Mini-couse on Dark Matter

Quantum Summer 2025

Iriri, ES, Brazil. April 07-11, 2025.

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Outline

- **Lecture 1:** Evidence for Dark Matter (DM) and its properties
- **Lecture 2:** DM inhomogeneities in the standard CDM model and others (WDM, SI-WDM)
- **Lecture 3:** Ultralight DM (spin 0 and 1). Can the spin of ULDM be distinguished on cosmological scales?

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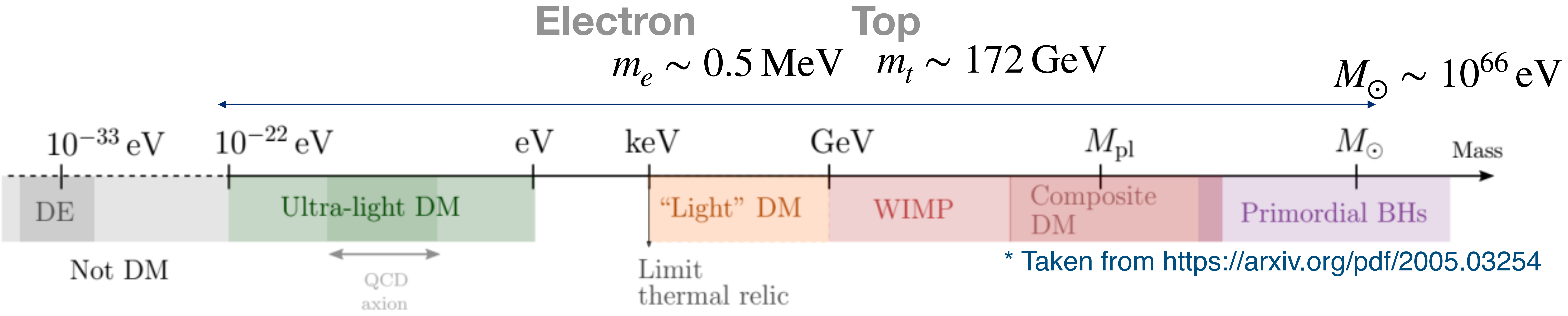
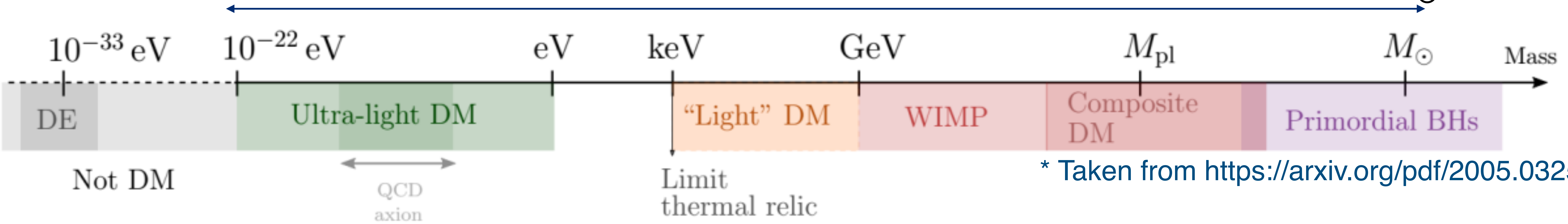
Sketch (not to scale) of the huge range of possible DM models that have been conceived *



* Taken from https://arxiv.org/pdf/2005.03254

Sketch (not to scale) of the huge range of possible DM models that have been conceived *

Electron $m_e \sim 0.5\,\mathrm{MeV}$ **Top** $m_t \sim 172\,\mathrm{GeV}$ $M_\odot \sim 10^{66}\,\mathrm{eV}$



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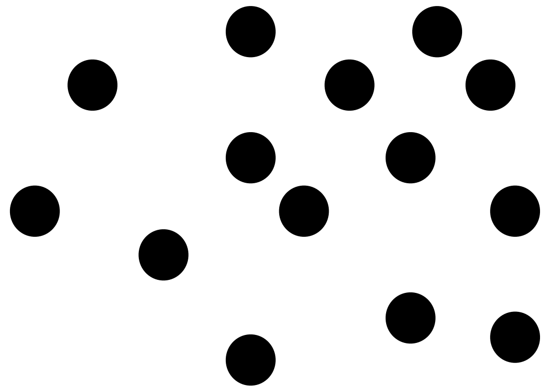
- Standard scenario: distribution of "cold" (small velocity dispersion) non-relativistic massive particles in an expanding FLRW universe



$$N = nV = na^3V_0 = \mathrm{cte}$$

$$E \simeq m$$

$$\rho_{DM} \simeq mn \propto a^{-3}$$

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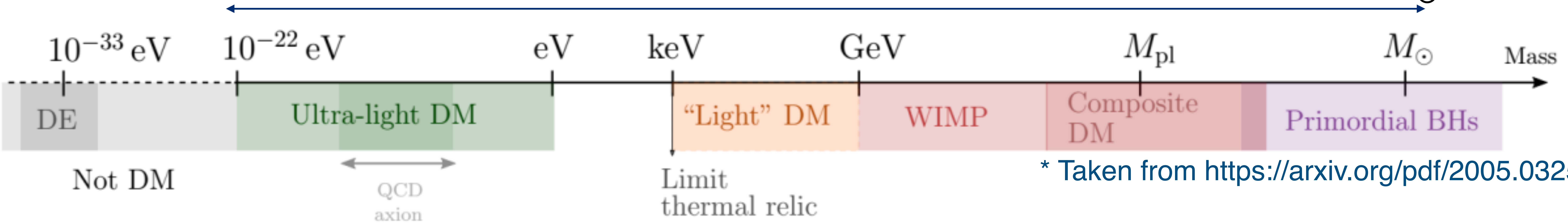

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- <u>An alternative scenario</u>: ultralight DM (standard candidates are axion- like particles and dilatons, but can also be vectors or spin 2 tensors).

Very light DM with large $n = \rho_{DM}/m$

Classical field approximation

$$H_{eq} \sim 10^{-28}\mathrm{eV} \ll m < \mathrm{eV}$$

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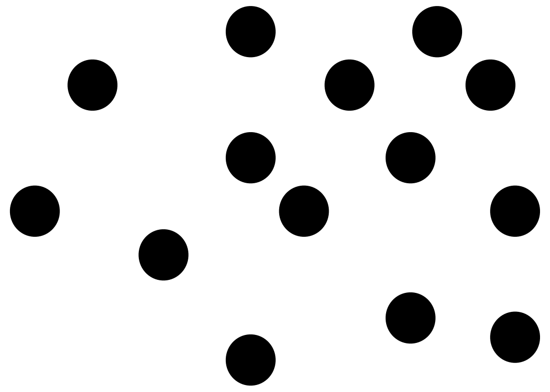

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ULDM as a classical scalar field *(spin 0)*

$$S_{DM} = \frac{1}{2}\int d^4x\sqrt{-g}\left[-\partial_\mu\Phi\partial^\mu\Phi - m^2\Phi^2\right]$$

Background dynamics

$$H = \frac{\dot{a}}{a}$$

$$ds^2 = -dt^2 + a^2(t)\delta_{ij}dx^i dx^j$$

$$\ddot{\Phi} + 3H\dot{\Phi} + m^2\Phi = 0$$

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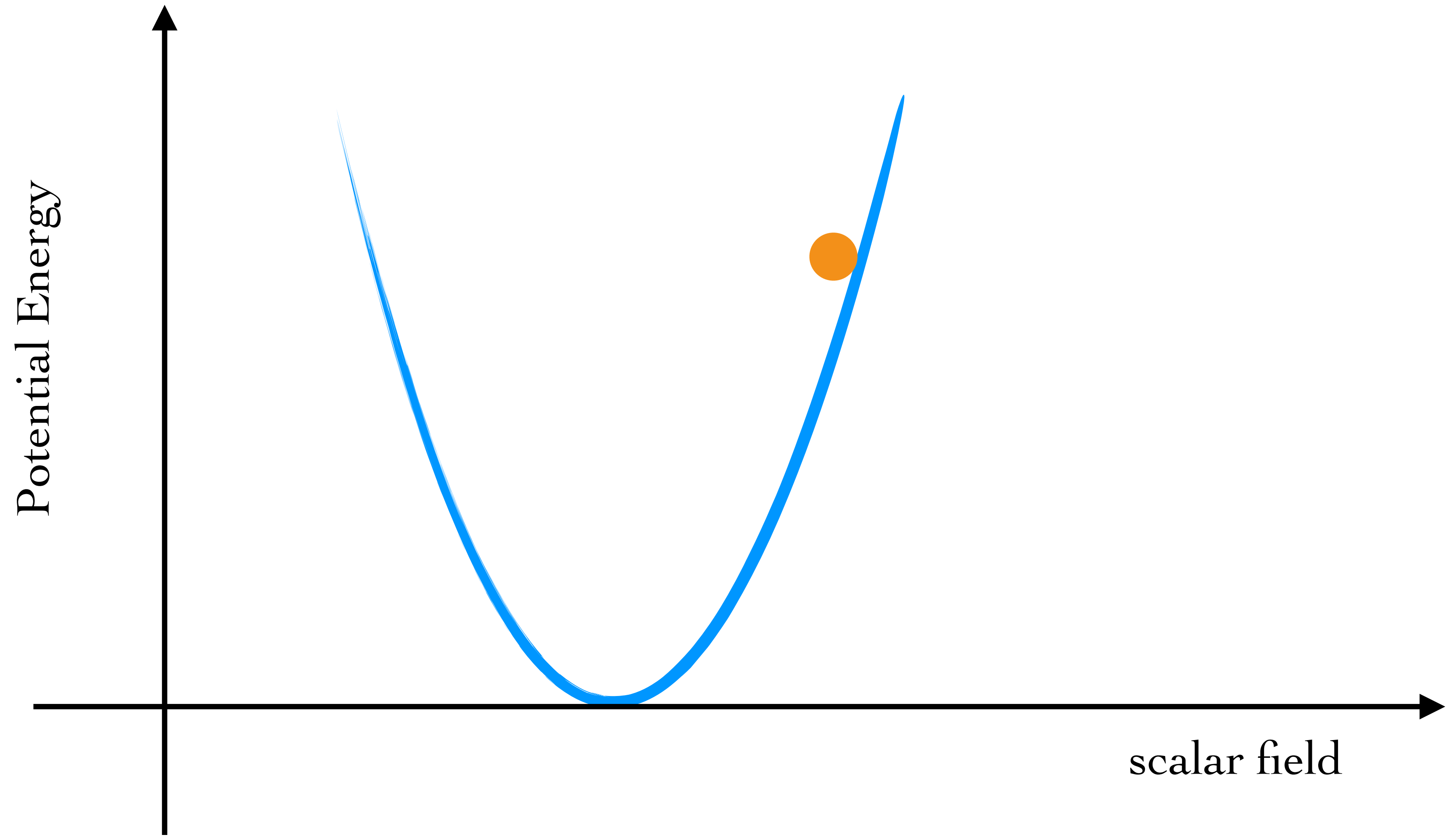
Initial conditions set by inflation
(very homogeneous)



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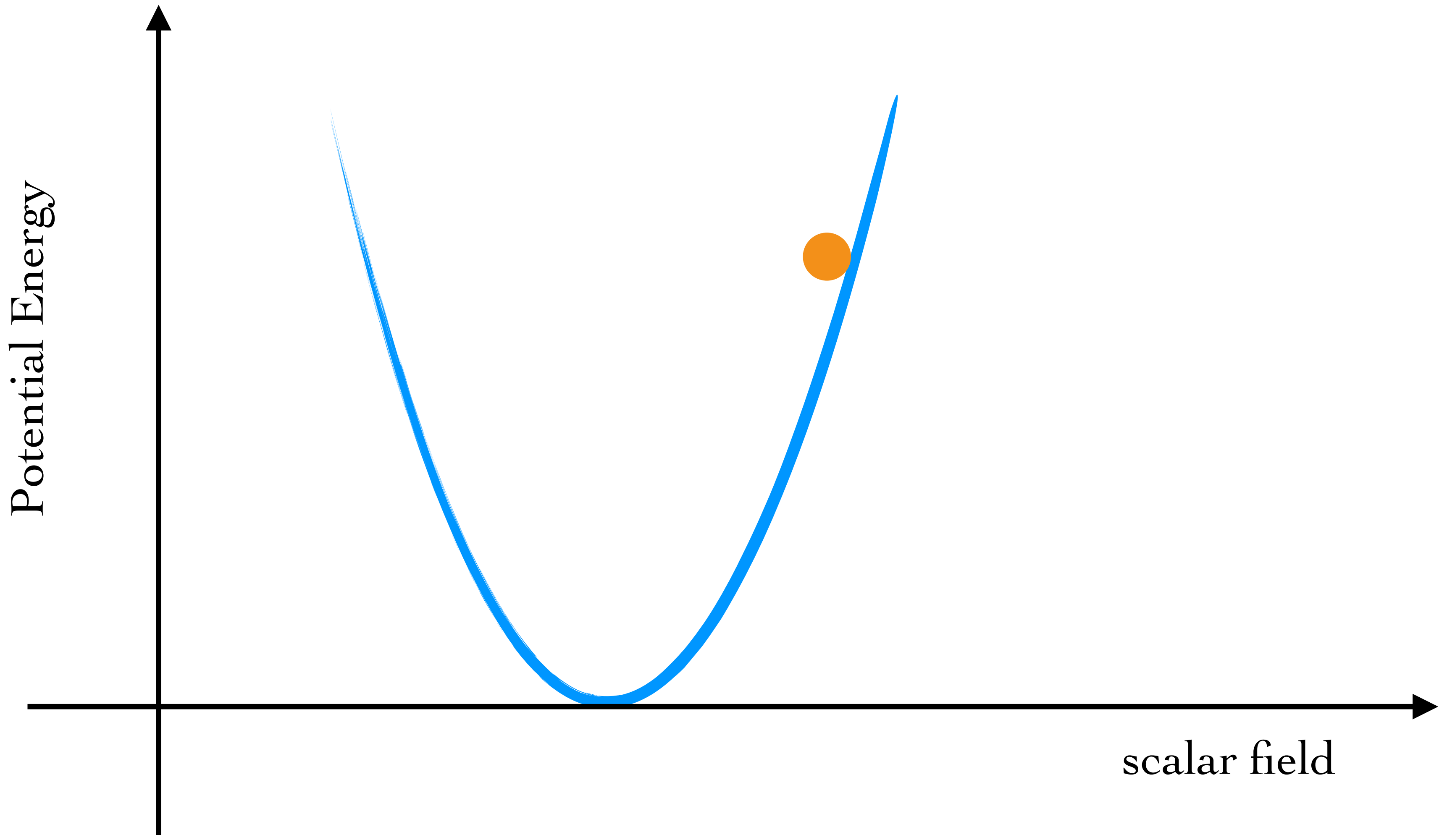

$$H \gg m \longrightarrow \Phi \simeq \text{constant} \quad p_\Phi \simeq -\rho_\Phi$$

$$H \ll m \longrightarrow \Phi \sim \frac{\Phi_0}{a^{3/2}}\cos(mt + \Upsilon)$$

$$\rho_\Phi \simeq \frac{m^2\Phi_0^2}{a^3} + \text{oscillations}$$

$$p_\Phi \simeq -\rho_\Phi \cos(2mt + 2\Upsilon)$$

(oscillations are irrelevant on long time scales)

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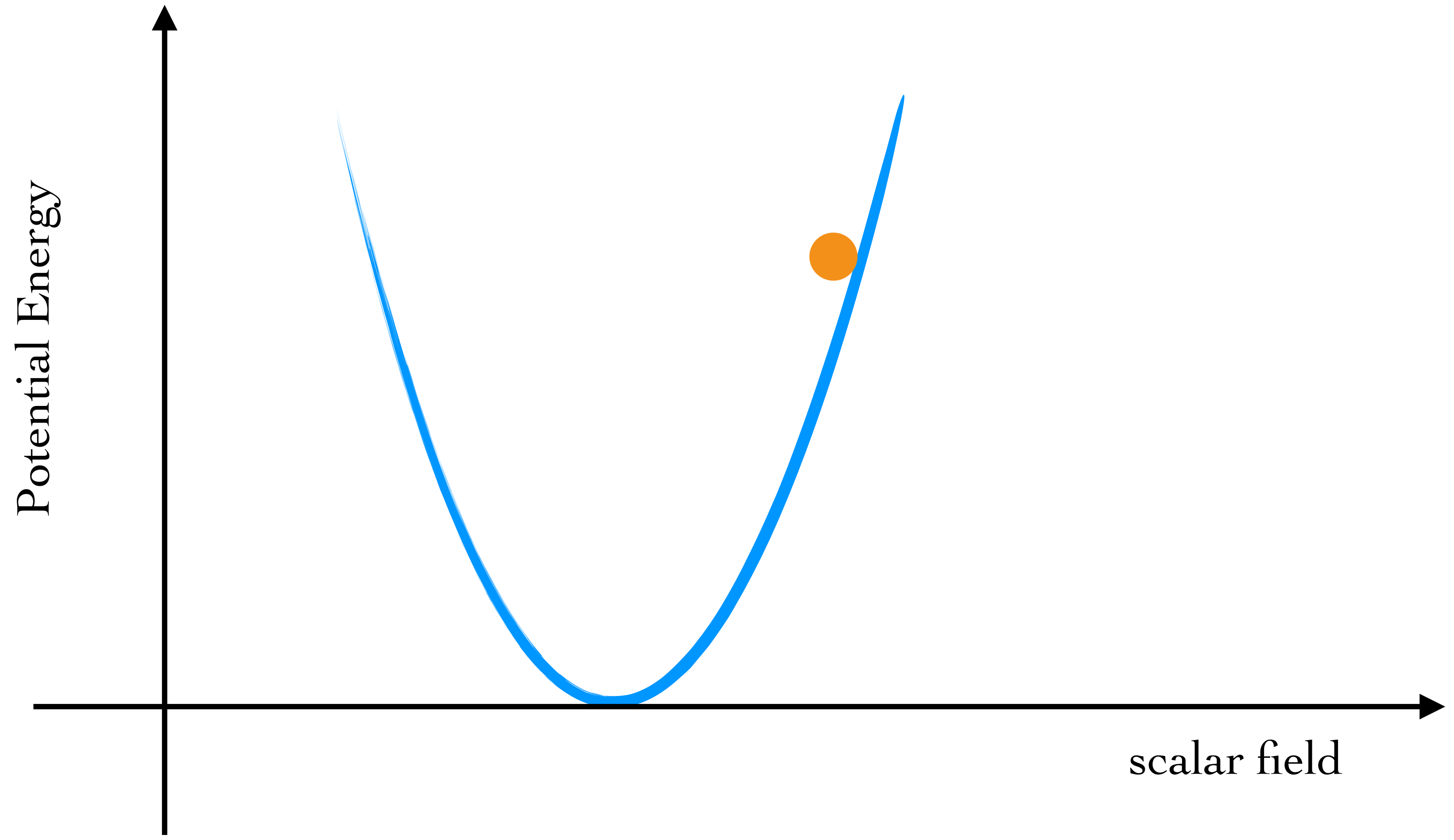

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$$H_{eq} \sim 10^{-28}\text{eV} \ll m$$

Similar dynamics can arise for s=1,2 on cosmological scales once $H < m$

ULDM as a classical scalar field (on shorter scales)

