String cosmology and evolving moduli fields after inflation.

Ed Copeland -- University of Nottingham

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The goal today - have fun thinking about

the fascinating dynamics that can occur between the end of inflation and reheating including:

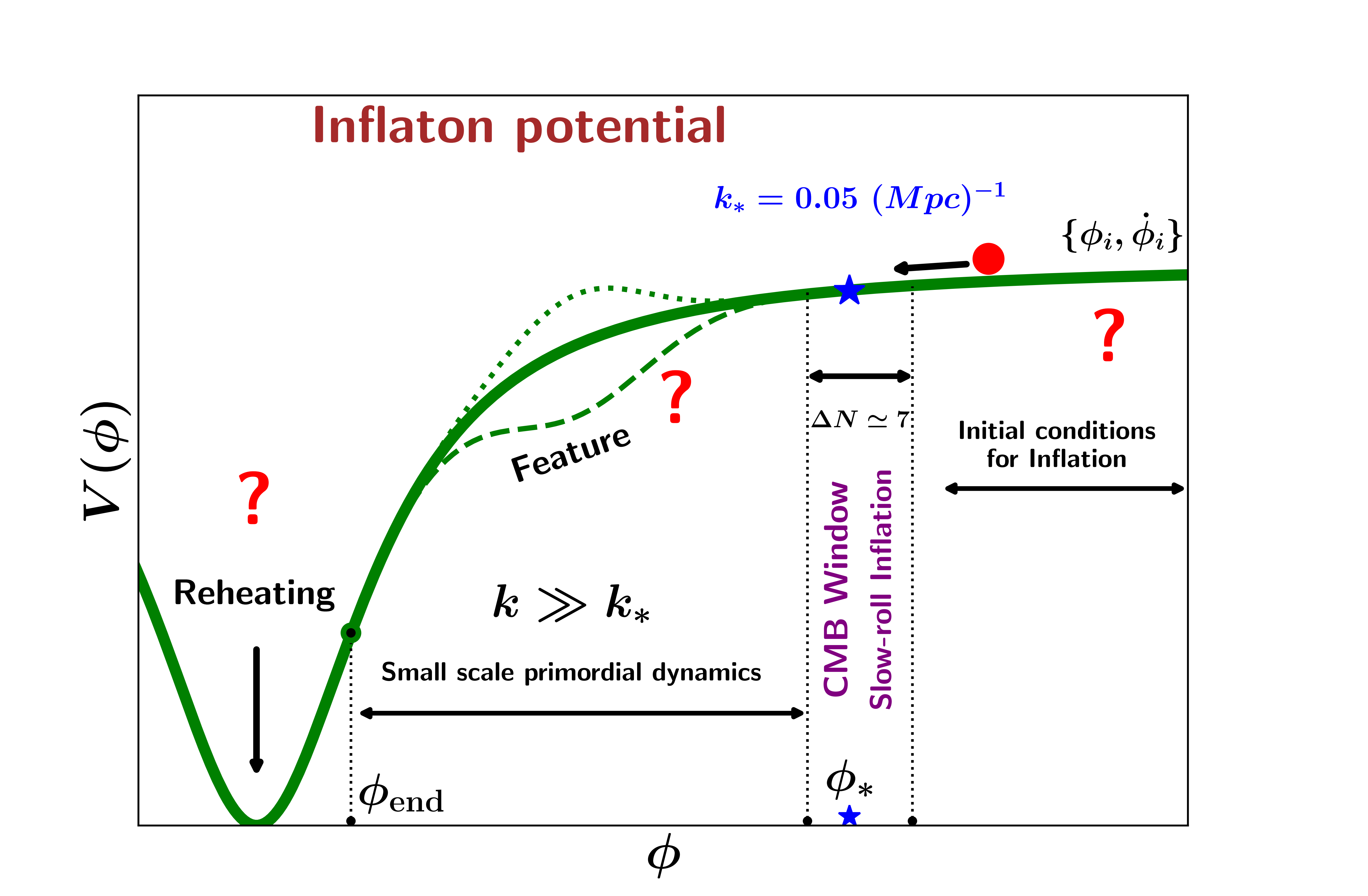
1. The formation of semi stable non-topological oscillons that emerge from the fragmentation of the inflaton field as inflation ends and can change the way the universe reheats.

2. The possibility within string cosmology of small string loops forming at the end of a period of inflation, evolving during Kination with tensions dependent on the underlying evolving volume moduli, which itself is evolving towards the asymptotic regimes of moduli space.

3. The string loops can actually grow and percolate as their tensions decrease, and as they contribute to the energy density of the universe along with radiation and the moduli, we enter a new stable loop tracking solution where they contribute of order 75% of the energy density of the universe before moduli stabilisation and reheating.

4. Such loops can have interesting cosmological consequences.

Although not the main theme of today let's have a brief recap of Inflation



$$S[g_{\mu\nu},\phi] = \int \mathrm{d}^4x\,\sqrt{-g}\,\left[\frac{m_p^2}{2}\,R - \frac{1}{2}\,\partial_\mu\phi\,\partial_\nu\phi\,g^{\mu\nu} - V(\phi)\right]$$

Einstein's equations assuming scalar field dominates the energy density

$$H^2 \equiv \frac{1}{3m_p^2}\,\rho_\phi = \frac{1}{3m_p^2}\left[\frac{1}{2}\dot{\phi}^2 + V(\phi)\right]$$

$$\dot{H} \equiv \frac{\ddot{a}}{a} - H^2 = -\frac{1}{2m_p^2}\,\dot{\phi}^2\,,$$

$$\ddot{\phi} + 3\,H\dot{\phi} + V_{,\phi}(\phi) = 0\,.$$

Credit: Swagat Mishra

Inflation can occur when potential dominated $\boxed{\dot{\phi}^2 < V(\phi)}$

When $\dot{\phi}^2 \ll V(\phi)$ with nearly flat potential dominating we obtain nearly exponential expansion at the background level

$$a \sim e^{Ht}$$

Inflation - allows us to predict the form of the fluctuations for a given model

In particular during slow roll inflation, where the potential is flat enough and dominates the energy density

We have

$$\dot{\phi}^2 \ll V(\phi) \text{ and } \ddot{\phi} \ll V'(\phi)$$

We quantify the power spectrum and deviations from scale invariance in terms of slow roll parameters

$$\Rightarrow \boxed{\epsilon_H,\ |\eta_H| \ll 1} \quad \text{where} \quad \boxed{\epsilon_H = \frac{\dot{\phi}^2}{2m_p^2 H^2}, \quad \eta_H = \frac{-\ddot{\phi}}{H\dot{\phi}}}$$

The Power Spectrum for scalar and tensor fluctuations on large scales

$$\mathcal{P}_\zeta = \frac{1}{8\pi^2}\left(\frac{H}{m_p}\right)^2 \frac{1}{\epsilon_H} = A_S \left(\frac{k}{k_*}\right)^{n_S-1} \qquad \mathcal{P}_\mathcal{T} = \frac{2}{\pi^2}\left(\frac{H}{m_p}\right)^2 = A_\mathcal{T}\left(\frac{k}{k_*}\right)^{n_T}$$

Slow roll predictions:

$$n_S-1 = -4\epsilon_H + 2\eta_H, \qquad n_\tau = -2\epsilon_H, \qquad r \equiv \frac{A_\tau}{A_S} = 16\epsilon_{H*}$$

CMB observations:

$$A_s = 2.1 \times 10^{-9}$$

BICEP/Keck 2024:

$$A_\mathcal{T} \leq 3.6\%\, A_S$$

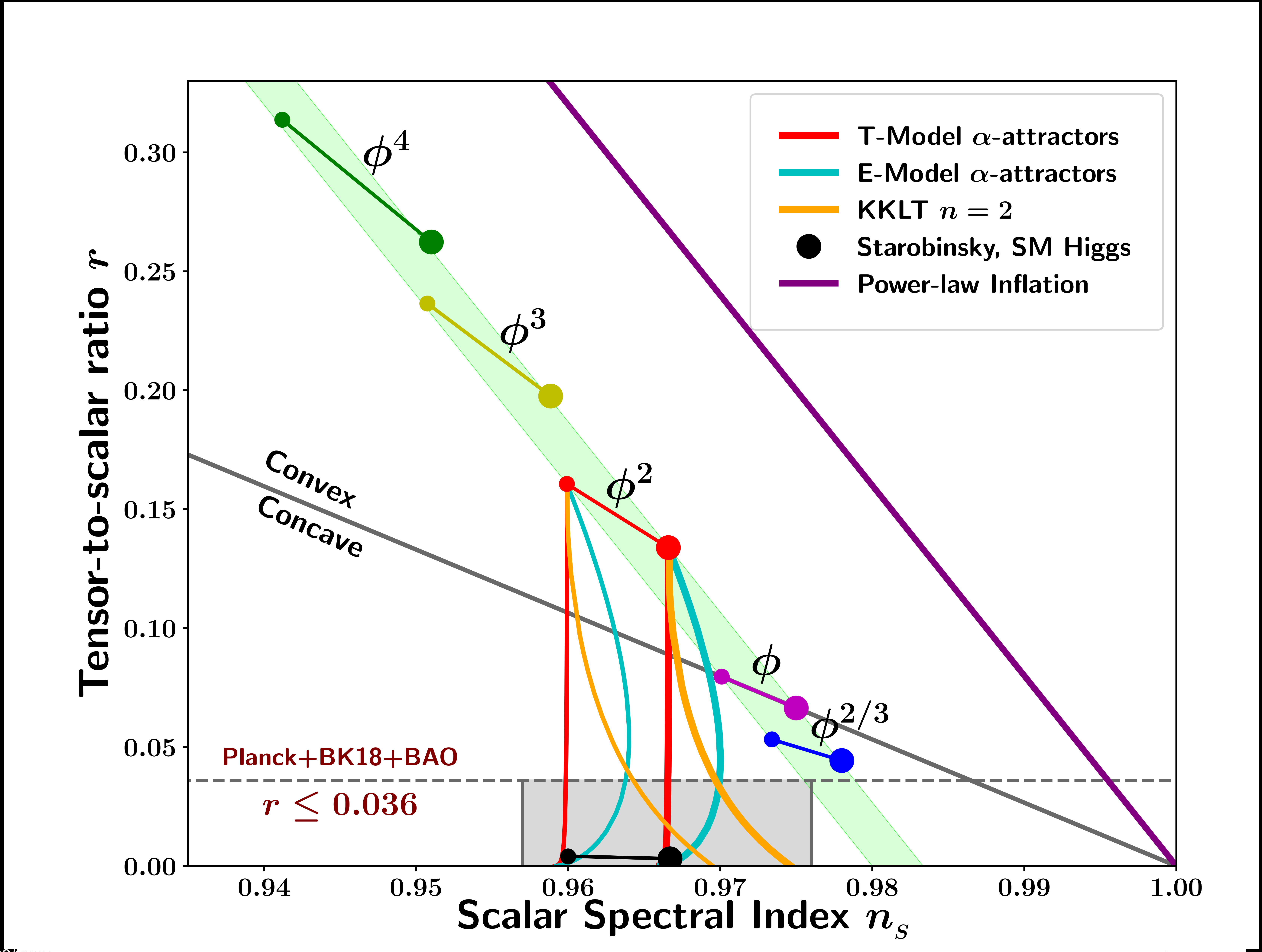
Scalar Spectral index: Red tilt $\boxed{n_S-1 \approx -0.033}$

Tensor spectra index: $\boxed{|n_\tau| \lesssim 0.0045}$

Prediction is nearly scale invariant and corrections are very small on large scales

Implies $\epsilon_H < 0.002$ and $\eta_H > 0.01$ — we have a new hierarchy emerging - has implications for $V(\phi)$!

