Direct *Deflection* of Dark Matter

Asher Berlin-NYU

TRIUMF
March 11th, 2020

A. Berlin, R. D'Agnolo, S. Ellis, P. Schuster, N. Toro
Phys. Rev. Lett. 2020

Direct Detection Below an MeV

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predictive cosmology

(freeze-in)

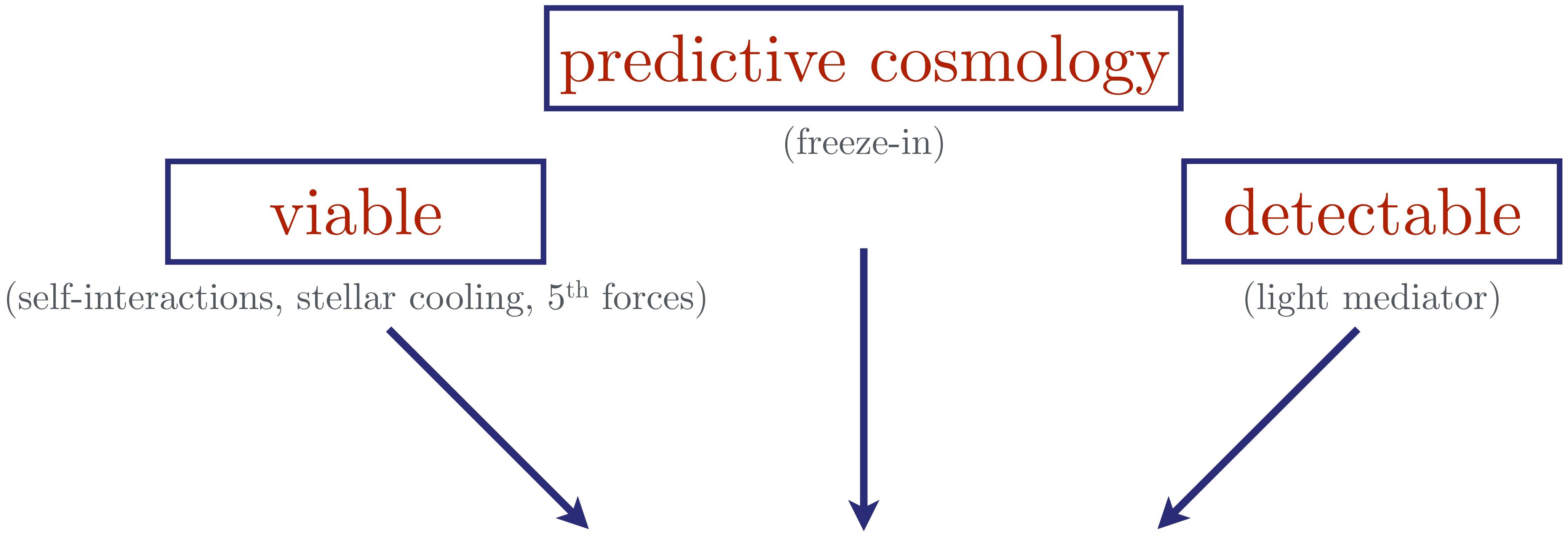
viable

(self-interactions, stellar cooling, 5^{th} forces)

detectable

(light mediator)

Direct Detection Below an MeV



$$m_{\text{force}} \ll \text{meter}^{-1}$$

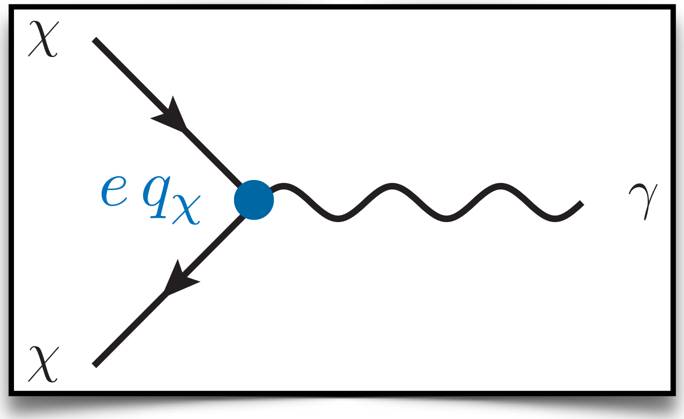
millicharge-like on meter length scales

Millicharges

New Long-Ranged Forces

"millicharged"

at low-energy and laboratory-distances:



$(q_\chi << 1)$

How can this interaction arise?

New Long-Ranged Forces

The visible universe is governed by a rich spectrum of forces and particles.

What particle physics governs most of the matter in the universe?

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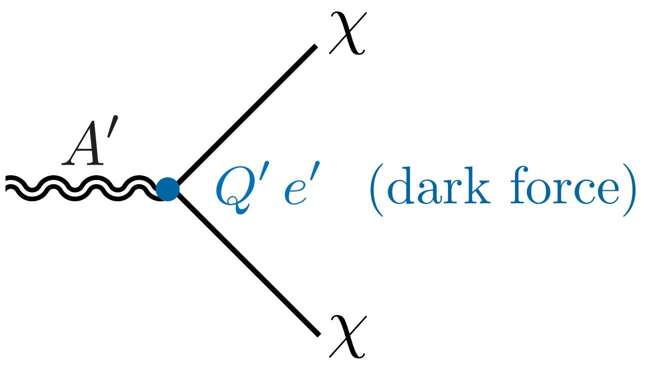

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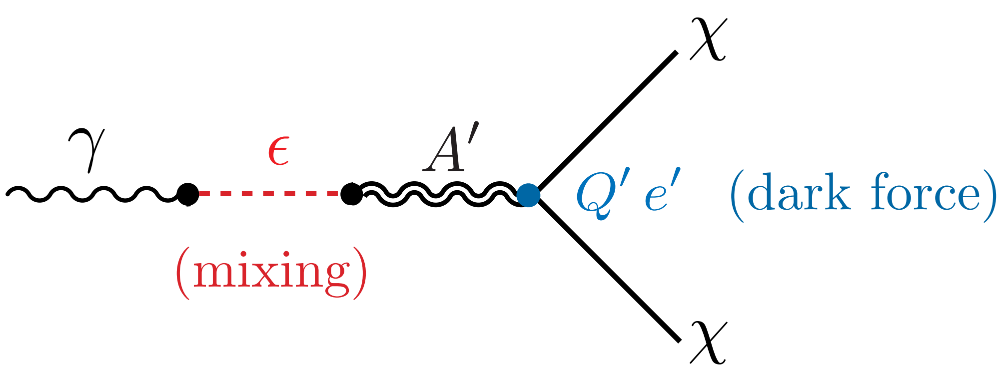

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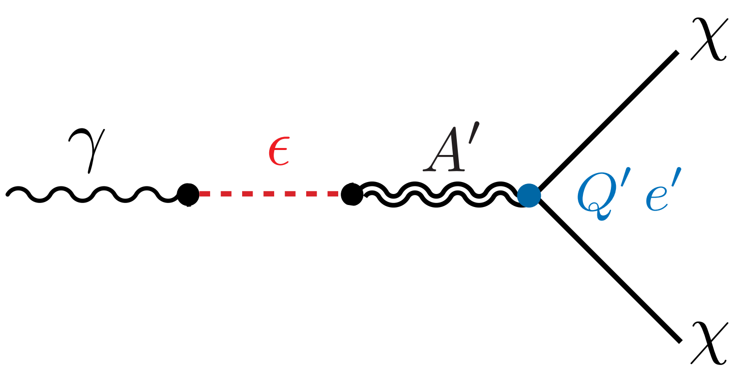

$$\Longrightarrow \; q_\chi \sim \epsilon\, Q'\, e'/e \quad \text{(effective DM charge)}$$

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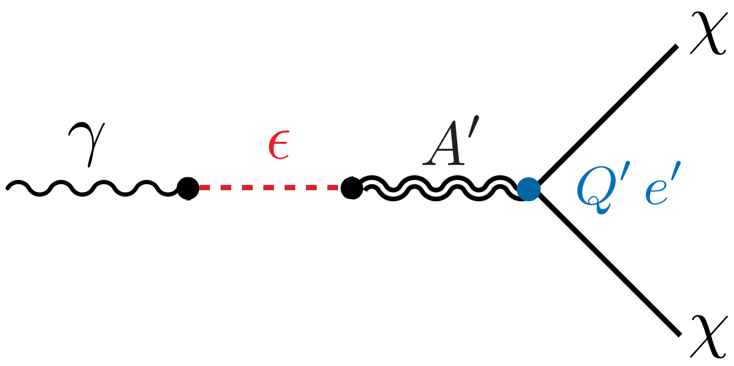

$\Longrightarrow \quad q_\chi \sim \epsilon\, Q'\, e'/e$ (effective DM charge)

small millicharges from radiatively induced mixing

T. Gherghetta, J. Kersten, K. Olive, M. Pospelov, Phys. Rev. D 2019

small millicharges from extra dimensions

B. Batell, T. Gherghetta, Phys. Rev. D 2006

Pseudo-Millicharge

$$\boxed{\mathcal{L} \supset j_\mu (A^\mu + \epsilon A'^\mu) + j'_\mu A'^\mu}$$ (kinetic mixing)

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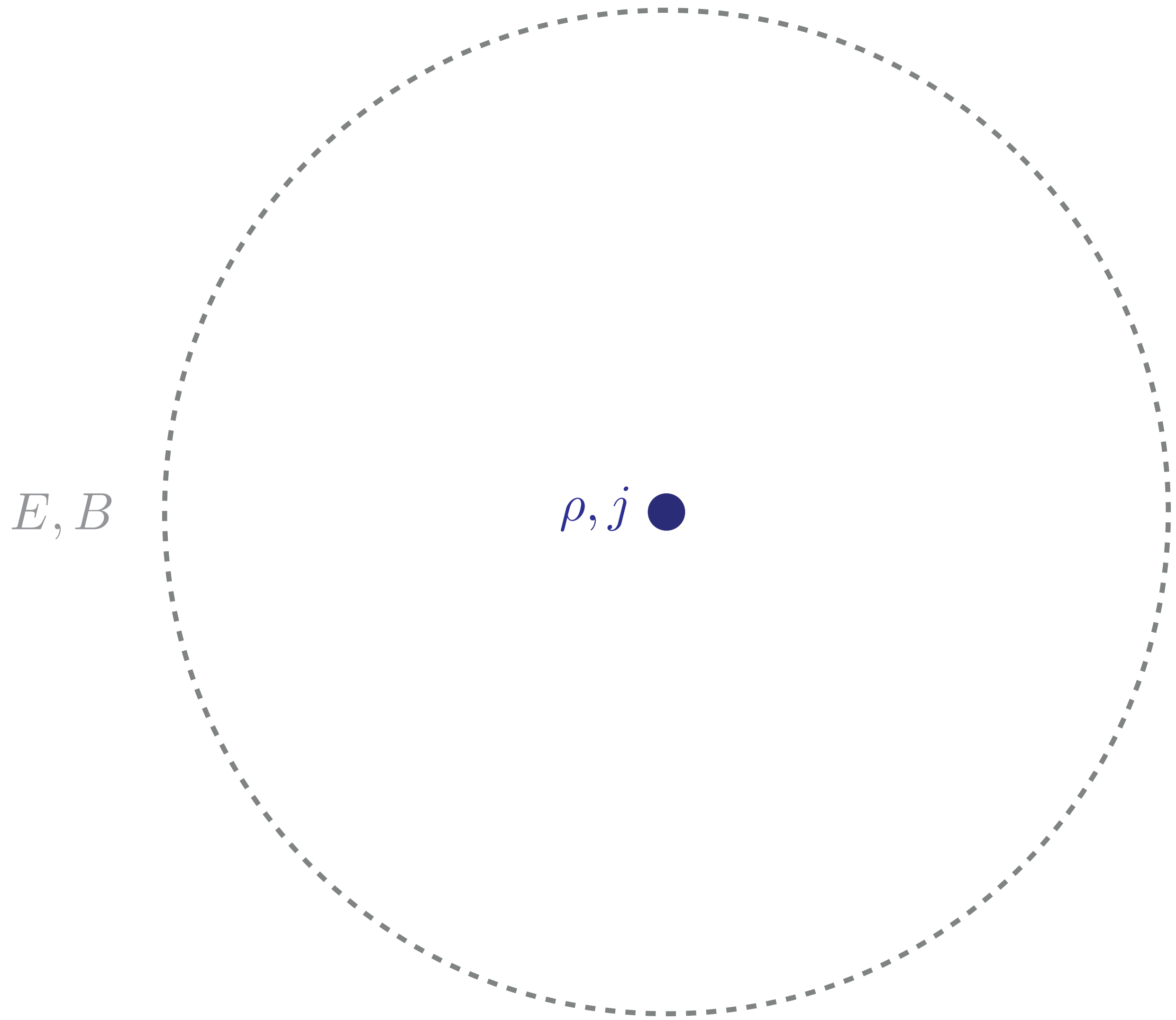

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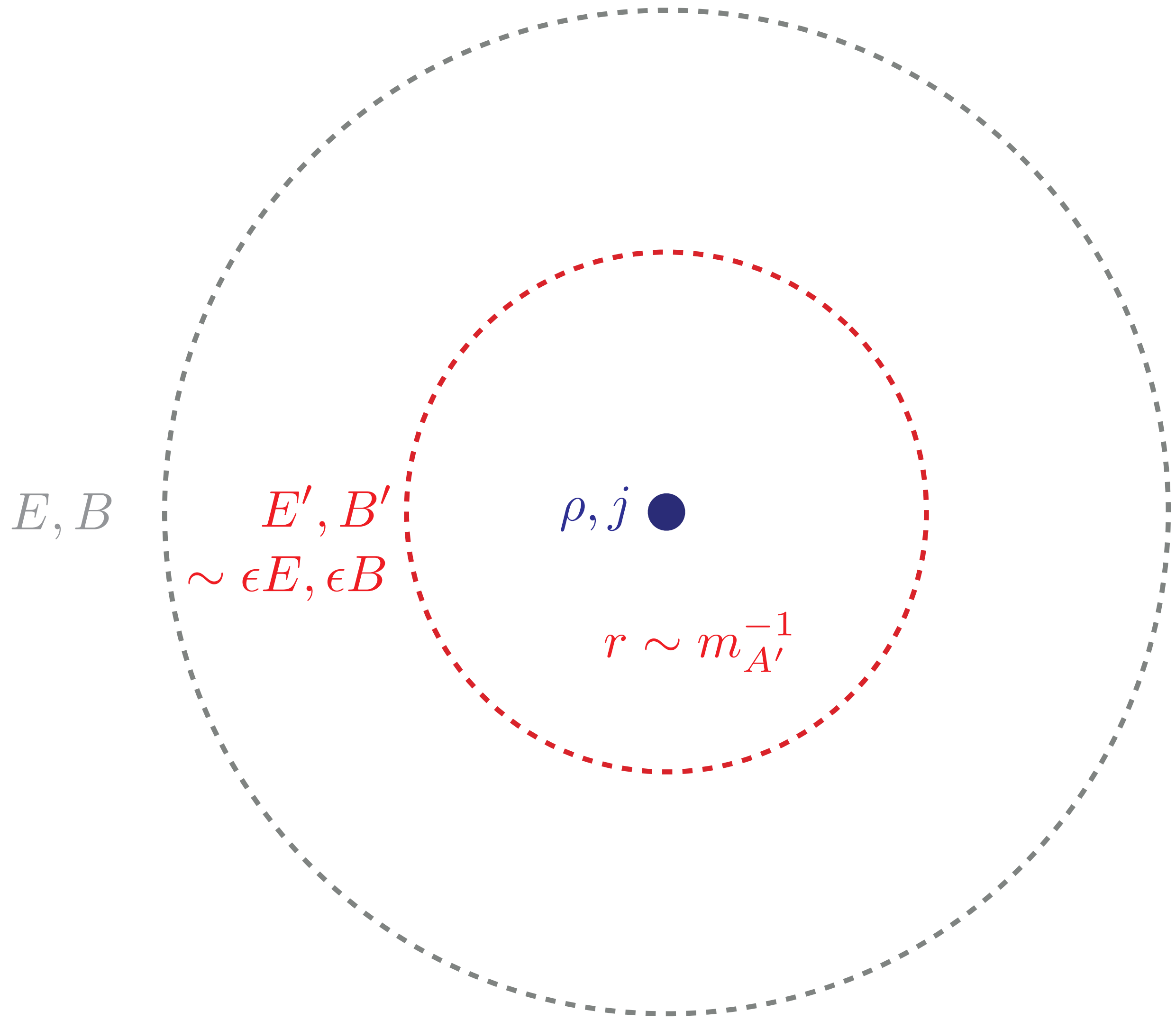

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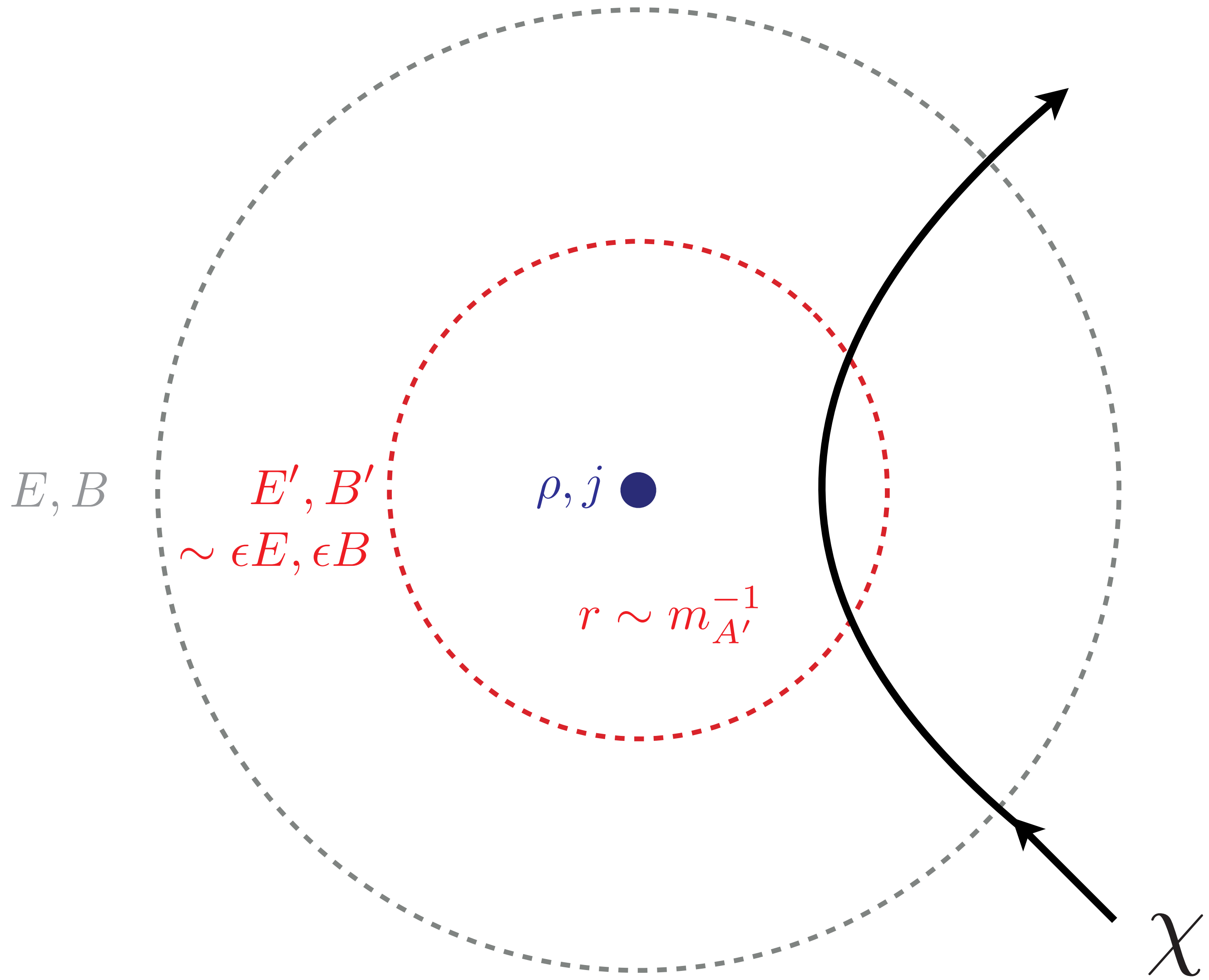

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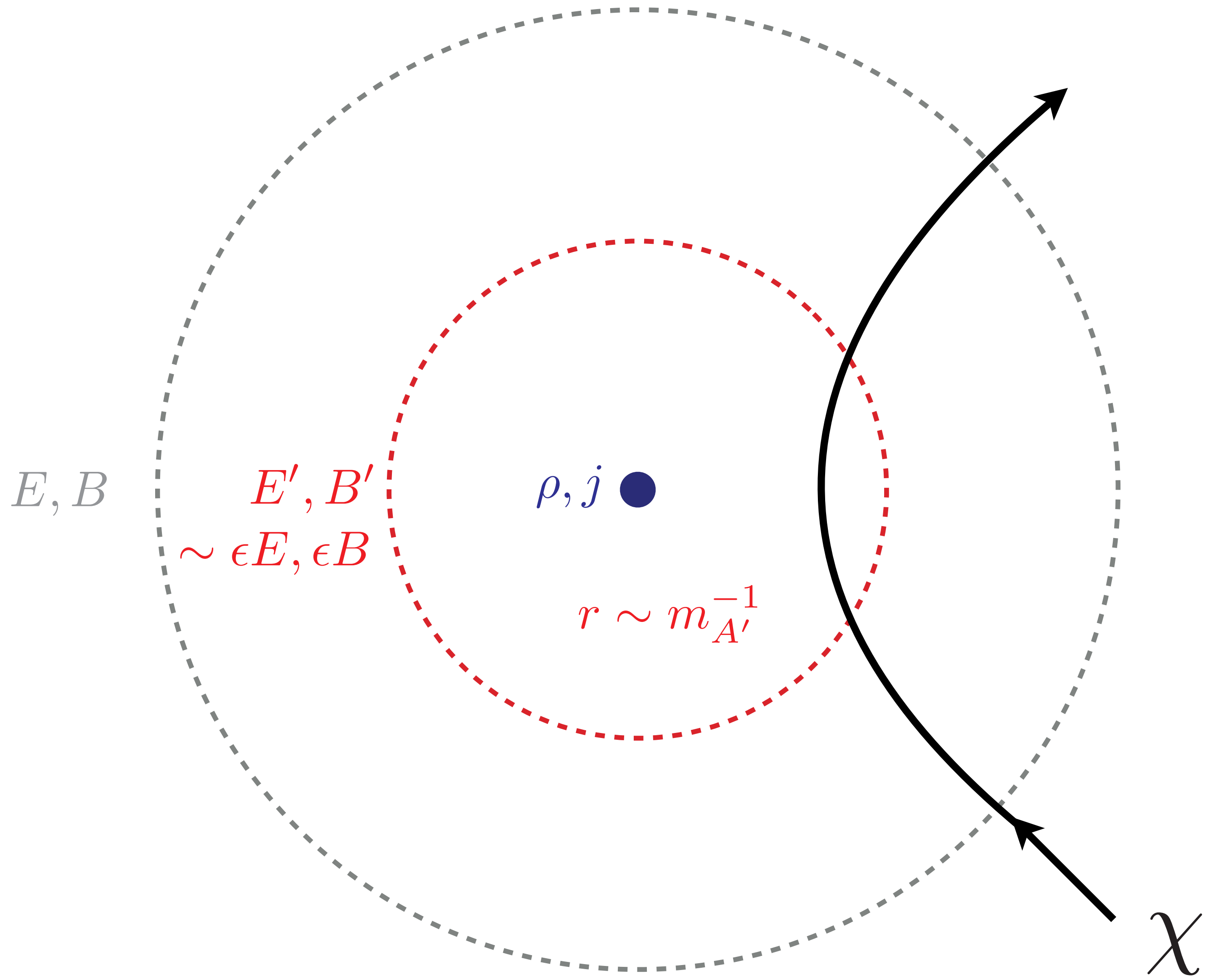
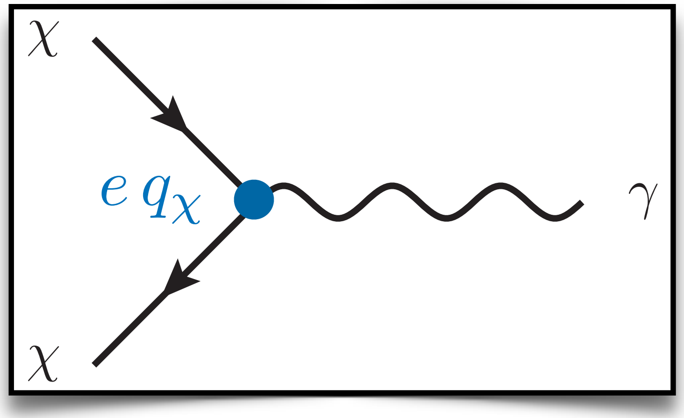


$$q_\chi \sim \epsilon e'/e \text{ for } r \ll 1/m_{A'}$$

New Long-Ranged Forces

at low-energy and laboratory-distances:



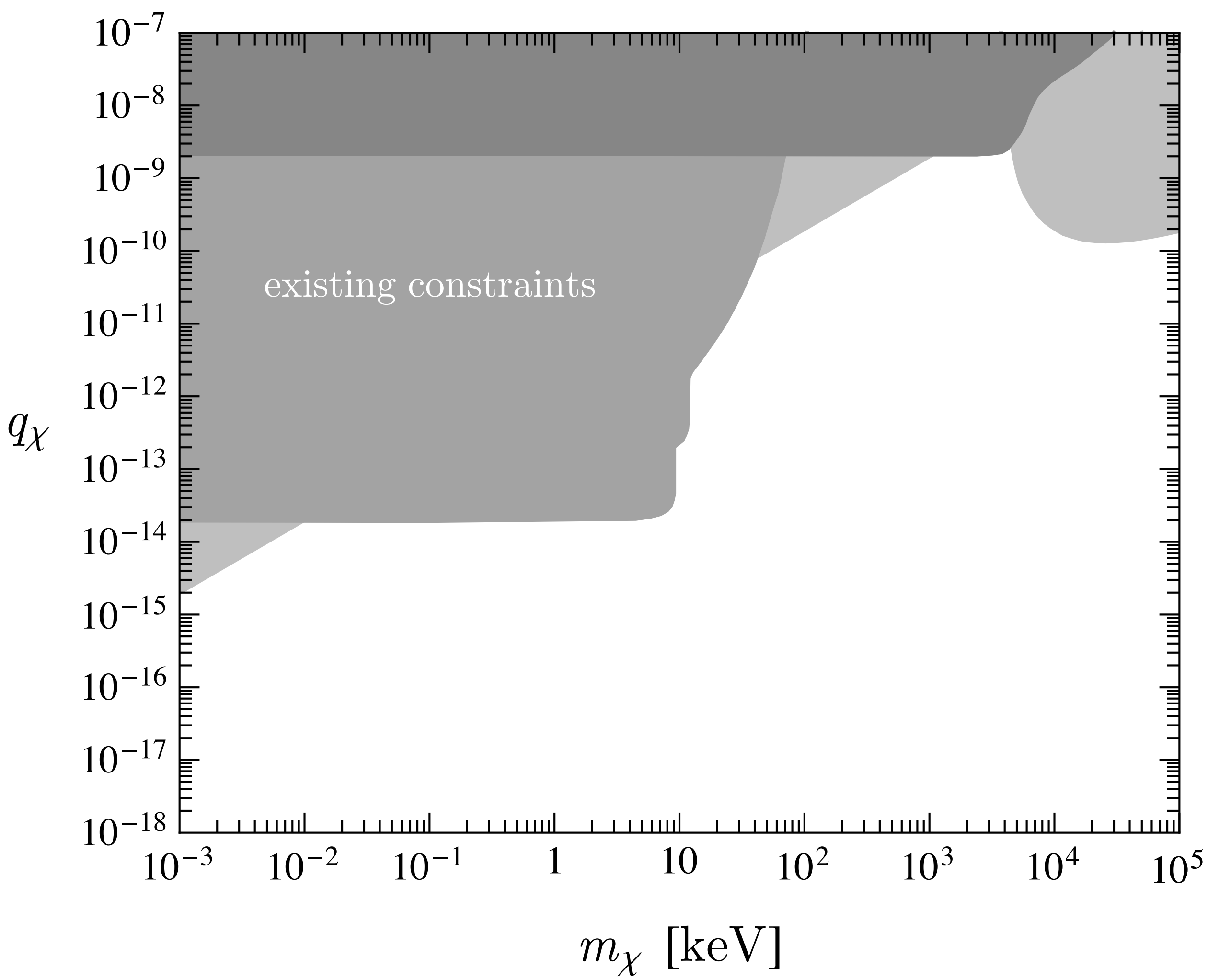
"millicharged"

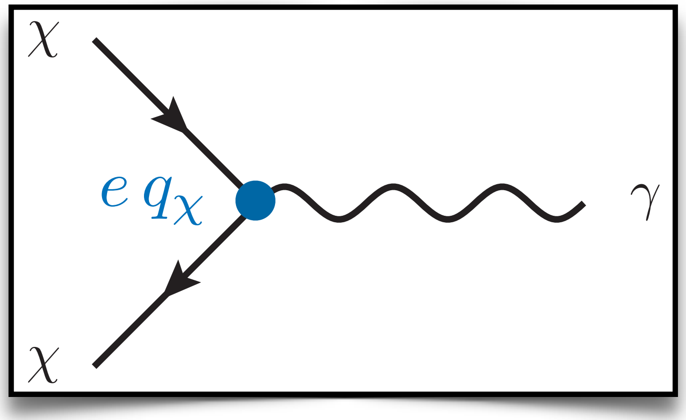
How is this cosmologically viable/motivated?

