The cosmological history of axion minihalos

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NERSC
National Energy Research Scientific Computing Center

Axions

- Axions originally introduced to solve the **strong CP problem**:

$$\mathcal{L} = \theta \frac{1}{16\pi^2} F^a_{\mu\nu} \tilde{F}^{\mu\nu a} \longrightarrow \mathcal{L}_{axion} = (\partial_\mu a)^2 + \frac{(a/f_a + \theta)}{32\pi^2} F\tilde{F}$$

- U(1) PQ symmetry **spontaneously broken** at high scale

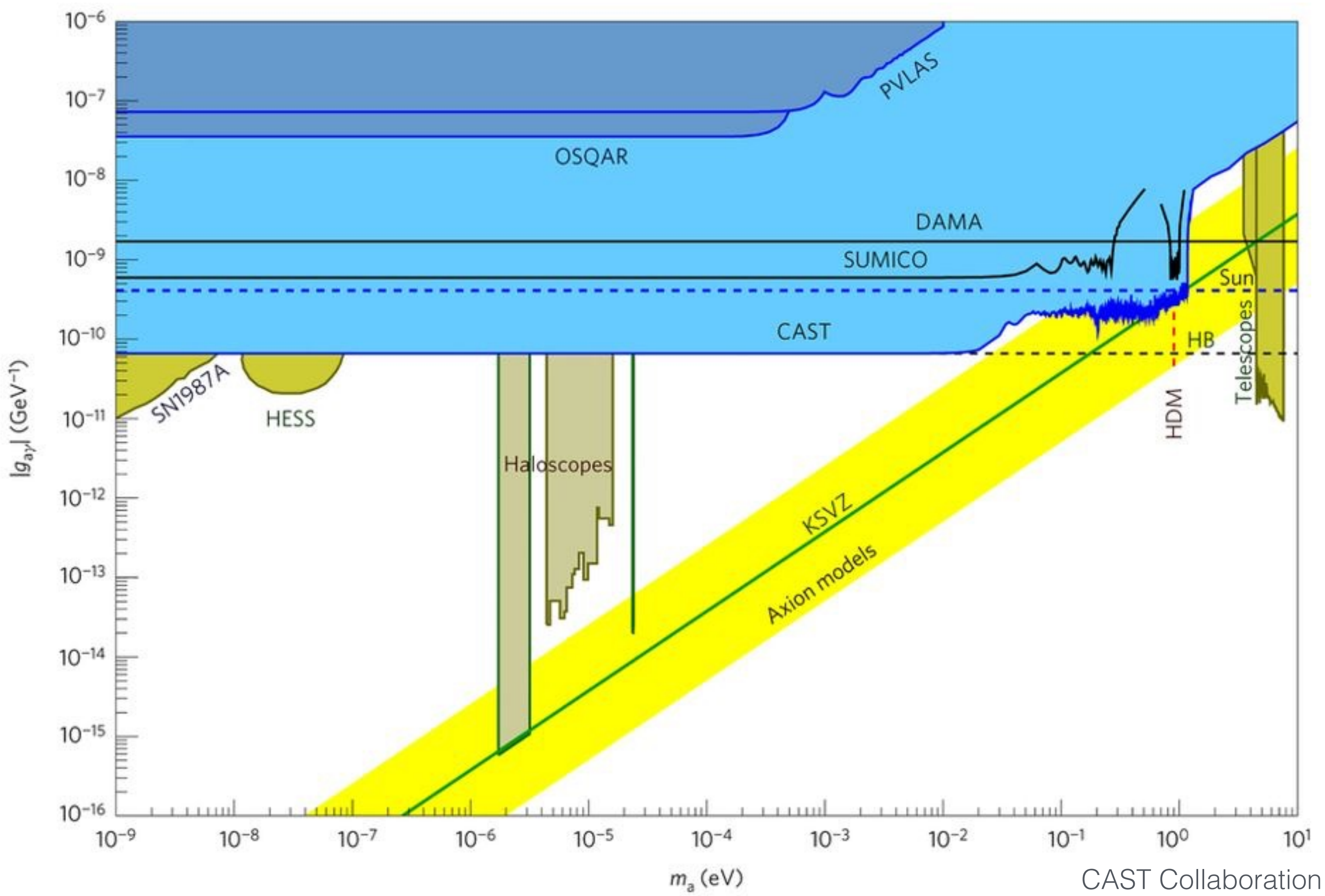
- **Axion mass** is small (QCD effects),

$$m_a^2 \approx \frac{m_\pi^2 f_{\pi^2}}{f_a^2}$$

as are its couplings

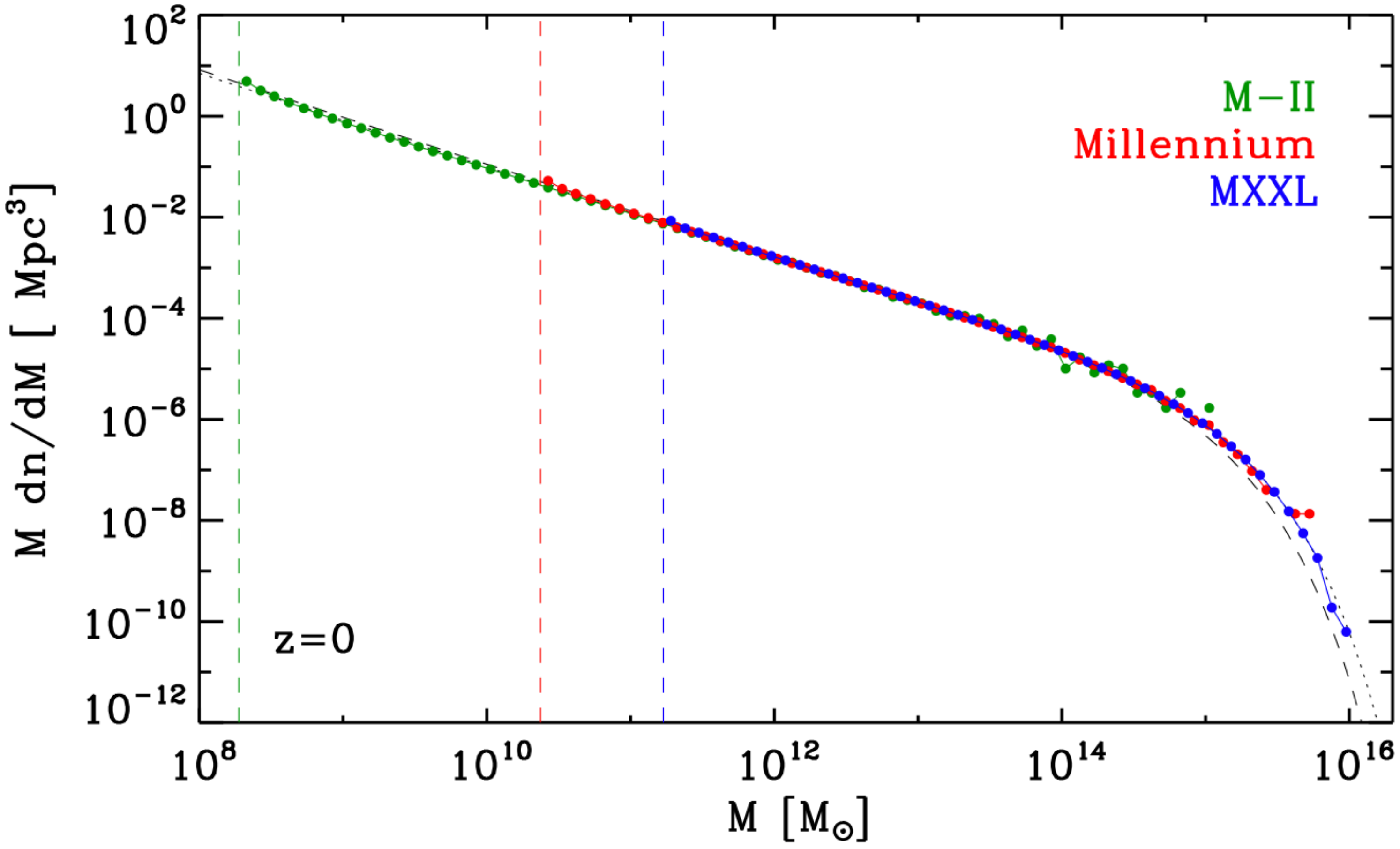
↓

good cold **DM candidate**



CAST Collaboration

What are axion minihalos?



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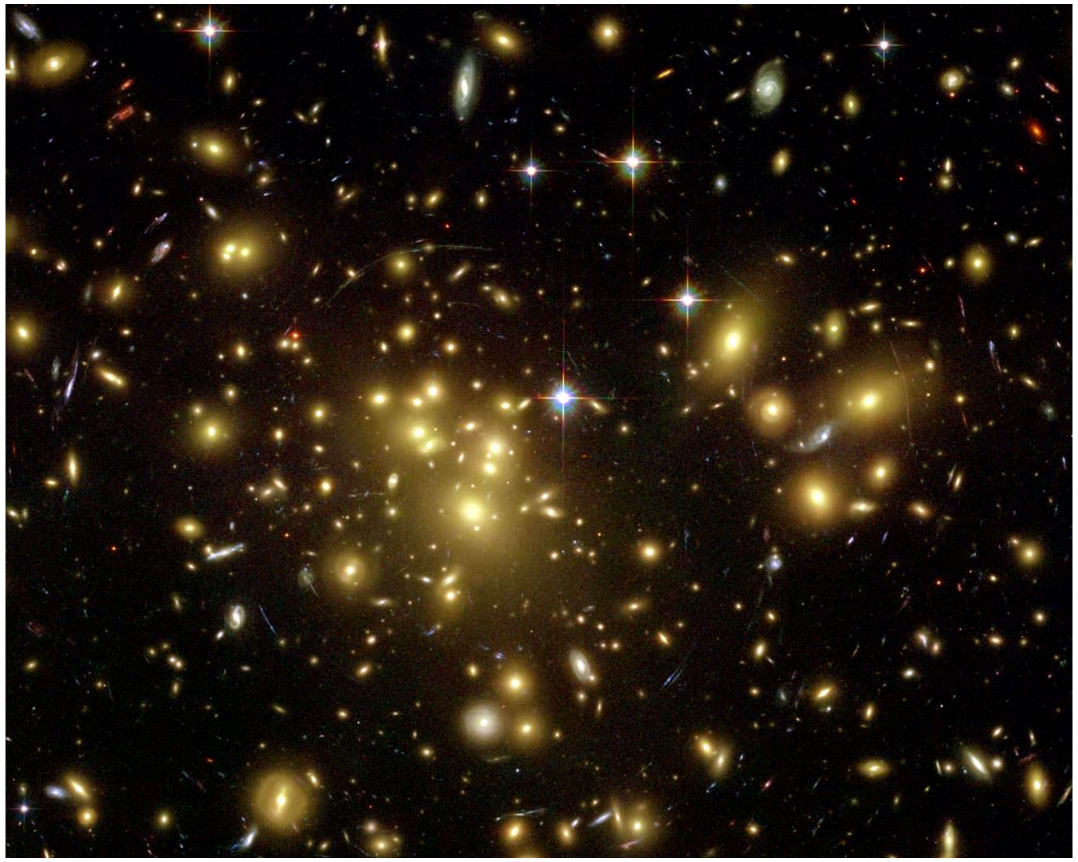
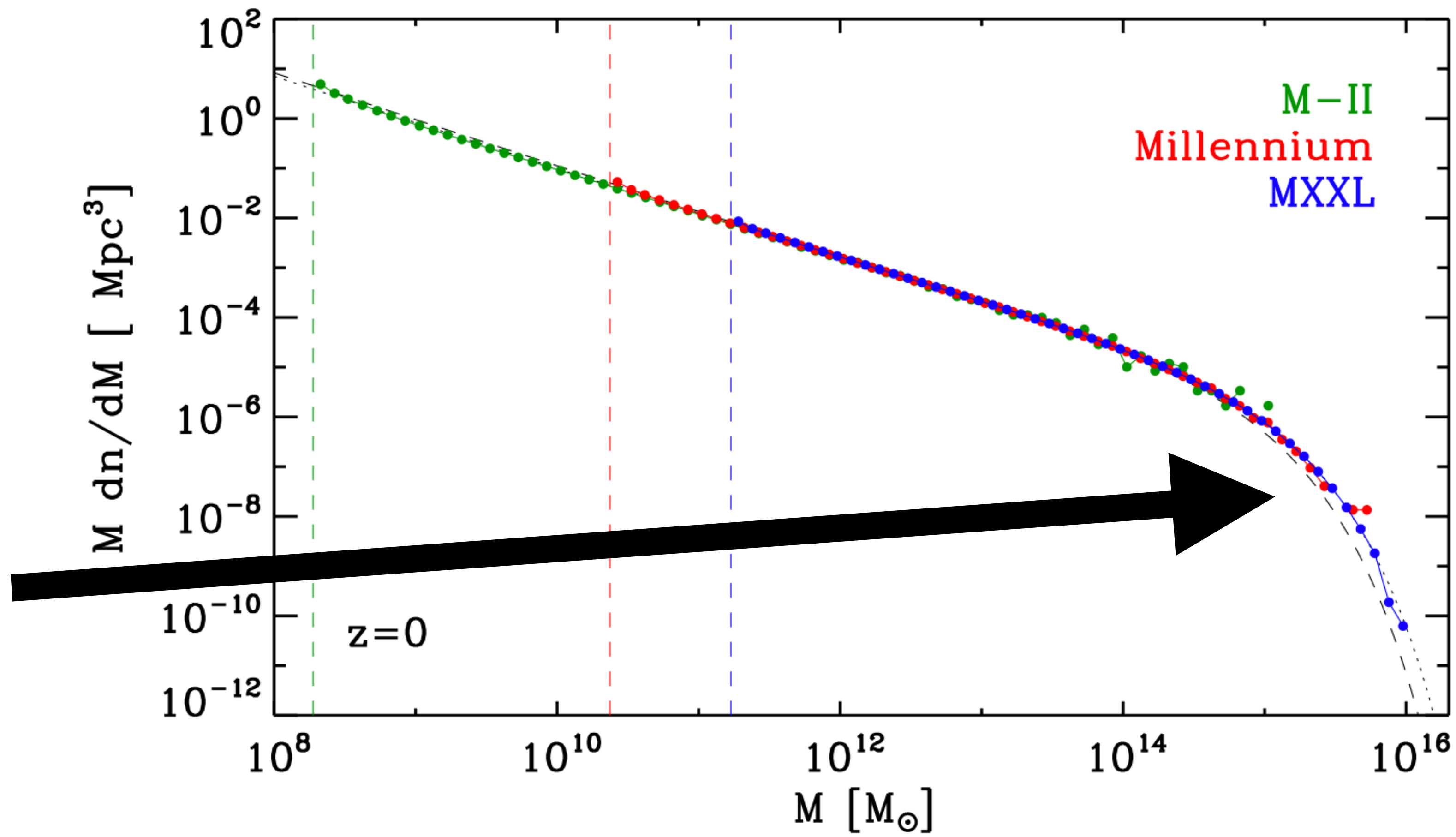
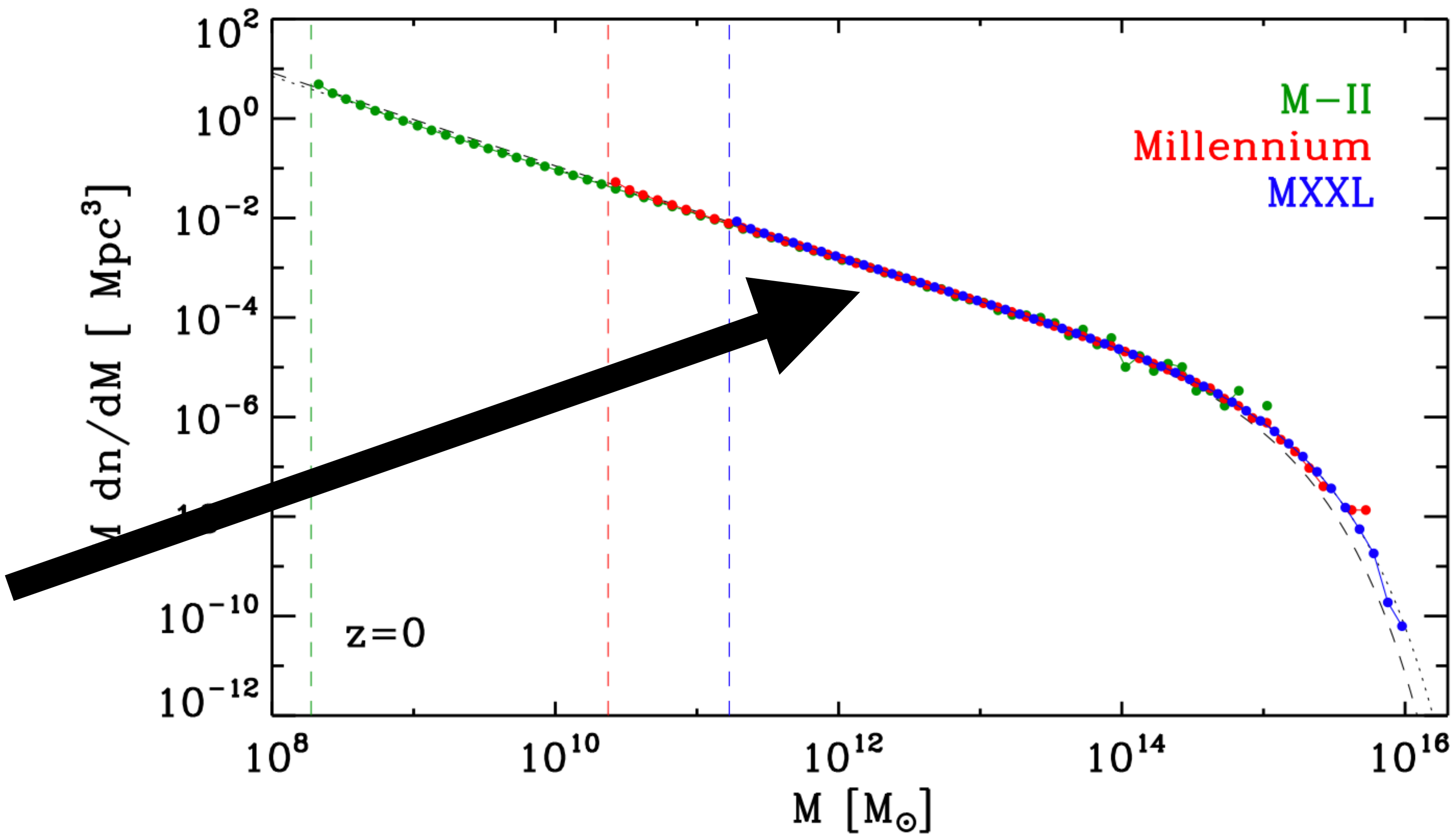




Galaxy Clusters

What are axion minihalos?

Galaxies



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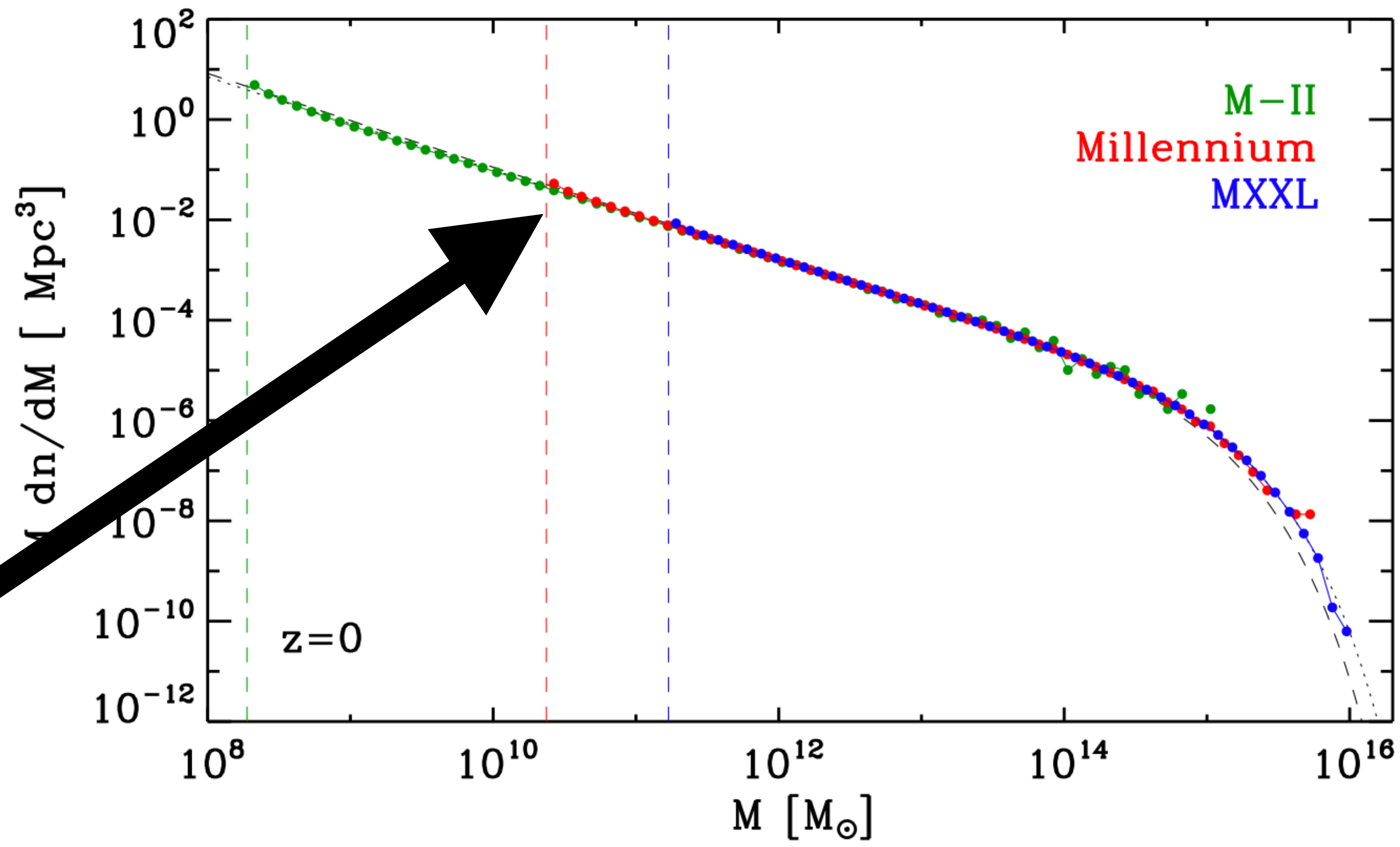
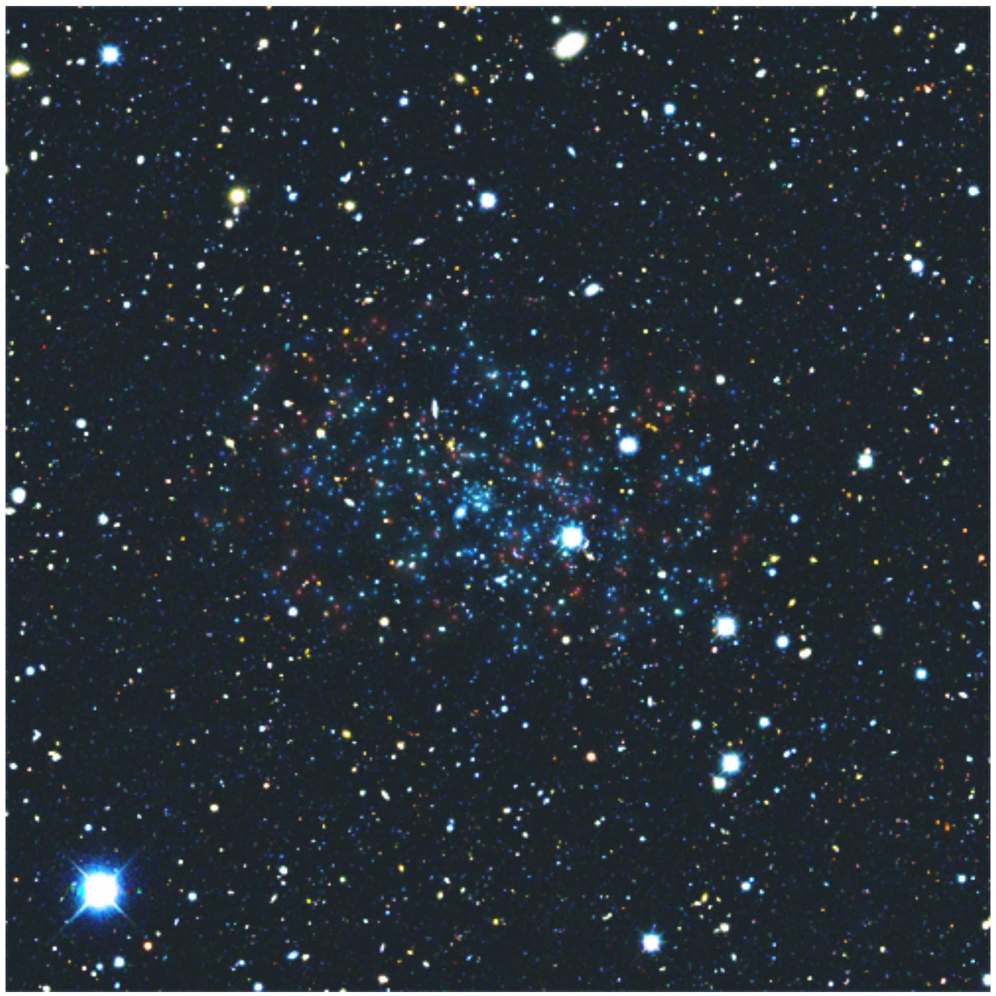
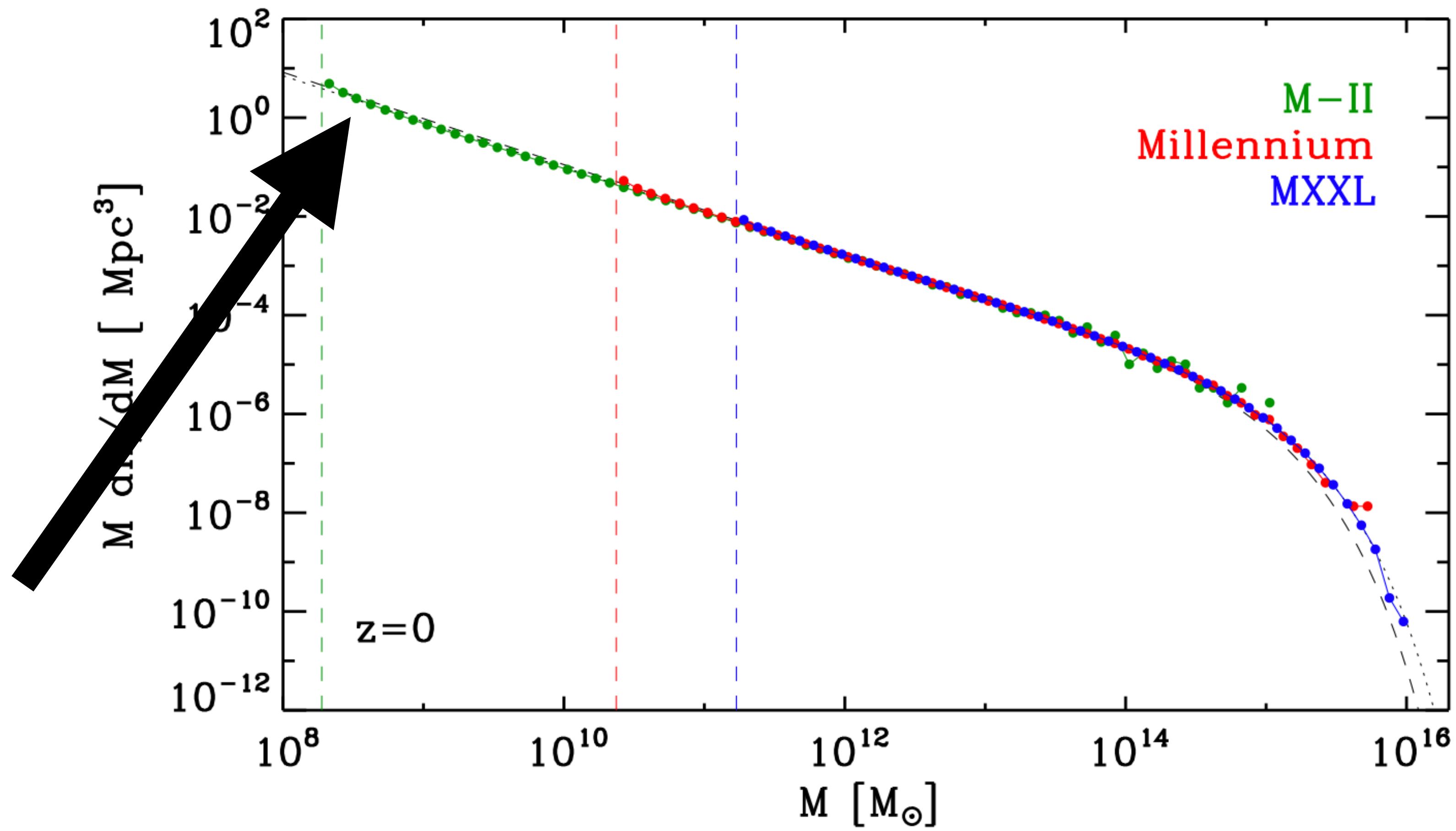


Dwarf Galaxies

What are axion minihalos?



