Inducing and Detecting Collective Effects of Particle Dark Matter

Asher Berlin

Fermilab

New Directions in the Search for Light Dark Matter Particles

June 7, 2019

ongoing with R. D'Agnolo, S. Ellis, P. Schuster, N. Toro

Direct Detection at a keV-MeV

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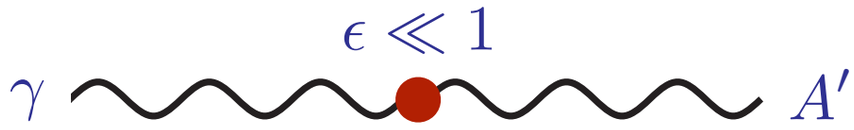
cosmology, detectability, self-interactions, stellar cooling, fifth forces, ...

$\implies$ $m_{\text{force}} \ll \text{meter}^{-1}$ and induce coupling of DM to electromagnetism



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DM effectively couples to
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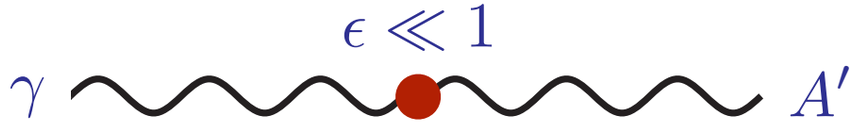

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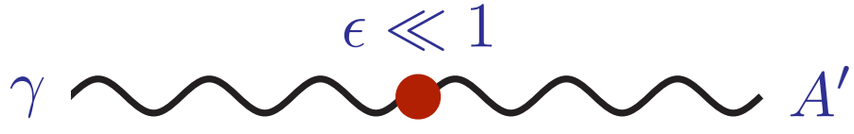
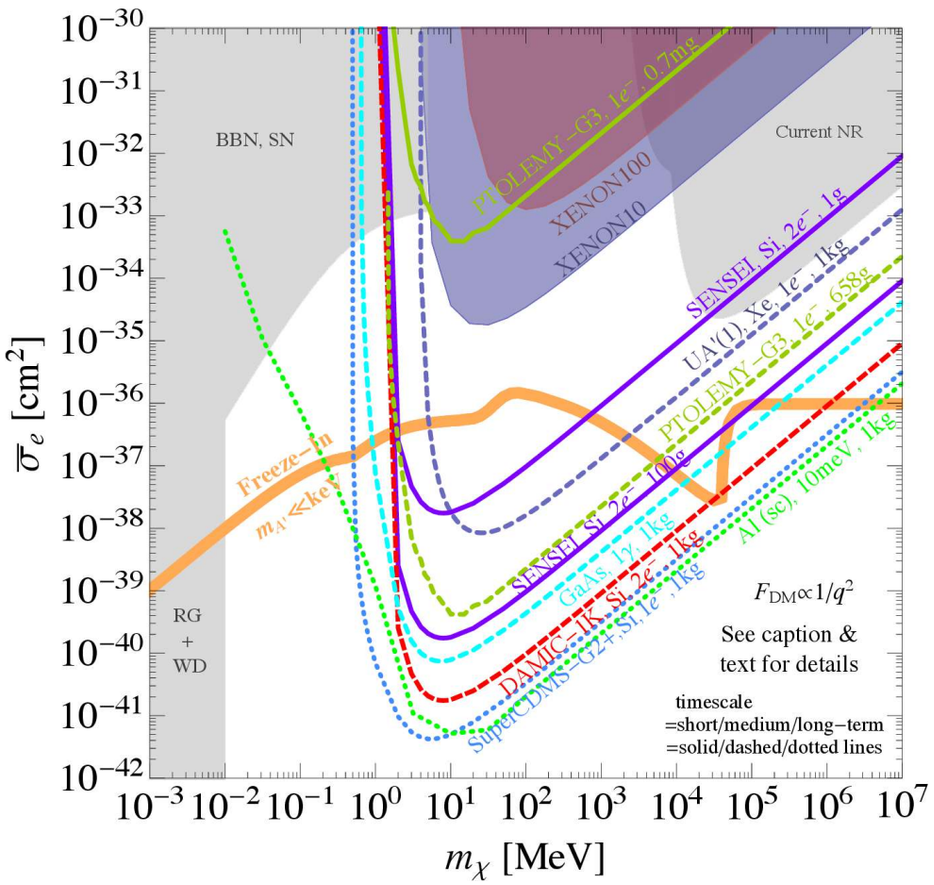


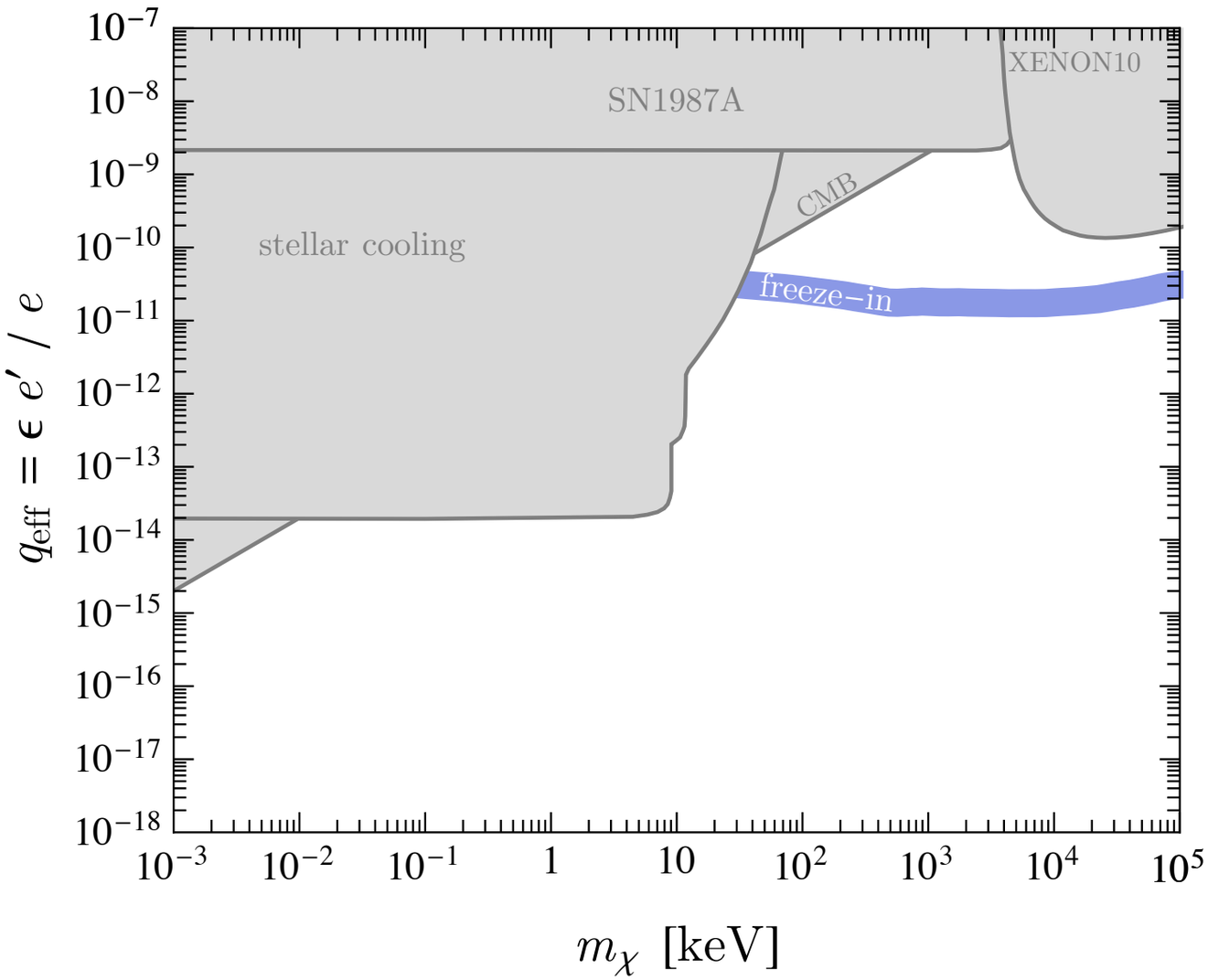


- new scattering targets
- new read-out technologies
- similar philosophy

arXiv:1707.04591

Millicharges

Parameter Space



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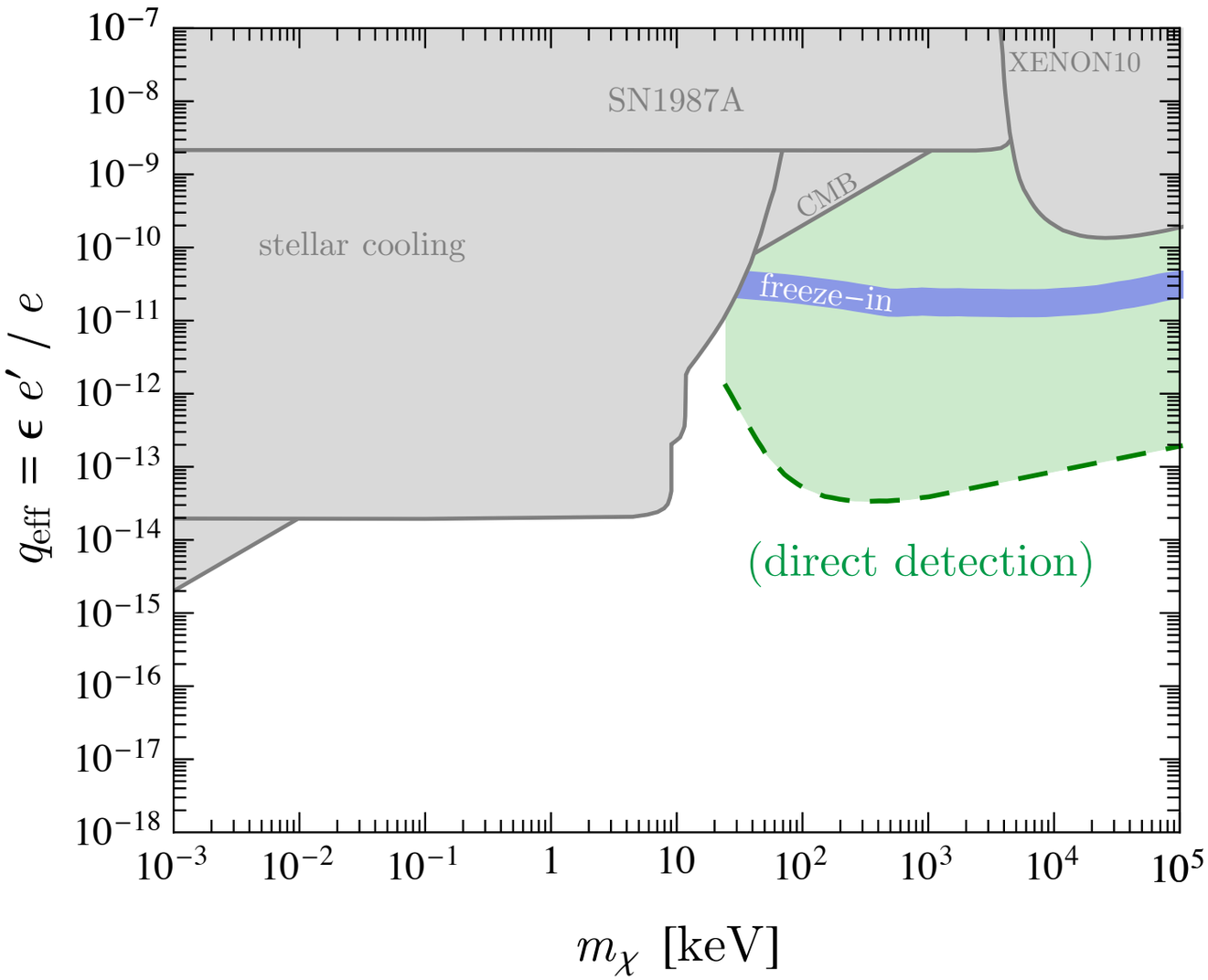

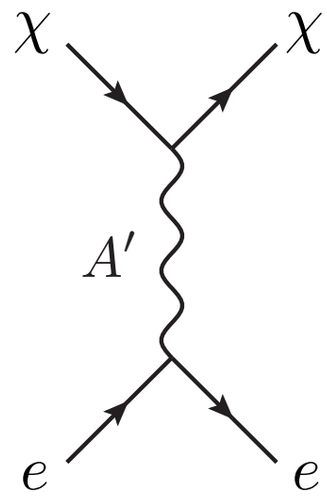

Active Direct Detection

$$q_{\rm eff} \sim \epsilon e'/e \sim 10^{-11} \left(\frac{m_\chi}{\rm MeV}\right)^{-1/2}$$

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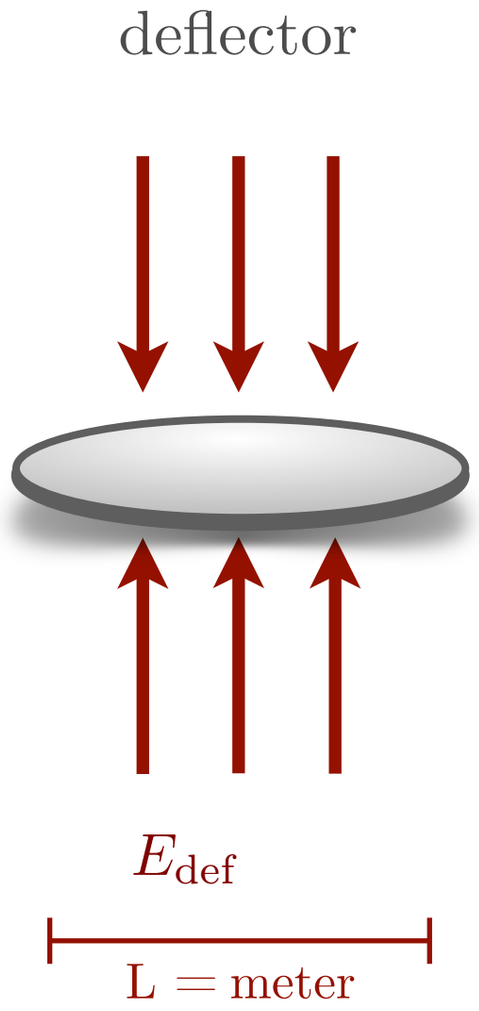
- stop it: $m_\chi\, v_\chi^2 \sim q_{\rm eff}\, e\, \Delta V \implies \Delta V \sim \text{MV} \times \left(\dfrac{m_\chi}{\rm keV}\right)^{3/2}$

Inducing Dark Matter Waves

Disturbing the Dark Matter Wind



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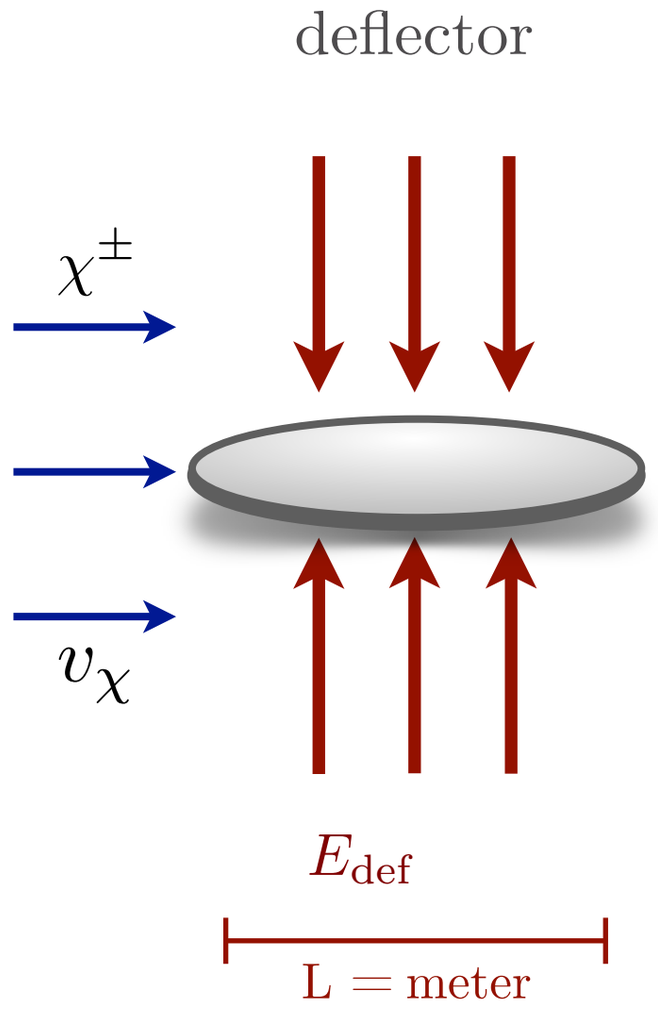

