Title: Direct Deflection of Particle Dark Matter

Speakers: Asher Berlin

Series: Particle Physics

Date: October 15, 2019 - 1:00 PM

URL: http://pirsa.org/19100077

Abstract: Detecting light dark matter that interacts weakly with electromagnetism has recently become one of the benchmark goals of near-term and futuristic direct detection experiments. In this talk, I will discuss an alternative technique to directly detecting such particles below the GeV-scale. The approach involves distorting the local flow of dark matter with time-varying fields and measuring these distortions with shielded resonant detectors, such as LC circuits.

Direct *Deflection* of Particle Dark Matter

Asher Berlin

Perimeter
October 15, 2019

1908.06982 with R. D'Agnolo, S. Ellis, P. Schuster, N. Toro

Direct Detection Below an MeV

predictive cosmology

(freeze-in)

viable

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

detectable

(light mediator)

Direct Detection Below an MeV

predictive cosmology

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viable

(self-interactions, stellar cooling, 5th forces)

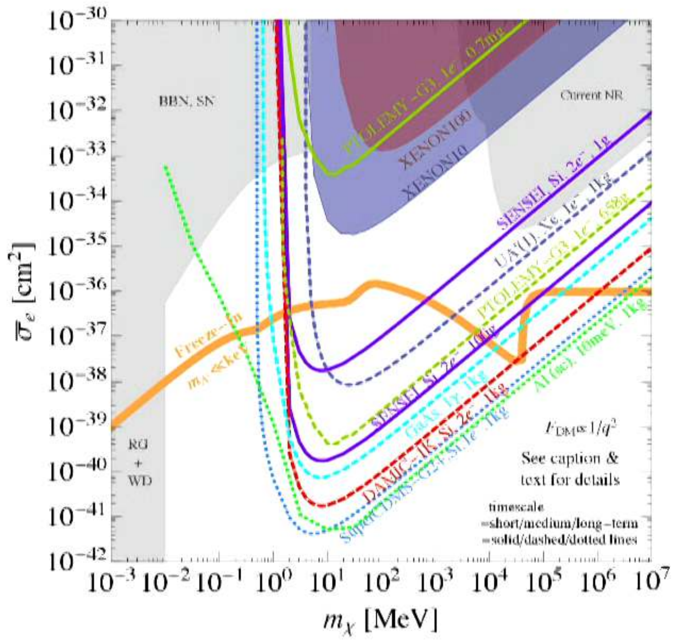
detectable

(light mediator)

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

millicharge-like on meter length scales

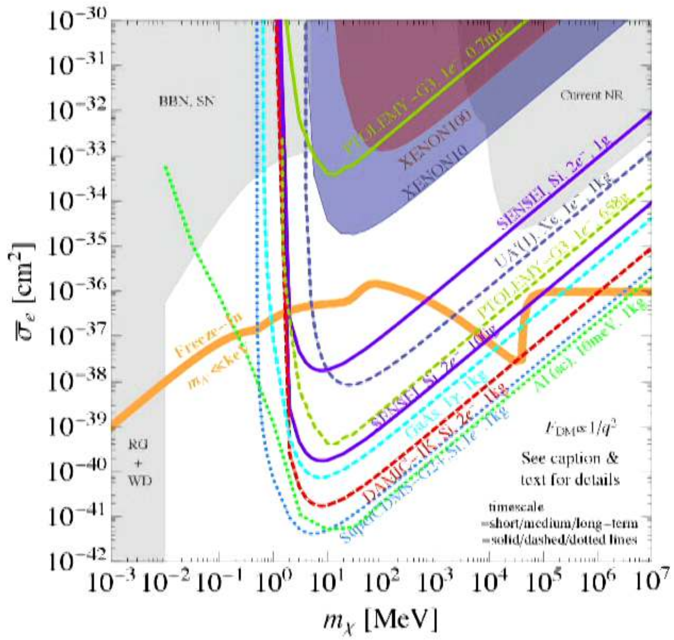
Direct Detection via Scattering



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

arXiv:1707.04591

Direct Detection via Scattering



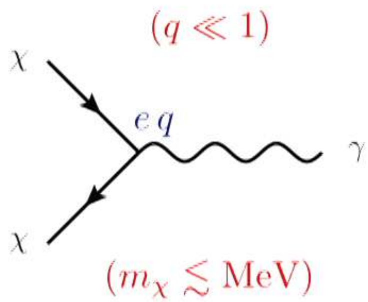
- new scattering targets
- new read-out technologies
- similar philosophy

instead, take advantage of:

small mass → large number density, small momentum → easier to manipulate

arXiv:1707.04591

Millicharge Cosmology

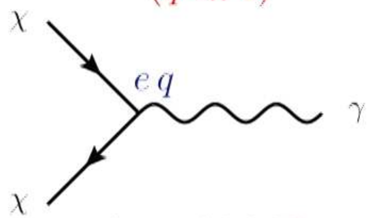


χ thermalizes $\Longrightarrow$ in conflict with BBN and CMB

How small does q have to be?

Millicharge Cosmology

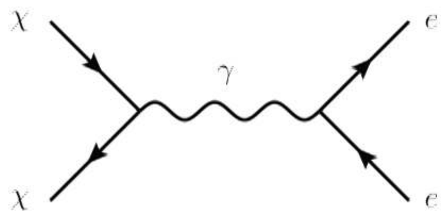
$(q \ll 1)$



$(m_\chi \lesssim \text{MeV})$

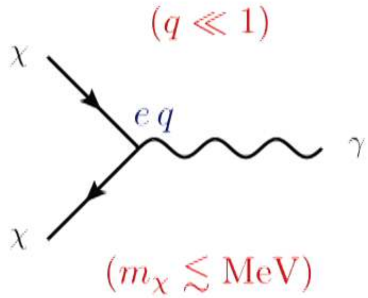
χ thermalizes $\Longrightarrow$ in conflict with BBN and CMB

How small does q have to be?



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

Millicharge Cosmology



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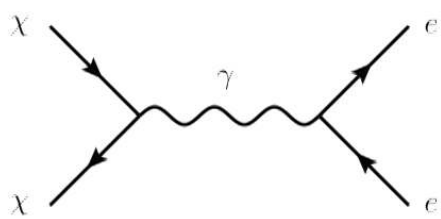
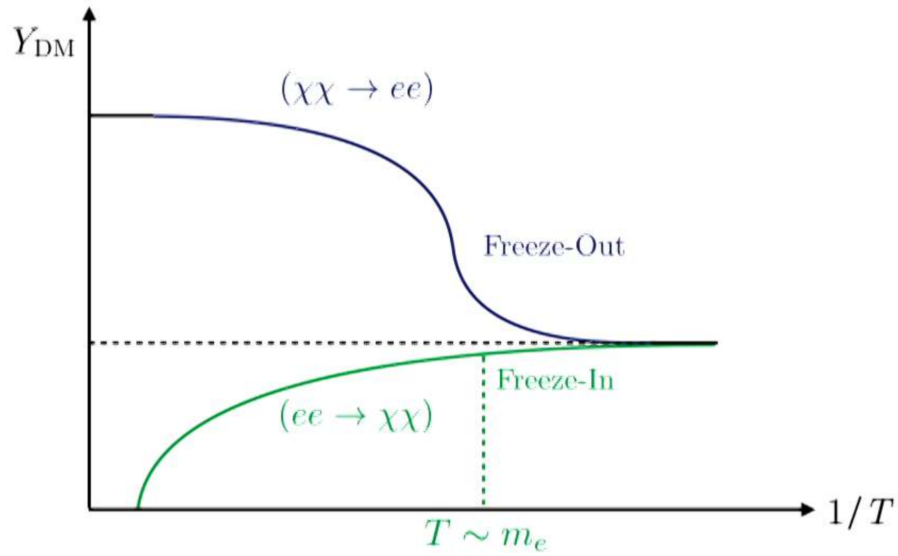
How small does q have to be?



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

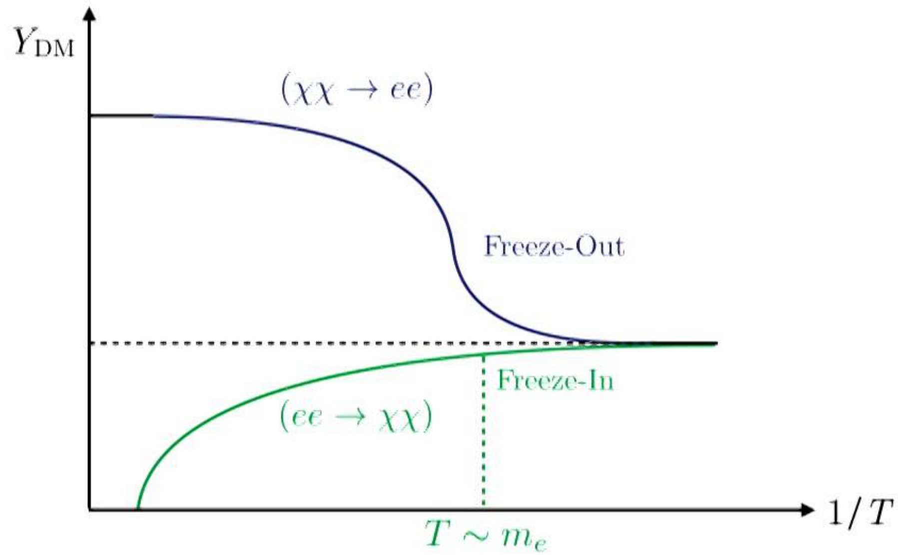
If this is the dark matter, how is it populated?

