Axion dark matter minicluster

Thomas Schwetz

with Jonas Enander, Andreas Pargner, 1708.04466

Unravelling the dark matter mystery — IPPP Durham, UK, March 2018

Karlsruher Institut für Technologie

elusives
neutrinos, dark matter &

The strong CP problem

$$\mathcal{L}_{\theta\mathrm{QCD}} = \frac{\theta_{\mathrm{QCD}}}{32\pi^2}\mathrm{Tr}\ G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \theta_{\mathrm{QCD}} = \tilde{\theta}_{\mathrm{QCD}} + \arg\ \det M_u M_d$$

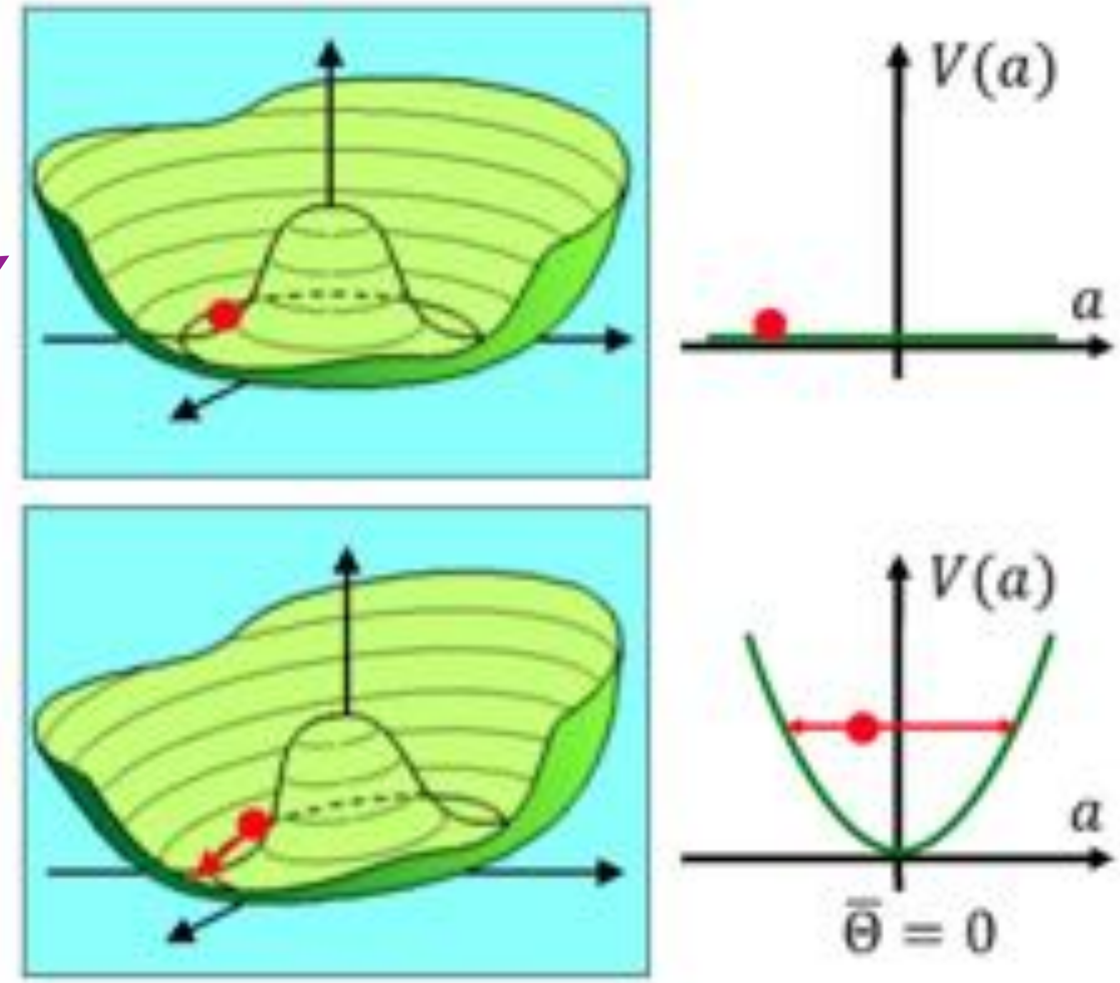
- limit on neutron electric dipole moment:

$$\boxed{\theta_{\mathrm{QCD}} \lesssim 10^{-10}}$$

- requires cancellation between bare angle and contribution from quark masses at the 10^{-10} level.

Axion solution

plots from G. Raffelt



- introduce a global U(1) symmetry (PQ)
- gets broken at high scale f_{PQ}
- axion is the p-Goldstone of the U(1)
- receives a mass by non-perturbative QCD instanton effects
- axion potential drives the theta-angle dynamically to zero

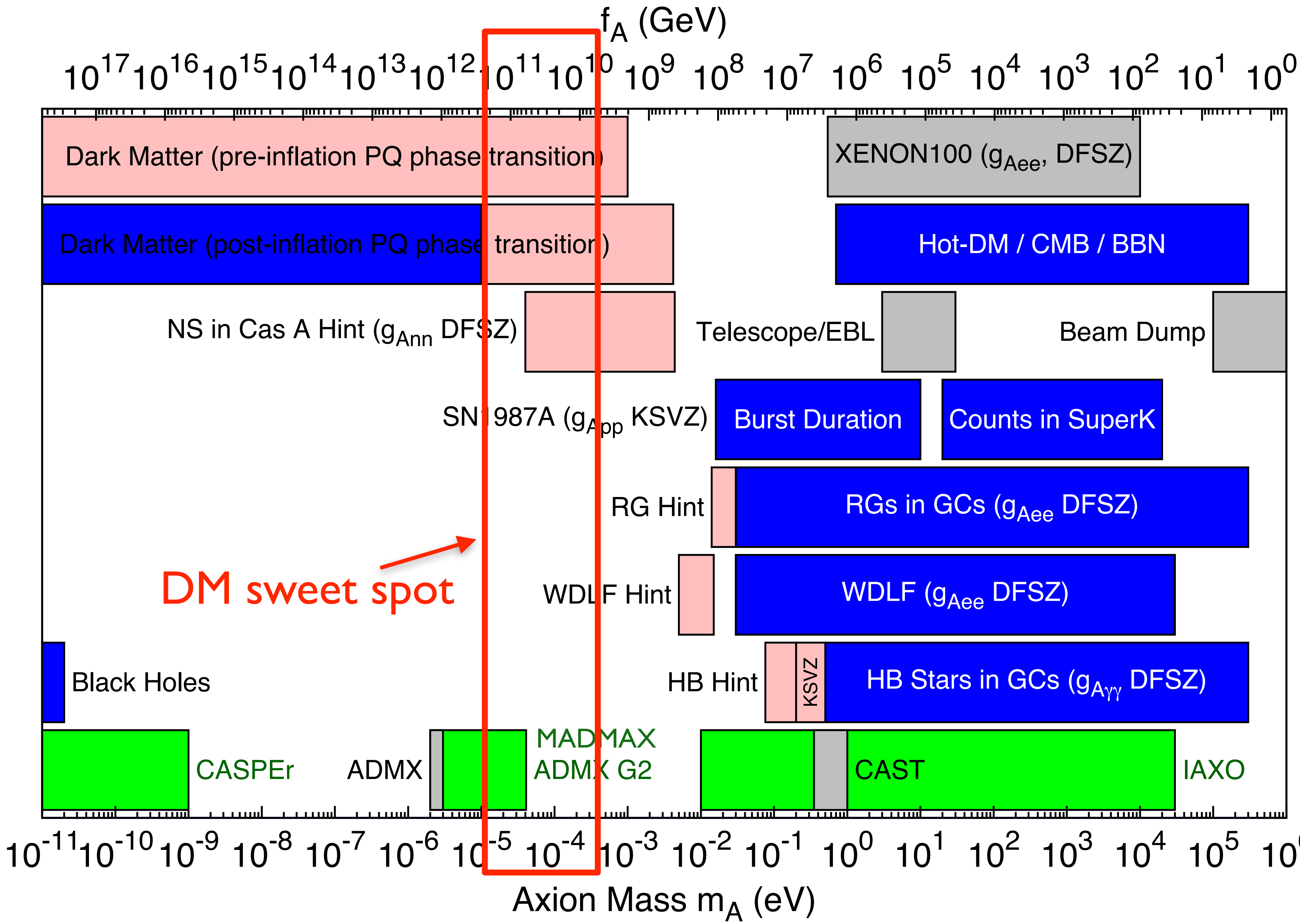
The QCD Axion

- mass determined by PQ breaking scale:

$$m_0 \simeq \frac{m_\pi f_\pi}{f_{\rm PQ}} \frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 10^{-4}\ {\rm eV}\ \frac{6 \times 10^{10}\,{\rm GeV}}{f_{\rm PQ}}\,.$$

- all interactions with SM suppressed by $f_{\rm PQ}$

- single parameter model!



PDG 2015, A. Ringwald, L. Rosenberg, G. Rybka

experimentally excluded, astro/cosmo excluded,
sensitivity of planned experiments, „preferred“ region

Axion cosmology

$$\boxed{\phi = f_a \theta}$$

- the action (ignoring gravity for the moment)

$$\mathcal{S} = f_a^2 \int d^4x \sqrt{-g} \left[-\frac{1}{2} g_{\mu\nu} \partial^\mu \theta \partial^\nu \theta - V(\theta, T) \right]$$

- equation of motion

$$\ddot{\theta} + 3H\dot{\theta} - \frac{\nabla^2}{a^2}\theta + V'(\theta, T) = 0$$

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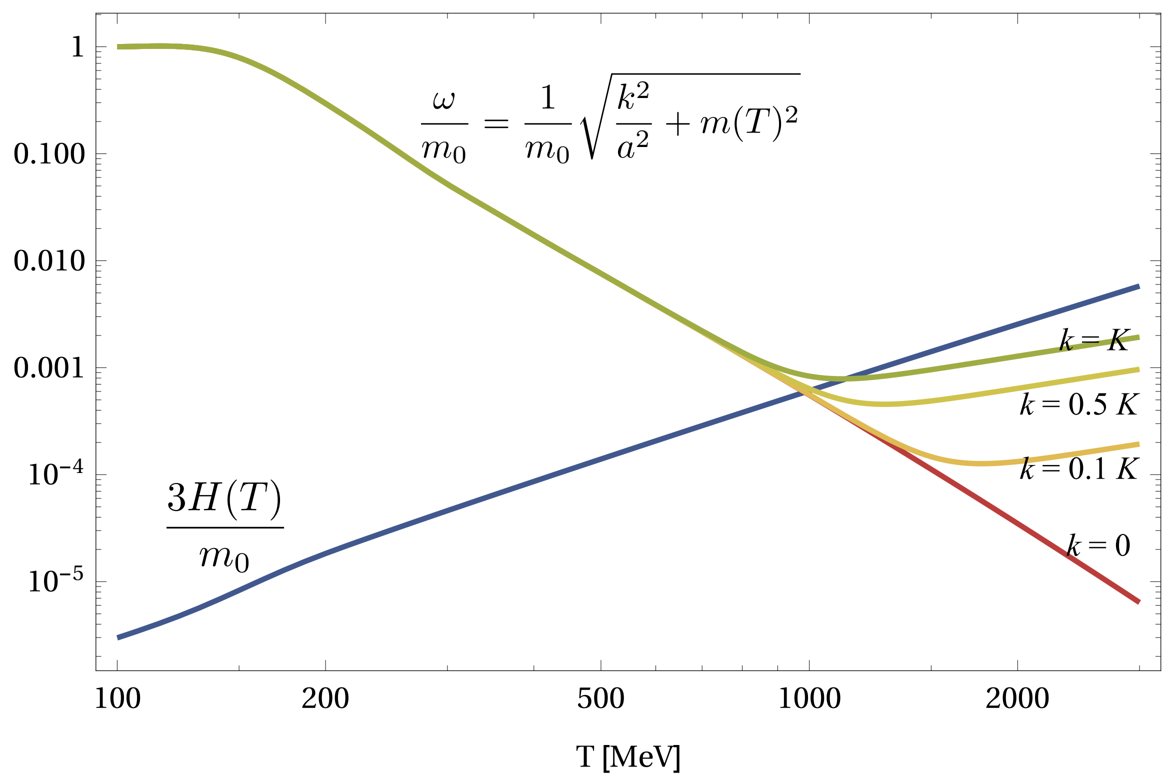
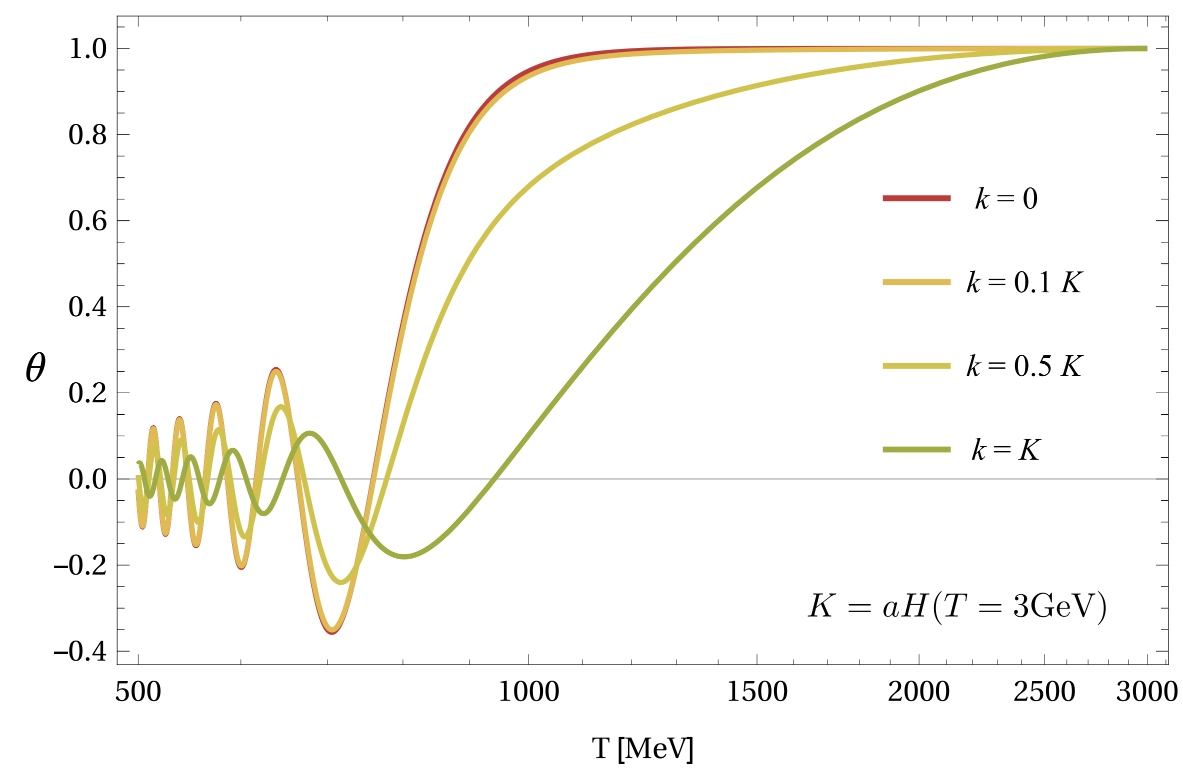
- periodic potential $V(\theta, T) = m^2(T)(1 - \cos\theta)$
- harmonic approximation $V(\theta, T) \approx \frac{1}{2} m^2(T) \theta^2$

