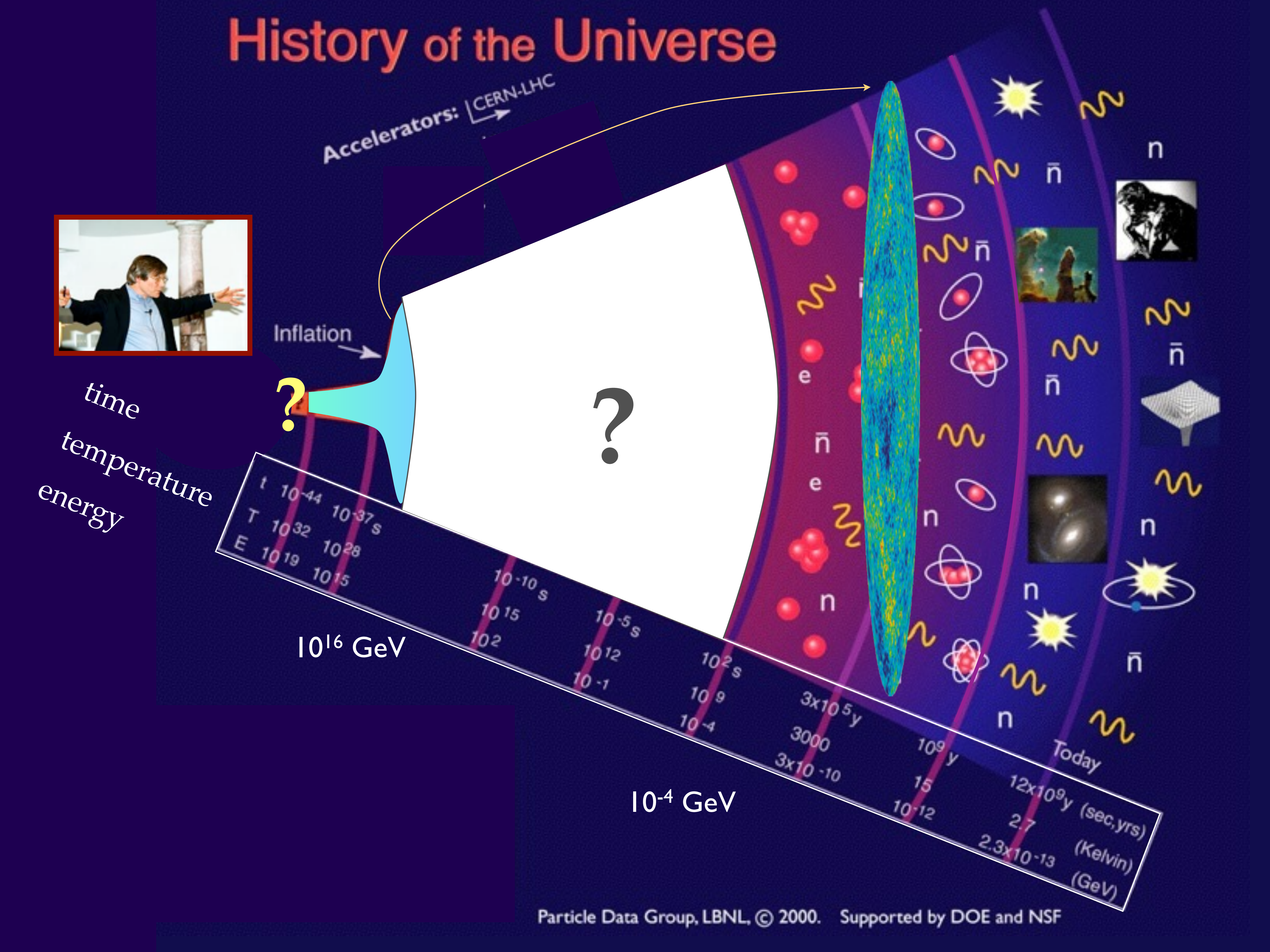
Inflaton Fragmentation
&
The Matter-Antimatter Asymmetry

Mustafa Amin
with
Kaloian Lozanov

arXiv:1408.1811


History of the Universe
Accelerators: CERN-LHC
Inflation
?
?
time
temperature
energy
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
10¹⁶ GeV
10⁻⁴ GeV
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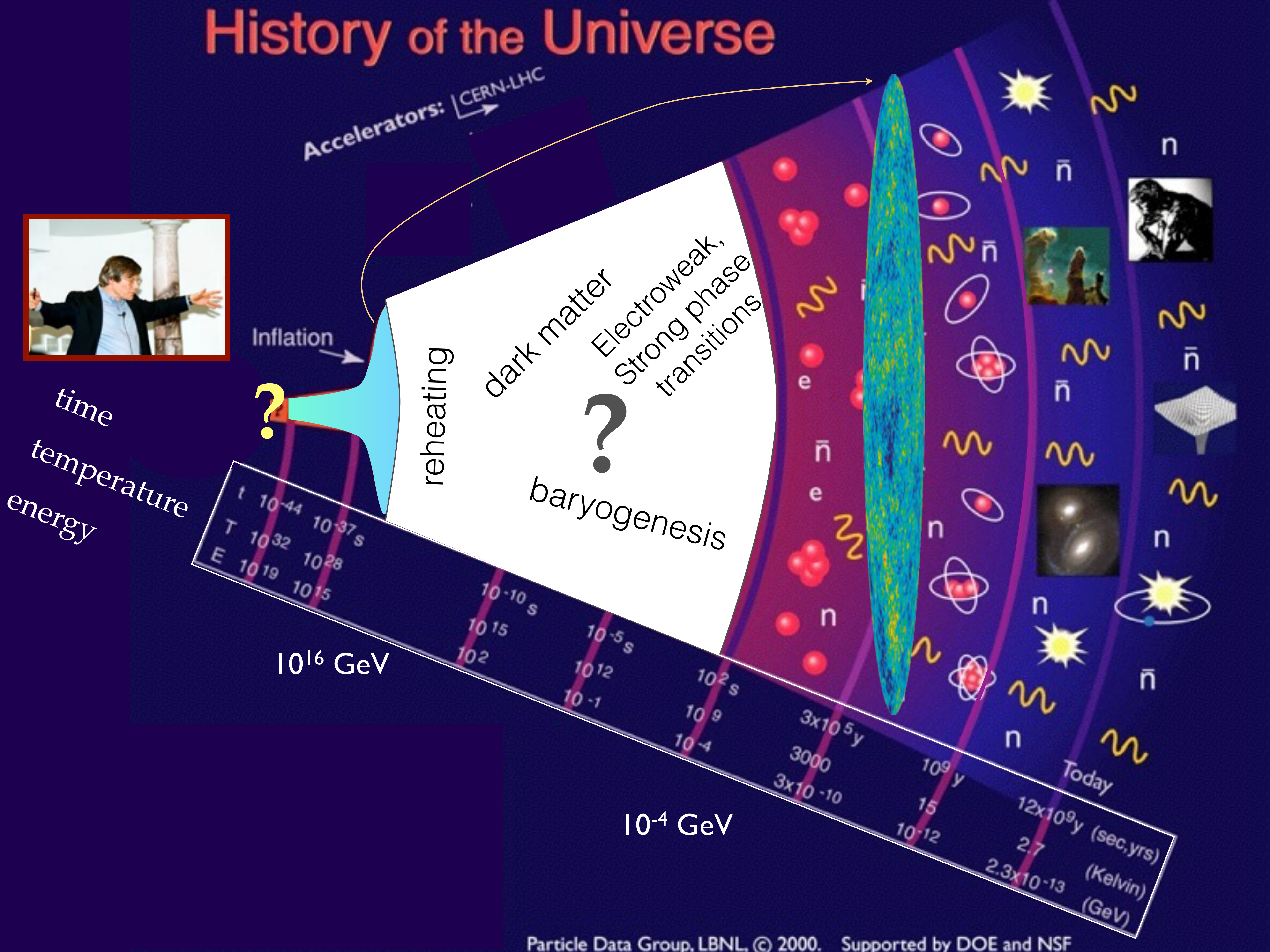
History of the Universe
Accelerators:
CERN-LHC
Inflation
time
temperature
energy
?
reheating
dark matter
Electroweak,
Strong phase
transitions
?
baryogenesis
e
n
n̄
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
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10-5 s
10 12
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10 2 s
10 9
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3x10 5 y
3000
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Today
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2.7 (Kelvin)
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10^16 GeV
10^-4 GeV
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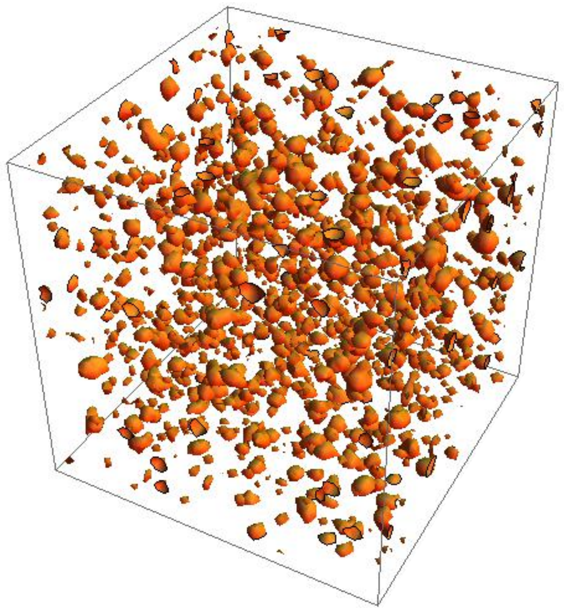
main idea

inflation $\longrightarrow$ end of Inflation $\longrightarrow$ matter-antimatter asymmetry

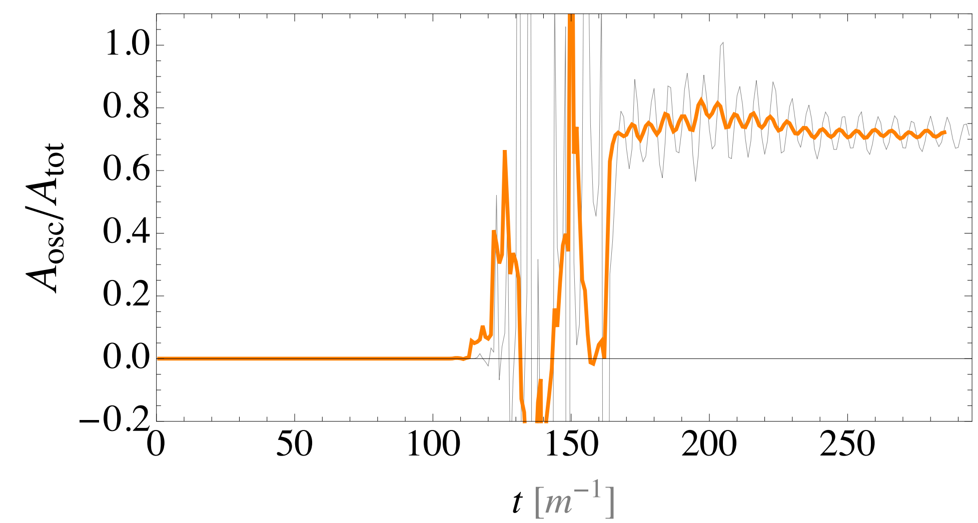
$\eta \approx 6 \times 10^{-10}$

main idea

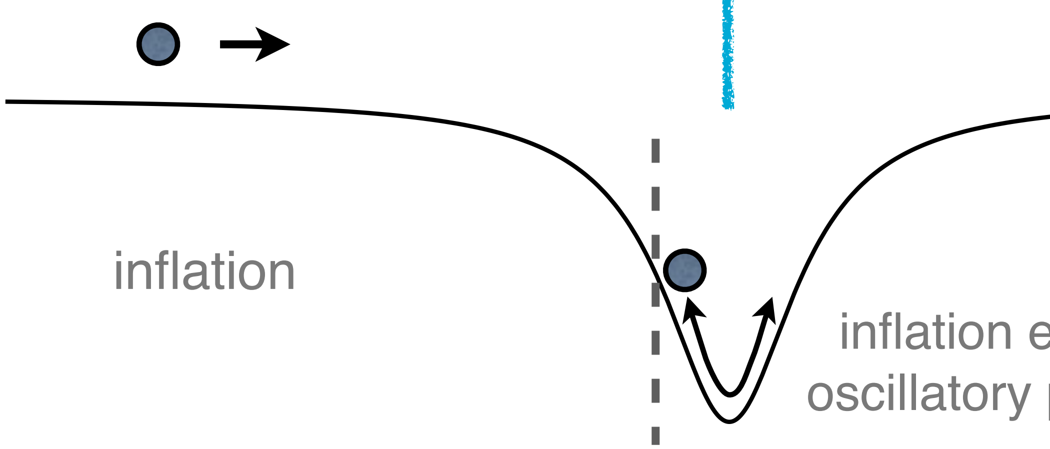


inflaton/anti-inflaton asymmetry locked in solitons (oscillons!)

