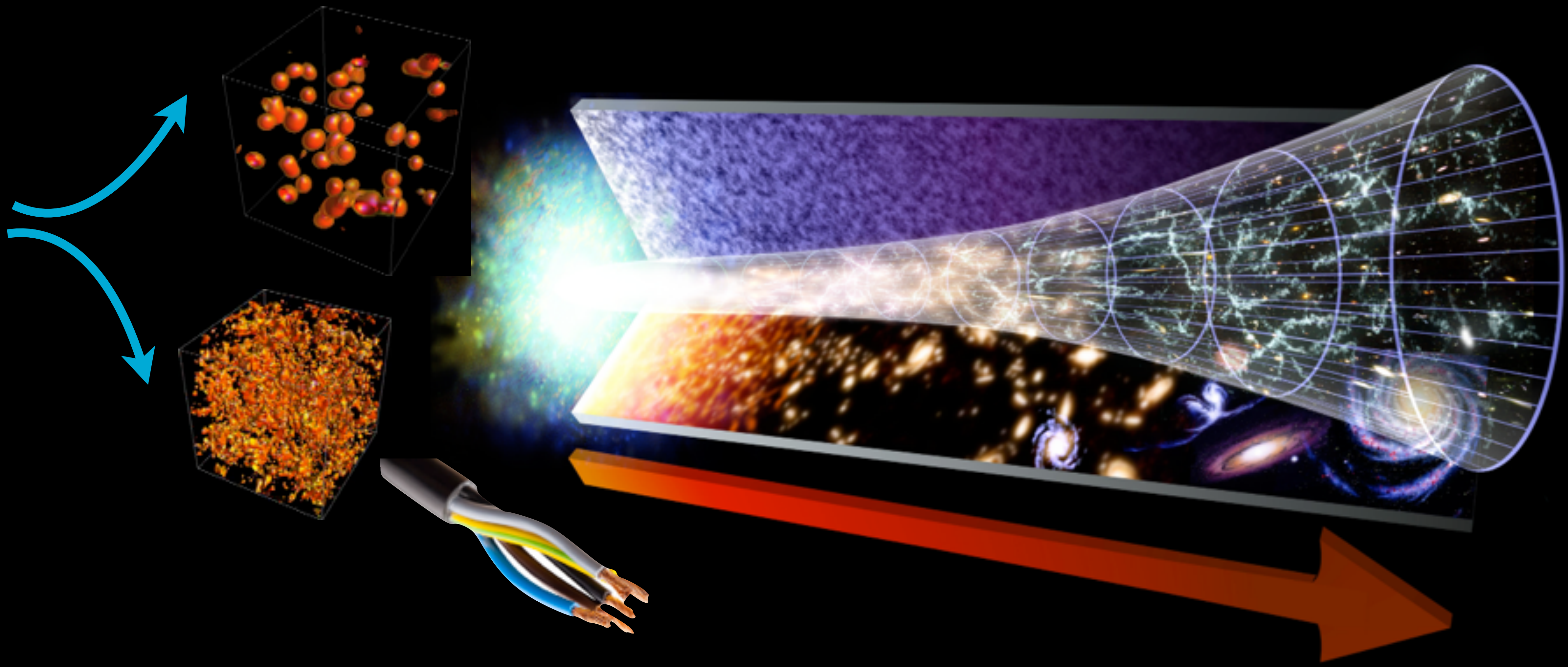
How did the hot big bang begin?



Mustafa Amin

RICE

Outline

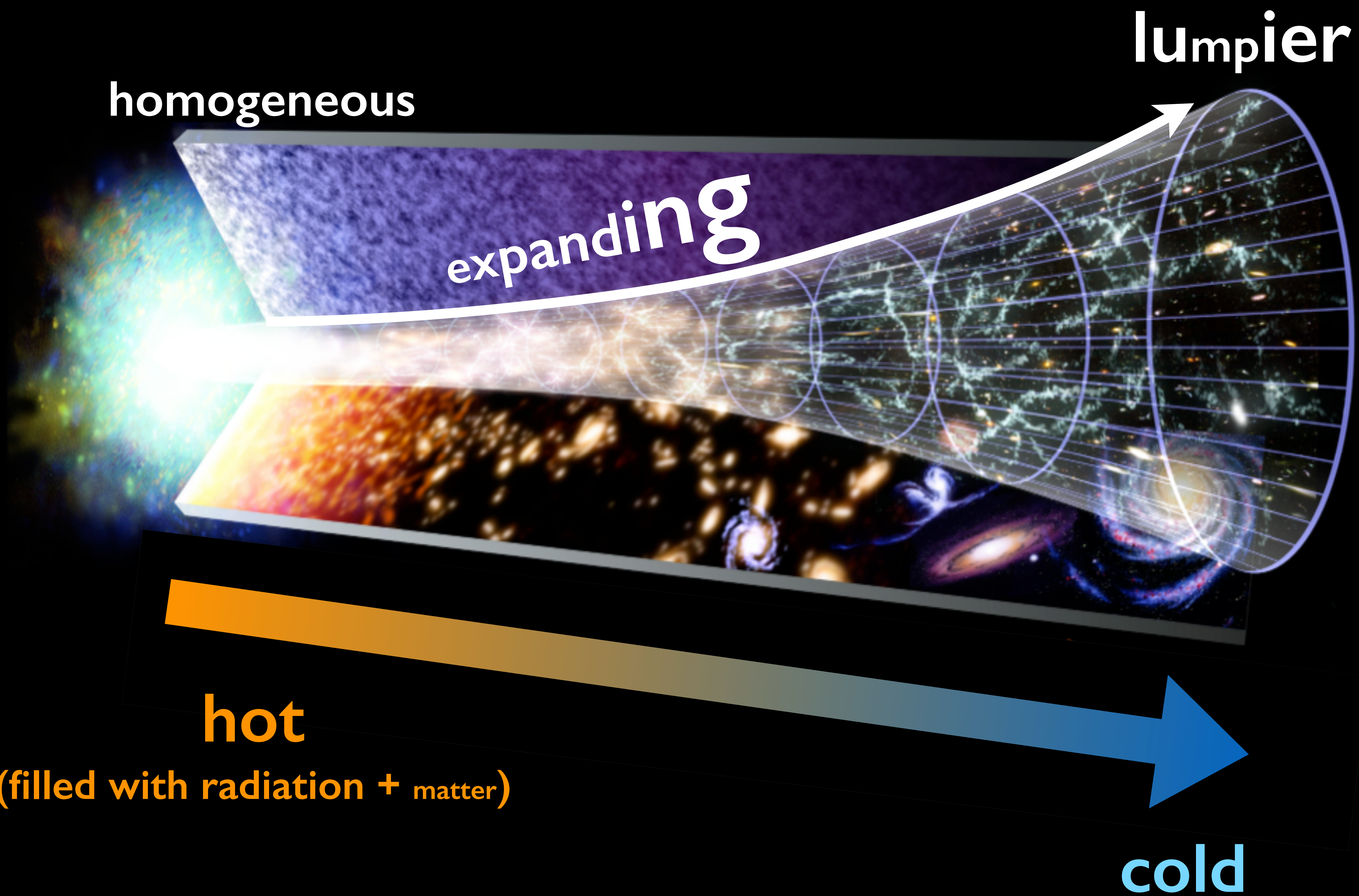
- our origins ?

➡ inflation & reheating

◉ two approaches:

1. simple enough models — general predictions
2. complex enough models — new statistical approach

The Standard Big Bang Cosmology

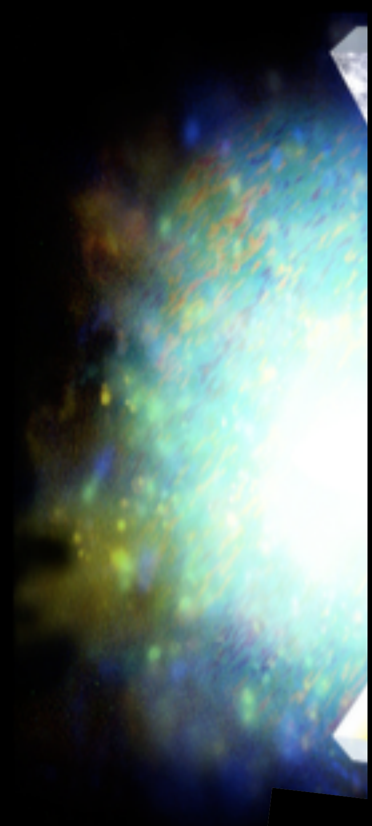


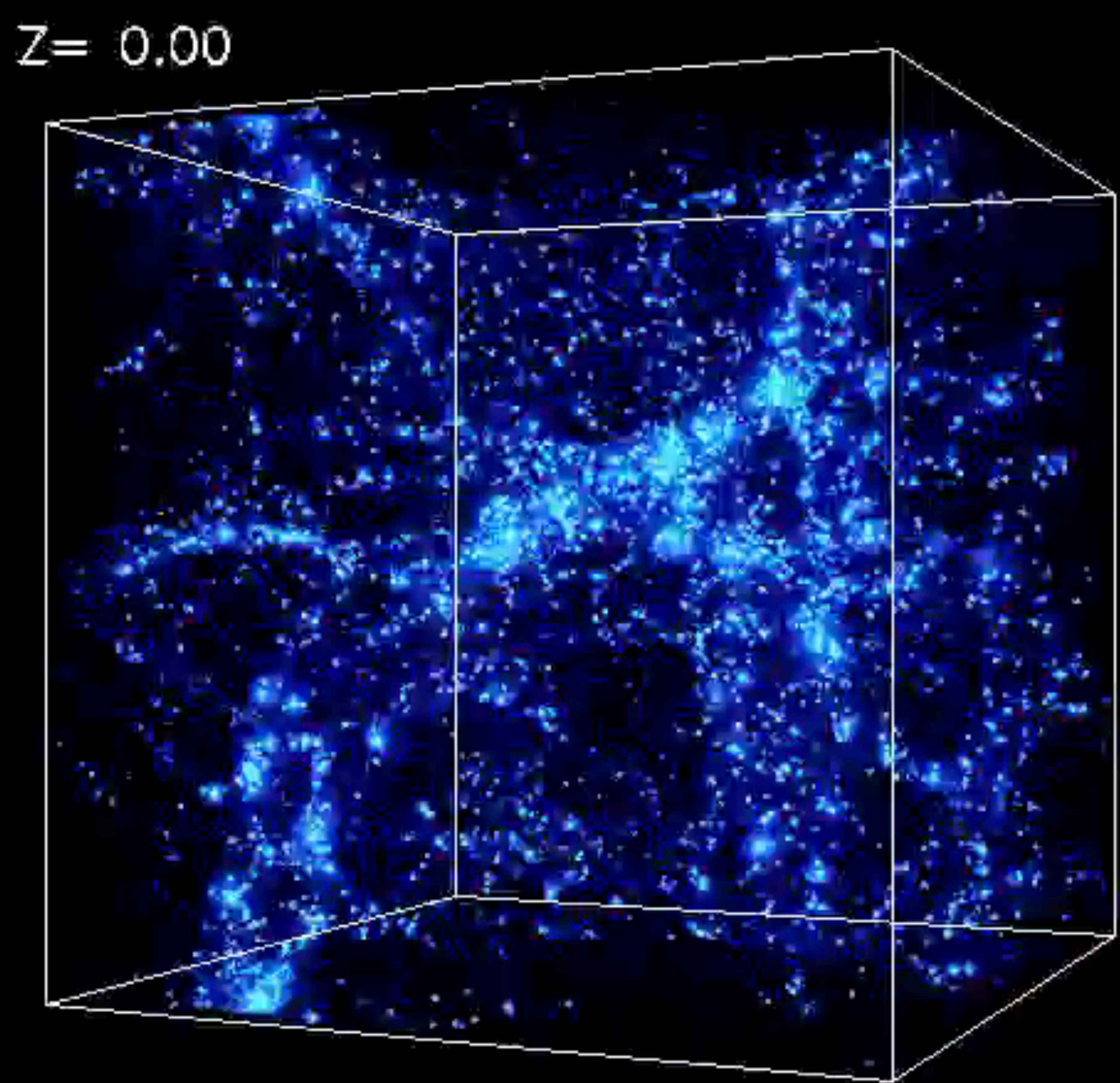
credit: adapted from NASA

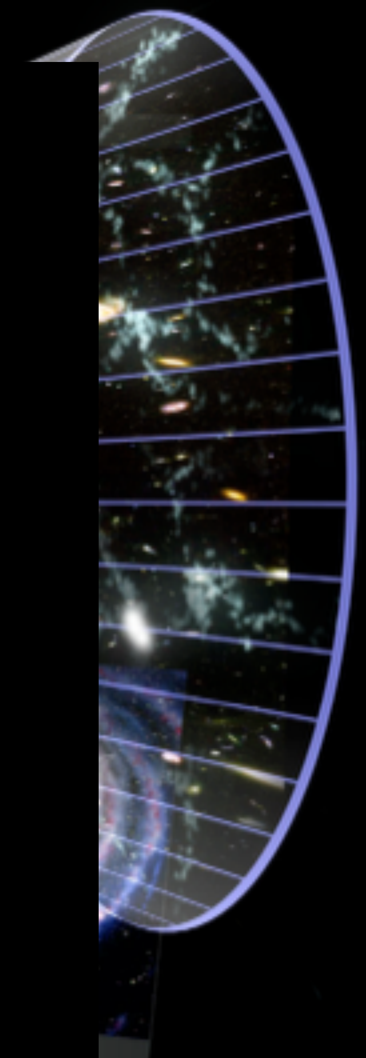
The Standard Big Bang Cosmology

homogeneous

lumpier



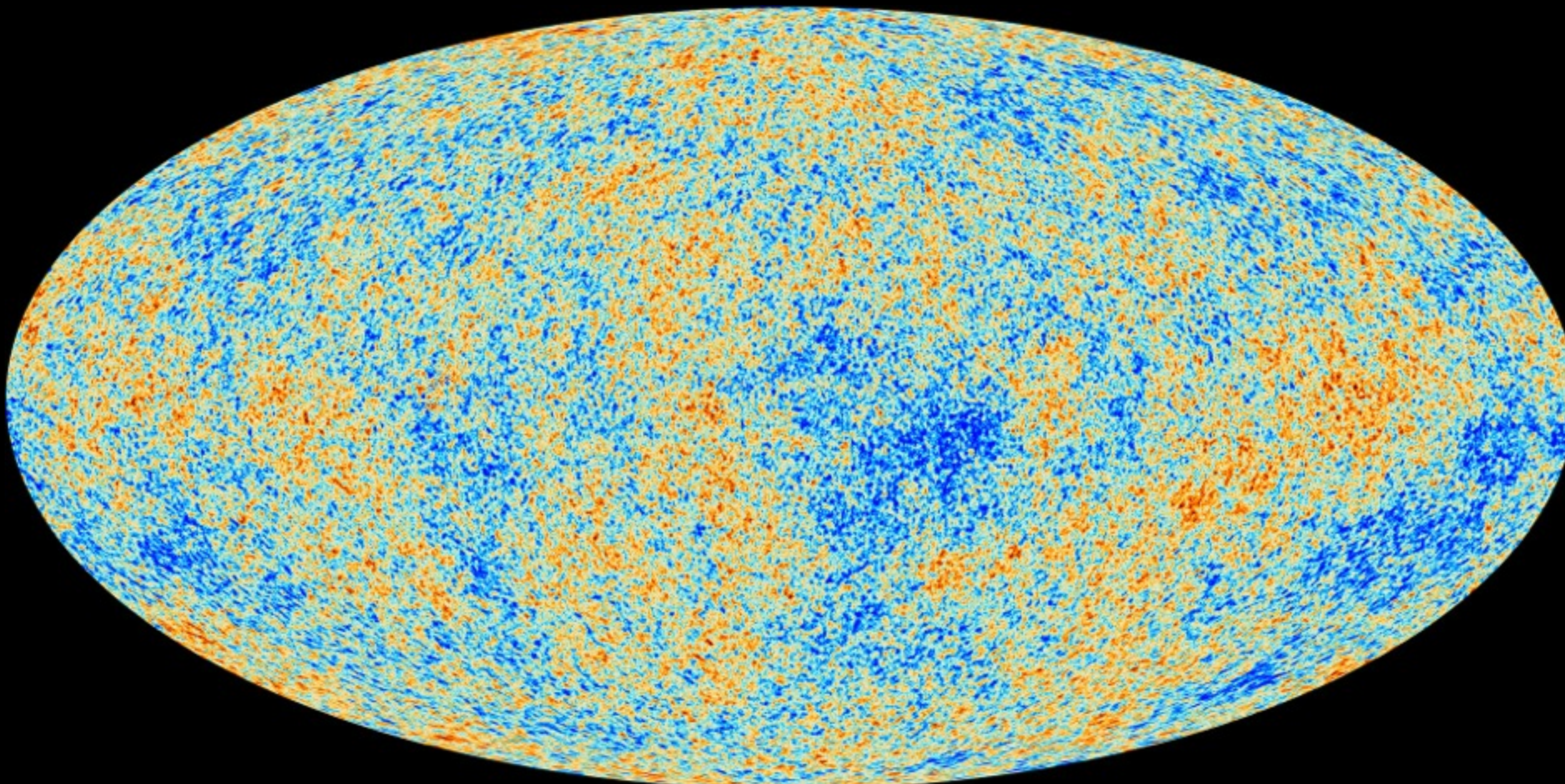




credit:NASA

initial conditions
for density perturbations ?

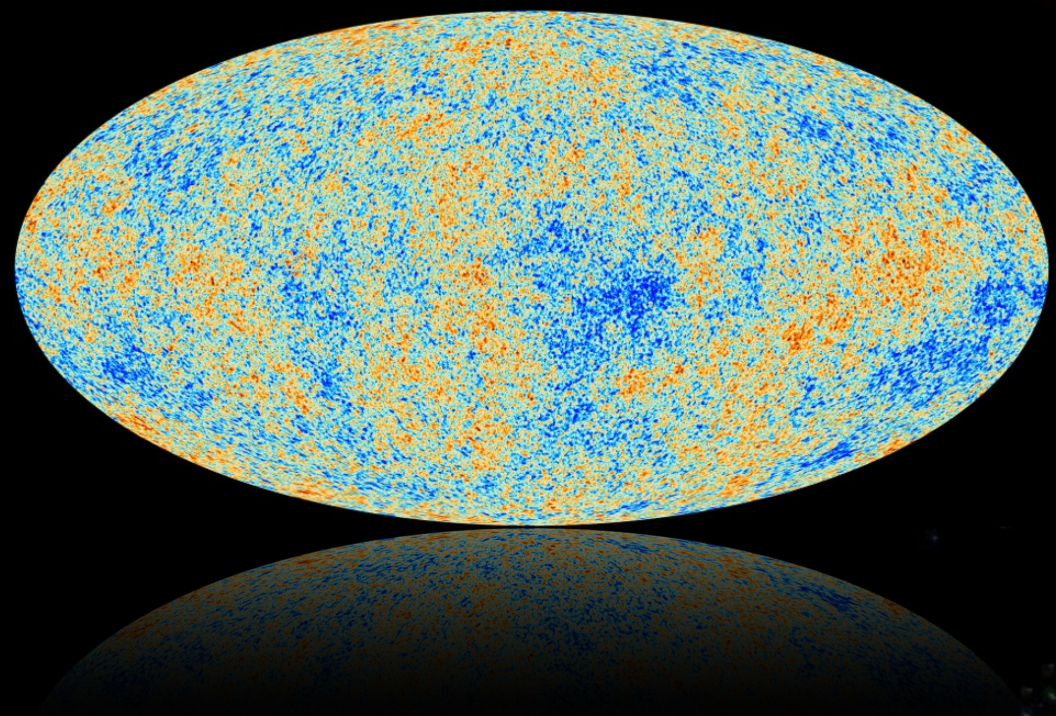
CMB temperature anisotropies

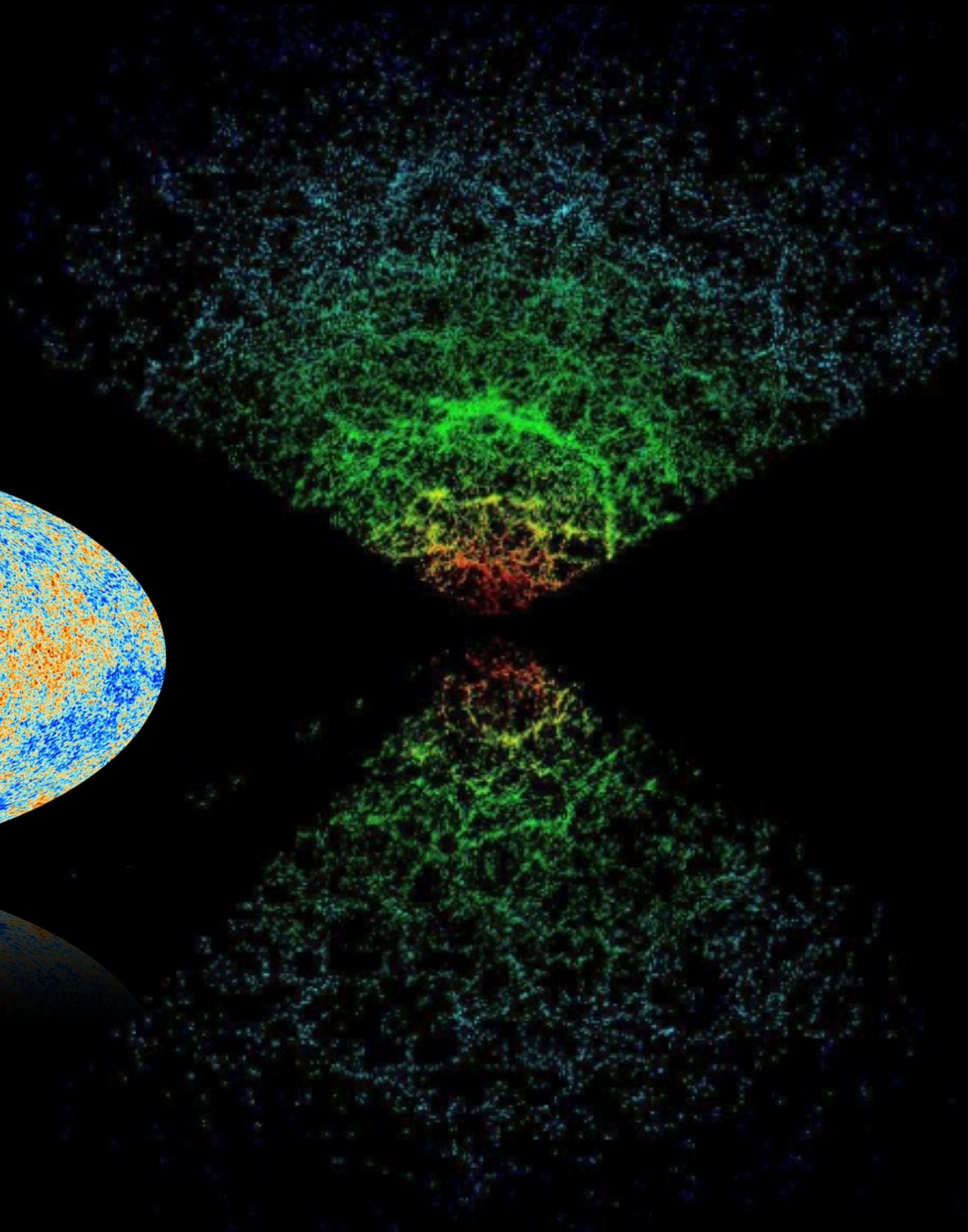


$$\delta T/T \sim 10^{-5}$$

Planck 2015

initial conditions — gravity — observed structure

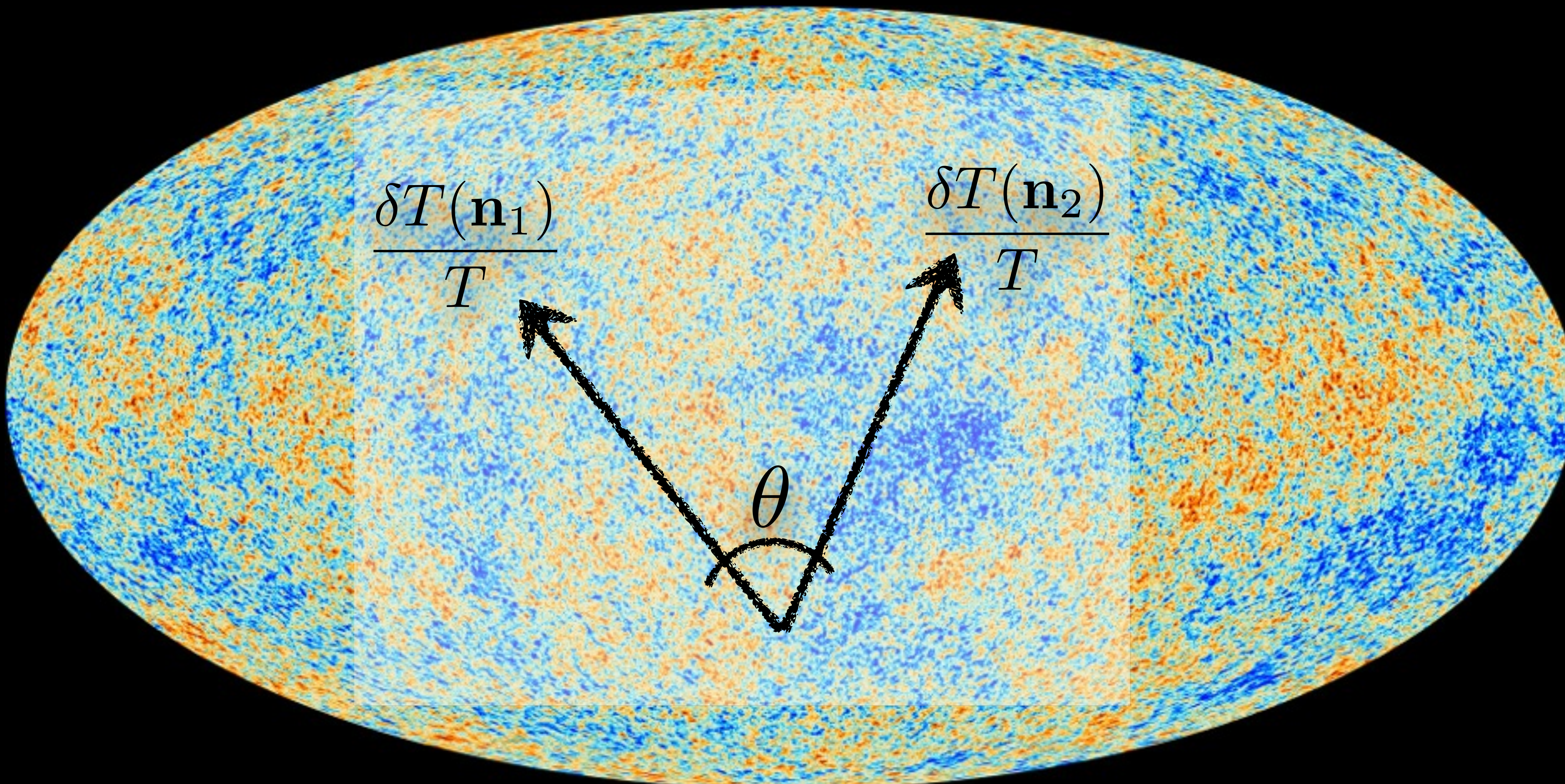




caveat: need dark matter to make this work

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

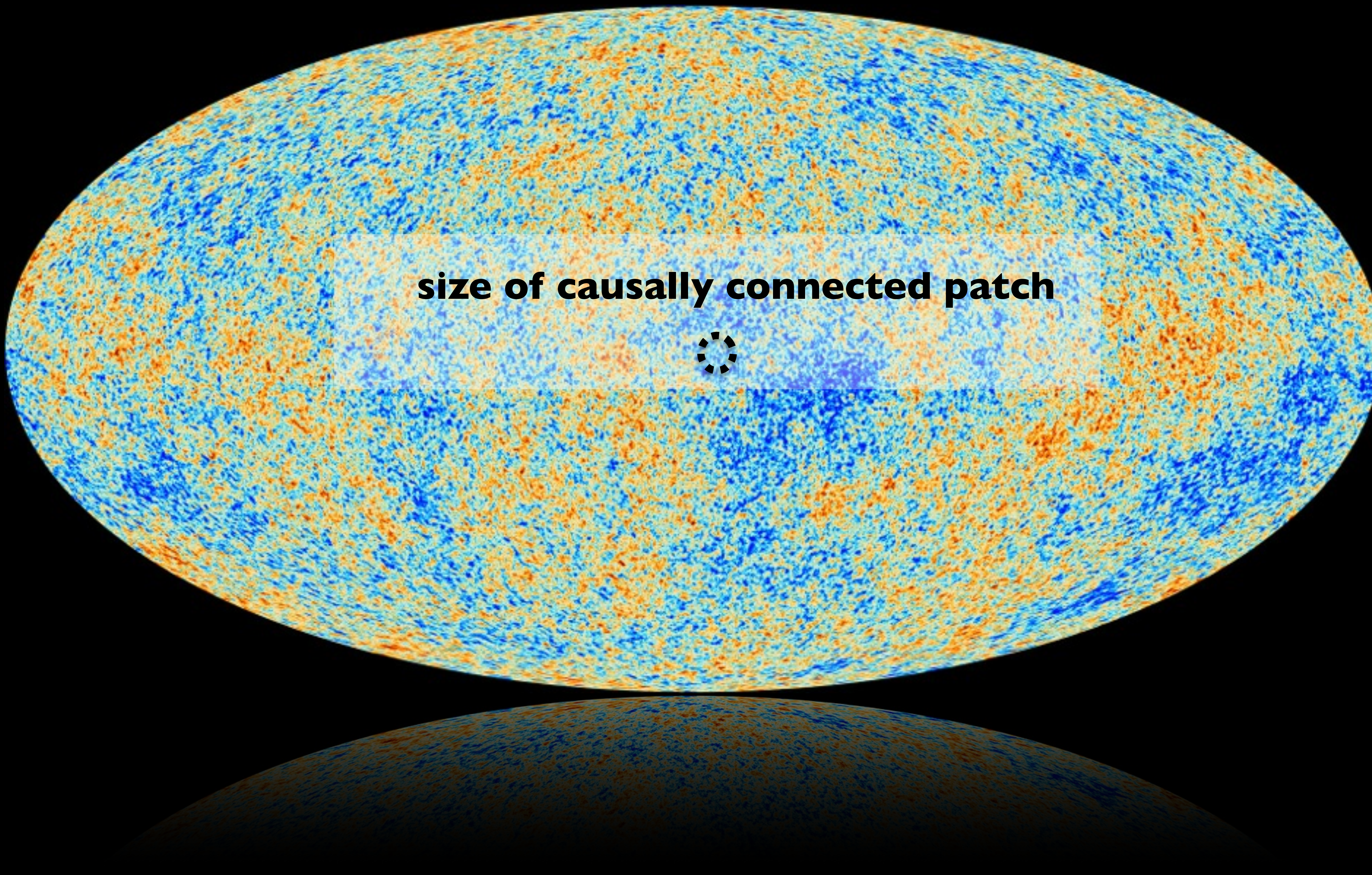
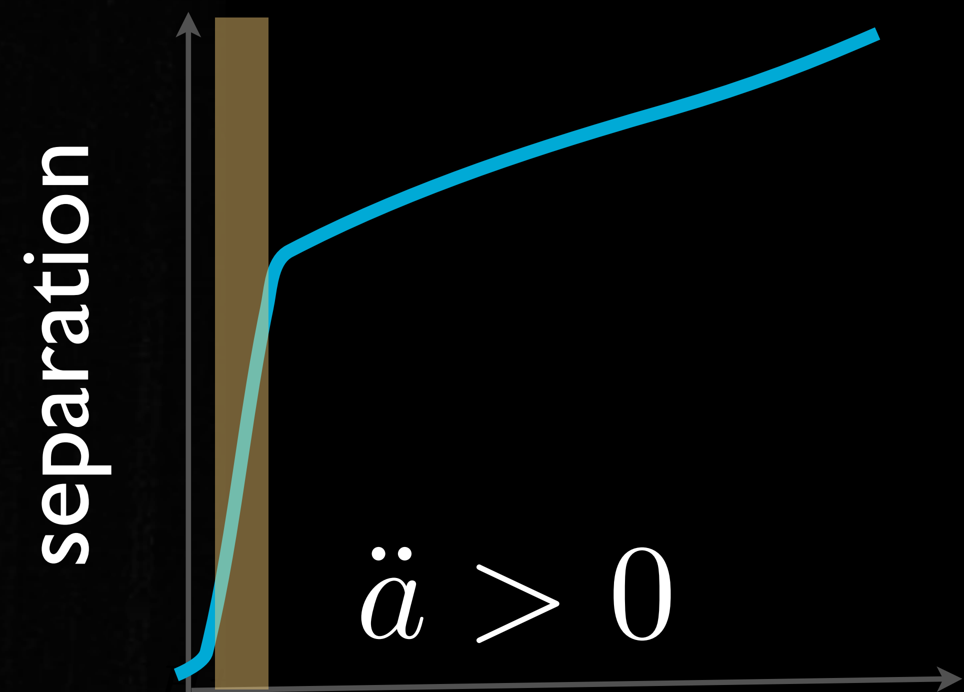


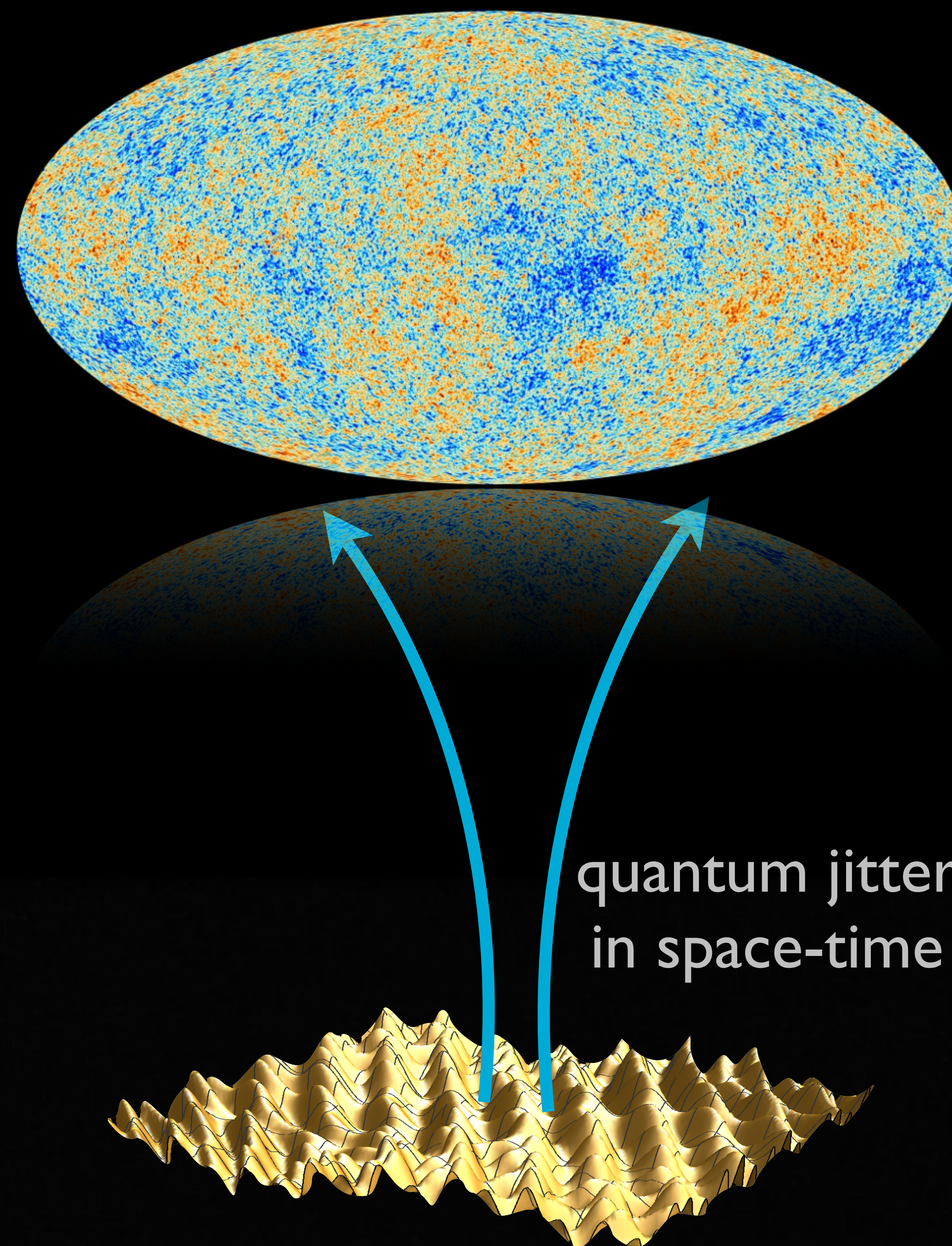
image credit: Planck

Inflationary Cosmology

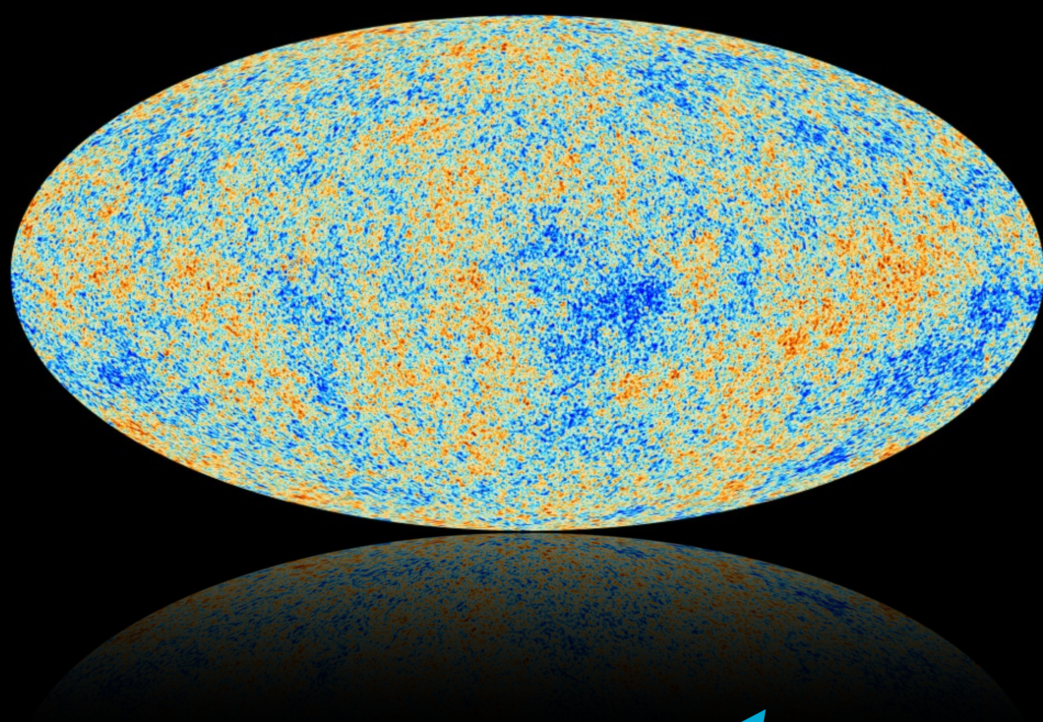
credit: adapted from NASA

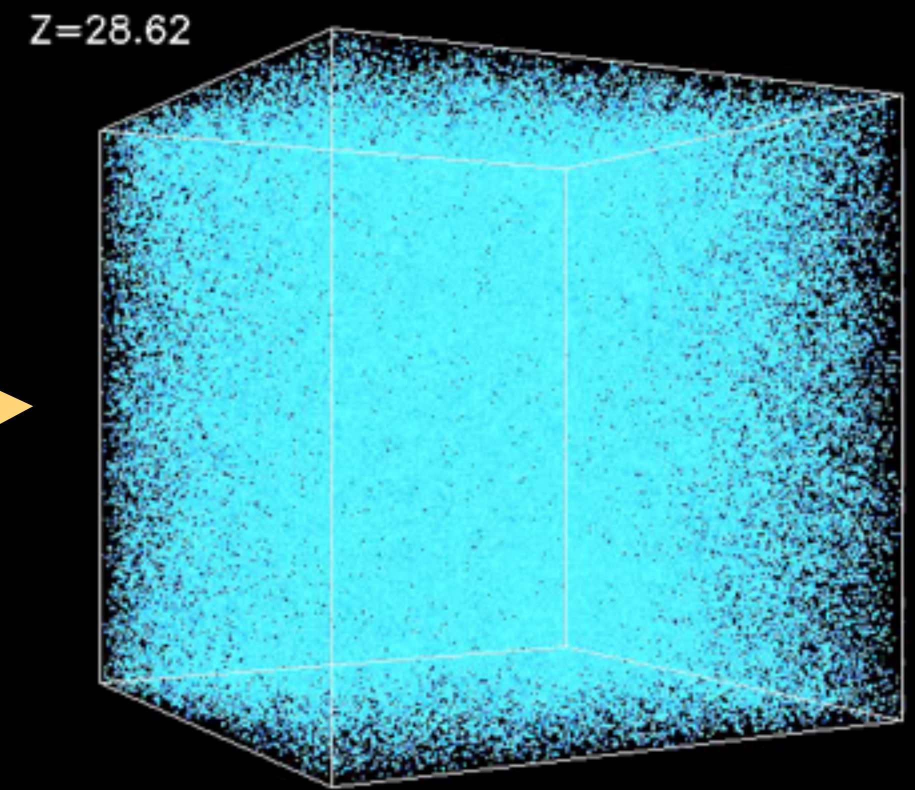
inflation and long distance correlations

