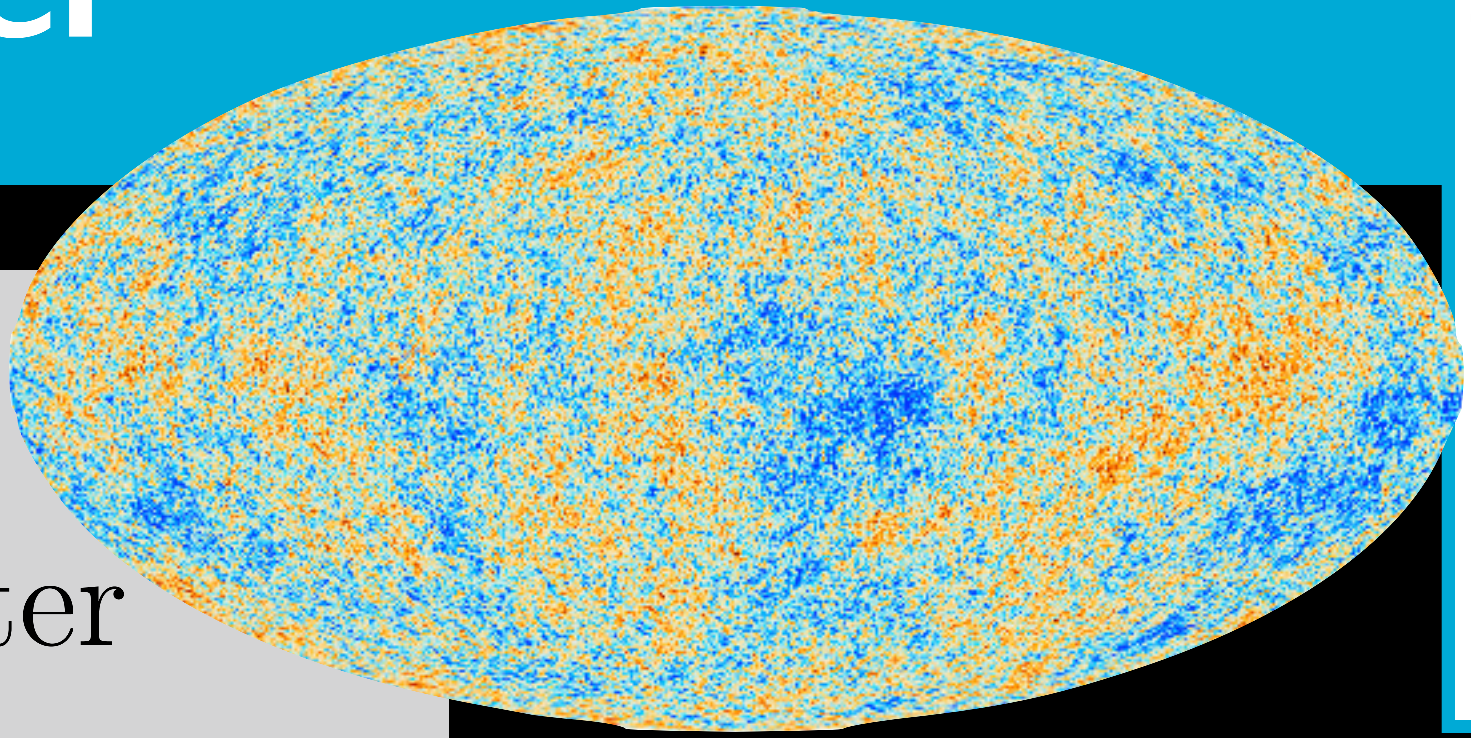
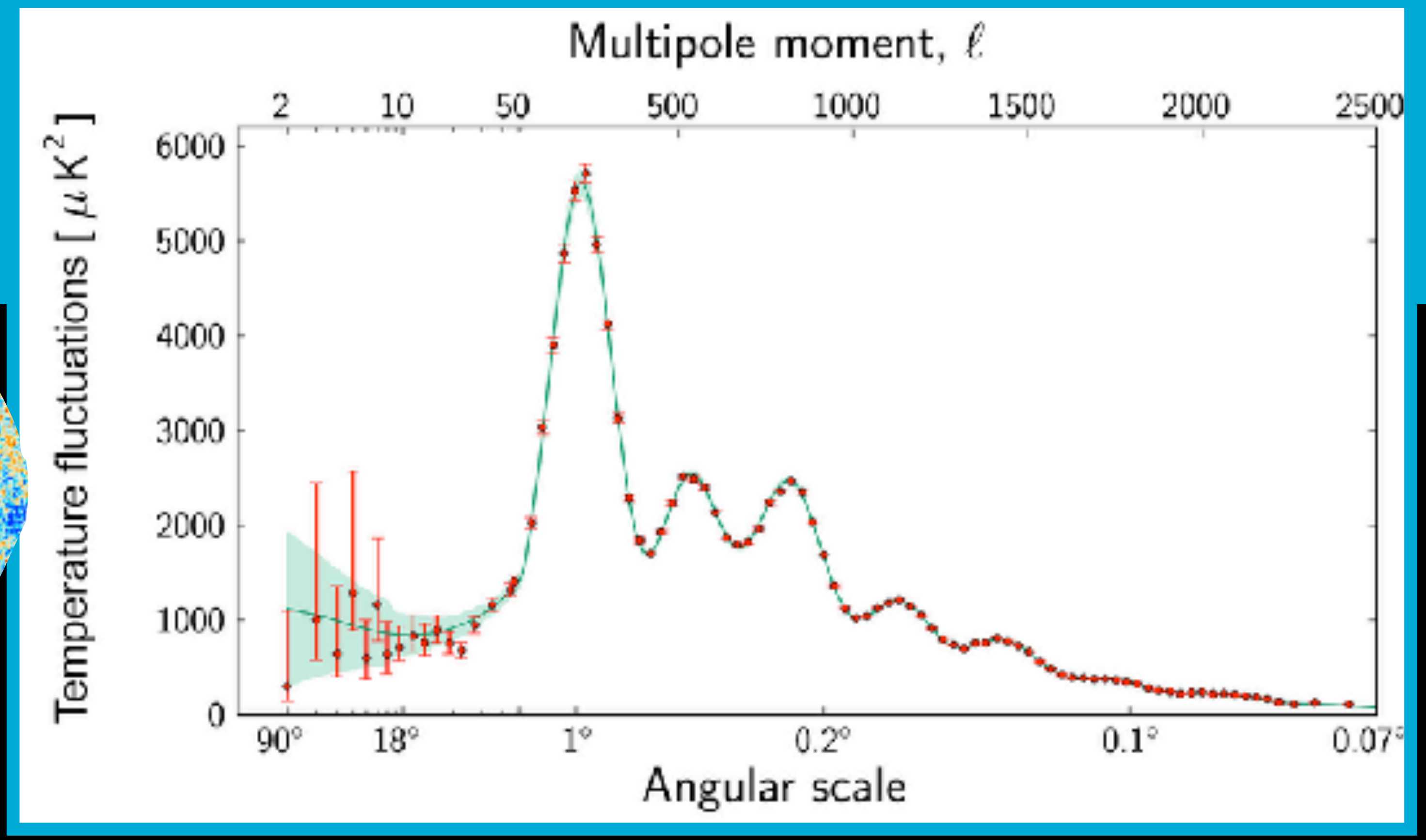
A lower bound on the mass of dark matter

Mustafa A. Amin

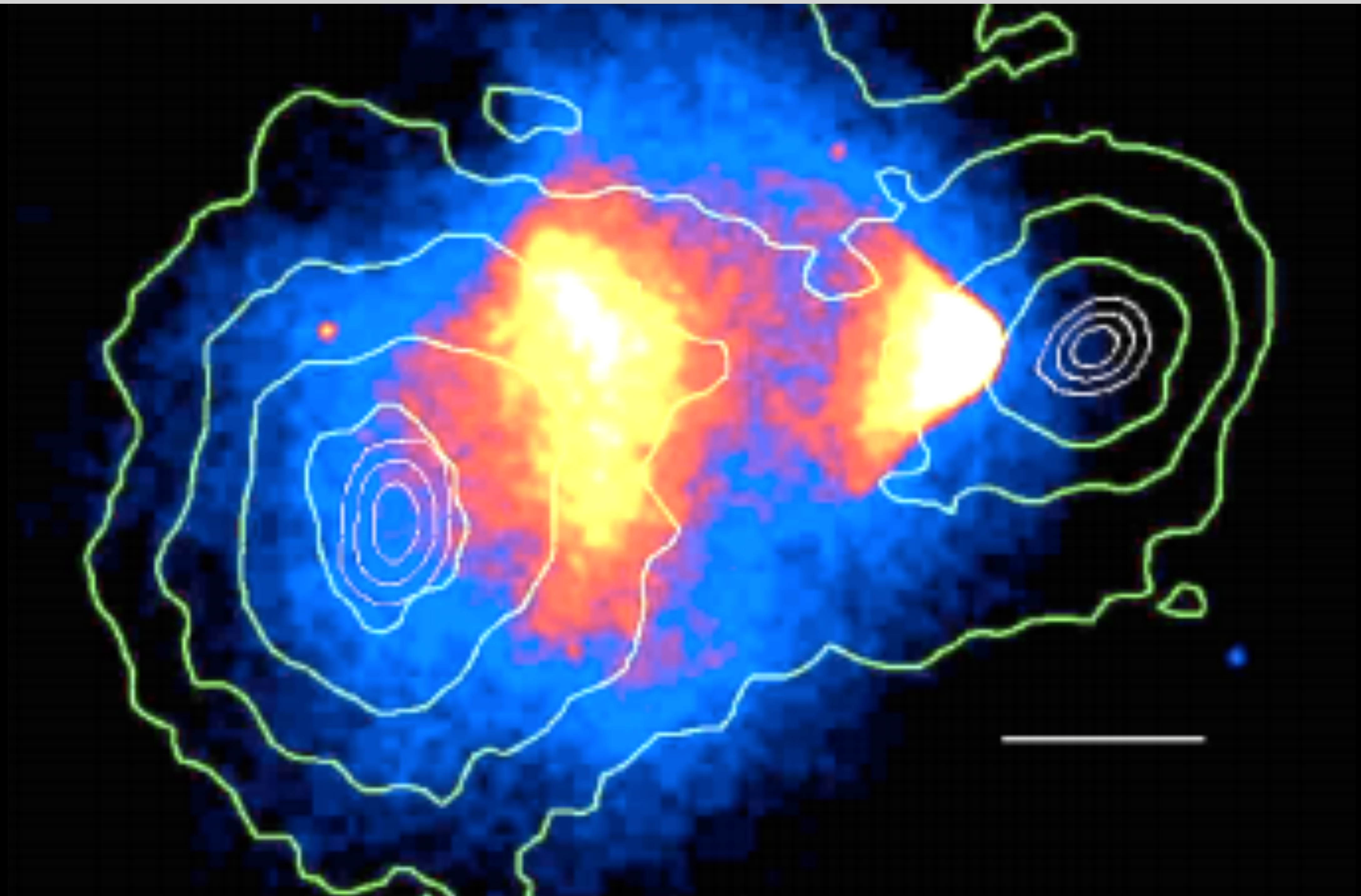
RICE

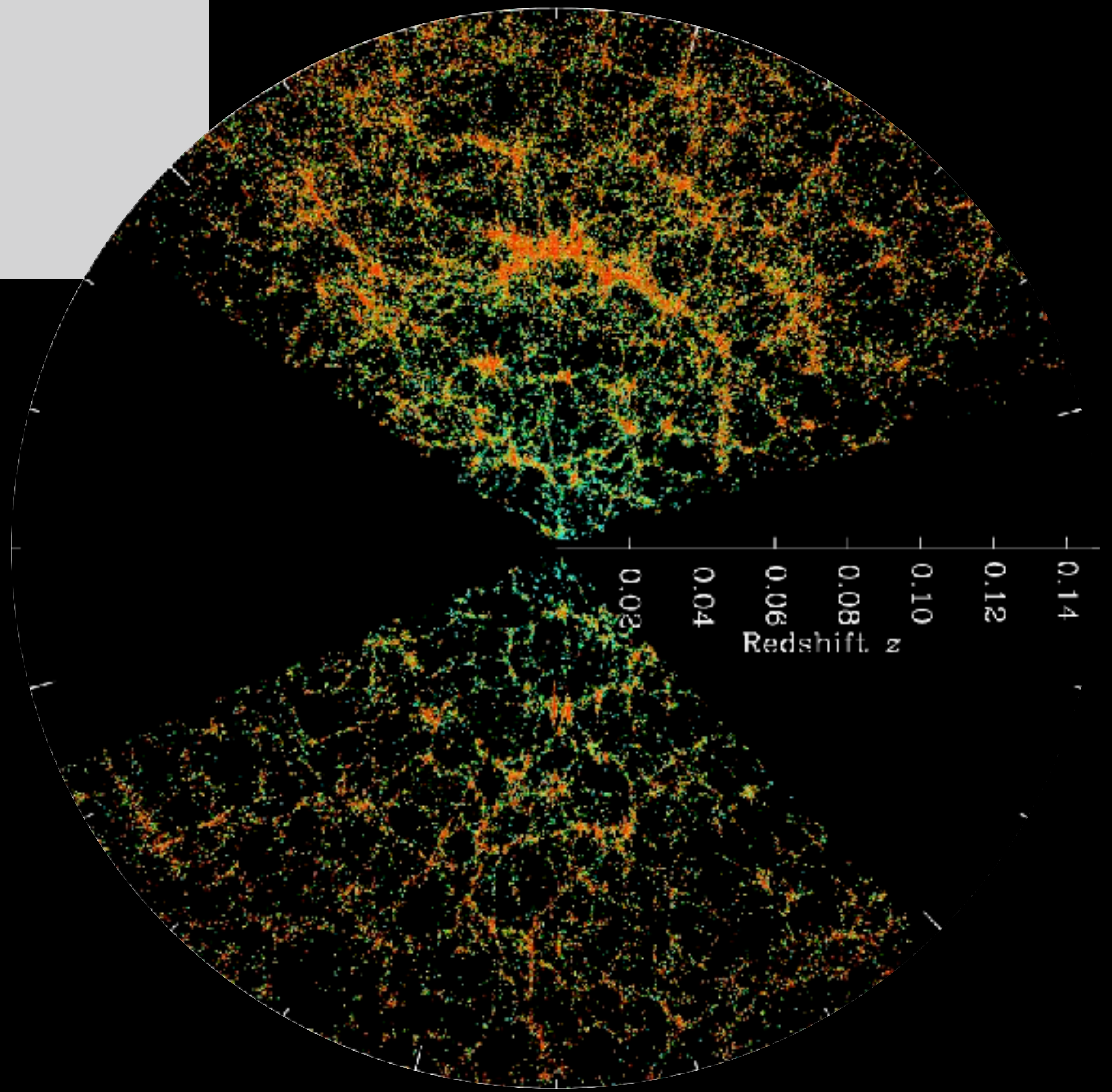
evidence for dark matter

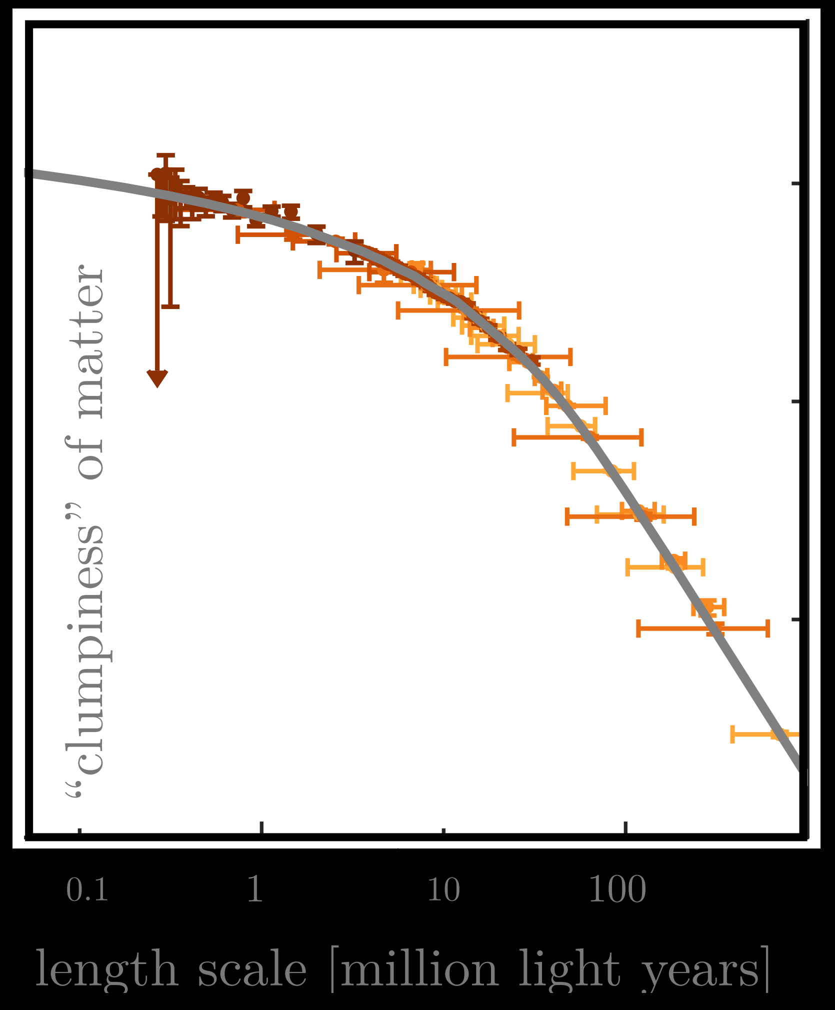




- dark matter exists-85% of matter
- gravitational interactions ✓







*incomplete sample

mass of dark matter "particle" ?

