Direct Deflection of Particle Dark Matter

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Based on:

A. Berlin, R. T. D'Agnolo, SARE, P. Schuster, N. Toro

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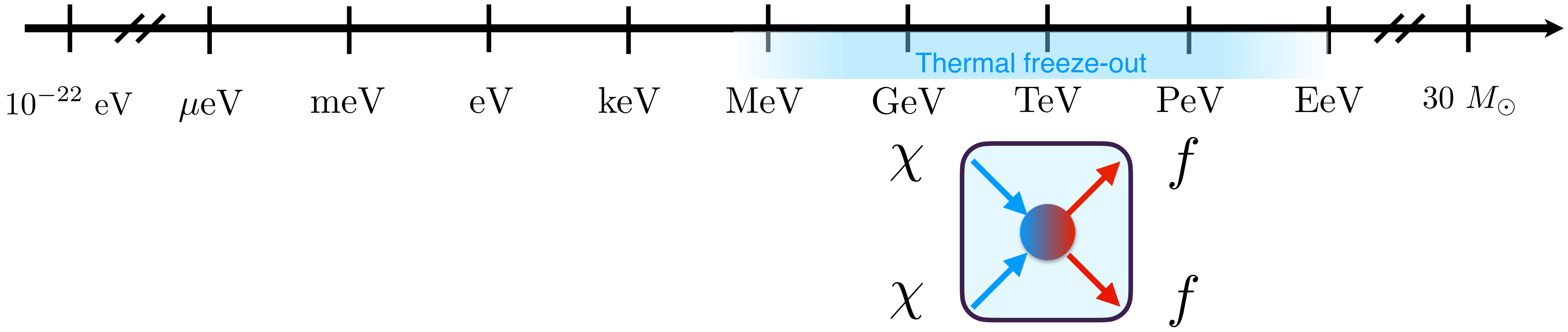
COSMIC WISPERS
CA21106

The Dark Matter Landscape



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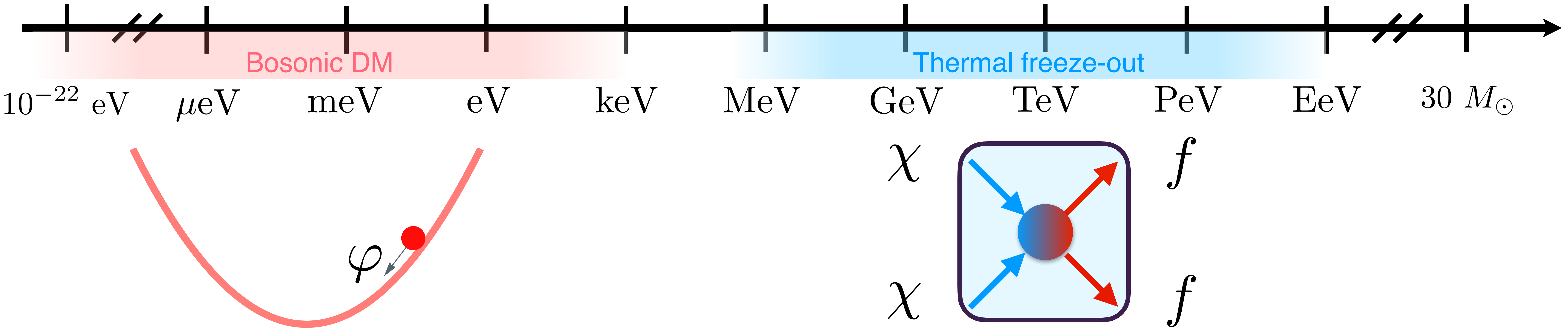
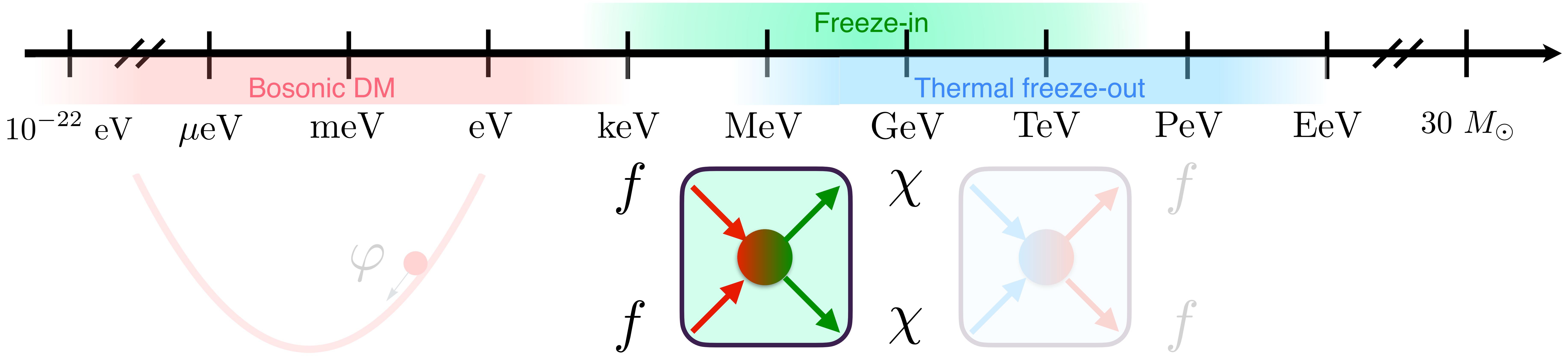


The Dark Matter Landscape



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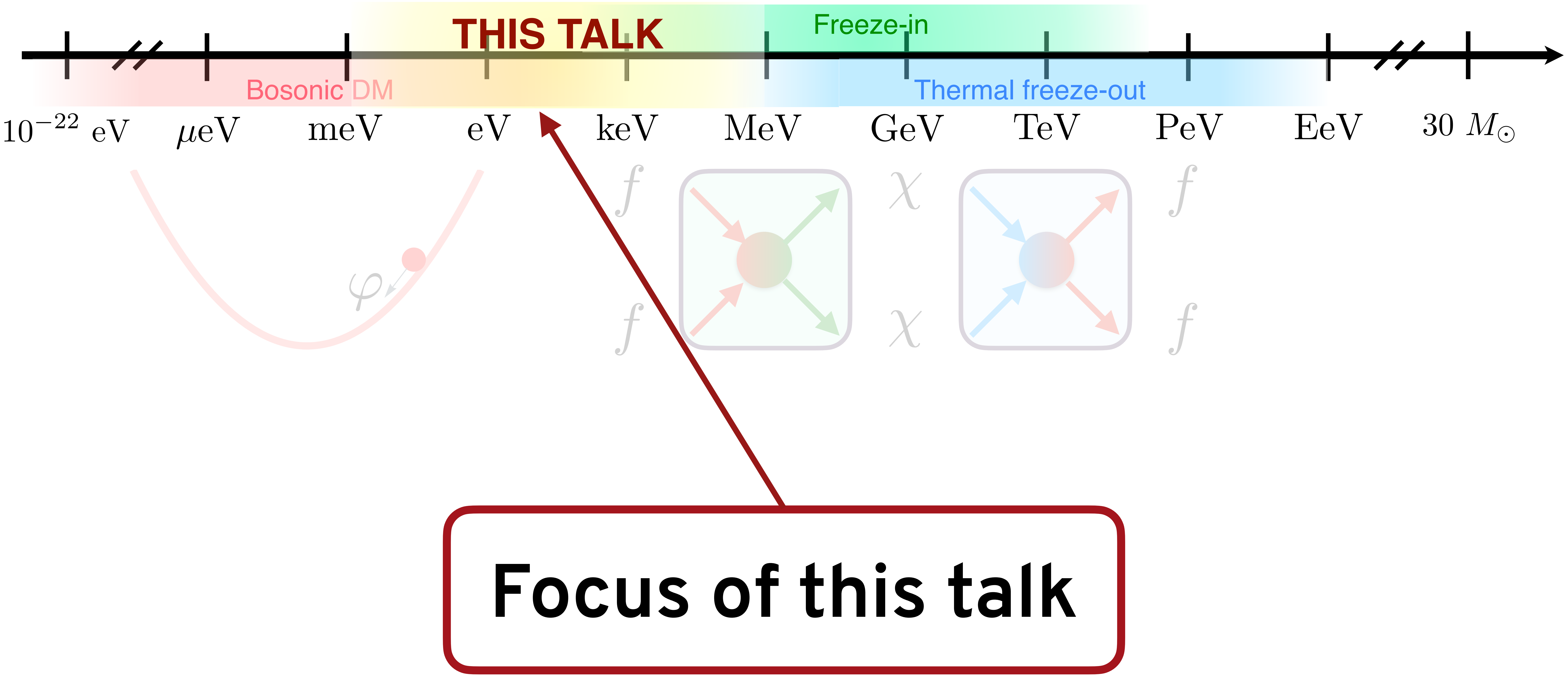
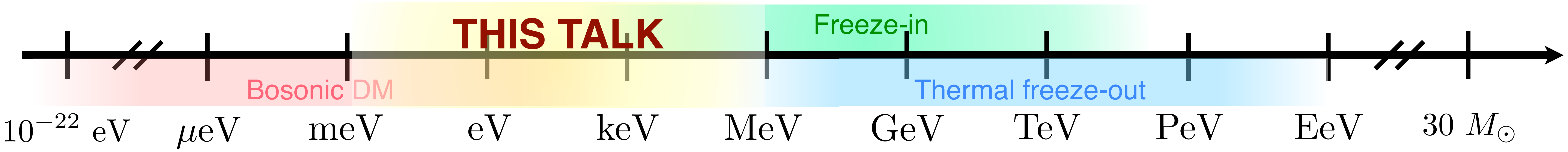


The experimental landscape



- Torsion Balances
- Interferometry
- NMR
- Resonant Cavities
- LStW

Collective Effects

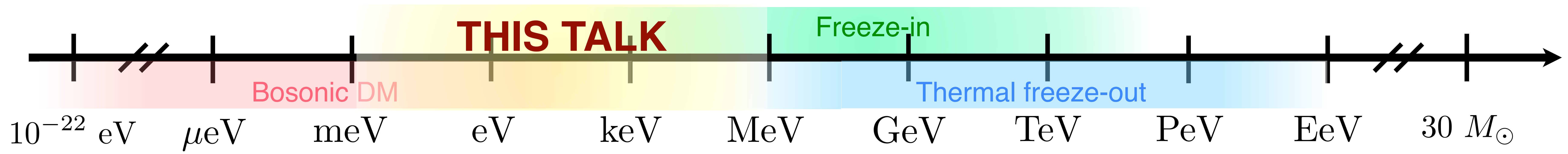
- Direct Detection
- Beam Dumps
- LLP Searches (e.g. FASER)
- Direct LHC production

Particle Effects

Astrophysics

Macroscopic

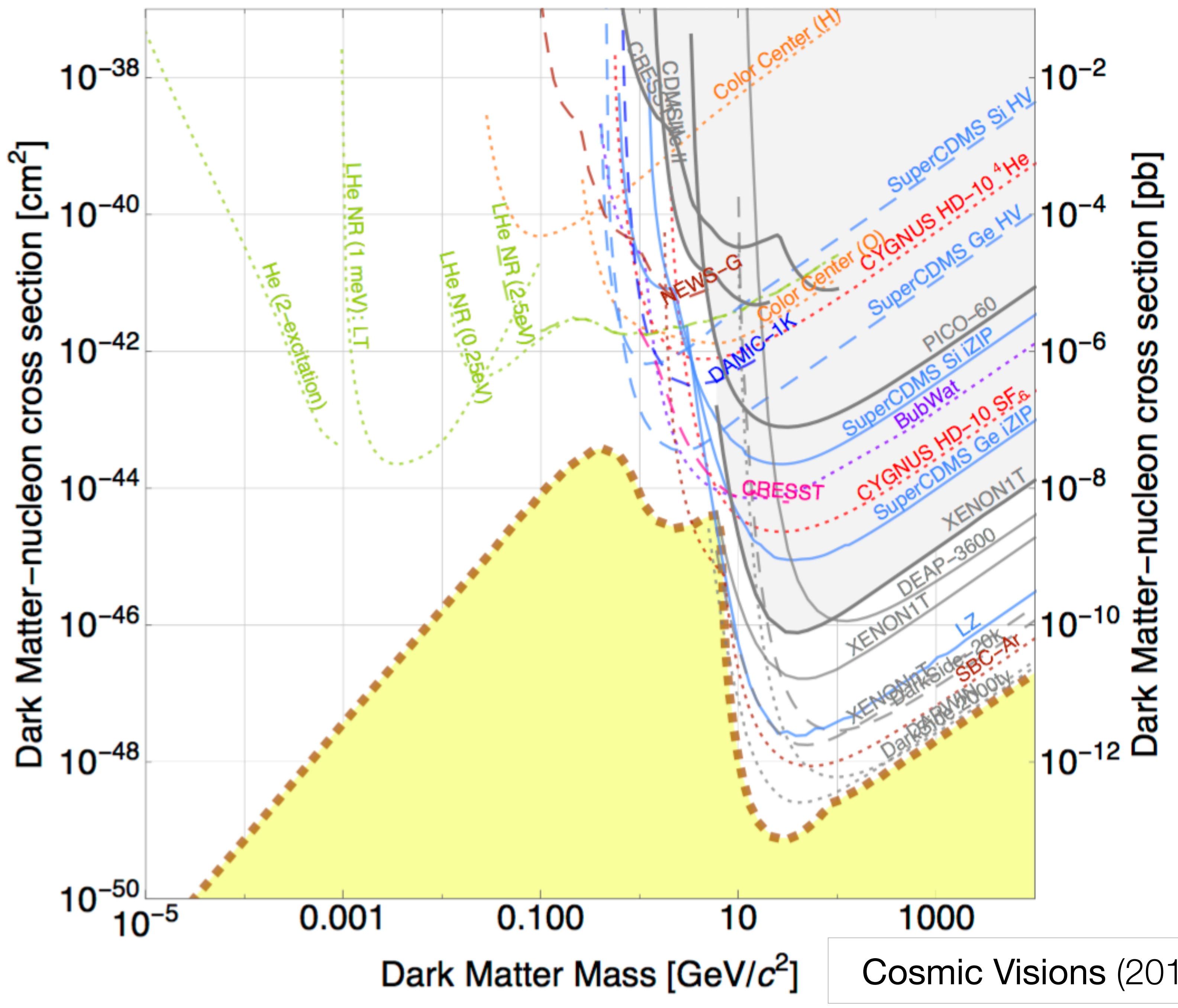
Experimental techniques > keV: *particle effects*



Nuclear recoils:

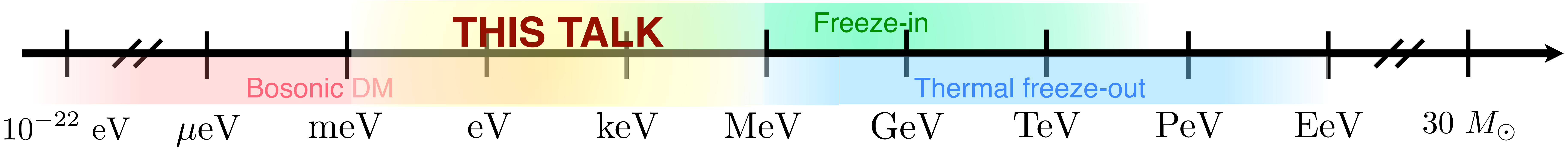
quickly drops below threshold for sub-GeV DM mass

$$E_{\rm N} = \frac{q^2}{2m_N} \lesssim 800 \text{ eV} \left(\frac{m_\chi}{1 \text{ GeV}}\right)^2 \left(\frac{16 \text{ GeV}}{m_N}\right)$$



Cosmic Visions (2017)

