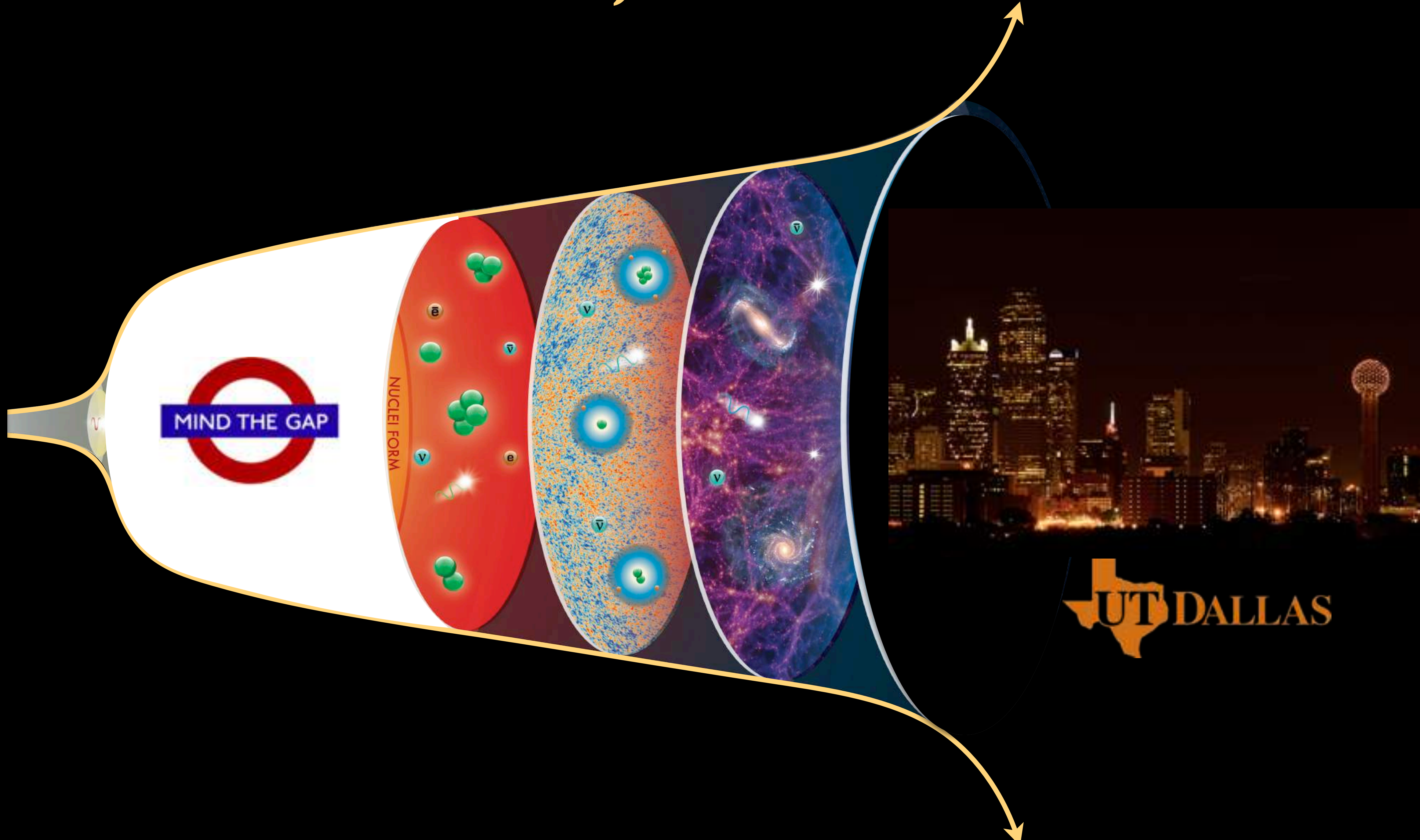
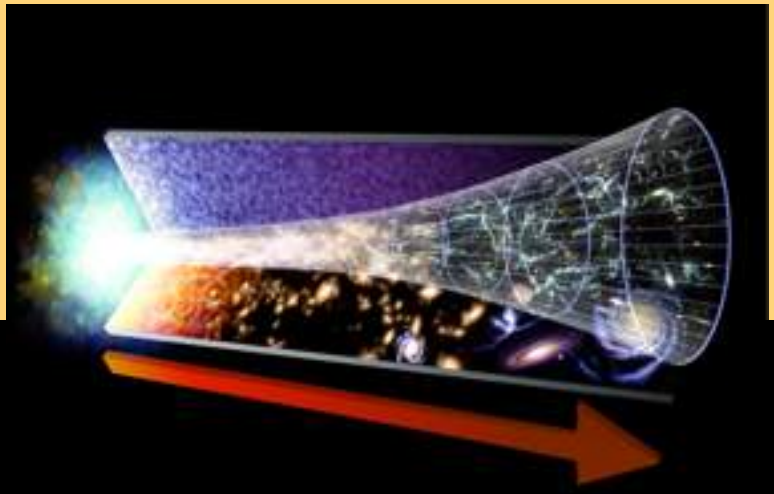
Inflation Ends, What's Next ?



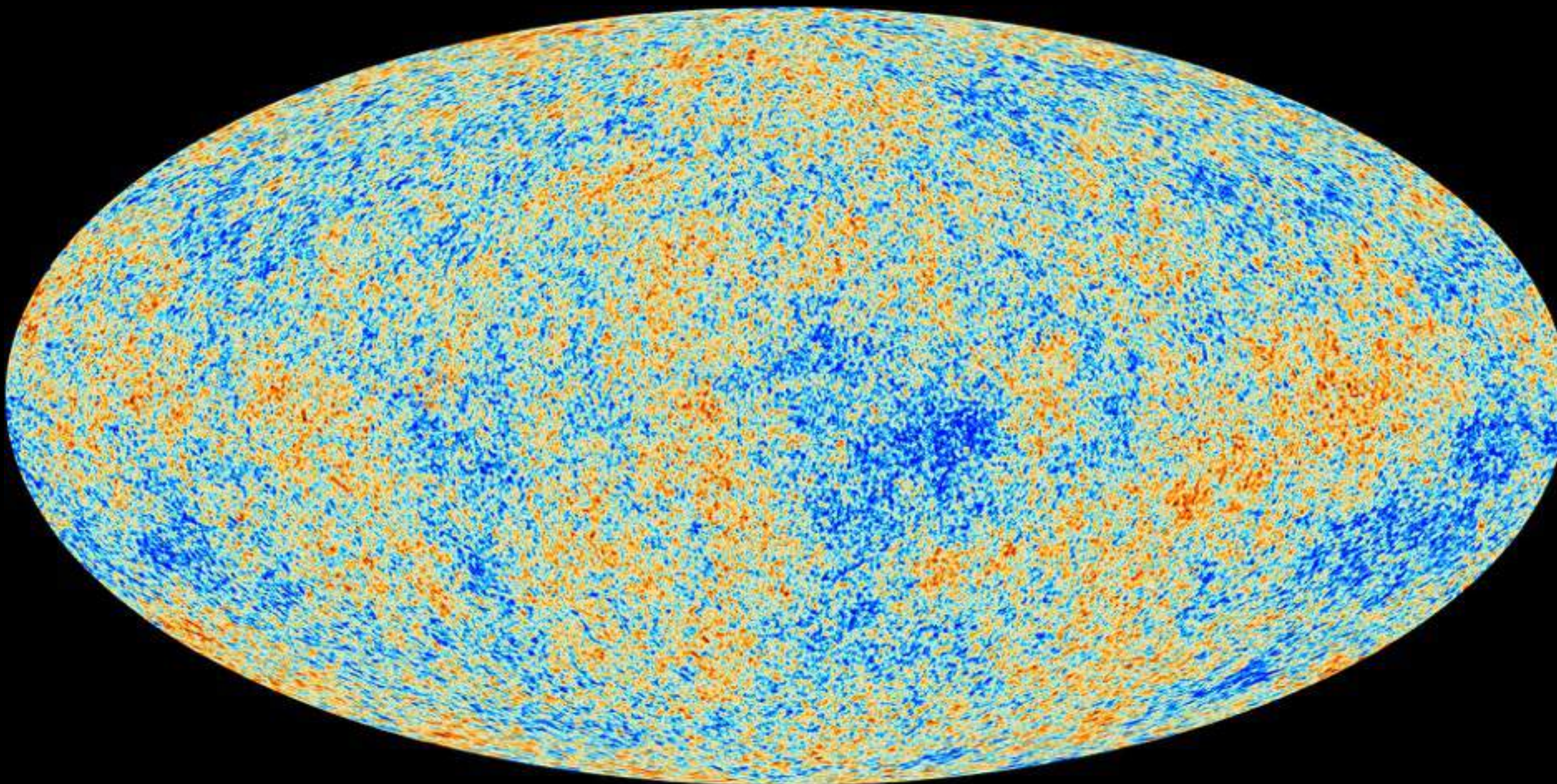
Mustafa A. Amin



Outline

- ◉ inflation
- ◉ **cosmic history gap - <u>aftermath of inflation</u>**
  - non-perturbative, nonlinear dynamics
  - obs. consequences
- ◉ what's next ?

Cosmic Microwave Background (CMB) temperature anisotropies

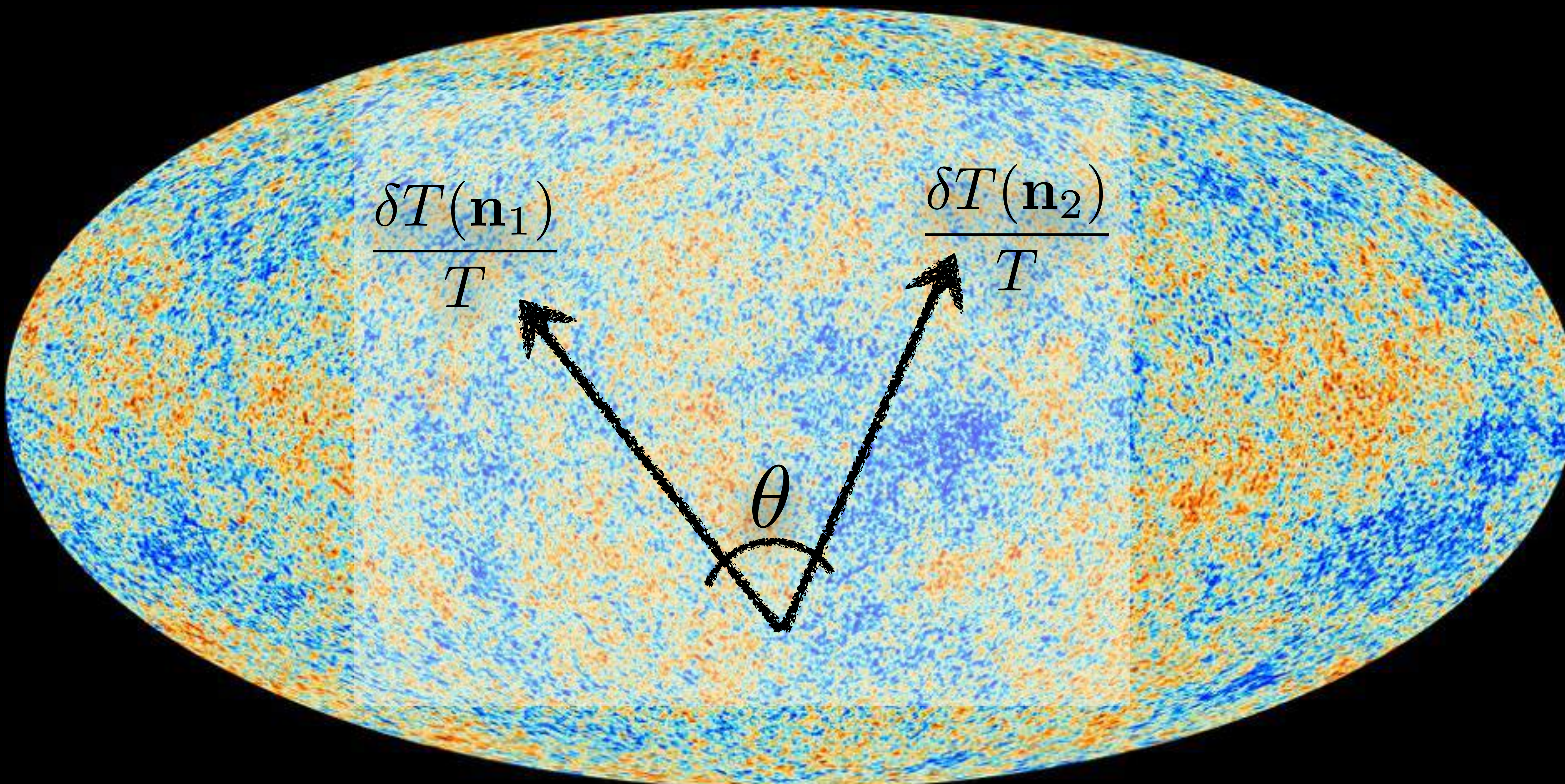


$$\delta T/T \sim 10^{-5}$$

Planck 2015

a conundrum … and a solution

large angle correlations?



$$C(\theta) = \left\langle \frac{\delta T(\mathbf{n}_1)}{T} \frac{\delta T(\mathbf{n}_2)}{T} \right\rangle$$

image credit: Planck

standard big bang cosmology

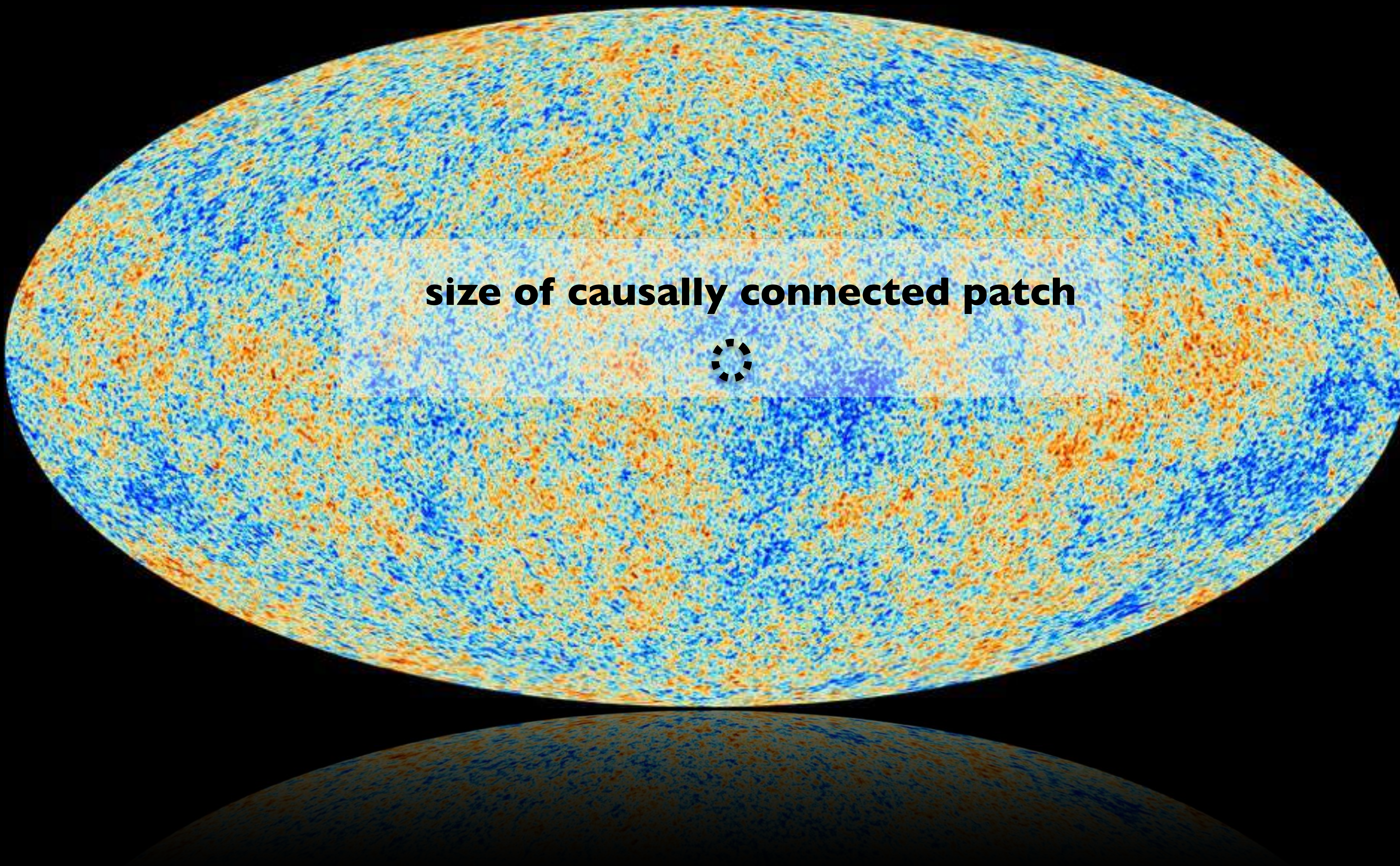
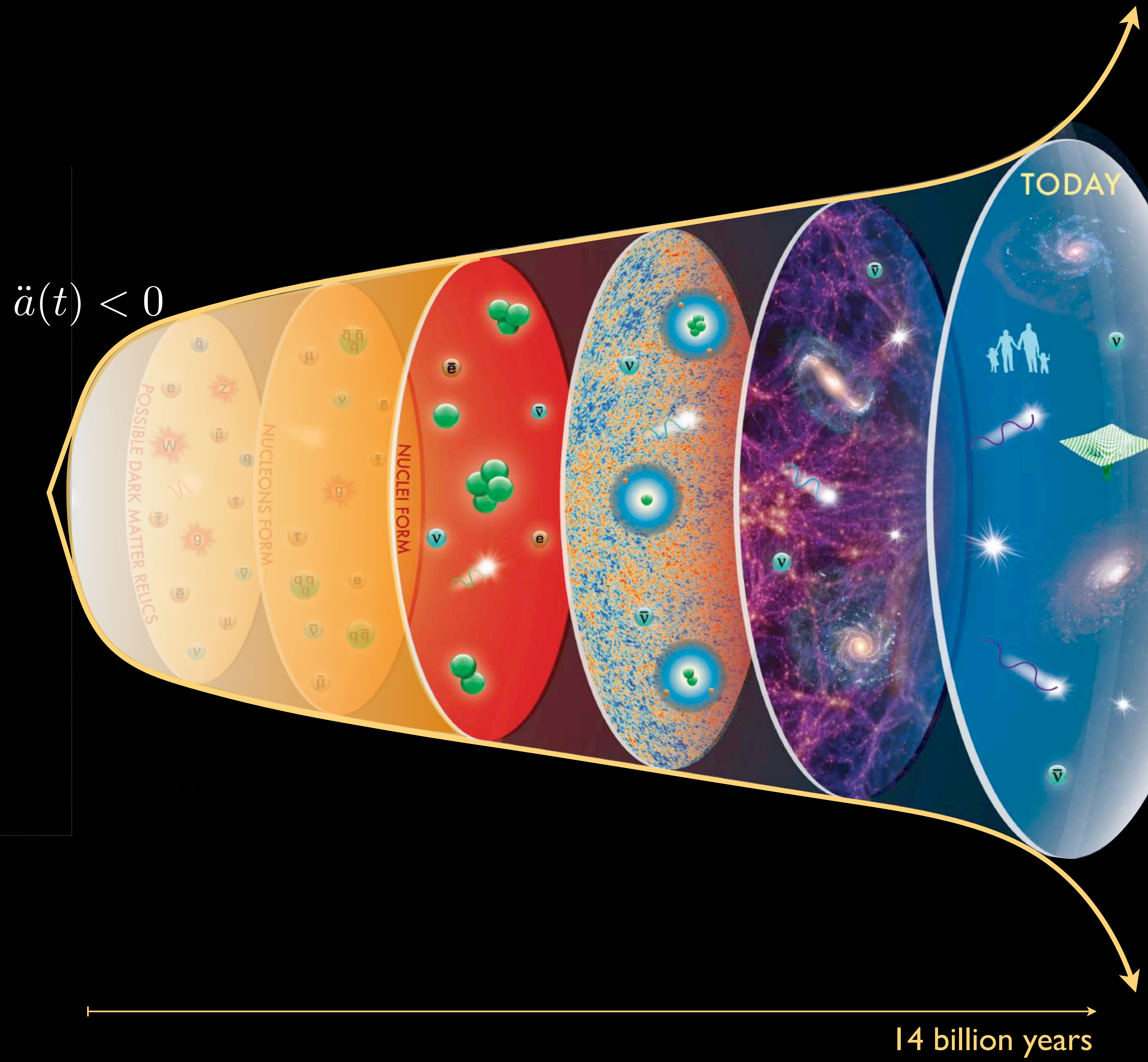
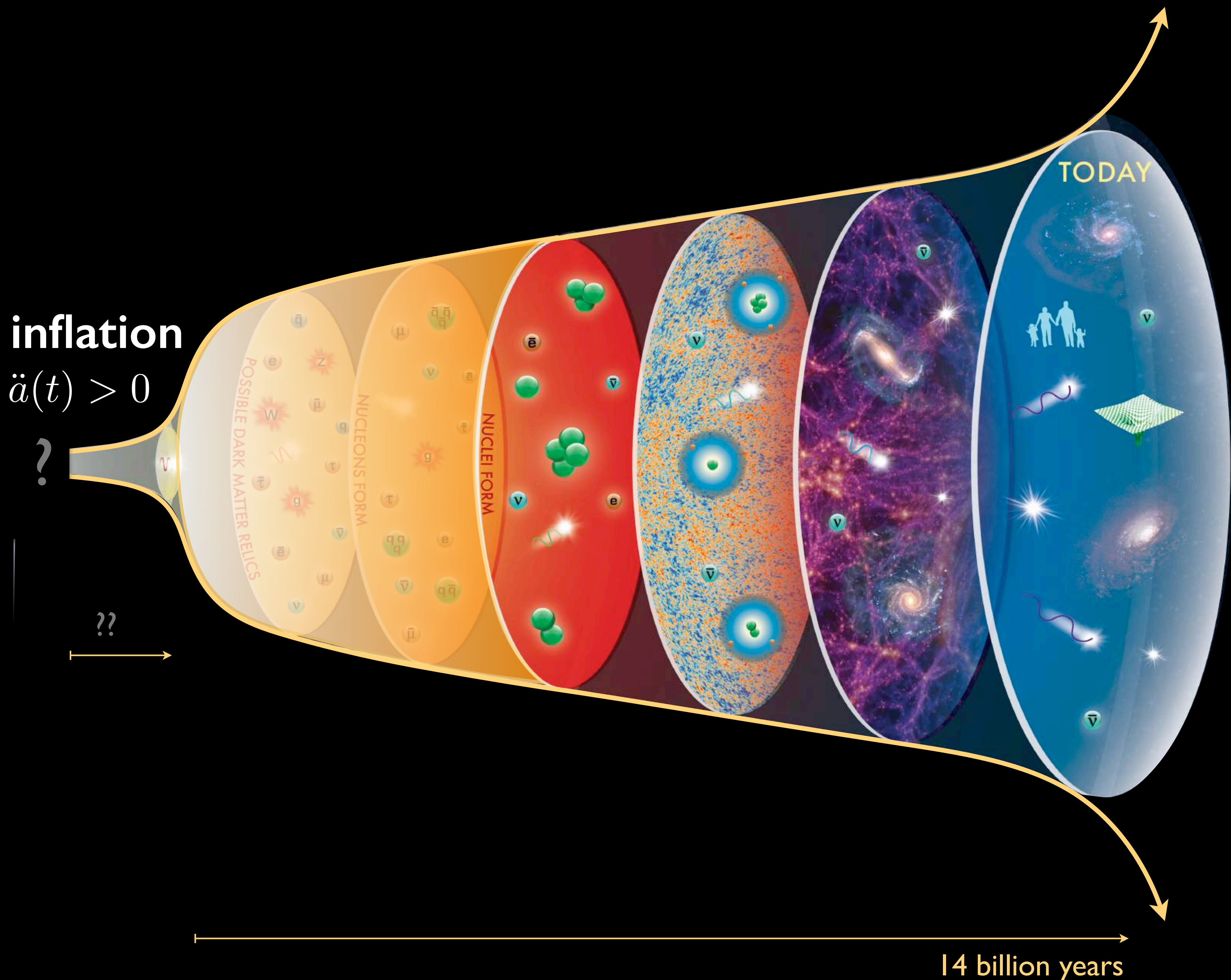


image credit: Planck

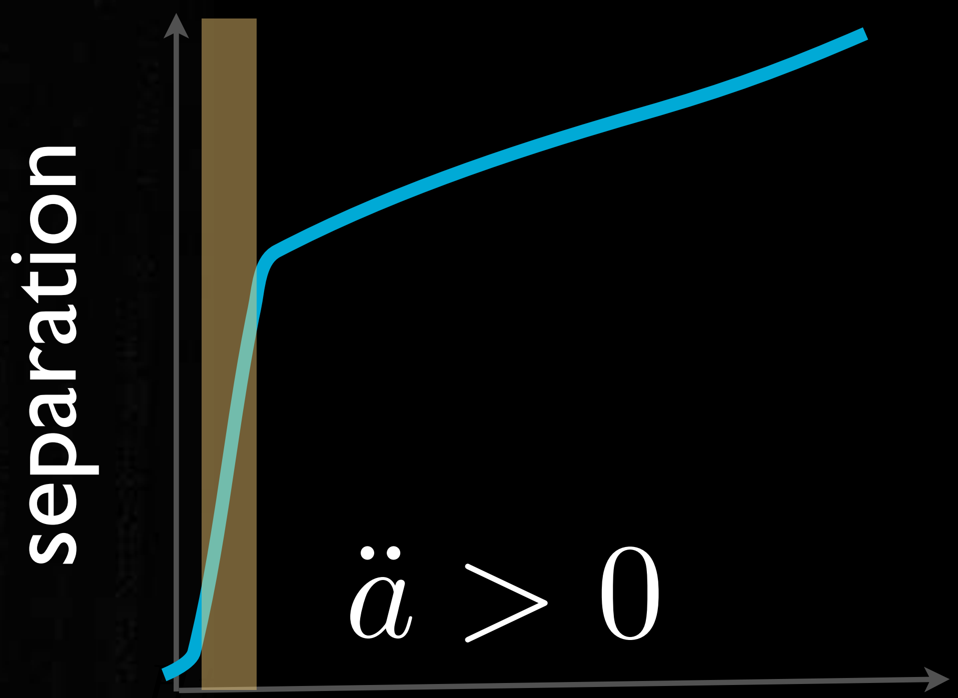
standard cosmology

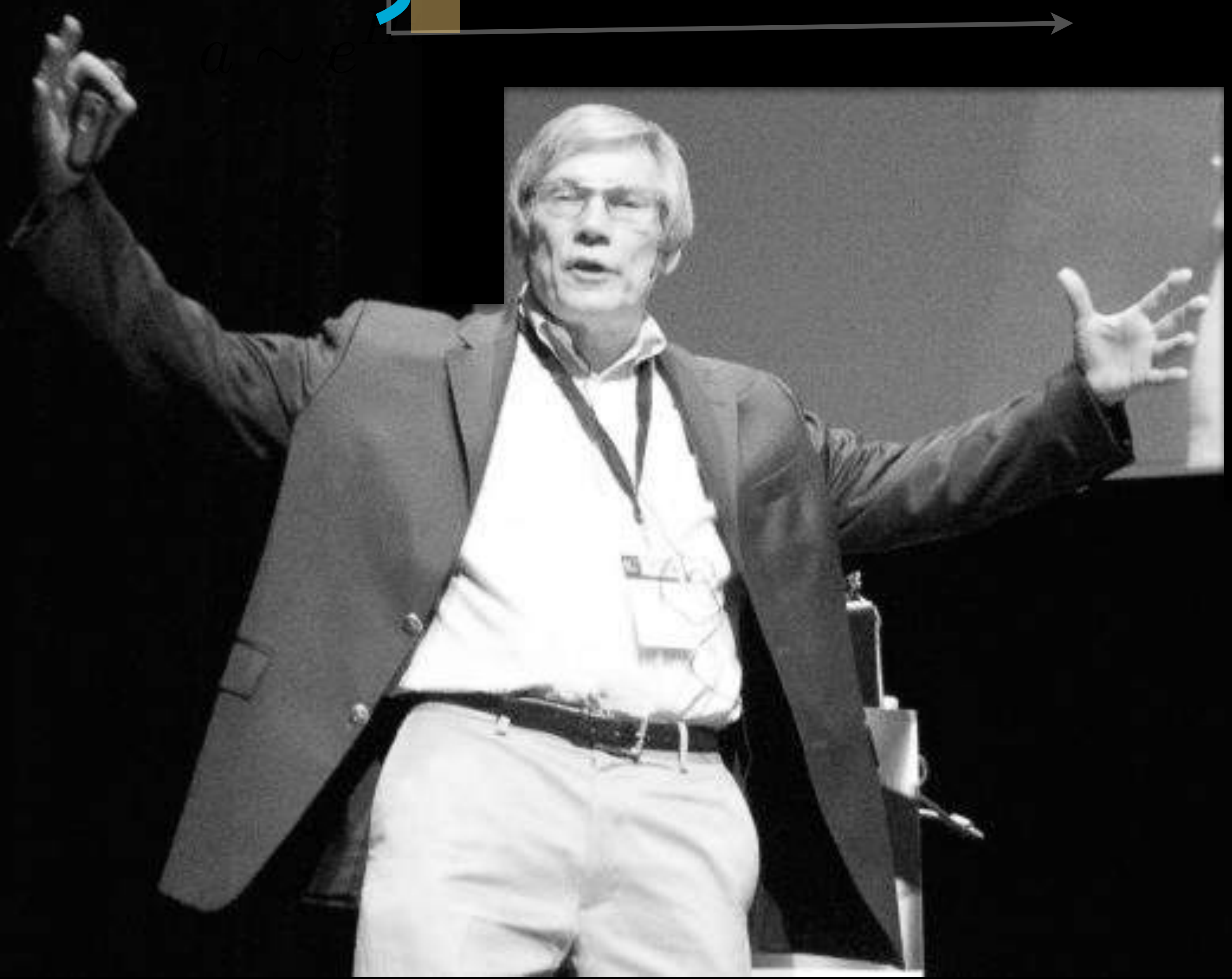


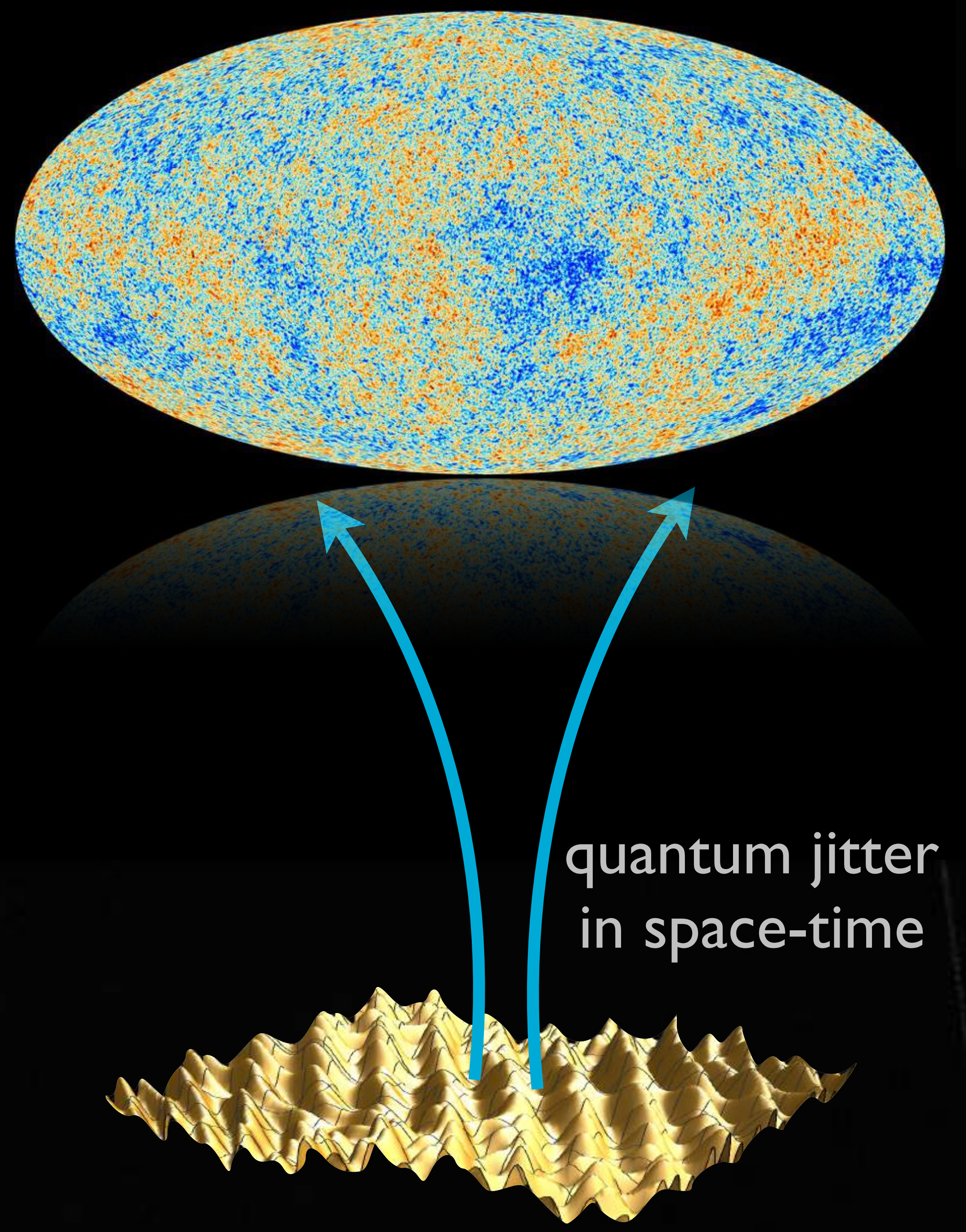
inflationary cosmology



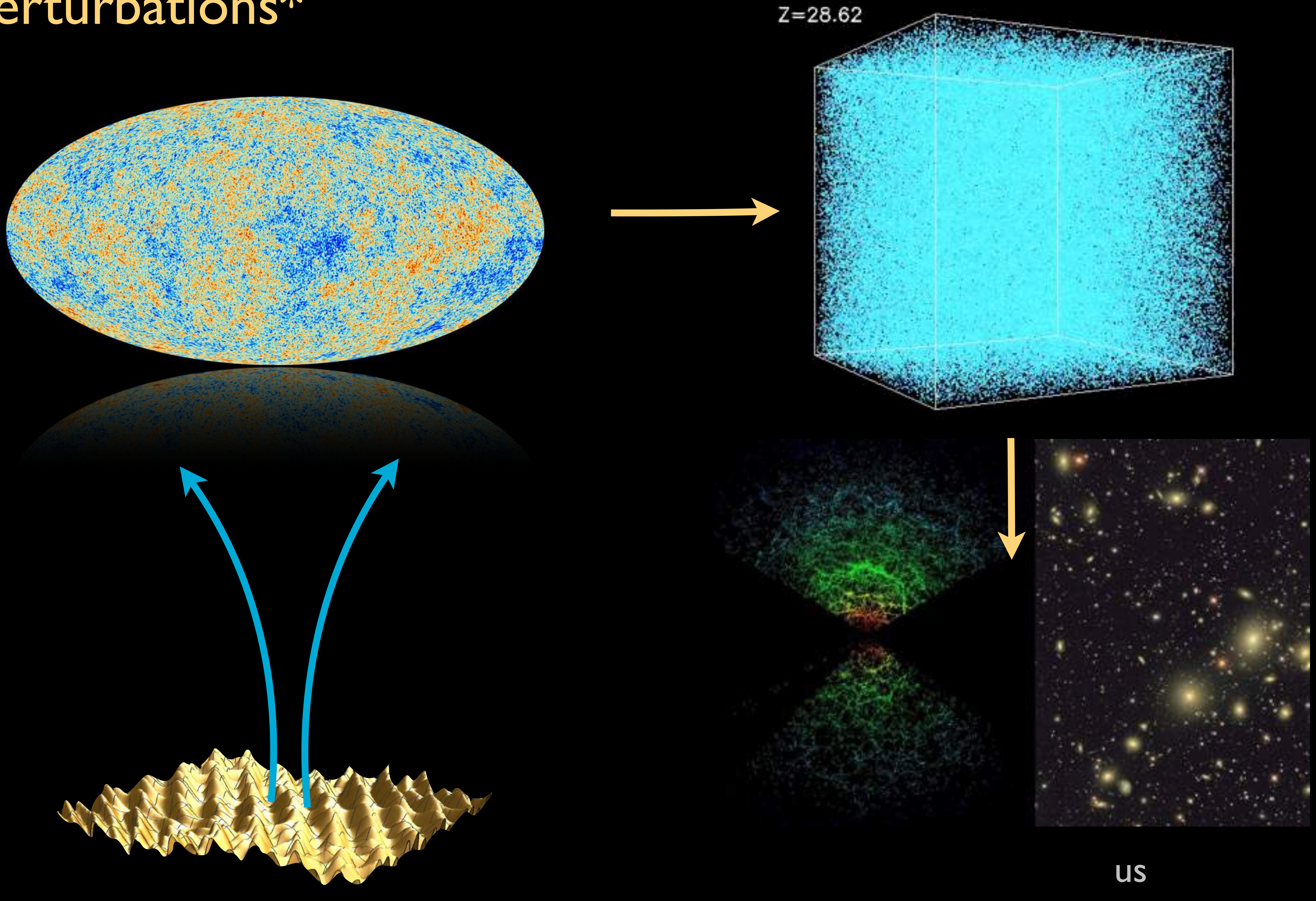
large angle correlations



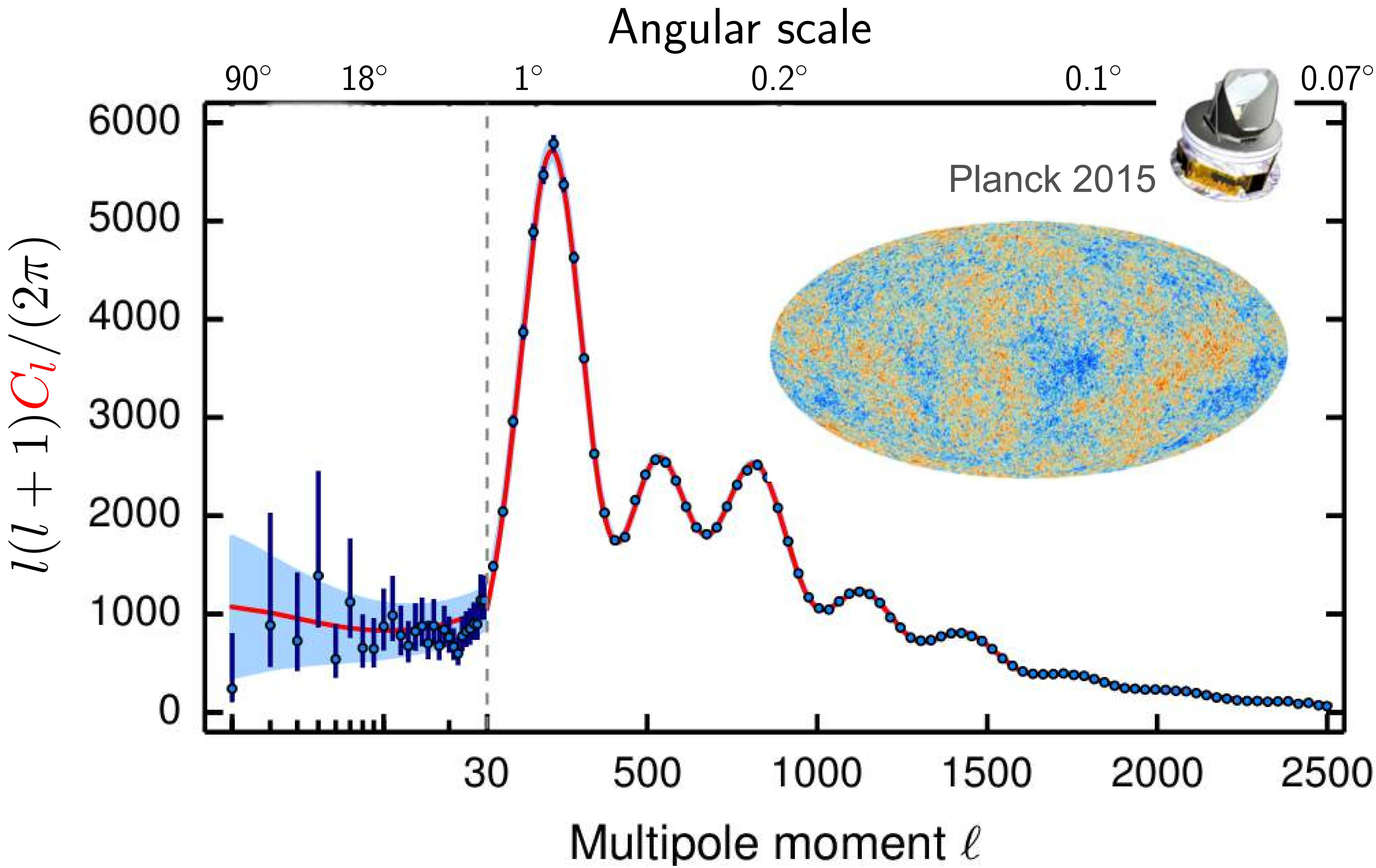




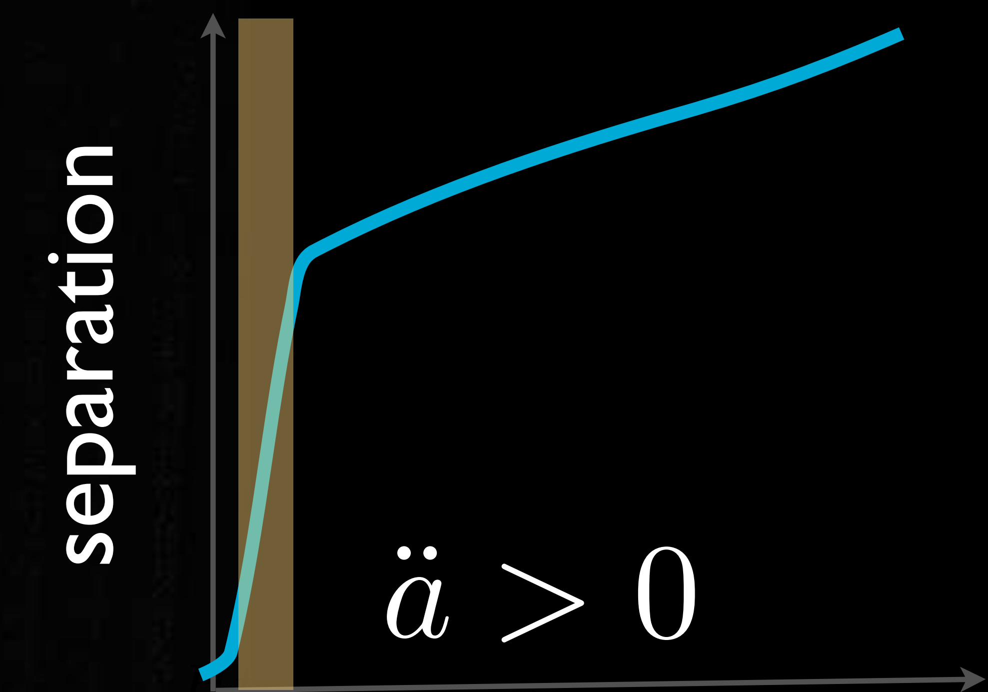
inflationary cosmology: a calculable framework of initial perturbations*



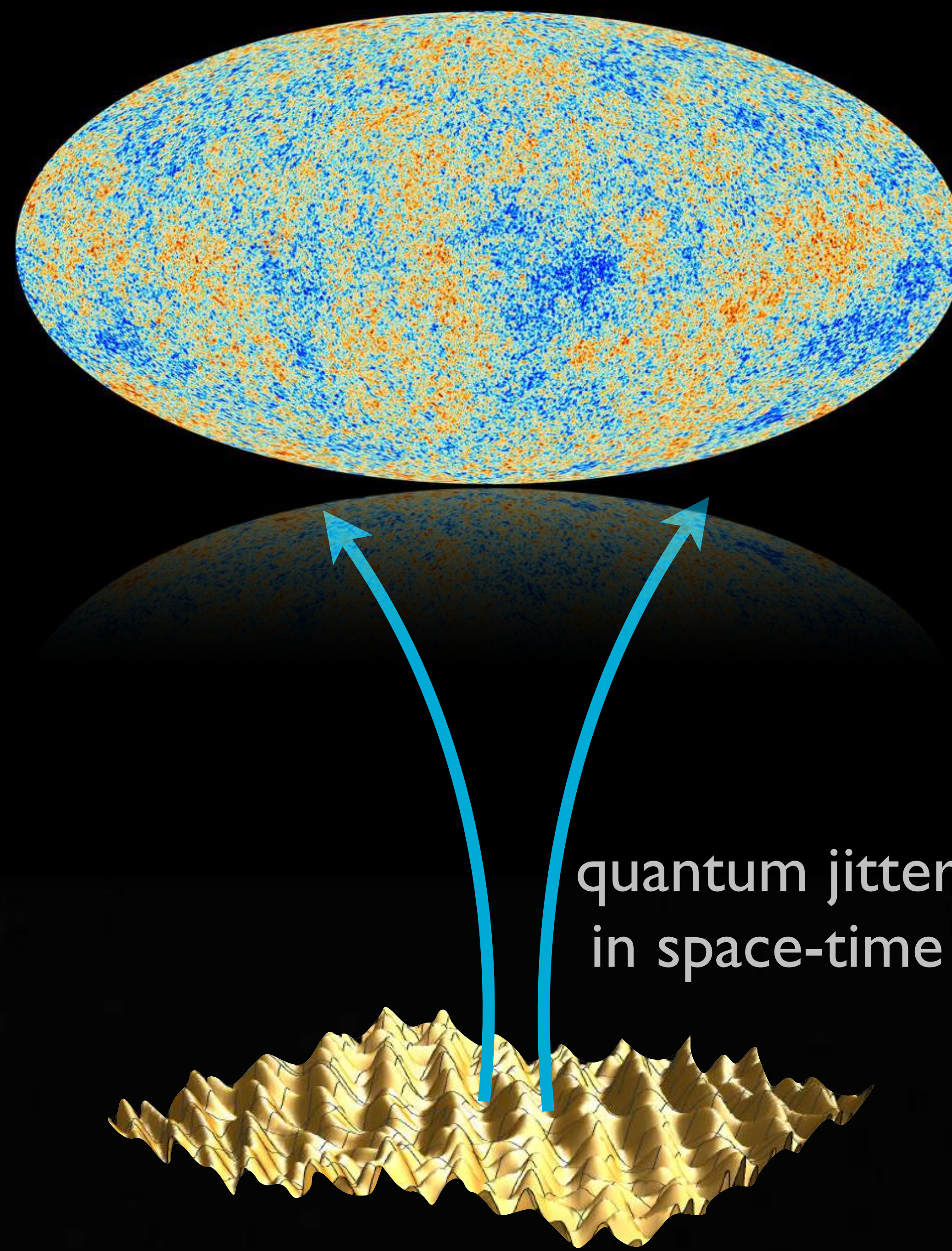
inflation consistent with observations



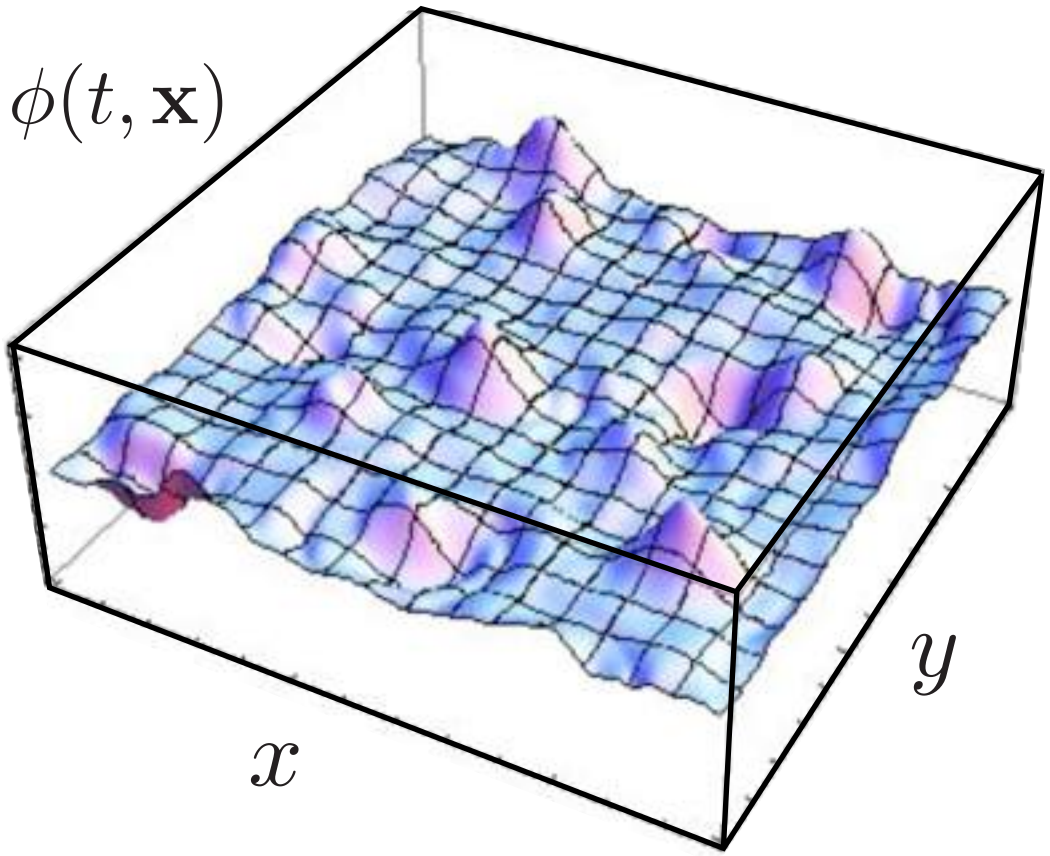
what drives inflation ?