$a\dot{\rho}_{DM} \ll c\,|\nabla \rho_{DM}|$

Collection of plane waves: $\Phi = e^{-ict/\lambda_c}\Psi + e^{ict/\lambda_c}\Psi*$

$$\left(\lambda_c = \frac{\hbar}{mc}\right)$$

Reduced Compton wavelength

$$\Psi = \sqrt{\frac{c\rho_{DM}(\vec{x},t)}{2}}\lambda_c \exp\left\{-i\frac{\pi(\vec{x},t)}{c\lambda_c}\right\}$$

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Coherence of the oscillations require

$$|\partial_t \pi|, |\nabla \pi|^2 \ll c^2$$

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Oscillations relevant at time scales ~ Compton time

$t_c = \lambda_c/c$

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$T_{\mu\nu}$

<...> "Fast" oscillations
+ leading order in 1/c
$(a = 1)$

$$\langle T_{00}\rangle \simeq c^2 \rho_{DM}$$

$$\langle T_{0i}\rangle \simeq c\rho_{DM}\partial_i \pi \longrightarrow v_i = -\partial_i \pi/a$$

$$\langle T_{ij}\rangle \simeq \rho_{DM}\partial_i\pi\partial_j\pi + \frac{\hbar^2}{m^2}\partial_i\sqrt{\rho_{DM}}\partial_j\sqrt{\rho_{DM}} - \frac{\delta_{ij}}{2}\left[\frac{\hbar^2}{m^2}\partial_i\sqrt{\rho_{DM}}\partial_i\sqrt{\rho_{DM}} + \rho_{DM}\partial_i\pi\partial_i\pi + \rho_{DM}\phi_N - \rho_{DM}\dot{\pi}\right]$$

$(\phi_N = c^2\phi)$

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$$\langle T_{ij}\rangle \simeq \rho_{DM}\partial_i\pi\partial_j\pi + \frac{\hbar^2}{m^2}\partial_i\sqrt{\rho_{DM}}\partial_j\sqrt{\rho_{DM}}$$

$$-\frac{\delta_{ij}}{2}\left[\frac{\hbar^2}{m^2}\partial_i\sqrt{\rho_{DM}}\partial_i\sqrt{\rho_{DM}} + \rho_{DM}\partial_i\pi\partial_i\pi + \rho_{DM}\phi_N - \rho_{DM}\dot{\pi}\right]$$

$$(\phi_N = c^2\phi)$$

Gradients are relevant at length scales ~ De Broglie length

$$\lambda_{dB} = \frac{c}{v}\lambda_c = \frac{\hbar}{mv}$$

$(\hbar = c = 1)$

Effective fluid equations for ULDM

$$\nabla_\mu T^{\mu\nu} = 0 \rightarrow$$

$$\frac{1}{a^3}\frac{d}{d\tau}(a^3\rho_{DM}) + \nabla\cdot(\rho_{DM}\vec{v}) = 0,$$

$$\frac{d}{d\tau}\vec{v} + \mathscr{H}\vec{v} + (\vec{v}\cdot\nabla)\vec{v} = -\nabla\phi_N + \nabla Q$$

$$\nabla\phi_N = 4\pi G a^2 \rho_{DM}$$

"Quantum pressure"

$$Q = \frac{1}{2m^2a^2}\frac{\nabla^2\sqrt{\rho_{DM}}}{\sqrt{\rho_{DM}}}$$

$(\hbar = c = 1)$

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$$\nabla\phi_N = 4\pi G a^2\rho_{DM}$$

Jeans suppression

$$\delta''_{DM} + 2\mathscr{H}\delta'_{DM} + \left(\frac{\nabla^4}{4m^2a^2} - 4\pi G a^2\bar{\rho}_{DM}\right)\delta_{DM} = 0$$

Using: $a^2H^2 = \mathscr{H}^2 = 8\pi G\bar{\rho}_{DM}/3$

(MD era, neglecting baryons)

$$\delta''_{DM} + 2\mathscr{H}\delta'_{DM} + \left(\frac{k^4}{6k_J^4} - 1\right)4\pi G a^2\bar{\rho}_{DM}\delta_{DM} = 0$$

$$k_J = a\sqrt{mH}$$

$k > k_J$ Oscillations

$k < k_J$ Gravitational growth

Scalar Ultralight DM models have been the most studied

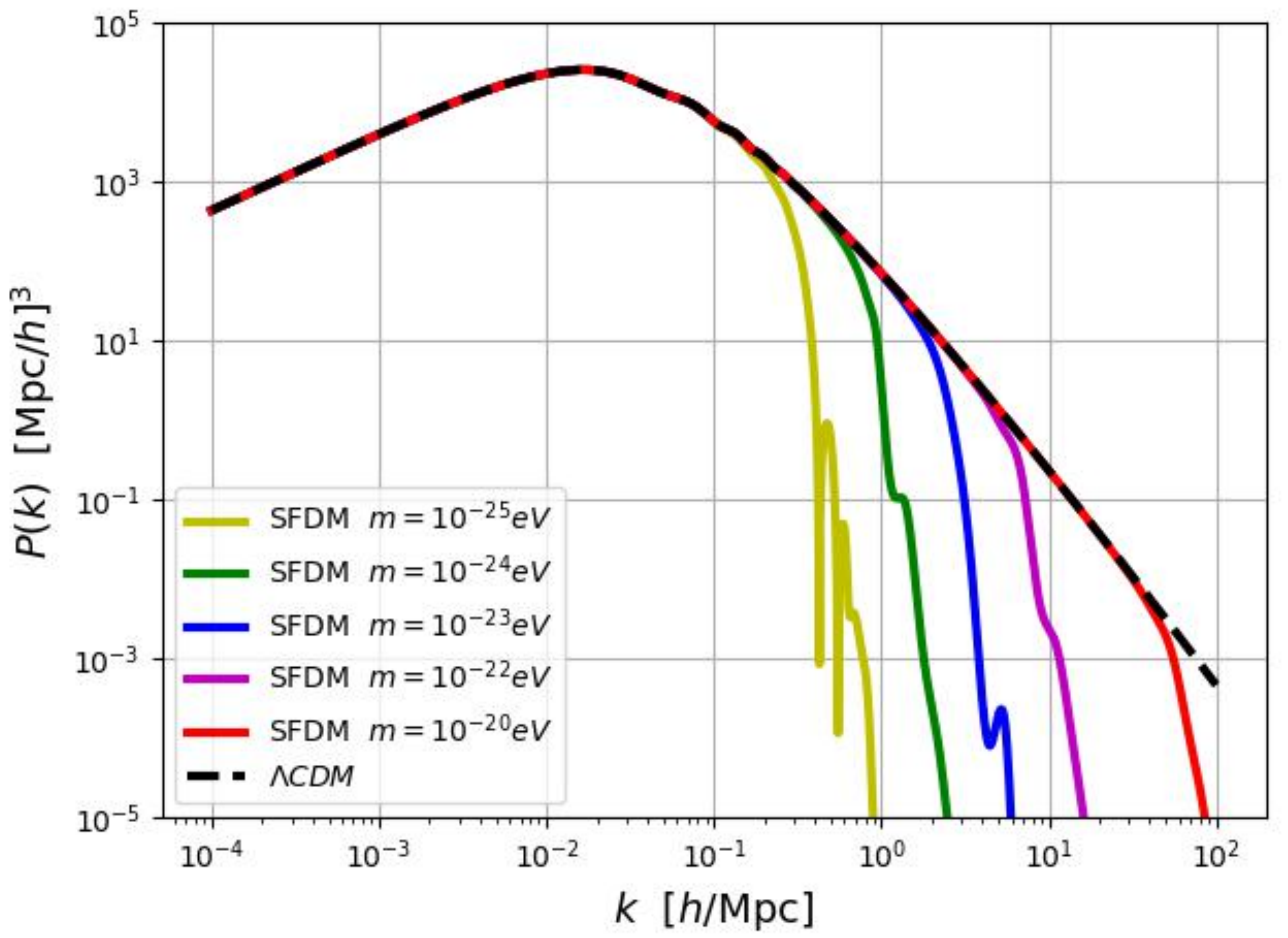
- Public codes (e.g. AxionCamb[a], class.FreeSF[b]),

  based on standard CAMB[c] or CLASS[d].
- Different predictions from ΛCDM at **small scales**.
- Observables are highly dependant on boson mass.
- Precision cosmological data is used to set constrains on the models, mainly

  - CMB & LSS[e] $m \gtrsim 10^{-25}\mathrm{eV}$

  - Lyman-alpha forest[f] $m > 2 \times 10^{-20}\mathrm{eV}$

Scalar Ultralight Dark Matter
[Ureña-López & Gonzalez-Morales (2016)]



[a]R. Hlozek, et al. 2015; [b]Ureña-López&Gonzalez-Morales 2016; [c]http://camb.info; [d]https://lesgourg.github.io/class_public/class.html
[e]see for instance: Hlozek et al MNRAS 2018 & Laguë et al JCAP 2021 [f]Roger&Peiris PRL 2021.

Schrödinger-Poisson equations

$$\frac{i}{a^{3/2}}\frac{\partial}{\partial t}(a^{3/2}\Psi) = \left[\frac{-\nabla^2}{2a^2m} + m\phi_N\right]\Psi$$

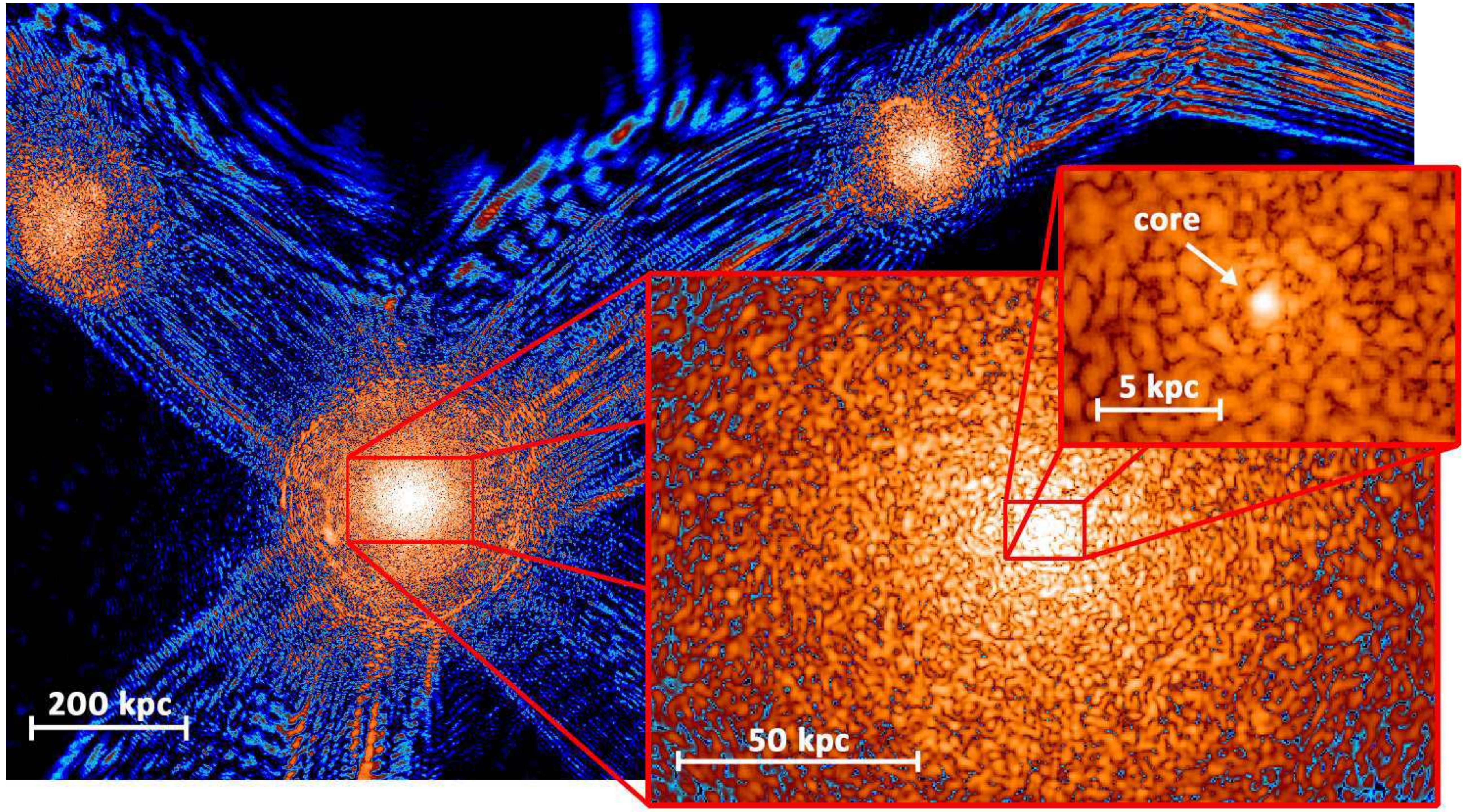
$$\frac{\nabla^2}{a^2}\phi_N = 4\pi G\rho_{\mathrm{DM}} \qquad \rho_{\mathrm{DM}} = 2m^2|\Psi|^2$$

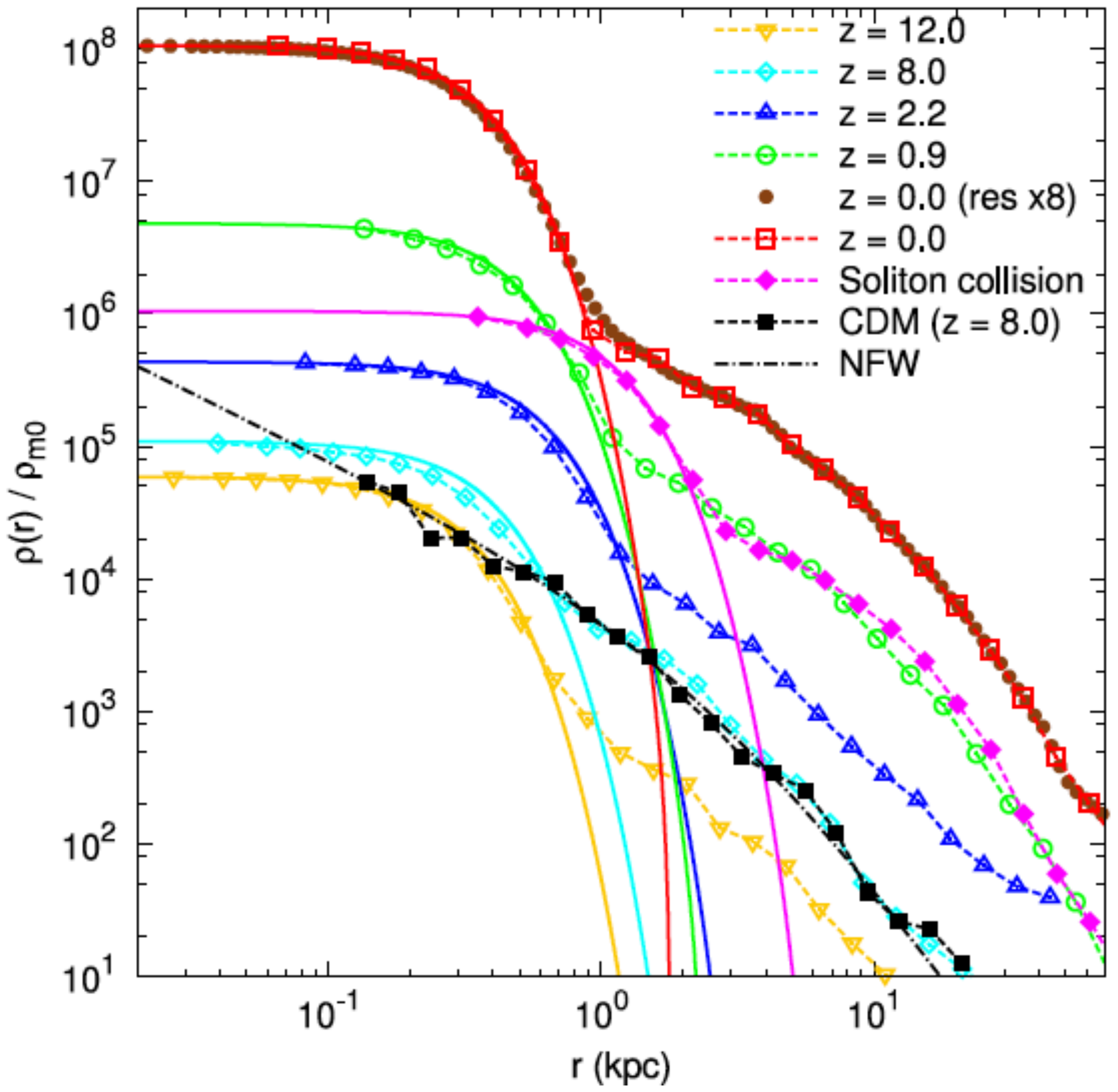
$$\lambda_{dB} = \frac{1}{mv} \sim 10^{16}\,\mathrm{km}\left(\frac{10^{-3}\mathrm{c}}{v}\right)\left(\frac{10^{-22}\mathrm{eV}}{m}\right)$$

$$\tau_{coh} \sim \frac{\lambda_{dB}}{2v} \sim 6.5\times 10^5\,\mathrm{years}\left(\frac{10^{-3}\,c}{v}\right)^2\left(\frac{10^{-22}\mathrm{eV}}{m}\right)$$

$$\tau_{osc} \simeq \frac{2\pi}{m} \sim 1.3\,\mathrm{years}\left(\frac{10^{-22}\mathrm{eV}}{m}\right)$$

