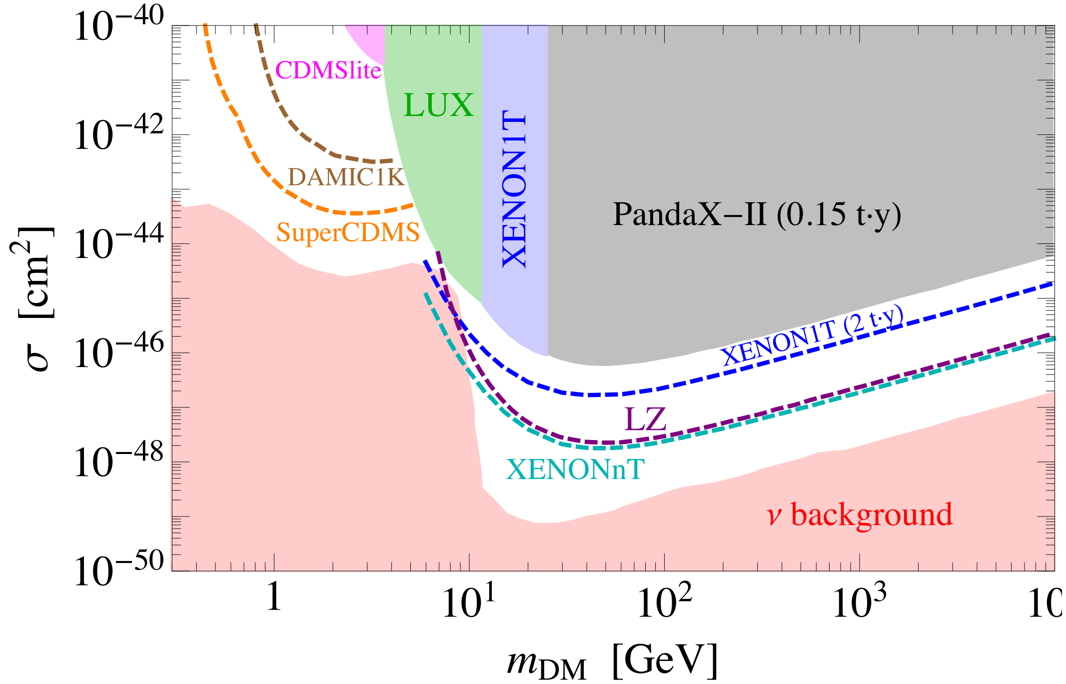
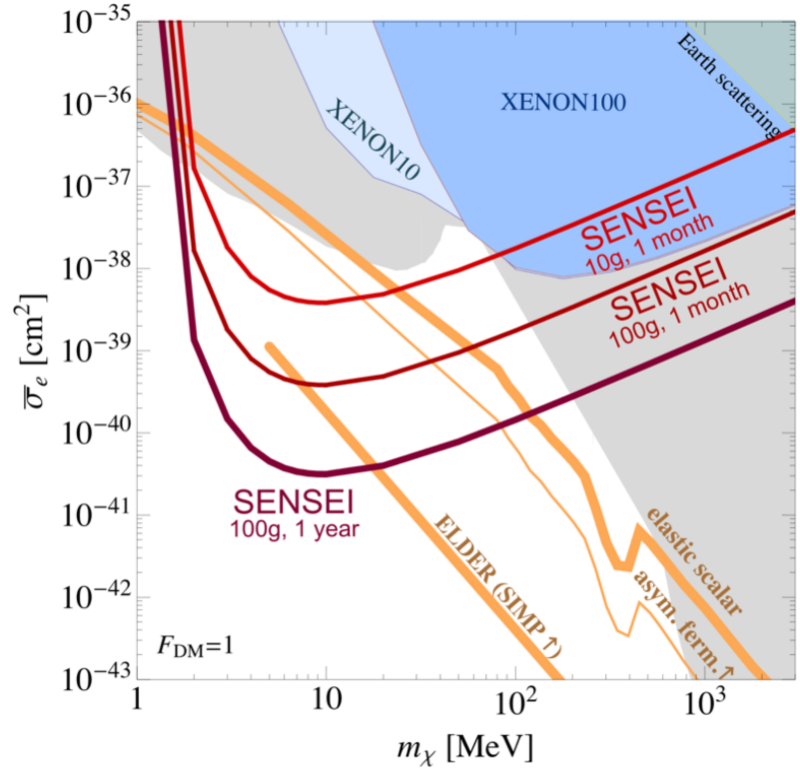
Dark exceptions

Duccio Pappadopulo

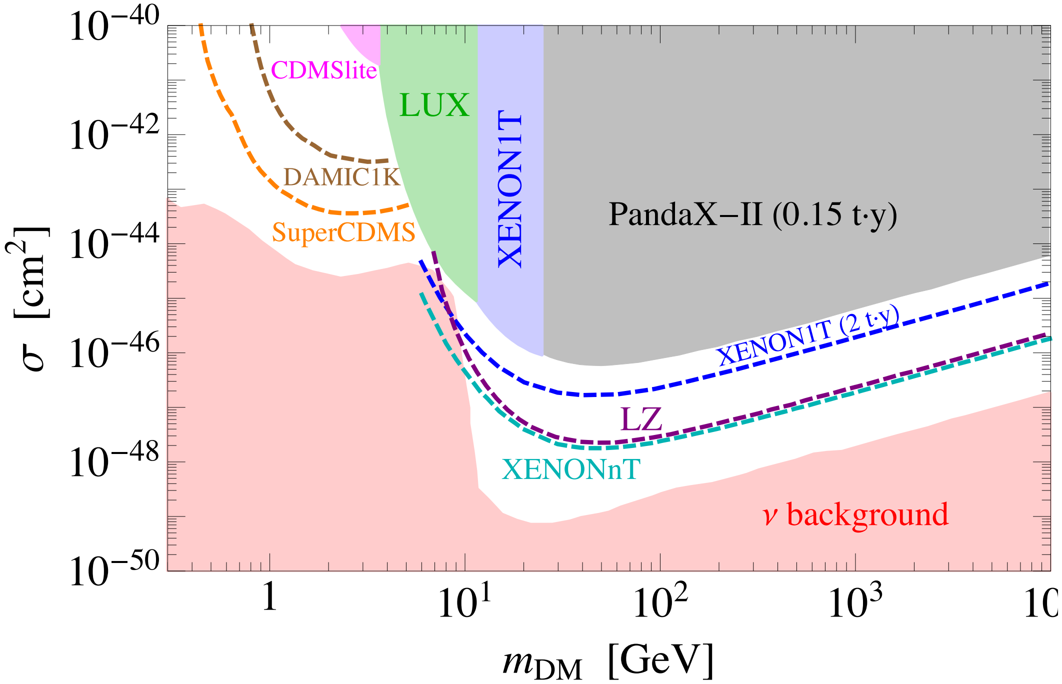
work in collaboration with: Josh Ruderman and Raffaele Tito D'Agnolo
arXiv:1705.08450 PhysRevLett.119.061102

