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Alps 2024: Dark Matter

Towards a theory of dissipative Dark Matter

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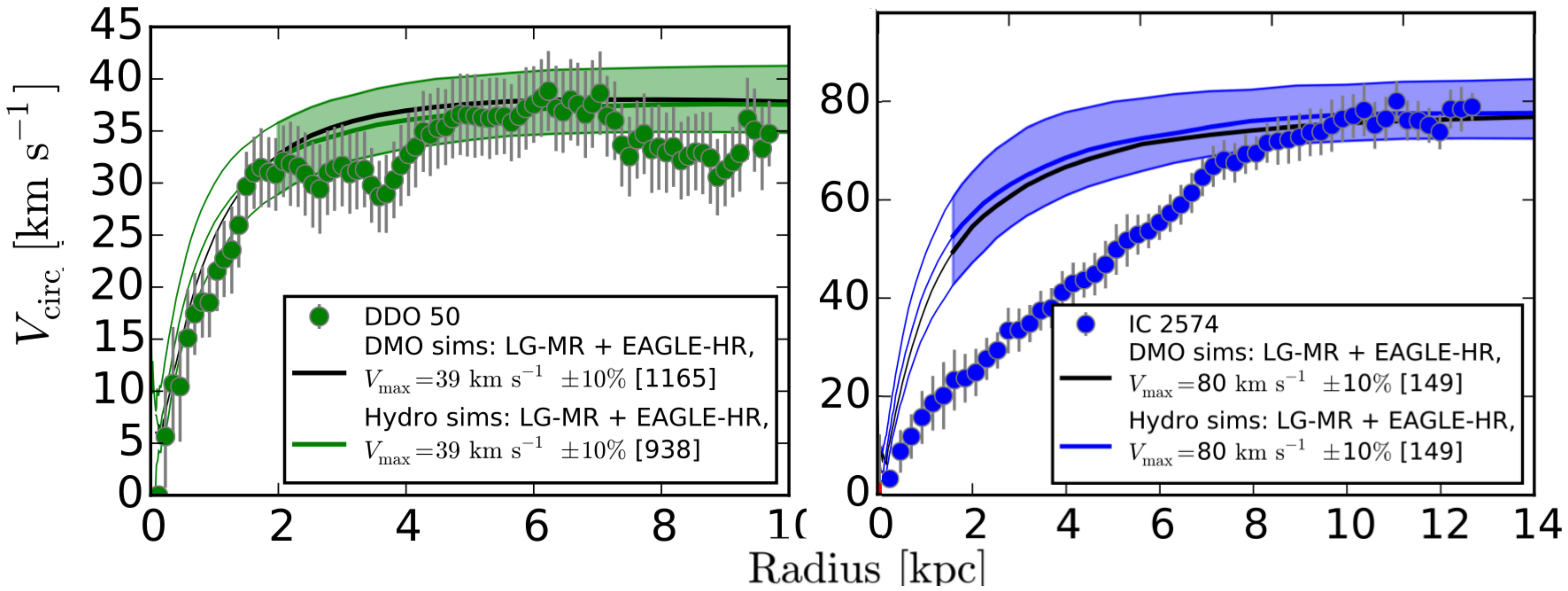
Self Interacting Dark Matter

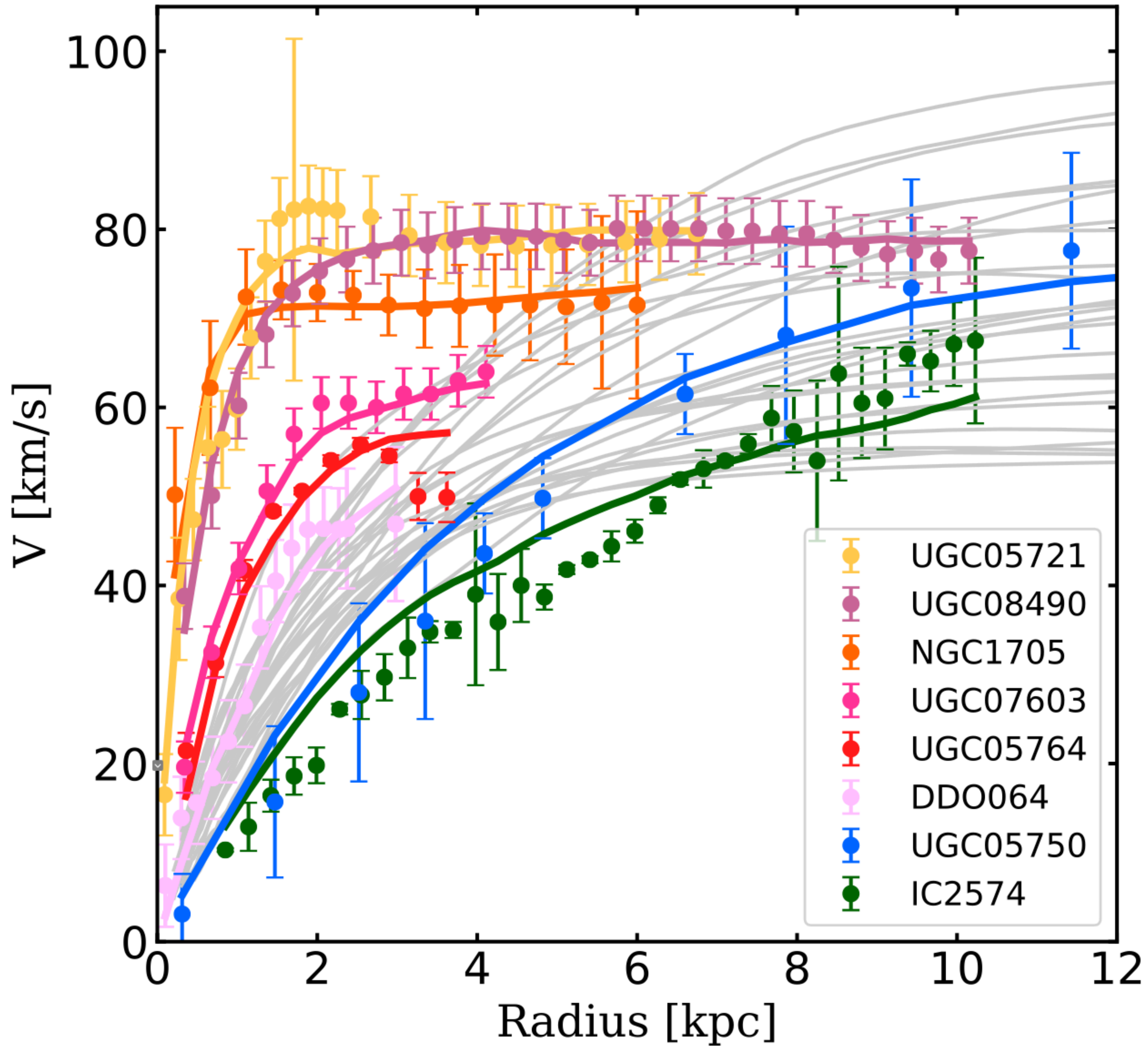
For example: diversity of dwarf galaxy rotation curves[1]