  → Fourier-modes evolve independently

$$\ddot{\theta}_k + 3H(T)\dot{\theta}_k + \omega^2\theta_k = 0 \qquad \omega^2 = \frac{k^2}{a^2} + m(T)^2$$

- modes outside the horizon $3H(T) > \omega$:
  over-damped oscillator, field frozen: $\theta_k = const$
- modes inside the horizon $3H(T) < \omega$:
  oscillator with frequency ω, amplitude decays with expansion
  relativistic modes are red shifted relative to non-relativistic modes





Axion energy density

$$\rho(\vec{x}) = \frac{f_a^2}{2}\left[\dot{\theta}^2 - \frac{(\vec{\nabla}\theta)^2}{a^2} + m^2(T)\theta^2\right]$$

Example:

- homogeneous field (no gradient terms), adiabatic evolution

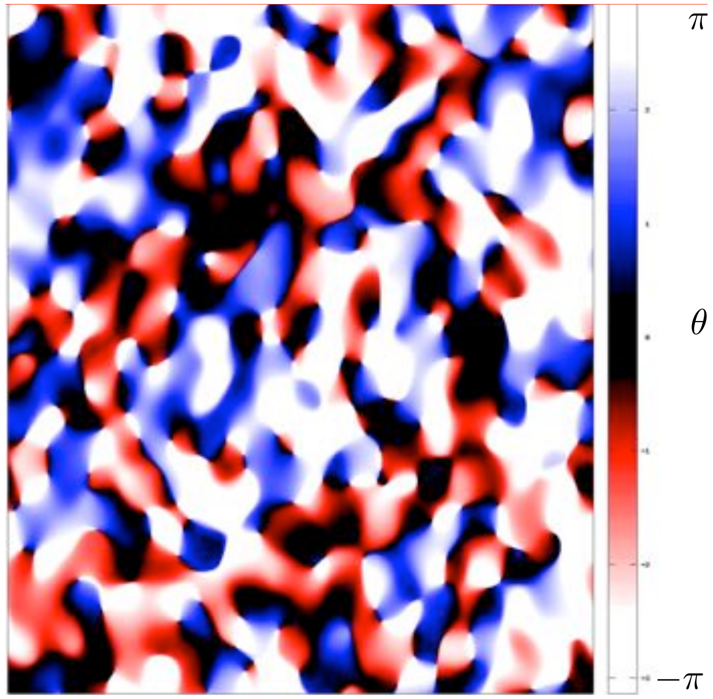
$$\theta \sim \frac{\overline{\theta}}{a^{3/2}}\cos[m(T)t]$$

- late time energy density:

$$\rho \sim f_a^2 m(T_{\rm osc}) m_0 \left(\frac{a_{\rm osc}}{a}\right)^3 \overline{\theta}^2 \qquad\qquad m(T_{\rm osc}) = 3H(T_{\rm osc})$$

behaves as cold dark matter (also true in perturbation theory)

Initial conditions



J. Redondo

pre-inflation case: PQ phase transition before end of inflation $\Rightarrow$ constant initial field value $\bar{\theta} \in [-\pi, \pi]$ in whole observable Universe

$$\Omega_a h^2 \approx 0.24\, \bar{\theta}^2 g(\bar{\theta}) \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6}$$

$$\approx 0.13\, \bar{\theta}^2 g(\bar{\theta}) \left(\frac{10^{-5}\,\mathrm{eV}}{m_0}\right)^{7/6}$$

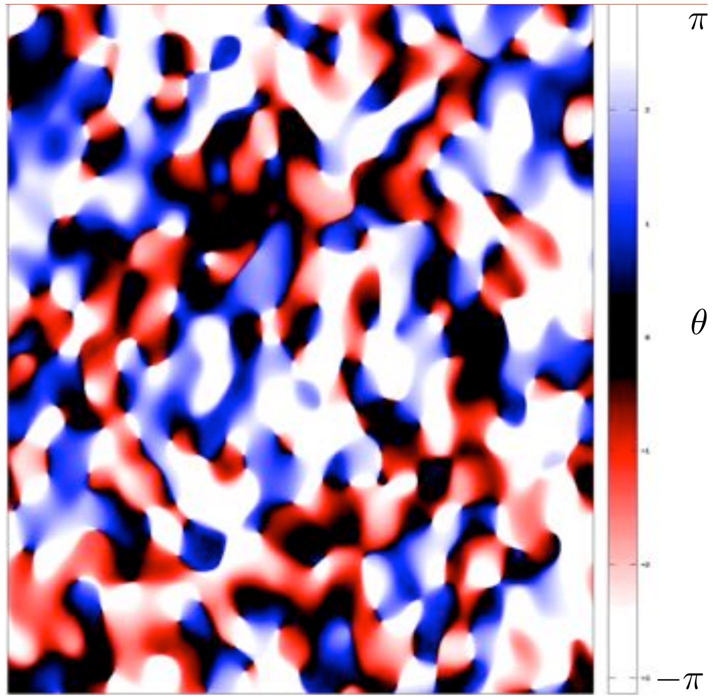
$g(\bar{\theta})$ anharmonic correction

Gondolo, Visinelli, 09

- $m_0 \ll 10^{-5}\,\mathrm{eV}$: tune $\bar{\theta}$ to small values
- $m_0 \gg 10^{-5}\,\mathrm{eV}$: not enough dark matter

possibly constrained by iso-curvature perturbations

Initial conditions



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pre-inflation case: PQ phase transition before end of inflation $\Rightarrow$ constant initial field value $\overline{\theta} \in [-\pi, \pi]$ in whole observable Universe

post-inflation case: PQ phase transition after end of inflation $\Rightarrow$ random field value $\overline{\theta} \in [-\pi, \pi]$ in causally disconnected regions

- before axion mass turns on: random field values $\overline{\theta} \in [-\pi, \pi]$ in regions of order of horizon size at QCD epoch $\rightarrow$ order one density fluctuations $\Rightarrow$ axion minicluster

Axion minicluster

Hogan, Rees, 1988;
Kolb, Tkachev, 93, 94, 95
Zurek, Hogan, Quinn, 06

- PQ symmetry breaking after inflation: Axion field takes random values in different Hubble volumes
- O(1) density fluctuations when Axion mass switches on
- expect gravitationally bound objects with size ~ Hubble volume @ QCD PT

$$M \sim \frac{4\pi}{3} d_H^3(T_{\rm osc})\overline{\rho}(T_{\rm osc}) \qquad d_H \sim 1/H$$

$$M \sim 10^{-12} M_\odot (f_{\rm PQ}/10^{11}\,\mathrm{GeV})^2$$

$$\left[10^{-12} M_\odot \sim 10^{18}\,\mathrm{kg}\,, \quad M_{\rm Earth} \simeq 6\times 10^{24}\,\mathrm{kg}\,, \quad M_{\rm Moon} \simeq 10^{23}\,\mathrm{kg}\right]$$

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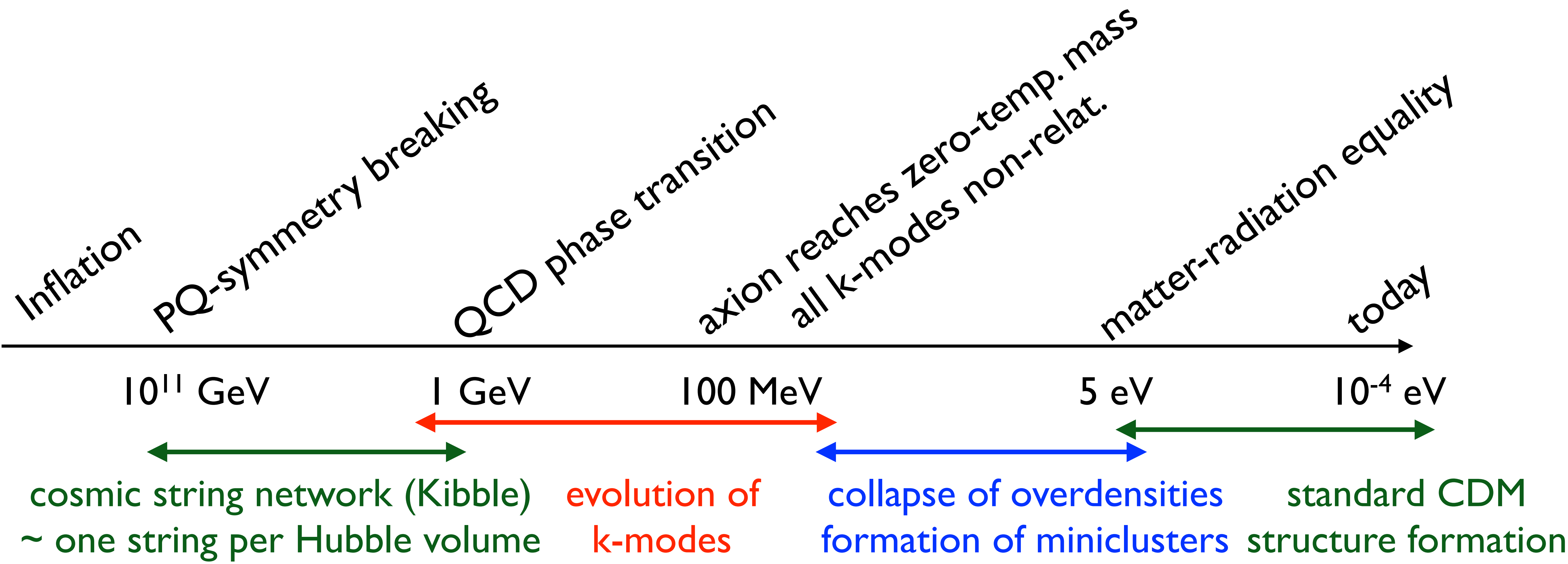
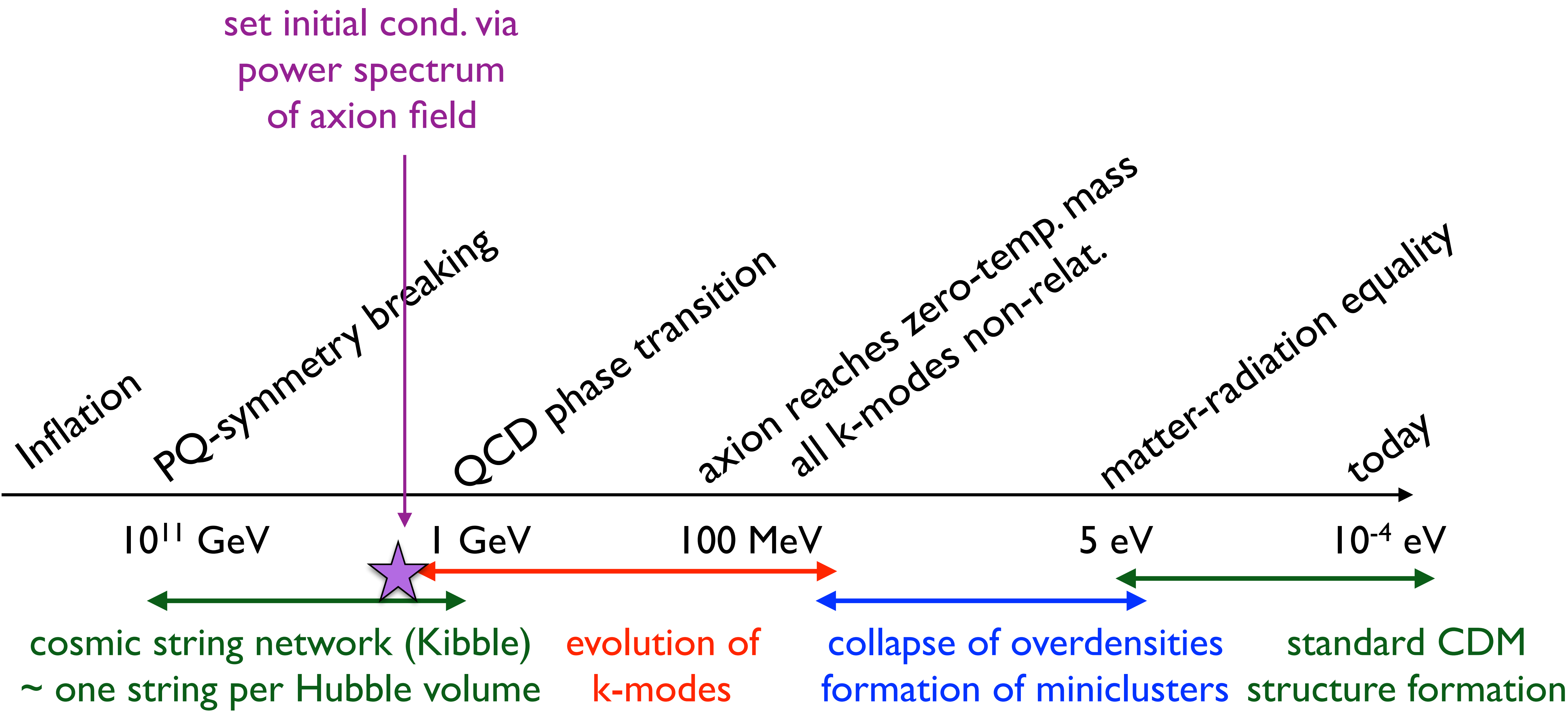

