DARK MATTER DIRECT DEFLECTION

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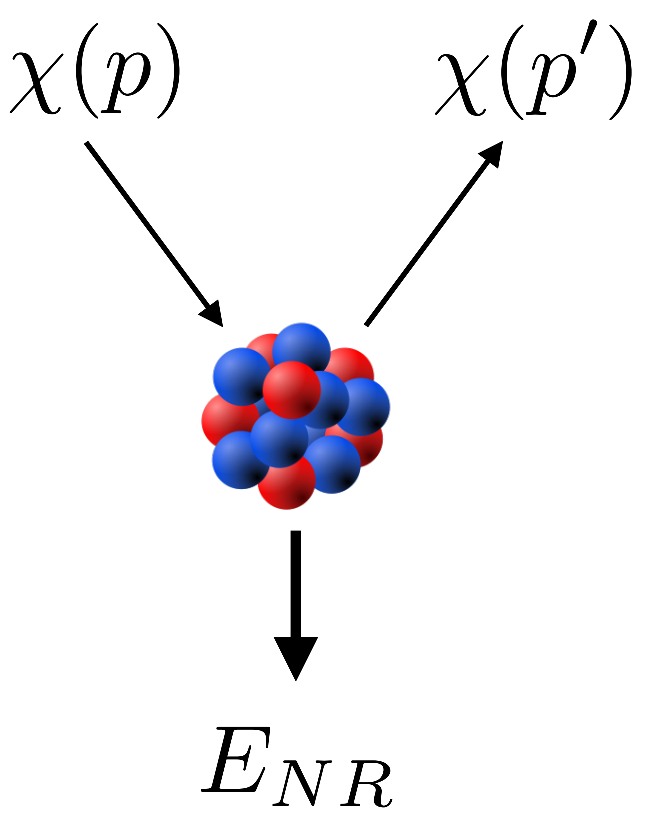
w/ A. Berlin, S. Ellis, P. Schuster, N. Toro [1908.06982]

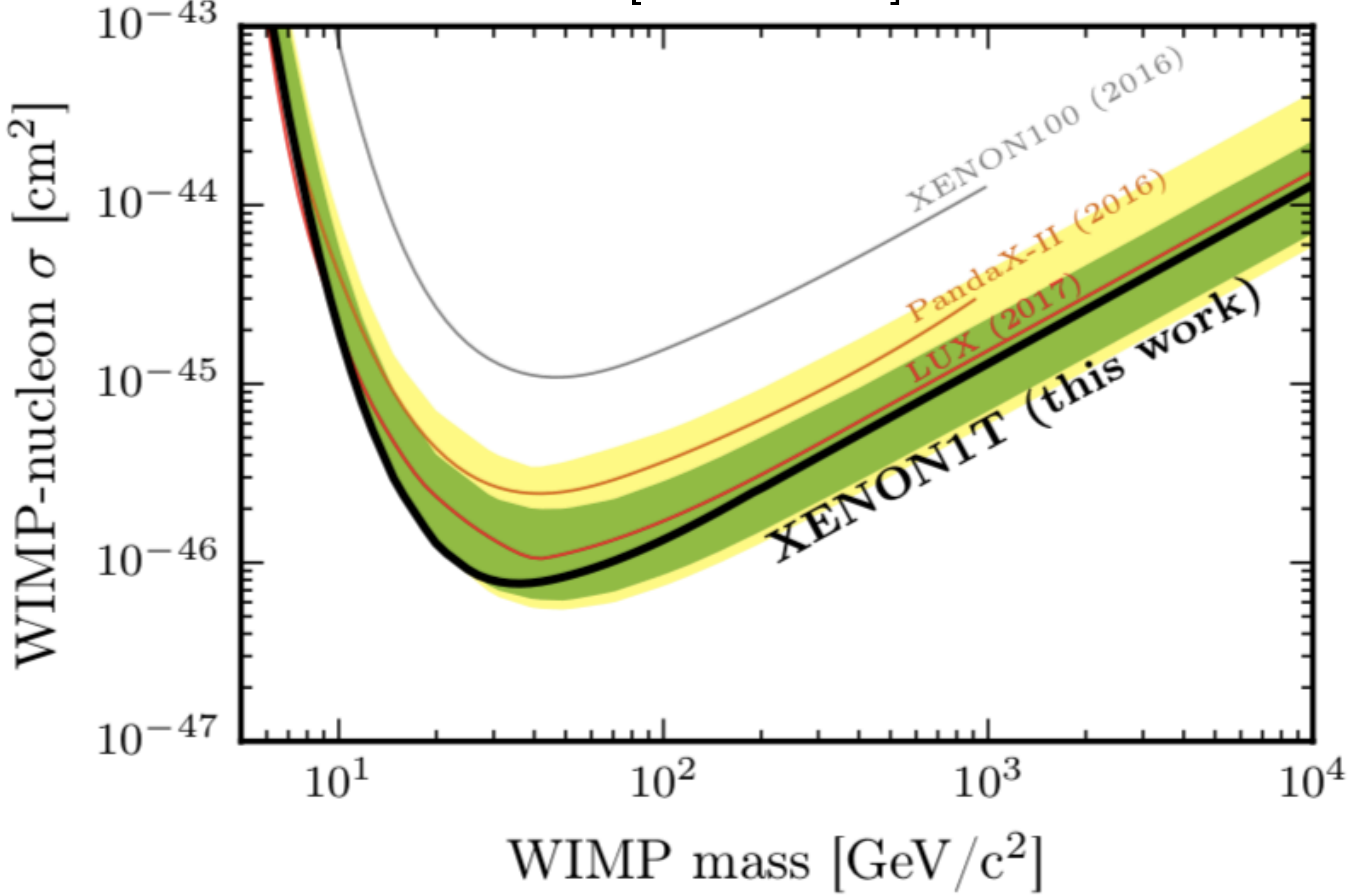
10^{-22} eV
m_χ
10^{48} GeV
$\mathcal{O}(10^{-50})$
$\alpha_{\rm self}$
$\mathcal{O}(1)$
$\mathcal{O}(10^{-50})$
$\alpha_{\rm SM}$
$\mathcal{O}(1)$
???? PIECES!
WORLD'S largest puzzle!
8 BAGS OF PUZZLE PIECES
KING-SIZE-DOLLY FOR TRANSPORTATION
NO REFERENCE ILLUSTRATION
Ravensburger Puzzle

DIRECT DETECTION

$$\vec{q} = \vec{p} - \vec{p}'$$



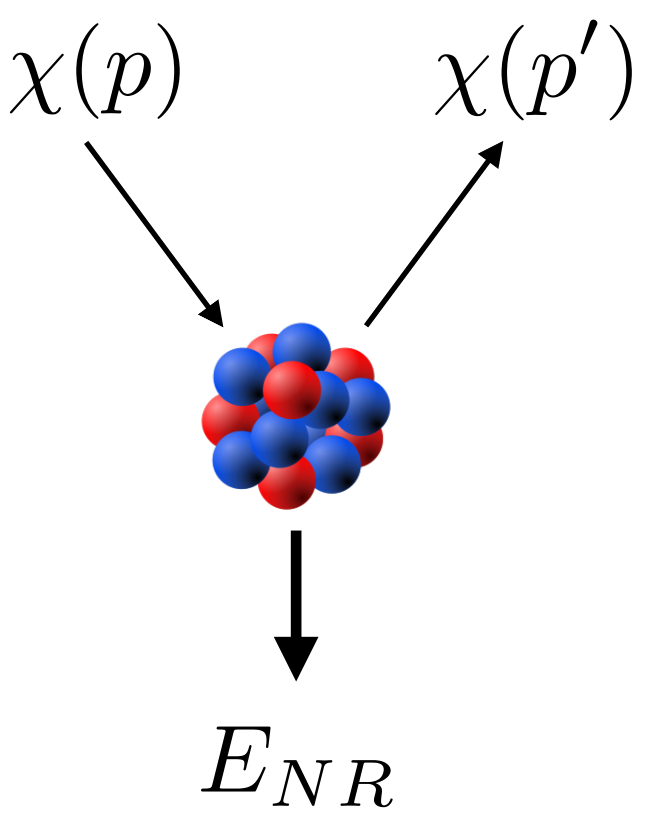
[1705.06655]



$$E_{NR} = \frac{q^2}{2m_N} \approx 50\ \mathrm{keV}\ \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2$$

