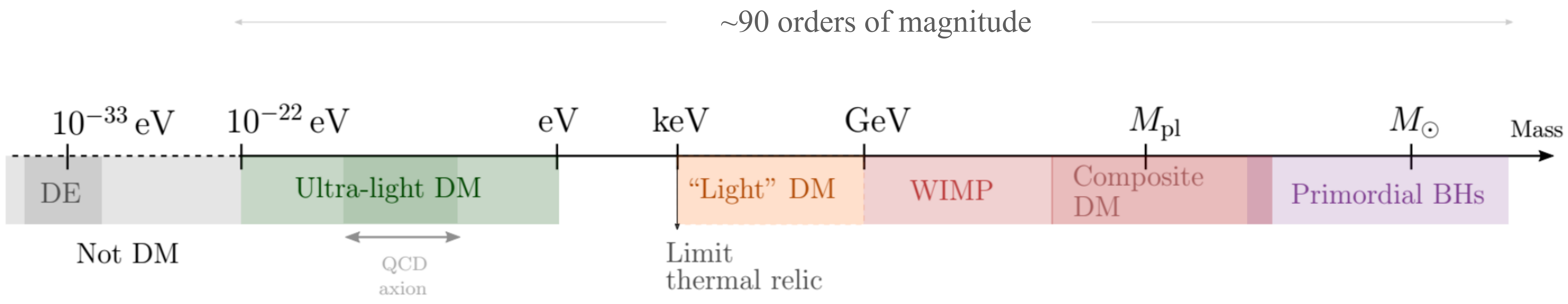
Cold and fuzzy dark sector

Christian Capanelli (McGill $\longrightarrow$ IPMU)

with Evan McDonough and Elisa GM Ferreira [2509.15299]

Zoo of ultralight models



[E.G.M. Ferreira 2020]

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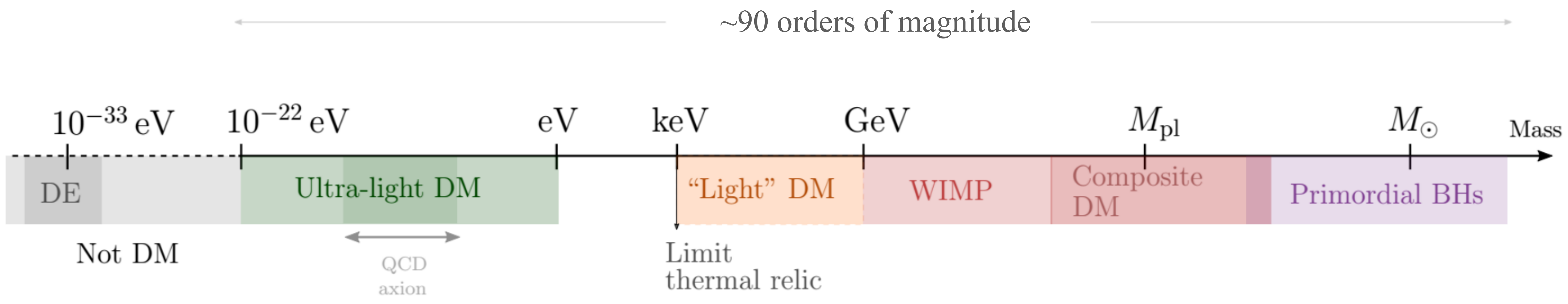

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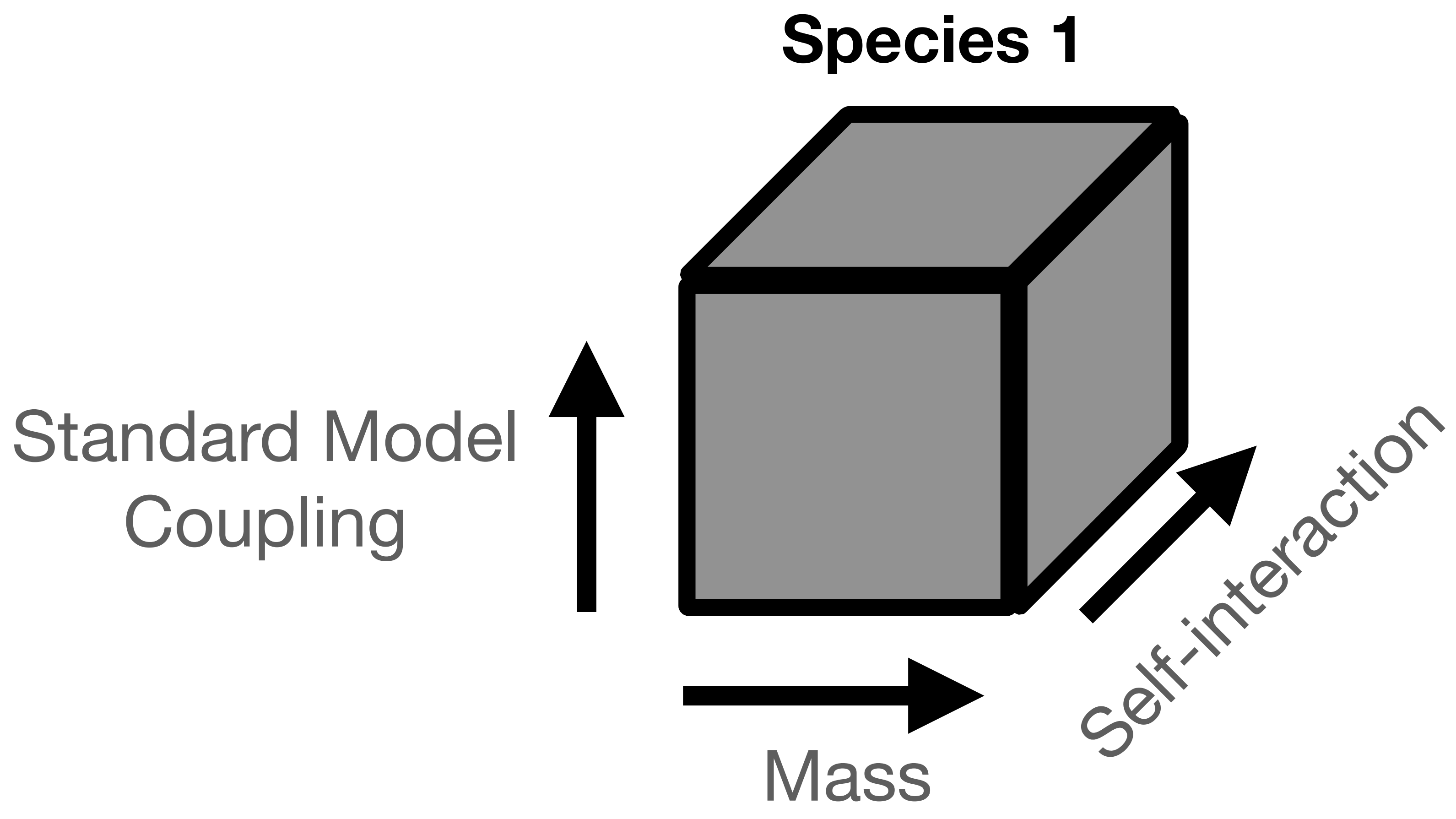

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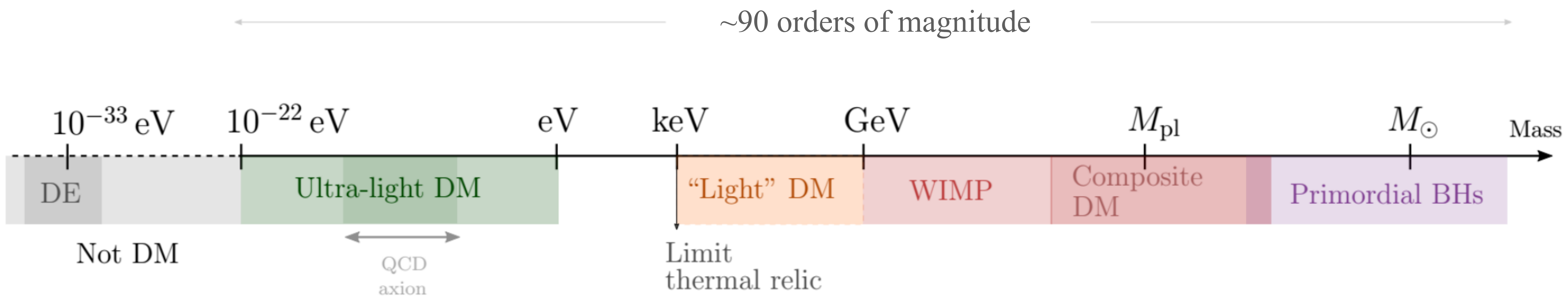

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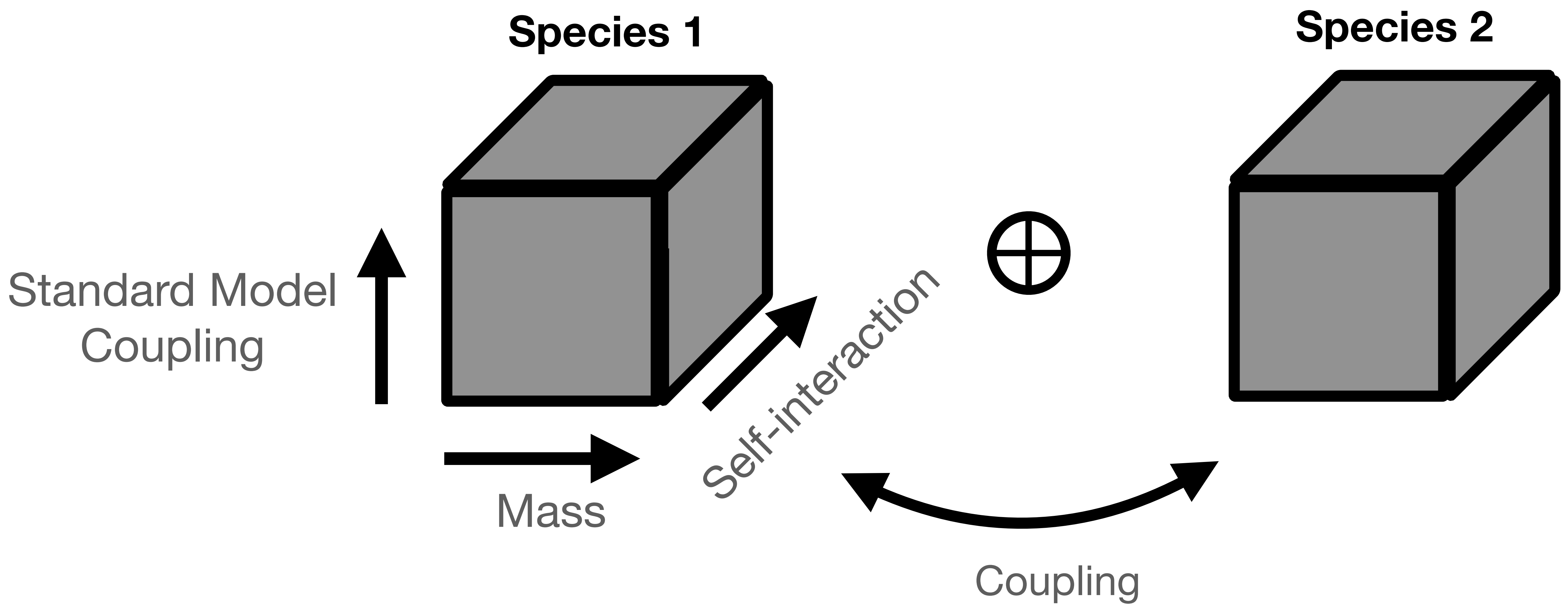

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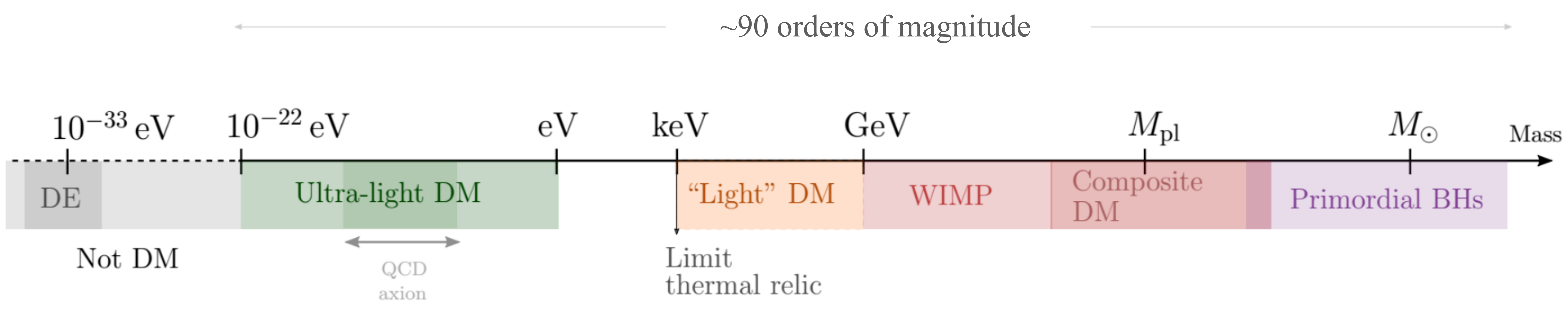

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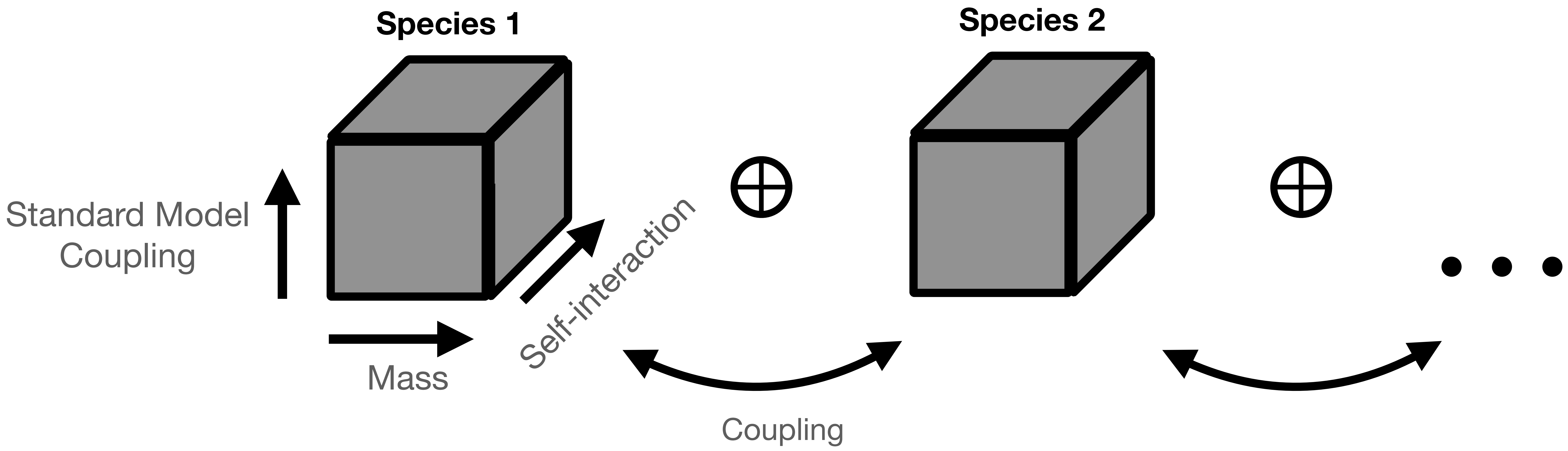

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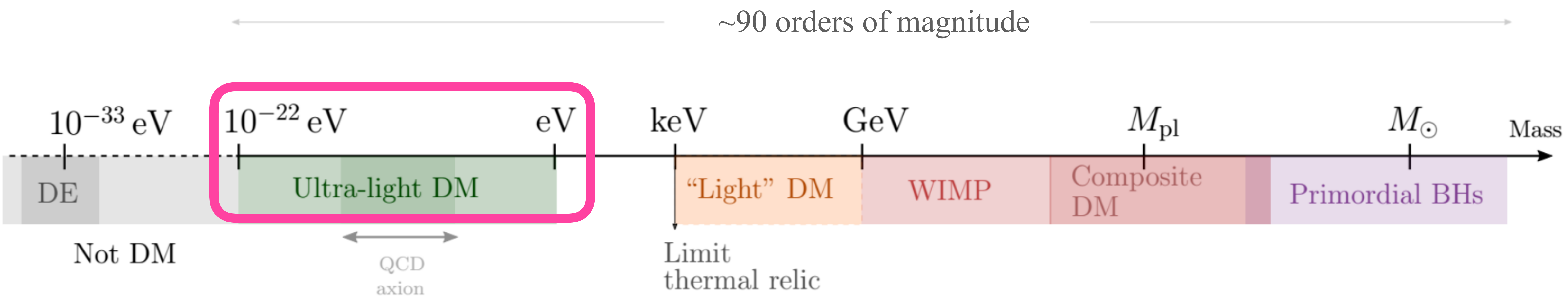

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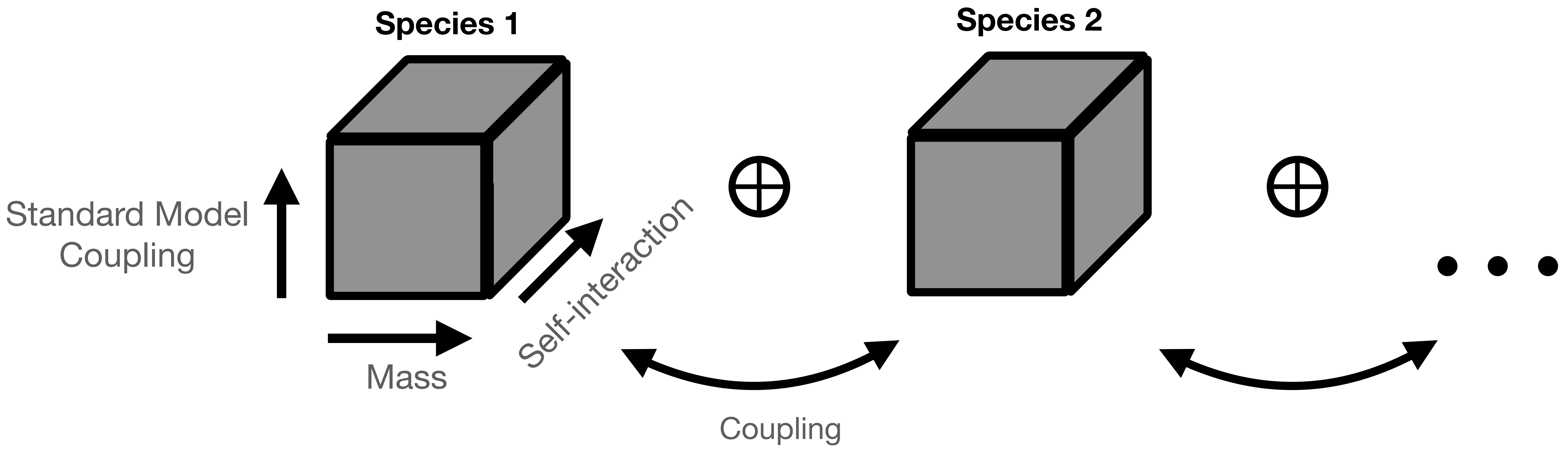