DM subhalos
(ultra-faint)



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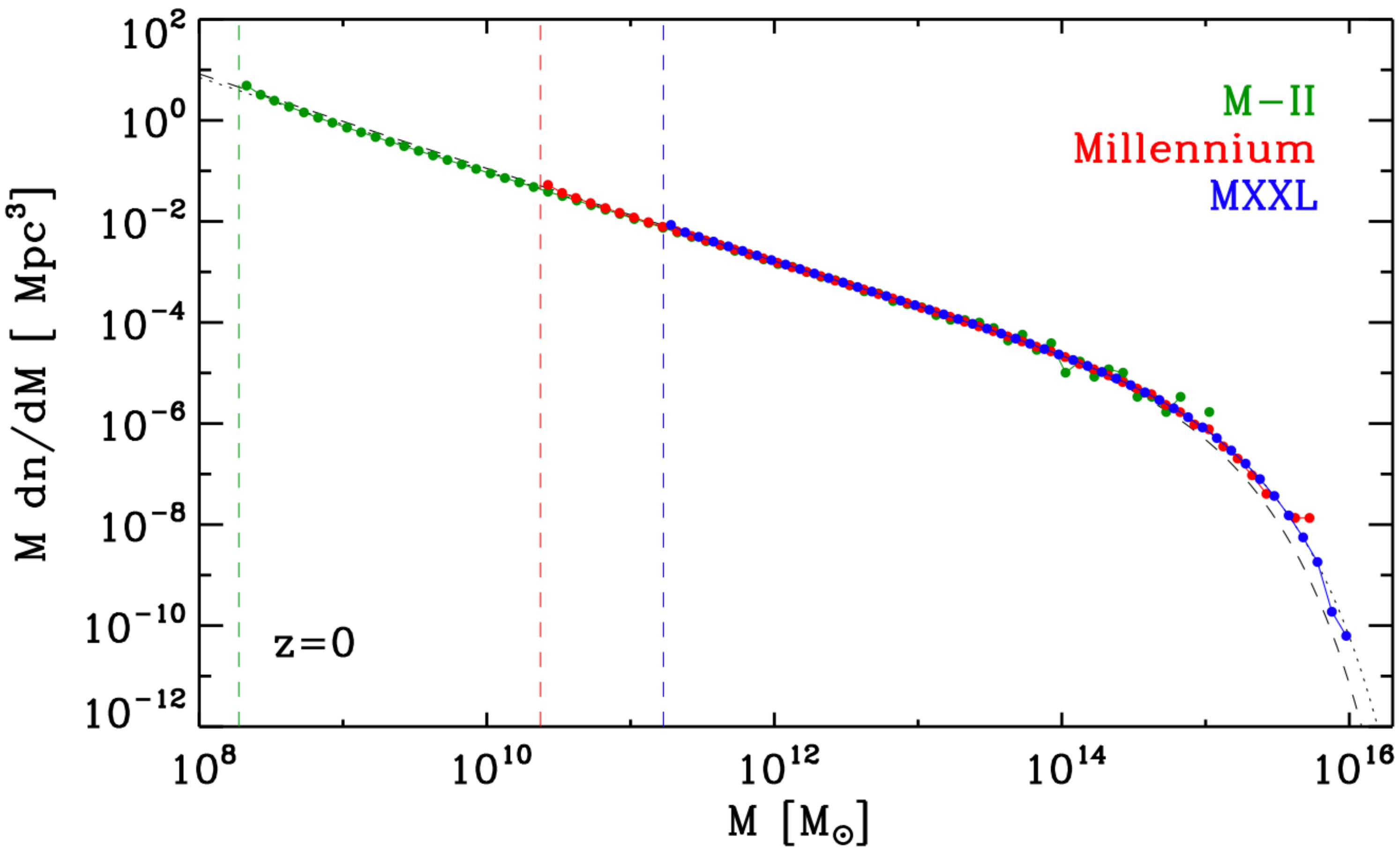

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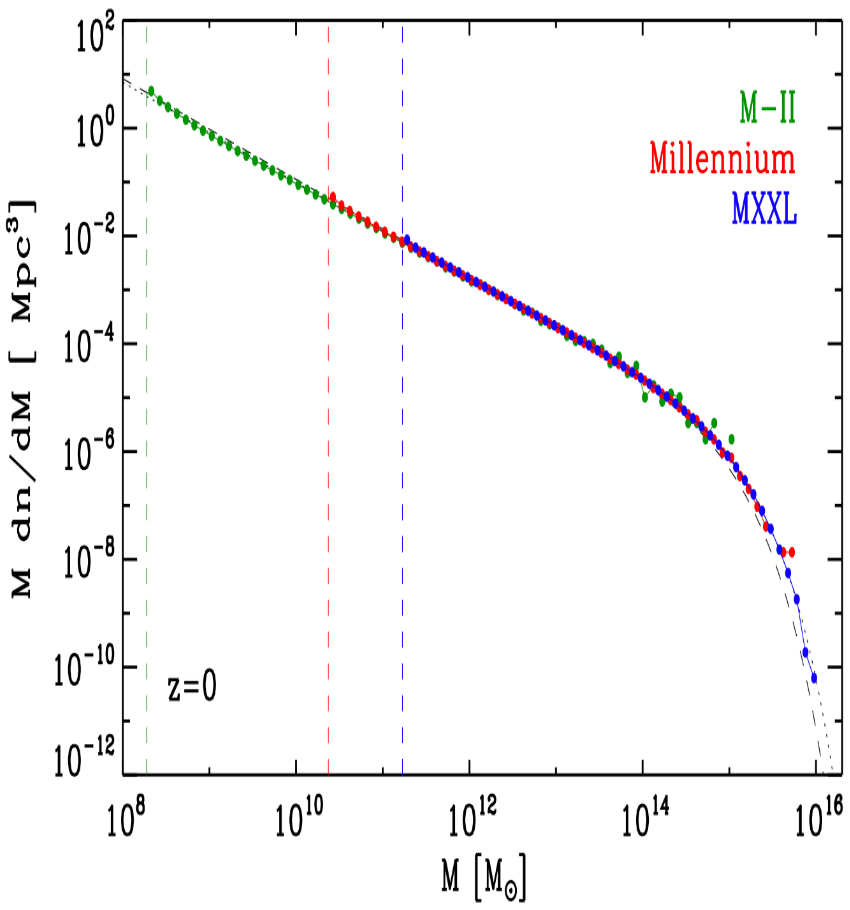

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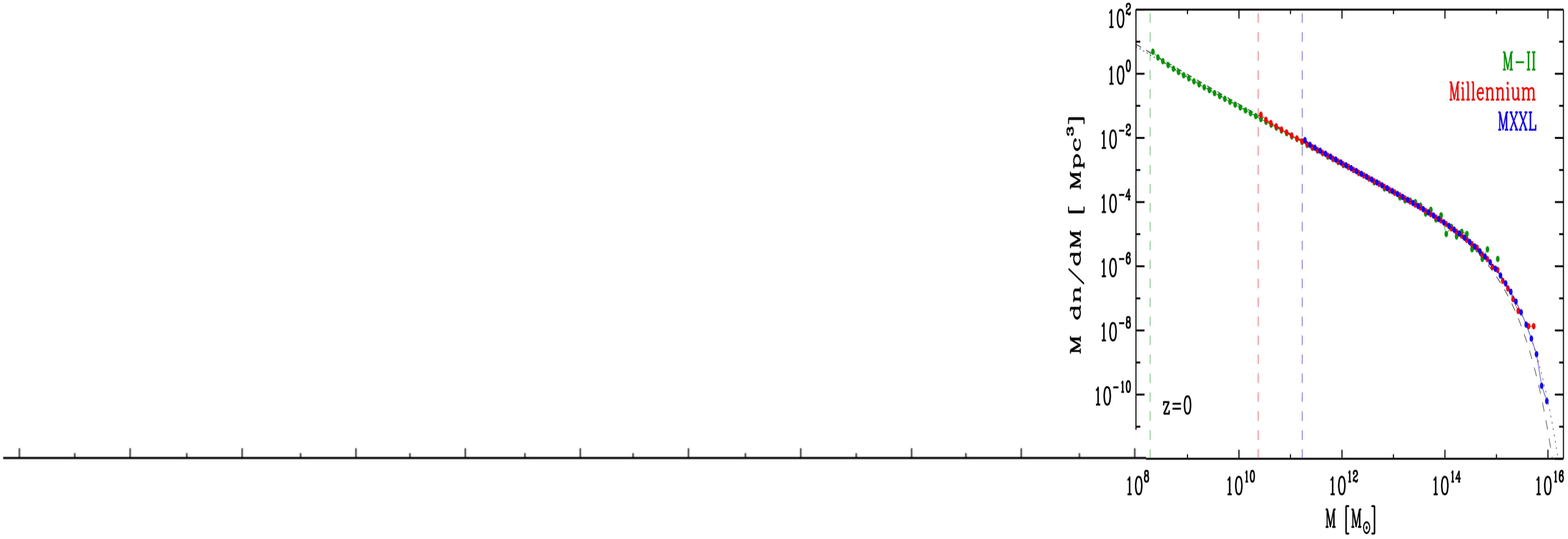

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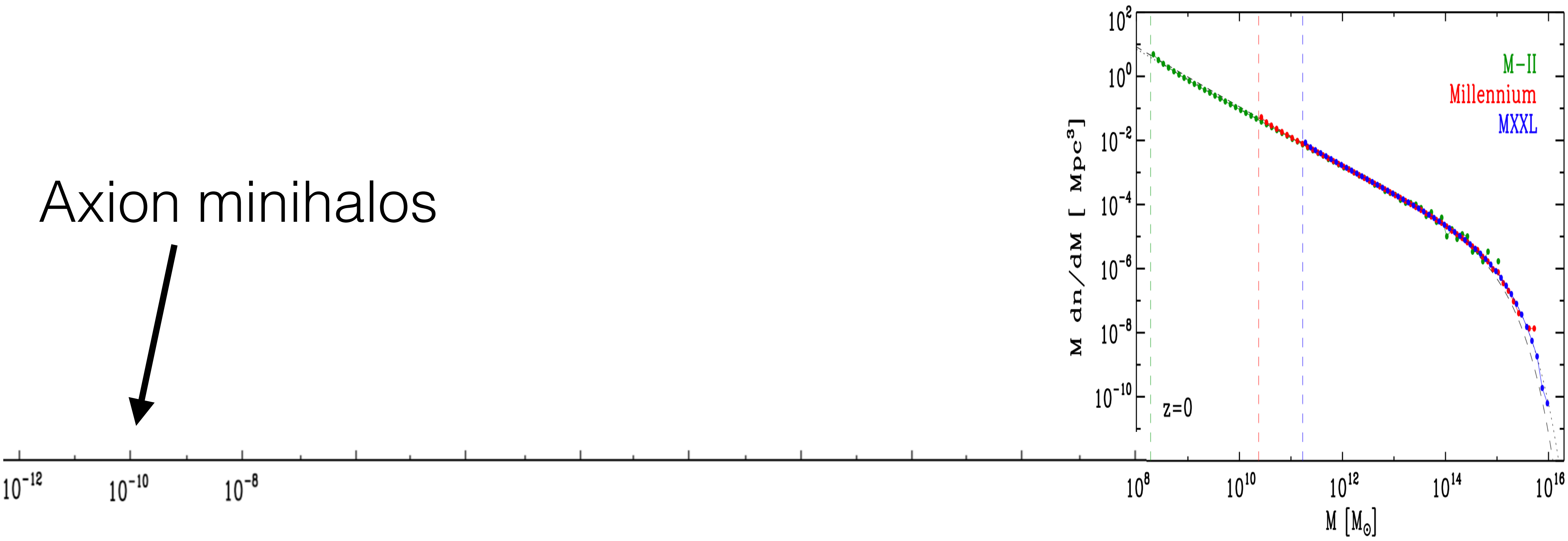
Axion minihalos



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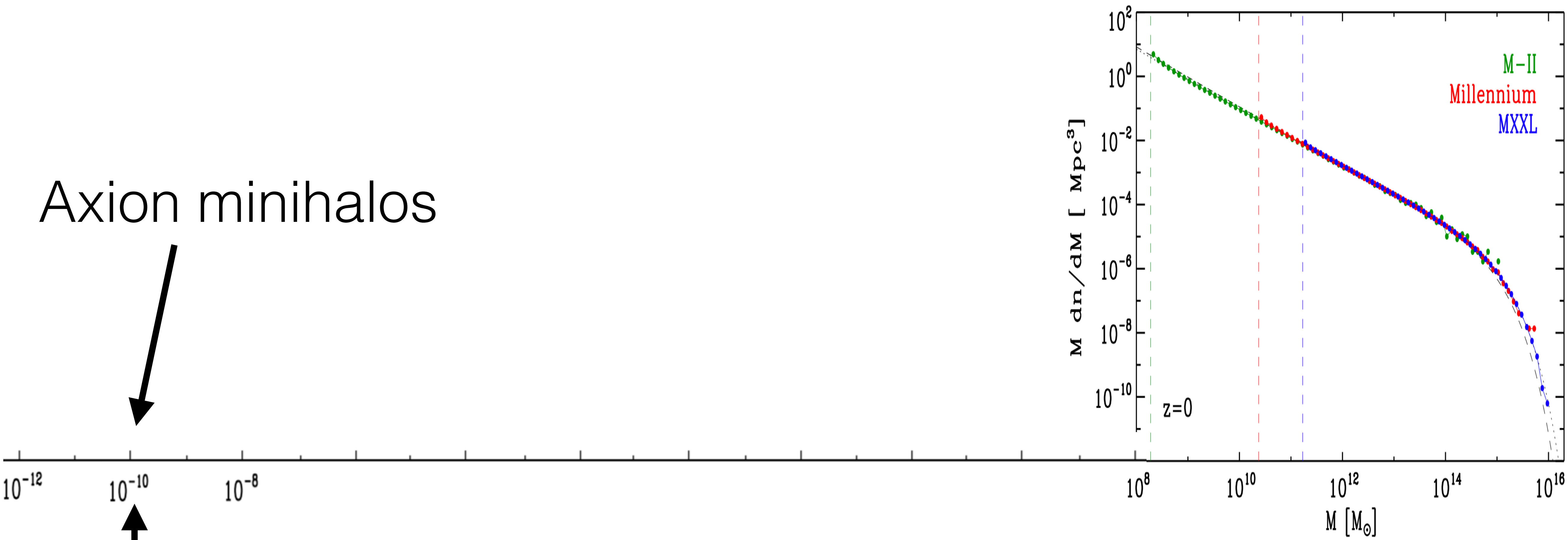
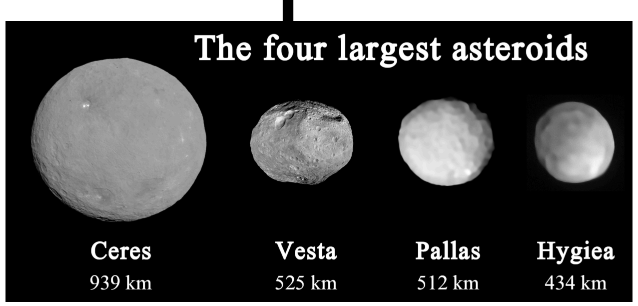
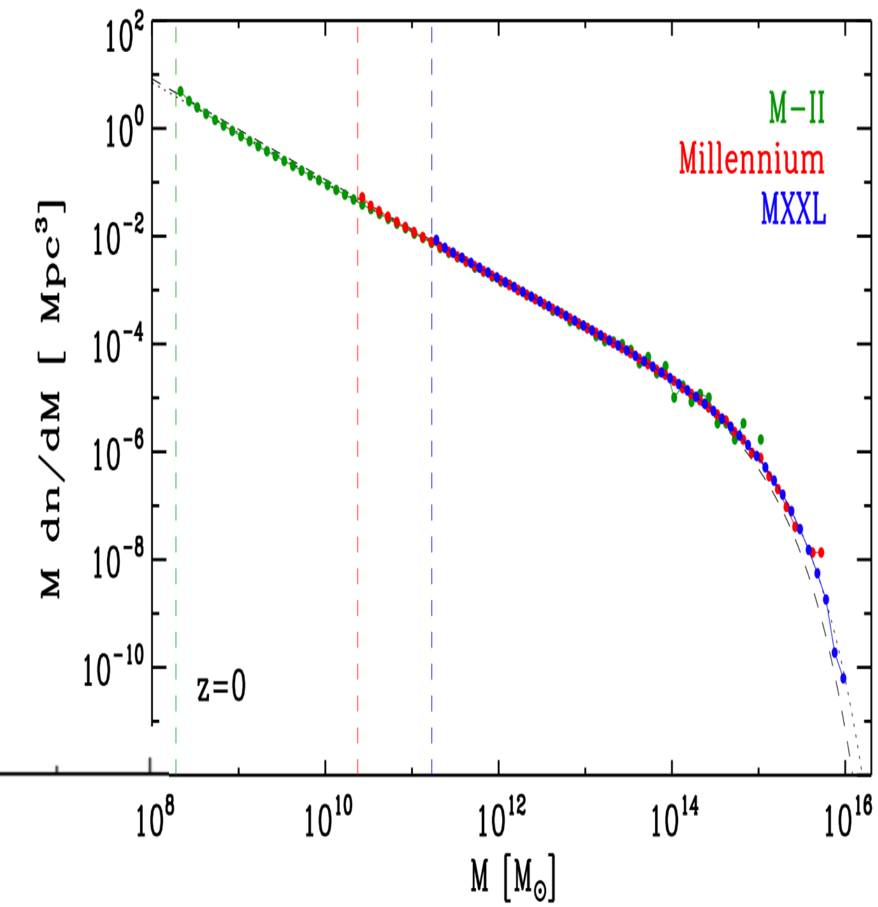


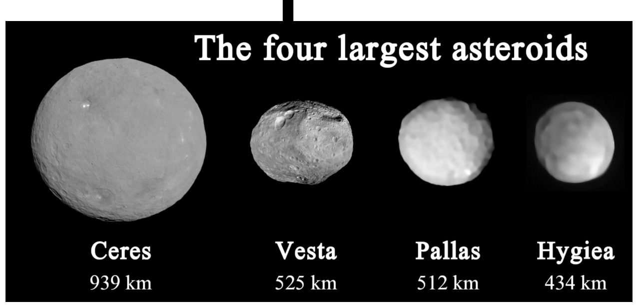


What are axion minihalos?

Axion minihalos

10^{-12} 10^{-10} 10^{-8}





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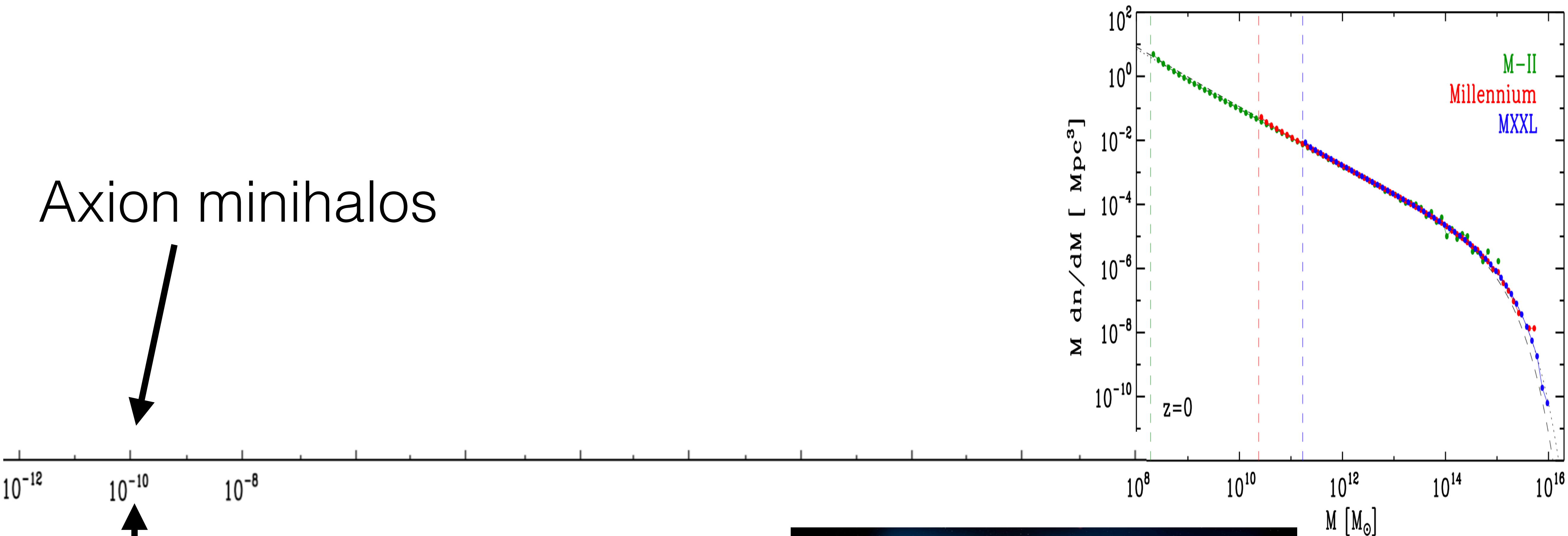

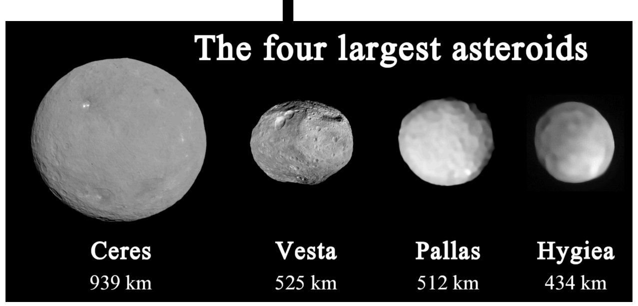

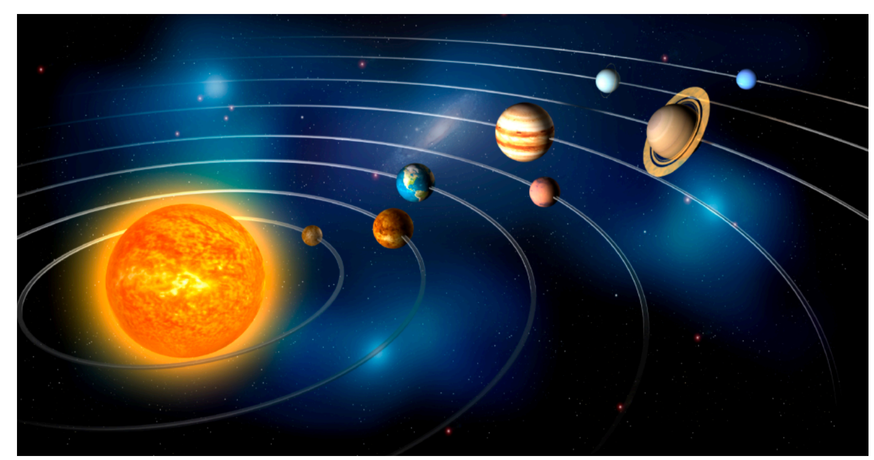

Pallas spread out over
our solar system (roughly)

What are axion minihalos?

Facts:

- 10^{-10} solar masses heavy
- solar system sized

} True within a few orders of magnitude

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  They are formed through axion self-interactions

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- Requirement: PQ symmetry is broken after inflation!
  They are formed through axion self-interactions

- Why should we care about them?
  - Direct detection (are we sitting in a local void?)
  - We can search for them (e.g. through neutron stars)
  - Scenario provides prediction for axion mass
  - Can they host axion stars?

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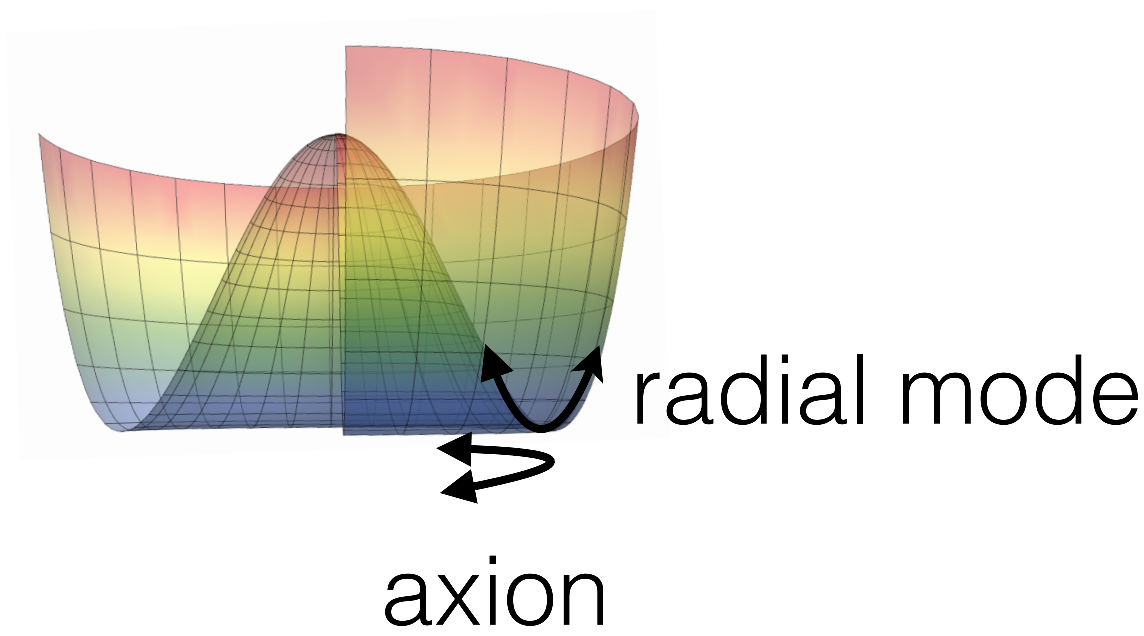
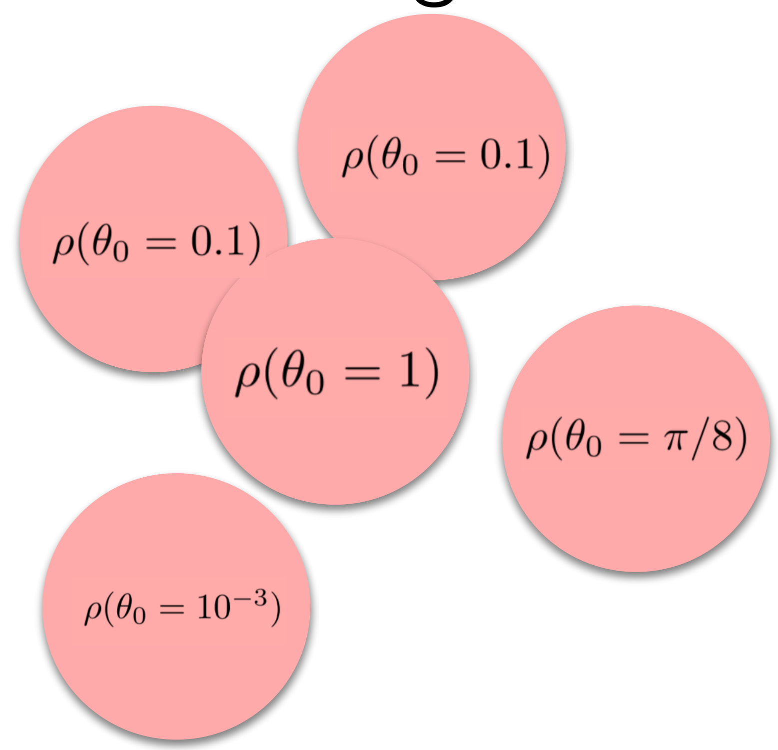
$$V(\Phi, T) = \frac{\lambda}{4}\left(|\Phi|^2 - f_a^2\right)^2$$



Breaking PQ:



Hubble-sized patches

Post- vs Pre-inflationary scenario

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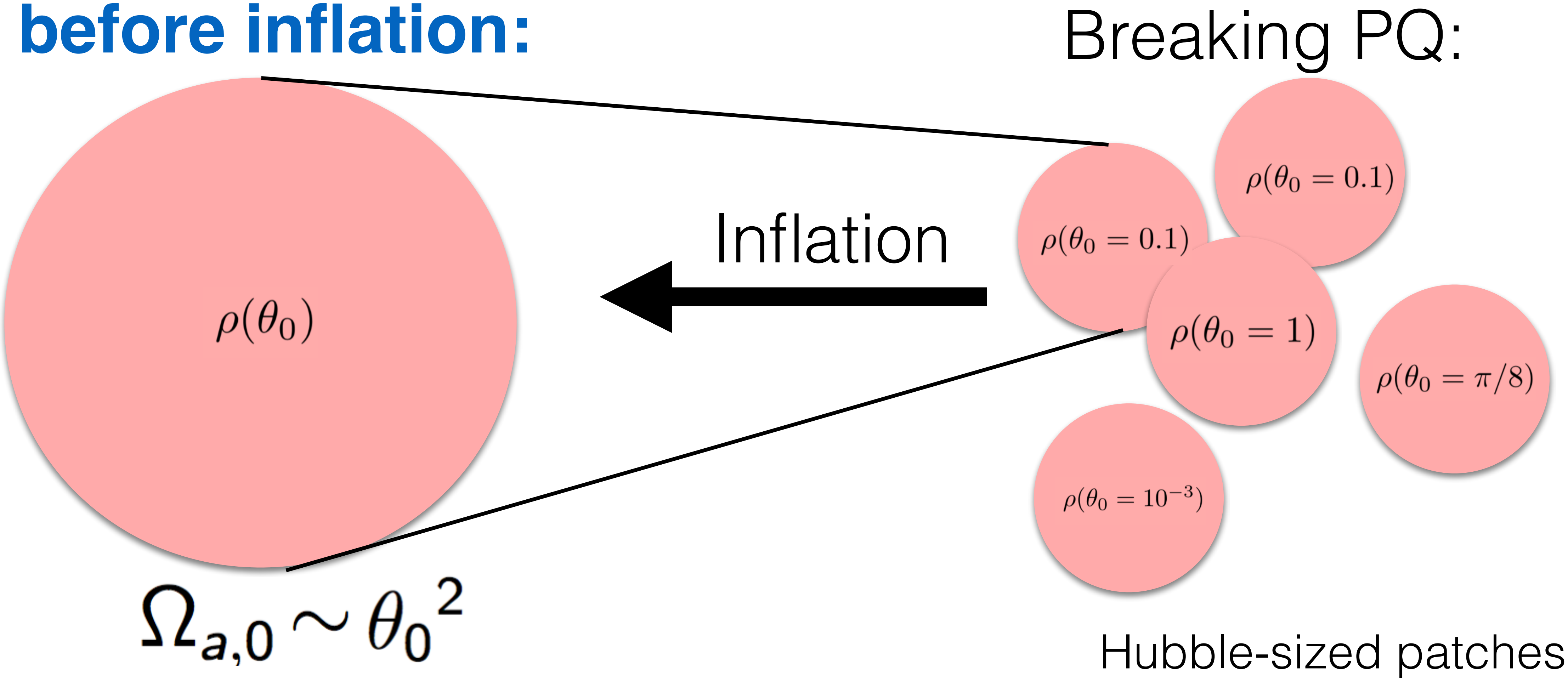

$\Omega_{a,0} \sim {\theta_0}^2$

two free parameters:
$\theta_0,\ f_a$

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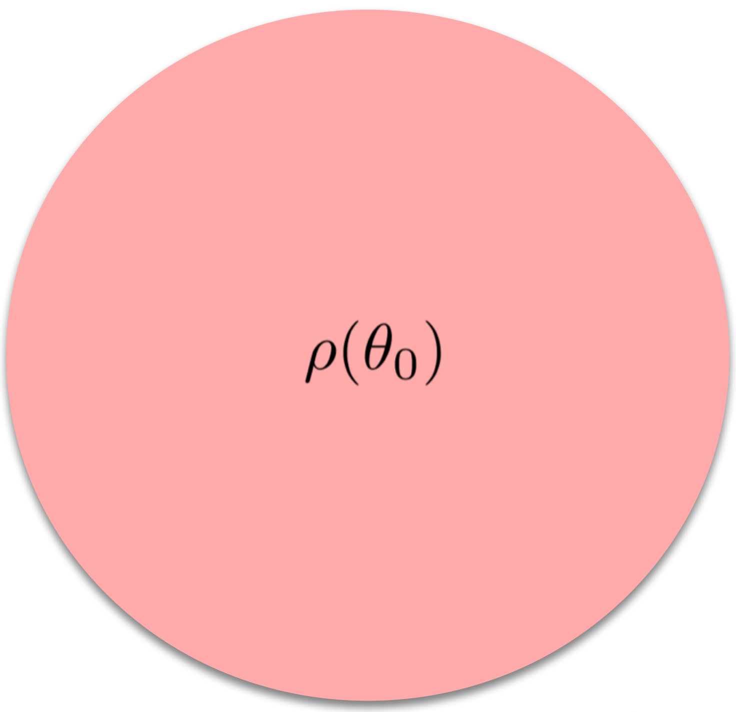

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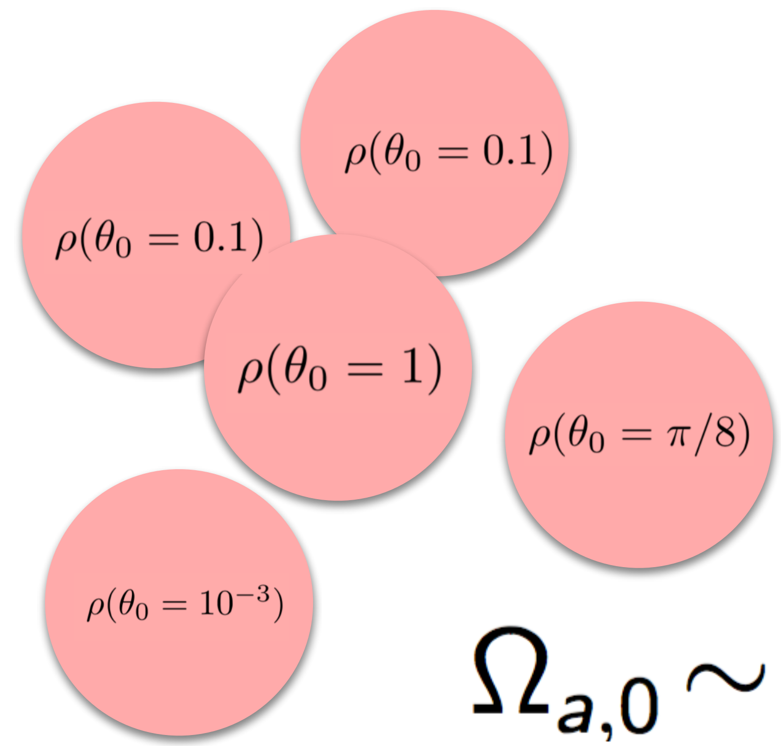
after inflation:

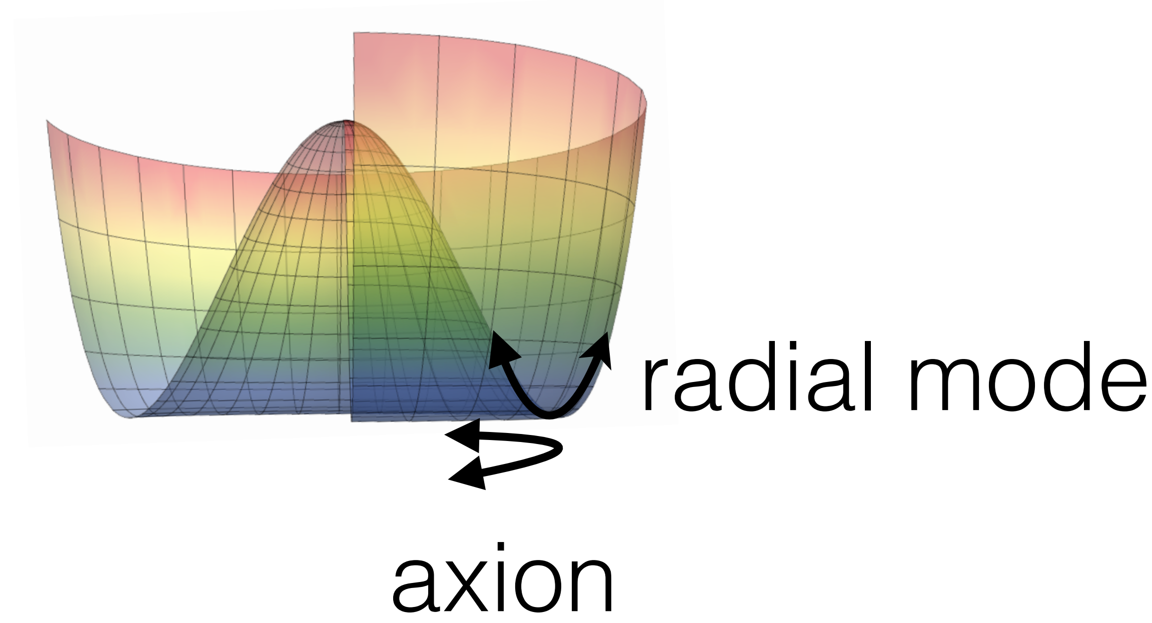


$$\Omega_{a,0} \sim \langle {\theta_0}^2 \rangle$$

one free parameter: f_a

@ $T \approx f_a$

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



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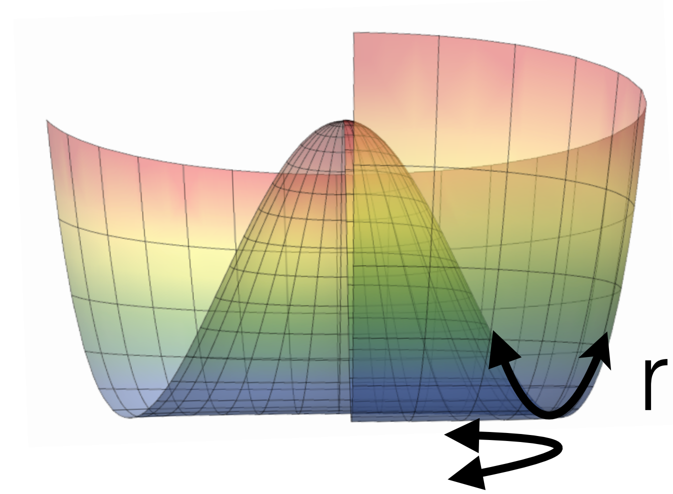

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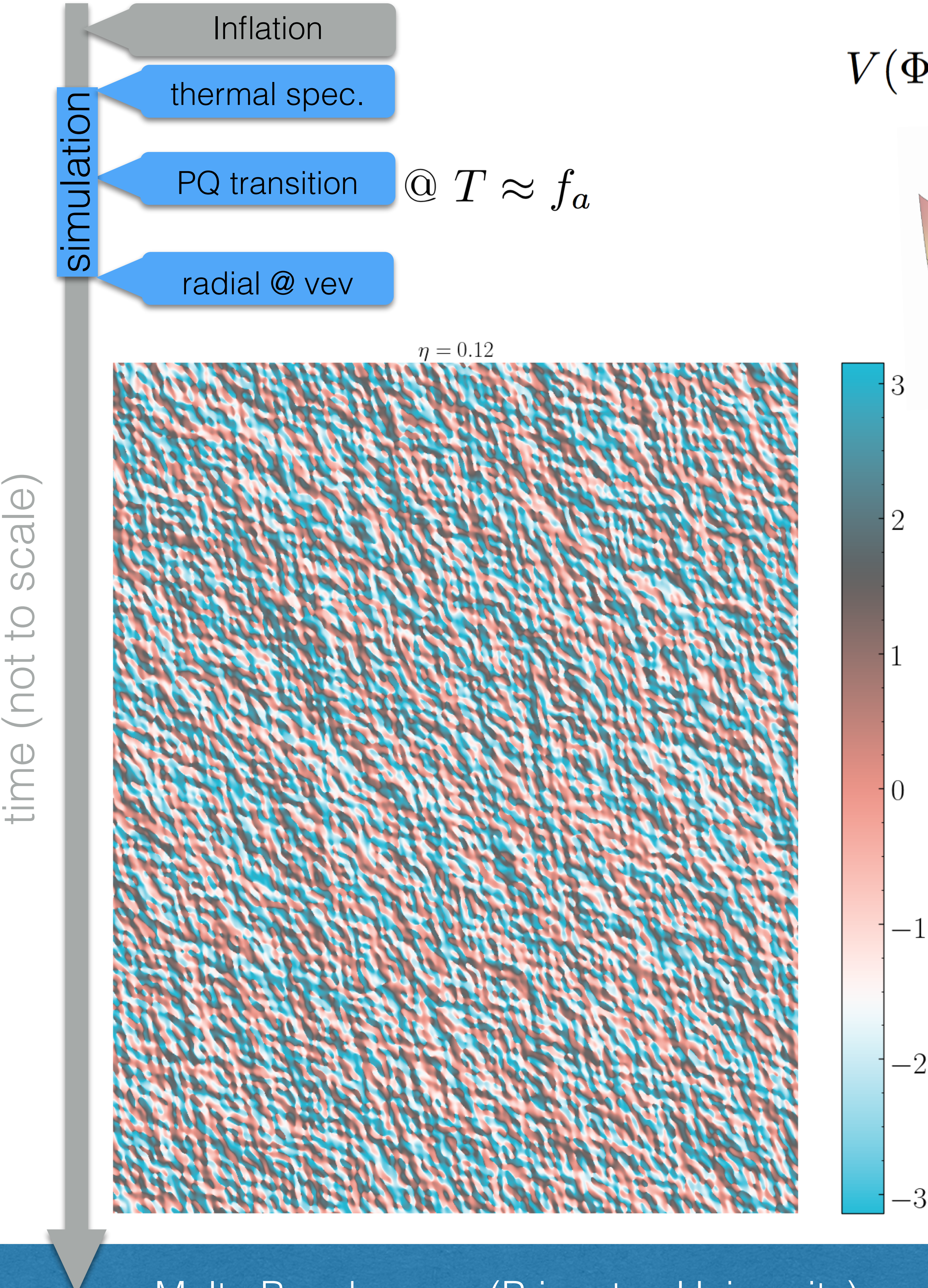
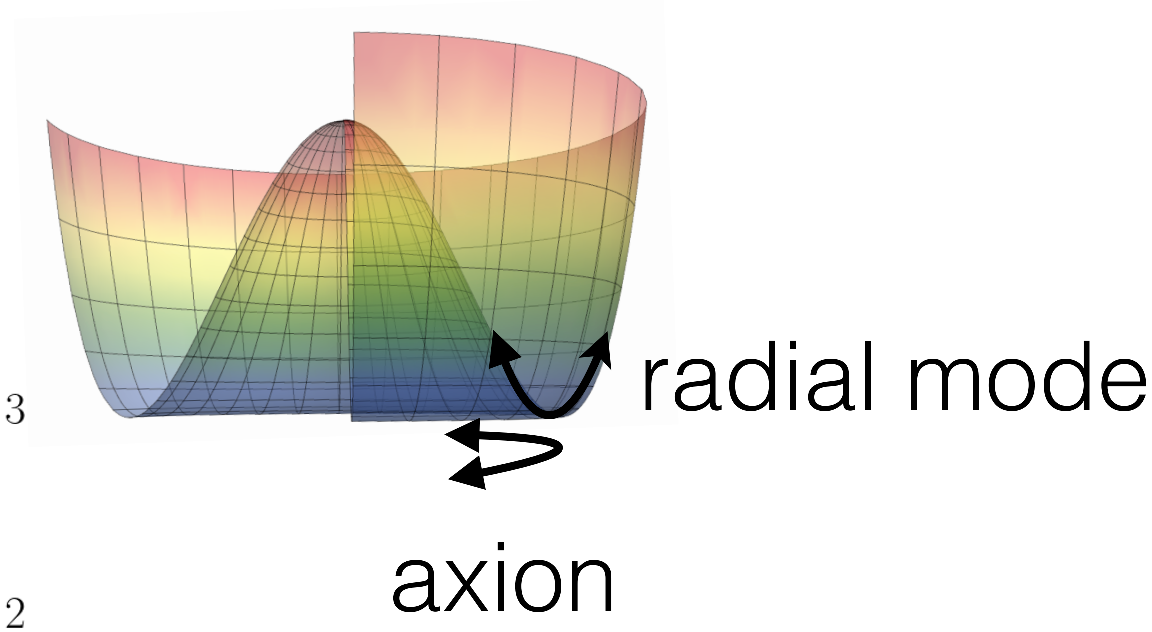
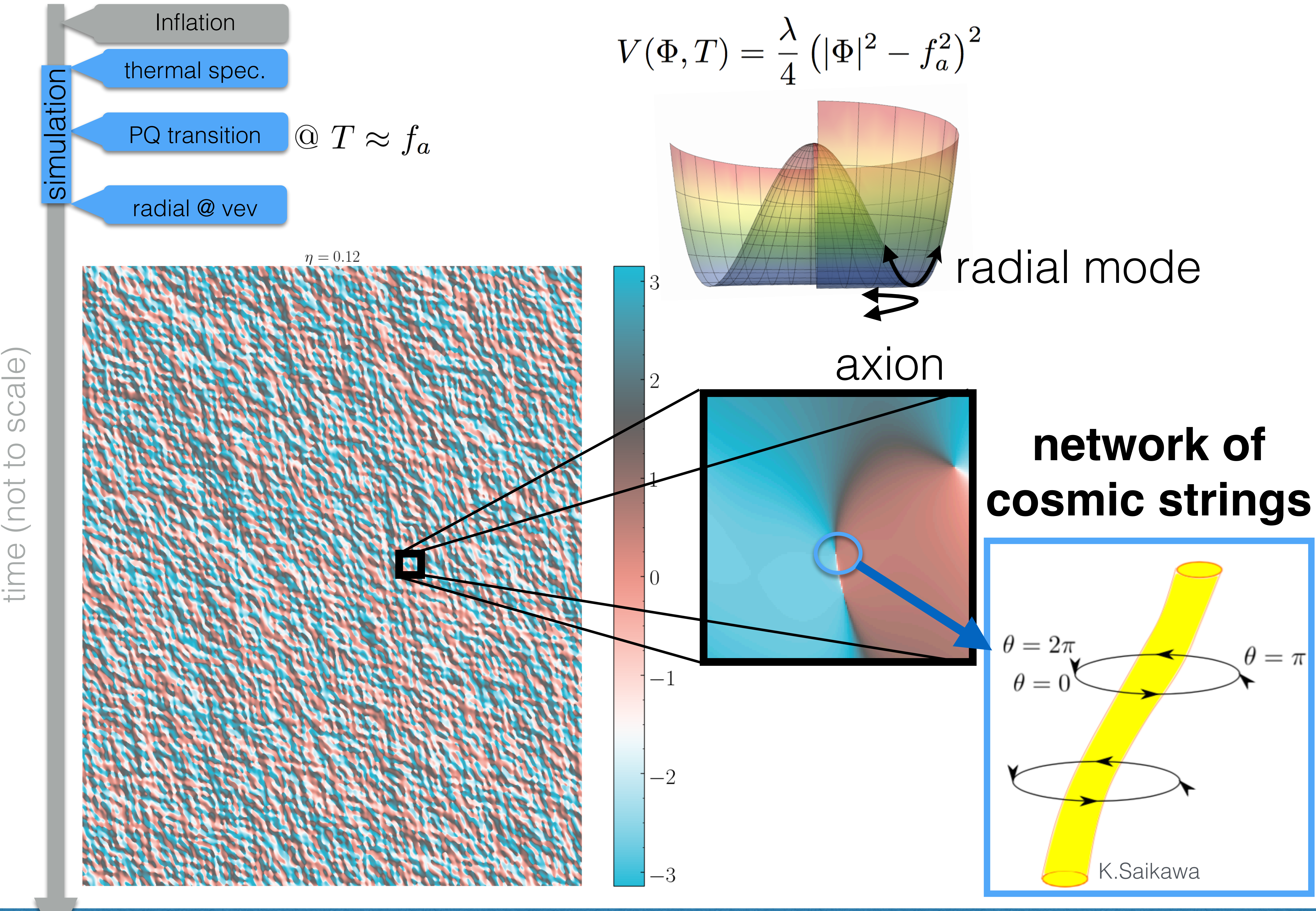




Solve Equations of Motion on a large 3D grid

(about 10^{11} grid sites)


Inflation
thermal spec.
PQ transition
@ $T \approx f_a$
radial @ vev
simulation
time (not to scale)
$V(\Phi, T) = \frac{\lambda}{4}\left(|\Phi|^2 - f_a^2\right)^2$
radial mode
axion
$\eta = 0.12$
3
2
1
0
−1
−2
−3
network of cosmic strings
$\theta = 2\pi$
$\theta = 0$
$\theta = \pi$
K.Saikawa

Inflation

simulation

thermal spec.

PQ transition @ $T \approx f_a$

radial @ vev

time (not to scale)

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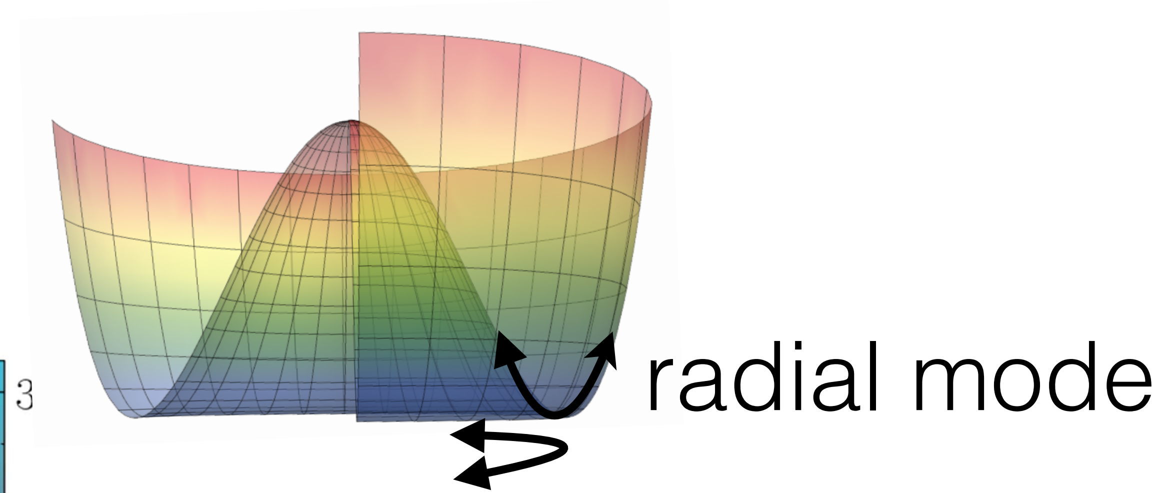
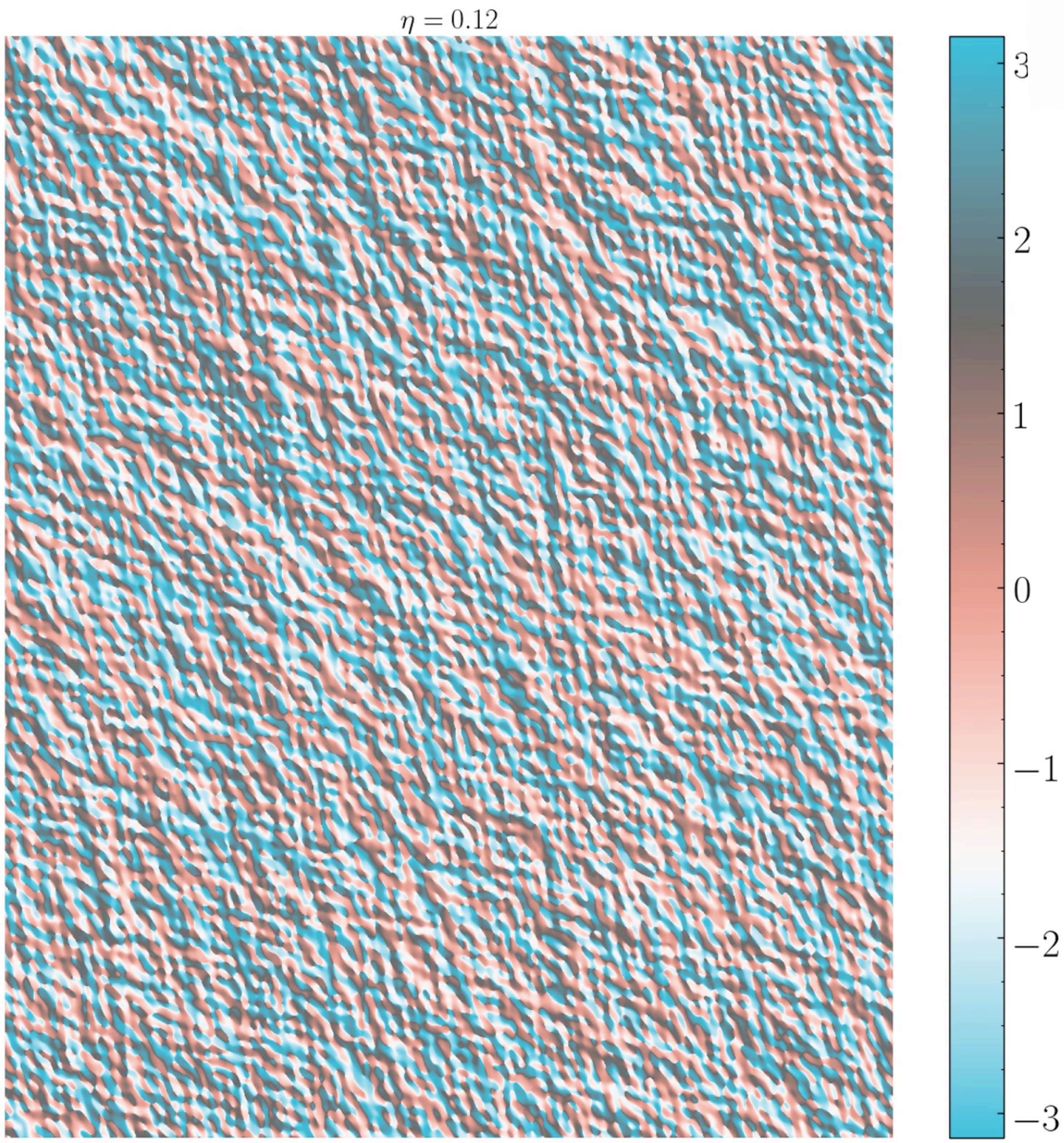




K.Saikawa

time (not to scale)

Inflation

simulation

thermal spec.

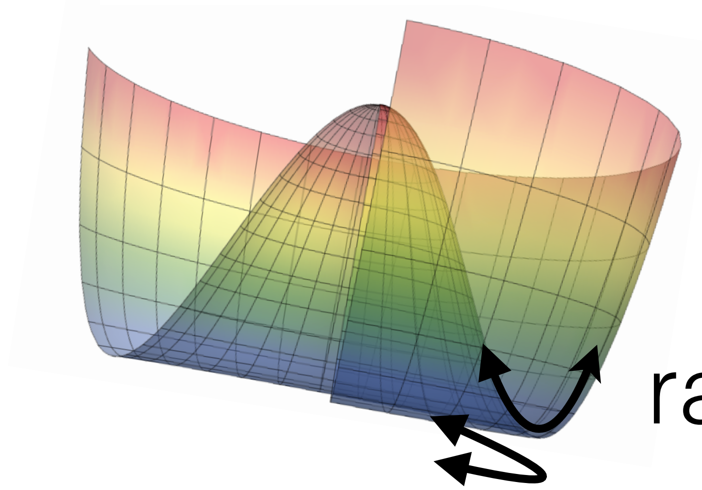
PQ transition

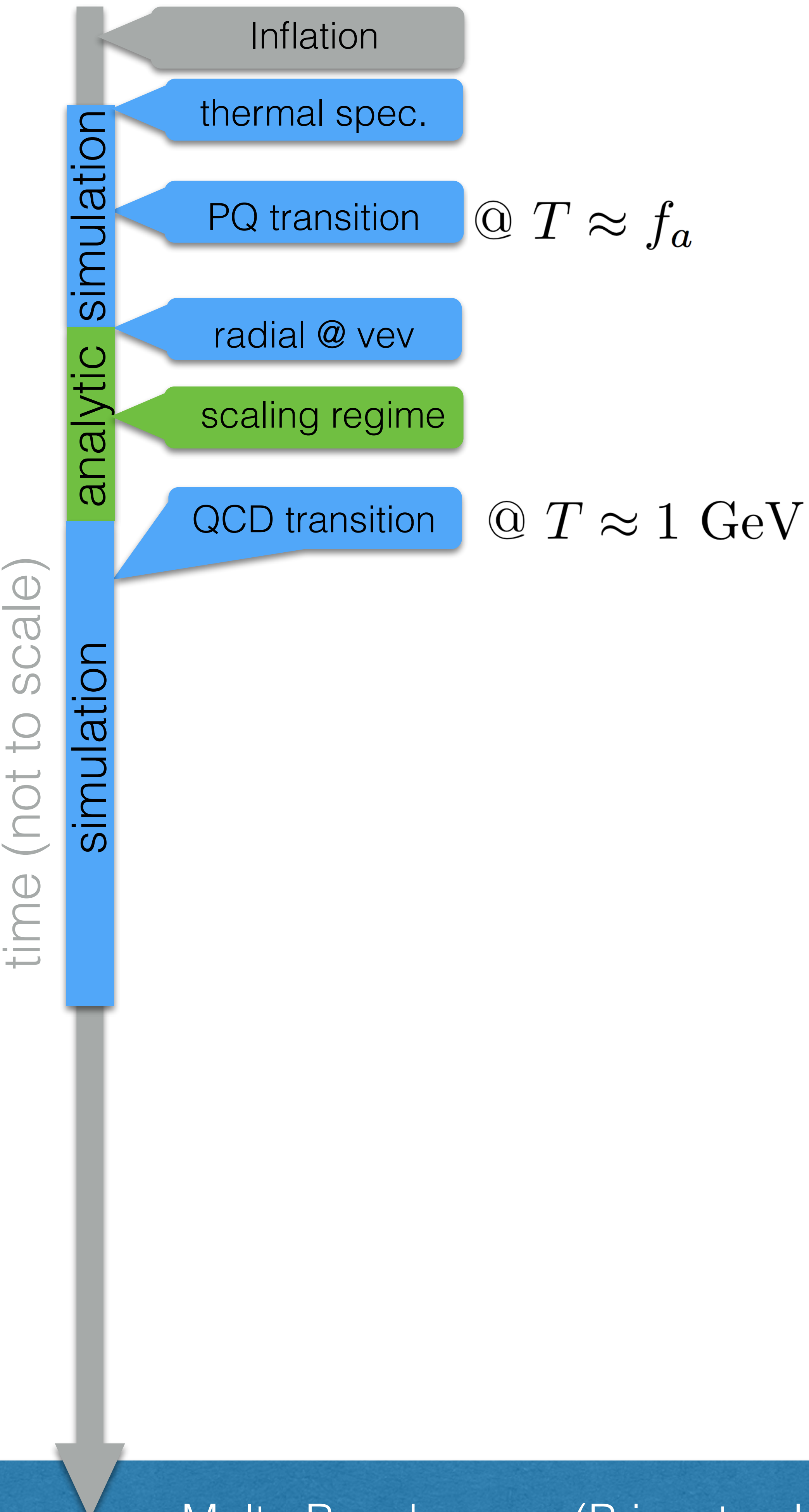
radial @ vev

QCD transition $@\ T \approx 1\ \mathrm{GeV}$

simulation

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





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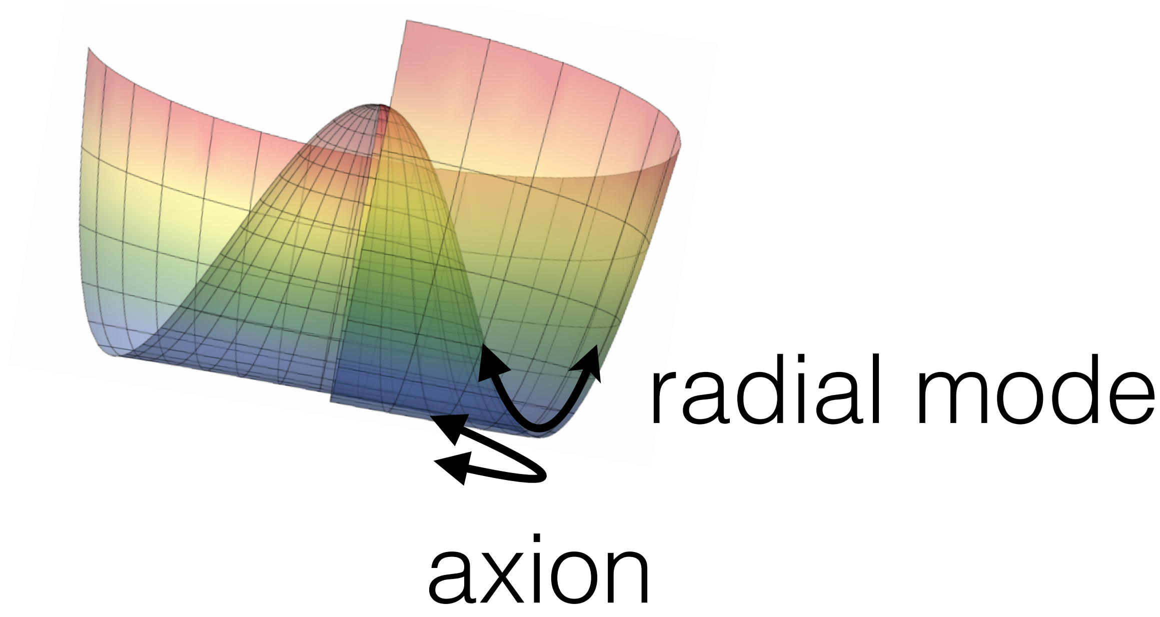

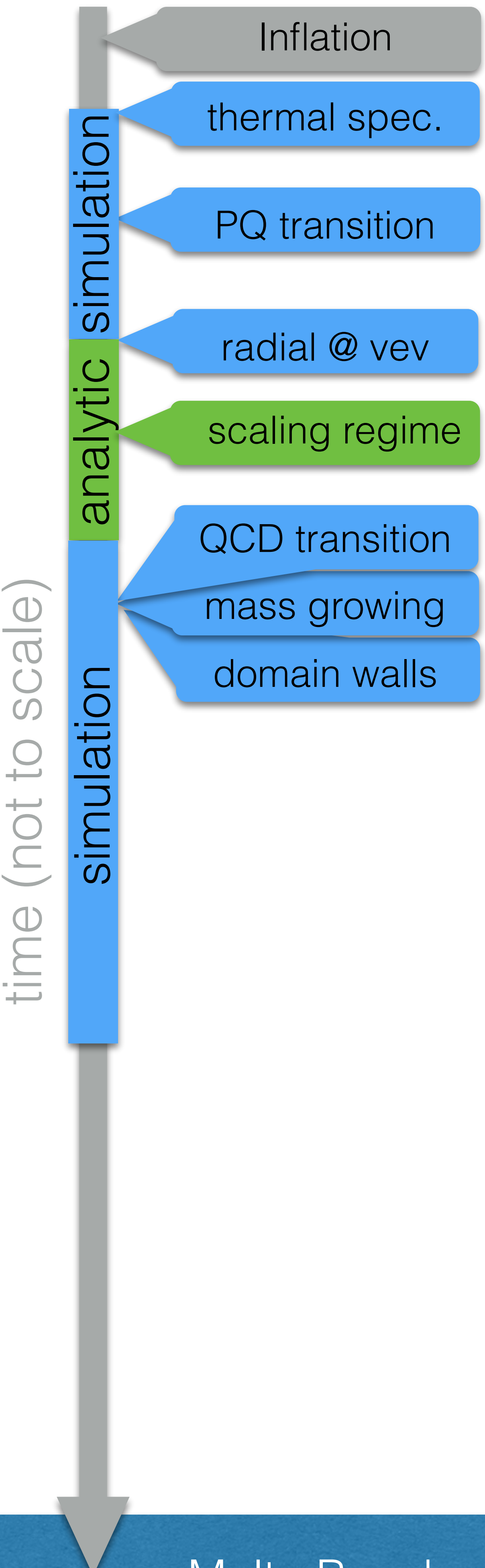

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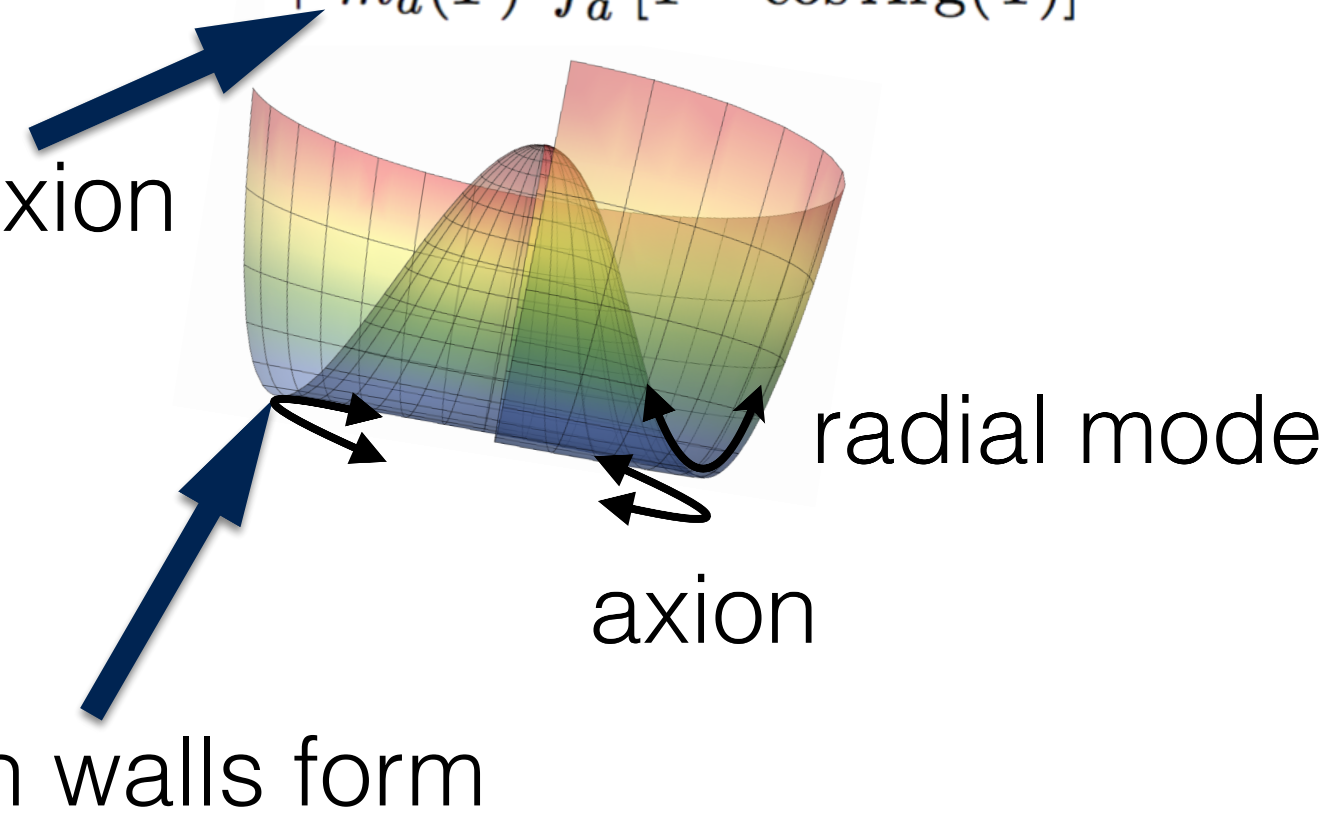
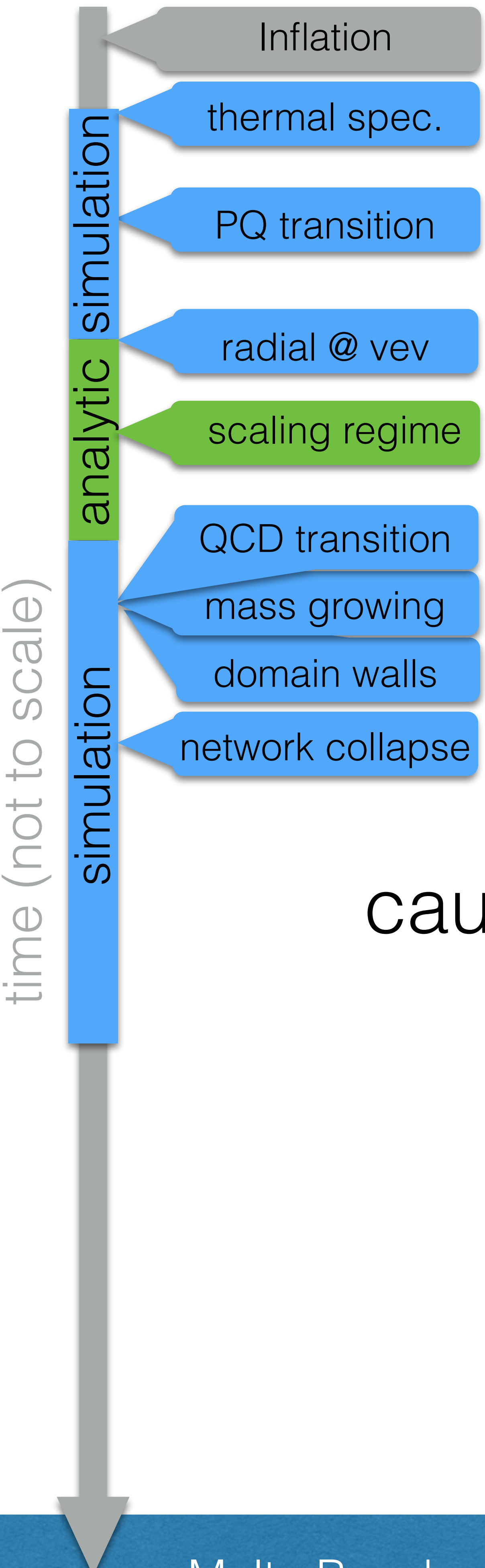
$@\ T \approx 1\ \mathrm{GeV}$