DIRECT DETECTION

$$\vec{q} = \vec{p} - \vec{p}'$$



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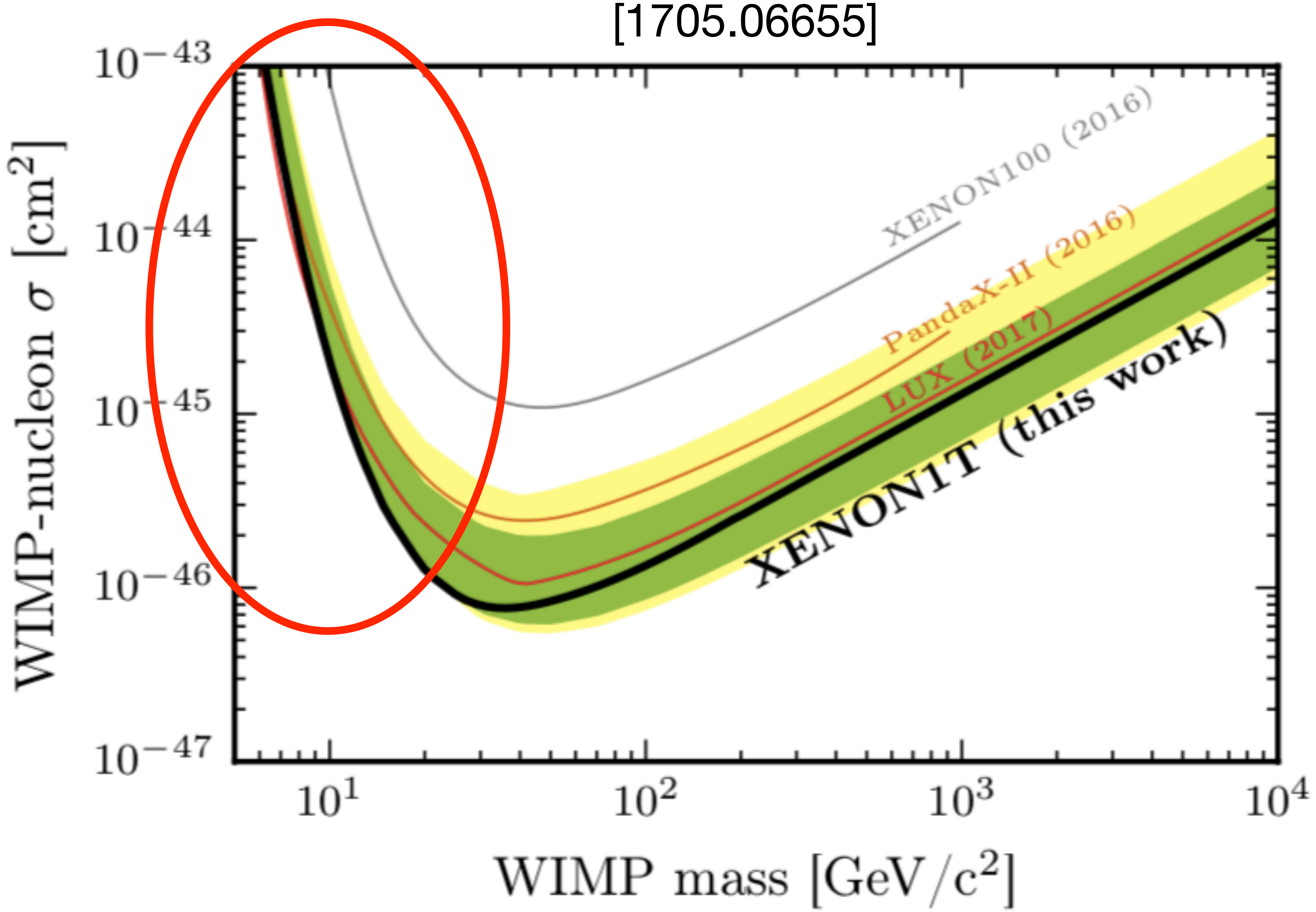
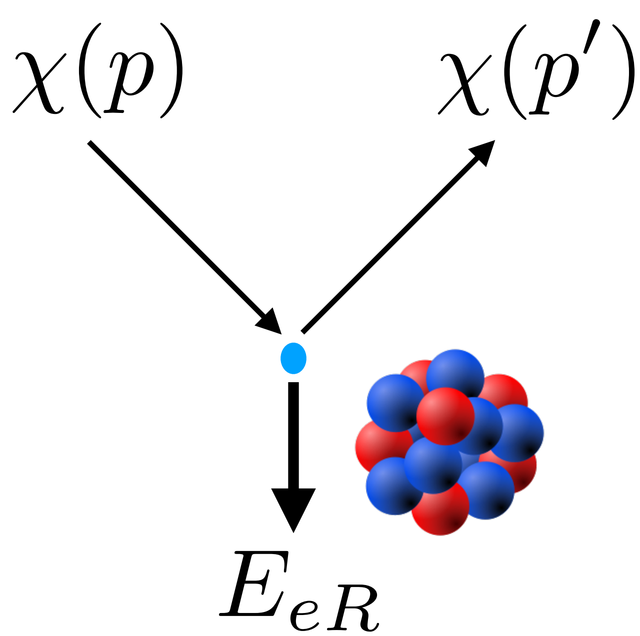


$$E_{NR} = \frac{q^2}{2m_N} \approx 50\ \text{keV}\ \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2$$

ELECTRON DIRECT DETECTION

$$\vec{q} = \vec{p} - \vec{p}'$$



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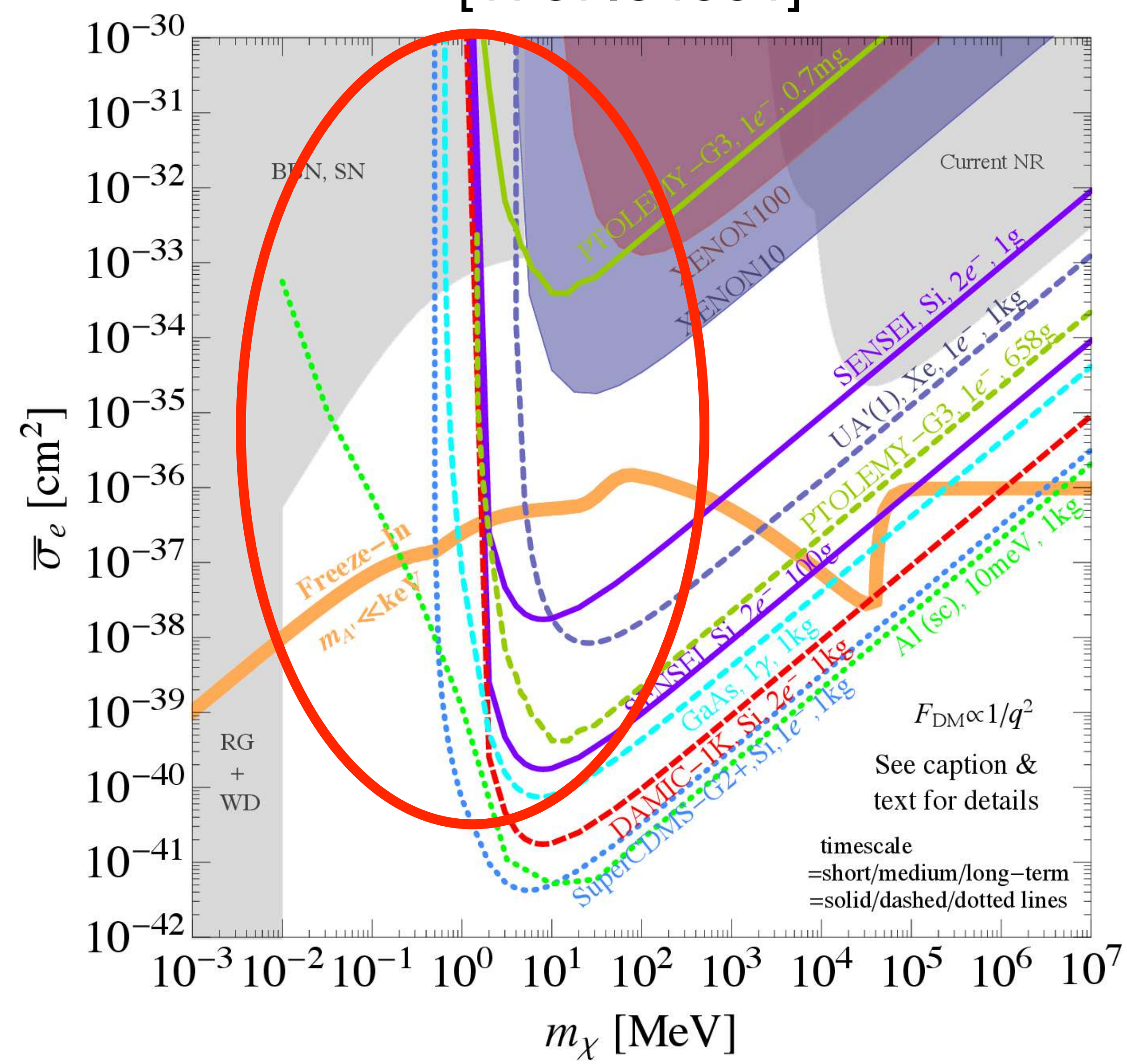
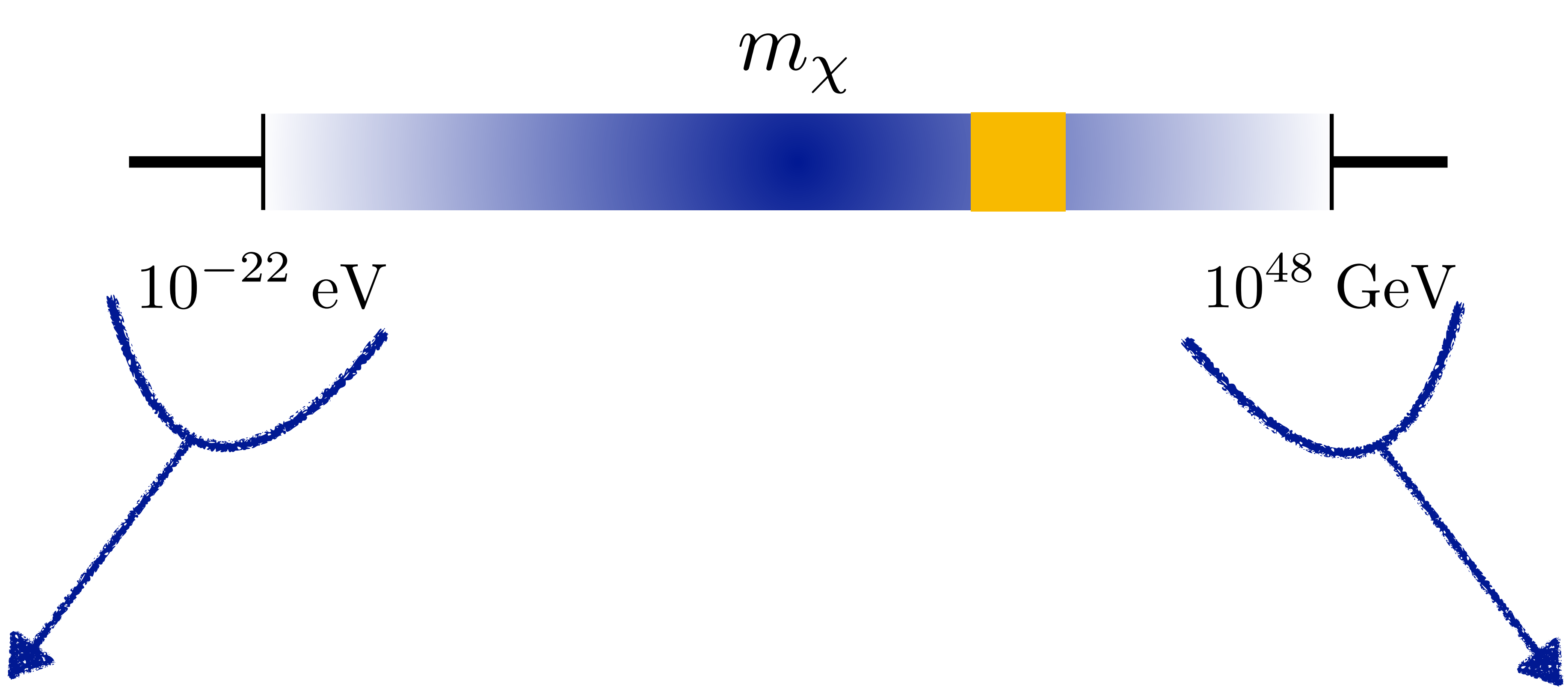


$$E_{eR} \leq \frac{\mu_{\chi N} v^2}{2} \approx 0.5 \text{ eV} \left(\frac{m_\chi}{\text{MeV}}\right) \gg E_{NR}$$