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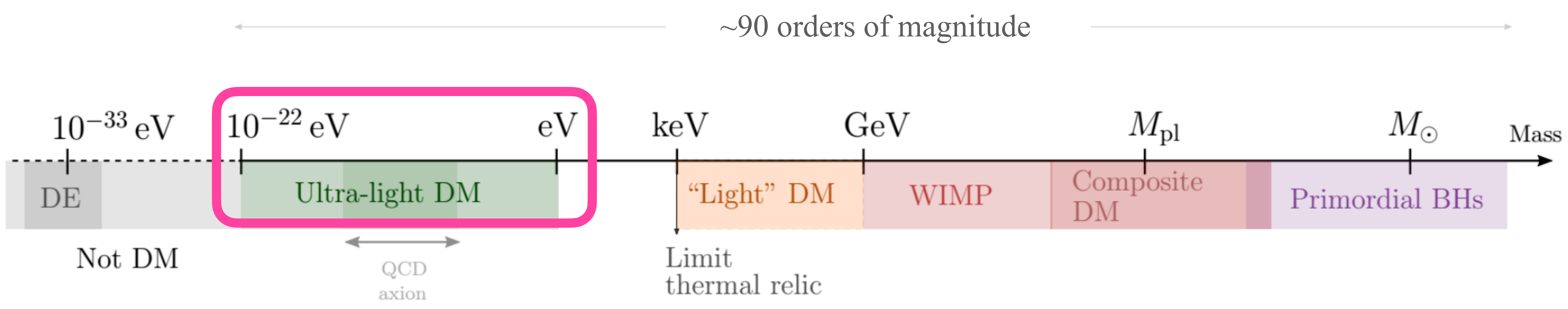

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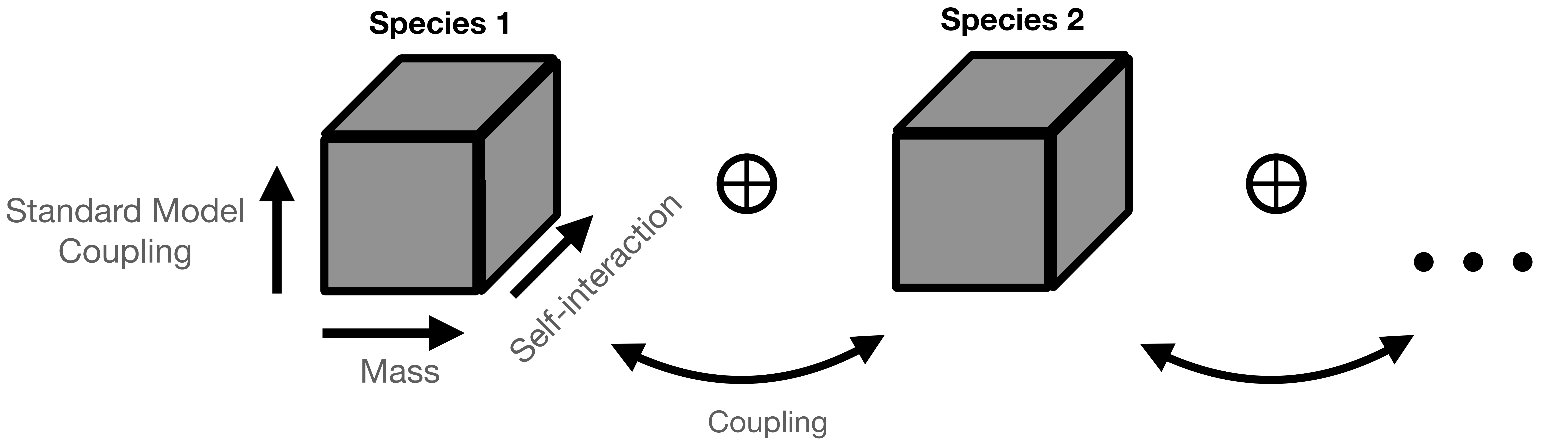
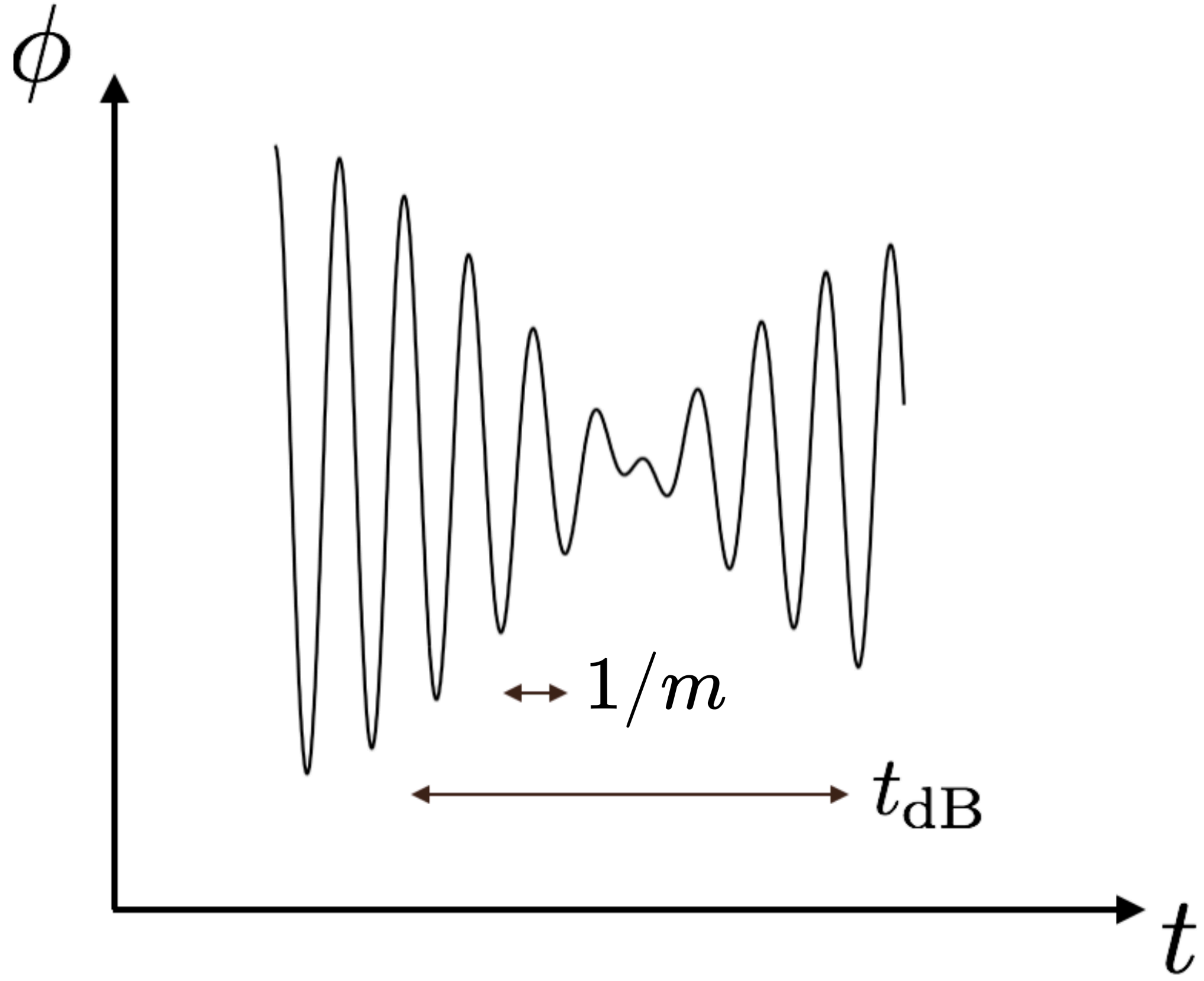


Non-stringy spectrum of ultralight bosons?

Secluded dark sector?

Single field non-relativistic limit

Slow and fast modes



[L. Hui 2101.11735]

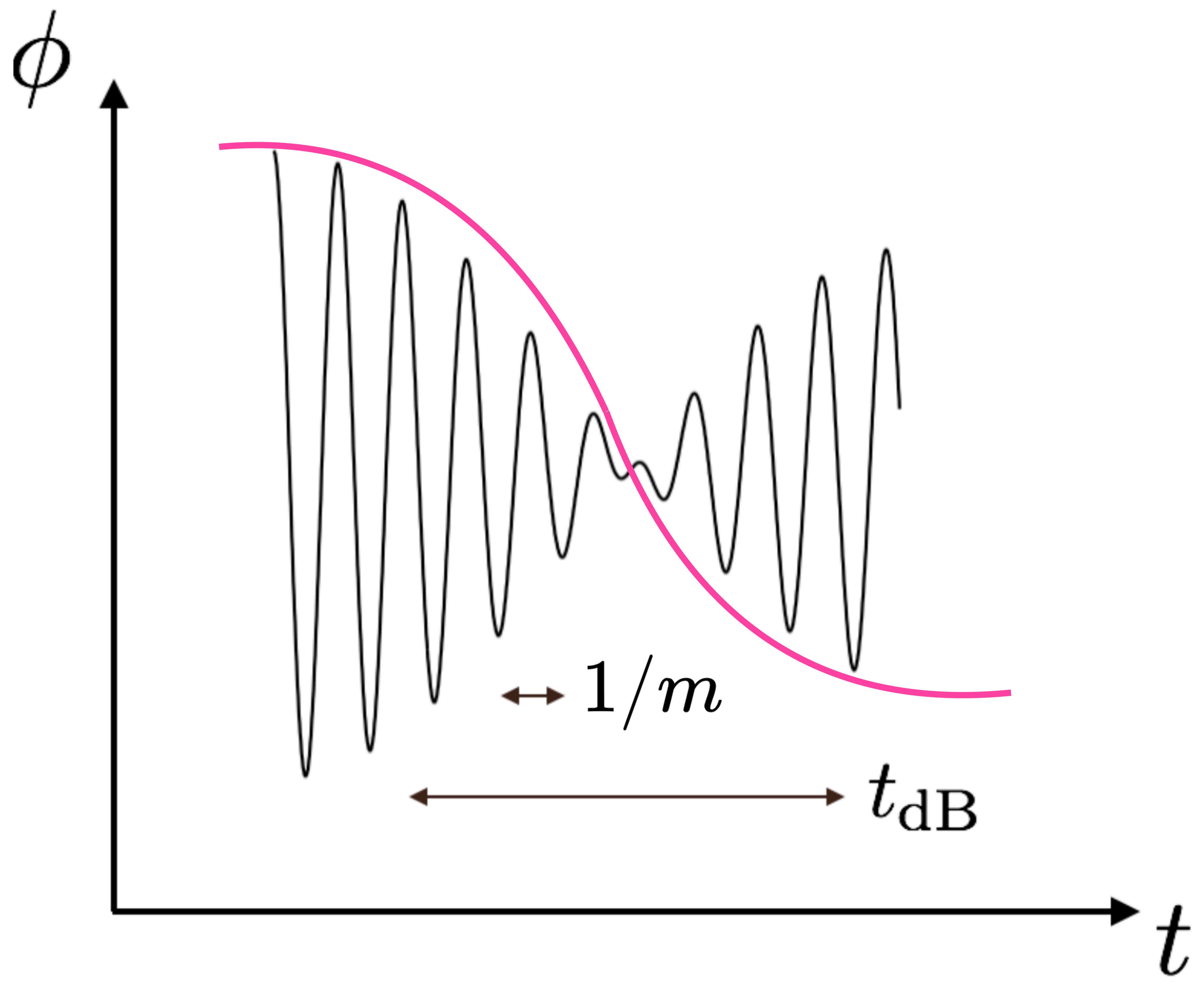
Decompose a real scalar field:

$$\phi = \frac{1}{\sqrt{2m}}\left(\psi e^{-imt} + \psi^* e^{imt}\right)$$

where $\dot{\psi} \ll m\psi$

Single field non-relativistic limit

Slow and fast modes



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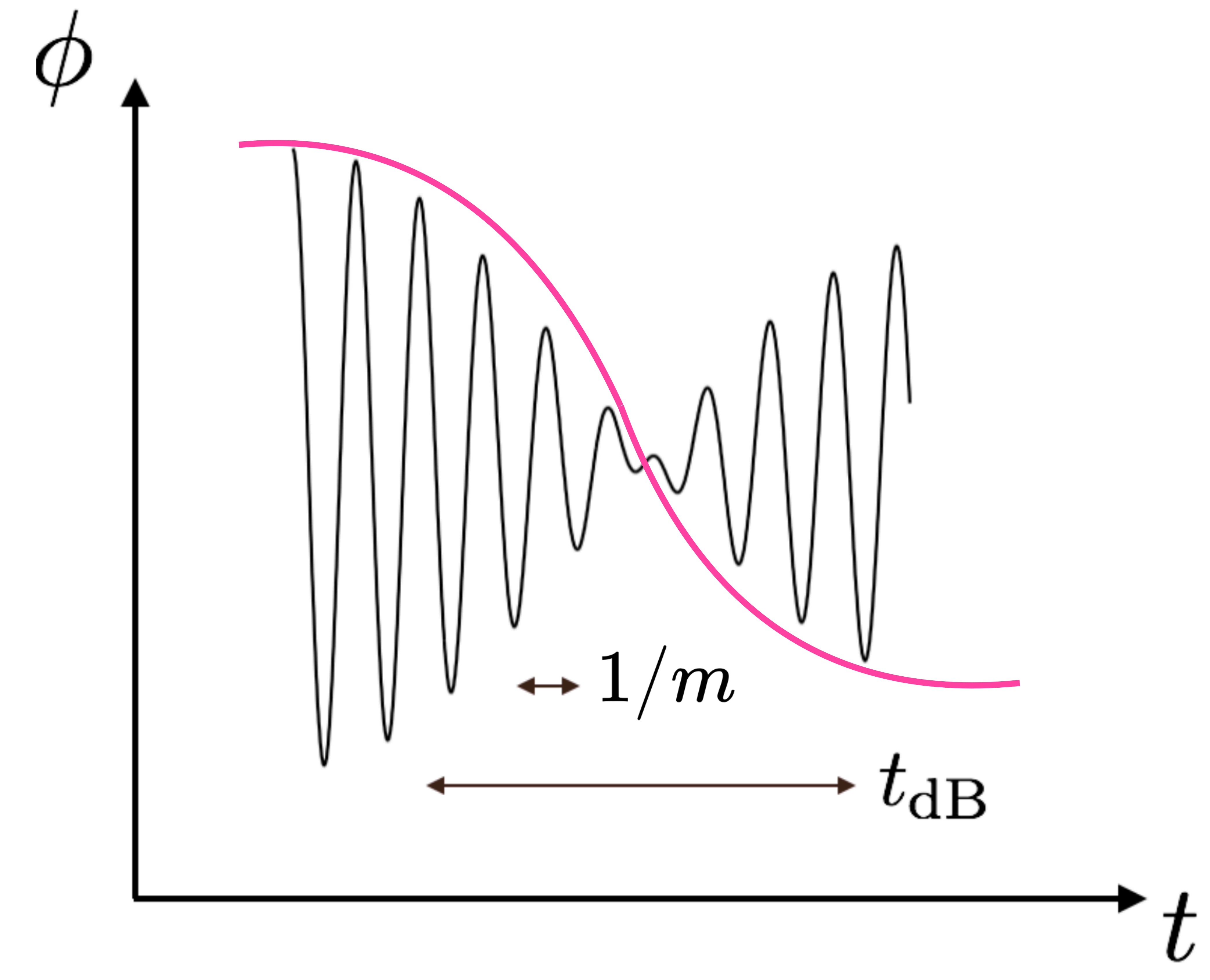