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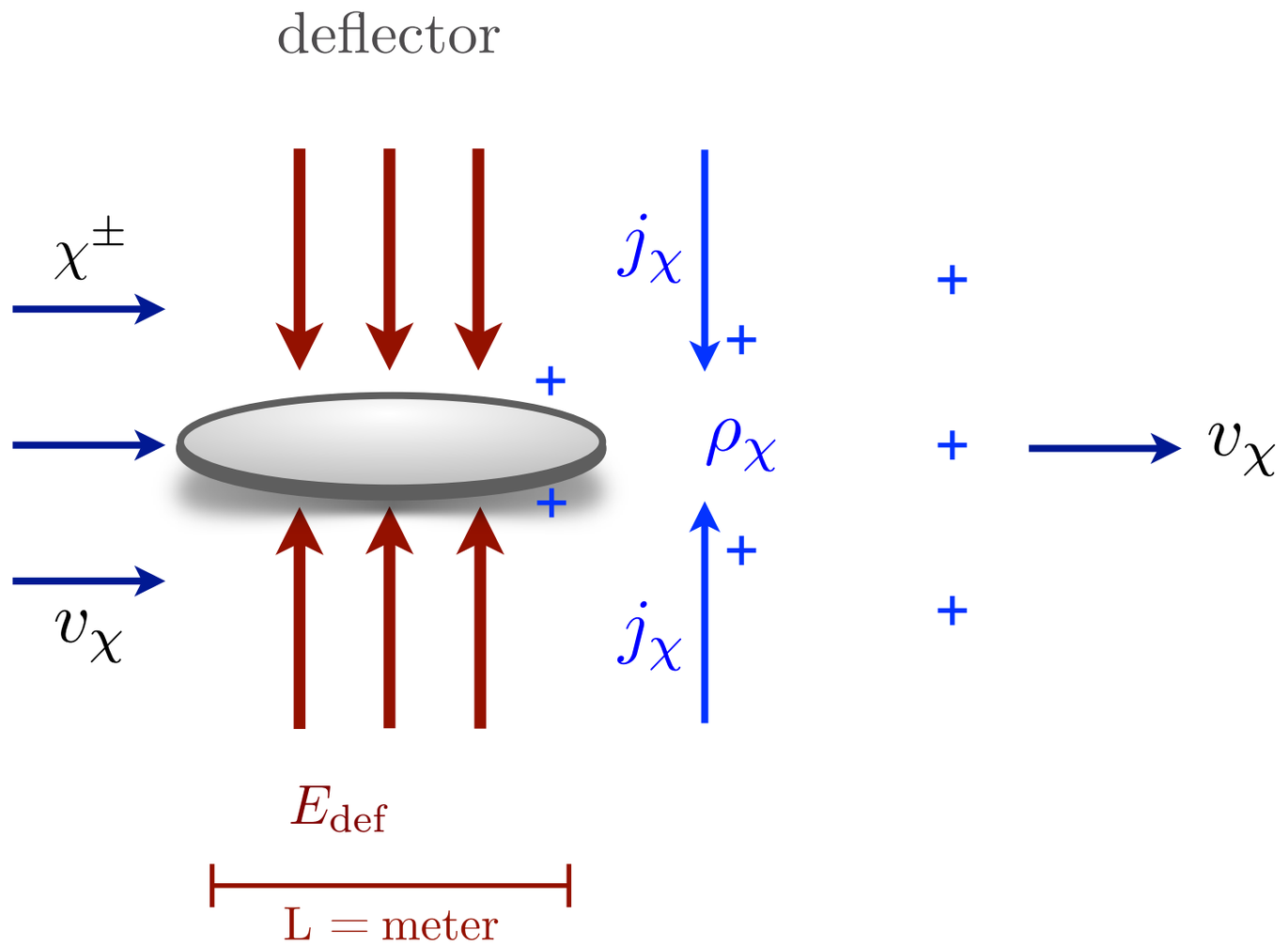

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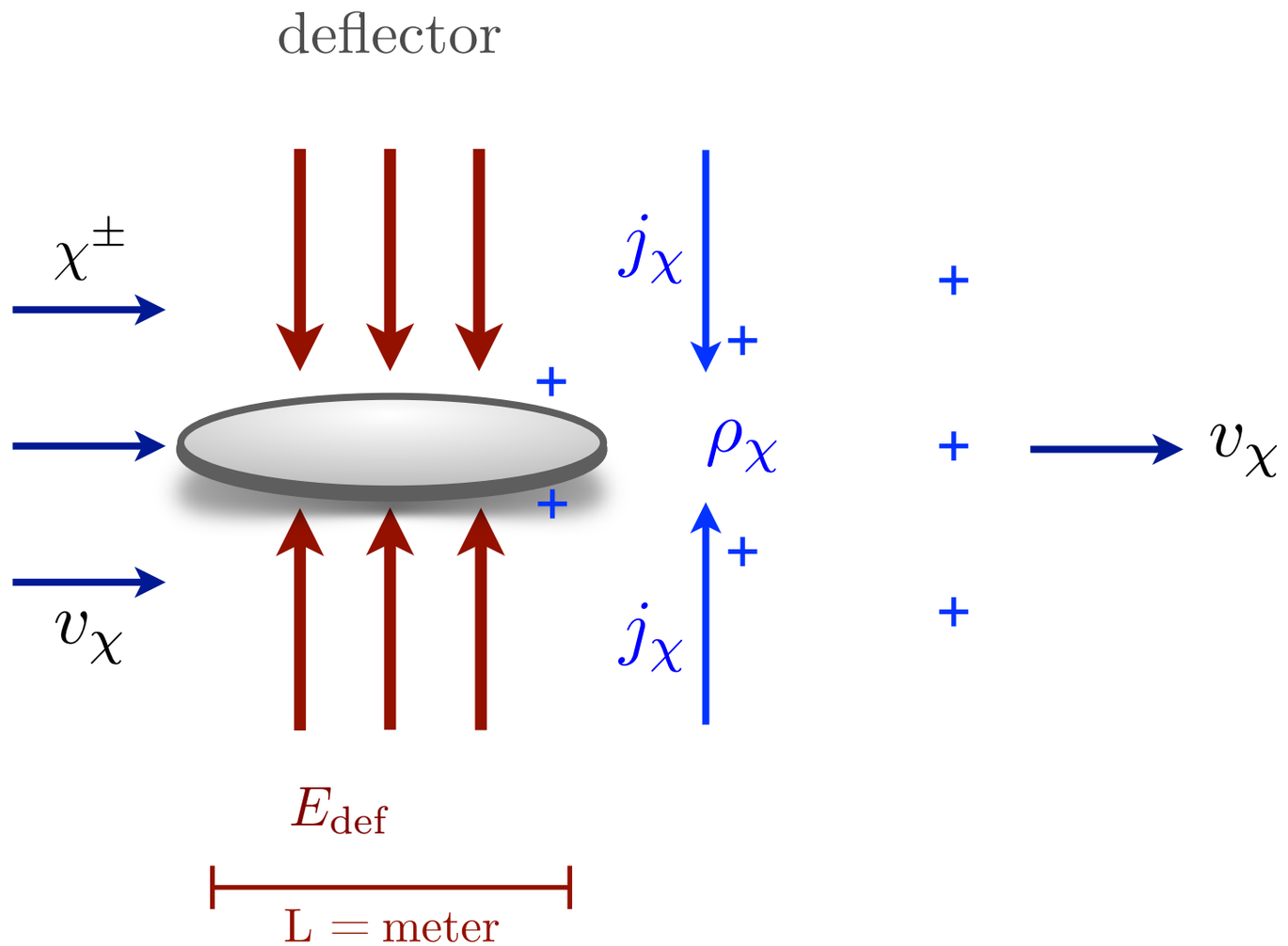

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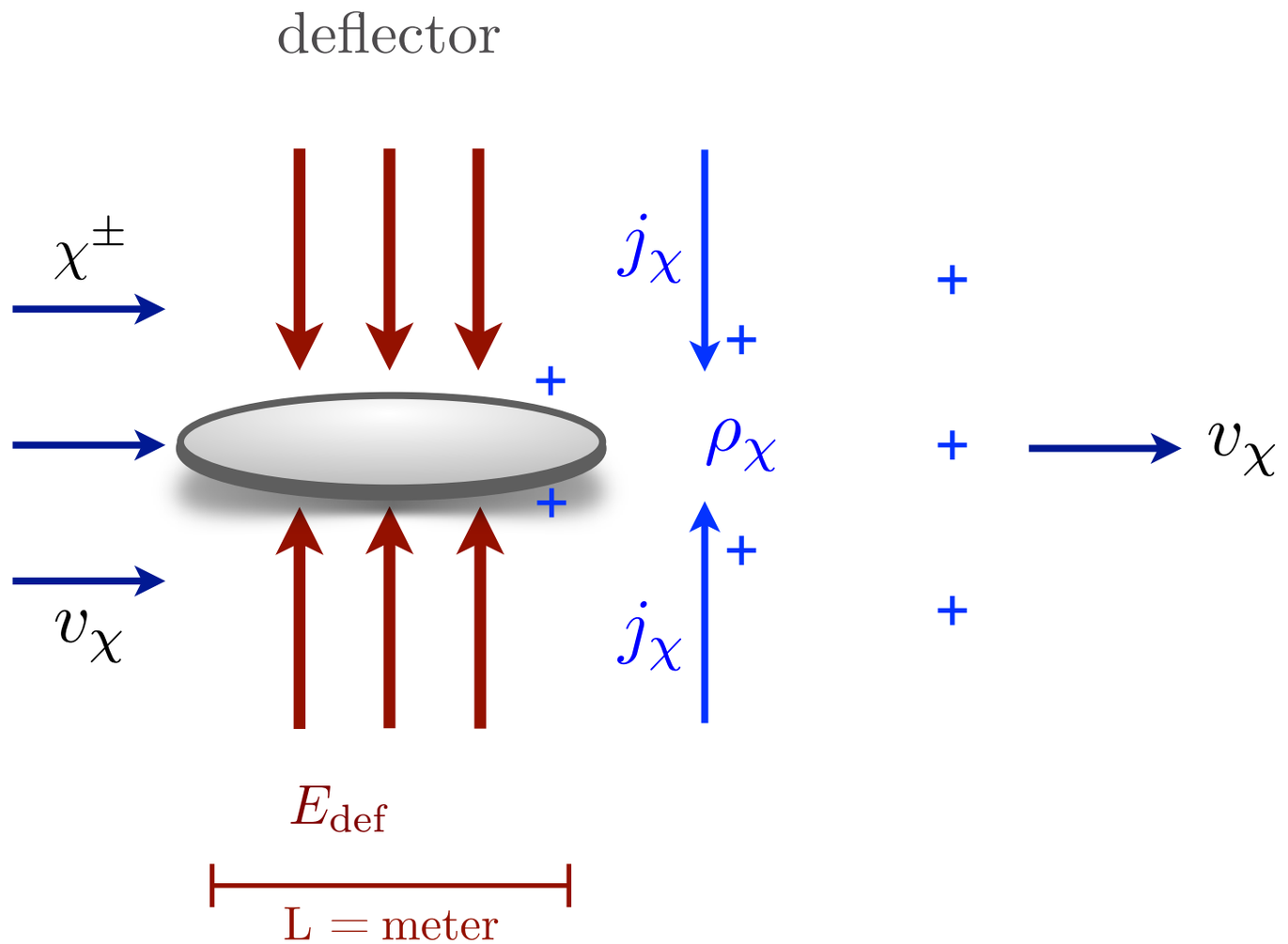

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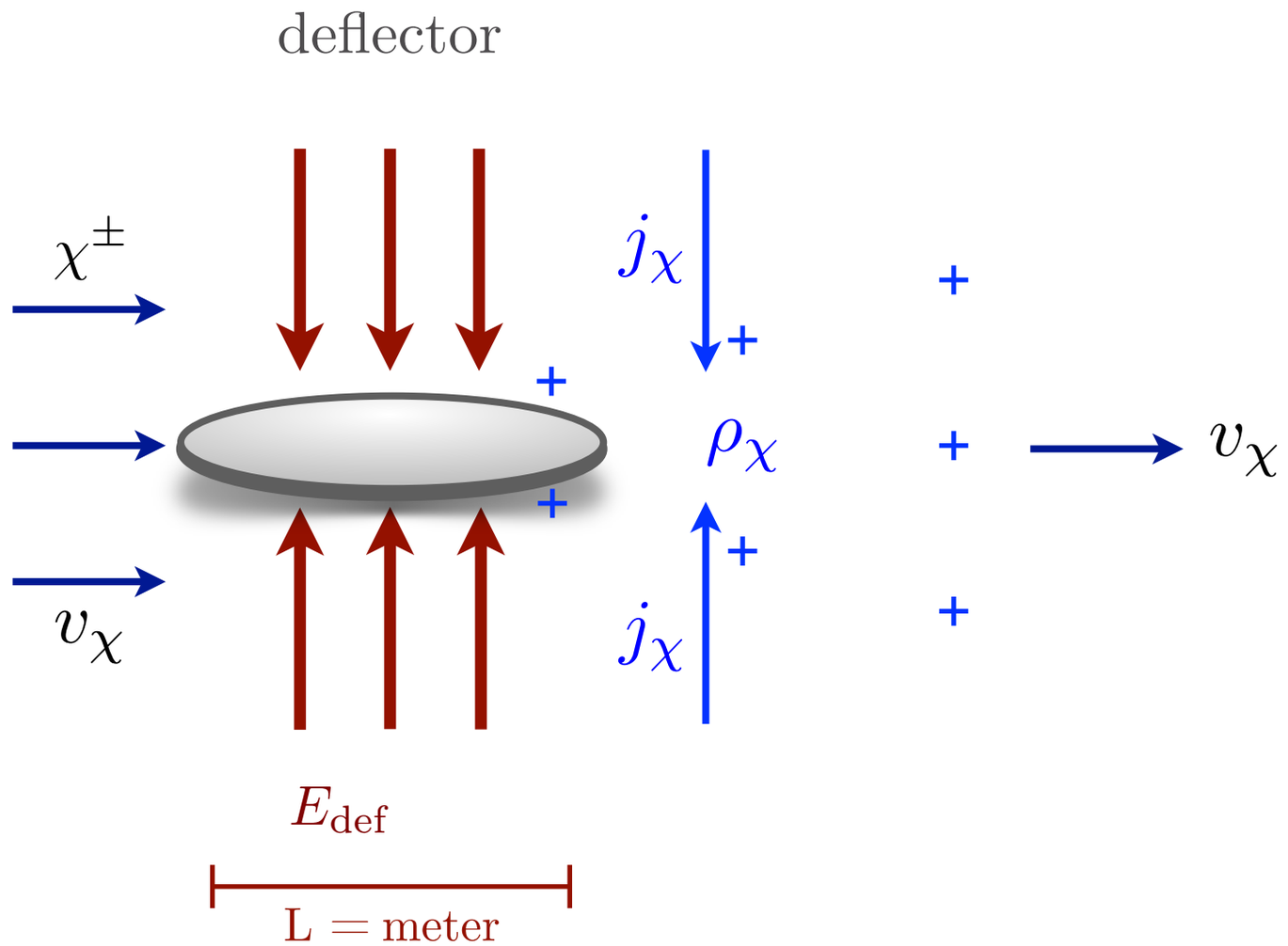

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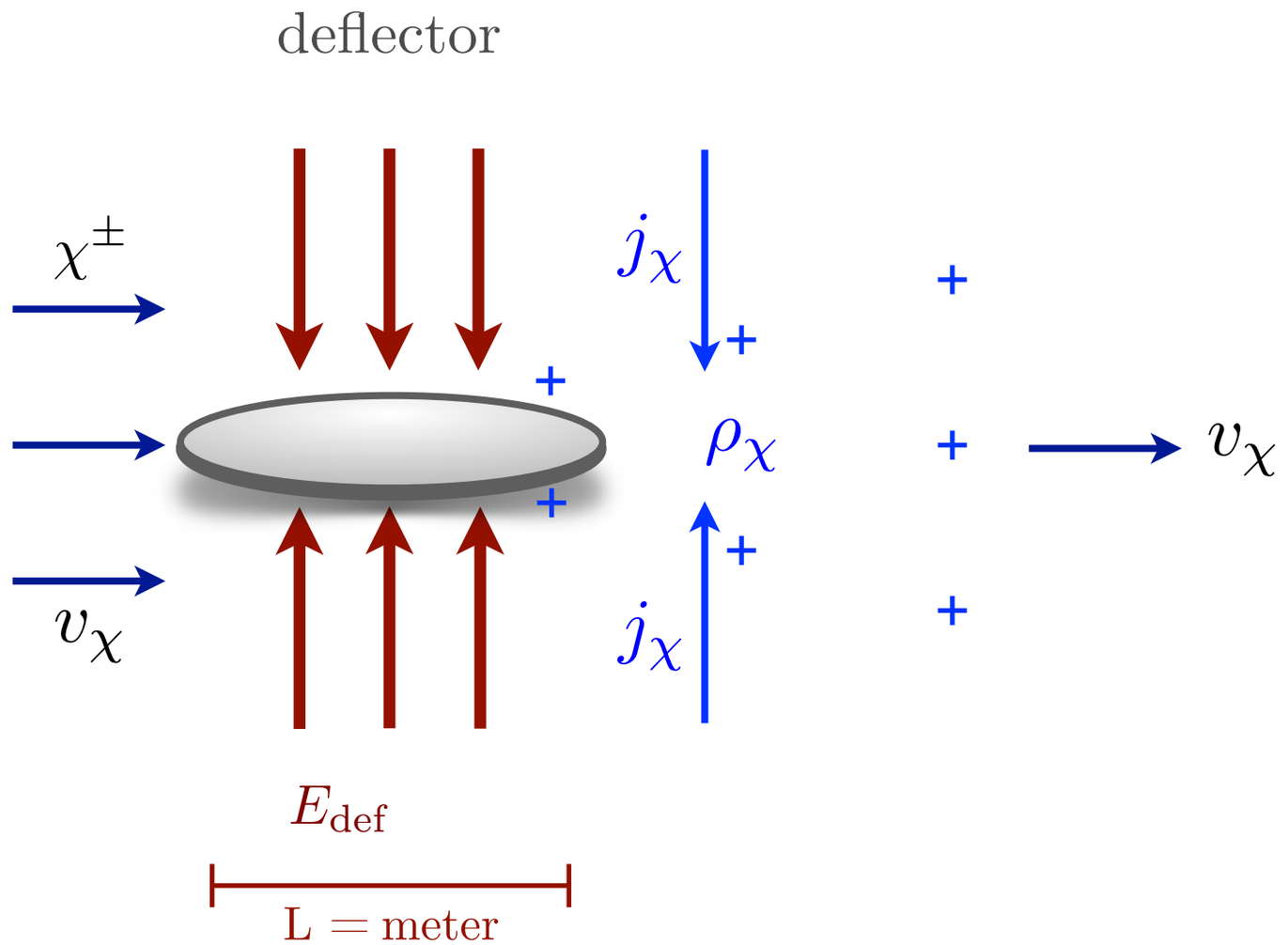
$$\text{screening length} \simeq \left(\frac{4\pi\,\alpha_D\,n_\chi}{m_\chi v_\chi^2}\right)^{-1/2} \gtrsim {\rm km} \times \left(\frac{m_\chi}{\rm keV}\right)^{1/4}$$

