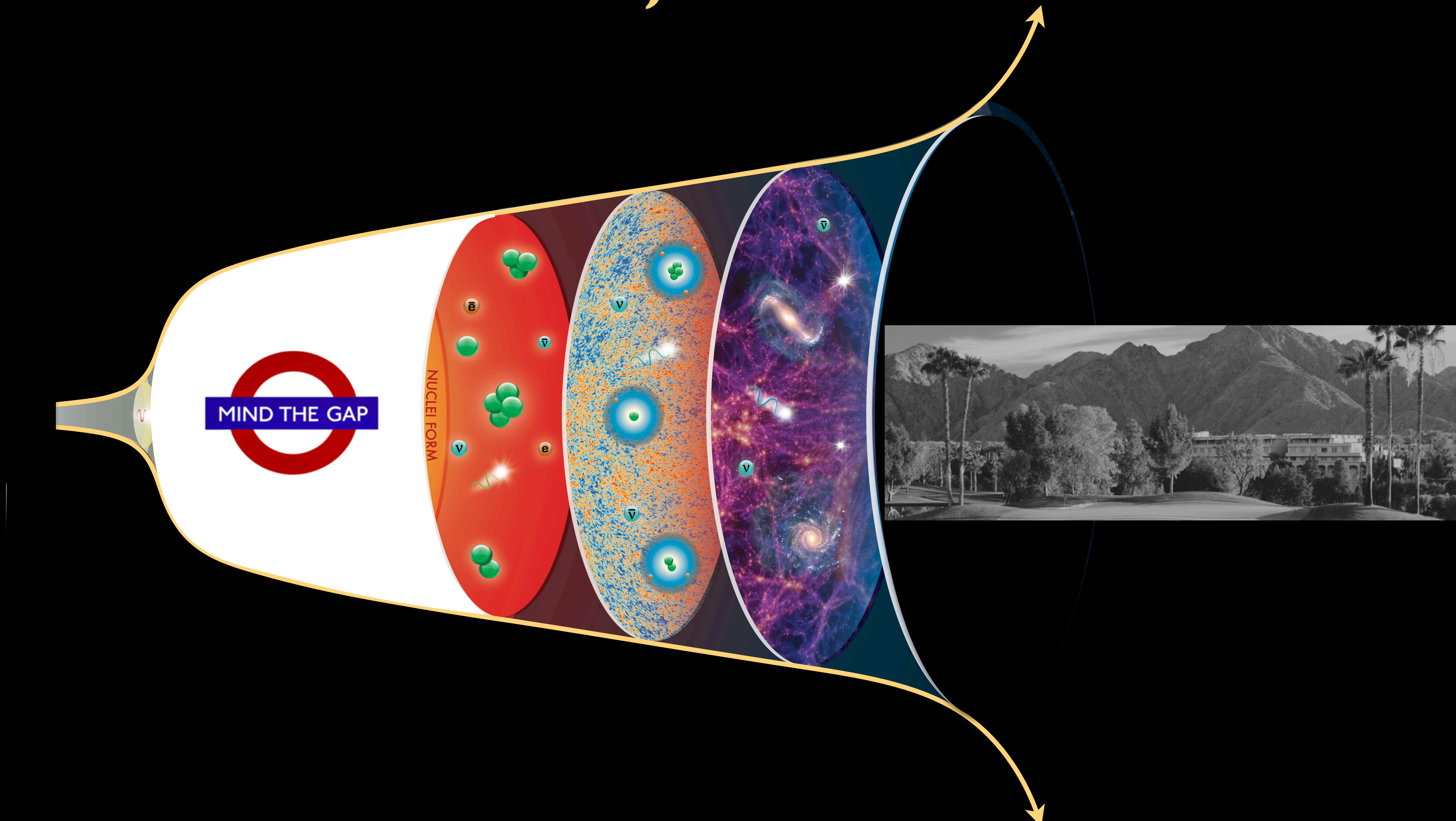
Inflation Ends, What's Next ?



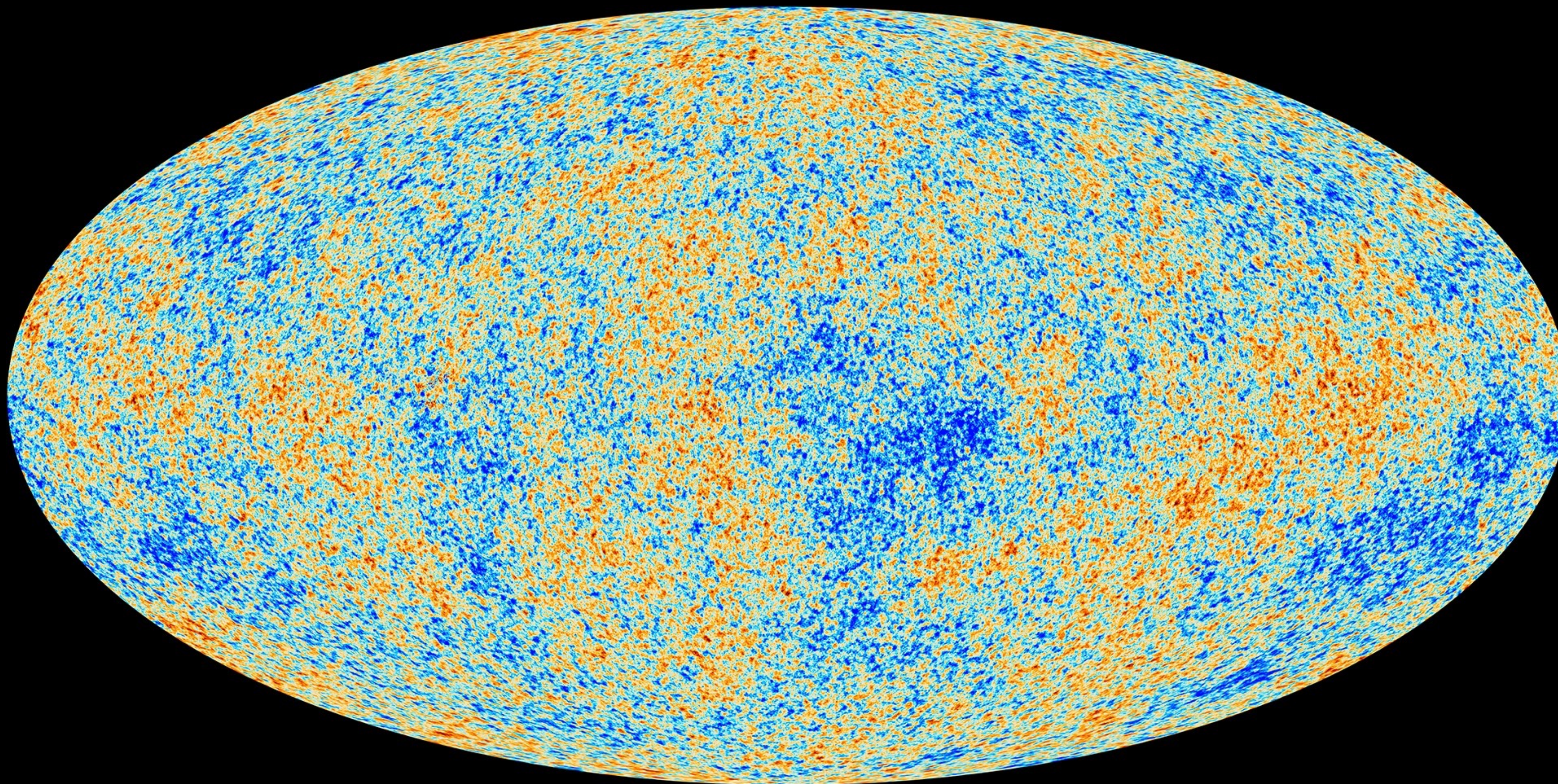
Mustafa A. Amin

RICE

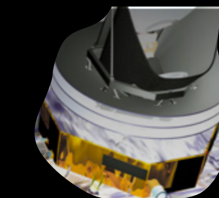
CIPANP 2018

motivation

anisotropies: cosmic microwave background



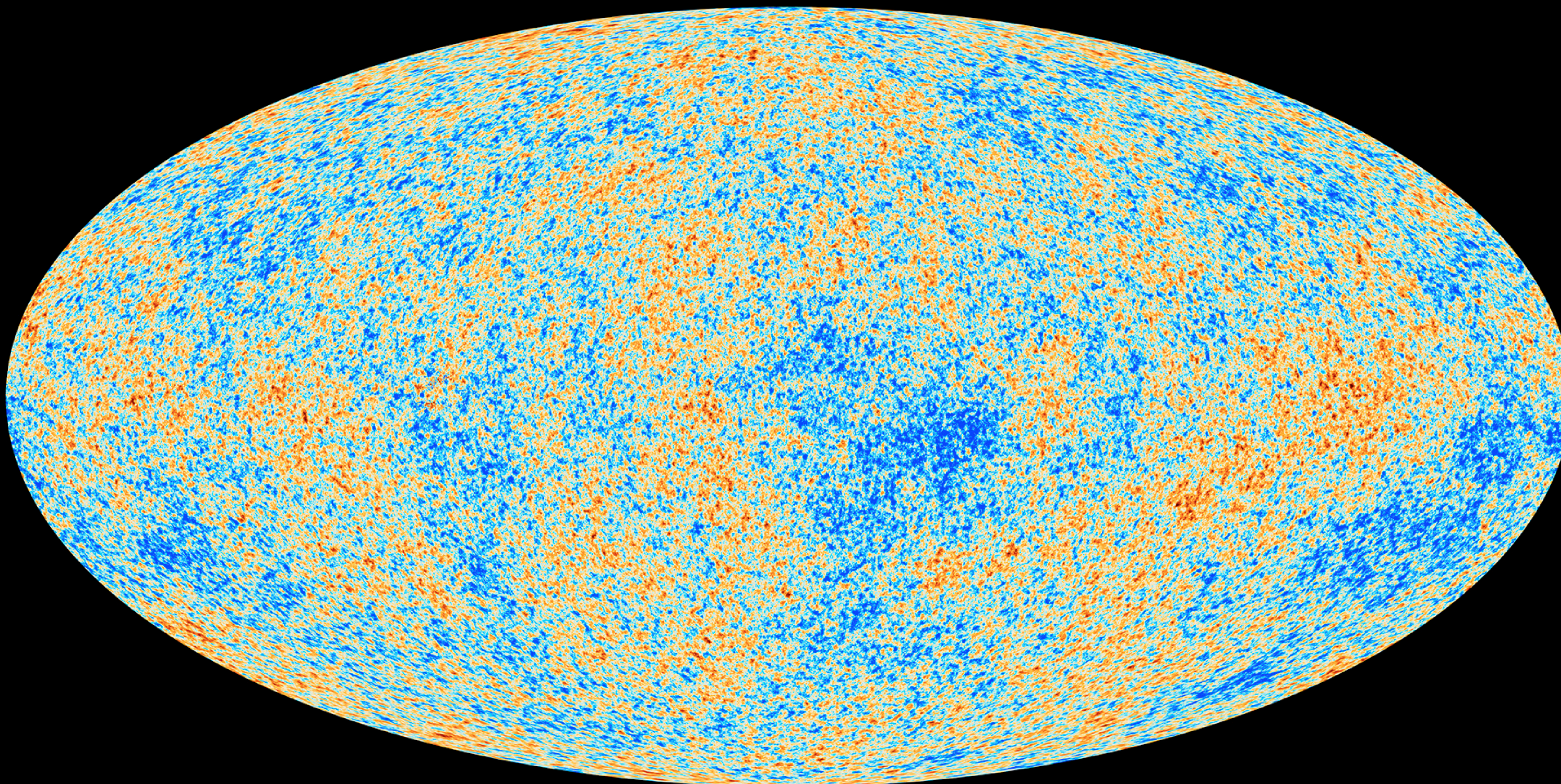
$$\delta T/T \sim 10^{-5}$$



Planck 2015

~ gaussian

almost scale invariant



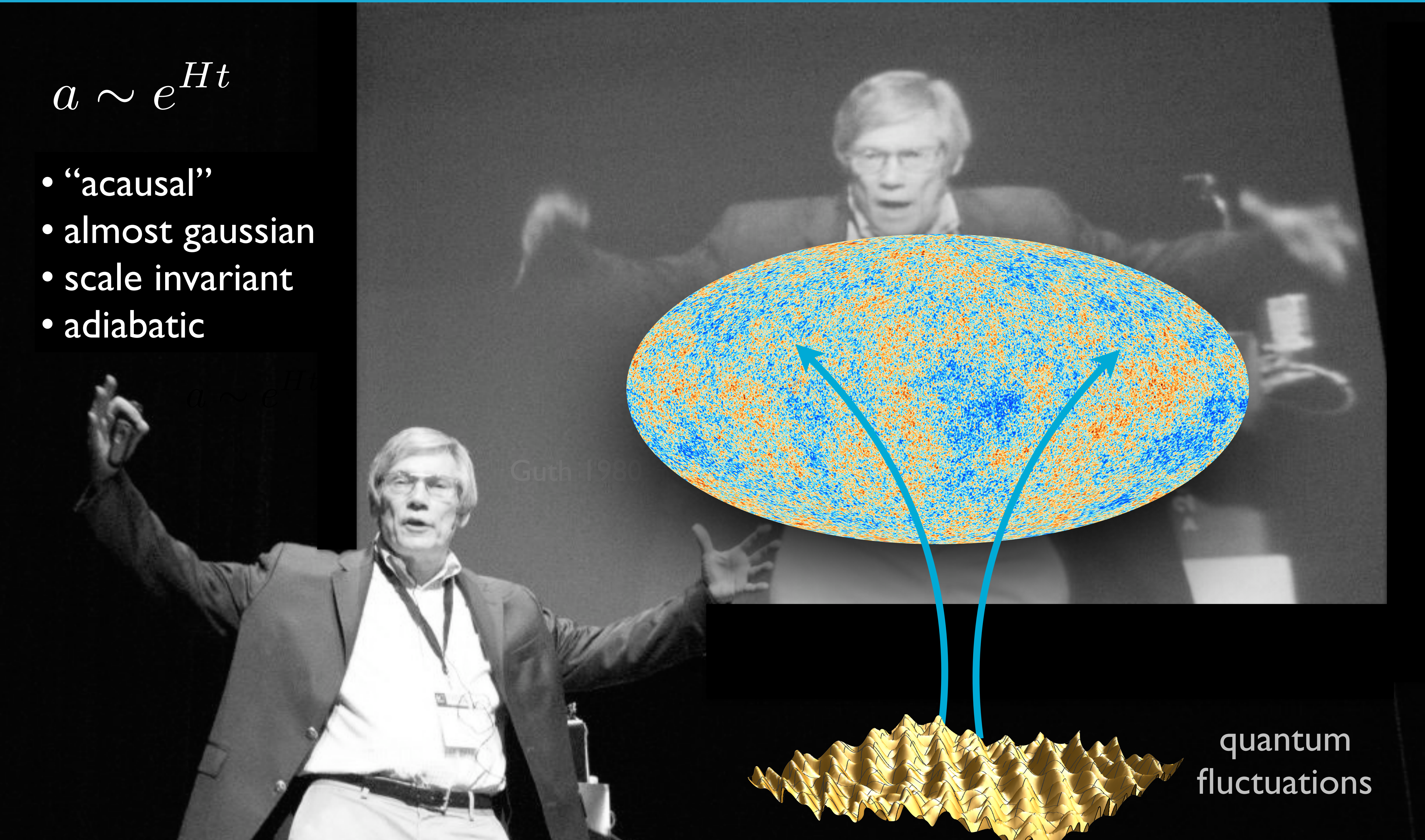
seemingly “acausal”

~ adiabatic

inflation: a "simple" explanation?

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

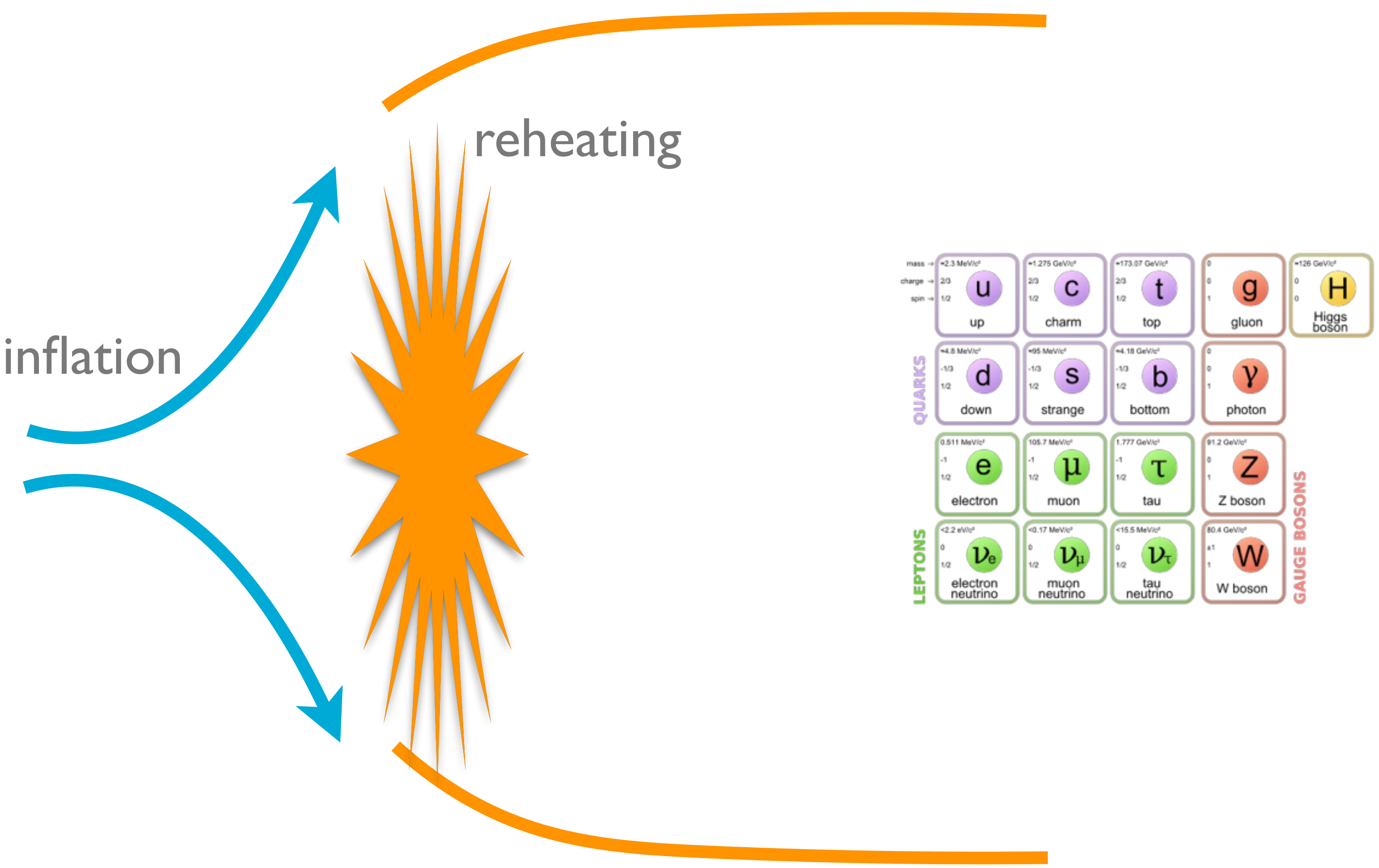
- "acausal"
- almost gaussian
- scale invariant
- adiabatic



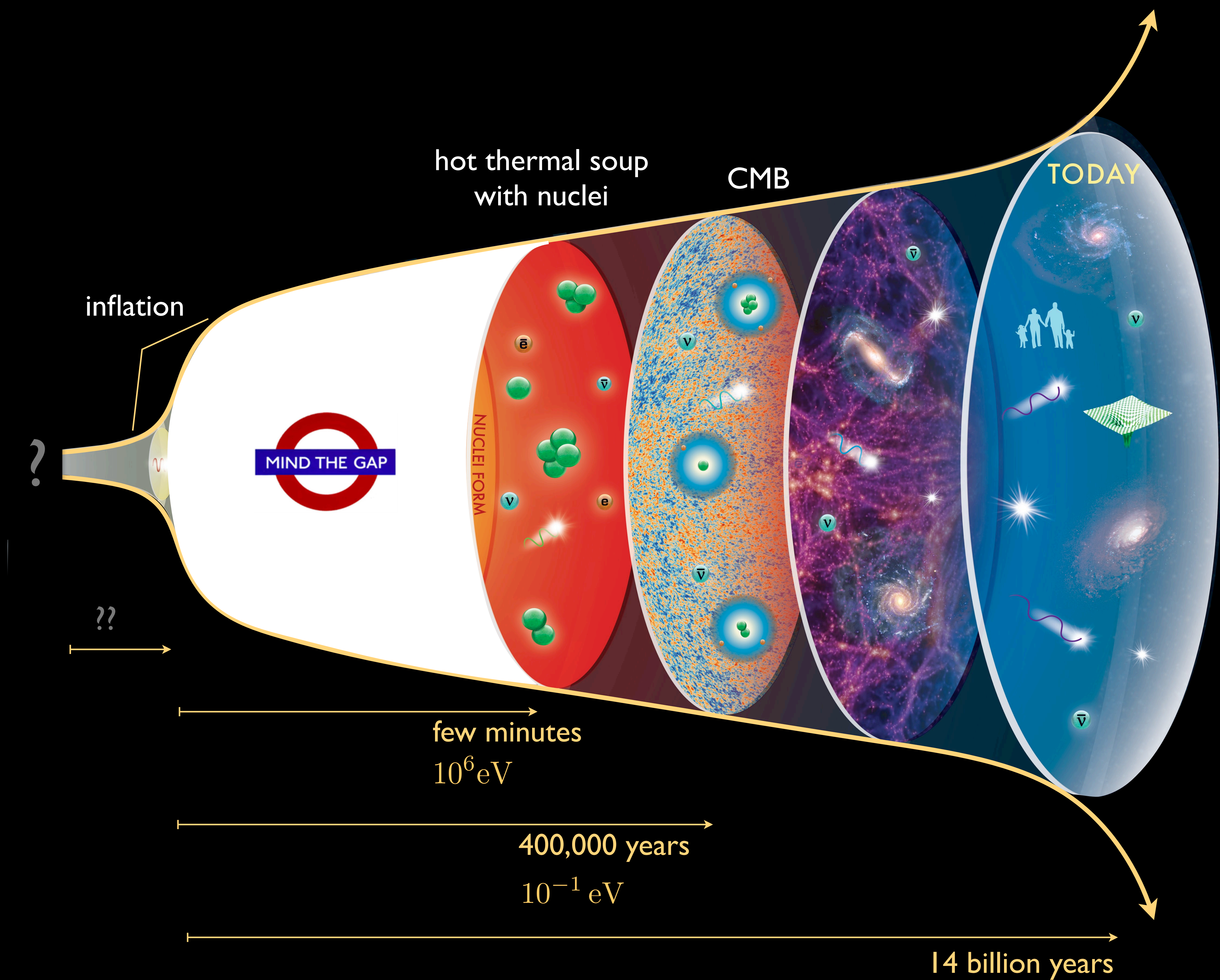
Guth, Linde, Starobinsky, Steinhardt, Albrecht, Mukhanov, Hawking …

physics of inflation <u>and its end</u>?