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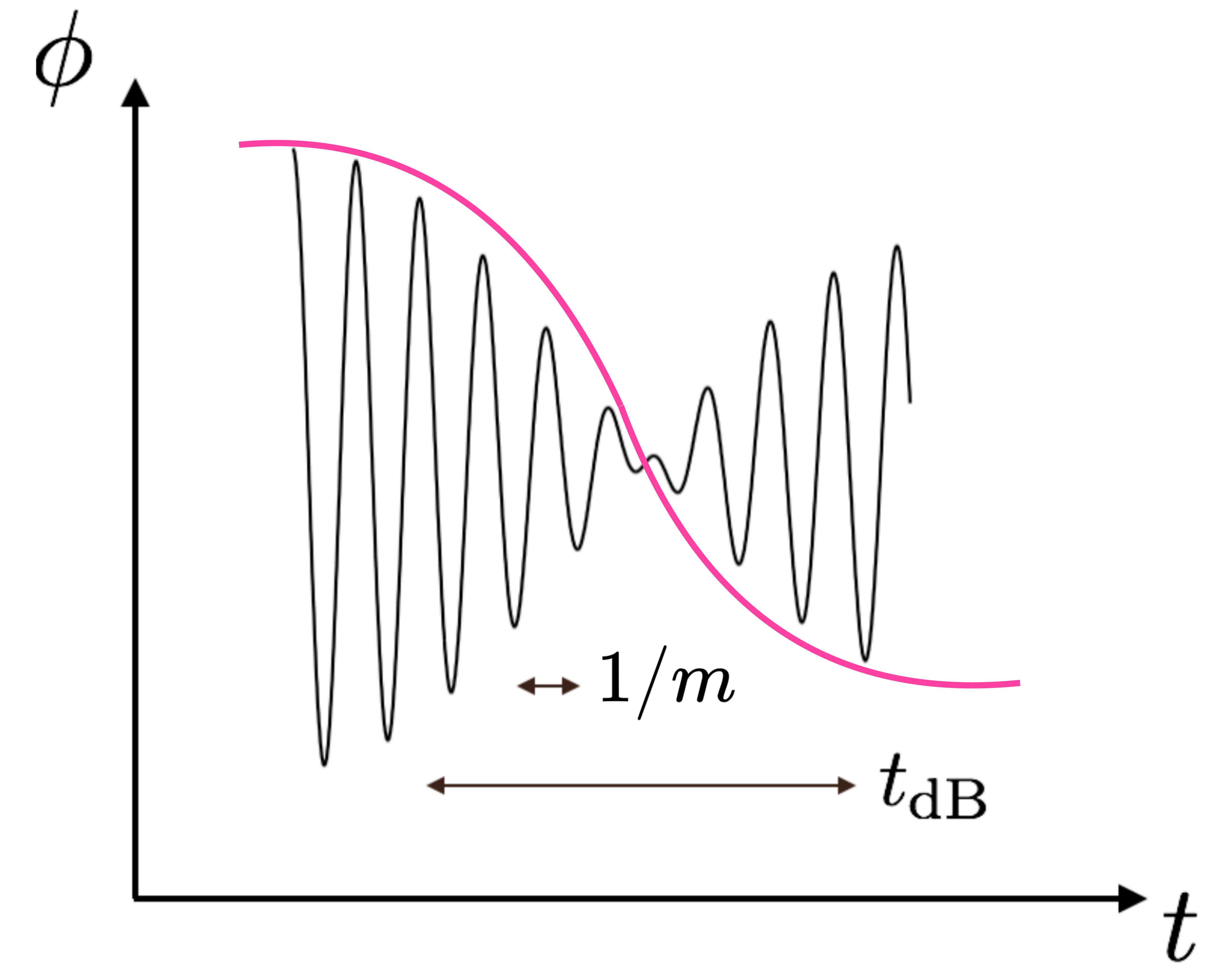

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Interpretation: $\rho = m|\psi|^2$

$$\boxed{i\dot{\psi} = -\frac{1}{2m}\nabla^2\psi + m\Phi_N\psi + \frac{g}{2}|\psi|^2\psi}$$

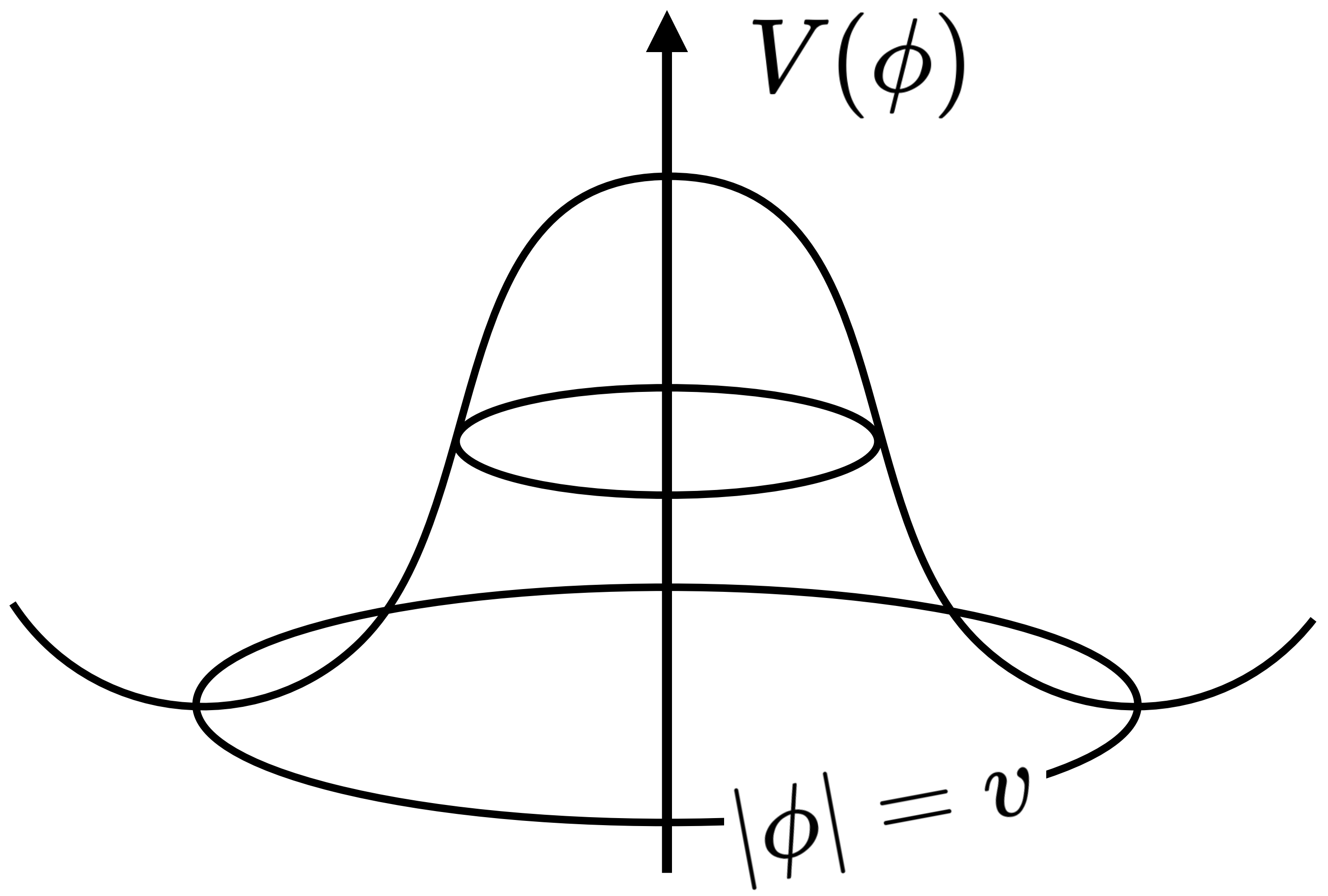
Model

Dawn of the fuzzy dark sector

CC, Ferreira, McDonough [2509.15299]

Ultra-light Abelian Higgs

$$S = \int \mathrm{d}^4x \sqrt{-g}\left[\frac{R}{16\pi G} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\left|D_\mu\phi\right|^2 - \frac{\lambda}{4!}\left(|\phi|^2 - v^2\right)^2\right]$$



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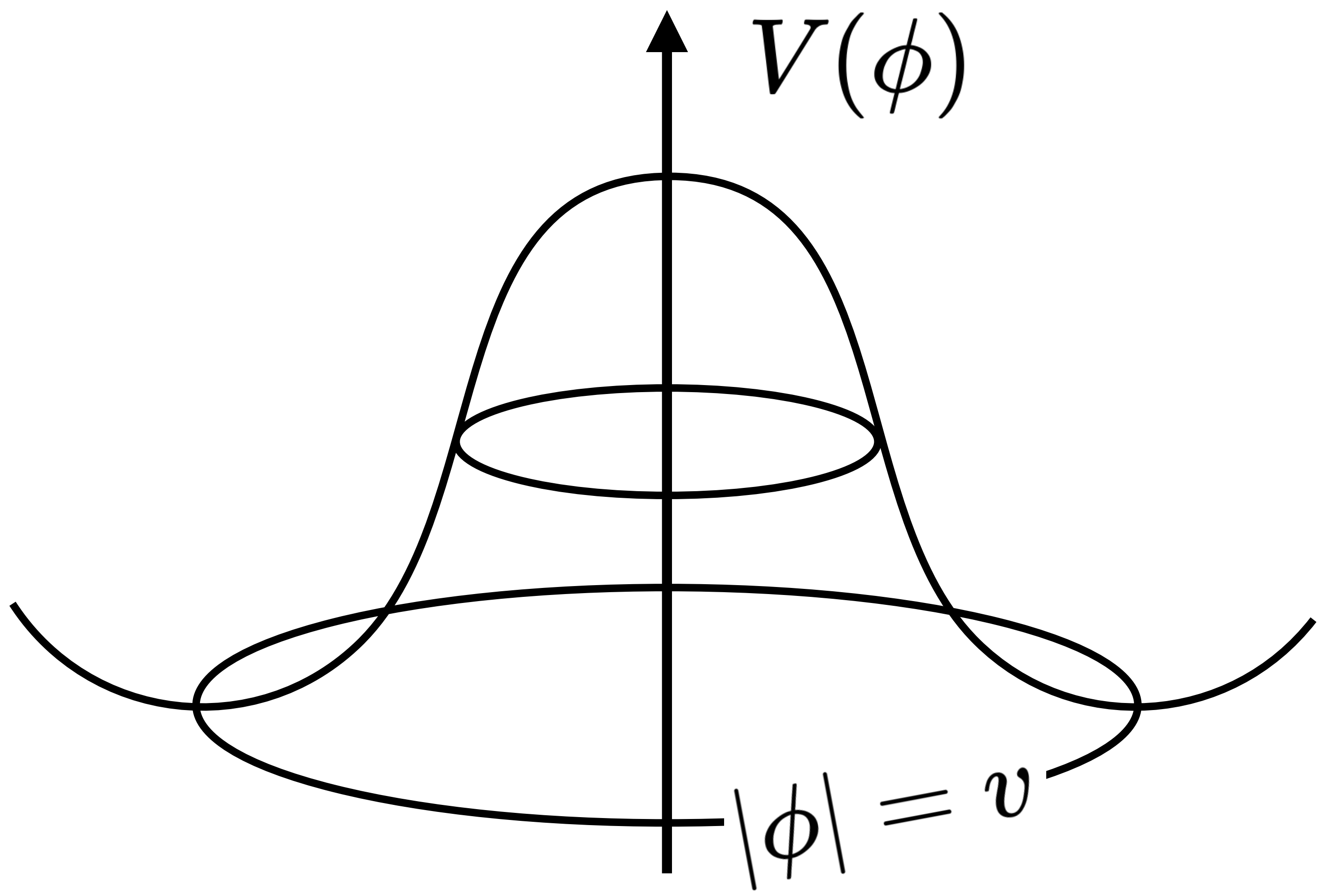

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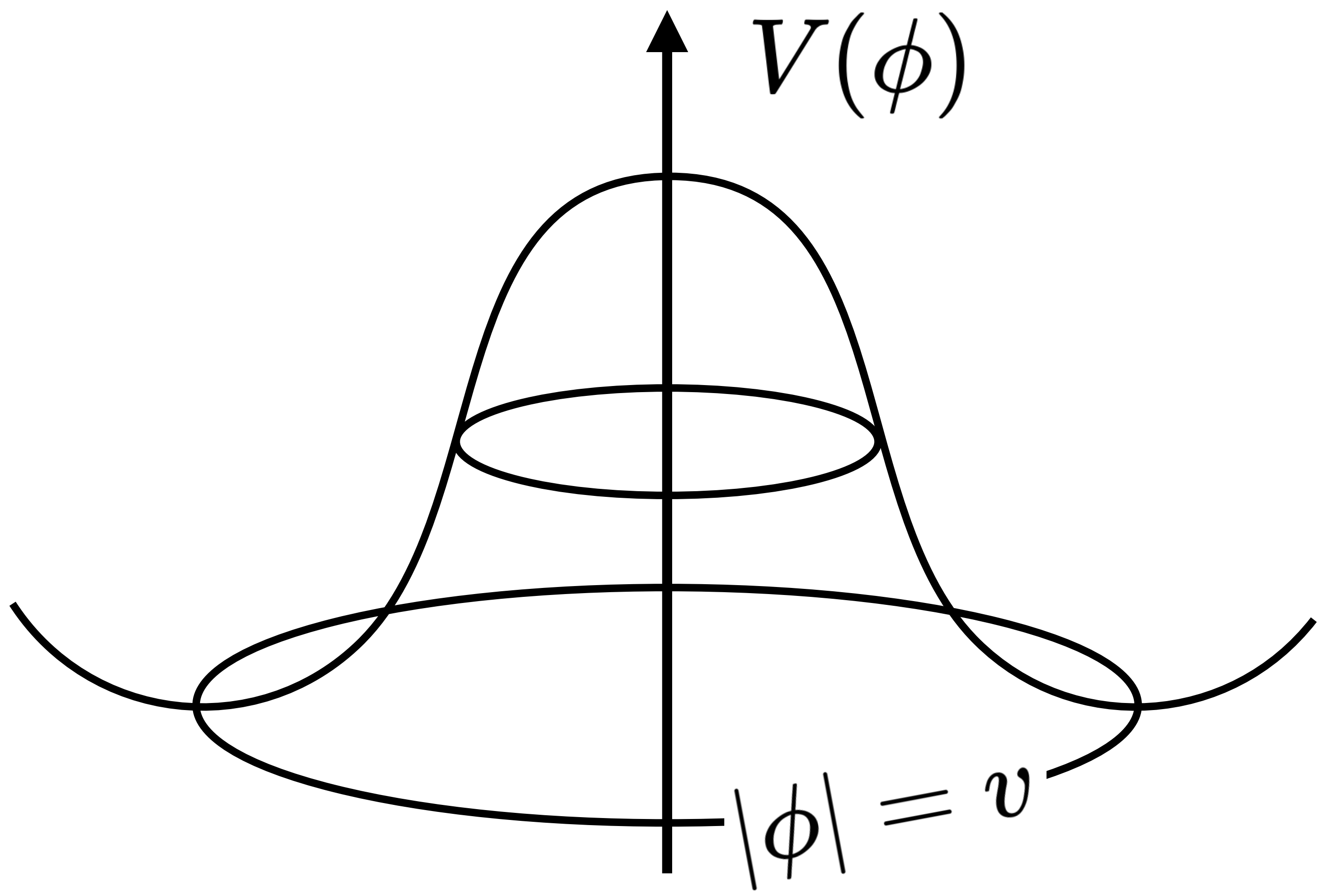

Particle masses

$$m_A^2 \equiv g^2v^2$$
$$m_h^2 \equiv 2\lambda v^2$$

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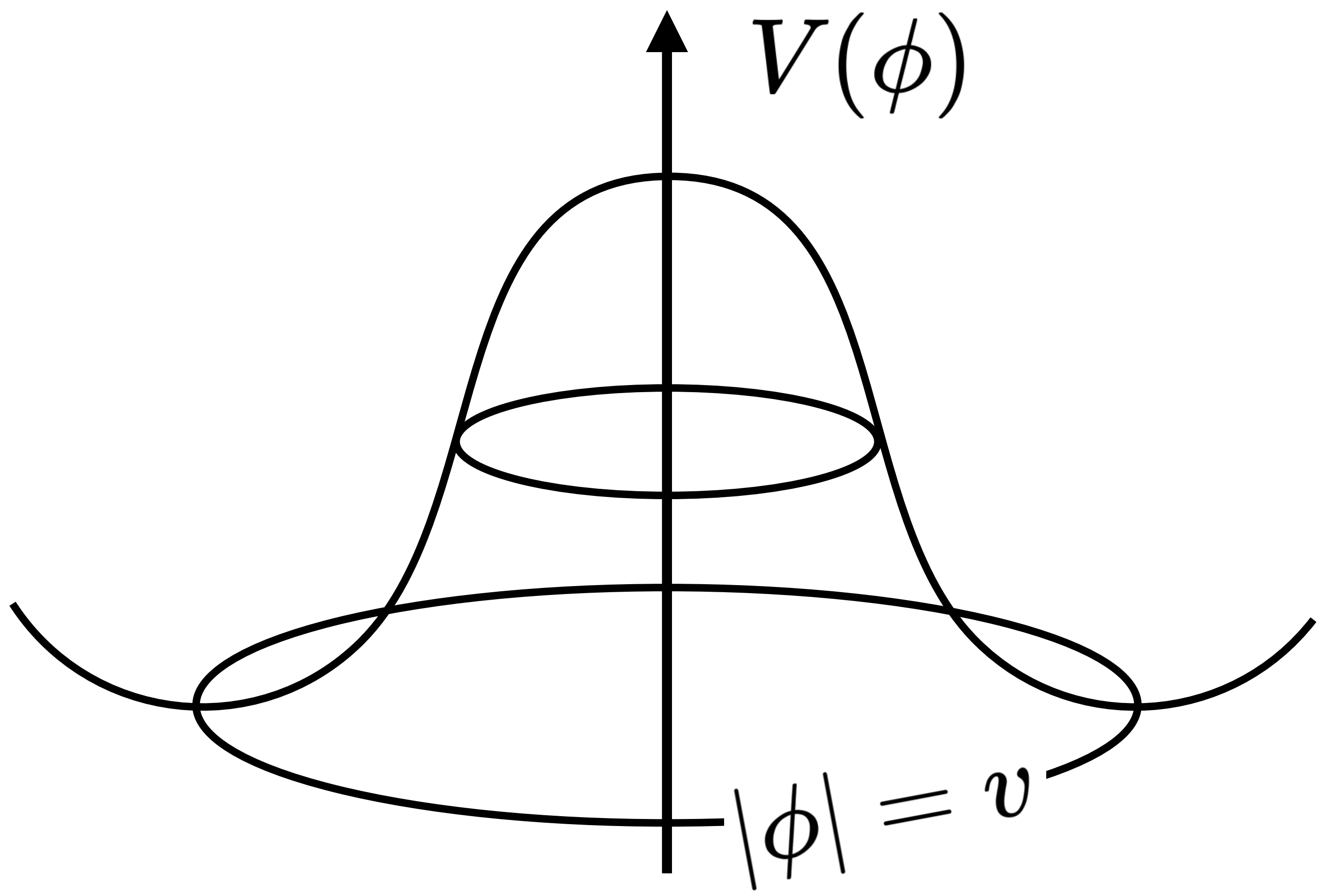

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For the Fuzzy Dark Sector

$$\lambda \sim g^2$$

$$m_A, m_h \ll \mathrm{eV} \Rightarrow \lambda, g \ll 1$$

Fuzzy dark sector

Non-relativistic limit

CC, Ferreira, McDonough [2509.15299]