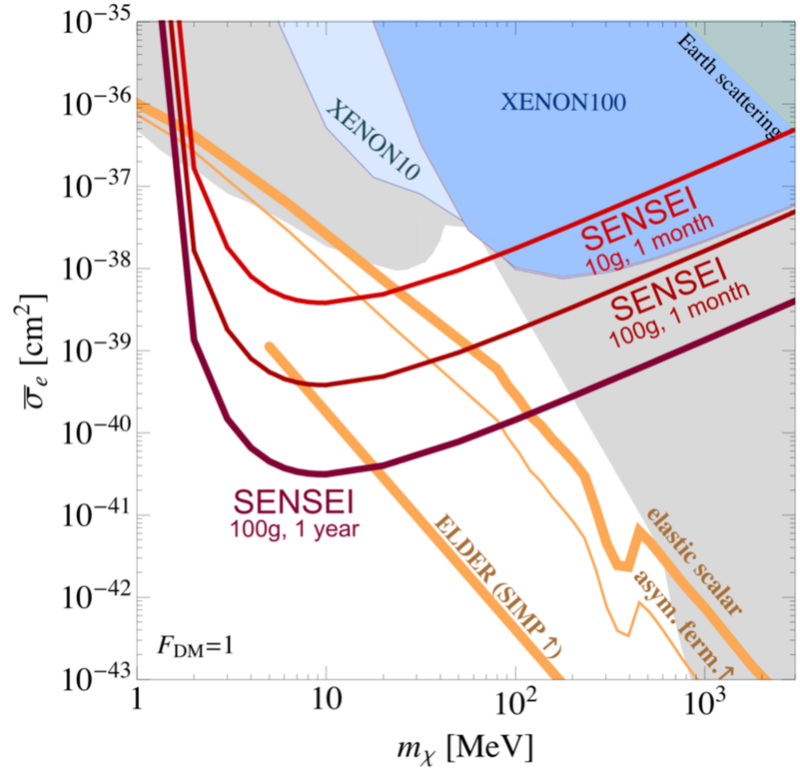
NYU





What’s the natural region for thermal DM direct detection signal?





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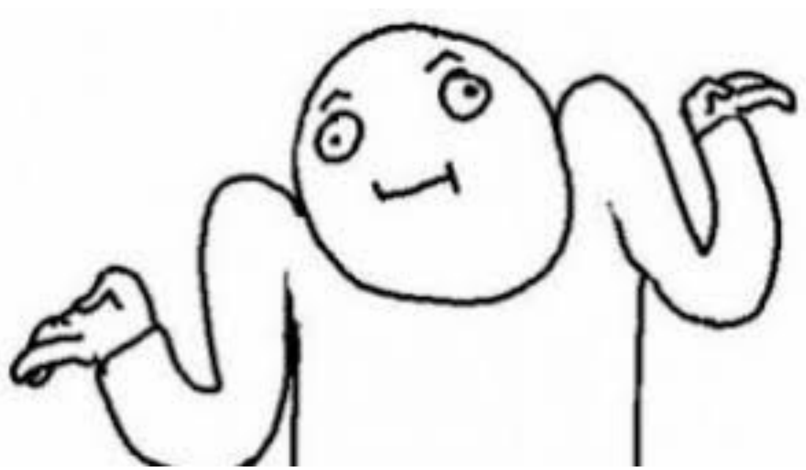
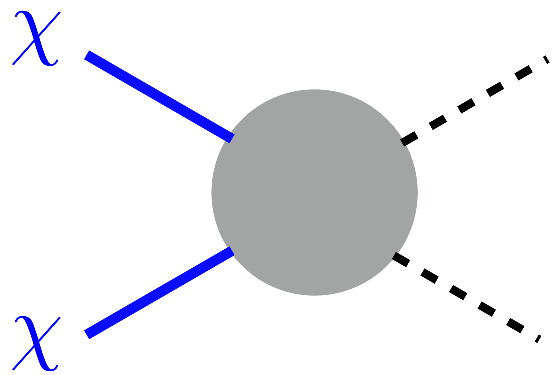