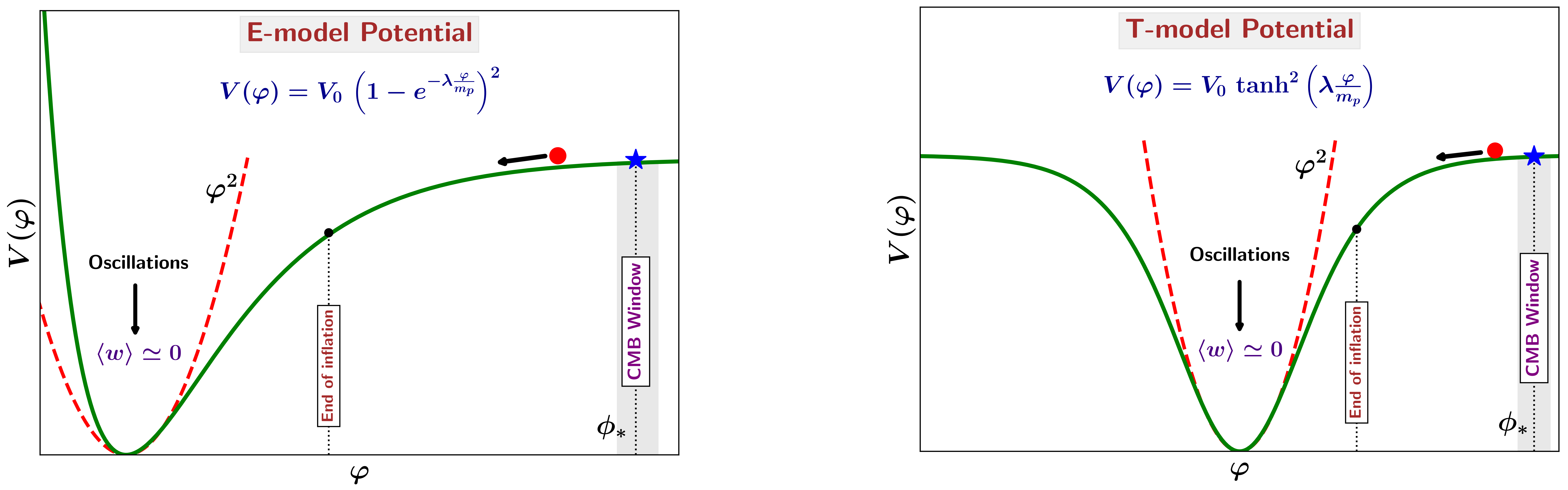
The cmb - main way we constrain models of inflation from observation



Credit: Swagat Mishra

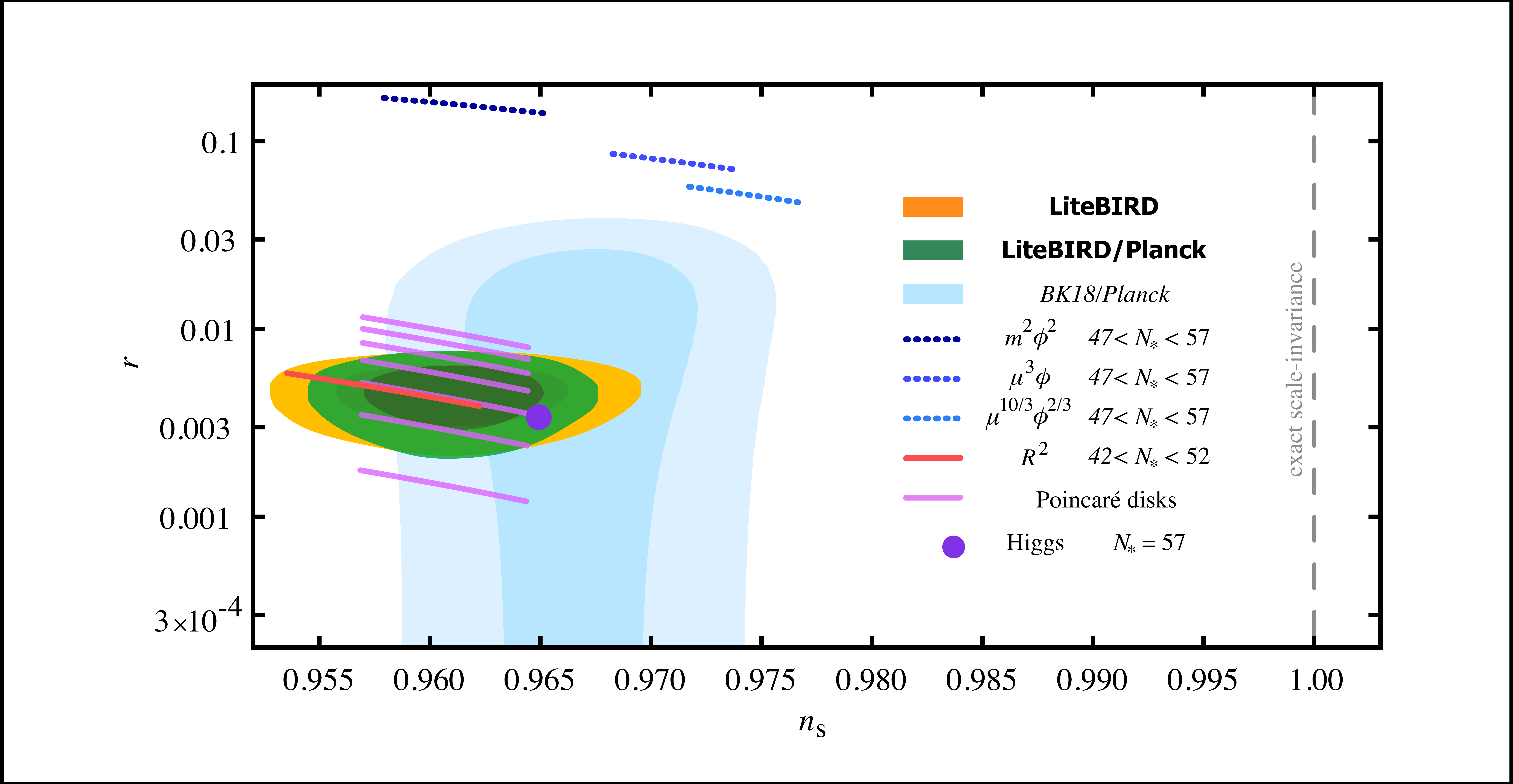
Alpha attractor E and T models of inflation (Kallosh and Linde 2013)

$$V(\phi) = \frac{1}{2}m^2\phi^2 - |U(\phi)| \quad (\textbf{E-Model} \ \& \ \textbf{T-Model})$$



These fit more naturally with the recent Planck bounds on n and r.

The future — LiteBIRD will further constrain inflation models

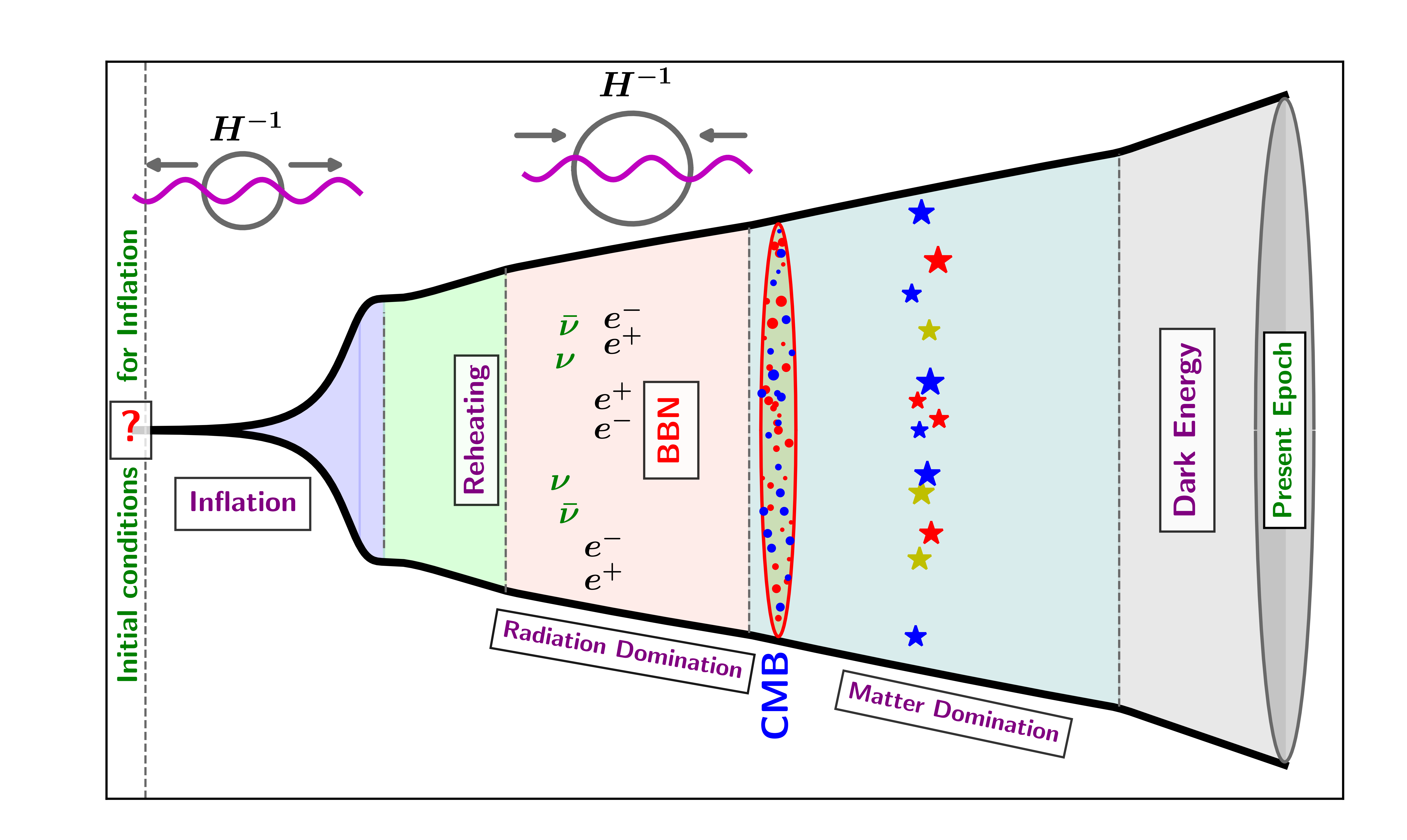


From: arXiv:2202.02773

Reheating the Universe after inflation has finished

Inflation is the ultimate vacuum cleaner, it clears out pretty much everything, particles get diluted, radiation gets red shifted, we end inflation with a cold, empty large universe, not quite what we experience today.

We need to reheat the universe - we convert the remaining energy stored in the inflaton field into primordial particles through their interactions. We could consider this the beginning of the Hot Big Bang



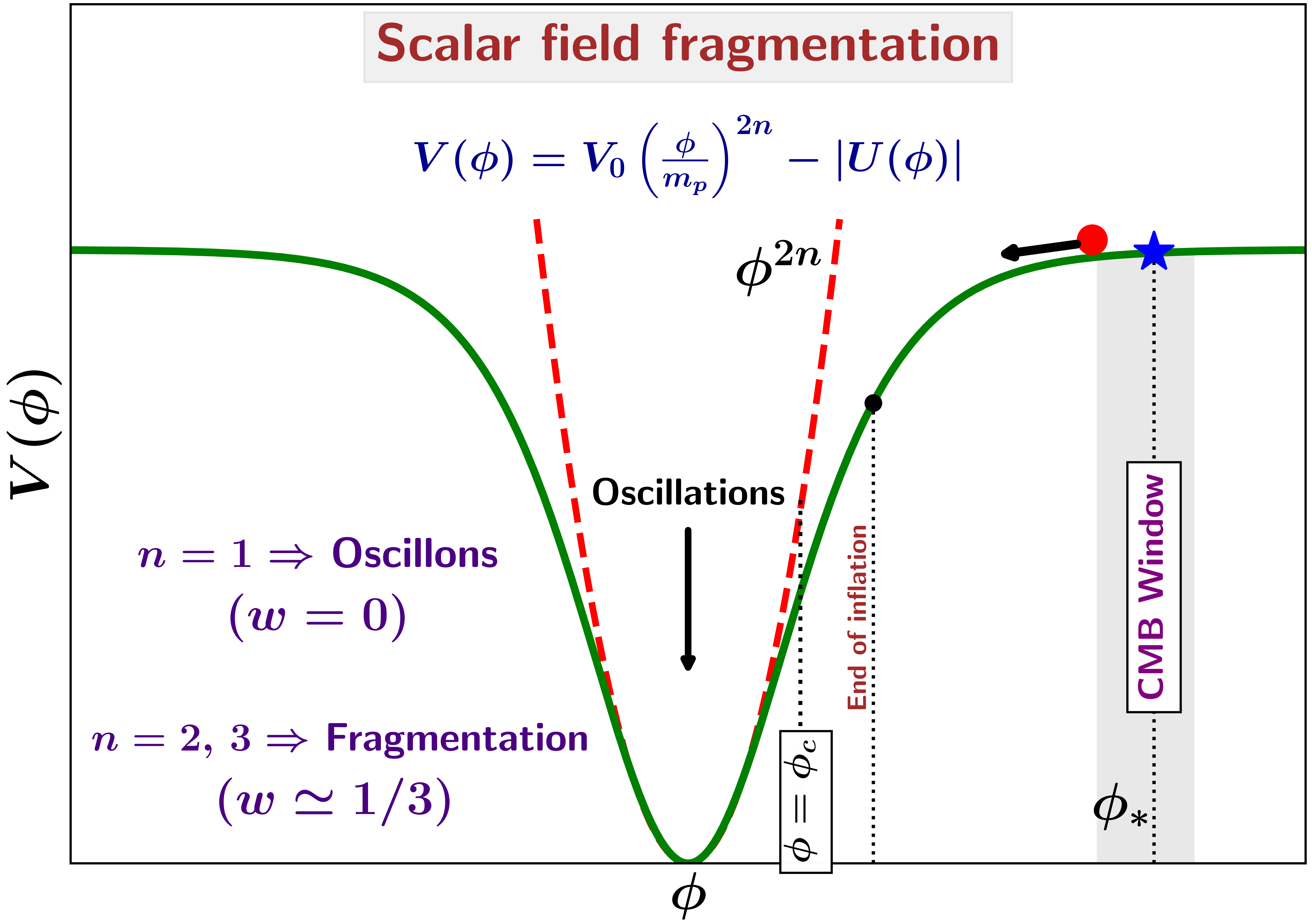
Credit: Swagat Mishra

New possible feature not included so far arises from asymptotically flat potentials - motivated from CMB observations

$$V(\phi) = V_0 \left(\frac{\phi}{m_p}\right)^{2n} - |U(\phi)|$$

They have attractive self interactions allowing for the formation of long lived non-topological solitons like oscillons — provide a new route to reheating

