SLAC NATIONAL ACCELERATOR LABORATORY

Direct Deflection of Particle Dark Matter

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Based on 1908.06982 with:
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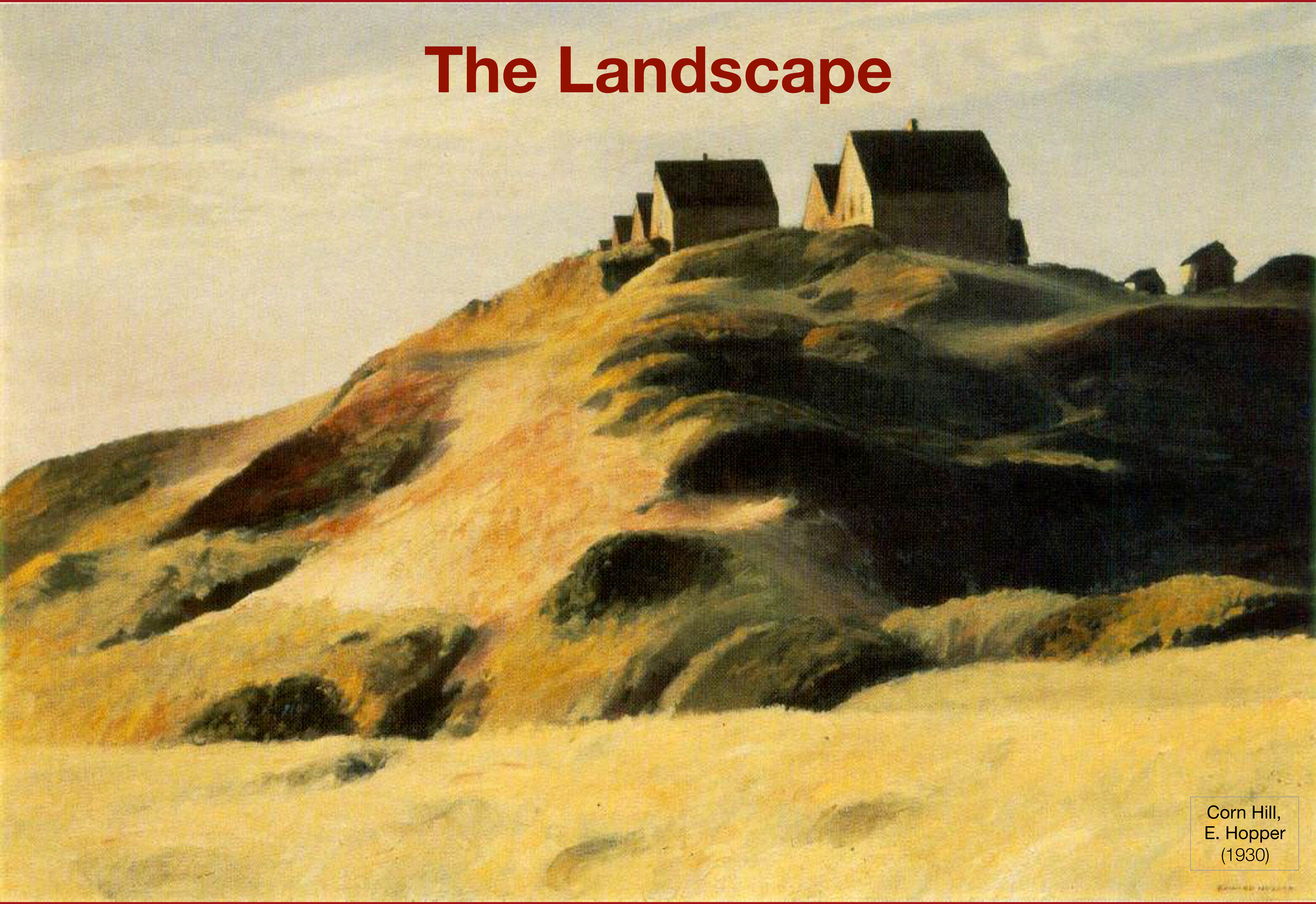
Outline