THE DARK MATTER MASS

80 ORDERS OF MAGNITUDE



De Broglie wavelength

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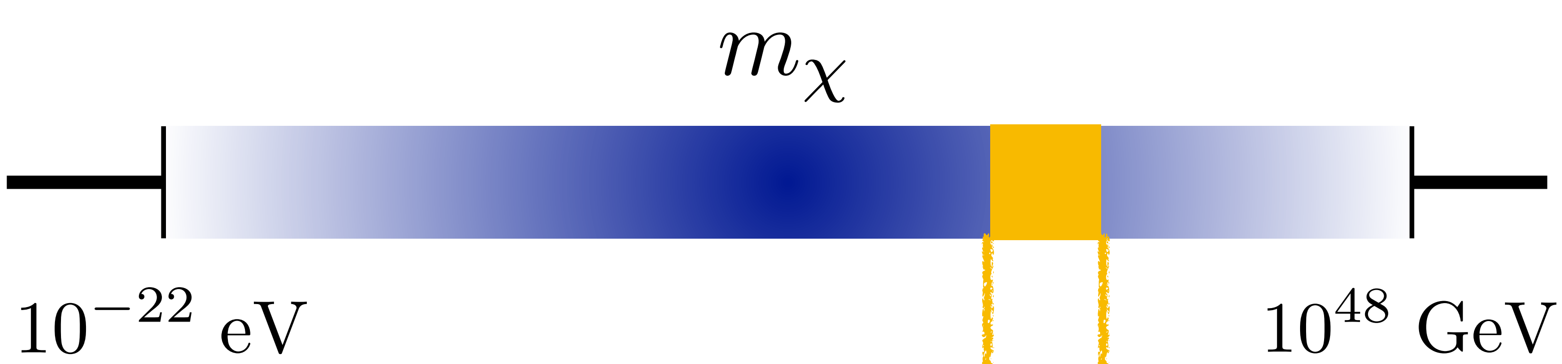
Size of galaxies

Lensing inside

the Milky Way

THE DARK MATTER MASS

DIRECT DETECTION ~ 6-10 Orders of Magnitude



Low Threshold = General problem
for **ALL** particle DM experiments,
beyond direct detection