Dark Photon $$i\partial_t\vec{\mathcal{A}} = -\frac{1}{2m_A}\nabla^2\vec{\mathcal{A}} + m_A\Phi\vec{\mathcal{A}}$$

Fuzzy dark sector

Non-relativistic limit

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Dark Photon $$i\partial_t \vec{\mathcal{A}} = -\frac{1}{2m_A}\nabla^2 \vec{\mathcal{A}} + m_A \Phi \vec{\mathcal{A}}$$

Scalar (Higgs) $$i\partial_t h = -\frac{1}{2m_h}\nabla^2 h + m_h \Phi h$$

$$\nabla^2 \Phi = 4\pi G \left(m_A |\mathcal{A}|^2 + m_h |h|^2 \right)$$

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Higgs (repulsive) self-interaction

Fuzzy dark sector

Non-relativistic limit

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Higgs-photon coupling

Dark Photon $$i\partial_t \vec{\mathcal{A}} = -\frac{1}{2m_A}\nabla^2\vec{\mathcal{A}} + m_A\Phi\vec{\mathcal{A}} - g^2\frac{\vec{\mathcal{A}}}{2m_A}\frac{|h|^2}{m_h}$$

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Fuzzy dark sector

EFT pitfalls

$$\mathcal{L} \supset hA^2 \sim \exp\left(\pm i\left(m_h - 2m_A\right)t\right)$$

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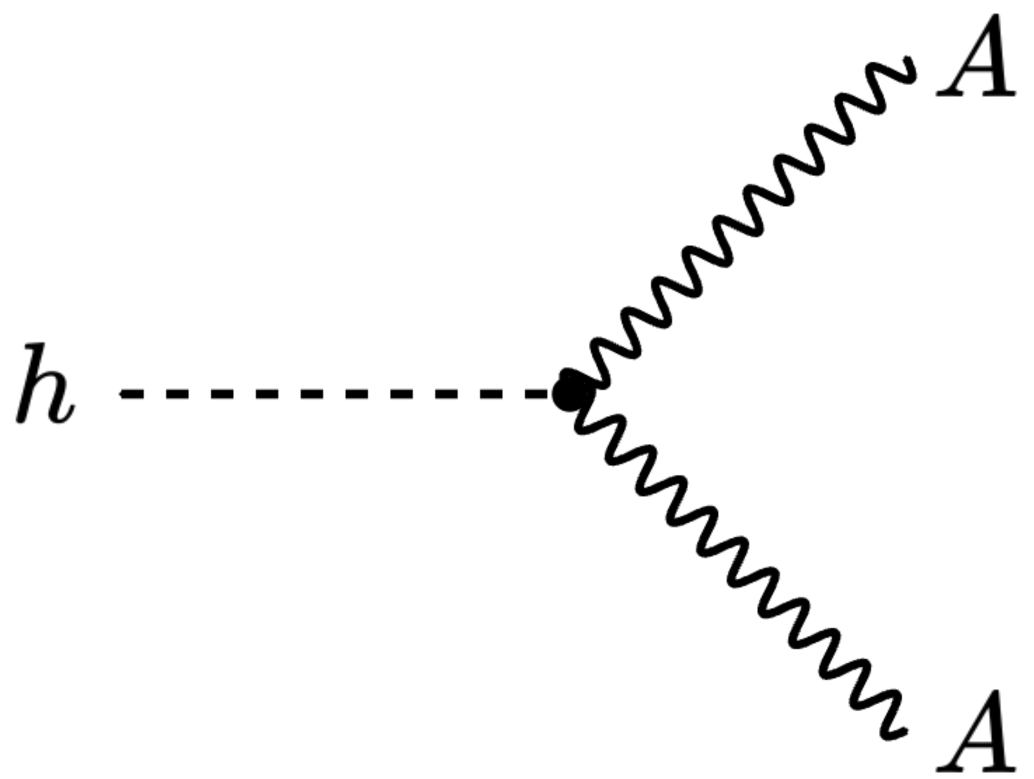

Violates particle number

Fuzzy dark sector

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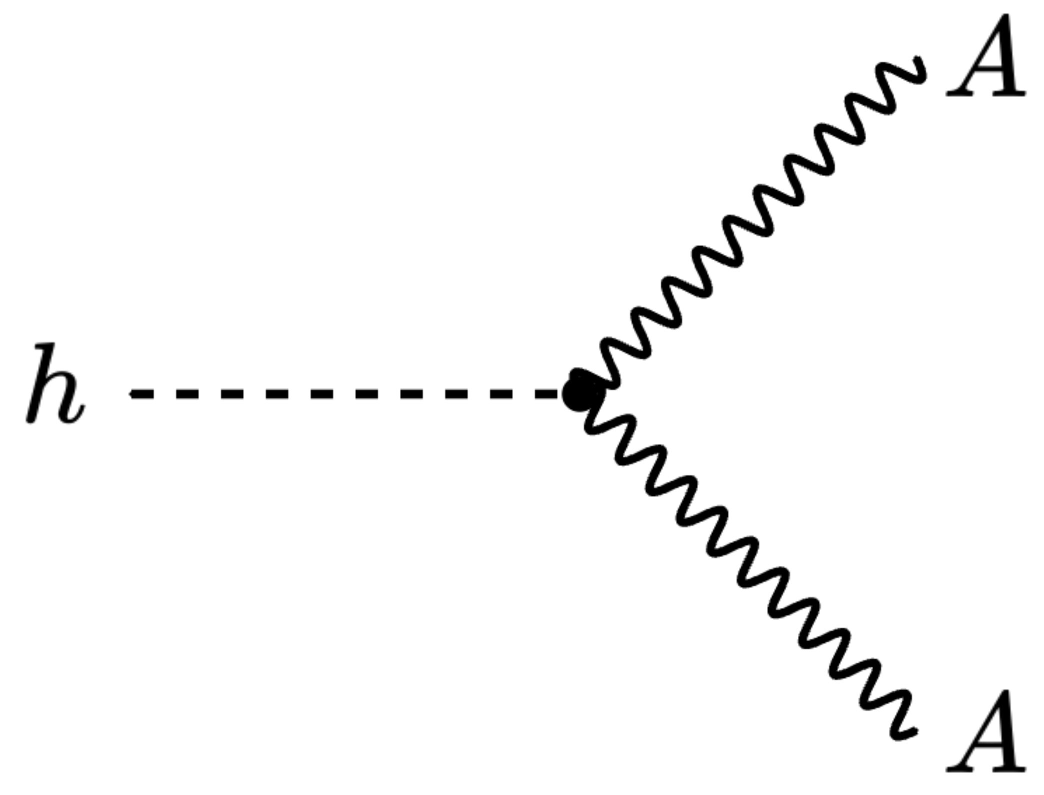

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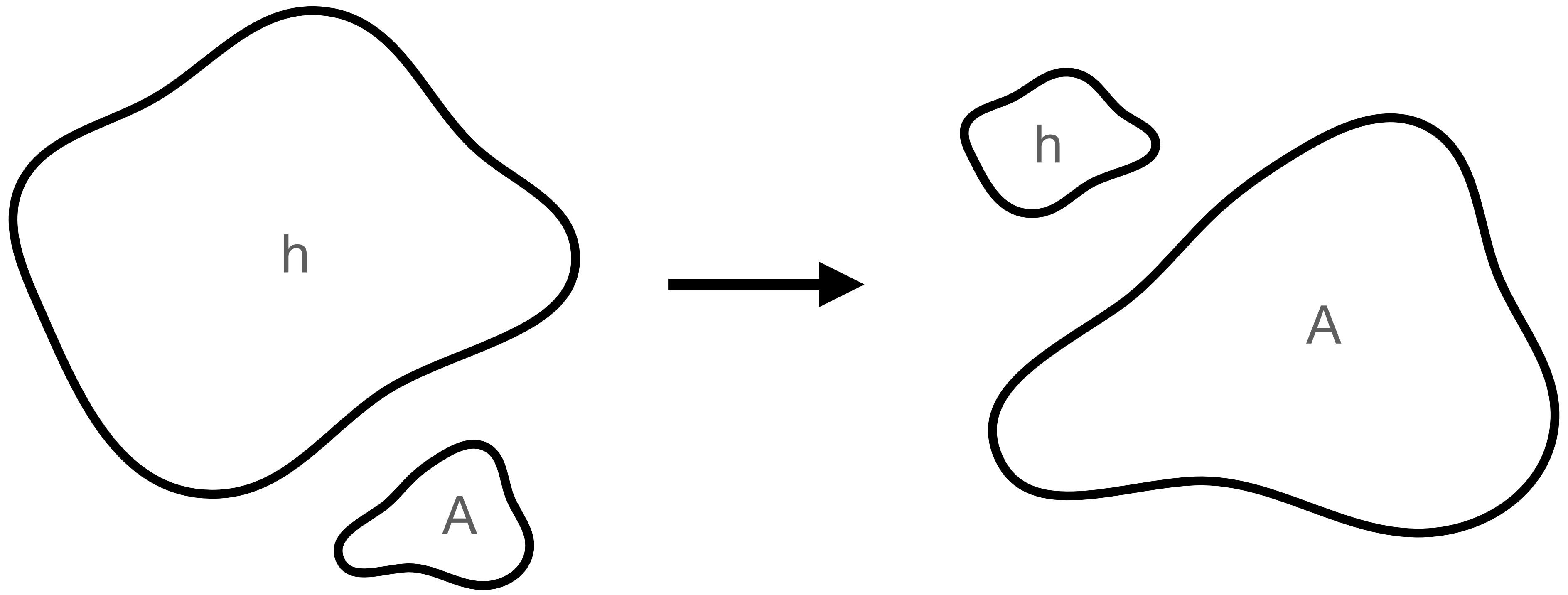

Large and small scale probes

Fuzzy dark sector

Fluid description

Euler:

$$\frac{D\vec{v}_A}{Dt} = \frac{1}{2m_A^2}\nabla\left(\frac{\nabla^2\sqrt{\rho_A}}{\sqrt{\rho_A}}\right) - \nabla\Phi + \frac{1}{\rho_A}\nabla P_{\mathrm{int},h}$$

$$\frac{D\vec{v}_h}{Dt} = \frac{1}{2m_h^2}\nabla\left(\frac{\nabla^2\sqrt{\rho_h}}{\sqrt{\rho_h}}\right) - \nabla\Phi - \frac{1}{\rho_h}\nabla P_{\mathrm{SI}} + \frac{1}{\rho_h}\nabla P_{\mathrm{int},A}$$

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Gradient pressure

Fuzzy dark sector

Fluid description

Mutual interaction pressure

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Gradient pressure

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Fuzzy dark sector

Fluid description

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Gradient pressure

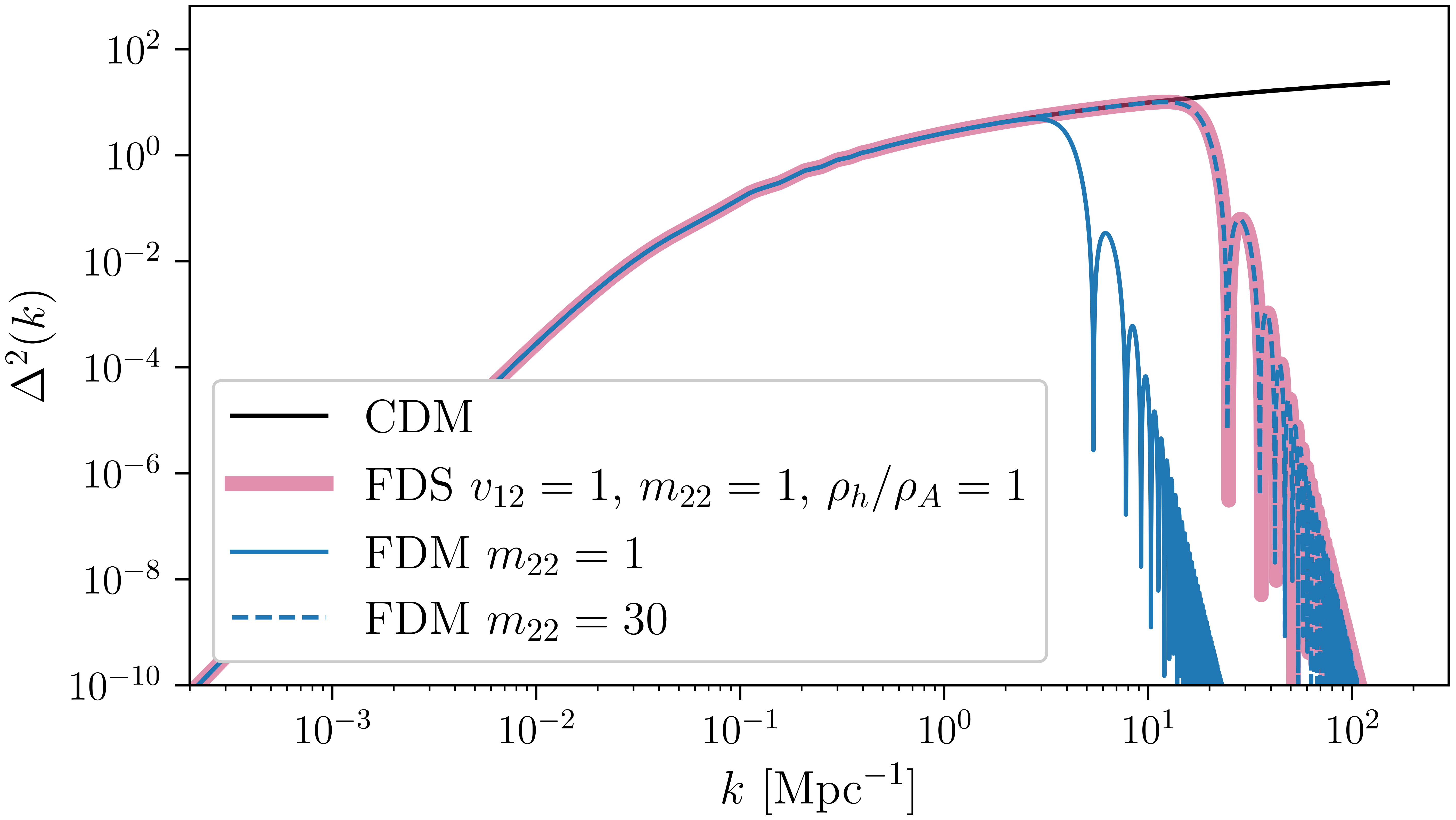
Self-interaction pressure

+ a copy of the continuity equation for each degree of freedom

Large scale structure

CC, Ferreira, McDonough [2509.15299]

FDM 🤝 FDS: apparent degeneracy



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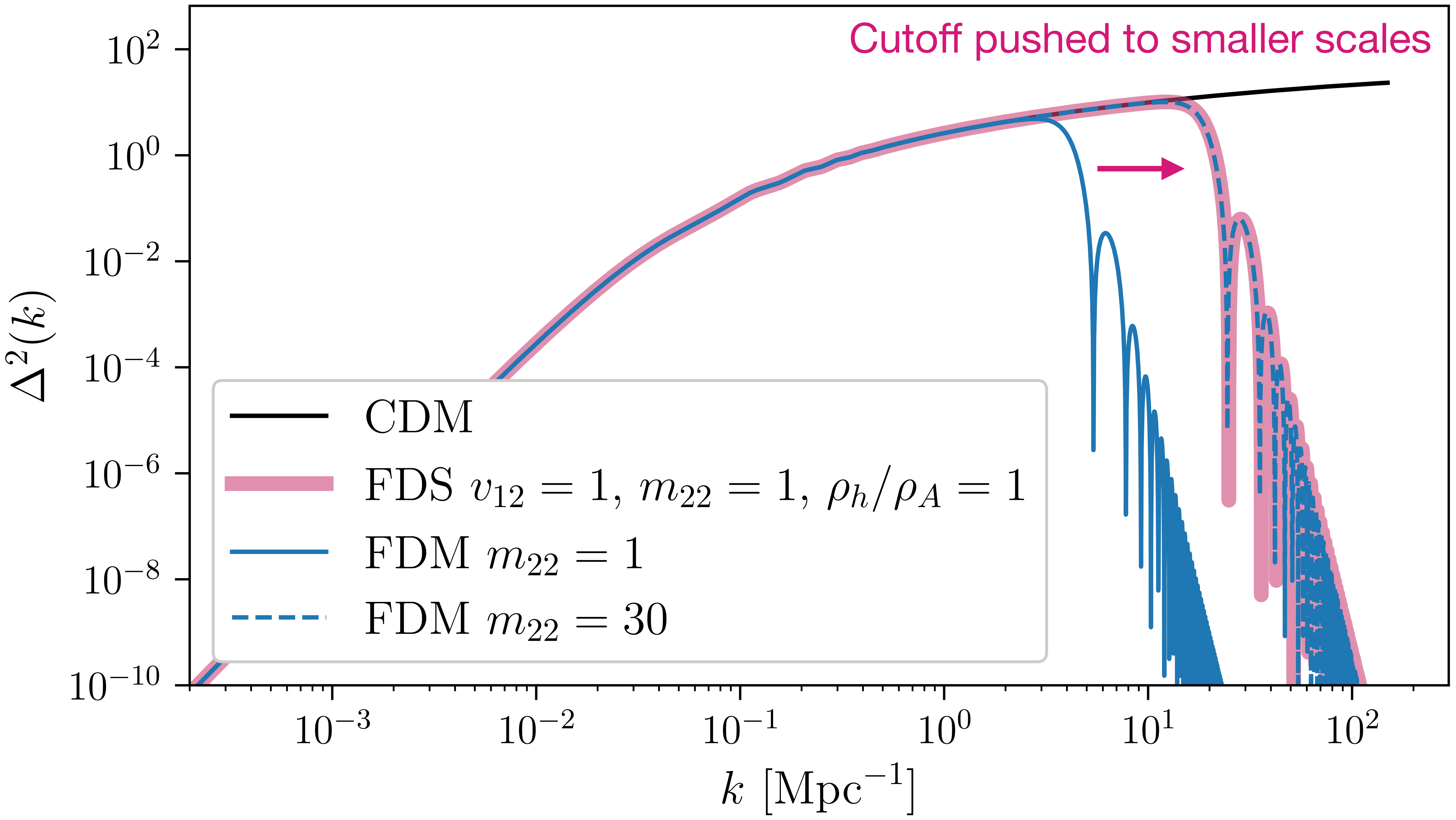

