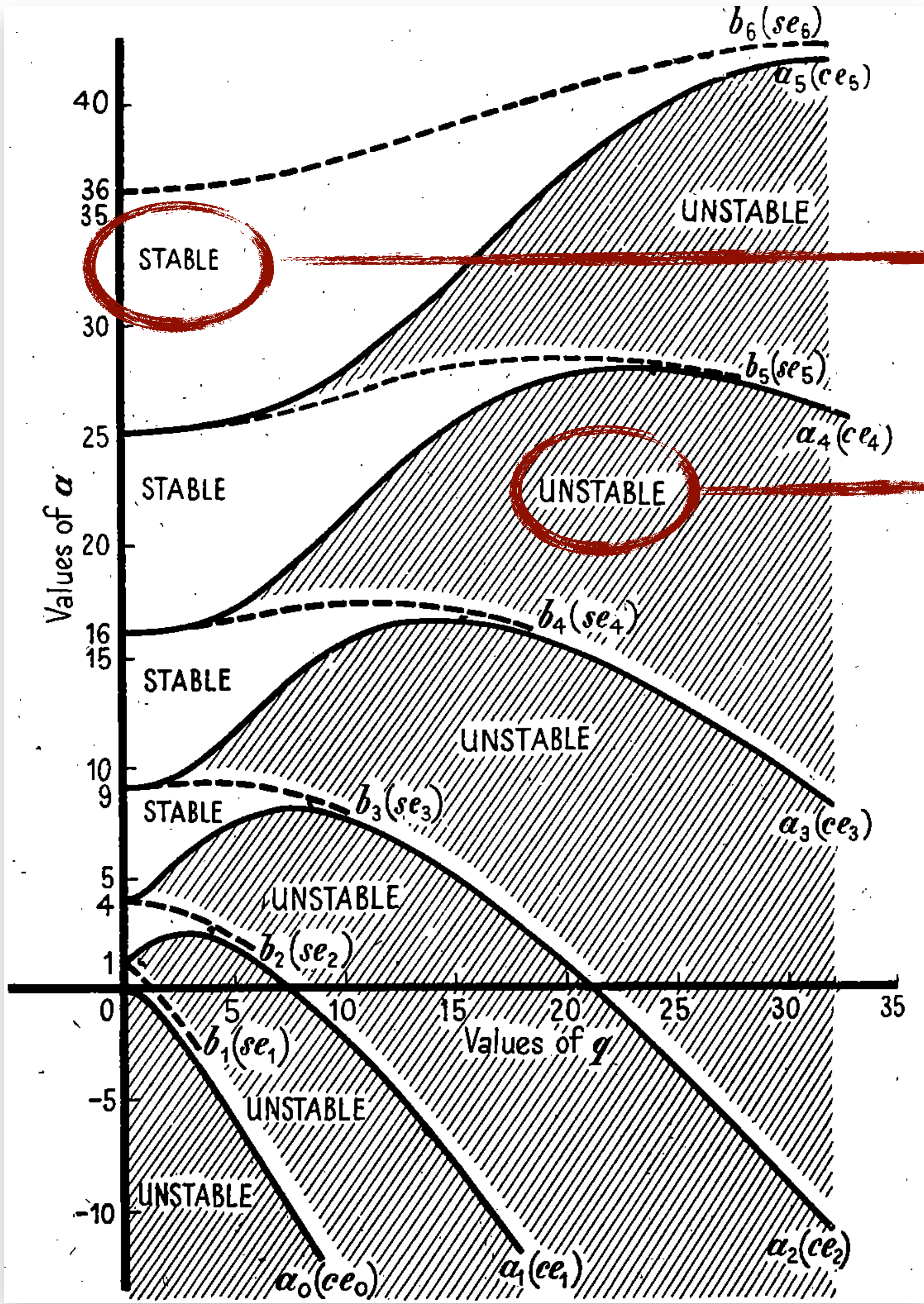
Linearized EoMs

McLachlan 1947



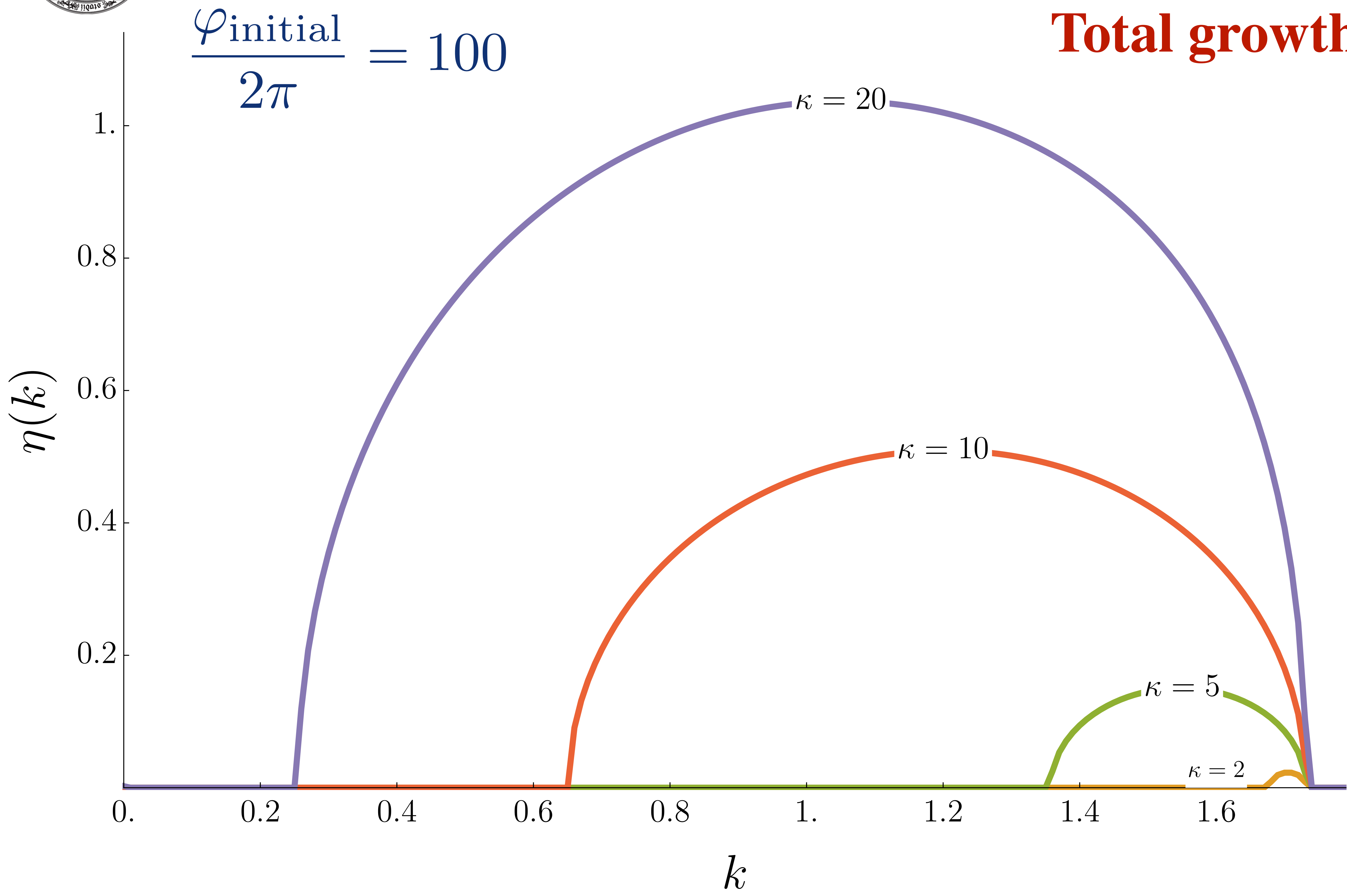
no growth, purely oscillatory