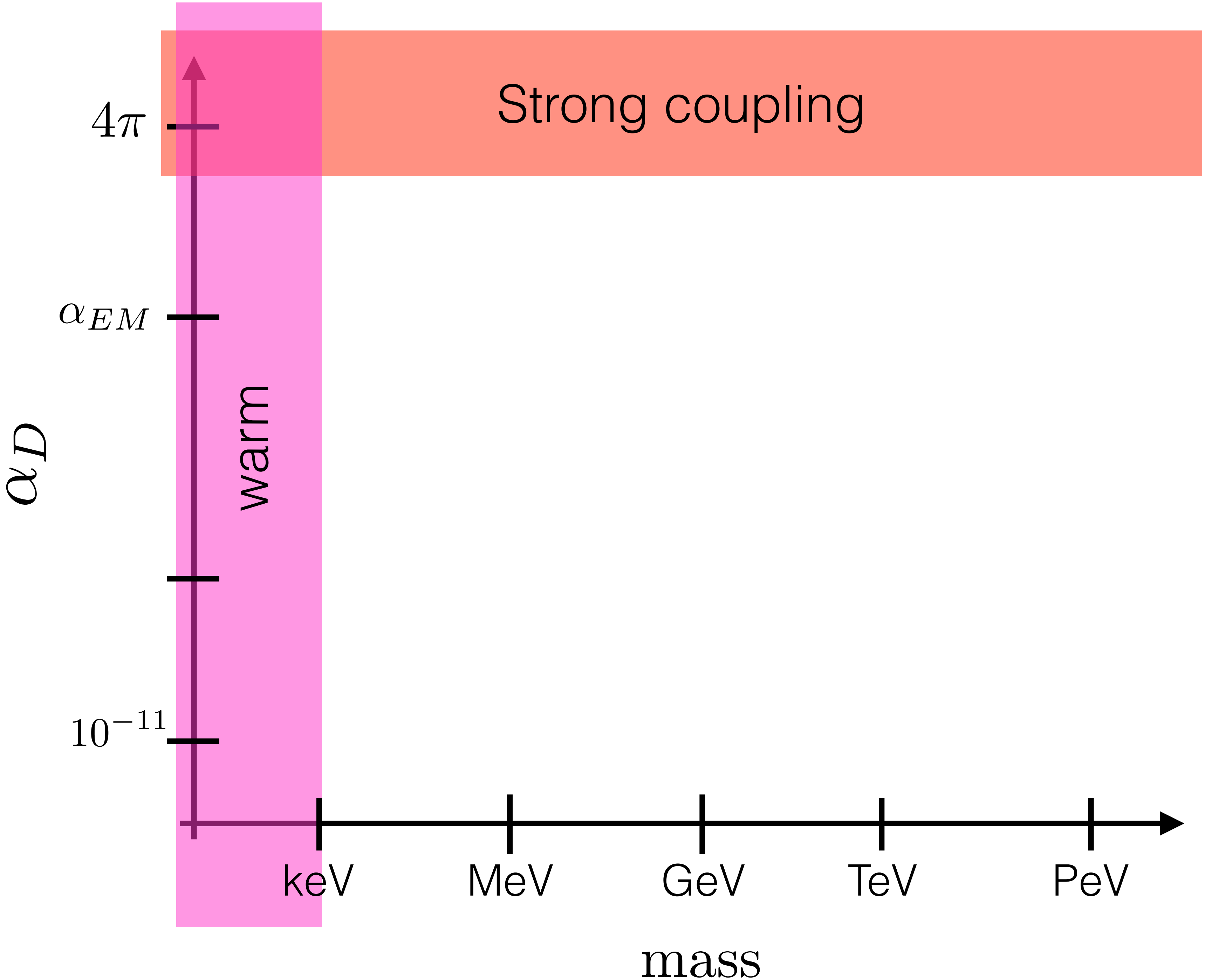
WIMPs



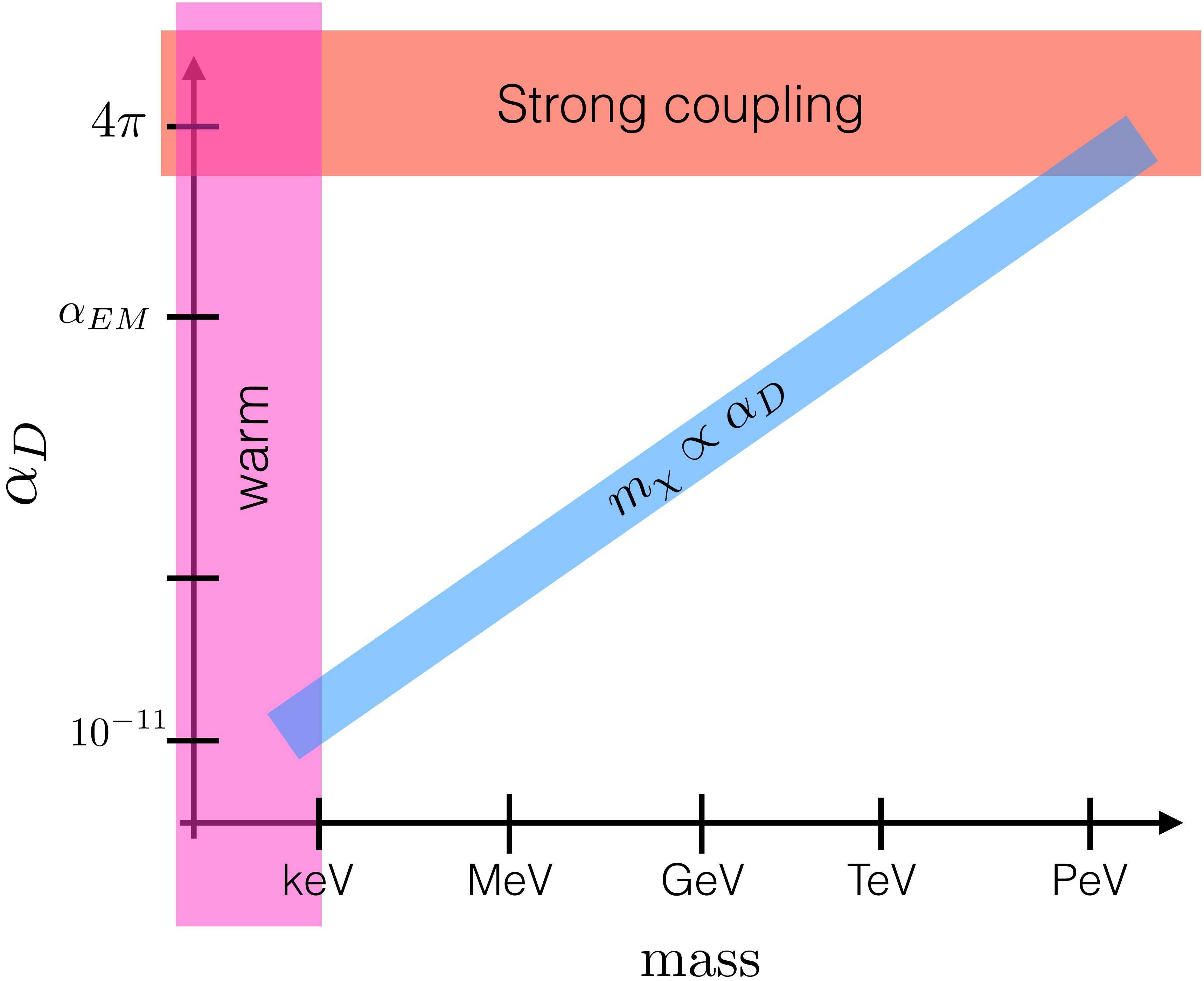
$$\langle \sigma v \rangle \sim \frac{\alpha_D^2}{m_\chi^2}$$

$$T_{\rm eq} \sim \frac{1}{\langle \sigma v \rangle M_P}$$

$$m_\chi \sim 1\,\mathrm{TeV} \times \frac{\alpha_D}{\alpha_{EM}}$$



Strong coupling
4π
α_{EM}
α_D
warm
10^{-11}
keV
MeV
GeV
TeV
PeV
mass



Strong coupling
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$m_\chi \propto \alpha_D$
keV
MeV
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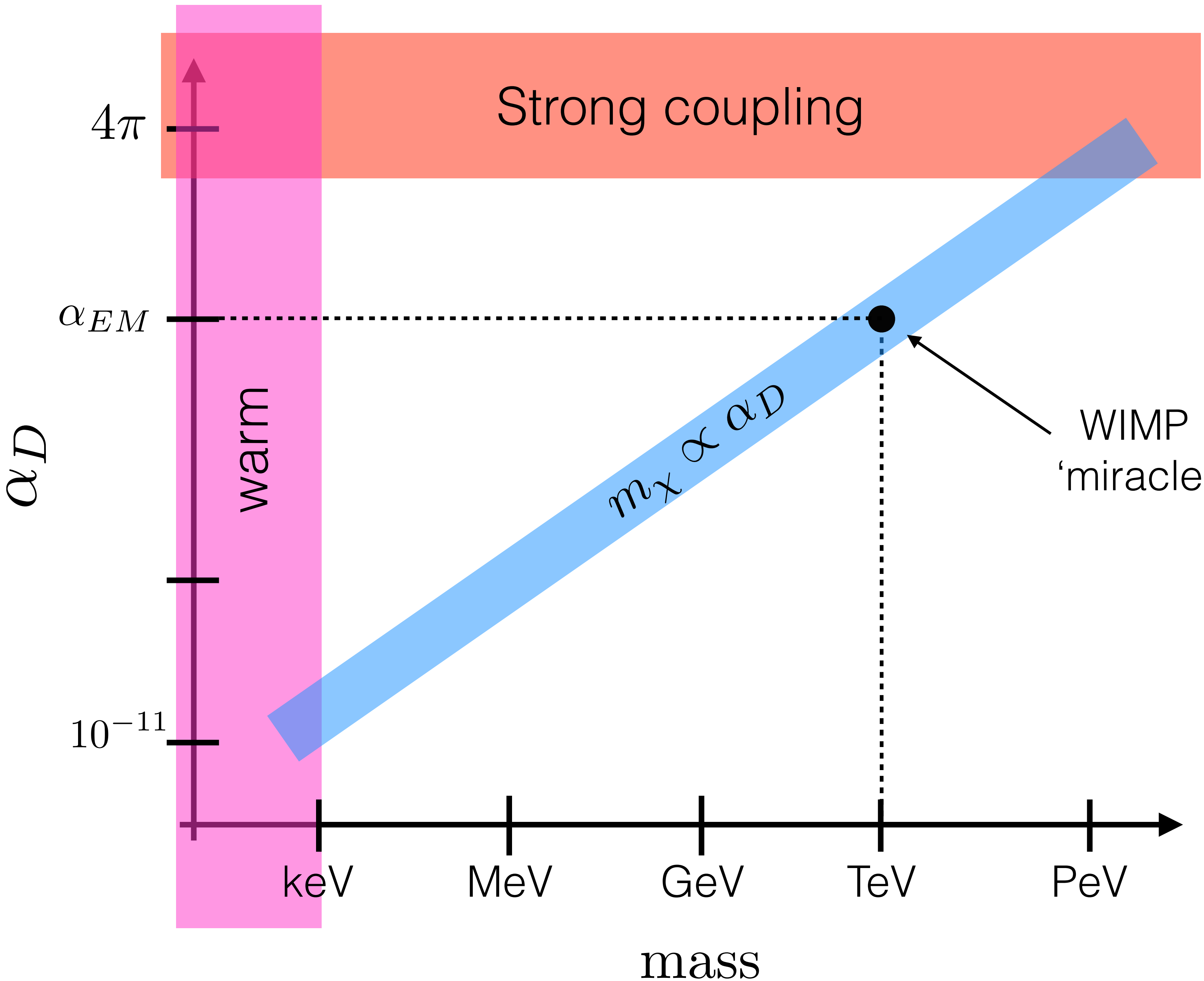
TeV
PeV
mass