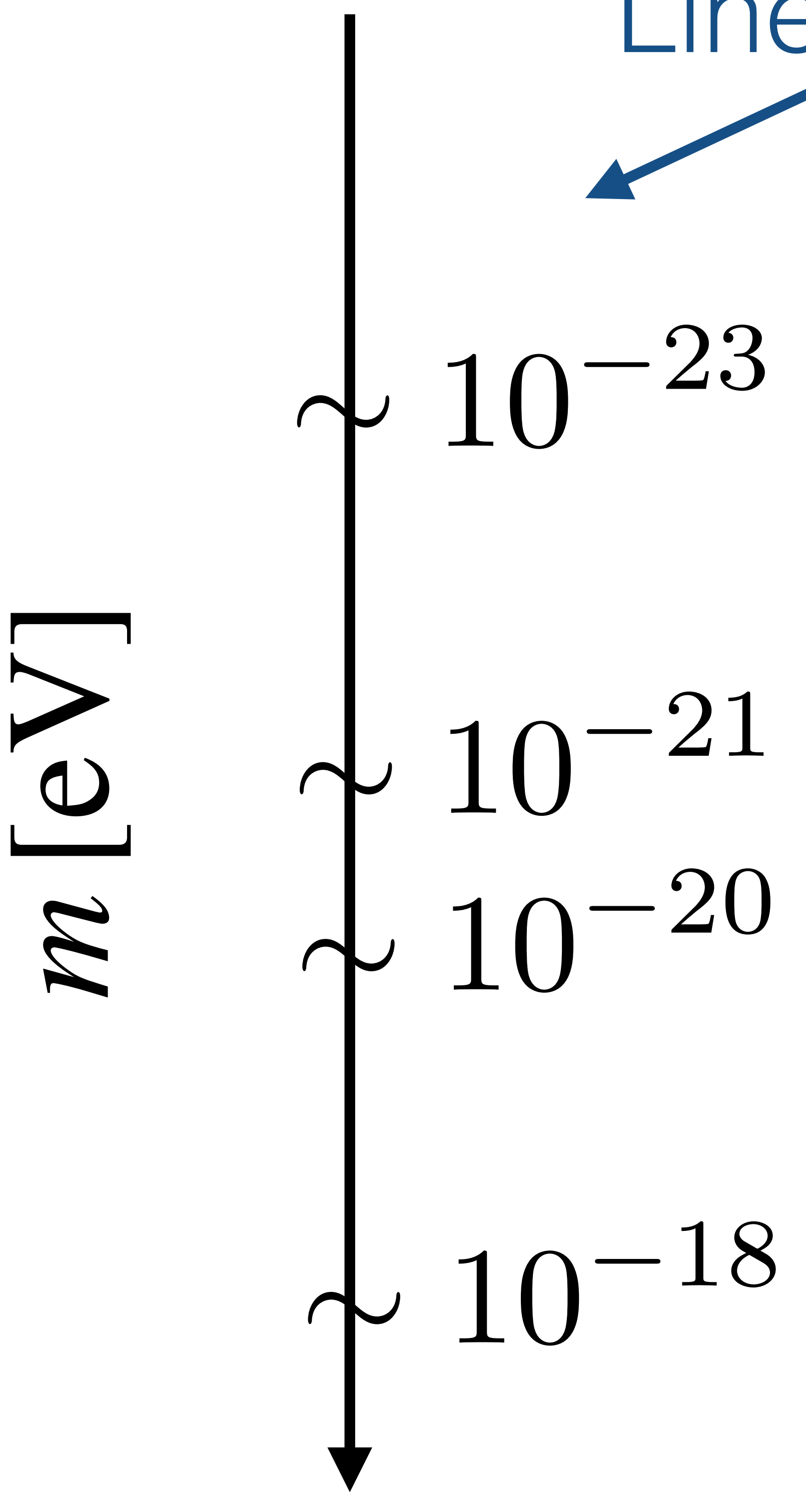
Schive, Chiueh, Broadhurst (2014) $m \sim 10^{-22}\mathrm{eV}$





Observation on diverse scales can probe different mass ranges

Linear dynamics



Cosmic Microwave Background, Large Scale Structure

Lyman-alpha forest,
Galaxy formation,
halos structure, 21cm,
Dynamics of stellar clusters,
Black Hole physics

Pulsar-Timing-Arrays (PTA)

Binary Pulsars

Observation on diverse scales can probe different mass ranges

m [eV]

Linear dynamics

Cosmic Microwave Background, Large Scale Structure

$\sim 10^{-23}$

Lyman-alpha forest,
Galaxy formation,
halos structure, 21cm,
Dynamics of stellar clusters,
Black Hole physics

Pulsar-Timing-Arrays (PTA)

$\sim 10^{-21}$

$\sim 10^{-20}$

Binary Pulsars

$\sim 10^{-18}$

- Robustness depends on the observable: theoretical uncertainties, modeling…
- These observations can probe ULDM interacting only through gravity
- If ULDM is directly coupled to the Standard Model -> many other (but model-dependent) possibilities: atomic clocks, accelerometers, resonant-mass detectors, laser and atom interferometry…

Vector Field Dark Matter - Setup

Can different spins of ULDM fields be distinguished on cosmological scales?

(*) Based on:
- Ferreira Chase and DLN, Phys. Rev. D 109, 083521 (2024)
- Ferreira Chase, Leizerovich, DLN, Landau, arXiv:2408.12052

Codes available at:
https://github.com/classULDM/class.SFDM (Spin 0) https://github.com/classULDM/class.VFDM (Spin 1)

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Goals

- **Cosmological perturbations** with **VFDM**.
- **Anisotropic background metric**.
- Calculate cosmological **observables**.

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$$S = S_{Gravity} + S_{SM} - \int d\tau\, dx^3 \sqrt{-g}\left[\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{m^2}{2}A^{\mu}A_{\mu}\right]$$

$$\boxed{G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G(T^{Matter}_{\mu\nu} + T^{A}_{\mu\nu})}$$

$$F_{\mu\nu} = \nabla_{\mu}A_{\nu} - \nabla_{\nu}A_{\mu}$$

$$\nabla^{\mu}T^{Matter}_{\mu\nu} = 0 \qquad \nabla_{\nu}F^{\mu\nu} + m^2A^{\mu} = 0$$

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Anisotropic background dynamics

Conformal time

$$dt = a d\tau$$

- Bianchi I metric: $$ds^2 = a(\tau)^2\left[-d\tau^2 + \gamma_{ij}\,dx^i dx^j\right]$$

Metric shear: $$\sigma_{ij} = \frac{1}{2}\gamma'_{ij}$$

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- SM & Λ: $$P_I = w_I\,\rho_I \qquad I = \Lambda, r, b \qquad P'_I = -\,3\mathscr{H}(P_I + \rho_I) \qquad \left(\mathscr{H} = \frac{a'}{a} = aH\right)$$

Hubble rate

$$w_\Lambda = -\,1,\ w_r = 1/3,\ w_b = 0$$

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- VFDM: $\bar{A}_\mu = A_\mu(\tau) \to A_0 = 0 \quad \& \quad A_i'' - 2\sigma^k{}_i A_k' + m^2 a^2 A_i = 0$

$T^{A\mu}_{\ \ \nu} \to$ fluid variables: $\rho_A, P_A,\ \Sigma^{Aj}_{\ \ i} =$ traceless part of $T^{Ai}_{\ \ j}$

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We assume: $A_i(\tau) = A(\tau)\,\hat{A}_i \quad \& \quad \rho_A(t_0) = \rho_{DM}(t_0)$

Anisotropic background dynamics

Conformal time

$$dt = ad\tau$$

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We assume: $A_i(\tau) = A(\tau)\,\hat{A}_i \quad \& \quad \rho_A(t_0) = \rho_{DM}(t_0)$

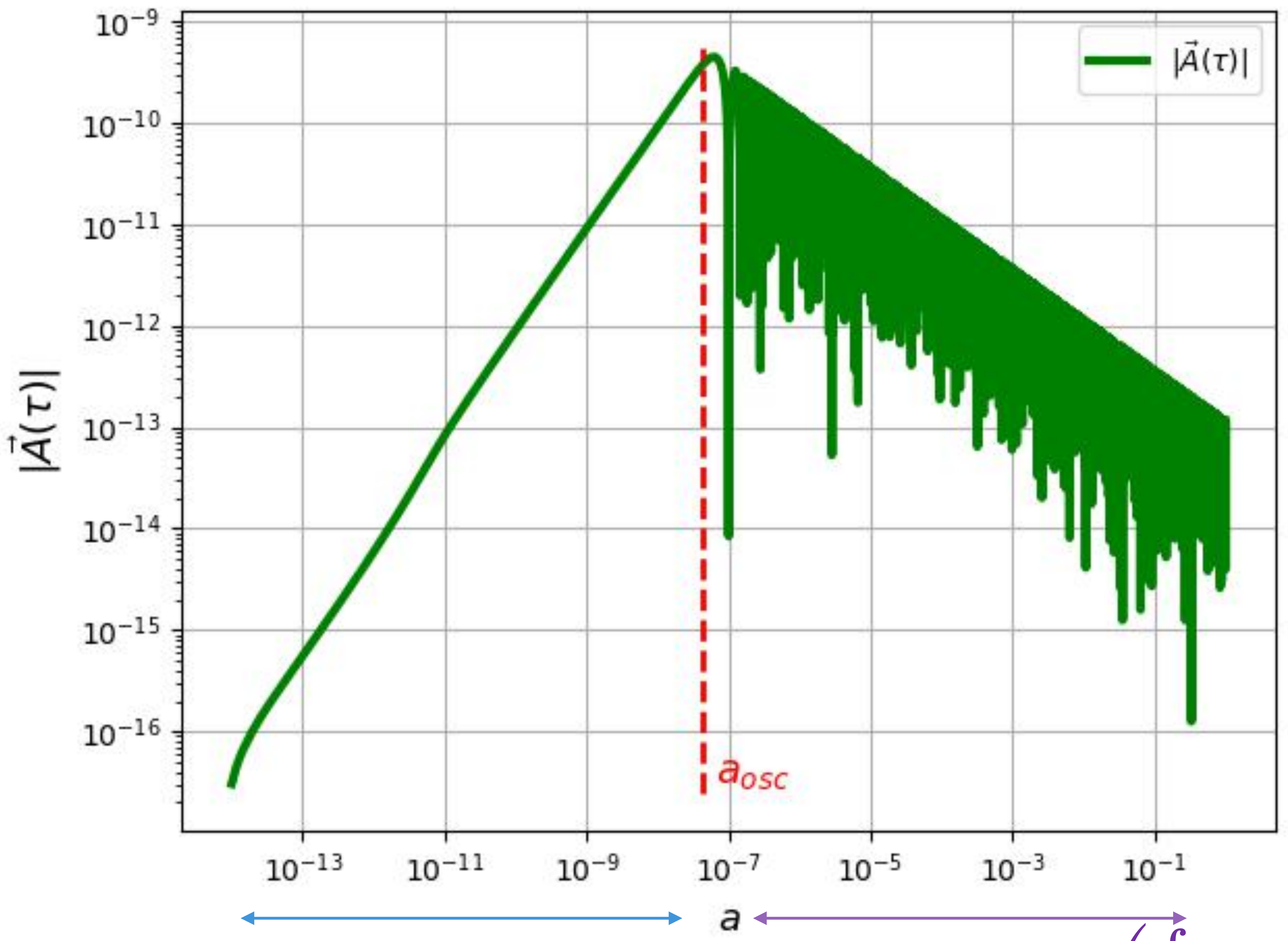
We solve perturbatively in the shear $|\sigma_{ij}| \ll \mathscr{H}$

Background evolution - VFDM

(Here and below we use Planck 2018 parameters)

$$A_i(\tau) = A(\tau)\,\hat{A}_i \quad \& \quad \rho_A(t_0) = \rho_{DM}(t_0)$$

$$\mathcal{H}(a_{osc}) = m a_{osc} \quad (H(a_{osc}) = m)$$



$$A(\tau) \sim a \qquad H \gg m$$

$$A(\tau) \sim a^{-\frac{1}{2}} \cos\left(\int m a \, d\tau\right) \qquad H \ll m$$

Background evolution - **VFDM**

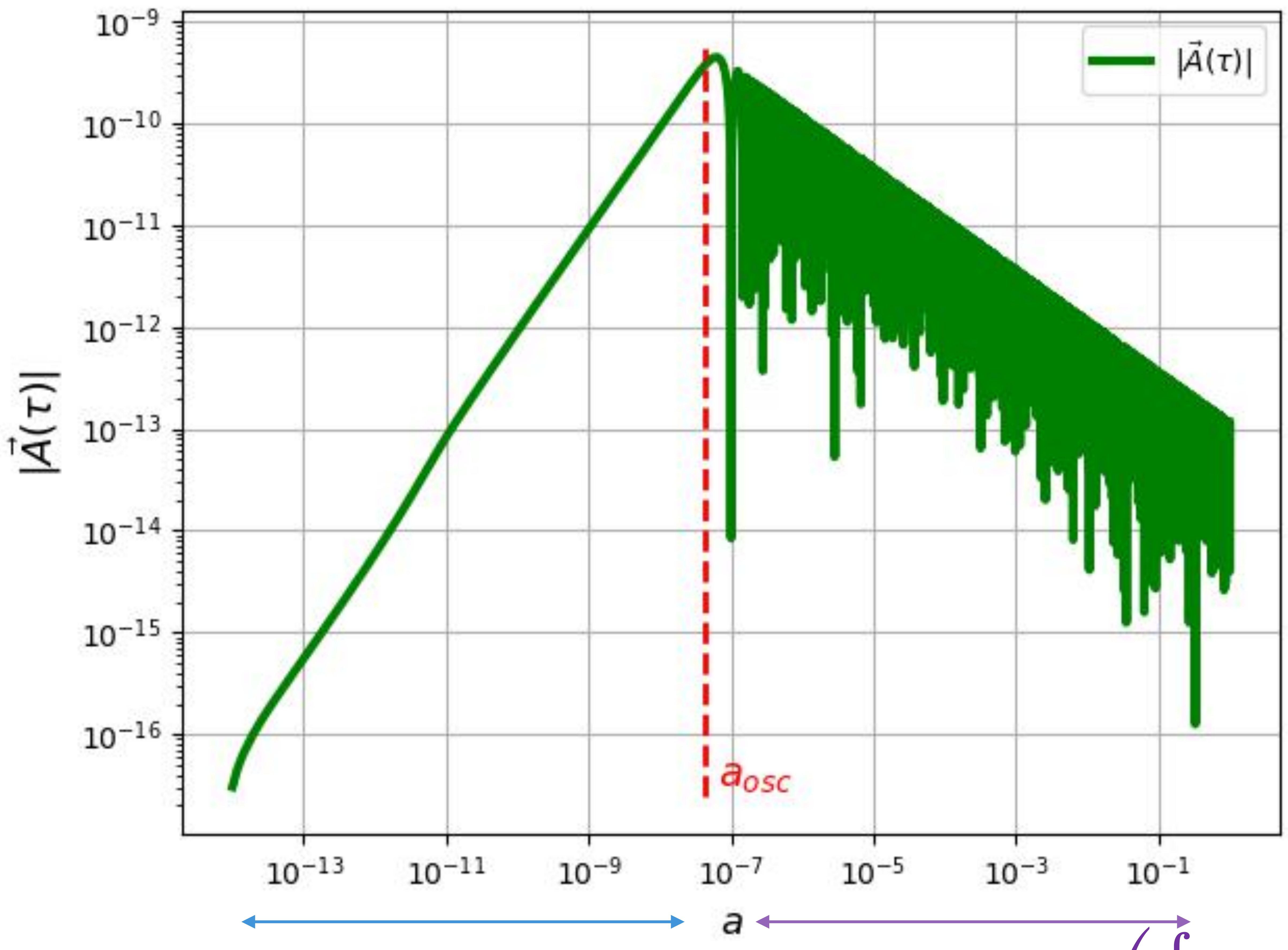
(Here and below we use Planck 2018 parameters)

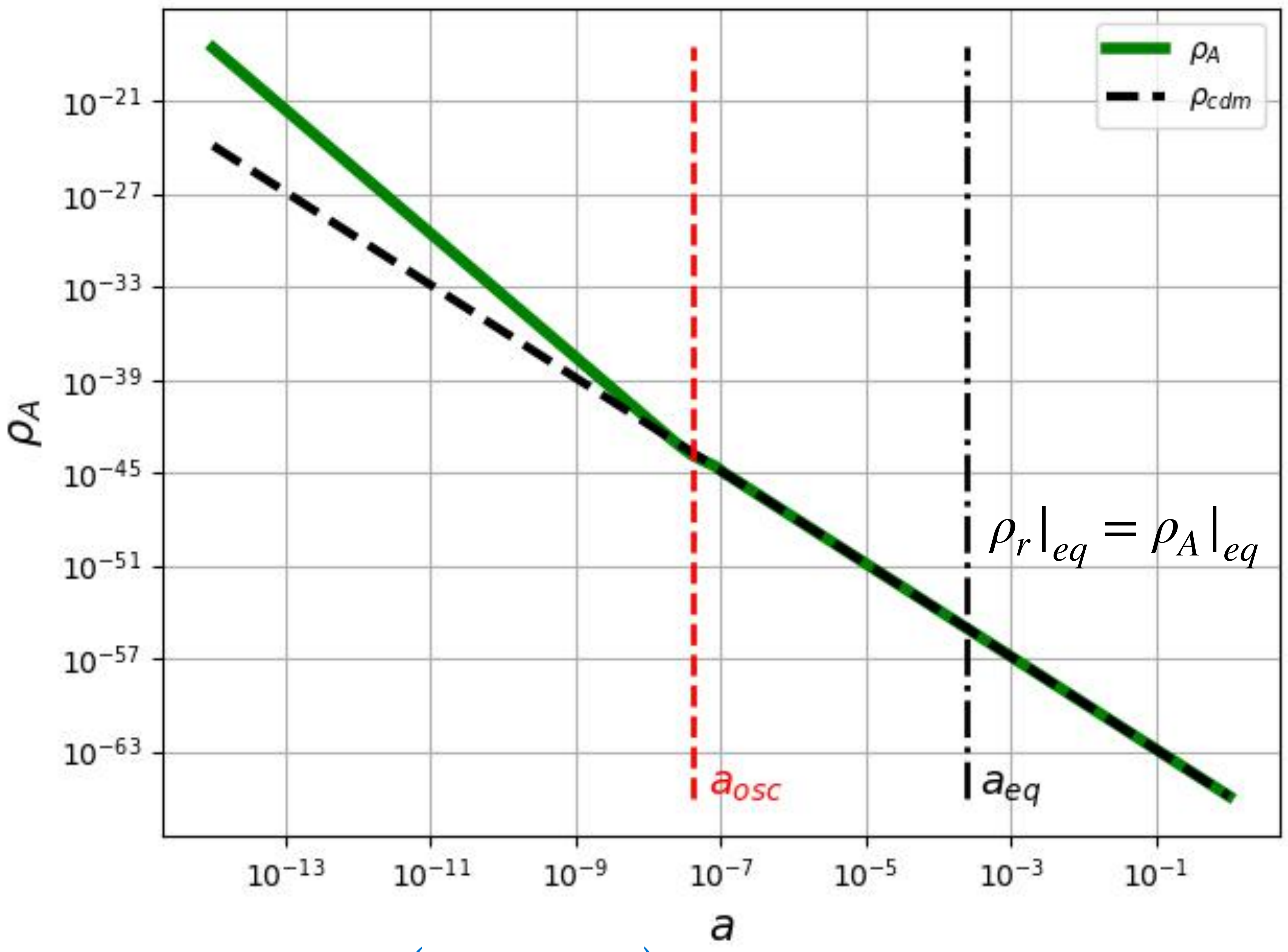
$$A_i(\tau) = A(\tau)\,\hat{A}_i \quad \& \quad \rho_A(t_0) = \rho_{DM}(t_0)$$

$$H_{eq} \sim 10^{-28}\text{eV} \ll H(a_{osc}) = m$$

$$\mathscr{H}(a_{osc}) = m a_{osc} \quad (\,H(a_{osc}) = m\,)$$

$$\rho_A \sim a^{-4}\,, P_A = \rho_A/3 \qquad \rho_A \sim a^{-3}\,, \langle P_A \rangle \simeq 0$$





$$A(\tau) \sim a \qquad H \gg m$$

$$A(\tau) \sim a^{-\frac{1}{2}} \cos\left(\int m a \, d\tau\right) \qquad H \ll m$$

$$\Sigma^A_{ij} \simeq -2\rho_A \left(\hat{A}_i \hat{A}_j - \frac{\gamma_{ij}}{3}\right) \qquad \langle \Sigma^A_{ij} \rangle \simeq 0$$

Background evolution - Einstein eqns and shear abundance

$$\mathscr{H}^2 - \frac{1}{6}\sigma^2 = \frac{a^2}{3m_P^2}\left(\sum_{I=\Lambda,r,b}\rho_I + \rho_A\right) \qquad (\sigma^i{}_j)' + 2\mathscr{H}\,\sigma^i{}_j = \frac{a^2}{m_P^2}\Sigma^{A\,i}{}_j$$

Shear abundance:

$$\Omega_\sigma = \frac{\sigma^2}{6\mathscr{H}^2} \qquad (\sigma^2 = \sigma^{ij}\sigma_{ij})$$