$$c_{\mathbf{k}} \sim \exp[\eta(k)\tau]\exp(-i\omega_k\tau)$$

$\eta(k) > 0$ $\qquad$ $\omega_k \sim n, \ \forall n \in \mathbb{N}$

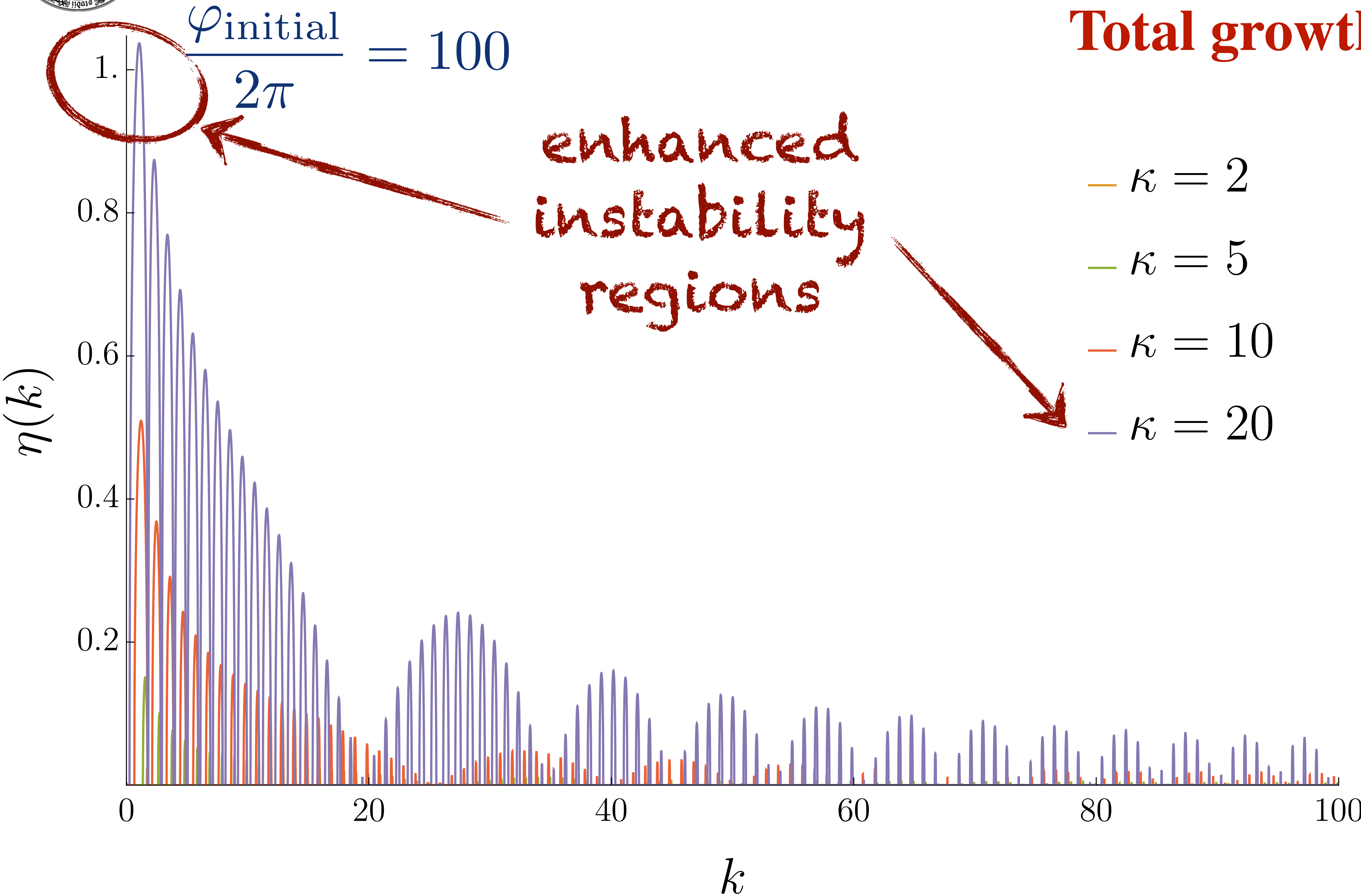
Monodromy Dark Matter

Total growth



Monodromy Dark Matter

Total growth