Strong coupling
4π
α_{EM}
10^{-11}
α_D
warm
$m_\chi \propto \alpha_D$
WIMP
'miracle'
keV
MeV
GeV
TeV
PeV
mass

Assumptions for WIMP-like relics

$1)$ DM stabilized by Z2 symmetry

(excludes: semi-annihilations)

$2)$ $\mu = 0$ by 2-to-2 annihilations

(excludes: asymmetric DM, SIMP, ELDER,…)

$3)$ $T_{SM} \sim T_D$

(exclides: freeze-in, cannibal,…)

$4)$ No entropy dump

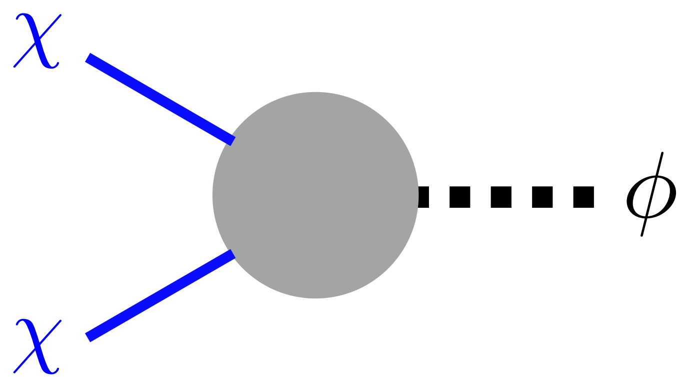
Three known exceptions

Griest, Seckel, 1991

Three known exceptions

Griest, Seckel, 1991

i) Resonant enhancement

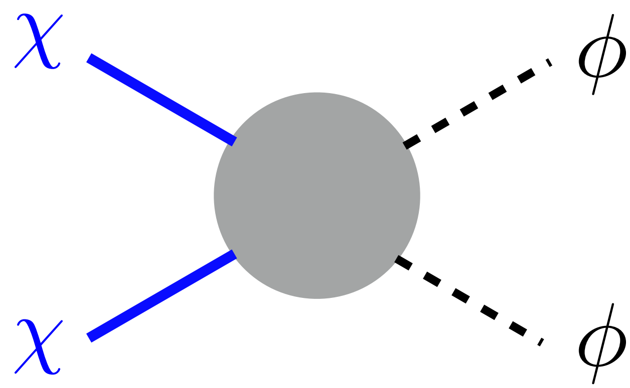


$$m_\phi = 2m_\chi + O(\Gamma_\phi)$$

Three known exceptions

Griest, Seckel, 1991

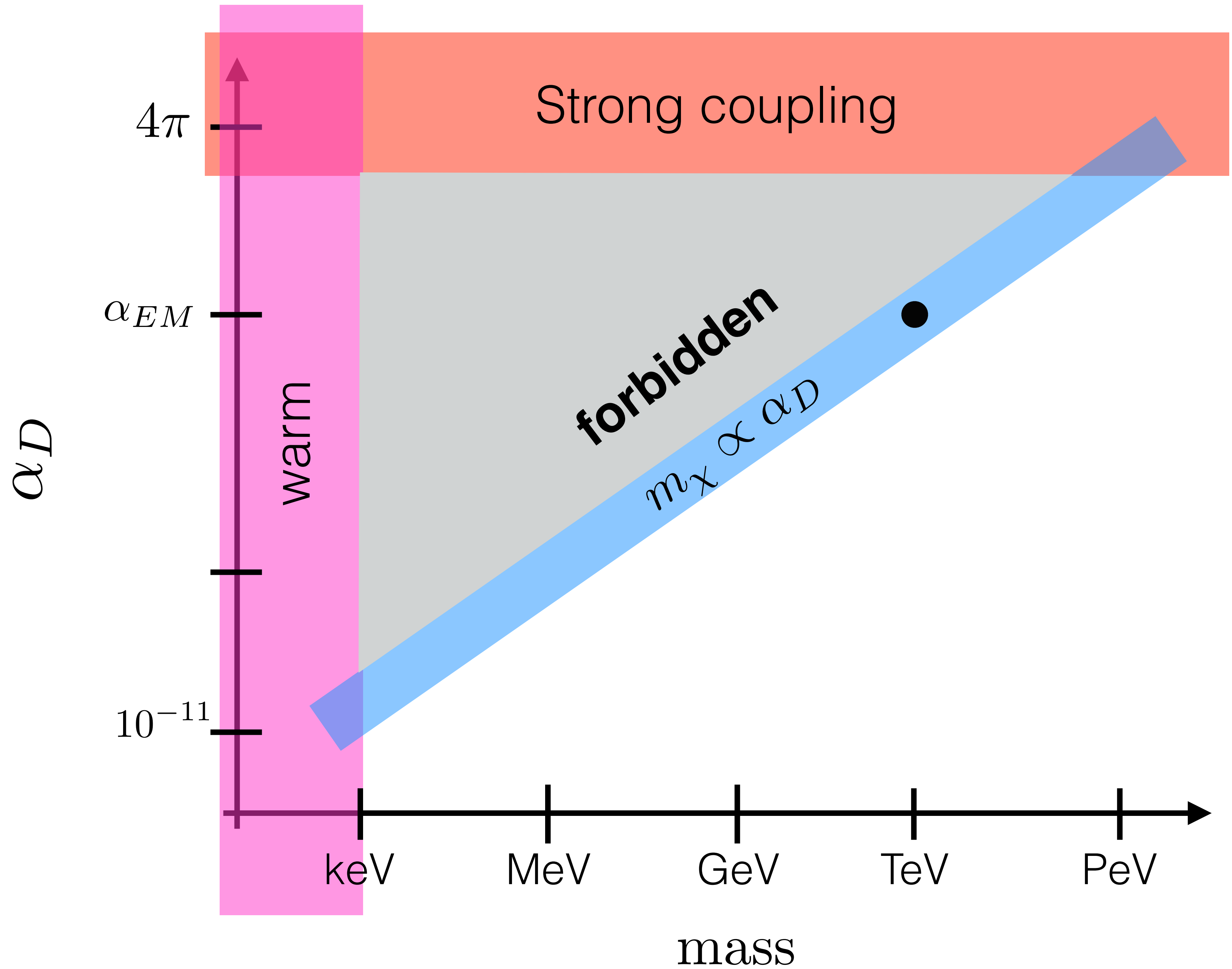
ii) Forbidden channels



$$m_\phi > m_\chi : \qquad \langle \sigma v \rangle \sim \frac{\alpha_D^2}{m_\chi^2} e^{-2\Delta m/T}$$

Boltzmann suppression in the thermal average allows DM to have O(1) couplings but exponentially lighter that the weak scale.