"freeze-in"

- produced from interactions with normal matter
- cosmologically viable down to keV-scale masses

Millicharged Dark Matter





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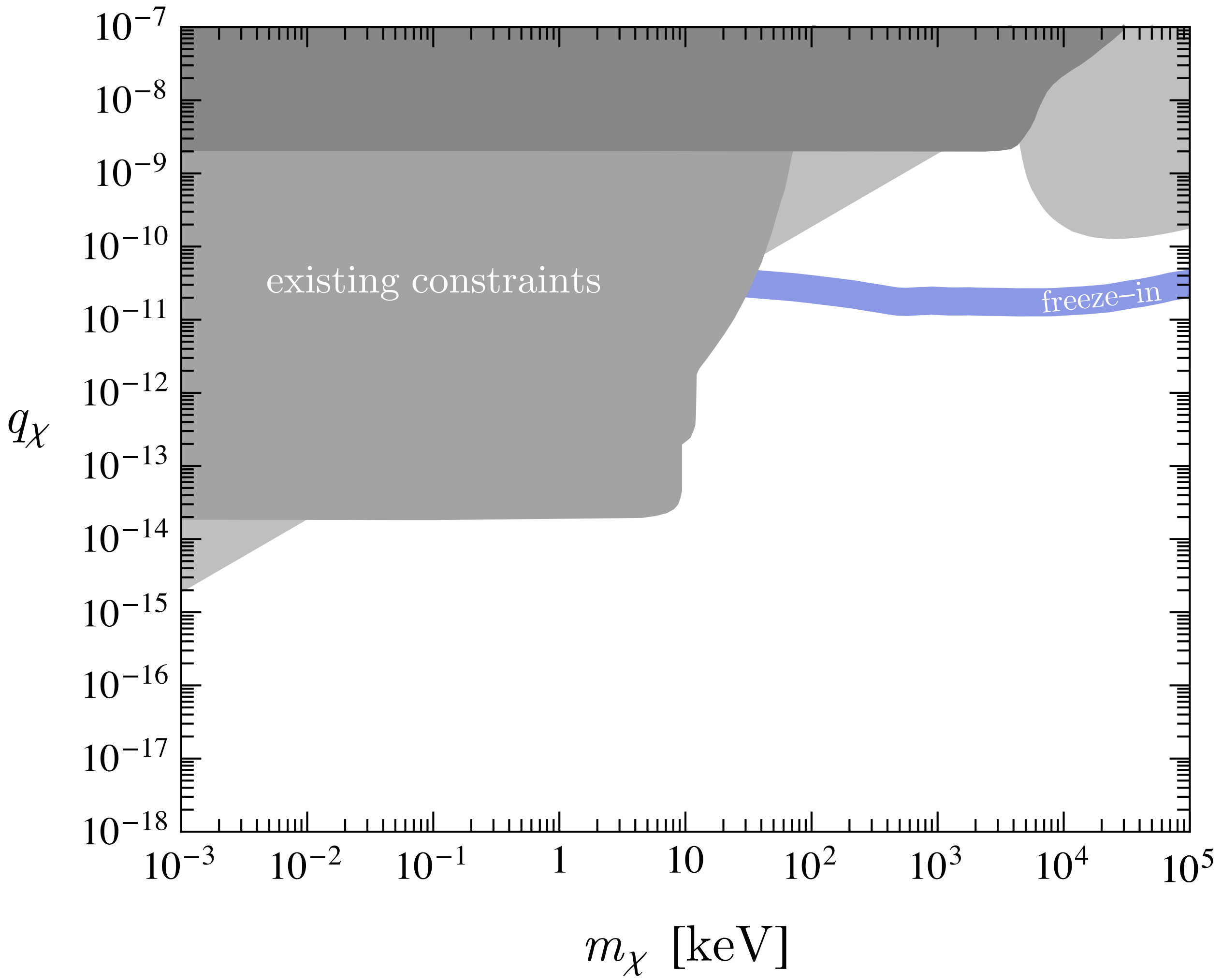

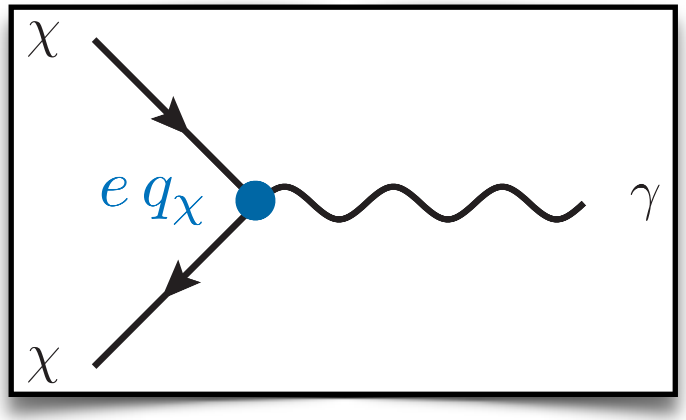

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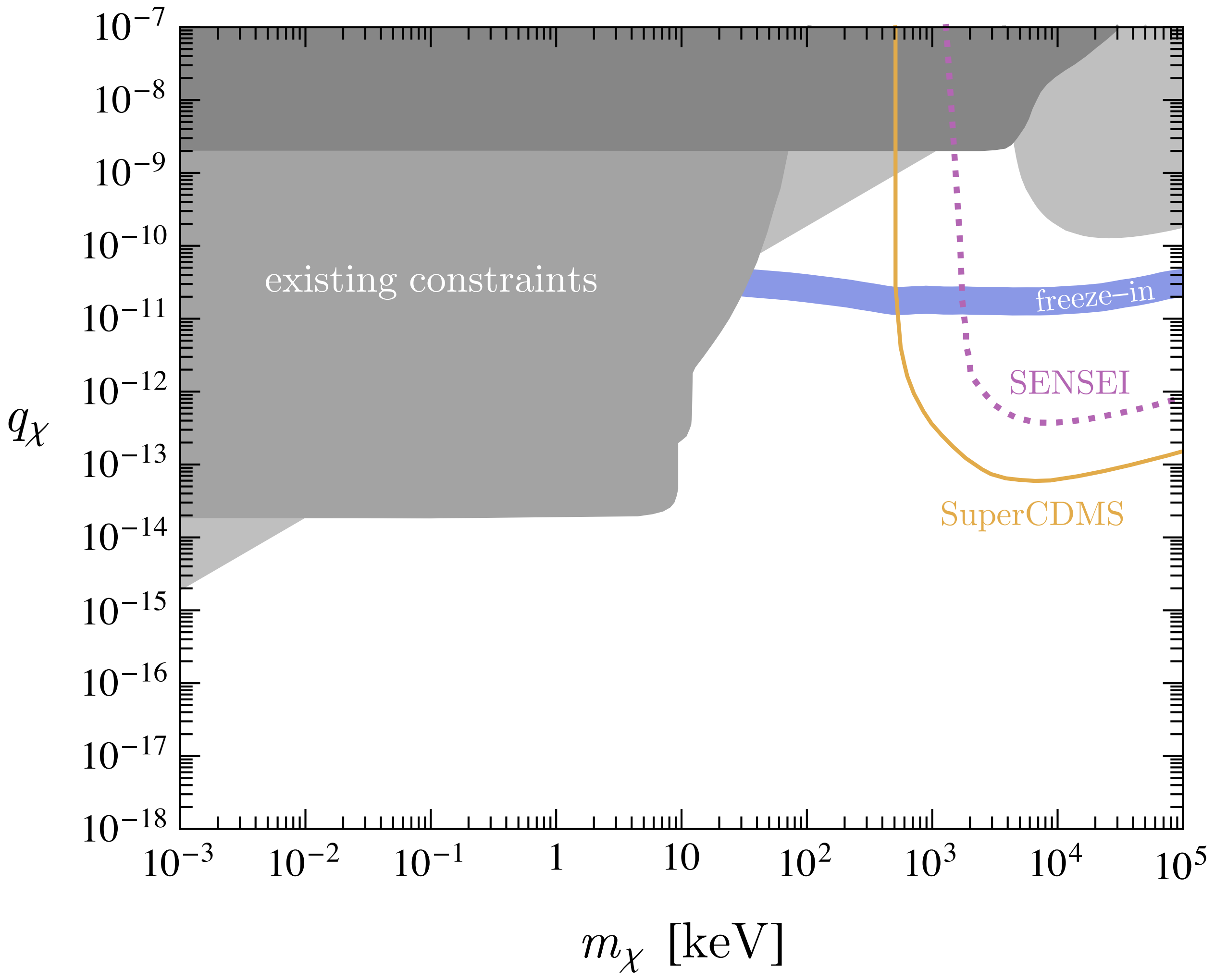
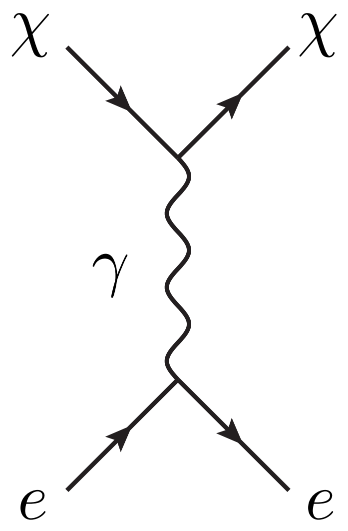


near-future
direct detection



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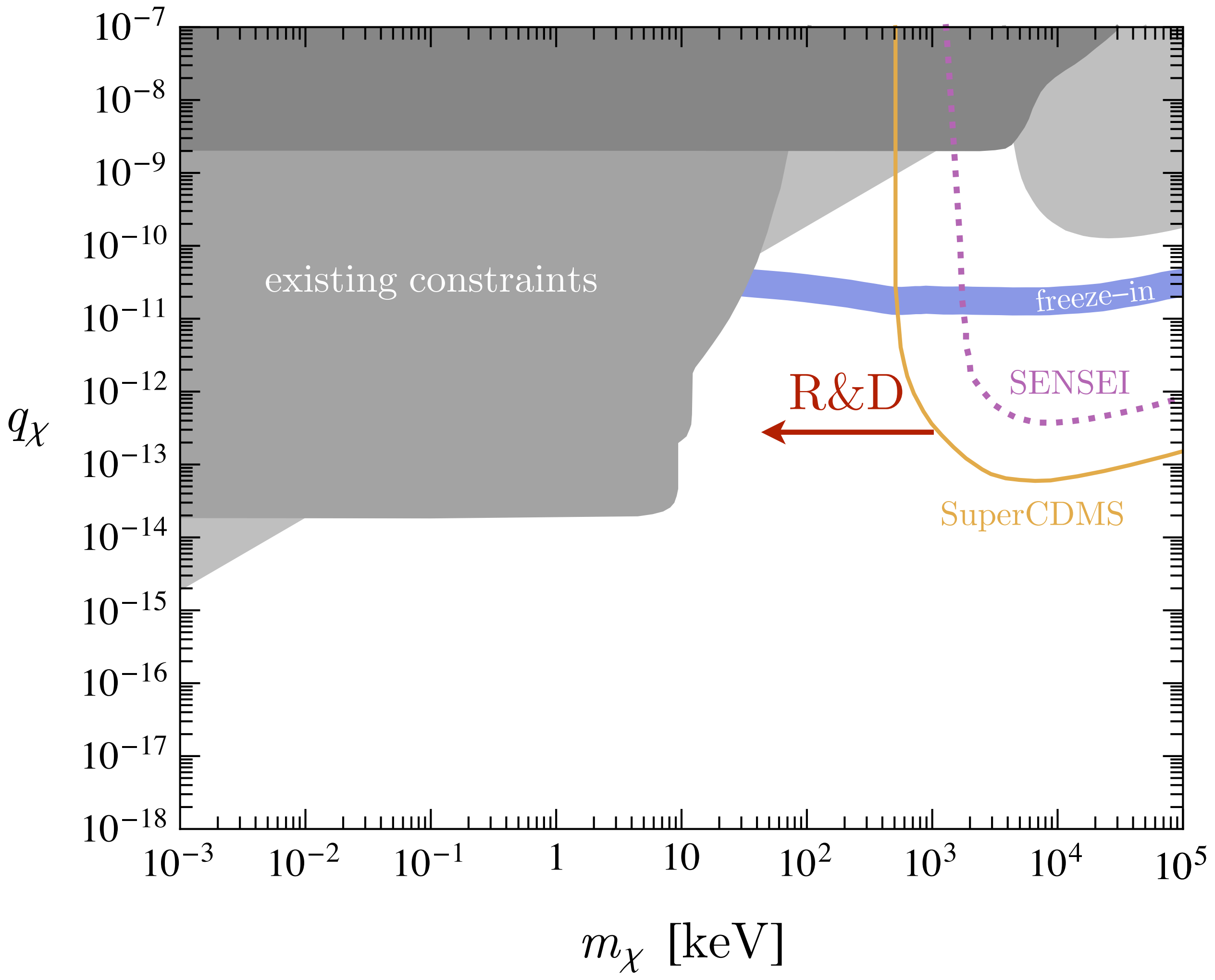

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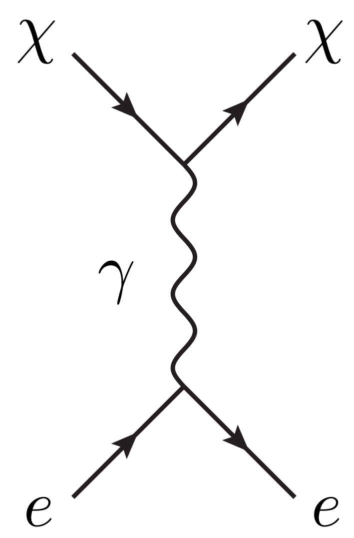
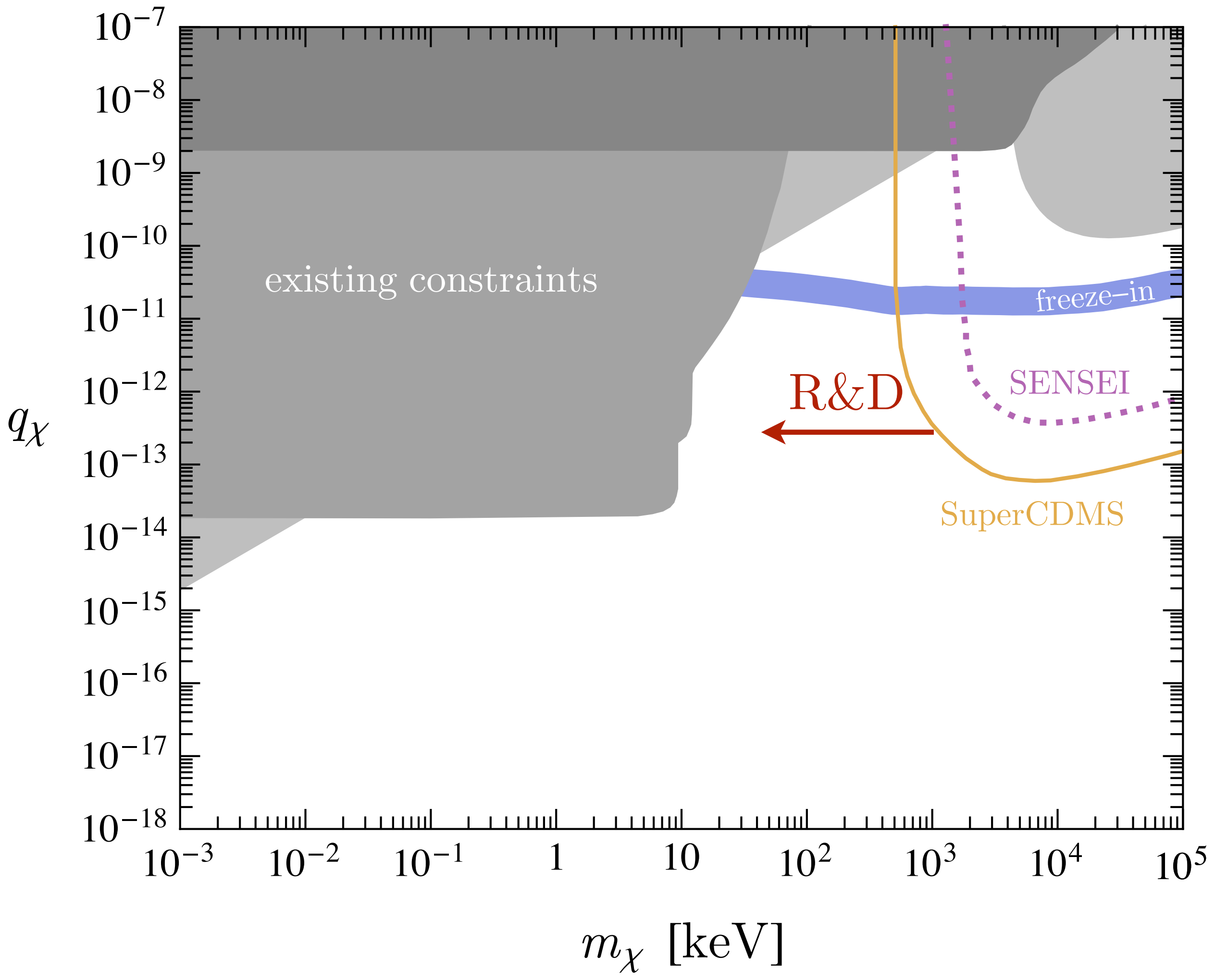


sub-MeV R&D

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

Millicharged Dark Matter



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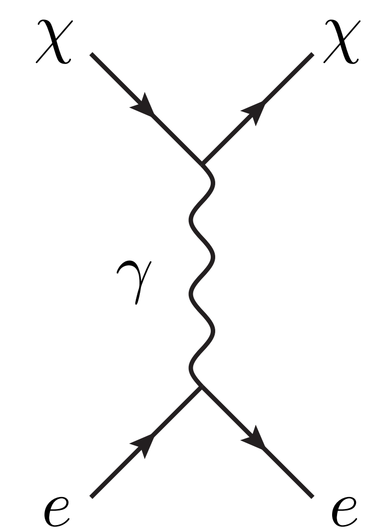


<u>sub-MeV R&D</u>

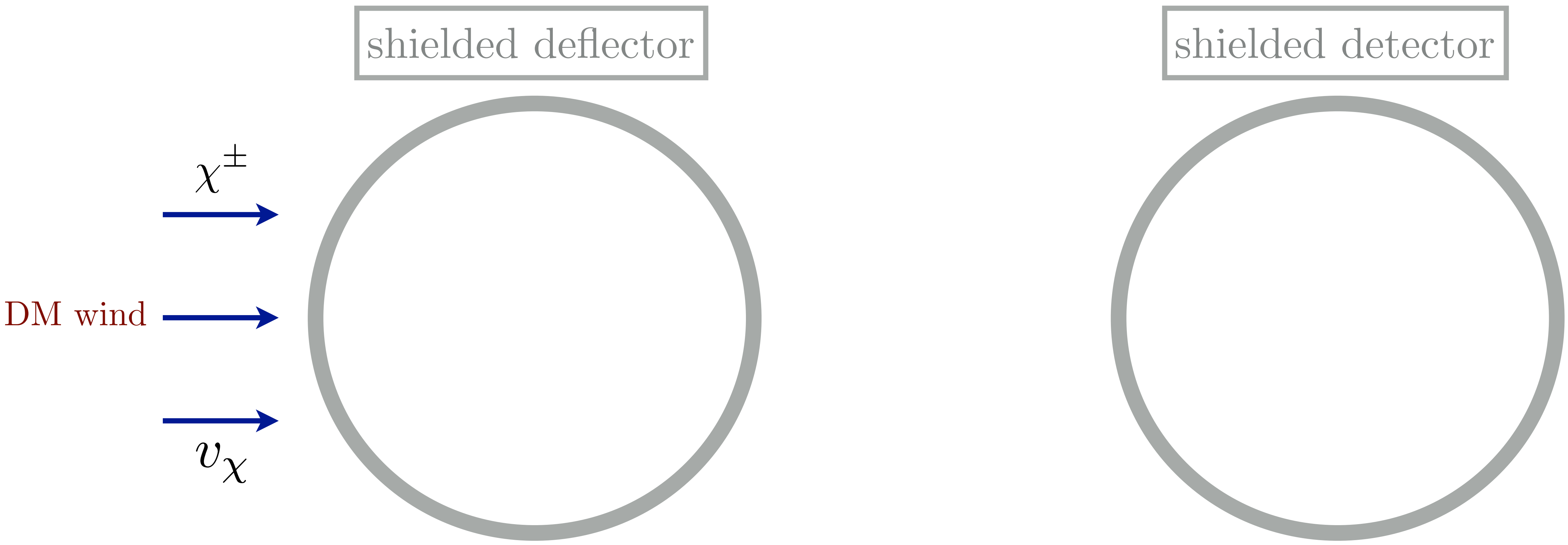
- new scattering targets
- new read-out technologies
- same philosophy

<u>direct *deflection*</u>

instead, take advantage of:

small mass → small momentum → easier to manipulate

Direct *Deflection*



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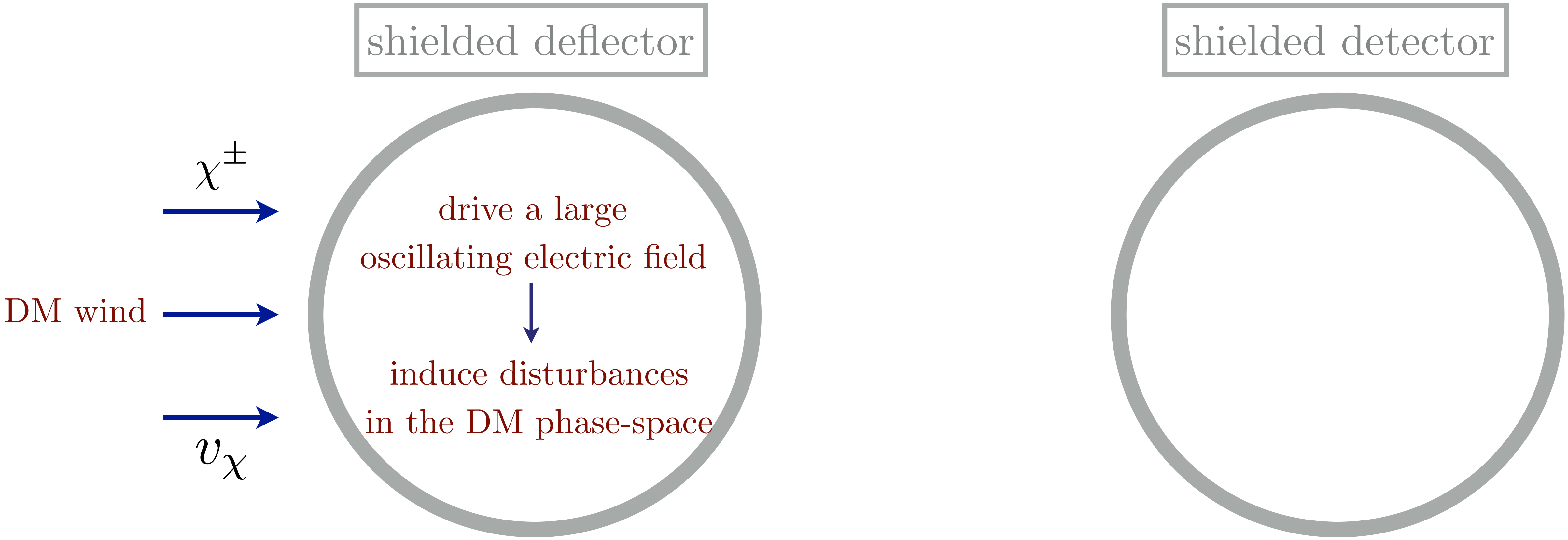

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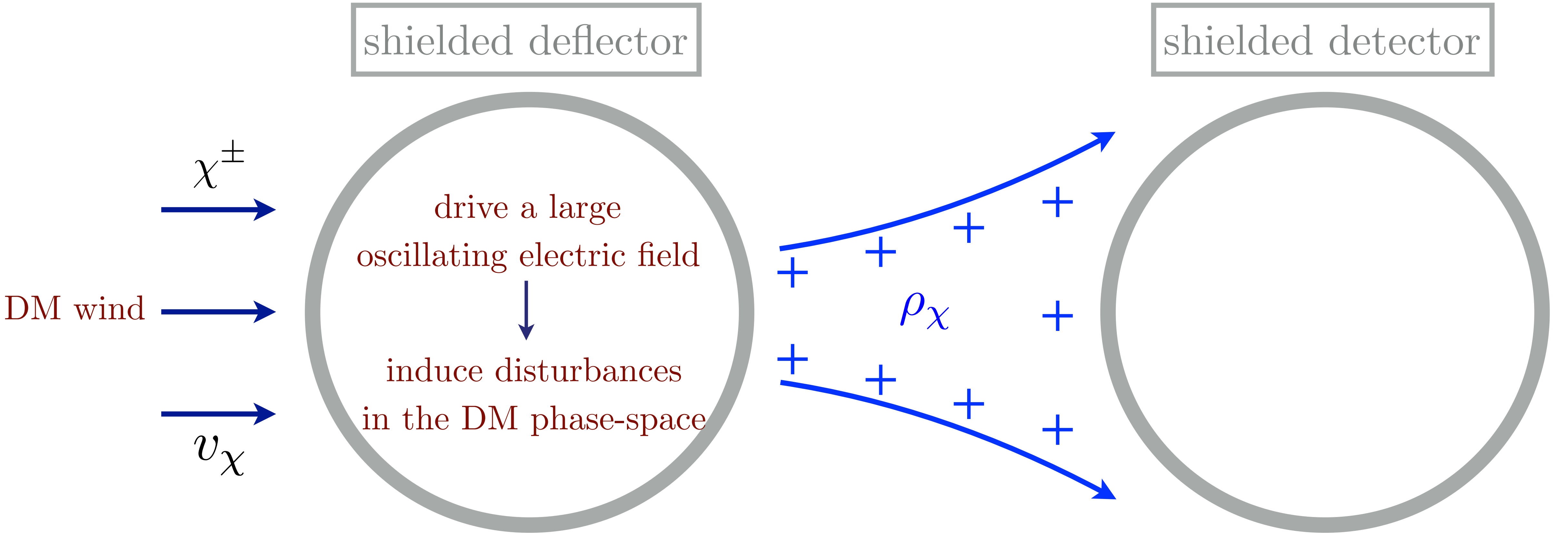