particle mass ?

$$\rho_{\rm dm} \sim 0.3\,{\rm GeV\,cm^{-3}}$$

astrophysics cares about mass density

$$\rho_{\rm dm} = m\uparrow \times n_{\rm dm}\downarrow = m\downarrow \times n_{\rm dm}\uparrow$$

limits on dark matter particle mass

not allowed

allowed

not allowed

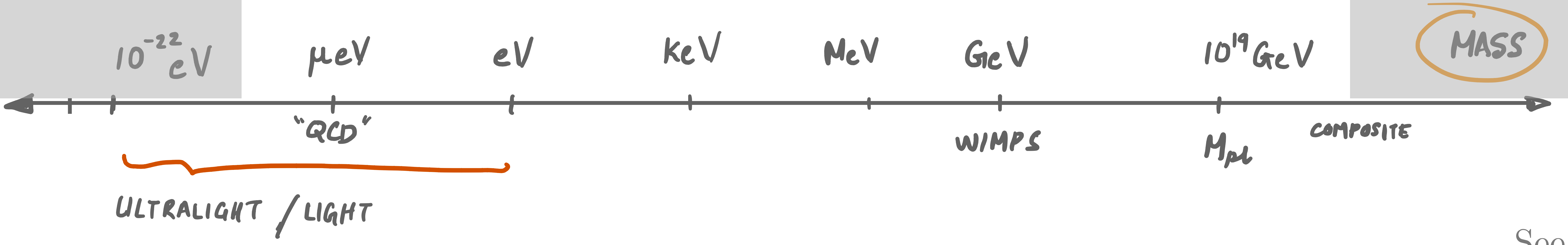
$m \gtrsim 10^{-19}\,\mathrm{eV}$

from dynamical heating of stellar orbits

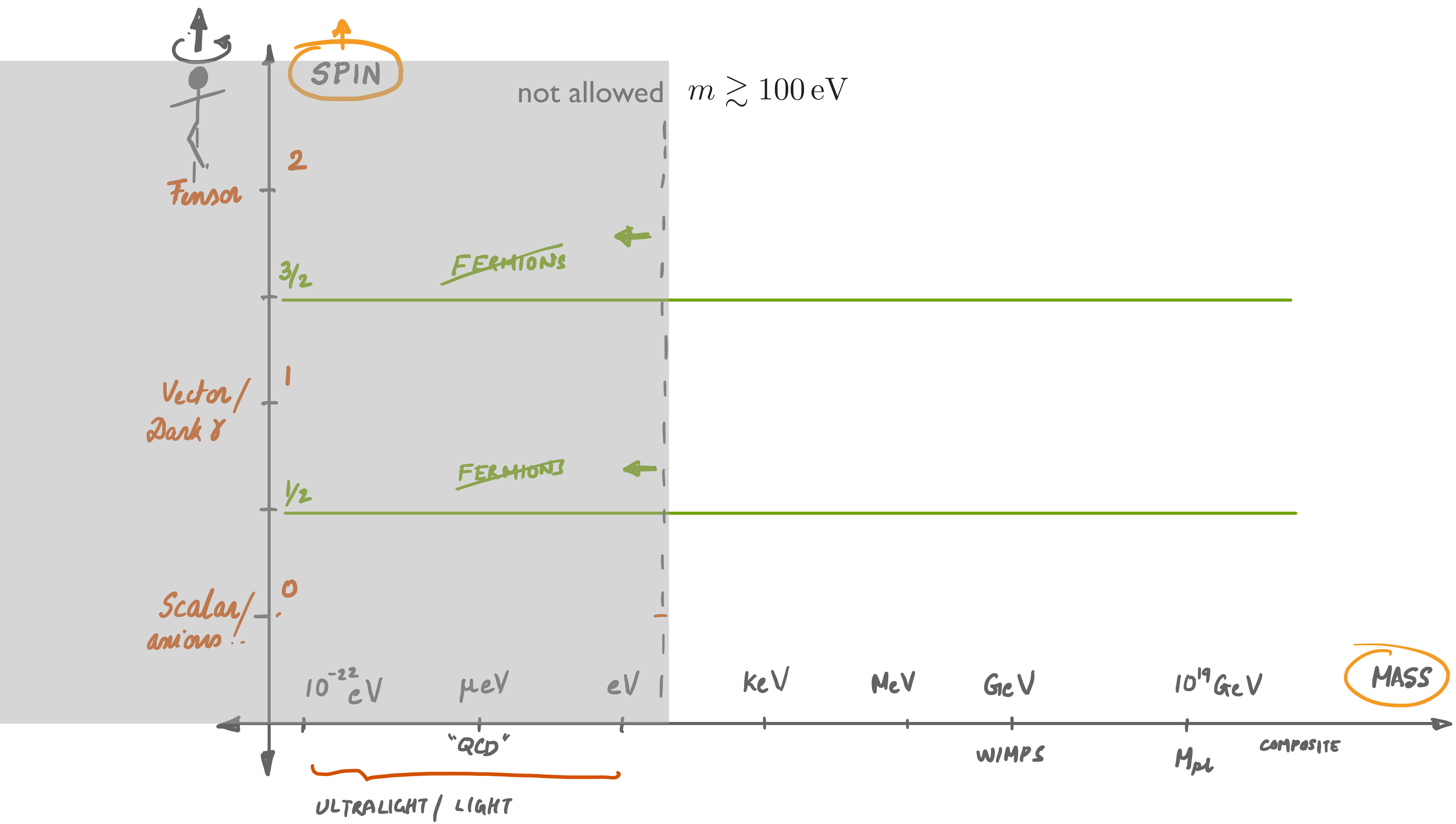
Dalal & Kravtsov (2022)

Brandt (2016)

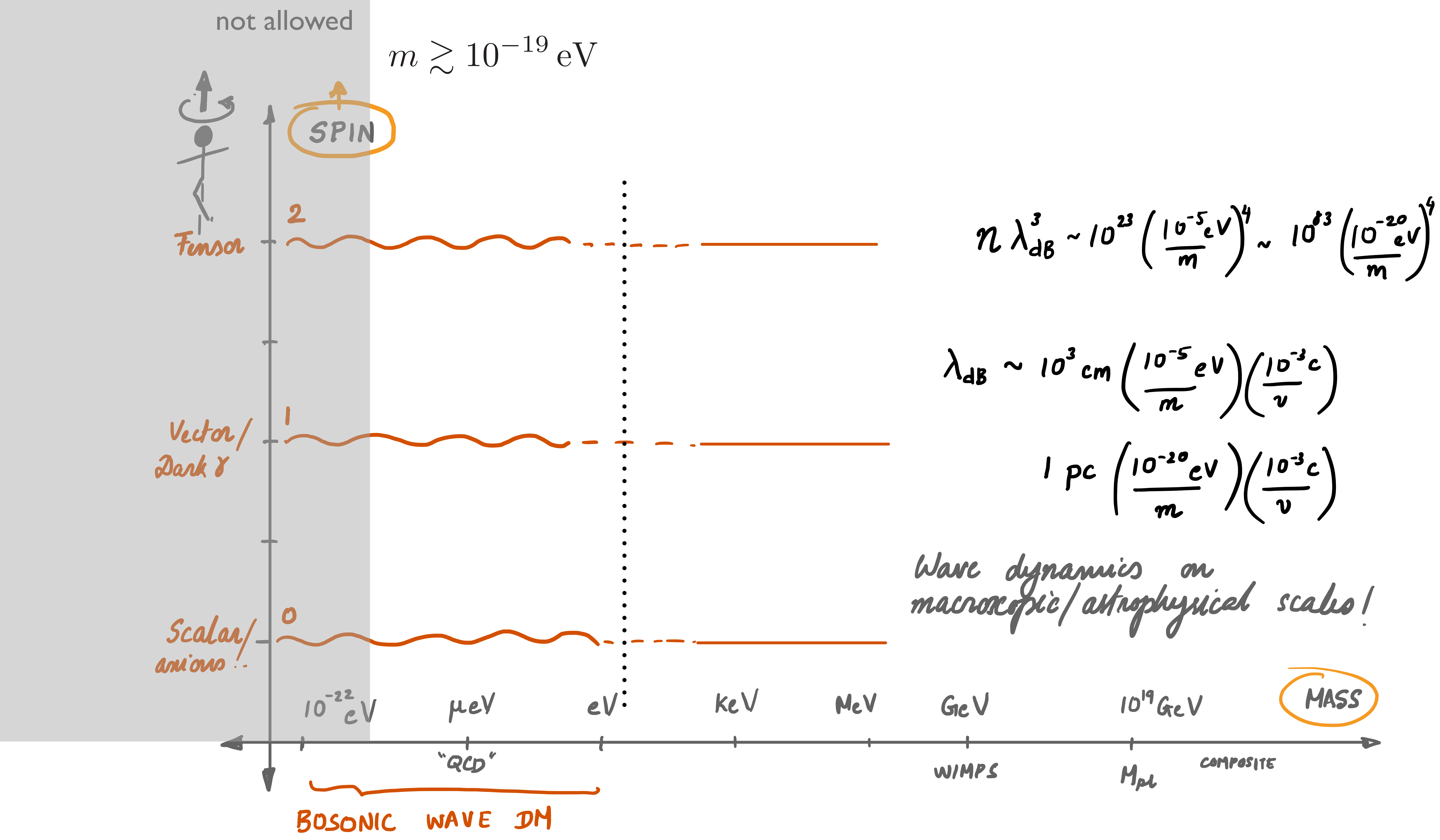
$m \lesssim \text{few } M_\odot$



See PDG for more



SPIN
not allowed
$m \gtrsim 100\,\mathrm{eV}$
2
Tensor
3/2
FERMIONS
1
Vector/
Dark γ
FERMIONS
1/2
0
Scalar/
axions ..
10^{-22} eV
μeV
eV
KeV
MeV
GeV
10^{19} GeV
MASS
"QCD"
WIMPS
M_{pl}
COMPOSITE
ULTRALIGHT / LIGHT



not allowed
$m \gtrsim 10^{-19}\,\mathrm{eV}$
SPIN
2
Tensor
1
Vector/
Dark γ
0
Scalar/
axions ..
$n \lambda_{dB}^3 \sim 10^{23} \left(\frac{10^{-5}\,eV}{m}\right)^4 \sim 10^{83} \left(\frac{10^{-20}\,eV}{m}\right)^4$
$\lambda_{dB} \sim 10^3\,cm \left(\frac{10^{-5}\,eV}{m}\right)\left(\frac{10^{-3}\,c}{v}\right)$
$1\,pc \left(\frac{10^{-20}\,eV}{m}\right)\left(\frac{10^{-3}\,c}{v}\right)$
Wave dynamics on macroscopic/astrophysical scales!
$10^{-22}\,eV$
μeV
eV
KeV
MeV
GeV
$10^{19}\,GeV$
MASS
"QCD"
WIMPS
M_{pl}
COMPOSITE
BOSONIC WAVE DM

limits on dark matter particle mass

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allowed

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from dynamical heating of stellar orbits

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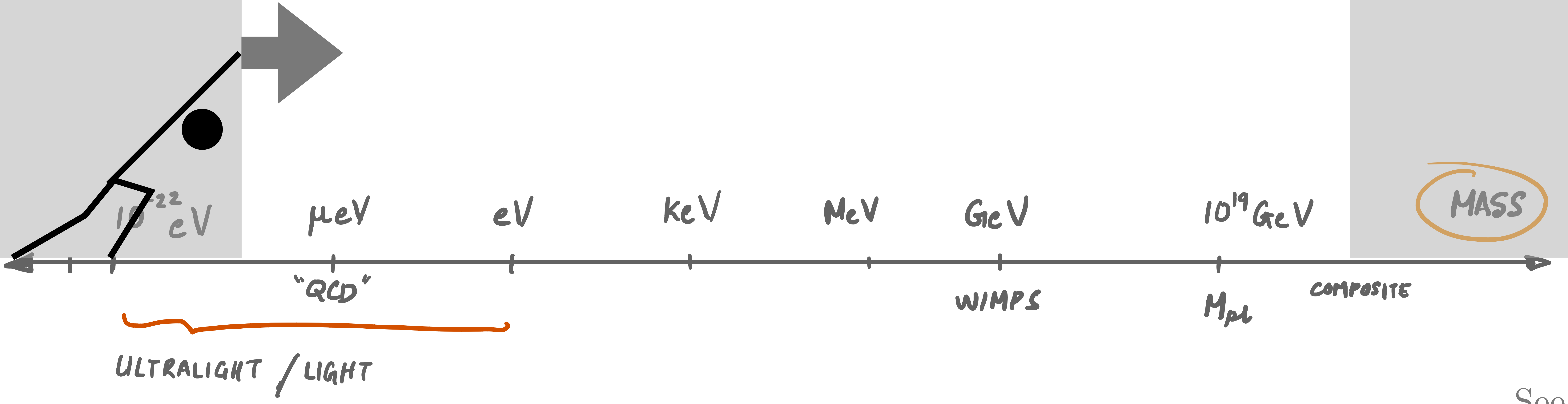


See PDG for more

15 min

A lower bound on dark matter mass

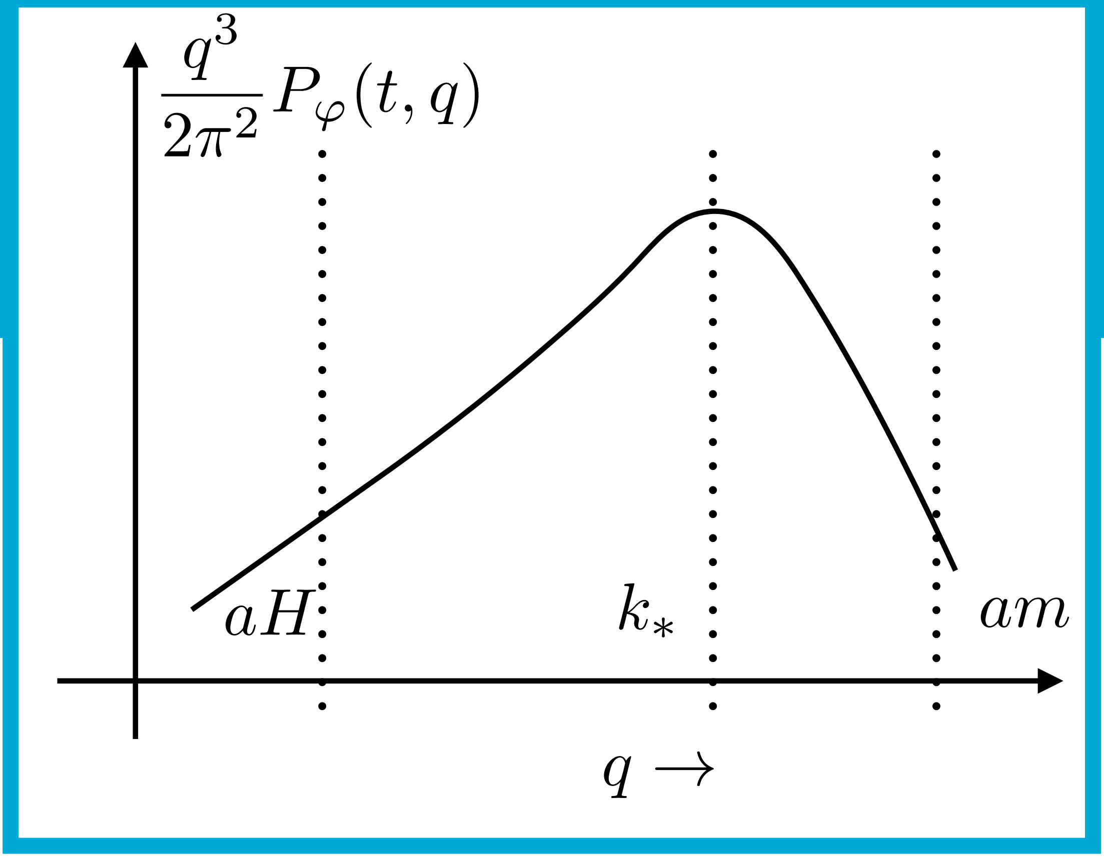
Mustafa A. Amin

RICE

with Mehrdad Mirbabayi

arXiv:2211.09775

main point



Dark matter density dominated by sub-Hubble field modes

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

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, similar arguments can lead to $m > 10^{-12}$ eV!

