UNIVERSAL ACCELERATING COSMOLOGIES FROM 10D SUPERGRAVITY

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based on [2210.10813] with Dimitrios Tsimpis

Motivations

- Account for the observed **accelerated expansion** of our (homogeneous + isotropic) universe within **string theory**

- **Aim**: construct solutions of 10d SUGRA where the 4d spacetime is **FLRW**,

$$\mathrm{d}s_4^2 = -\mathrm{d}t^2 + a(t)^2 \left(\frac{1}{1-kr^2}\mathrm{d}r^2 + r^2 \mathrm{d}\Omega_2^2 \right) \quad \Rightarrow \quad R_{00} = -\ddot{a}$$

  with good phenomenological properties so to model **dark energy/inflation,** and good control on the SUGRA solution as a low-energy limit of string theory

- **Problems**: even the "simplest" instances = de Sitter seem to be ruled out
  Early 21st century: accelerating cosmologies from compactifications were thought to be as difficult as de Sitter

Strong Energy Condition and a no-go theorem

- **Strong Energy Condition:** $R_{00} = T_{00} + g^{ij}T_{ij} \geq 0$
  $\Rightarrow$ needs to be violated for accelerated expansion

- Can be done with *e.g.* a **positive scalar potential**,

$$R_{00} = 2\left(\dot{\phi}^2 - V(\phi)\right) \Rightarrow \text{ acceleration whenever } E_p > 2E_k$$

$\Rightarrow$ *All we need is a compactification for which the 4d EFT has a positive scalar potential?*

- **Problem**: (1) all 10d/11d pure supergravities have their bosonic EMT satisfiying the SEC, (2) **the SEC is hereditary** [Gibbons '84, Maldacena, Nuñez '00]

Strong Energy Condition and a no-go theorem

- Cosmic acceleration is forbidden in models descending from 10d/11d SUGRAs, with **time-indep.** compactifications on **non-singular** manifolds **without boundary**

$$\mathrm{d}s^2_{10} = H(y)^2 \mathrm{d}s^2_4 + \mathrm{d}s^2_6 \quad \Rightarrow \quad R^{(10)}_{00} = R^{(4)}_{00} - \frac{1}{4} H^{-2} \nabla^2_{\mathcal{M}} H^4$$

$$\left(\int_{\mathcal{M}} H^2\right) R^{(4)}_{00} = \int_{\mathcal{M}} H^2 \, R^{(10)}_{00} \quad \Rightarrow \quad \boxed{R^{(10)}_{00} \geq 0 \Rightarrow R^{(4)}_{00} \geq 0}$$

- **Evade the no-go**: (1) SUGRA is not the relevant starting point, (2) $\mathcal{M}$ is not compact, (3) Include brane/orientifold singularities, **(4) $\mathcal{M}$ is time-dependent**

- (4) $\Rightarrow$ **Transient acceleration** is in fact generic in flux compactifications, [Townsend, Wohlfarth '03] although de Sitter space is still ruled out
  Late-time acceleration is ***not*** ruled out [Russo, Townsend '03]

- Still have to engineer a **positive scalar potential**

Positive scalar potential, recipe

- Fluxes: $$V_{\text{fluxes}} \sim \sum_p \frac{1}{2p!} \int \sqrt{g_6} e^{a_p \phi} |F_p|^2$$
- Internal curvature: $$V_{\text{curvature}} \sim -\int \sqrt{g_6} R^{(6)}$$
- Brane/orientifold sources: $$V_{\text{source}} \sim -\text{tension} \times \int \sqrt{g_n}$$

$$\boxed{V_{\text{scalar}} = V_{\text{fluxes}} + V_{\text{curvature}} + V_{\text{source}}}$$

The set-up

- **10d massive Type IIA SUGRA** with **fluxes,**

$$S=\frac{1}{4\kappa^2}\int d^{10}x\sqrt{g}\Big(-2R^{(10)}+|\partial\phi|^2+\frac{1}{2!}e^{3\phi/2}|F_2|^2+\frac{1}{3!}e^{-\phi}|H|^2+\frac{1}{4!}e^{\phi/2}|F_4|^2+m^2e^{5\phi/2}\Big)+\text{Chern-Simons}$$

- **Cosmological ansatz** = fields only depend on time
- Ansatz which ''solves the fluxes'' [Terrisse, Tsimpis '19]
- Ansatz for the 10d metric, two time-dep. **warp factors,**

$$\mathrm{d}s^2_{10}=e^{2A(t)}\left(e^{2B(t)}\mathrm{d}s^2_{\mathrm{FLRW}}+\underbrace{g_{mn}\mathrm{d}y^m\mathrm{d}y^n}_{\text{Calabi-Yau, Einstein, Einstein-Kähler, ...}}\right)$$

- In 4d Einstein frame,

$$\mathrm{d}s^2_{4E}=-\mathrm{d}t^2+a(t)^2\mathrm{d}\Omega_k^2\,,\qquad a(t)=e^{4A(t)+B(t)}$$

Equations of motion

$$\mathrm{d}_\tau^2 A = -\tfrac{1}{48}\left(\partial_A U - 4\partial_B U\right)$$
$$\mathrm{d}_\tau^2 B = \tfrac{1}{12}\left(\partial_A U - 3\partial_B U\right)$$
$$\mathrm{d}_\tau^2 \phi = -\partial_\phi U$$
$$U(A, B, \phi) = 72(\mathrm{d}_\tau A)^2 + 6(\mathrm{d}_\tau B)^2 + 48\mathrm{d}_\tau A \mathrm{d}_\tau B - \tfrac{1}{2}(\mathrm{d}_\tau \phi)^2$$