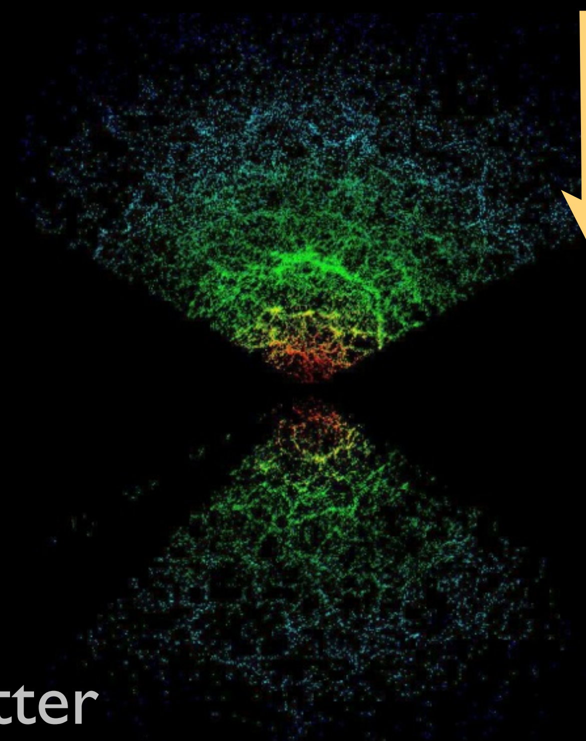


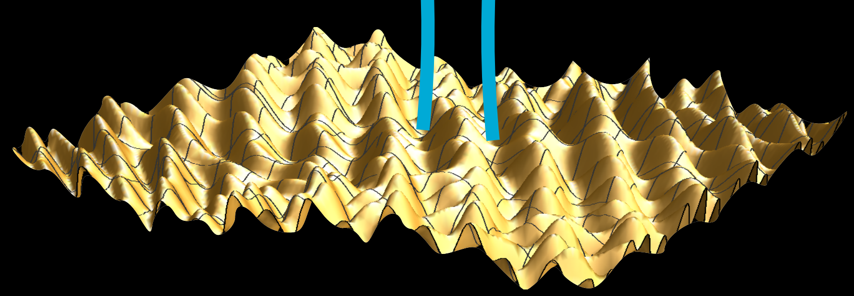


gravity — correlations in galaxies









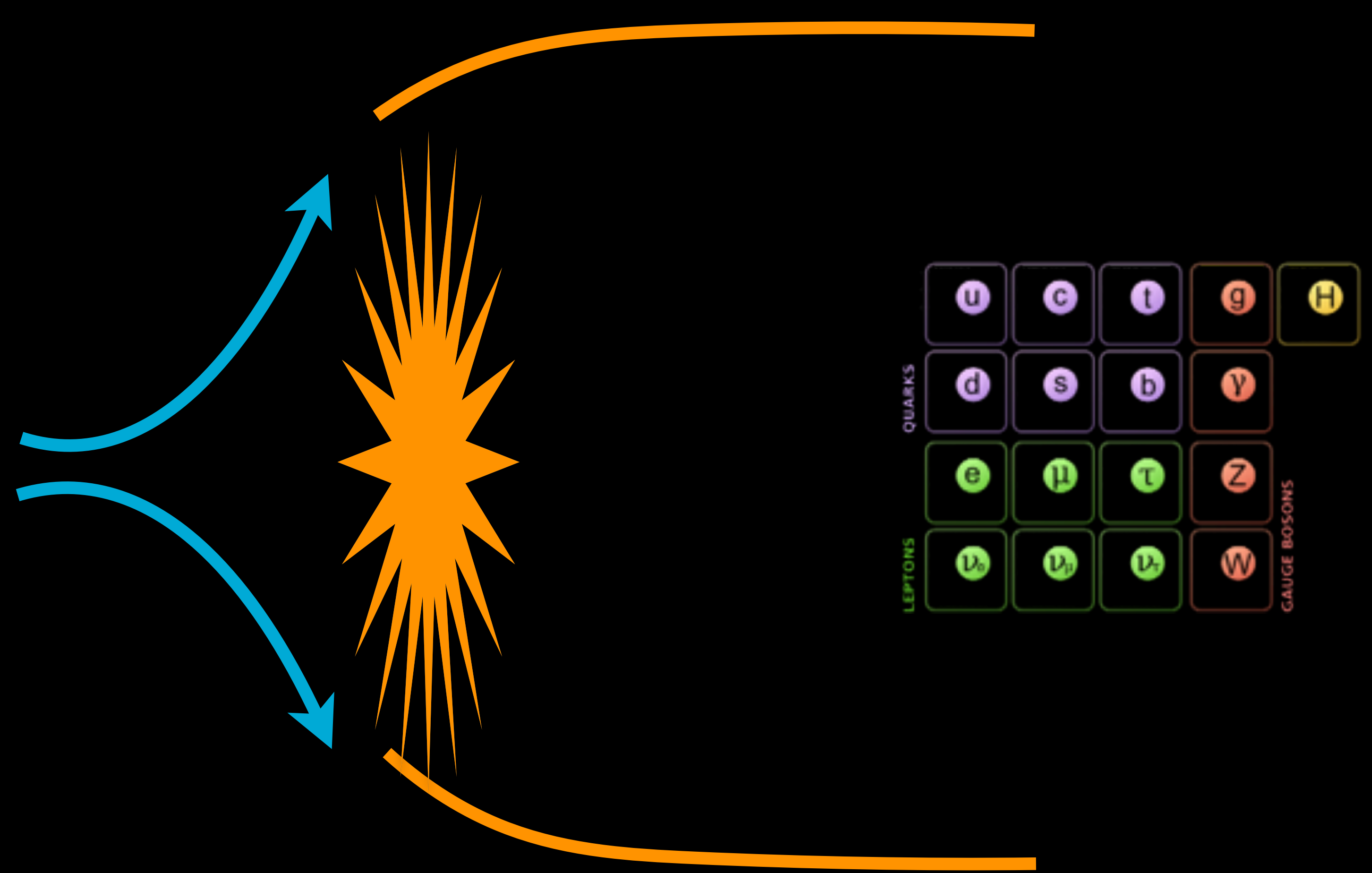
quantum jitter
in space-time

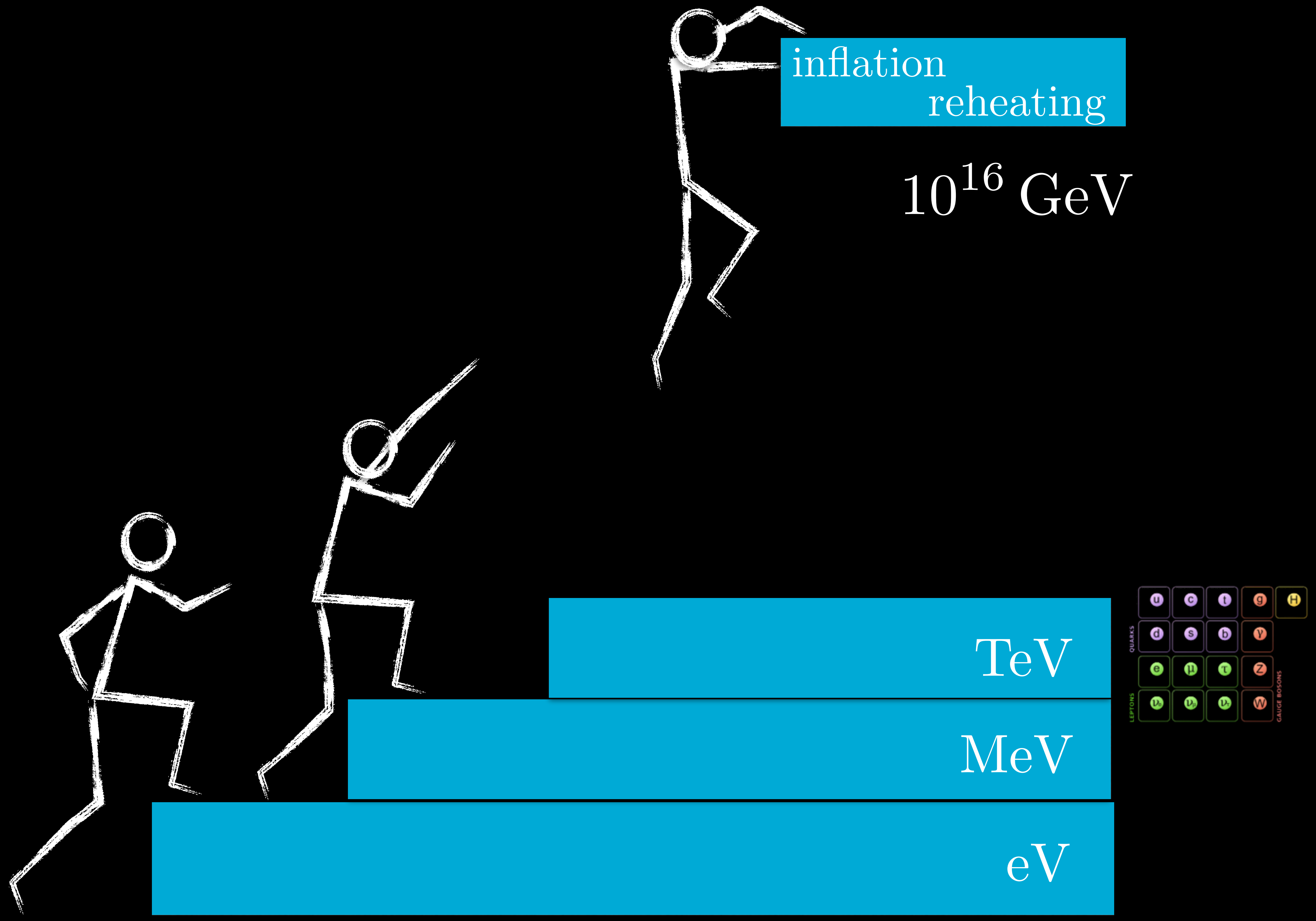
happened in 14 billion years!

- what is the physics of inflation ?

- how did inflation end ? (reheating)

- Standard model? (or an UV complete theory)





inflation
reheating
10^16 GeV
TeV
MeV
eV

two approaches

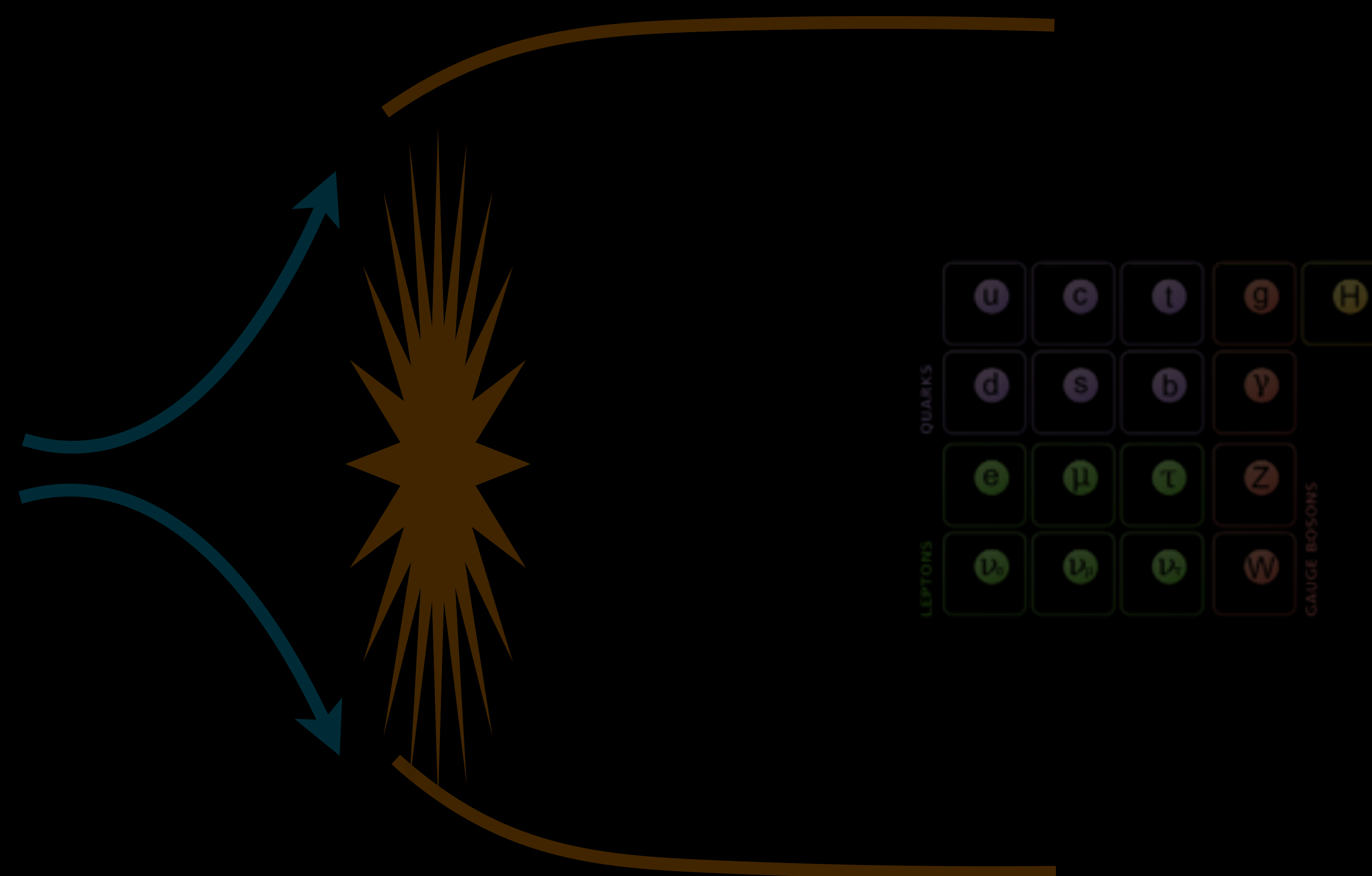
SIMPLE enough

COMPLEX enough

1. Simple models
& their general phenomenology

* simplest things I can get away with

- what drives inflation ?
- how did inflation end ?
- Standard model?



a scalar field drives inflation

$$\varphi(t, \mathbf{x})$$

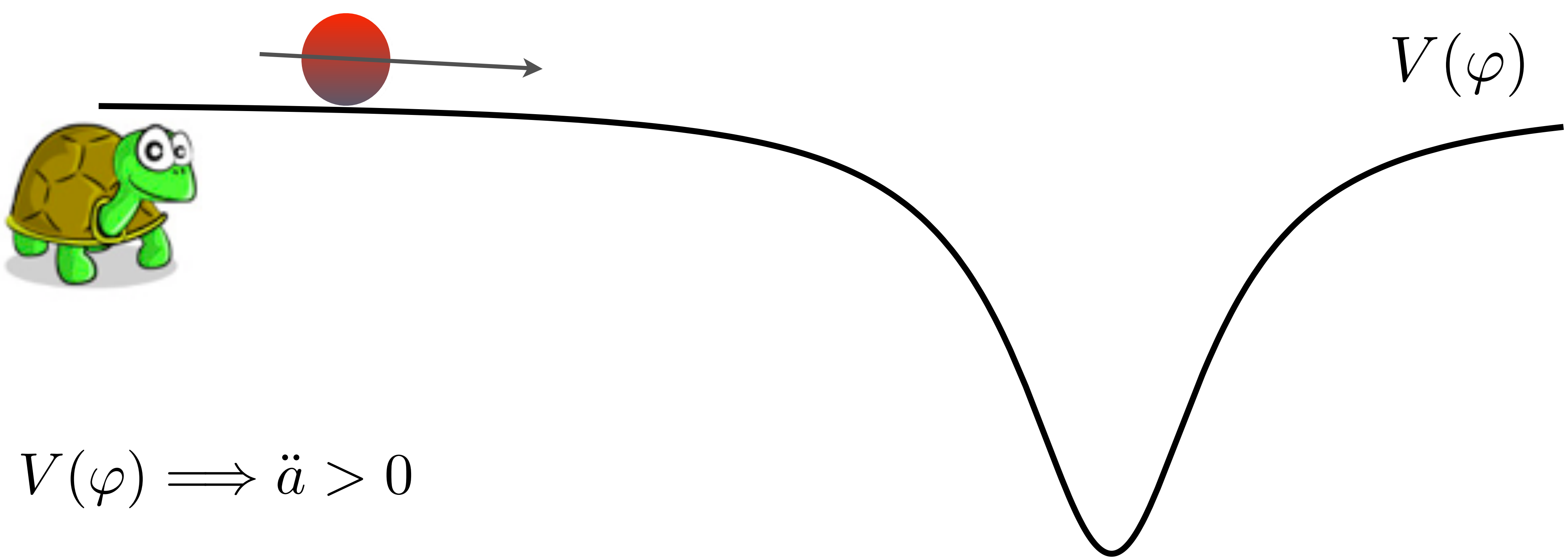
Lagrangian: $$\mathcal{L} = \frac{1}{2}(\partial\varphi)^2 - V(\varphi)$$

* for inflation including gauge fields, see P. Adshead & M. Wyman's (2012)

scalar field driven inflation

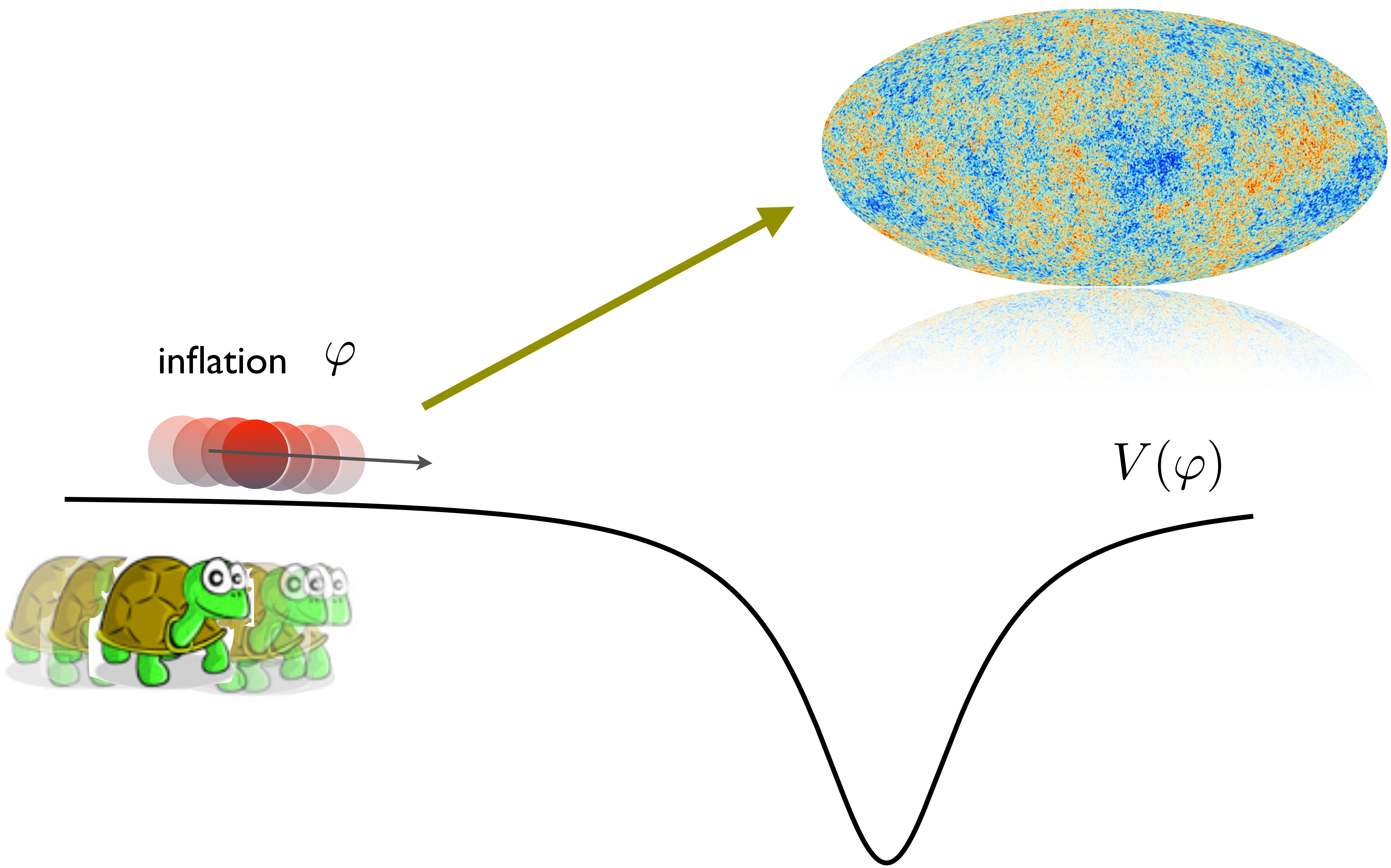
$$\frac{\ddot{a}}{a} = -\frac{1}{3m_{\mathrm{pl}}^2}(\dot{\varphi}^2 - V(\varphi))$$

inflation φ

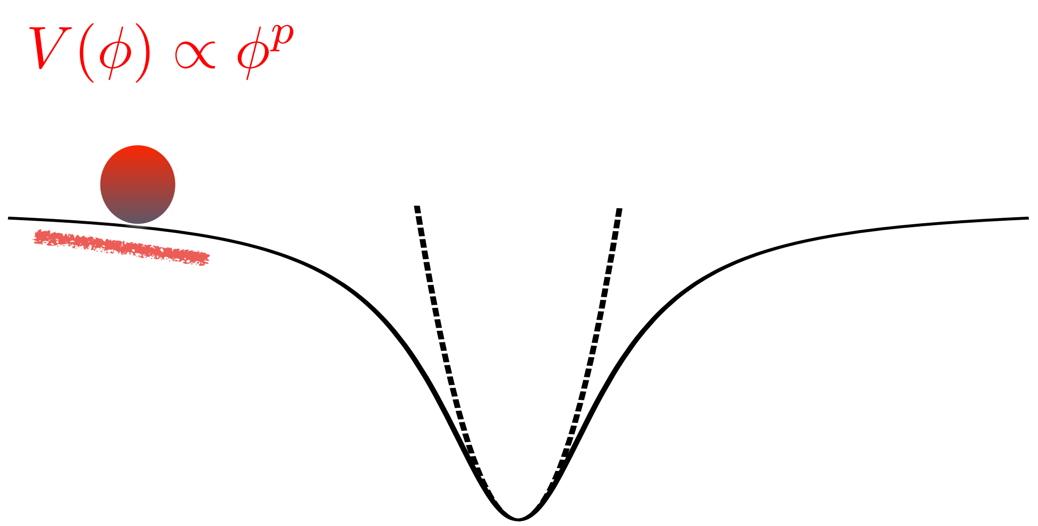


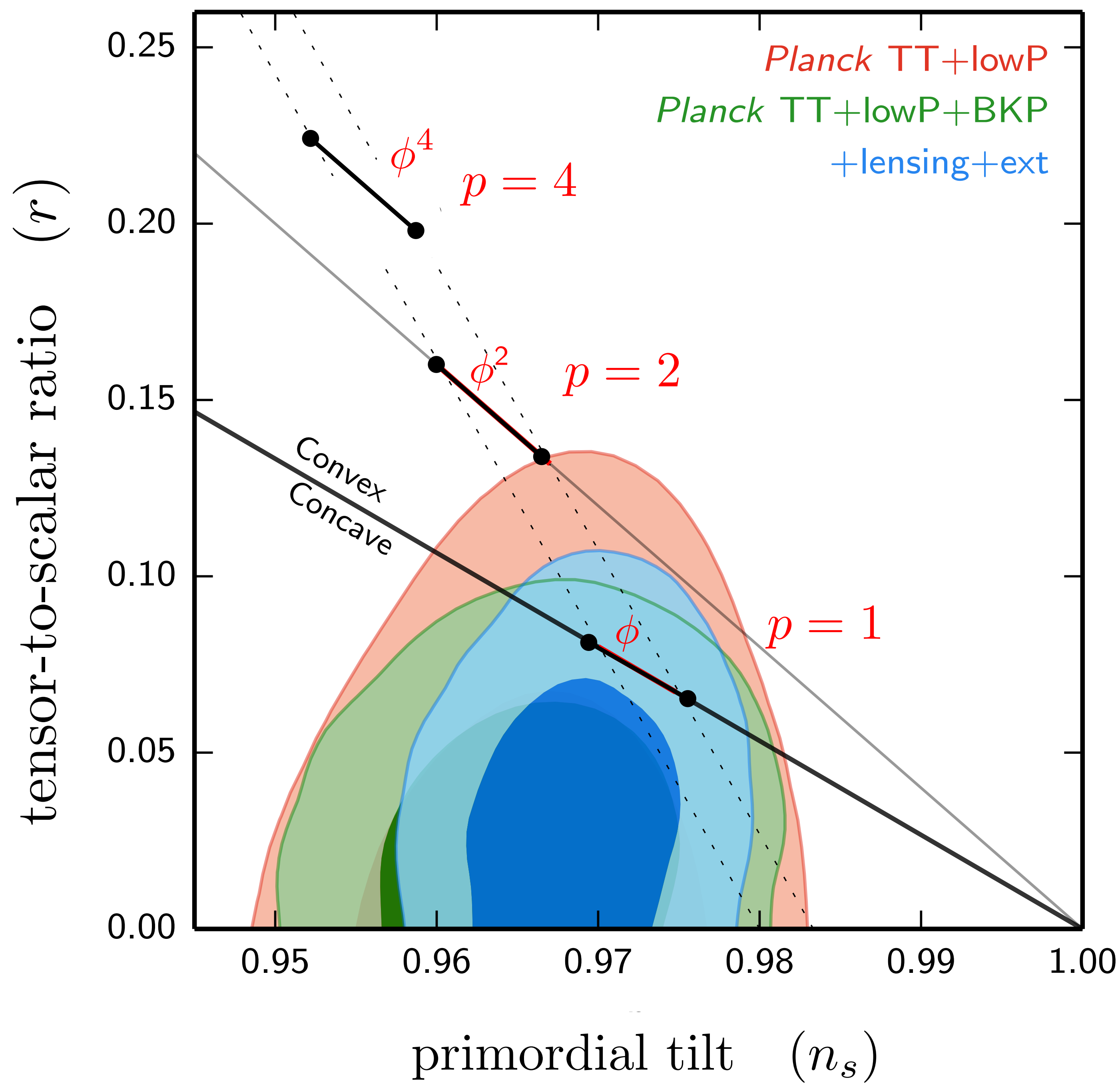
$$\dot{\varphi}^2 \ll V(\varphi) \Longrightarrow \ddot{a} > 0$$

inflationary quantum perturbations



constraints from observations



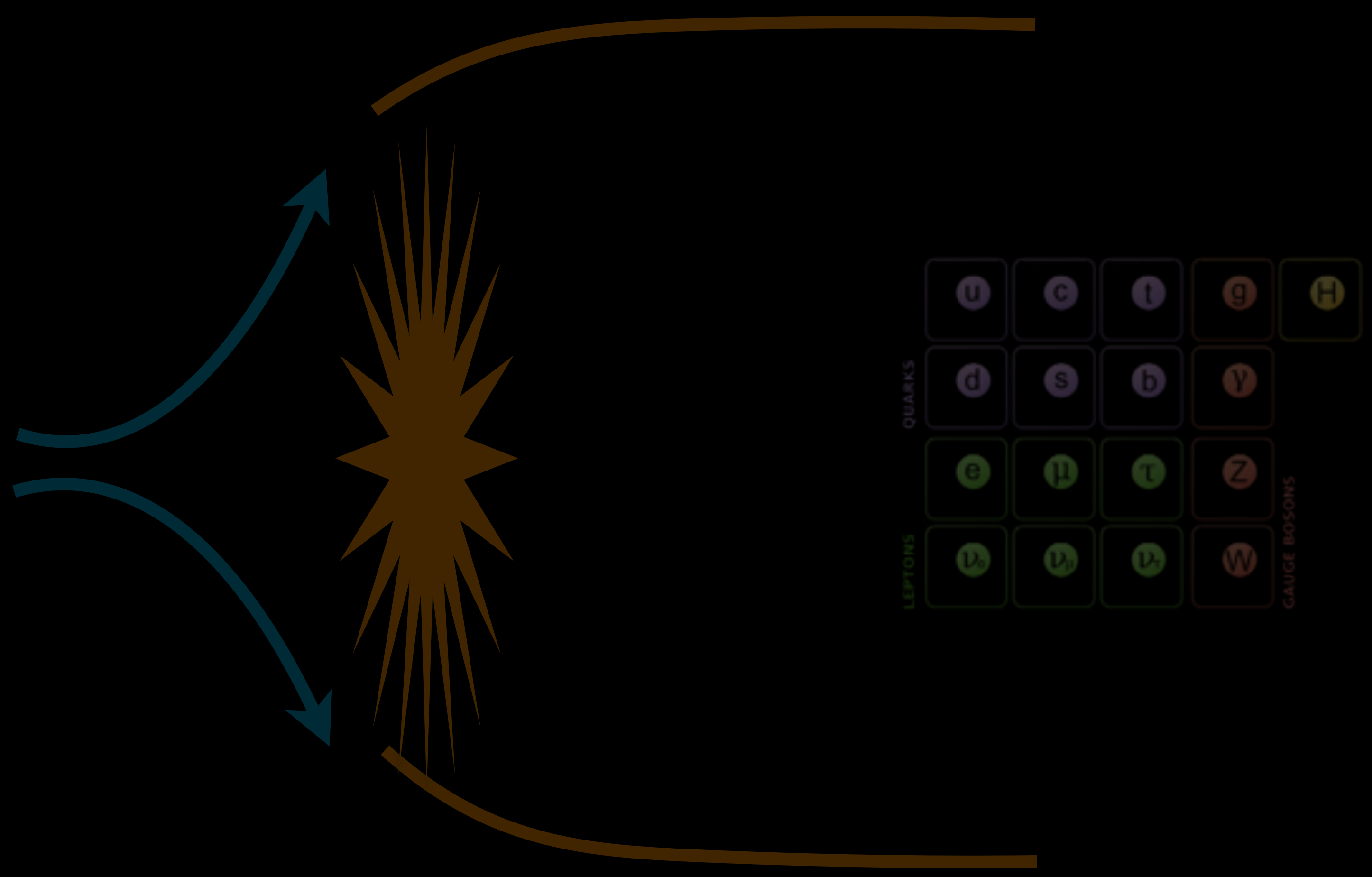


$$\mathcal{P}_{\text{inf}}(k) \propto k^{n_s - 1}$$

for example:

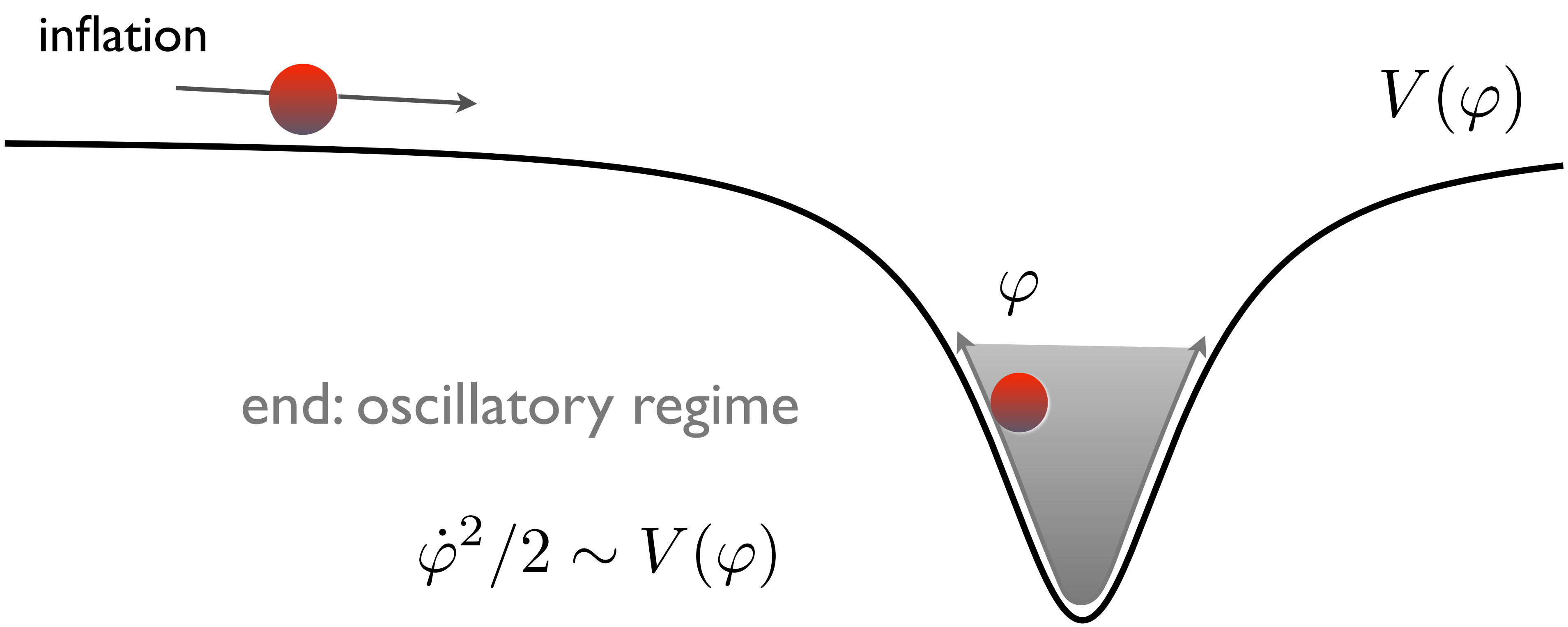
Silverstein & Westhpal (2008)
McAllister et. al (2014)
Kallosh & Linde (2014)

- what drives inflation ?
- how did inflation end ?
- Standard model?