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.

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

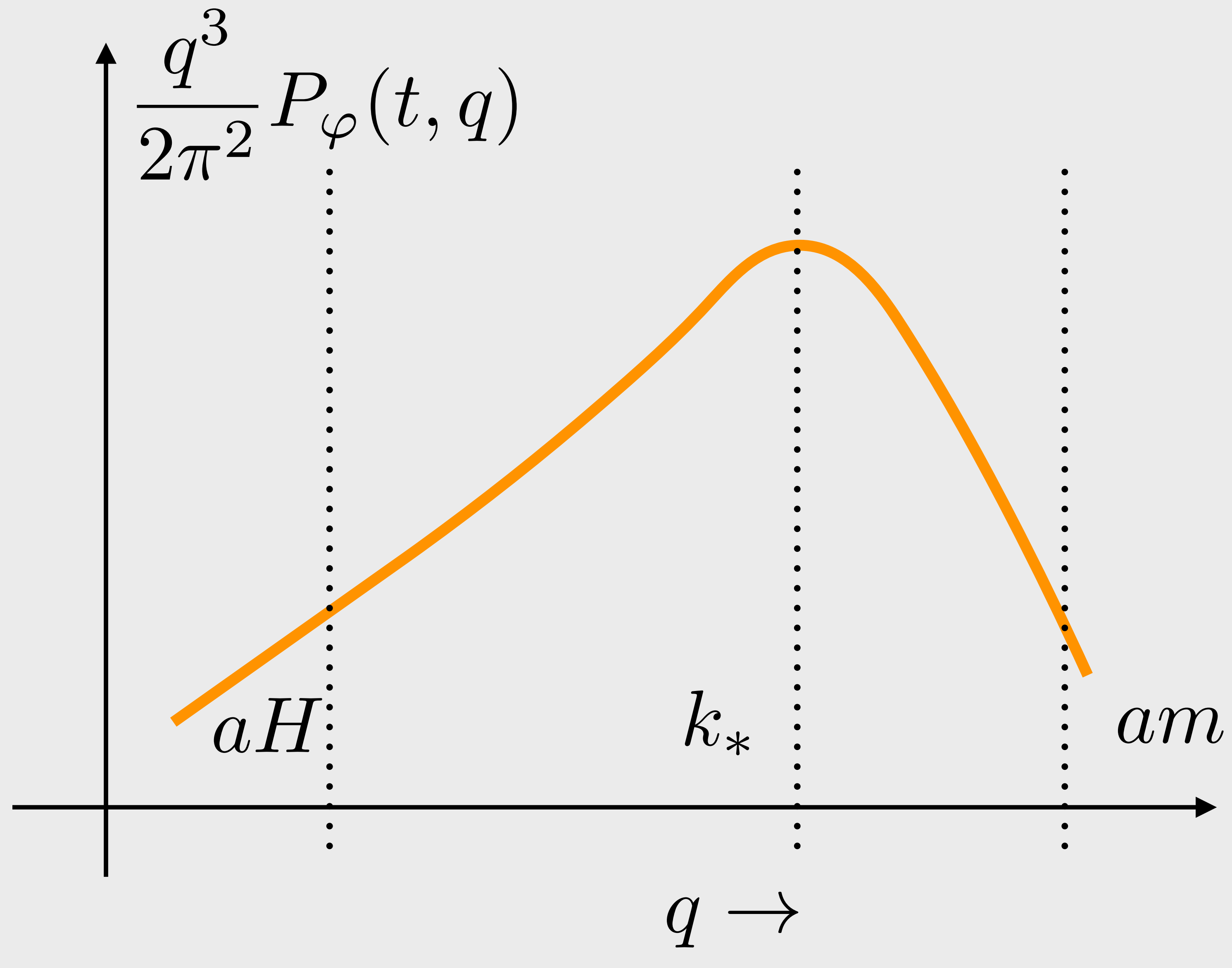
dark matter density close to matter radiation eq.

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

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

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

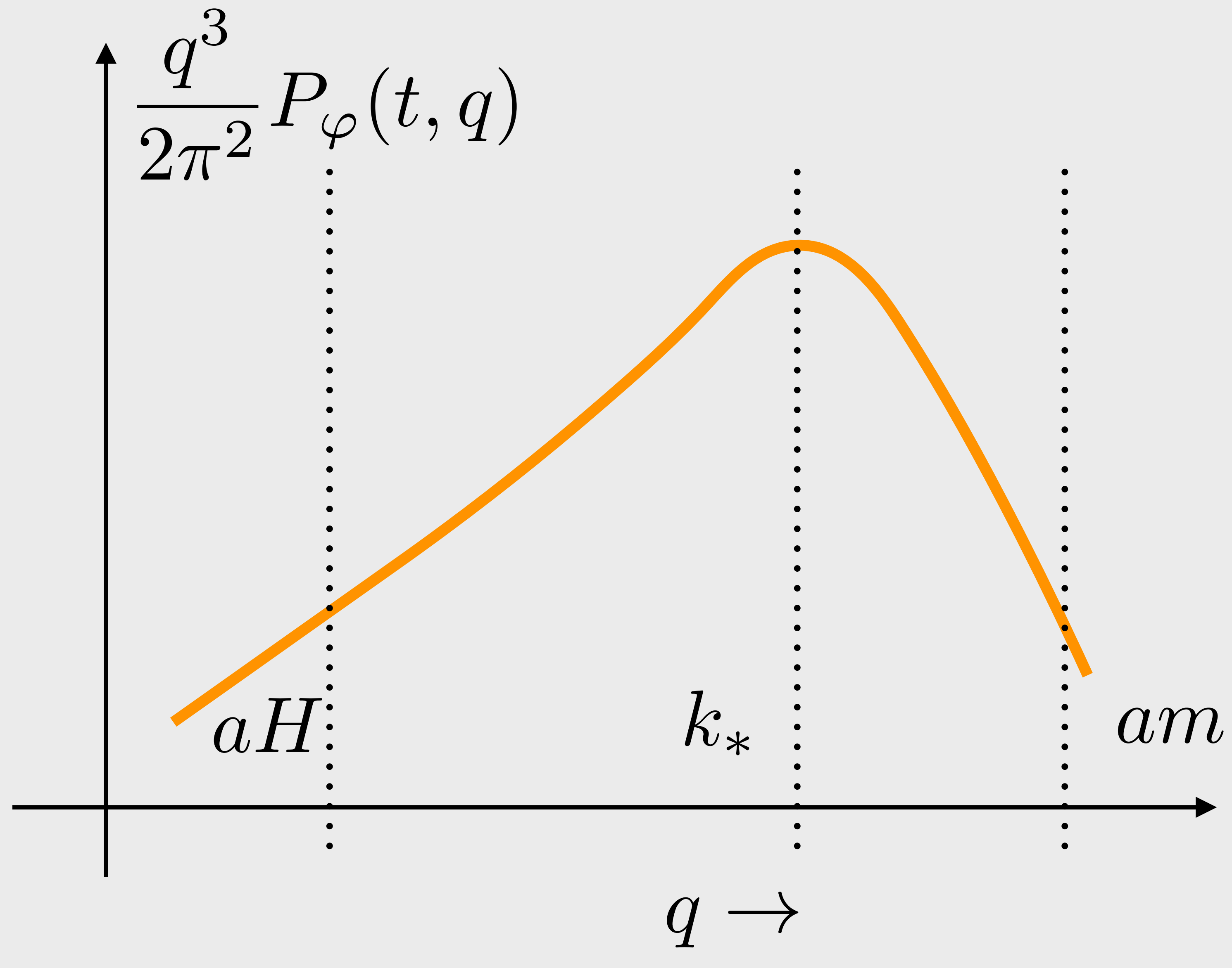
non-gravitational production *after* inflation

phase transitions

- *axion-like fields (including QCD)*

resonant/tachyonic energy transfer from fields, strings

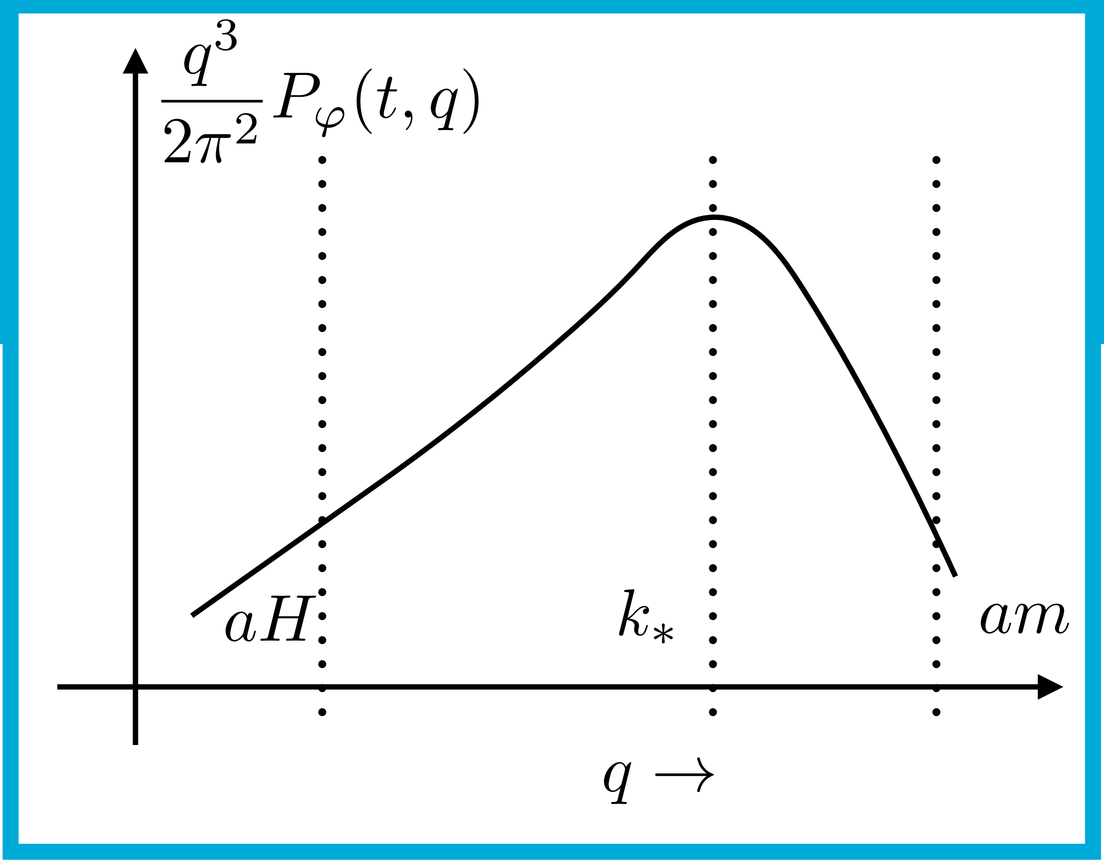
- *eg. dark photon dark matter*



Note: no significant zero mode of the field

also works for thermal production, but nothing new there

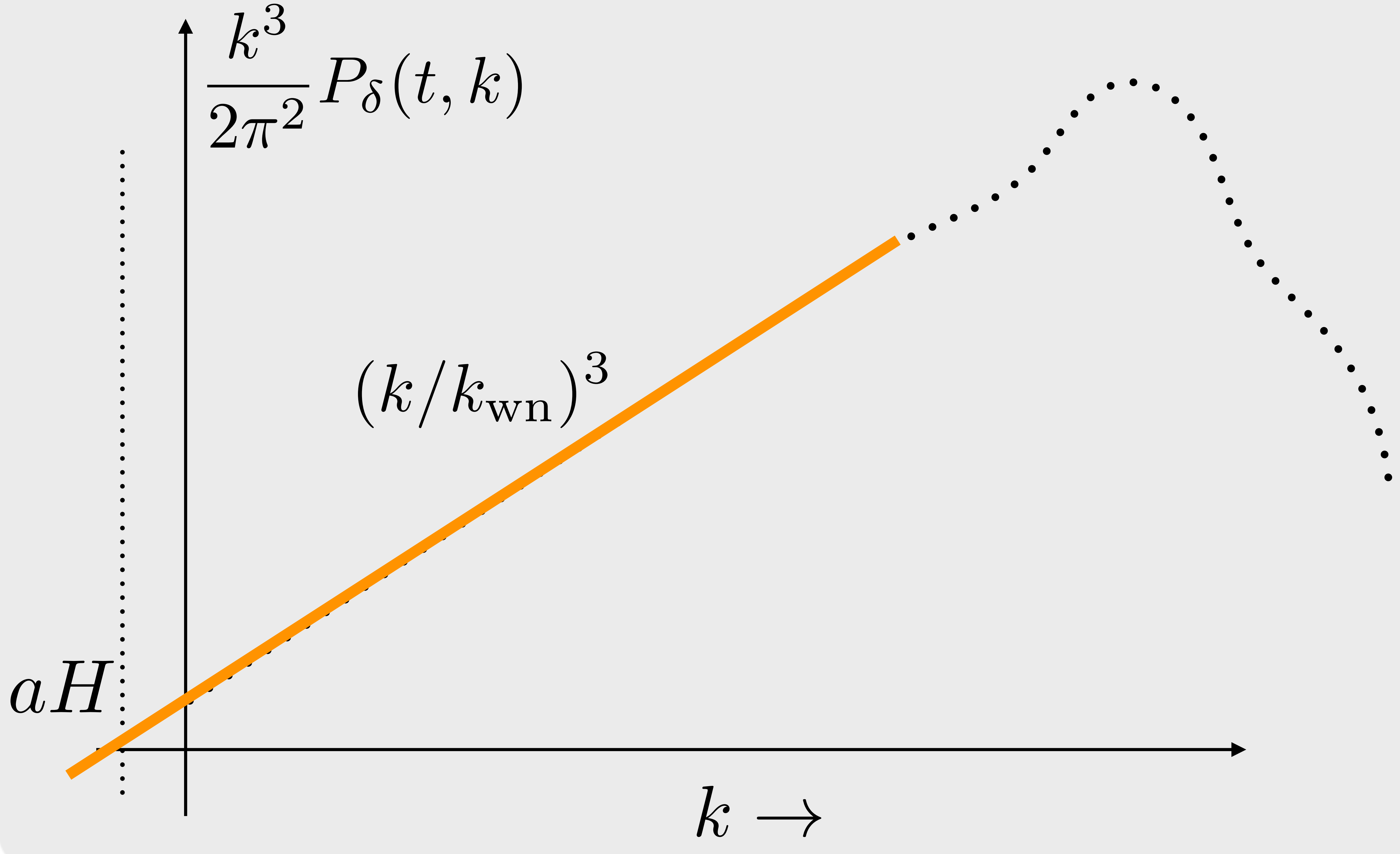
density power spectrum (isocurvature)



