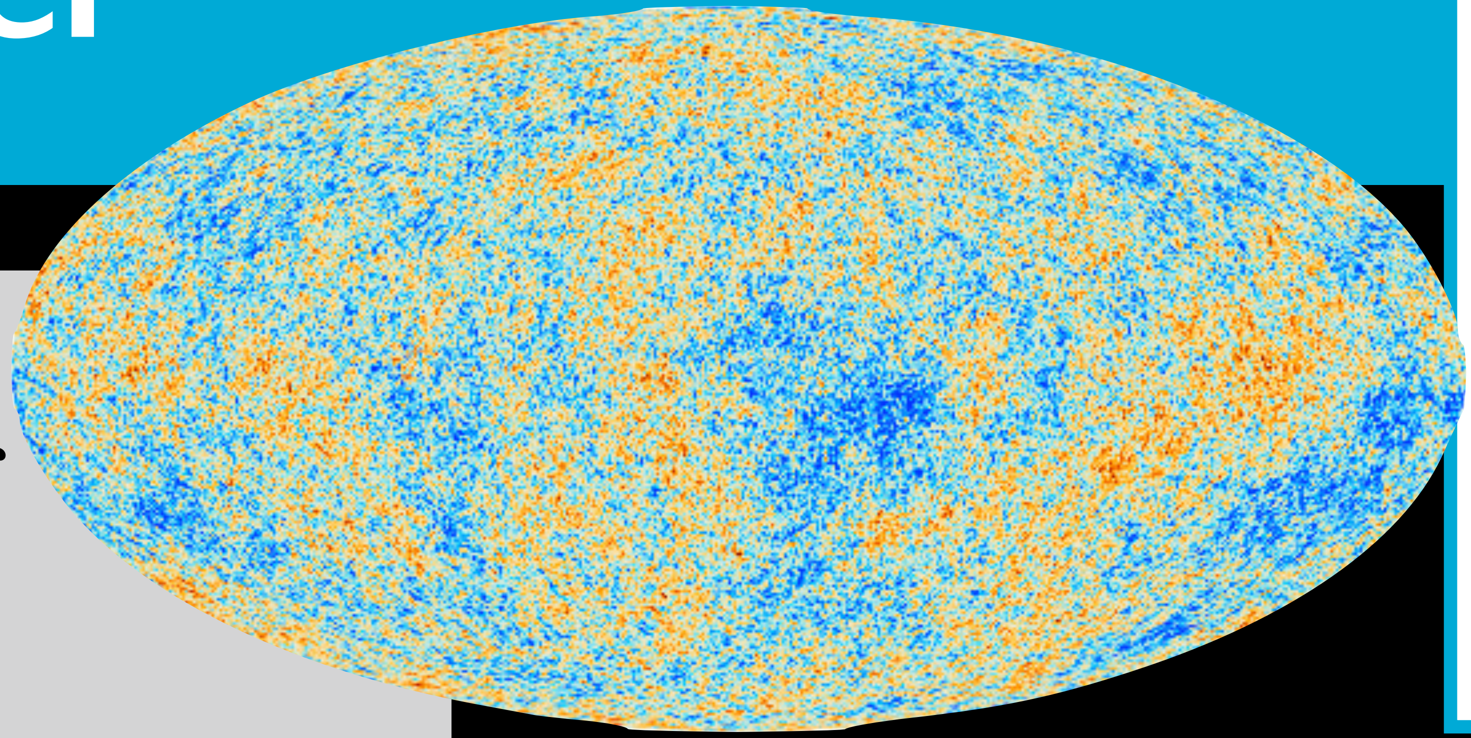
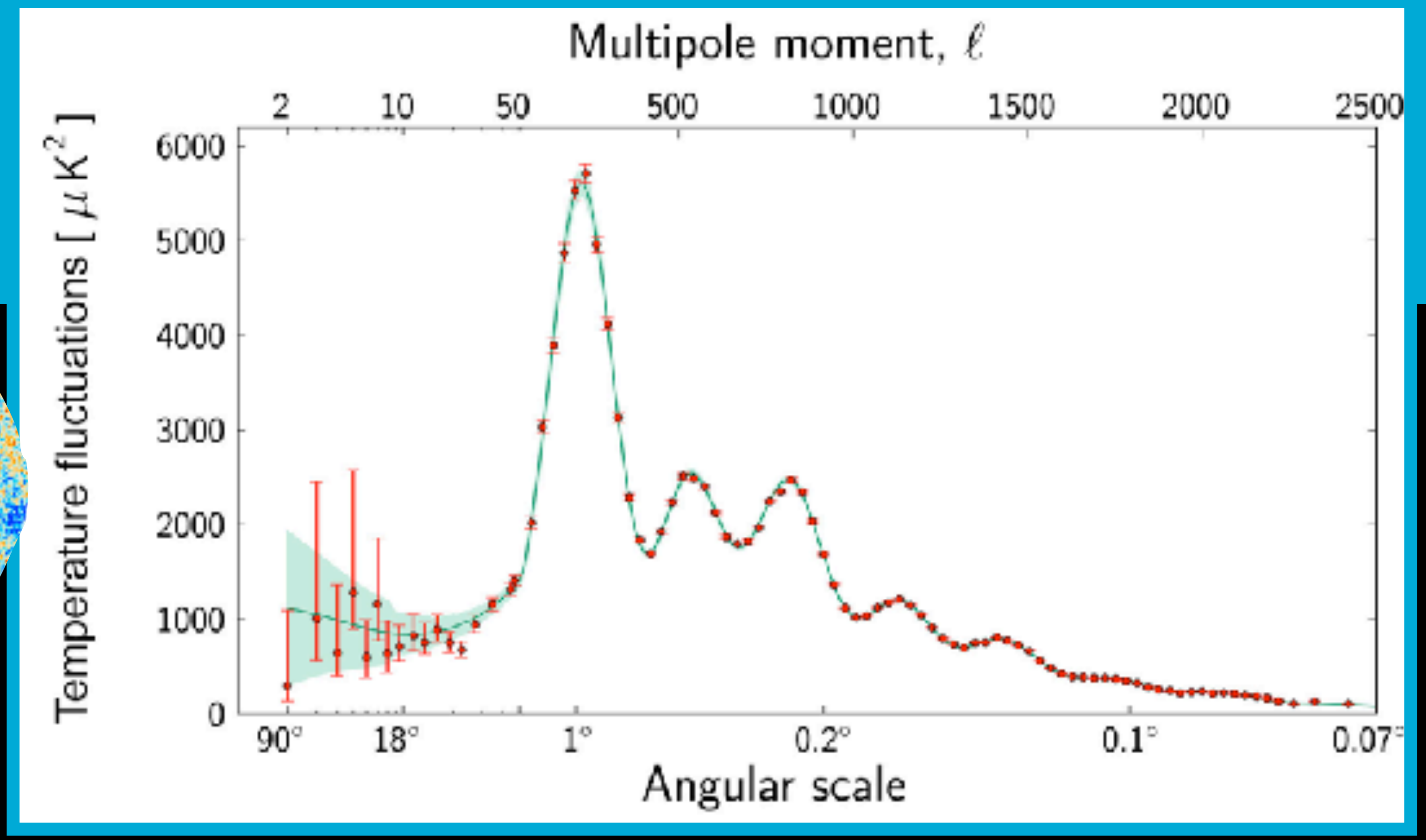
How light can dark matter particles be?

Mustafa A. Amin

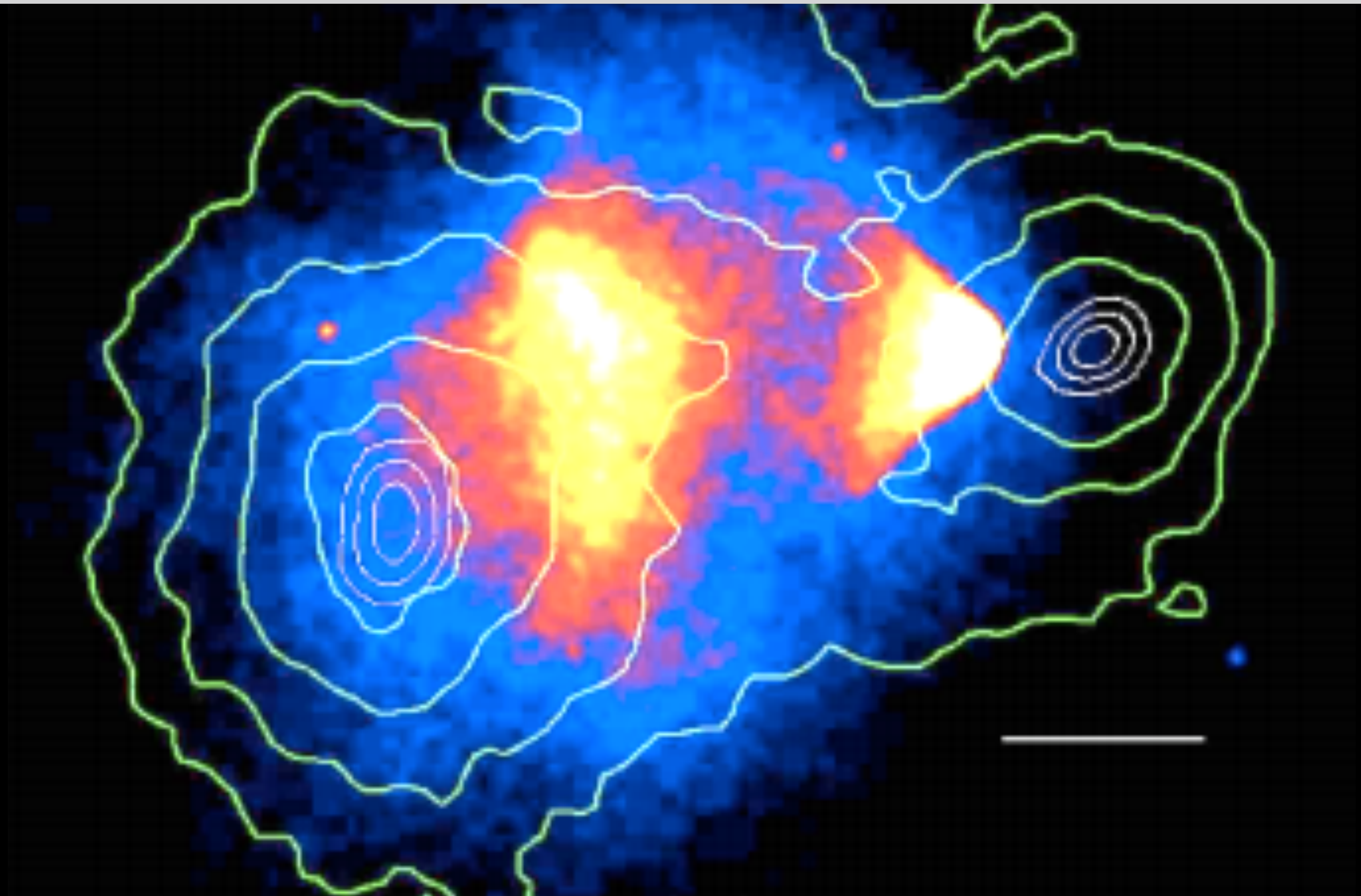
RICE

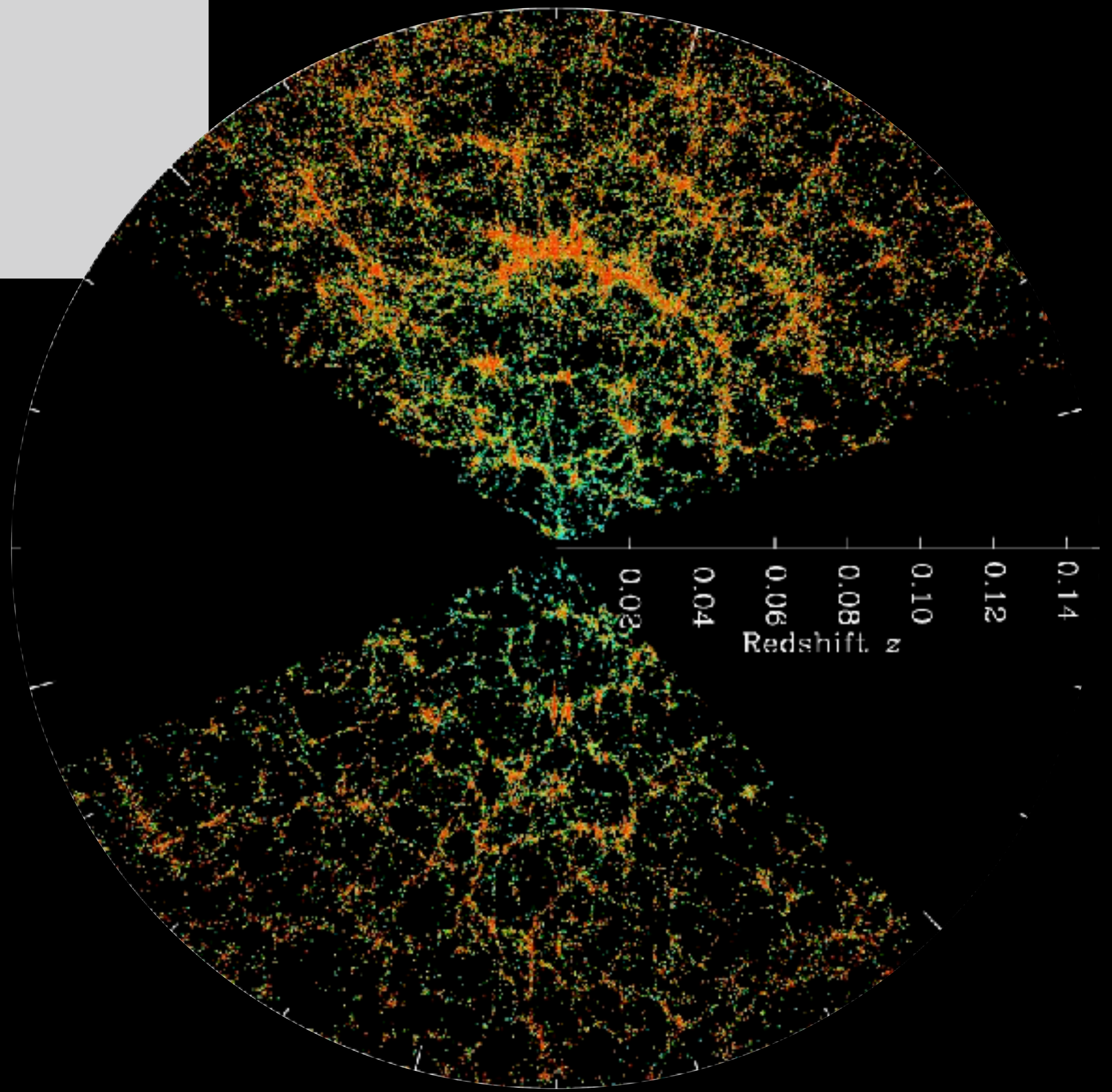
evidence for dark matter

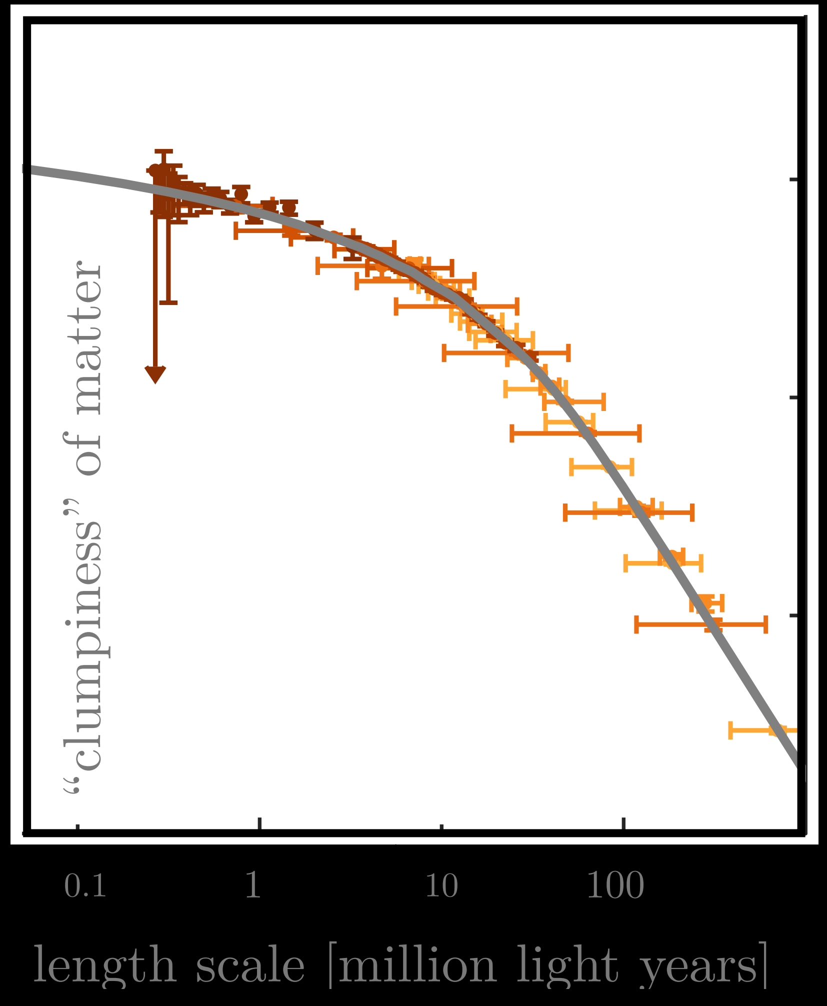




- dark matter exists-85% of matter
- gravitational interactions
- mass, charge, spin