- what is the physics of inflation ?
- how did inflation end ?
- how did the universe get populated with particles after inflation ? (reheating)



aftermath of inflation: a GAP in our cosmic history

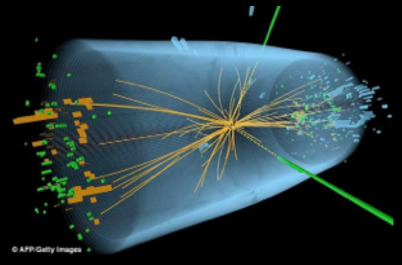


inflation 10^{16} GeV

- inflation ends
- populate the universe (Standard Model)
- baryon asymmetry
- dark matter
- phase transition

MIND THE GAP

TeV



MeV

eV

modeling inflation & its' aftermath

SIMPLE

problem oriented

COMPLEX

modeling inflation & its’ aftermath

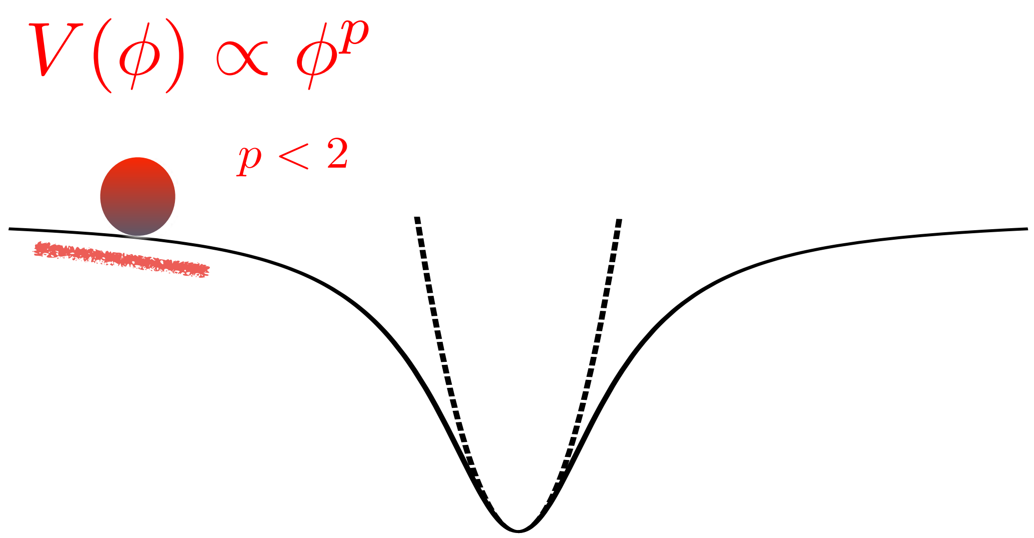
SIMPLE

problem oriented

COMPLEX

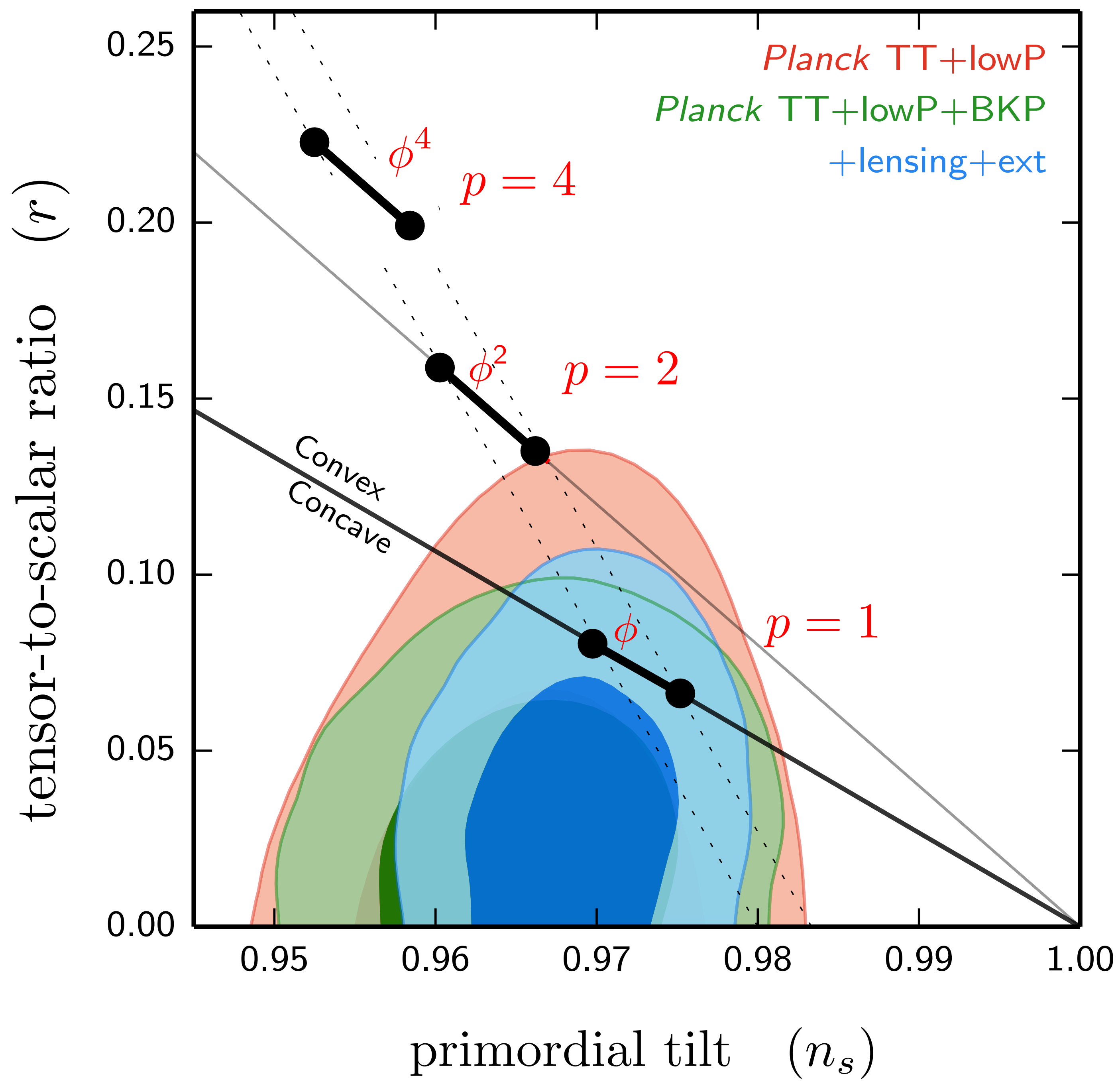
simplest models: single scalar field driven inflation

constraints from observations

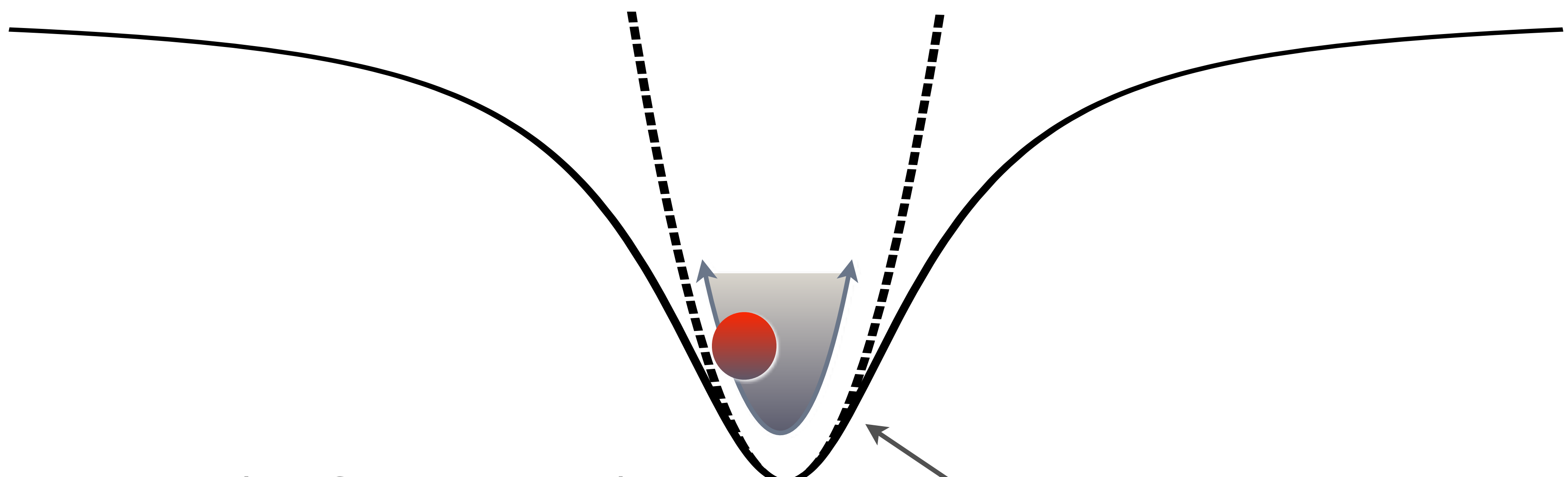


for example:

Starobinsky Inflation (1979)
Silverstein & Westhpal (2008)
Kallosh & Linde (2013)

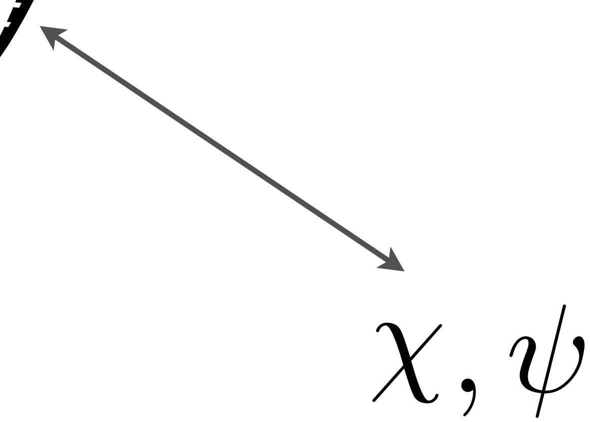


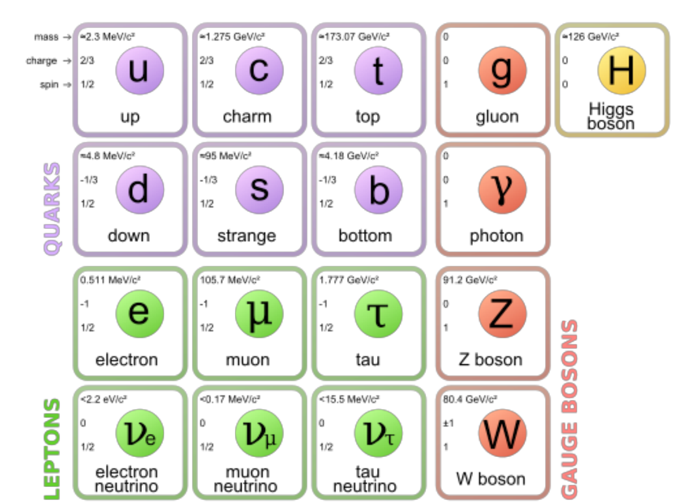
detailed dynamics after inflation ?



- shape of the potential (self couplings)

- couplings to other fields

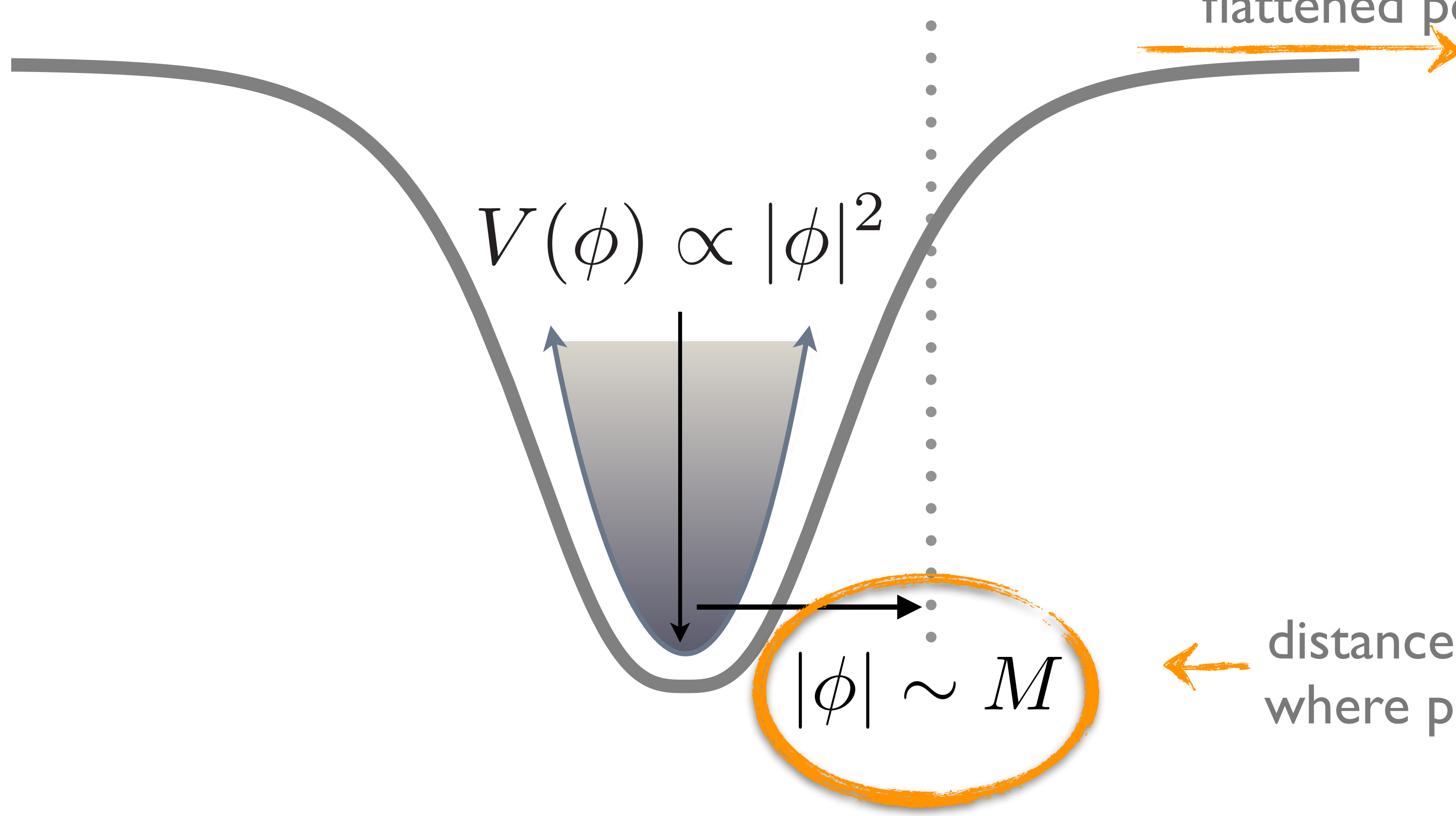




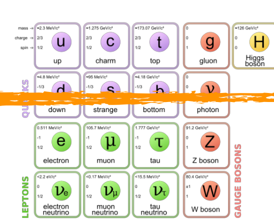
Traschen & Brandenburger (1990)
Kofman, Linde & Starobinsky (1994, 97)
Shtanov, Traschen & Brandenberger (1995)
Kofman, Linde & Starobinsky (1997)

review: MA, Kaiser, Karouby & Hertzberg (2014)

end of inflation in “simple” models

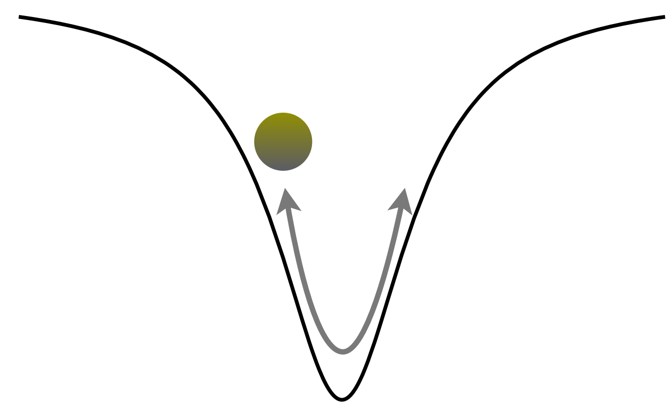


- shape of the potential (self couplings)

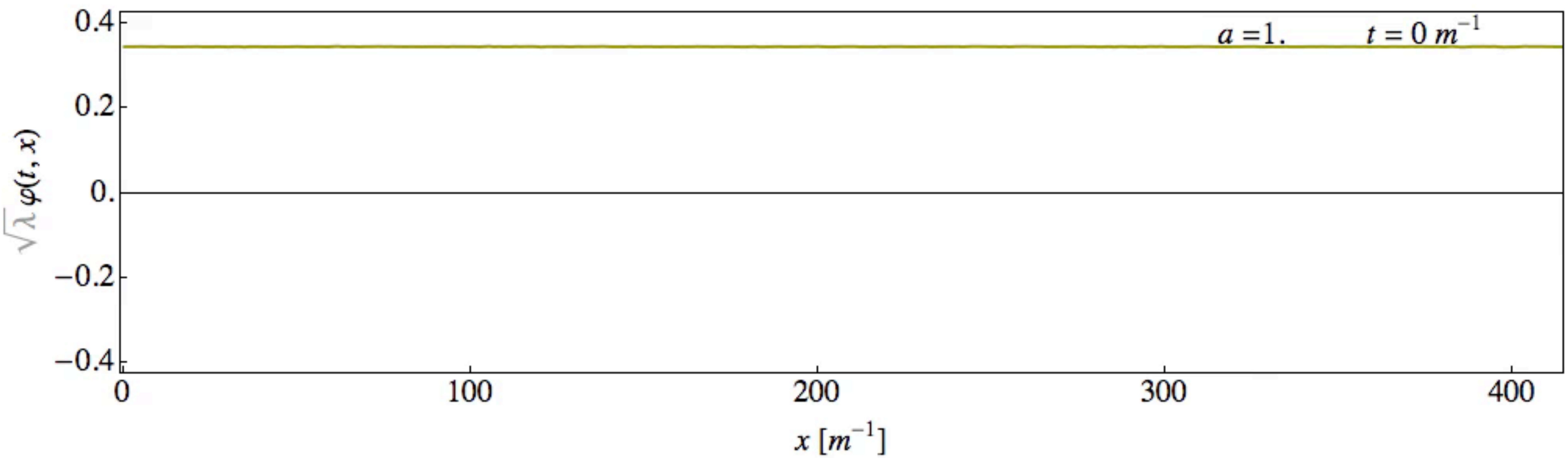
- ~~couplings to other fields~~  $\chi\ ,\psi$

  ~ gravitational strength

dynamics after inflation

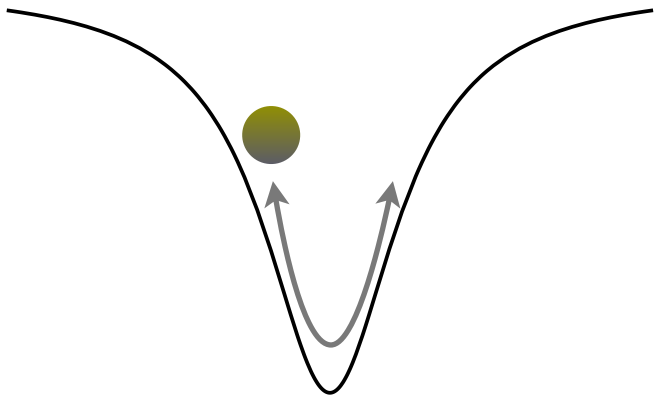


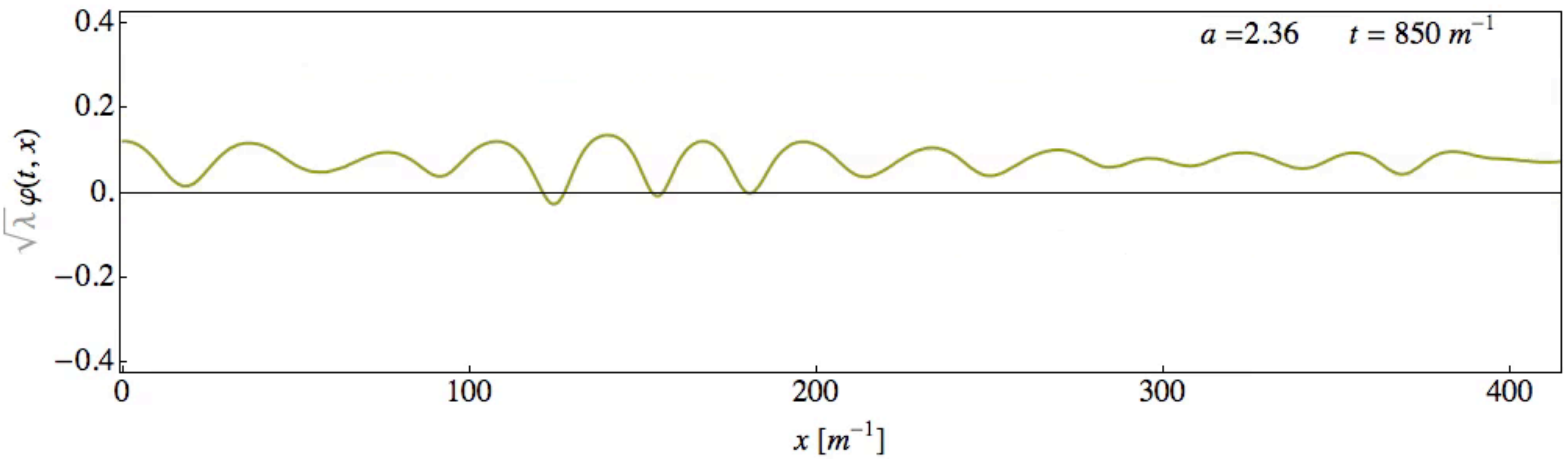
$$\Box\phi = V'(\phi)$$



dynamics after inflation

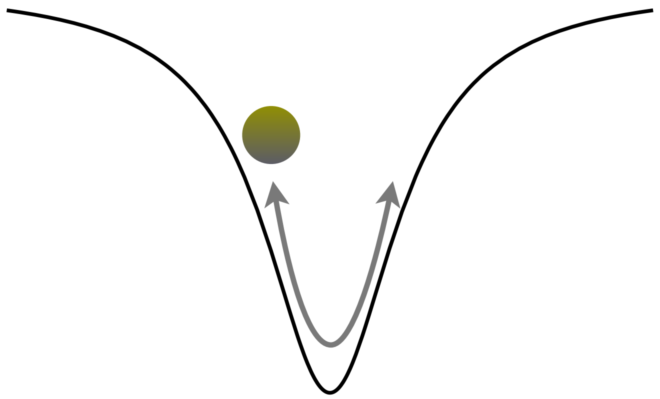
$$\Box\phi = V'(\phi)$$

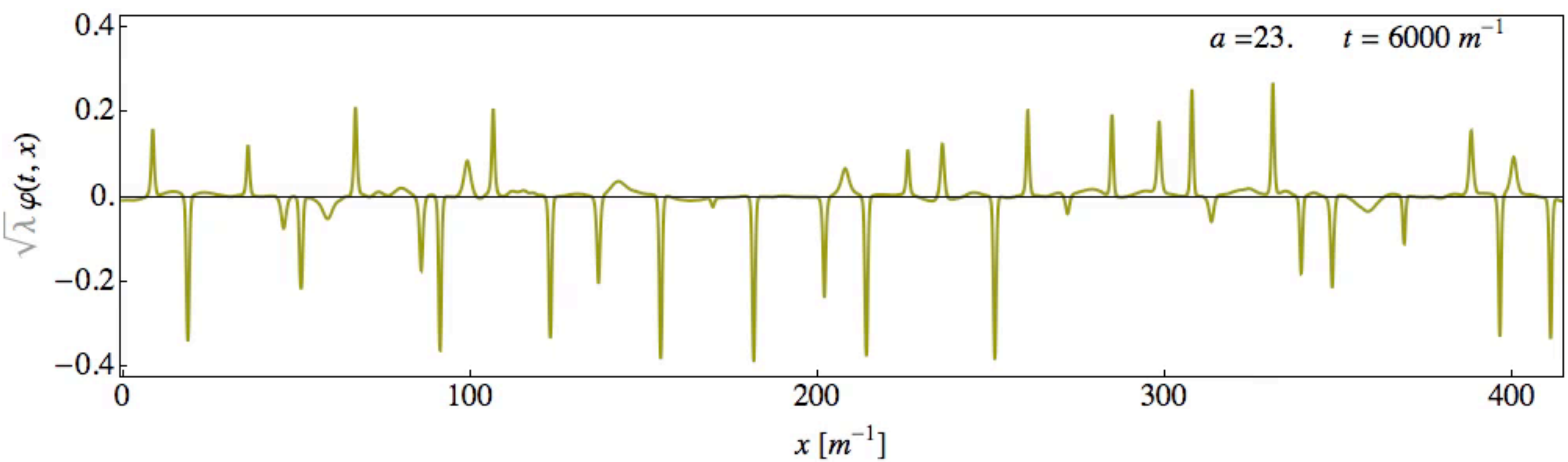




dynamics after inflation

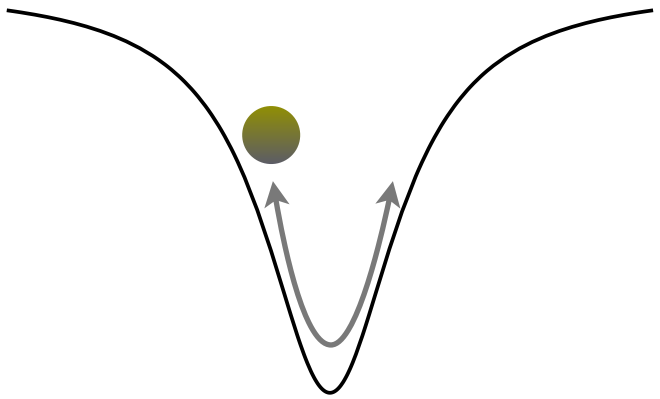
$$\Box\phi = V'(\phi)$$



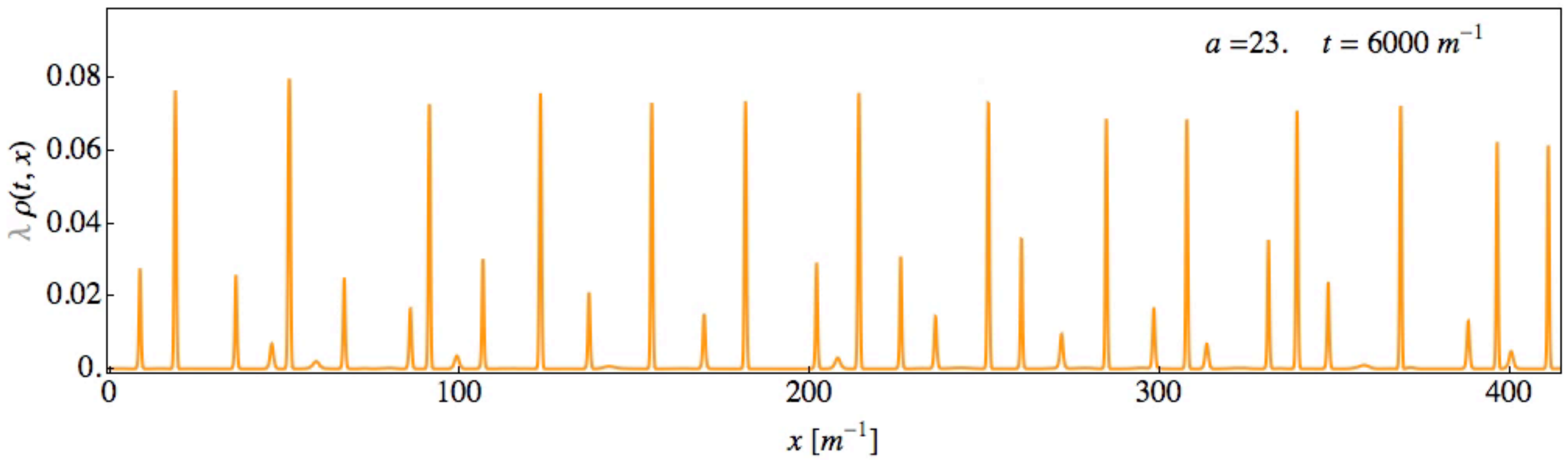


MA (2010)
Khlopov, Malomed & Zeldovich (1985)

