Quintessential Acceleration and its End

Mustafa Amin (MIT)

with P. Zukin and E. Bertschinger

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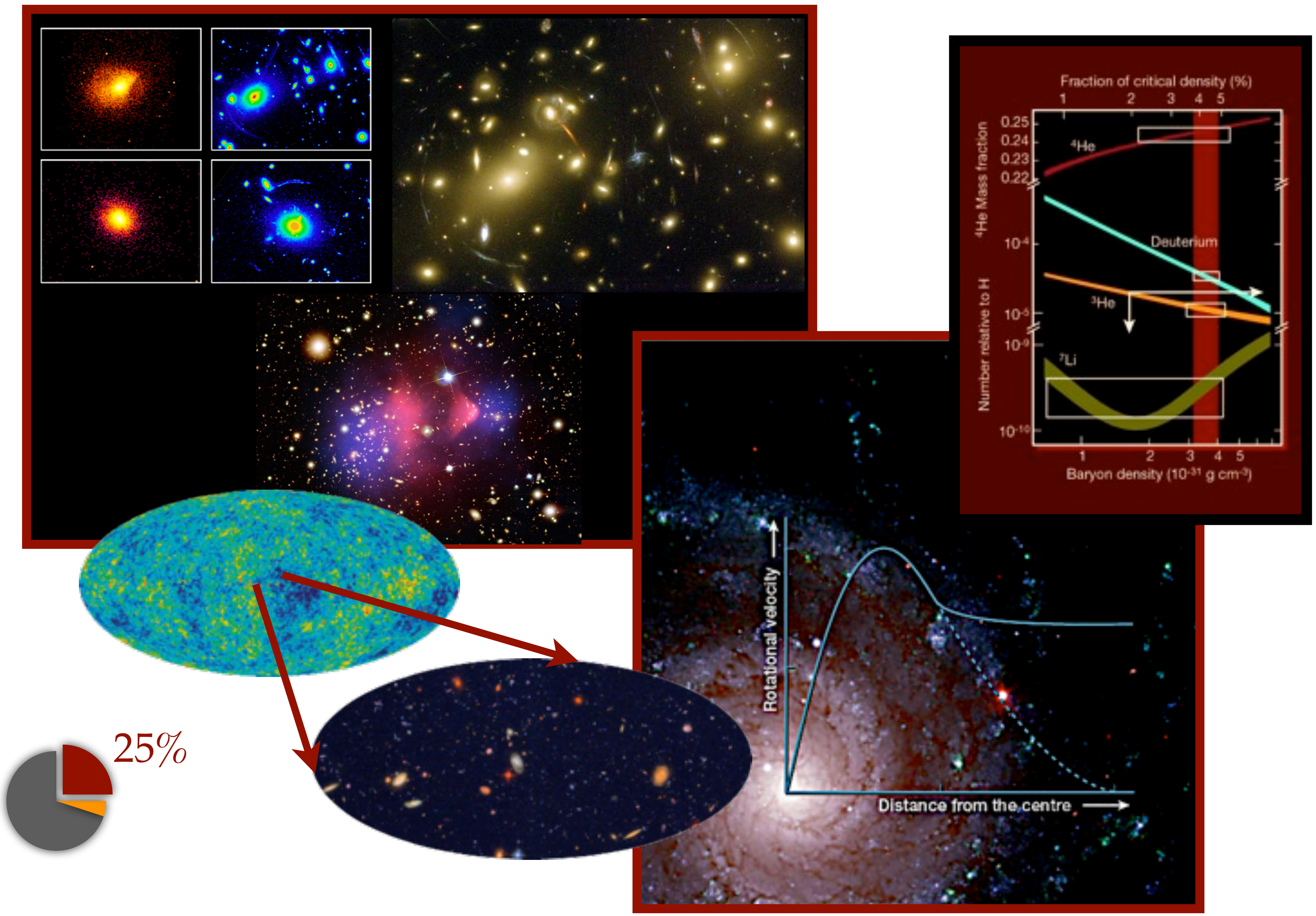
Scale dependent growth from a late (z<0.2) transition in dark energy dynamics

(similar to (p)reheating after inflation, but from quintessence)

synopsis

- why?
- phenomenology:
  - ➡ end of accelerated expansion
  - ➡ resonant growth of structure
- observational consequences
- shortcomings

“we” are not important or liked



“we” are not important or liked

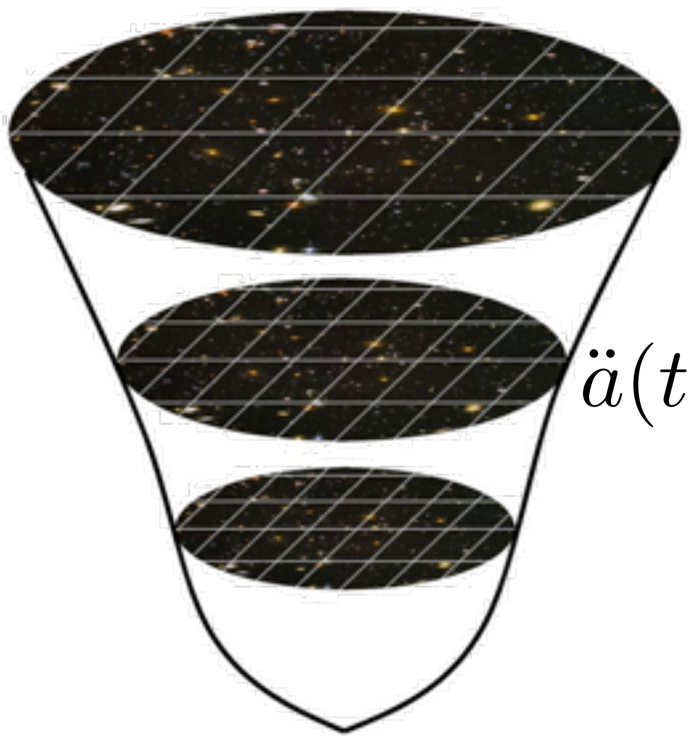


image: High Z Supernova Search Team, HST

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3}(\rho + 3P) > 0$$

$$w = P/\rho \sim -1$$

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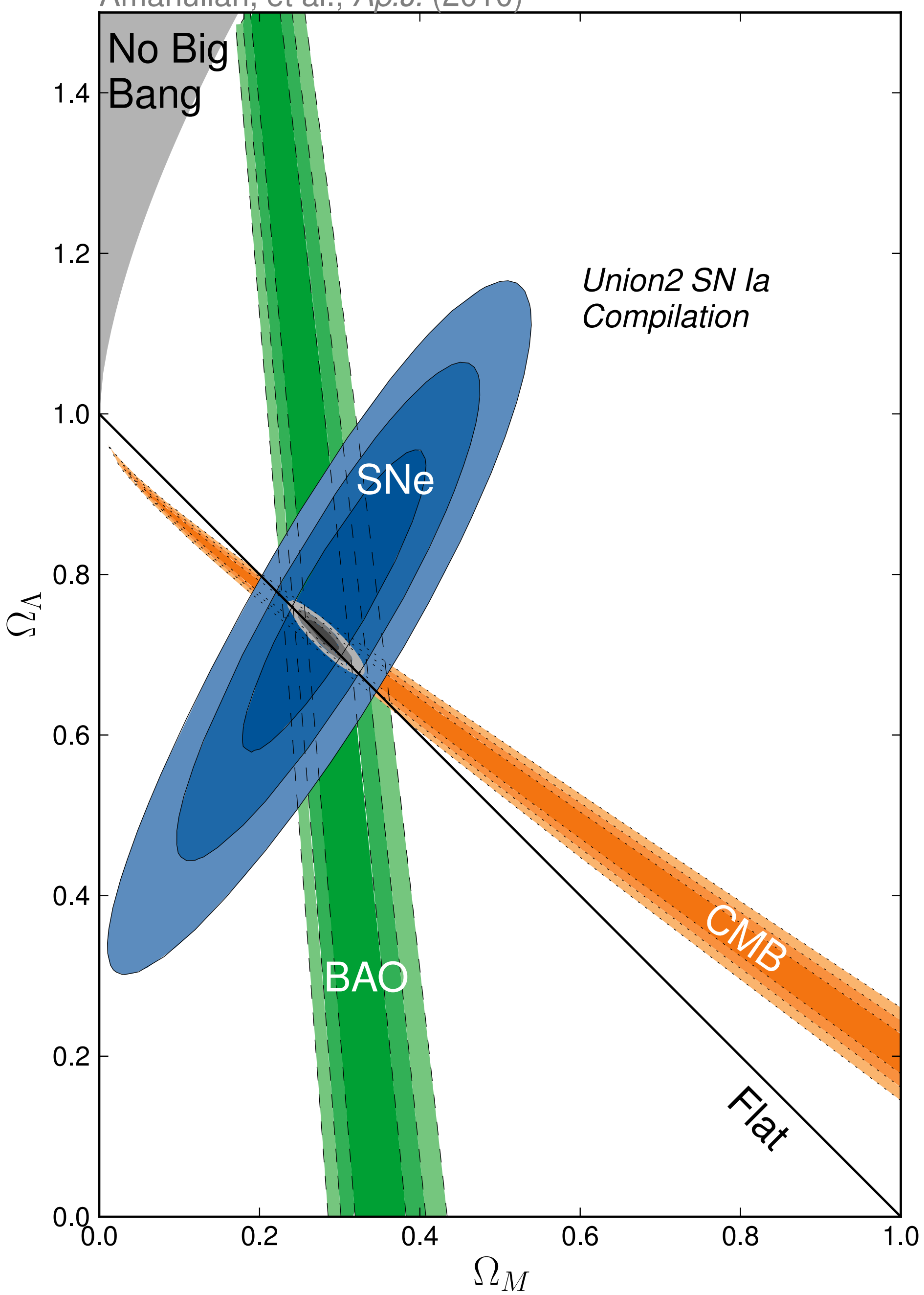
a working model: ΛCDM



$$\mathcal{L} = \frac{1}{16\pi G}[R - 2\Lambda] + [\mathcal{L}_{sm} + \mathcal{L}_{WIMP}]$$

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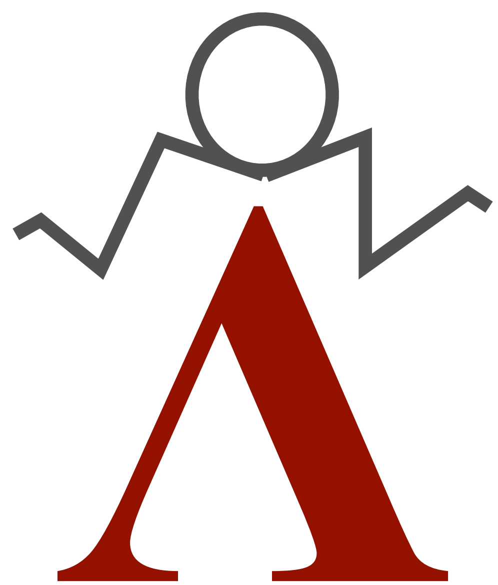
but ...

$$\frac{\Lambda(theory)}{\Lambda(obs)} \sim 10^{120}$$



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an alternative

$$\mathcal{L} = \frac{1}{16\pi G} R + [\mathcal{L}_{sm} + \mathcal{L}_{WIMP} + \mathcal{L}(\varphi)]$$

quintessence

- Important: does not solve the Λ problem, it is an alternative, not a solution.

$$\mathcal{L}(\varphi) = \frac{1}{2}(\partial\varphi)^2 + U(\varphi)$$

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what is needed

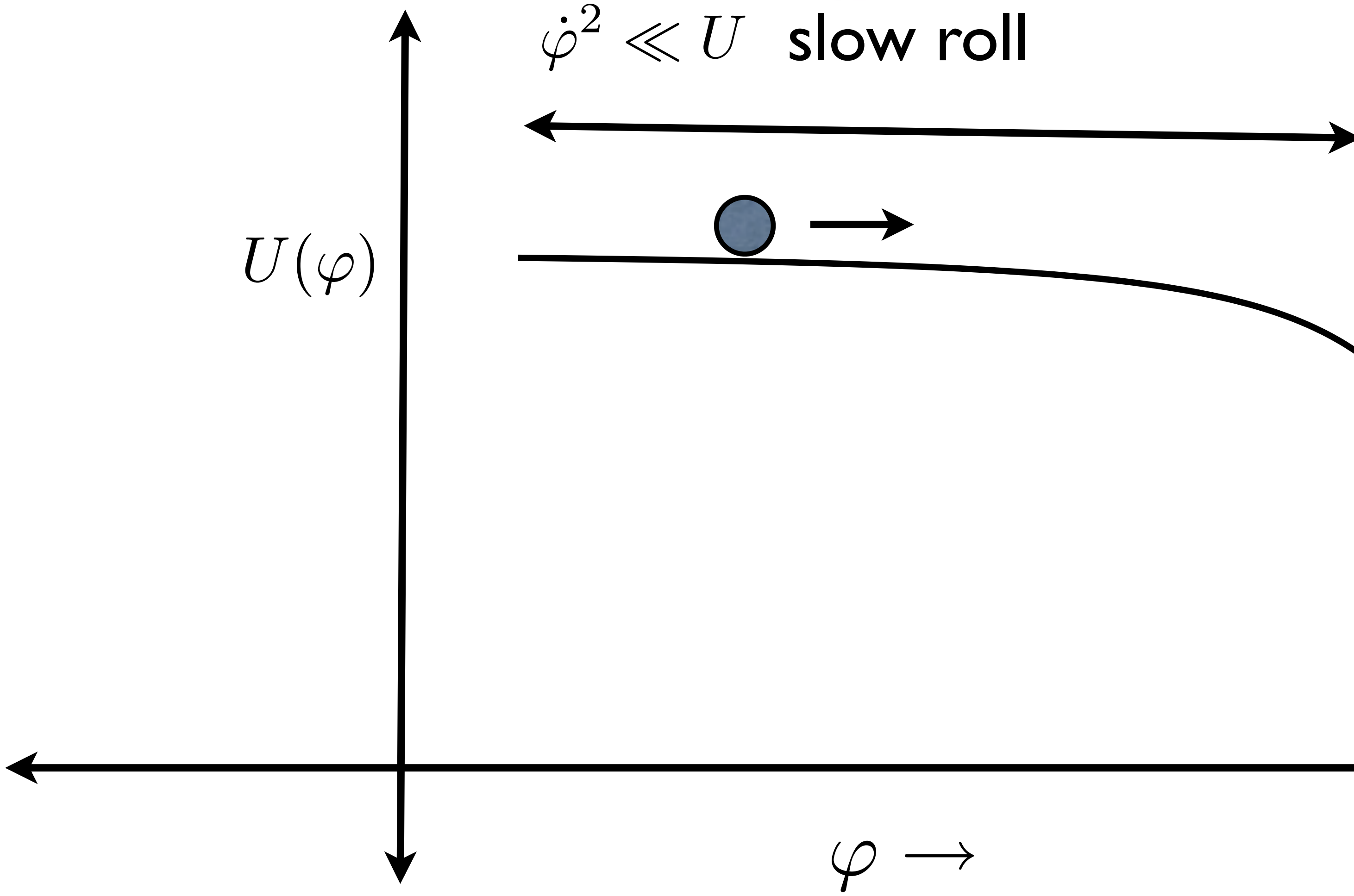
$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3}(\rho + 3P) > 0$$

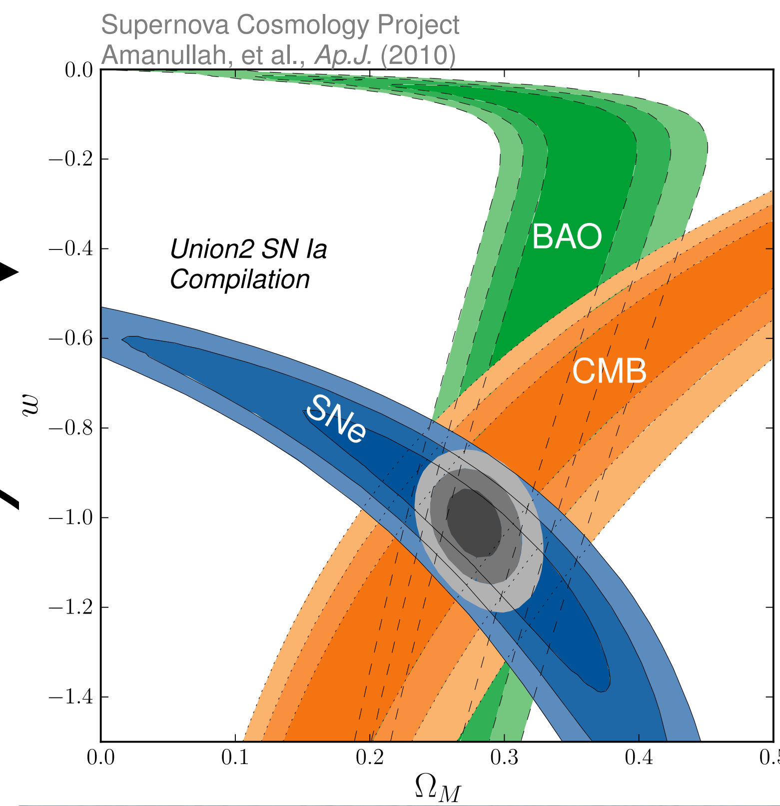
$$w = \frac{P}{\rho} = \frac{\frac{1}{2}\dot{\varphi}^2 - U}{\frac{1}{2}\dot{\varphi}^2 + U} \sim -1$$

$\dot{\varphi}^2 \ll U$ slow roll !

quintessence potential

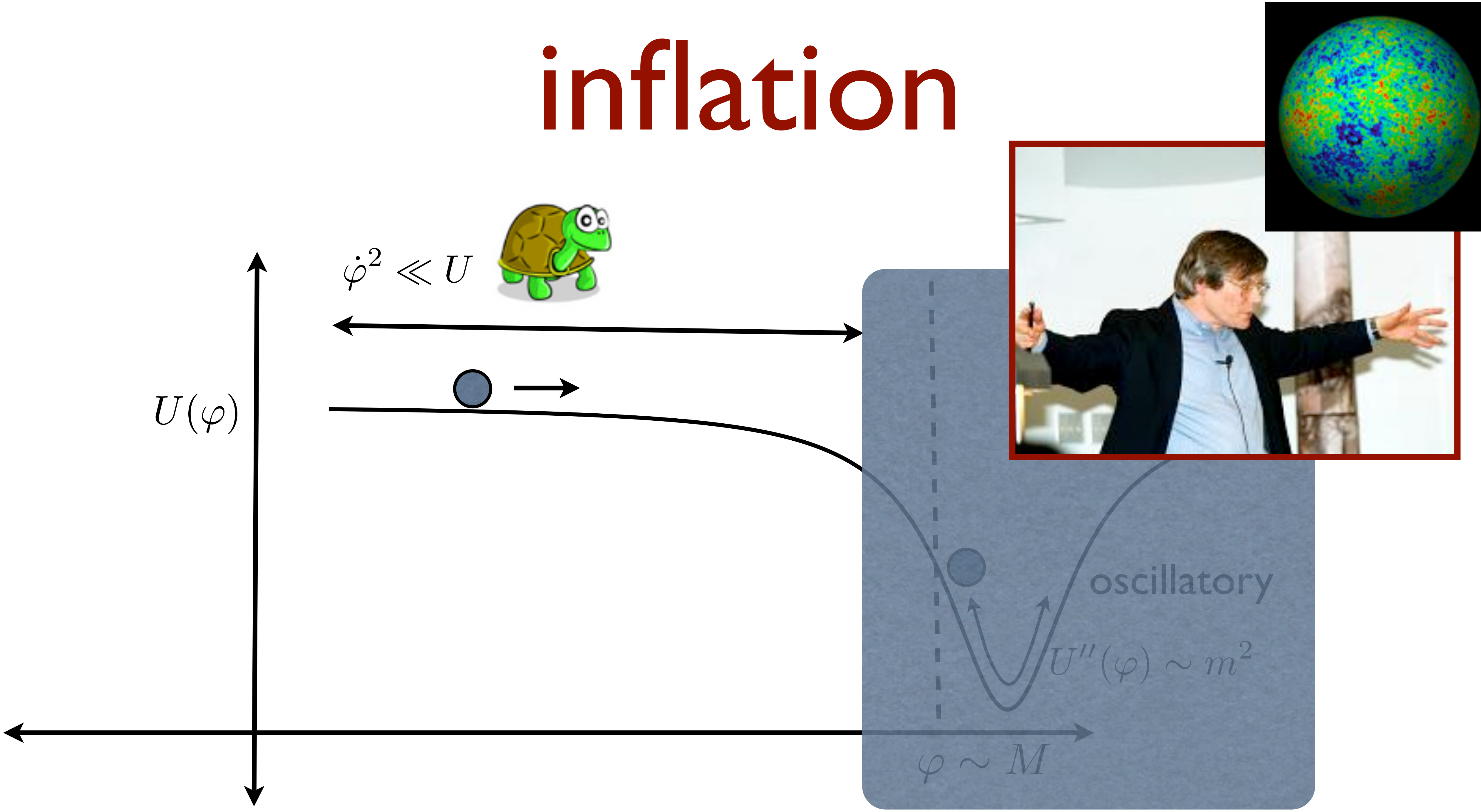
$\dot{\varphi}^2 \ll U$ slow roll



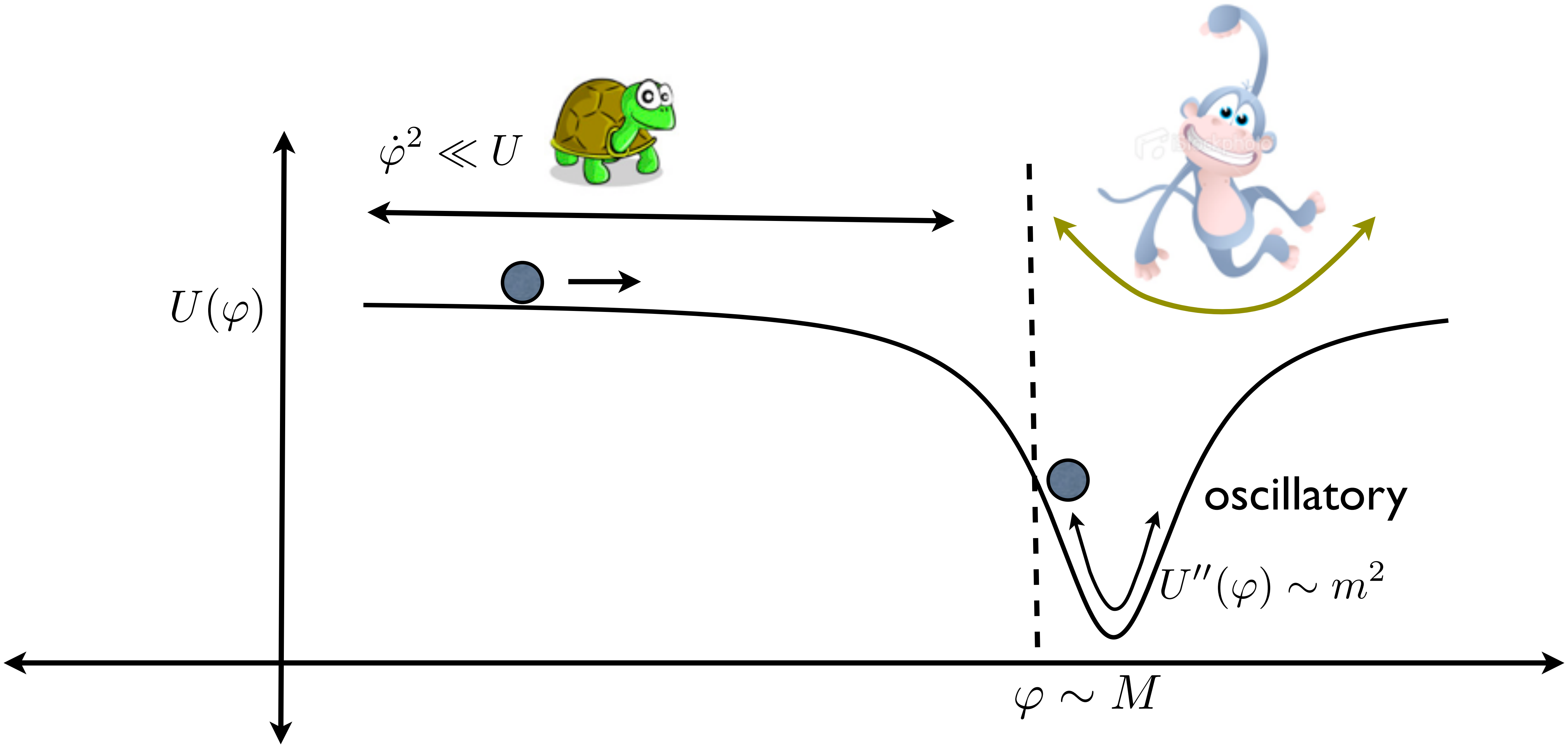


$$w = \frac{P}{\rho} = \frac{\frac{1}{2}\dot{\varphi}^2 - U}{\frac{1}{2}\dot{\varphi}^2 + U}$$