- The ''potential'' *U* encodes all the info about the **fluxes** and internal **geometry,**

$$U(A, B, \phi) = \sum_i c_i e^{\alpha_i A + \beta_i B + \gamma_i \phi}$$

- Changing flux configuration/internal geometry ⇔ tuning constants $c_i, \alpha_i, \beta_i, \gamma_i$

- Equations cannot be solved analytically except for a few particular cases

Consistent truncations

Equations can be integrated in:

- In all cases, a **1d action**,

$$S_{1d} = \int \mathrm{d}\tau \left\{ \frac{1}{\mathcal{N}} \Big(-72(\mathrm{d}_\tau A)^2 - 6(\mathrm{d}_\tau B)^2 - 48\mathrm{d}_\tau A \mathrm{d}_\tau B + \tfrac{1}{2}(\mathrm{d}_\tau \phi)^2 \Big) - \mathcal{N} U(A, B, \phi) \right\}$$

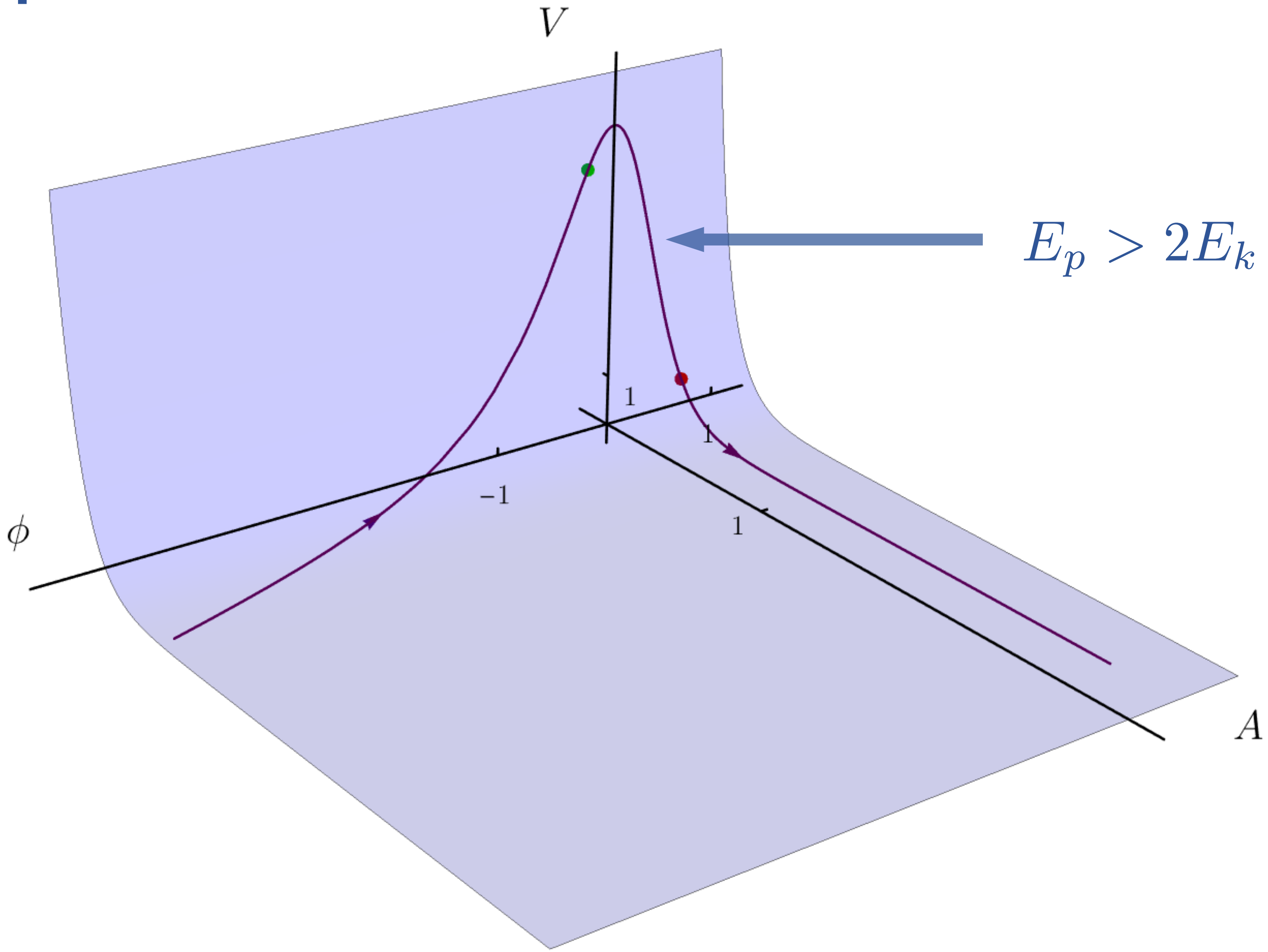
- In most cases, a **4d action**,

$$S_{4d} = \int \mathrm{d}^4 x \sqrt{g} \Big(R^{(4)} - \frac{1}{2} g^{\mu\nu} \partial_\mu A \partial_\nu A - \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(A, \phi) \Big)$$