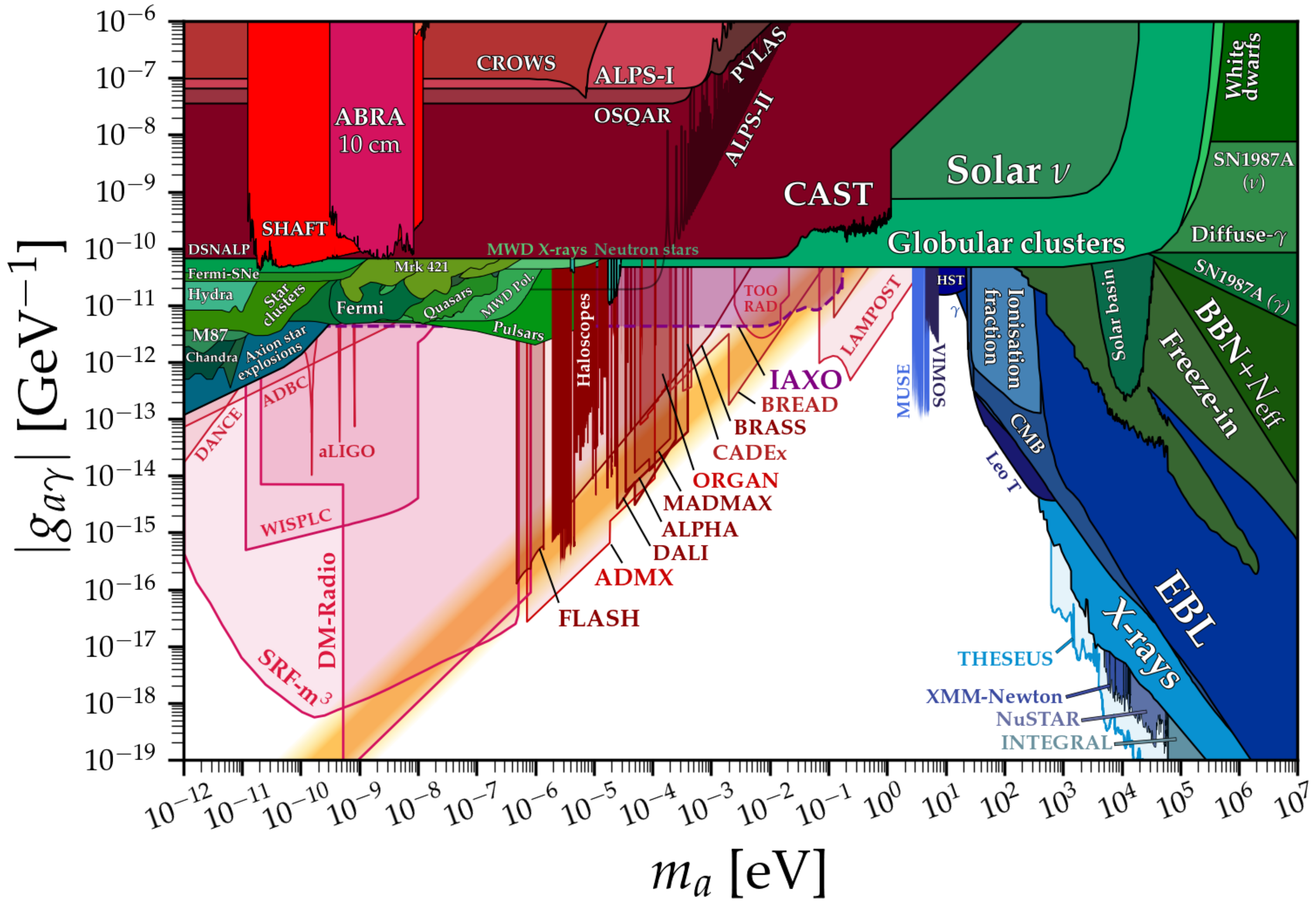
Experimental techniques ≪ keV: *collective effects*

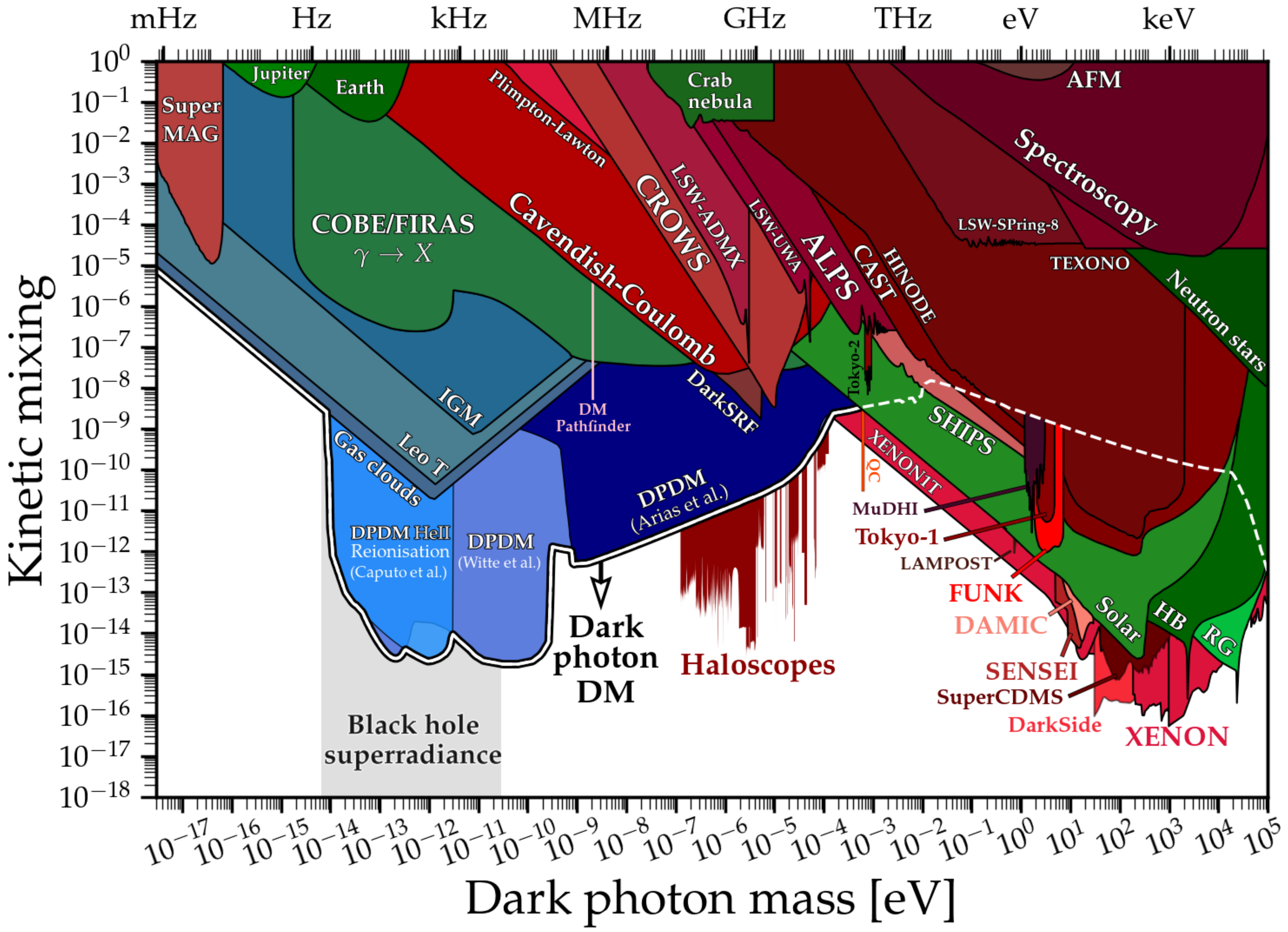


Coupling to EM:

E.g. Axion searches, DP searches

Rely on large n



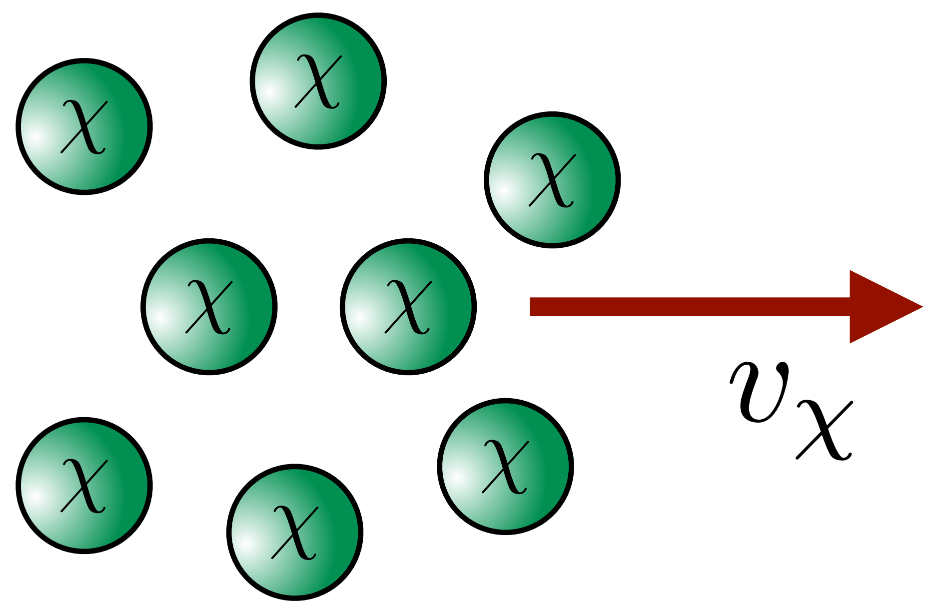


C. O'Hare (2023)

A General Approach

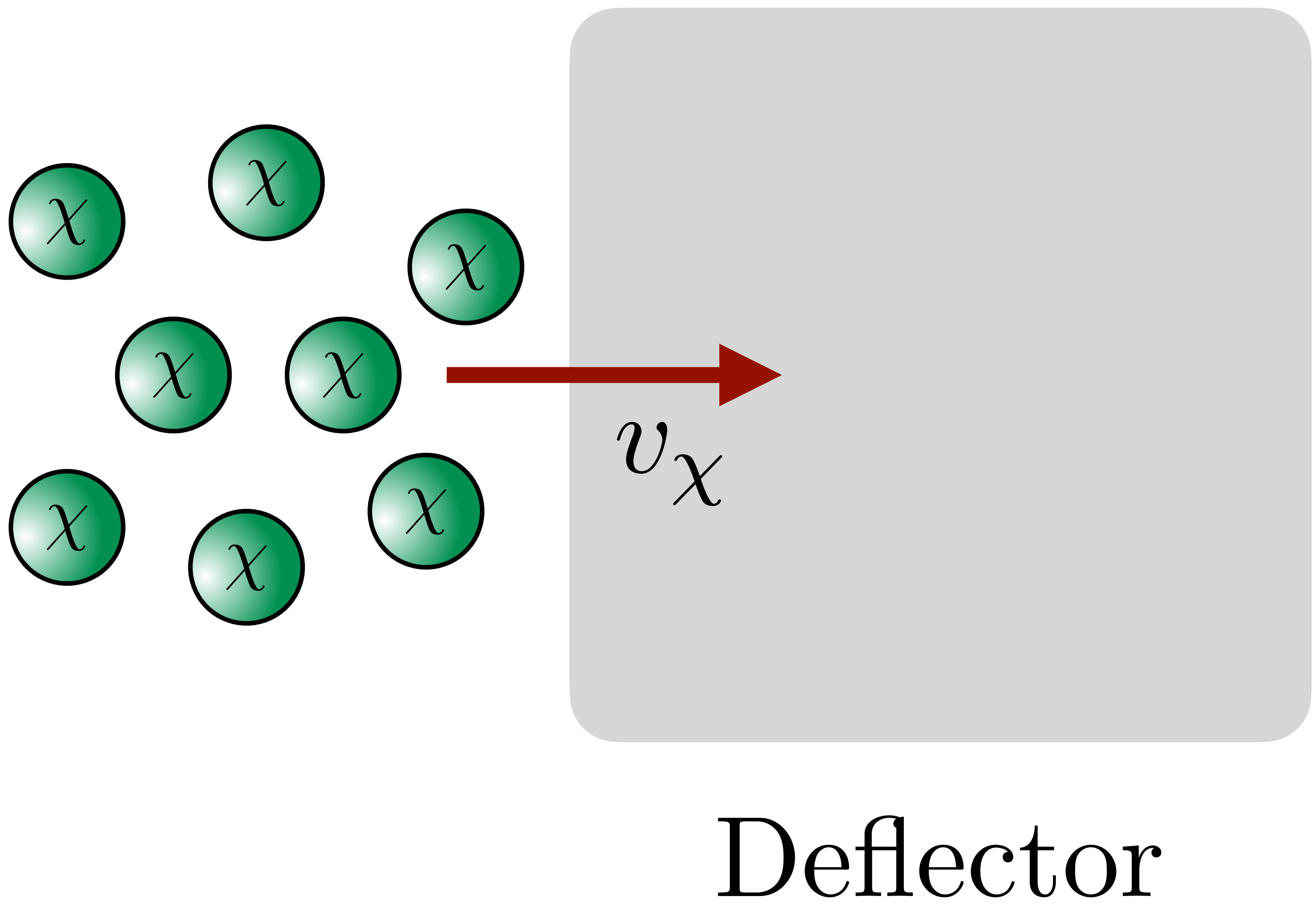
Sub-keV particle DM — low recoil

Assume interacts via long-range mediator



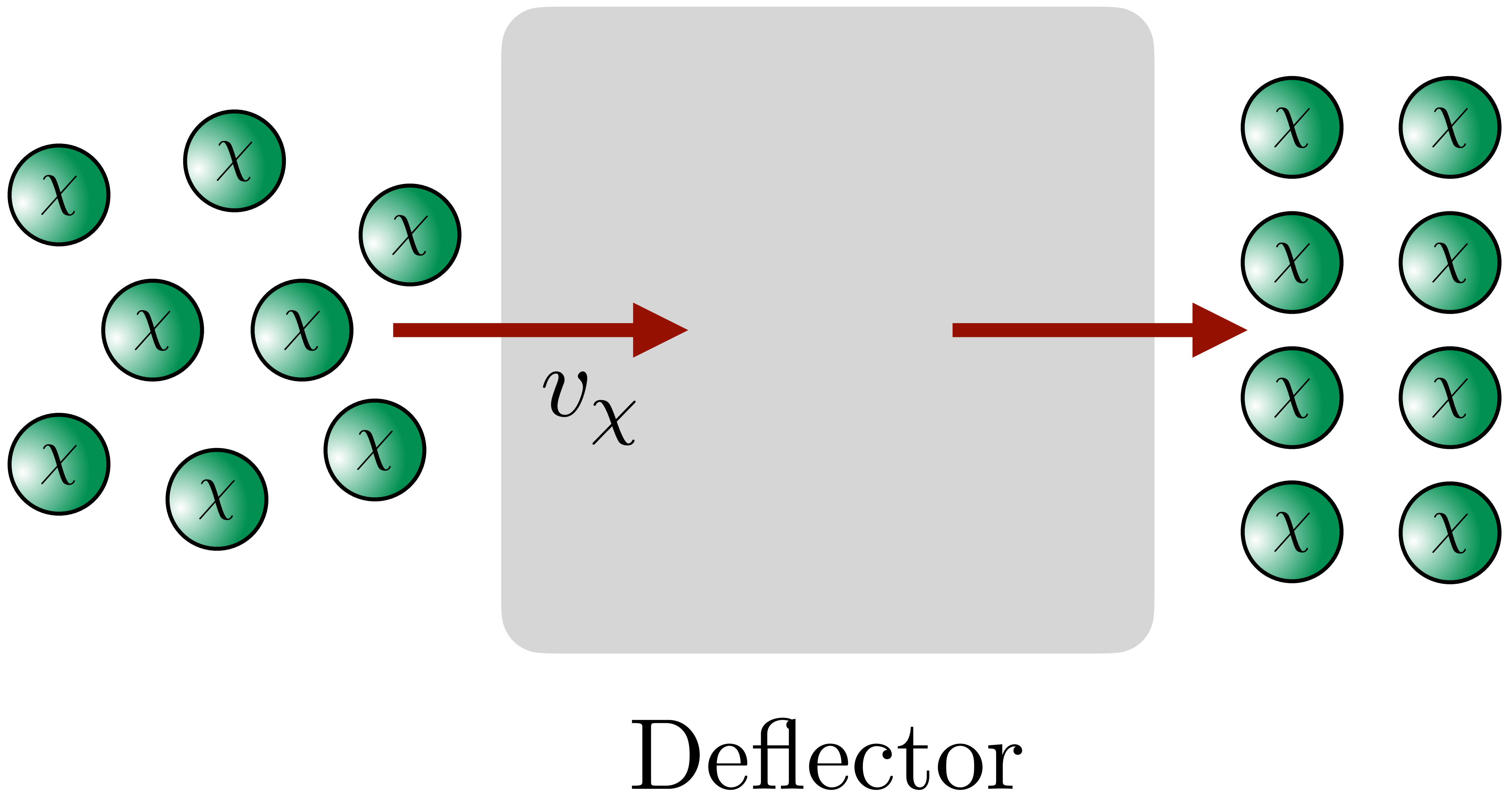
A General Approach

Interaction-dependent



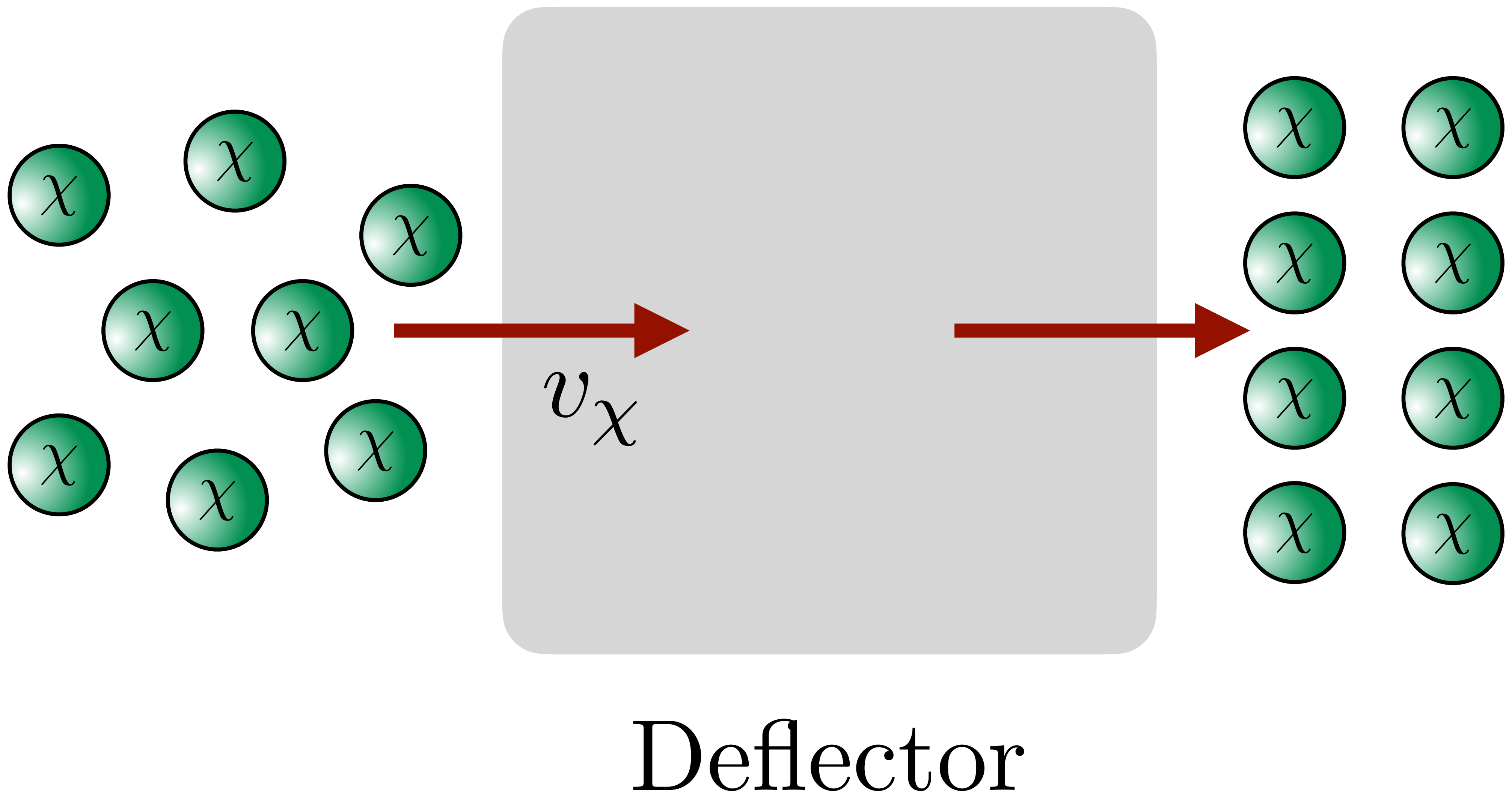
A General Approach

Coherent effect induced



A General Approach

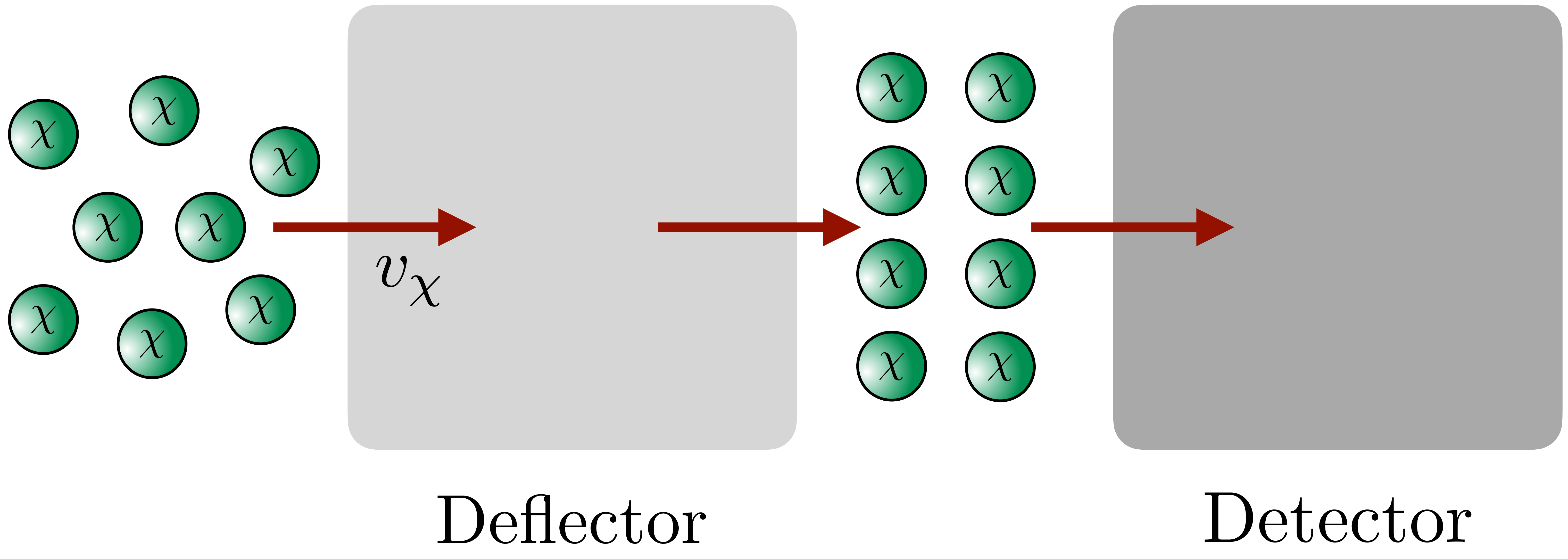
Coherent effect induced



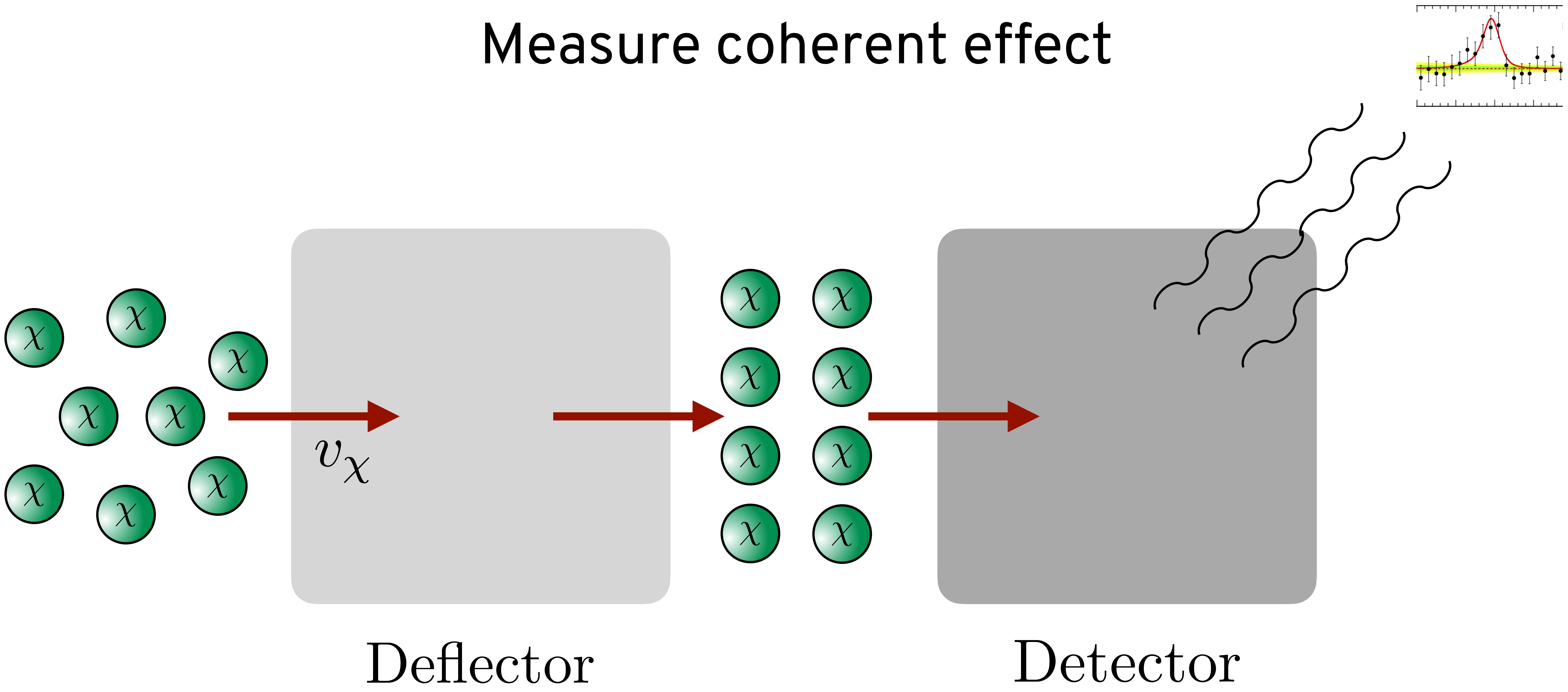
Effect magnitude set by deflector, not DM