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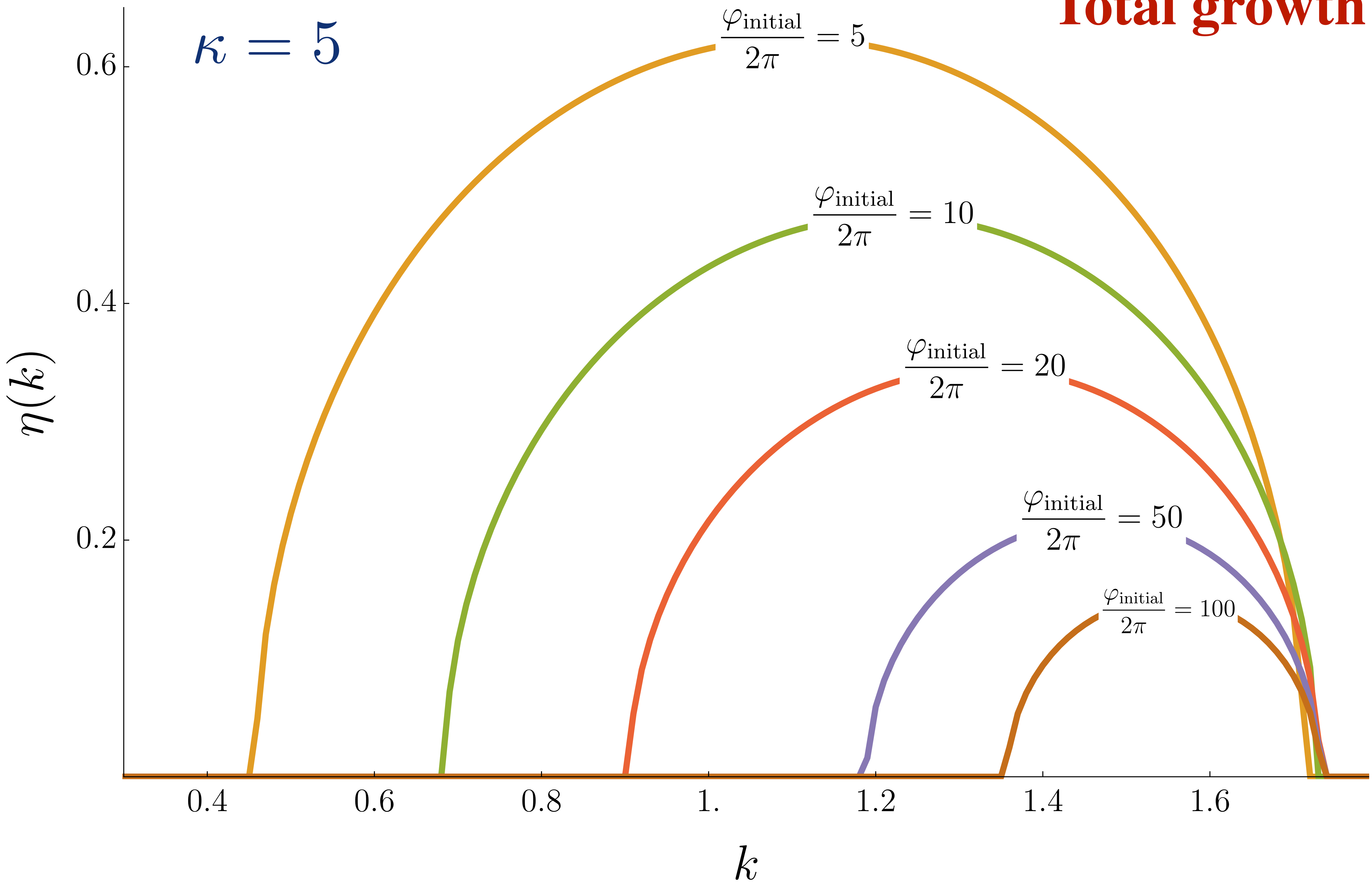
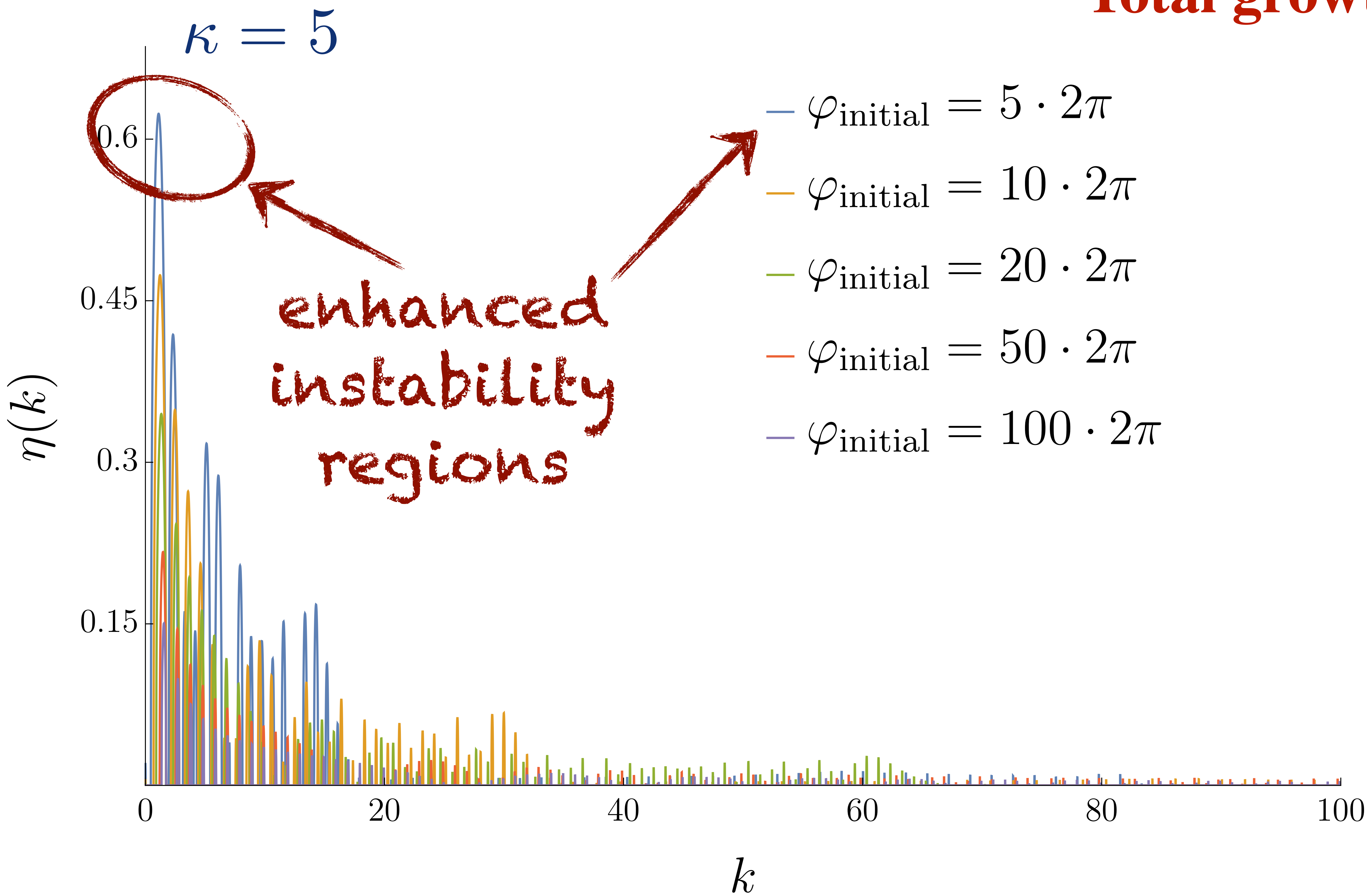
Monodromy Dark Matter

