Early-Universe Simulations of the Cosmological Axion

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University of Michigan

7/15/2019
CERN

arXiv:1906:00967
MB, Joshua W Foster, Benjamin R Safdi

LEINWEBER CENTER FOR THEORETICAL PHYSICS
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National Energy Research Scientific Computing Center

Post- vs Pre-inflationary scenario

Two different scenarios can be considered:
Breaking the PQ symmetry **before** or **after** inflation

Post- vs Pre-inflationary scenario

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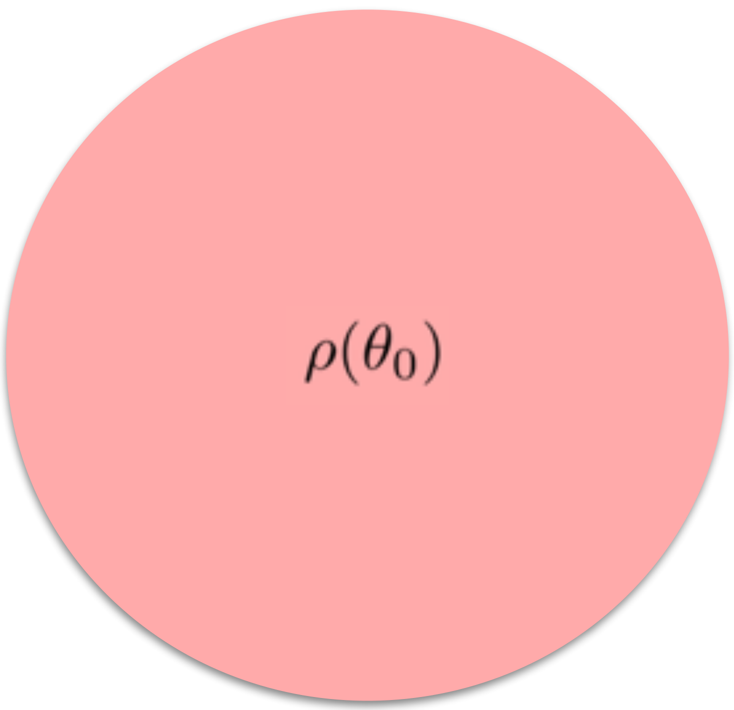
Breaking the PQ symmetry **before** or **after** inflation

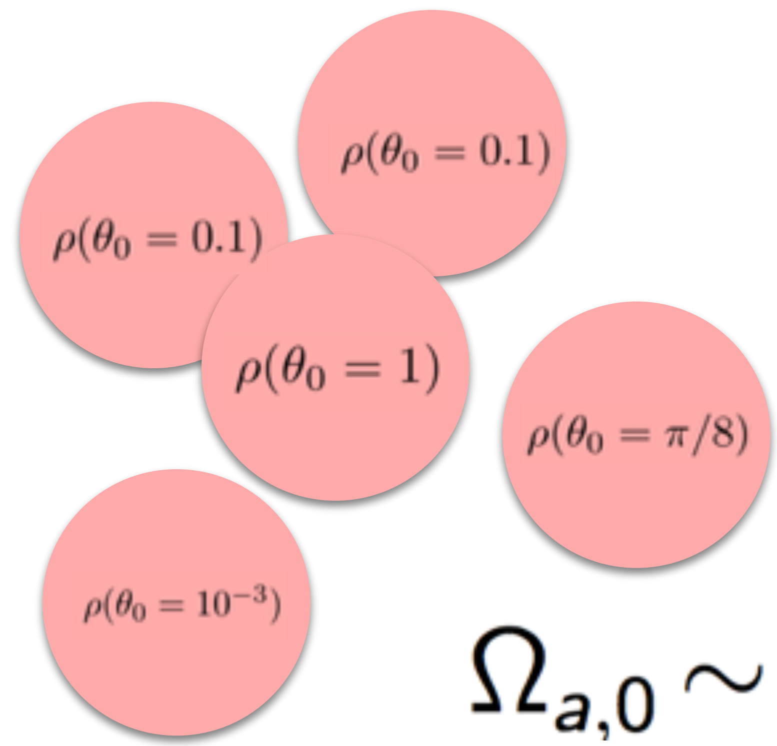
before inflation:



$$\Omega_{a,0} \sim {\theta_0}^2$$

two free parameters:
θ_0 , f_a

after inflation:



$$\Omega_{a,0} \sim \langle {\theta_0}^2 \rangle$$

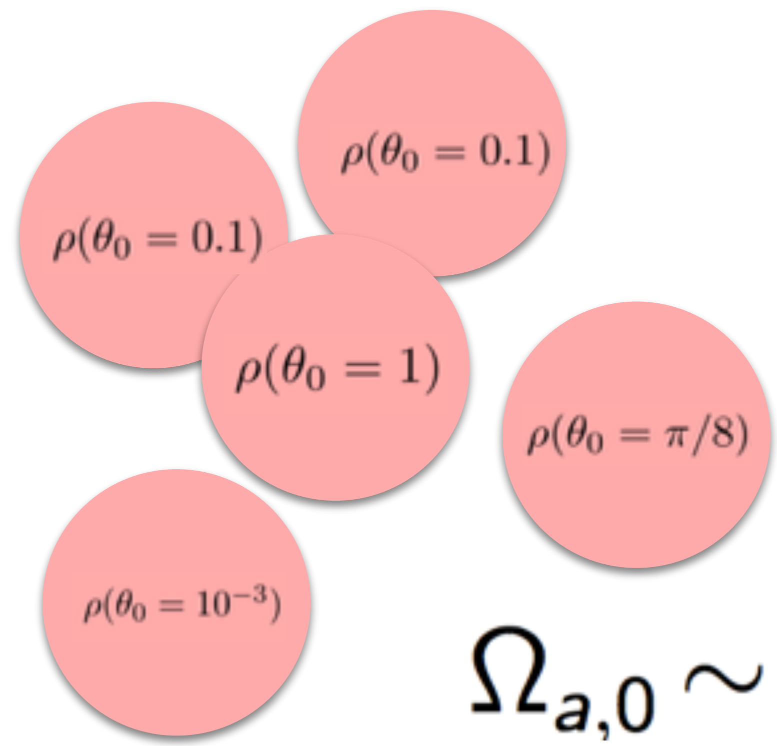
one free parameter: f_a
inhomogeneous at small scales

Post- vs Pre-inflationary scenario

Two different scenarios can be considered:
Breaking the PQ symmetry **before** or **after** inflation

Focus of this discussion!

after inflation:

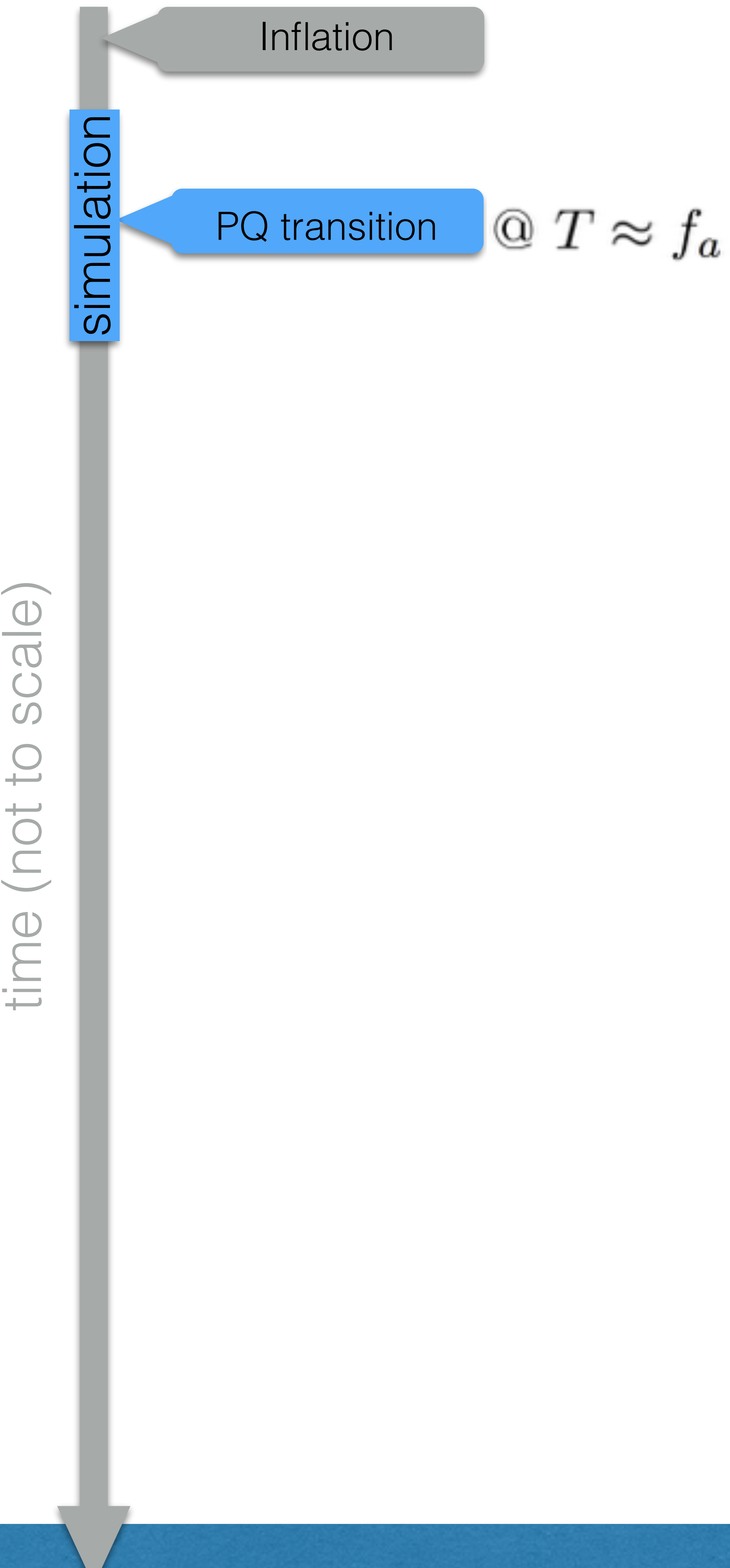


$$\Omega_{a,0} \sim \langle {\theta_0}^2 \rangle$$

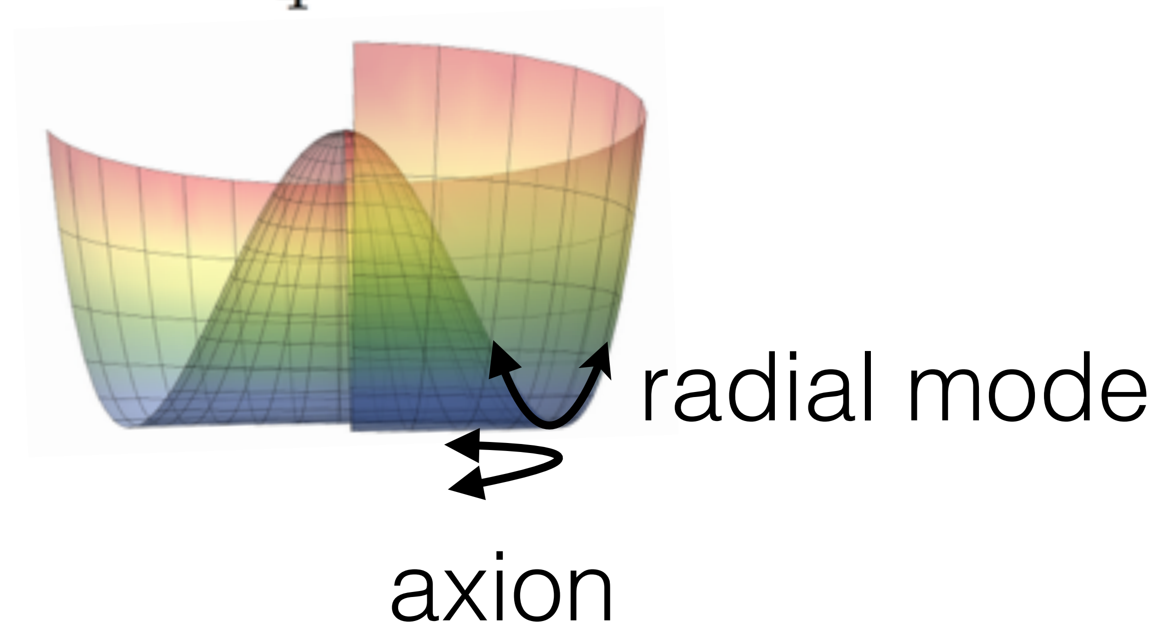
one free parameter: f_a
inhomogeneous at small scales

Main goals:

1. Obtain **axion mass** with which correct relic abundance is reached
2. Characterise **inhomogeneities**



$$V(\Phi, T) = \frac{\lambda}{4}\left(|\Phi|^2 - f_a^2\right)^2$$



Inflation

thermal spec.

PQ transition @ $T \approx f_a$

radial @ vev

simulation

time (not to scale)

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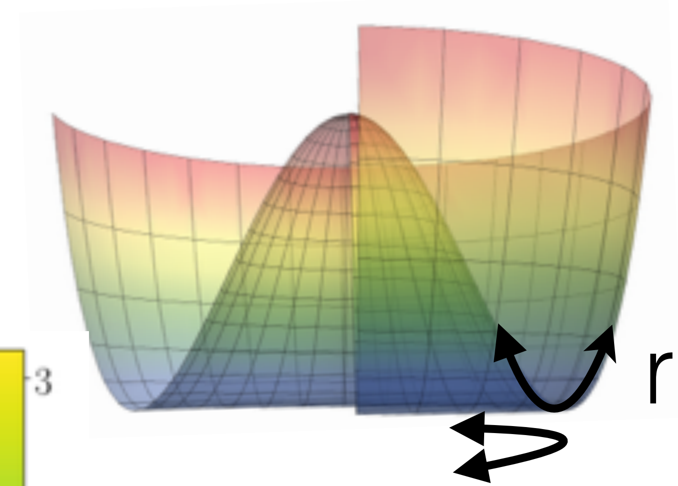
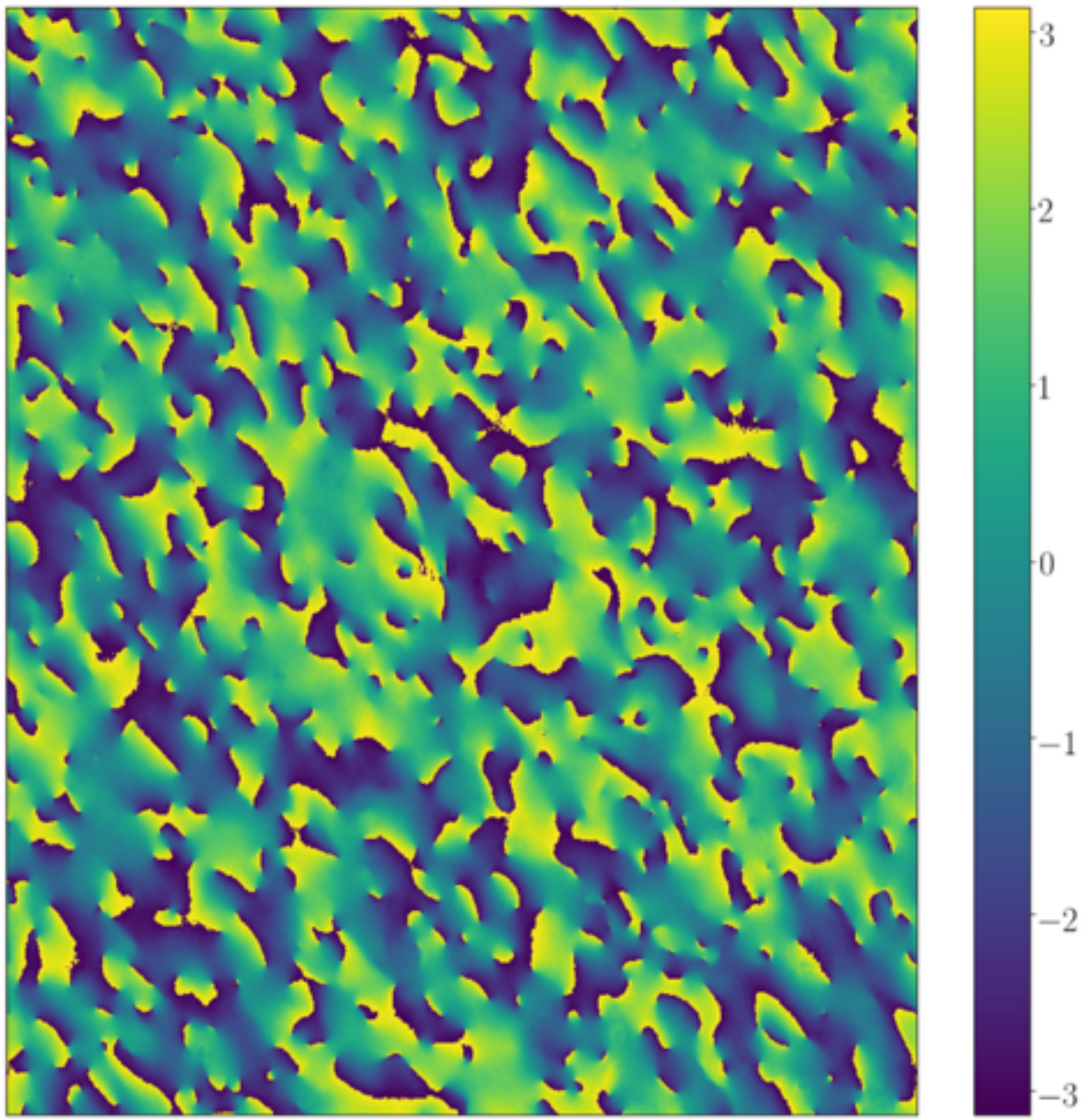
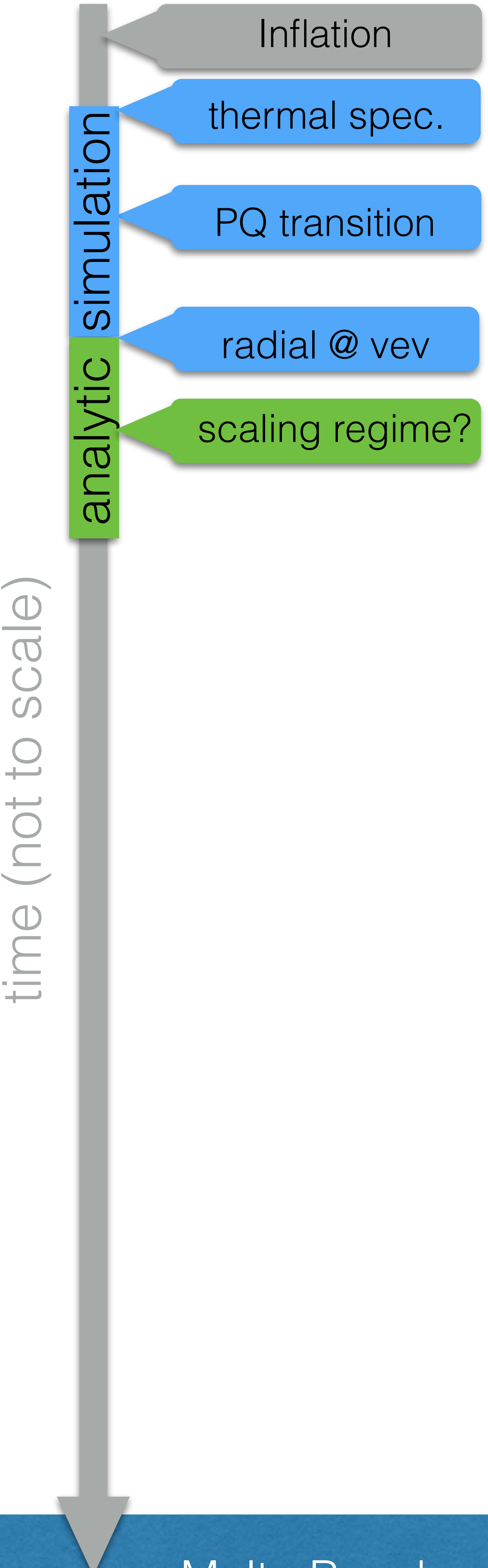




MB, Foster, Safdi (1906:00967)