Freeze-In



arXiv:0911.1120

Freeze-In



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

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

arXiv:0911.1120

Kinetic Mixing

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

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

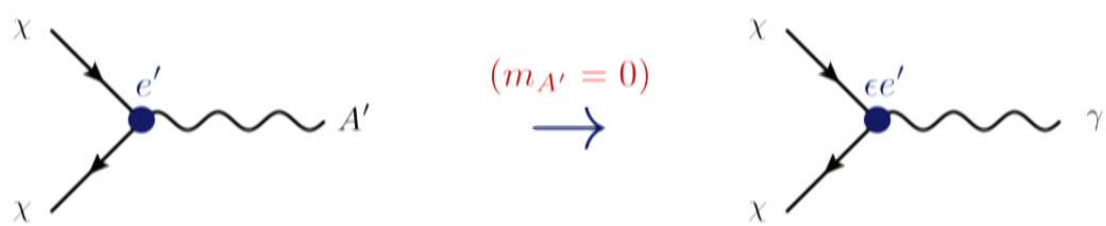
$$\mathcal{L} \supset j_\mu A^\mu + j_\mu' A'^\mu \implies \boxed{\mathcal{L} \supset \boxed{j_\mu(A^\mu + \epsilon A'^\mu)} + j_\mu' A'^\mu + \mathcal{O}(\epsilon^2)}$$

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

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

Kinetic Mixing

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



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

(exact millicharge limit)

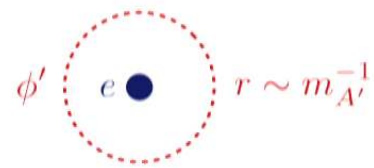
Pseudo-Millicharge

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

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

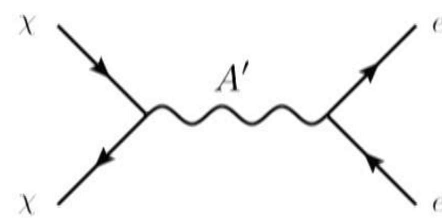
$$(\partial^2 + m_{A'}^2) A'^\mu = j'^\mu + \epsilon\, j^\mu$$

$$A'^\mu = (\phi', \mathbf{A}') \implies \begin{cases} (\nabla^2 - \partial_t^2 - m_{A'}^2)\phi' = -(\rho' + \epsilon\rho) \\ (\nabla^2 - \partial_t^2 - m_{A'}^2)\mathbf{A}' = -(\mathbf{j}' + \epsilon \mathbf{j}) \end{cases}$$



$$\rho' = 0\ ,\ \ \rho = e\, \delta^3(x)$$

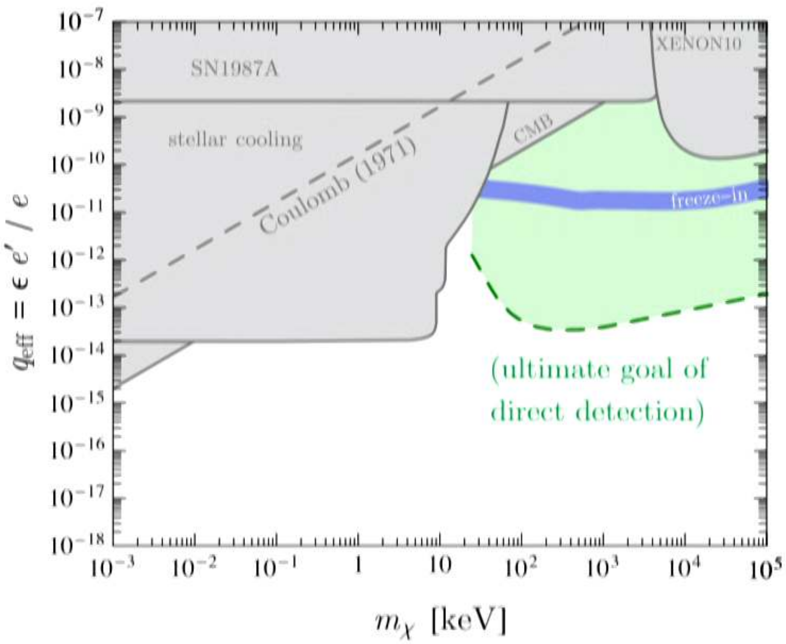
$$\implies \phi'(r) = \frac{\epsilon\, e}{4\pi} \frac{e^{-m_{A'} r}}{r}$$

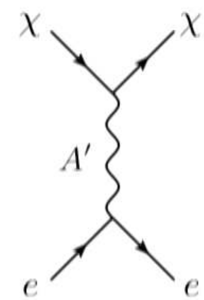


$$m_{A'} \ll \sqrt{s} \implies \sigma \sim \frac{(e' \epsilon e)^2}{s} \sim \frac{(q_{\rm eff}\ e^2)^2}{s}$$

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

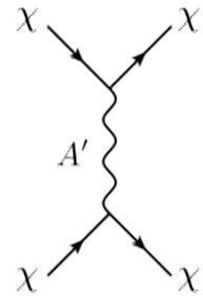
Parameter Space



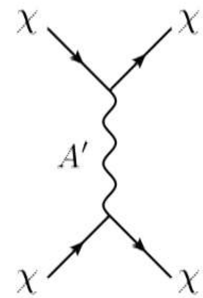


$$\sigma(\chi e \to \chi e) \propto \frac{1}{q_{\text{tr}}^4} \sim \frac{1}{(\alpha_{\text{em}}\, m_e)^4} \quad (m_{A'} \ll \text{keV})$$

Self-Interactions



Self-Interactions



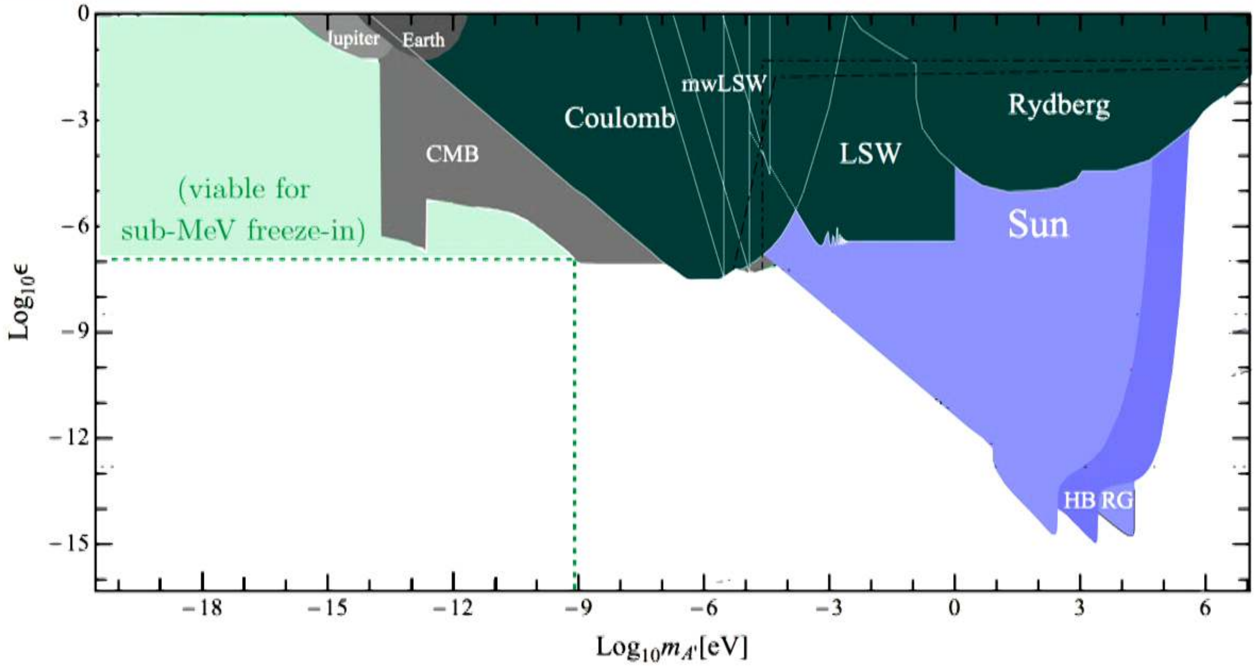
e.g., galaxy clusters $\implies \alpha' \lesssim 10^{-10} \left(\frac{m_\chi}{\text{MeV}}\right)^{3/2}$

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

$\therefore$ SIDM + 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?