Low Threshold

$$E_{eR} \sim m_\chi$$

High Multiplicity

$$\frac{N_\chi}{V} = n_\chi \sim \frac{1}{m_\chi}$$

High Threshold

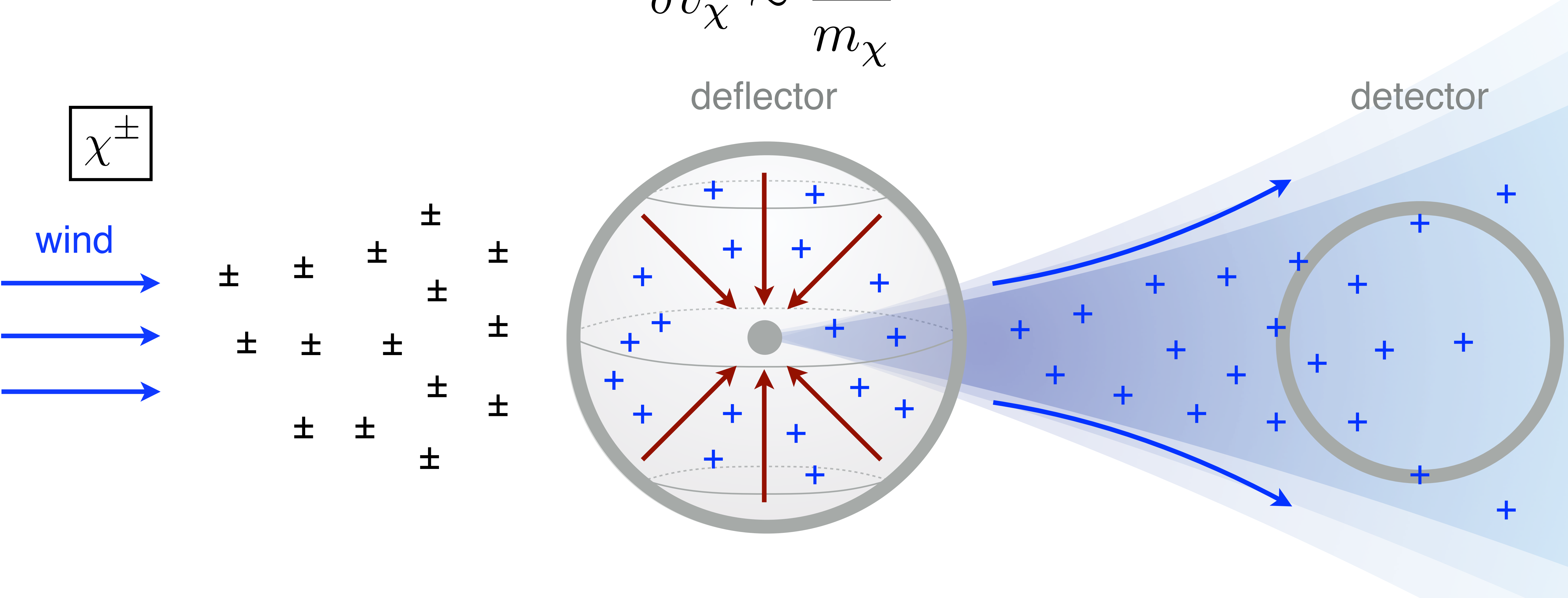
$$E_{NR} \sim m_\chi^2$$

Low Multiplicity

DIRECT DEFLECTION

$$\frac{N_\chi}{V} = n_\chi \sim \frac{1}{m_\chi}$$

$$\delta v_\chi \sim \frac{1}{m_\chi}$$

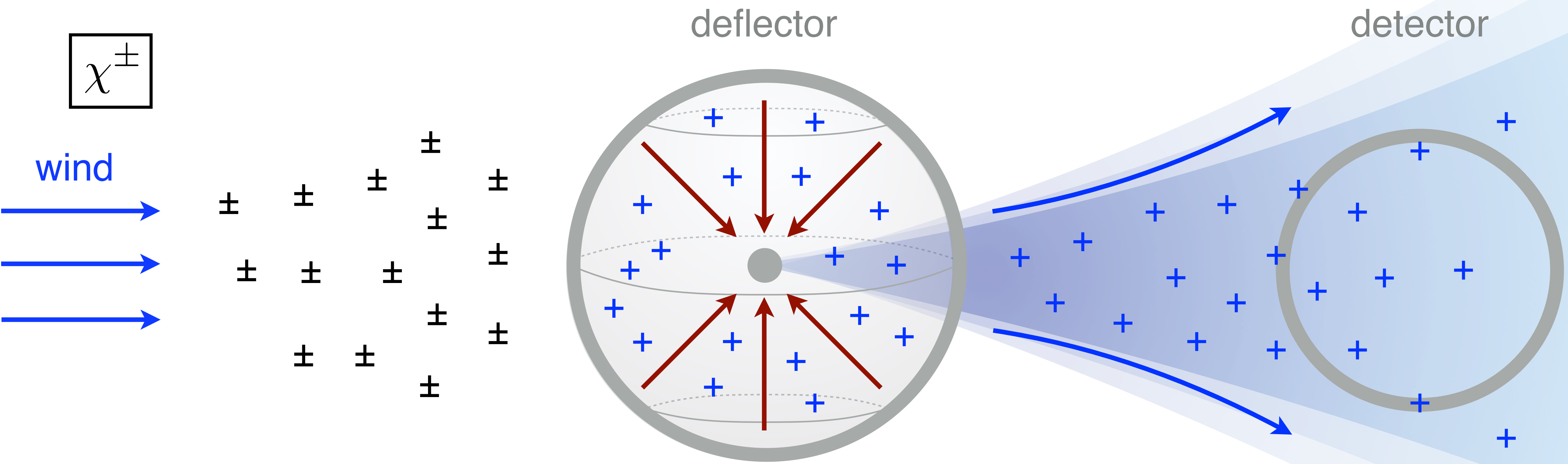


We create a coherent **COLLECTIVE** perturbation

DIRECT DEFLECTION

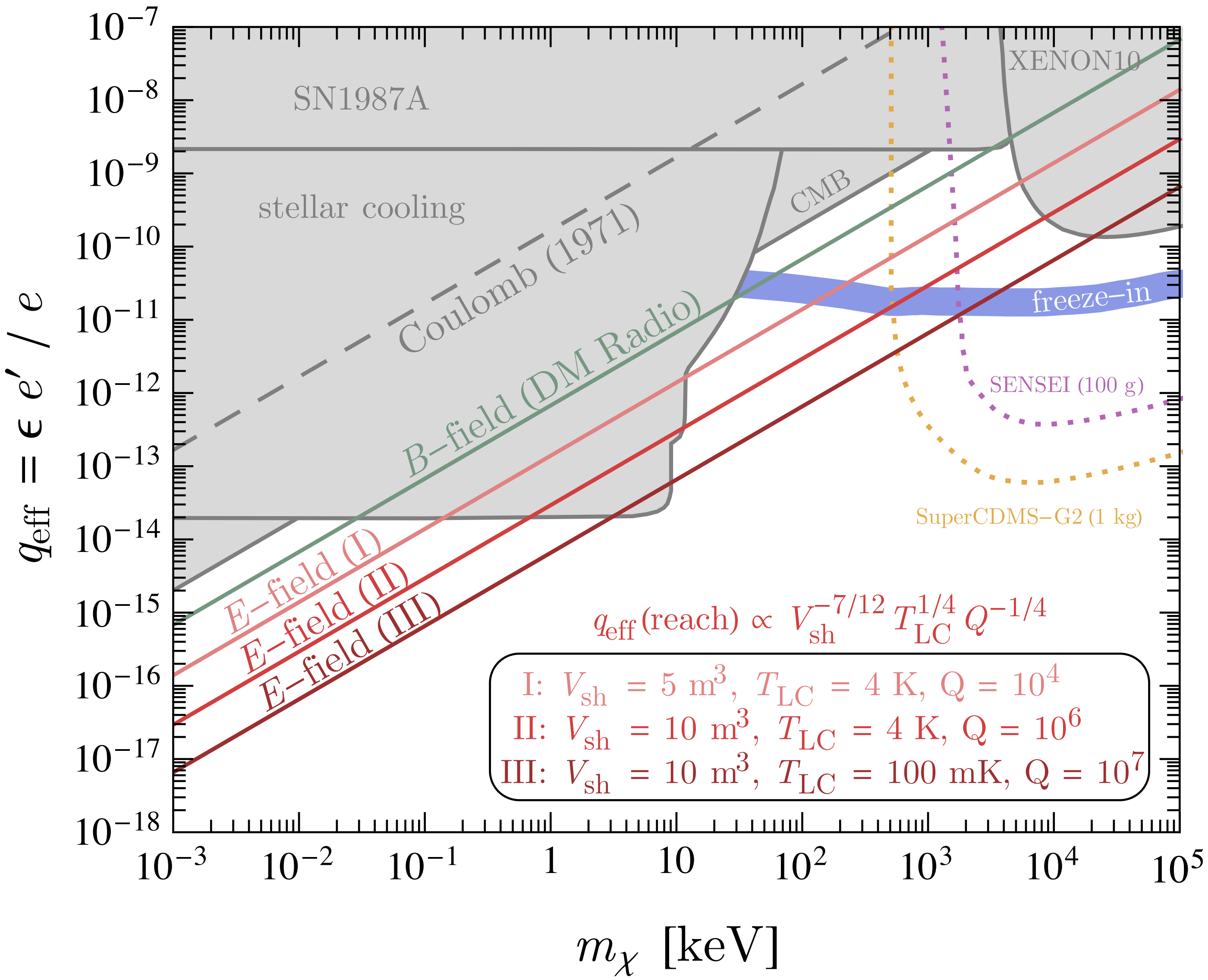
Ingredient: Long-Range force between DM and SM

$$R \gtrsim \left(\frac{E_{\rm threshold}}{\rho_\chi}\right)^{1/3} \simeq 10^{-2}\ {\rm mm}\ \left(\frac{E_{\rm threshold}}{\rm eV}\right)^{1/3}$$



We create a coherent **COLLECTIVE** perturbation

DIRECT DEFLECTION SNEAK PREVIEW



A CONCRETE CASE STUDY: PREDICTIVE COSMOLOGIES BELOW ONE MEV

LIGHT DARK MATTER COUPLINGS

$$m_\chi < \mathrm{MeV}$$

Thermalization is forbidden by the precise measurement of the expansion of the Universe at the time of Nucleosynthesis (T~MeV)

$$\Gamma_\chi \lesssim H(\mathrm{MeV})$$

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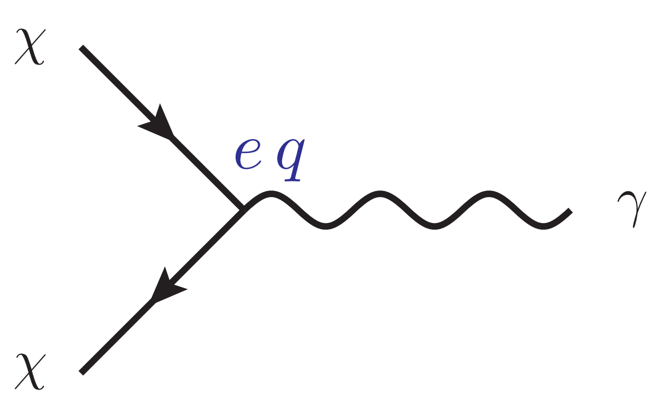
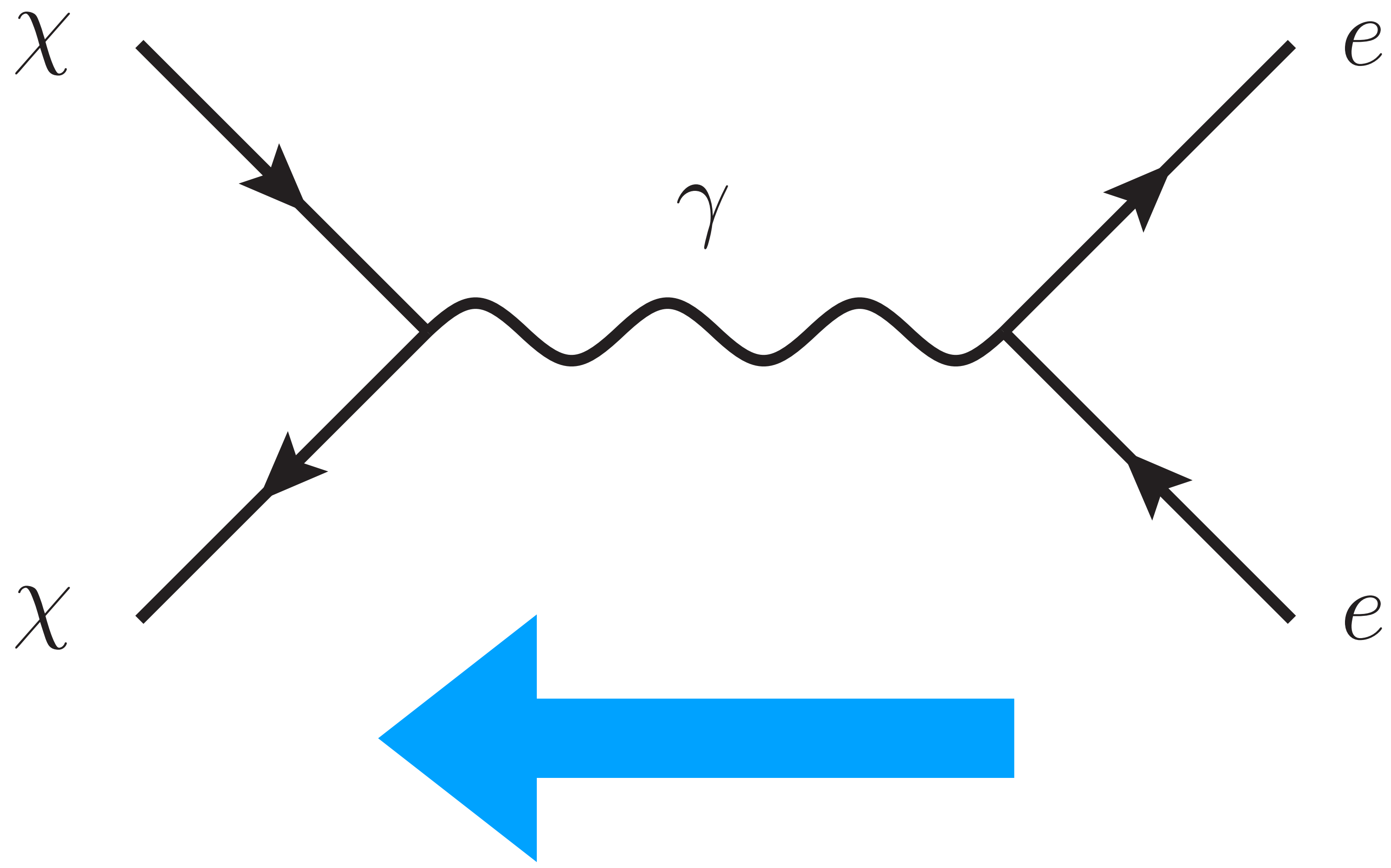


$$\Gamma_\chi \lesssim H(\text{MeV}) \quad \rightarrow \quad q \lesssim 10^{-9}$$