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For $a_{\rm ini} \ll a \ll a_{osc}$:

$$\sigma_{ij} \simeq -6R_A\mathscr{H}\left(\hat{A}_i\hat{A}_j - \frac{\gamma_{ij}}{3}\right), \qquad R_A = \frac{\rho_A}{\rho_r} \ll 1 \qquad \text{(RD)}$$

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For $a_{osc} \ll a \quad (H \ll m) \to \langle \Sigma^{A\,j}{}_i \rangle \simeq 0$

Background evolution - BBN constrains

$$\Omega_\sigma \propto \begin{cases} m^{-1} & a < a_{osc} \\ a^{-2} & a_{osc} < a < a_{eq} \\ a^{-3} & a_{eq} < a \end{cases}$$

BBN constrains [Akarsu et al 2019]

$$\Omega_\sigma|_{BBN} \lesssim 10^{-2}$$

$$m \gtrsim 10^{-26}\text{eV}$$

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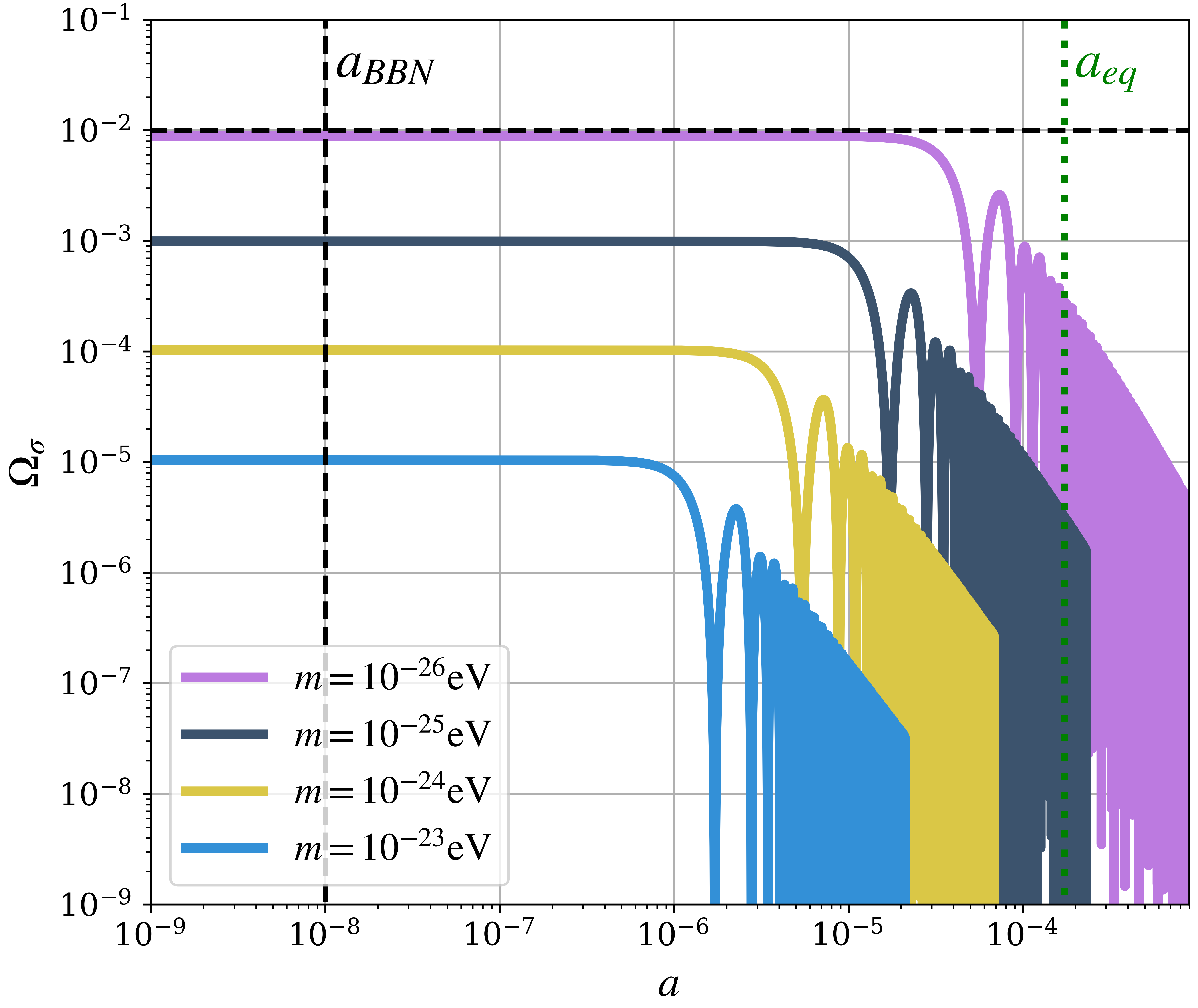

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We expect stronger bounds from the analysis of the perturbations....

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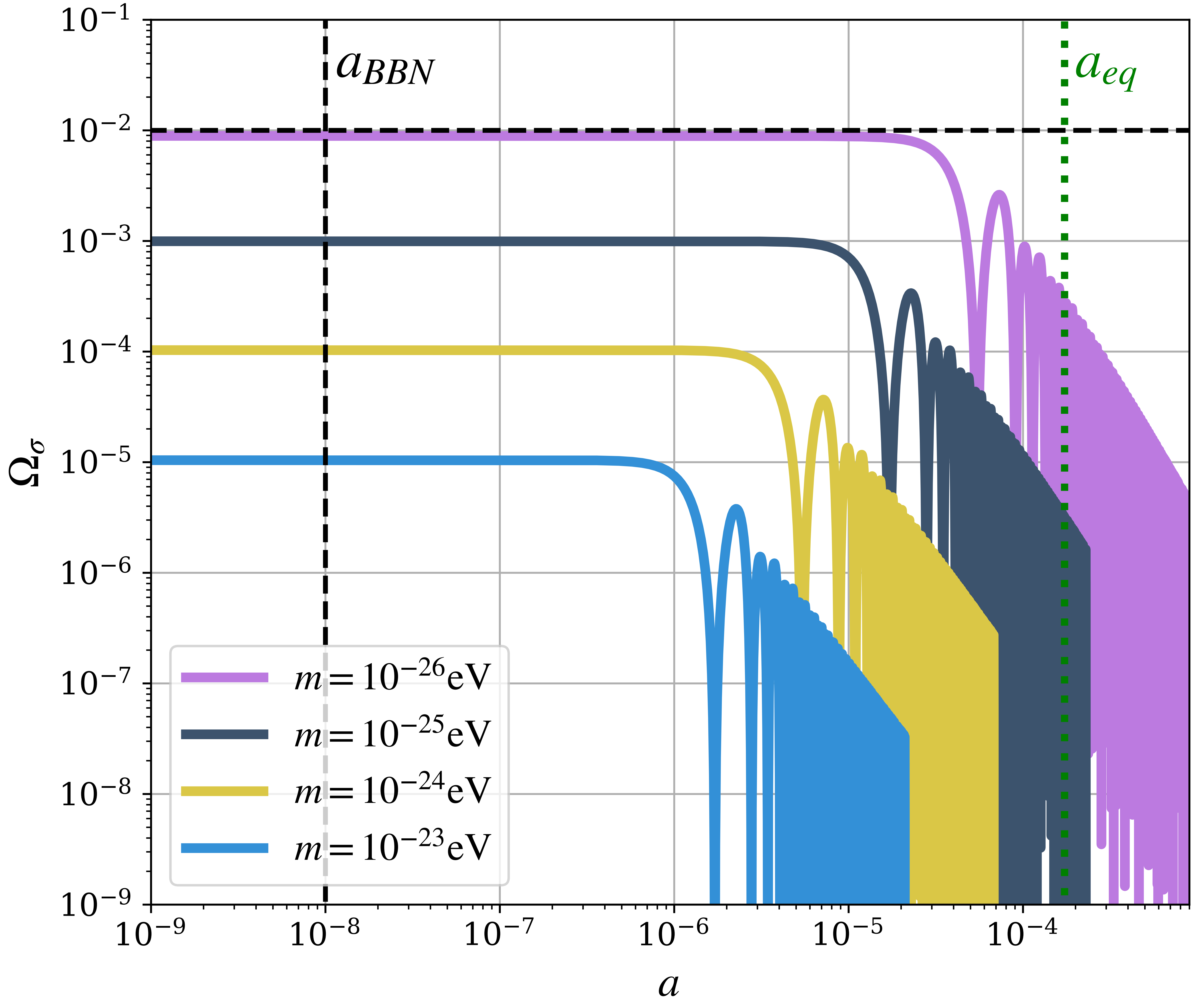
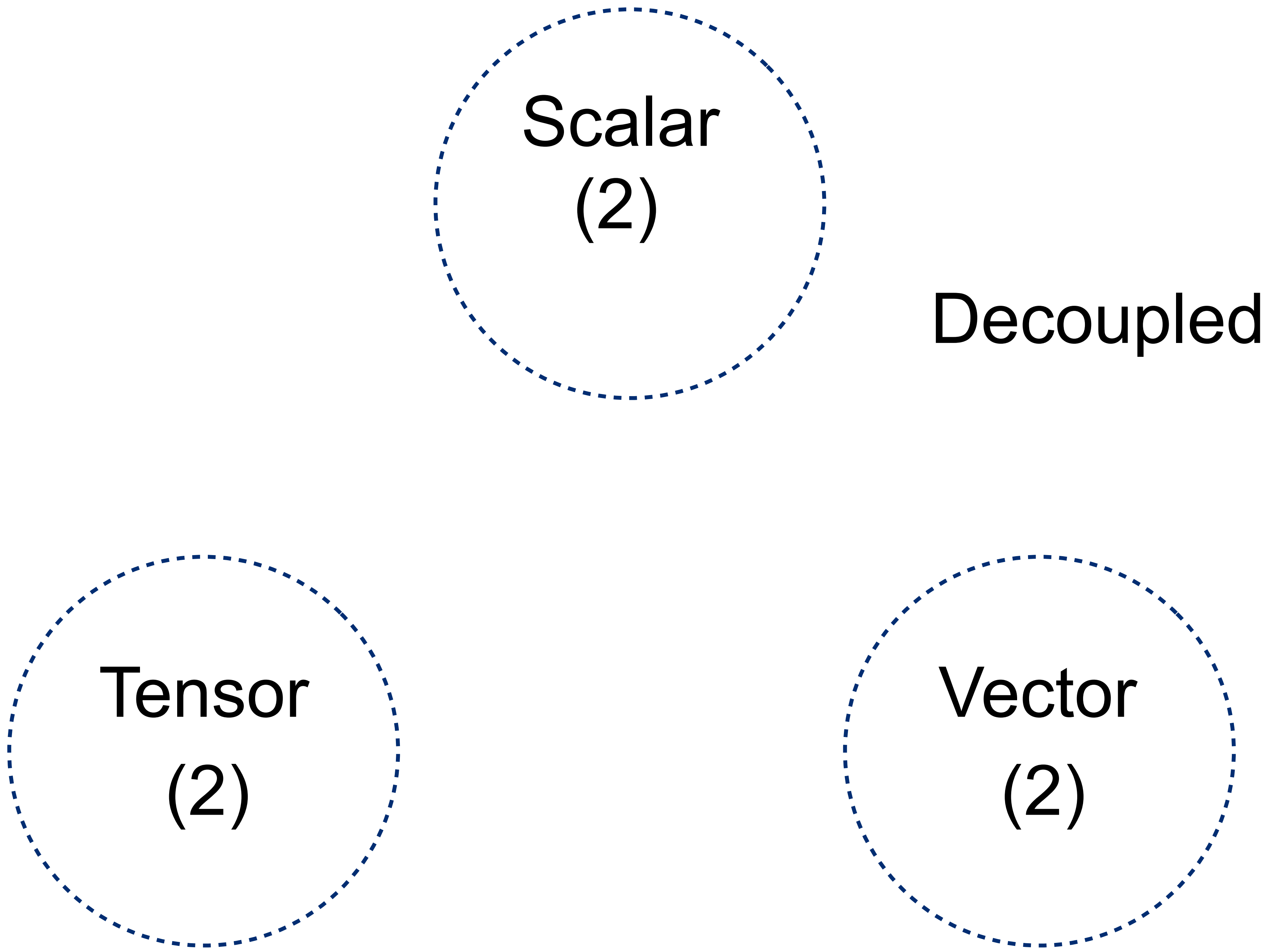


Scalar-Vector-Tensor decomposition

Isotropic FLRW background



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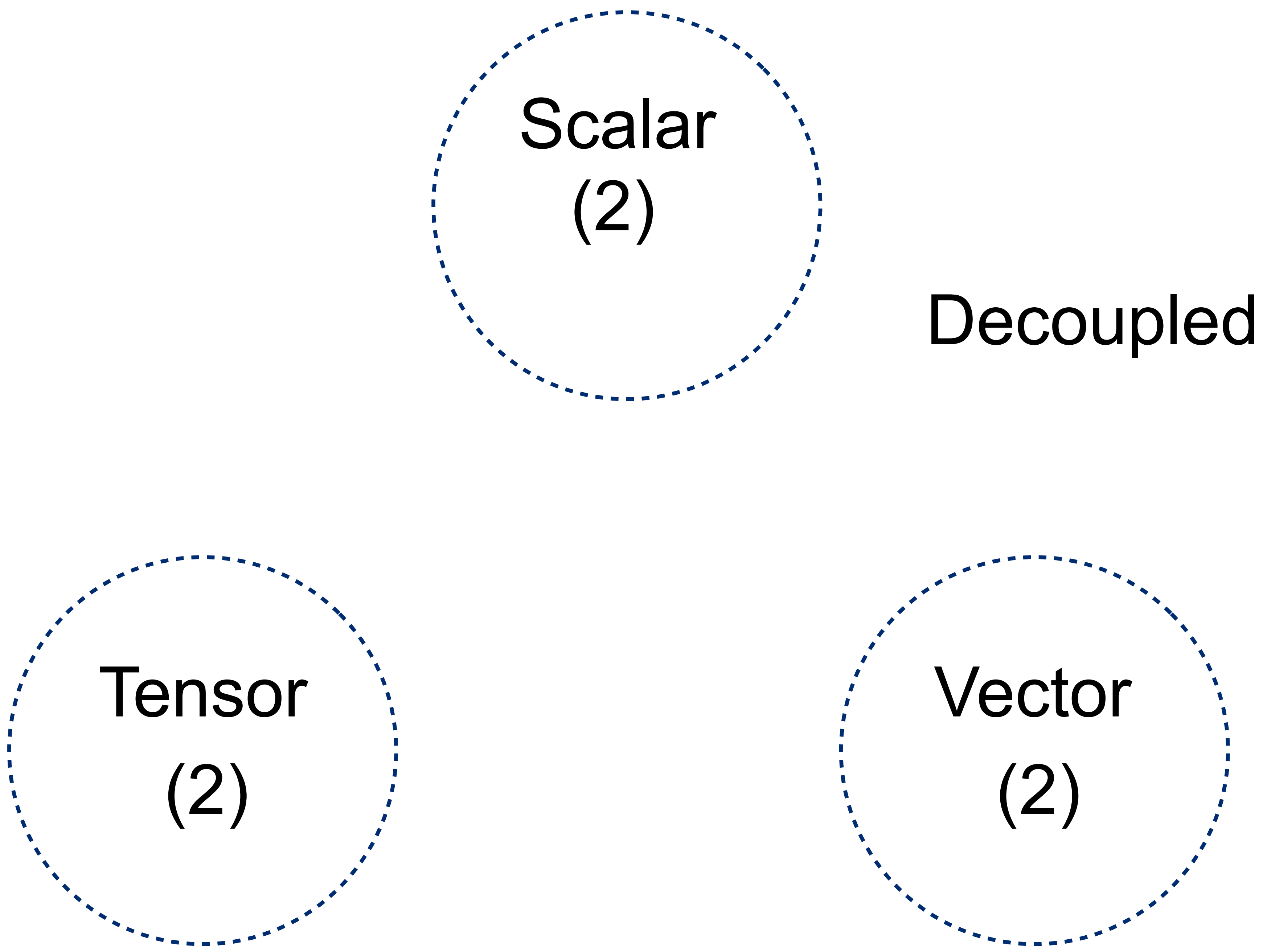
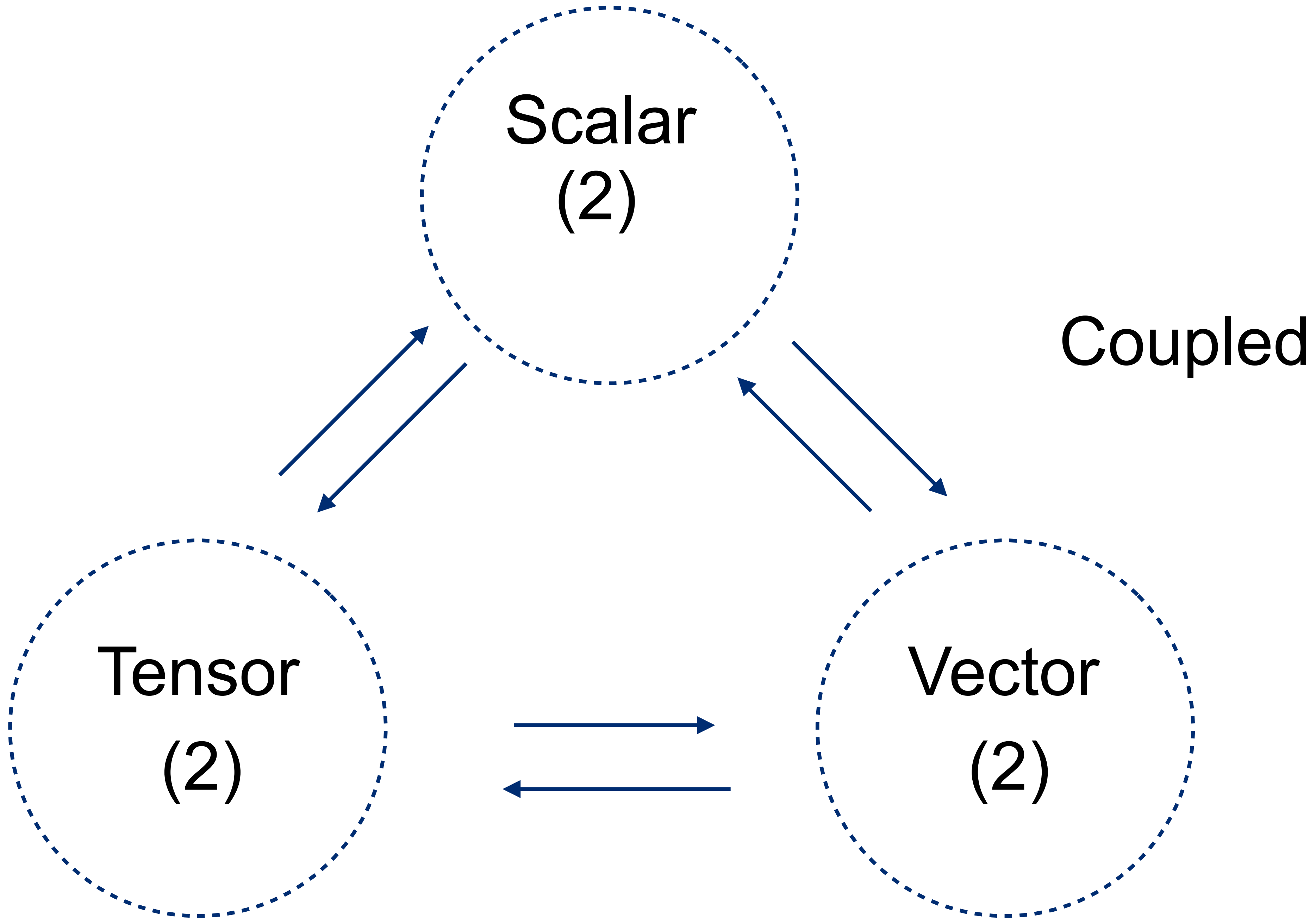