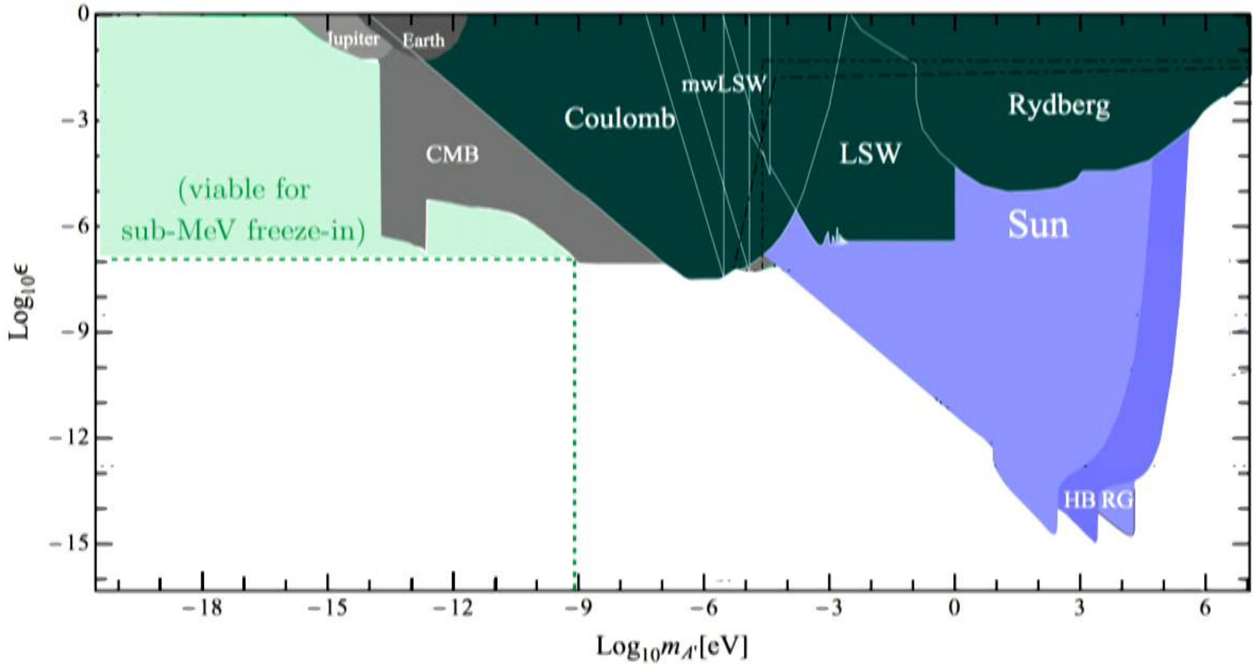
Parameter Space



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

arXiv:1704.05081
arXiv:1401.6077

Parameter Space

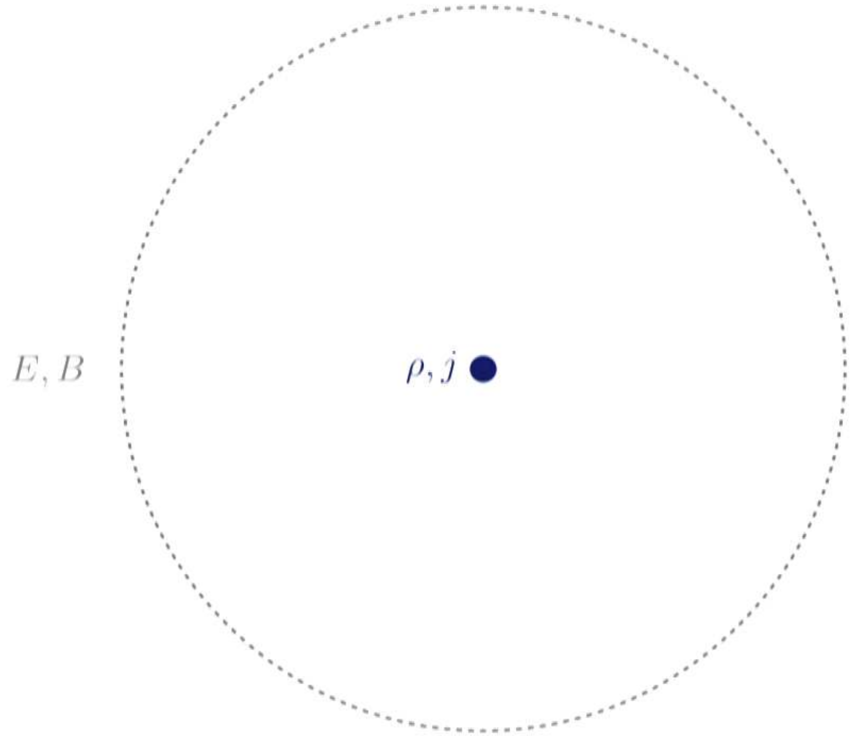


$$m_{A'} \lesssim 10^{-9}\ \mathrm{eV} \sim \frac{1}{100\ \mathrm{m}}$$

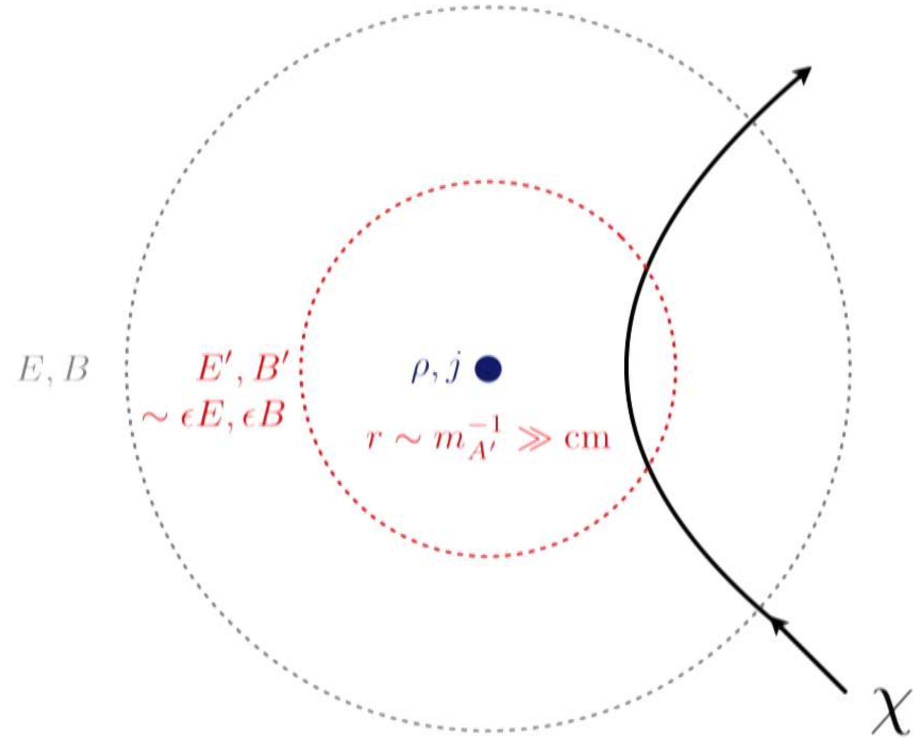
long-range forces

arXiv:1704.05081
arXiv:1401.6077

Electromagnetic Fields



Electromagnetic Fields



Active Direct Detection

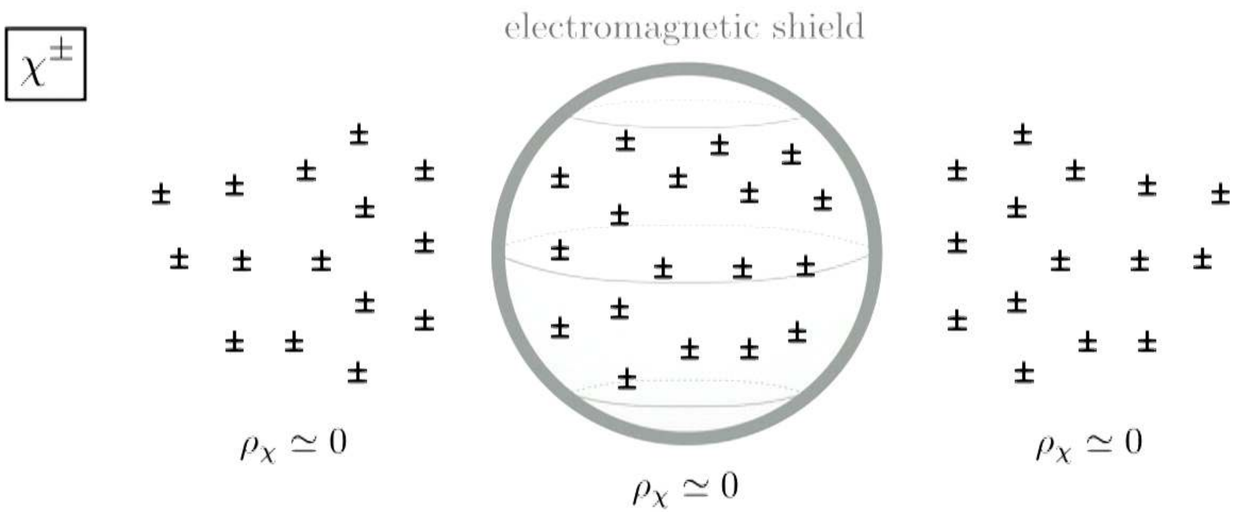
$$q_{\rm eff} \sim \epsilon e'/e \sim 10^{-11} \left(\frac{m_\chi}{\rm MeV}\right)^{-1/2}$$

(freeze-in)