Disturbing the Dark Matter Wind



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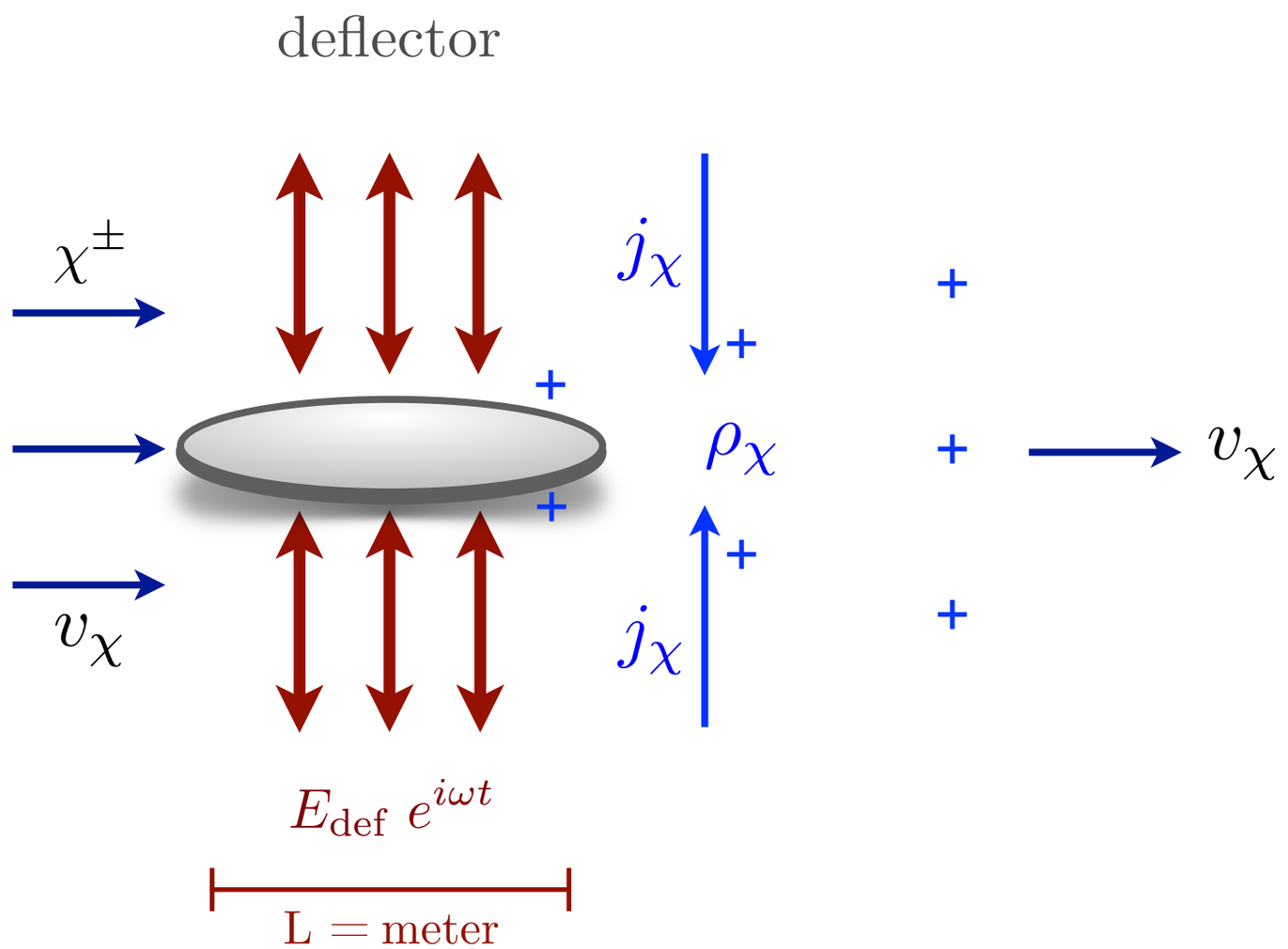

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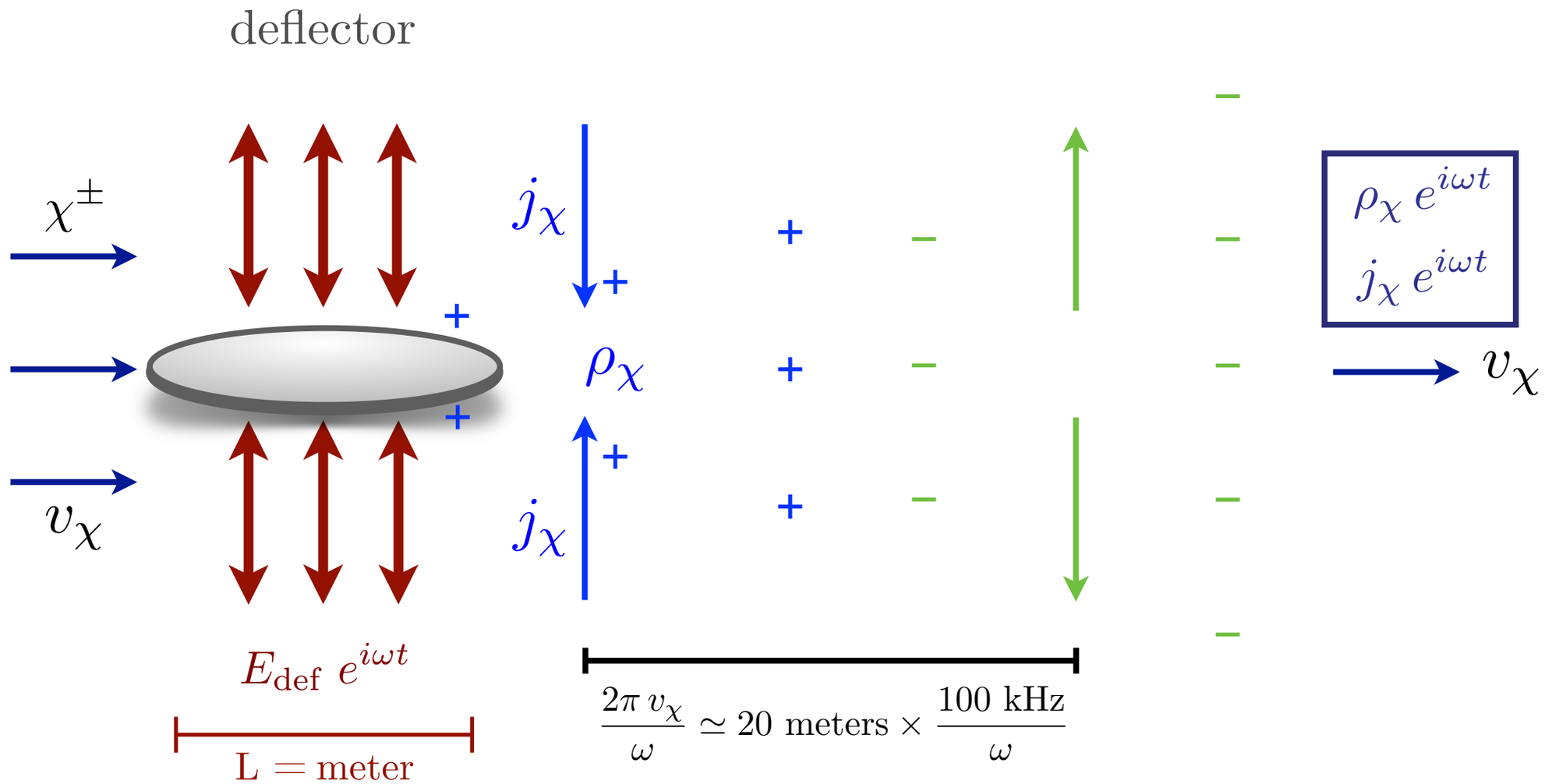

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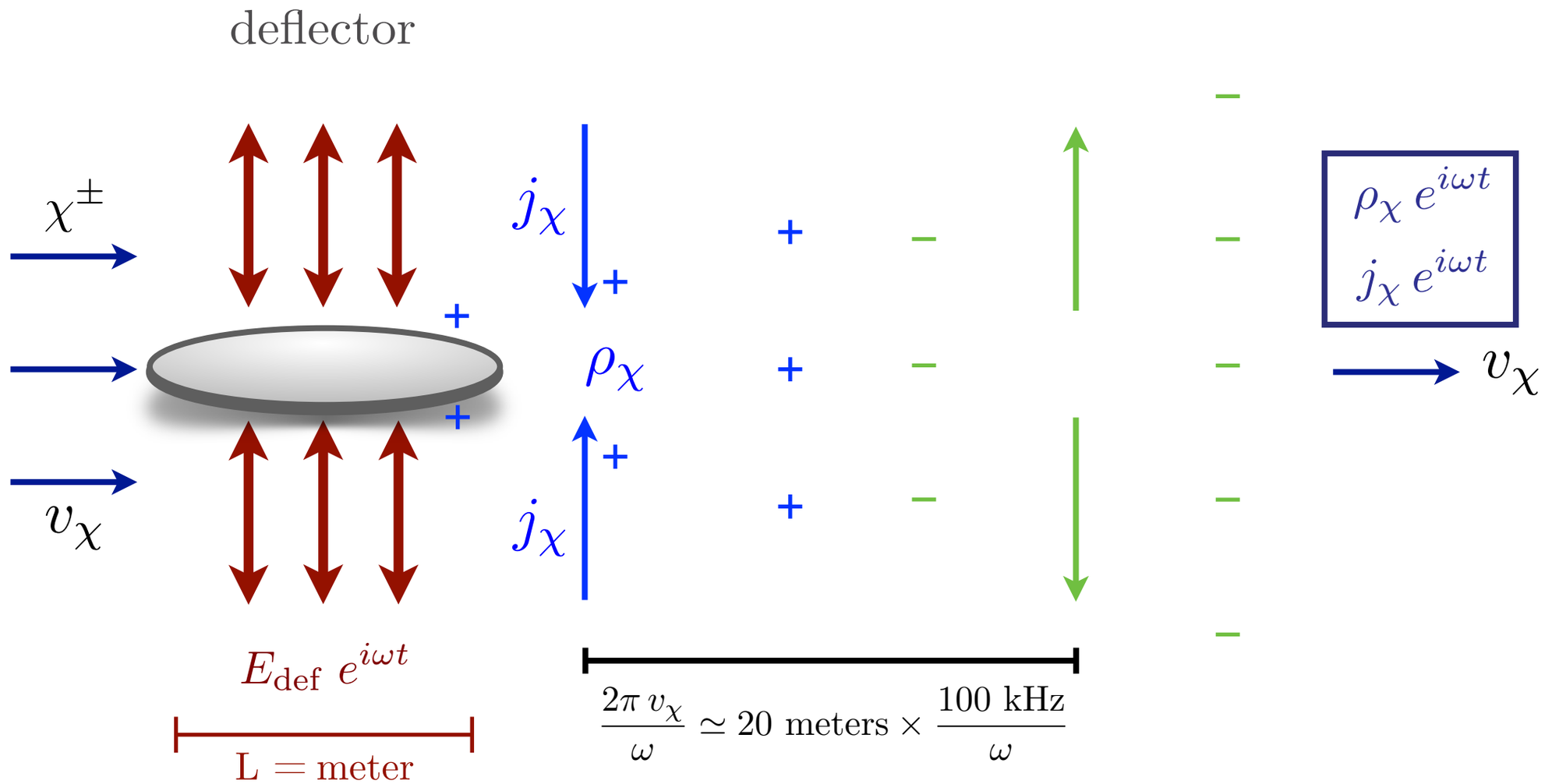

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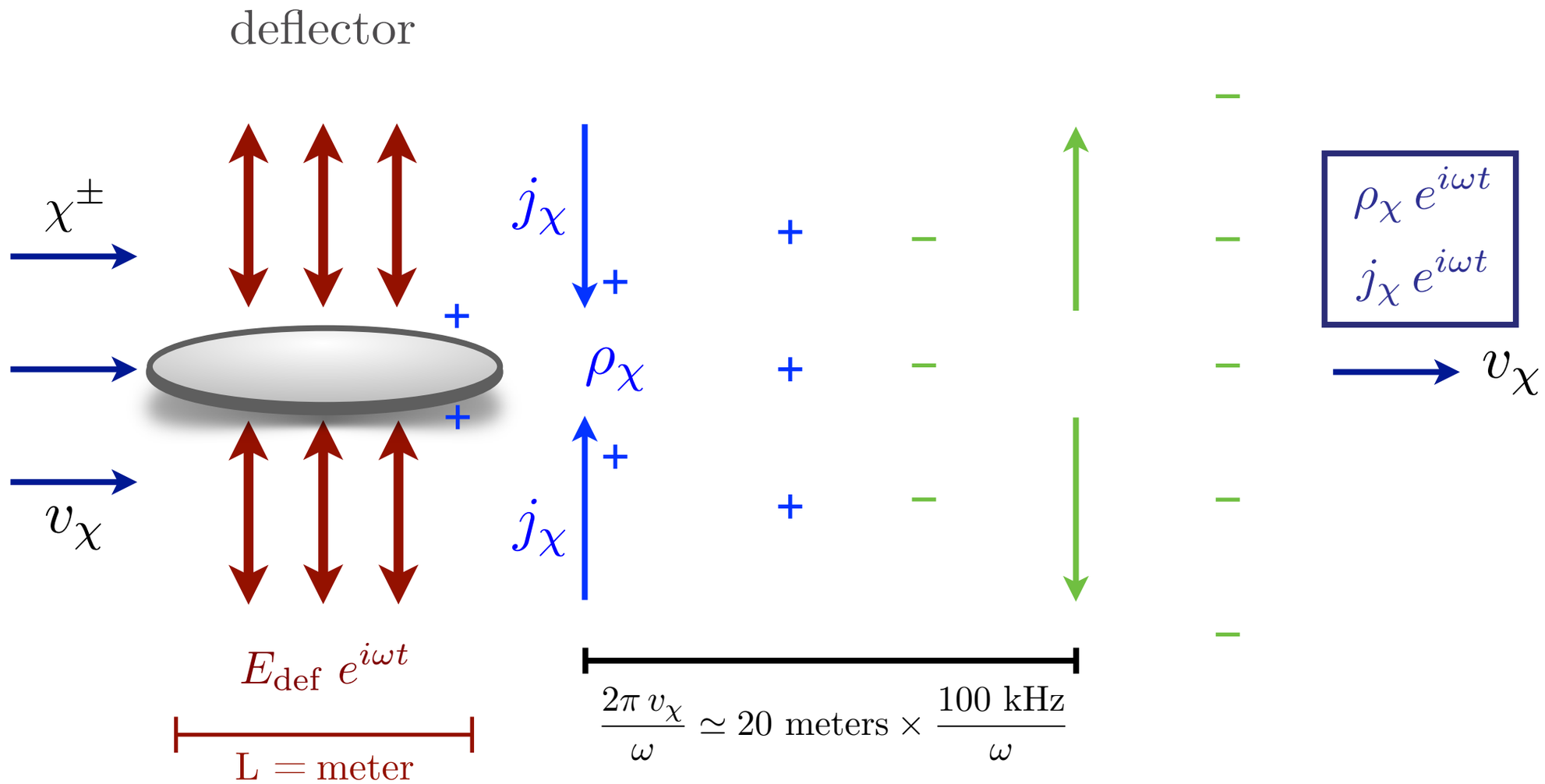

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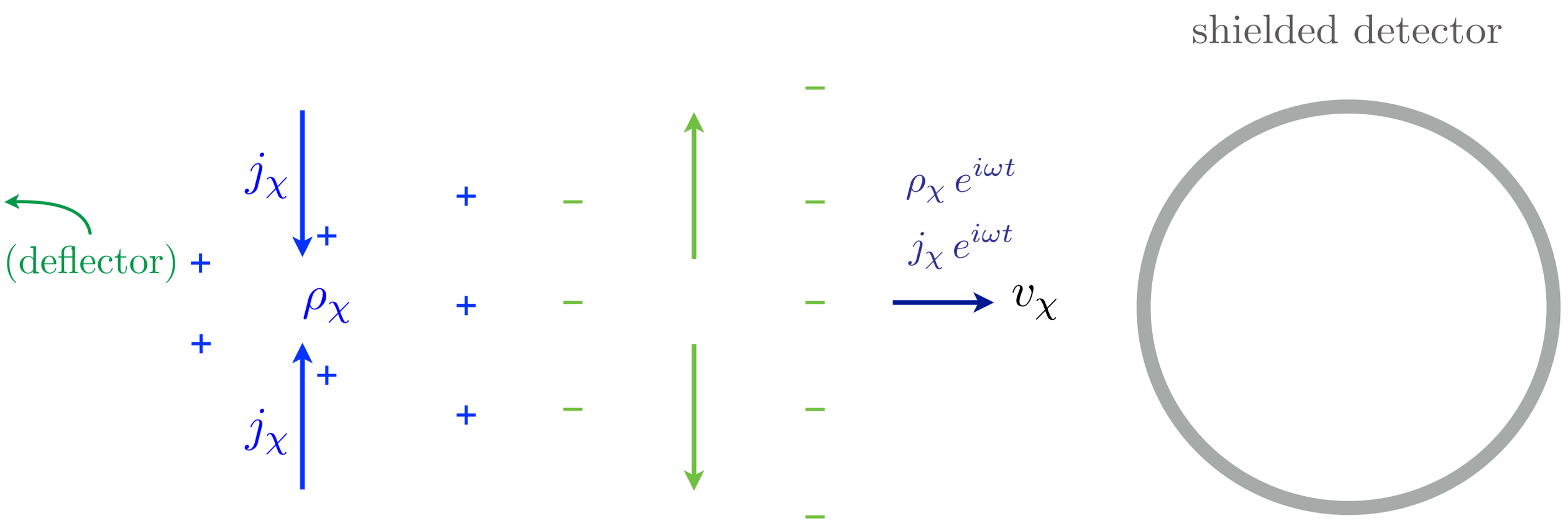
$$\text{power input} \lesssim (\omega/2\pi)\, E_{\rm def}^2\, L^3 \simeq 100\ \text{kW} \times \left(\frac{\omega}{100\ \text{kHz}}\right) \left(\frac{E_{\rm def}}{10\ \text{kV/cm}}\right)^2 \left(\frac{L}{\text{meter}}\right)^3$$