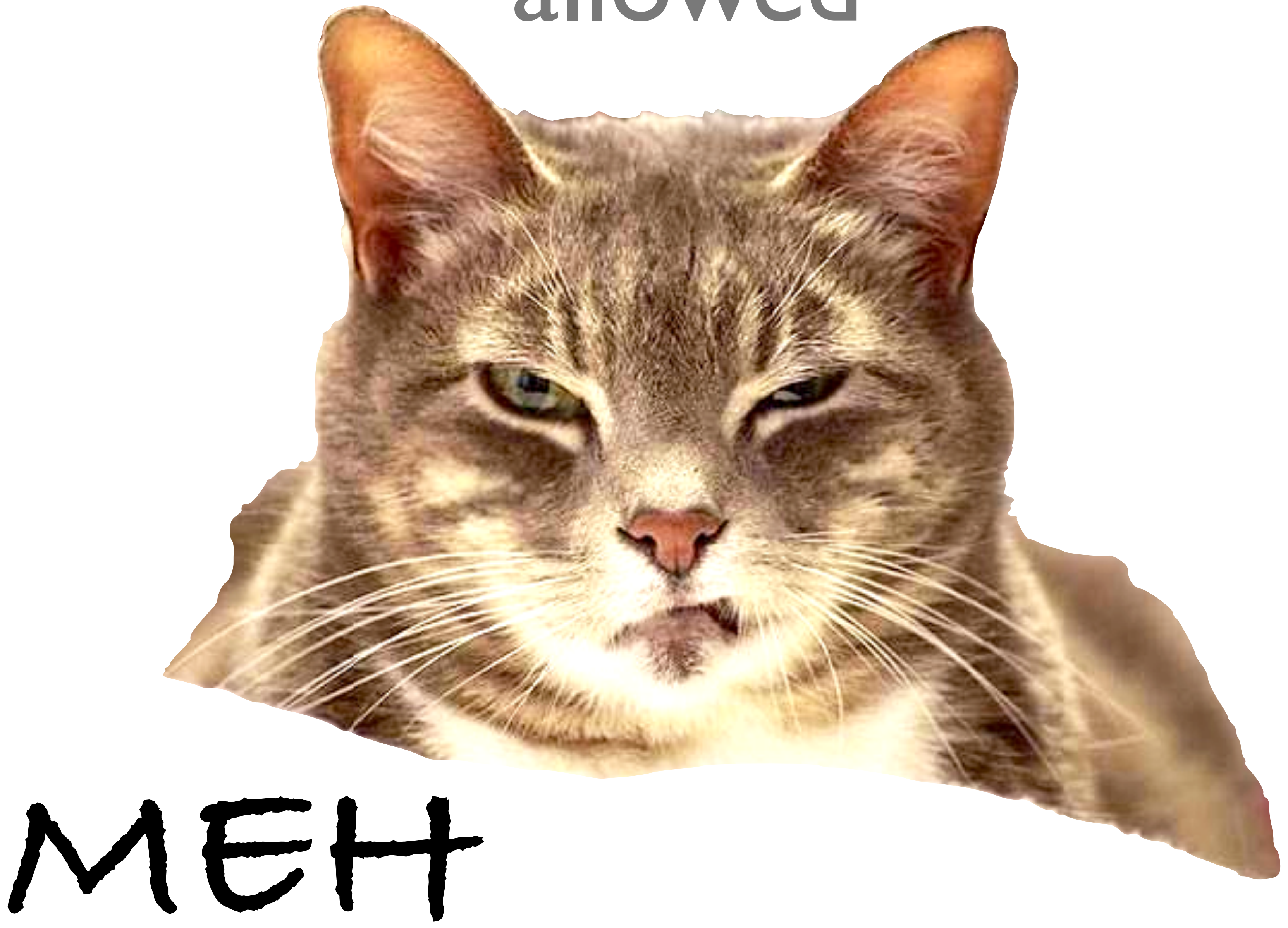
*incomplete sample

limits on dark matter particle mass

not allowed

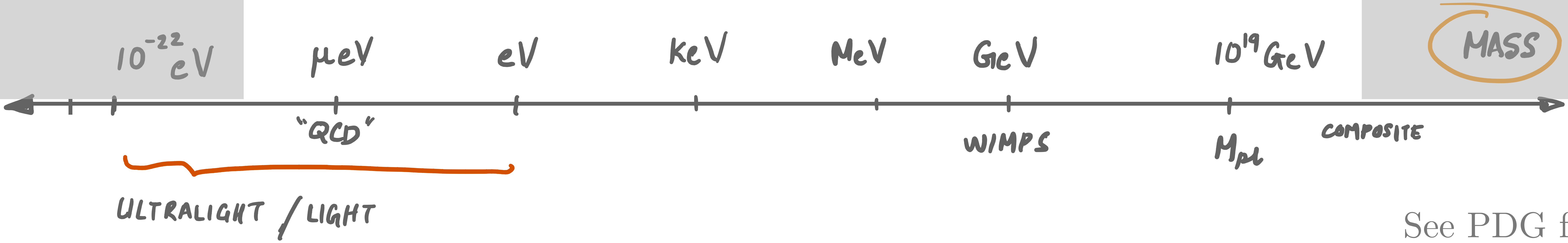
$m \gtrsim 10^{-19}\,\mathrm{eV}$

allowed



not allowed

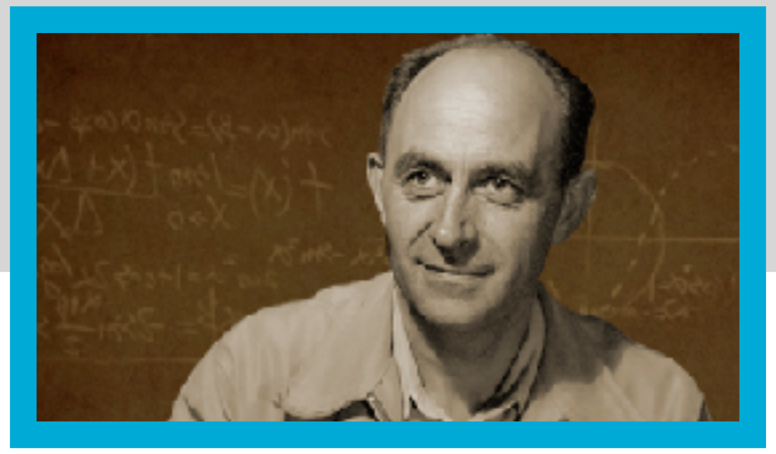
$m \lesssim \text{few } M_\odot$

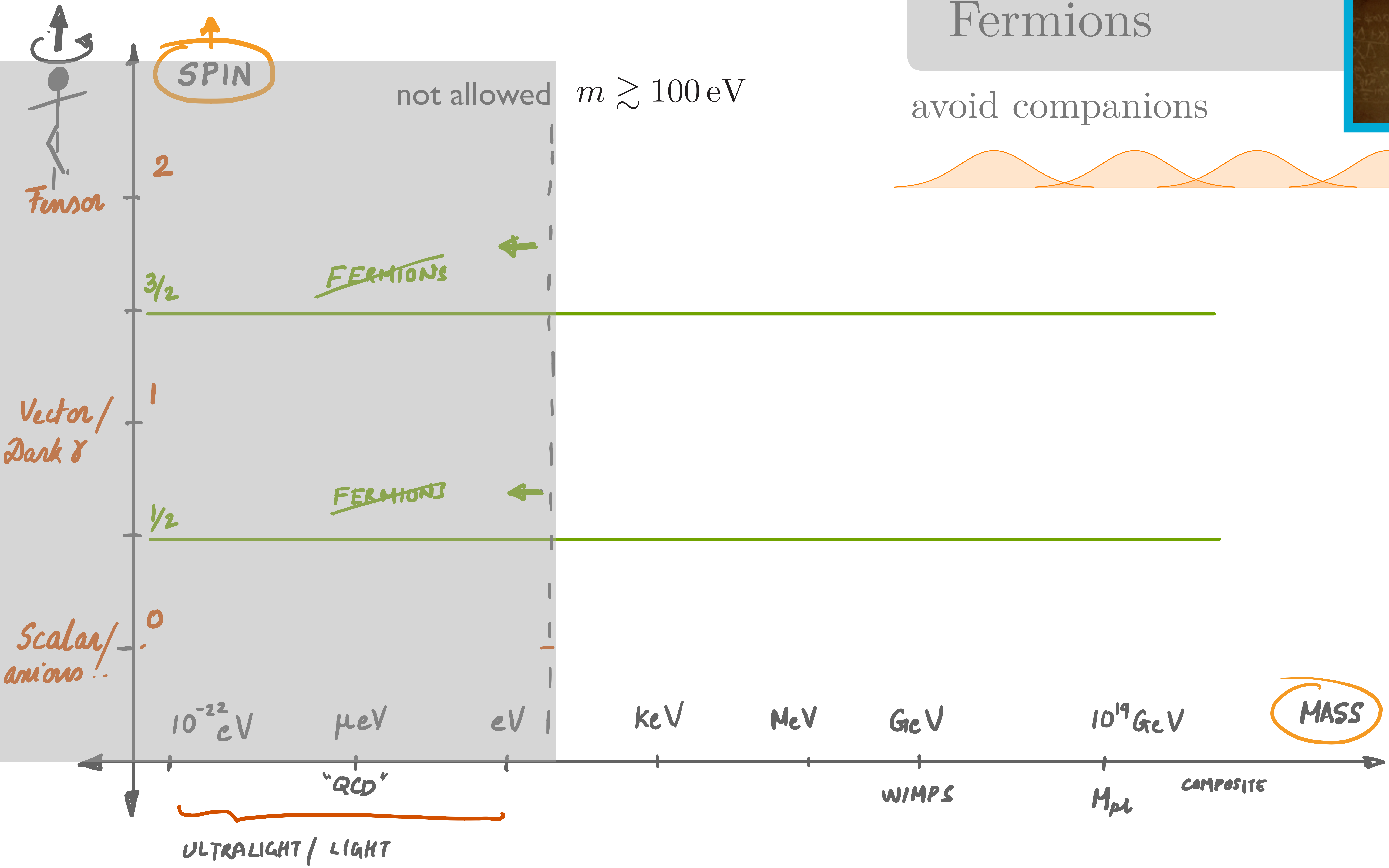


See PDG for more details

Fermions

avoid companions





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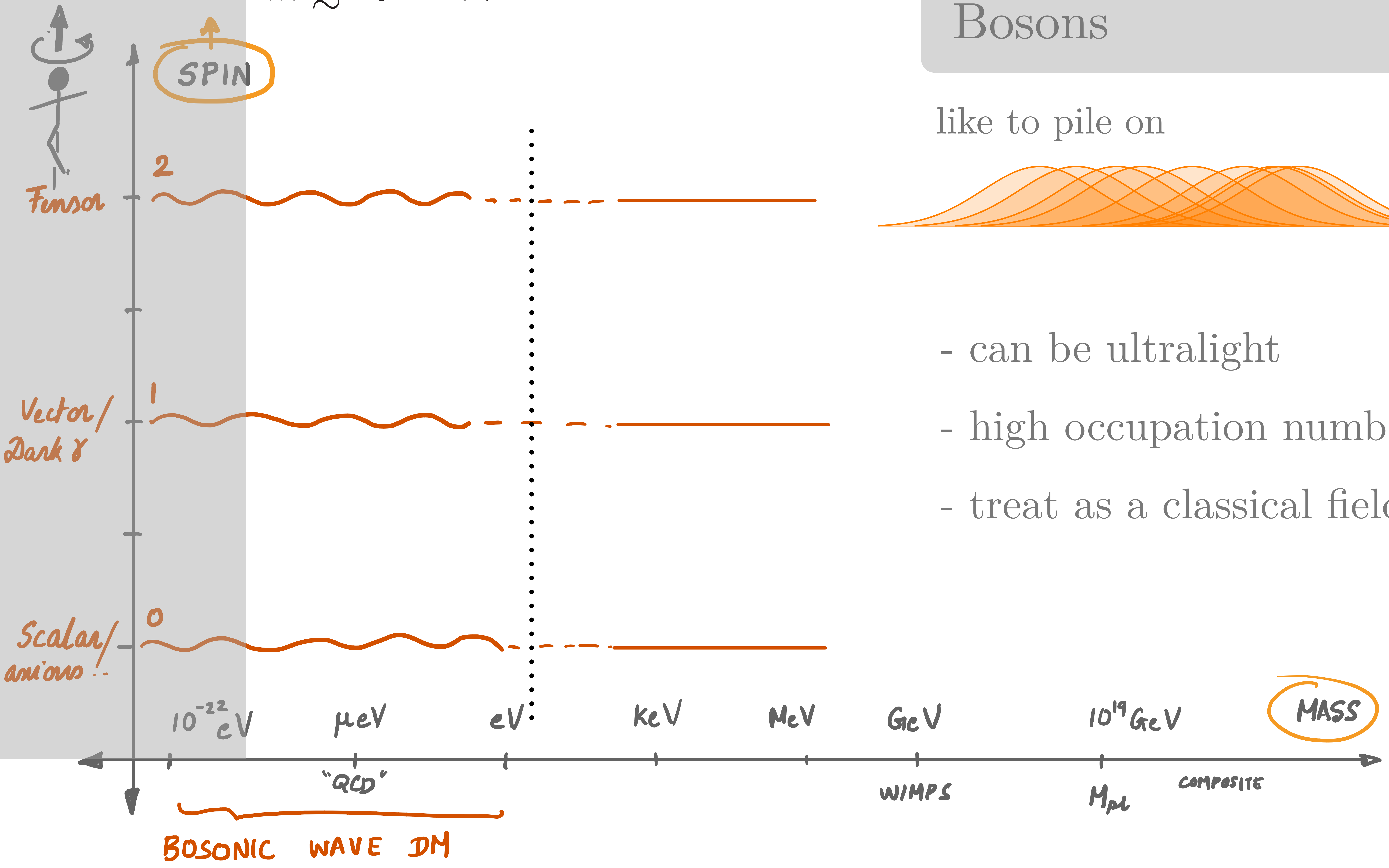
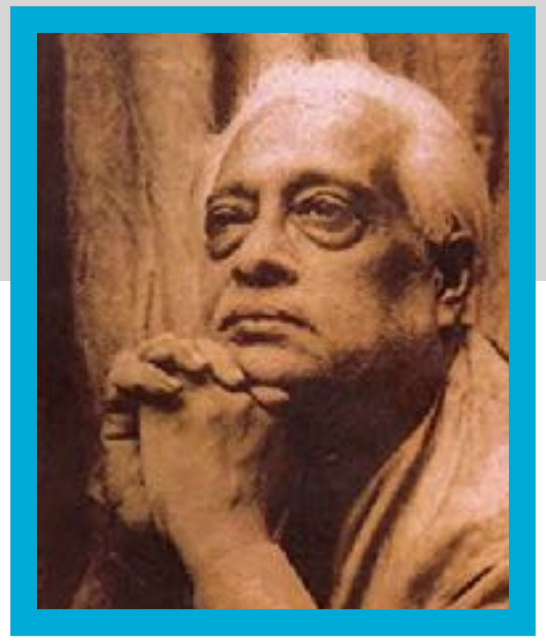


Bosons



like to pile on

- can be ultralight
- high occupation numbers
- treat as a classical field

improved limits on dark matter particle mass ?