Anisotropic background



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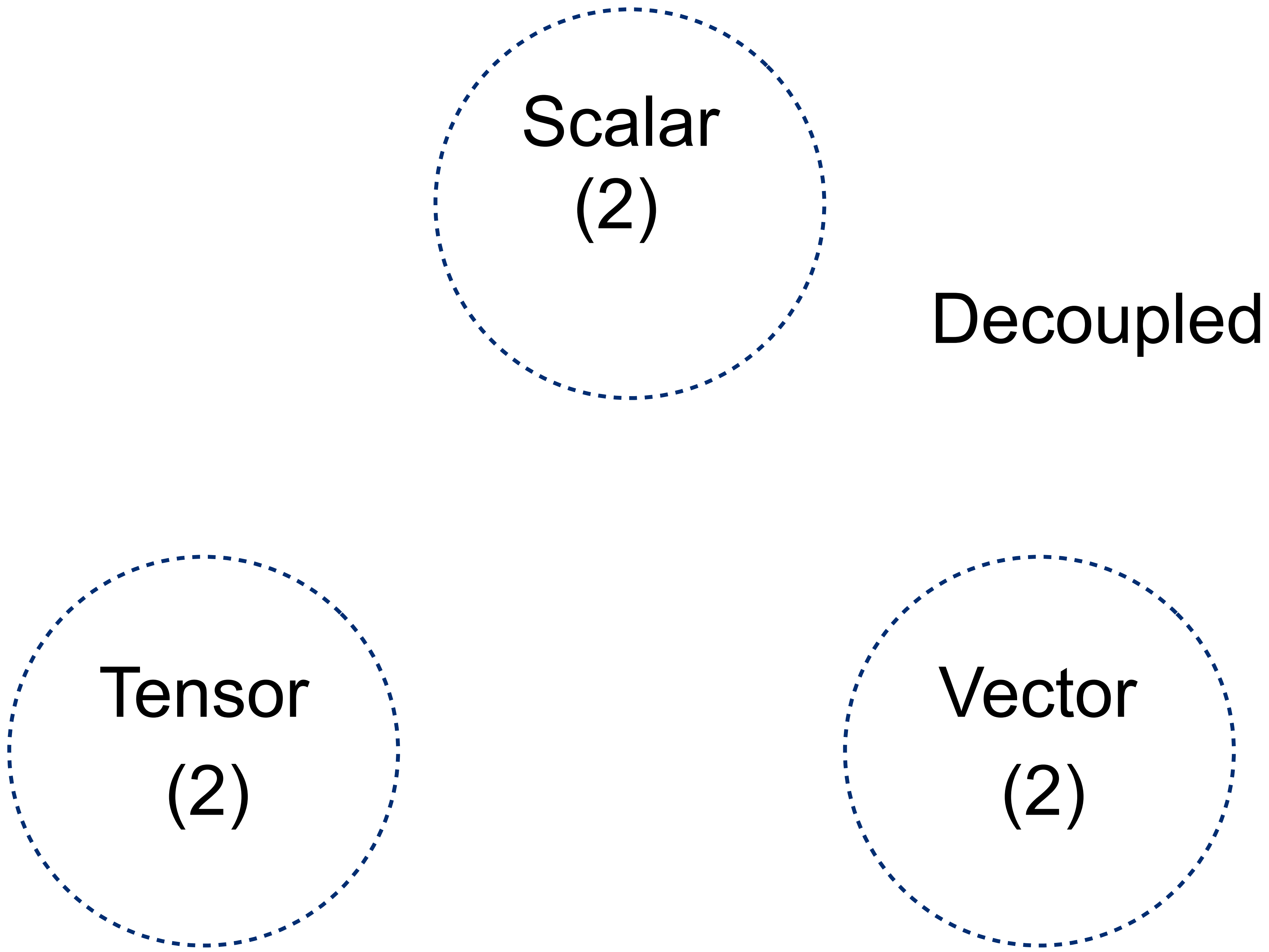

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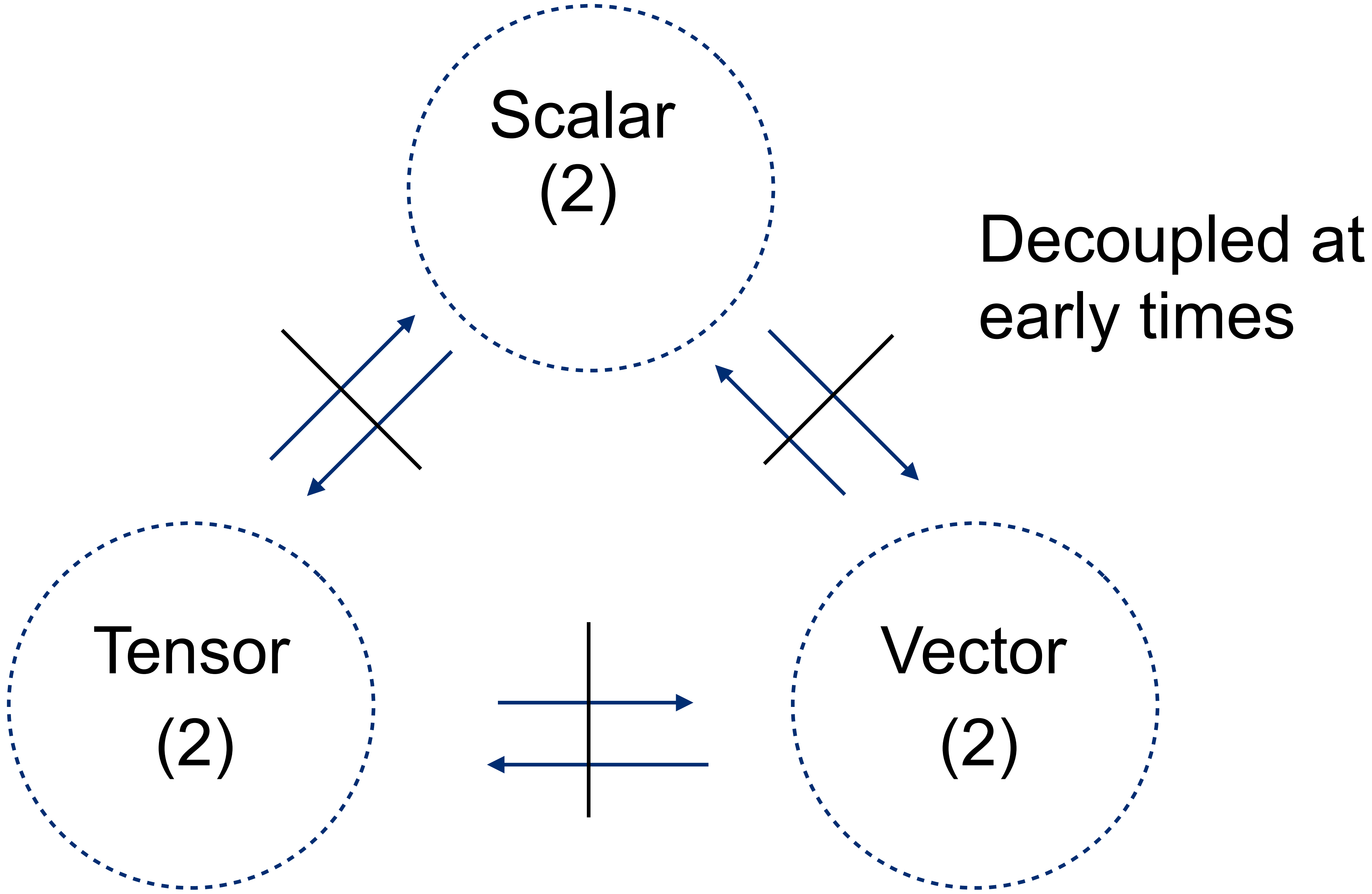

Linear regime - Scalar sector

- **Cosmological perturbation theory:** $S(\tau,\vec{x}) = S(\tau) + \delta S(\tau,\vec{x})$

  Vector Field: $A_i(\tau,\vec{x}) = A(\tau)\hat{A}_i + \delta A_i(\tau,\vec{x})$

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- **Linearized Einstein eqns. in Fourier space:** $\delta G^{\mu}{}_{\nu} = 8\pi G \delta T^{\mu}{}_{\nu}$

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Synchronous gauge:

Two scalar perturbations

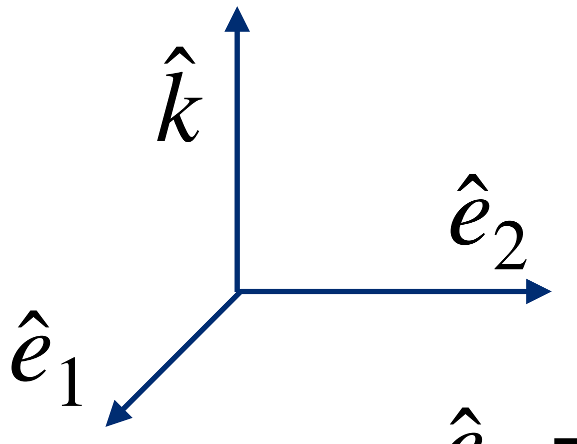
$$\delta g_{00} = \delta g_{0i} = 0 \qquad \delta g_{ij} = a^2\left[-2\left(\gamma_{ij} + \frac{\sigma_{ij}}{\mathscr{H}}\right)\eta + \hat{k}_i\hat{k}_j(h+6\eta)\right]$$

Newtonian gauge:

Two scalar perturbations

$$\delta g_{00} = -2a^2\phi, \quad \delta g_{0i} = 0, \quad \delta g_{ij} = -2a^2(\gamma_{ij} + \frac{\sigma_{ij}}{\mathscr{H}})\psi$$

Orthogonal basis



$$\hat{e}_2 = \hat{k} \times \hat{A}$$

$$\hat{e}_1 = \hat{k} \times \hat{e}_2$$

Adiabatic initial conditions (IC) during radiation domination (RD) era: Synchronous gauge

- Imposed when $k\tau \ll 1$

  $(k \ll \mathcal{H},\ k/a \ll H)$

$$\delta G^\mu_\nu = 8\pi G \delta T^\mu_\nu$$

$$\frac{\delta\rho_I}{\rho'_I} = \frac{\delta\rho_\gamma}{\rho'_\gamma}$$

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Reduce to ΛCDM for $|\sigma_{ij}| \ll \mathscr{H}$ $(\rho_A \ll \rho_r)$

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*Ma & Bertschinger (1995)

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This **dominates** for $m \lesssim 0.55 \times 10^{-22}\mathrm{eV}\left(\frac{0.1}{\mathrm{k}\tau_{\mathrm{ini}}}\right)^4$

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Exactly cancel

This **dominates** for $m \lesssim 0.55\times 10^{-22}\mathrm{eV}\left(\frac{0.1}{\mathrm{k}\tau_{\mathrm{ini}}}\right)^4$

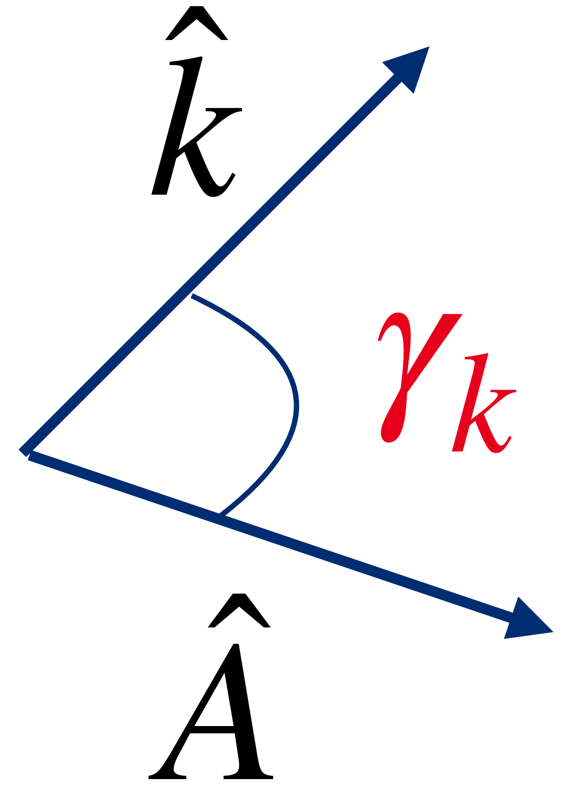
For attractor adiabatic IC $\delta\vec{A} = A'\left[2(\hat{A}\cdot\hat{k})\,\hat{k} - (\hat{e}_1\cdot\hat{k})\,\hat{e}_1\right]\tau\,\eta_0 \rightarrow \delta T^0_{A_i} = -\frac{3m_P^2}{a^2}k^2\sigma_\parallel\tau$

*Ma & Bertschinger (1995)

Matter Power spectrums *- Implementation in CLASS*

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

$$\delta = \delta\rho/\rho$$



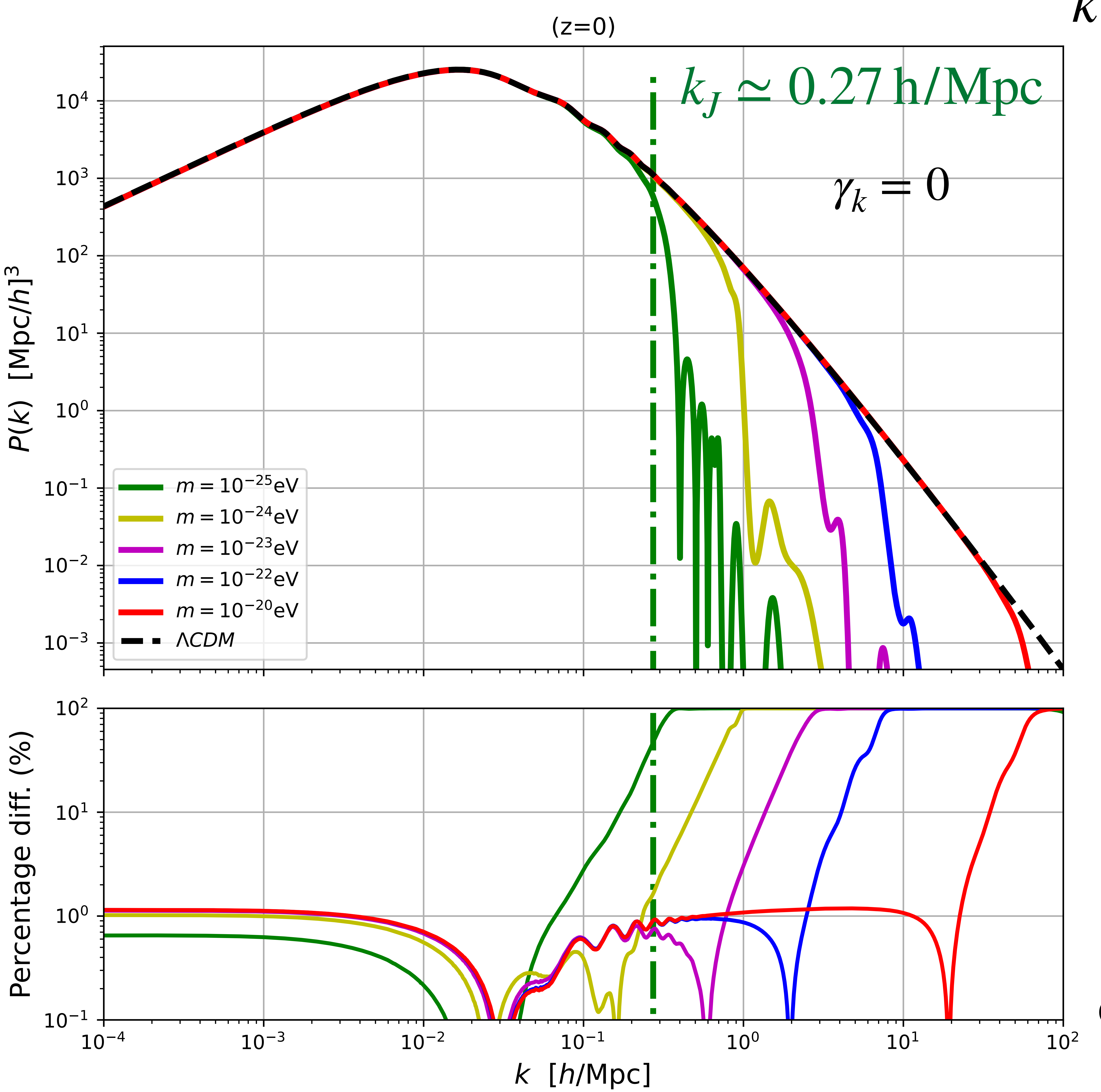
CLASS

- Assumes **background isotropy** $\vec{k} \rightarrow k$

- **Solves for** the evolution of each k

We implemented the equations in CLASS- we can solve them for any γ_k -

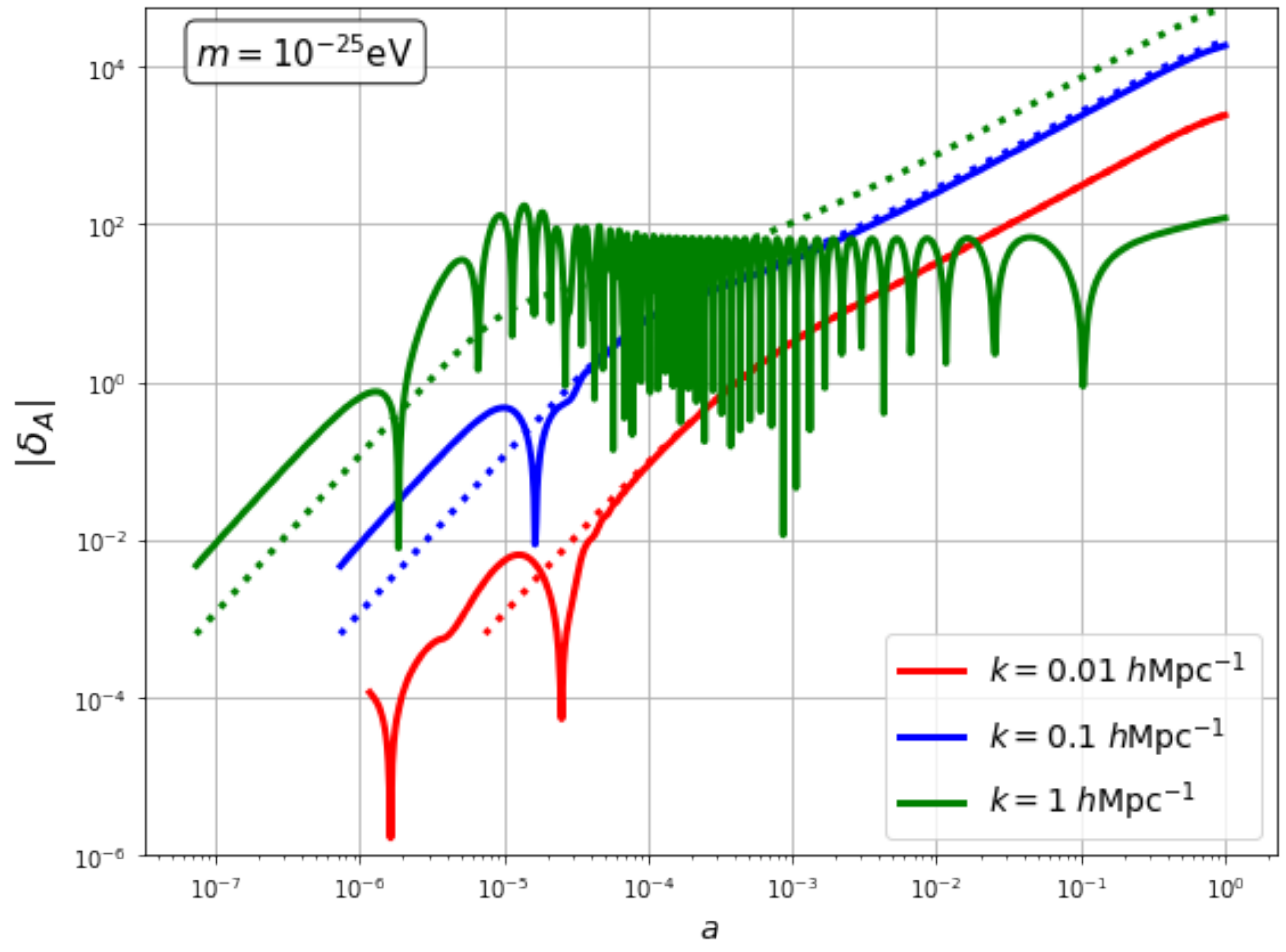
Matter Power spectrums



Combining Einstein & VFDM equations in MD for $k \gg \mathcal{H}$:

$$\delta_A'' + \frac{\delta_A'}{2} + \left(\frac{k^4}{k_J^4} - \frac{3}{2}\right)\delta_A = 2\frac{k^2}{\mathcal{H}^2}\eta$$

$$k_J = \sqrt{ma\mathcal{H}} \begin{cases} k \gg k_J & \rightarrow \delta_A \sim \text{oscillate} \\ k \ll k_J & \rightarrow \delta_A \sim a \end{cases}$$