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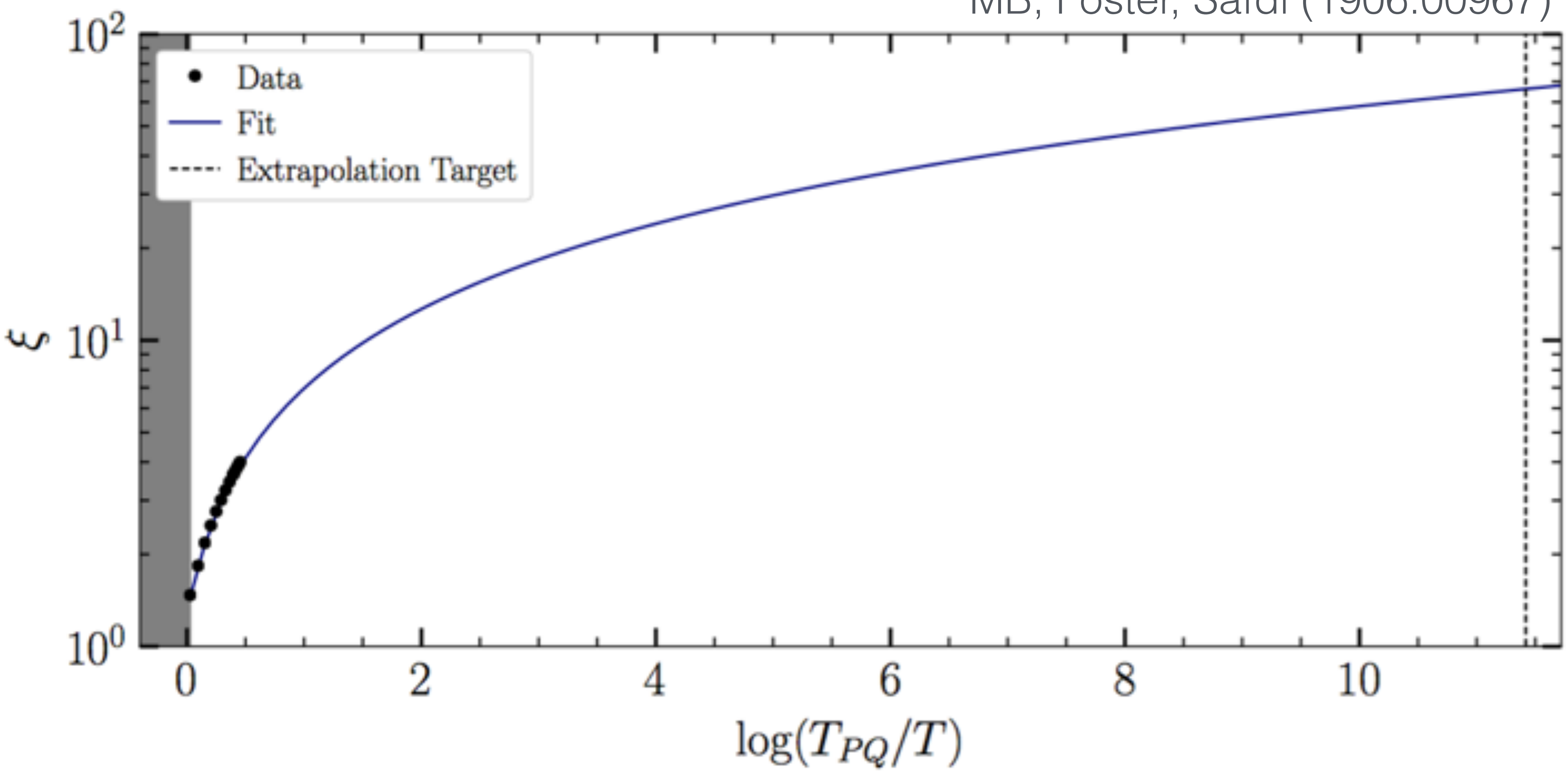
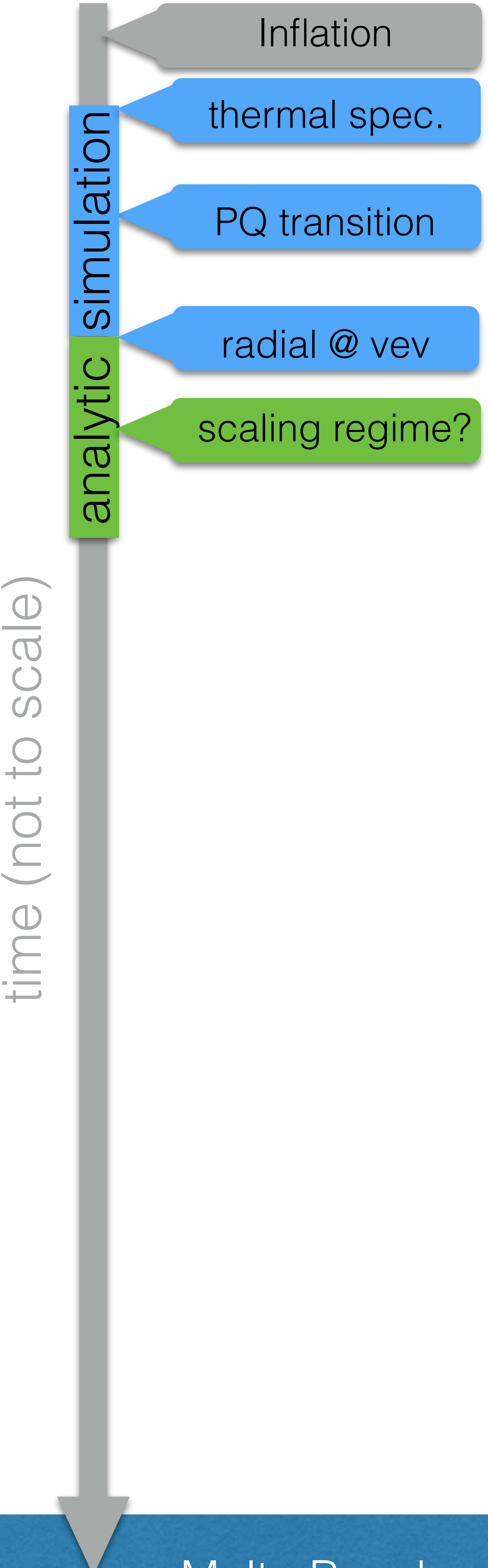


Scaling regime: 1 string per Hubble volume

We see logarithmic deviations from this assumption similar to *M. Gorghetto & G. Villadoro 2018*!

More on this later!



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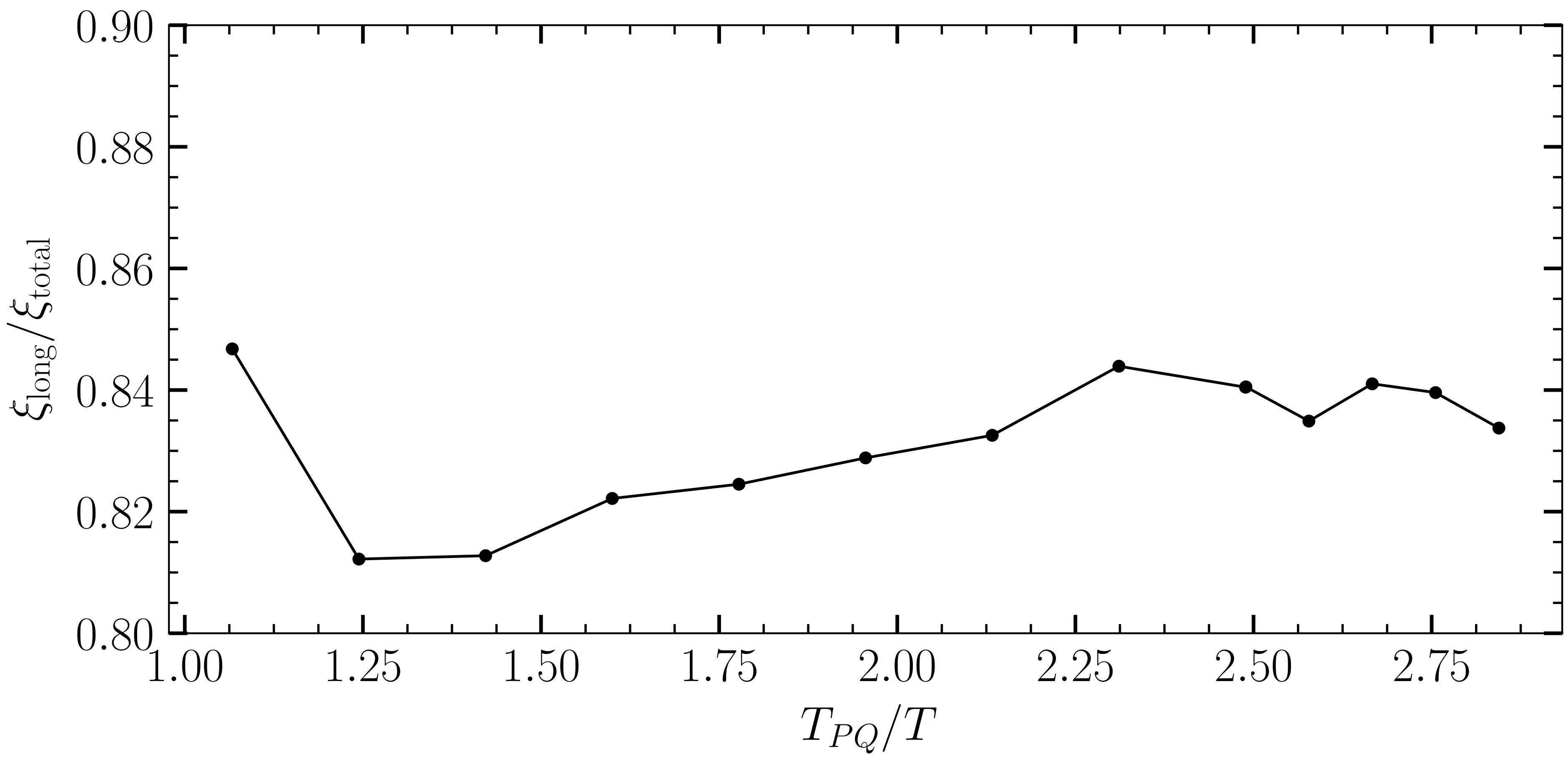

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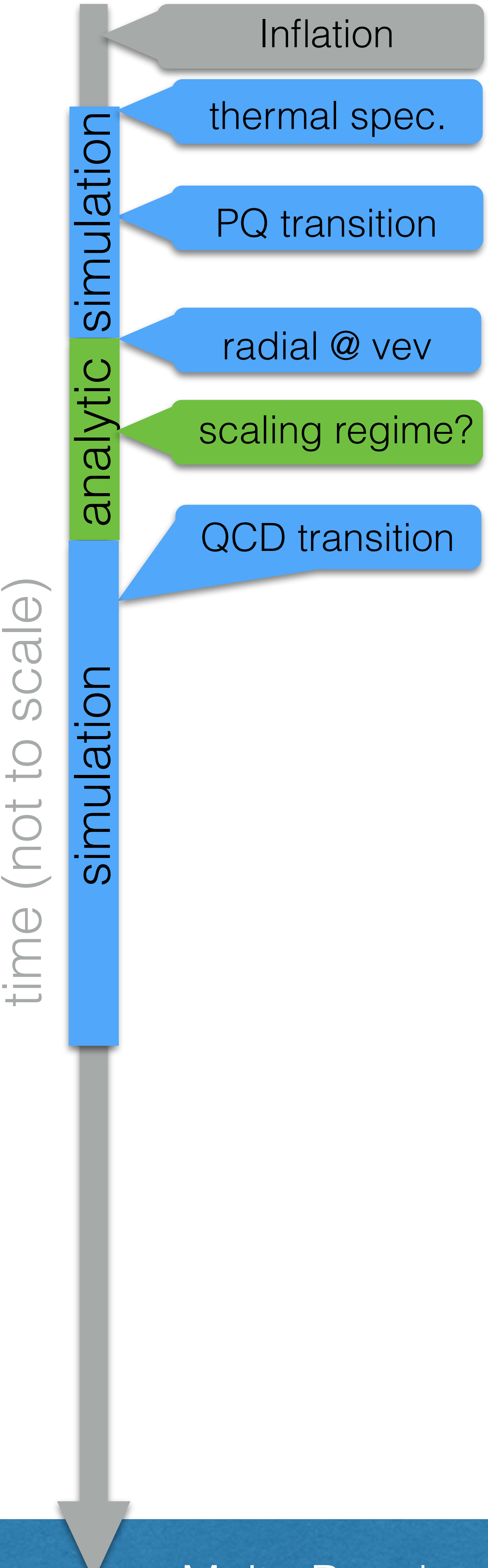
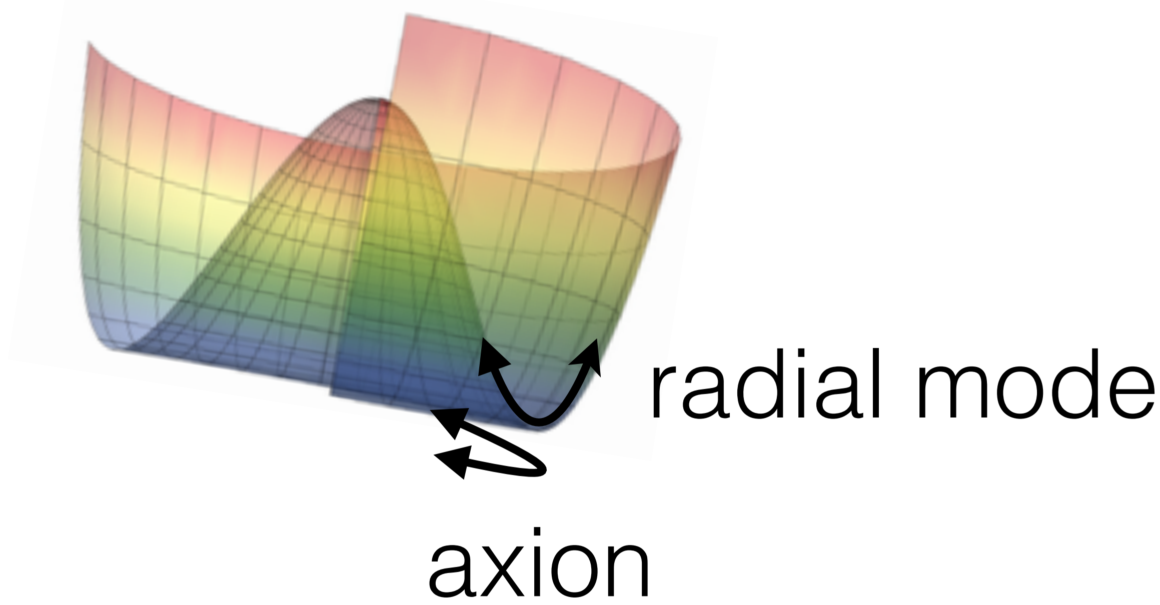
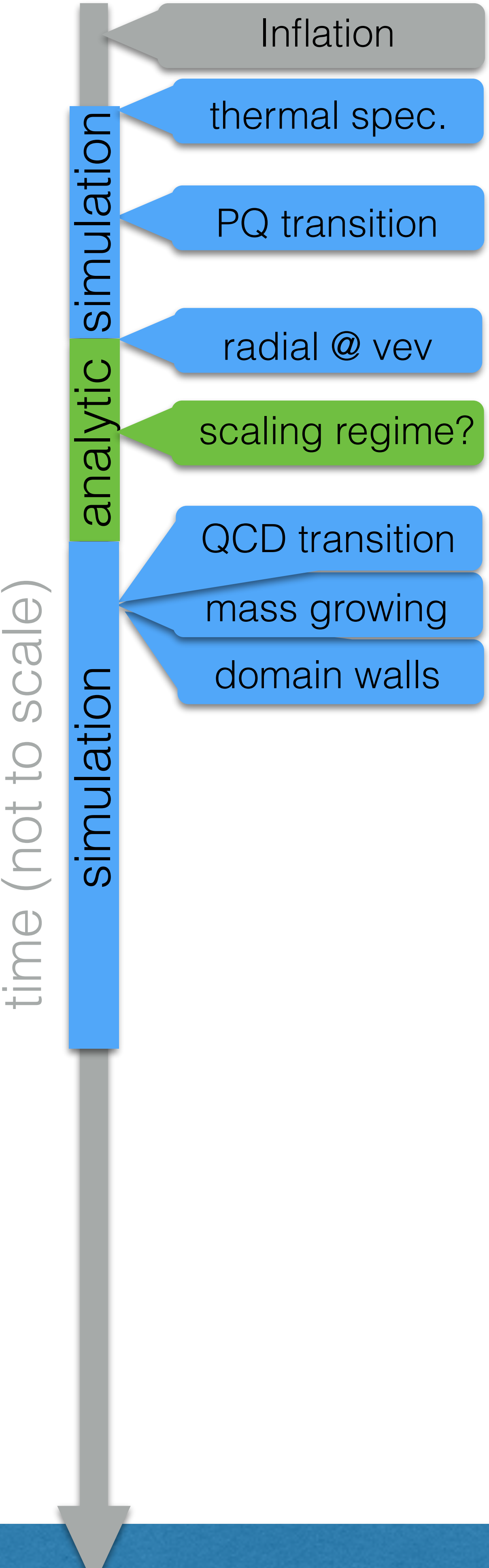


$@ \, T \approx 1 \text{ GeV}$

$$V(\Phi, T) = \frac{\lambda}{4}\left(|\Phi|^2 - f_a^2\right)^2 + m_a(T)^2 f_a^2 \left[1 - \cos \text{Arg}(\Phi)\right]$$





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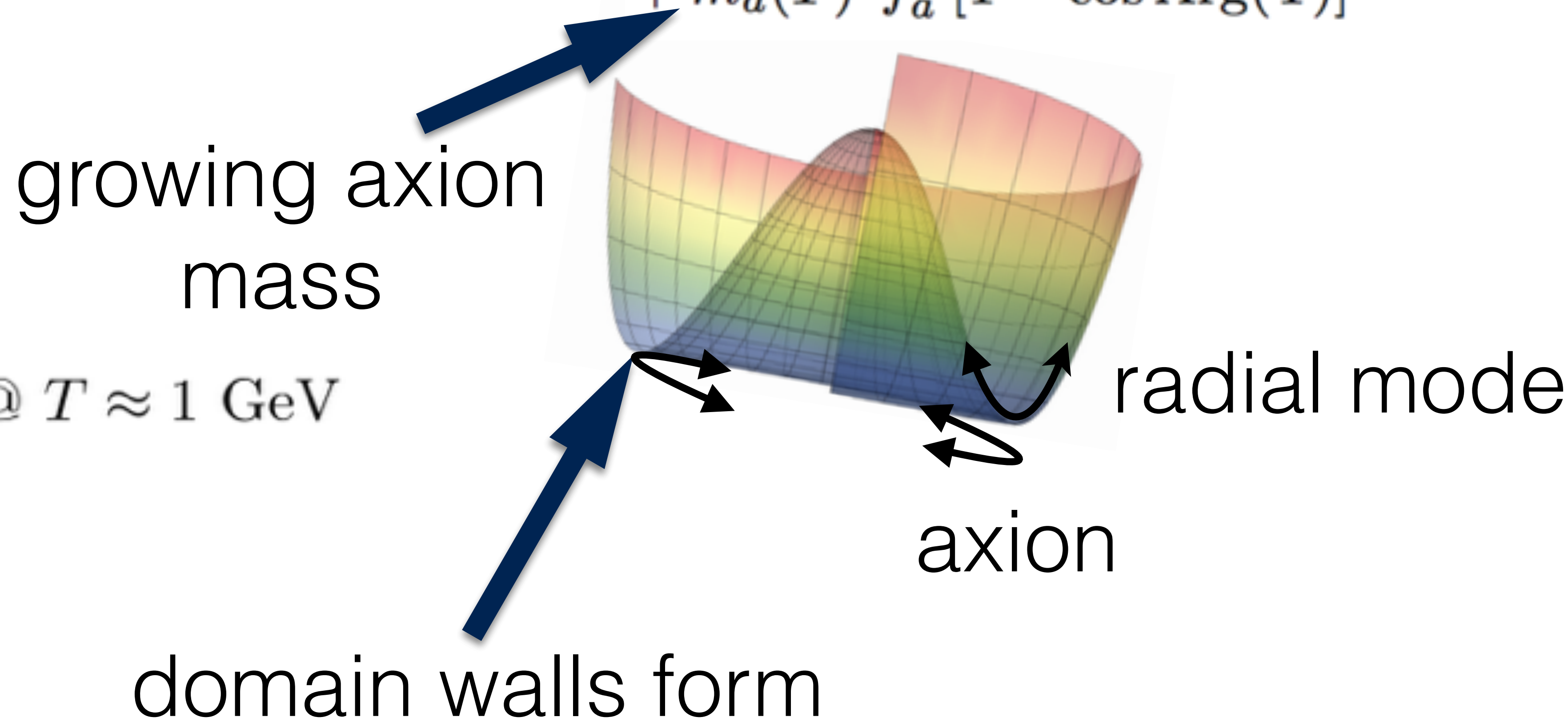