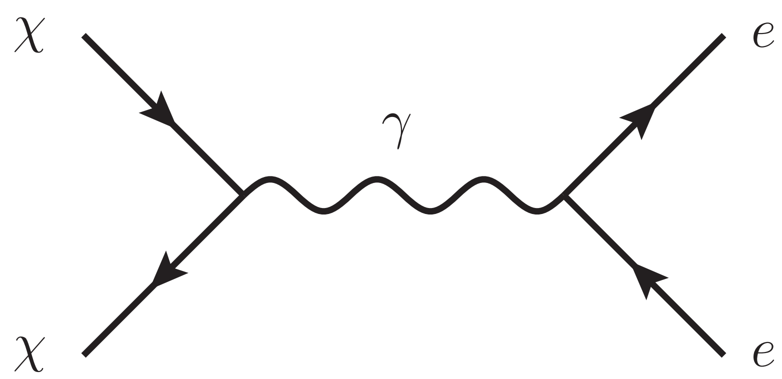
FREEZE-IN

Assumption: the dark sector is initially empty



Slow Energy Leakage from SM to Dark Matter

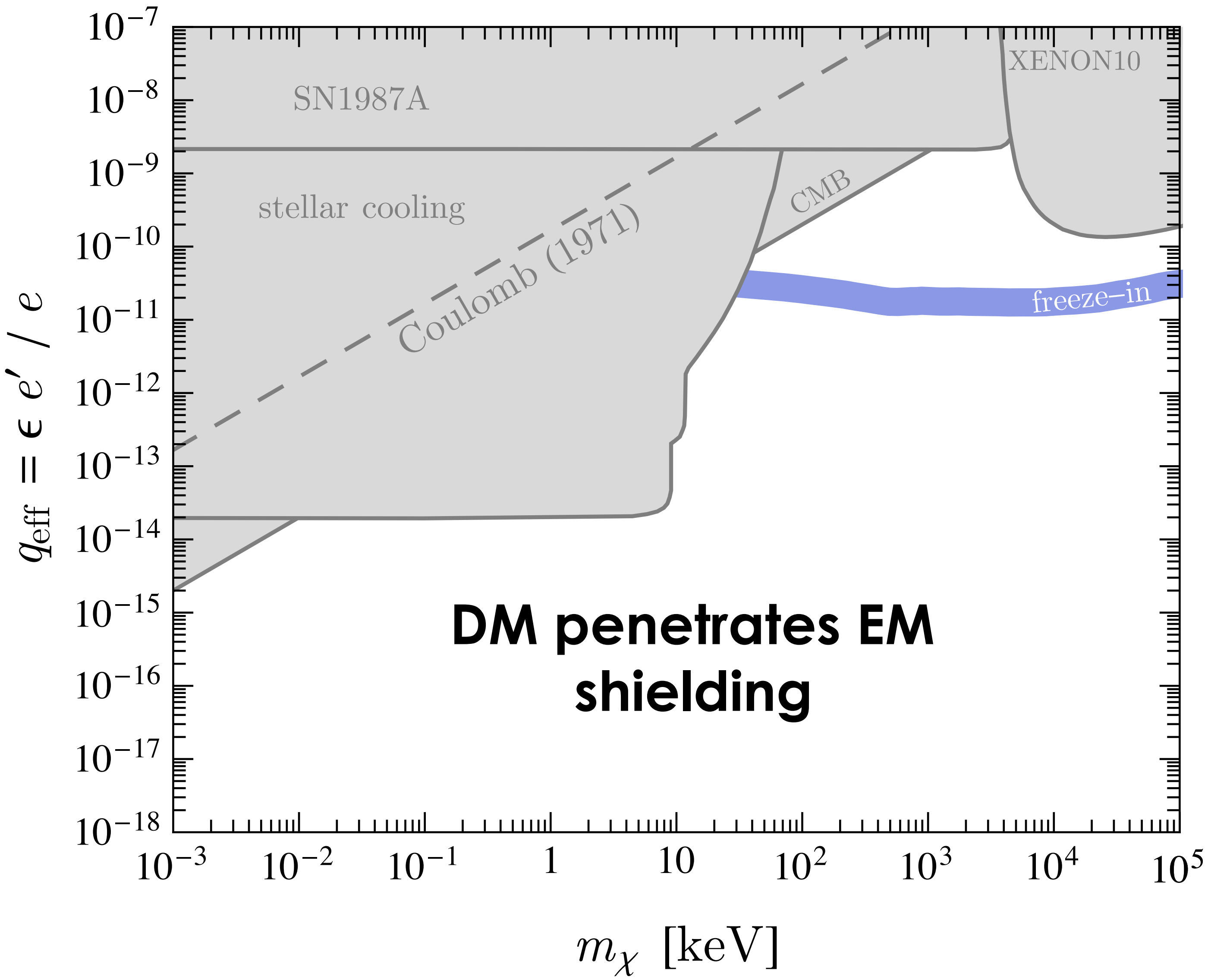
FREEZE-IN



$$\frac{dn_\chi}{dt} + 3Hn_\chi = n_e \langle \sigma v \rangle \sim n_e \frac{\alpha q^2}{m_e^2}$$

1. Energy Leakage Stops at $T \sim m_e$ when most electrons have converted into photons
2. The DM Coupling determines its abundance

PARAMETER SPACE



DM Coupling

Determines its Abundance

$$q_{\text{eff}} \simeq 10^{-10}\sqrt{\frac{\text{keV}}{m_\chi}}$$

ALTERNATIVE MEDIATORS

$$\mathcal{L} \supset -\frac{1}{4}F^2 - \frac{1}{4}F'^2 + \frac{\epsilon}{2}FF' + \frac{m_{A'}^2}{2}A'^2$$

$$\mathcal{L} \supset j_\chi A' + j_{\rm SM} A$$

$$A \rightarrow A + \epsilon A'$$

$m_{A'} \neq 0$

$\mathcal{L} \supset j_{\rm SM}(A + \epsilon A') + j_\chi A'$

$m_{A'} = 0$

$\mathcal{L} \supset j_\chi A' + j_{\rm SM} A$

ALTERNATIVE MEDIATORS

$$\mathcal{L} \supset -\frac{1}{4}F^2 - \frac{1}{4}F'^2 + \frac{\epsilon}{2}FF' + \frac{m_{A'}^2}{2}A'^2$$

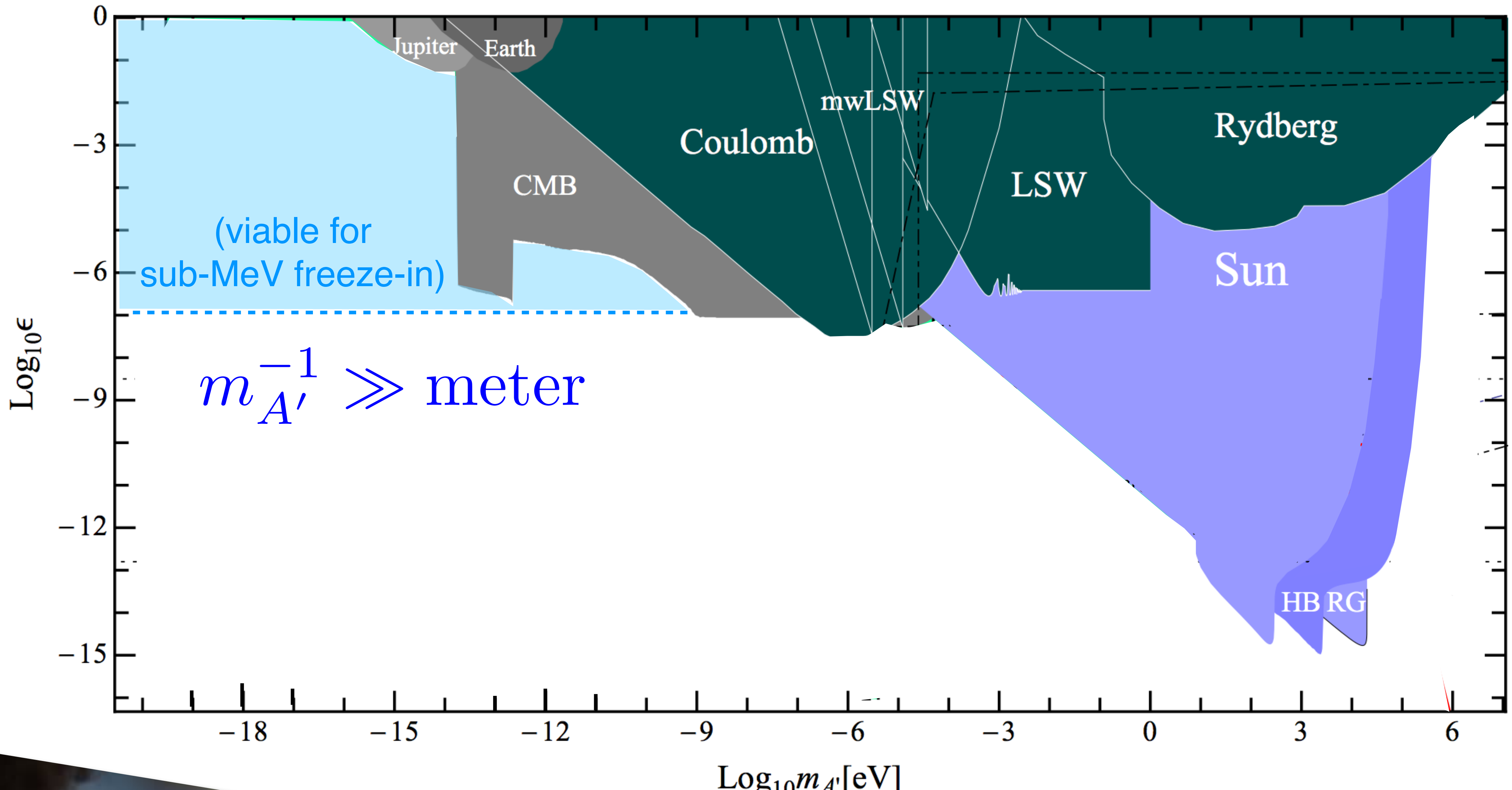
$$\mathcal{L} \supset j_\chi A' + j_{\mathrm{SM}} A$$

$$j_\chi \propto e', \quad j_{\mathrm{SM}} \propto e$$

$$q_{\mathrm{eff}} = \begin{cases} \epsilon e'/e \\ q \end{cases}$$

VECTOR MEDIATORS

$$g_{\rm SM} \sim m_{A'}^2$$



SUMMARY

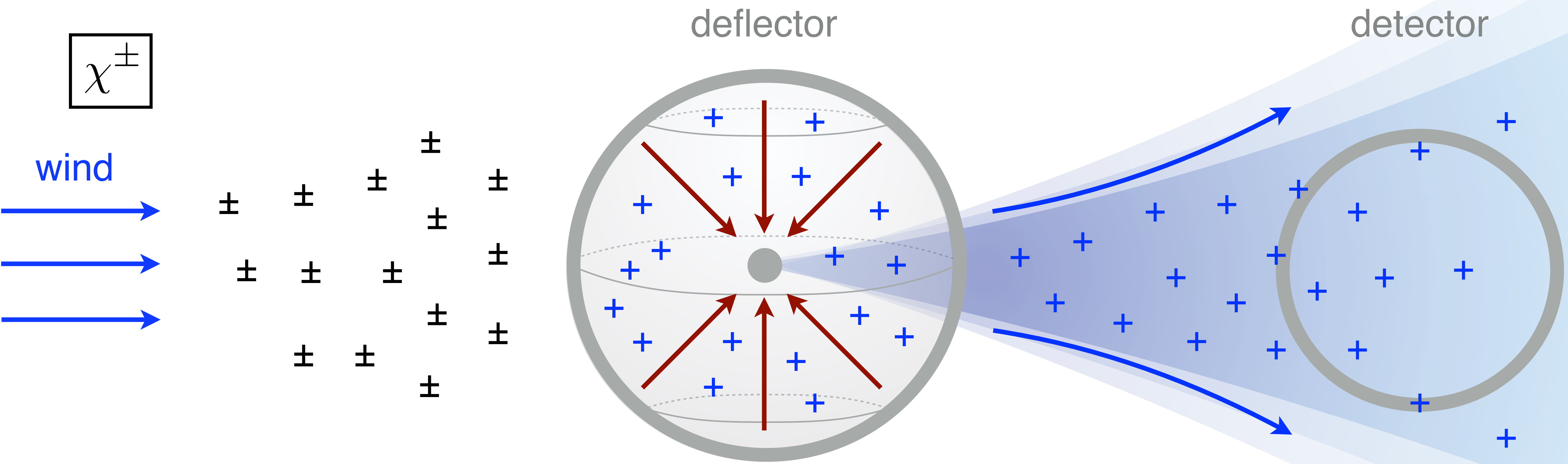
1. **Two Predictive Models**: Millicharged DM (SM photon only) and pseudo-Millicharged (heavy photon). **Same phenomenology** if the heavy photon mass is smaller than the detector size. [N.B. controversies on MilliQ being expelled by the galactic B-field]

2. **Vector mediators** are the **natural first step** experimentally (require manipulating electric fields).