Code available at: https://github.com/classULDM/class.VFDM

The Jeans wavevector

$$k_J = \sqrt{ma\mathscr{H}} = a\sqrt{mH}$$

$$k_J \propto \begin{cases} \sim \text{constant} & \text{RD } (a < a_{eq}) \\ \sim a^{1/4} & \text{MD } (a > a_{eq}) \end{cases}$$

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- Modes with $k = k_J$ enter the horizon in RD when the field starts oscillating, that is

$$k = \mathscr{H}_* = \sqrt{ma_*\mathscr{H}_*} \rightarrow ma_* = \mathscr{H}_* \rightarrow a_* = a_{osc} \quad \text{(note } k = ma_*\text{)}$$

Horizon crossing at $a = a_*$

k_J

Condition for the field to start oscillating

The Jeans wavevector

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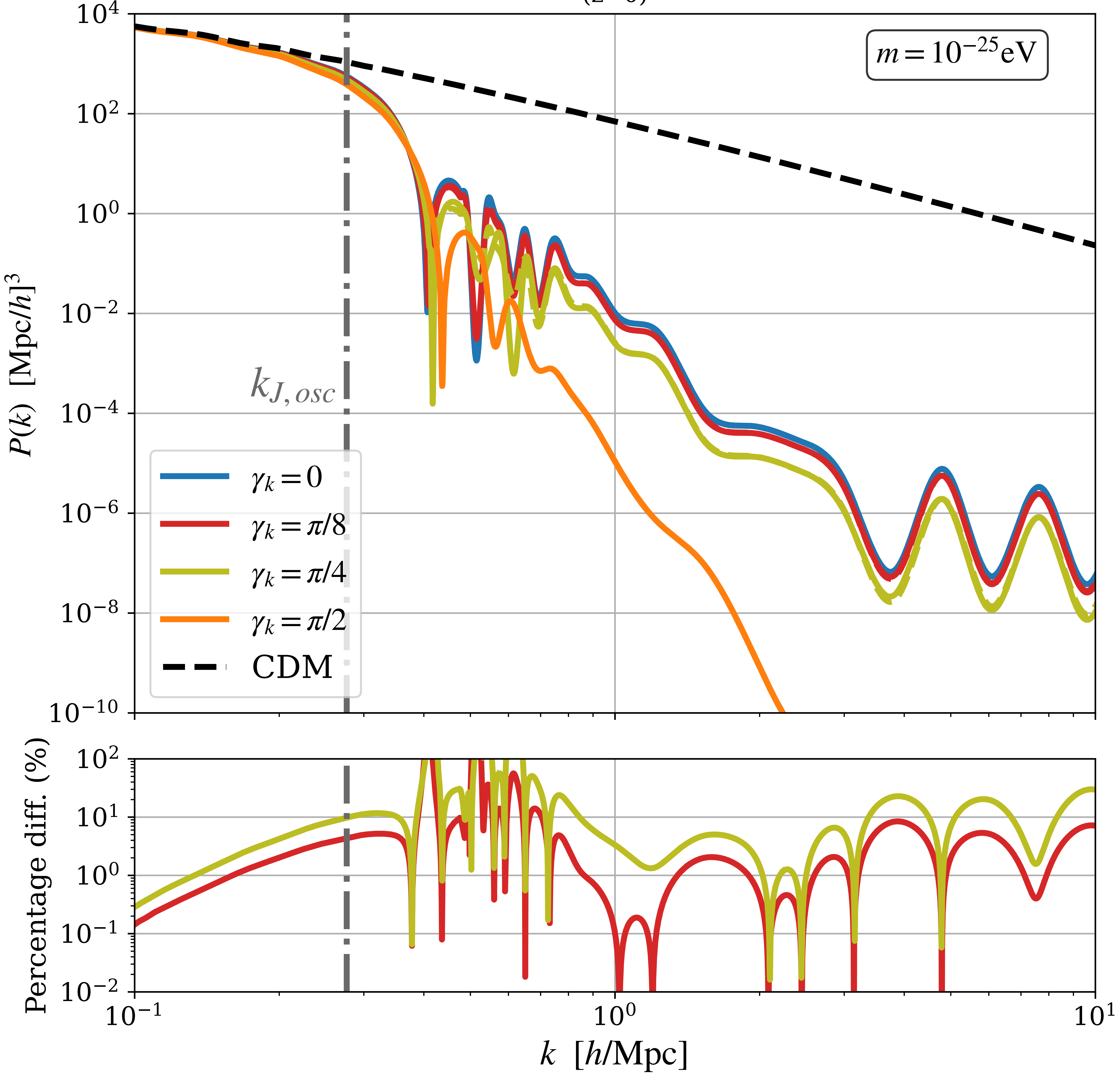
Horizon crossing at $a = a_*$ $\qquad k_J \qquad$ Condition for the field to start oscillating

- Modes with $k < k_J$ $(k > k_J)$ enter the horizon being non-relativistic $k < ma_*$ (relativistic $k > ma_*$)

Angular dependence

$k_J \simeq 0.27\,\mathrm{h/Mpc}$ (z=0)



$$\%\mathrm{Diff} = 100 \times \left(\frac{P(k,\gamma_k) - P(k,0)}{P(k,0)} \right)$$

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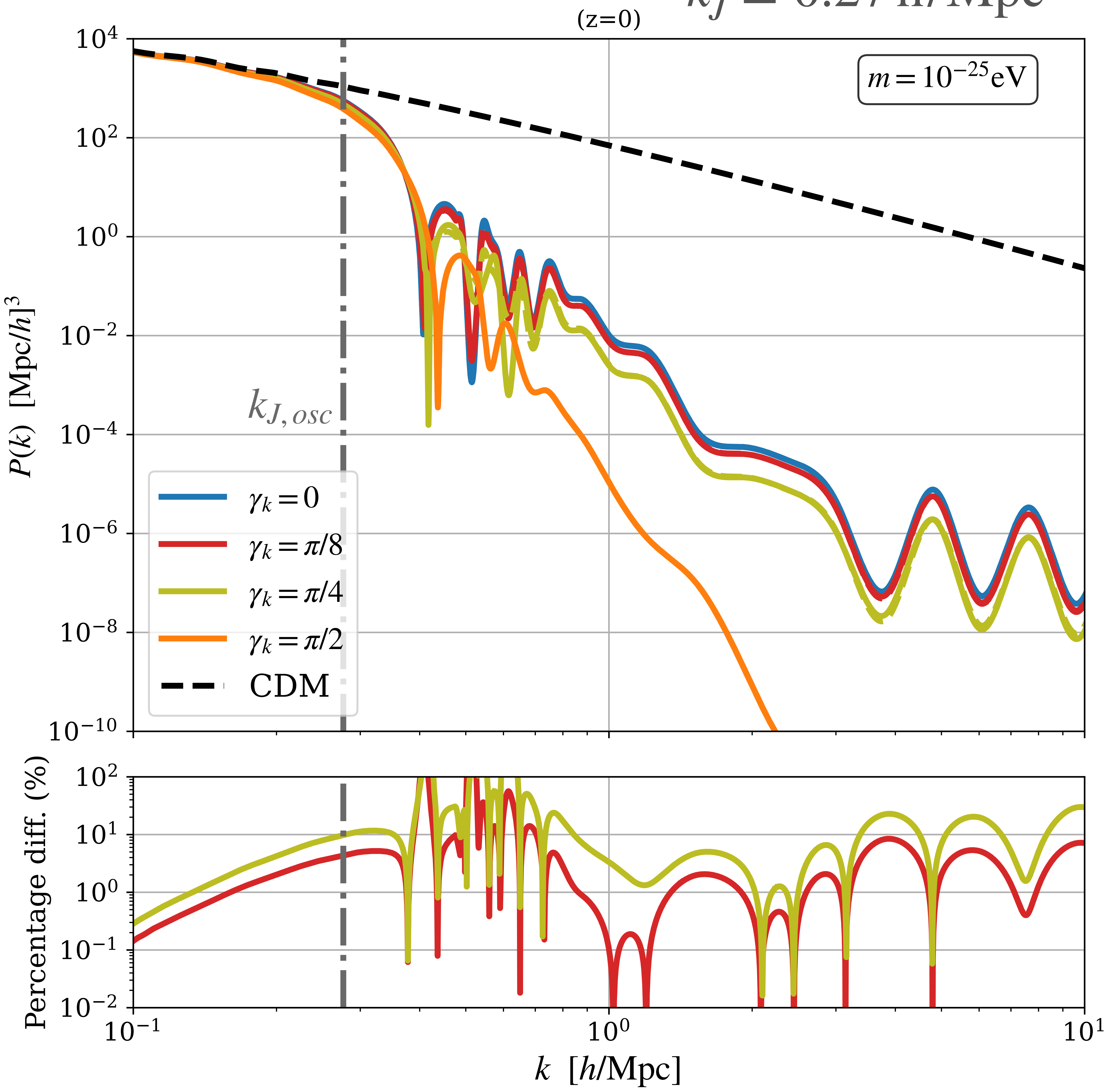
$k_J \simeq 0.27\,\mathrm{h/Mpc}$



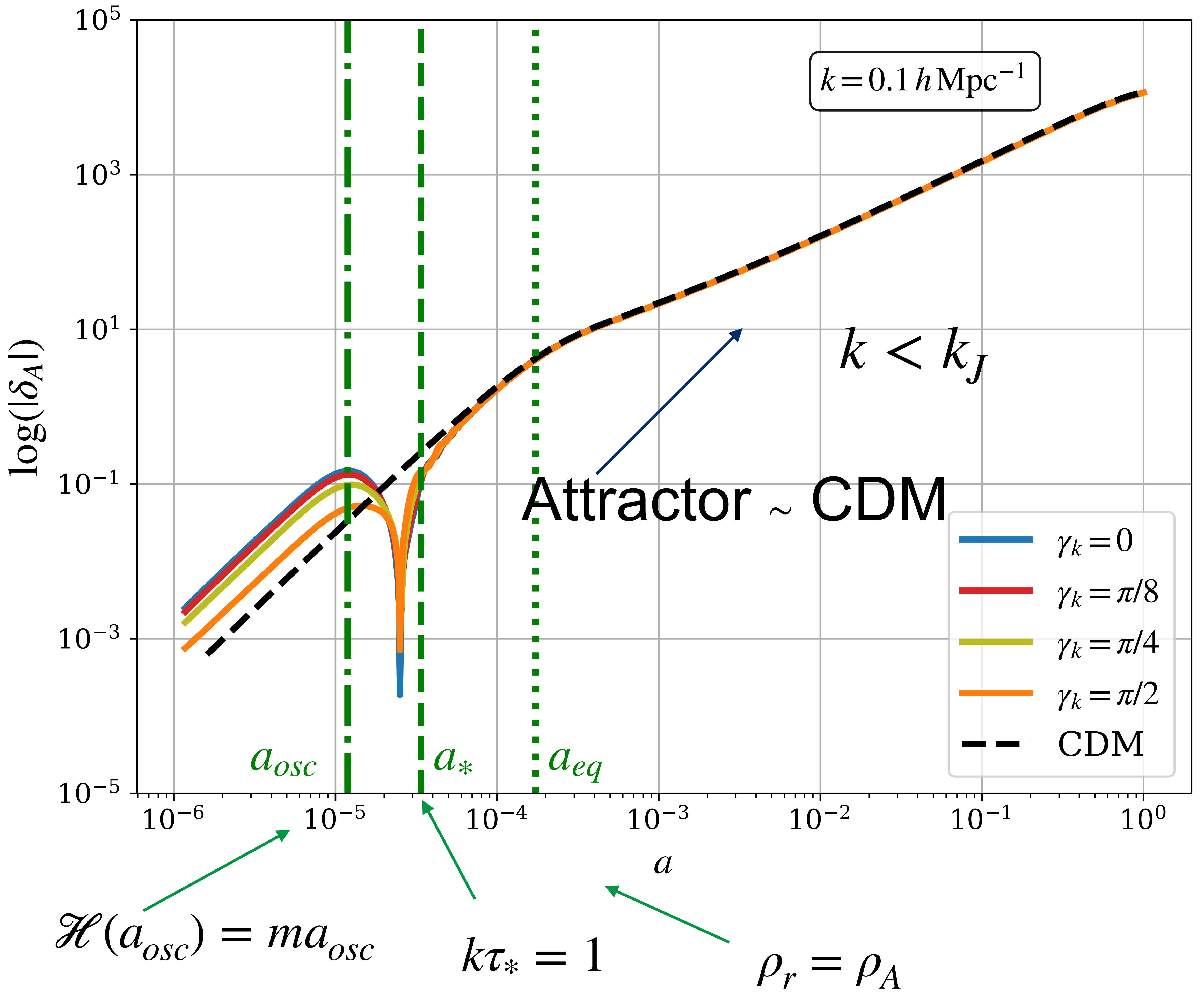
Parametrization

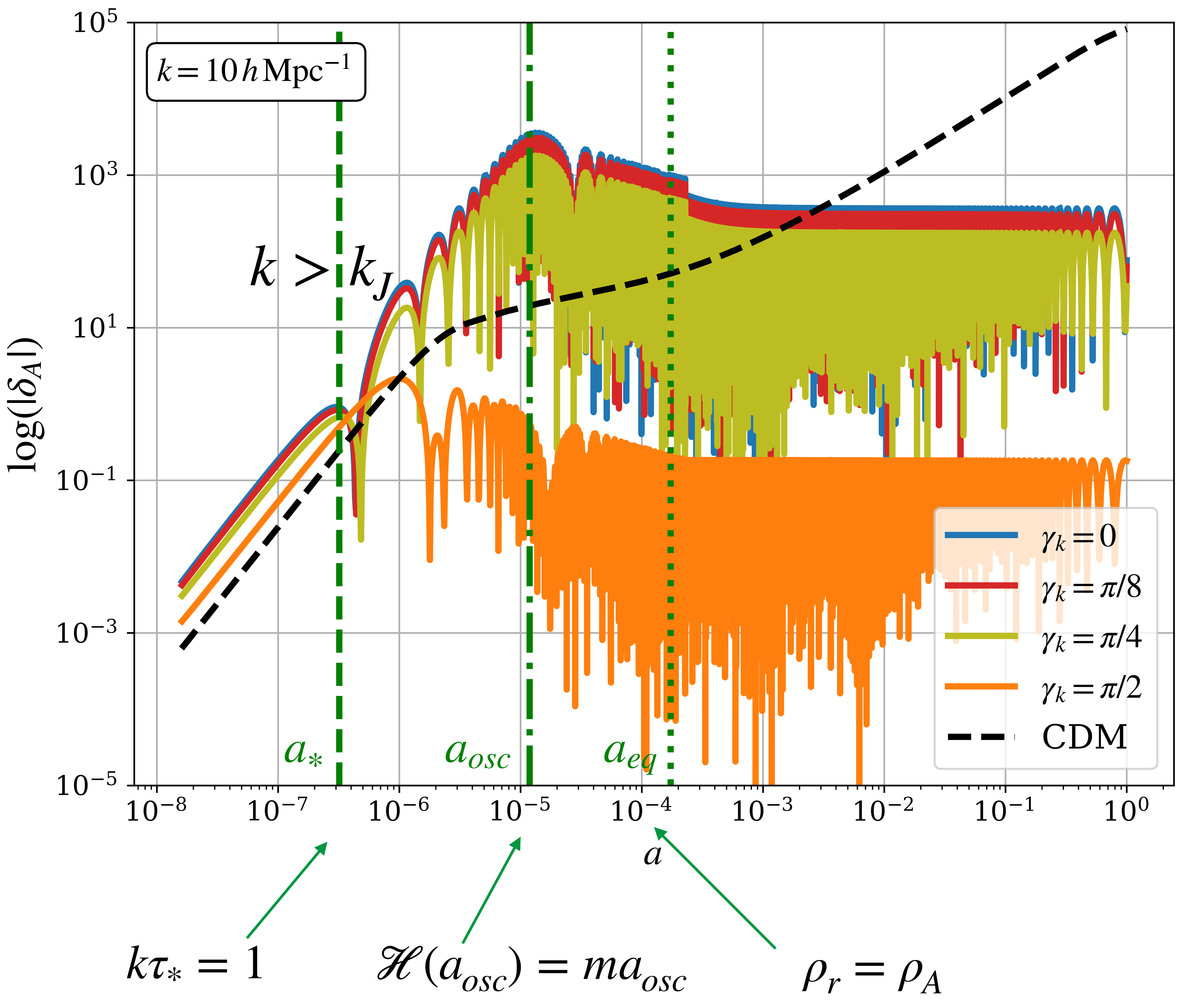
$$P(k, \gamma_k) = P(k, \frac{\pi}{2})\left(1 - g(k)\cos(\gamma_k)^4\right)$$

$$g(k) = 1 - P(k,0)/P(k, \frac{\pi}{2})$$

$$\%\mathrm{Diff} = 100 \times \left(\frac{P(k,\gamma_k) - P(k,0)}{P(k,0)}\right)$$

Angular dependence





%Diff = 100 × (PA − PB)/PB , where the spectrum PB corresponds to the VFDM model with $\gamma_k = 0$.