ratio of asymmetry in solitons/ total asymmetry



inflaton fragmentation and generation of A_ϕ: inflaton/anti-inflaton asymmetry



inflation

inflation ends: oscillatory phase

complex inflaton + ~~U~~(1)

decay into baryons/anti-baryons

$$\eta \sim \mathcal{O}[10^2] \times A_\phi \left(\frac{T_{\rm reh}}{m_\phi}\right)$$

observed asymmetry (baryon-to-photon ratio)

synopsis

- the inflaton model & asymmetry
- dynamics:
  - homogeneous
  - linearized dynamics - instabilities
  - nonlinear dynamics - fragmentations & solitons
- asymmetry generation
  - dependence on params.
  - inflaton asymmetry — baryon asymmetry
- observational consequences

the model details

A variation of the Affleck-Dine Mechanism (1985)

Hertzberg & Karouby (2013)

$$S = \int d^4x \sqrt{-g}\left[\frac{m_{\rm Pl}^2}{2}R - g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi^* - V(\phi,\phi^*)\right]$$

$$V(\phi,\phi^*) = V_{\rm s}(|\phi|) + V_{\rm br}(\phi,\phi^*)$$

respects U(1) symmetry

responsible for inflation

$$V_{\rm s}(|\phi|) = m^2M^2\left[\sqrt{1+2\frac{|\phi|^2}{M^2}} - 1\right]$$

observationally consistent choice

breaks U(1) symmetry

responsible for generating
inflation/antiinflaton asymmetry
small, symmetry breaking …

$$V_{\rm br}(\phi,\phi^*) = \frac{c_3}{3}\frac{m^2}{M}\frac{\left(\phi^3+\phi^{*3}\right)}{f(|\phi|)}$$

our choice: subdominant during and after inflation

inflaton asymmetry — baryon asymmetry

$$\Delta N_\phi = N_\phi - N_{\bar{\phi}} = i\int d^3x a^3 \left(\phi^* \dot{\phi} - \dot{\phi}^* \phi\right)$$

inflaton number (**not conserved!**)
- generated at end of inflation

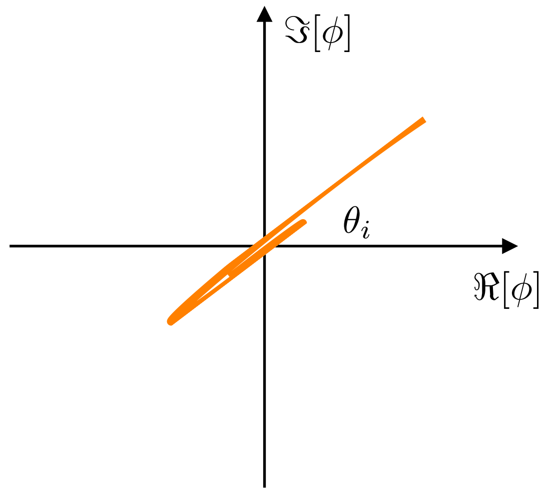
$$\phi \to b$$

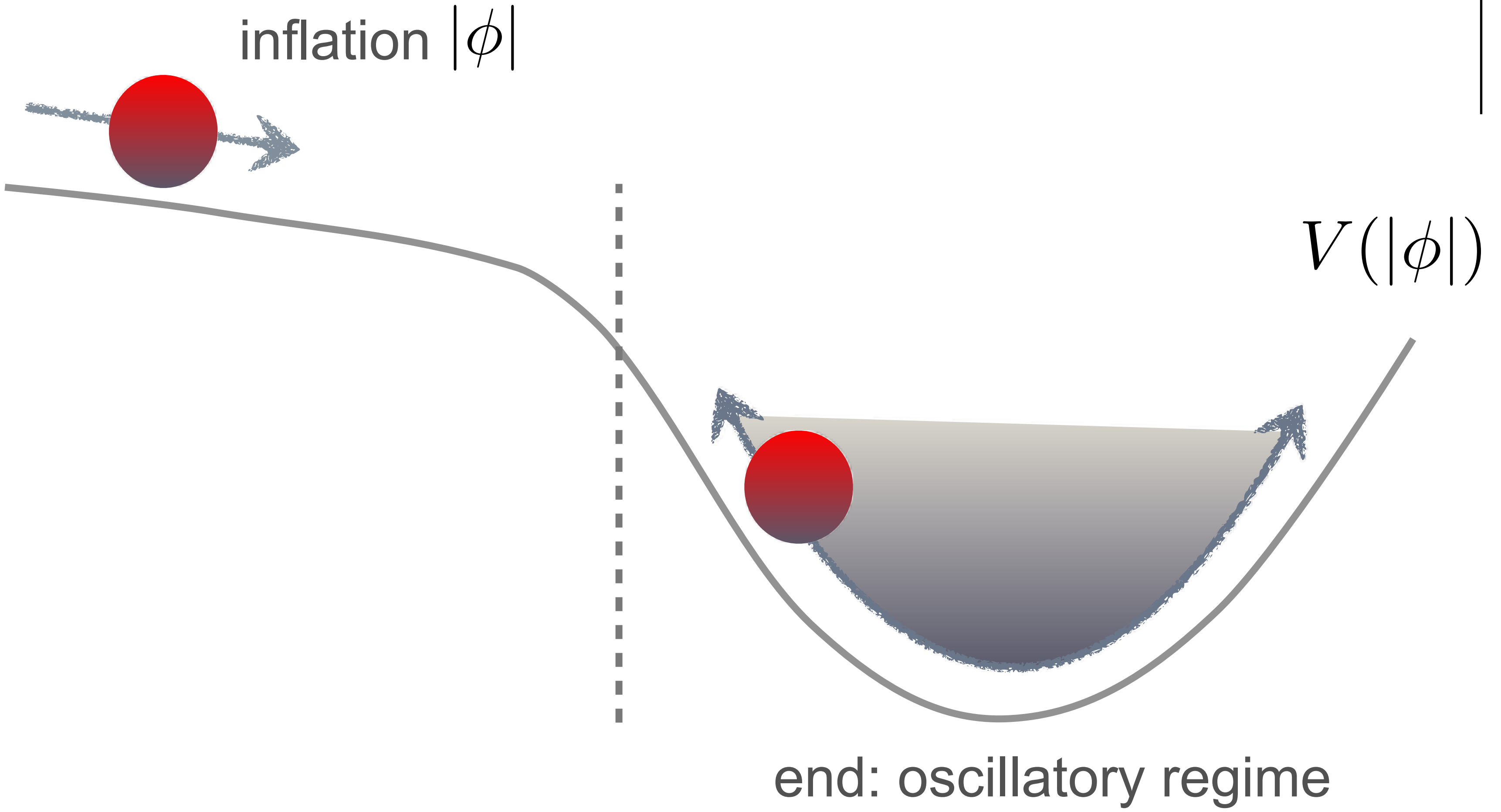
decay

$$N_b - N_{\bar{b}} = b_\phi (N_\phi - N_{\bar{\phi}})$$

baryon number

inflaton dynamics





Linearized Perturbations: Initial Conditions

$$\delta\ddot{\varphi}^I_{\mathbf{k}} + 3H\delta\dot{\varphi}^I_{\mathbf{k}} + \left[\delta^I_J \frac{k^2}{a^2} + \partial^I \partial_J \mathcal{V}\right] \delta\varphi^J_{\mathbf{k}}$$
$$= -2\Psi_{\mathbf{k}} \partial^I \mathcal{V} + 4\dot{\Psi}_{\mathbf{k}} \dot{\varphi}^I .$$

includes metric perturbations

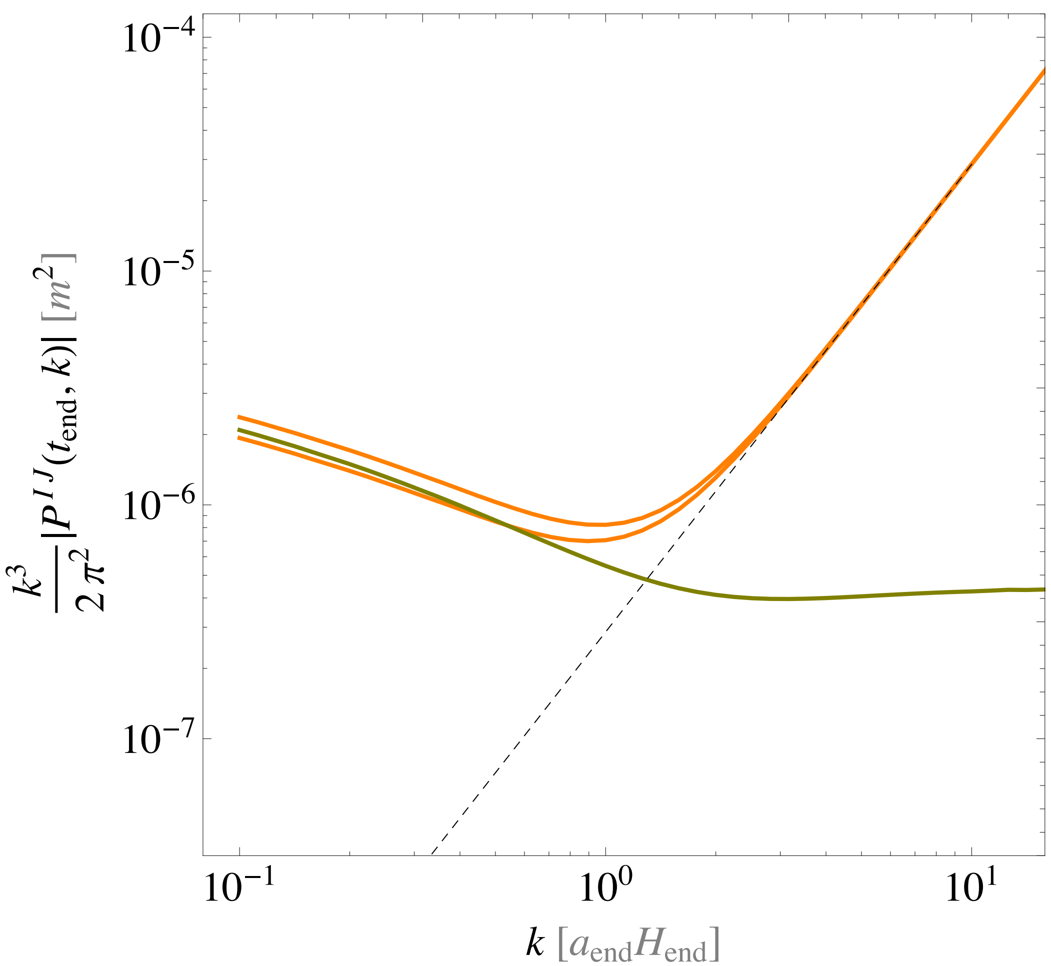
$$\dot{\Psi}_{\mathbf{k}} + H\Psi_{\mathbf{k}} = \frac{1}{2m_{\rm Pl}^2} \delta_{IJ} \dot{\varphi}^I \delta\varphi^J_{\mathbf{k}},$$
$$\left(\dot{H} + \frac{k^2}{a^2}\right)\Psi_{\mathbf{k}} = \frac{1}{2m_{\rm Pl}^2} \delta_{IJ} \left[-\dot{\varphi}^I \delta\dot{\varphi}^J_{\mathbf{k}} + \delta\varphi^J_{\mathbf{k}} \ddot{\varphi}^I\right]$$

$$\delta\varphi^J_{\mathbf{k}}(t) = \sum_{n=1}^{N} a_{\mathbf{k}n} u^J_n(t,k) + a^*_{-\mathbf{k}n} u^{J*}_n(t,k).$$

$$[\hat{a}_{\mathbf{q}n}, \hat{a}_{\mathbf{k}m}] = 0,$$
$$\left[\hat{a}_{\mathbf{q}n}, \hat{a}^\dagger_{\mathbf{k}m}\right] = \delta(\mathbf{q} - \mathbf{k})\delta_{nm}.$$

$$\langle 0|\delta\hat{\varphi}^I_{\mathbf{q}}(t)\delta\hat{\varphi}^{J\dagger}_{\mathbf{k}}(t)|0\rangle = \delta(\mathbf{q} - \mathbf{k}) P^{IJ}(t,k)$$

$$P^{IJ}(t,k) = \sum_{n=1}^{N} u^I_n(t,k) u^{J*}_n(t,k).$$

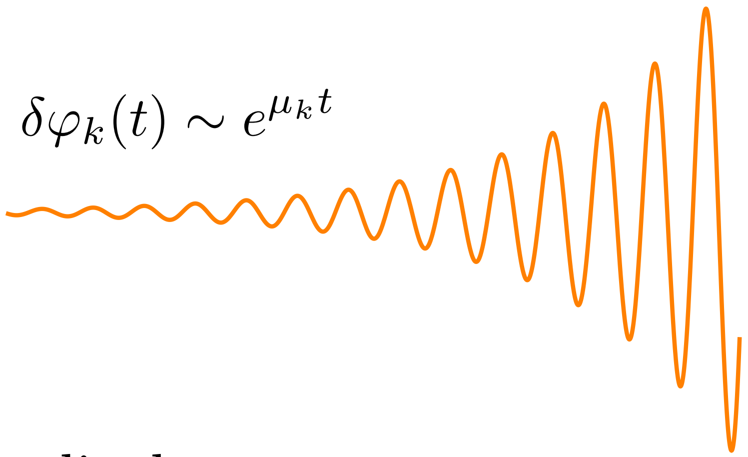


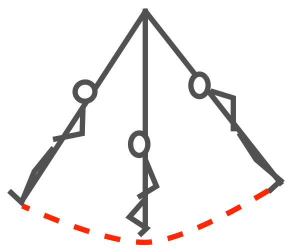
Full multified evolution with metric fluctuations on super and subhorizon scales.