Inflation
PQ-symmetry breaking
QCD phase transition
axion reaches zero-temp. mass
all k-modes non-relat.
matter-radiation equality
today
10^11 GeV
1 GeV
100 MeV
5 eV
10^-4 eV
cosmic string network (Kibble)
~ one string per Hubble volume
evolution of
k-modes
collapse of overdensities
formation of miniclusters
standard CDM
structure formation


set initial cond. via
power spectrum
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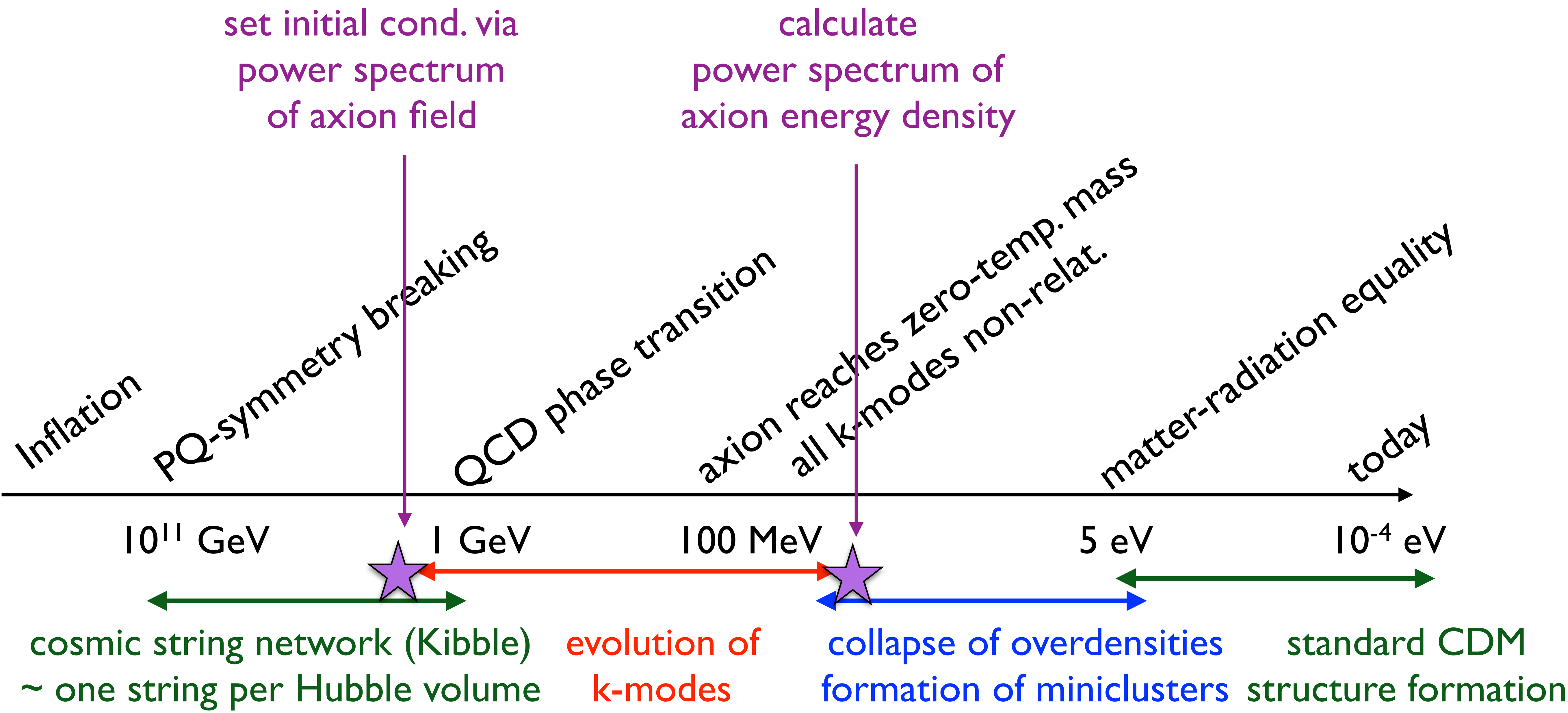

set initial cond. via power spectrum of axion field
calculate power spectrum of axion energy density
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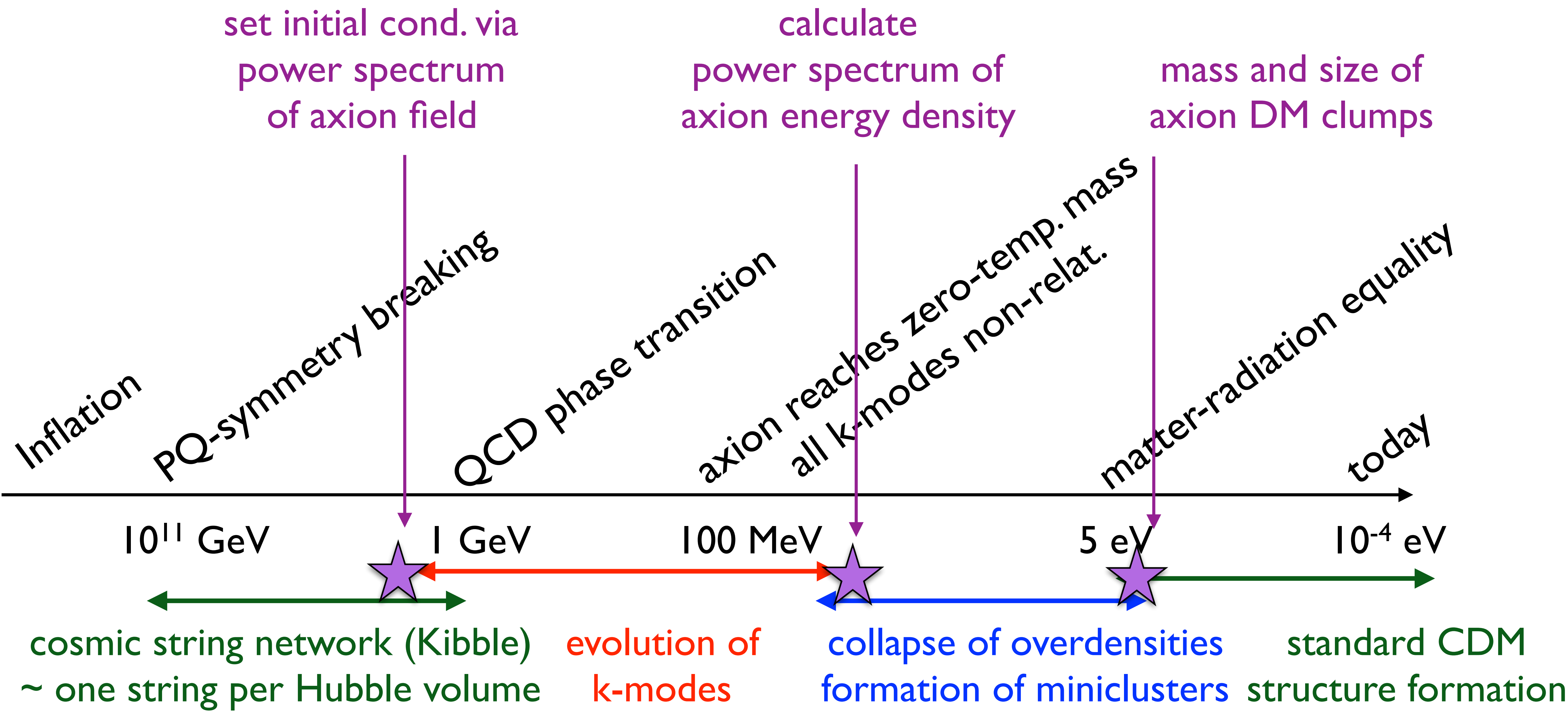

set initial cond. via
power spectrum
of axion field
calculate
power spectrum of
axion energy density
mass and size of
axion DM clumps
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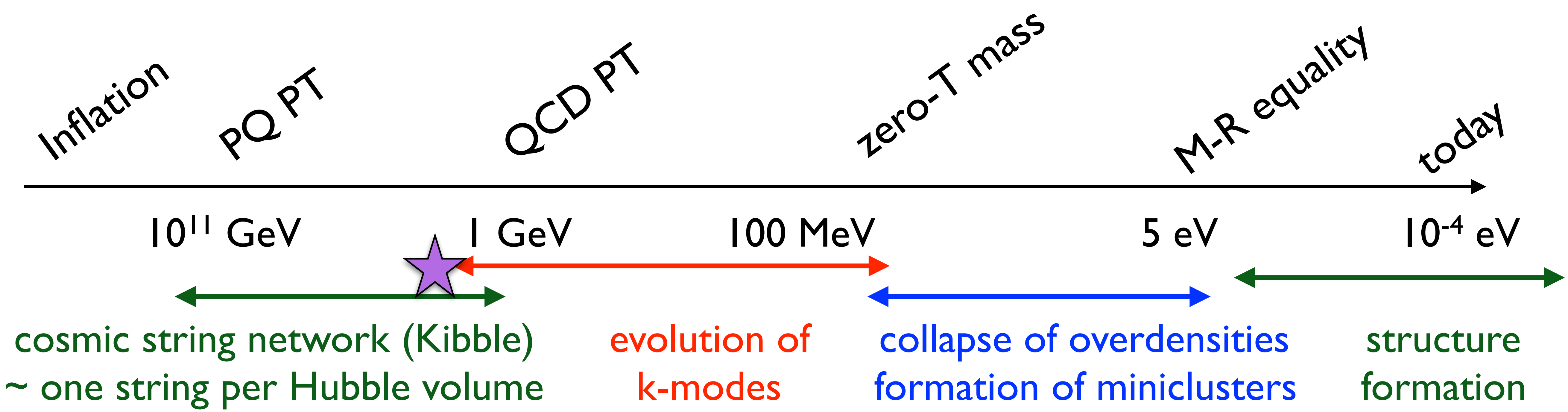
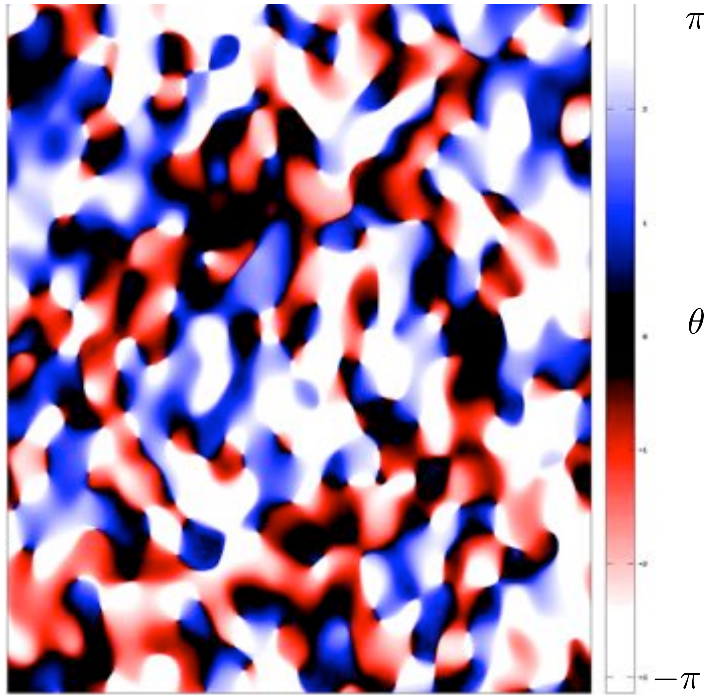
Initial condition



From the PQ PT down to the QCD PT

- random values of periodic field → cosmic strings
- Kibble mechanism:
  \`scaling´ of string network: roughly one string per Hubble volume during expansion of Universe
- Before onset of QCD PT remains one string per Hubble volume and

$$\langle\theta(\vec{x})^2\rangle = \pi^2/3$$



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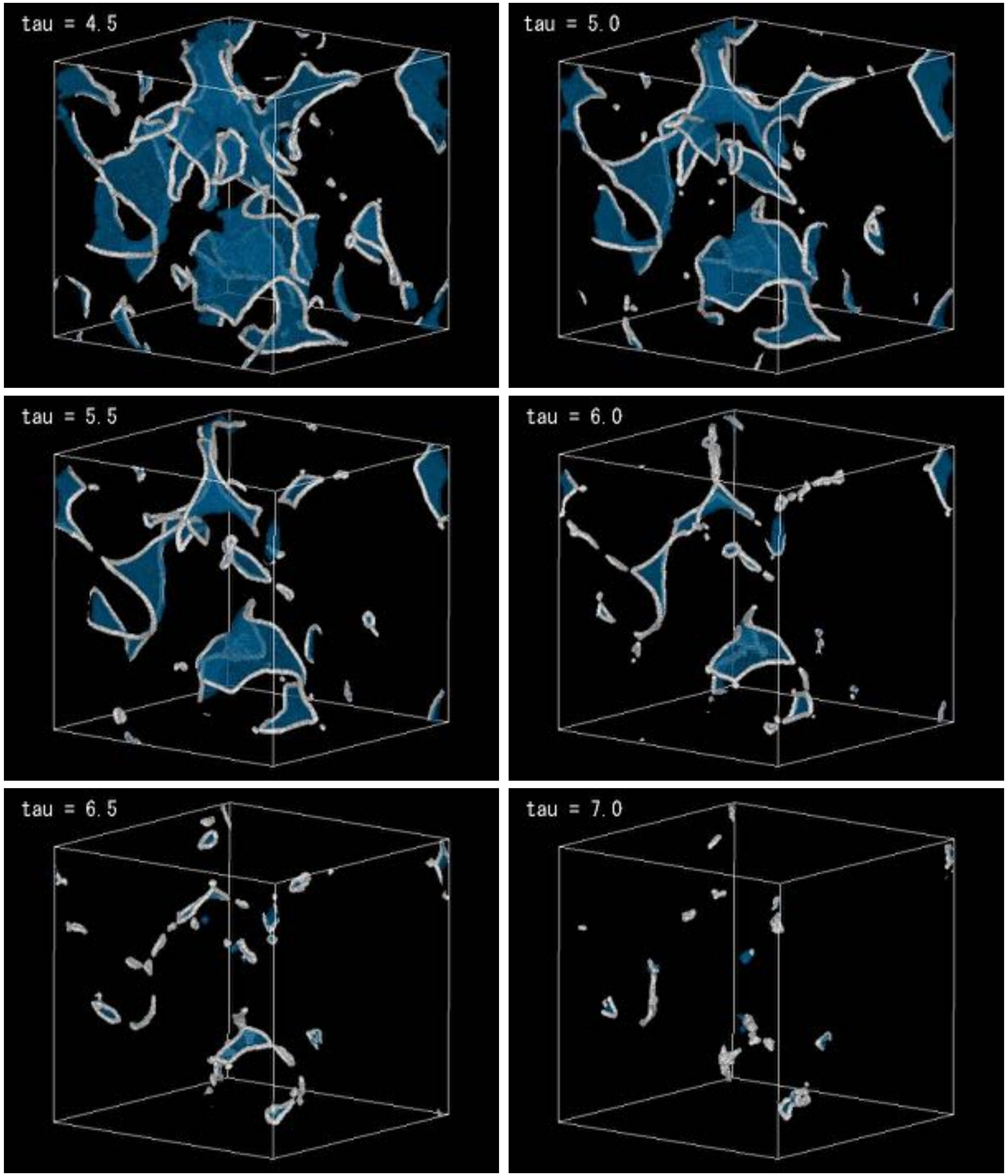
String-domain wall network at QCD PT