- **Two-scalar cosmology** with **multi-exponential potential**

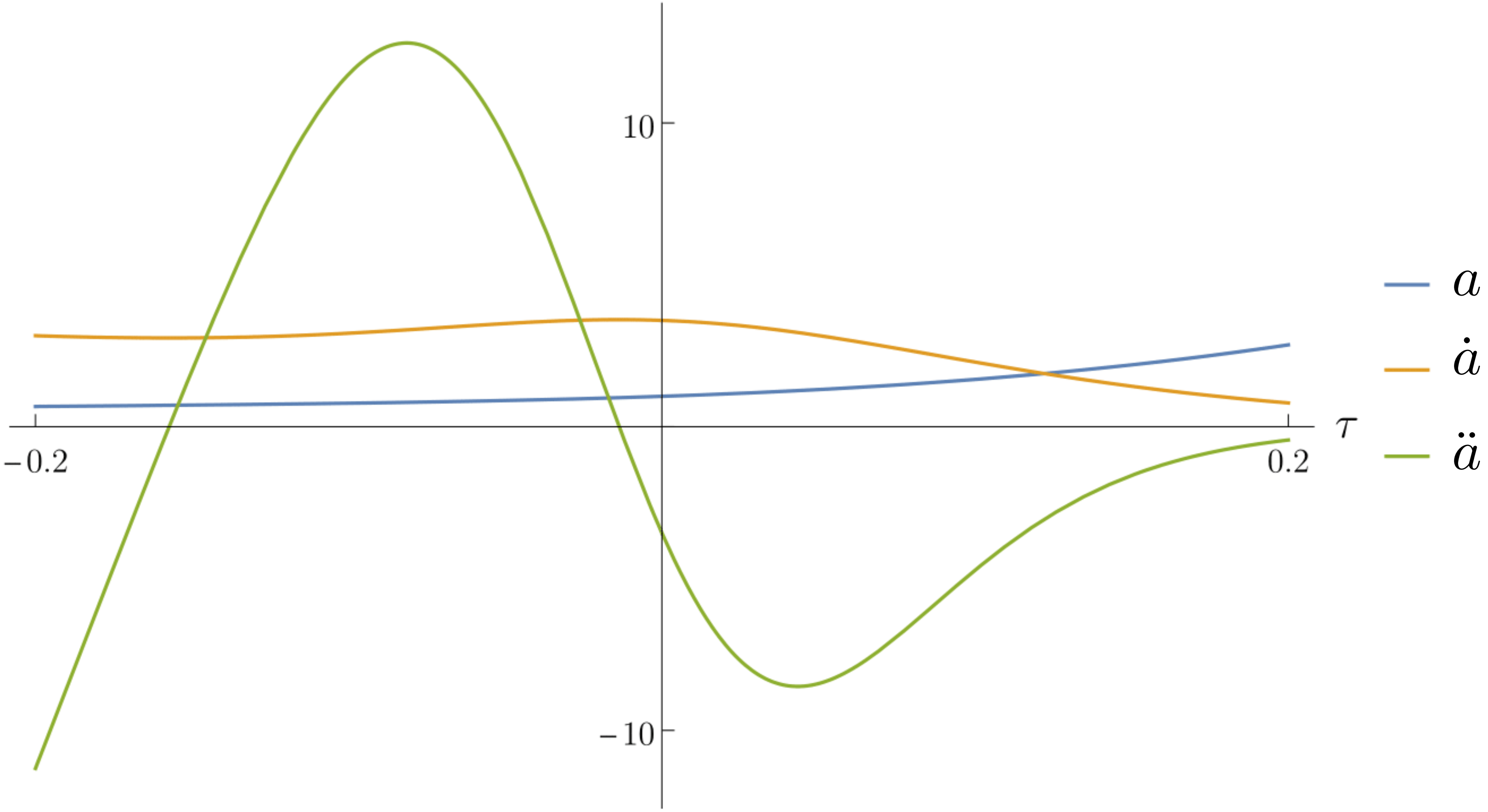
  The B-field dependency is hidden in the scale factor, in the metric

Field space picture



$E_p > 2E_k$

Transient acceleration



Dynamical system analysis

For a two-exponential potential, $U(A,B,\phi) = c_1 e^{\alpha_1 A + \beta_1 B + \gamma_1 \phi} + c_2 e^{\alpha_2 A + \beta_2 B + \gamma_2 \phi}$

E.O.M.'s can be recast into an **autonomous dynamical system,**

$$x' = \frac{1}{4}\Big([\alpha_2 + 2\beta_2(-2+x)](-1+x^2+y^2+z^2) + [-\alpha_1 - 2\beta_1(-2+x)]z^2\Big)$$

$$y' = \frac{1}{2}\Big((2\sqrt{3}\gamma_2 + \beta_2 y)(-1+x^2+y^2+z^2) - (2\sqrt{3}\gamma_1 + \beta_1 y)z^2\Big)$$

$$z' = \frac{1}{4}z\Big(\alpha_1 x + 4\sqrt{3}\gamma_1 y - 2\beta_1(-1+2x+z^2) + 2\beta_2(-1+x^2+y^2+z^2)\Big)$$

with the constraint, $c_1(1-x^2-y^2-z^2) = c_2\, z^2 e^{A(\alpha_2-\alpha_1)+B(\beta_2-\beta_1)+\phi(\gamma_2-\gamma_1)}$

