Inflation Ends, What's Next ?

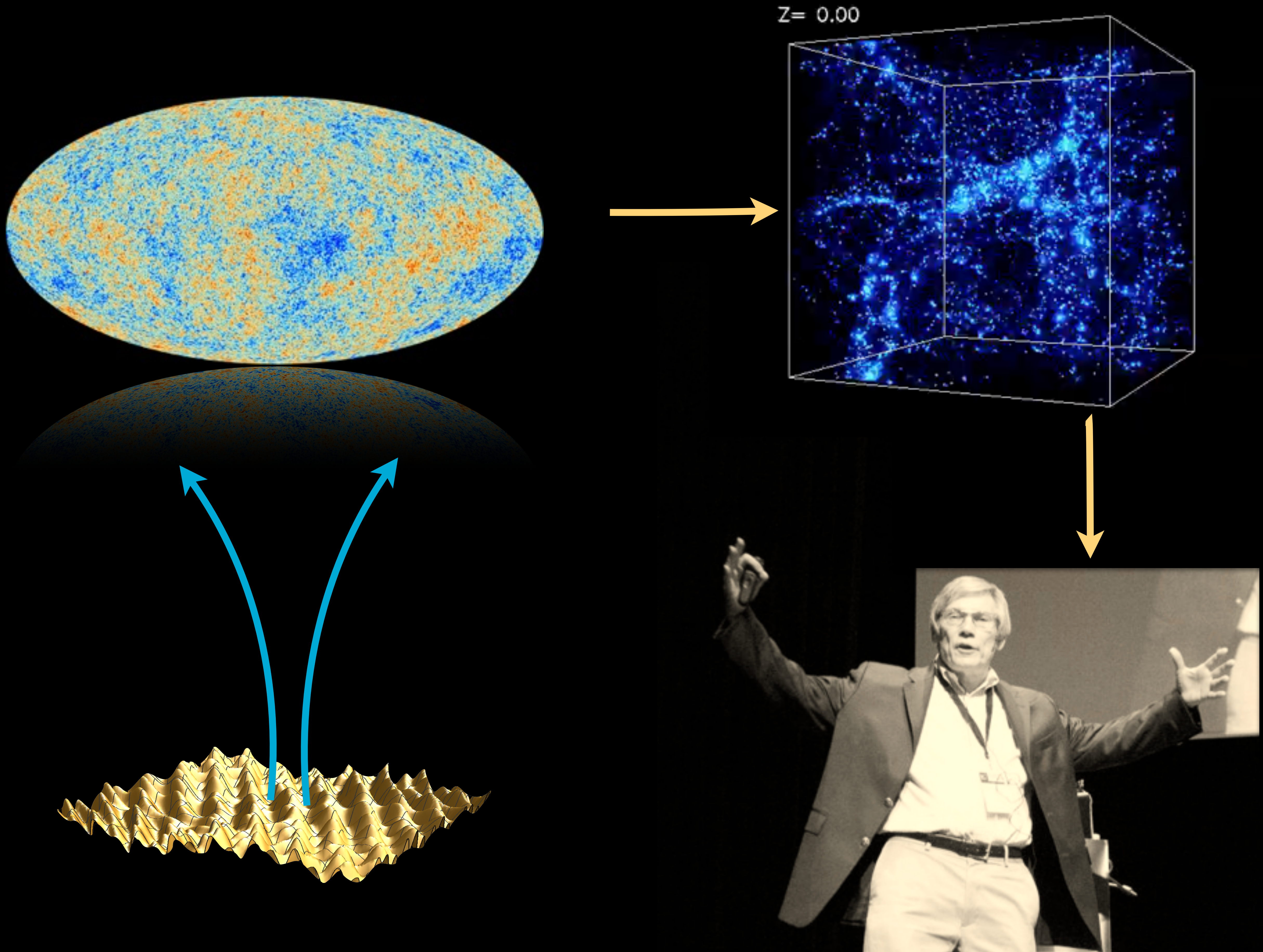
Mustafa A. Amin

RICE

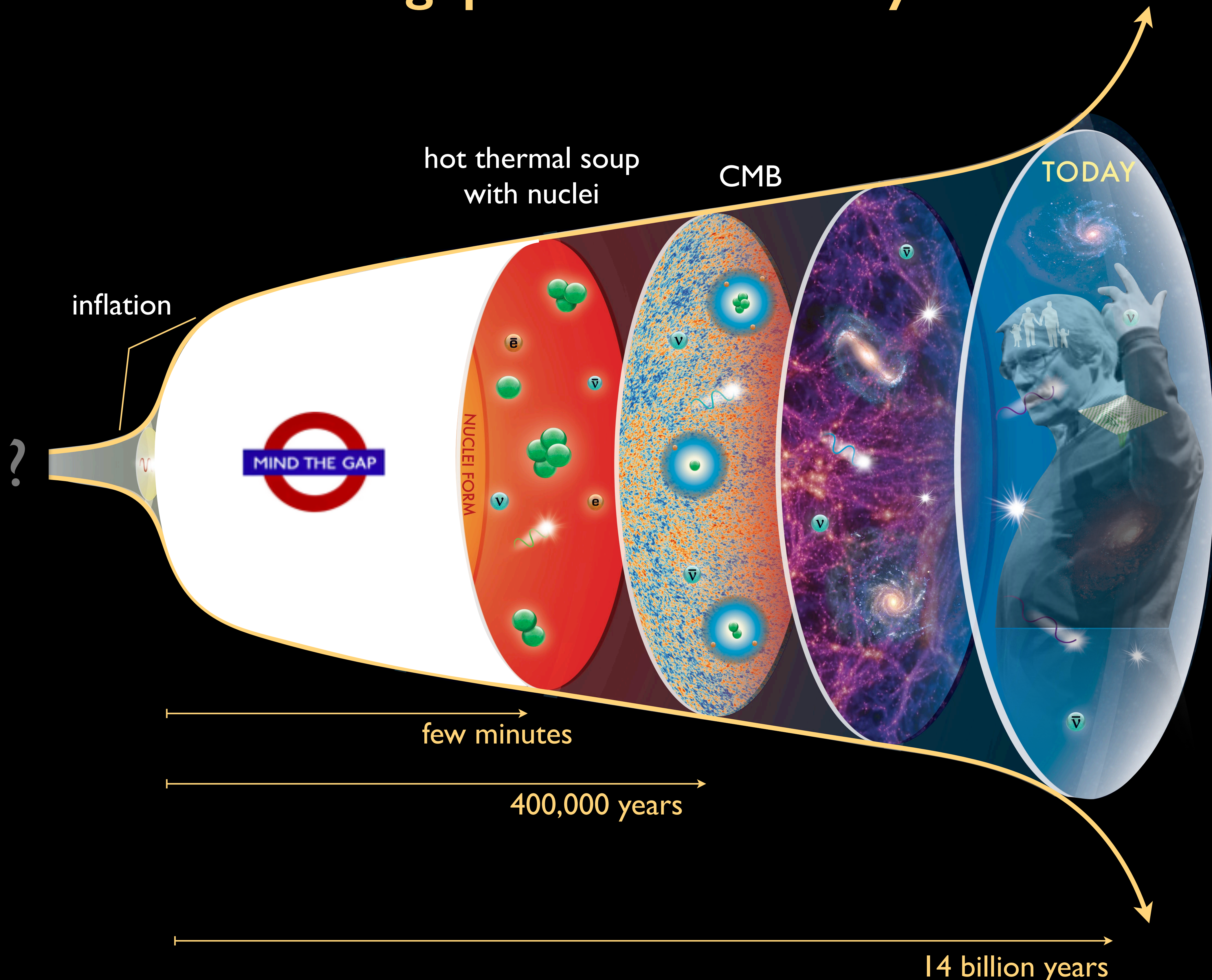
image credit: the Story Collider

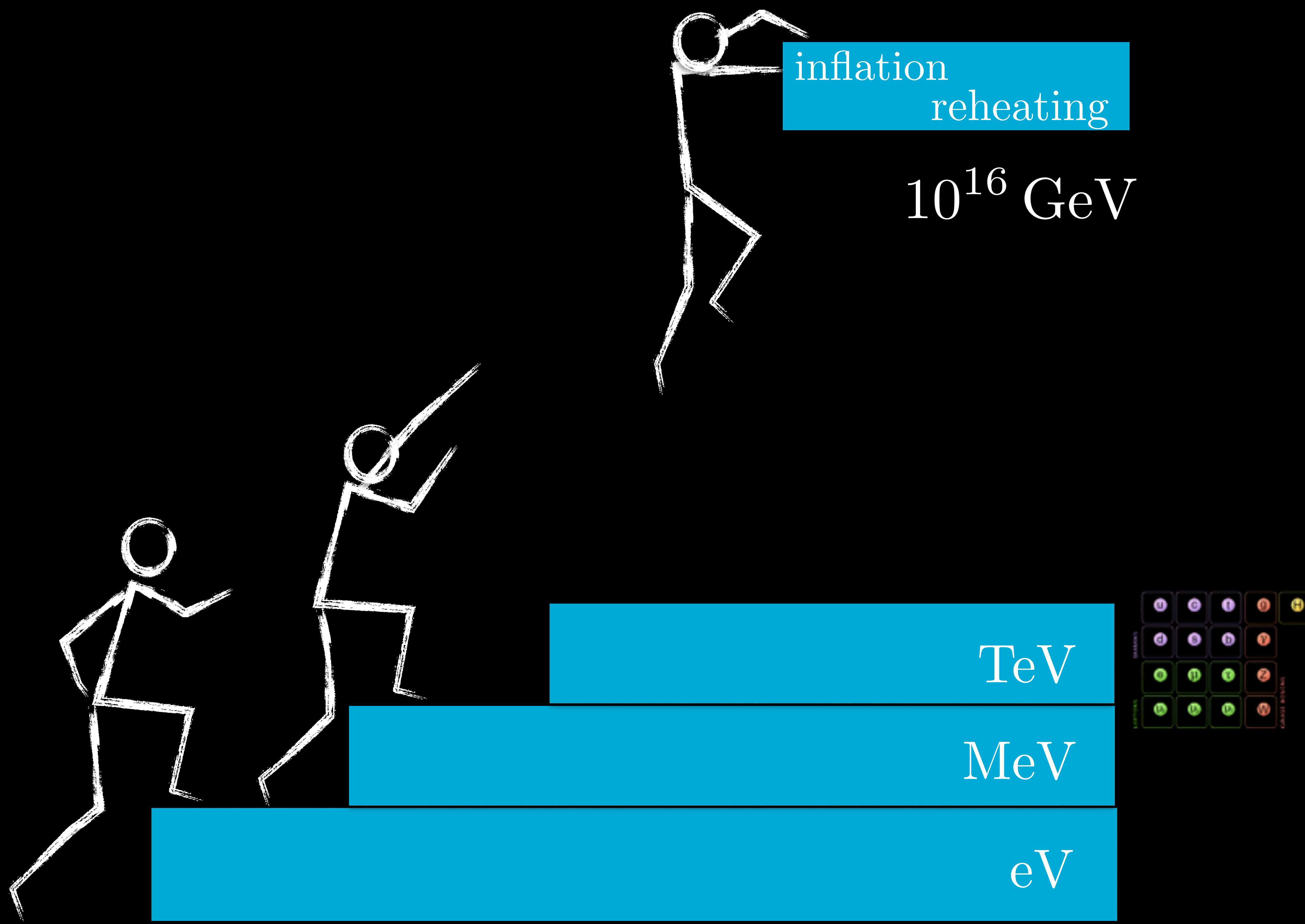

EXIT
of the Milner
WOW!! — I still


Alan's cosmic history



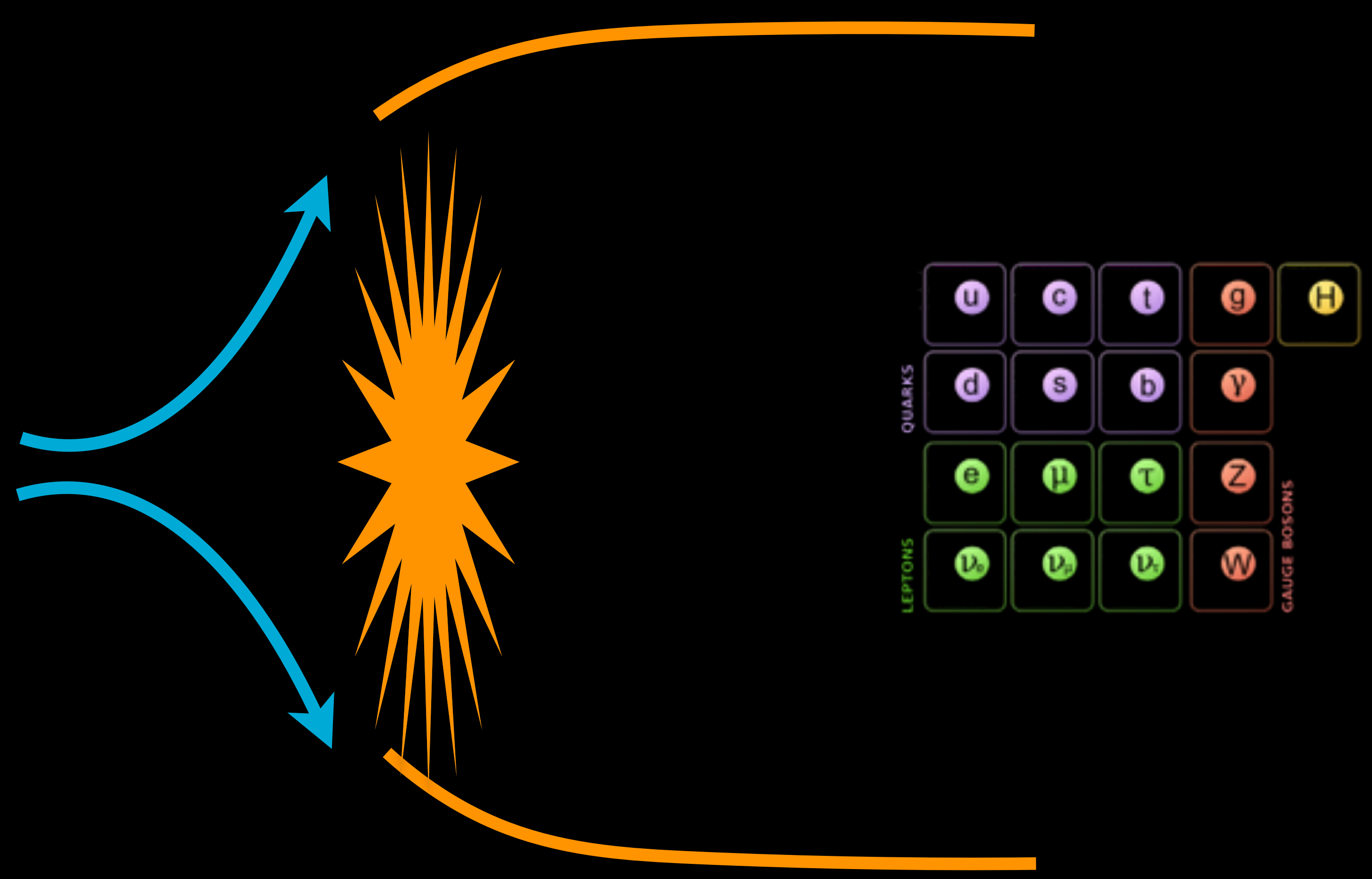
a gap in Alan's history





inflation
reheating
10^{16} GeV
TeV
MeV
eV

what happens at the end of inflation ?



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Has Alan thought about it ?

COULD THE UNIVERSE HAVE RECOVERED FROM A SLOW FIRST-ORDER PHASE TRANSITION?*

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Department of Physics, Columbia University, New York, New York 10027, USA

Received 3 March 1982
(Revised 6 September 1982)

We investigate the cosmological consequences of a phase transition which is driven primarily by slow nucleation of bubbles of the new phase via the effectively zero temperature quantum tunneling process of Coleman and Callan. These bubbles will asymptotically fill an arbitrarily large fraction of the space, yet they never percolate. Instead they form finite clusters, with each cluster dominated by a single largest bubble. The large scale thermalization required by the original "inflationary universe" scenario does not take place. The Coleman-De Luccia formalism for bubble formation in curved space is reviewed, with minor extensions. We argue that a single uncollided bubble would contain much less total entropy than the observed universe, unless the Higgs field potential involves widely disparate mass scales, as in the new inflationary universe scenario. We also argue that finite clusters are unlikely to yield a homogeneous and isotropic region containing sufficient entropy. Thus, unless the Higgs potential has the special form required by the new inflationary scenario, it appears quite implausible that there was such a phase transition in our past.