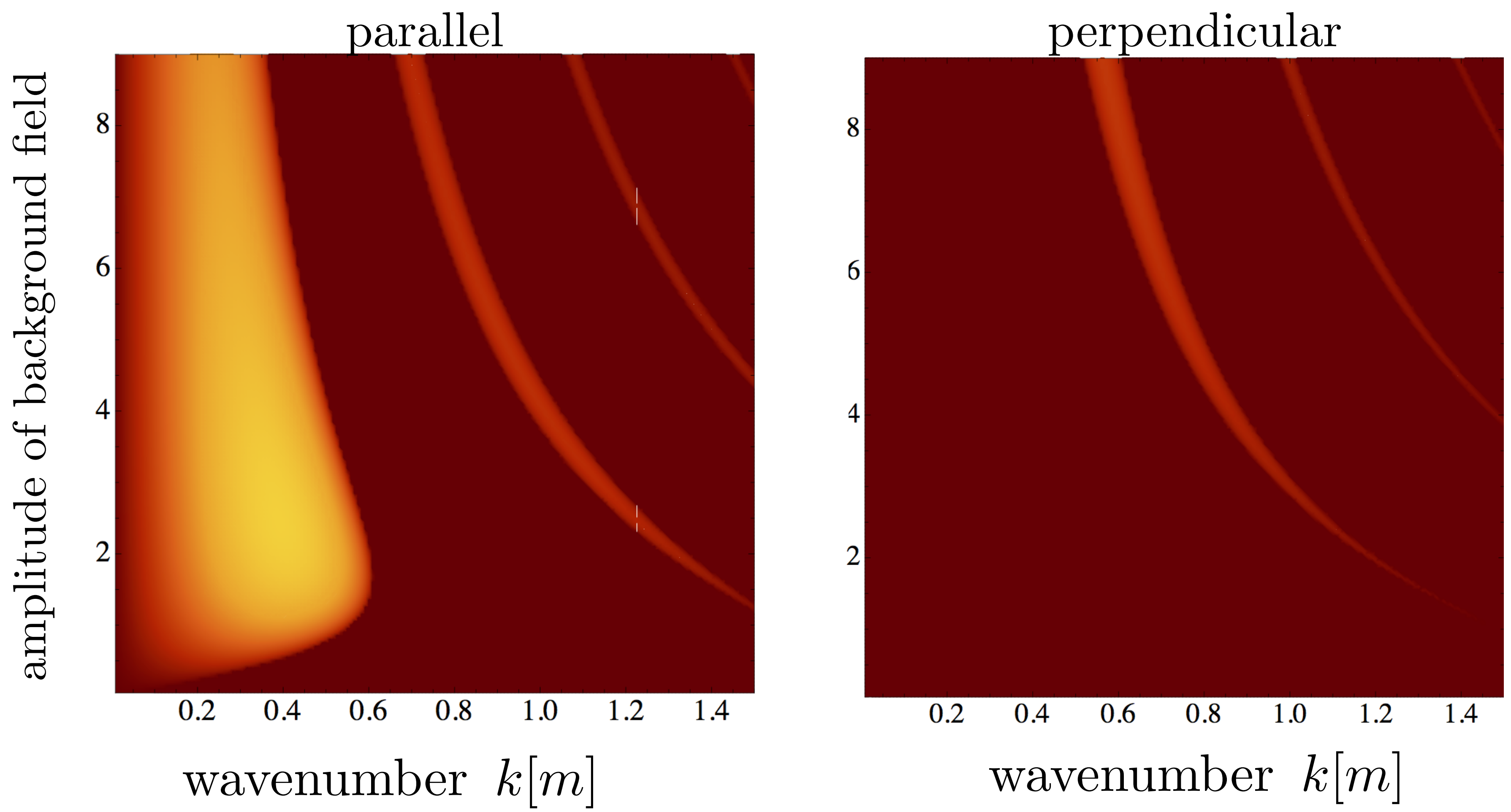
Linearized Perturbations: instabilities

$$\delta\ddot{\varphi}^I_{\mathbf{k}} + 3H\delta\dot{\varphi}^I_{\mathbf{k}} + \left[\delta^I_J \frac{k^2}{a^2} + \partial^I\partial_J \mathcal{V}\right]\delta\varphi^J_{\mathbf{k}}$$
$$= -2\Psi_{\mathbf{k}}\partial^I\mathcal{V} + 4\dot{\Psi}_{\mathbf{k}}\dot{\varphi}^I.$$

$\delta\varphi_k(t) \sim e^{\mu_k t}$





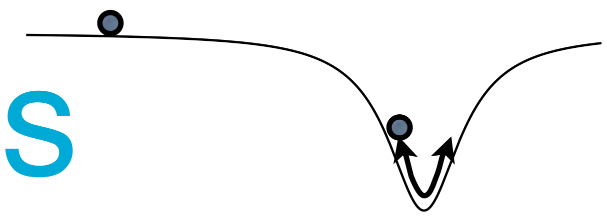


unstable when

$$\frac{\Re(\mu_k)}{H} \gg 1$$

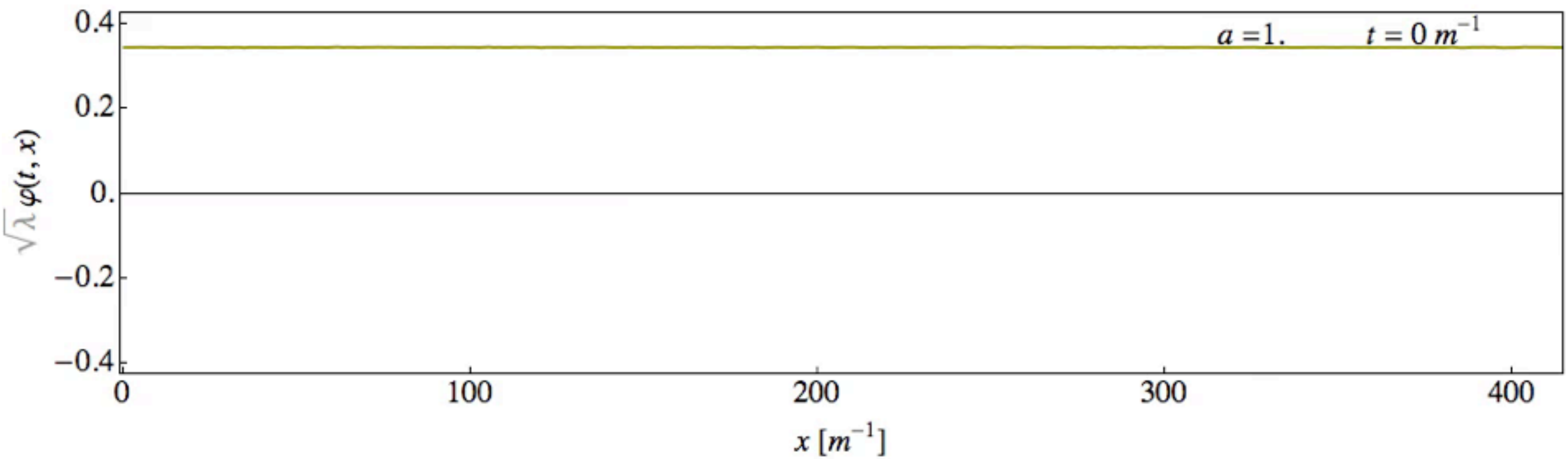
Also See: Hertzberg, Karouby, William G. Spitzer, Juana C. Becerra, Lanqing Li (2014)

“actual” dynamics



Fragmentation!

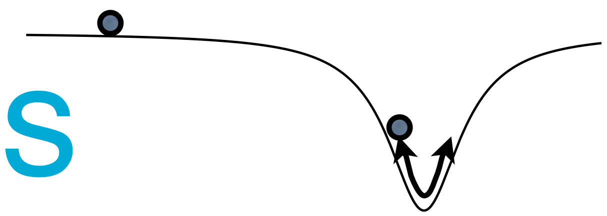
(1) highly nonlinear
(2) homogeneous analysis fails
(3) linear analysis helps to see the instability, but fails soon after …



***MA* (2010)**

Also see: *Khlopov, Molamed and Zeldovich (1985)*

“actual” dynamics



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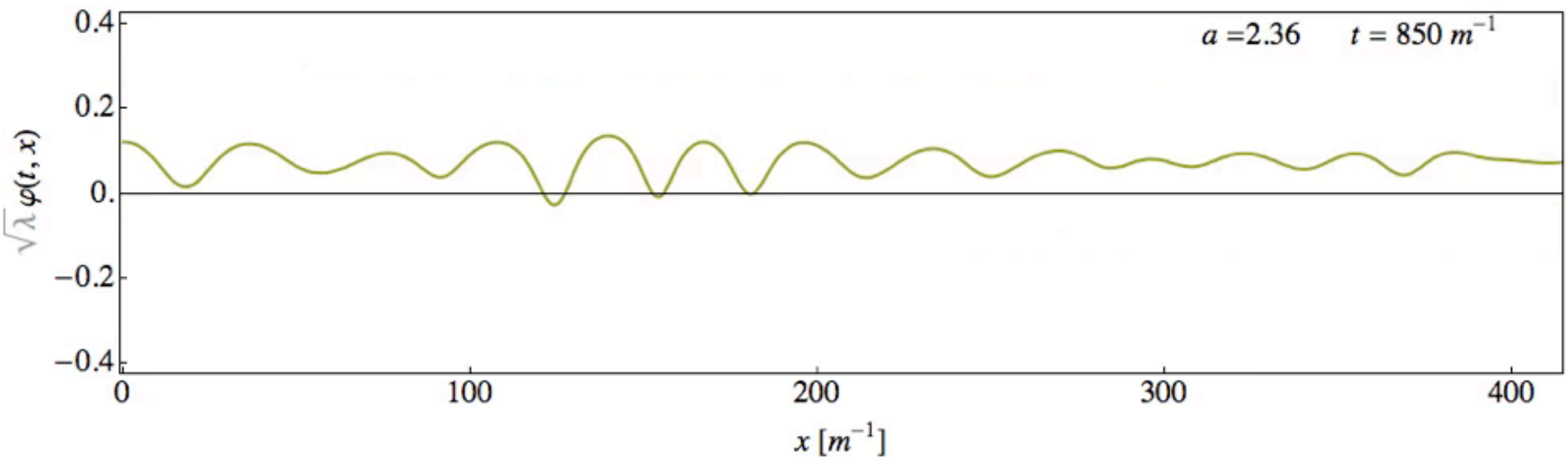

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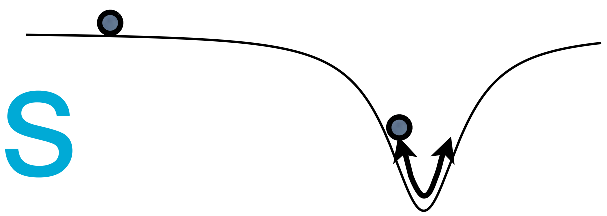

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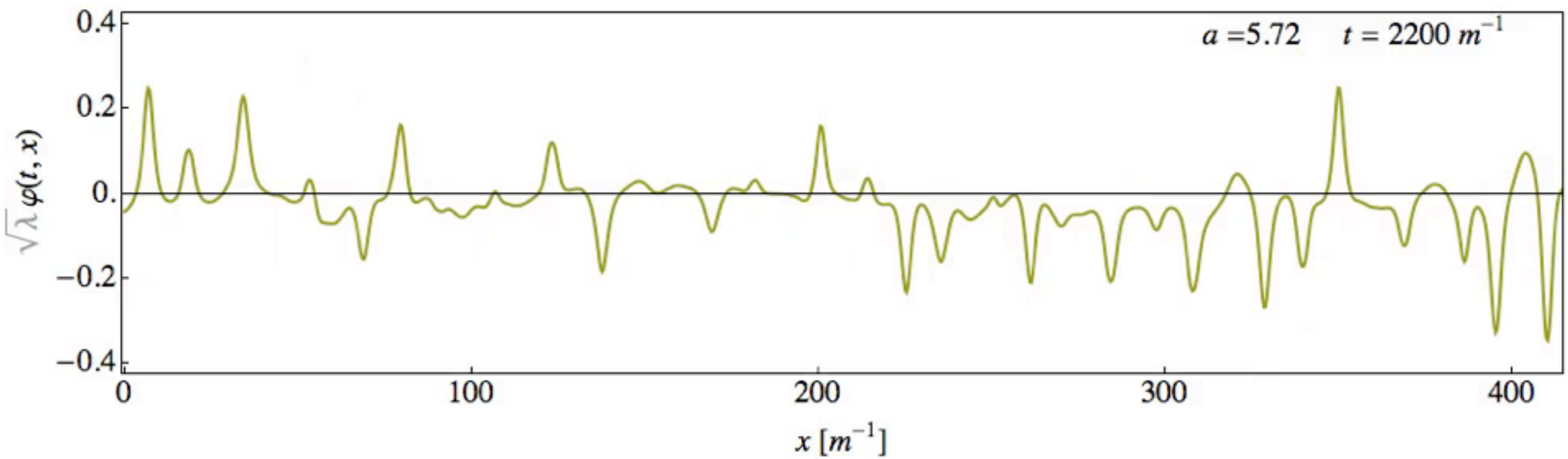