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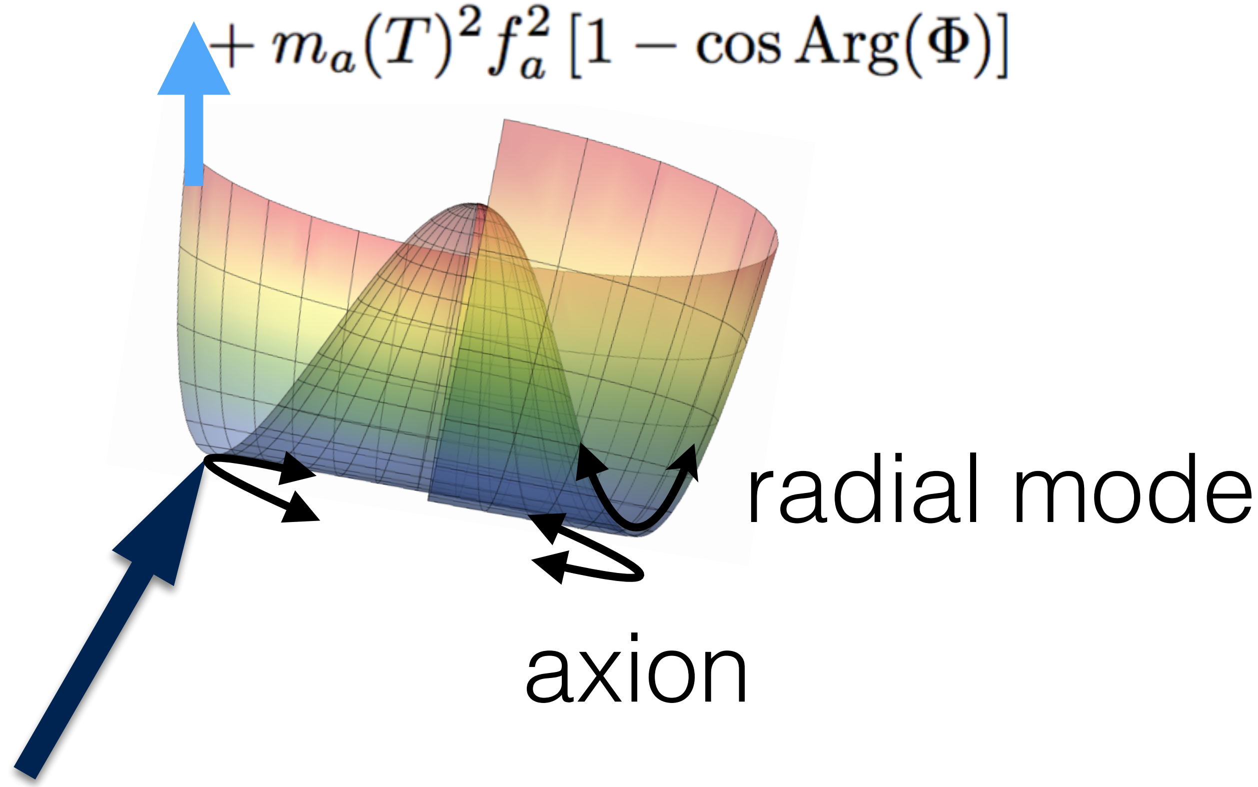
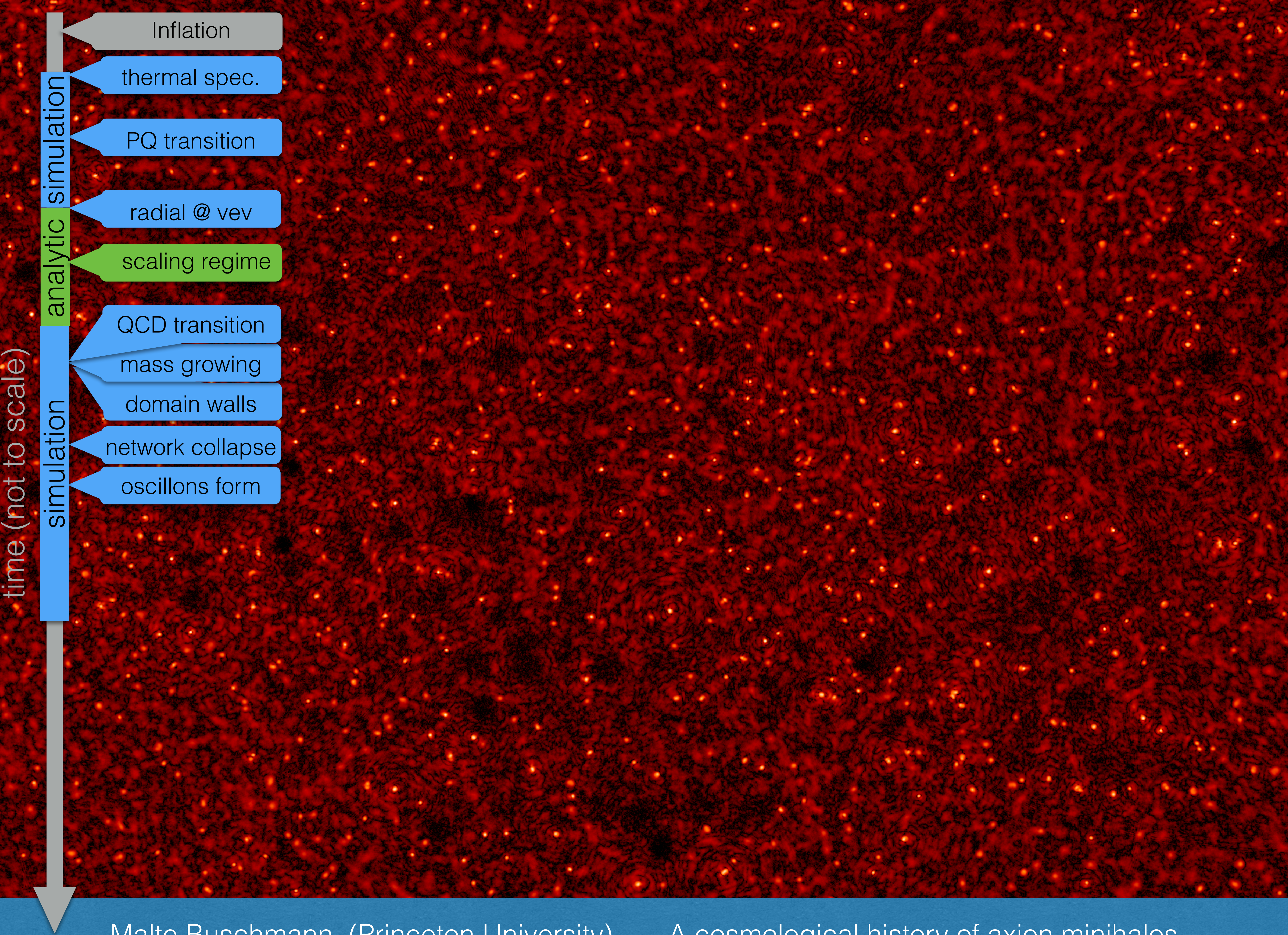
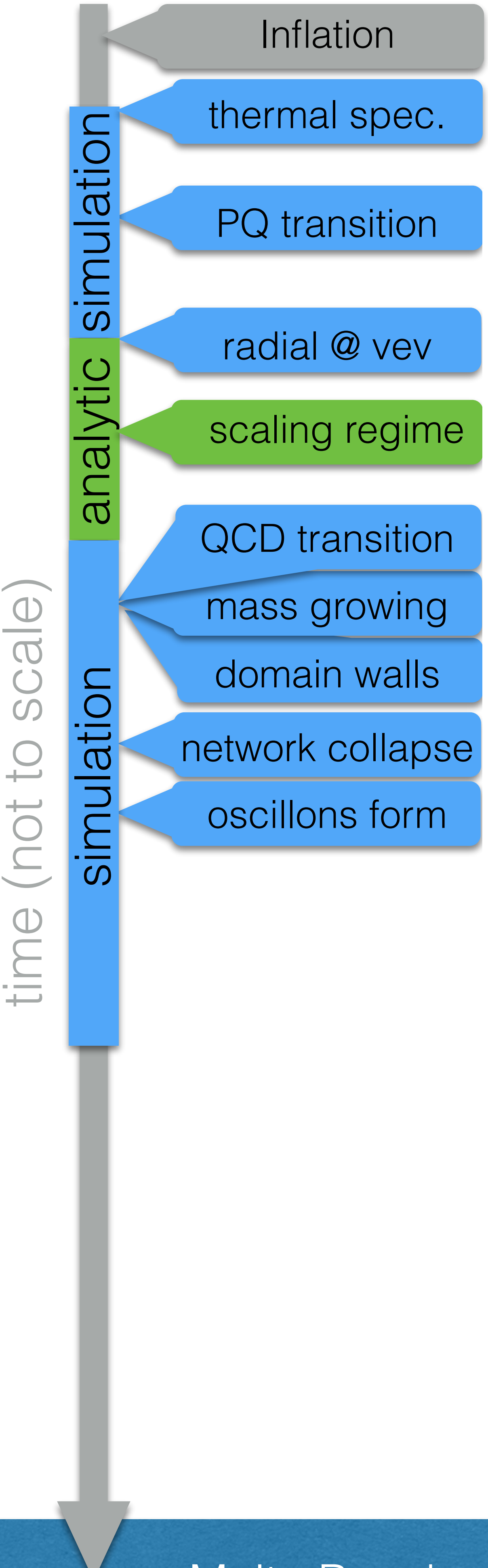


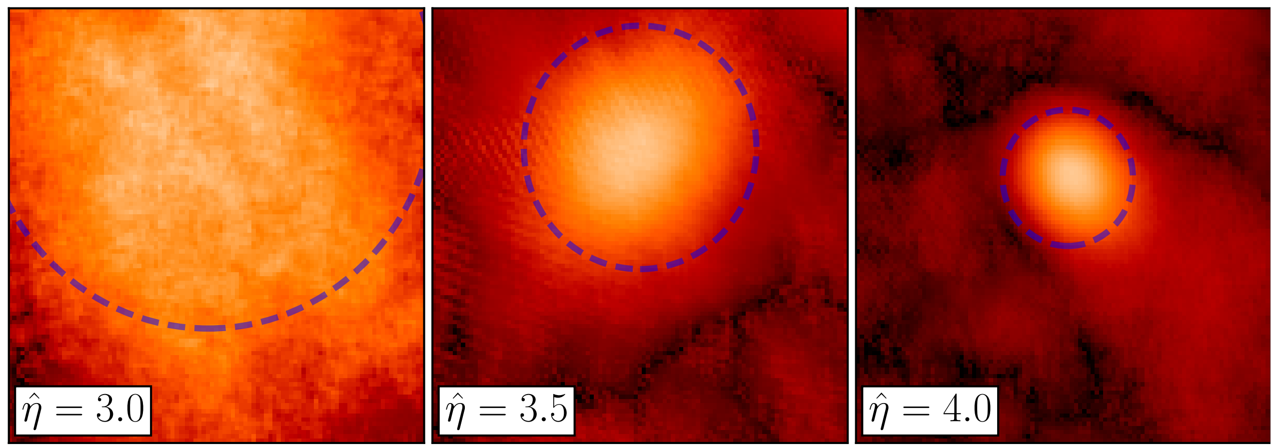
tension in domain walls
causes string-domain wall network
to collapse

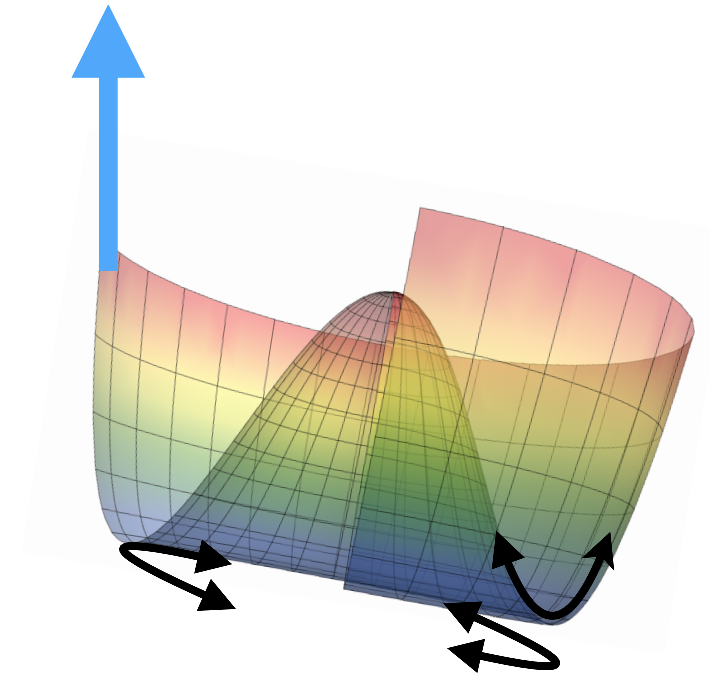

Inflation
thermal spec.
PQ transition
radial @ vev
scaling regime
QCD transition
mass growing
domain walls
network collapse
oscillons form
simulation
analytic
simulation
time (not to scale)



Evolution of Oscillons

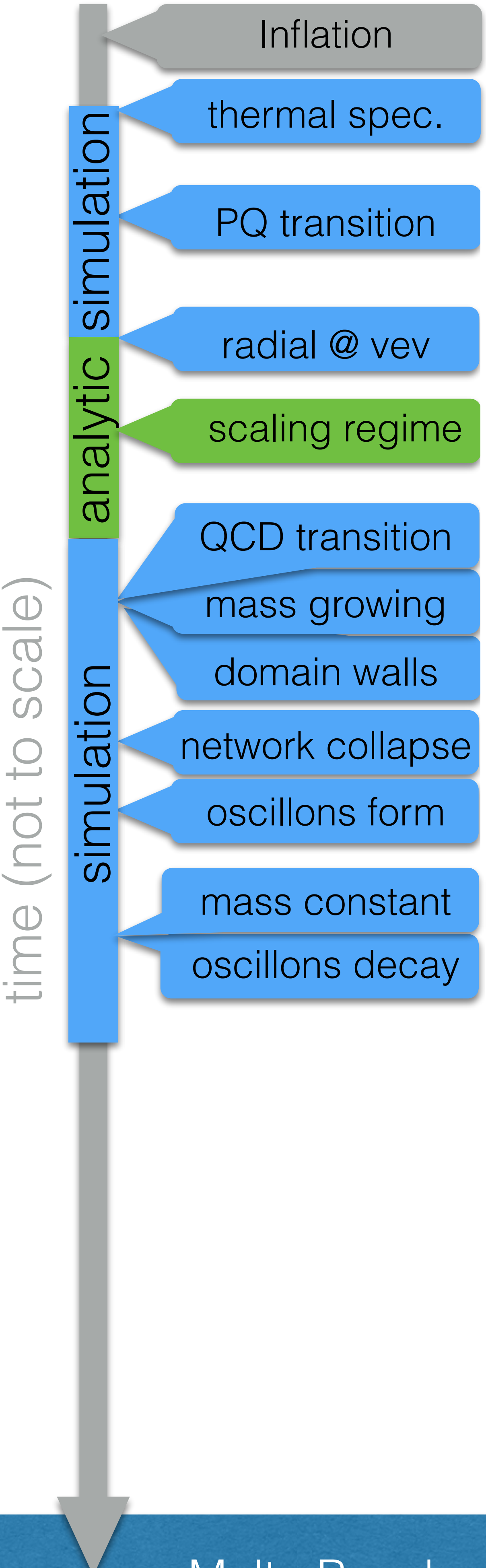
$$m_a(T)^2 f_a^2 \left[1 - \cos \mathrm{Arg}(\Phi)\right]$$





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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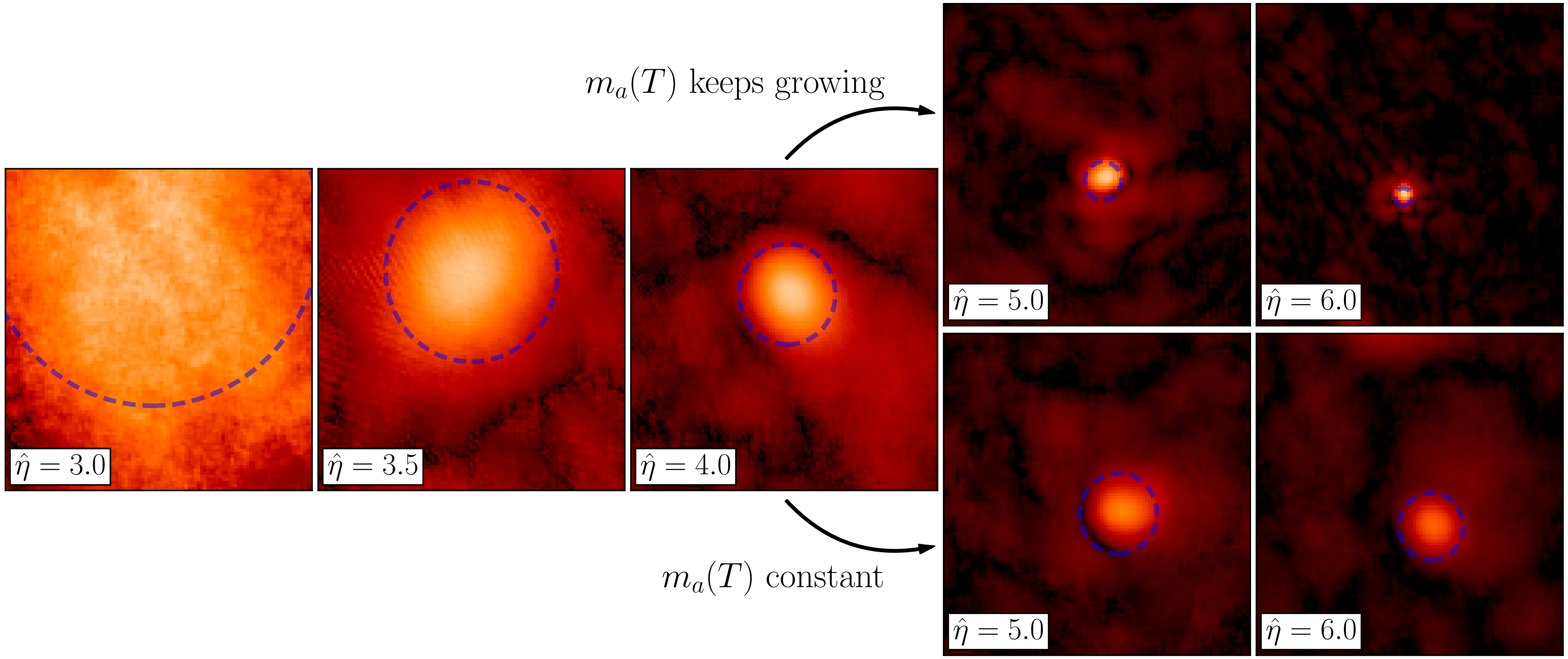

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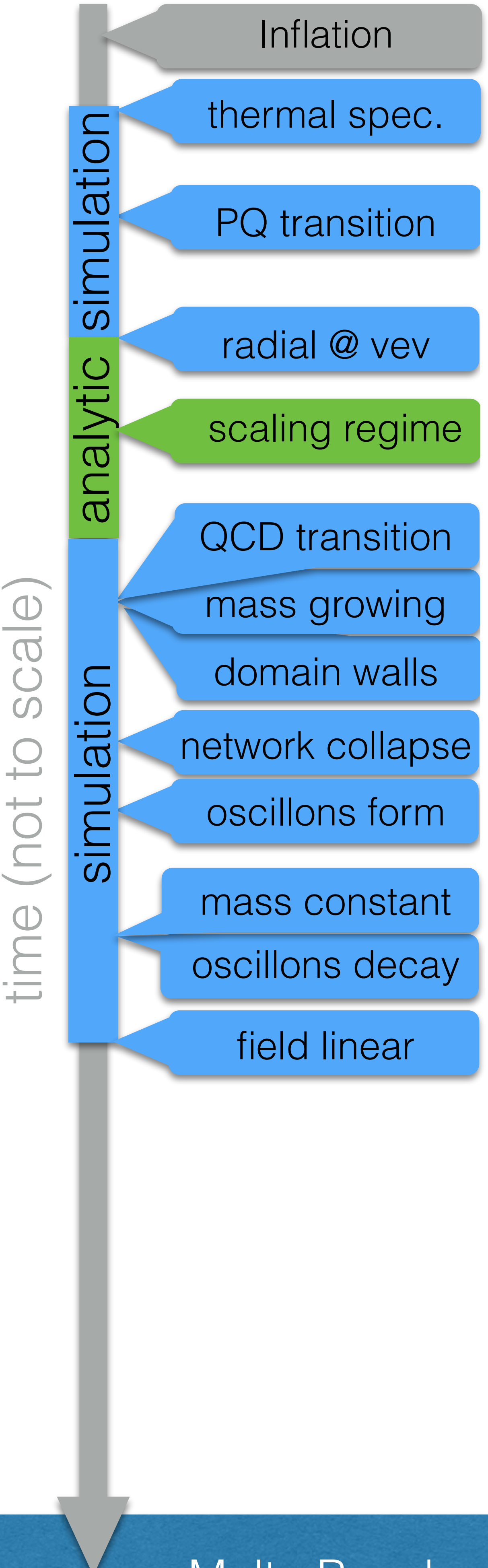

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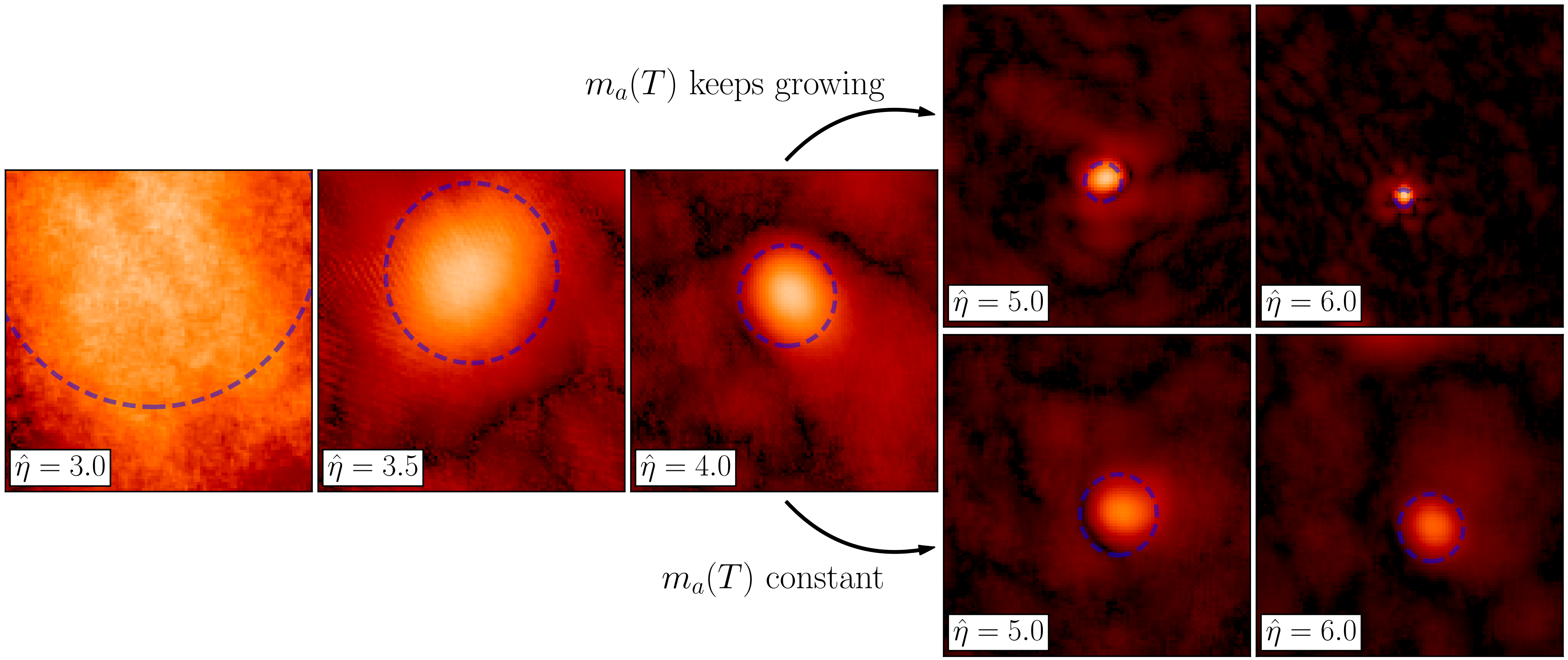

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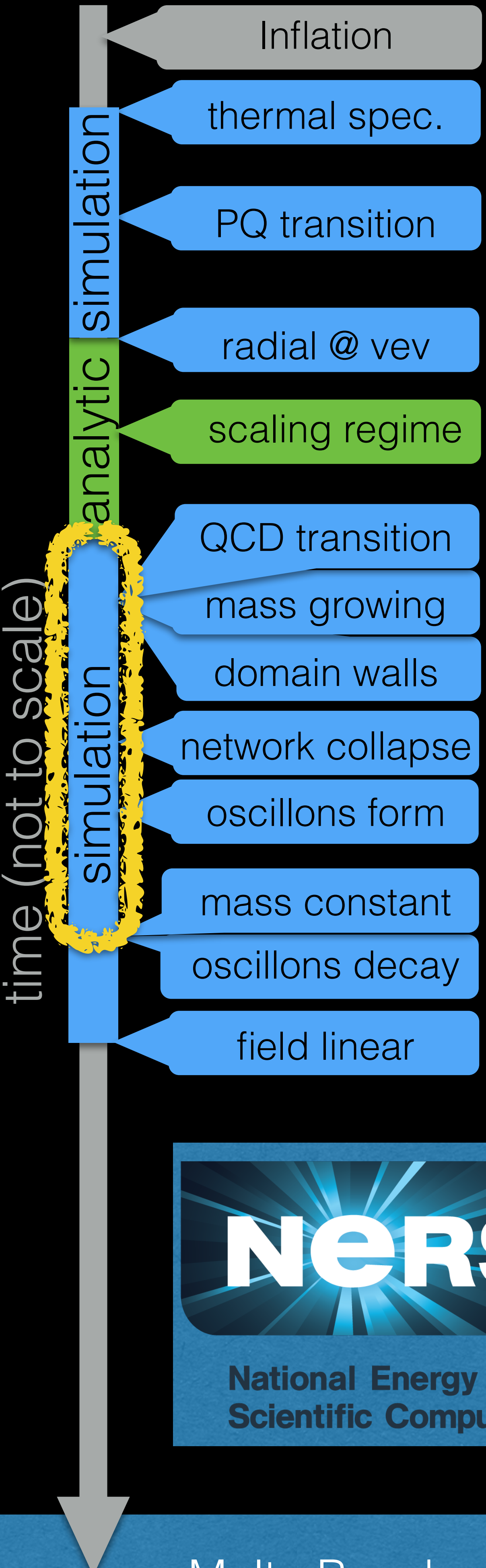