See PDG for more

15 min

A lower bound on dark matter mass

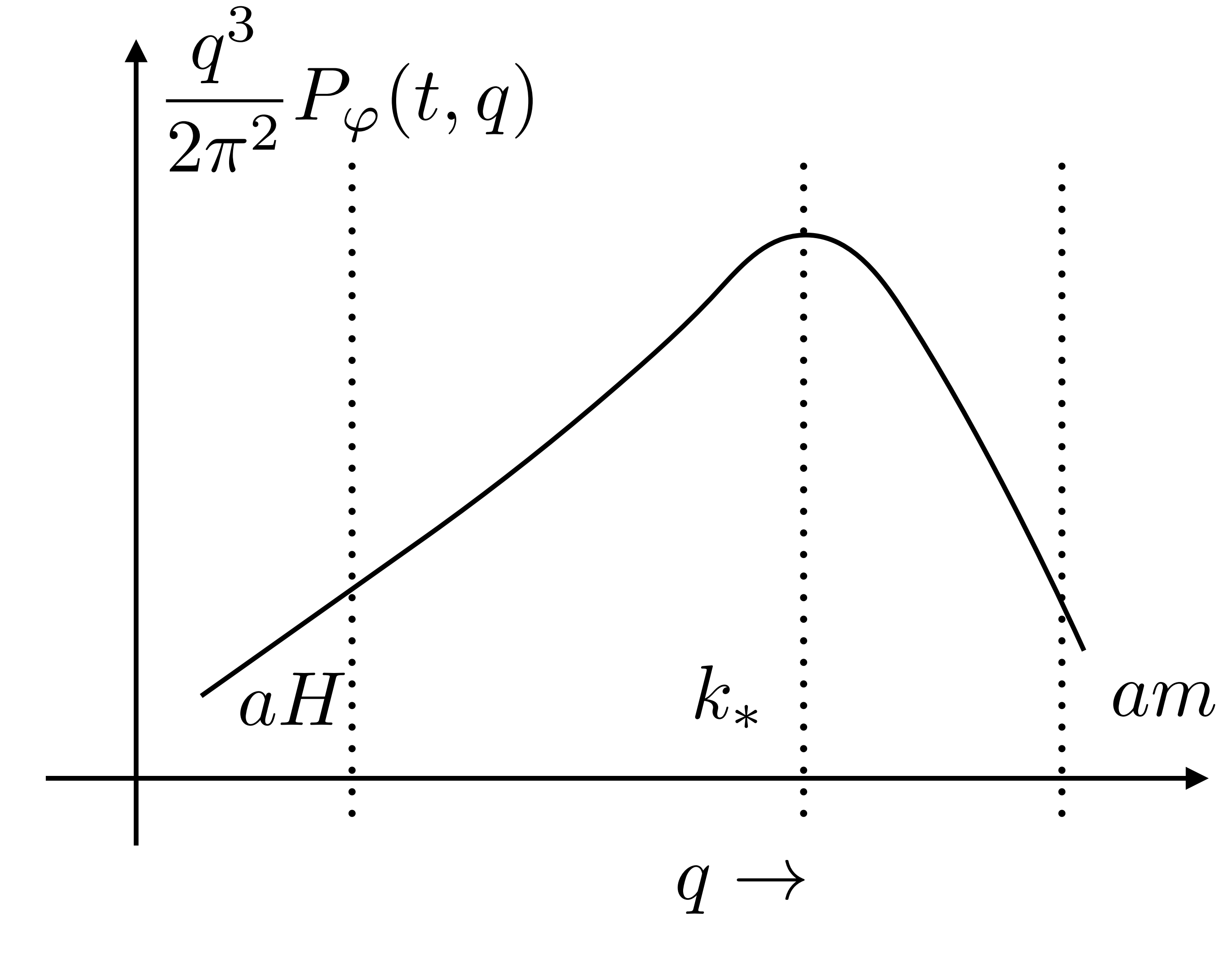
Mustafa A. Amin RICE

with Mehrdad Mirbabayi

arXiv:2211.09775

Phys. Rev. Lett (2024, *in press*)

main point



Dark matter density dominated by sub-Hubble field modes

$\implies m \gtrsim 10^{-19}\,\mathrm{eV}$

our argument

Dark matter density dominated by sub-Hubble field modes

1. white-noise excess in isocurvature density pert.
2. free-streaming suppression in adiabatic density pert.

1. and 2. not seen for $k < k_{\rm obs} \sim 10\,{\rm Mpc}^{-1}$

$$m \gtrsim 10^{-19}\,{\rm eV}$$

comparison with literature

$m \gtrsim 2 \times 10^{-21}\,\mathrm{eV}$	Irsic et. al (2017) — Lyα
$m \gtrsim 3 \times 10^{-21}\,\mathrm{eV}$	Nadler et. al (2021) — MW satellites
$m \gtrsim 3 \times 10^{-19}\,\mathrm{eV}$	Dalal & Kravtsov (2022) — dynamical heating of stars
$m \gtrsim 4 \times 10^{-21}\,\mathrm{eV}$	Powell et. al (2023) — lensing
$m \gtrsim 10^{-19}\,\mathrm{eV}$	MA & Mirbabayi (2022)

*Above are model independent constraints, stronger constraints exist for particular models (Irsic, Xiao & McQuinn, 2020)

We are being very conservative here by insisting on model independence. For some explicit models (eg. with strings), similar arguments can lead to $m > 10^{-12}$ eV! For thermal production, this becomes a keV!

details

*to us, results were "intuitively convincing" but quantitative calculation is non-trivial

*analytic calculation of density spectra, see appendix of MA & Mirbabayi (2022)

*numerical simulations + self-interactions, MA & Ling (in progress)

average density from field

$\varphi(t, \boldsymbol{x})$ $\rho \approx m^2\varphi^2$ light, but non-relativistic scalar field during rad. dom.

$$\bar{\rho}(t) \approx m^2 \int d\ln q \, \frac{q^3}{2\pi^2} P_\varphi(t,q)$$

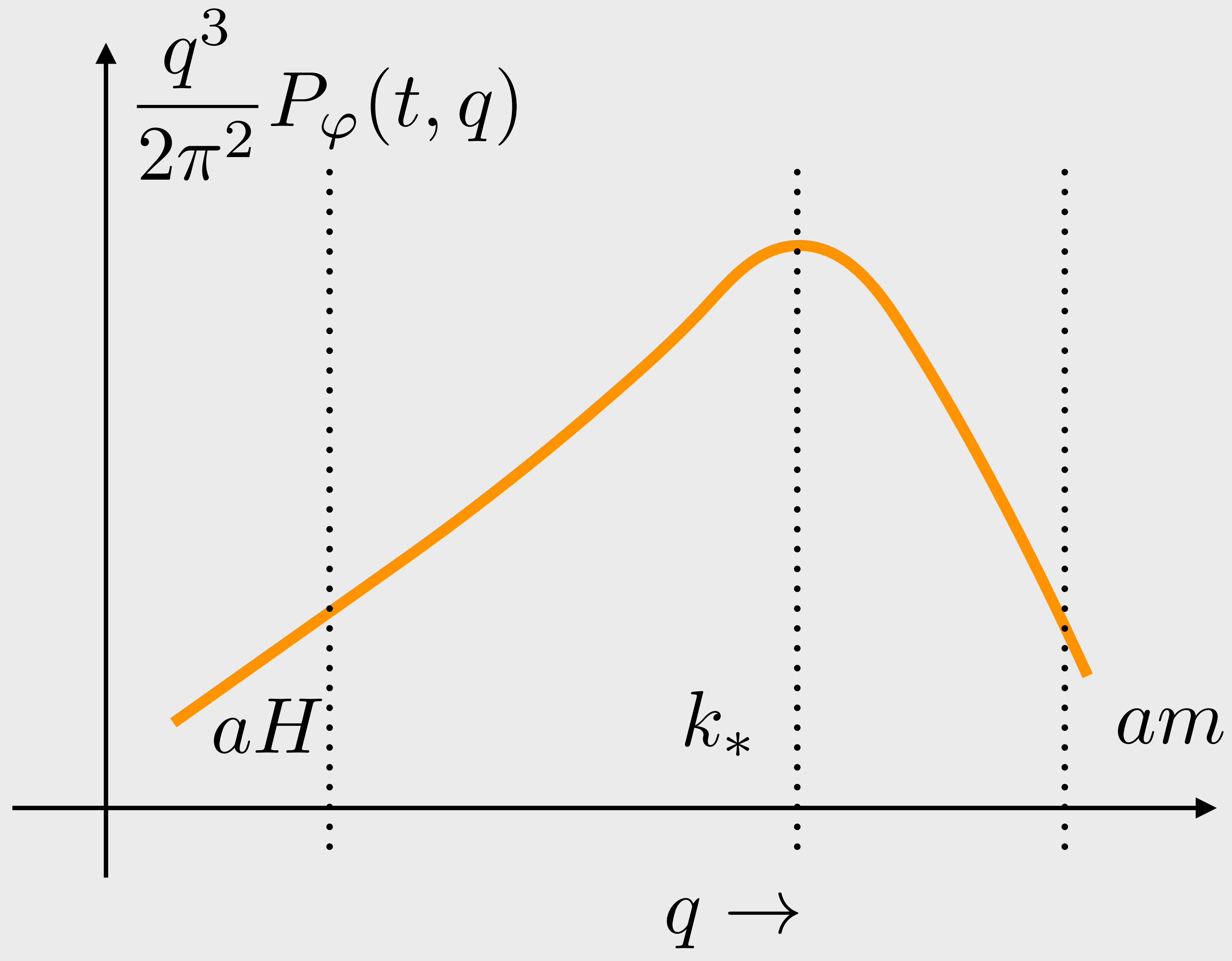
dark matter density close to matter radiation eq.

$$\frac{q^3}{2\pi^2} P_\varphi(t,q)$$

power spectrum of *field*, peaked at k_*

$a(t)H(t) \ll k_*$ holds for field produced after inflation

$k_* \ll a(t)m$ eventually non-relativistic to be DM



Note: no significant zero mode of the field!

examples of models that can produce such spectra

inflationary gravitational particle production

(see review by Kolb & Long, 2023)

- dark photon dark matter
- scalars with non-minimal coupling
- ~~gravitational production minimal coupling~~

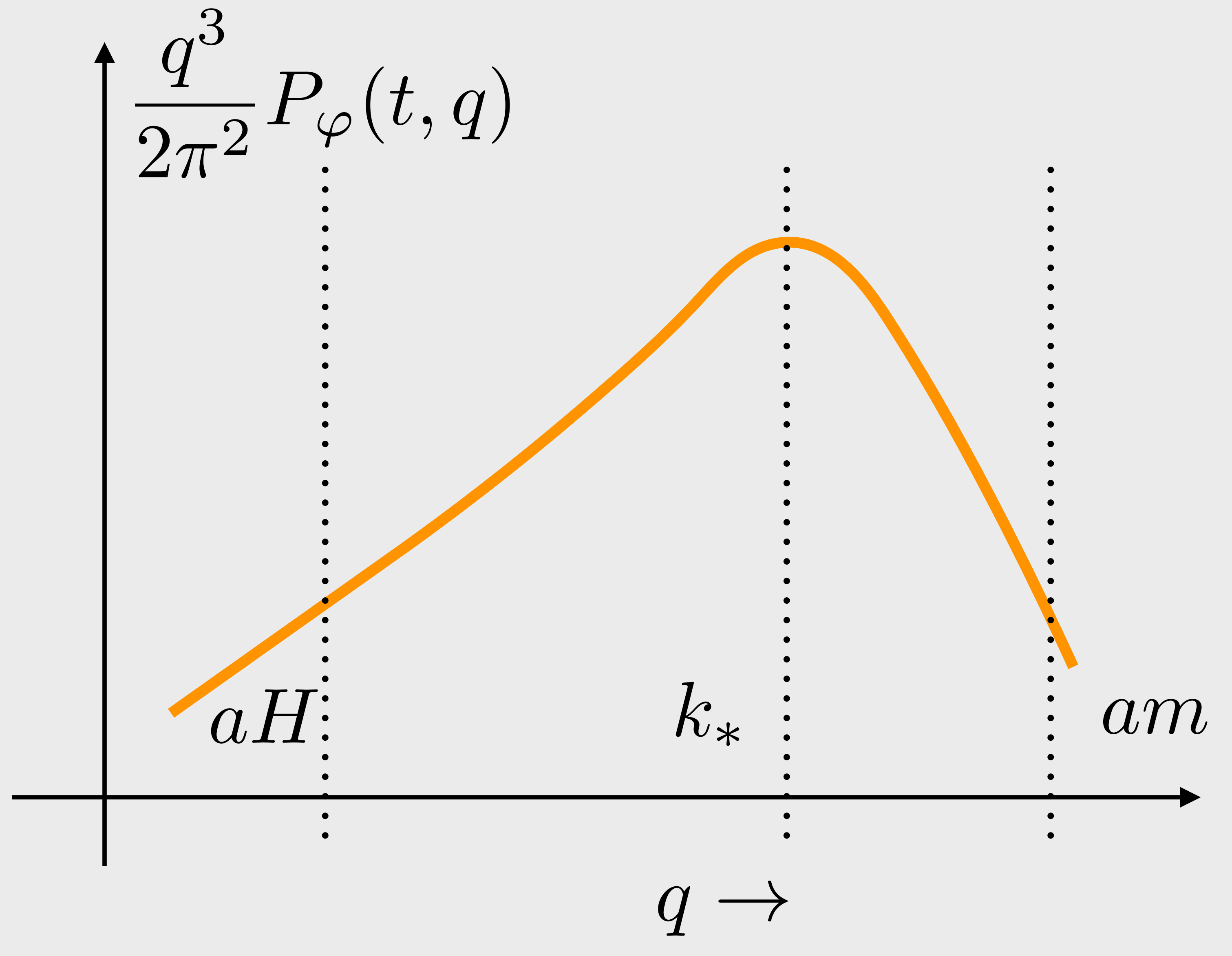
non-gravitational production *after* inflation