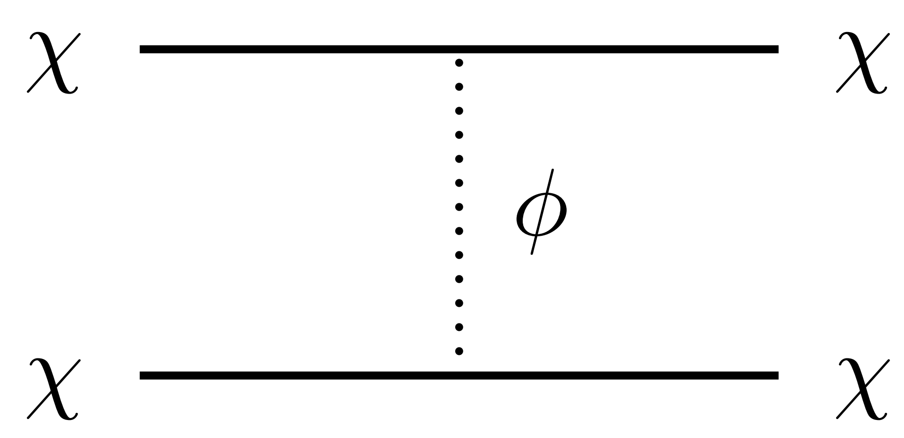
Discrepancies between
N-body simulations and observations at **small scales (< Mpc)**:

« Small-scale problems » in ΛCDM

SIDM[2]:



Principal mechanism: heat transfer from the hotter outer regions to the central part through DM collisions.



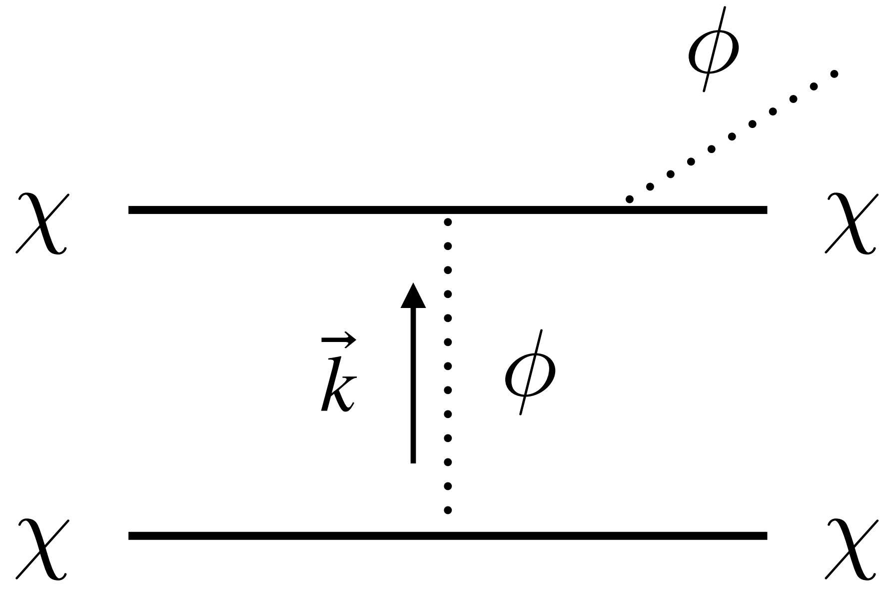
Light mediator[5] → velocity dependent cross-section

$$\sigma \overset{[6]}{\approx} 5 \times 10^{-23} cm^2 \left(\frac{g_\chi}{0.01}\right)\left(\frac{m_\chi}{10\mathrm{GeV}}\right)^2\left(\frac{m_\phi}{10\mathrm{MeV}}\right)^4$$

[1].arXiv:1504.01437 [astro-ph.GA], [2] arXiv:1911.00544v1 [astro-ph.GA]
[3]. Phys.Rev.Lett. 84 (2000) 3760-3763 [4]arXiv:astro-ph/9909386 [5] arXiv:1302.3898v1 [hep-ph]

SIDM: dissipative channel

Built in dissipative channel:
Radiative processes



$|\vec{k}|^2 \gg m_\phi^2$: quasi-**Coulomb potential**.

Could have many impacts:

- evolution of super-massive black holes[2]
- formation and history of halos[3]
- dark disk formation[1]

[1] arXiv:1807.04750 [astro-ph.GA], [2] arXiv:1303.1521 [astro-ph.CO], [3] arXiv:1812.07000 [hep-ph]
Build on Weinberg: Phys. Rev. D 99, 076018 [4] Coulomb emission rate: arXiv:2007.06592v3, arXiv:2105.13362v2, arXiv:2103.03248v2