[Amin et al 2010]



Credit: Swagat Mishra

Oscillons : a type of soliton, self supported localised long lived due to non-linear interactions
[Bogolyubsky & Makhankov 1978, Gleiser 1993, EJC et al 1995]

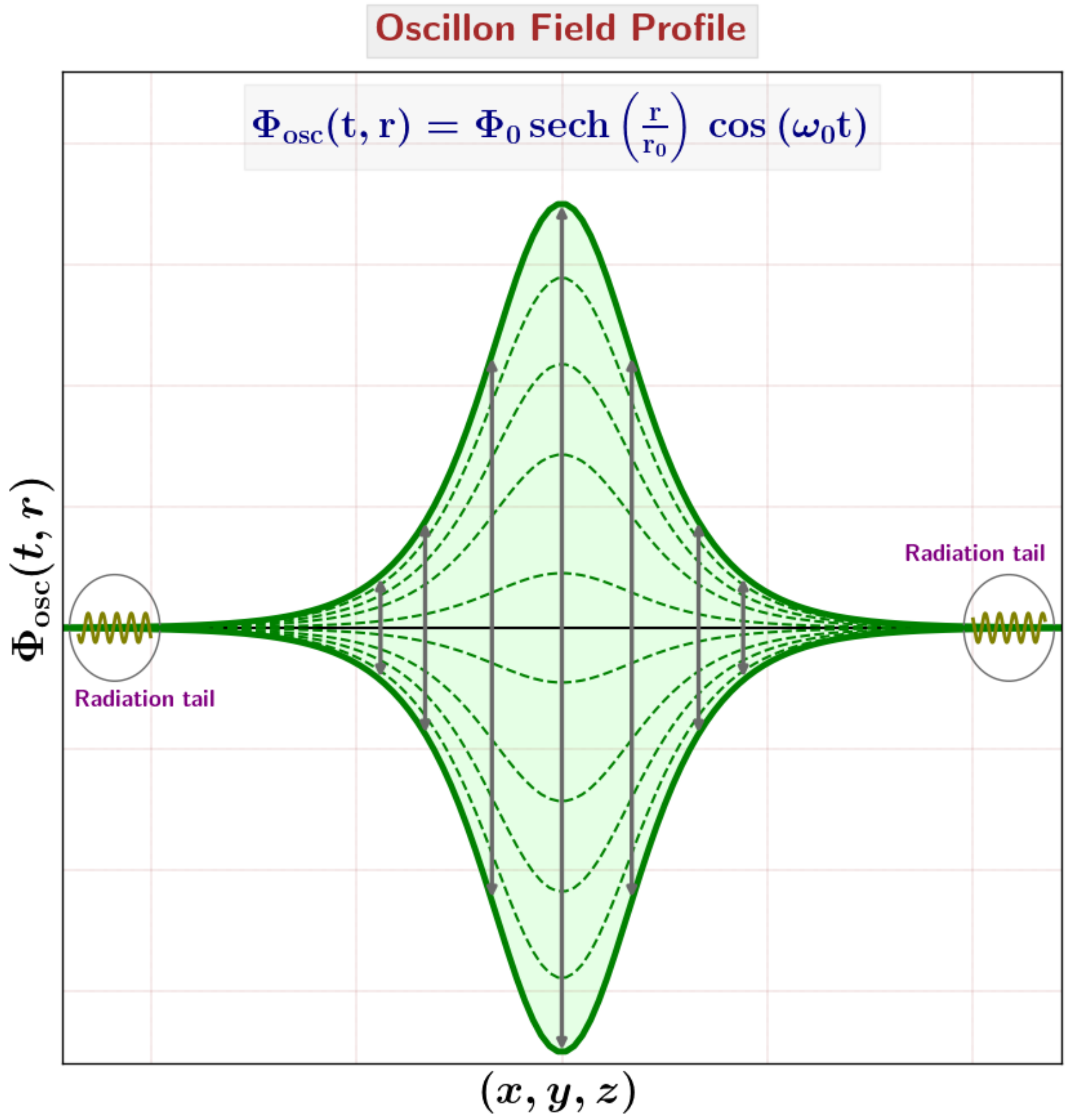
Can obtain semi-analytic solutions from small amplitude oscillations: $$V(\varphi) \approx \frac{1}{2} m^2 \varphi^2 - \frac{\lambda}{4} \mu \varphi^4 + \frac{g}{6} \lambda \varphi^6$$

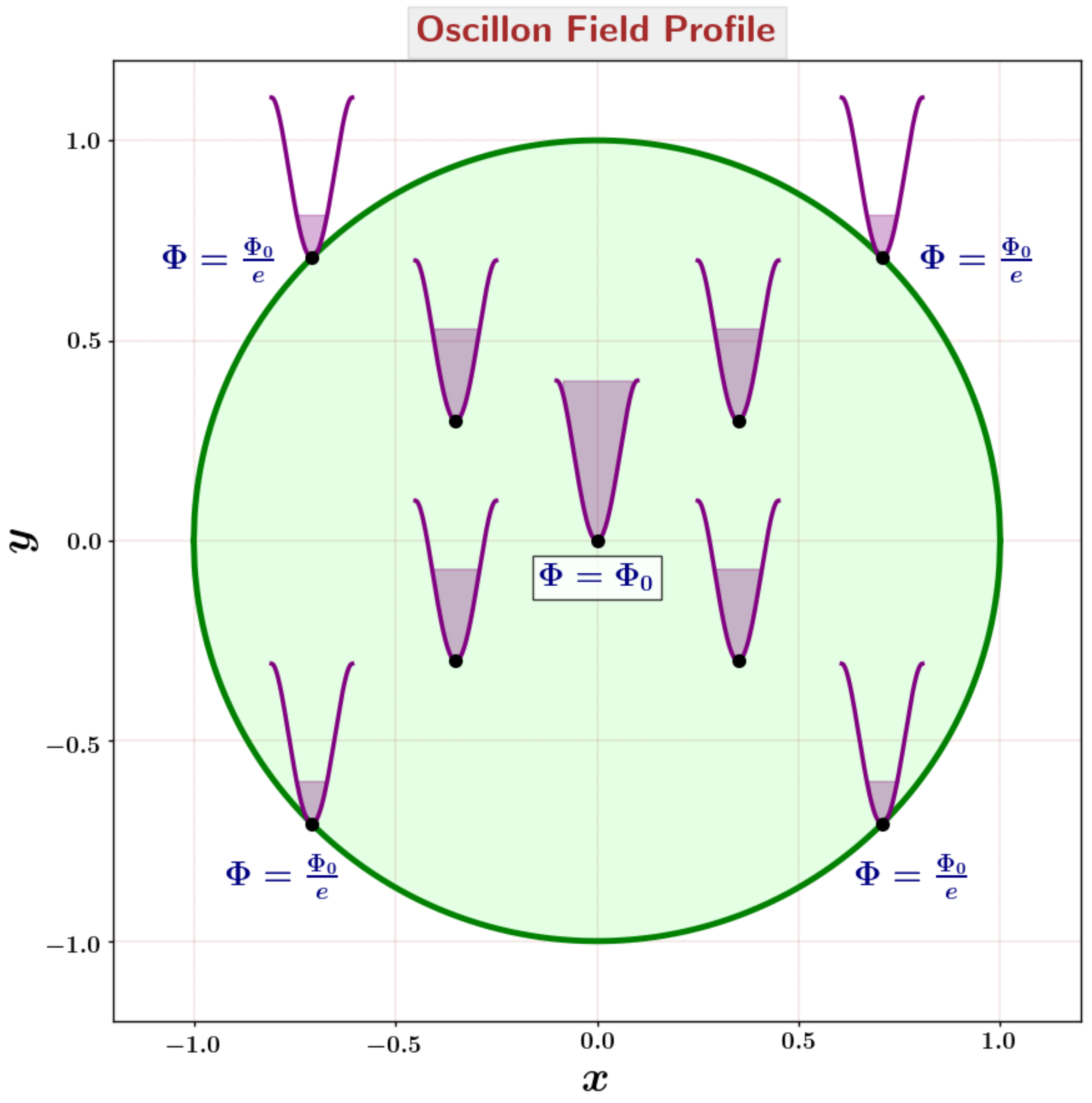
$$\boxed{\varphi_{\mathrm{osc}}(t, r) \approx \Phi(r) \cos(\omega_0 t) + \ldots} \; ; \quad \omega_0 = m \sqrt{1 - \frac{\lambda^2 \alpha^2}{m^2}}$$

With core profile: $$\boxed{\Phi(r) \approx \Phi_0 \,\mathrm{sech}\left(\frac{r}{r_0}\right)} \; ; \; \alpha^2 = \frac{g \Phi_0^2}{8\lambda} \left[3 - \frac{5}{3} g \Phi_0^2\right] \; ; \; r_0 = \frac{1}{\Phi_0} \sqrt{\frac{6}{\lambda} - \frac{10}{3\lambda} g \Phi_0^2}$$ [Amin et al, Mahbub and Mishra]

Oscillon field $$\boxed{\Phi(t, r) = \phi_0 \,\mathrm{sech}\left(\frac{r}{r_0}\right) \cos(\omega_0 t)}$$

Can survive for of order 10^9 oscillations depending on the interactions. [Zhang et al 2020]

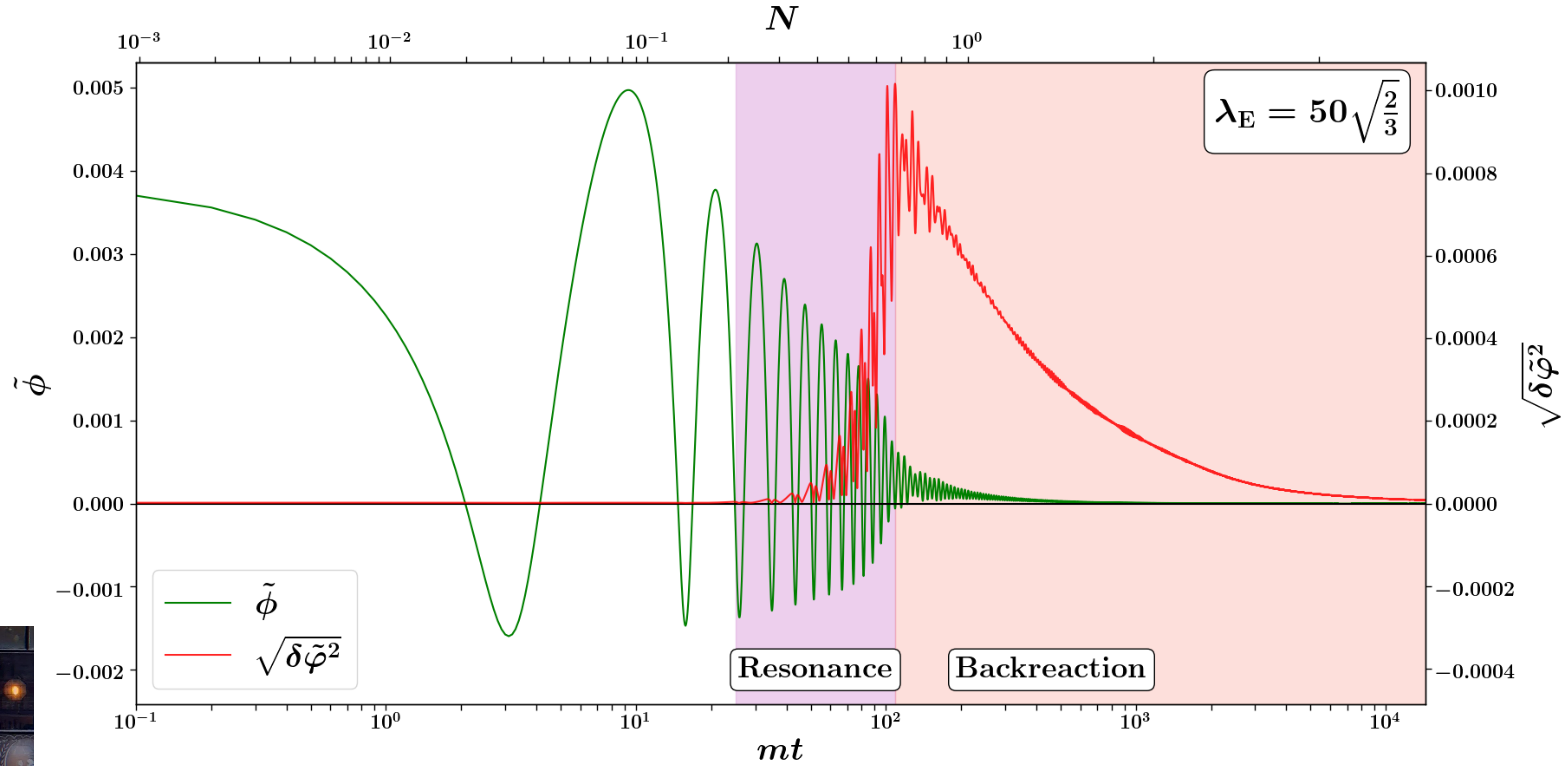




Credit: Swagat Mishra

Oscillons : full non -linear evolution using CosmoLattice [Shafi et al 2024] - no external coupling