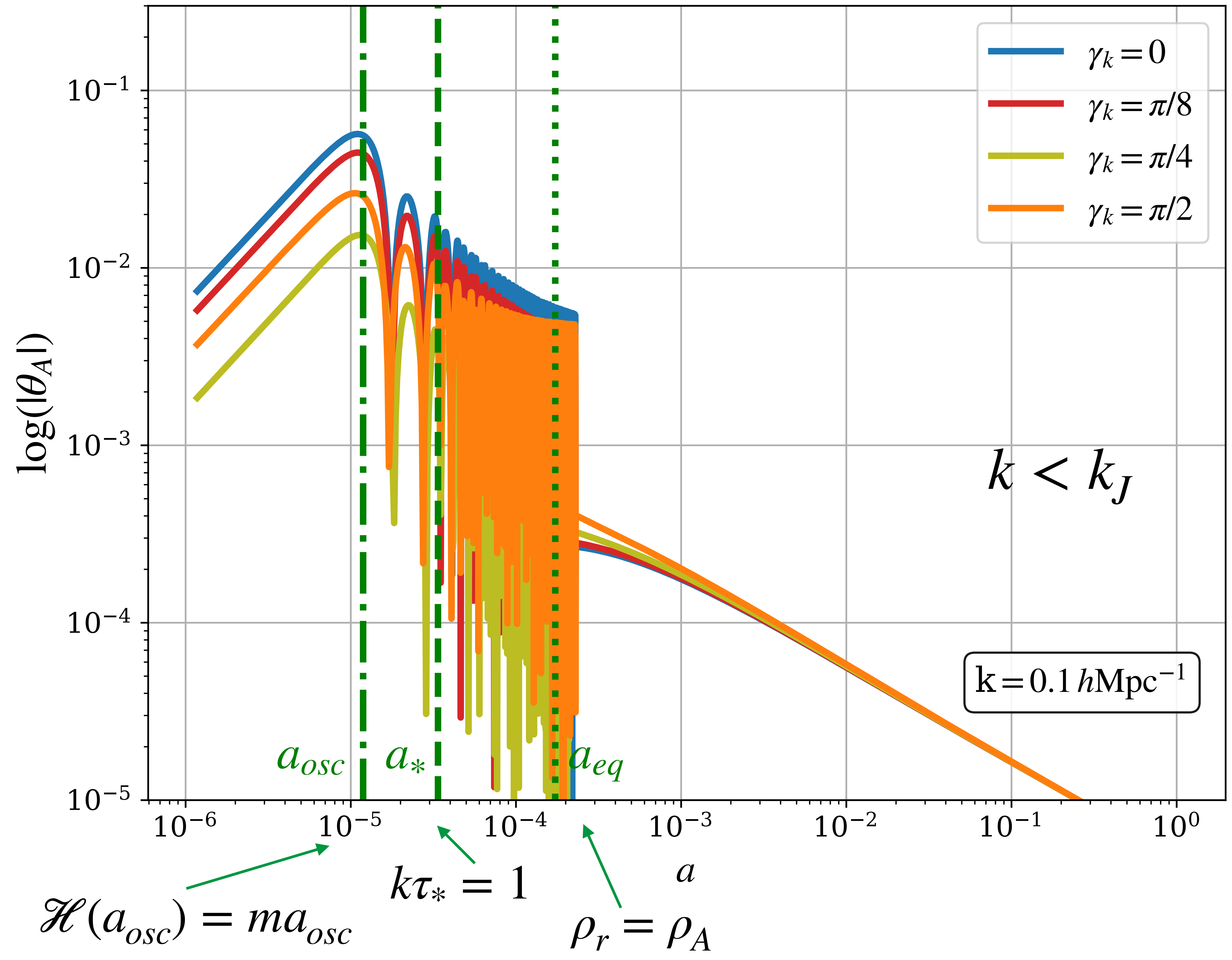
Velocity divergence evolution

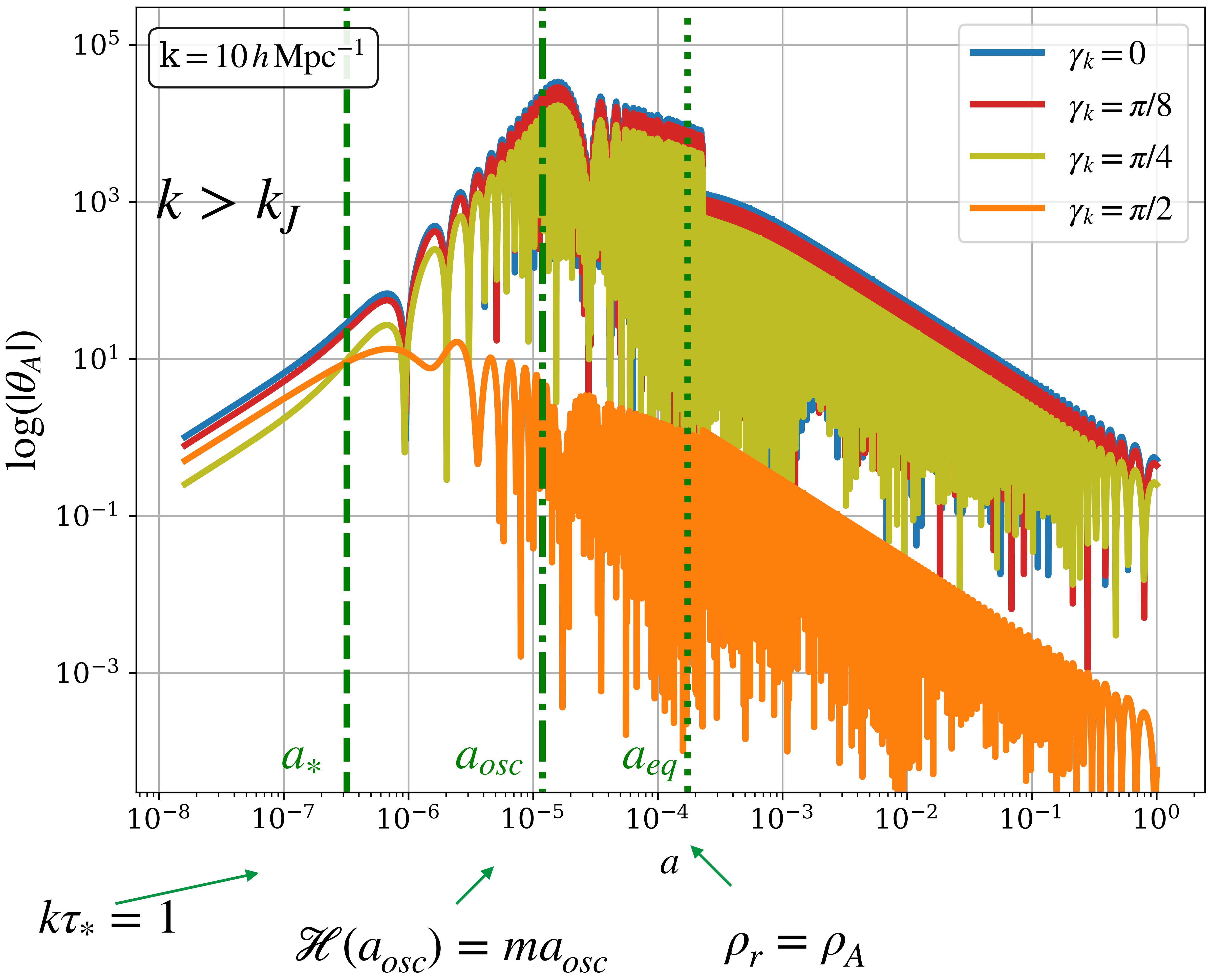
$$(\rho + P)\theta = ik^i \delta T^{A\,0}{}_i$$

E.g. $m = 10^{-25}\mathrm{eV}$ $\quad k_J \simeq 0.27\,\mathrm{h/Mpc}$

Combining Einstein & VFDM equations in MD for $k \gg \mathscr{H}$:

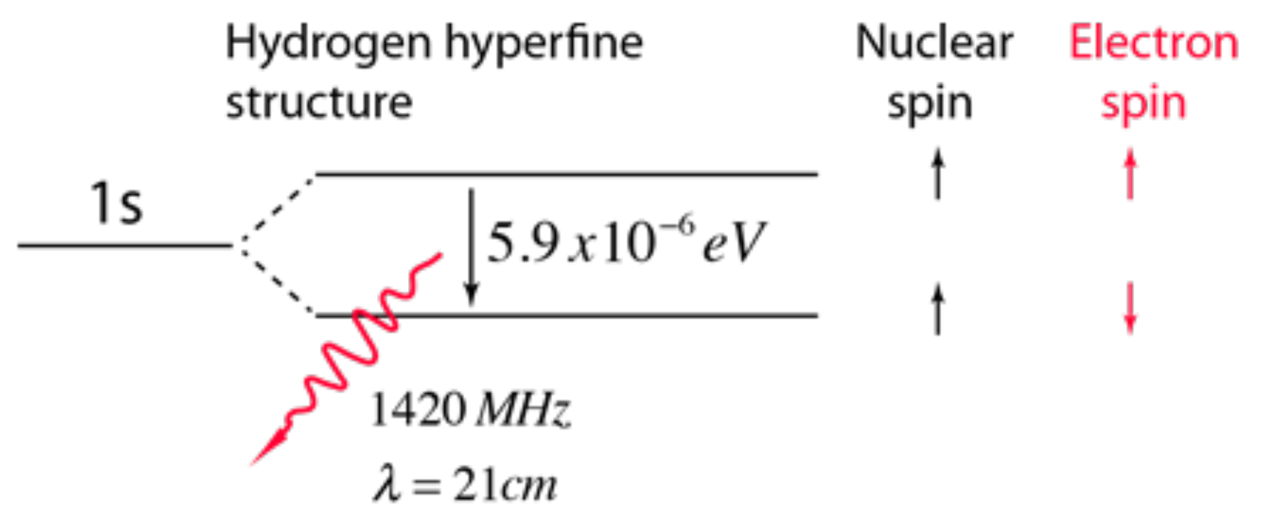
$$\theta'' + 3\,\theta' + \left(\frac{k^4}{k_j^4} + 2\right)\theta = -\frac{k^4}{k_J^4}\frac{k^2}{4\mathscr{H}}\eta$$





Power Spectums on small scales and observations

21-cm experiments: Use the redshifted 21 cm line emission from HI observed with radio telescopes to explore the large-scale structure



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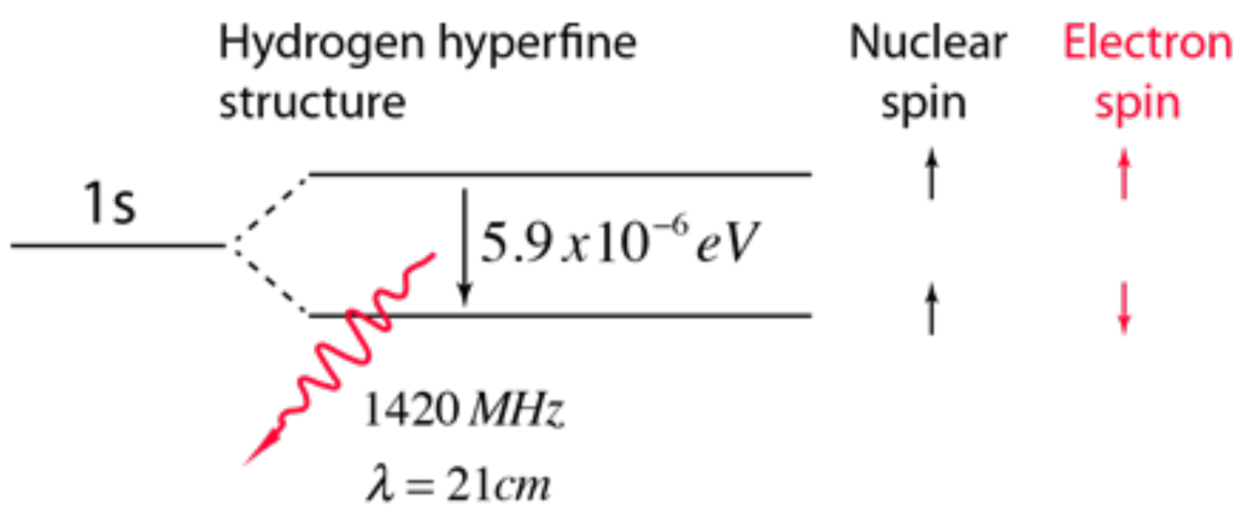

- According to forecasts in [Muñoz et al PRD 2020] on how well 21-cm experiments could probe the matter power spectrum (PS) during cosmic dawn ($z = 12 - 25$):

  - A global-signal experiment could measure the amplitude of the PS integrated over $k = (40 - 80)\,\mathrm{Mpc}^{-1}$ with a precision of tens of percent.

  - A fluctuation experiment could constrain the PS to a similar accuracy in bins covering $k = (40 - 60)\,\mathrm{Mpc}^{-1}$ and $k = (60 - 80)\,\mathrm{Mpc}^{-1}$ even without astrophysical priors.

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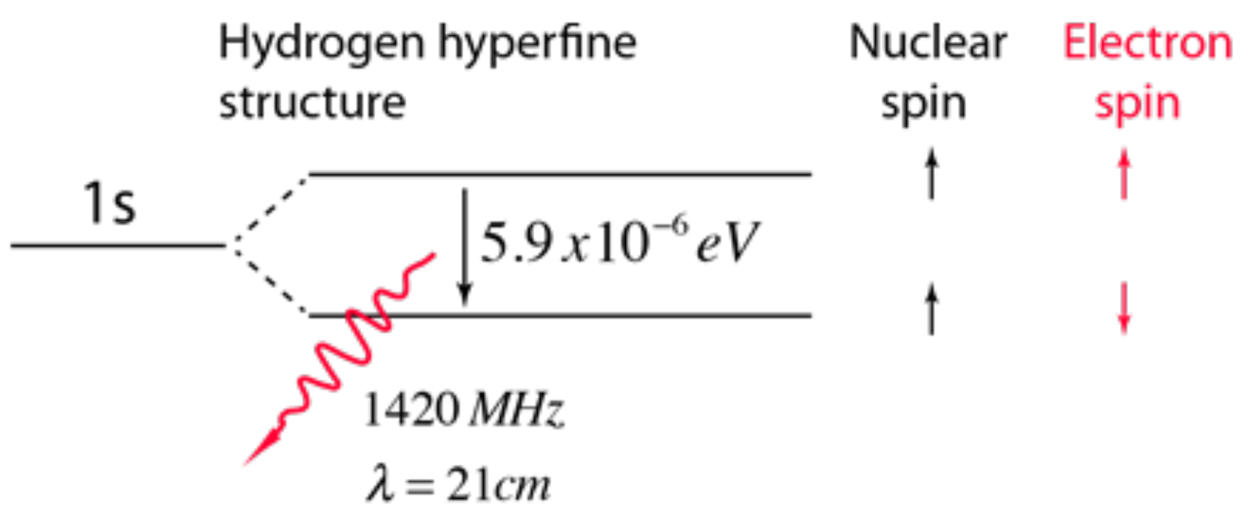

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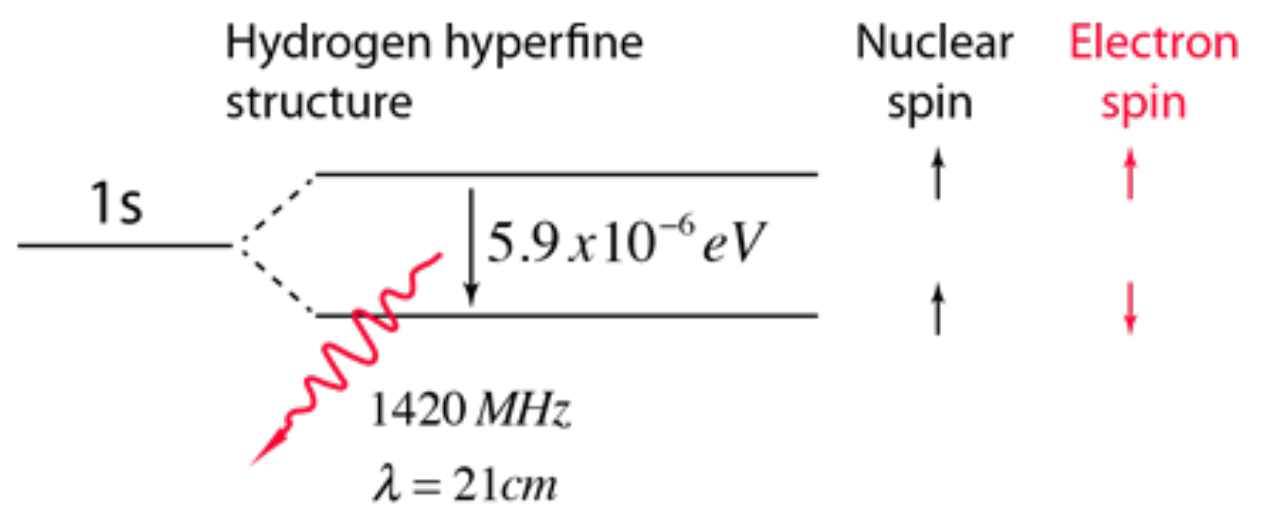

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- Forecasts generally assume that the relative velocity between CDM and baryons PS around recombination is the same for any DM candidate.

Baryon-DM *relative velocity Power Spectrum*

Baryon-DM relative velocity: $\overrightarrow{v_{bd}} = \overrightarrow{v_b} - \overrightarrow{v_d}$

$$\langle v_{bd}^2 \rangle = \int \frac{dk}{k} \Delta_{vbd}^2(k)$$

Primordial scalar power spectrum

$$\Delta_v^2(k) = \Delta_\zeta^2(k) \left(\frac{\theta_b - \theta_d}{k} \right)^2$$

Relative velocity divergence of baryons “b” and DM “d”

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- It is known that the Baryon-DM relative velocity can have an observable effect by suppressing star formation in the first structures at high redshift. This affects the 21 cm signal during Cosmic Dawn.

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- It is known that the Baryon-DM relative velocity can have an observable effect by suppressing star formation in the first structures at high redshift. This affects the 21 cm signal during Cosmic Dawn.
- For SFDM, the effect on the 21 cm power spectrum was studied in [Marsh PRD 2015, Hotinli et al PRD 2022], in particular the **VAO** features, reaching at the *optimistic* conclusion that eventually future experiments may be sensitive to $m \sim 10^{-18}\,\mathrm{eV}$!!