A General Approach

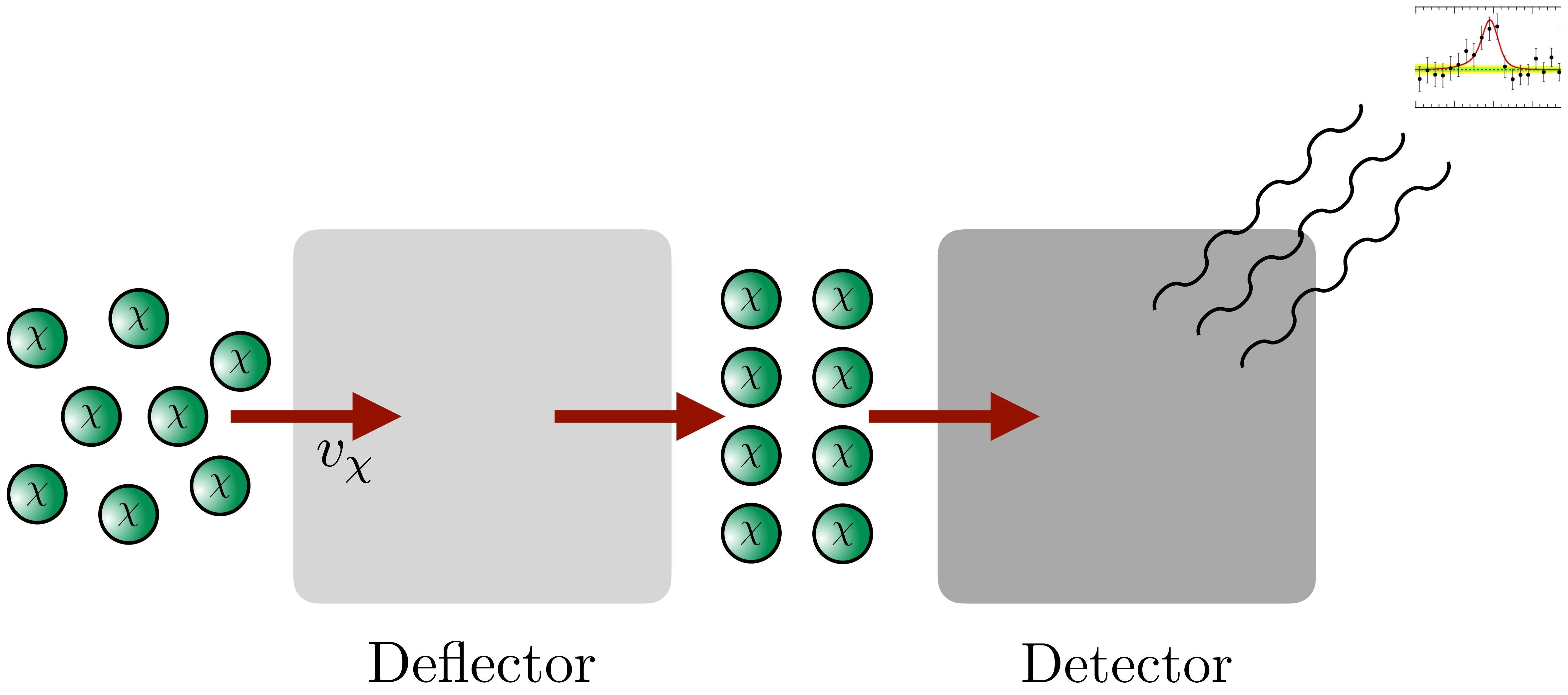
Coherent flow into detector



A General Approach



A General Approach

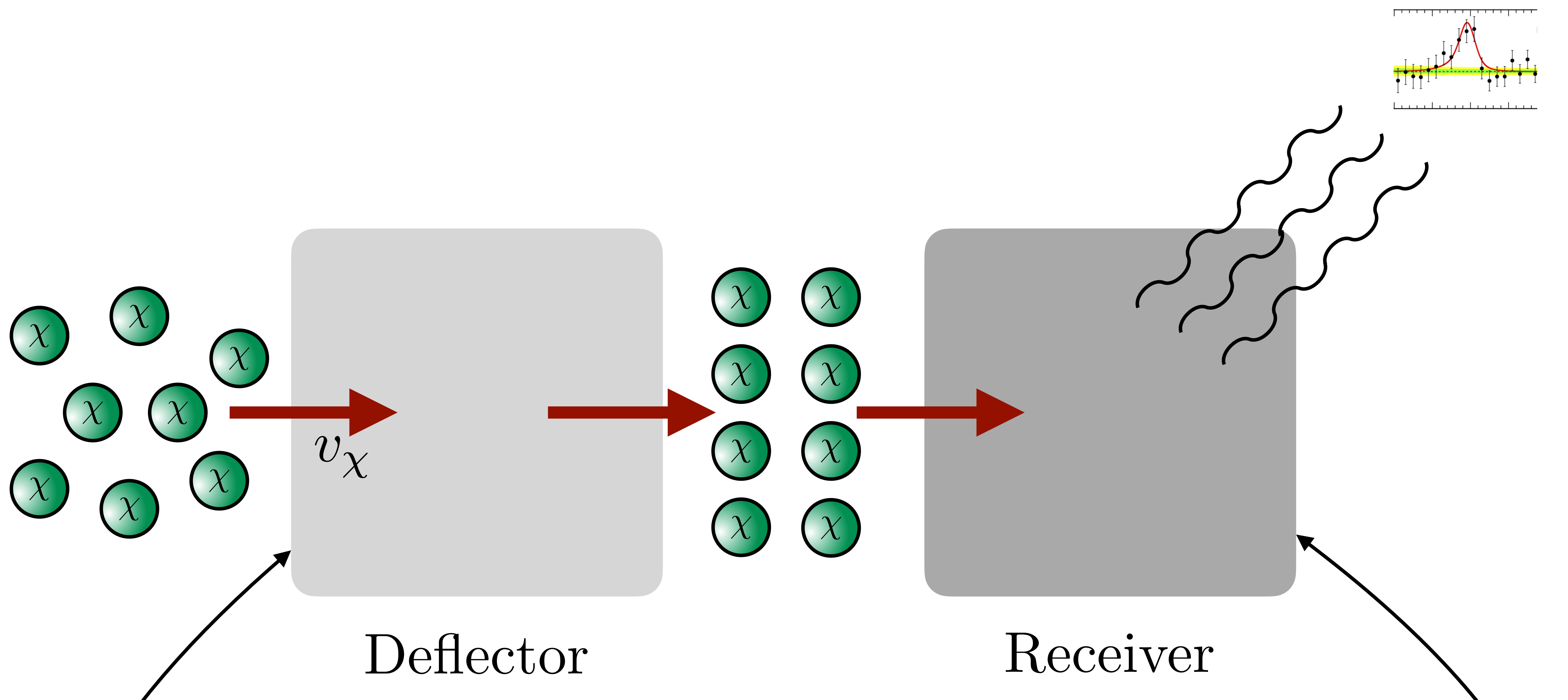


Makes use of large number density at low DM mass

Advantage: ~~requires sensitivity to small energy transfer~~

Health warning: requires low-mass mediator

A Concrete Example: (Effectively) Millicharged DM



EM field region

Magnetometer/Voltmeter

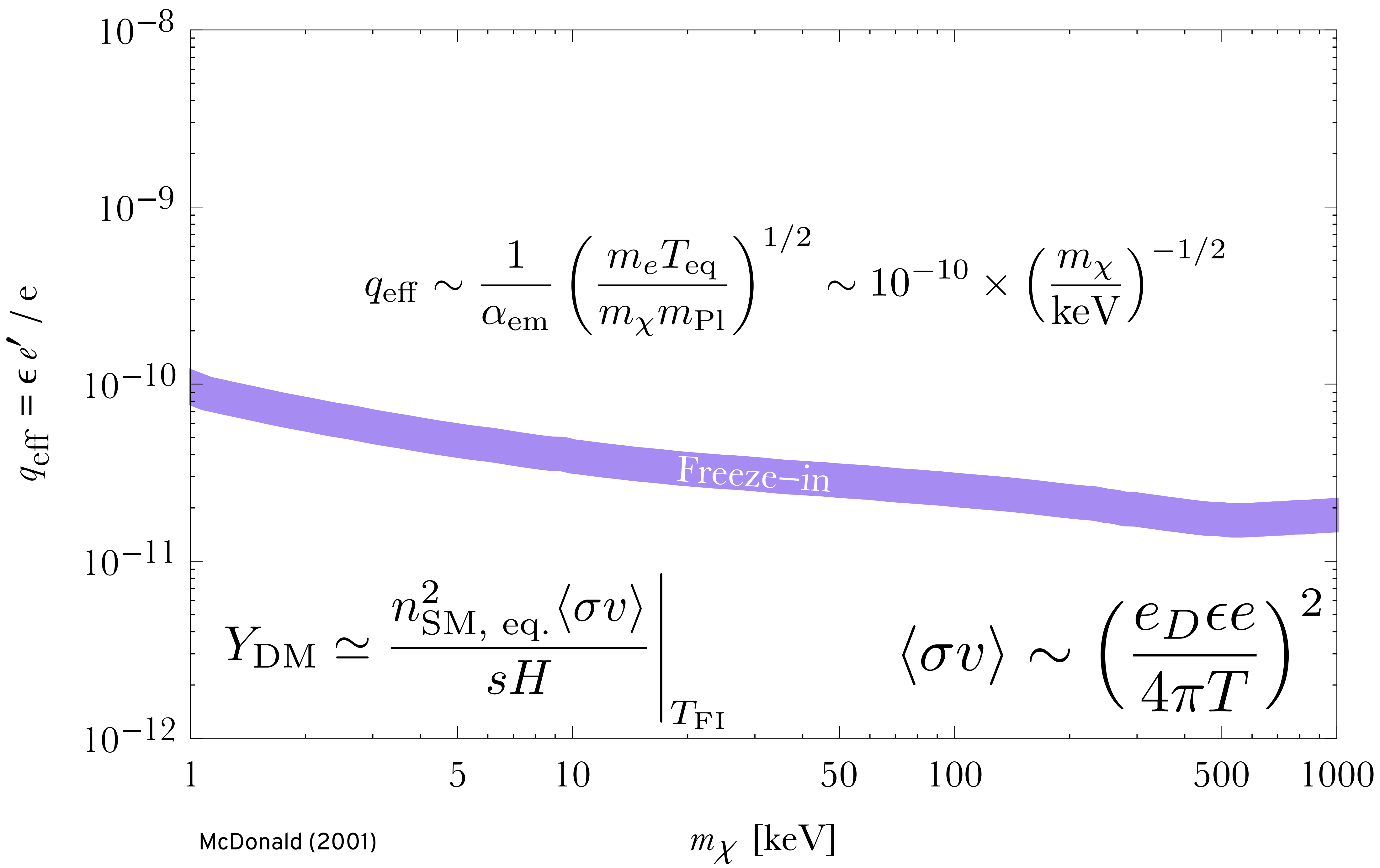
Dark Matter coupled to a Dark Photon

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon}{2}F_{\mu\nu}F'_{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu + eA_\mu J^\mu_{\rm EM} + e_D A'_\mu J^\mu_{\rm D}$$

$$J^\mu_{\rm D} = \quad \bar{\chi}\gamma^\mu\chi, \quad \left(\varphi^\dagger\partial^\mu\varphi - (\partial^\mu\varphi)^\dagger\varphi\right)$$

Fermion **Scalar**

Allows for DM abundance through Freeze-in

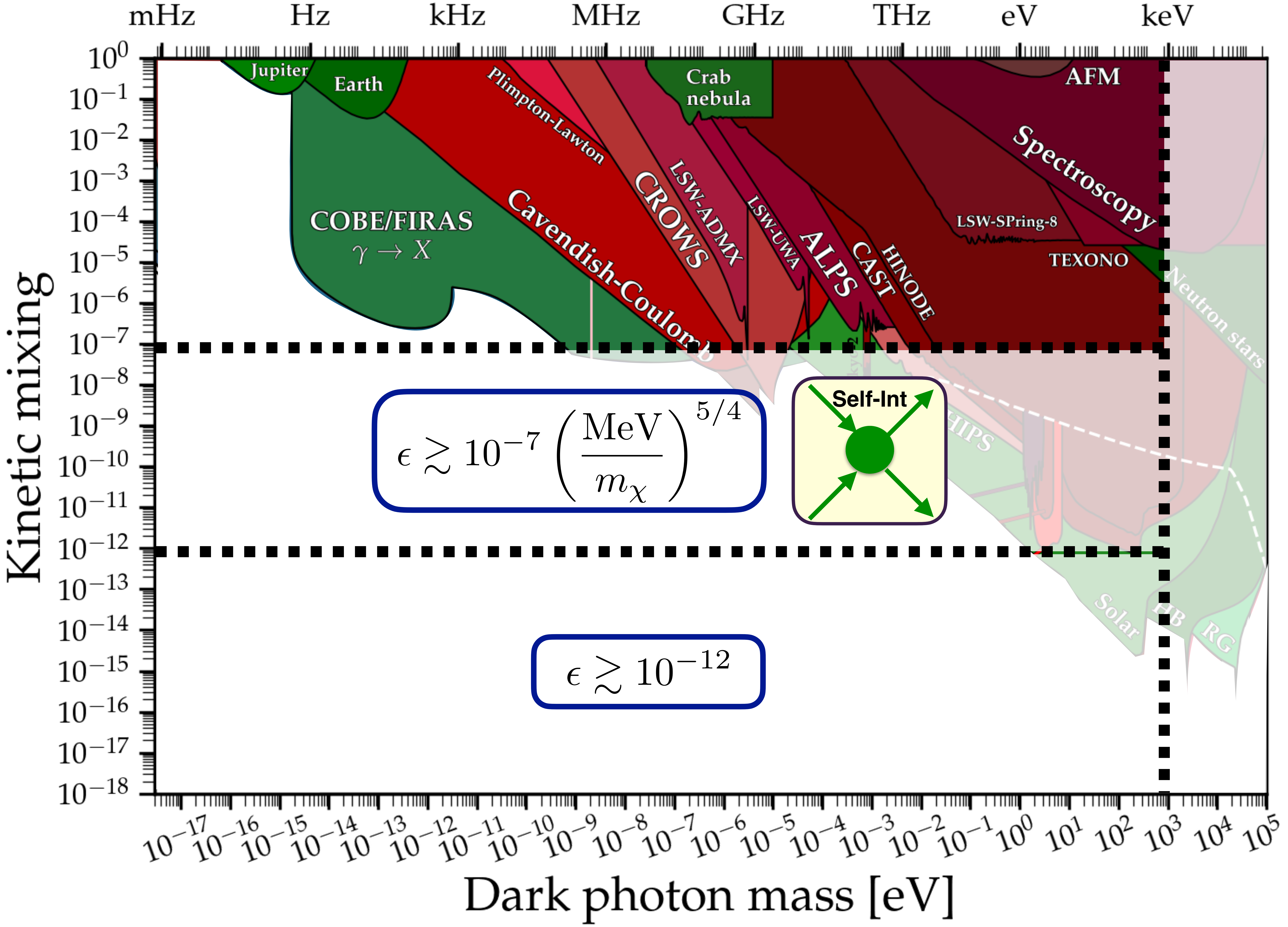


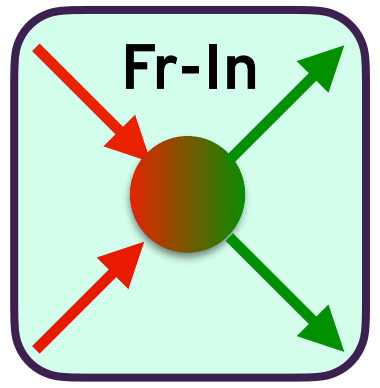
McDonald (2001)
Hall, Jedamzik, March-Russell, West (2009)
Chu, Hambye, Tytgat (2012)
Dvorkin, Lin, Schutz (2019)

Dark Photon Mass?

Only $m_{A'} \lesssim 10^{-9}$ eV allowed!

Force range $\lambda \gg$ m





$m_{A'} <$ keV

Key Implication

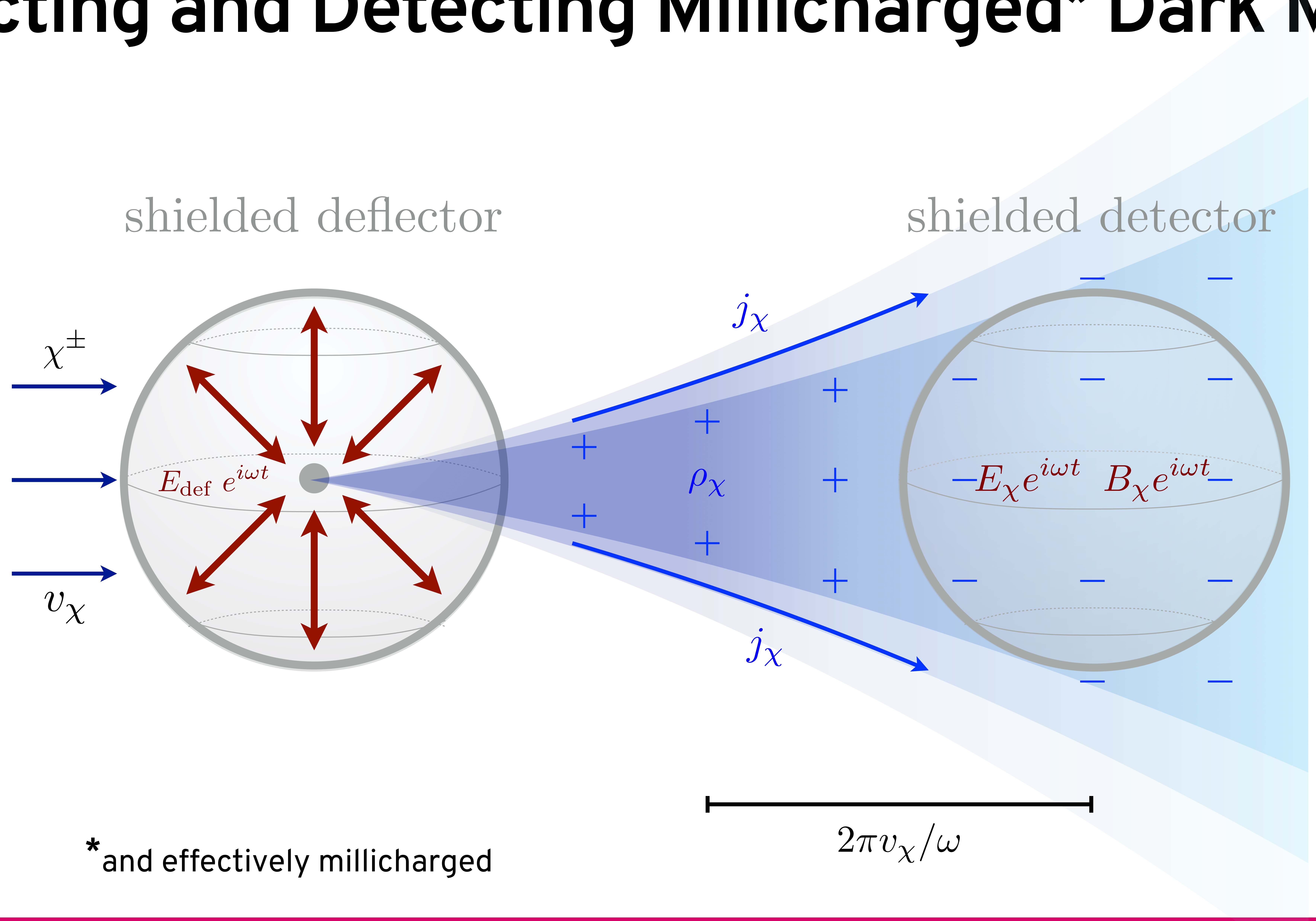
$$A_\mu \to A_\mu + \epsilon A'_\mu \;\; \text{\&} \;\; A'_\mu \to \frac{A'_\mu}{\sqrt{1-\epsilon^2}} \;\; \text{rotation:}$$

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{A'}}{2(1-\epsilon^2)}A'_\mu A'^\mu$$
$$+ e\left(A_\mu + \epsilon A'_\mu\right) J^\mu_{\mathrm{EM}} + \frac{e_D}{\sqrt{1-\epsilon^2}} A'_\mu J^\mu_{\mathrm{D}}$$

When SM charges set up a visible EM field,
also set up a macroscopic hidden field

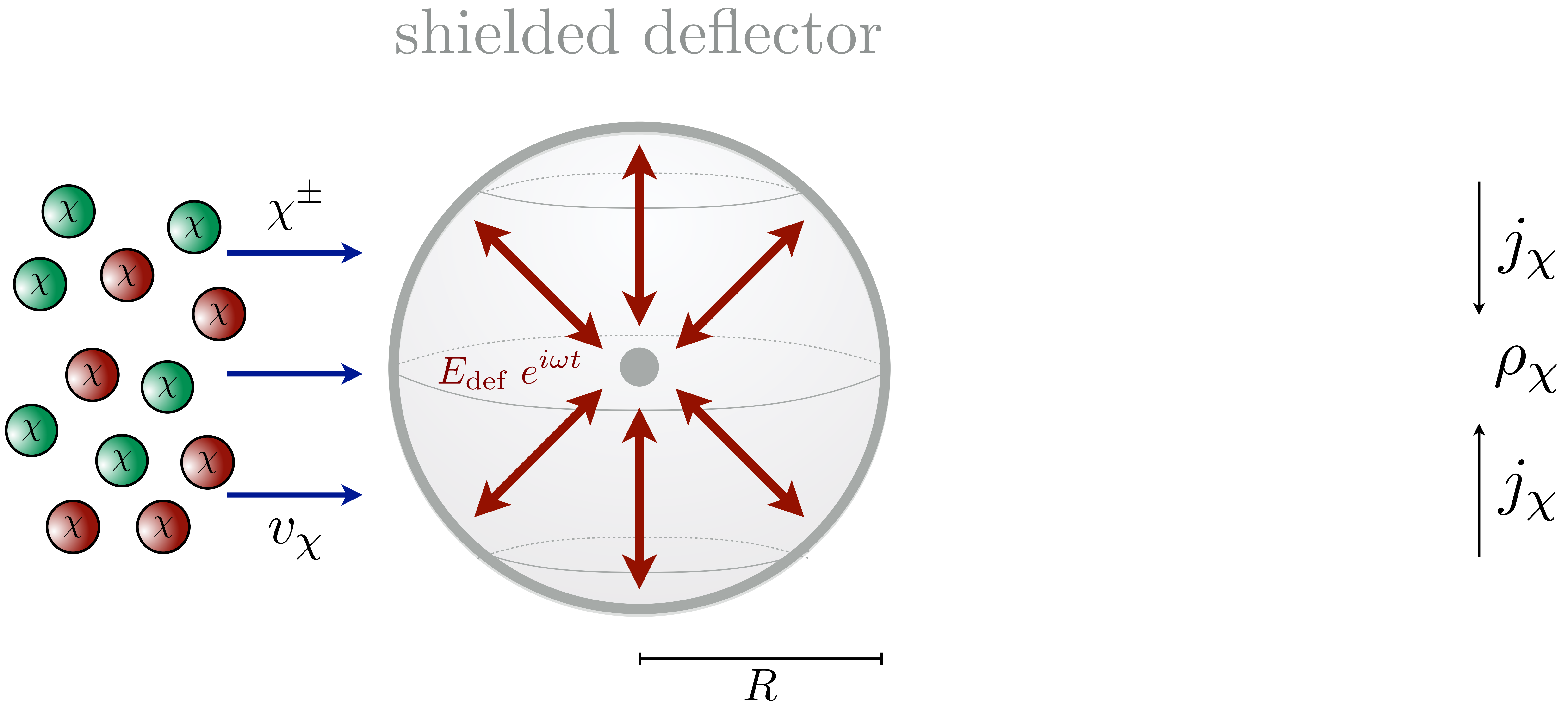
c.f. true milliQ: $\mathcal{L} \supset e A_\mu \left(J^\mu_{\mathrm{EM}} + q_{\mathrm{eff}} J^\mu_{\mathrm{D}}\right)$ $\quad q_{\mathrm{eff}} = \frac{\epsilon e_D}{e}$

Deflecting and Detecting Millicharged* Dark Matter



*and effectively millicharged

Inducing Dark Matter Waves



$$\omega \lesssim \pi\, v_\chi / R \sim \mathrm{MHz} \times (R/\mathrm{meter})^{-1}$$