Detecting Dark Matter Waves

Measuring the Disturbance



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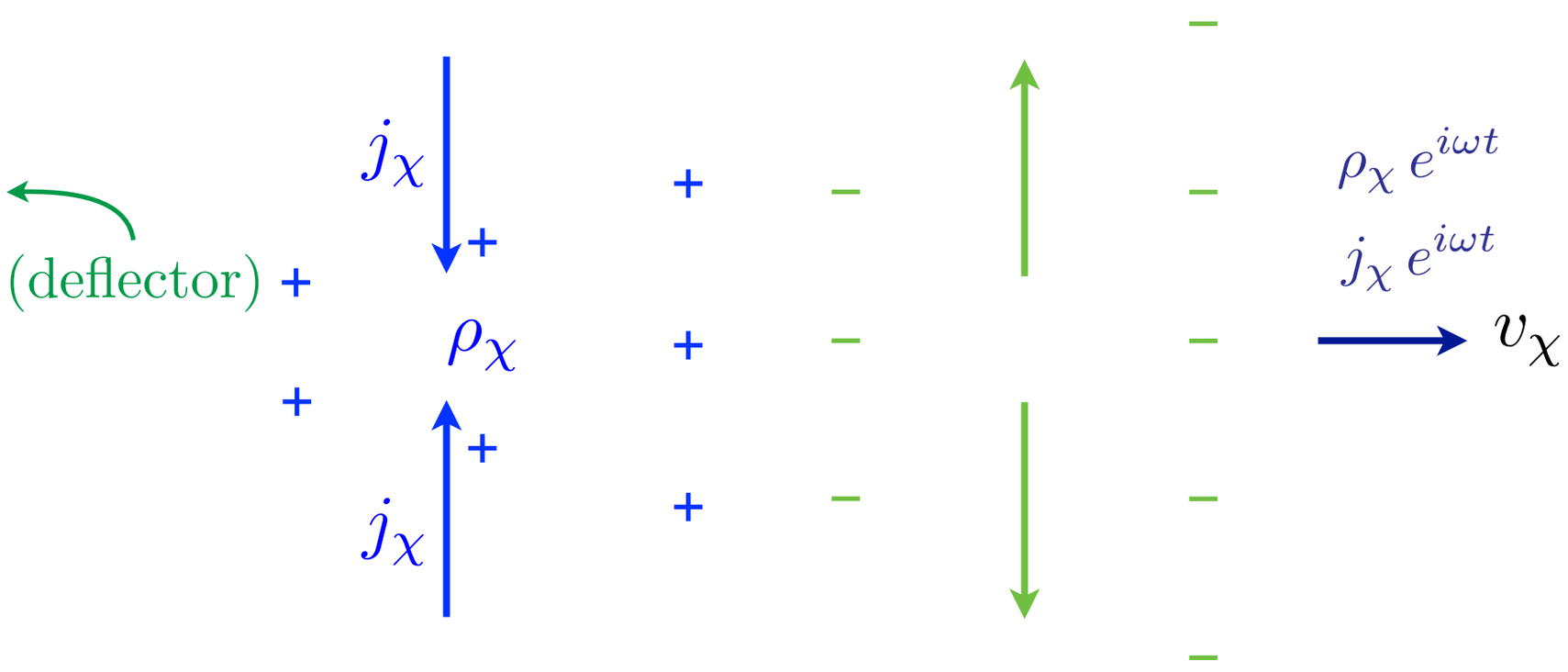

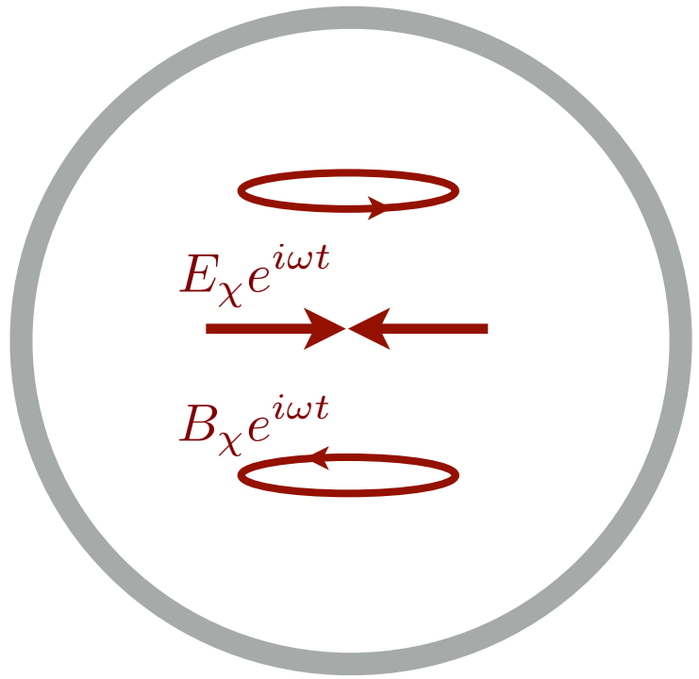

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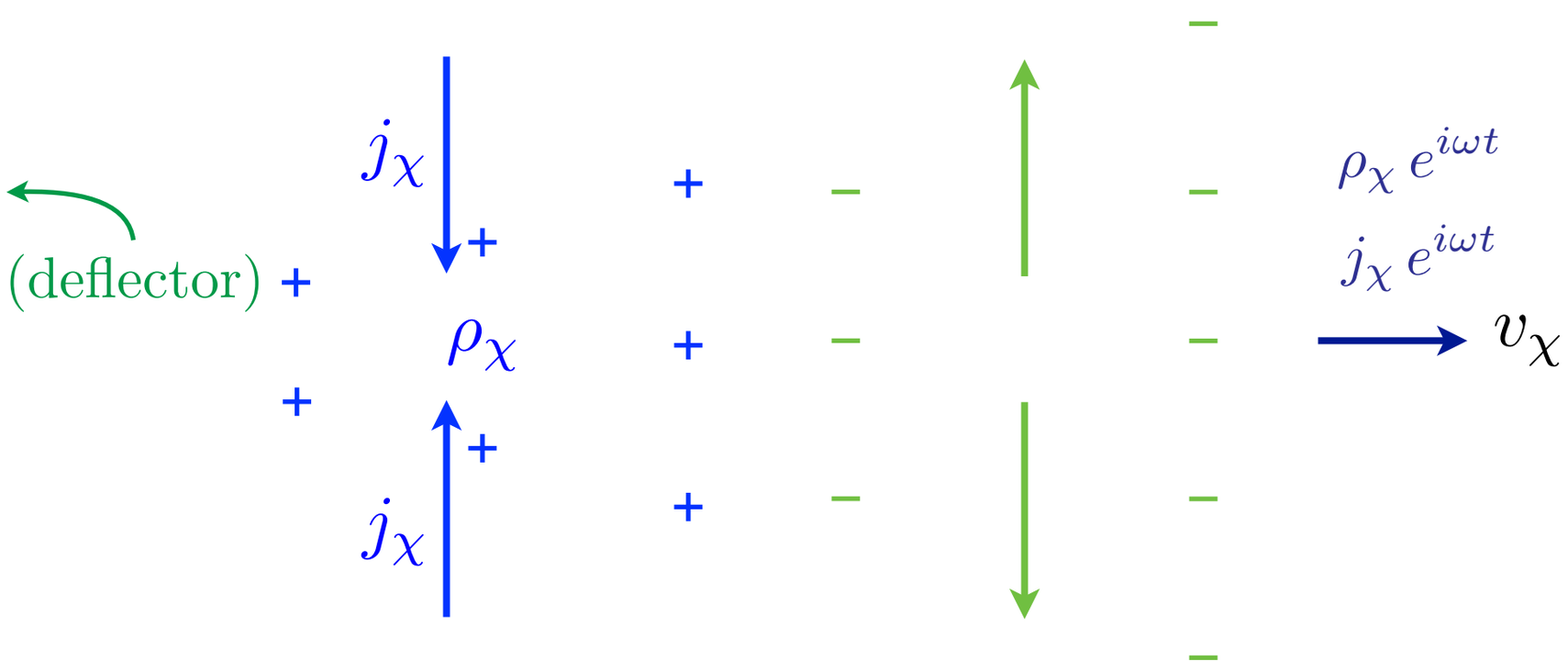

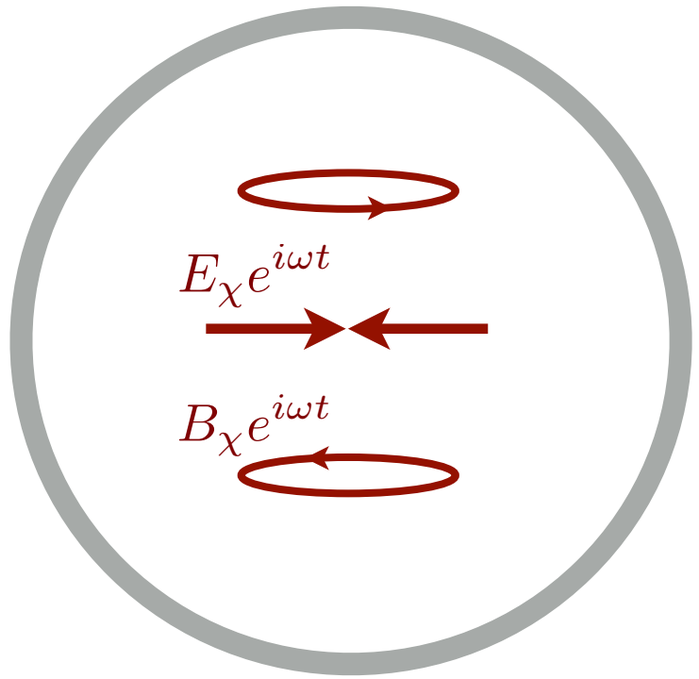

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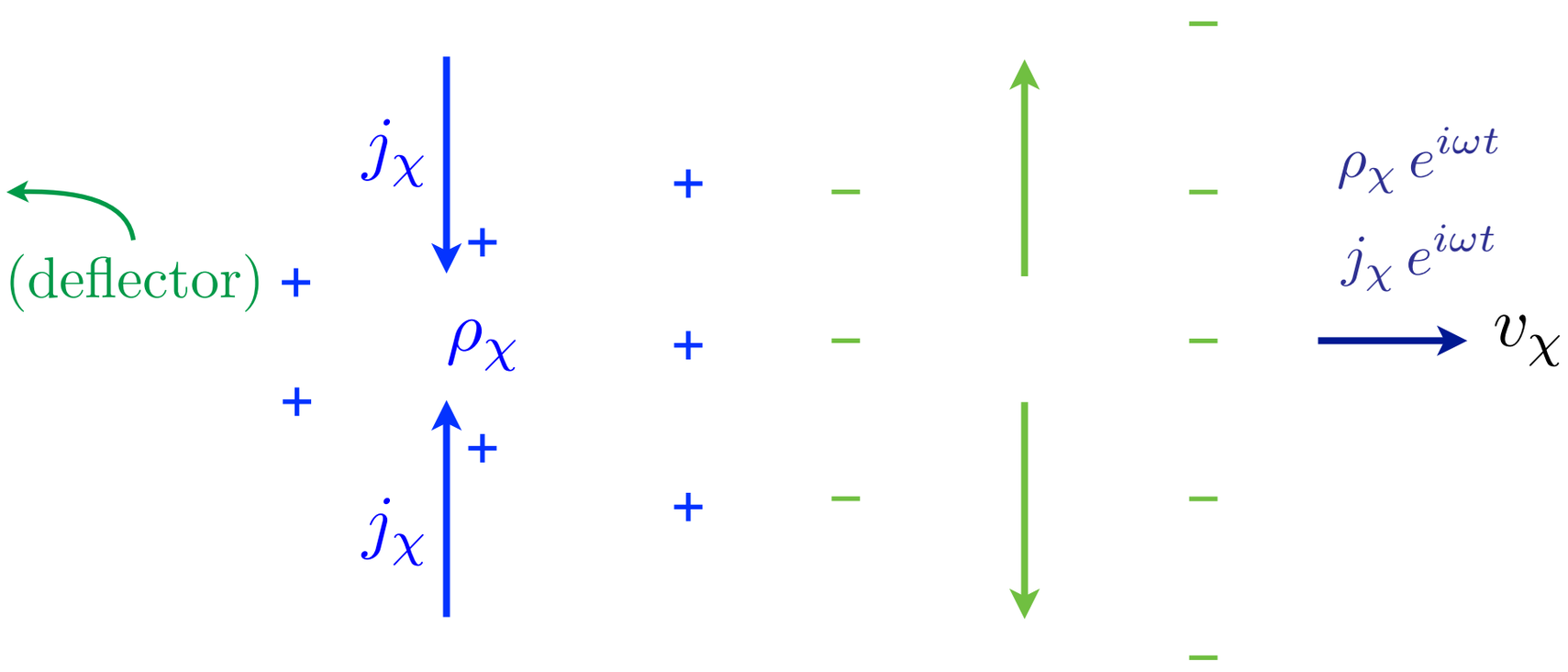

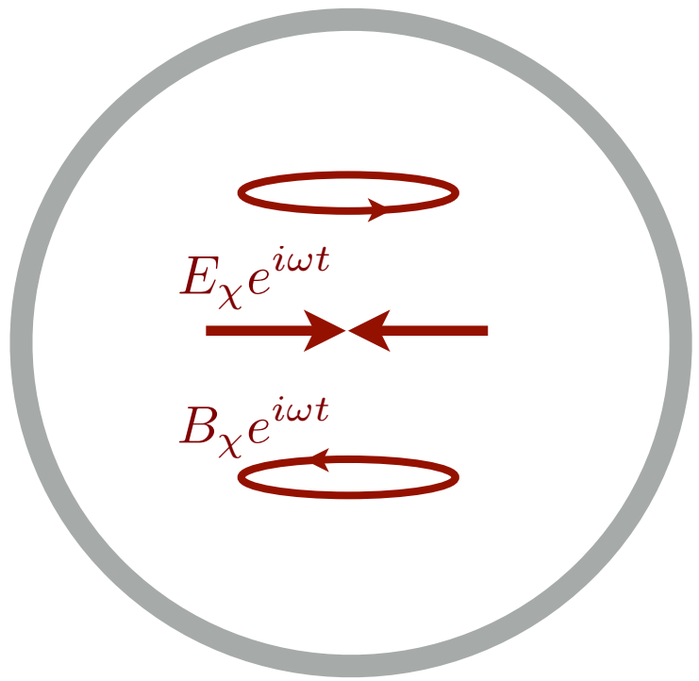

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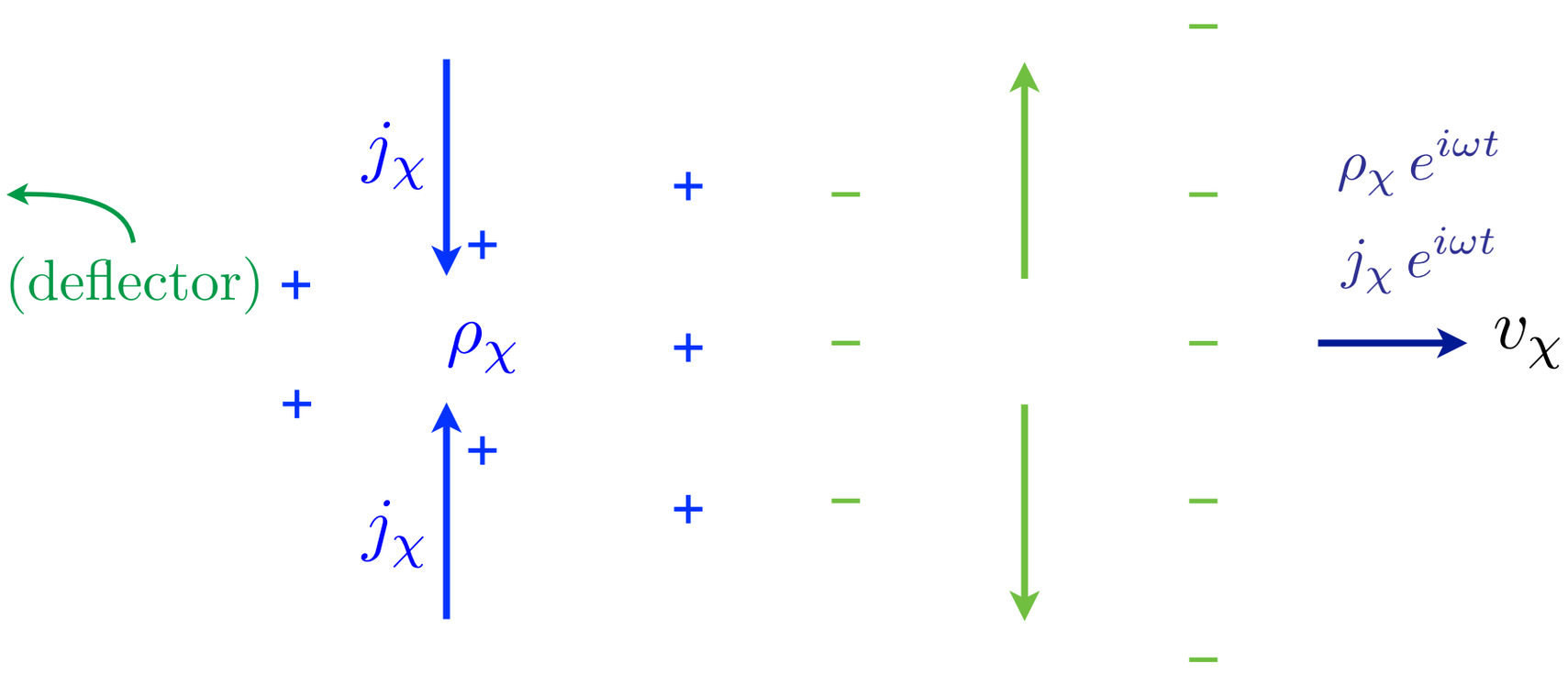