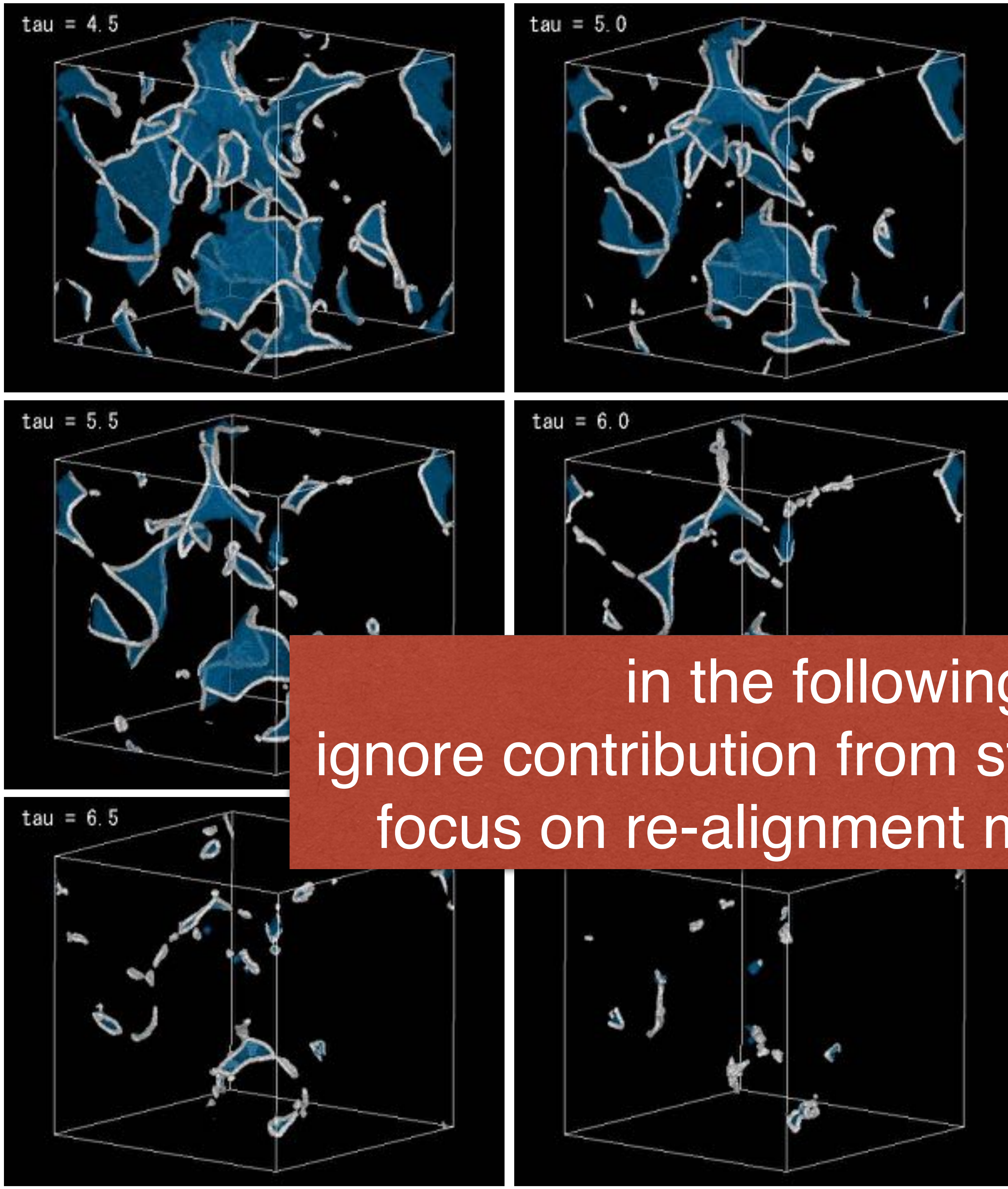
white: strings
blue: domain walls
$\tau_f/\tau_i = 24$
$T = 0$ mass at $\tau = 3.3$

Hiramatsu, Kawasaki, Saikawa, Sekiguchi, 12

string/domain wall system decays by radiating axions

significant contribution to the axion energy density e.g. up to 75% KSS14
large uncertainty

String-domain wall network at QCD PT



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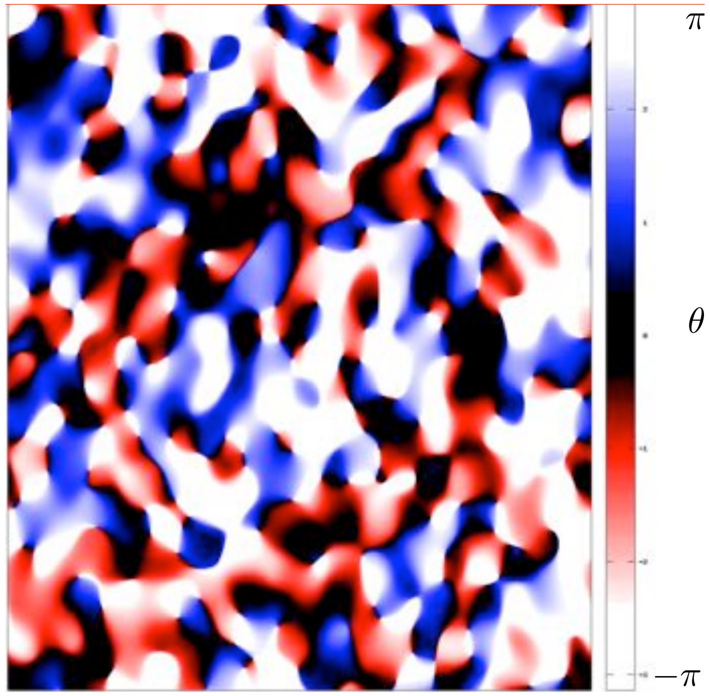
contribution to the
axion energy density
e.g. up to 75% KSS14
large uncertainty

in the following:
ignore contribution from string network
focus on re-alignment mechanism

Initial condition

- axion field smooth on scales < horizon
  uncorrelated on scales > horizon
- assume power spectrum for axion field
  w Gaussian cut-off



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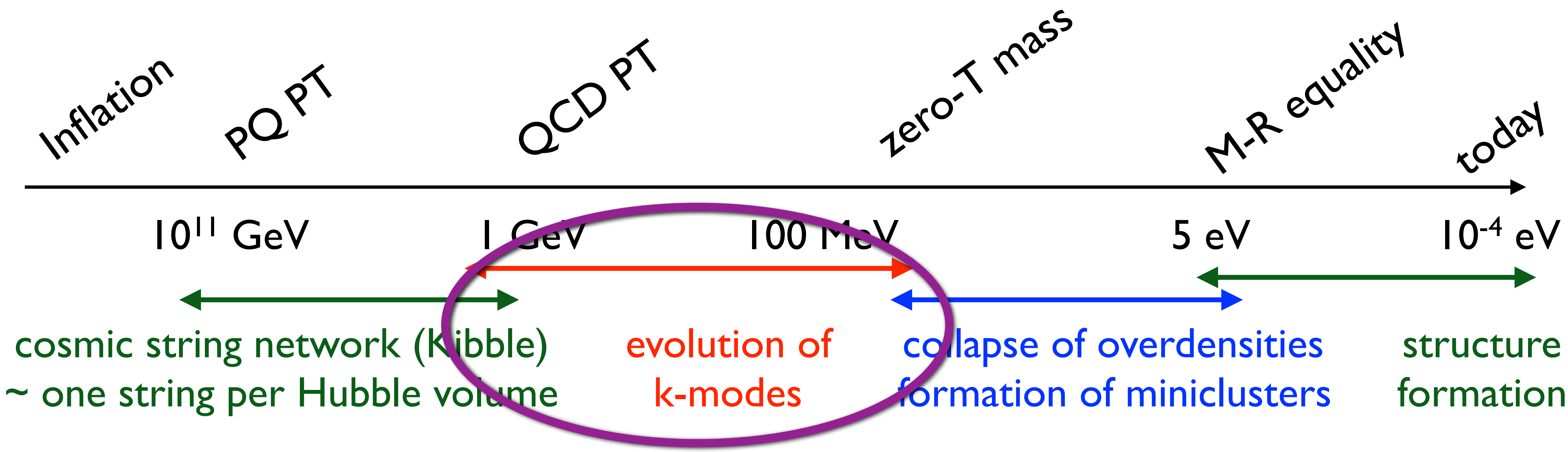
$$\langle \theta_k \theta^*_{k'} \rangle = (2\pi)^3\, \delta^3(\vec{k} - \vec{k}')P_\theta(k)$$

$$\boxed{P^{\rm G}_\theta(k) = \frac{8\pi^4}{3\sqrt{\pi}K^3} \exp\left(-\frac{k^2}{K^2}\right)}$$

- normalization: fixed by flat distribution $\langle \theta(\vec{x})^2 \rangle = \pi^2/3$
- cut-off: comoving horizon wave-number $K = a_i H_i$

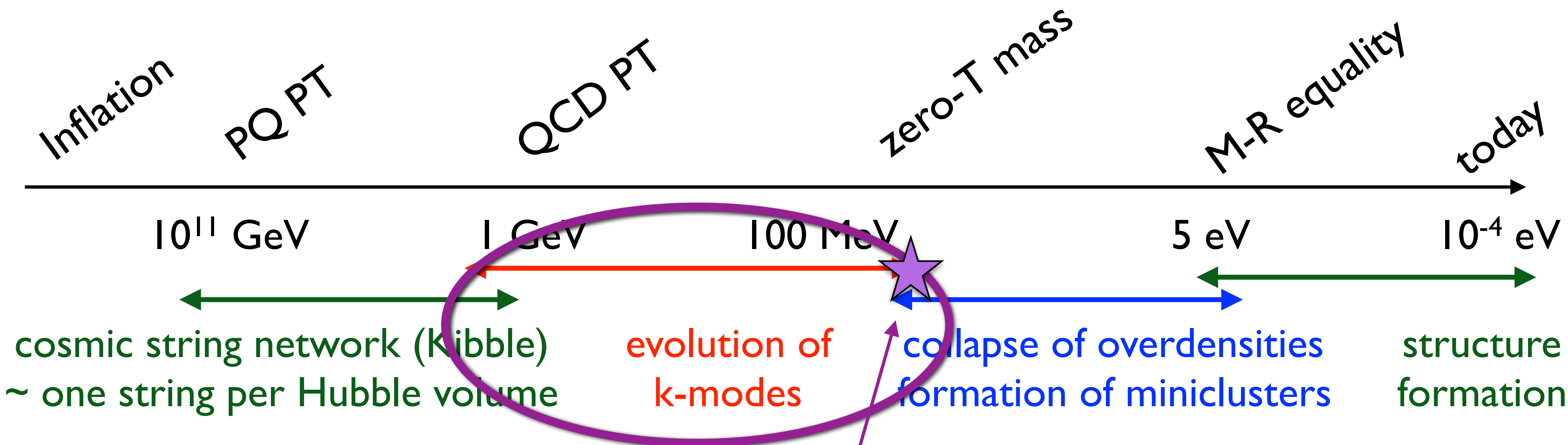
Axion field evolution



- harmonic approximation of axion potential
- equation of motion including gradient terms:

$$\ddot{\theta}_k + 3H(T)\dot{\theta}_k + \omega_k^2 \theta_k = 0\,, \qquad \omega_k^2 \equiv \frac{k^2}{a^2} + m(T)^2$$

Axion field evolution



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- solve EoM to calculate axion energy density and density power spectrum

Axion energy density

$$\rho(\vec{x}) = \frac{f_{\rm PQ}^2}{2}\left[\dot{\theta}^2 - \frac{1}{a^2}(\vec{\nabla}\theta)^2 + m^2(T)\,\theta^2\right]$$

$$\theta_k(a) = \theta_k\, f_k(a)$$

- go to Fourier space for field

$$\rho(\vec{x}) = \frac{1}{(2\pi)^6}\frac{f_{\rm PQ}^2}{2}\int d^3k d^3k'\, \theta_k \theta^*_{k'} F(k,k') e^{-i\vec{x}(\vec{k}-\vec{k}')}$$

$$F(k,k') = \dot{f}_k \dot{f}_{k'} + \left(\frac{\vec{k}\cdot\vec{k}'}{a^2} + m^2(T)\right) f_k f_{k'}$$