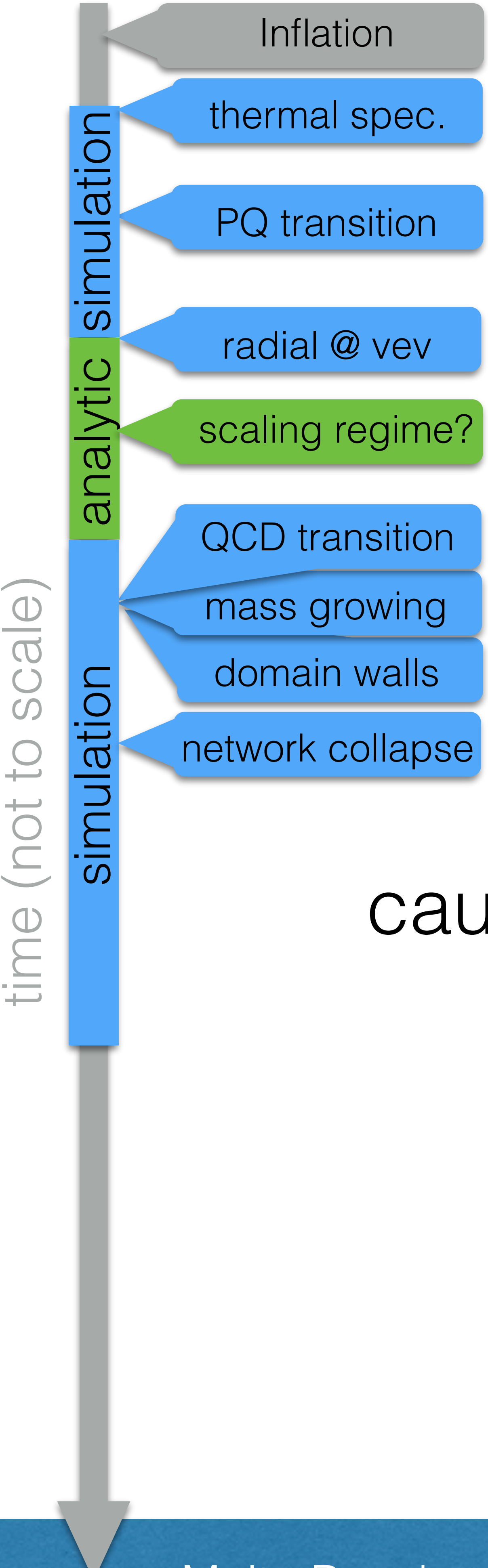

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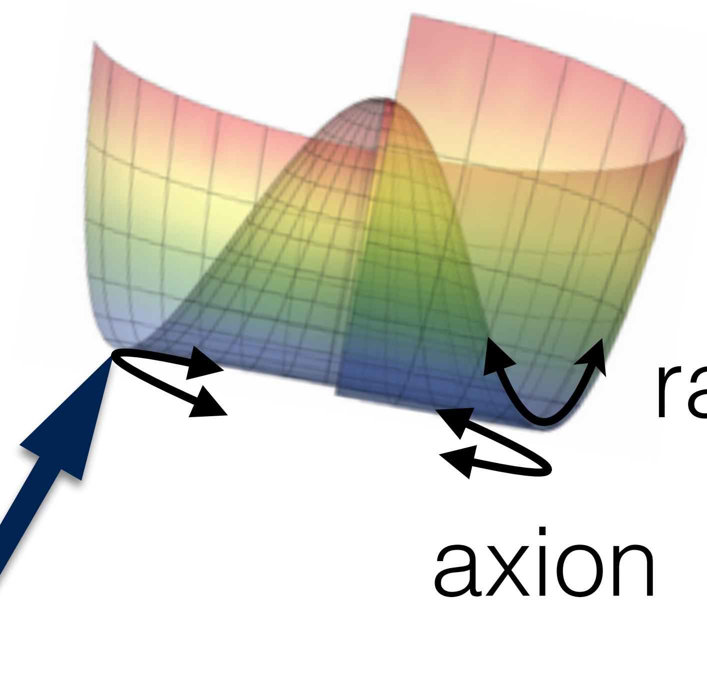
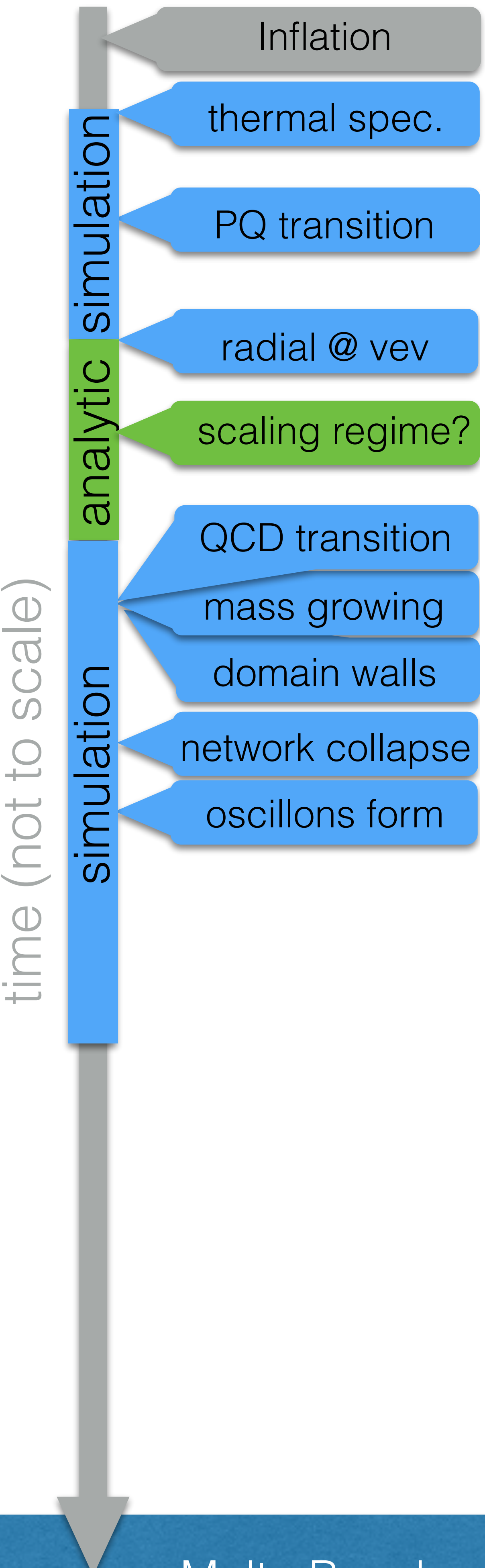
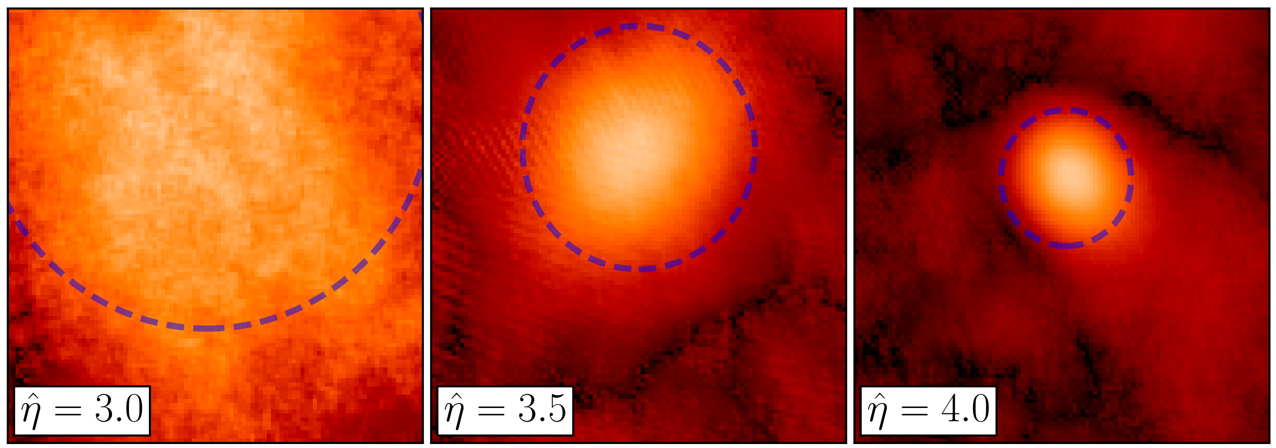


tension in domain walls
causes string-domain wall network
to collapse



Evolution of Oscillons

MB, Foster, Safdi (1906:00967)



Facts about Oscillons:

1. They are regions with large field values/large energy density
2. Their size is given by the axion wavelength ~ inverse $m_a(T)$
3. They remain stable as long as $m_a(T)$ is increasing
4. Start to dilute once the axion reaches its zero-temperature mass

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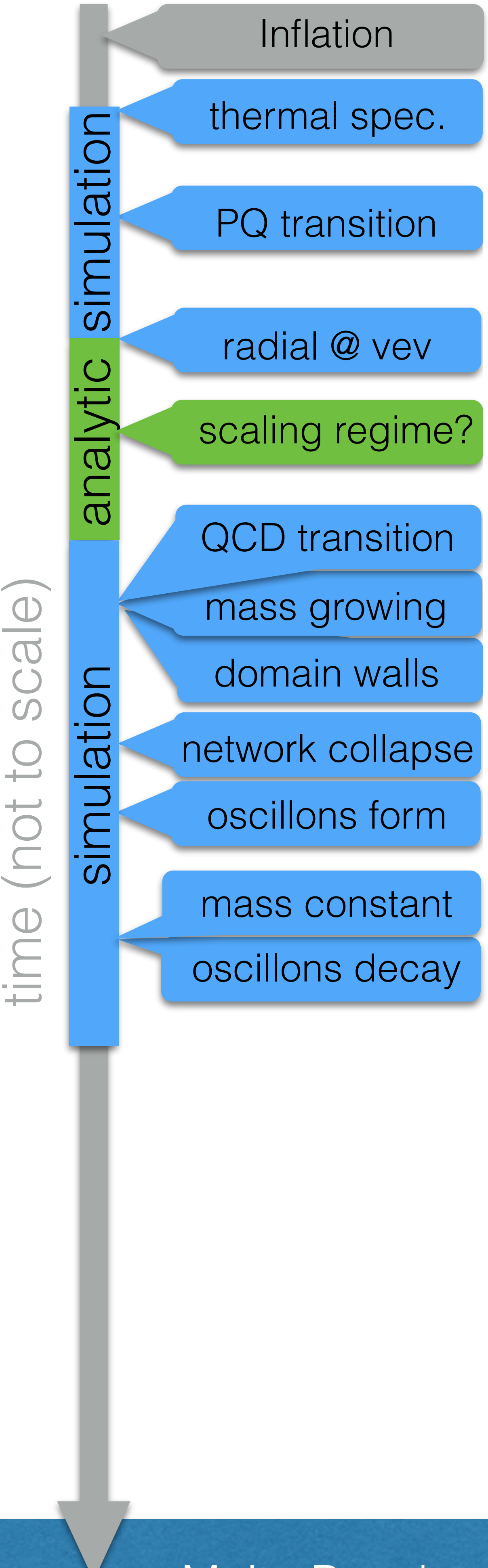

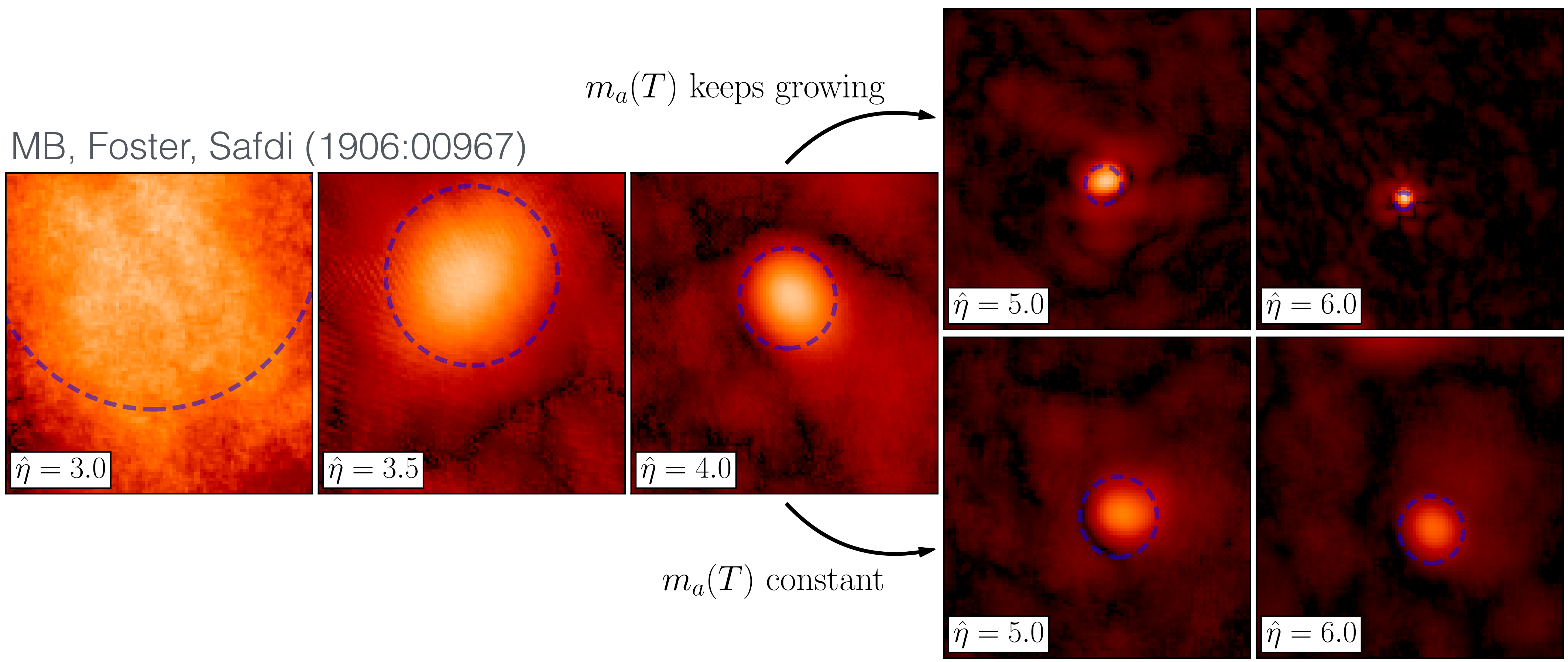

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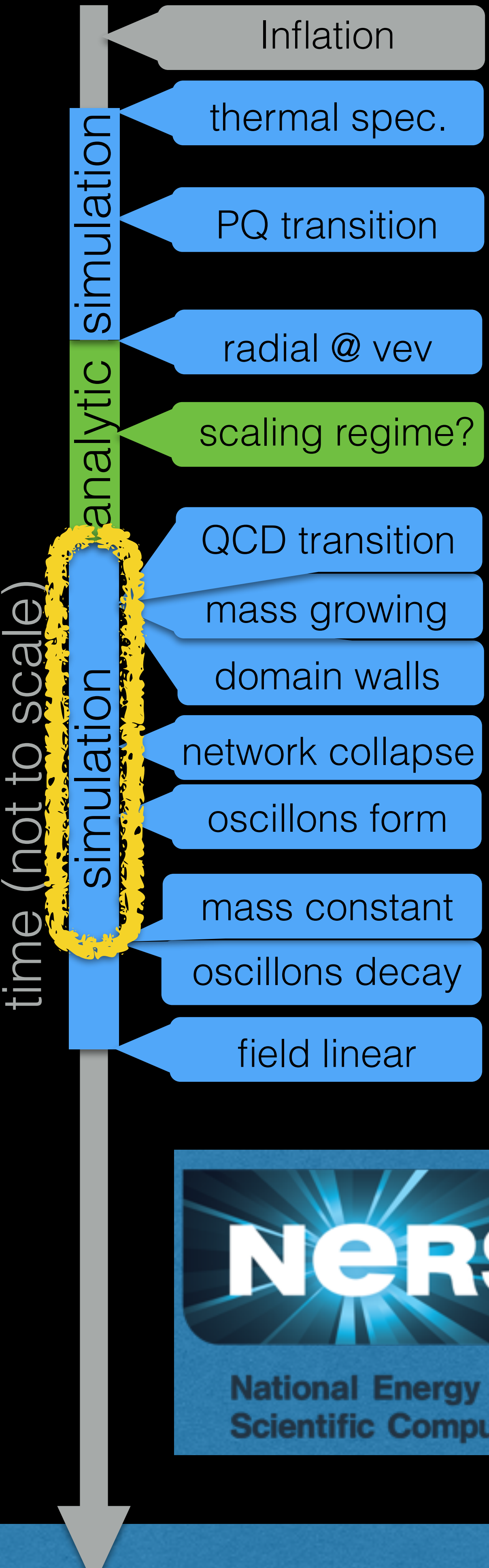

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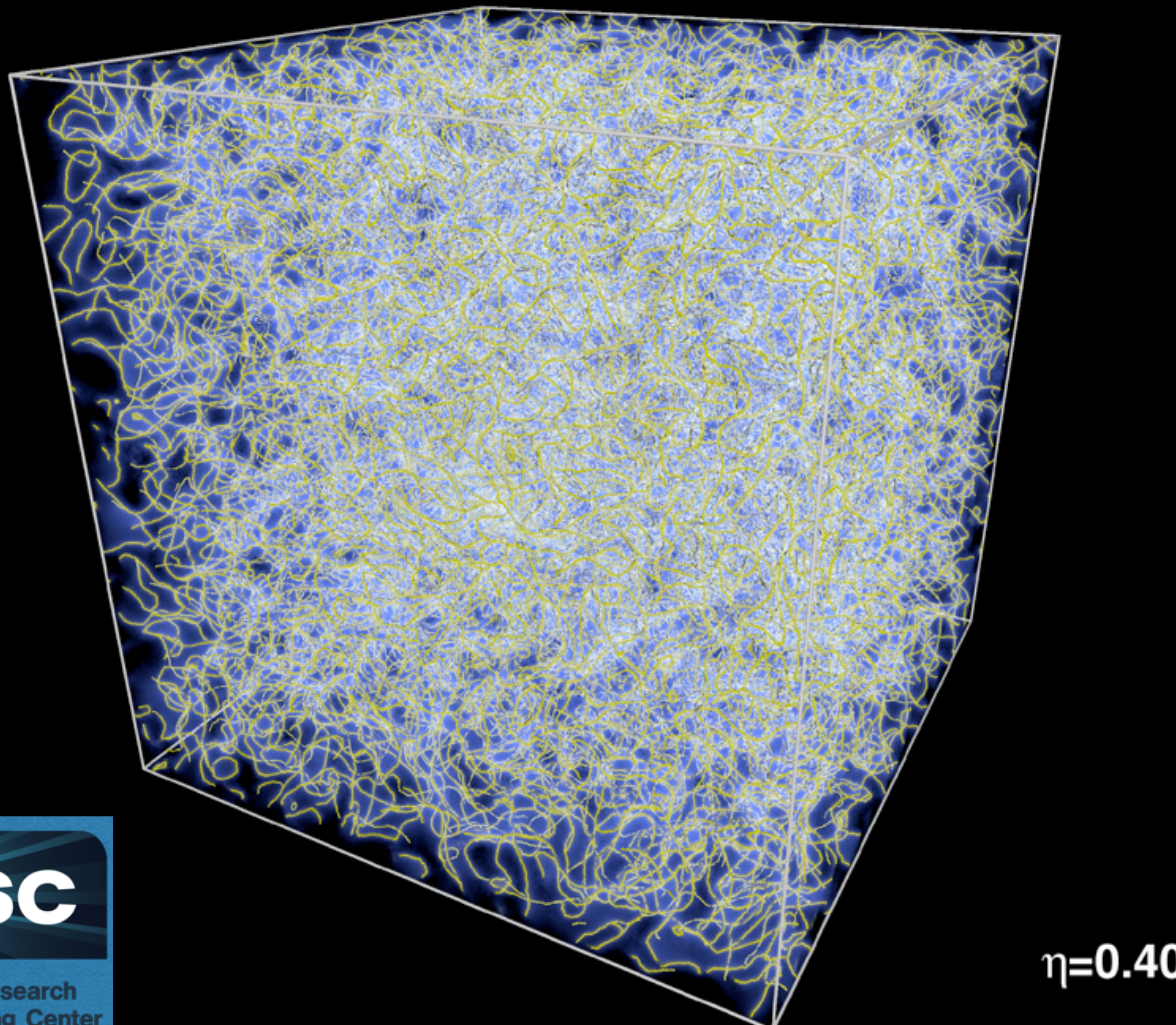
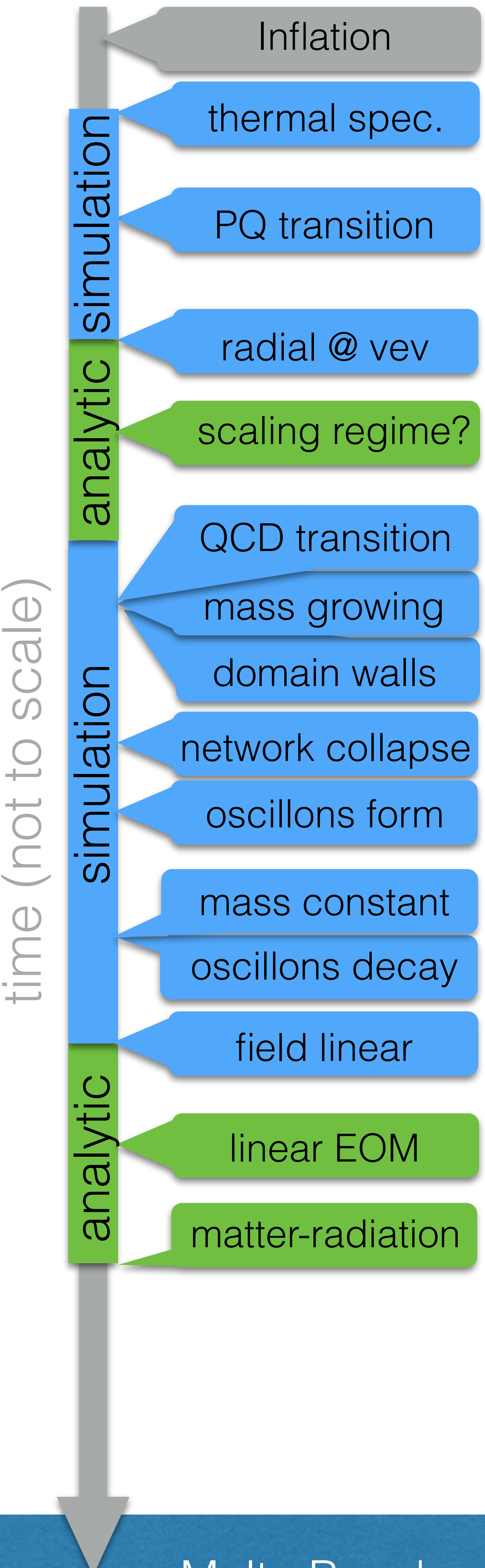