Guth 1980



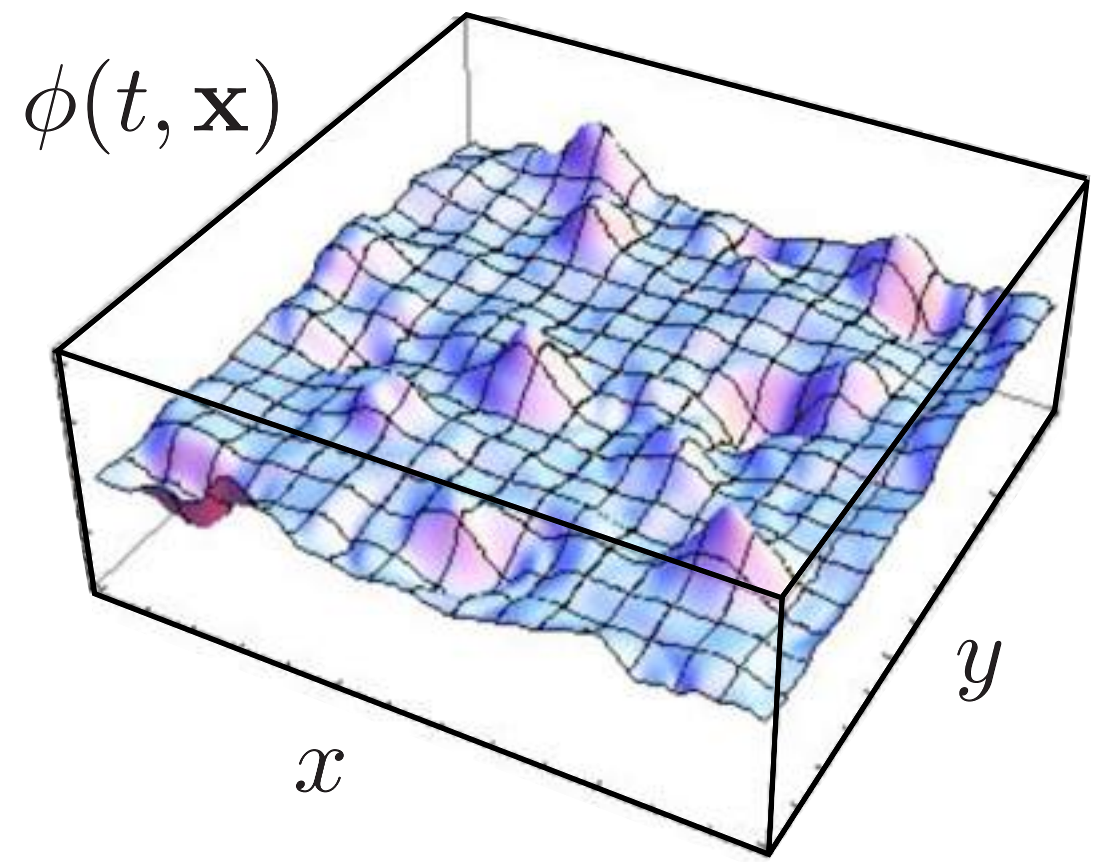
simplest:
single scalar field driven inflation



simplest:
single scalar field driven inflation

Lagrangian: $\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi)$

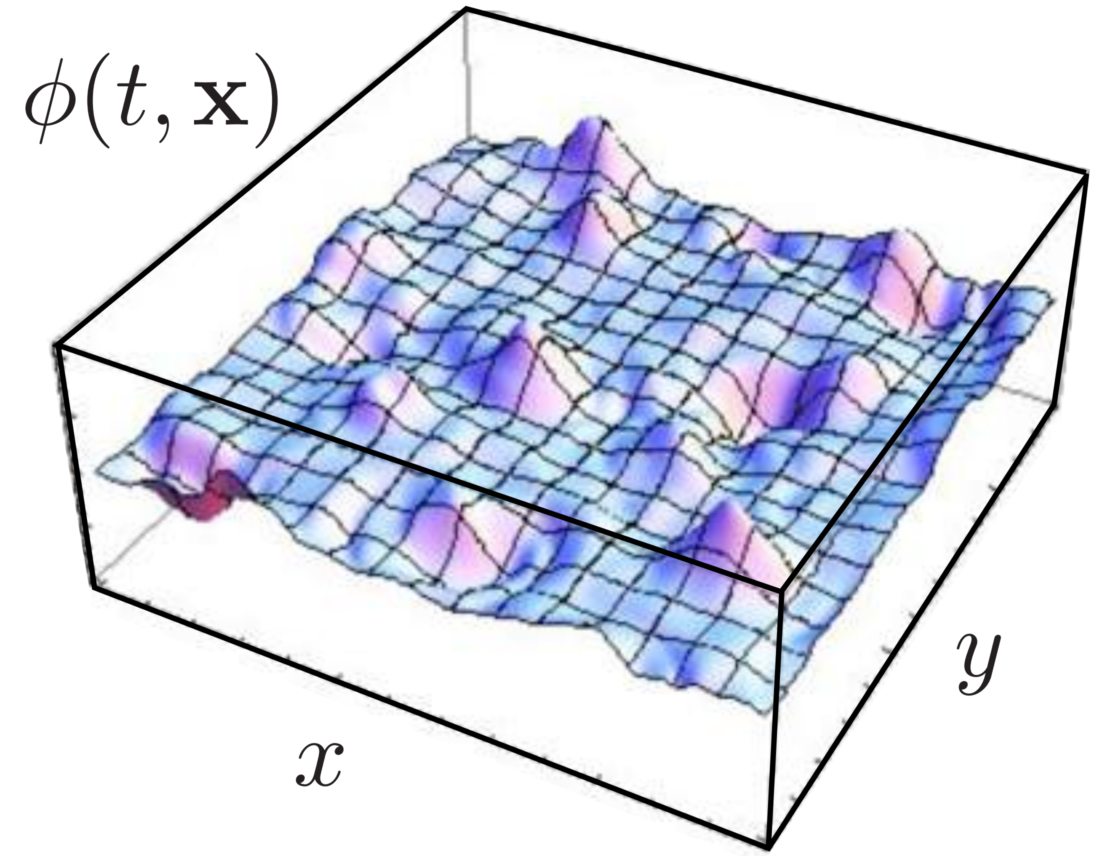
kinetic & gradient energy density



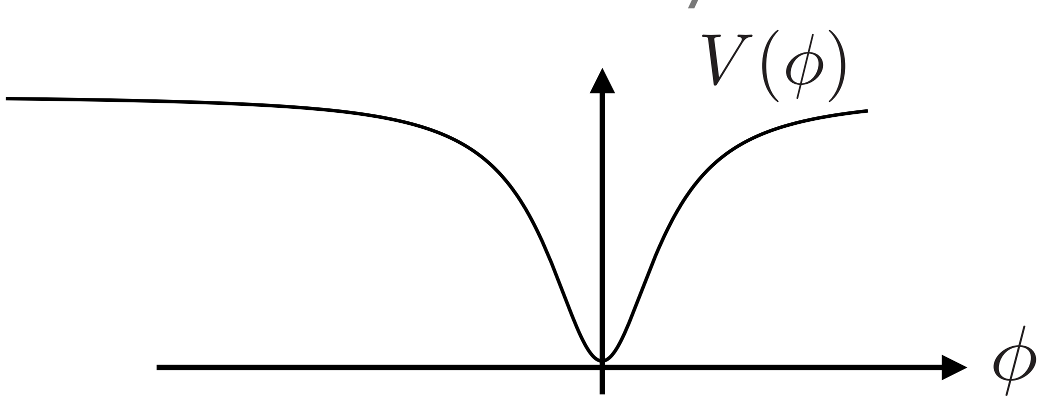
simplest:
single scalar field driven inflation

Lagrangian: $\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi)$

kinetic & gradient energy density



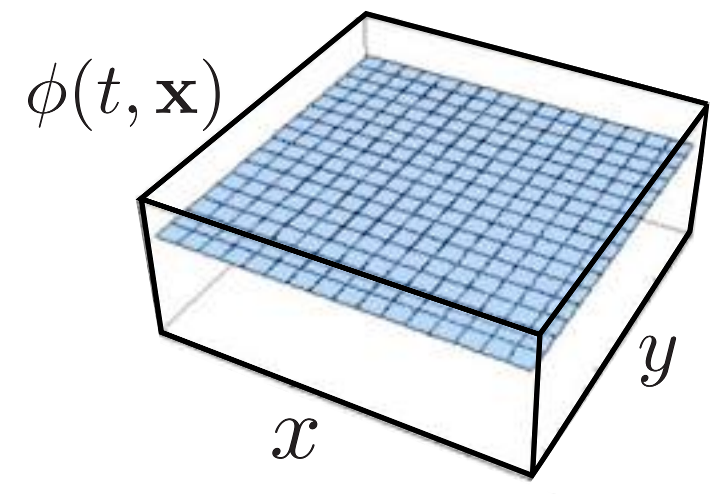
potential: determines the dynamics

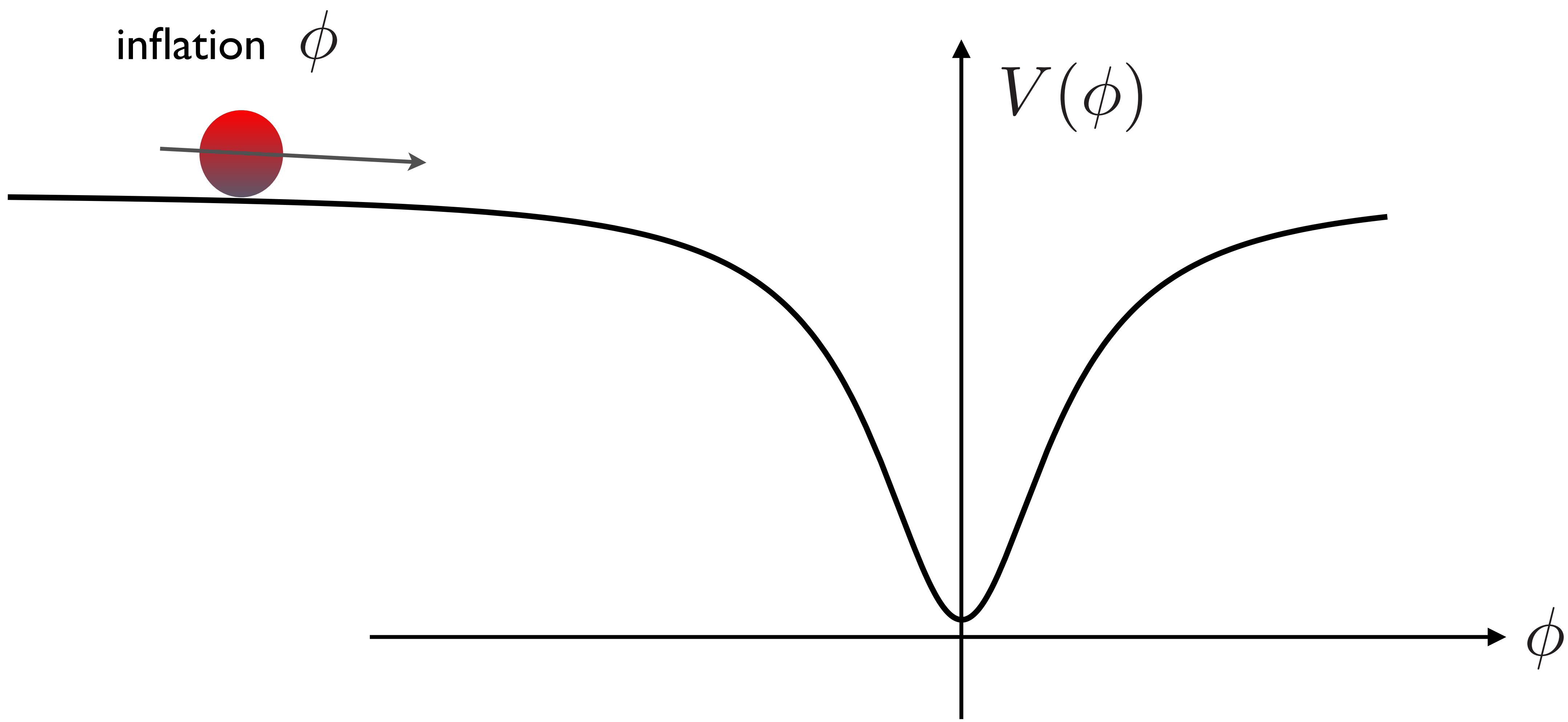


scalar field driven inflation

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\Longrightarrow \ddot{a}(t) \propto V(\phi) - \dot{\phi}^2$$

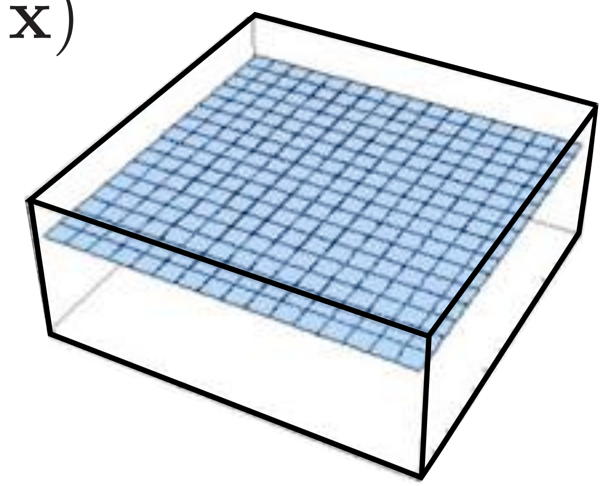


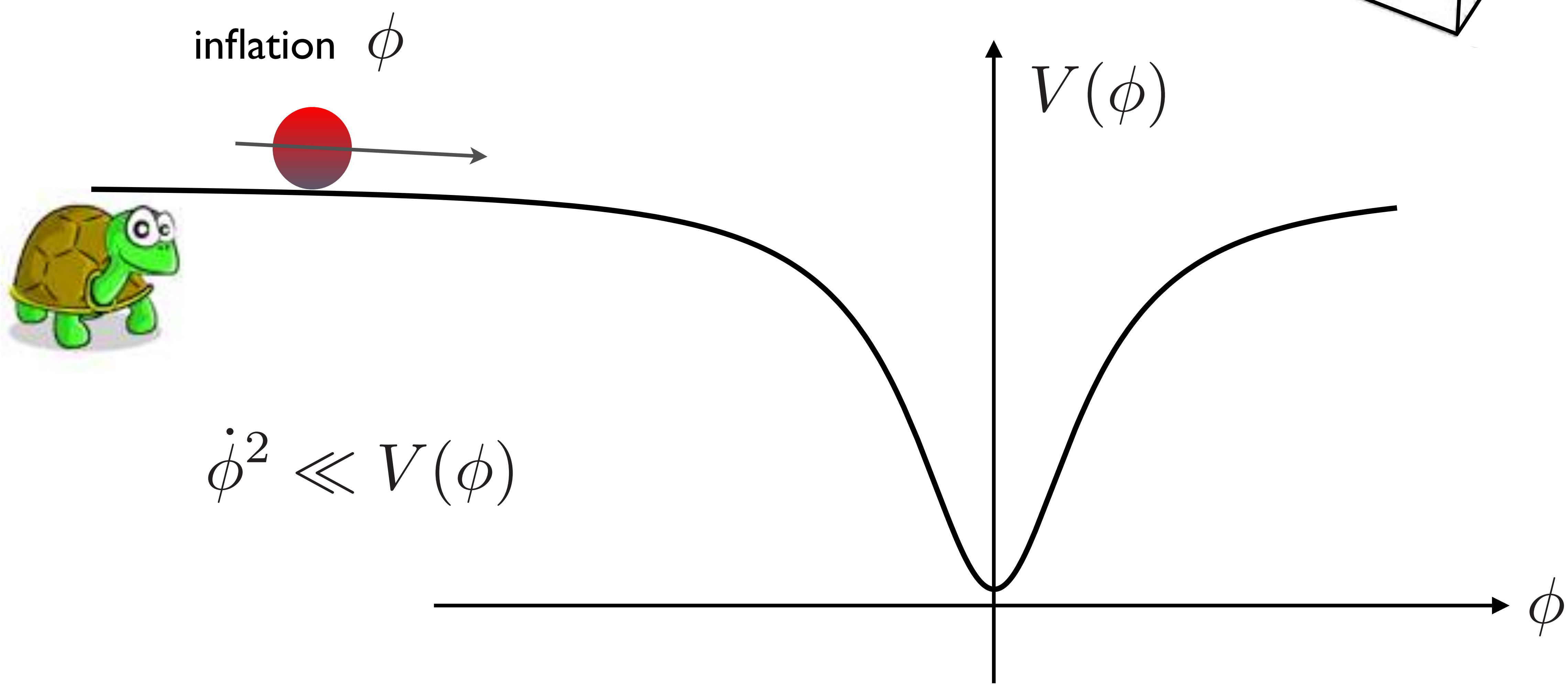


slowly "rolling" field
= accelerated expansion

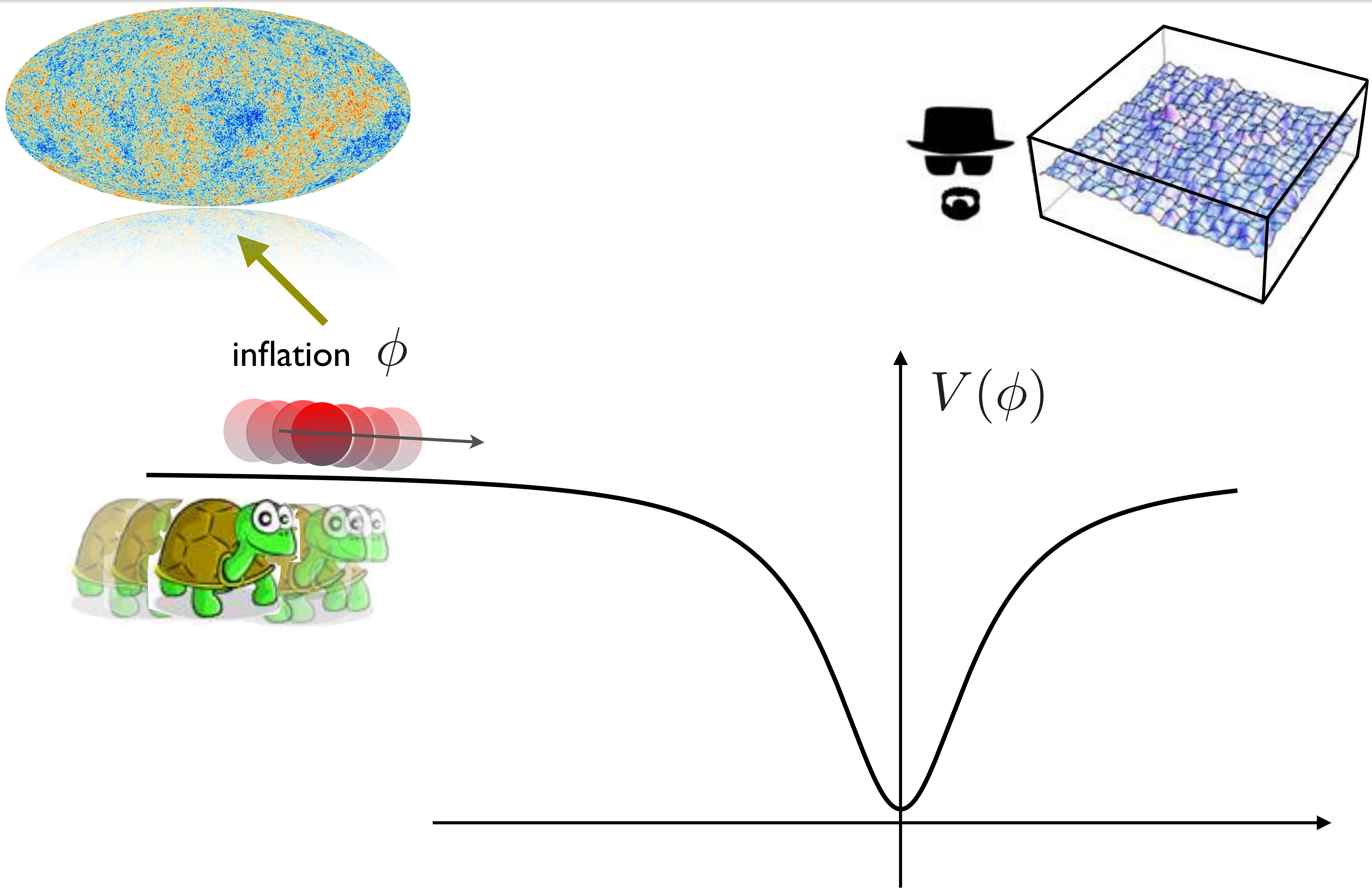
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\implies \ddot{a} \propto V(\phi) - \dot{\phi}^2 > 0$$



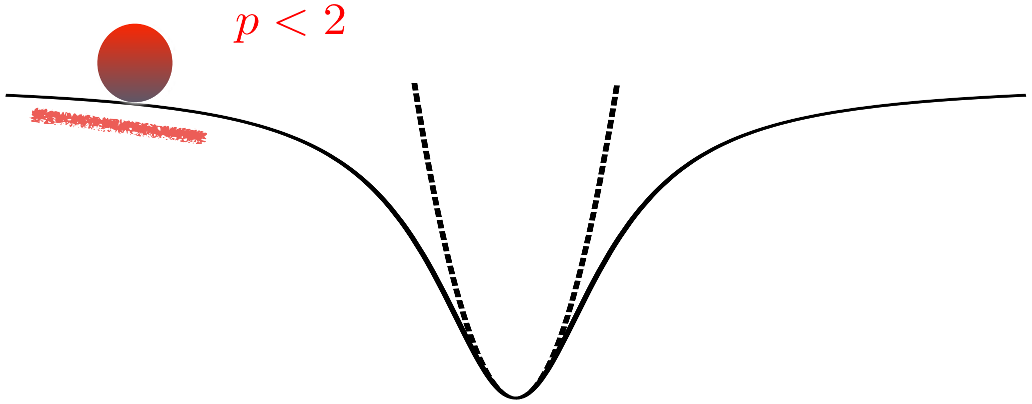


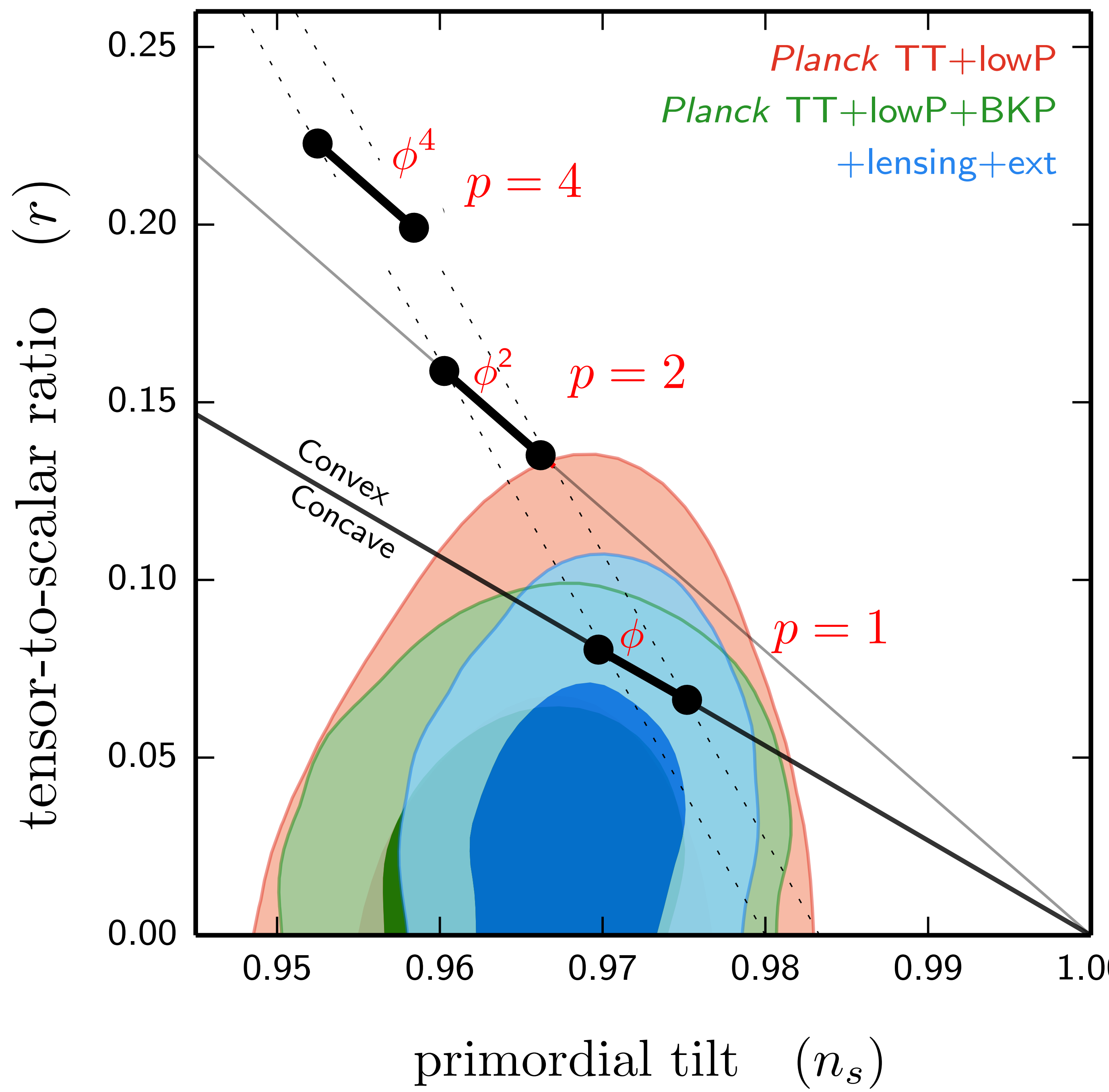
inflationary quantum perturbations



constraints from observations

$V(\phi) \propto \phi^p$



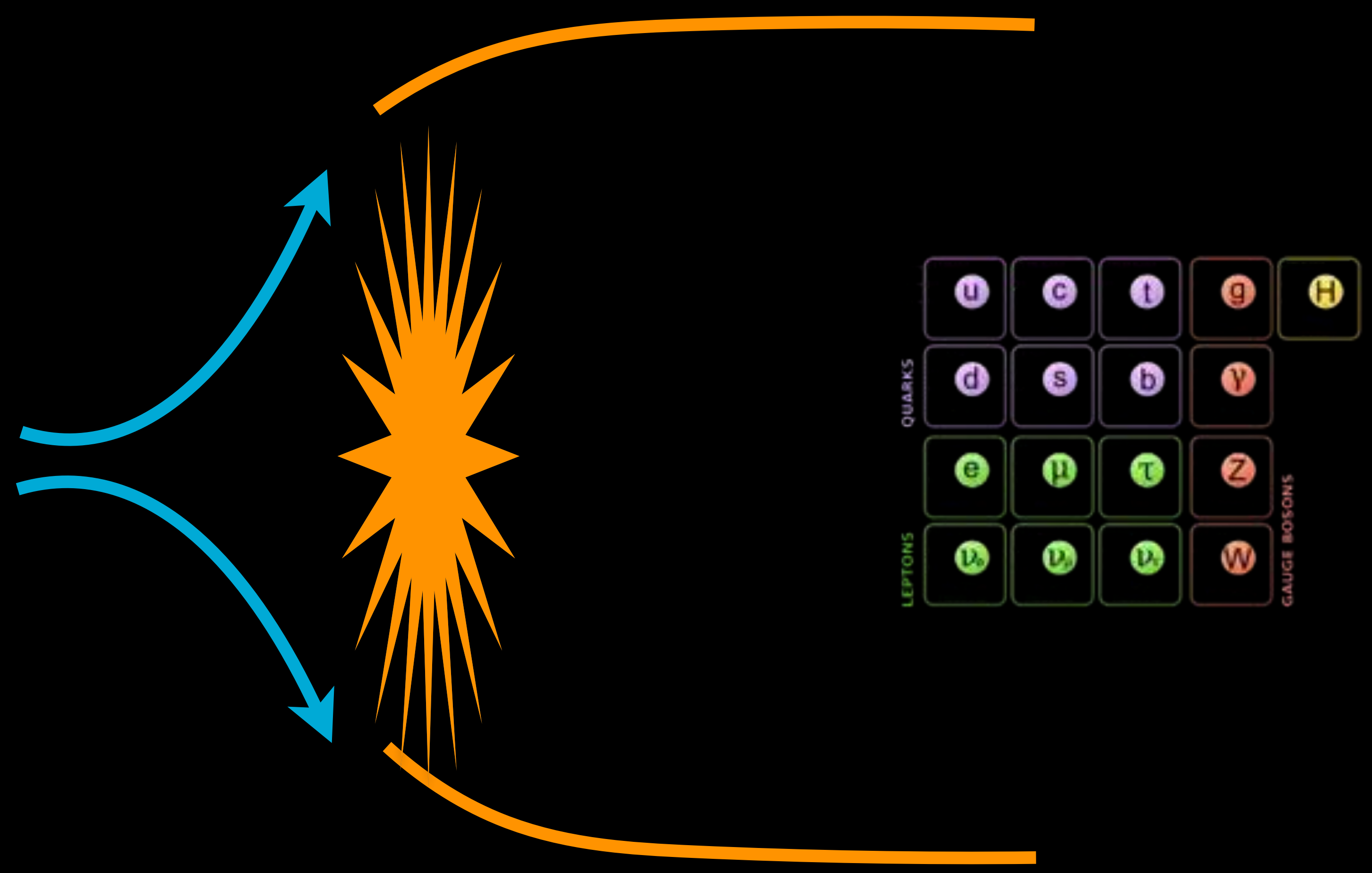


for example:

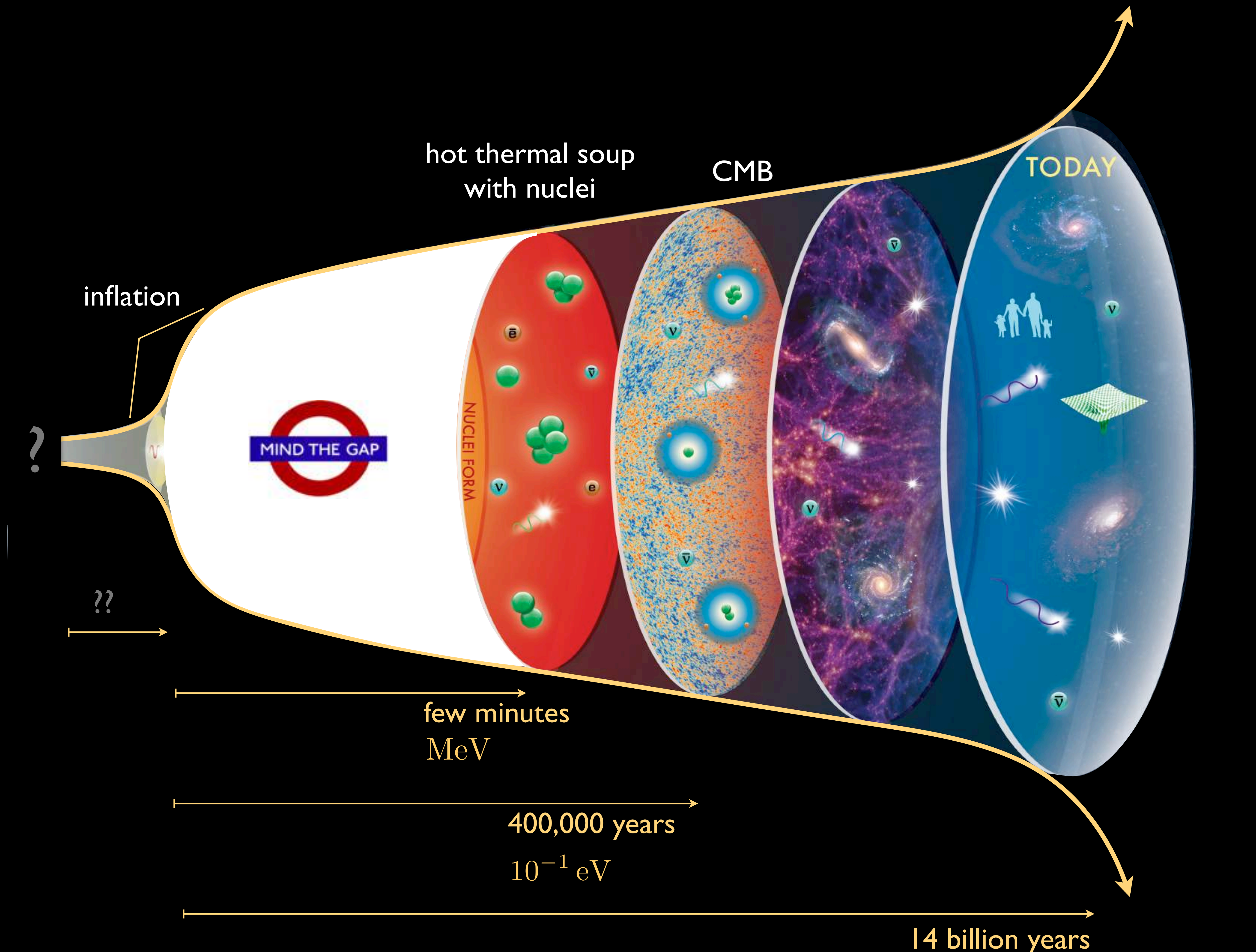
Silverstein & Westhpal (2008)
McAllister et. al (2014)
Kallosh & Linde (2014)

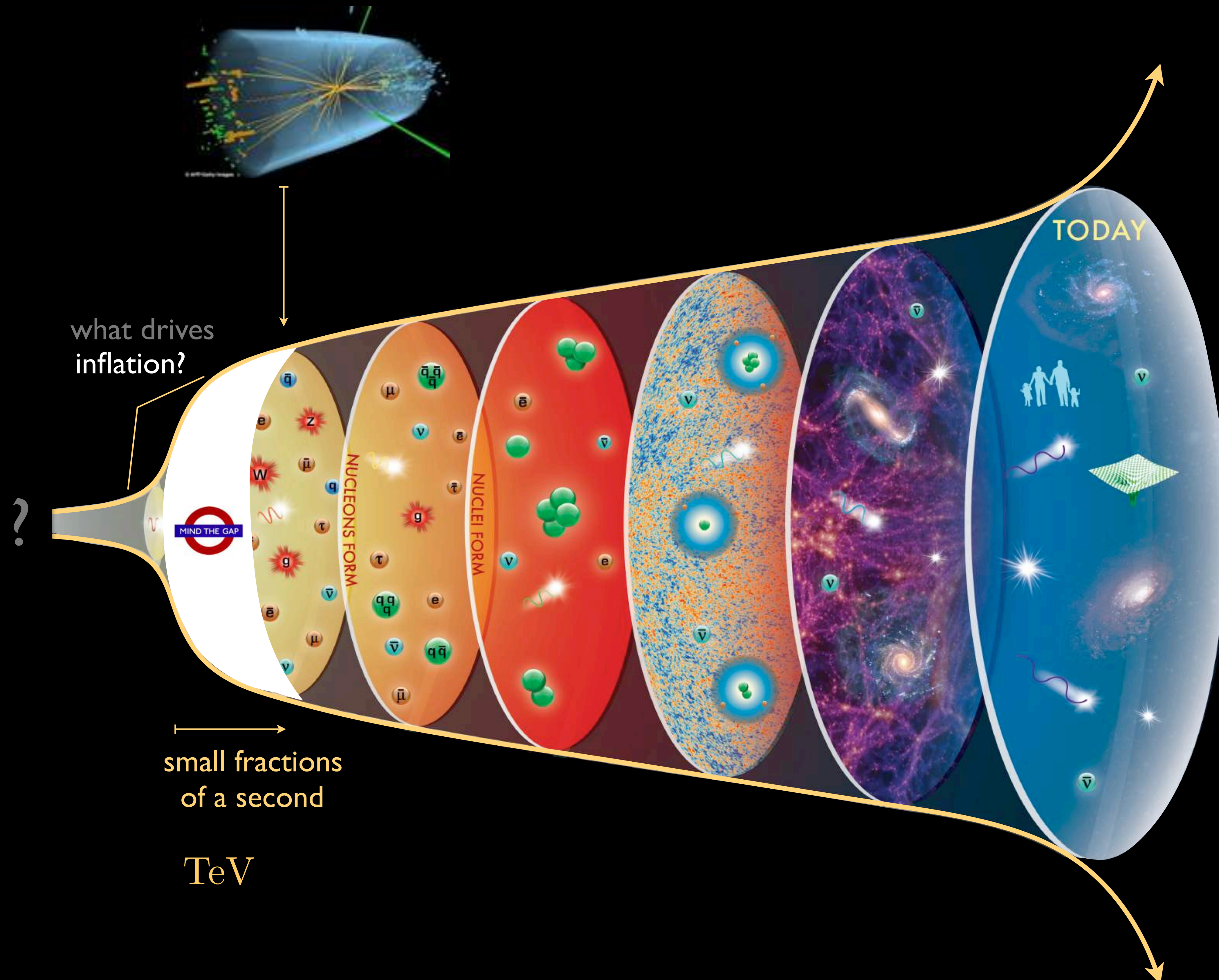
- <u>**aftermath of inflation**</u> **(reheating)?**

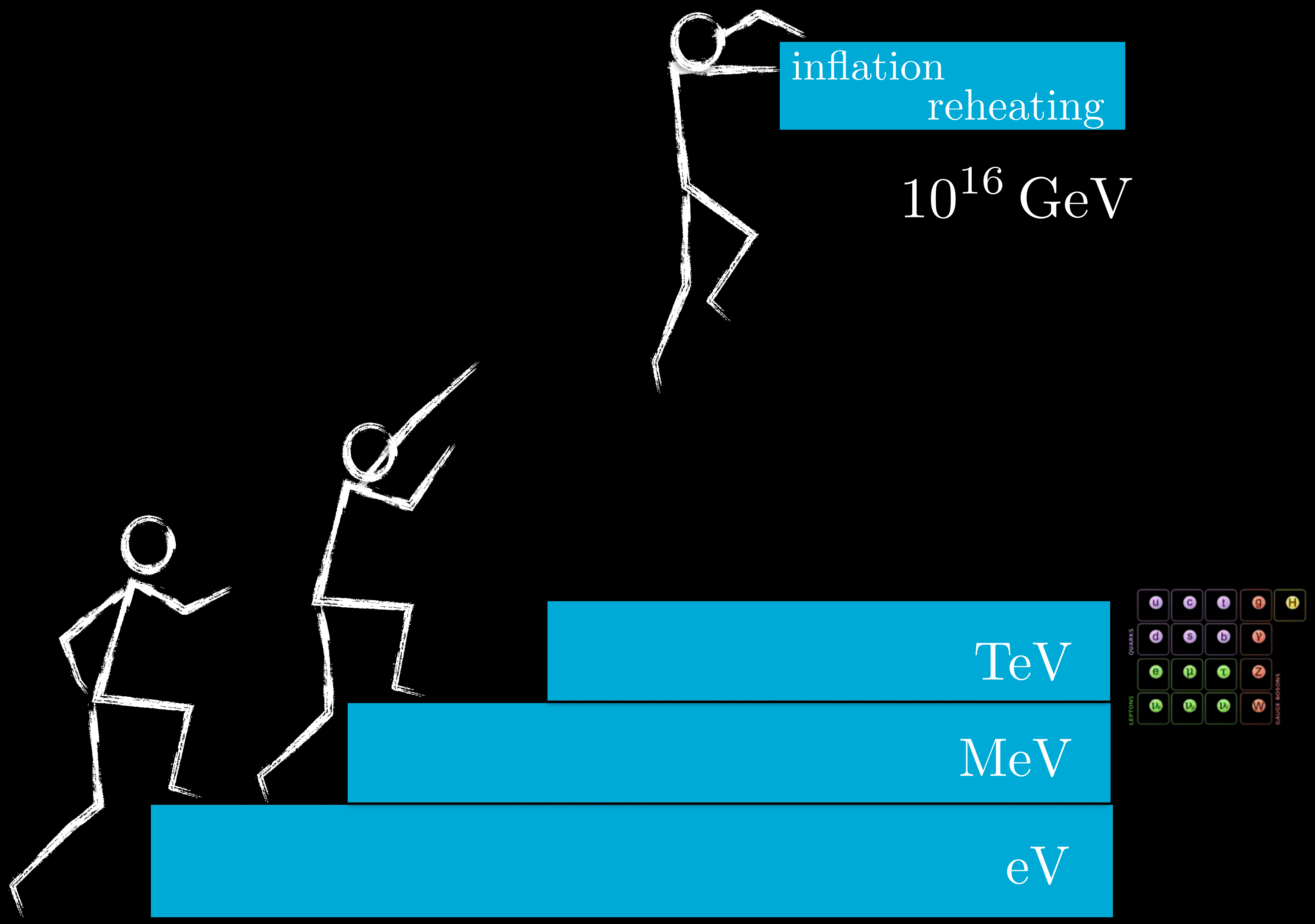
- Standard Model ?