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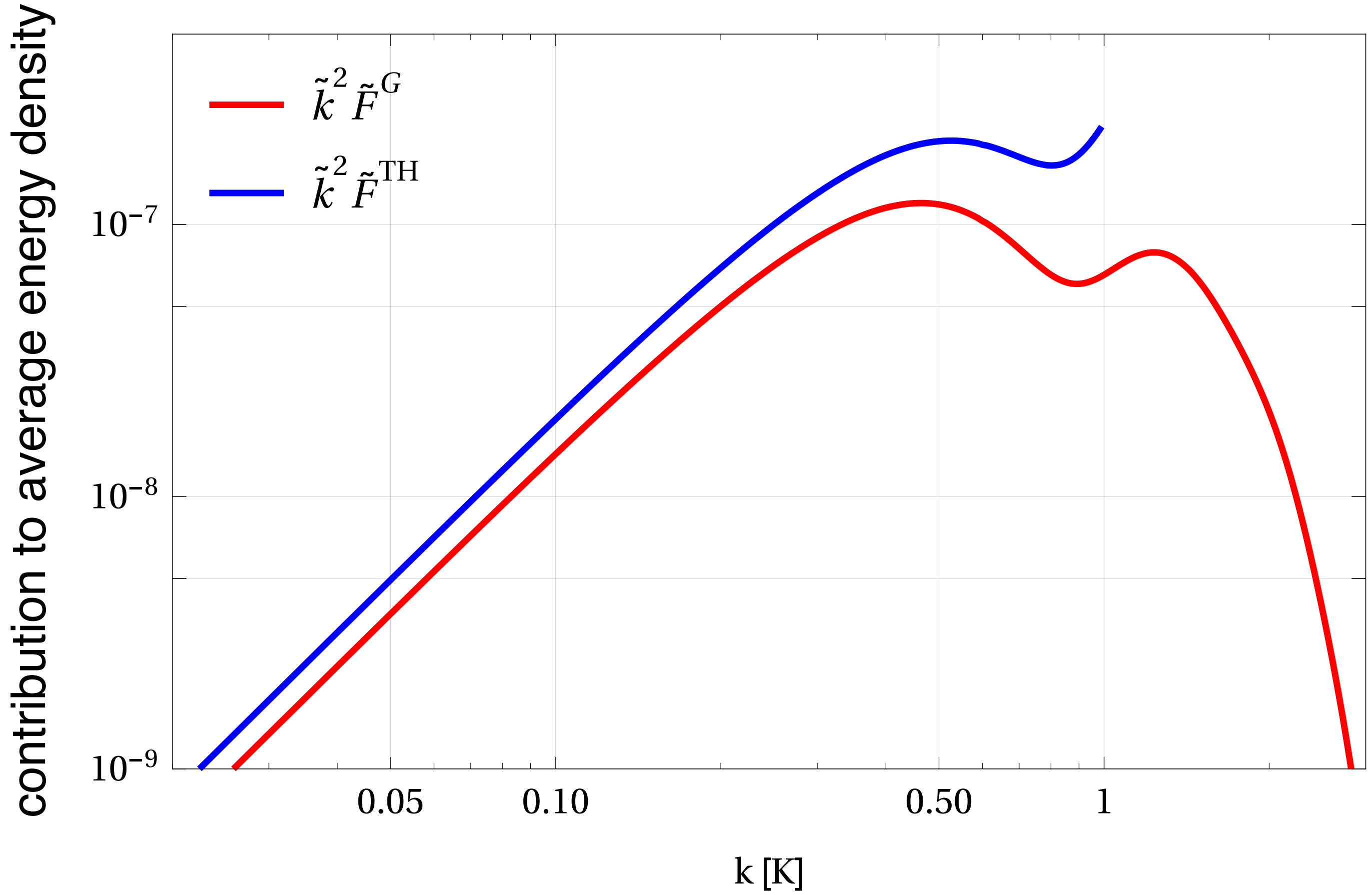
- average energy density (without string contribution):

$$\boxed{\bar\rho \equiv \langle\rho(\vec{x})\rangle = \frac{1}{2\pi^2}\frac{f_{\rm PQ}^2}{2}\int_0^\infty dk\, k^2\, P_\theta(k)F(k,k)}$$

$$F(k,k) = \dot f_k^2 + \omega_k^2 f_k^2$$

Axion energy density



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$$F(k,k) = \dot{f}_k^2 + \omega_k^2 f_k^2$$

Density power spectrum

Fourier transform of the density:

$$\rho_q = \frac{1}{(2\pi)^3}\frac{f_{\rm PQ}^2}{2}\int d^3k\,\theta_k\theta^*_{k-q}F(k,k-q)$$

variance (use Wick's theorem):

$$\langle|\rho_q|^2\rangle = \left[\frac{1}{(2\pi)^3}\frac{f_{\rm PQ}^2}{2}\right]^2\int d^3k d^3k'\,\langle\theta_k\theta^*_{k-q}\theta^*_{k'}\theta_{k'-q}\rangle F(k,k-q)F^*(k',k'-q)$$

$$= 2\frac{V}{(2\pi)^3}\left(\frac{f_{\rm PQ}^2}{2}\right)^2\int d^3k\,P_\theta(|\vec{k}|)P_\theta(|\vec{k}-\vec{q}|)\,F(k,k-q)^2$$

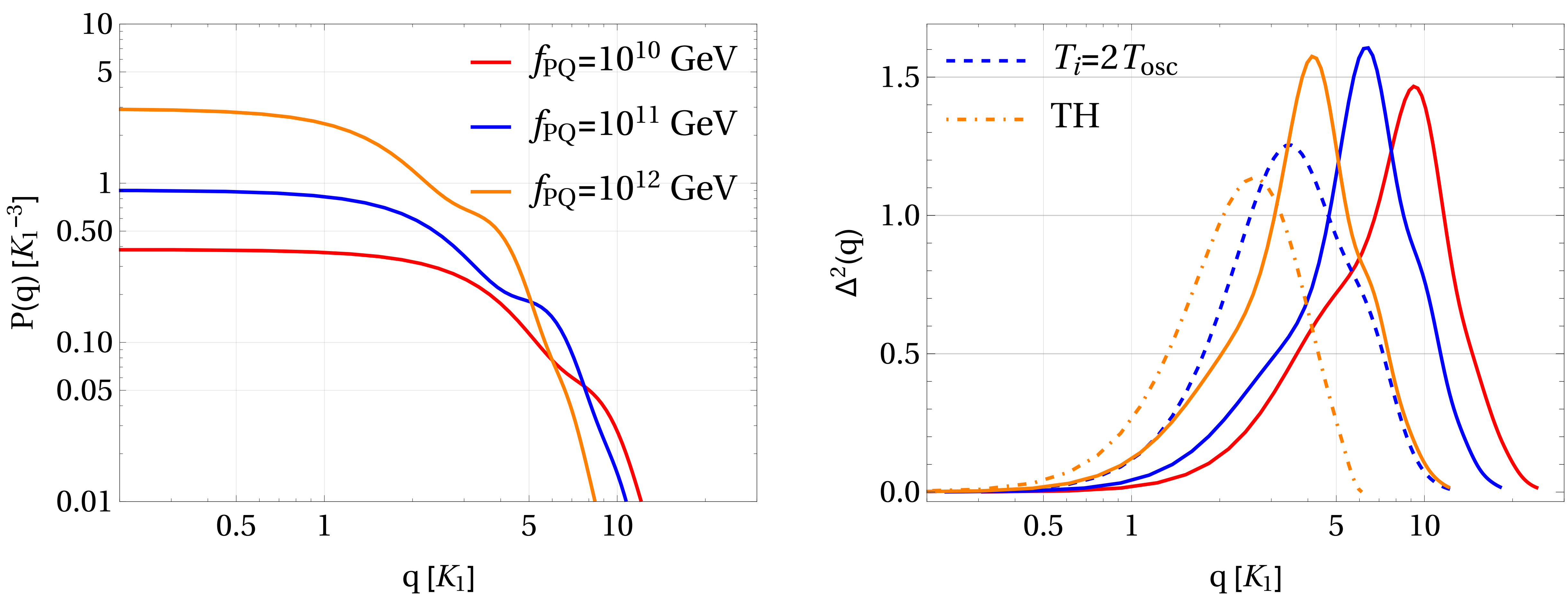
this gives for the power spectrum

$$\boxed{P(q) = \frac{1}{V}\frac{\langle|\rho_q|^2\rangle}{\overline{\rho}^2} = 2(2\pi)^3\frac{\int d^3k\,P_\theta(|\vec{k}|)P_\theta(|\vec{k}-\vec{q}|)\,F(k,k-q)^2}{\left[\int d^3k\,P_\theta(k)F(k,k)\right]^2}}$$

Density power spectrum

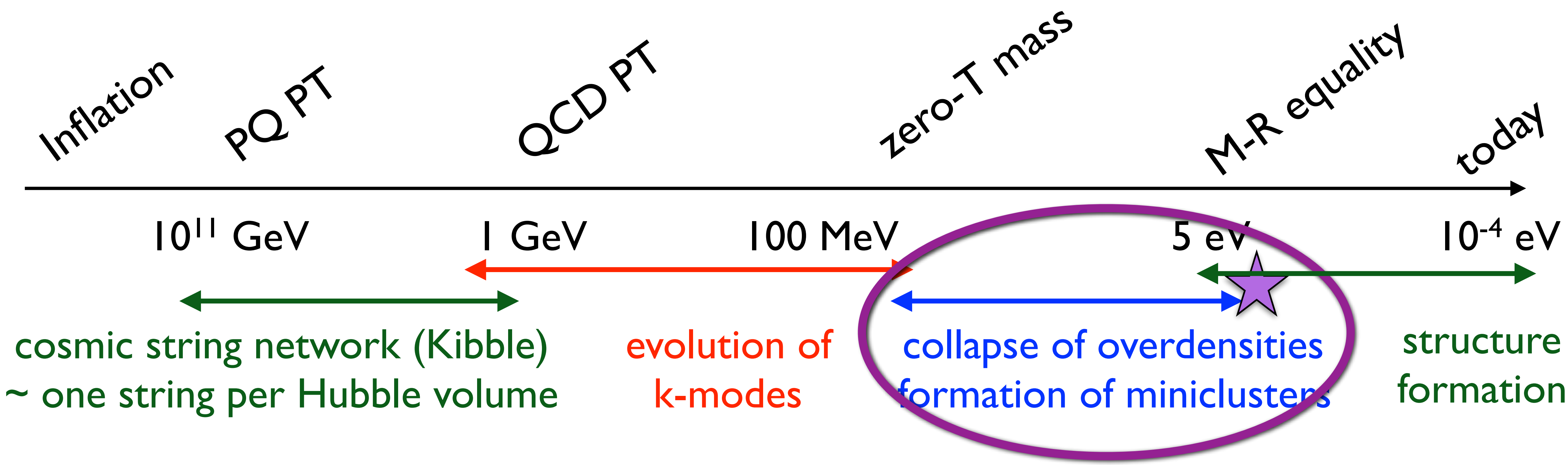
Enander, Pargner, TS, 1708.04466

$$\Delta^2(q) = \frac{q^3}{2\pi^2} P(q)$$



- density fluctuations of order one
- charact. size a few times smaller than horizon @ T_{osc}

Collapse of over-densities



- spherical collapse model for non-linear density fluctuations during radiation domination
  [Kolb, Tkachev, 94]

- modified Press-Schechter ansatz to calculate double-differential minicluster distribution in mass and size

Double-differential pdf for density fluctuations

- variance of the smoothed density contrast

$$\sigma_R^2 \equiv \langle \delta_R(\vec{x})^2 \rangle = \frac{1}{2\pi^2} \int_0^\infty dk\, k^2 P(k) \left| \tilde{W}_R(k) \right|^2$$

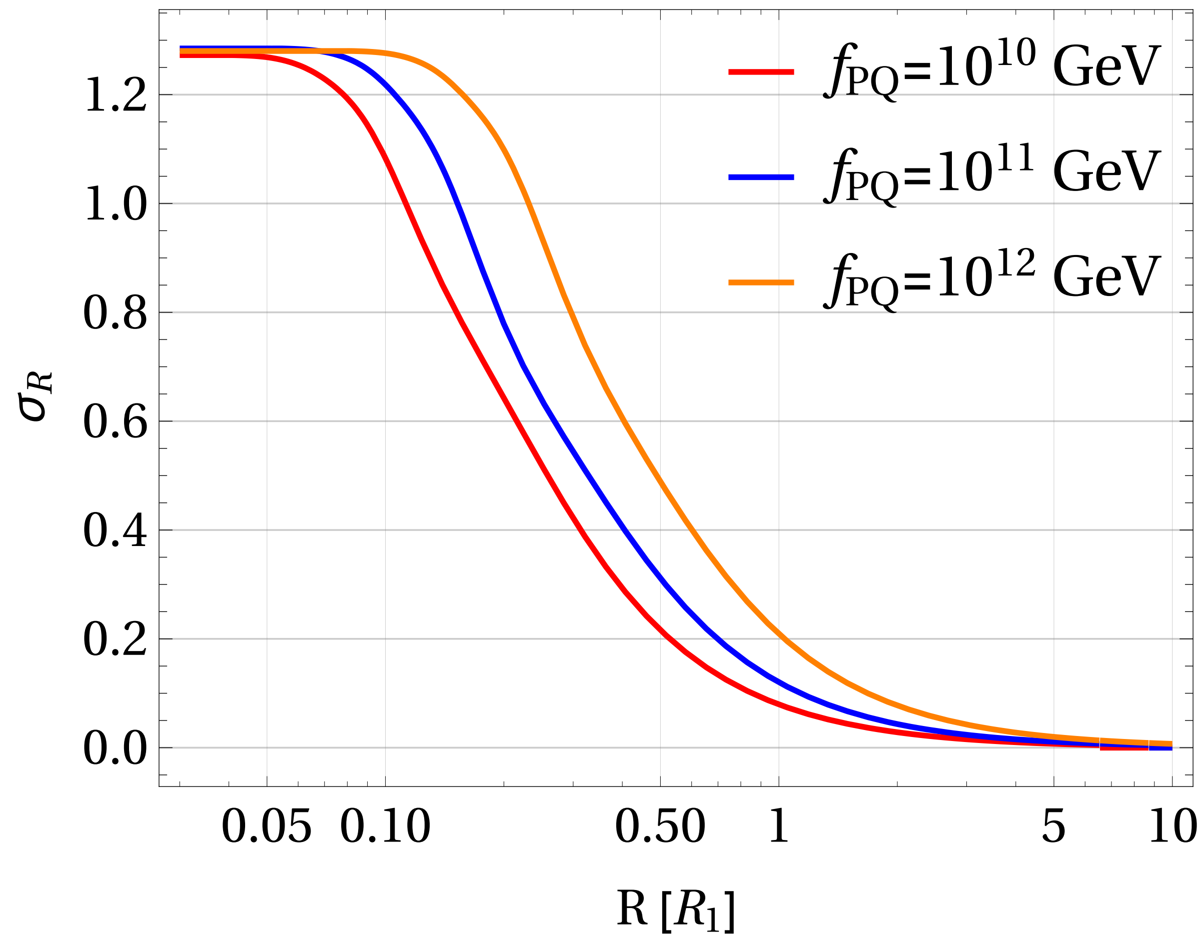
- Gaussian distribution for the smoothed contrast