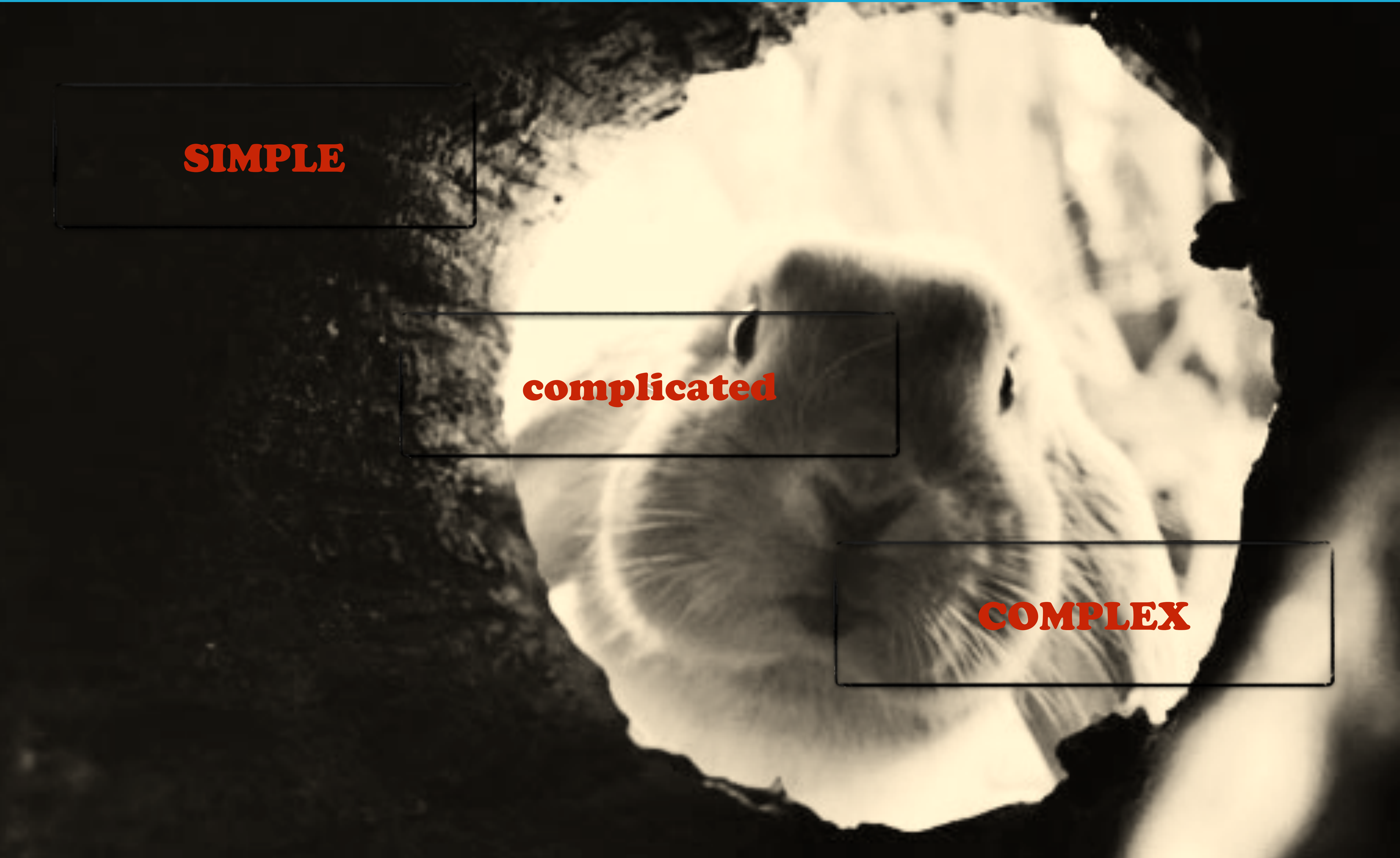
end of inflation

SIMPLE

complicated

COMPLEX

end of inflation



end of inflation

SIMPLE

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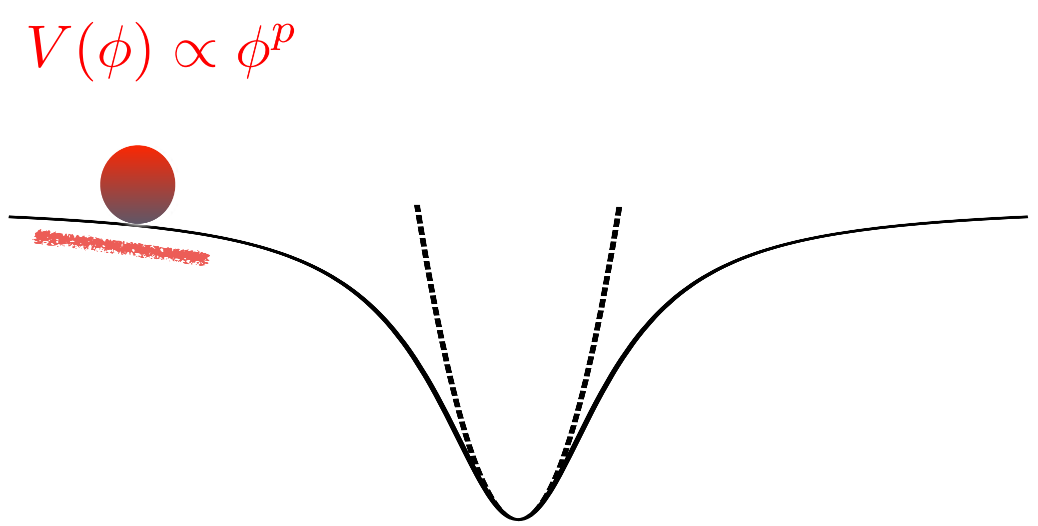
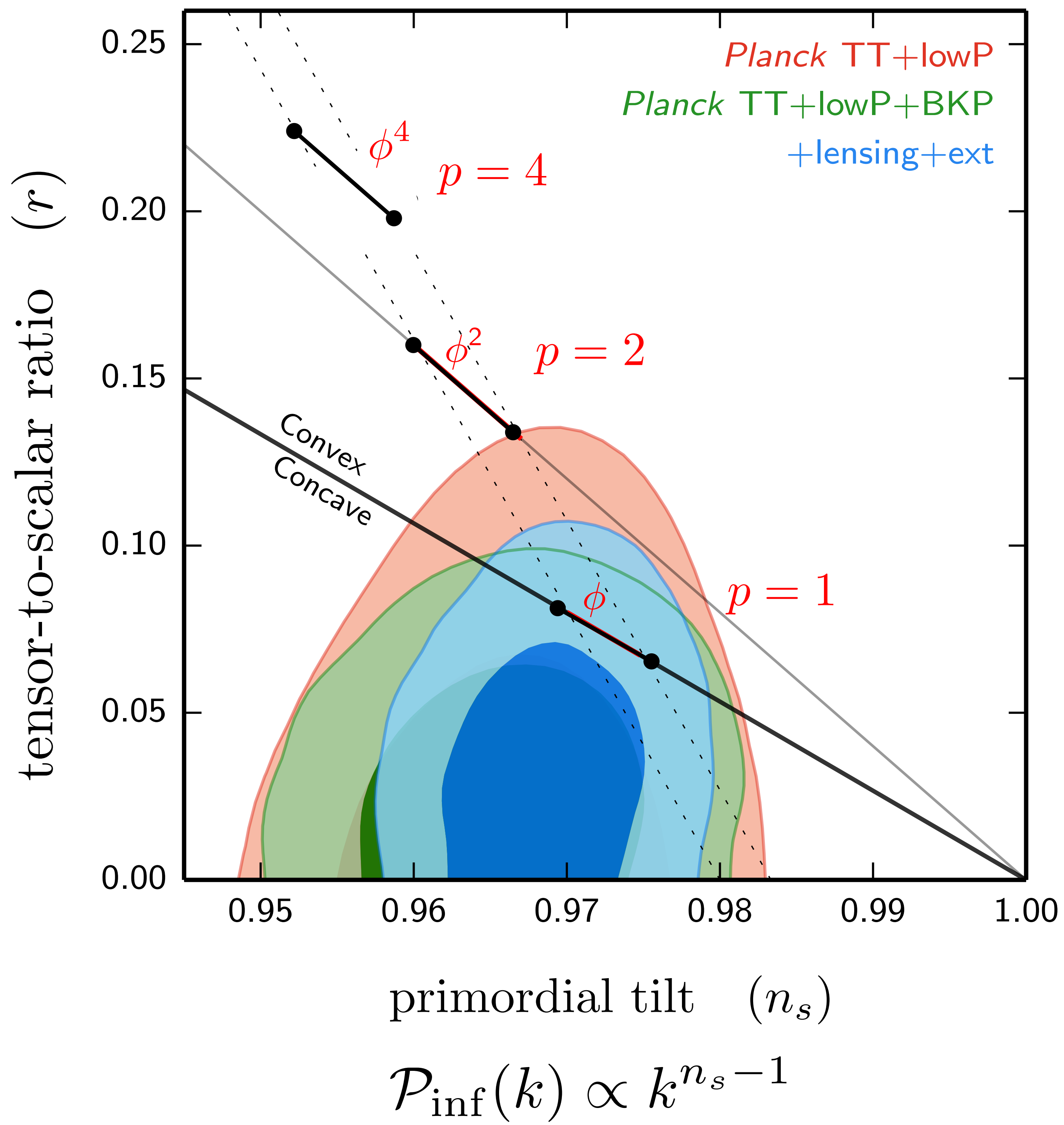
COMPLEX

constraints from observations

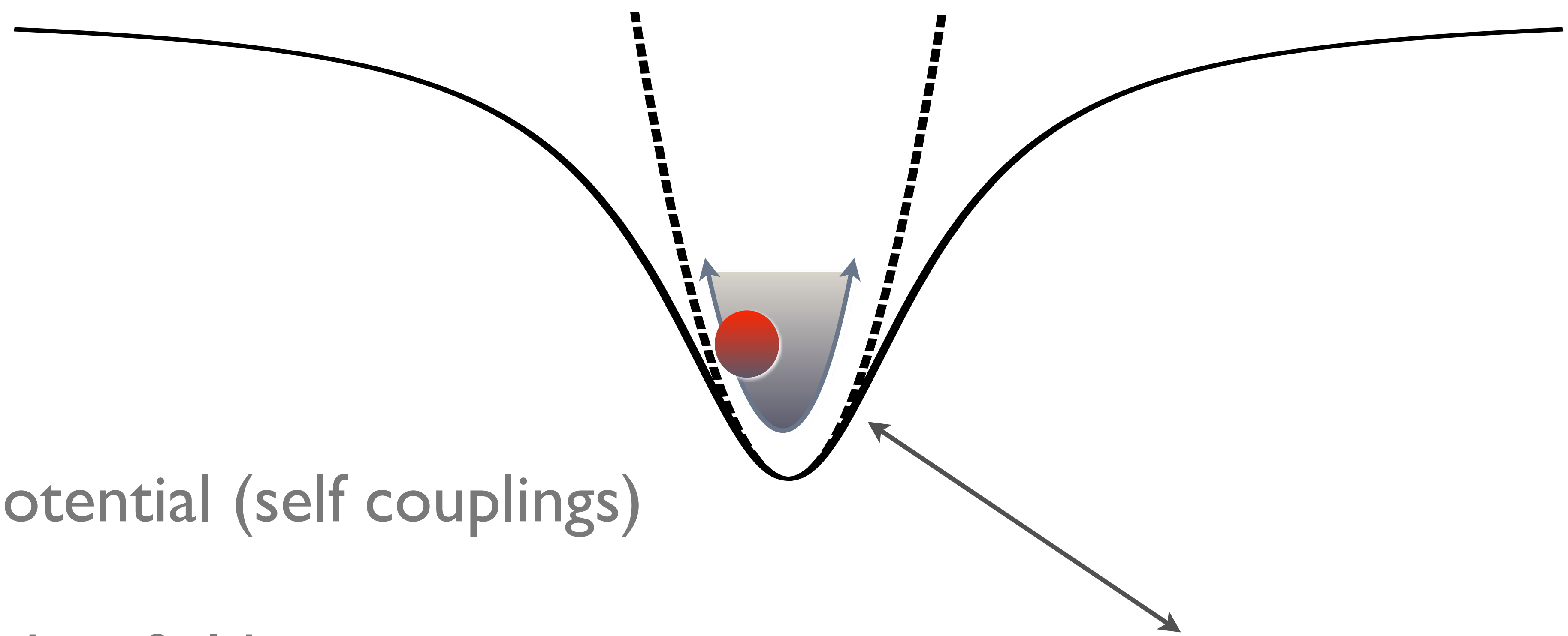




for example:

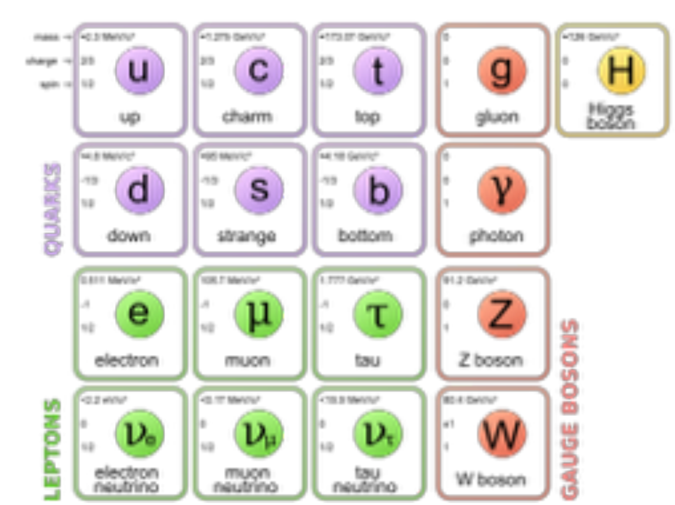
Silverstein & Westhpal (2008)
McAllister et. al (2014)
Kallosh & Linde (2014)

inflation ends, details depend on:



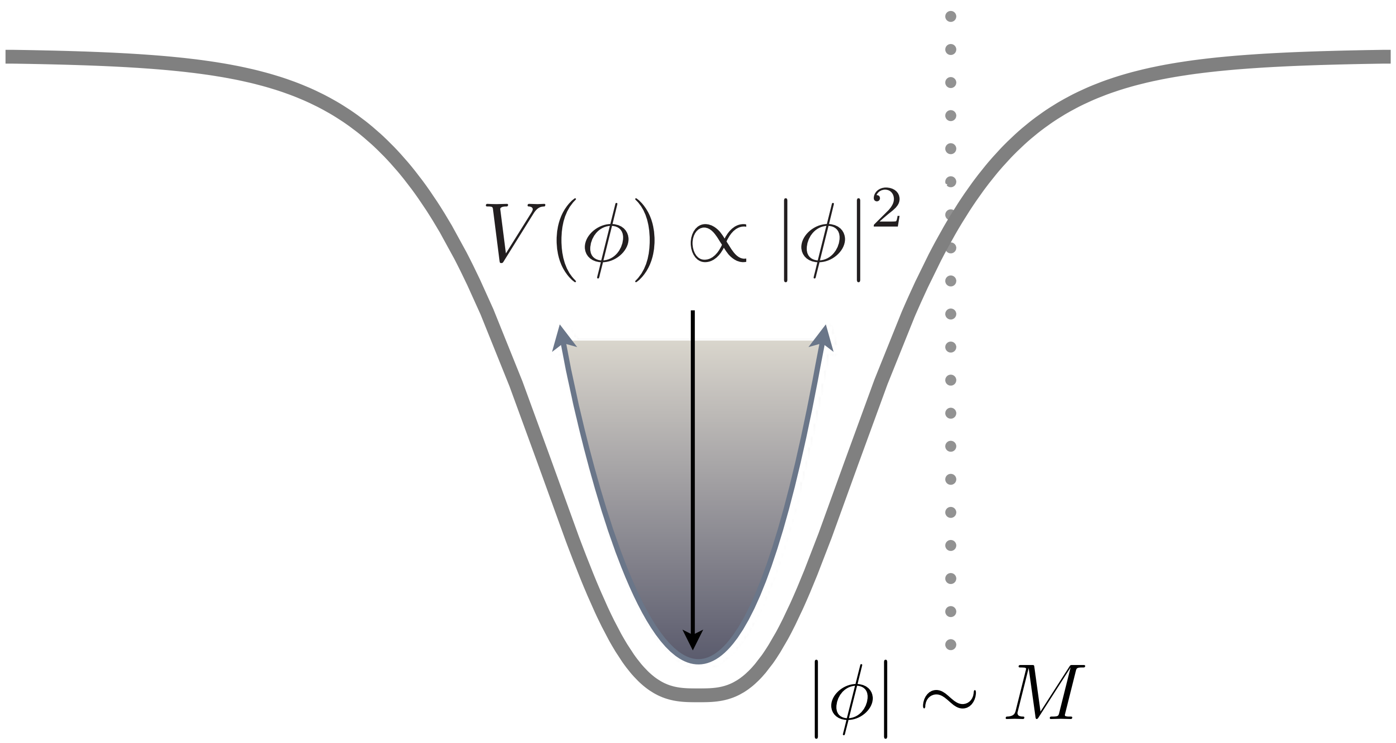
- shape of the potential (self couplings)
- couplings to other fields

$\chi\,,\,\psi$



for example:
Kofman, Linde & Starobinsky (1994)
Shtanov, Traschen & Brandenberger (1995)
review: MA, Kaiser, Karouby & Hertzberg (2014)

end of inflation in "simple" models



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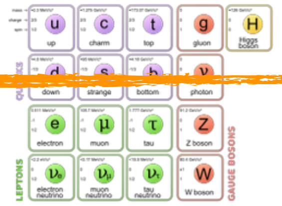
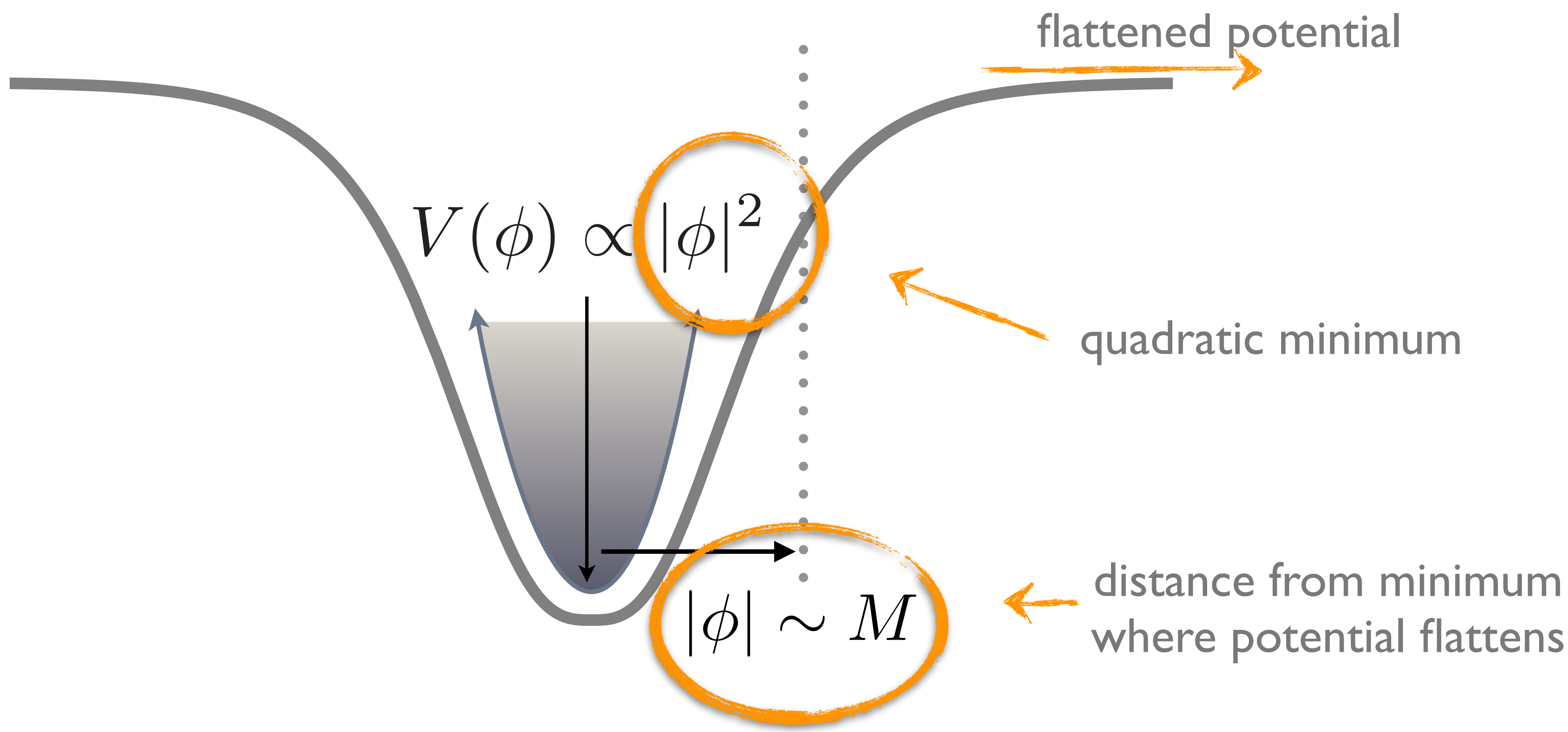
- ~~couplings to other fields~~  $\chi\ ,\psi$

end of inflation in “simple” models



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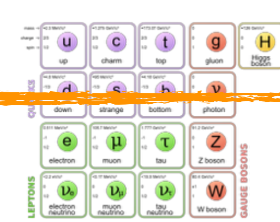
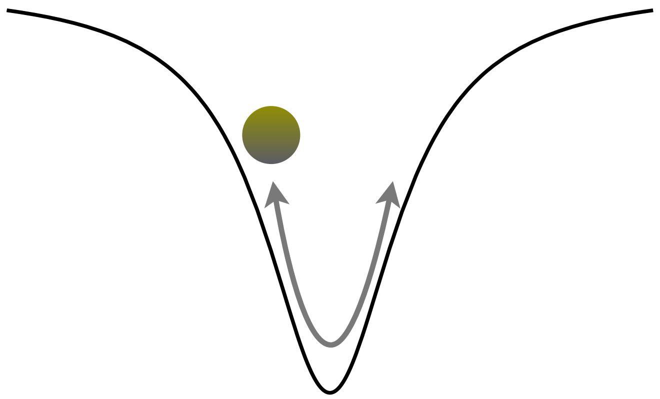
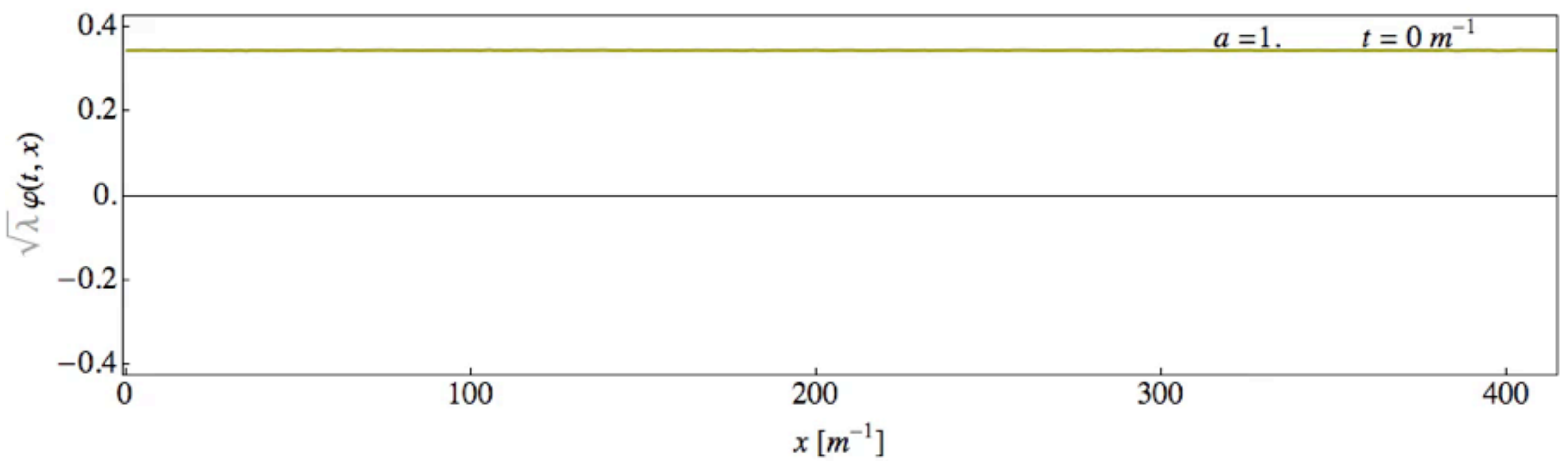
- ~~couplings to other fields~~  ~~$\chi\ ,\psi$~~

dynamics after inflation

$$\Box\varphi = V'(\varphi)$$





MA (2010)
Khlopov et. al (1985)

dynamics after inflation

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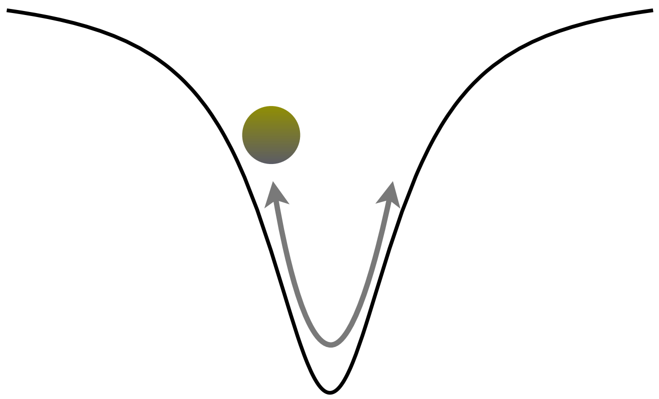