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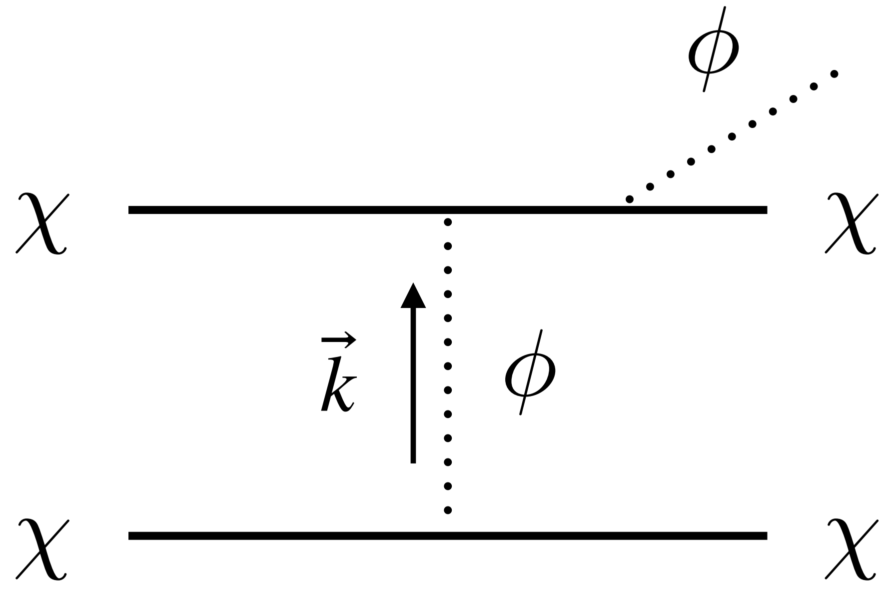

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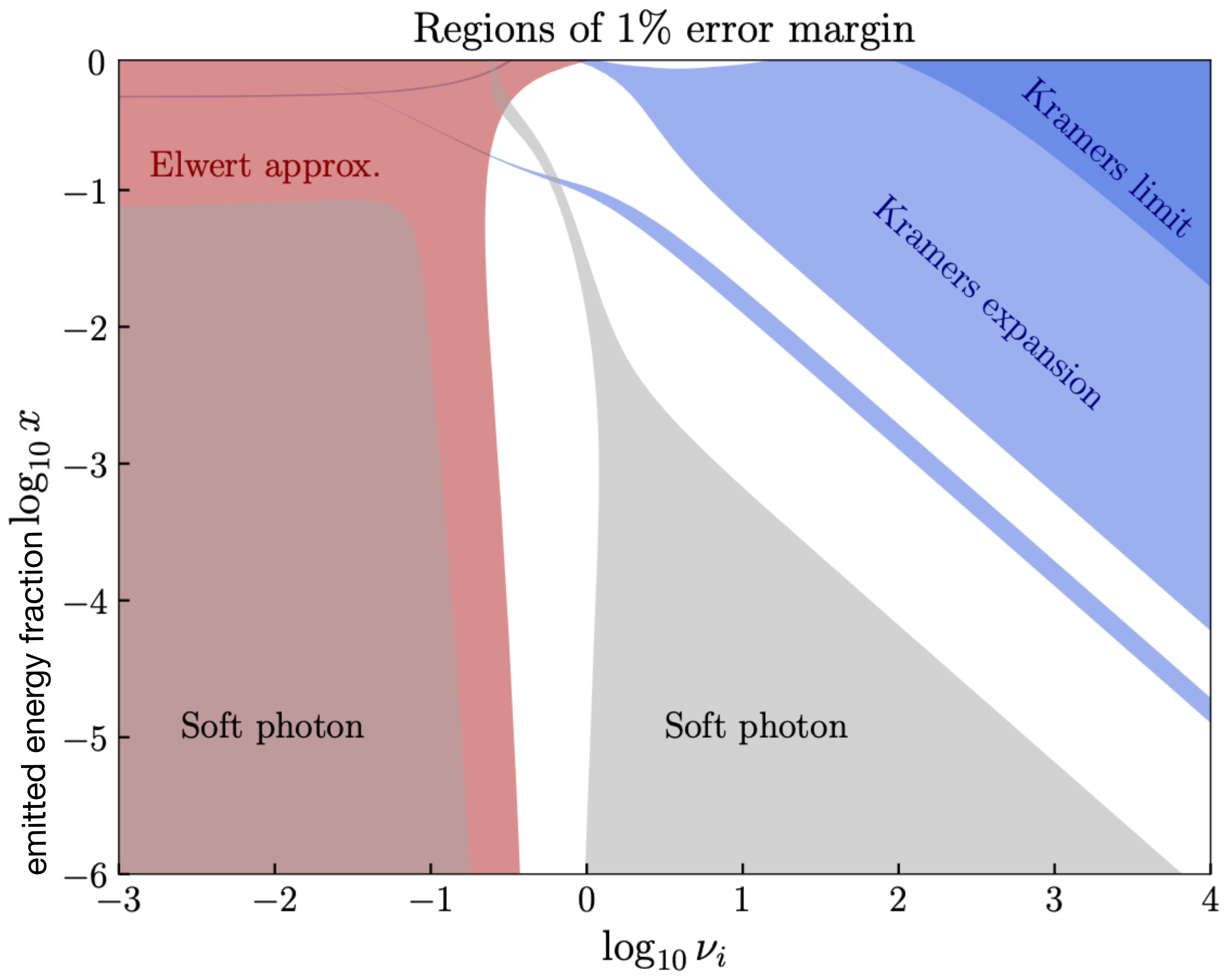
Recent $e^\pm - e^\pm$ quadrupole and dipole Non-Relativistic **emission calculations**[4], valid in all kinetic regimes: from born to classical, from soft to hard mediated emission.