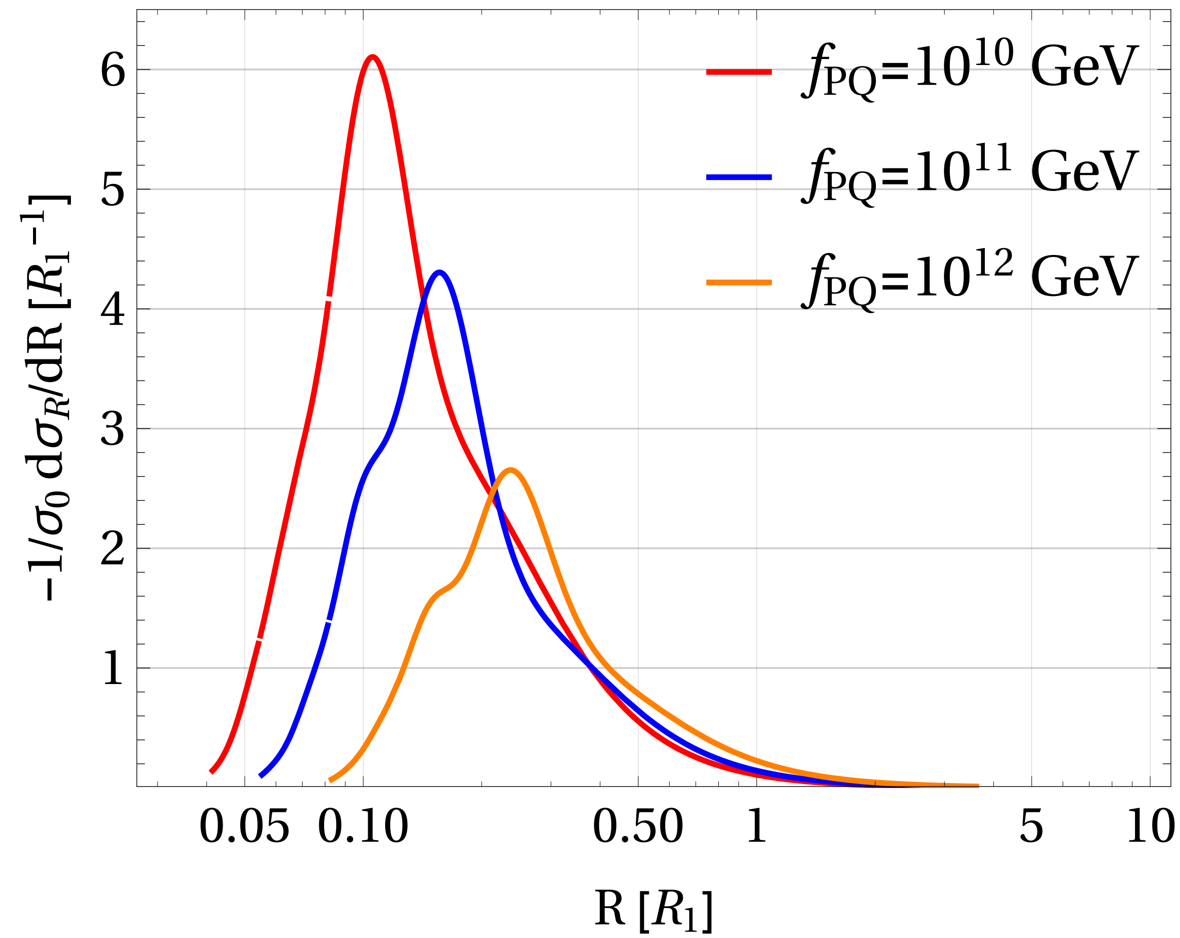
$$f_{\rm sm}(\delta; R) = \frac{1}{\sqrt{2\pi}\sigma_R} \exp\left(-\frac{\delta^2}{2\sigma_R^2} \right) .$$

- derive distribution in δ and R:

$$f(\delta, R) = -\frac{1}{\sigma_0} \frac{d\sigma_R}{dR} \frac{\delta^2}{\sigma_R^2} f_{\rm sm}(\delta; R)$$

Variance of the smoothed density field





Spherical collapse model

following Kolb&Tkachev, 94

- EoM for spherical shell of matter on homogeneous radiation background

$$\ddot{r} = -\frac{8\pi G}{3}\rho_{\rm rad} r - \frac{GM}{r^2} \qquad M = \frac{4\pi}{3}\overline{\rho}\,(1+\delta)\,r^3$$

- over-density `turn around´ for $\dot{r} = 0$
- an initial over-density δ(x_i) is collapsed at $x > x_i$ if

$$\delta > \delta_c \text{ with } \quad \delta_c(x) \approx \frac{0.7}{x} \qquad x \equiv a/a_{\rm eq}$$

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- holds for radiation as well as matter domination!

Double-differential mass function

- given distribution in δ and R (before self-gravity becomes imporant):

$$f(\delta, R) = -\frac{1}{\sigma_0}\frac{d\sigma_R}{dR}\frac{\delta^2}{\sigma_R^2} f_{\rm sm}(\delta; R)$$

- derive double-differential distribution of collapsed objects with mass M and size R using:

$$M = \frac{4\pi}{3}\overline{\rho}\,(1+\delta)\,r^3$$

$$\boxed{\frac{dn}{dM\,dR} = \frac{3}{2\pi M R^3} f(\delta, R)\Theta[\delta - \delta_c(x)]}$$

Dimensionless double-differential mass function

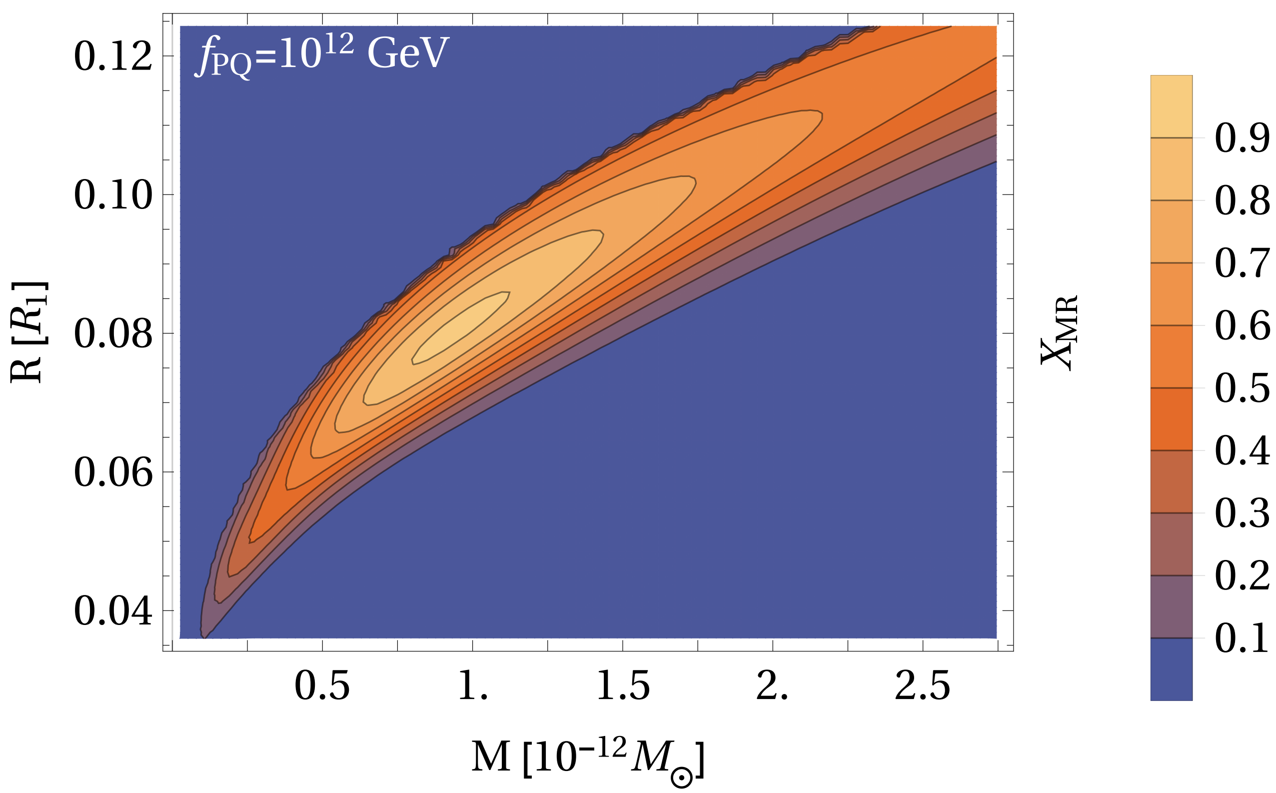
physical sizes at turn around

$f_{\rm PQ}$ [GeV]	$M_{\rm peak}$ [$M_\odot$]	M range [$M_\odot$]	$r_{\rm ta}^{\rm peak}$ [km]	$r_{\rm ta}$ range [km]
10^{10}	4×10^{-16}	$[2 \times 10^{-17}, 1 \times 10^{-14}]$	4×10^4	$[2 \times 10^4, 2 \times 10^5]$
10^{11}	2×10^{-14}	$[5 \times 10^{-16}, 3 \times 10^{-13}]$	2×10^5	$[4 \times 10^4, 7 \times 10^5]$
10^{12}	8×10^{-13}	$[6 \times 10^{-14}, 2 \times 10^{-11}]$	2×10^6	$[7 \times 10^5, 7 \times 10^6]$

- MC masses span 3 orders, sizes span 1 order of magn.
- peak-masses 2 orders of mag. smaller than naive estimates

  $$M \sim 10^{-12} M_\odot (f_{\rm PQ}/10^{11}\ {\rm GeV})^2$$

  (typical fluctuations smaller than horizon at $T_{\rm osc}$)