phase transitions

- *axion-like fields (including QCD)*

resonant/tachyonic energy transfer from fields, strings

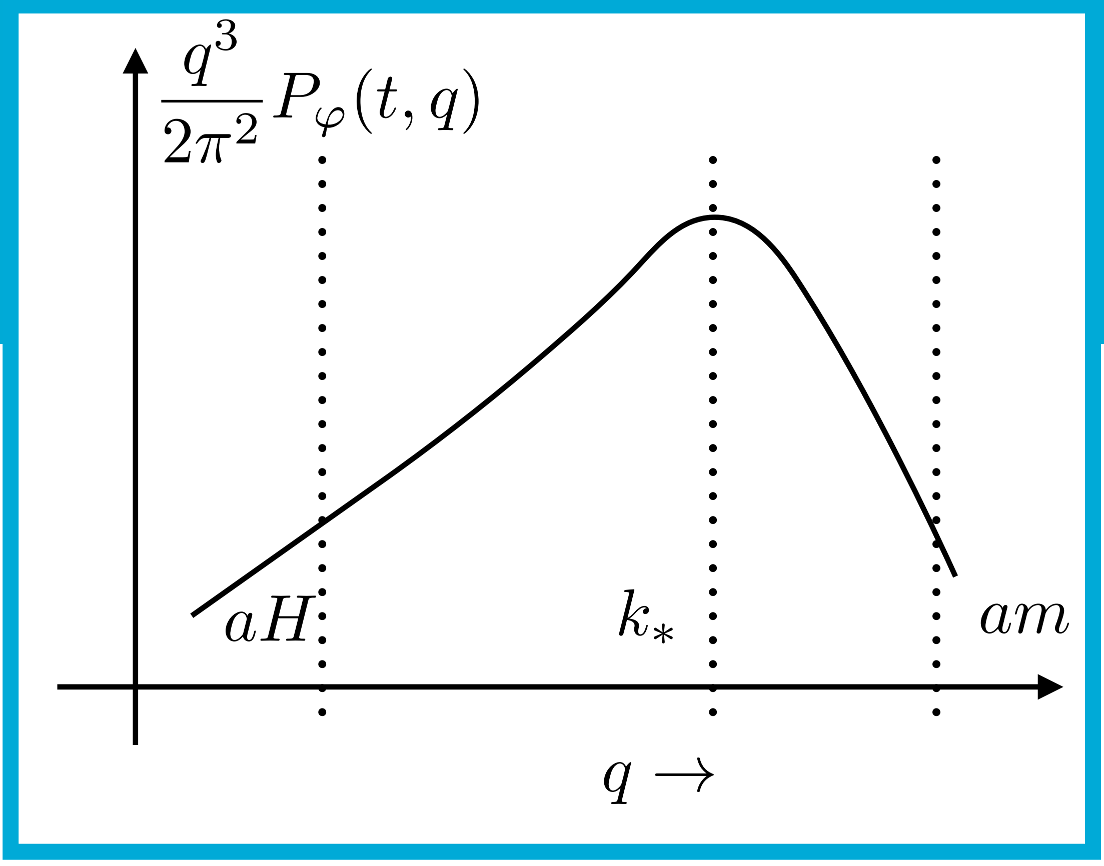
- *eg. dark photon dark matter*



Note: no significant zero mode of the field

also works for thermal production, but nothing new there

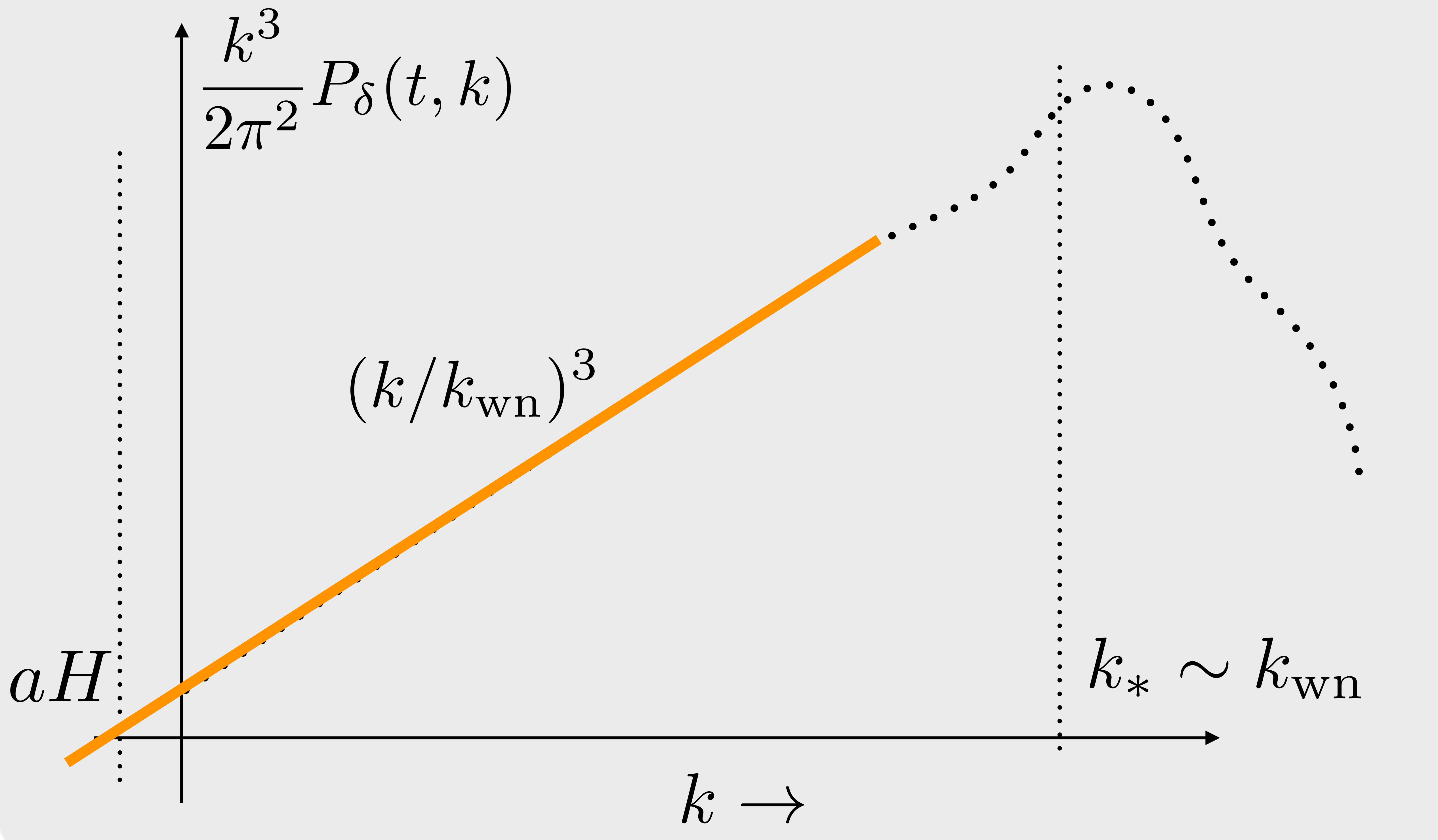
density power spectrum (isocurvature)



$$P_\delta^{(\mathrm{iso})}(t,k) = \frac{m^4}{\bar\rho^2(t)}\int d\ln q\,\frac{q^3}{2\pi^2}\left[P_\varphi(q,t)P(|\boldsymbol{q}-\boldsymbol{k}|,t)\right]$$
$$\approx \frac{m^4}{\bar\rho^2(t)}\int d\ln q\,\frac{q^3}{2\pi^2}\left[P_\varphi(q,t)\right]^2$$
$$\equiv \frac{2\pi^2}{k_{\mathrm{wn}}^3}$$

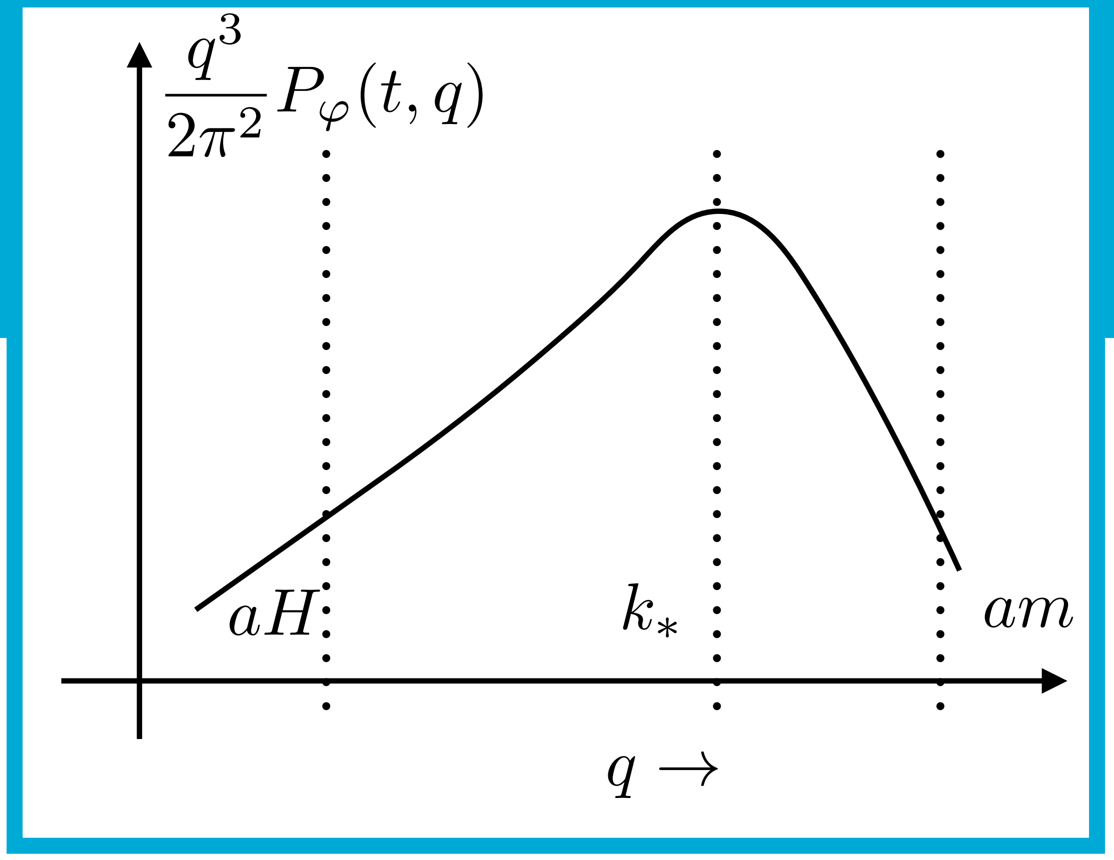
independendent of k for $k \ll k_*$

k_{wn} is defined by the above relation

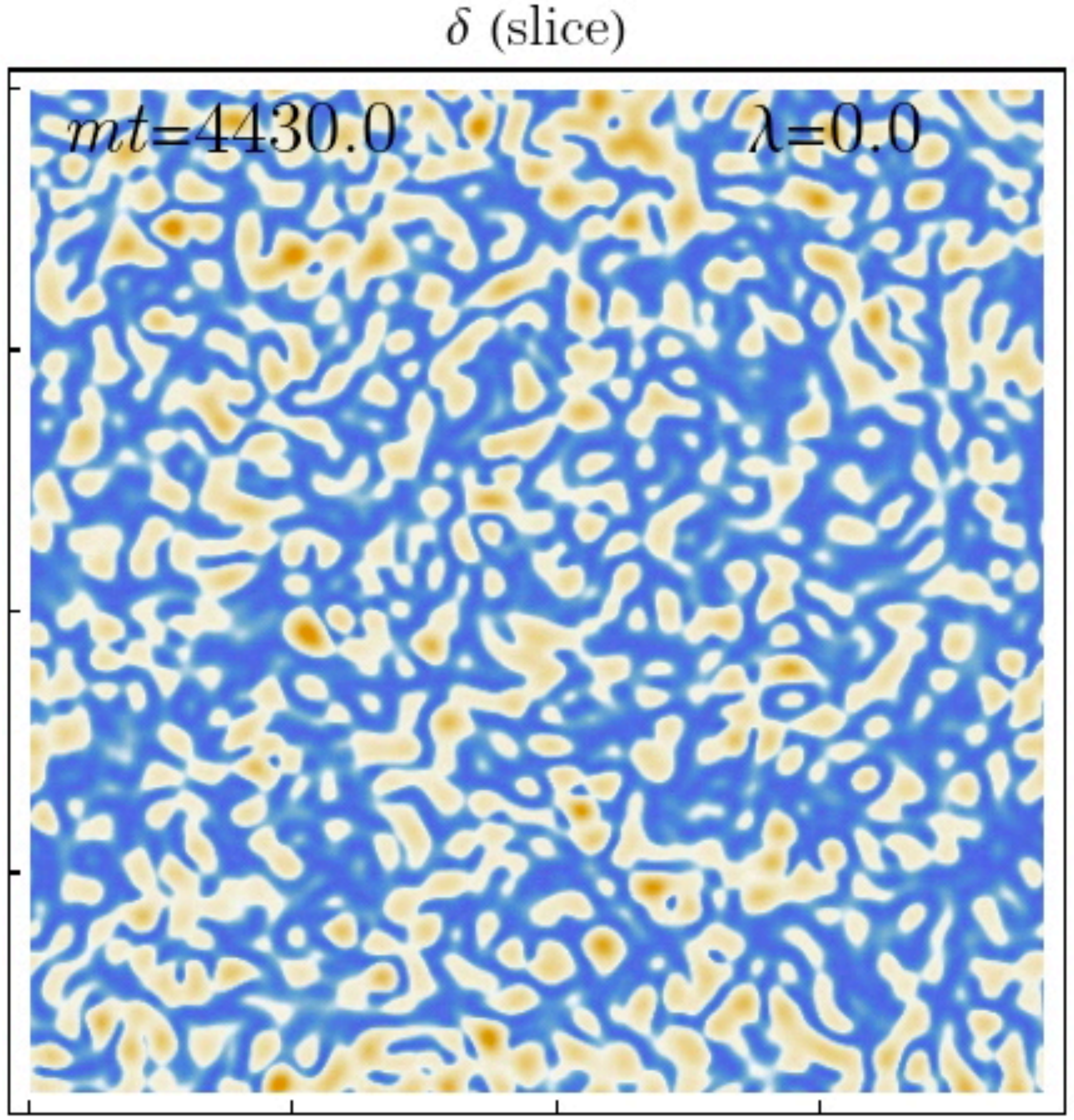


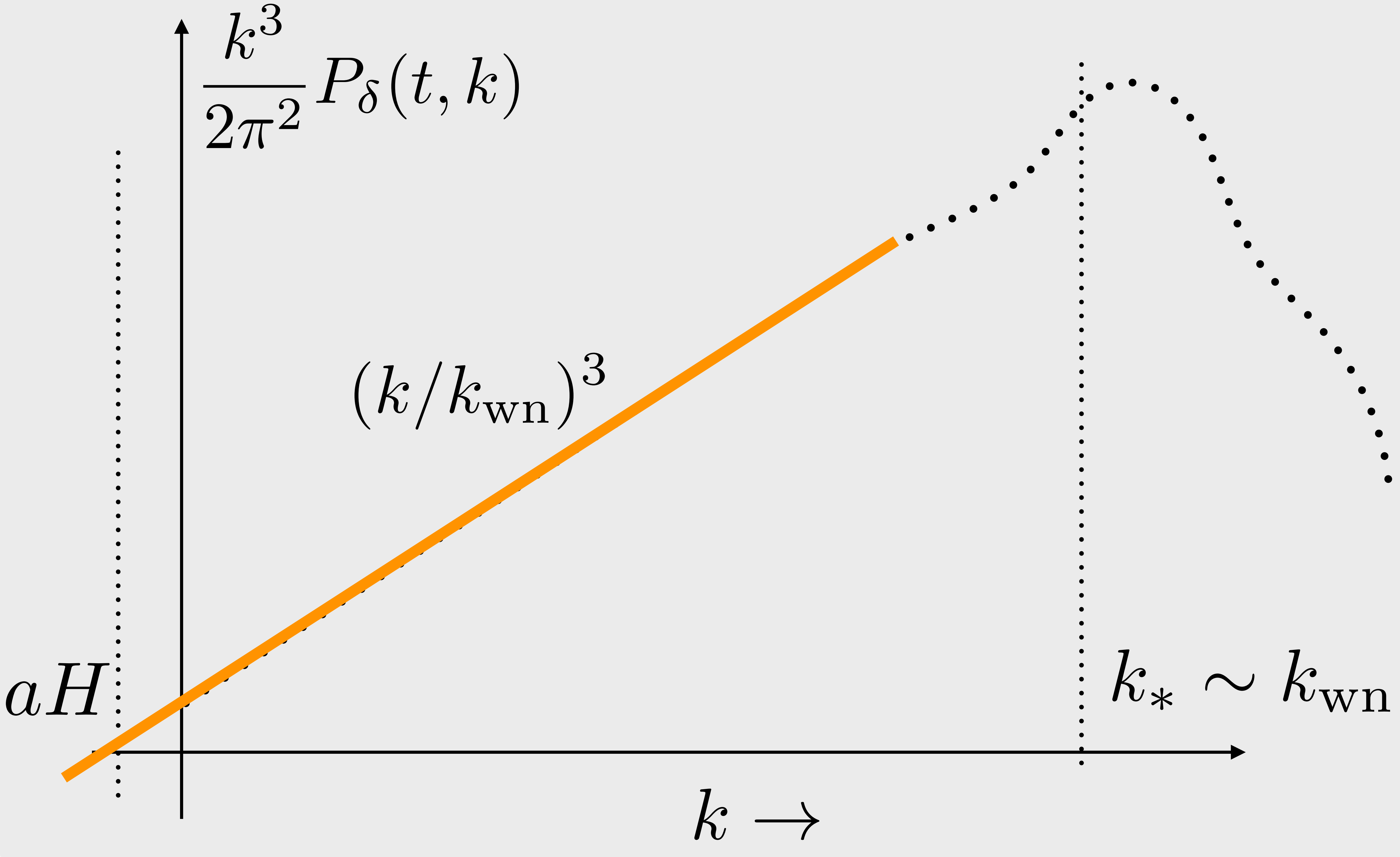
*ignore gravitational potentials on these scales during radiation domination

density power spectrum (isocurvature)



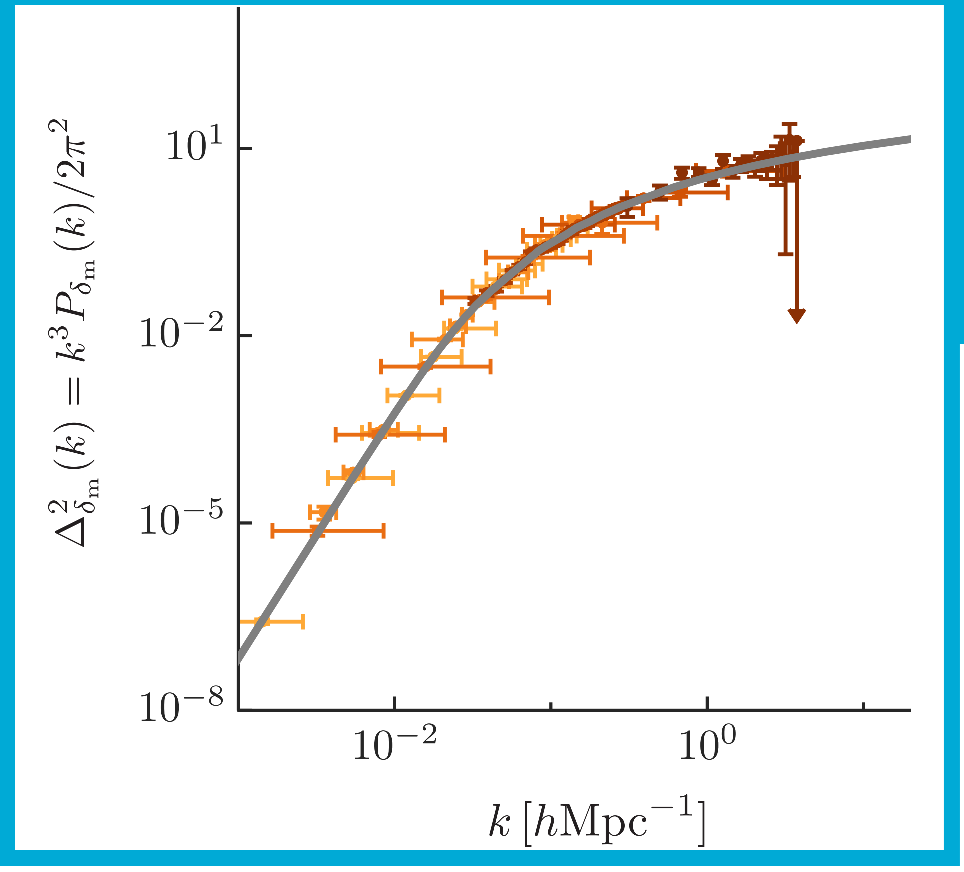
$$P_\delta^{(\mathrm{iso})}(t,k) \approx \frac{m^4}{\bar{\rho}^2(t)} \int d\ln q \, \frac{q^3}{2\pi^2} \left[P_\varphi(q,t)\right]^2 \equiv \frac{2\pi^2}{k_{\mathrm{wn}}^3}$$