$\psi_{i,f}$ are a function of the Sommerfeld parameters :

$$\nu_{i,f} = -Z_1 Z_2 \frac{\alpha}{v_{i,f}}$$

$|\nu_{i,f}| \ll 1$ Born Regime

$|\nu_{i,f}| \gg 1$ Classical Regime

[1] arXiv:1807.04750 [astro-ph.GA], [2] arXiv:1303.1521 [astro-ph.CO], [3] arXiv:1812.07000 [hep-ph]
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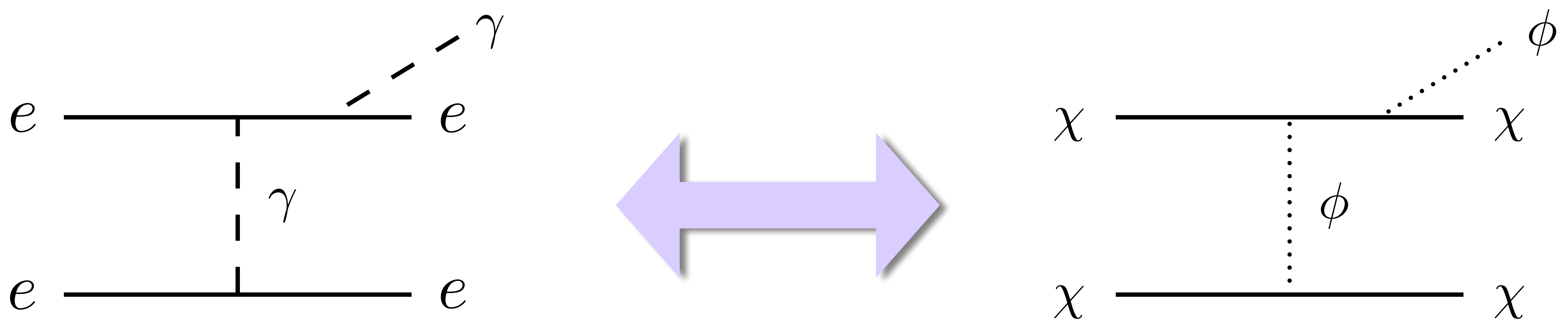


Goal: to obtain Non-Relativistic dissipative rates valid in all kinetic regimes for a wide variety of DM models.

***Our work so far*:** description of five DM models in the Born regime using QFT tree level calculations.

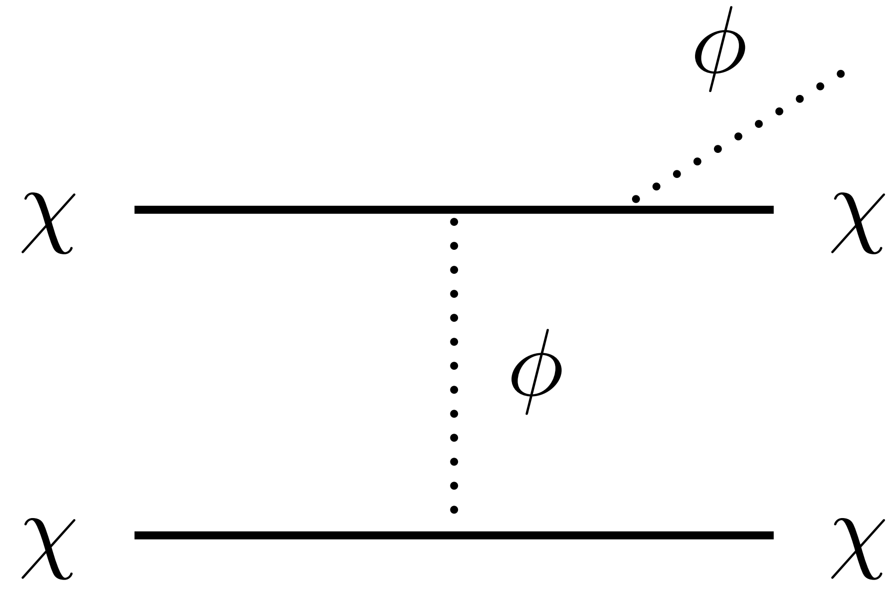
Our dissipative models:

- DM χ : from scalar to fermion.
- Mediator V_μ, ϕ : gauge to scalar.

General assumptions :

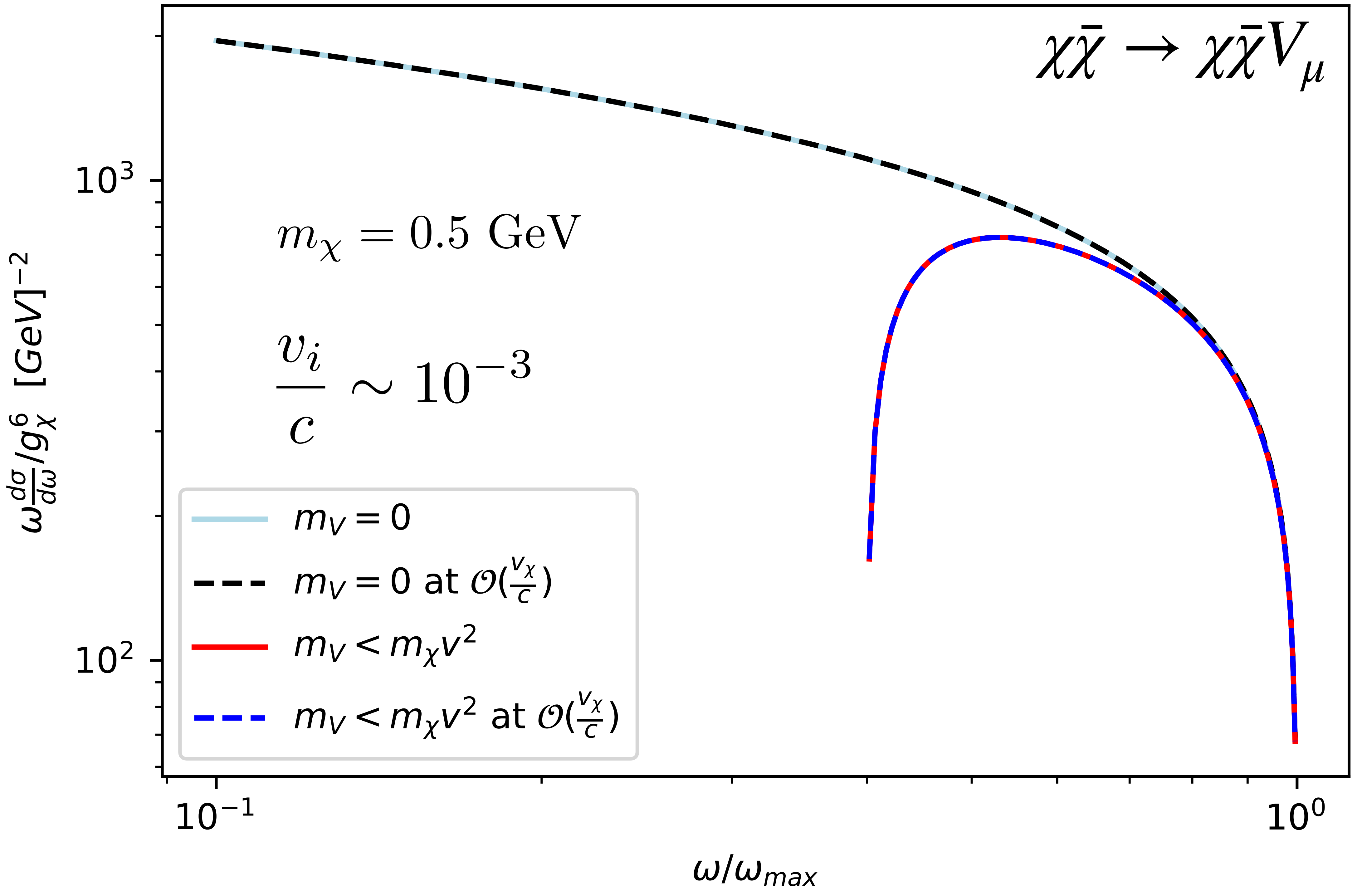
- Non relativistic particles: $v_\chi \lesssim 100 - 1000\text{km.s}^{-1}$
- Light emitted particles: $m_{\phi,V} \ll m_\chi v_\chi^2$