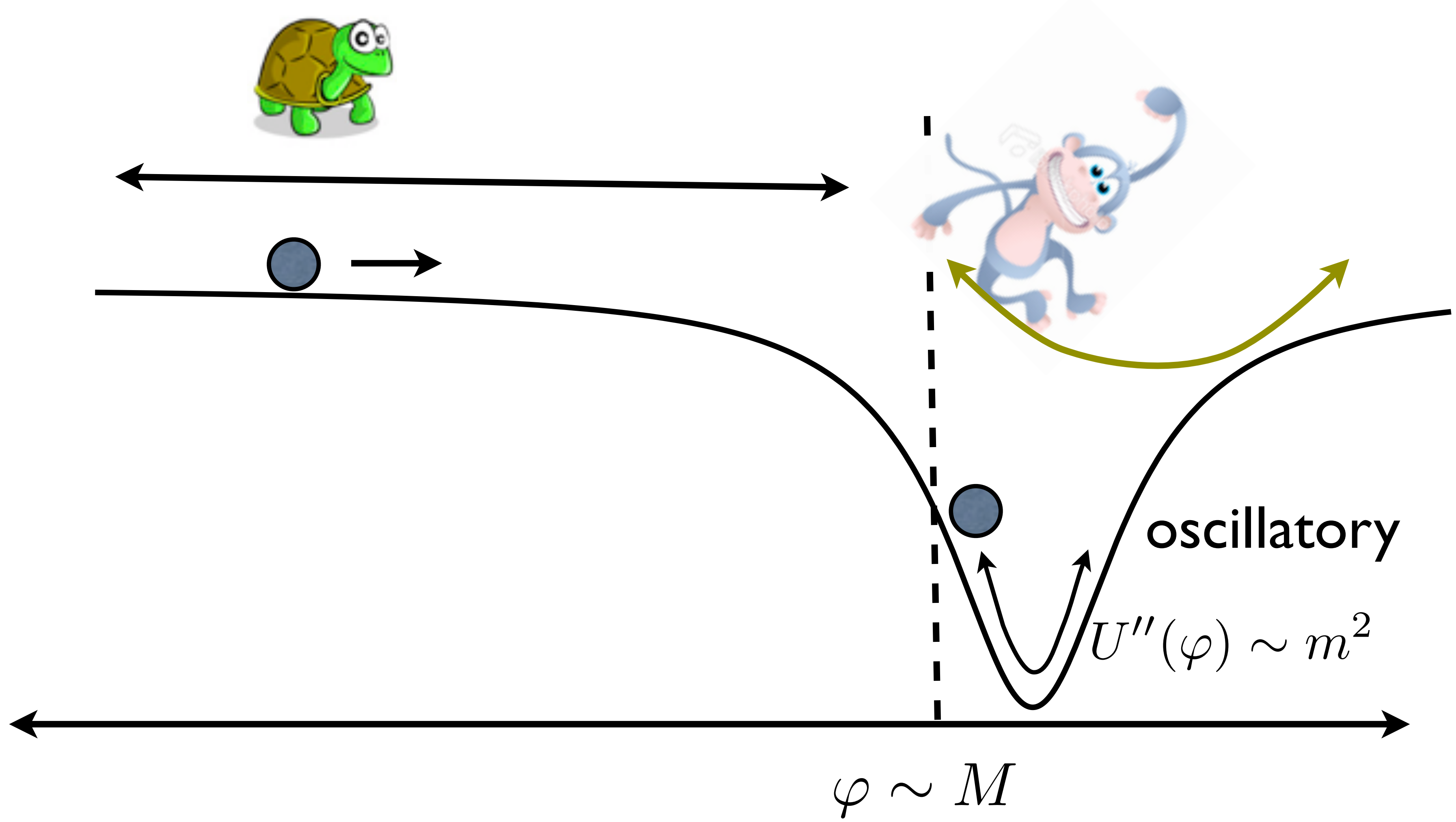
successful before: inflation



but inflation ends



end of quintessential acceleration?



z < 0.2

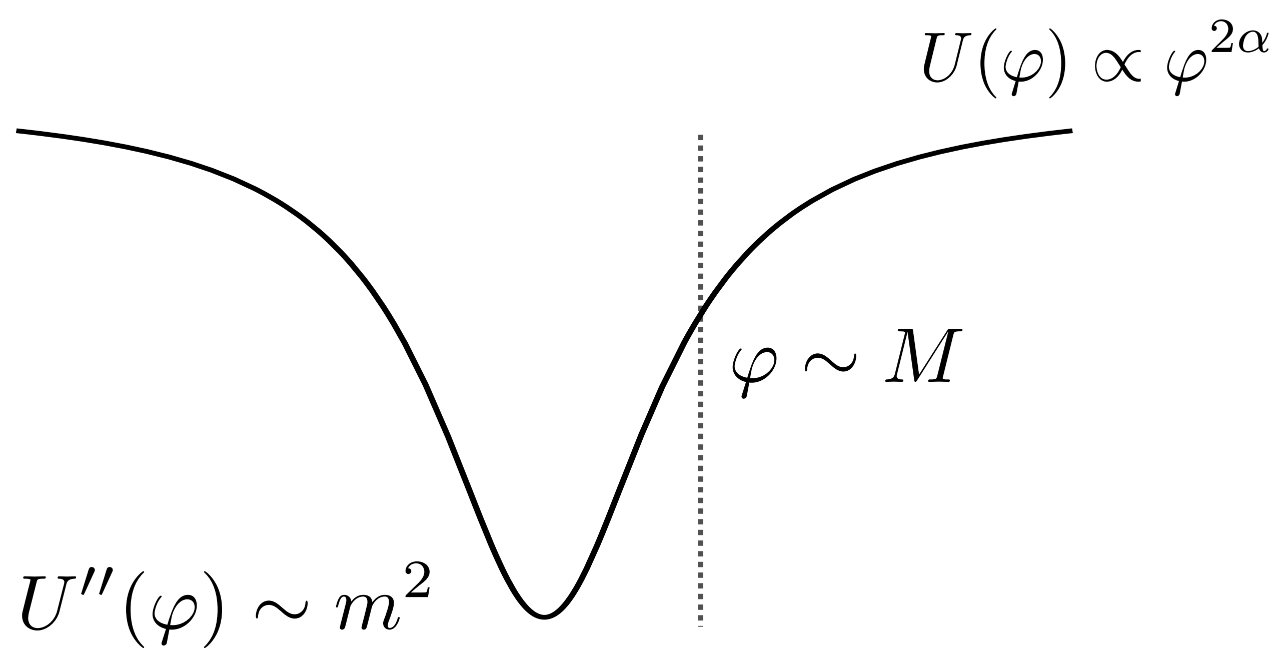
possible, but not necessary

motivation

- explicit models: eg axion monodromy quintessence (Panda et. al), axiverse (Arvanitaki et. al) etc.
- [usually, difficult to maintain flat potentials]
- And ...
  - ➡ extremely rich phenomenology
  - ➡ observationally constrainable

quintessence potential

$$U(\varphi) = \frac{m^2 M^2}{2}\left[\frac{(\varphi/M)^2}{1+(\varphi/M)^{2(1-\alpha)}}\right]$$



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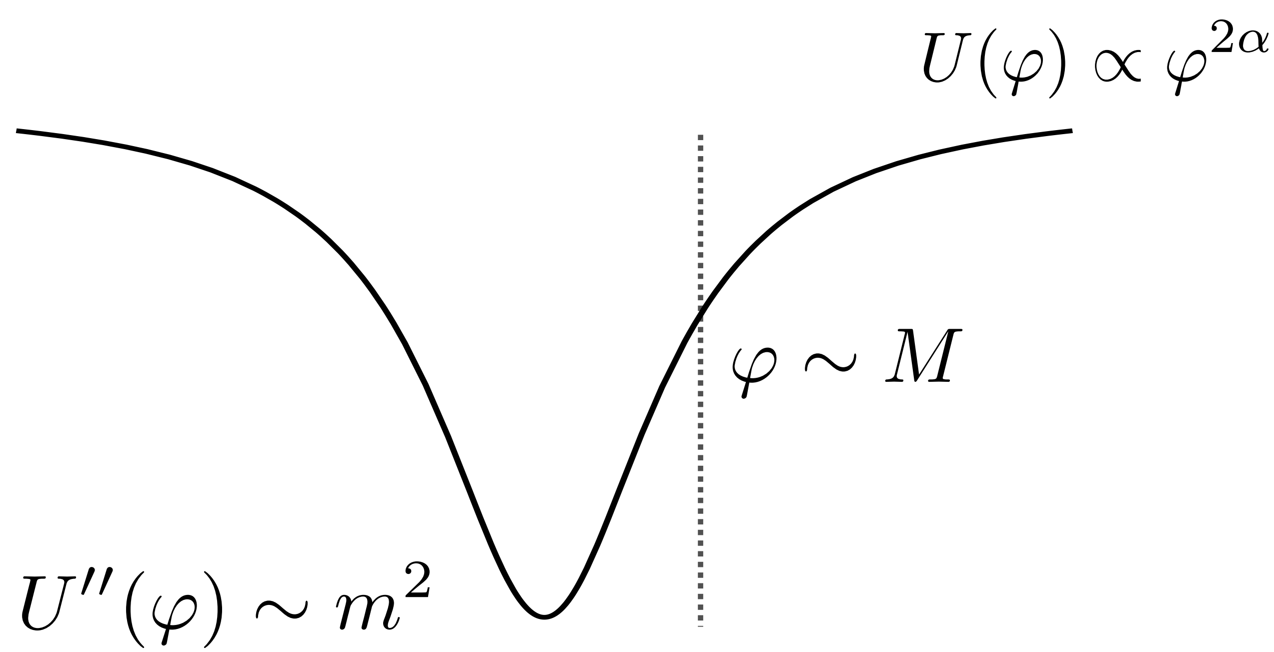
a worked example

$$\alpha \approx 0$$

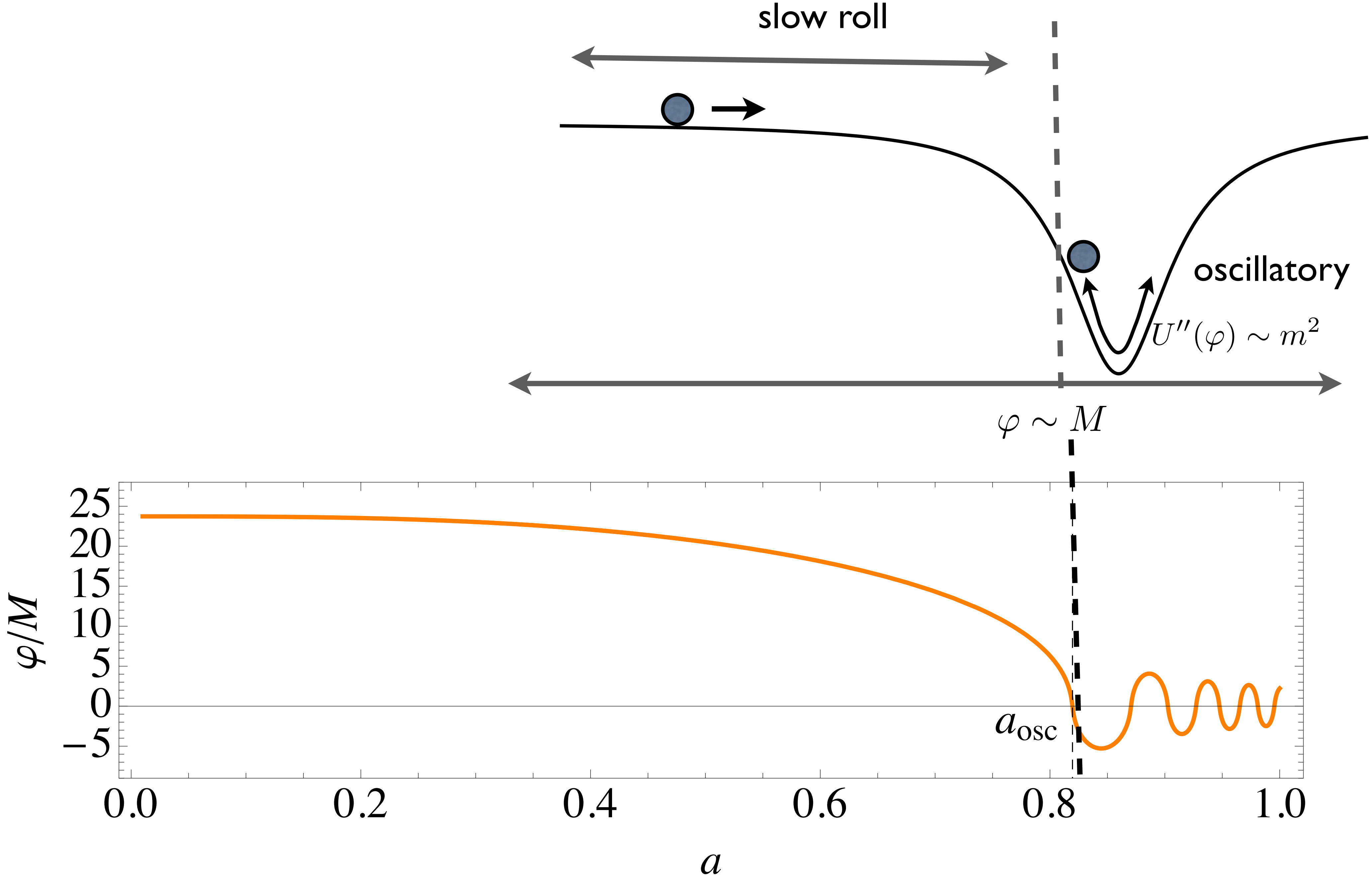
$$M \approx 10^{-3} m_{\rm pl}$$

$$m \approx 10^{3} H_0$$

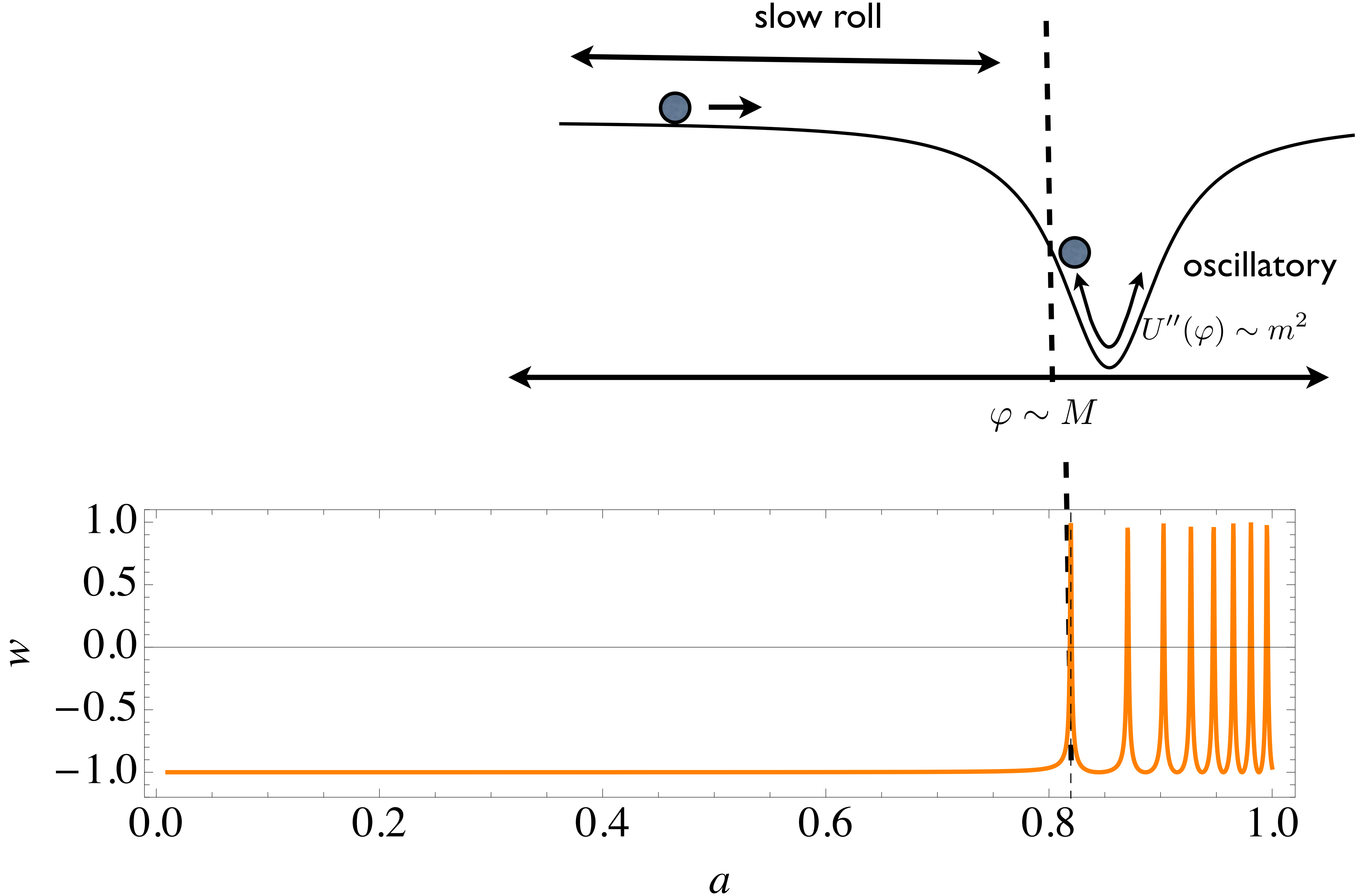
$$\rho \sim m^2 M^2 \sim m_{\rm pl}^2 H_0^2$$



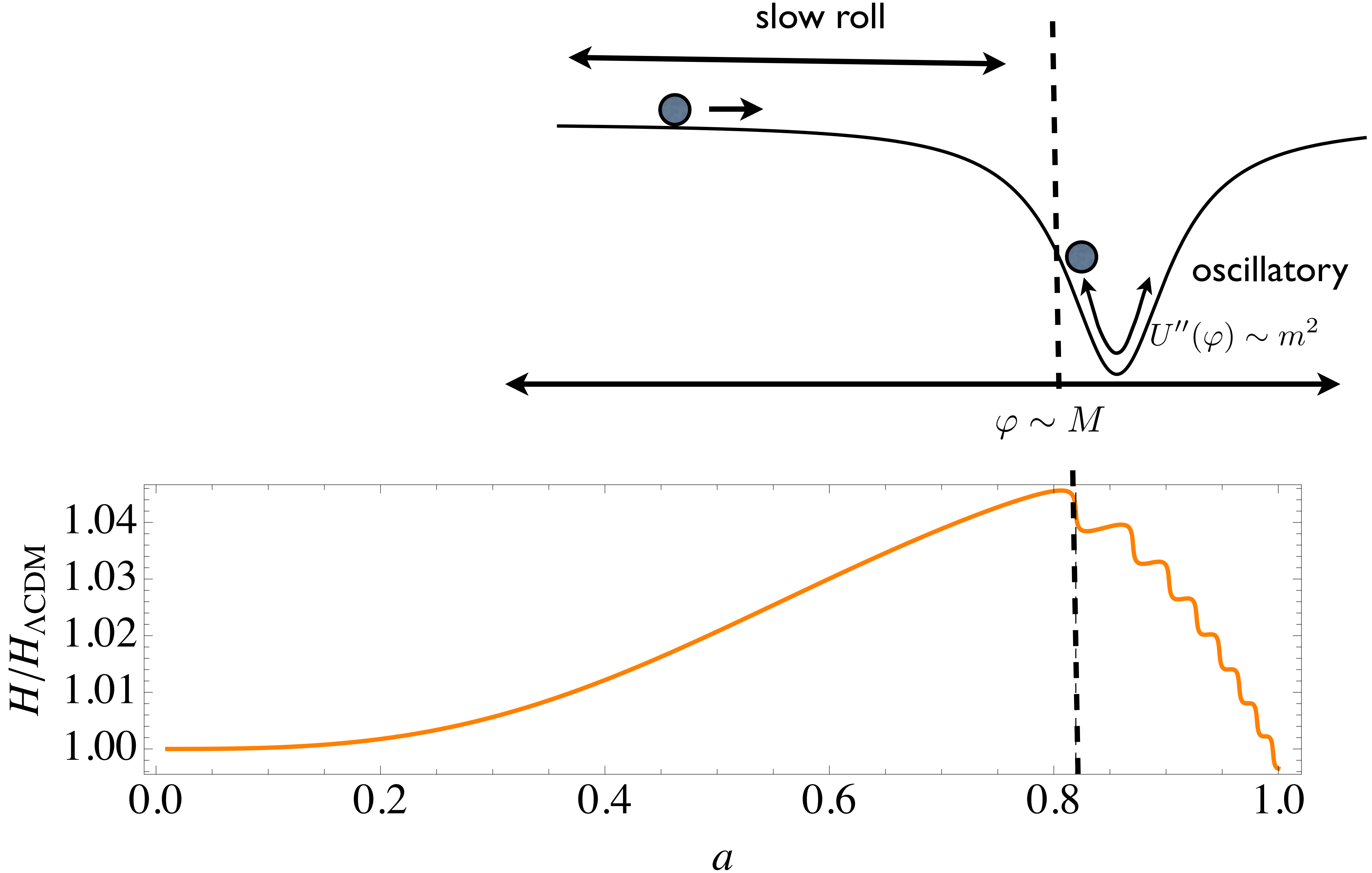
field evolution



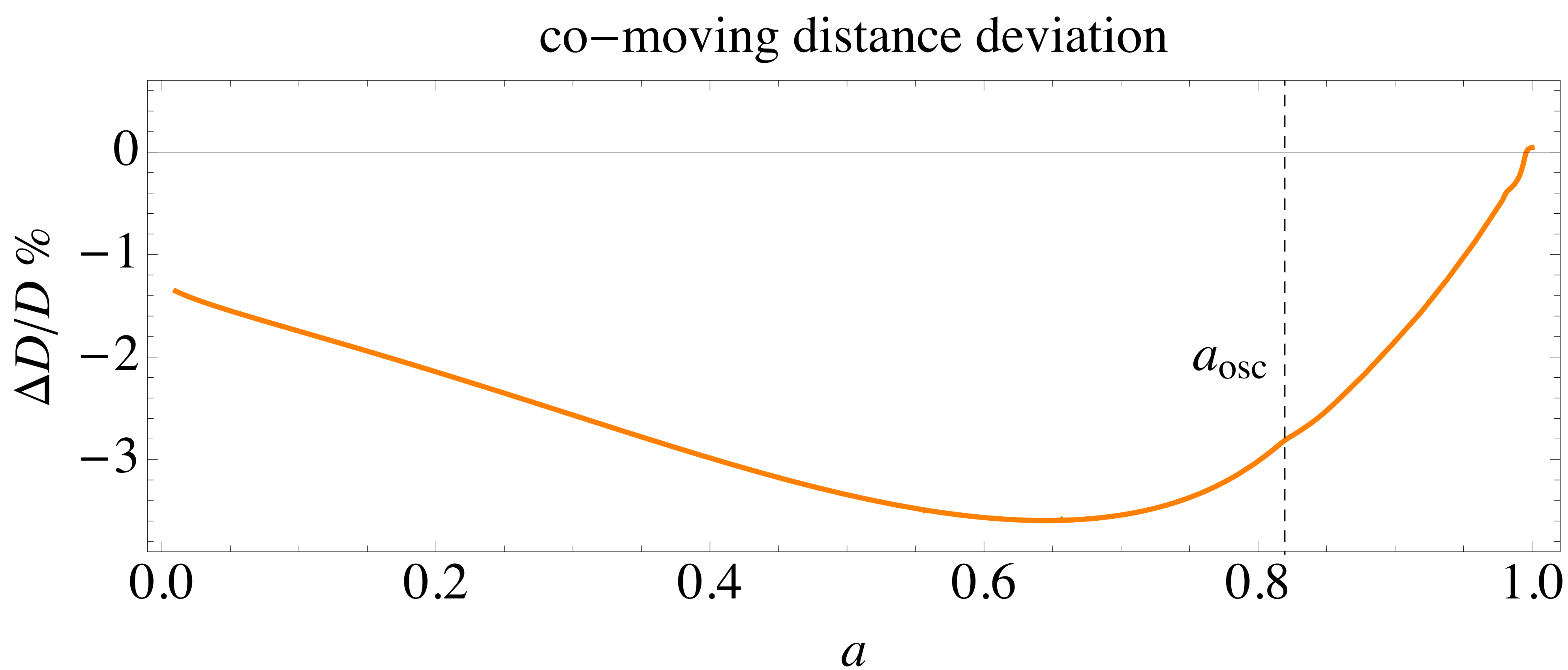
equation of state



Hubble


slow roll
oscillatory
$U''(\varphi) \sim m^2$
$\varphi \sim M$
$H/H_{\Lambda CDM}$
1.04
1.03
1.02
1.01
1.00
0.0
0.2
0.4
0.6
0.8
1.0
a

expansion history



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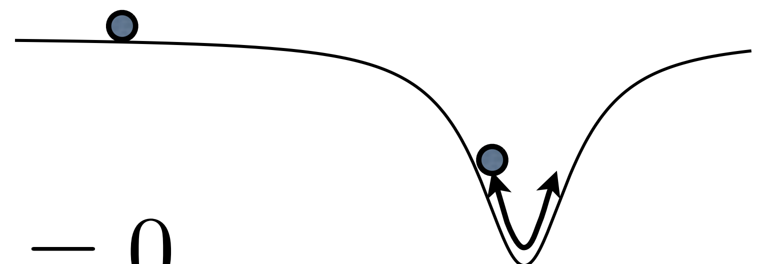
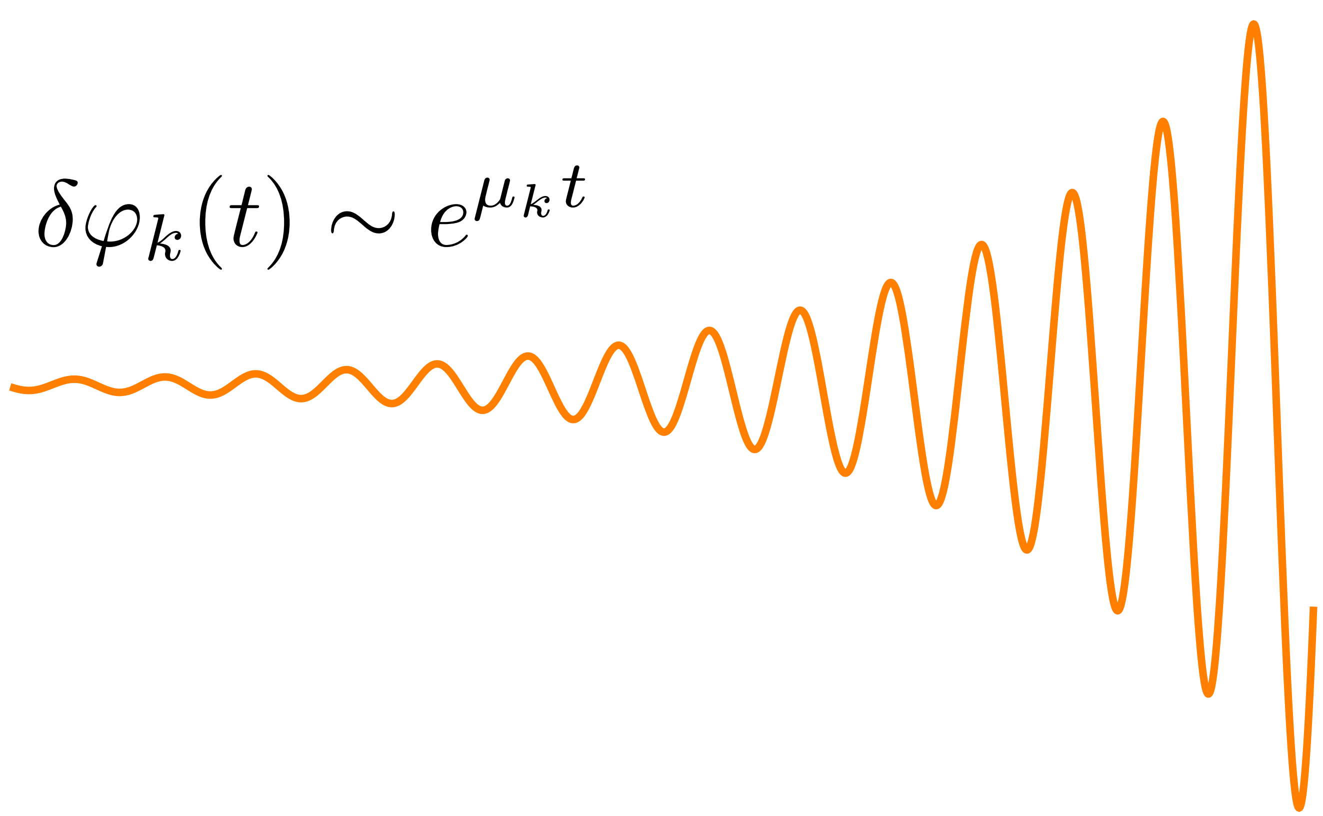
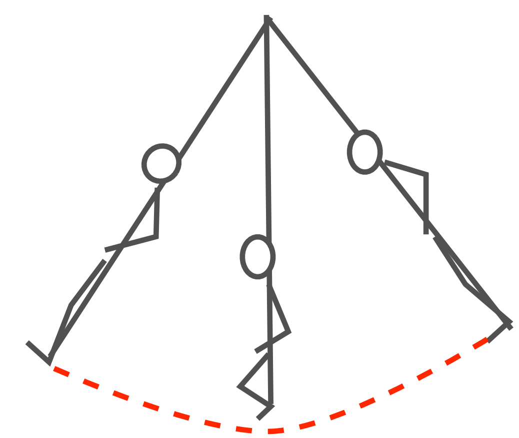
what about perturbations ?