*ignore gravitational potentials on these scales during radiation domination

density power spectrum (adiabatic)

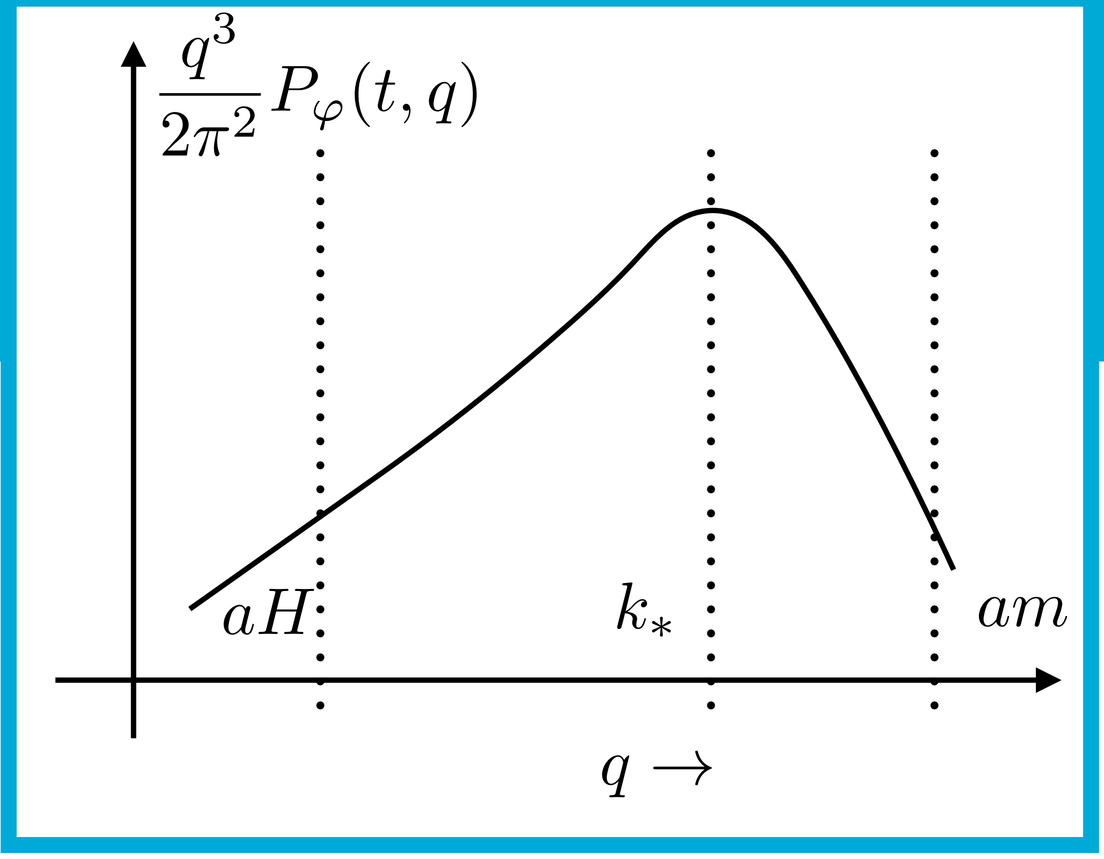


density perturbations in DM sourced by gravitational potentials in rad.

density power spectrum (adiabatic)

density perturbations in DM sourced by gravitational potentials in rad.

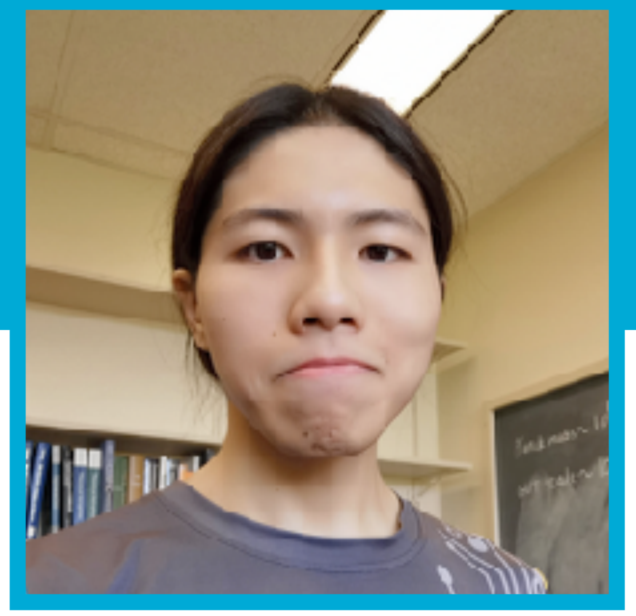
free streaming !



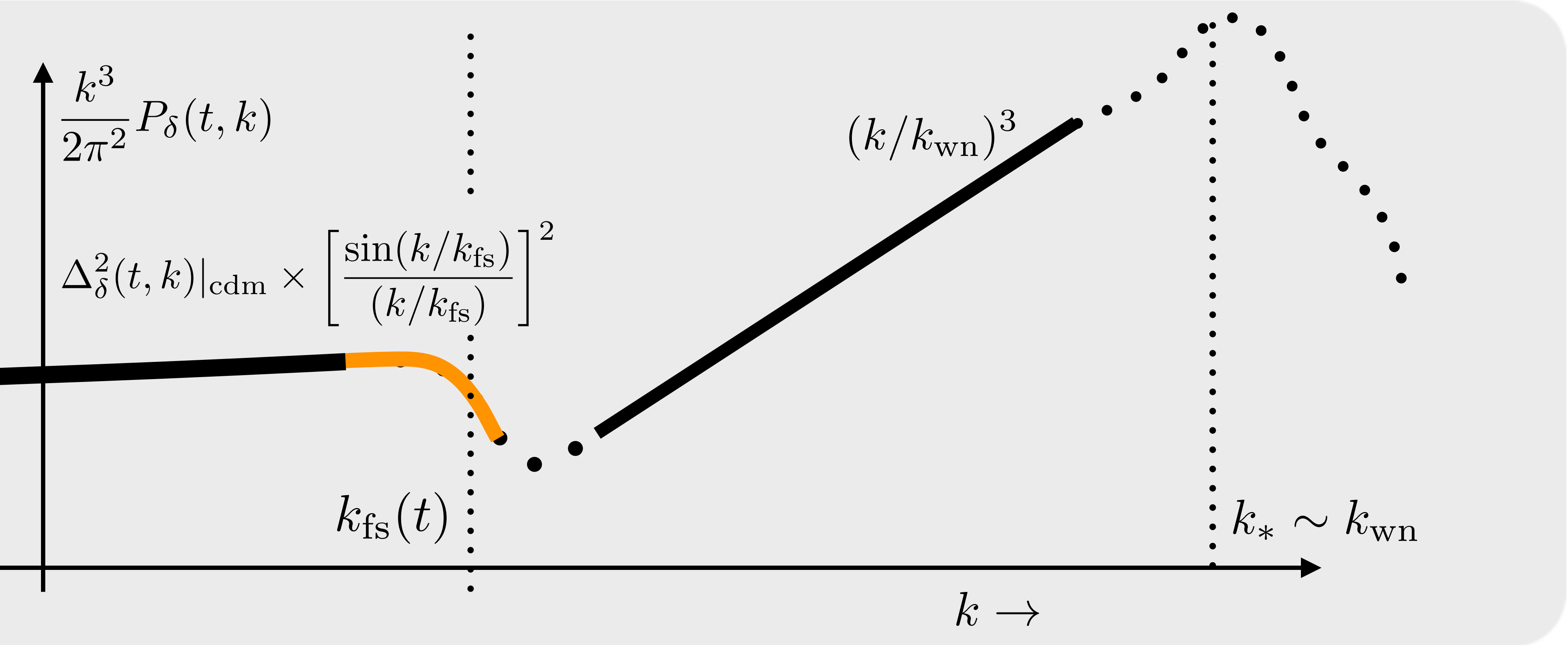
field power at $k_* \Longrightarrow k_{\rm fs}(t) \approx \dfrac{a^2 H m}{k_* \ln(2am/k_*)}$

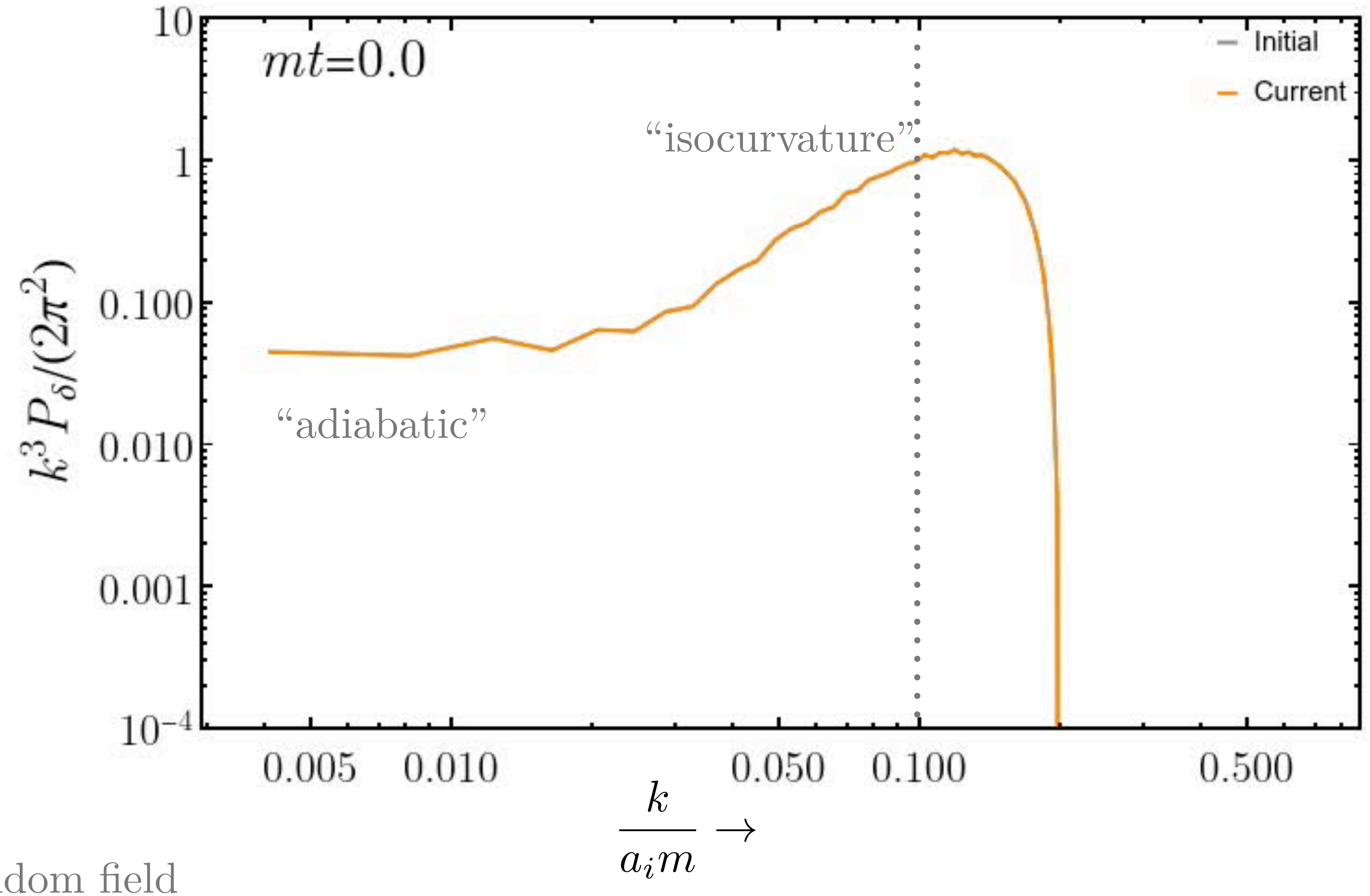
*main idea is mostly "straightforward", but the detailed calculation is not — see MA & Mirbabayi (2022)'s Appendix.

free streaming — numerical



with S. Ling (Rice)





*initial conditions = inhomogeneous gaussian random field

free streaming — numerical

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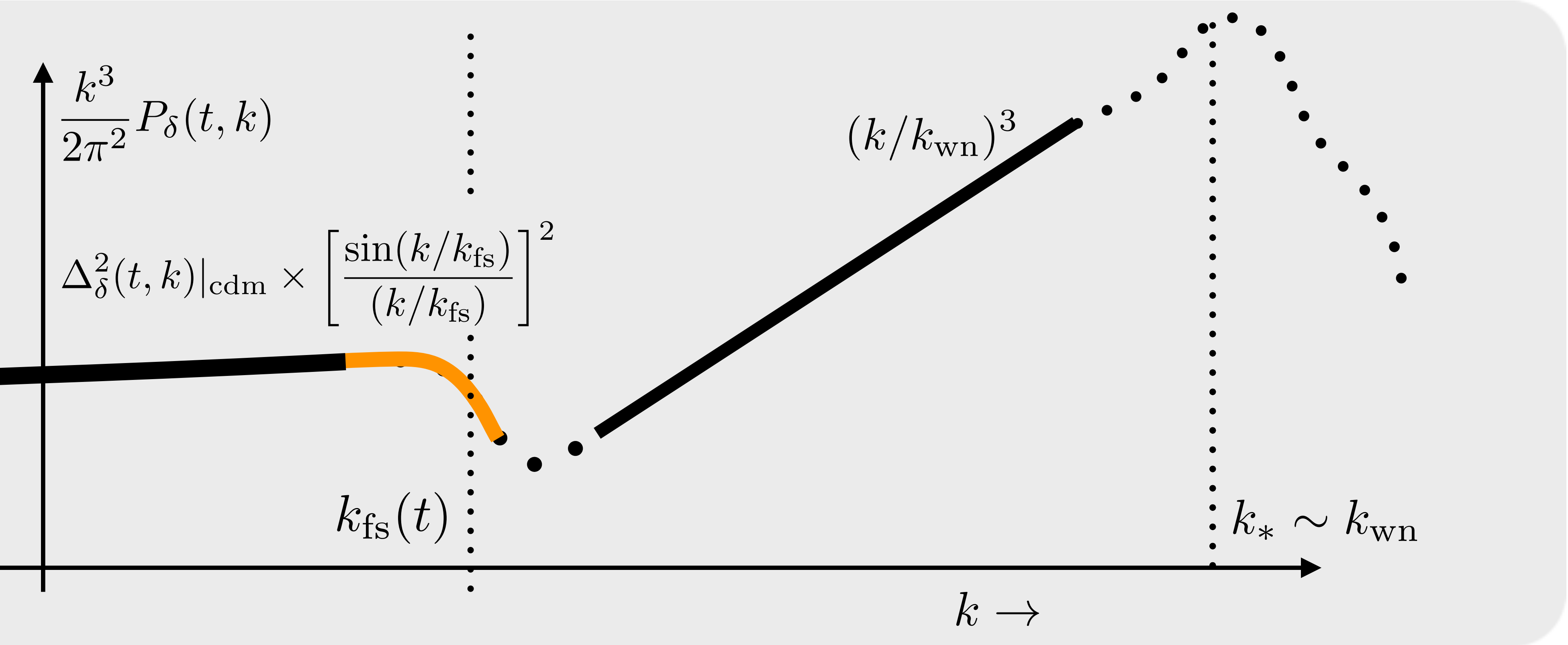