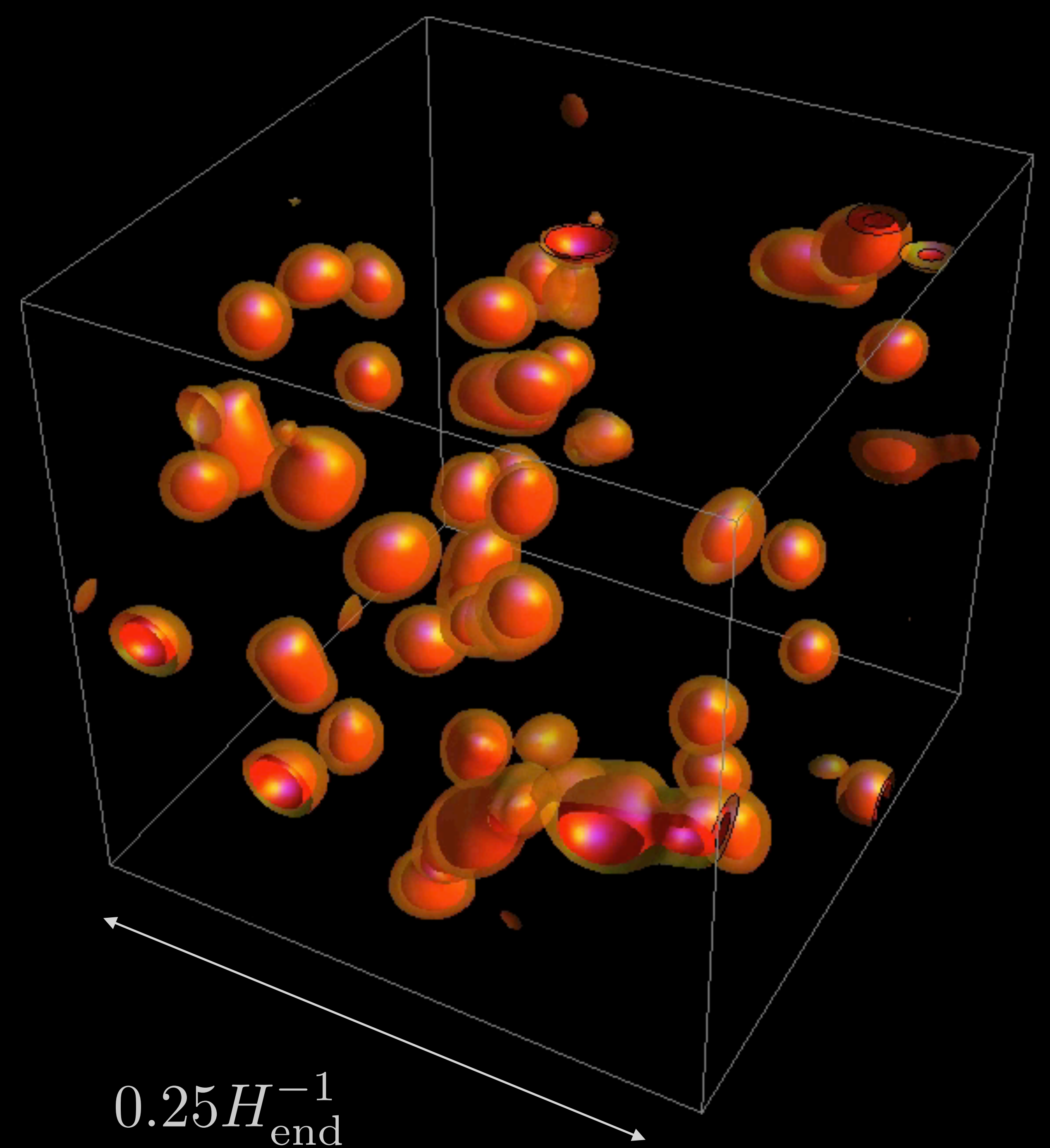
dynamics after inflation



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



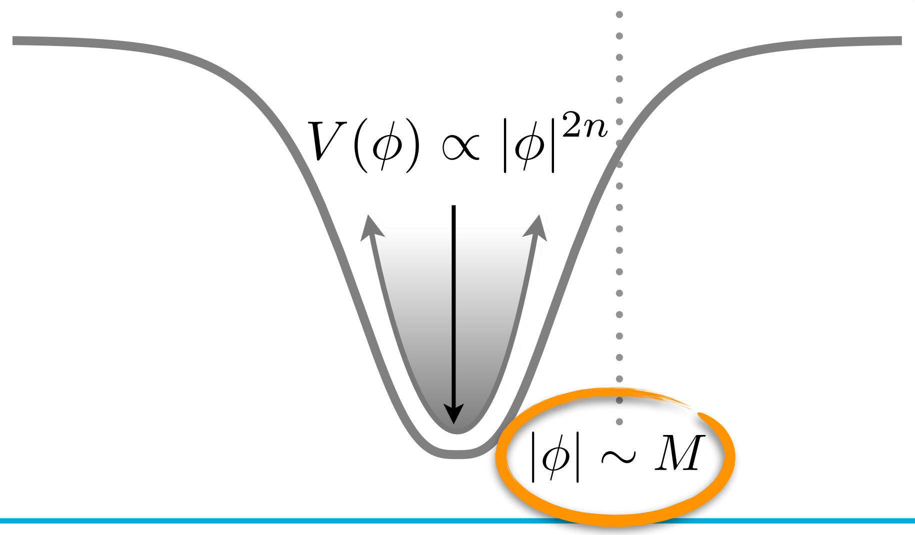
now in 3D:
(iso-density surfaces)

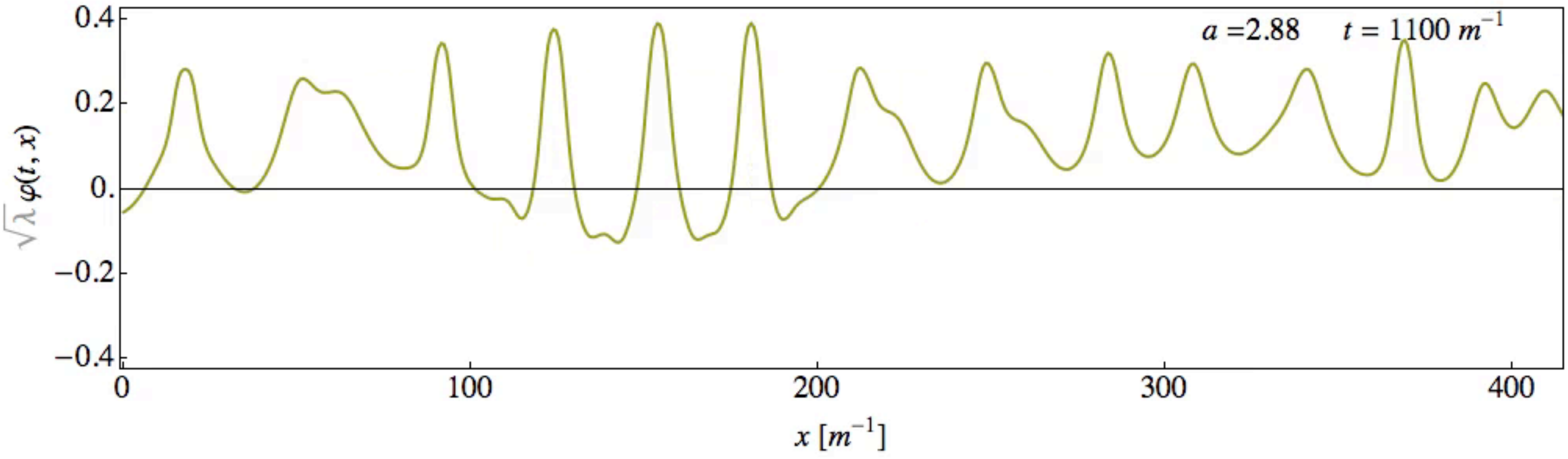


MA, Easther, Finkel, Flaugher & Hertzberg (2011)

condition for rapid fragmentation ?

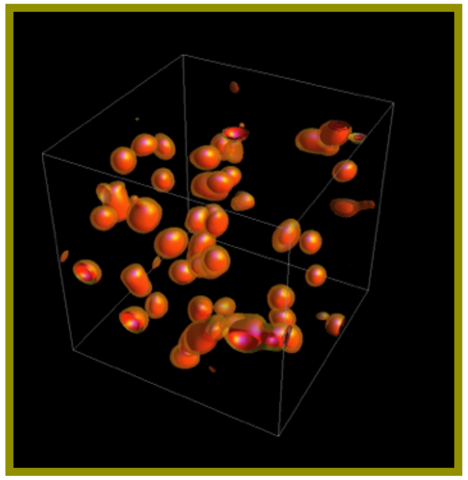
$$\frac{\text{growth-rate of fluctuations}}{\text{expansion rate}} \sim \frac{m_{\text{pl}}}{M} \gg 1$$



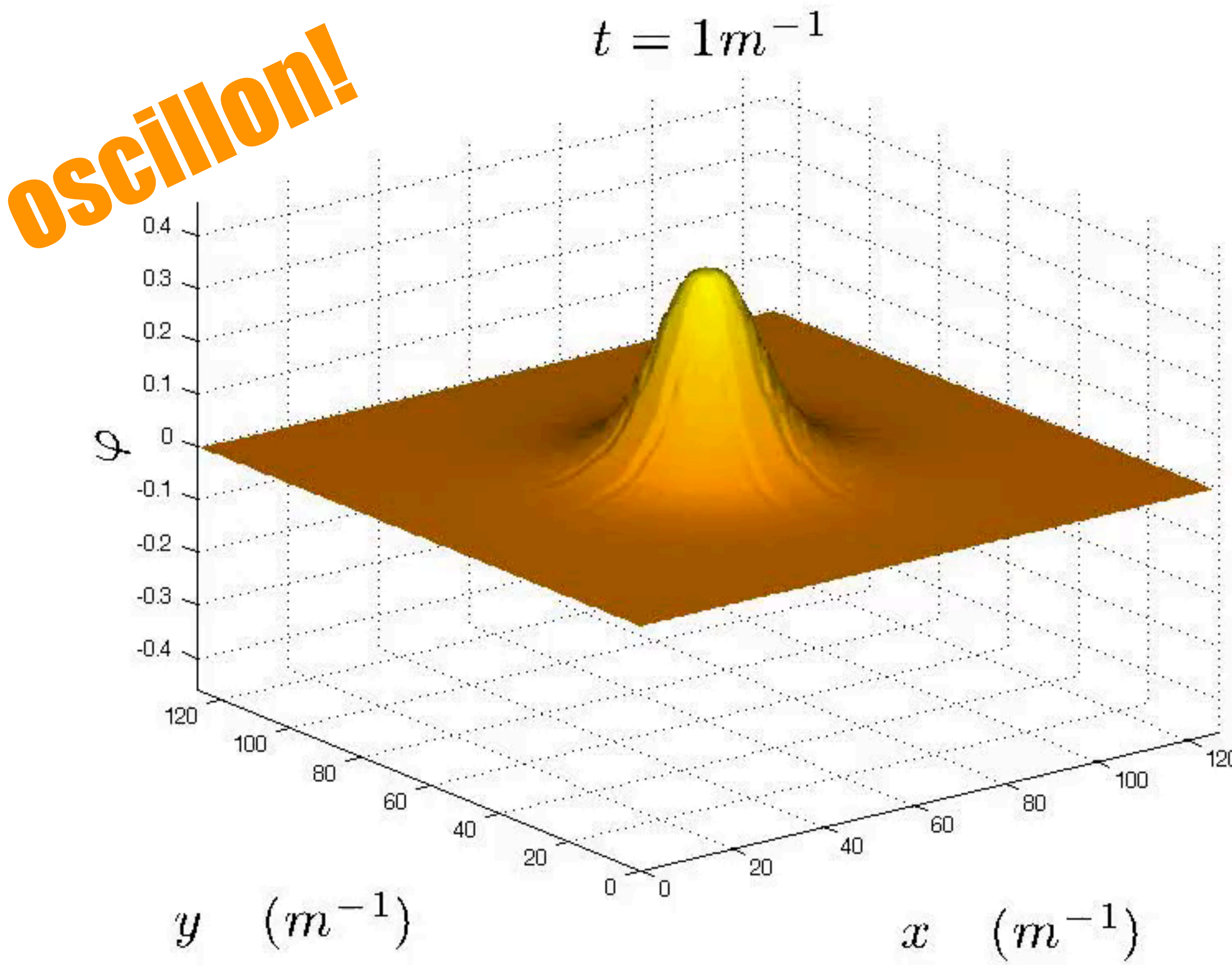


MA (2010)

lumps ?



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



existence and stability:

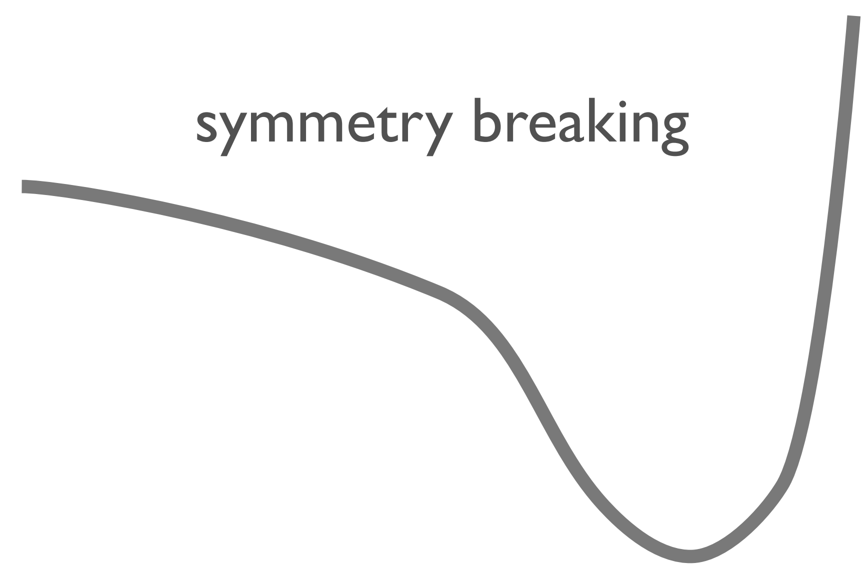
Segur & Kruskal (1987)
MA & Shirokoff (2010)
MA (2013)
Hertzberg (2011)
Mukaido et. al (2016,17)

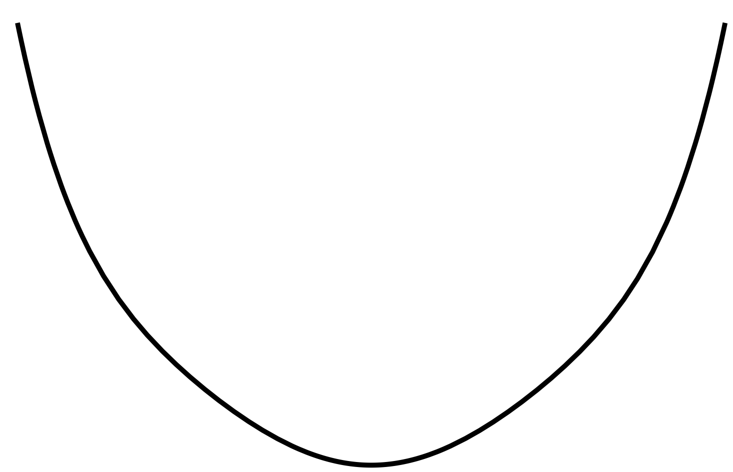
Bogolubsky & Makhankov (1976), Gleiser (1994), Copeland et. al (1995)

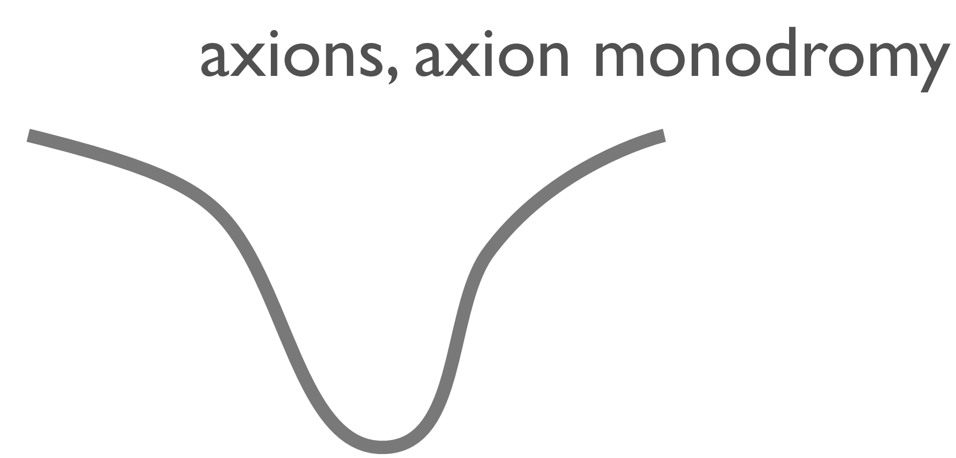
existence conditions

$$V(\varphi) = \frac{1}{2}\varphi^2 + \frac{1}{3}\lambda_3\varphi^3 + \frac{1}{4}\lambda_4\varphi^4 + \dots$$

$$\Delta \equiv -\lambda_4 + \frac{10}{9}\lambda_3^2 > 0$$







existence conditions

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

$$X = \frac{1}{2}(\partial\varphi)^2$$

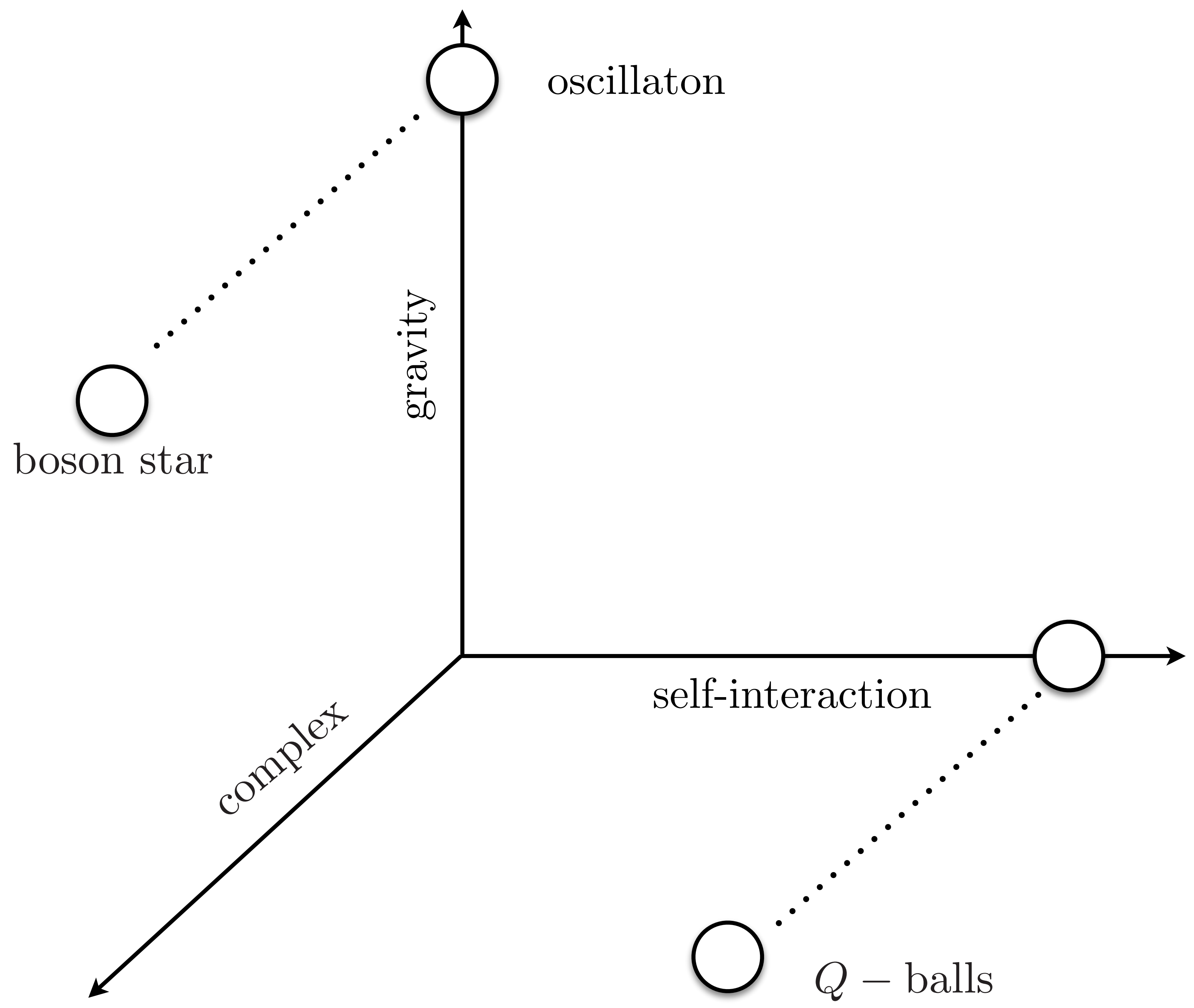
$$T(X,\varphi) = X + \xi_2 X^2 + \xi_3 \varphi X^2 + \ldots$$

$$V(\varphi) = \frac{1}{2}\varphi^2 + \frac{\lambda_3}{3}\varphi^3 + \frac{\lambda_4}{4}\varphi^4 + \frac{\lambda_5}{5}\varphi^5 + \ldots$$