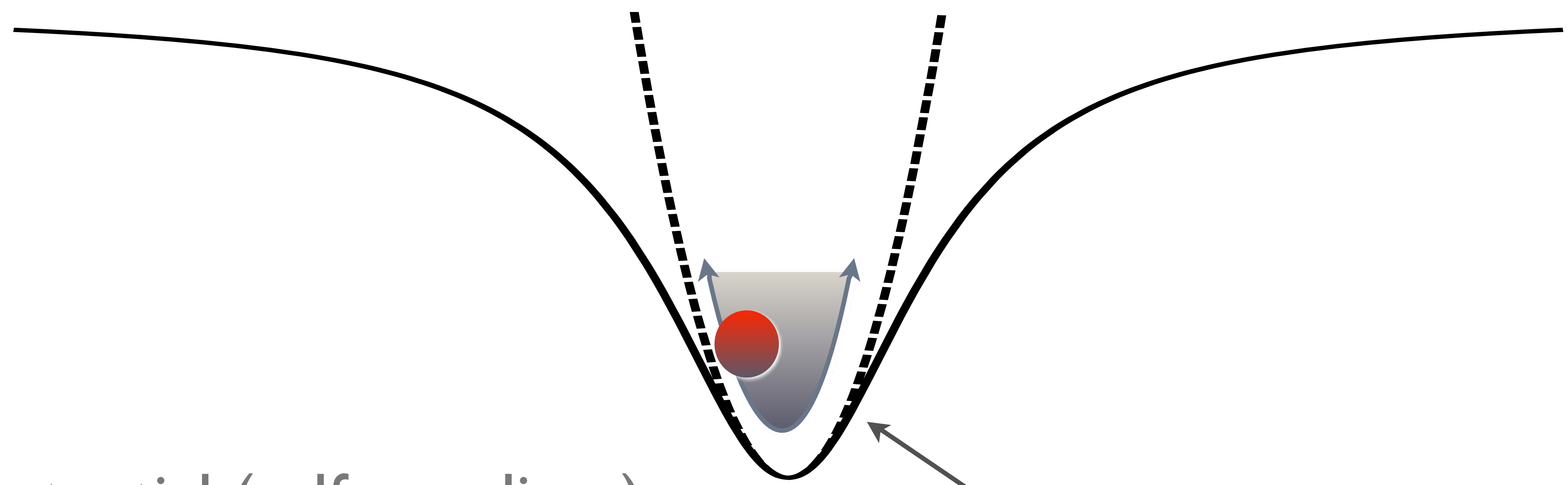


ending inflation

$$\frac{\ddot{a}}{a} = -\frac{1}{3m_{\rm pl}^2}(\dot{\varphi}^2 - V(\varphi))$$



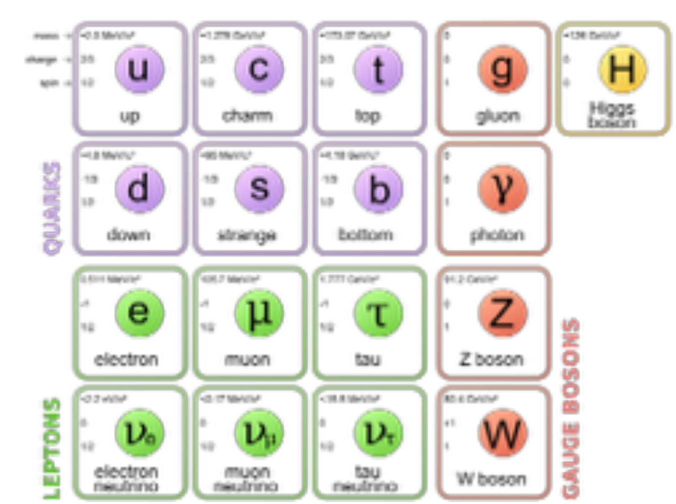
energy transfer: “reheating”



- shape of the potential (self couplings)

- couplings to other fields

$\chi\,,\,\psi$

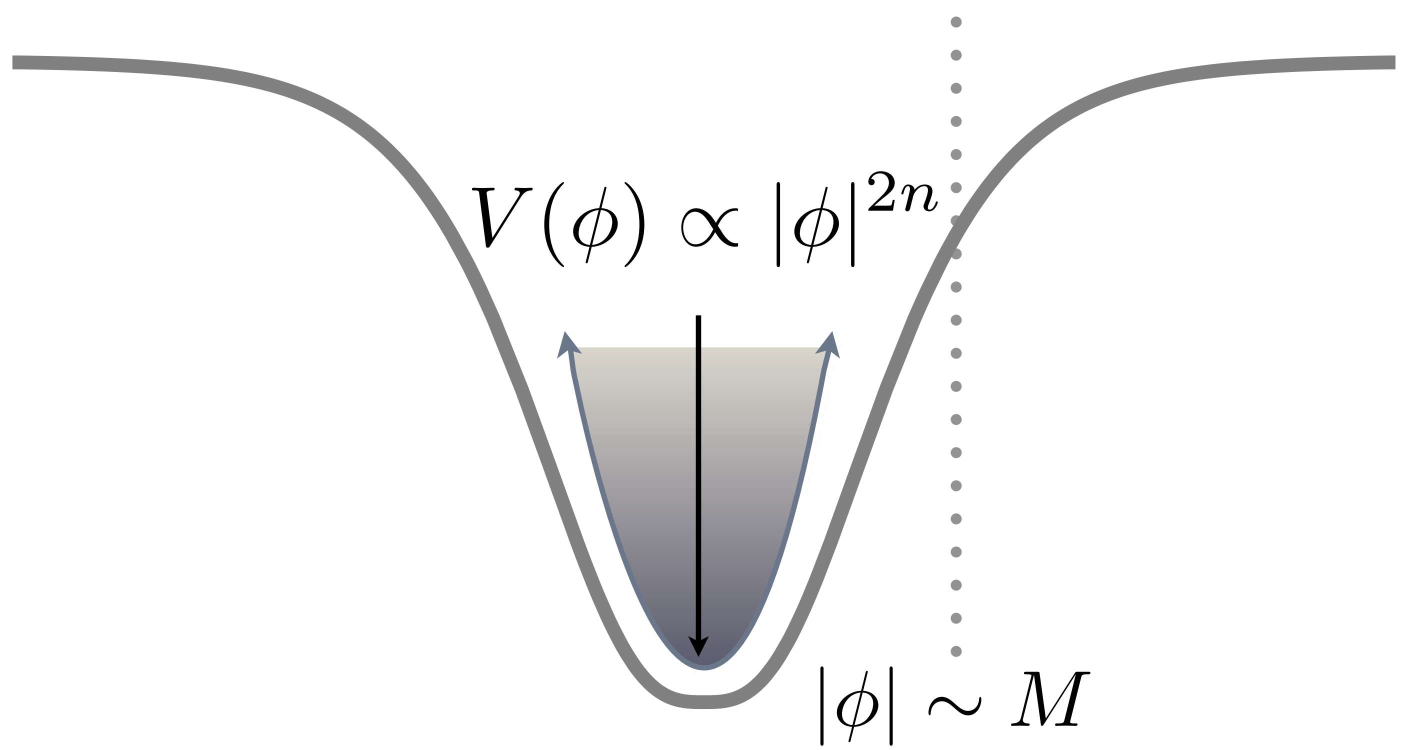


for example:
Kofman, Linde & Starobinsky (1994)
review: MA, Kaiser, Karouby & Hertzberg (2014)

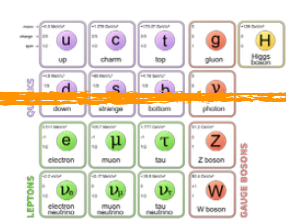
end of inflation in "simple" models

for example:

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



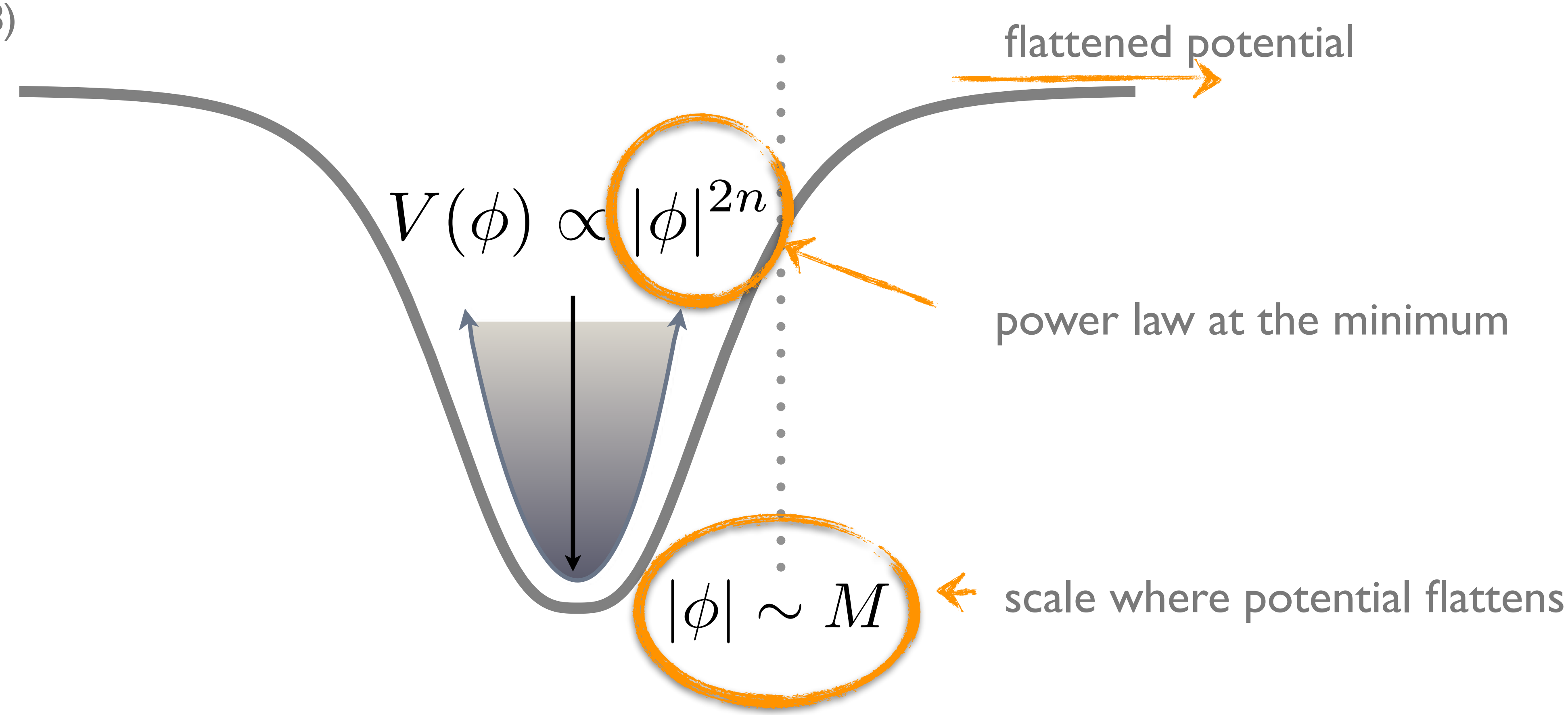
- shape of the potential (self couplings)

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

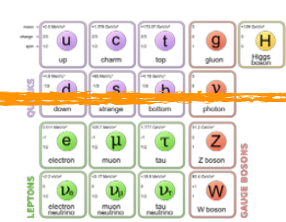
end of inflation in “simple” models

for example:

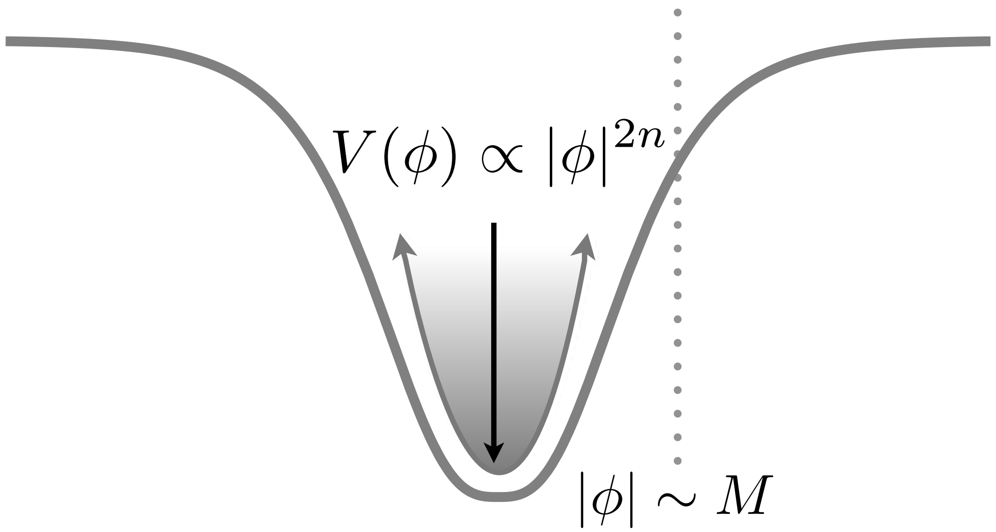
Silverstein & Westhpal (2008)
McAllister et. al (2014)
Kallosh & Linde (2014)



- shape of the potential (self couplings)

- ~~couplings to other fields~~  ~~χ , ψ~~

end of inflation in “simple” models



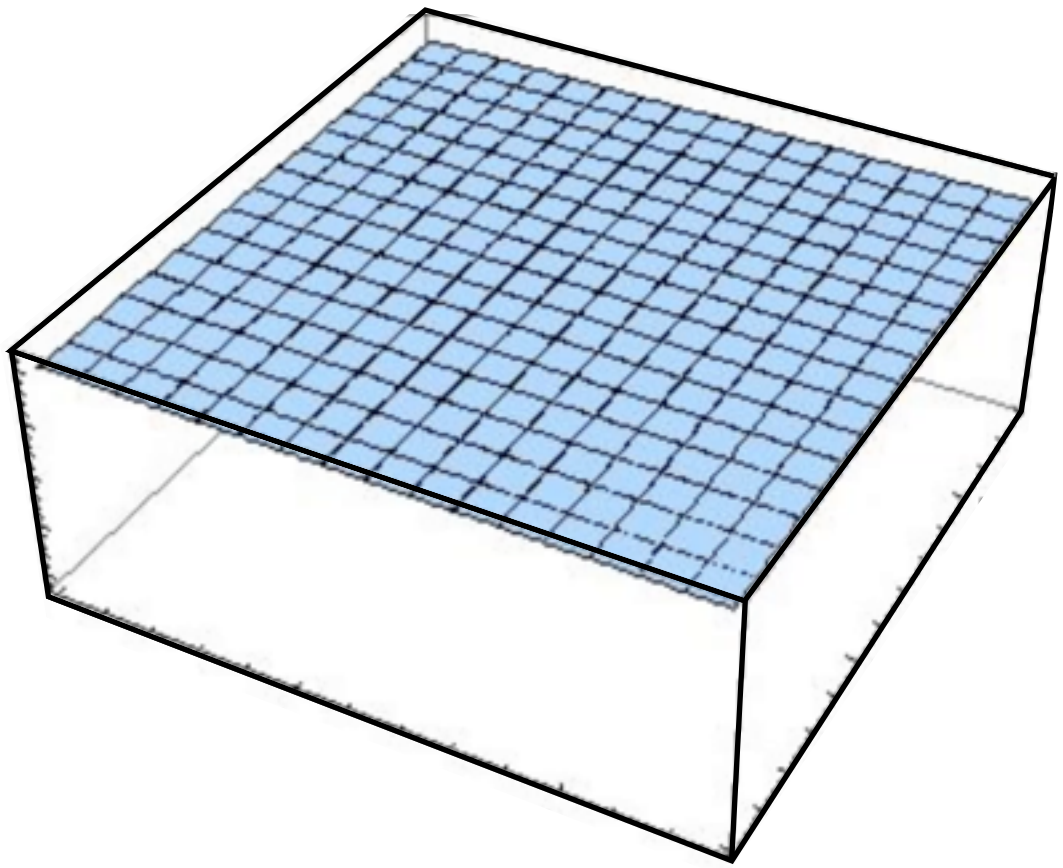
(i) what are the dynamics ?

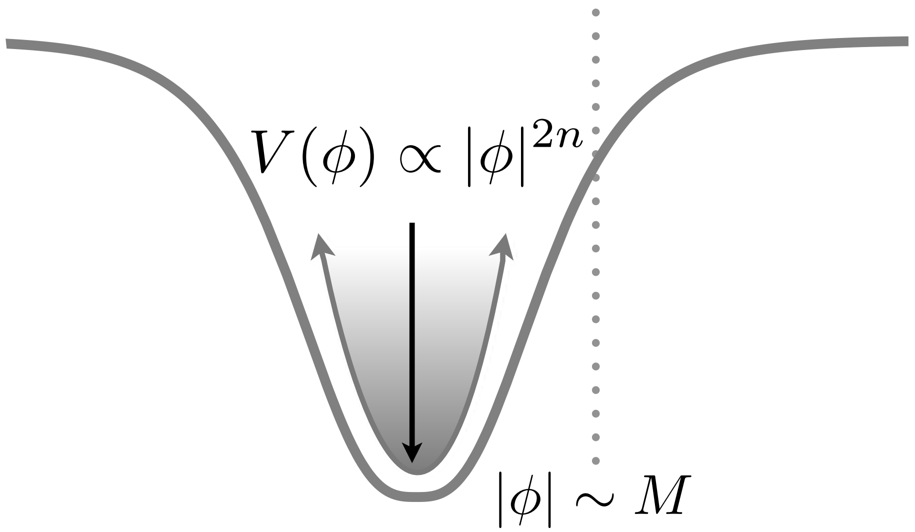
(ii) eq. of state & how long to radiation domination ?

(iii) obs. consequences ?

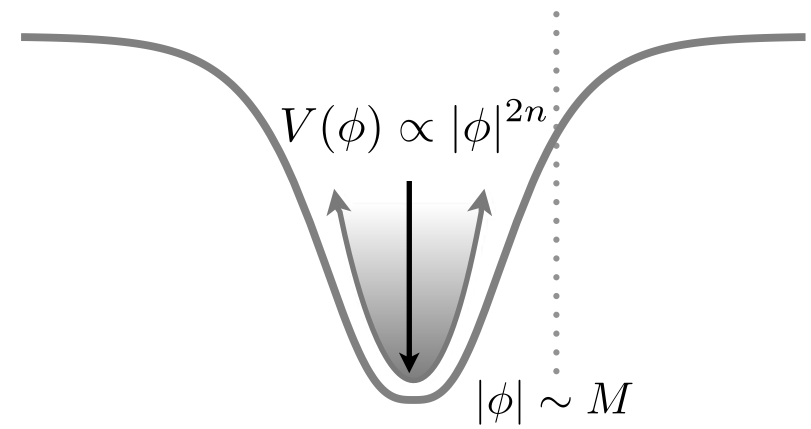
Lozanov & MA (2016) + earlier works

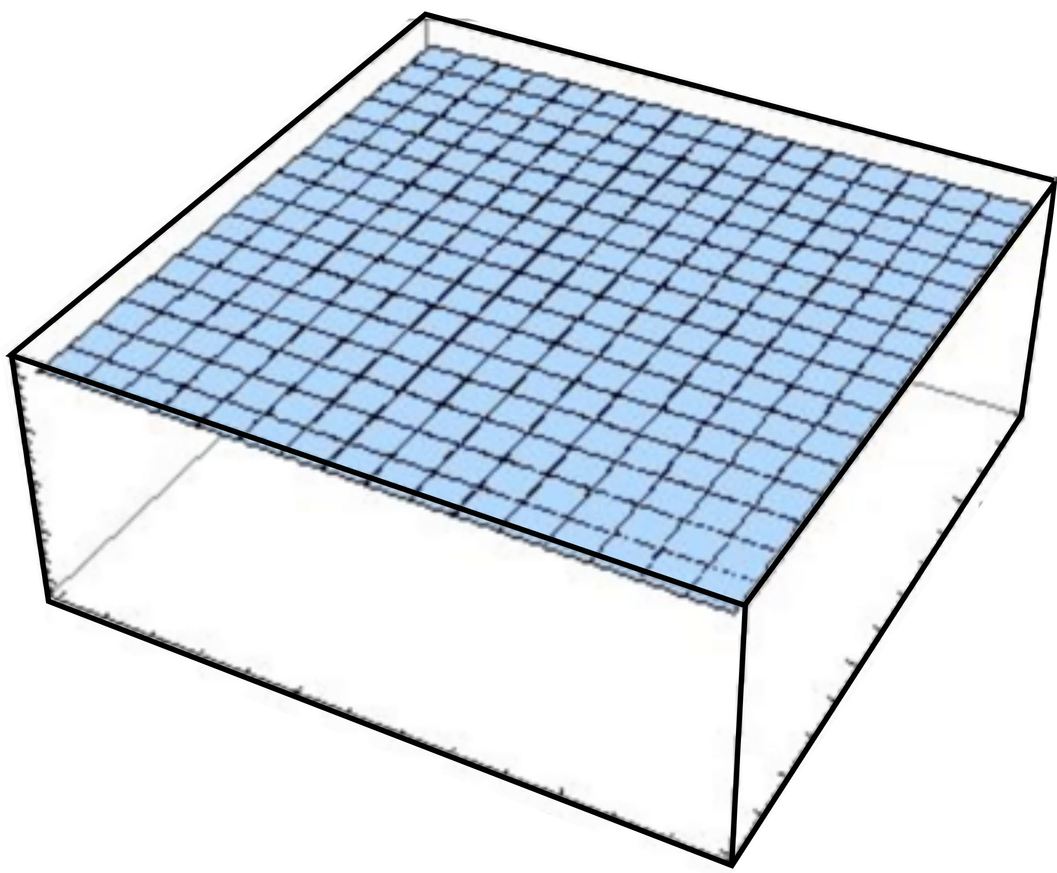
homogeneous dynamics





homogeneous eq. of state



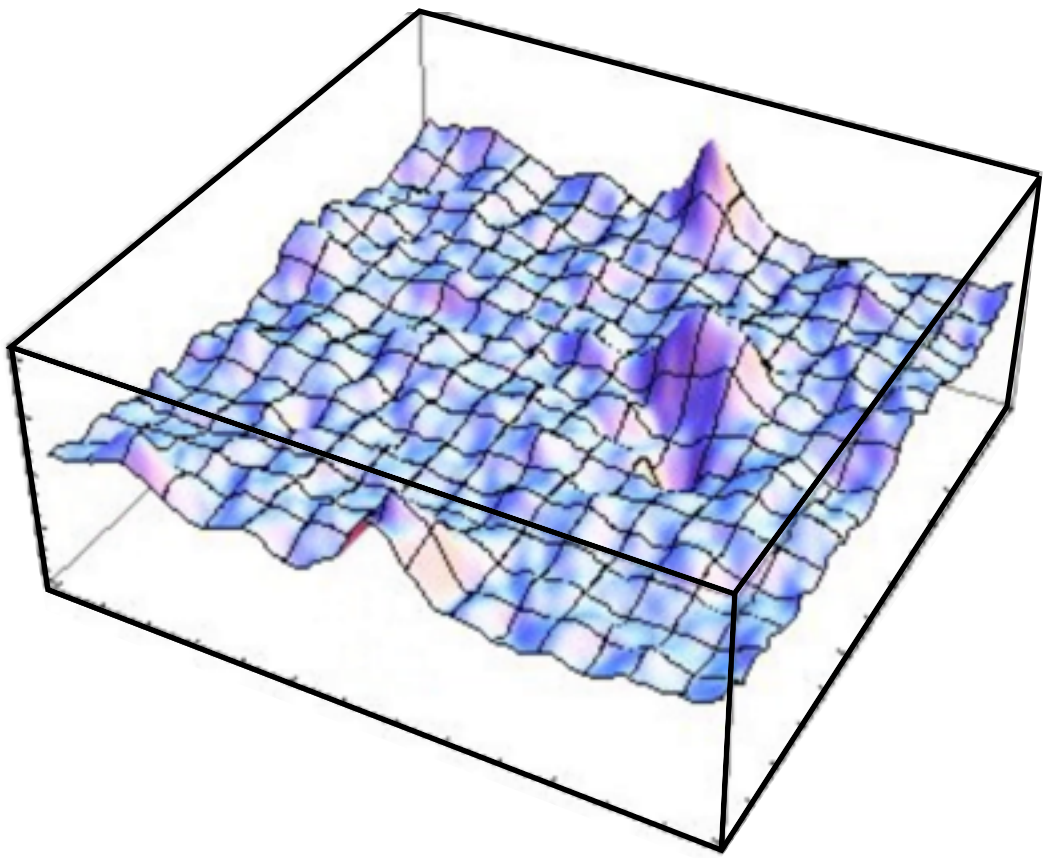


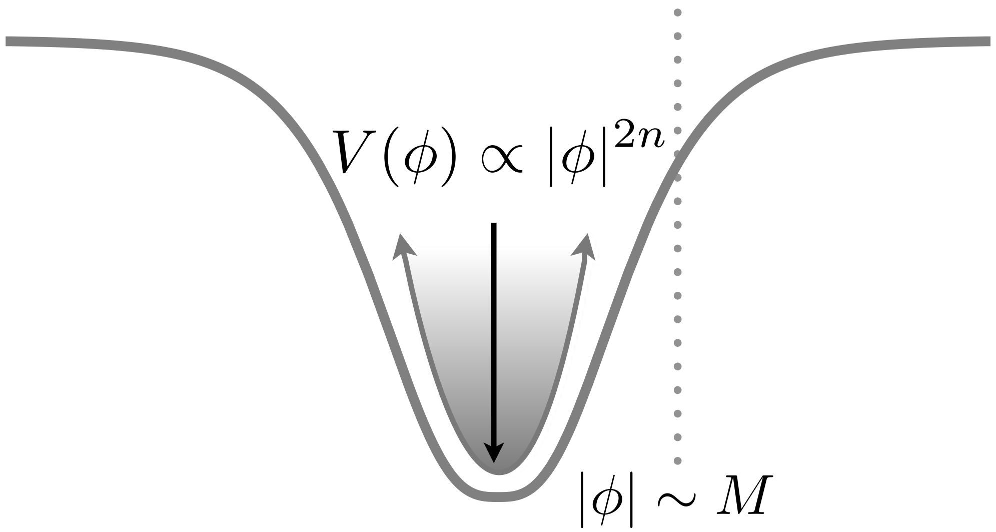
$$\text{eq. of state } w = \frac{\text{pressure}}{\text{density}}$$

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

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

fragmentation is (almost) inevitable





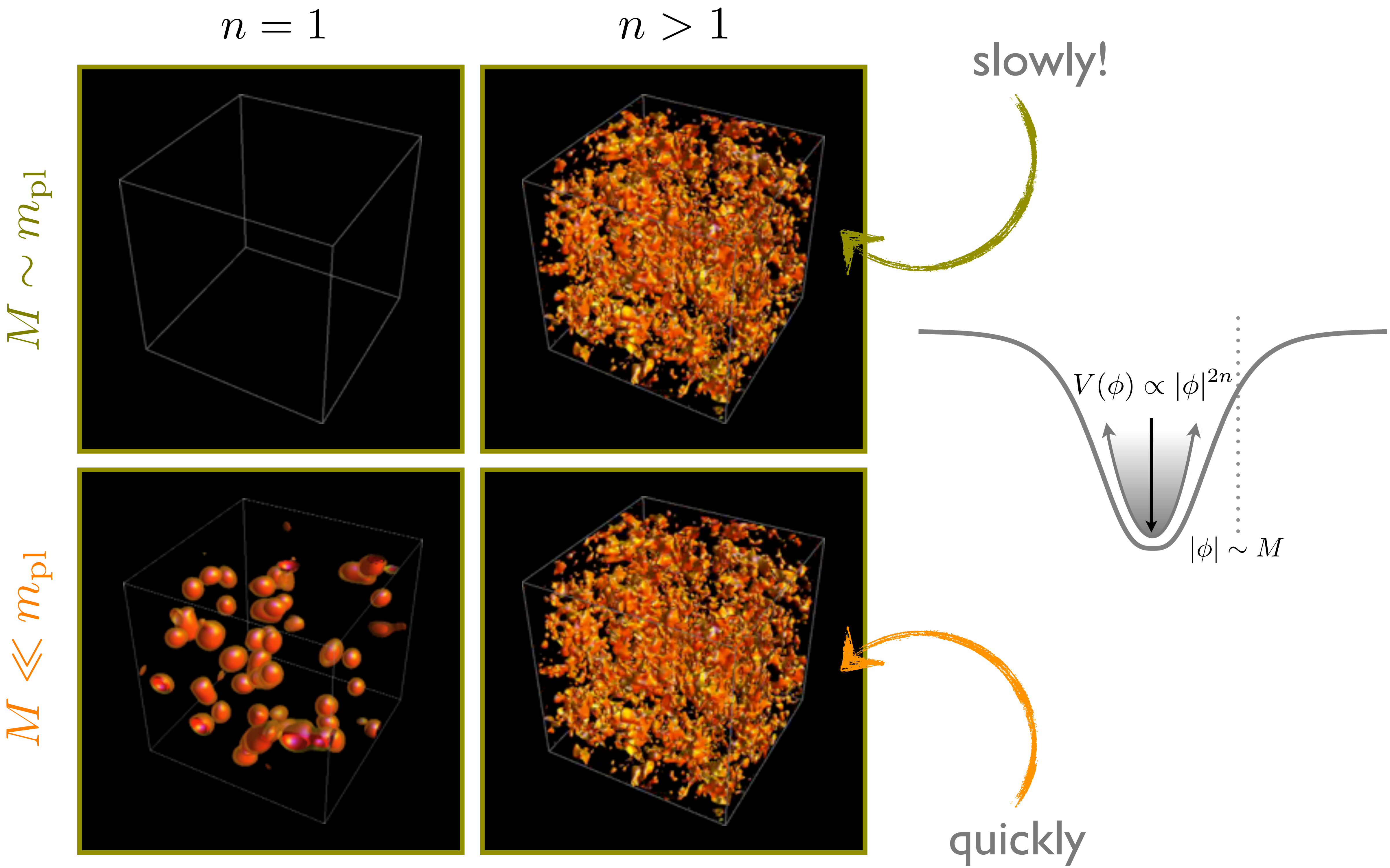
(i) existence of wings (self-couplings) $M \lesssim m_{\rm pl}$

and/ or

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

* but might take a while depending on parameters

result of fragmented dynamics
* after sufficient time



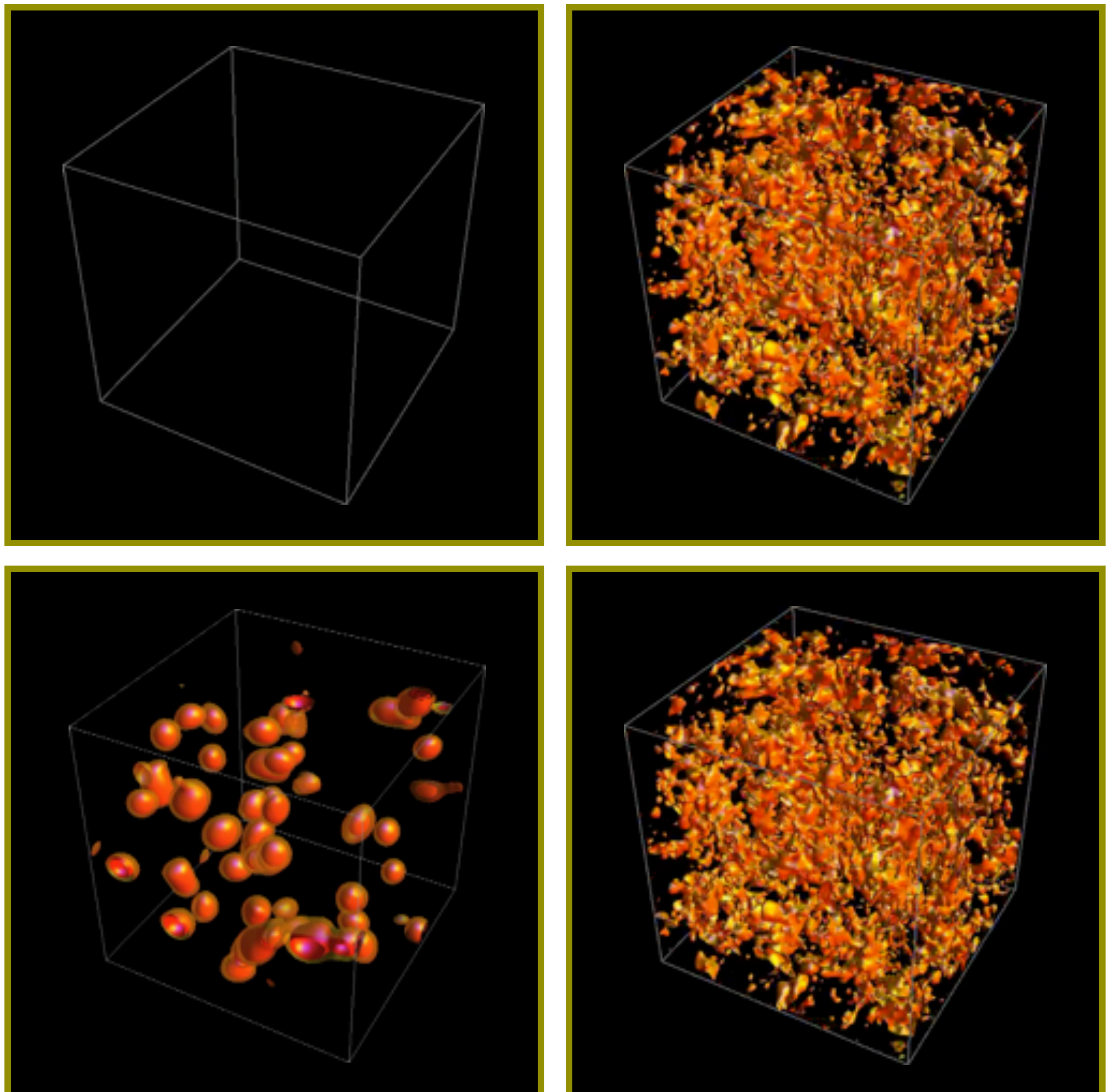
eq. of state

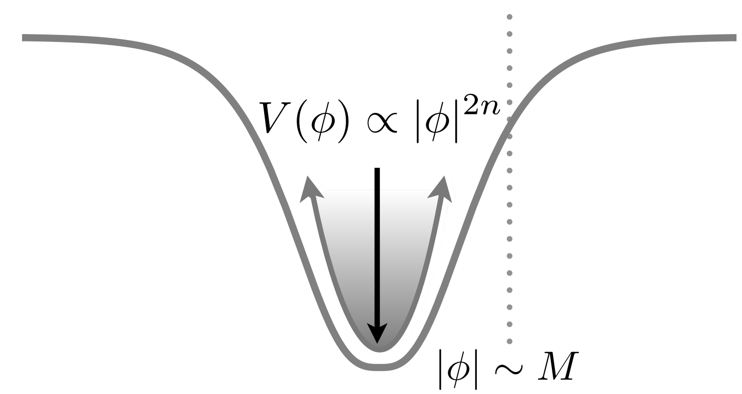
* after sufficient time

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

$M \sim m_{\rm pl}$

$M \ll m_{\rm pl}$

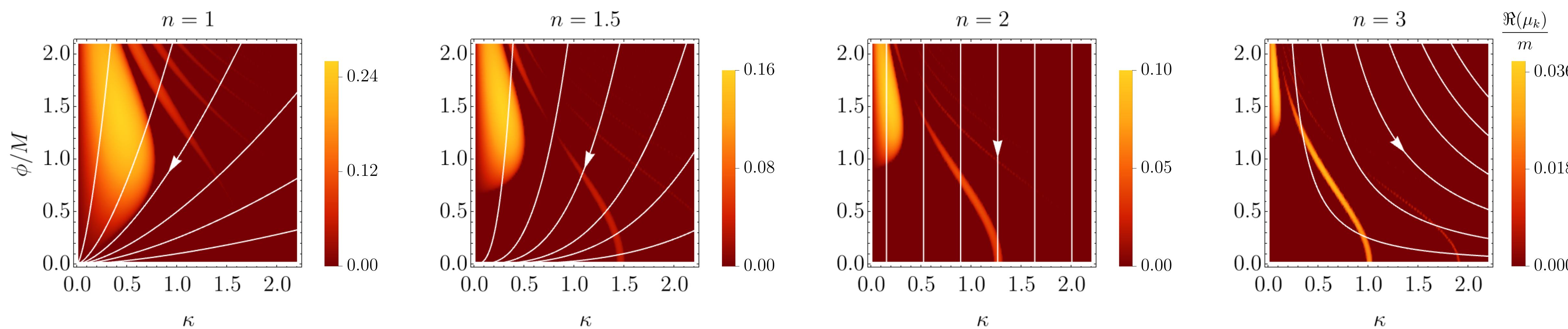




$$\boxed{w \to \begin{cases} 0 & \text{if } n = 1 \\ 1/3 & \text{if } n > 1 \end{cases}}$$

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

eq. of state — Floquet & expansion



rapid fragmentation due to broad band $\left[|\Re(\mu_k)|/H\right]^0_{\max} = f(n)(m_{\rm Pl}/M)$ $M \ll m_{\rm pl}$