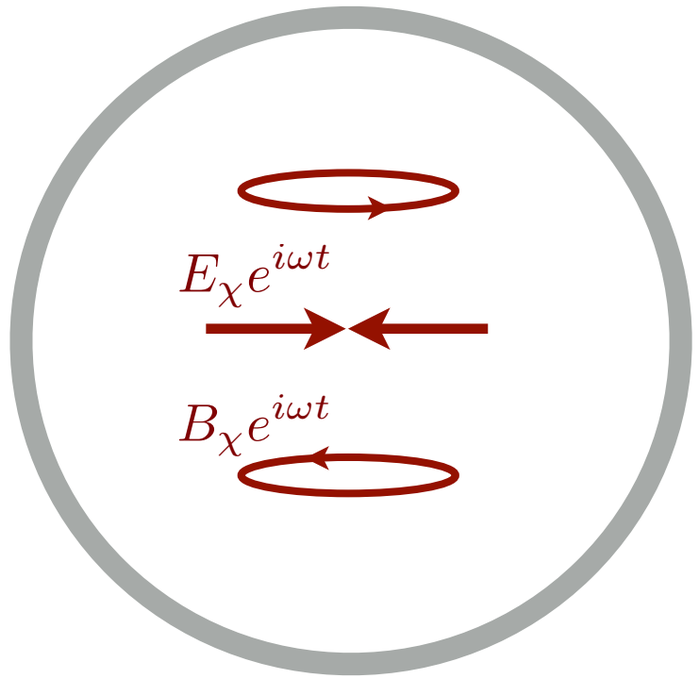

high-Q resonant detector

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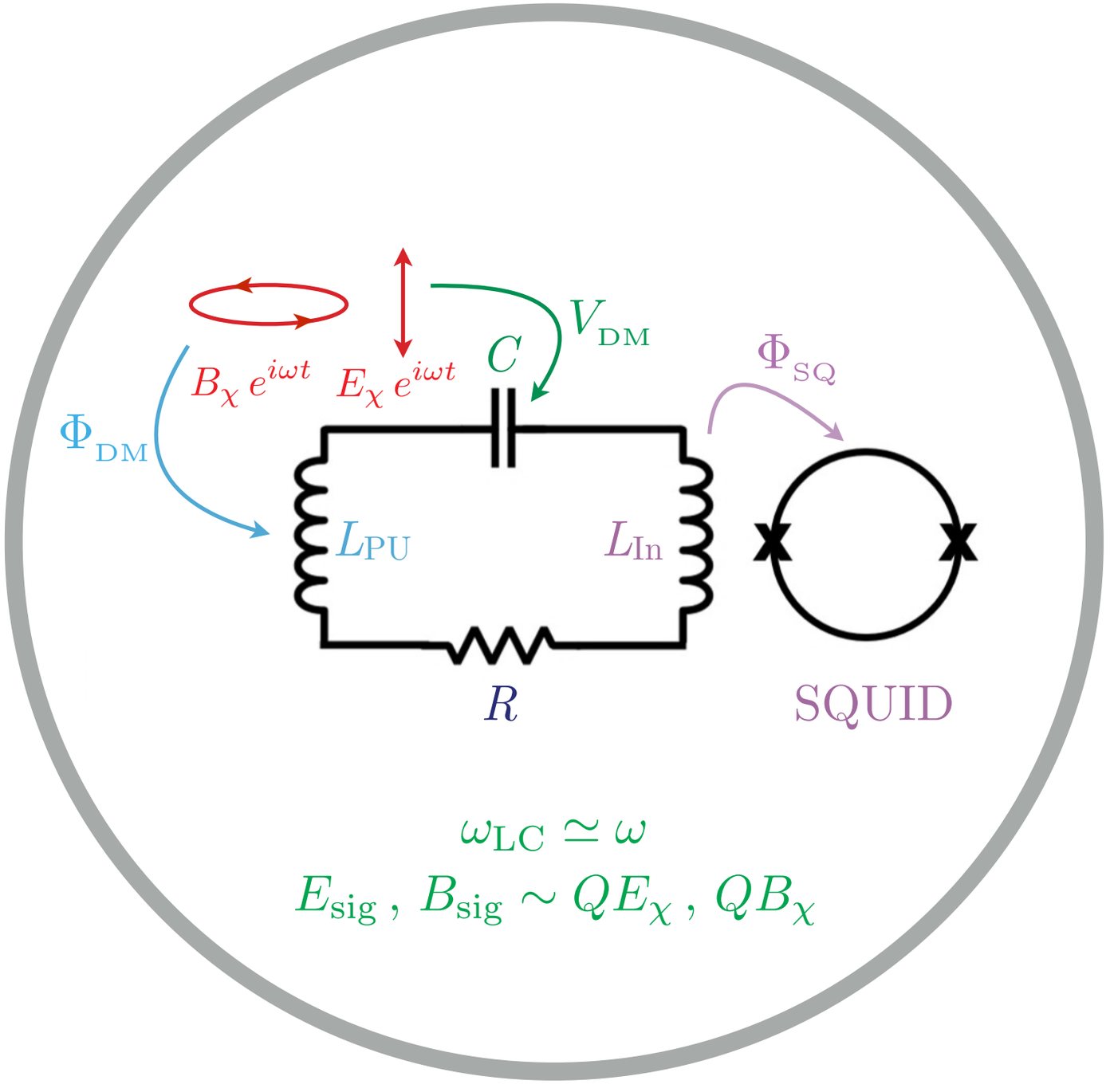
LC Resonators

shielded detector

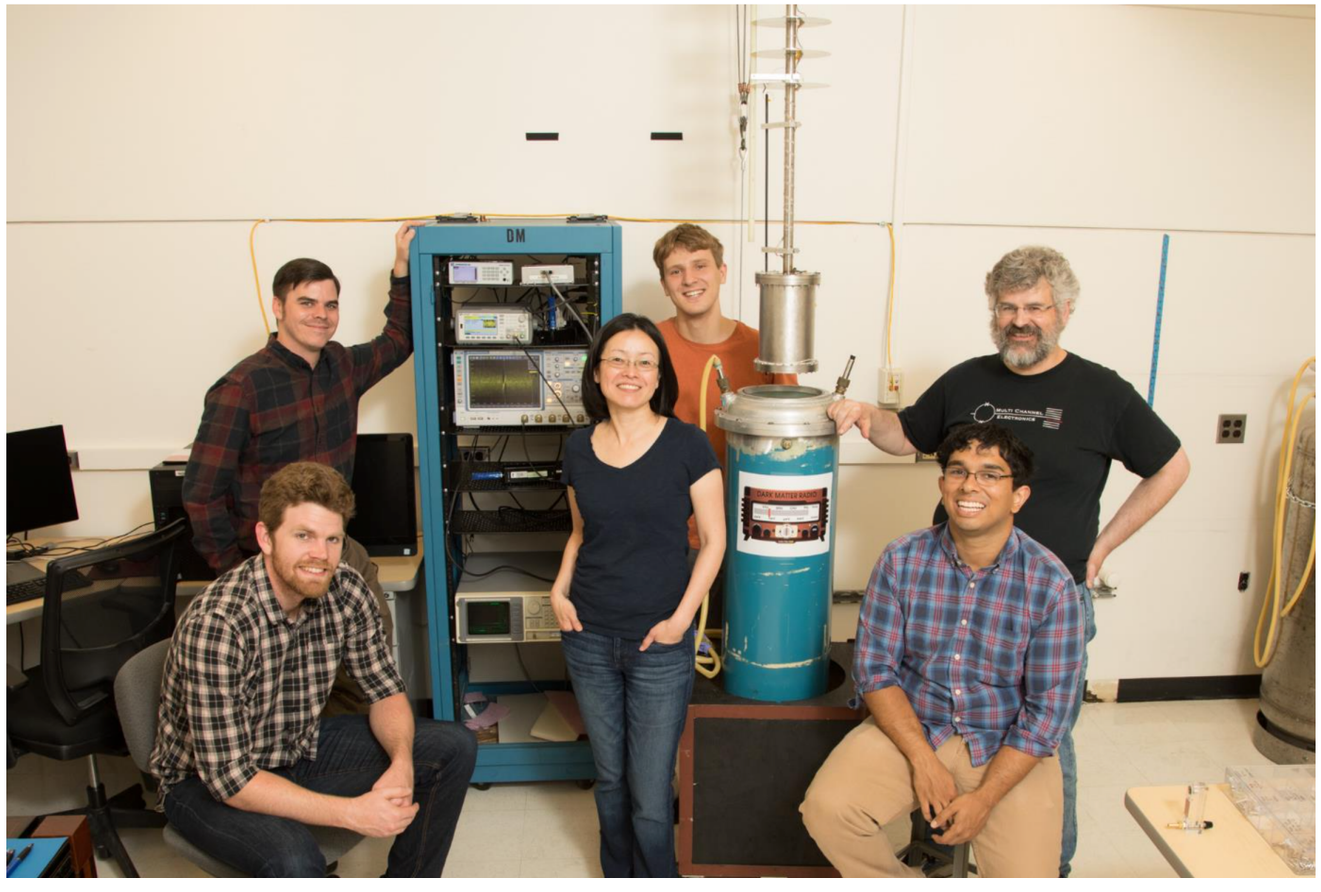


= DM Radio, Auriga...

LC Resonators

Auriga

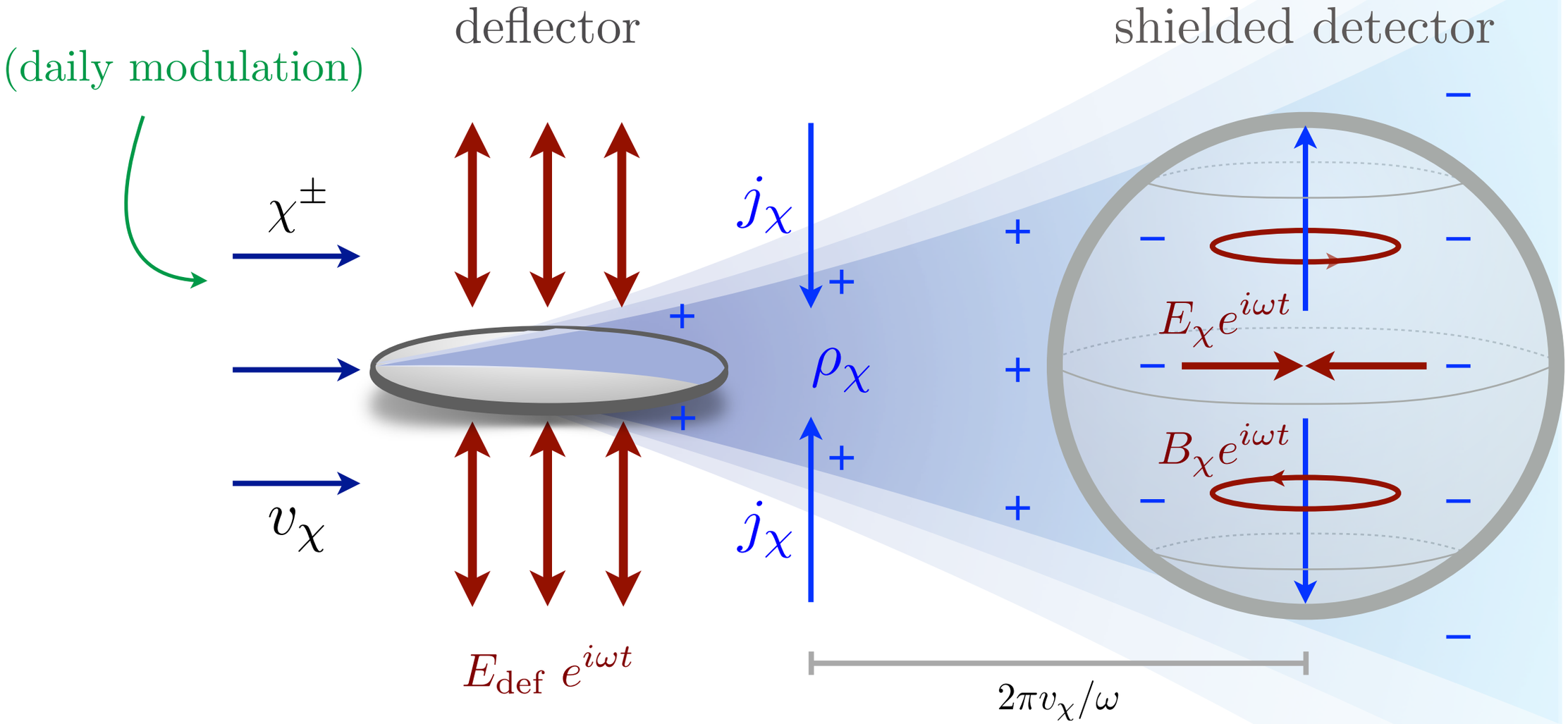
DM Radio



no need to scan or operate at kHz frequencies

Wind Blowing through Walls

similar to light shining through wall



Noise/Systematics

handles: directional dependence, daily modulation

- **SQUID noise**
  imprecision, backaction

(sub-dominant, 1411.7382 & 1803.01627)

- **deflector noise**
  magnetic, electric

(sub-dominant)

(DM radio) penetration depth $\lesssim 50$ nm , critical field ~ 0.1 T ~ 100 kV/cm

- **thermal noise**
  $T \lesssim$ K , Johnson/Nyquist

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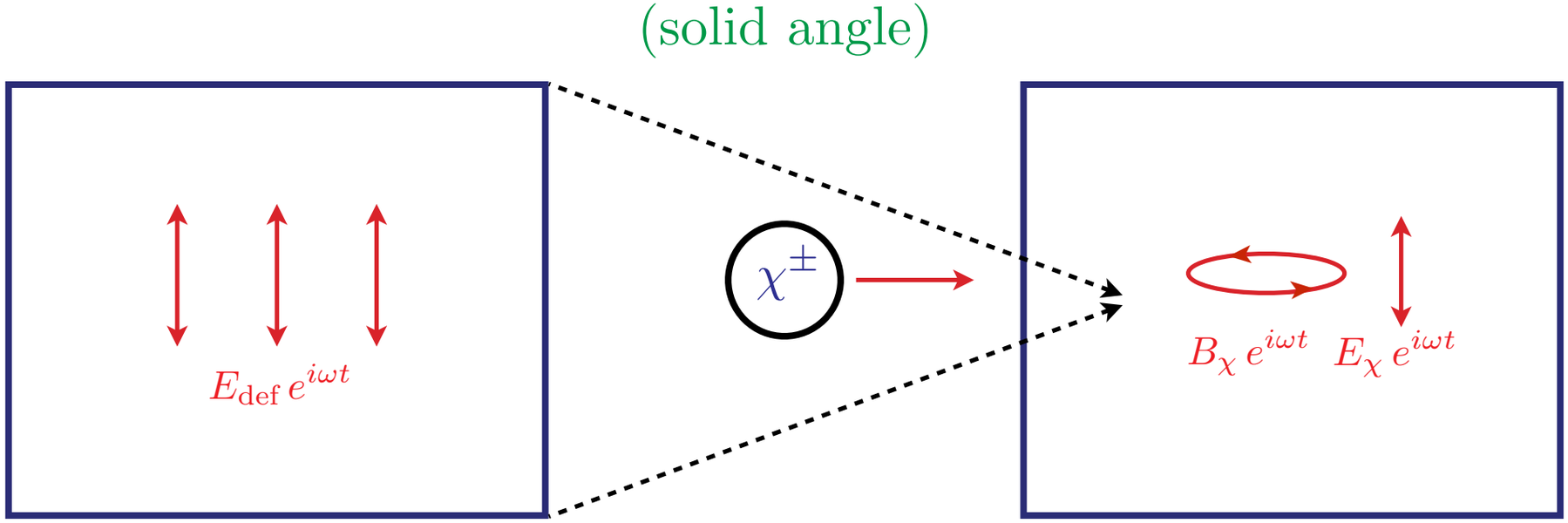
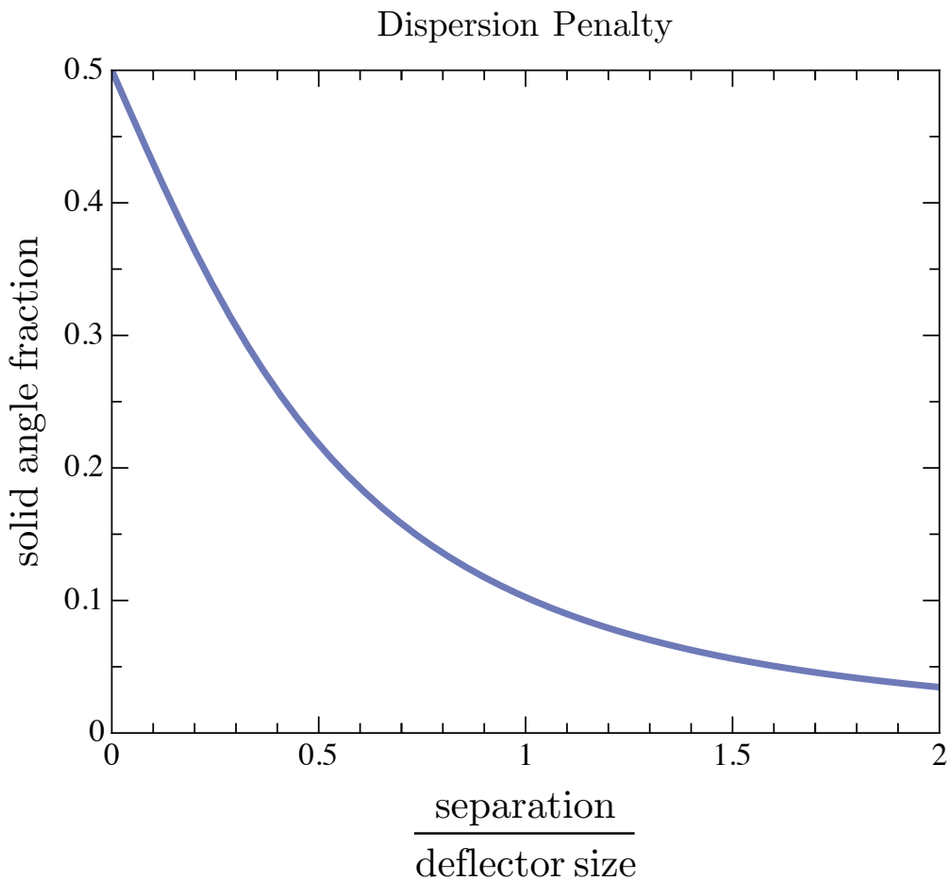
what about dispersion?