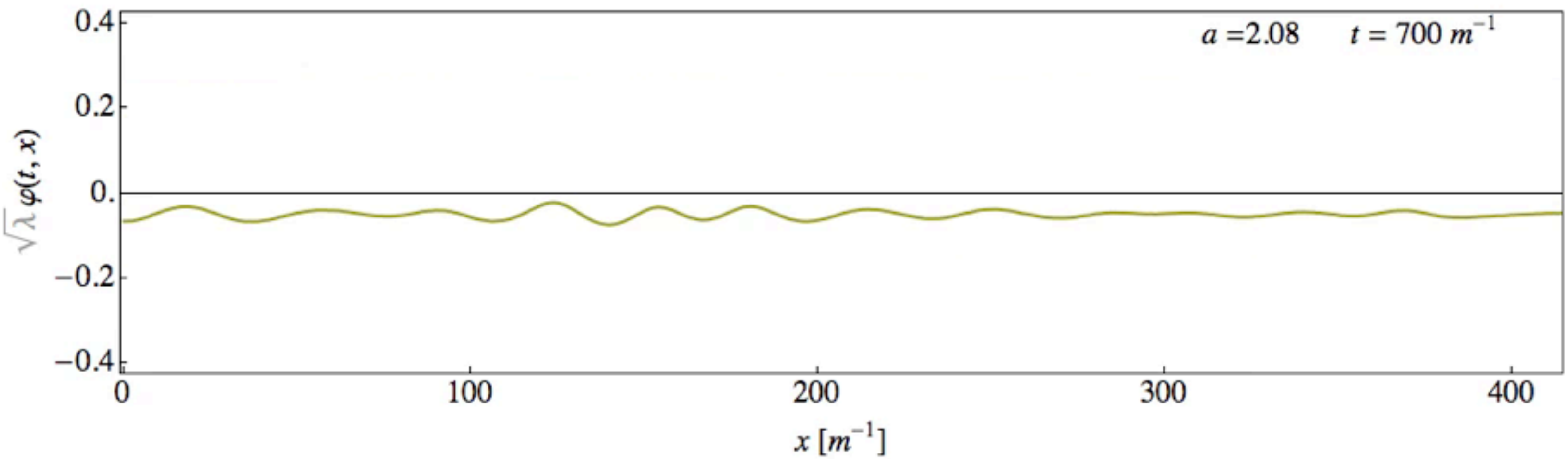

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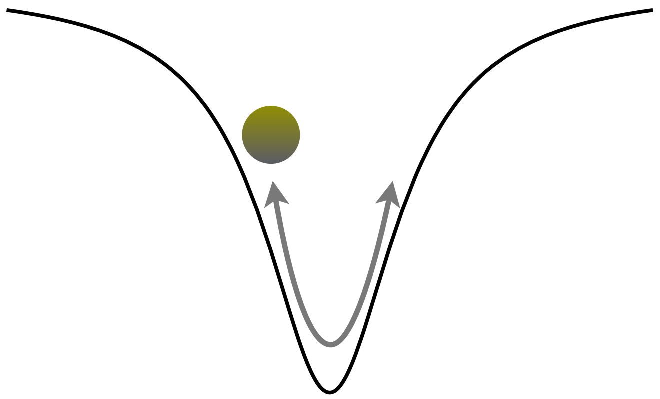

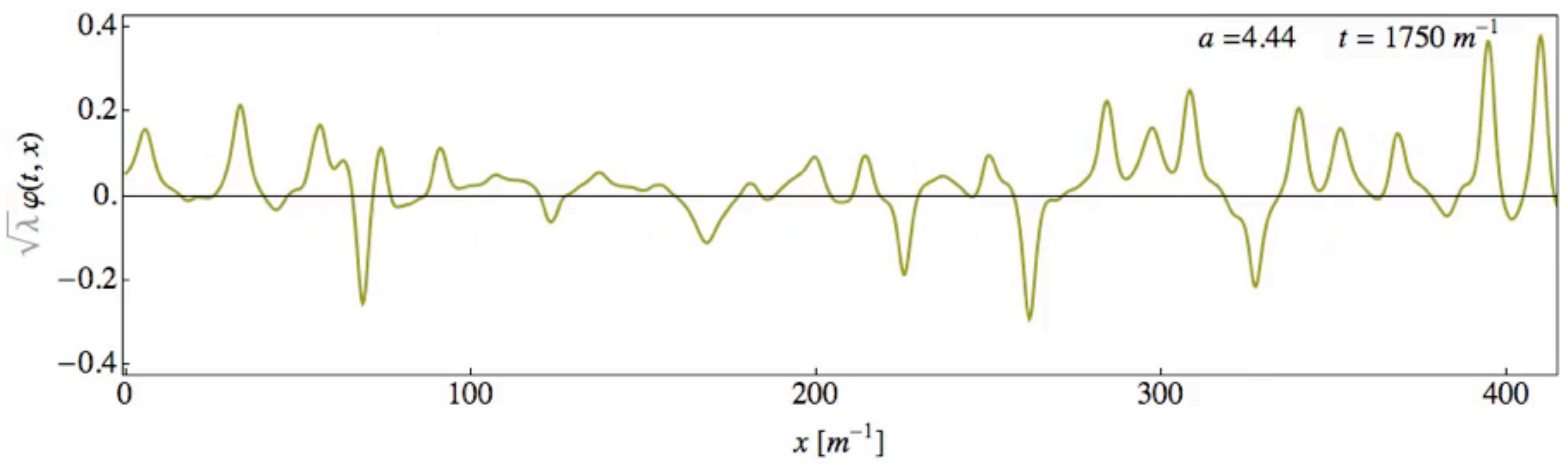

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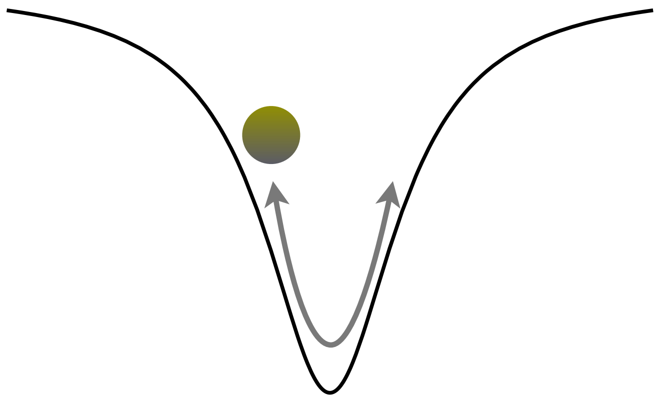

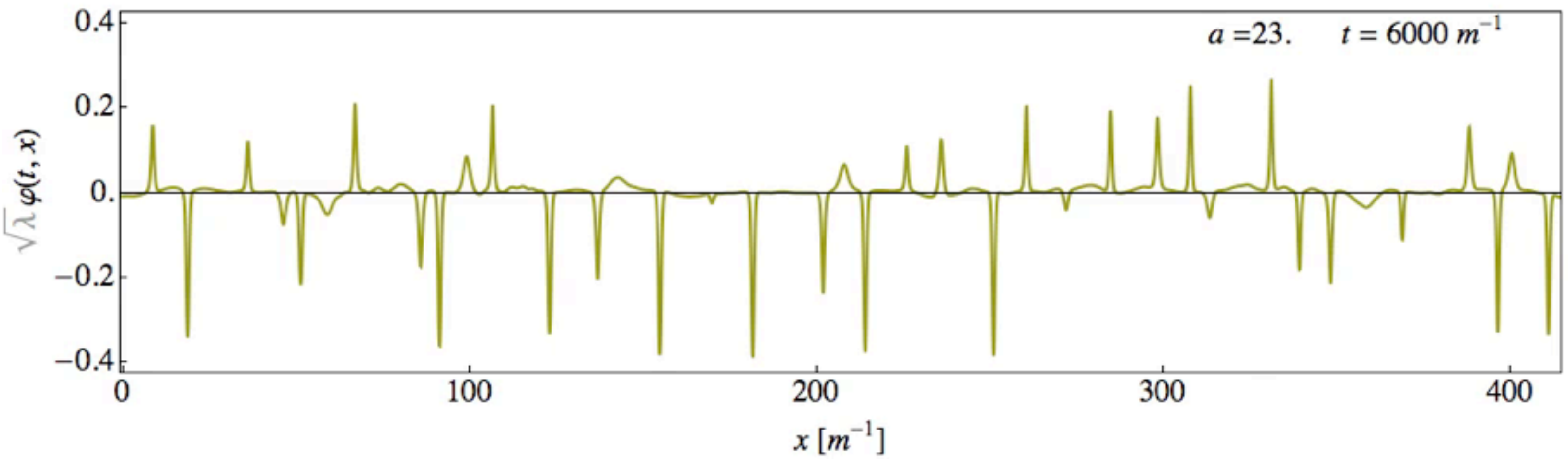

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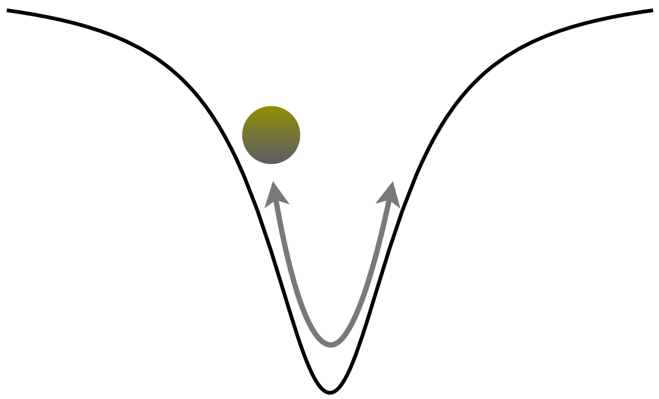

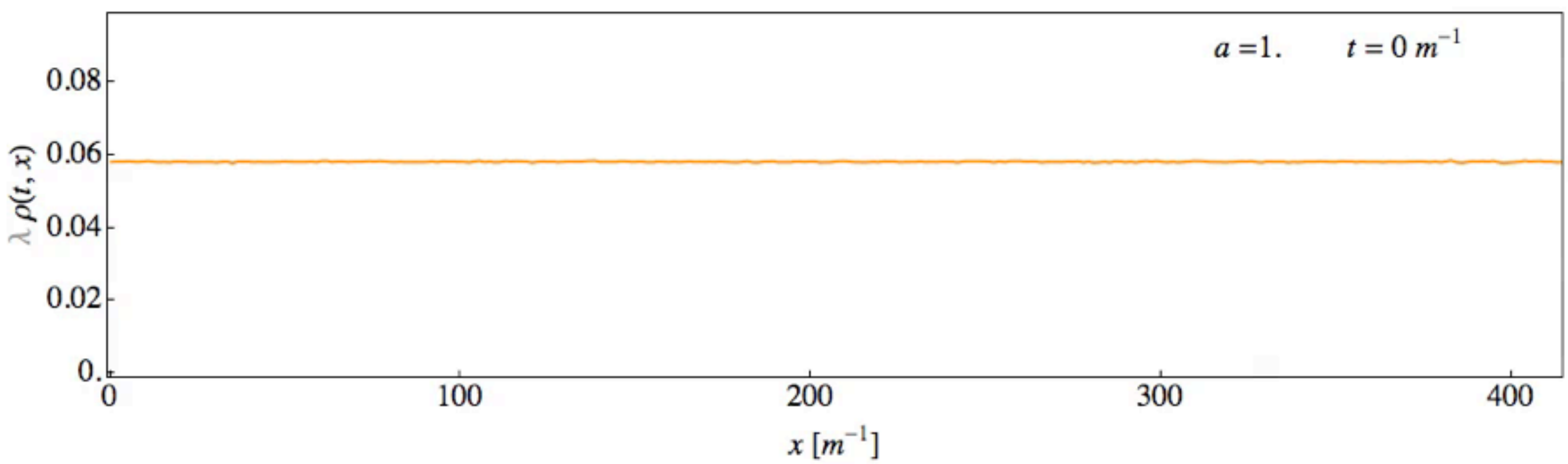

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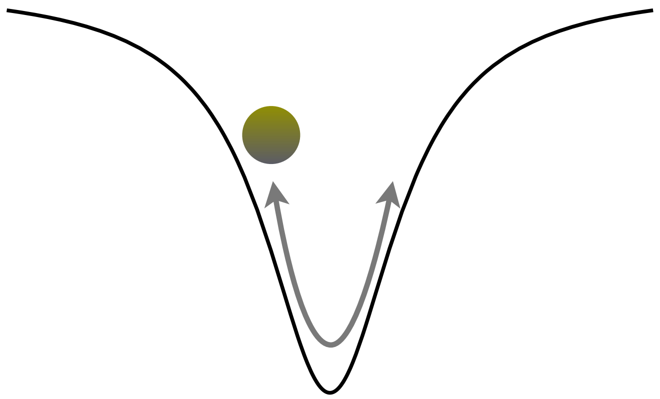

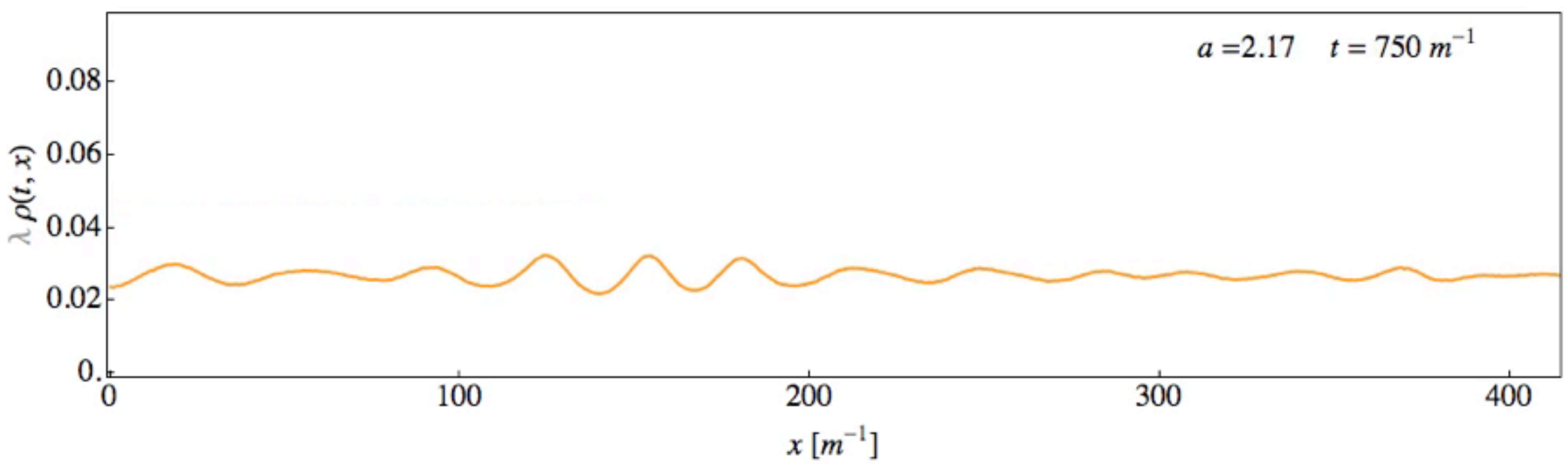

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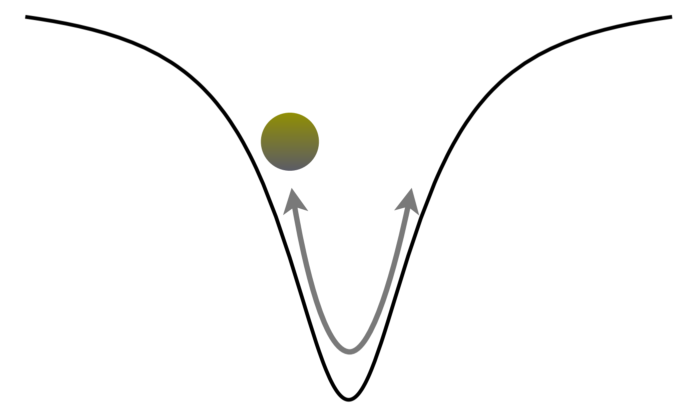
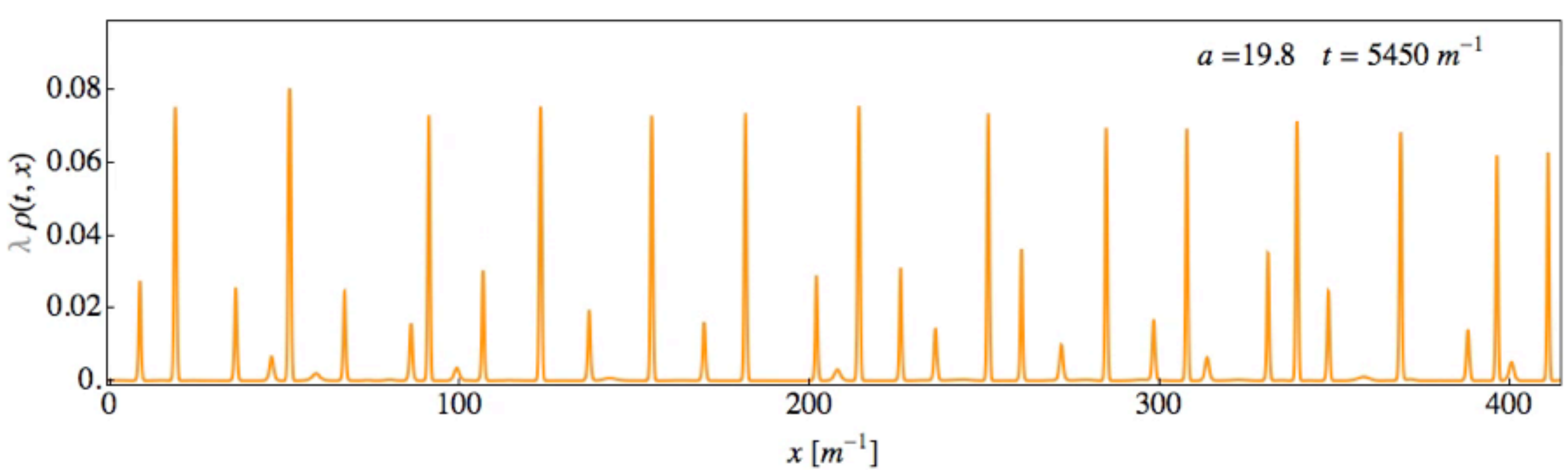
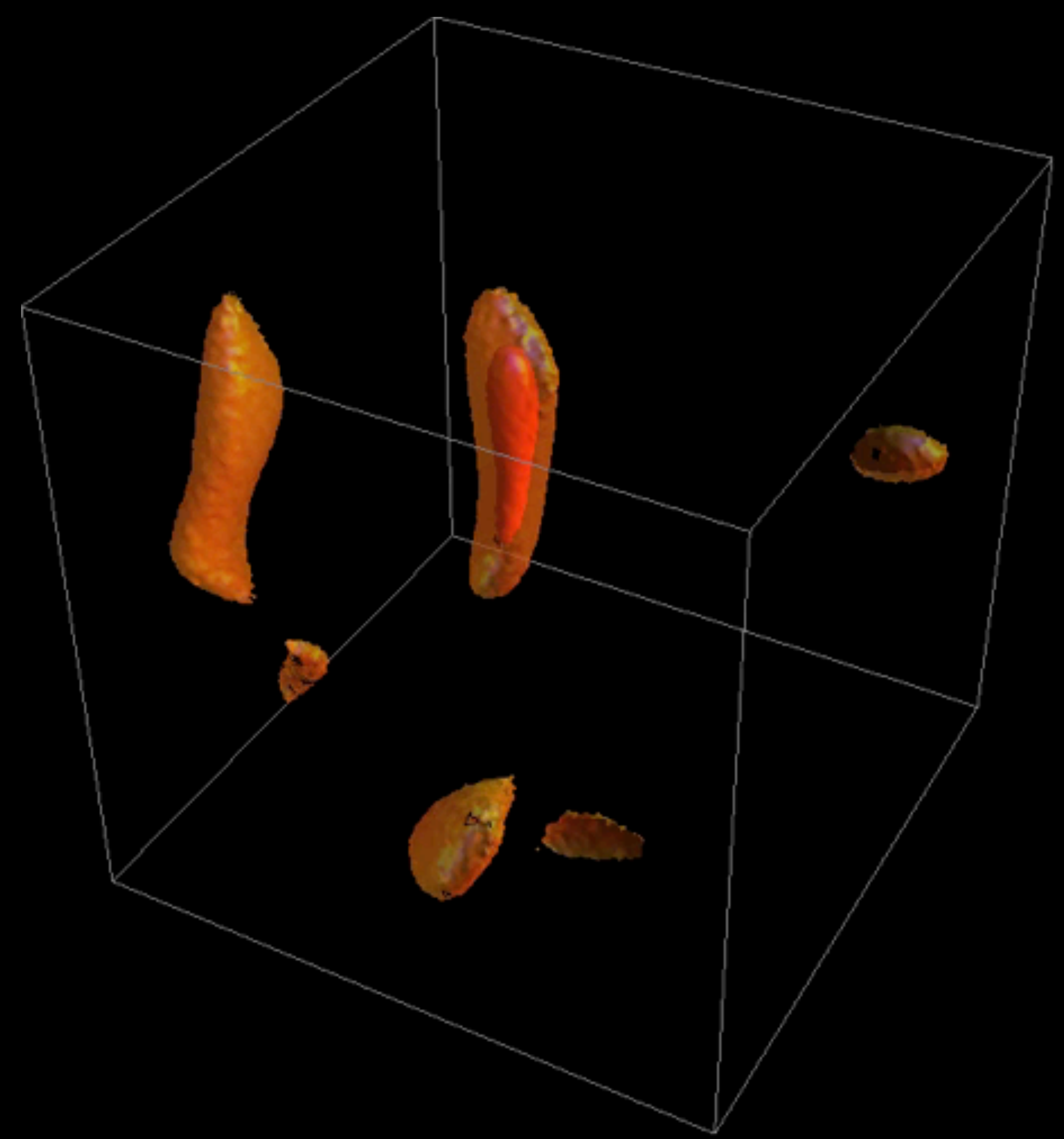