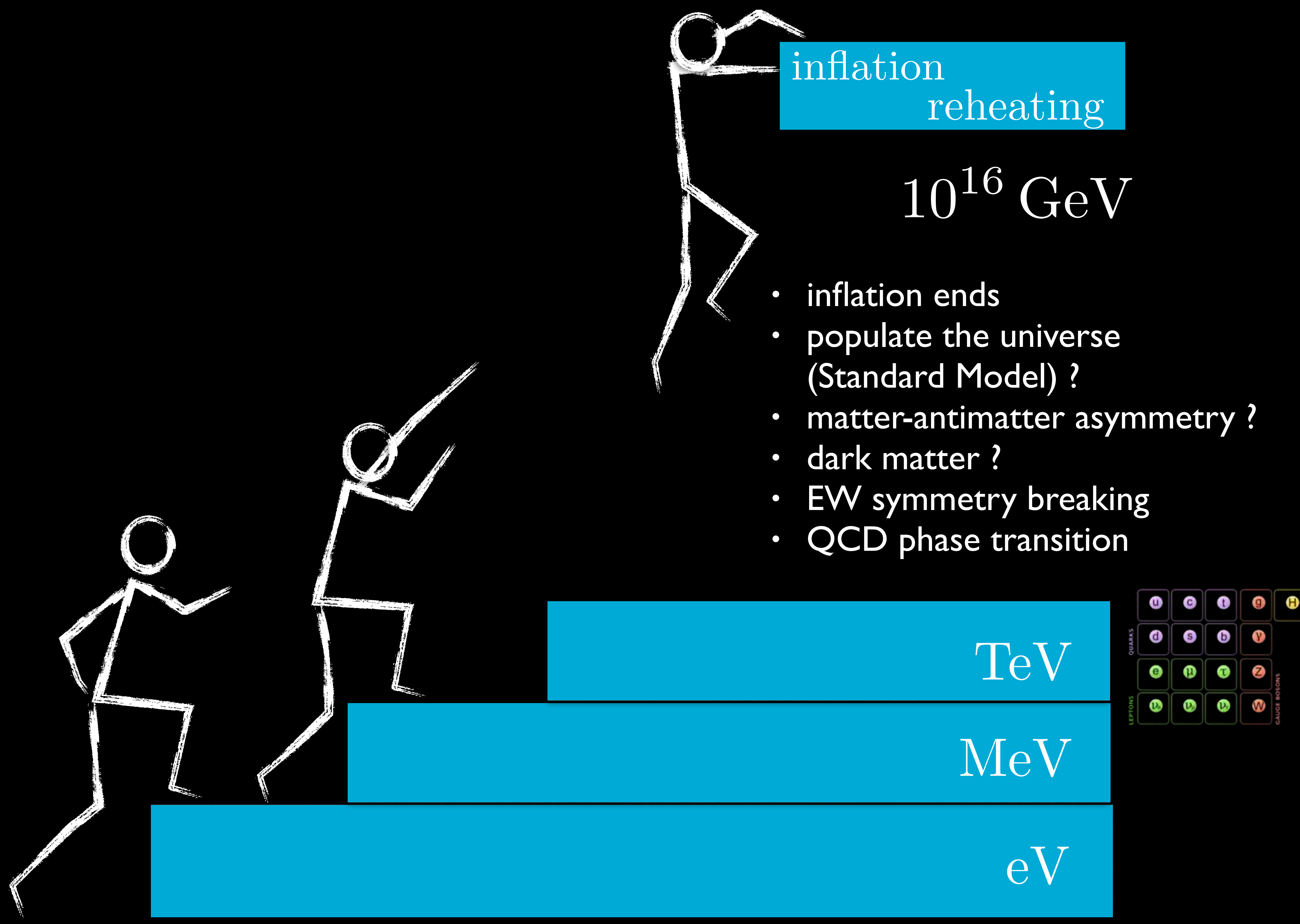


aftermath of inflation: a GAP in our cosmic history




?
what drives
inflation?
MIND THE GAP
NUCLEONS FORM
NUCLEI FORM
TODAY
small fractions
of a second
TeV


inflation
reheating
10^{16} GeV
TeV
MeV
eV


inflation
reheating
10^{16} GeV
• inflation ends
• populate the universe (Standard Model) ?
• matter-antimatter asymmetry ?
• dark matter ?
• EW symmetry breaking
• QCD phase transition
TeV
MeV
eV

modeling inflation and its aftermath

SIMPLE

problem oriented

COMPLEX

modeling inflation and its aftermath

SIMPLE

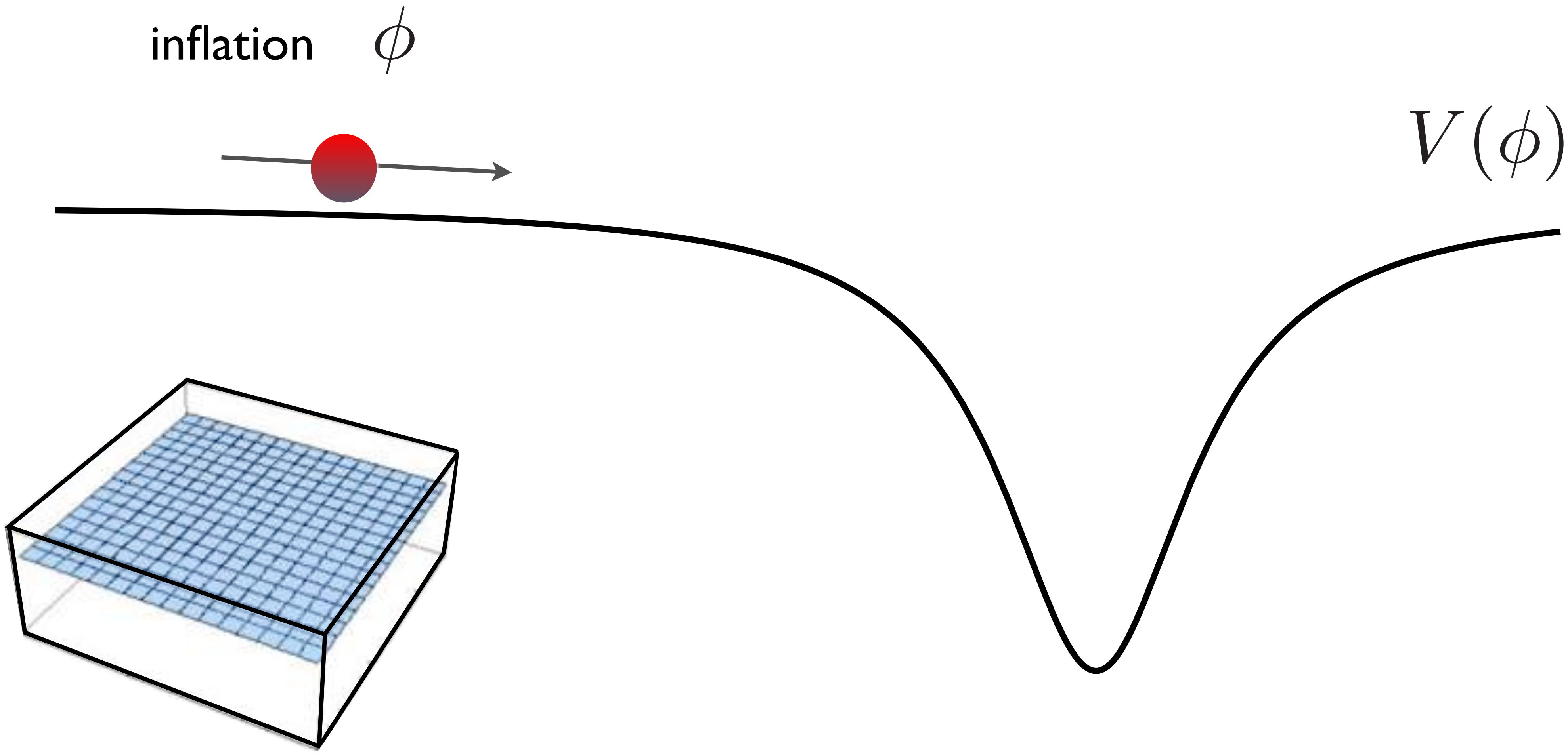
problem oriented

COMPLEX

during inflation

$$\ddot{a}(t) \propto V(\phi) - \dot{\phi}^2 > 0$$

$$\dot{\phi}^2 \ll V(\phi)$$



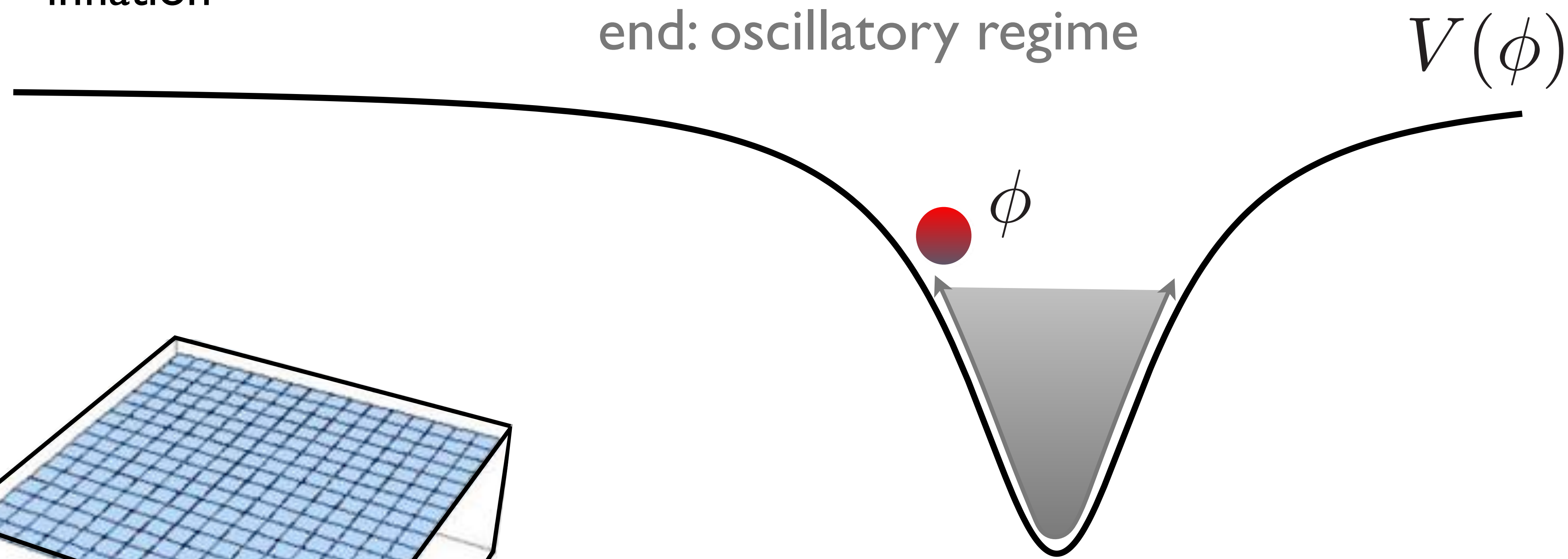
ending inflation

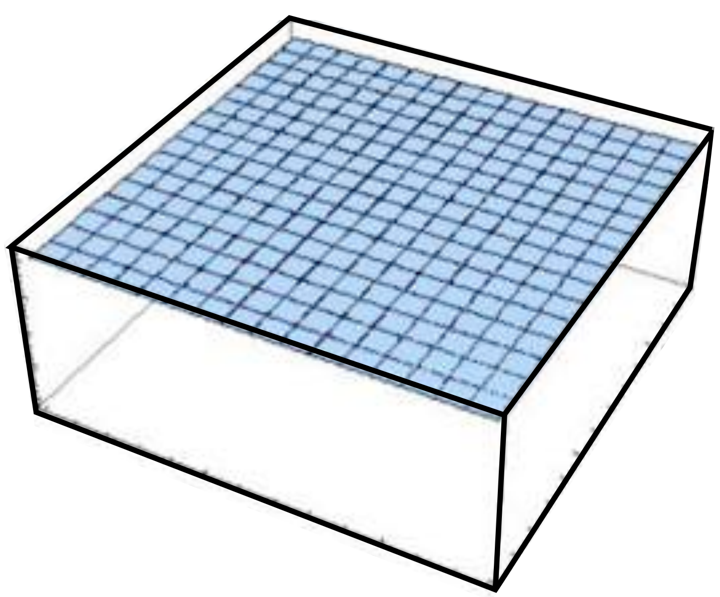
$$\ddot{a}(t) \propto V(\phi) - \dot{\phi}^2 < 0$$

$$\frac{1}{2}\dot{\phi}^2 \sim V(\phi)$$

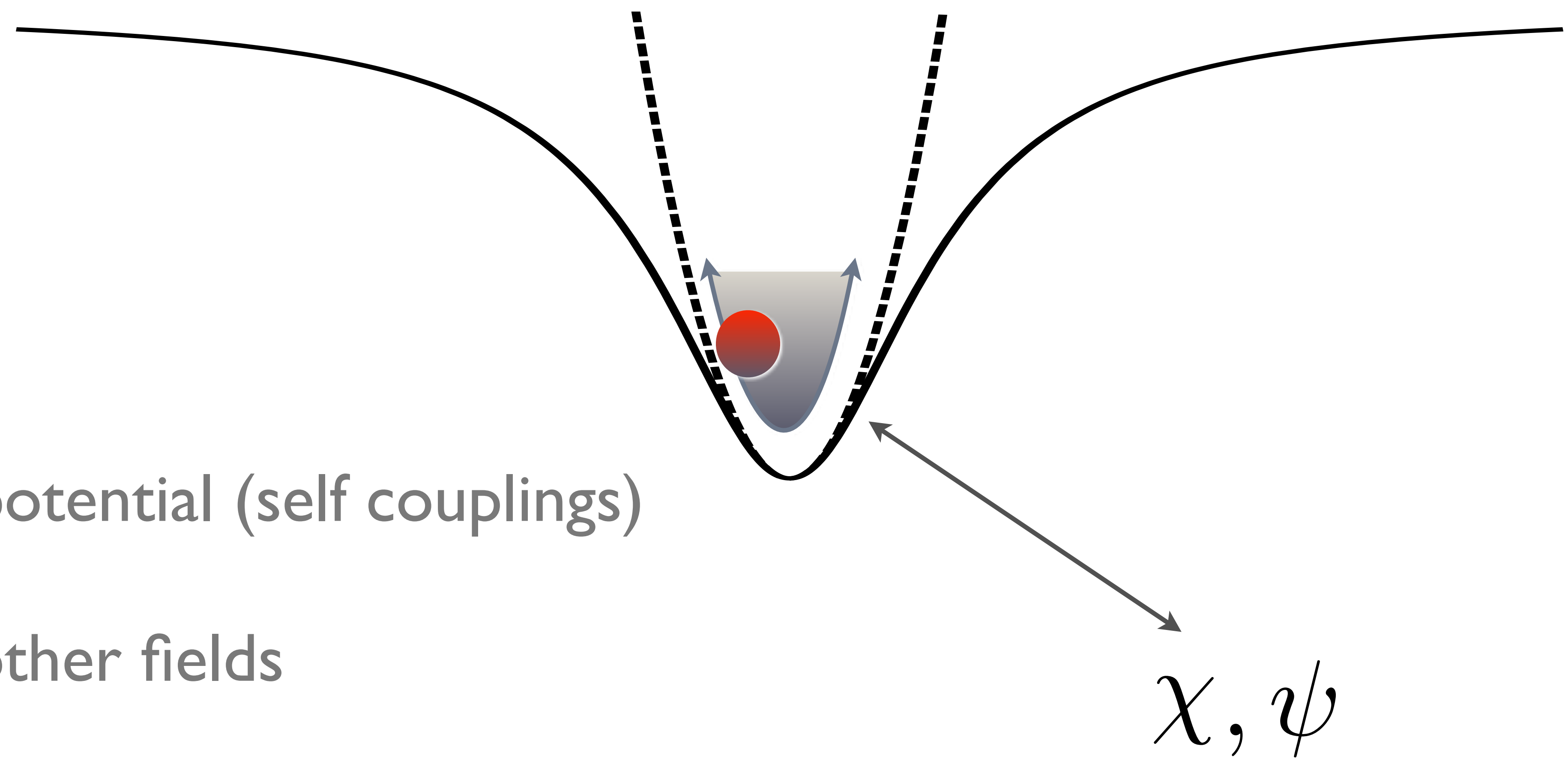
inflation

end: oscillatory regime

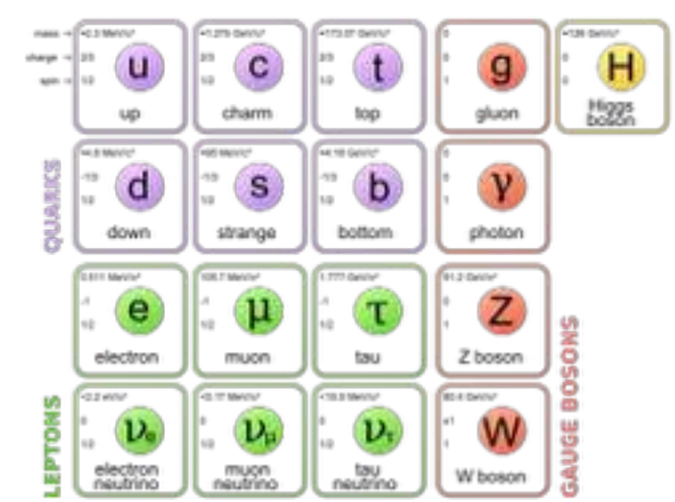




detailed dynamics ?

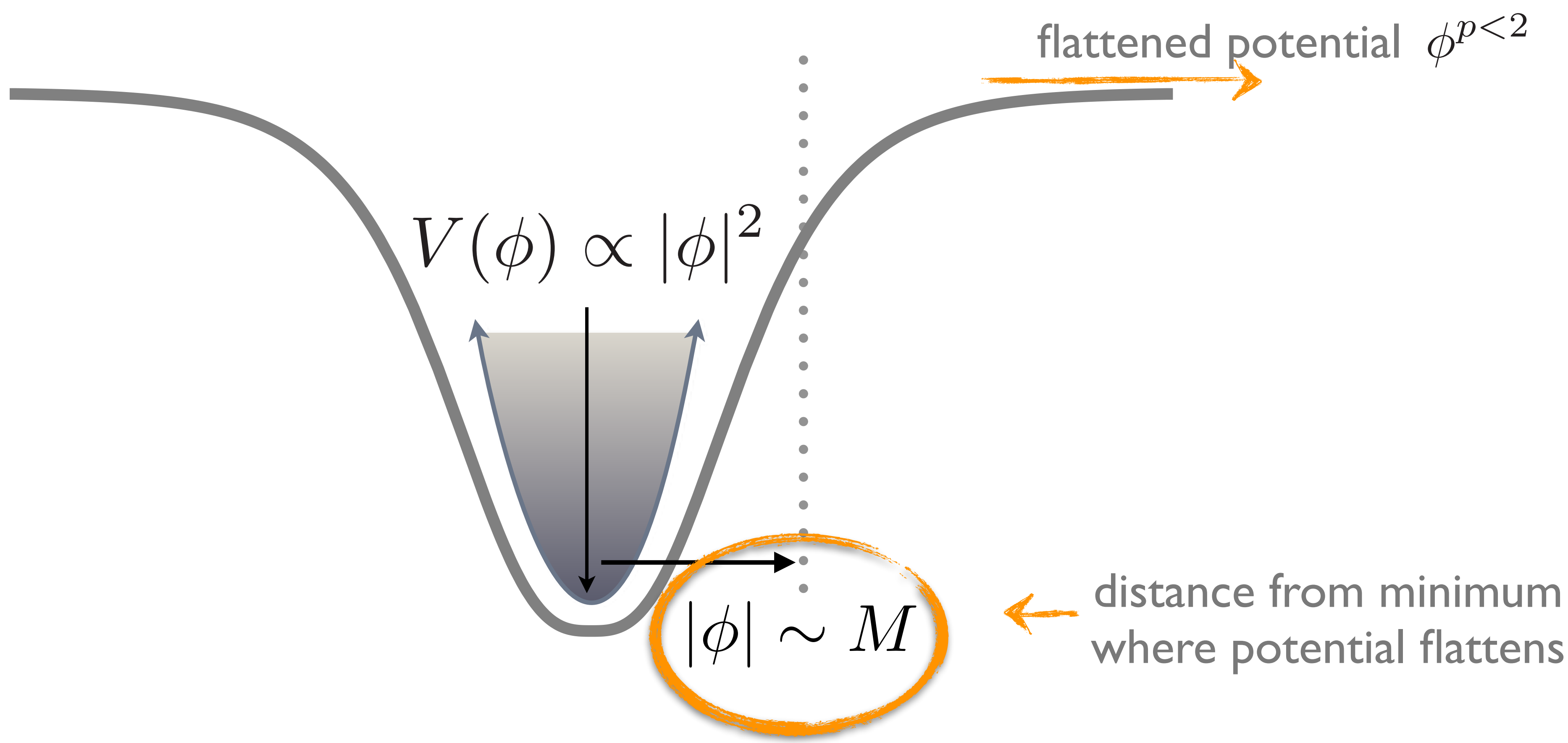


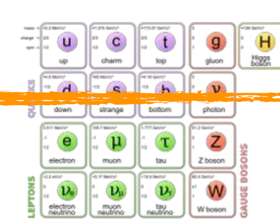
- shape of the potential (self couplings)
- couplings to other fields



Traschen & Brandenburger (1990)
Kofman, Linde & Starobinsky (1994)
Shtanov, Traschen & Brandenberger (1995)
Kofman, Linde & Starobinsky (1997)
review: MA, Kaiser, Karouby & Hertzberg (2014)

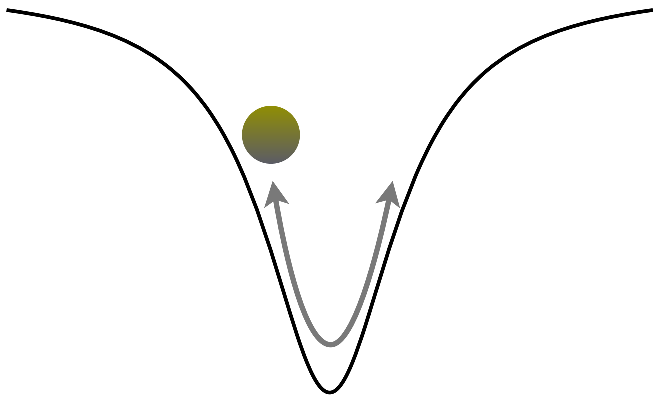
end of inflation in “simple” models

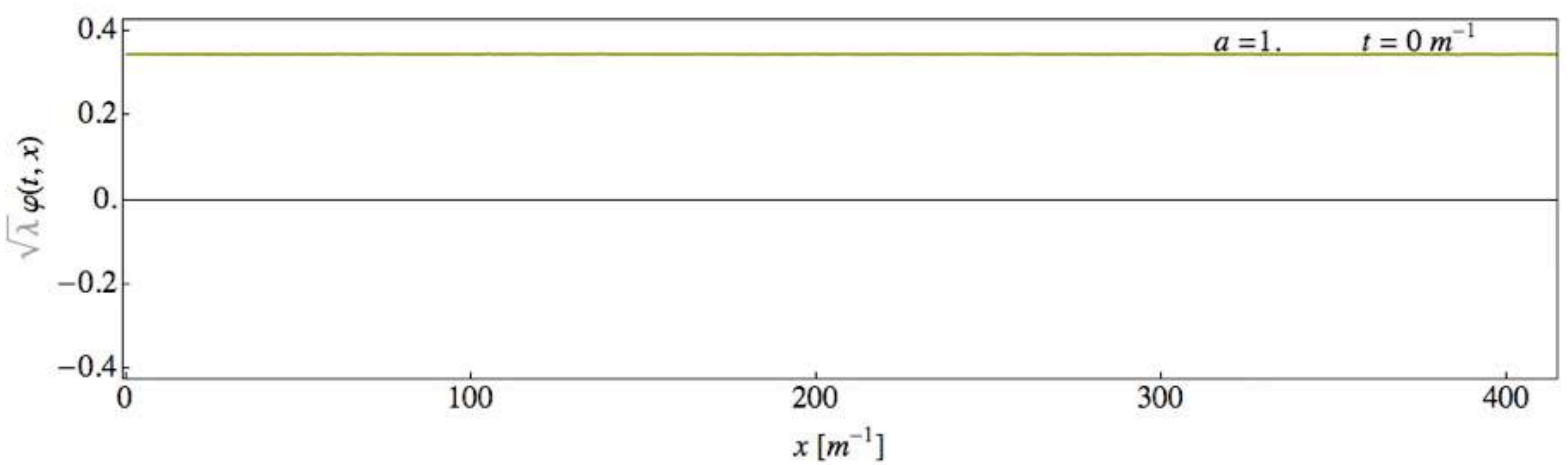


- shape of the potential (self couplings)
- couplings to other fields  $\chi \, , \psi$

dynamics after inflation

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

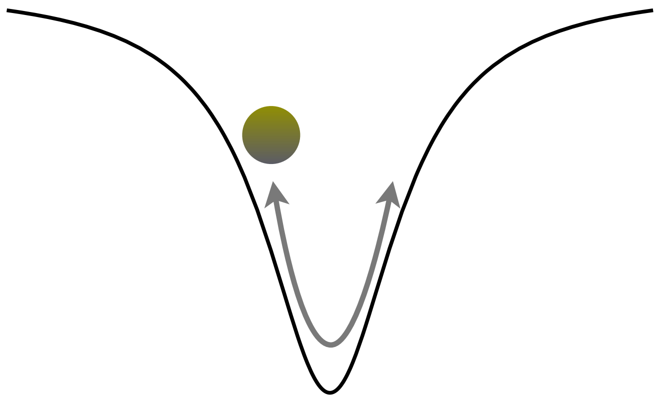


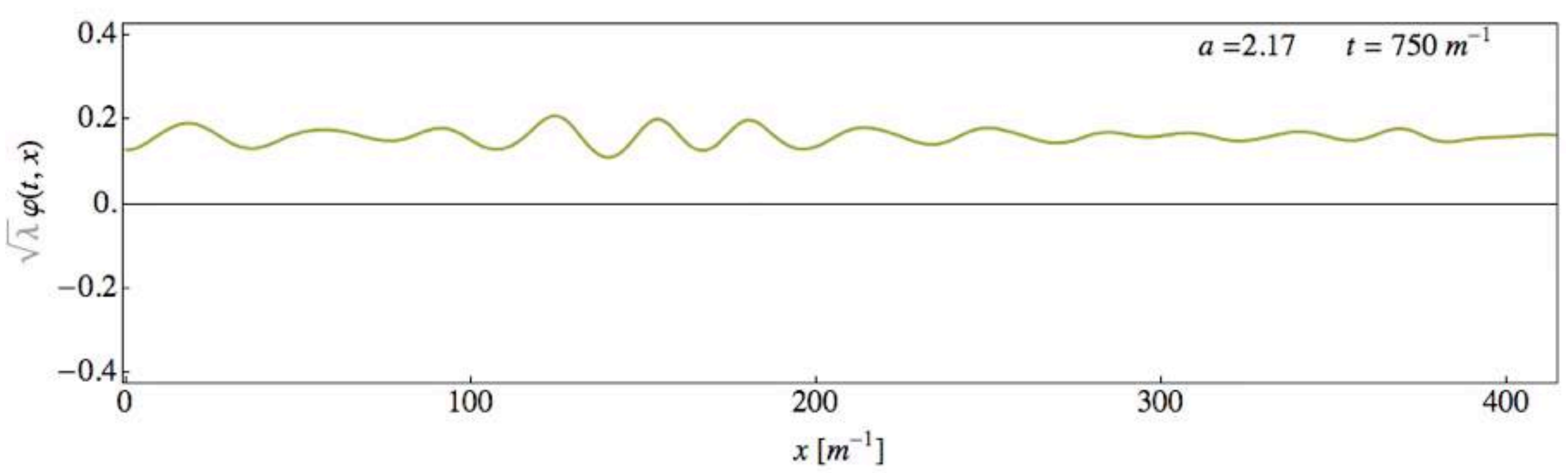


MA (2010)
Khlopov et. al (1985)

dynamics after inflation

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

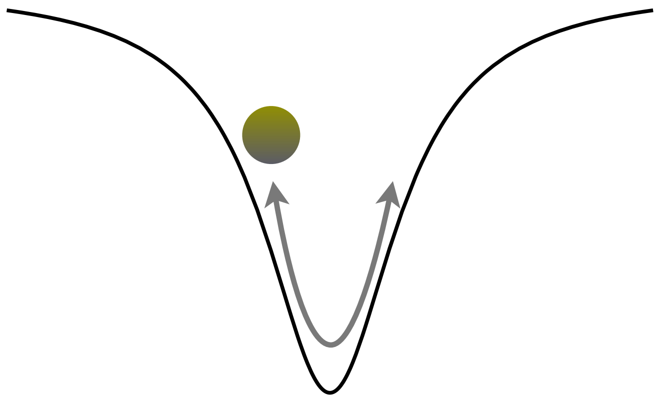


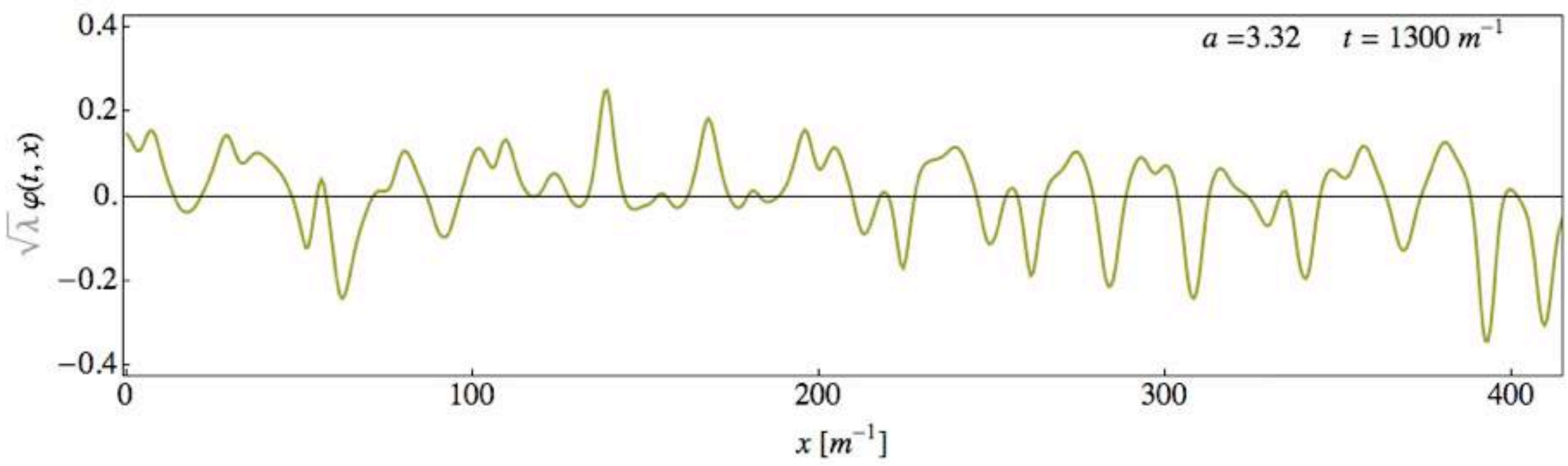


MA (2010)
Khlopov et. al (1985)

dynamics after inflation

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

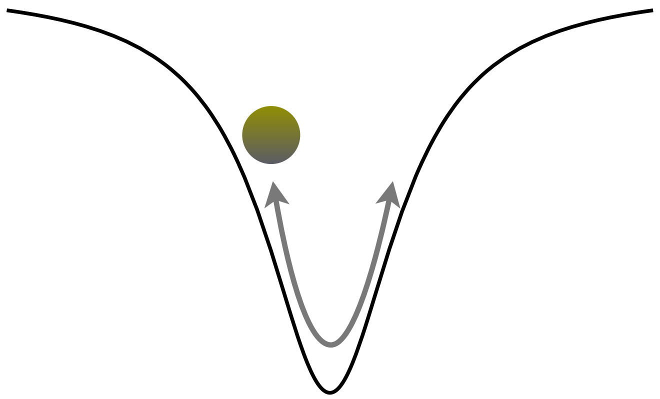


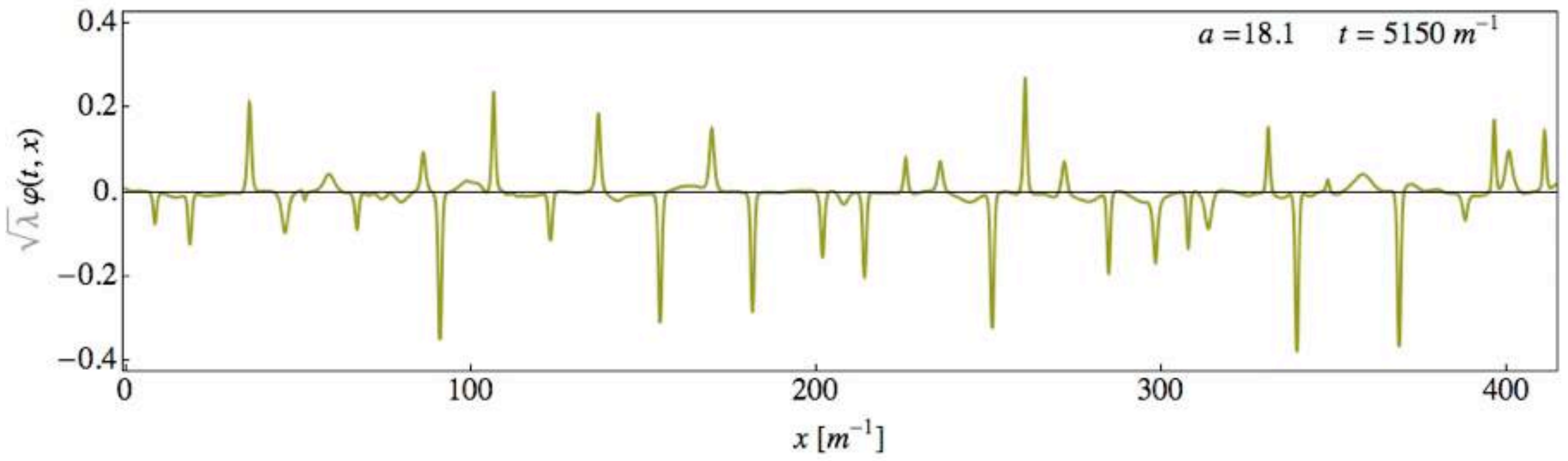


MA (2010)
Khlopov et. al (1985)

dynamics after inflation

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

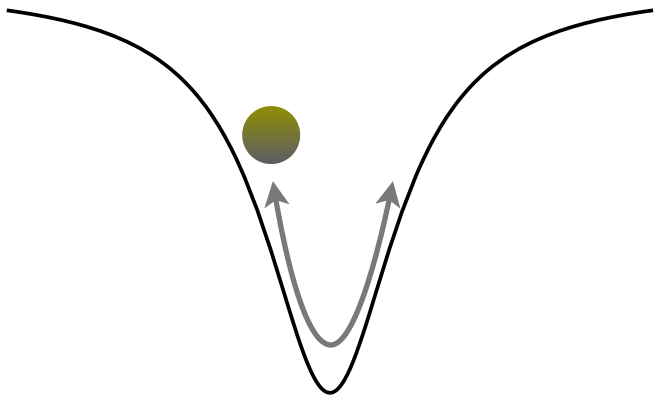


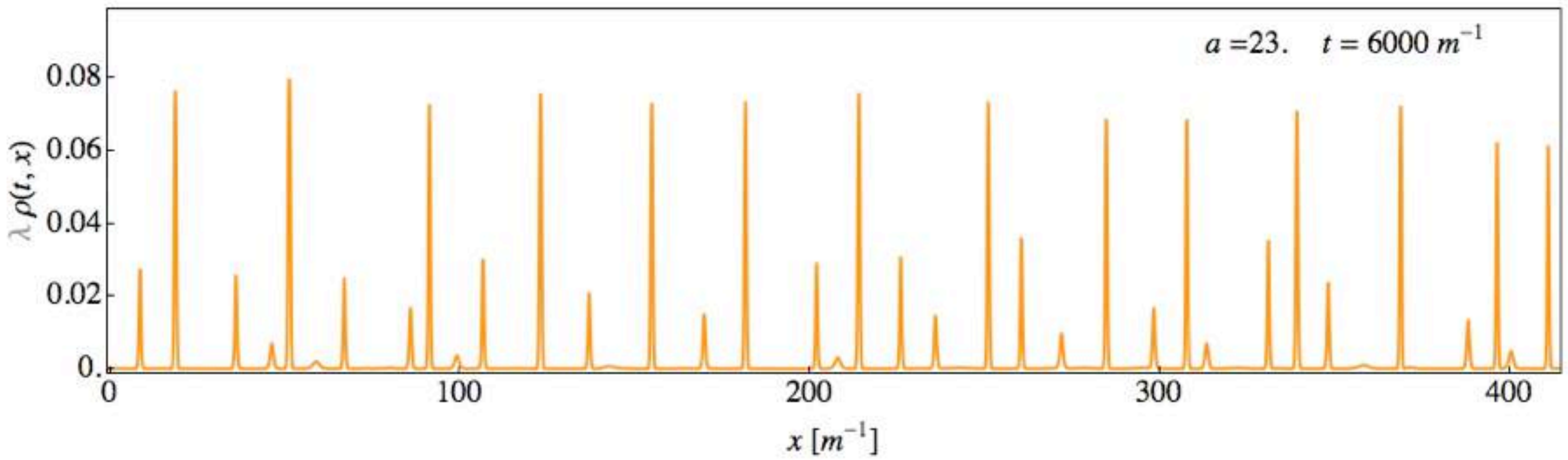


MA (2010)
Khlopov et. al (1985)

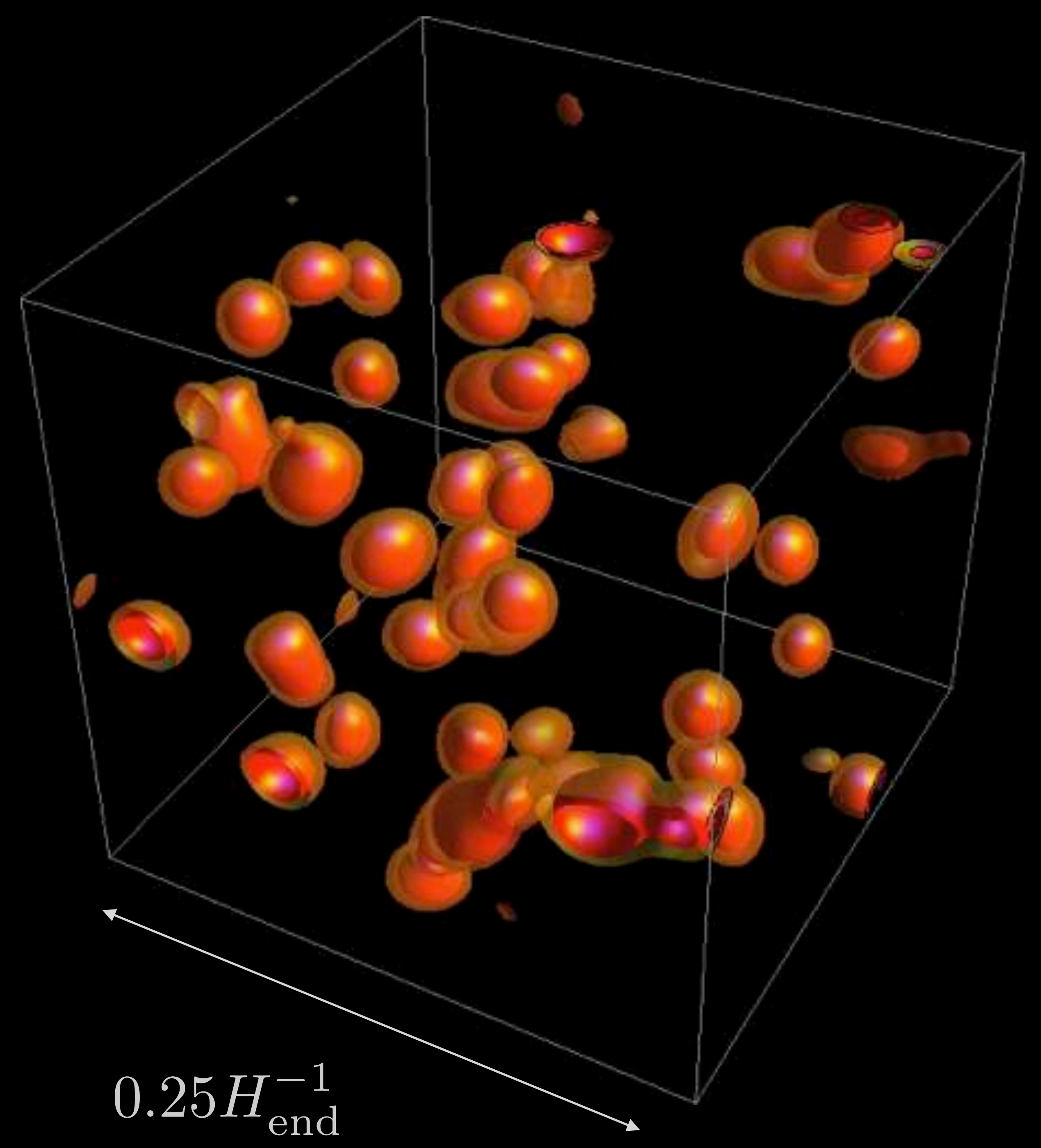
dynamics after inflation

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





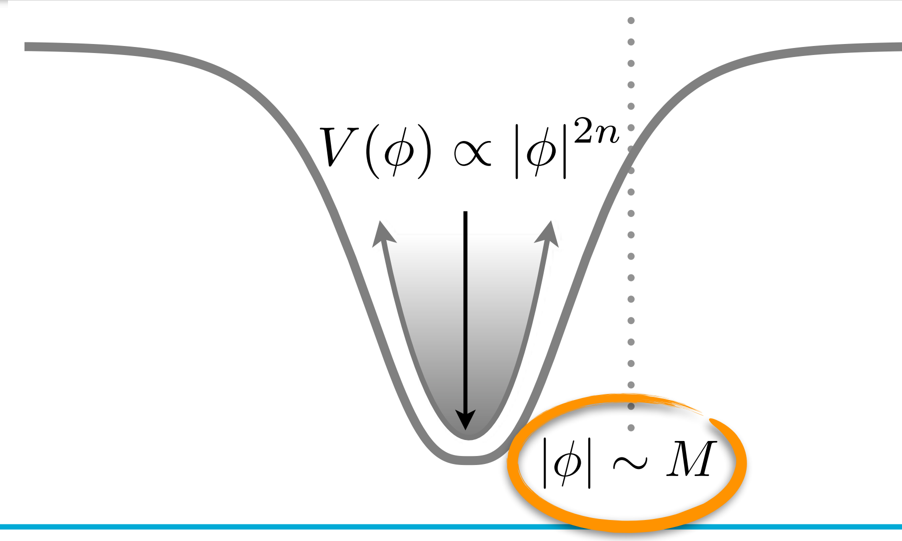
now in 3D:
(iso-density surfaces)

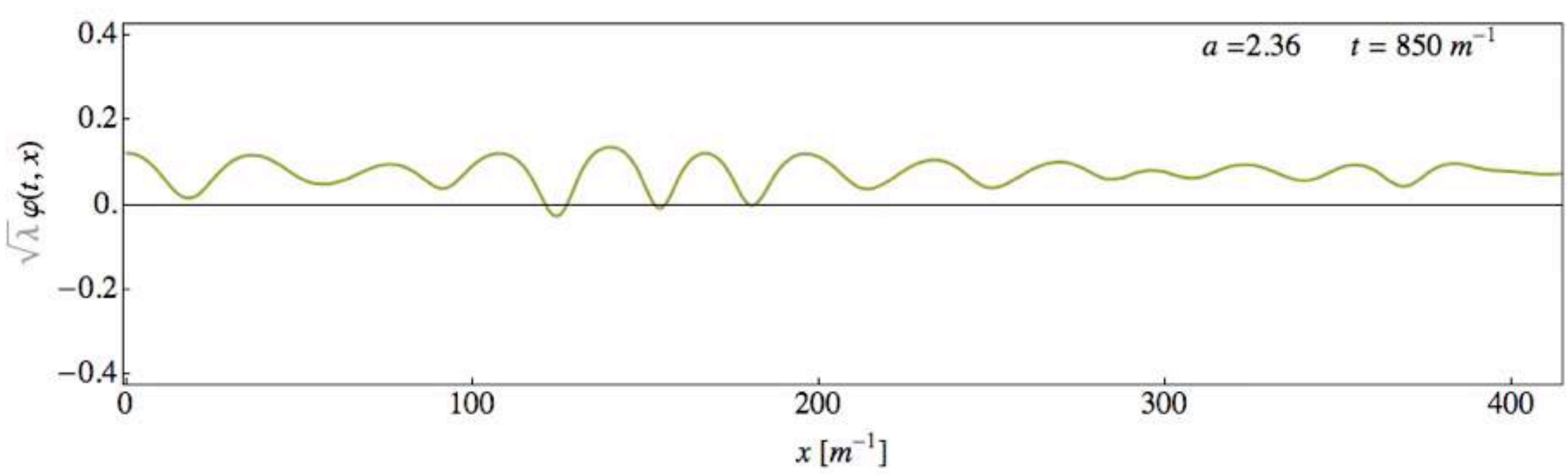


MA, Easther, Finkel, Flaugher & Hertzberg (2011)

condition for rapid fragmentation ?

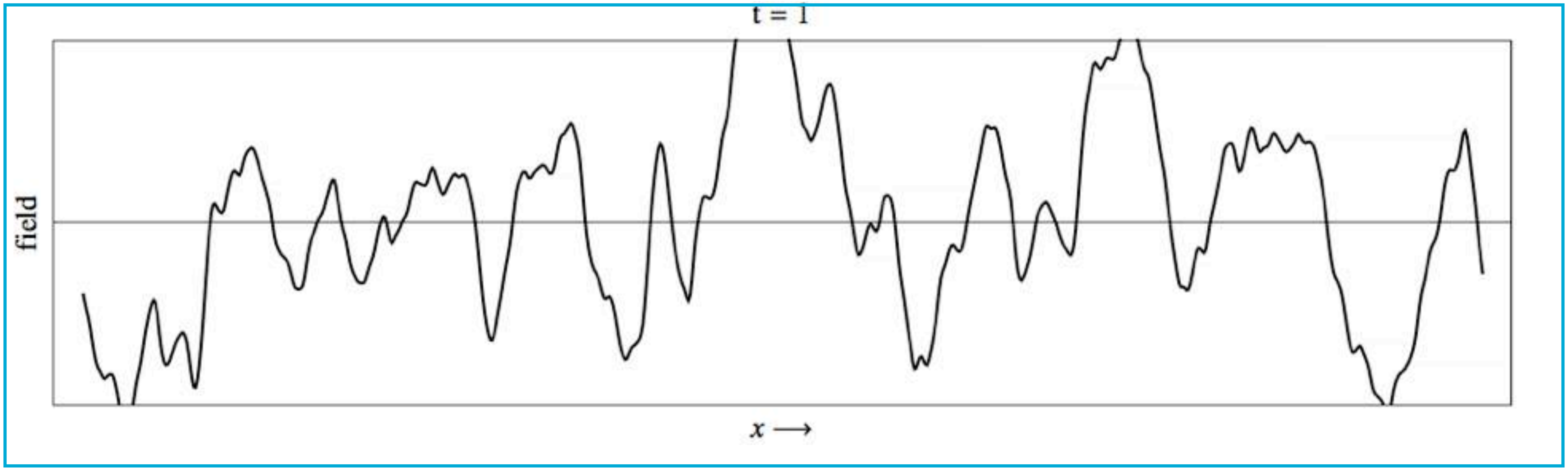
$$\frac{\text{growth-rate of fluctuations}}{\text{expansion rate}} \sim \frac{m_{\rm pl}}{M} \gg 1$$





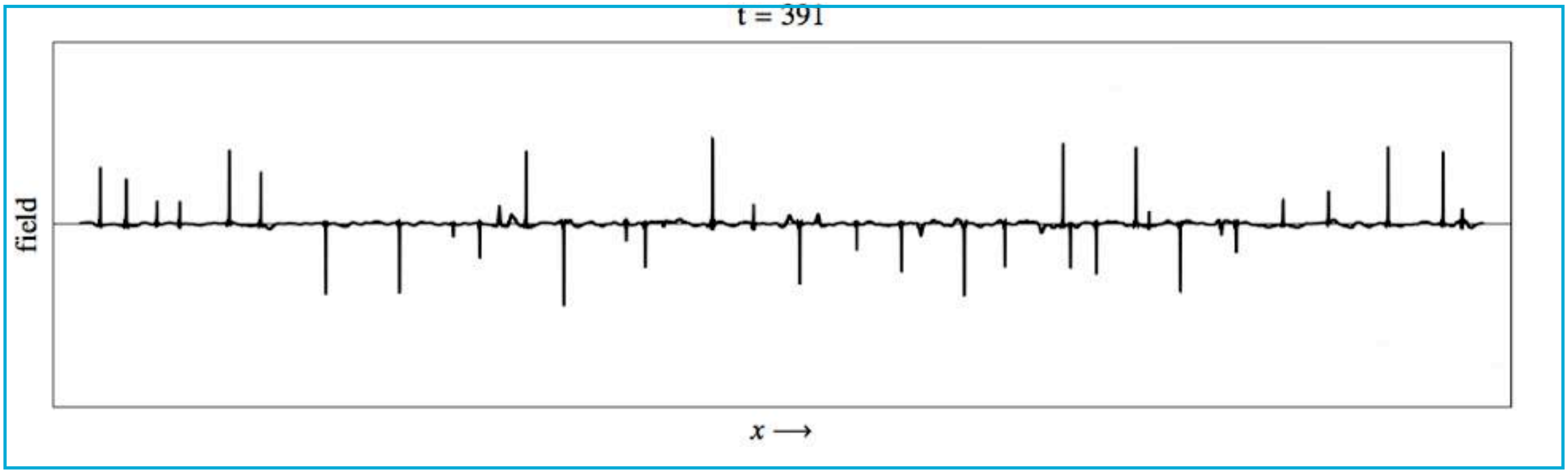
MA (2010)

insensitive to initial conditions



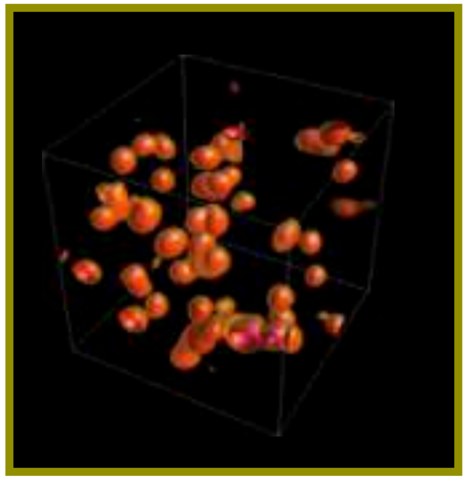
simulation of "quasi-thermal" example in Farhi et. al 2008

insensitive to initial conditions

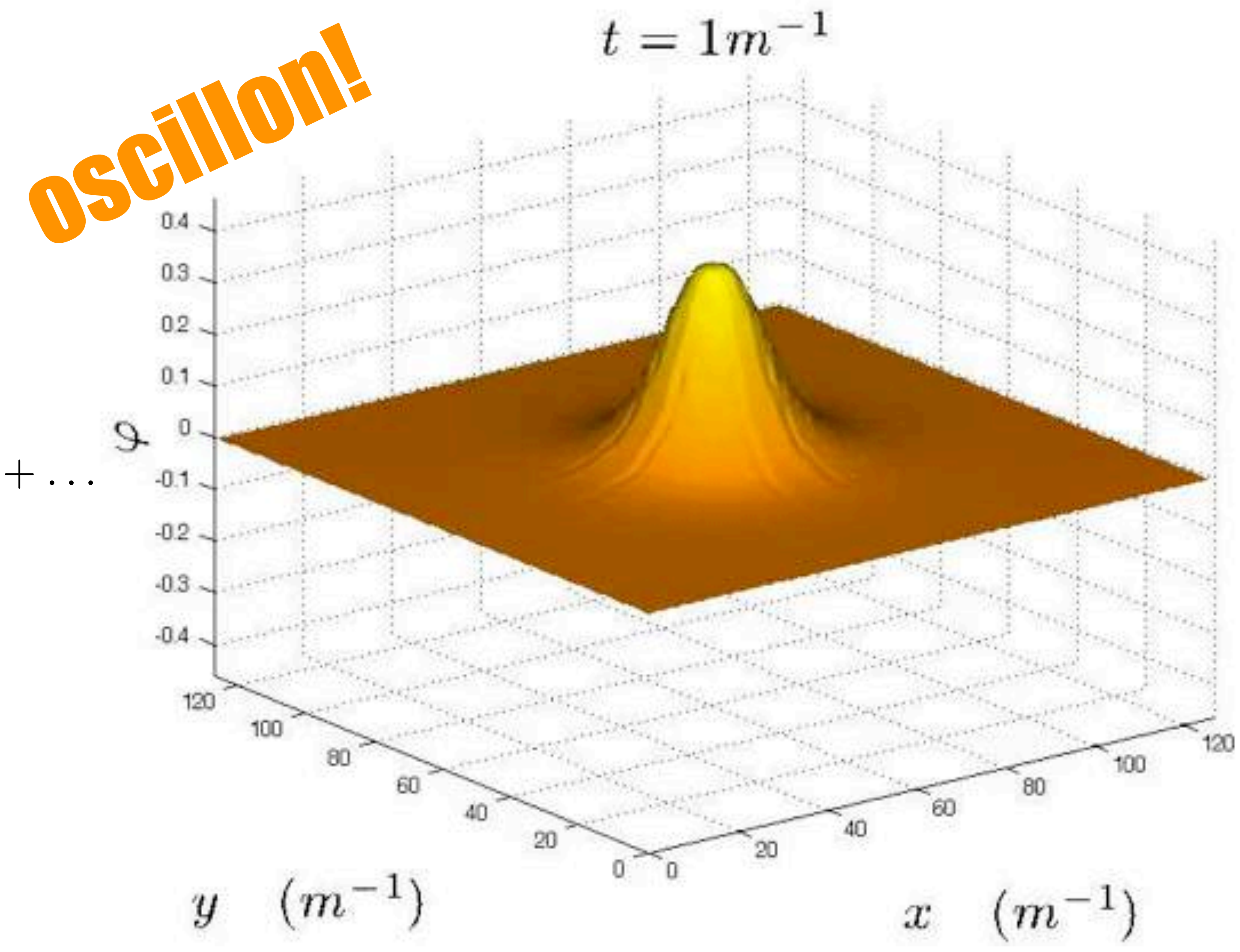


simulation of "quasi-thermal" example in Farhi et. al 2008

lumps ?