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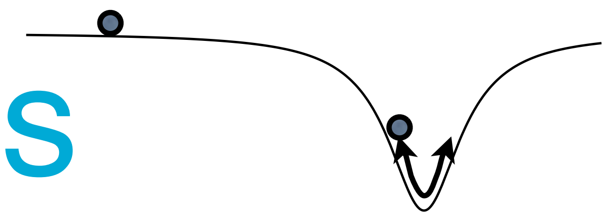

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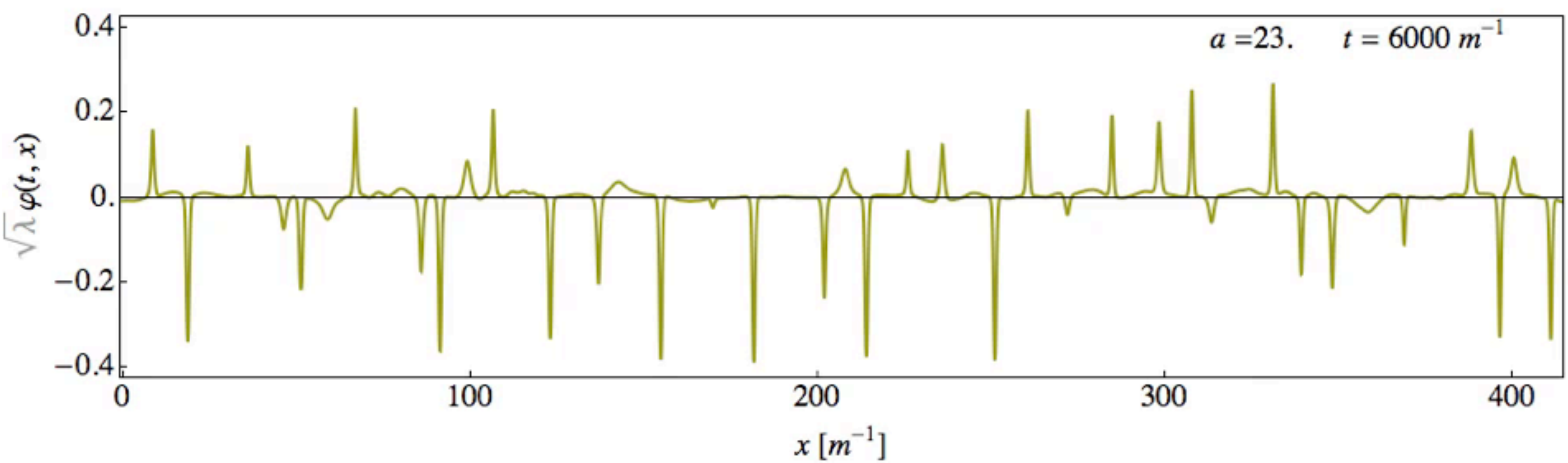

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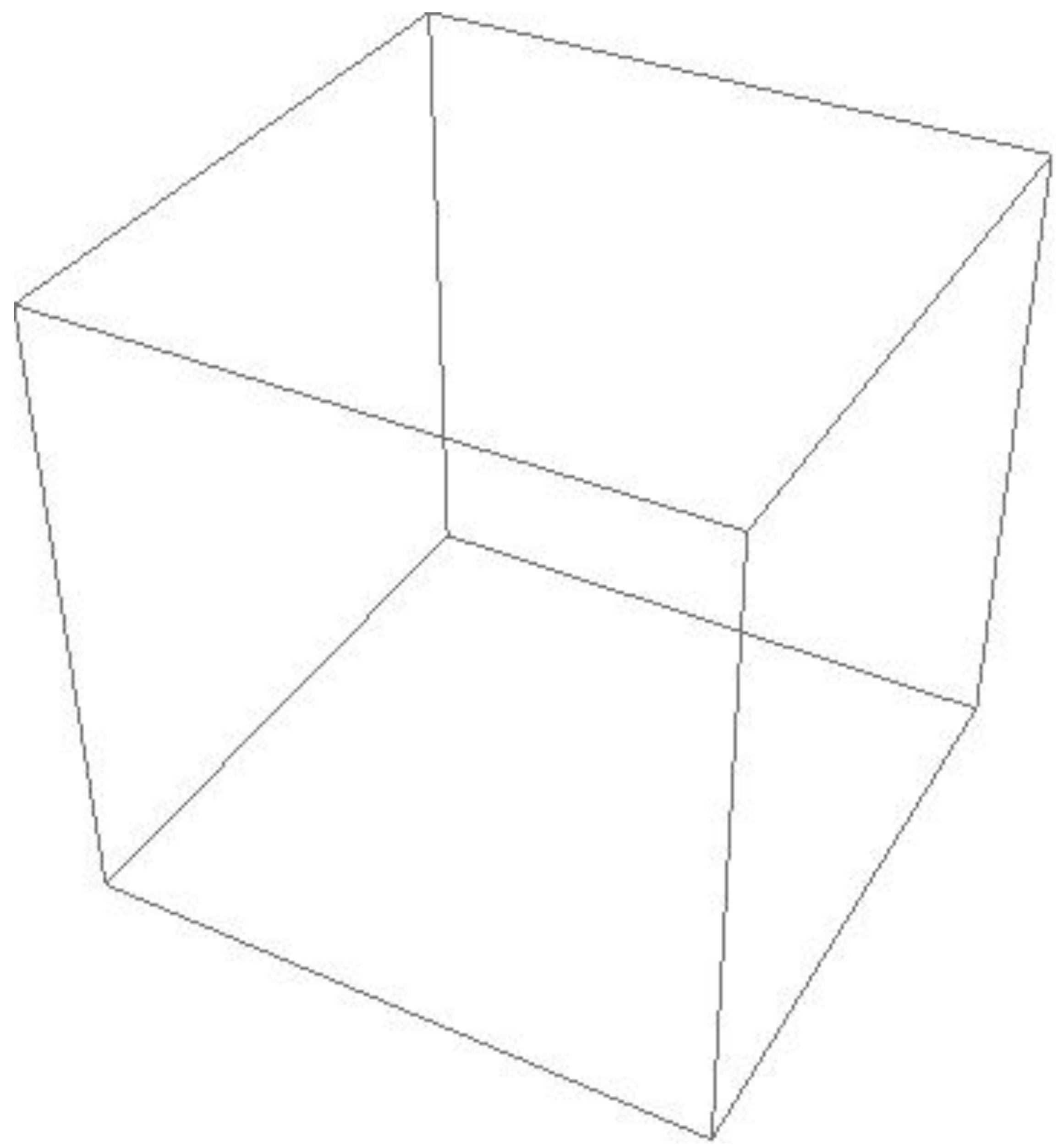
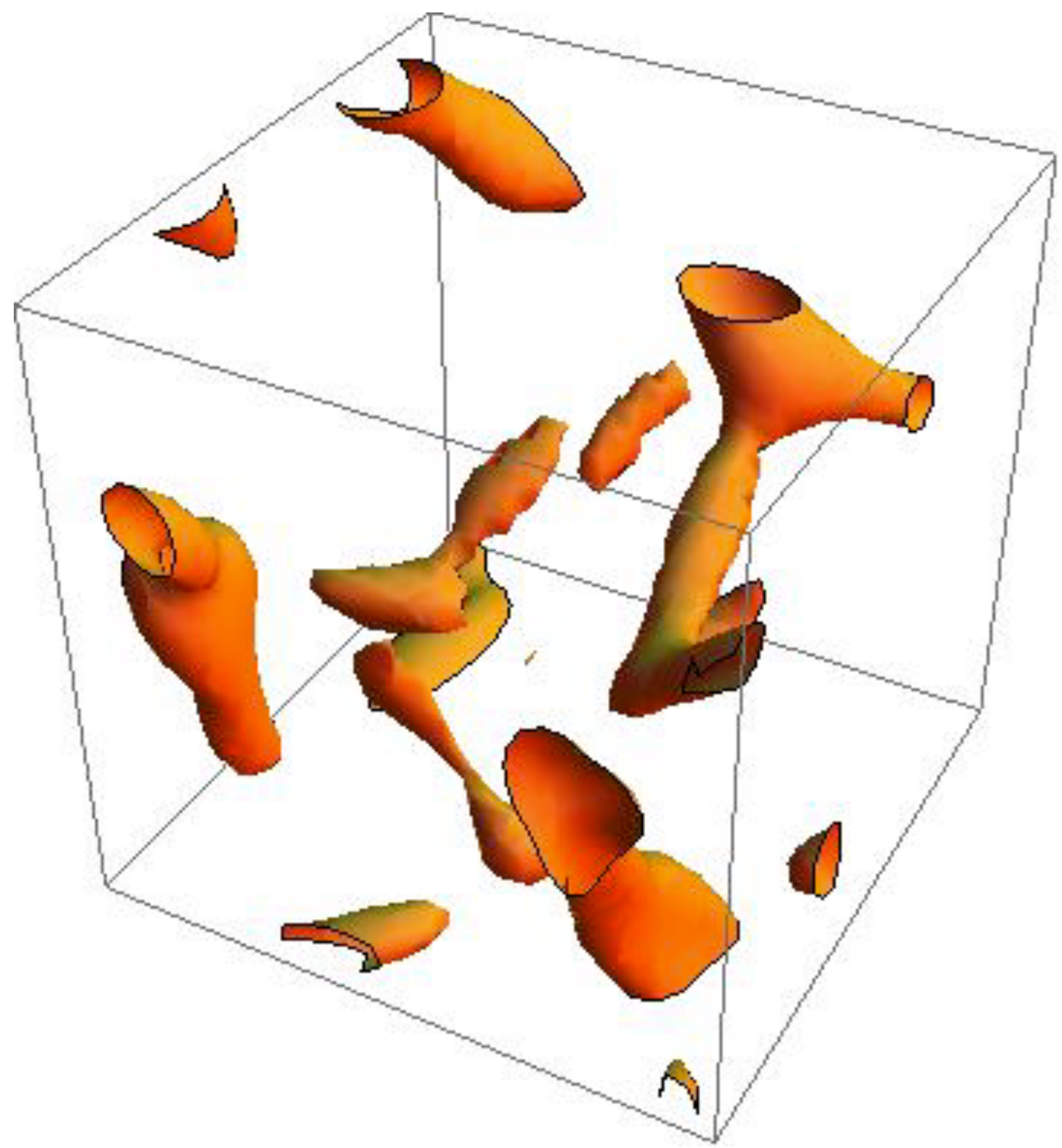
“actual” dynamics