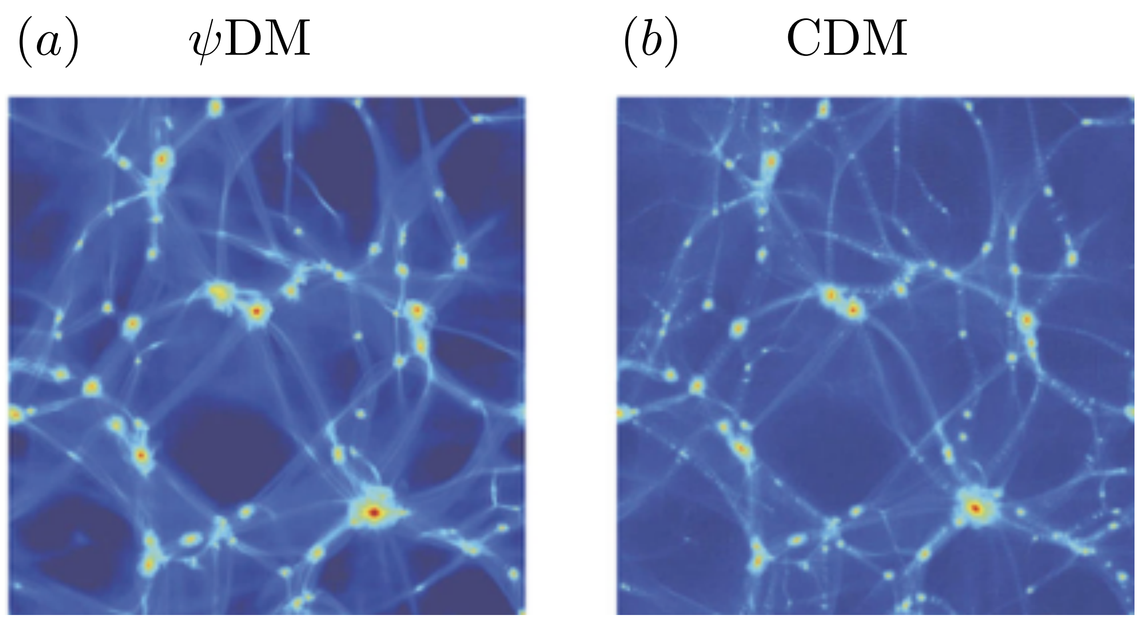
$$\boxed{\Delta = \xi_2 - \lambda_4 + \frac{10}{9}\lambda_3^2 > 0.}$$

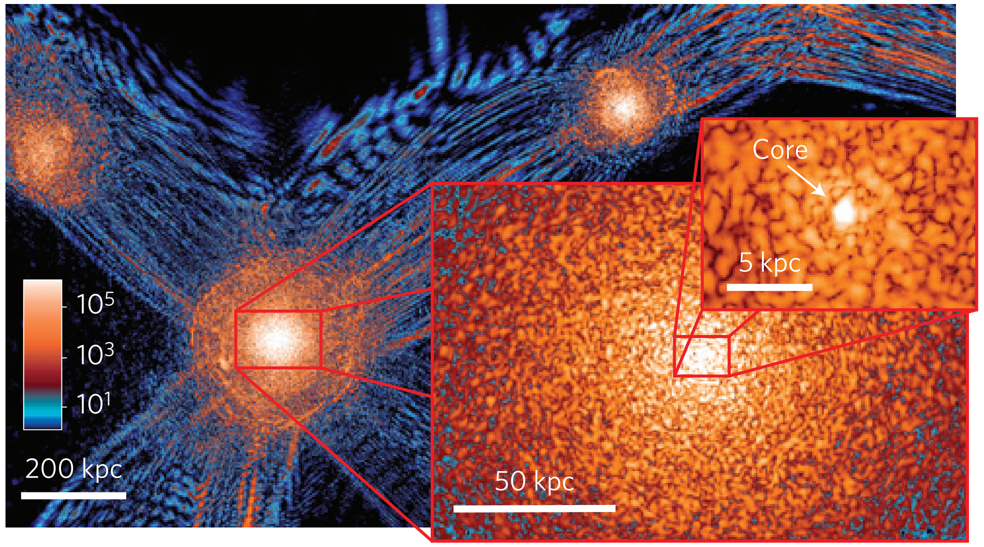
MA (2013)

family of related solitons



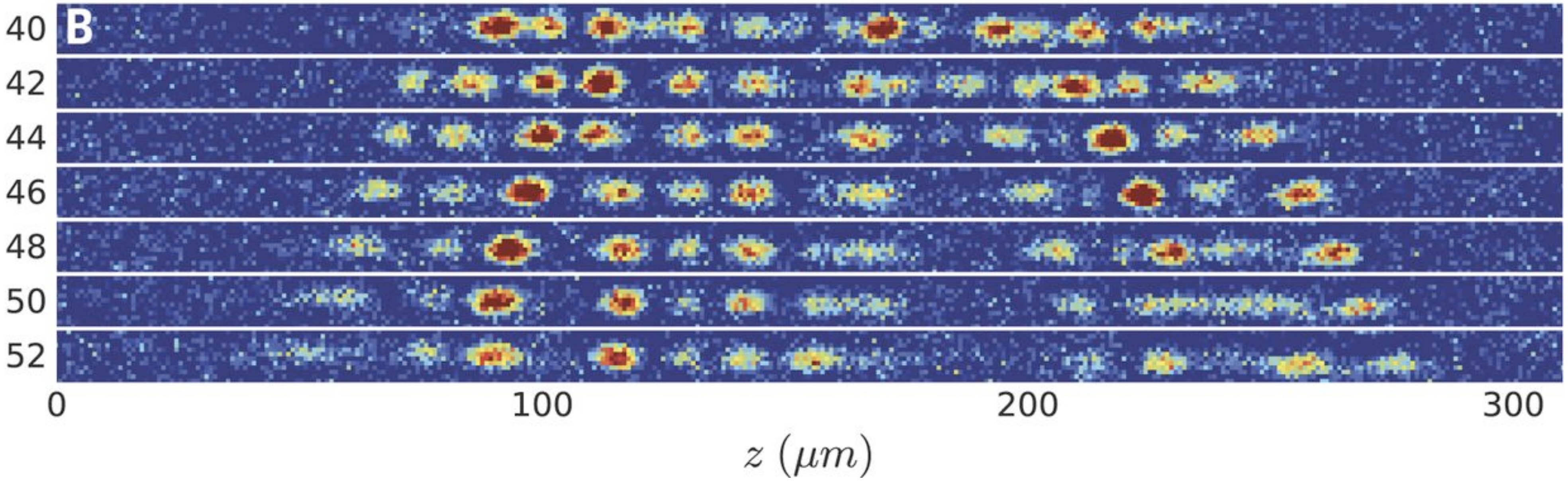
axions, moduli fields, BECs etc





Schive et. al (2014)

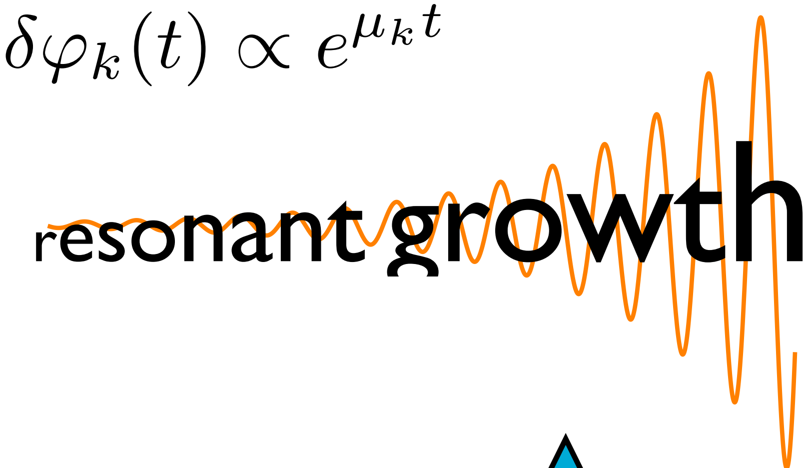
Nguyen, Luo & Hulet (2017)

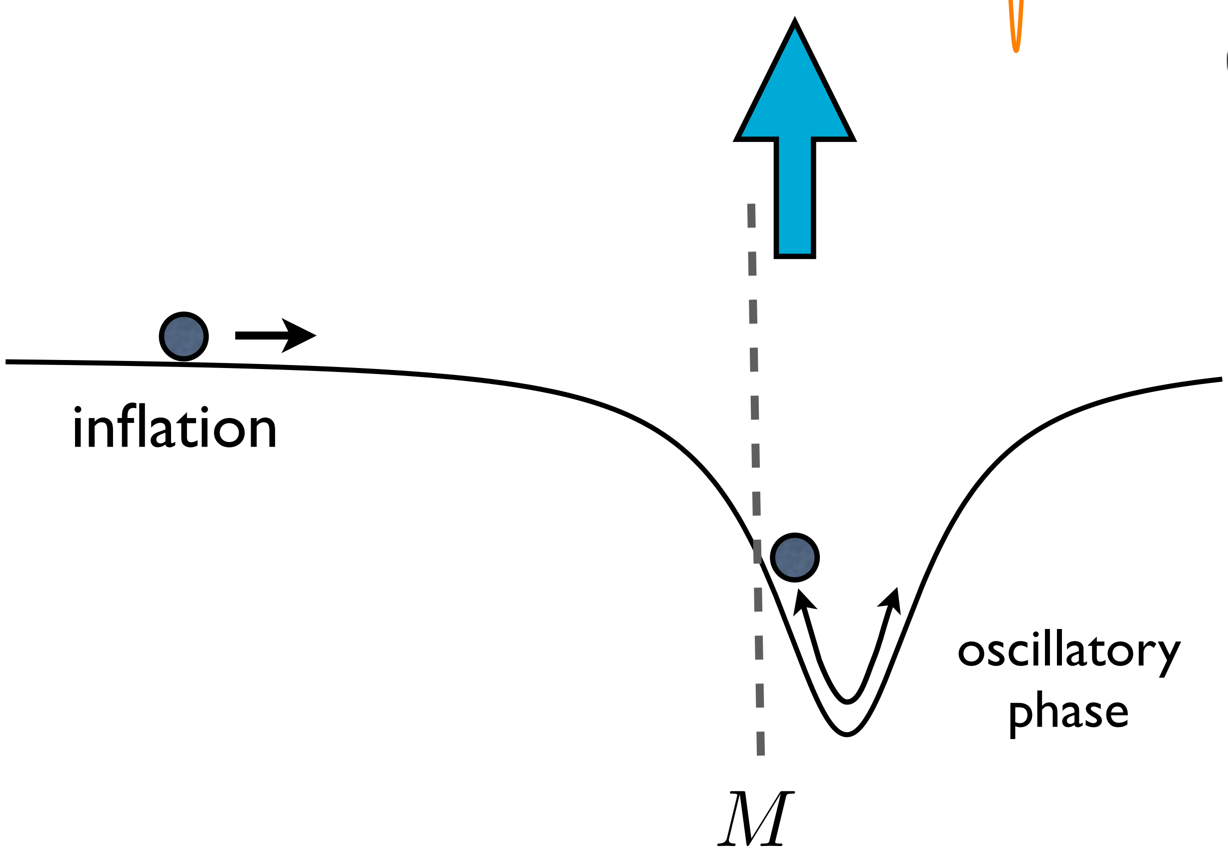


Also see: Kolb & Tkachev 1994 Mocz et. al 2017

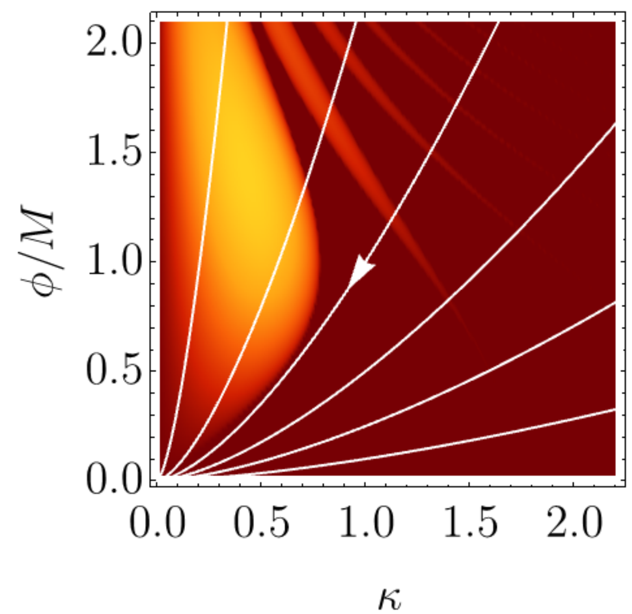
so far : end of inflation

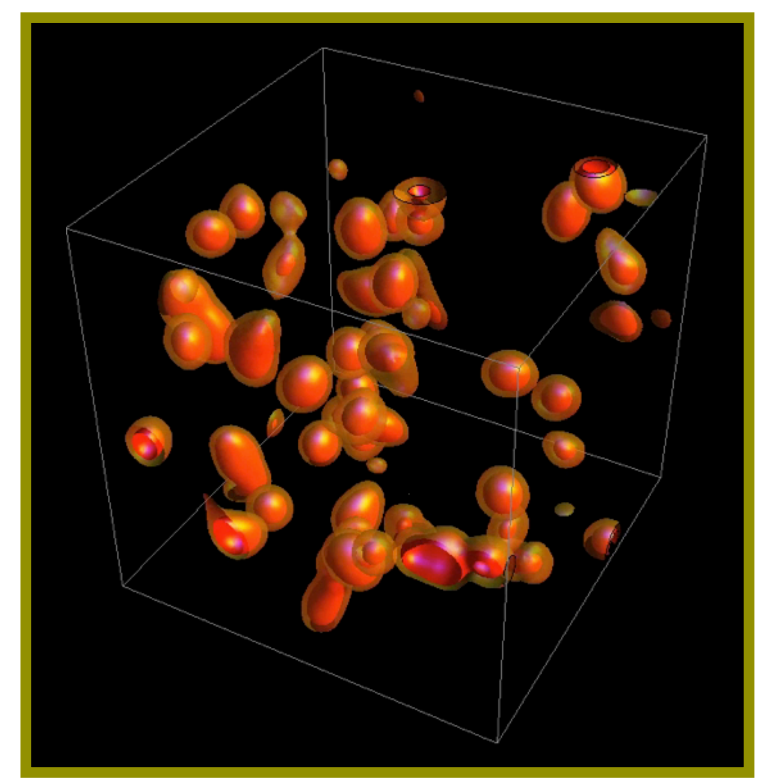
$$\delta\varphi_k(t) \propto e^{\mu_k t}$$





$$\frac{\mu_k}{H} \sim \frac{m_{\rm pl}}{M} \gg 1$$

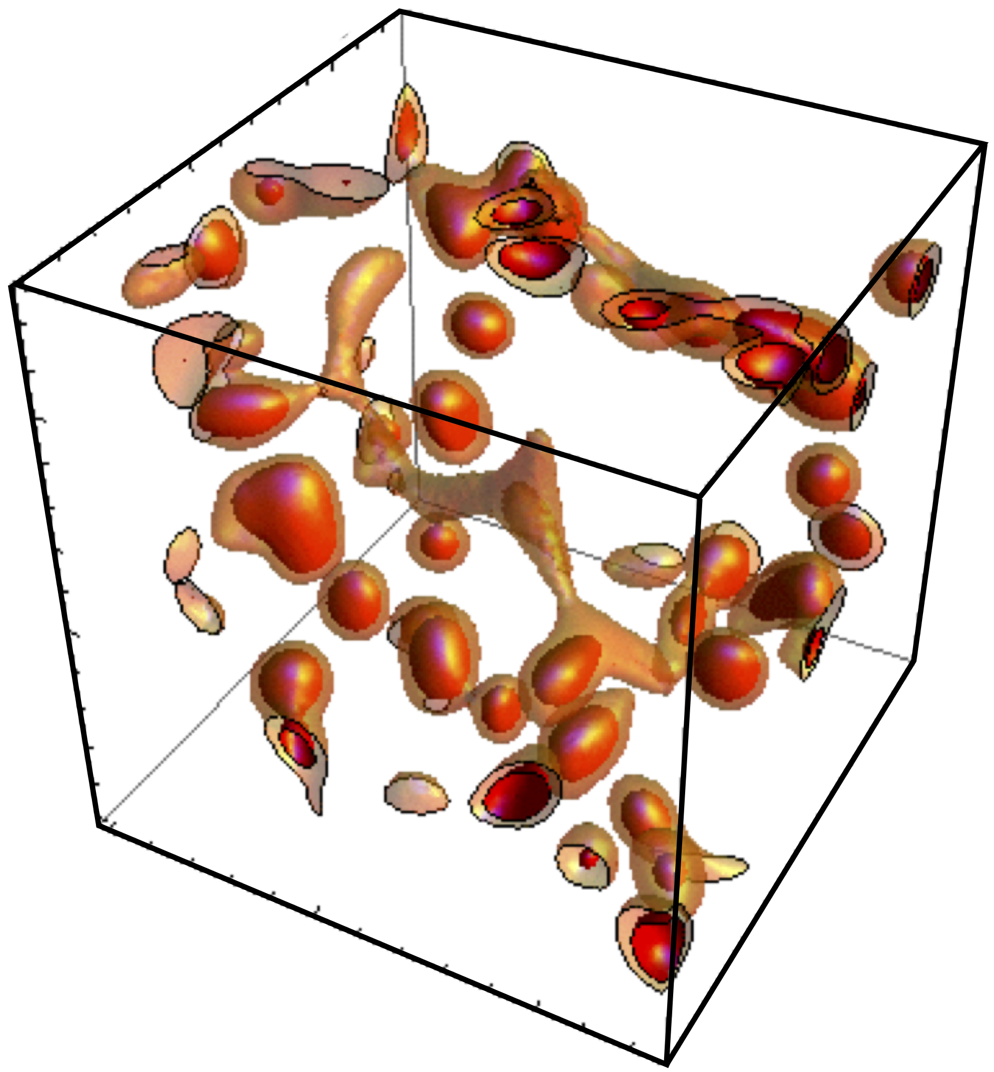


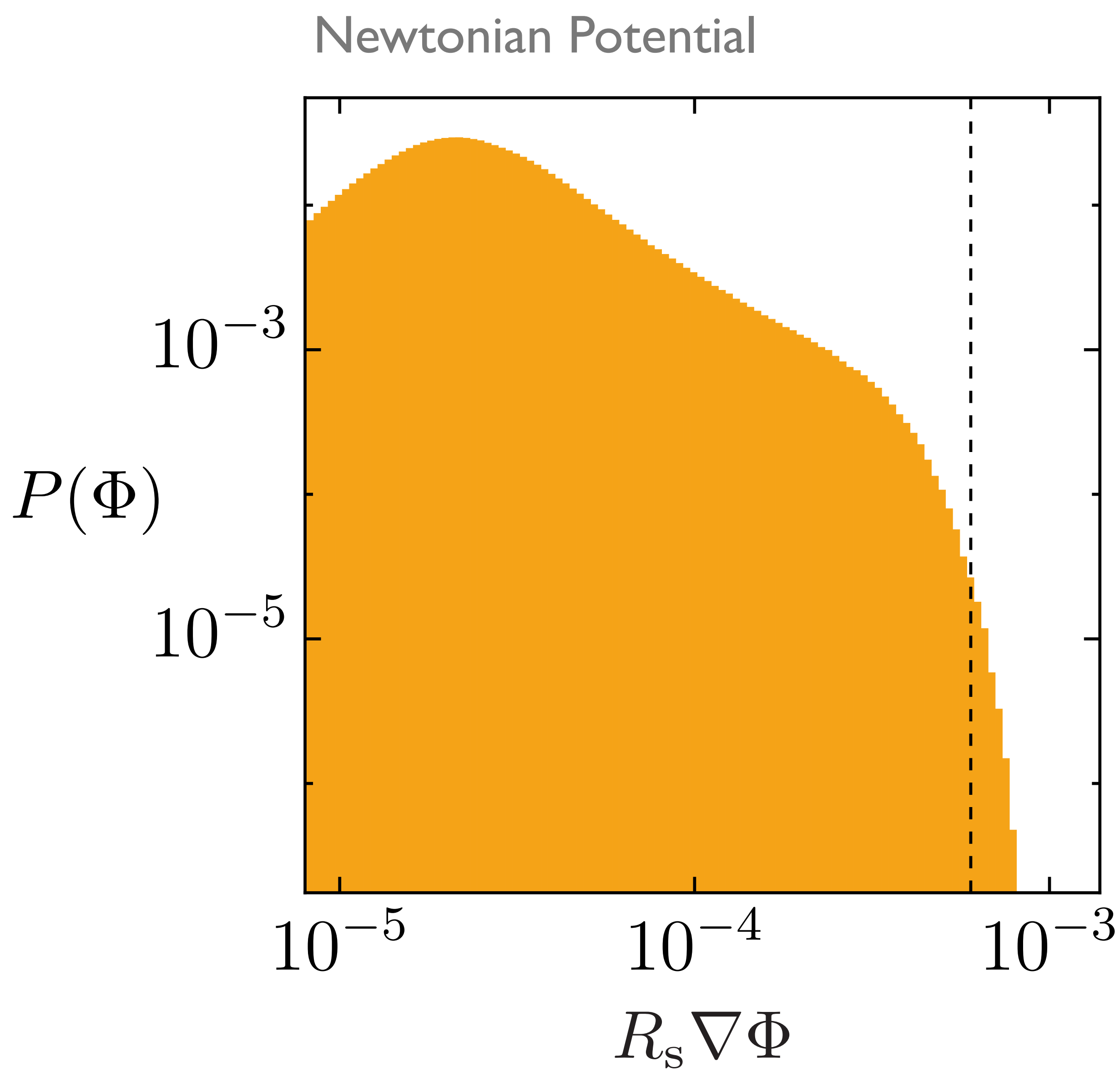


consequences ?