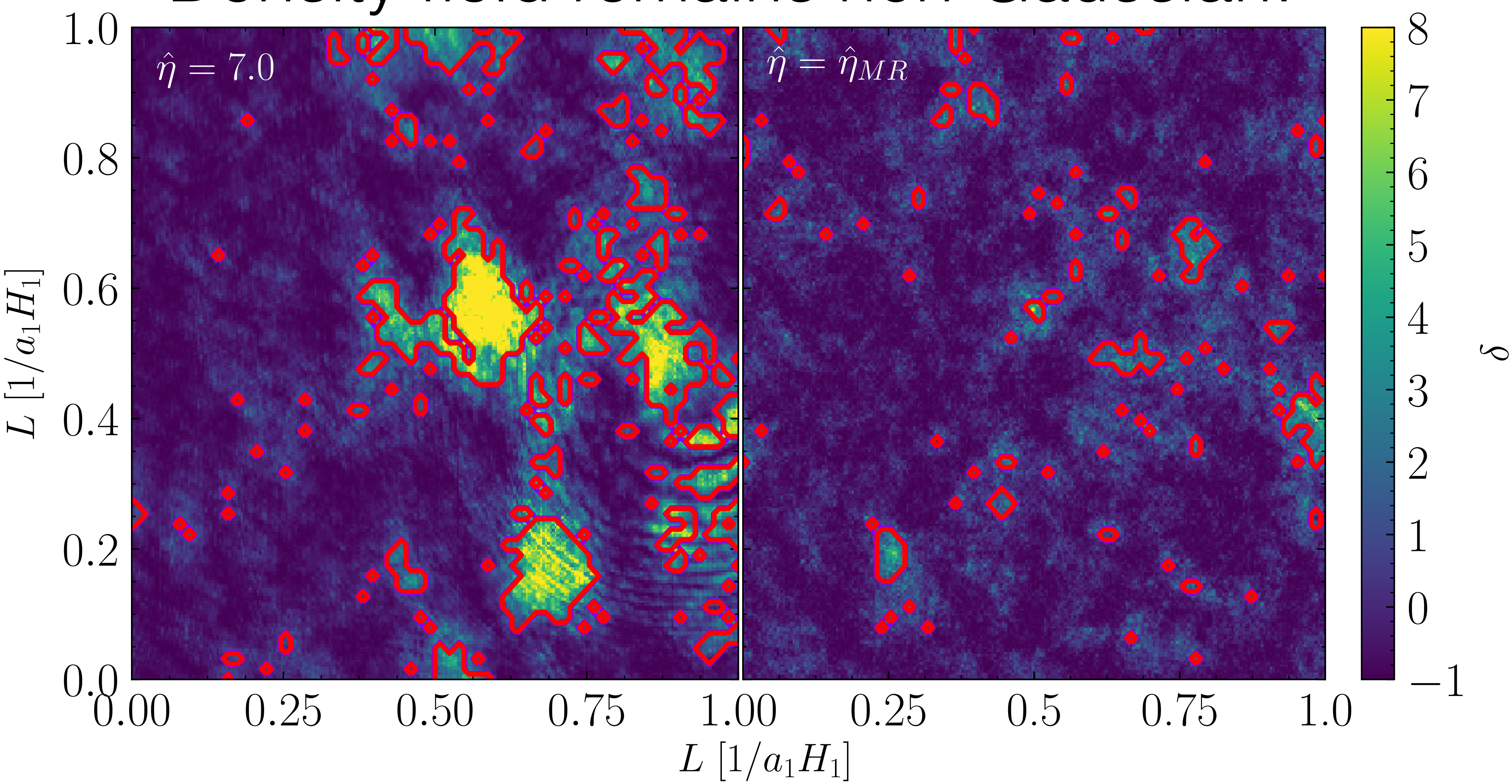
https://youtu.be/1By1DMq1EpI



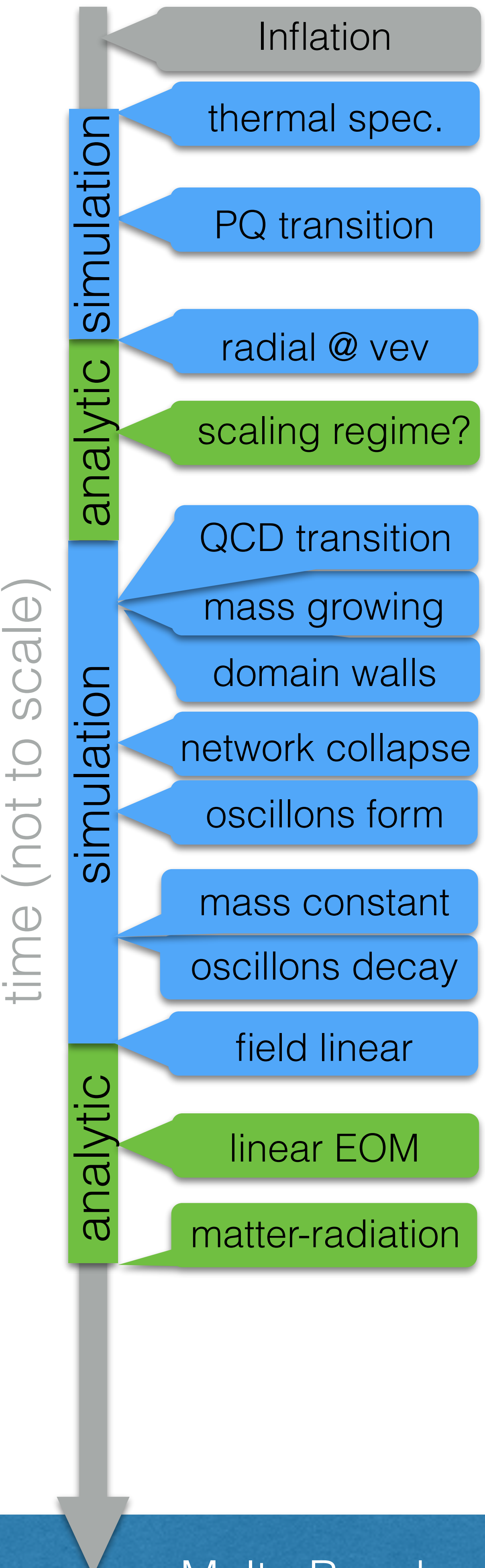
After the simulation ends:

1. Analytic evolution to matter-radiation equality
2. Identify over-dense regions $\delta = (\rho - \bar{\rho})/\rho$

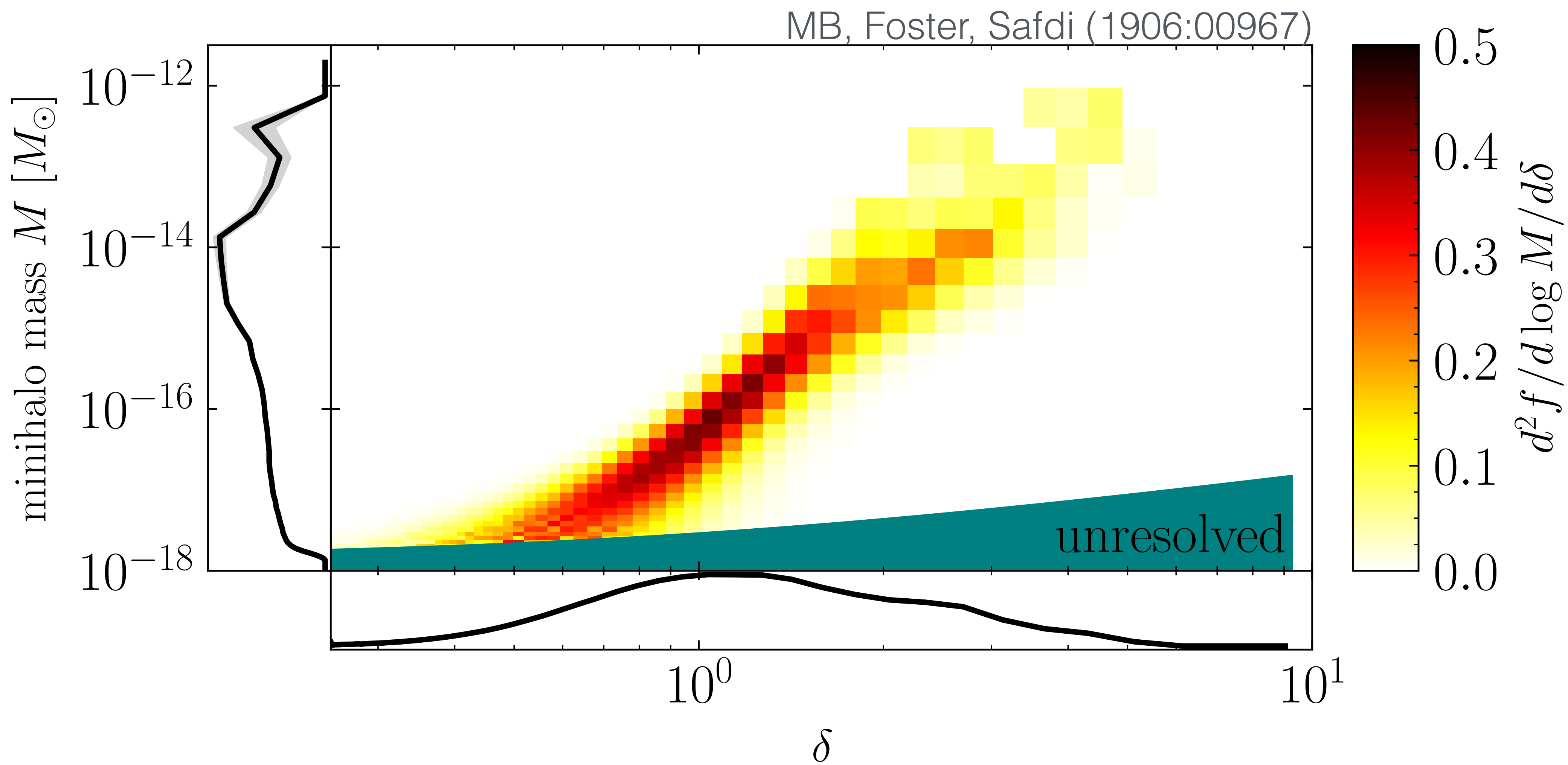
Density field remains non-Gaussian!



Assign each over-density a mass and a concentration parameter δ

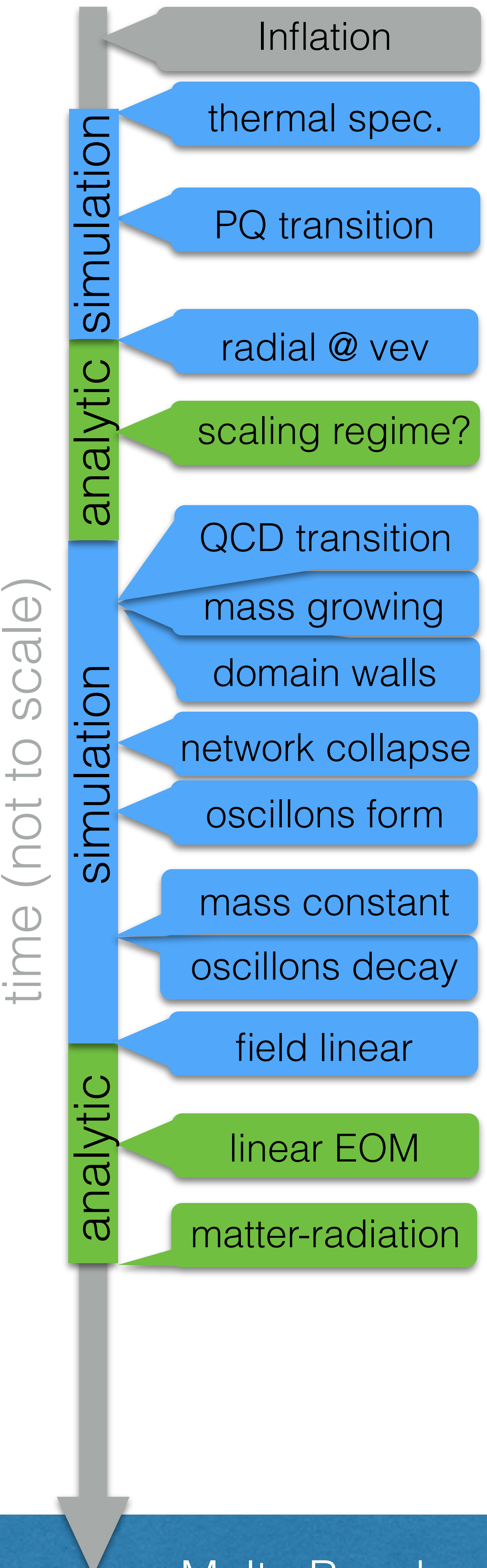


Characterising the minihalo spectrum



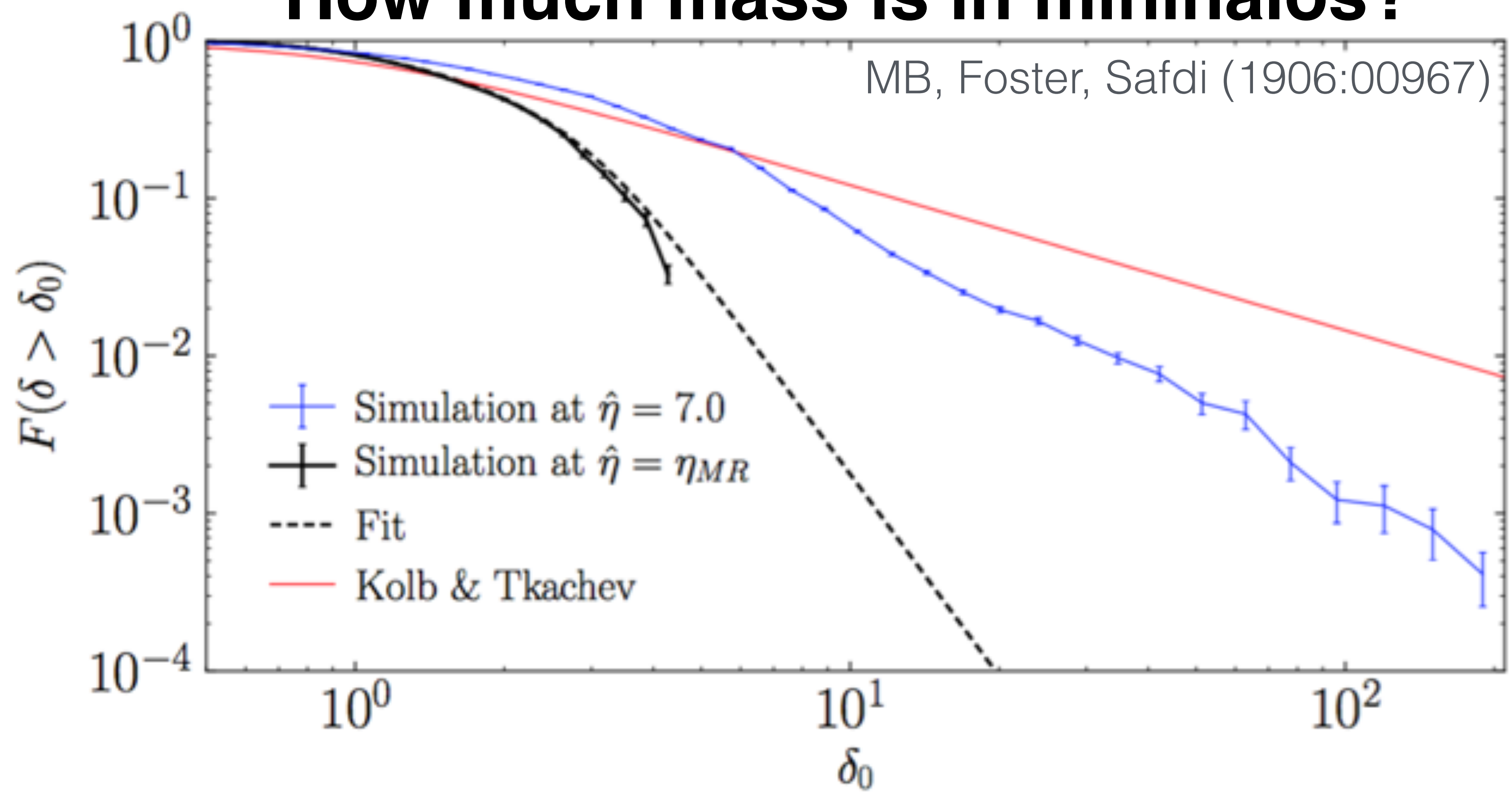
Typical minihalo mass: 10^{-14} solar masses

Important information for:
microlensing, pulsar timing surveys, (in)direct detection, …



Characterising the minihalo spectrum

How much mass is in minihalos?



Kolb & Tkachev in 1994: 100 x 100 x 100 grid
According to Moore's law that corresponds to a 1800 x 1800 x 1800 grid in 2018

This work: 2048 x 2048 x 2048 grid

Important information for:
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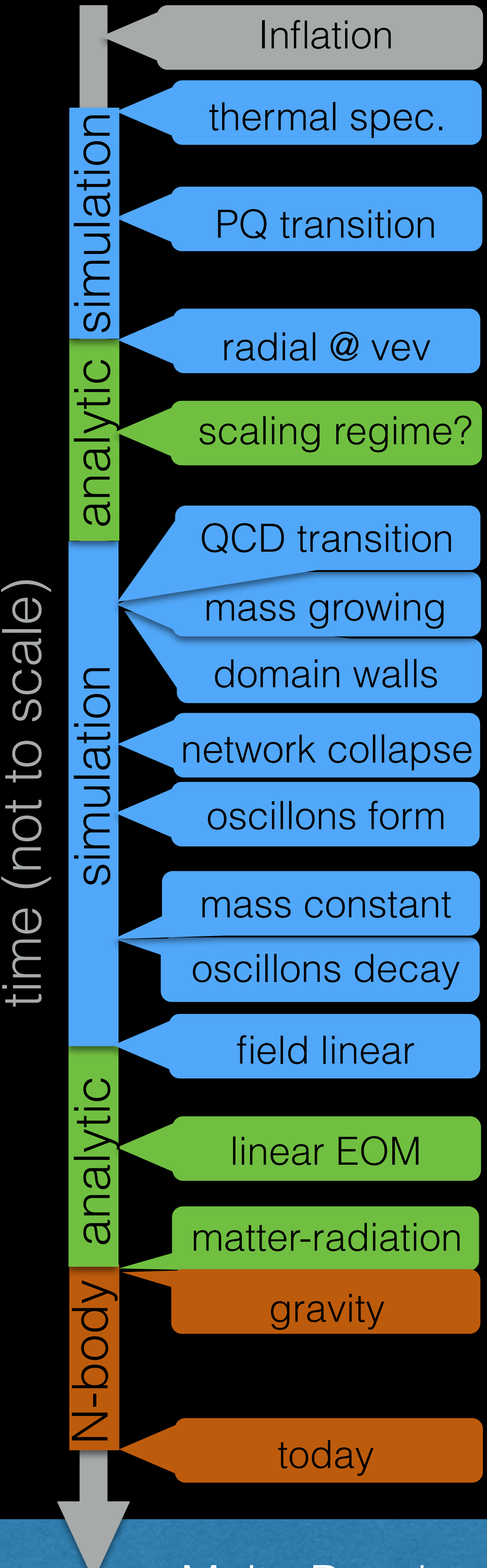
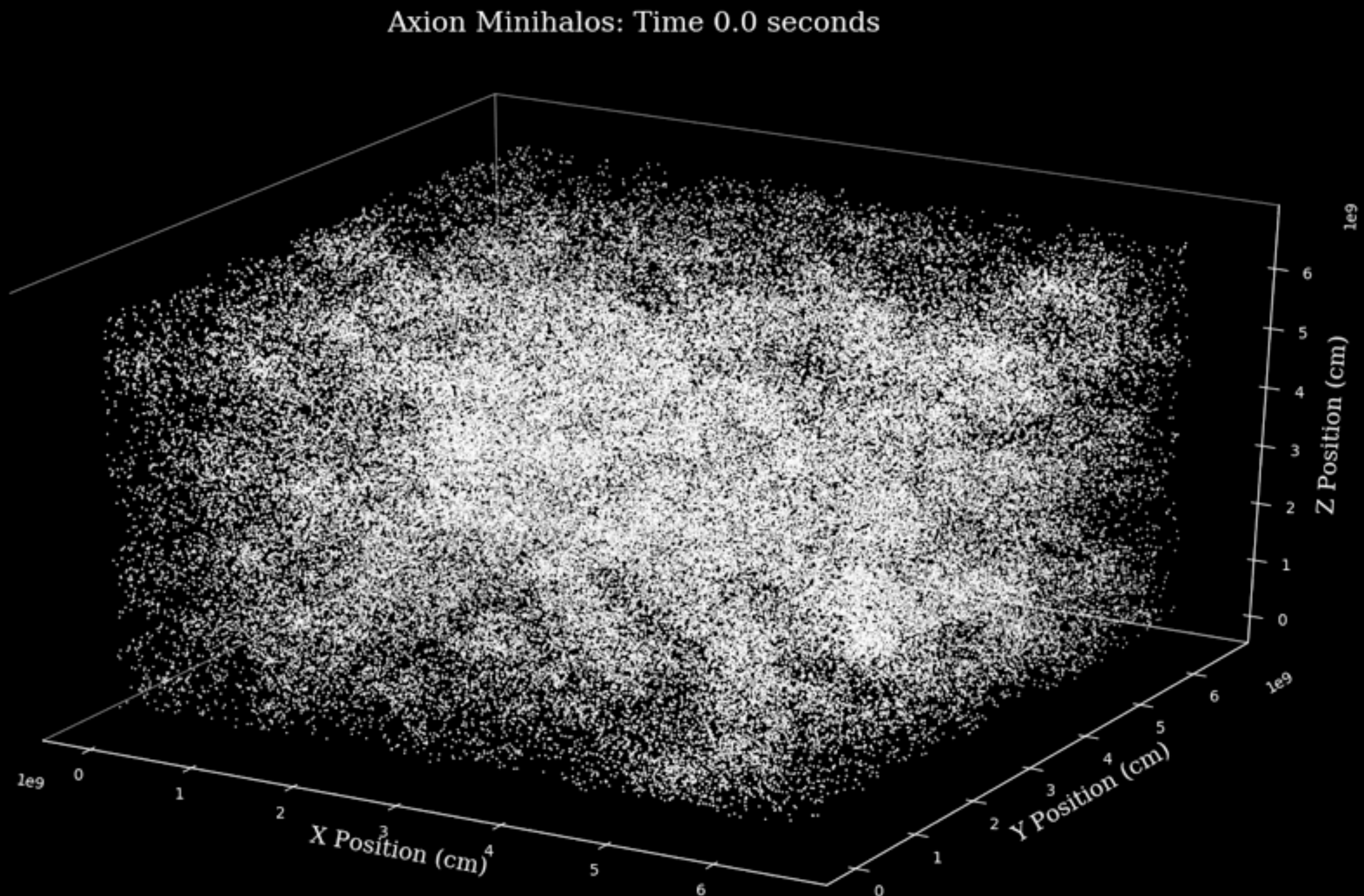
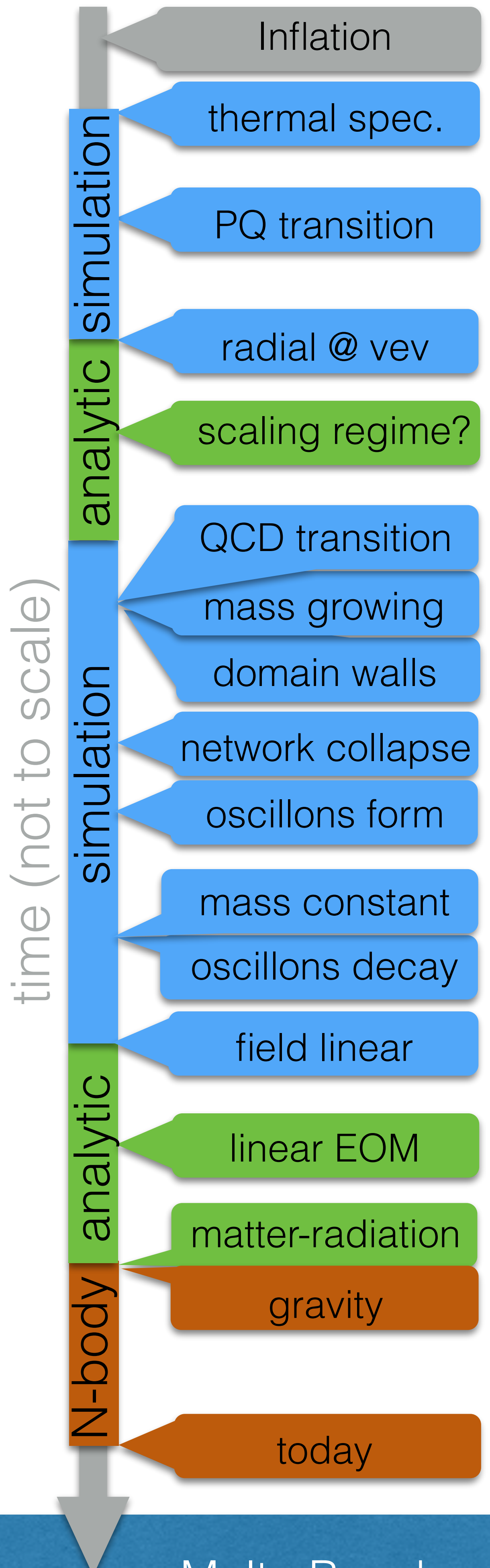