$$V(\varphi) = V_0 \left[1 - e^{-\lambda_E \frac{\varphi}{m_P}}\right]^2$$

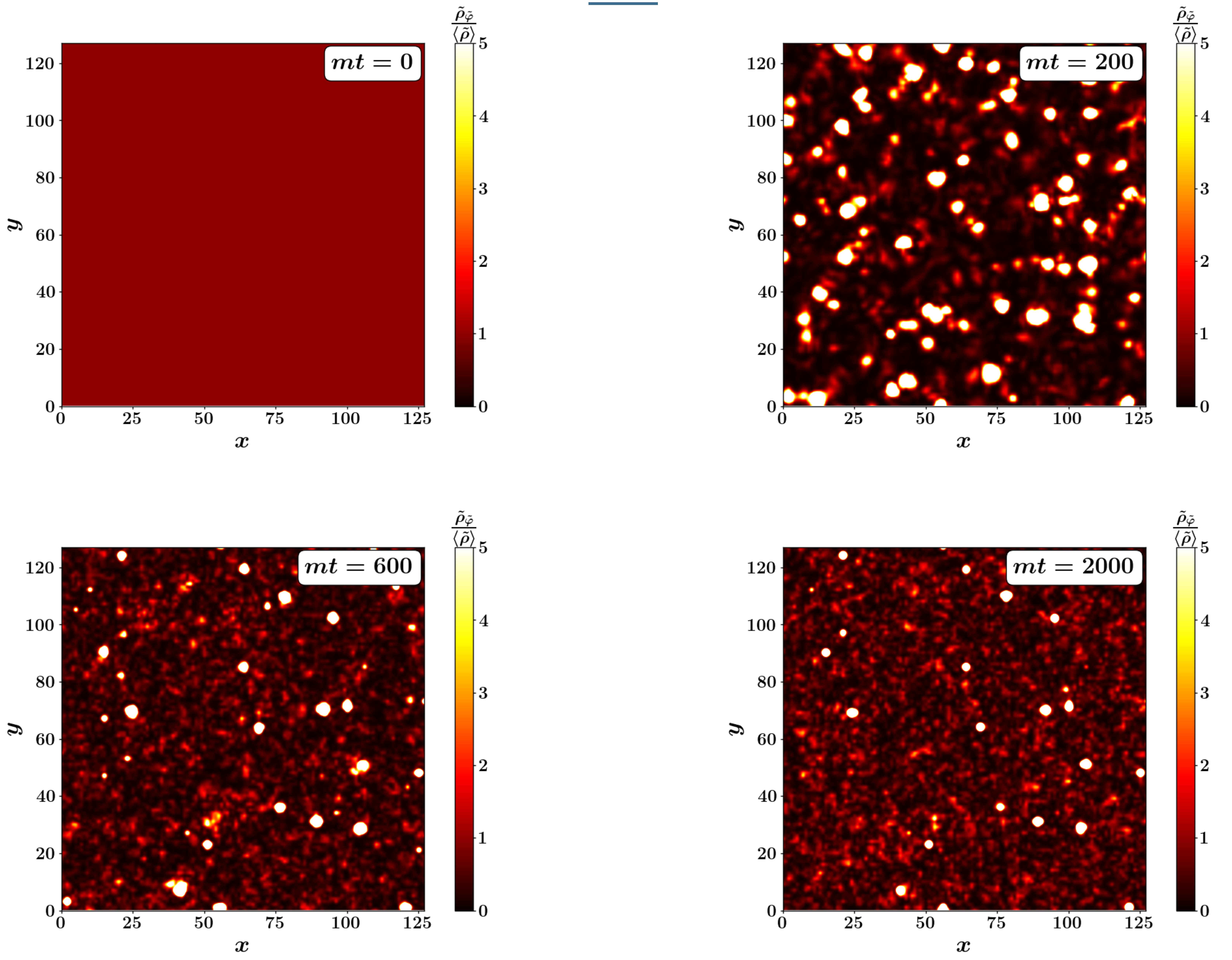


Strong self-resonance —> Inflaton fragmentation

Swagat Mishra

Lattice details: N=128^3 (also 256^3), 0.05 m^{-1} ≤ 5 m^{-1}

Oscillons formation - Asymmetric potential [Shafi et al 2024]



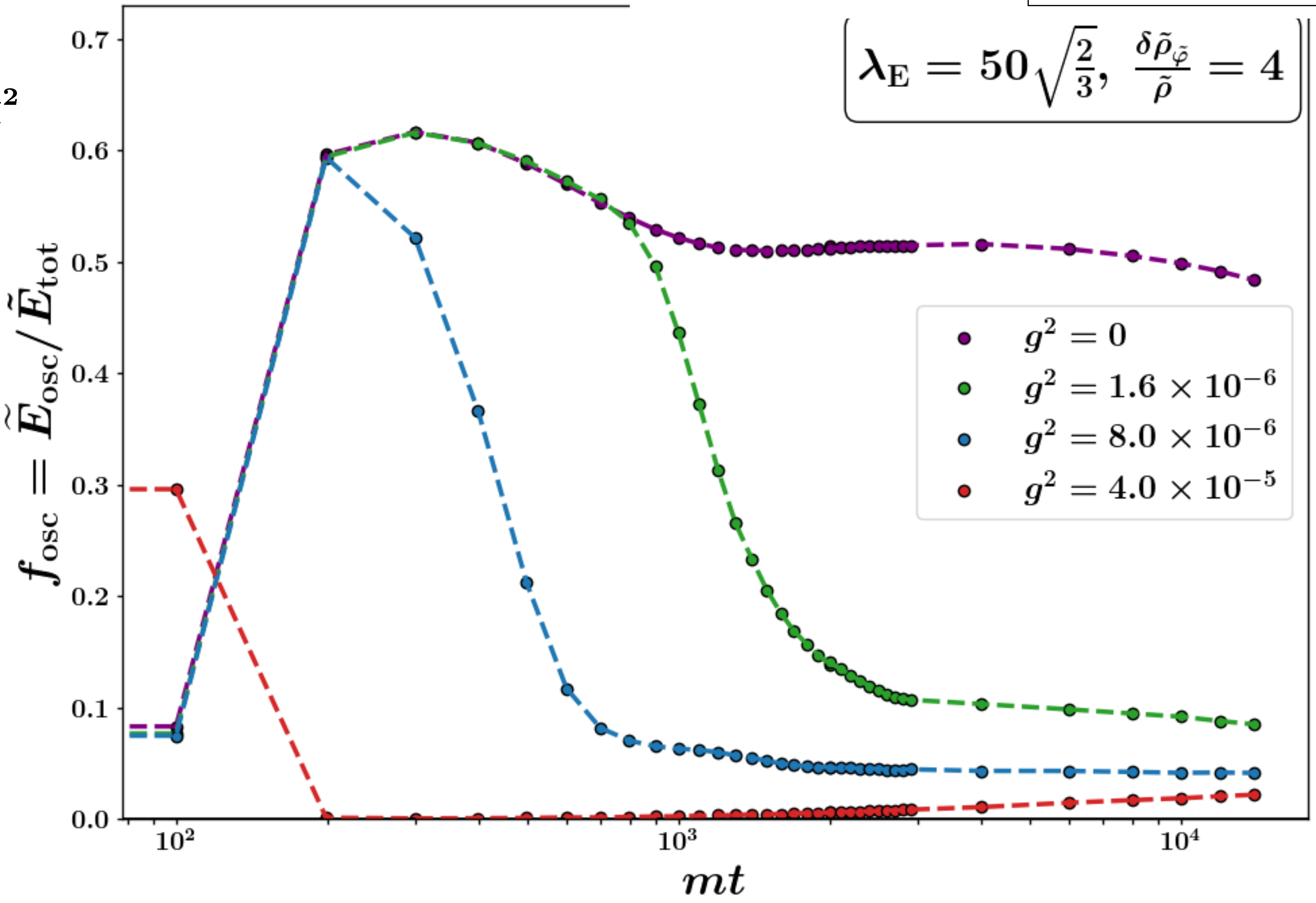

Mohammed Shafi

Oscillon fractional abundance [Shafi et al 2024]

Energy/Mass fraction $f_{\rm osc} \equiv \frac{E_{\rm osc}}{E_{\rm tot}} = \frac{\int_{\delta\rho_\varphi \gtrsim 4\bar{\rho}_\varphi} \mathrm{d}^3\boldsymbol{x}\,\rho_\varphi(\boldsymbol{x},t)}{\int \mathrm{d}^3\boldsymbol{x}\,\rho_\varphi(\boldsymbol{x},t)}$

$\mathcal{I}(\phi,\,\chi) = \frac{1}{2}g^2\varphi^2\chi^2$

External coupling



We find in the absence of external couplings oscillons form for both types of potentials and for generic initial conditions at the end of inflation. Remains to be seen how significant they can be and whether they can leave any hints of being present in say the GWs produced.

String Cosmology in Large Volume Scenarios - After inflation - evolving moduli fields !

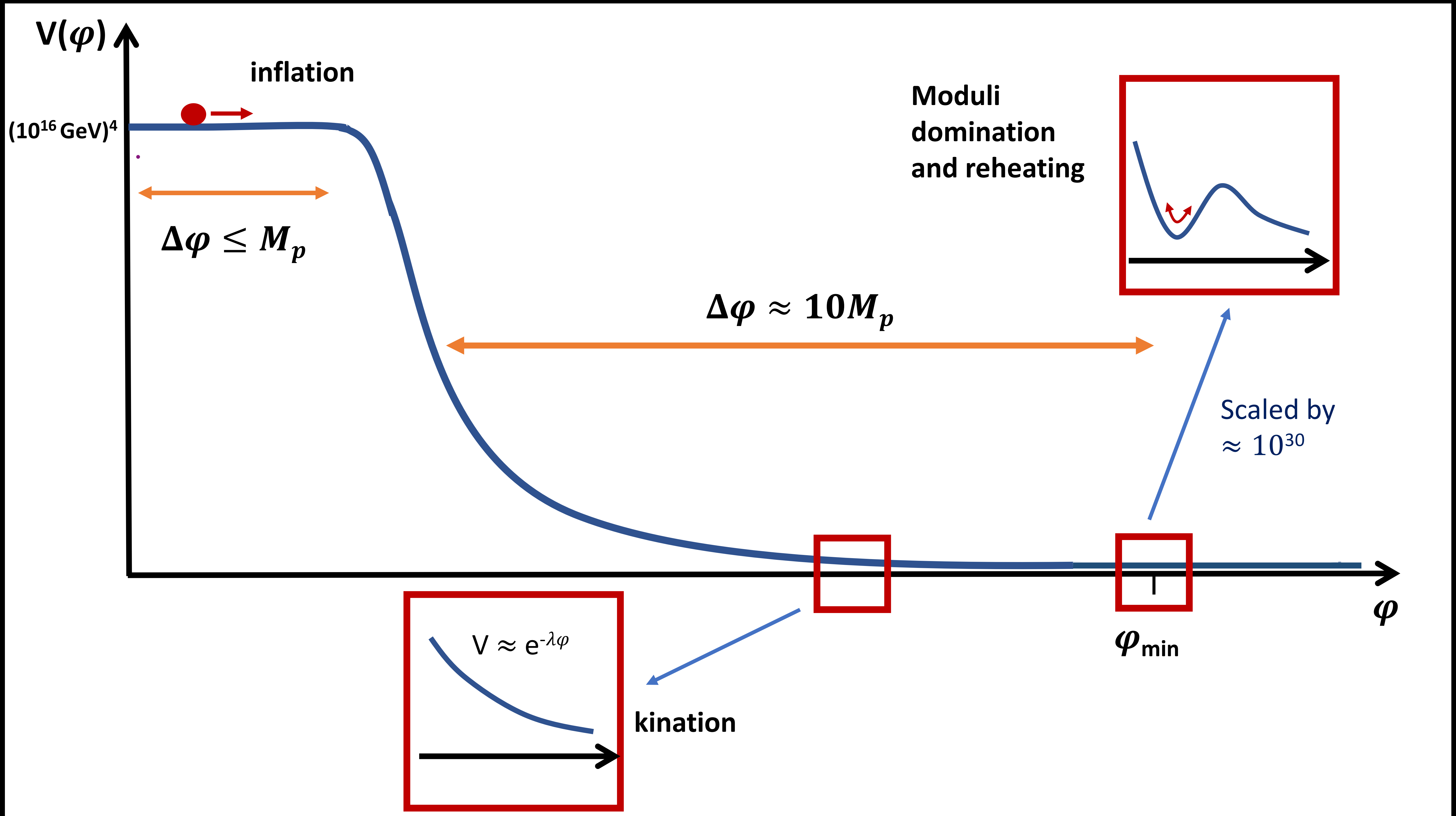
The bit between the end of inflation and the thermal HBB - some 30 orders of magnitude in time.