Cross-section

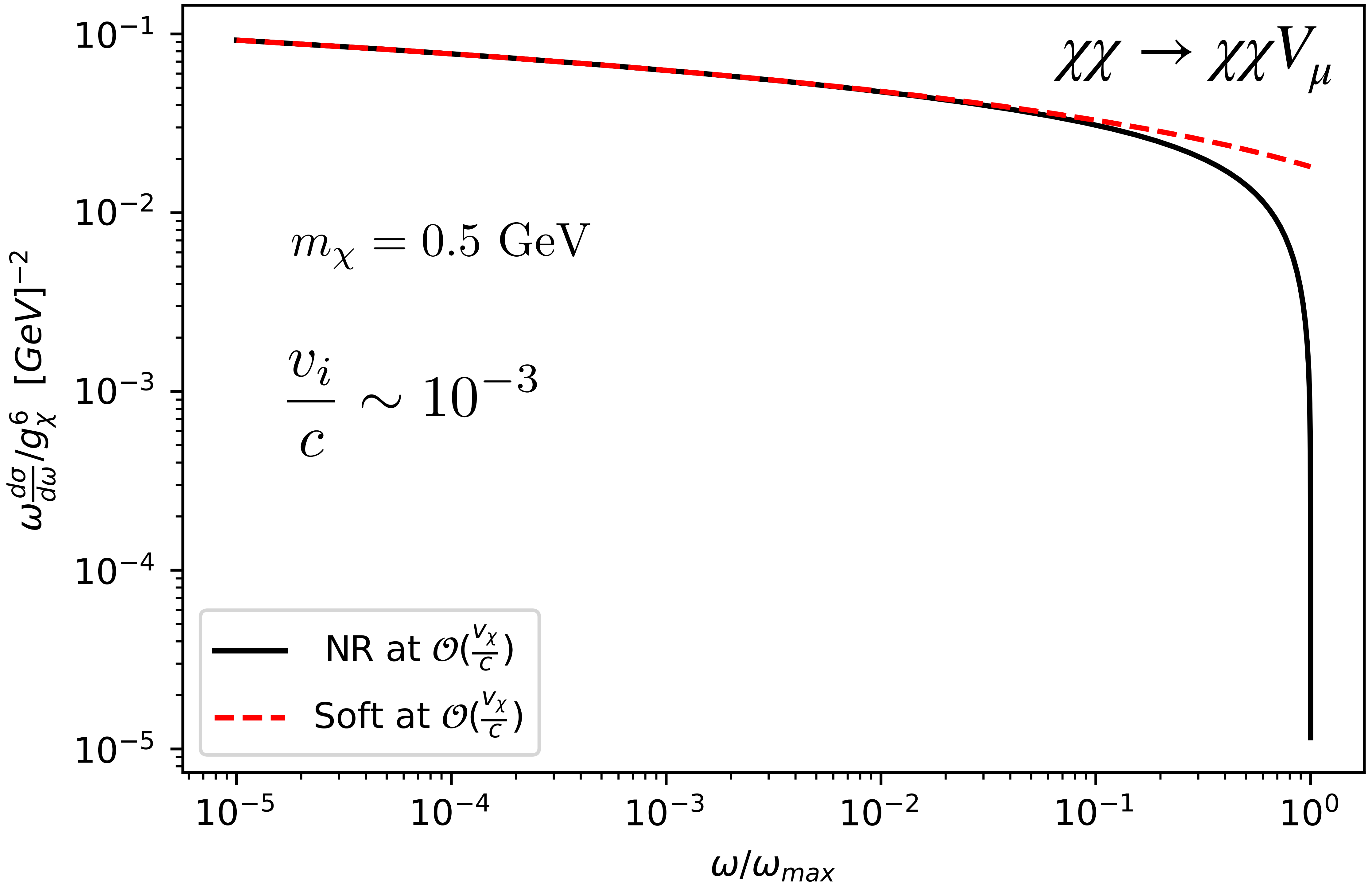


We have obtained simplified analytical expressions of the NR scattering amplitude from a ***systematic expansion in velocity***[1] both for a massless and massive mediator.

full QFT numerical result vs our simplified expression



soft limit $\omega \to 0$ simplified expression



Leading to a simplified $\frac{d\sigma}{d\omega}$ in agreement with the full QFT numerical results in the NR.