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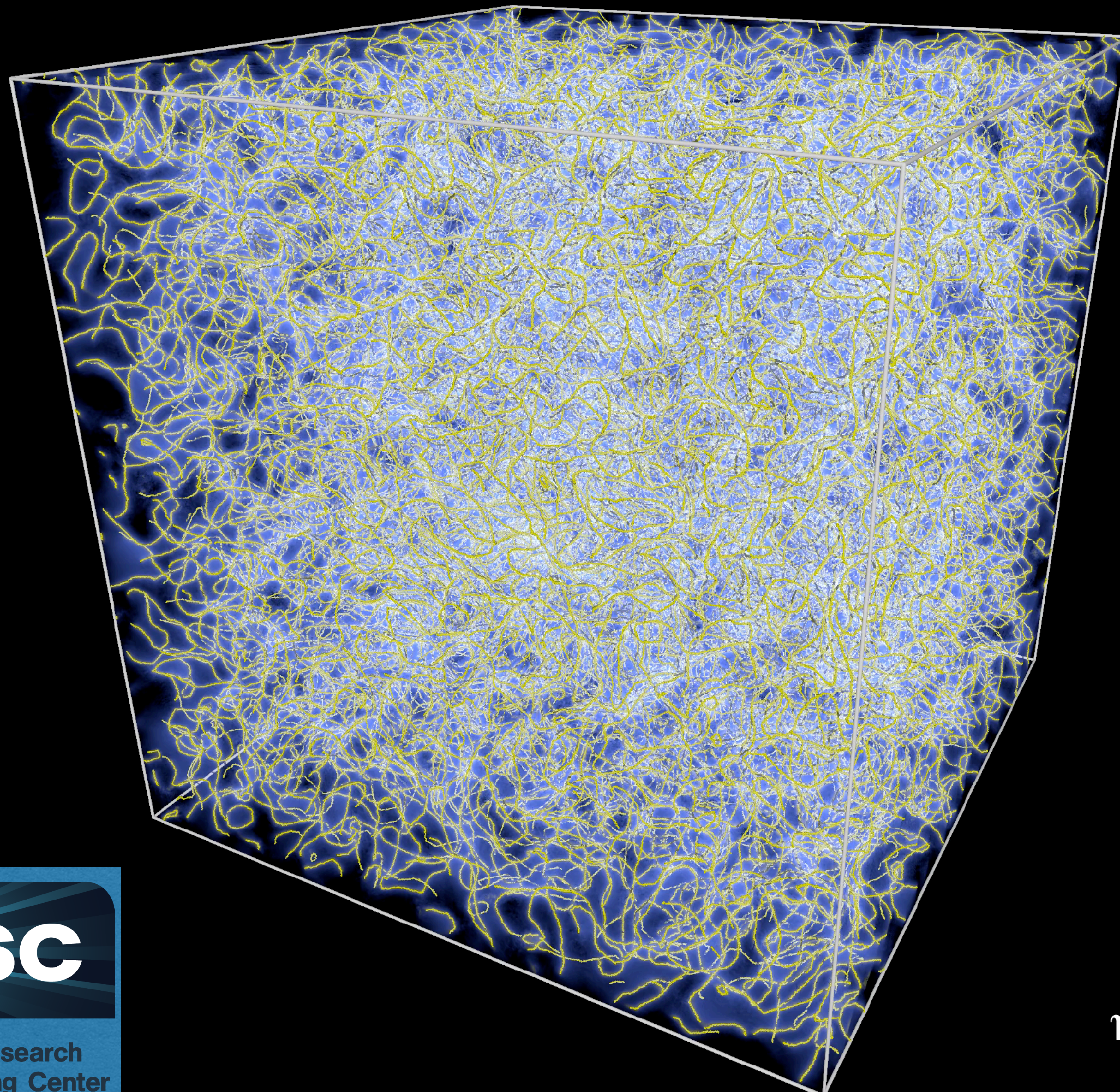

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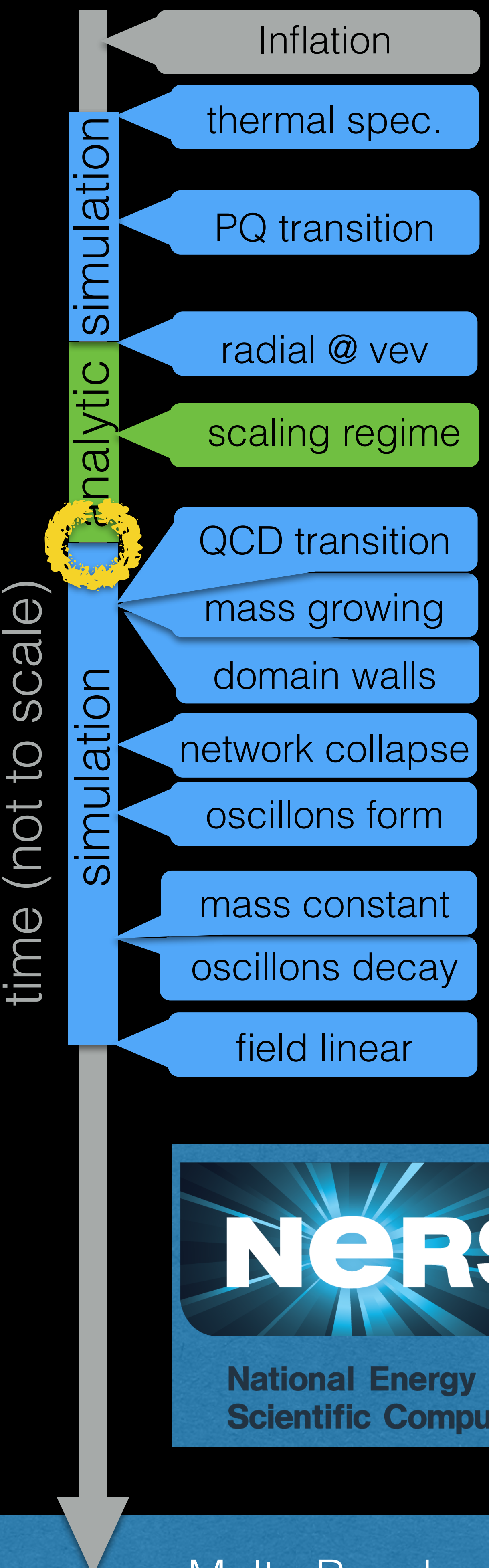
https://youtu.be/1By1DMq1EpI



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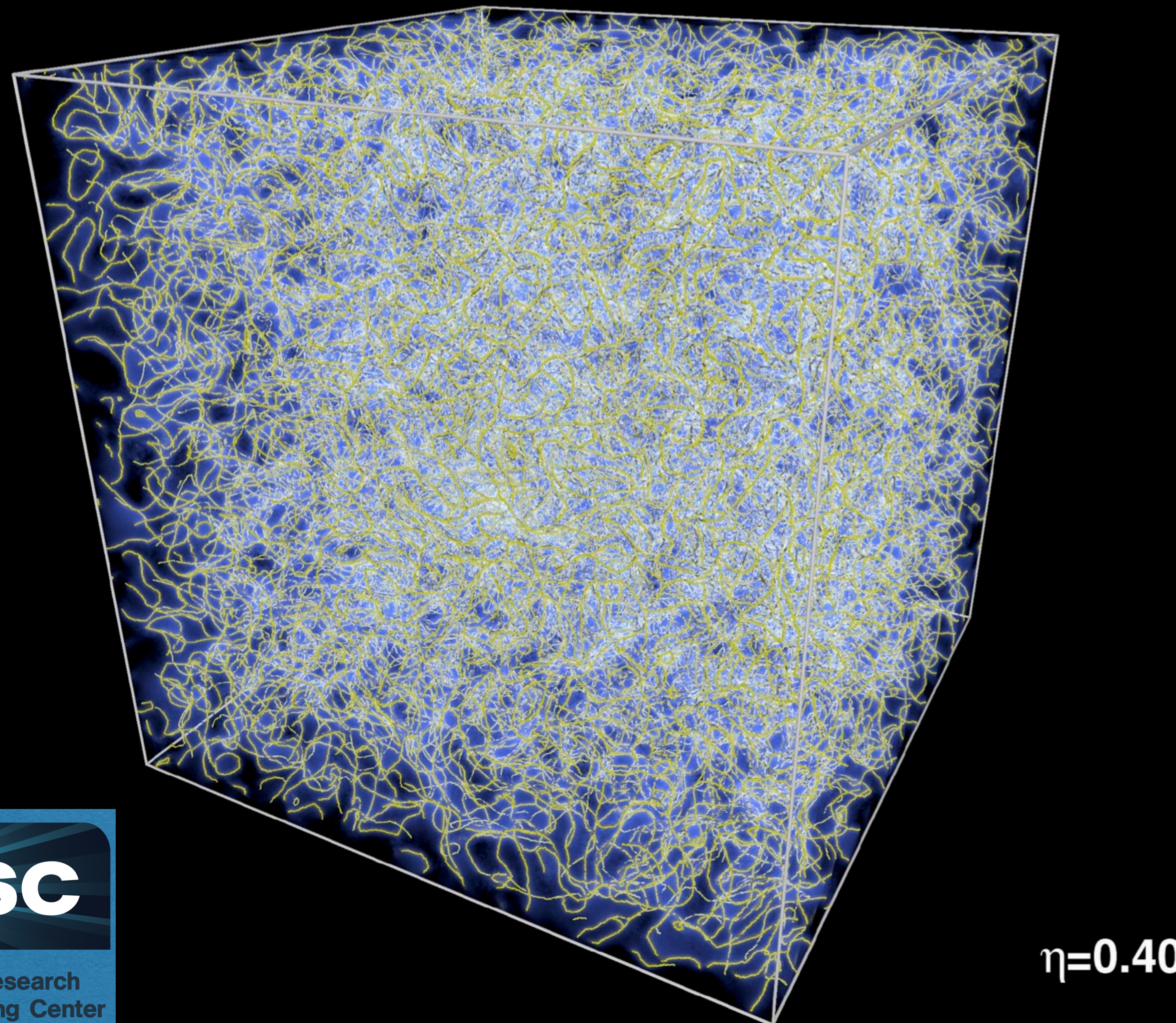

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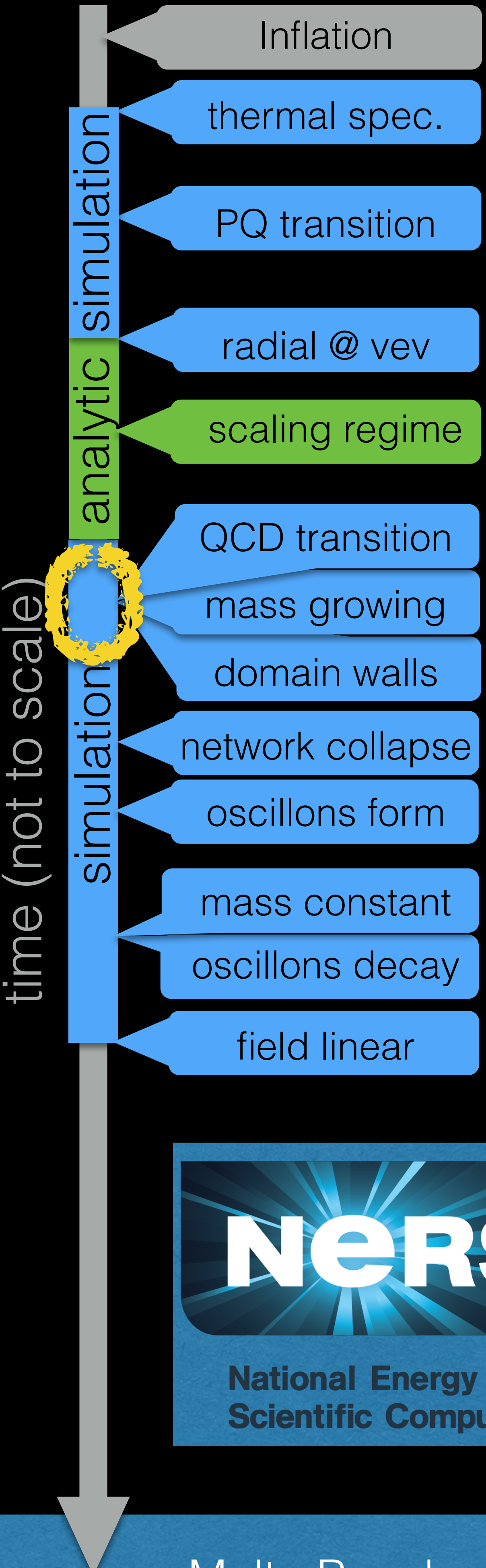

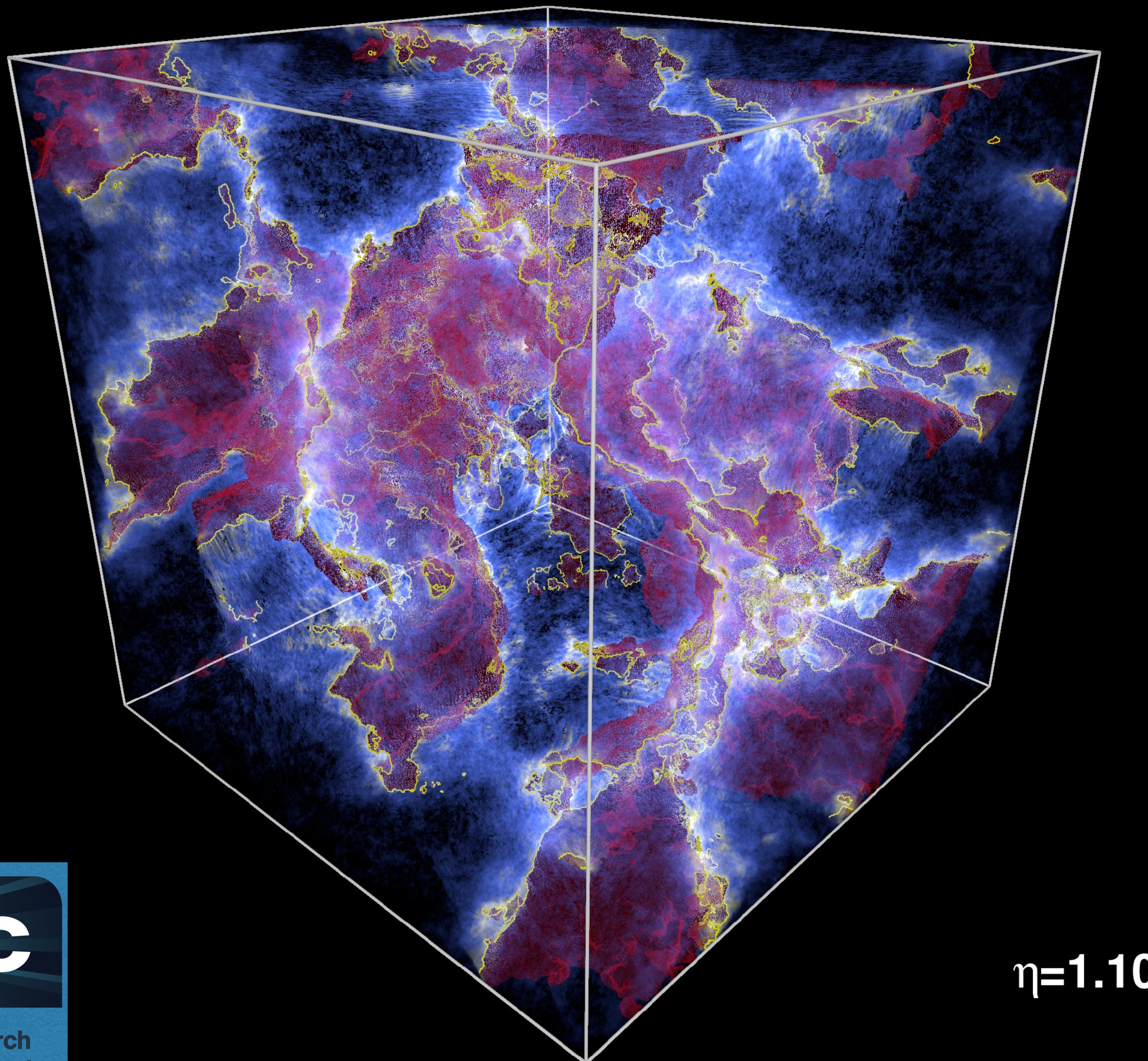

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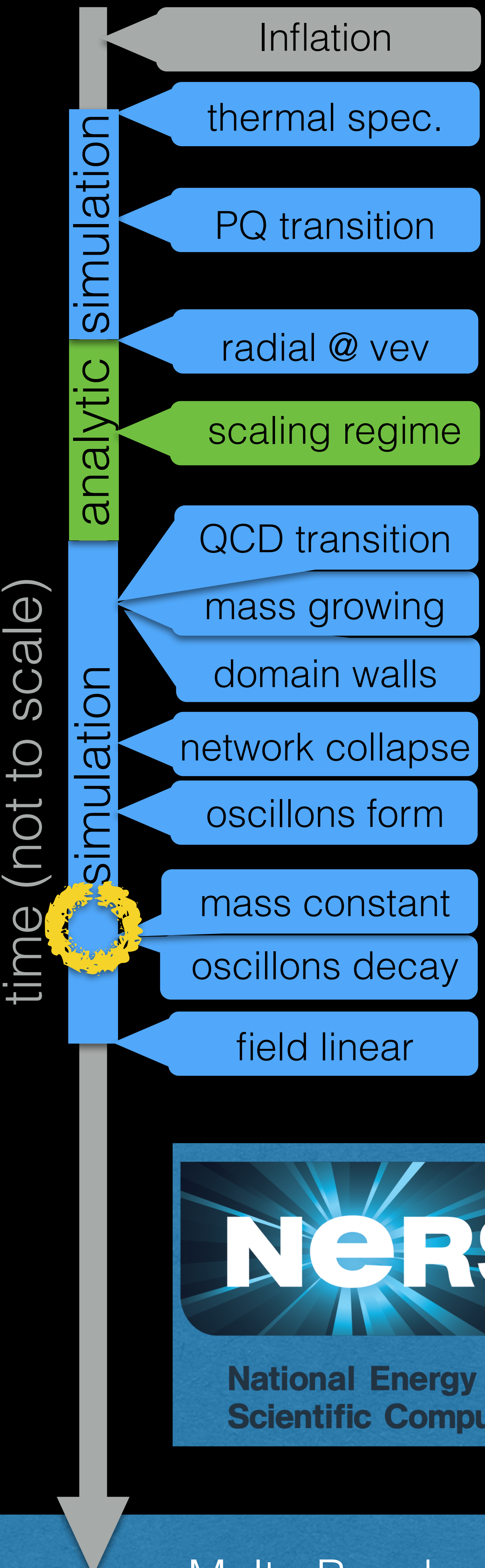

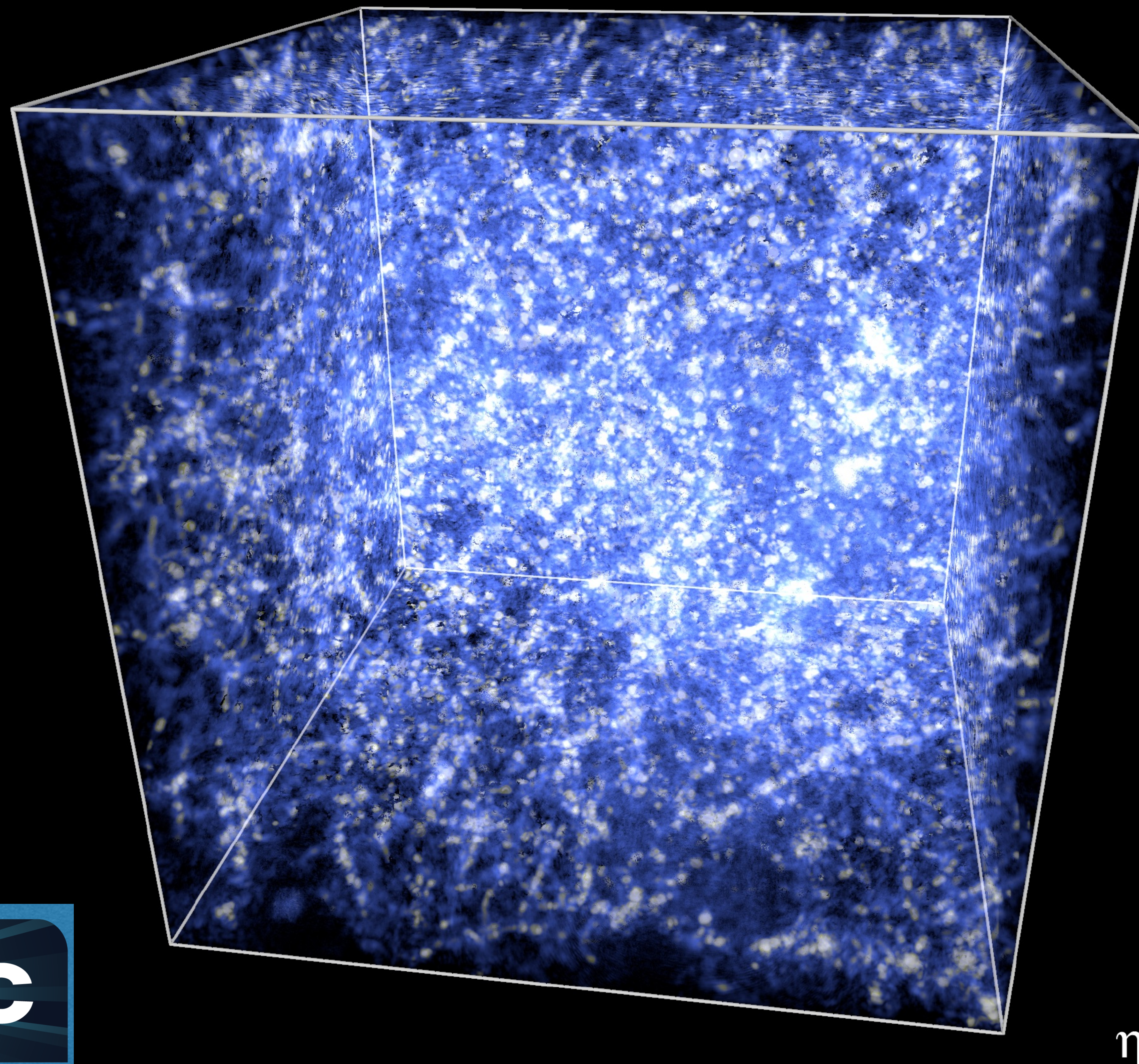

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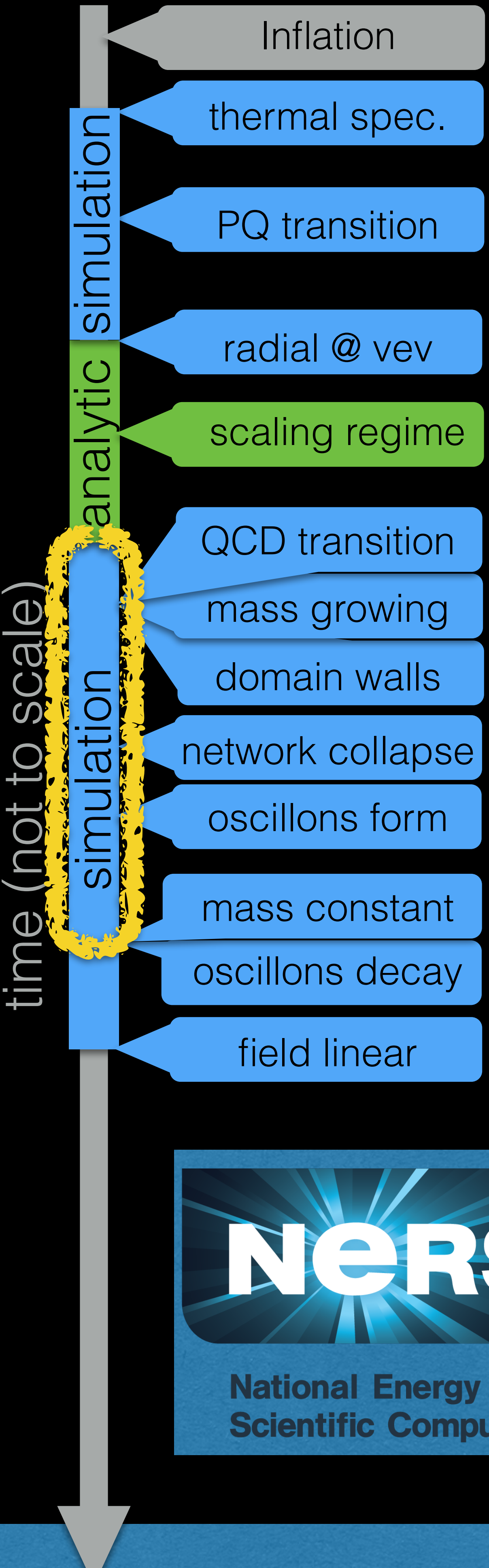