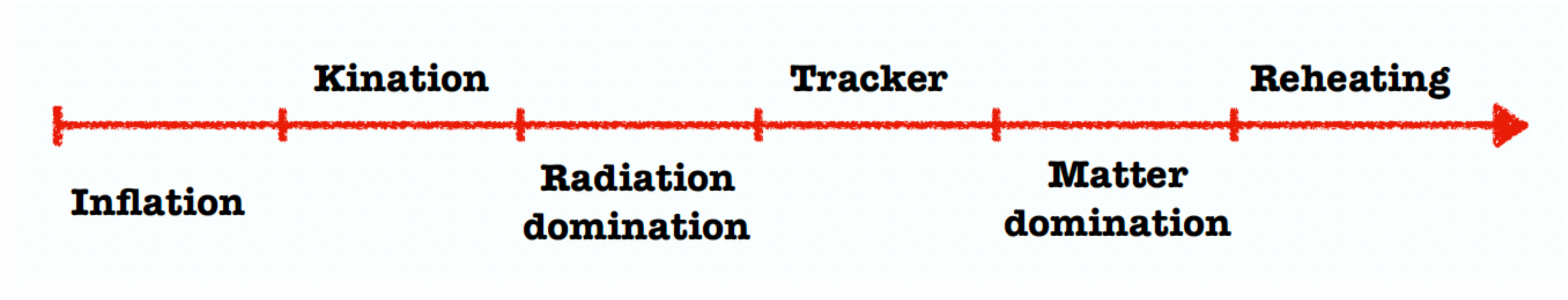
Potentially new stringy features could emerge which would modify the standard picture.

For example, large field displacements between end of inflation and final vacuum - under control !

No necessary relationship between inflaton field and field responsible for reheating. In fact in D3-anti D3 brane case, inflaton disappears.

Long Kination and moduli dominated epoch leading to moduli driven reheating





[Cicoli et al 2023]

As inflation ends we enter a Kination dominated period [Apers, Conlon, EJC, Mosny and Revello - 2401.04064; Gouttenoire, Servant and Simakachorn - 2111.01150]:

During Kination - potential term subdominant:

$$\ddot{\Phi} + 3H\dot{\Phi} = 0,$$
$$3H^2 M_P^2 = \frac{\dot{\Phi}^2}{2}$$

$$\frac{\Phi}{M_P} = \sqrt{\frac{2}{3}} \ln \mathcal{V}$$

Volume modulus $\mathcal{V}$

Kinating field satisfies : $\Phi(t) = \Phi(t_0) + \sqrt{\frac{2}{3}} M_P \ln\left(\frac{t}{t_0}\right)$ with : $a(t) \sim t^{1/3}$

Travels roughly one Planck distance in one Hubble time

Example of Kination with : $V(\Phi) = V_0 e^{-\lambda\Phi/M_P}$ with : $\lambda > \sqrt{6}$

But as V decreases during Kination and as: $\rho_{kin} \sim \frac{1}{a(t)^6},$

eventually any residual radiation or matter becomes dominant and we enter Tracker regime where the radiation and ϕ track each other

Tracker field satisfies : [EJC, Liddle & Wands 1998] $\Phi(t) = \Phi(t_0) + \frac{2M_P}{\lambda} \ln\left(\frac{t}{t_0}\right)$ with : $a(t) \sim t^{1/2}$

Fien Apers

Again travels roughly one Planck distance in one Hubble time

Heads towards large field values and guides the field into the min of the moduli potential where reheating can occur

Nice feature we recently realised [Mosney, Conlan and EJC - 2507.04161]

Sub horizon perturbations of the scalar field can act as massless radiation, effectively decouple from the background scalar field and source the tracking solution without the need for background radiation

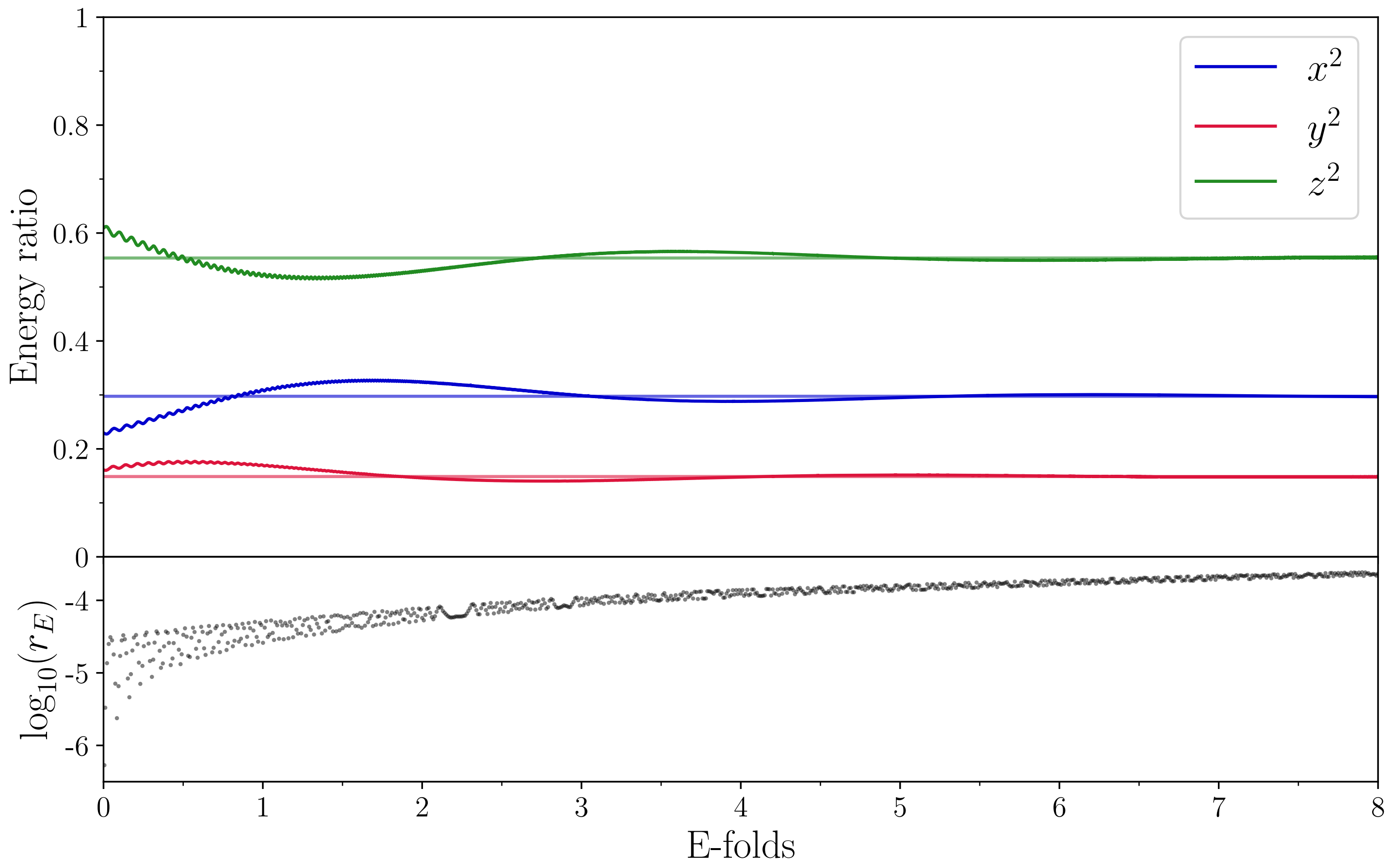
$$V = V_0 e^{-\lambda\phi/M_P}$$

$$x^2 = \frac{\dot{\bar{\phi}}^2}{6H^2M_P^2}, \qquad y^2 = \frac{V(\bar{\phi})}{3H^2M_P^2}, \qquad z^2 = \frac{\rho^2_{\delta\phi}}{3H^2M_P^2}.$$

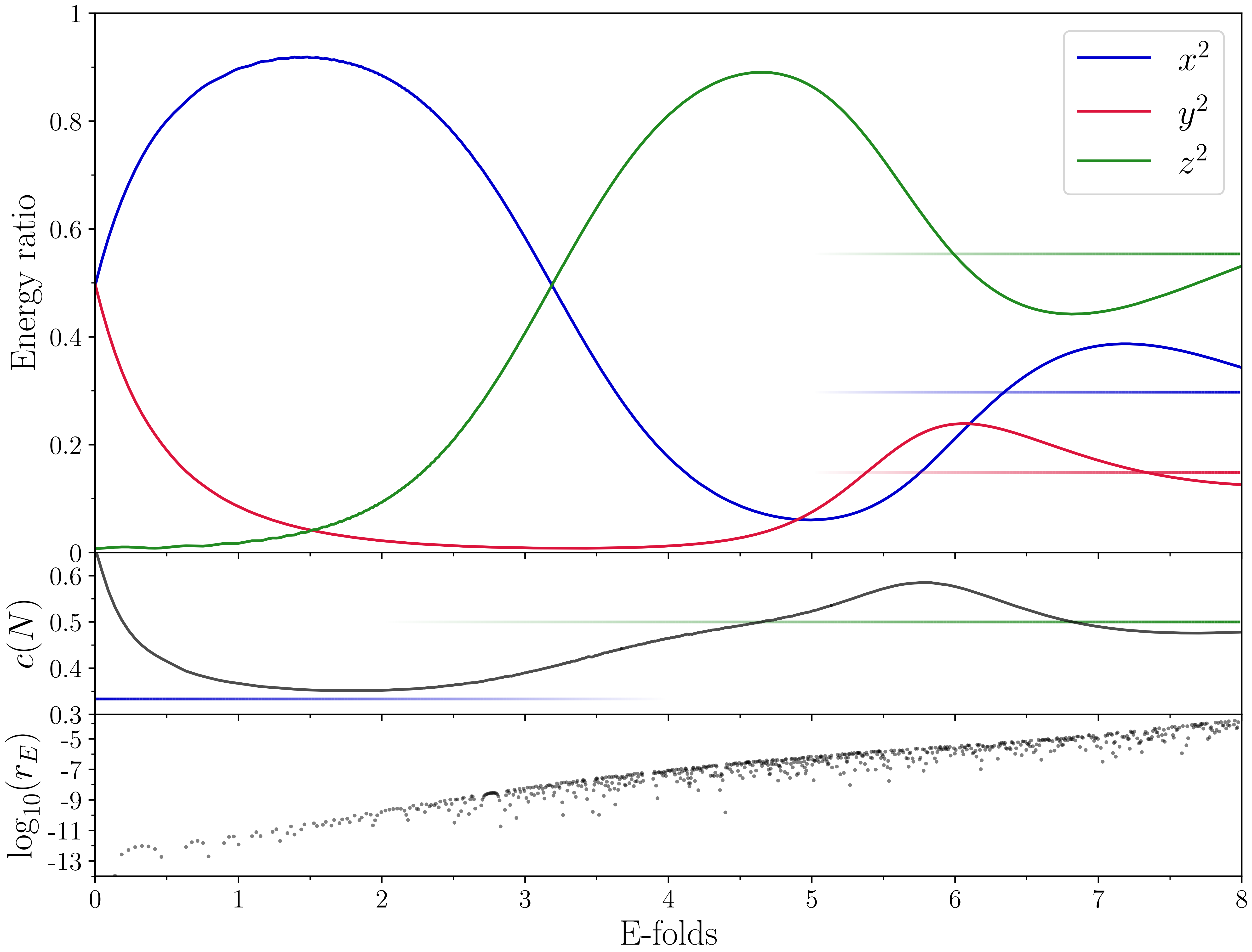
$$\downarrow \qquad\qquad \downarrow \qquad\qquad \downarrow$$

$$x^2 = \frac{8}{3\lambda^2}, \qquad y^2 = \frac{4}{3\lambda^2}, \qquad z^2 = 1 - \frac{12}{3\lambda^2}.$$