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



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

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

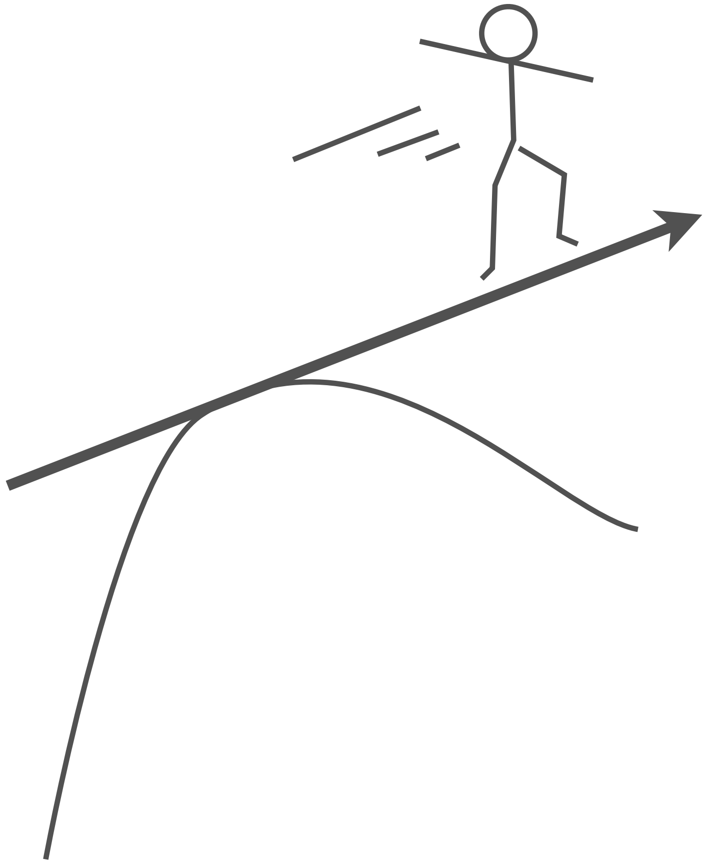
$$V(\varphi) = \frac{1}{2}\varphi^2 + \frac{\lambda_3}{3}\varphi^3 + \frac{\lambda_4}{4}\varphi^4 + \frac{\lambda_5}{5}\varphi^5 + \dots$$

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

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

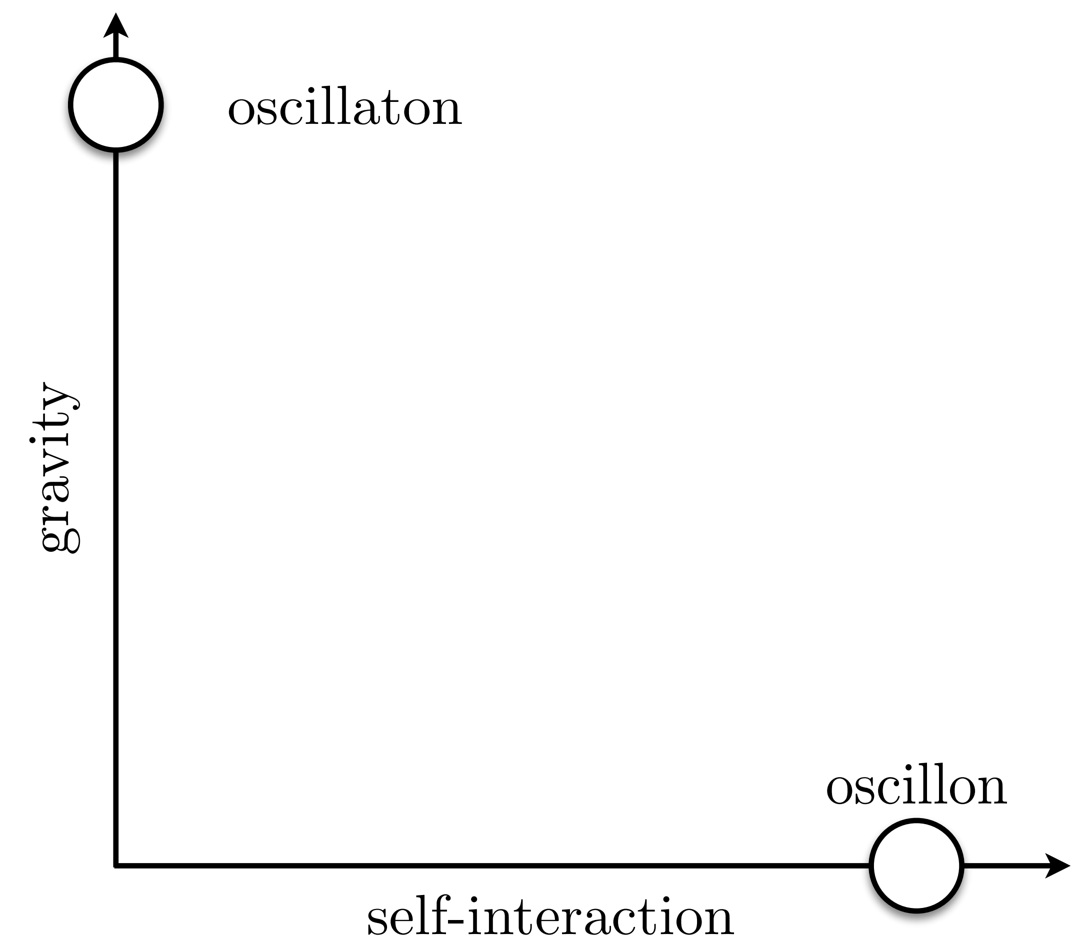
Bogolubsky & Makhankov (1976), Gleiser (1994), Copeland, Gleiser and Mueller et al. (1995) …

tangential digression

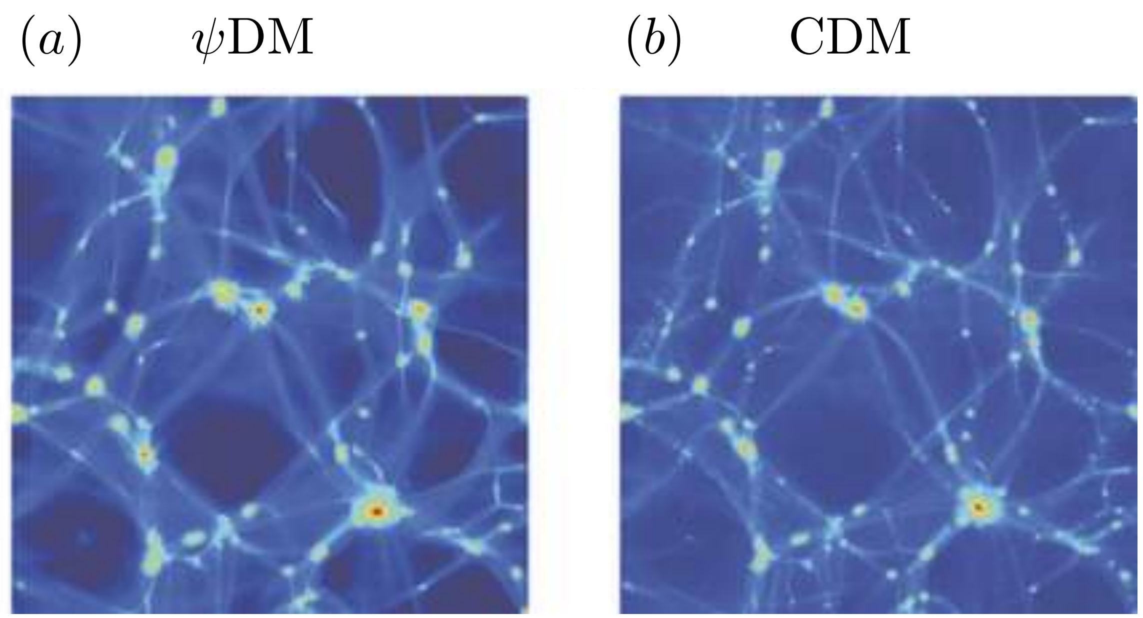


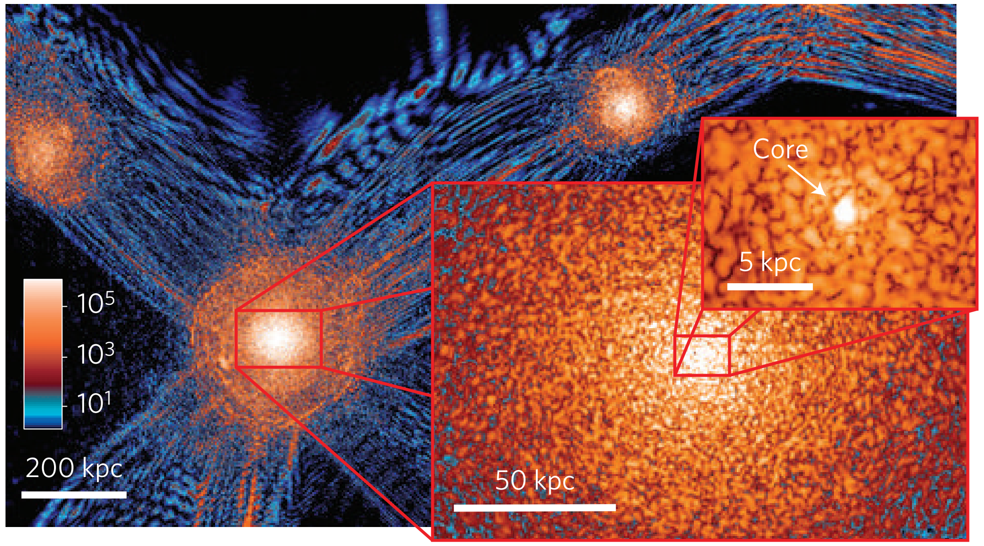
oscillons and friends

non-topological solitons

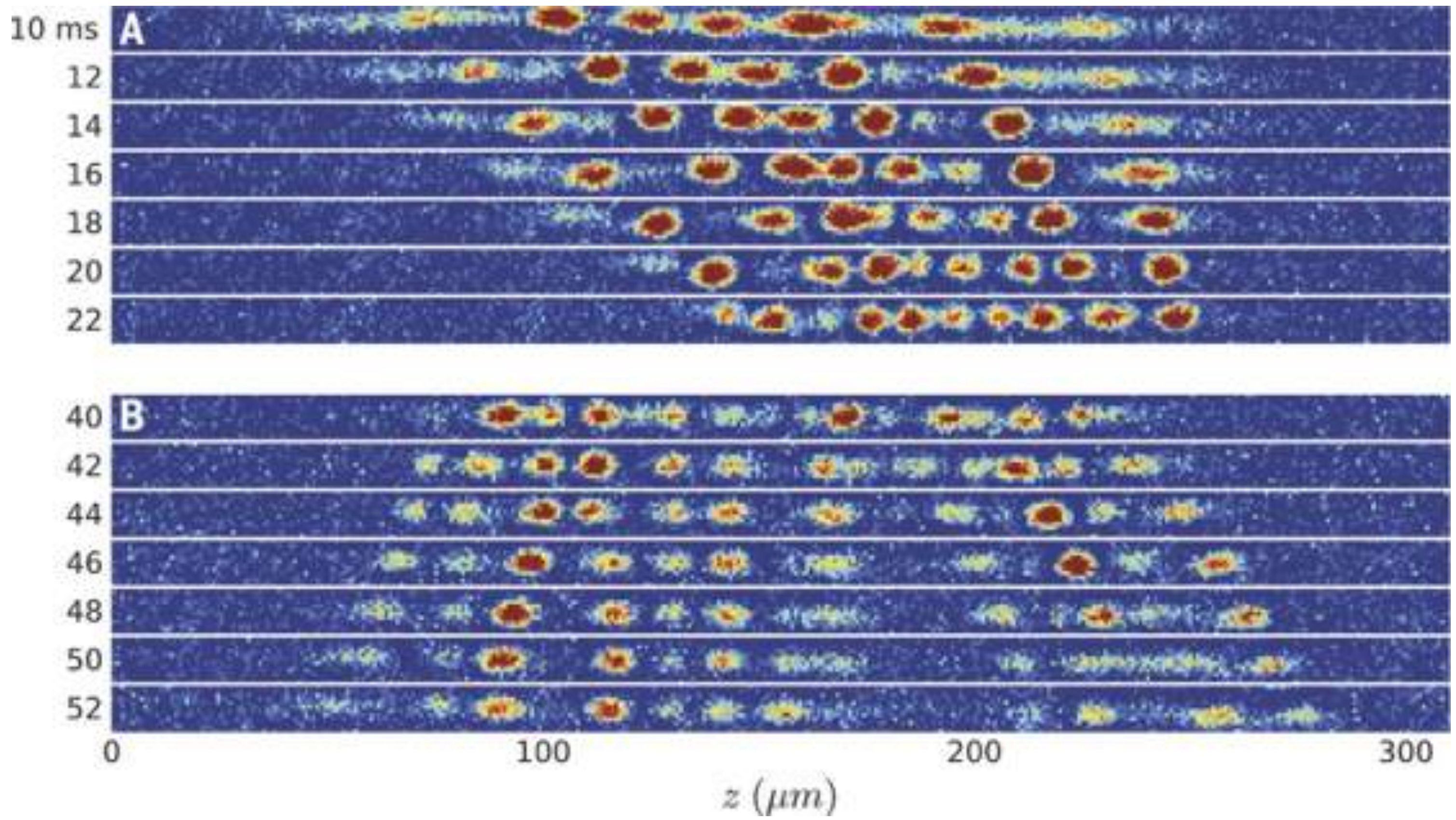


oscillons and friends
- late universe





Schive et. al (2014)



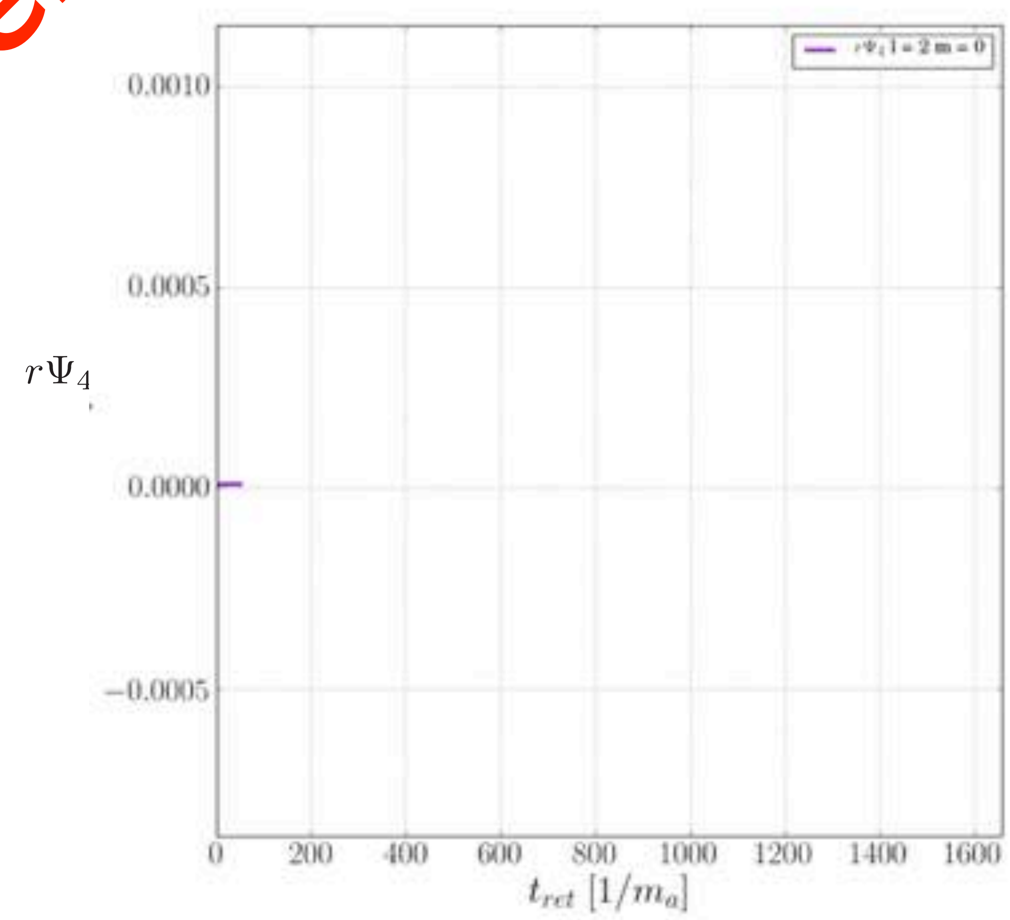
Nguyen, Luo & Hulet (2017)

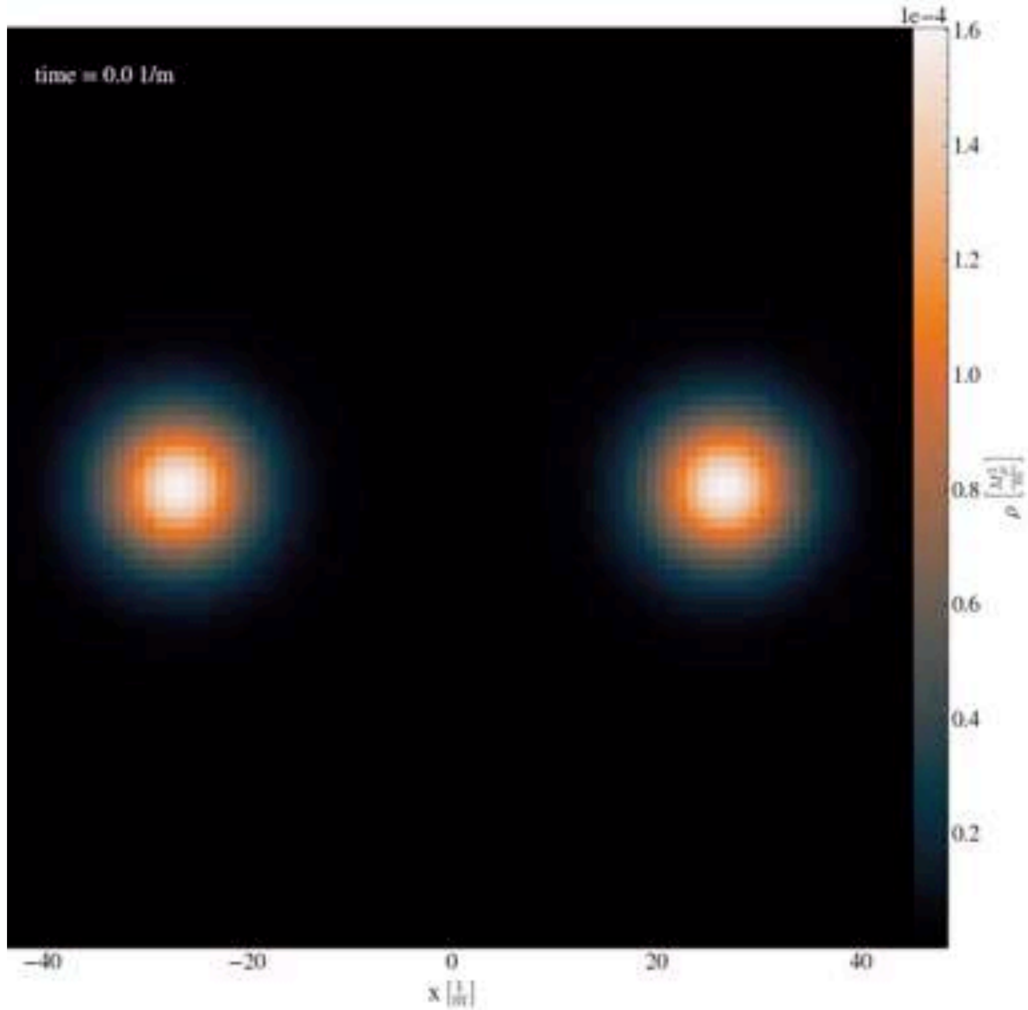
gravitational waves from dense oscillaton collisions

preliminary

relevance for late universe processes — axion stars

Helfer, Lim, Garcia & Amin (in prep)



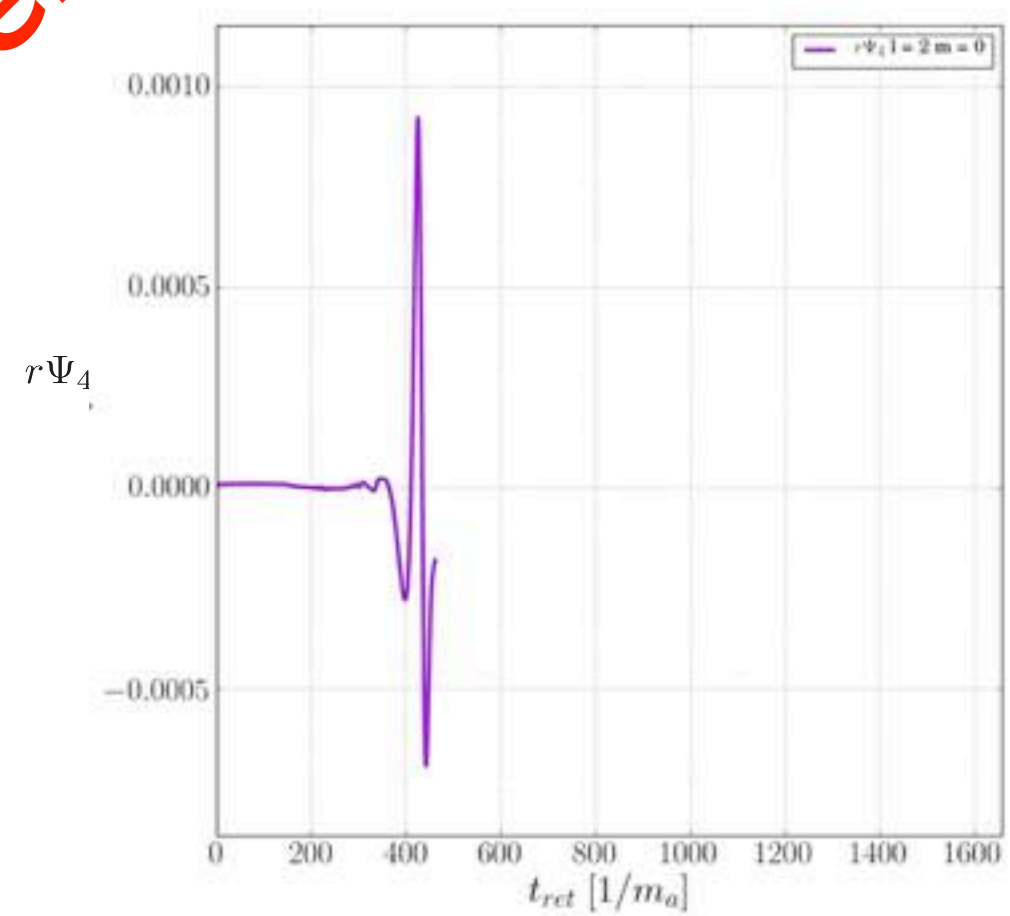


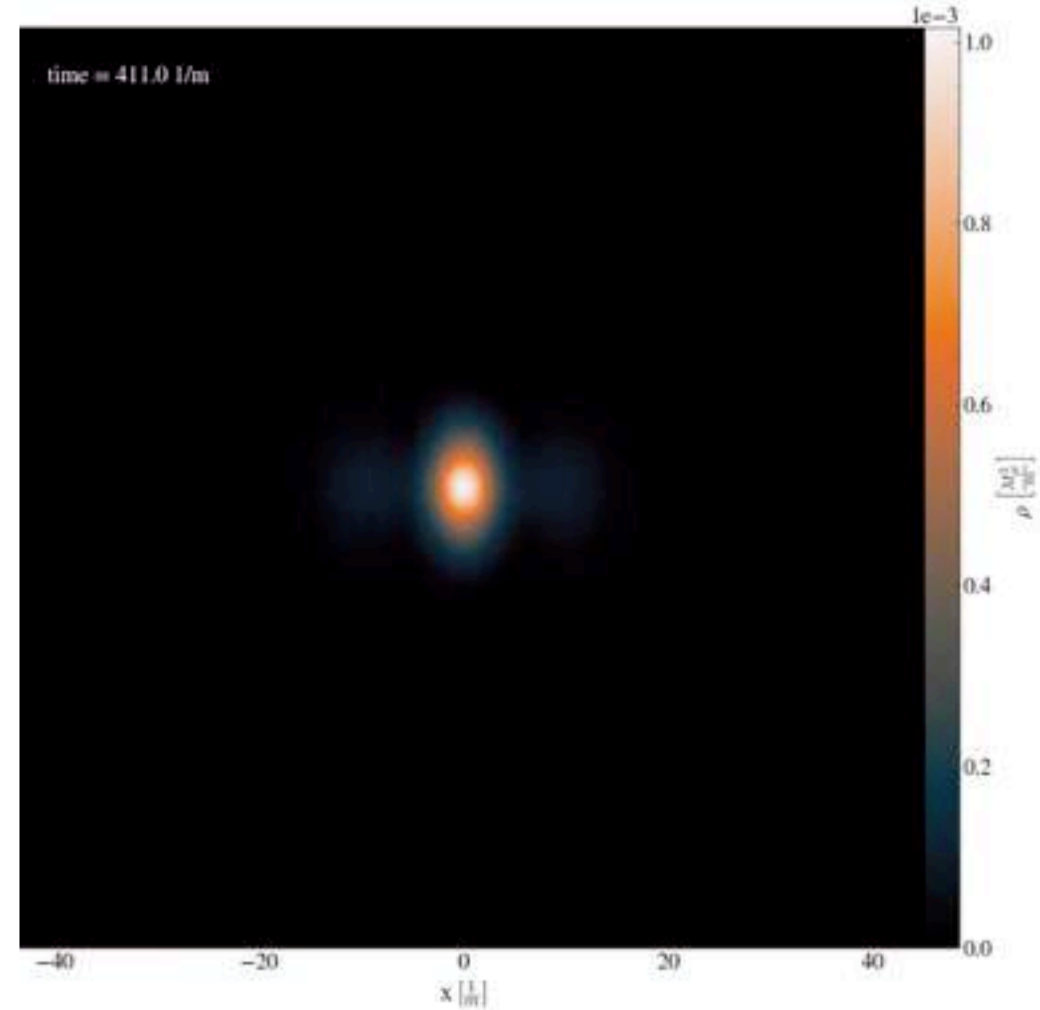
gravitational waves from dense oscillaton collisions

preliminary

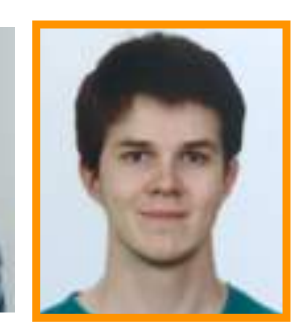
relevance for late universe processes — axion stars

Helfer, Lim, Garcia & Amin (in prep)







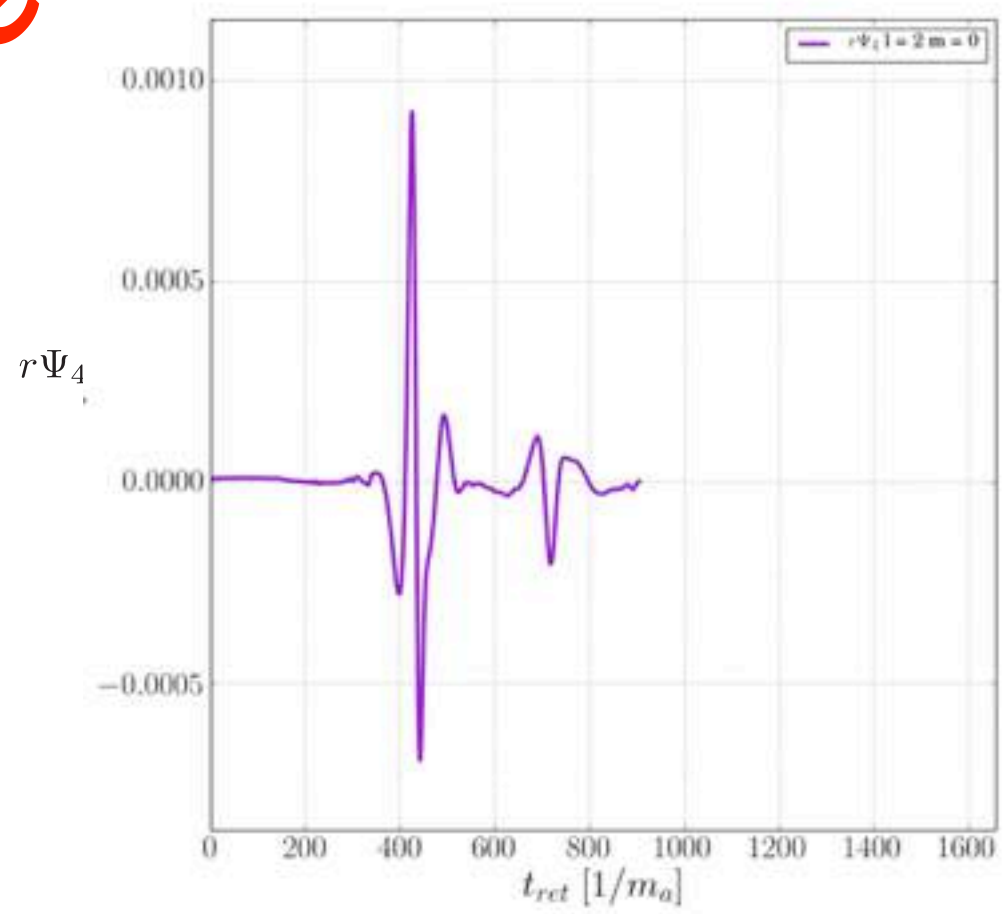


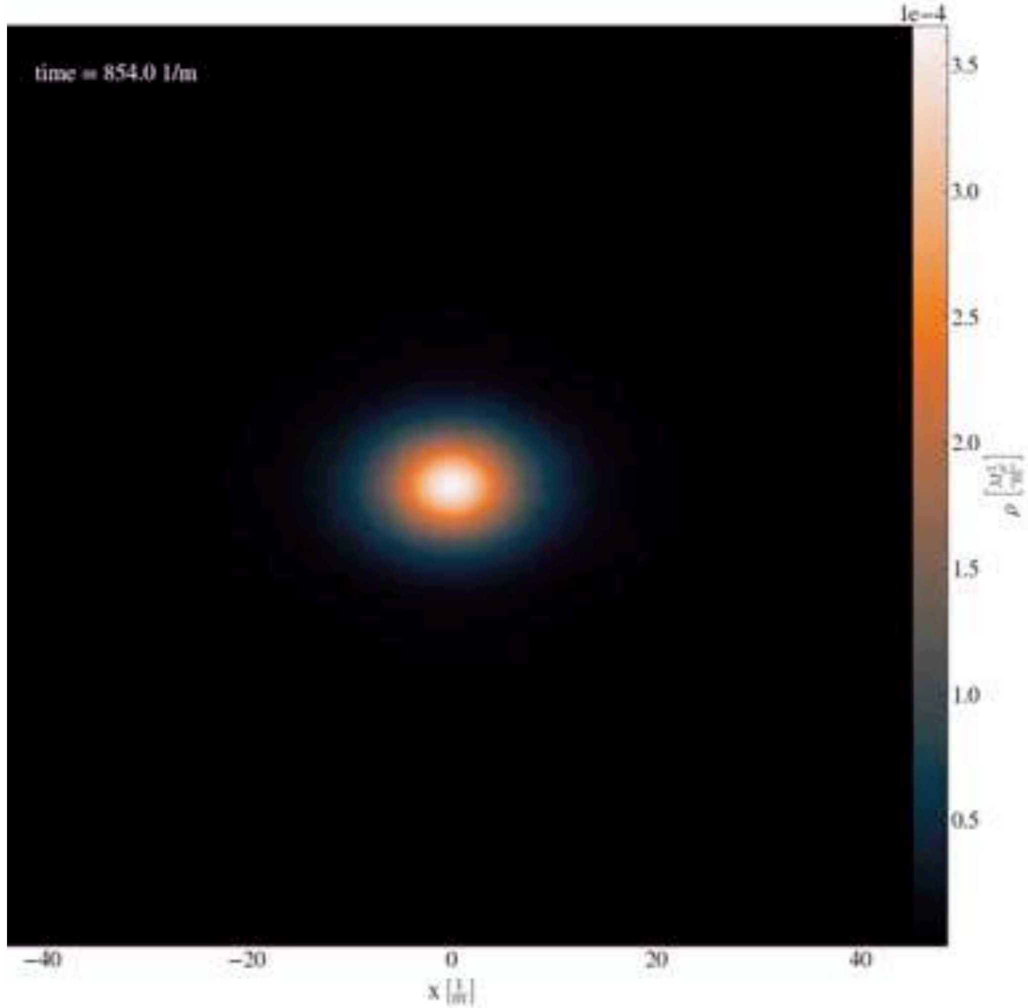
gravitational waves from dense oscillaton collisions

preliminary

relevance for late universe processes — axion stars

Helfer, Lim, Garcia & Amin (in prep)

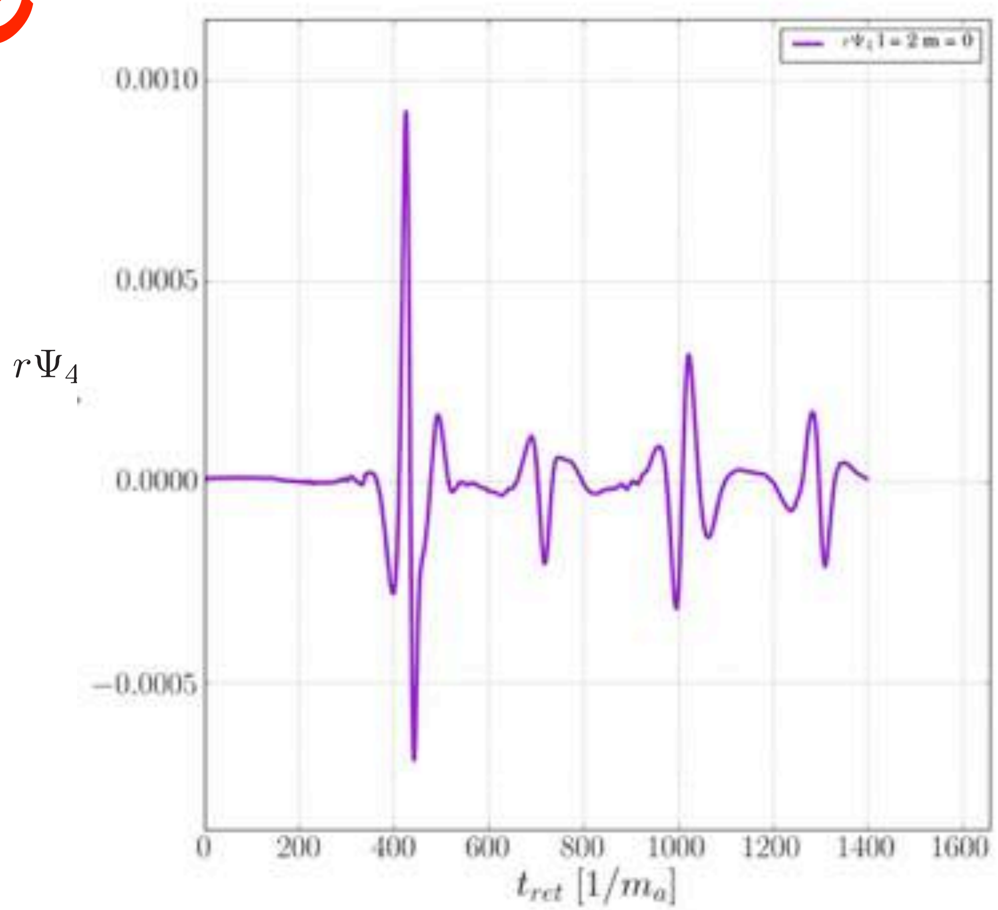




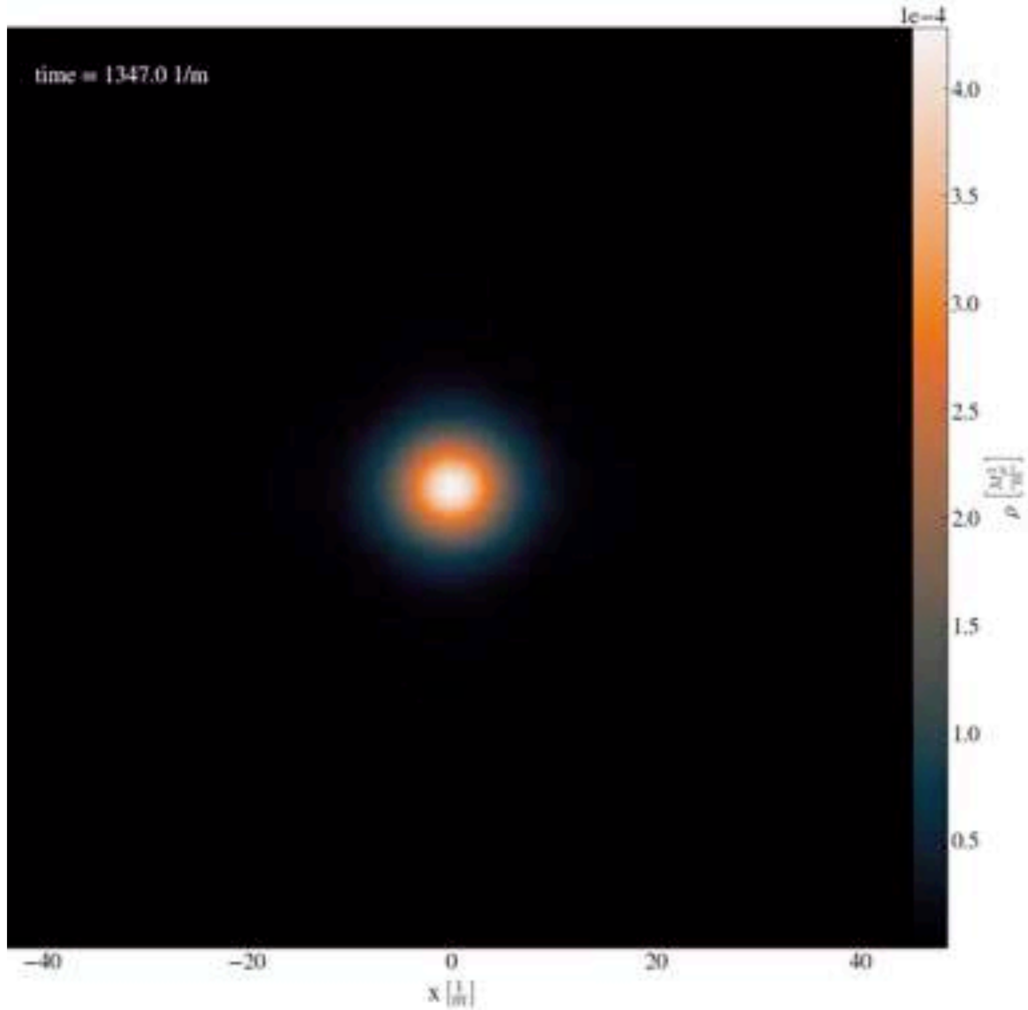
gravitational waves from dense oscillaton collisions

preliminary

relevance for late universe processes — axion stars



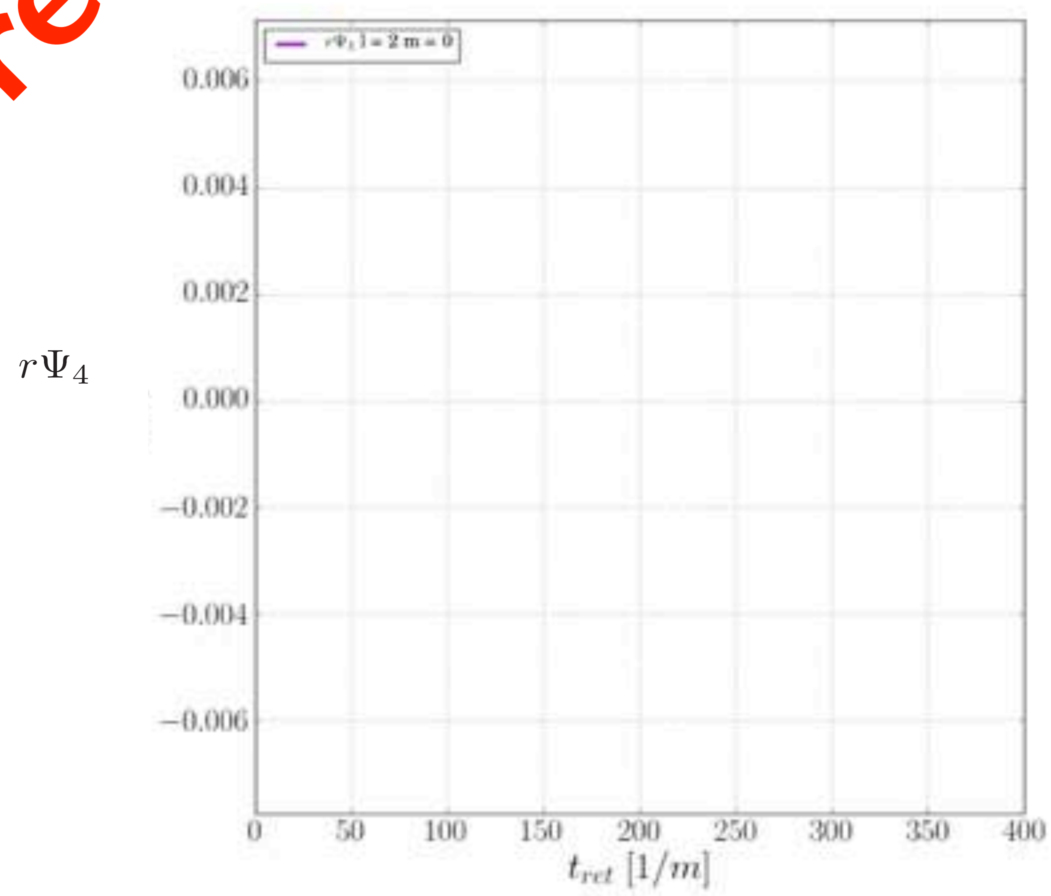
Helfer, Lim, Garcia & Amin (in prep)



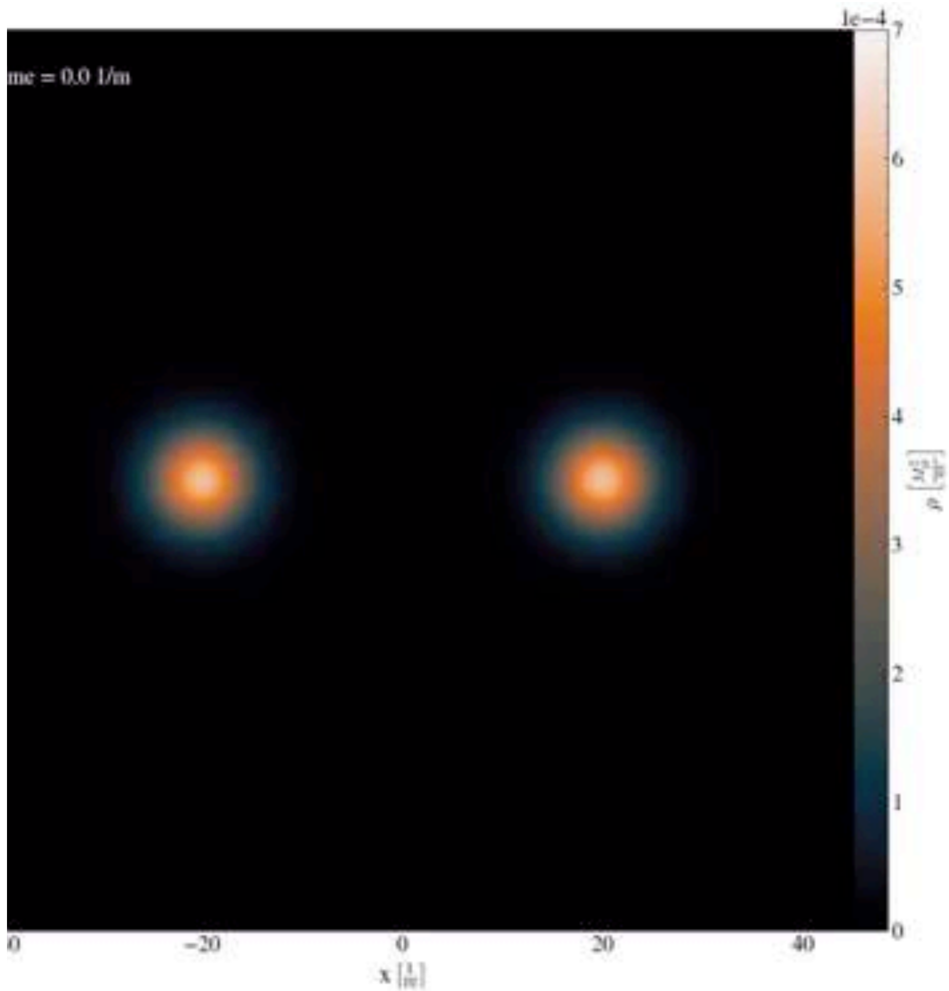
gravitational waves from oscillaton collisions
* critical case

preliminary

relevance for late universe processes — axion stars



Helfer, Lim, Garcia & Amin (in prep)