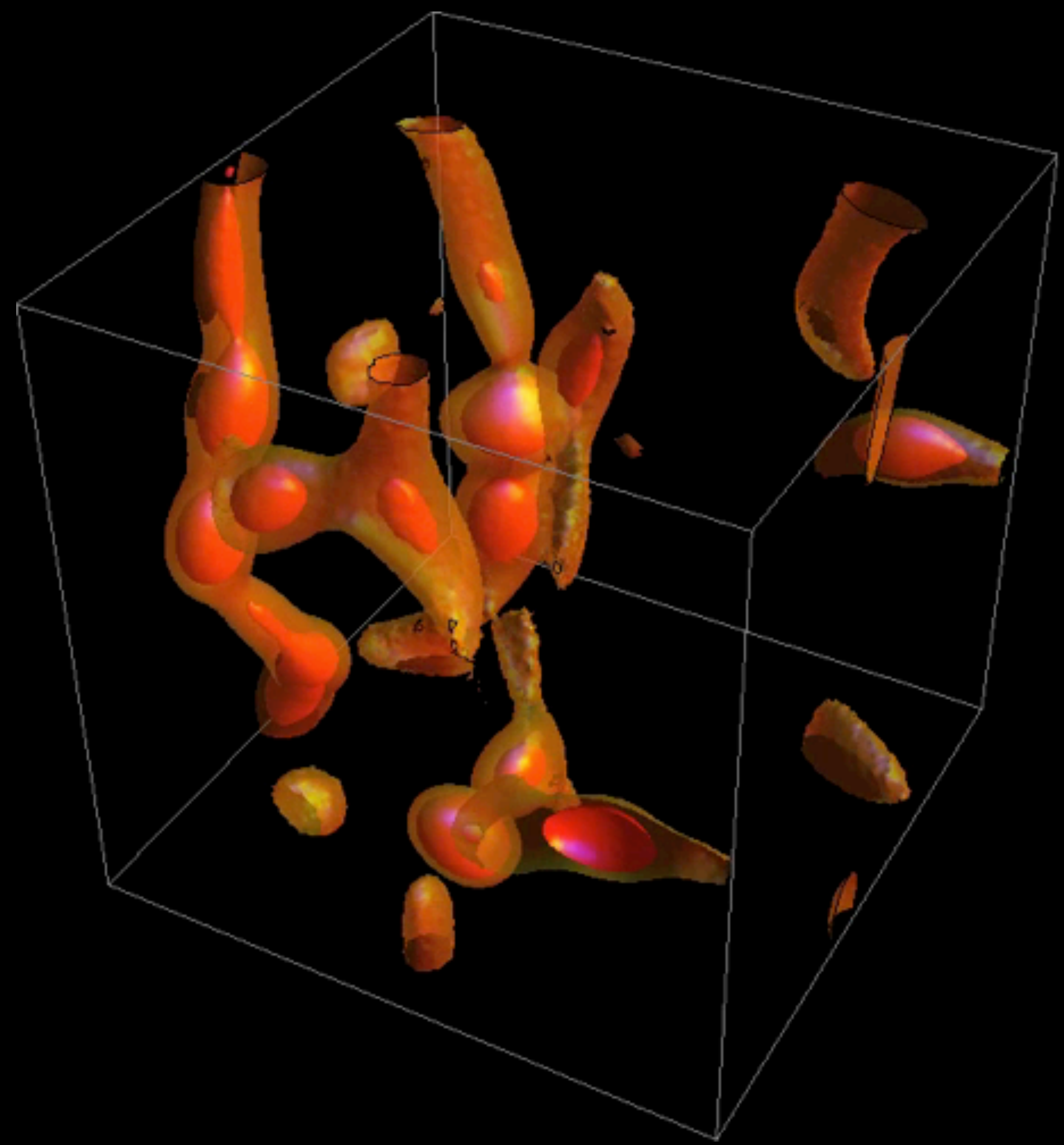


now in 3D:
(iso-density surfaces)



MA, Easther, Finkel, Flaugher & Hertzberg (2011)

now in 3D:
(iso-density surfaces)



MA, Easther, Finkel, Flaugher & Hertzberg (2011)

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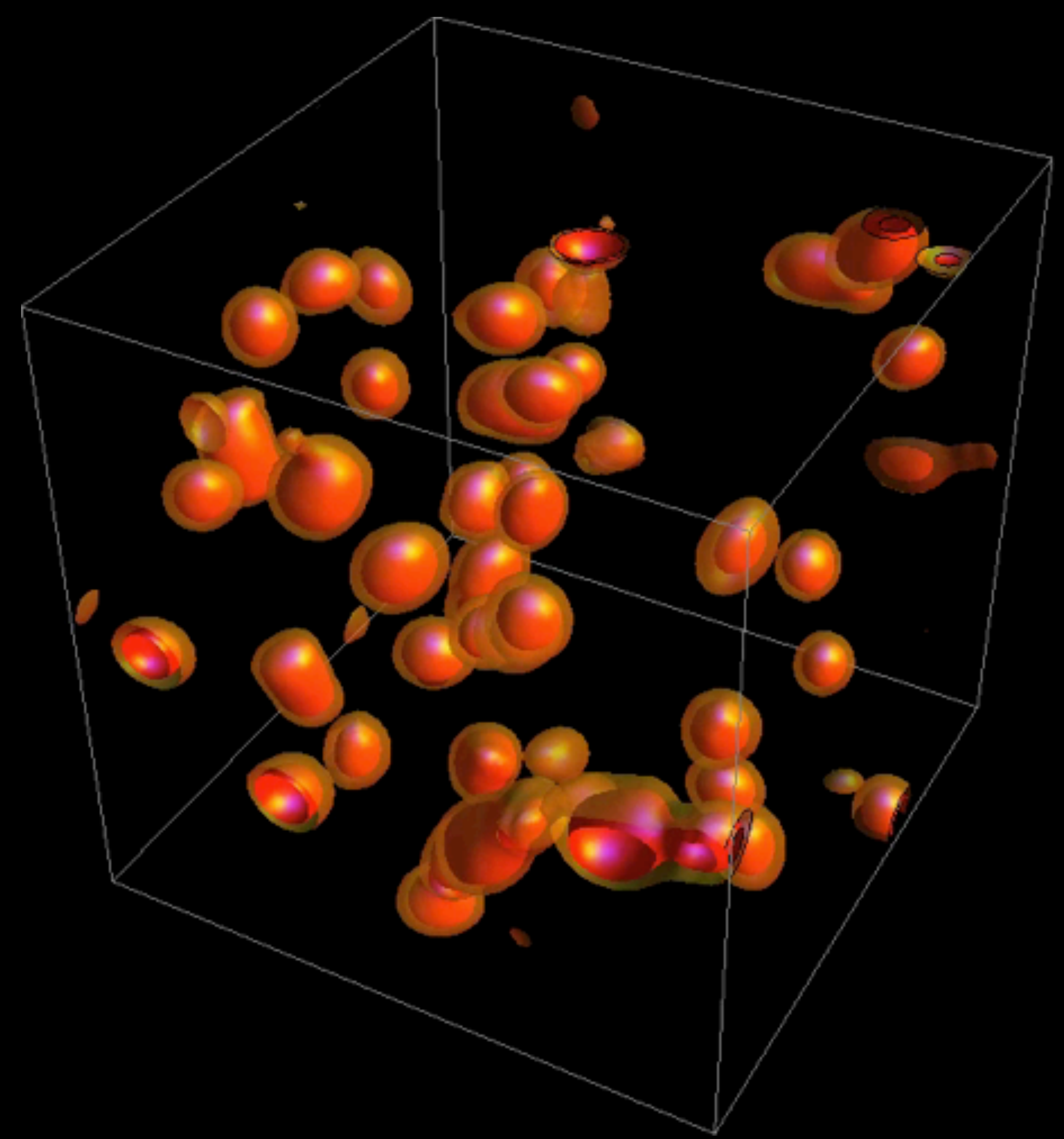
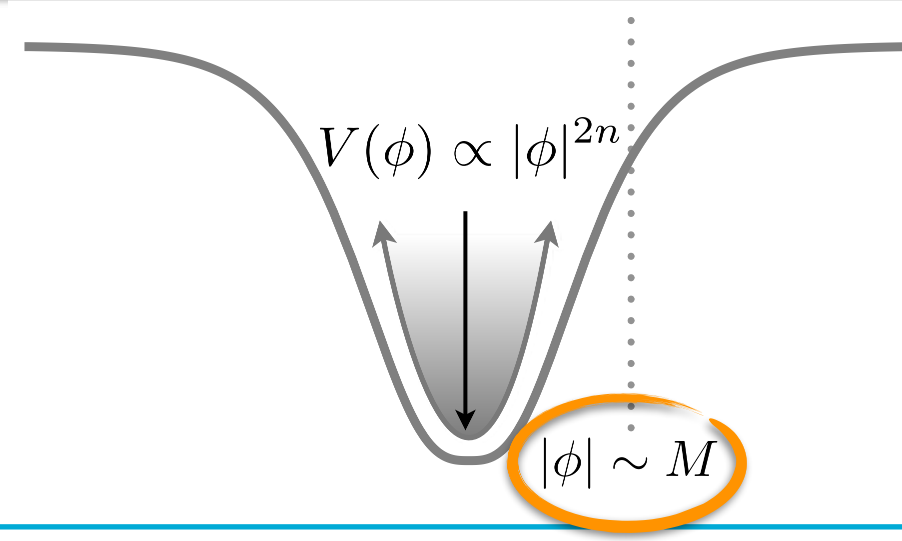
(iso-density surfaces)

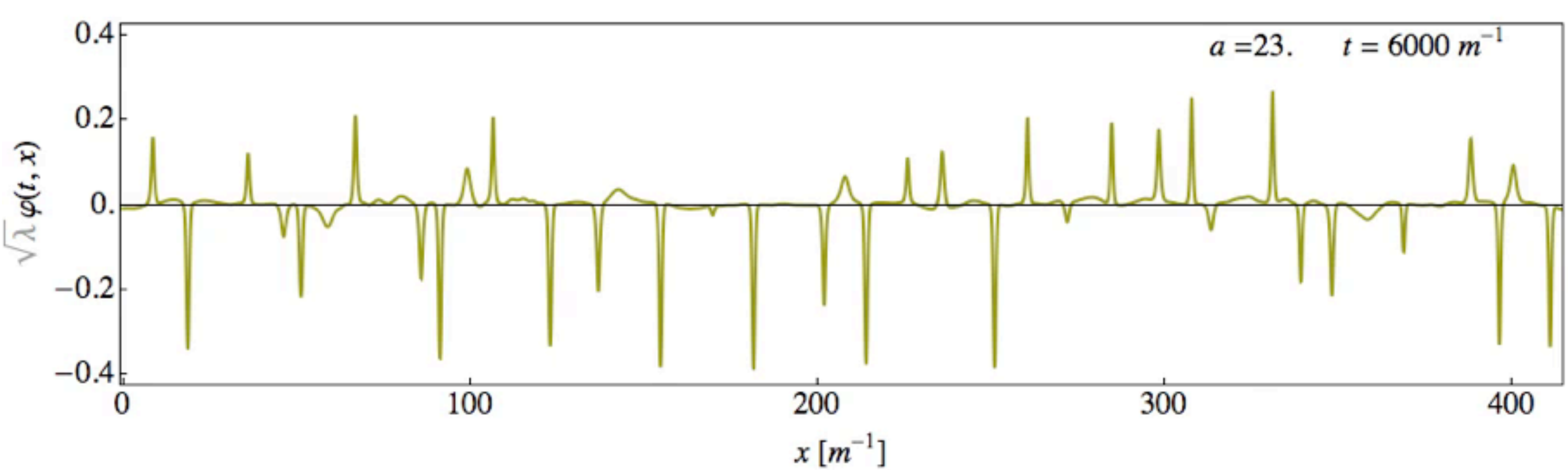


MA, Easther, Finkel, Flaugher & Hertzberg (2011)

condition for emergence of oscillons after inflation

$$\frac{\text{growth-rate of fluctuations}}{\text{expansion rate}} \sim \frac{m_{\rm pl}}{M} \gg 1$$

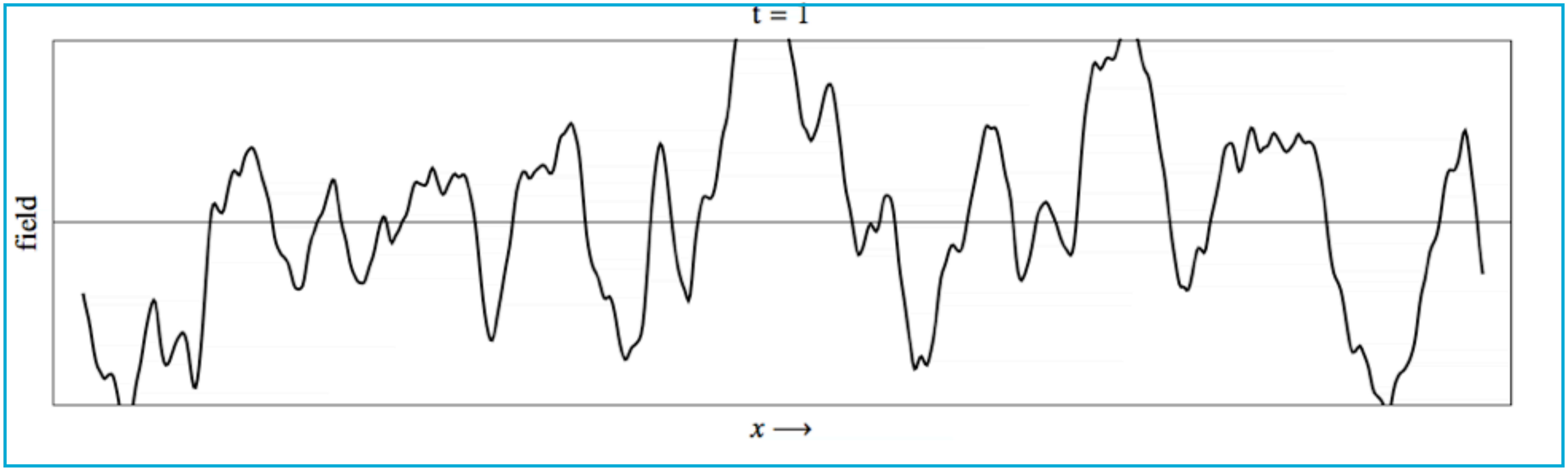




MA (2010)

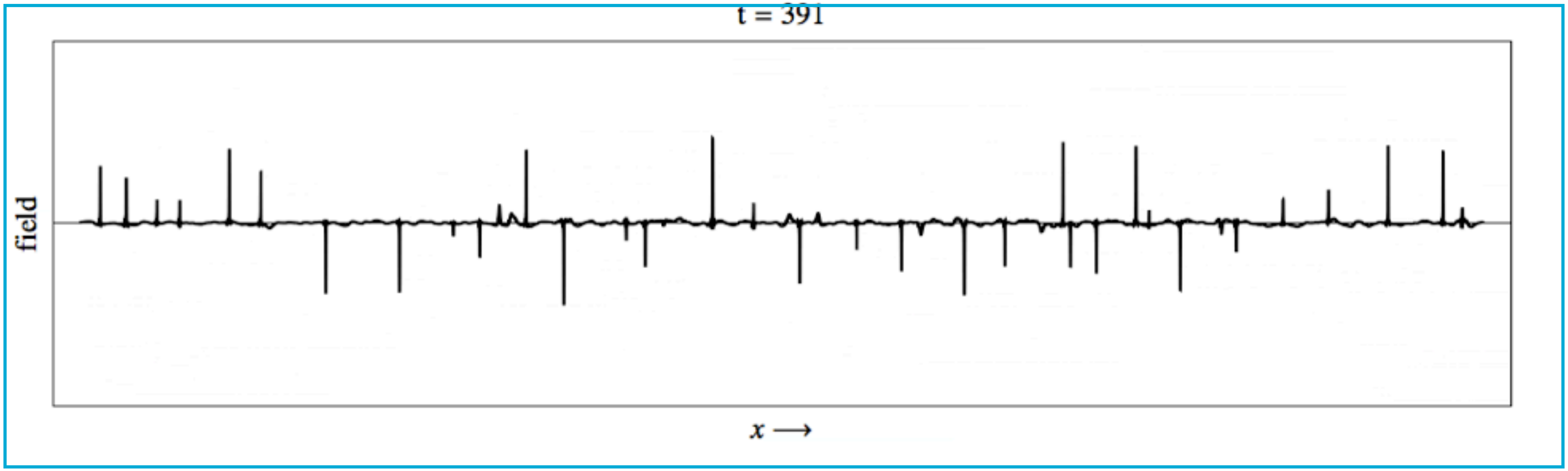
has Alan though about this ?

“quasi-thermal” field configuration



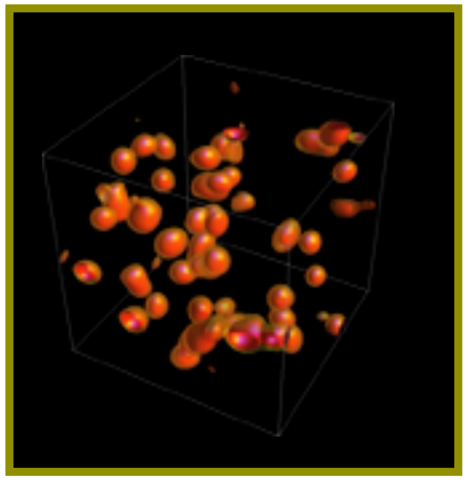
simulation of “quasi-thermal” example in
Farhi, Graham, **Guth**, Iqbal, Rosales, Stamatopoulos 2008

“quasi-thermal” field configuration

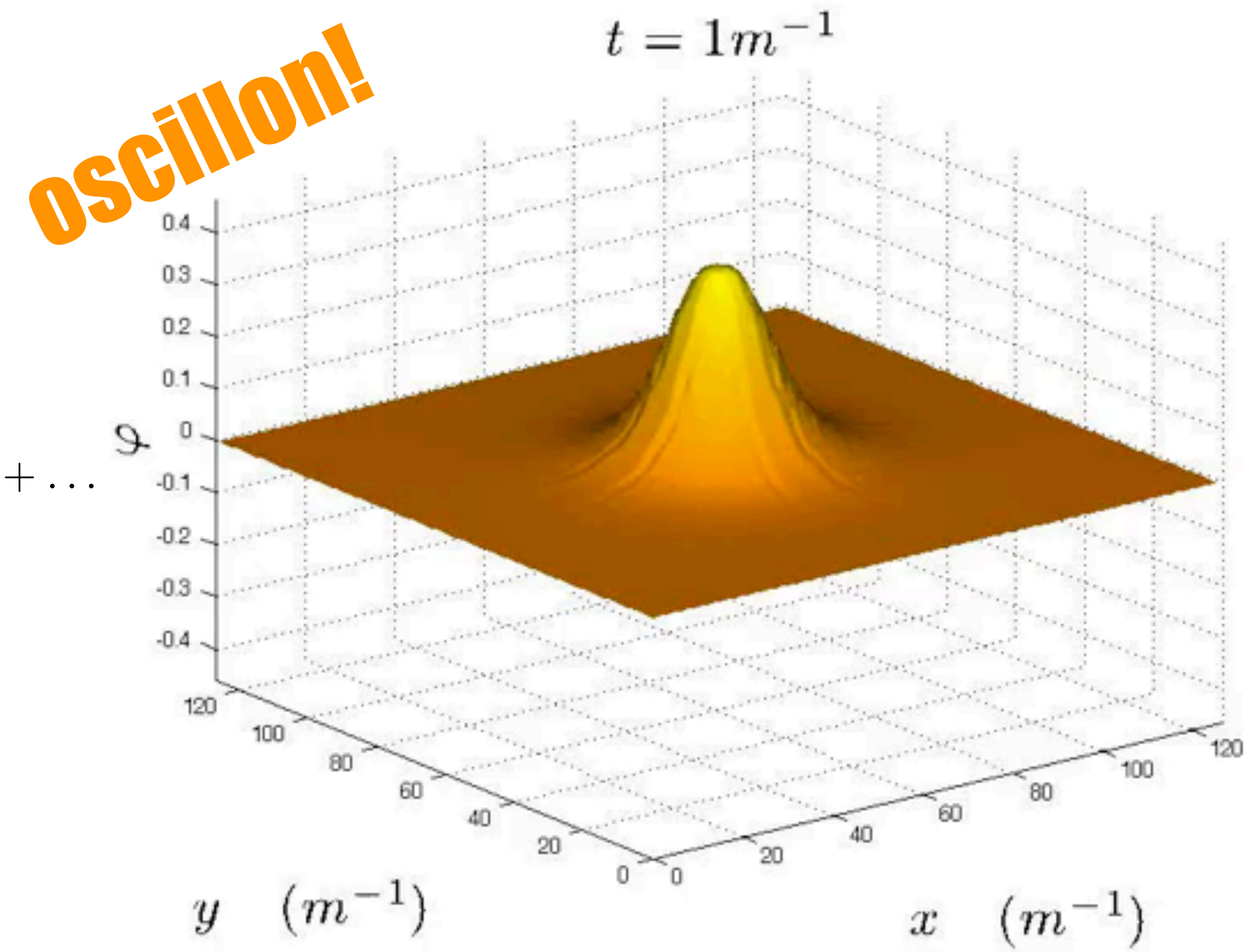


simulation of “quasi-thermal” example in
Farhi, Graham, **Guth**, Iqbal, Rosales, Stamatopoulos 2008

lumps ?