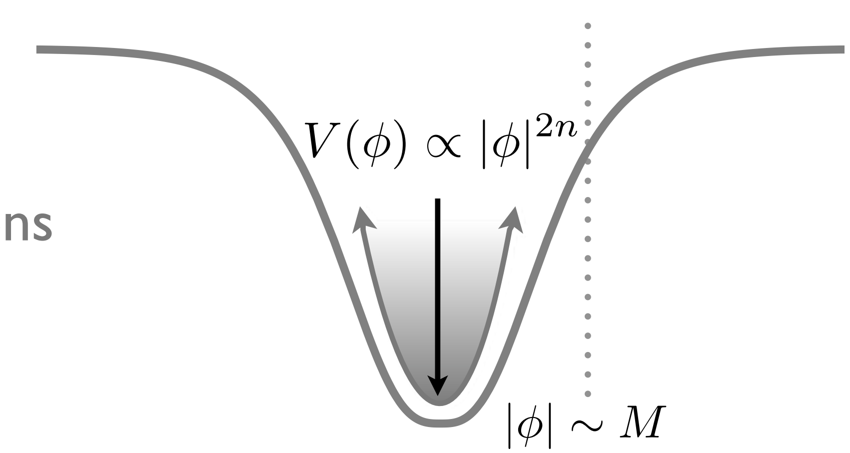
importance of the narrow band $\left[\Re(\mu_k)/H\right]^1 \propto m_{\rm Pl}/|\bar{\phi}|$ $|\bar{\phi}| \ll M$

getting stuck in the instability band $|\dot{\kappa}| \sim H\kappa$

how gradients redshift compared to the potential energy

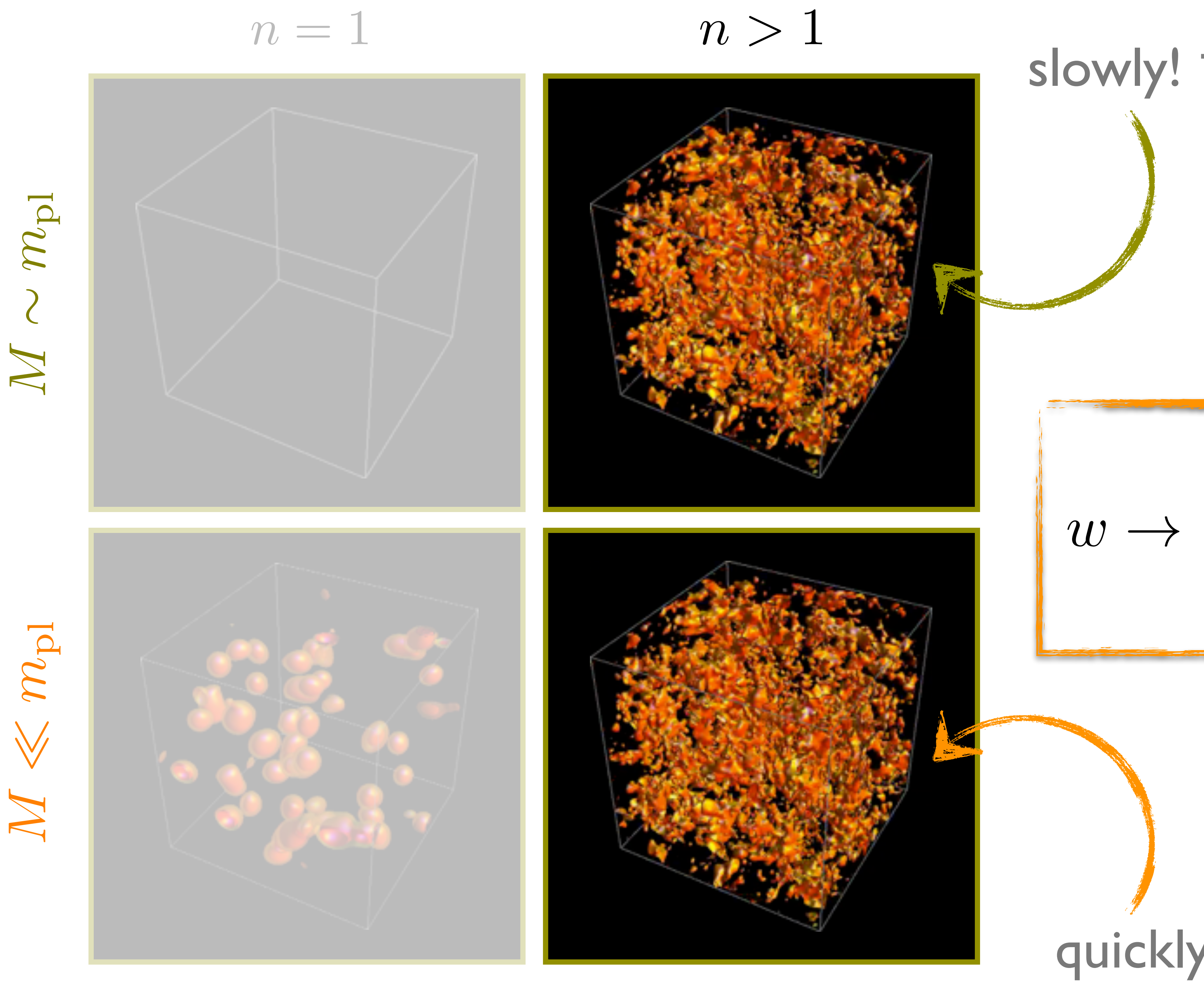
$$w \rightarrow \begin{cases} 0 & \text{if } n = 1 \\ 1/3 & \text{if } n > 1 \end{cases}$$

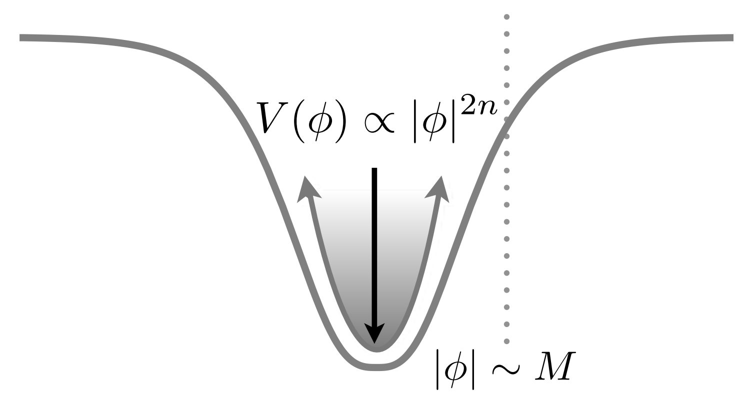
* formation of solitons



eq. of state

* after sufficient time

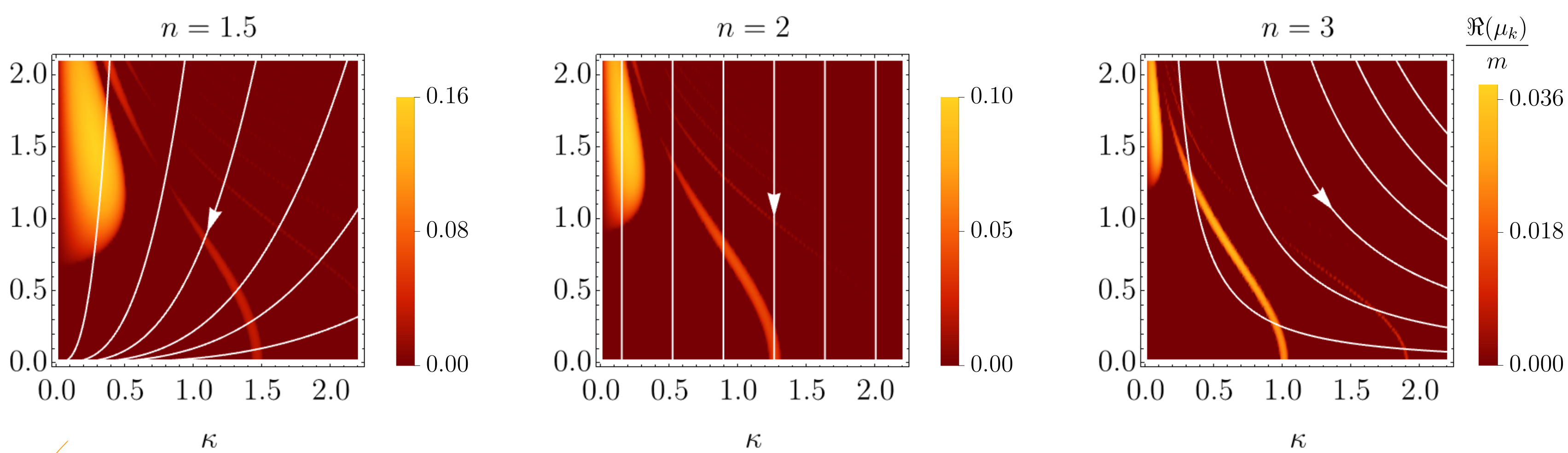


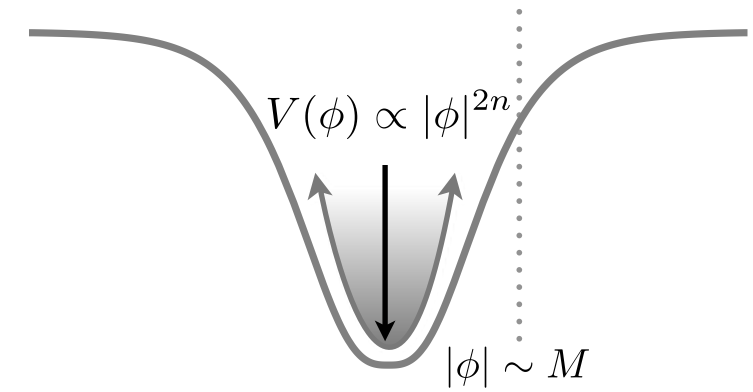


$$\boxed{w \rightarrow \begin{cases} 0 & \text{if } n = 1 \\ 1/3 & \text{if } n > 1 \end{cases}}$$

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

duration to radiation domination
* non-quadratic minima





e-folds to radiation domination

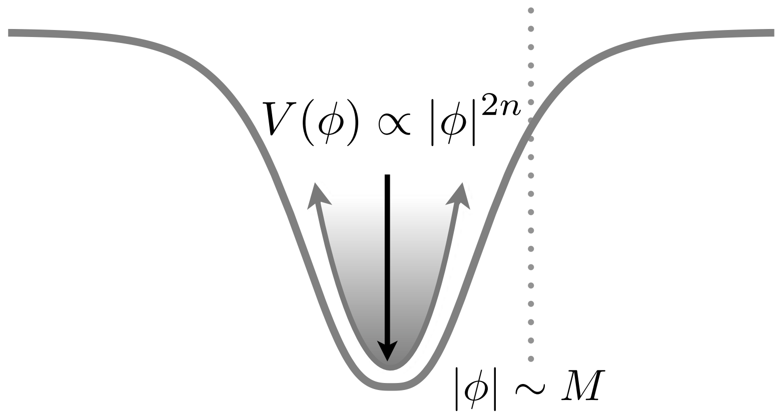
$$\Delta N_{\rm rad}\sim\begin{cases}1 & M\lesssim 10^{-2}m_{\rm Pl}\,,\\ \dfrac{n+1}{3}\ln\left(\dfrac{\kappa}{\Delta\kappa}\,\dfrac{10M}{m_{\rm Pl}}\right) & M\gtrsim 10^{-2}m_{\rm Pl}\,.\end{cases}$$

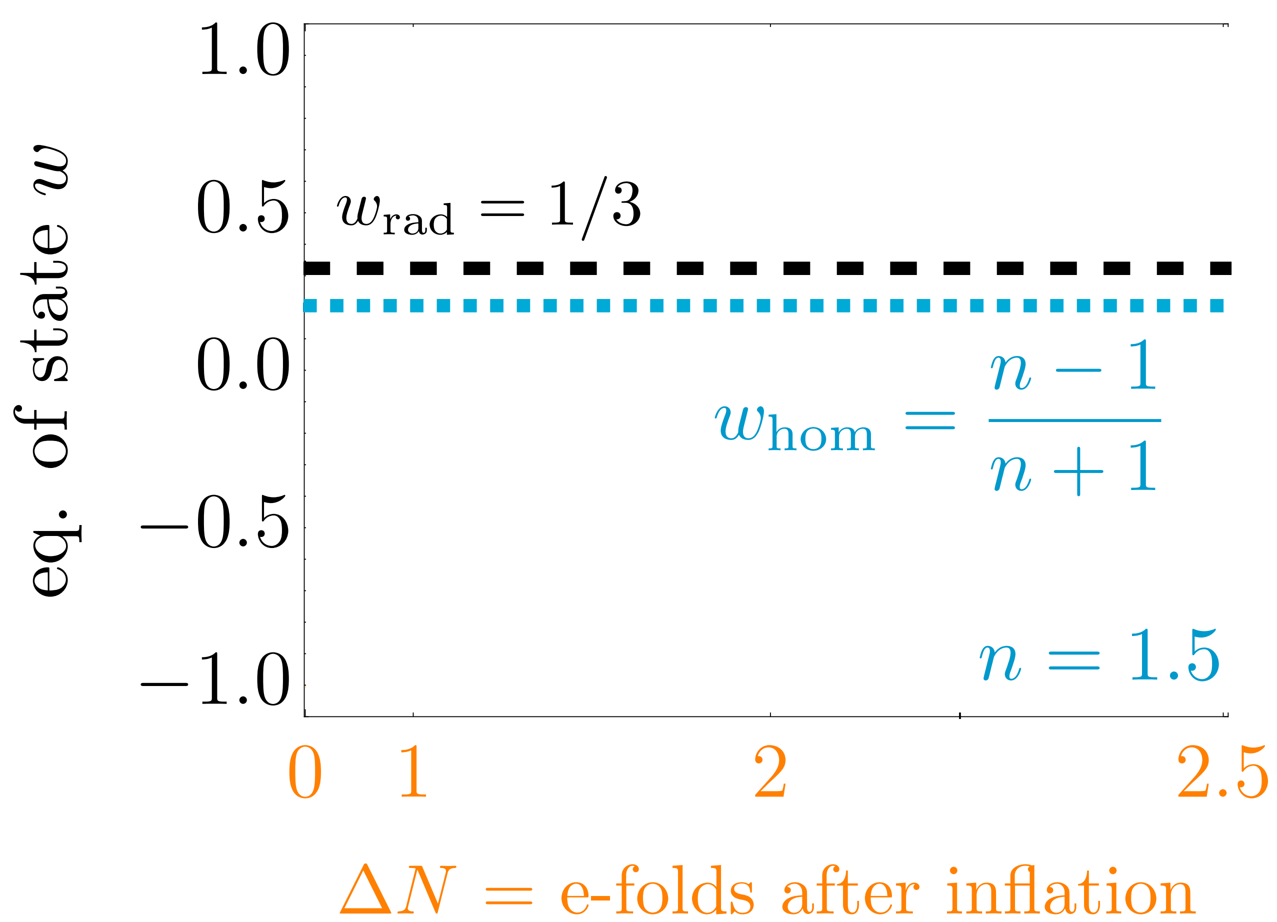
$$\Delta N_{\rm rad}\equiv\int_{a_{\rm end}}^{a_{\rm rad}}d\ln a$$

summary of simulations

№	n	α	w	N	$L_{\rm phys}H_{\rm init}$	$\Delta N^{\rm reh}_{\rm efolds}$	$\Delta N^{\rm br}_{\rm efolds}$	$\Delta N^{\rm final}_{\rm efolds}$	$\delta^{\rm conserv}_{\rm energy}$	$\frac{\Delta^2_{\rm Grad,kmax}}{\Delta^2_{\rm Grad,peak}}$	CPUhrs	Clockhrs
1	1	10^{-5}	0.03	512	0.18	–	<1	2.2	10^{-4}	10^{-4}	320	2.5
2	1	10^{-3}	0	128	2.5	–	<1	4.4	10^{-4}	$<10^{-20}$	16	0.5
3	1.5	10^{-5}	0.316	512	0.12	1.2	<1	2.5	10^{-3}	10^{-3}	1536	12
4	1.5	10^{-5}	0.316	512	0.06	1.2	<1	2.5	10^{-3}	10^{-5}	1536	12
5	1.5	10^{-5}	0.327	512	0.06	1.2	<1	3.3	10^{-3}	10^{-3}	+3072	+24
6	1.5	10^{-3}	0.324	256	0.077	4.3	3.9	5.3	10^{-5}	10^{-5}	3072	48
7	1.5	10^{-2}	0.321	256	0.17	4.8	4.5	5.9	10^{-5}	10^{-5}	3072	48
8	1.5	1	0.320	256	1.1	5.9	5.8	6.9	10^{-5}	10^{-4}	2304	36
9	1.5	1	0.320	256	0.55	5.9	5.8	6.9	10^{-5}	10^{-5}	2304	36
10	1.5	1	0.329	256	0.55	5.9	5.8	7.8	10^{-5}	10^{-4}	+6144	+96
11	1.5	1	–	512	1.1	–	–	–	–	–	–	–
12	2	10^{-5}	0.330	512	0.36	1.0	<1	1.5	10^{-3}	10^{-4}	192	12
13	2	10^{-5}	0.330	512	0.36	1.0	<1	1.5	10^{-3}	$<10^{-3}$	192	12
14	2	10^{-5}	0.330	1024	0.73	1.0	<1	1.5	10^{-3}	$<10^{-3}$	1536	12
15	2	10^{-5}	0.330	256	0.18	1.0	<1	1.5	10^{-3}	$<10^{-3}$	48	3
16	2	1	0.333	128	10.7	<1	5.0	8.2	10^{-4}	10^{-5}	132	132
17	3	10^{-5}	0.341	256	0.20	<1	<1	3.6	10^{-4}	10^{-4}	320	10
18	3	10^{-5}	0.361	1024	0.79	<1	<1	1.4	10^{-3}	$<10^{-4}$	3072	12
19	3	10^{-5}	0.361	512	0.39	<1	<1	1.4	10^{-3}	$<10^{-4}$	384	12
20	3	10^{-5}	0.361	256	0.20	<1	<1	1.4	10^{-3}	$<10^{-4}$	48	1.5
21	3	10^{-3}	0.338	256	6.6	6.7	6.1	9.0	10^{-3}	$<10^{-5}$	3072	48
22	3	1	0.336	256	1740	10.7	10.5	13.2	10^{-3}	$<10^{-5}$	5120	120
23	4	10^{-5}	0.345	256	0.21	<1	<1	3.7	10^{-3}	$<10^{-4}$	768	12
24	6	10^{-5}	0.348	256	0.17	<1	<1	3.7	10^{-3}	$<10^{-4}$	768	12

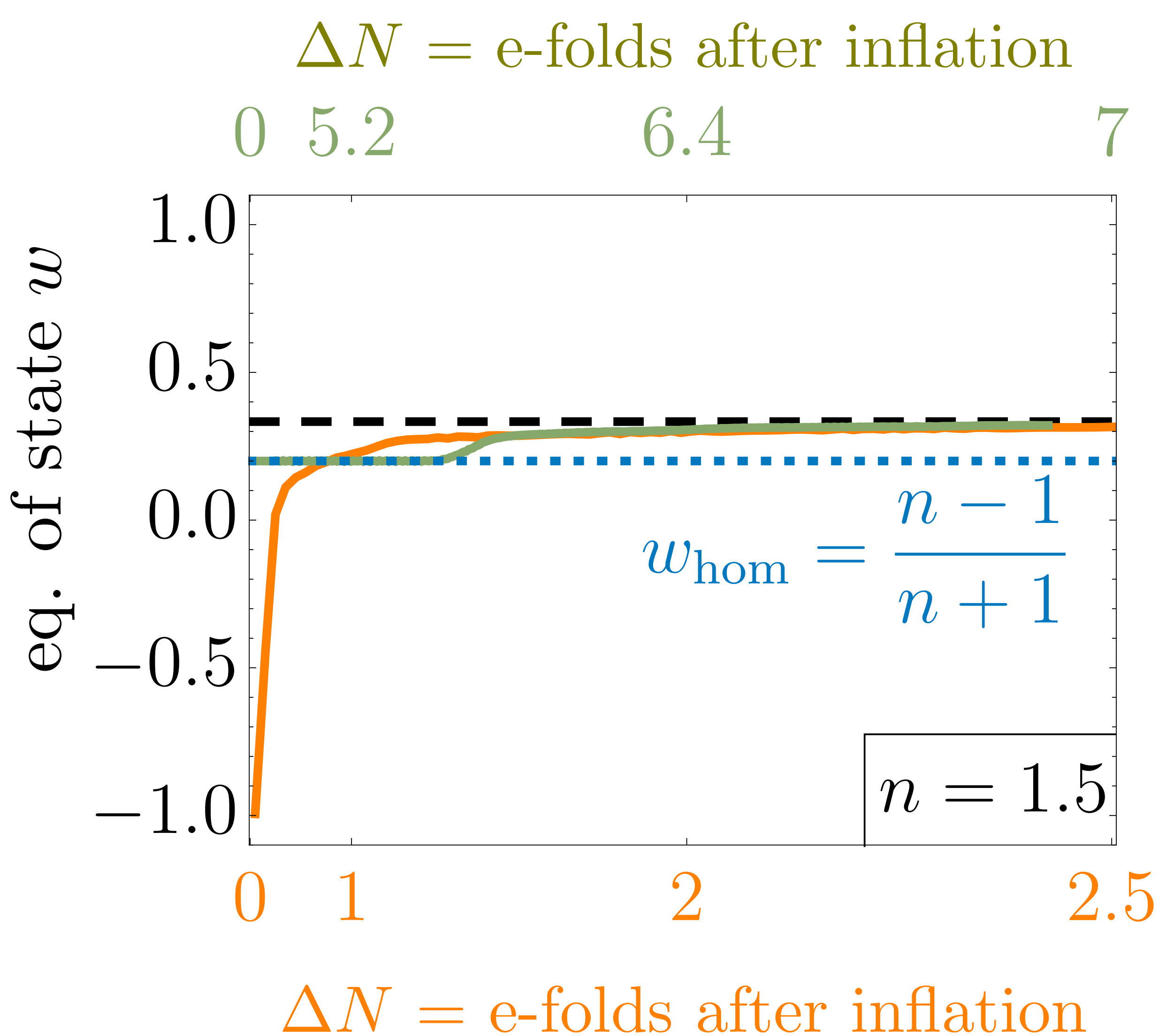
duration to radiation domination
* non-quadratic minima

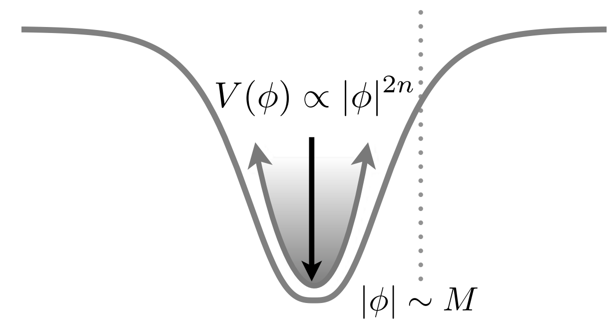




duration to radiation domination
* non-quadratic minima

from detailed 3+1 dimensional lattice simulations





$M \sim m_{\text{pl}}$

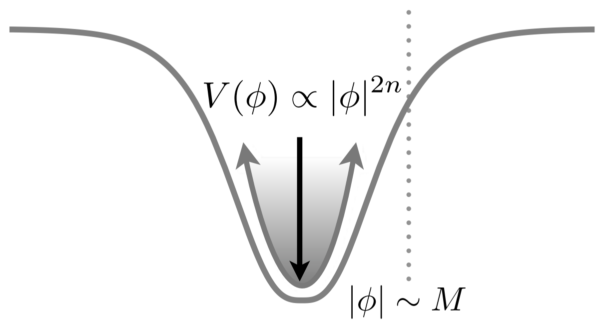
inefficient initial resonance

$M \ll m_{\text{pl}}$

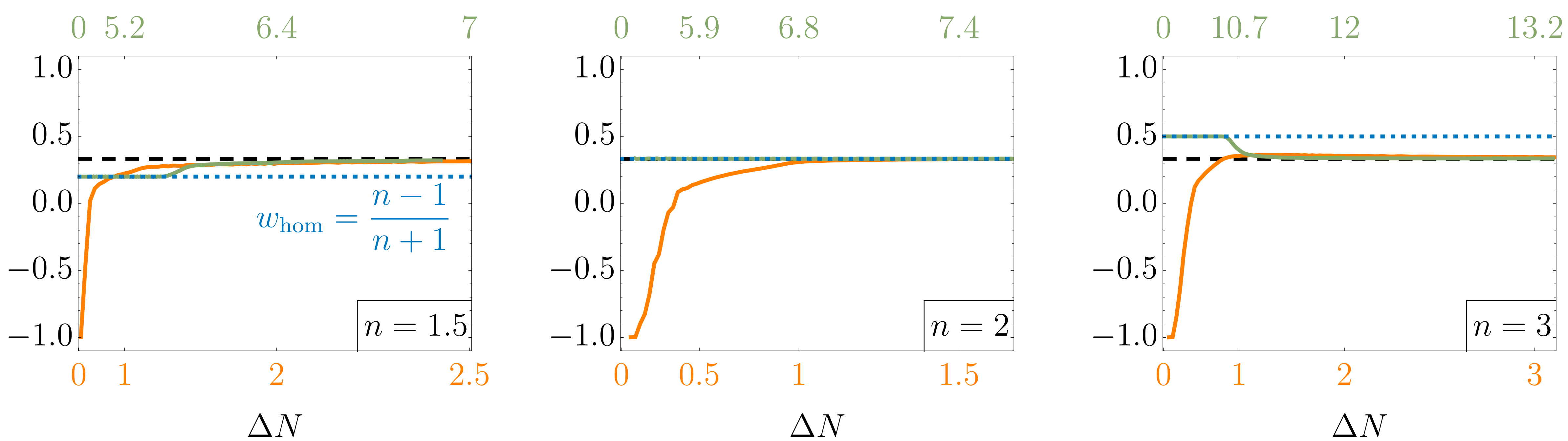
efficient initial resonance

duration to radiation domination
* non-quadratic minima

from detailed 3+1 dimensional lattice simulations



green = inefficient initial resonance
orange = efficient initial resonance

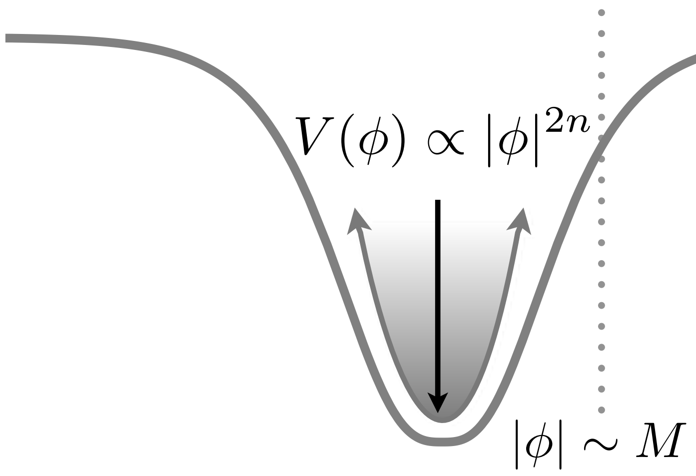


from analytic considerations

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

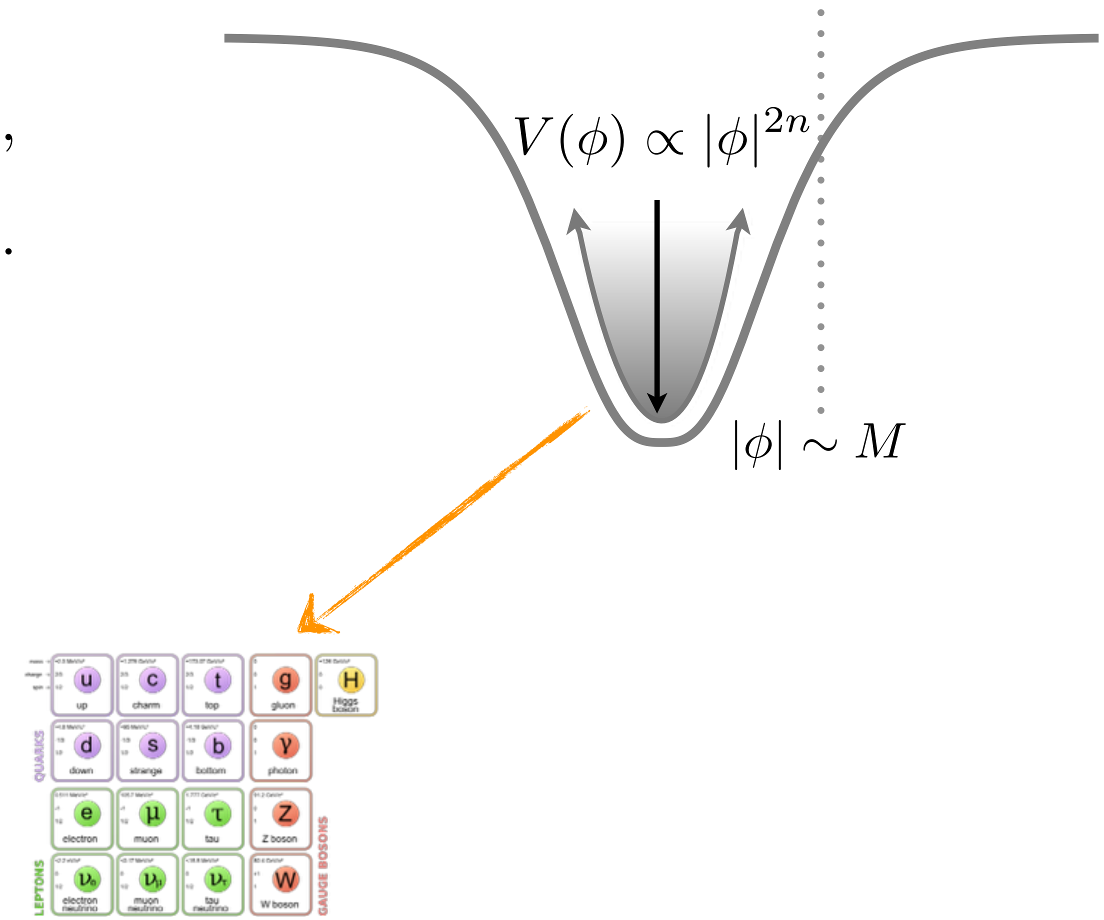
an upper bound on duration to radiation domination

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



an upper bound on duration to radiation domination

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

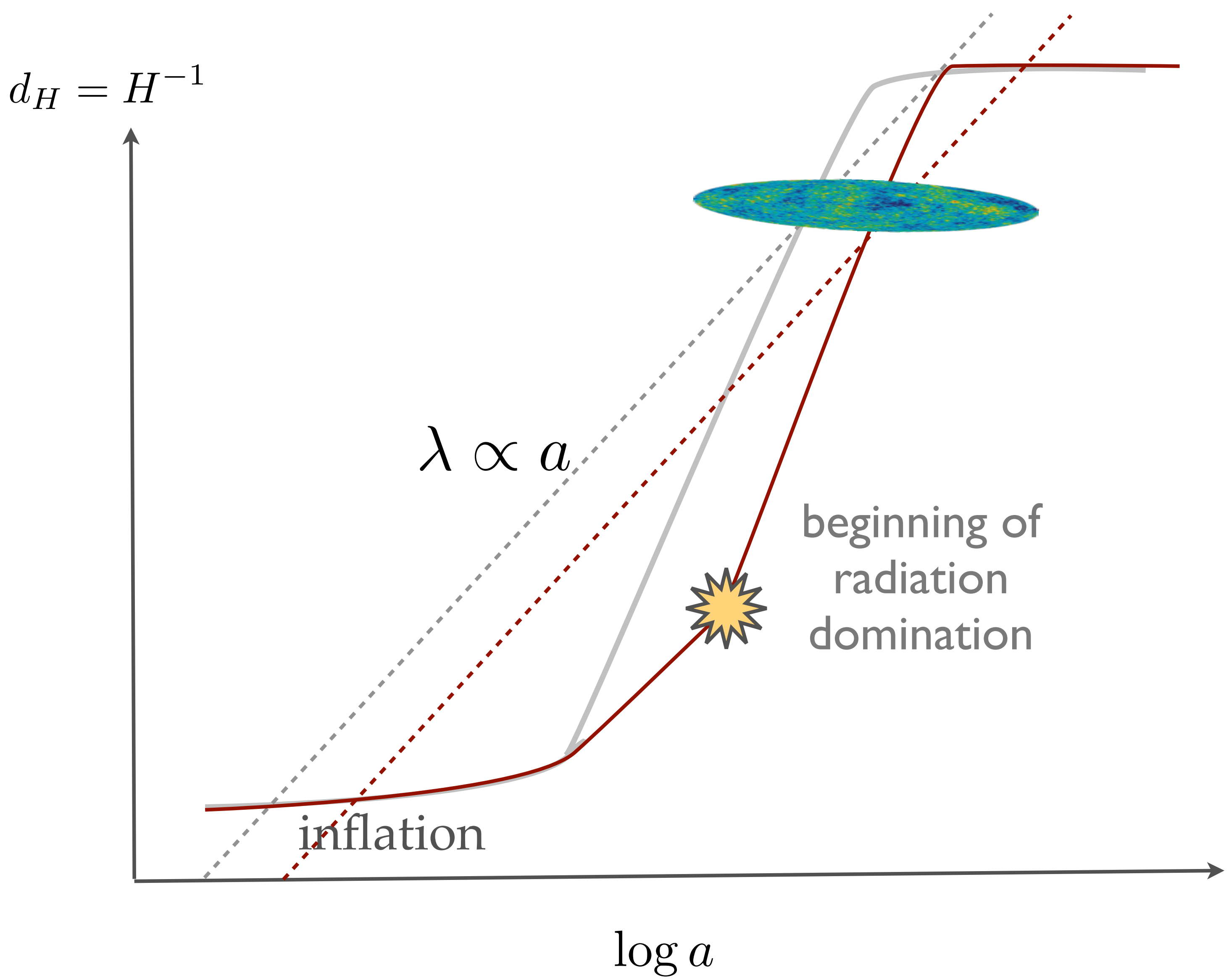


additional *light (massless) fields* can only decrease the duration!

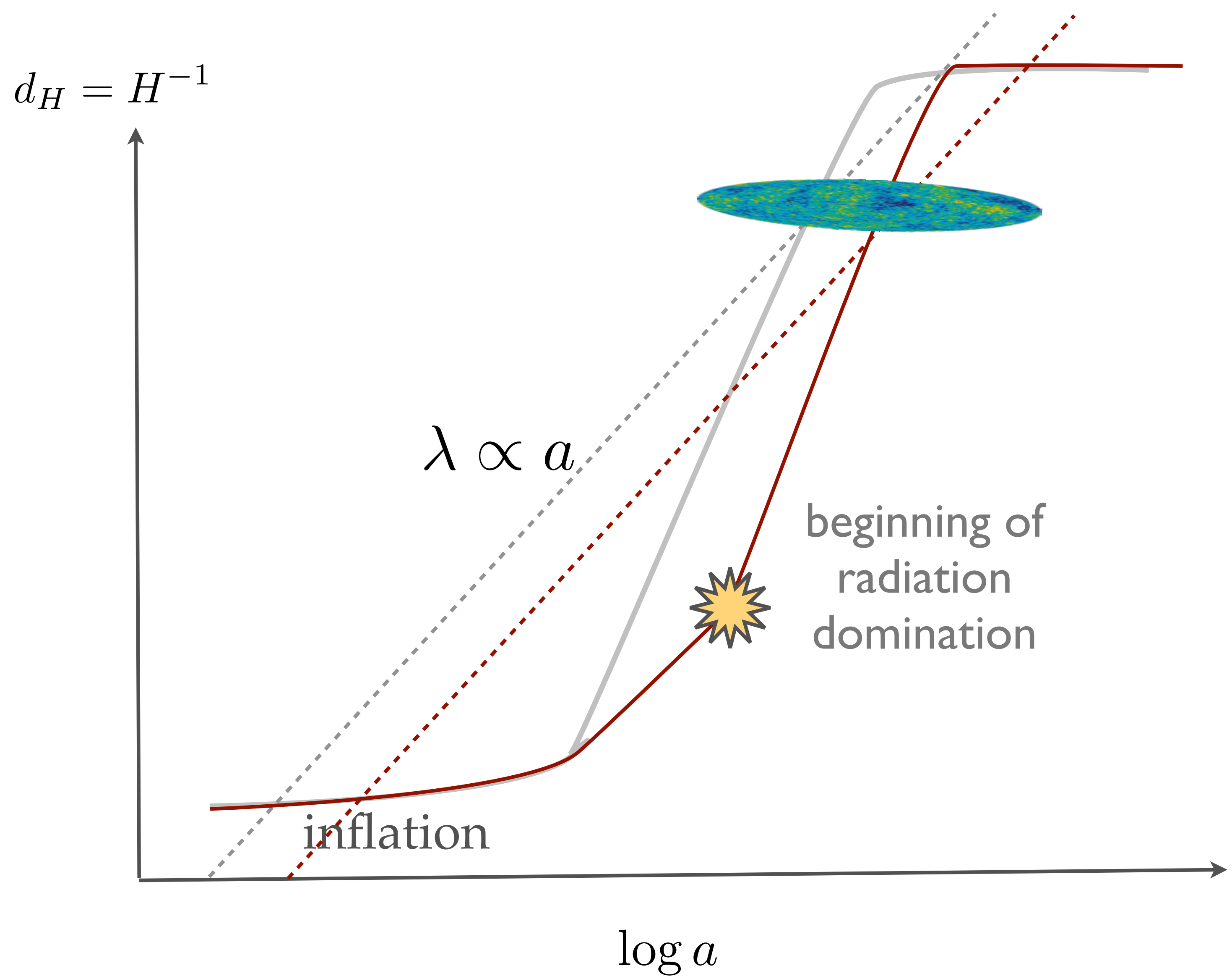
* decay to significantly massive fields can change this conclusion

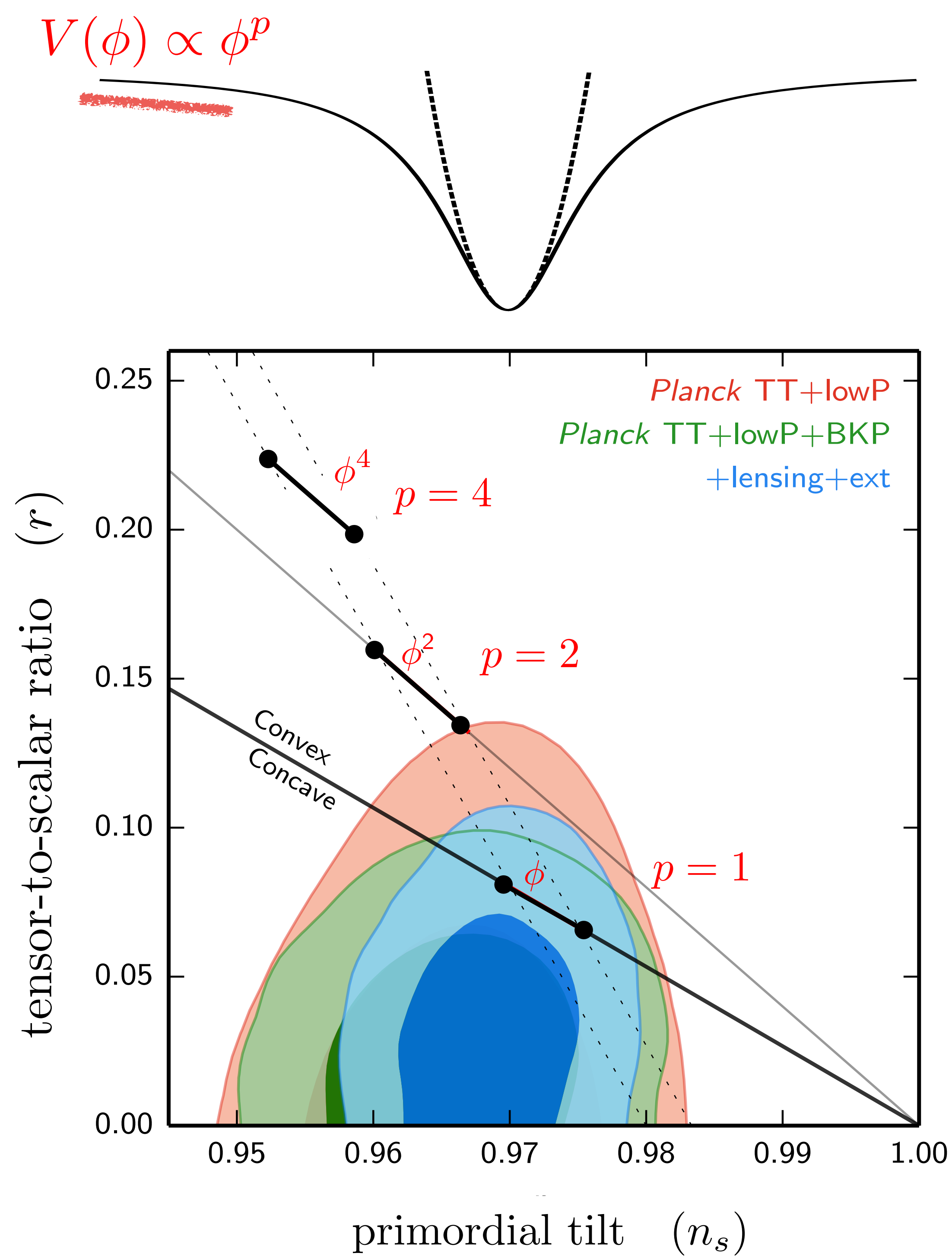
- what drives inflation ?
- how did inflation end ?
- observable implications ?