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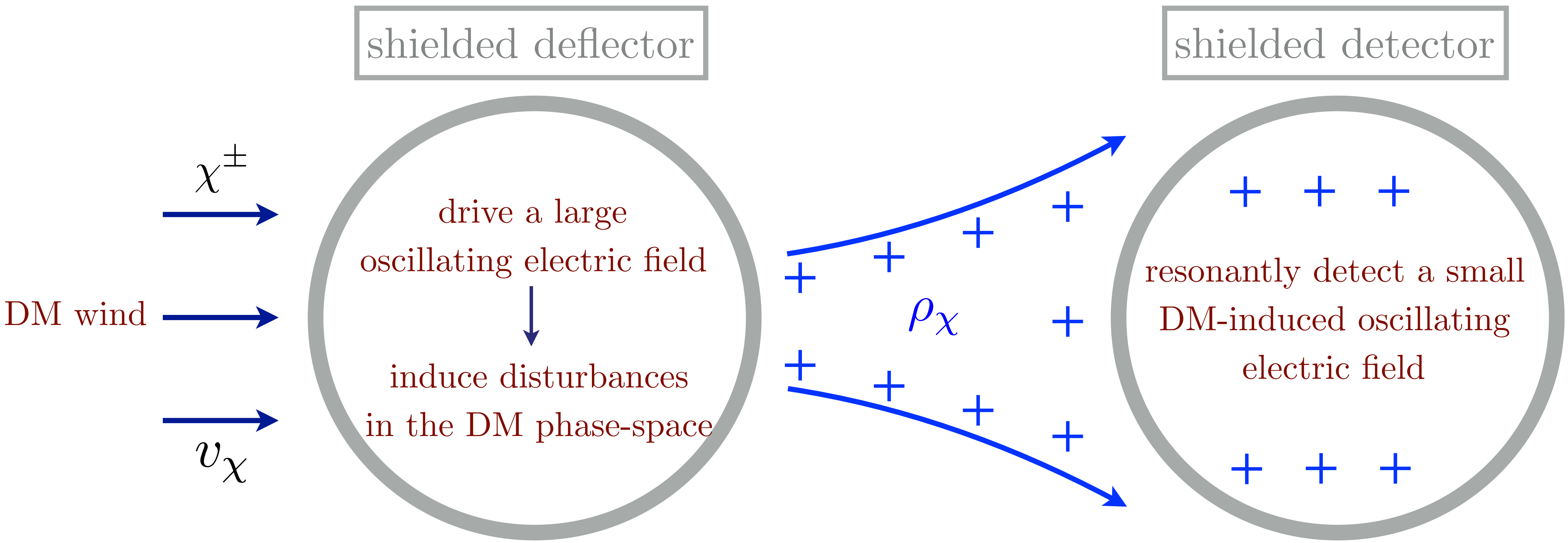

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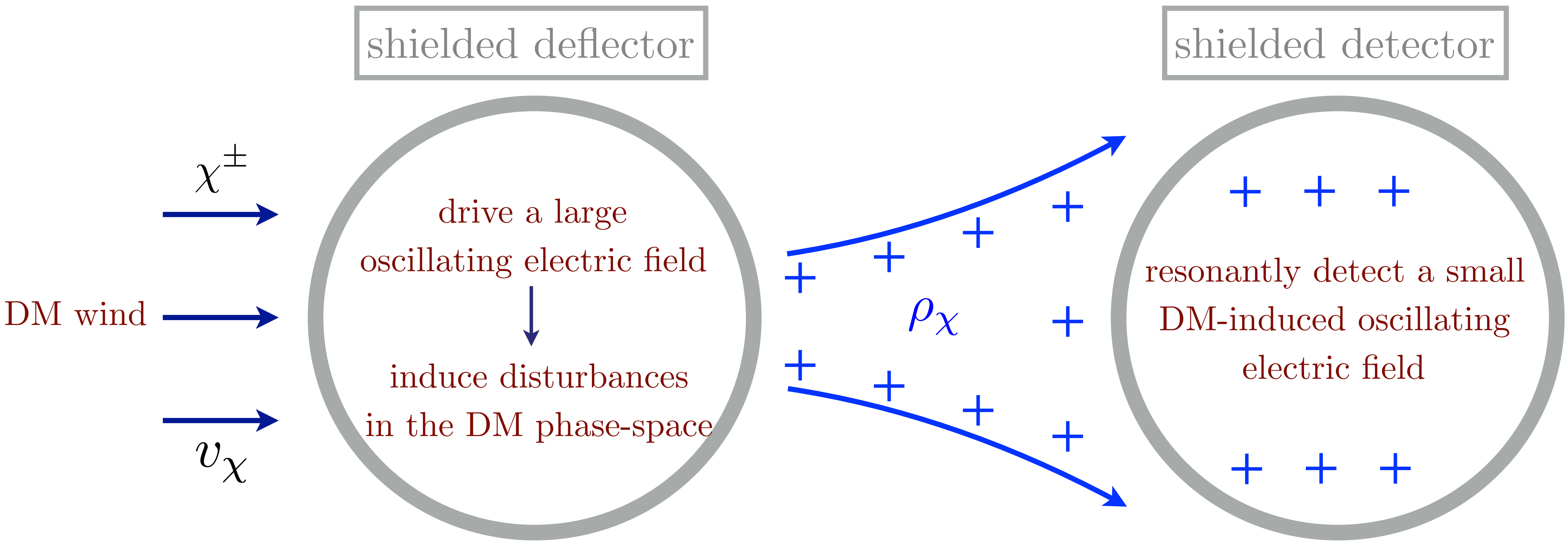
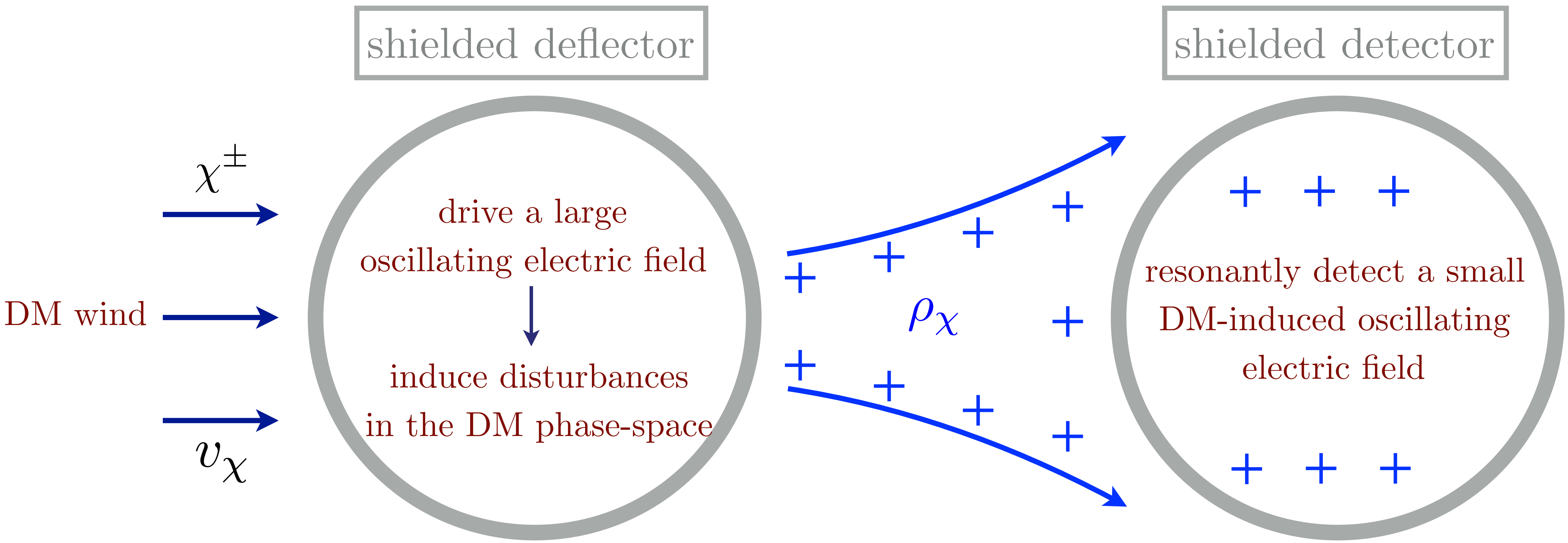


(similar to "~~light-shining~~ *wind-blowing*-through-wall" experiments)

Direct *Deflection*



Goal

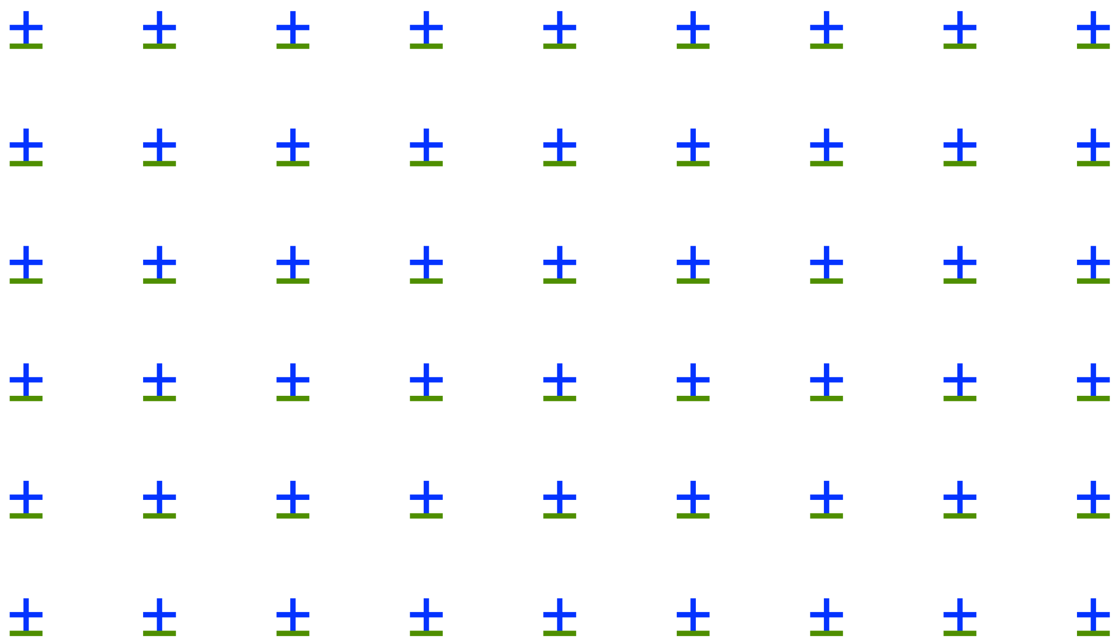
Induce and measure disturbances of the dark matter "fluid," without relying on single-particle scattering.

Advantages

No kinematic barrier at small masses.

Classical collective effects take advantage of the small inertia of the dark matter fluid.

Debye Screening



net-neutral plasma

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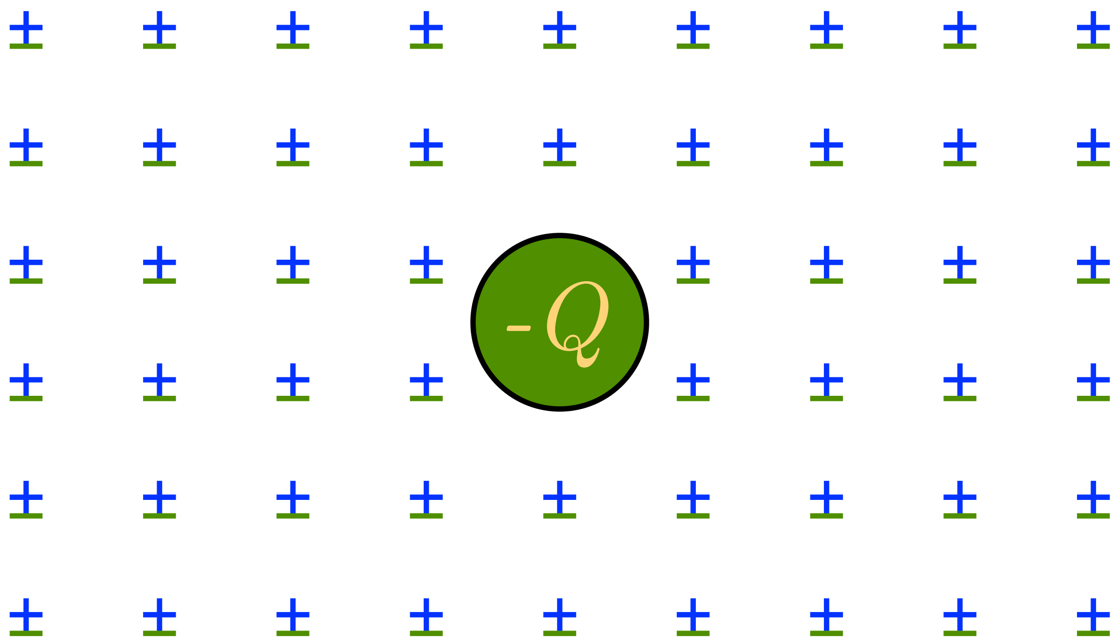

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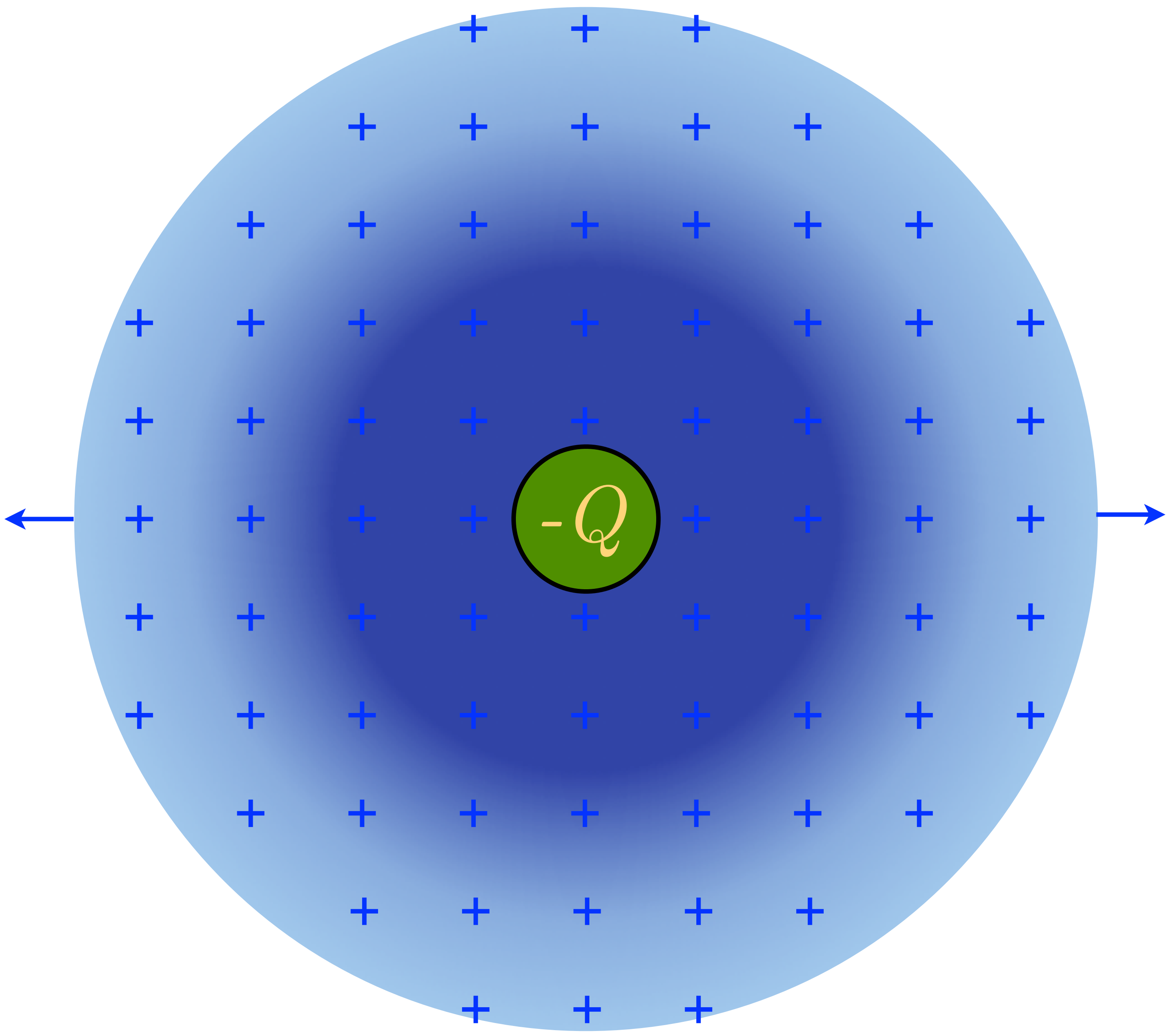
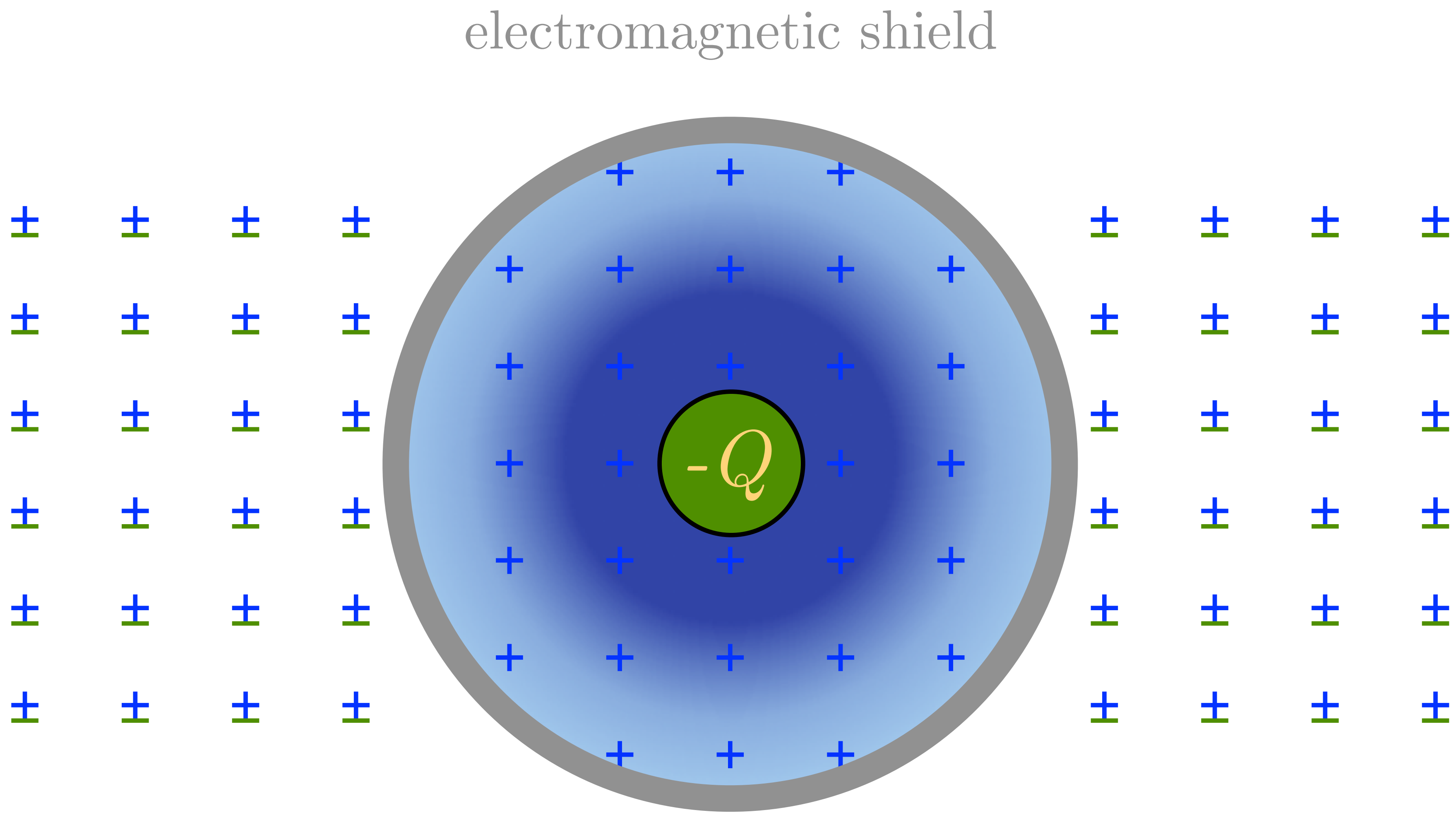