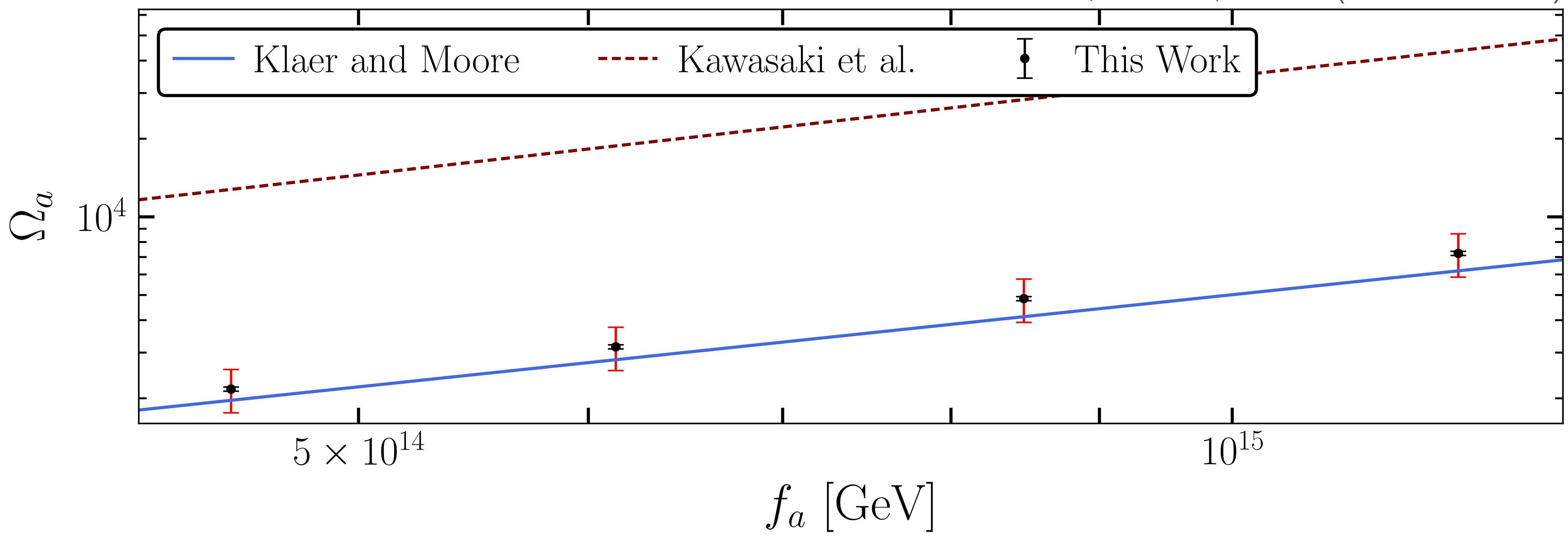


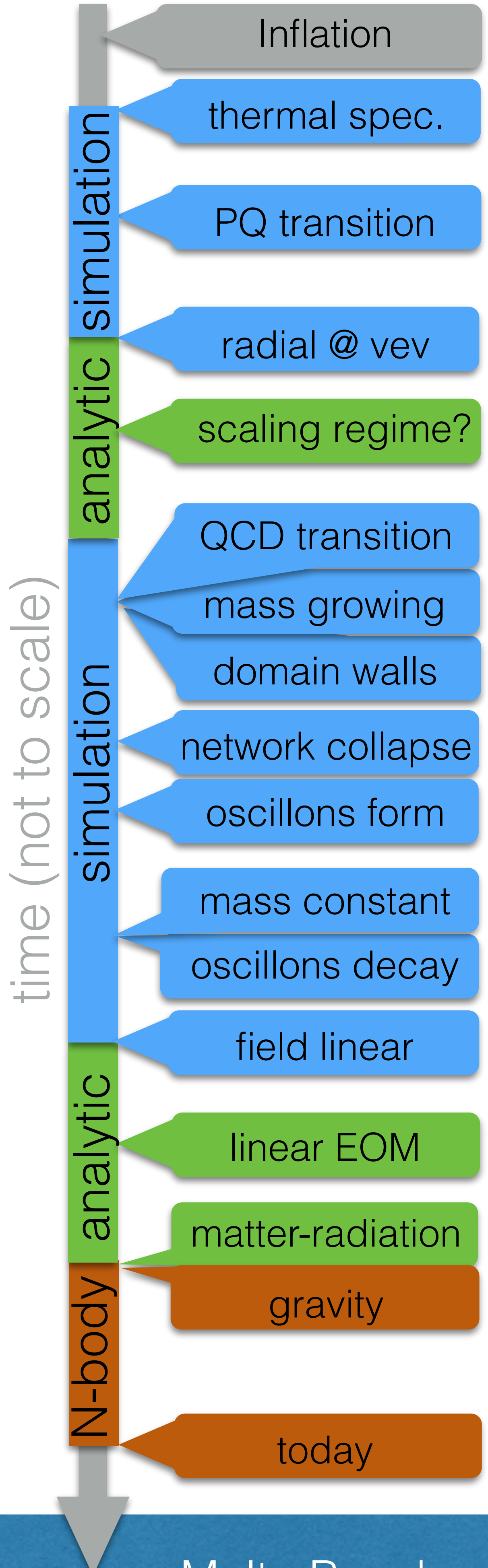
MB, Foster, Safdi, Wentzel (work in progress!)



Obtaining the relic abundance

MB, Foster, Safdi (1906:00967)





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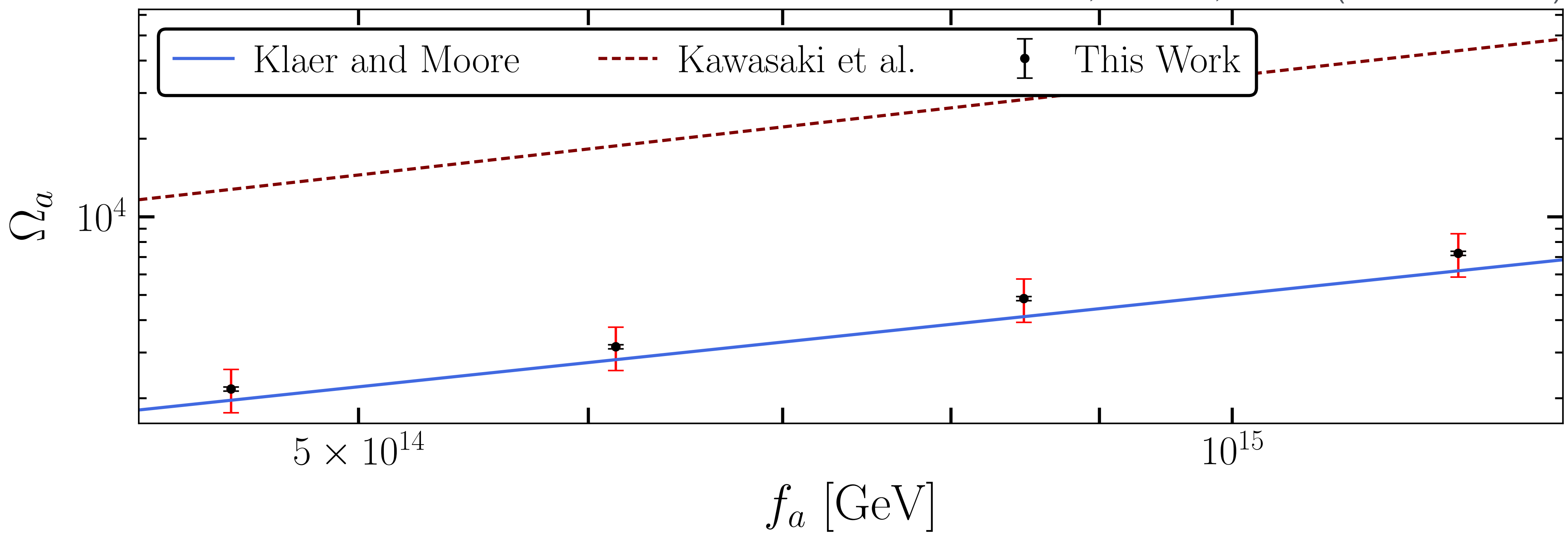
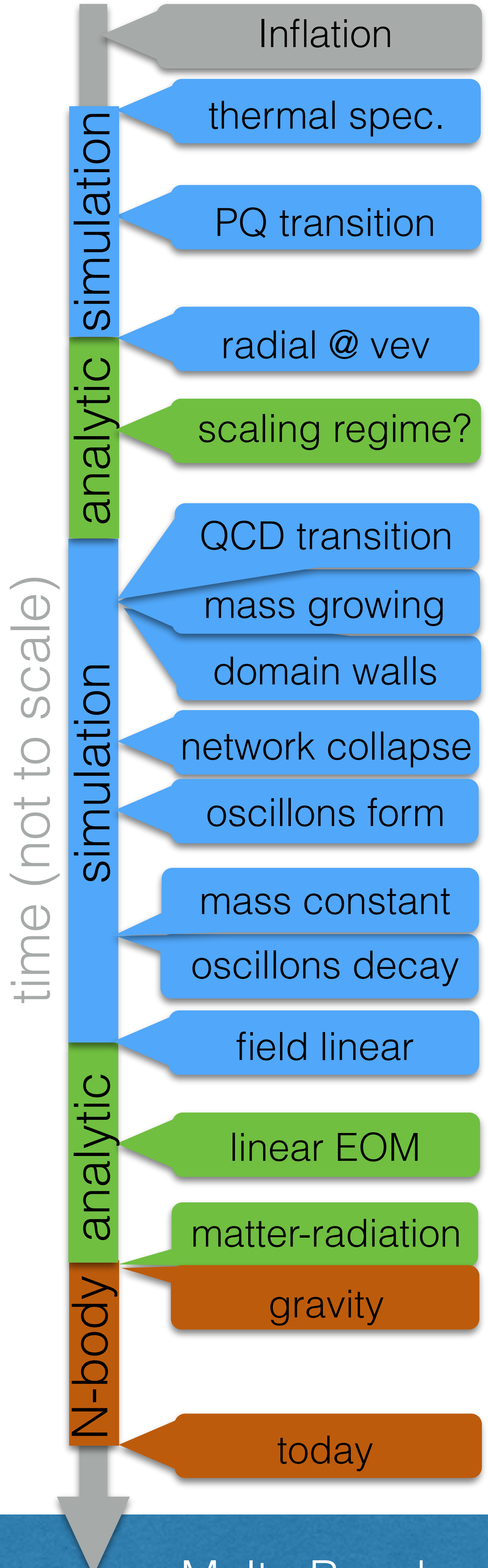


Correct relic abundance reached for:

$$m_a = 25.2 \pm 11.0\ \mu\text{eV}$$



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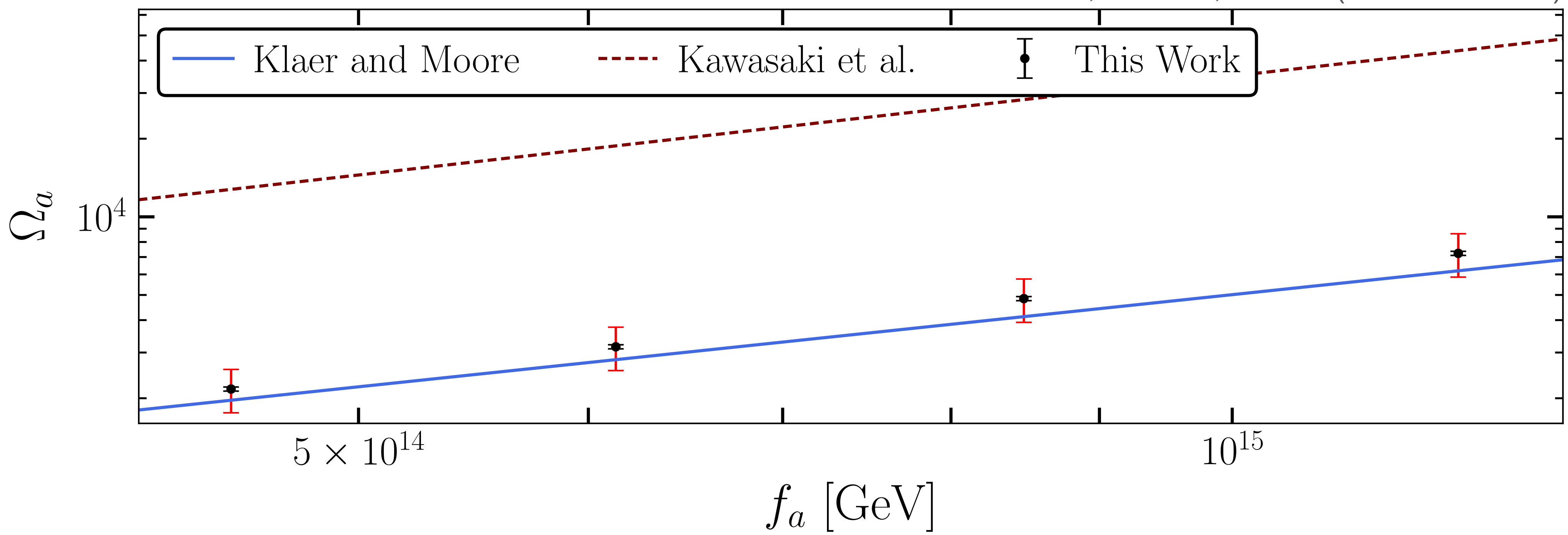

Correct relic abundance reached for:

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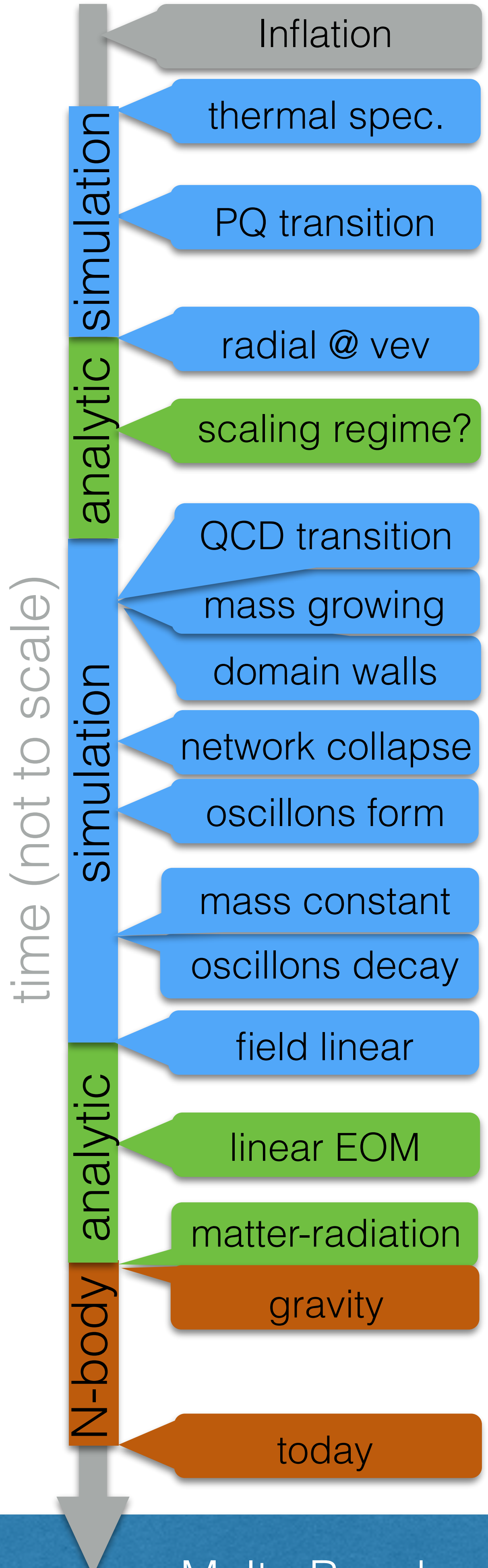
Uncertainties coming from:

31% uncertainty on the relation between abundance and f_a

27% uncertainty from mass growth $m_a(T)$

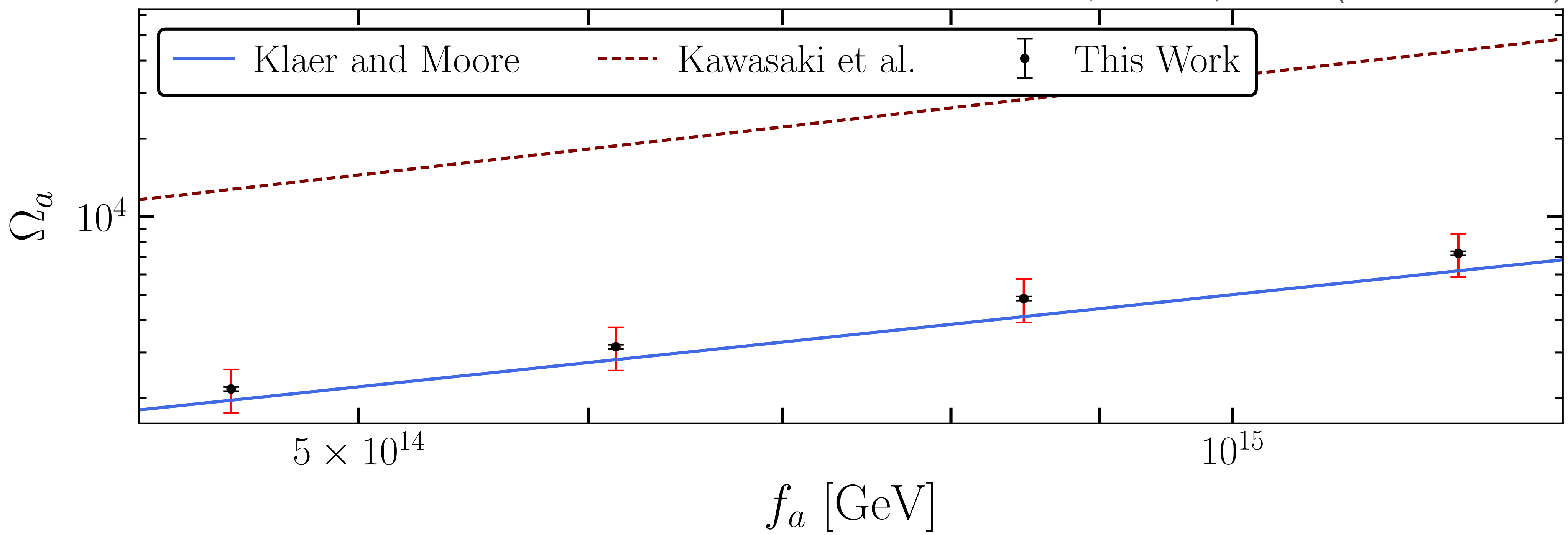
15% from violation of scaling regime

~10% others: statistical, fixed degrees of freedom,…



Sources of Uncertainties on the Axion Mass

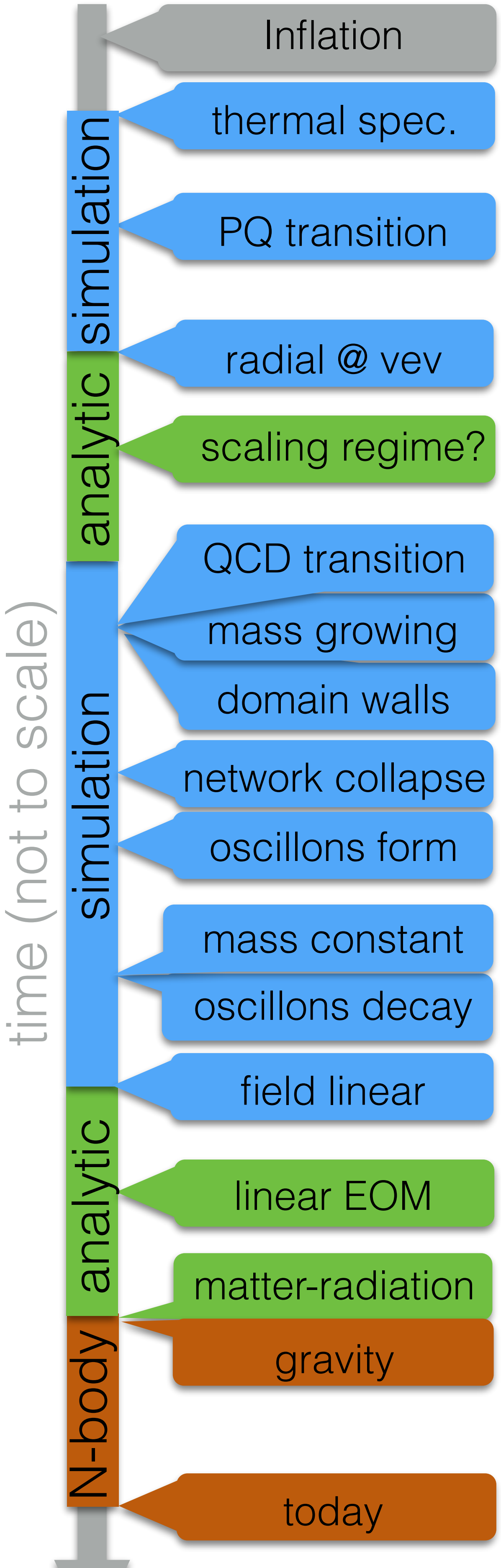
MB, Foster, Safdi (1906:00967)