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

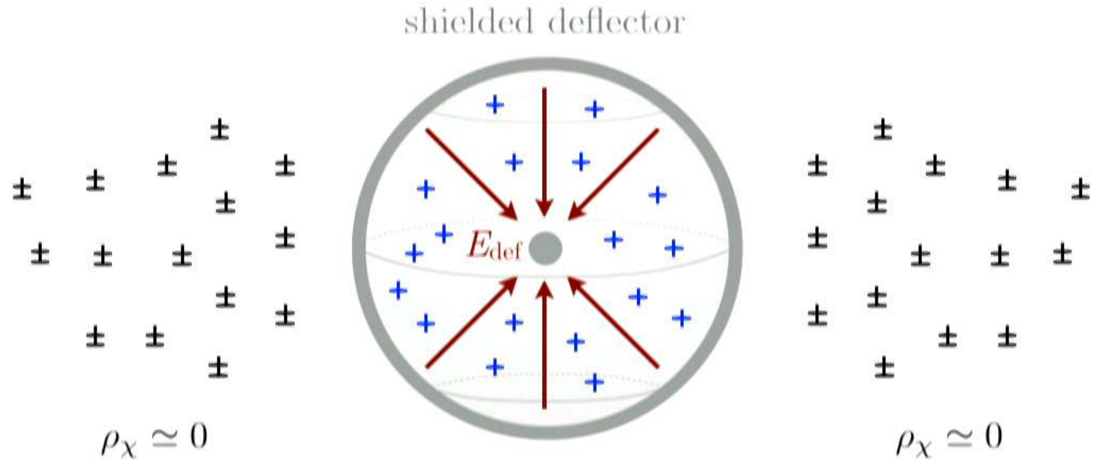
•stop it: $$m_\chi\, v_\chi^2 \sim q_{\rm eff}\, e\, \Delta V \implies \Delta V \sim {\rm MV} \times \left(\frac{m_\chi}{\rm keV}\right)^{3/2}$$

Debye Screening



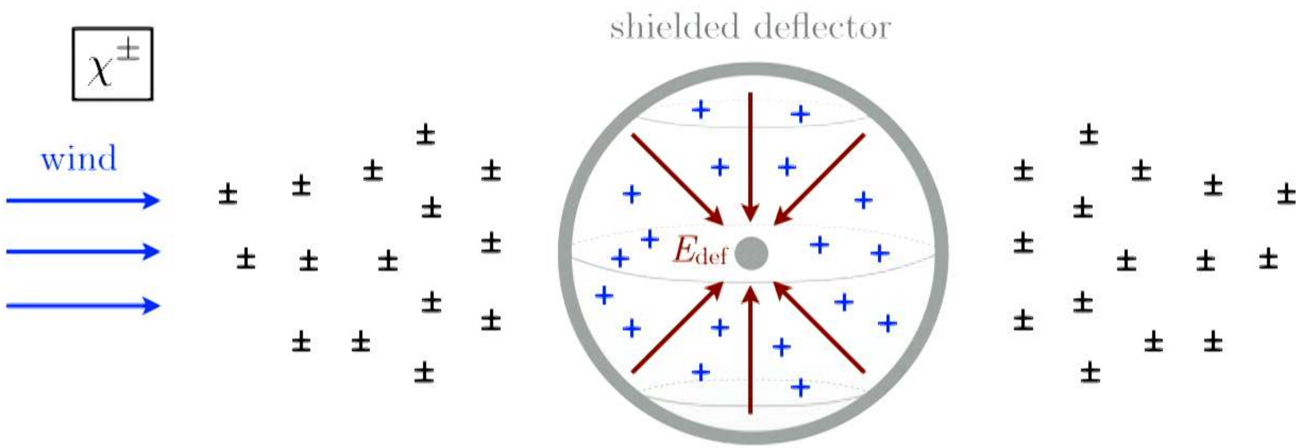
Debye Screening

$\boxed{\chi^{\pm}}$

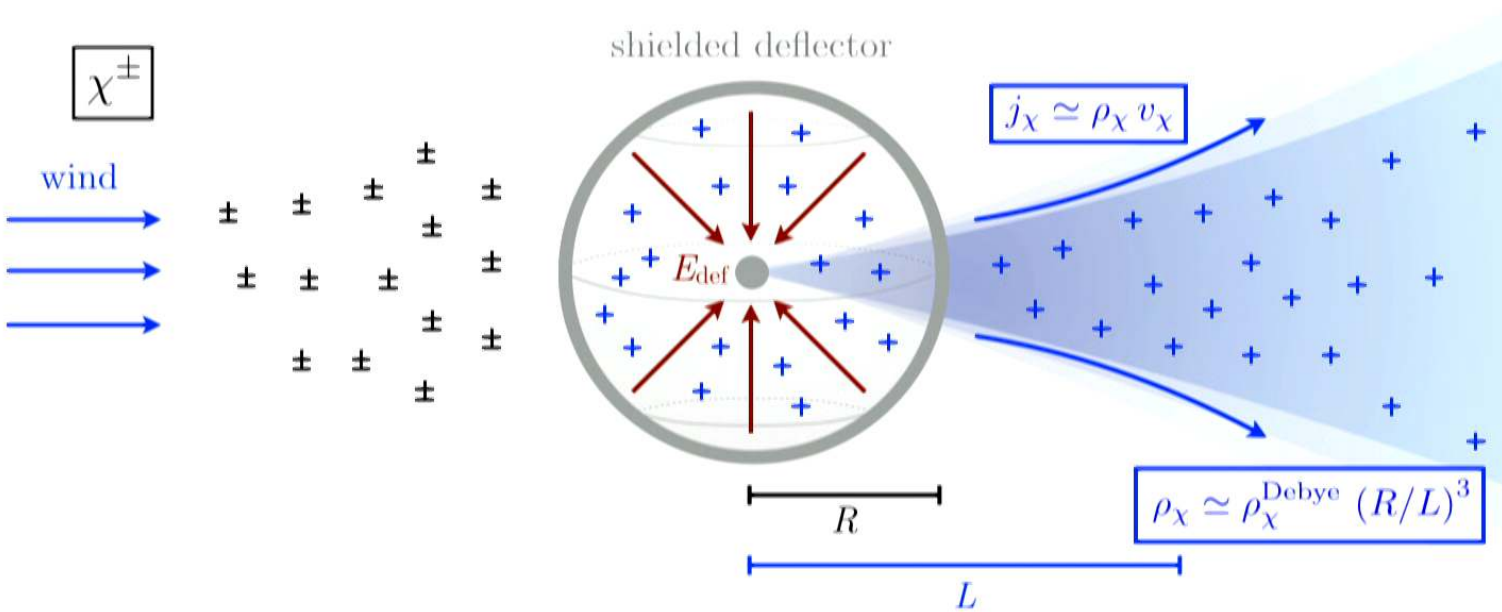


$$\rho_\chi^{\rm Debye} \simeq -\frac{(eq_{\rm eff})^2\,\rho_{\rm DM}\,V_{\rm def}}{m_\chi^2\,v_\chi^2}$$