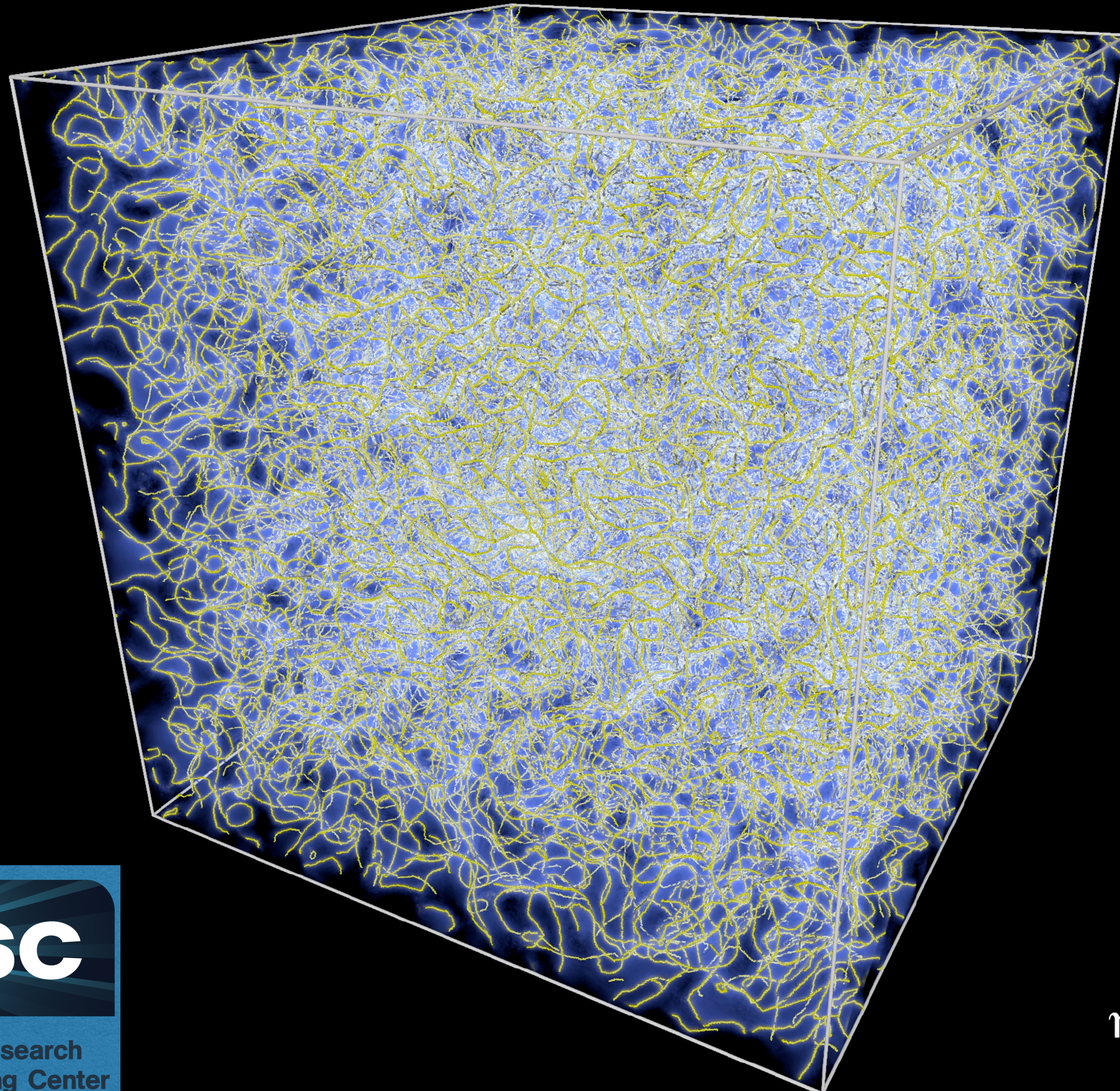

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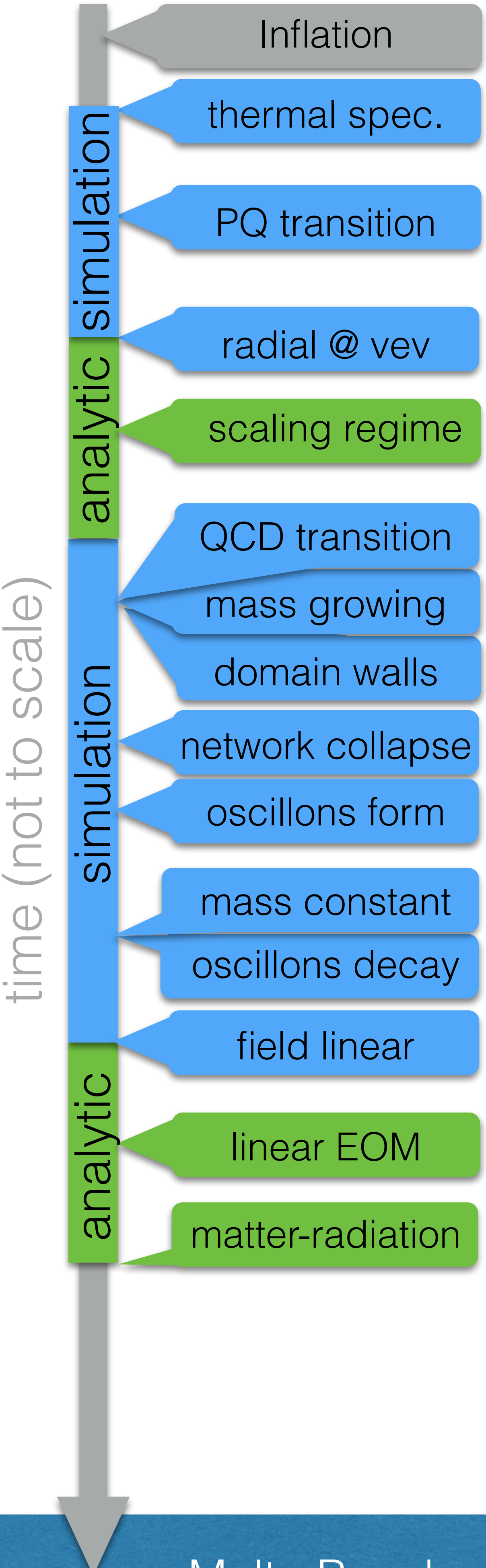
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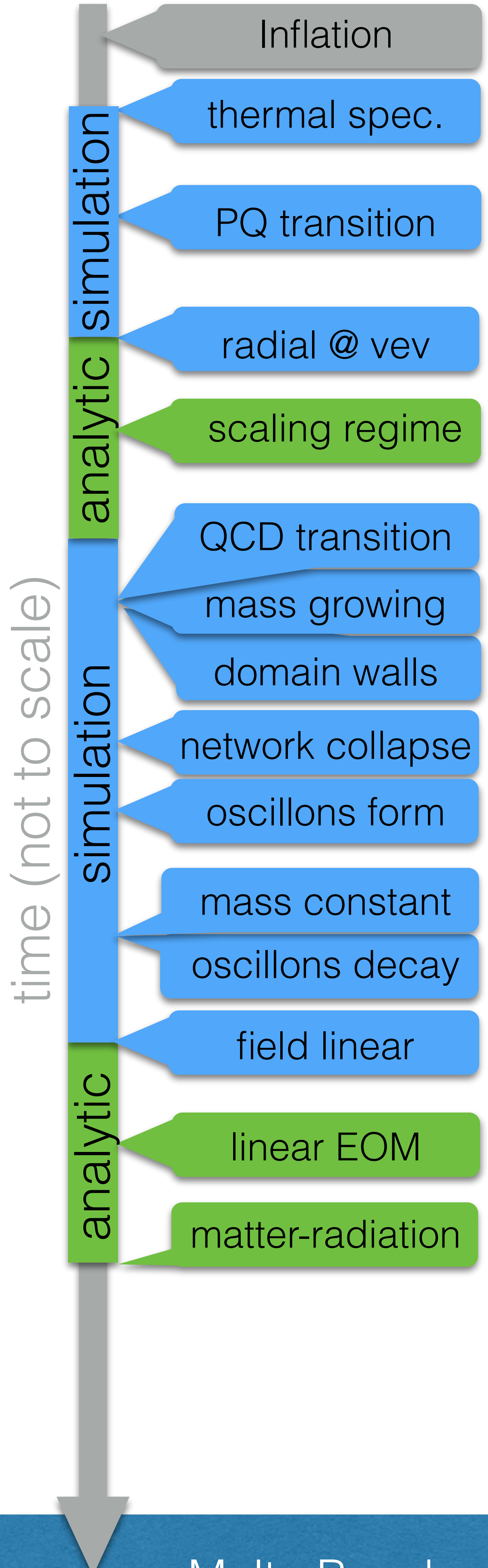
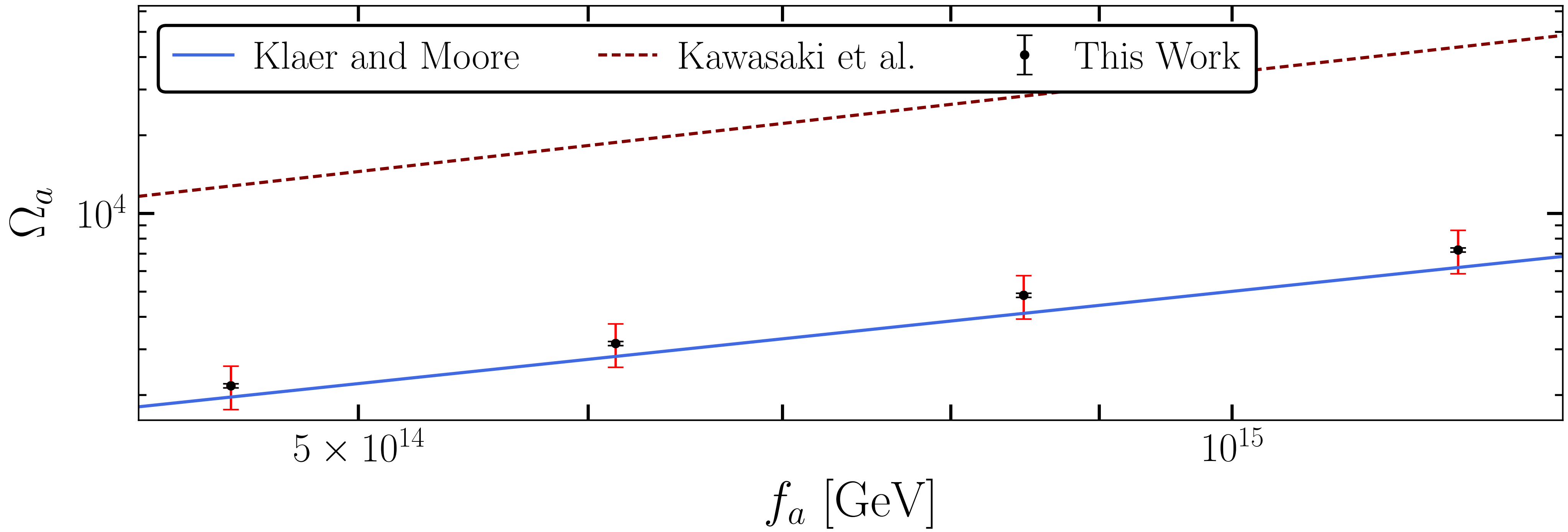
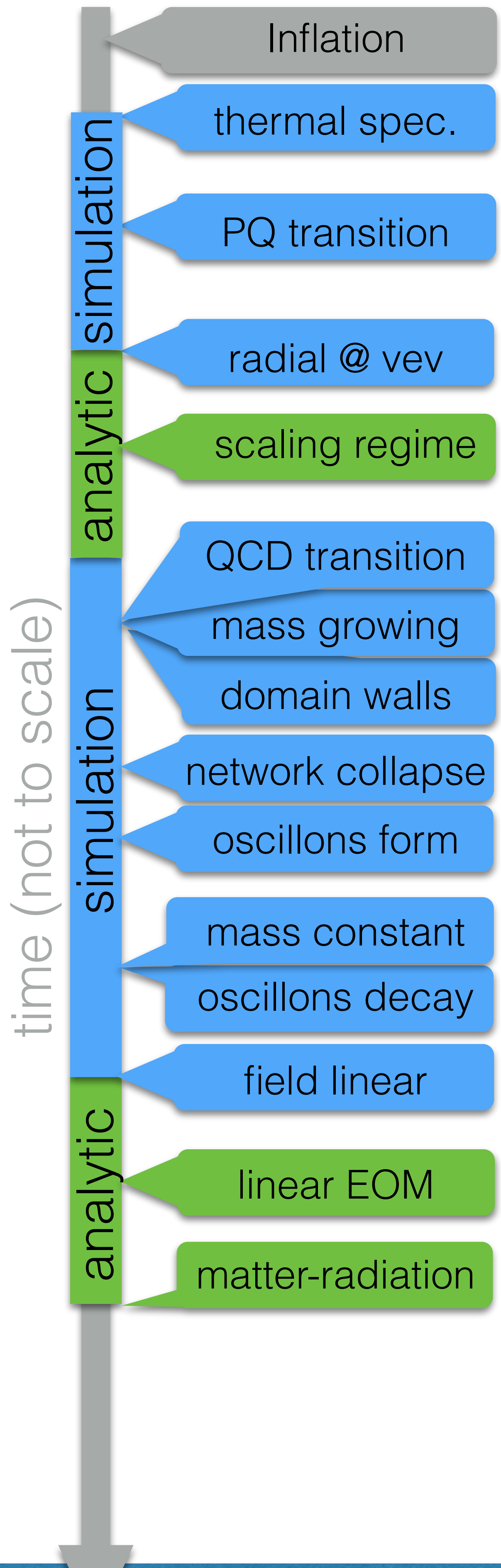
QCD transition
mass growing
domain walls
network collapse
oscillons form
mass constant
oscillons decay
field linear
linear EOM
matter-radiation
simulation
analytic
simulation
analytic
time (not to scale)

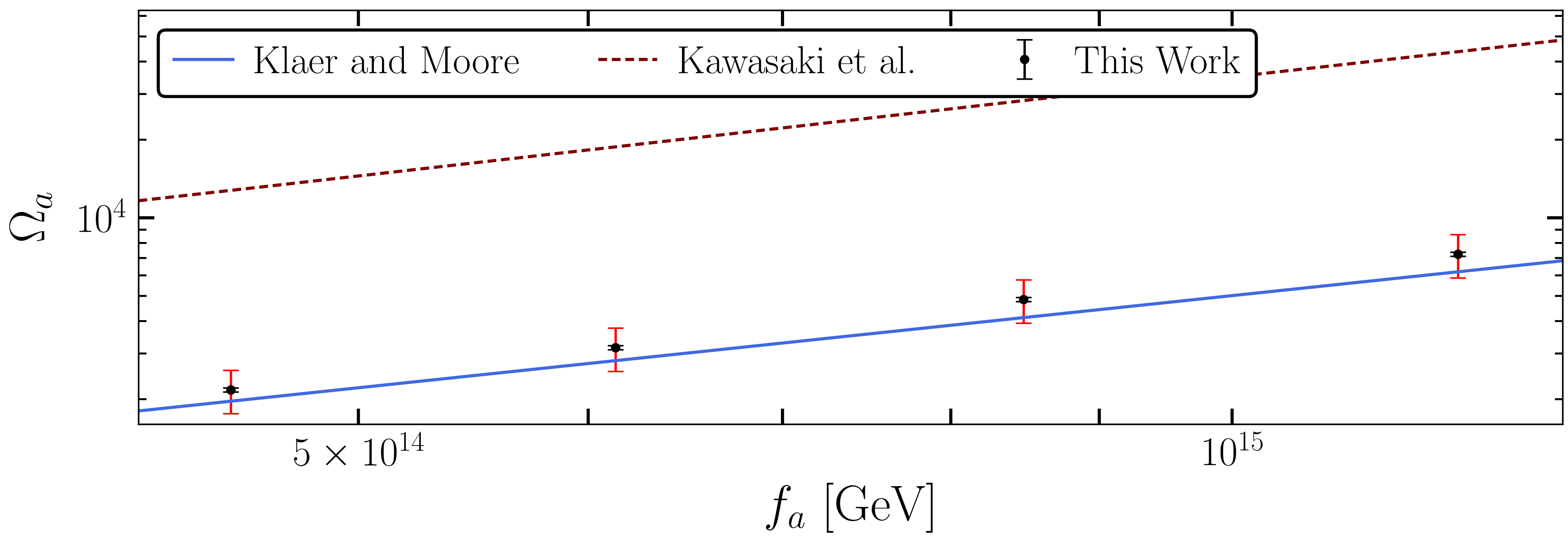


Obtaining the relic abundance



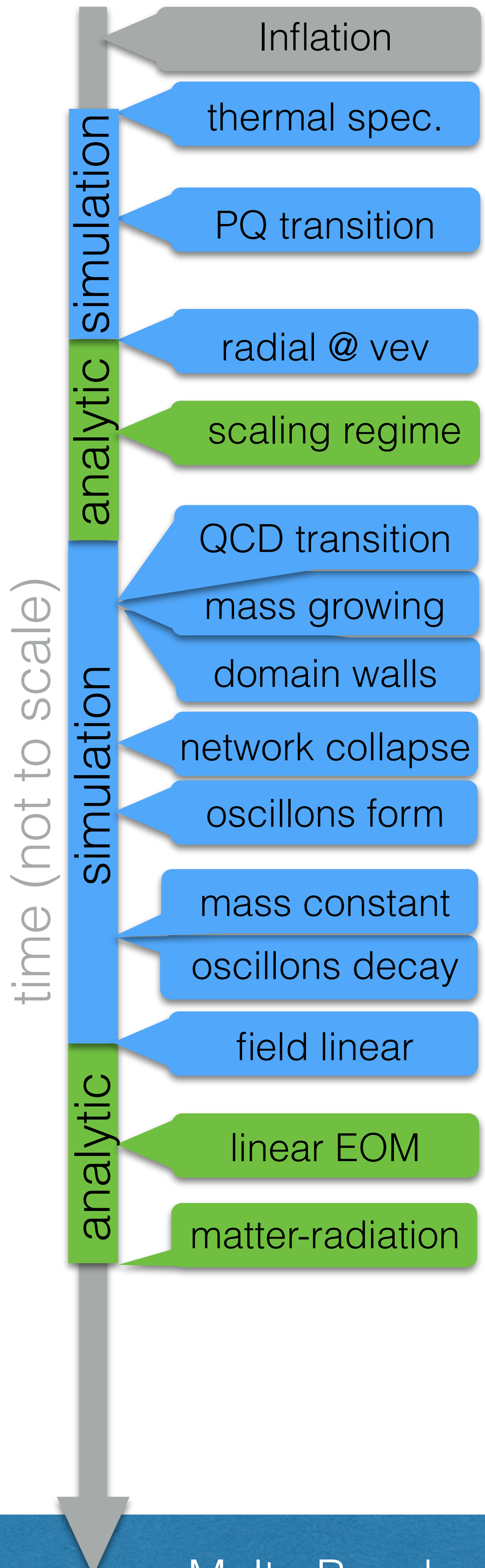


Obtaining the relic abundance



Correct relic abundance reached for:

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



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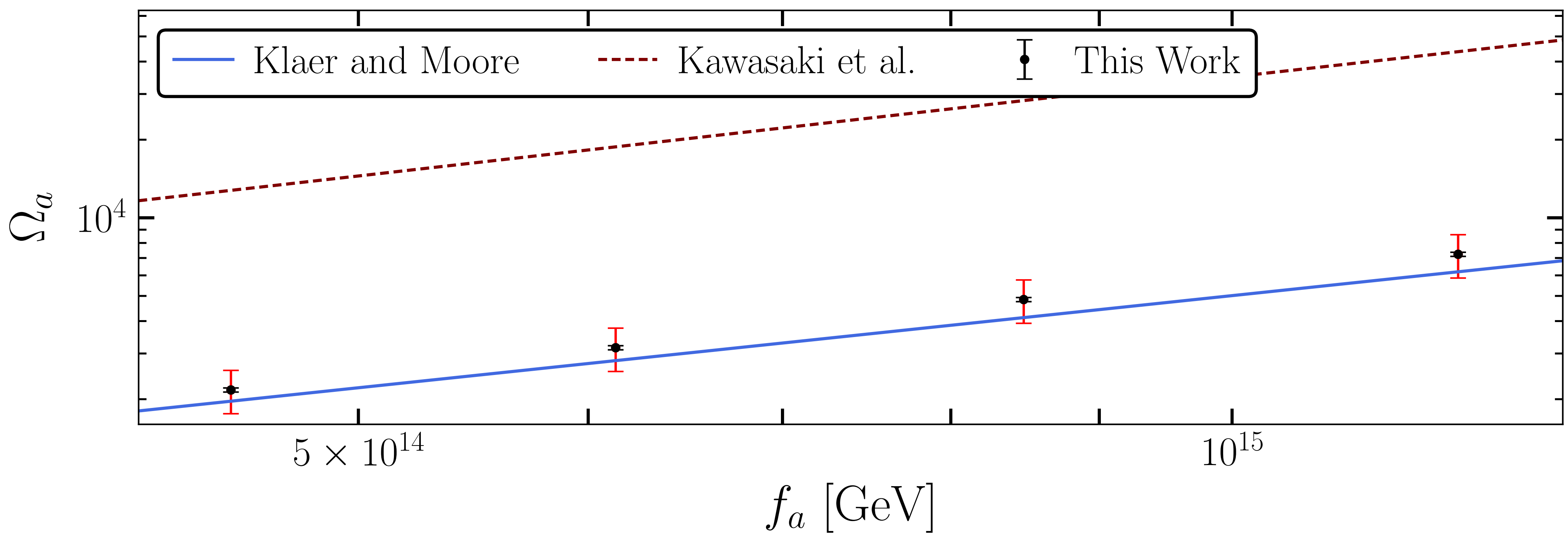


Correct relic abundance reached for:

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

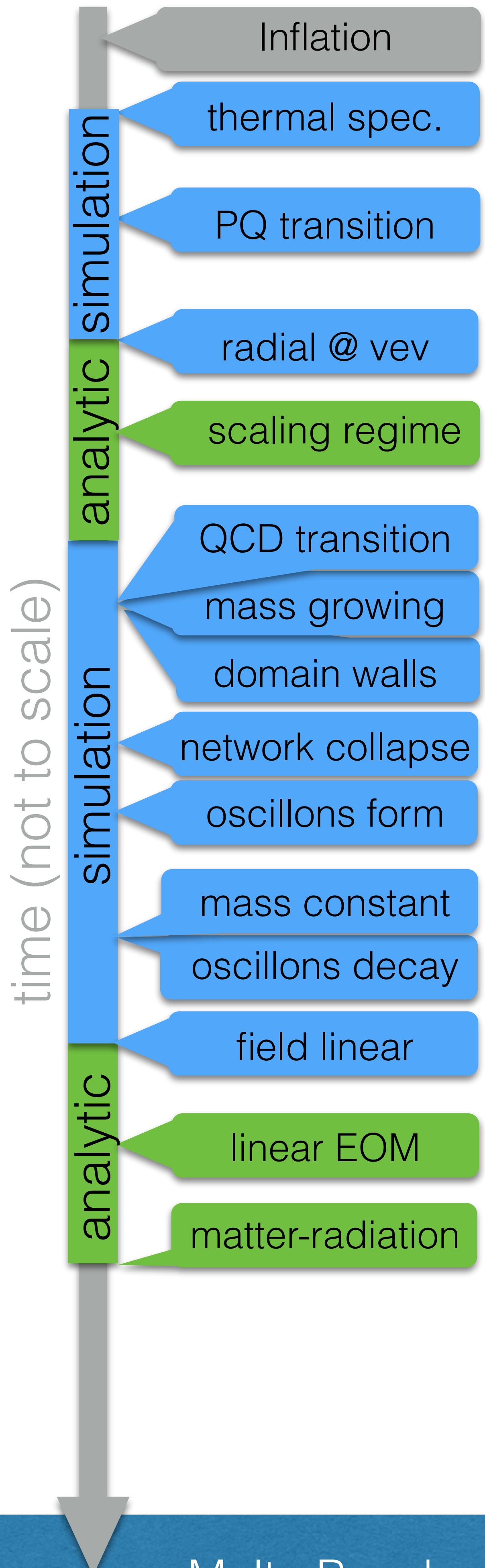
Uncertainties coming from:

31% uncertainty on the relation between abundance and f_a

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

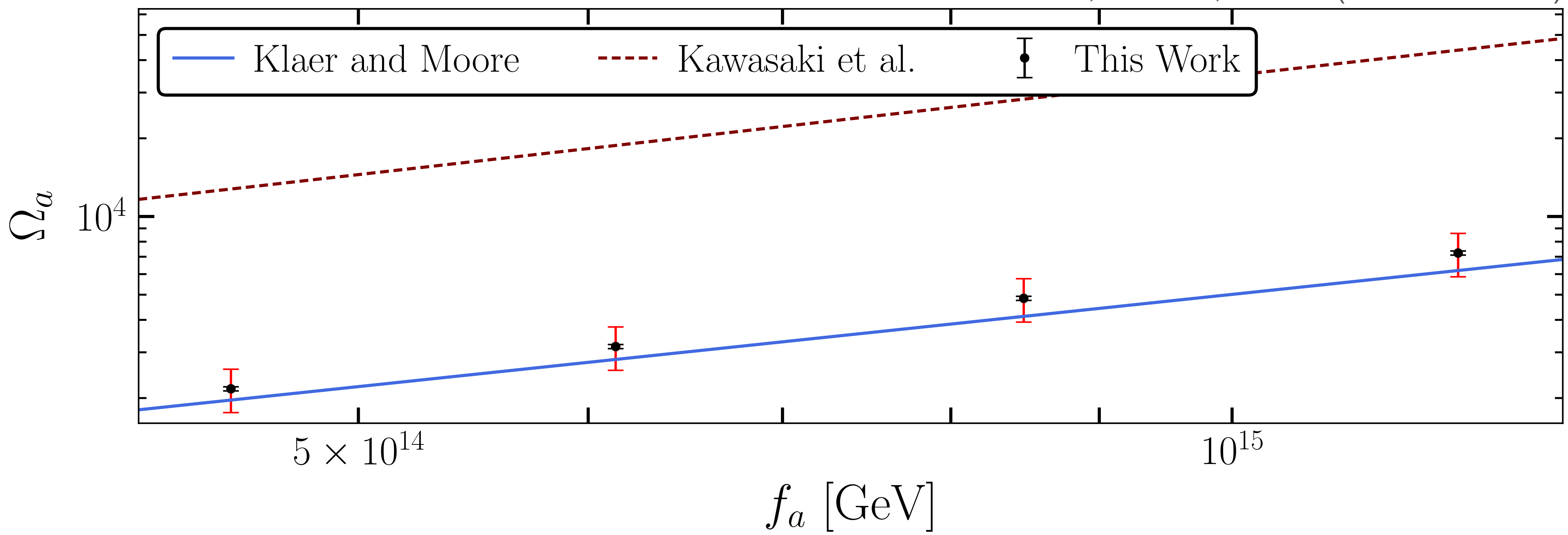
15% from violation of scaling regime

~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:

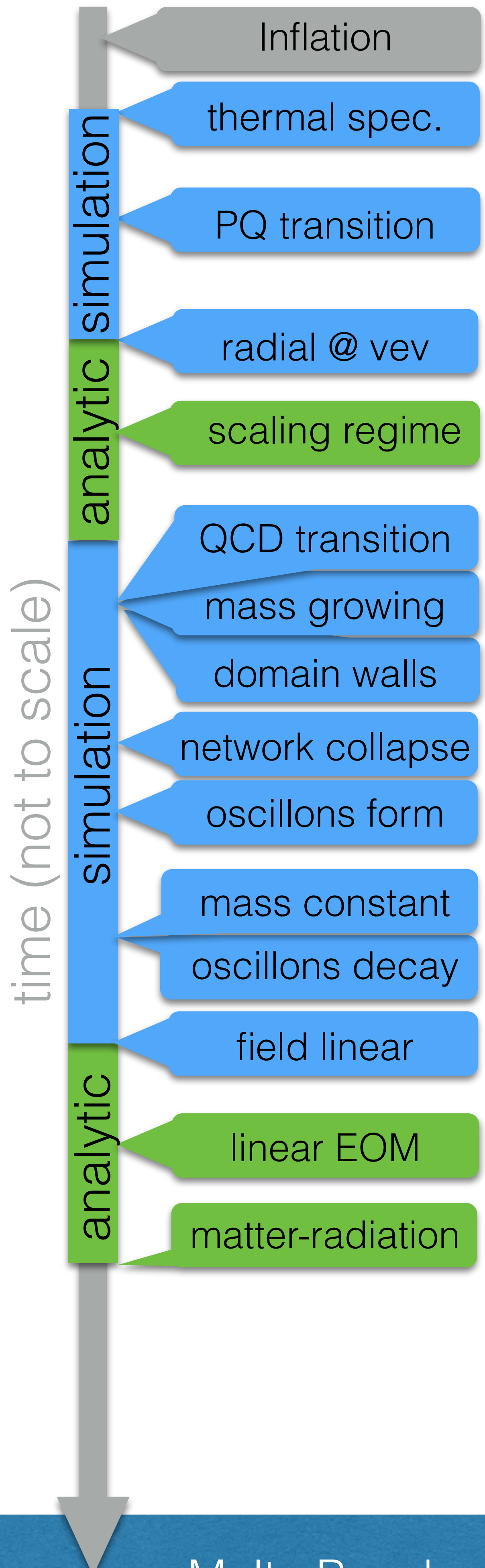
$$\rho_a \propto f_a^{(6+n)/(4+n)}$$

with n=6.68 from lattice simulations

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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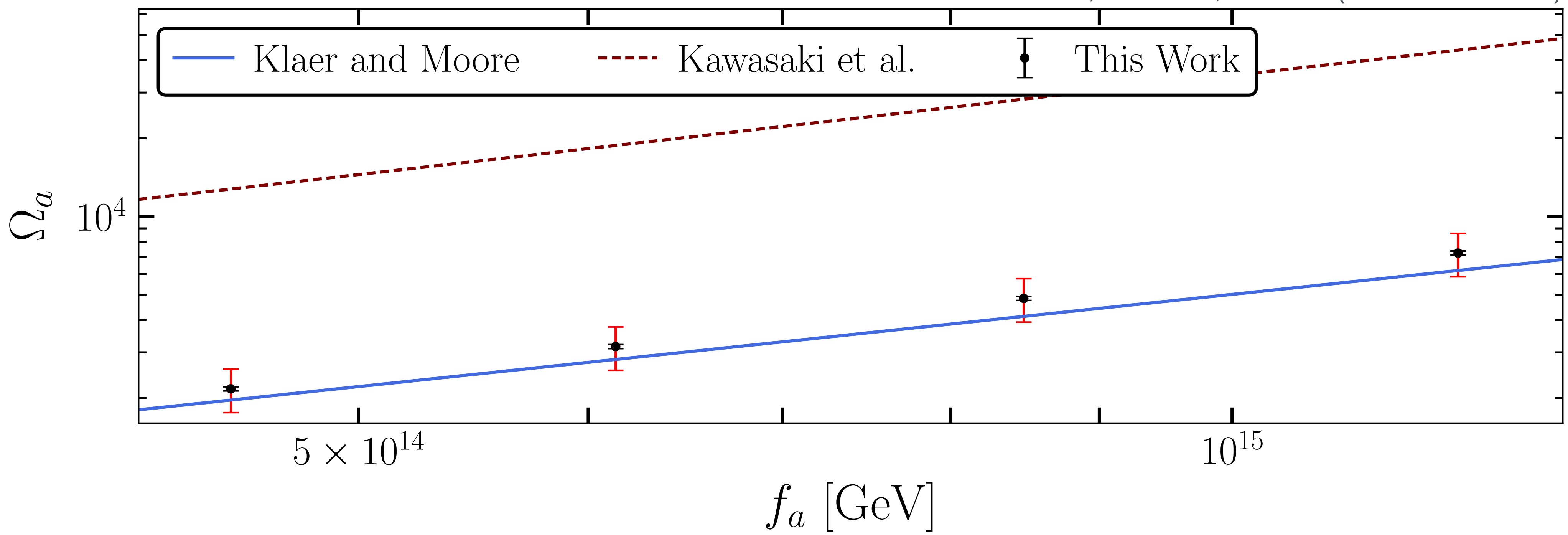


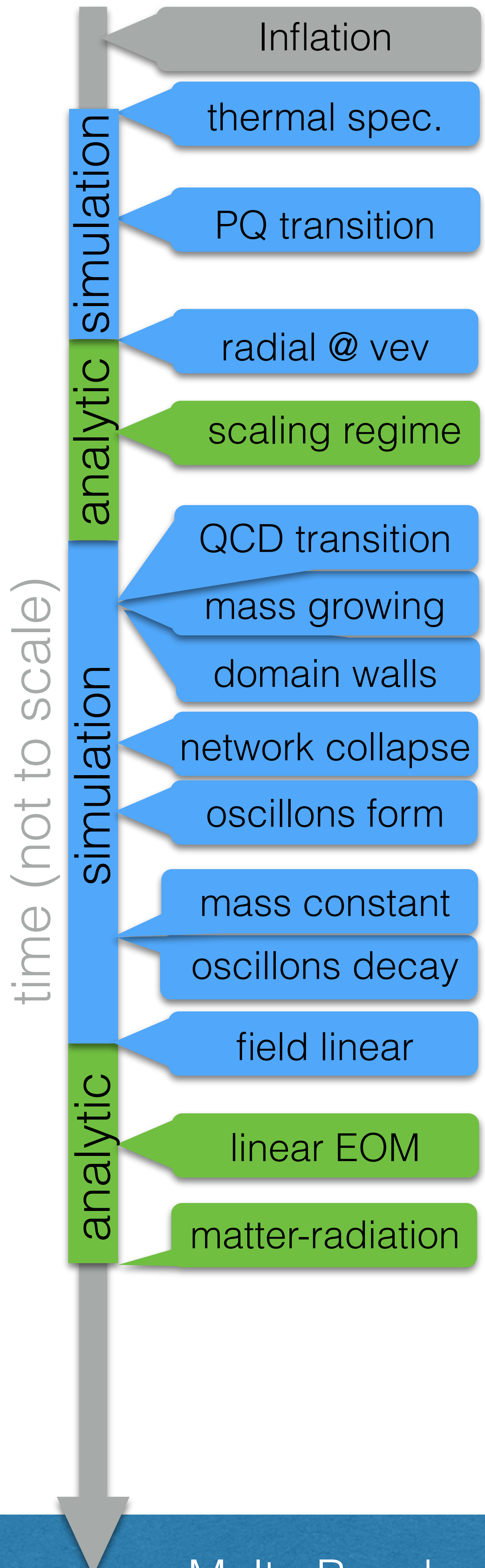
In particular oscillons make it impossible to simulate at low breaking scales. Extrapolations needed:

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

with n=6.68 from lattice simulations

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

Leads to 27% uncertainty on axion mass


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
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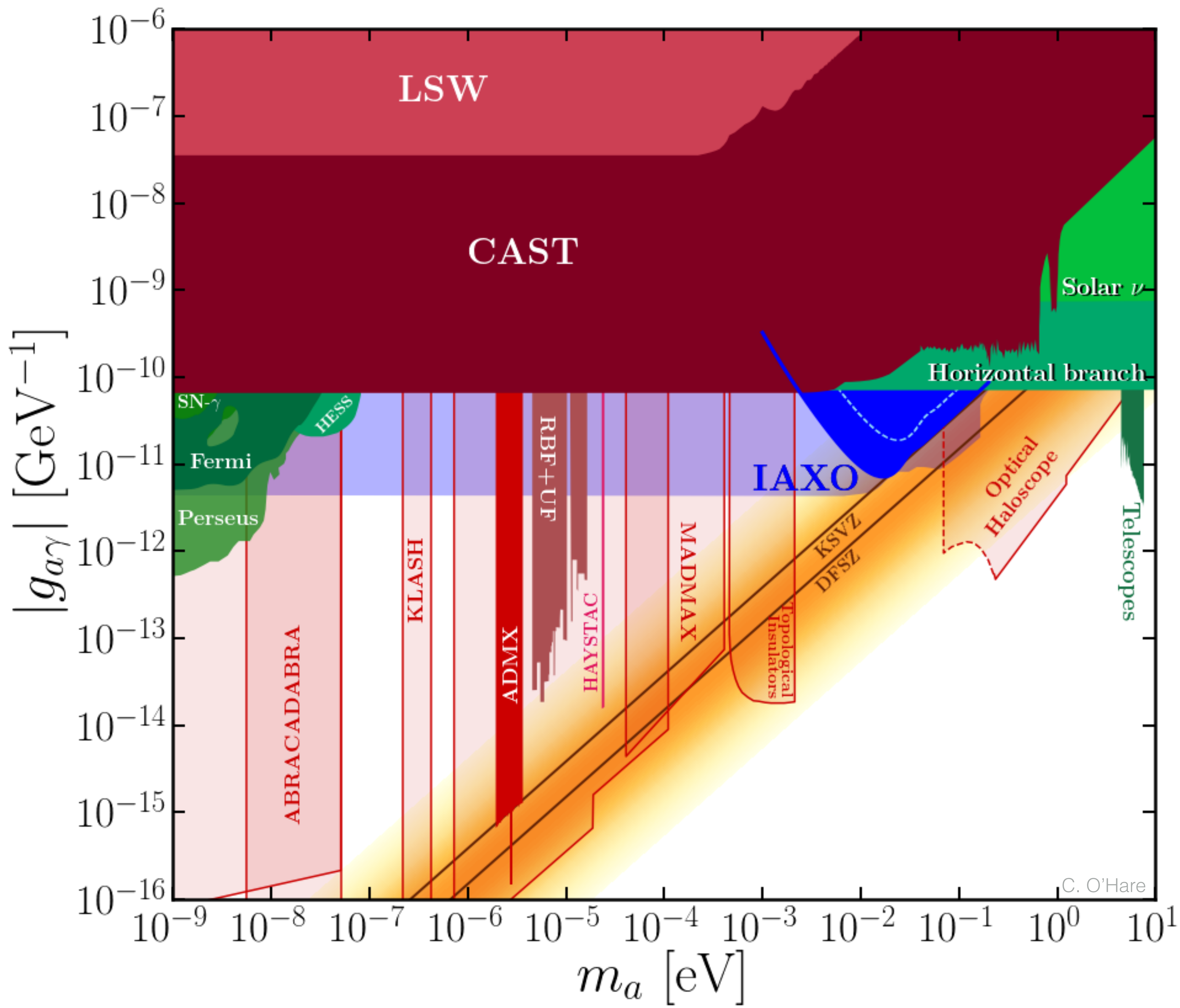
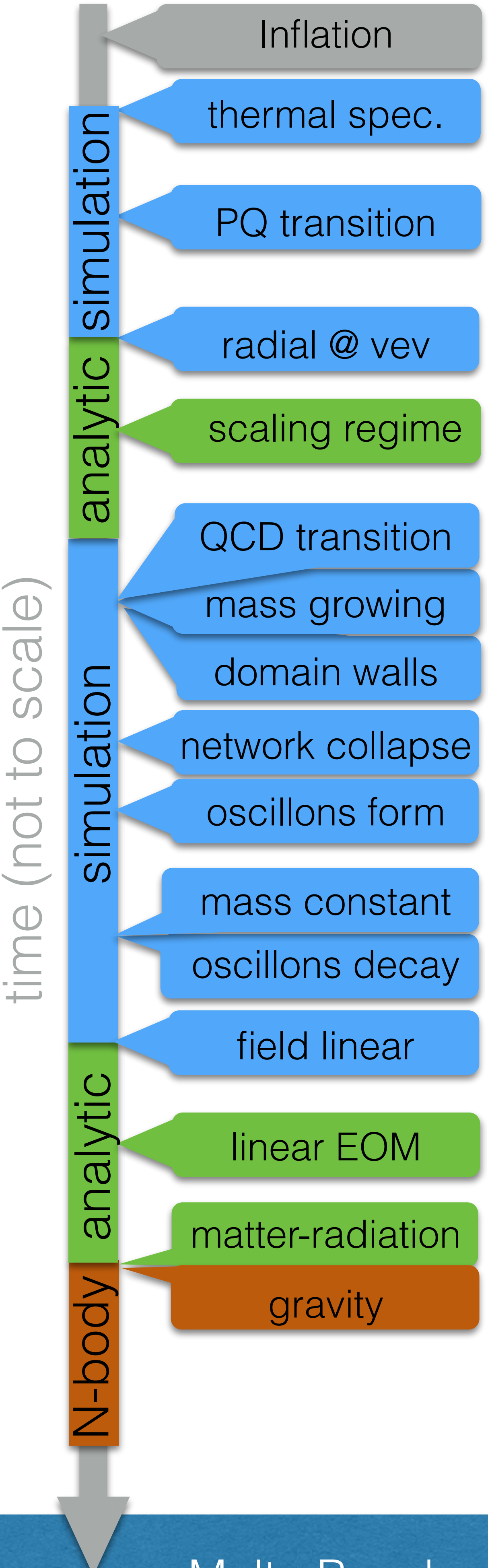
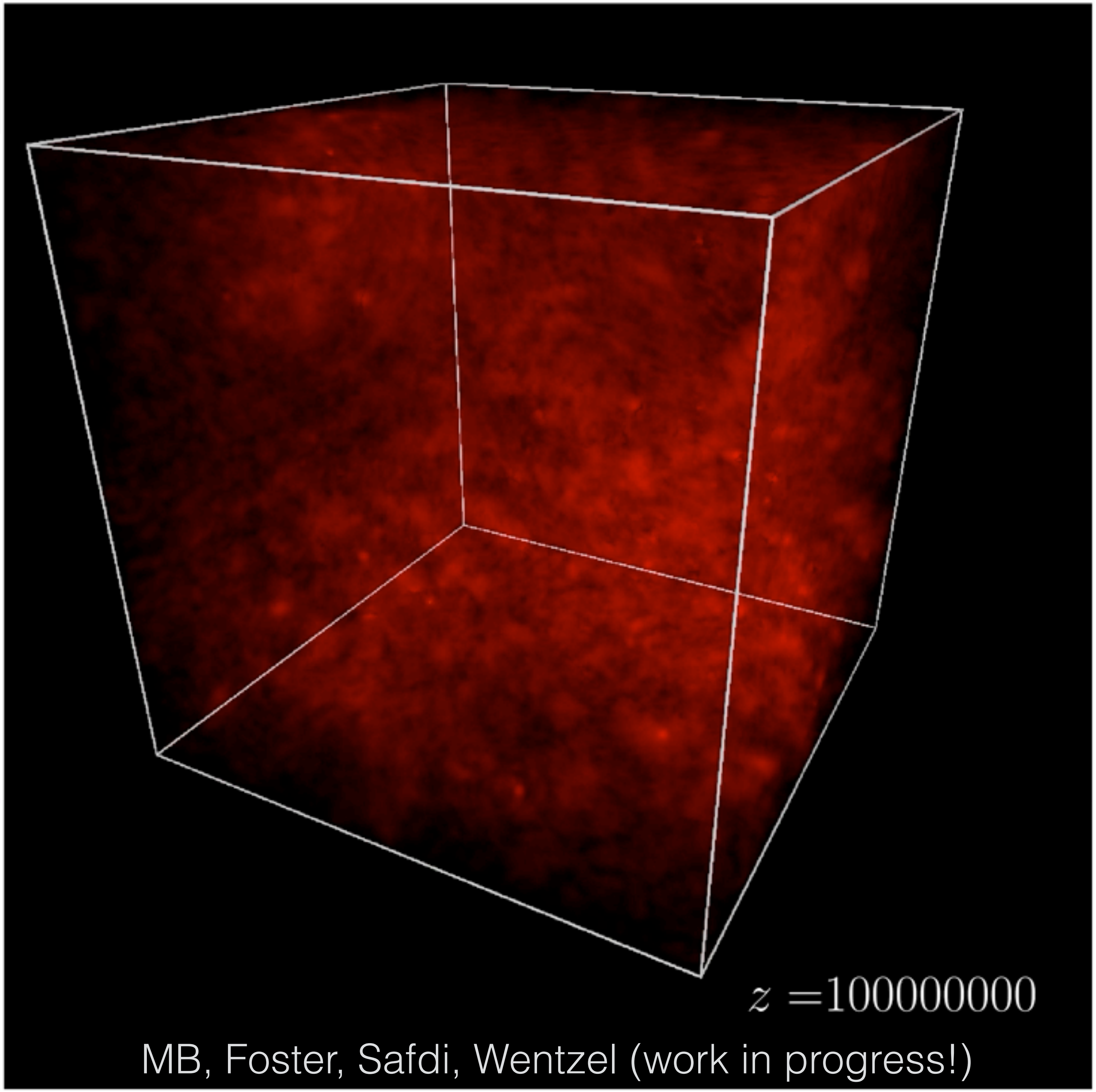