eq. state — expansion history — CMB observables



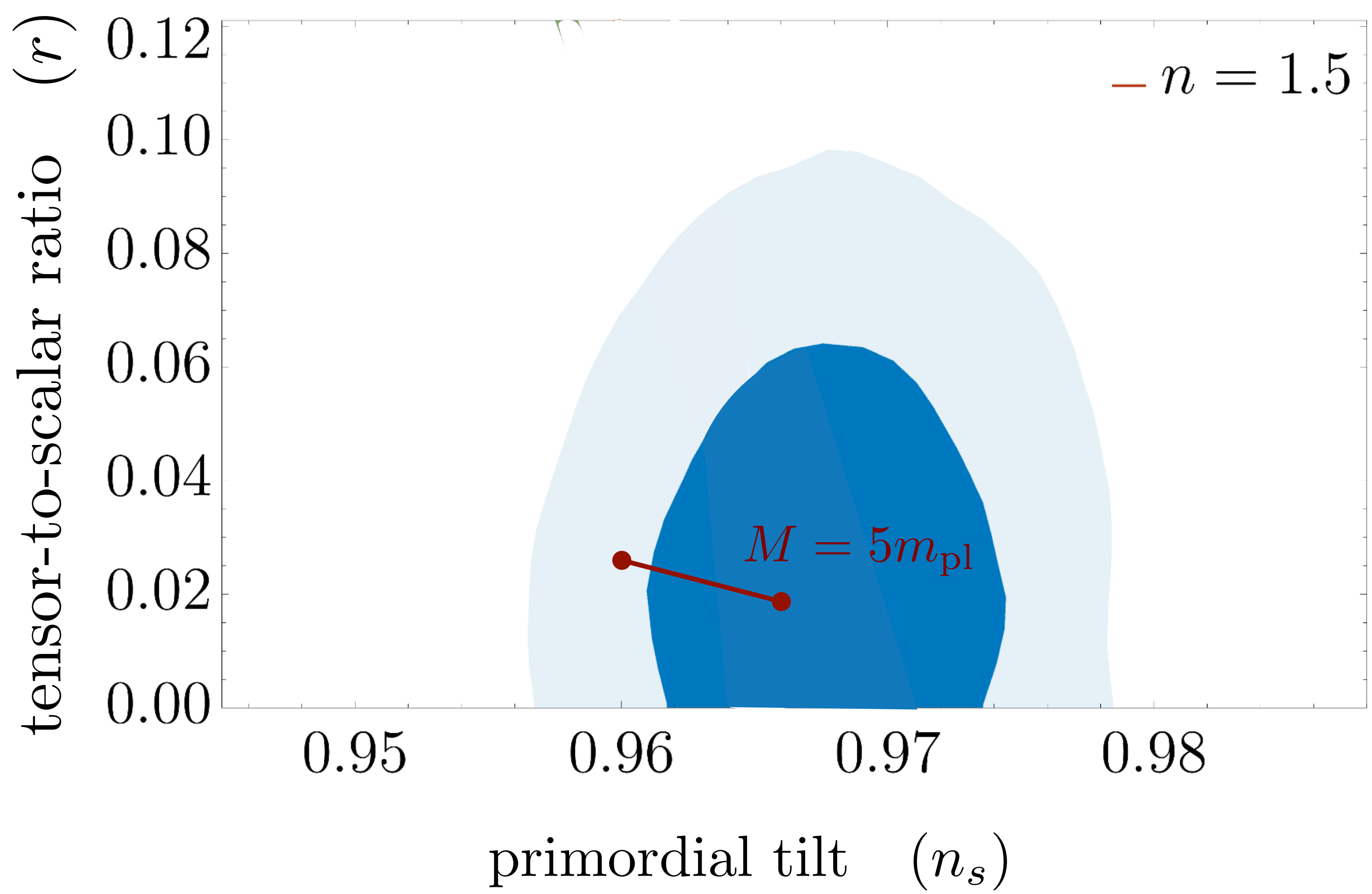
eq. state — expansion history — CMB observables

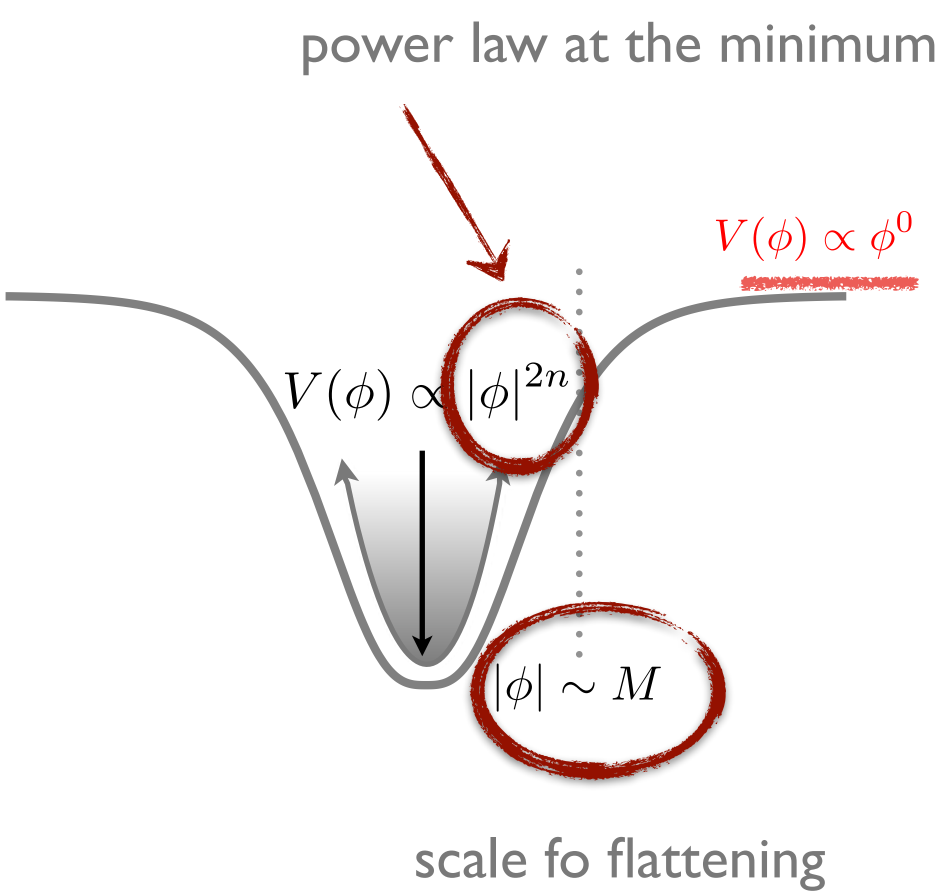




for example: Liddle & Leach (2003), Adshead et. al (2011), Dai & Kamionkowski (2014)

implications for CMB observables

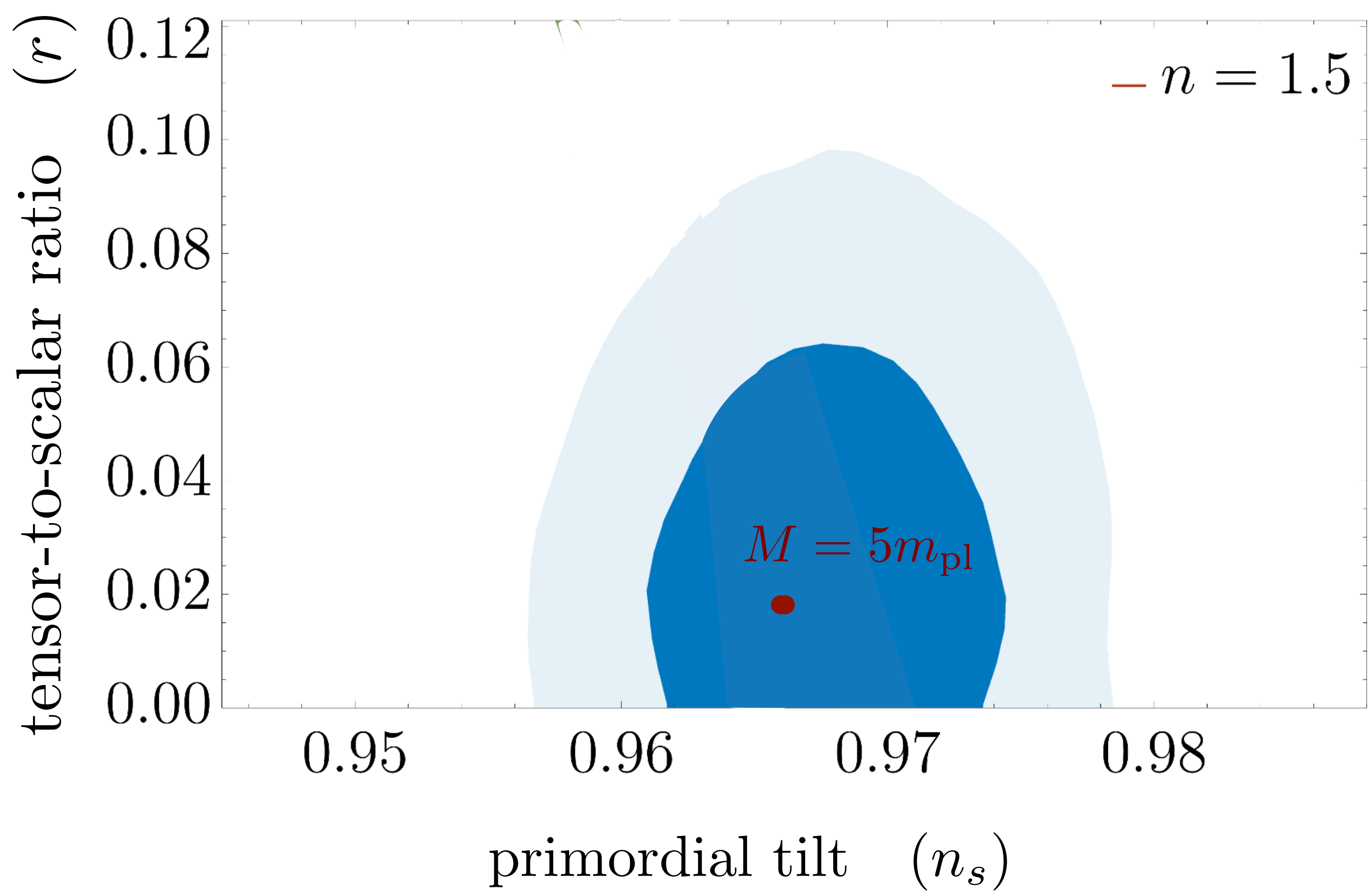


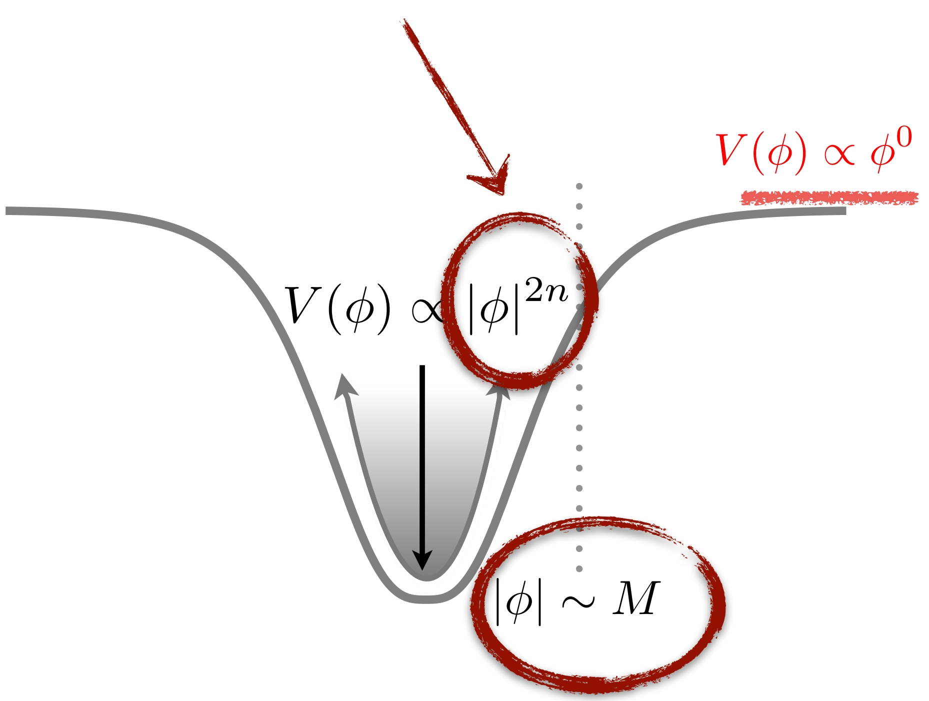


* width of the lines account for couplings to other light fields

* non-quadratic minimum

reduction in uncertainty!





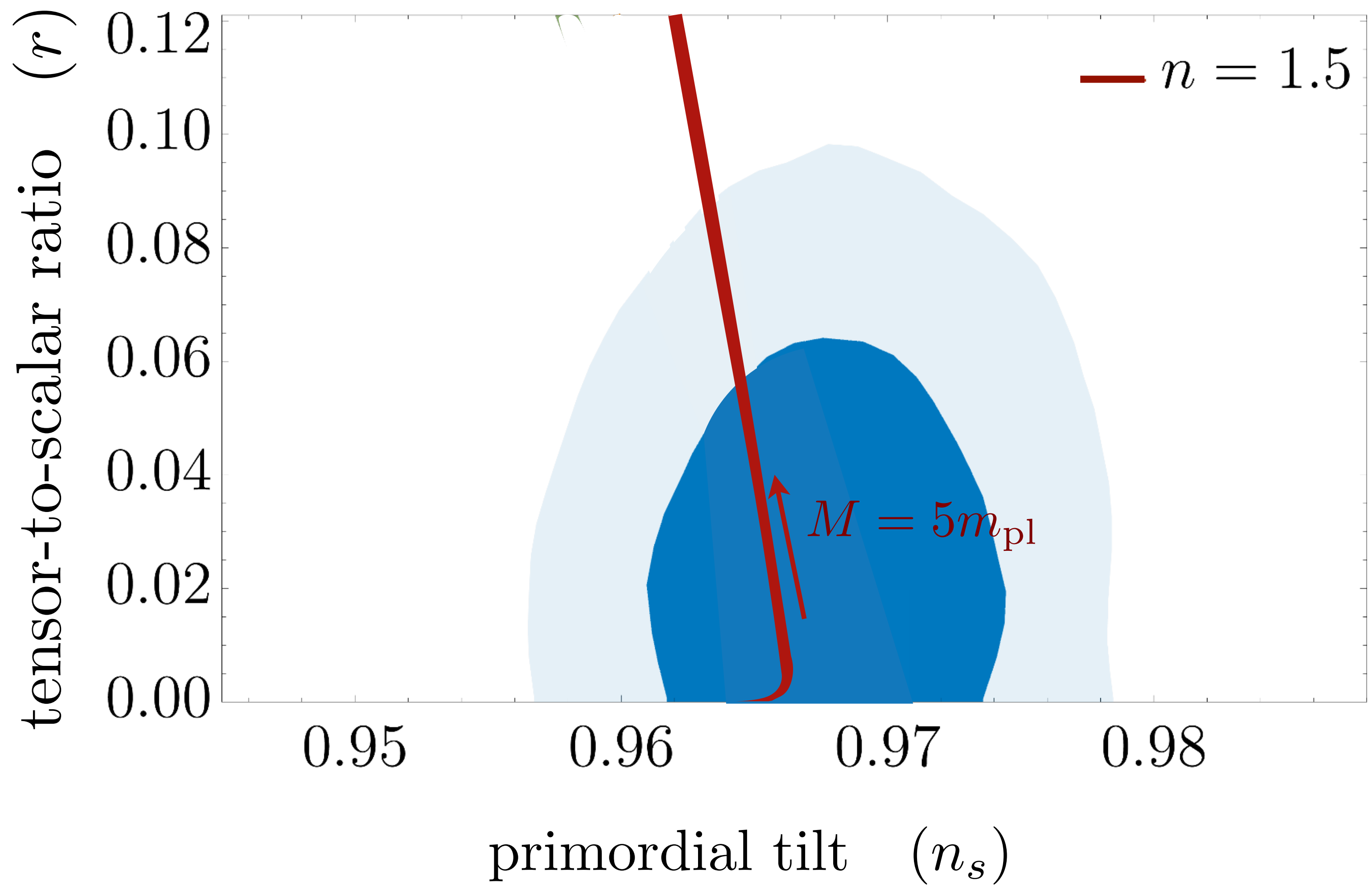
$$\Delta N_{\rm rad} \sim \begin{cases} 1 & M \lesssim 10^{-2} m_{\rm Pl}\,, \\ \dfrac{n+1}{3} \ln\left(\dfrac{\kappa}{\Delta\kappa}\dfrac{10M}{m_{\rm Pl}}\right) & M \gtrsim 10^{-2} m_{\rm Pl}\,. \end{cases}$$

* width of the lines account for couplings to other light fields

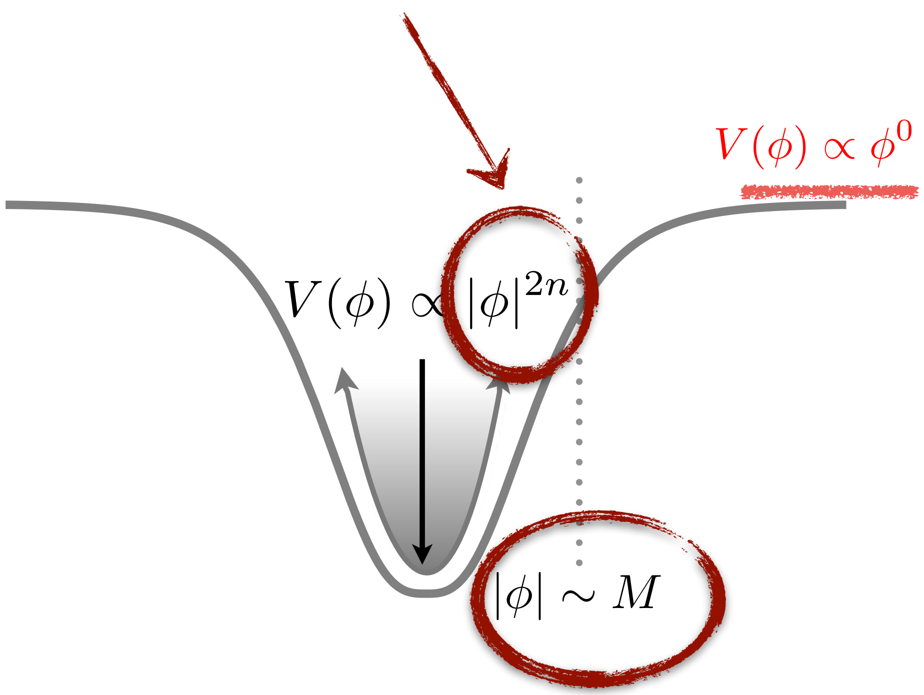
* non-quadratic minimum

implications for CMB observables

width is the uncertainty due to additional light fields!



power law at the minimum



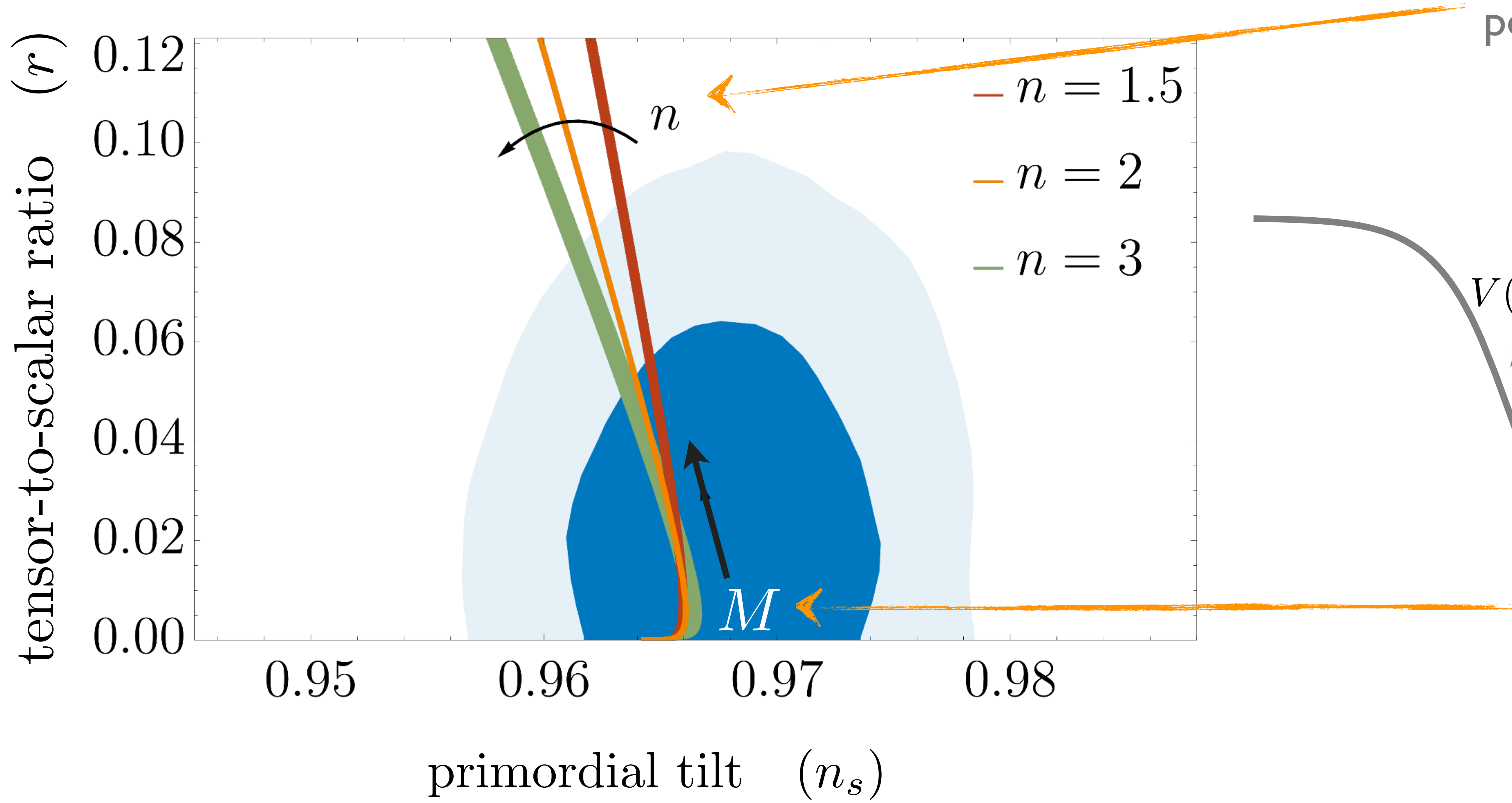
scale fo flattening

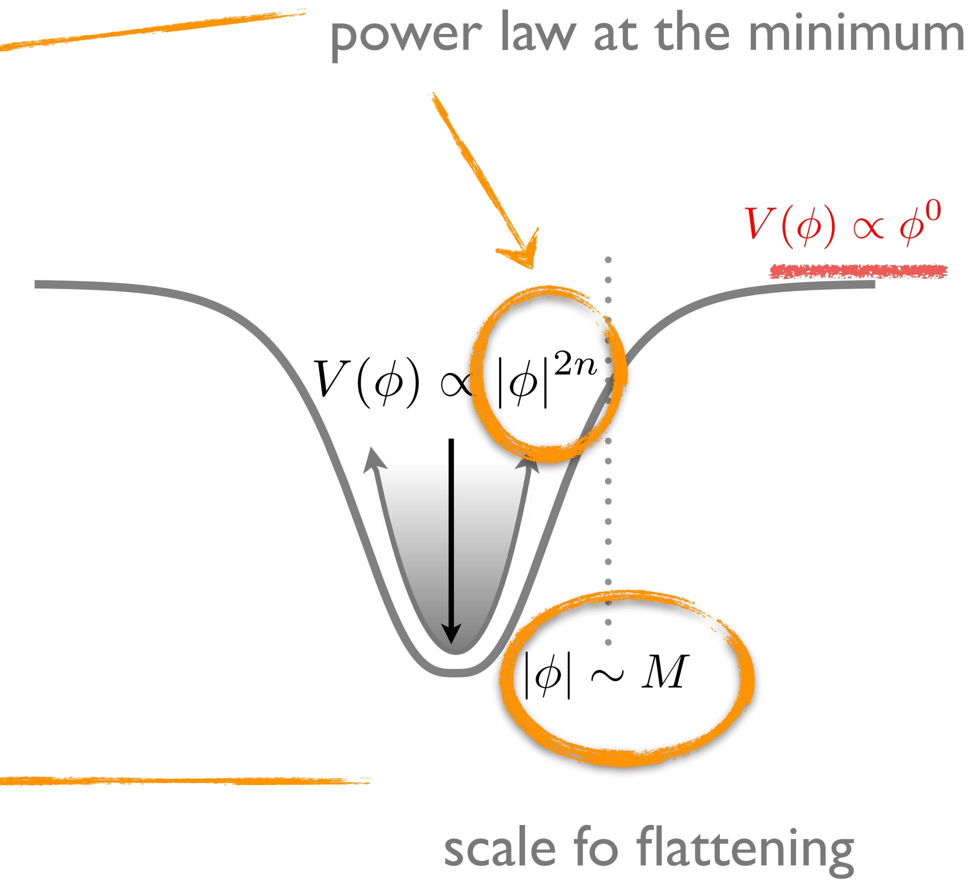
$$\Delta N_{\rm rad} \sim \begin{cases} 1 & M \lesssim 10^{-2} m_{\rm Pl}\,, \\ \dfrac{n+1}{3} \ln\left(\dfrac{\kappa}{\Delta\kappa}\dfrac{10M}{m_{\rm Pl}}\right) & M \gtrsim 10^{-2} m_{\rm Pl}\,. \end{cases}$$

* width of the lines account for couplings to other light fields

* non-quadratic minimum

implications for CMB observables



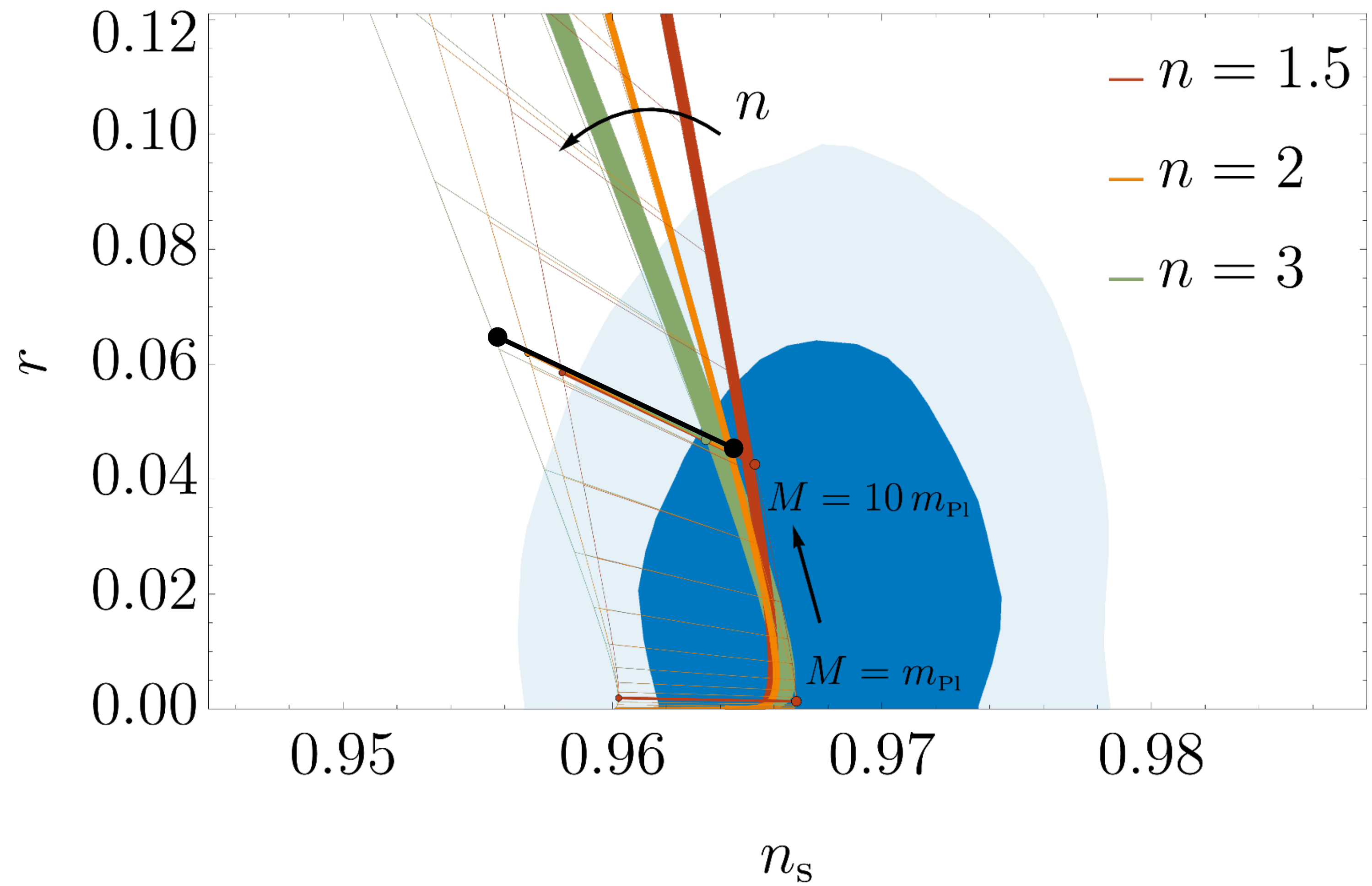


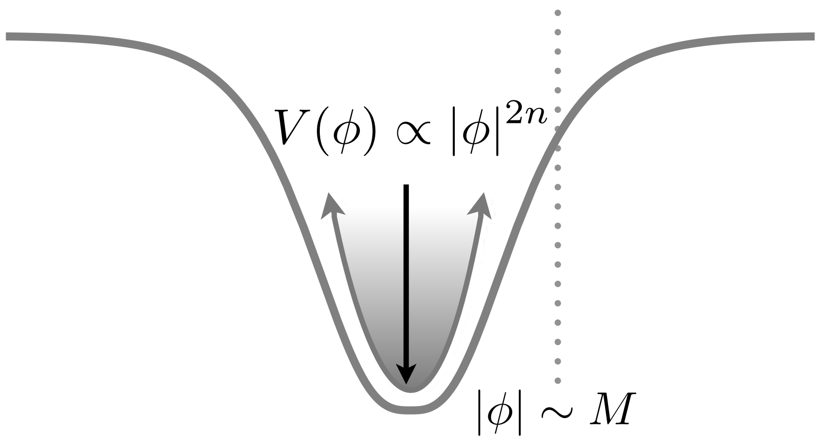
$$\Delta N_{\rm rad} \sim \begin{cases} 1 & M \lesssim 10^{-2} m_{\rm Pl}\,, \\ \dfrac{n+1}{3} \ln\left(\dfrac{\kappa}{\Delta\kappa}\dfrac{10M}{m_{\rm Pl}}\right) & M \gtrsim 10^{-2} m_{\rm Pl}\,. \end{cases}$$

* width of the lines account for couplings to other light fields

* non-quadratic minimum

including upper bound — significant reduction in uncertainty !