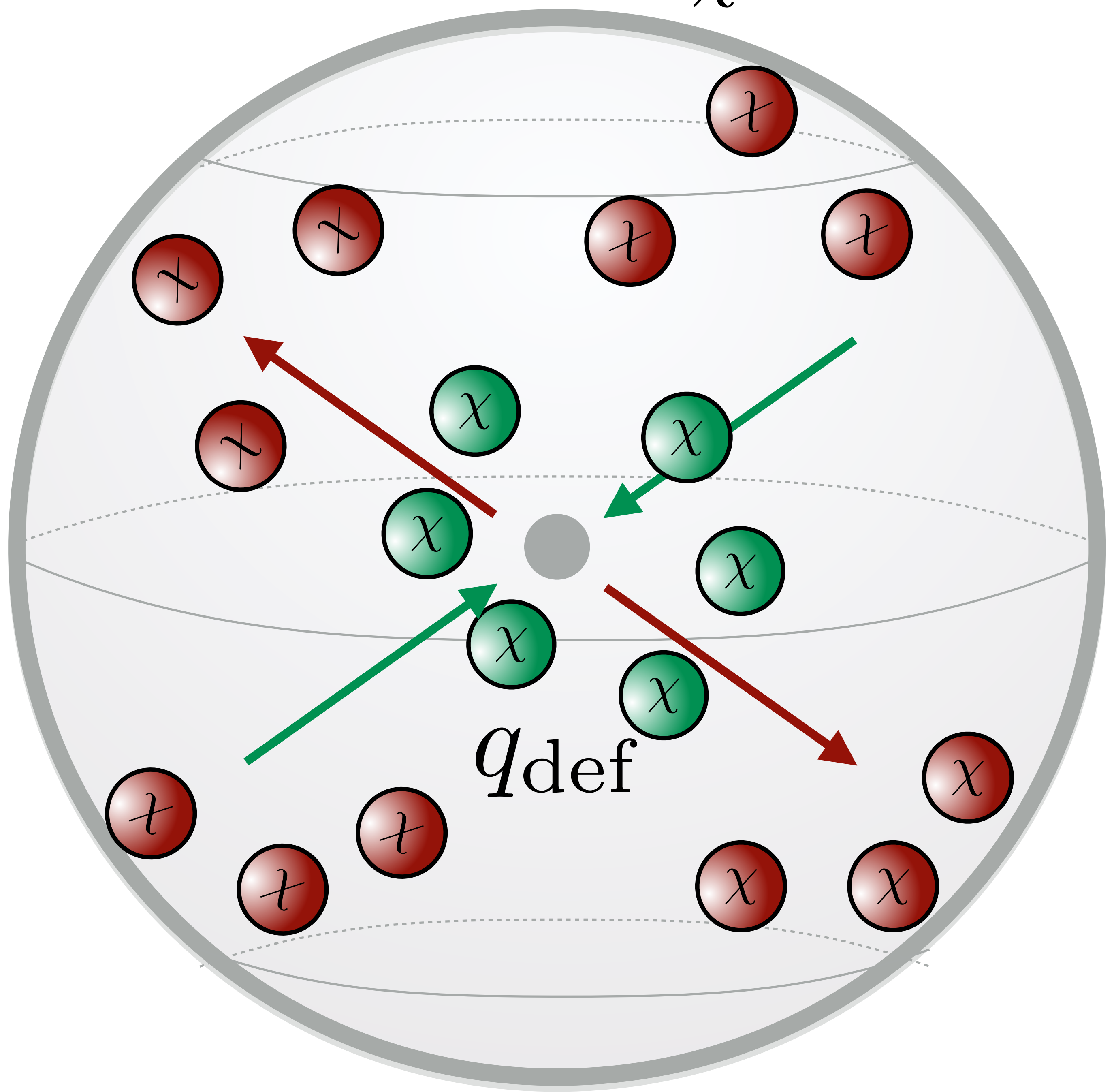
quasi-static limit

Charge Density Calculation

Debye Screening of a potential in a thermal plasma: $T \equiv (m_\chi/3)\langle v^2\rangle \simeq (m_\chi/2)v_0^2$

$$\rho_\chi(\mathbf{x}) \simeq -\frac{(eq_{\rm eff})^2\rho_{\rm DM}}{m_\chi}\frac{\phi_{\rm def}(\mathbf{x})}{T}$$

DM charges attempt to screen deflector charge



$\phi_{\rm def}(\mathbf{x}) \sim eq_{\rm def}/|\mathbf{x}|$

$\omega_{\rm p} \ll \omega$

No backreaction

But, potential is shielded — need exact computation of this effect

Charge Density Calculation w/ Shield

Resultant charge density:

$$\rho_\chi(\mathbf{x},t) \simeq -\frac{(eq_{\text{eff}})^2 \rho_{\text{DM}}}{m_\chi^2}\, e^{i\omega t} \int dv\; d^3\mathbf{x}'\; f(v\,\hat{\mathbf{v}})\, \frac{\rho_{\text{def}}(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|}\, e^{-i\omega|\mathbf{x}-\mathbf{x}'|/v} \qquad \hat{\mathbf{v}} \equiv \frac{\mathbf{x}-\mathbf{x}'}{|\mathbf{x}-\mathbf{x}'|}$$

Expand in multipole moments — first non-zero is charge radius

$$\rho_\chi(\mathbf{x},t) \simeq -\frac{(eq_{\text{eff}})^2 \rho_{\text{DM}}}{m_\chi^2}\, e^{i\omega t} \left(\rho_\chi^{(1)} + \rho_\chi^{(2)} + \rho_\chi^{(3)} + \cdots\right)$$

$$\rho_\chi(\mathbf{x}) \simeq -\frac{(eq_{\text{eff}})^2\, \rho_{\text{DM}}\, \mathcal{R}_{\text{def}}^2}{6 m_\chi^2} \int dv\; \nabla^2 \frac{f(v\,\hat{\mathbf{x}})}{|\mathbf{x}|}$$

Comparison w/ Debye estimate

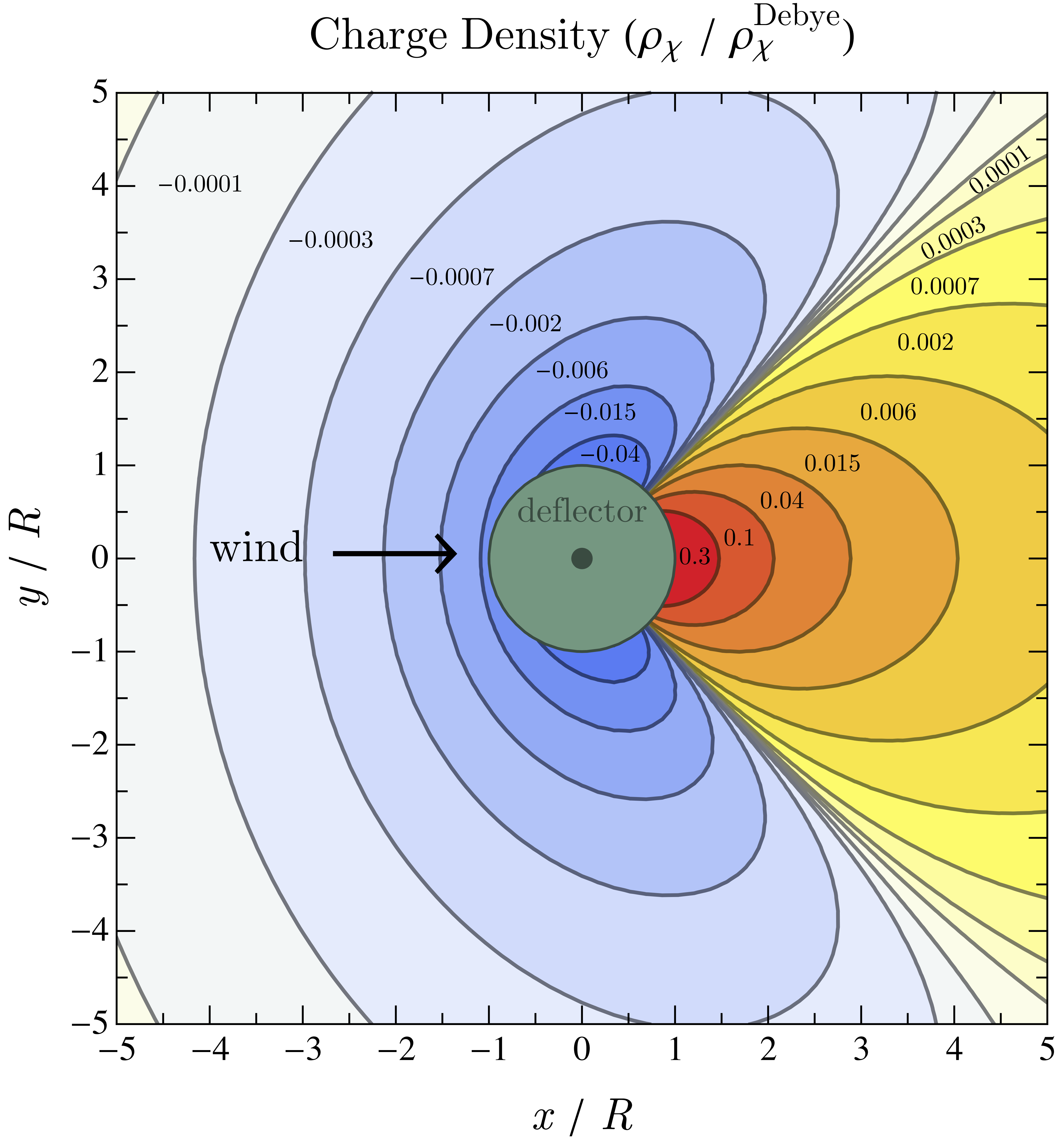
$$\rho_\chi^{\text{Debye}}(\mathbf{x}) \sim -\frac{(e q_{\text{eff}})^2 \, \rho_{\text{DM}}}{m_\chi^2 \, v_0^2} \frac{e q_{\text{def}}(\mathbf{x})}{|\mathbf{x}|}$$

Suppression due to charge radius:

$$\rho_\chi(\mathbf{x}) \propto \rho_\chi^{\text{Debye}}(R) \left(\frac{R}{|\mathbf{x}|}\right)^3$$

Effect vanishes in limit where $v_{\text{wind}} \to 0$

$$\rho_\chi(\mathbf{x}) \sim \rho_\chi^{\text{Debye}}(R) \left(\frac{v_{\text{wind}}}{v_0}\right)^2 \left(\frac{R}{|\mathbf{x}|}\right)^3$$



Current density

Calculation proceeds in same manner as for charge density

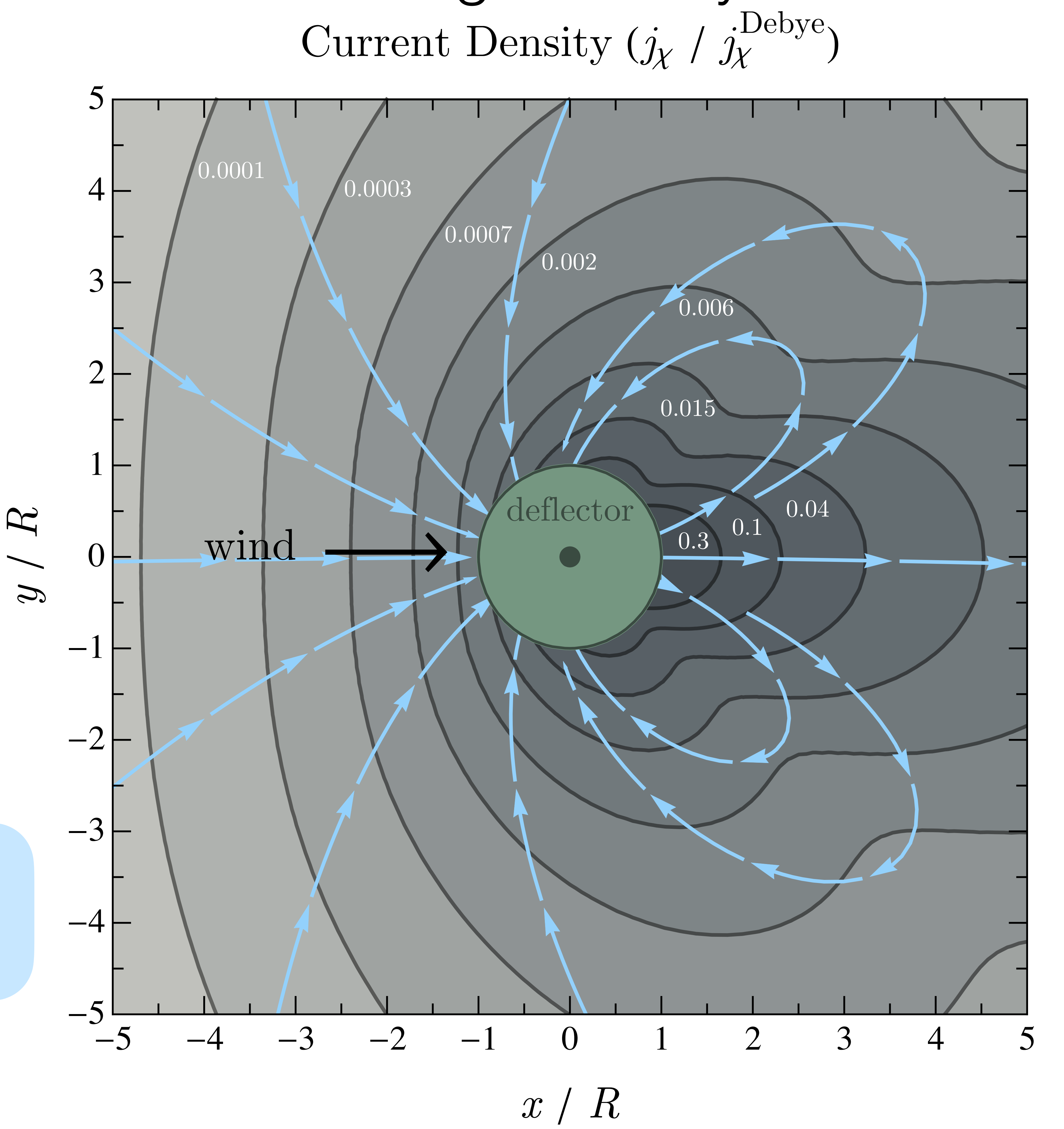
$$j_\chi(\mathbf{x}) \sim \rho_\chi(\mathbf{x})\, v_{\rm wind}$$

Compare with Debye estimate:

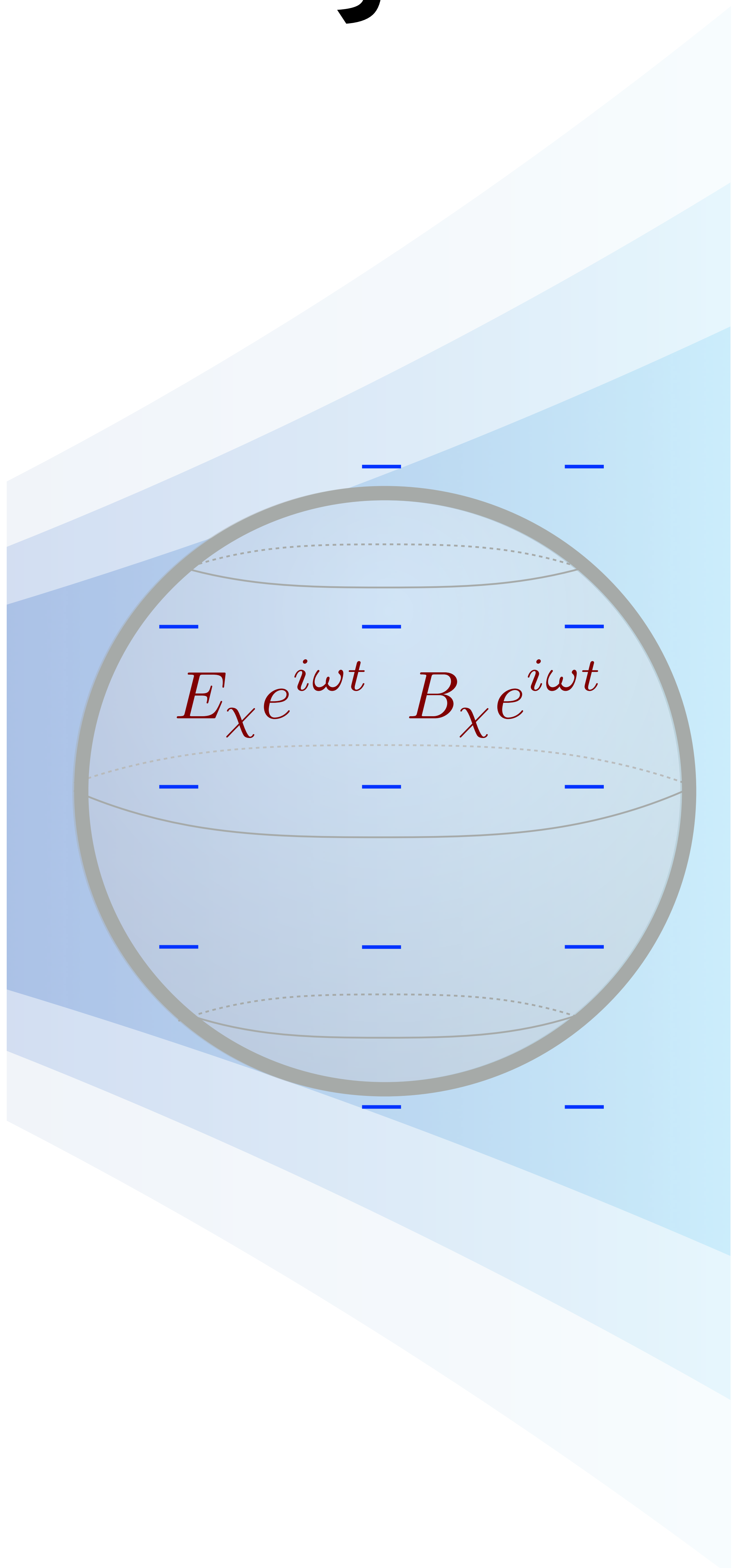
$$j_\chi^{\rm Debye} \equiv \rho_\chi^{\rm Debye} v_{\rm wind}$$