surfaces drawn at 5 x the avg. density

time after inflation = 120 m^{-1} — 300 m^{-1}

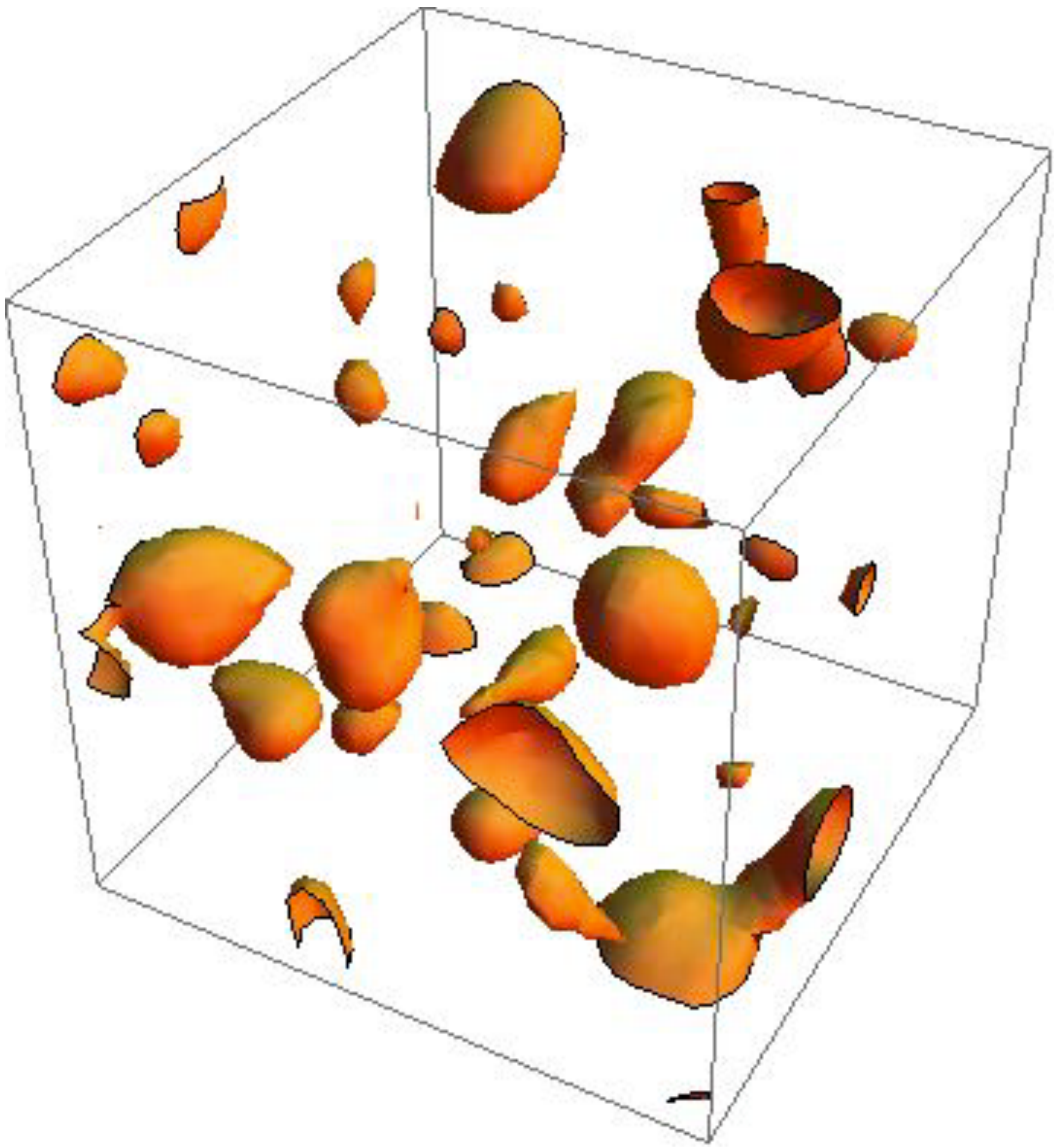
“actual” dynamics



surfaces drawn at 5 x the avg. density

time after inflation = 120 m^{-1} — 300 m^{-1}

“actual” dynamics



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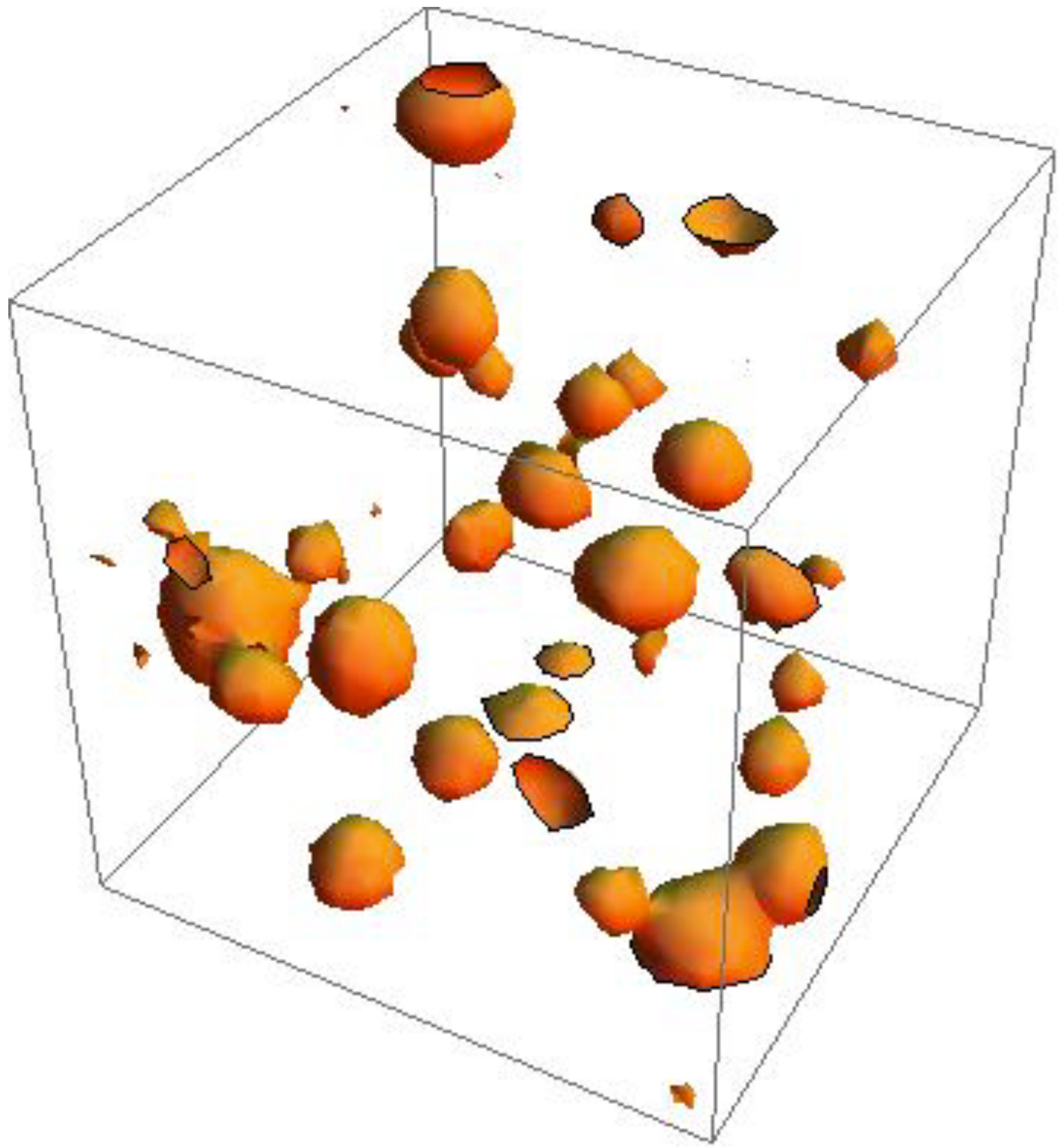
"actual" dynamics

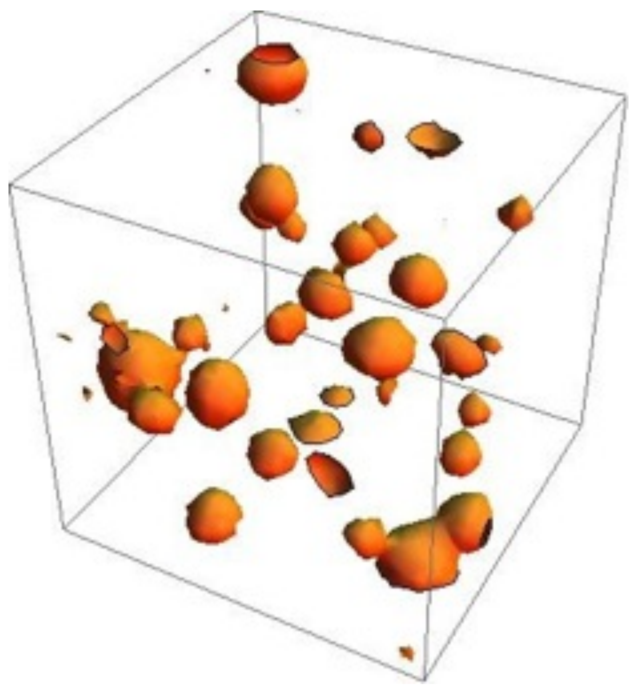


surfaces drawn at 5 x the avg. density

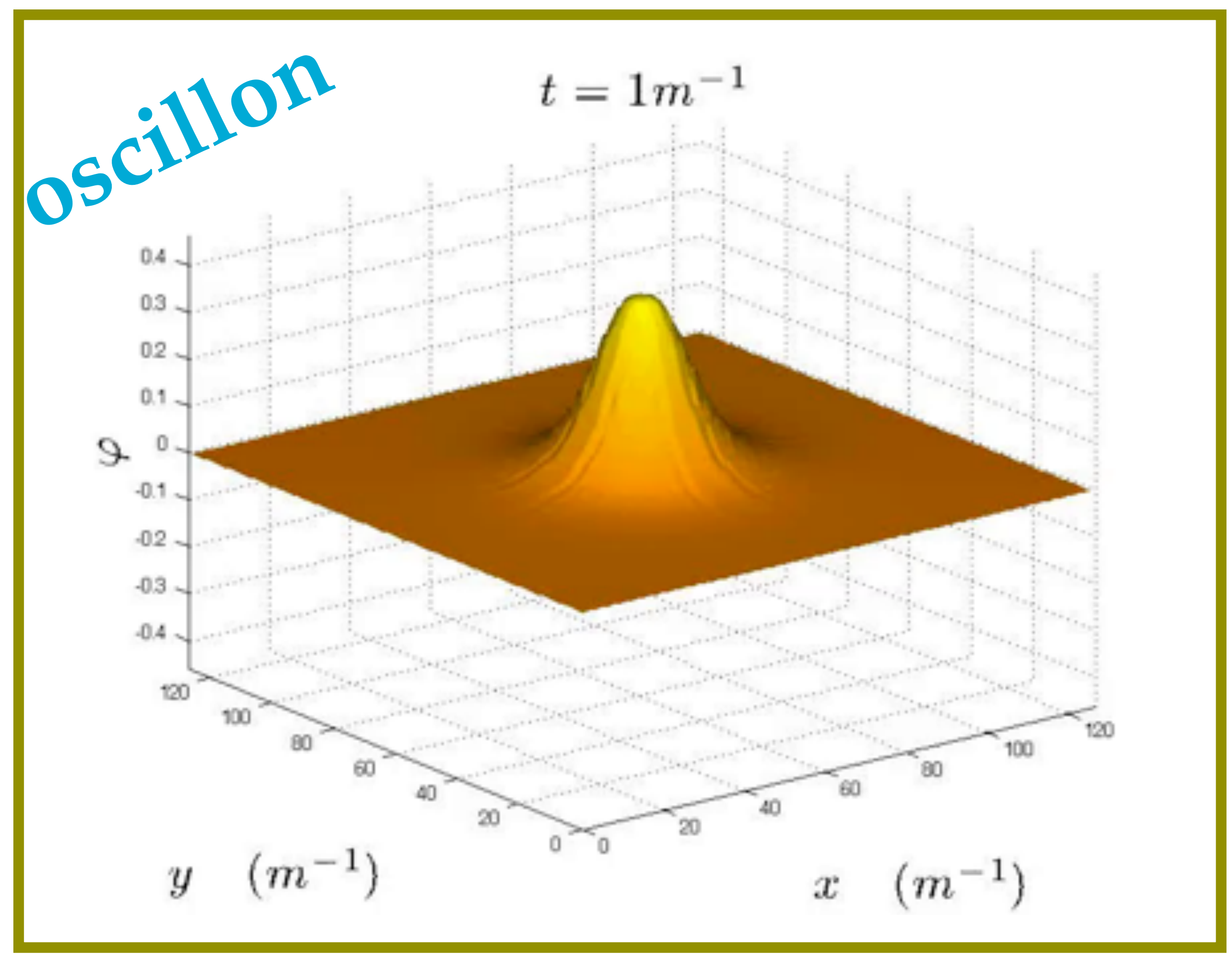
$L_i \lesssim H_{\rm end}^{-1}$

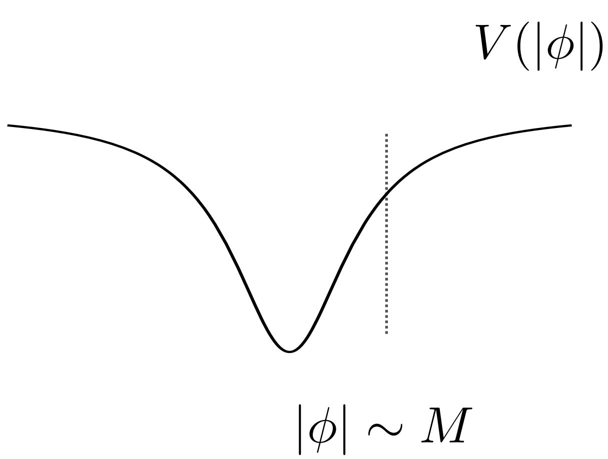
time after inflation = 120 m^{-1} — 300 m^{-1}

what are these lumps?