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

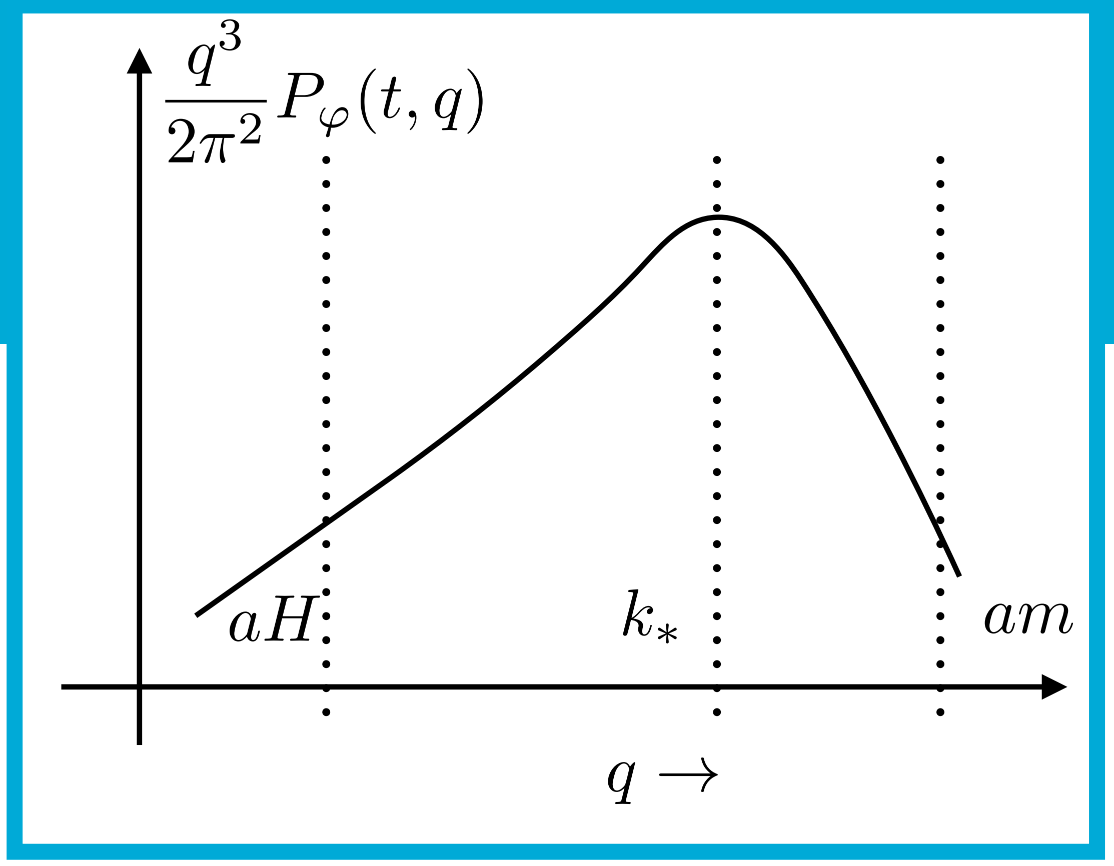
independendent of k for $k \ll k_*$

k_{wn} is defined by the above relation



*ignore gravitational potentials on these scales during radiation domination

density power spectrum (isocurvature)



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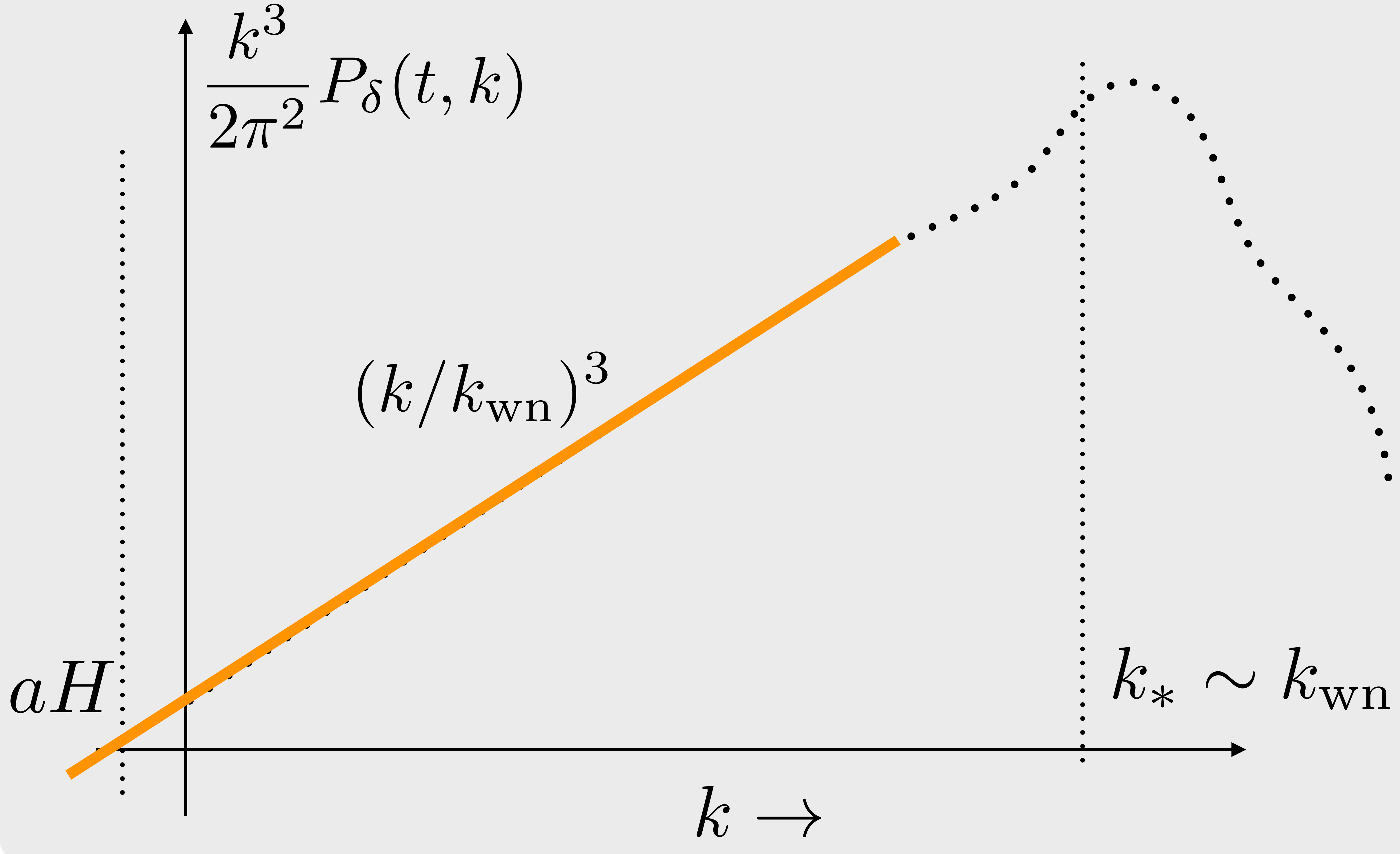

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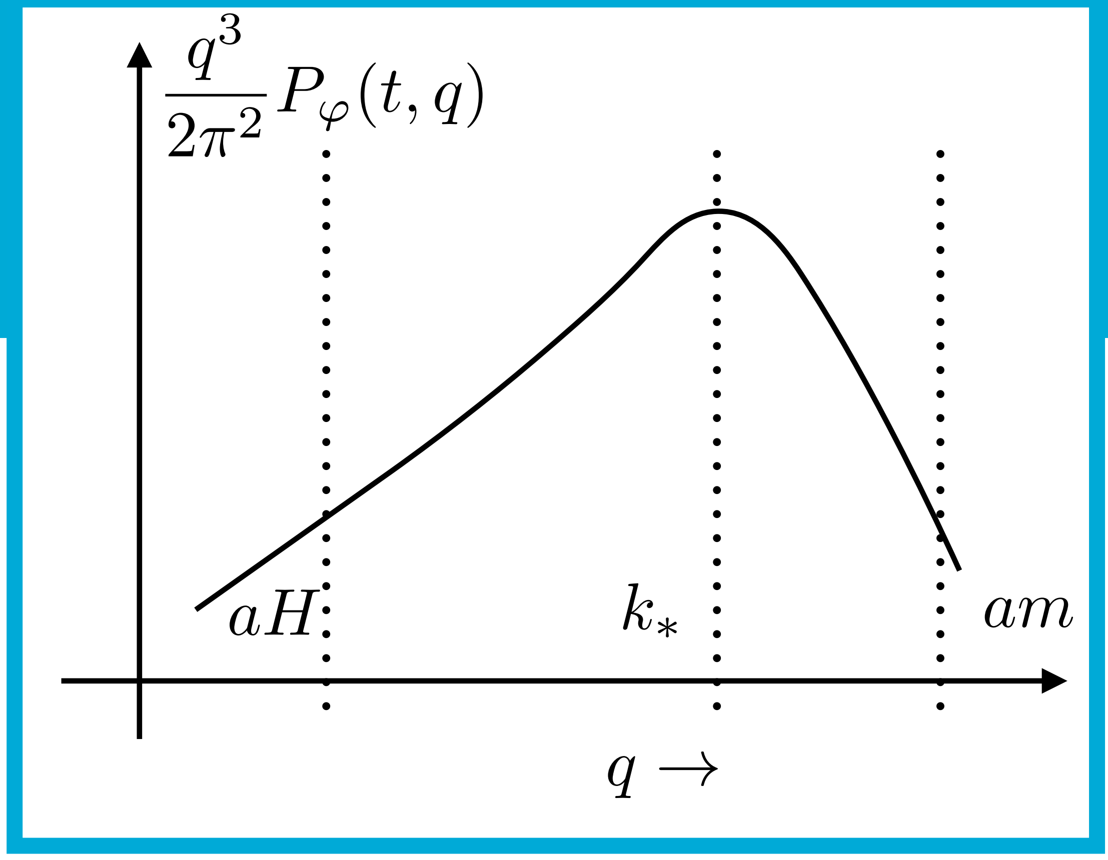
density power spectrum (isocurvature)



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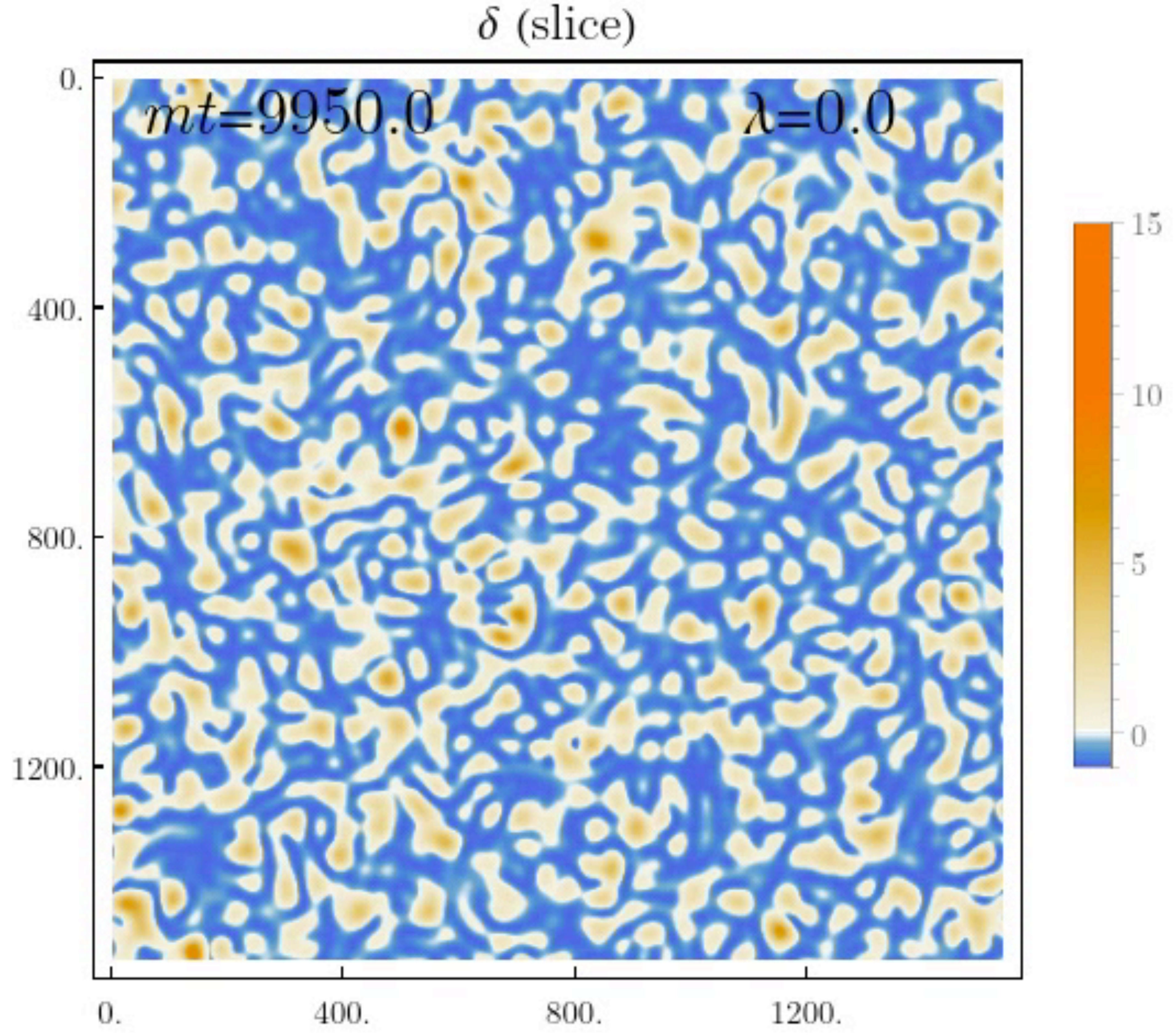
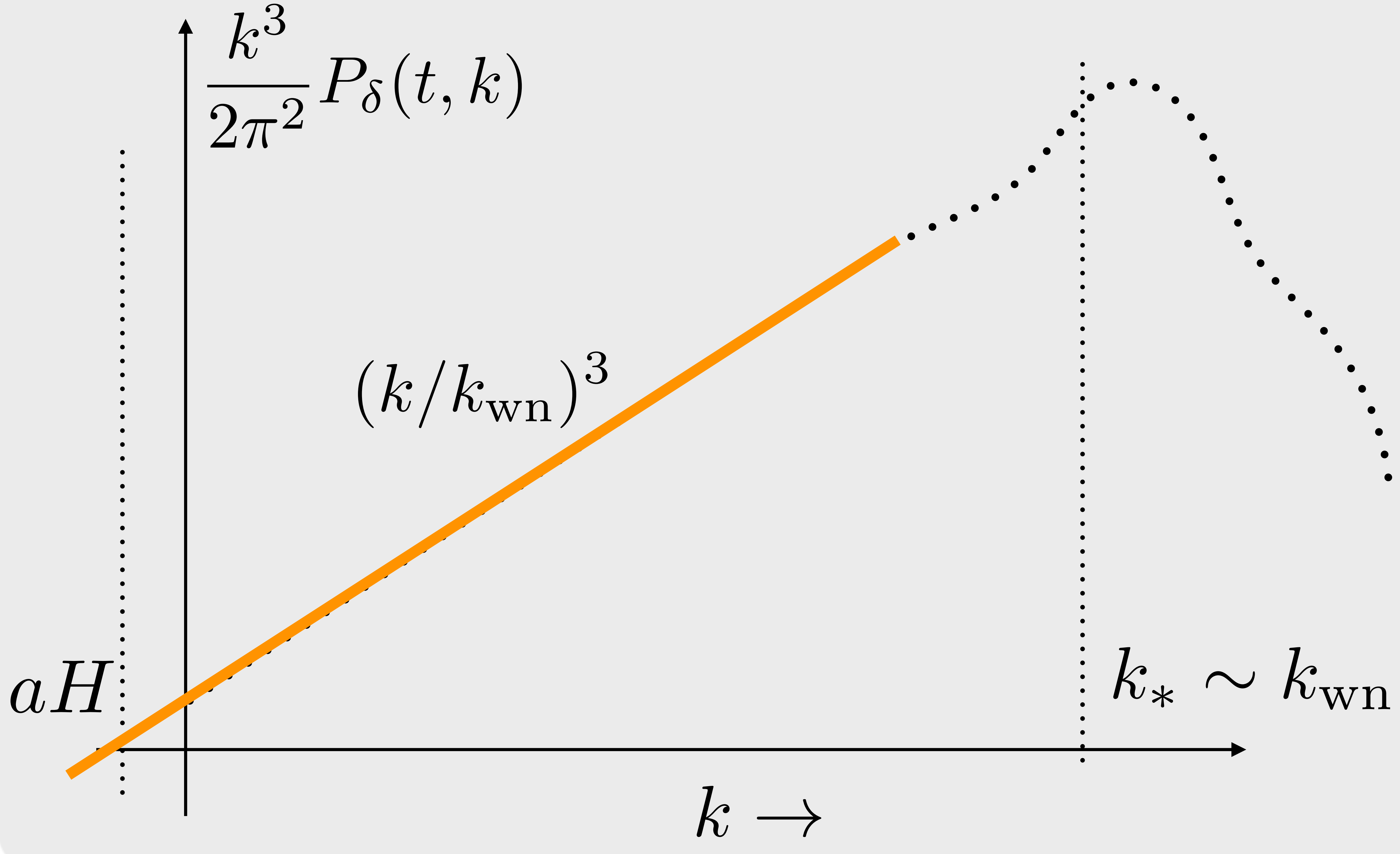
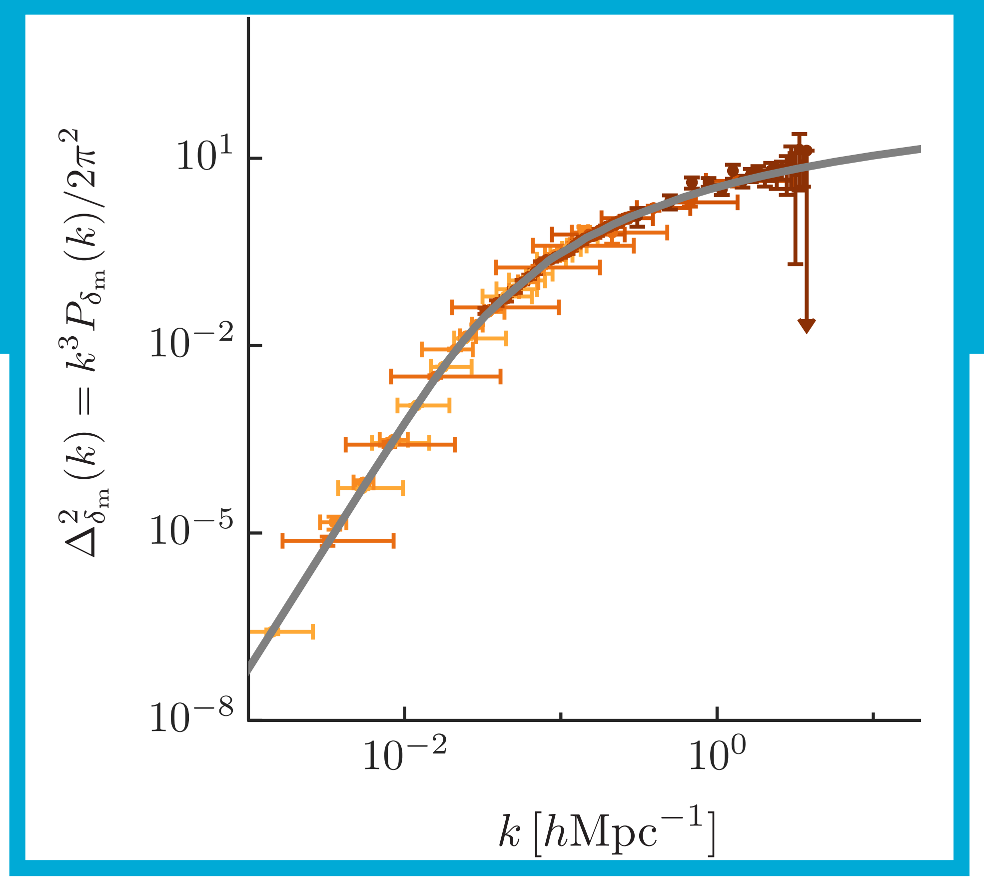