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



$$\mathcal{L} = T(X,\varphi) - V(\varphi)$$

$$T(X,\varphi) = X + \xi_2 X^2 + \xi_3 \varphi X^2 + \dots$$
$$V(\varphi) = \frac{1}{2}\varphi^2 + \frac{\lambda_3}{3}\varphi^3 + \frac{\lambda_4}{4}\varphi^4 + \frac{\lambda_5}{5}\varphi^5 + \dots$$

$$\boxed{\Delta = \xi_2 - \lambda_4 + \frac{10}{9}\lambda_3^2 > 0.}$$

existence and stability:
MA (2013)
MA & Shirokoff (2010)
Hertzberg (2011)
Sfakianakis (2015)

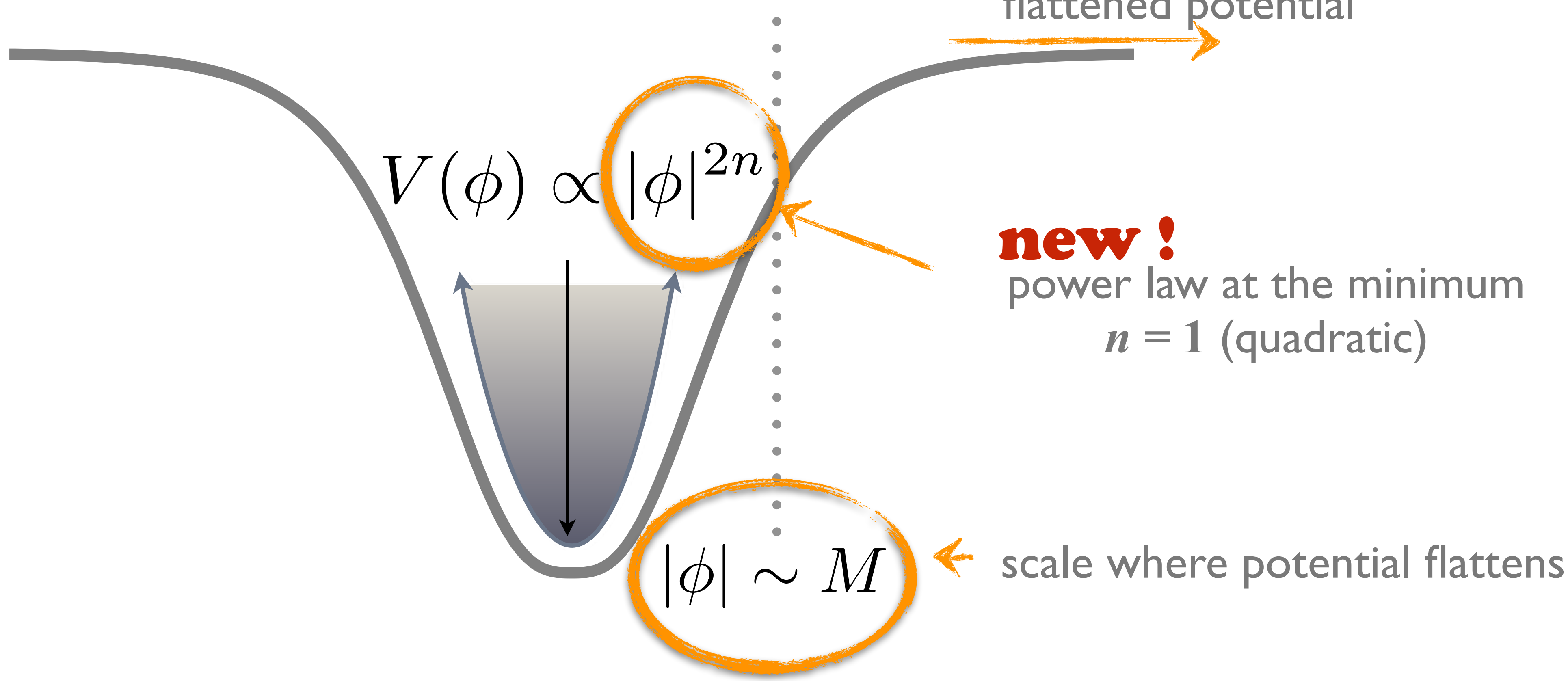
Bogolubsky & Makhankov (1976), Gleiser (1994), Copeland, Gleiser and Mueller et al. (1995) …

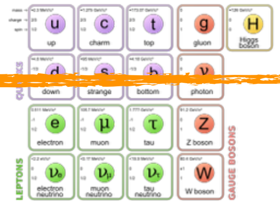
consequences ?

- equation of state/duration to radiation domination ? (if coupled to other fields)
- black holes ?
- gravitational waves ?

  Zhou, Copeland, Easther, Finkel, Mou & Saffin (2013)
  Antusch, Cefala, Krippendorf, Muia, Orani, Quevedo (2017)

end of inflation in “simple” models

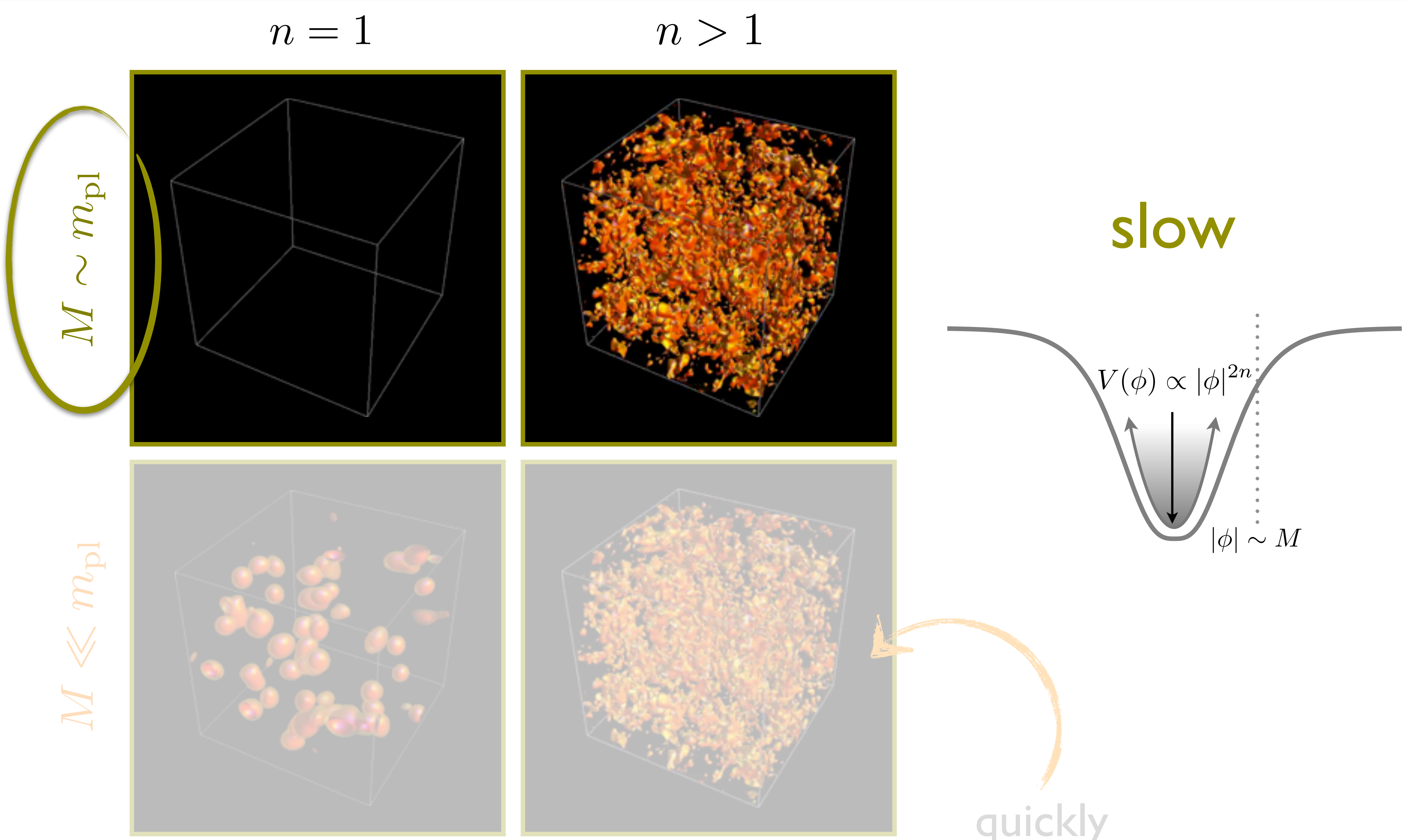


- shape of the potential (self couplings)
- ~~couplings to other fields~~  $\cancel{\chi\ ,\psi}$

Lozanov & MA (2017)

result of fragmented dynamics

* after sufficient time



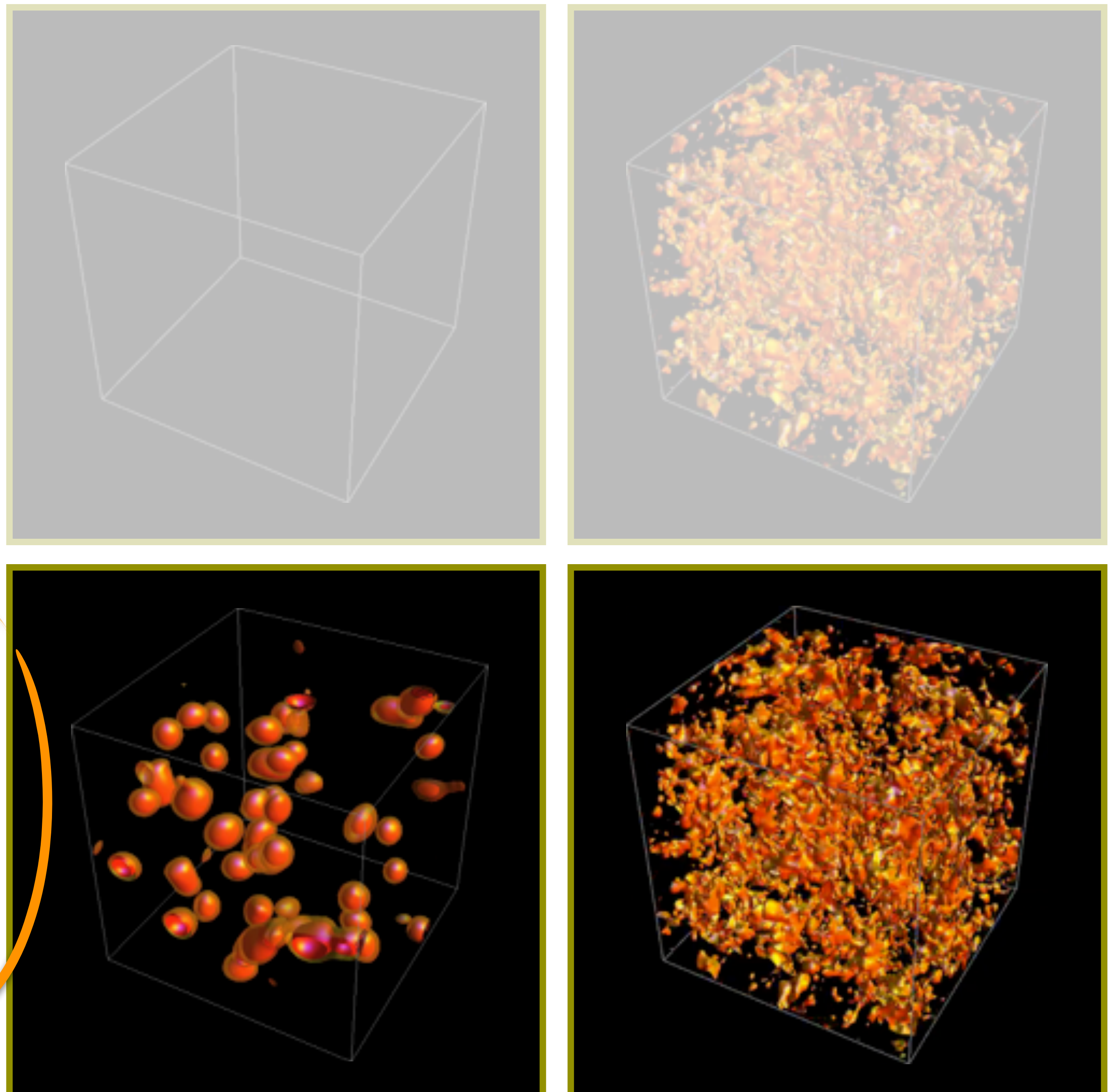
result of fragmented dynamics

* after sufficient time

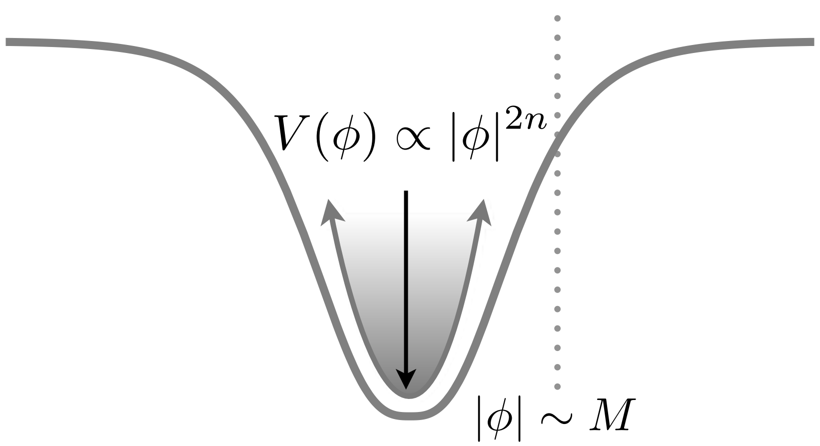
$n = 1$ $\qquad$ $n > 1$

$M \sim m_{\rm pl}$

$M \ll m_{\rm pl}$



slow



fast

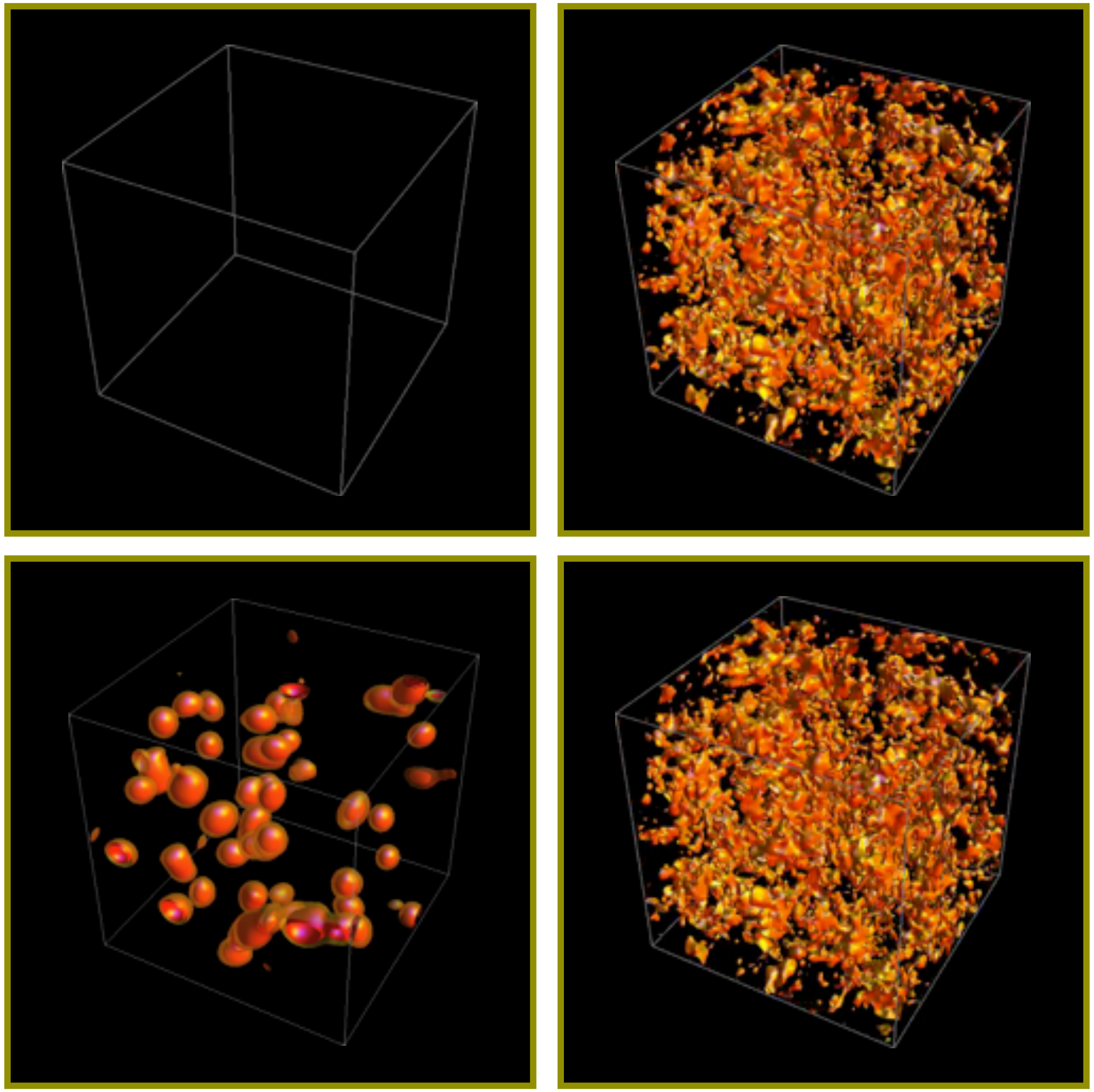
eq. of state

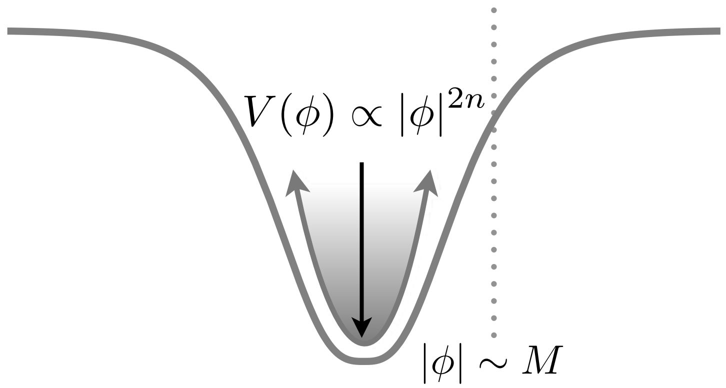
* after sufficient time

$n = 1$ $\qquad$ $n > 1$

$M \sim m_{\rm pl}$

$M \ll m_{\rm pl}$





$$\boxed{w \rightarrow \begin{cases} 0 & \text{if } n = 1 \\ 1/3 & \text{if } n > 1 \end{cases}}$$

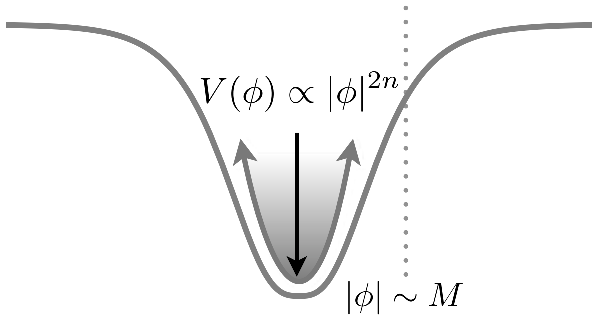
independent of M

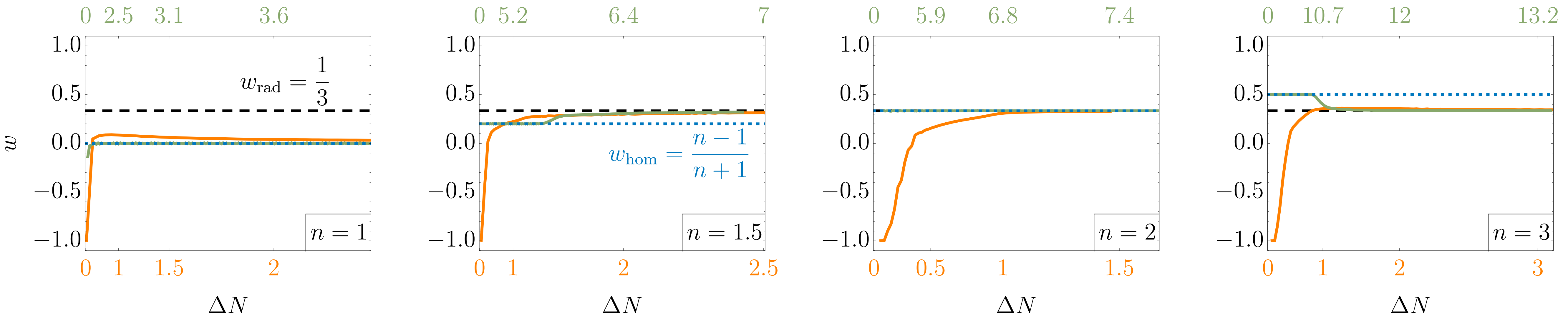
$$w \neq \frac{n-1}{n+1}$$

Lozanov & MA (2017)

duration to radiation domination

green = inefficient initial resonance
orange = efficient initial resonance





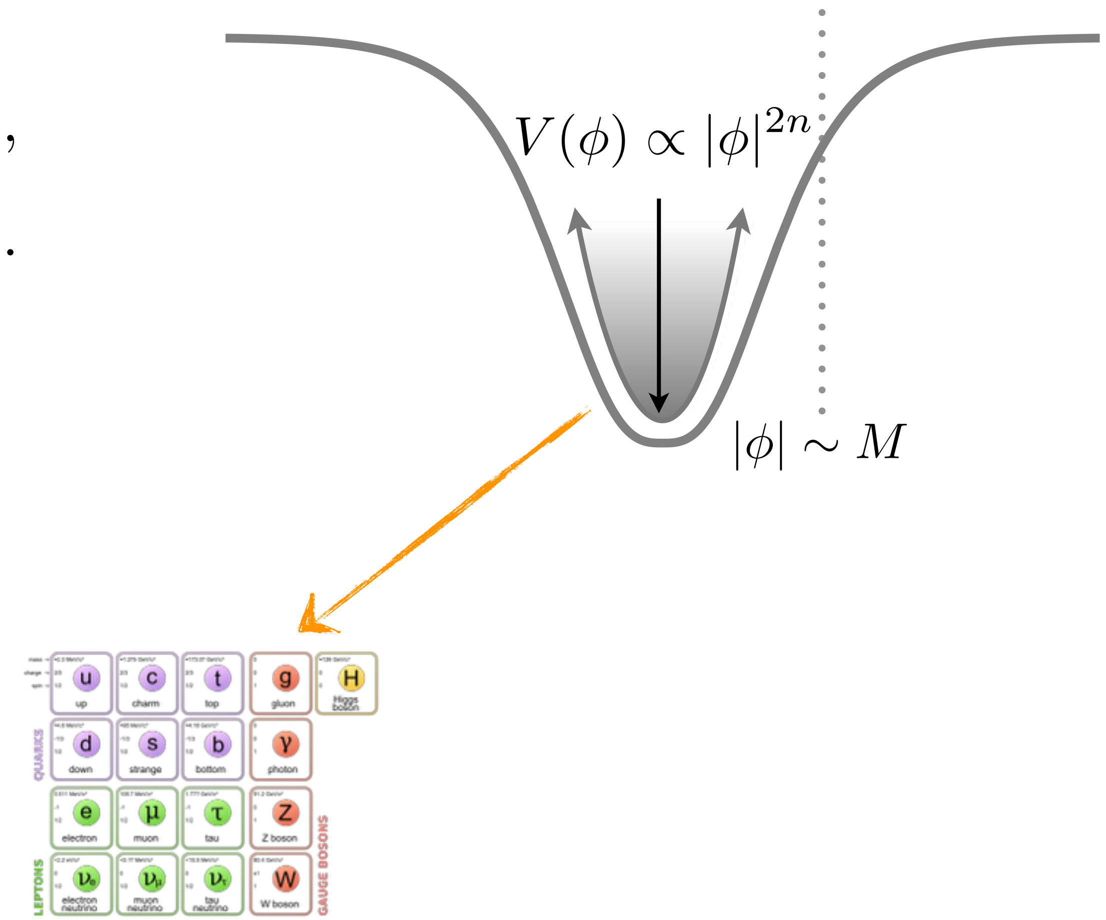
from analytic considerations

$$\Delta N_{\rm rad} \sim \begin{cases} 1 & M \lesssim 10^{-2} m_{\rm Pl}\,, \\ \frac{n+1}{3} \ln\left(\frac{\kappa}{\Delta\kappa}\frac{10M}{m_{\rm Pl}}\right) & M \gtrsim 10^{-2} m_{\rm Pl}\,. \end{cases}$$