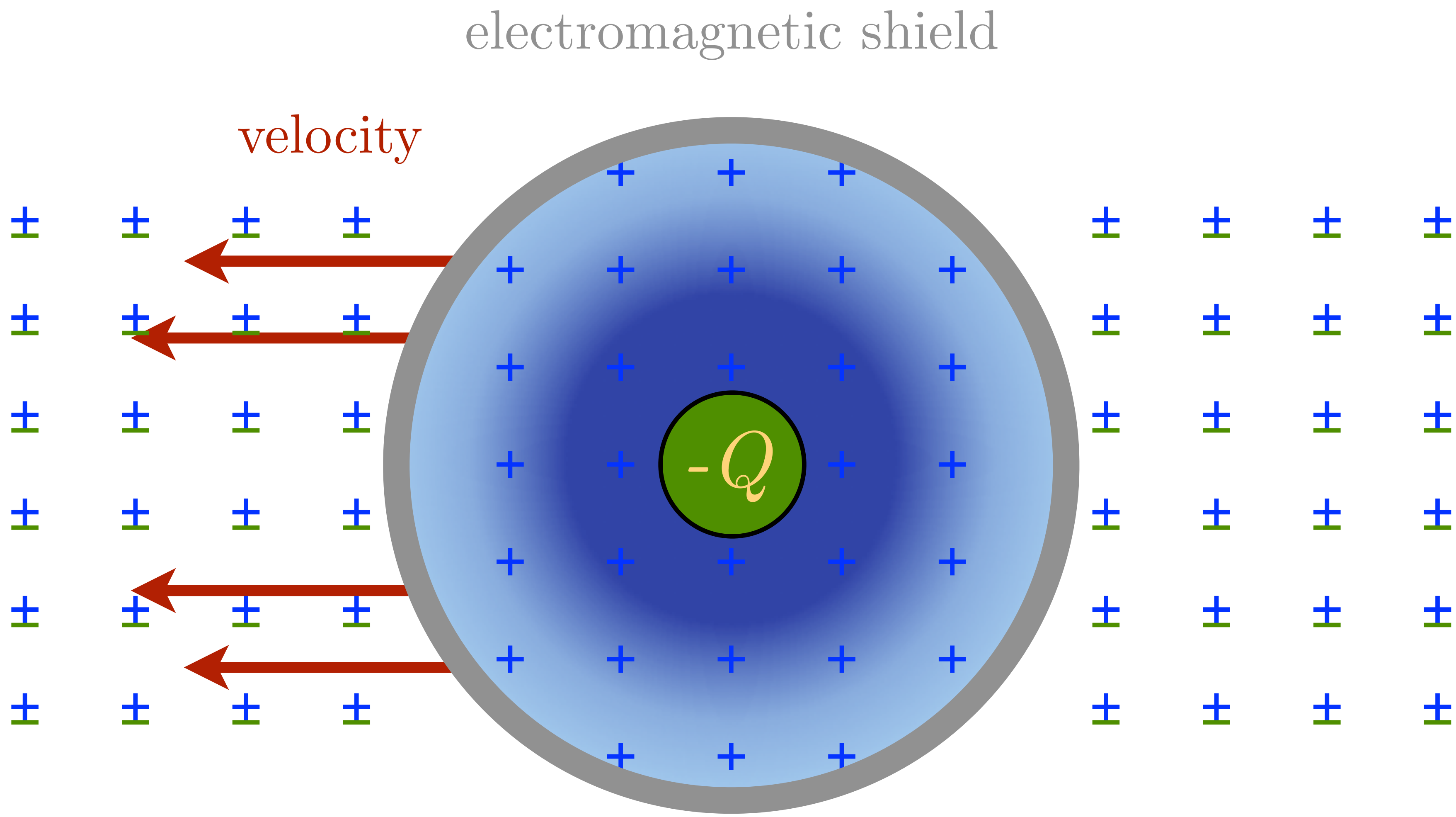
plasma screens test charge

Debye Screening



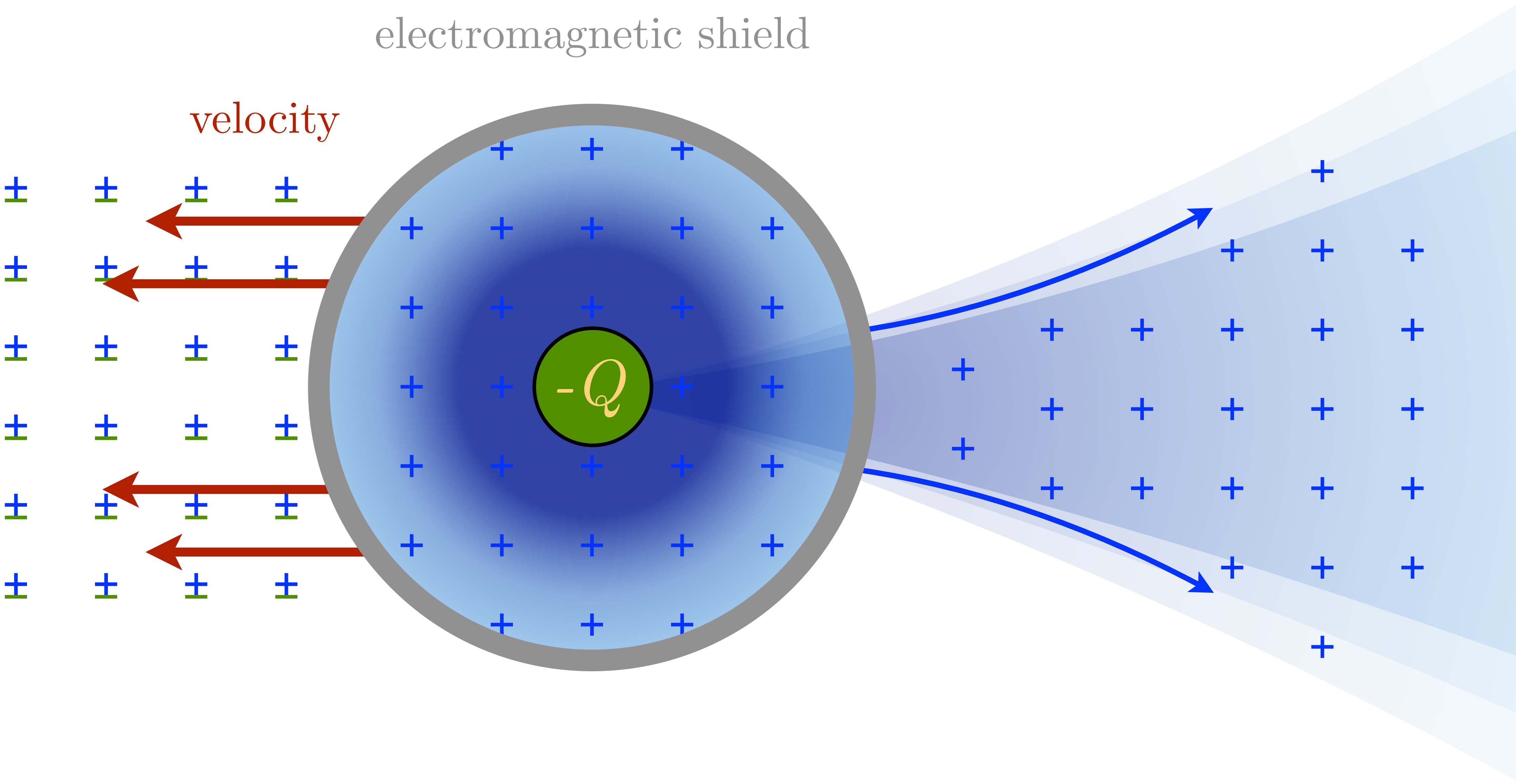
plasma screens interior of shield

Debye Screening



throw the shielded test charge through the plasma

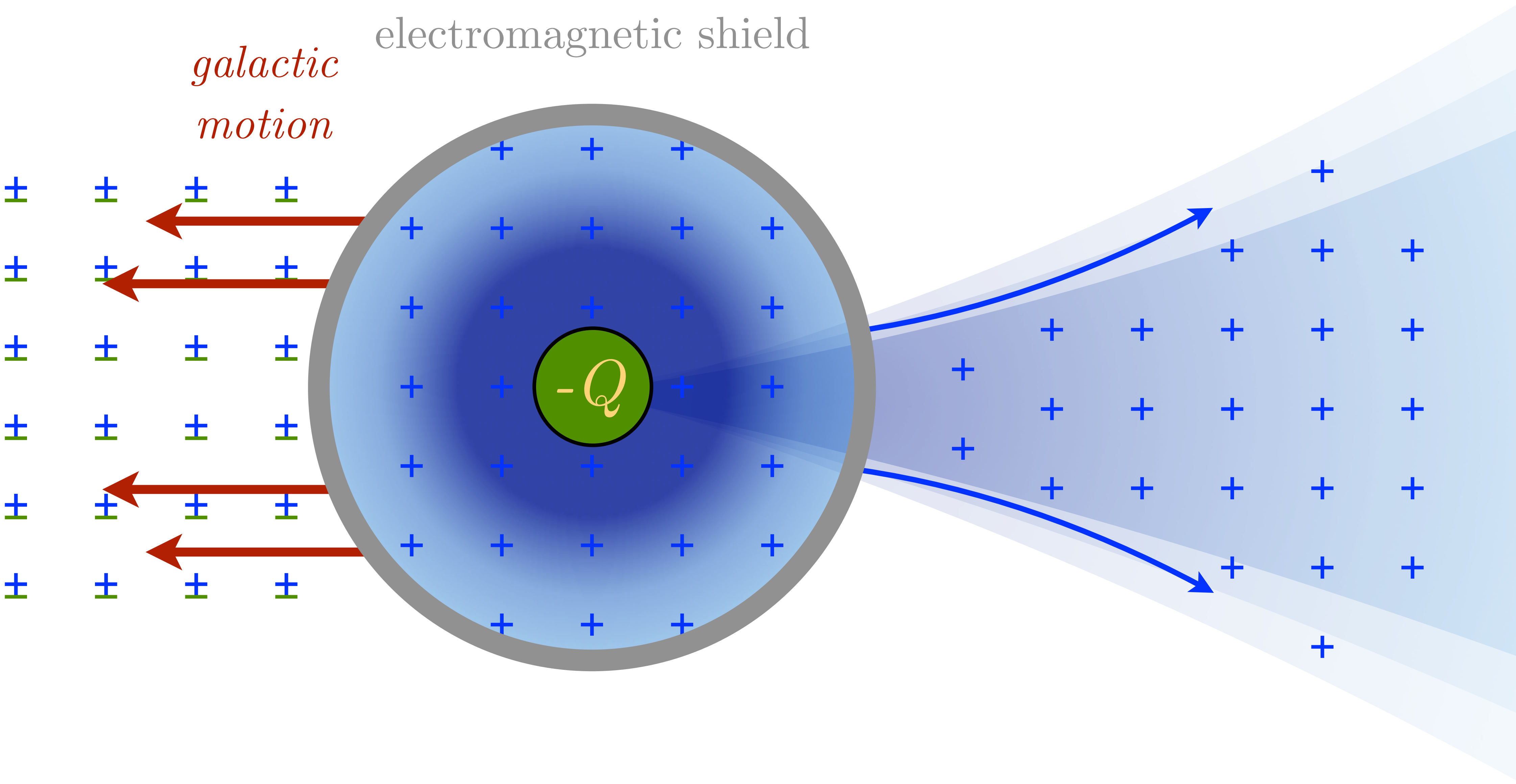
Debye Screening



screening charges leak out

source electric field outside shield

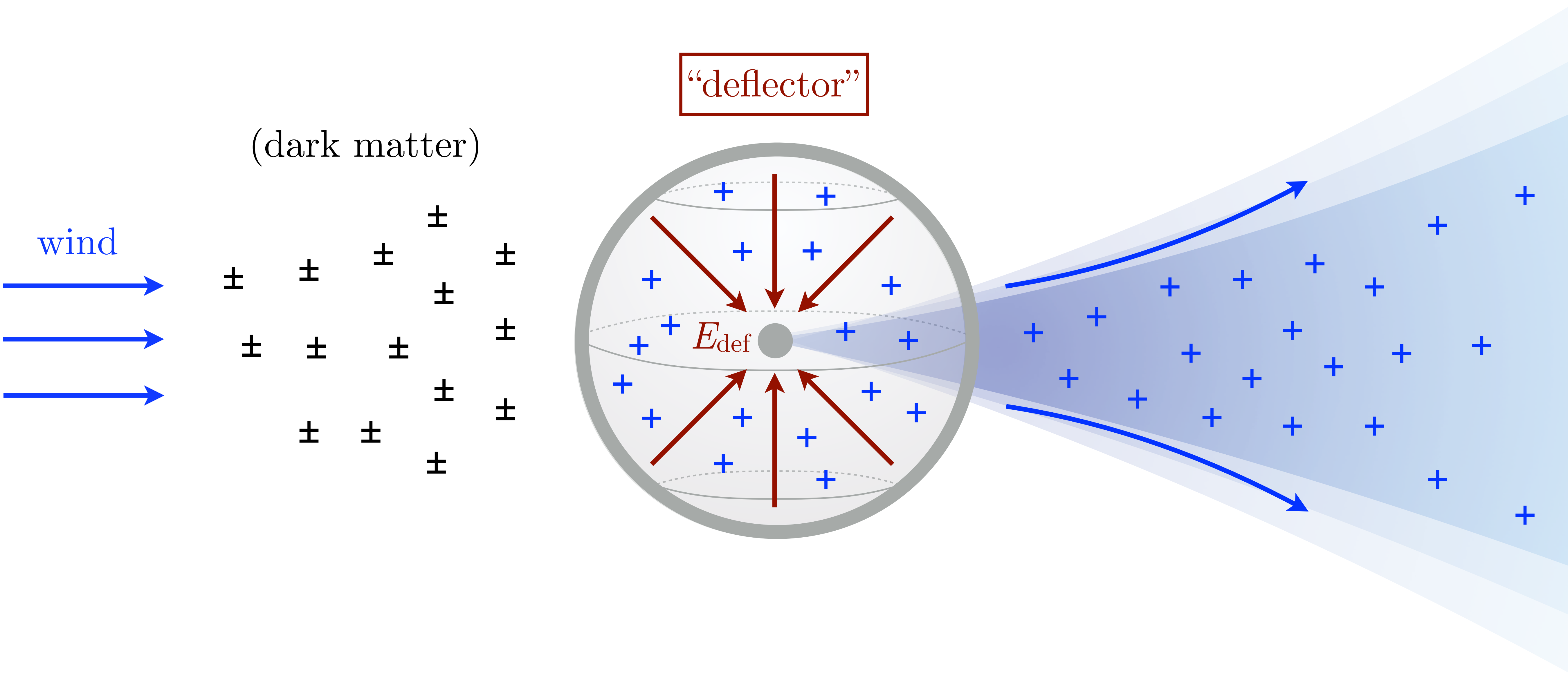
Debye Screening



dark matter charges leak out

(plasma = galactic dark matter)

Debye Screening



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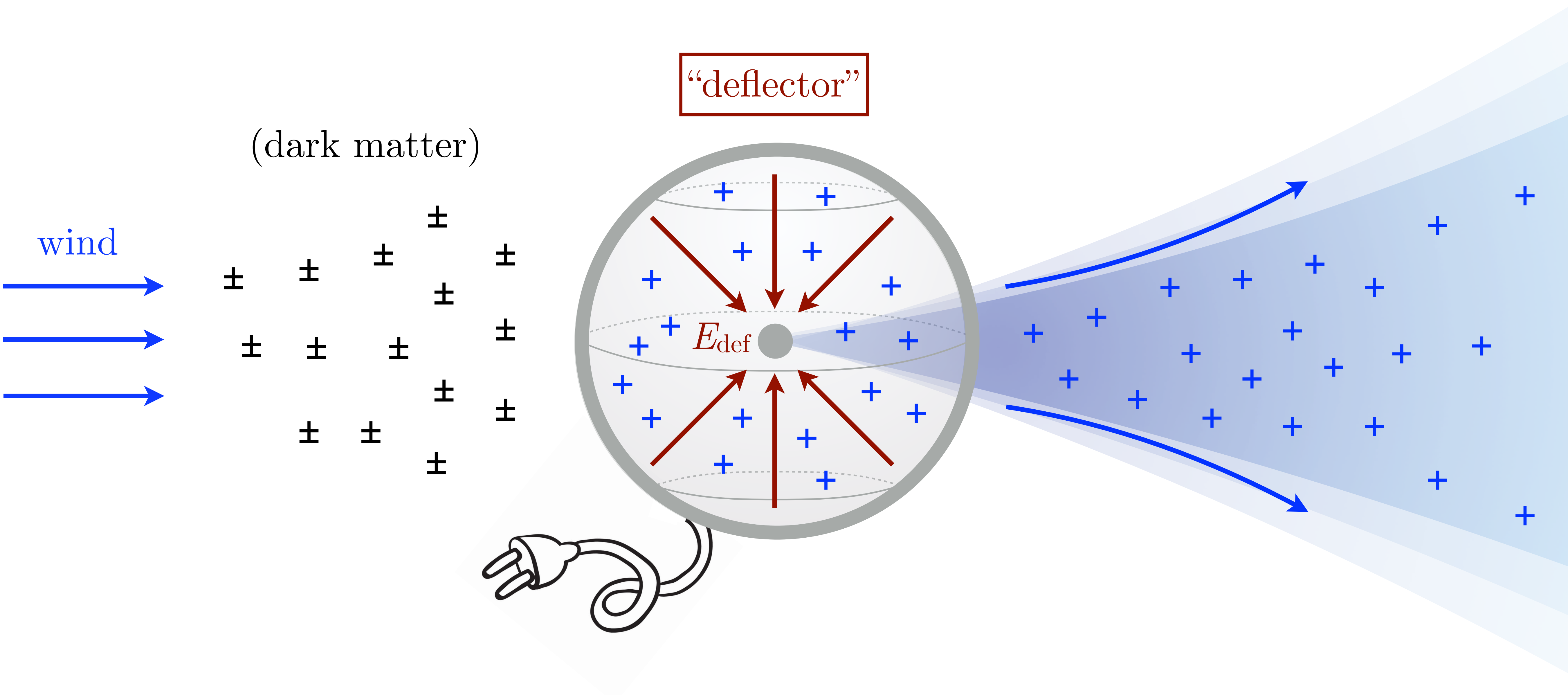

$$E_{\rm def} \to E_{\rm def}\, e^{i\omega t} \implies \rho_\chi \to \rho_\chi\, e^{i\omega t}$$

allows for resonant detection

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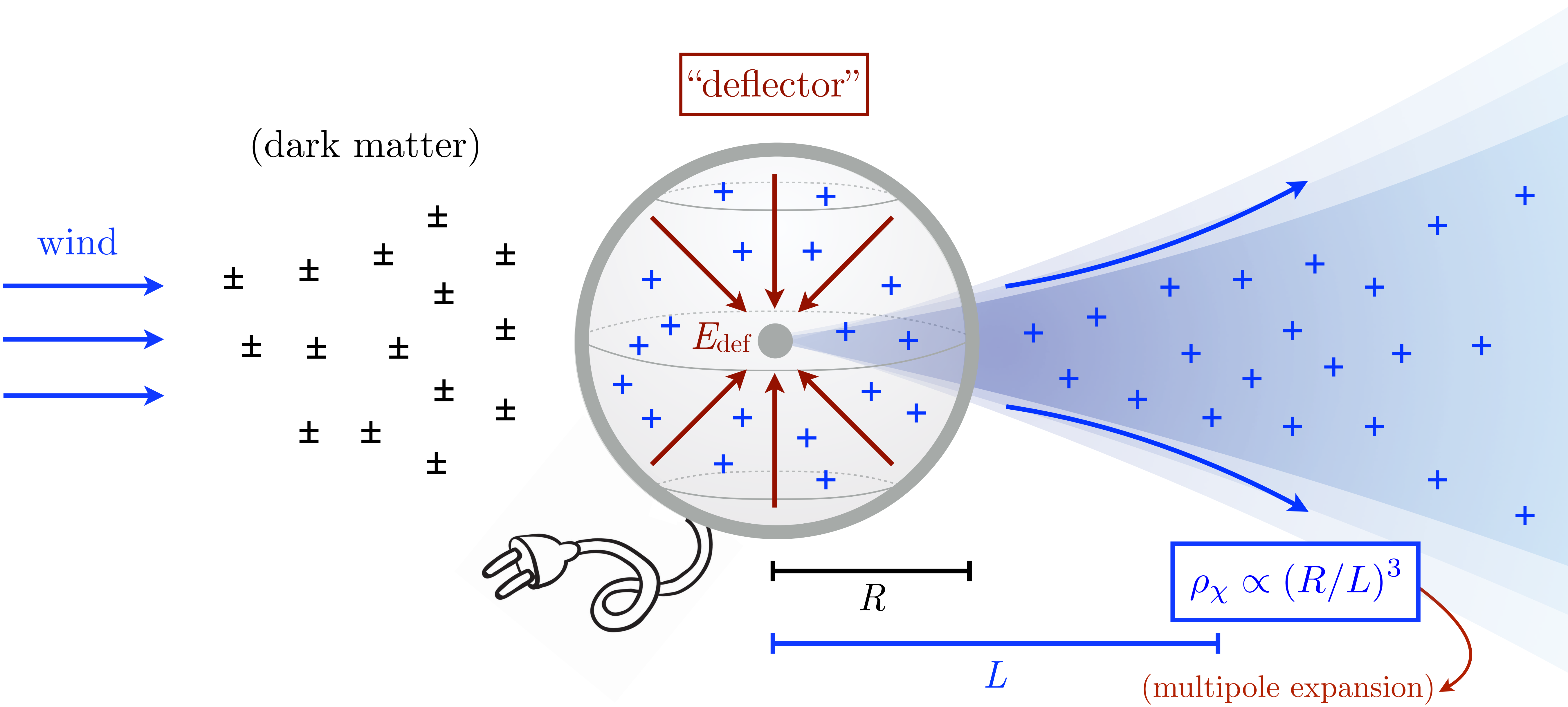

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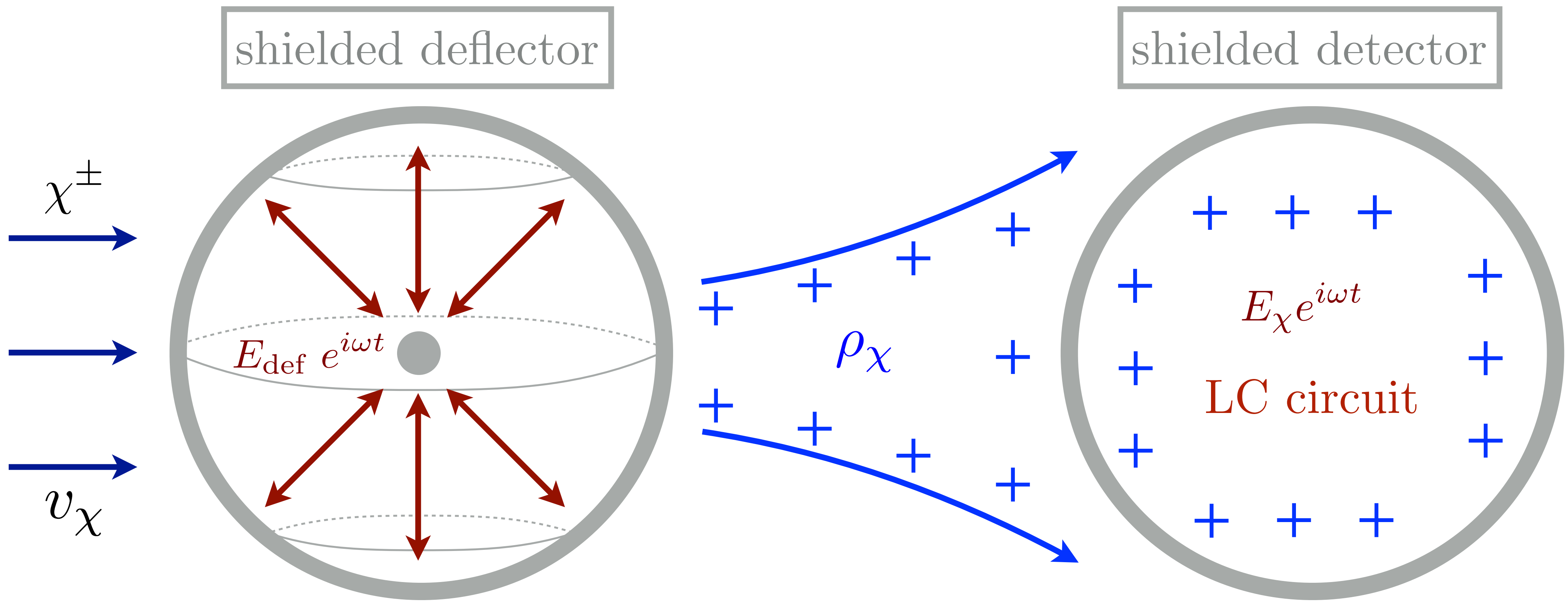
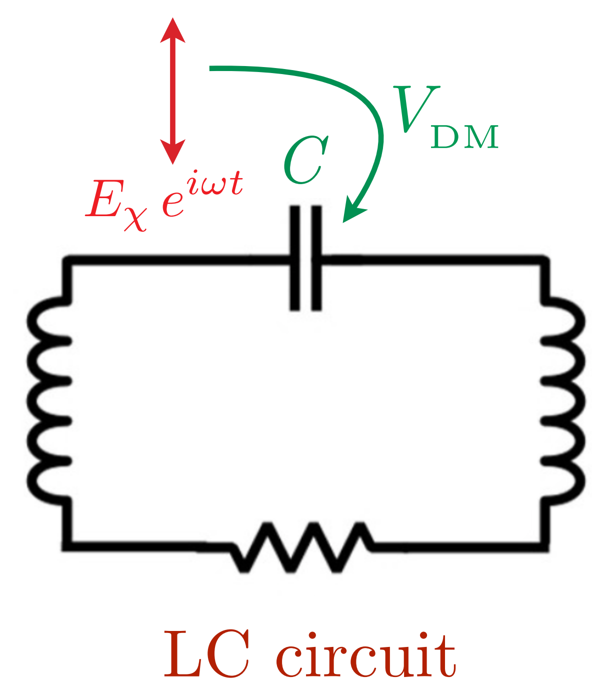
Direct *Deflection*





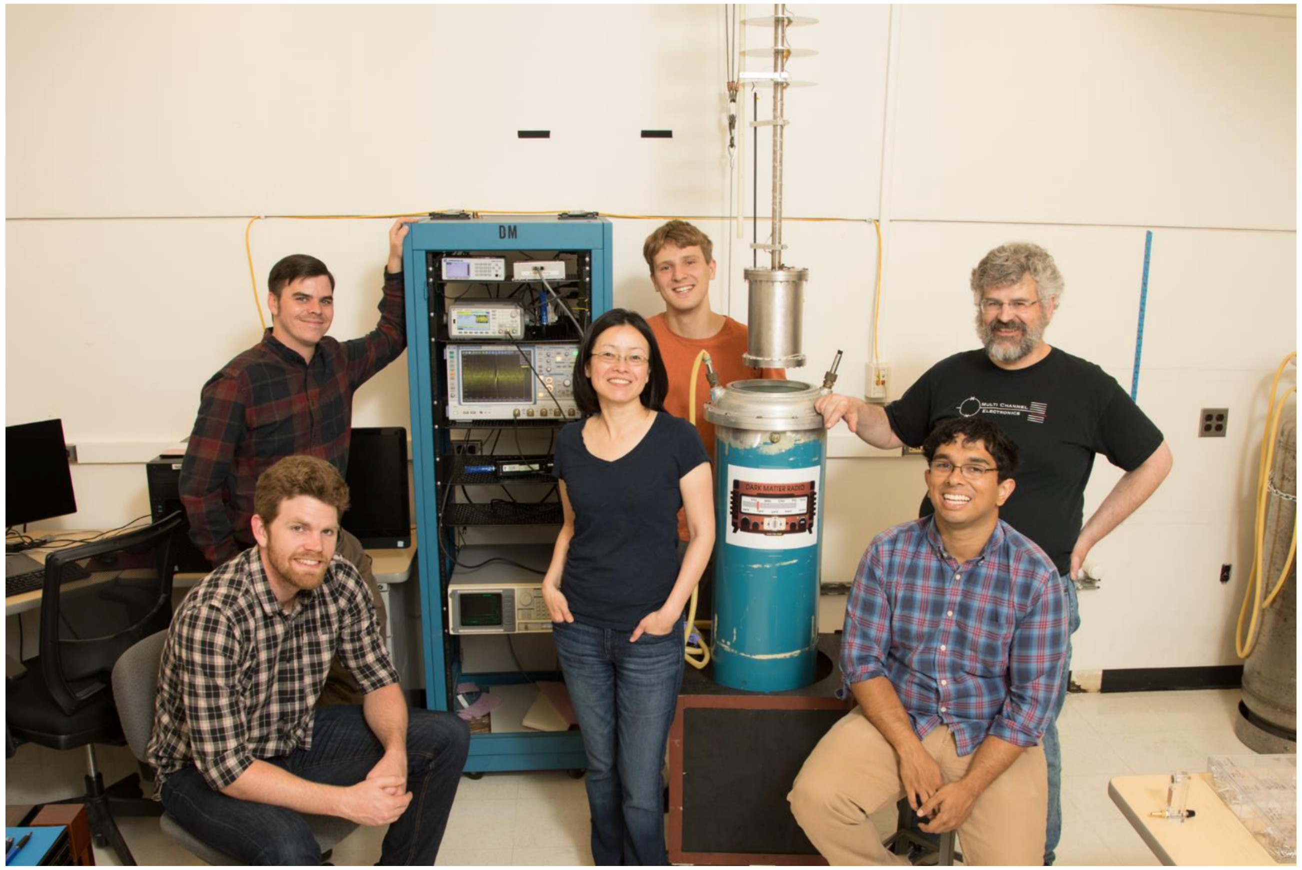
$\omega_{\rm LC} \simeq \omega \implies E_{\rm sig} \sim Q\, E_\chi$

high-Q radio = DM Radio, Auriga

LC Resonators

Auriga
(gravity waves)

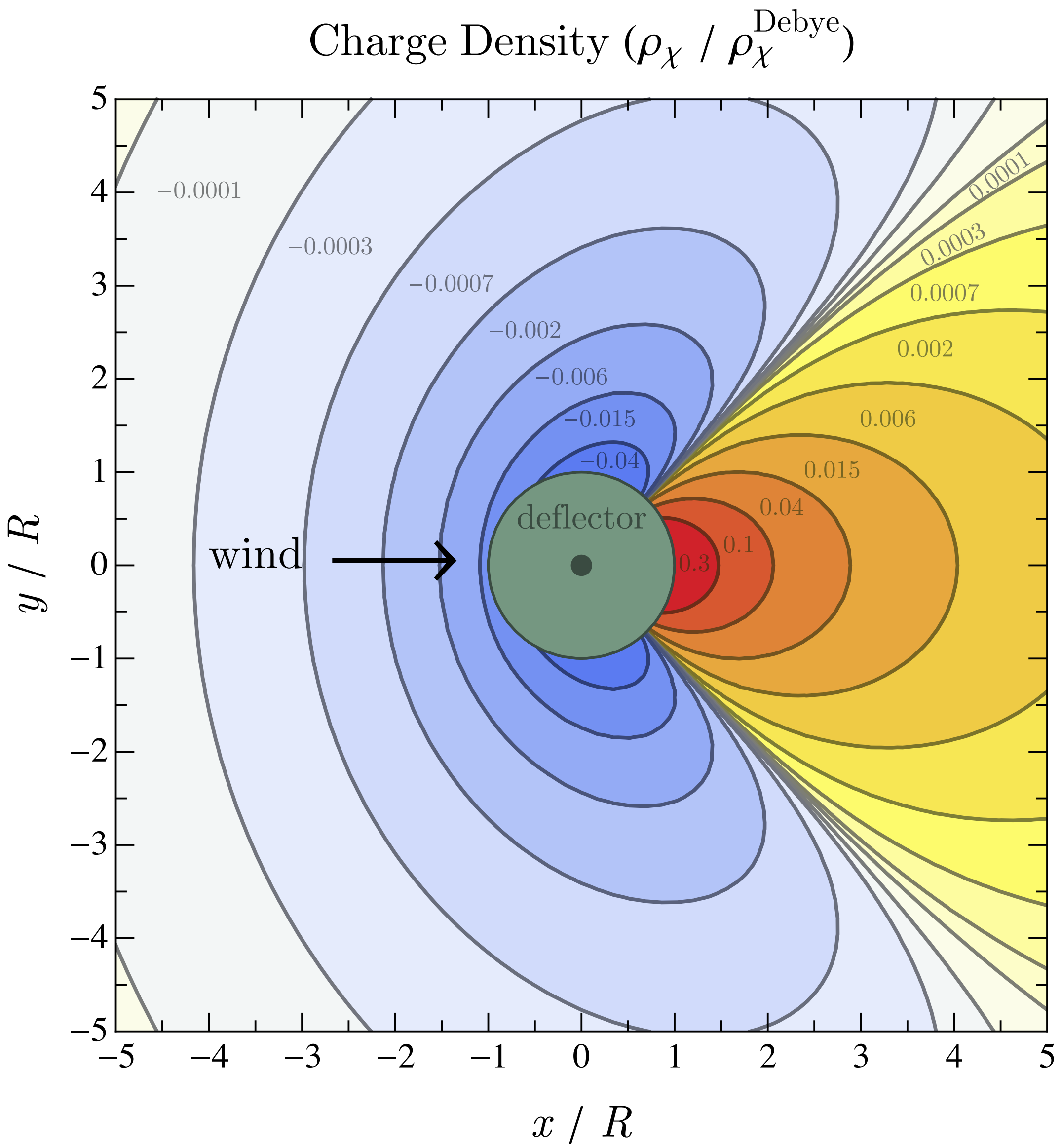
DM Radio
(effective currents via ultralight DM)