D'Agnolo, Ruderman 1505.07107



Strong coupling
4π
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α_D
warm
forbidden
$m_\chi \propto \alpha_D$
keV
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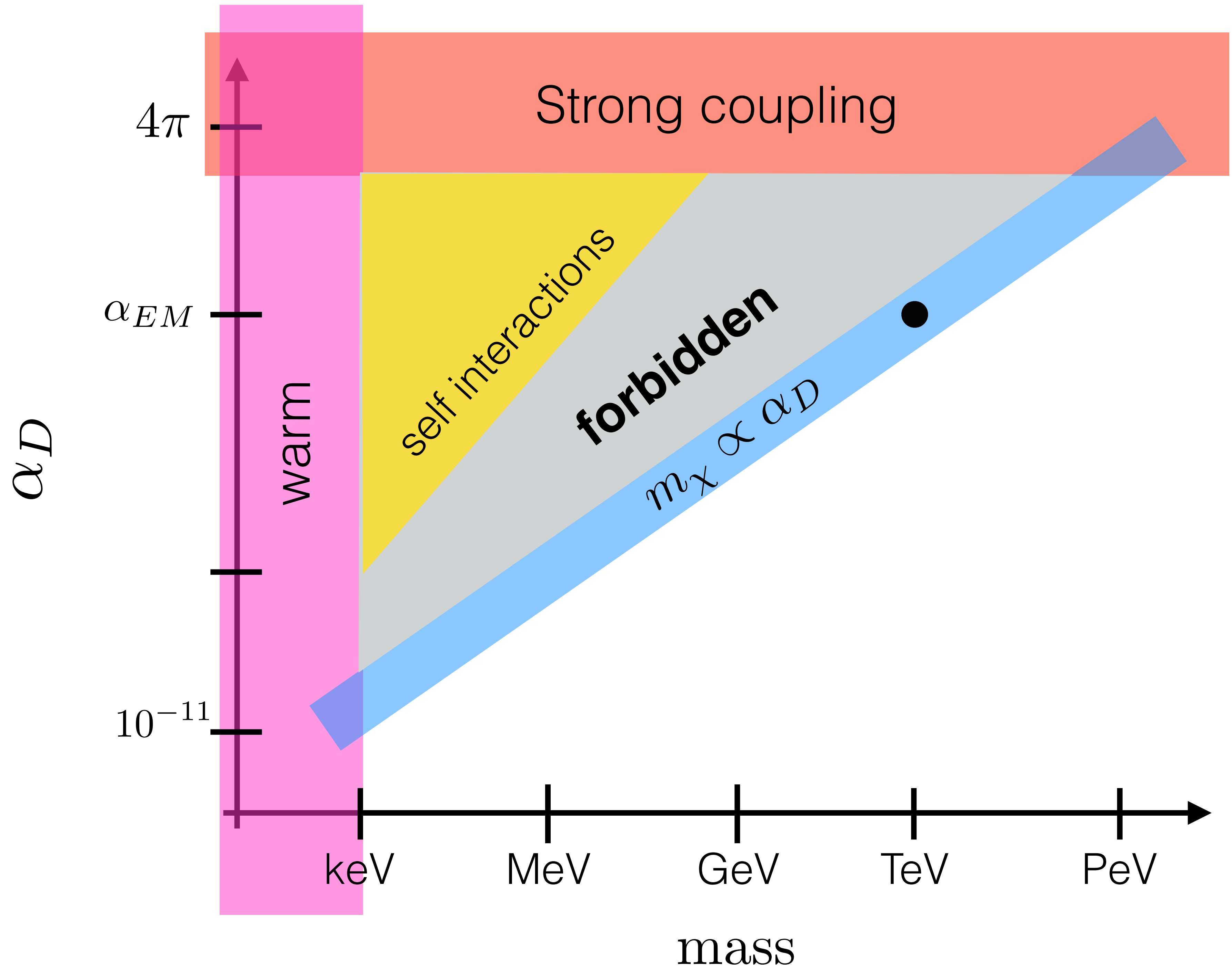
TeV
PeV
mass



Strong coupling
4π
α_{EM}
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warm
self interactions
forbidden
$m_\chi \propto \alpha_D$
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Three known exceptions

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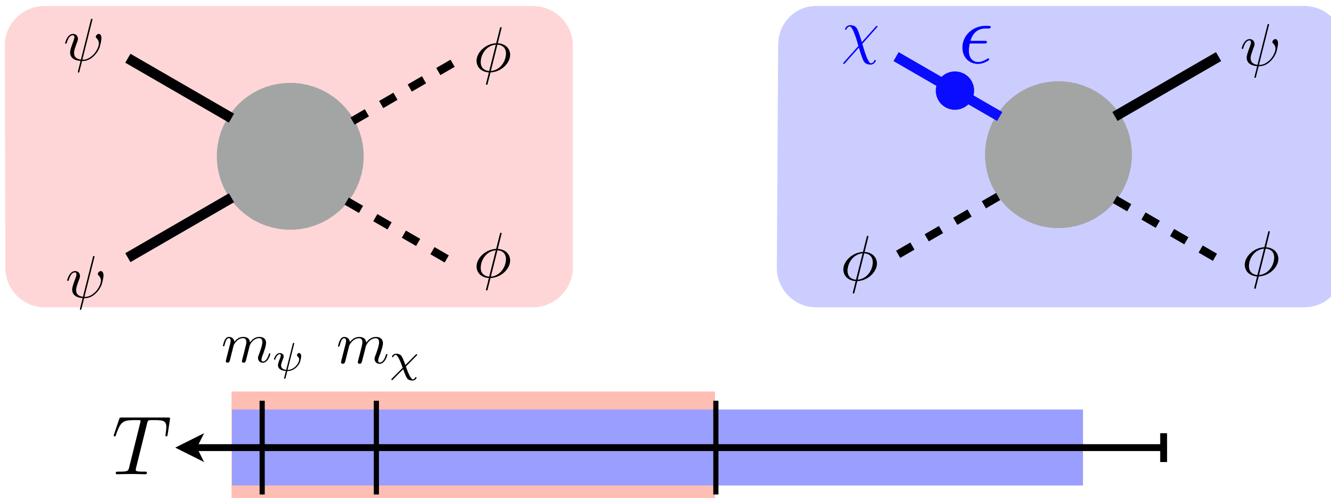
iii) Coannihilations

$\alpha_D \ll \alpha_\psi$



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iii) Coannihilations

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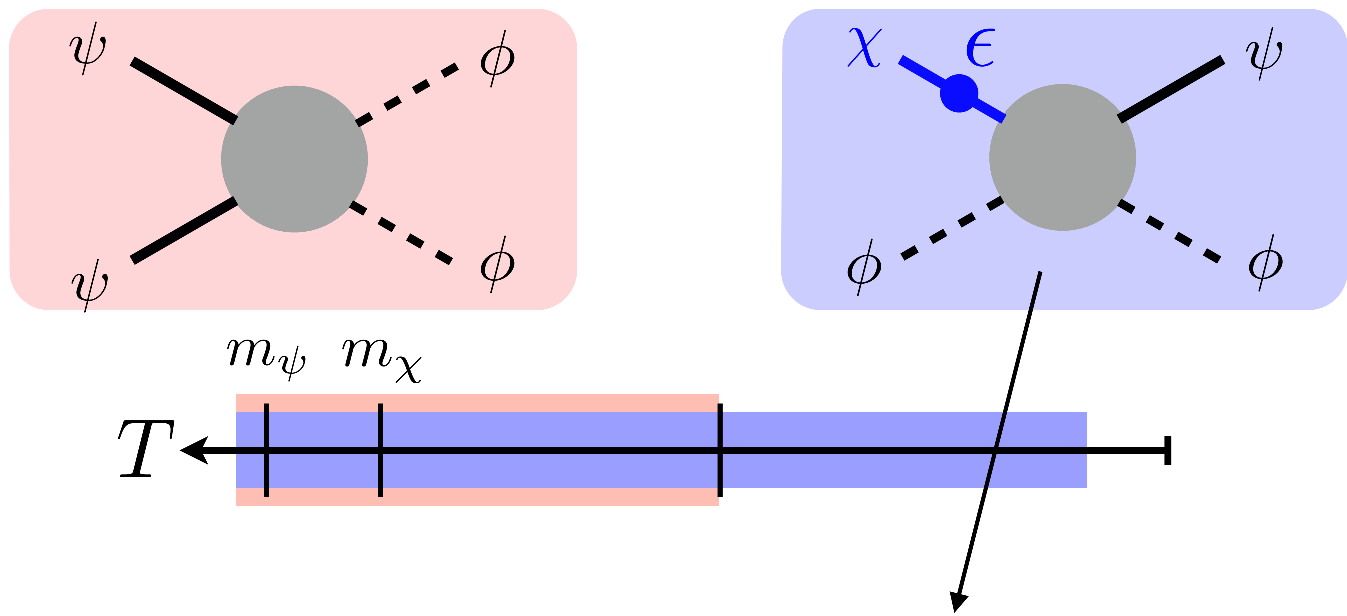


The exchange reaction keeps the chemical potential of the two species equal, and fast reactions that deplete psi will deplete chi.