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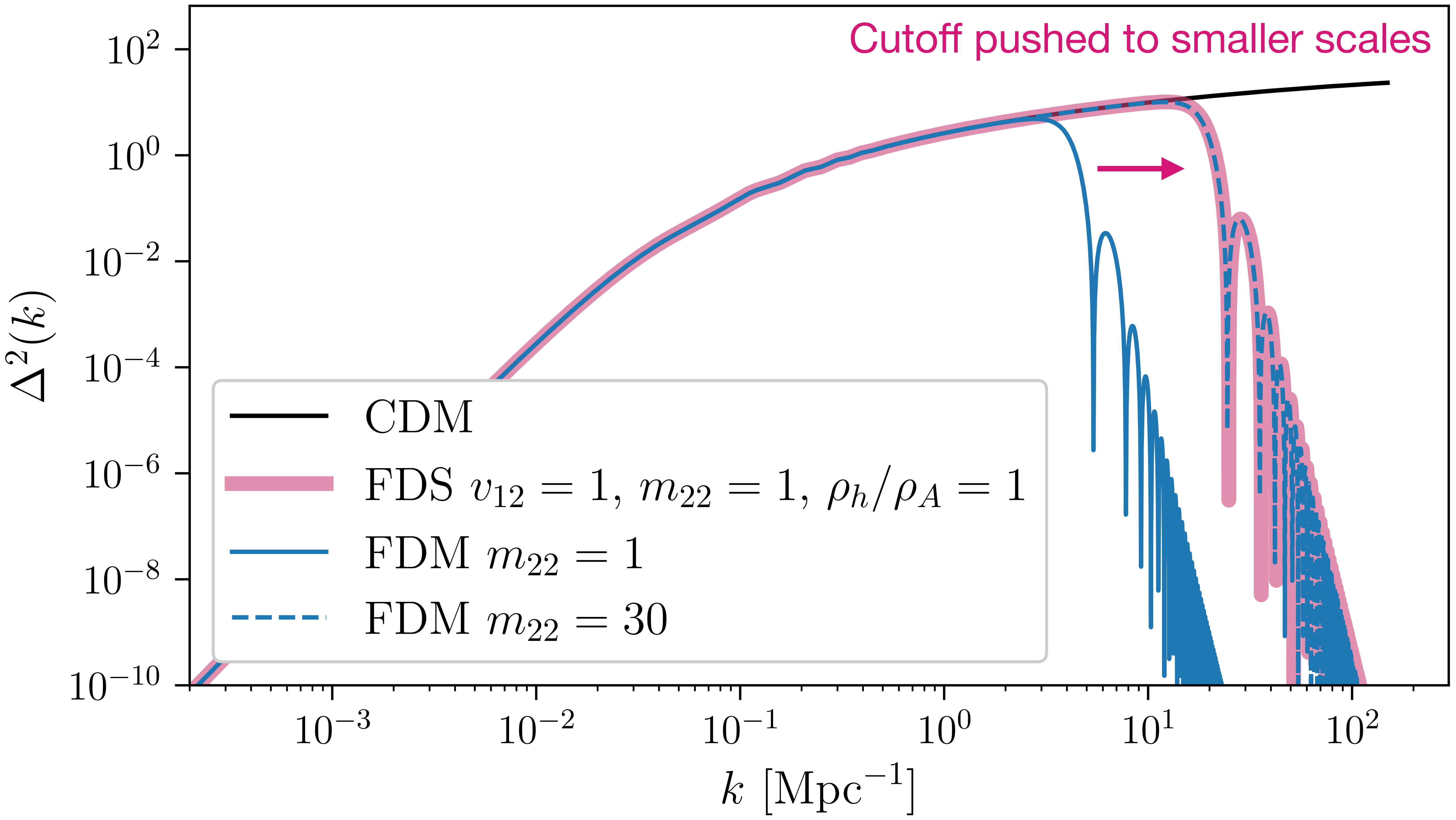

$$k_*^2 \approx \sqrt{k_{G,h}^4 + k_{G,A}^4} + 2m_h^2 c_{s,h}^2 \left(4 - \frac{5}{1 + \frac{k_{G,A}^4}{k_{G,h}^4}} \right)$$

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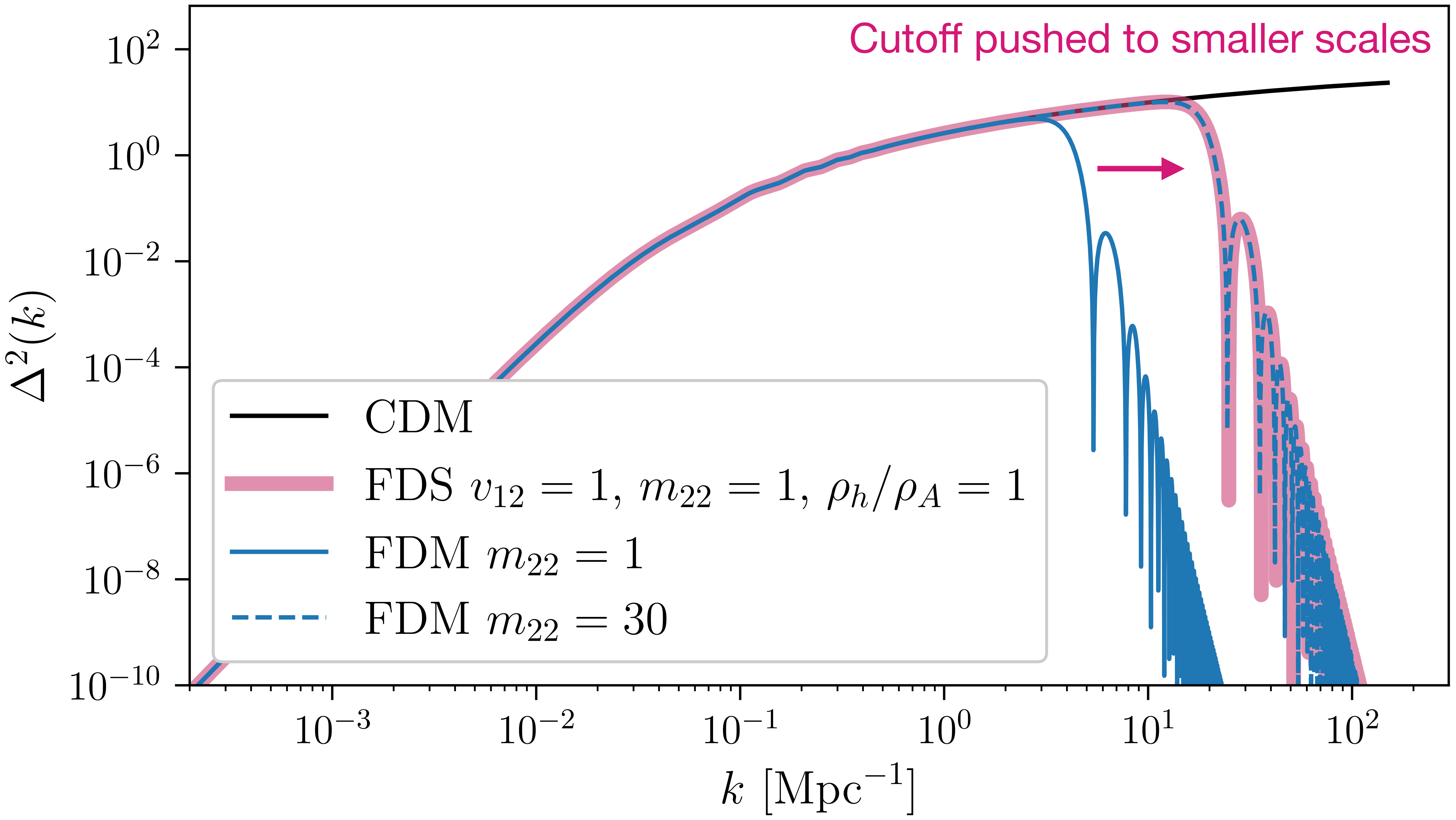

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Where $k_{G,X}^4 = 16\pi G m_X^2 \rho_X$

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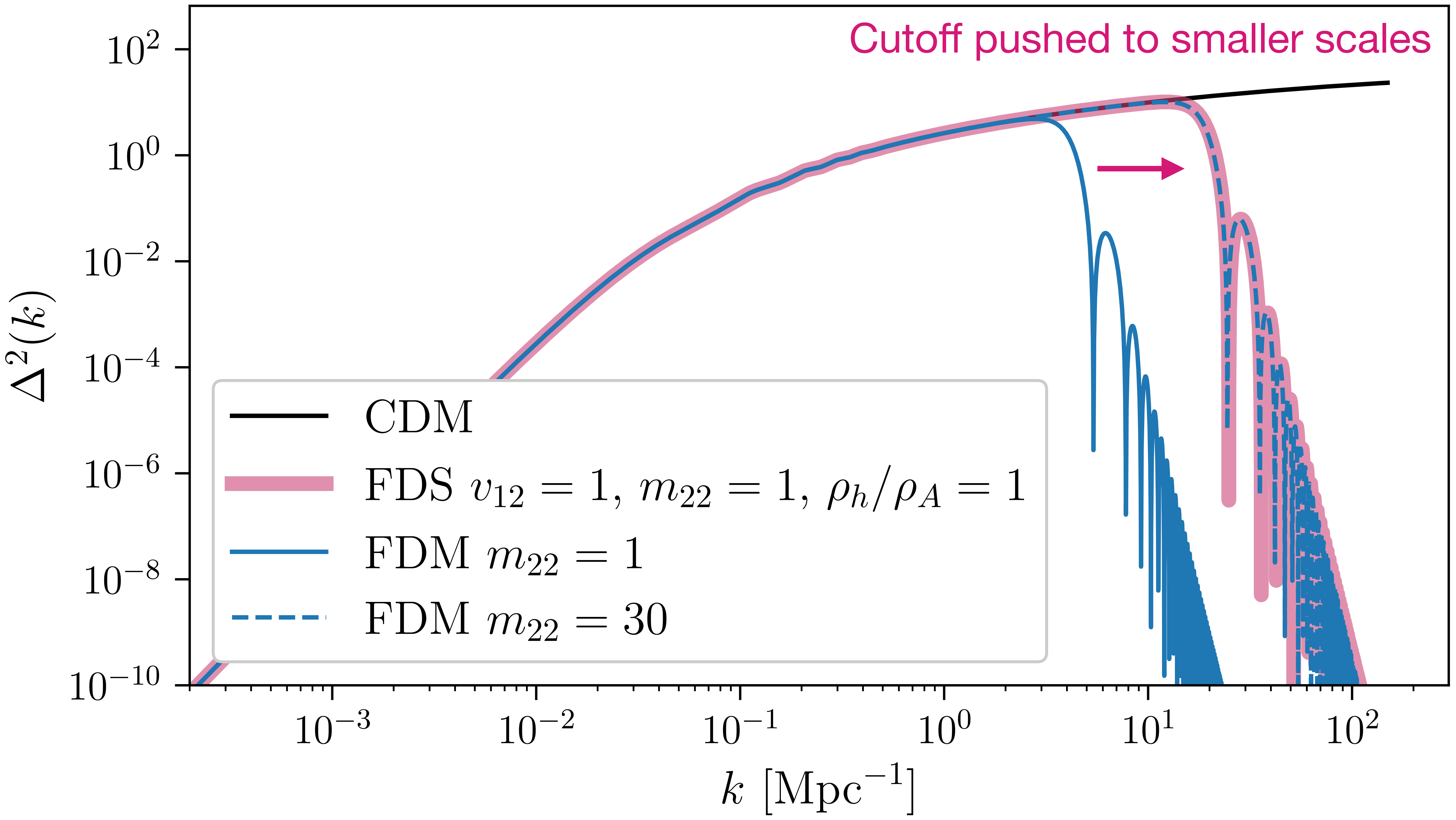

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Where $k_{G,X}^4 = 16\pi G m_X^2 \rho_X$

large or small Jeans scale compared to FDM based on model parameters

Small scales

Formation of halos

In FDM, halos have “soliton” cores

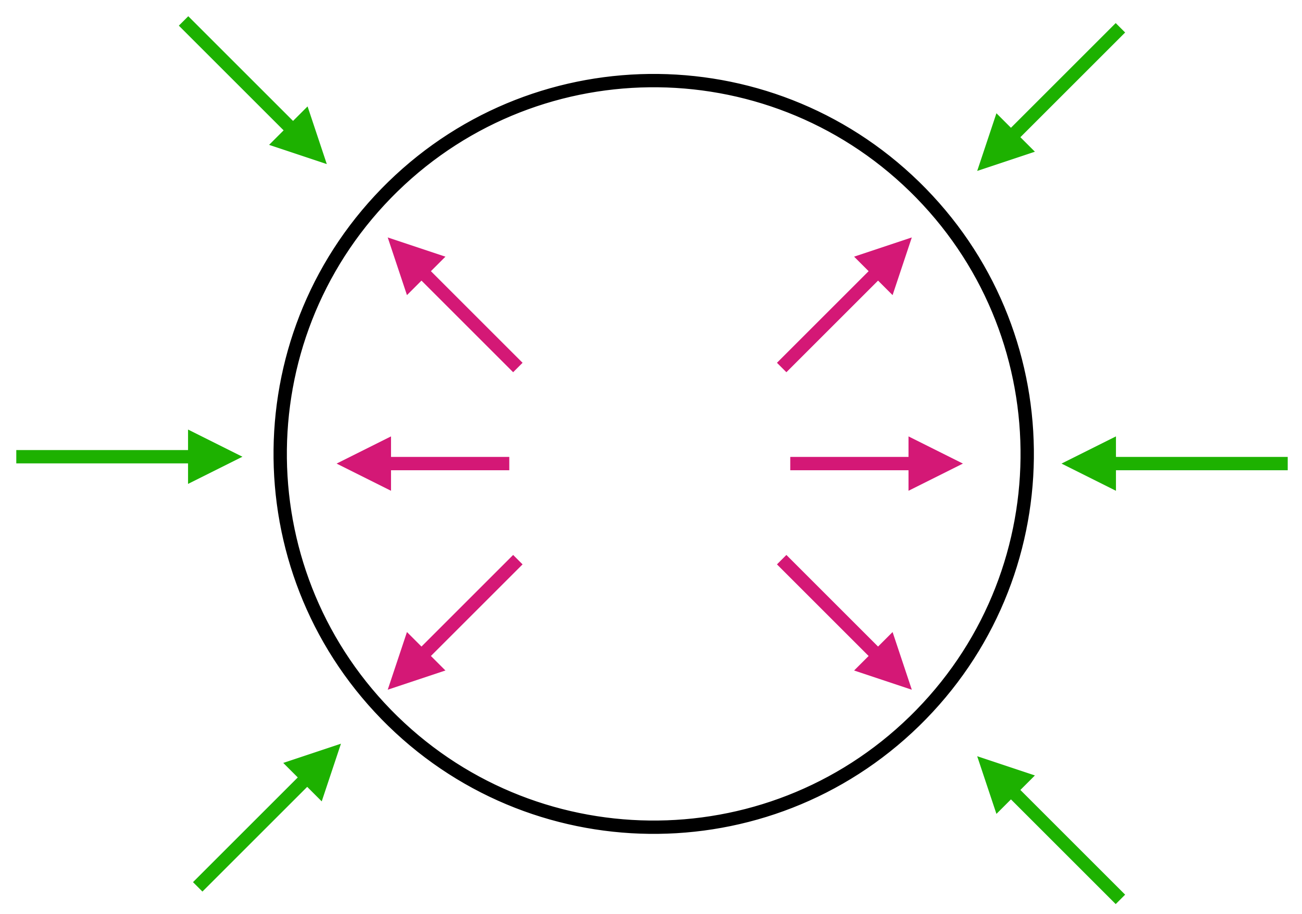
Stable clump balancing gravity with gradient pressure:

Small scales

Formation of halos

In FDM, halos have “soliton” cores

Stable clump balancing gravity with gradient pressure:



$$R \sim \frac{1}{GMm^2}$$

Small scales

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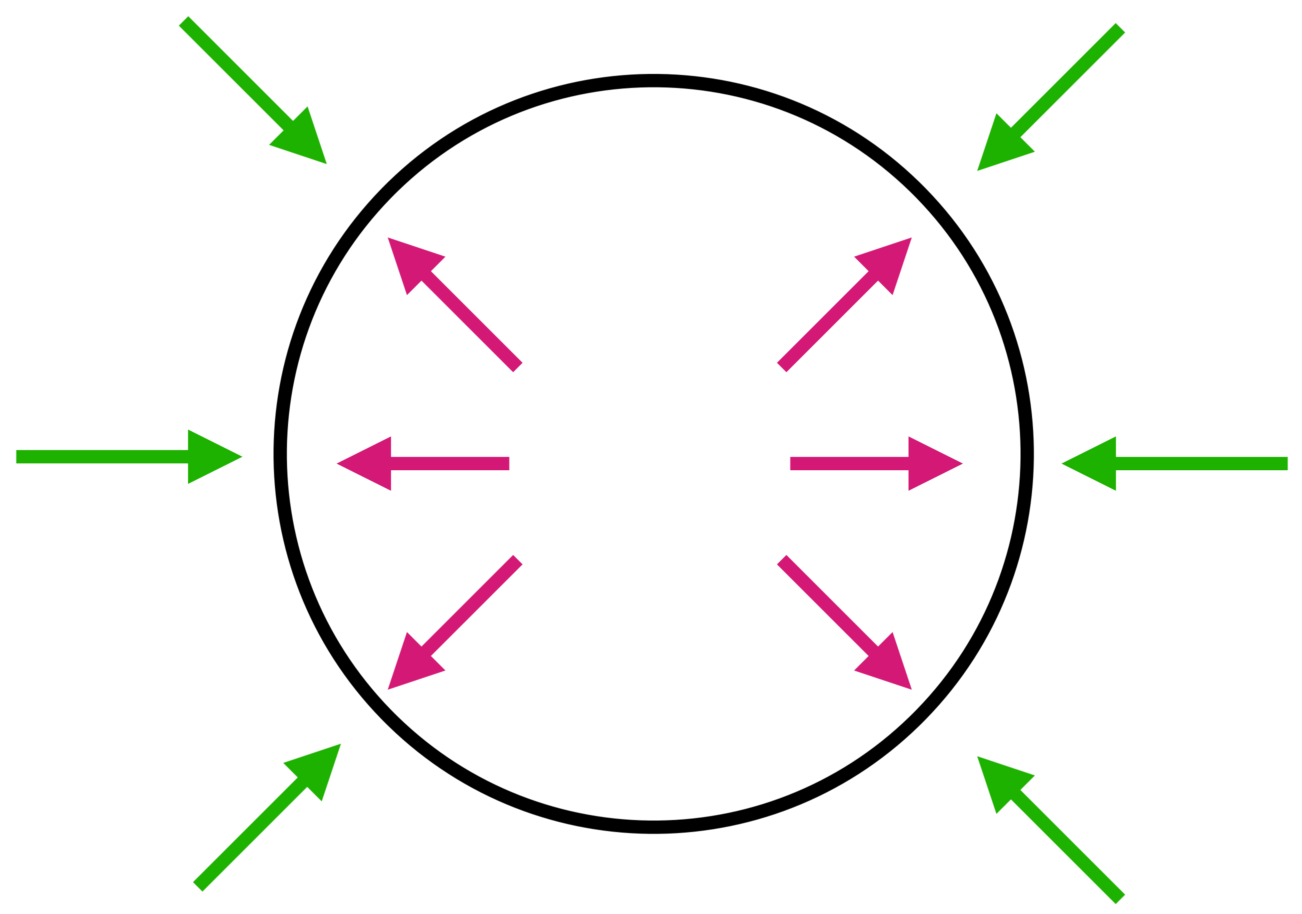

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What about multi-field, interacting FDM?