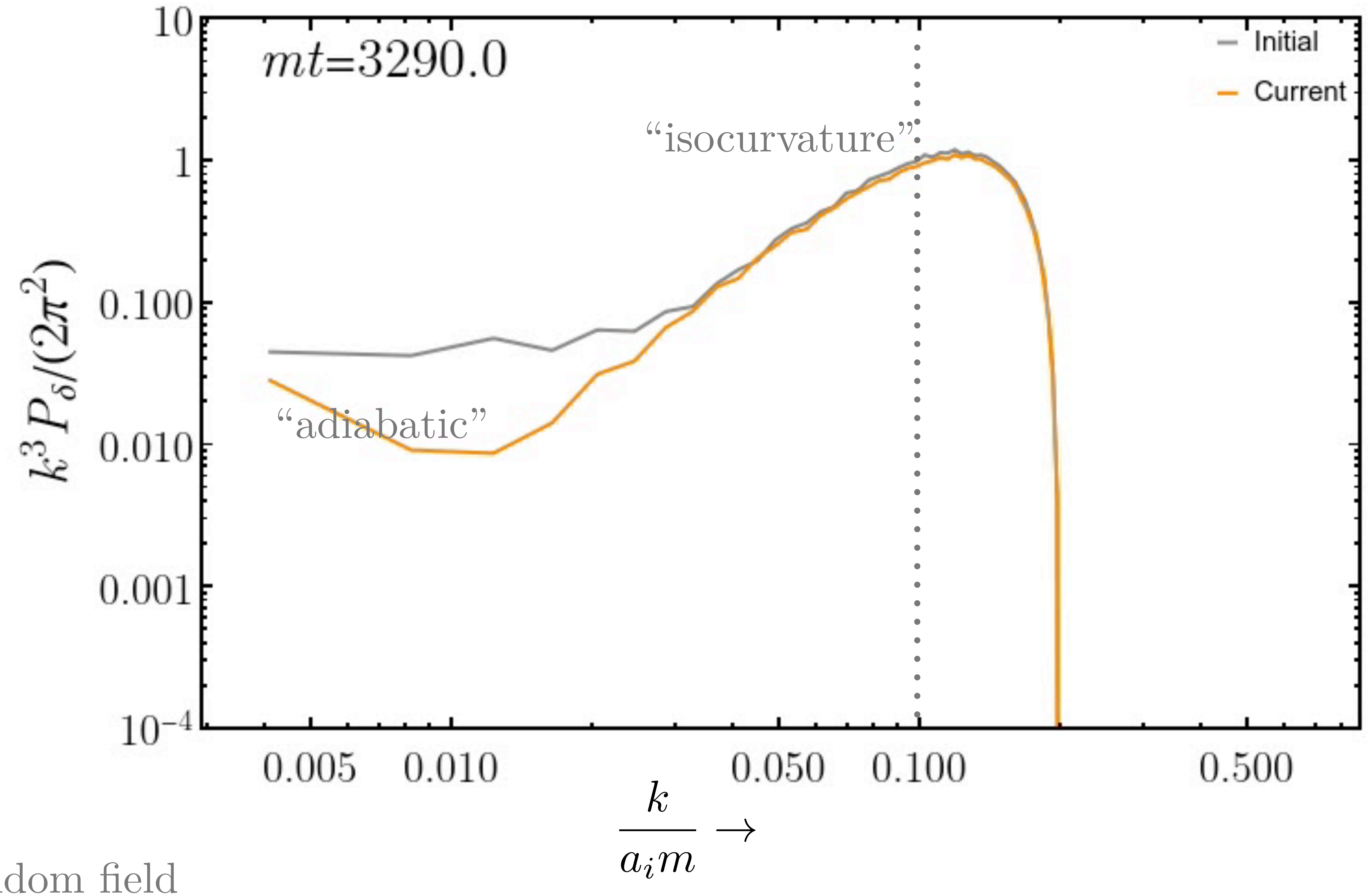

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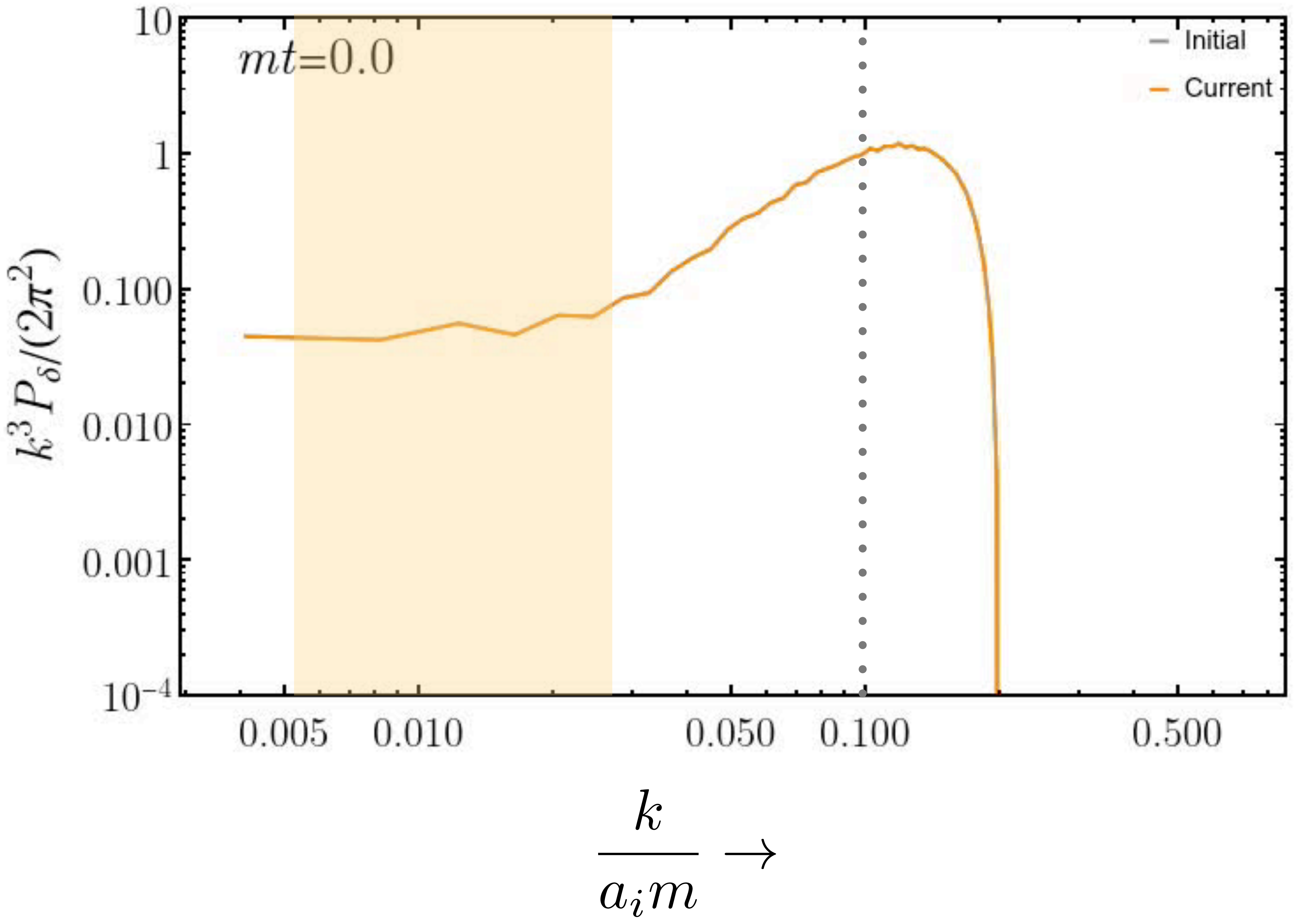
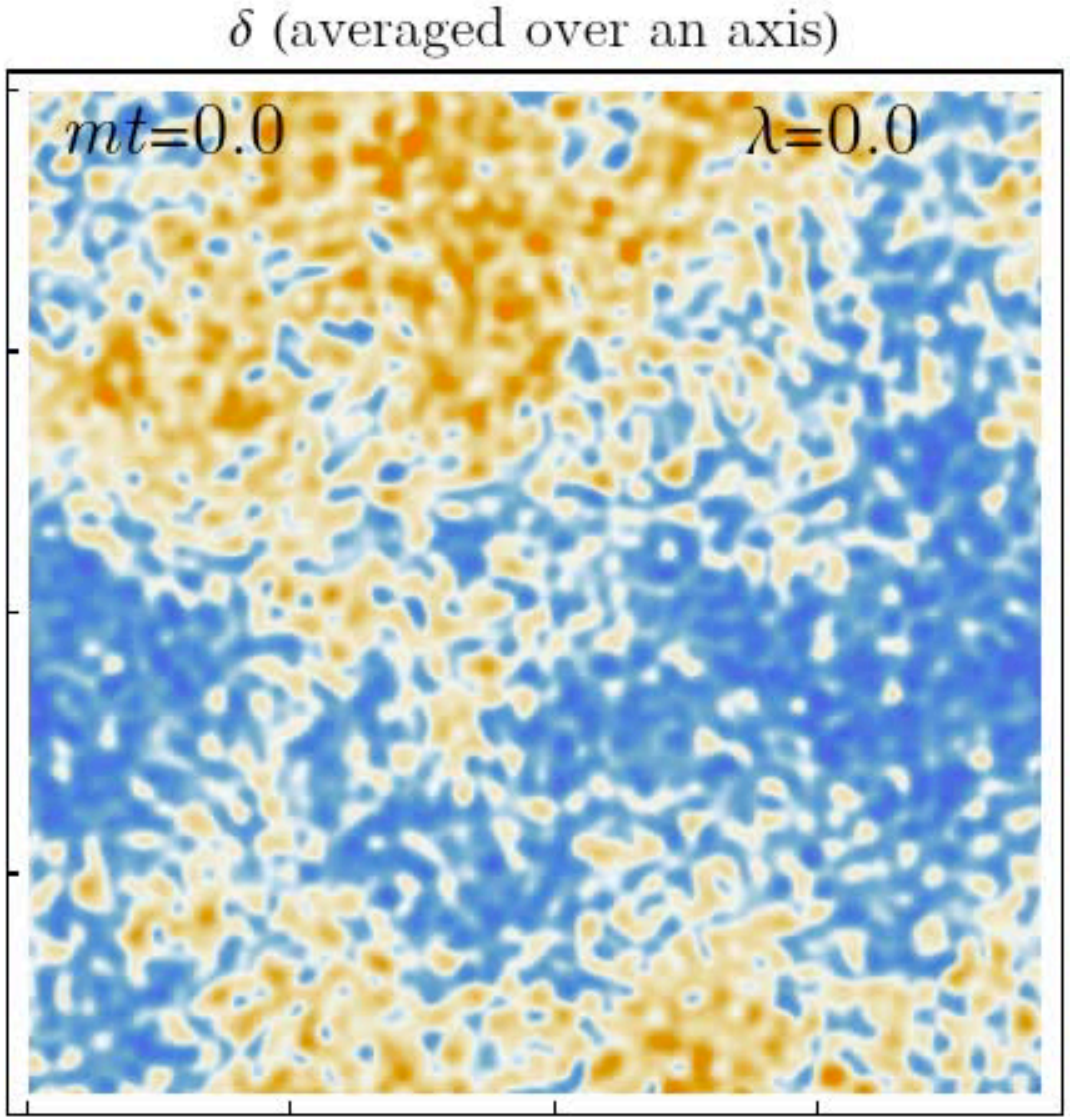
free streaming — numerical

S. Ling





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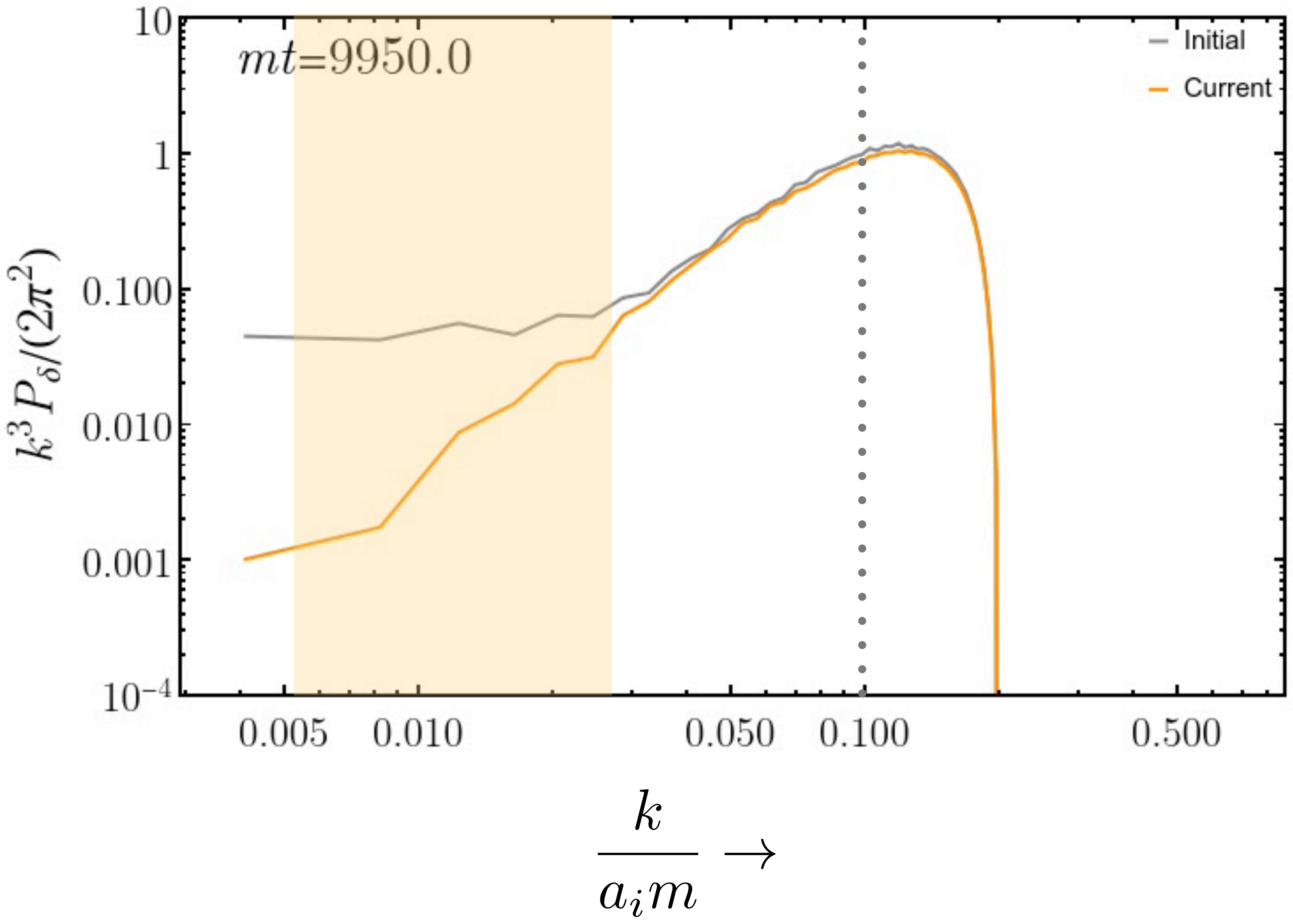
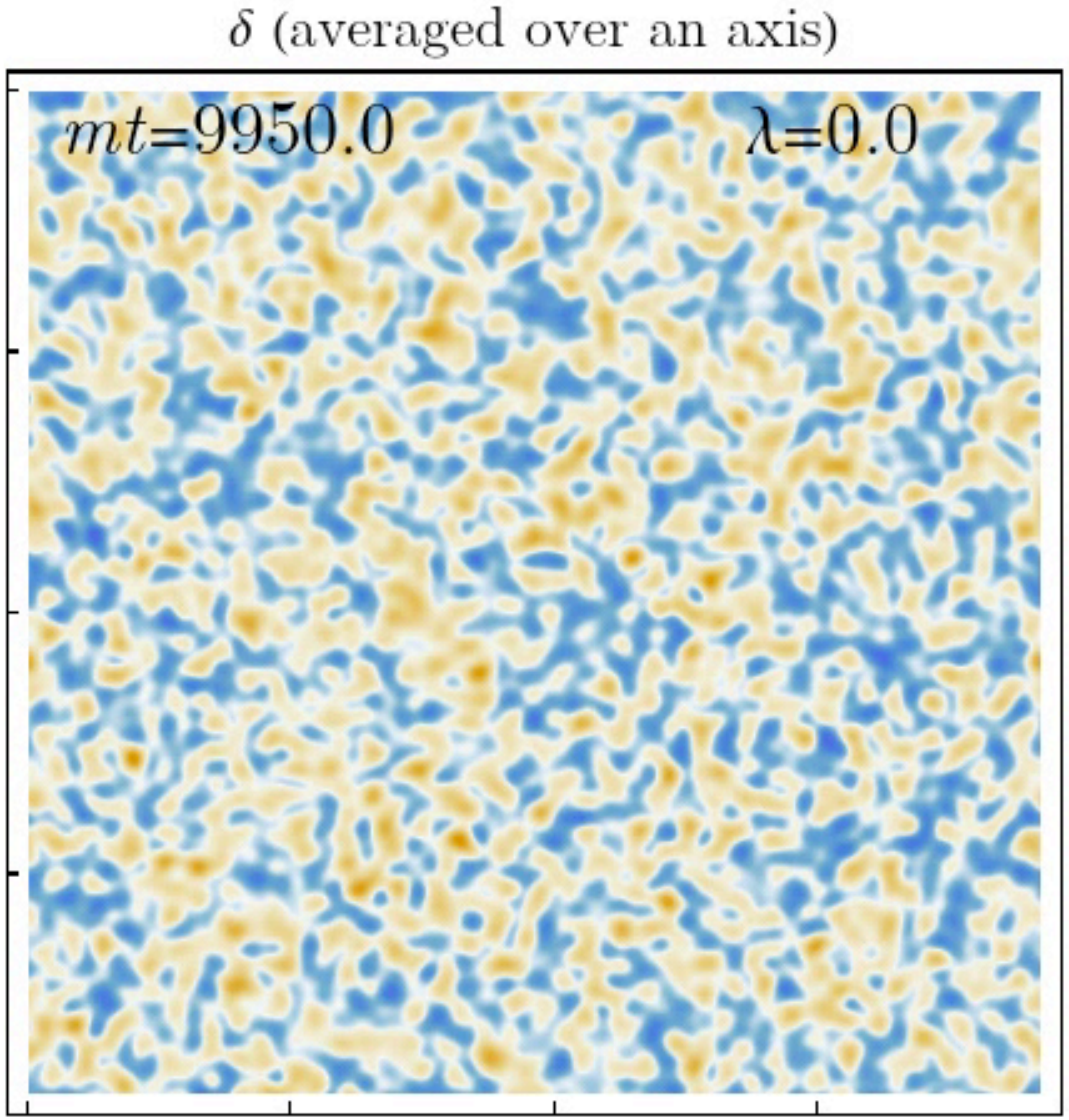




our argument — quantitative

Dark matter density dominated by sub-Hubble field modes

↓

1. white-noise isocurvature excess in isocurvature density pert. $k_{\rm dev} \approx 10^{-2} k_*$
2. free-streaming suppression in adiabatic density pert. $k_{\rm fs}(t) \approx \dfrac{a^2 H m}{k_* \ln(2am/k_*)}$