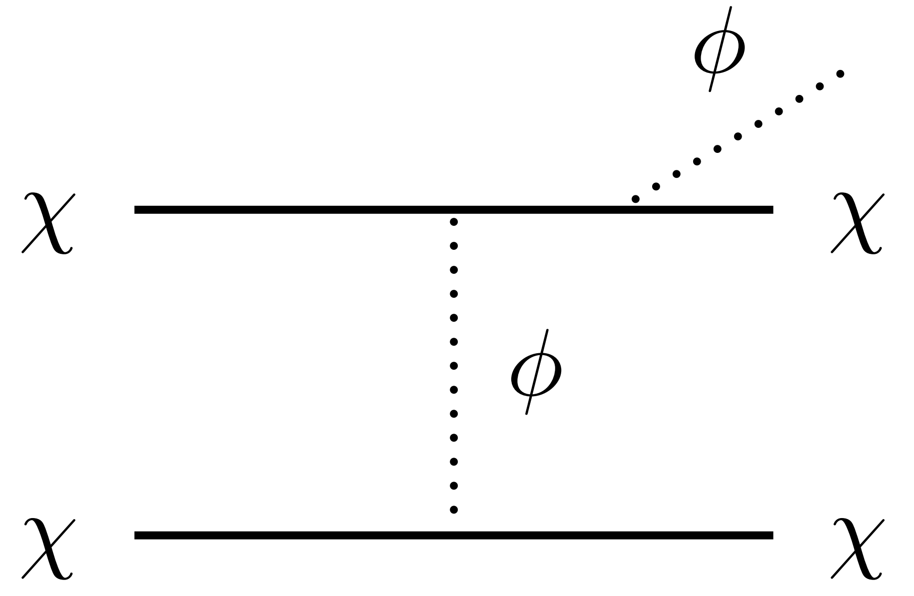
[1] Similar methodology in the case of Axion Bremsstrahlung:
Massless: Phys. Rev. D 38, 2338, Phys. Rev. Lett. 53, 1198, Massive: arXiv:hep-ph/0505090

Dissipative rates

Dilute DM gas: Maxwell-Boltzmann Distribution

$$\frac{1}{2}m_\chi\langle v_\chi^2\rangle = \frac{3}{2}k_B T$$

$$\frac{\dot\epsilon}{n_\chi^2} \propto \int d^3p_i\,|\vec{p}_i|e^{-\frac{|\vec{p}_i|^2}{m_\chi T}}\int d\omega\,\omega\frac{d\sigma}{d\omega}$$



Fermion χ	Gauge emission V^μ	Scalar emission ϕ
$\chi\chi\to\chi\chi M$	$\dot\epsilon = (44-3\pi^2)\frac{5n_\chi^2 g^6 T^{3/2}}{144\pi^{7/2}m_\chi^{5/2}}$	$\dot\epsilon = (44-3\pi^2)\frac{n_\chi^2 g^6 T^{3/2}}{36\pi^{7/2}m_\chi^{5/2}}$
$\bar\chi\chi\to\bar\chi\chi M$	$\dot\epsilon = \frac{2g^6 n_\chi^2 T^{\frac{1}{2}}}{3\pi^{7/2}m_\chi^{3/2}}$	$\dot\epsilon = \frac{8n_\chi^2 g^6 T^{3/2}}{9\pi^{7/2}m_\chi^{5/2}}$

$\neq$ potential

Dipole emission

Quadrupole emission

Next step:
Exact Non-Relativistic dissipative rates

Similar methodology in the case of Axion Bremsstrahlung:
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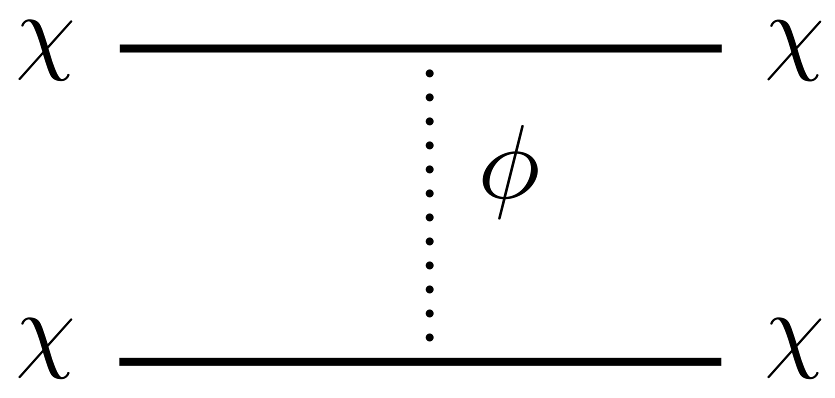
Summary

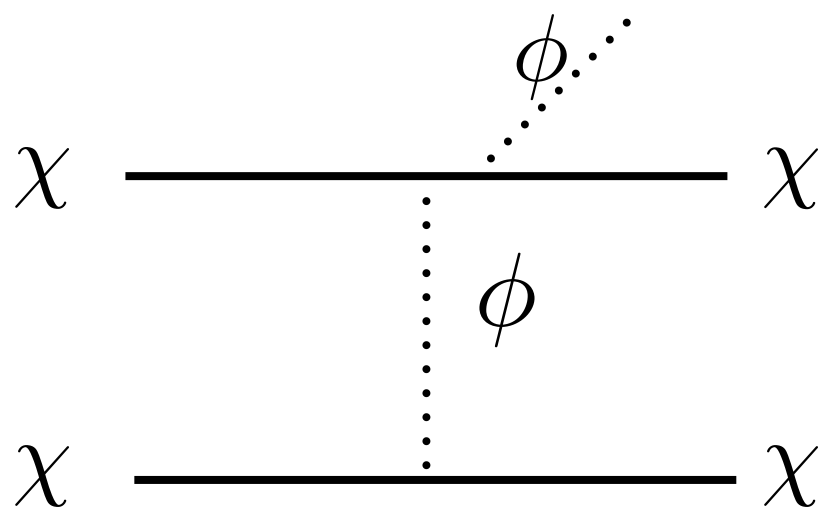
- Small scale problems in LCDM: → SIDM

Elastic processes:
heat transfers



+

Radiative processes:
cooling



- In addition to heat processes, radiative processes could have some impact on structure formation.