Current density velocity-*suppressed*

B-field signal therefore suppressed w.r.t. **E**-field signal



Detecting Dark Matter Waves



Oscillation of deflector induces oscillation of charge and current densities in detector:

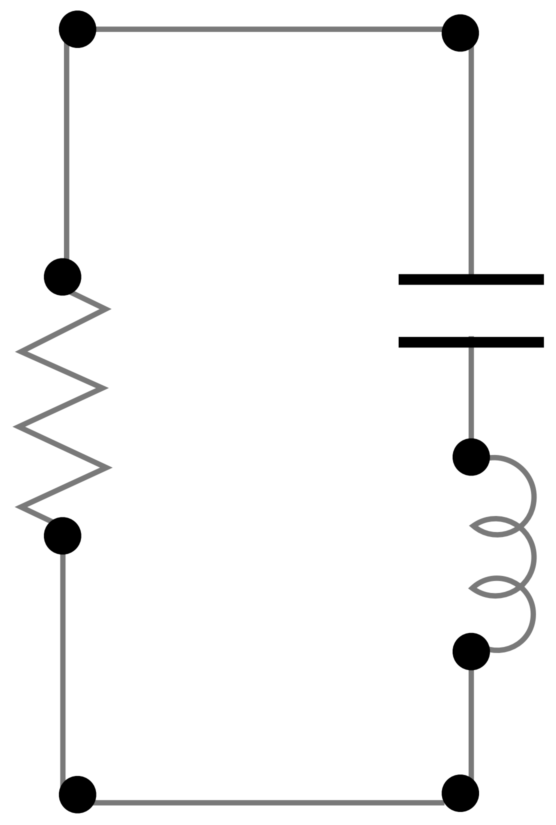
$$\rho_\chi(t) \simeq \rho_\chi\, e^{i\omega t}\ ,\ \boldsymbol{j}_\chi(t) \simeq \boldsymbol{j}_\chi\, e^{i\omega t}$$

Recall requirement

$$\omega \lesssim \pi\, v_\chi/R \sim \mathrm{MHz} \times (R/\mathrm{meter})^{-1}$$

Solution: **Lumped LC Resonator**

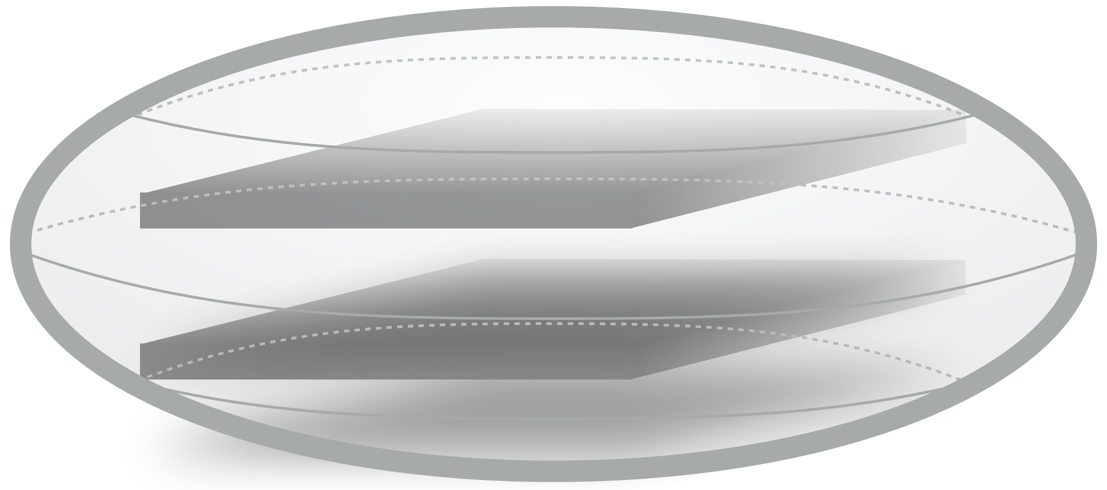
$$\omega_{\mathrm{LC}} = \frac{1}{\sqrt{LC}}$$



Ring up signal over Q cycles

Detecting Dark Matter Waves

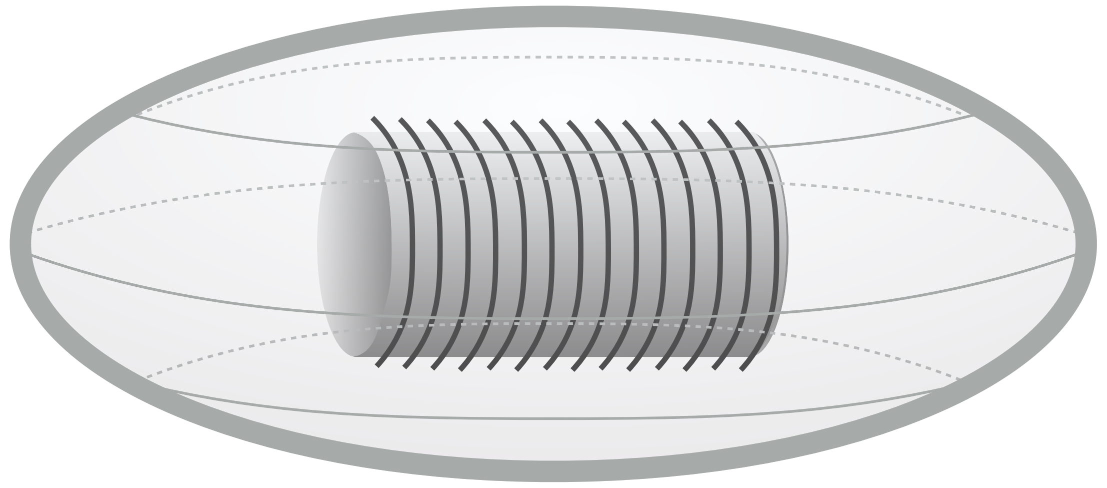
Since E-field signal dominant, capacitative pickup optimal



$$U_{\mathrm{s}} = \int_V \frac{1}{2}\epsilon \mathbf{E}^2$$

Effective volume of capacitor/antenna – bounded by shielded volume

DM Radio being built for B-field signal – large effective inductor volume



$$U_{\mathrm{s}} = \frac{1}{2}LI^2 = \int_V \frac{1}{2}\frac{\mathbf{B}^2}{\mu}$$

Effective volume of inductor – many coils

Signal to Noise

$$\text{SNR} \simeq \frac{\omega\, Q\, t_{\text{int}}}{4\, T_{\text{LC}}} \int_{\text{det}} d^3\mathbf{x}\, (E_\chi^2 \text{ or } B_\chi^2) \propto \left(\frac{q_{\text{eff}}}{m_\chi}\right)^4$$

Unpack this expression

$$4R_{\text{LC}}T_{\text{LC}}$$

Thermal (Johnson-Nyquist) noise limited power spectral density

$$\langle V_{\text{LC}}\rangle^2 \simeq \frac{1}{C_{\text{LC}}} \int_{\text{det}} d^3\mathbf{x}\, E_\chi^2$$

Signal voltage power spectral density (E-field)

$$\text{SNR} = \frac{\langle V_{\text{LC}}\rangle^2}{4R_{\text{LC}}T_{\text{LC}}}$$

SNR is ratio of PSDs

$$Q_{\text{LC}} \equiv \frac{1}{\omega C_{\text{LC}} R_{\text{LC}}}$$

Signal to Noise

$$\text{SNR} \simeq \frac{\omega\, Q\, t_{\text{int}}}{4\, T_{\text{LC}}} \int_{\text{det}} d^3\mathbf{x}\ (E_\chi^2 \text{ or } B_\chi^2) \propto \left(\frac{q_{\text{eff}}}{m_\chi}\right)^4$$

Unpack this expression

$\propto Q$ resonant detector allows ring-up of signal over Q cycles

e.g. AURIGA searching for Grav. Waves – achieved Q~10^6

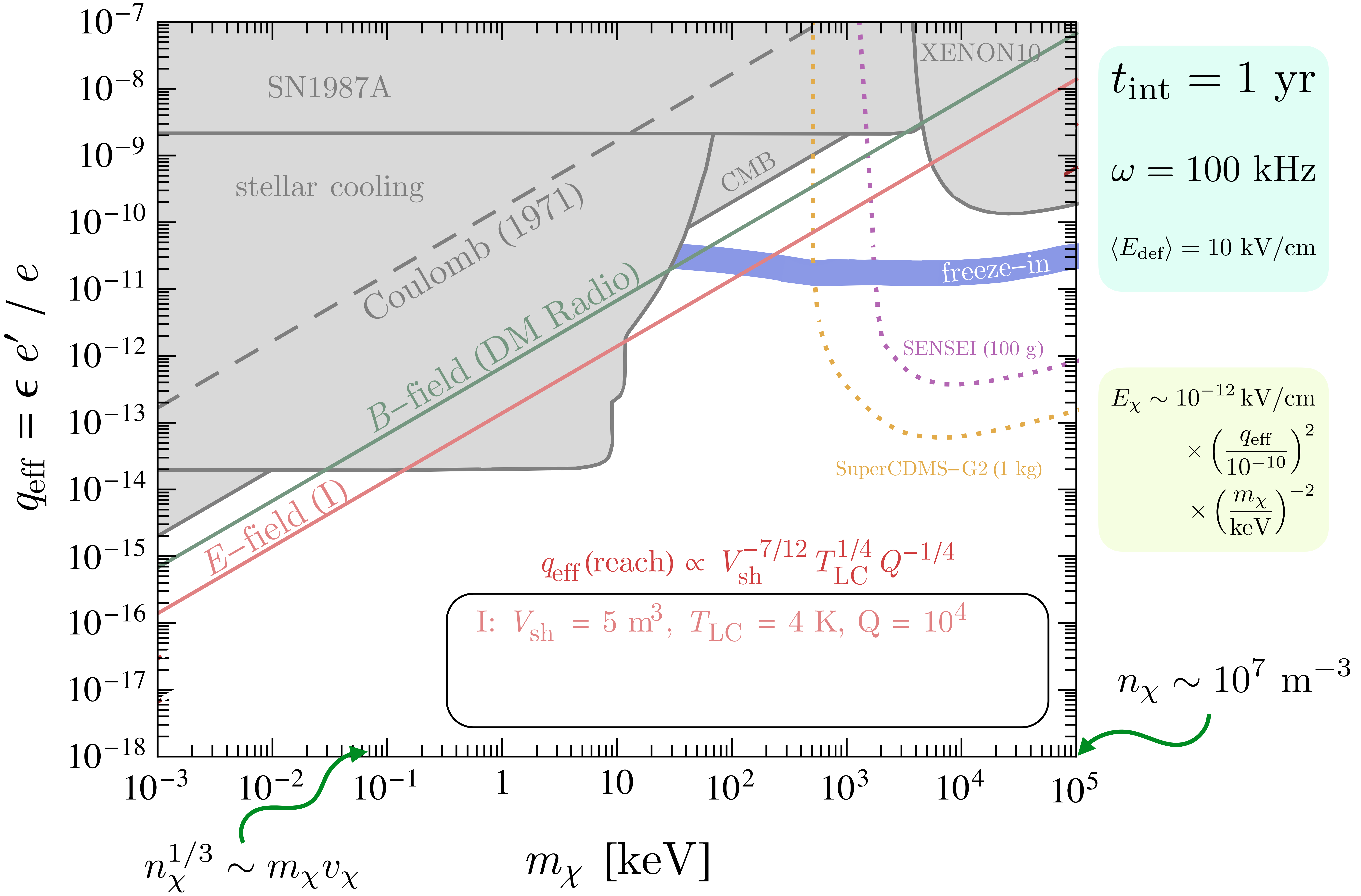
DM Radio planning on Q≳10^6

$\propto t_{\text{int}}$ requires coherence time > integration time

achieved by phase-locking *deflector* to e.g. NIST atomic clock

phase can drift small amounts: $P_{\text{s}} \propto \left(1 - \mathcal{O}(\delta\phi^2)\right)$

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



$t_{\rm int} = 1$ yr

$\omega = 100$ kHz

$\langle E_{\rm def}\rangle = 10$ kV/cm

$E_\chi \sim 10^{-12}$ kV/cm $\times \left(\frac{q_{\rm eff}}{10^{-10}}\right)^2 \times \left(\frac{m_\chi}{\rm keV}\right)^{-2}$

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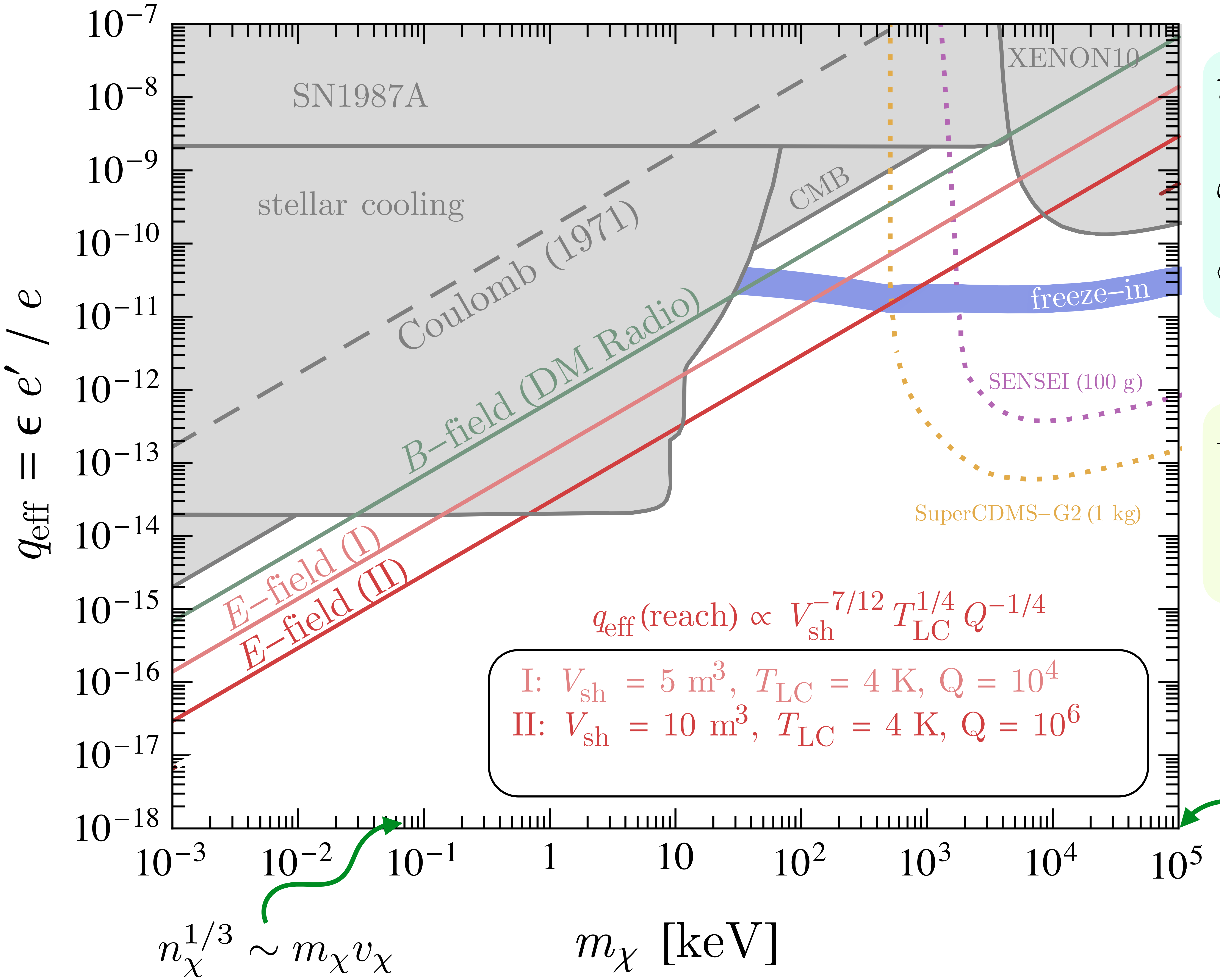