1\. and 2. not seen for $k < k_{\rm obs} \sim 10\,{\rm Mpc}^{-1}$ e.g. [Lyα]

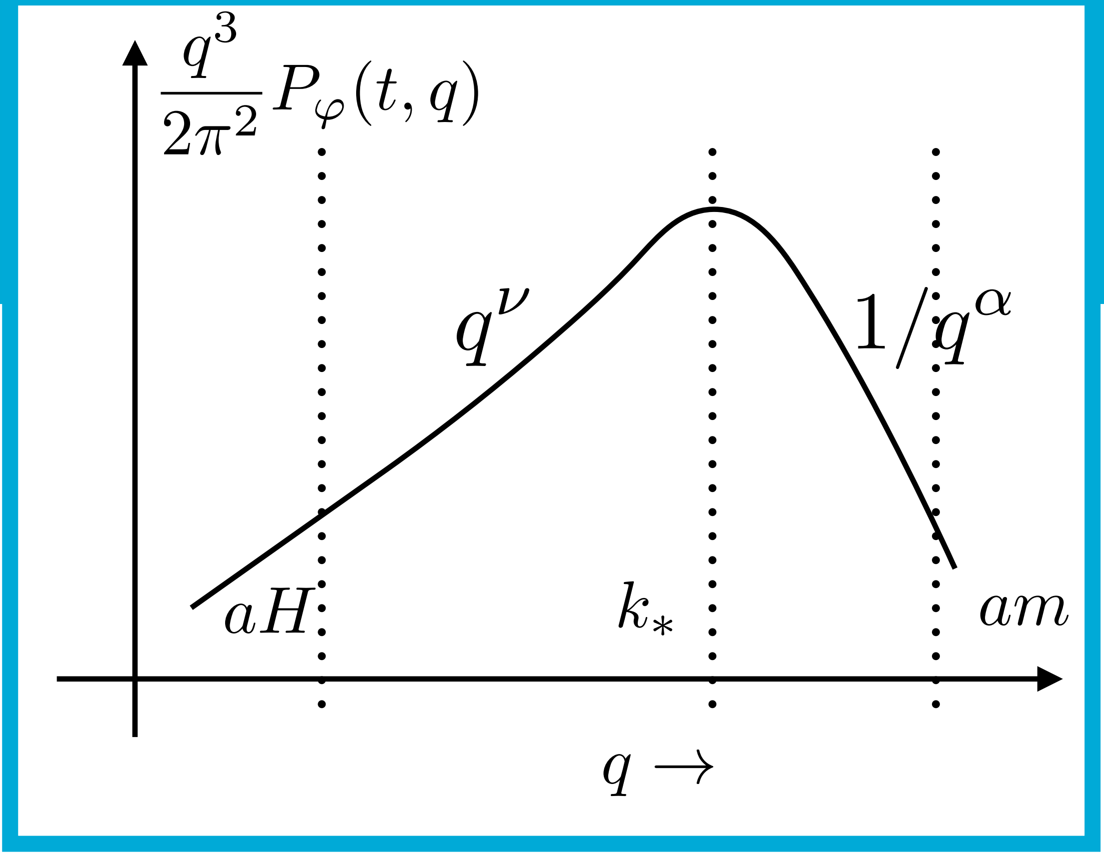
$k_{\rm dev}, k_{\rm fs} \gtrsim k_{\rm obs}$

↓

$$m \gtrsim 10^{-19}\,{\rm eV}$$

Note that we did not need to know k_*!

is our bound conservative?



$$\frac{q^3}{2\pi^2}P_\varphi(t,q) = A(t)\left[\left(\frac{q}{k_*}\right)^\nu \theta(k_* - k) + \left(\frac{k_*}{q}\right)^\alpha \theta(k - k_*)\right]$$

$$m \geq \begin{cases} 4 \times 10^{-19}\,\text{eV} & \text{for} \quad \{\nu,\alpha\} = \{3,3\}, \\ 1 \times 10^{-12}\,\text{eV} & \text{for} \quad \{\nu,\alpha\} = \{2,1\}, \\ 2 \times 10^{-12}\,\text{eV} & \text{for} \quad \{\nu,\alpha\} = \{3,1\}. \end{cases}$$

sharp UV fall off (our conservative choice)
gravitational produced dark photons (but better bounds exist)
axion-like particles with strings (preliminary)

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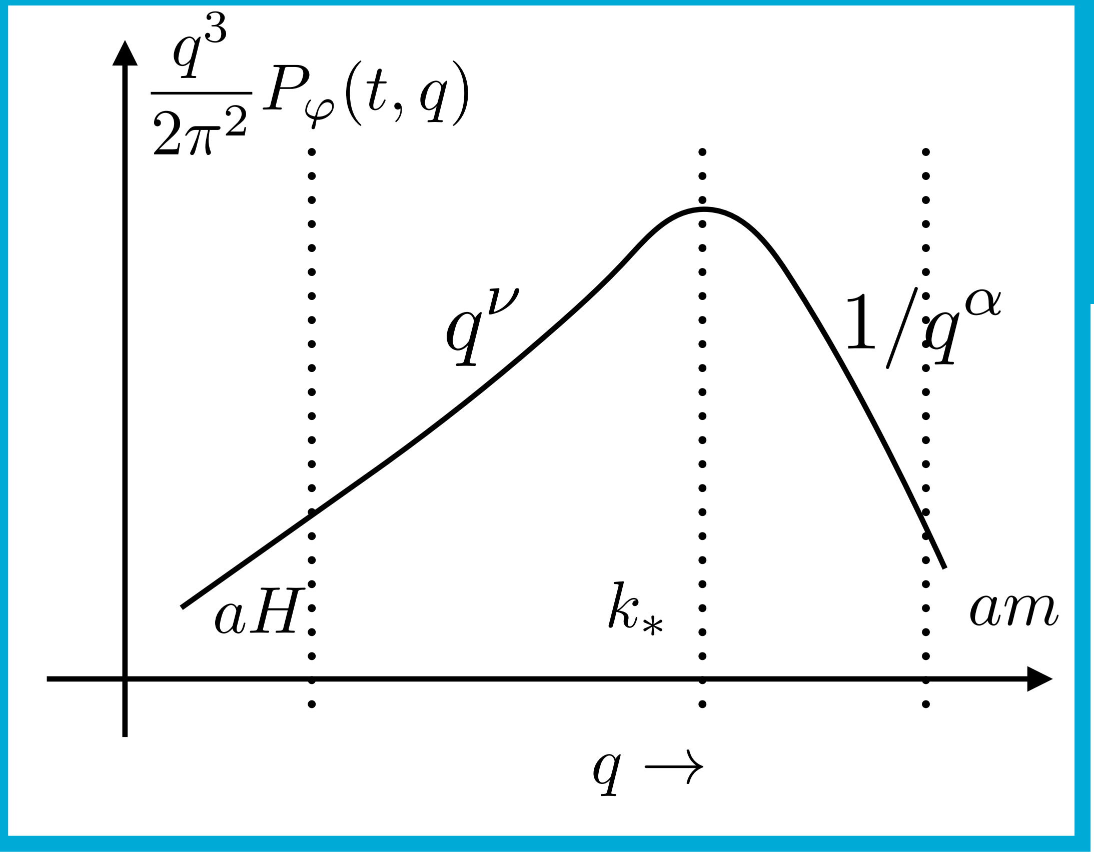

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$$\frac{(k_*)^{\mathrm{th}}}{(k_*)^{\mathrm{non.th}}} \sim \sqrt{\frac{m_{\mathrm{pl}}}{m}} \gg 1 \quad \Longrightarrow m \gtrsim \text{few} \times \mathrm{keV}$$

thermal warm DM bounds

strengths

"model independent" -- applies to all gravitationally interacting,

non-relativistic fields (scalar, vector, tensor ...)

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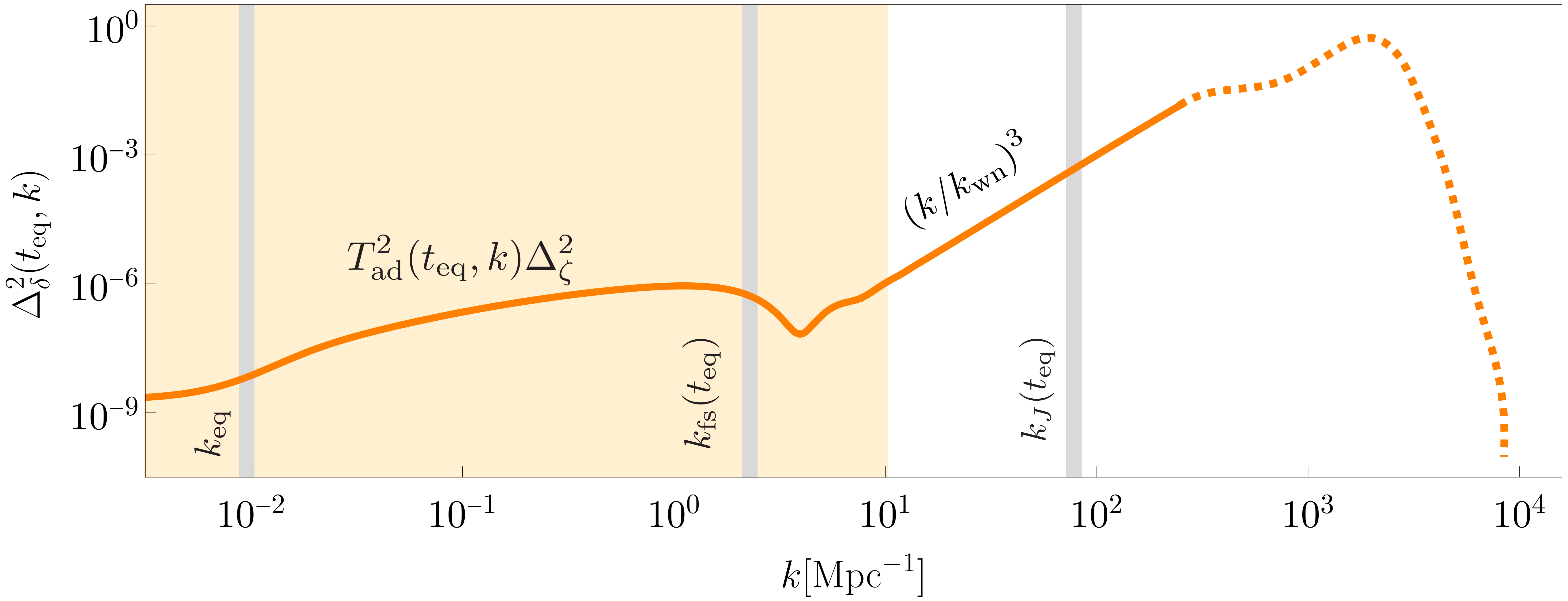
“model independent” -- applies to all gravitationally interacting, non-relativistic fields (scalar, vector, tensor ...)

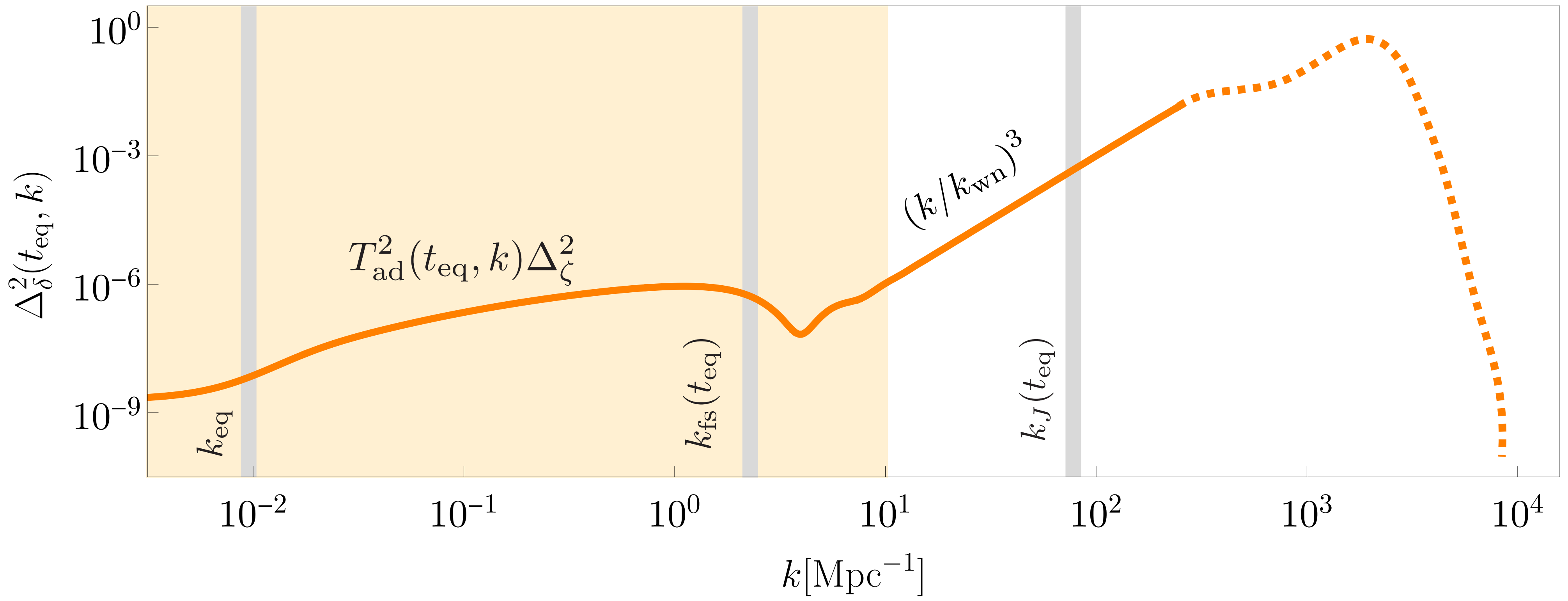


$$k_{fs} \ll k_J \sim a\sqrt{mH} \implies \text{stronger bound}$$

stronger than Jeans bound

strengths

"model independent" -- applies to all gravitationally interacting, non-relativistic fields (scalar, vector, tensor ...)