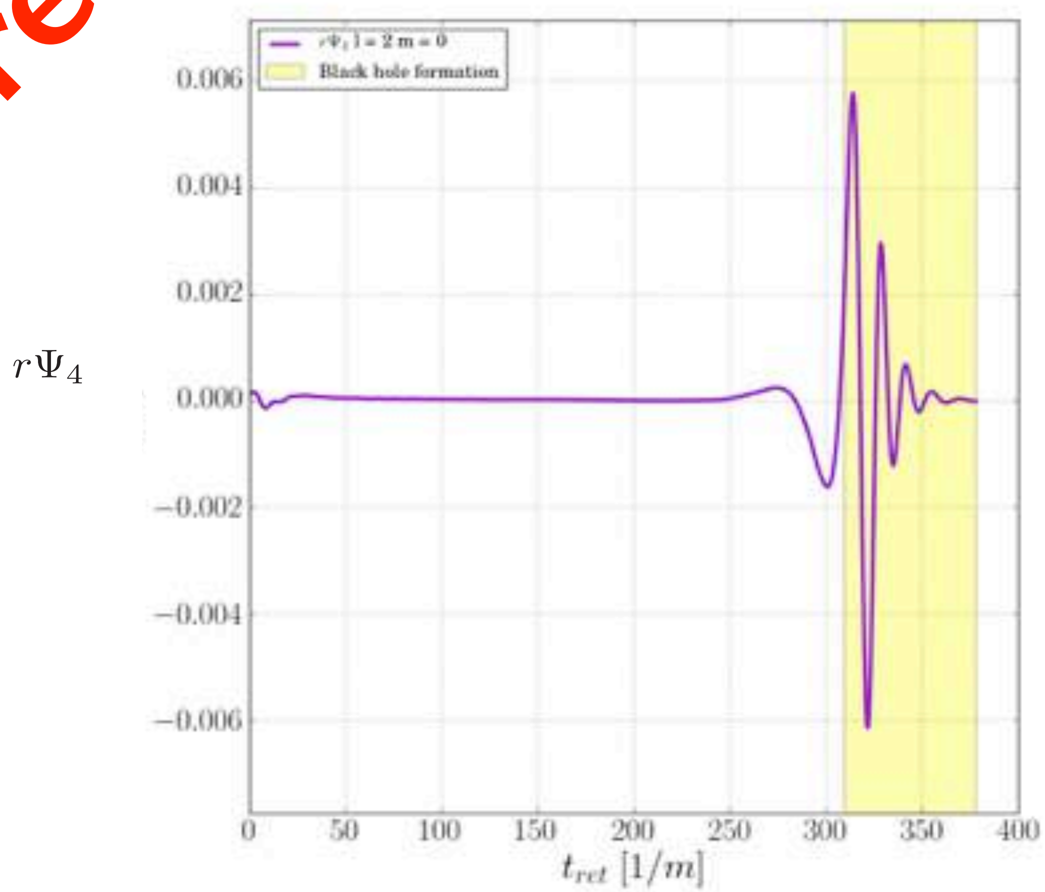


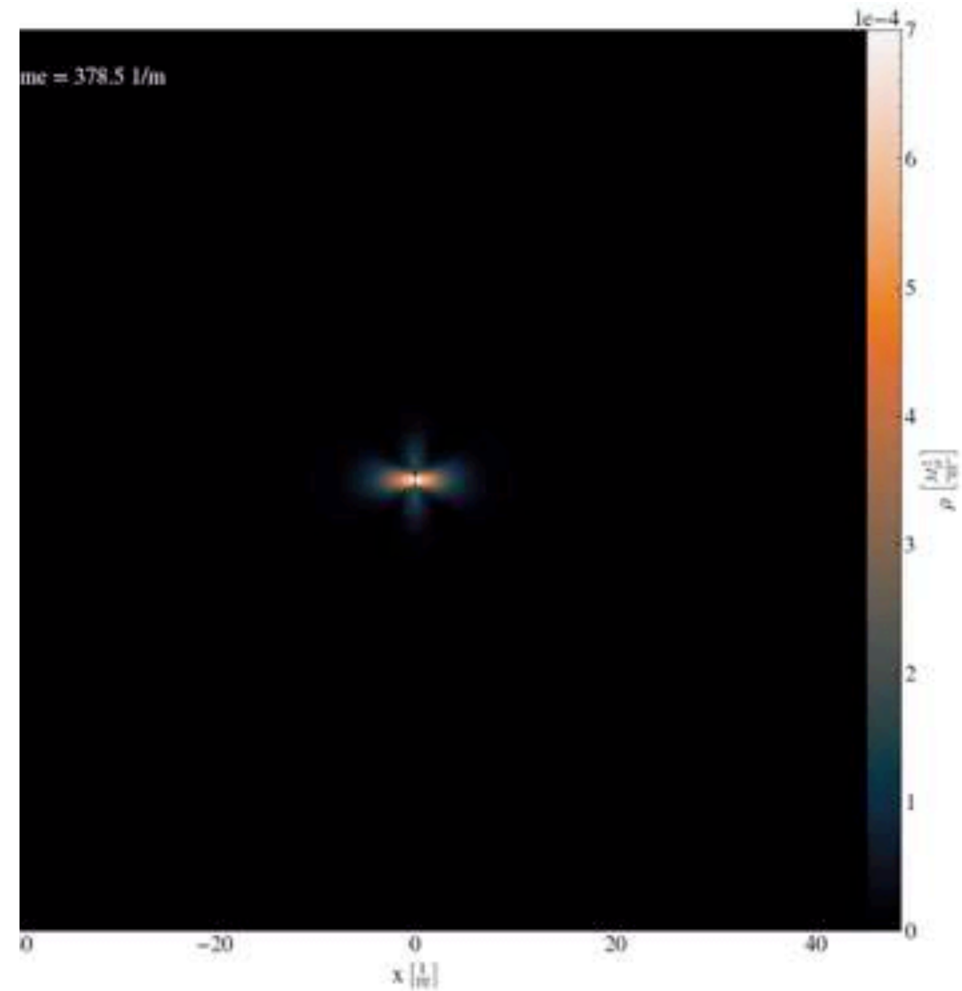
gravitational waves from oscillaton collisions

relevance for late universe processes — axion stars

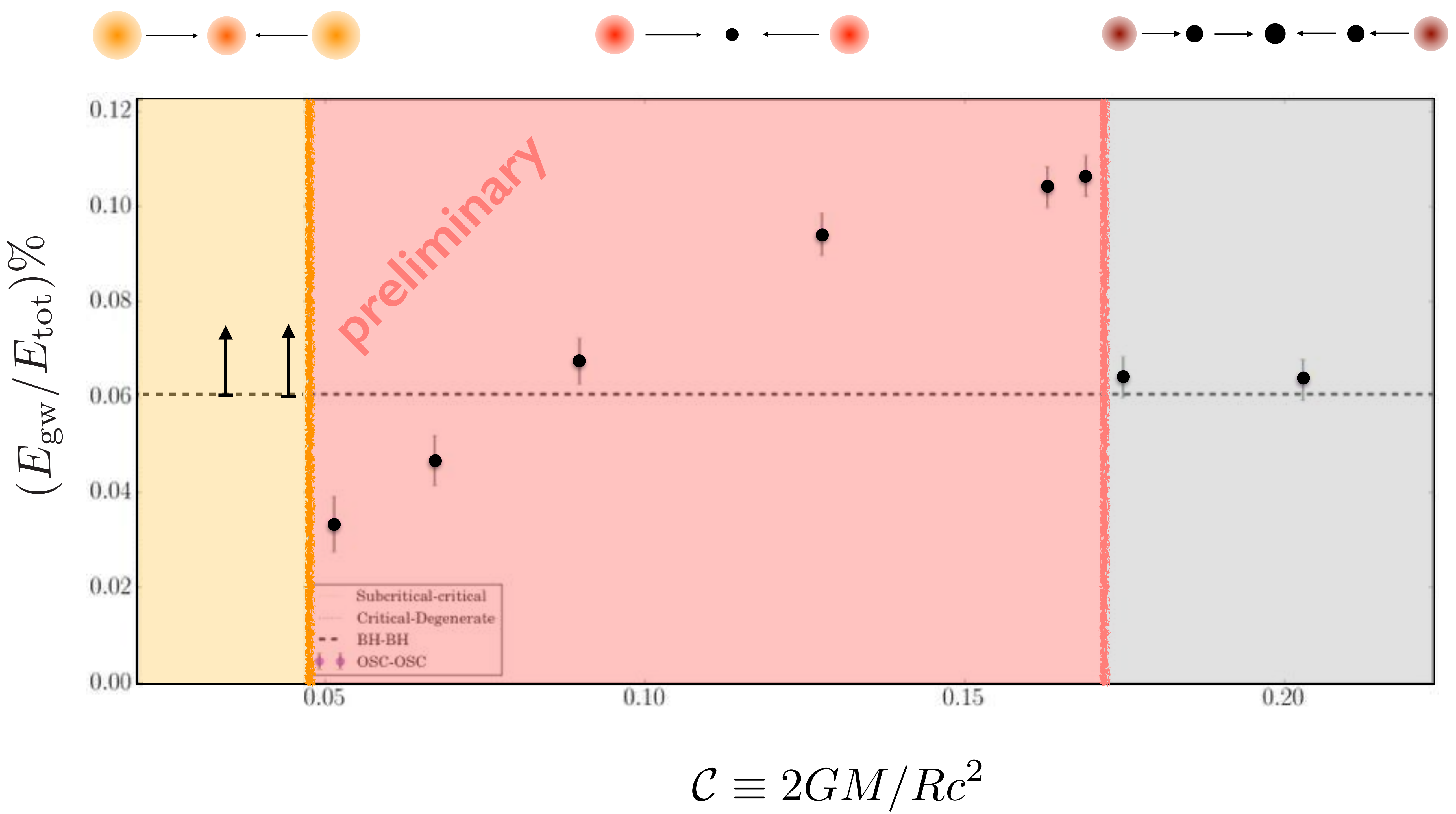
preliminary

Helfer, Lim, Garcia & Amin (in prep)

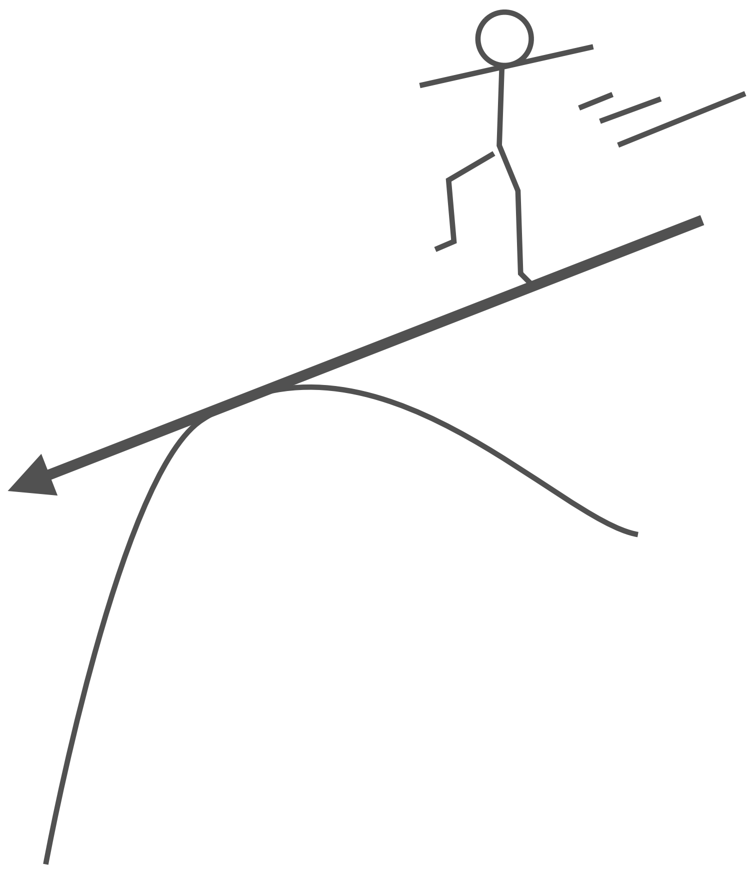




super emitters +
“sharp” transitions in gravitational wave output



end tangential digression



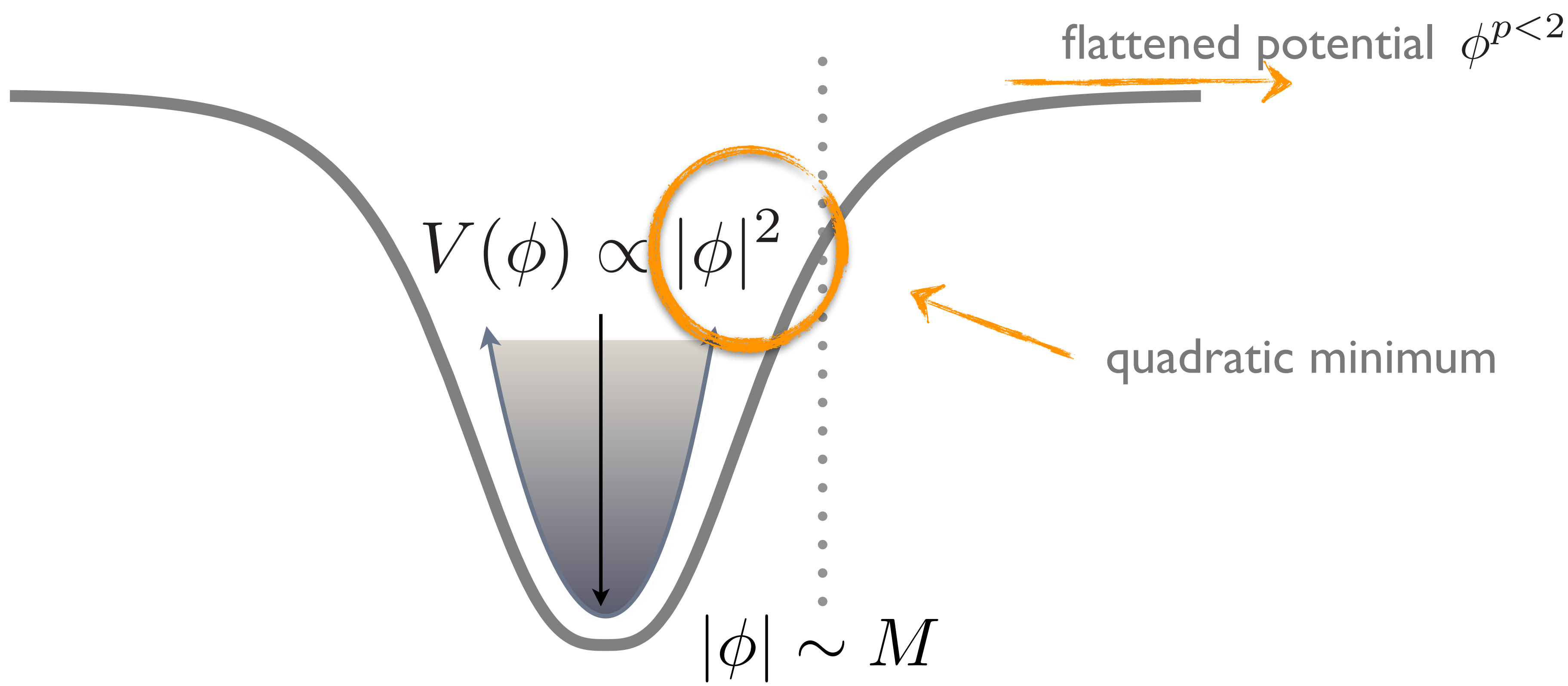
modeling end of inflation

SIMPLE

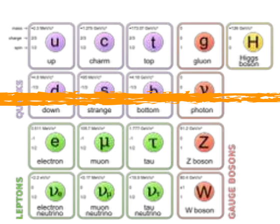
problem oriented

COMPLEX

end of inflation in "simple" models

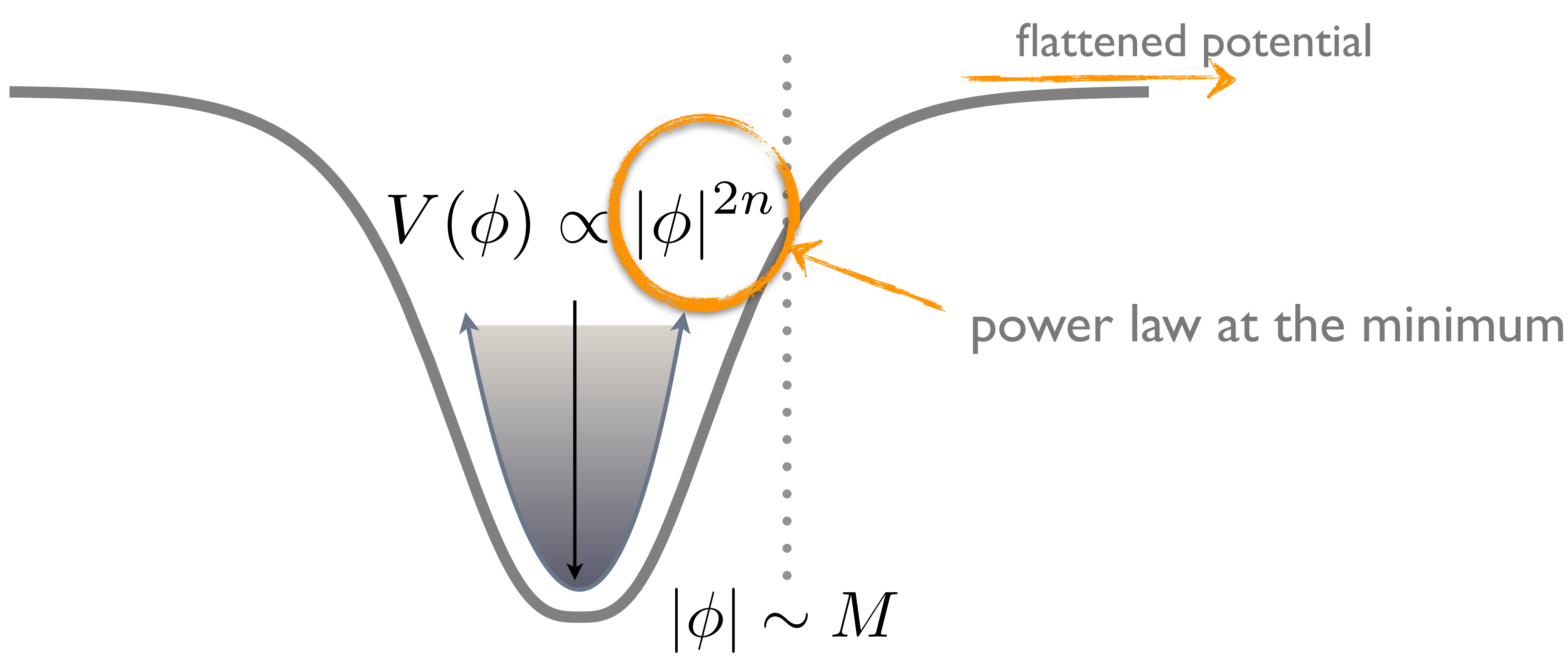


- shape of the potential (self couplings)
- ~~couplings to other fields~~

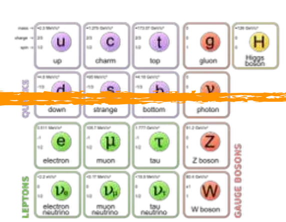


~~χ , ψ~~

end of inflation in “simple” models



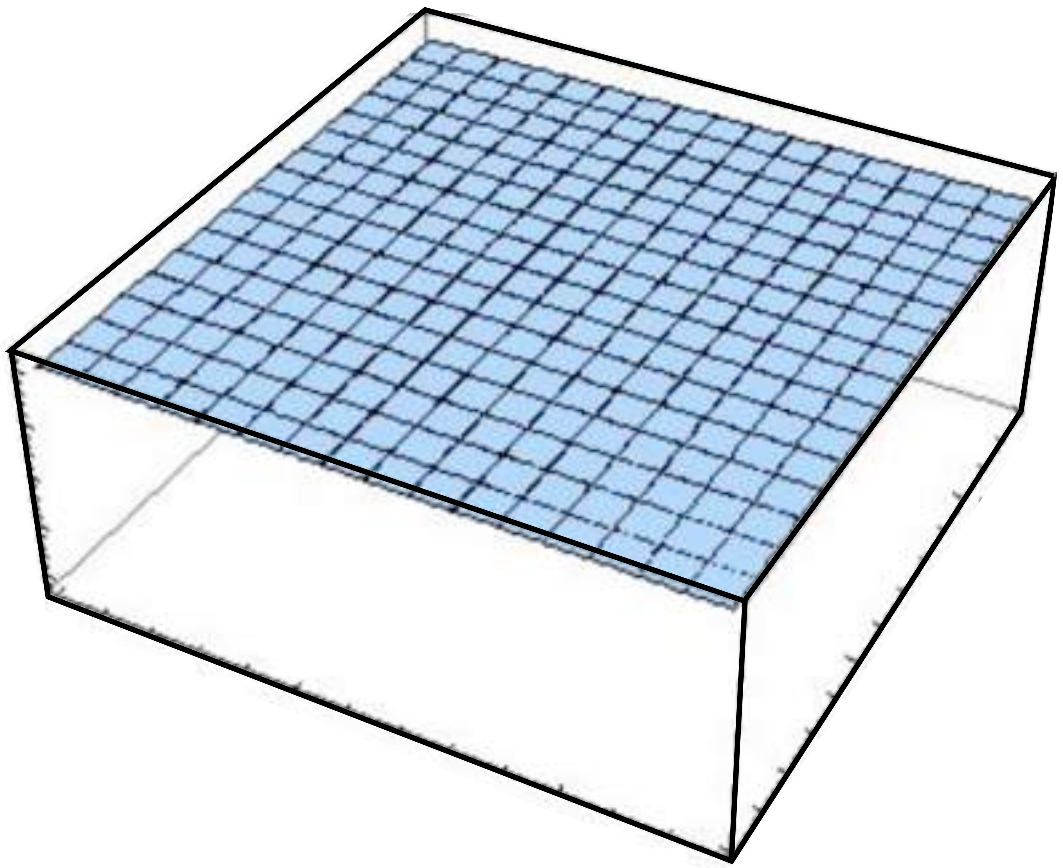
- shape of the potential (self couplings)
- ~~couplings to other fields~~

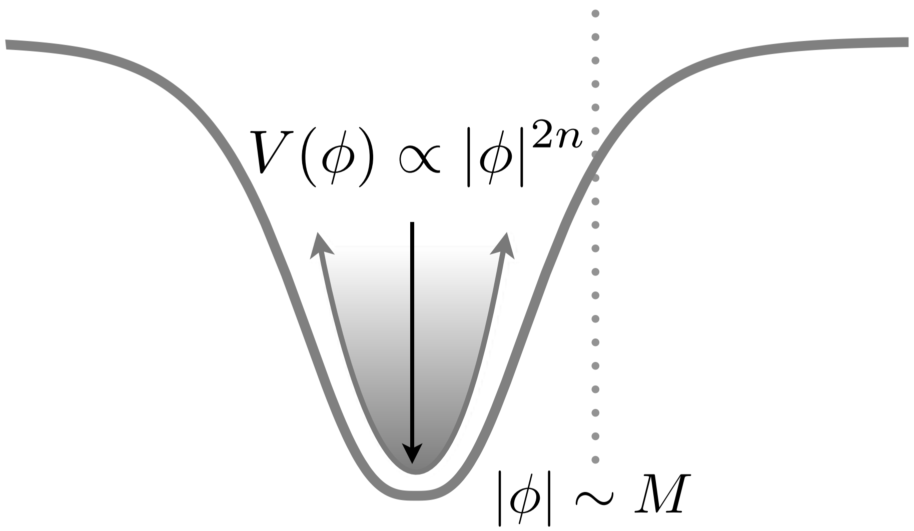


~~$\chi\ ,\psi$~~

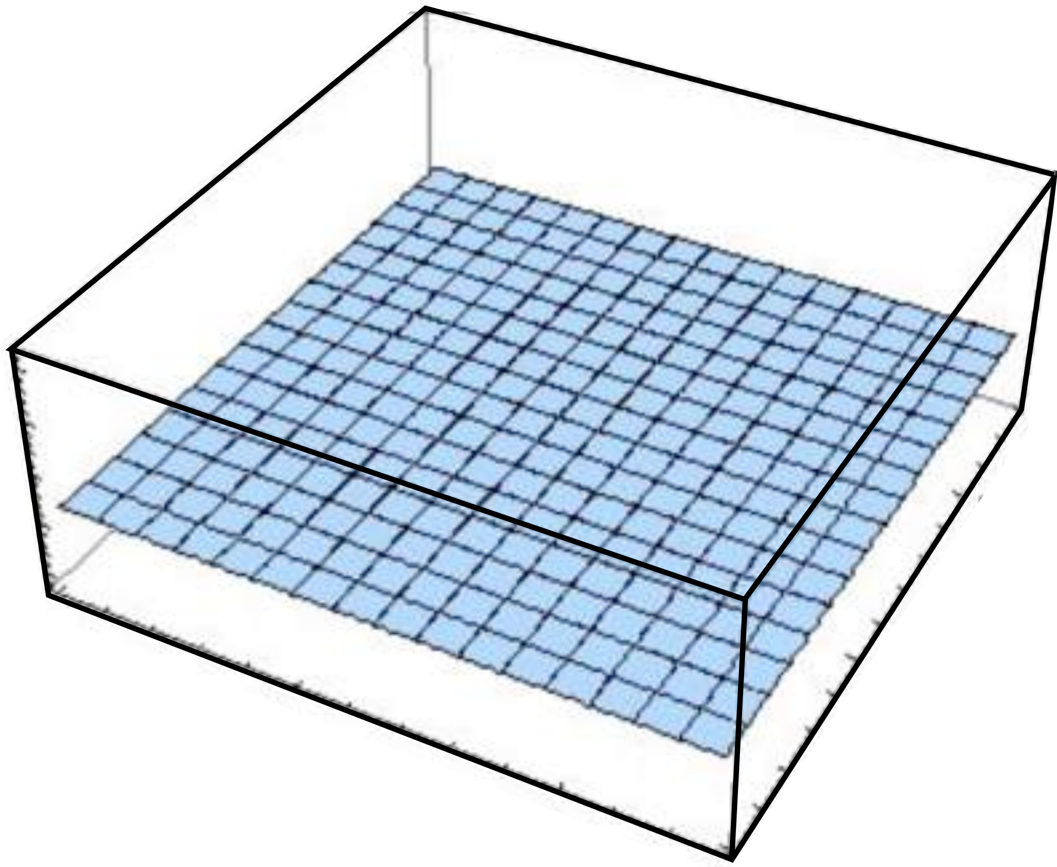
Lozanov & MA, 2017

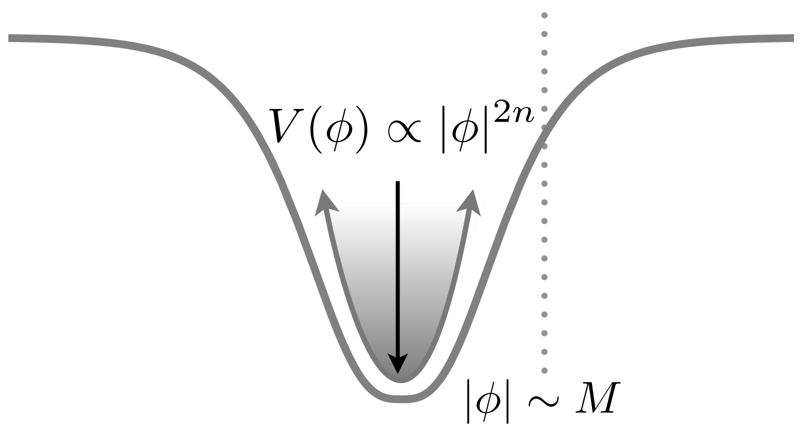
homogeneous dynamics





homogeneous eq. of state



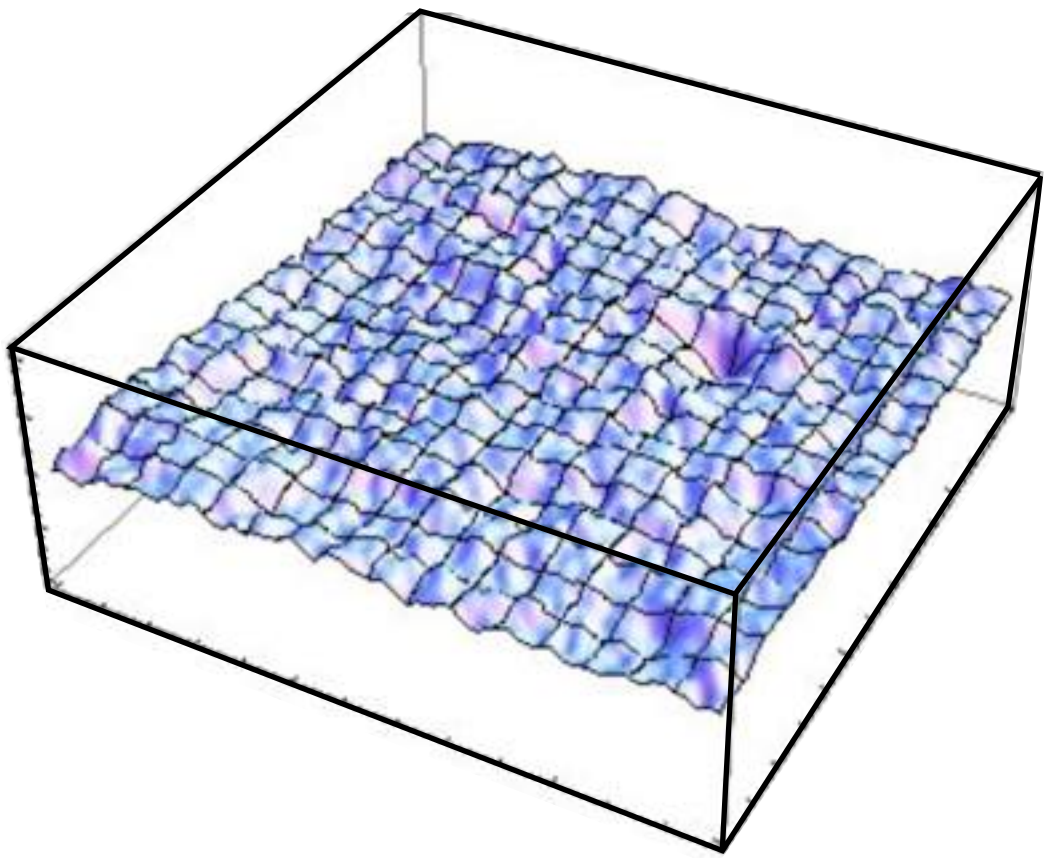


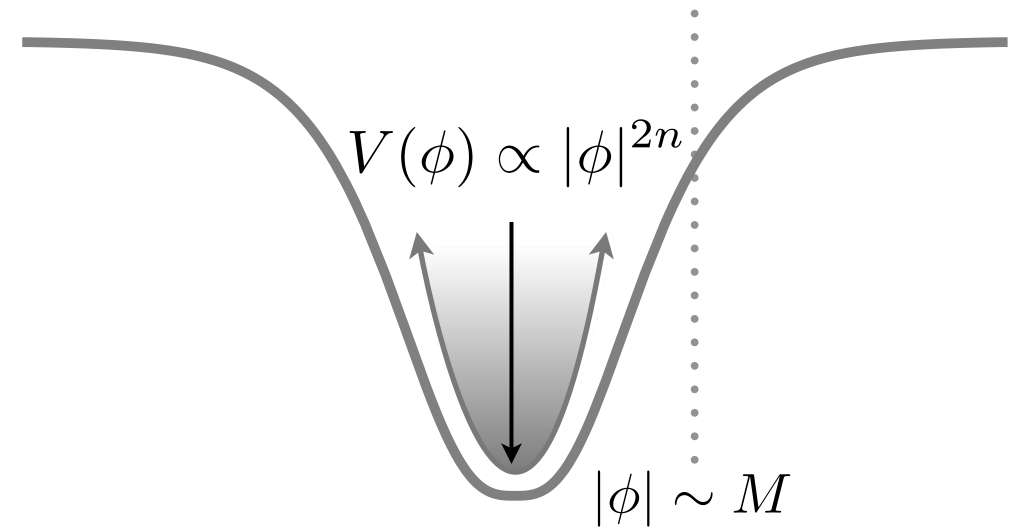
$$\text{eq. of state } w = \frac{\text{pressure}}{\text{density}}$$

$$w \equiv \frac{\langle p \rangle_s}{\langle \rho \rangle_s} = \frac{\langle \dot{\phi}^2/2 - (\nabla\phi)^2/6a^2 - V \rangle_s}{\langle \dot{\phi}^2/2 + (\nabla\phi)^2/2a^2 + V \rangle_s} \approx \frac{n-1}{n+1}$$

Turner (1983)
* can be obtained from a viral theorem

fragmentation is (almost) inevitable





(i) existence of wings (self-couplings) $M \lesssim m_{\rm pl}$

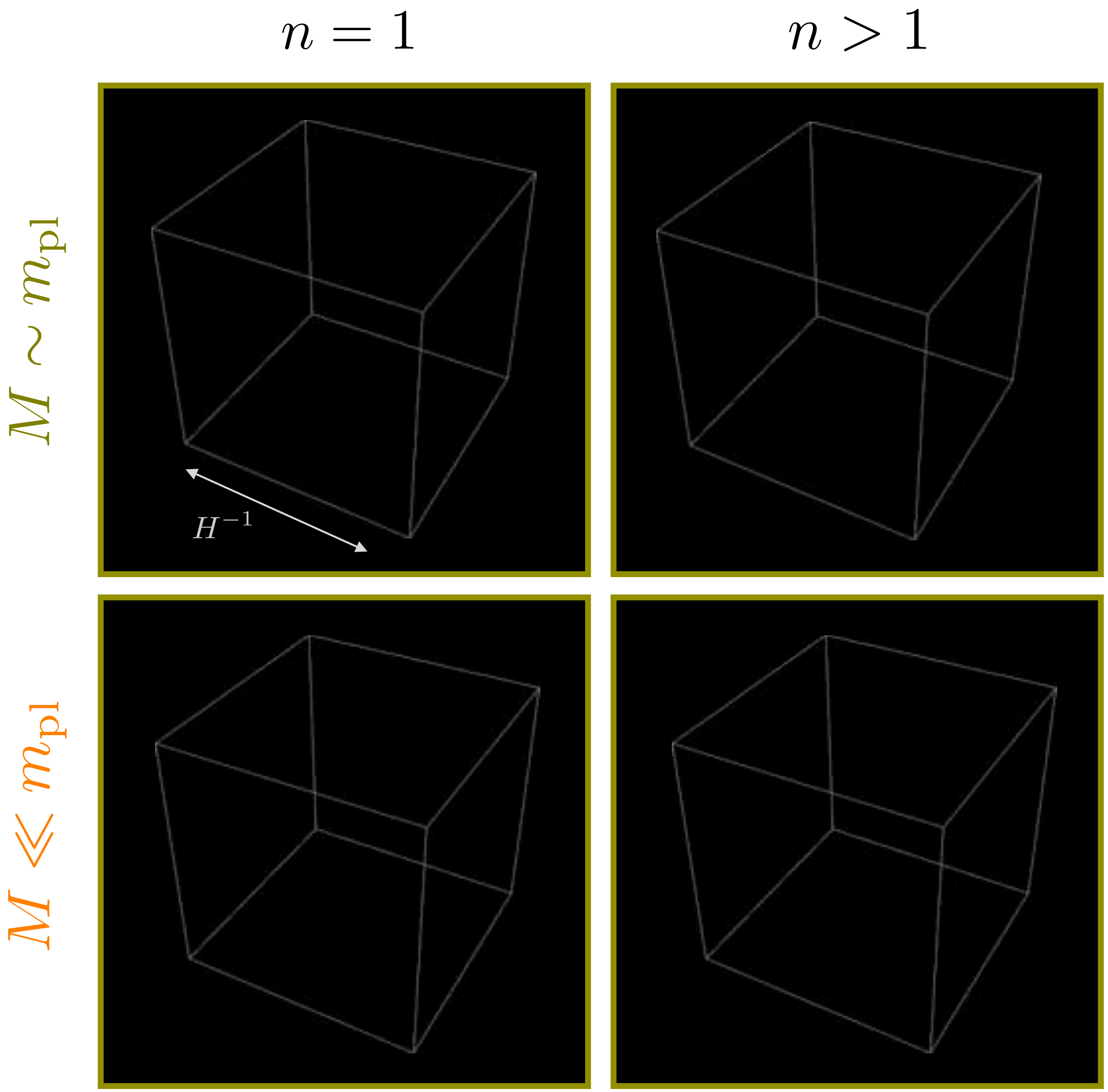
and/ or

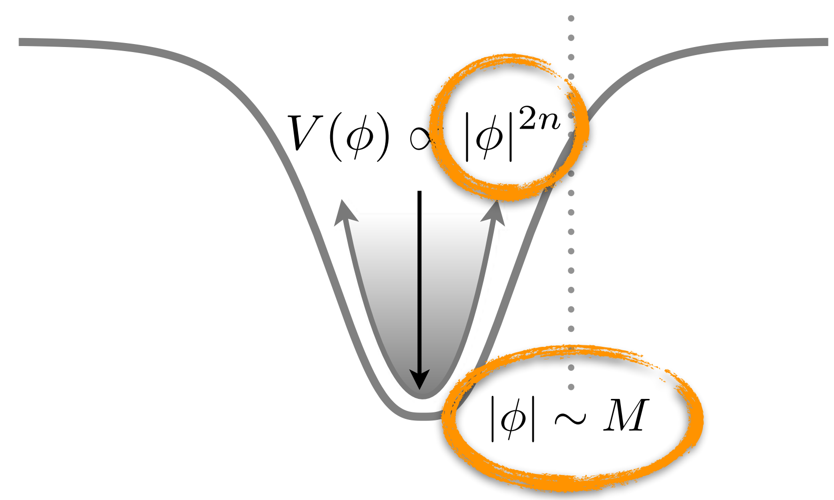
(ii) non-quadratic minimum $n > 1$

* directly related to competition between growth rate and expansion, but duration depends on parameters