(1) oscillatory (2) spatially localized (3) very long lived



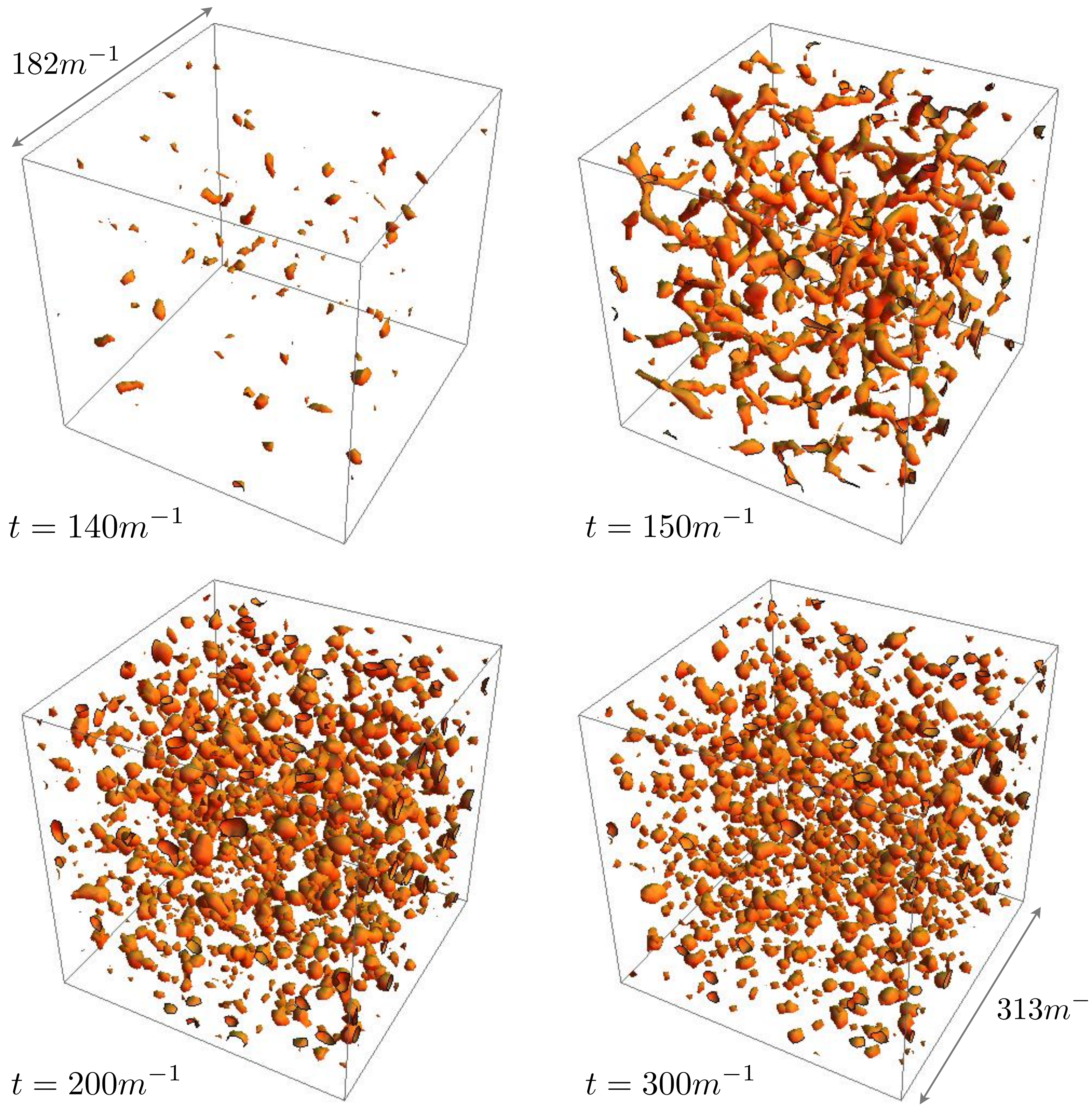


Bogolubsky & Makhankov 1976, Gleiser 1994, Copeland 1995

Long wavelength stability: MA & Shirokoff 2010
Existence conditions (including non-canonical cases): MA 2013
Oscillons after Inflation: MA, Easther, Finkel, Hertzberg 2011

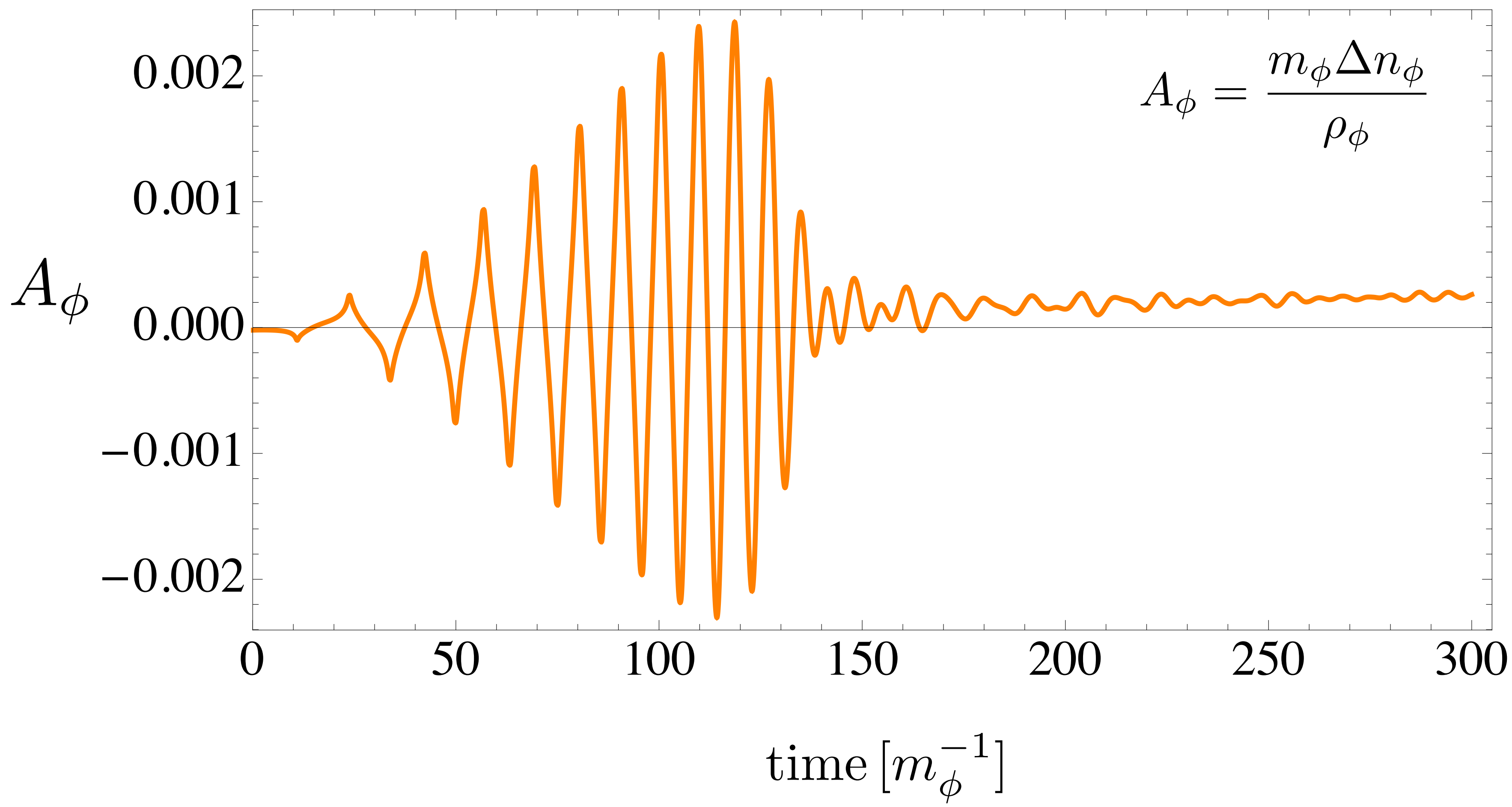
“actual” dynamics

surfaces drawn at 5 x the avg. density



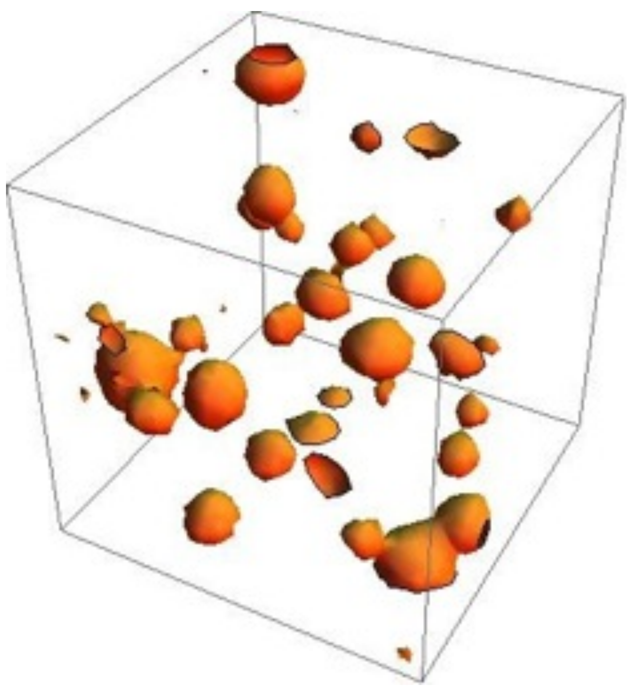
inflaton dynamics — asymmetry generation

inflaton asymmetry

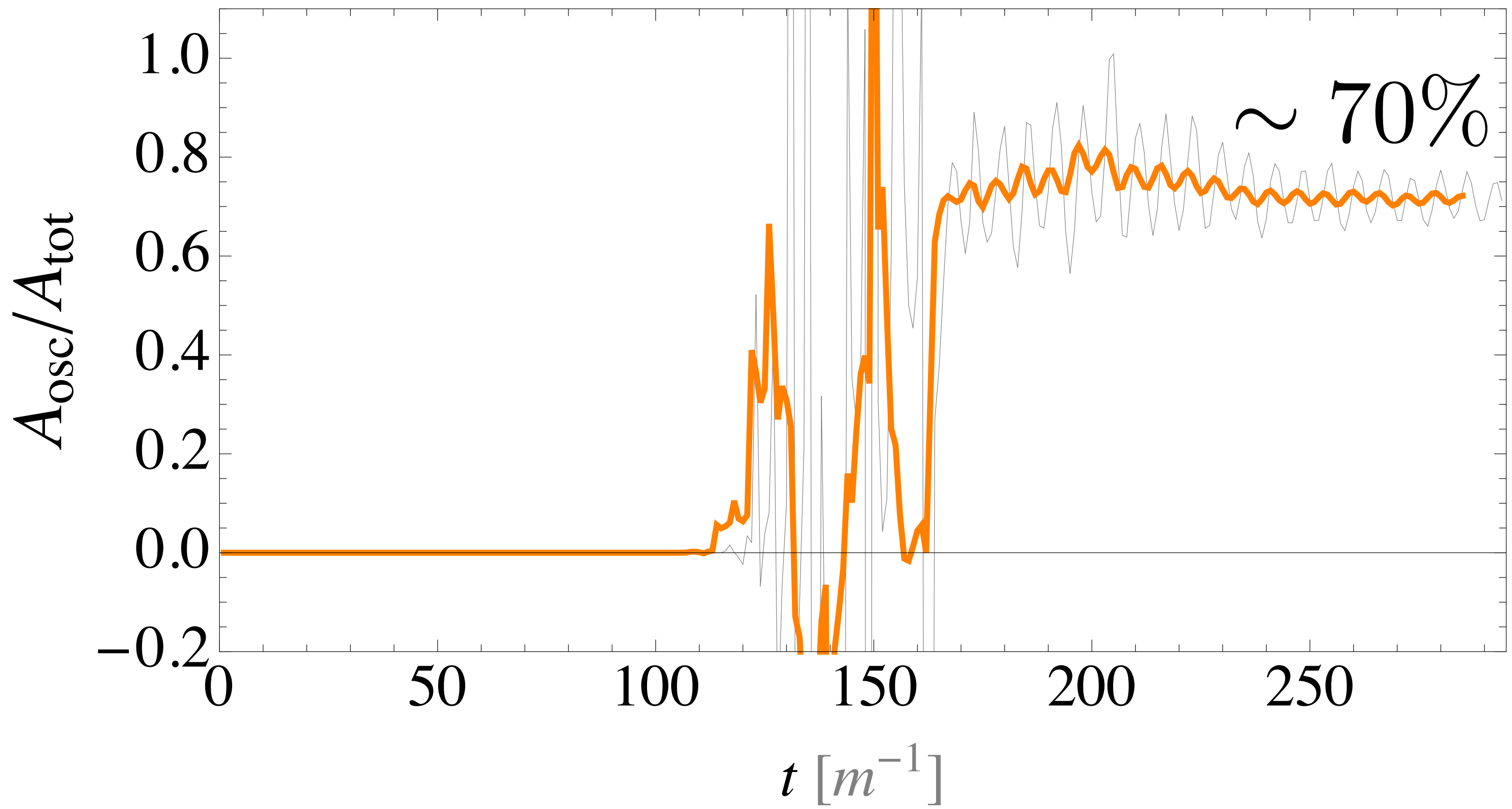


Asymmetry generated at the end of inflation, and freezes after fragmentation

where is the asymmetry?