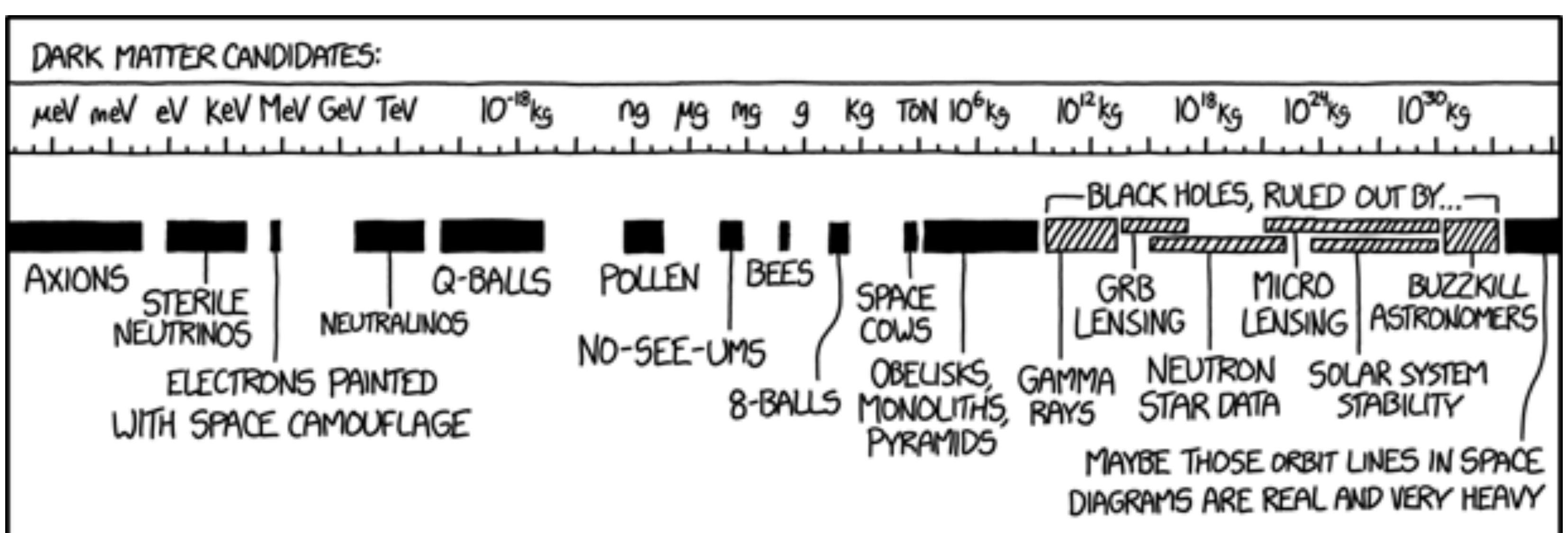
- The dark matter landscape
- Contrasting experimental techniques
  - m_{DM} > keV
  - m_{DM} < keV
- Bridging the gap — presenting a general approach
- A specific model: (pseudo-)millicharge
- Implications of (pseudo-)millicharge
  - New observables
- An experimental proposal
- Outlook

The Landscape



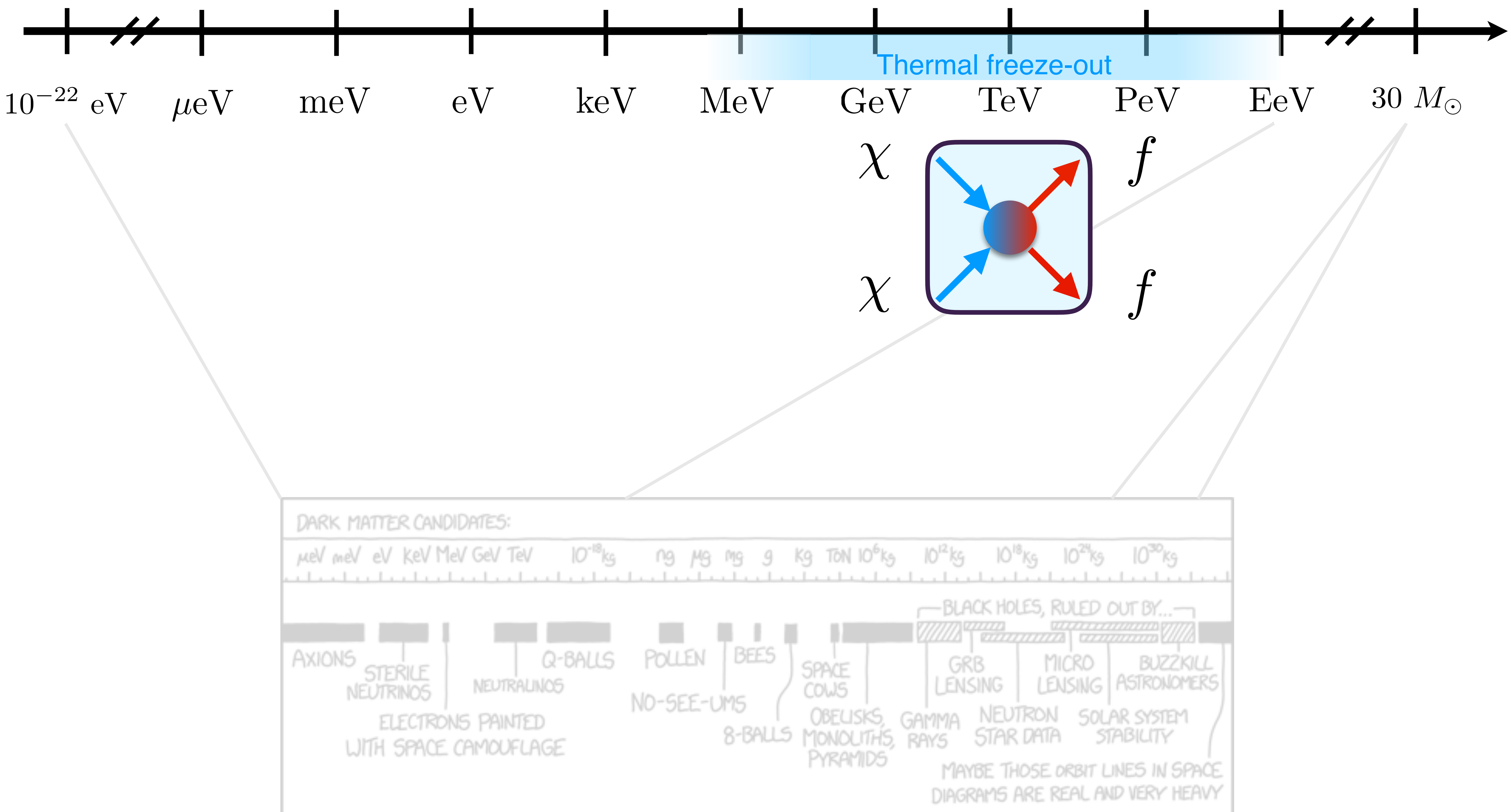
Corn Hill,
E. Hopper
(1930)