resolve thermal noise

no need to scan or operate down at kHz frequencies $\Longrightarrow Q > 10^6$

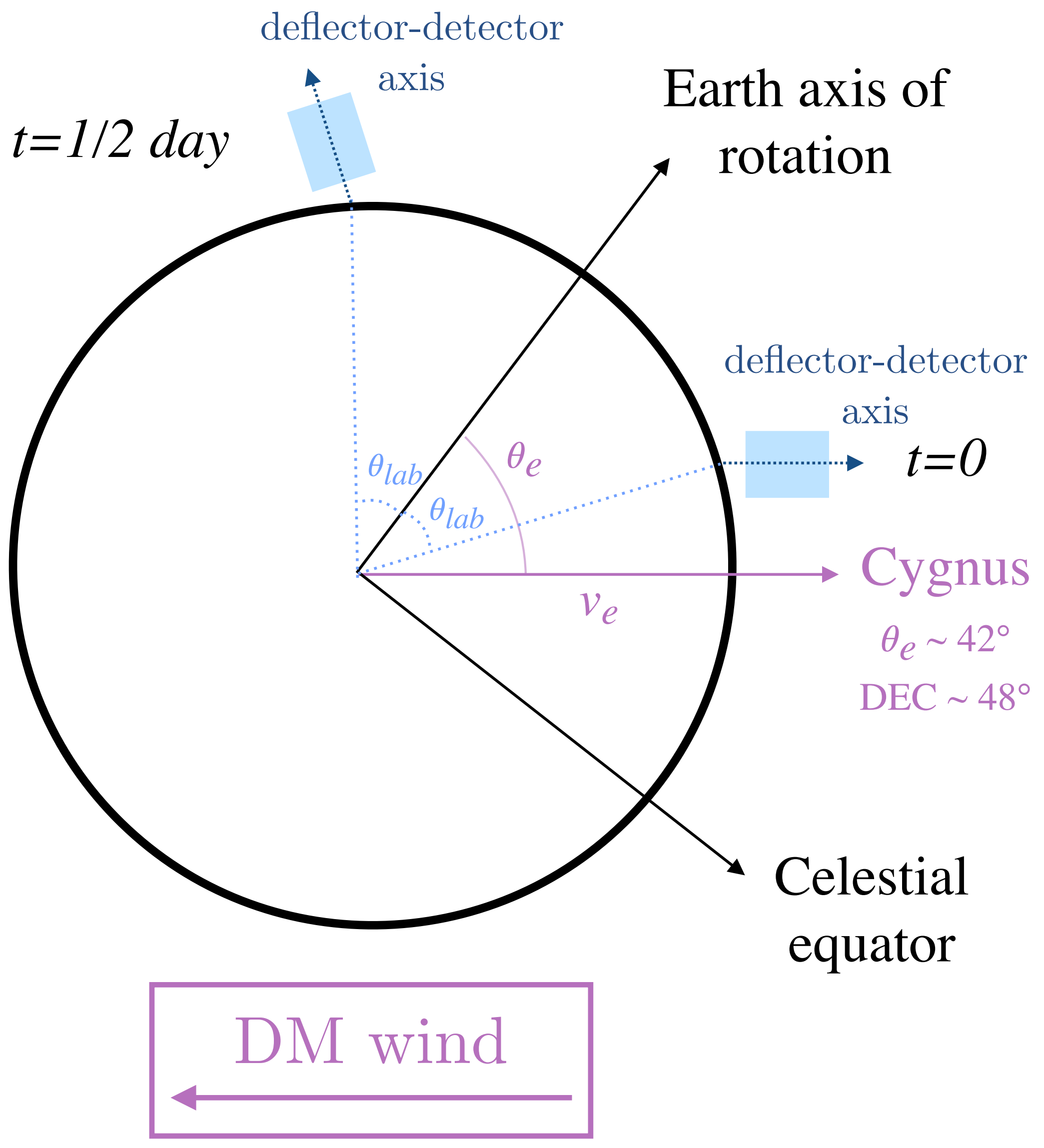
Directional Dependence



strong directional/daily dependence

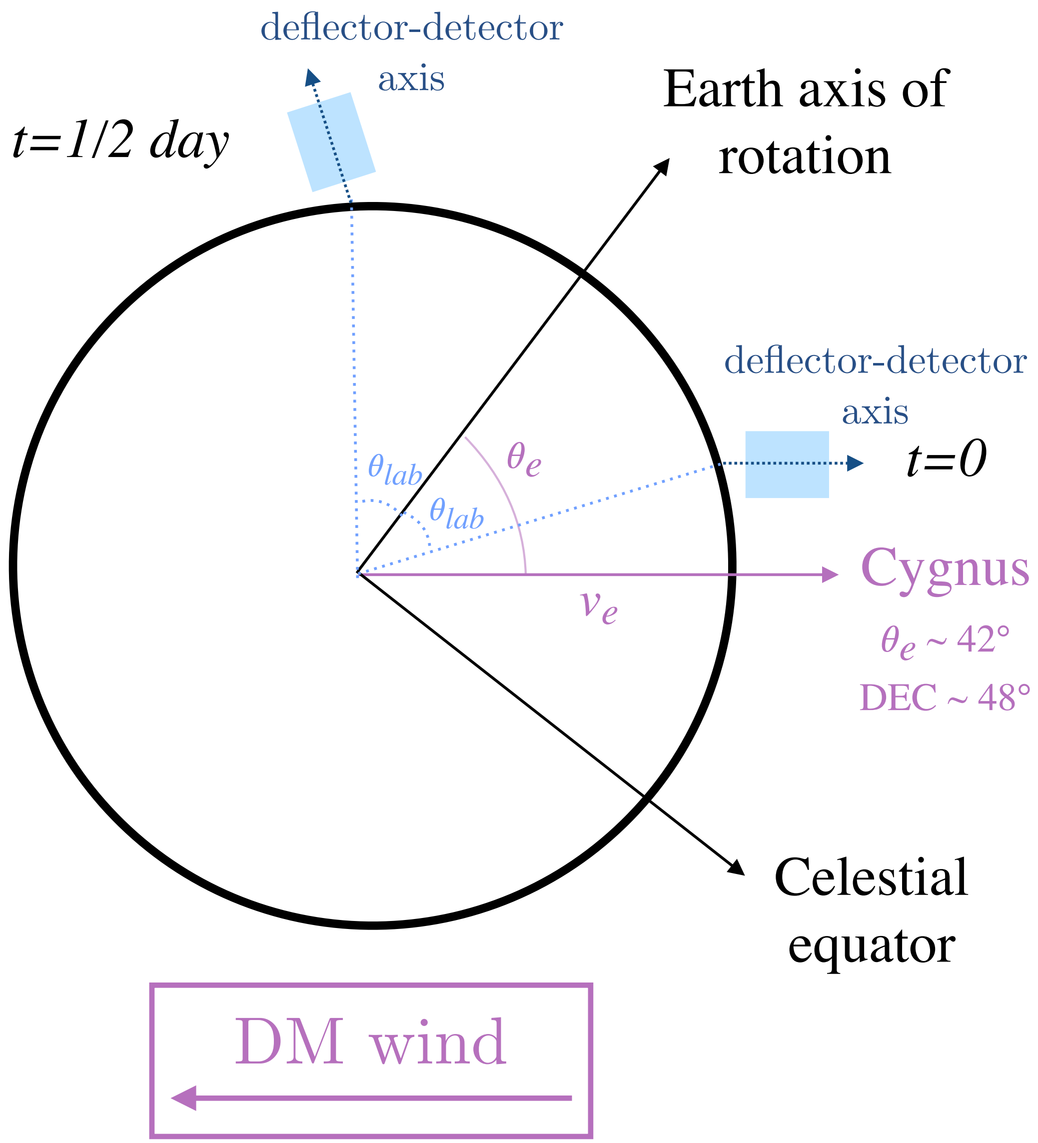
Daily Modulation

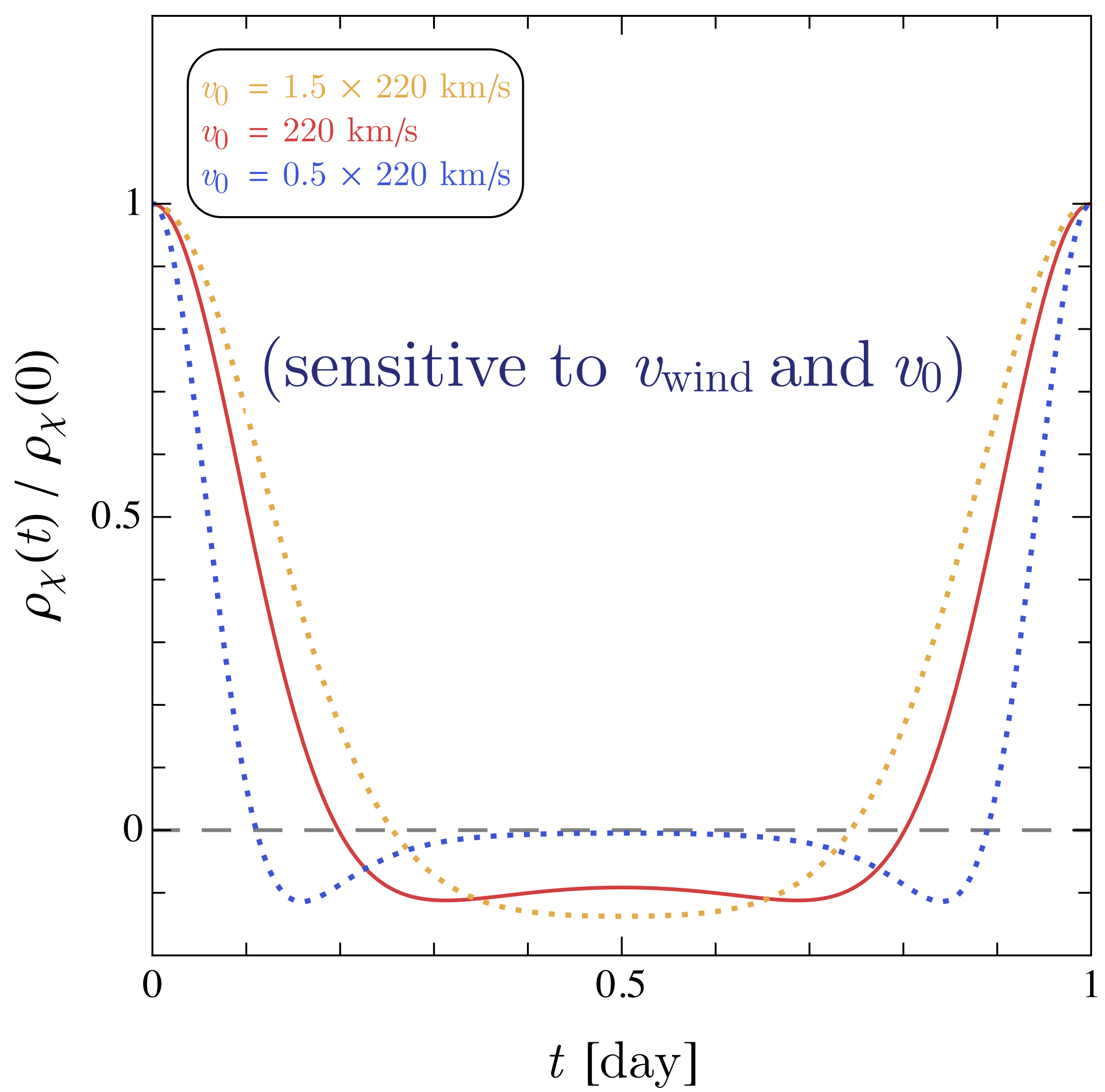
Daily Modulation



arXiv:1807.10291

Daily Modulation





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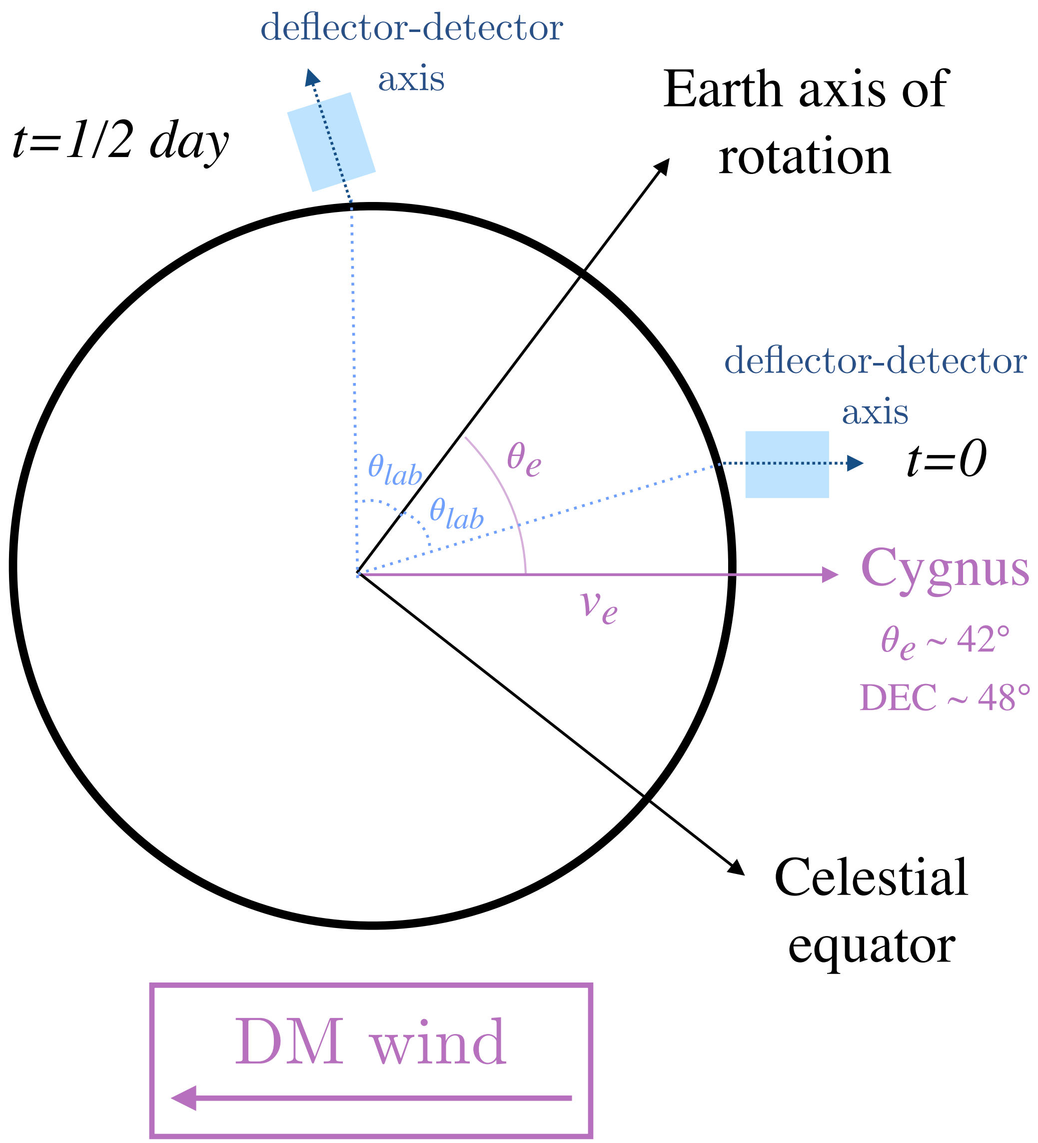
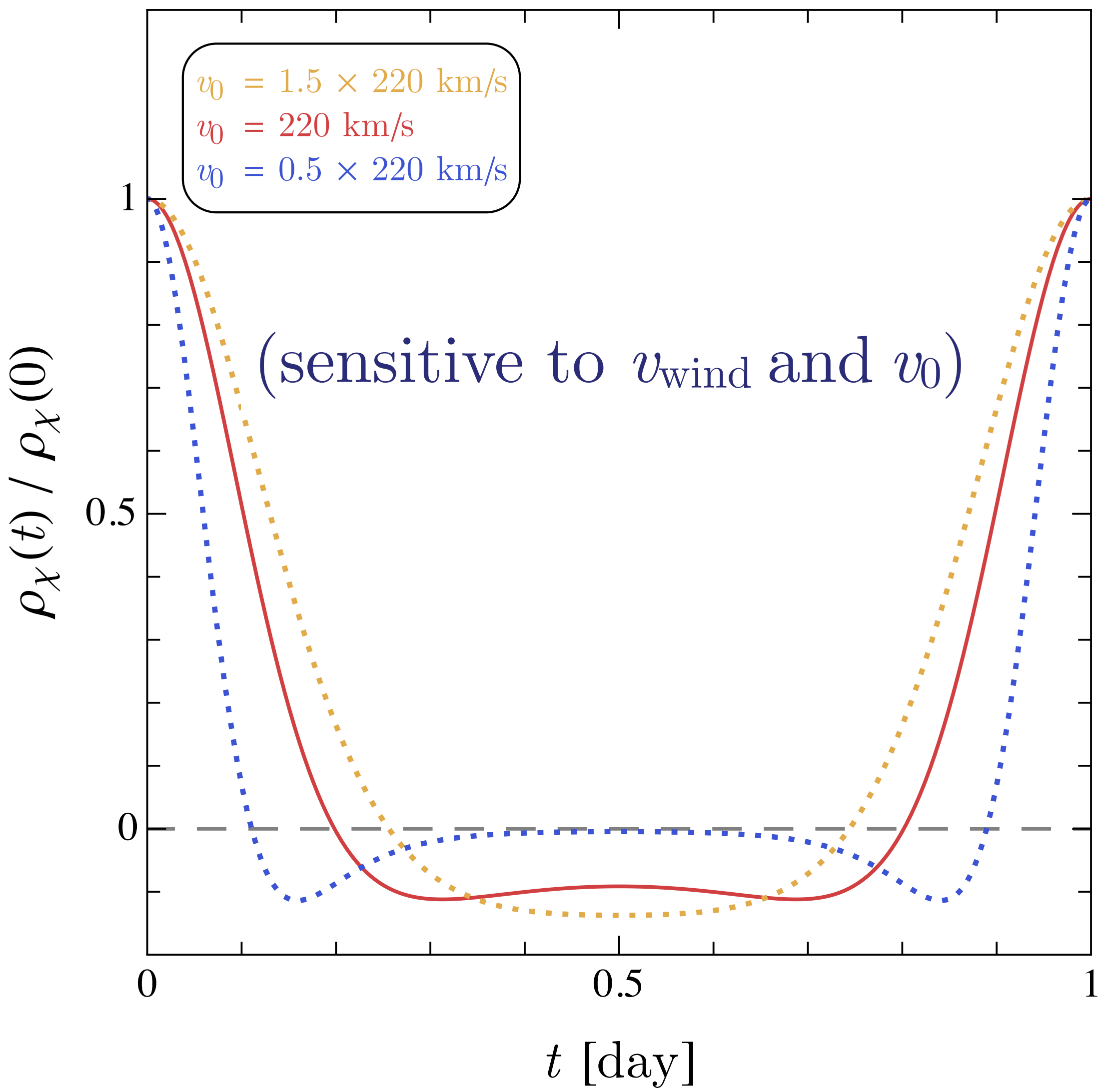




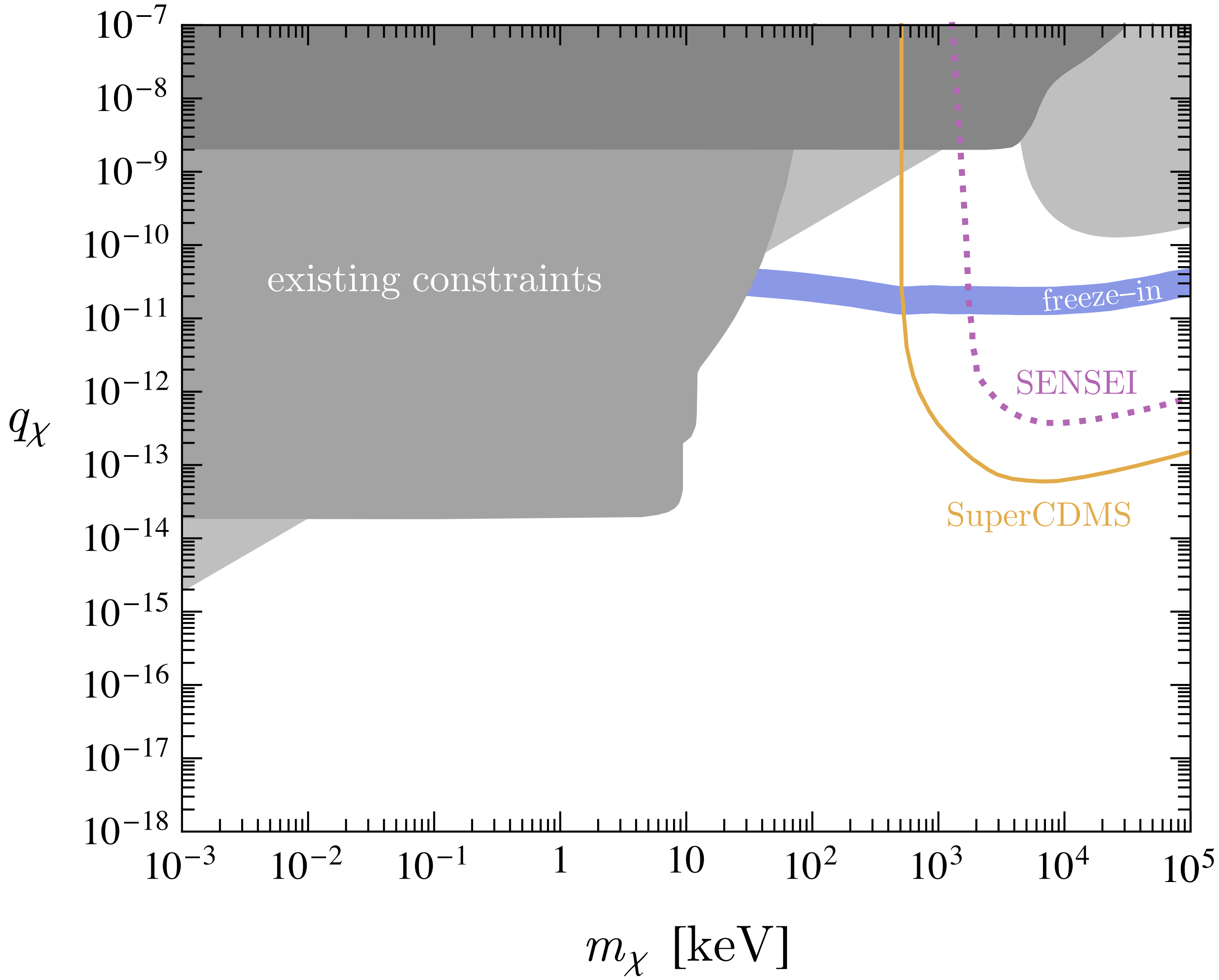
deflector: ω

signal: $\omega \pm \omega_\oplus$

arXiv:1807.10291

Direct *Deflection*

Direct *Deflection*



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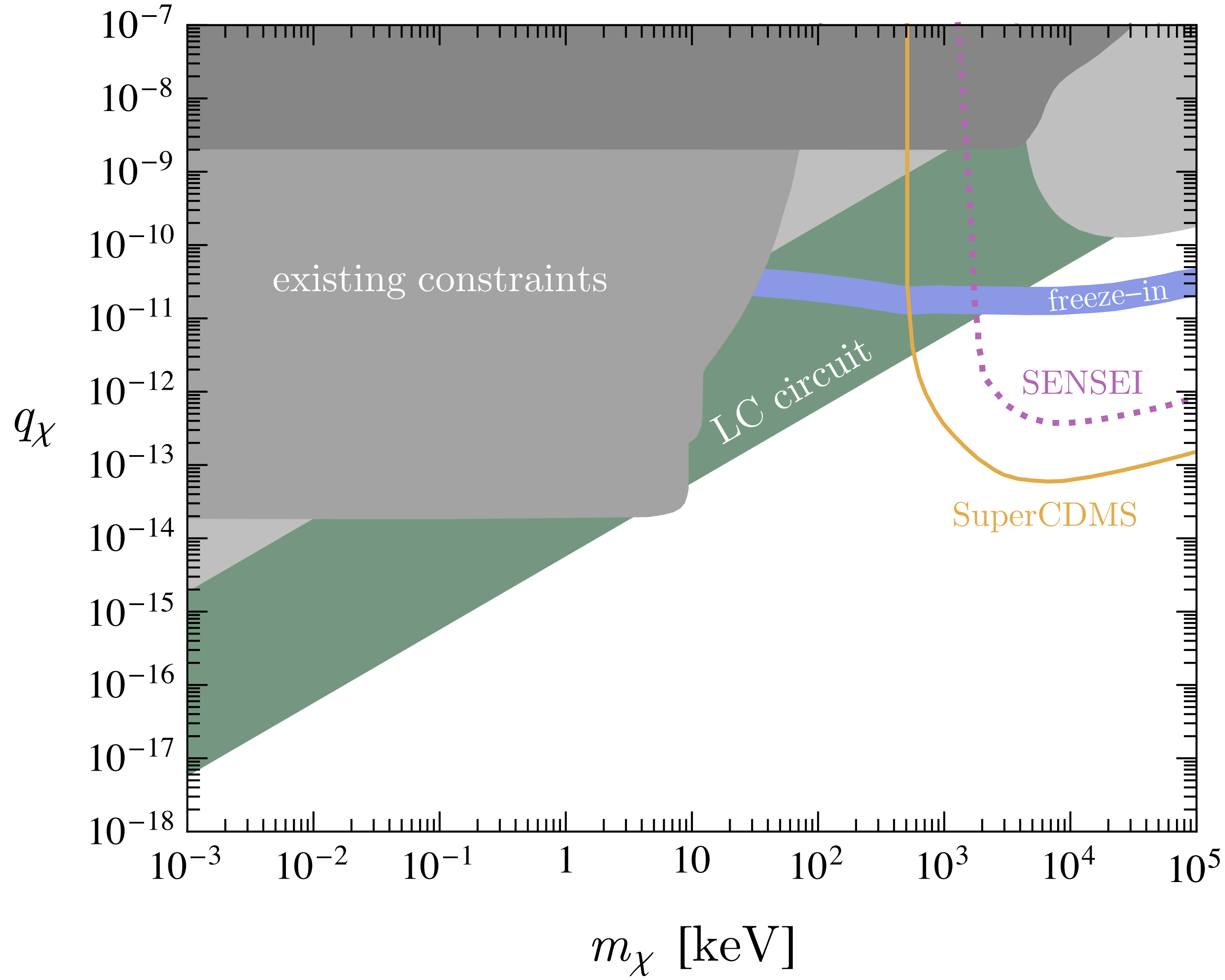

Direct *Deflection*

Take Away

- Inducing collective disturbances takes advantage of small dark matter inertia.
- Enhanced reach at small masses.
- Proposed setups could decisively test sub-MeV freeze-in benchmarks.

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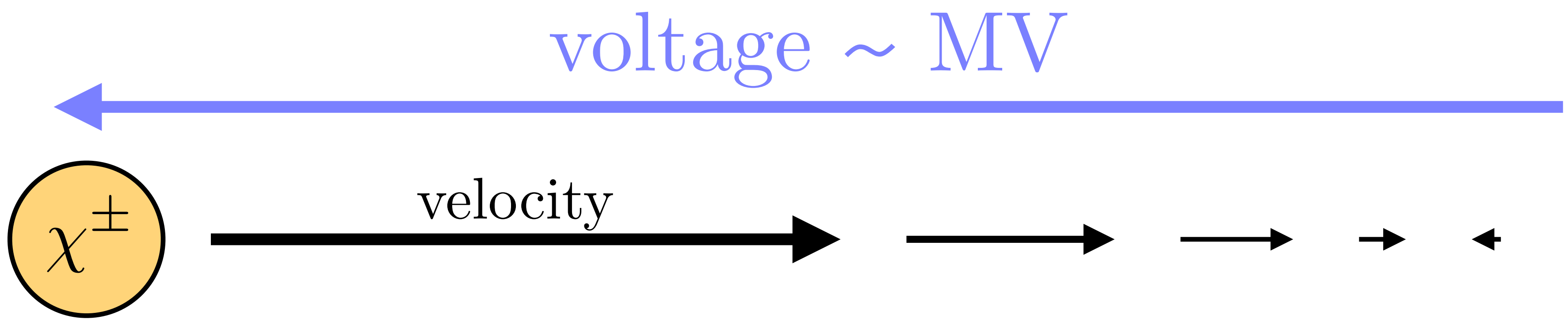
Future Goals

- Induced daily modulation.
- Electromagnetic focusing/trapping.
- Optimal geometry for wind.
- Deflection-detection for other forces.
- Cosmology of ultralight millicharges.