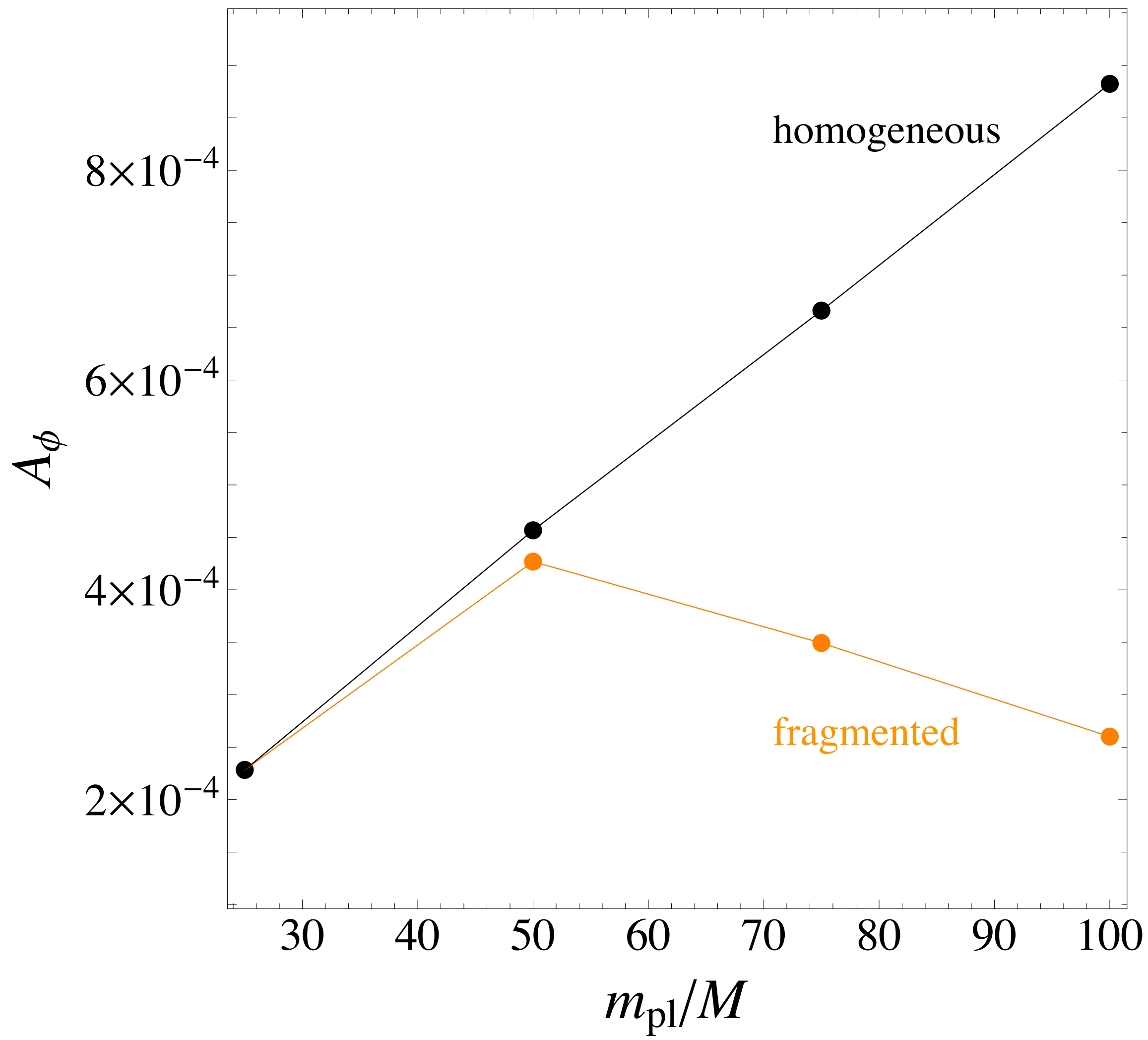


small volume occupied by solitons
— most of asymmetry!

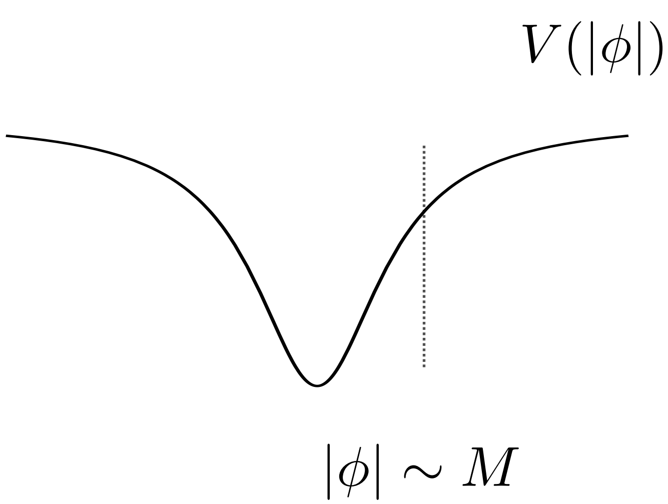


asymmetry- fragmentation

inflaton asymmetry



efficiency of fragmentation



where the potential changes shape

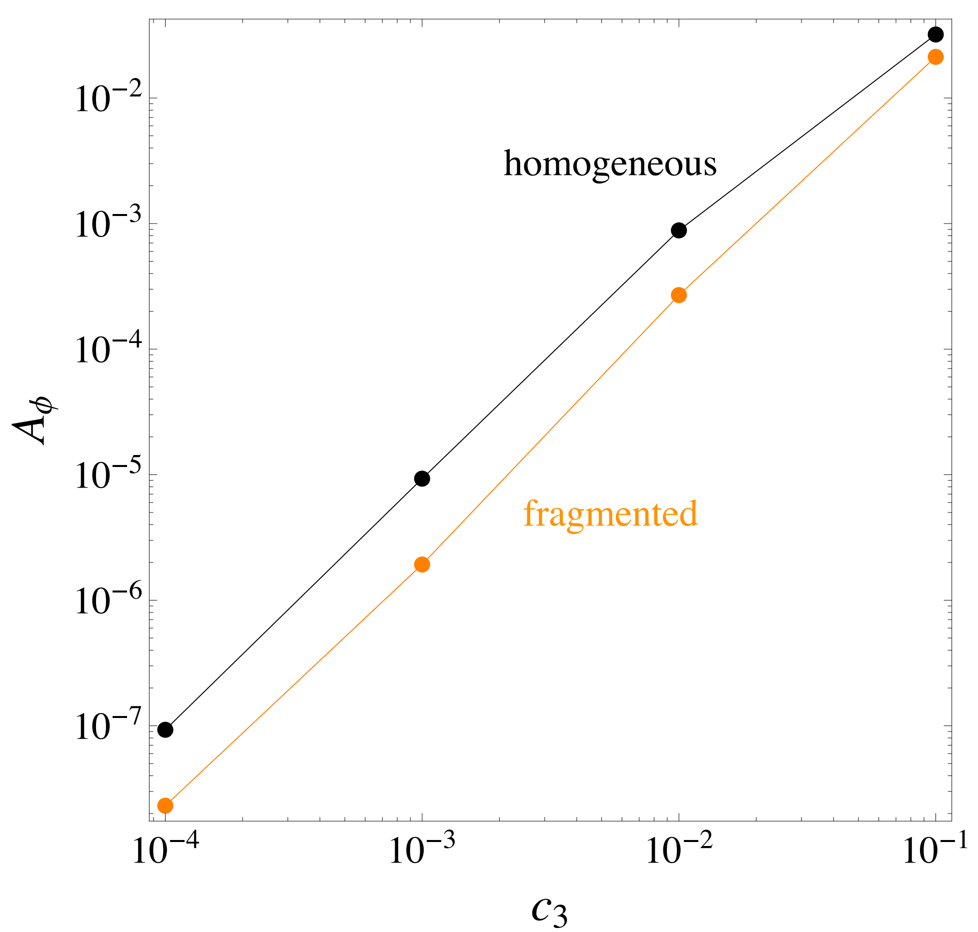
non-trivial, depends on fragmentation *and* likely on the form of the symmetry-breaking term!

dependence on params.

dependence on magnitude of symmetry breaking term

$A_\phi \propto c_3^2$ **important!**

inflaton asymmetry



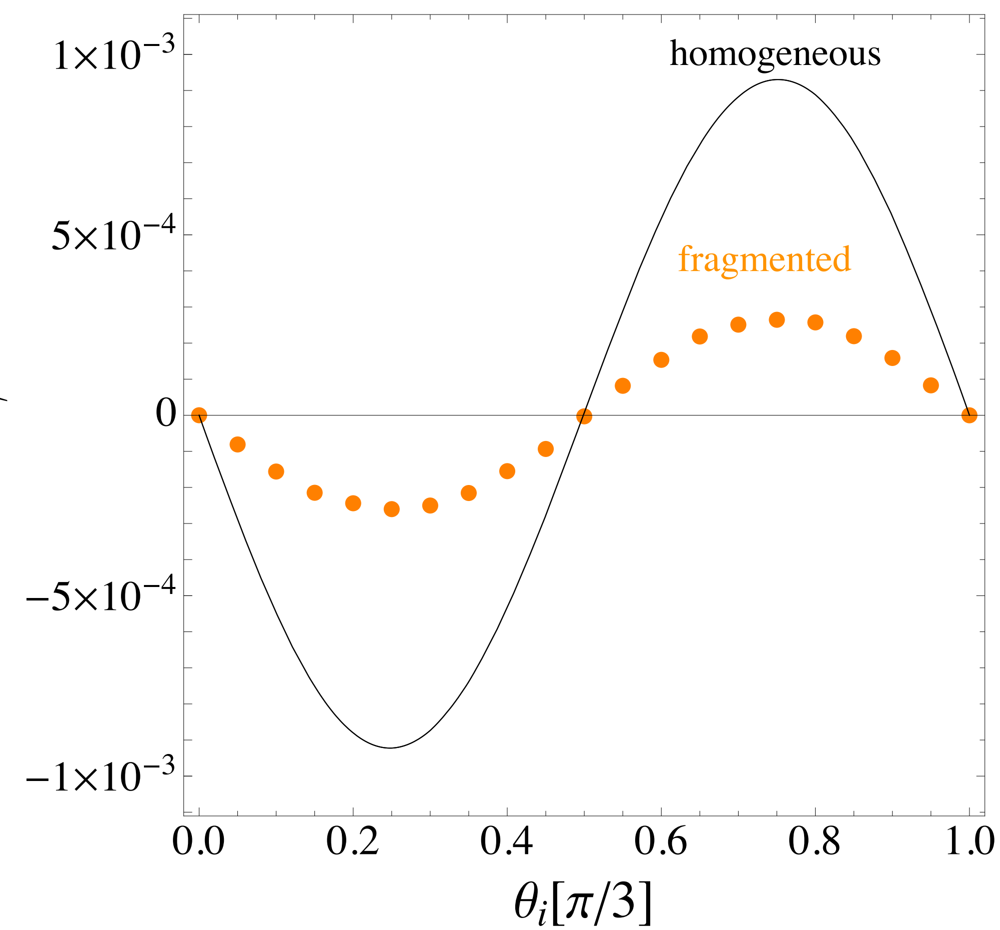
magnitude of symmetry breaking term

$$V_{\rm br}(\phi, \phi^*) = \frac{c_3}{3}\frac{m^2}{M}\frac{(\phi^3 + \phi^{*3})}{f(|\phi|)}$$

$$c_3 \ll 1$$

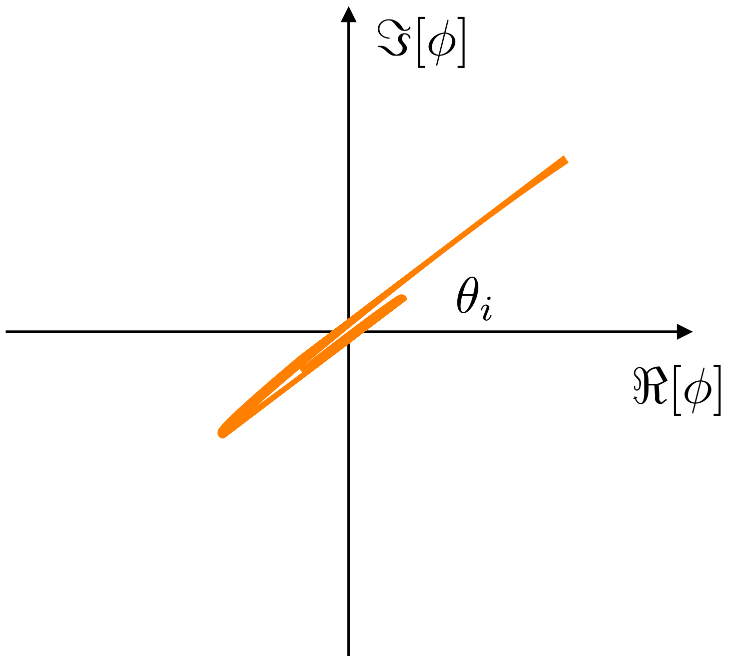
dependence on initial angle

$A_\phi \propto \sin 3\theta_i$



inflaton asymmetry

initial angle

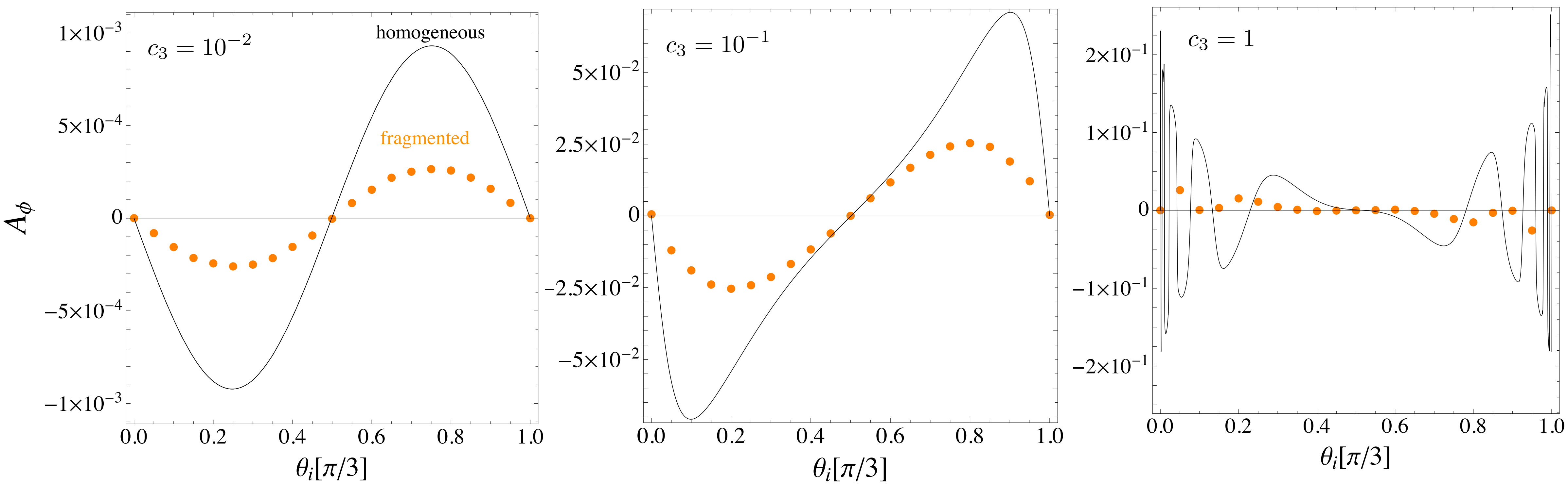


$$V_{\rm br}(\phi,\phi^*) = \frac{c_3}{3}\frac{m^2}{M}\frac{\left(\phi^3+\phi^{*3}\right)}{f(|\phi|)} \qquad c_3 \ll 1$$

asymmetry- parameters

increasing c_3

inflaton asymmetry



initial angle

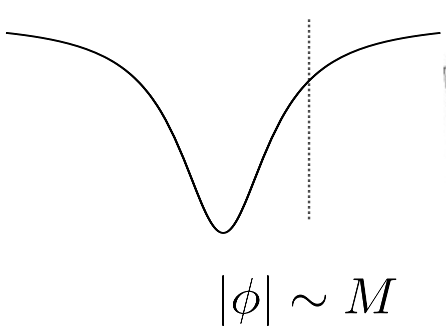
inflaton asymmetry— dependence on parameters