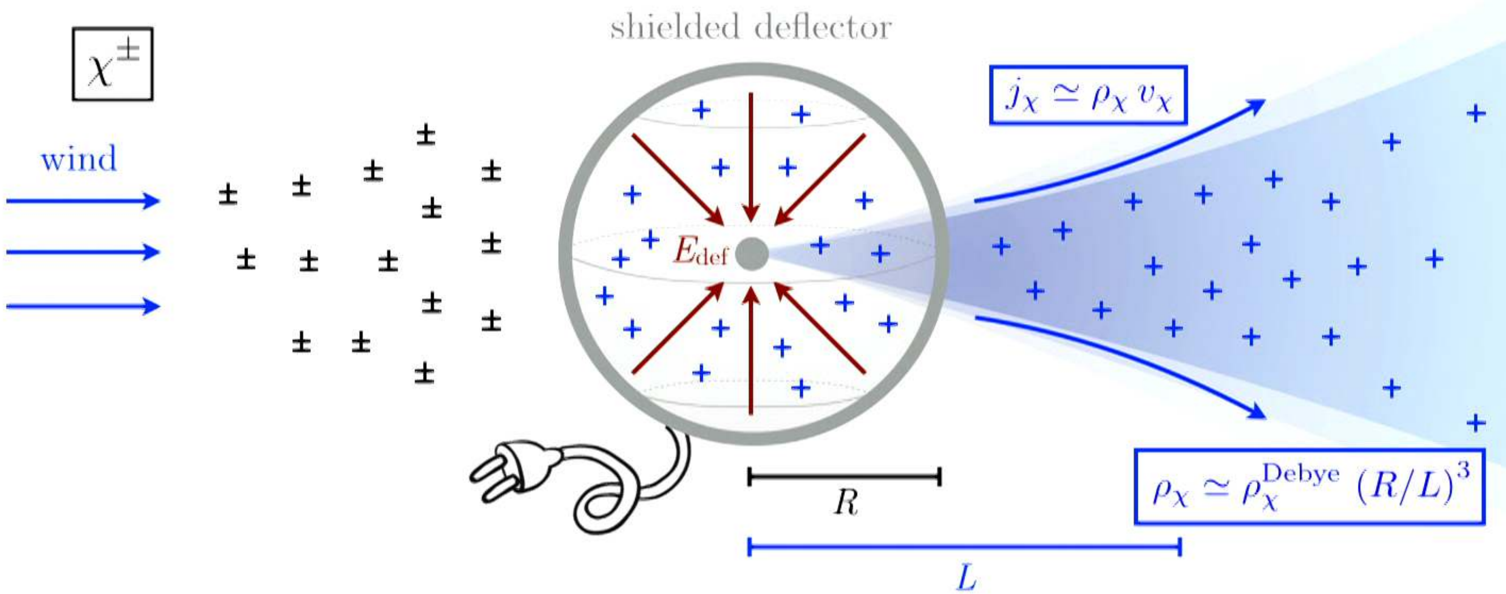
Non-Adiabatic Debye Screening



Non-Adiabatic Debye Screening



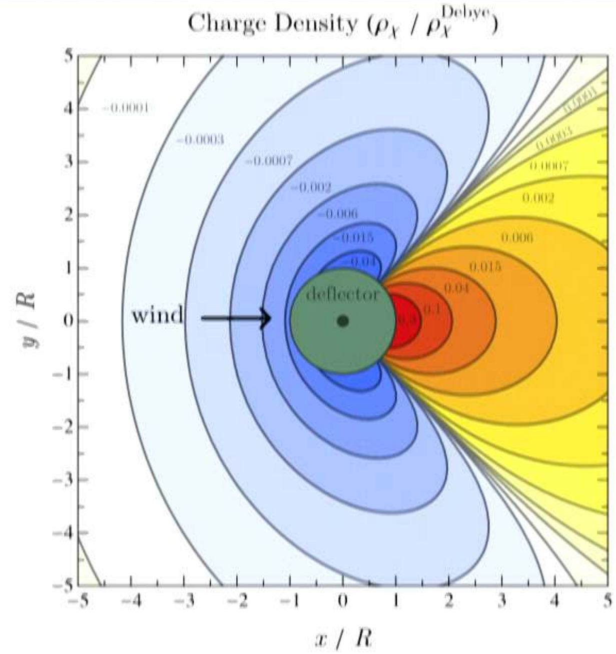
Non-Adiabatic Debye Screening

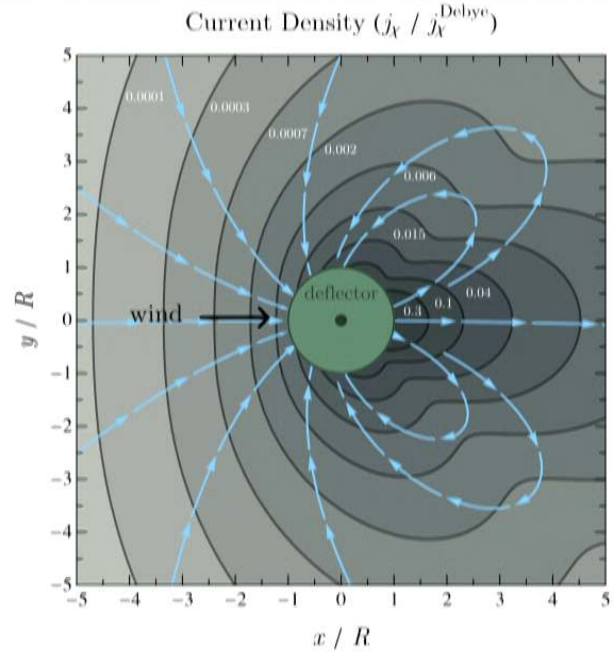


$$E_{\text{def}} \to E_{\text{def}}\, e^{i\omega t} \implies \rho_\chi \to \rho_\chi\, e^{i\omega t}\ ,\ j_\chi \to j_\chi\, e^{i\omega t}$$

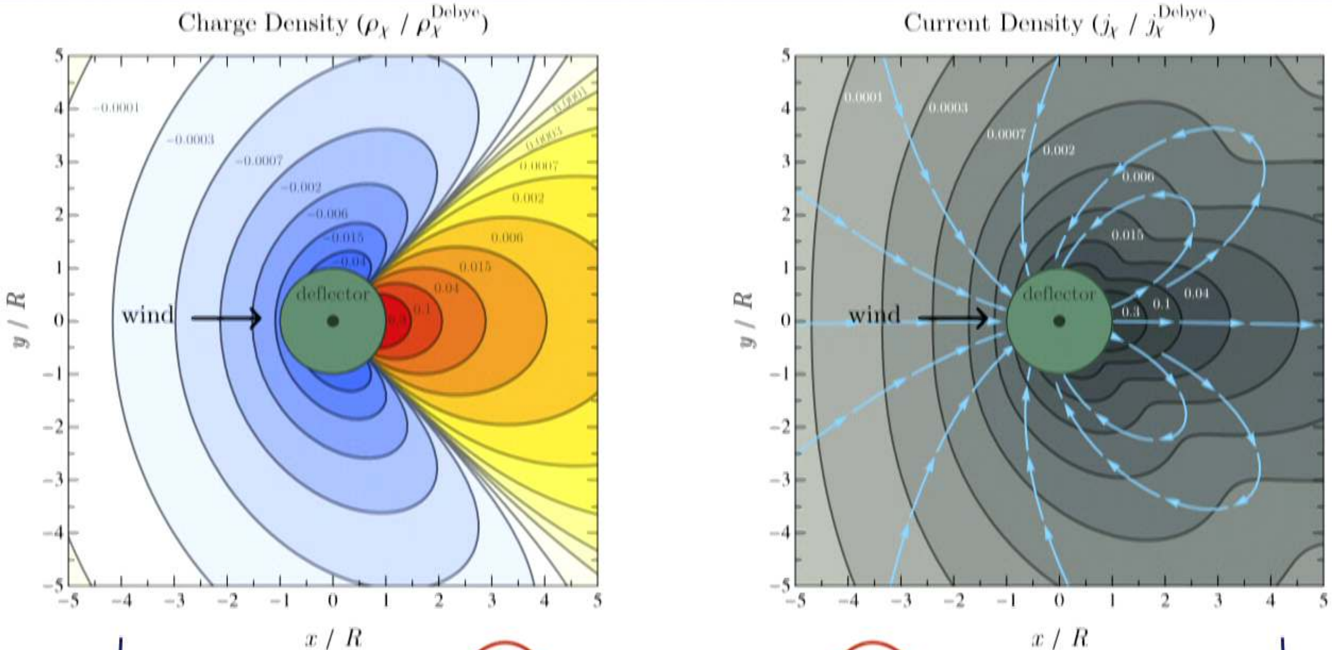
allows for resonant detection

Non-Adiabatic Debye Screening





Non-Adiabatic Debye Screening



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

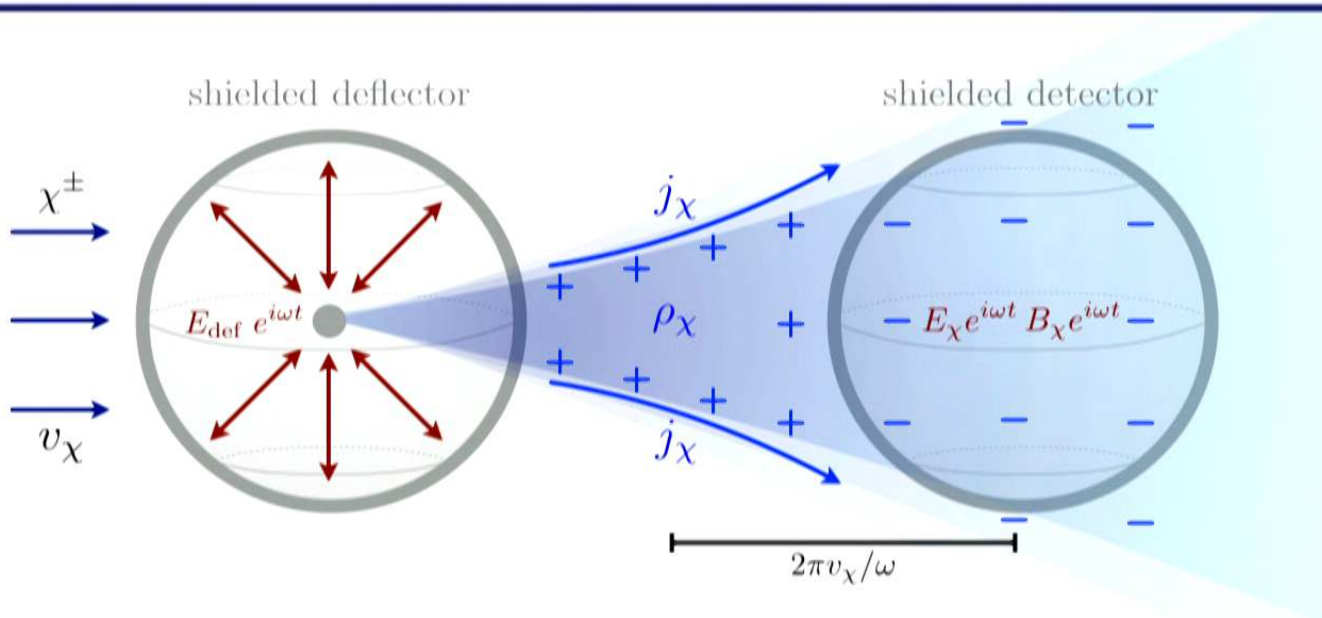
$$\Longrightarrow \text{kHz} \times (m_\chi/\text{eV})^{-1/4} \ll \omega \ll \text{MHz} \times (R/\text{meter})^{-1}$$

electric fields

100 kHz
(quasi-static)