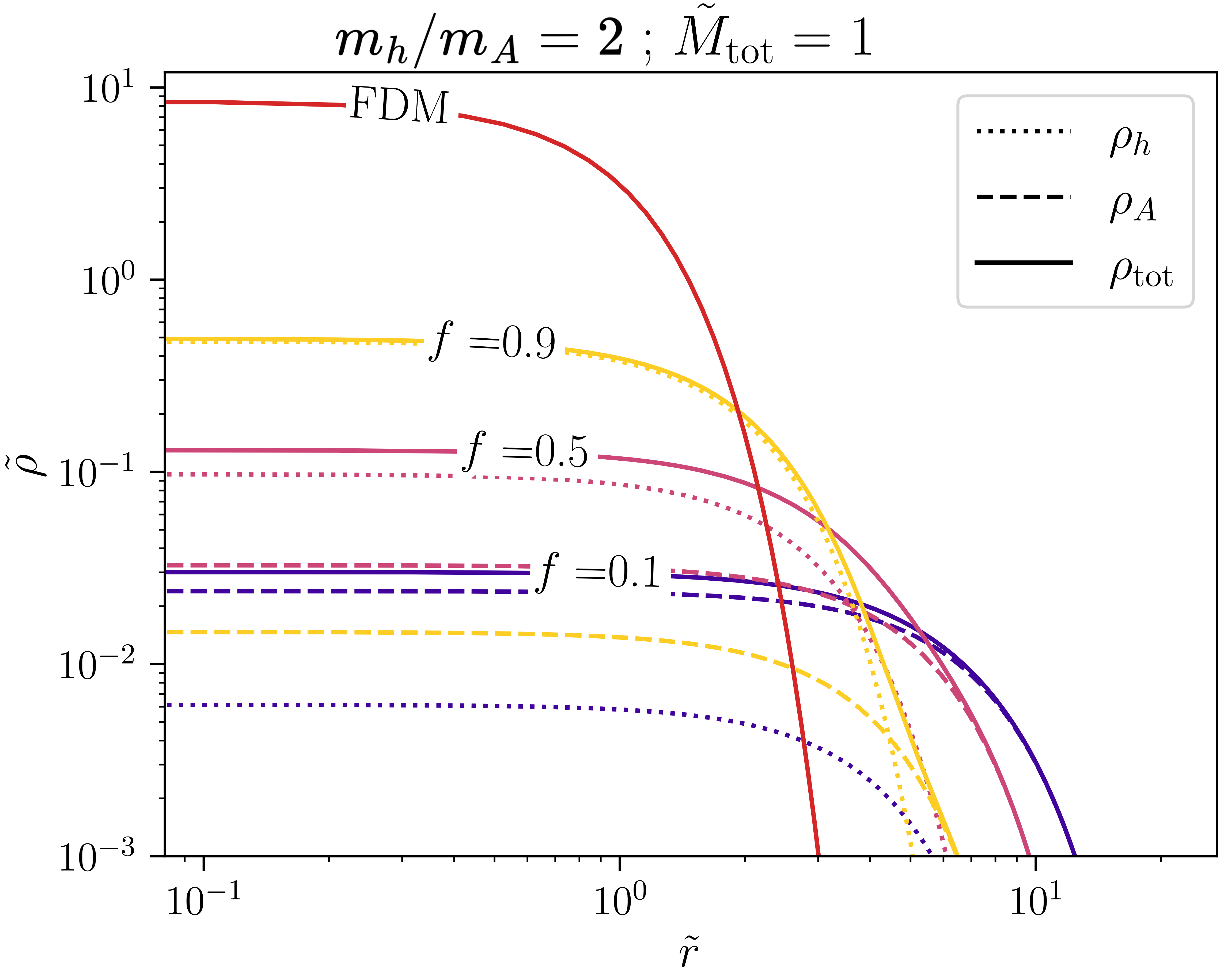
Small scales

Halo diversity

CC, Ferreira, McDonough [2509.15299]

Large FDS parameter space for halos to explore!

$$\{M_{\rm tot}, f, \frac{m_h}{m_A}, \vec{\epsilon}\}$$



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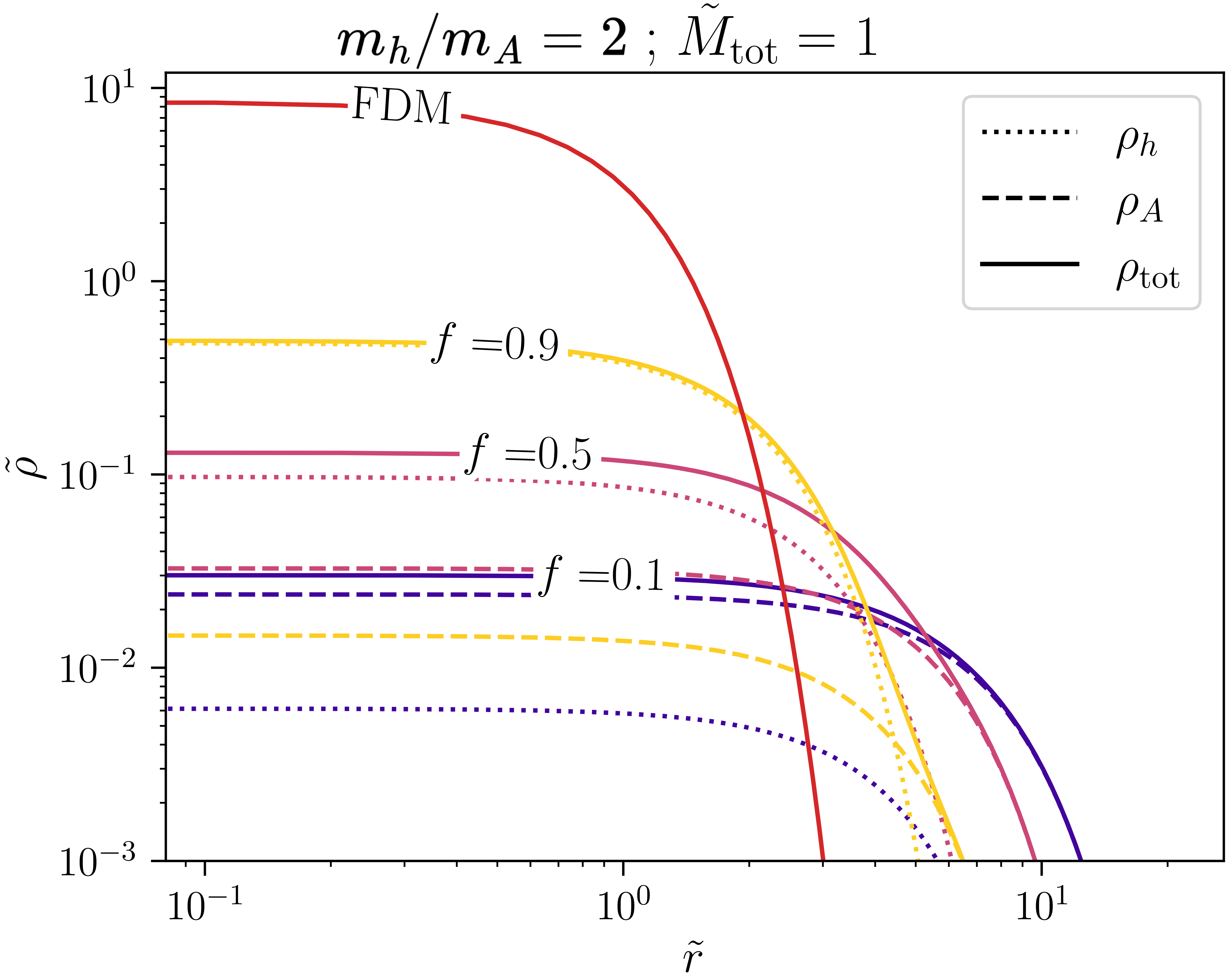
→ Total soliton mass



Small scales

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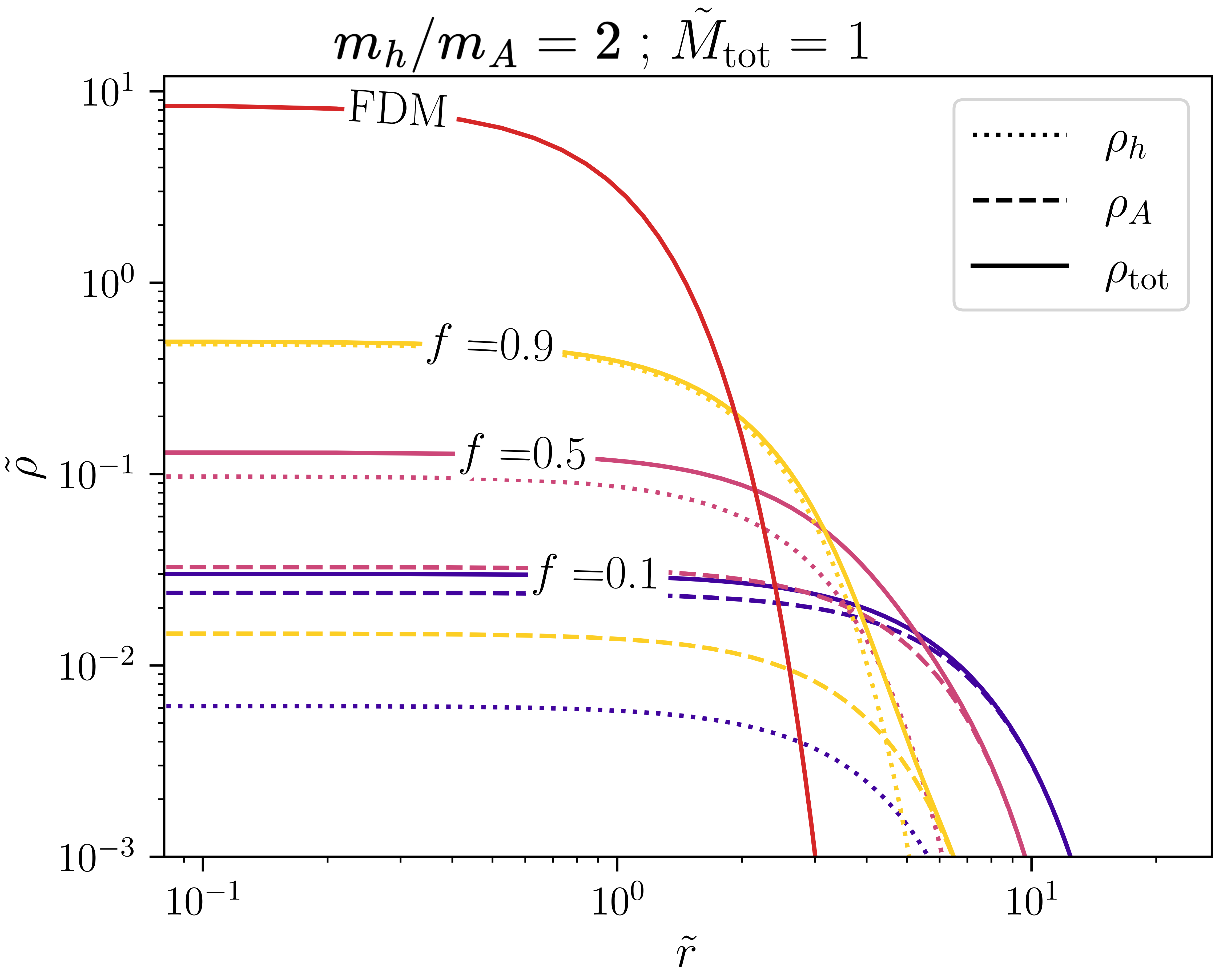
$$\{\boxed{M_{\rm tot}}, \boxed{f}, \frac{m_h}{m_A}, \vec{\epsilon}\}$$

→ Total soliton mass

→ Halo mass fraction



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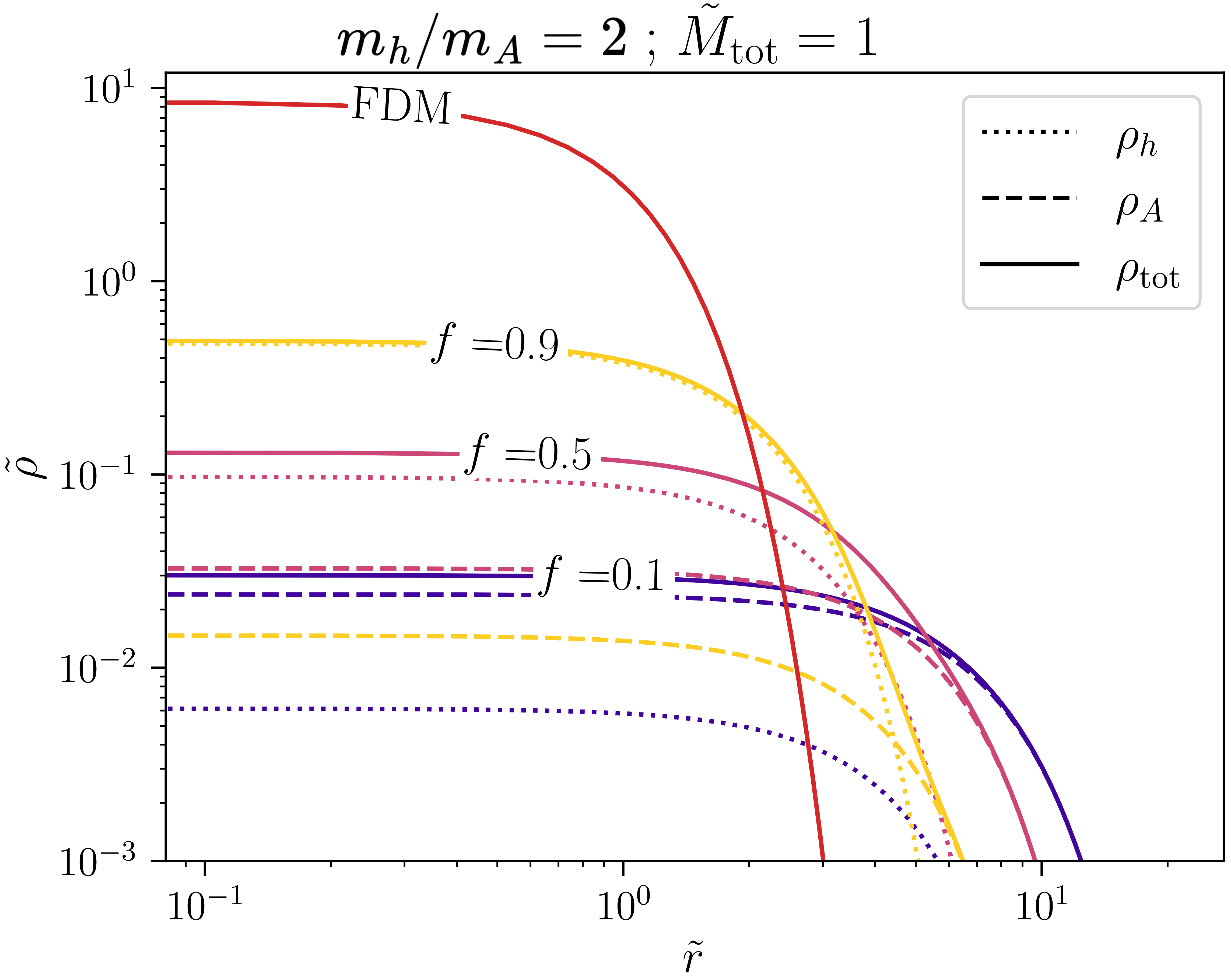
→ Total soliton mass

→ Halo mass fraction

→ Particle mass ratio



Small scales

Halo diversity

CC, Ferreira, McDonough [2509.15299]

Large FDS parameter space for halos to explore!