Departure from a Perfect Wind

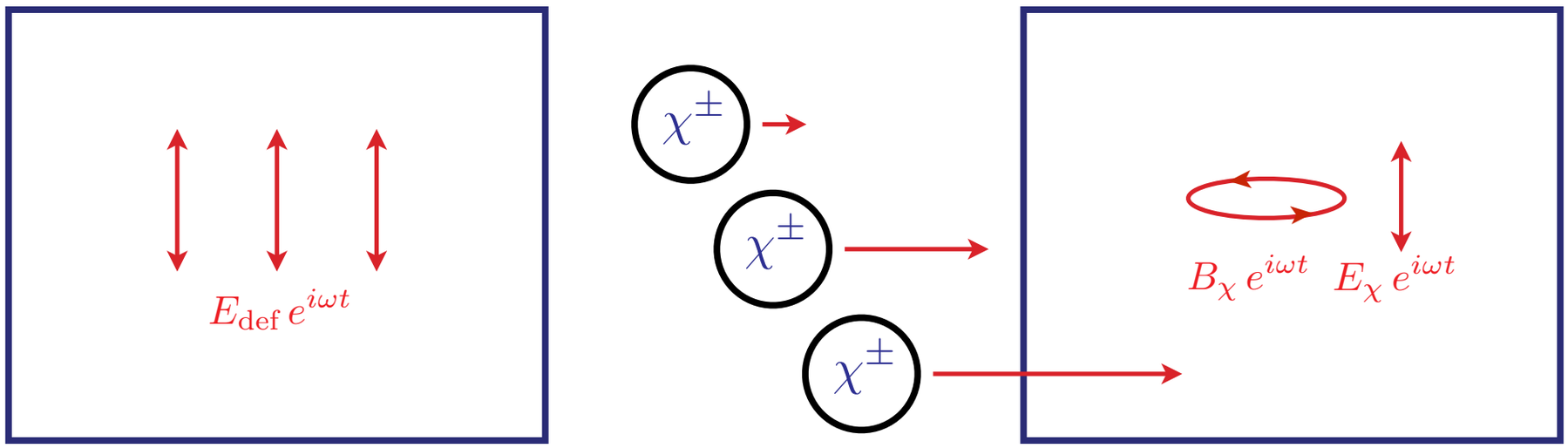




(verified with MC)

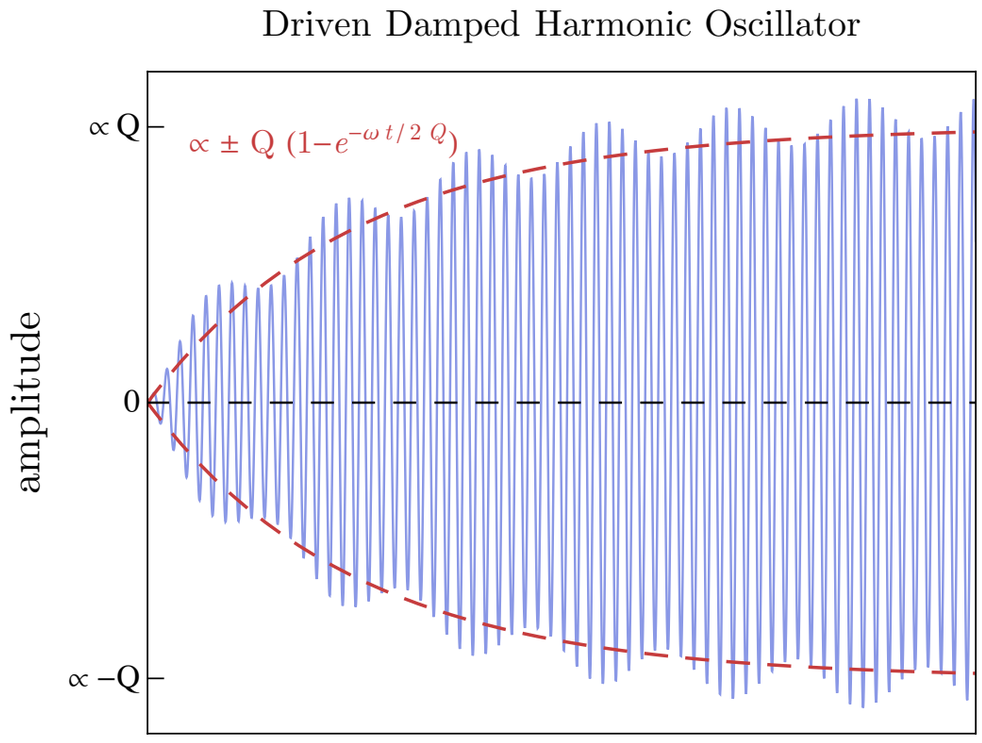
Departure from a Perfect Wind

(Poisson)



deflector

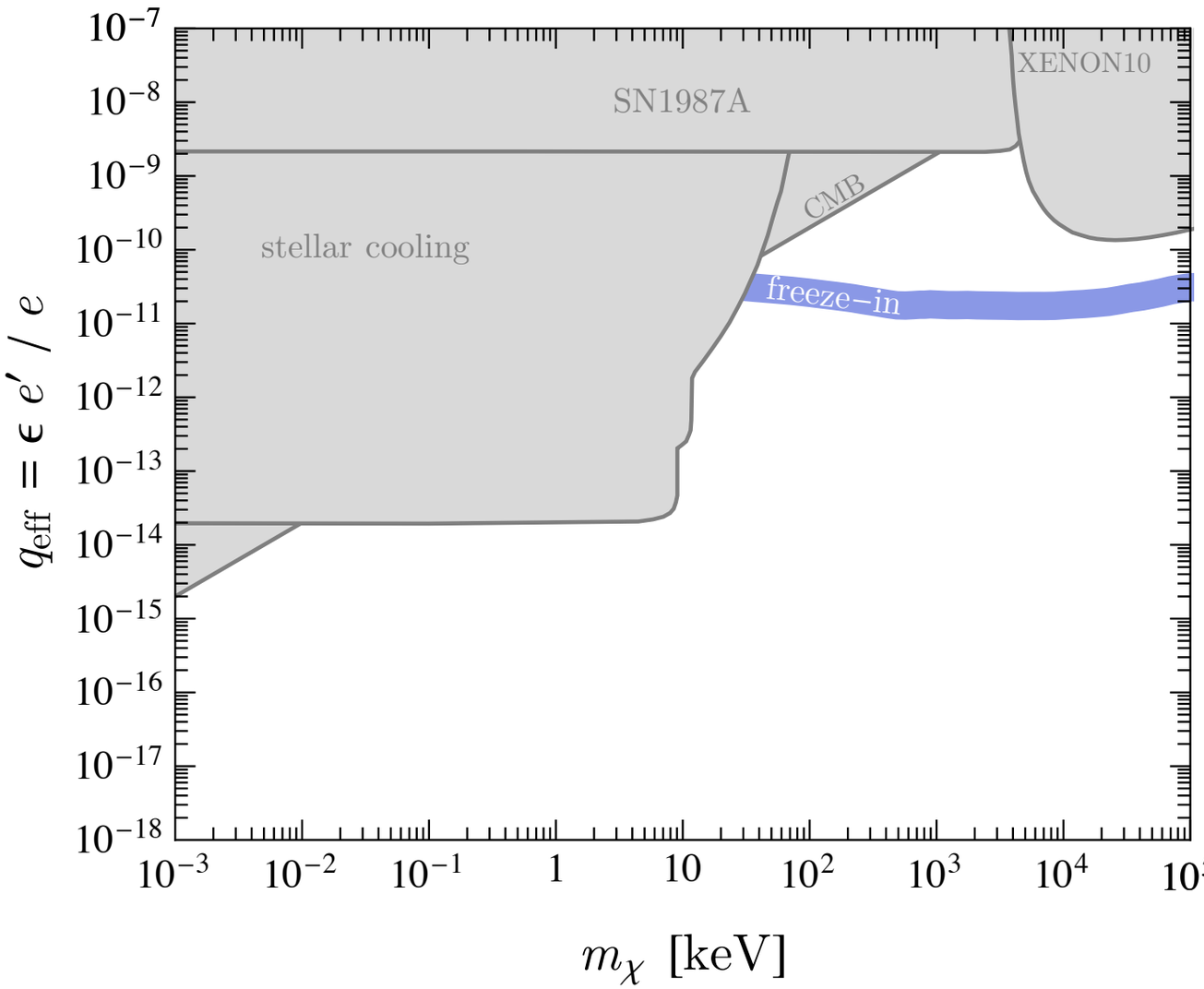
detector



$m_\chi \lesssim$ GeV

relative fluctuations $\lesssim 10^{-3}$

Reach Summary



$\omega = 100$ kHz
$t_{\rm int} =$ year

$$q_{\rm eff}(\text{reach}) \propto m_\chi \; V_{\rm sh}^{-\frac{7}{12}} \; E_{\rm def}^{-\frac{1}{2}} \; (Q\,\omega\,t_{\rm int}/T)^{-\frac{1}{4}}$$

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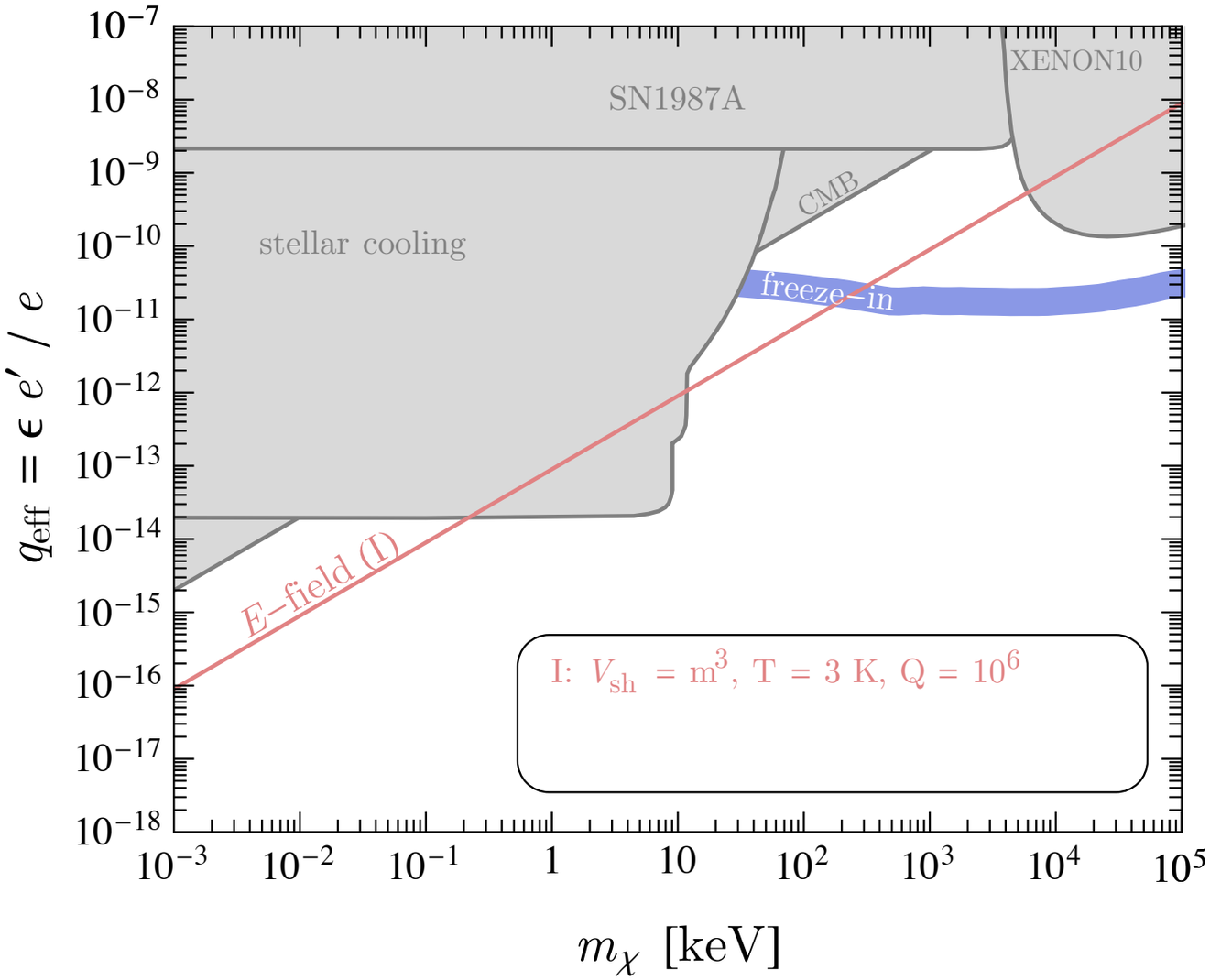

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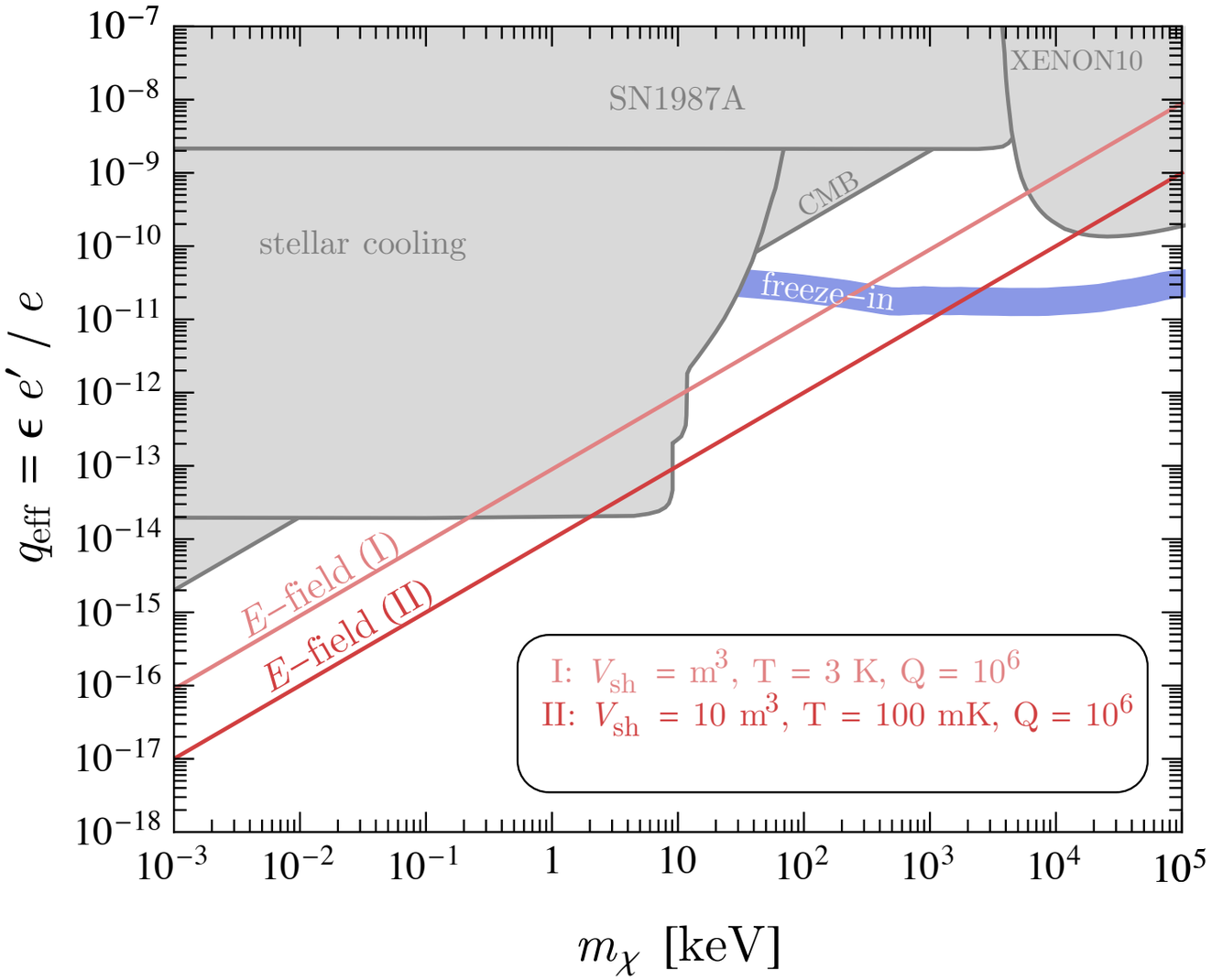

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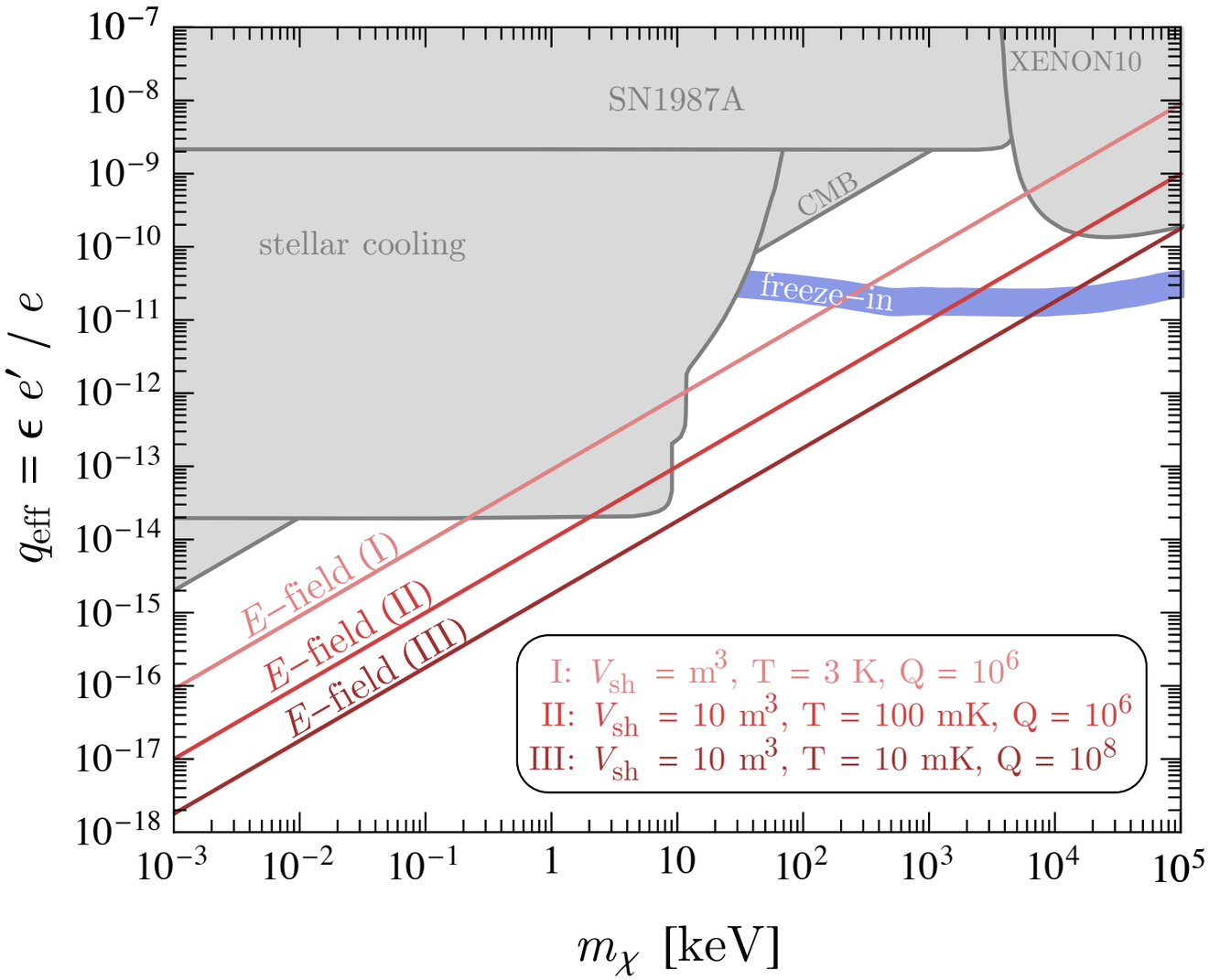