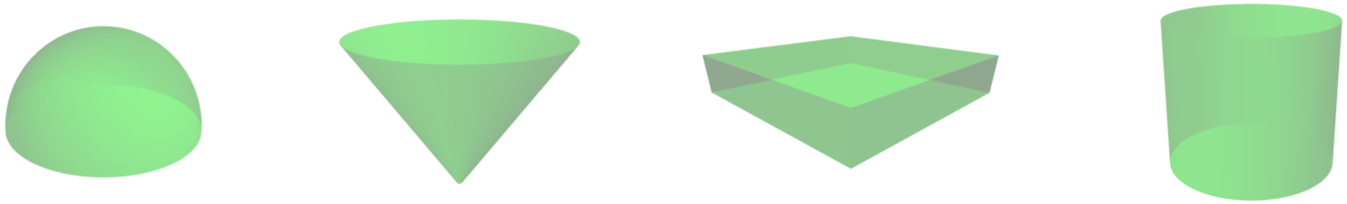
$c_1, c_2 > 0 \Rightarrow$ **the phase space is the unit-ball**

Dynamical system analysis, interpretation

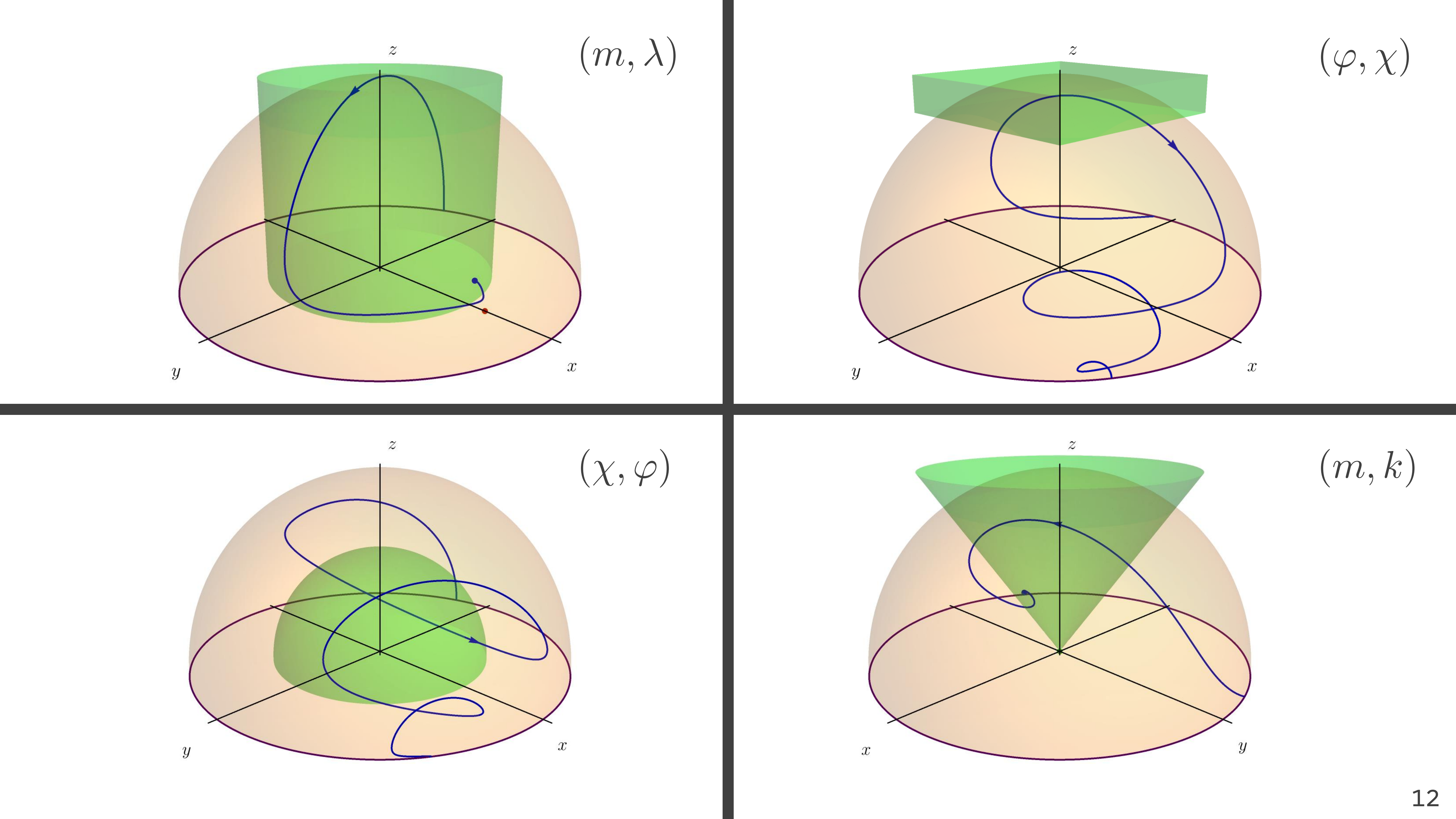
- Condition for **expansion,** $z > 0 \Leftrightarrow$ North hemisphere
- Condition for **acceleration,**

$$\ddot{a} > 0 \quad \Longleftrightarrow \quad (\beta_1 - \beta_2)z^2 - \beta_2(x^2 + y^2) + \beta_2 - 4 > 0$$

defines a geometrical **acceleration region** in phase space,



- **Number of efolds,** $N = \int_{\text{in}}^{\text{out}} \mathrm{d}\omega = \omega_{\text{out}} - \omega_{\text{in}}$
- **Fixed points = power law** expansions, $a(t) = t^p \,, \quad p \leq 1$
- Generic trajectories interpolate between fixed points