Lozanov & MA (2017)

an upper bound on duration to radiation domination

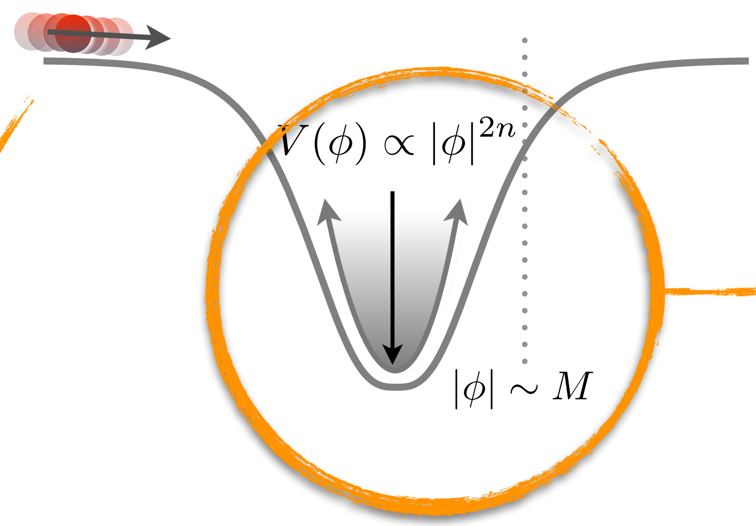
$$\Delta N_{\mathrm{rad}} \sim \begin{cases} 1 & M \lesssim 10^{-2} m_{\mathrm{Pl}}\,, \\ \dfrac{n+1}{3} \ln\left(\dfrac{\kappa}{\Delta\kappa}\,\dfrac{10M}{m_{\mathrm{Pl}}}\right) & M \gtrsim 10^{-2} m_{\mathrm{Pl}}\,. \end{cases}$$

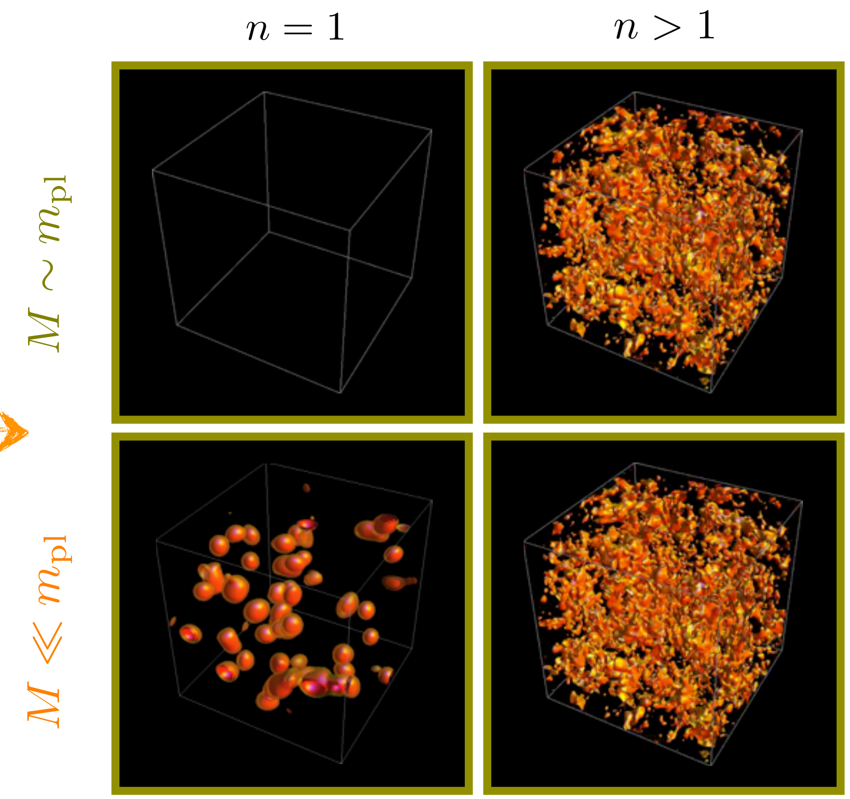


additional *light (massless) fields* can only decrease the duration!

* decay to significantly massive fields can change this conclusion

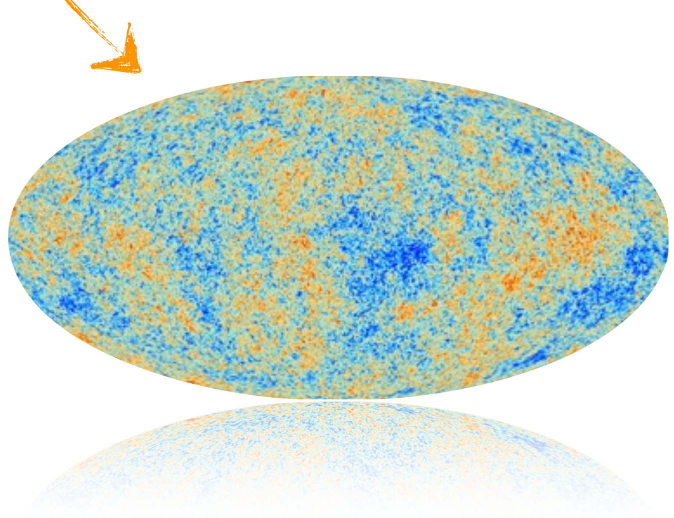
summary: “simple” models of cosmological scalar field dynamics

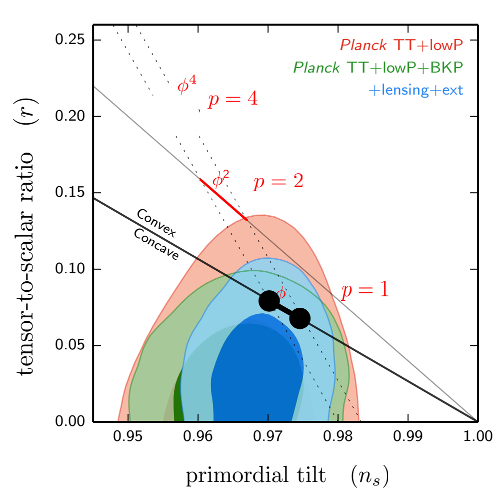


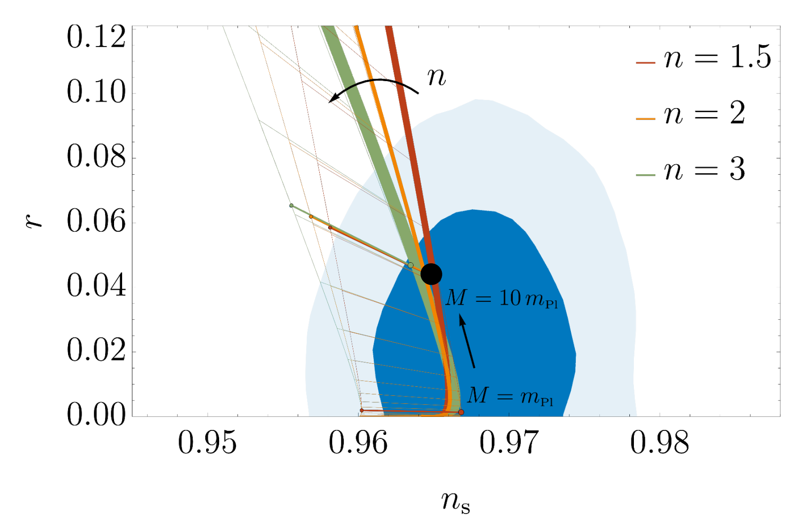


$$w \to \begin{cases} 0 & \text{if } n = 1 \\ 1/3 & \text{if } n > 1 \end{cases}$$

$$\Delta N_{\rm rad} \sim \begin{cases} 1 & M \lesssim 10^{-2} m_{\rm Pl}\,, \\ \frac{n+1}{3} \ln\left(\frac{\kappa}{\Delta\kappa}\frac{10M}{m_{\rm Pl}}\right) & M \gtrsim 10^{-2} m_{\rm Pl}\,. \end{cases}$$







end of inflation

SIMPLE

complicated

COMPLEX

end of inflation

SIMPLE

$\phi F^{\mu\nu} F_{\mu\nu}$

$\phi \bar{\psi} \psi$

$\phi^2 \chi^2$

complicated

$J^\mu(\phi) A_\mu$

$\phi \chi^2$

COMPLEX

things that can happen

inflaton dominated, "cold" universe

scalar & gauge bosons + fermions

particle production

time

inflation

preheating

non-linear regime

perturbative regime

thermalization

gravitational perturbations
(non-gaussianity, gravitational waves)

topological & non-topological solitons
(strings, textures, bubbles, Q-balls, oscillons)

+

expansion history, baryogenesis …

radiation dominated, thermal universe

from review: MA, Kaiser, Karouby & Hertzberg (2013)

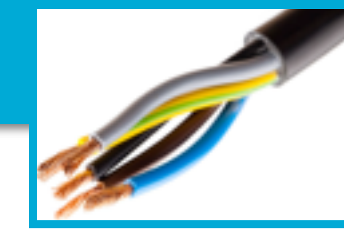
end of inflation

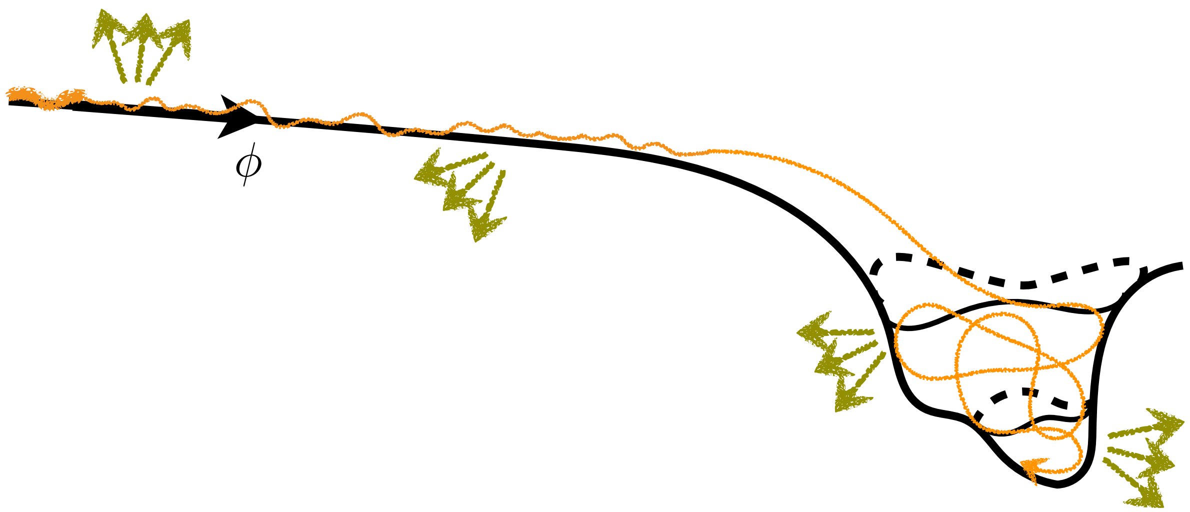
SIMPLE

complicated

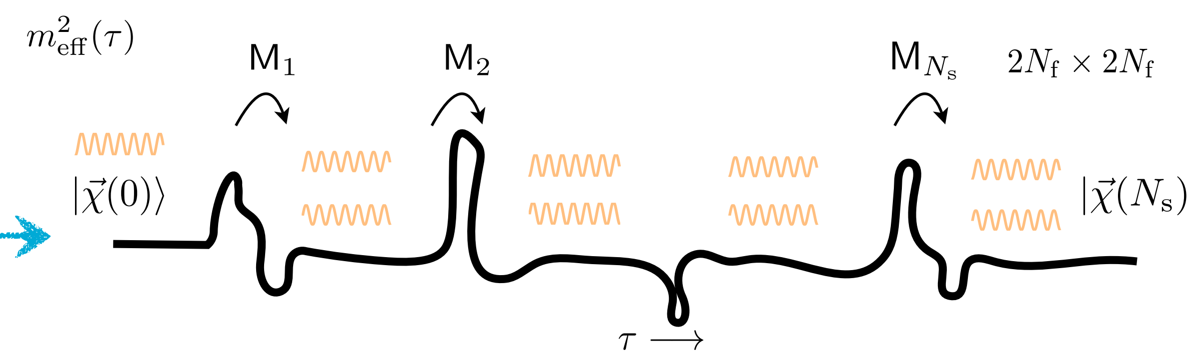
COMPLEX

complex enough: "universal" results

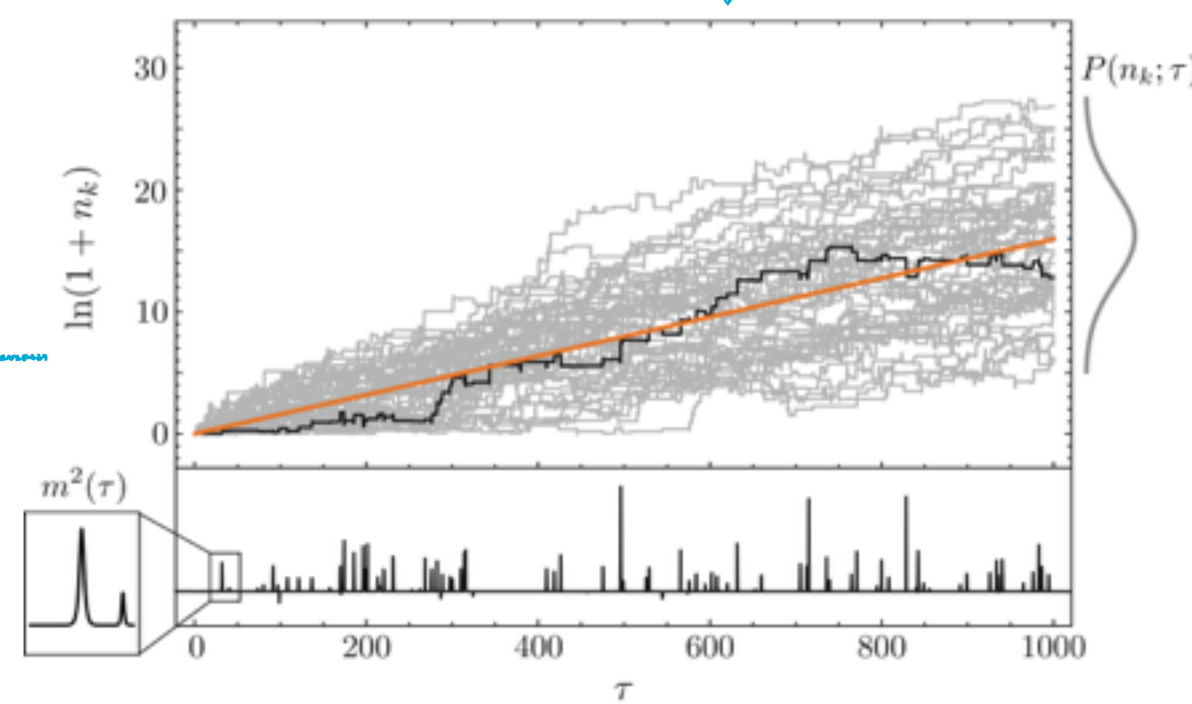




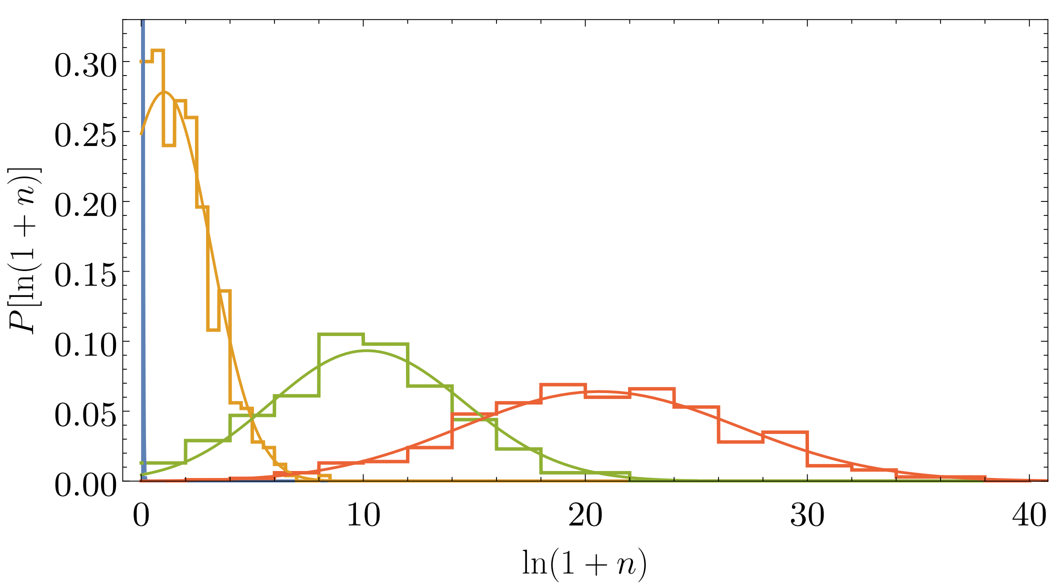
complex non-perturbative particle production



treat as scattering problems
(similar to that when dealing with impurities in wires)



occupation numbers grow exponentially
(universality similar to Anderson localization)

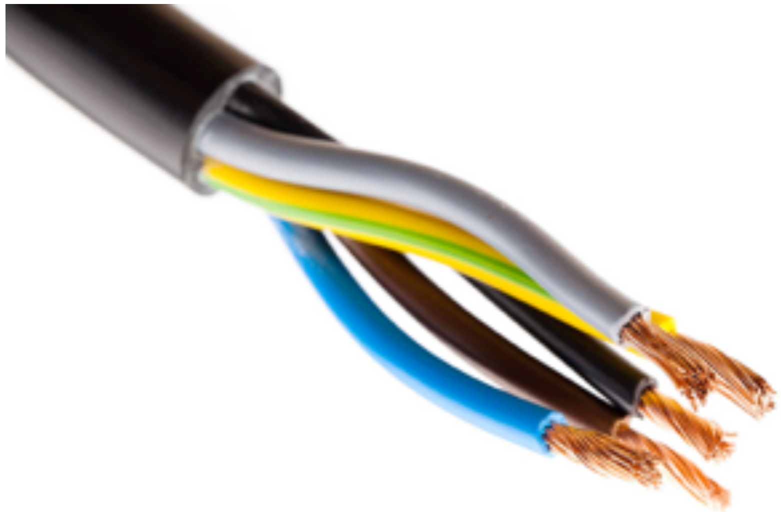


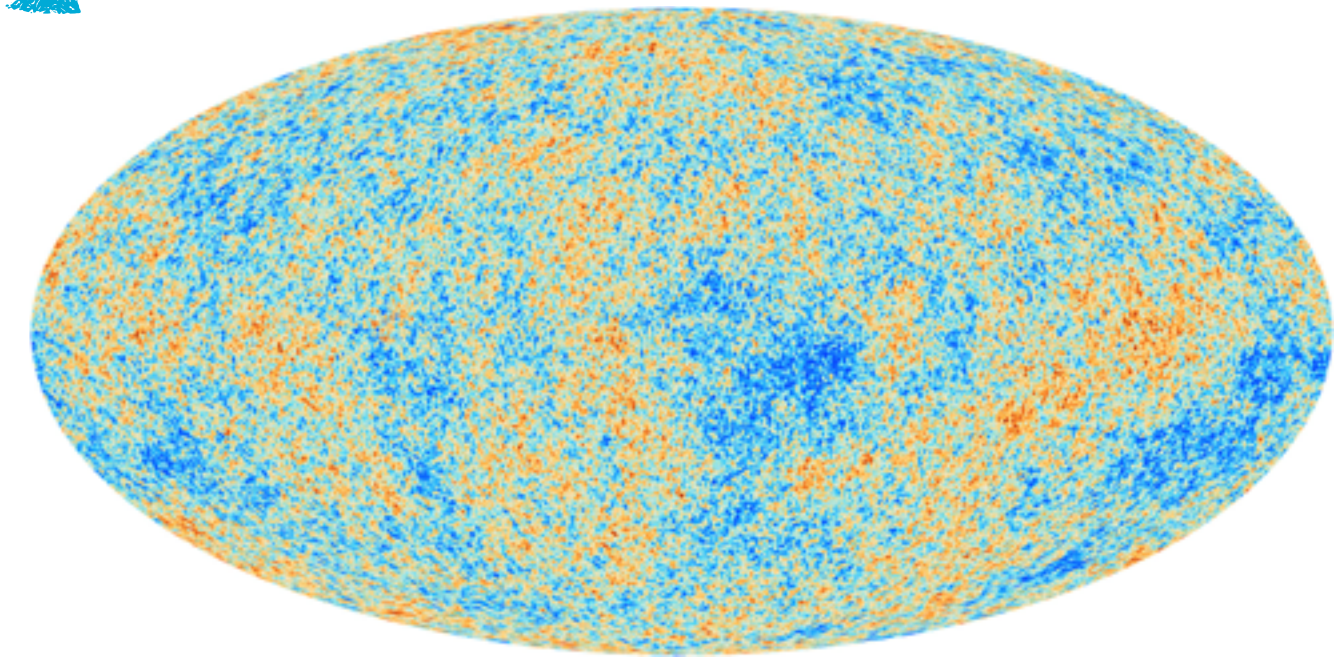
universally log-normal distributions

theory : its complicated (probably)