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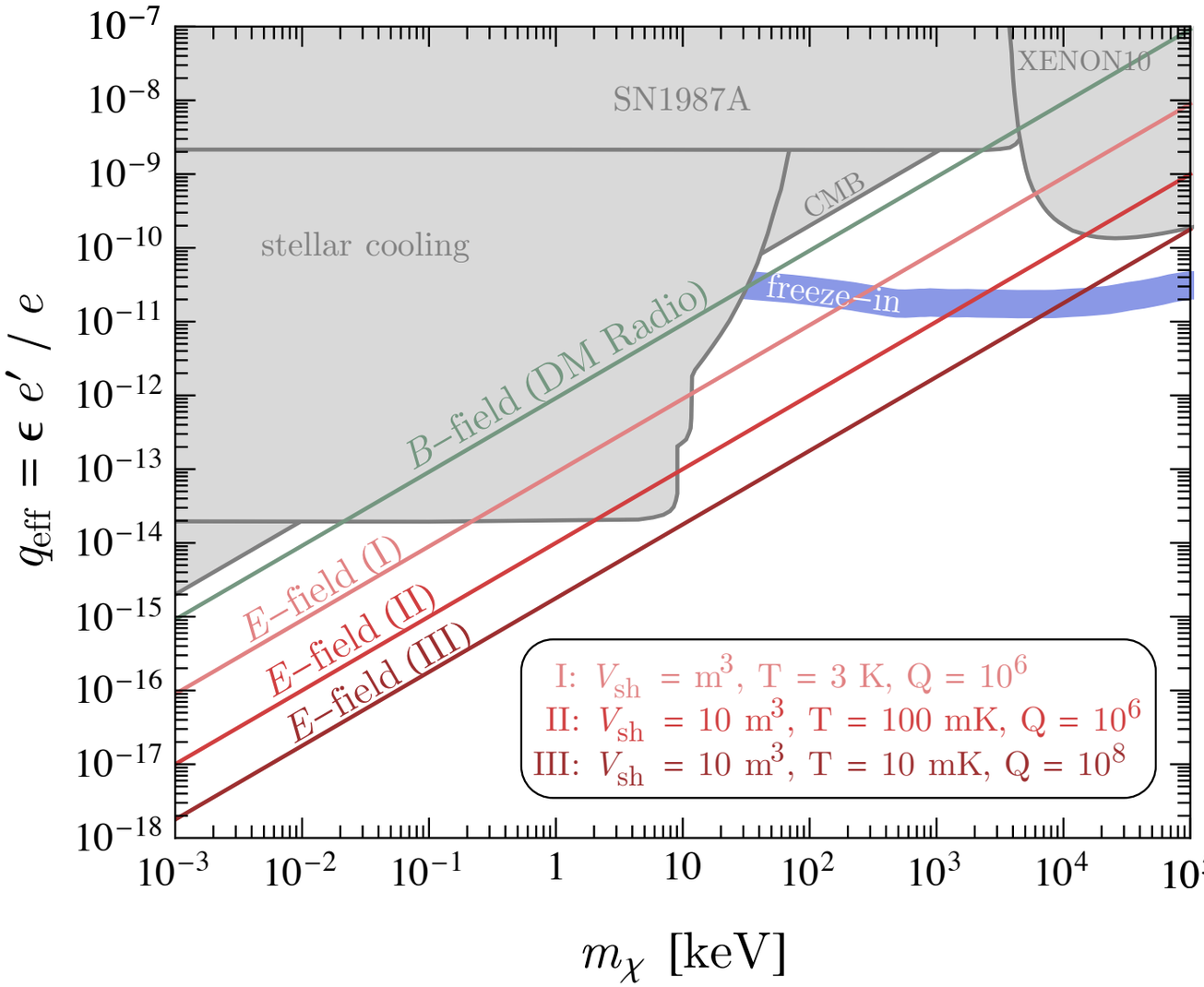

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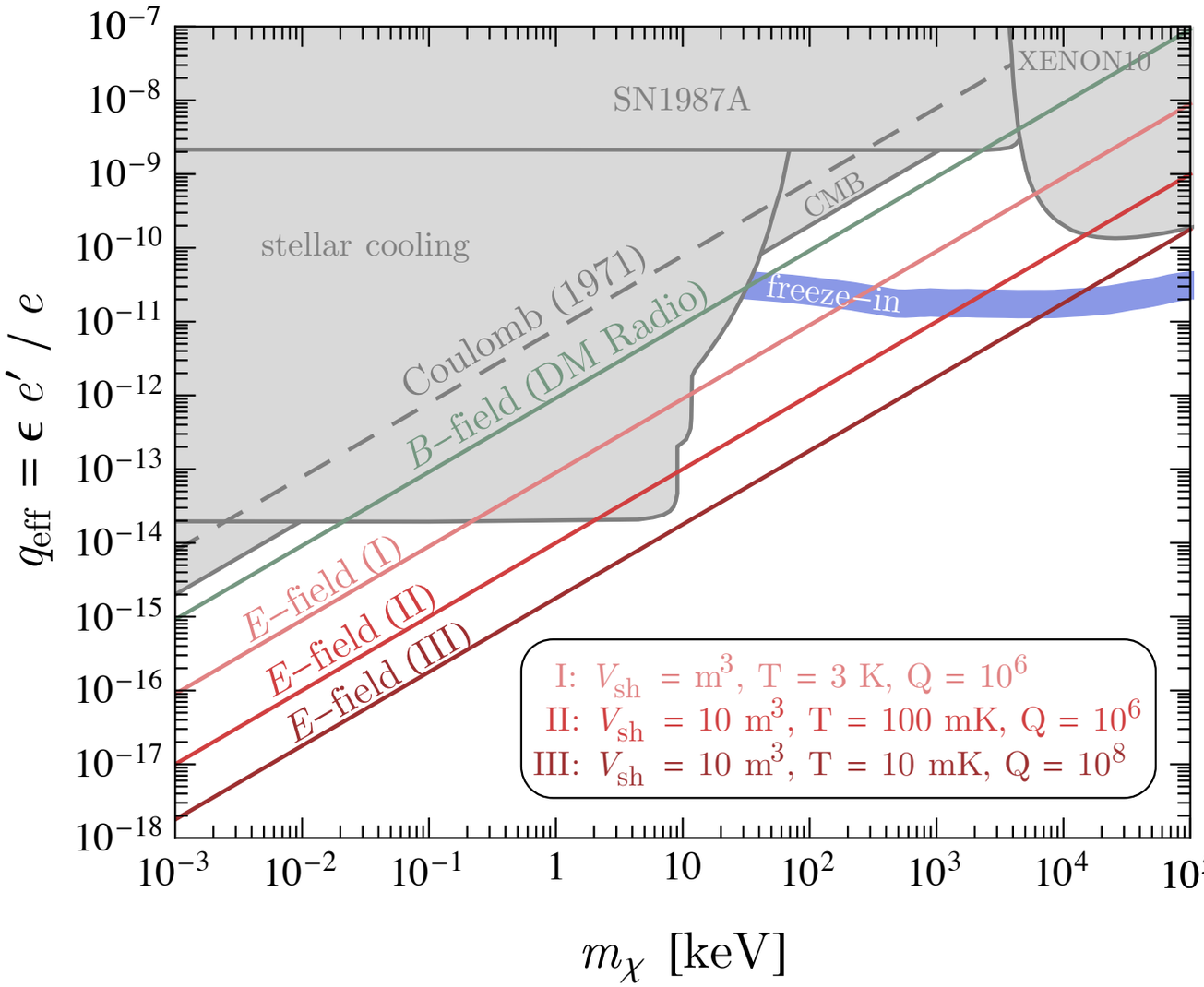

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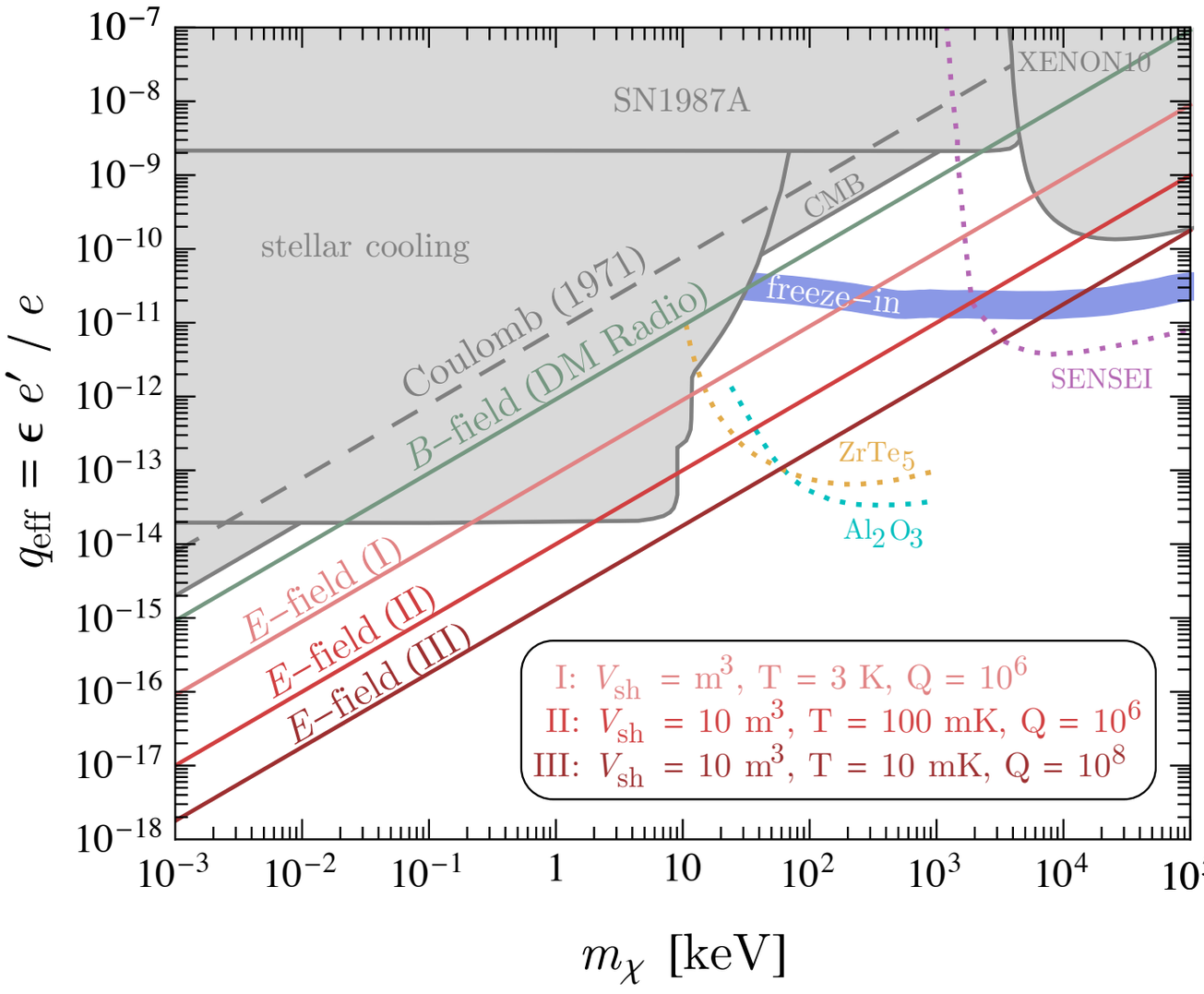

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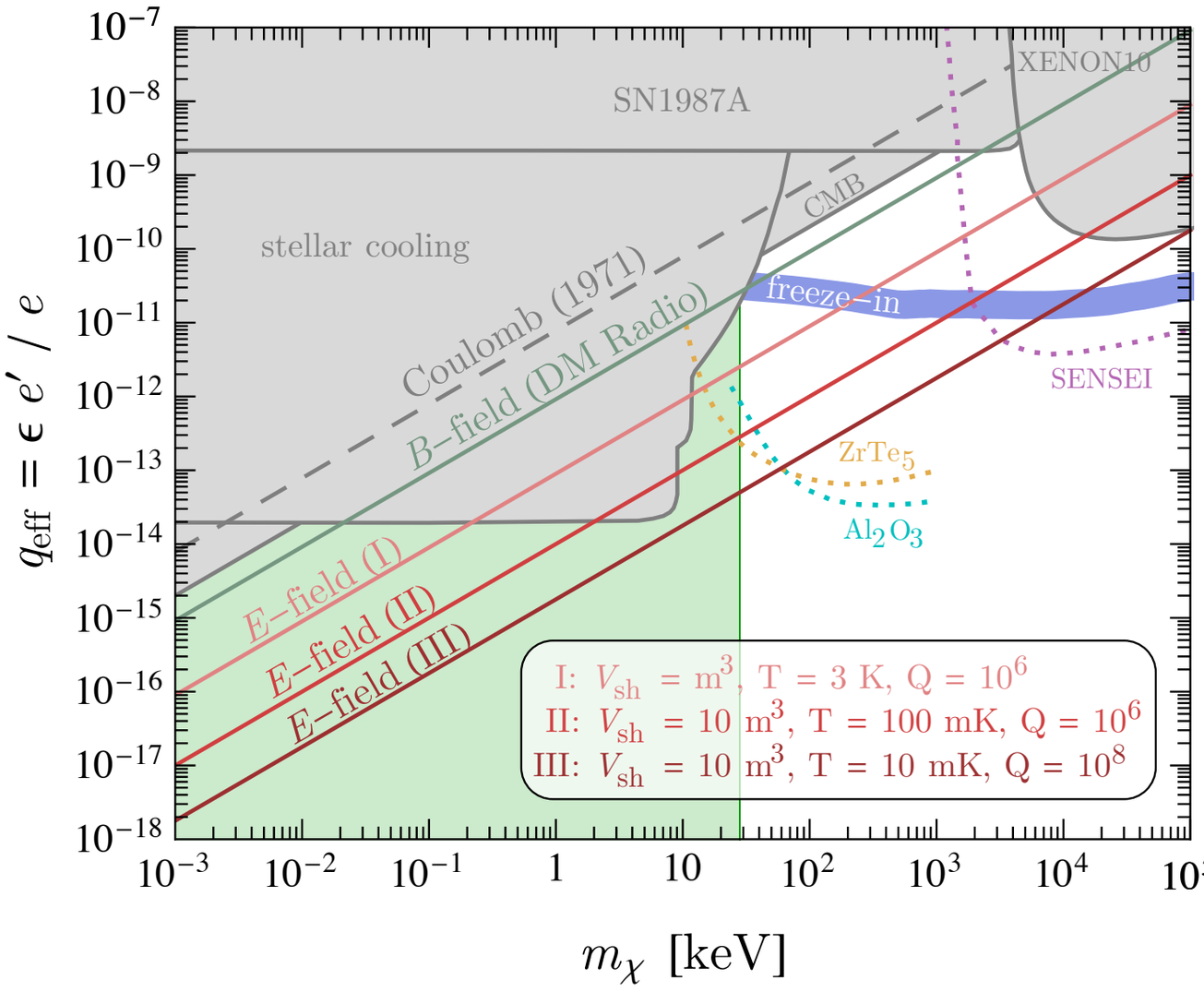
$$q_{\rm eff}({\rm reach}) \propto m_\chi \; V_{\rm sh}^{-\frac{7}{12}} \; E_{\rm def}^{-\frac{1}{2}} \; (Q\,\omega\,t_{\rm int}/T)^{-\frac{1}{4}}$$

Reach Summary

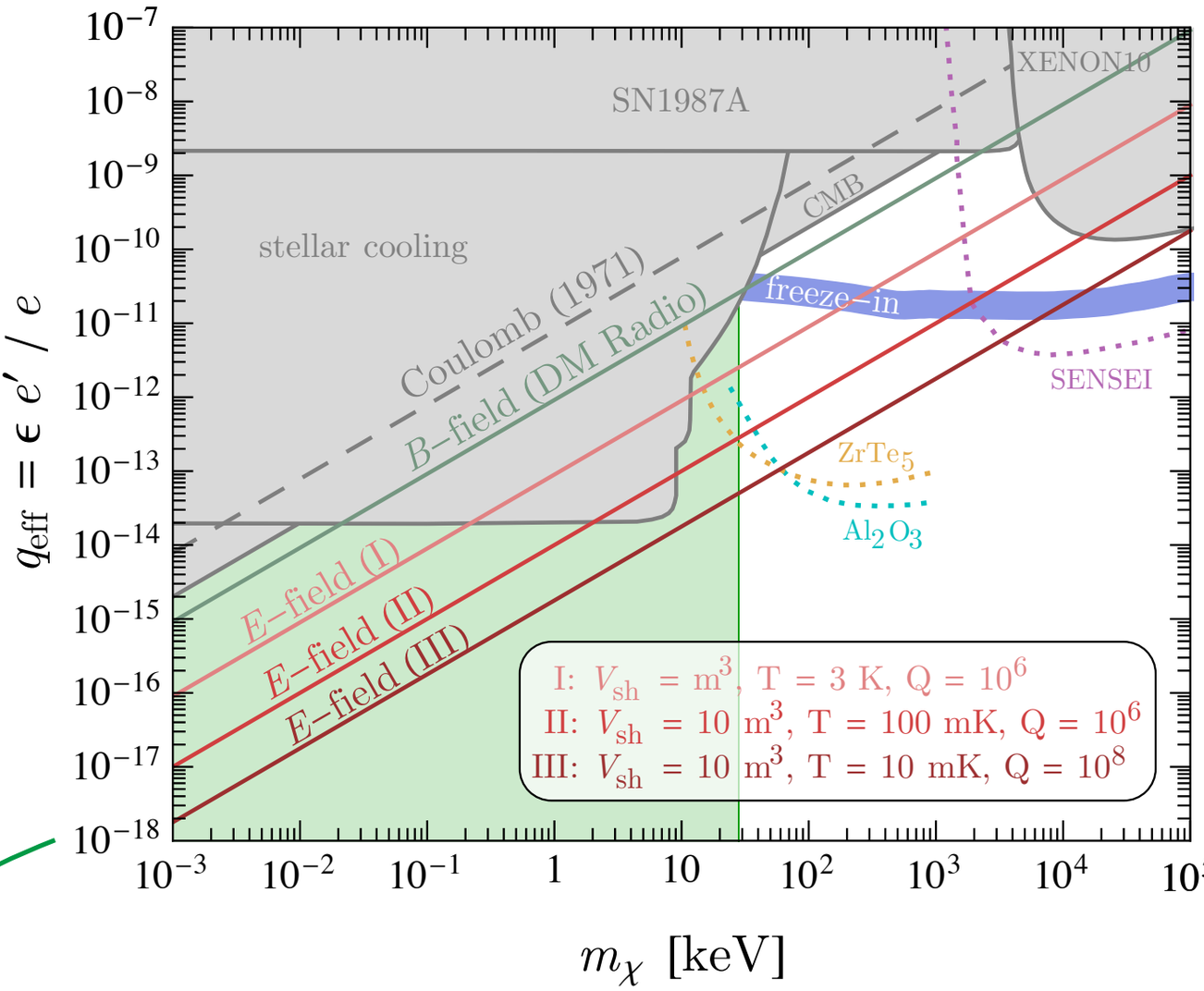


$\omega = 100$ kHz
$t_{\rm int} =$ year

Q: is this interesting?
A: probably...