$$\partial_t^2 \delta\varphi_k + \left(k^2 + U''(\bar{\varphi})\right) \delta\varphi_k = 0$$

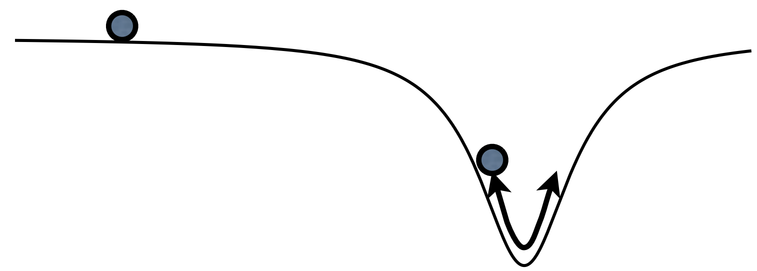
$$\delta\varphi_k(t) \sim e^{\mu_k t}$$

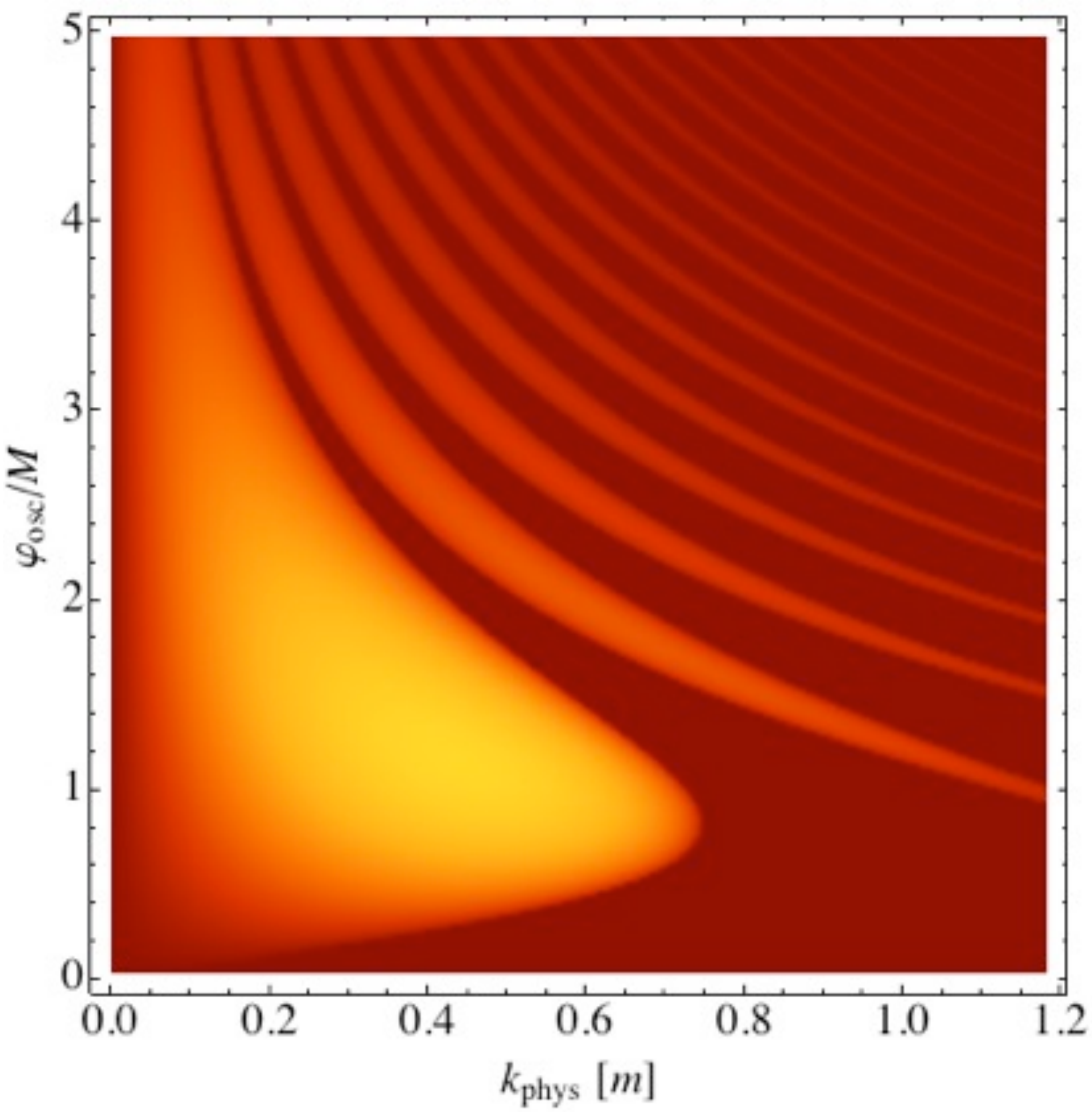




Floquet analysis

$$\partial_t^2 \delta\varphi_k + \left(k^2 + U''(\bar{\varphi})\right) \delta\varphi_k = 0$$





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

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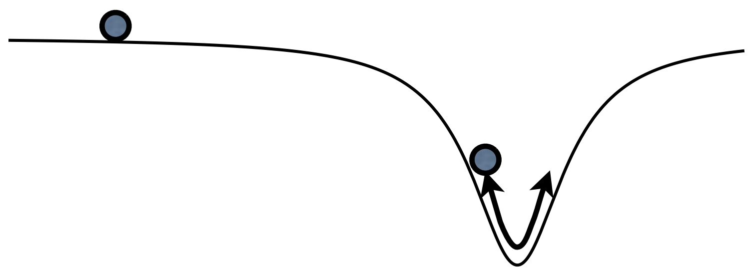
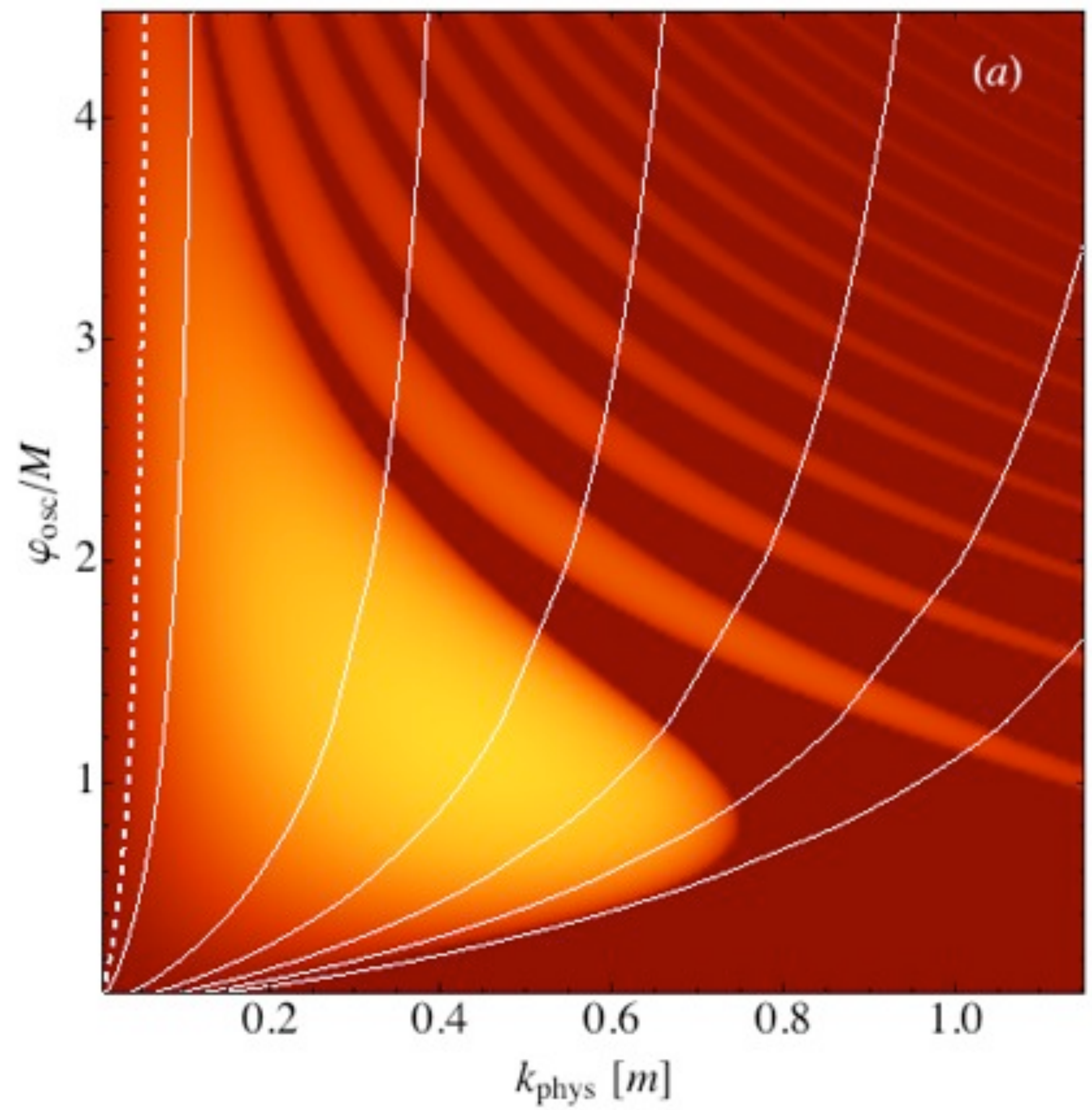
include expansion

$$\partial_t^2 \delta\varphi_k + 3H\partial_t\delta\varphi_k + \left(\frac{k^2}{a^2} + U''(\bar{\varphi})\right)\delta\varphi_k = 0$$





$$\delta\varphi_k \approx \frac{\delta\varphi_k(t_i)}{a^{3/2}(t)} \exp\left[\int dt \mu_k(t)\right]$$

$$= \frac{\delta\varphi_k(a_i)}{a^{3/2}} \exp\left[\int d\ln a \frac{\mu_k(a)}{H(a)}\right]$$

$$\Re(\mu_k) \gg H$$

related interpretations

- imaginary sound speed at low wave-numbers only Johnson & Kamionkowski
- resonant particle production Traschen & Brandenberger, Linde, Kofman& Starobinski

resonant growth: important

- growth on limited range of scales
- growth rate can be much faster than H

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include gravity

$$ds^2 = -(1+2\Phi)dt^2 + a^2(1-2\Psi)dx^2$$

$$\ddot{\delta\varphi}_k + 3H\dot{\delta\varphi}_k + \left[\frac{k^2}{a^2} + U''(\varphi)\right]\delta\varphi_k = -2U'(\varphi)\Psi_k + 4\dot{\varphi}\dot{\Psi}_k$$

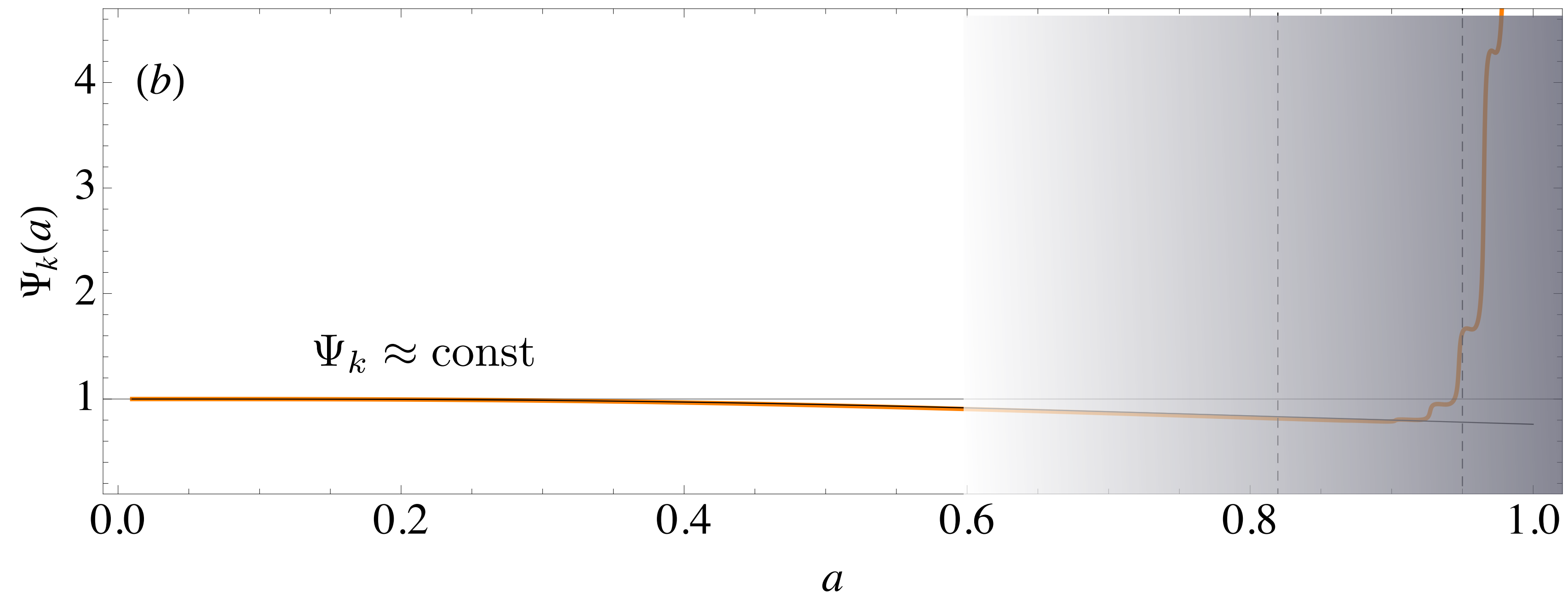
$$\ddot{\Psi}_k + 4H\dot{\Psi}_k + \frac{1}{m_{\rm pl}^2}U(\varphi)\Psi_k = \frac{1}{2m_{\rm pl}^2}\left[\dot{\varphi}\dot{\delta\varphi}_k - U'(\varphi)\delta\varphi_k\right]$$

$\Phi_k = \Psi_k$ no anistropic stress

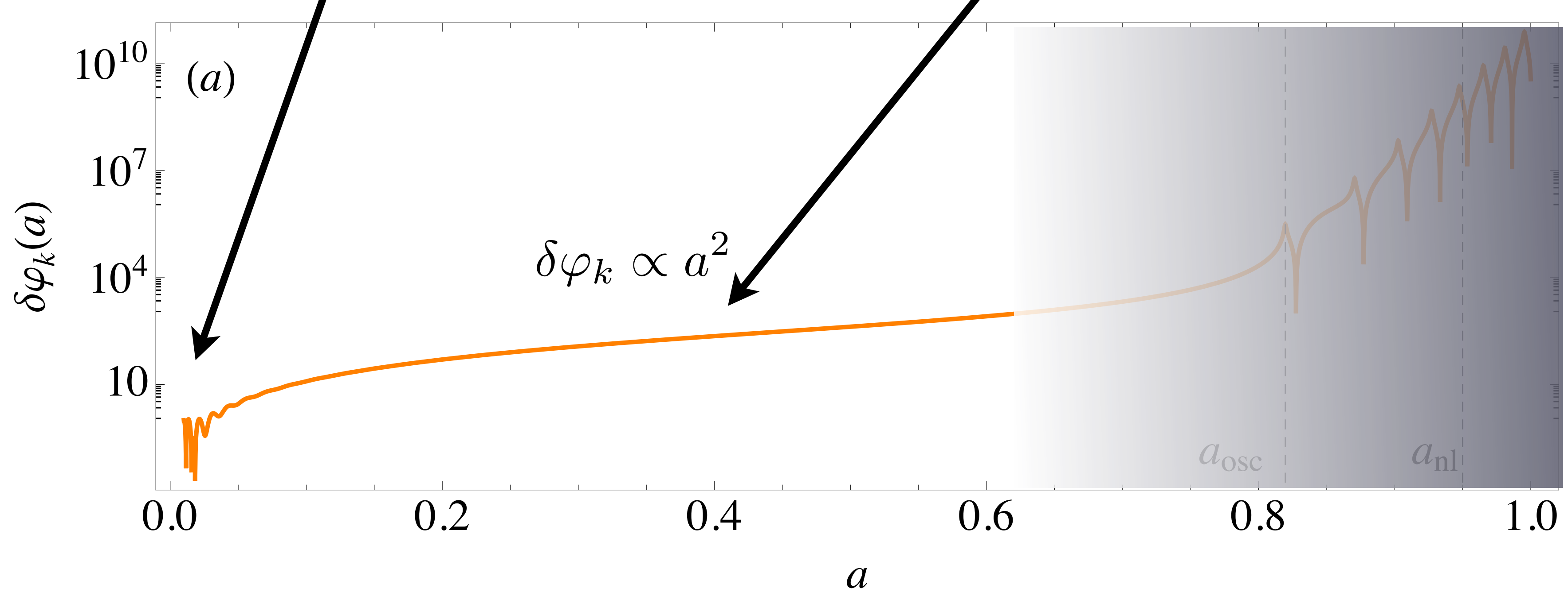
Note: dark matter perturbations included via constraints

initial conditions

(during matter domination)



$$\delta\varphi_k = \frac{c_k}{k_H^3}\left[\cos(2k_H + \Delta_k) + 2k_H \sin(2k_H + \Delta_k)\right] - 2\Psi_k \frac{U'(\varphi)}{H^2}\frac{1}{k_H^2}\left[1 - \frac{7}{k_H^2} + \frac{35}{2k_H^4}\right]$$



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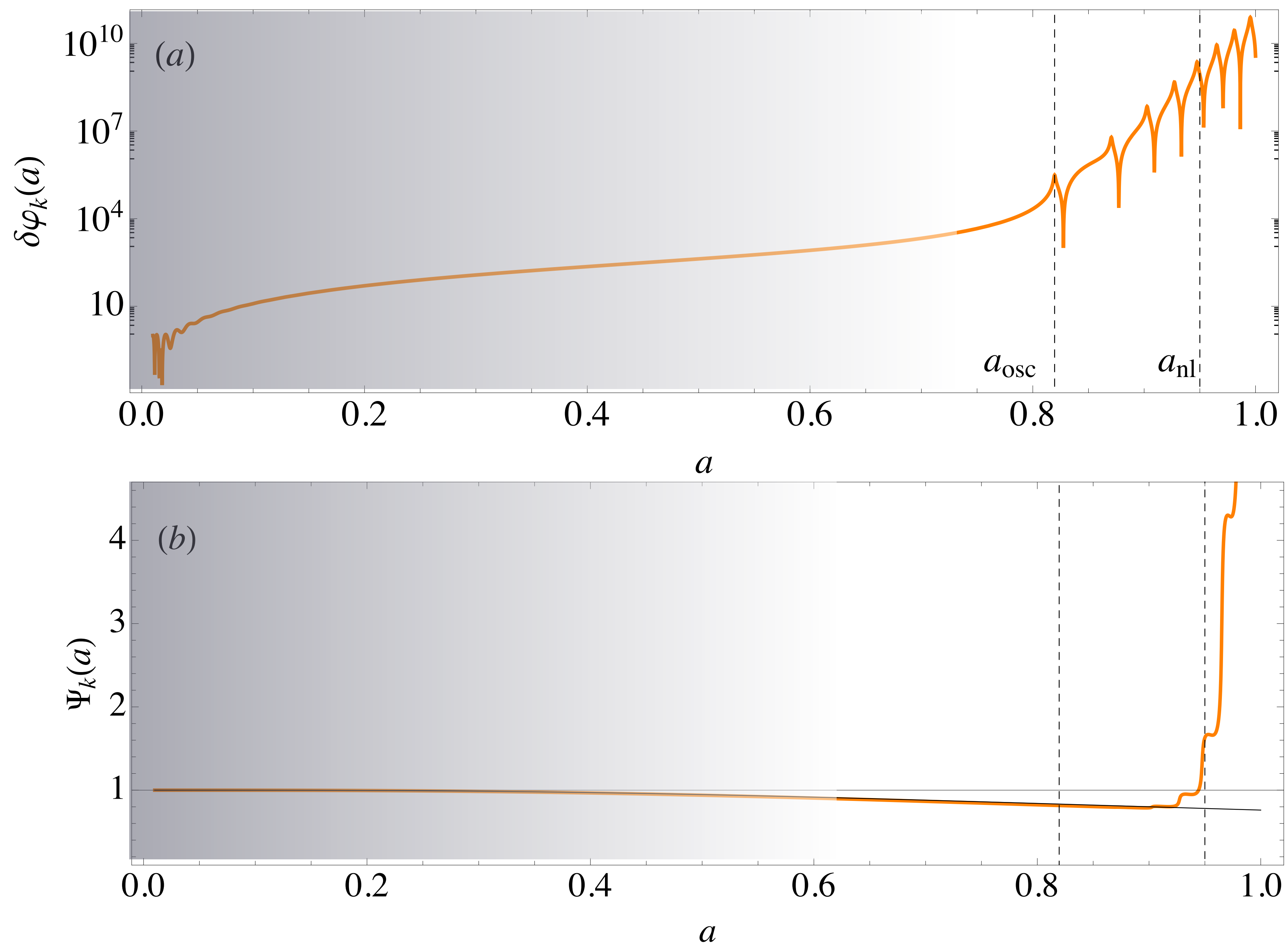
quintessence + gravitational potential



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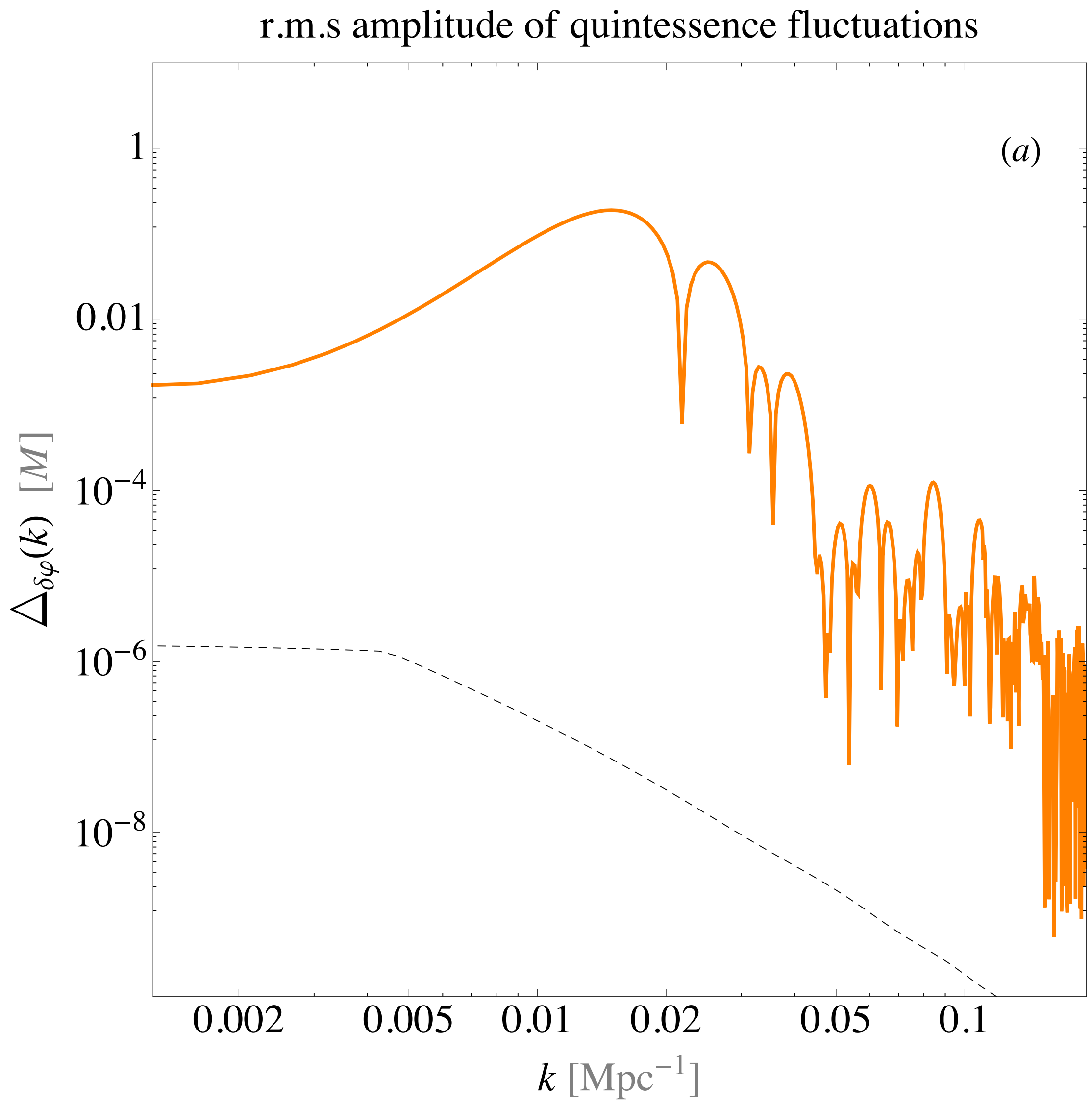
limits of linear analysis



$$\langle \delta\varphi^2 \rangle_L^{1/2} = [\Delta_{\delta\varphi}(k,a)]_{k\sim L^{-1}}$$