- inflation
- reheating after inflation

inspiration from disordered wires

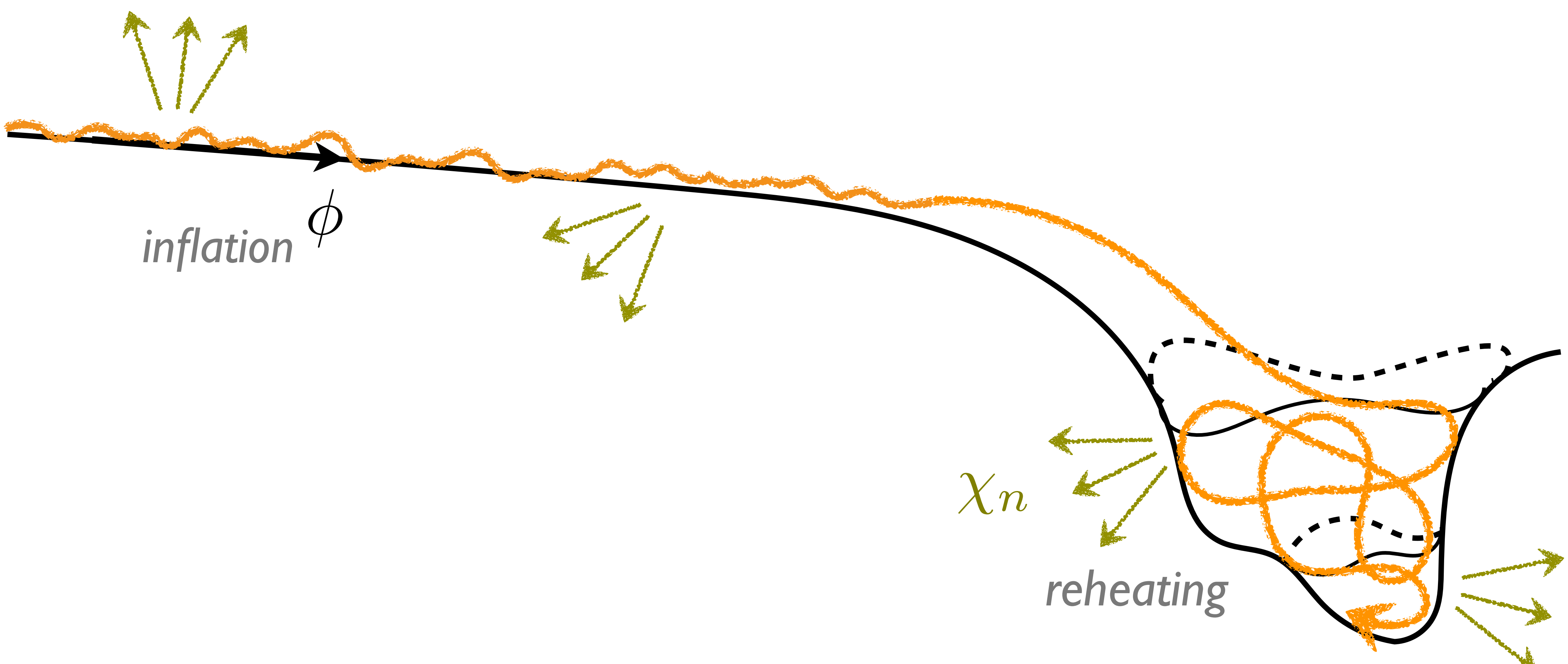




the framework

multifield inflation/reheating

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}R - \frac{1}{2}G_{ab}(\phi^c)\partial^\mu\phi^a\partial_\mu\phi^b - V(\phi^c) + \cdots\right]$$



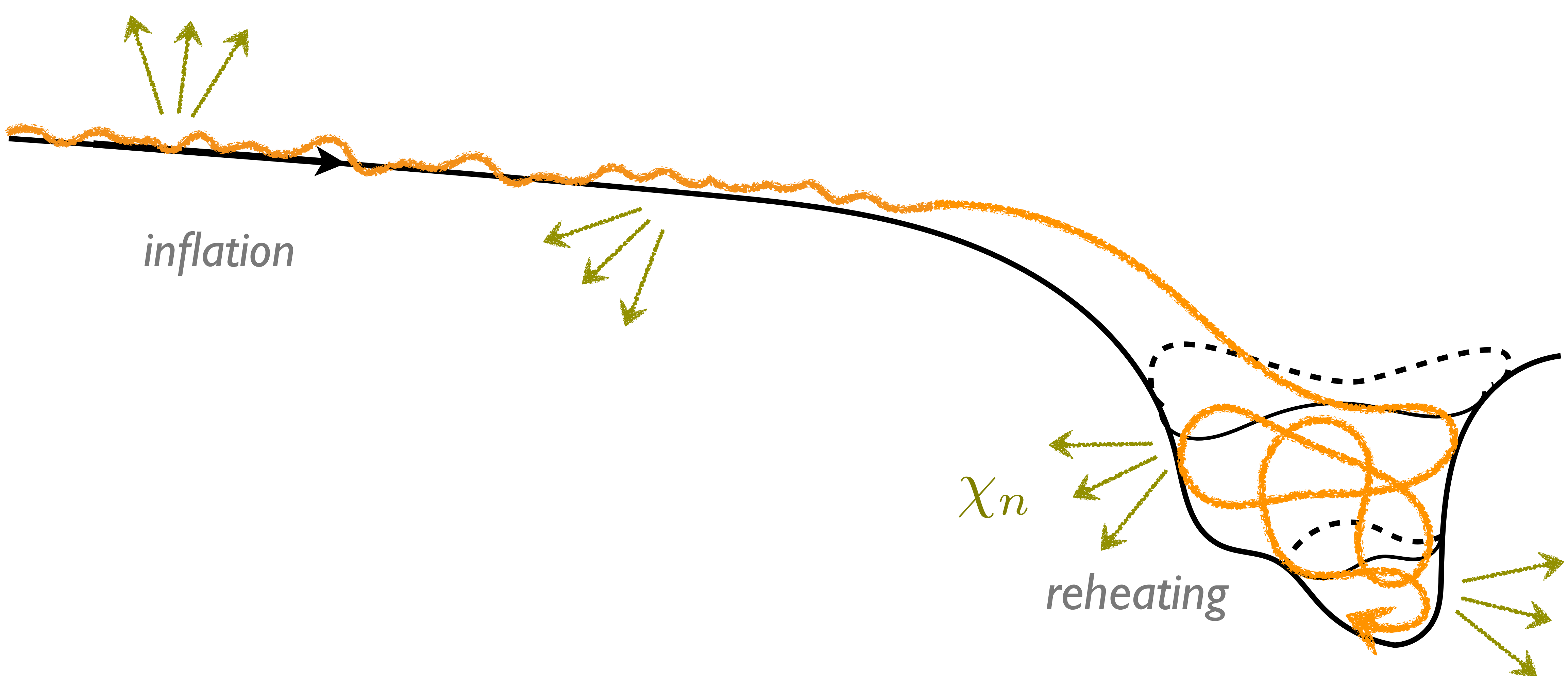
see for example: DeCross, Kaiser, Prabhu, Prescod-Weinstein, Sfakianakis (2016)

focus on perturbations

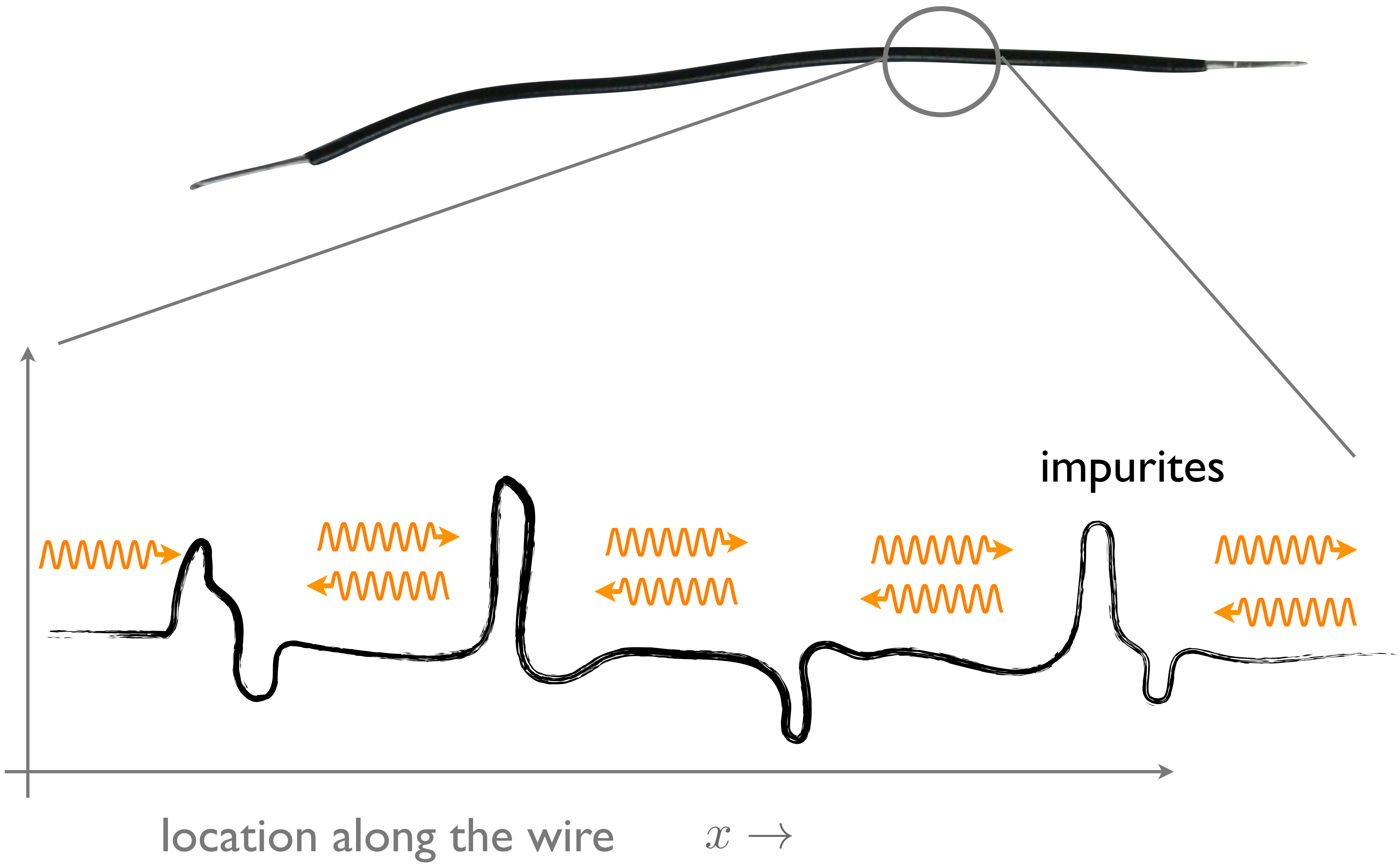
mode functions in Fourier space

$$\left(\frac{d^2}{d\tau^2}+\omega_I^2\right)\chi_k^I(\tau)+\sum_{J=1}^{N_\mathrm{f}} m^{\mathrm{s}}_{IJ}(\tau)\chi_k^J(\tau)=0\,,$$

$$\omega_I^2(k)=k^2+m_I^2\,,$$

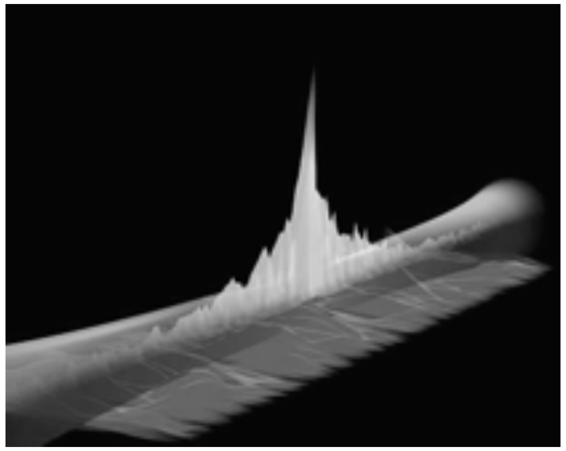


electron wave function: disordered wires

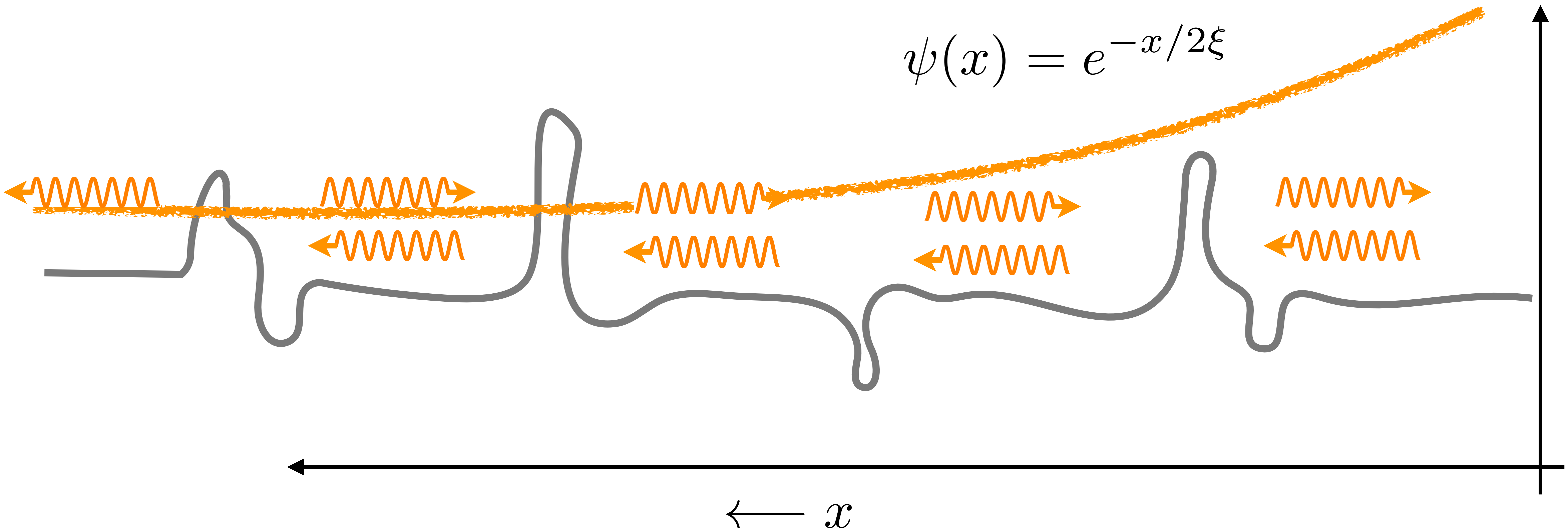


Anderson localization !

$$\psi''(x) + \left[k^2 - V(x)\right]\psi(x) = 0$$



Anderson 1957



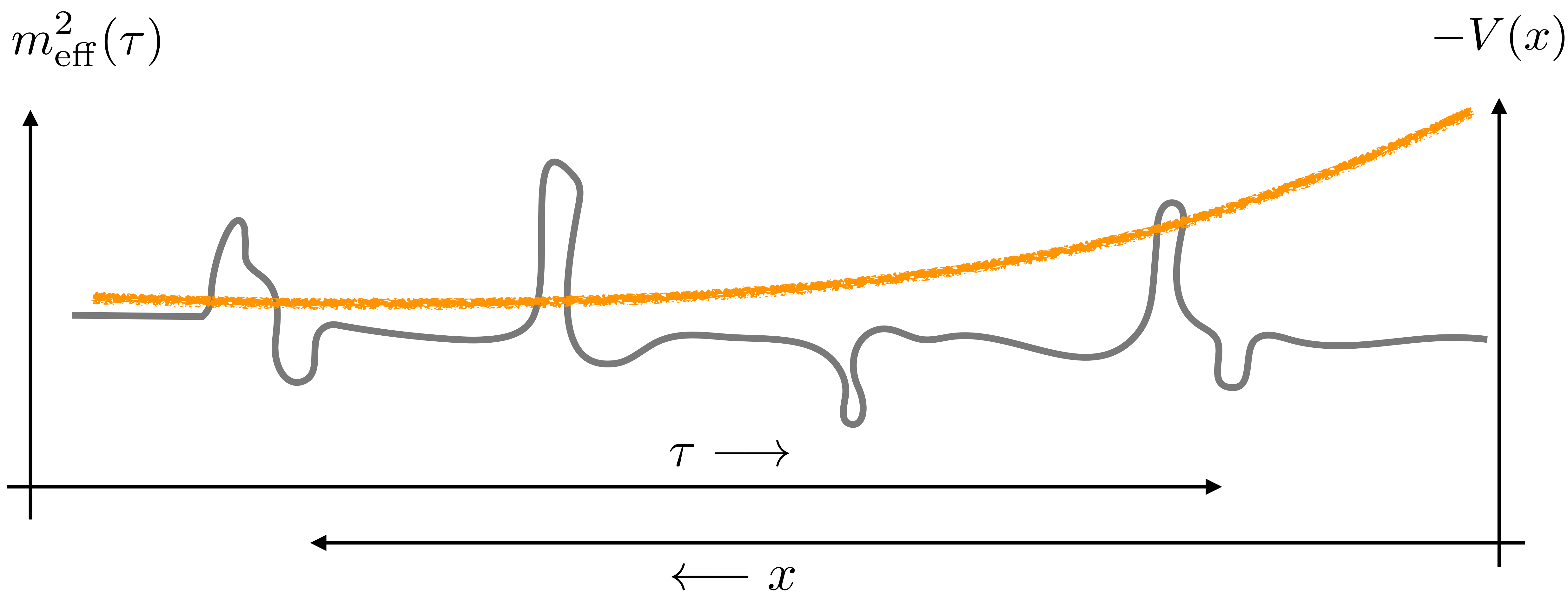
complexity in time ⟷ complexity in space
cosmology ⟷ wires

exponential growth in occupation number

Anderson localization

$$\ddot{\chi}_k(\tau) + \left[k^2 + m^2_{\rm eff}(\tau)\right]\chi_k(\tau) = 0 \quad \longleftrightarrow \quad \psi''(x) + \left[k^2 - V(x)\right]\psi(x) = 0$$

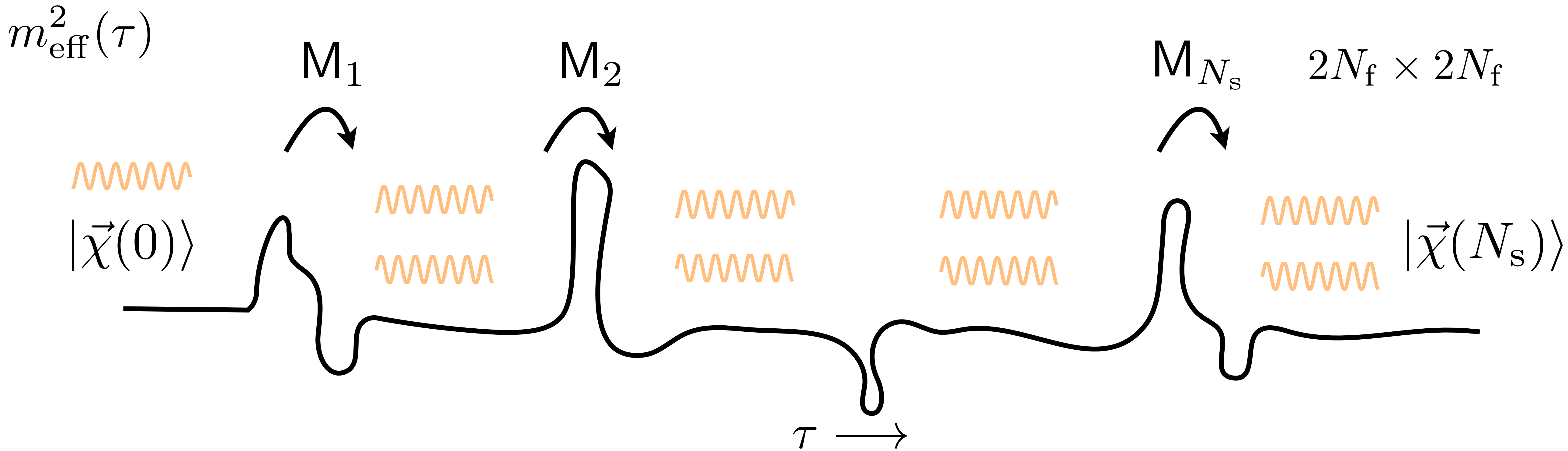
simplified version!