SFDM and velocity acoustic oscillations (VAO)

[Hotinli, Marsh & Kamionkowski PRD 2022]

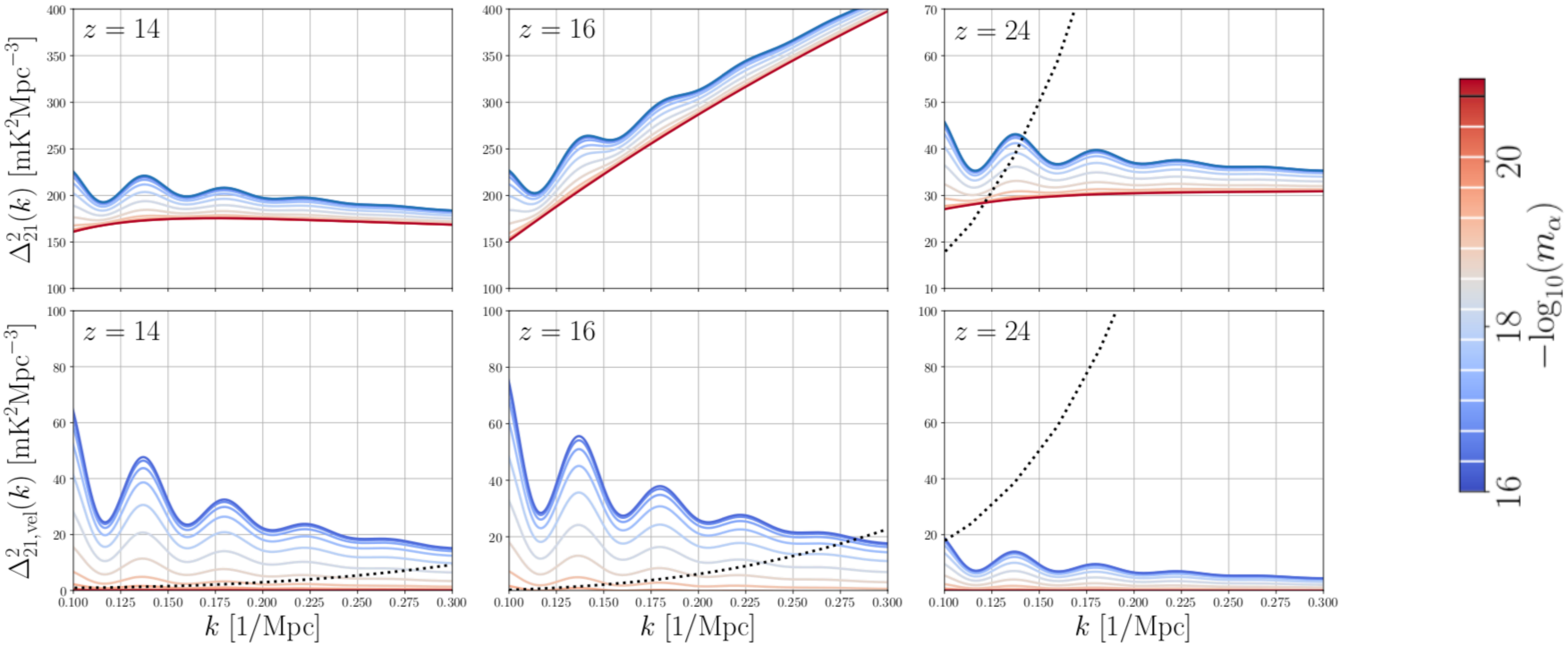
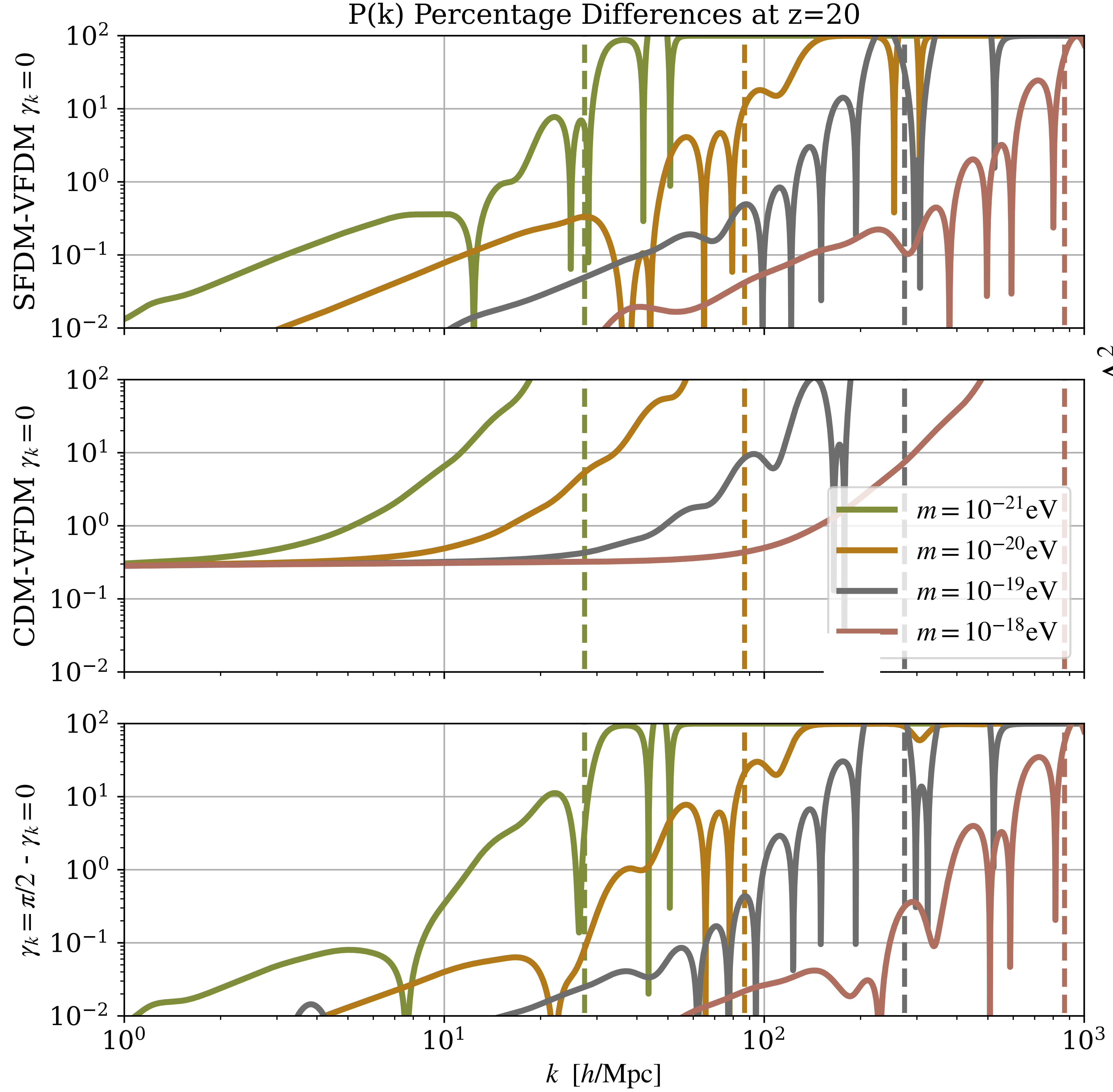
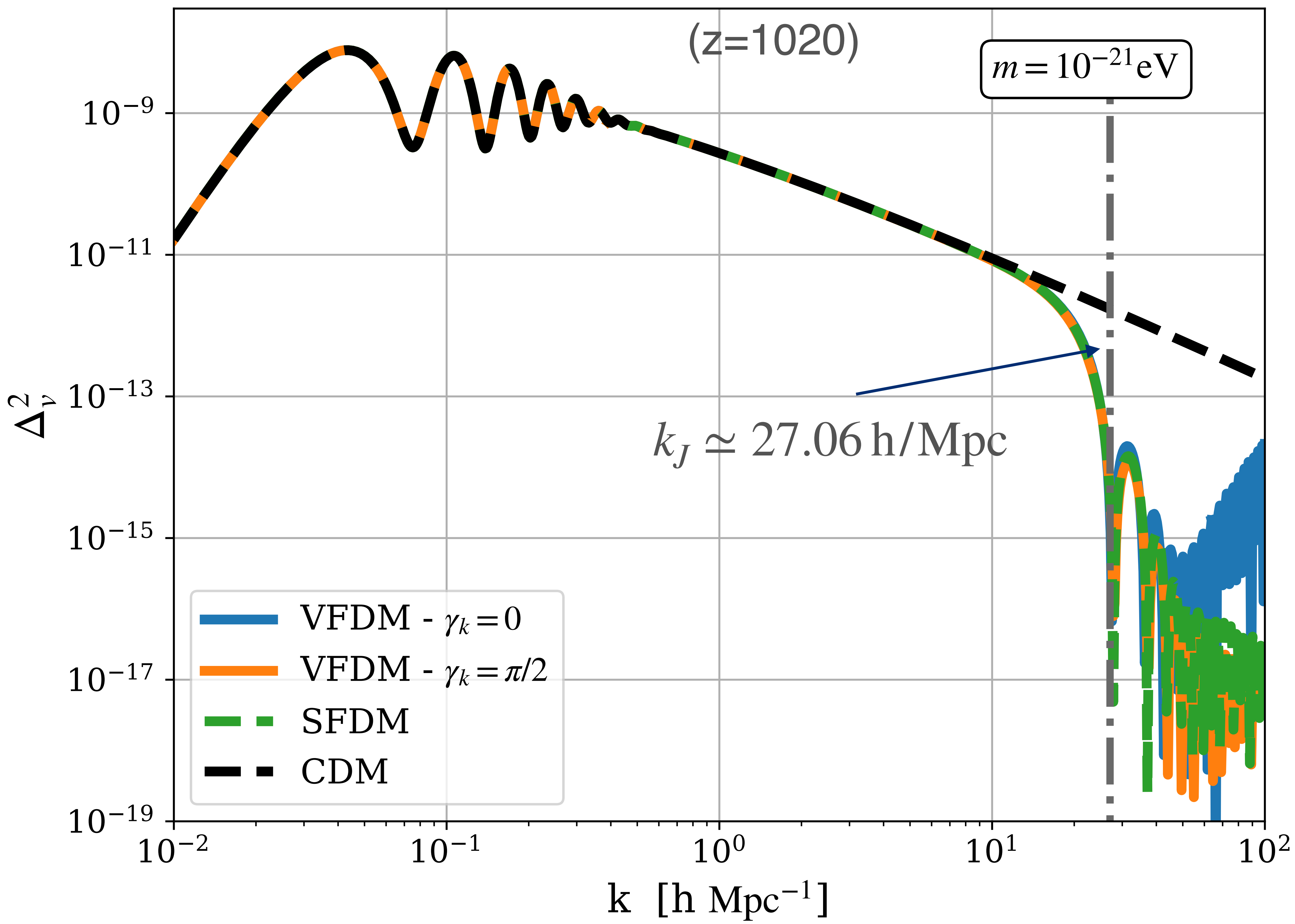


FIG. 3. **The effect of ULAs on the VAO signature in the 21-cm power-spectra for redshift bins centred at $z = \{14, 16, 24\}$**. The VAO amplitude can be shown to vary with m_α. The dotted black lines correspond to the anticipated noise (cosmic variance and thermal noise combined) for the HERA experiment, which we calculate with `21cmSense`. We discuss the binning in wavenumber k in Sec. IV. Upper plots correspond the 21-cm signal. The blue end of the color spectrum corresponds to the prediction from the ΛCDM cosmology, averaged over 20 simulations with `21cmvFAST`.

Matter & relative velocity power spectrums -VFDM vs SFDM





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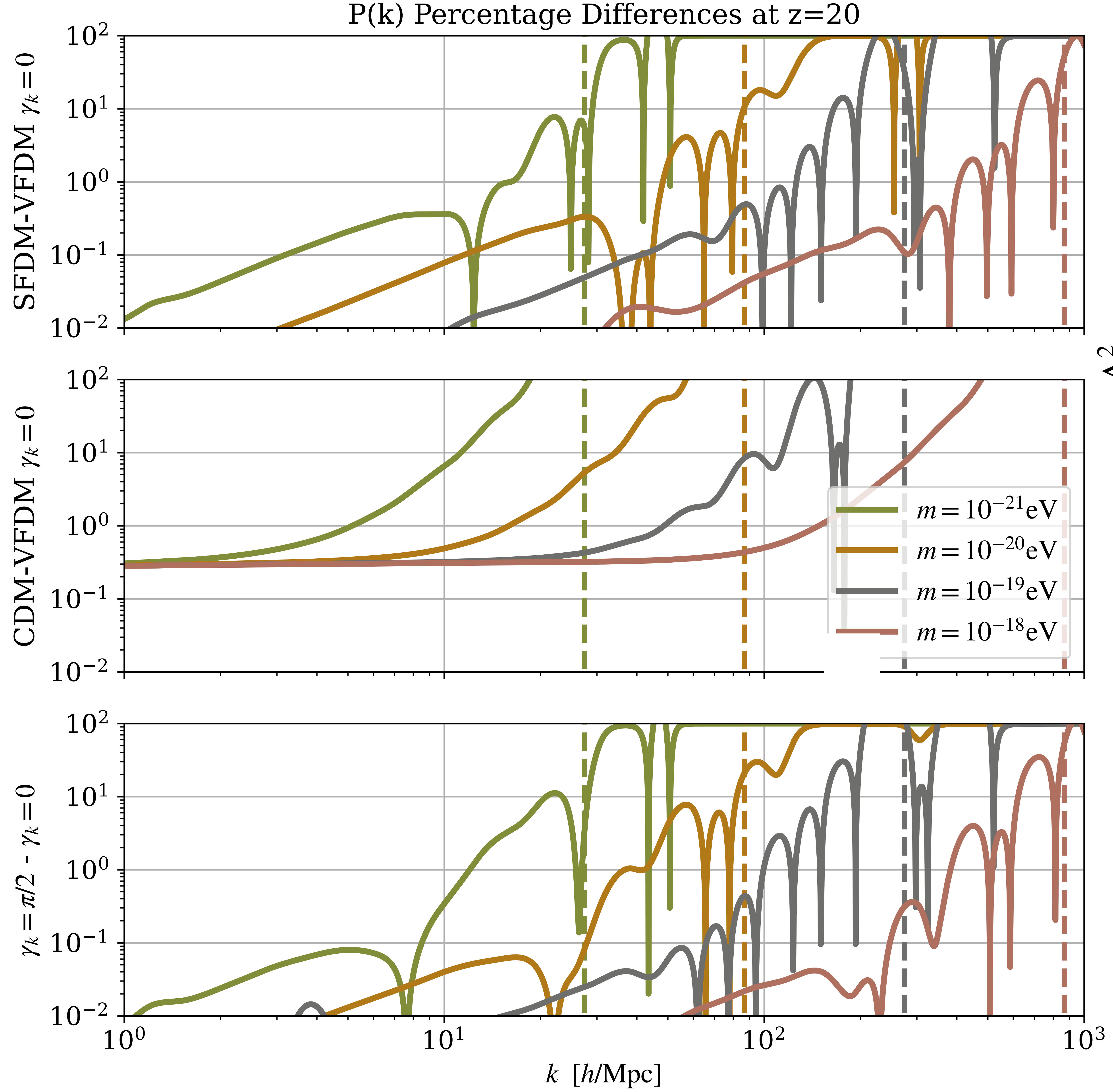

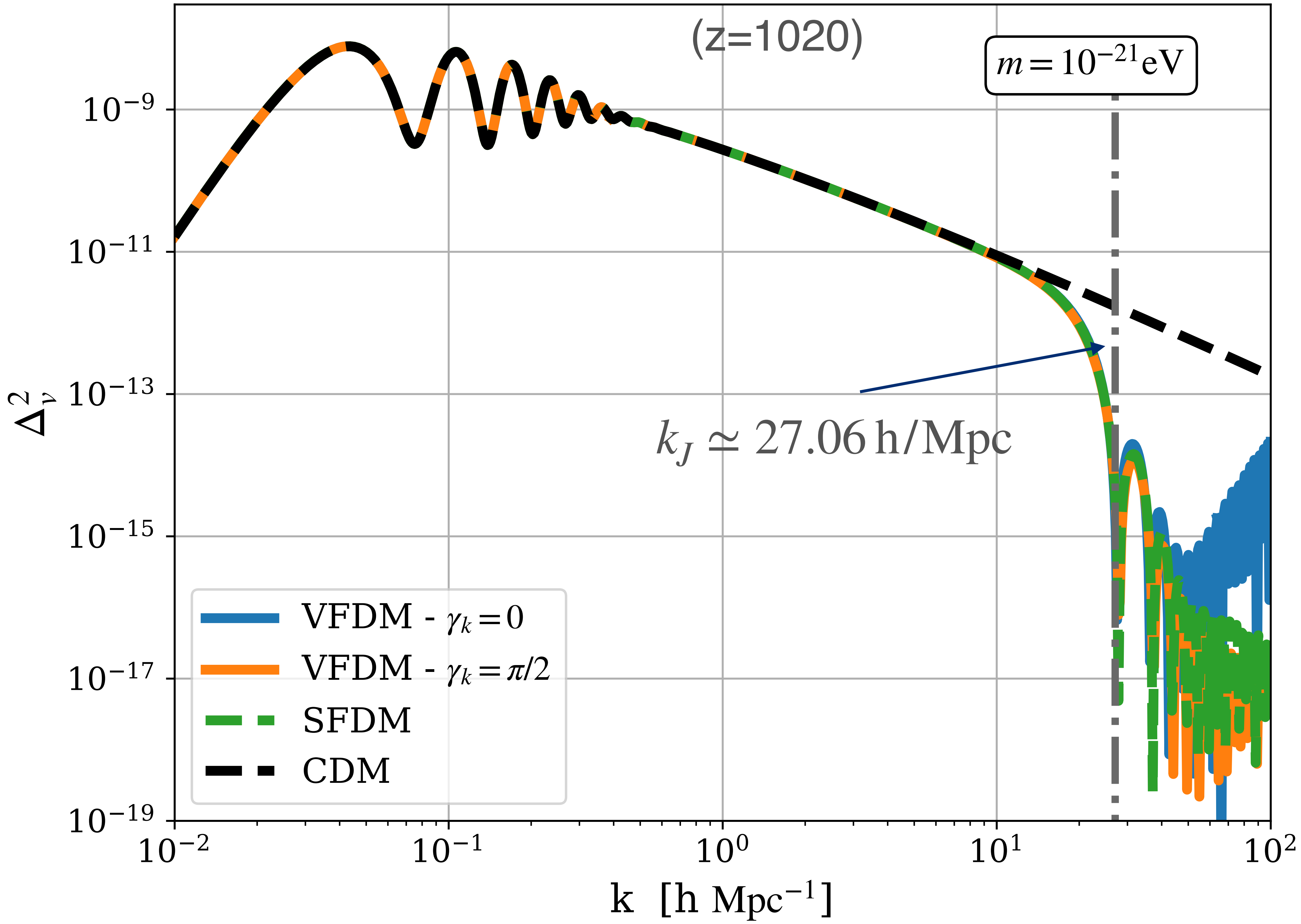

VFDM and SFDM have the same Jeans scale k_J but anisotropies and the enhancement of $\gamma_k \simeq 0$ modes make the analysis for VFDM more complicated than for the SFDM case…

Summary on Ultralight Dark Matter

Early-time evolution: SFDM behaves as isotropic Dark Energy. For VFDM σ_{ij} has to be considered in the early universe, BBN gives $m \gtrsim 10^{-26}\mathrm{eV}$.

Suppression effect at Jeans scale:

- *In both SFDM and VFDM models, we obtain a suppression in the power spectrums at small scales characterized by the same scale, namely the Jeans scale* $k_J = \sqrt{ma\mathscr{H}}$.

- For VFDM the amplitude depends on $\vec{k} \cdot \overrightarrow{A}$, leaving eventually possible anisotropic imprints in structure formation.

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Beyond the linear regime: constrains are sensitive to uncertainties in the modeling of small scale structure $\rightarrow$ crucial to have complementary independent probes

Phenomenological descriptions on small scales: necessary and under development

Thanks for your attention!!

Quantum Summer 2025

Iriri, ES, Brazil. April 07-11, 2025.

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