In particular oscillons make it impossible to simulate at low breaking scales. Extrapolations needed:

$$\rho_a \propto f_a^{(6+n)/(4+n)}$$

with n=6.68 from lattice simulations



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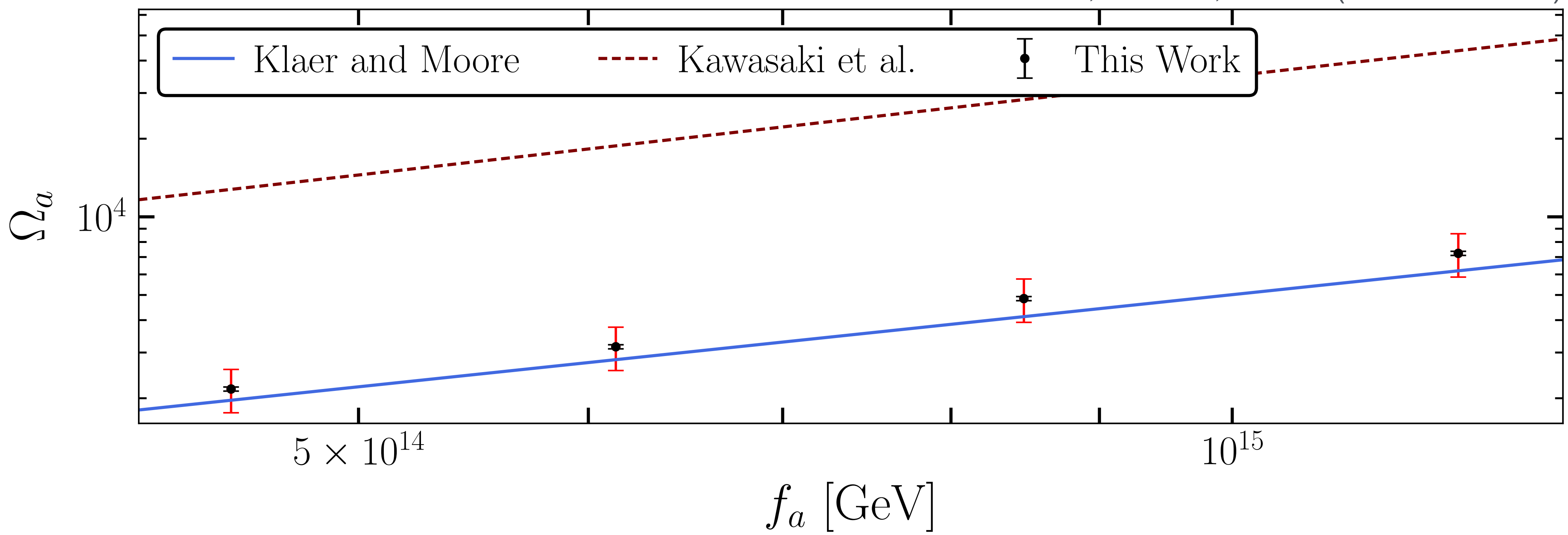

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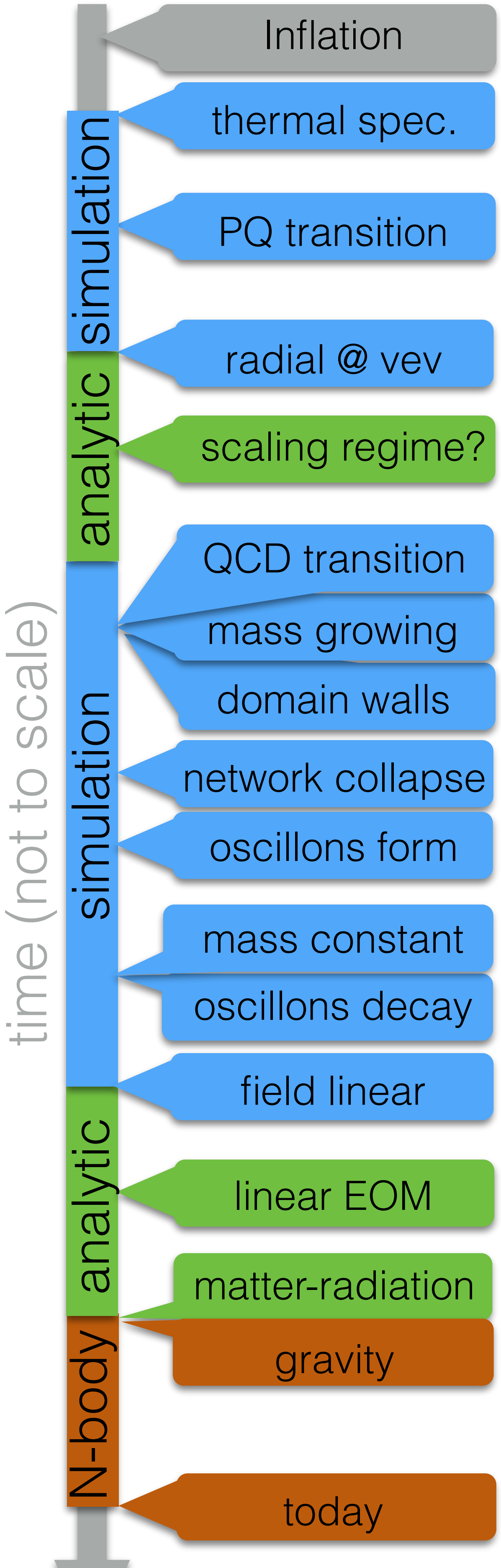
Expected: $\alpha = (n+6)/(n+4) \approx 1.187$

Simulation: $\alpha = 1.24 \pm 0.04$

Leads to 31% uncertainty on axion mass



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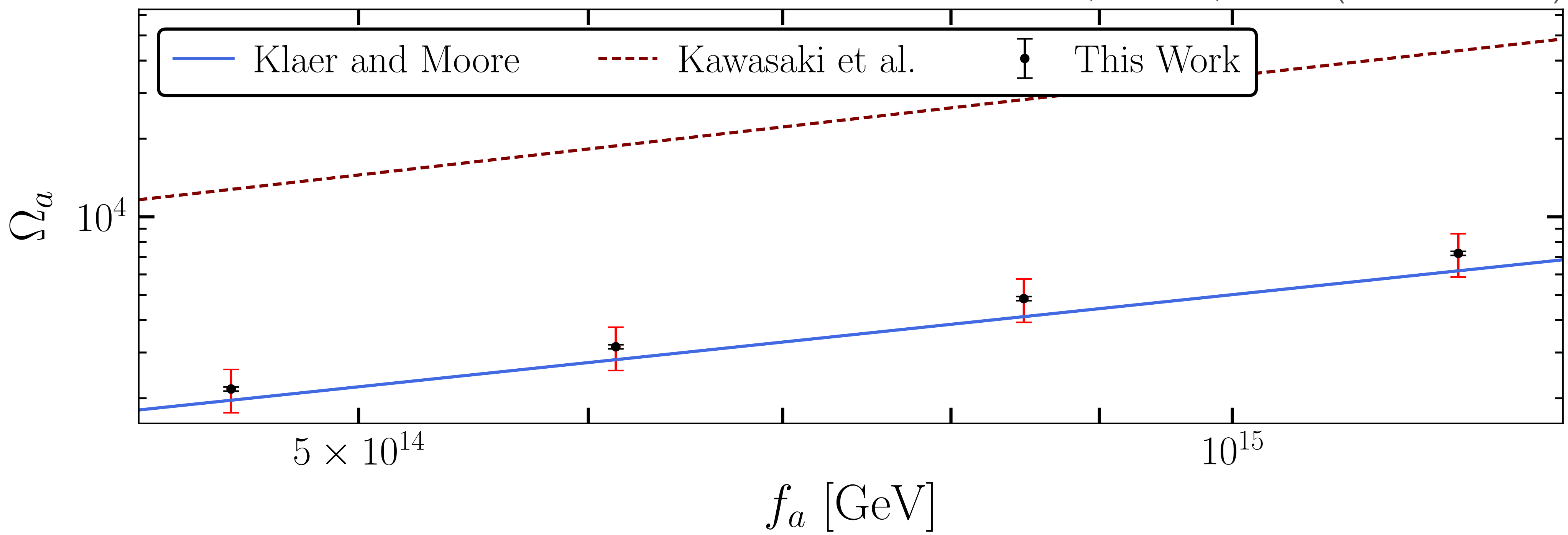

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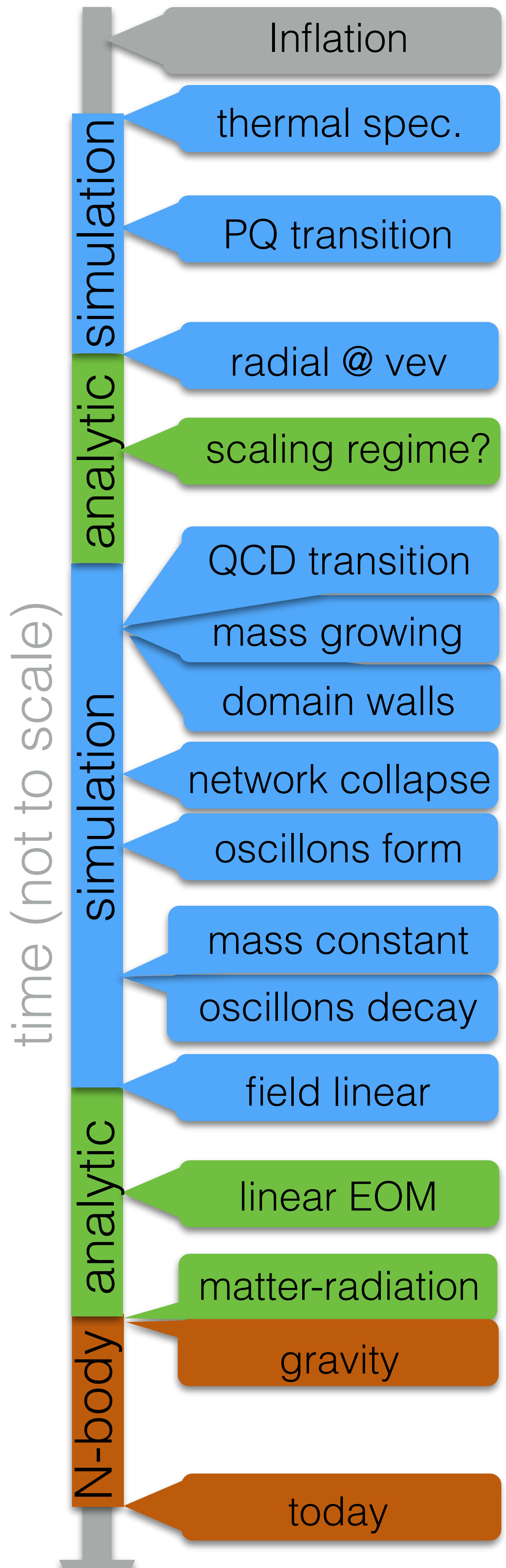
Could be as high as 8.2!
We rerun simulation with 8.2 (in 2D)

Leads to 27% uncertainty on axion mass



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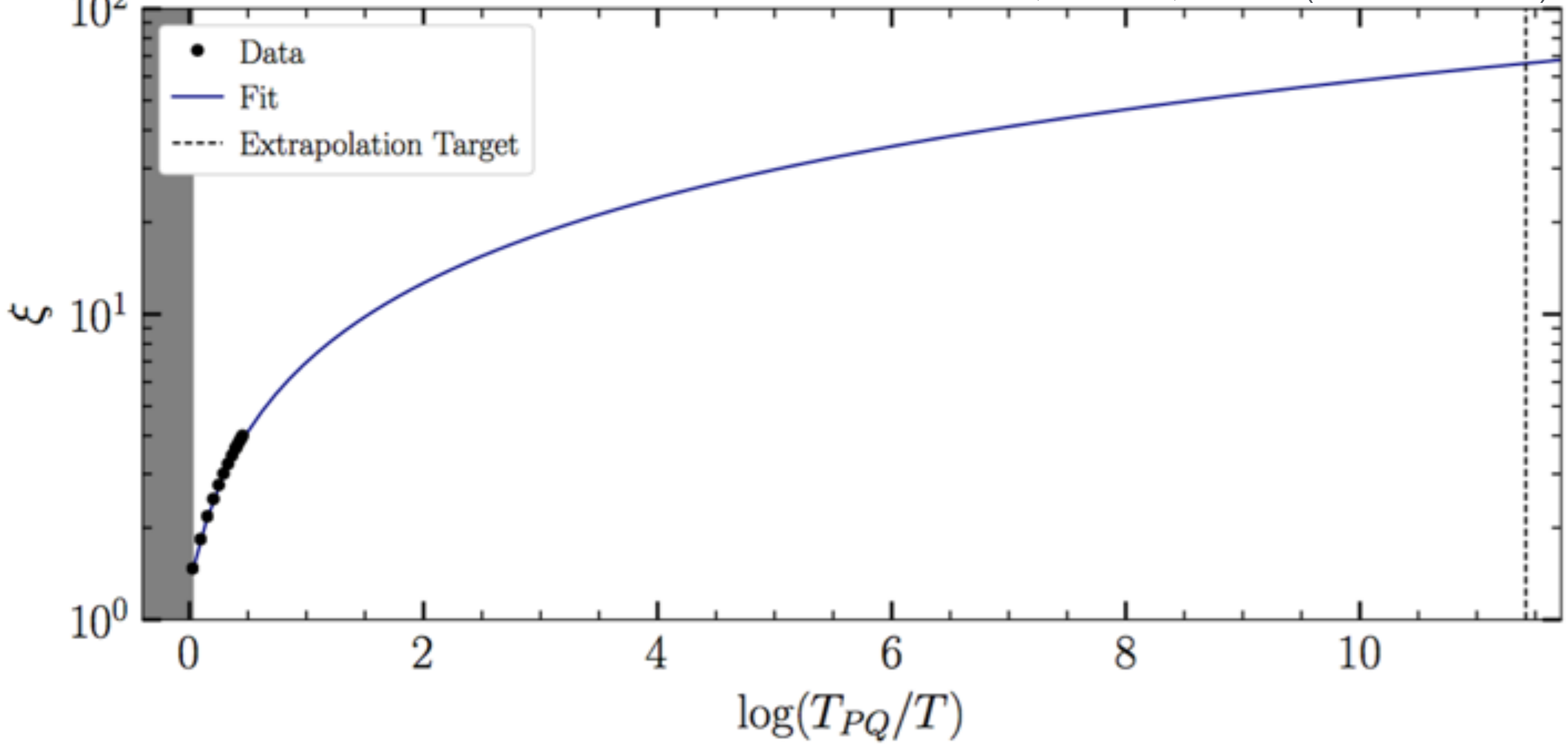
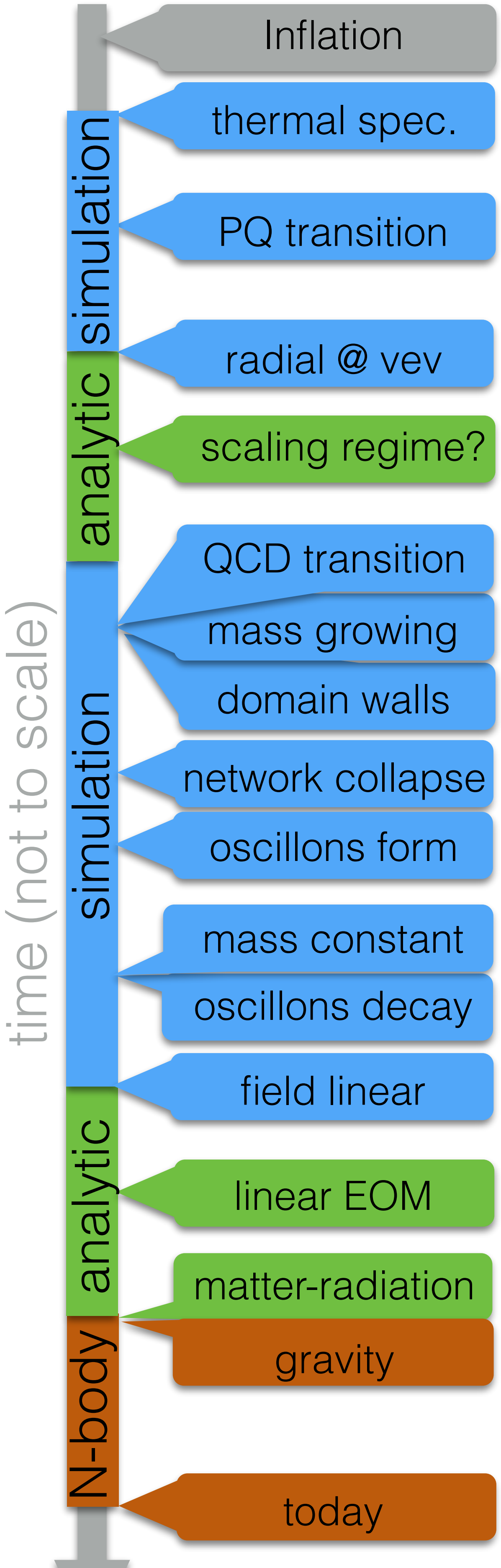


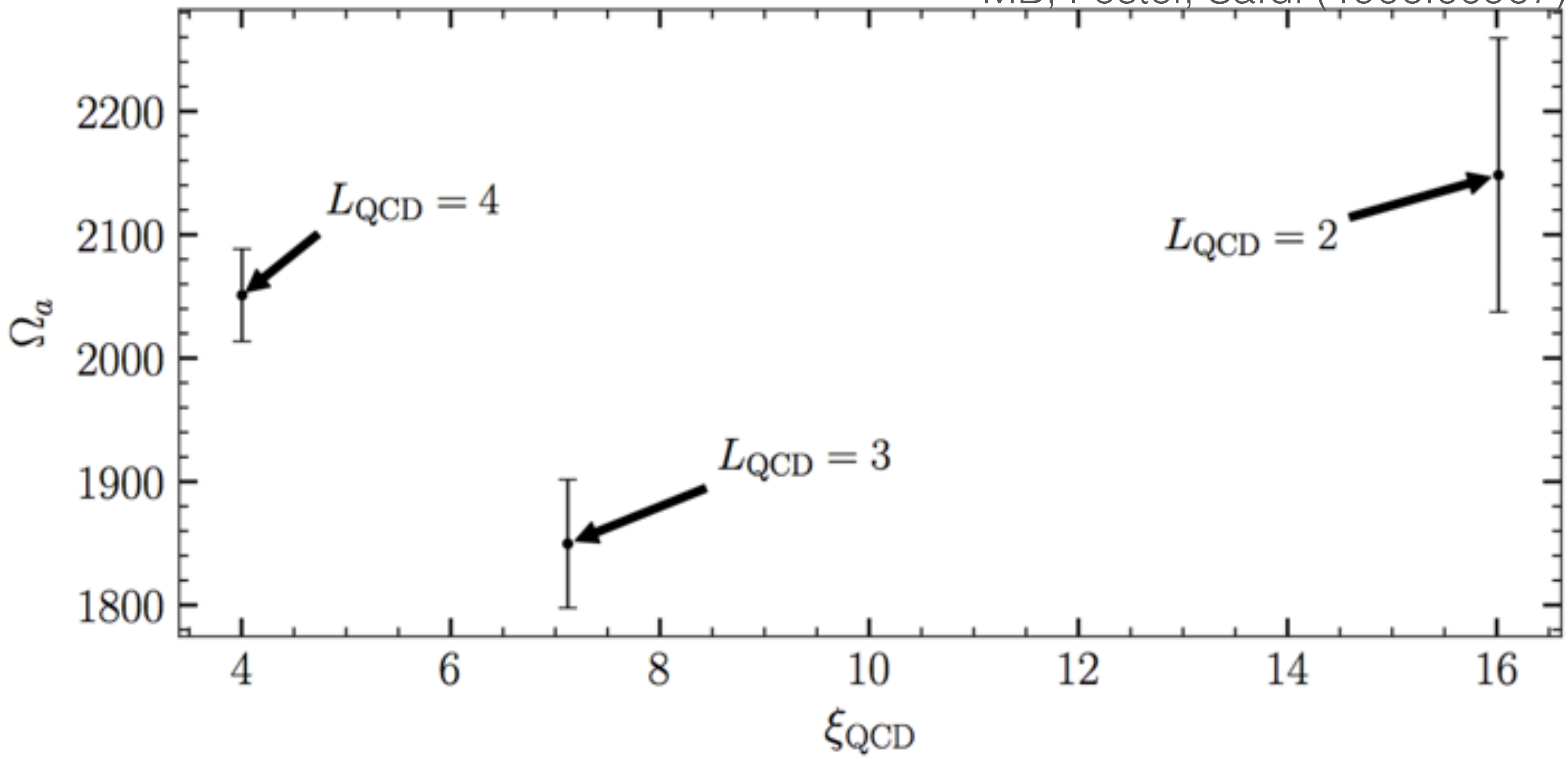
We observe violation of the scaling regime. But what affect do about 15 times as many strings have on the relic density?