Back Up Slides

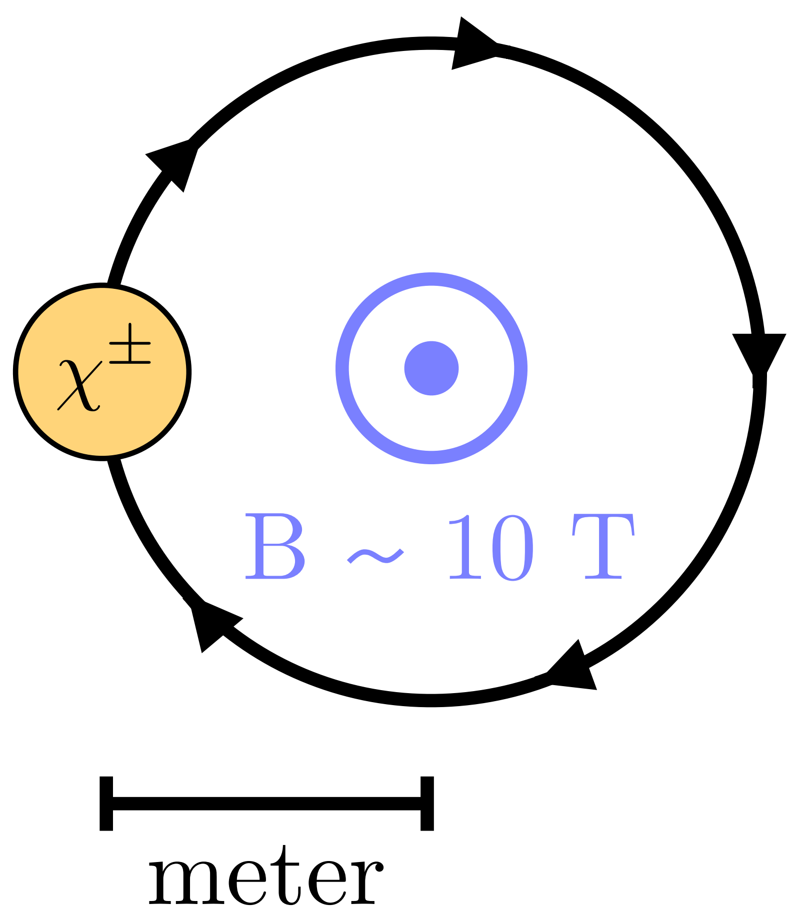
Direct *Deflection*

stop it

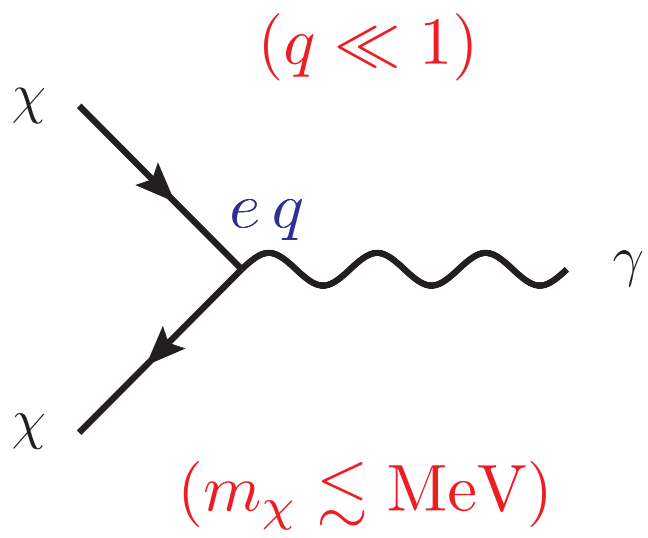


($v_\chi \sim 100$ km/s $\Longrightarrow$ electric fields are more efficient than magnetic fields)

bend it

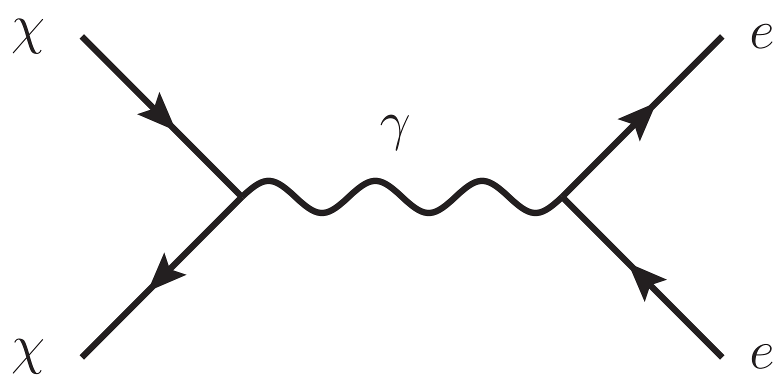


Millicharge Cosmology



χ thermalizes $\Longrightarrow$ in conflict with BBN and CMB

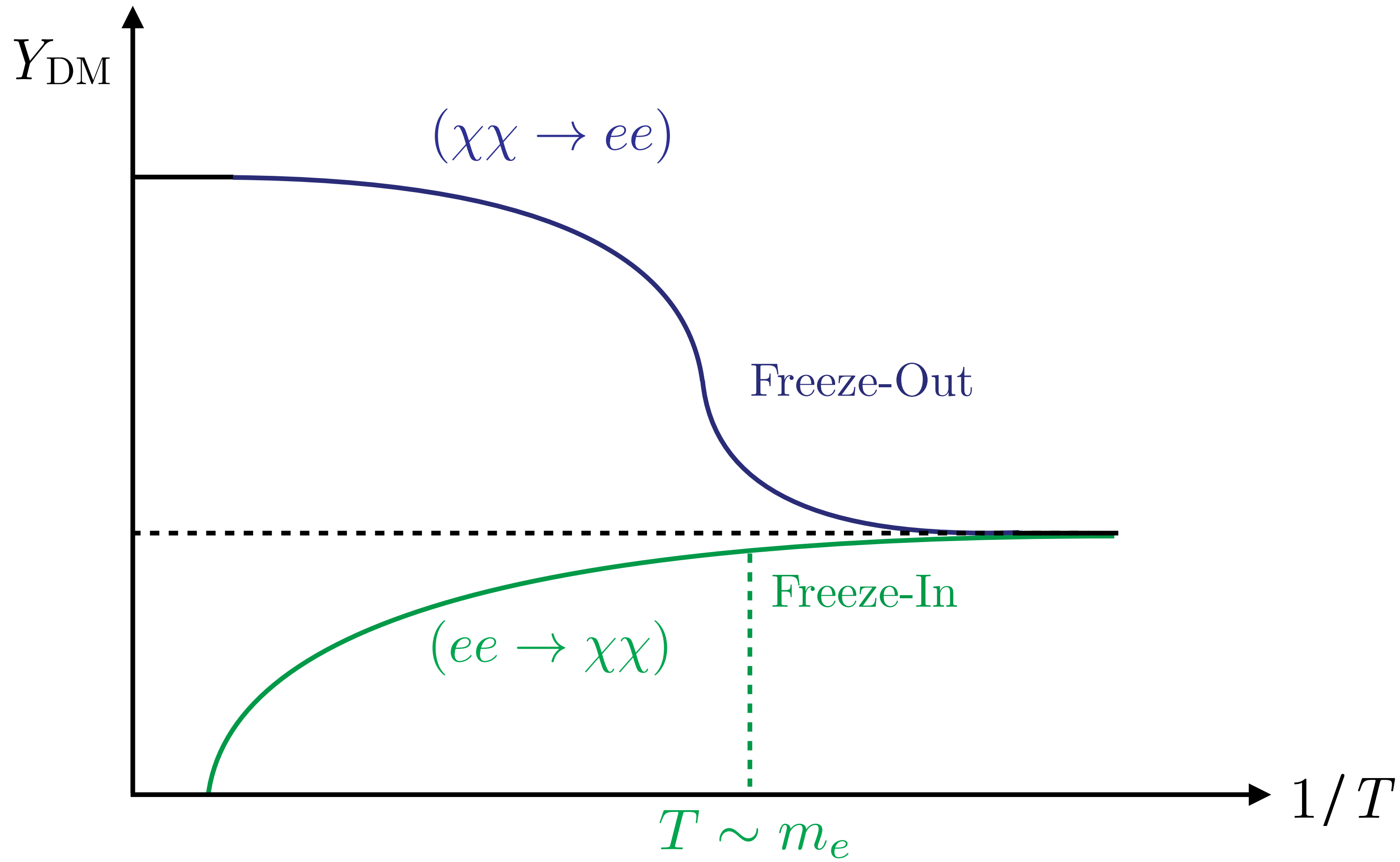
How small does q have to be?



$$\Gamma \lesssim H \Longrightarrow \boxed{q \lesssim 10^{-9} \left(\frac{\max(m_\chi, m_e)}{\text{MeV}}\right)^{1/2}}$$

If this is the dark matter, how is it populated?

Freeze-In



$$\Gamma(ee \to \chi\chi) \sim \alpha_{\rm em}^2\, q^2\, T \ , \ n_\chi \sim n_e(\Gamma/H) \ , \ \rho_{\rm DM} \sim T_{\rm eq}\, T^3$$

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

how to generate this coupling?

arXiv:0911.1120

Kinetic Mixing

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}F_{\mu\nu}'^2 + \frac{1}{2}m_{A'}^2 A_\mu'^2 + \frac{\epsilon}{2}\, F_{\mu\nu}F'^{\mu\nu}$$

$$A_\mu \to A_\mu + \epsilon A_\mu' \;,\; A_\mu' \to \frac{1}{\sqrt{1-\epsilon^2}}\, A_\mu' \implies \mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}F_{\mu\nu}'^2 + \frac{1}{2}m_{A'}^2 A_\mu'^2 + \mathcal{O}(\epsilon^2)$$

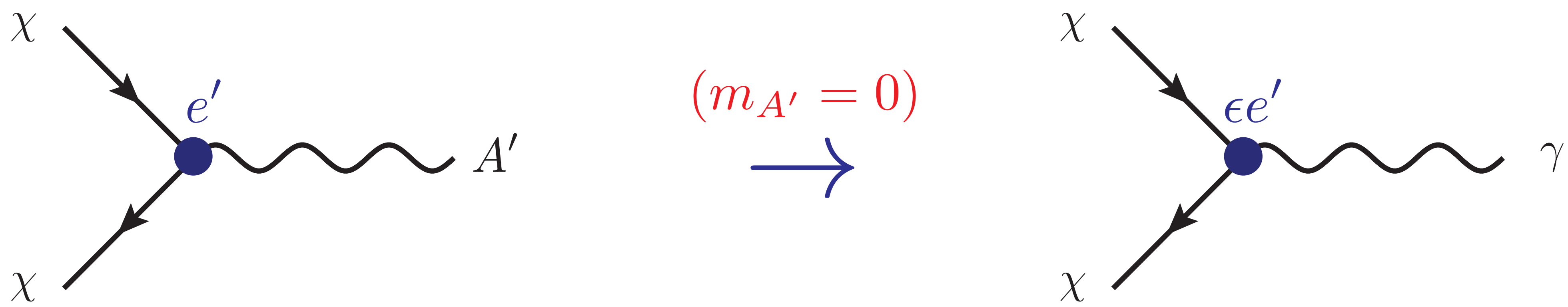
$$\mathcal{L} \supset j_\mu A^\mu + j_\mu' A'^\mu \implies \boxed{\mathcal{L} \supset \boxed{j_\mu(A^\mu + \epsilon A'^\mu)} + j_\mu' A'^\mu + \mathcal{O}(\epsilon^2)}$$

$$\begin{cases} A_{\text{vis}} = A + \epsilon A' & \text{(the massless photon)} \\ A_{\text{inv}} = A' - \epsilon A \end{cases}$$

$$\boxed{m_{A'} = 0 \implies \mathcal{L} \supset -\frac{1}{4}F_{\text{vis}}^2 - \frac{1}{4}F_{\text{inv}}^2 + j_\mu A_{\text{vis}}^\mu + j_\mu'(A_{\text{inv}}^\mu + \epsilon A_{\text{vis}}^\mu)}$$

Kinetic Mixing

$$\mathcal{L} \supset -\frac{1}{4}F_{\rm vis}^2 - \frac{1}{4}F_{\rm inv}^2 + j_\mu A^\mu_{\rm vis} + j'_\mu (A^\mu_{\rm inv} + \epsilon A^\mu_{\rm vis})$$



$$q_{\rm eff} \sim \epsilon e'/e$$

(exact millicharge limit)

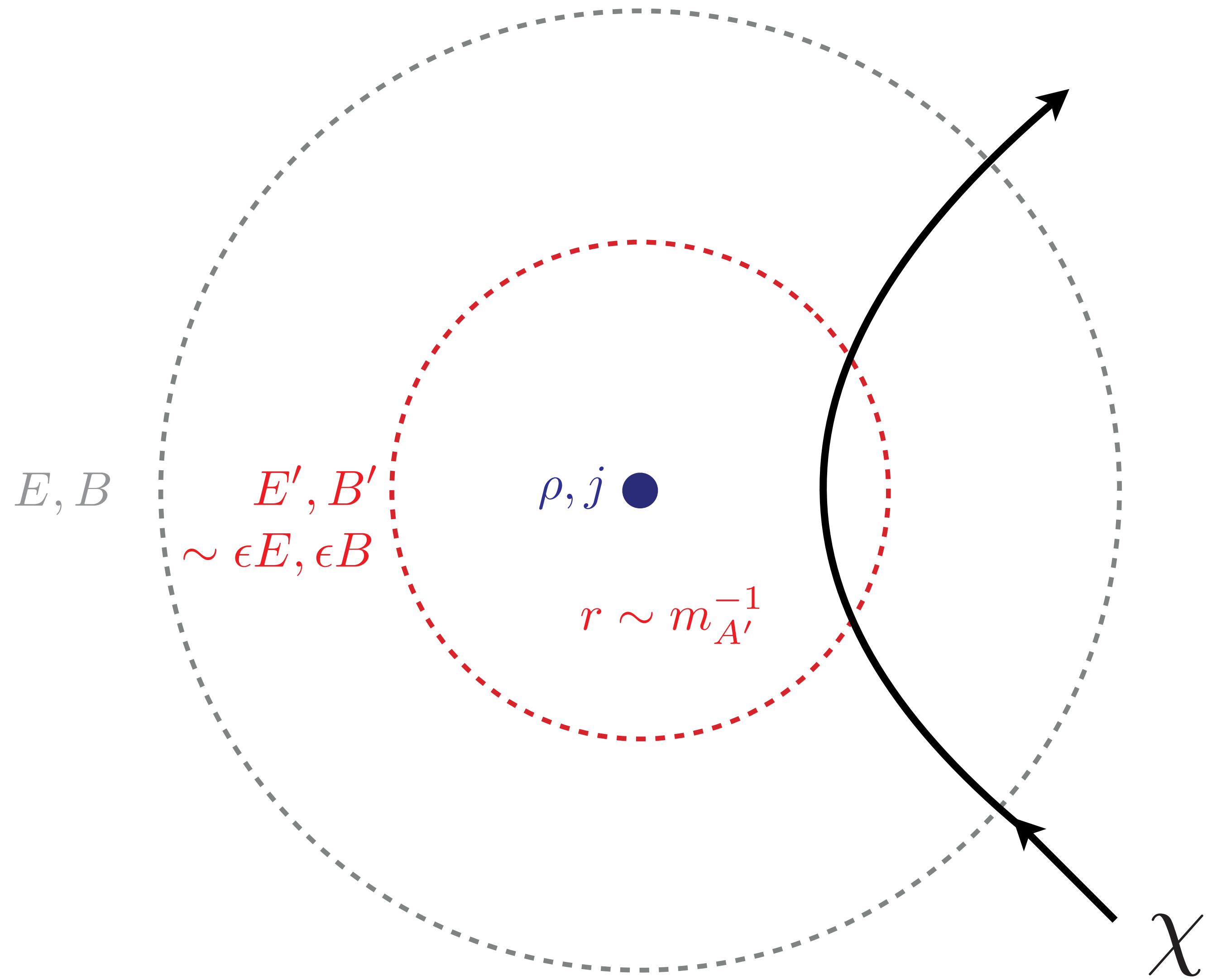
Pseudo-Millicharge

$(m_{A'} \neq 0)$

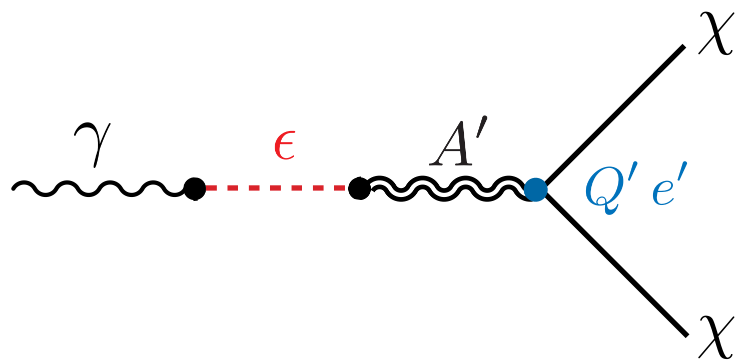
$$\mathcal{L} \supset j_\mu (A^\mu + \epsilon A'^\mu) + j'_\mu A'^\mu$$

↓

$$q_{\text{eff}} \sim \epsilon e'/e \text{ for } r \ll 1/m_{A'}$$



New Long-Ranged Forces

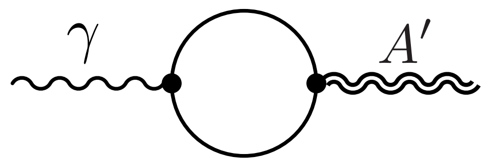


$\Longrightarrow \; q_\chi \sim \epsilon \, Q' \, e' / e$ (effective DM charge)

ϵ

theory expectation

10^{-3}



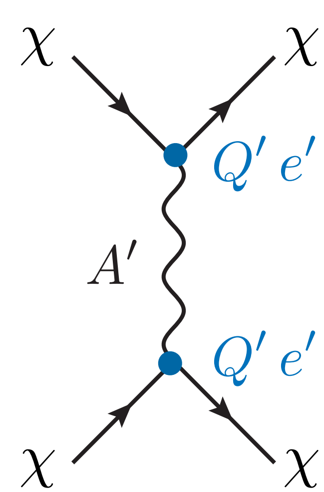
10^{-6} + small gauge coupling

10^{-10} + mass degeneracy

10^{-15} + multi-loops, Yukawa, gravitational, ...

...

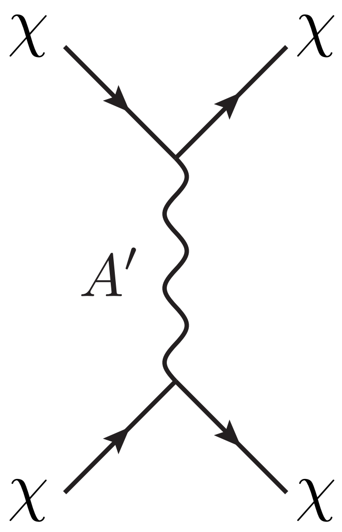
astrophysically viable



$$\Longrightarrow \; Q' \, e' \lesssim 10^{-7} \times \left(\frac{m_\chi}{\text{keV}}\right)^{3/4}$$

T. Gherghetta, J. Kersten, K. Olive, M. Pospelov, Phys. Rev. D 2019

Self-Interactions



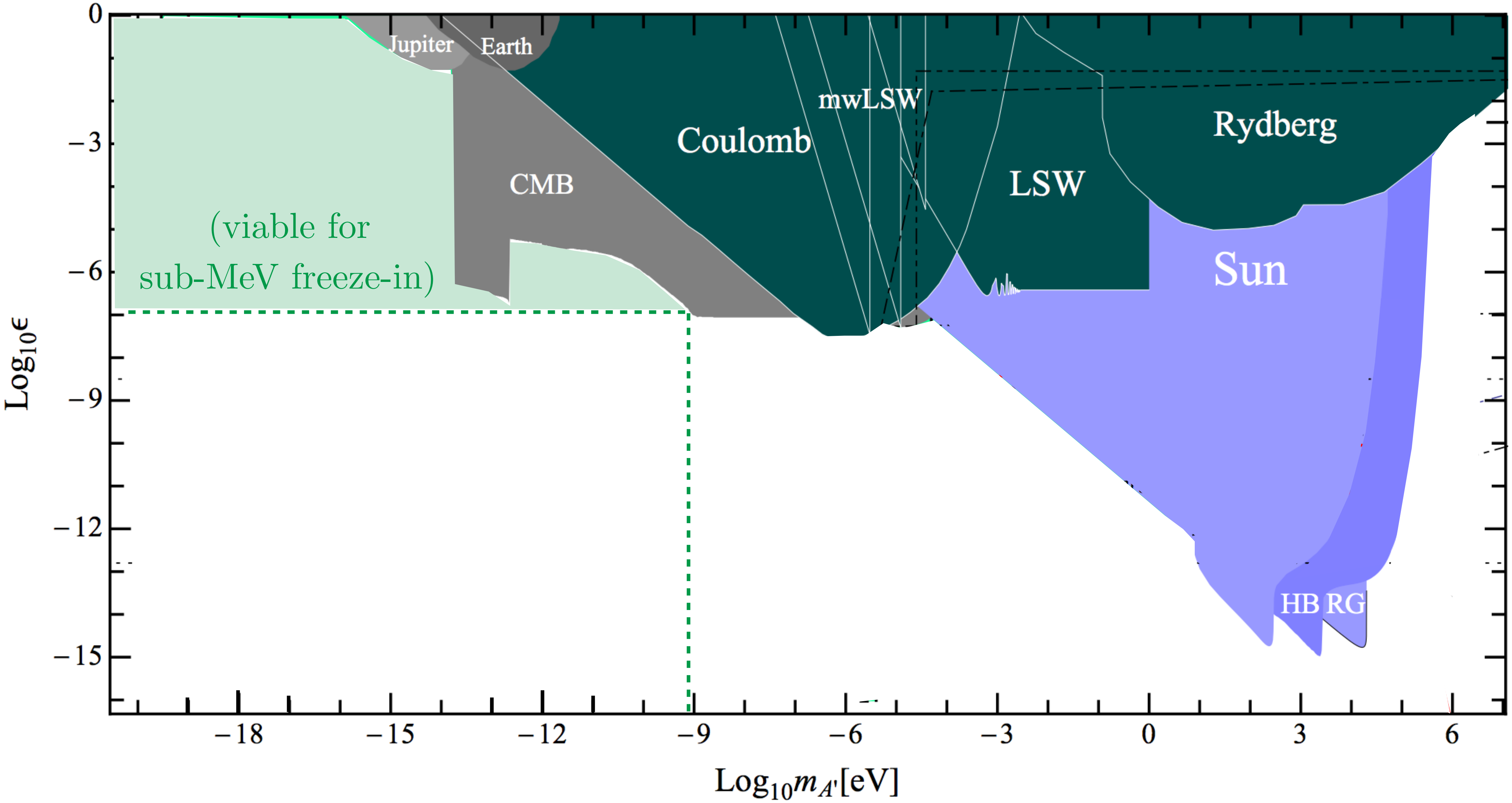
$$\text{e.g., galaxy clusters} \implies \alpha' \lesssim 10^{-10}\left(\frac{m_\chi}{\text{MeV}}\right)^{3/2}$$

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

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

what does this imply
for the dark photon mass?

Parameter Space



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

long-range forces: DM is pseudo-millicharged on lab-scales

arXiv:1704.05081
arXiv:1401.6077

Active Direct Detection

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

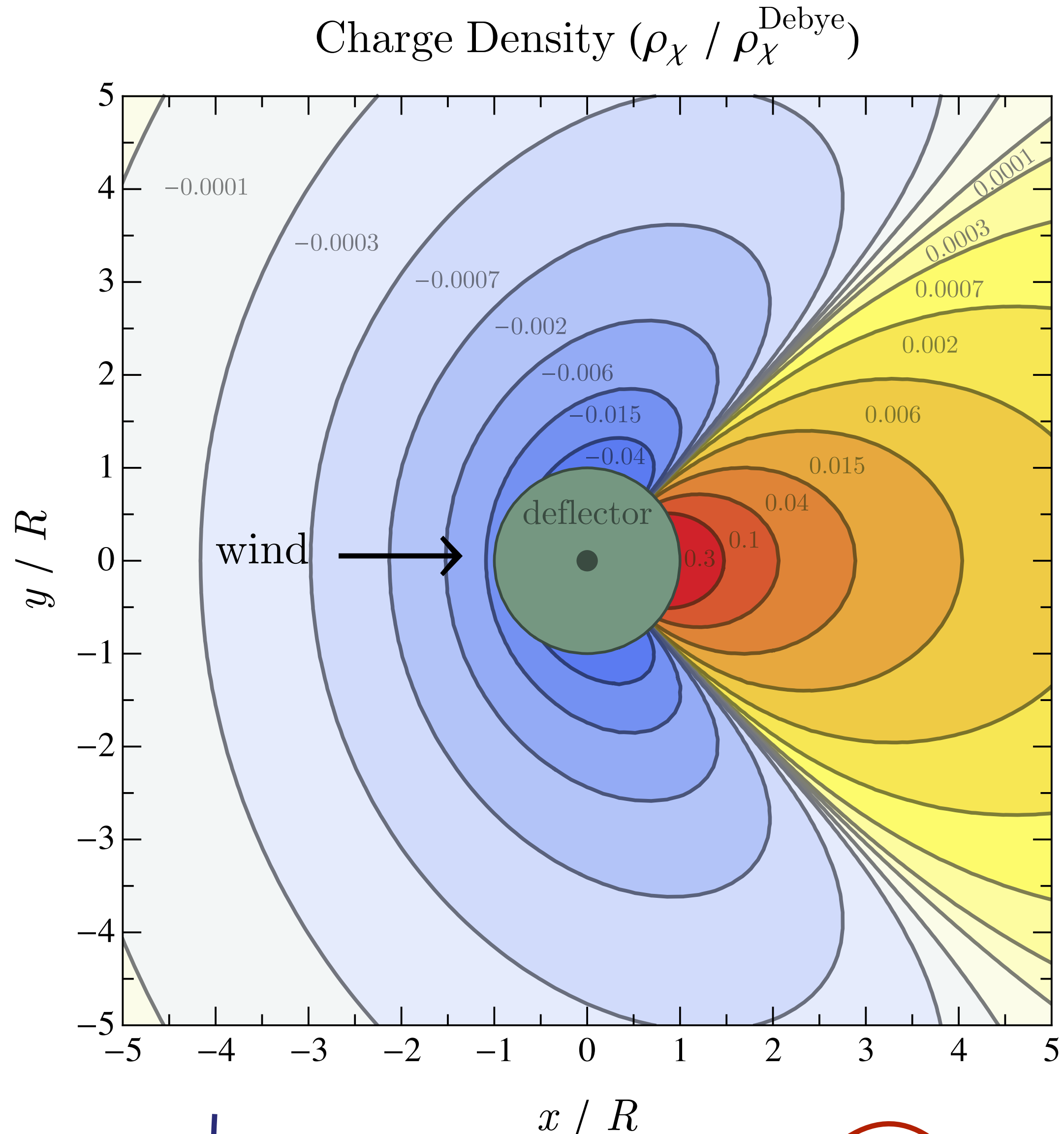
(freeze-in)

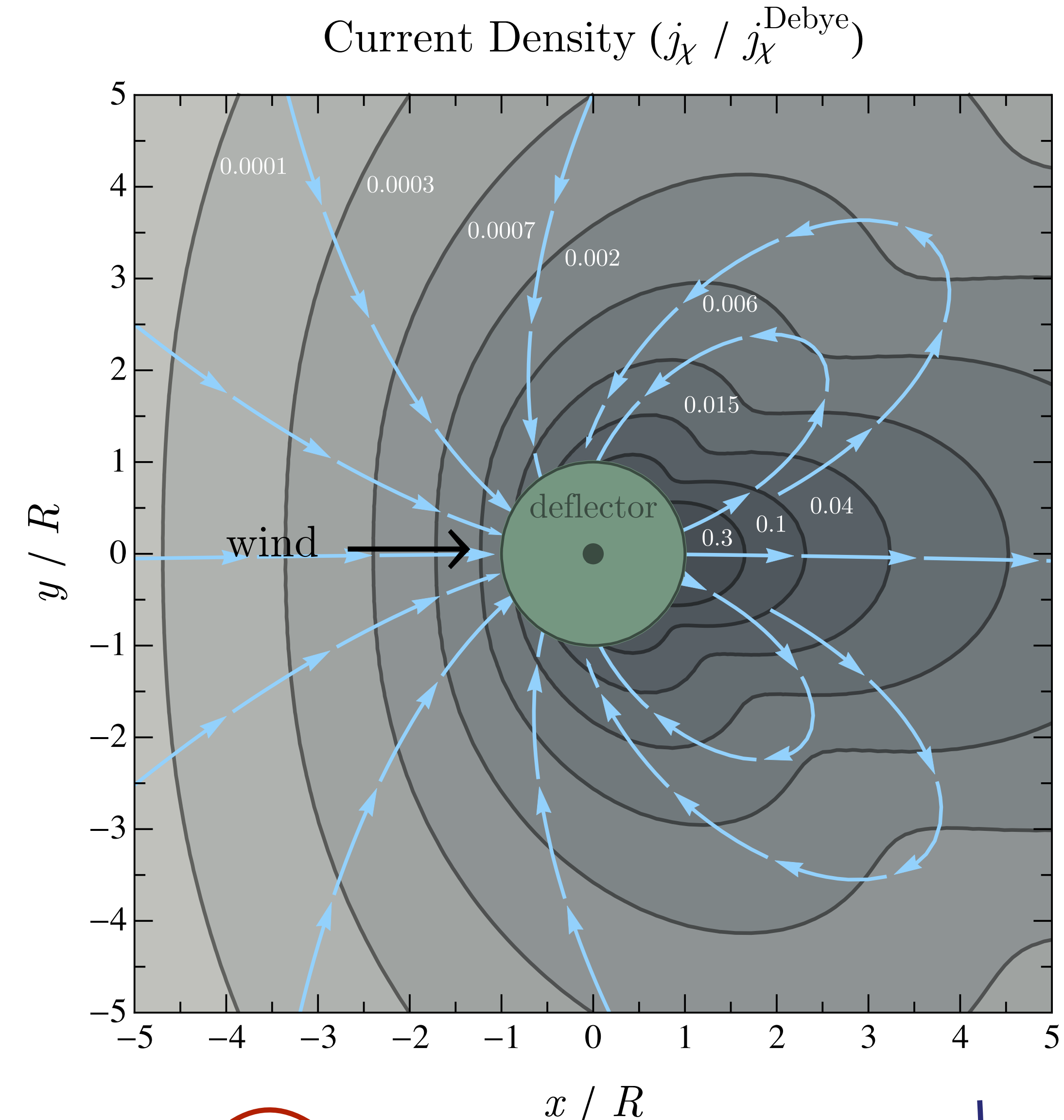
$(v_\chi \ll 1 \implies$ electric fields are more efficient than magnetic fields$)$

•bend it: $r_g \sim \dfrac{m_\chi\, v_\chi}{q_{\rm eff}\, e\, B} \sim {\rm meter} \times \left(\dfrac{m_\chi}{\rm keV}\right)^{3/2} \left(\dfrac{10\ {\rm T}}{B}\right)$

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

Non-Adiabatic Debye Screening





(ignore backreaction) $\omega_{\text{p}} \ll \omega \ll \pi\, v_\chi / R$ (maximum deflection)