- equation of state/duration to radiation domination ?
  Lozanov & MA (2017, 2018)
- black holes ?
- gravitational waves ?
  Zhou et. al (2013), Antusch et. al (2015), MA et. al (2018)

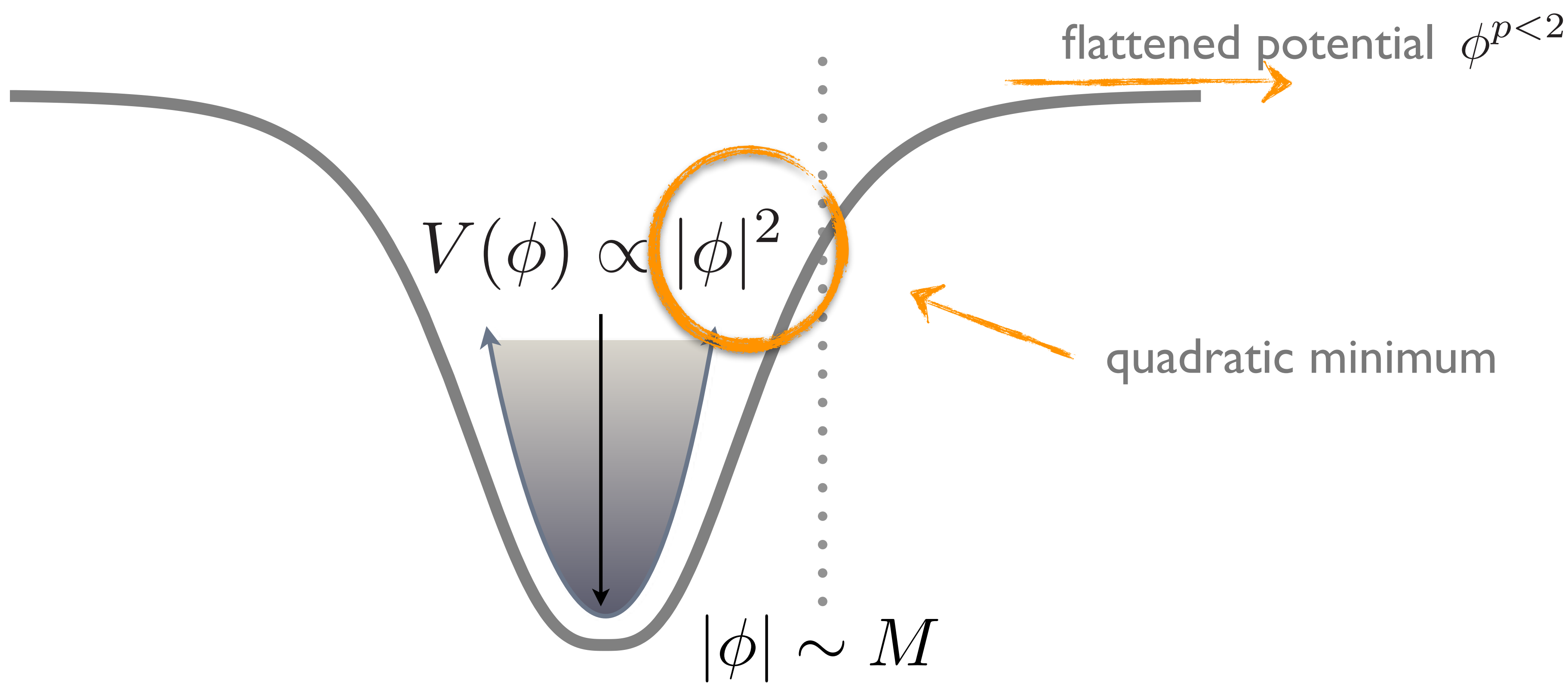
primordial black holes?
gravitational clustering ?

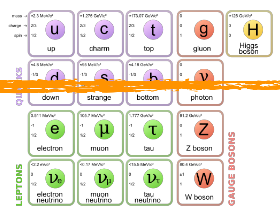




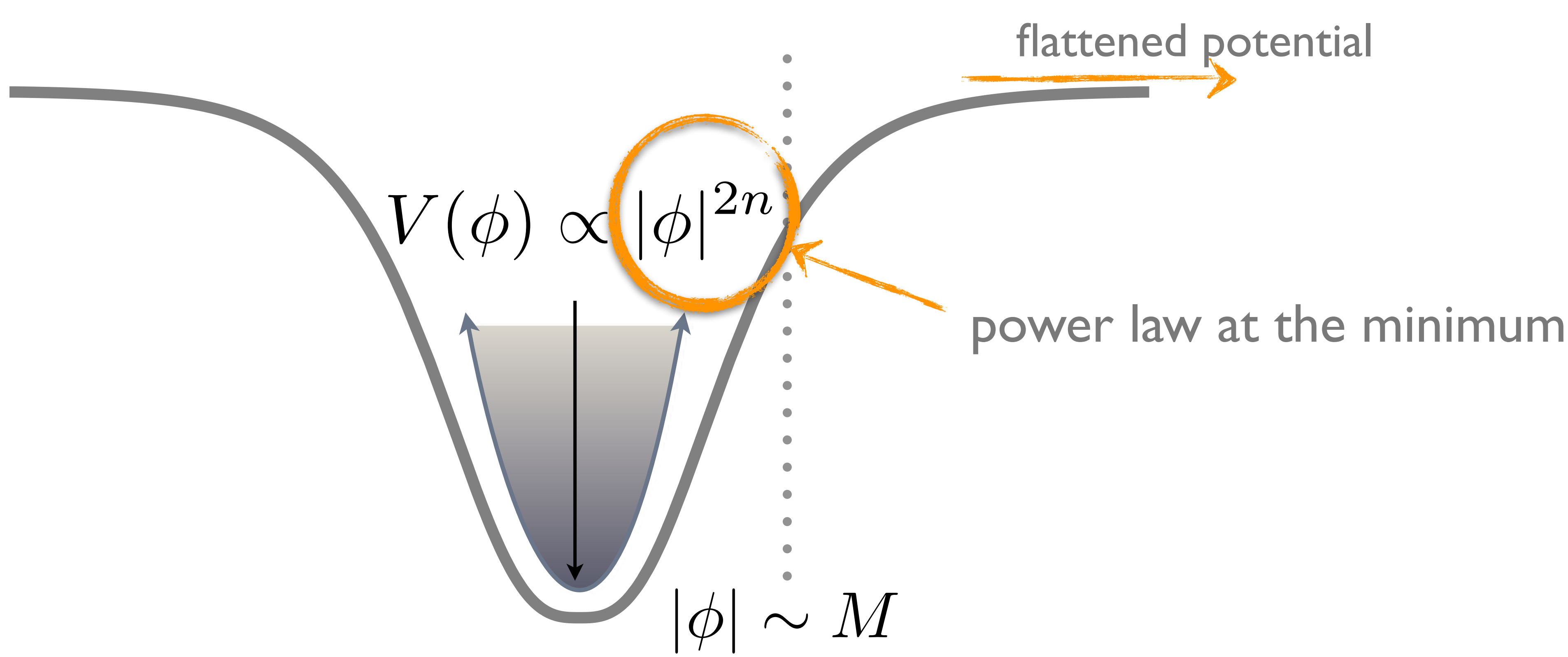
Lozanov & MA (in progress)
Mocz & MA (in progress)

end of inflation in “simple” models



- shape of the potential (self couplings)
- ~~couplings to other fields~~  χ , ψ

end of inflation in “simple” models



- shape of the potential (self couplings)
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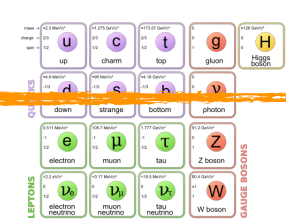