Total growth



Monodromy Dark Matter

Total growth



Monodromy Dark Matter

Total growth

mode-by-mode $\longleftrightarrow$ at a point

Fourier transform:

$$\varphi(\varkappa,\tau) = \varphi_0(\tau) + \int \frac{d^3k}{(2\pi)^3} c_{\mathbf{k}}(\tau) \exp(i\mathbf{k}\cdot\varkappa)$$

leading order

$$\int \frac{d^3k}{(2\pi)^3} c_{\mathbf{k}}(0) \exp(\eta(k)\tau) \exp(-i\omega_{\mathbf{k}}\tau) \exp(i\mathbf{k}\cdot\varkappa)$$

Monodromy Dark Matter

Total growth

approximate as Gaussian ensemble

spectrum: $\langle c_{\mathbf{k}} c^{\star}_{\mathbf{k}'} \rangle = \mathcal{F}(k)(2\pi)^3 \delta(\mathbf{k} - \mathbf{k}')$

correlation function:

$$\langle \varphi(\varkappa)\varphi(\varkappa)\rangle(\tau) \sim \int \frac{d^3k}{(2\pi)^3} \mathcal{F}(k, \tau = 0) \exp(2\eta(k)\tau)$$

initial spectra → $\displaystyle\int \frac{d^3k}{(2\pi)^3} \mathcal{F}(k, \tau = 0) = \infty$

renormalise to remove divergence?

Only care about growth, i.e. difference → FINITE!