result of fragmented dynamics

* after sufficient time





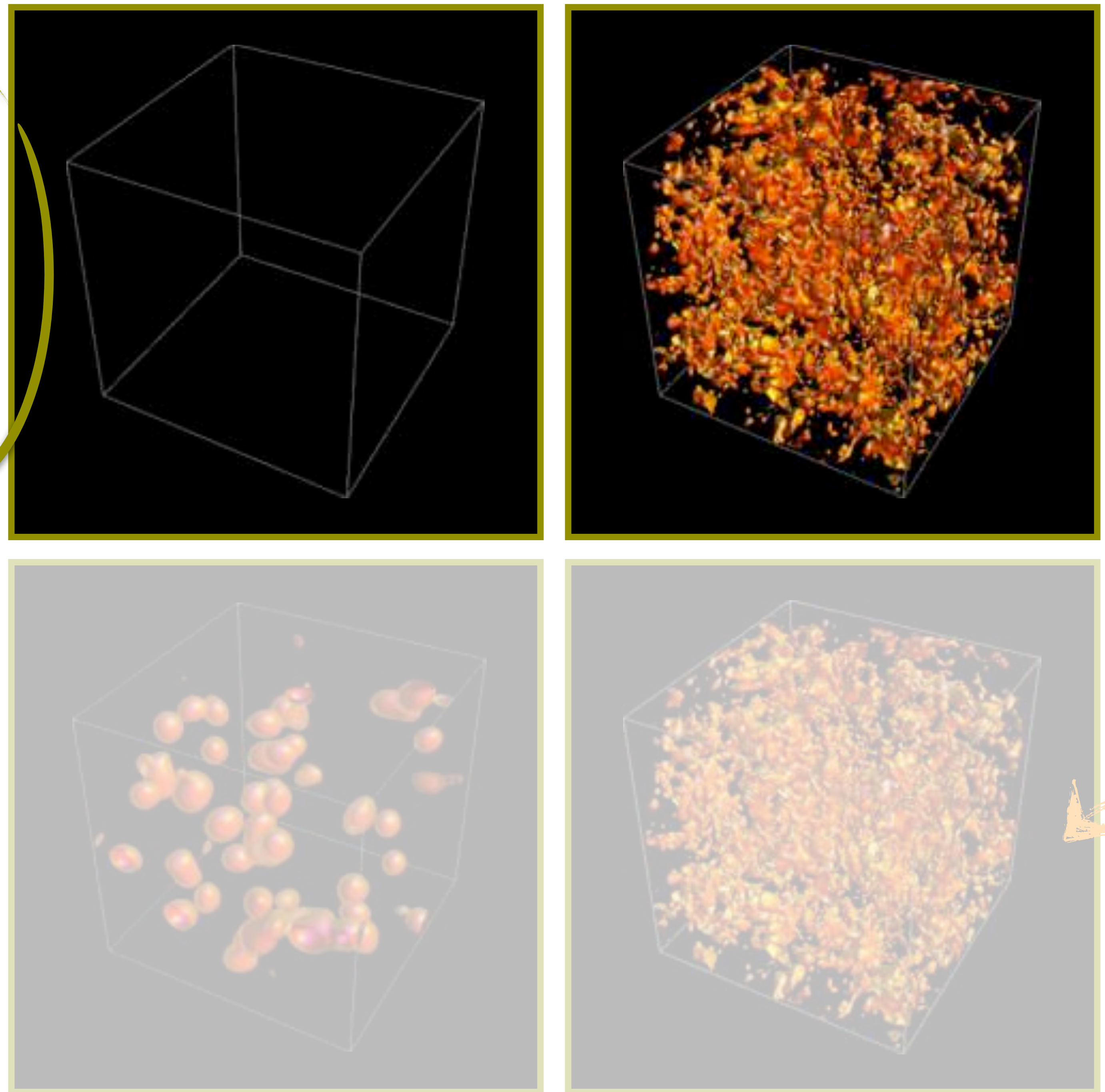
result of fragmented dynamics

* after sufficient time

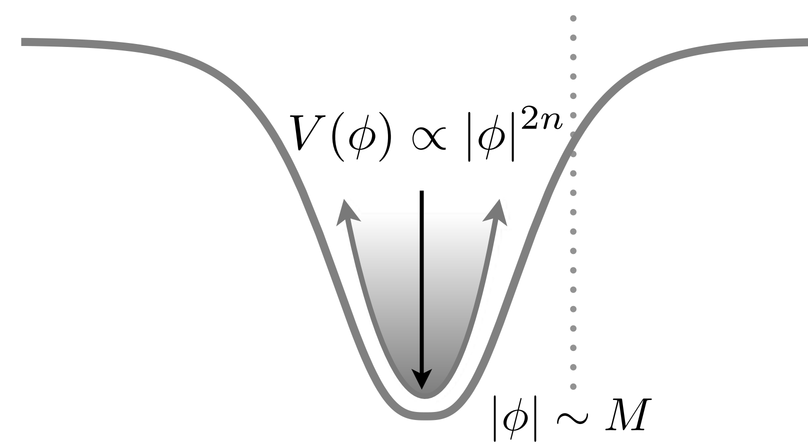
$n = 1$ $\quad$ $n > 1$

$M \sim m_{\rm pl}$

$M \ll m_{\rm pl}$

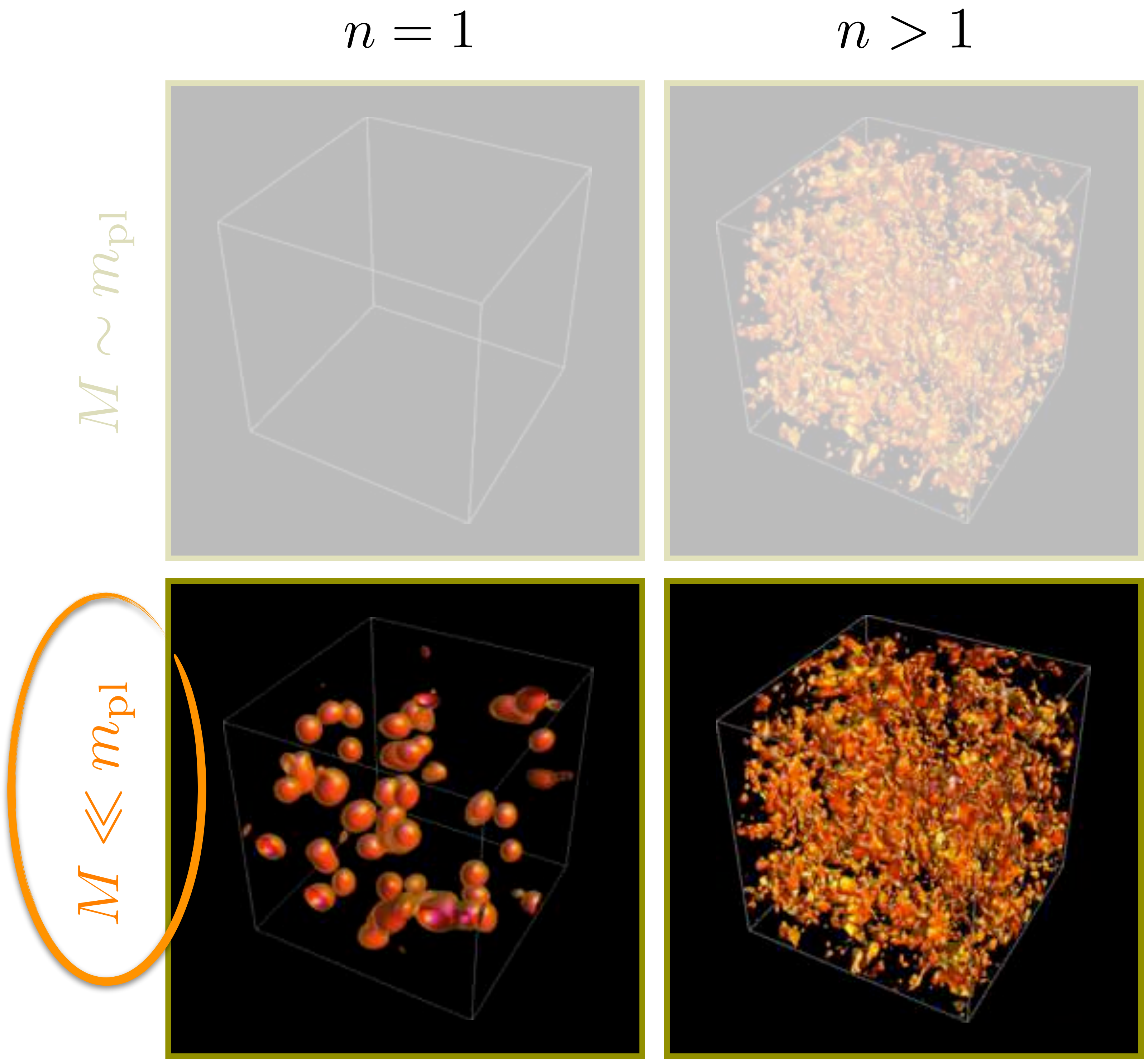


slow

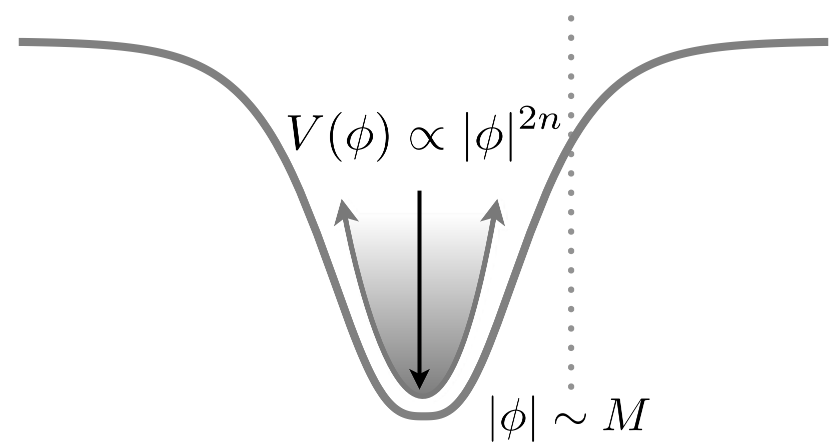


quickly

result of fragmented dynamics
* after sufficient time



slow



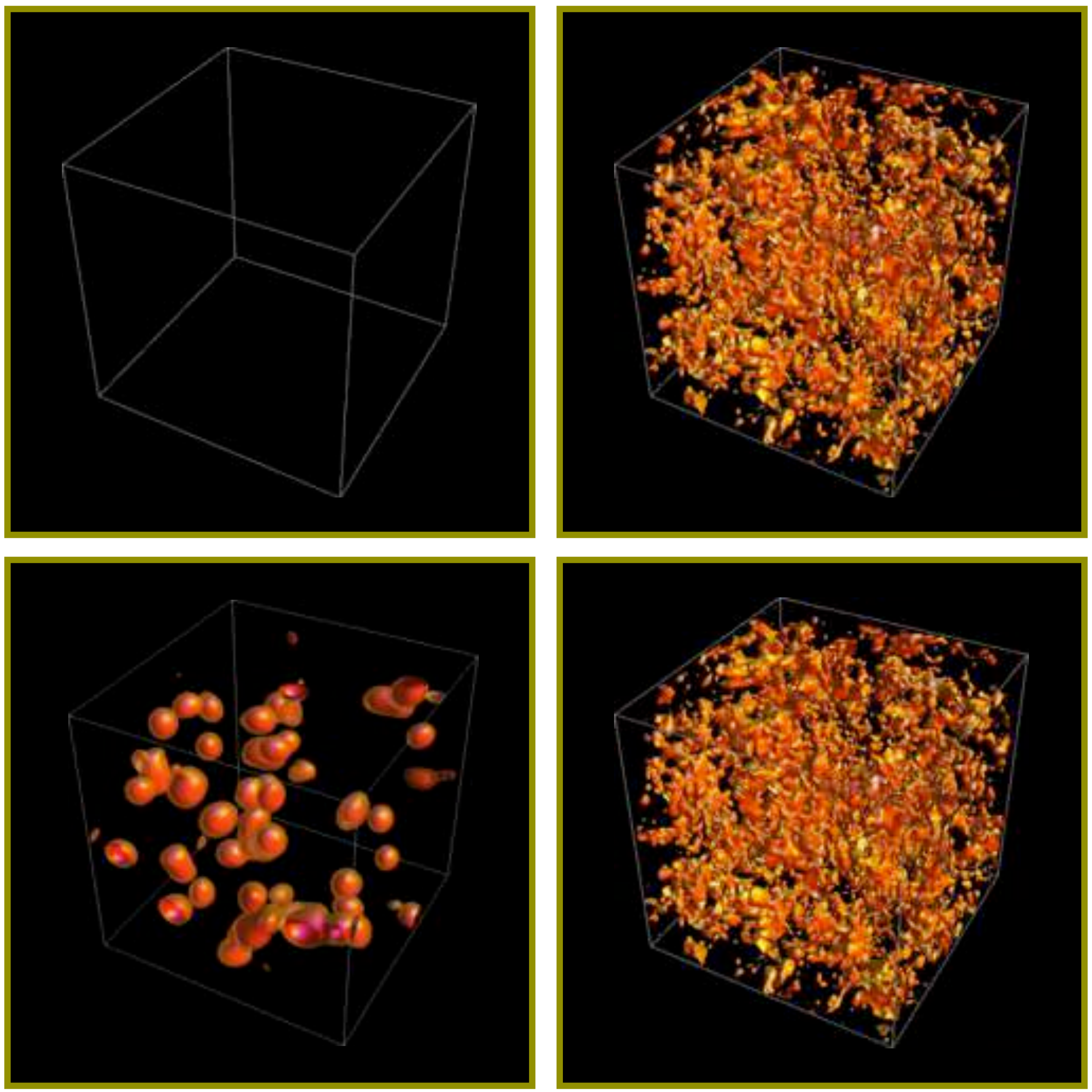
fast

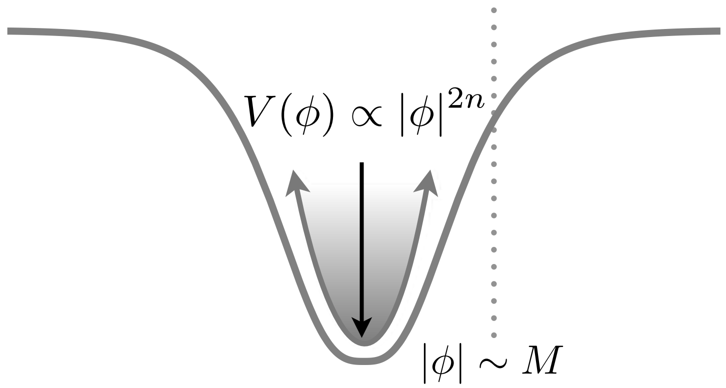
eq. of state
* after sufficient time

$n = 1$ | $n > 1$

$M \sim m_{\rm pl}$

$M \ll m_{\rm pl}$





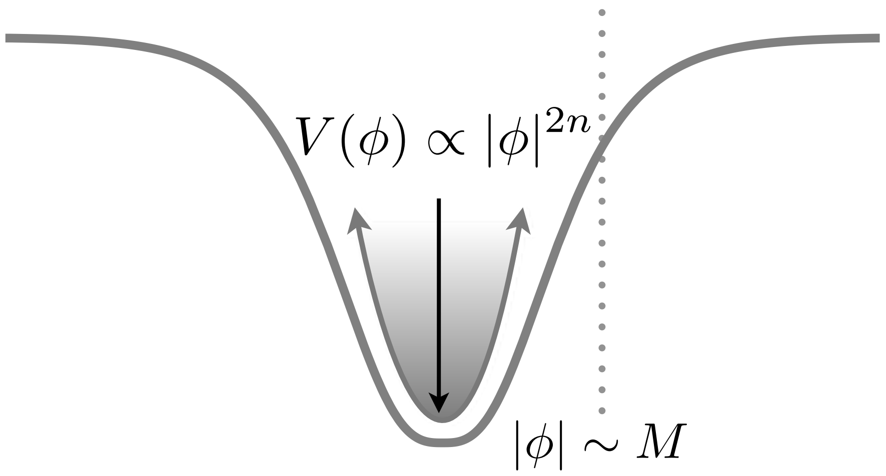
$$w \to \begin{cases} 0 & \text{if } n = 1 \\ 1/3 & \text{if } n > 1 \end{cases}$$

independent of M

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

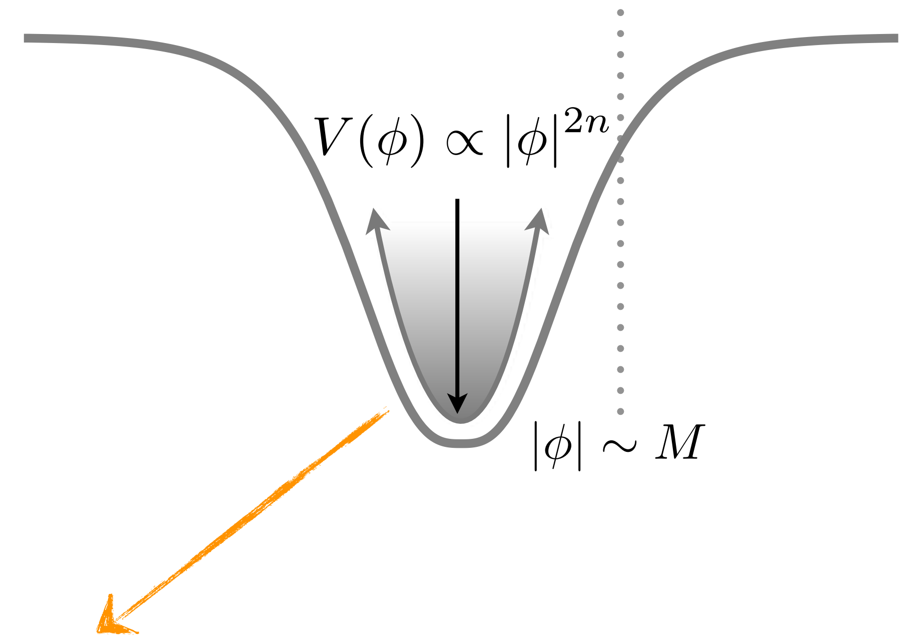
an upper bound on duration to radiation domination $n > 1$

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

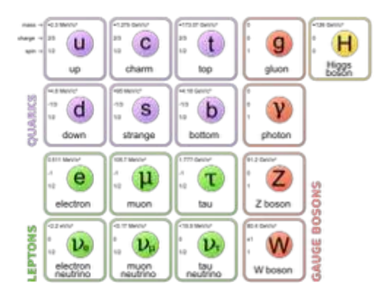


an upper bound on duration to radiation domination

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

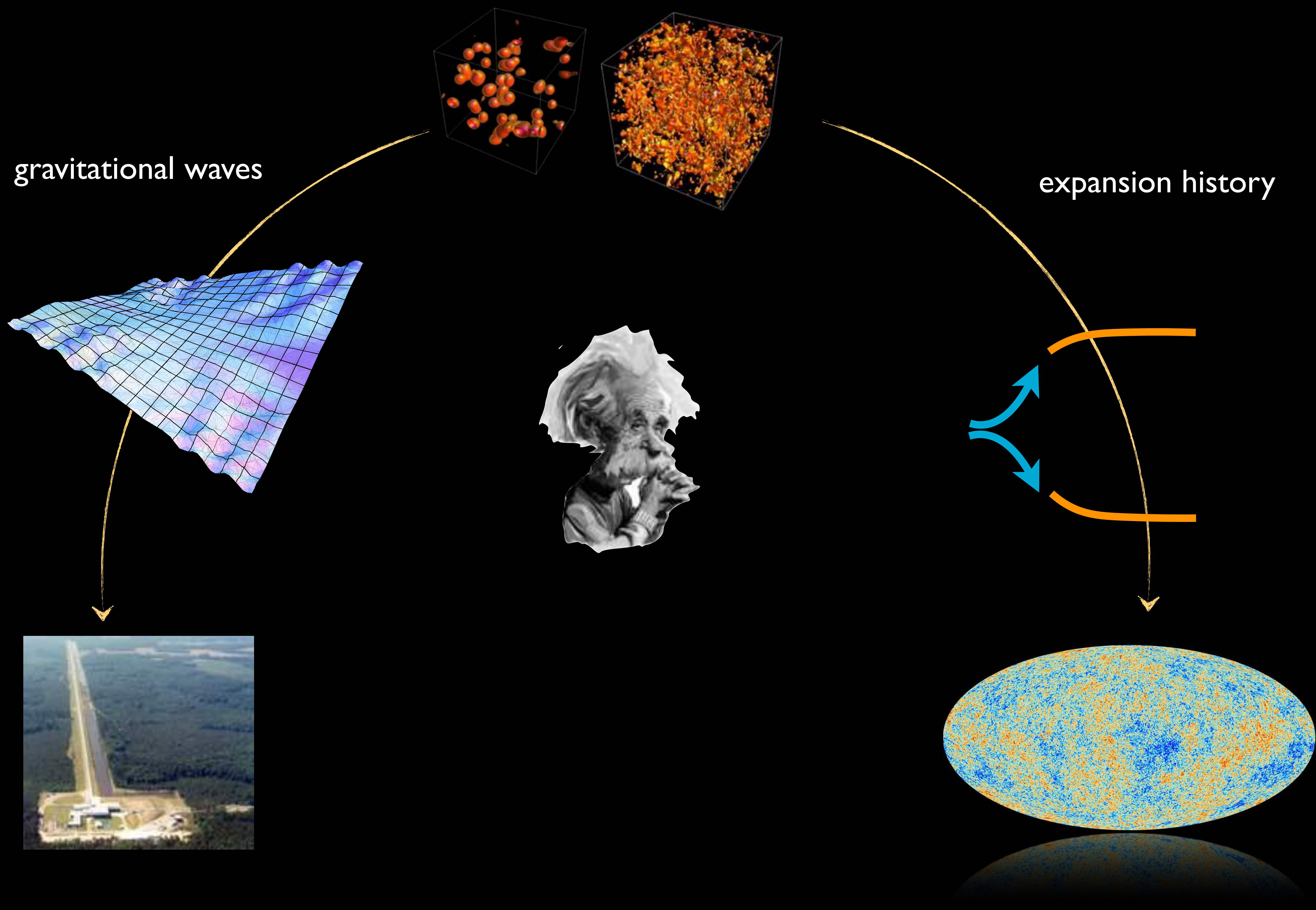


additional *light (massless) fields* can only decrease the duration!

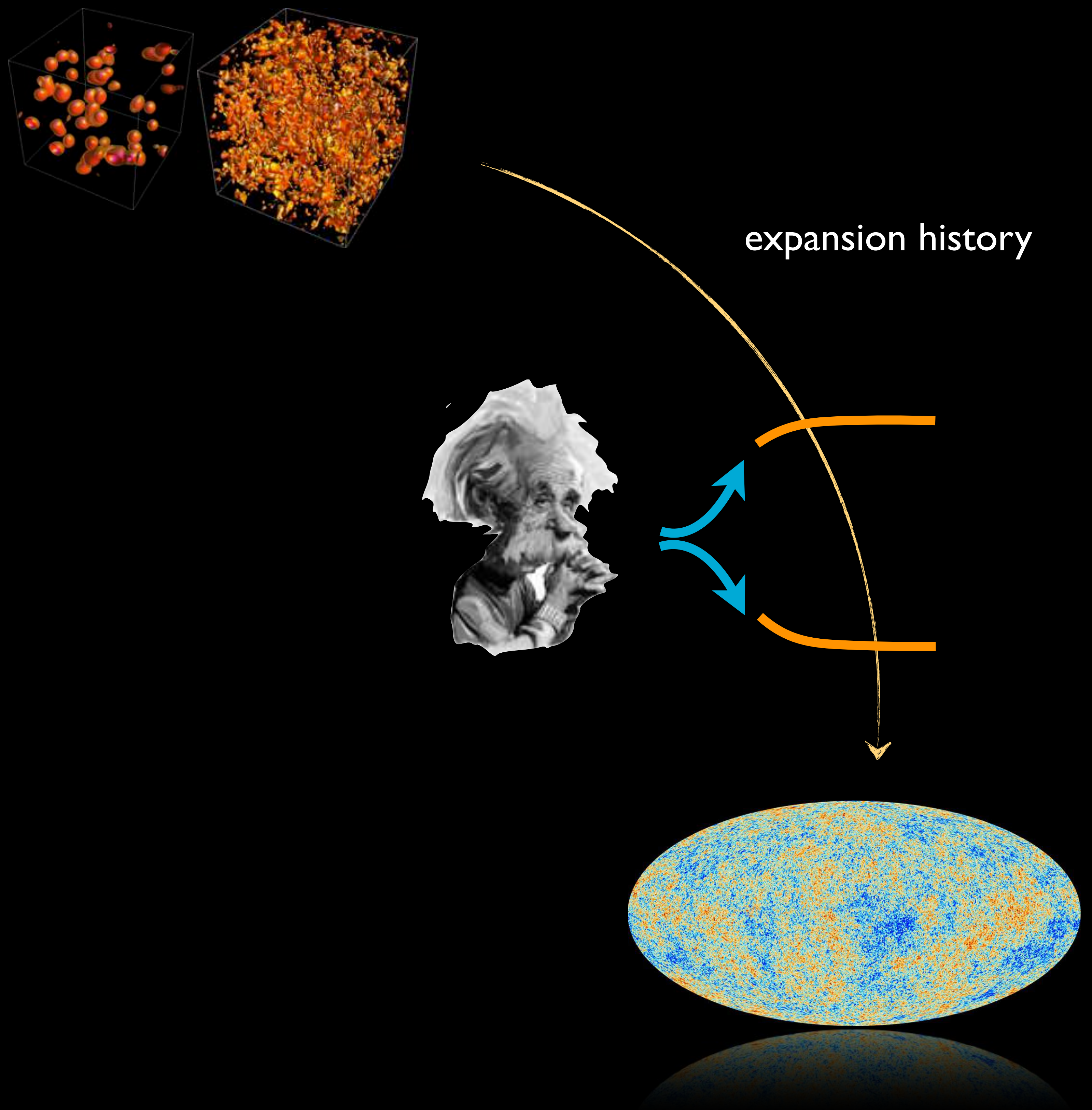


* decay to significantly massive fields can change this conclusion

consequences ?



expansion history



expansion history — eq. of state

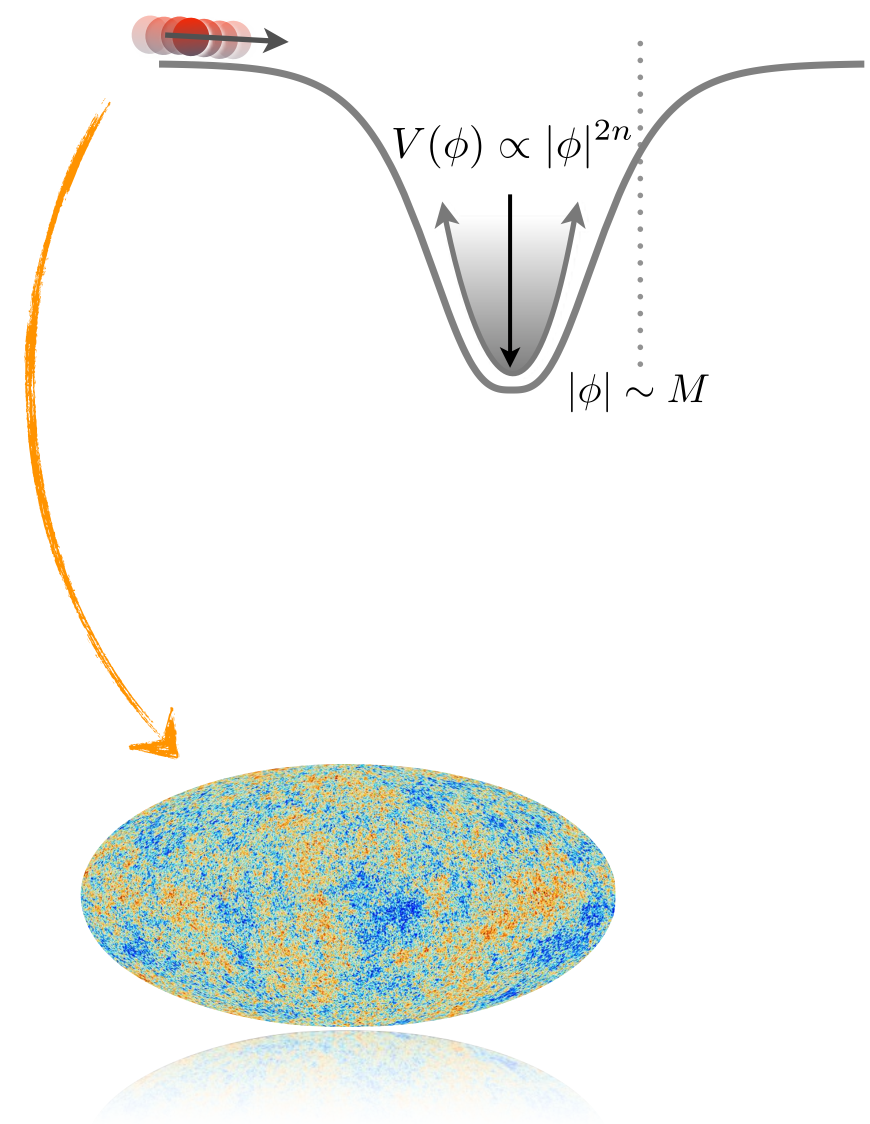
Einstein's Equations

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

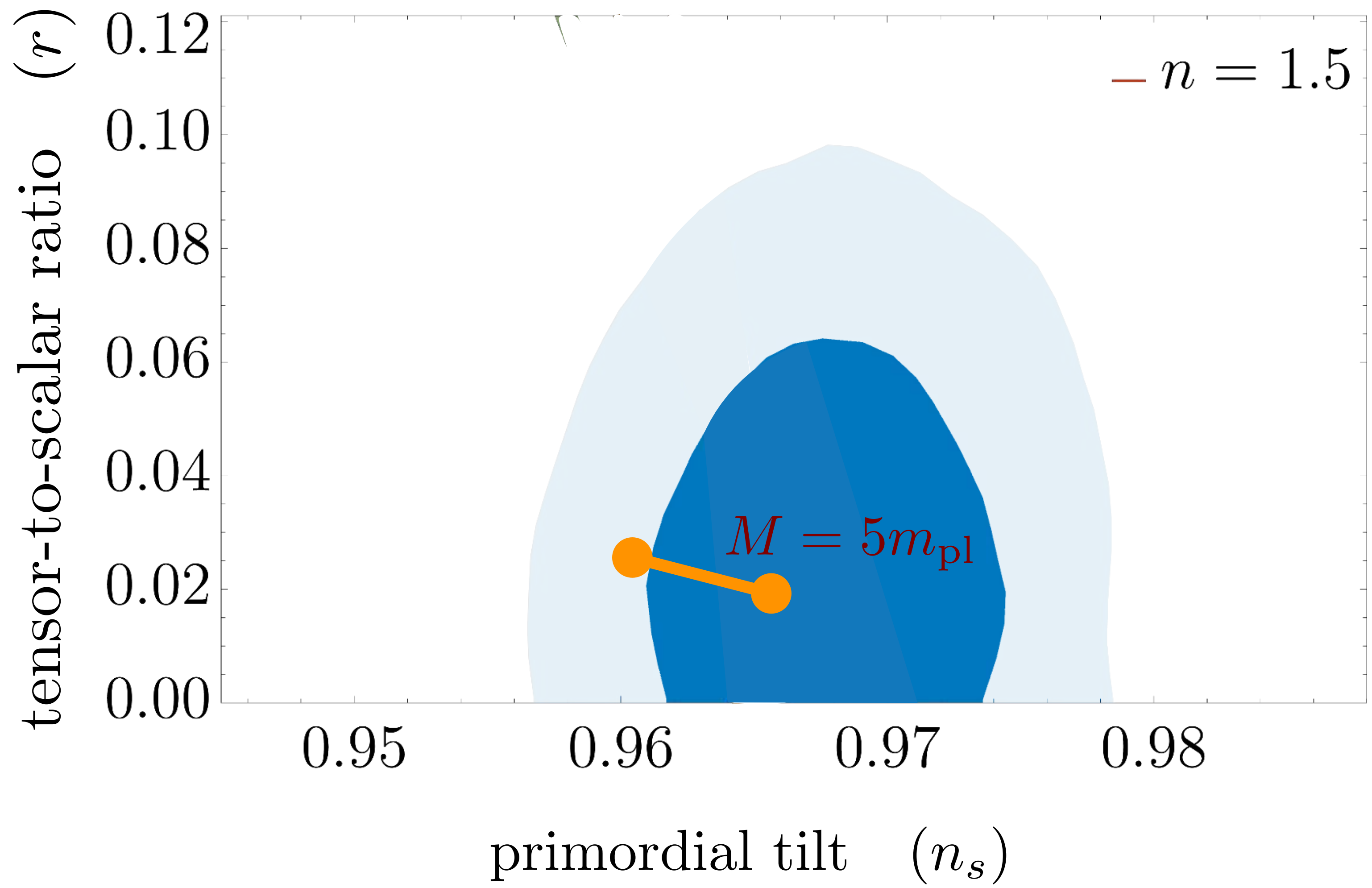
$$a(t) \propto t^{\frac{2}{3(1+w)}}$$

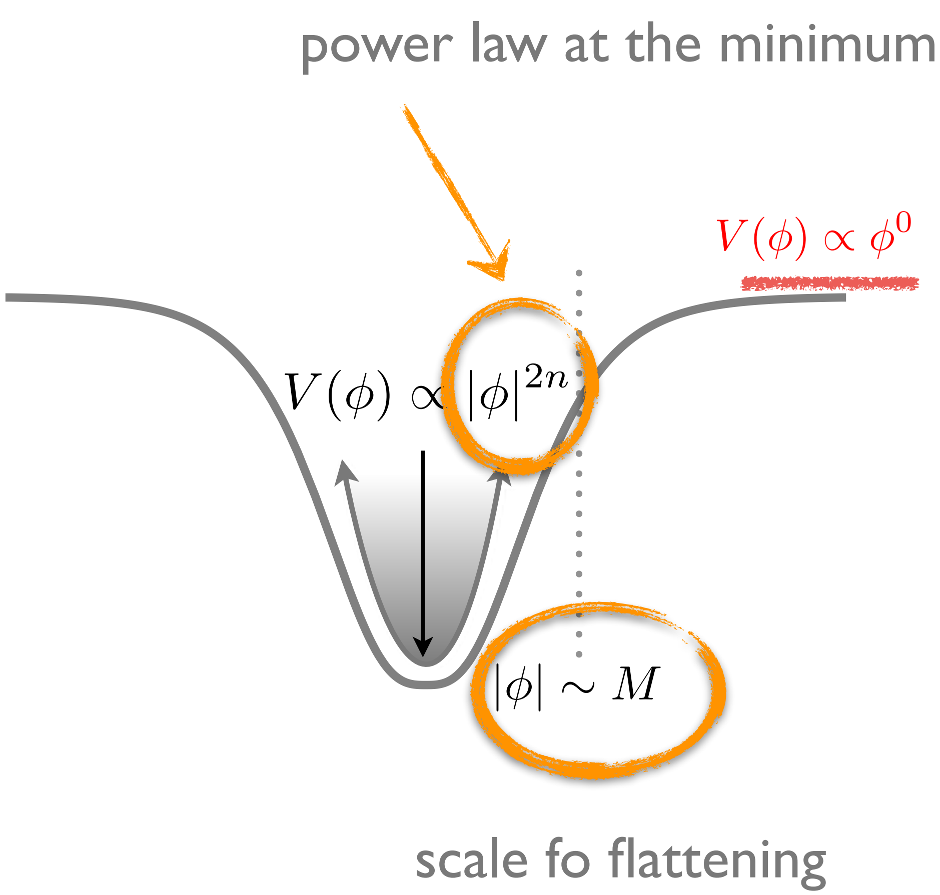
$$\text{eq. of state } w = \frac{\text{pressure}}{\text{density}}$$

impacts
mapping of scales



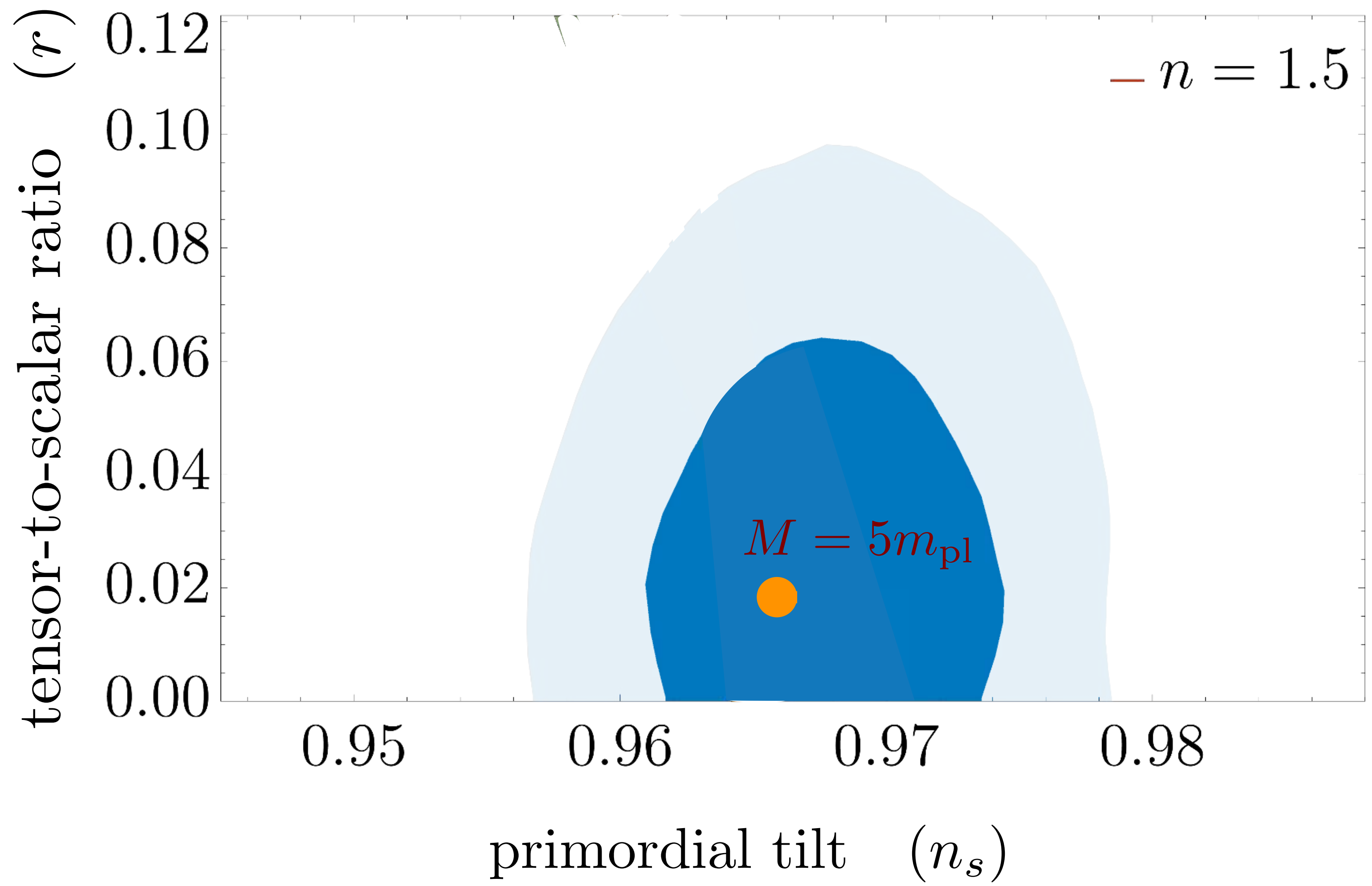
implications for CMB observables

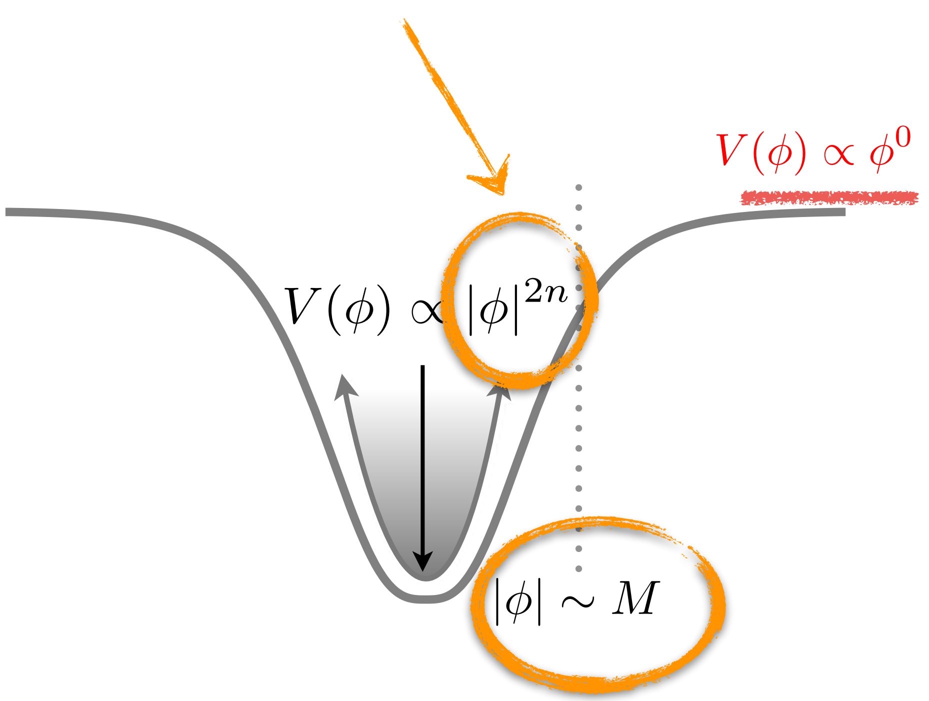




* non-quadratic minimum

reduction in uncertainty!

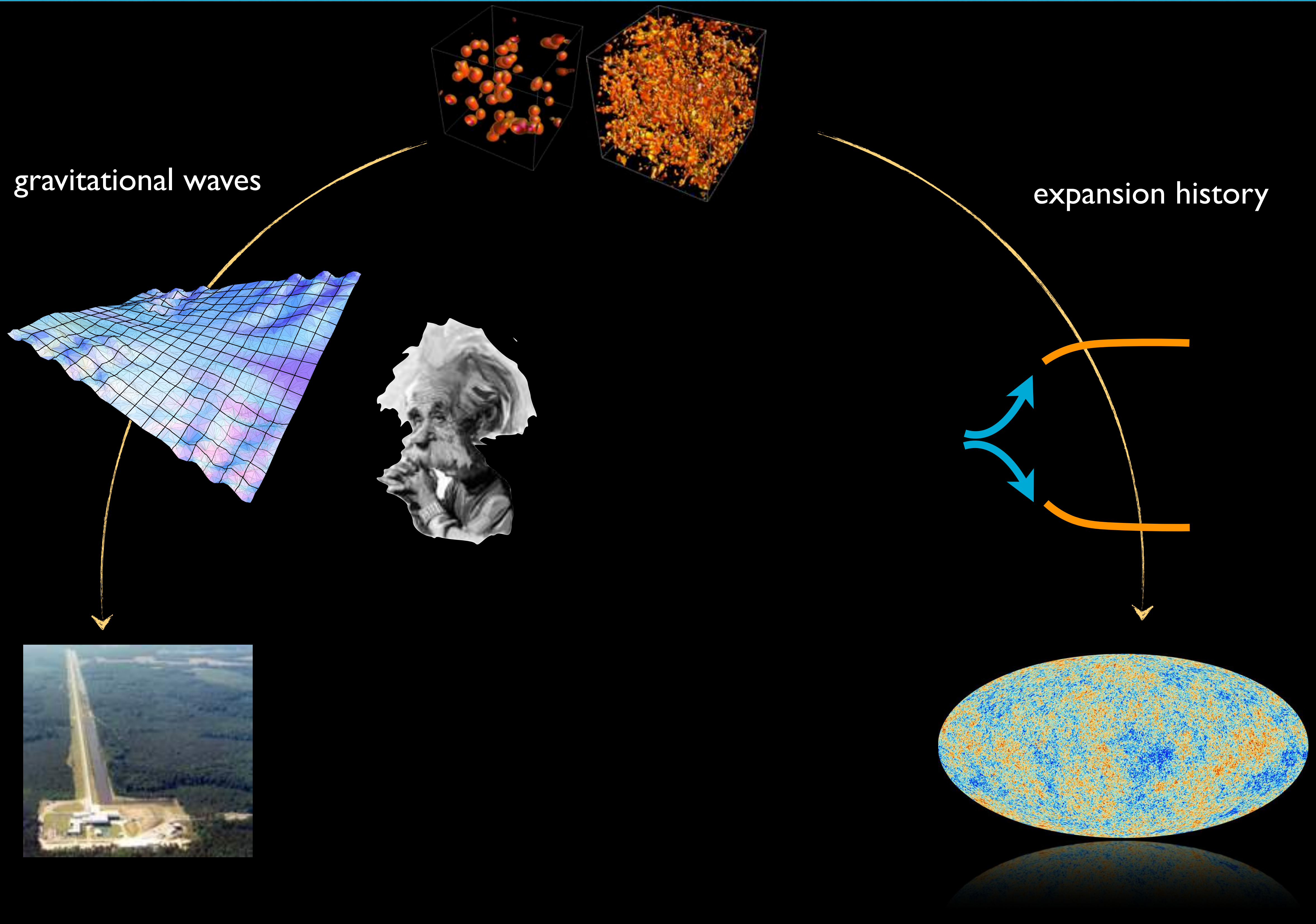




$$\Delta N_{\rm rad} \sim \begin{cases} 1 & M \lesssim 10^{-2} m_{\rm Pl}\,, \\ \dfrac{n+1}{3} \ln\left(\dfrac{\kappa}{\Delta\kappa}\, \dfrac{10M}{m_{\rm Pl}}\right) & M \gtrsim 10^{-2} m_{\rm Pl}\,. \end{cases}$$

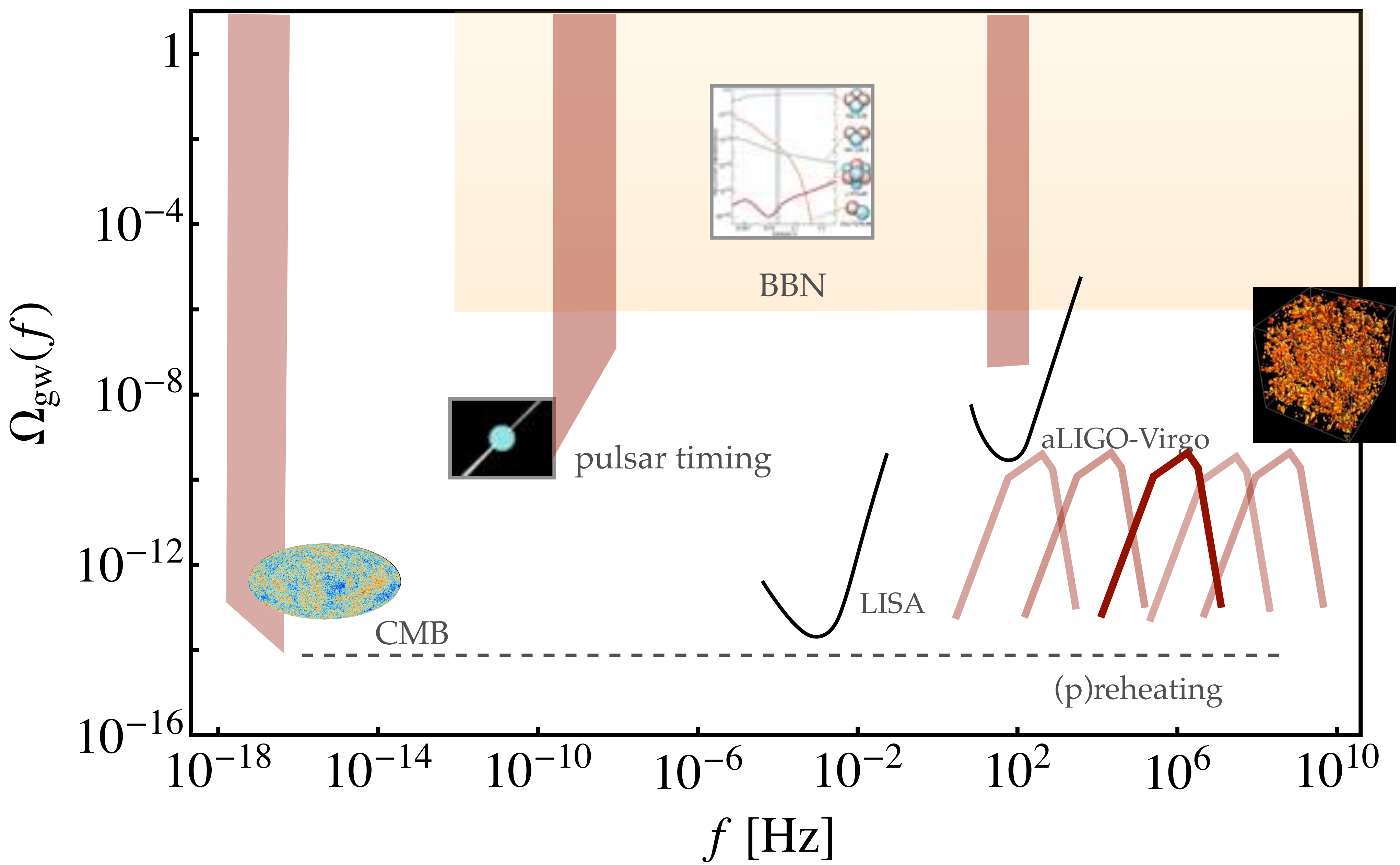
* non-quadratic minimum

consequences ?



stochastic gravitational waves

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



aLIGO-Virgo 2017
Amin et. al 2014

end of inflation

SIMPLE

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

detailed models

COMPLEX

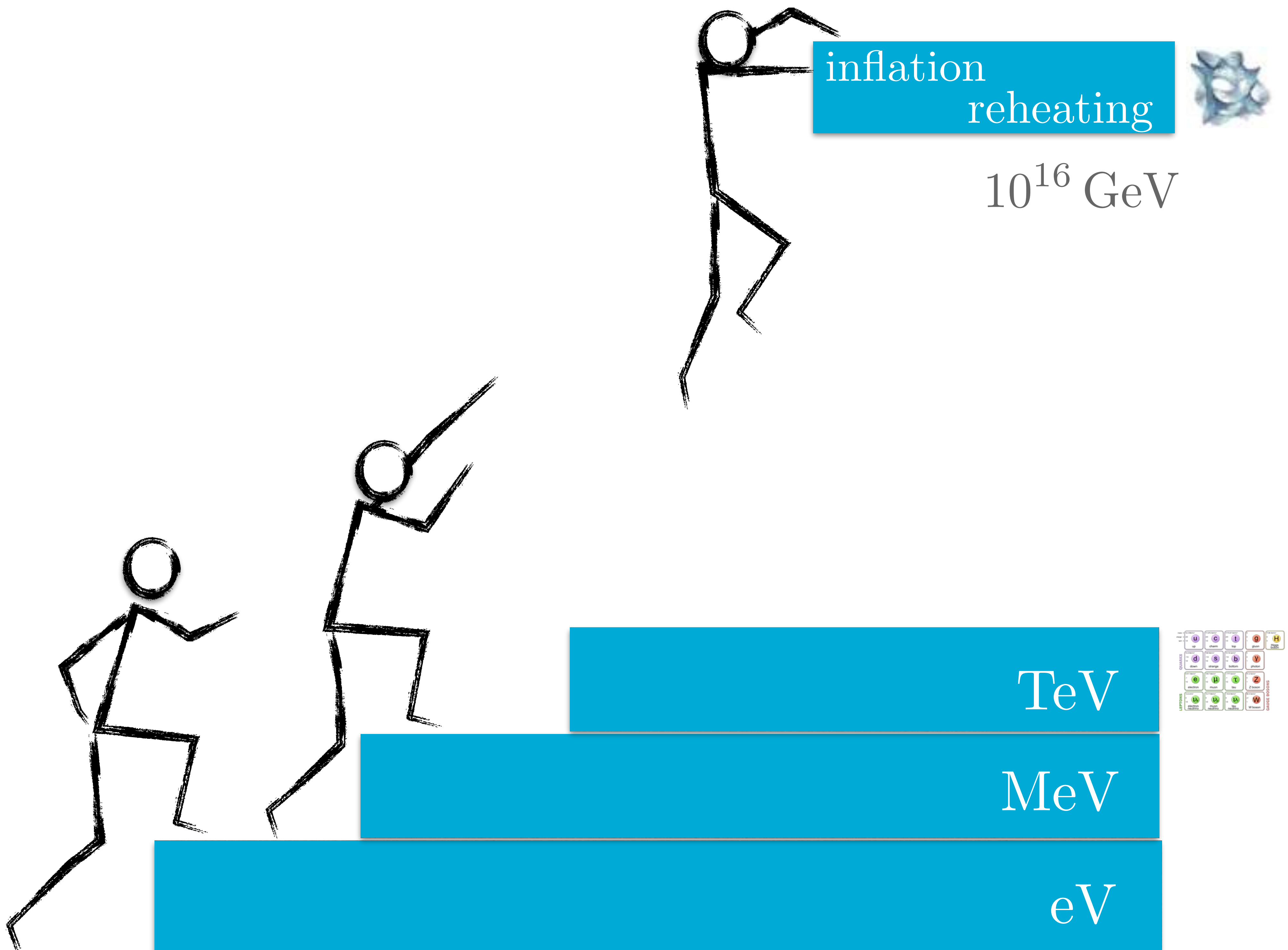
end of inflation

SIMPLE

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

detailed models

COMPLEX

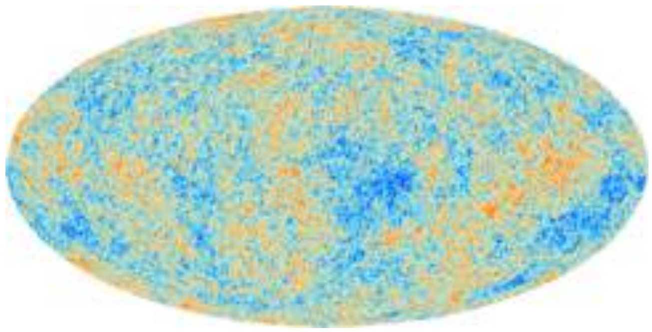

inflation
reheating
10^{16} GeV
TeV
MeV
eV

theory : its complicated (probably)

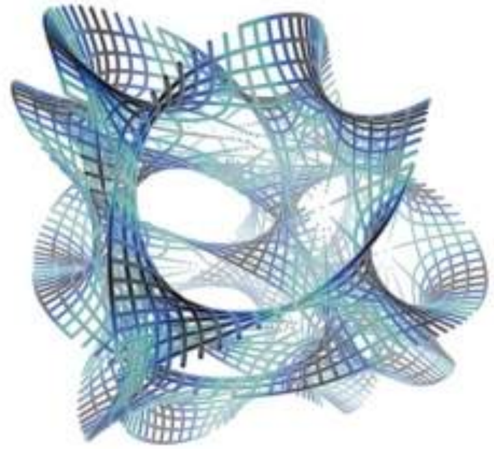
- inflation
- reheating after inflation

a statistical approach?