The Dark Matter Landscape



Munroe (xkcd/2035)

The Dark Matter Landscape



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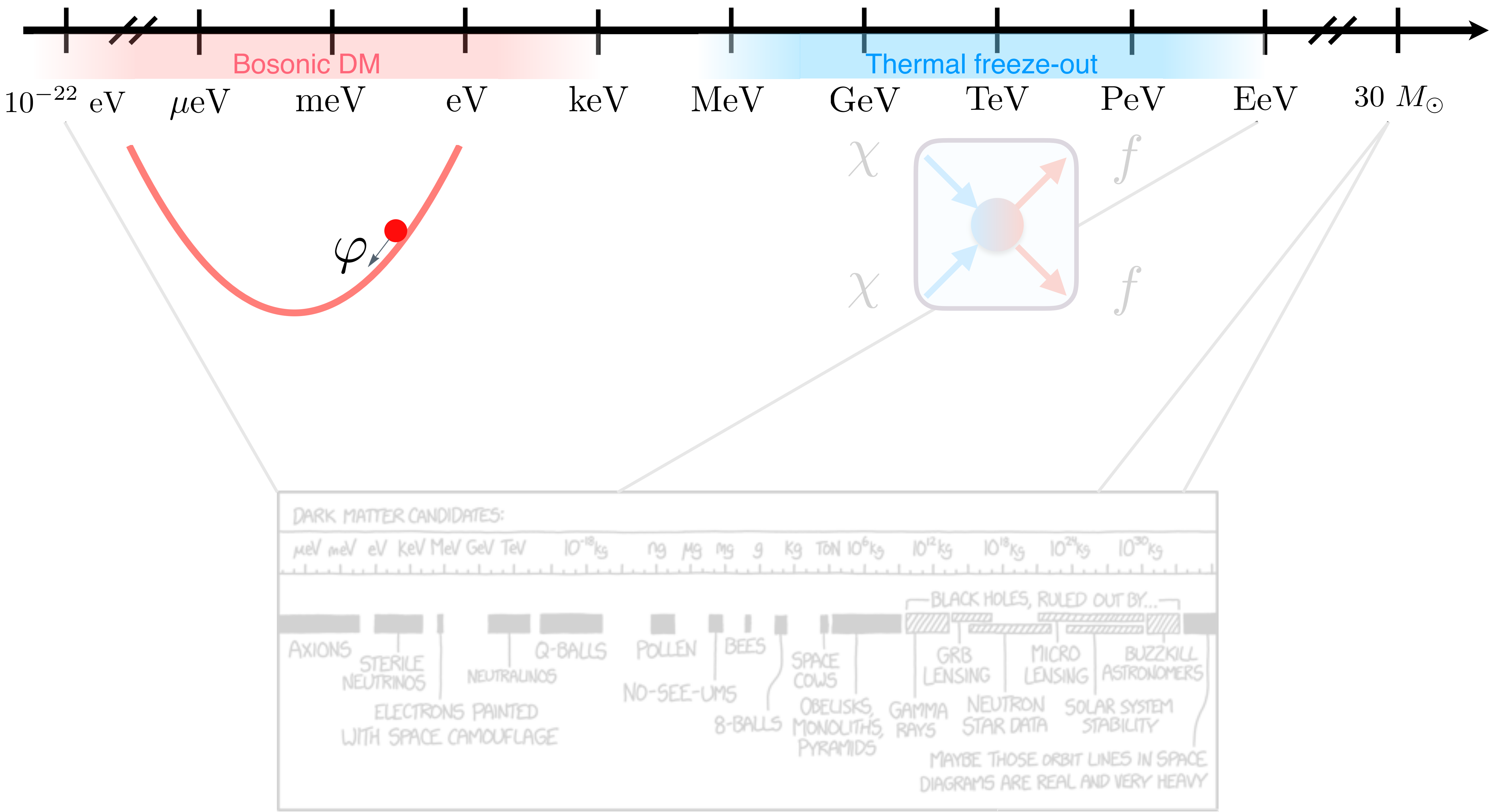