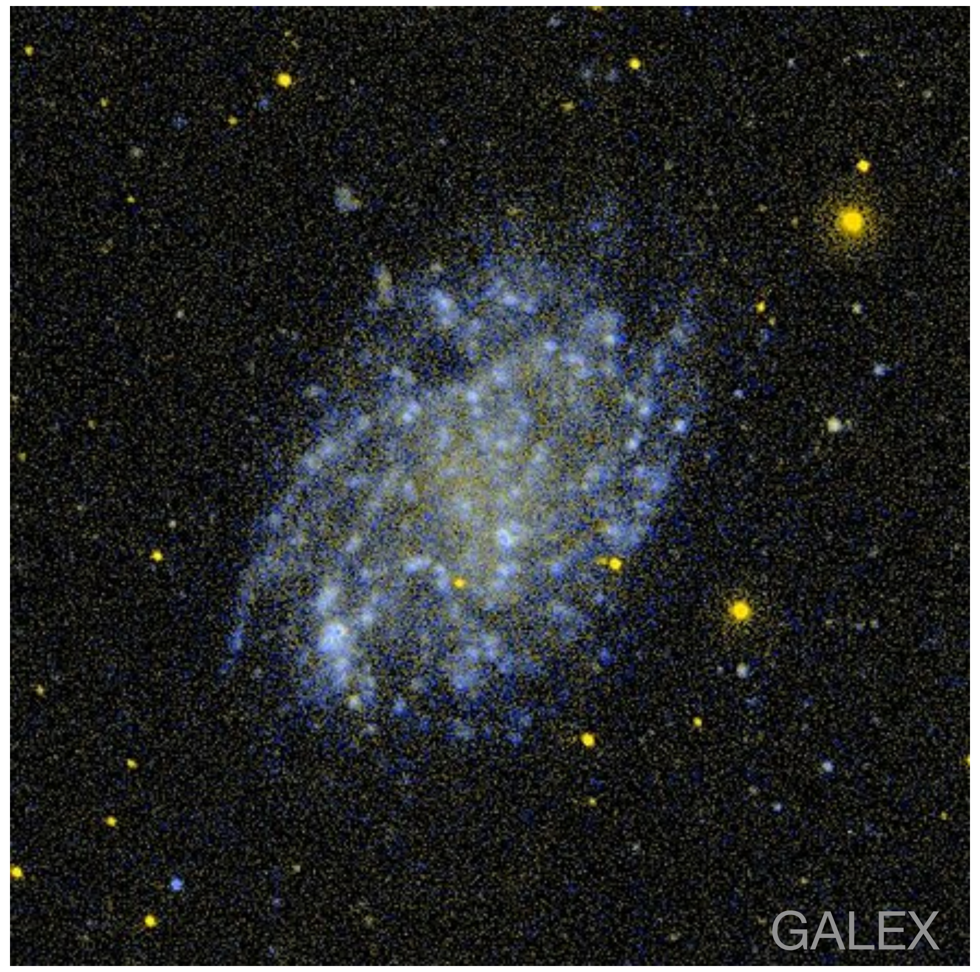
This project: Systematic study of « dissipative DM » for a wide variety of models in order to obtain emission rates valid in all kinetic regimes.

Thank you !

Back up: Galaxies and Halos

Dwarf Galaxy: composed of a few billion stars, usually orbit around larger galaxy.

Low Bright Surface galaxy: Very diffuse galaxies that emit much less light per unit area than other galaxy.



Formation of DM halo:

Final result of the non-linear evolution of a dark matter density perturbation: decouple from cosmic expansion and gravitationally collapse to create bound state of matter.

Cosmic Microwave background: Imprint of the recombinaison 380.000 after Big Bang

Before recombinaison phase (first atoms to form) , universe opaque to light as photon exchanged in pair production. After the recombinaison phase, universe became transparent and photon are free to travel everywhere.

Sources: European space agency, Galaxy Evolution and Formation H.MO, F. Van den Bosh, S. White

Back up: Our Models

- Fermion-scalar:

$$\mathcal{L} = i\overline{\chi}\partial\chi - m_\chi\overline{\chi}\chi + \frac{1}{2}[(\partial_\mu\phi)^2 - m_\phi^2\phi^2] - \frac{1}{3!}A_\phi\phi^3 - \frac{1}{4!}\lambda\phi^4 - g_\phi\overline{\chi}\chi\phi$$

- Fermion-gauge:

$$\mathcal{L} = i\overline{\chi}\partial\chi - m_\chi\overline{\chi}\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_v^2V^2 + g_vV_\mu\overline{\chi}\gamma^\mu\chi$$

- Scalar complex-gauge:

$$\mathcal{L} = \mathcal{L}_s + \mathcal{L}_v + ig_vV^\mu[(\partial_\mu\chi^\dagger)\chi - \chi^\dagger\partial_\mu\chi] - \frac{1}{4}\lambda(\chi^\dagger\chi)^2 + g_v^2\chi^\dagger\chi V^2$$

- Scalar complex-Scalar:

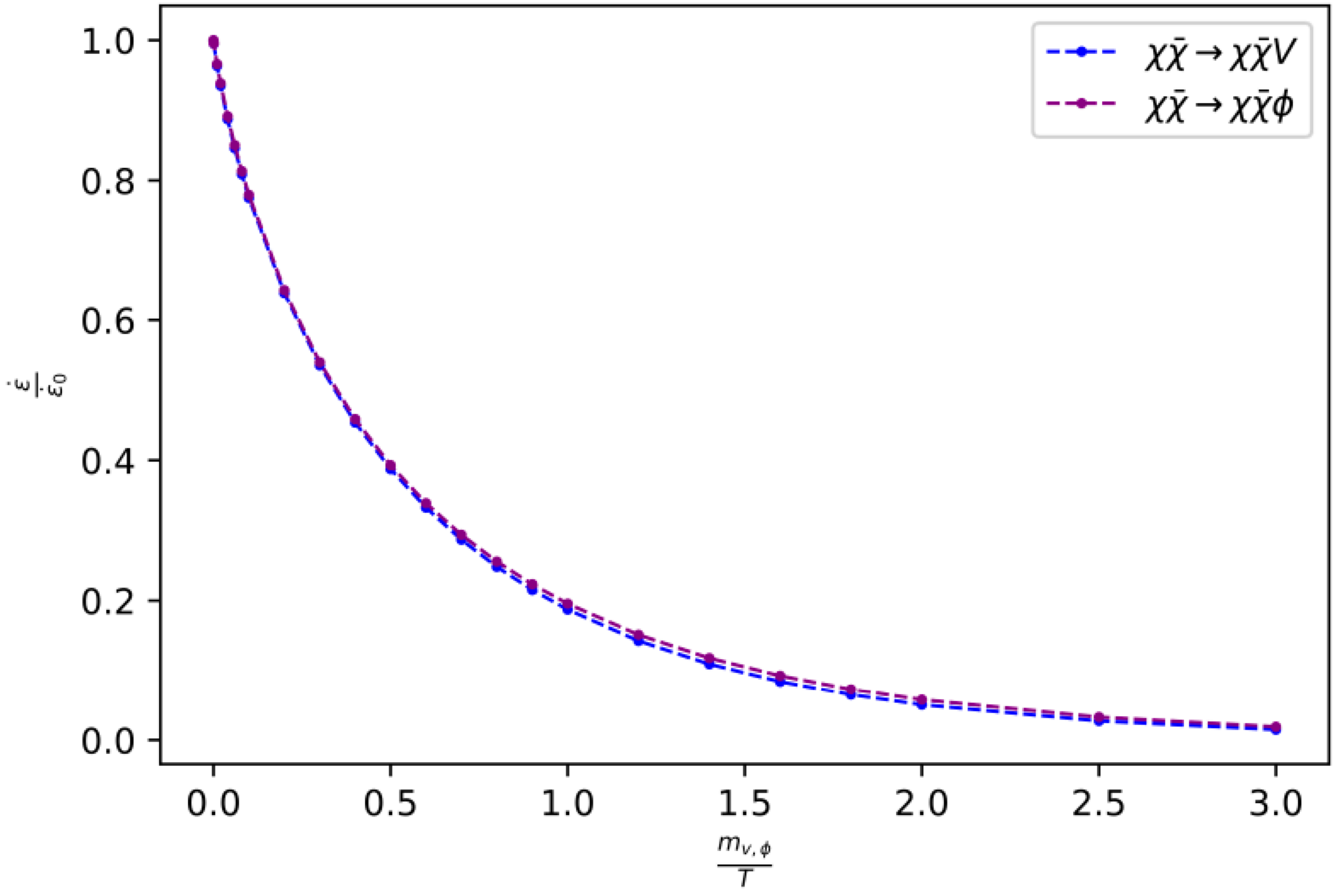
$$\mathcal{L} = \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}(\partial_\mu\chi)^2 - \frac{1}{2}m_\chi^2\chi^2 - \frac{1}{3!}A_\phi\phi^3 - \frac{1}{4!}\lambda_\phi\phi^4 - \frac{1}{3!}A_\chi\chi^3 - \frac{1}{4!}\lambda_\chi\chi^4 - \frac{1}{4}g_\chi^2\chi^2\phi^2 - \frac{1}{2}A_{\chi\phi}\chi^2\phi$$

- Scalar-Scalar:

$$\mathcal{L} = (\partial_\mu\chi^\dagger)(\partial^\mu\chi) + \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{3!}A_\phi\phi^3 - \frac{1}{4!}\lambda_\phi\phi^4 - m_\chi^2\chi^\dagger\chi - \frac{1}{4}\lambda(\chi^\dagger\chi)^2 - \frac{1}{2}g_\phi^2\chi^\dagger\chi\phi^2 - A_{\chi\phi}\chi^\dagger\chi\phi$$

Back up: full emission rate

$\chi\chi \to \chi\chi M$	Gauge emission V^μ	Scalar emission ϕ
Fermion	$\dot{\epsilon} = (44 - 3\pi^2)\frac{5n_\chi^2 g^6 T^{3/2}}{144\pi^{7/2} m_\chi^{5/2}}$	$\dot{\epsilon} = (44 - 3\pi^2)\frac{n_\chi^2 g^6 T^{3/2}}{36\pi^{7/2} m_\chi^{5/2}}$
Scalar Complex	$\dot{\epsilon} = (3\pi^2 - 20)\frac{5n_\chi^2 g^6 T^{3/2}}{72\pi^{7/2} m_\chi^{5/2}}$	$\frac{A_{\phi\chi}}{m_\chi} \ll g_\phi : \dot{\epsilon} = \frac{n_\chi^2 T^{3/2}}{\pi^{7/2} m_\chi^{5/2}} \frac{(3\pi^2 - 20) g_\phi^4 \left(\frac{A_{\phi\chi}}{m_\chi}\right)^2}{192}$ $\frac{A_{\phi\chi}}{m_\chi} \gg g_\phi : \dot{\epsilon} = \frac{n_\chi^2 T^{3/2}}{\pi^{7/2} m_\chi^{5/2}} \frac{(3\pi^2 - 20)\left(\frac{A_{\phi\chi}}{m_\chi}\right)^6}{768}$
$\chi\bar{\chi} \to \chi\bar{\chi} M$		
Fermion χ	$\dot{\epsilon} = \frac{2g^6 n_\chi^2 T^{\frac{1}{2}}}{3\pi^{7/2} m_\chi^{3/2}}$	$\dot{\epsilon} = \frac{8n_\chi^2 g^6 T^{3/2}}{9\pi^{7/2} m_\chi^{5/2}}$
Scalar Complex χ	$\dot{\epsilon} = \frac{2g^6 n_\chi^2 T^{\frac{1}{2}}}{3\pi^{7/2} m_\chi^{3/2}}$	$\frac{A_{\phi\chi}}{m_\chi} \ll g_\phi : \dot{\epsilon} = \frac{1}{12}\frac{n_\chi^2 T^{3/2}}{\pi^{7/2} m_\chi^{5/2}} g_\phi^4 \left(\frac{A_{\phi\chi}}{m_\chi}\right)^2$ $\frac{A_{\phi\chi}}{m_\chi} \gg g_\phi : \dot{\epsilon} = \frac{1}{48}\frac{n_\chi^2 T^{3/2}}{\pi^{7/2} m_\chi^{5/2}} \left(\frac{A_{\phi\chi}}{m_\chi}\right)^6$



Mass have large consequences on the emission rate !