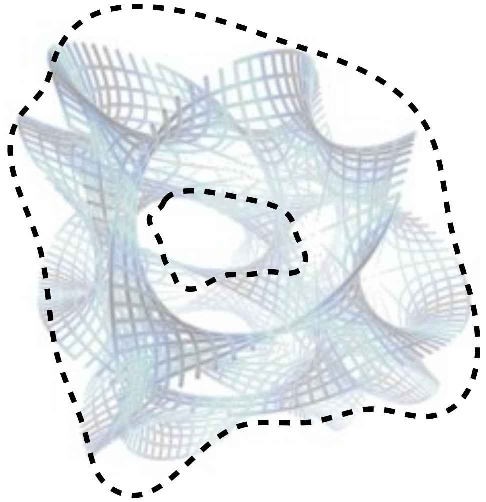
- **observations:** early universe is simple



- **theory:** not so much …

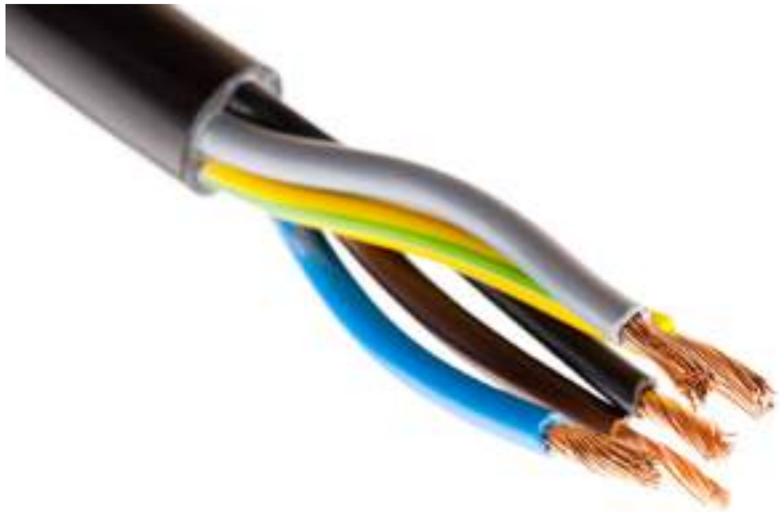


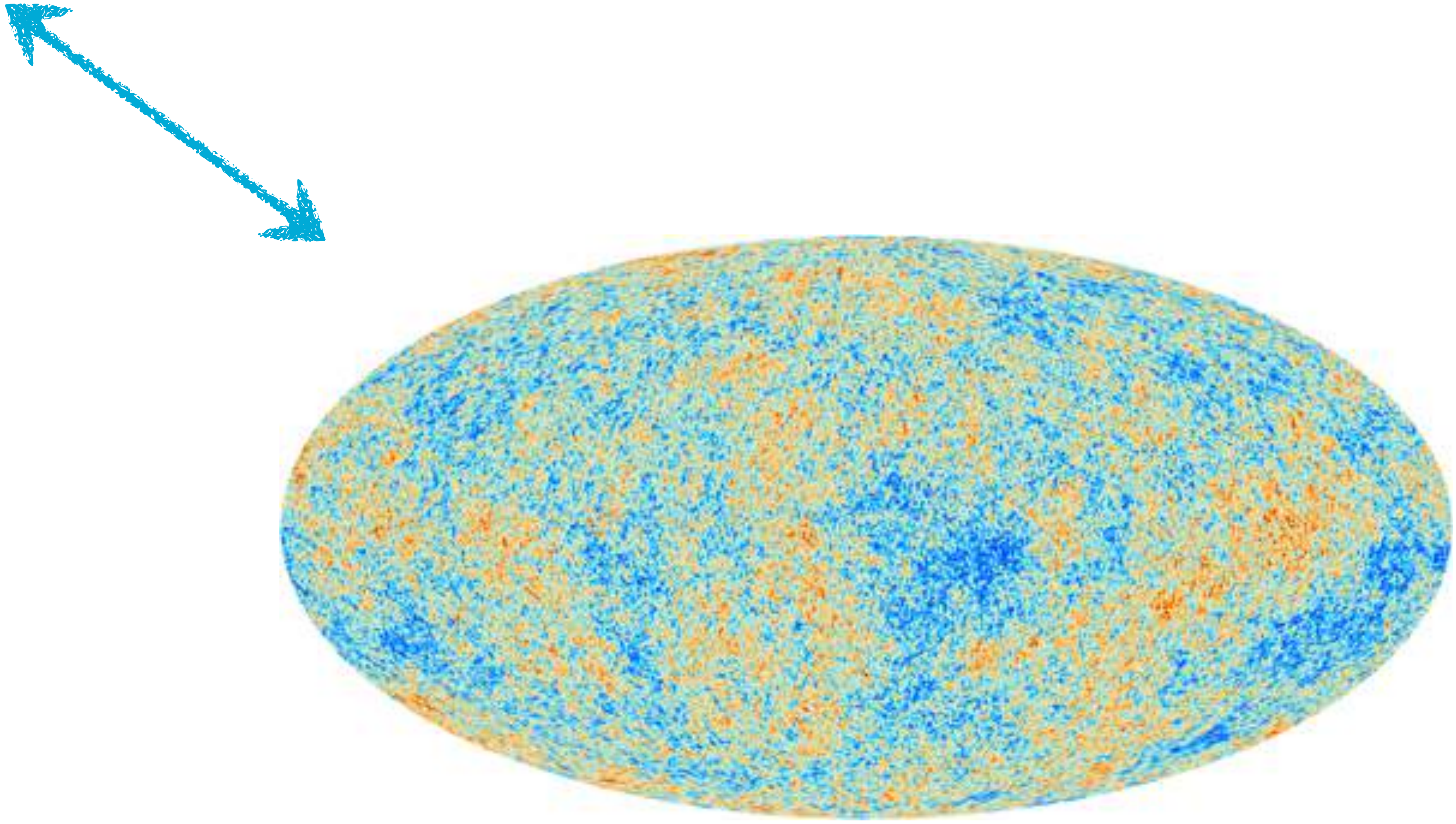
- **coarse grained view ?**
- **calculational tools ?**



inspiration from disordered wires

MA & Baumann 2015

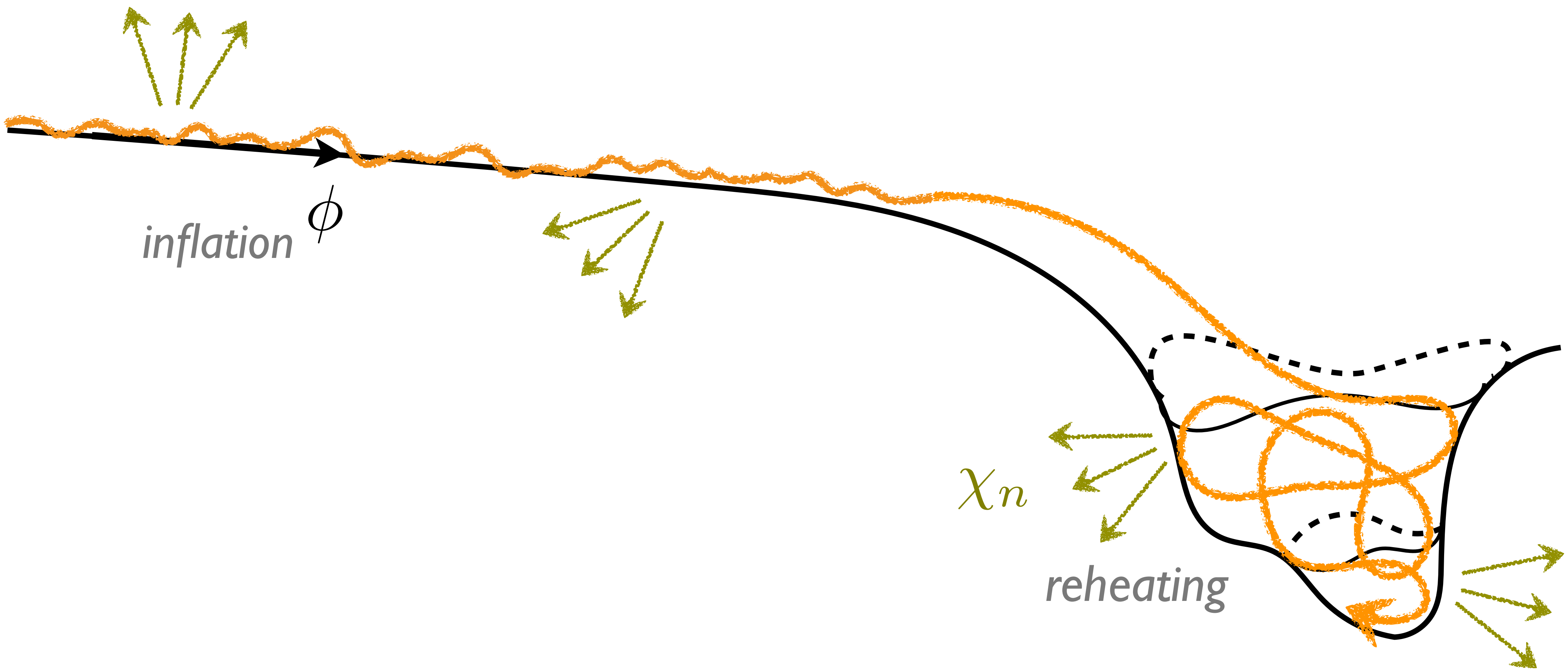




the framework

multifield inflation/reheating

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

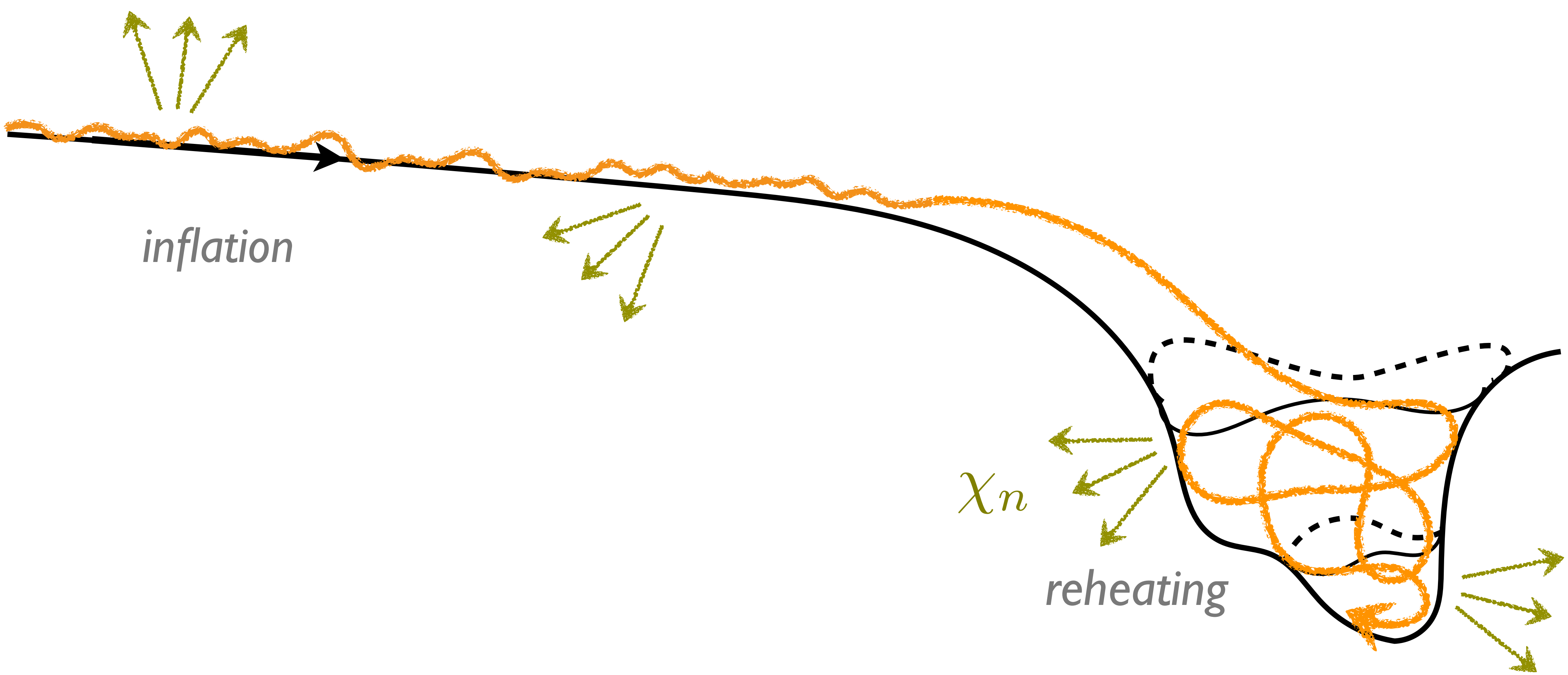


focus on perturbations

mode functions in Fourier space

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

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

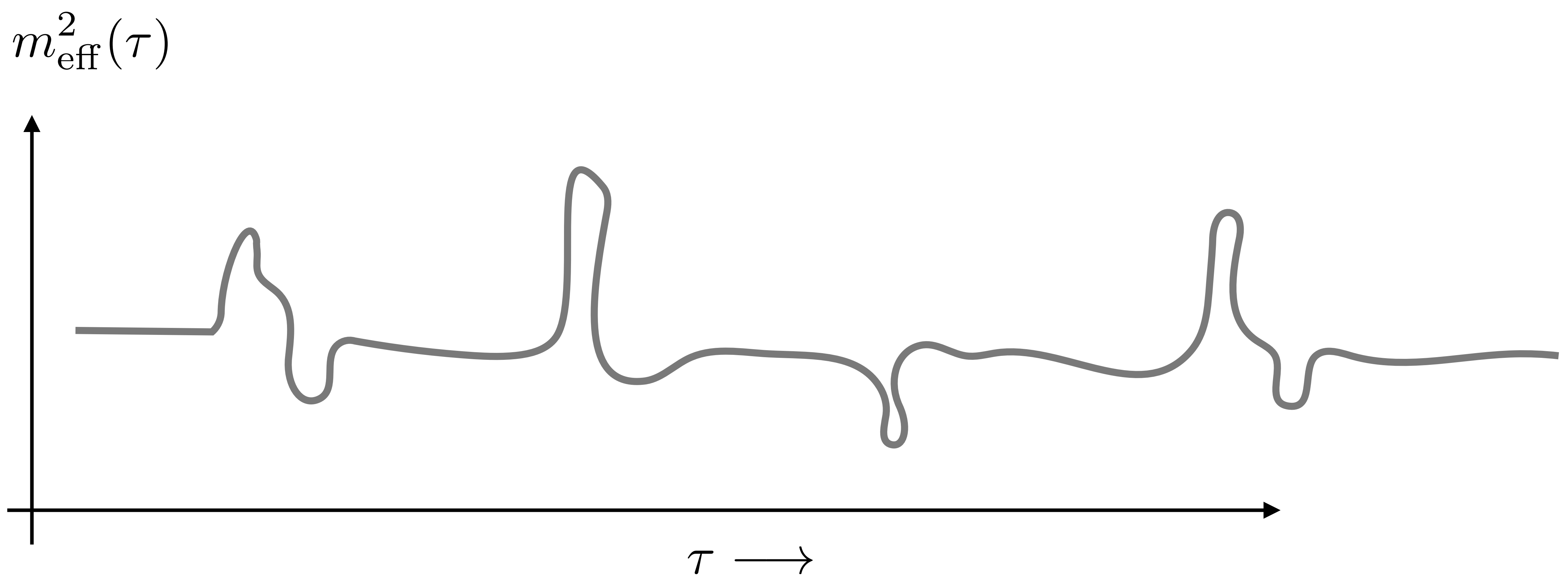


complexity in the "effective mass"/ interactions

simplified version!

$$\ddot{\chi}_k(\tau) + \left[k^2 + m_{\rm eff}^2(\tau)\right]\chi_k(\tau) = 0$$

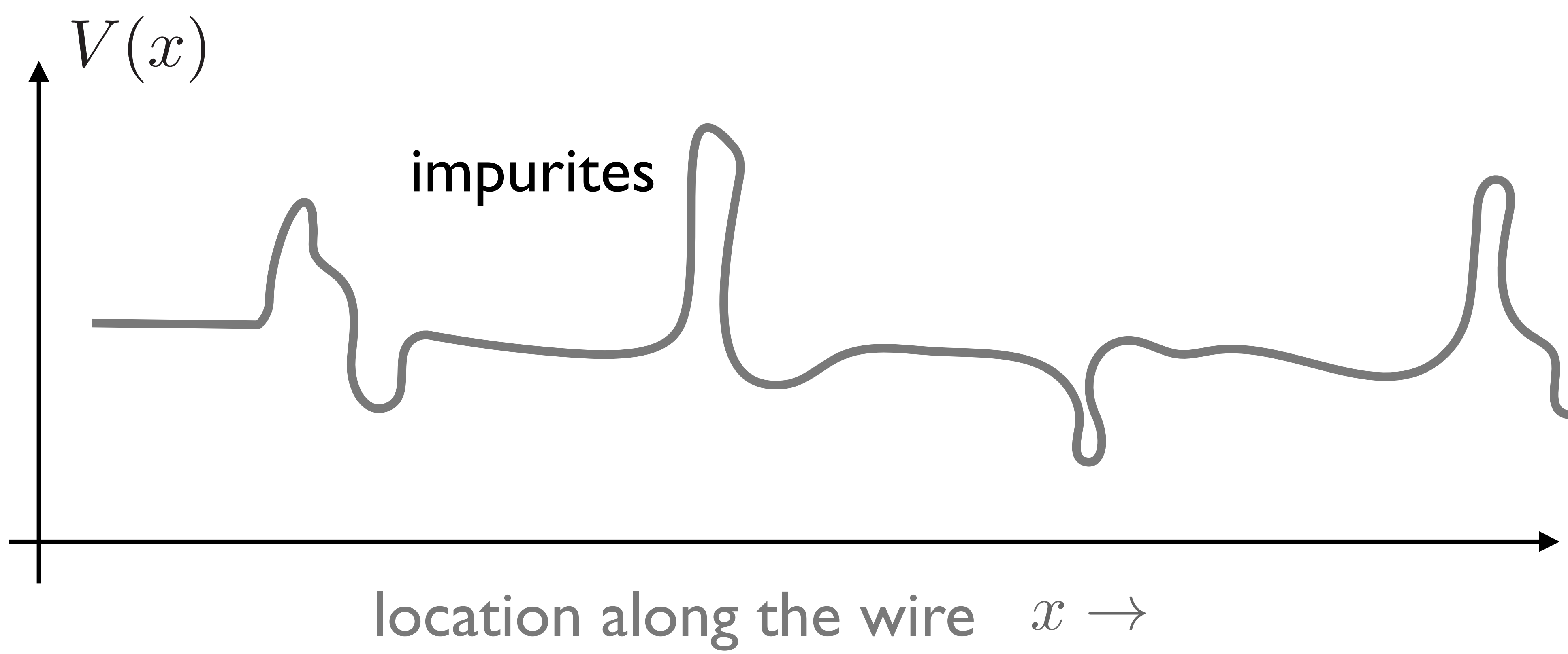
$$m_{\rm eff}^2(\tau) = -\frac{\ddot{a}(\tau)}{a(\tau)} + a^2(\tau)m_\varphi^2 + a^2(\tau)g^2(\phi(\tau) - \phi_*)^2 + \dots$$



similar problem seen before …

simplified version!

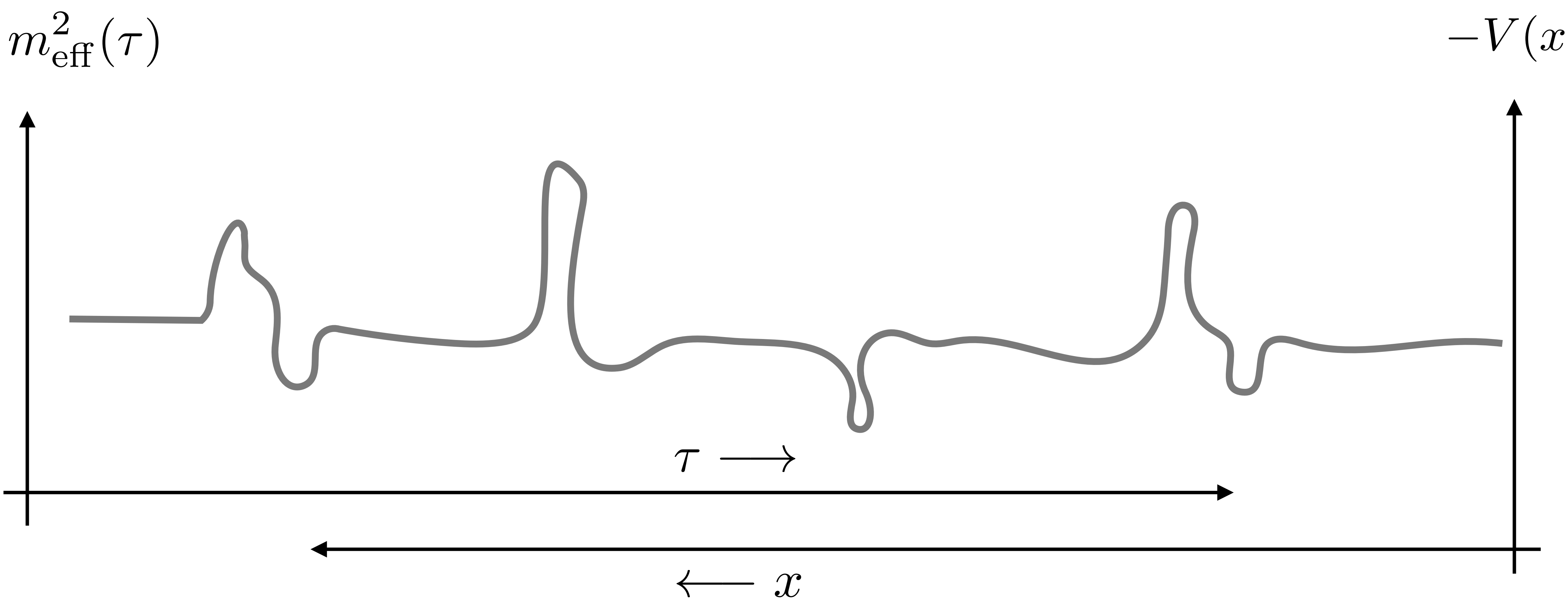
$$\frac{d^2\psi}{dx^2} + \left[k^2 - V(x)\right]\psi = 0$$



complexity in time ⟷ complexity in space
cosmology ⟷ wires

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

simplified version!

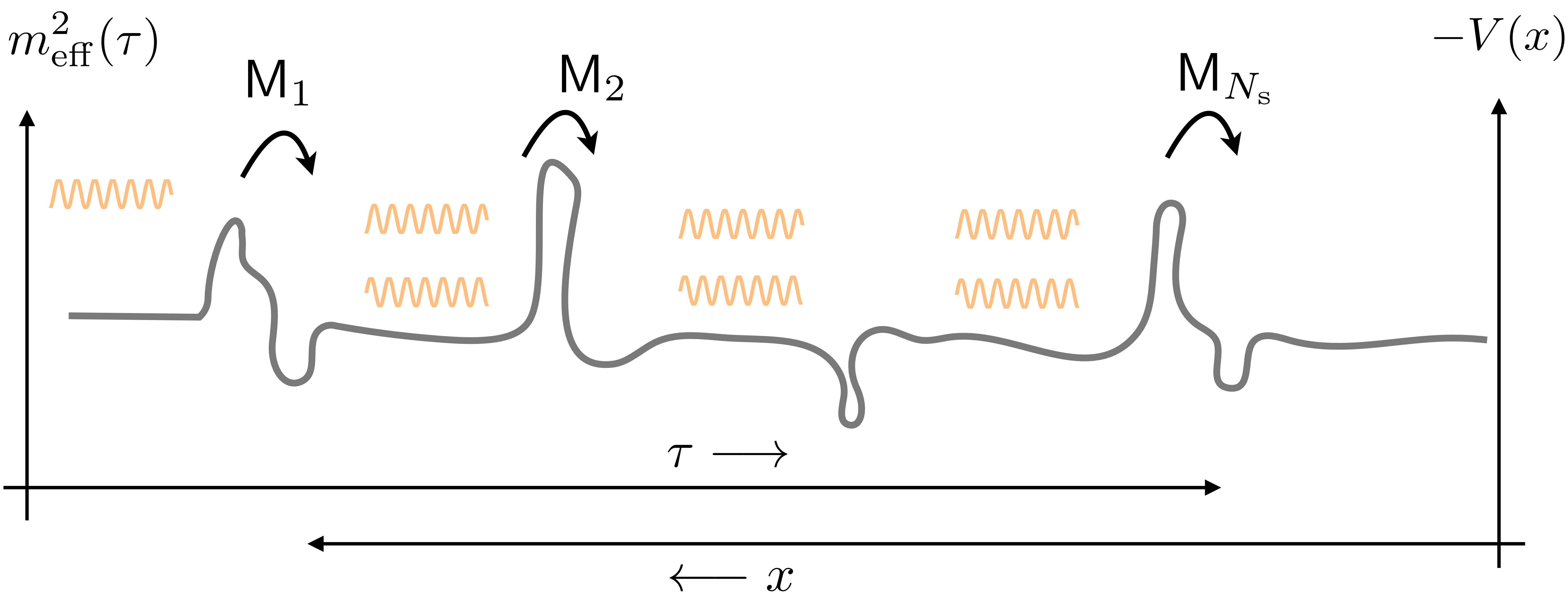


see also: Zanchin et. al 1998, Basset 1998, Brandenberger & Craig 2008

solve using scattering matrices !

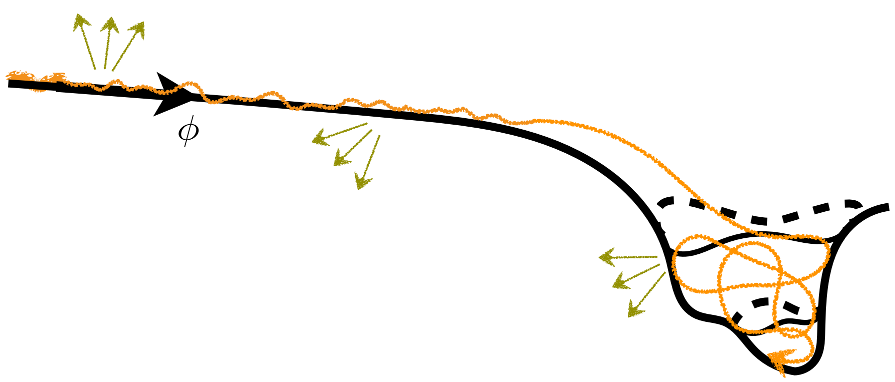
$$\ddot{\chi}_k(\tau) + \left[k^2 + m_{\rm eff}^2(\tau)\right]\chi_k(\tau) = 0 \quad \longleftrightarrow \quad \psi''(x) + \left[k^2 - V(x)\right]\psi(x) = 0$$

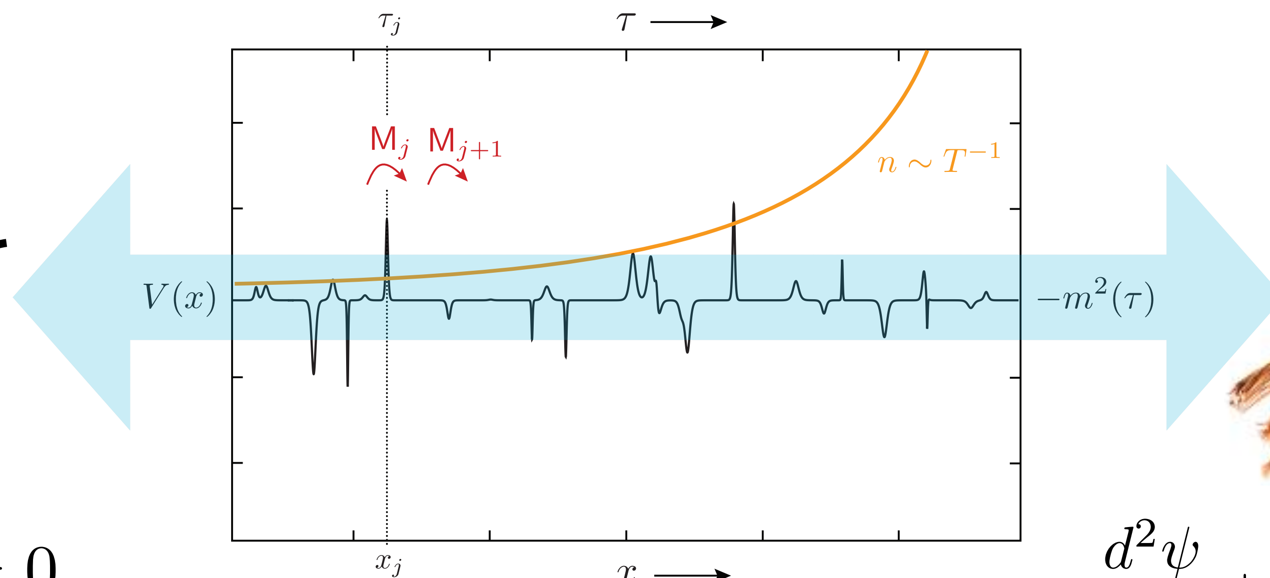
simplified version!

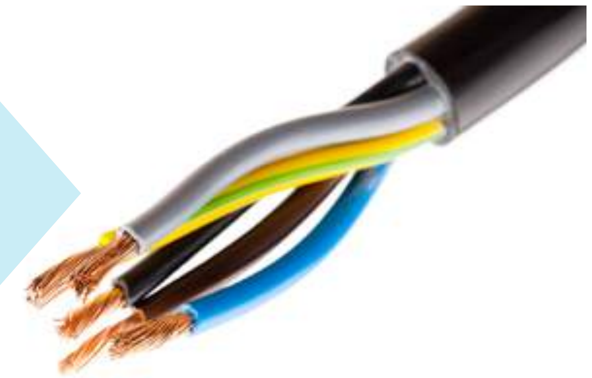


see also: Zanchin et. al 1998, Basset 1998, Brandenberger & Craig 2008

temporal complexity ⟷ spatial complexity







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

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

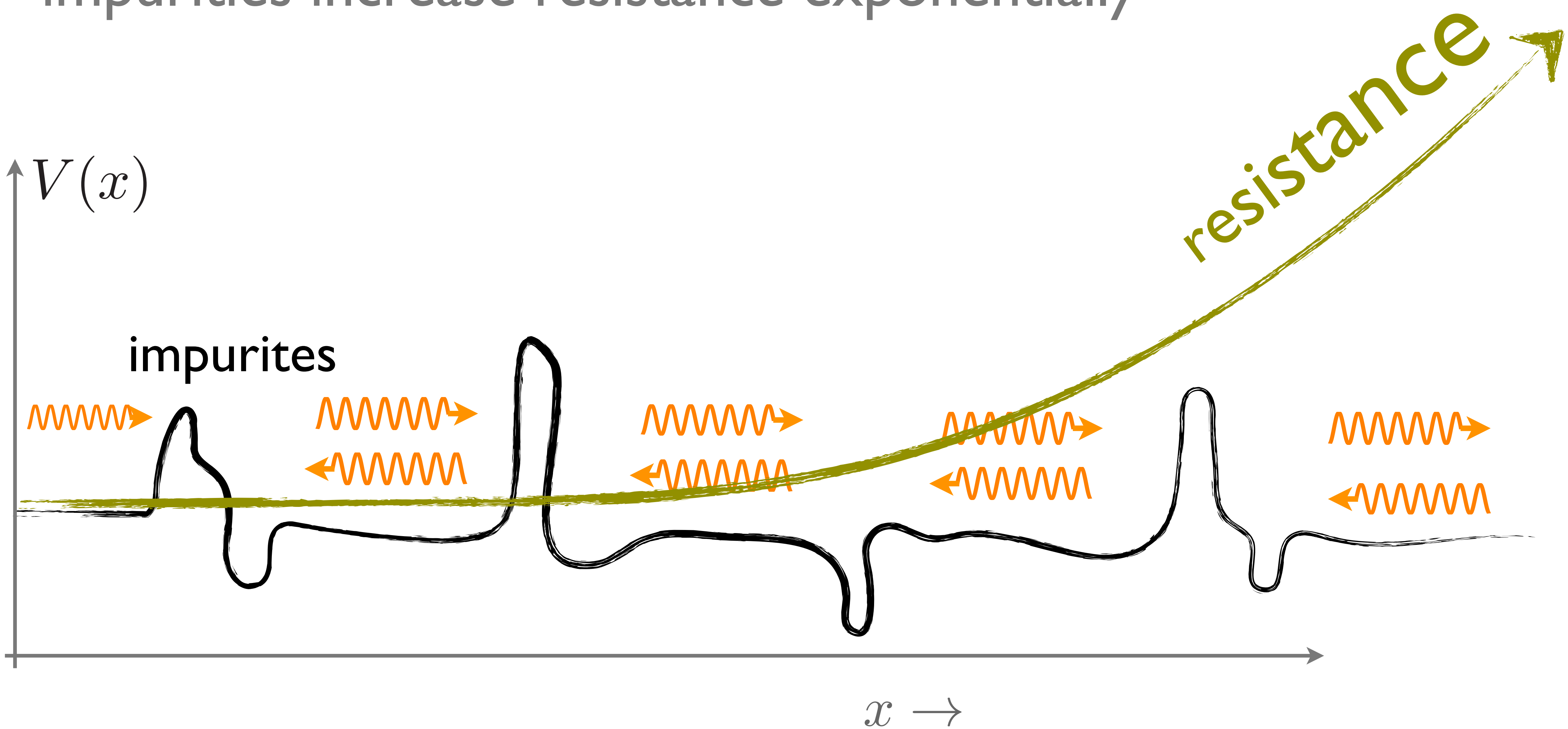
- time
- number of particles
- complicated temporal behavior

- position along wire
- resistance
- impurities in wires

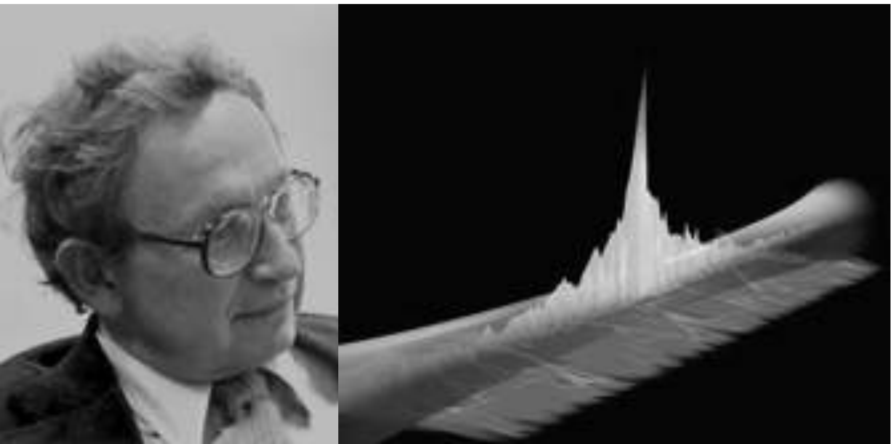
MA & Baumann (2015)

universal behavior: Anderson Localization!

- impurities increase resistance exponentially



location along the wire

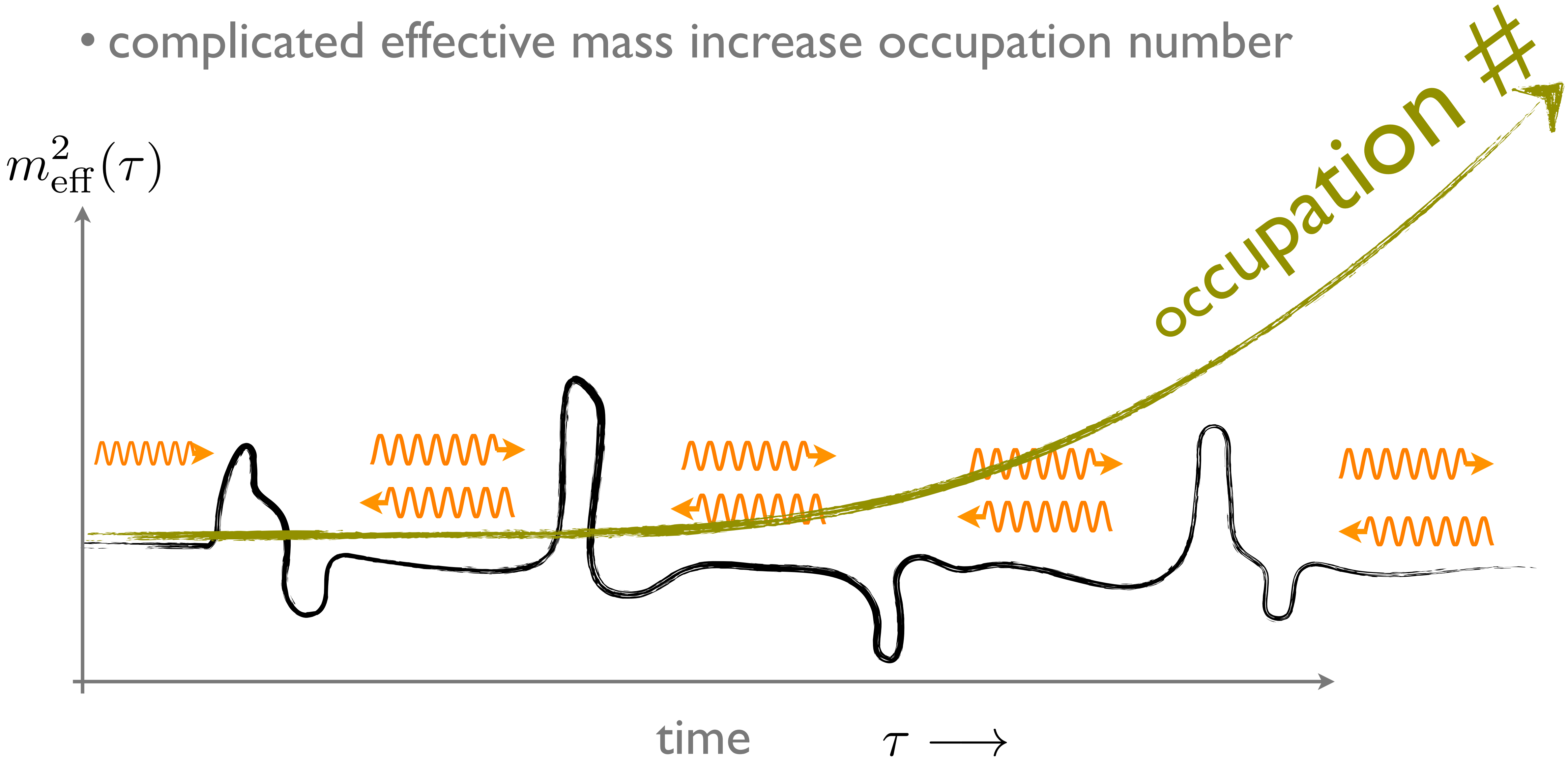


Anderson 1957

at low temperatures, one dimensional wires are insulators

universal behavior: exponential increase in occupation number

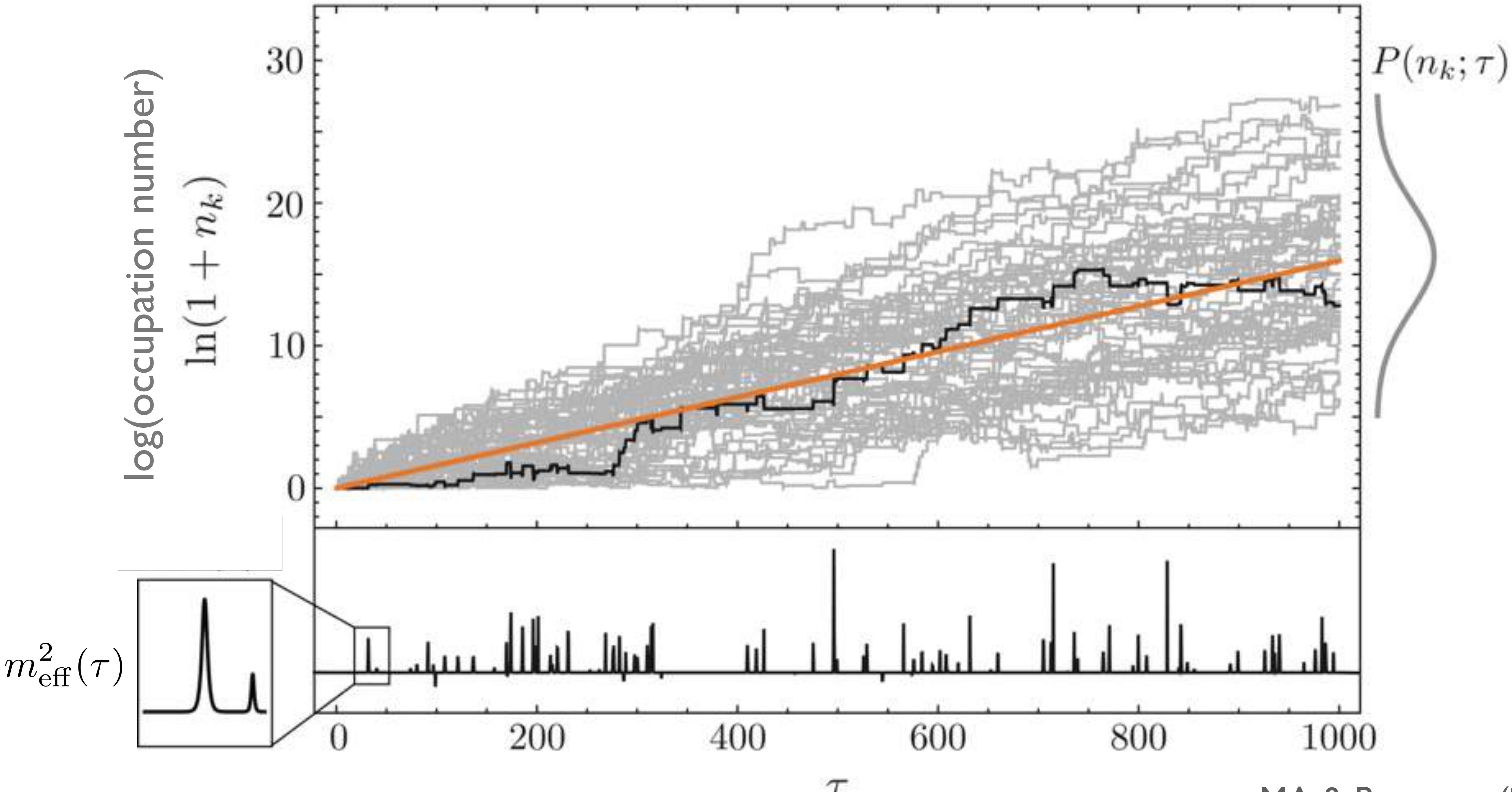
- complicated effective mass increase occupation number



understood in terms of **Bose enhancement**

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.