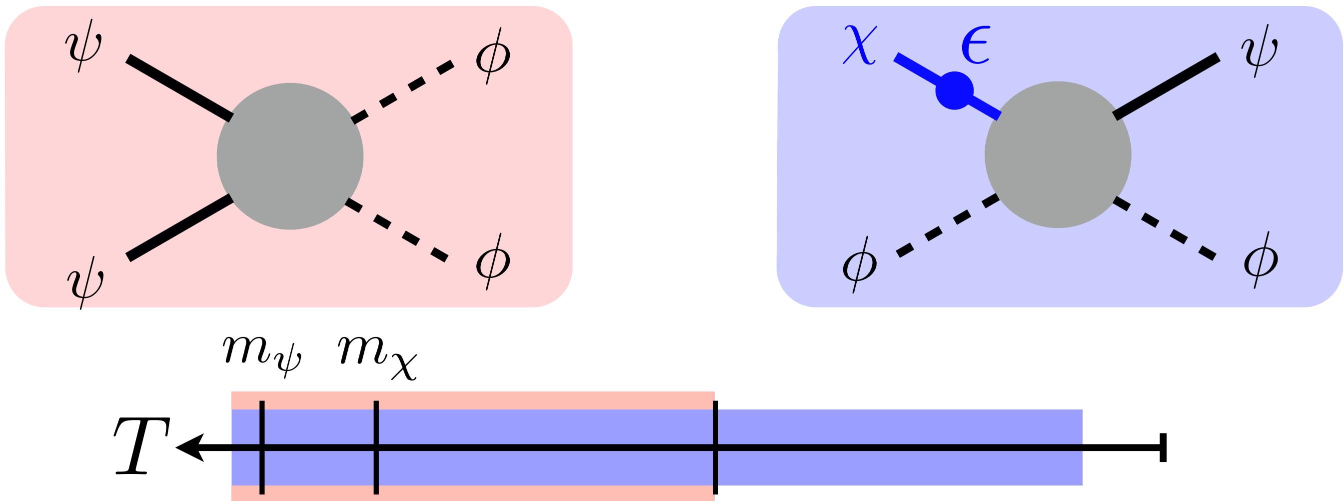
$$n_\chi = n_\psi \frac{n_\chi^{\mathrm{eq}}}{n_\psi^{\mathrm{eq}}}$$

Three known exceptions

Griest, Seckel, 1991

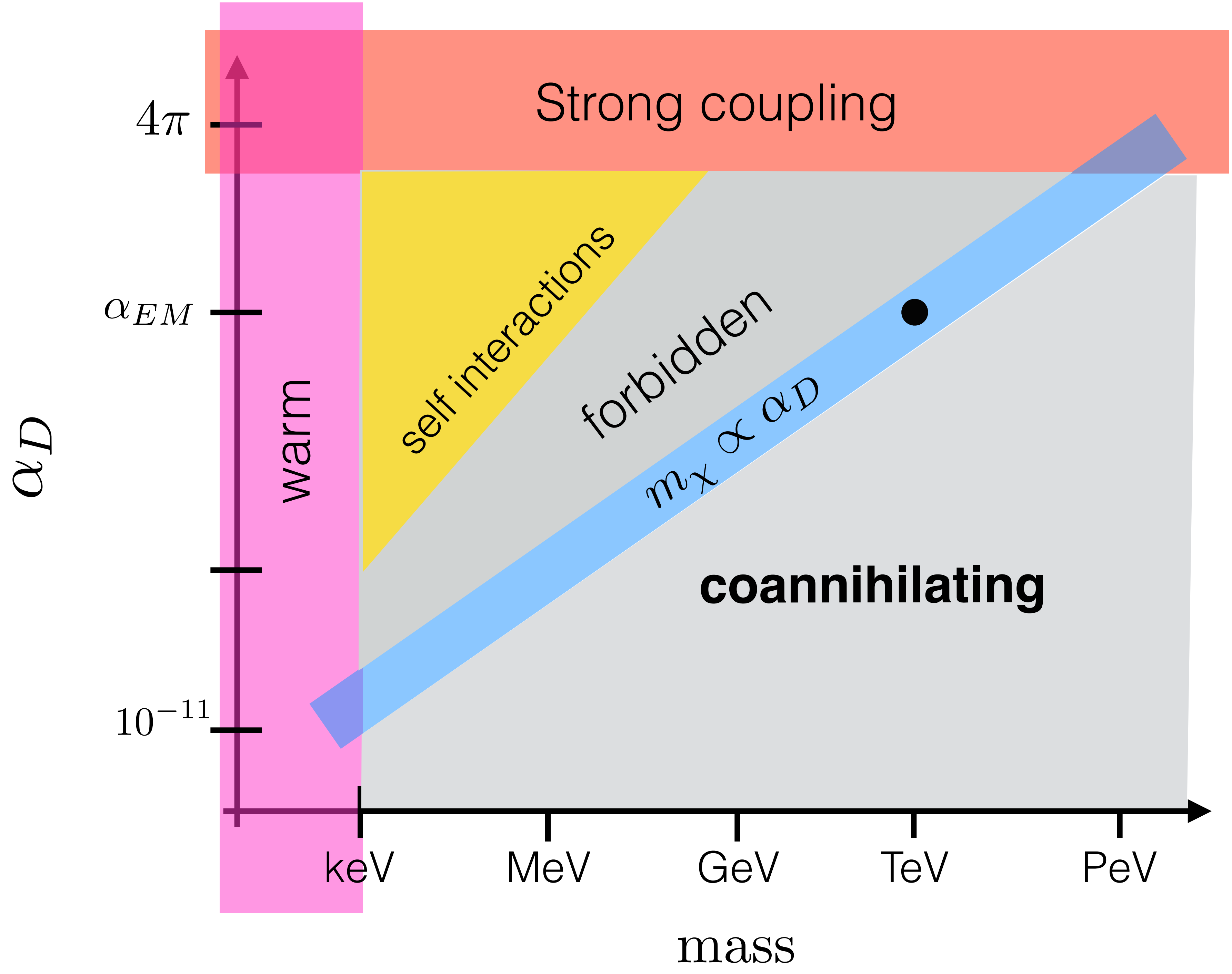
iii) Coannihilations

$\alpha_D \sim \epsilon^2 \alpha_\psi$



$$\langle \sigma v \rangle_{\rm eff} \sim \frac{\alpha_\psi^2}{m_\psi^2} e^{-2\Delta m/T} \gg \langle \sigma v \rangle$$

$$(\epsilon^4 \ll e^{-2\Delta m/T})$$



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coannihilating
keV
MeV
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A fourth exception

D'Agnolo, Pappadopulo, Ruderman 1705.08450

What if exchange reactions decouple earlier than annihilations?

A fourth exception

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What if exchange reactions decouple earlier than annihilations?