LSW
CAST
IAXO
Solar ν
Horizontal branch
SN-γ
HESS
Fermi
Perseus
ABRACADABRA
KLASH
ADMX
RBF+UF
HAYSTAC
MADMAX
Topological insulators
KSVZ
DFSZ
Optical Haloscope
Telescopes
C. O'Hare
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15}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

Halos collapse further under gravity





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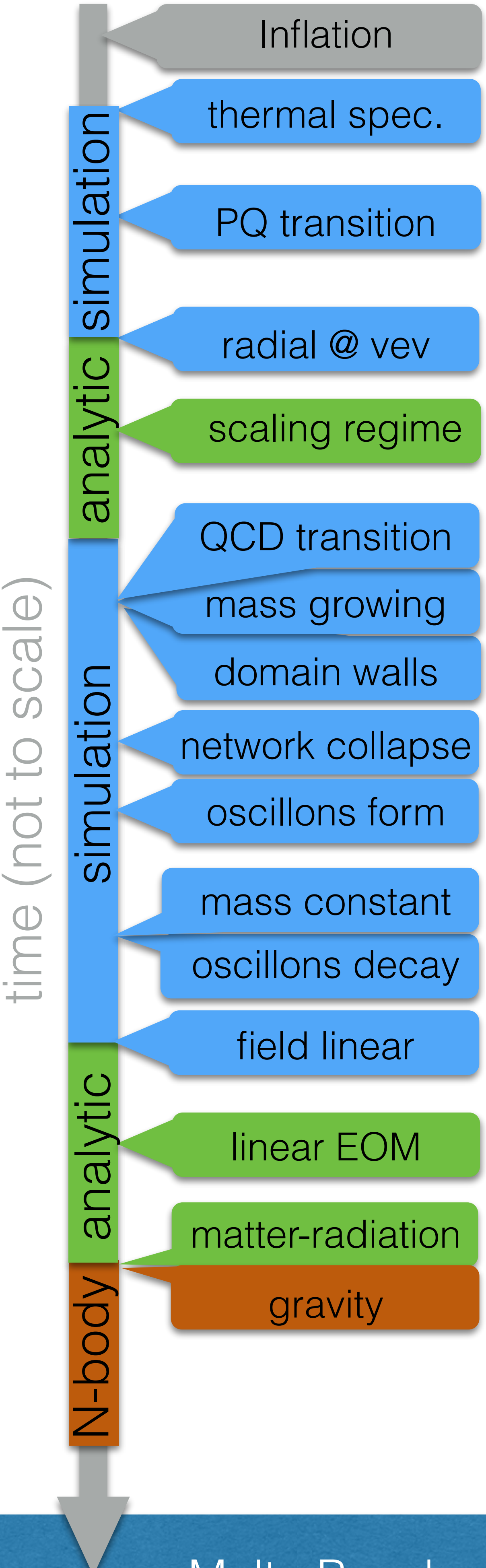
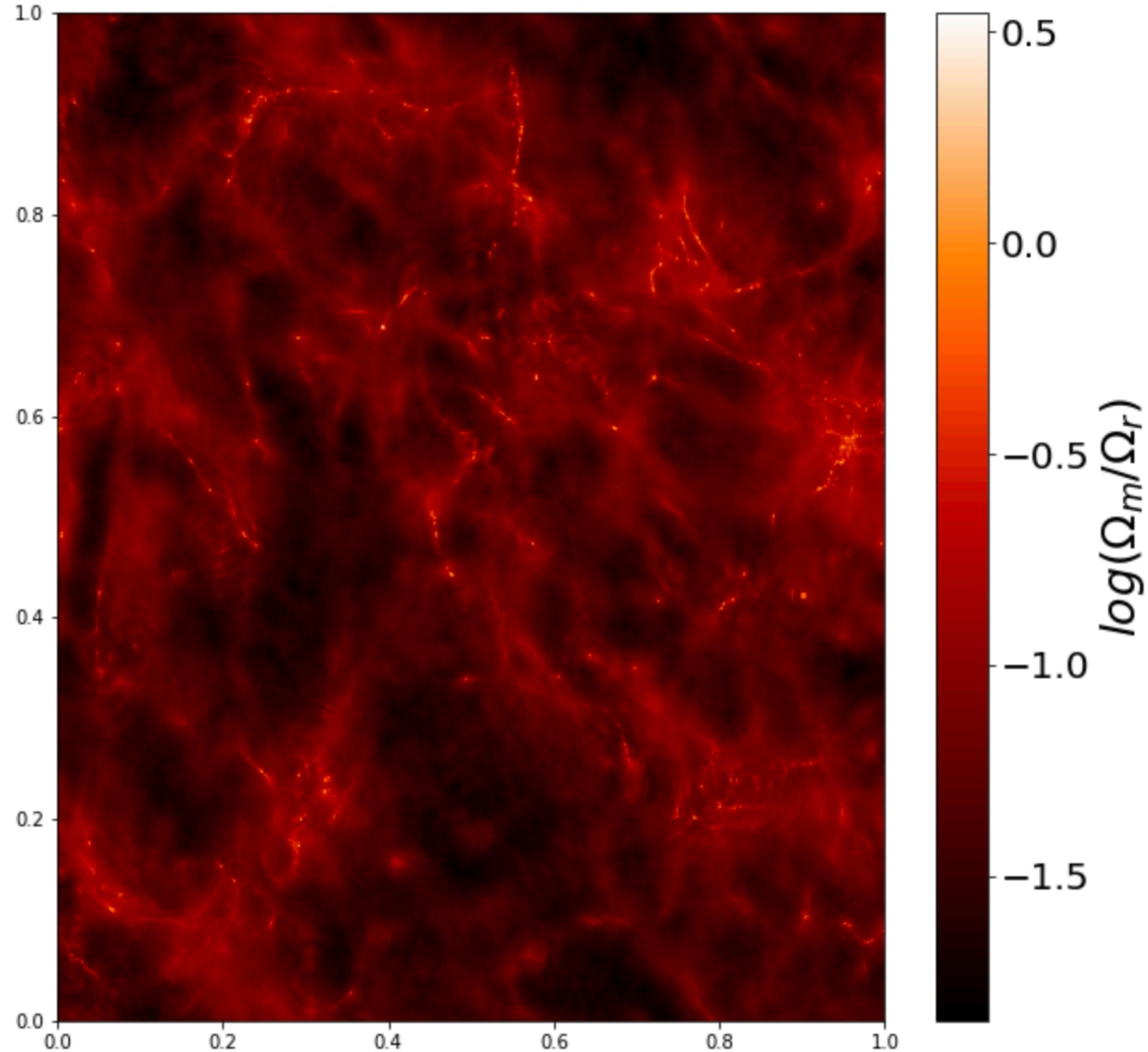
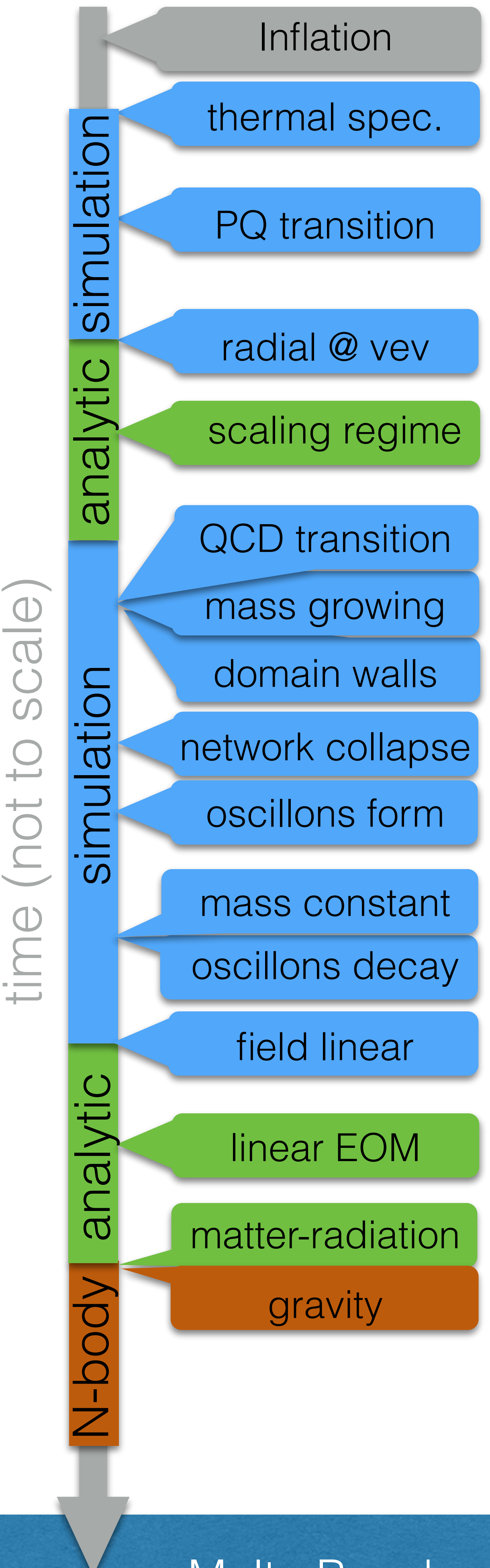
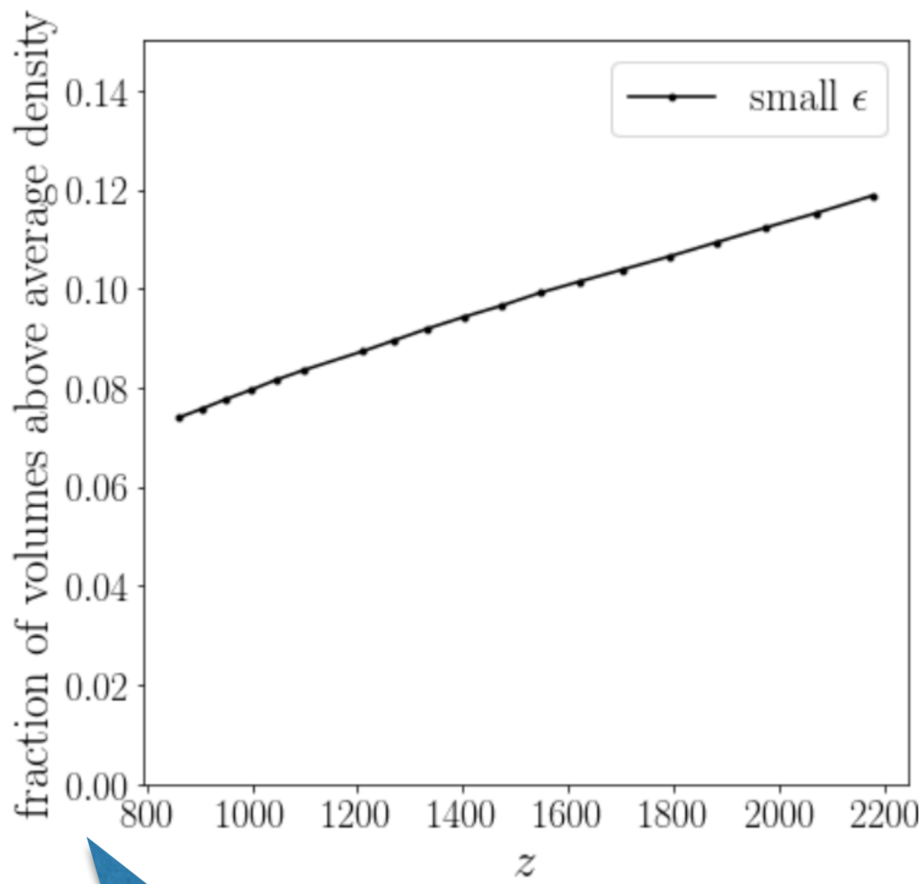


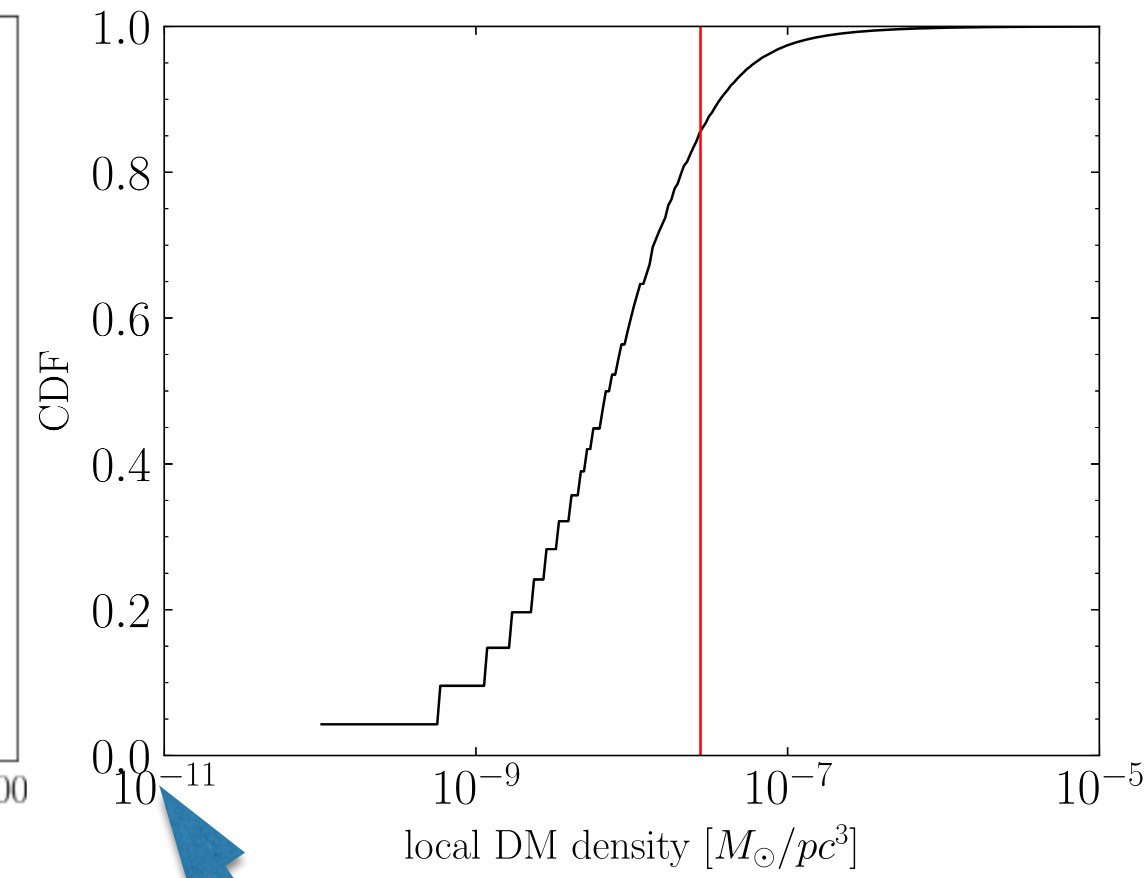


MB, Foster, Safdi, Wentzel (work in progress!)



Are we sitting in a void?



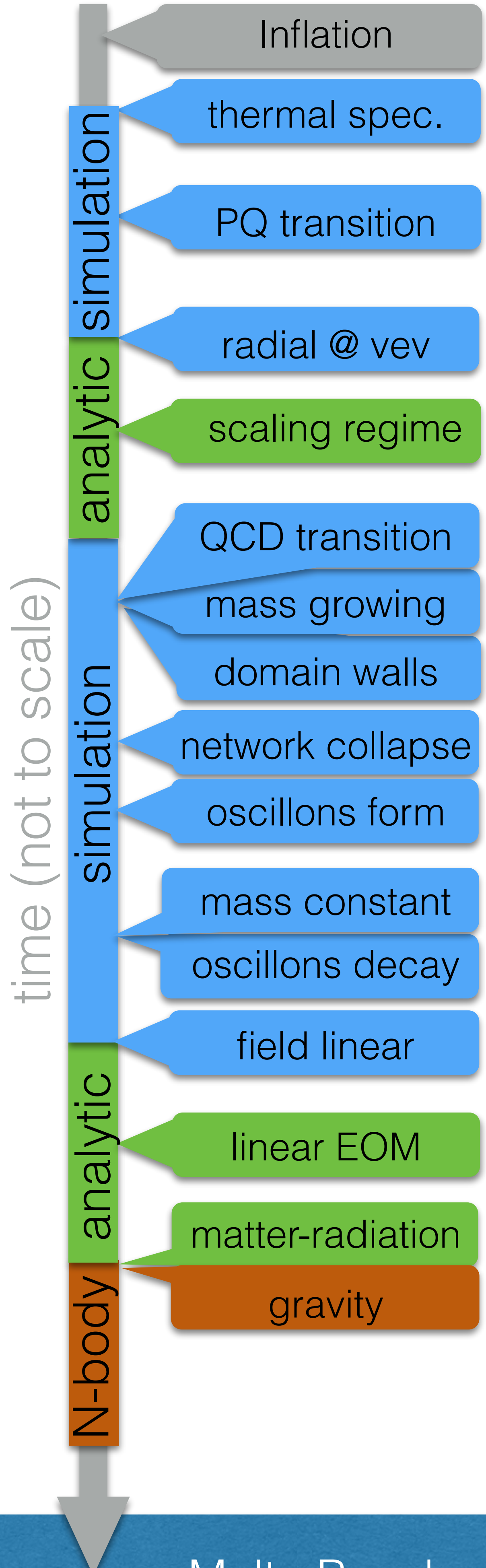


Probability of Earth being at location with a more-than-average DM density

Probability of Earth being at location with a particular DM density or less

Experiments like ADMX might not be able to detect a QCD axion in a post-inflationary scenario!

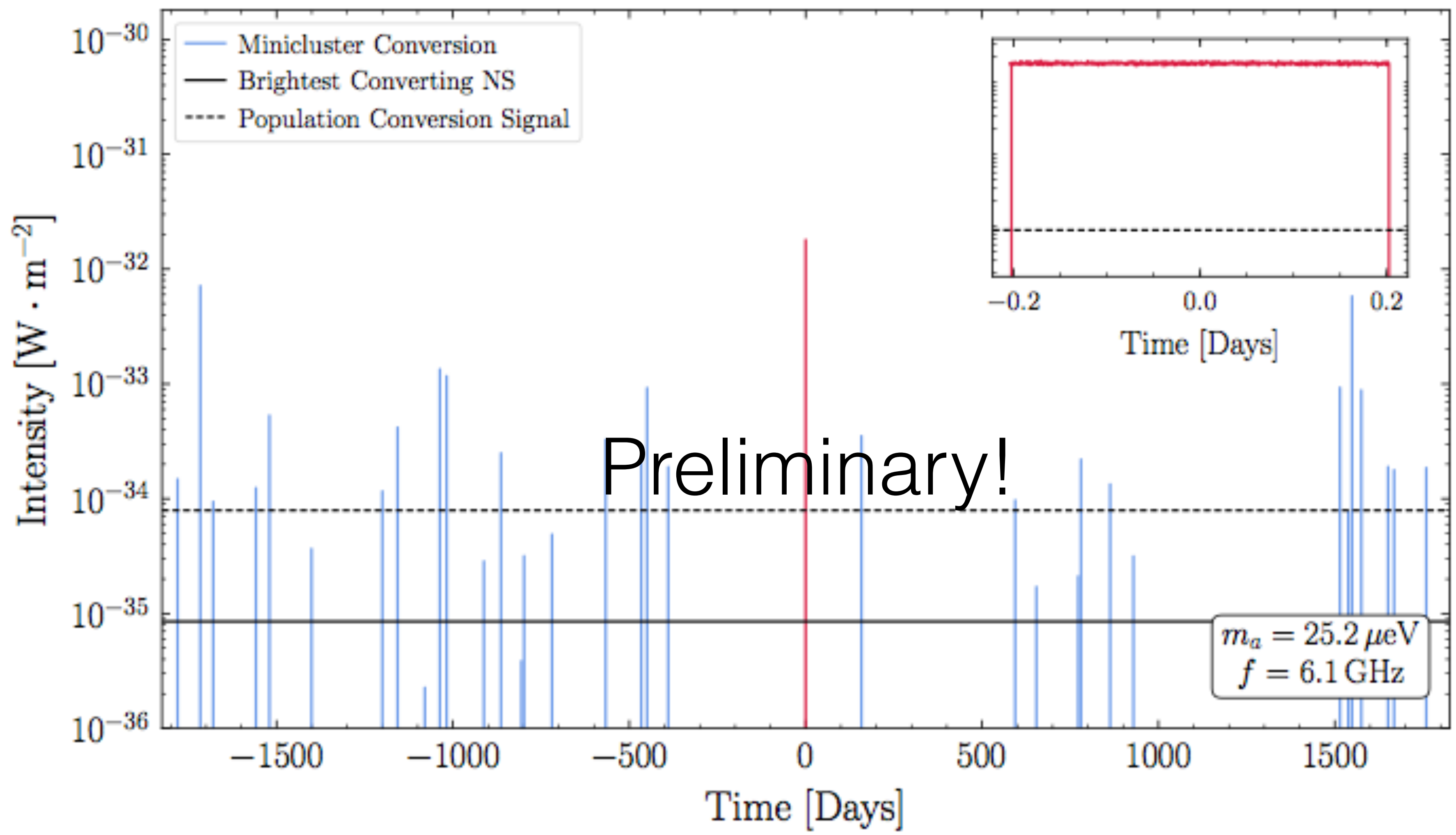
MB, Foster, Safdi, Wentzel (work in progress!)

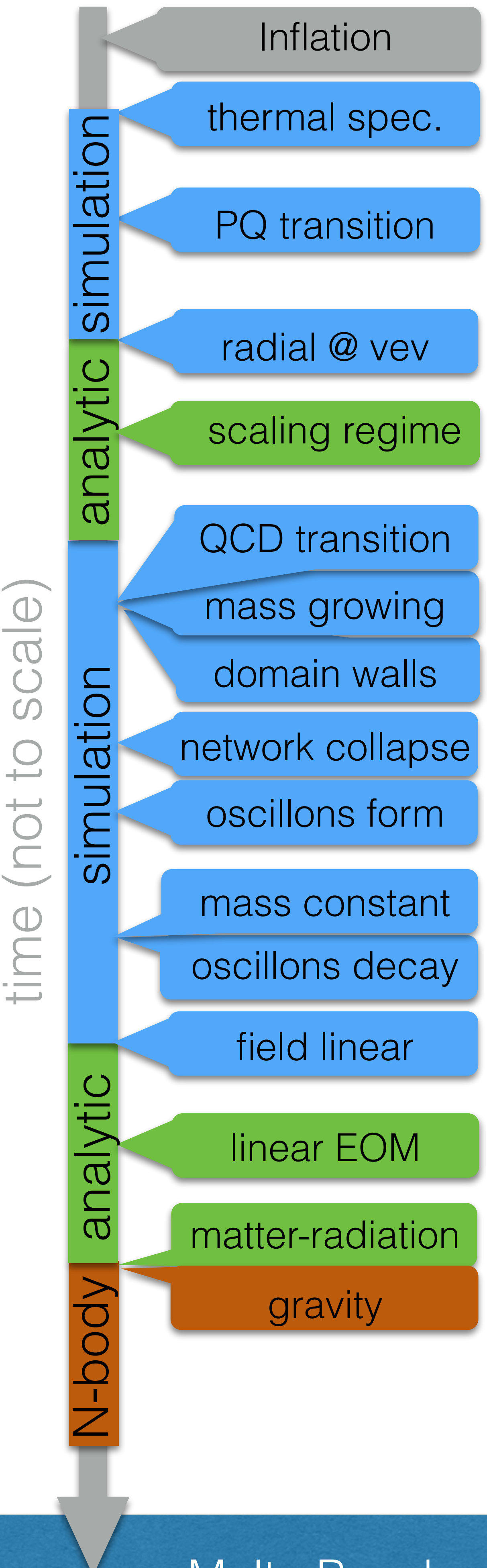


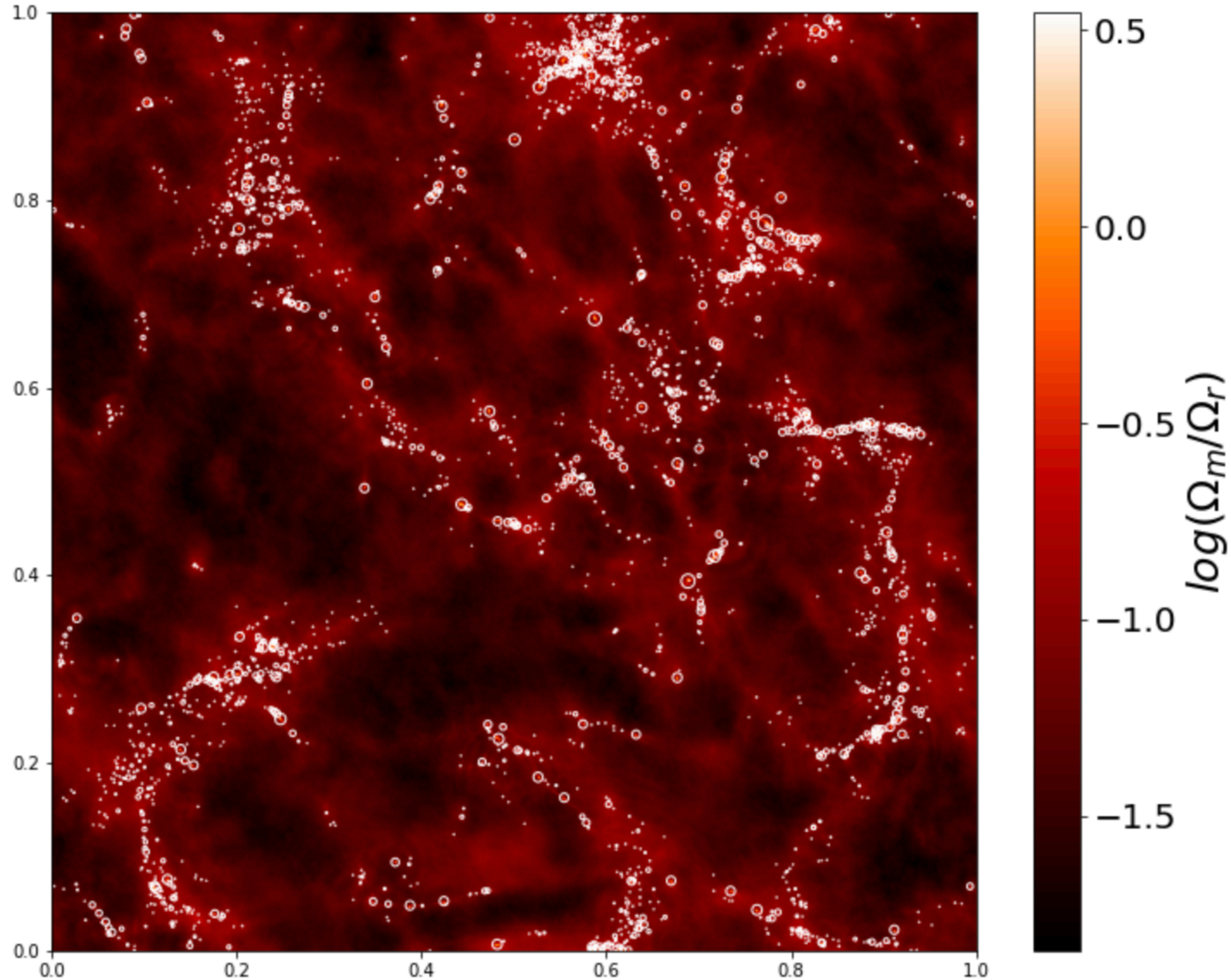
Radio signals from Neutron Stars

Axions convert to radio photons in magnetic field of neutron star

Large peak in flux when neutron star moves through an axion minihalo!