~~$\chi\ ,\psi$~~

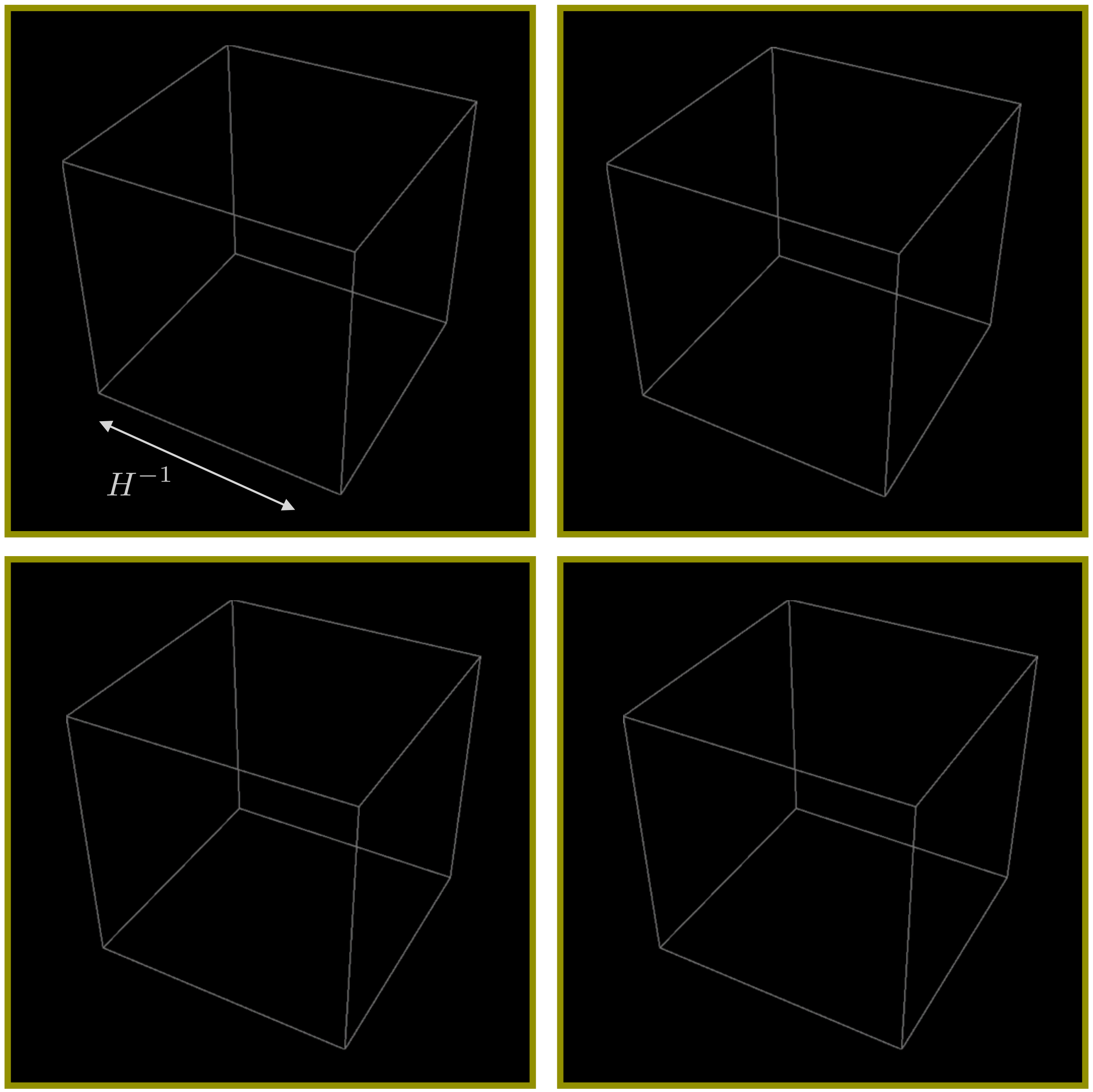
result of fragmented dynamics

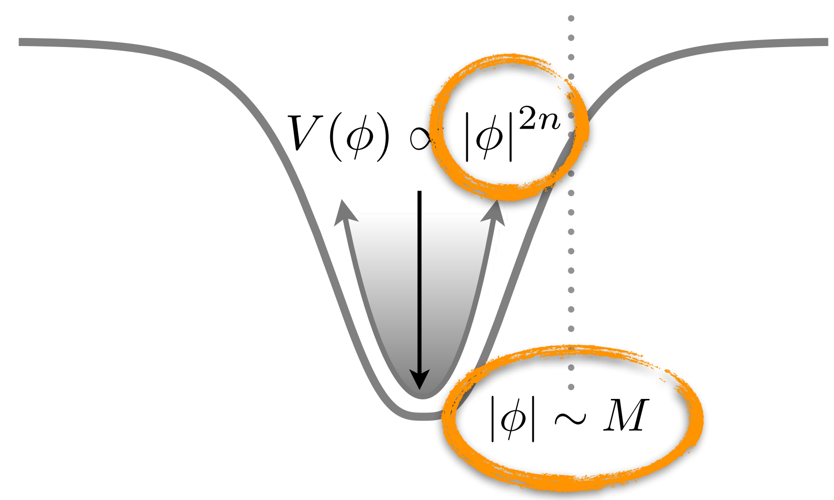
* after sufficient time

$n = 1$ $\quad$ $n > 1$

$M \sim m_{\rm pl}$

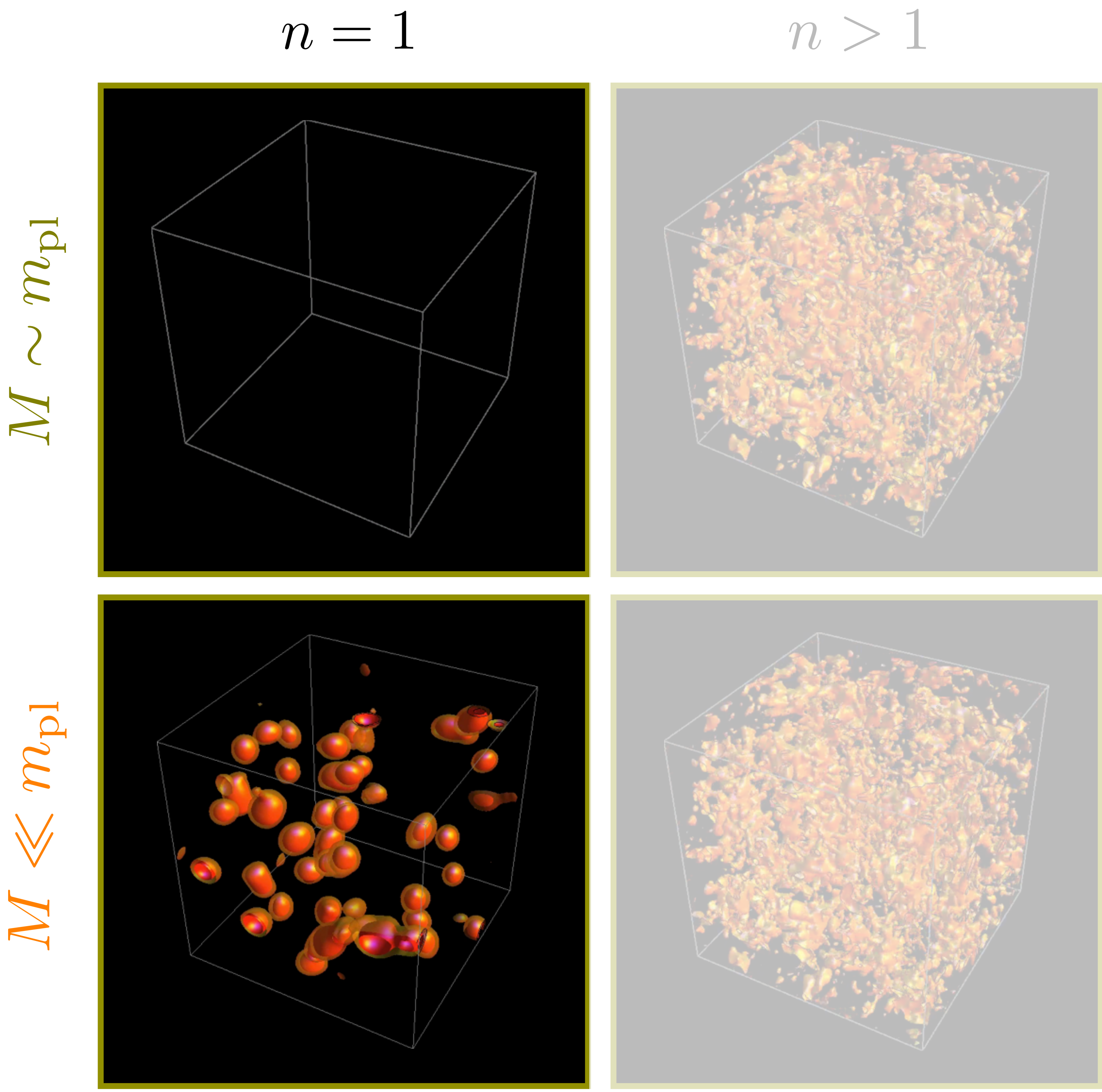
$M \ll m_{\rm pl}$

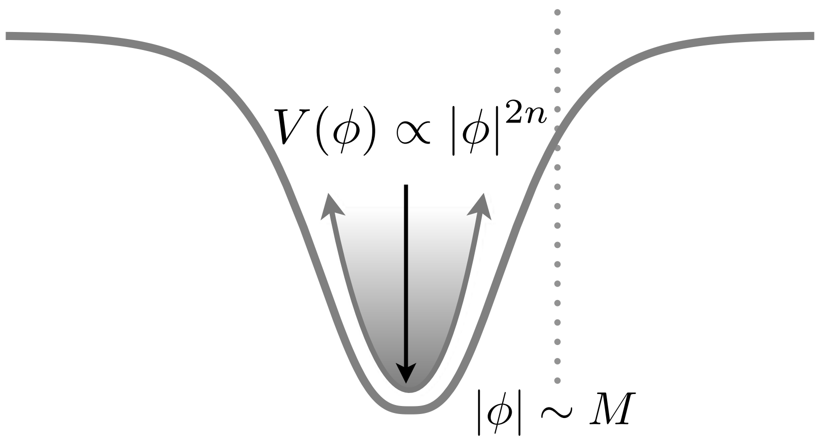




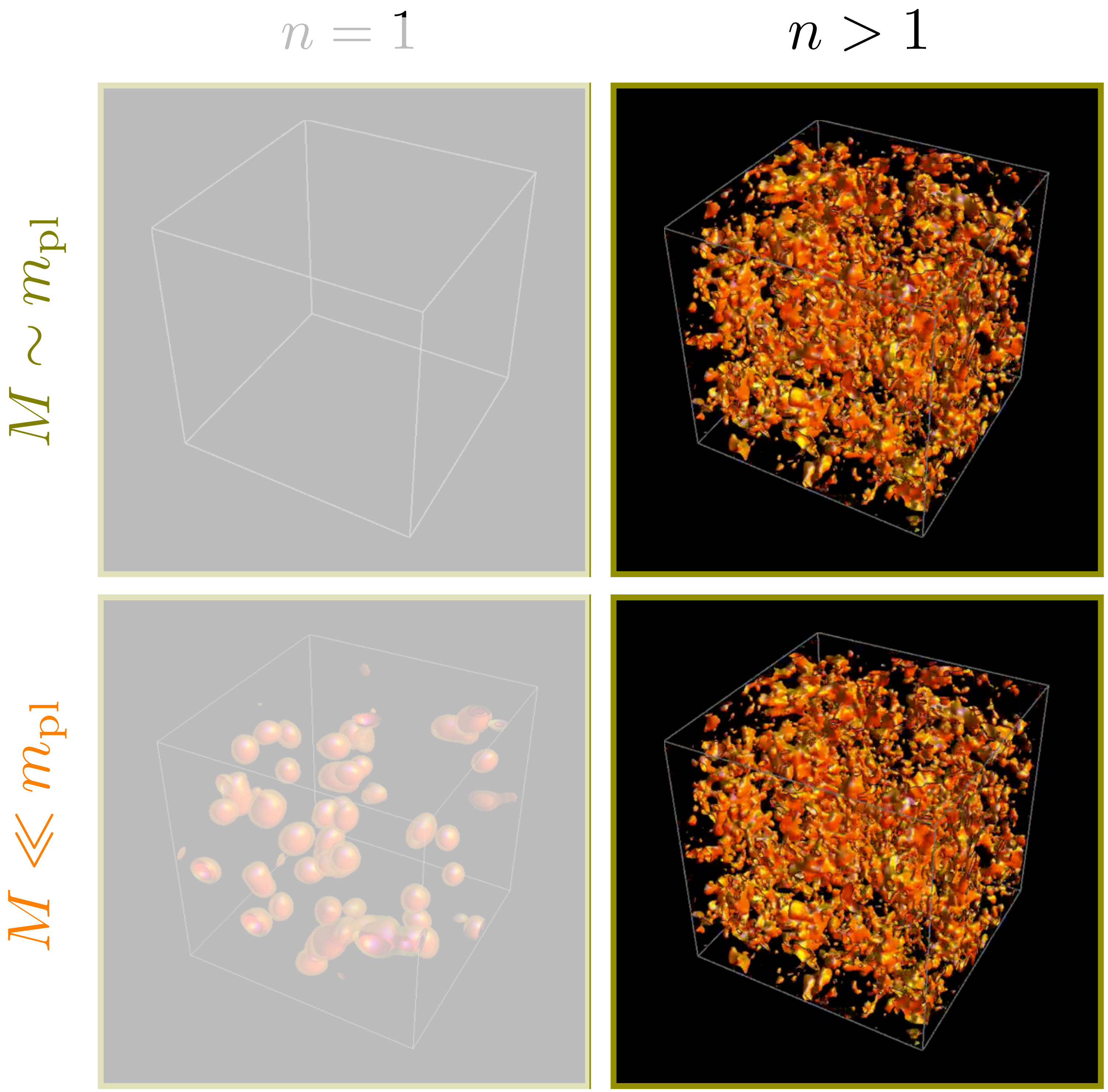
result of fragmented dynamics

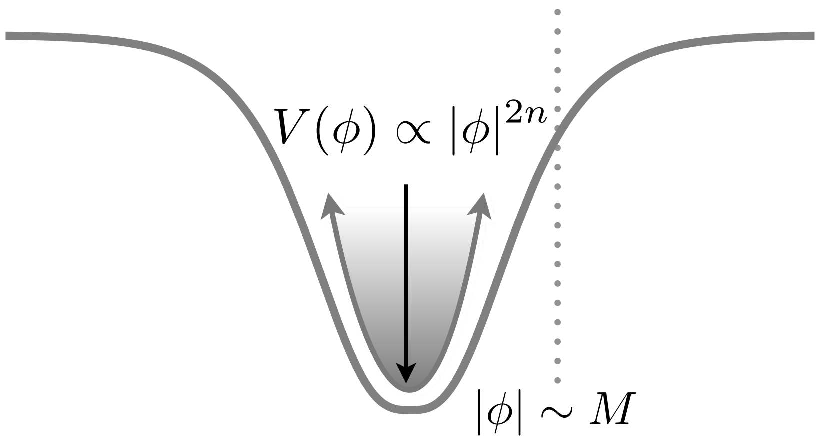
* after sufficient time



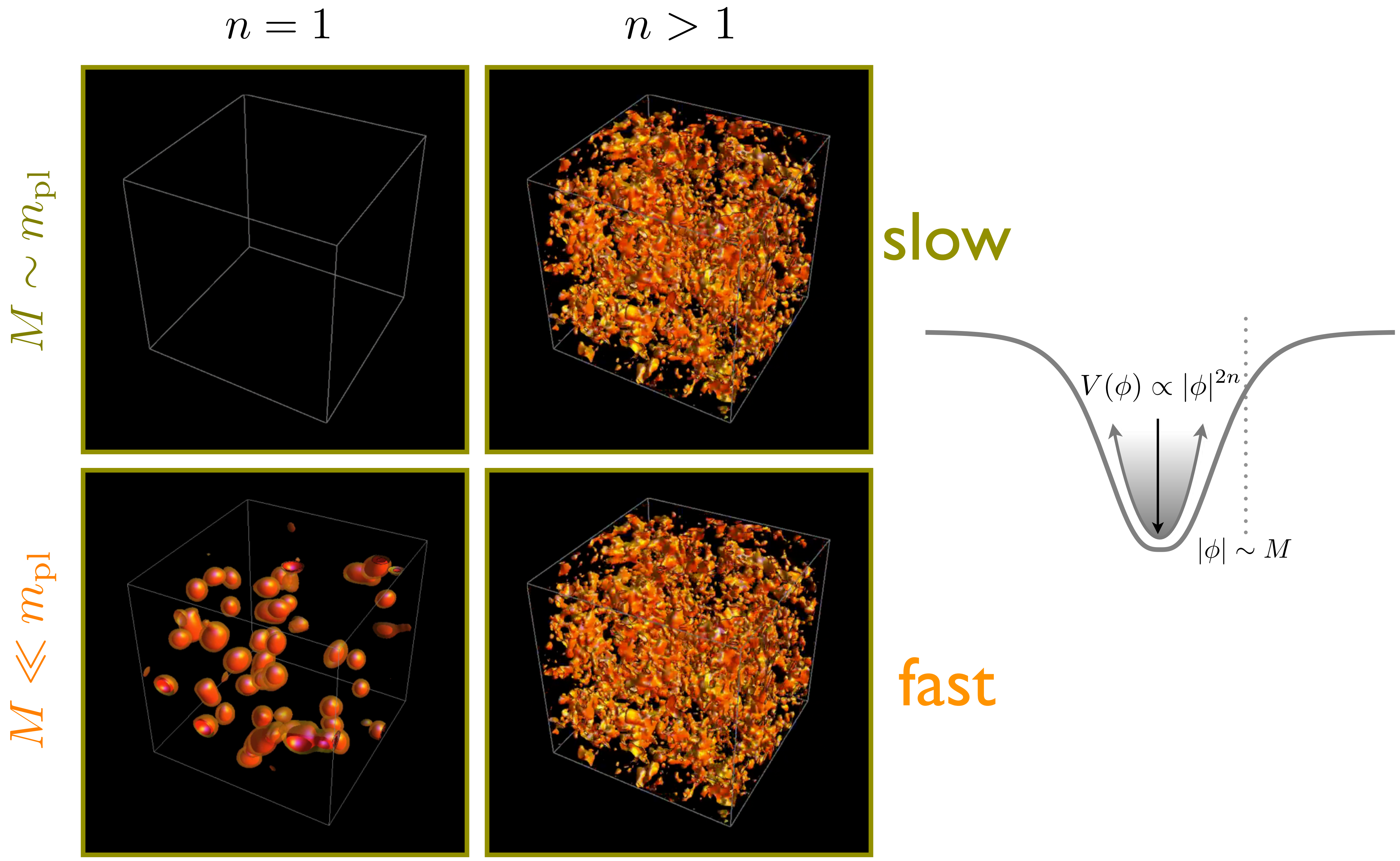


result of fragmented dynamics
* after sufficient time





result of fragmented dynamics
* after sufficient time



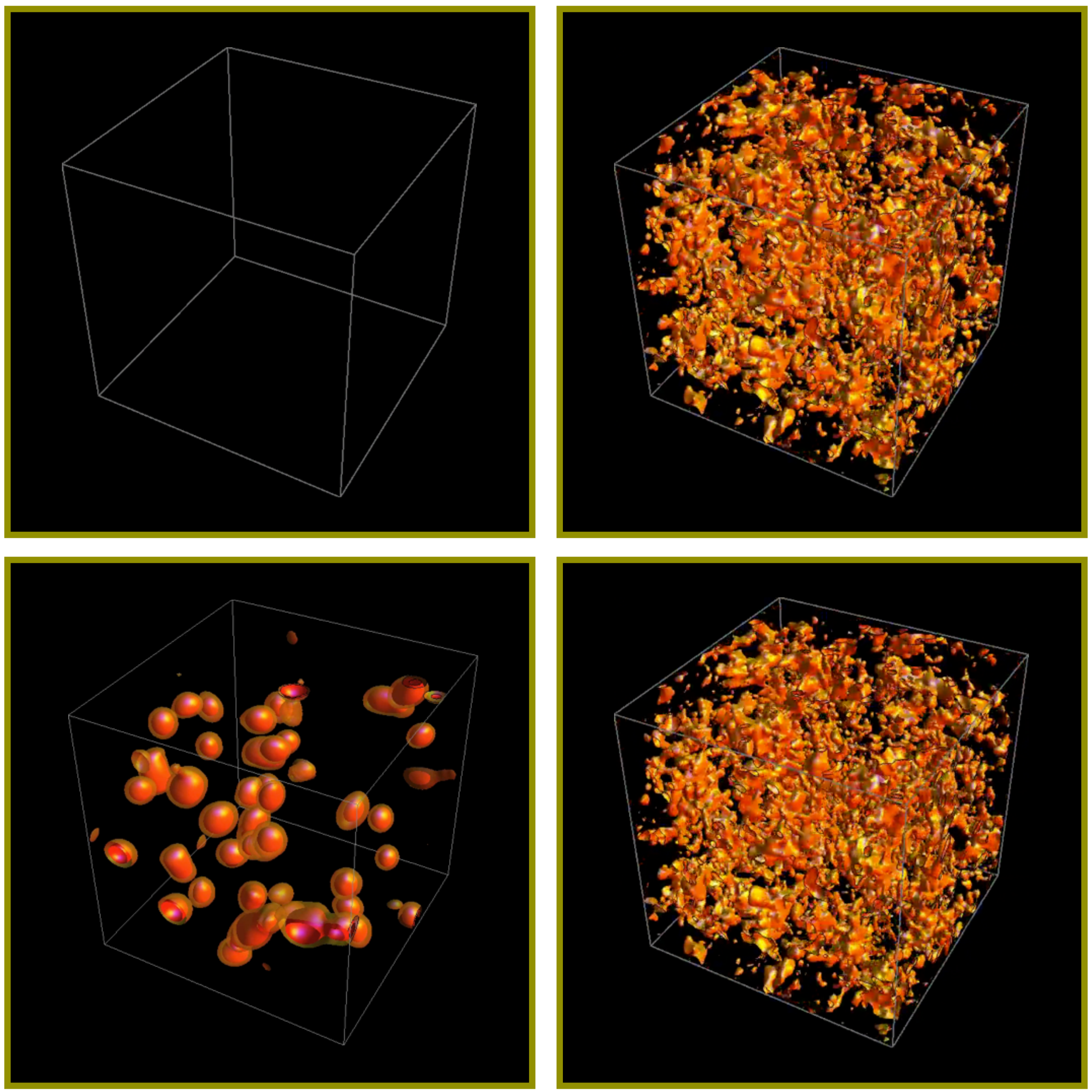
eq. of state $w = \text{pressure}/\text{density}$

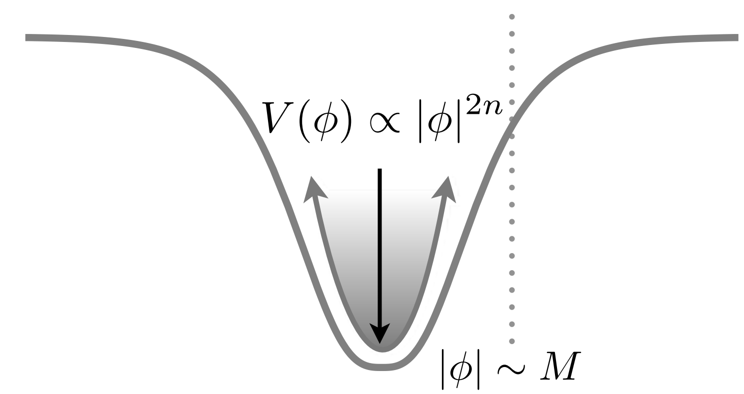
* after sufficient time

$n = 1$ $\quad$ $n > 1$

$M \sim m_{\mathrm{pl}}$ — slow

$M \ll m_{\mathrm{pl}}$ — fast





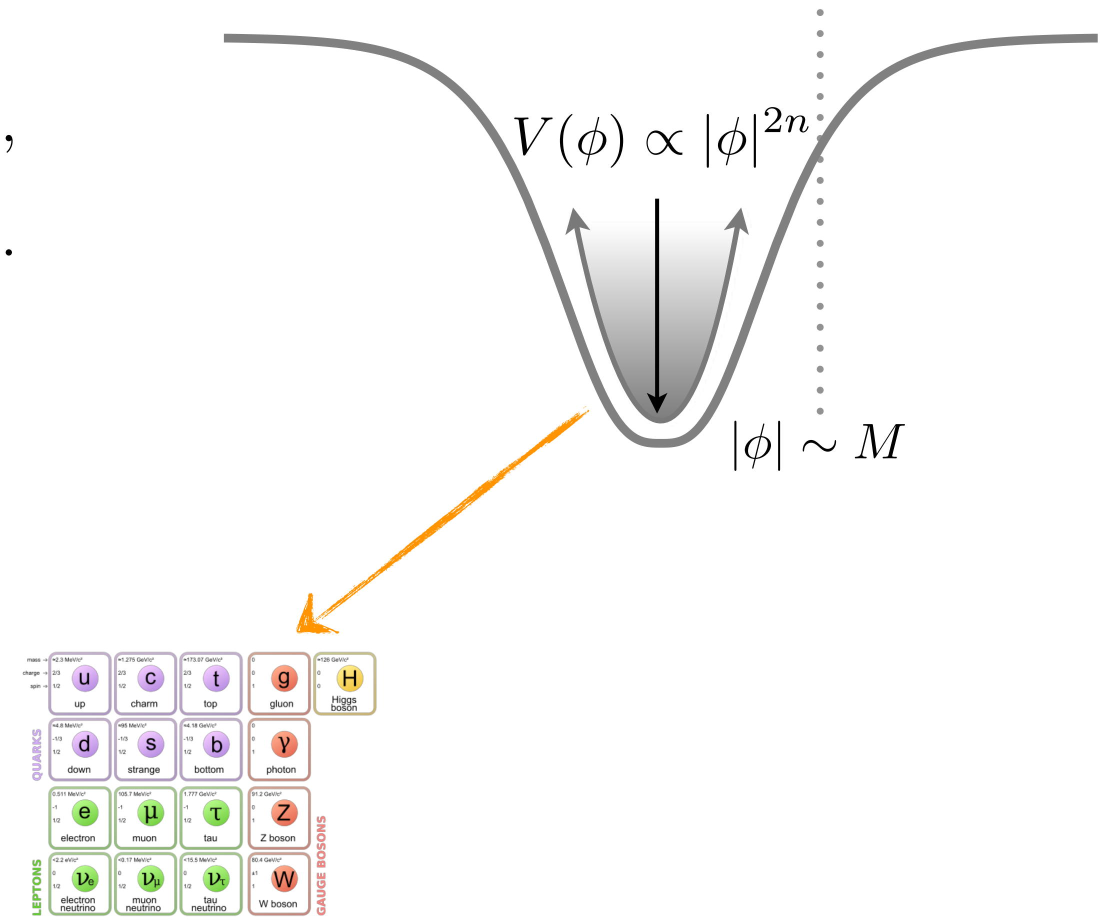
$$w \to \begin{cases} 0 & \text{if } n = 1 \\ 1/3 & \text{if } n > 1 \end{cases}$$

independent of M

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

an upper bound on duration to radiation domination

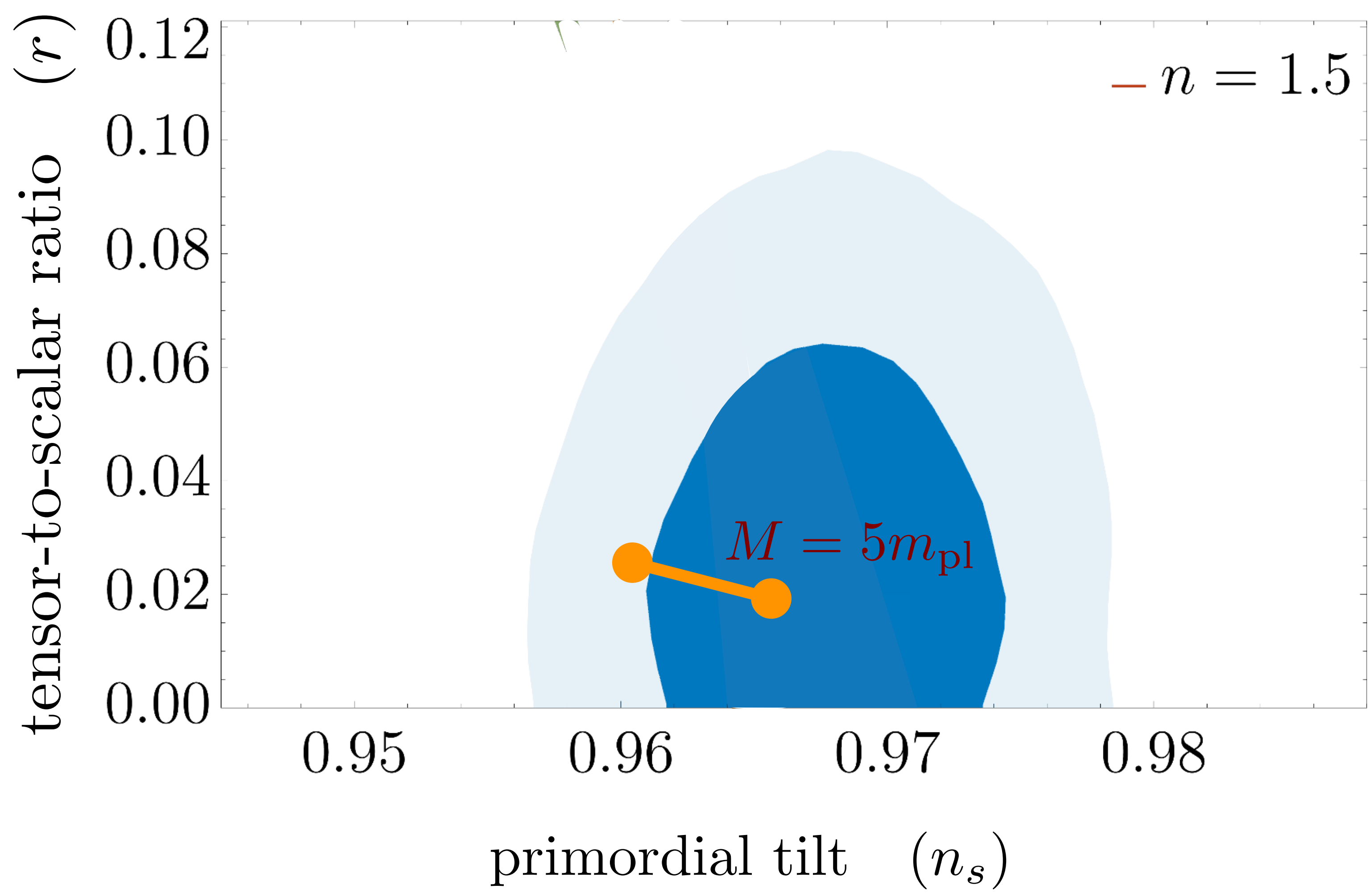
$$\Delta N_{\rm rad} \sim \begin{cases} 1 & M \lesssim 10^{-2} m_{\rm Pl}\,, \\ \dfrac{n+1}{3} \ln\left(\dfrac{\kappa}{\Delta\kappa} \dfrac{10 M}{m_{\rm Pl}} \right) & M \gtrsim 10^{-2} m_{\rm Pl}\,. \end{cases}$$



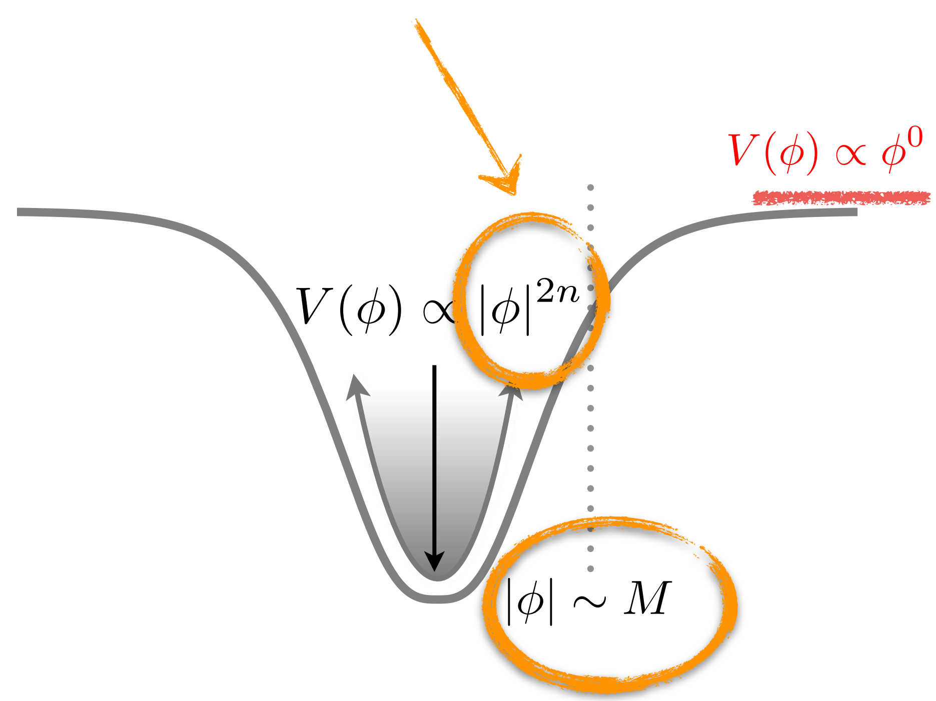
additional *light (massless) fields* can only decrease the duration!

* decay to significantly massive fields can change this conclusion

implications for CMB observables



power law at the minimum

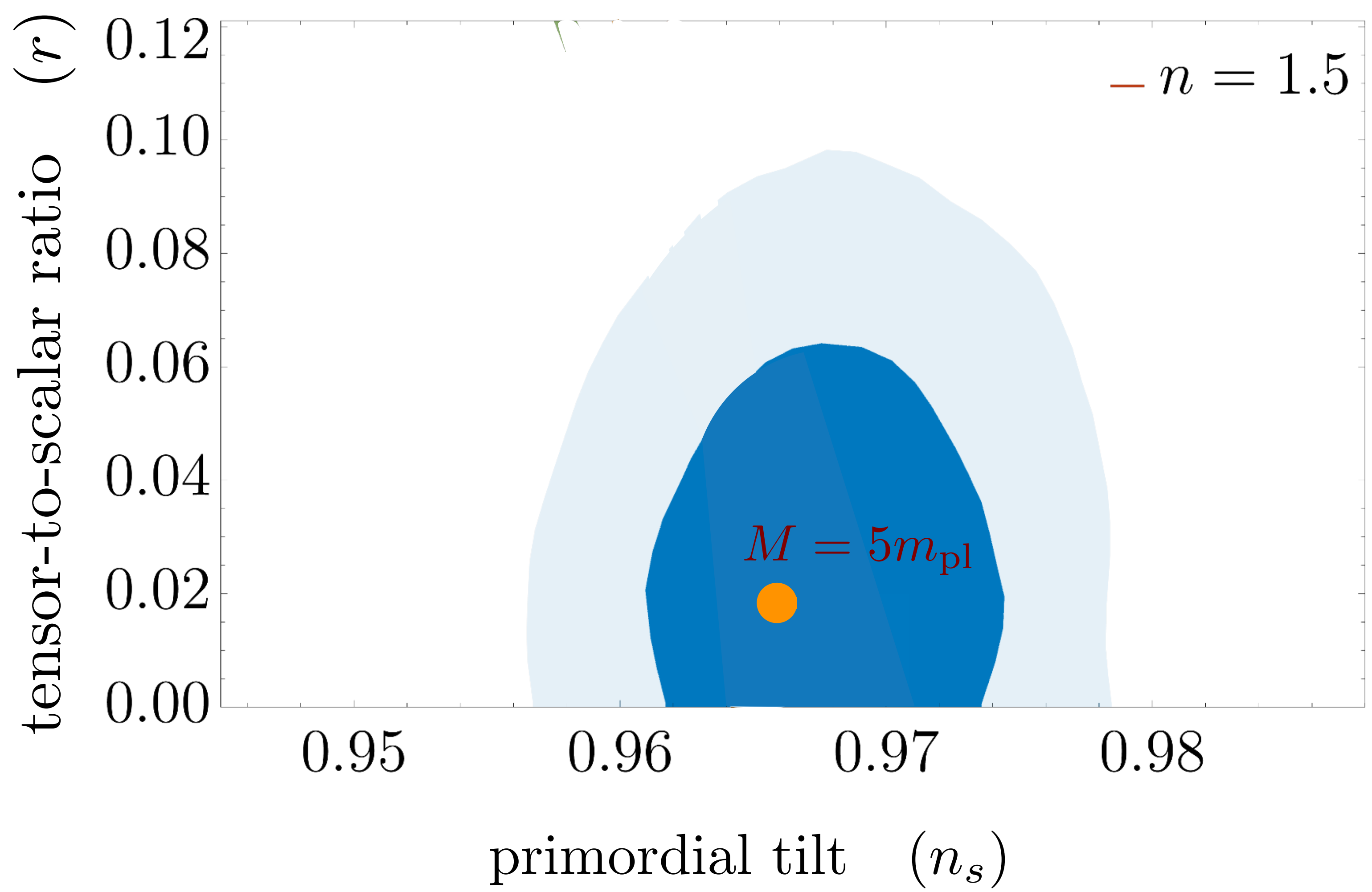


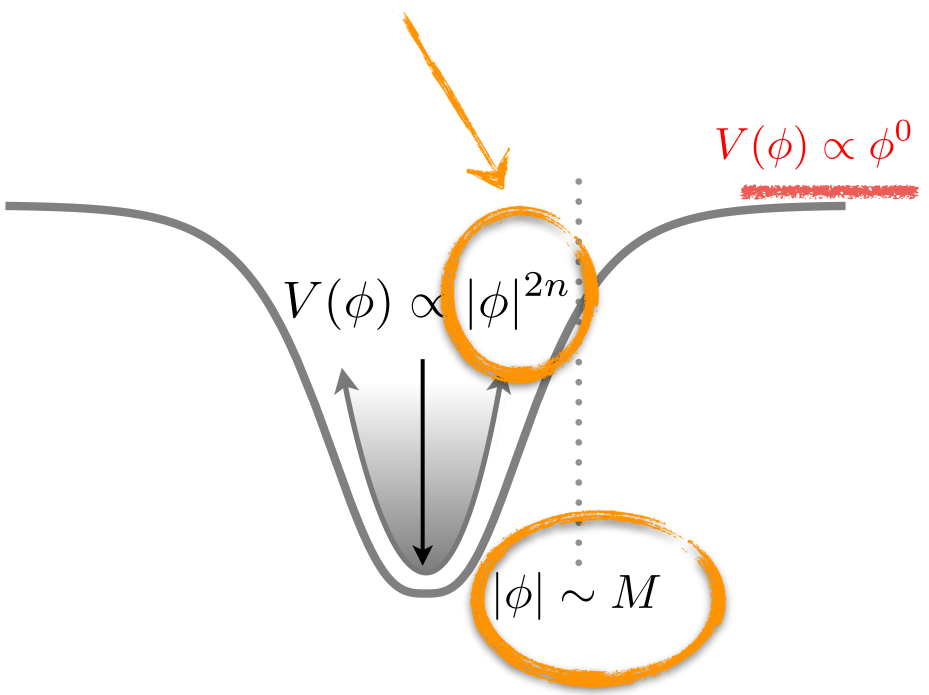
scale fo flattening

also see: Kamionkowski & Munoz 2014

* non-quadratic minimum

reduction in uncertainty!