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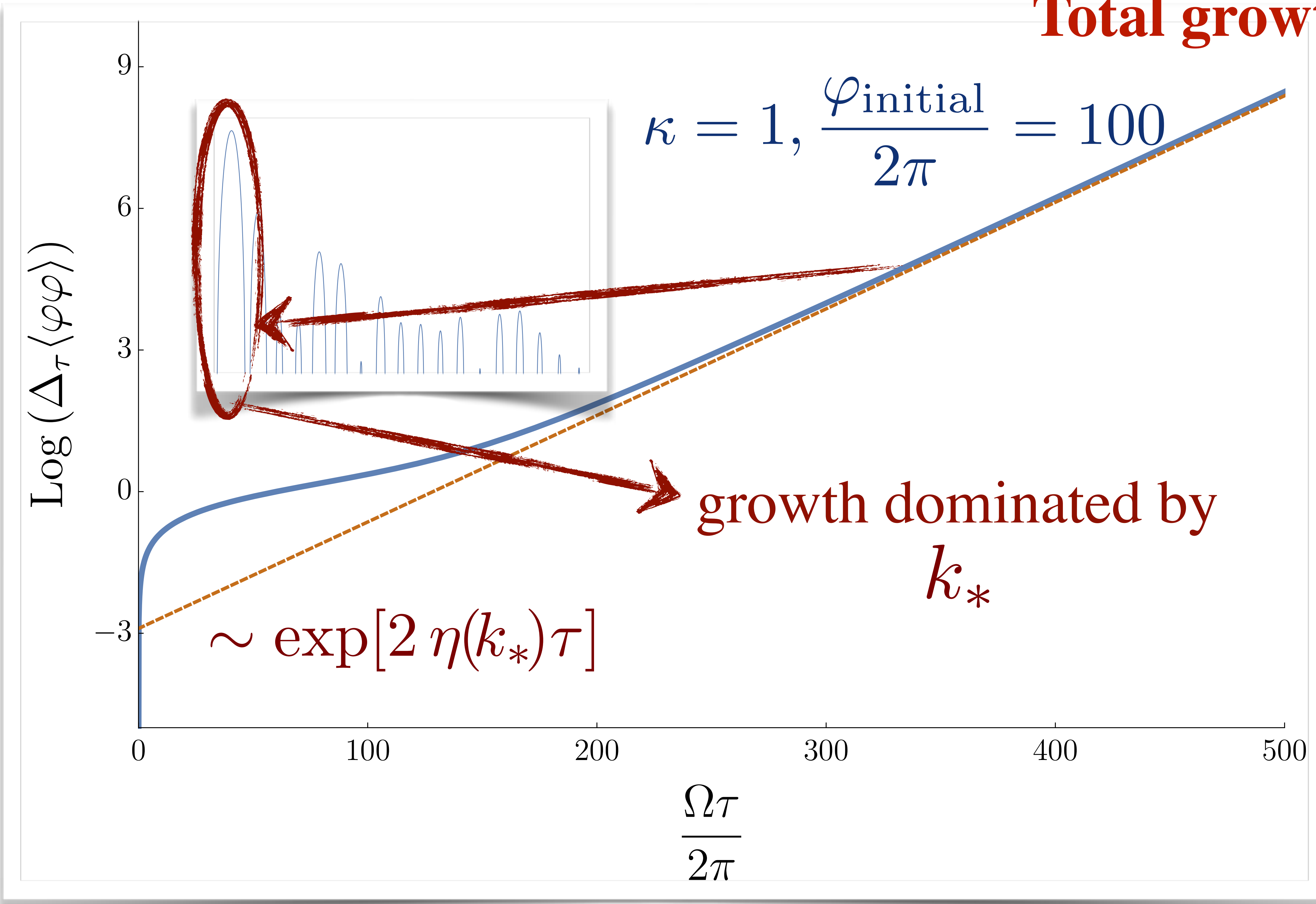
Total growth



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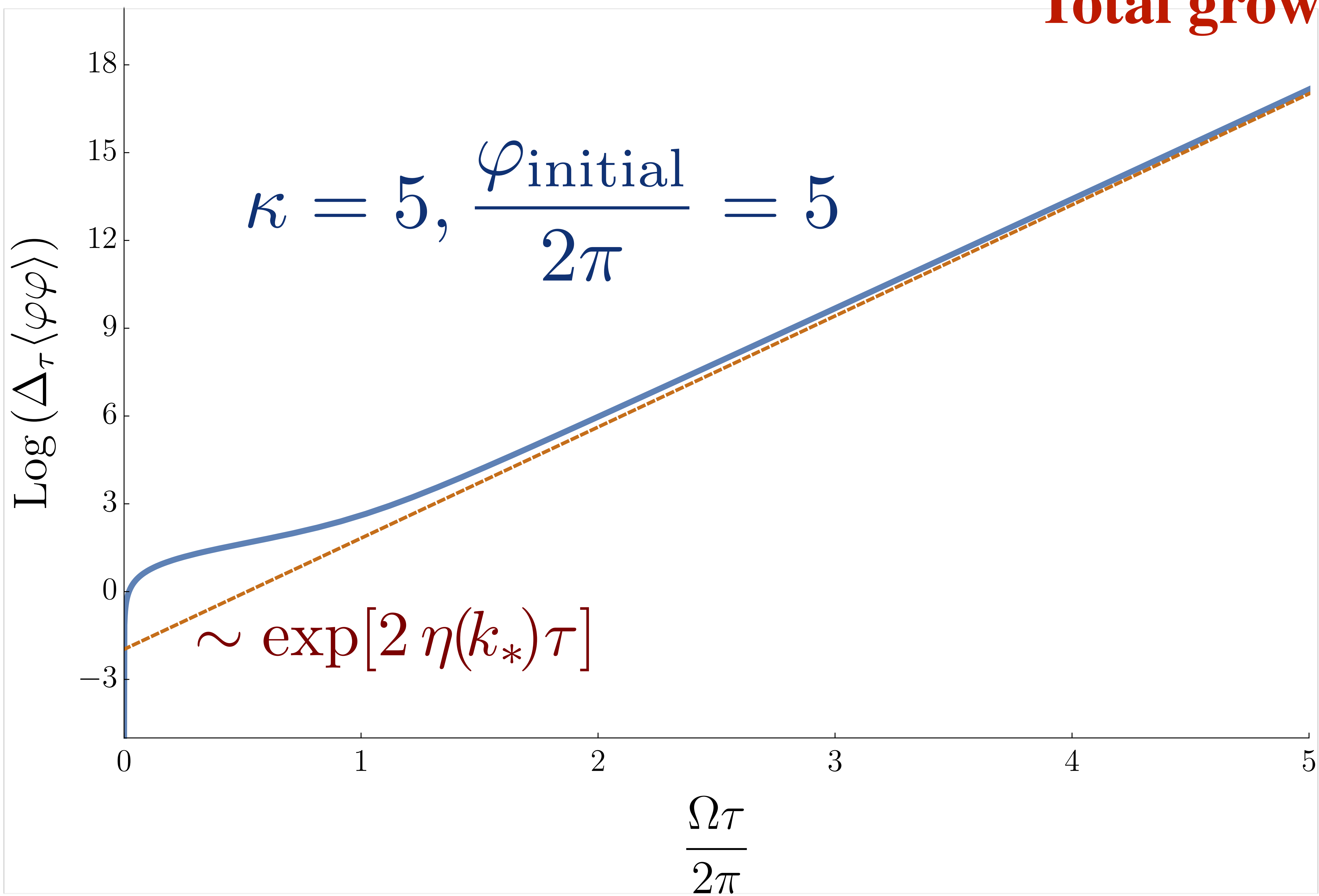
Total growth