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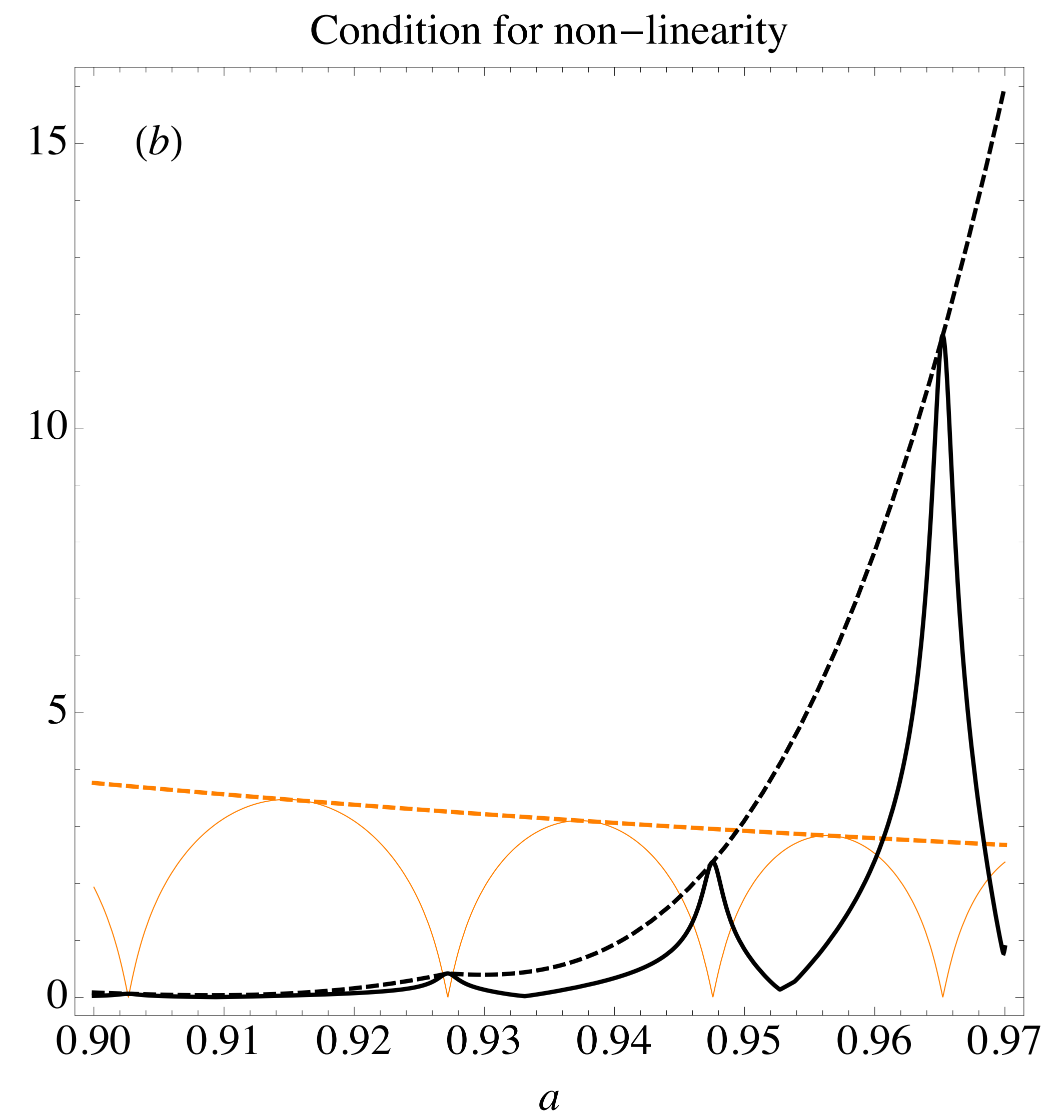
limits of linear analysis

$$\Delta_{\delta\varphi}(k, a_{\rm nl}) \sim \varphi_{\rm osc}(a_{\rm nl}).$$



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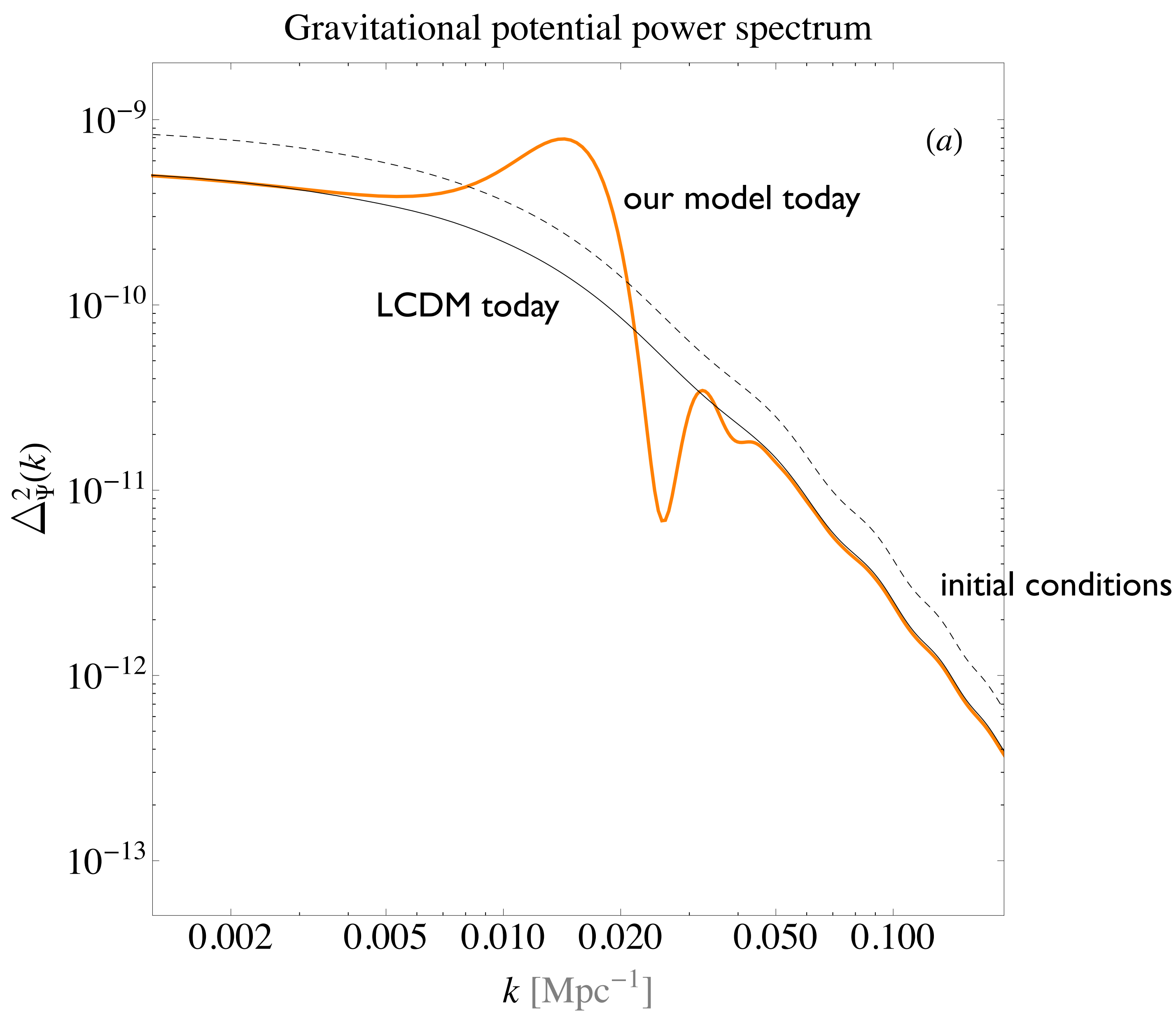
power spectra

(i) gravitational potential
(ii) dark matter (WIMP)

potential power spectrum



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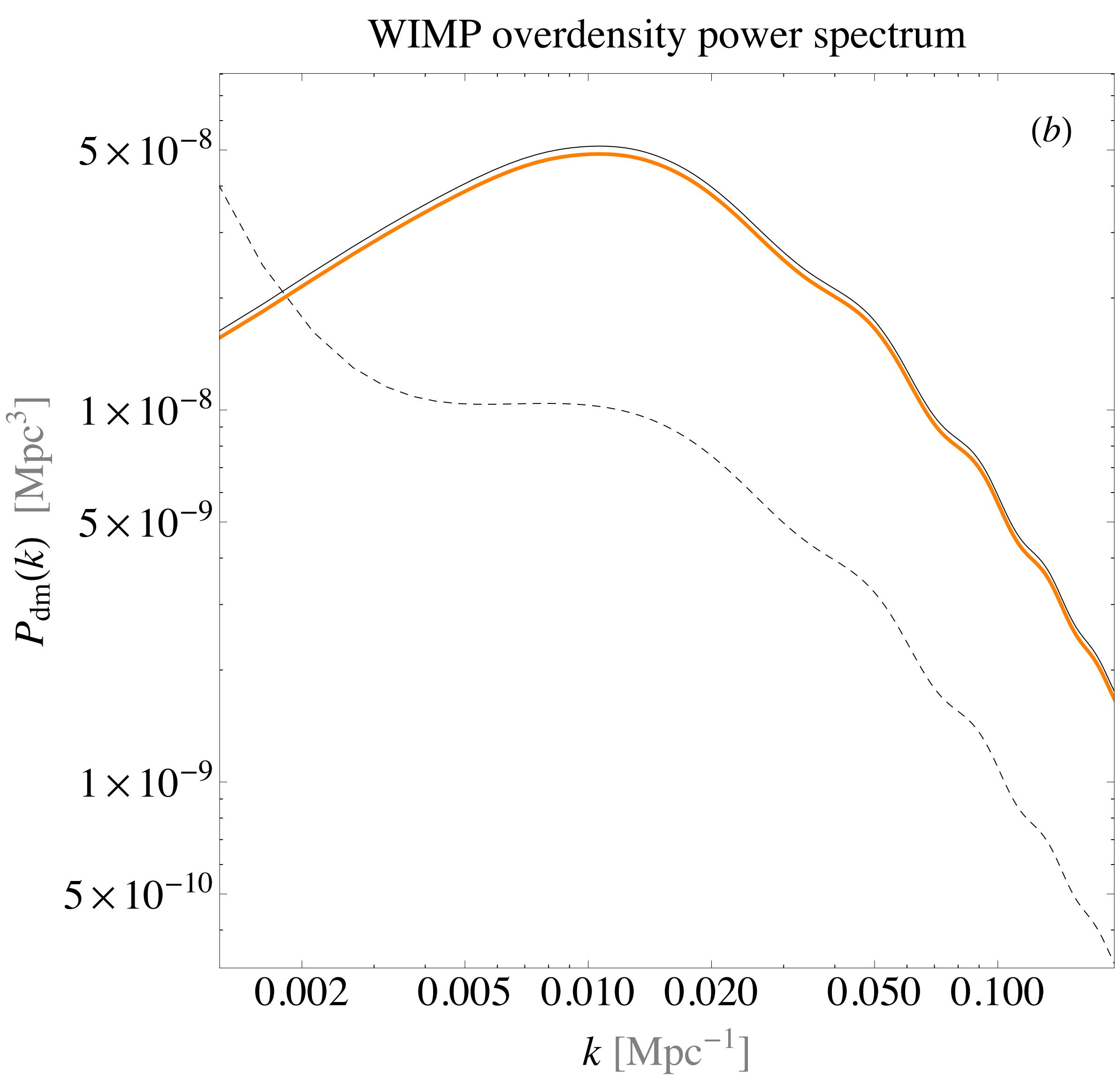
initial condition consistent with LCDM at early times (CAMB/CMBFast)

matter power spectrum



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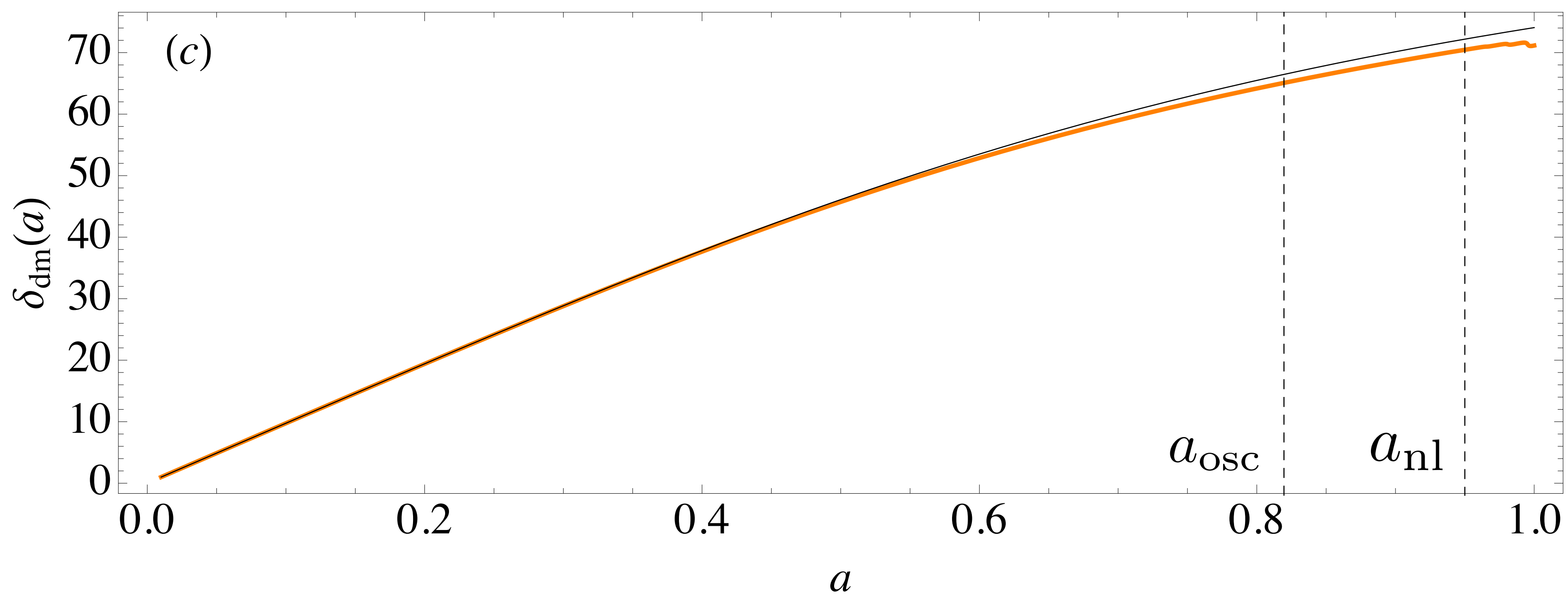
dark matter (WIMP) growth

$$\delta_{\rm dm} = -\frac{a^3}{3H_0^2\Omega_{\rm dm}}\left[\left(6H^2 - \frac{\dot\varphi^2}{m_{\rm pl}^2} + 2\frac{k^2}{a^2}\right)\Psi_k + 6H\dot\Psi_k + \frac{\dot\varphi}{m_{\rm pl}^2}\dot{\delta\varphi}_k + \frac{1}{m_{\rm pl}^2}U'(\varphi)\delta\varphi_k\right]$$



$$\ddot\delta_{\rm dm} + 2H\dot\delta_{\rm dm} = -\frac{k^2}{a^2}\Psi_k + 3\left(2H\dot\Psi_k + \ddot\Psi_k\right).$$

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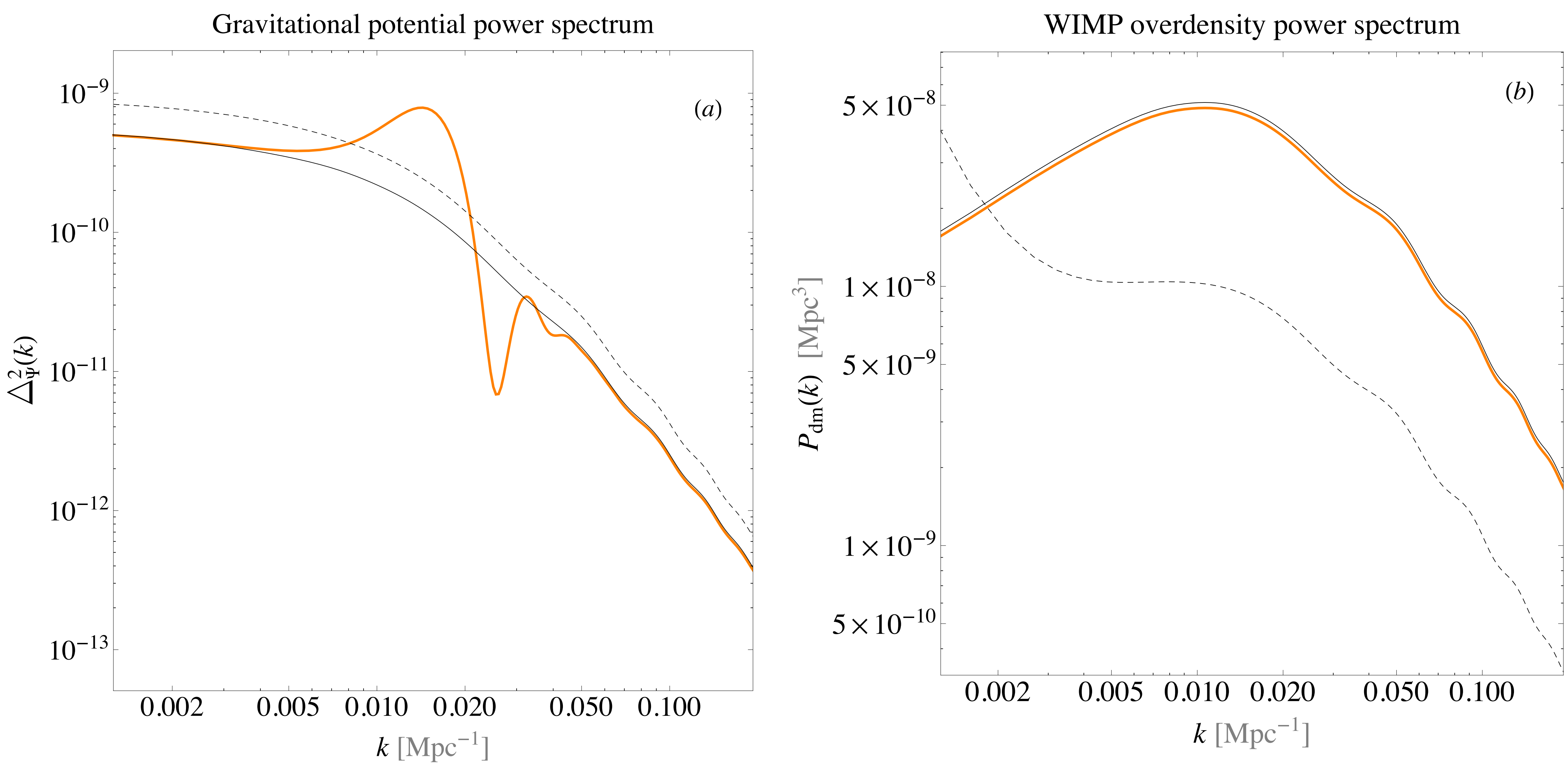
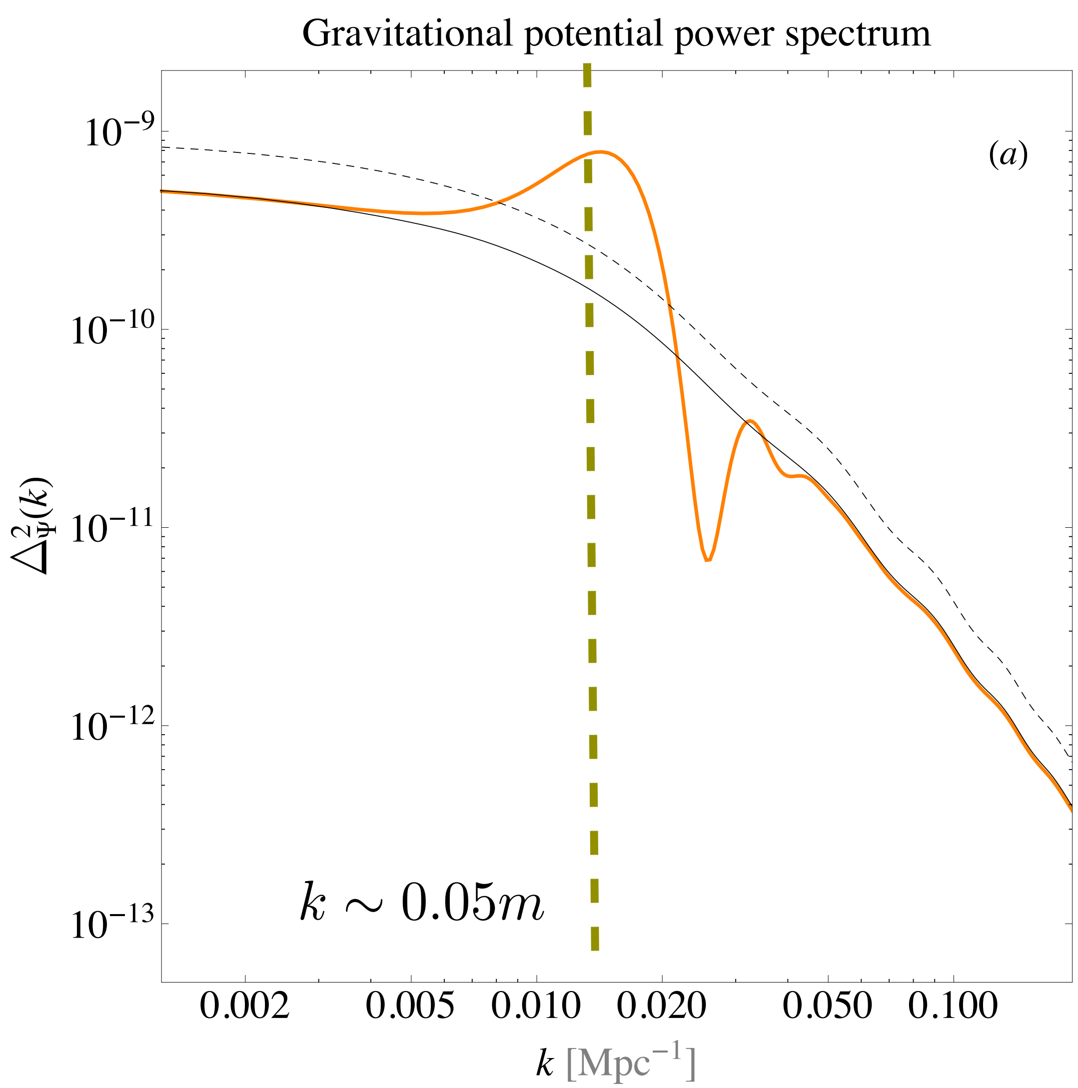
important

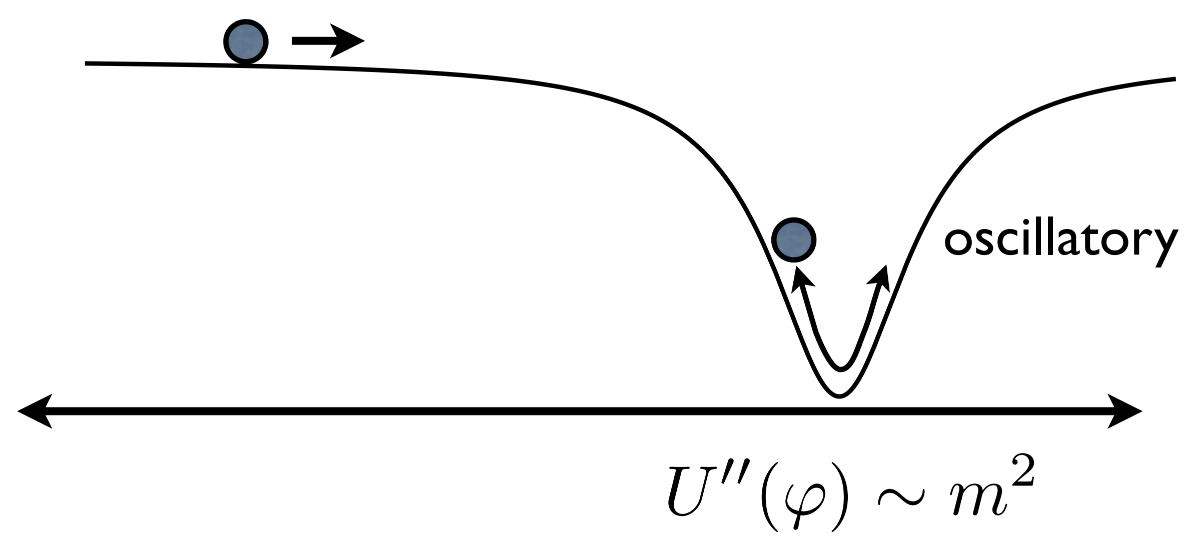


Gravitational potential power spectrum
(a)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$\Delta^2_\Psi(k)$
0.002 0.005 0.010 0.020 0.050 0.100
k [Mpc^{-1}]
WIMP overdensity power spectrum
(b)
5×10^{-8}
1×10^{-8}
5×10^{-9}
1×10^{-9}
5×10^{-10}
$P_{\rm dm}(k)$ [Mpc^3]
0.002 0.005 0.010 0.020 0.050 0.100
k [Mpc^{-1}]

one important scale

after fixing expansion history





galaxies and dark matter respond more slowly

observational signature!