*ignore gravitational potentials on these scales during radiation domination

density power spectrum (adiabatic)

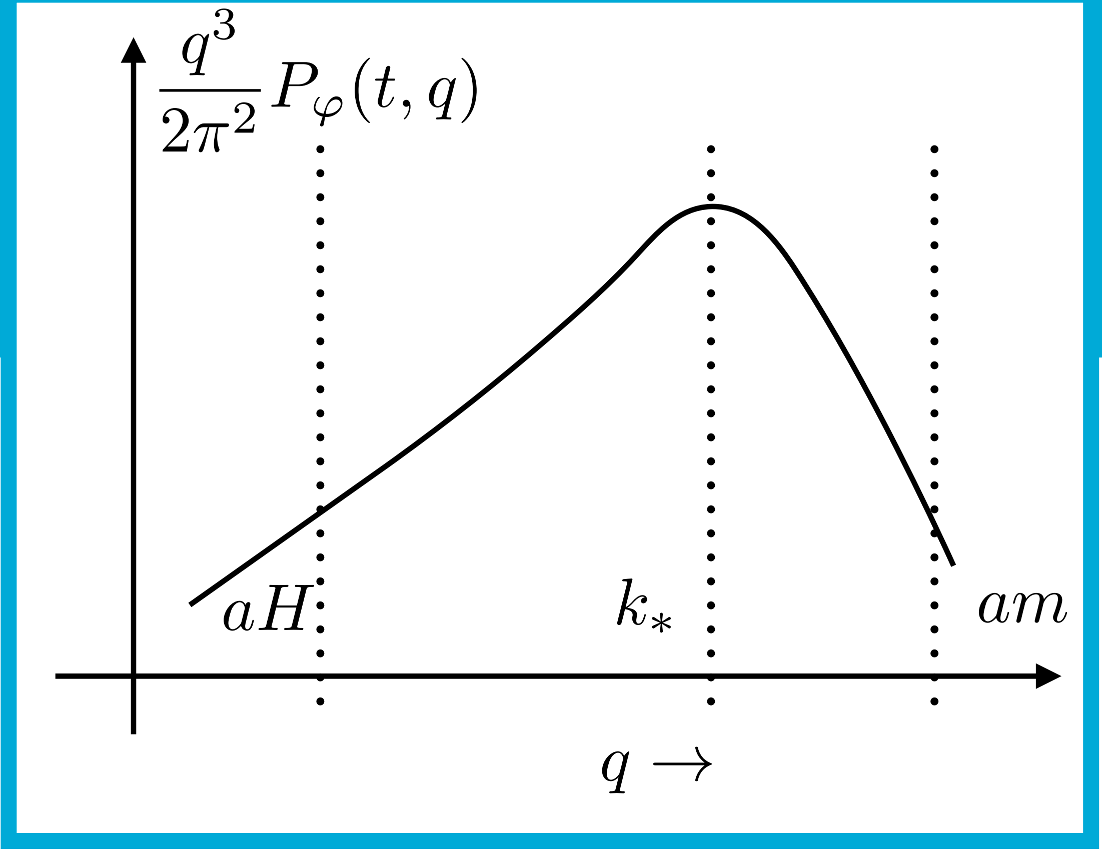


density perturbations in DM sourced by gravitational potentials in rad.

density power spectrum (adiabatic)

density perturbations in DM sourced by gravitational potentials in rad.

free streaming !

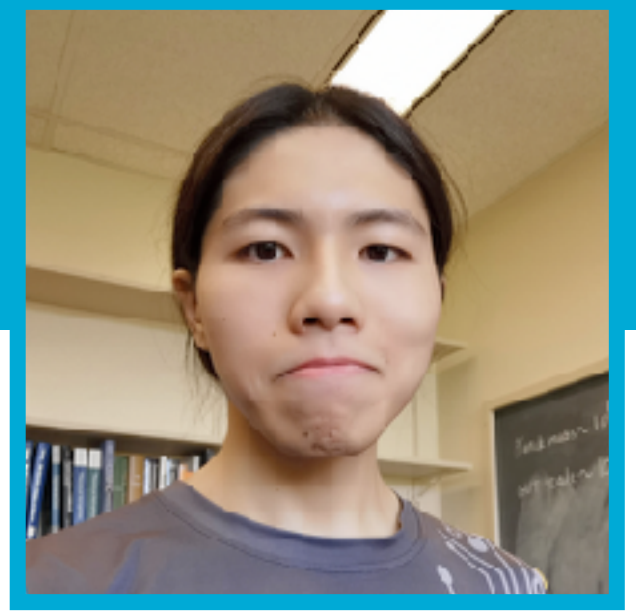


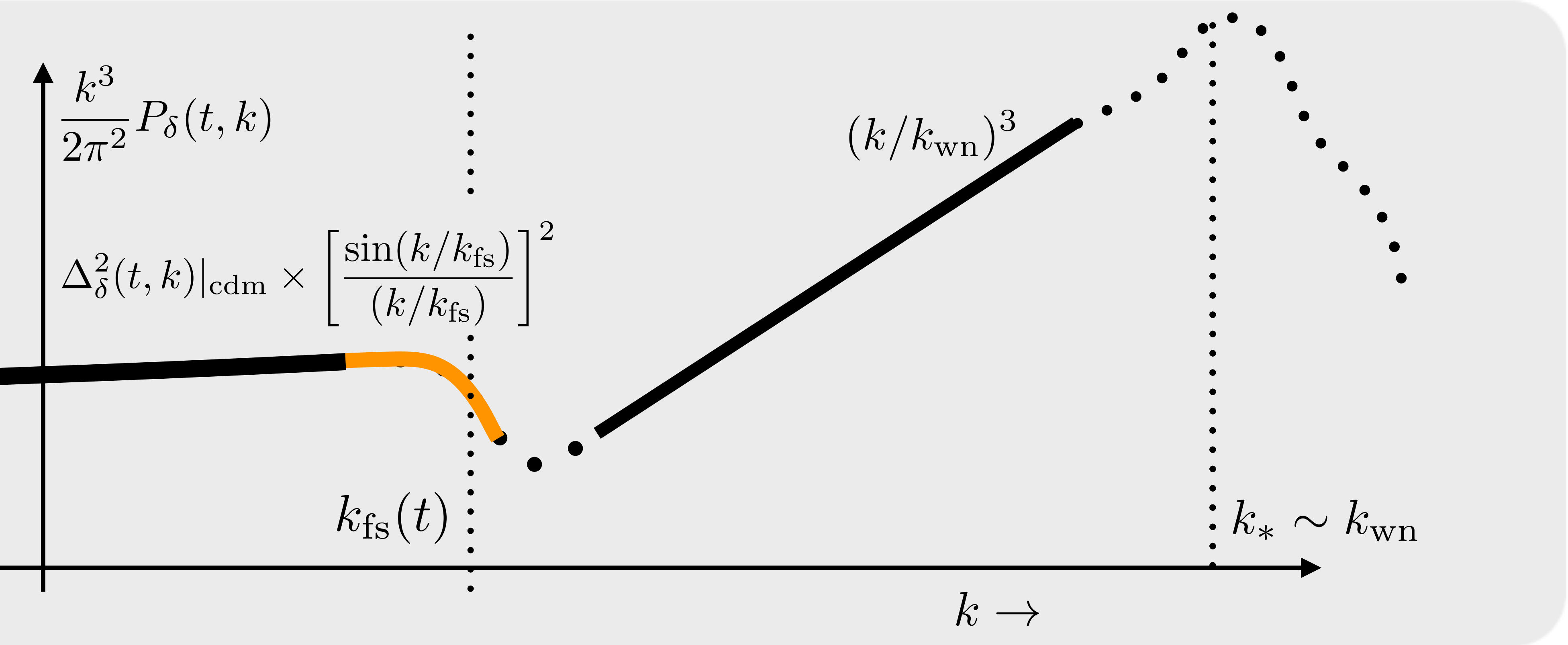
field power at $k_* \Longrightarrow k_{\rm fs}(t) \approx \dfrac{a^2 H m}{k_* \ln(2am/k_*)}$

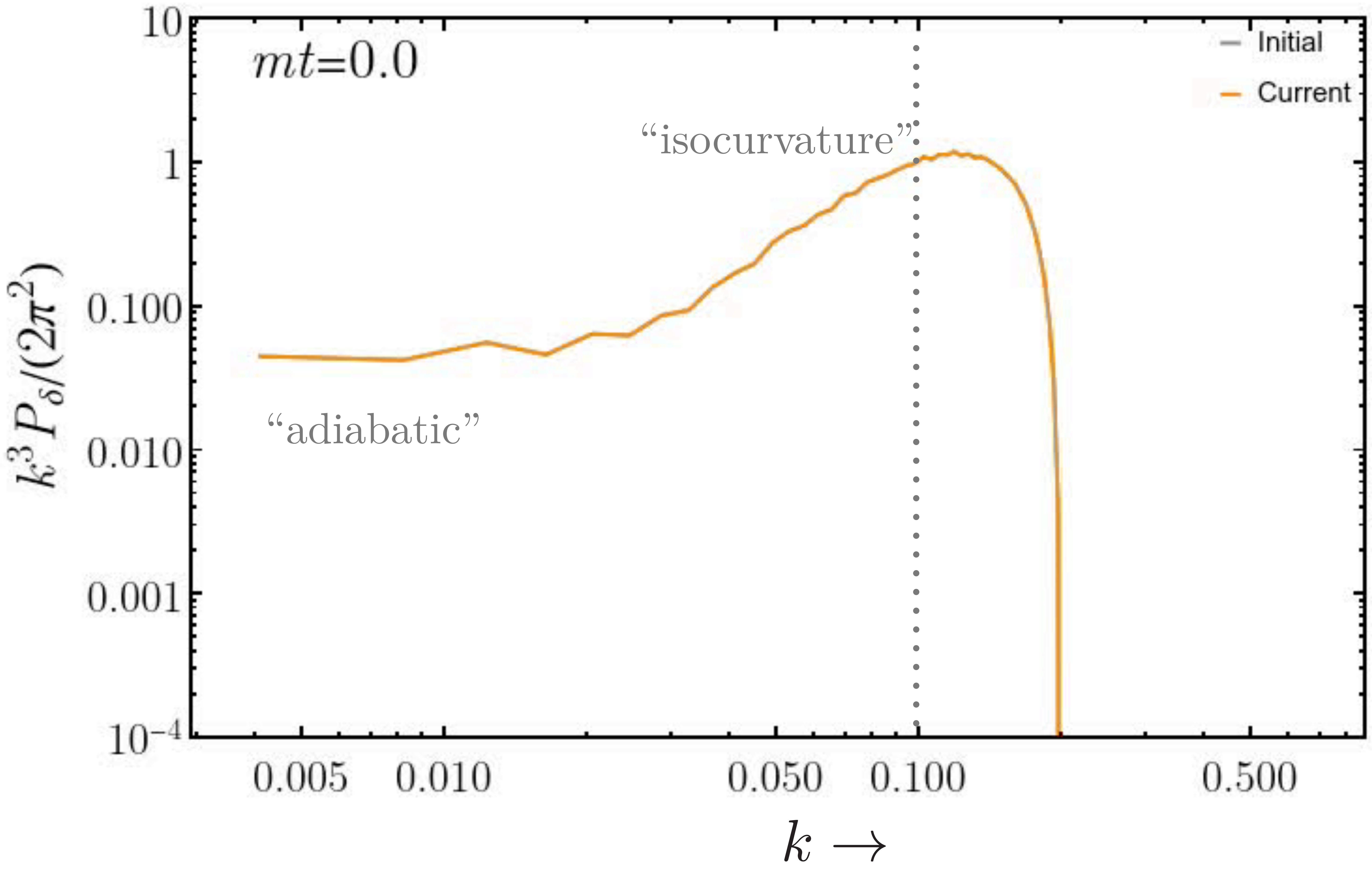
*main idea is mostly "straightforward", but the detailed calculation is not — see MA & Mirbabayi (2022)'s Appendix.