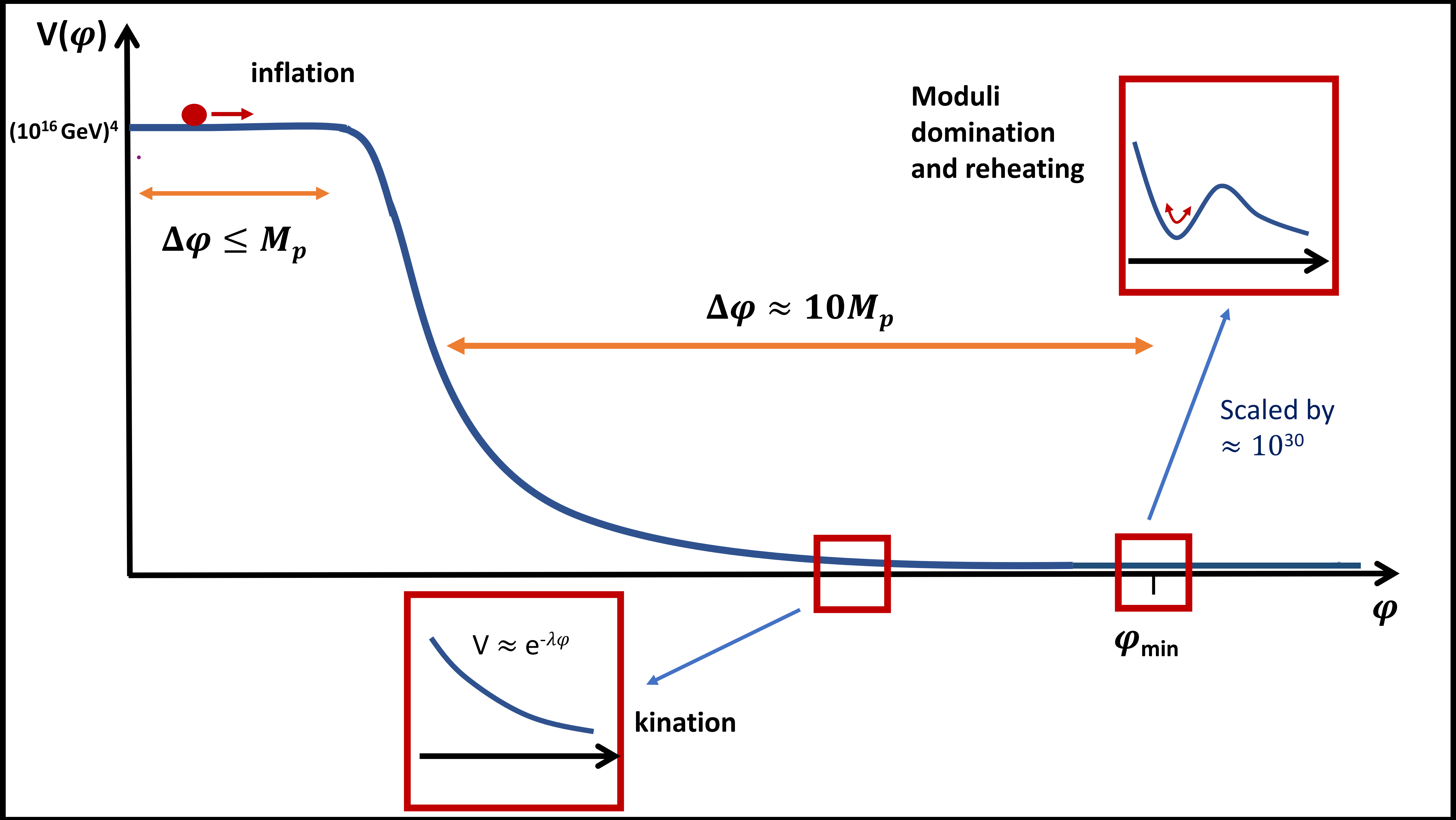
Martin Mosny



Details of radiation tracker



Kination followed by radiation tracker



Time varying standard model parameters because determined by evolving moduli fields !

Gauge couplings, Yukawa couplings and axion decay constants - could be different from today.

Perturbations in the field grow during Kination and into the tracker regime before the moduli are stabilised and reheating occurs - potential for new exciting pre BBN physics ! [Apers et al 2024]

Cosmic superstring tensions will evolve in time, and a new network formation process could emerge from the formation of loops

$m_s \sim \frac{M_P}{\sqrt{\mathcal{V}}}$ with $G\mu \sim m_s^2$ hence during Kination $G\mu \sim t^{-1}$

Percolating cosmic string networks from kination [Conlon, EJC, Hardy and Sanchez Gonzalez - 2406.12637]

Oscillating string loops grow when their tension decreases with time.

If 2H + d/dt (ln(μ)) < 0 —> loops grow faster than the scale factor, hence an initial population of isolated small loops can grow, percolate and form a network.

This condition is the case for fundamental strings in the bgd of a kinating volume modulus rolling towards the asymptotic large volume region of moduli space.

The tension of the string network is eventually set by the final vacua of the kinating moduli.

Kinating field satisfies :

$$\frac{\Phi}{M_P} = \sqrt{\frac{2}{3}} \ln \mathcal{V}$$

$$\Phi(t) = \Phi(t_0) + \sqrt{\frac{2}{3}} M_P \ln\left(\frac{t}{t_0}\right)$$

with : $a(t) \sim t^{1/3}$

In string theory there are no fixed couplings (or tensions) - the couplings and tensions arise as vevs of moduli. The volume modulus rolls to the asymptotic regions of moduli space satisfying $\mathcal{V} \sim$ t

$$m_s \sim \frac{M_P}{\sqrt{\mathcal{V}}}$$ with $G\mu \sim m_s^2$ hence $G\mu \sim t^{-1}$

Volume sets the string scale, and all other physical scales depend on the string scale

Hence: 2H + d/dt (ln(μ)) = 2/(3t) - 1/t = -1/(3t) < 0

Noelia Sanchez Gonzalez

A few details

Nabu Goto action but allowing time dependent tension

$$S_{\rm NG} = -\int d^2\xi \mu(x^\nu)\sqrt{-\gamma},$$

Eqns of motion:

$$x^{\nu\ ;a}_{,a} + \Gamma^\nu_{\beta\rho}(g)\,\gamma^{ad}x^\beta_{,d}x^\rho_{,a} + \frac{\mu_{,\rho}}{\mu}\gamma^{ab}x^\rho_{,a}x^\nu_{,b} - \frac{\mu^{,\nu}}{\mu} = 0$$

World sheet metric in suitable gauge:

$$(\gamma_{ab}) = \begin{pmatrix} 1 - a^2\dot{\vec{x}}^2 & 0 \\ 0 & -a^2\vec{x}'^2 \end{pmatrix}$$

Define: $\varepsilon(t,\sigma) \equiv \sqrt{\frac{-x'^2}{\dot{x}^2}} = \sqrt{\frac{a^2\vec{x}'^2}{1-a^2\dot{\vec{x}}^2}}.$

Consider circular loop: $\vec{x}(t,\sigma) = R(t)\vec{u}(\sigma)$ $\quad \vec{u}(\sigma) = (\sin\sigma, \cos\sigma, 0)$

Eqns of motion:

$$\frac{\dot{\varepsilon}}{\varepsilon} = H - a^2\dot{R}^2\left(2H + \frac{\dot{\mu}}{\mu}\right),$$

with $\varepsilon = \sqrt{\frac{a^2R^2}{(1-a^2\dot{R}^2)}} \equiv aR_{\rm max}$

$$\ddot{R} + H\dot{R} + \varepsilon^{-2}R + \left(2H + \frac{\dot{\mu}}{\mu}\right)(1-a^2\dot{R}^2)\dot{R} = 0,$$

Small loops oscillate rapidly and satisfy $\langle a^2\dot{R}^2\rangle = 1/2.$

Hence when $\dot{\mu} = 0, \ \frac{\dot{\varepsilon}}{\varepsilon} = 0$

Loops oscillate with constant physical size while scale factor grows, so shrink in comoving coords

But loops grows in comoving coords when $2H + \frac{\dot{\mu}}{\mu} < 0.$ with $R_{\rm max}(t) = R_{{\rm max},i}\left(\frac{t}{t_i}\right)^{1/6}$ and $L(t) = L_i\sqrt{\frac{G\mu_i}{G\mu(t)}} = L_i\left(\frac{t}{t_i}\right)^{1/2}.$

We want :

$$2H + \frac{\dot{\mu}}{\mu} < 0.$$

Make H as small as possible and d/dt(ln μ) as large and negative as possible

Volume Kination is ideal as $a(t) \sim t^{1/3}$ which is slower than any other fluid.

All the energy is in the kinetic energy of a modulus field, and the tension depends on the field, so the rate of change of the tension is maximised

During volume kination, the volume modulus rolls down an exponential potential $$V(\Phi) = M_P^4 \; e^{-\sqrt{3/2}\,\lambda\Phi/M_P}$$

Small loops of cosmic superstring grow relative to the scale factor

As they grow, they become more important, rather than simply evaporating through GW emission.

Eventually they percolate forming a new network of strings before reheating.

For related ideas with fixed tension strings see EJC, Kibble and Steer (1998), Frey et al. (2023 and 2024) :

Dynamics of the new cosmic superstring network [Sanchez Gonzalez, Conlon, EJC and Hardy - 2505.14187]

In the presence of an exponential potential, we have an evolving network of loops with time dependent tensions, with background radiation. What are the stable attractors of such a network ? With no loops we know there are tracker solutions where the field mimics the dominant radiation or matter, but in the presence of loops ?

Moduli potenital: $$V(\Phi) = M_P^4 \, e^{-\sqrt{3/2}\,\lambda\Phi/M_P}$$ [λ=3 corresponds to LVS where potential falls off as $\mathcal{V}^{-3}$]

Loop length: $$\ell(\Phi) = \ell_i \sqrt{\frac{\mu_i}{\mu(\Phi)}}.$$

String tension: $$\mu(\Phi) = M_P^2 \, e^{-\sqrt{6}\beta\Phi/M_P},$$ [β depends on particular model - is 1/2 in LVS]

Loop density: $$\rho(a,\Phi) = n \cdot \mu \cdot \ell = \rho_i \cdot \left(\frac{a_i}{a}\right)^{-3} \cdot e^{-\sqrt{3/2}\beta\,(\Phi-\Phi_i)/M_P}$$

Friedmann, accn and fluid equations:

$$3M_P^2 H^2 = \frac{\dot{\Phi}^2}{2} + V(\Phi) + \rho_{\rm loops}(a,\Phi) + \rho_{\rm rad}(a)$$

$$-2M_P^2 \dot{H} = \dot{\Phi}^2 + \rho_{\rm loops}(a,\Phi) + \frac{4}{3}\rho_{\rm rad}(a) \; ,$$

$$0 = \ddot{\Phi} + 3H\dot{\Phi} + \frac{\partial V(\Phi)}{\partial \Phi} + \frac{\partial \rho_{\rm loops}}{\partial \Phi} \; ,$$

$$0 = \dot{\rho}_\ell + 3H\rho_\ell - \frac{\partial \rho_{\rm loops}}{\partial \Phi}\dot{\Phi} \; ,$$

$$0 = \dot{\rho}_{\rm rad} + 4H\rho_{\rm rad} \; .$$

Write as a dynamical system ala EJC, Liddle and Wands [1998]

Intro:

$$x^2 \equiv \dot{\Phi}^2/6M_P^2H^2,$$
$$y^2 \equiv V/3M_P^2H^2,$$
$$z^2 \equiv \rho_{\rm loops}/3M_P^2H^2,$$
$$w^2 \equiv \rho_{\rm rad}/3M_P^2H^2,$$