- extra power in potential (see it in lensing)
- rapid change in potential (see in ISW)
- not so in the matter power spectrum (see in galaxy power spectrum)

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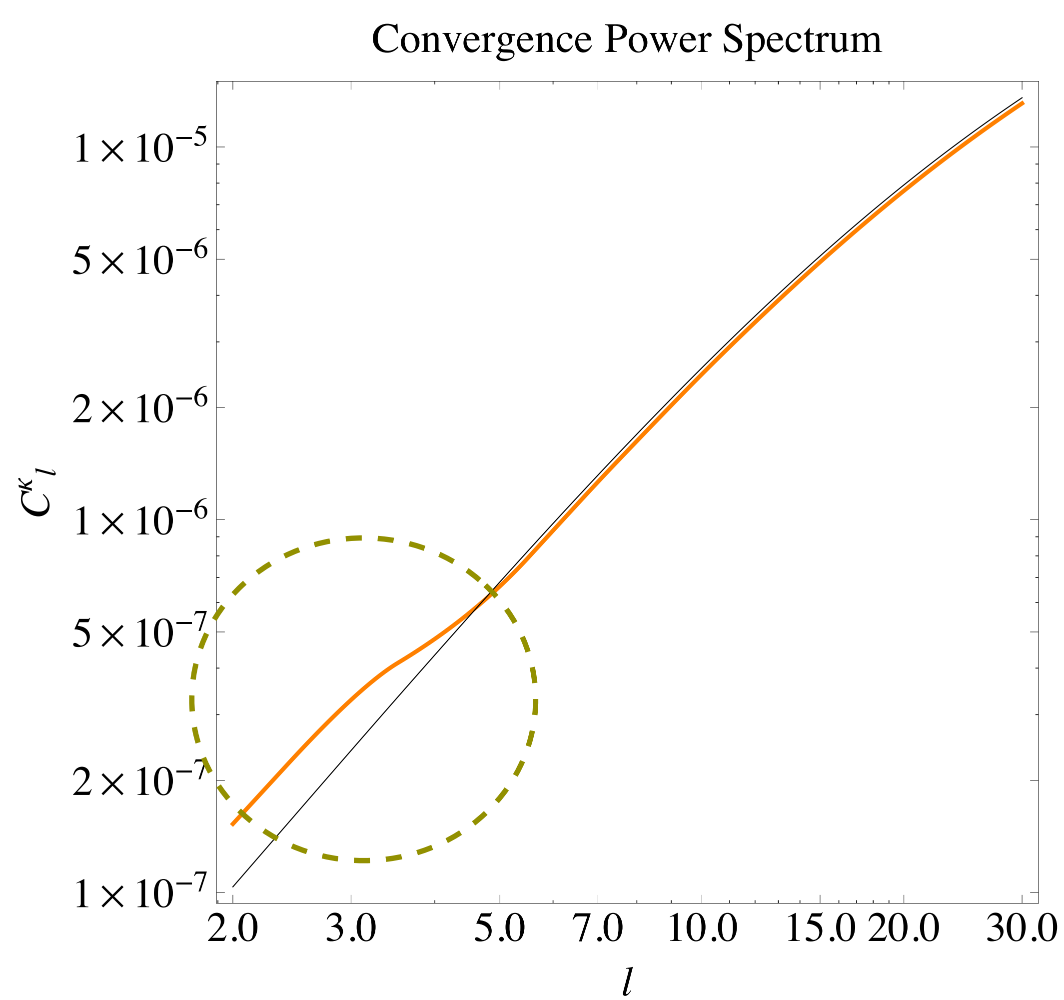
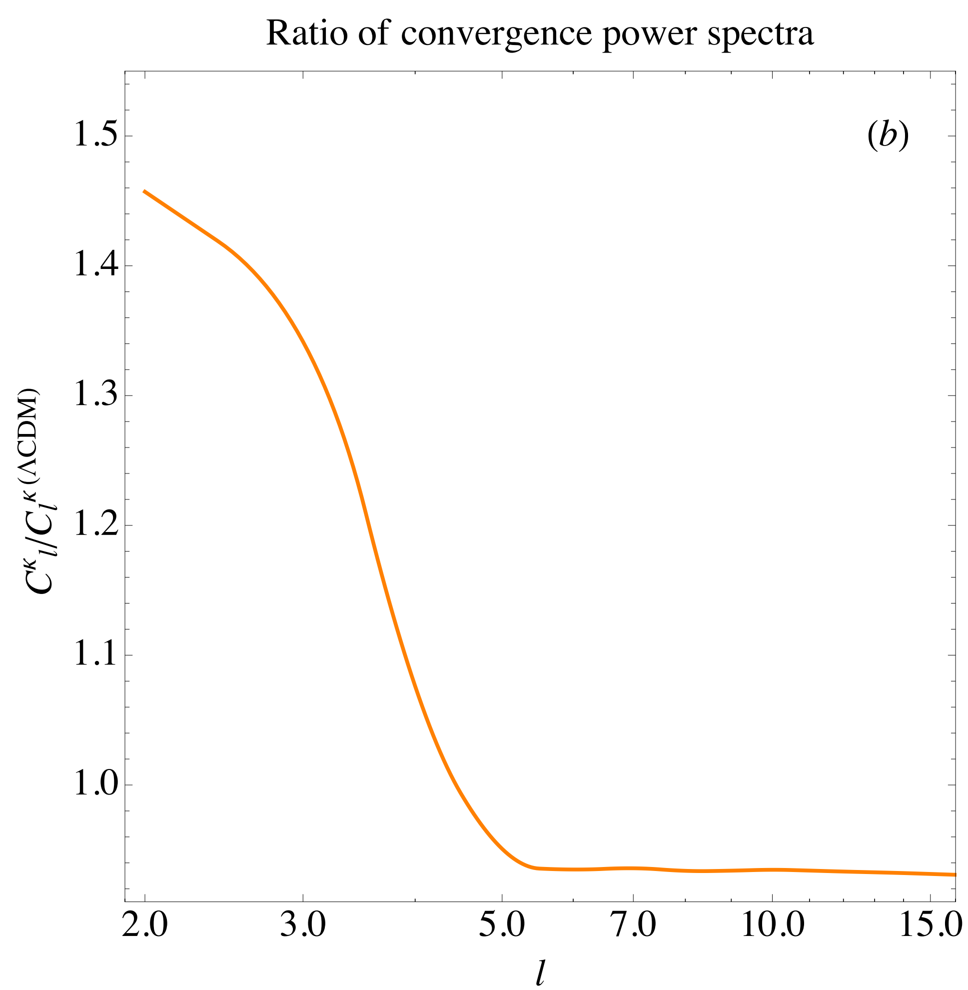
weak lensing

recent growth implies large angles

$$l \sim \theta^{-1} \sim k_{\rm res} D_A$$





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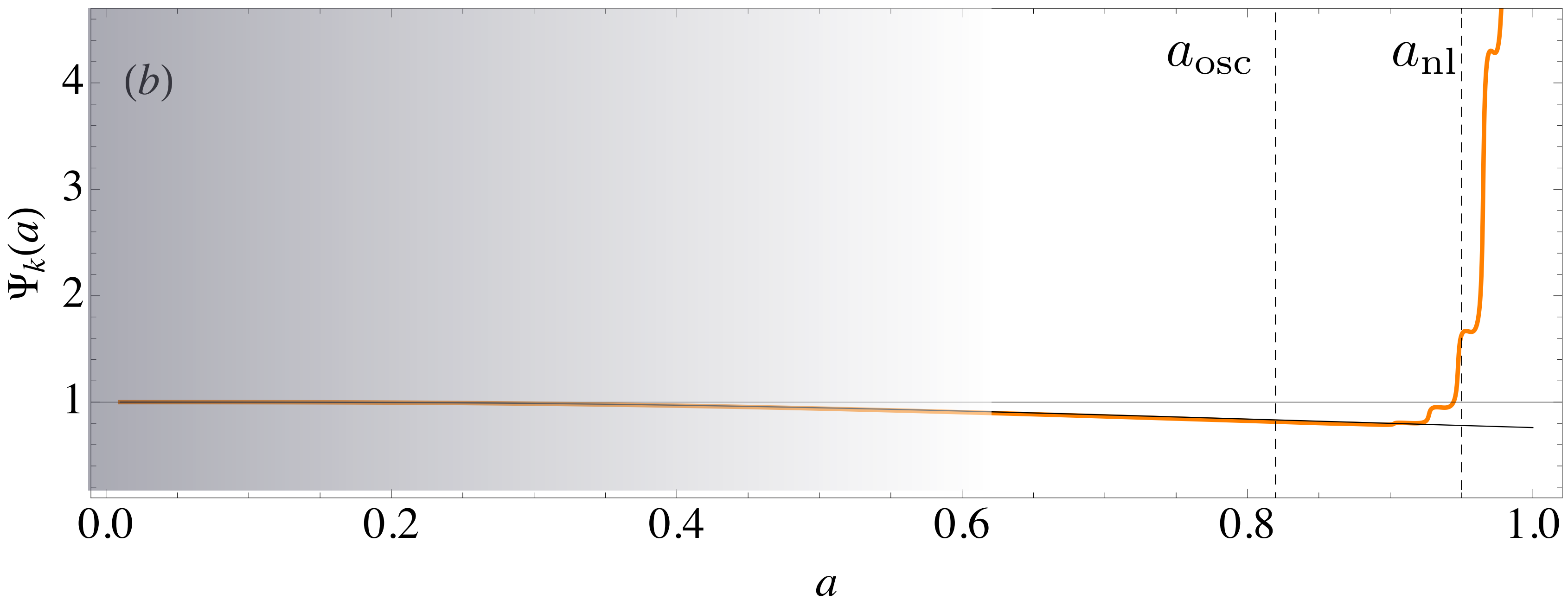
assumed LCDM expansion history

integrated sachs-wolfe



$$\Delta_l^{ISW}(k) = \int_{a_i}^{a_{\rm nl}} da\; j_l(k\chi_a)[\partial_a(\Psi_k + \Phi_k)]$$

$$\approx 2\sum_j j_l(k\chi_{a_j})\Delta\Psi_k(a_j)$$

$$\Delta_l(k) = \Delta_l^{SW}(k) + \Delta_l^{ISW}(k)$$

$$C_l = \int d\ln k\; k^3 \Delta_l^2(k)$$

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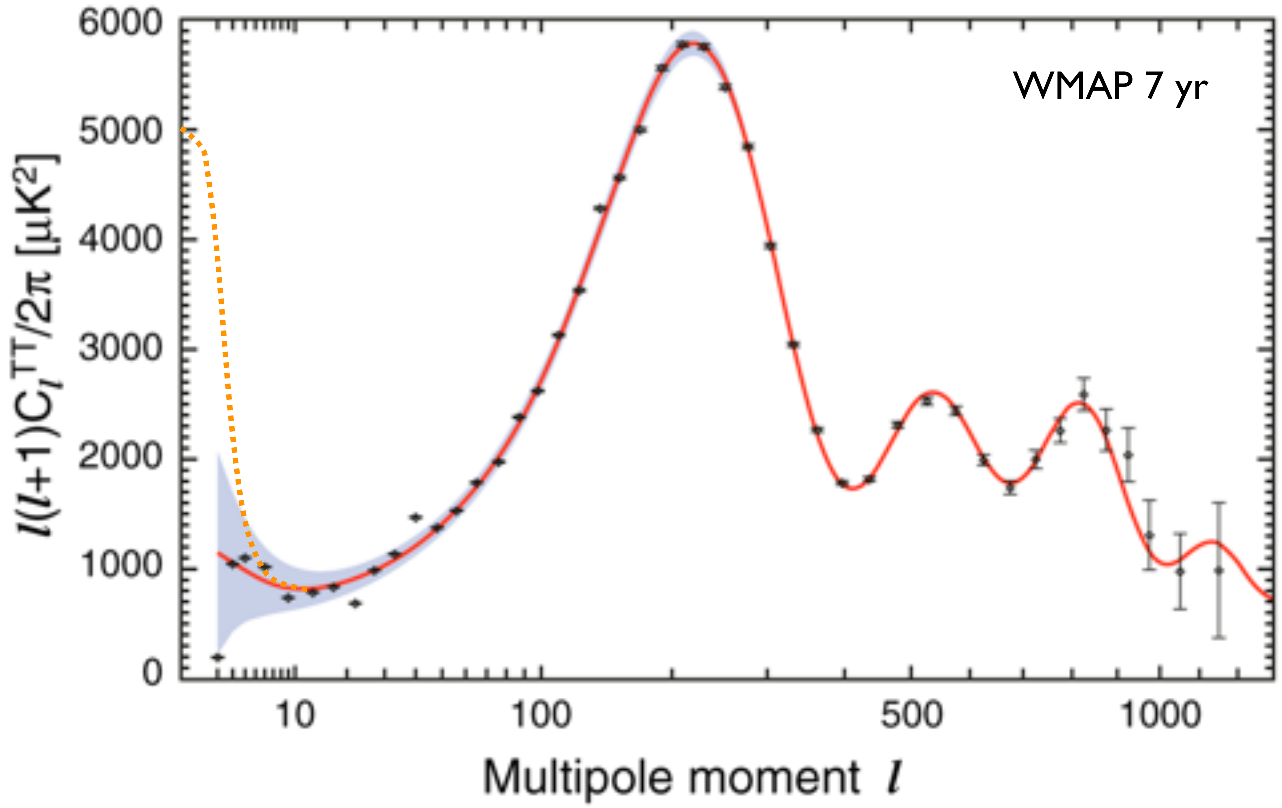
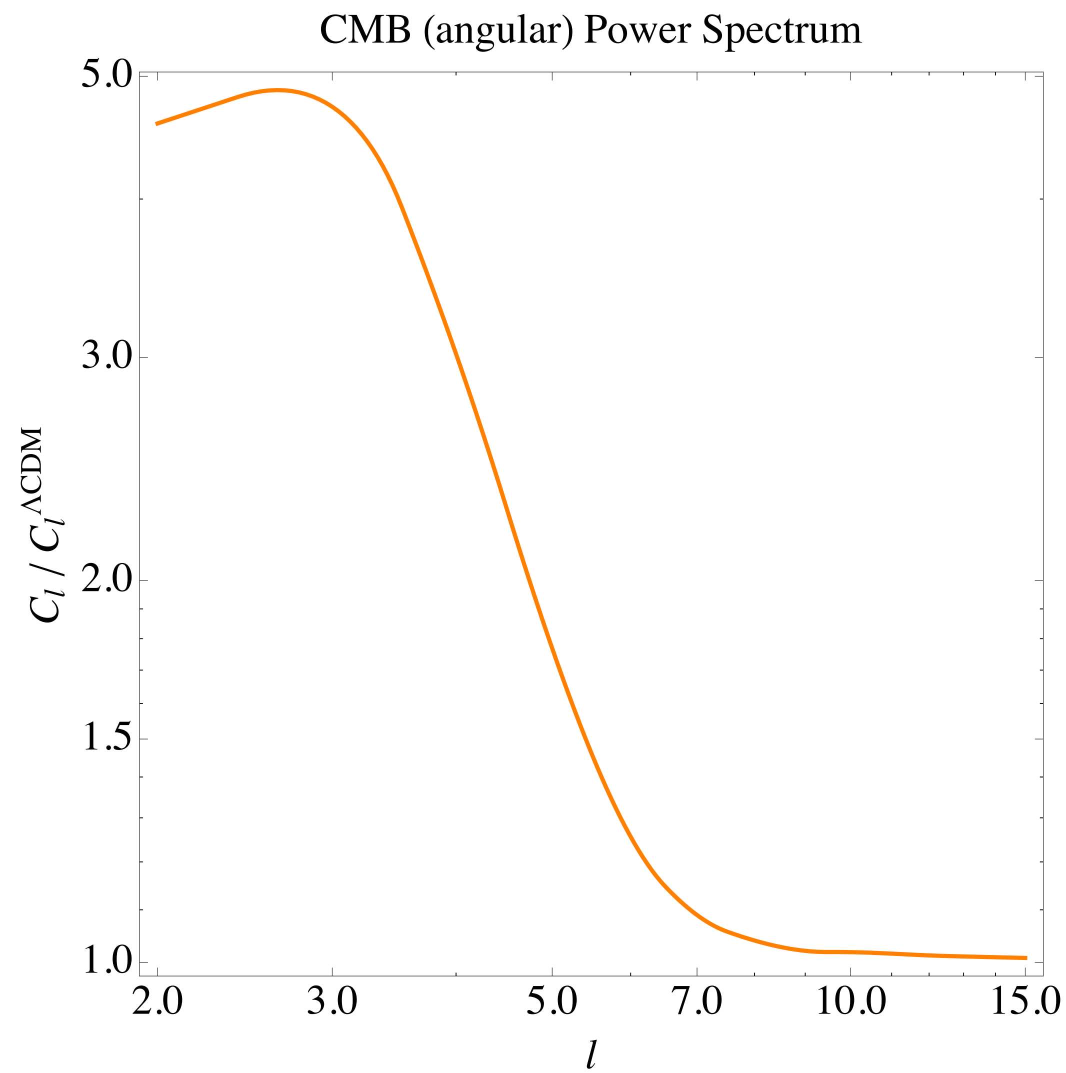
integrated Sachs-Wolfe





assumed LCDM expansion history

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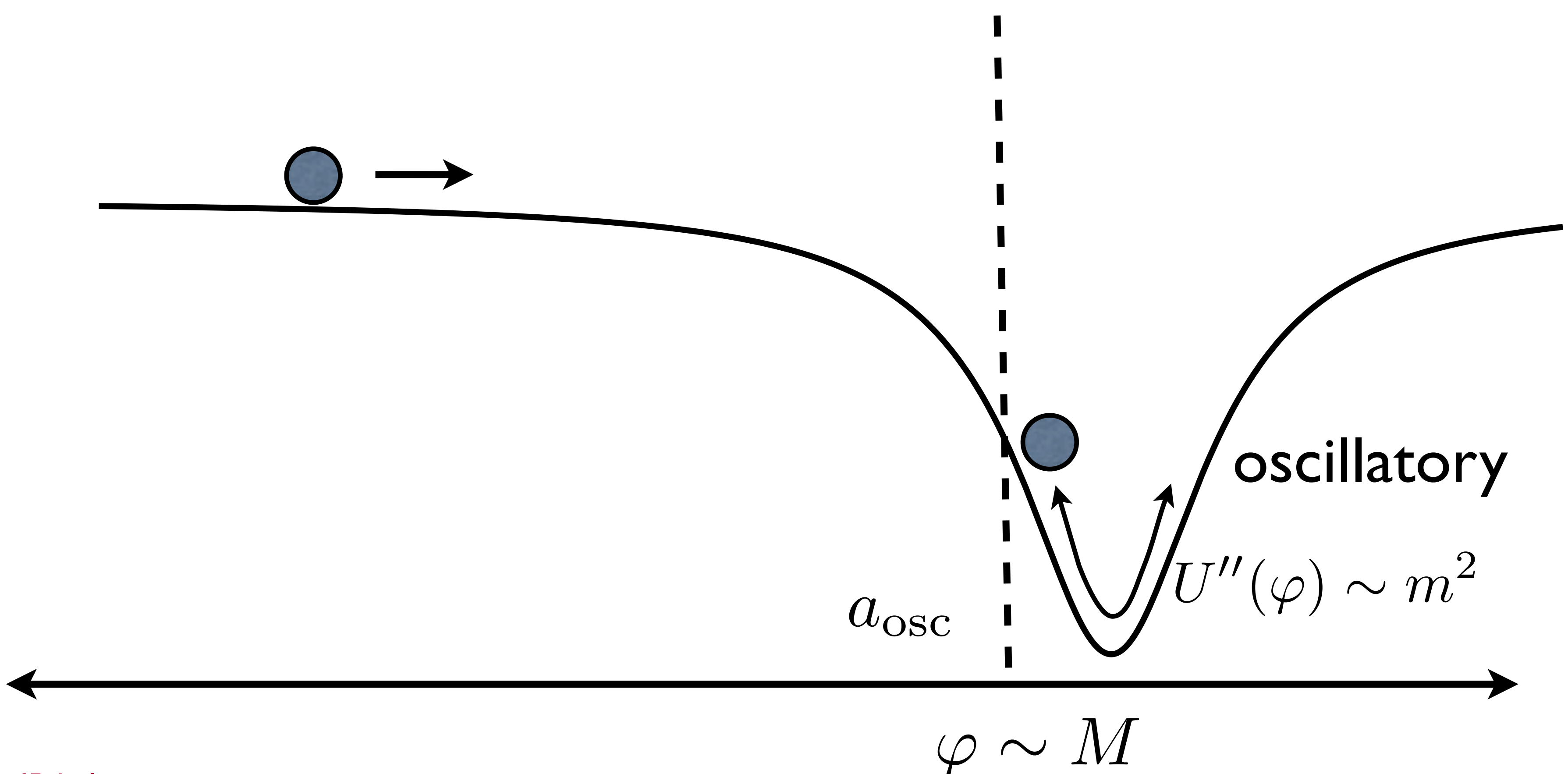
choice of params.

- change time of transition a_{osc}
- change m to change number of oscillations
- M (linked to m) determines rate of growth
- change slope of potential (not easy)



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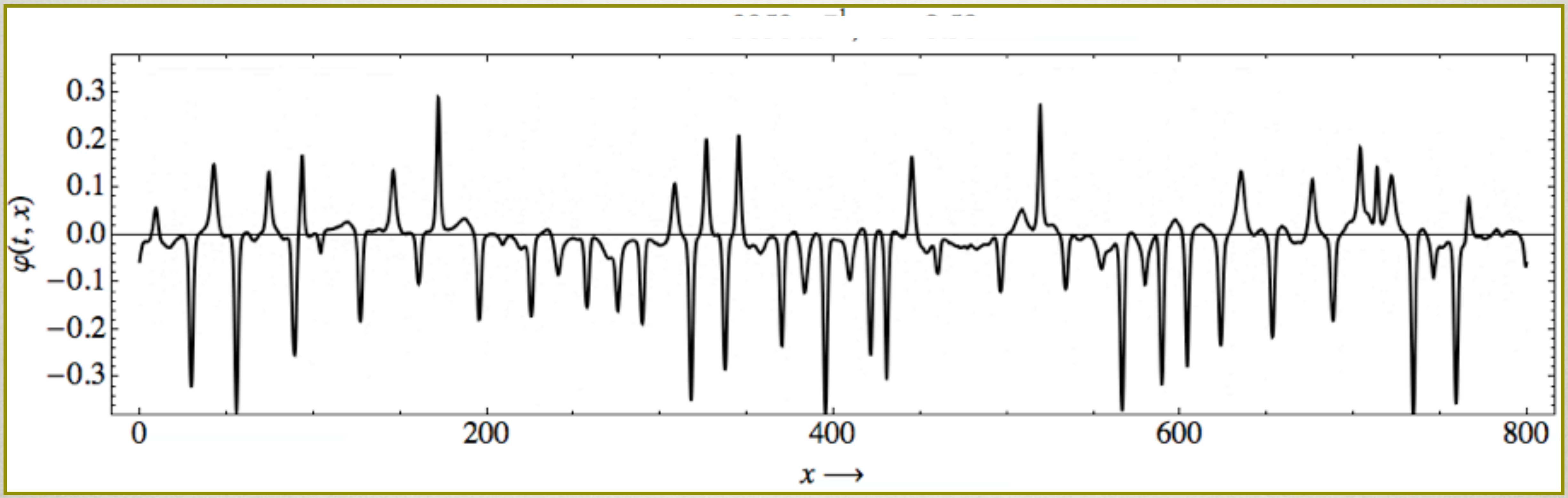
Qualitative

Non-Linearity

Qualitative

non-linearity and fragmentation

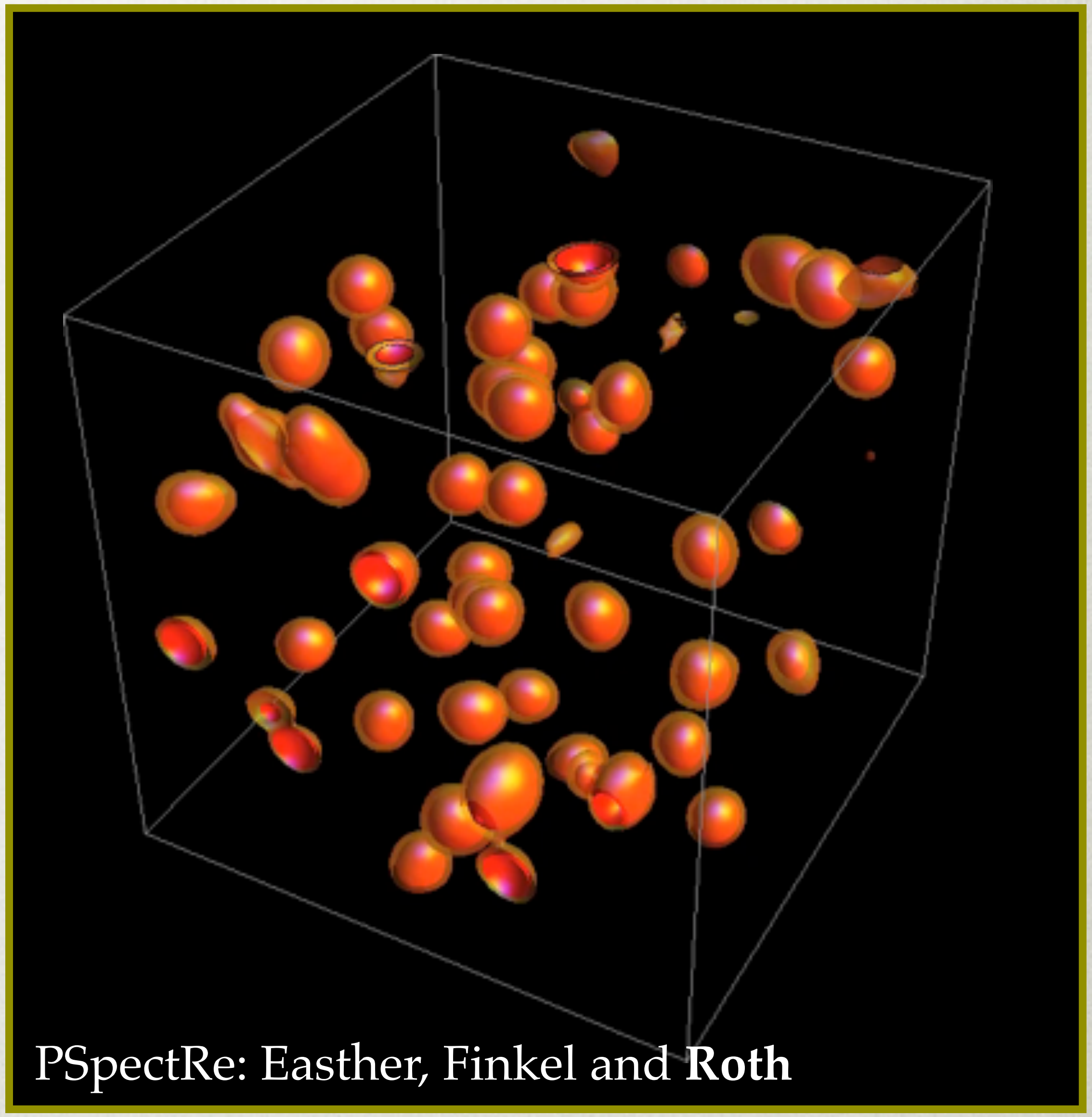


MA (2010)

rich non-linear phenomenology

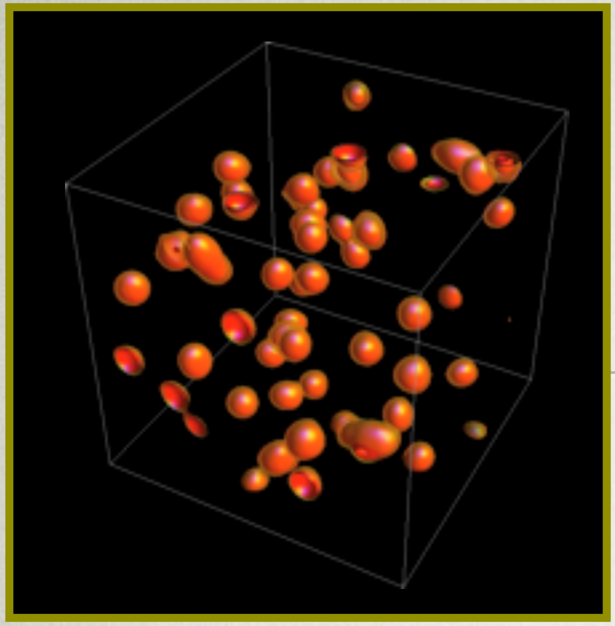
nonlinear fragmentation!