free streaming — numerical

with S. Ling (Rice)







*initial conditions = inhomogeneous gaussian random field

free streaming — numerical

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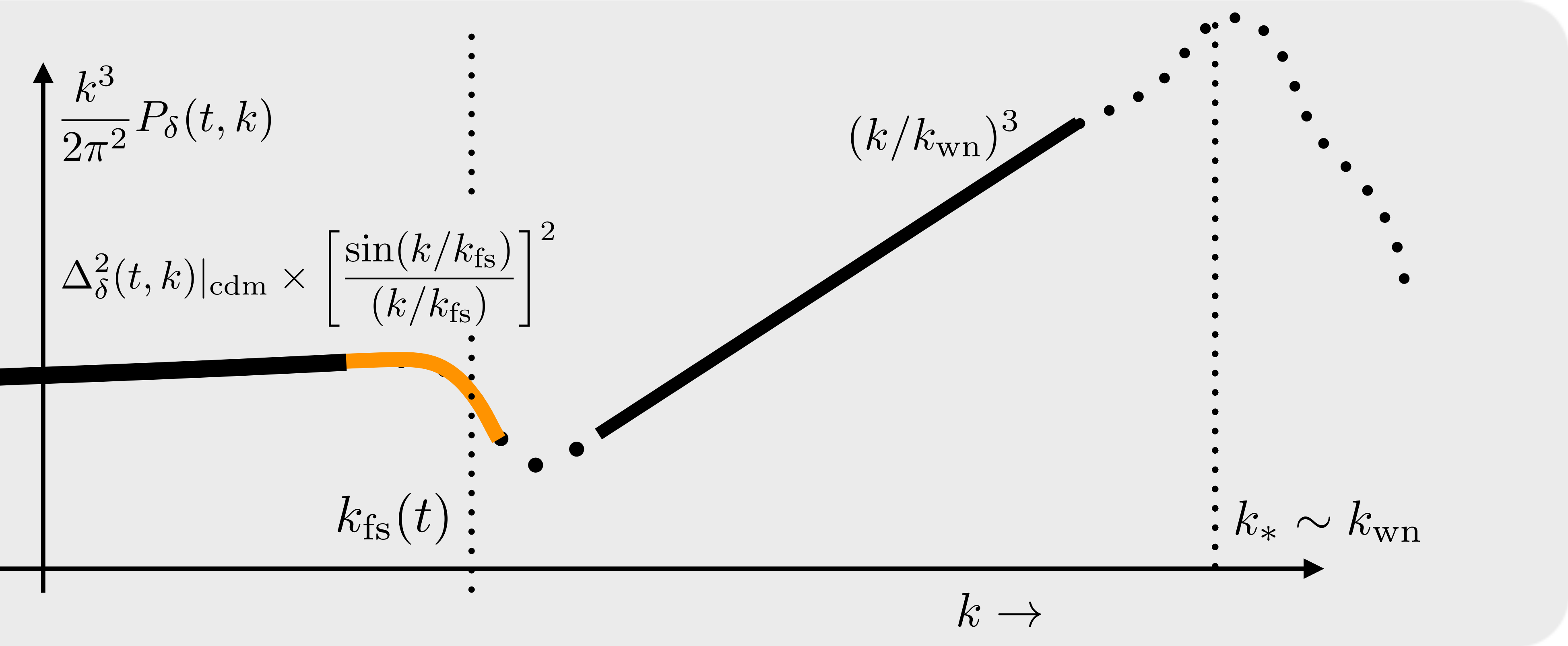

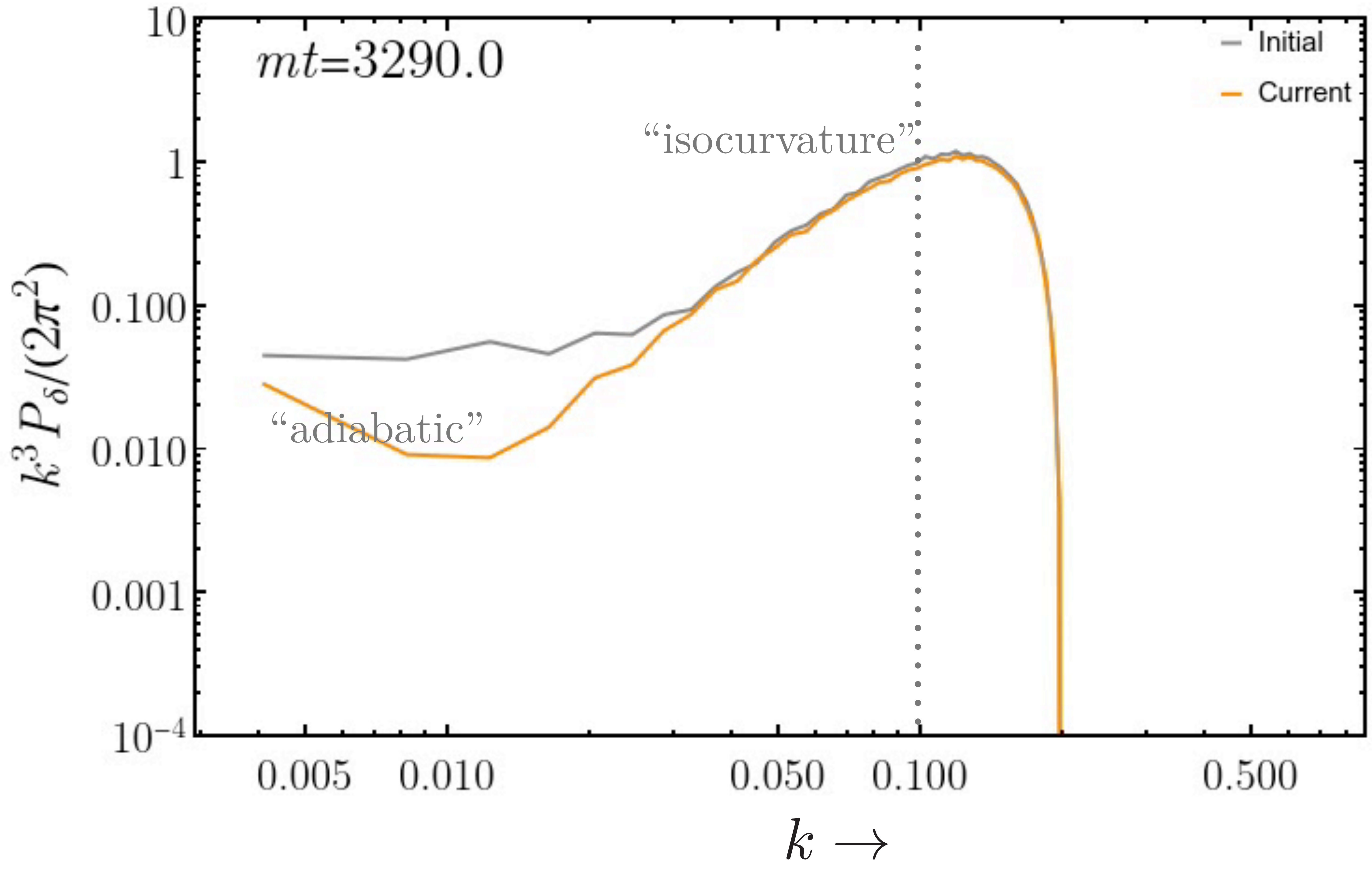

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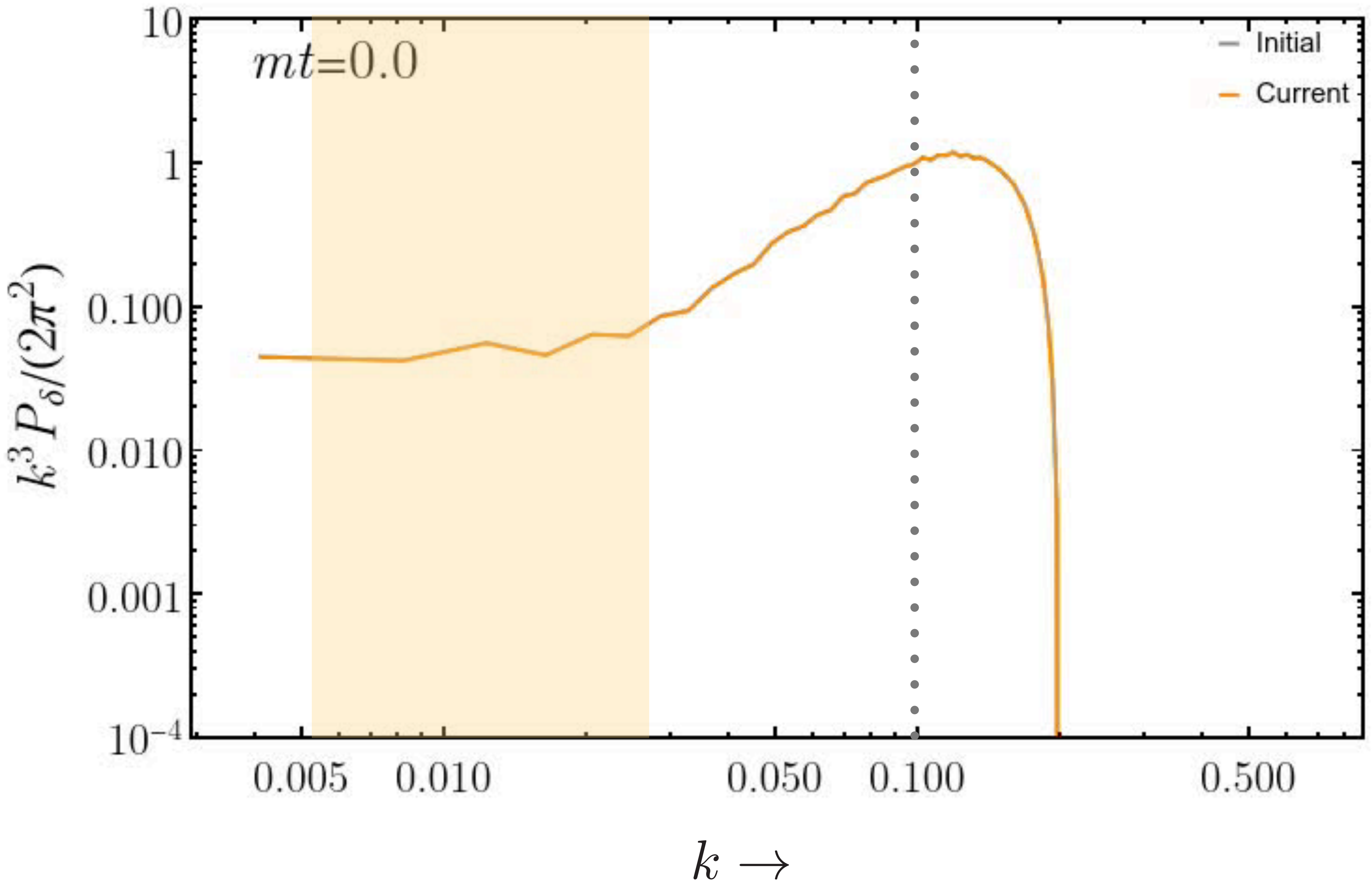
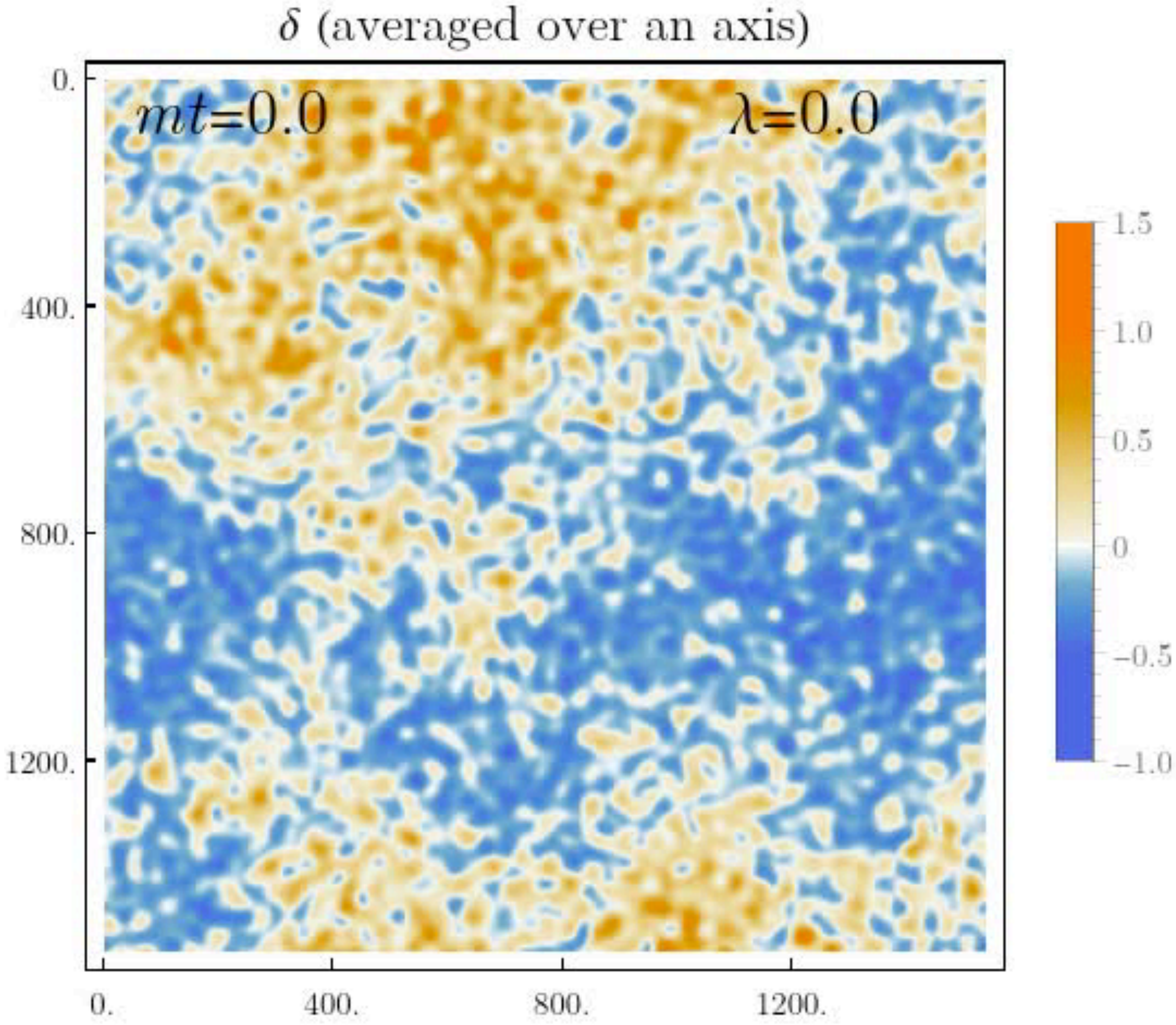
free streaming — numerical