Friedmann constraint: $x^2 + y^2 + z^2 + w^2 = 1$

Evoln equations:

$$x' = \frac{3}{2}\left[x(x^2 - y^2 + \frac{w^2}{3} - 1) + \beta(1 - x^2 - w^2) + (\lambda - \beta)y^2)\right]$$
$$y' = \frac{3}{2}y\left[x^2 - y^2 + \frac{w^2}{3} - \lambda x + 1\right],$$
$$w' = \frac{3}{2}w\left[x^2 - y^2 + \frac{1}{3}(w^2 - 1)\right],$$

Fixed point solution including string loop tracker - enter reheating with non - negligible density of loops:

Fixed points	Ω_V	$\Omega_{\dot\Phi}$	$\Omega_{\rm loops}$	Existence conditions
A. Kination	0	1	0	$\forall\lambda,\beta$
B. String Loop tracker	0	β^2	$1-\beta^2$	$\forall\lambda,\ \beta\leq 1$
C. Scalar field domination	$1-\frac{\lambda^2}{4}$	$\frac{\lambda^2}{4}$	0	$\forall\beta\ ,\ \lambda\leq 2$
D. Mixed tracker I	$\frac{\beta^2-\lambda\beta+1}{(\lambda-\beta)^2}$	$\frac{1}{(\lambda-\beta)^2}$	$\frac{\lambda^2-\lambda\beta-2}{(\lambda-\beta)^2}$	$\beta\leq 1,$ $\frac{\beta}{2}+\sqrt{\frac{\beta^2}{4}+2}\leq\lambda\leq\beta+\frac{1}{\beta}$

Evolution in absence of radiation

Evolution in presence of radiation

Fixed points	Ω_V	$\Omega_{\dot\Phi}$	$\Omega_{\rm loops}$	$\Omega_{\rm rad}$	Existence conditions
E. Radiation Tracker	$\frac{8}{9\lambda^2}$	$\frac{16}{9\lambda^2}$	0	$1-\frac{8}{3\lambda^2}$	$\forall\beta\neq\frac{\lambda}{4},$ $2\sqrt{\frac{2}{3}}\leq\lambda$
F. Loop-Radiation Tracker	$y_{\rm fp}^2$	$\frac{16}{9\lambda^2}$	$\frac{32}{9\lambda^2}-4y_{\rm fp}^2$	$1-\frac{16}{3\lambda^2}+3y_{\rm fp}^2$	$\beta=\frac{\lambda}{4}$, $2\sqrt{\frac{2}{3}}\leq\lambda$
G. Mixed Tracker II	0	$\frac{1}{9\beta^2}$	$\frac{2}{9\beta^2}$	$1-\frac{1}{3\beta^2}$	$\forall\lambda,\ \frac{1}{\sqrt{3}}\leq\beta$
H. Radiation Domination	0	0	0	1	$\forall\lambda,\beta$

Table 2. Fixed points in the evolution of the system with a scalar field Φ on an exponential potential $V(\Phi)$, radiation $\rho_{\rm rad}$ and a population of string loops (energy density $\rho_{\rm loops}$) coupled to the modulus Φ. The parameters β and λ are defined as $\lambda\equiv-\sqrt{2/3}M_P(\partial_\Phi V)/V$ and $\beta\equiv-\sqrt{2/3}M_P(\partial_\Phi\rho_{\rm loops})/\rho_{\rm loops}$.

From kination through transient radiation tracker through to late time string loop tracker - loop energy density grows relative to the background - the stable attractor is the loop tracker with

$\Omega_{\rm loops} = 3/4$, $\Omega_{\rm kin} = 1/4$

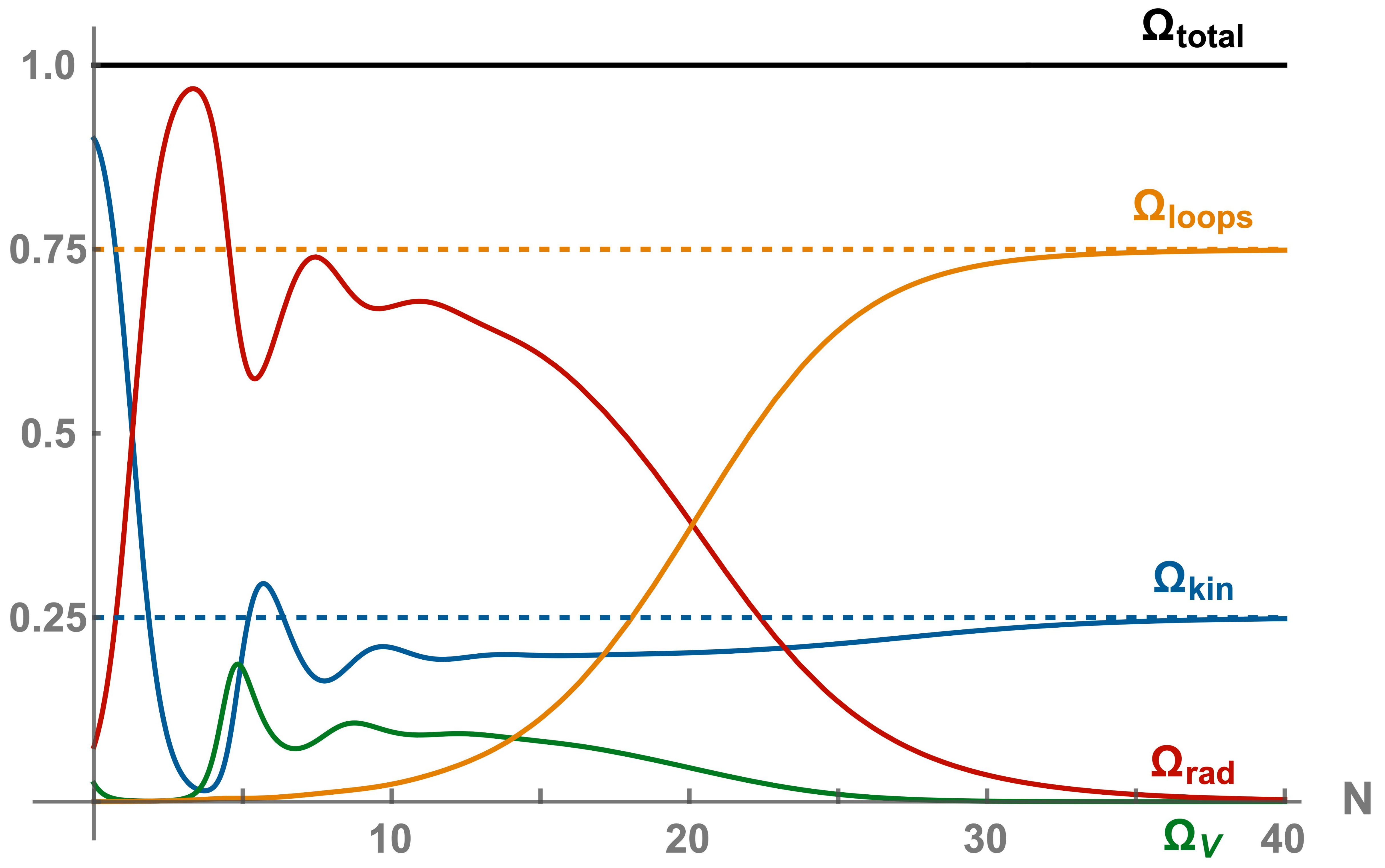


Figure 6. Evolution of the energy fractions starting from kination and going towards a string loop tracker through a transient radiation tracker, characterised by $\Omega_r \simeq 0.7$ and $\Omega_{\dot{\Phi}} = 2\Omega_V \simeq 0.2$, for fundamental strings in LVS ($\beta = 1/2$ and $\lambda = 3$).

For those who like phase plane plots - the same evolution showing the stability of the loop tracker

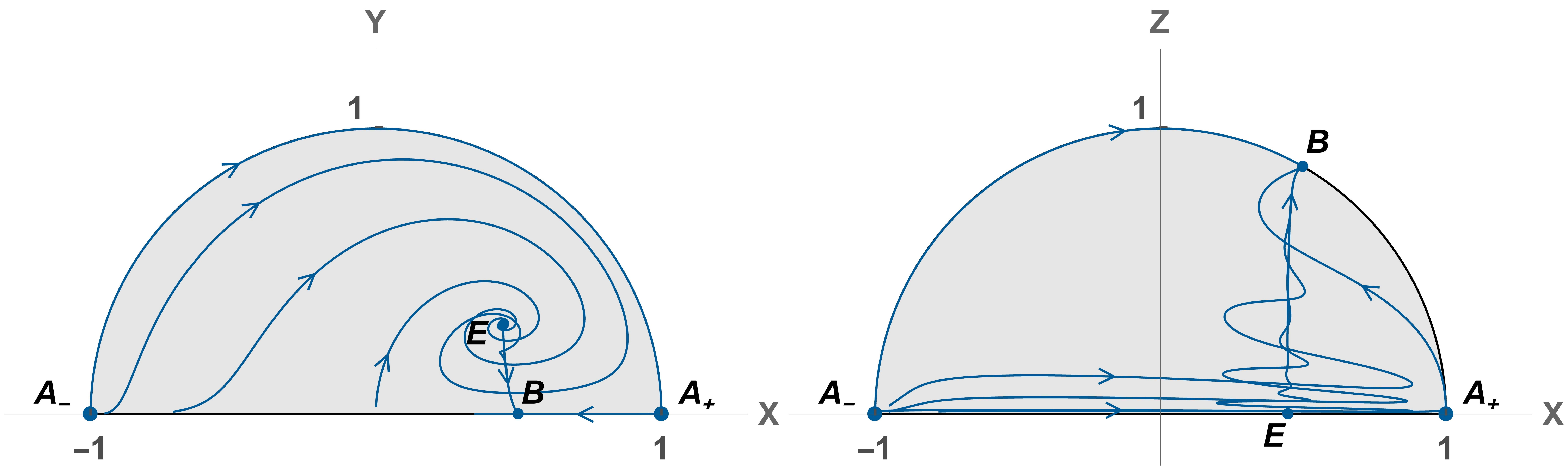


Figure 5. Evolution in phase space towards the loop tracker attractor (B) through a transient radiation tracker (E) for fundamental strings in LVS (with $\beta = 1/2$ and $\lambda = 3$).

We have seen that:

Can start with a volume modulus rolling down an exponential potential

With a small initial population of fundamental string loops formed towards the end of inflation

Leads to an attractor which is a loop tracker solution with 75% of the stored energy density being in the form of superstring loops, an interesting new way to enter reheating

They leave an imprint in the GW bgd as they oscillate grow, then decay - test case from LVS.

Preliminary - Conlon, EJC, Hardy and Sanchez Gonzalez - [In preparation 2025].