3. **Alternatives** (~keV spin-0 mediators) **are possible**, but currently invisible experimentally (both to DD and our concept).

DIRECT DEFLECTION

$$\frac{N_\chi}{V} = n_\chi \sim \frac{1}{m_\chi}$$



MANIPULATING MILLICHARGES

DARK MATTER MOTION

Velocity distribution inside the galaxy:

$$f(v) \sim e^{-v^2/v_0^2}, \quad v_0 \simeq 10^{-3}$$

Boost to the lab frame:

$$\mathbf{v} \to \mathbf{v} + \mathbf{v}_\odot + \mathbf{v}_\oplus$$

$$v_\odot \simeq 10^{-3}, \quad v_\oplus \simeq 10^{-4}$$

DARK MATTER MOTION

Velocity distribution inside the galaxy:

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DISPERSION

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WIND

DARK MATTER MOTION

Velocity distribution inside the galaxy:

$$f(v) \sim e^{-v^2/v_0^2}, \quad \boxed{v_0 \simeq 10^{-3}}$$

DISPERSION

Boost to the lab frame:

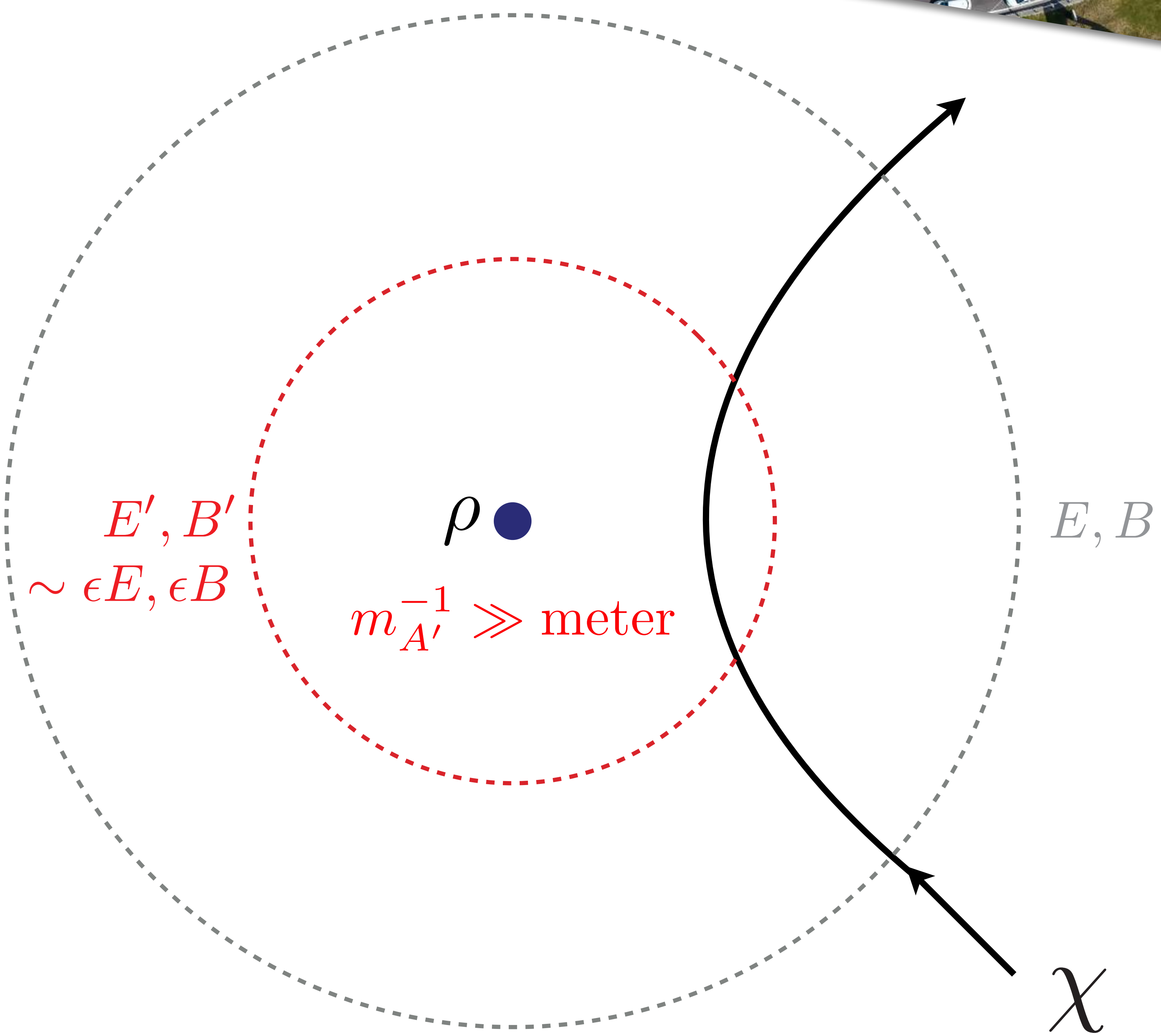
$$\mathbf{v} \to \mathbf{v} + \mathbf{v}_\odot + \mathbf{v}_\oplus$$