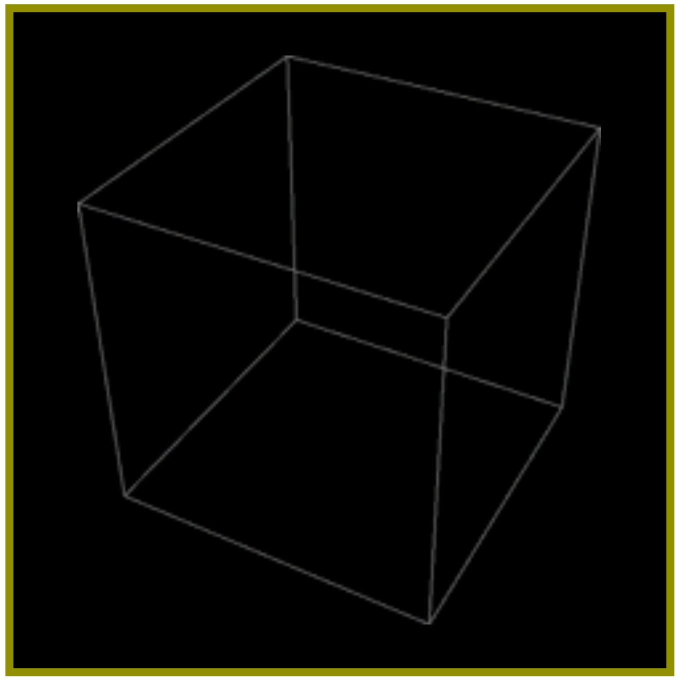
$$\Delta N_{\rm rad} \sim \begin{cases} 1 & M \lesssim 10^{-2} m_{\rm Pl}\,, \\ \dfrac{n+1}{3} \ln\left(\dfrac{\kappa}{\Delta\kappa}\dfrac{10M}{m_{\rm Pl}}\right) & M \gtrsim 10^{-2} m_{\rm Pl}\,. \end{cases}$$

* non-quadratic minimum

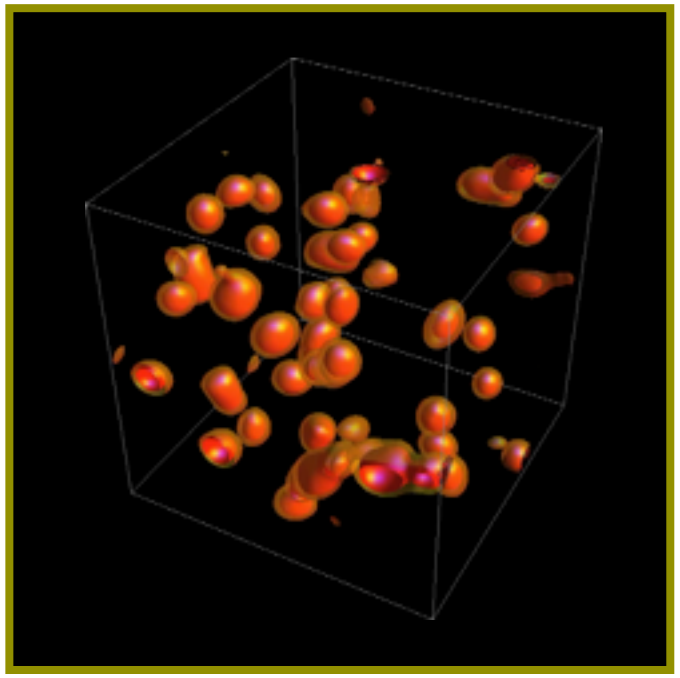
* quadratic minimum

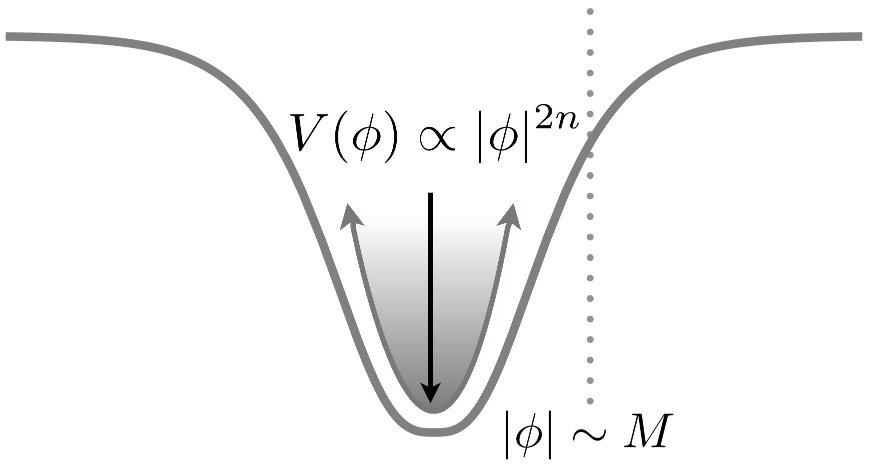
$n = 1$

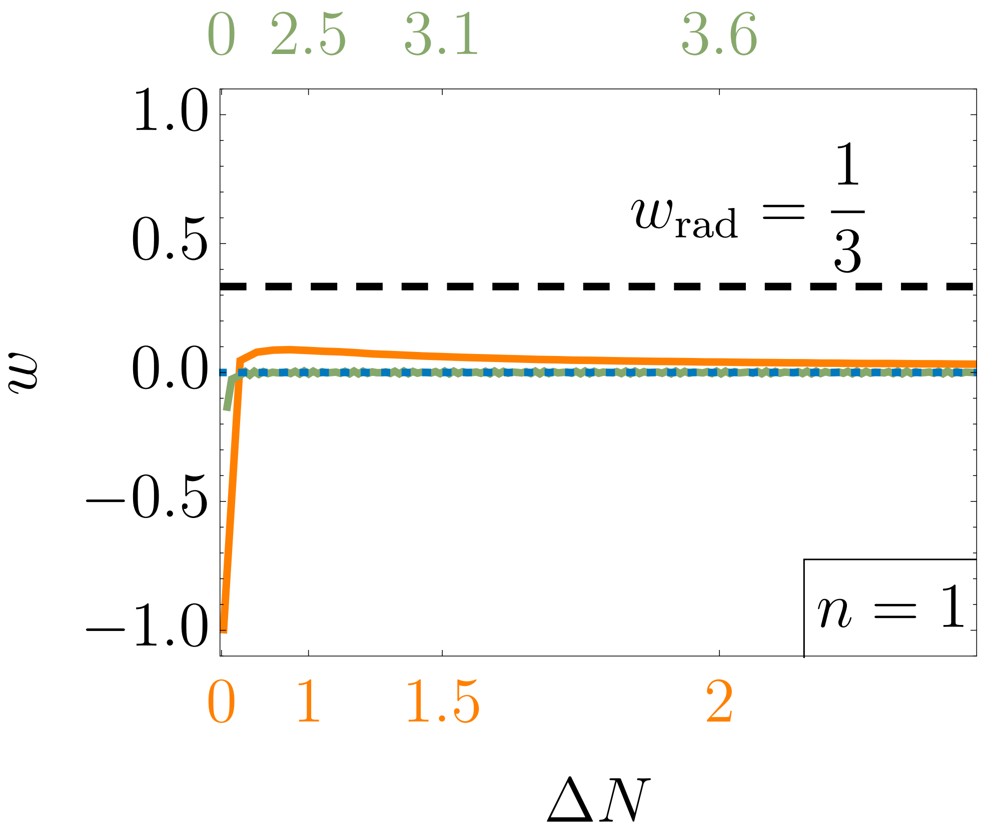
$M \sim m_{\mathrm{pl}}$



$M \ll m_{\mathrm{pl}}$



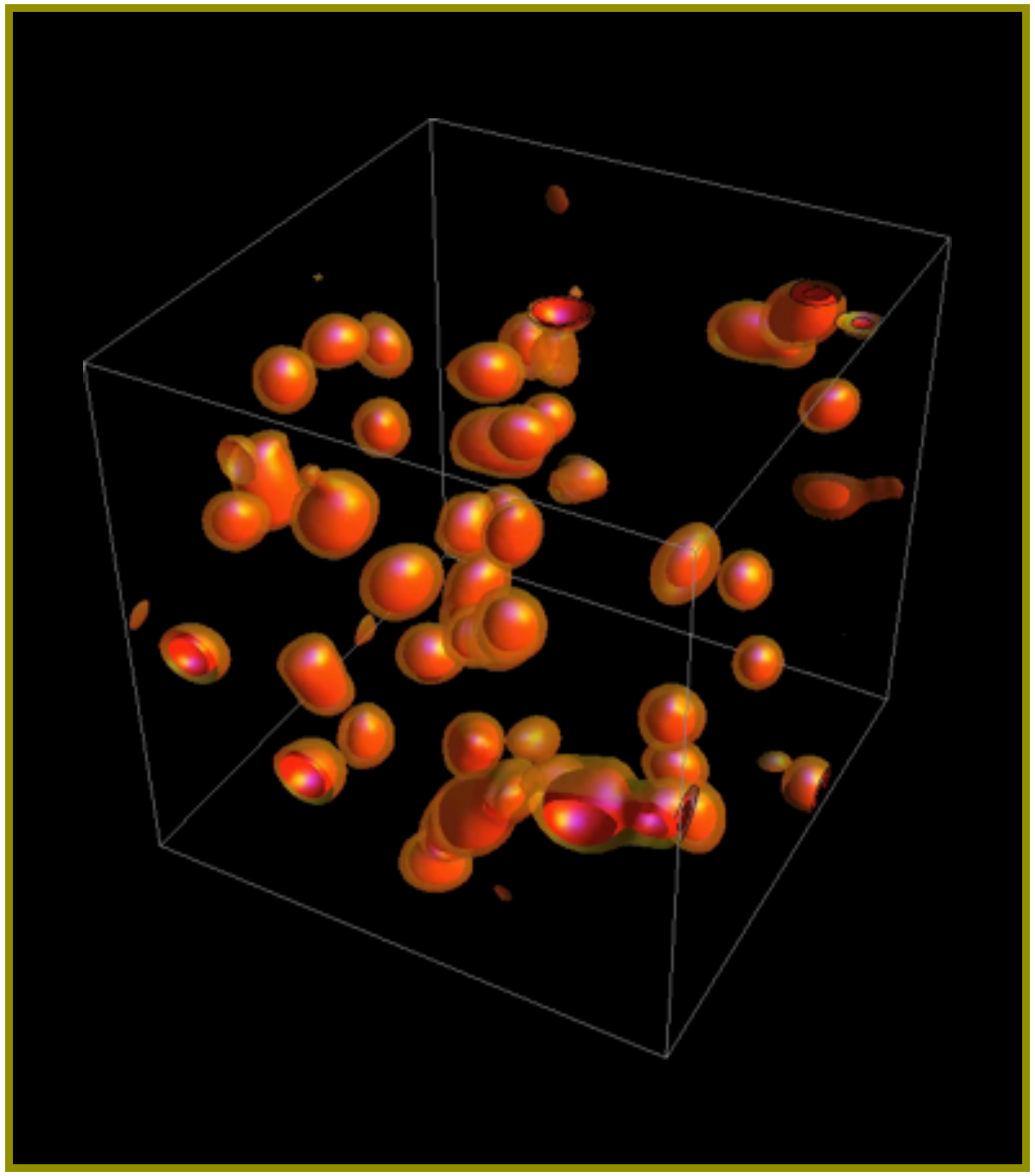




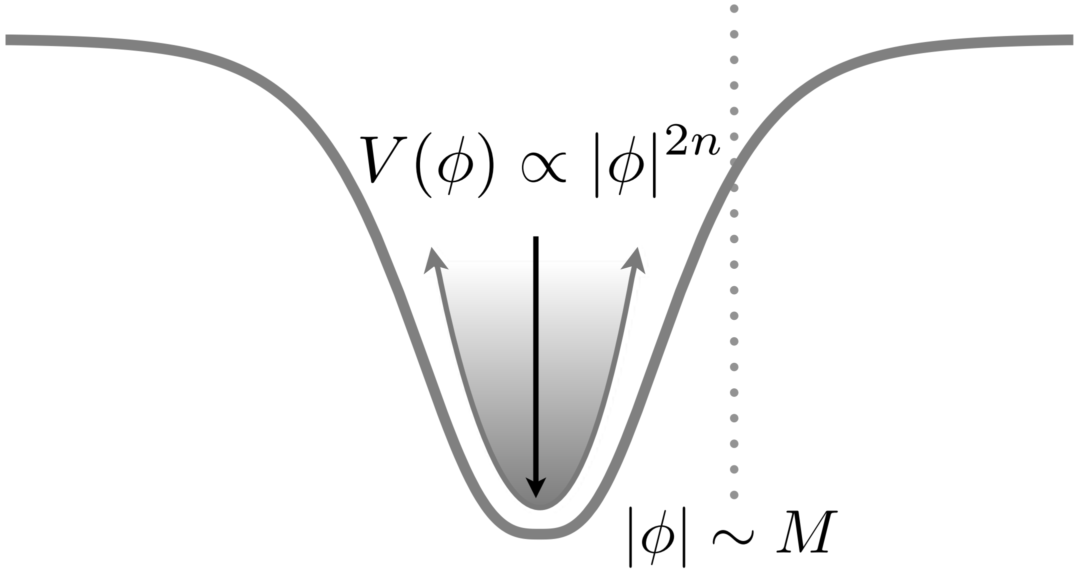
oscillons after inflation

$n = 1$

$M \ll m_{\rm pl}$



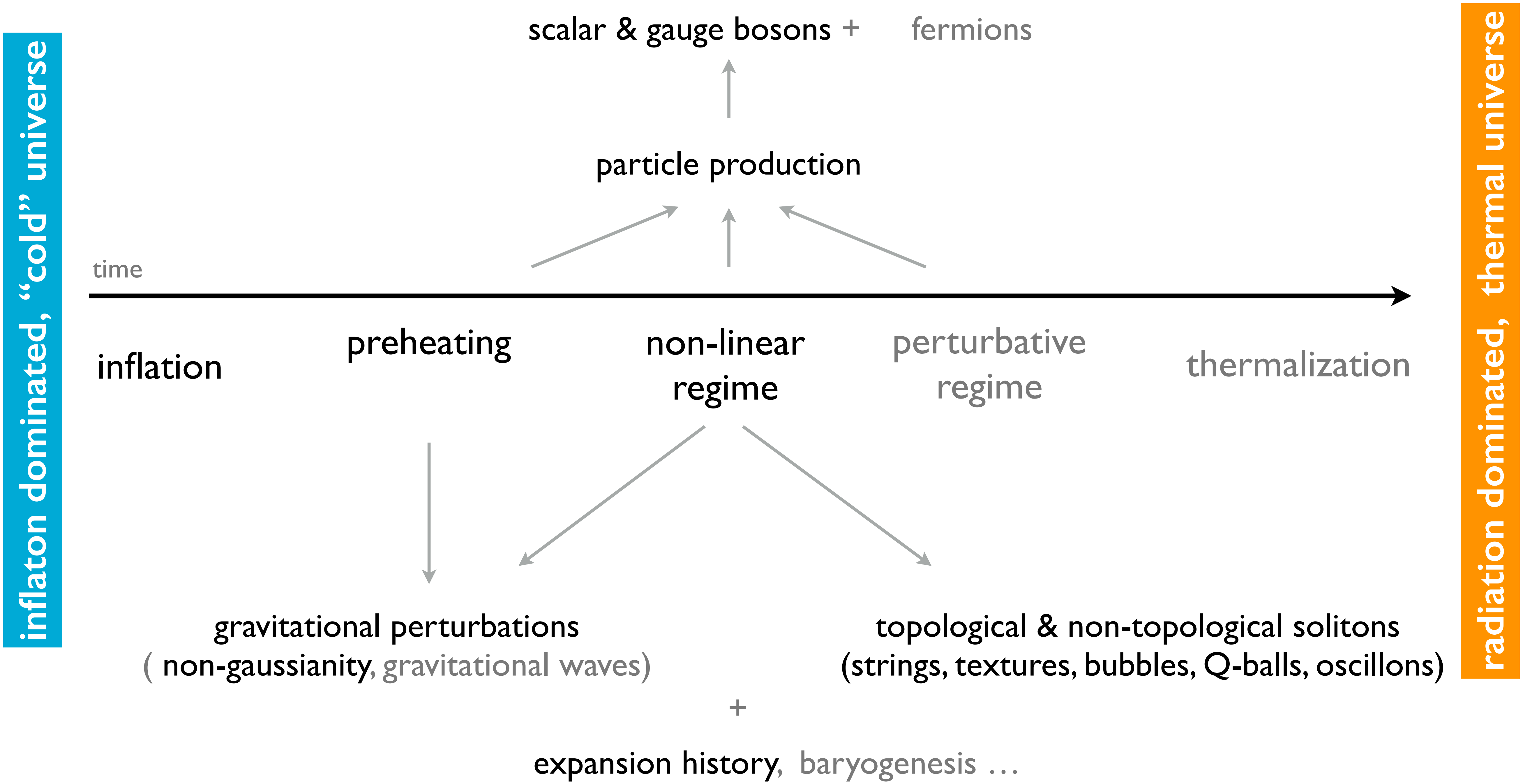
Oscillons — non-topological solitons!



- approach to radiation domination with additional fields can be complex when additional fields are included

see for example:
Gleiser (1994)
MA, Easther, Finkel, Flaugher & Hertzberg (2011)
MA (2013)
and @ UIUC Adshead, Giblin, Scully, Sfakianakis (2014)

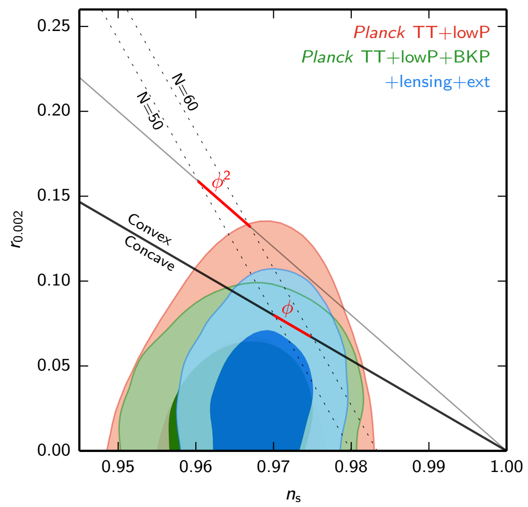
left out …



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

related work at UIUC, for example:
Adshead, Cui & Shelton (2016), Adshead, Skully, Giblin & Sfakianakis (2015, 2016), Adshead & Sfakianakis (2015)

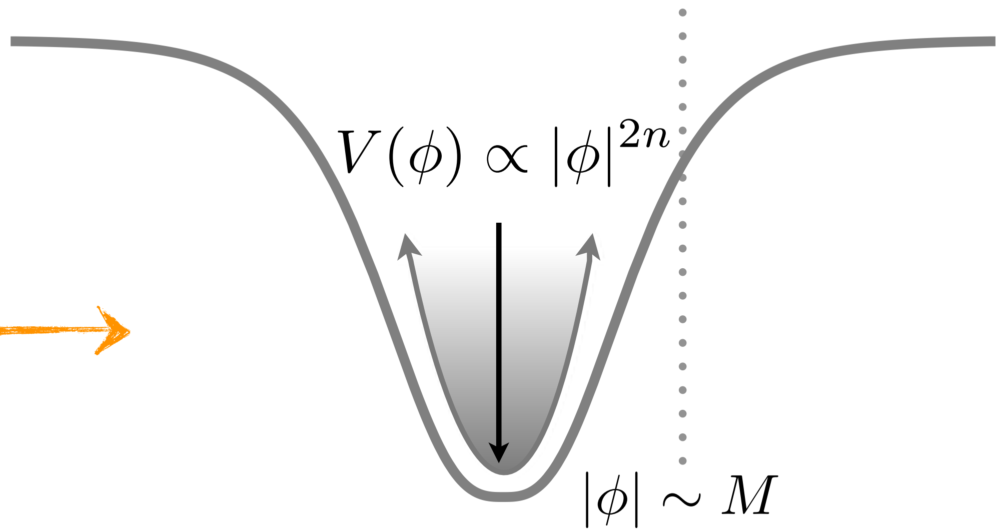
inflation and its end
"simple" models



+

for example:

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

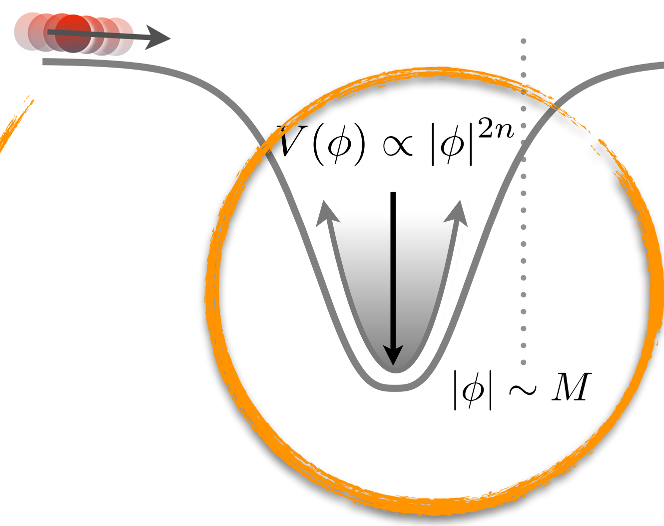


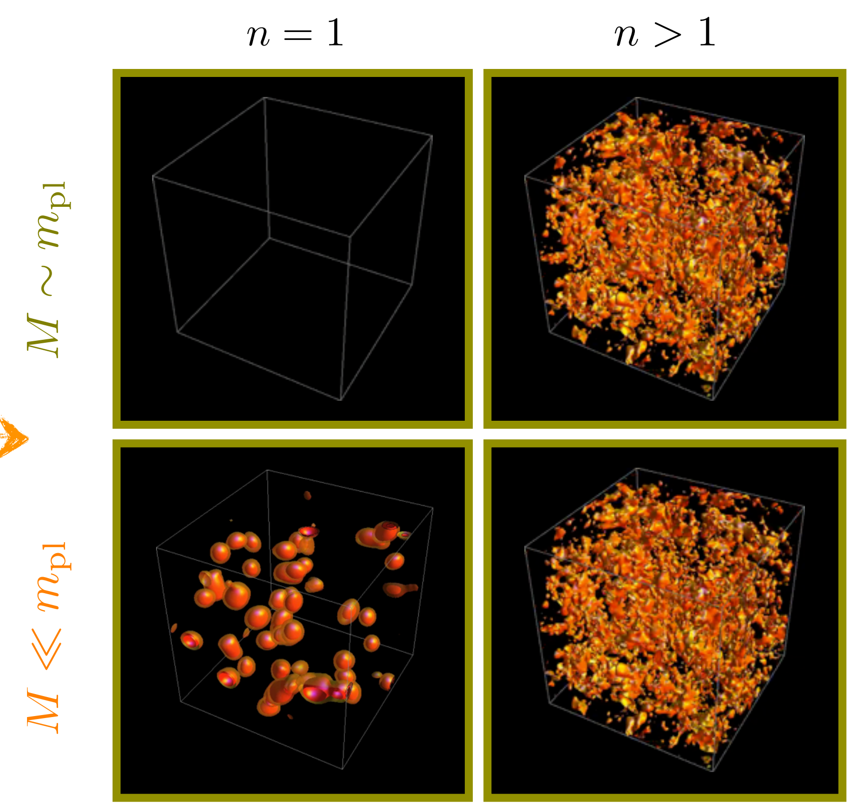
(i) what are the dynamics ?

(ii) eq. of state & how long to radiation domination ?

(iii) obs. consequences ?

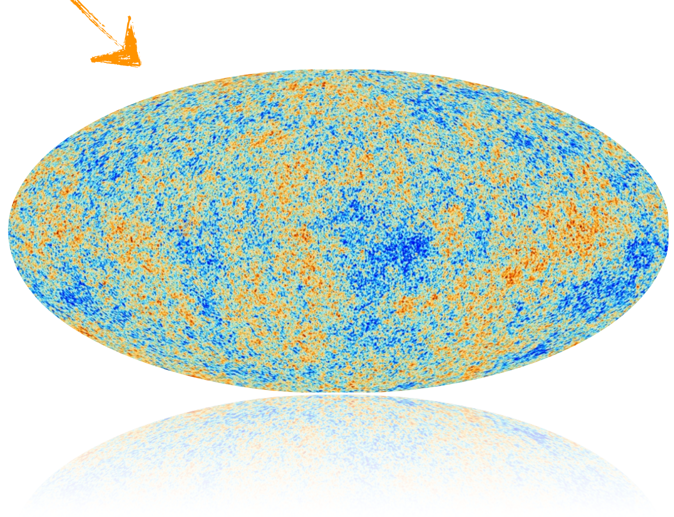
summary: “simple” models of our origins

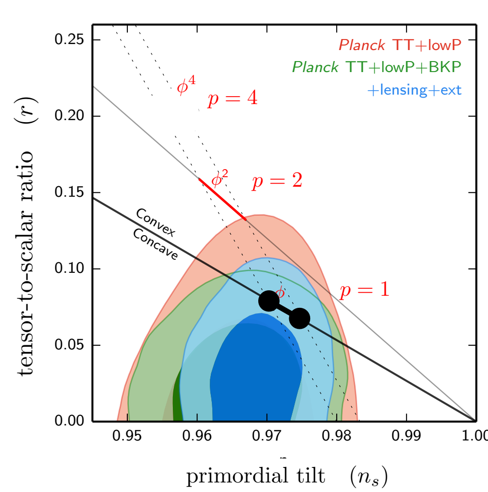


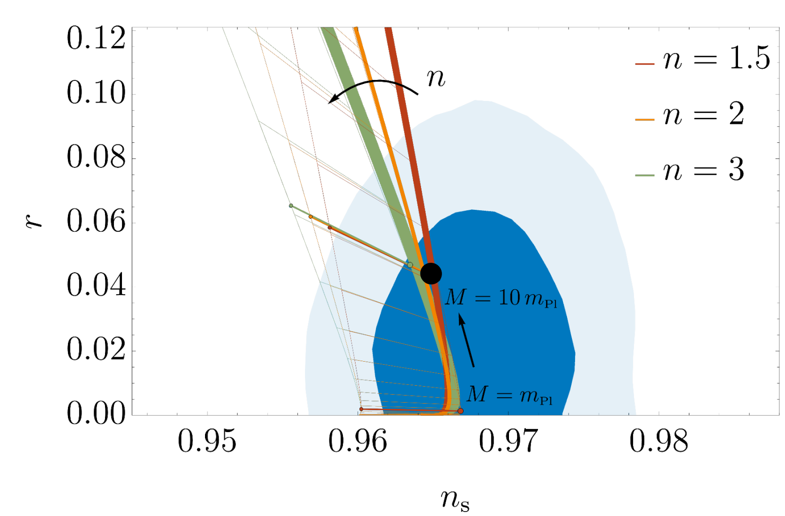


$$w \to \begin{cases} 0 & \text{if } n = 1 \\ 1/3 & \text{if } n > 1 \end{cases}$$

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







two approaches

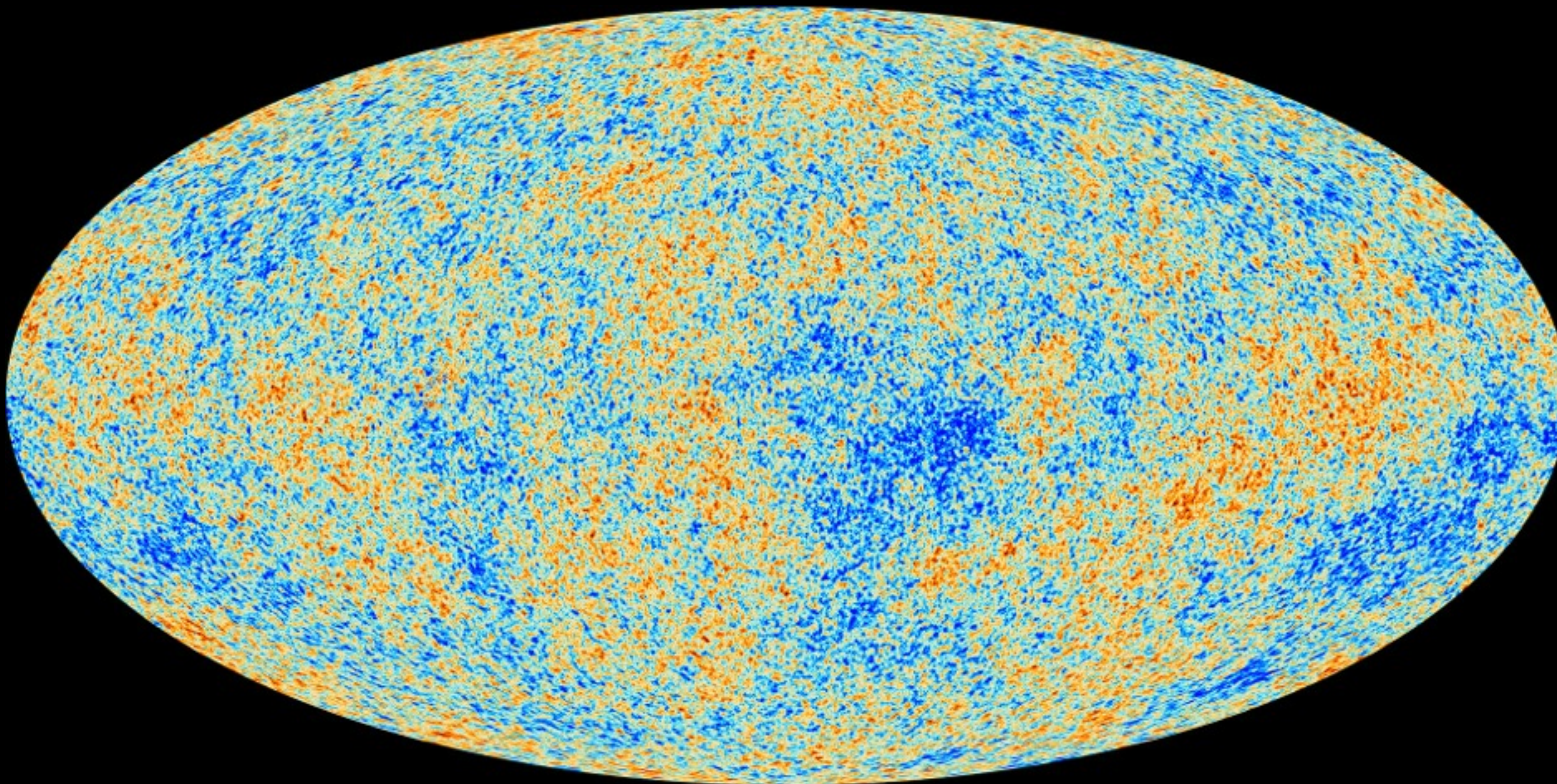
SIMPLE enough

COMPLEX enough

Lozanov & MA (2016) + earlier works

MA & Baumann (2015)

simple early universe



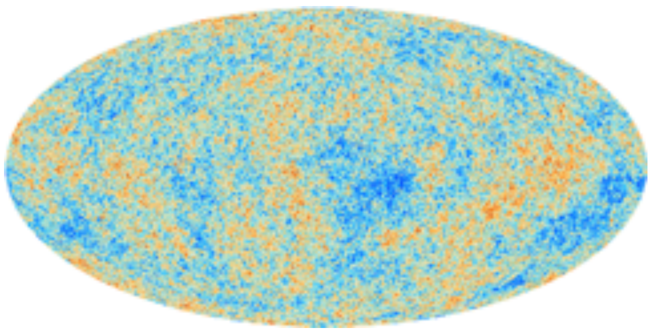
$$\delta T/T \sim 10^{-5}$$

Planck 2015

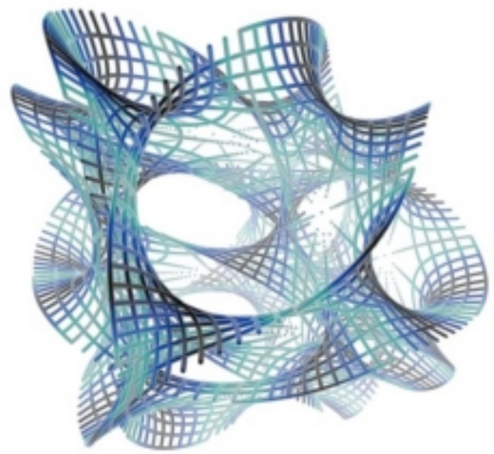
theory : its complicated (probably)

- inflation
- reheating after inflation

a statistical approach?



- **observations**: early universe is simple
- **fundamental theory**: not so much …

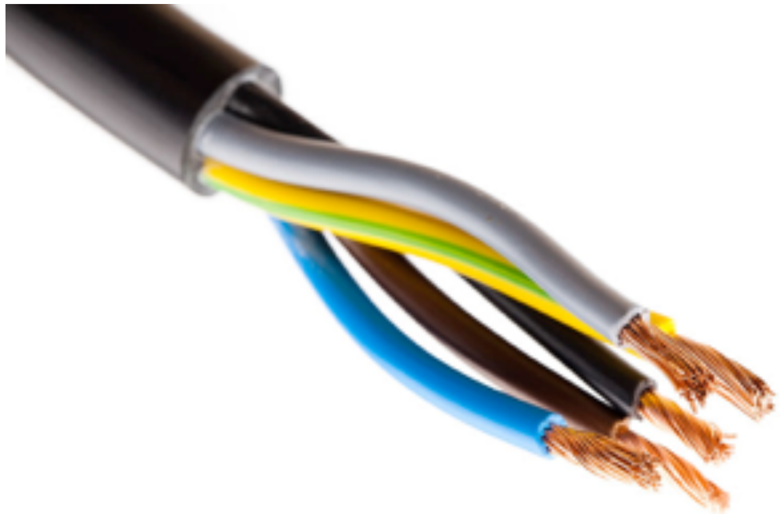


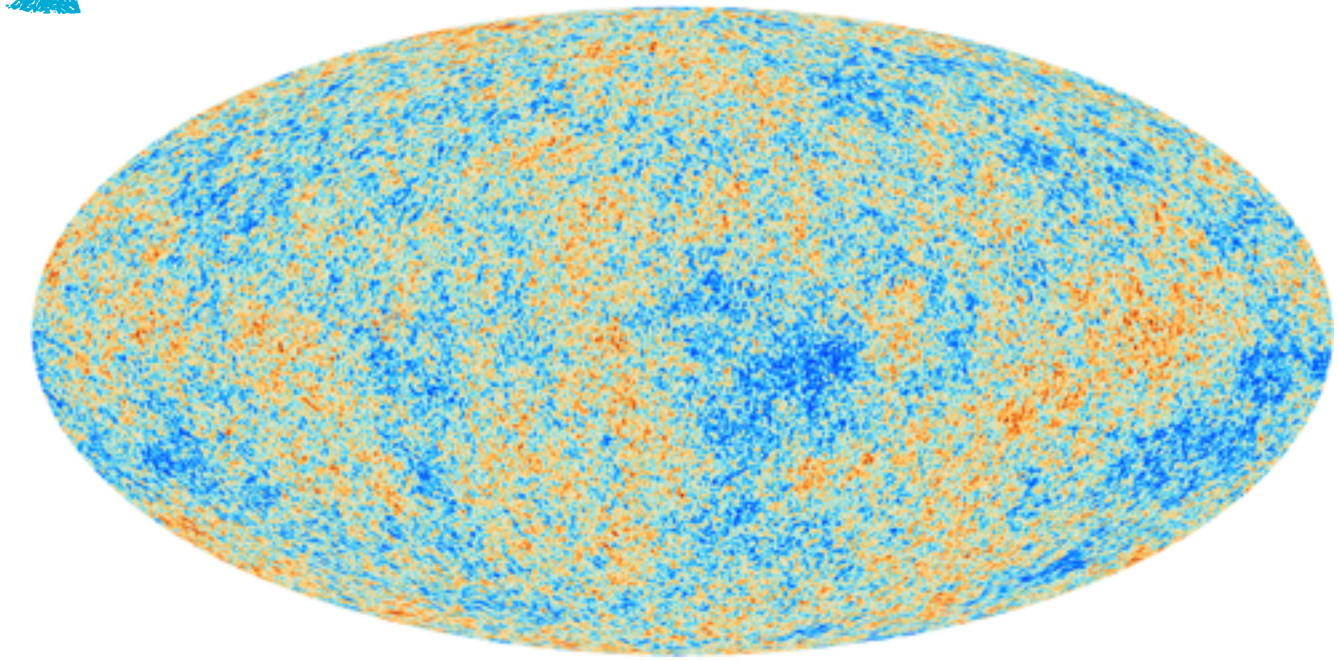
- **coarse grained view ?**
- **calculational tools ?**

MA & Baumann (2015)

from wires to cosmology

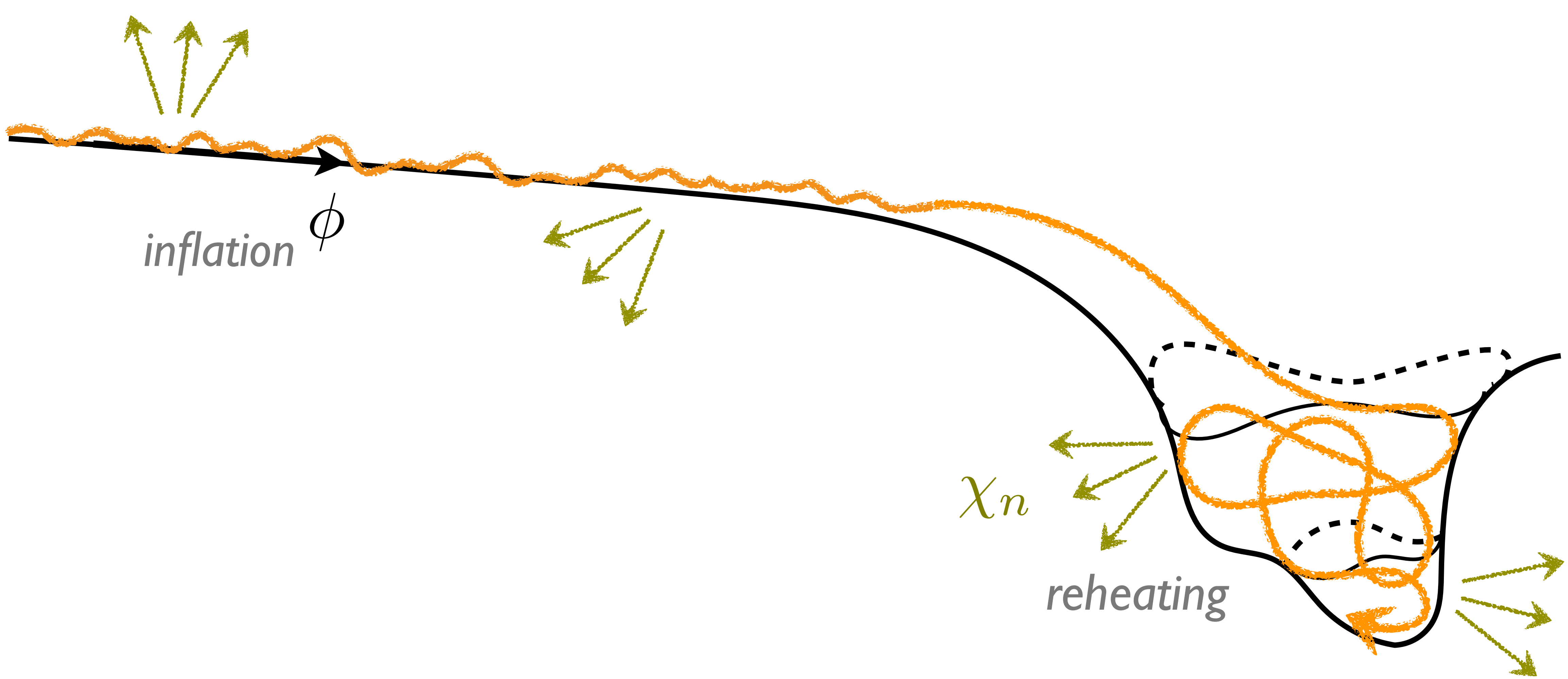
MA & Baumann (2015)





multifield inflation/reheating

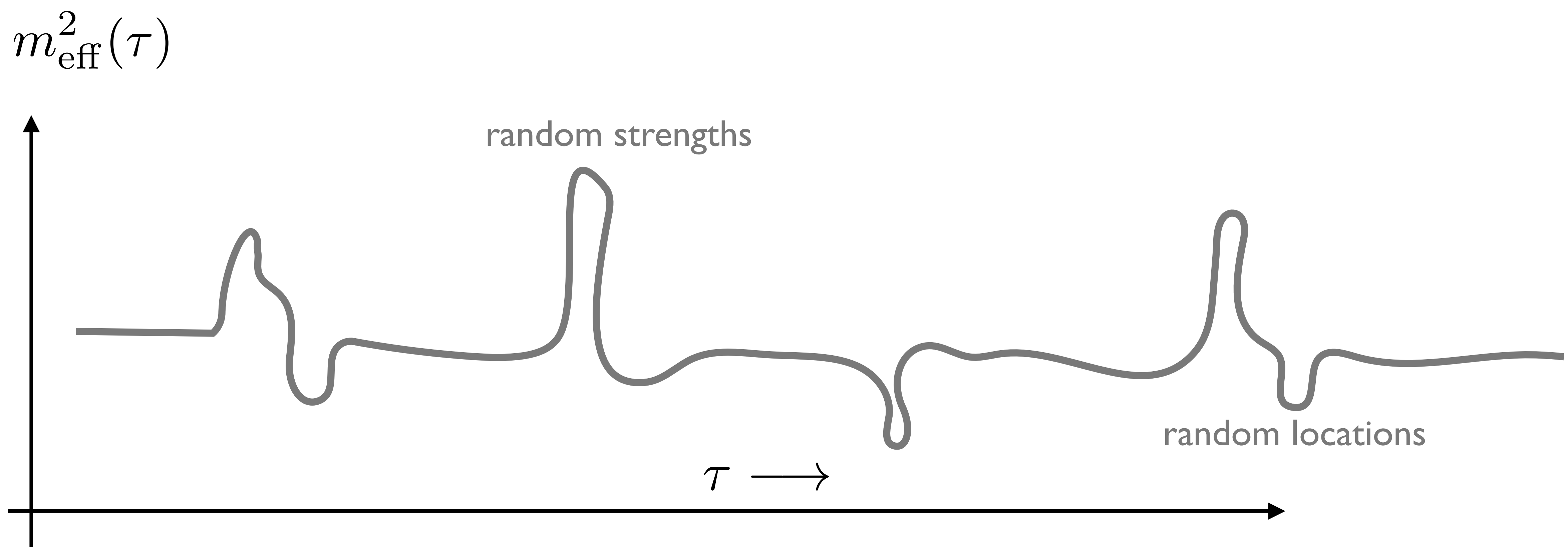
- inflation/reheating: many interacting fields
- fluctuations: coupled, non-perturbative



complexity in time: cosmology

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

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



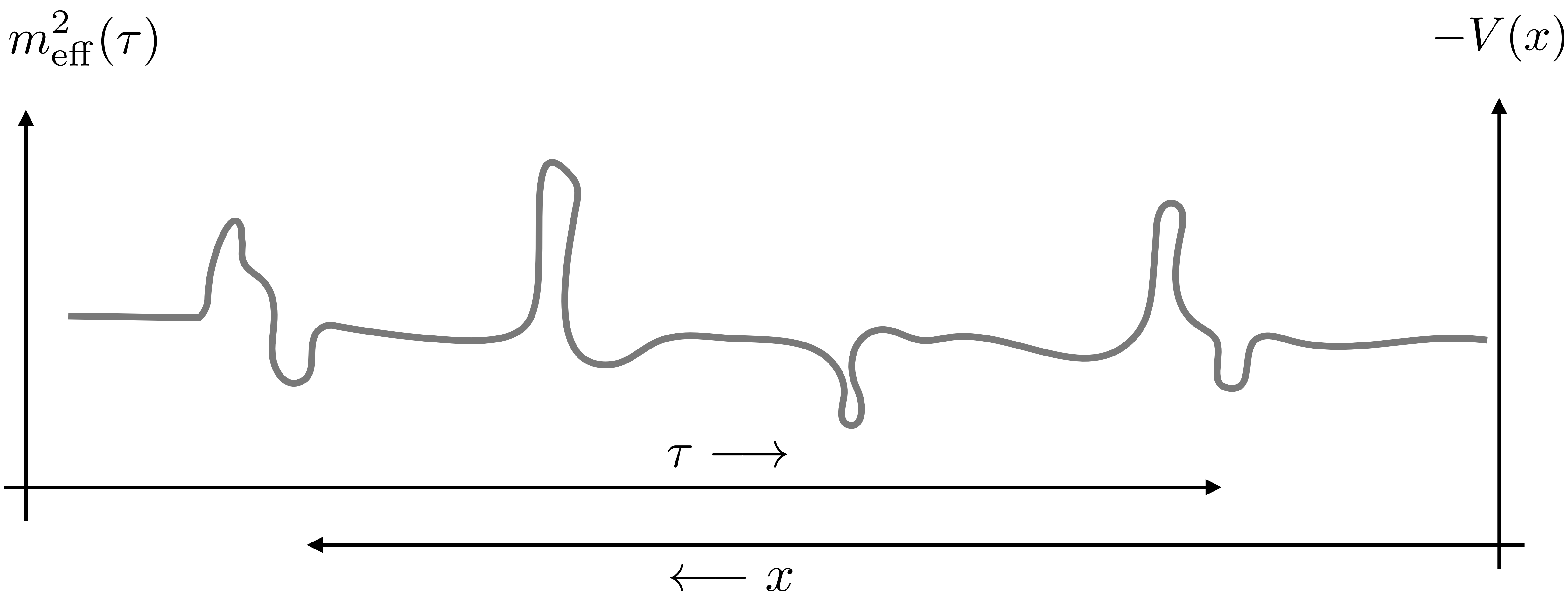
simplified version!

complexity in time ⟷ complexity in space
cosmology ⟷ wires

particle production

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

Schrodinger

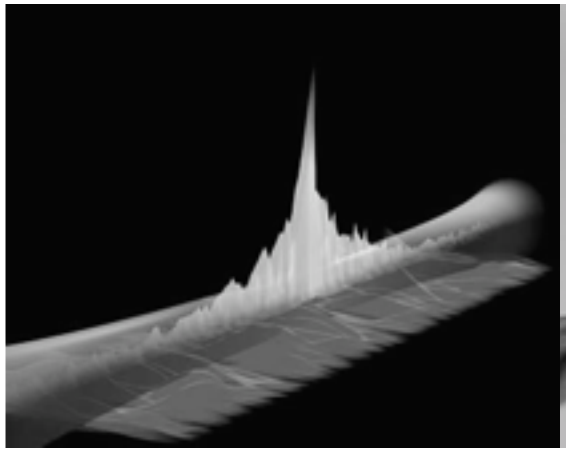


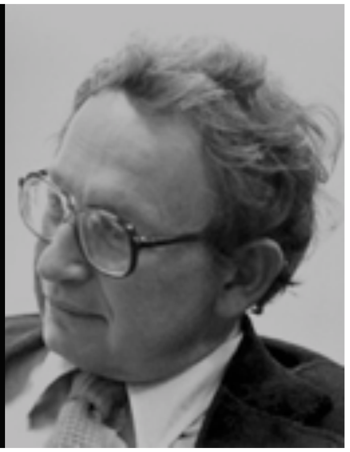
simplified version!