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$n_\chi \sim 10^7$ m^{-3}

$n_\chi^{1/3} \sim m_\chi v_\chi$

Experimental Reach

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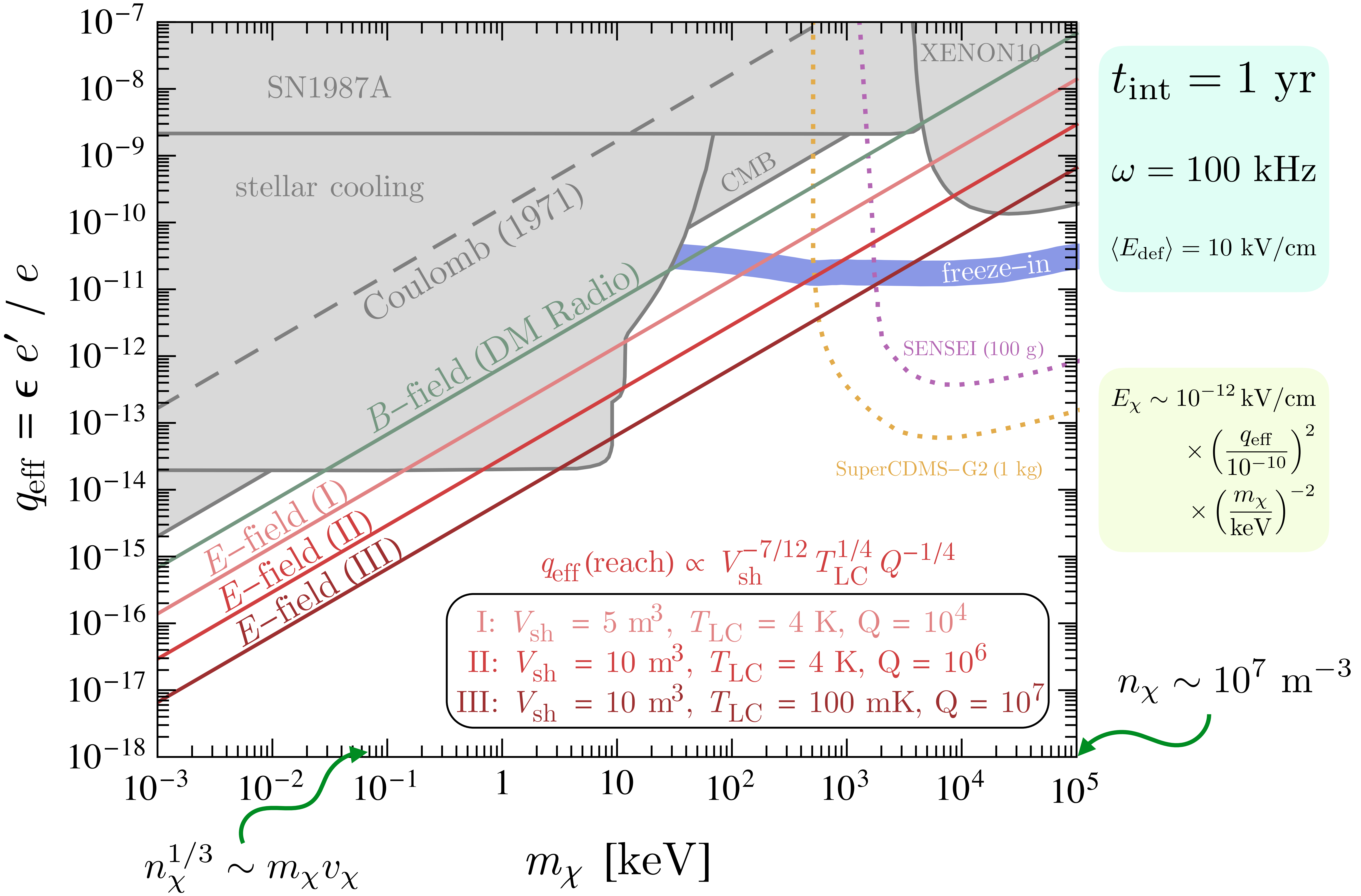

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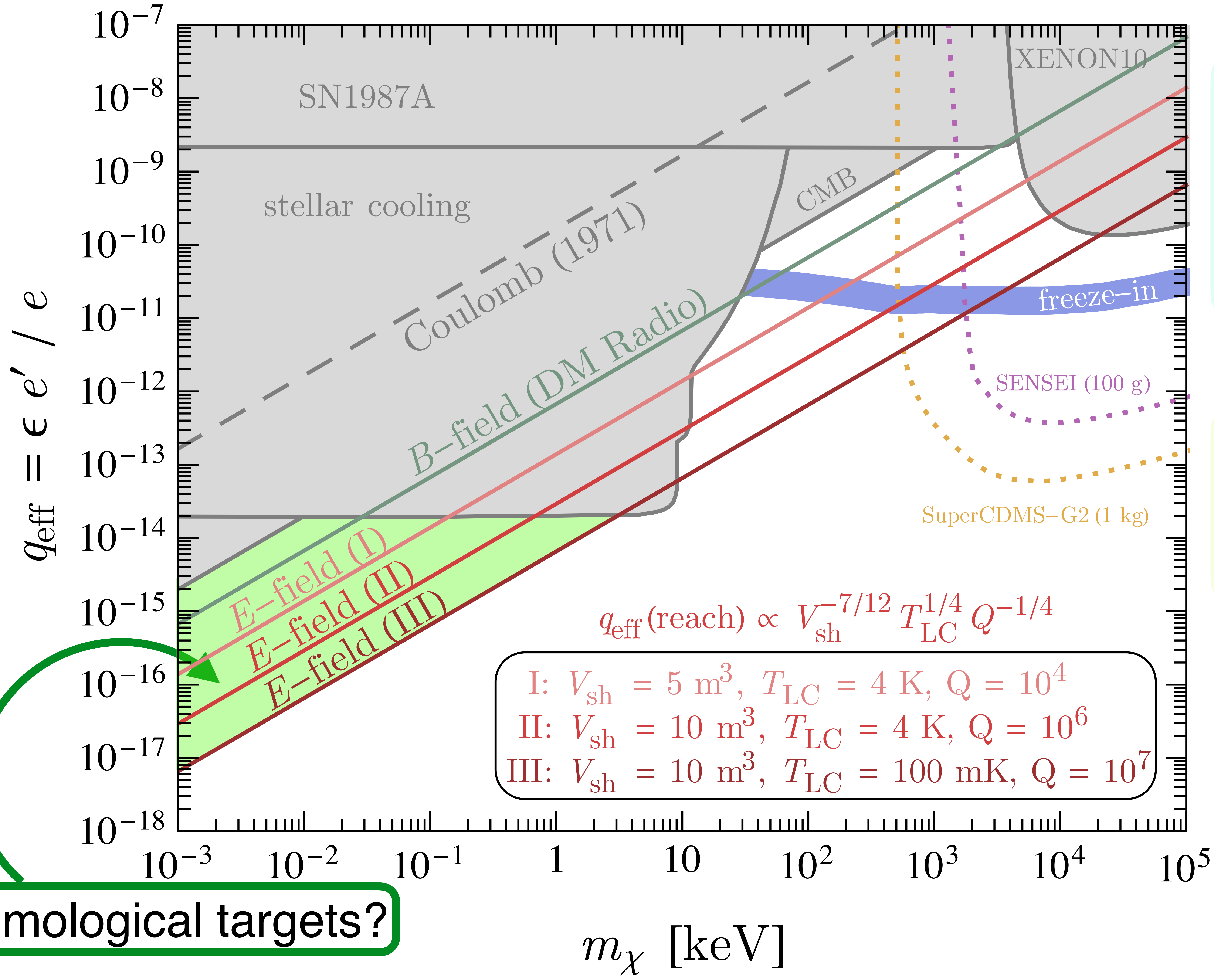

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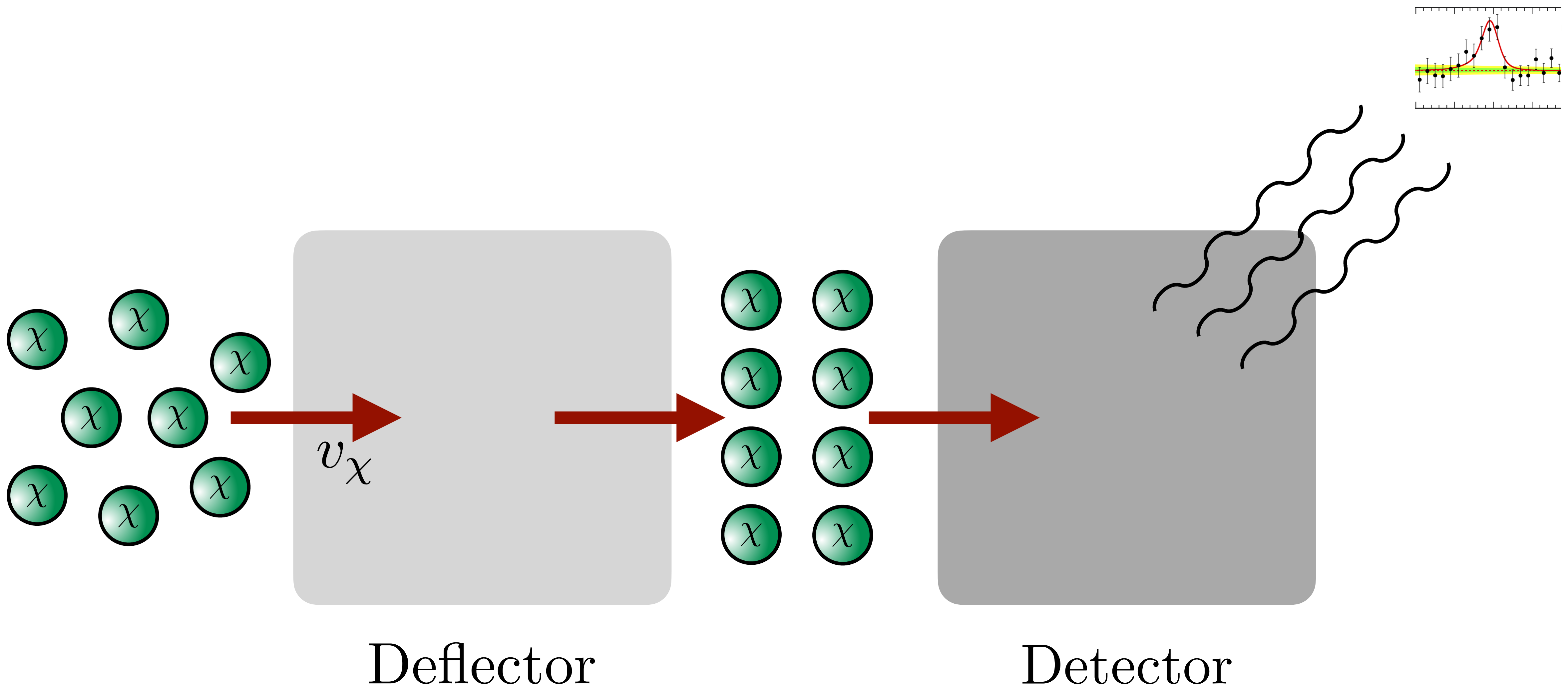
Any cosmological targets?

Outlook

For DM masses < MeV – Non-Thermal History

Such models may be accompanied by an ultralight mediator

Active Direct Detection through two-step process:



Backup

Charge Density Calculation w/ Shield

Charge density as sum of charges:

$$\rho_\chi(\mathbf{x},t) = e q_{\text{eff}} \sum_{j=0}^{1} (-1)^j \int d^3\mathbf{v}\ f_j(\mathbf{x},\mathbf{v},t)$$

$$= \frac{1}{2} e q_{\text{eff}}\ n_\chi \sum_{j=0}^{1} (-1)^j \int d^3\mathbf{x}_i\, d^3\mathbf{v}_i\ f(\mathbf{v}_i)\ \delta^{(3)}(\mathbf{x} - \mathbf{x}_{\text{def}}(t;\mathbf{x}_i,\mathbf{v}_i))$$

Treat effect of deflector as small perturbation:

$$\mathbf{x}_{\text{def}} \equiv \mathbf{x}_{\text{free}} + \Delta\mathbf{x}_{\text{def}}\ ,\ \ \mathbf{v}_{\text{def}} \equiv \mathbf{v}_{\text{free}} + \Delta\mathbf{v}_{\text{def}} \qquad \mathbf{x}_{\text{free}}(t) \equiv \mathbf{x}_i + \mathbf{v}(t-t_0)\ ,\ \ \mathbf{v}_{\text{free}}(t) \equiv \mathbf{v}_i$$

$$\Delta\mathbf{x}_{\text{def}}(t) \simeq (-1)^j \frac{e q_{\text{eff}}}{m_\chi} \iint_{t_0<t'<t''<t} dt'\, dt''\ \boldsymbol{E}_{\text{def}}(\mathbf{x}_{\text{free}}(t'))\, e^{i\omega t'}$$