Simple estimate:

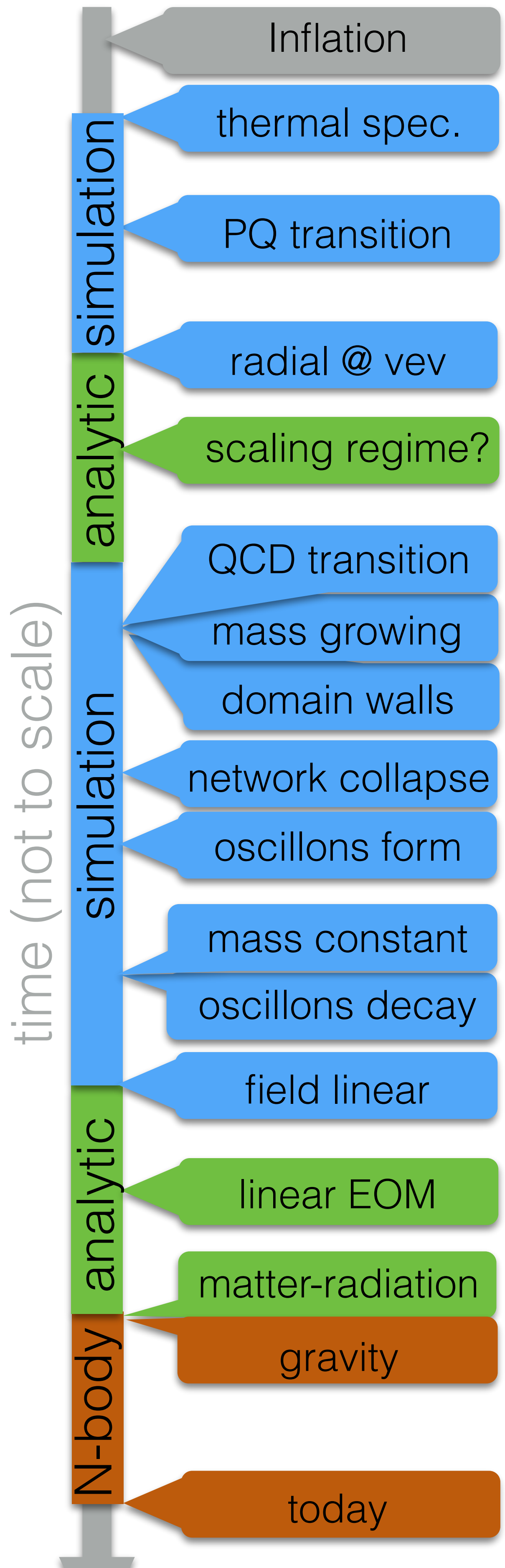
Reinterpretation of the volume of the initial state changes string density

MB, Foster, Safdi (1906:00967)



Seems to be a small affect. No trend visible.

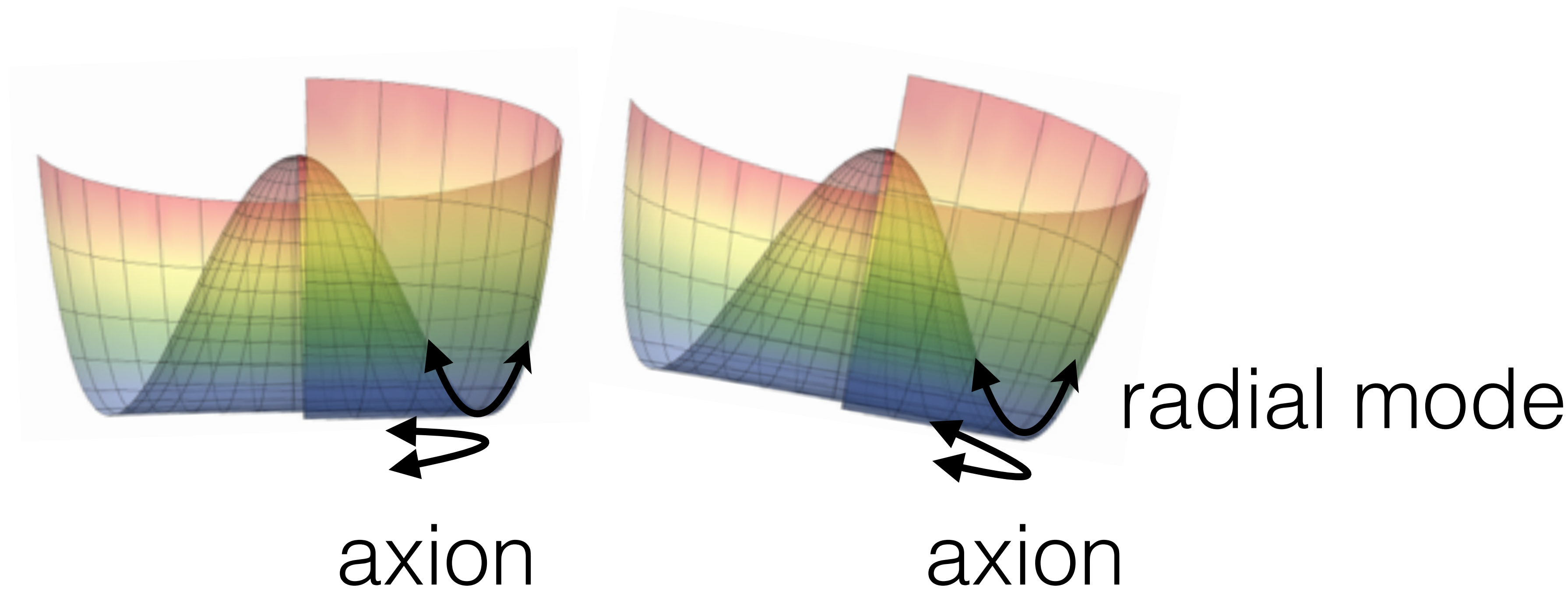
We estimate a 15% uncertainty related to scaling violation.

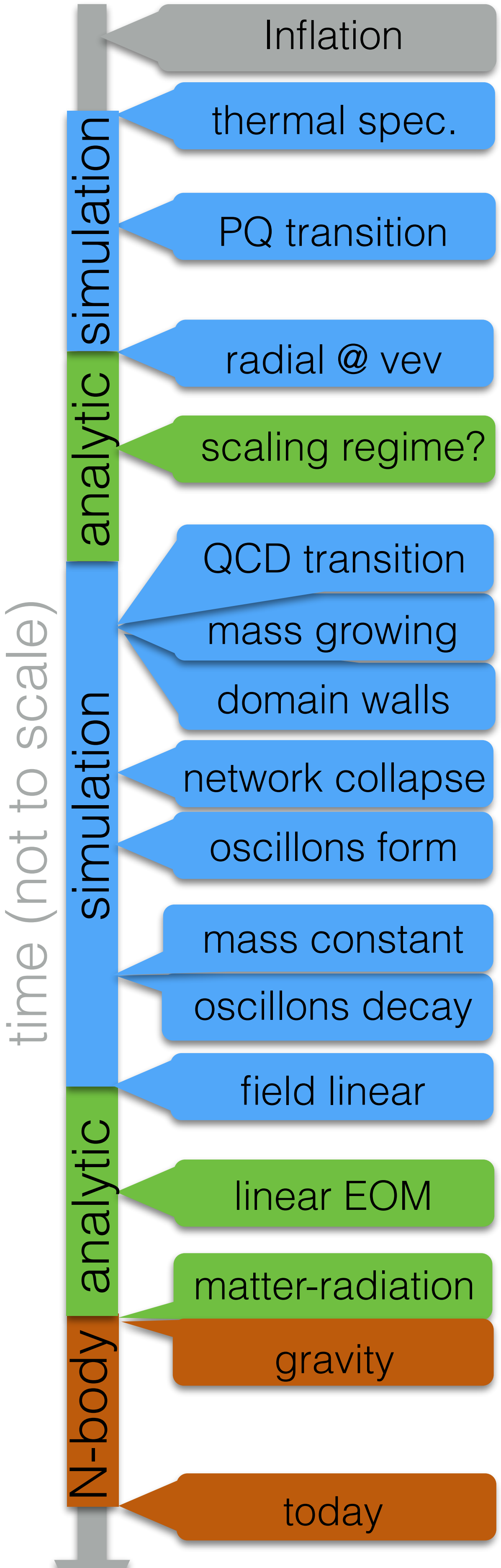


What is the reason for this?

Number density not conserved

Axion has to still live on the circle





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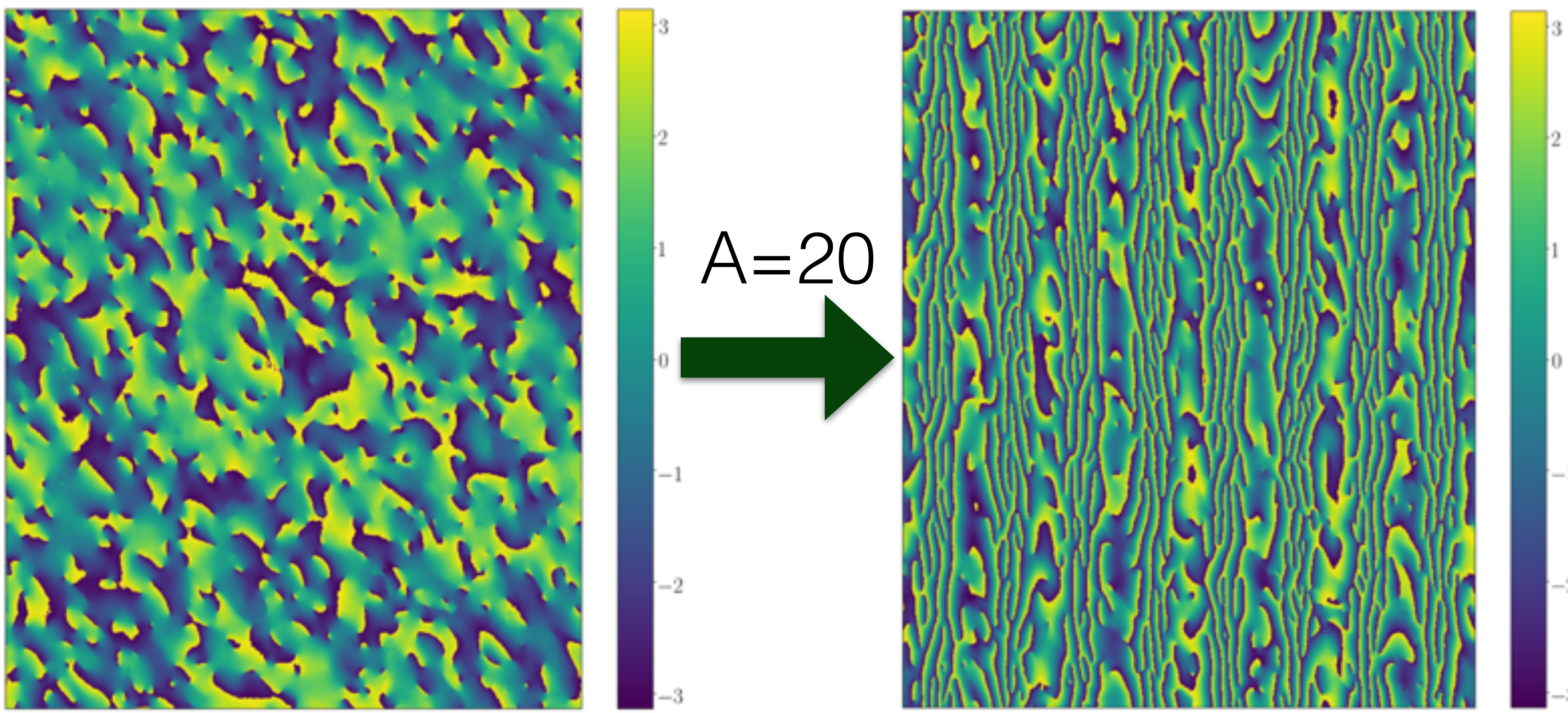
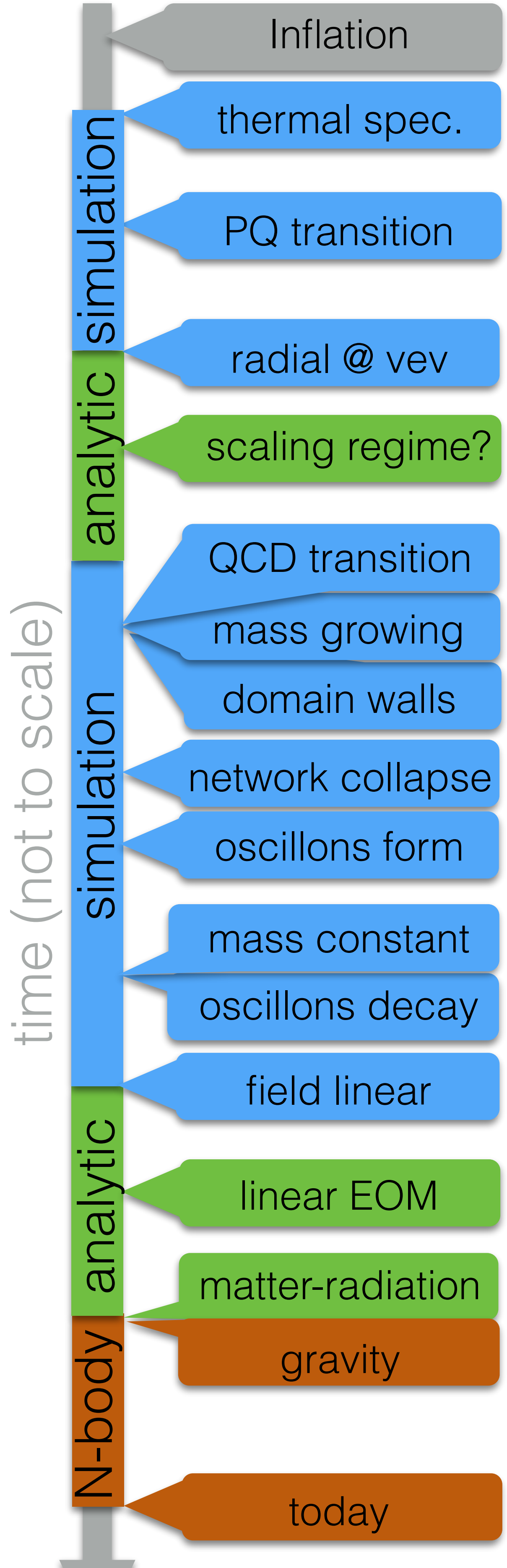
Inject mode large amplitude mode into field:

PQ field + A cos(H x)



Large amplitude always wraps back.



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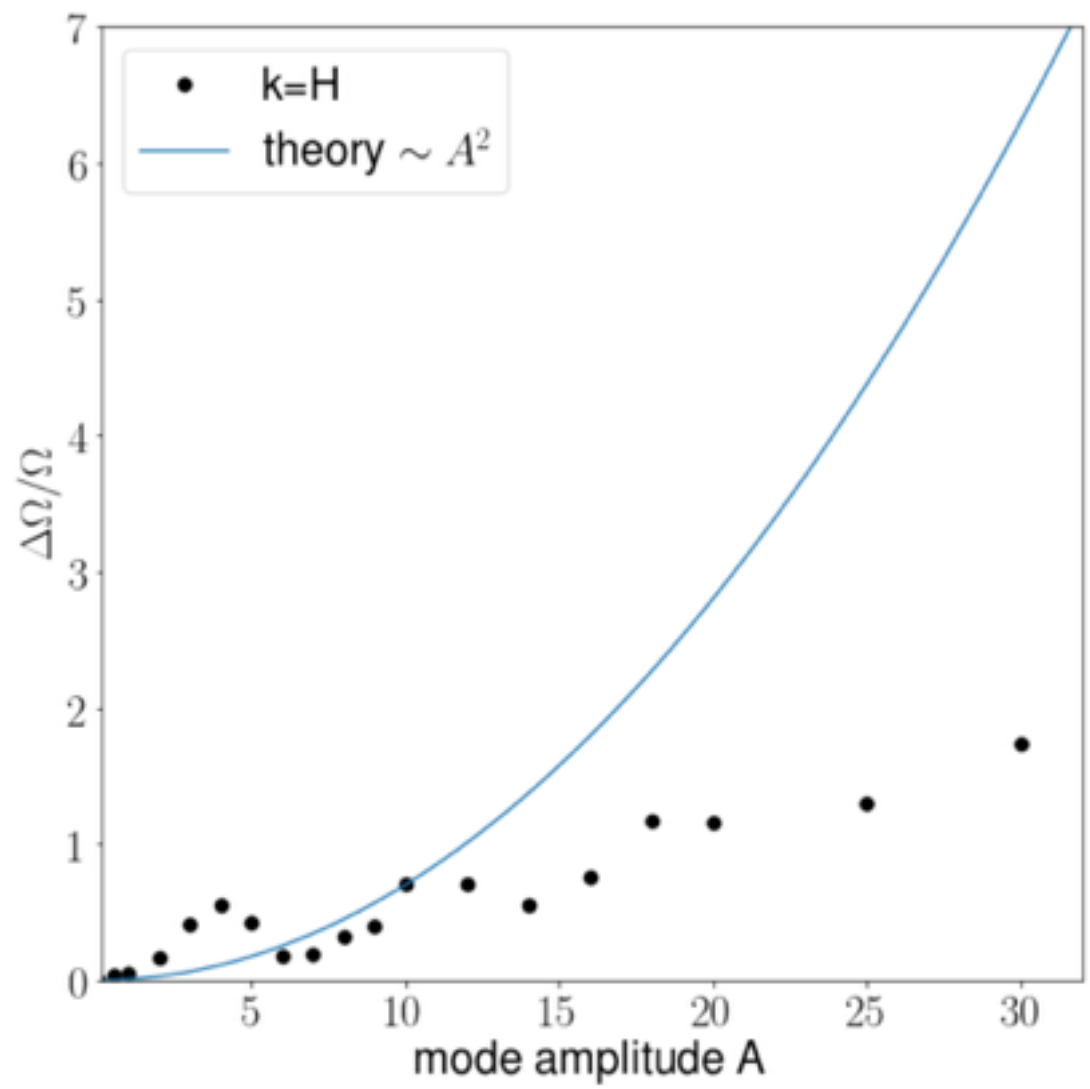
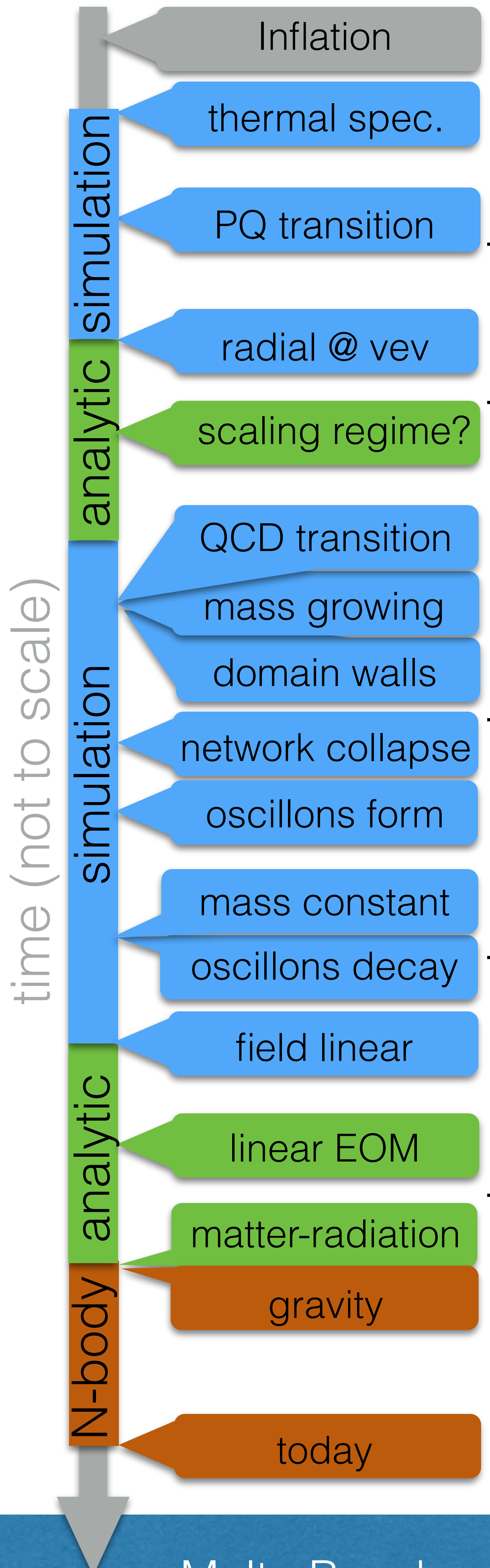


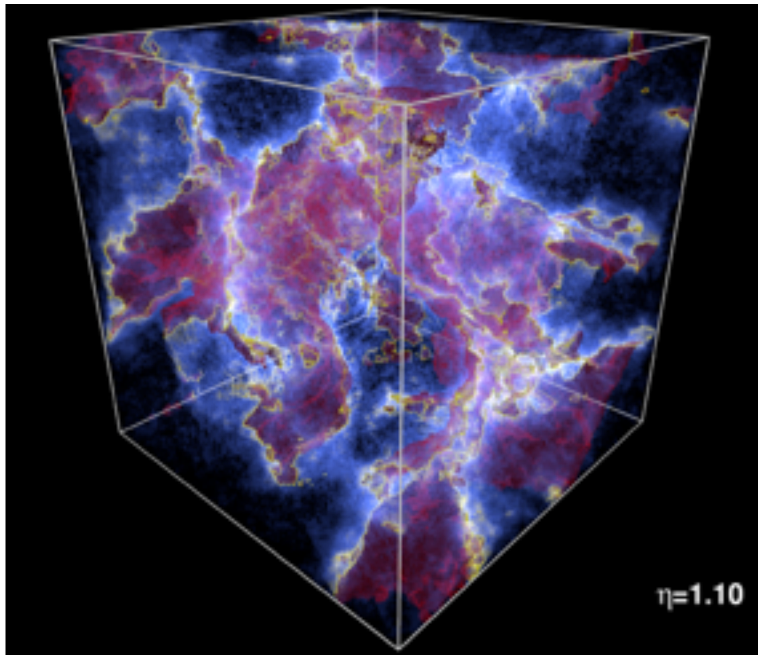
Thank you!