Anderson localization!
complexity in space — emergent simplicity

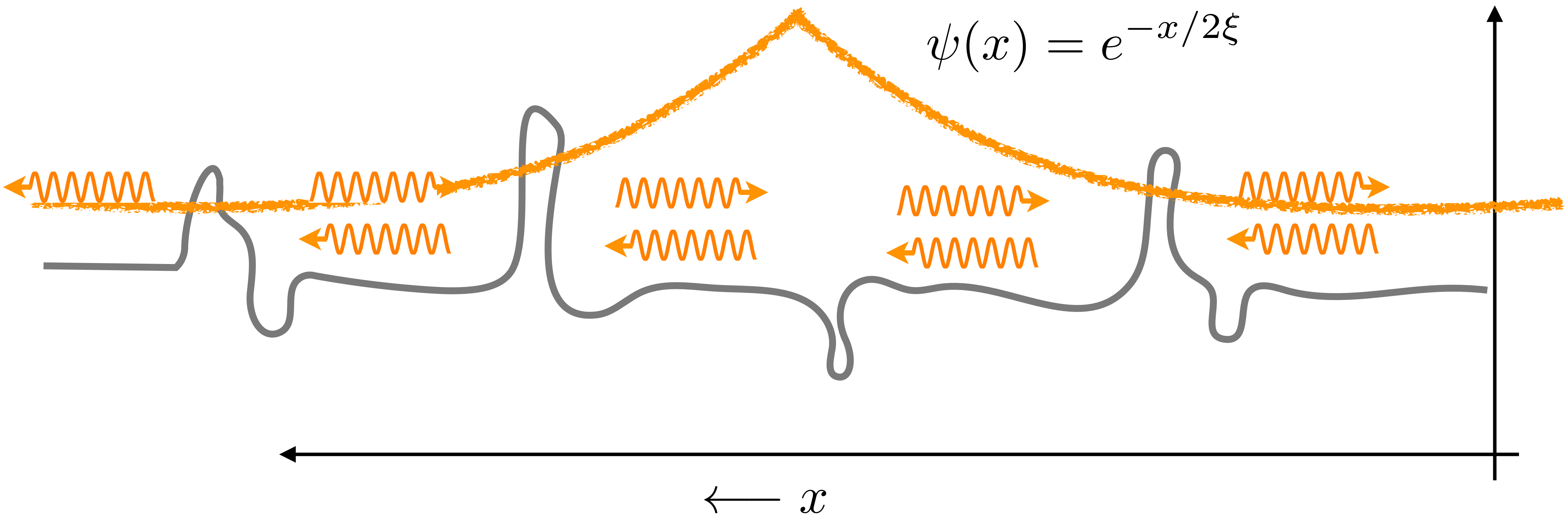
$$\psi''(x) + \left[k^2 - V(x)\right]\psi(x) = 0$$

at low temperatures, one dimensional wires are insulators



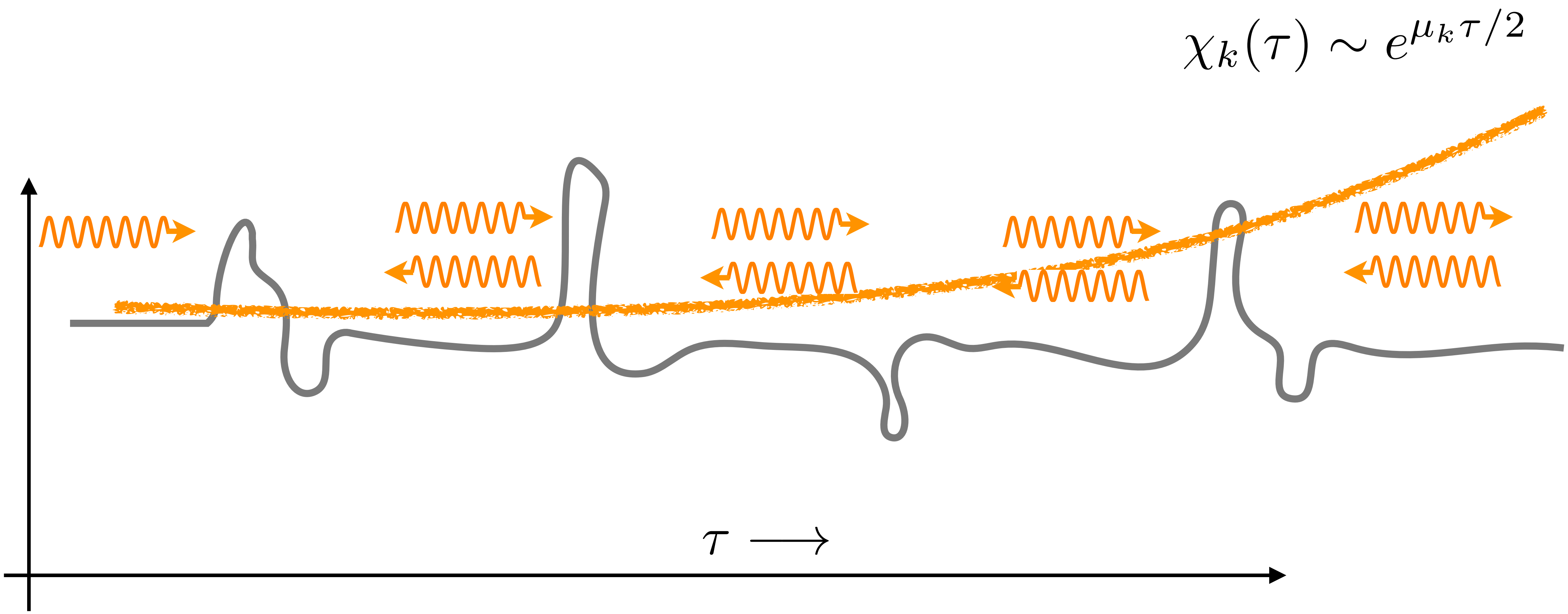


Anderson 1957

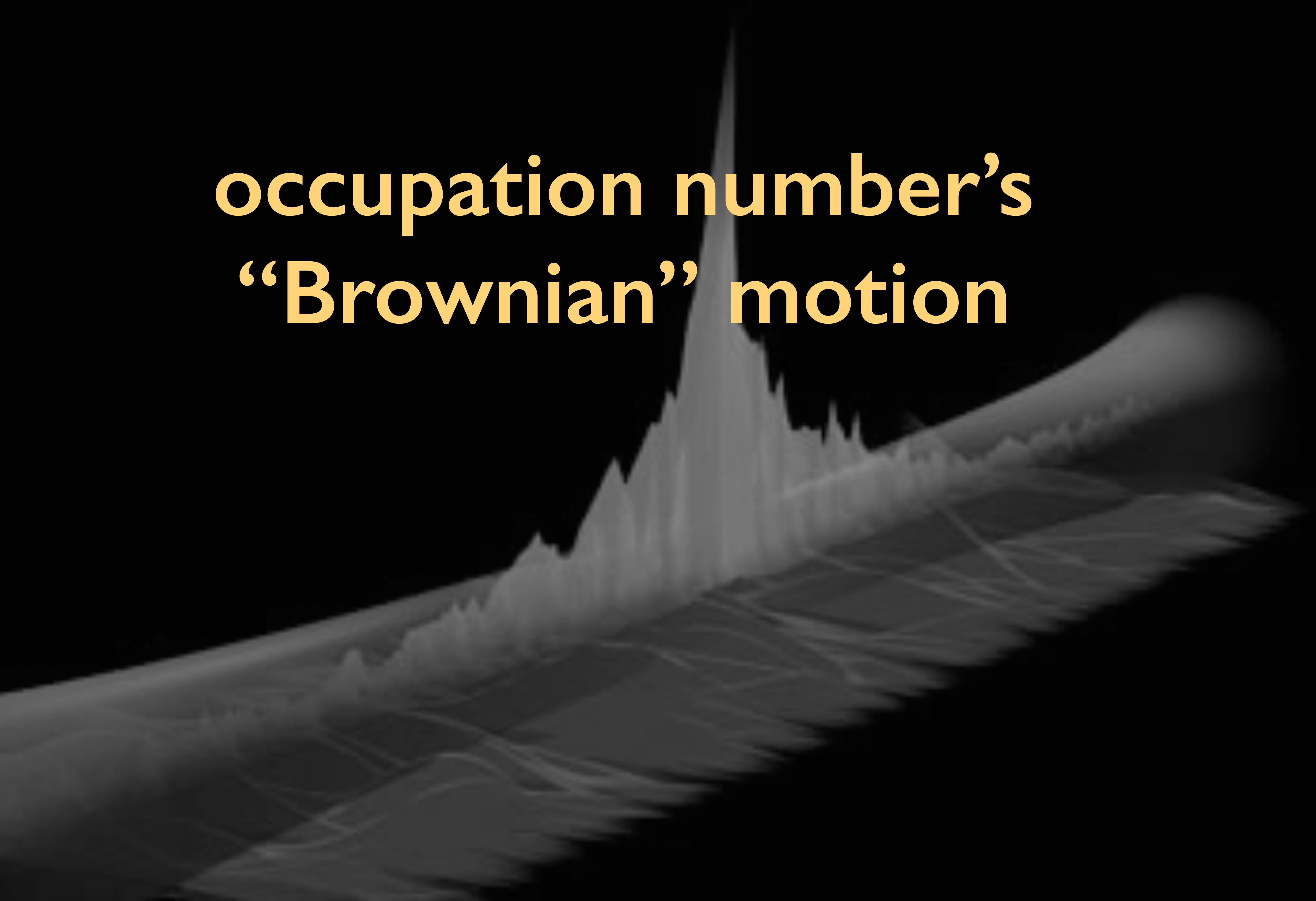


complexity in time — exponential particle production

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

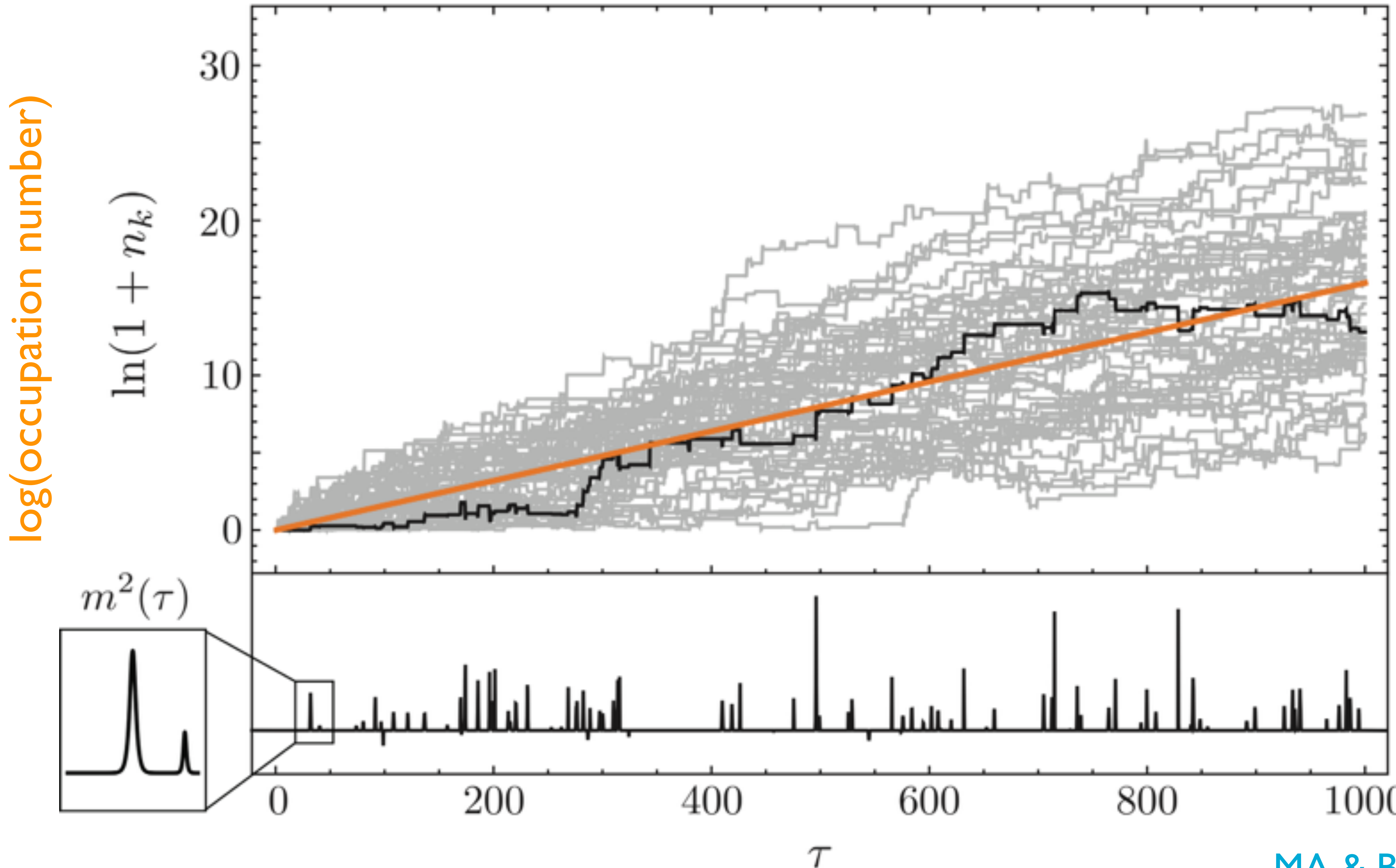


occupation number's "Brownian" motion



occupation number performs a drifted random walk

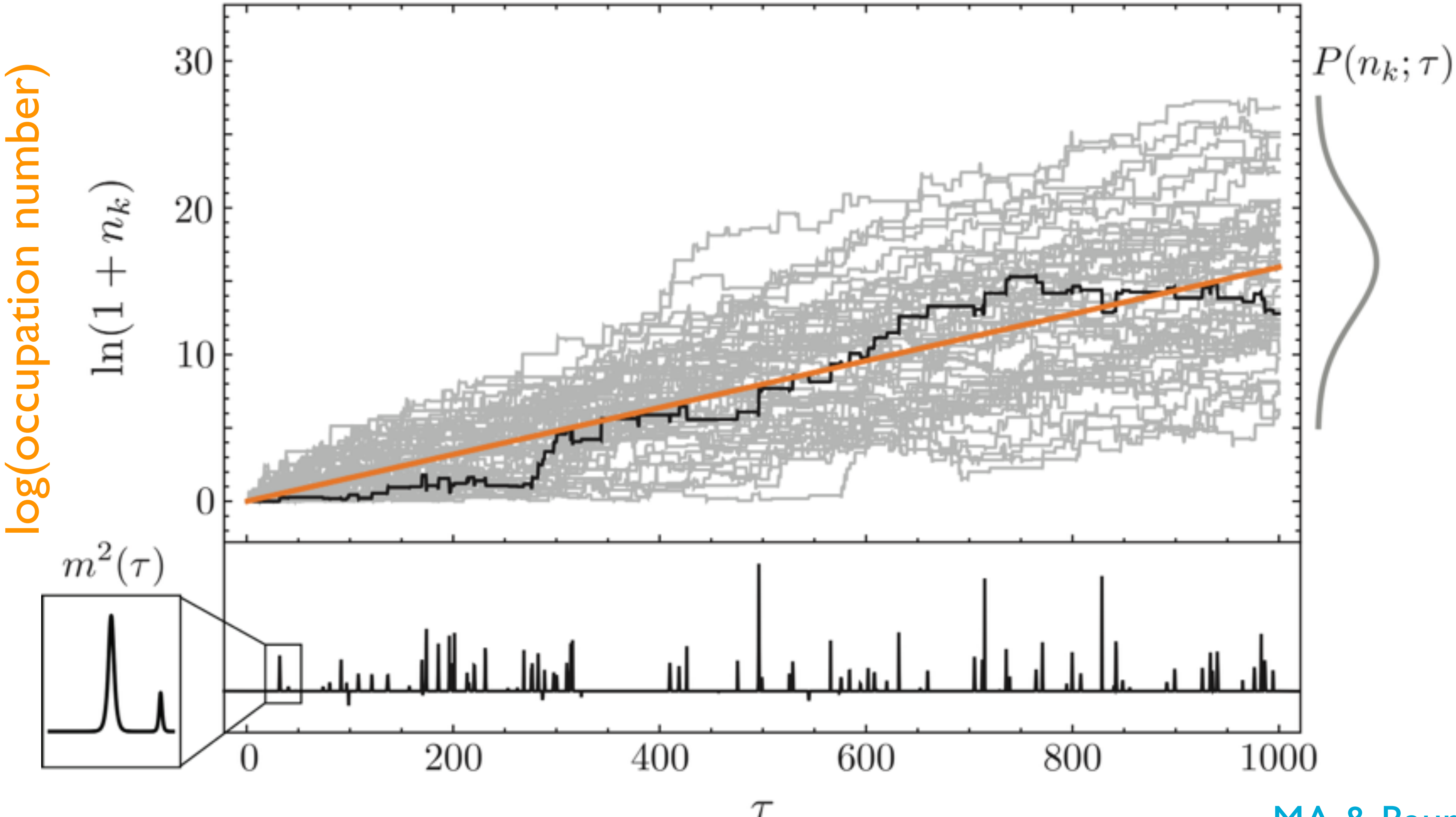
$$n(k,\tau) = \frac{1}{2\omega_k}\left(|\dot{\chi}_k|^2 + \omega_k^2|\chi_k|^2\right)$$



MA & Baumann (2015)

a Fokker Planck equation

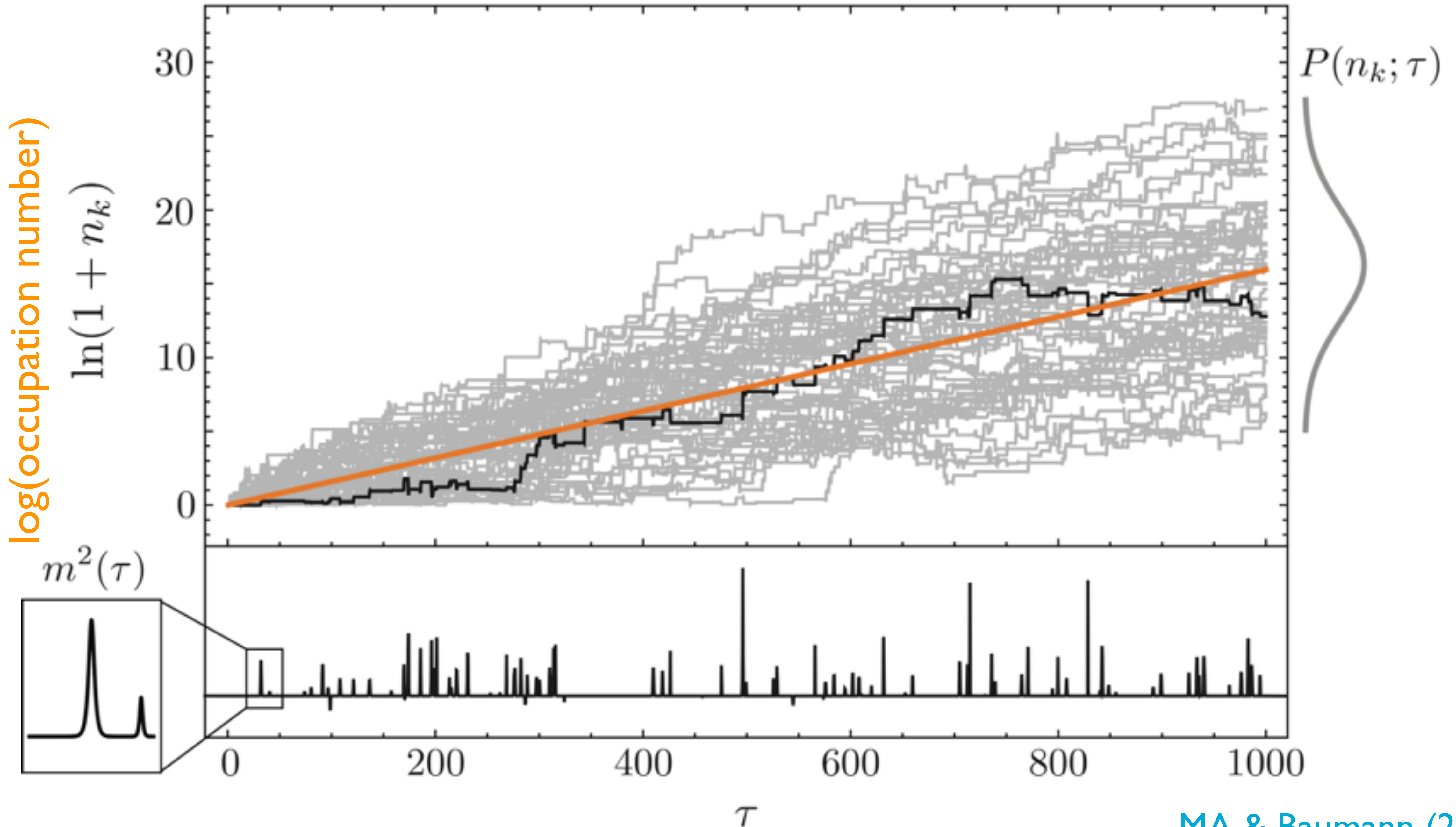
$$\frac{1}{\mu_k}\frac{\partial}{\partial \tau}P(n,\tau) = \frac{\partial}{\partial n}\left[n(1+n)\frac{\partial}{\partial n}P(n,\tau)\right]$$



MA & Baumann (2015)

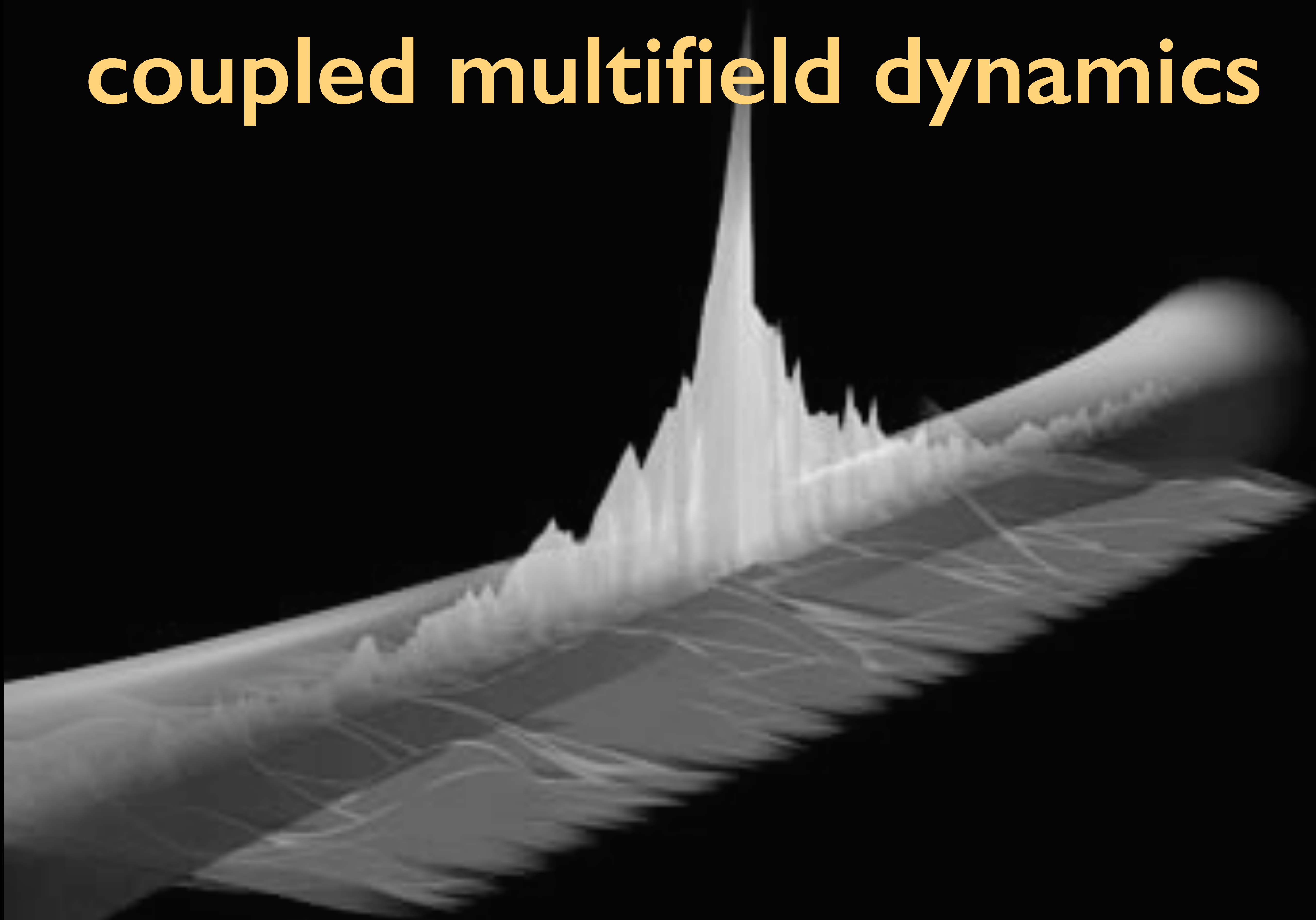
the typical occupation number

$$\boxed{n_{\rm typ} \equiv \exp\langle \ln(1+n)\rangle = e^{\mu_k \tau}}$$

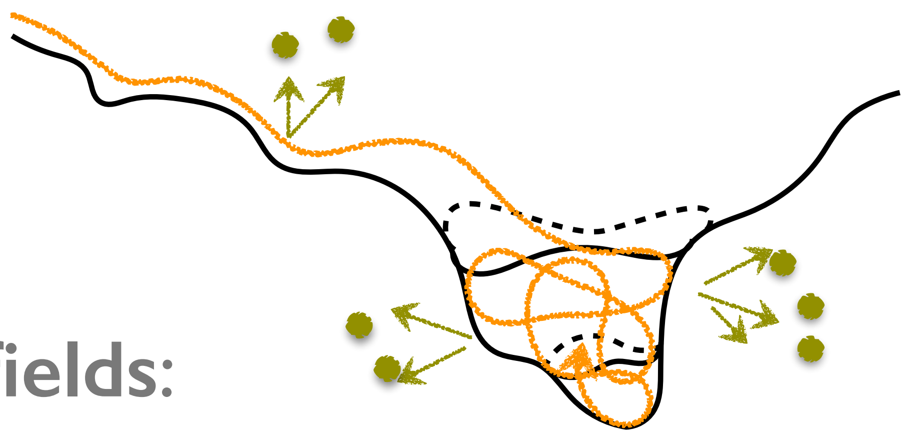


MA & Baumann (2015)

coupled multifield dynamics



many interacting fields (thick wires)



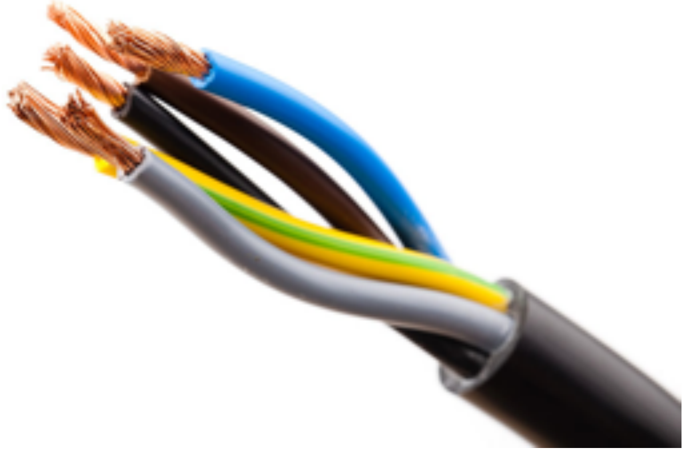
early universe: **multiple interacting fields:**

$$\ddot{\chi}_a + \left[k^2 \delta^b_a + \mathcal{M}^b{}_a(\tau)\right] \chi_b = 0$$

$$a, b = 1, \ldots, N_\mathrm{f}$$

real wires are not one-dimensional.

current conduction: **multiple channels.**



multifield Fokker Planck equation

joint probability for occupation numbers satisfies the DMPK equation:

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

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

Dokhorov, Mello, Pereyra & Kumar

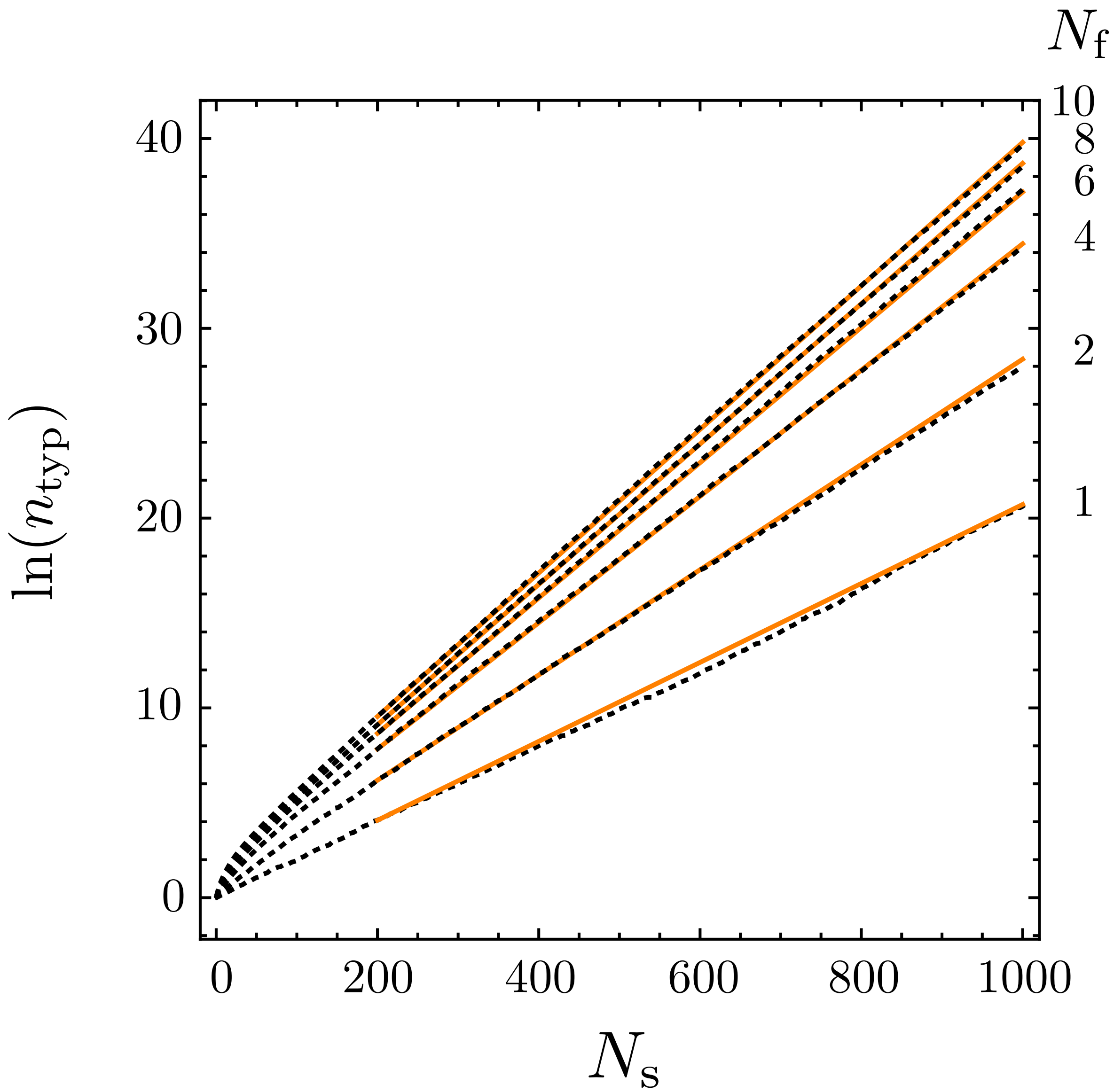
local mean particle production rate

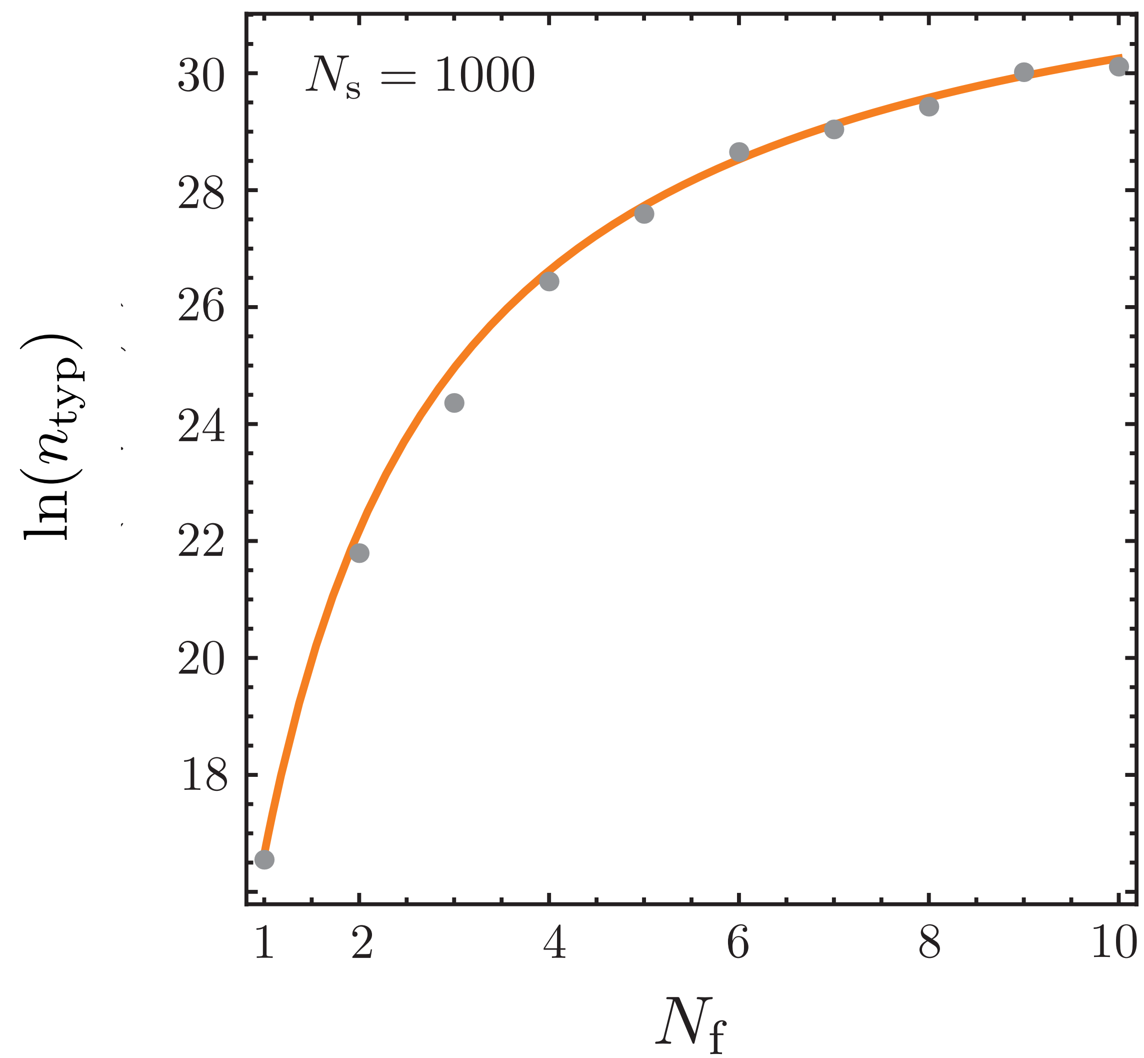
$$\mu_k \equiv \frac{1}{N_\mathrm{f}}\lim_{\delta\tau\to 0}\frac{\langle n\rangle}{\delta\tau} \qquad \text{where} \qquad n = \sum_{a=1}^{N_\mathrm{f}} n_a$$

numerical tests
[typical occupation numbers]

$$\boxed{\ln(n_{\mathrm{typ}}) \propto \frac{2N_{\mathrm{f}}}{1+N_{\mathrm{f}}} N_{\mathrm{s}}}$$

where $N_{\mathrm{f}} =$ number of fields
$N_{\mathrm{s}} =$ number of scatterings