magnetic fields

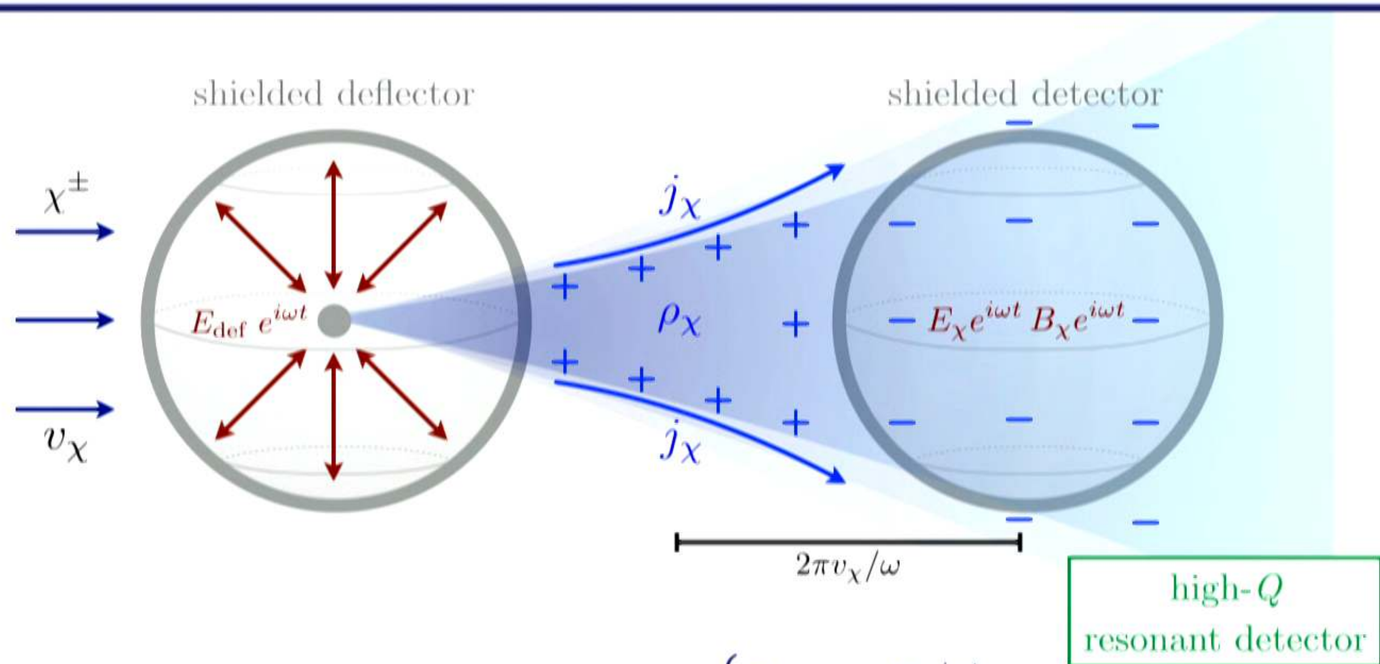
Direct Deflection



$$\text{quasi-static } (\omega \ll 1/R) \implies \begin{cases} E_\chi \sim \rho_\chi\, R\, e^{i\omega t} \\ B_\chi \sim v_\chi\, \rho_\chi\, R\, e^{i\omega t} \end{cases}$$

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

Direct Deflection



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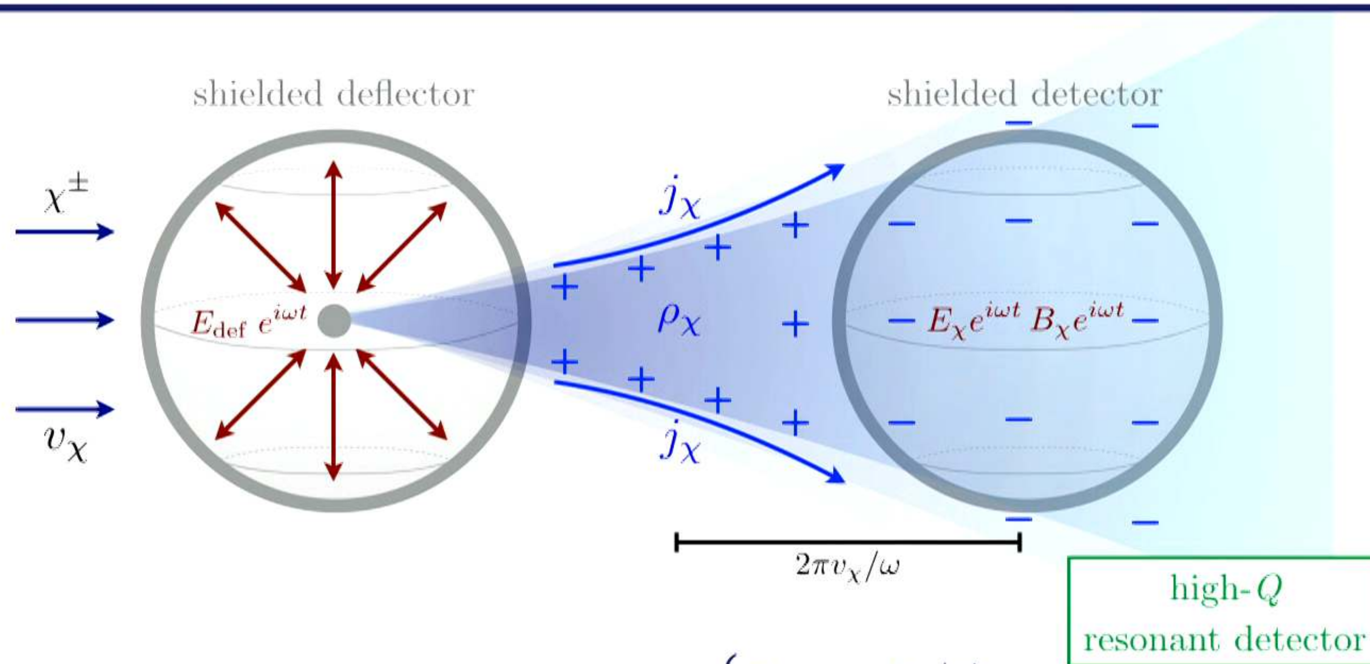
Direct Deflection



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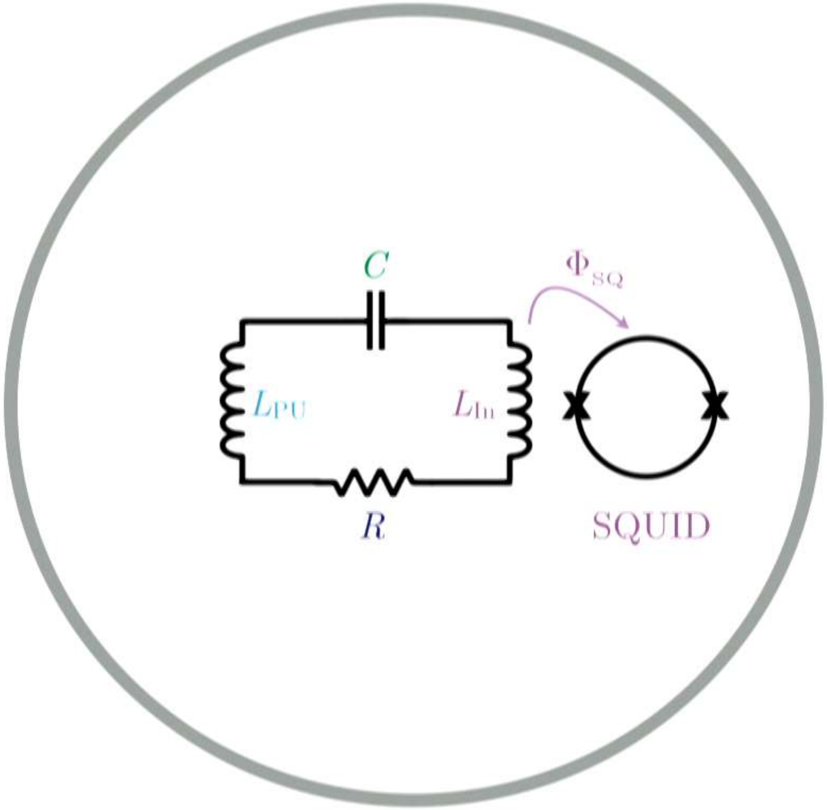
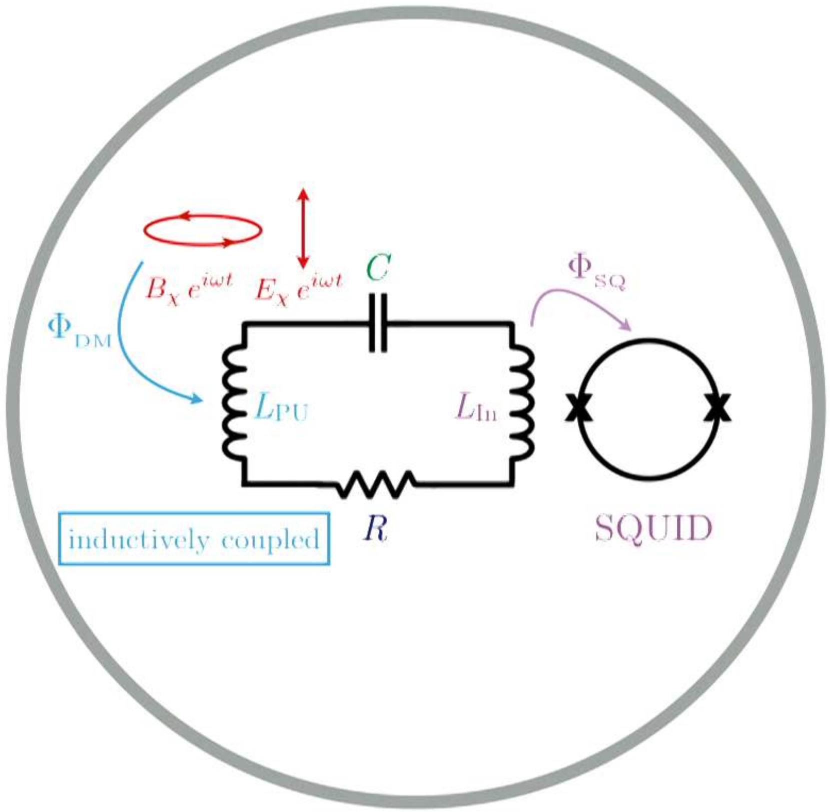
LC Resonators