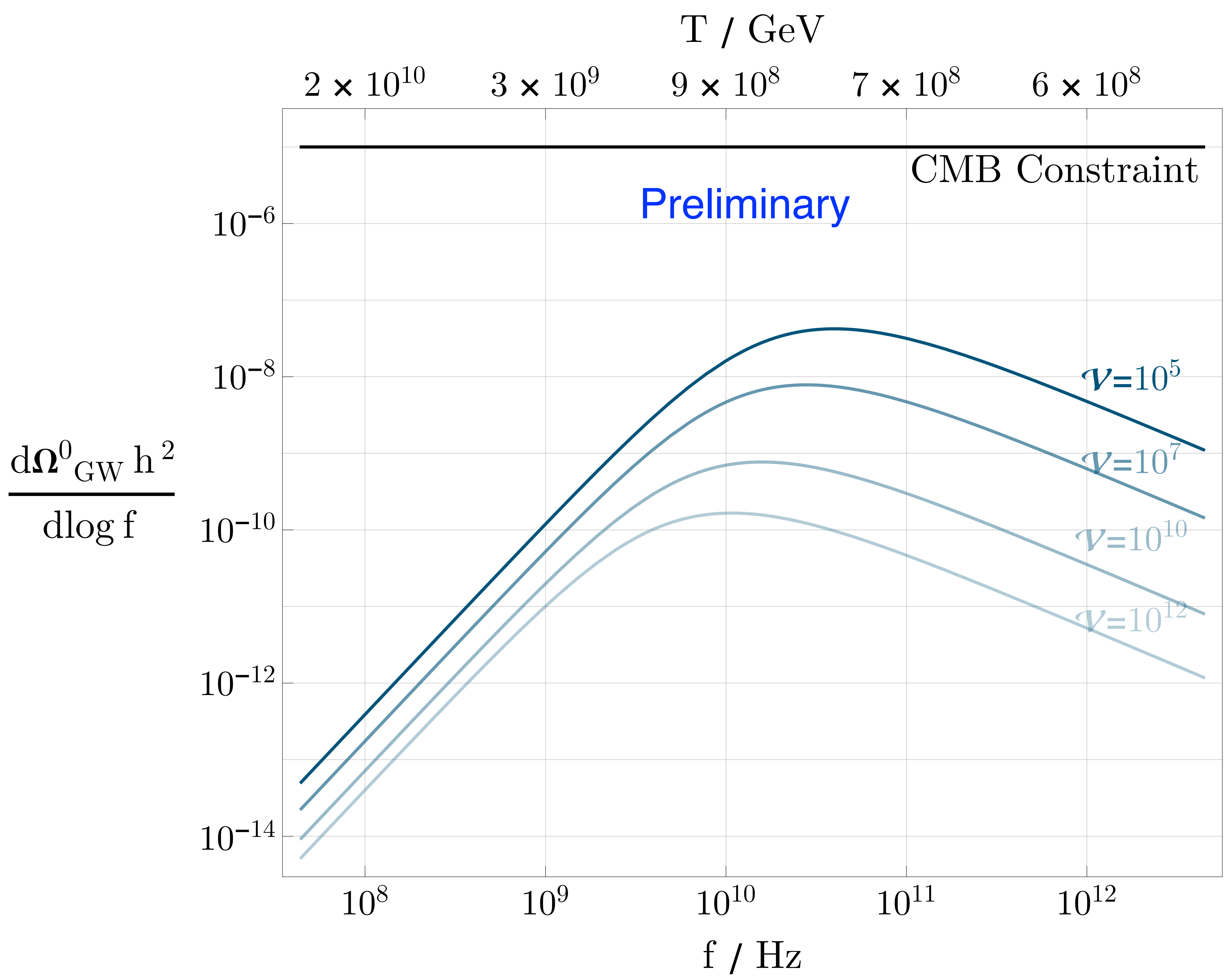


Figure 1. Gravitational power spectrum of a population of loops emitting during moduli domination given a volume of the extra dimensions $\mathcal{V} \sim 10^{5-12}$ in string units and a decay rate $\Gamma_\phi \sim (M_P/m_\phi)^{4/3} \cdot M_P^2/m_\phi^3$. The size of the loops is taken to be $\varepsilon = \sqrt{G\mu}$.

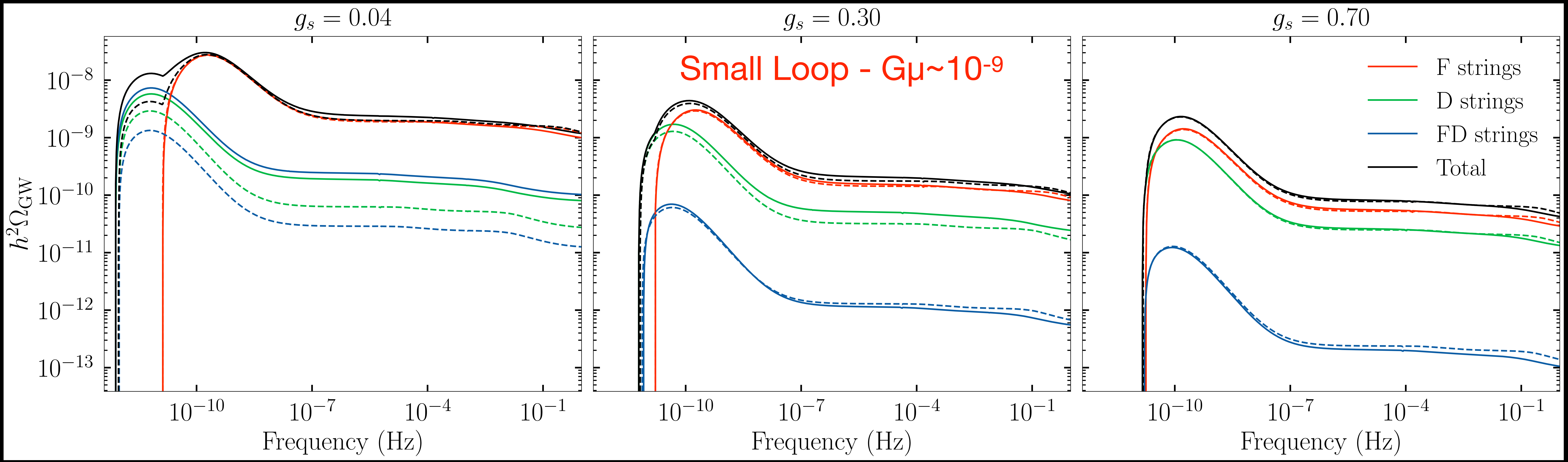
Just started analysing the possible signals.

Strings surviving inflation: - constant tension case

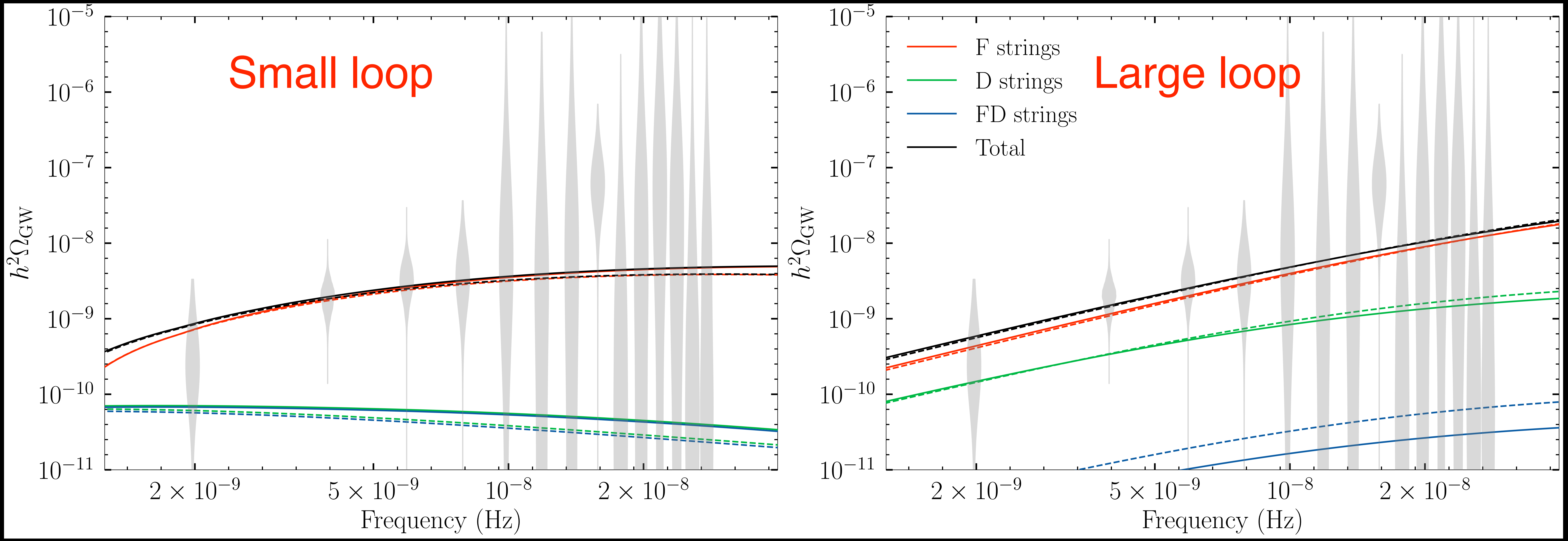
D-brane-antibrane inflation leads to formation of D1 branes in non-compact space [**Dvali & Tye; Burgess et al; Majumdar & Davis; Jones, Sarangi &Tye; Stoica & Tye**]

Find low string tensions - $G\mu < 10^{-9}$

In general for cosmic strings to be cosmologically interesting today we require that they are not too massive (from CMB constraints), are produced after inflation (or survive inflation) and are stable enough to survive until today. Depending on the model, if the CY space has sufficiently warped throat regions there can be fundamental F strings, D1 branes or combinations of (p,q) strings. [**Dvali and Vilenkin (2004); EJC,Myers and Polchinski (2004)**].

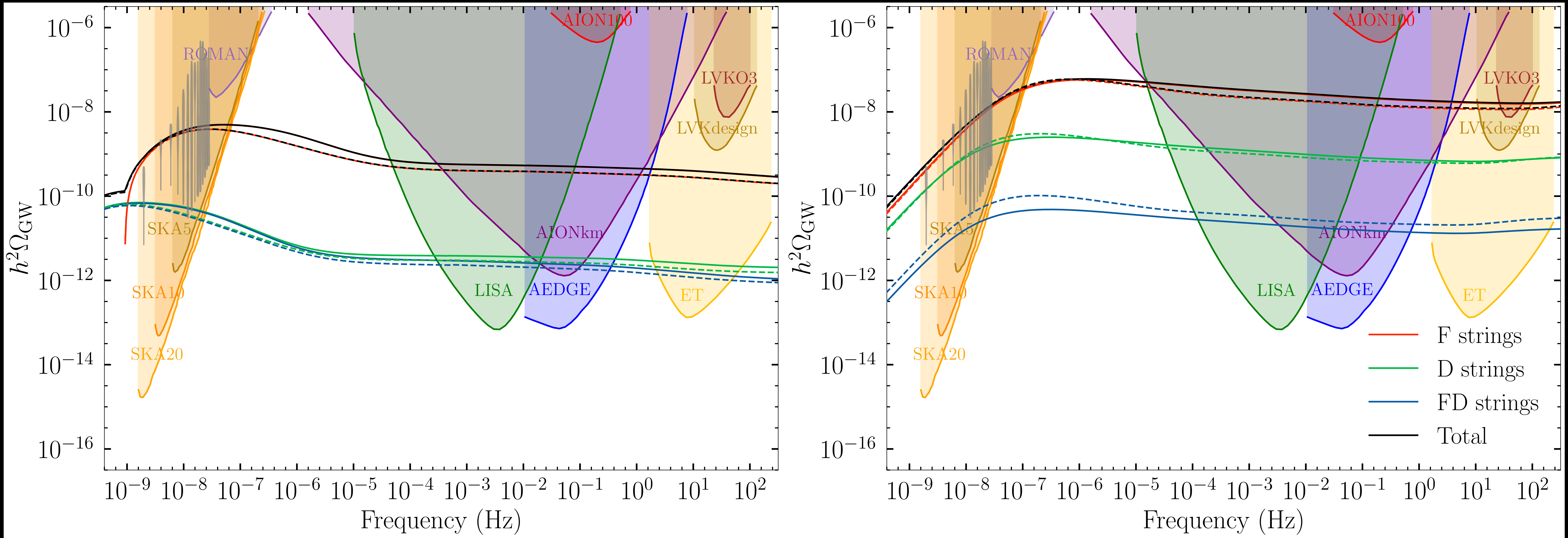


The cosmic superstring network evolves, reaches scaling, and as it does so emits gravitational waves which are redshifted into the nanohertz regime, ready to be discovered by NANOGrav if we are lucky ! [Avgoustidis et al (2025)]



[See earlier work by: Afzal eta al (NANOGrav) (2024), Figueroa et al (2024), Ellis et al (2023)]

Best fit spectra - left small loop case, right large loop case



Bounds on Fundamental string tension, string coupling and size of extra dimensions.

[Avgoustidis, EJC, Moss and Raidal - 2503.10361]

Model	$-2\ln\mathcal{L}_{\rm max}$	$\log_{10}(G\mu_1)$	g_s	w
Cuspy big loops	47.9	$-11.4^{+0.3}_{-0.2}$	< 0.69	< 0.90
		-11.8	0.22	0.01
Kinky big loops	47.8	$-11.5^{+0.3}_{-0.2}$	< 0.70	< 0.91
		-11.9	0.26	0.01
Cuspy small loops	53.6	$-9.7^{+0.7}_{-0.7}$	< 0.63	< 0.88
		-10.8	0.04	0.01
Kinky small loops	53.5	$-9.9^{+1.0}_{-0.5}$	< 0.61	< 0.83
		-10.9	0.05	0.01

Juhan Raidal

Conclusions

Single field Inflation has become the standard paradigm for primordial density fluctuations.

Tight constraints are emerging on the slow roll parameters — possible two scales emerging

Reheating the Universe is an area that has received relatively little attention.

Possible role of non-topological solitons like oscillons in models with asymptotically flat potentials - a new observational route

Where is the inflaton in string theory? Have looked at a particular example and seen the possible importance of the kinating period between the end of inflation and the onset of reheating - some 30 orders of magnitude in time, when lots could happen !

Have seen cosmic superstring loops could form which percolate, reach new scaling solutions during and after kination with 75% of the energy density stored in them .

Might lead to novel GW signatures from their evolution and subsequent decay during radiation and matter dom.

Have seen how cosmic superstrings can leave distinctive signatures at the nano Hertz scale - exciting possibility

Great fun thinking about these periods and asking whether they can really be probed in the data.

Thank you for listening