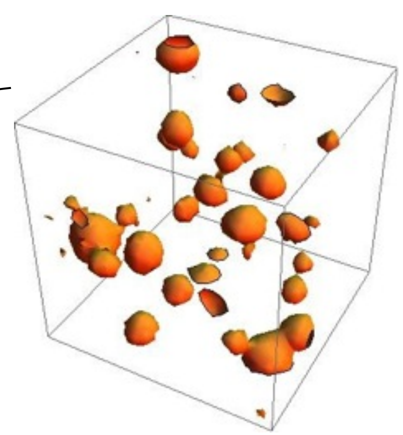
$$A_\phi \sim \mathcal{O}[10^2] \times \frac{M}{m_{\rm Pl}}\, c_3^2 \sin 3\theta_i$$

(inverse) strength of instability

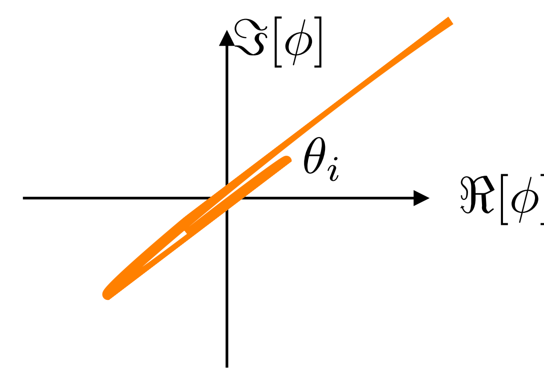
symmetry breaking

initial conditions—inflation





$$V_{\rm br}(\phi,\phi^*) = \frac{c_3}{3}\frac{m^2}{M}\frac{(\phi^3+\phi^{*3})}{f(|\phi|)}$$



$c_3 \ll 1, M \ll m_{\rm pl}$

inflaton to baryons (incomplete!)

$$\eta \sim \mathcal{O}[10^2] \times A_\phi \left(\frac{T_{\rm reh}}{m_\phi} \right) \sim 10^{-9}$$

from end of inflation

decay rate to baryons

sample numbers: $A_\phi \sim 10^{-4},\ T \sim 10^7\,\mathrm{GeV},\ m_\phi \sim 10^{14}\,\mathrm{GeV}$

caveats: uncertainty here!! particle physics details, inhomogeneous decay …

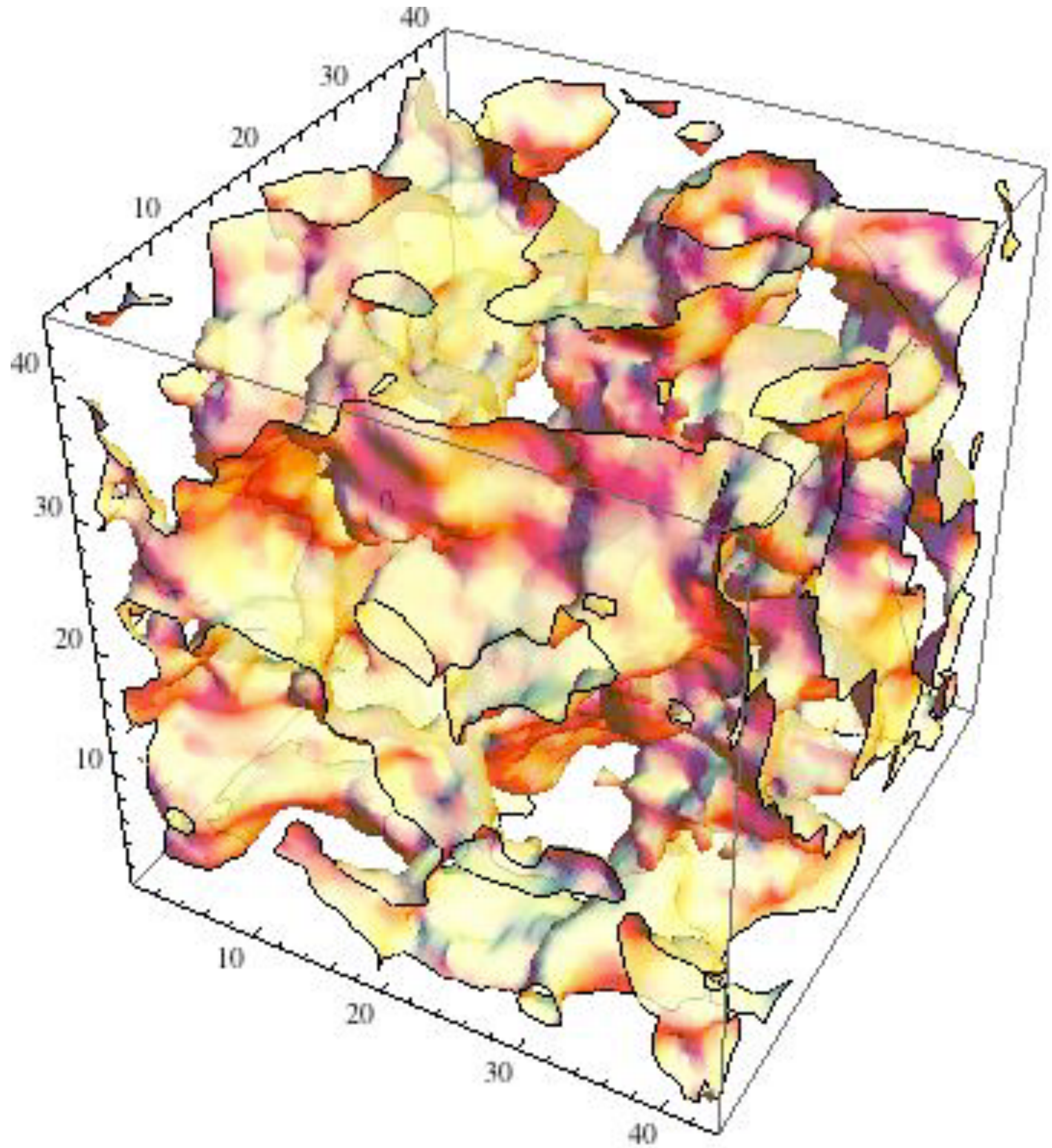
other connections …

- isocurvature fluctuations $\alpha_{II} \sim 2.6 \times 10^{-4}$
- (usual Affleck-Dine runs into problems with isocurvature for high scale inflation)
- dark matter
- change in expansion history — number of e-folds

to do

- careful analysis needed:
    - inhomogeneous decay and annihilation to baryons
    - connection to isocurvature perturbations
    - dark matter connection?
    - detailed properties of the solitons (we have checked that they are **oscillons** *NOT* Q-balls)
    - particle physics model building

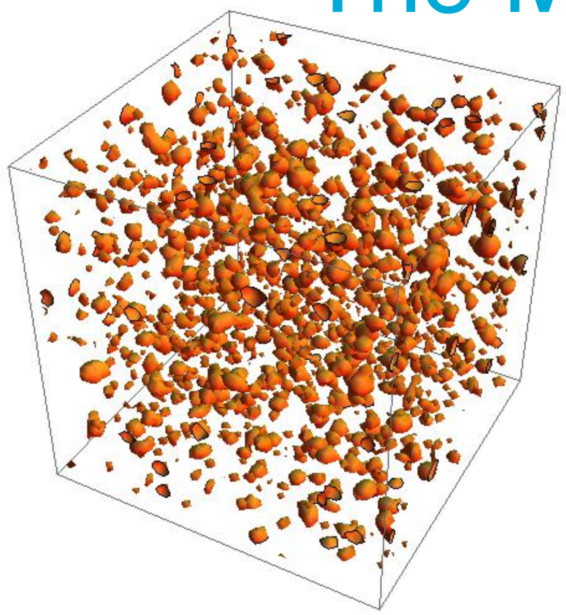
different model: “long” wavelength asymmetry



$$V(|\phi|) = m^2|\phi|^2 + \lambda|\phi|^4$$

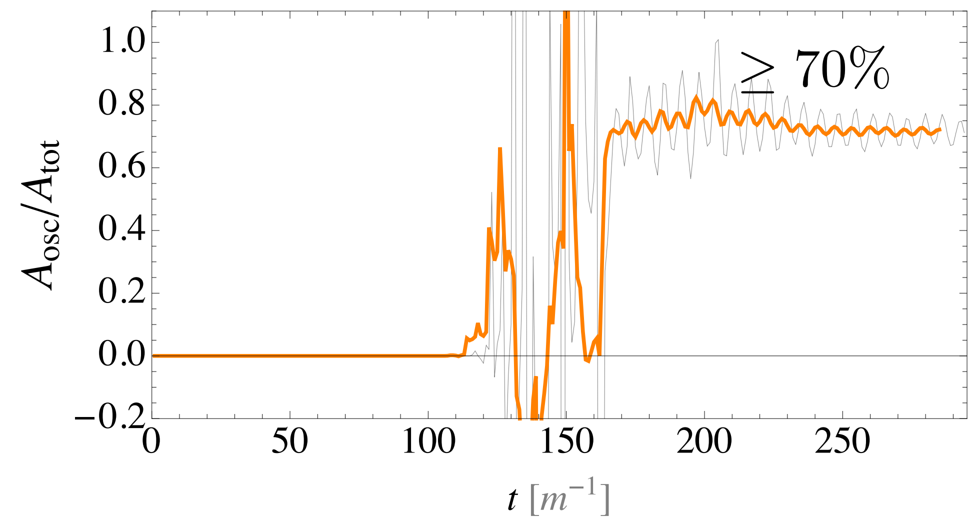
Lozanov & MA (in progress)

The End of Inflation, Oscillons & The Matter-Antimatter Asymmetry



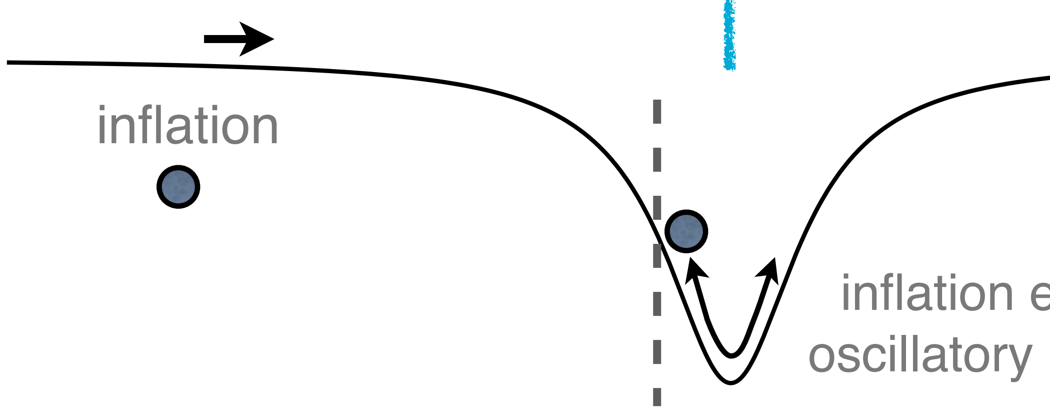
inflaton/anti-inflaton asymmetry locked in solitons (oscillons!)

ratio of asymmetry in solitons/ total asymmetry



inflaton fragmentation and generation of A_ϕ: inflaton/anti-inflaton asymmetry

decay into baryons/anti-baryons



inflation ends: oscillatory phase

complex inflaton + ~~U~~(1)

$$\eta \sim \mathcal{O}[10^2] \times A_\phi \left(\frac{T_{\rm reh}}{m_\phi}\right)$$

observed asymmetry (baryon-to-photon ratio)

connects reheating and baryon asymmetry, with additional observational implications

- Our understanding: ?-Inflation **– ? –** Nucleosynthesis

- Reheating — populating our universe

  - non-perturbative, complex dynamics with obs. implications …
  - analytic and numerical techniques available (but long way to go)

- connect inflationary physics to known physics and obs. beyond fluctuations

- Help! — include end of inflation physics with inflation models