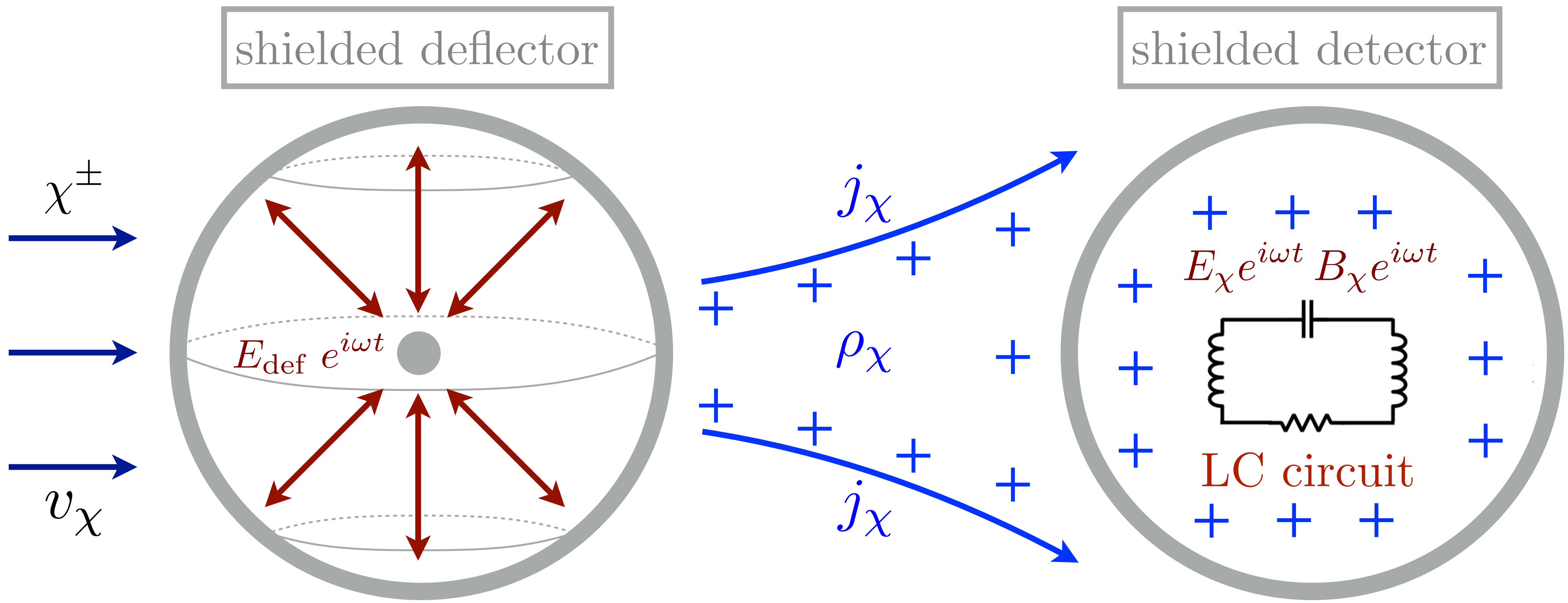
$$\Longrightarrow \;\text{kHz} \times (m_\chi/\text{eV})^{-1/4} \ll \omega \ll \text{MHz} \times (R/\text{meter})^{-1}$$

electric fields

100 kHz
(quasi-static)

magnetic fields

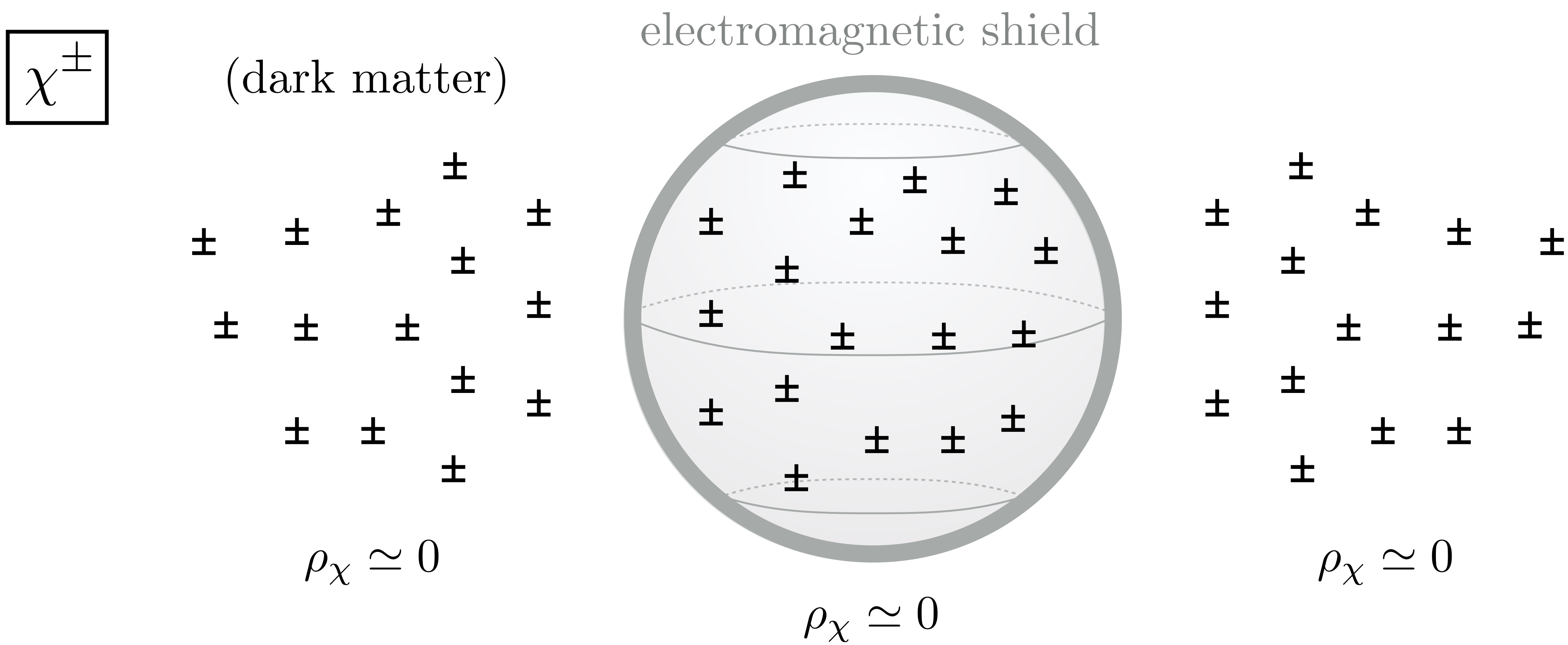
Direct *Deflection*



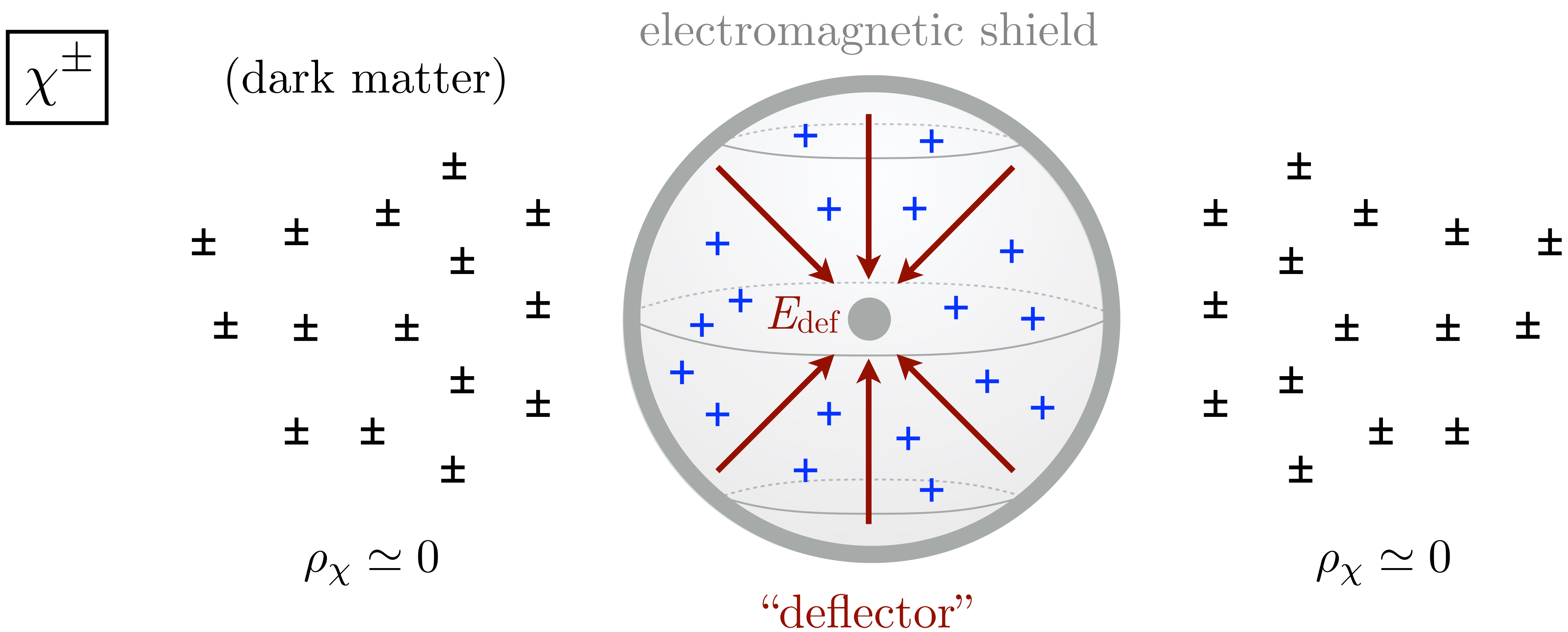
$$E_{\rm def} \sim 10\ {\rm kV/cm}\ ,\ \ R \sim {\rm meter} \implies \begin{cases} E_\chi \sim 10^{-12}\ {\rm kV/cm} \times (q_\chi/10^{-10})^2\,(m_\chi/{\rm keV})^{-2} \\ B_\chi \sim 10^{-19}\ {\rm T} \times (q_\chi/10^{-10})^2\,(m_\chi/{\rm keV})^{-2} \end{cases}$$

high-Q radio (DM Radio, Auriga)

Debye Screening

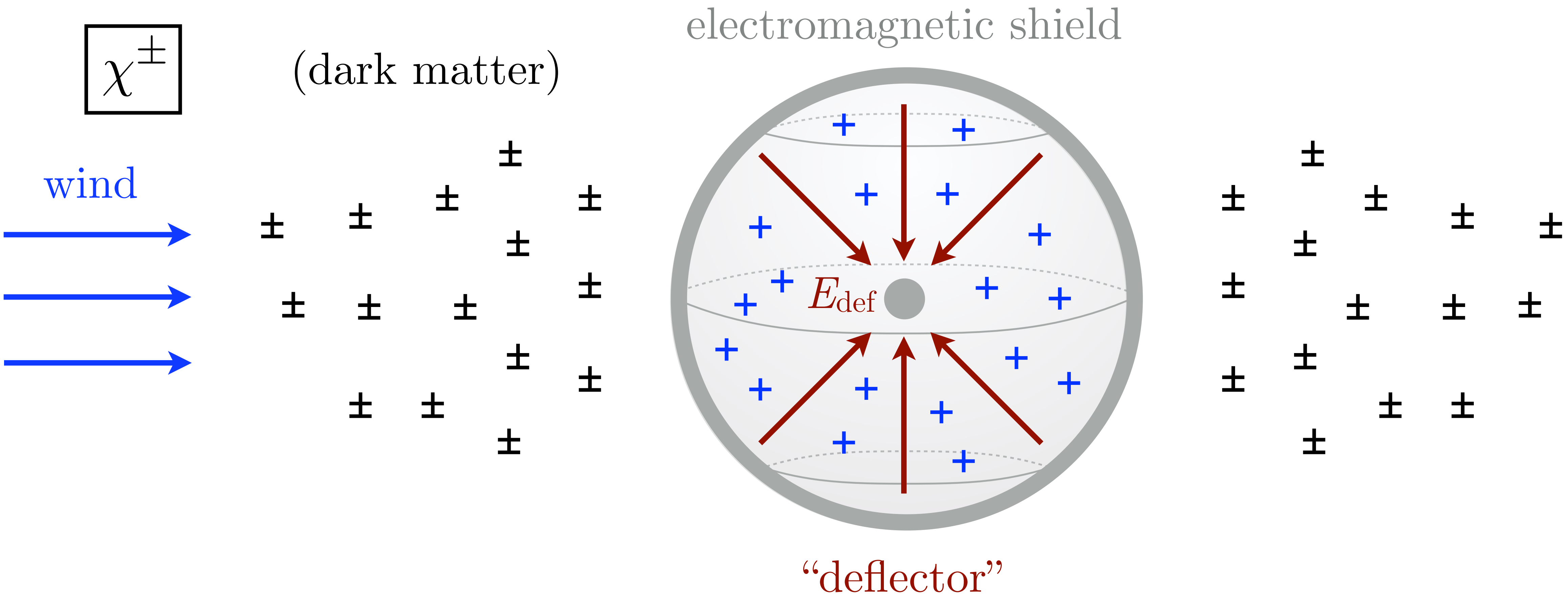


Debye Screening



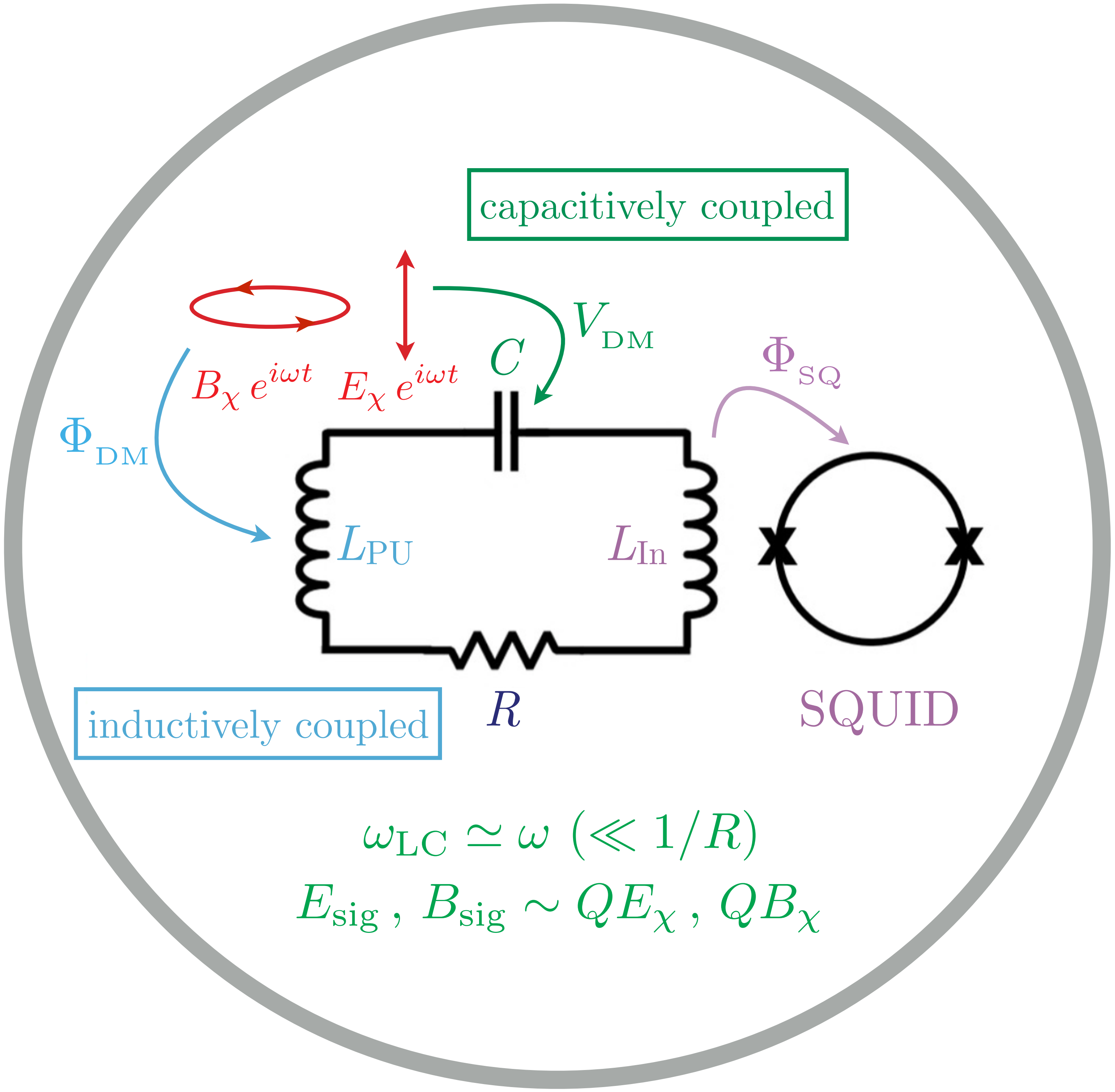
$$\rho_\chi^{\rm Debye} \simeq -\frac{(eq_\chi)^2\, \rho_{\rm DM}\, V_{\rm def}}{m_\chi^2\, v_\chi^2}$$

Non-Adiabatic Debye Screening



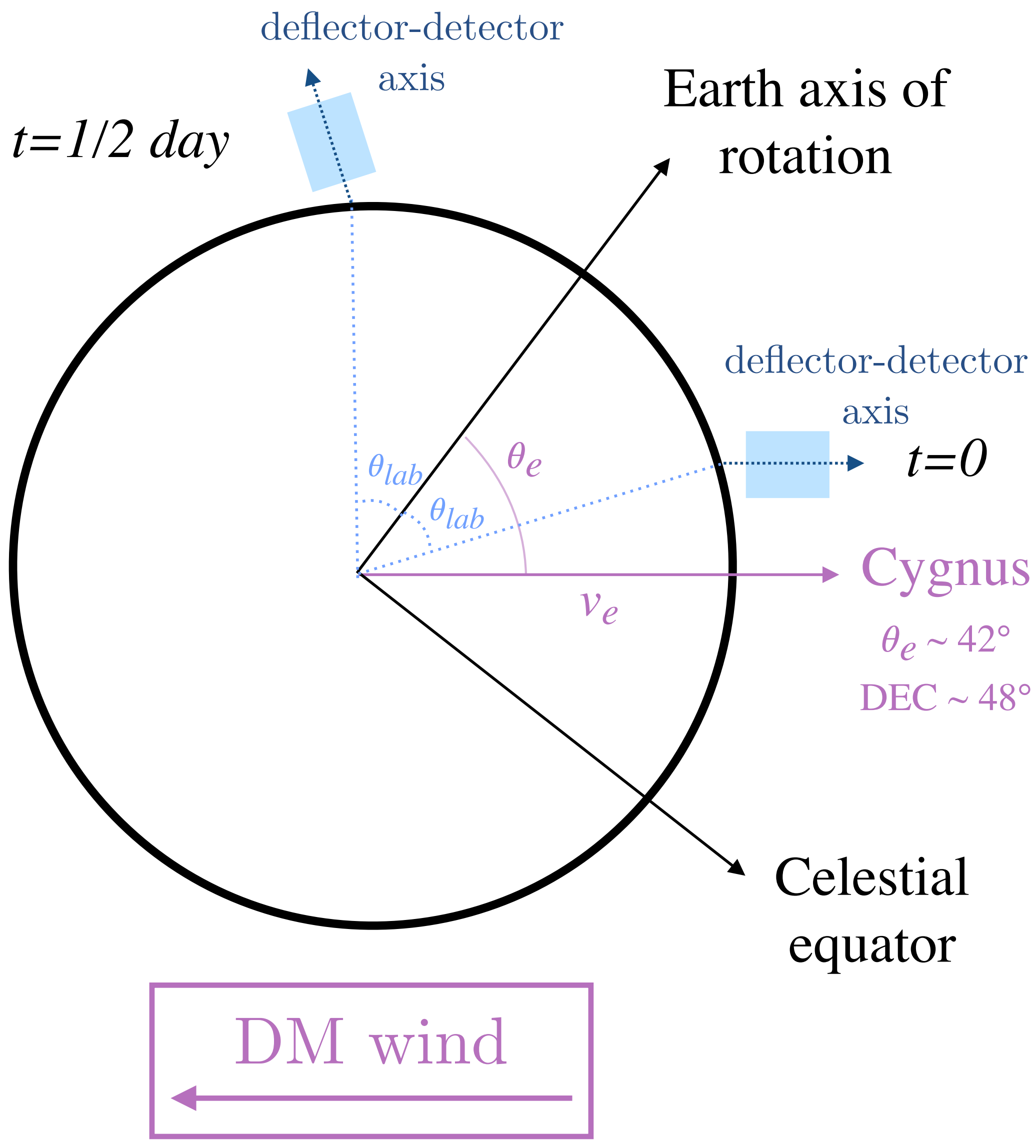
LC Resonators

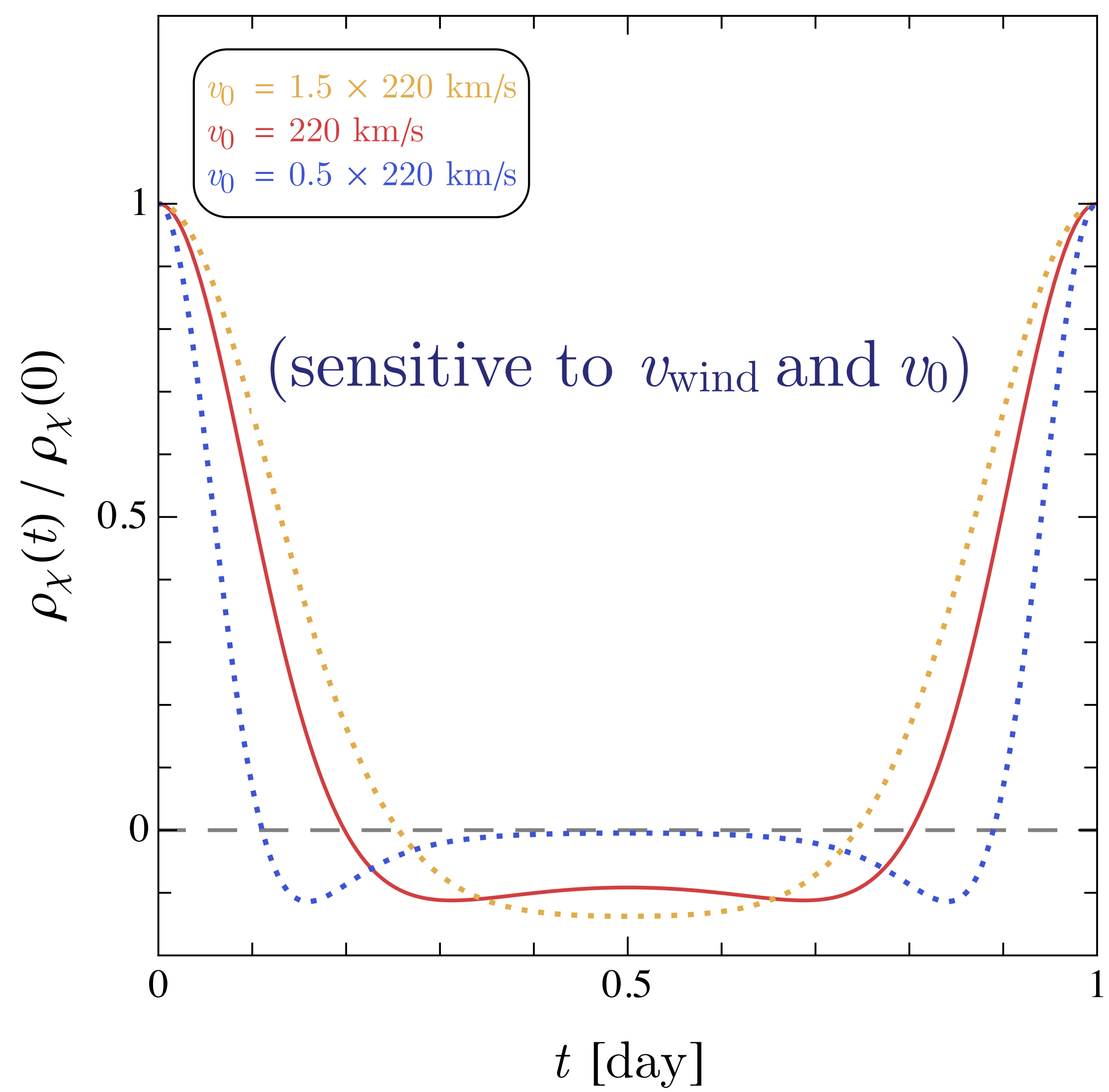
shielded detector



= DM Radio, Auriga...

Daily Modulation



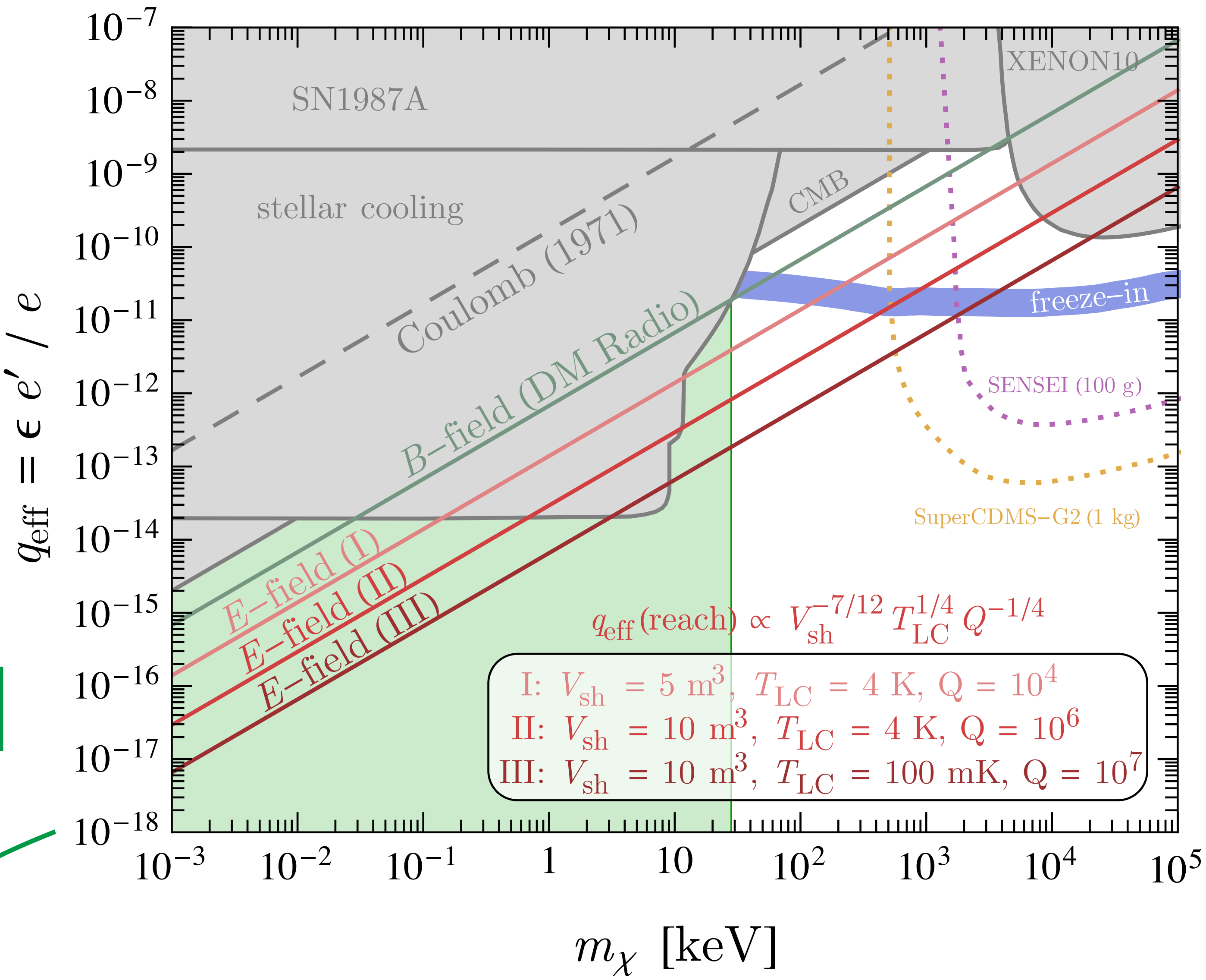


deflector: ω

signal: $\omega \pm \omega_\oplus$

arXiv:1807.10291

Reach Summary



$\langle E_{\rm def}\rangle = 10$ kV/cm
$\omega = 100$ kHz
$t_{\rm int} =$ year

ultralight cosmology?