Summary

- Assumption: PQ symmetry broken after inflation

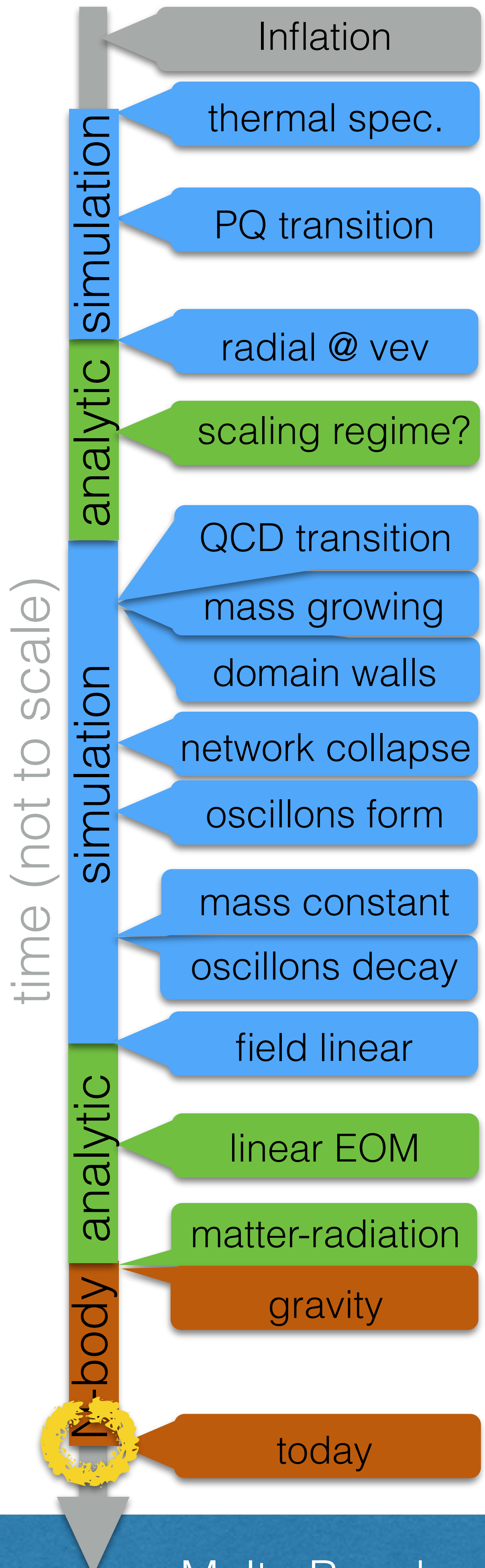
- We performed simulations through the PQ and QCD phase transition to matter-radiation equality



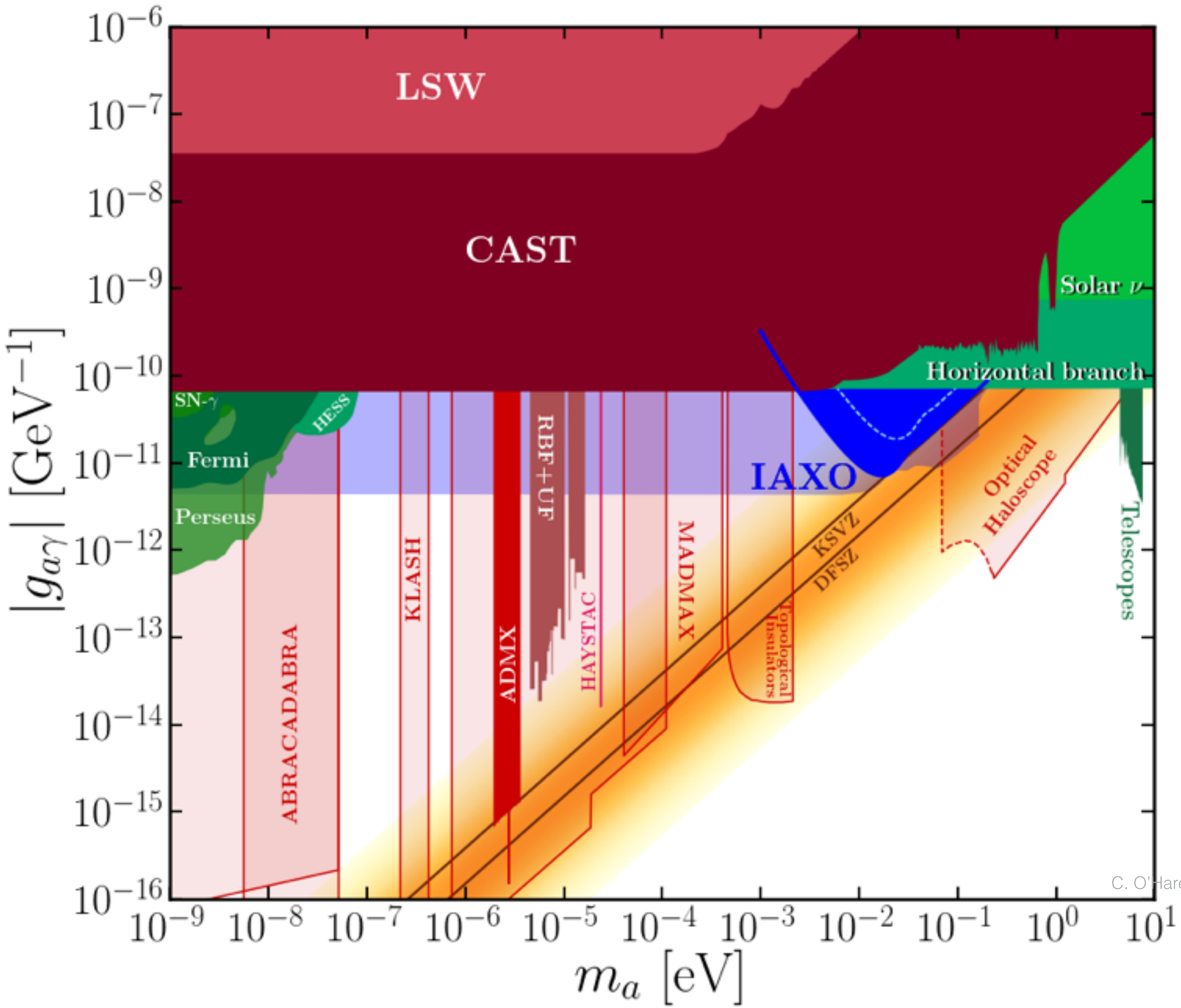
- Identified minihalo mass spectrum
  Typical mass: 10^{-14} solar masses

- Determined the axion mass that reproduces the correct relic abundance: $m_a = 25.2 \pm 11.0 \ \mu\text{eV}$

- Furthermore: Simulation data publicly available for further studies: https://zenodo.org/record/2653964 (e.g. gravitational N-body simulations)

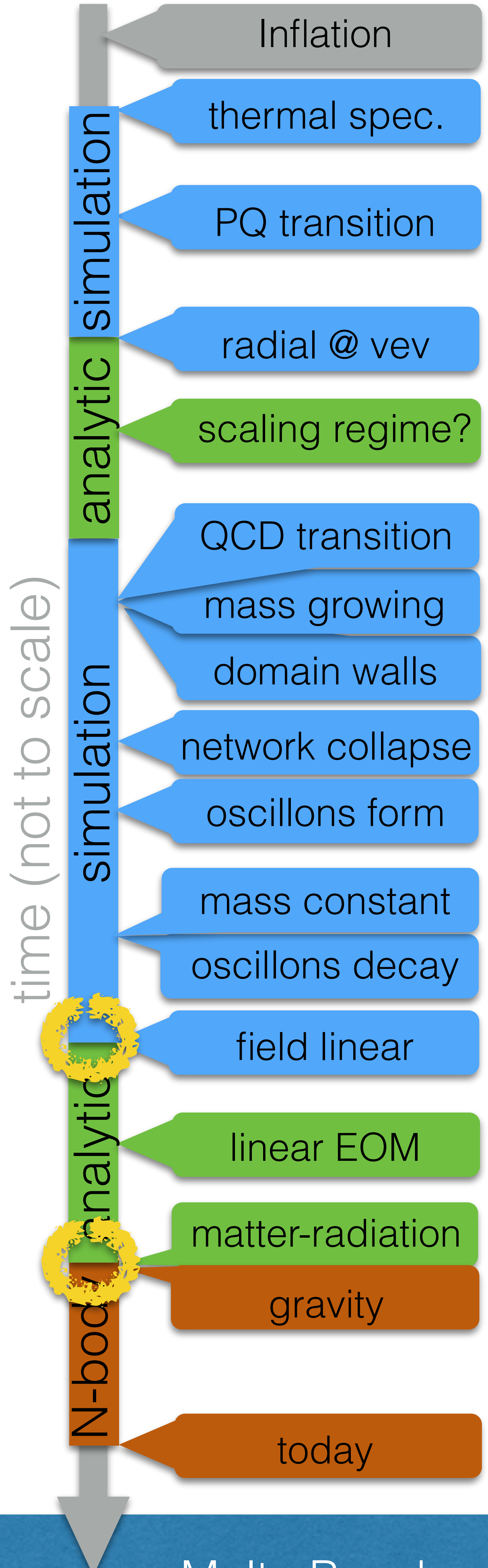


Inflation
thermal spec.
PQ transition
radial @ vev
scaling regime?
QCD transition
mass growing
domain walls
network collapse
oscillons form
mass constant
oscillons decay
field linear
linear EOM
matter-radiation
gravity
today
simulation
analytic
simulation
analytic
N-body
time (not to scale)



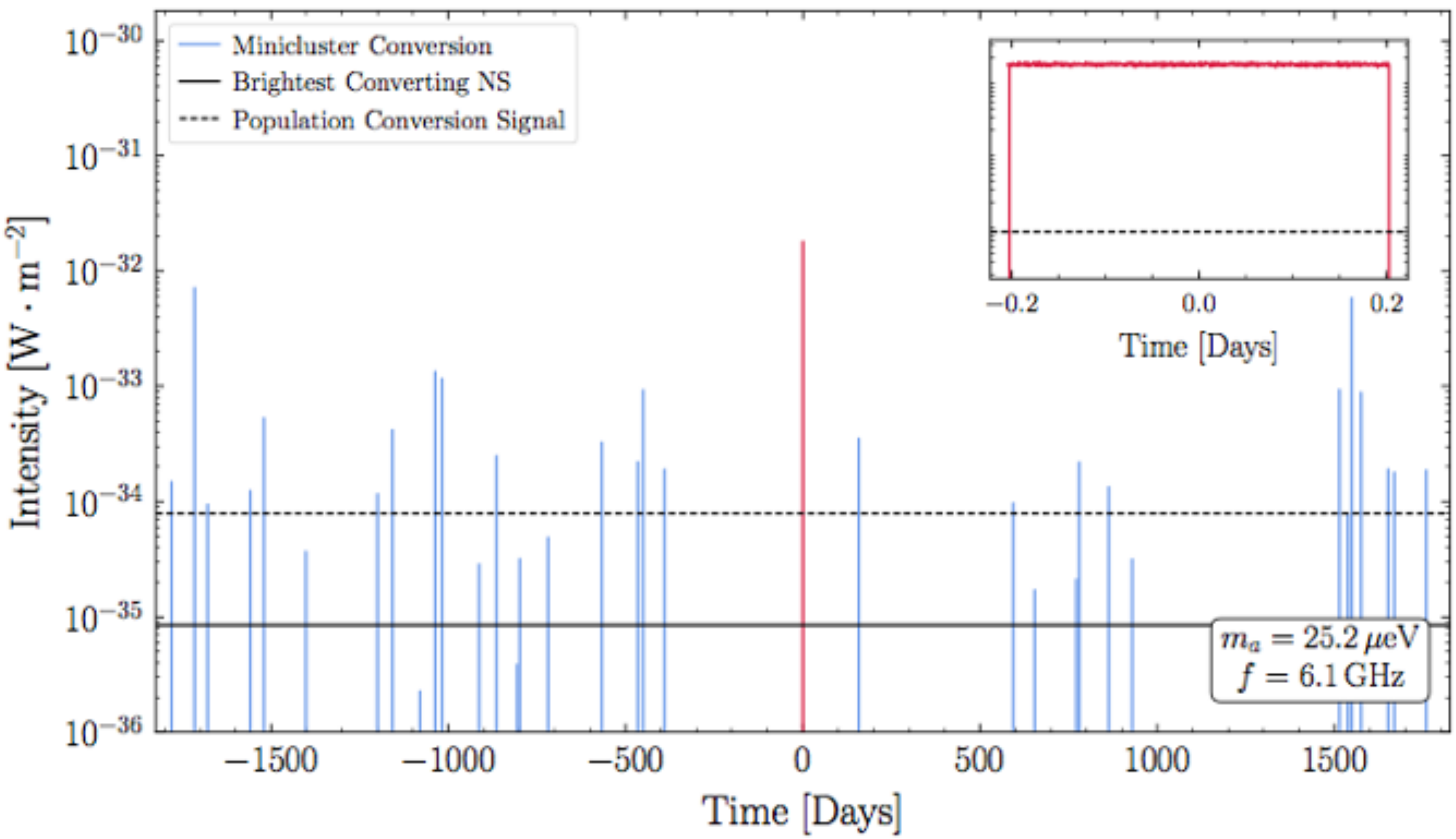
LSW
CAST
Solar ν
Horizontal branch
IAXO
SN-γ
HESS
Fermi
Perseus
ABRACADABRA
KLASH
ADMX
RBF+UF
HAYSTAC
MADMAX
KSVZ
DFSZ
Topological Insulators
Optical Haloscope
Telescopes
C. O'Hare
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16}
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}

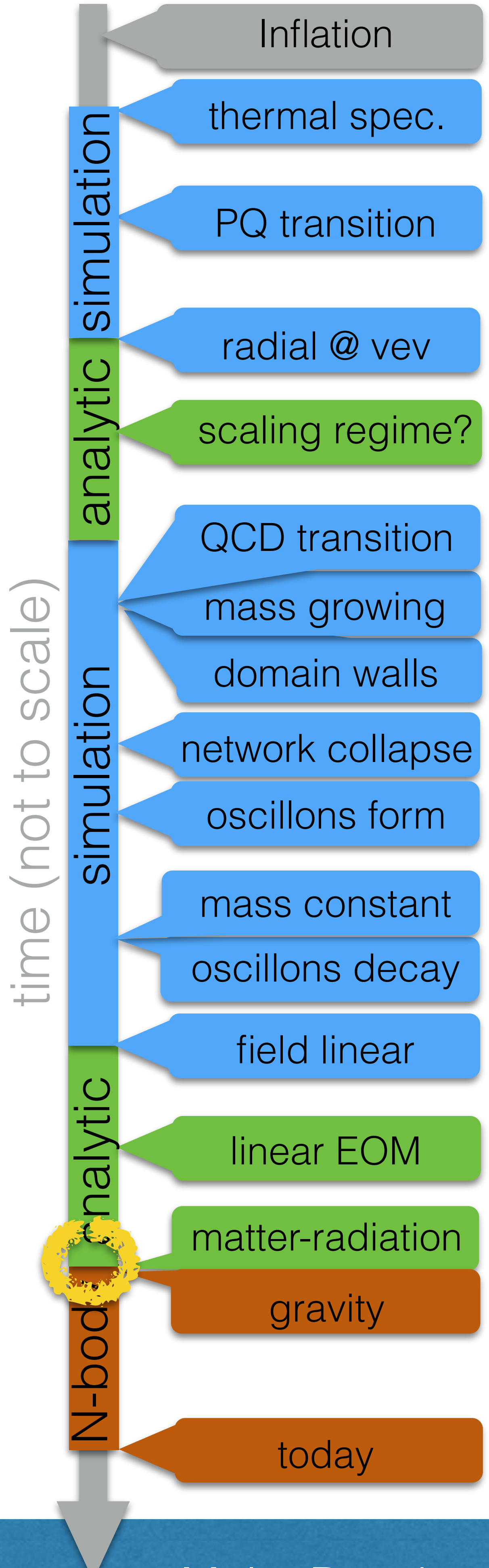
Radio signals from neutron stars

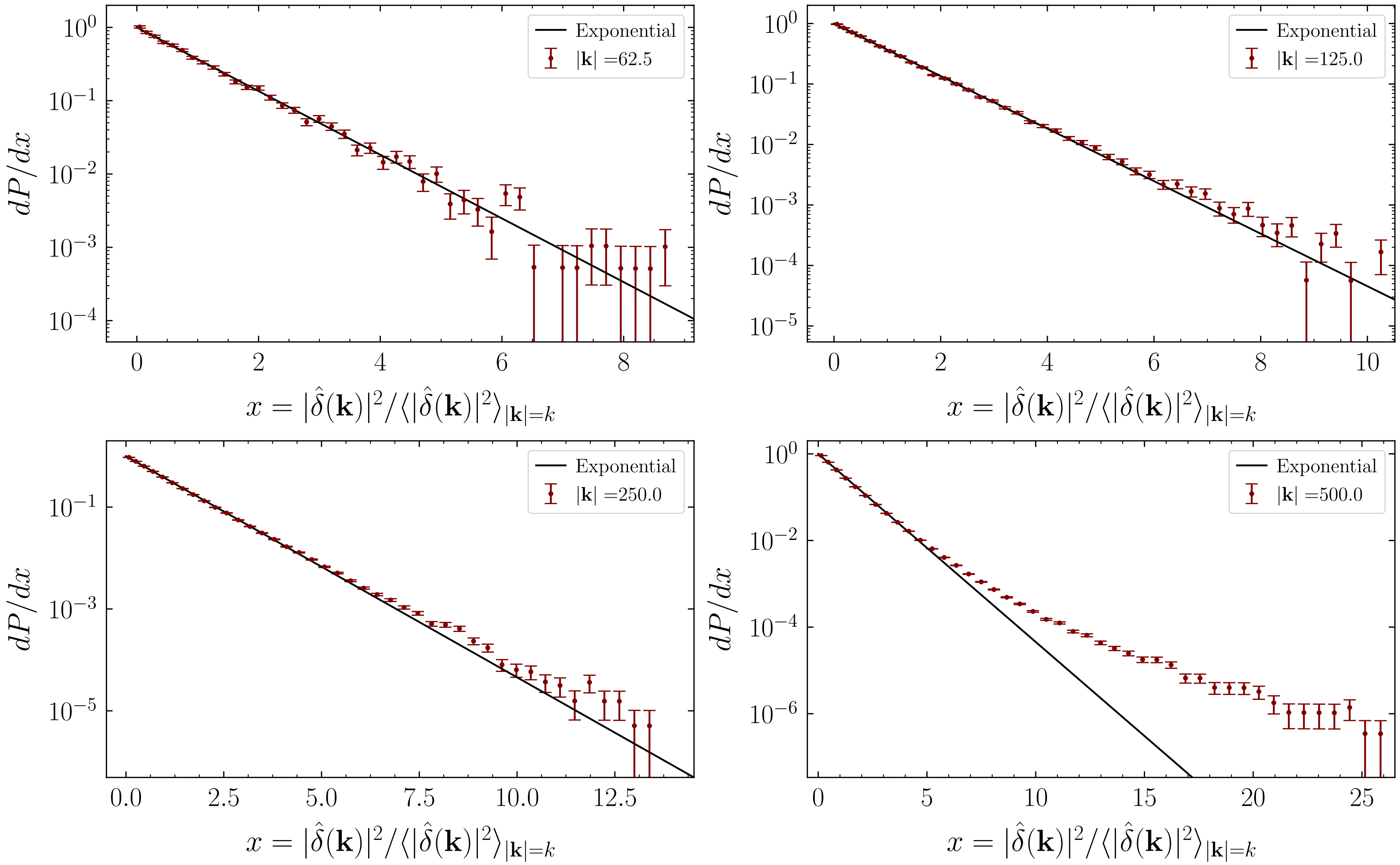


Axions convert to radio photons in magnetic field of neutron star

Large peak in flux when neutron star moves to a axion minihalo!







Field is non-Gaussian at small scales!

Power spectrum insufficient to describe the final state

We provide our data at: https://zenodo.org/record/2653964