shielded detector



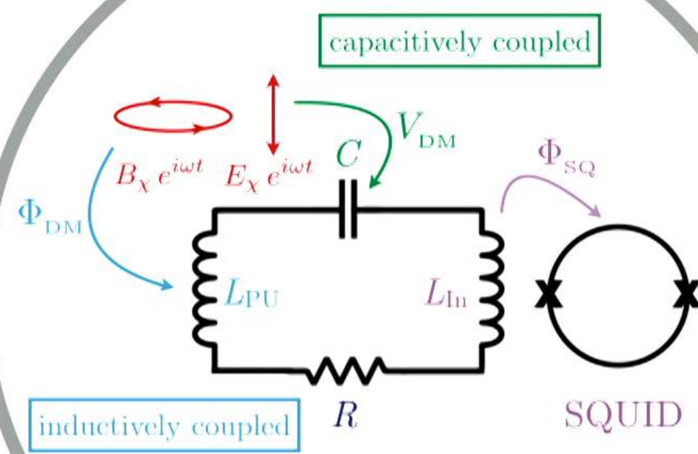
LC Resonators

shielded detector



LC Resonators

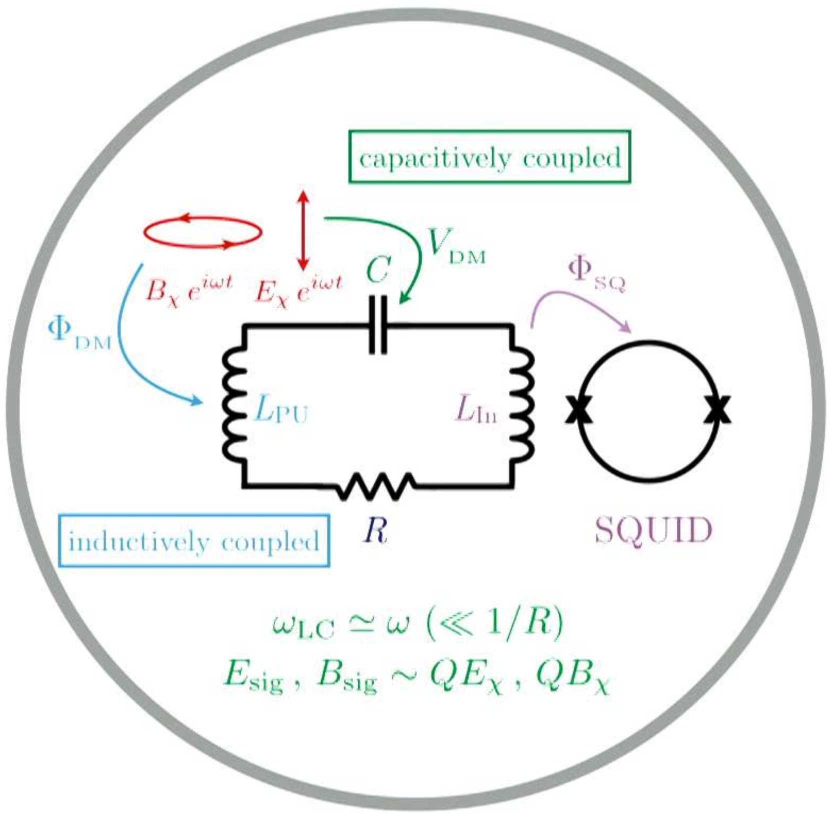
shielded detector



$$\omega_{\rm LC} \simeq \omega \ (\ll 1/R)$$
$$E_{\rm sig}\,,\ B_{\rm sig} \sim QE_\chi\,,\ QB_\chi$$

LC Resonators

shielded detector



= DM Radio, Auriga...

LC Resonators

Auriga
(gravity waves)

DM Radio
(effective currents via ultralight DM)

resolve thermal noise

LC Resonators

Auriga

(gravity waves)

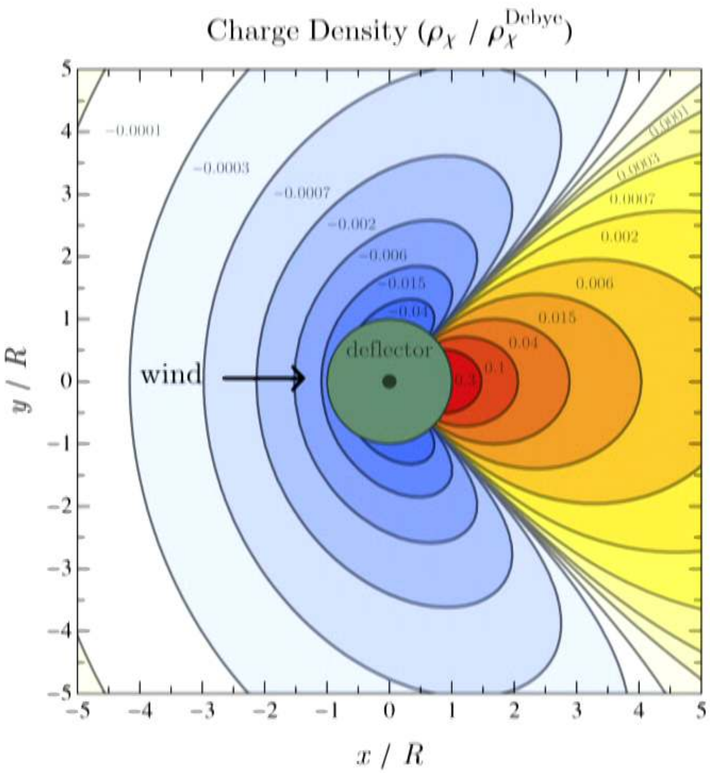
DM Radio

(effective currents via ultralight DM)