EM force, neglecting $\mathbf{v}_\chi$-suppressed B-field effect

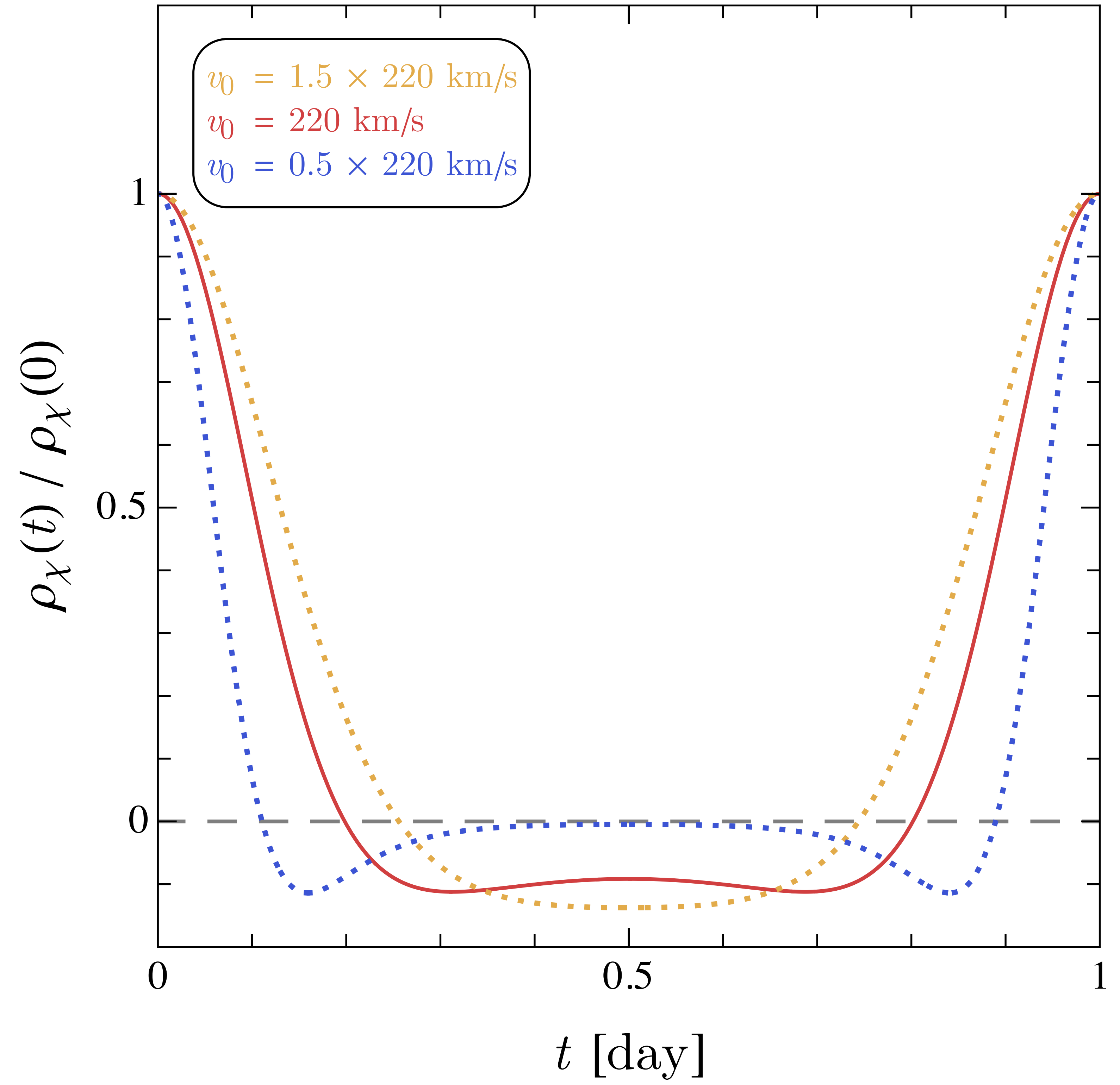
Effect of the Dark Matter Wind

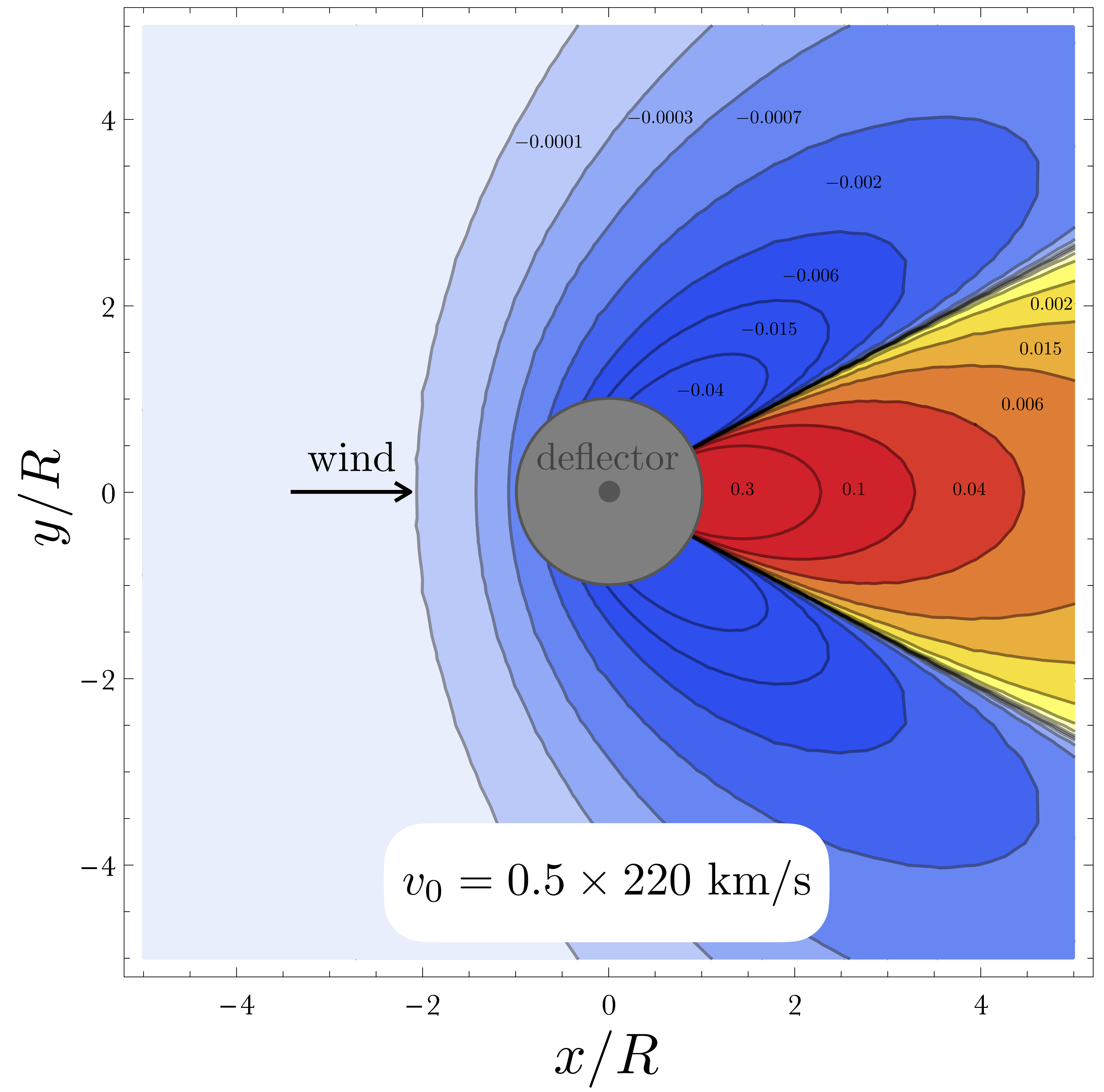
Recall that charge and current density zero without wind

$$\xi \equiv \left(\frac{v_{\rm wind}}{v_0}\right)$$

Far-field limit

$$\rho_\chi(\mathbf{x},t) \simeq \frac{2}{9}\, e^{i\omega t}\, \rho_\chi^{\rm Debye} \left(\frac{R}{|\mathbf{x}|}\right)^3 \xi\, e^{-\xi^2} \left[2\pi^{-1/2} c_{\rm w}(1 - s_{\rm w}^2\xi^2) + e^{c_{\rm w}^2\xi^2}\xi\left(2c_{\rm w}^2(1 - s_{\rm w}^2\xi^2) - s_{\rm w}^2\right)\mathrm{erfc}(-c_{\rm w}\xi)\right]$$





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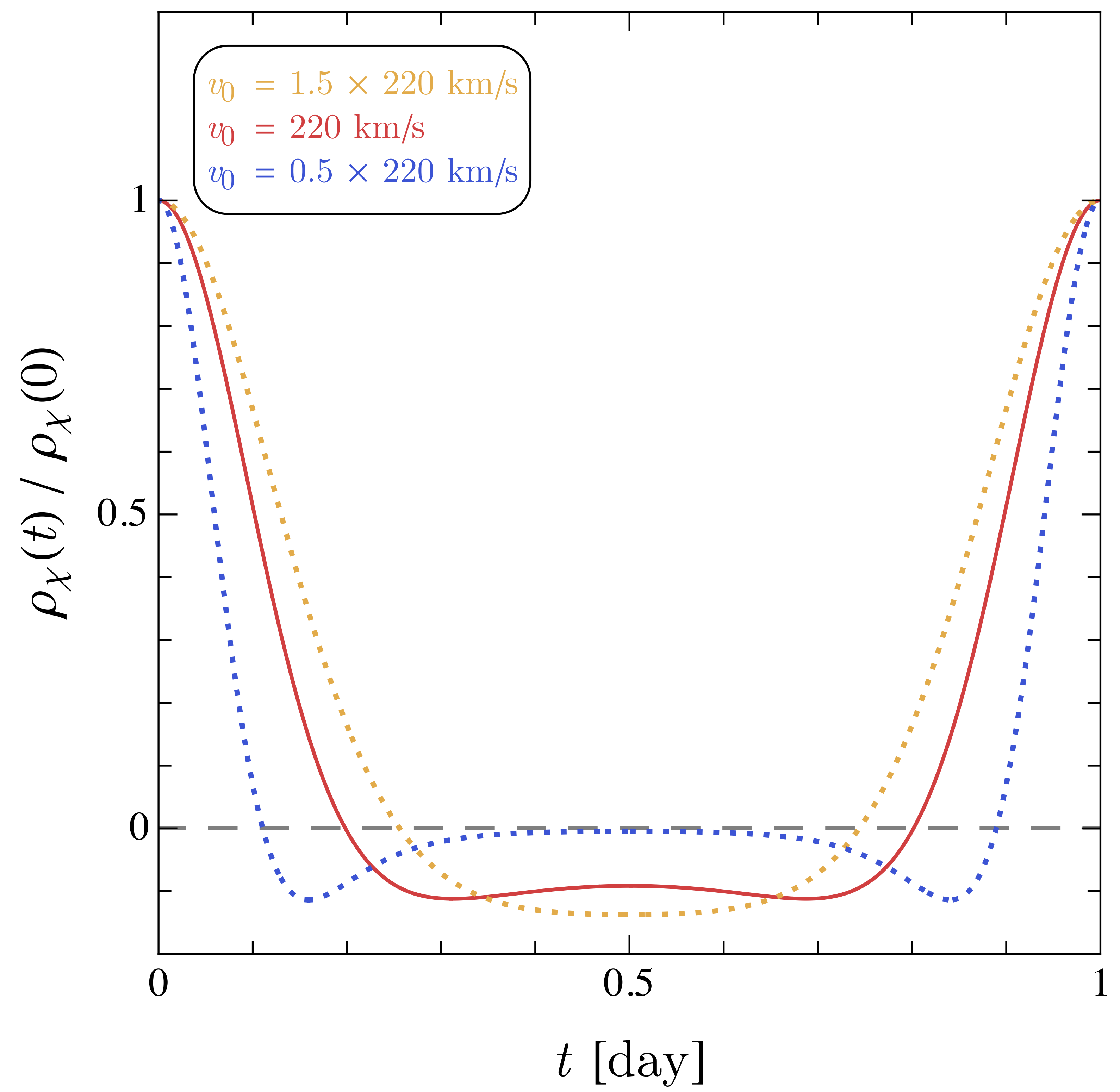
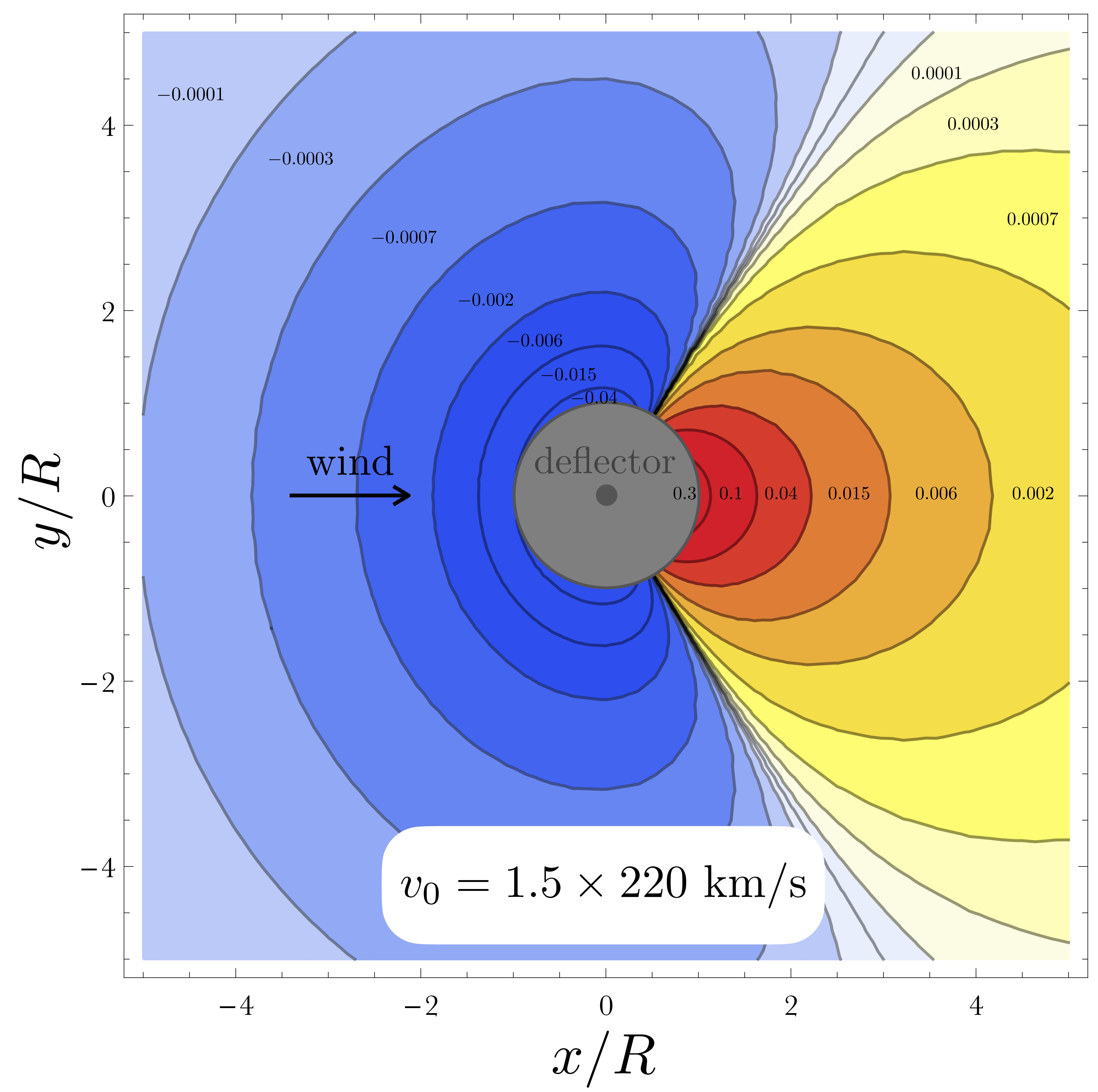
$$\xi \equiv \left(\frac{v_{\rm wind}}{v_0}\right)$$

Far-field limit

$$\rho_\chi(\mathbf{x},t) \simeq \frac{2}{9}\, e^{i\omega t}\, \rho_\chi^{\rm Debye} \left(\frac{R}{|\mathbf{x}|}\right)^3 \xi\, e^{-\xi^2} \left[2\pi^{-1/2} c_{\rm w}(1 - s_{\rm w}^2\xi^2) + e^{c_{\rm w}^2\xi^2}\xi\left(2c_{\rm w}^2(1-s_{\rm w}^2\xi^2) - s_{\rm w}^2\right) {\rm erfc}(-c_{\rm w}\xi)\right]$$





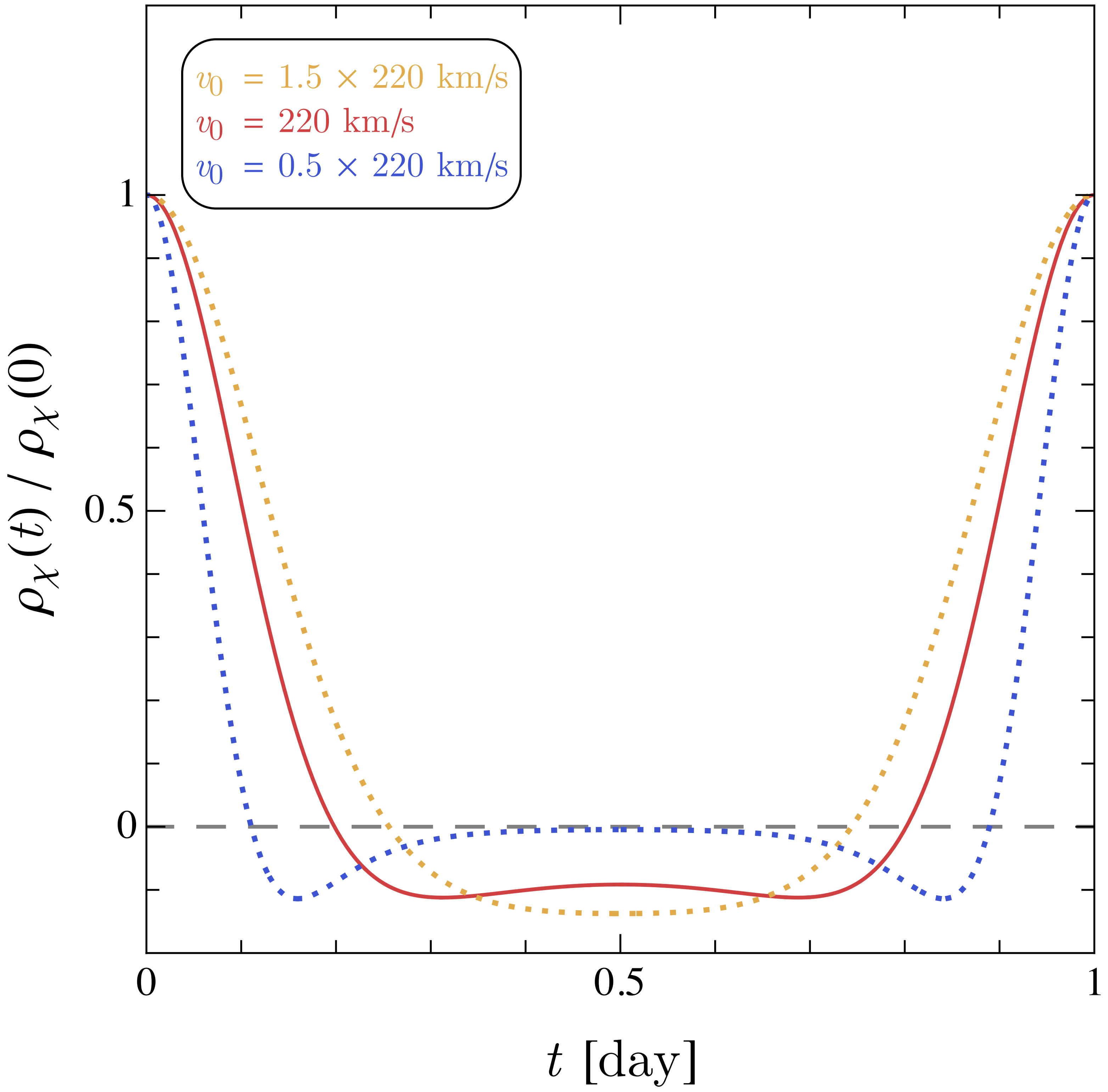
Effect of the Dark Matter Wind

Recall that charge and current density zero without wind

$$\xi \equiv \left(\frac{v_{\rm wind}}{v_0}\right)$$

Far-field limit

$$\rho_\chi(\mathbf{x},t) \simeq \frac{2}{9}\, e^{i\omega t}\, \rho_\chi^{\rm Debye} \left(\frac{R}{|\mathbf{x}|}\right)^3 \xi\, e^{-\xi^2} \left[2\pi^{-1/2} c_{\rm w}(1 - s_{\rm w}^2\xi^2) + e^{c_{\rm w}^2\xi^2}\xi\left(2c_{\rm w}^2(1-s_{\rm w}^2\xi^2) - s_{\rm w}^2\right)\mathrm{erfc}(-c_{\rm w}\xi)\right]$$



Sensitive to both wind and dispersion

Daily modulation of signal:

$$\omega_{\rm s} = \omega \pm \omega_\oplus$$

deflector

sidereal