(m, λ)
z
y
x
(φ, χ)
z
y
x
(χ, φ)
z
y
x
(m, k)
z
x
y

Results

- Continuum of **transient accelerations** with **parametric control on the number of e-folds**, by tuning initial conditions

- **Semi-eternal inflation** whenever there is a fixed point lying on the boundary of the acceleration region

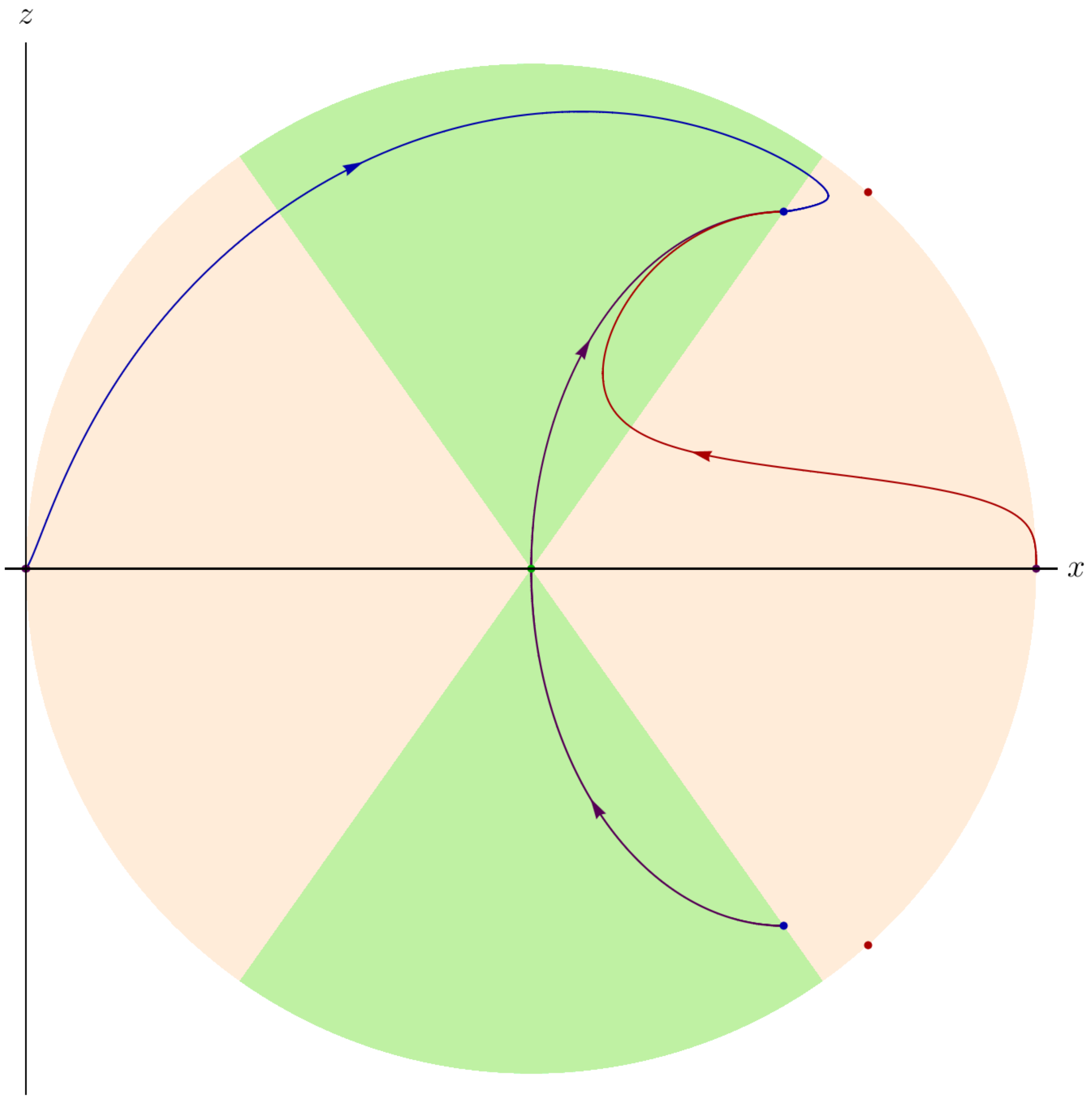
- **Eternal inflation** (unique trajectory) whenever there is also a fixed point at the origin of phase space: becomes **de Sitter** around the origin, can be geodesically completed in the past by gluing its mirror in the southern hemisphere