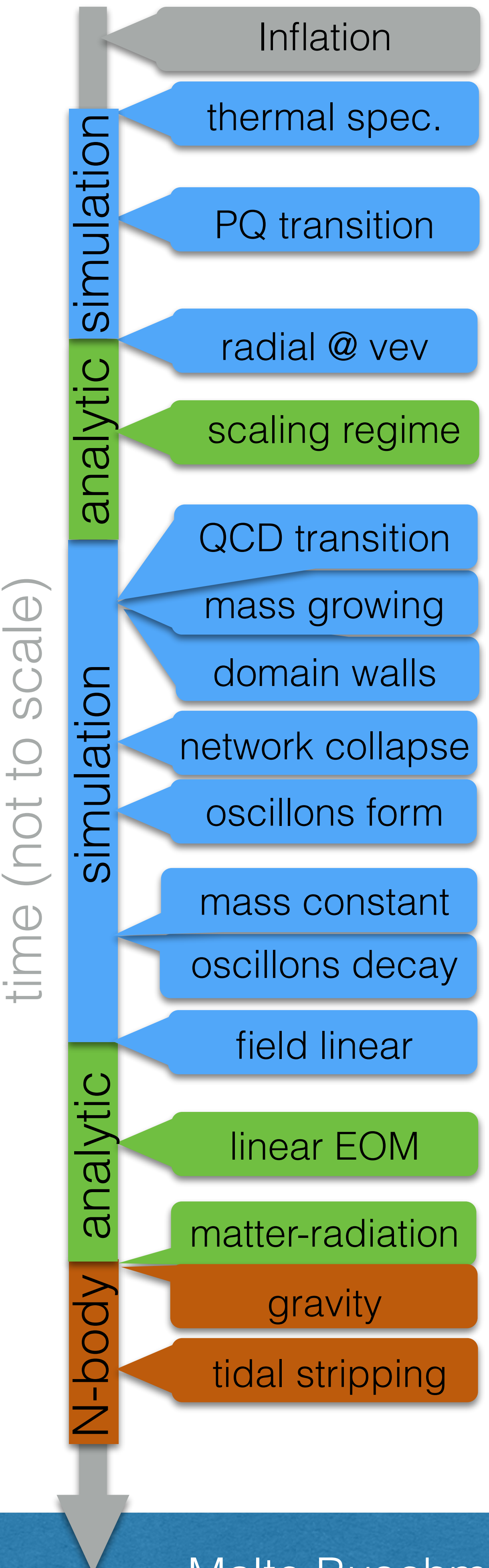


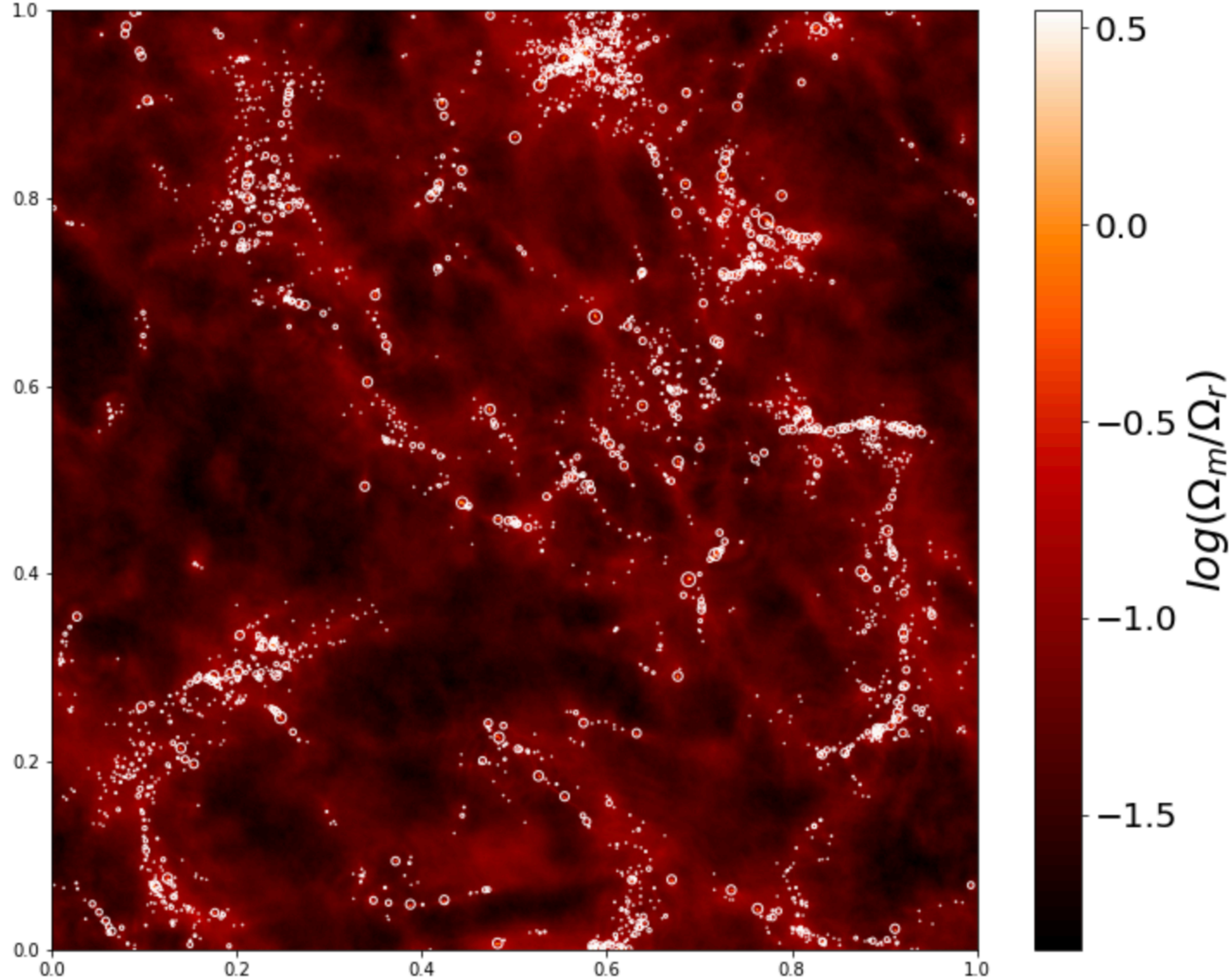




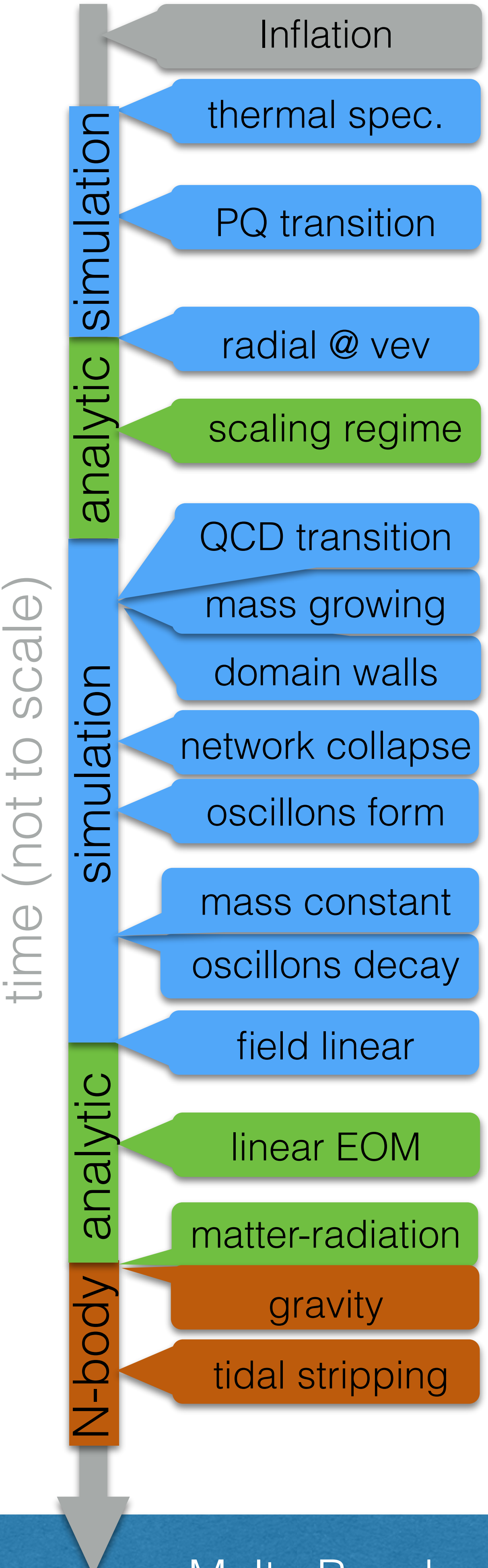
MB, Foster, Safdi, Wentzel (work in progress!)

Halos are tidally disrupted in Milky Way potential





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



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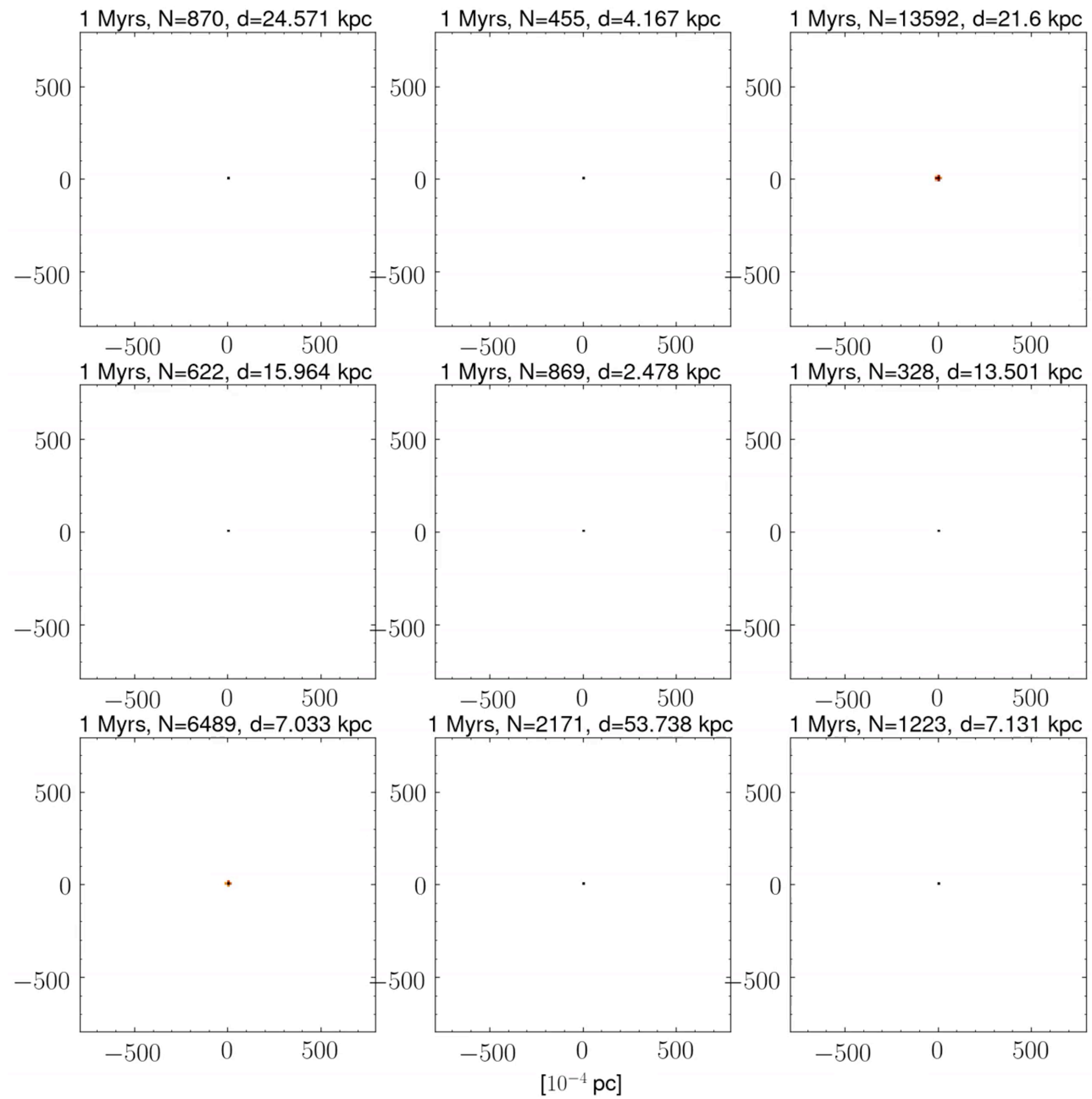
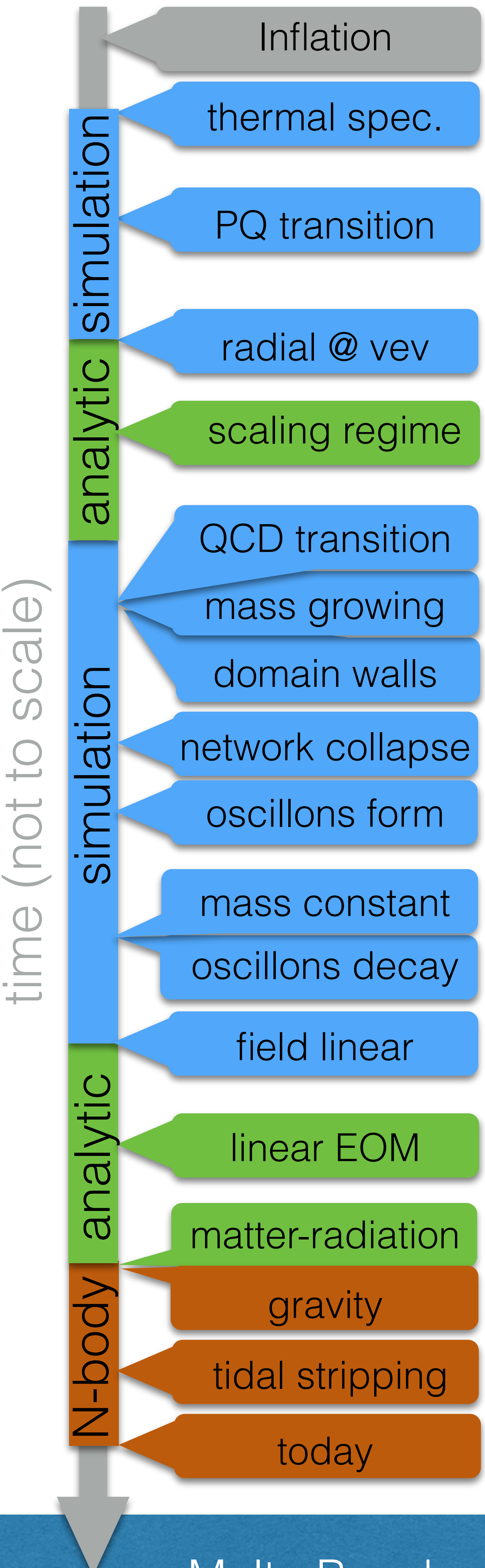
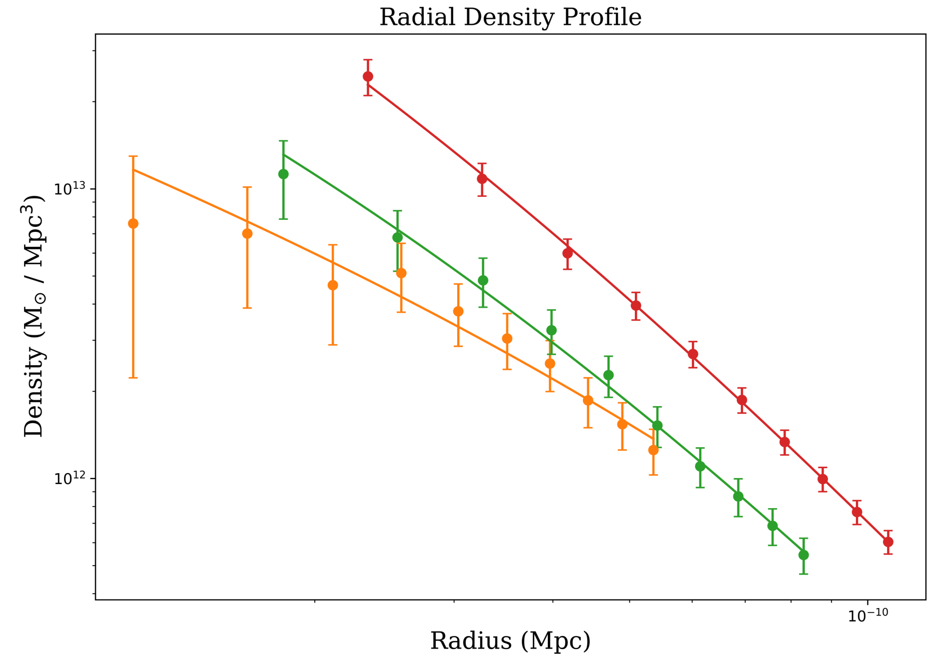
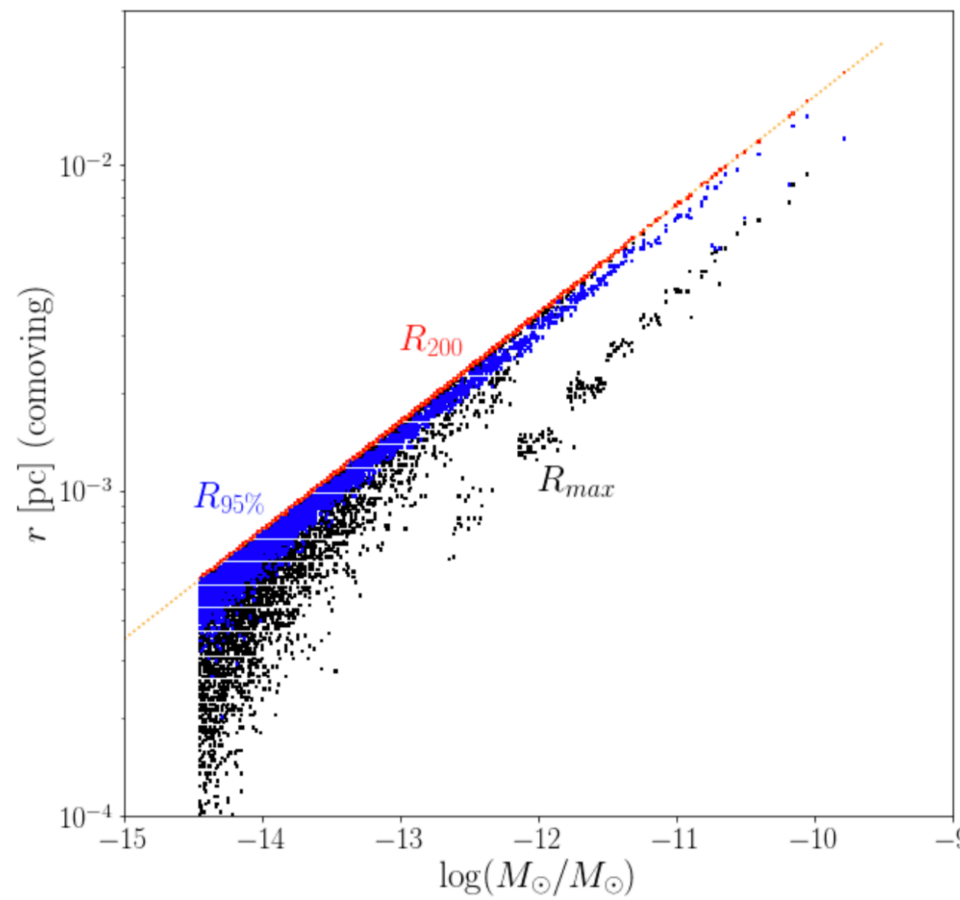


MB, Foster, Safdi, Wentzel (work in progress!)



Characterizing radial profiles and halo mass functions





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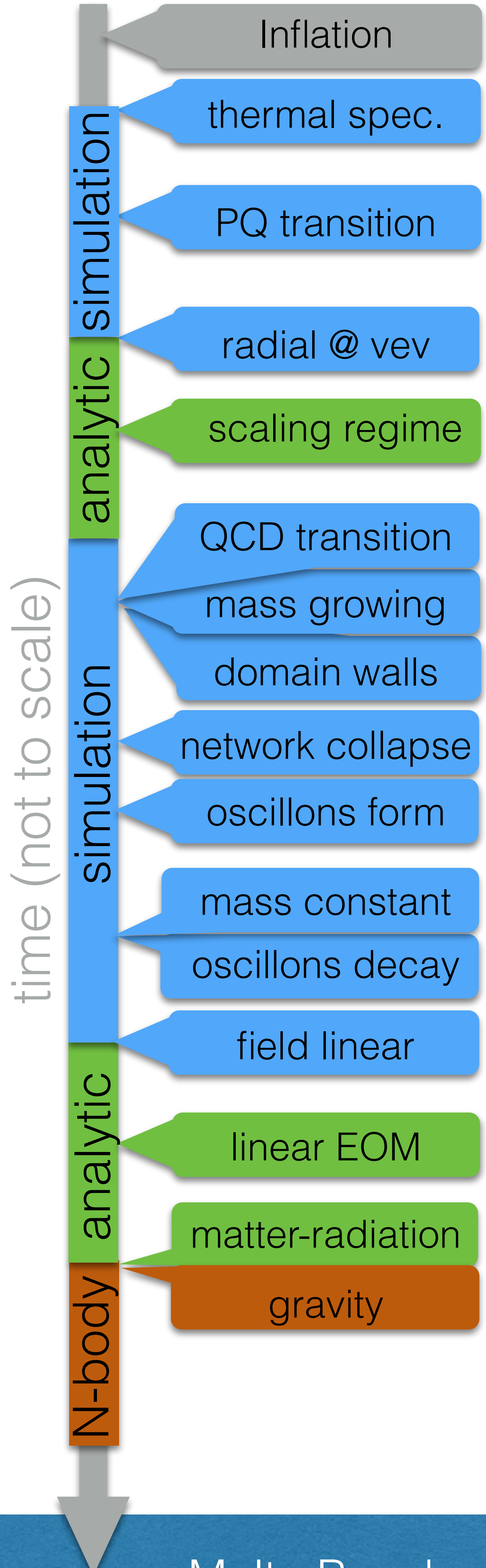

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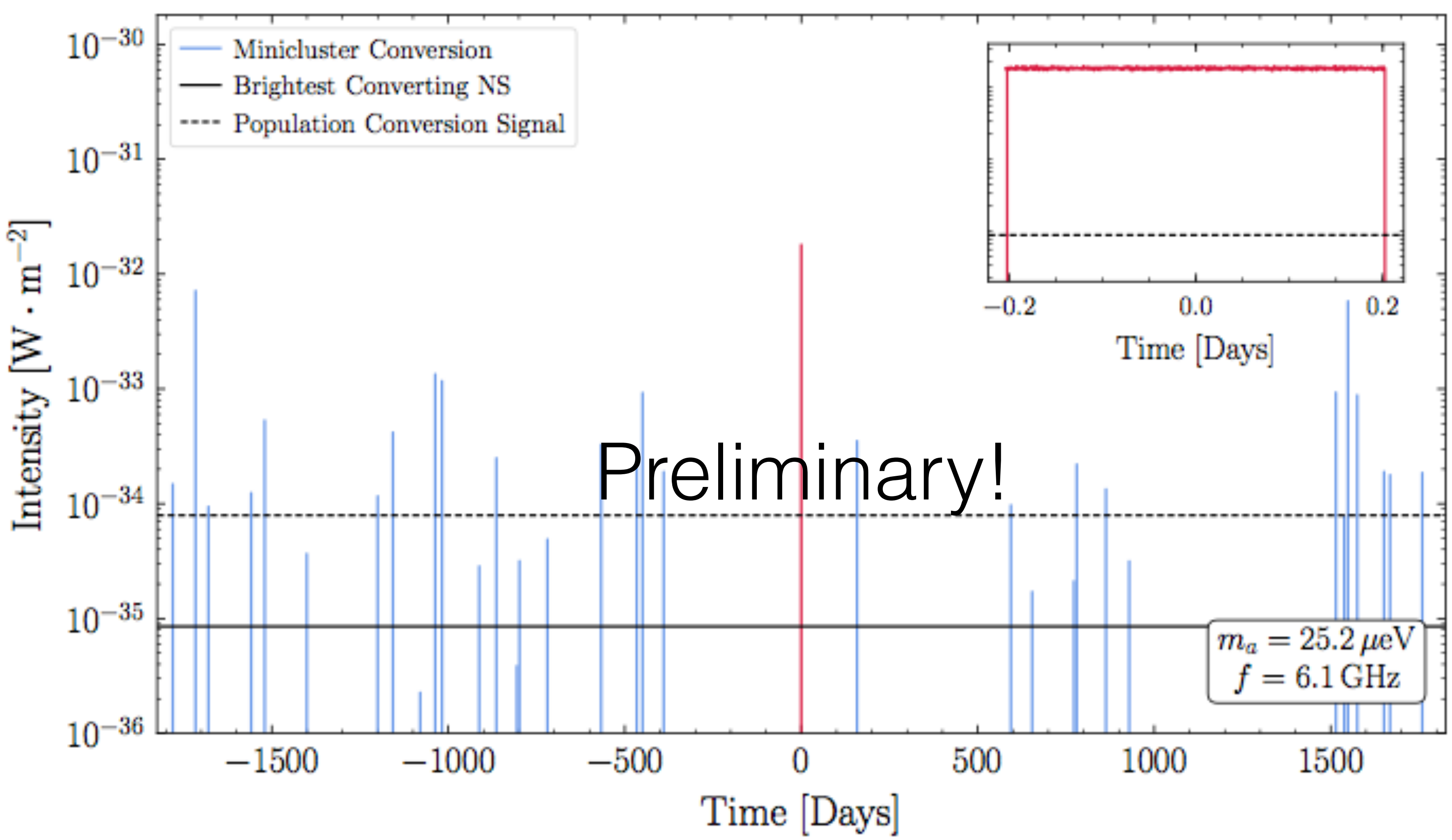
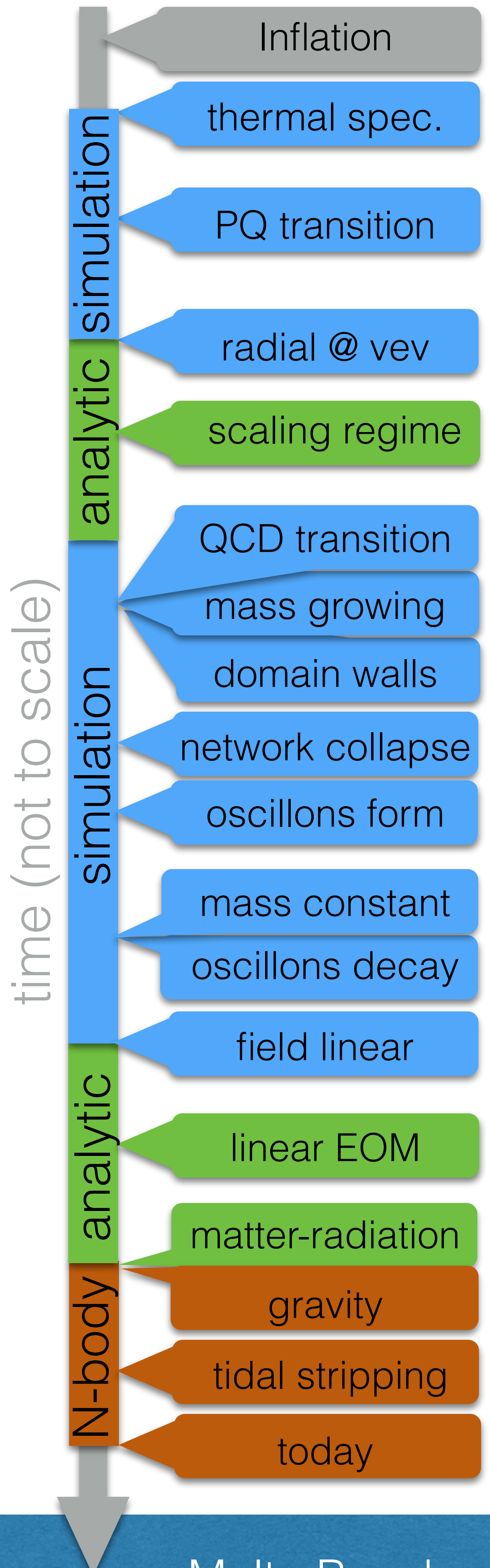
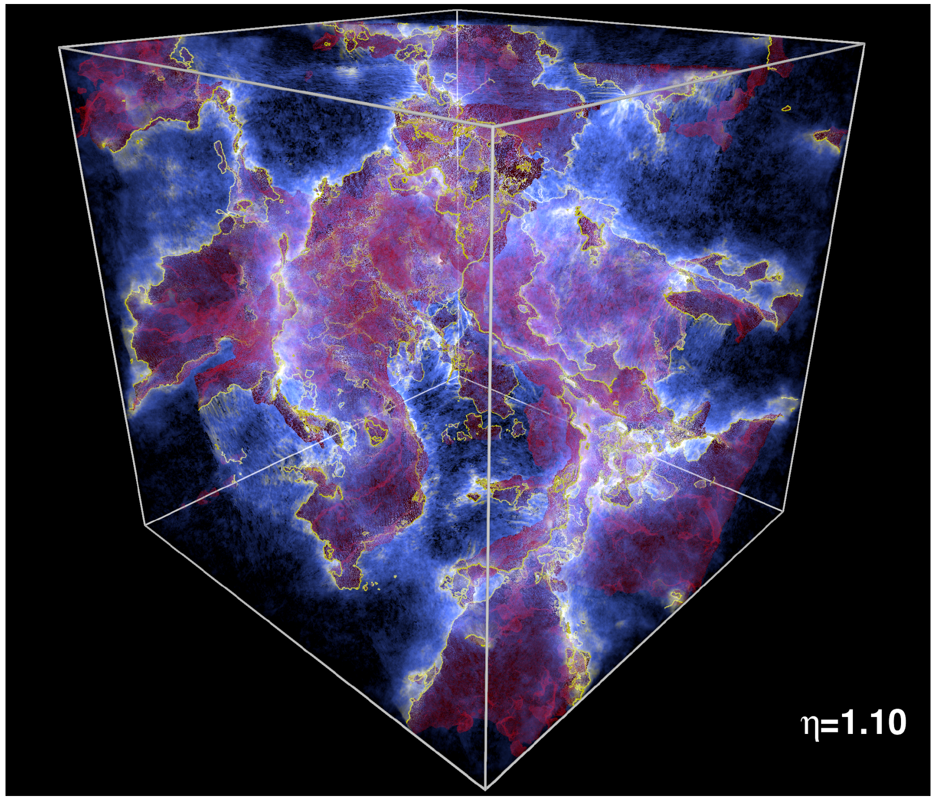


Summary



- Assumption: PQ symmetry broken after inflation
- We performed simulations through the PQ and QCD phase transition to matter-radiation equality
- N-body simulations until Milky Way forms
- Simulated tidal stripping
- Identified minihalo mass spectrum
  Typical mass: 10^{-10} solar masses
- Determined the axion mass that reproduces the correct relic abundance: $m_a = 25.2 \pm 11.0\ \mu\text{eV}$
- We are most likely sitting in a DM void (bad news for e.g ADMX)
  But: We can look for signals of minihalo - NS collision!



Thank you!