$$q_{\rm eff}({\rm reach}) \propto m_\chi \; V_{\rm sh}^{-\frac{7}{12}} \; E_{\rm def}^{-\frac{1}{2}} \; (Q\,\omega\,t_{\rm int}/T)^{-\frac{1}{4}}$$

Reach Summary



$\omega = 100$ kHz
$t_{\rm int} =$ year

Q: is this interesting?
A: probably...

transition when
$m_\chi\, v_\chi \lesssim \text{meter}^{-1} \implies m_\chi \lesssim 10^{-7}$ keV

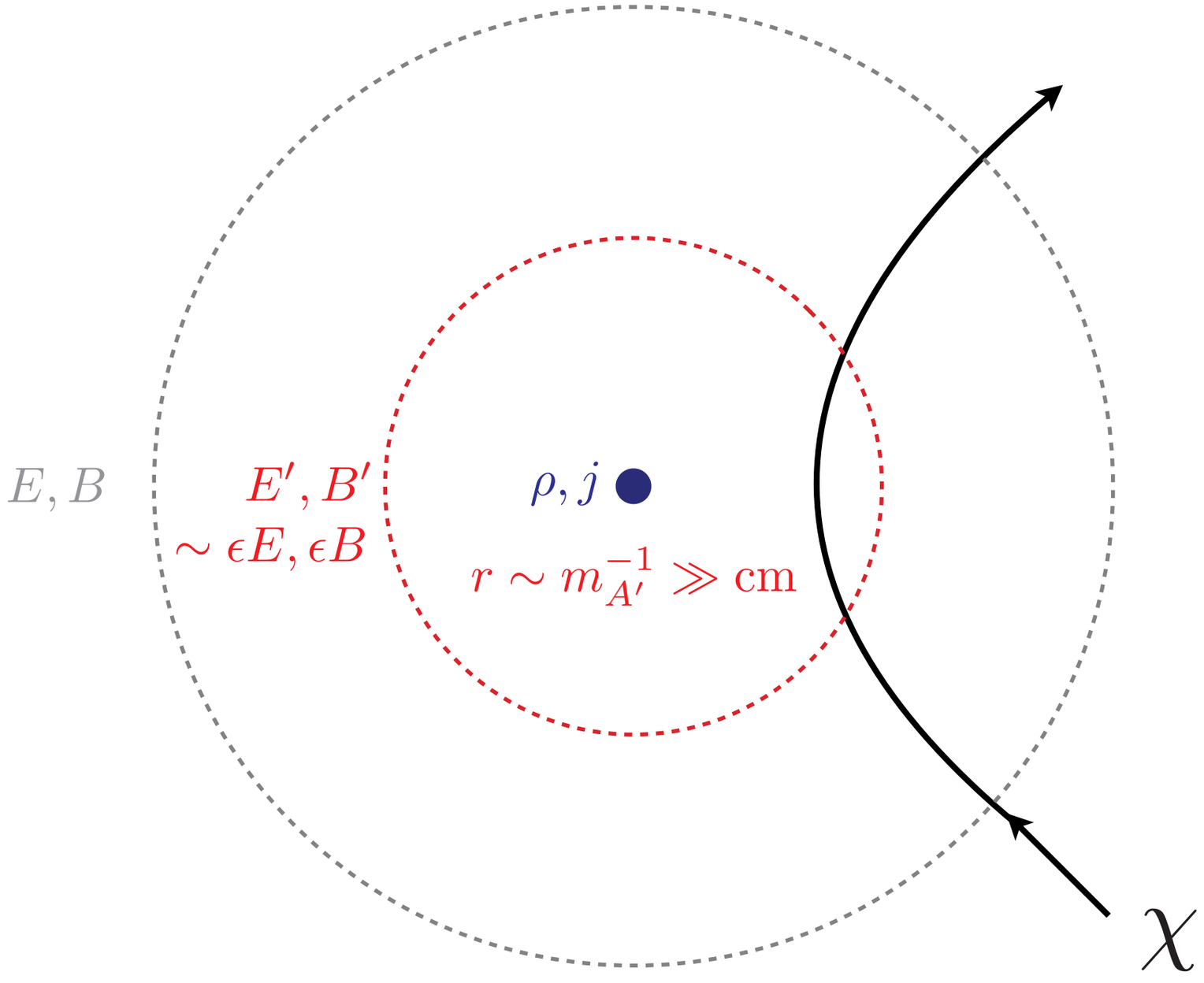
$$q_{\rm eff}(\text{reach}) \propto m_\chi\, V_{\rm sh}^{-\frac{7}{12}}\, E_{\rm def}^{-\frac{1}{2}}\, (Q\,\omega\, t_{\rm int}/T)^{-\frac{1}{4}}$$

Active Direct Detection

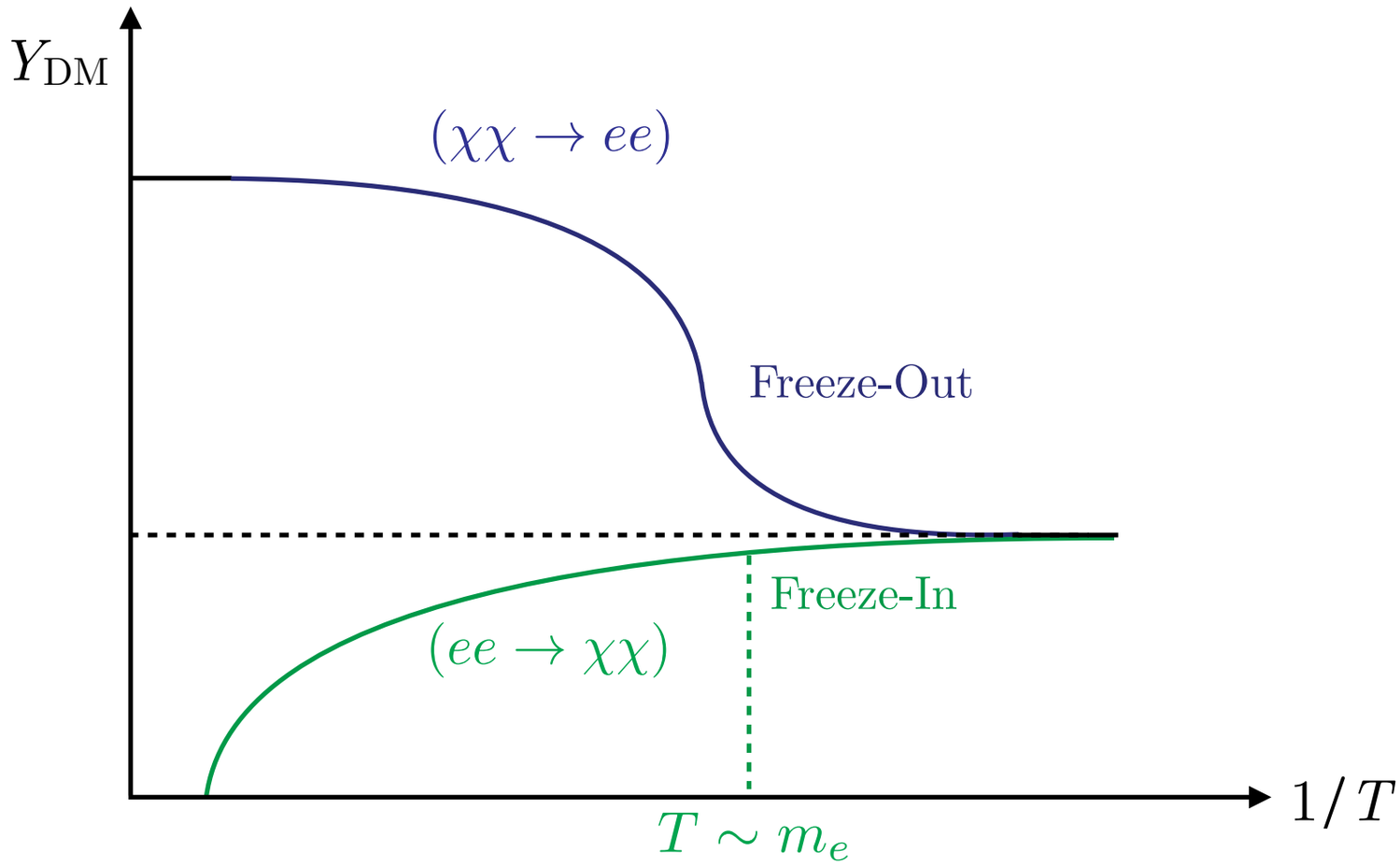
- induced daily modulation
- electromagnetic focusing/trapping of dark matter
- optimal geometry for wind
- spin-coupled forces, ...

Back Up Slides

Electromagnetic Fields



Freeze-In

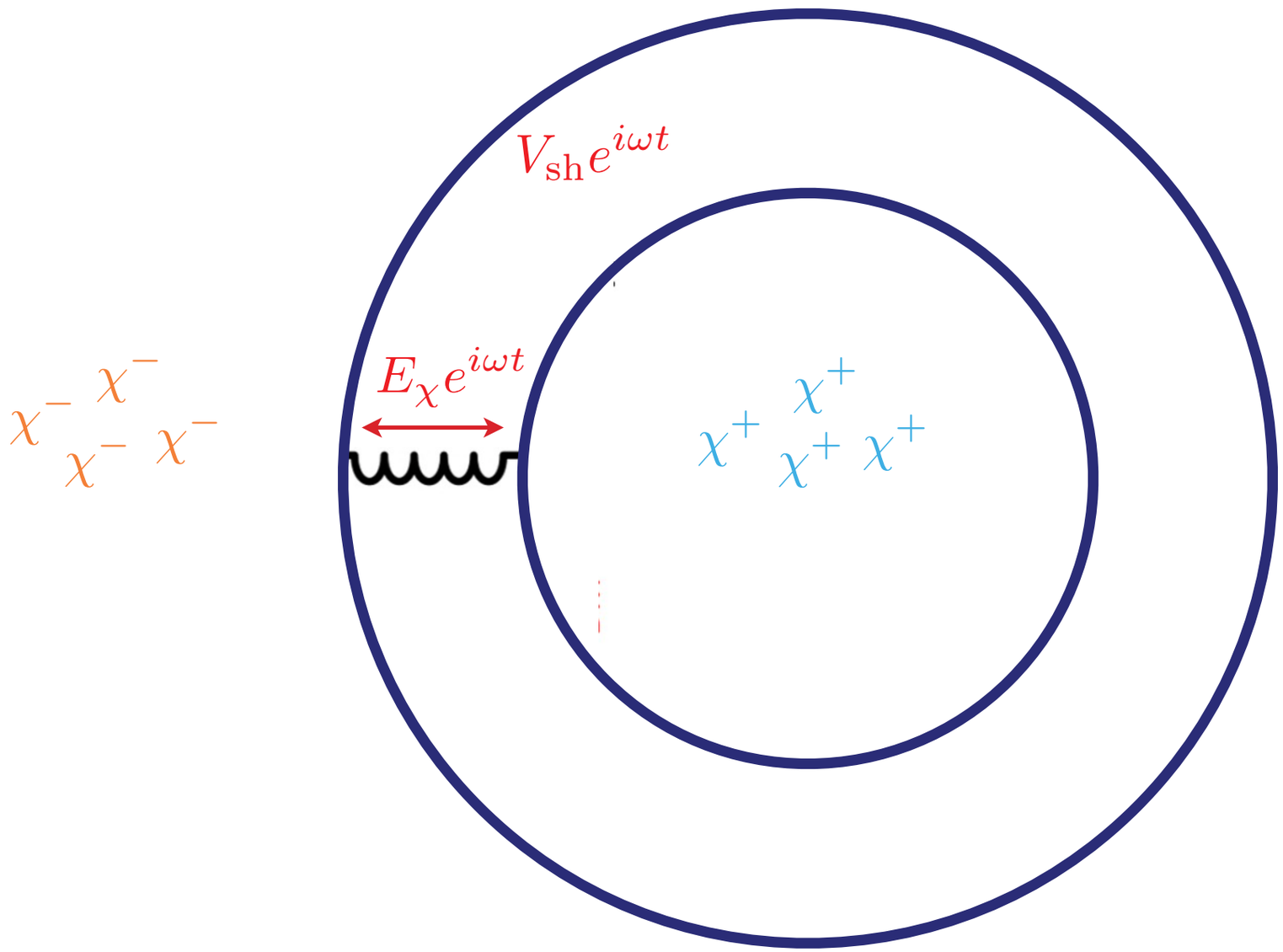


$$\Longrightarrow \boxed{q \sim \frac{1}{\alpha_{\rm em}} \left(\frac{m_e\, T_{\rm eq}}{m_\chi\, m_{\rm pl}}\right)^{1/2} \sim 10^{-11} \left(\frac{\rm MeV}{m_\chi}\right)^{1/2}}$$

Alternative Geometries

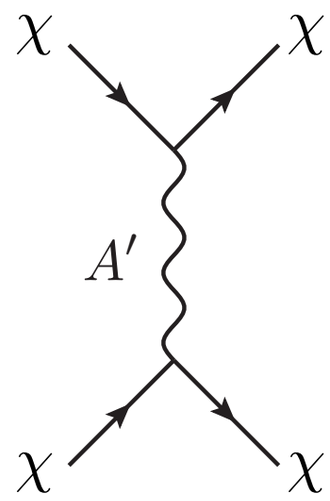
(enhanced solid angle)

$$\nabla \cdot E = \rho - m_\gamma^2 \, \varphi$$



Williams et al., 1971 $\Longrightarrow$ $m_{\rm Debye} \lesssim 10^{-11}$ eV

Self-Interactions



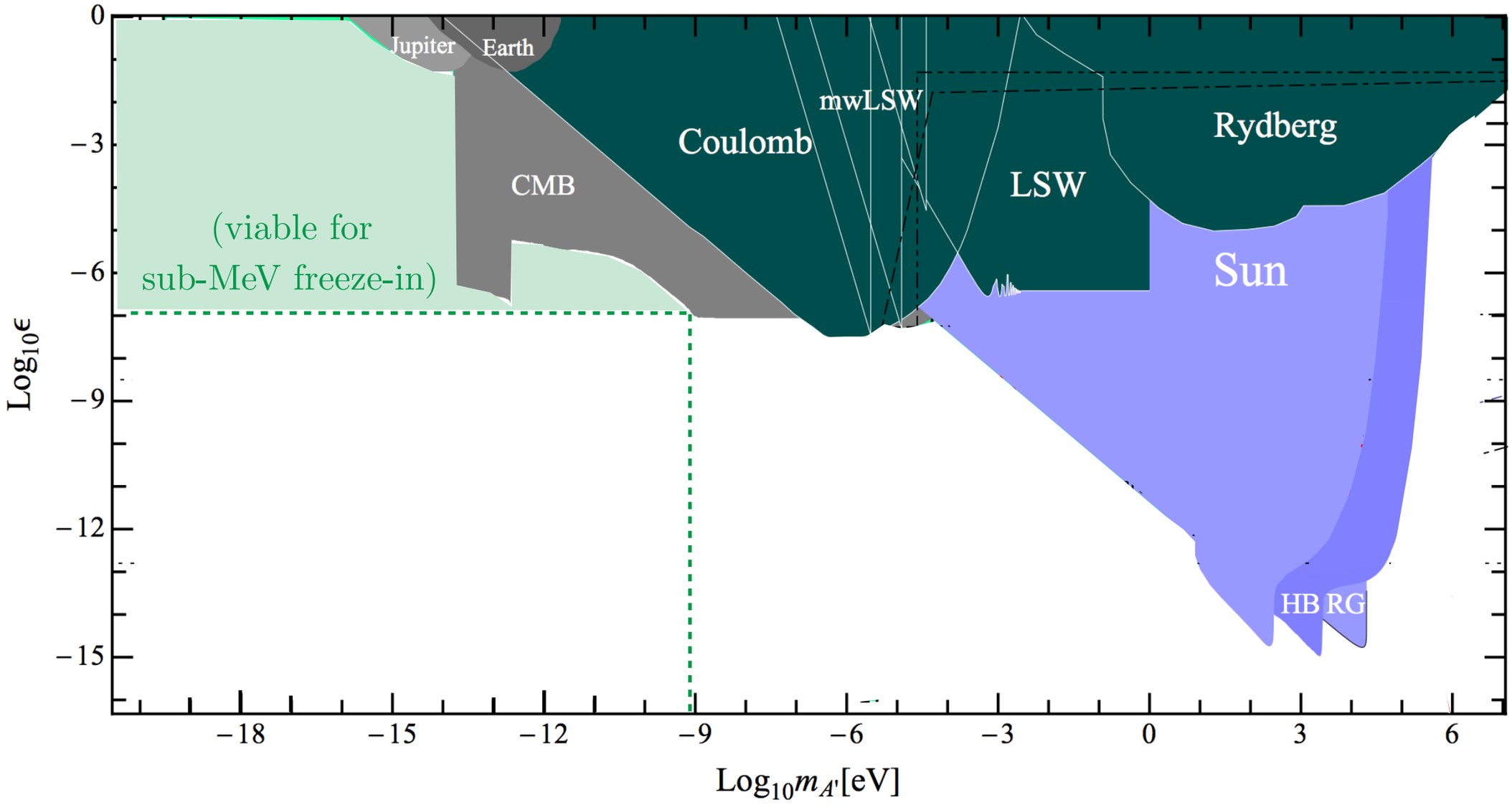
$$\text{galaxy clusters, ...} \implies \boxed{\alpha' \lesssim 10^{-10} \left(\frac{m_\chi}{\text{MeV}}\right)^{3/2}}$$

$$\text{freeze-in} \implies q_{\text{eff}} \sim \epsilon e'/e \sim 10^{-11} \left(\frac{m_\chi}{\text{MeV}}\right)^{-1/2} \implies \boxed{\alpha' \sim \frac{10^{-24}}{\epsilon^2} \left(\frac{m_\chi}{\text{MeV}}\right)^{-1}}$$

$$\therefore \ \text{SIDM} + \text{freeze-in} \implies \boxed{\epsilon \gtrsim 10^{-7} \left(\frac{m_\chi}{\text{MeV}}\right)^{-5/4}}$$

what does this imply
for the dark photon mass?

Parameter Space



$$m_{A'} \lesssim 10^{-9}\ \mathrm{eV} \sim \frac{1}{100\ \mathrm{m}}$$

long-range forces

arXiv:1704.05081
arXiv:1401.6077