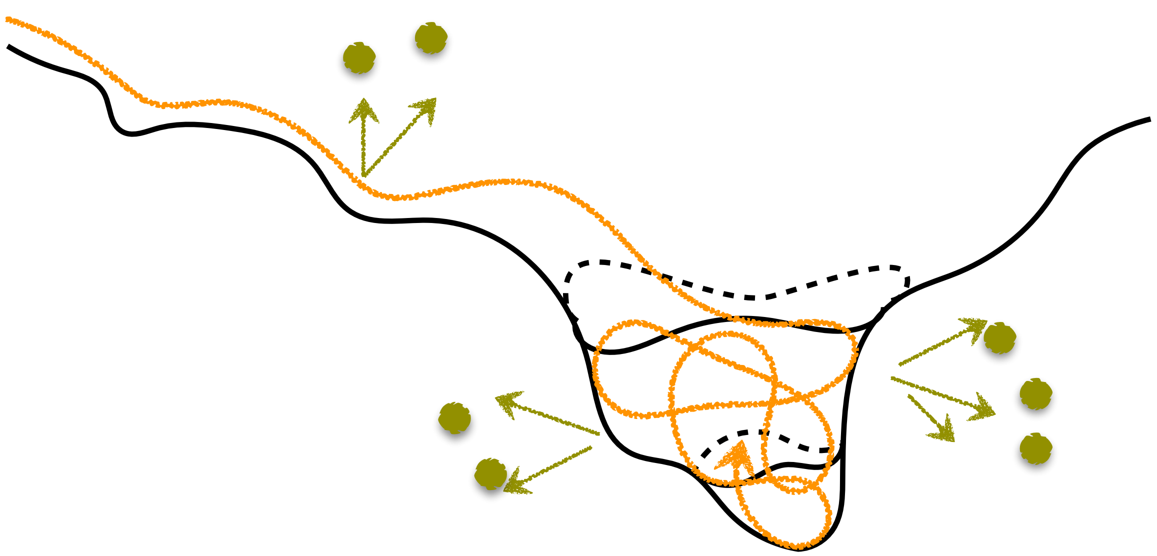




simplicity/universality

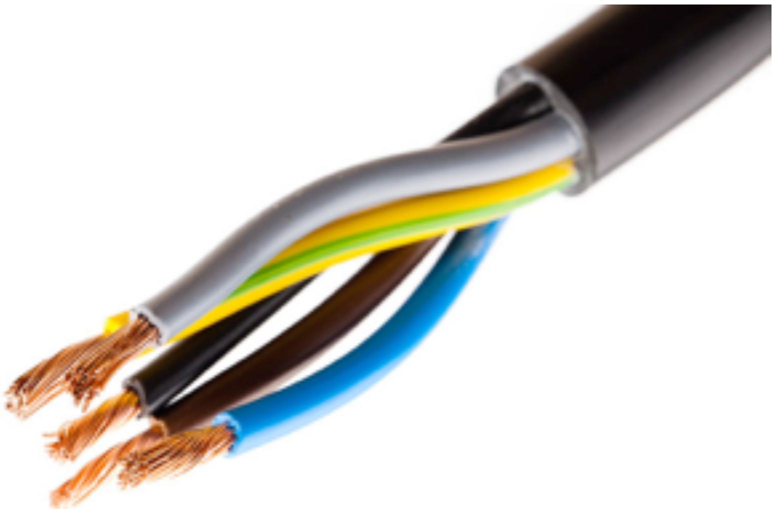
μ_k local mean particle production rate

N_f number of fields



l_mf mean ballistic mean free path

N_f number of channels

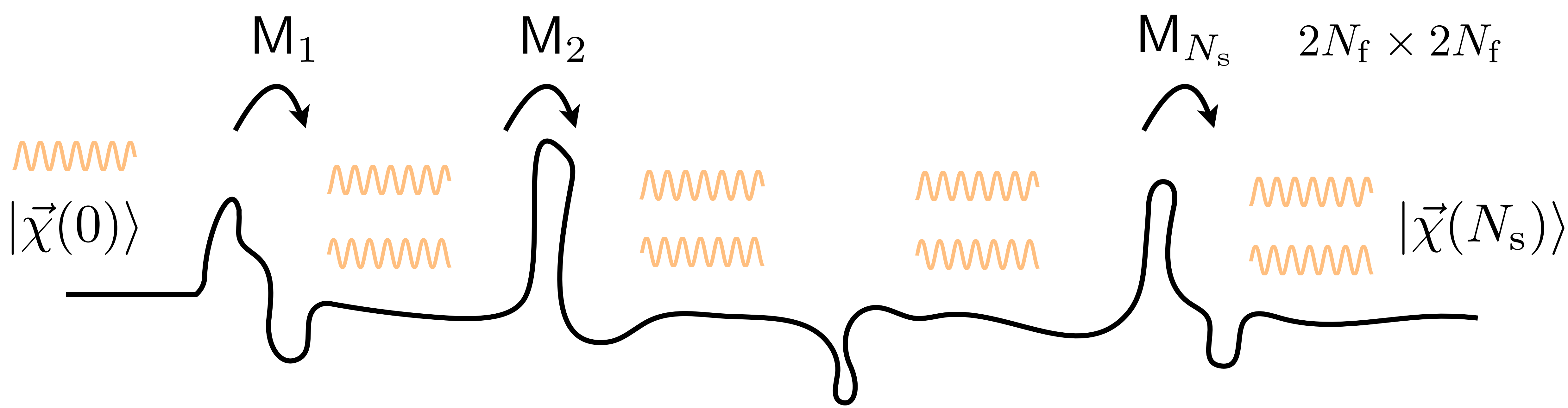


μ_k - calculate from ‘local” microphysics or parametrize

N_f - regimes exist where dependence vanishes

multifield particle production as scattering

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



total occupation number

$$n = \mathrm{Tr}(\mathsf{n}) = \sum_{a=1}^{N_f} n_a \quad \text{where} \quad \mathsf{n} \sim \mathsf{M}\mathsf{M}^\dagger \, .$$

particles in each "field" (eignevalues)

Universality from Random Matrix Theory

two large N's to make life easier:

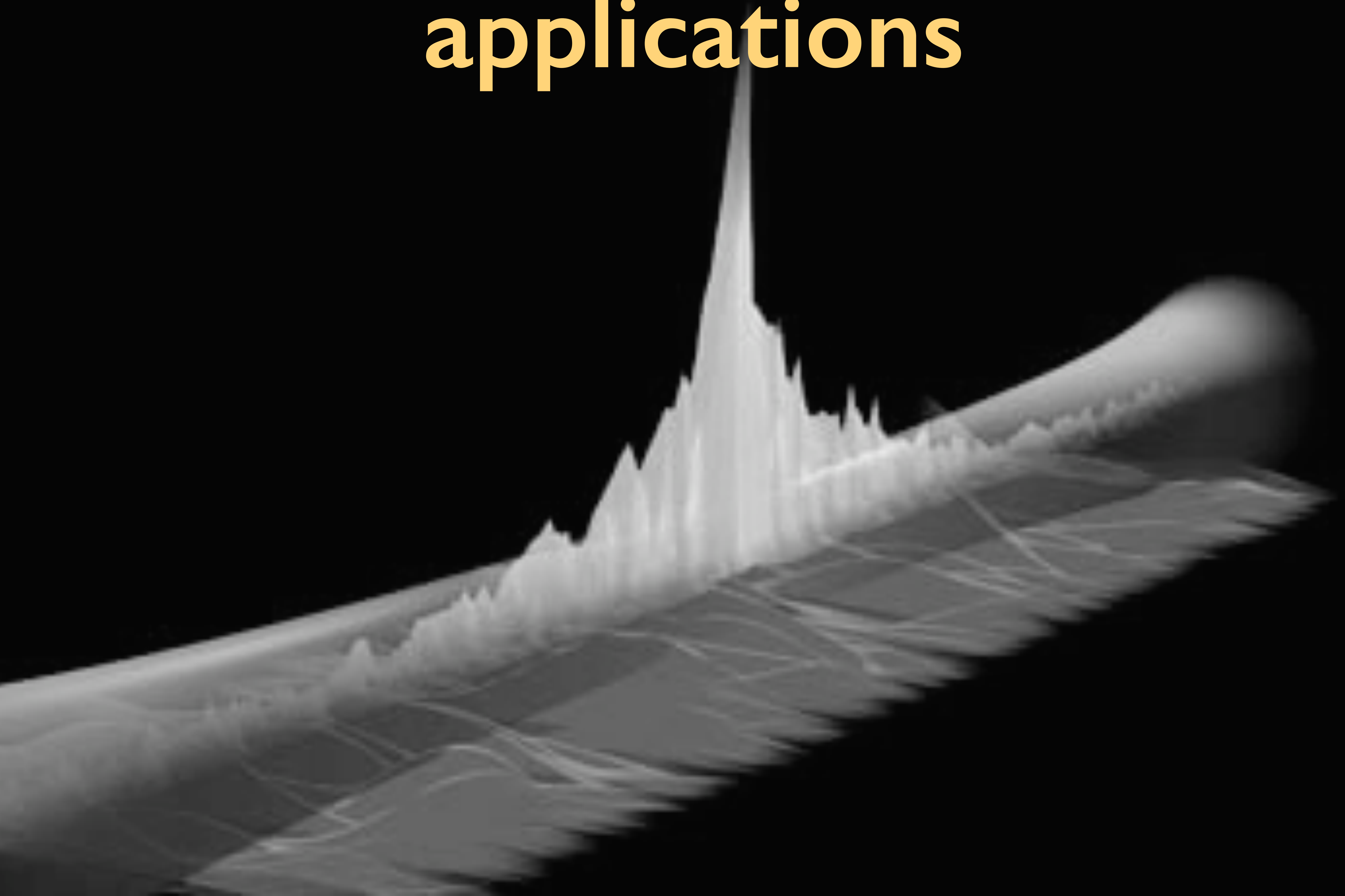
	• large number of fields:	• large number of scatterings:
	N_{f}	N_{s}
	$\updownarrow$	$\updownarrow$
from RMT:	• eigenvalue spectrum of M_j	• non-random limit of $\mathsf{M} = \prod_{j=1}^{N_{\mathrm{s}}} \mathsf{M}_j$

Pichard and Sarma

prediction for exponential behavior in time

non-random behavior of the exponent

applications



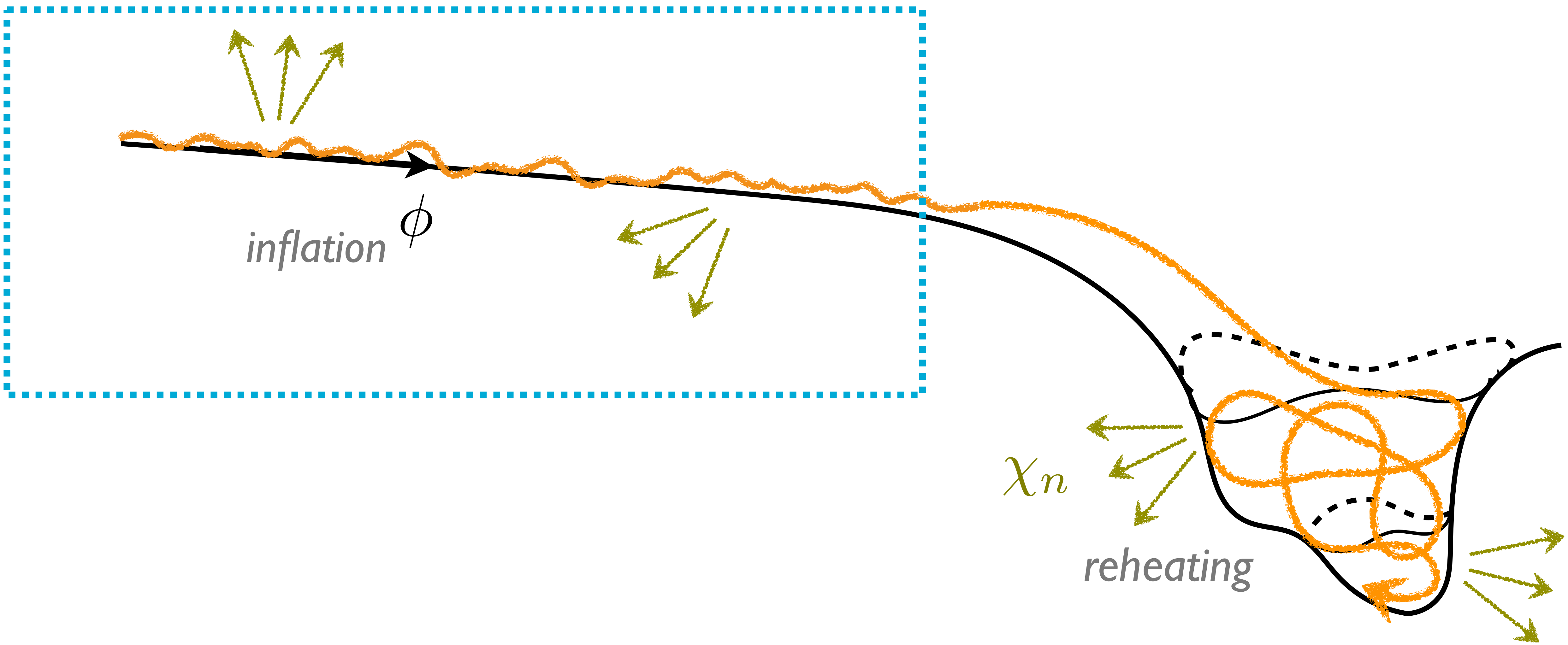
WORK IN PROGRESS

applications: inflation

MA, Baumann, Carlsten & Green (in progress)

background dynamics → particle production ↔ curvature fluctuations

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



WORK IN PROGRESS

combine particle production & EFT with driving and dissipation

Nacir, Porto, Senatore, and Zaldarriaga
Green, Horn, Senatore, and Silverstein

$$\mathcal{L} = \mathcal{L}_{\rm sr} - m^2(t+\pi)\,\chi^2$$

Goldstone boson $\zeta = -H\pi$

$$\left(\partial_t^2 + 3H\partial_t + \frac{k^2}{a^2}\right)\pi = \frac{dm^2}{dt}\,\chi^2$$

source

stochastic noise

$$(\chi^2)_S \equiv \langle\chi^2\rangle_{\pi=0}$$

linear response

$$(\chi^2)_R \equiv \int^t \mathrm{d}t'\, G_{\rm ret}^{\langle\chi^2\rangle}(t,t')\,\pi(t')$$

background dynamics

particle production

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

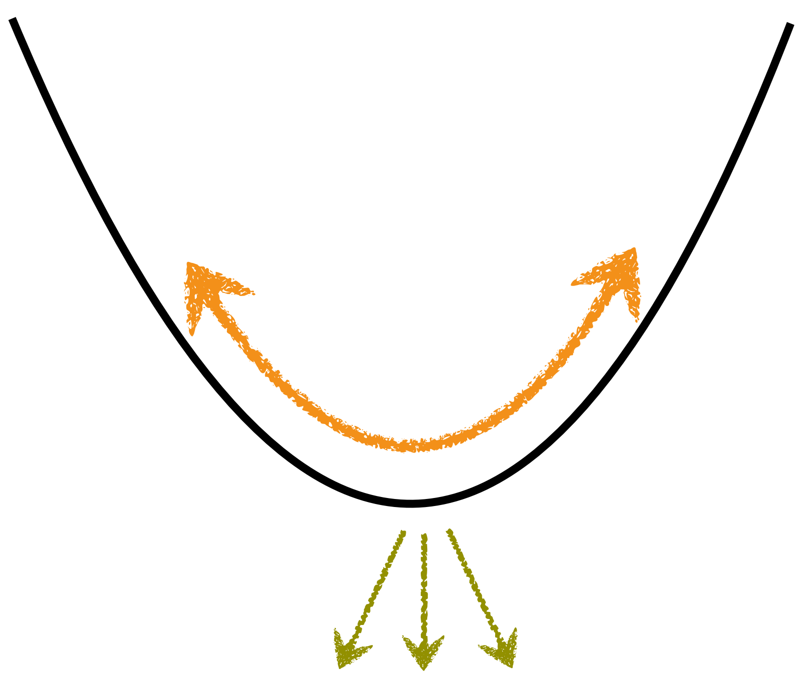
curvature fluctuations

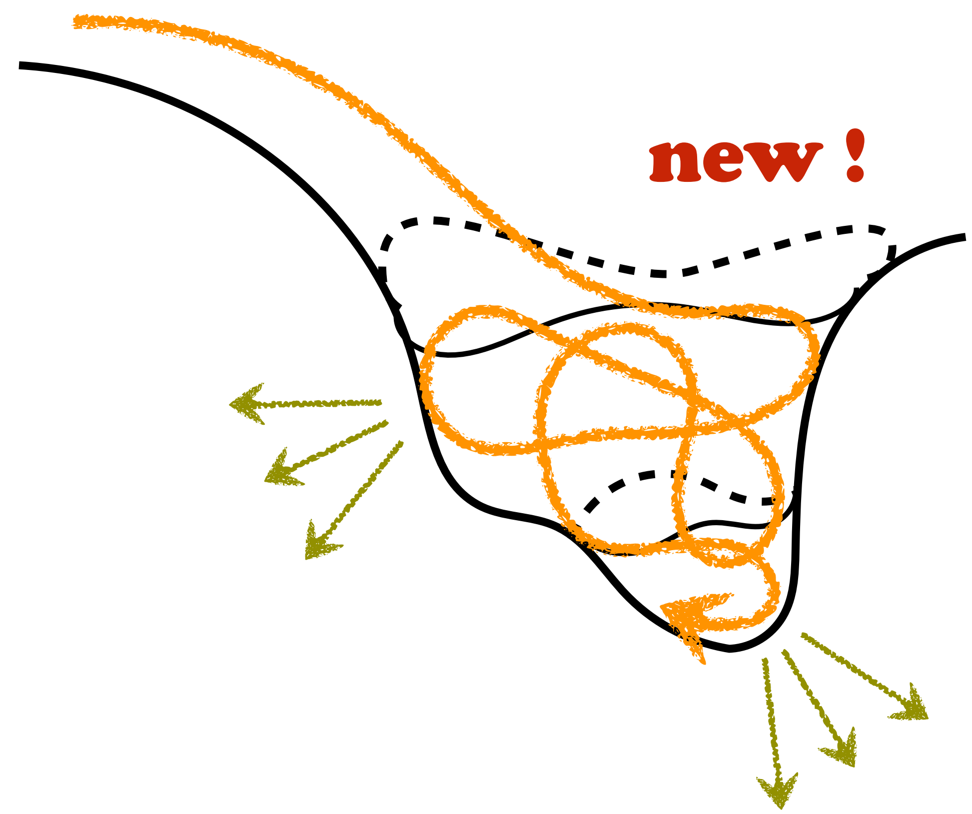
$\langle \zeta_{k_1} \zeta_{k_2} \ldots\rangle$

MA, Baumann, Carlsten & Green
(in progress)

WORK IN PROGRESS

applications : reheating





Kofman, Linde & Starobinsky (1994, 97)
Traschen & Brandenberger (1995)
Zanchin et. al + Bassett (1998) [noise added]

model-insensitive description of a complicated reheating process.

related work: condensed matter + cosmology

Anderson
Absence of diffusion in certain random lattices
(1957)

Mello, Pereyra Kumar
Macroscopic approach to multichannel disordered wires
(1987)

C. Beenakker,
Random matrix theory of quantum transport
(1997)

C. Muller and D. Delande,
Disorder and interference: localization phenomena
(2010)

Kofman, Linde & Starobinsky
(1994, 1997)

Traschen and Brandenberger
(1997)

Bassett
(1998)

Zanchin, Maia, Craig & Brandenberger
(1998)

Nacir, Porto, Senatore and Zaldarriaga
(2012)

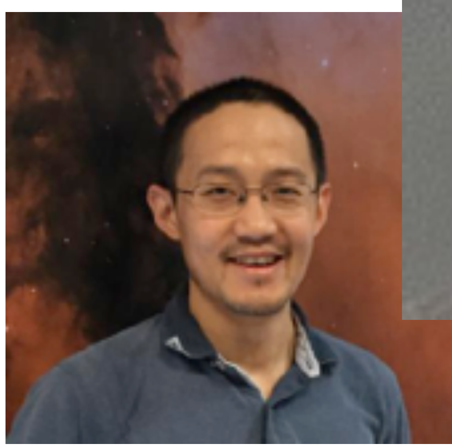
Marsh, McAllister, Pajer, Wrase
(2013)

Green
(2015)

Dias, Fraser & Marsh
(2016)

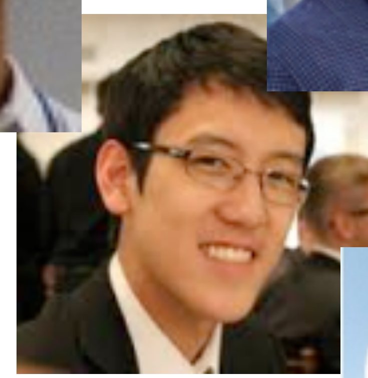
+ many works on particle production during and after inflation.

diverse collaboration(s) for a diverse problem

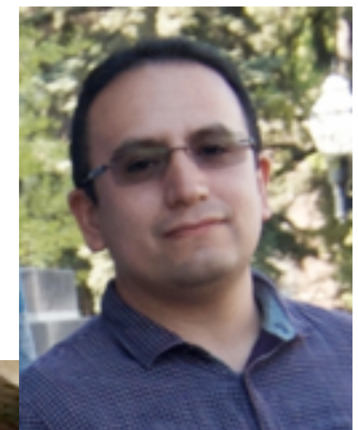


H. Xie
(condensed matter)

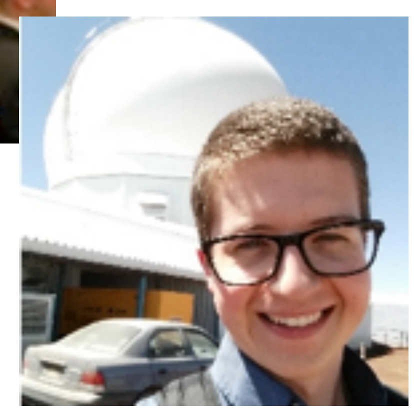
J. Shen



O. Wen



M. Garcia



S. Carlsten

RICE

D. Baumann

UNIVERSITY OF AMSTERDAM

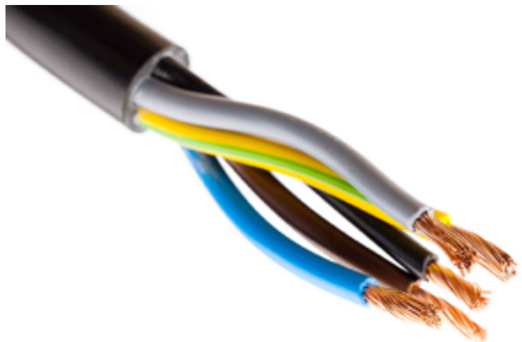
UNIVERSITY OF CAMBRIDGE

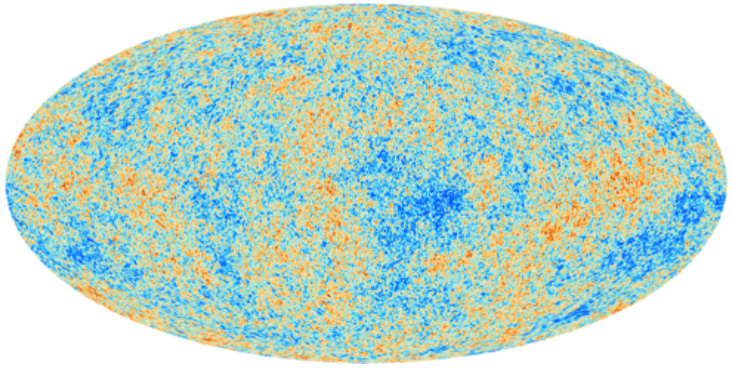
D. Green

Berkeley
UNIVERSITY OF CALIFORNIA

complex enough models: summary

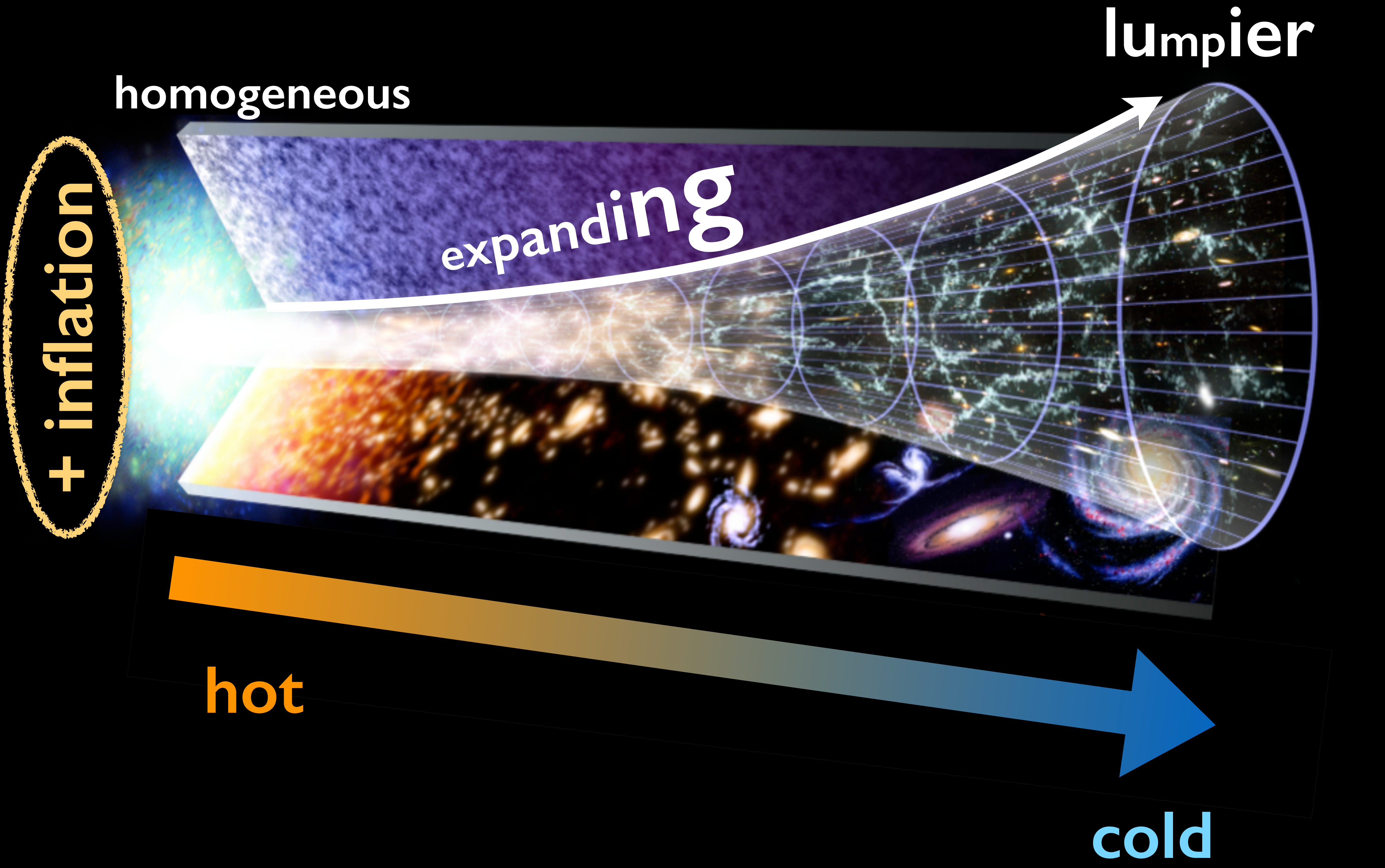
- statistical tool for theoretical complexity
- simplicity & hints of universality
- *observed simplicity* in spite of underlying complexity ?





ORIGINS ?

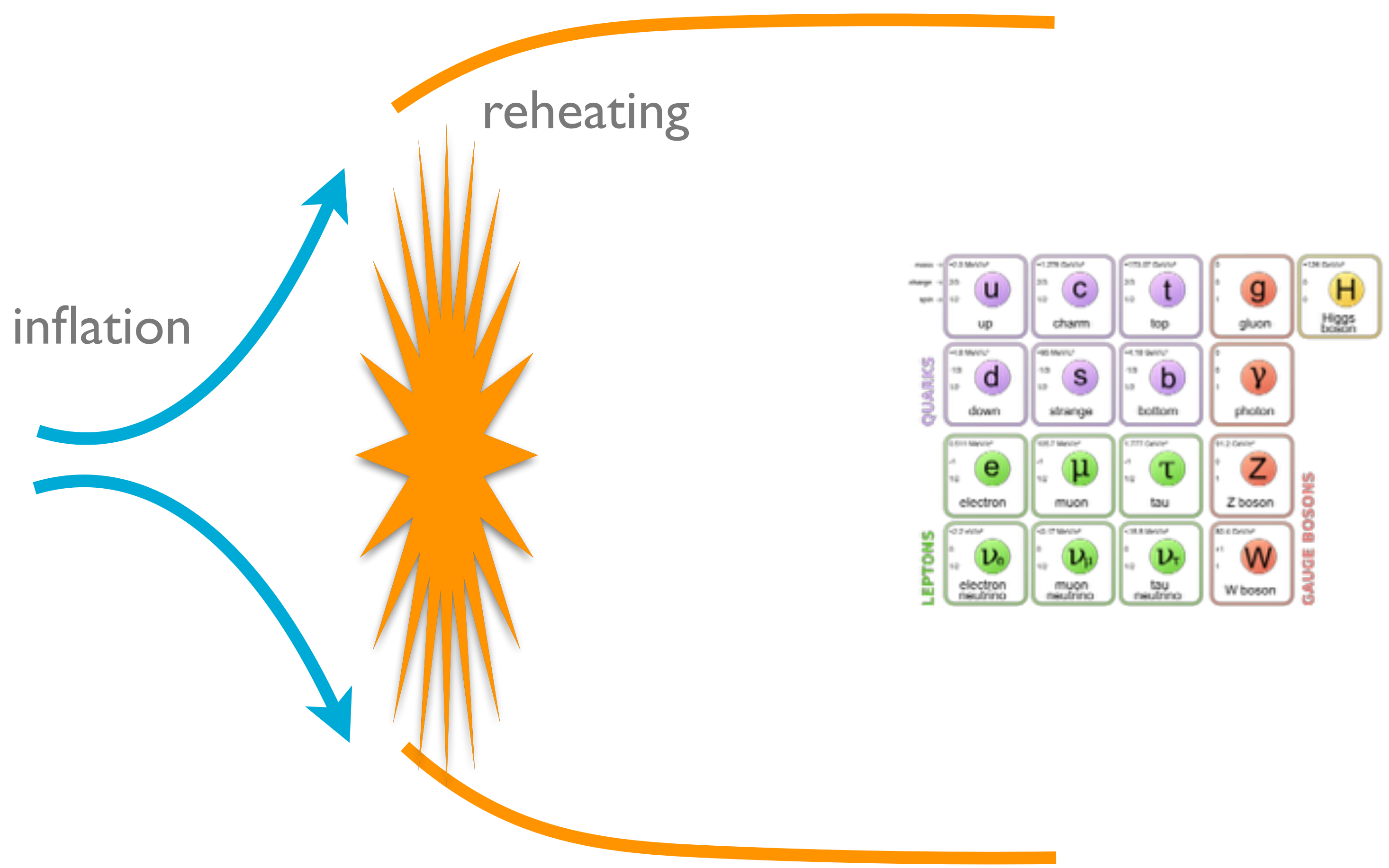
Inflationary Cosmology



credit: adapted from NASA

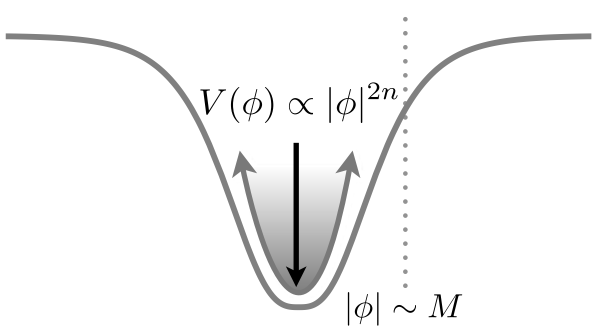
outstanding theory questions

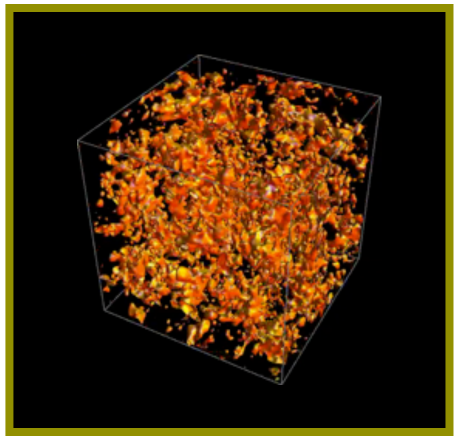
- what is the physics of inflation ?
- how did the universe get populated with particles after inflation ? (reheating)
- connecting with the standard model?

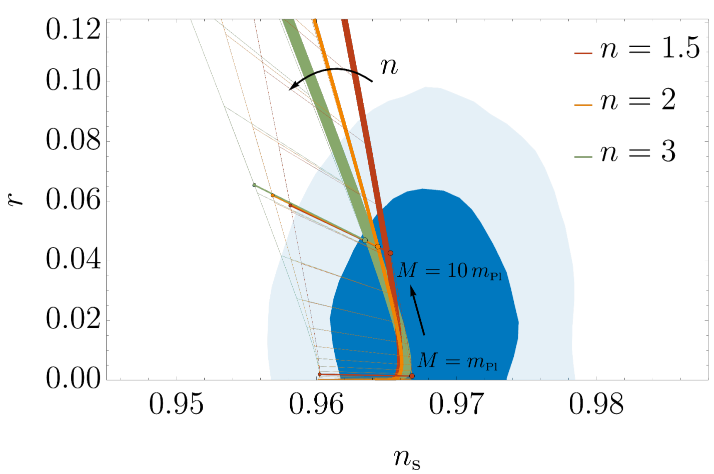


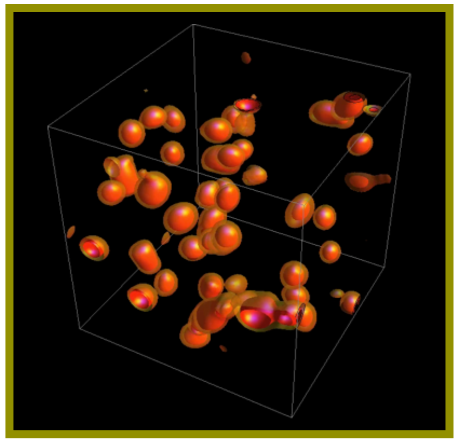
our origins: two approaches

SIMPLE enough



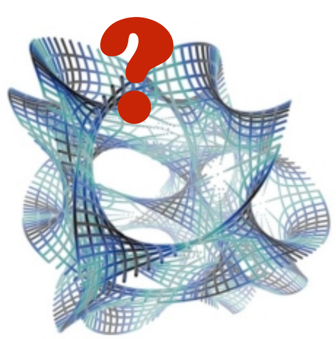


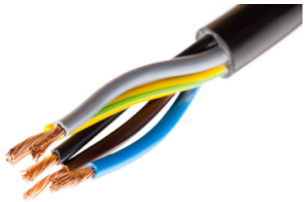




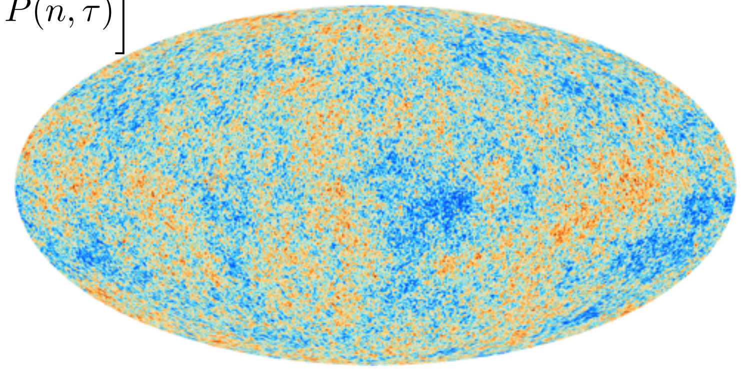
$$\Delta N_{\rm rad} \sim \begin{cases} 1 & M \lesssim 10^{-2} m_{\rm Pl}\,, \\ \dfrac{n+1}{3} \ln\left(\dfrac{\kappa}{\Delta\kappa}\dfrac{10M}{m_{\rm Pl}}\right) & M \gtrsim 10^{-2} m_{\rm Pl}\,. \end{cases}$$

COMPLEX enough





$$\frac{1}{\mu_k}\frac{\partial}{\partial\tau}P(n,\tau) = \frac{\partial}{\partial n}\left[n(1+n)\frac{\partial}{\partial n}P(n,\tau)\right]$$



Thanks!