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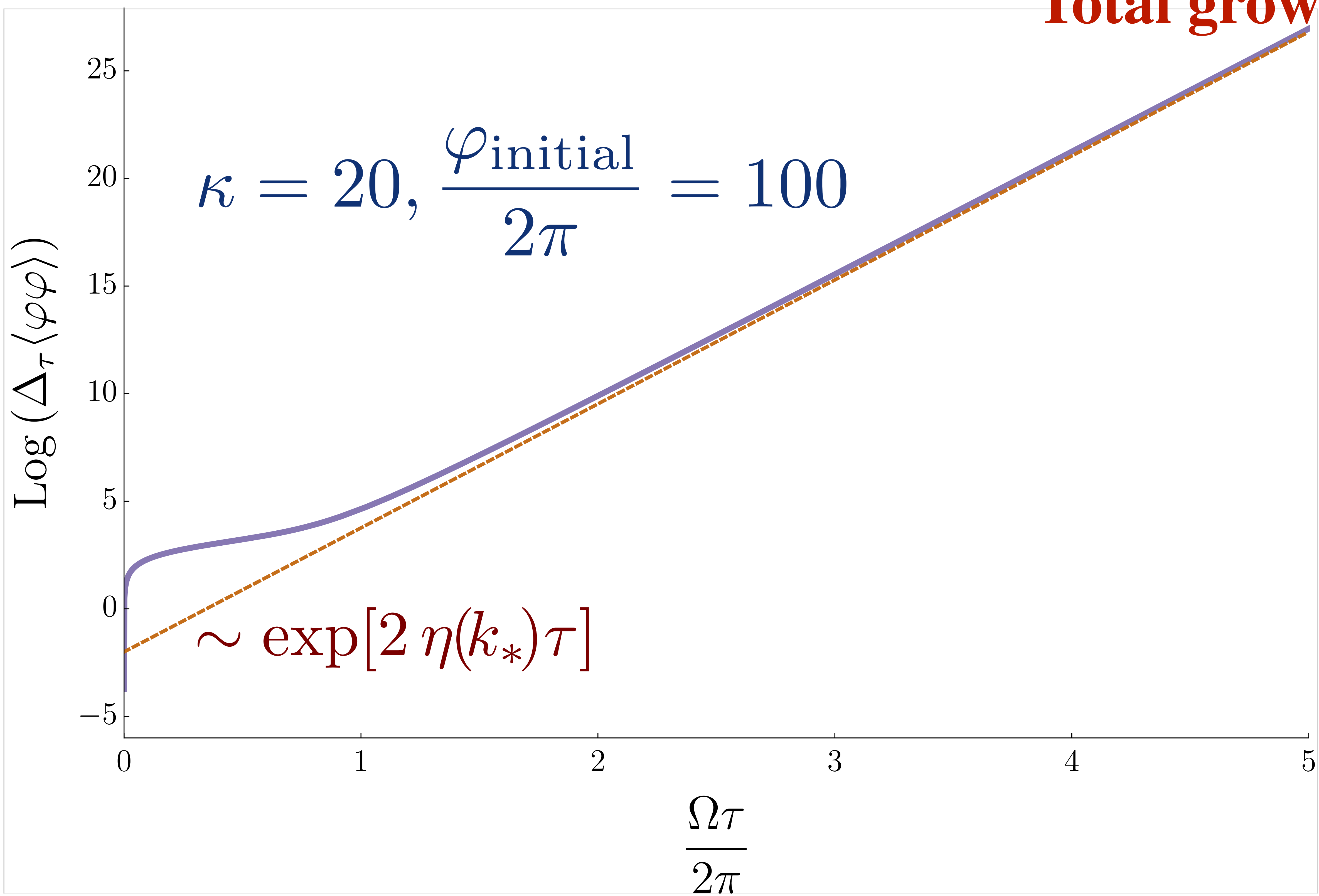
Total growth