↓

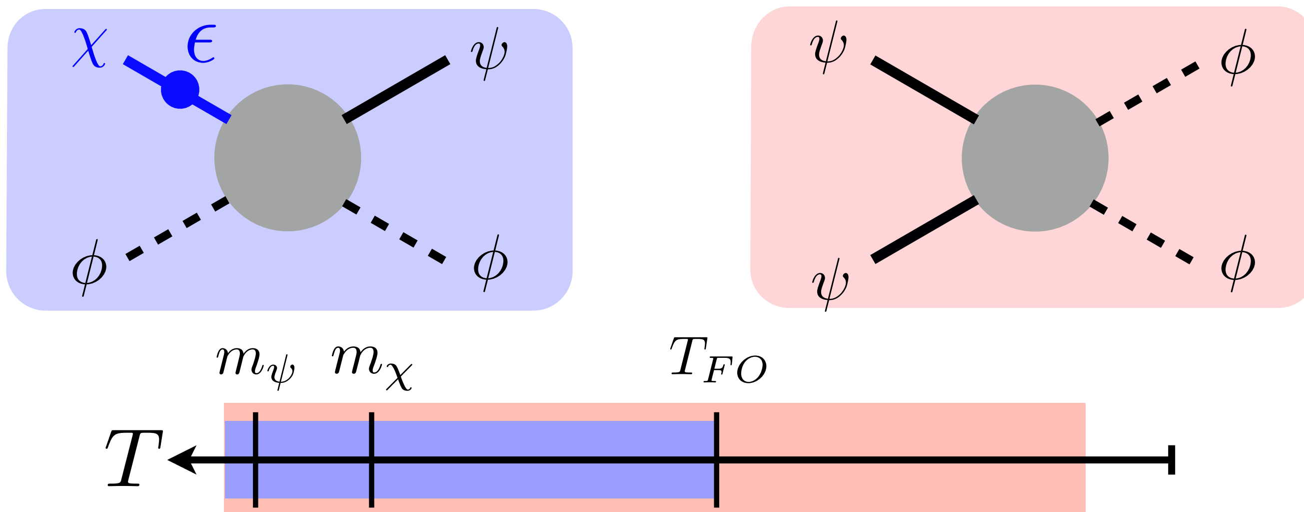
coscattering

Three known exceptions

Griest, Seckel, 1991

iv) **Coscattering**

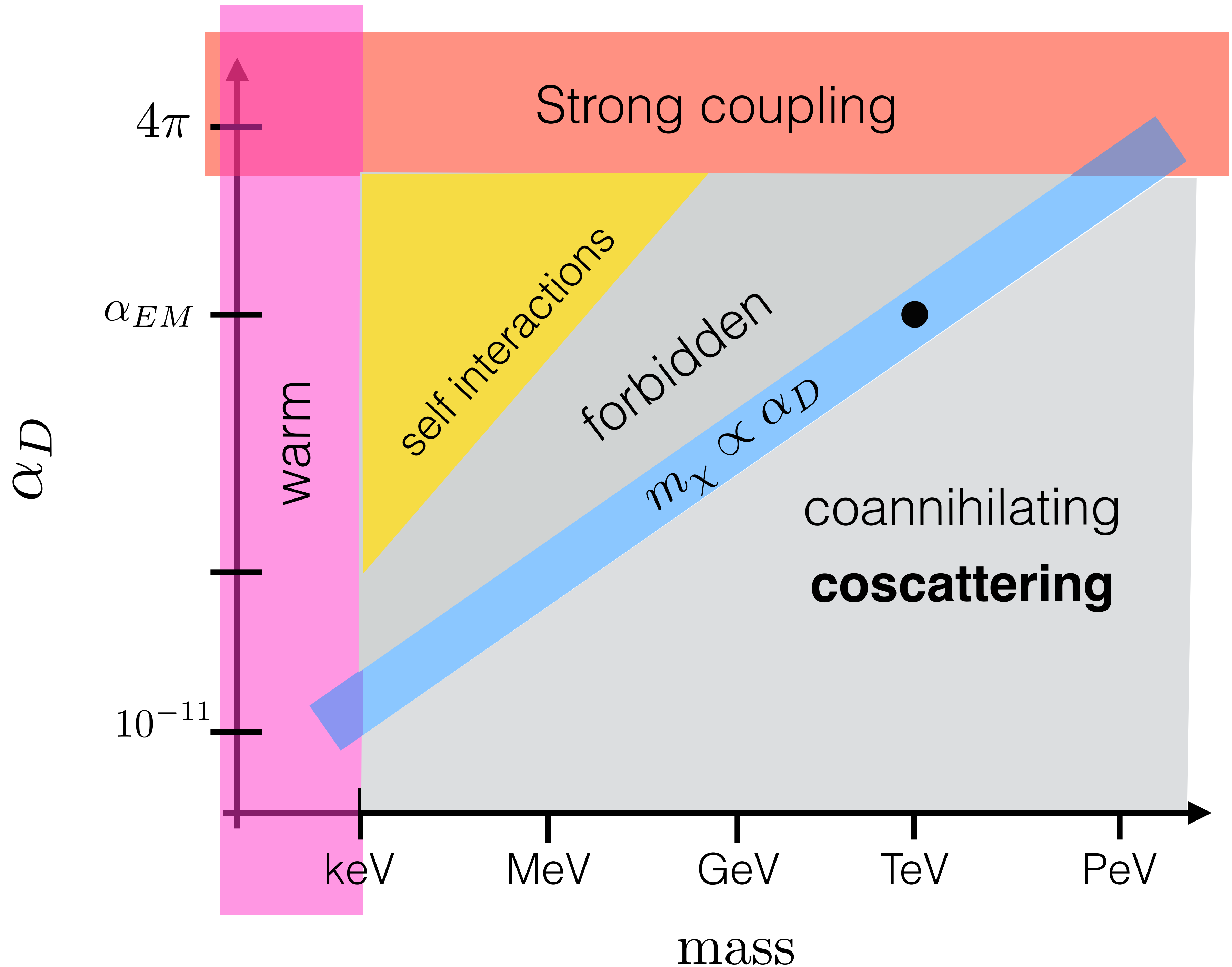
$\alpha_D \ll \alpha_\psi$



Freeze-out is set by decoupling of inelastic (endothermic) scatterings

$$\frac{\Omega_\chi}{\Omega_{DM}} \approx \frac{1\,\mathrm{pb}}{\langle \sigma_{\psi\to\chi}\rangle} e^{(m_\psi + m_\phi - 2m_\chi)/T_{FO}}$$