$$\boxed{v_\odot \simeq 10^{-3}} \quad v_\oplus \simeq 10^{-4}$$

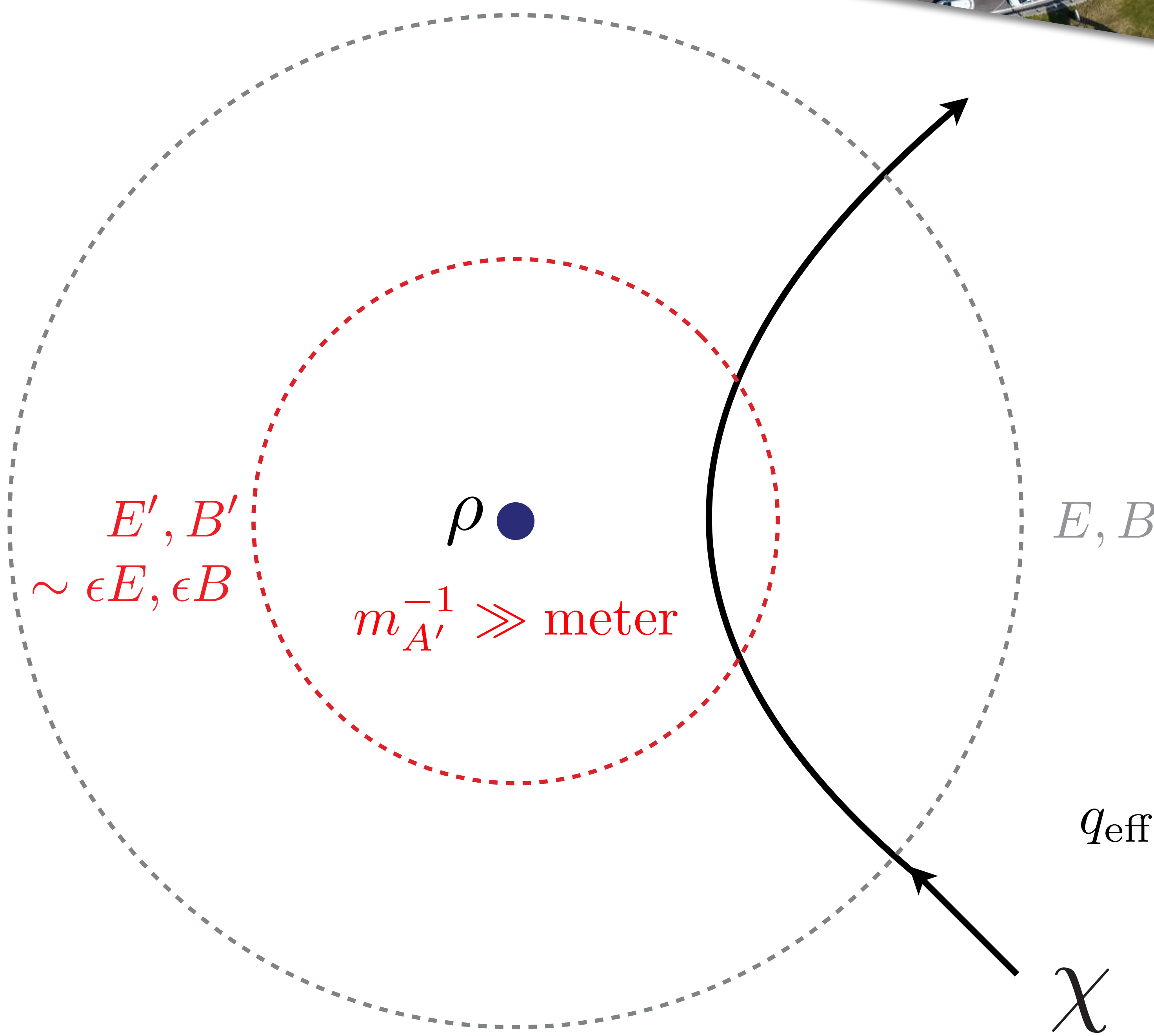
WIND

$v_\chi \simeq v_0, v_\odot \simeq 10^{-3}$ → **Use Electric Fields**

DEFLECTION



DEFLECTION



Freeze-In

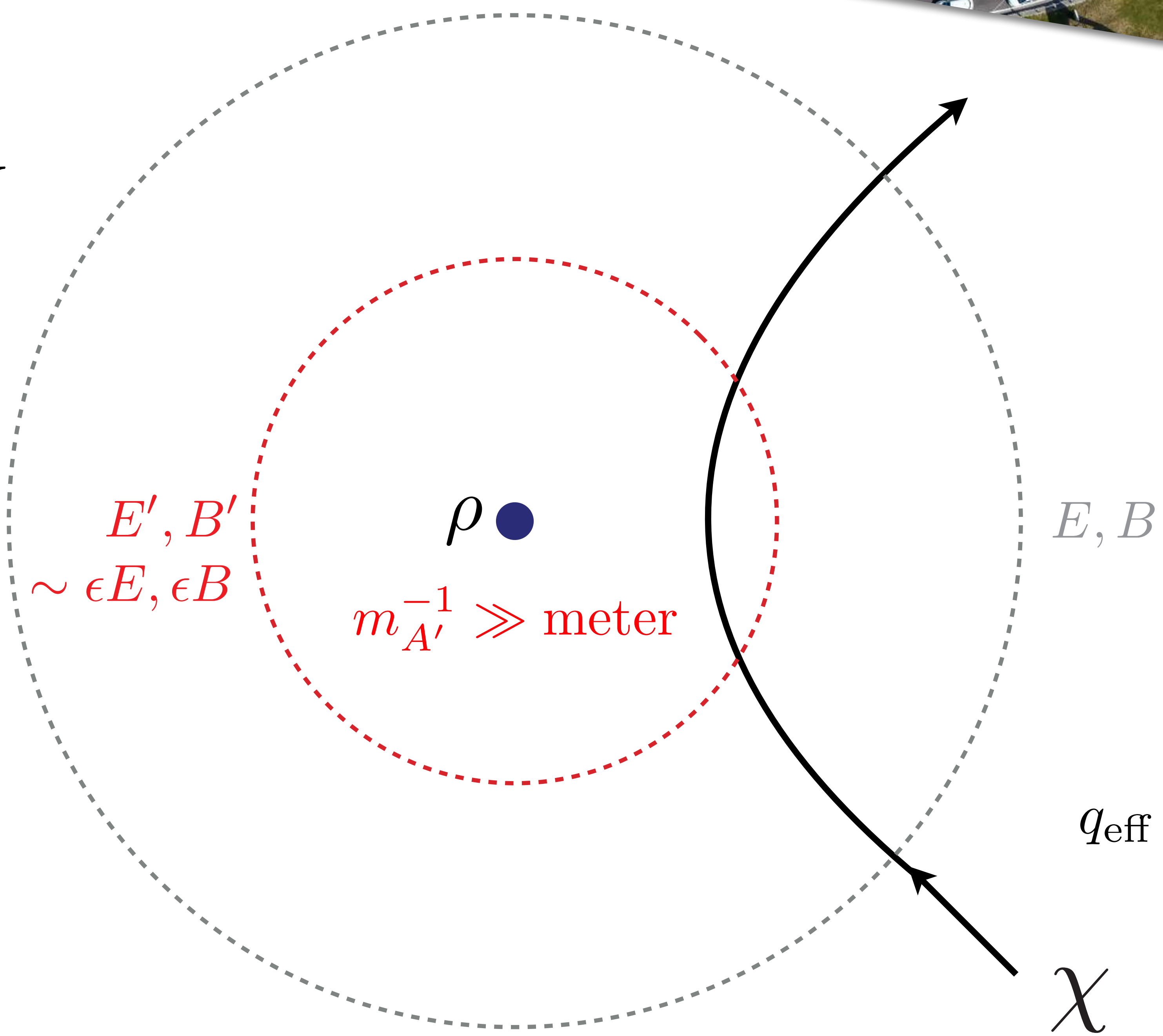
$$q_{\rm eff} \simeq 10^{-10}\sqrt{\frac{\rm keV}{m_\chi}}$$

DEFLECTION

O(1) deflection

$$m_\chi v_\chi^2 \simeq e q_{\text{eff}} \Delta V$$

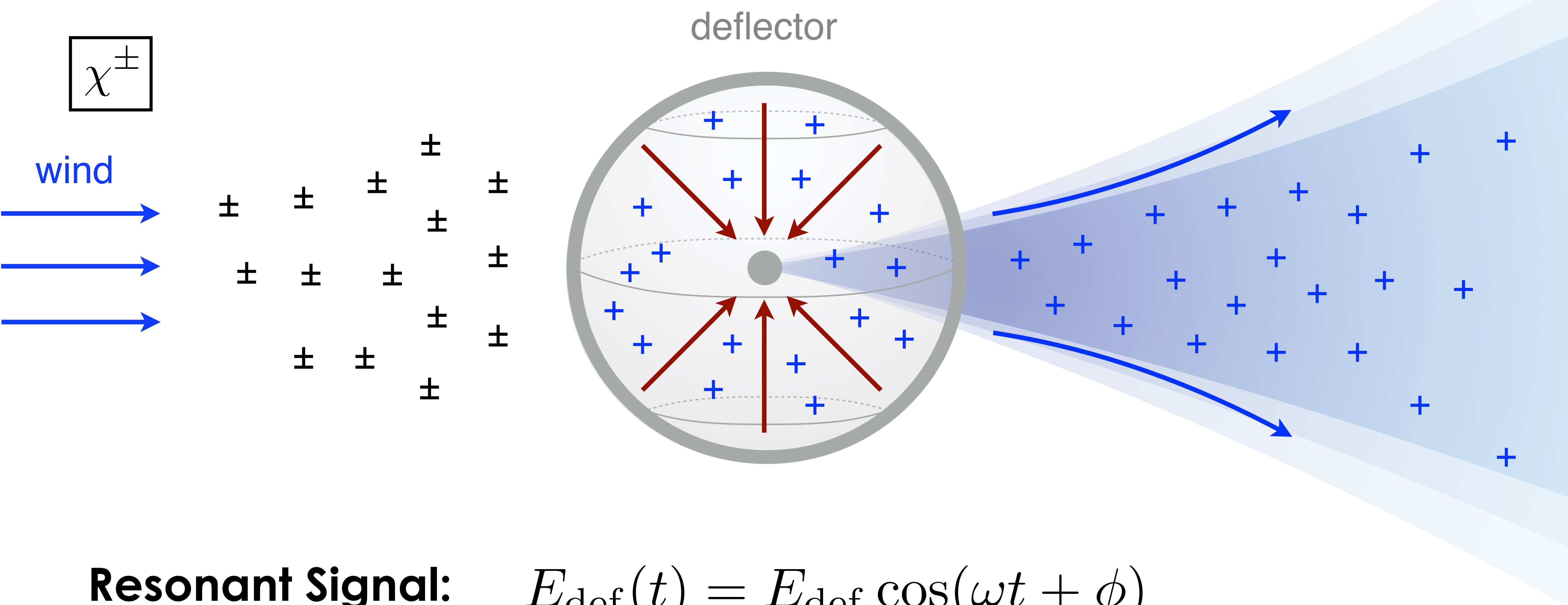
$$\Delta V \simeq \text{MV} \left(\frac{m_\chi}{\text{keV}}\right)^{3/2}$$



Freeze-In

$$q_{\text{eff}} \simeq 10^{-10} \sqrt{\frac{\text{keV}}{m_\chi}}$$

DEFLECTOR

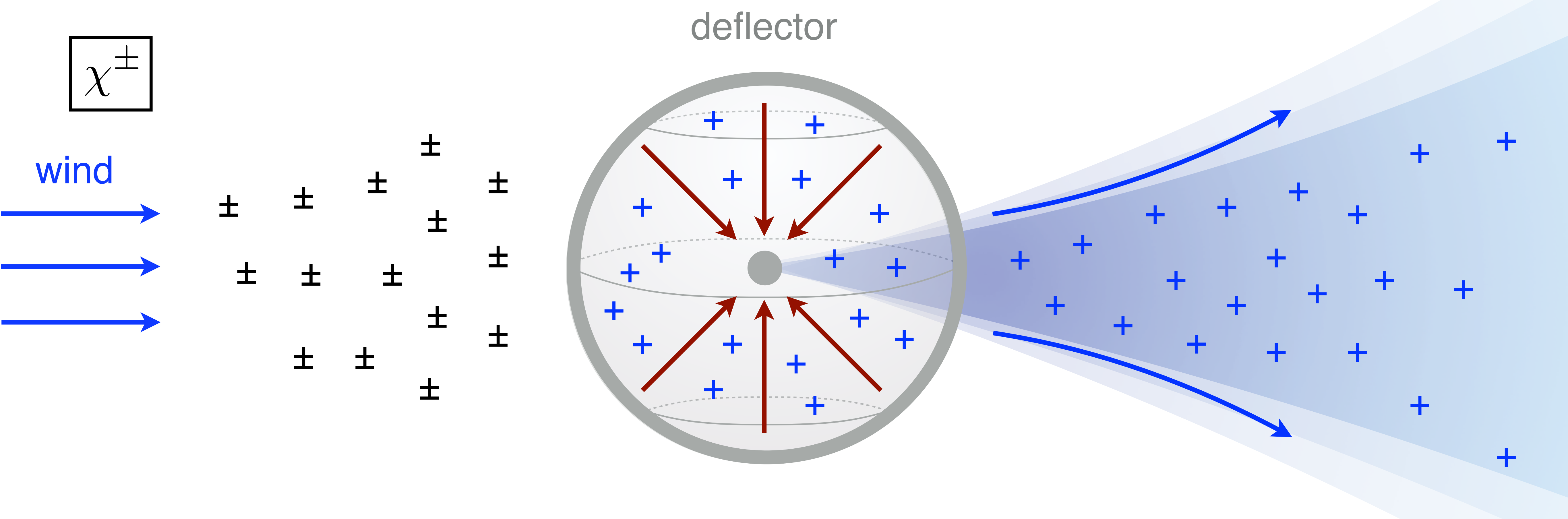


Resonant Signal: $$E_{\rm def}(t) = E_{\rm def}\cos(\omega t + \phi)$$

One sign per crossing: $$\omega \lesssim \frac{v_\chi}{L} \simeq \mathrm{MHz}\left(\frac{\mathrm{meter}}{L}\right)$$