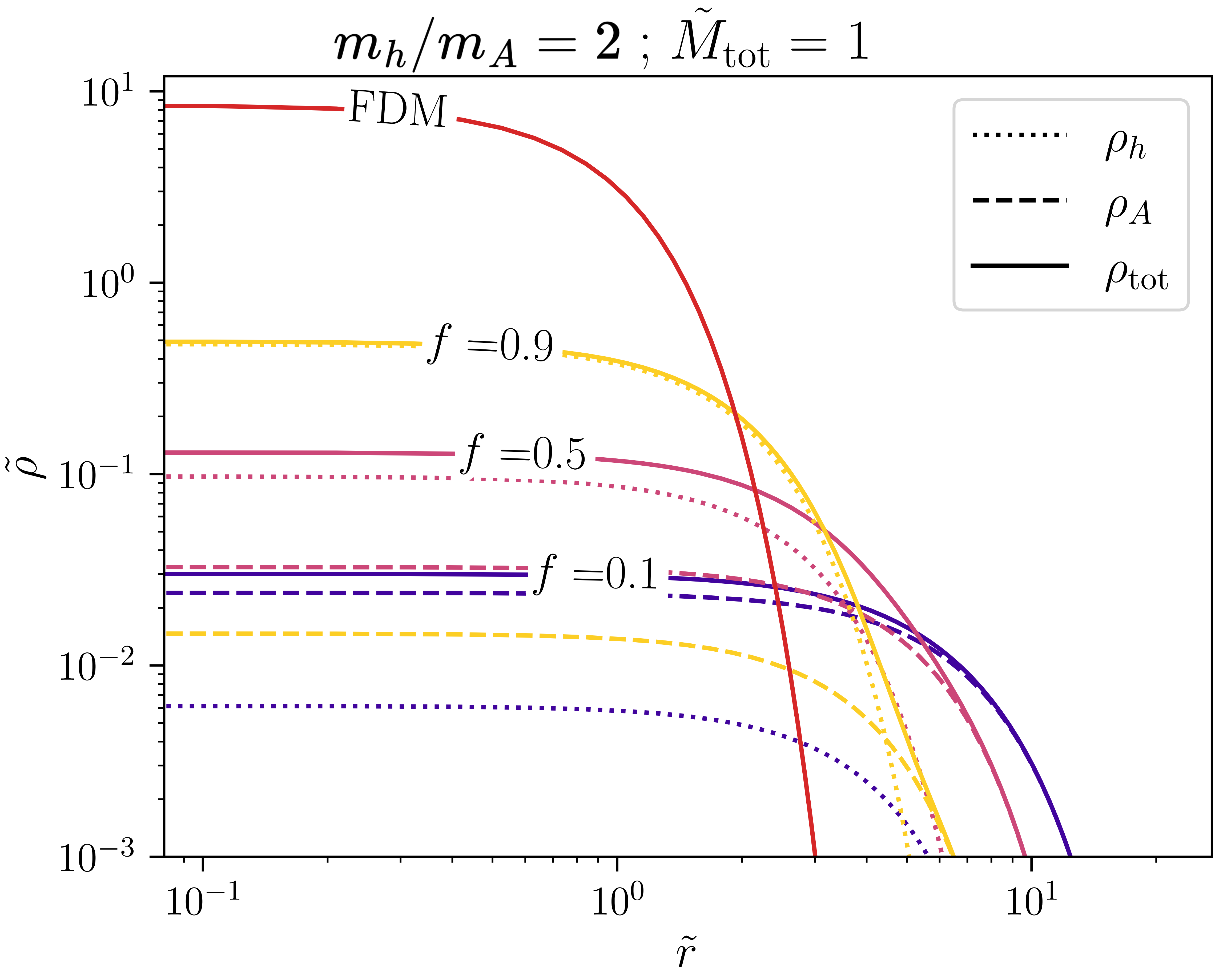
$$\left\{M_{\rm tot}, f, \frac{m_h}{m_A}, \vec{\epsilon}\right\}$$

Total soliton mass

Halo mass fraction

Particle mass ratio

Dark photon polarization



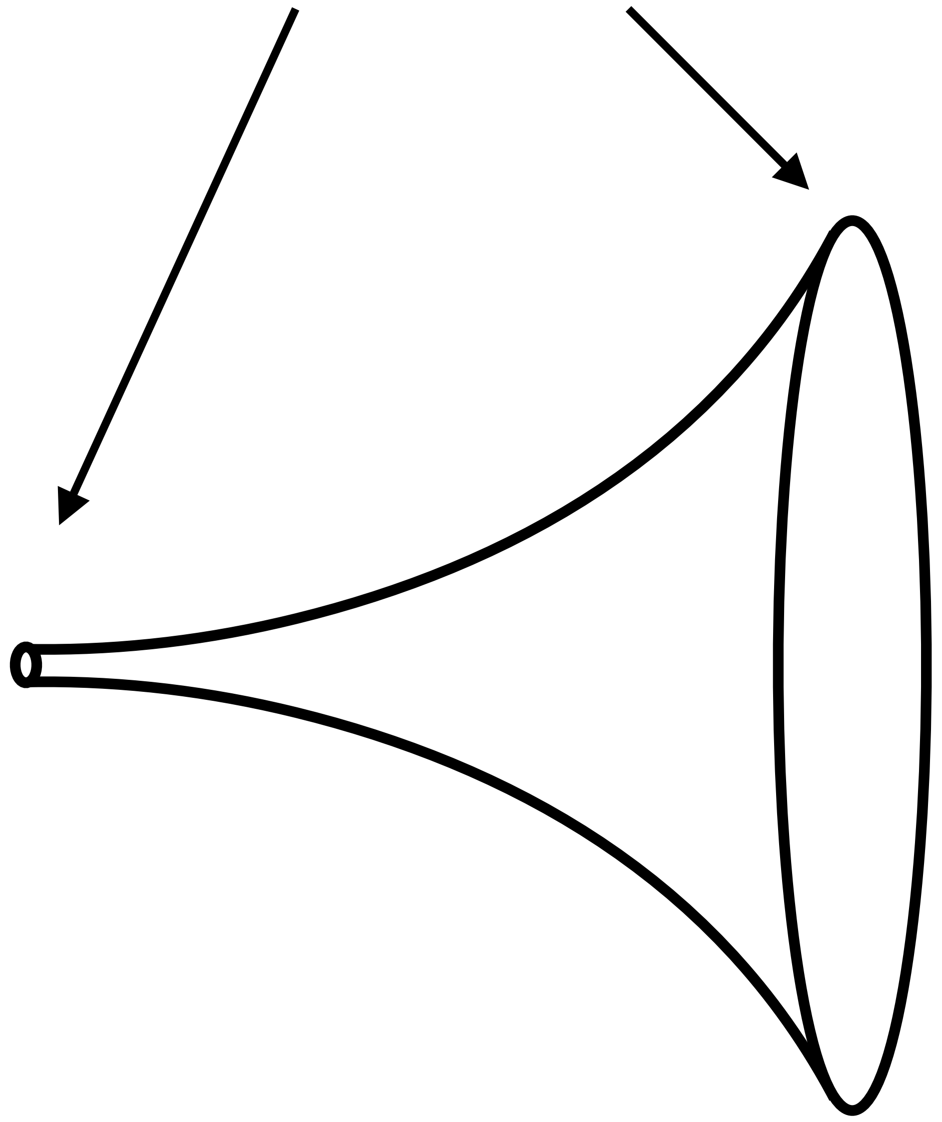
Production

Completely dark production of vectors

CC, Jenks, Kolb, McDonough
[2403.15536, 2405.19390]

Non-minimal couplings

$\hat{a}_k(\text{early})|0, \text{late}\rangle \neq 0$



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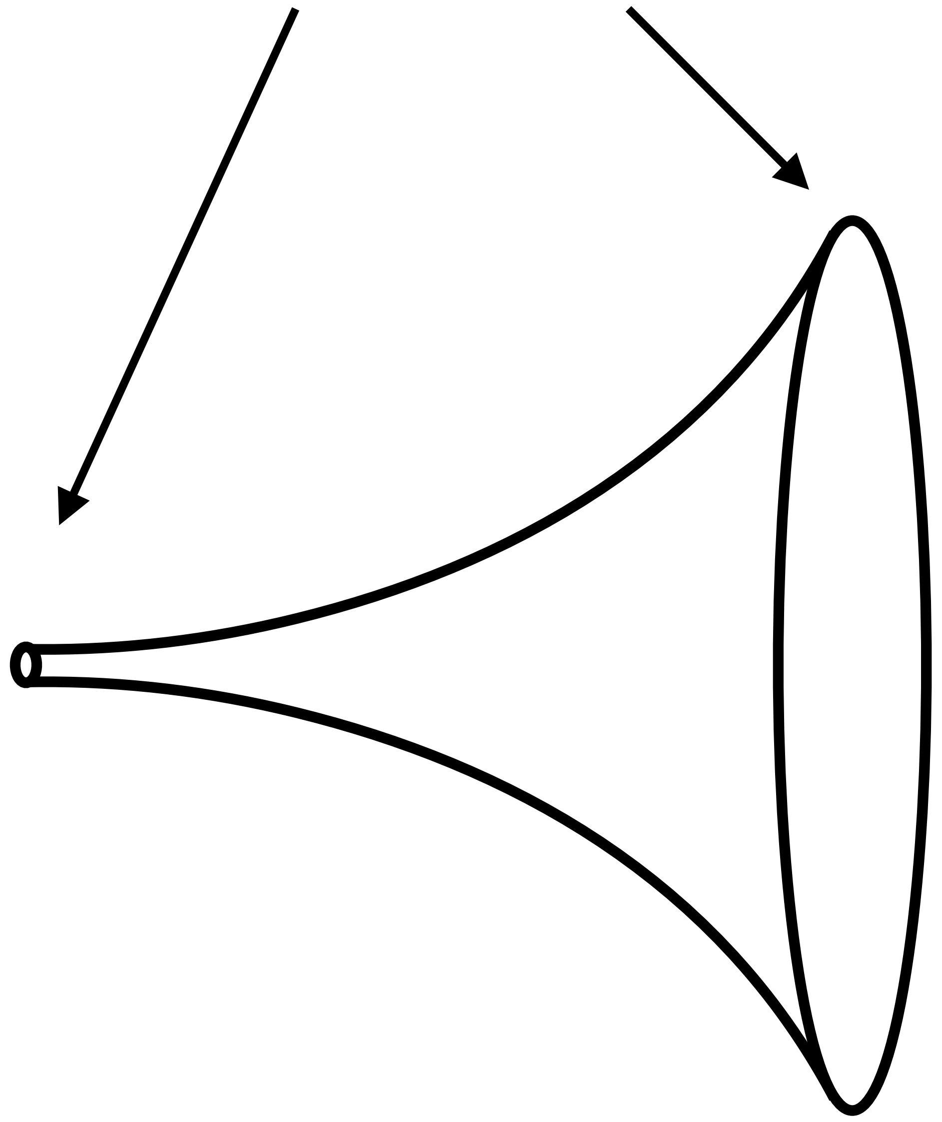

$$\langle 0,\text{late}|\hat{a}_k^\dagger \hat{a}_k|0,\text{late}\rangle \neq 0$$

Expanding universe
produces particles!

Completely dark production of vectors

Non-minimal couplings

CC, Jenks, Kolb, McDonough
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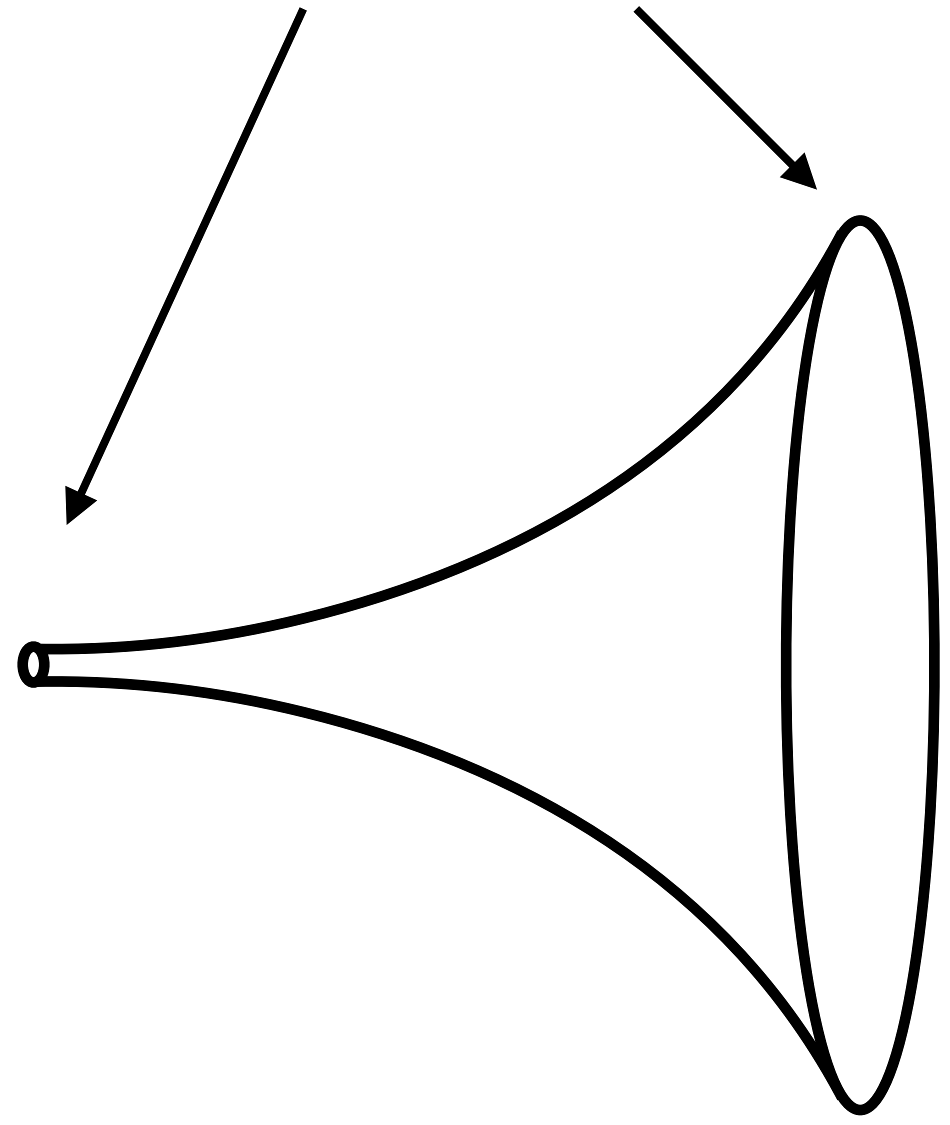
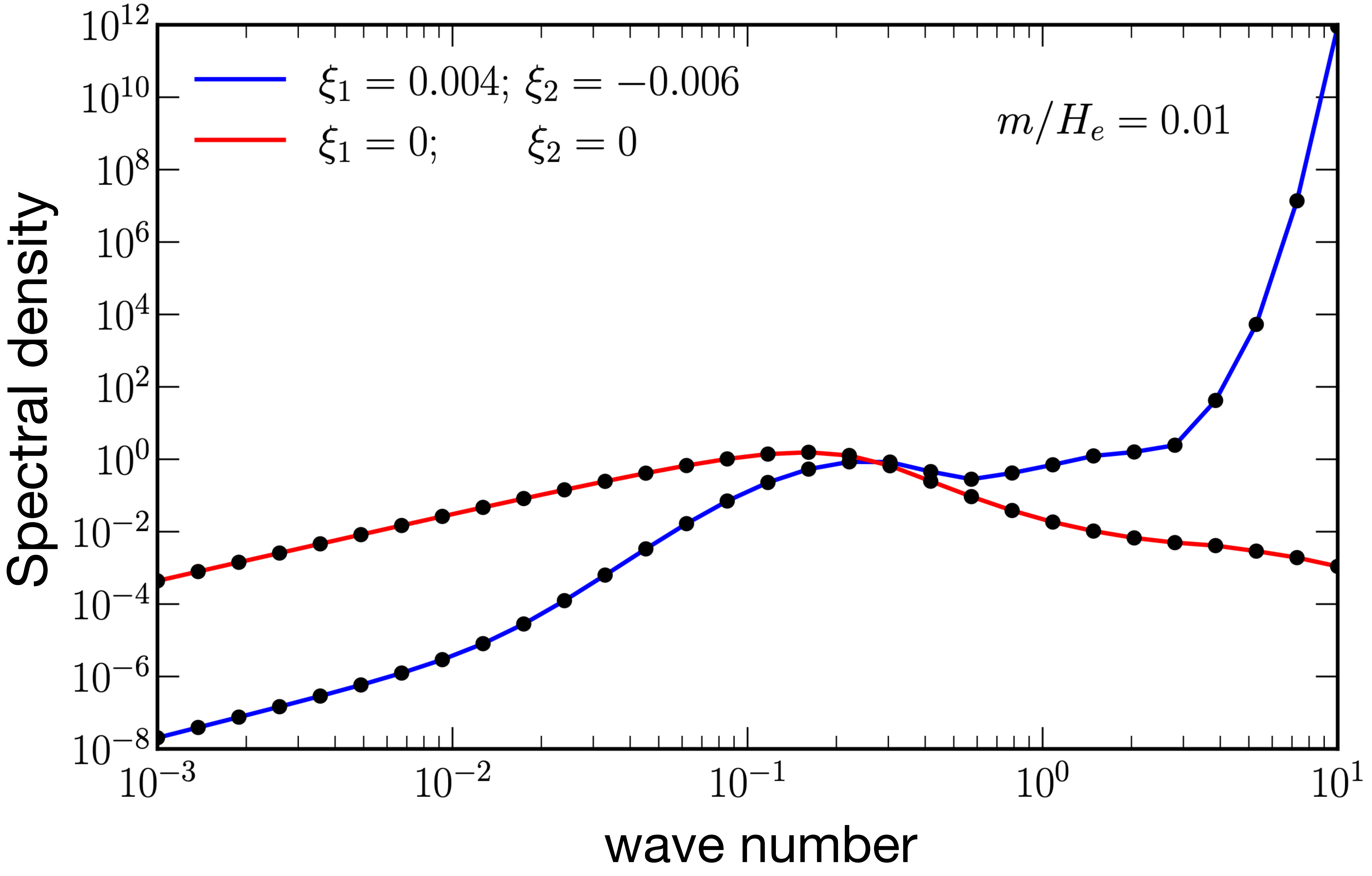


$$\langle 0,\mathrm{late}|\hat{a}_k^\dagger \hat{a}_k|0,\mathrm{late}\rangle \neq 0$$

Expanding universe produces particles!

$$\mathcal{L}_{\mathrm{NM}} = -\frac{1}{2}\xi_1 R g^{\mu\nu} A_\mu A_\nu - \frac{1}{2}\xi_2 R^{\mu\nu} A_\mu A_\nu$$