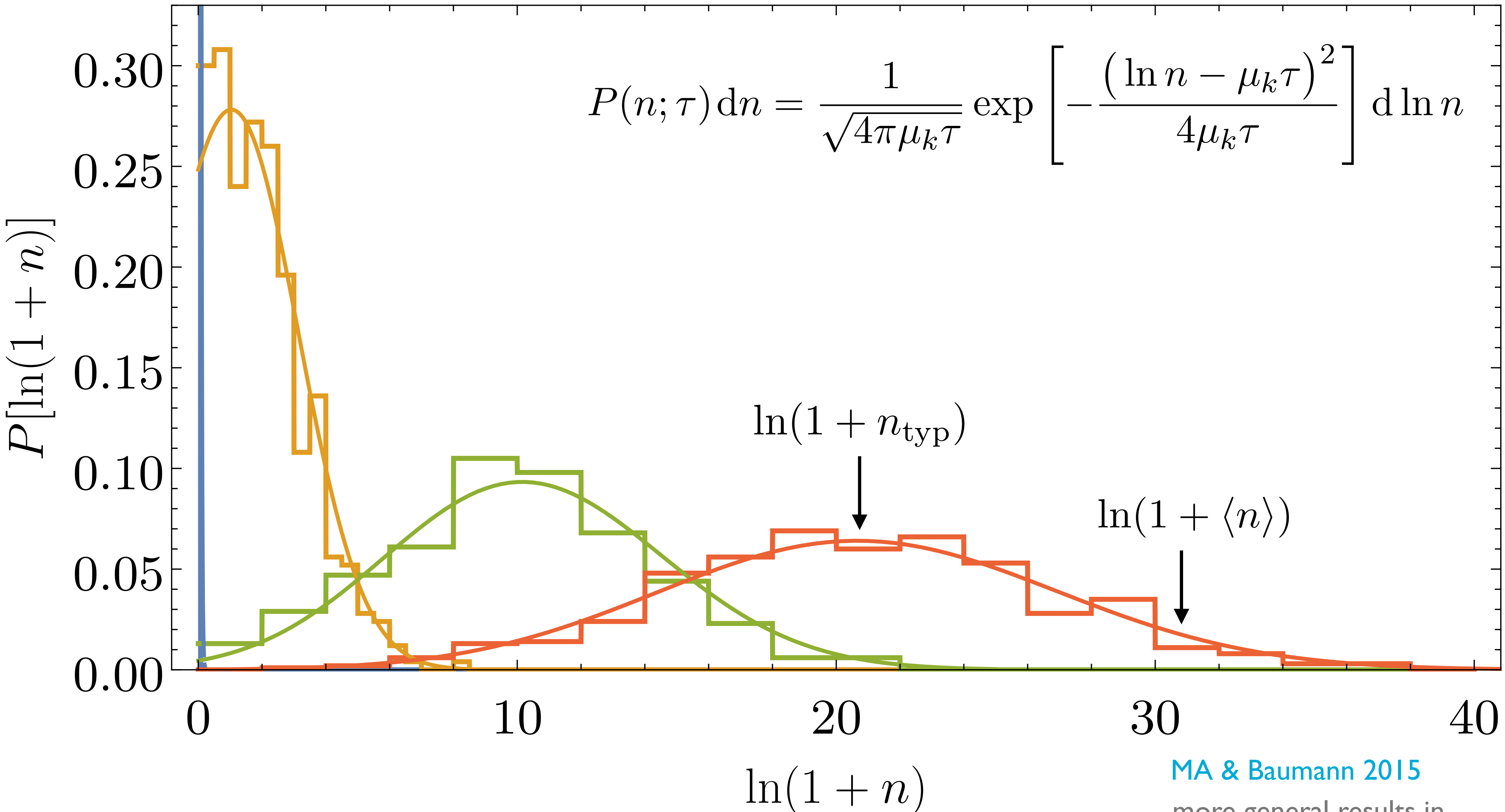
$$\frac{1}{\mu_k}\frac{\partial}{\partial\tau}P(n_a;\tau) = \sum_{a=1}^{N_\mathrm{f}}\left[(1+2n_a)+\frac{1}{N_\mathrm{f}+1}\sum_{b\neq a}\frac{n_a+n_b+2n_an_b}{n_a-n_b}\right]\frac{\partial P}{\partial n_a}$$

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

MA & Baumann 2015

For more general results in beyond statistical isotropy, see MA, Garcia, Xie and Wen 2017

solution: “universal” distributions



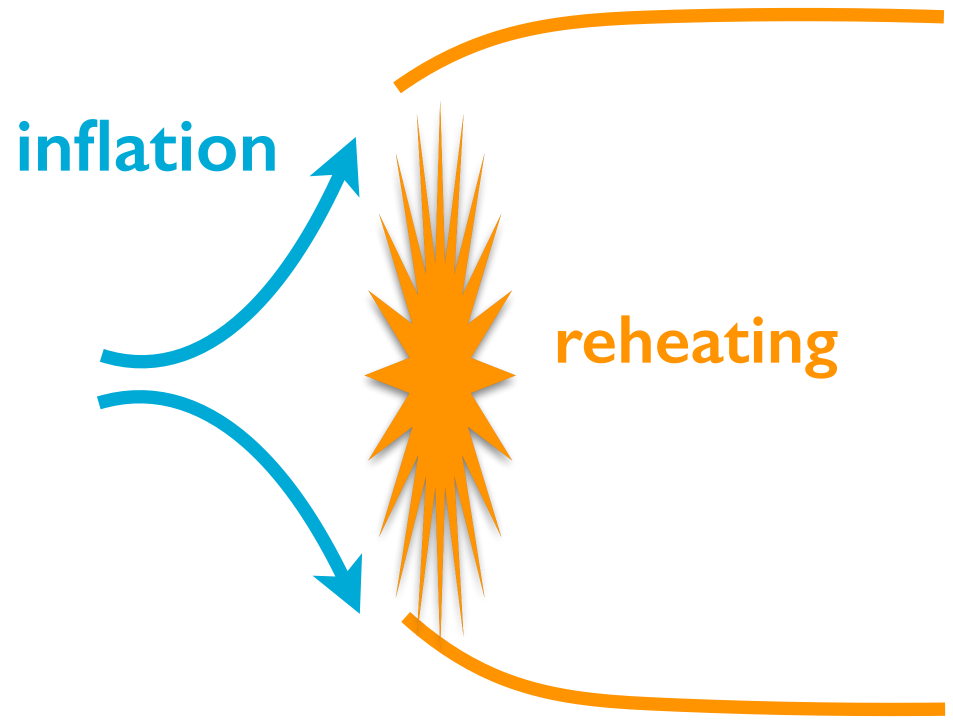
MA & Baumann 2015

more general results in

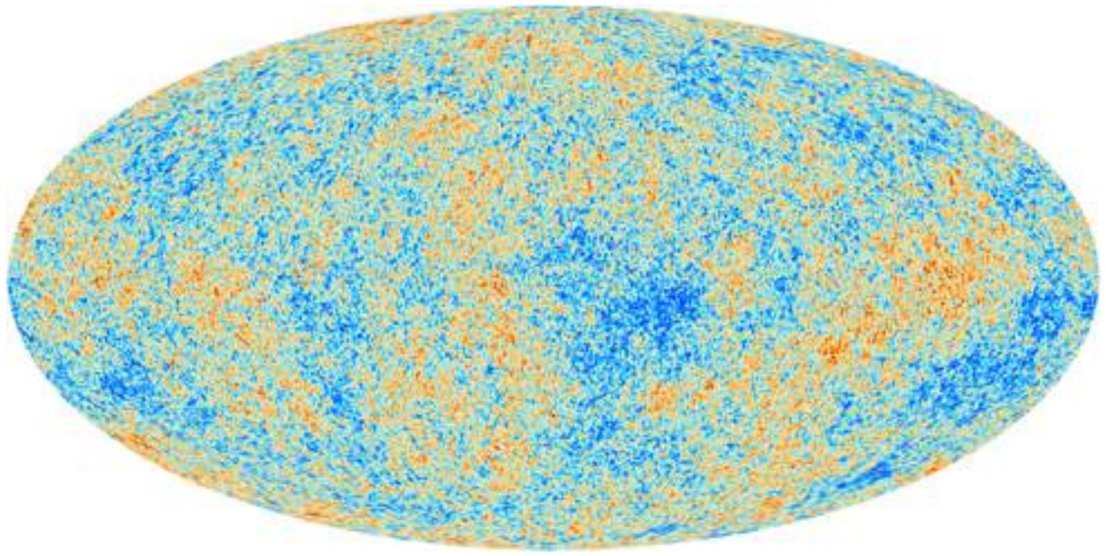
MA, Garcia, Xie and Wen 2017

MA, Carlsten, Garcia, Green, Baumann …

for superhorizon scales, use field amplitude rather than occupation number



applications

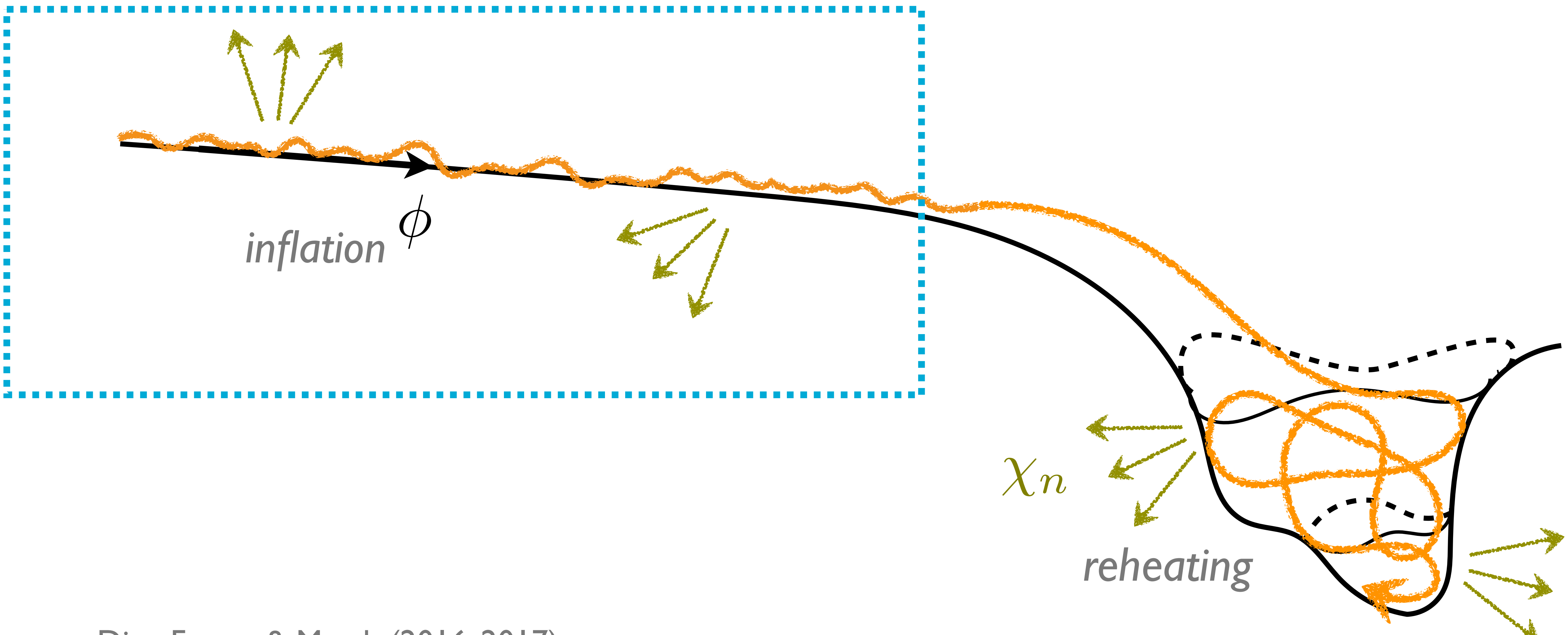


applications: inflation

MA, Garcia, Baumann, Carlsten, Chia & Green

background dynamics → particle production ↔ curvature fluctuations

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



also see: Dias, Fraser & Marsh (2016, 2017)

WORK IN PROGRESS

combine particle production with driving and dissipation

background dynamics → particle production ↔ curvature fluctuations

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

$$\zeta_k = -H\pi_k$$

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

dissipation — driving

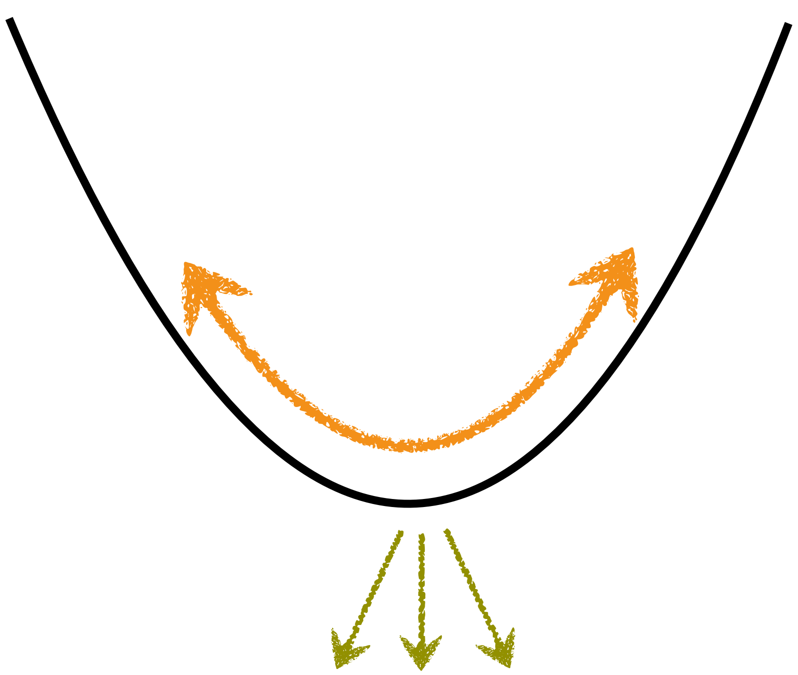
MA, Garcia, Baumann, Carlsten, Chia & Green

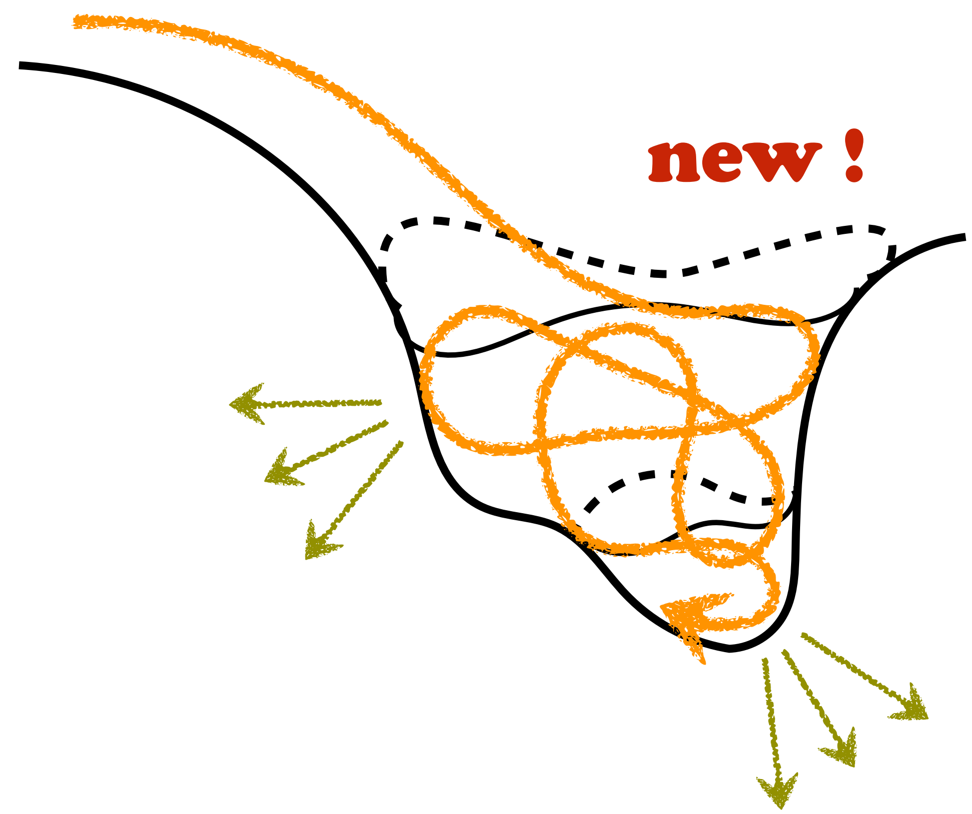
Green, Horn, Senatore, and Silverstein (2009), Nacir, Porto, Senatore, and Zaldarriaga (2012), Flauger, Mirbabayi, Senatore, Silverstein (2016), Chen, Namjoo and Wang (2015,16), Dias, Fraser & Marsh (2016, 17)

WORK IN PROGRESS

applications : reheating

multichannel — multifield — statistical





model-insensitive description of a complicated reheating process.

for example:
Shtanov, Traschen & Brandenberger (1995)
Kofman, Linde & Starobinsky (1997)
Zanchin et. al (1998) & Bassett (1998) [with noise]
Barnaby, Kofman & Braden et. al 2010 [quasiperiodic]
Giblin, Nesbit, Ozsoy, Sengor & Watson (2016-17)

MA, Garcia & Shen

end of inflation

SIMPLE

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

detailed models

COMPLEX

- universal dynamics independent of details
- Fokker-Plank/random matrix theory
- statistical properties of correlation functions

end of inflation

SIMPLE

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

detailed models

- universal dynamics independent of details
- Fokker-Plank/random matrix theory
- statistical properties of correlation functions

COMPLEX

non-perturbative dynamics to solve problems

- Higgs vacuum stability and inflation [East, Kearny, Shakya, Yoo, Zurek]
- Higgs fine tuning problem ? [MA, Fan, Lozanov, Reece (in progress)]
- matter-antimatter asymmetry ? [Lozanov & MA 2014, Hertzberg & Karouby 2014]
- primordial seeds for cosmological magnetic fields ? [MA & Lozanov 2016]
- primordial black holes ? [MA & Lozanov (in progress)]

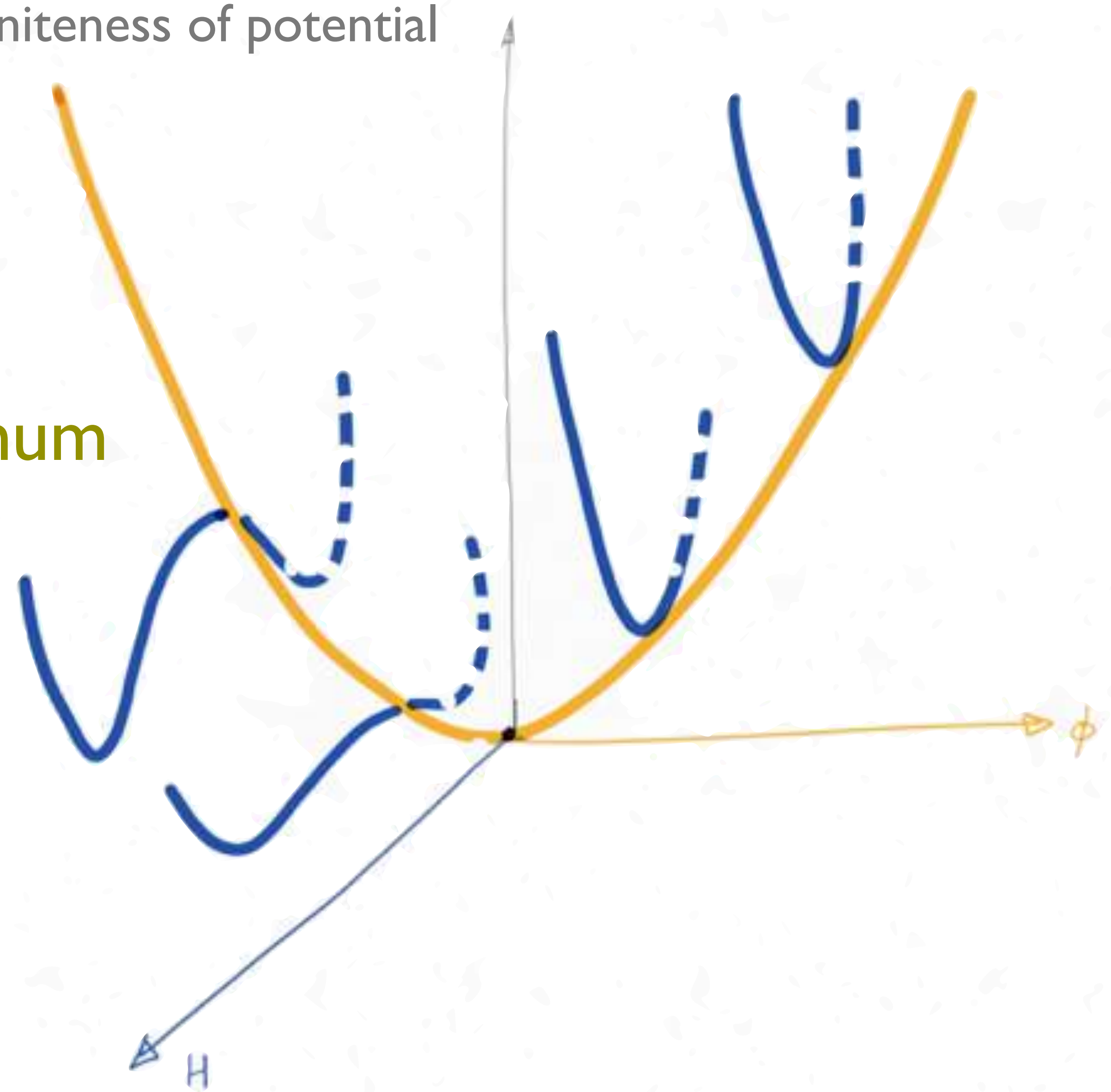
non-perturbative dynamics can lead to model specific observational signatures

- Higgs vacuum stability and inflation [East, Kearny, Shakya, Yoo, Zurek]
- Higgs fine tuning problem [MA, Fan, Lozanov, Reece (in progress)]
- matter-antimatter asymmetry ? [Lozanov & MA 2014, Hertzberg & Karouby 2014]
- primordial seeds for cosmological magnetic fields ? [MA & Lozanov 2016]
- primordial black holes ? [MA & Lozanov (in progress)]

inflaton (modulus) - Higgs system

$$V(\phi, H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{M^2}{f}\phi(H^\dagger H - v^2)$$

$$b \equiv \frac{M^4}{2\lambda m_\phi^2 f^2} \leq 1$$ for positive definiteness of potential



arrange the potentials to yield
small Higgs masses at the global minimum

MA, Fan, Lozanov, Reece (in progress)

implications?

$$V(\phi, H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{M^2}{f}\phi(H^\dagger H - v^2)$$

$$b \equiv \frac{M^4}{2\lambda m_\phi^2 f^2} \leq 1$$

for positive definiteness of potential

$$b \equiv \frac{M^4}{2\lambda m_\phi^2 f^2} \to 1$$

back-reaction
efficiency parameter

- inhomogeneous fragmentation of Higgs-modulus system with $\rho_H \sim \rho_\phi$
- generation of stochastic g-waves
- non-trivial equation of state

end of inflation

SIMPLE

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

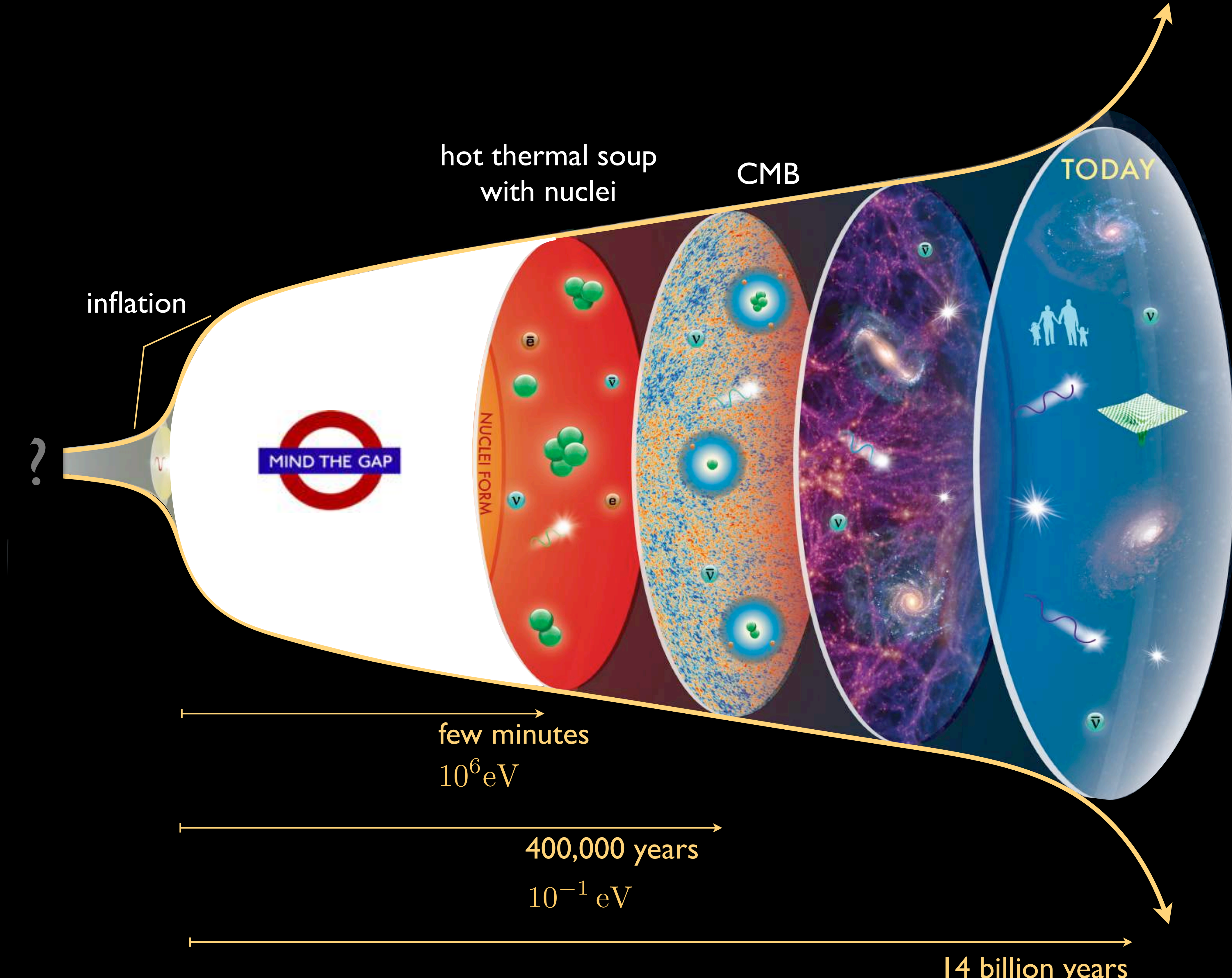
detailed models

- hierarchy problem
- matter-antimatter asymmetry
- primordial magnetic fields

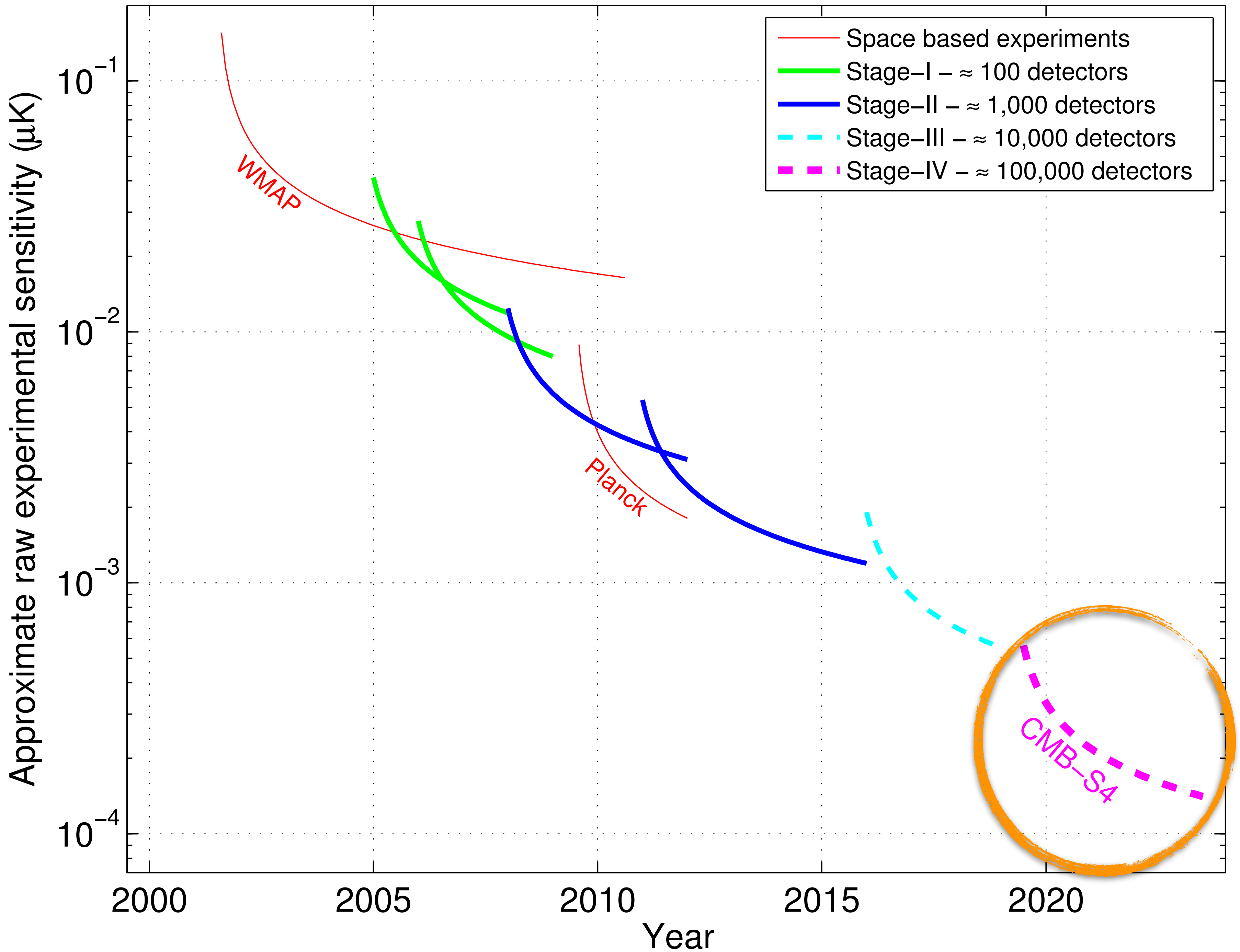
COMPLEX

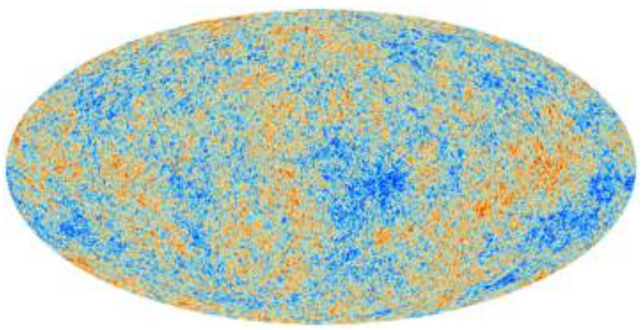
- universal dynamics independent of details
- Fokker-Plank/Random Matrix theory
- statistical properties of correlation functions

What 's Next ? — upcoming observations



significant improvement expected

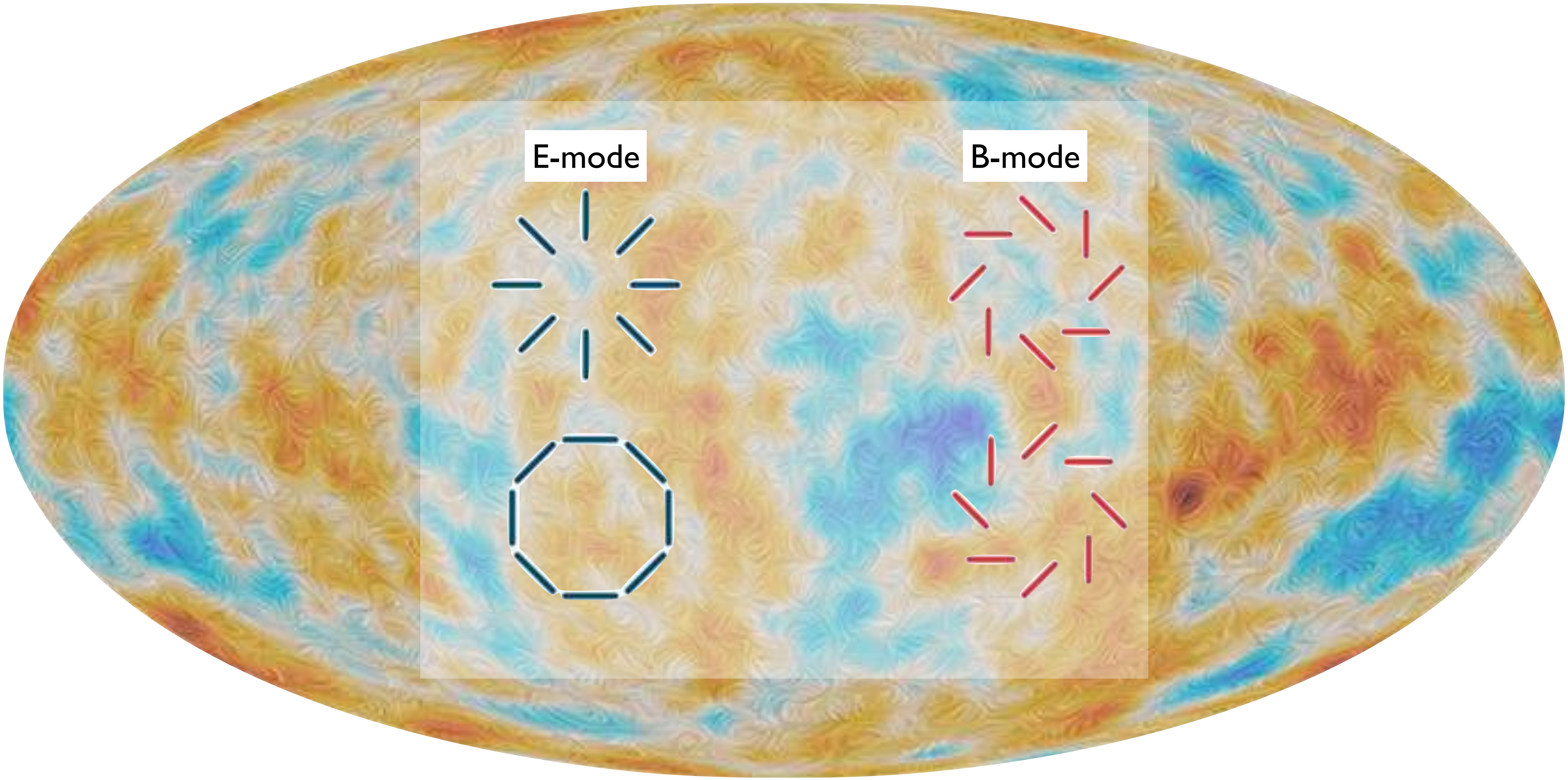




ground based

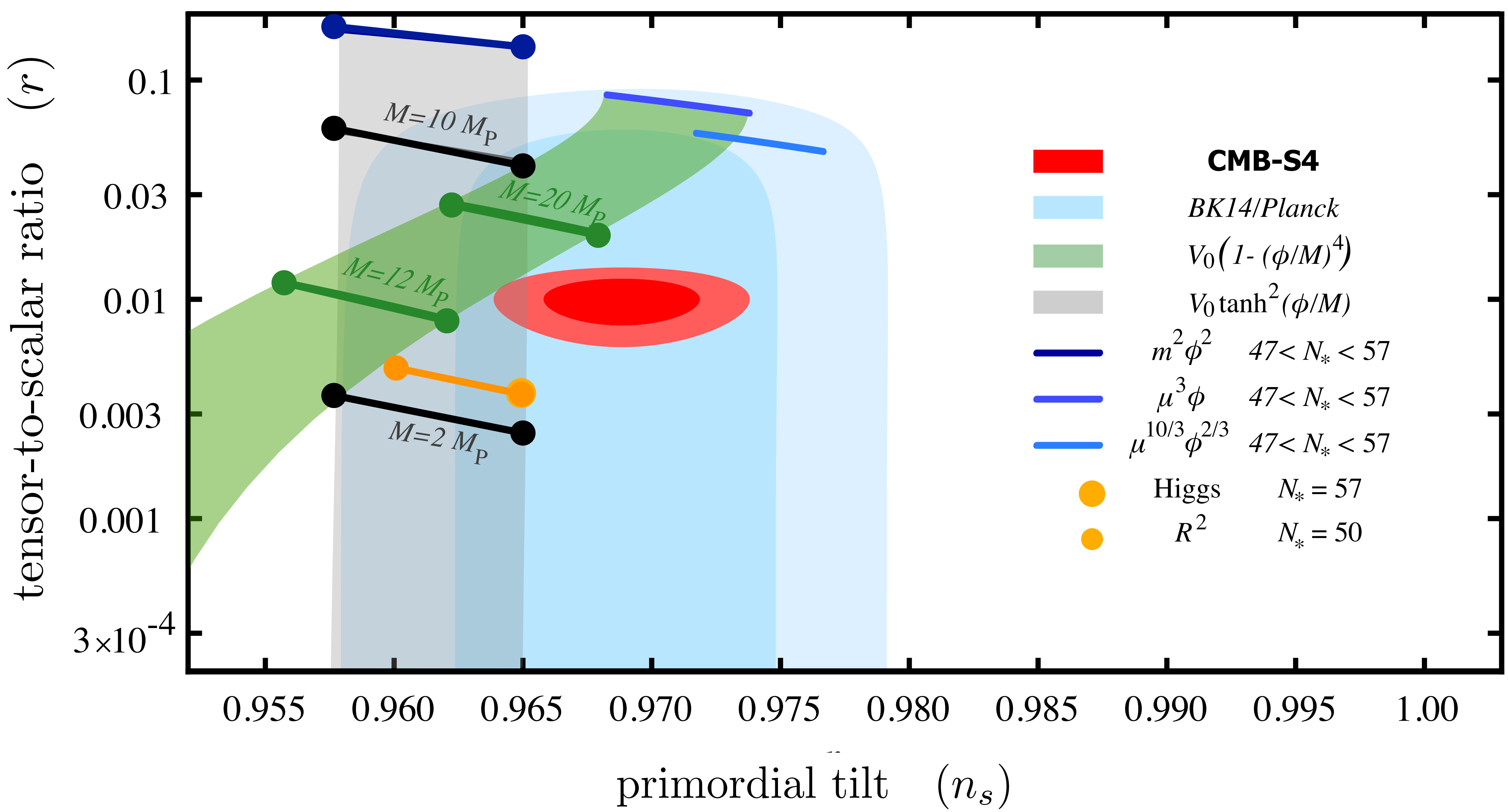
- Chilean Atacama Plateau
- South Pole
- Northern Hemisphere ?

additional information in CMB ?
CMB is polarized



improvement expected necessitates better theoretical understanding

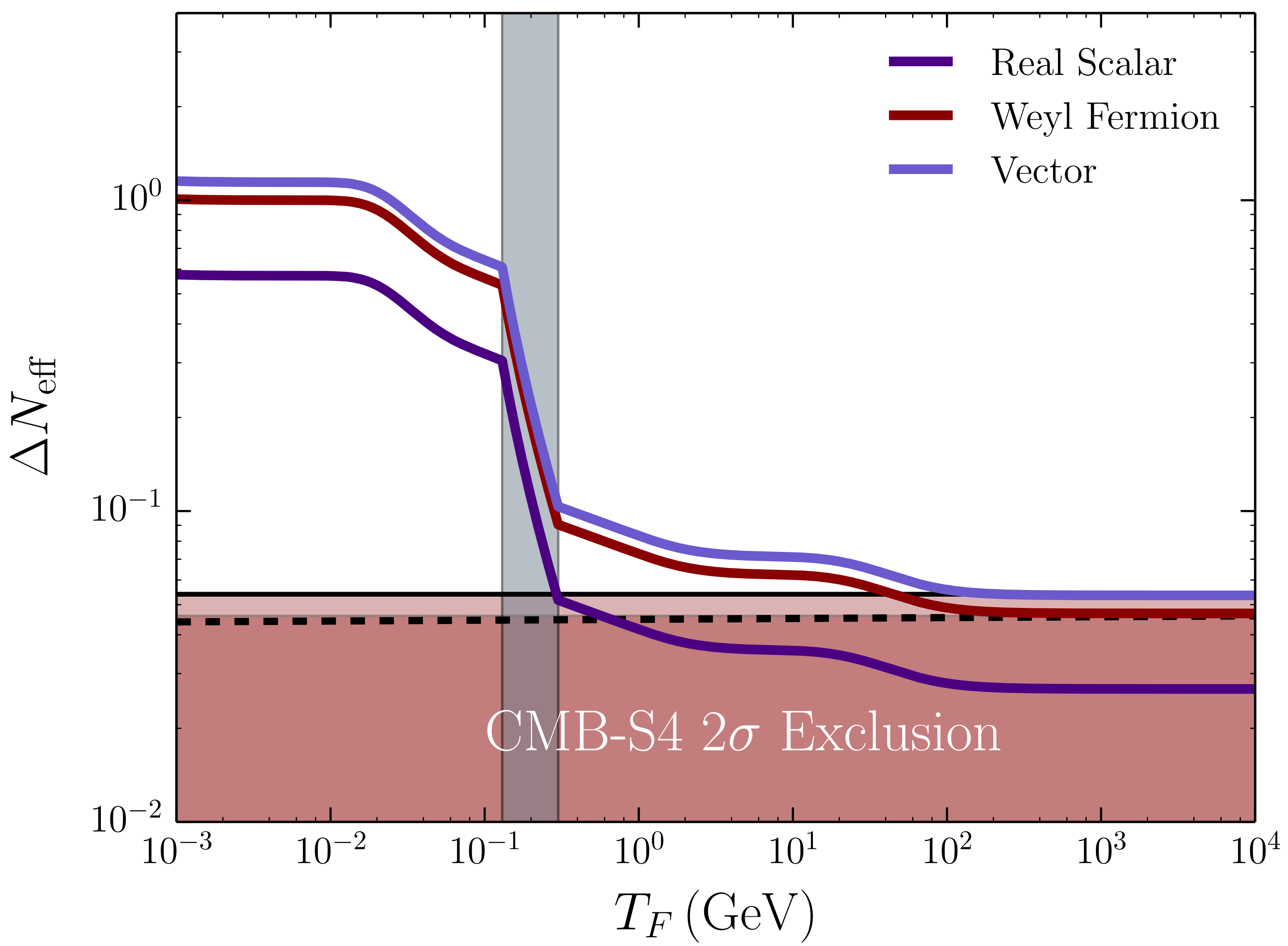
Will also require better understanding of the aftermath of inflation



CMB S4 Science Book

constraints on additional light species

will also require better understanding of the aftermath of inflation



will be able to constrain the the effective number of additional light species, beyond neutrinos!

Baumann, Green & Wallish (2016)

+ CMB S4 Science Book

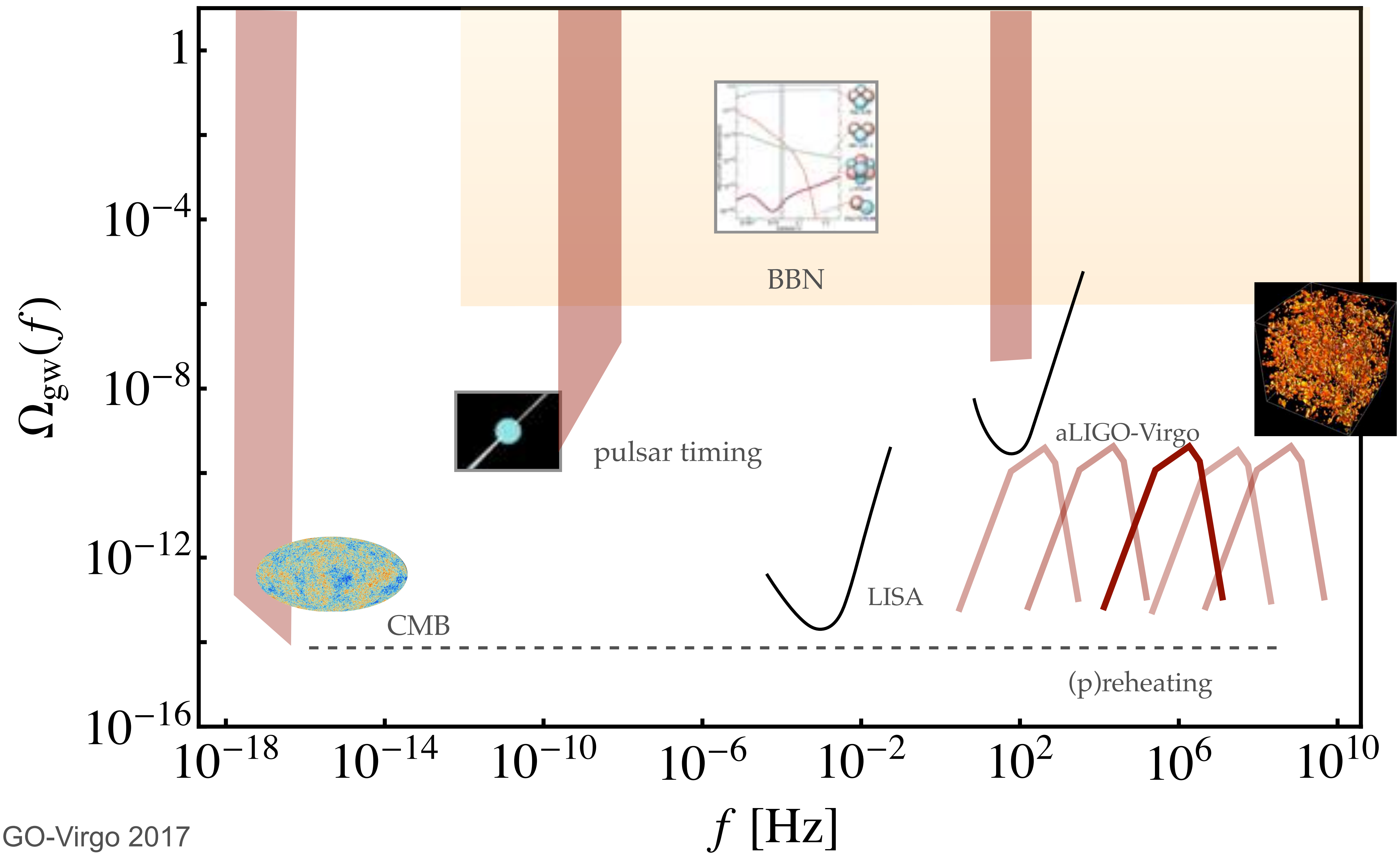
large scale structure

- 3D, more modes — lensing, spectroscopic, 21 cm etc.)

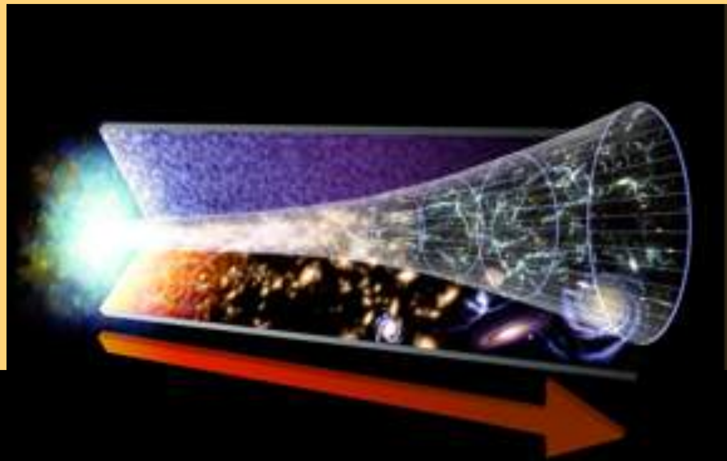
	LSST	DESI	Euclid	SPHEREx	CHIME
Survey type	photo	spectro	photo+spectro	low-res spectro	21-cm
Ground or space	ground	ground	space	space	ground
Previous surveys	CFHTLS, DES, HSC	BOSS, eBOSS, PFS	no direct precursor	PRIMUS, COMBO-17, COSMOS	GBT HIM
Survey start	2020	2020	2018	2020	2016
Redshift-range	$z < 3$ (1% sources above 3)	$z < 1.4$, $2 < z < 3.5$ (Lya)	$z < 3$	$z < 1.5$	$0.75 < z < 2.5$
Survey area [deg^2]	20k	14k	15k	40k	20k
Approximate number of objects	2×10^9 (WL sources)	22×10^6 gal., $\sim 2.4 \times 10^5$ QSOs	40×10^6 redshifts, 1.5×10^9 photo-zs	15×10^9 pixels	10^7 pixels
Galaxy clustering	✓✓$^\diamond$	✓	✓	✓	✓
Weak lensing	✓		✓		✓
RSD		✓	✓	✓✓	✓✓
Multi-tracer	✓✓	✓✓	✓✓	✓	

from Alvarez et. al 2014

stochastic gravitational waves



aLIGO-Virgo 2017
Amin et. al 2014



summary

- **inflation -** origin of density perturbations

- **aftermath -** ***gap*** **in our cosmic history**

  - simple models (solitons, eq. of state, g-waves)
  - complex (universal behavior)
  - model-specific (hierarchy problem etc.)

- **what's next** — light species ? g-waves ? polarization ? relics ?

Assistant Professor in Theoretical Astro-Particle Physics/Cosmology Position

COSMIC FRONTIER EFFORT

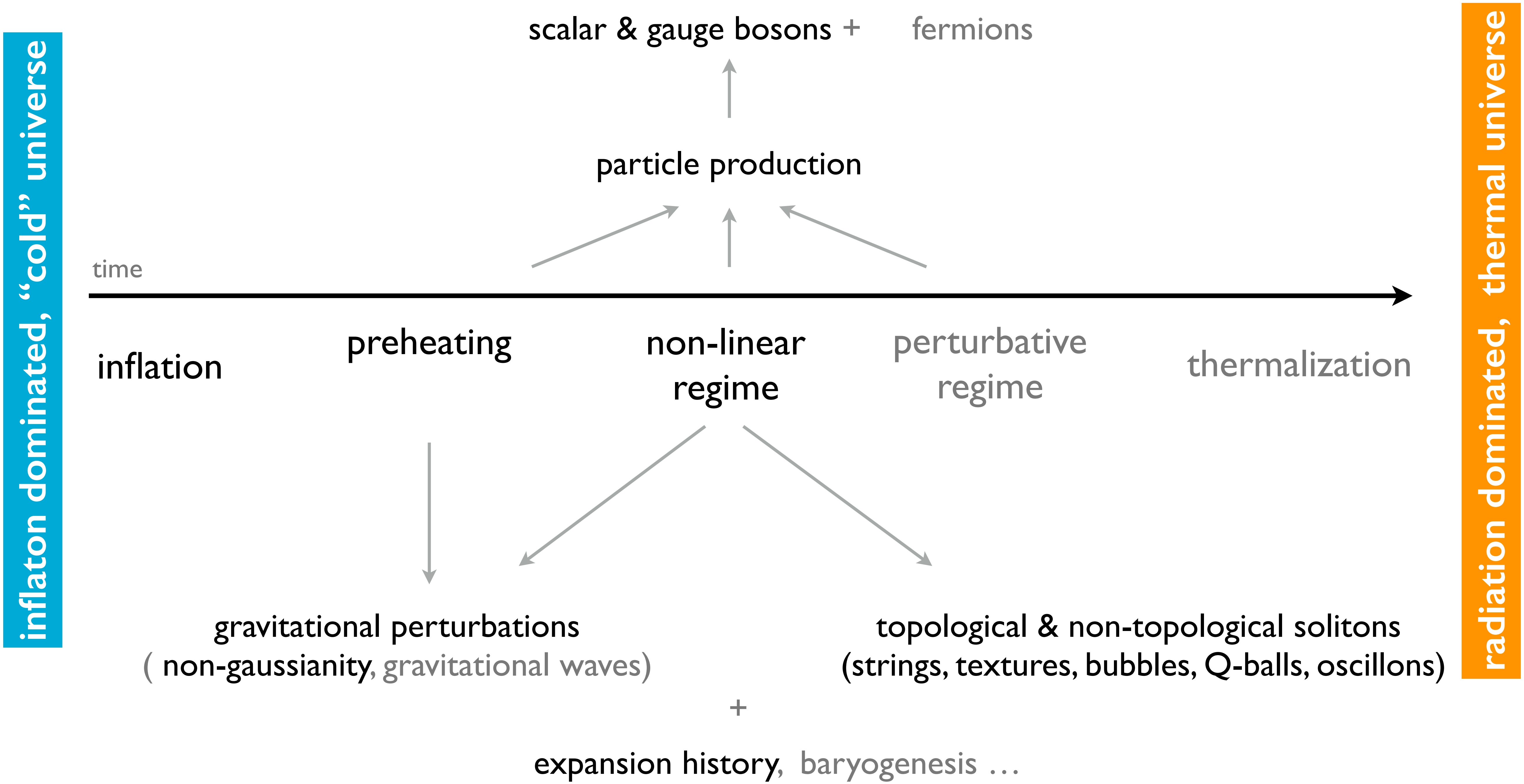
RICE

PHYSICS AND ASTRONOMY

http://www.physics.rice.edu/

apply: http://jobs.rice.edu/postings/11772

inflation ends, what’s next ?



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