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

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

Noise/Systematics

- **SQUID noise** (sub-dominant, 1411.7382 & 1803.01627)
  imprecision, backaction

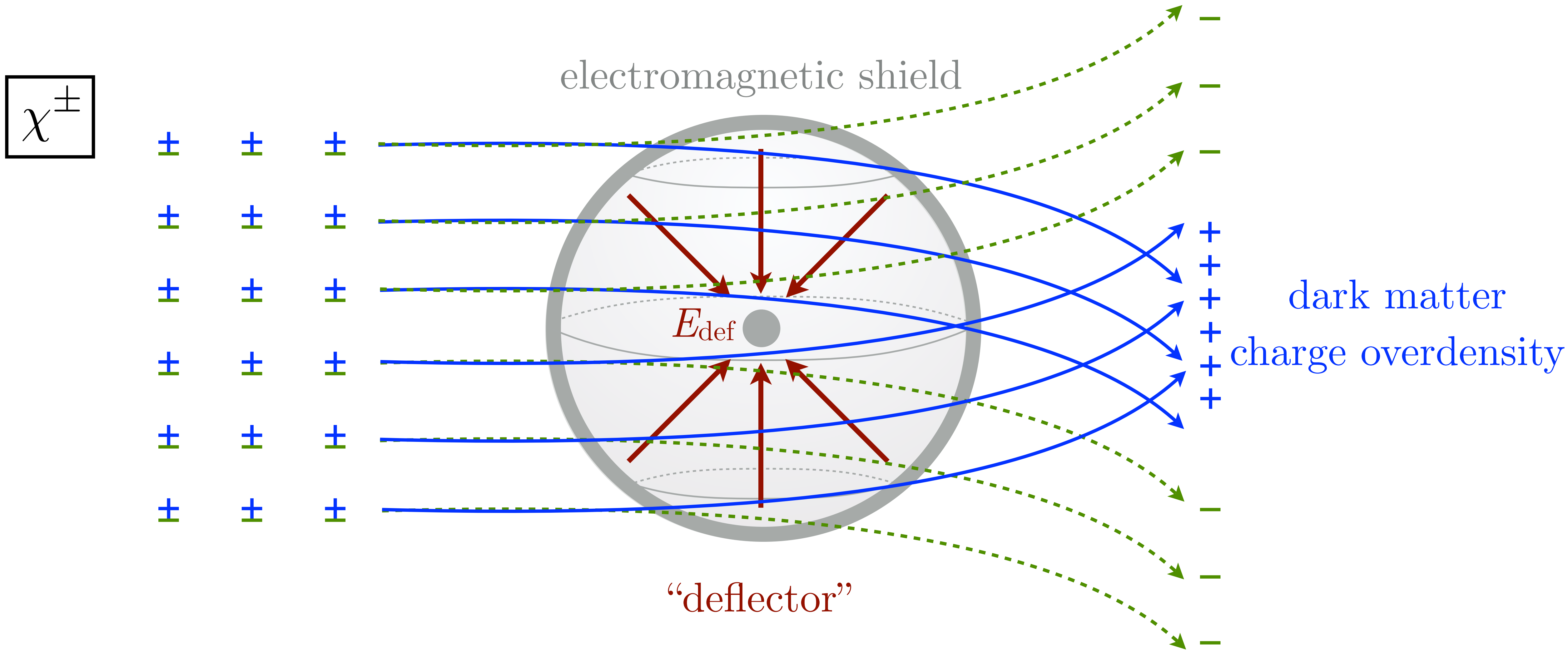
- **deflector noise** (sub-dominant)
  magnetic, electric

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

- **thermal noise** (dominant for $\omega \lesssim 10^8$ Hz, 1411.7382 & 1803.01627)
  $T \lesssim$ K , Johnson/Nyquist

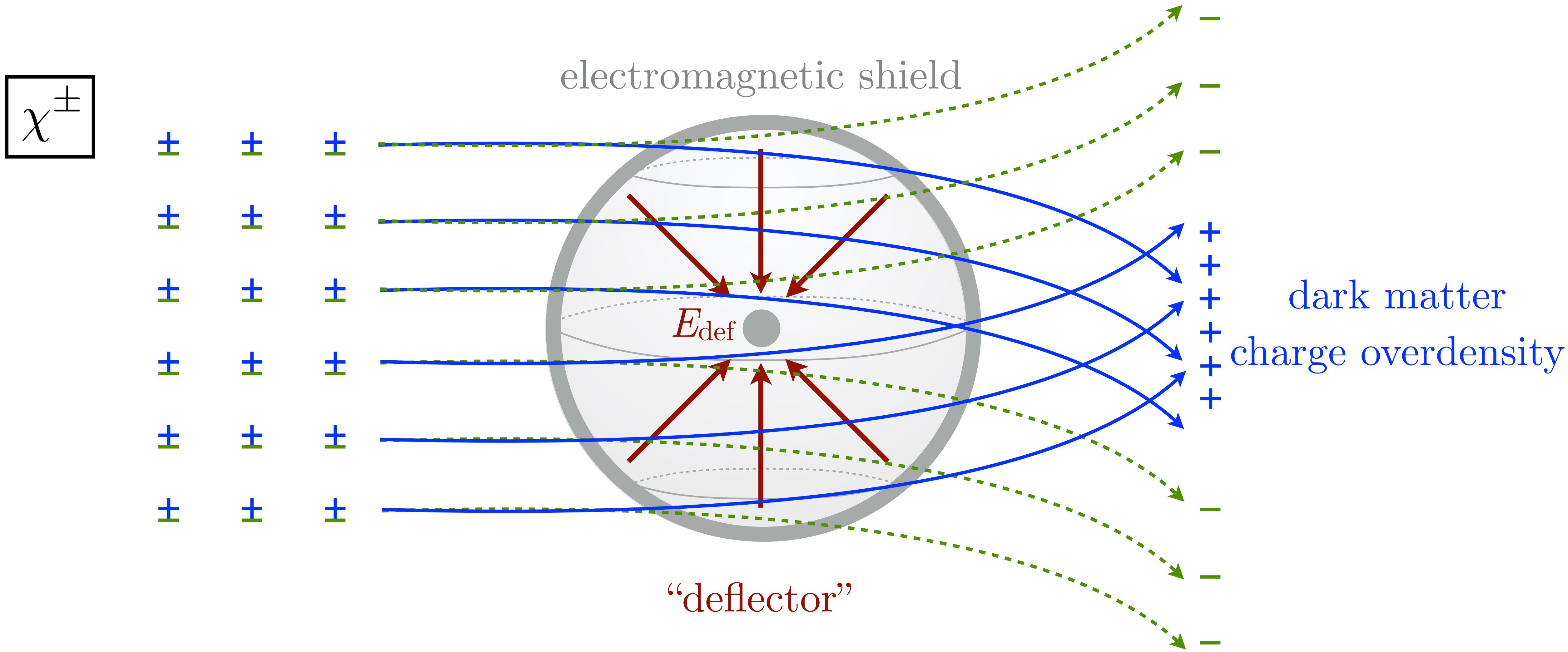
handles: directional dependence, daily modulation

Debye Screening



(ray tracing) $$\rho_\chi(\mathbf{x},t) \simeq \frac{1}{2}\, e q_\chi\, n_\chi \sum_{\pm} (\pm 1) \int d^3\mathbf{x}_i\, d^3\mathbf{v}\;\, f(\mathbf{v})\, \delta^3\big(\mathbf{x} - \mathbf{x}^{\pm}_{\text{traj.}}(t)\big)$$

Debye Screening



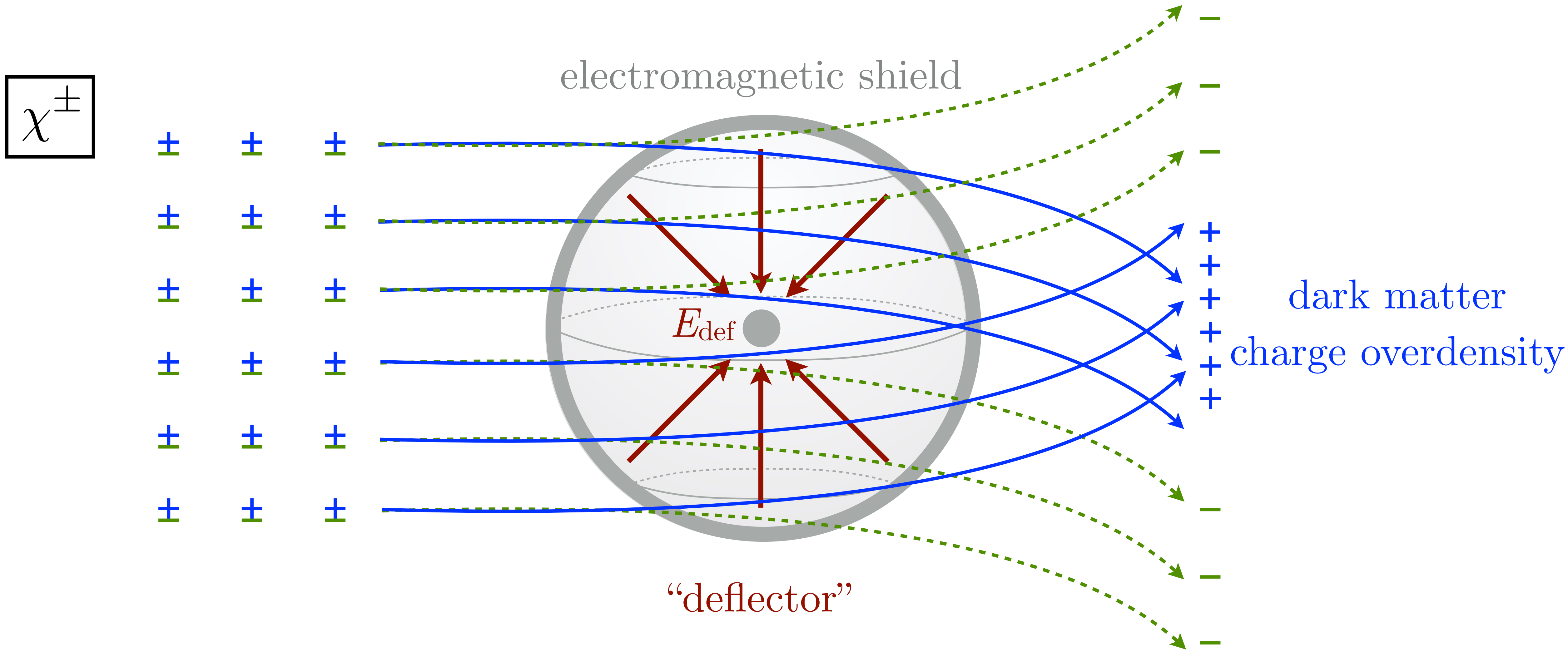
(ray tracing) $$\rho_\chi(\mathbf{x},t) \simeq \frac{1}{2} e q_\chi \, n_\chi \sum_{\pm} (\pm 1) \int d^3\mathbf{x}_i \, d^3\mathbf{v} \, f(\mathbf{v}) \, \delta^3\left(\mathbf{x} - \mathbf{x}^{\pm}_{\text{traj.}}(t)\right)$$

$d^3\mathbf{x}_i$ → initial position

$f(\mathbf{v})$ → velocity distribution

$\mathbf{x}^{\pm}_{\text{traj.}}(t)$ → deflected trajectory

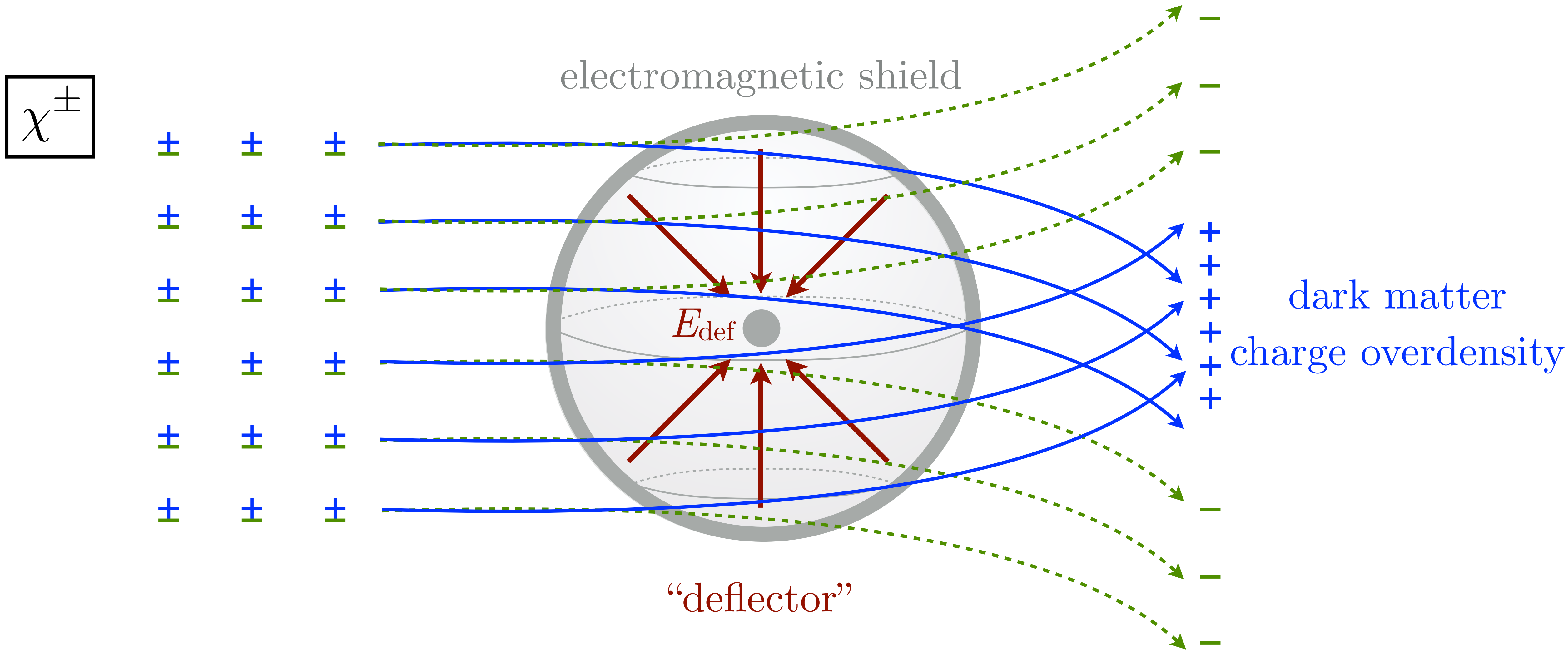
Debye Screening



(ray tracing) $$\rho_\chi(\mathbf{x},t) \simeq \frac{1}{2}\, e q_\chi \; n_\chi \sum_{\pm} (\pm 1) \int d^3\mathbf{x}_i \, d^3\mathbf{v} \;\; f(\mathbf{v})\, \delta^3\big(\mathbf{x} - \mathbf{x}^{\pm}_{\rm traj.}(t)\big)$$

(weak coupling) $$\simeq -\frac{(e q_\chi)^2 \rho_{\rm DM}}{m_\chi^2} \; e^{i\omega t} \int dv \;\, d^3\mathbf{x}' \;\, f\left(v \, \frac{\mathbf{x} - \mathbf{x}'}{|\mathbf{x} - \mathbf{x}'|}\right) \; \frac{\rho_{\rm def}(\mathbf{x}')}{|\mathbf{x} - \mathbf{x}'|} \; e^{-i\omega|\mathbf{x}-\mathbf{x}'|/v}$$

Debye Screening

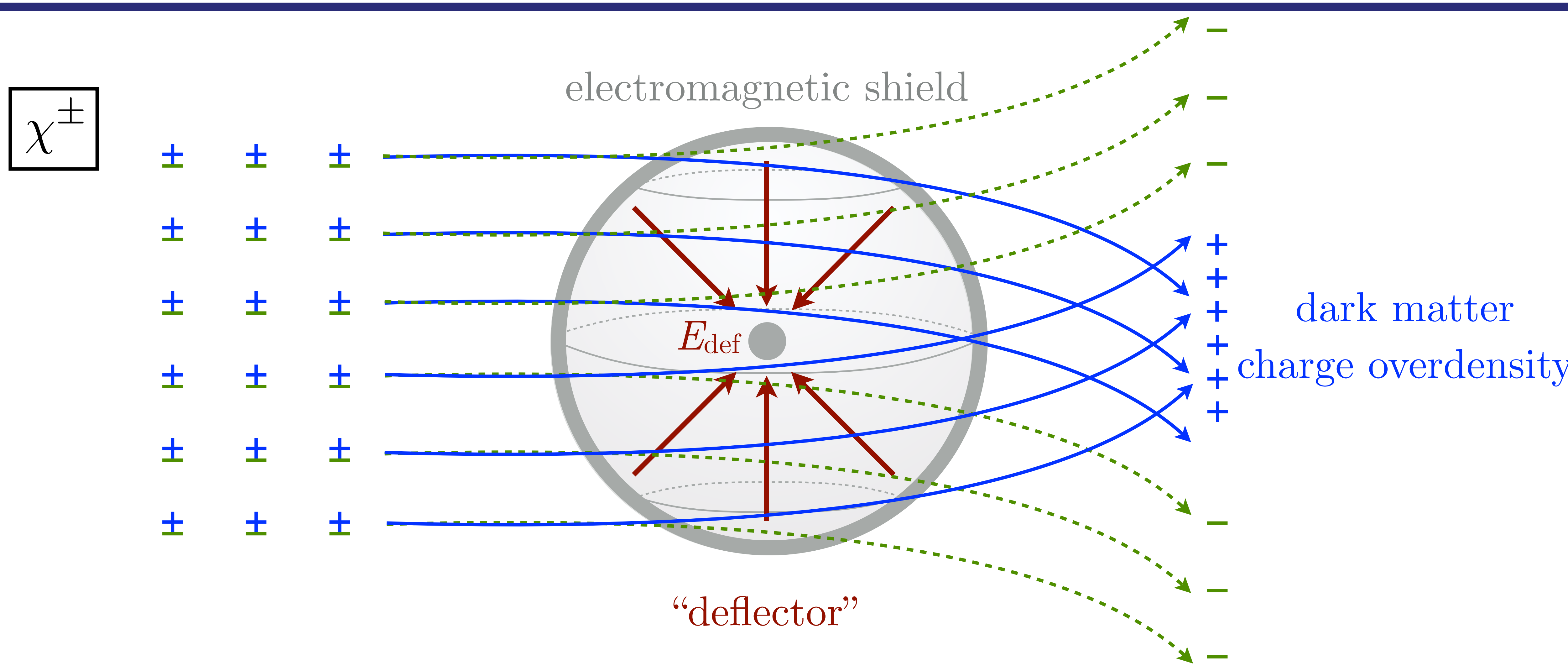


(ray tracing) $$\rho_\chi(\mathbf{x},t) \simeq \frac{1}{2}\, e q_\chi\; n_\chi \sum_{\pm} (\pm 1) \int d^3\mathbf{x}_i\, d^3\mathbf{v}\;\, f(\mathbf{v})\, \delta^3\big(\mathbf{x} - \mathbf{x}^{\pm}_{\rm traj.}(t)\big)$$

(weak coupling) $$\simeq -\frac{(e q_\chi)^2 \rho_{\rm DM}}{m_\chi^2}\; e^{i\omega t} \int dv\; d^3\mathbf{x}'\; f\left(v\,\frac{\mathbf{x}-\mathbf{x}'}{|\mathbf{x}-\mathbf{x}'|}\right) \frac{\rho_{\rm def}(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|}\; e^{-i\omega|\mathbf{x}-\mathbf{x}'|/v}$$

reduces to standard Debye screening
when there's no preferred direction

Debye Screening

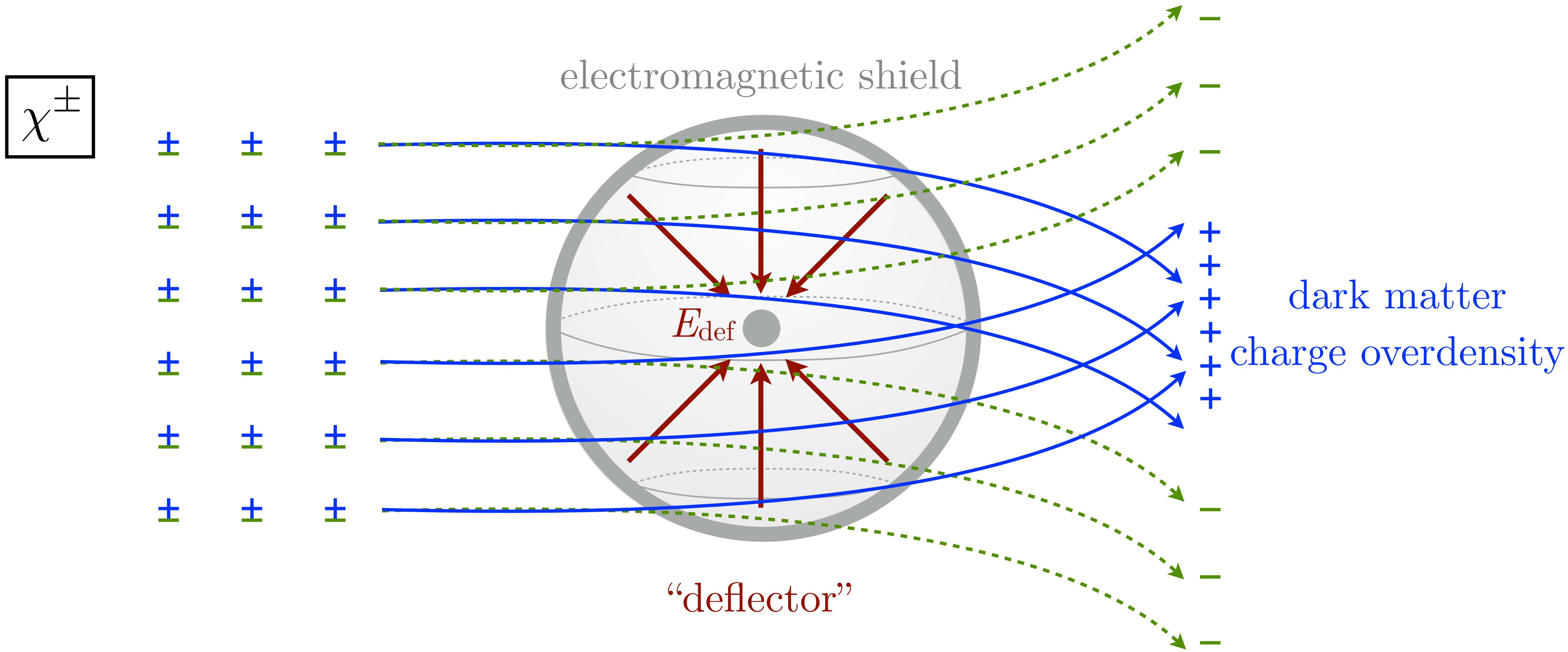


(ray tracing) $$\rho_\chi(\mathbf{x},t) \simeq \frac{1}{2}\, e q_\chi\, n_\chi \sum_{\pm} (\pm 1) \int d^3\mathbf{x}_i\, d^3\mathbf{v}\;\, f(\mathbf{v})\, \delta^3\big(\mathbf{x} - \mathbf{x}^{\pm}_{\rm traj.}(t)\big)$$

(weak coupling) $$\simeq -\frac{(e q_\chi)^2 \rho_{\rm DM}}{m_\chi^2}\, e^{i\omega t} \int dv\; d^3\mathbf{x}'\; f\left(v\, \frac{\mathbf{x}-\mathbf{x}'}{|\mathbf{x}-\mathbf{x}'|}\right) \frac{\rho_{\rm def}(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|}\, e^{-i\omega|\mathbf{x}-\mathbf{x}'|/v}$$

suppression when DM transit time
is much longer than period of oscillation

Debye Screening

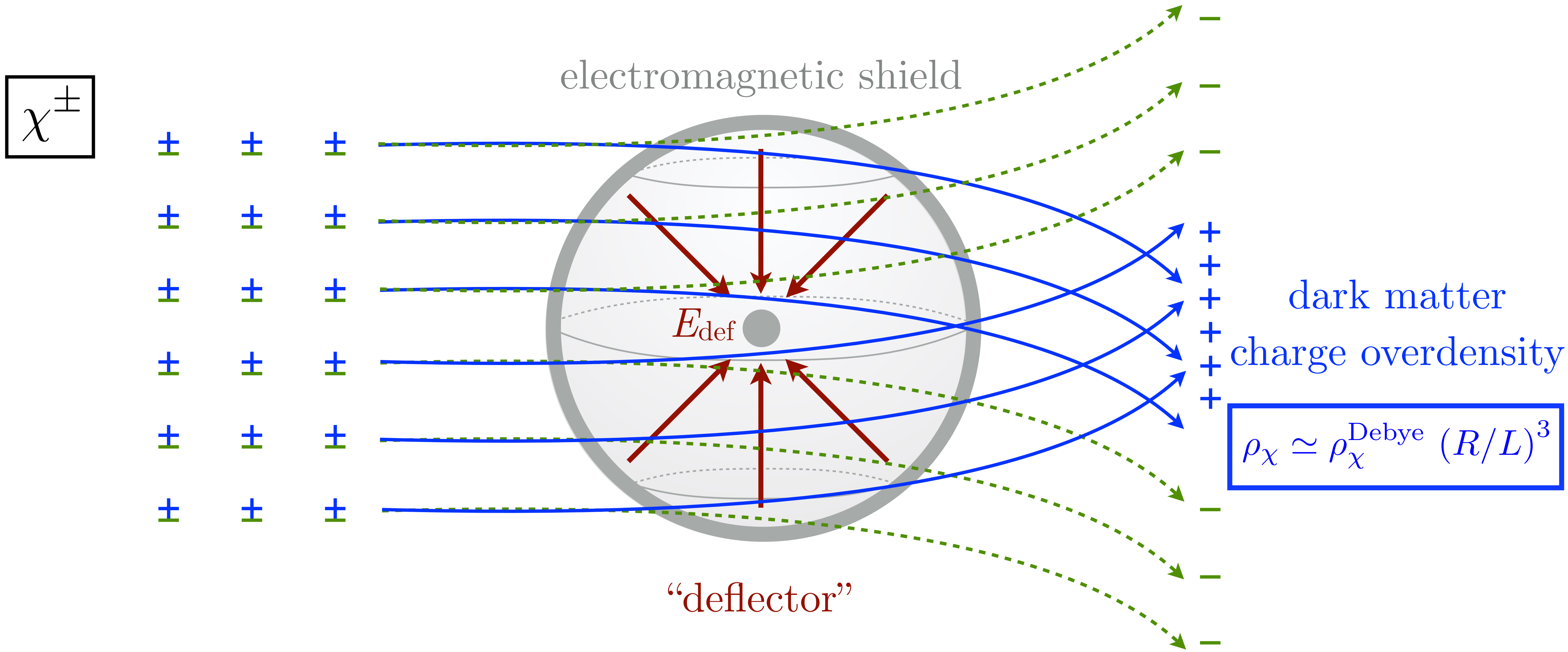


(far-field) (monopole) (dipole) (quadrupole) (charge-radius)

$$\rho_\chi(x,t) \simeq -\frac{(e q_\chi)^2 \rho_{\rm DM}}{m_\chi^2}\, e^{i\omega t} \left[Q_{\rm def}\, G(x) - p^i_{\rm def}\, \nabla_i G(x) + \frac{1}{6}\, Q^{ij}_{\rm def}\, \nabla_i \nabla_j G(x) + \frac{1}{6}\, \mathcal{R}^2_{\rm def}\, \nabla^2 G(x) \right]$$

$$G(x) \equiv \int dv\, \frac{f(v\, \hat{x})}{|x|}$$ (velocity distribution)

Debye Screening



(far-field)

(grounded shield)

$$\rho_\chi(x,t) \simeq -\frac{(eq_\chi)^2\rho_{\rm DM}}{m_\chi^2}\, e^{i\omega t}\left[\xcancel{Q_{\rm def}\,G(x) - p^i_{\rm def}\nabla_i G(x) + \frac{1}{6}Q^{ij}_{\rm def}\nabla_i\nabla_j G(x)} + \frac{1}{6}\mathcal{R}^2_{\rm def}\nabla^2 G(x)\right]$$

charge radius of "deflector"

$$G(x) \equiv \int dv\,\frac{f(v\,\hat{x})}{|x|}$$