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Monodromy Dark Matter

Cosmological implications

$$\phi(\mathbf{x}, t_0) = \phi(t_0) + \int \frac{d^3p}{(2\pi)^3} \sqrt{\frac{f_{\mathbf{p}} + 1/2}{\omega_{\mathbf{p}}}} a_{\mathbf{p}} \exp(i\mathbf{p} \cdot \mathbf{x})$$

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

$$h = \frac{H}{m}$$

$$\phi \to \varphi \equiv \frac{\phi}{f}$$

$$t \to \tau \equiv mt$$

$$\mathbf{x} \to \varkappa \equiv m\mathbf{x}$$

$$\langle \varphi(\varkappa)\varphi(\varkappa) \rangle = \frac{m^2}{f^2} \int \frac{d^3k}{(2\pi)^3} \frac{f_k + 1/2}{\omega_k}$$

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Cosmological implications

$$\mathcal{F}(k) = \frac{m^2}{f^2}\left(\cancel{f_{\mathbf{k}}} + \frac{1}{2}\right)$$

unexcited quantum state

using typical values:

$$\boxed{\mathcal{F}(k) \sim 10^{-50}\left(\frac{10^{10}\,\mathrm{GeV}}{f}\right)^2\left(\frac{m}{\mu\mathrm{eV}}\right)^2}$$

indeed very small...

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How many oscillations in a realistic model?

$$\frac{1}{h} \sim$$ # oscillations in 1 e-fold of expansion

expansion → dilution of fields → reduced fluctuations → smaller background → more growth? → increased fluctuations

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How long are we in an instability band?

$\mathbf{k} \to \frac{\mathbf{k}}{a}$ → expansion rescaling → high $|\mathbf{k}| \to$ low $|\mathbf{k}|$ modes

band width

$$\delta\tau \sim \log\left(1 + \frac{\Delta k_{\rm res}}{k_{\rm res}}\right)\frac{1}{h}$$

band centre

strong growth

$\frac{\Delta k_{\rm res}}{k_{\rm res}} \sim 1$

$h \ll 10^{-2}$

Monodromy Dark Matter

Cosmological effects

- Fluctuations are now radiation-like and thus, in this regime, would lead to observation/exclusion

- At this point, the linear approximation breaks down

➡ REQUIRE FULL THEORY SIMULATION!!

Recall, this is the regime that is potentially detectable!!

Monodromy Dark Matter

Cosmological implications

- requires only $\mathcal{O}(100)$ background oscillation periods for $\mathcal{O}(1)$ fluctuations
- axions now behave as hybrid dark matter: both warm and cold (fluctuations act as radiation)
- expansion also shifts high momentum modes to low momentum modes - increased growth
- classical approximation breaks down in certain regimes

Conclusions

- classical realm:
  - enhancement of $g_{\phi\gamma\gamma} - m$ parameter space, accessible?
  - field may settle in "wrong" minimum
    - different CC and DM mass
  - non-negligible cos-term has significant effects on EoS
- quantum realm:
  - growth of fluctuations is rapid;
  - significant contribution could lead to large observable effect or exclusion;
  - if detected, full simulation required
- results generic for pNGBs with monodromy

applications to inflation - Hebecker, et al. 2016

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Outlook

Future directions & open questions

- more elaborate analysis of parameter space required - realistic κ from UV?
- when are fluctuations important?
- what are the effects on EoS and structure formation?
- suitable description when linear approximation breaks down?
- numerical solutions of classical field equations underway

Outlook

Future directions & open questions

- more elaborate analysis of paramete... required - realistic κ from UV?
- when are fluctuations i...
- what are th... ...structure formati...
- su... ...on when linear approximation bre... ...n?
- numerical solutions of classical field equations underway

Thanks for listening!