$$\langle \sigma_{\psi\to\chi}\rangle \sim \epsilon^2 \frac{\alpha_\psi^2}{m_\psi^2}$$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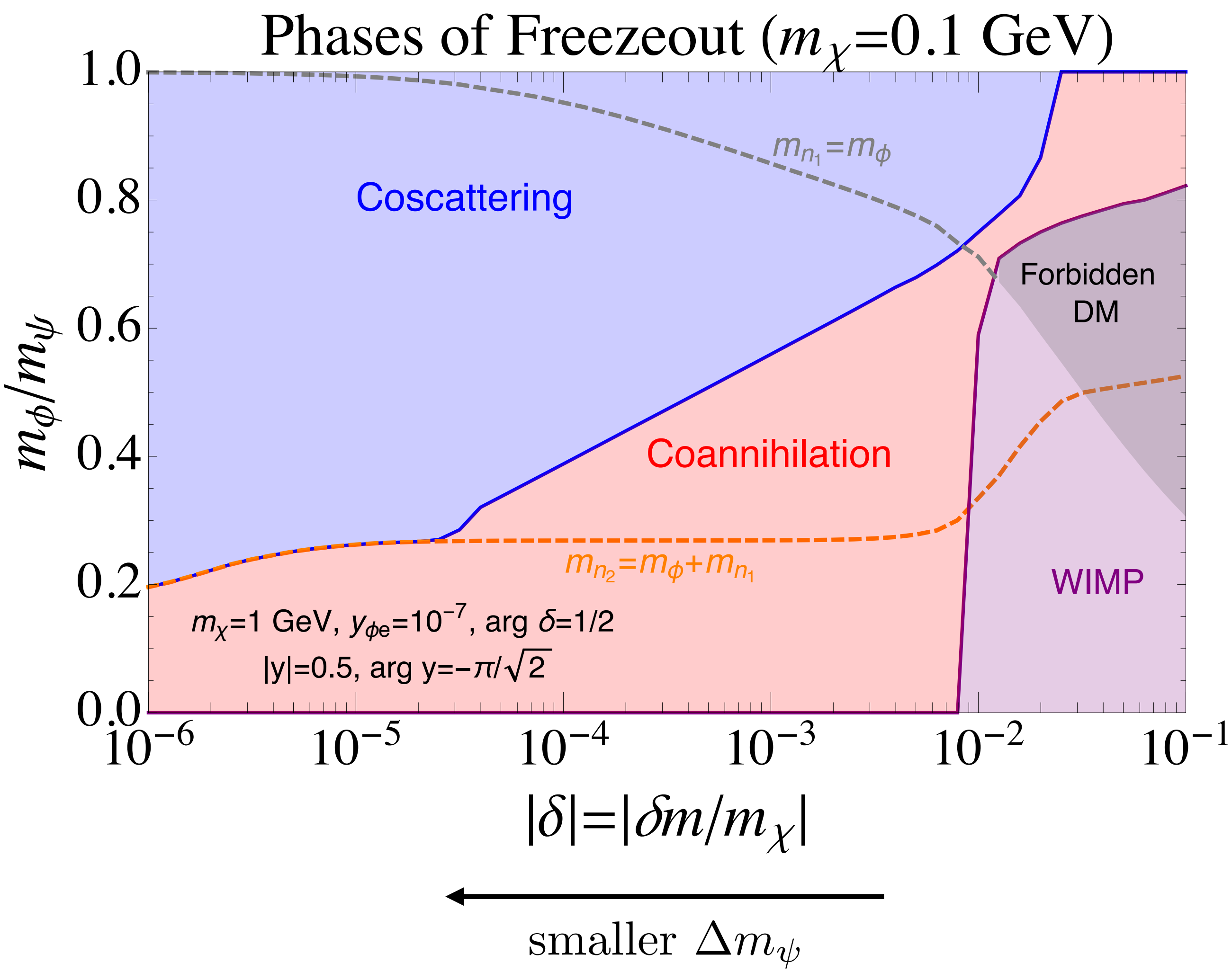
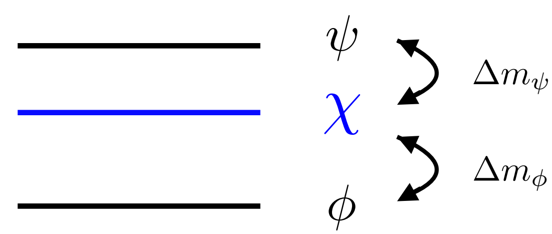
A simple model

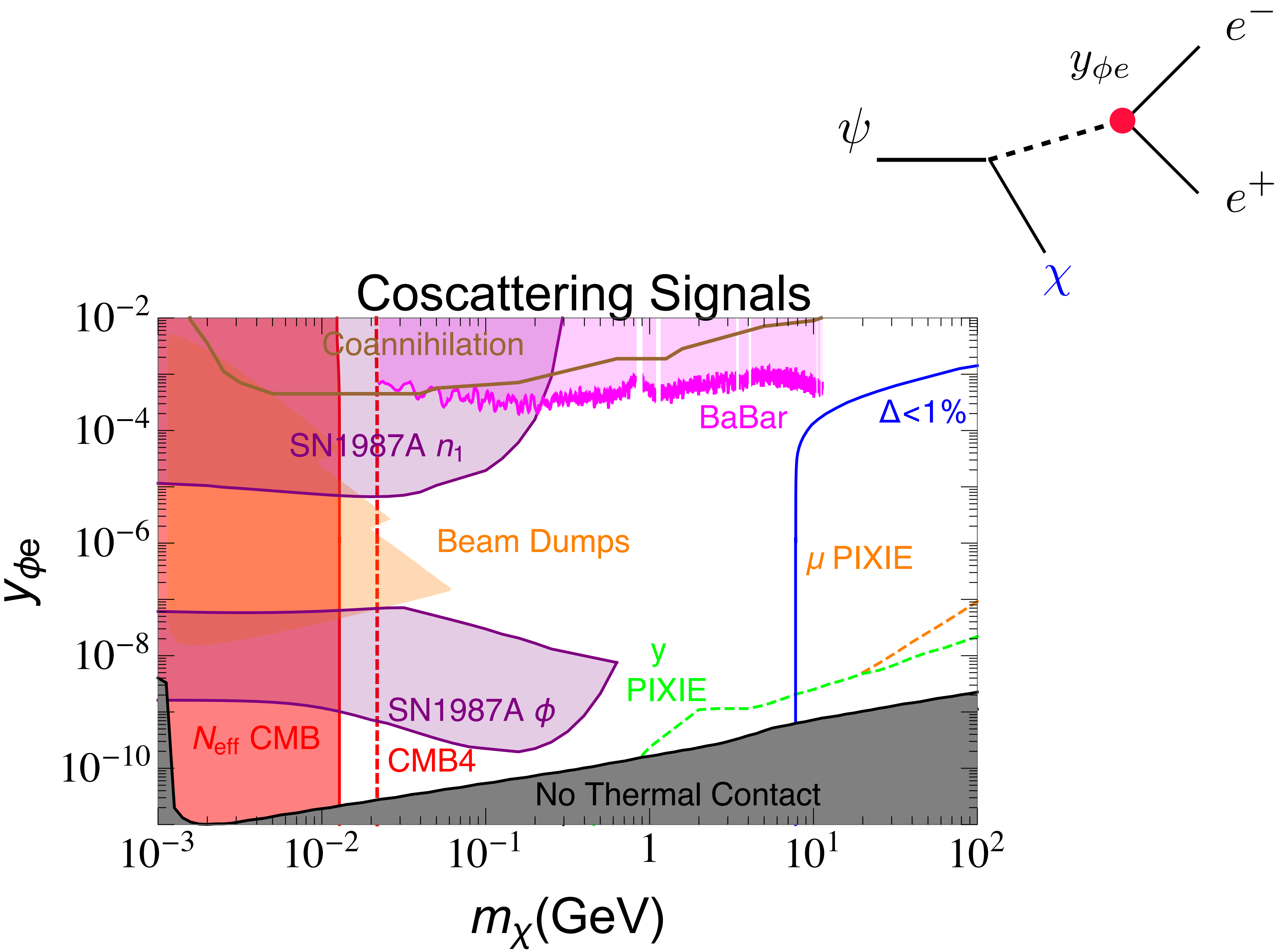
$$\mathcal{L} \supset -\frac{m_\chi}{2}\chi^2 - \frac{m_\psi}{2}\psi^2 - \delta m\,\chi\psi - \frac{y}{2}\phi\psi^2 + \epsilon\phi\,\mathcal{O}_{SM}$$



$$\delta m \ll m$$

$$m_\phi + m_\chi > m_\psi$$





Coscattering Signals
Coannihilation
BaBar
Δ<1%
SN1987A n1
Beam Dumps
μ PIXIE
y
PIXIE
SN1987A ϕ
Neff CMB
CMB4
No Thermal Contact
yϕe
mχ(GeV)
ψ
χ
e−
e+
yϕe

$$m_\psi = 0.9\, m_\chi$$

Conclusions

The parameter space of thermal DM is vast and the question about the existence of a DD target has a model dependent answer.

Identified a new generic mechanism for thermal DM, coscattering.

A lot is left to explore regarding the possible phenomenology of coscattering.