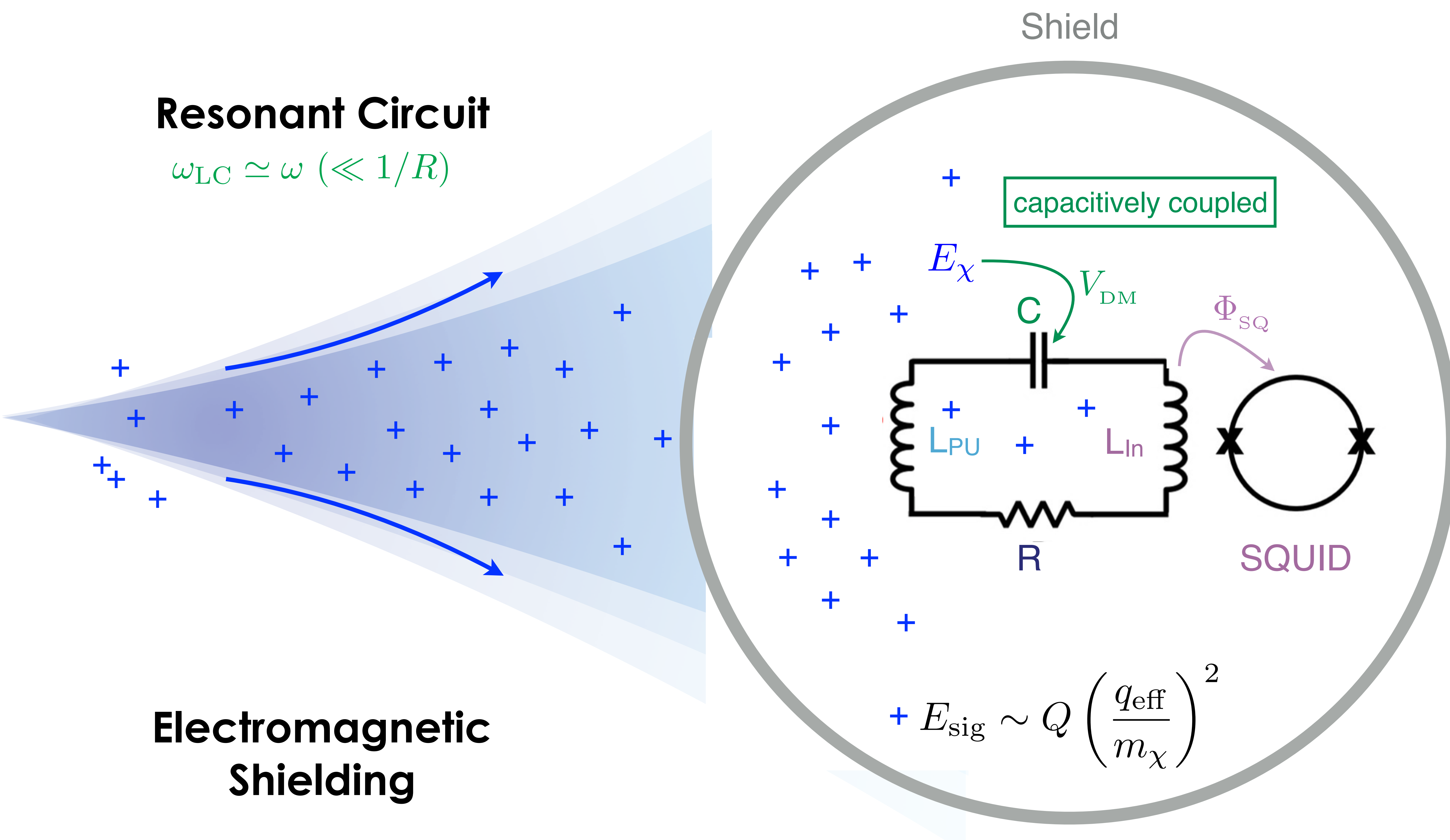
No RF cavities

DEFLECTOR SPECS



DM Deflector	One LHC RF Cavity (8 per beam)
$\langle E_{\rm def} \rangle = 10$ kV/cm	$\langle E \rangle = 50$ kV/cm
$R =$ meter	$L = 0.5$ meter
$\omega = 100$ kHz	$\omega = 400$ MHz

DETECTOR



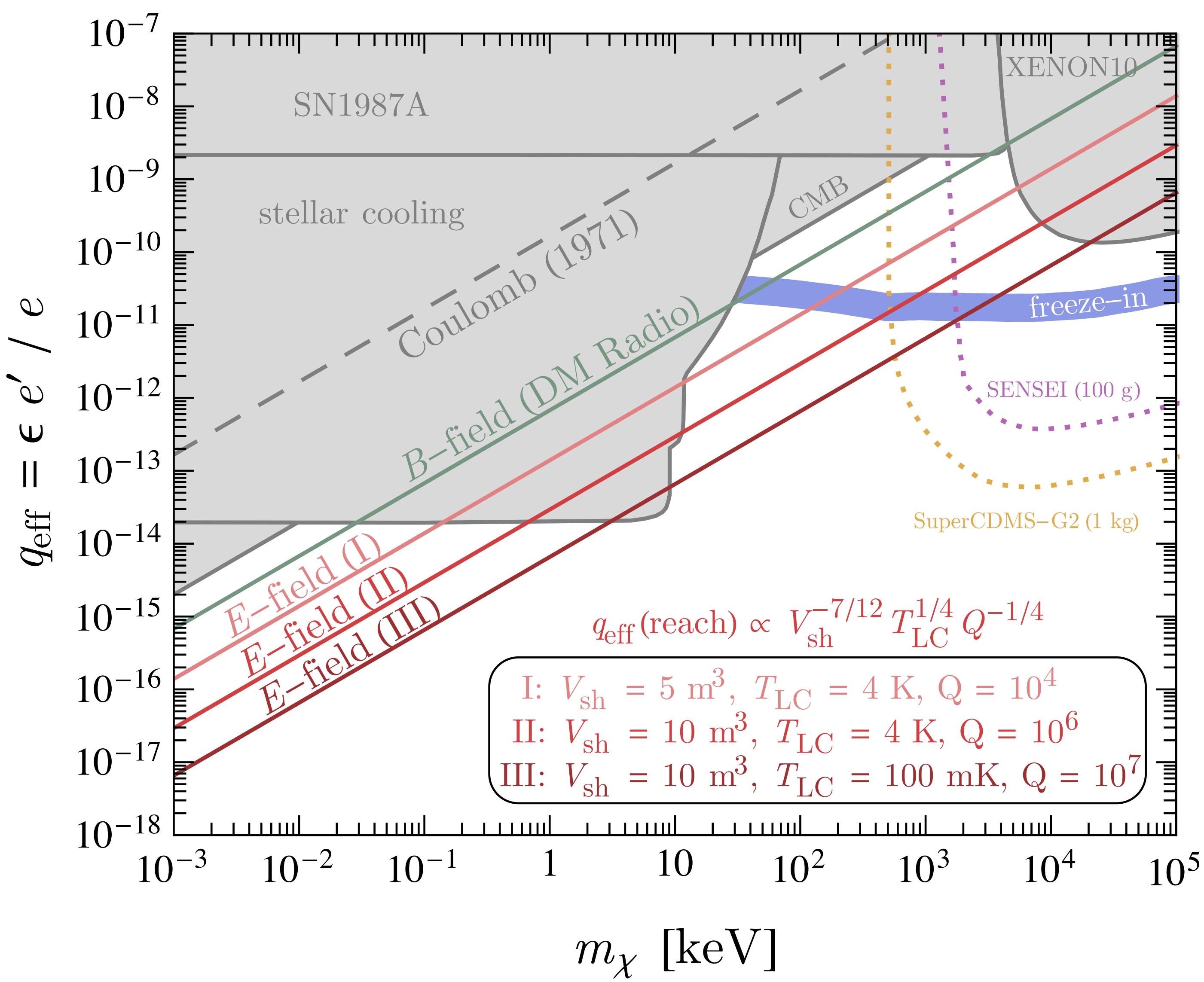
Resonant Circuit
$\omega_{\rm LC} \simeq \omega \; (\ll 1/R)$
Electromagnetic Shielding
Shield
capacitively coupled
E_χ
$V_{\rm DM}$
C
$\Phi_{\rm SQ}$
L_{PU}
L_{In}
R
SQUID
$E_{\rm sig} \sim Q \left(\frac{q_{\rm eff}}{m_\chi}\right)^2$

NOISE

- **SQUID** (imprecision, backaction): **Negligible** compared to thermal
- **Poisson fluctuations** of DM number density: **Negligible**
- **Oscillator Phase Drift**: Phase lock with commercially available atomic clocks
- **Deflector Field**: needs to be shielded, but it can be done [DM radio: penetration depth 50 nm, for $E = 10 \times \langle E_{\rm def} \rangle$]
- **Thermal Noise**: **Irreducible**, ultimate limitation $P_n = kT/t_{\rm int}$

REACH

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



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

$$\omega = 100\ \text{kHz}$$

$$t_{\rm int} = \text{year}$$

CONCLUSION

- Simple idea with the potential of solving some of the challenges of light dark matter detection
- Robust technological implementation for a well motivated target
- Interesting new avenues of investigation:
  - Focusing/trapping of DM
  - Spin-coupled forces

BACKUP

PARAMETRICS

$$\rho_\chi(\vec{x},t) = \frac{eq_{\rm eff}}{2} n_\chi \sum_{j=0}^{1} (1)^j \int d\vec{x}_i d\vec{v}_i f(\vec{v}_i) \delta^3(\vec{x} - \vec{x}_{\rm def})$$

$$\vec{x}_{\rm def} = \vec{x}_{\rm free} + \Delta\vec{x}$$

$$\rho_\chi(\vec{x},t) \approx \frac{eq_{\rm eff}}{2} n_\chi \sum_{j=0}^{1} (1)^j \int d\vec{v}_i f(\vec{v}_i) \nabla \cdot \Delta\vec{x}$$

$$\Delta\vec{x} \approx (-1)^j \frac{eq_{\rm eff}}{m_\chi} \int d\tau \tau E_{\rm def}(\vec{x}_{\rm free} - \vec{v}\tau, t-\tau)$$

$$\rho_\chi \sim q_{\rm eff}^2 \rho_{\rm def} R_{\rm def}^2 \sim q_{\rm eff}^2 E_{\rm def} R_{\rm def}$$

PARAMETRICS

$$\rho_\chi \sim q_{\text{eff}}^2 E_{\text{deflector}} R_{\text{deflector}}$$

$$E_{\text{signal}} \sim \rho_\chi R_{\text{detector}}$$

$$\text{SNR} \sim E_{\text{signal}}^2 V_{\text{detector}} \sim q_{\text{eff}}^4 E_{\text{deflector}}^2 V_{\text{deflector}}^{2/3} V_{\text{detector}}^{5/3}$$

SELF-INTERACTIONS

Self-Interaction Bound:

$$\alpha' \lesssim 10^{-10} \left(\frac{m_\chi}{\mathrm{MeV}}\right)^{3/2}$$

Freeze-In:

$$\alpha' \simeq \frac{10^{-24}}{\epsilon^2} \frac{\mathrm{MeV}}{m_\chi}$$

Minimum dark photon coupling:

$$\epsilon \gtrsim 10^{-7} \left(\frac{\mathrm{MeV}}{m_\chi}\right)^{5/4}$$

VECTOR MEDIATORS