$k_{\rm fs} \ll k_J \sim a\sqrt{mH} \Longrightarrow$ stronger bound

$m_{\rm bound} \propto k^2_{\rm obs}$ rapid improvement expected!

upcoming

redshift when DM becomes non-relativistic : $z_{\rm nr} \gtrsim 10^8$

* For MW satellites, only suppression is well constrained

with Nadler and Wechsler

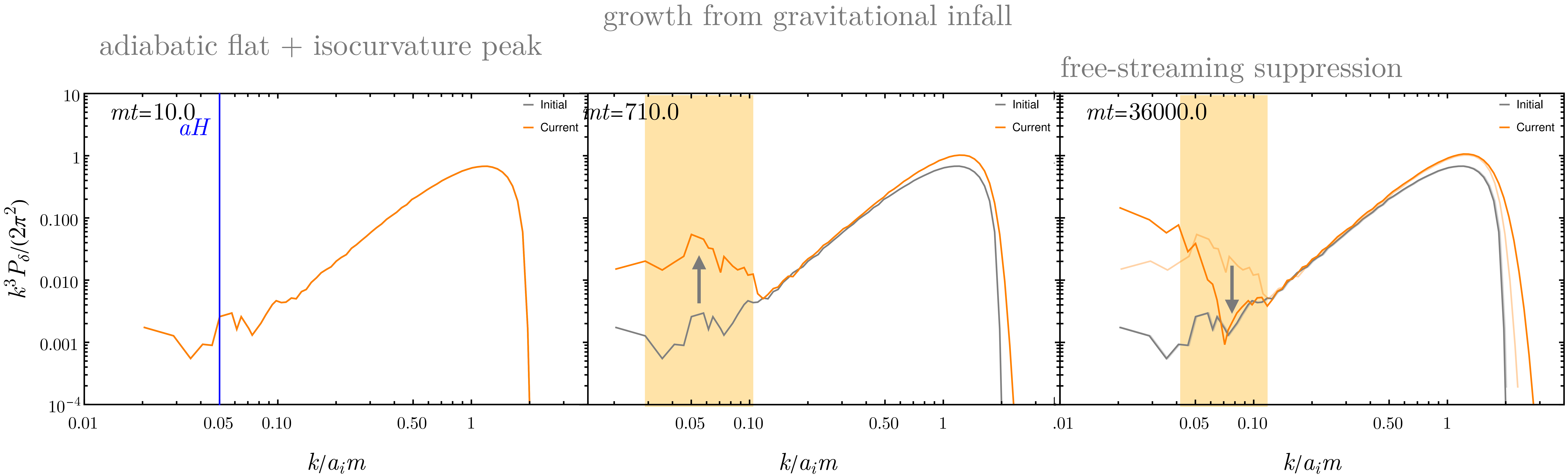
Relativistic + Non-relativistic lattice simulations

with Ling

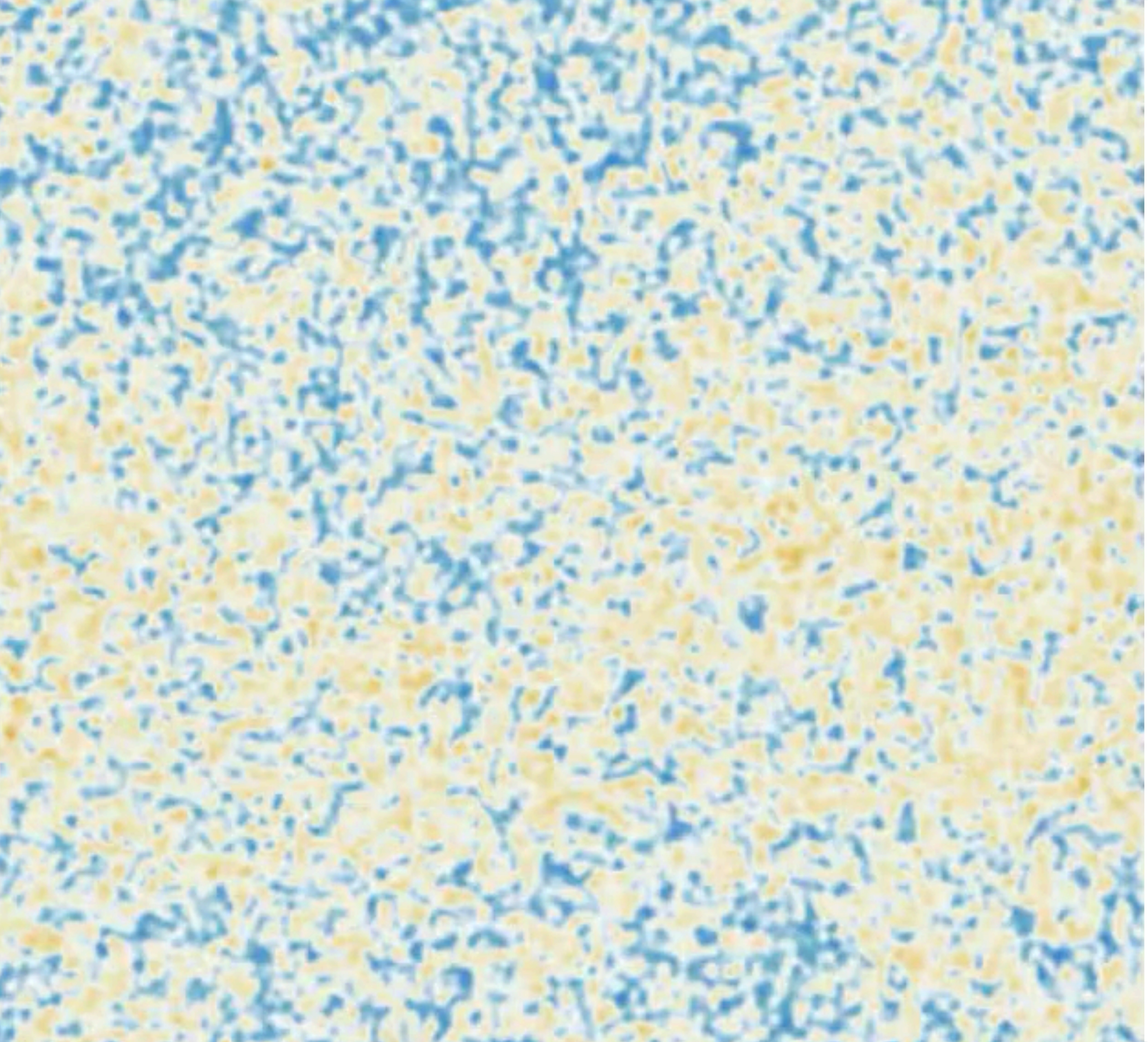
* cannot just use CLASS/CAMB from the beginning

* we can explore ICs, free-streaming, eventual self-gravity of "isocurvature", self-interactions etc.

including all relevant physics in 3+1 d lattice sims.



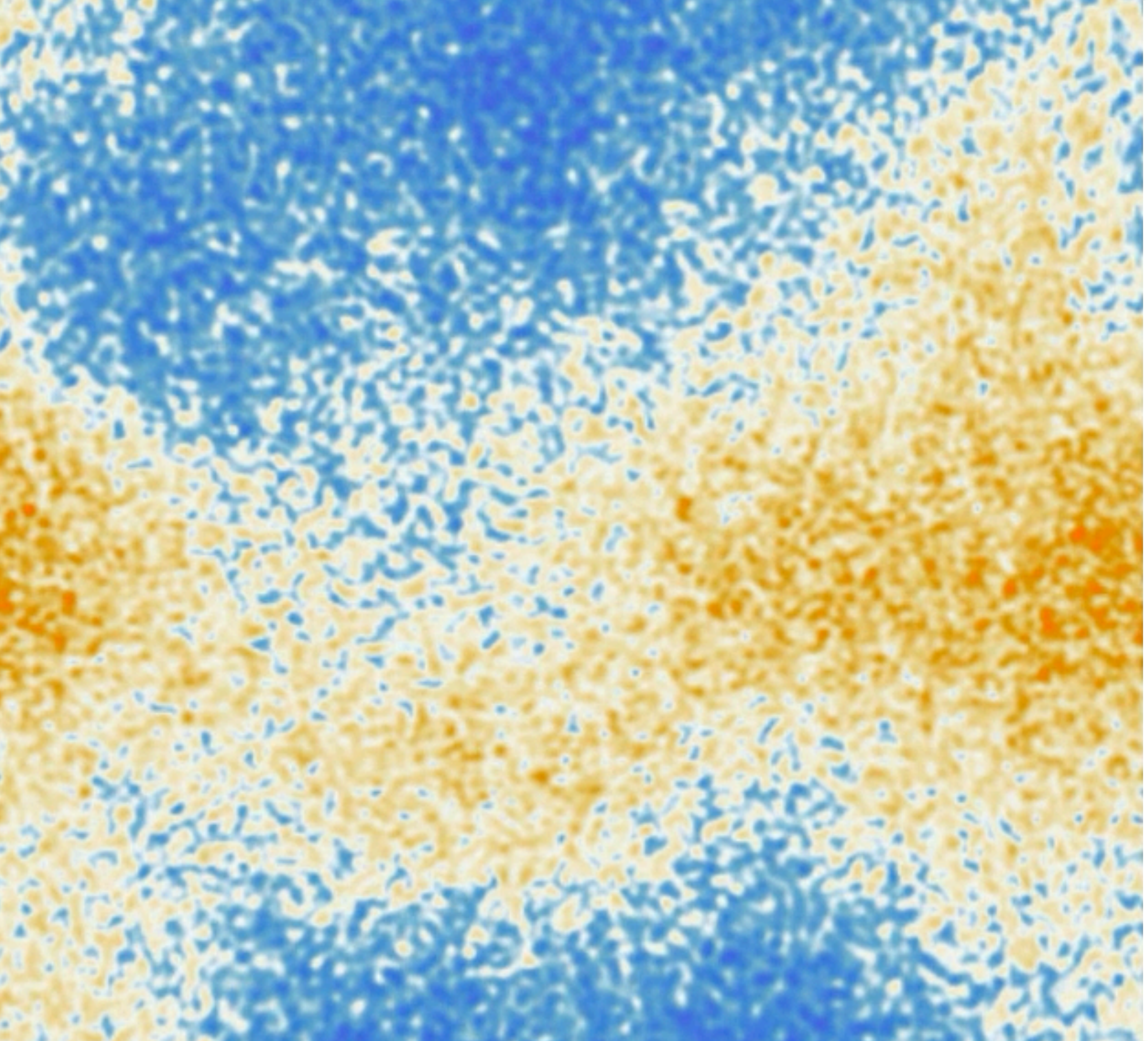
*goal — provide accurate initial conditions for DM density pert.



Initially we see growth of long wavelength structure due to **gravitational infall** during radiation domination

Later, in a very sped up movie, we see **free streaming** wiping out the structure.

*WKB solutions used for very late times



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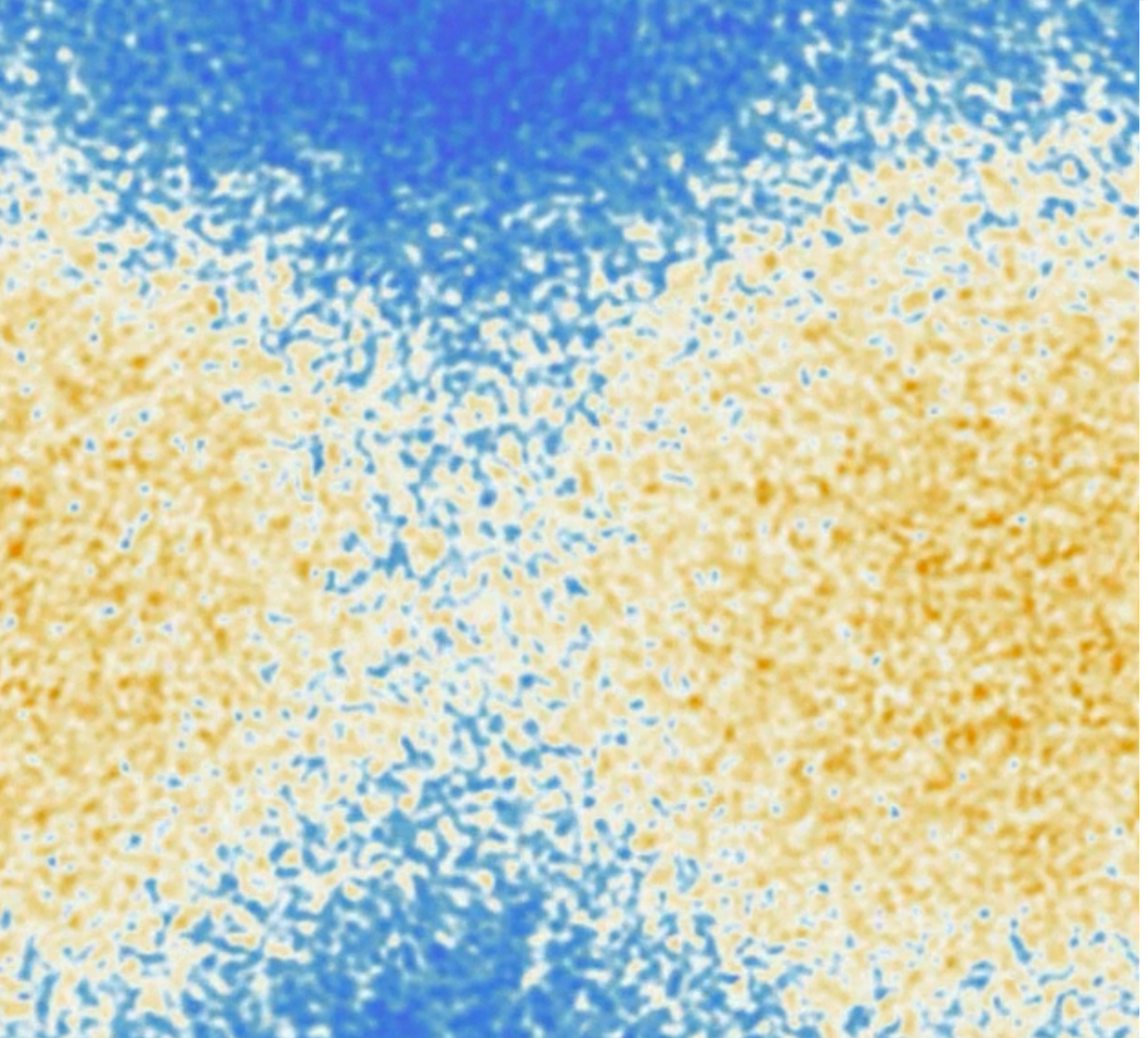

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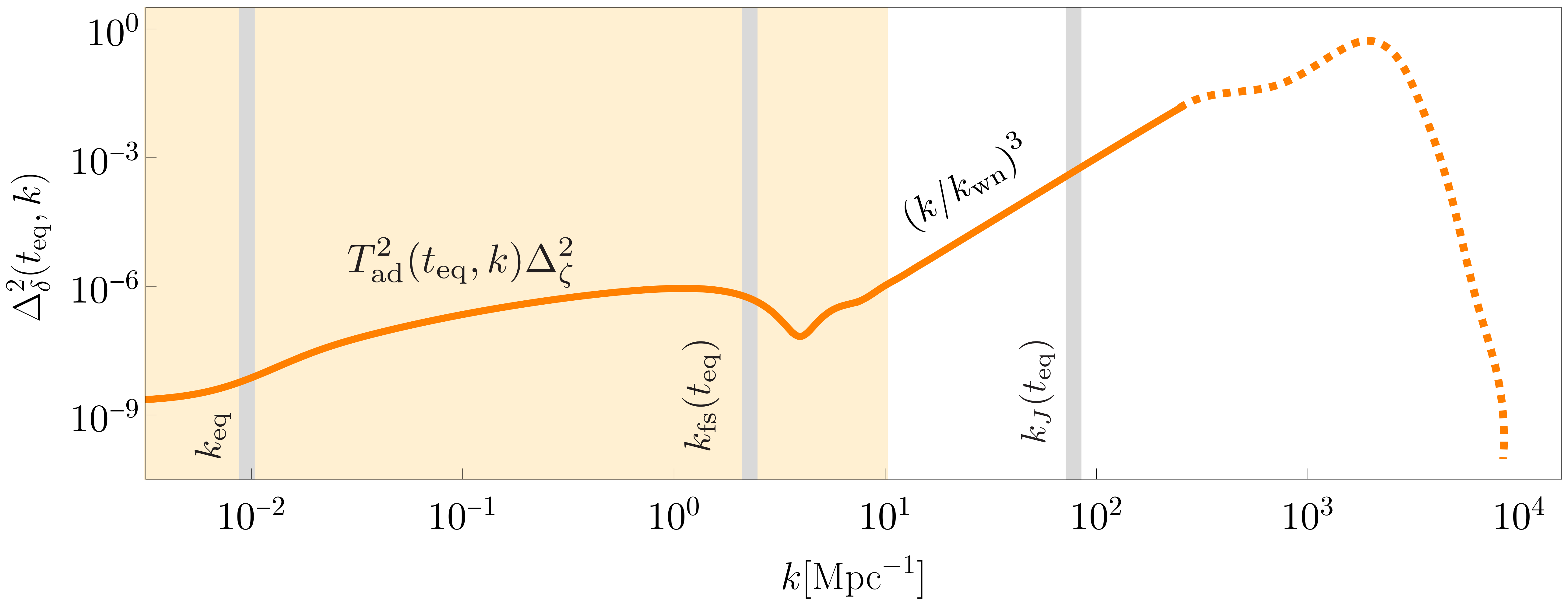
summary

Dark matter density dominated by sub-Hubble field modes

$\implies m \gtrsim 10^{-19}\,\mathrm{eV}$

* very few assumptions, conservative, with room for "improvement"
— observations + theory + numerics

bound good, detection better



extra small-scale structure

formation of mini-clusters/halos/solitons

some exciting phenomenology related to spin!