Completely dark production of vectors

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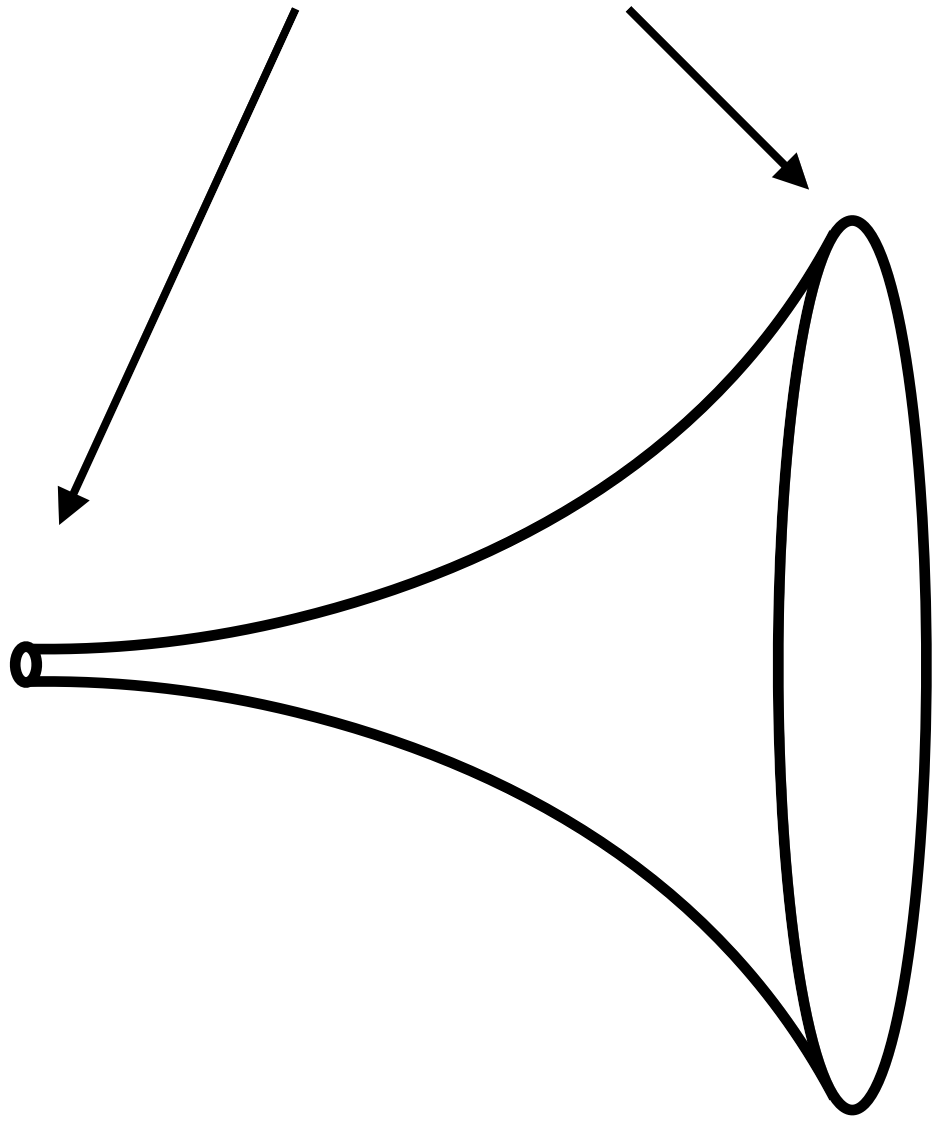

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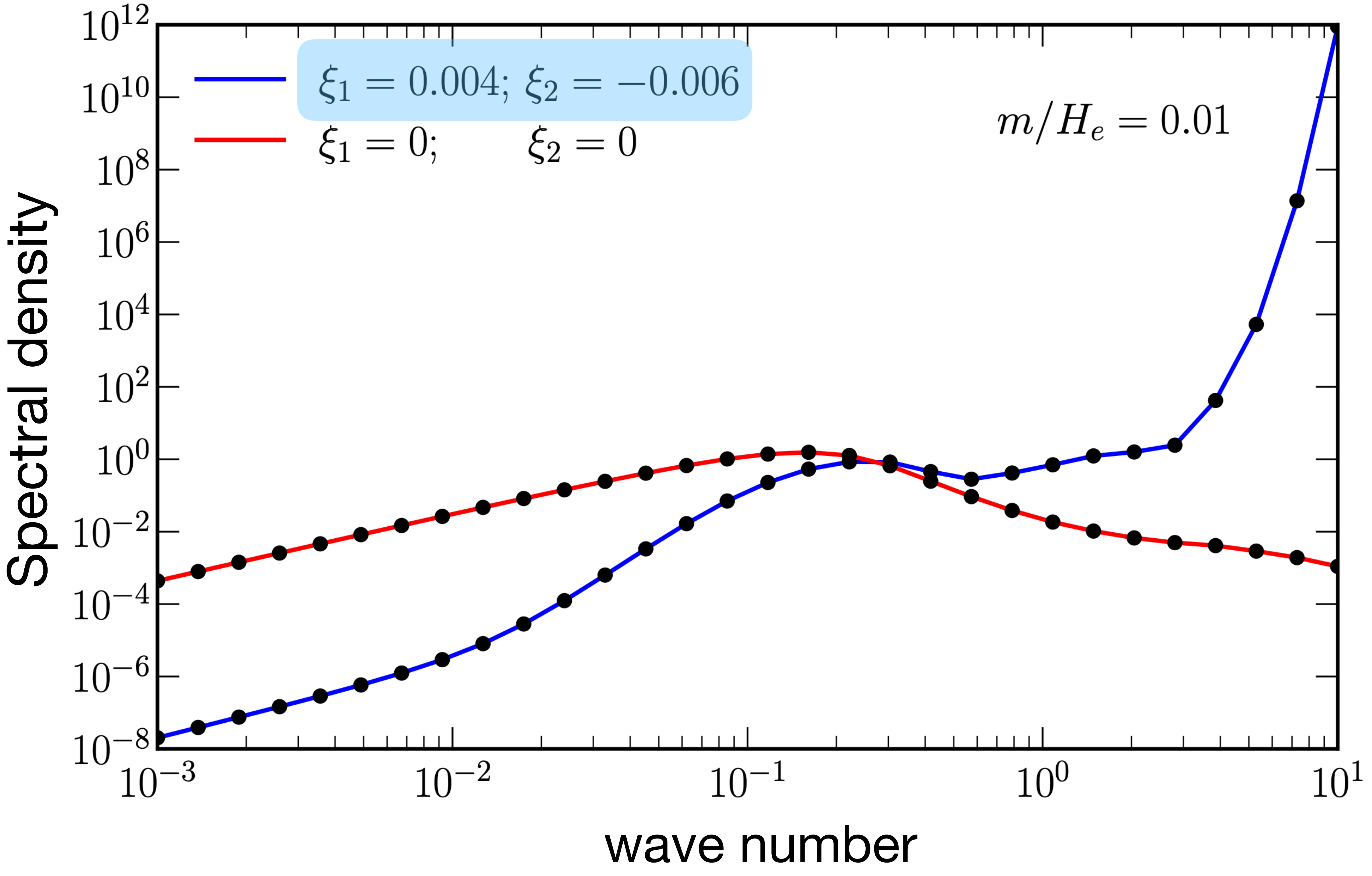

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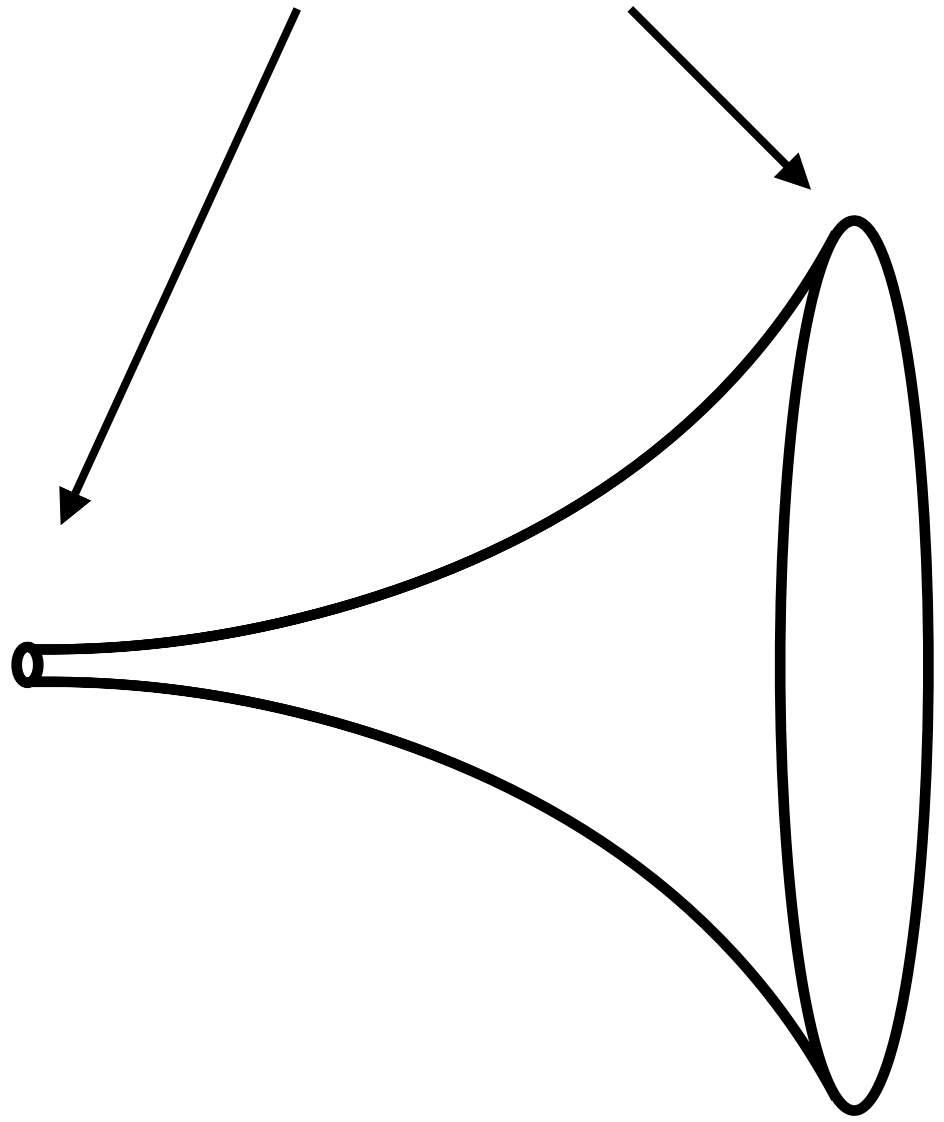

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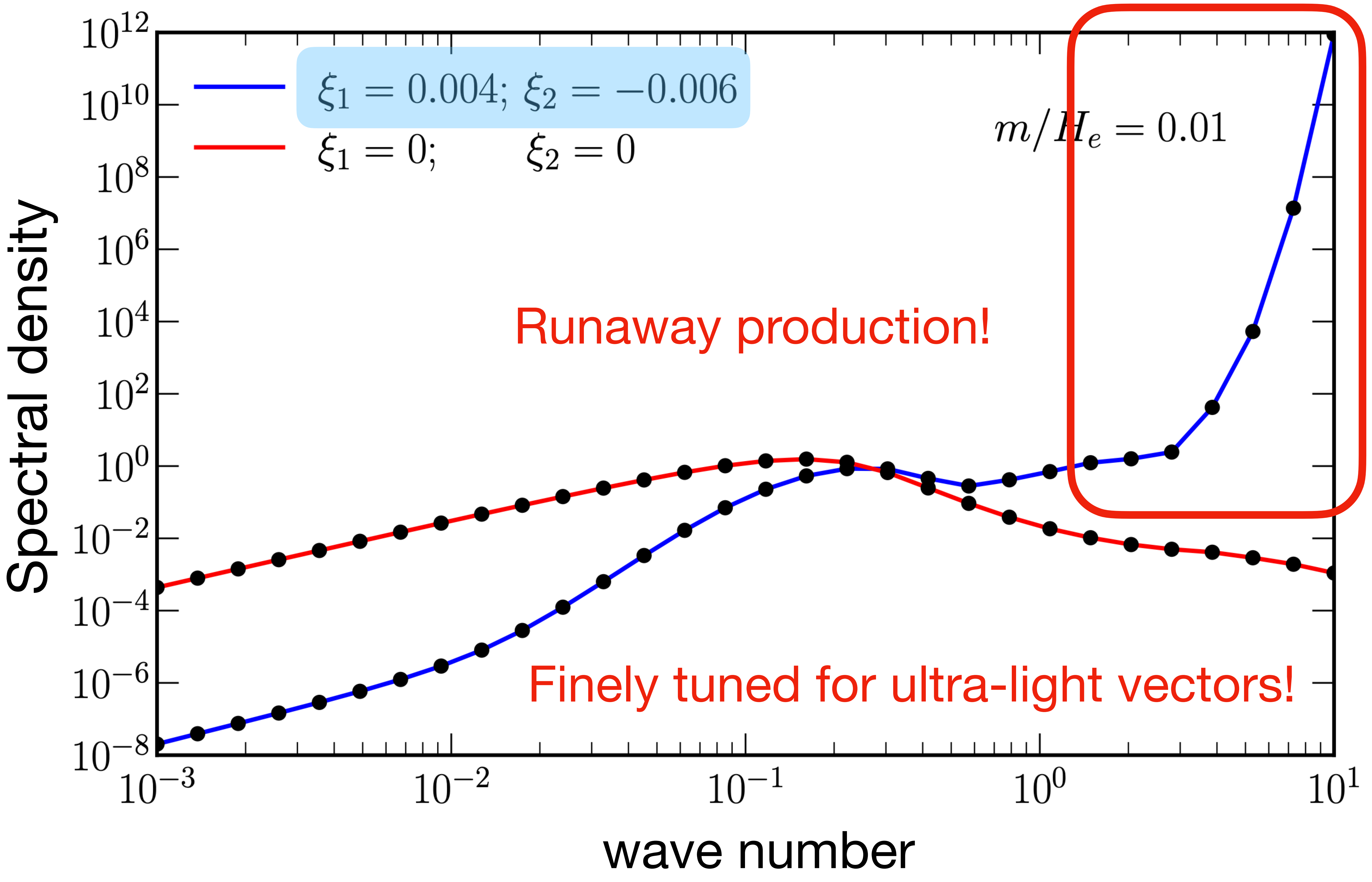
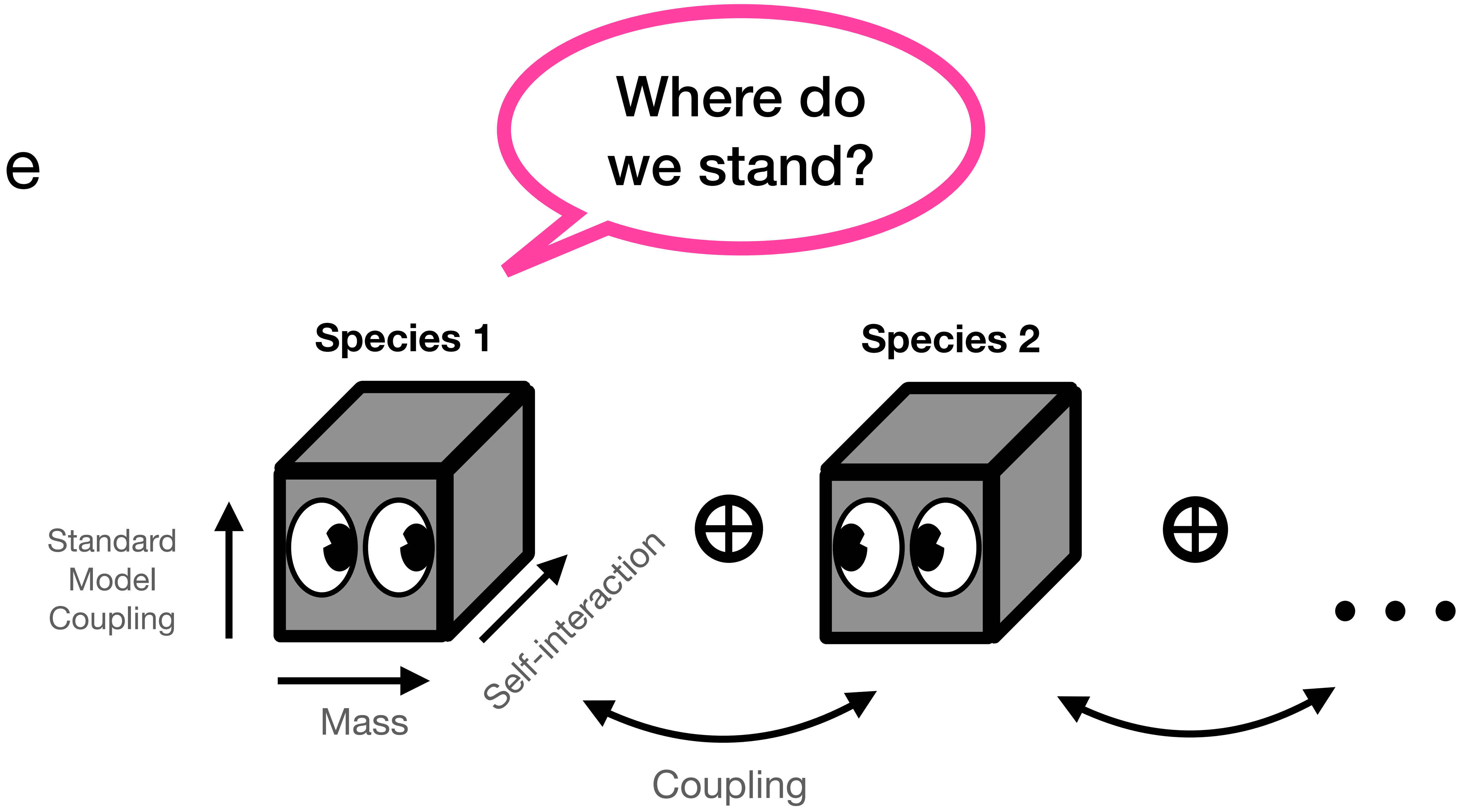


Lessons learned

Non-comprehensive list….

- Many potential non-stringy UL dark sectors
- Nontrivial non-relativistic EFT
- Hope of disentangling dark sector using multi-scale probes
- Light dark vectors can be efficiently produced via gravity



Thank you!