Enander, Pargner, TS, 1708.04466

Minicluster mass function

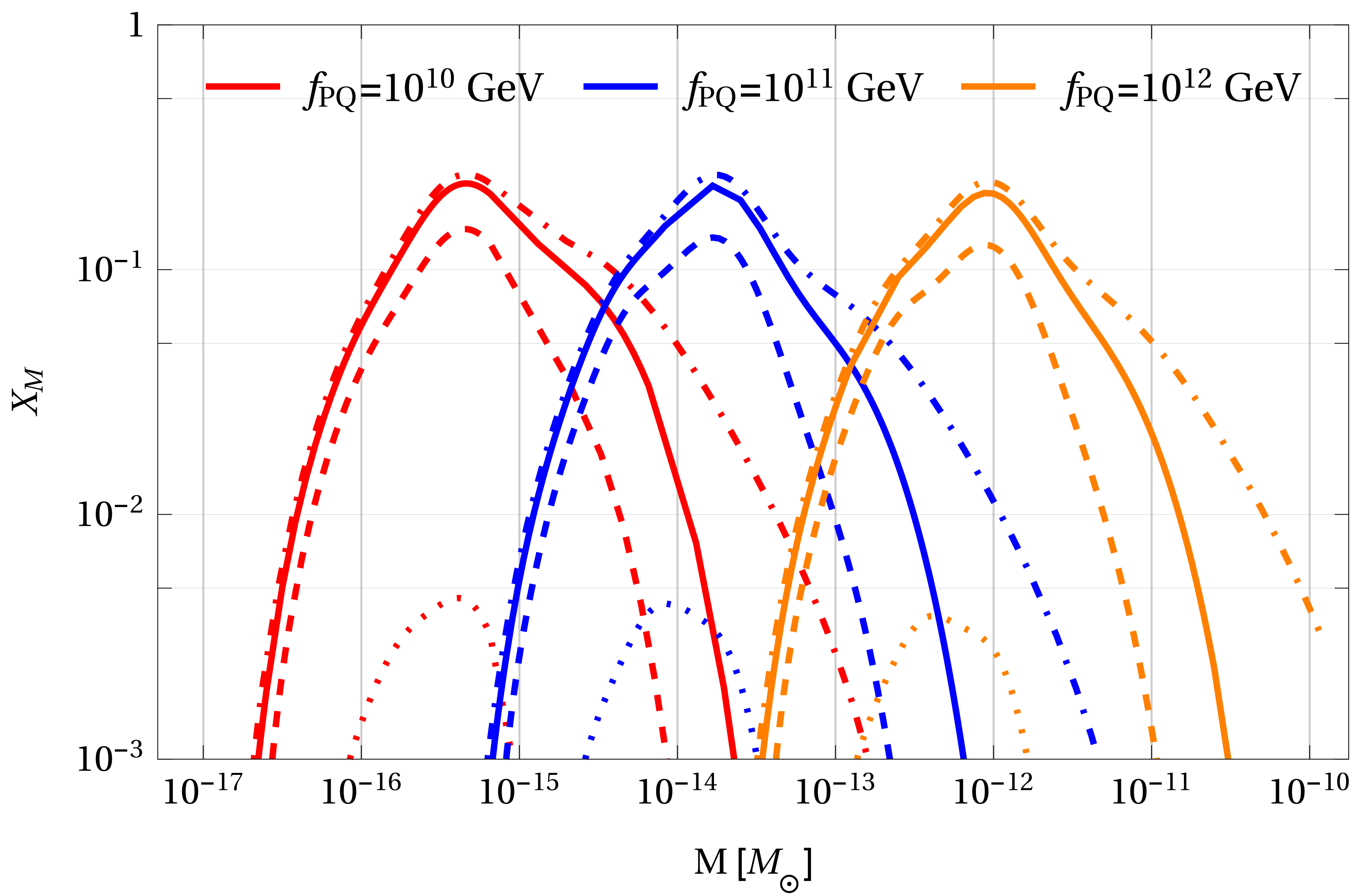


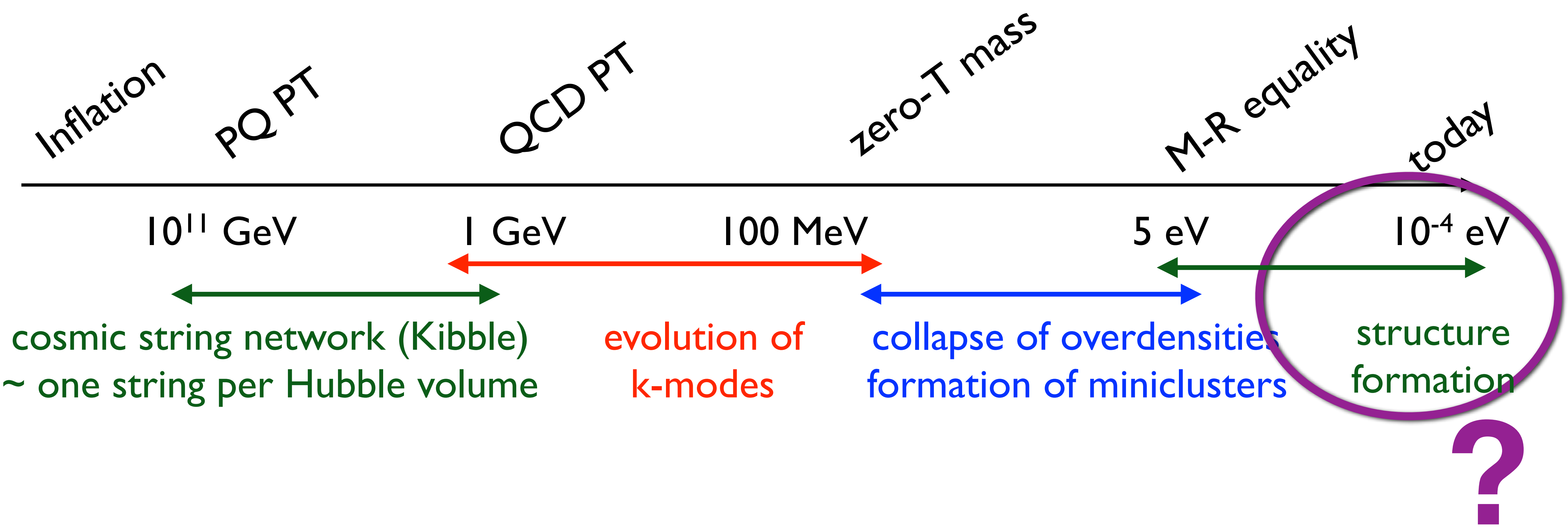
Figure 6. Dimensionless minicluster mass function $X_M \equiv M^2/\bar{\rho}(dn/dM)$ for three choices of $f_{\rm PQ}$. The different line-styles indicate the mass function at different times: dotted $x = 0.2$, dashed $x = 0.5$, solid $x = 1$, dot-dashed $x = 5$, where $x = a/a_{\rm eq}$.

Enander, Pargner, TS, 1708.04466

Assumptions

- initial power spectrum: should follow from evolution of string network (Kibble mechanism)
- harmonic approximation: anharmonic effects may lead to spikes in axion density [Kolb, Tkachev, 93]
- contribution from string/domain wall decays: likely to introduce additional energy density & fluctuations

Axion DM today - in our galaxy?



- Do minicluster survive non-linear structure formation?
- Do they collapse to dense Axion-stars?
  Are Axion-stars stable?

Bad news for direct detection

- suppose a fraction f_{MC} of DM is bound in objects of mass 10^{-13} M_{solar}
- the density in the Galaxy would be f_{MC}/solar system
- such a clump would pass through the Earth with a frequency

$$\frac{f_{\rm MC}}{t_{\rm Univ}} \left(\frac{\text{clump size}}{10^6\,\text{km}}\right)^2$$

How large are Minicluster today?

- do axions (particles) virialize?
  Transition from classical field to collection of particles?
- virialized system would have a size ~ 10^4 — 10^6 km
- do they survive hierarchical structure formation?
- may be disrupted and form tidal streams
  stream crossing 1/(20 yr) lasting for 2 to 3 days
  Tinyakov, Tkachev, Zioutas, 15
  Green, O'Hare, 17

Do minicluster condense to bose stars?

- static solution of a scalar field coupled to gravity (Klein-Gordon — Einstein / Schrödinger — Poisson)
- large literature (very incomplete)

Ruffini, Bonazzola, 1969
Rindler-Daller, Shapiro, 10, 12, 14
Chavanis, 11,17
applied to QCD axion:
J. Barranco and A. Bernal, 2011
J. Barranco, A. C. Monteverde and D. Delepine, 2013
J. Eby, P. Suranyi, L. Wijewardhana et al., 14, 15, 16, 17
Davidson, Schwetz, 2016
Braaten, Mohapatra, Zhang, 15, 16, 16
Hertzberg, Schiappacasse 17
Baum, Freese, Redondo, Visinelli, Wilczek, 17

Bose star — dimensional analysis

consider static solution of Euler equation, replace $\nabla \to 1/R$:

$$\frac{1}{2m^2R^2} - \frac{M}{8f_a^2 m^2 R^3} - G_N \frac{M}{R} \simeq 0$$

balance quantum pressure, axion self-interactions, gravity

has a solution only if $M < M_{max}$: Chavanis 2011; Davidson, TS, 16;...

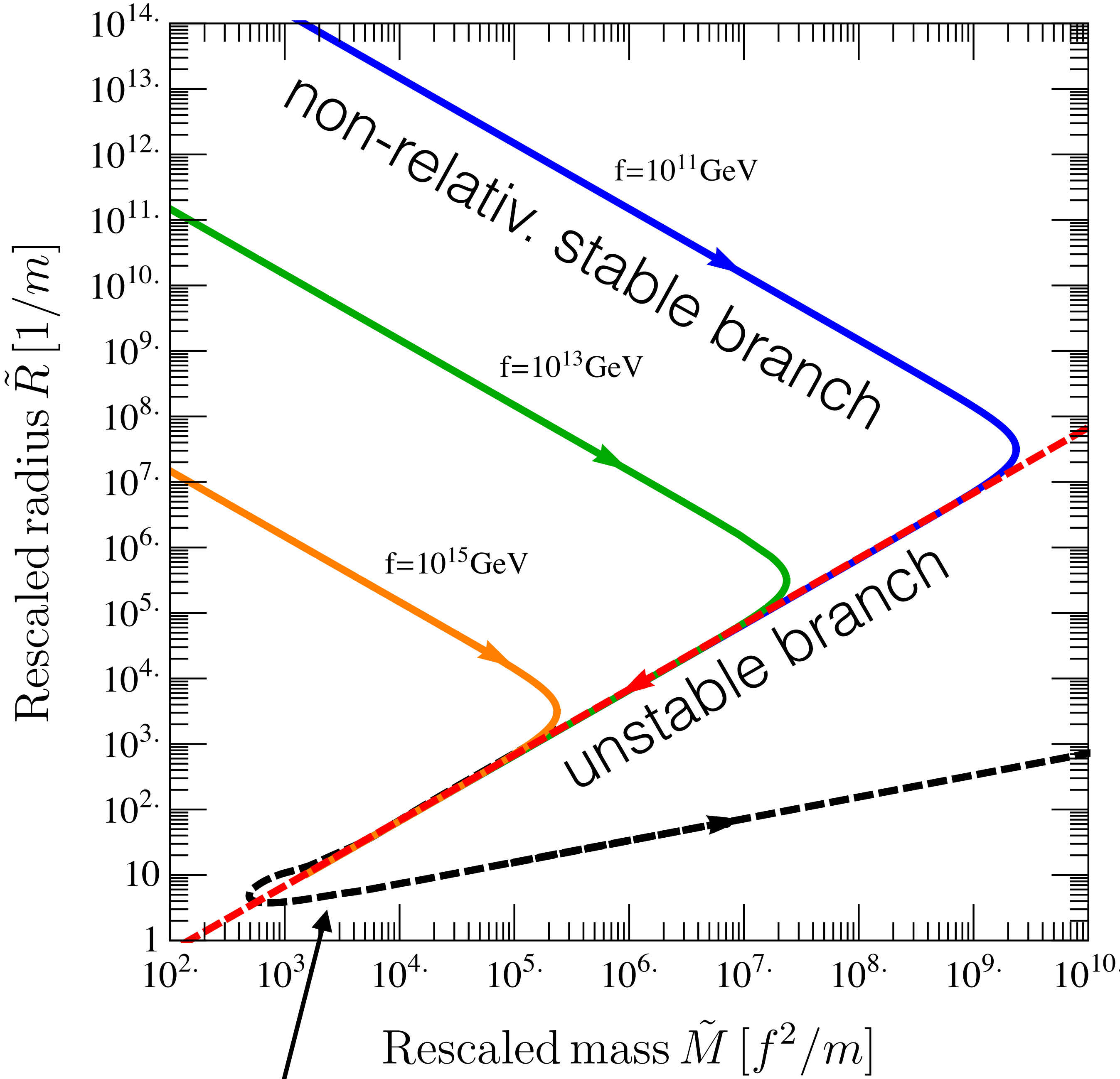
$$M \lesssim M_{max} \sim \frac{m_{\rm Pl} f_a}{m}\,, \qquad R \sim \frac{m_{\rm Pl}^2}{4m^2 M}$$

putting numbers:

$$M_{max} \simeq 10 \frac{m_{\rm Pl} f_a}{m} \sim 10^{-13} M_\odot \text{ (!)}$$

$$R \sim 100\,\mathrm{km}\,, \qquad \rho \sim 3\,\mathrm{g\,cm^{-3}} \left(\frac{\mathrm{f_a}}{10^{11}\,\mathrm{GeV}}\right)^2$$

Baum, Freese, Redondo, Visinelli, Wilczek, 17

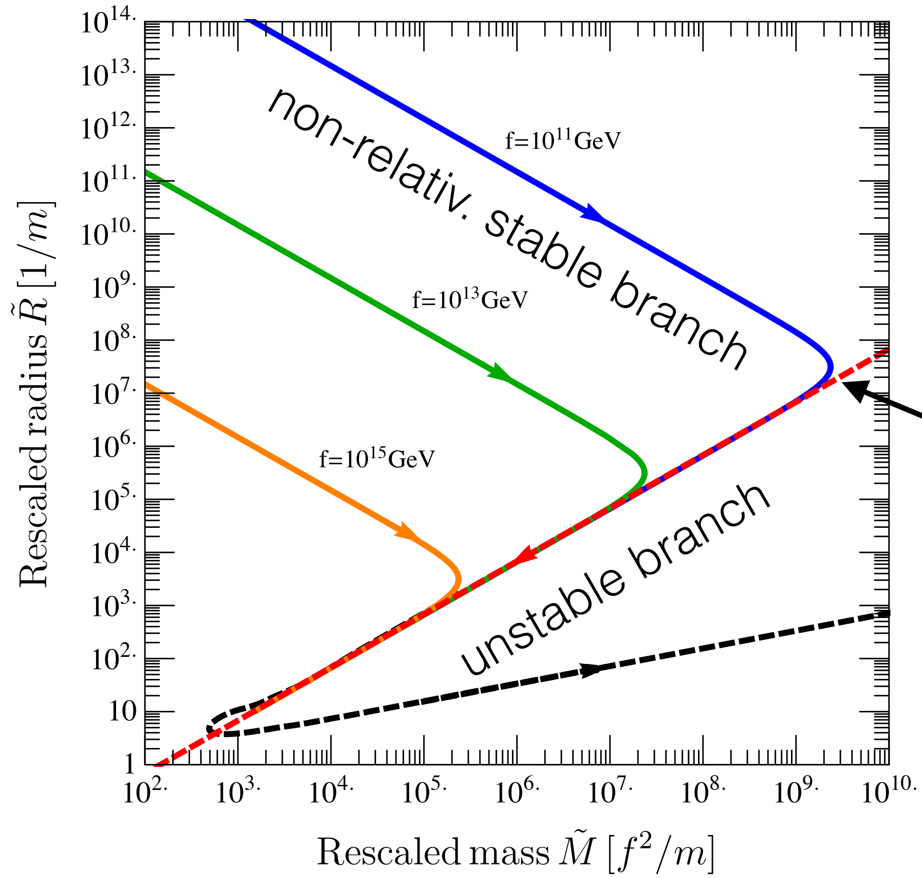


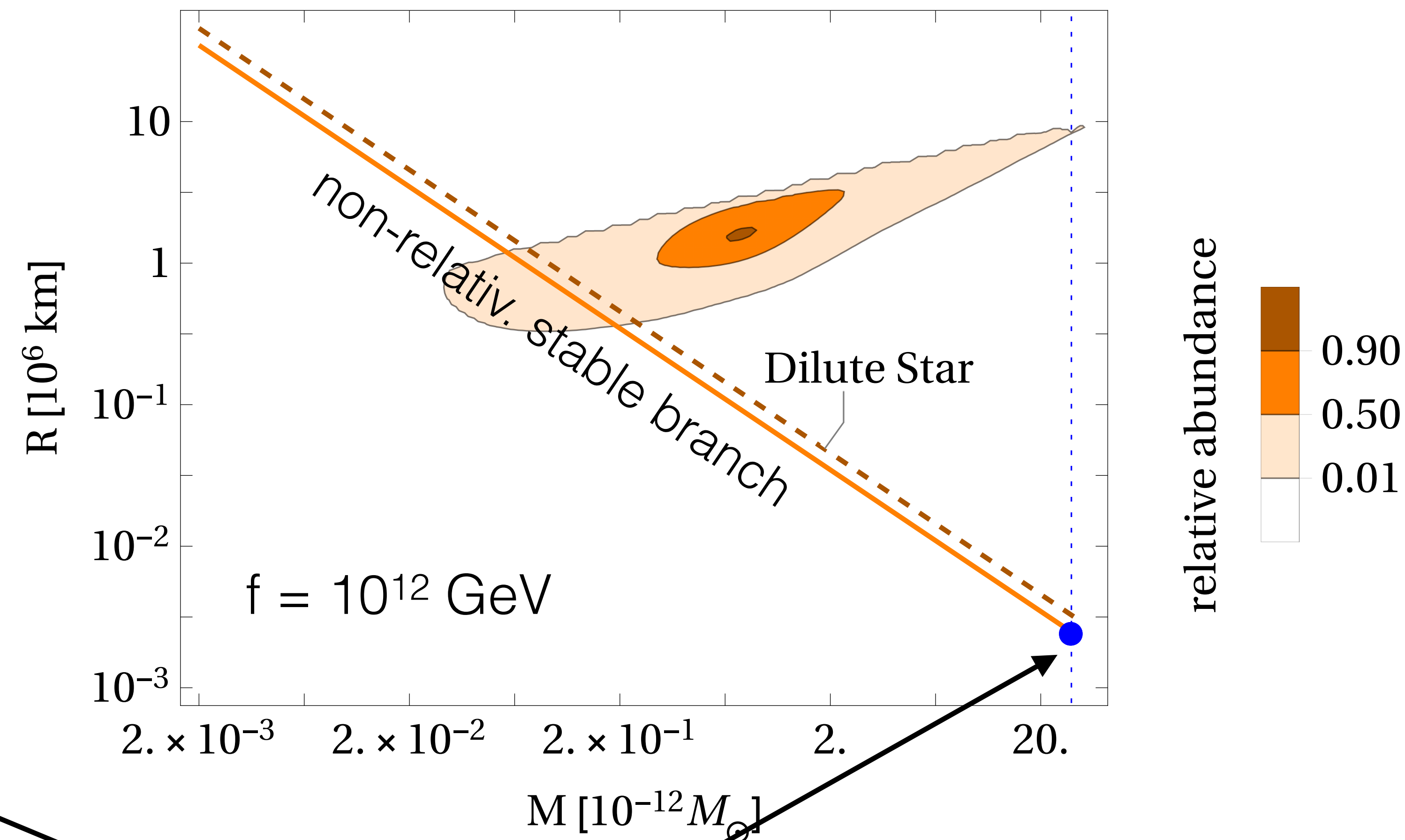
relativistic solution?