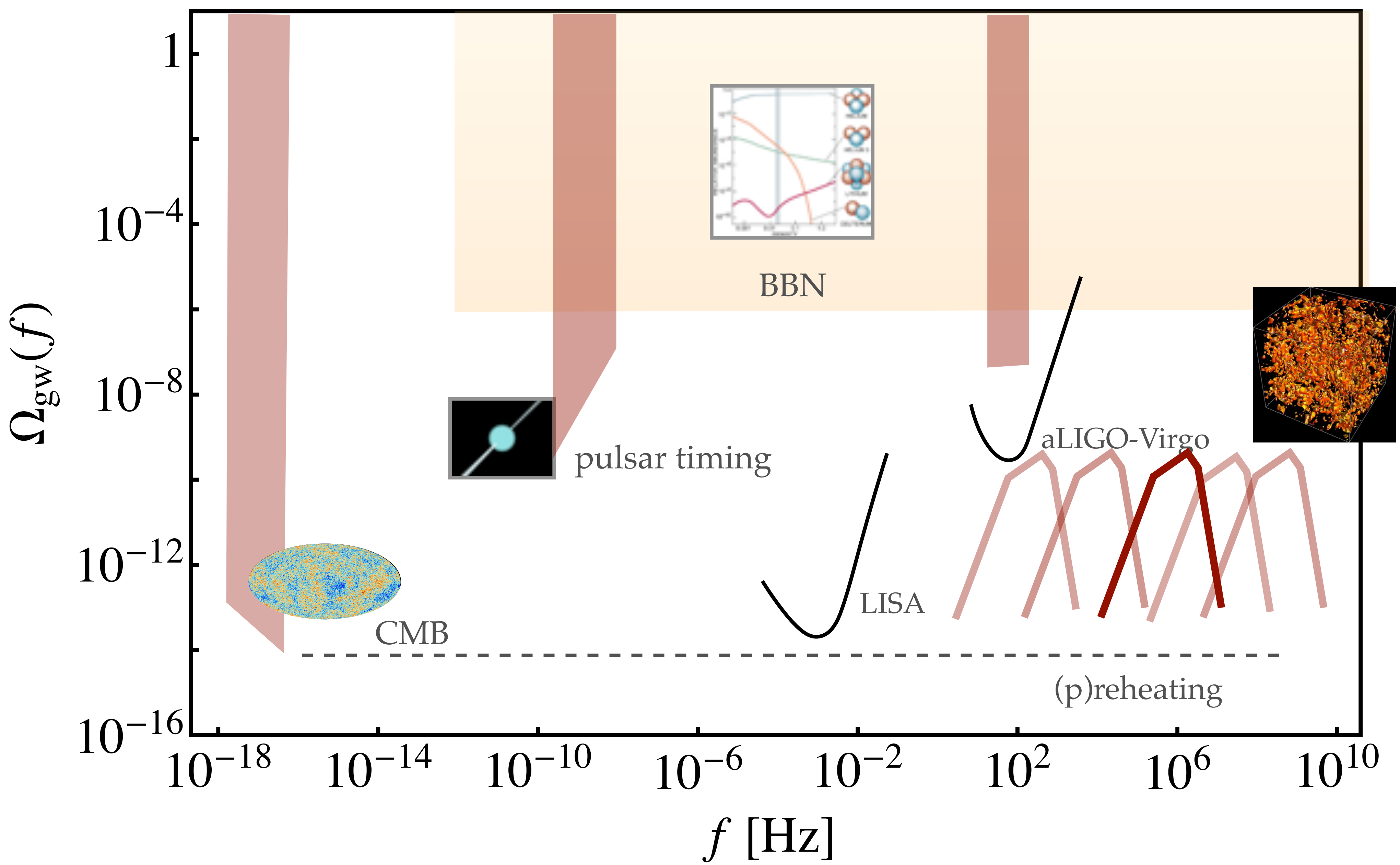


$$\Delta N_{\rm rad} \sim \begin{cases} 1 & M \lesssim 10^{-2} m_{\rm Pl}\,, \\ \dfrac{n+1}{3} \ln\left(\dfrac{\kappa}{\Delta\kappa}\dfrac{10M}{m_{\rm Pl}}\right) & M \gtrsim 10^{-2} m_{\rm Pl}\,. \end{cases}$$

* non-quadratic minimum

stochastic gravitational waves

$$\Omega_{\rm gw}(f) = \frac{d\ln\rho_{\rm gw}}{d\ln f} \sim \frac{\rho_{\rm gw}}{\rho_{\rm crit}}$$



end of inflation

“SIMPLE”

- single field
- non-trivial dynamics
- eq. of state + gravitational waves

after inflation

SIMPLE

problem oriented

conundrums in the present universe, with solutions/ implications in the early universe …

examples: dark matter abundance/ distribution, matter anti-matter asymmetry etc. See upcoming talk by E. Erikcek

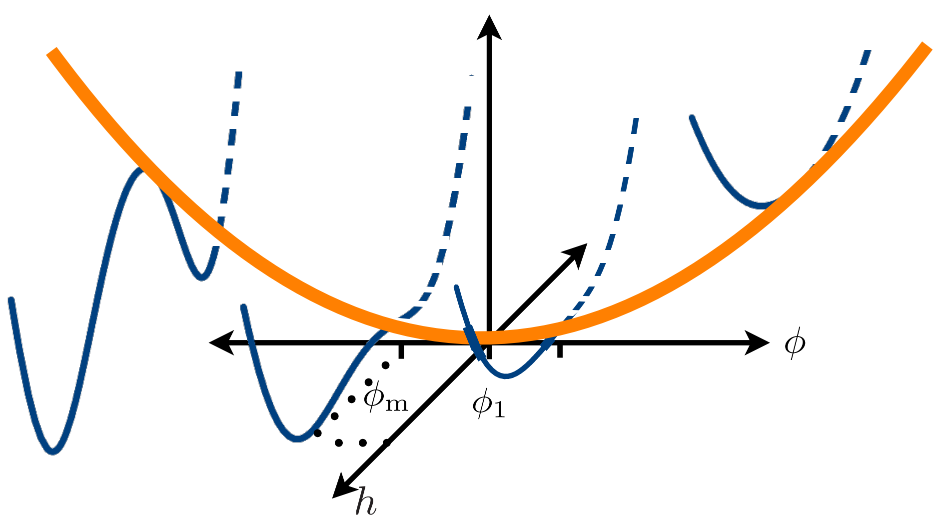
Early Universe implications of Higgs Fine Tuning

LHC: Higgs, but no SUSY particles (so far). Is SUSY wrong or is the Higgs accidentally light within SUSY ?

If the Higgs potential is fine-tuned (consistent with LHC so-far), are there
observable cosmological implications ?

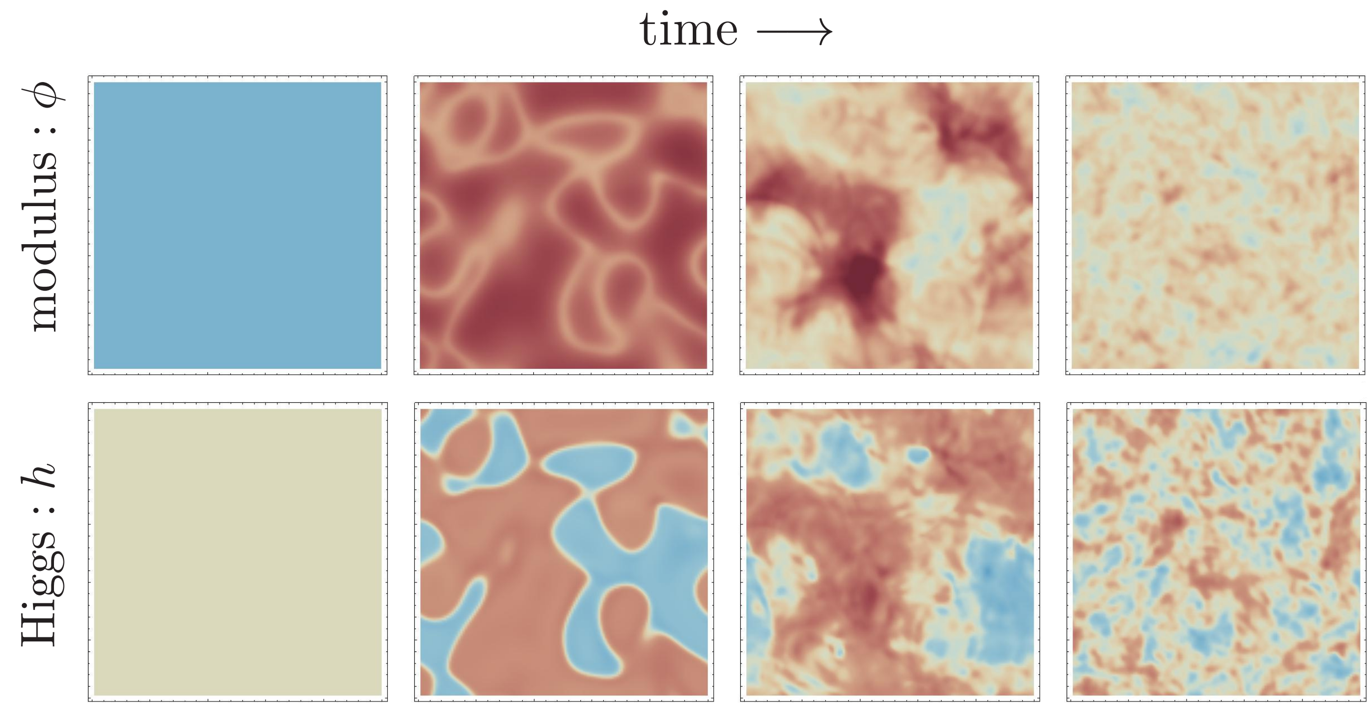
MA, Fan, Lozano & Reece (2018)

Higgs fine tuning — implications from the early universe



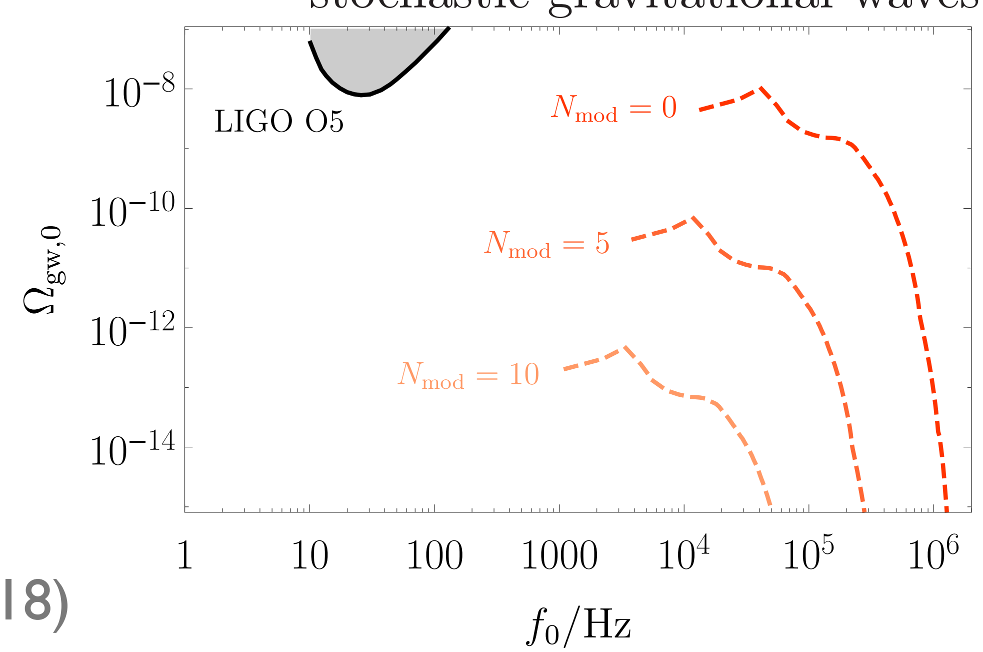
$$\frac{1}{2}m_\phi^2(\phi-\phi_1)^2 + M^2\frac{\phi-\phi_0}{f}h^\dagger h + \lambda(h^\dagger h)^2 + V_0$$

$$\text{Necessary Fine Tuning} \Leftrightarrow \quad \frac{\phi_{\rm m}-\phi_0}{f} \ll 1$$

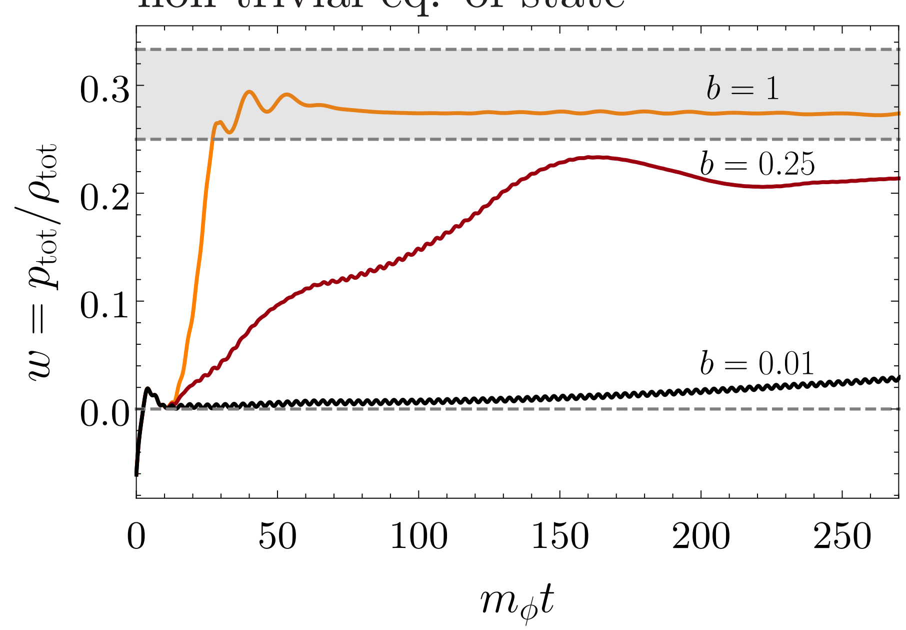


$$\frac{M^4}{2\lambda f^2 m_\phi^2} \to 1 \ \Leftrightarrow \text{rapid fragmentation}$$

stochastic gravitational waves



non-trivial eq. of state



MA, Fan, Lozano & Reece (2018)

after inflation

SIMPLE

problem oriented

COMPLEX

Early Universe implications of Higgs Fine Tuning

arXiv: 1802.00444

MA, Fan, Lozano & Reece

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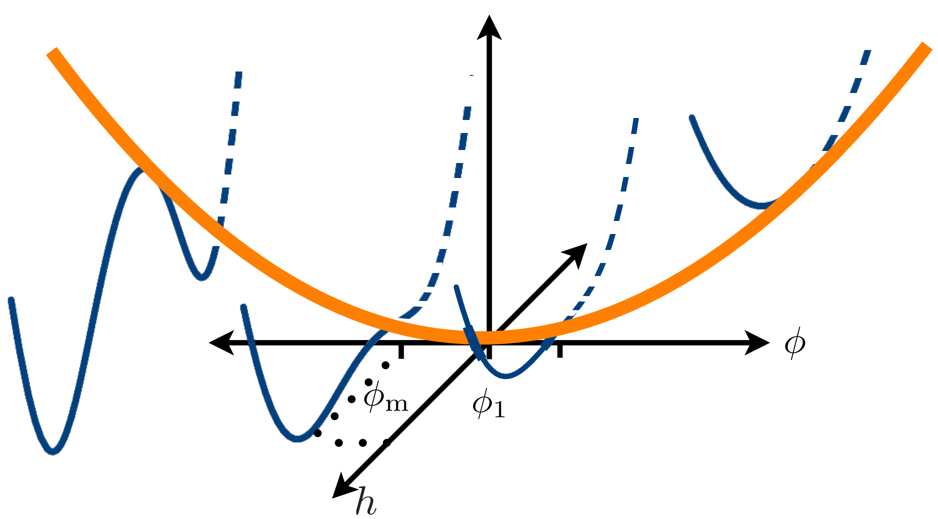

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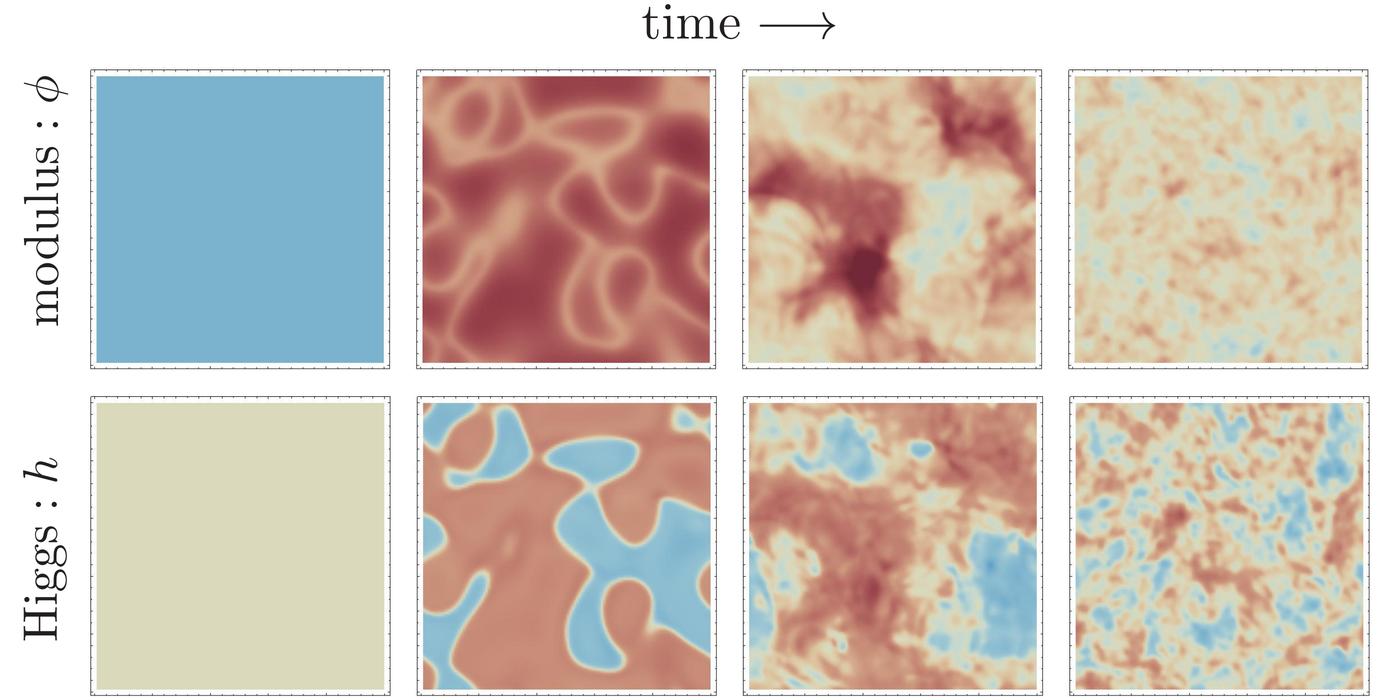

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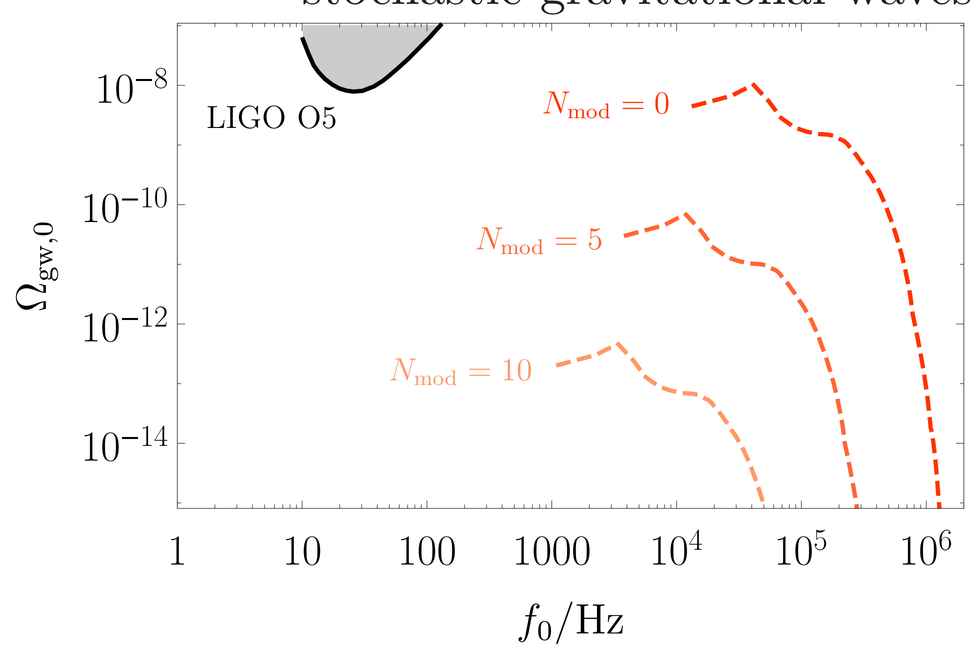

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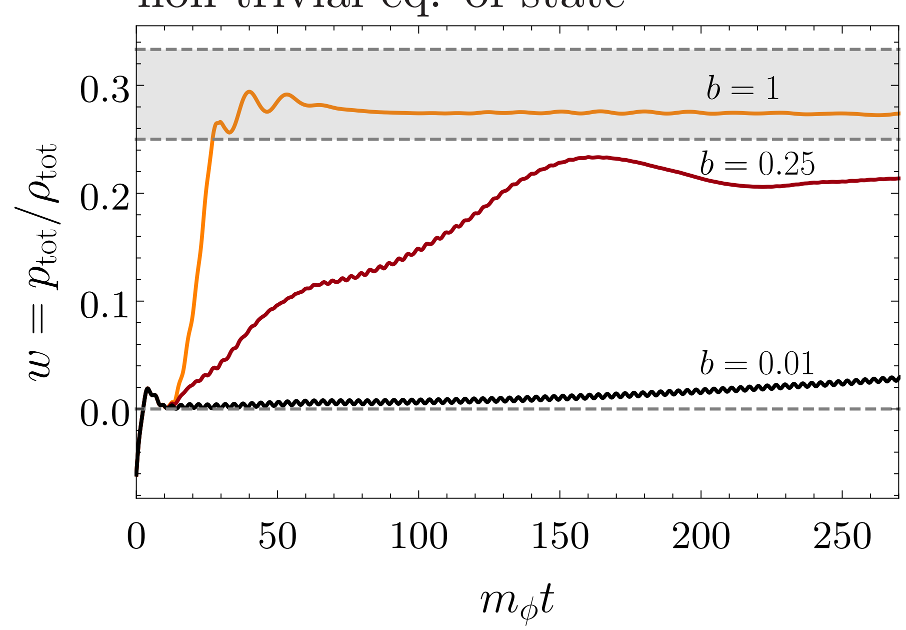