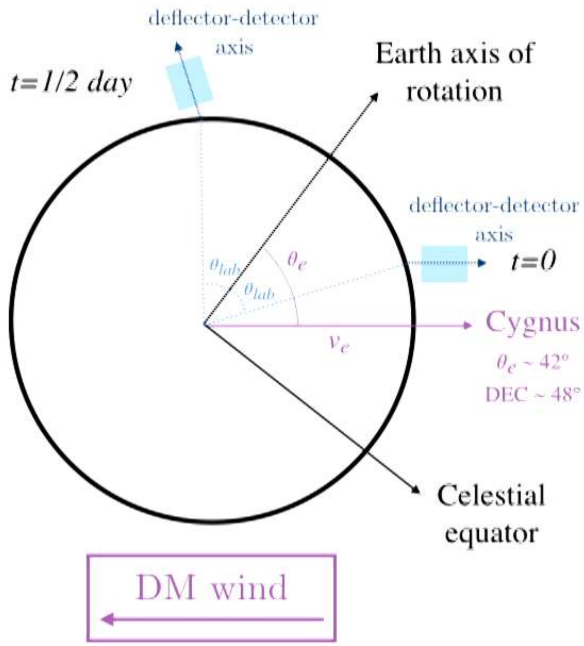
resolve thermal noise

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

Directional Dependence

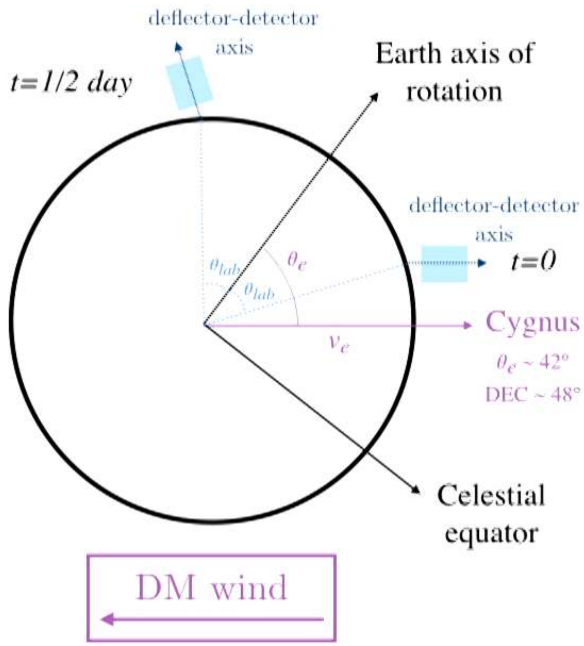


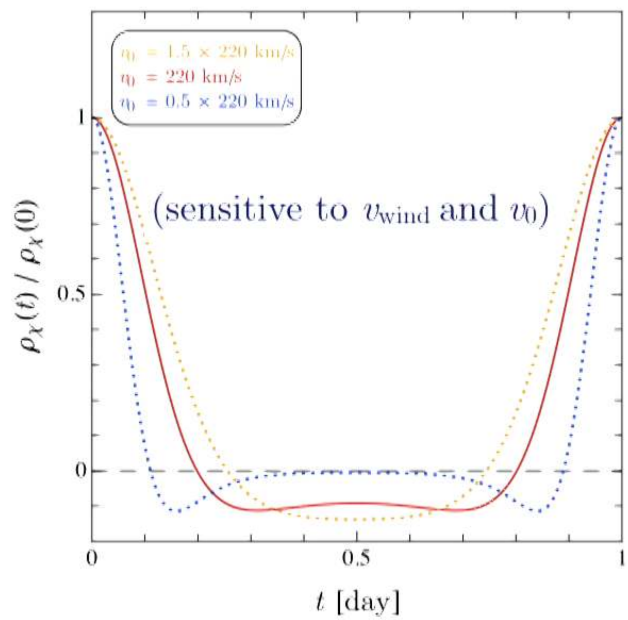
Daily Modulation



arXiv:1807.10291

Daily Modulation





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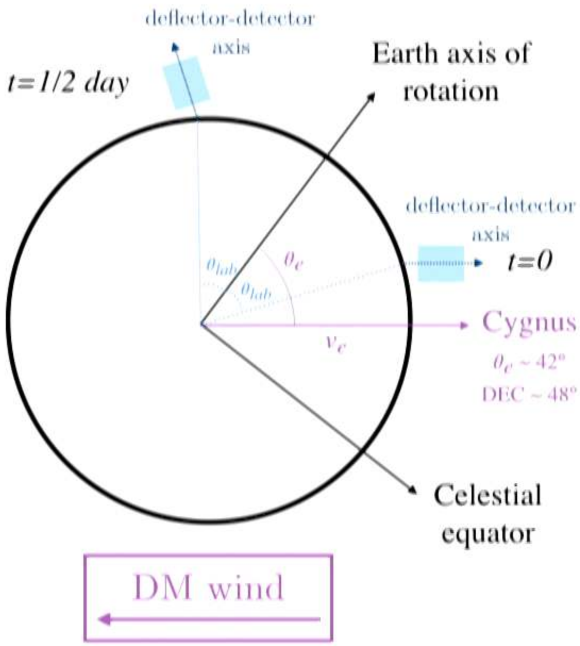
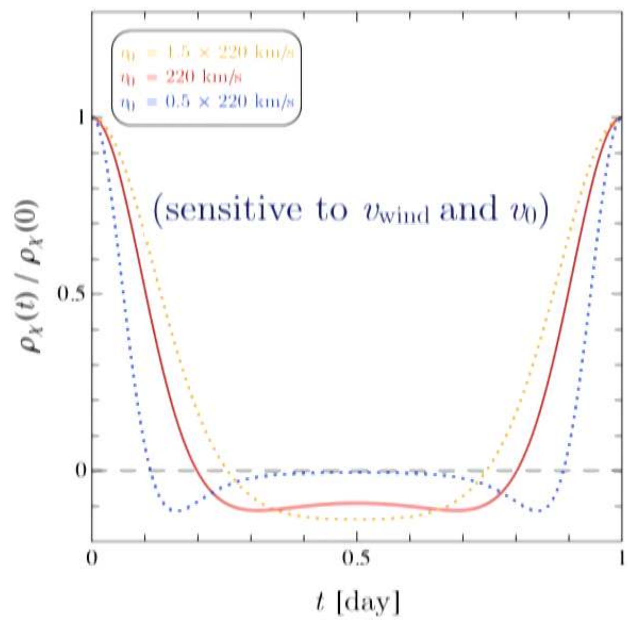
Daily Modulation



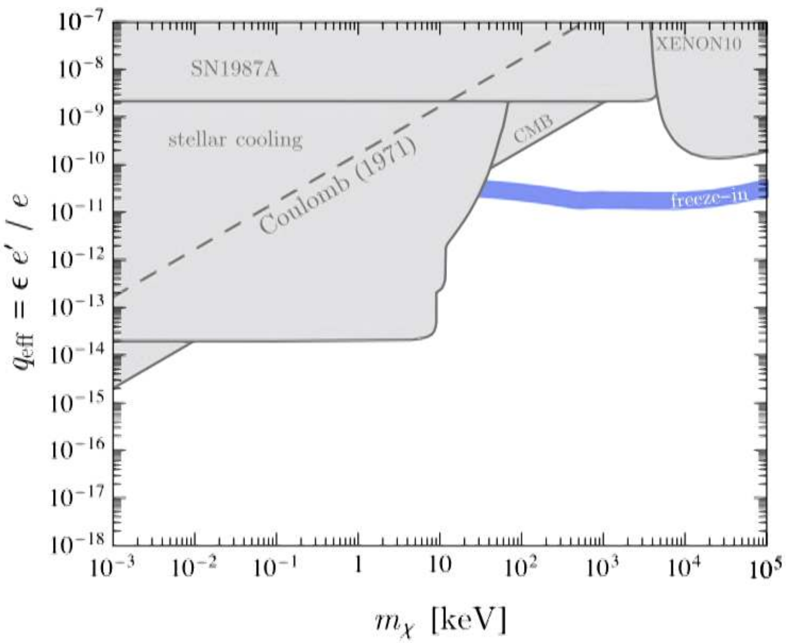


deflector: ω

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

arXiv:1807.10291

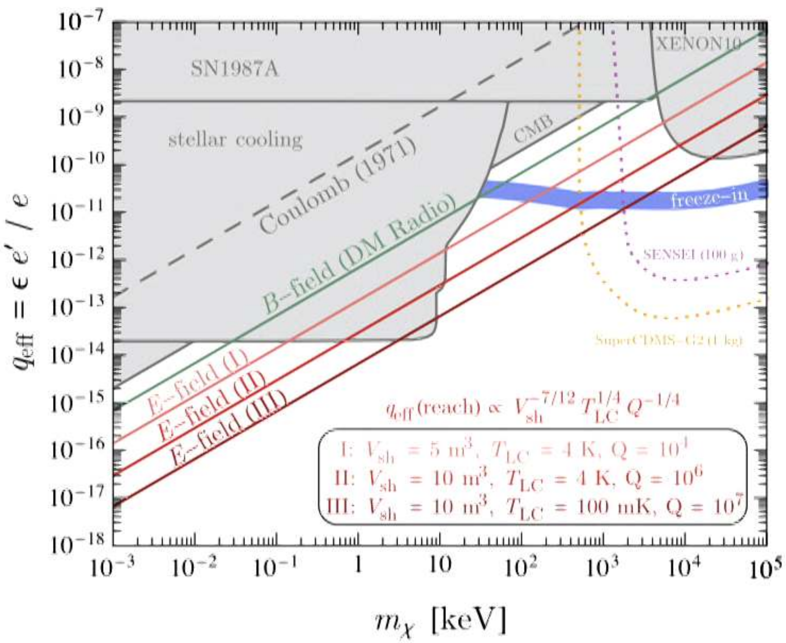
Reach Summary



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

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

Reach Summary



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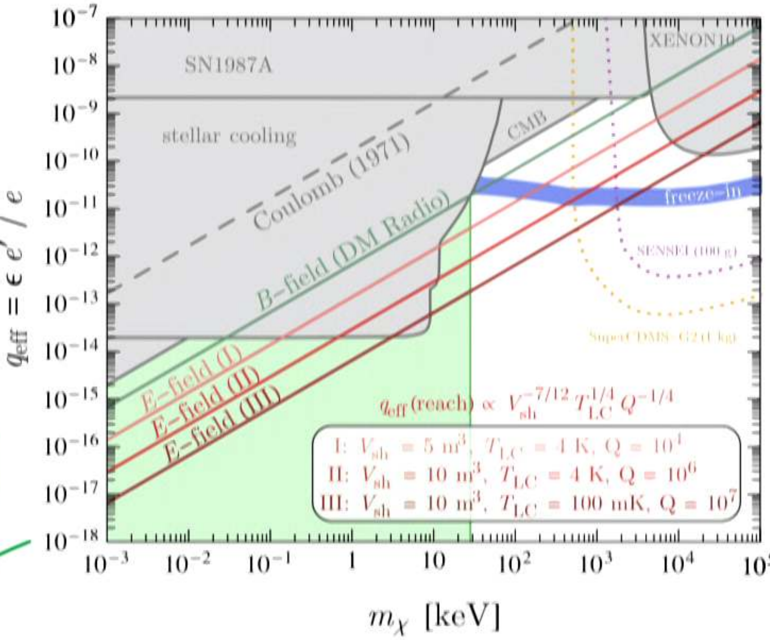
$$q_{\rm eff}(\text{reach}) \propto m_\chi\, V_{\rm sh}^{-\frac{7}{12}}\, \langle E_{\rm def}\rangle^{-\frac{1}{2}}\, \left(Q\,\omega\, t_{\rm int}/T_{\rm LC}\right)^{-\frac{1}{4}}$$

Reach Summary



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

ultralight cosmology?

transition when

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

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

Active Direct Detection

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