Hertzberg, Schiappacasse 17

distribution at turn-around

Baum, Freese, Redondo, Visinelli, Wilczek, 17

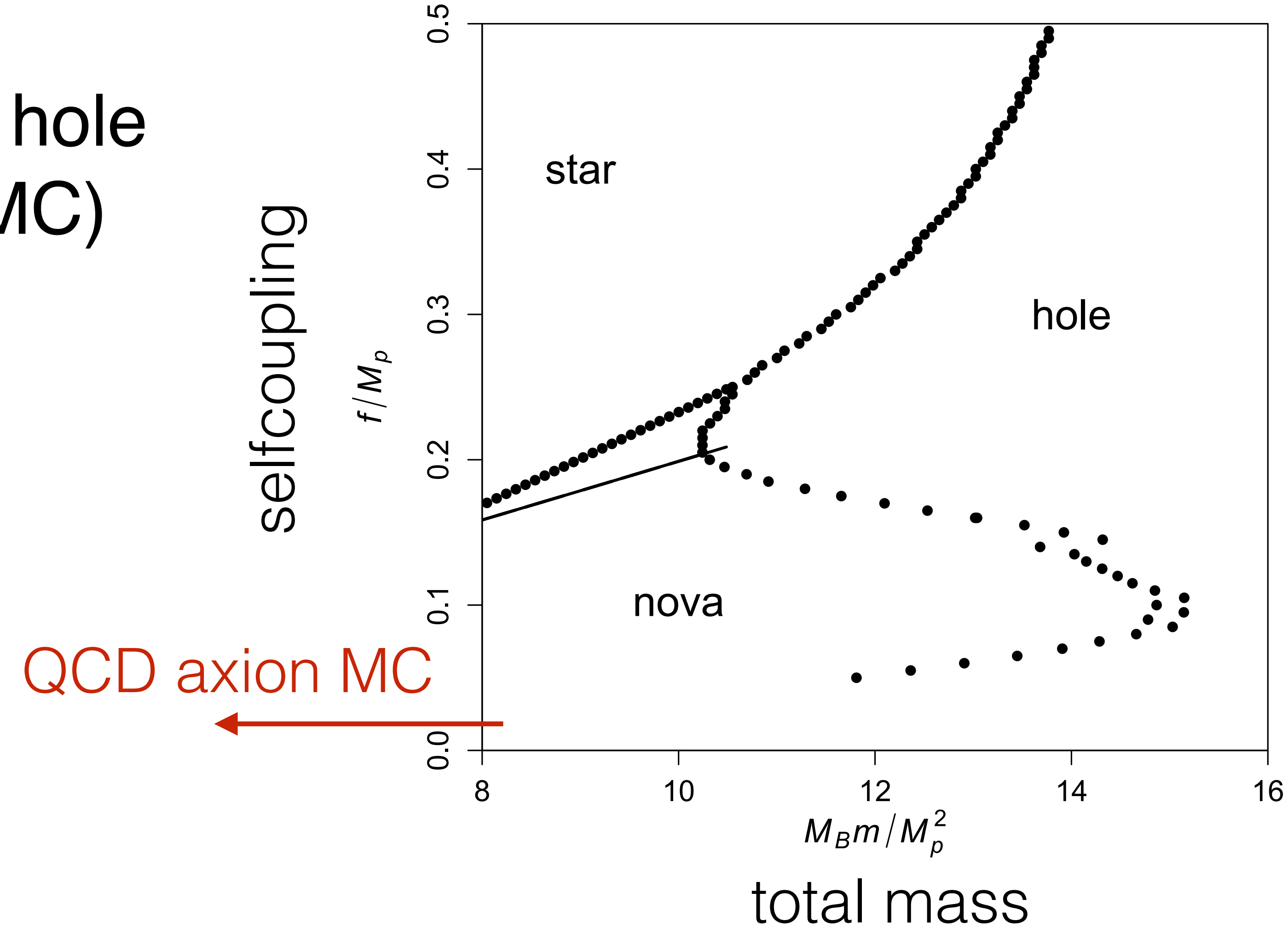




maximal stable mass

How can minicluster condense into bose stars?

- gravitational cooling Seidel, Suen, 1994: radiate away scalar field
- significant fraction of minicluster mass maybe radiated away in terms of (semi)relativistic axions
- possible collapse to a black hole (at much larger mass than MC)

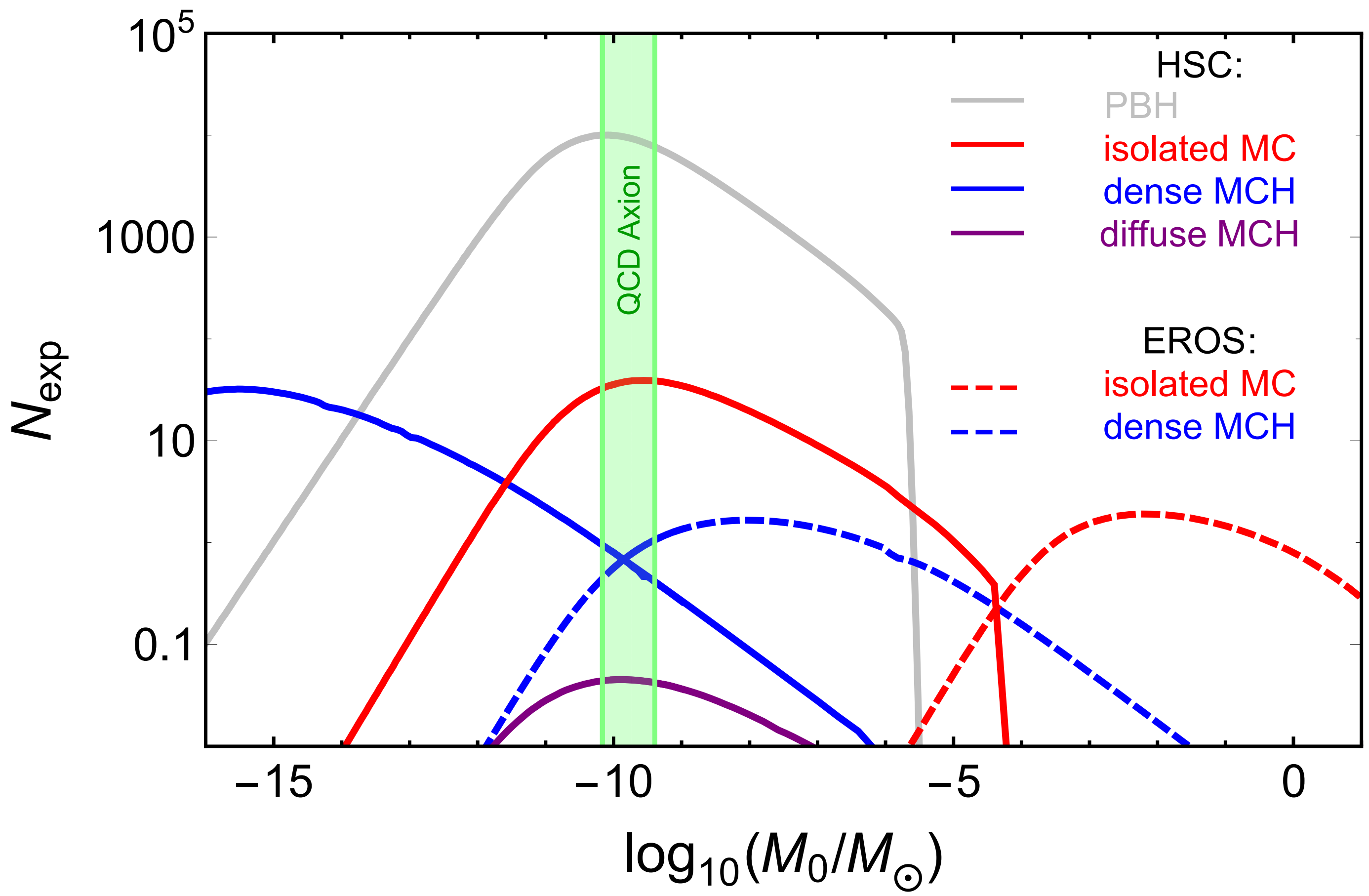


Michel, Moss, 1802.10085

see also:
Helfer, Marsh, Clough, Fairbairn, Lim, Becerril, 1609.04724; Levkov, Panin, Tkachev, 1609.03611

Sensitivity in lensing?

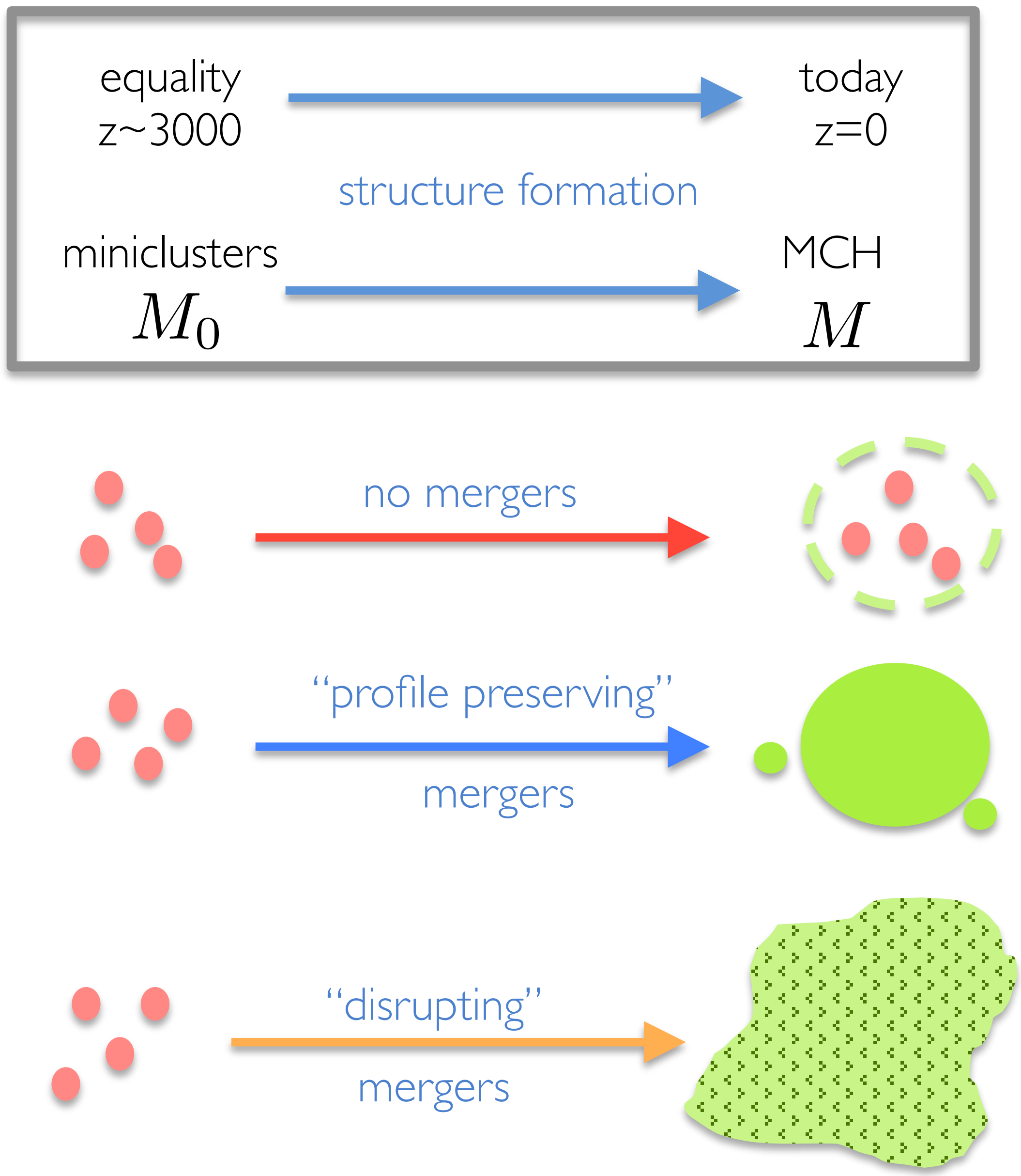
- depending on structure formation history, potentially interesting lensing signatures:
  femto-lensing Kolb, Tkachev, 95
  micro-lensing Fairbairn, Marsh et al, 17



requires extrapolation from equality till today assumptions on MC state today

Fairbairn, Marsh, Quevillon, Rozier, 1707.03310

Modeling of MCH mass function and density profiles



Effective mass function	concentration	Model name
Dirac-delta (M_0)	$c_{\mathrm{MC}}(\delta)$	isolated miniclusters
Press-Schechter	$c_{\mathrm{MC}}(\delta, M)$	dense MCH
"Cut" Press-Schechter	Assumed negligible $M>10\ M_0$	diffuse MCH

"most conservative"

REALITY?

"most pessimistic"

Fairbairn, Marsh, Quevillon, Rozier, 1707.03310

Summary — outlook

- Axion miniclusters are expected in the post-inflation scenario
- evolution till today not well understood
- generic feature also for ALP dark matter scenarios beyond the QCD axion
- important for direct detection
- potential lensing signature

P-spectrum dependence on assumptions