see also: Zanchin et. al 1998, Basset 1998, Brandenberger & Craig 2008

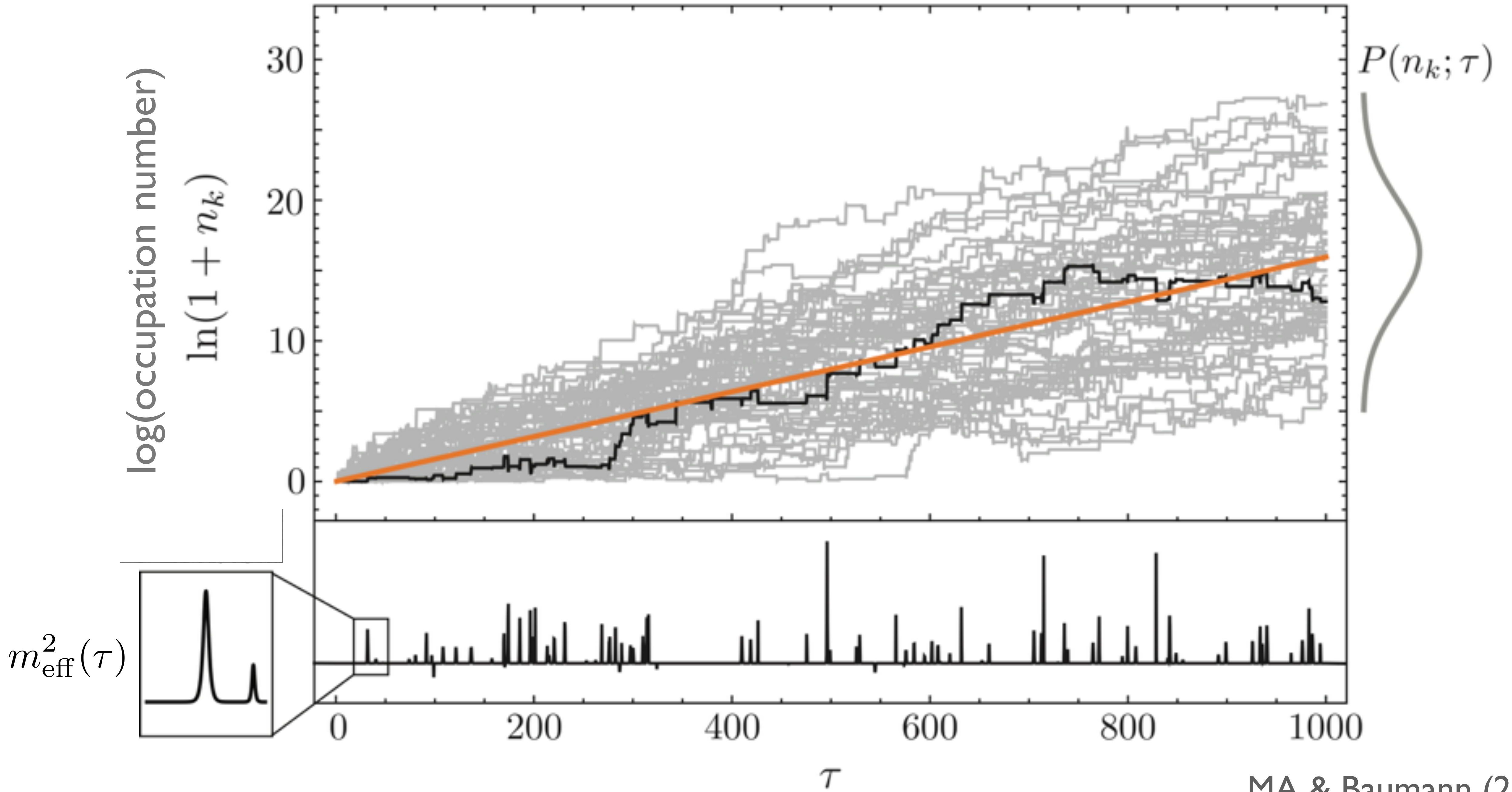
multifield particle production as scattering

$$|\vec{\chi}(N_\mathrm{s})\rangle \;=\; \mathsf{M}\,|\vec{\chi}(0)\rangle \quad \text{where} \quad \mathsf{M} \equiv \mathsf{M}_{N_\mathrm{s}} \cdots \mathsf{M}_2\mathsf{M}_1$$



occupation number performs a drifted random walk

$$n(k,\tau) = \frac{1}{2\omega_k}\left(|\dot{\chi}_k|^2 + \omega_k^2|\chi_k|^2\right)$$



MA & Baumann (2015)

multifield Fokker Planck equation

joint probability for occupation numbers satisfies the a Fokker Planck-like equation:

Dokhorov, Mello, Pereyra & Kumar = DMPK eq.

$$\frac{1}{\mu_k}\frac{\partial}{\partial\tau}P(n_a;\tau) = \sum_{a=1}^{N_\mathrm{f}}\left[(1+2n_a) + \frac{1}{N_\mathrm{f}+1}\sum_{b\neq a}\frac{n_a+n_b+2n_an_b}{n_a-n_b}\right]\frac{\partial P}{\partial n_a}$$

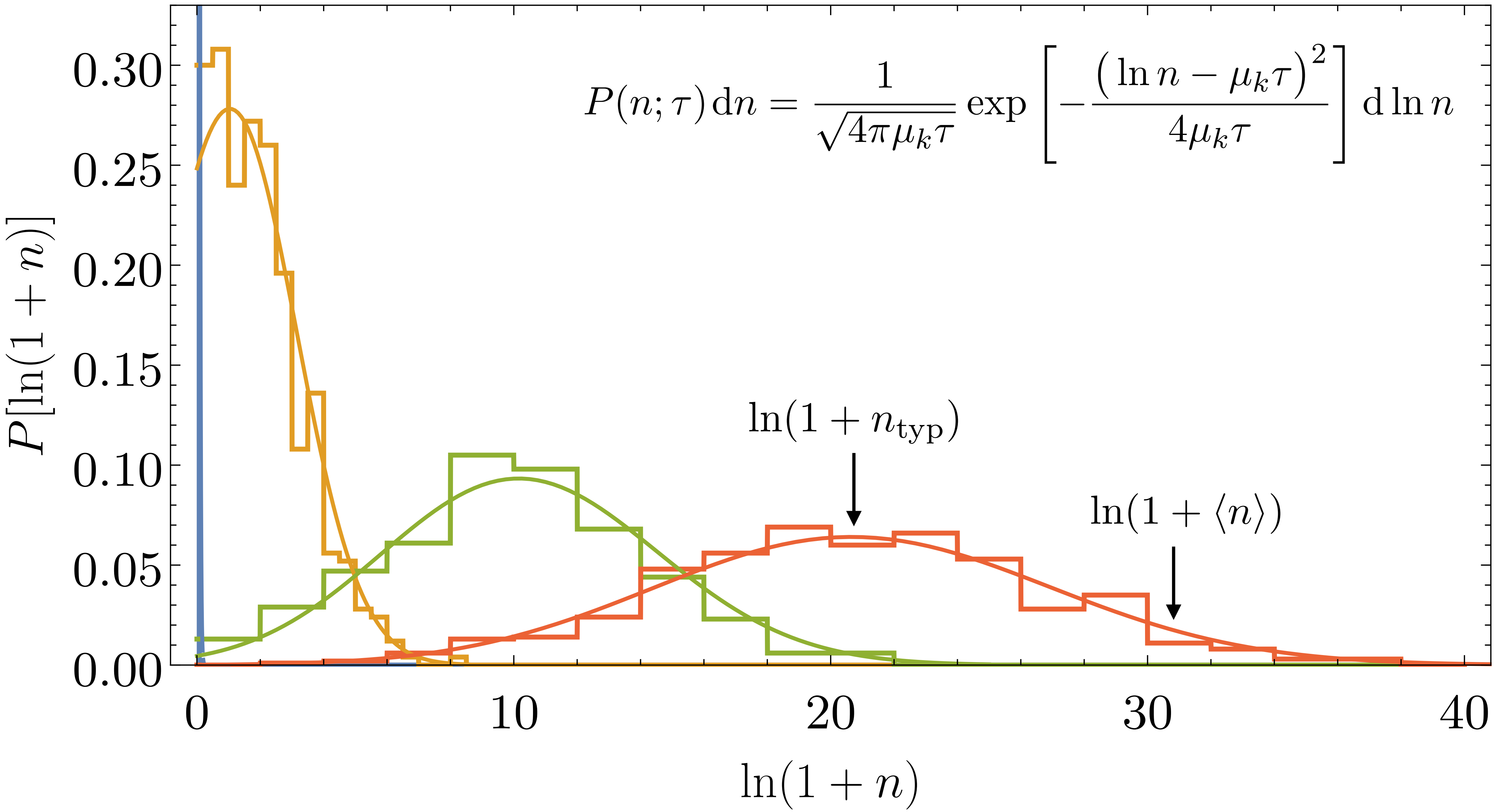
$$+\frac{2}{N_\mathrm{f}+1}\sum_{a=1}^{N_\mathrm{f}} n_a(1+n_a)\frac{\partial^2 P}{\partial n_a^2}$$

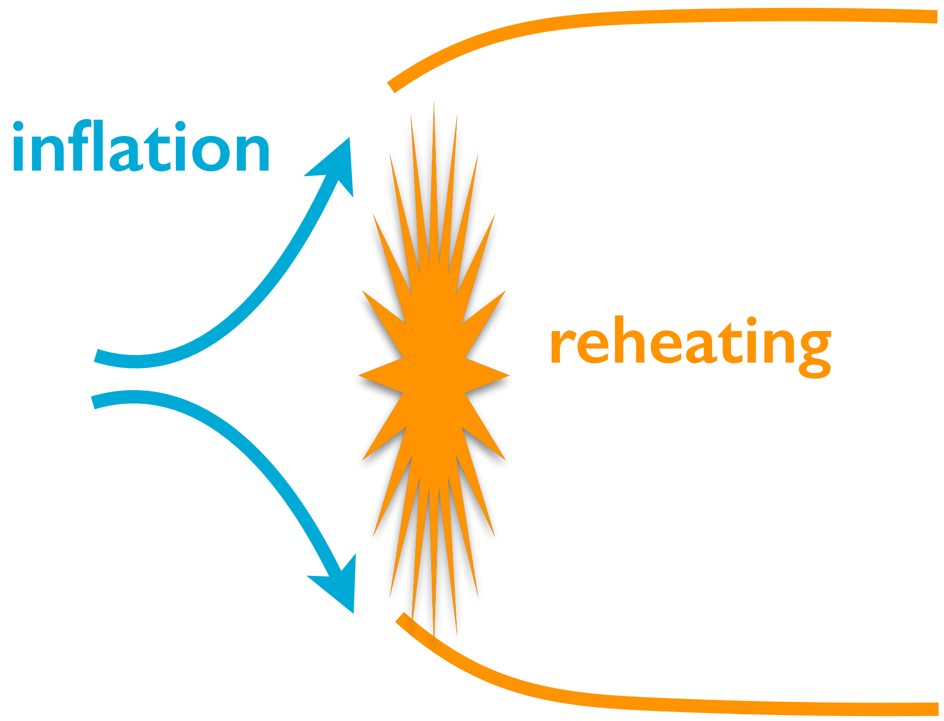
MA & Baumann 2015

more general results in

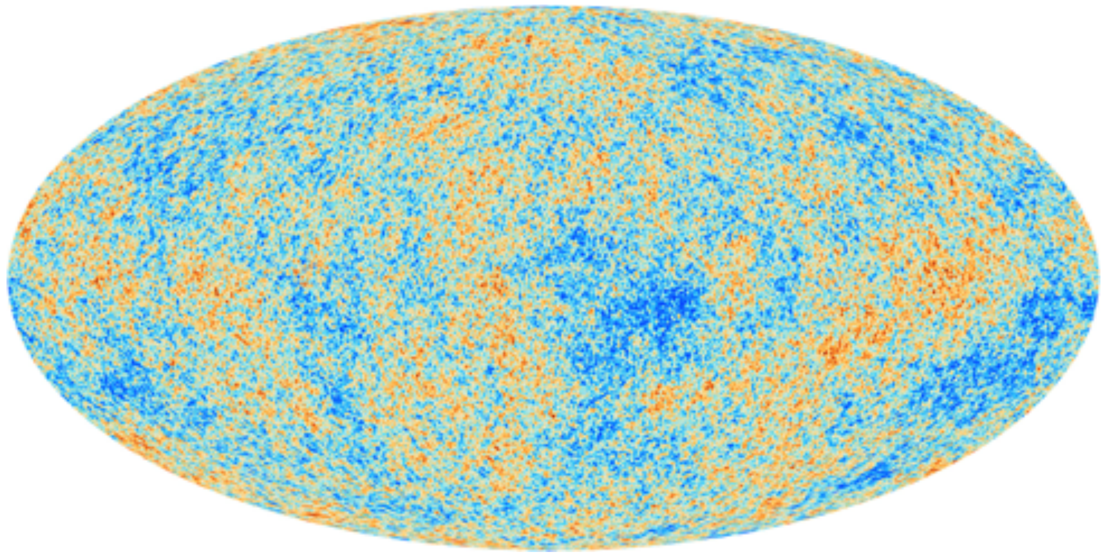
MA, Garcia, Xie and Wen 2017

solution: "universal" distributions





applications



combine particle production with driving and dissipation

background dynamics → particle production ↔ curvature fluctuations

$$\langle n_{k_1} n_{k_2} \ldots \rangle \qquad \langle \zeta_{k_1} \zeta_{k_2} \ldots \rangle$$

MA, Garcia, Baumann, Carlsten, Chia & Green

$$\zeta_k = -H\pi_k$$

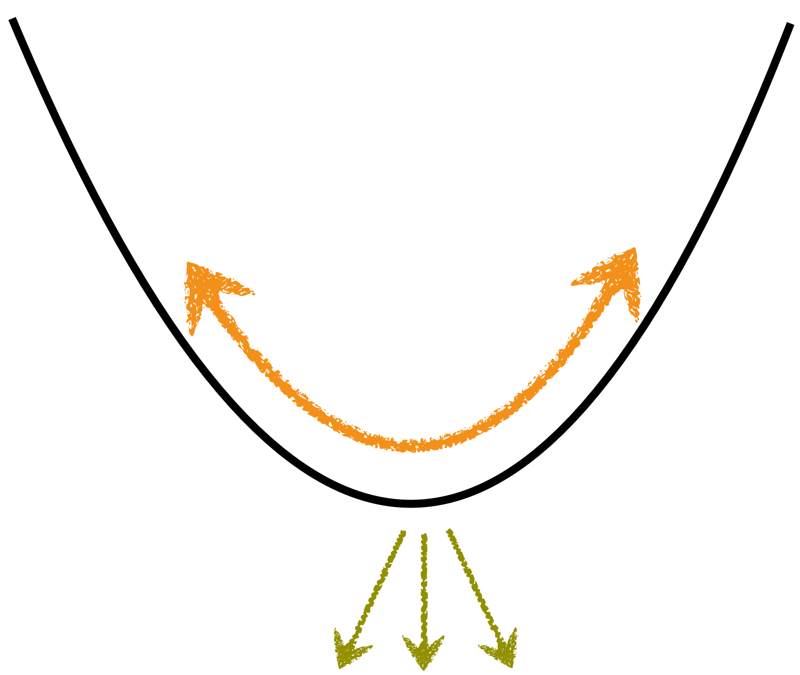
$$\ddot{\pi}_k + [3H + \mathcal{O}_{\rm d}]\,\pi_k + \frac{k^2}{a^2}\pi_k = \mathcal{O}_{\rm s}(\langle \chi\chi \ldots \rangle_k)$$

dissipation driving

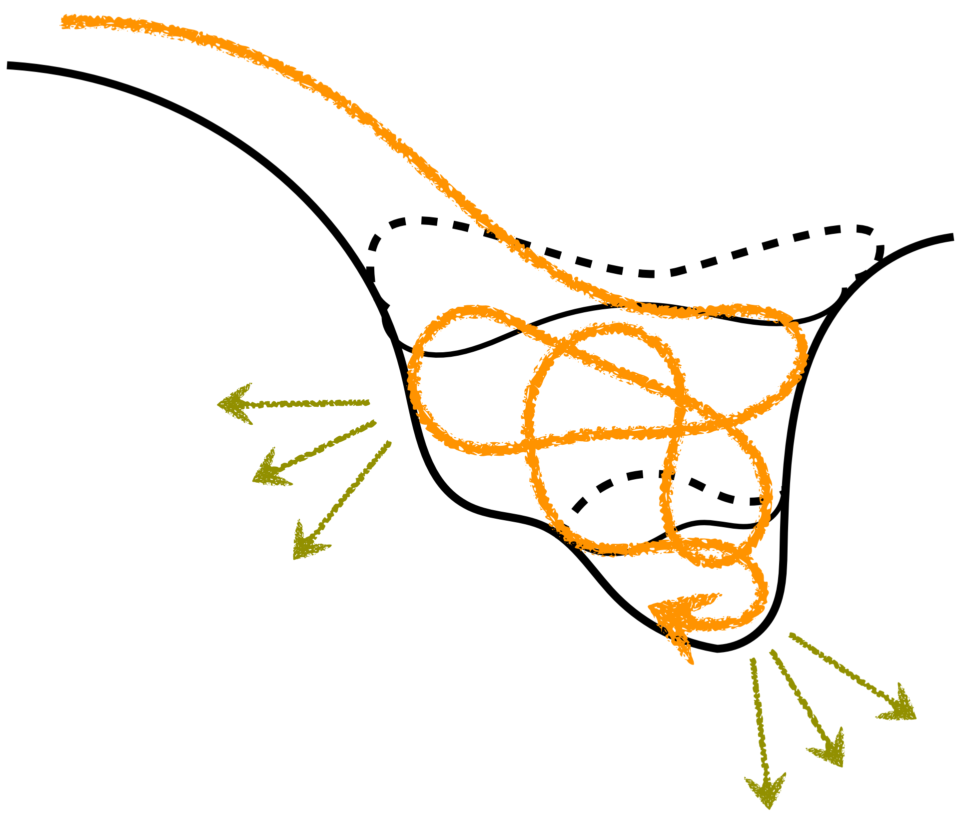
Green, Horn, Senatore, and Silverstein (2009), Nacir, Porto, Senatore, and Zaldarriaga (2012), Flauger, Mirbabayi, Senatore, Silverstein (2016), Chen, Namjoo and Wang (2015,16), Dias, Fraser & Marsh (2016)

applications : reheating

WORK IN PROGRESS



multichannel — multifield — statistical



model-insensitive description of a complicated reheating process.

Kofman, Linde & Starobinsky (1997)
Shtanov, Traschen & Brandenberger (1995)
Zanchin et. al (1998) & Bassett (1998) [with noise]
Barnaby, Kofman & Braden et. al 2010 [quasiperiodic]
Giblin, Nesbit, Ozsoy, Sengor & Watson (2017)

MA, Carlsten Garcia, & Shen

Inflation Ends, What's Next ?

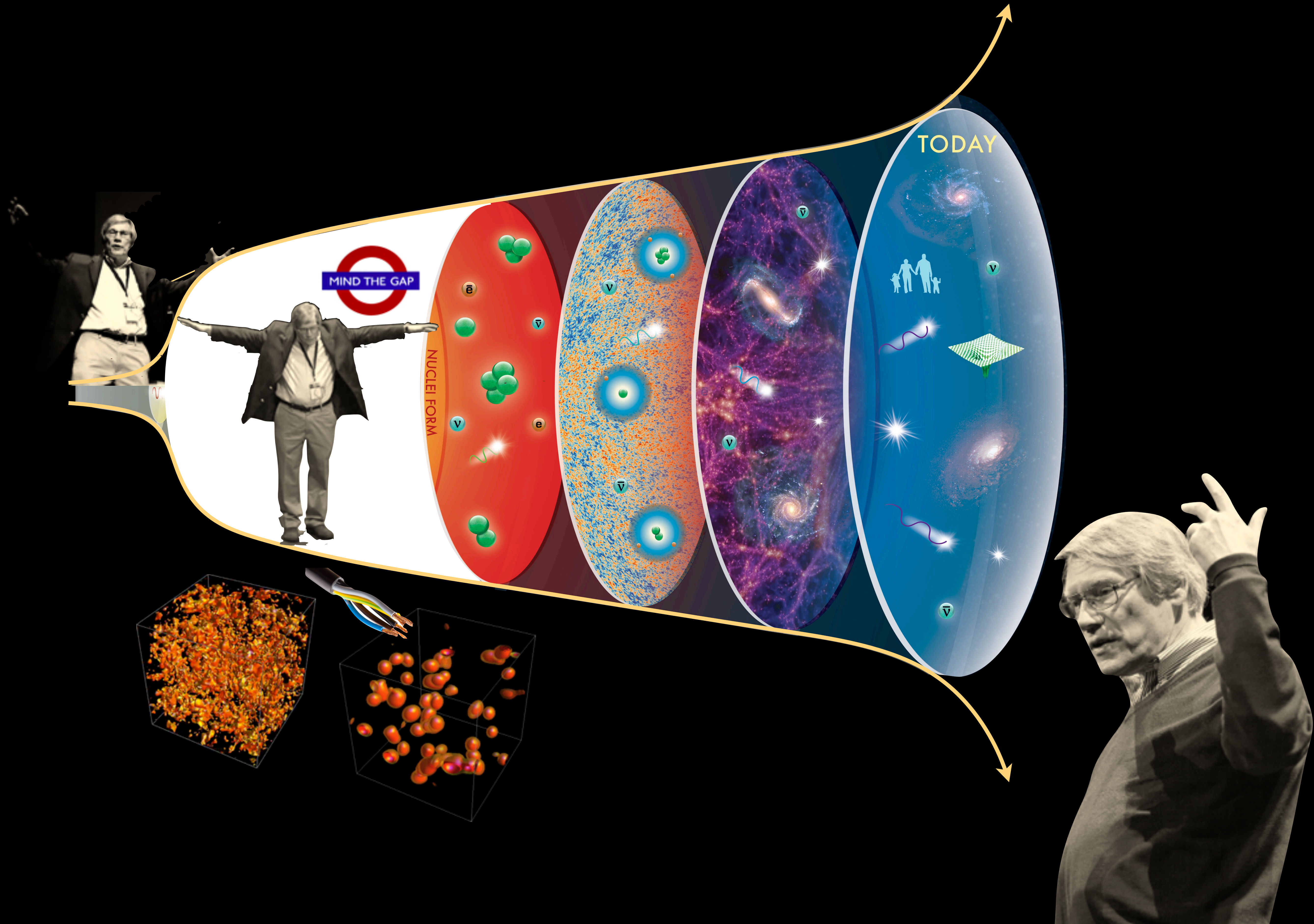


image from alchetron.com