(-- additional ISW --)



MA 2010
MA, Finkel, Easther 2010
MA, Easther, Finkel, Flauger, Hertzberg 2011

Also see McDonald&Broadhead, Hindmarsh & Salmi, Gleiser et. al ...



LUMPS?

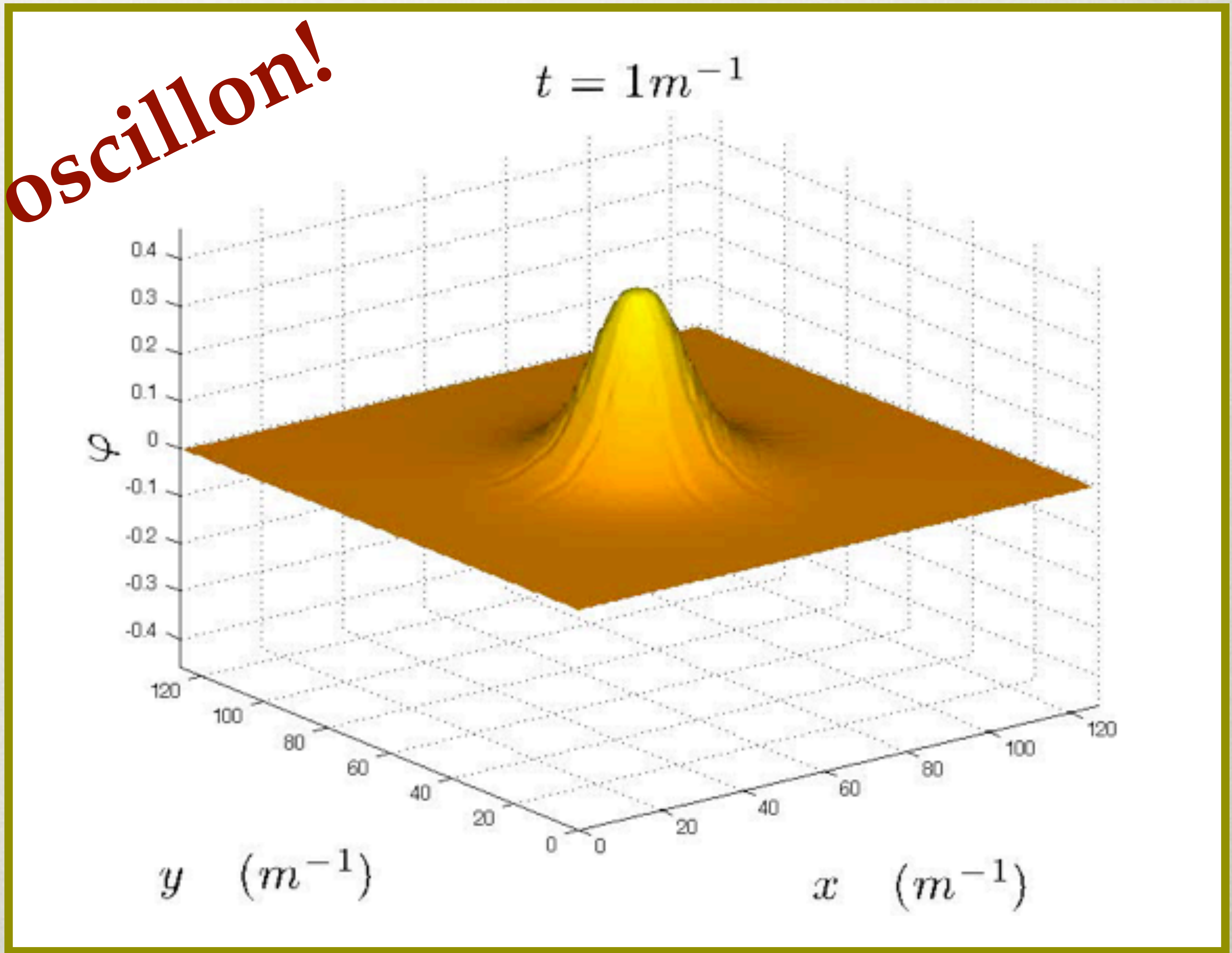
(1) oscillatory (2) spatially localized (3) **very long lived**

necessary:

$$V(\varphi) - \frac{1}{2}m^2\varphi^2 < 0$$

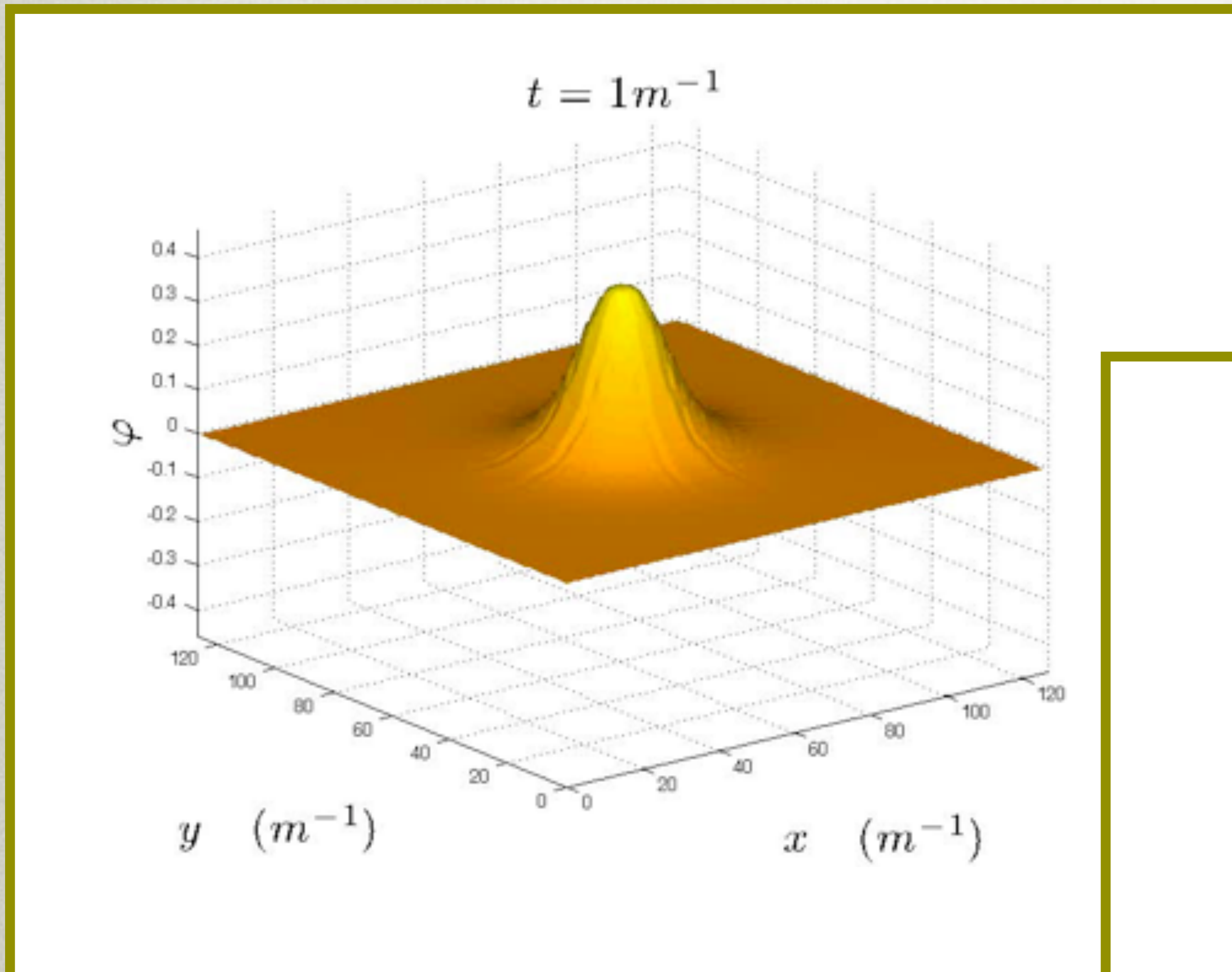
for some range of φ

satisfied if $\alpha < 1$

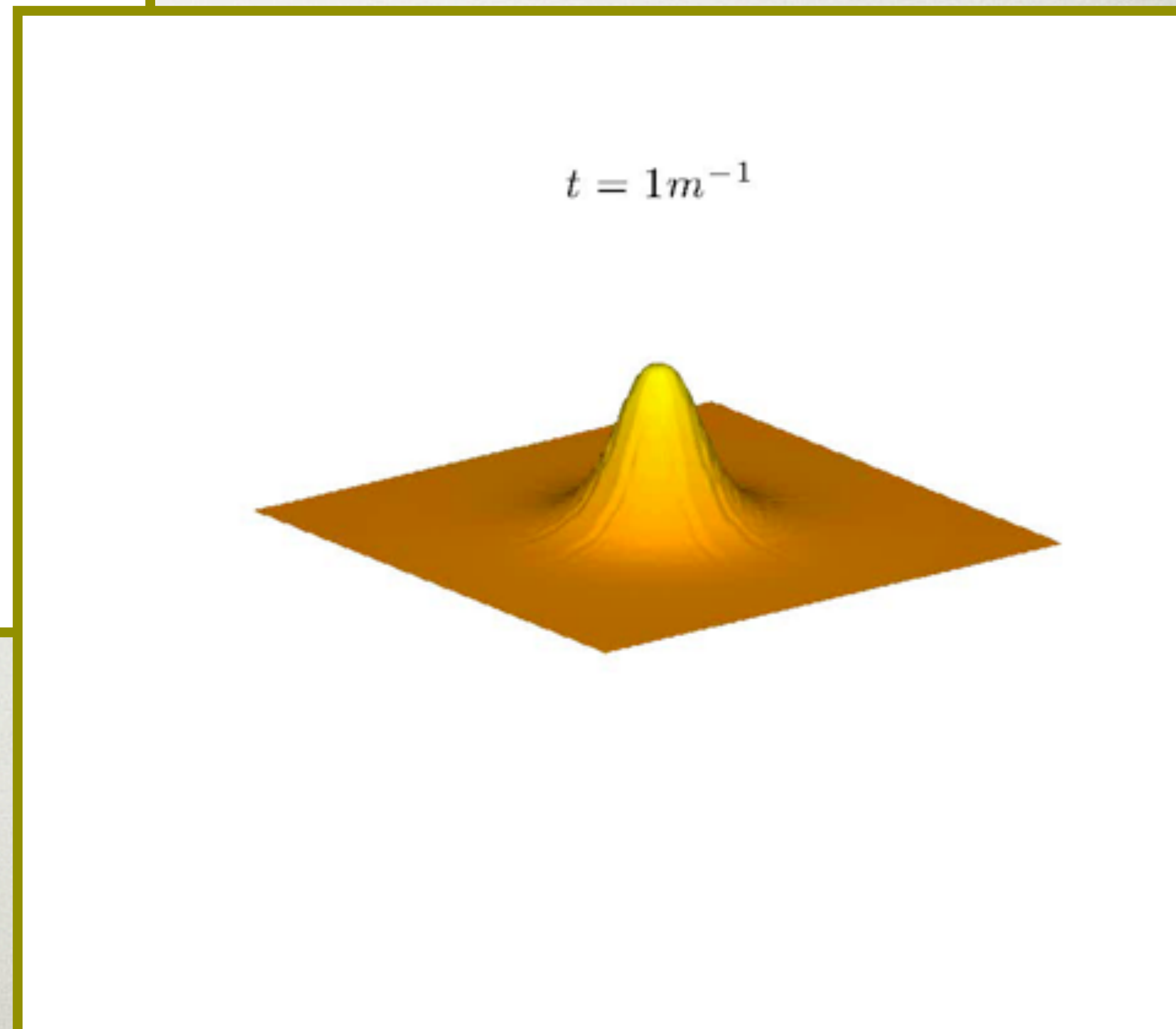


Bogolubsky & Makhankov 1976, *Gleiser* 1994, *Copeland* et al. 1995, ...

THE ALL IMPORTANT SIGN



$$V \sim \frac{1}{2}m^2\varphi^2 - \frac{\lambda}{4}\varphi^4 + \frac{g^2}{6m^2}\varphi^6 + \ldots + h\varphi\bar{\psi}\psi$$



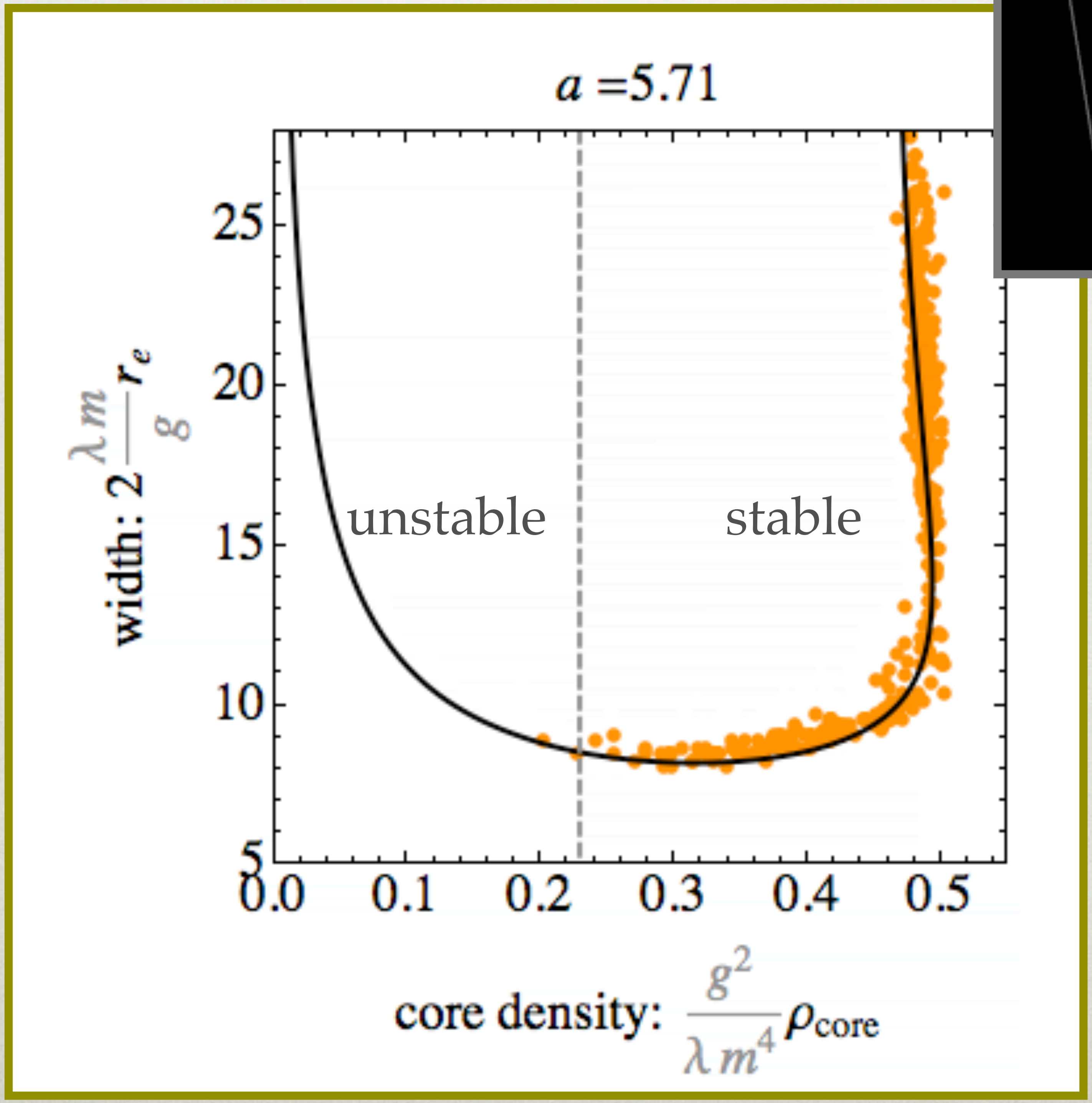
Movie: courtesy of A Speranza (MIT)

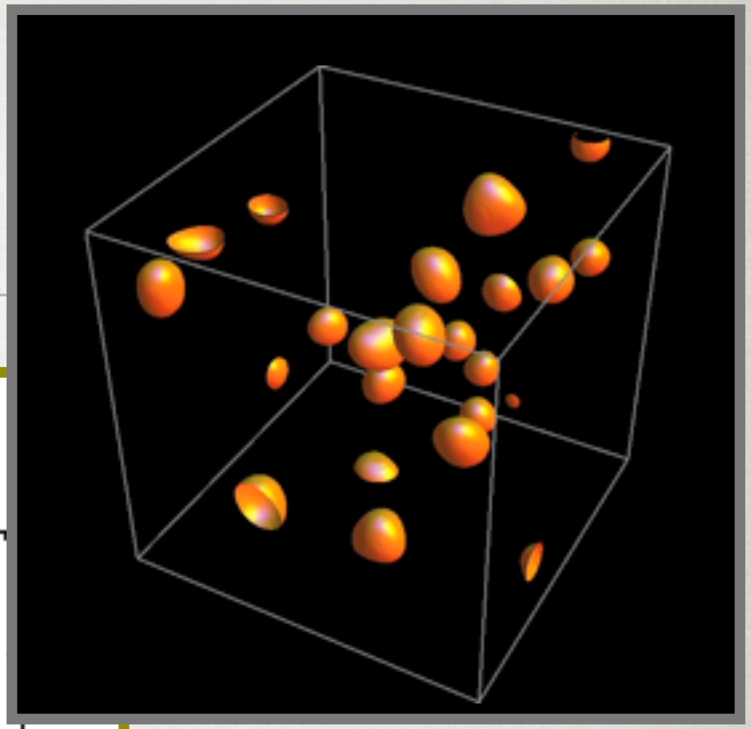
STABILITY

- linear stability analysis: (collapse) long wavelength (flat tops: MA & Shirokoff 2010)
- effects of expansion (Farhi et. al 2008)
- rate of energy loss by radiation, classical and quantum (Segur and Kruskal 1987, Hertzberg 2010)

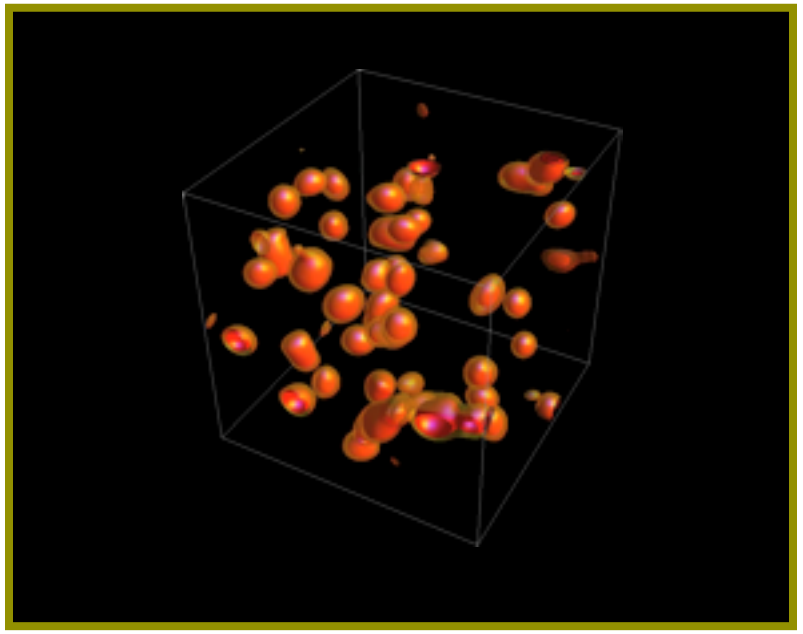
- *For a restricted class of potentials*

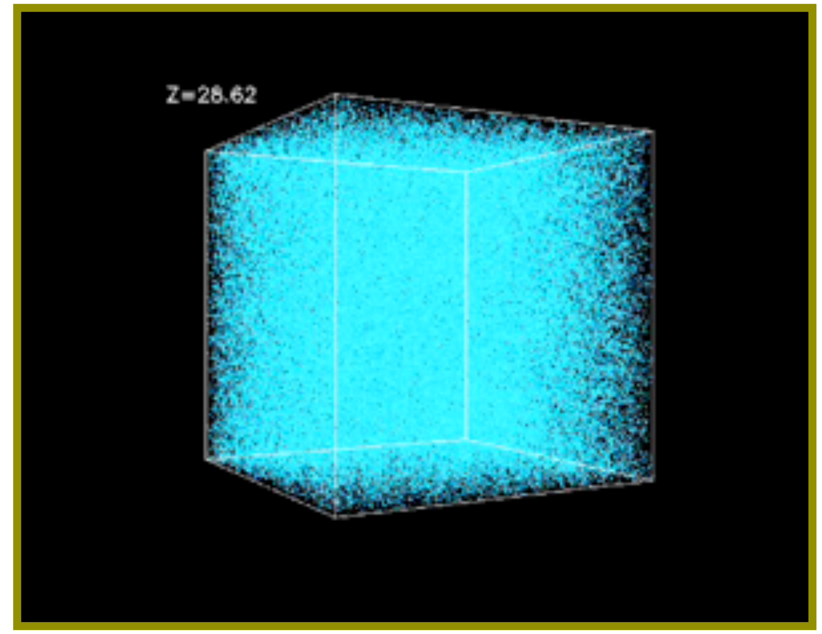
STABILITY


$a = 5.71$
width: $2\frac{\lambda m}{g}r_e$
core density: $\frac{g^2}{\lambda m^4}\rho_{core}$
unstable
stable
25
20
15
10
5
0.0
0.1
0.2
0.3
0.4
0.5



non-linear simulations





- include non-linear dark matter clustering
- include non-linear quintessence pert.
- additional observable signature

motivation: 2

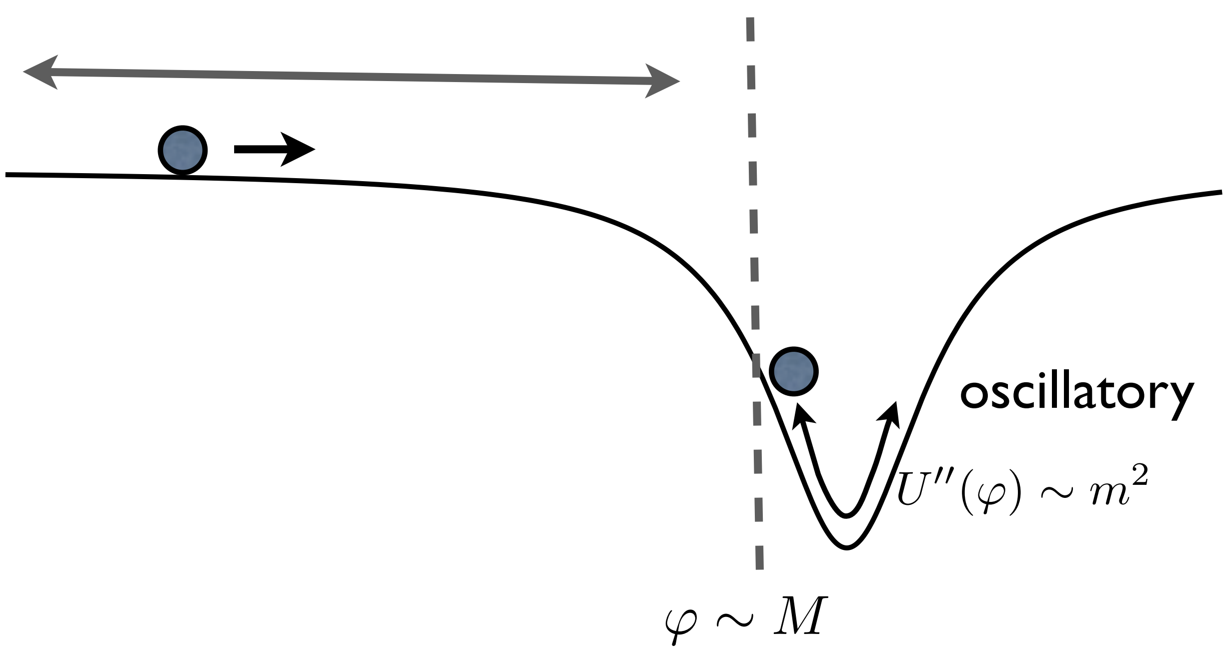
- scale dependent potential growth
  - ➡ simple, no gravity modification
  - ➡ no Chameleons or Vainshtein
- difference in lensing and matter spectrum
- No effective anisotropic stress (linear)
- Growth rate (from matter) and expansion history not enough

short comings

- why should the transition happen now and not in the distant future ? (extra)

summary

resonant growth → scale-dependent growth gravitational potential growth, dark clumps



constrain via
(i) lensing
(ii) integrated Sachs-Wolfe

An example with scale dependent potential growth + difference in matter and gravitational power spectrum without modified gravity/non-canonical kinetic terms