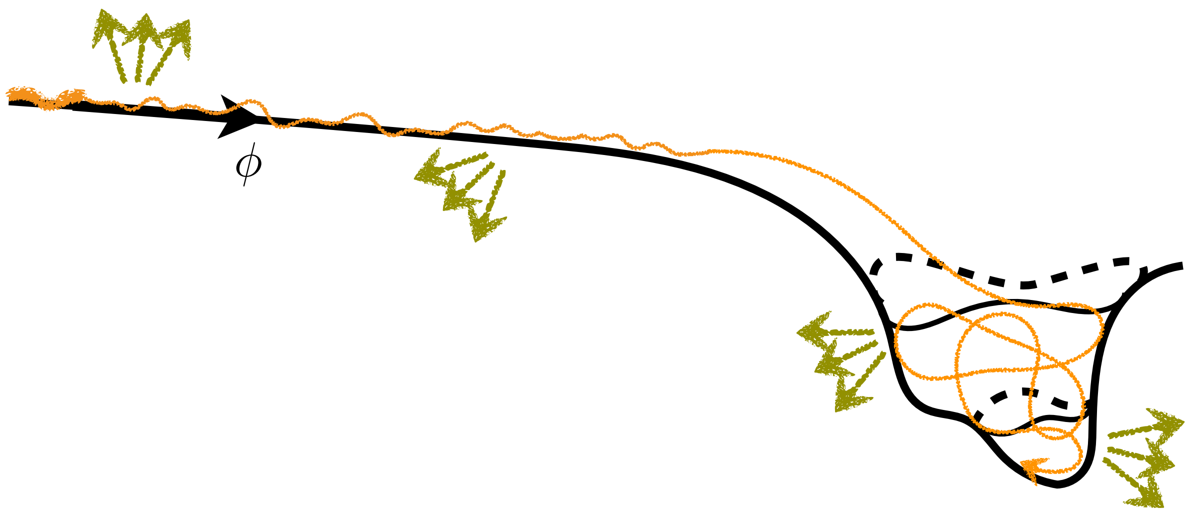
end of inflation

SIMPLE

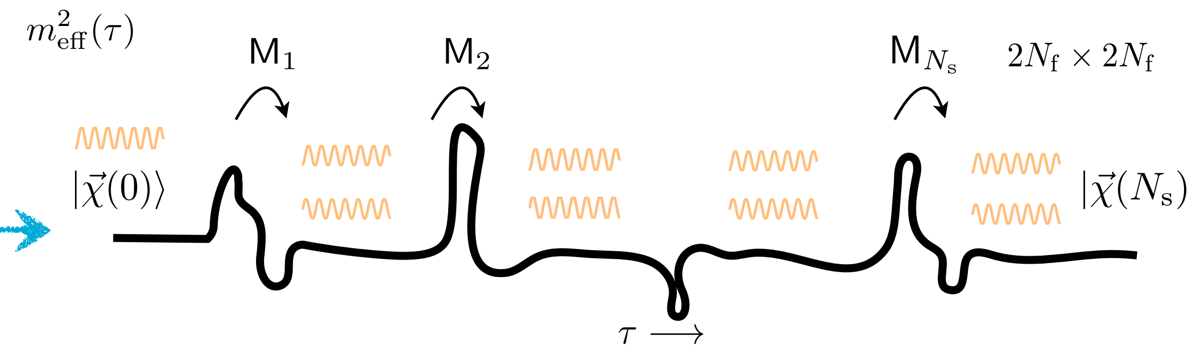
problem oriented

COMPLEX

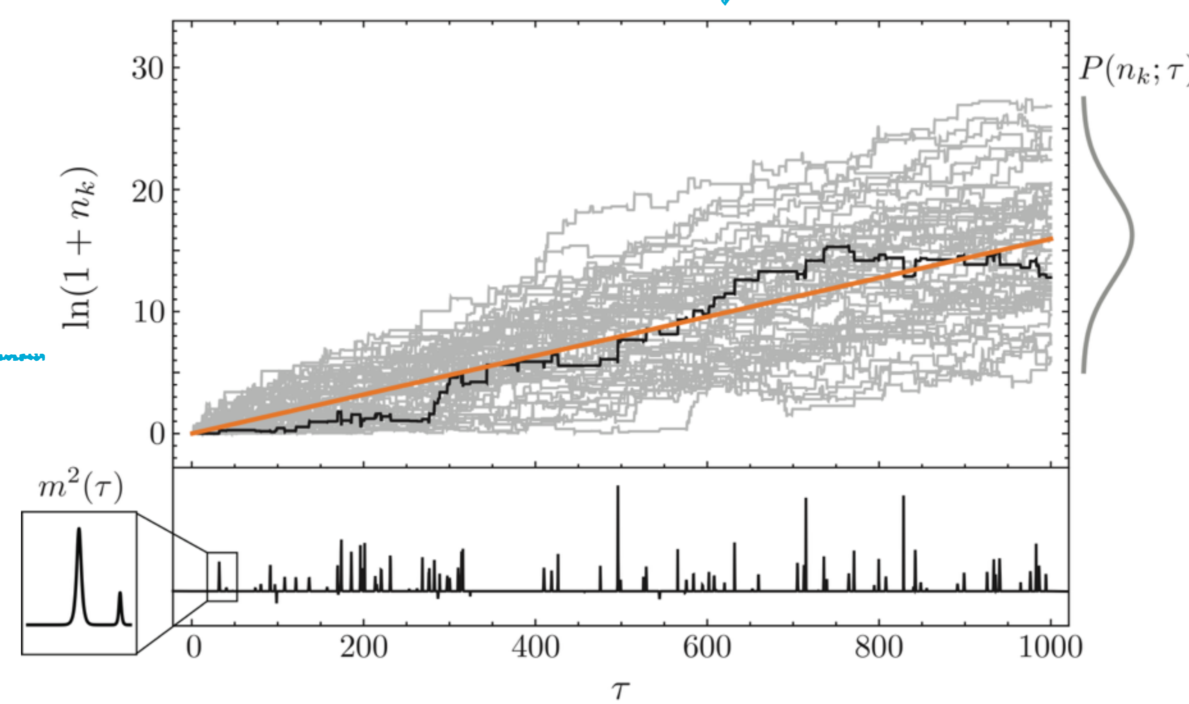
complex enough: “universal” results



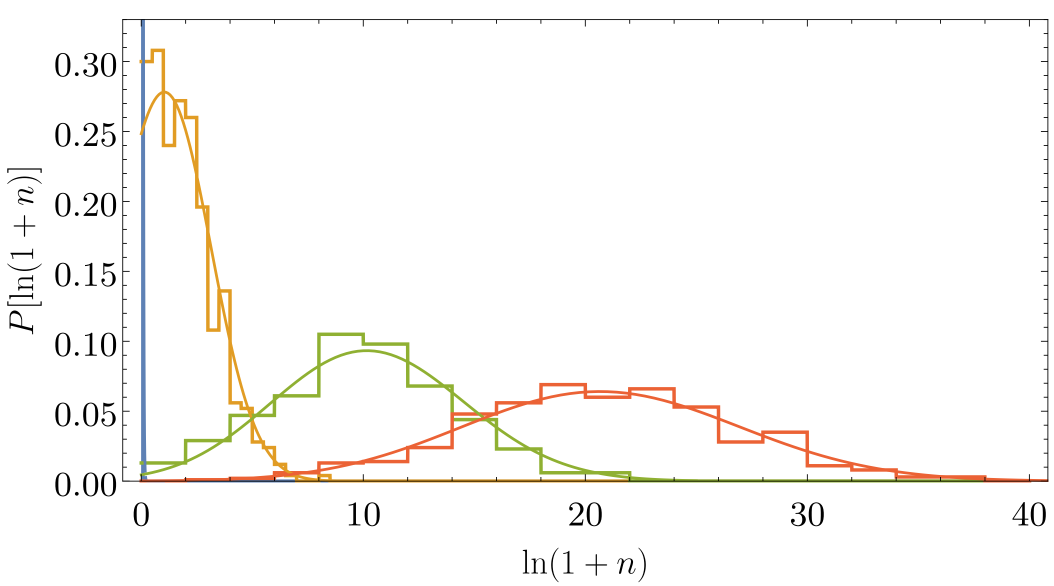
complex non-perturbative particle production



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



occupation numbers grow exponentially
(universality similar to Anderson localization)

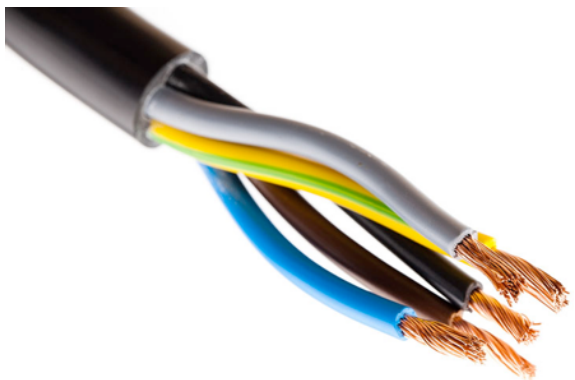


universally log-normal distributions

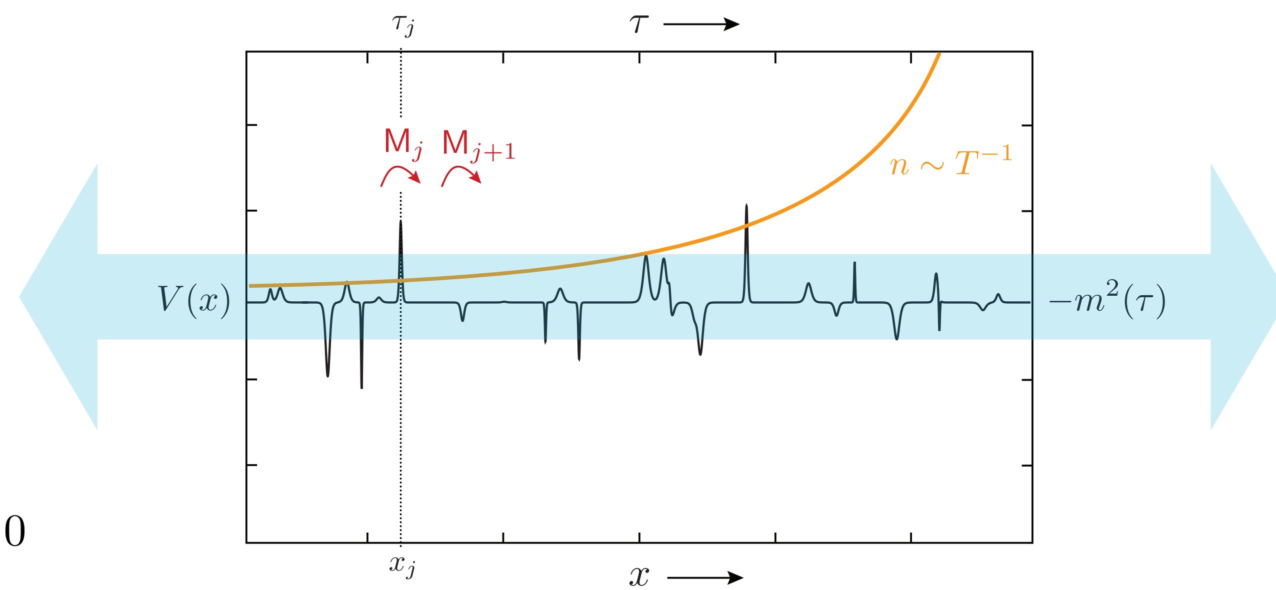
From Wires to Cosmology

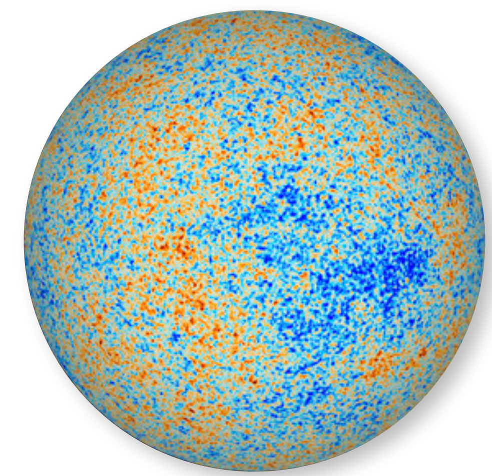
arXiv: 1512.02637 MA & Baumann

arXiv:1706.02319 MA, Garcia, Xie & Wen

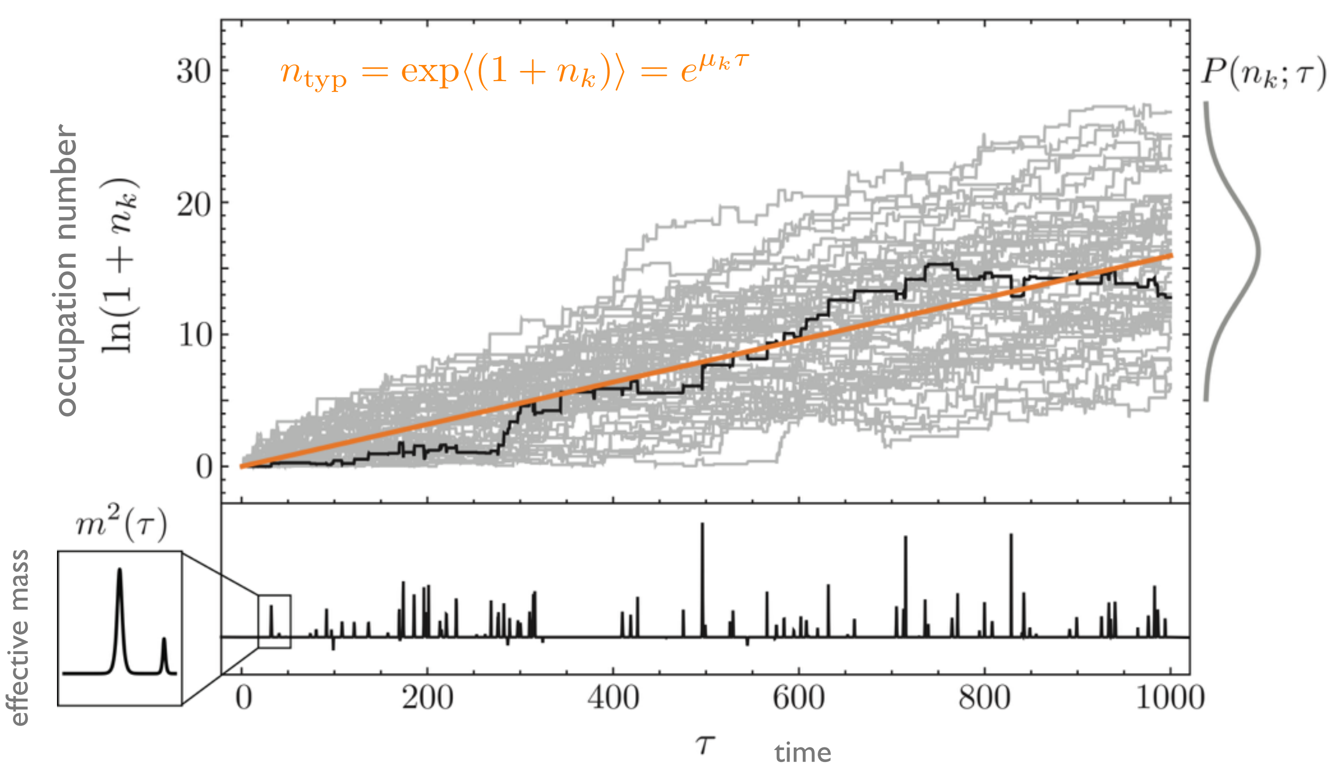


$$\frac{d^2\psi}{dx^2} + \left[k^2 - V(x)\right]\psi = 0$$





$$\frac{d^2\chi_k}{d\tau^2} + \left[k^2 + m^2(\tau)\right]\chi_k = 0$$



What did we do?

We developed a statistical framework to calculate stochastic particle production in the early universe in complex scenarios with multiple interacting fields.

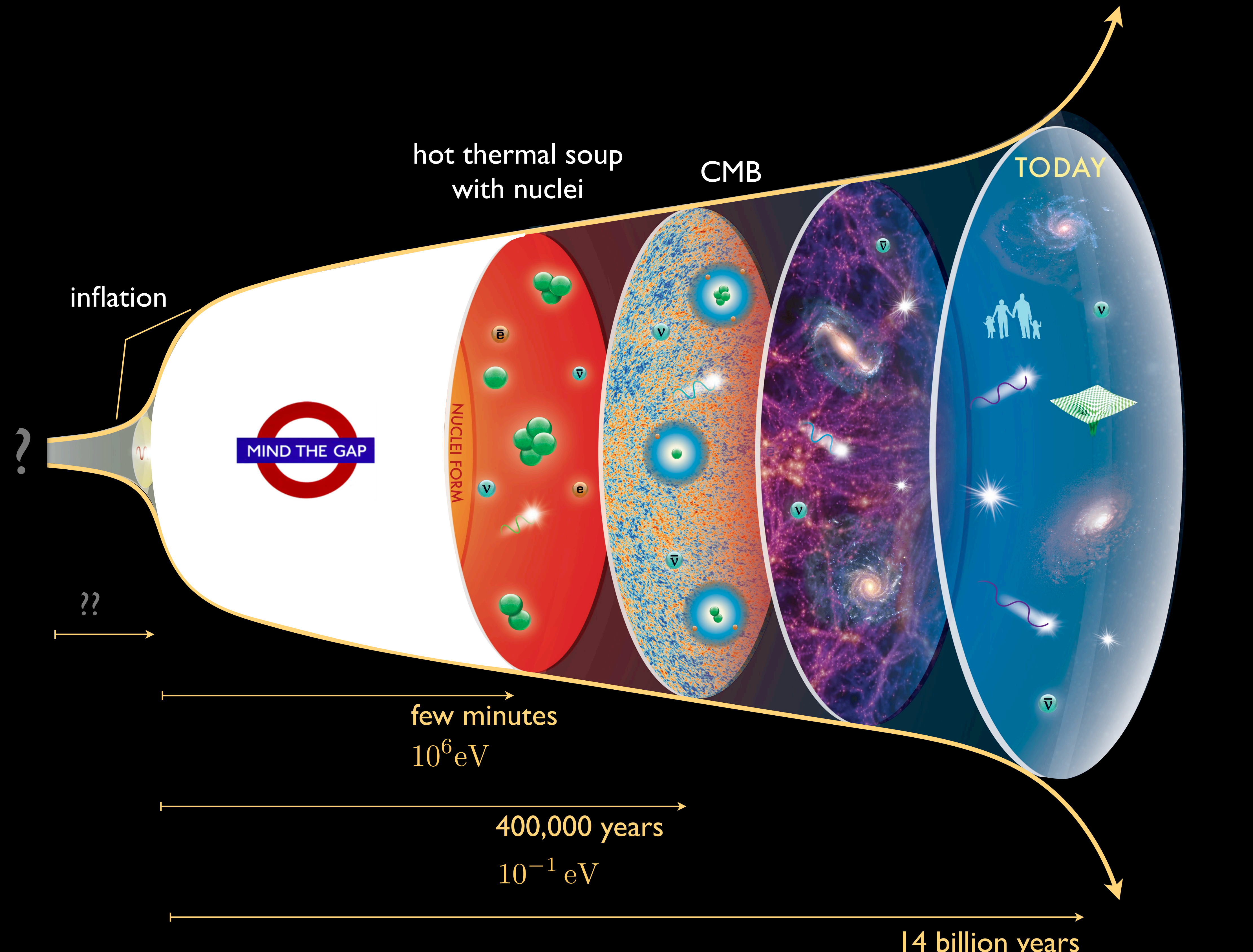
Potential benefits:

- useful when the microphysics is uncertain, dynamics are complex and only coarse grained predictions are needed.
- hints of universality in predictions when the no. of interactions and/or components is large.
- reduction in complexity to a few parameters

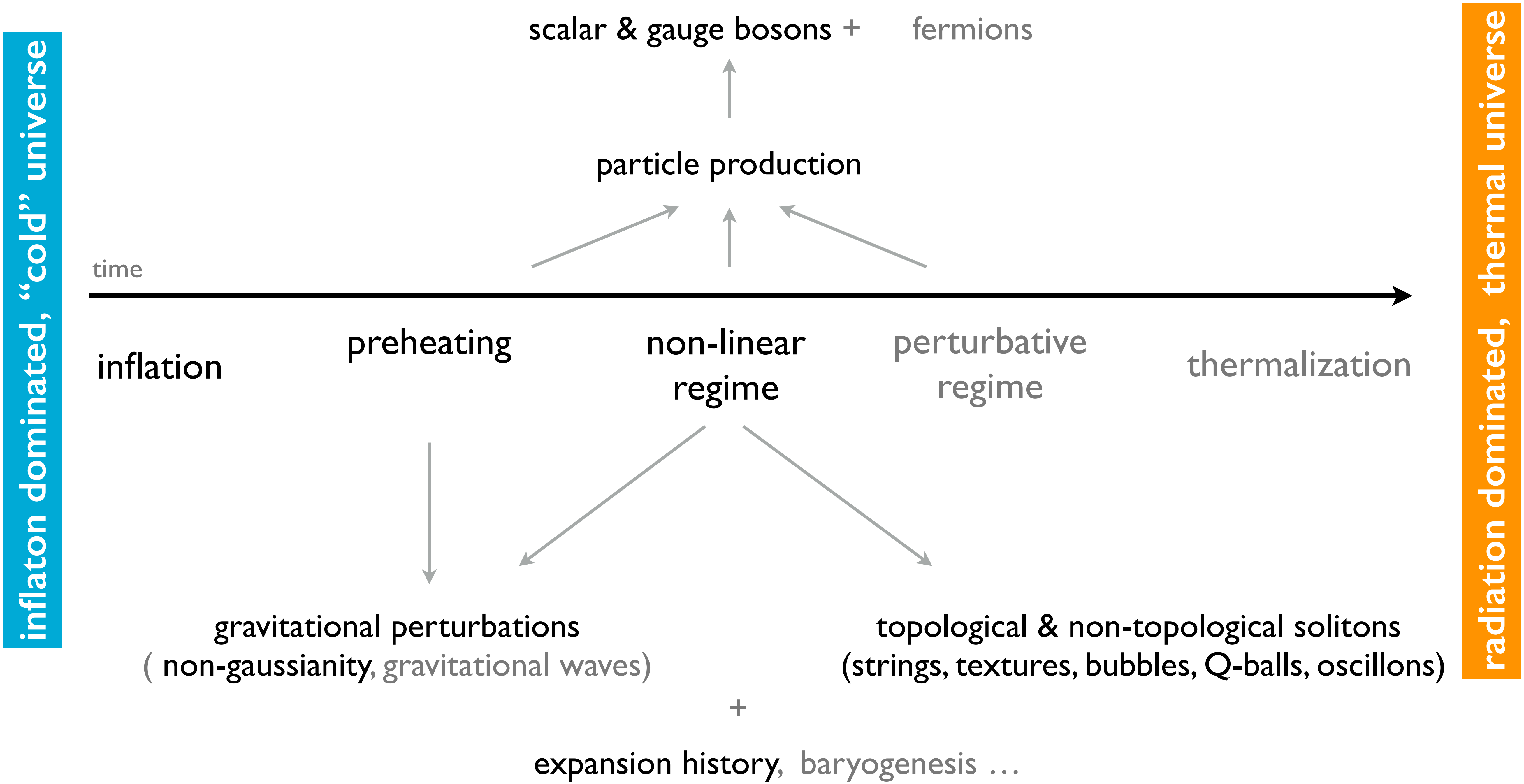
The fun bit:

By establishing a mathematical map between current conduction in wires with impurities and stochastic particle production in cosmology, we benefited a lot from work on *Anderson Localization* since the 1950s.

aftermath of inflation: a GAP in our cosmic history

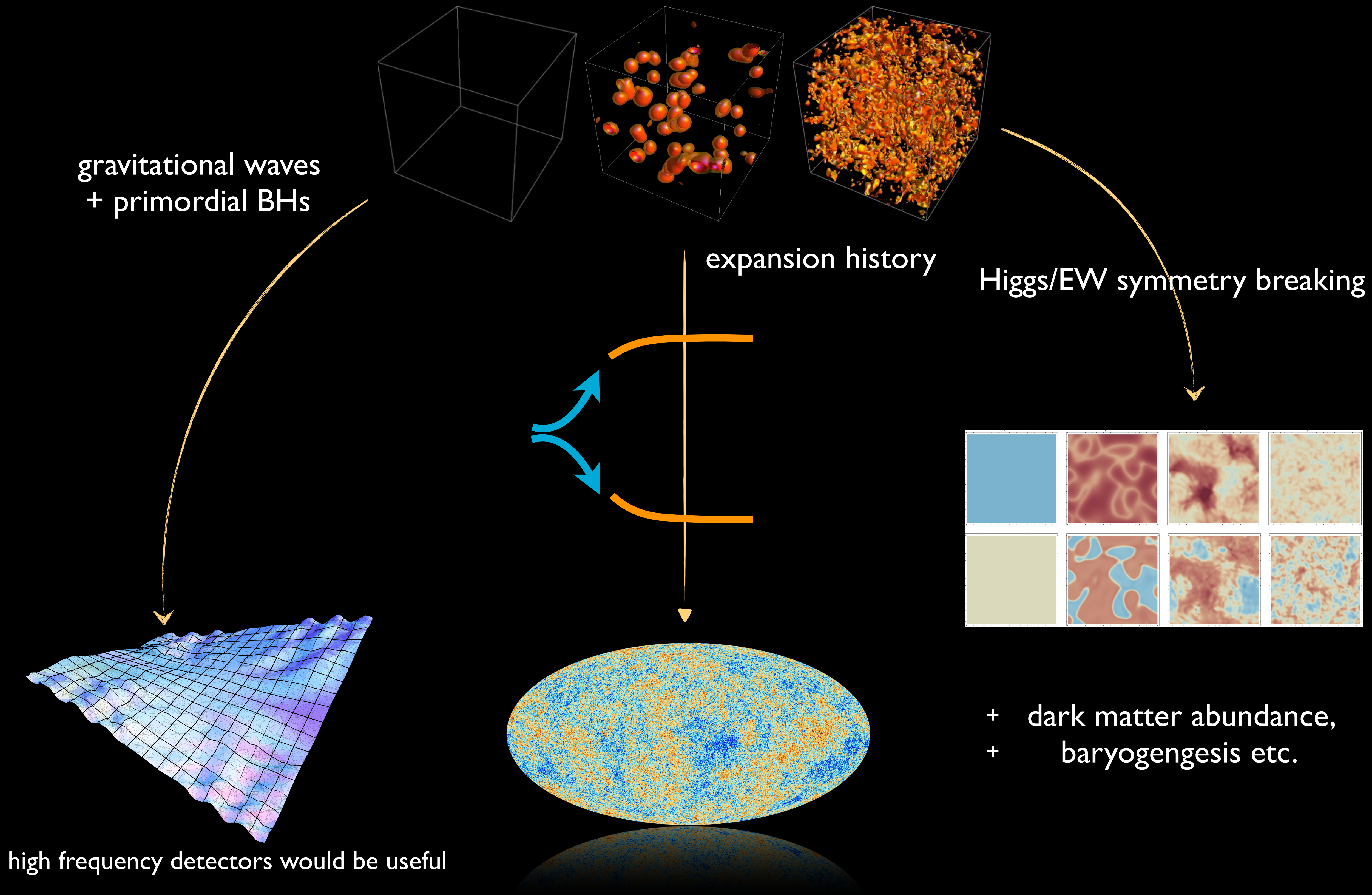


inflation ends, what’s next ?



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

sample probes/consequences



thanks!