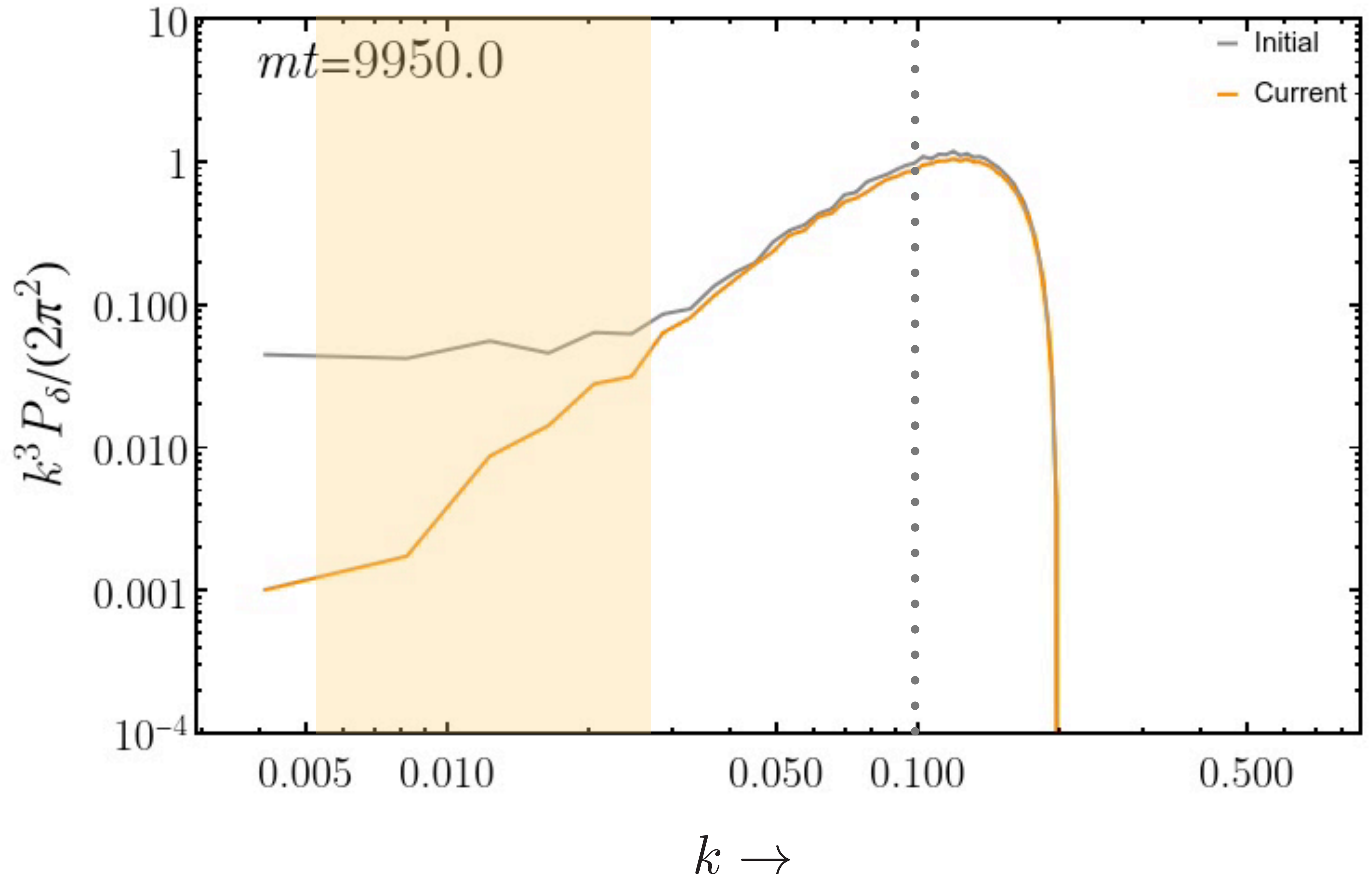
S. Ling

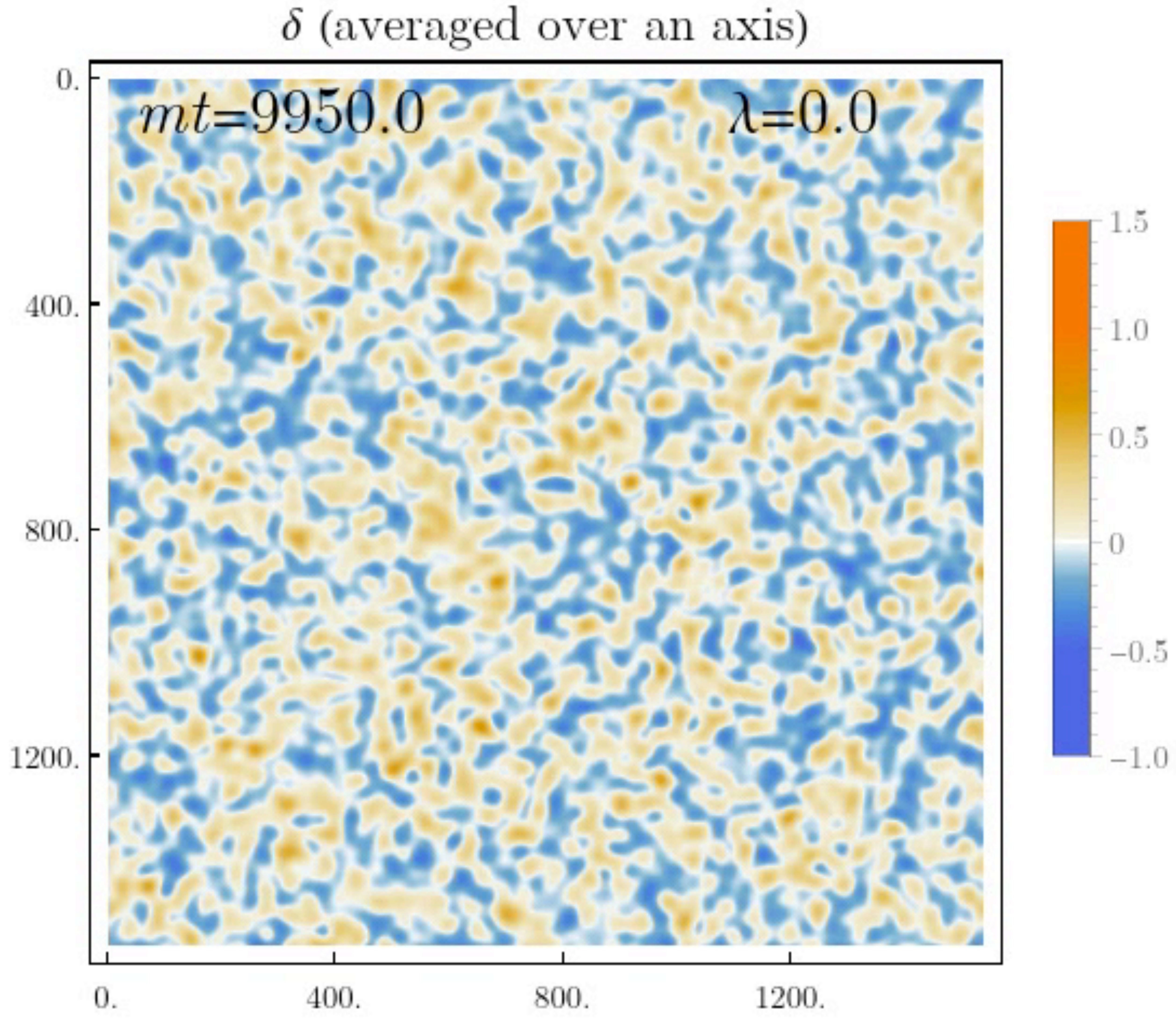




free streaming — numerical

with S. Ling (Rice)





our argument — quantitative

Dark matter density dominated by sub-Hubble field modes

1. white-noise isocurvature excess in isocurvature density pert. $k_{\rm dev} \approx 10^{-3} k_*$
2. free-streaming suppression in adiabatic density pert. $k_{\rm fs}(t) \approx \dfrac{a^2 H m}{k_* \ln(2am/k_*)}$

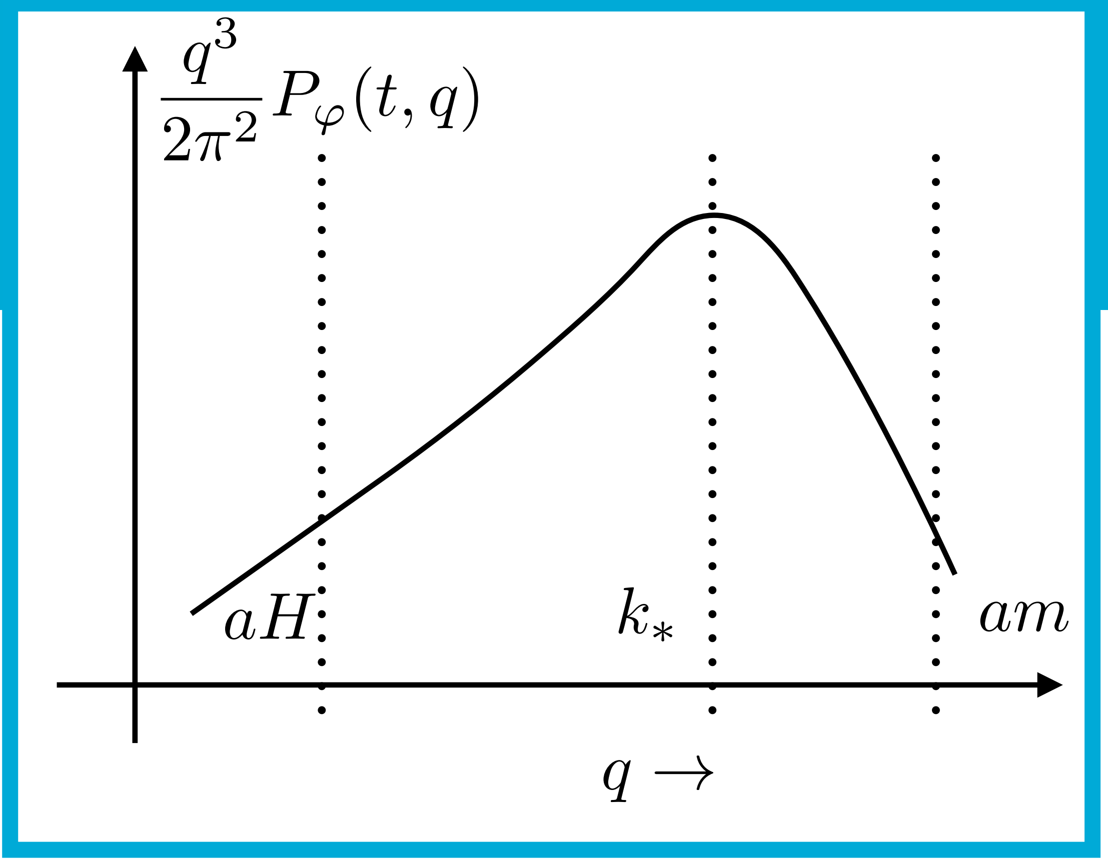
1. and 2. not seen for $k < k_{\rm obs} \sim 10\,{\rm Mpc}^{-1}$ e.g. [Lyα]

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

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

Note that we did not need to know k_*!

is our bound conservative?



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

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

sharp UV fall off (our conservative choice)

gravitational produced dark photons (but better bounds exist)

axion-like particles with strings (preliminary)

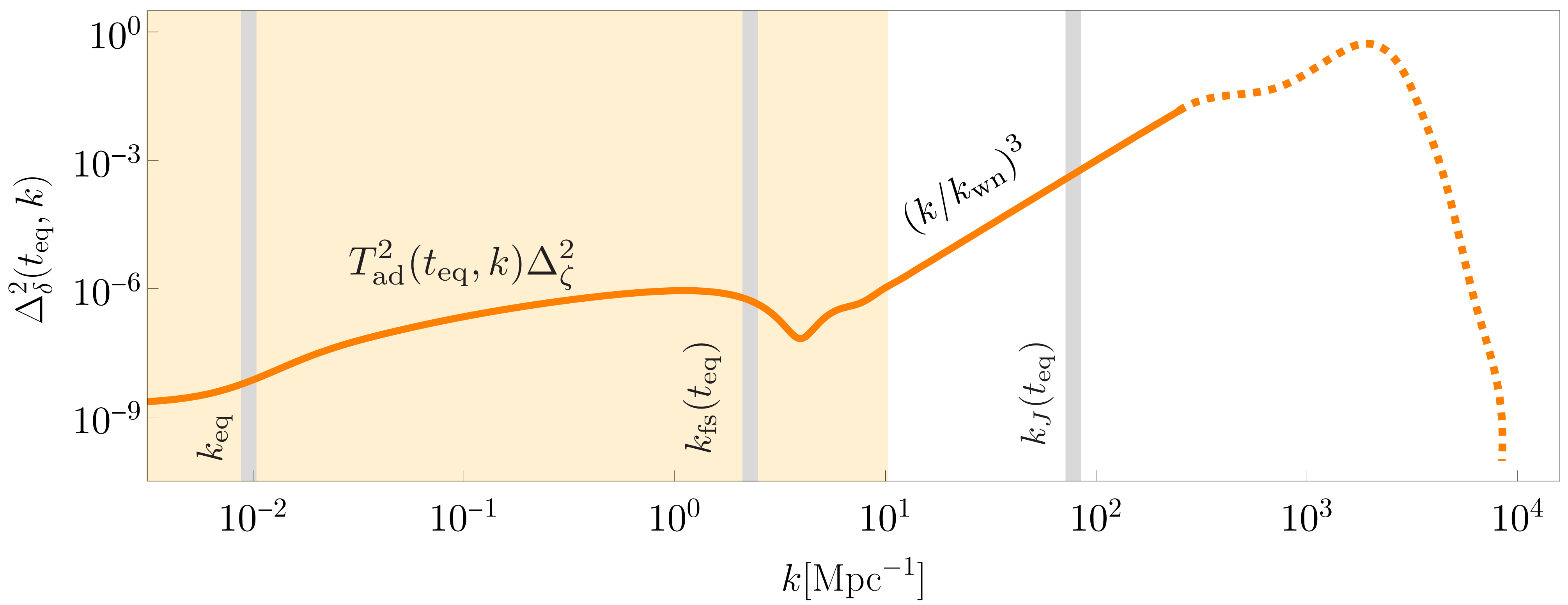
$$\frac{(k_*)^{\mathrm{th}}}{(k_*)^{\mathrm{non.th}}} \sim \sqrt{\frac{m_{\mathrm{pl}}}{m}} \gg 1 \quad \Longrightarrow m \gtrsim \text{few} \times \mathrm{keV}$$

thermal warm DM bounds

strengths

“model independent” -- applies to all gravitationally interacting,

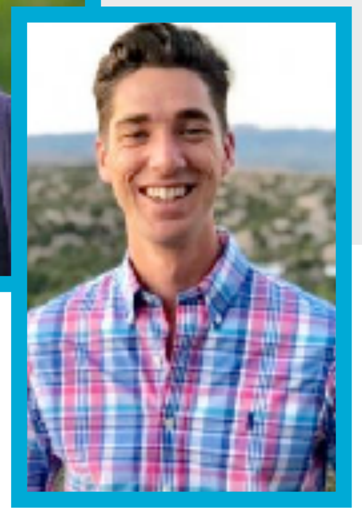
non-relativistic fields (scalar, vector, tensor ...)