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LUMPS AND BUMPS AT THE END OF INFLATION

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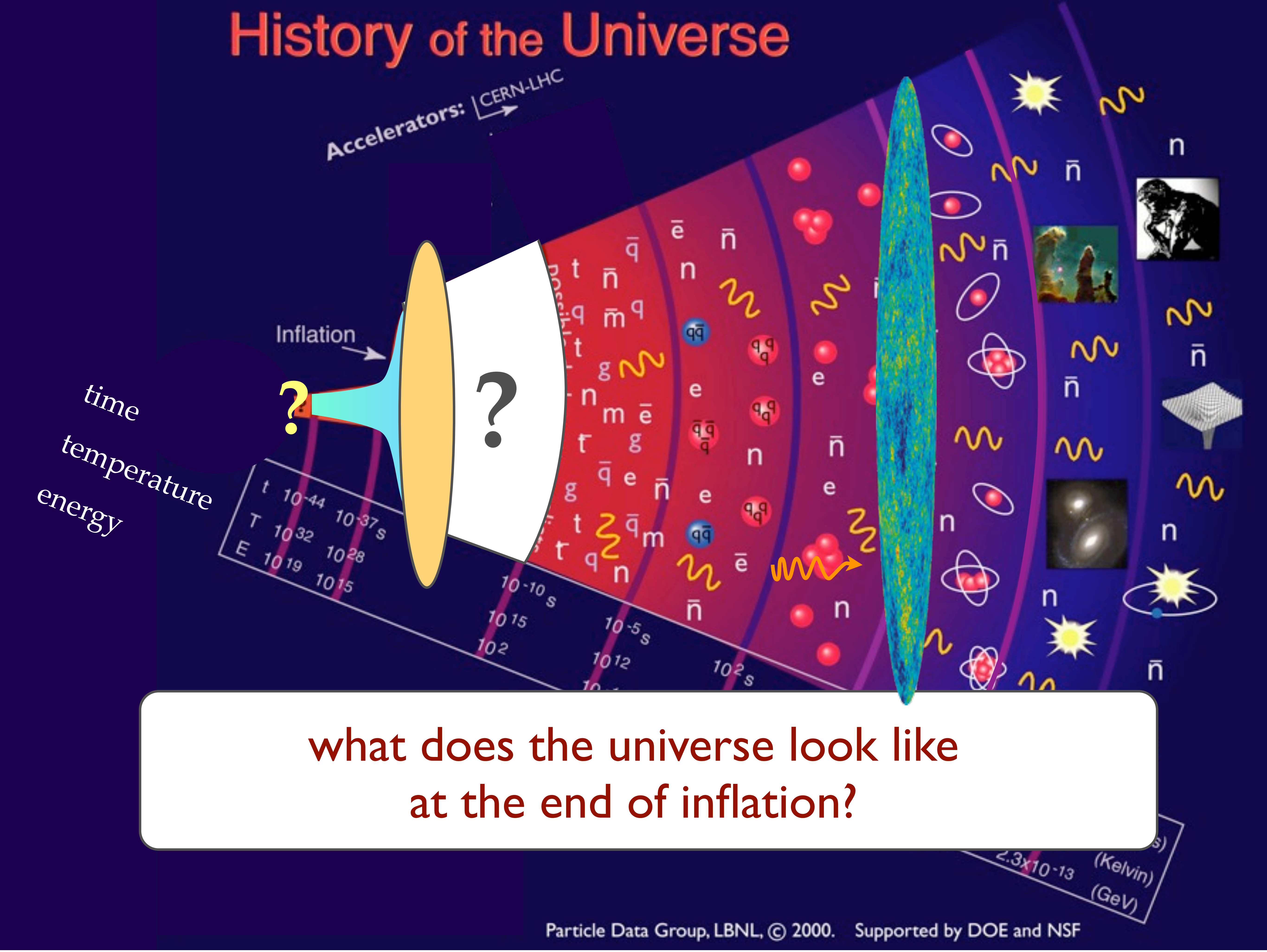
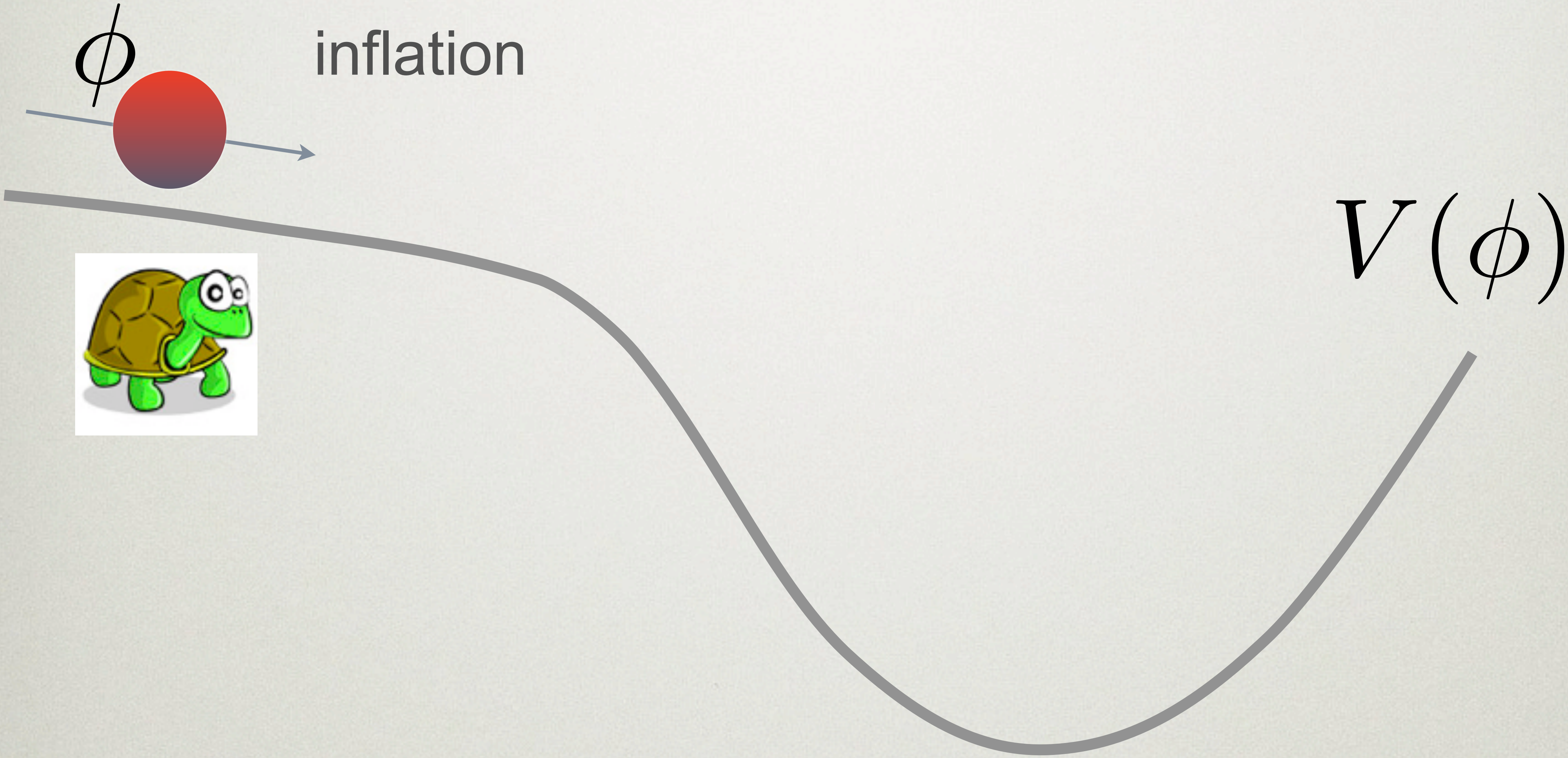
PAPERS AND COLLABORATORS

1) 1002.3380 with D. Shirokoff (MIT)
2) 1006.3075 MA
3) 1009.2505 MA, Easther and Finkel (Yale)
4) 1106.3335 MA, Easther, Finkel, Flauger (Yale) & Hertzberg(Stanford)

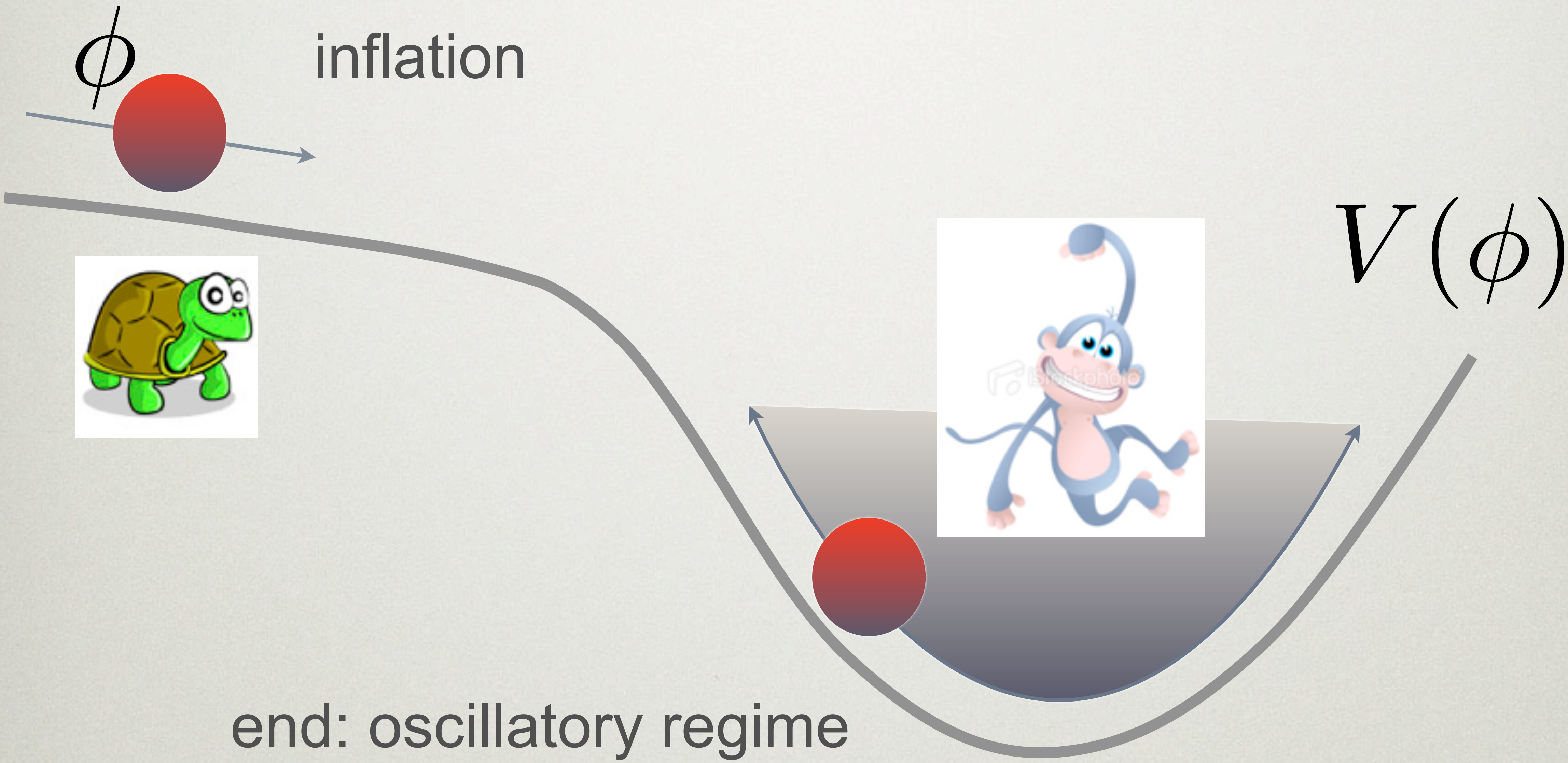


what does the universe look like at the end of inflation?

INFLATION



END OF INFLATION



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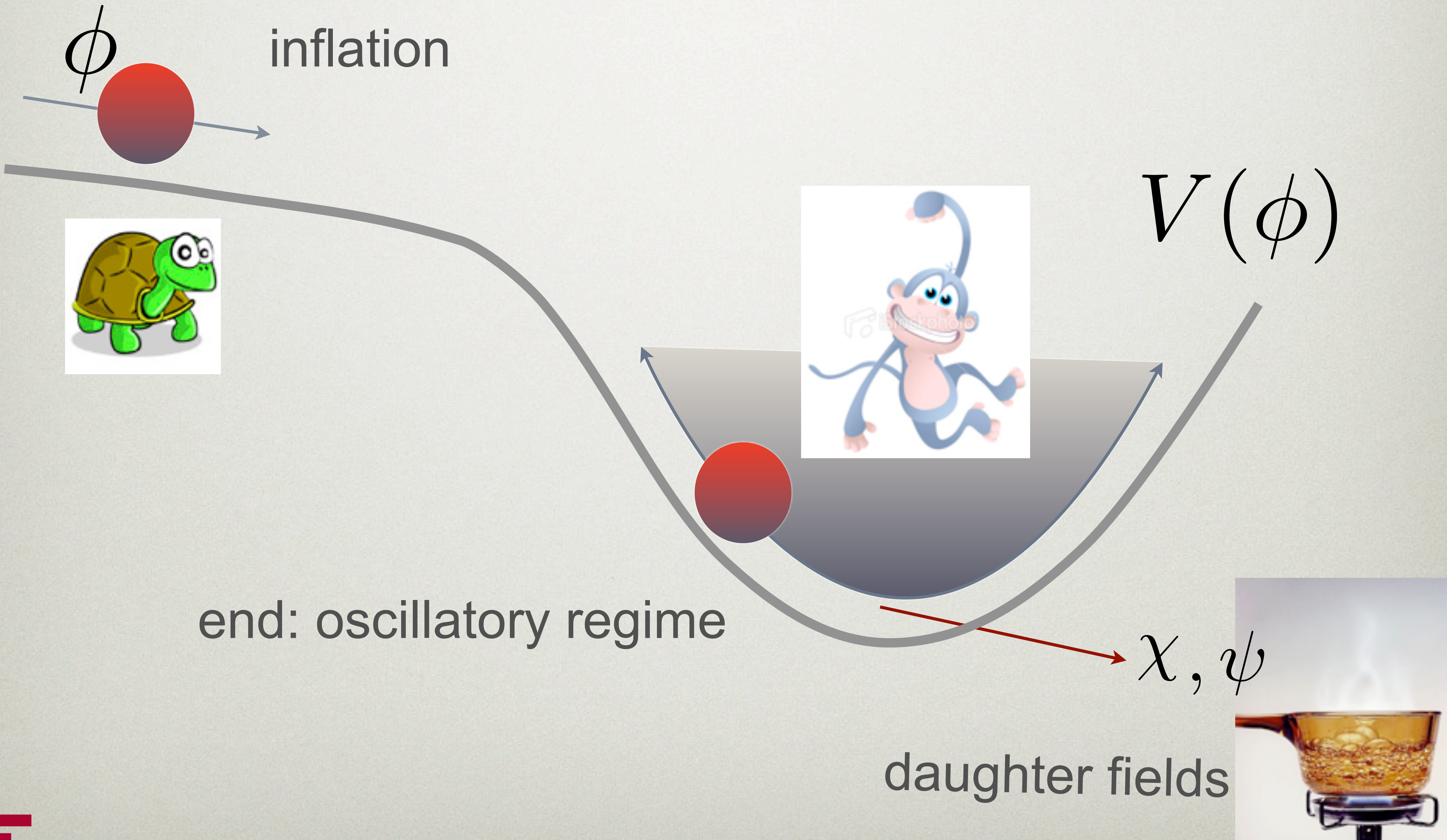
END OF INFLATION



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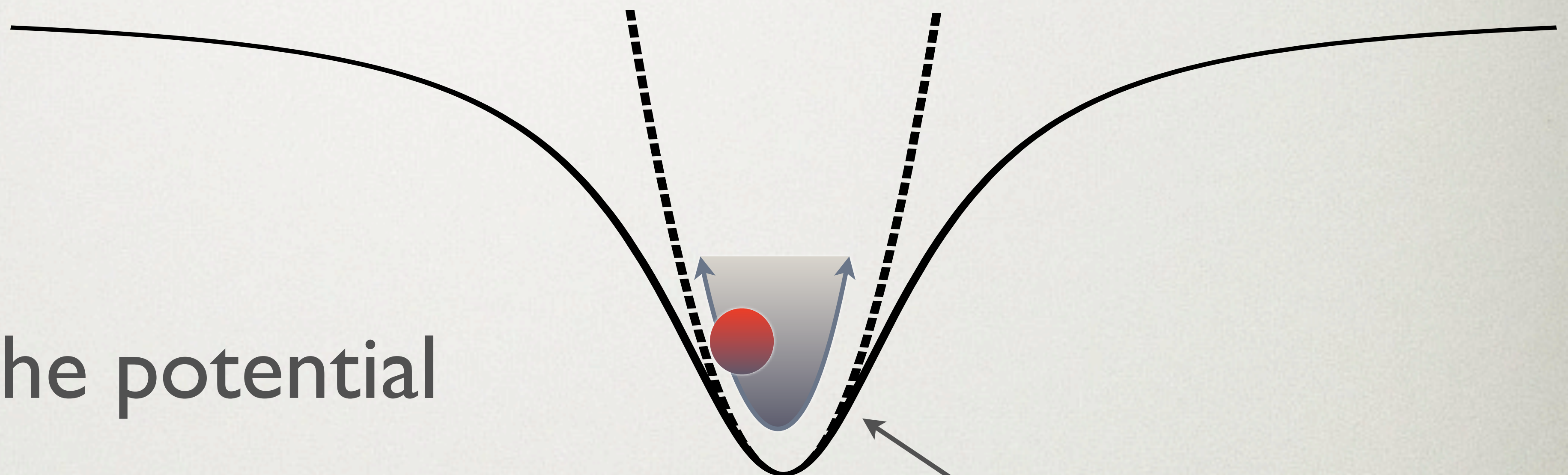
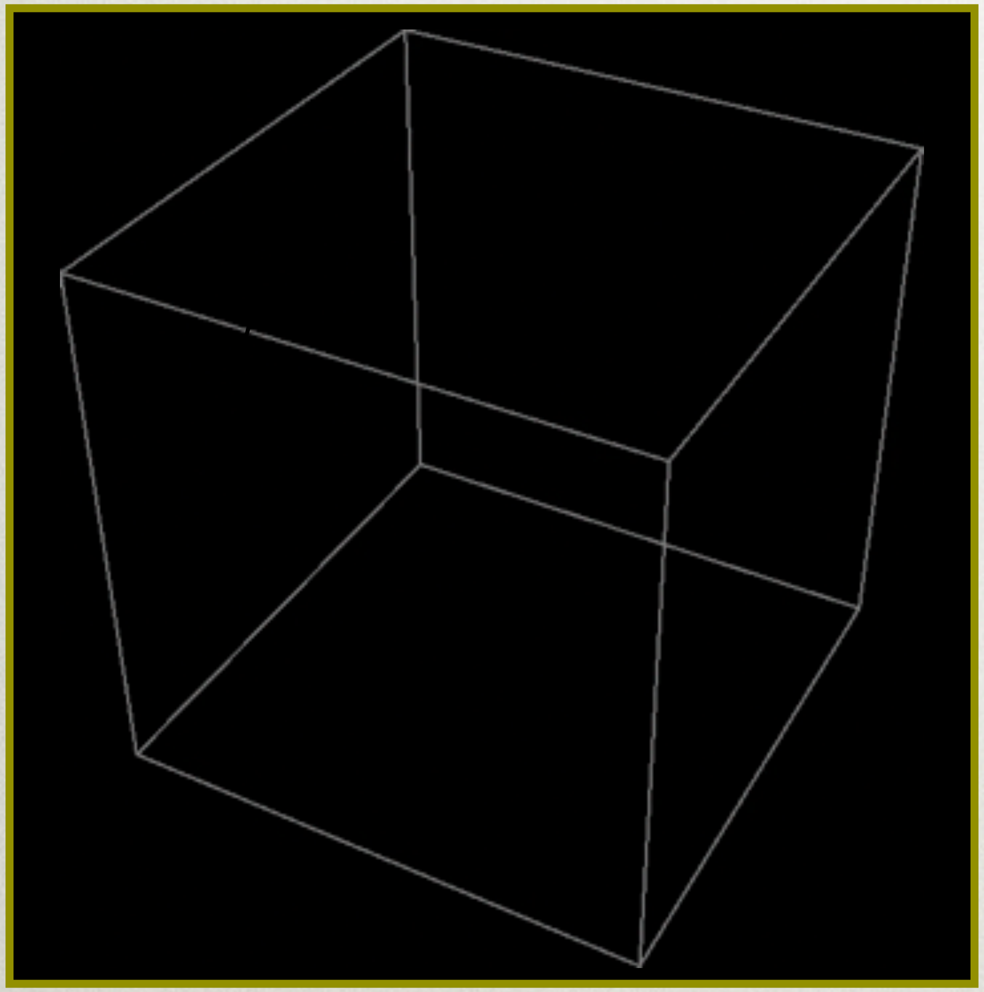
FIELD DYNAMICS AT THE END OF INFLATION



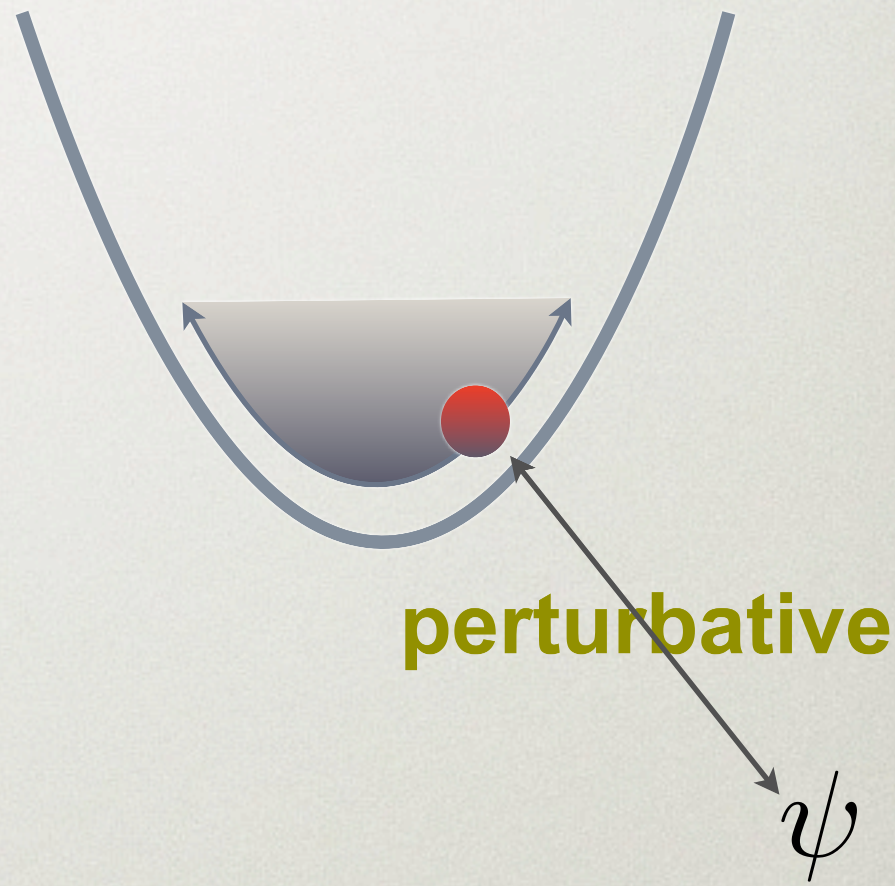
- shape of the potential
- how does it couple to other fields

χ, ψ

SCENARIO I

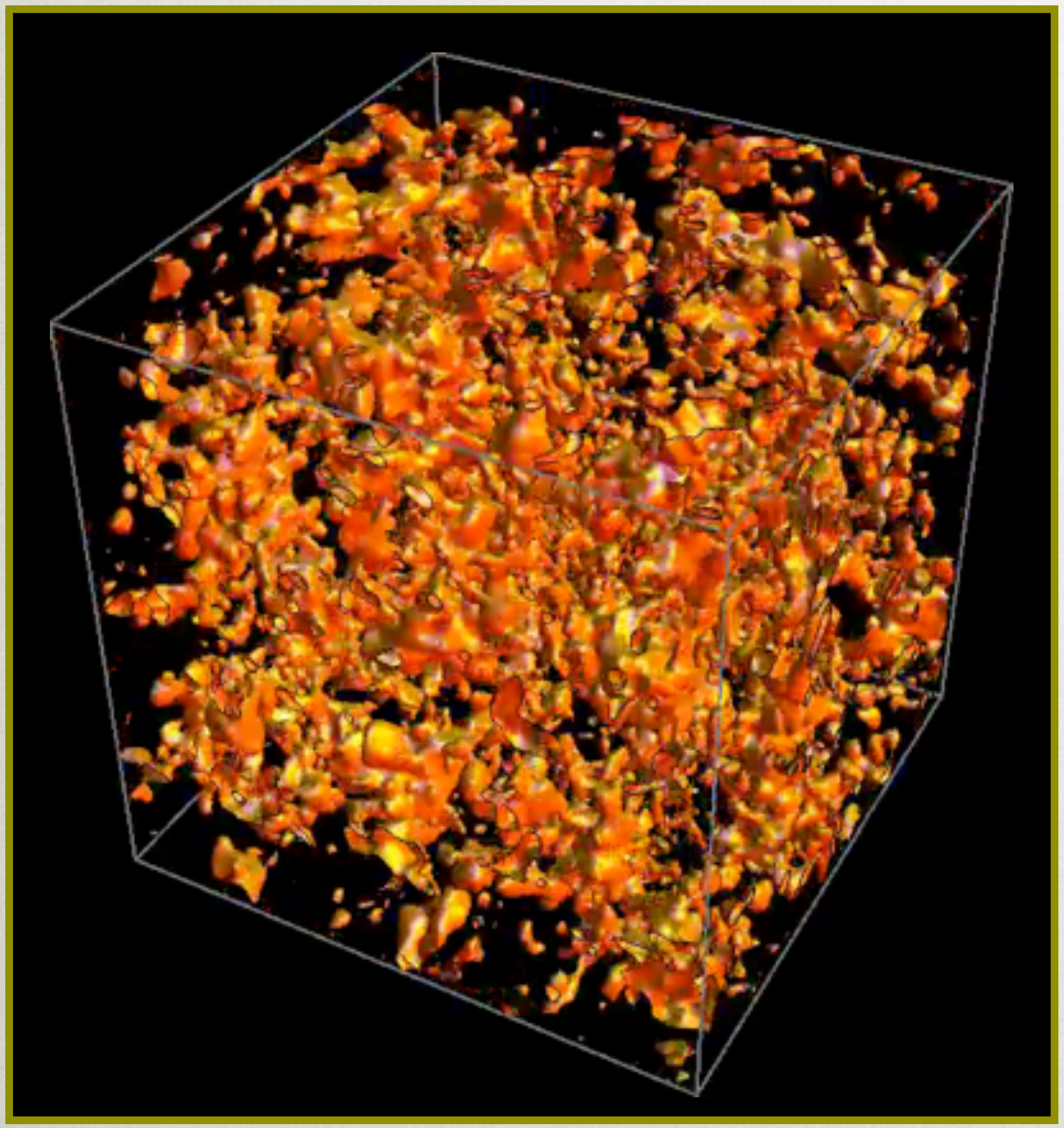


$$V \sim \frac{1}{2} m_\varphi^2 \varphi^2 + g^2 \varphi^2 \chi^2 + h \varphi \bar{\psi} \psi + \dots$$