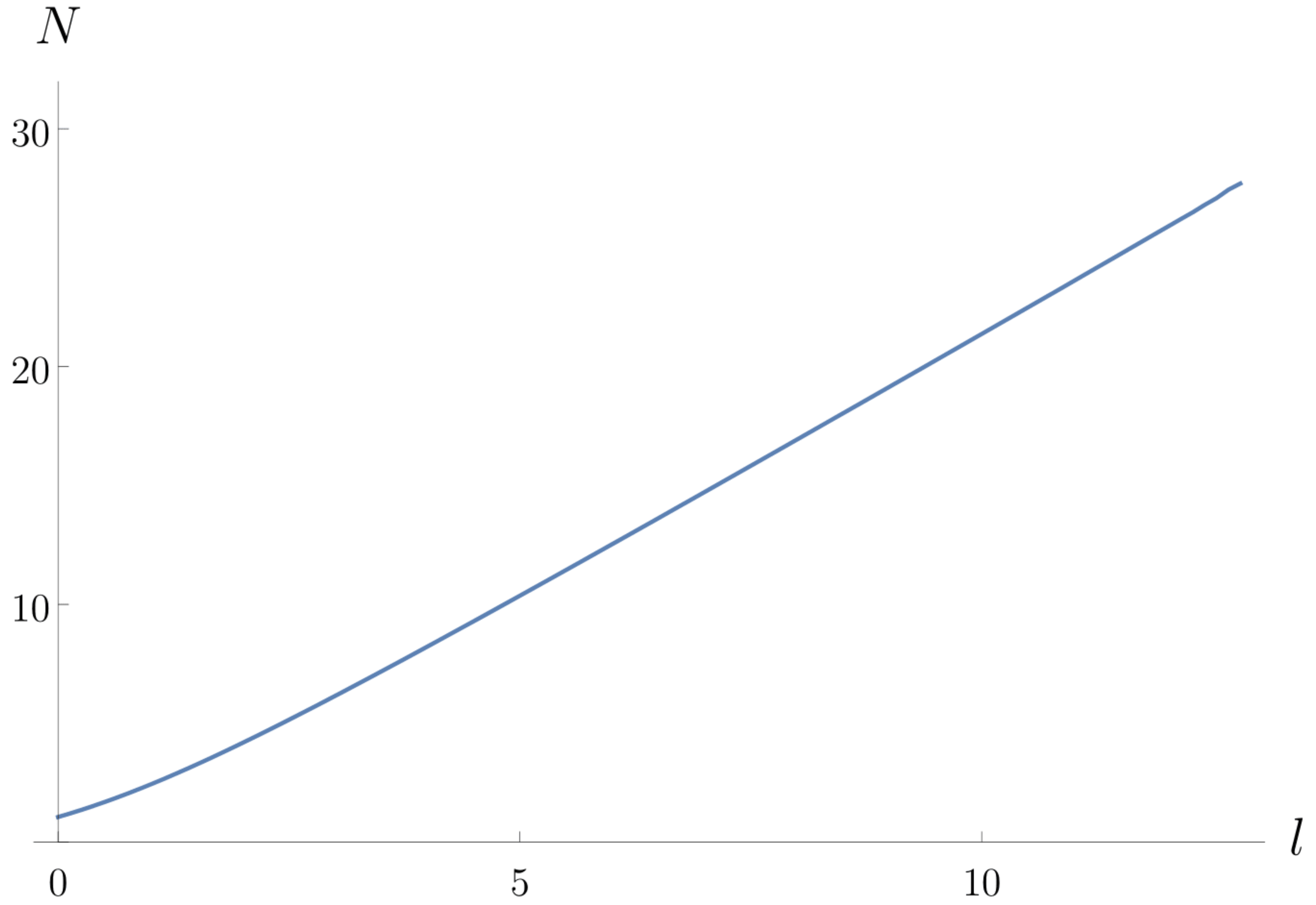
- Alternating phases of acceleration/deccelaration with **spiraling trajectories** around a fixed point on the boundary

$\Rightarrow$ Can be used for ‘‘rollercoaster’’ models of inflation [D’Amico, Kaloper ‘20]

(λ, k)