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

$m_{bound} \propto k^2_{obs} \implies$ look at MW satellites

with Nadler and Wechsler



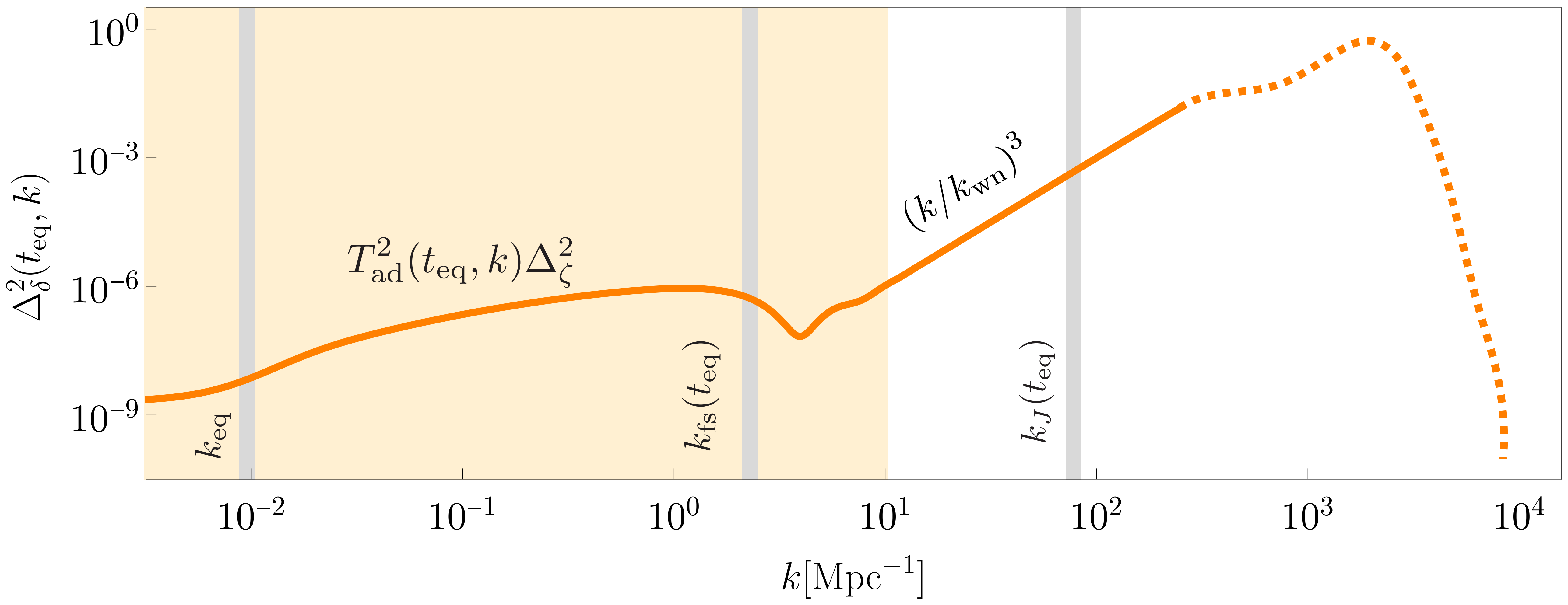
* For MW satellites, only suppression is well constrained — we get constraints only on $z_{nr} = m/k_*$

summary

Dark matter density dominated by sub-Hubble field modes

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

bound good, detection better



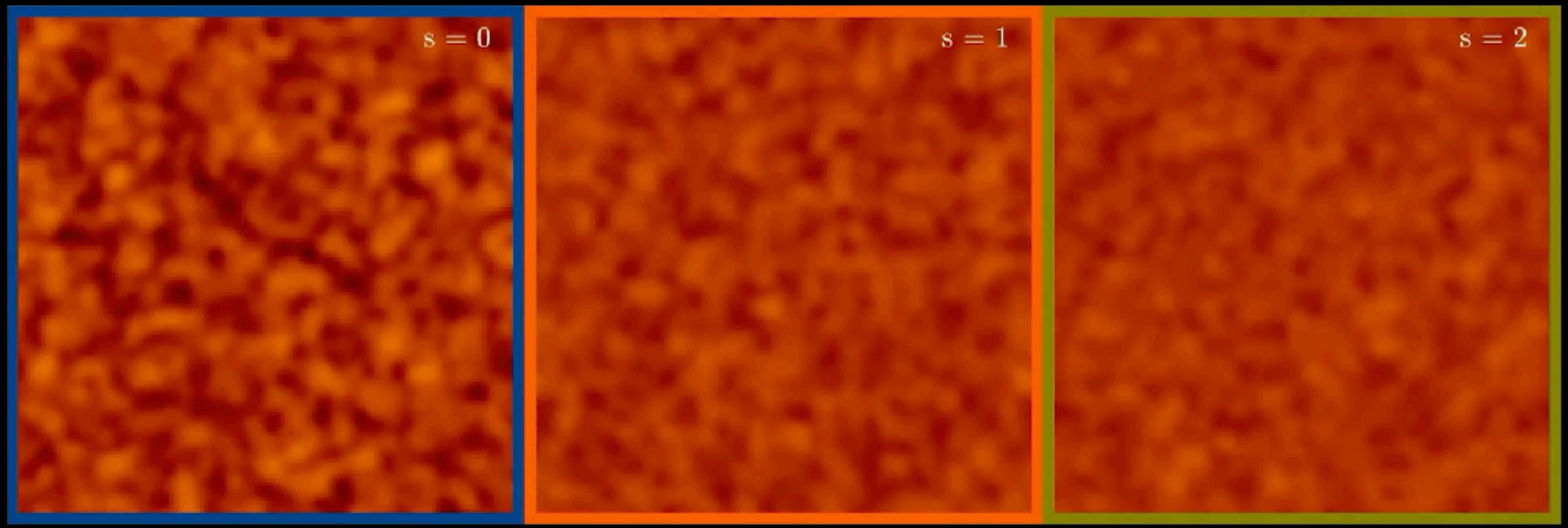
extra small-scale structure

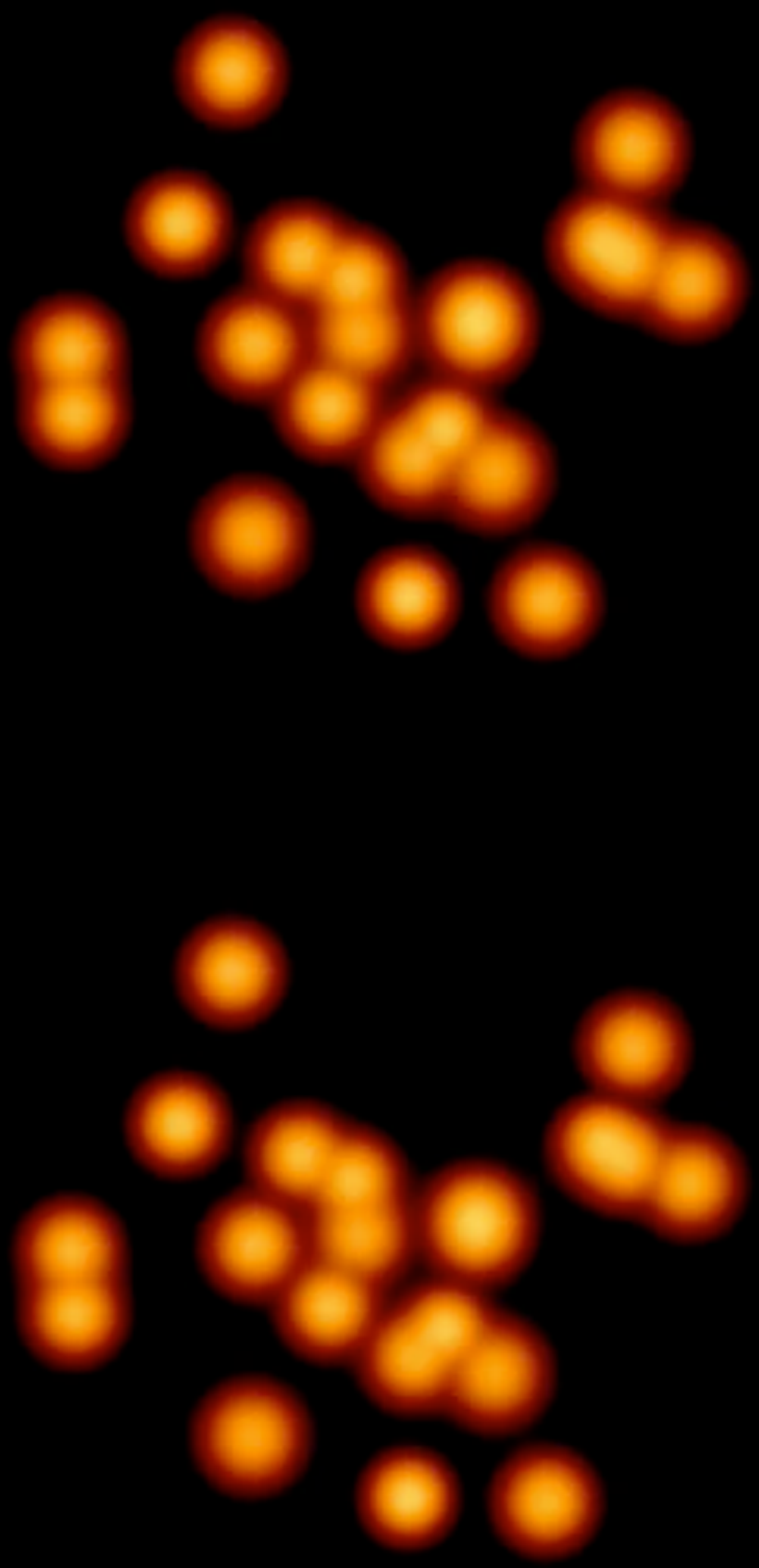
formation of mini-clusters/halos/solitons

some exciting phenomenology related to spin!

A Spin on Wave Dark Matter

with Jain	2109.04892
Jain, Zhang	2111.08700
Jain, Karur, Mocz	2203.11935
Jain	2211.08433
Long, Schiappacasse	2301.11470
Jain, Thomas, Wanischarungarung	2304.01985

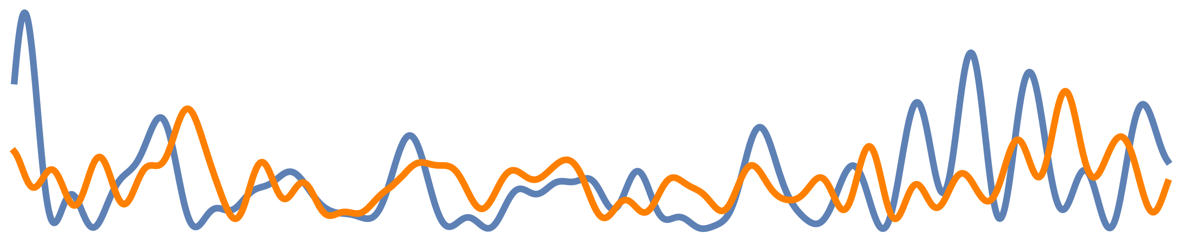


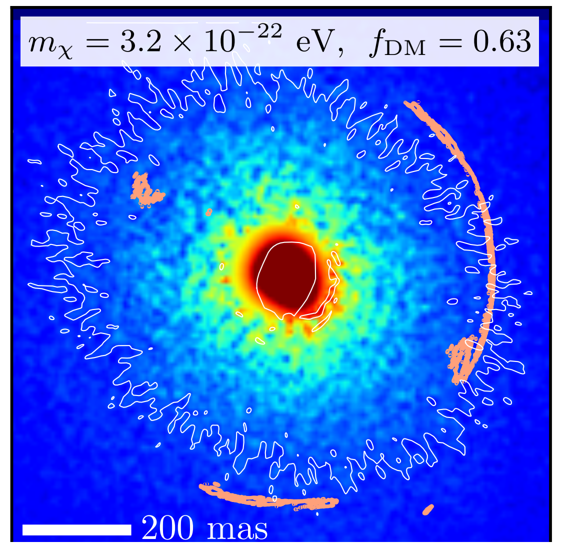


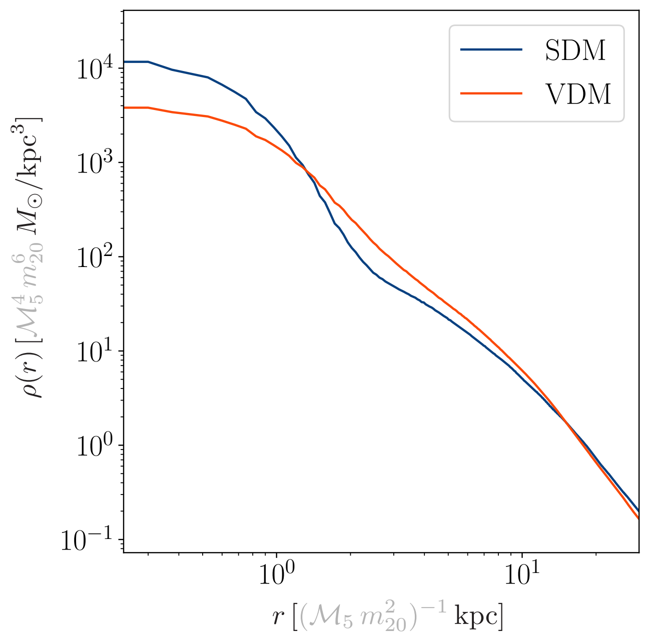
spin and dark matter sub-structure

Phenomenology

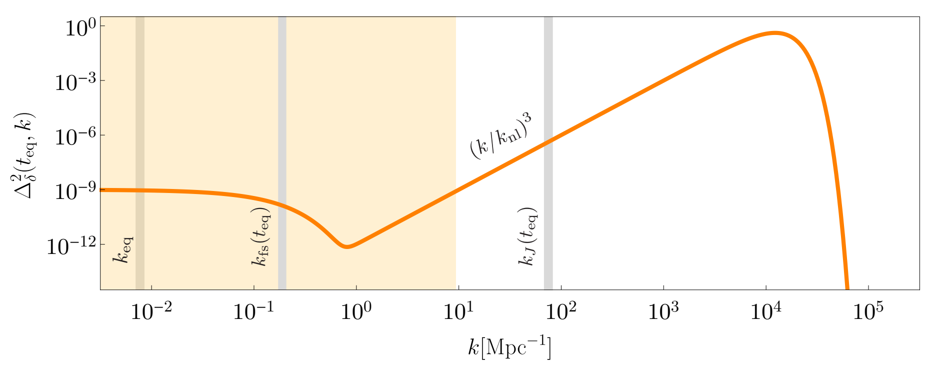
- reduced interference



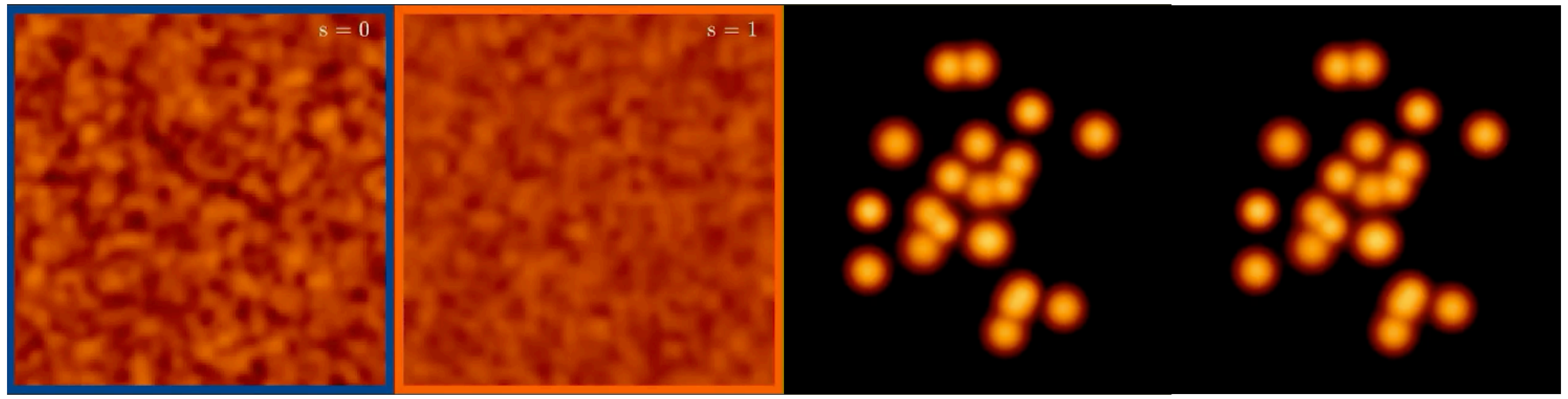




- growth of structure, nucleation time-scales



$\Longrightarrow$



- polarized solitons, with macroscopic spin