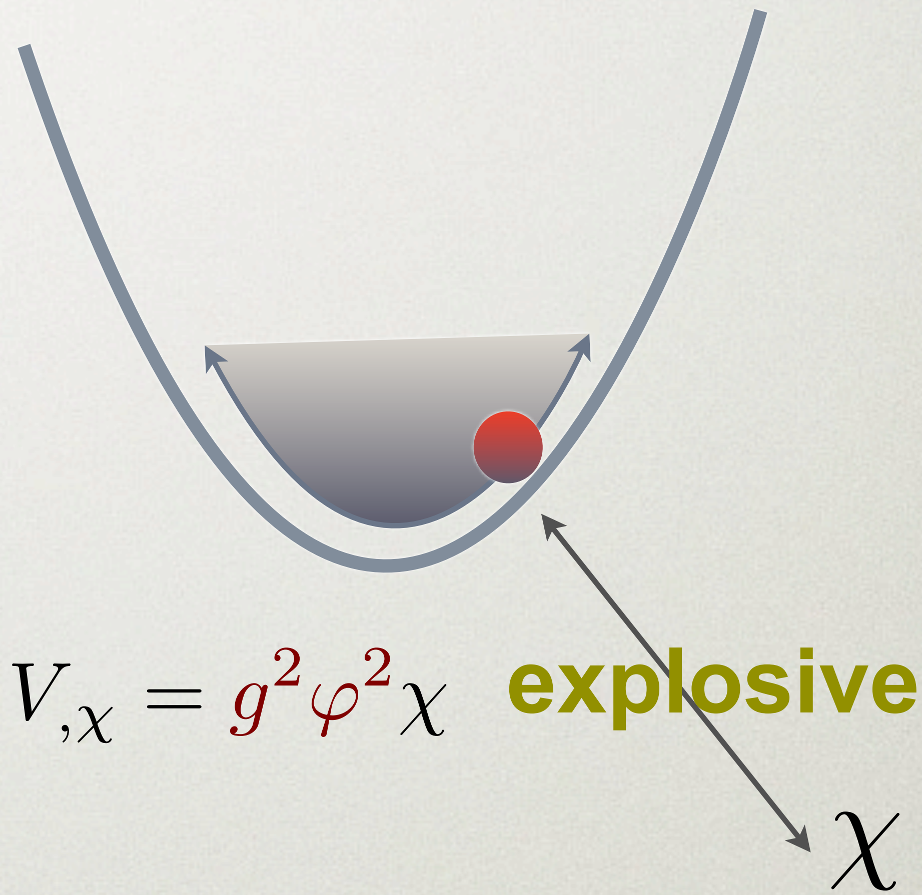
$$\Gamma(\varphi \to \psi\psi) \sim \frac{h^2\, m_\varphi}{8\pi} \ll H$$

SCENARIO II



Movie: courtesy of R. Easther

$$V \sim \frac{1}{2}m_\varphi^2\varphi^2 + g^2\varphi^2\chi^2 + h\varphi\bar{\psi}\psi + \ldots$$

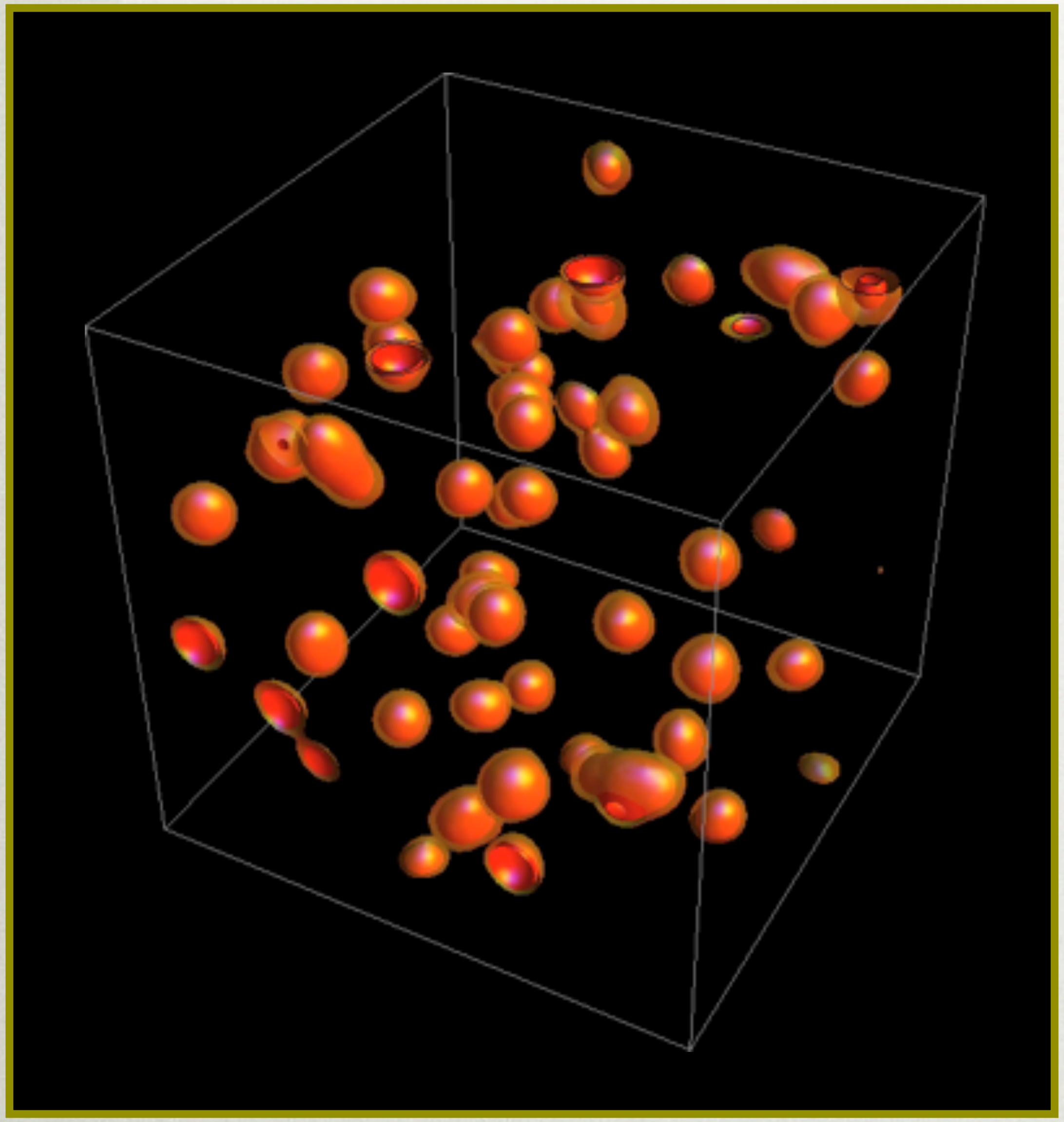


$$\Box\chi = V_{,\chi} = g^2\varphi^2\chi$$

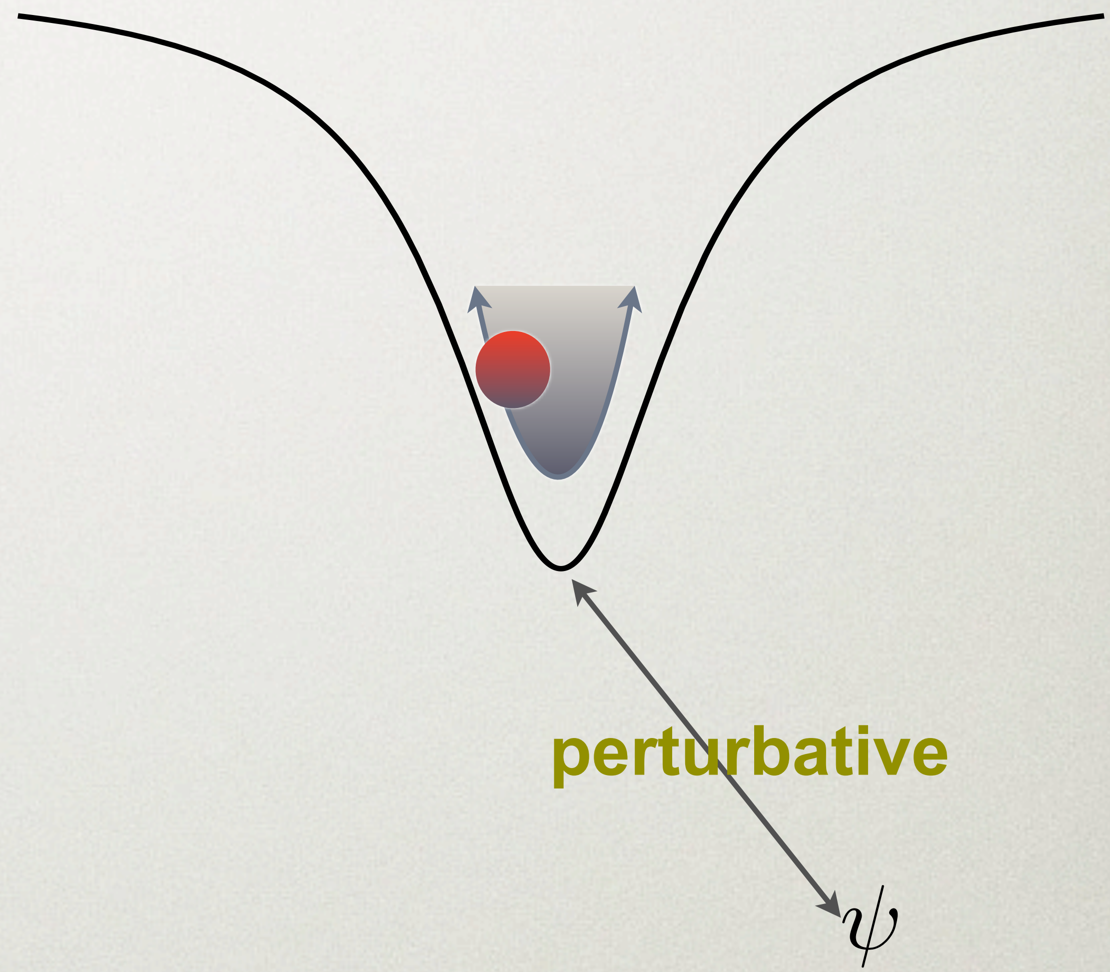
decay rate >> H

Trachen & Brandenberger (1990), Kofman, Linde, Starobinsky et. al (1994) ...

SCENARIO III



$$V \sim \frac{1}{2}m^2\varphi^2 - \frac{\lambda}{4}\varphi^4 + \frac{g^2}{6m^2}\varphi^6 + \ldots + h\varphi\bar{\psi}\psi$$



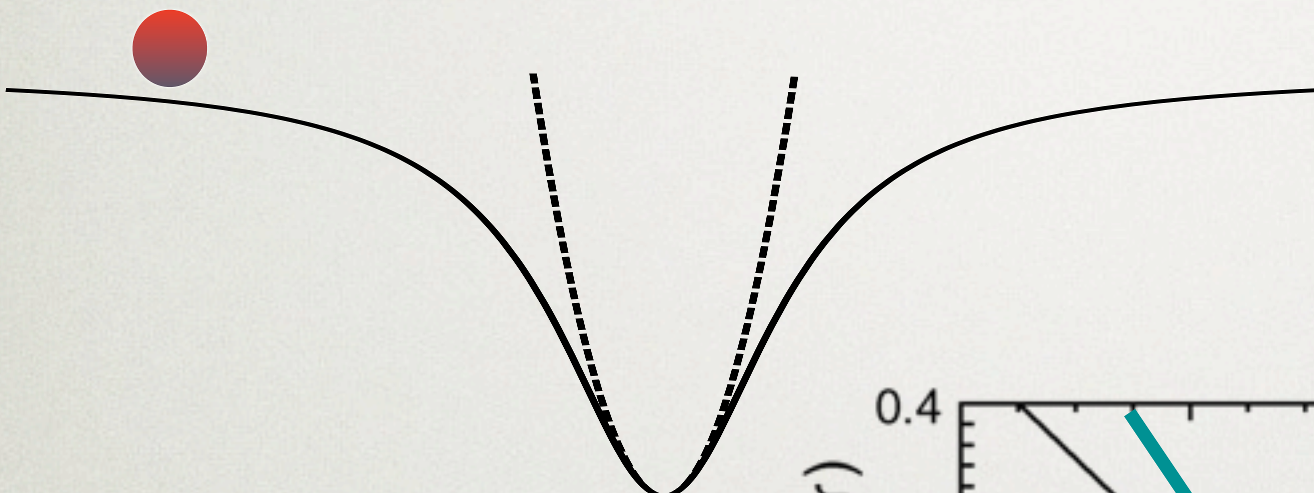
MA 2010
MA, Finkel, Easther 2010
MA, Easther, Finkel, Flauger, Hertzberg 2011

decay rate << H

Also see: McDonald & Broadhead, Rajantie & Copeland, Gleiser et. al.

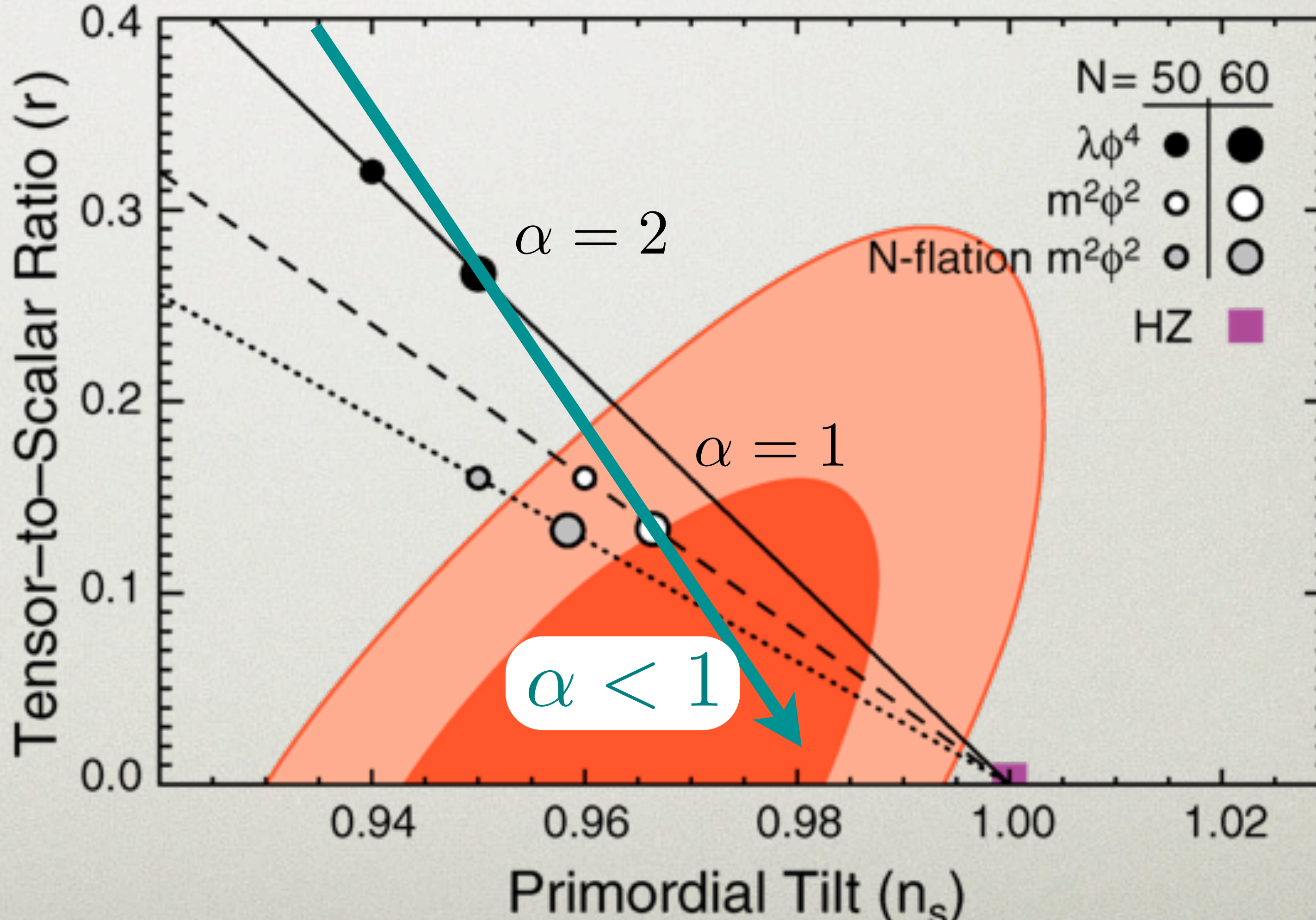
MOTIVATION: SHALLOW POTENTIALS

$$V(\varphi) \propto \varphi^{2\alpha}$$



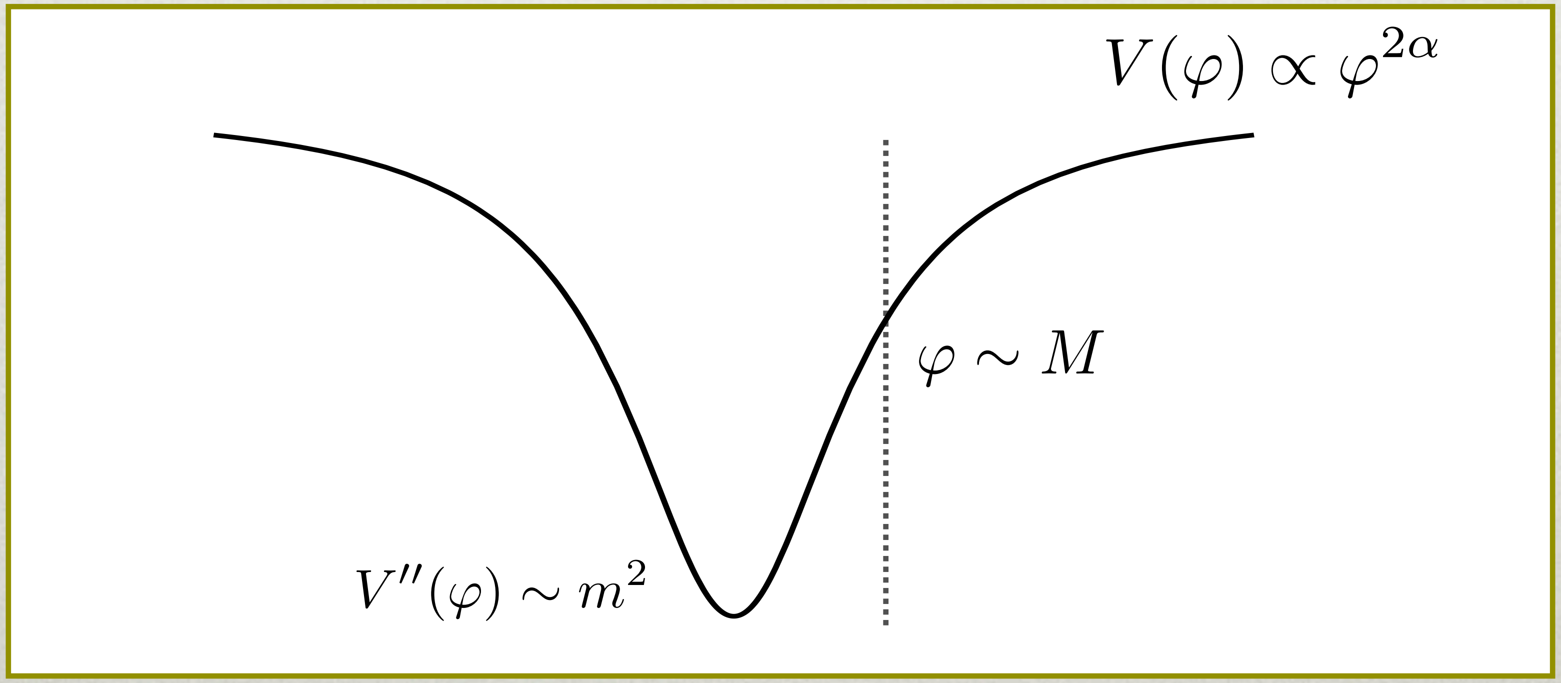
$$r \approx \frac{8\alpha}{N}$$

$$n_s \approx 1 - \frac{\alpha + 1}{N}$$

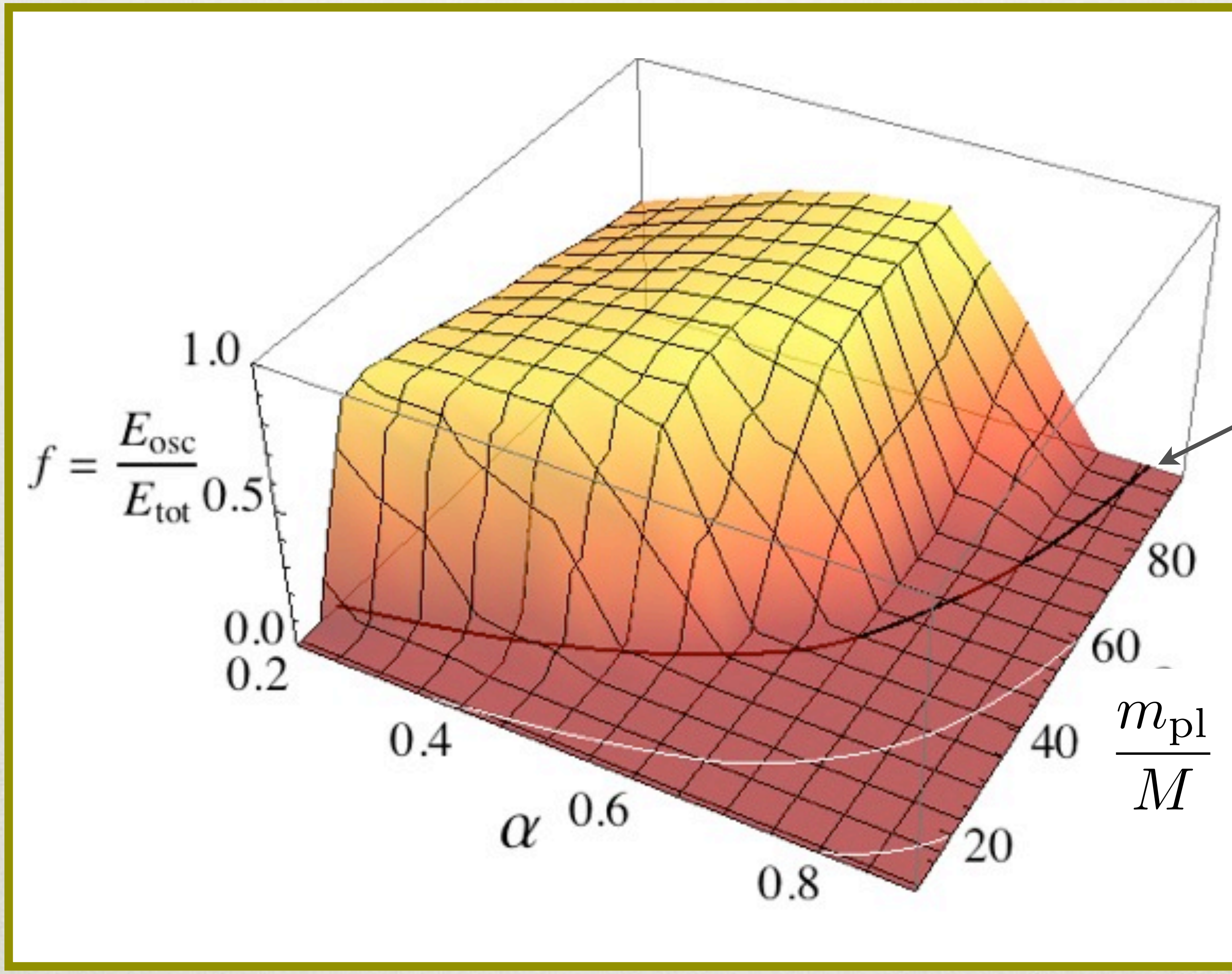


MOTIVATION: SHALLOW POTENTIALS

- monodromy (Silverstein & Weshtpal) $\alpha = 1/3$
- axion monodromy (McAllister, Silverstein & Westphal) $\alpha = 1/2$
- supergravity (Kallosh & Linde) $\alpha < 1$
- generic flattening of potentials (Dong et. al) $\alpha < 1$



energy fraction: >> 50%



analytic curves from Floquet analysis

$$\left[\frac{|\Re(\mu_k)|}{H}\right]_{\max} \gtrsim 10$$

(inverse)scale where potential changes shape $m_{pl}/M \gg 1$

asymptotic slope $\alpha \lesssim 1$

WHAT TO DO WITH THEM?

- inhomogeneous reheating *(with J.T. Giblin and H. Childs)*
- gravitational effects:
  - black holes ?
  - expansion history and influence on inflationary observables (Adshead et. al)?
  - g-waves ?

other ongoing projects

- distinguishing (light) axions and WIMPs from astrophysics (with E. Bertschinger)
- strong lensing: flux anomalies (with T. Cheung and D. Bulmash)
- analytic approach to non-linear structure formation (with A. Schulz)