$y = 0$




N
30
20
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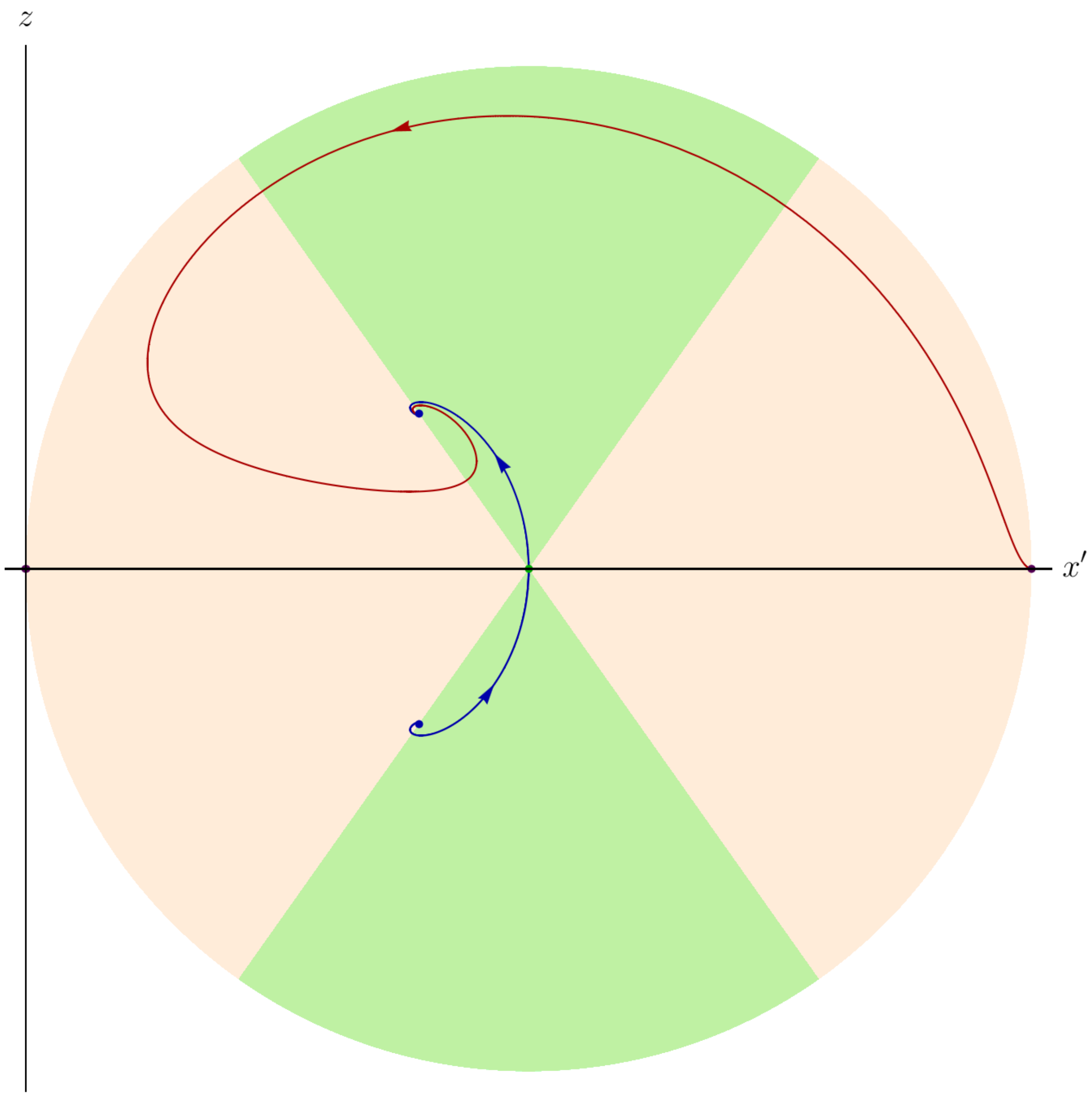
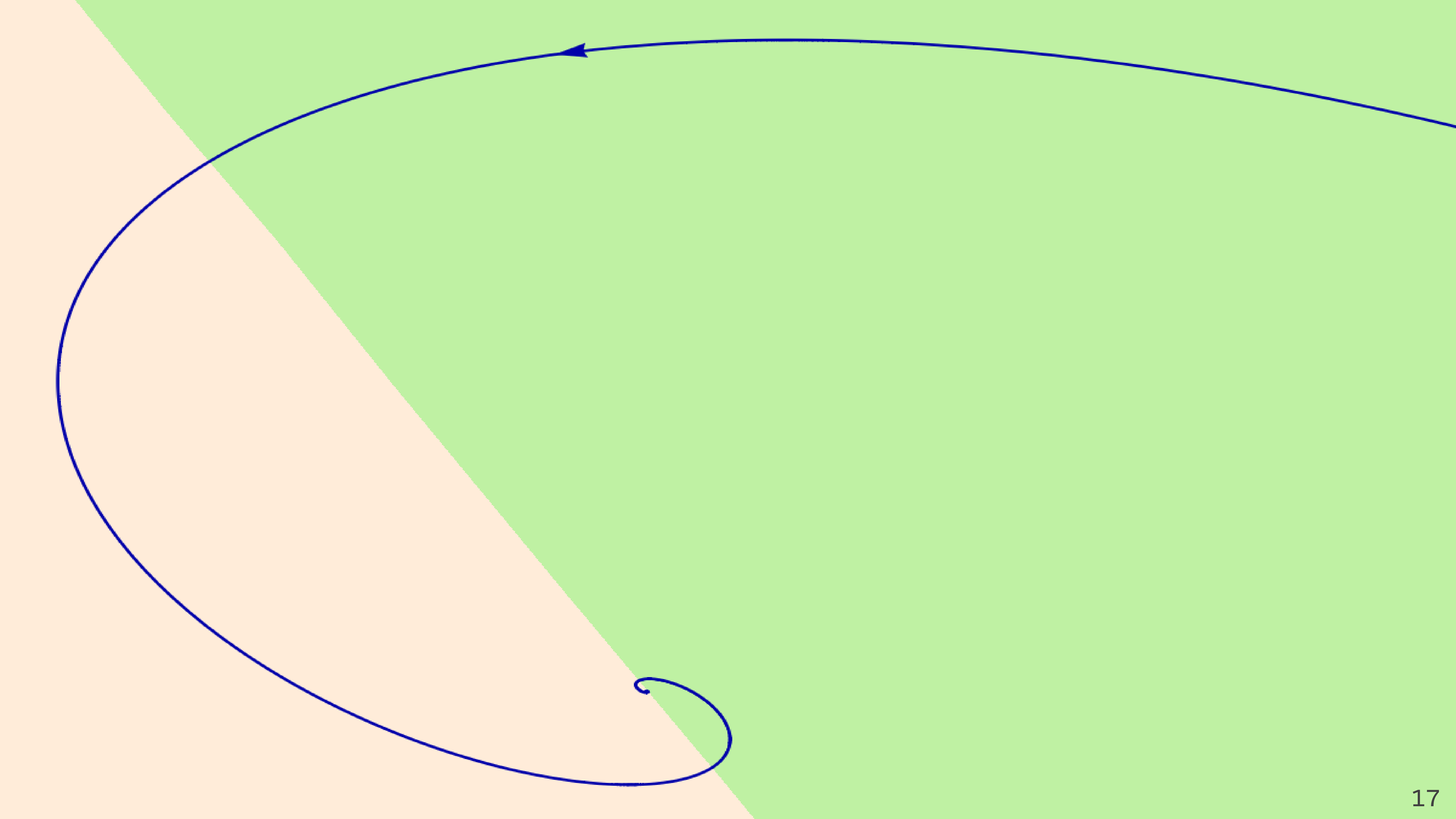
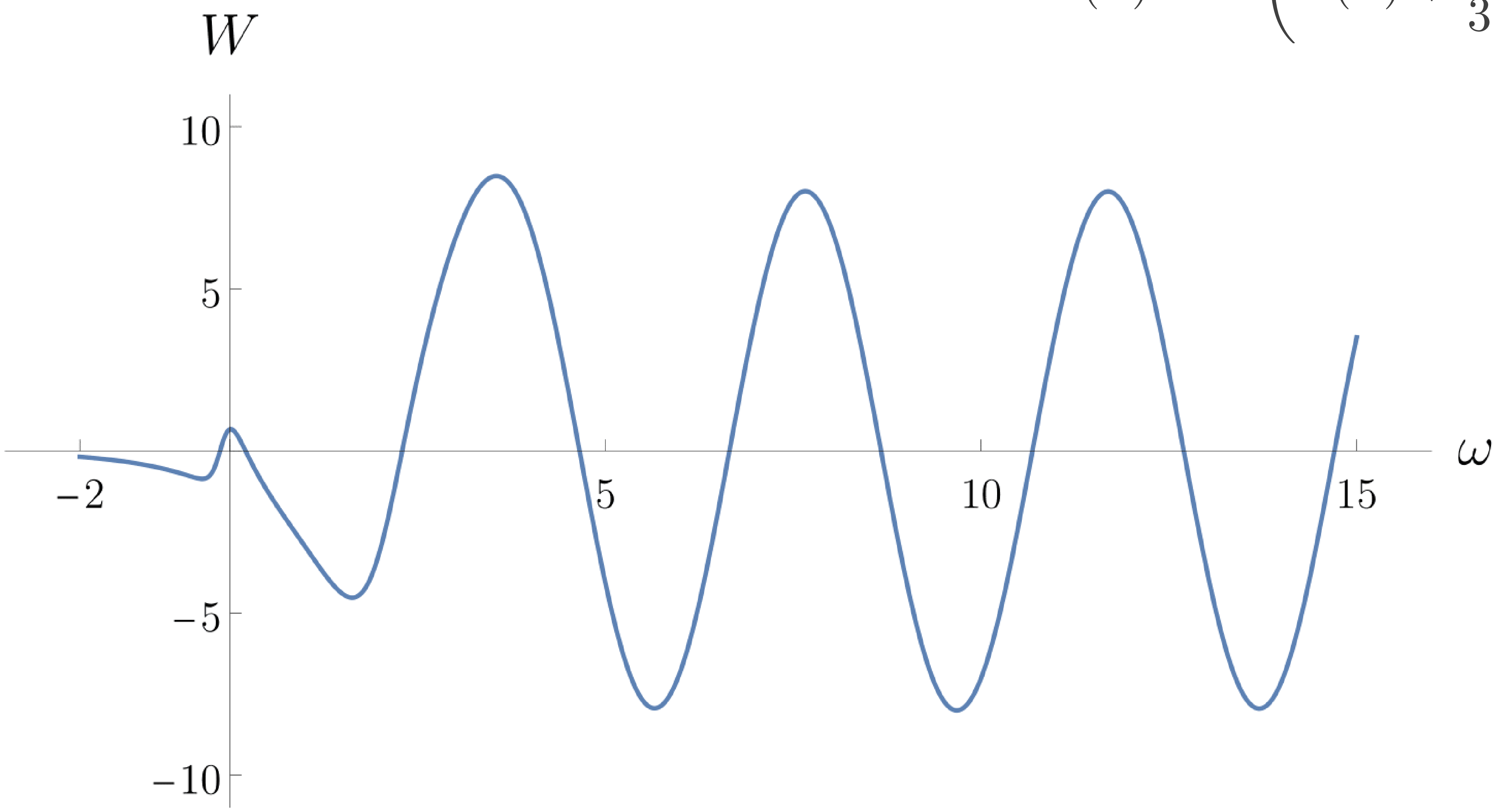
(m, k)

$y = 0$





$$W(\omega) = -\left(w(\omega) + \frac{1}{3}\right) e^{\omega}$$



Conclusion

- **Transient acceleration** is generic in flux compactifications
- Cosmologies featuring **(semi-) eternal acceleration**, or a **parametric control** on the number of e-folds also seem **generic**!
  They have $k = -1$ and asymptotically vanishing acceleration
- Existence of **“rollercoaster” cosmologies** with infinite number of cycles alternating between accelerated and deccelerated expansion

Outlook

- Extend the dynamical system analysis **beyond 2 fluxes**
- Inclusion of **orientifolds**, dynamical system analysis of **dS fixed points**
- Study the **phenomenological properties** of these models beyond the mere number of e-folds. Can one hope for **realistic cosmologies**?

THANK YOU!