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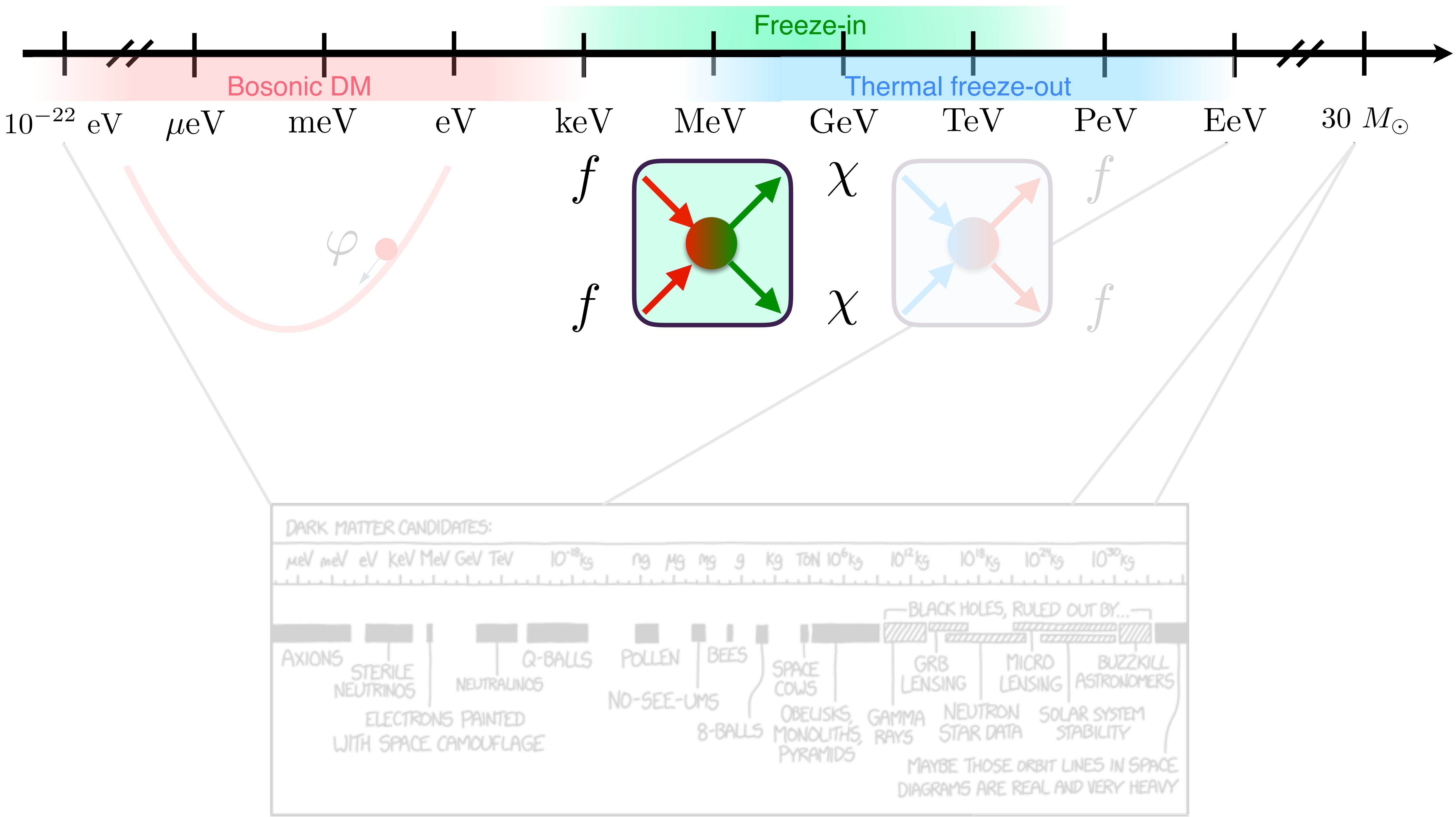

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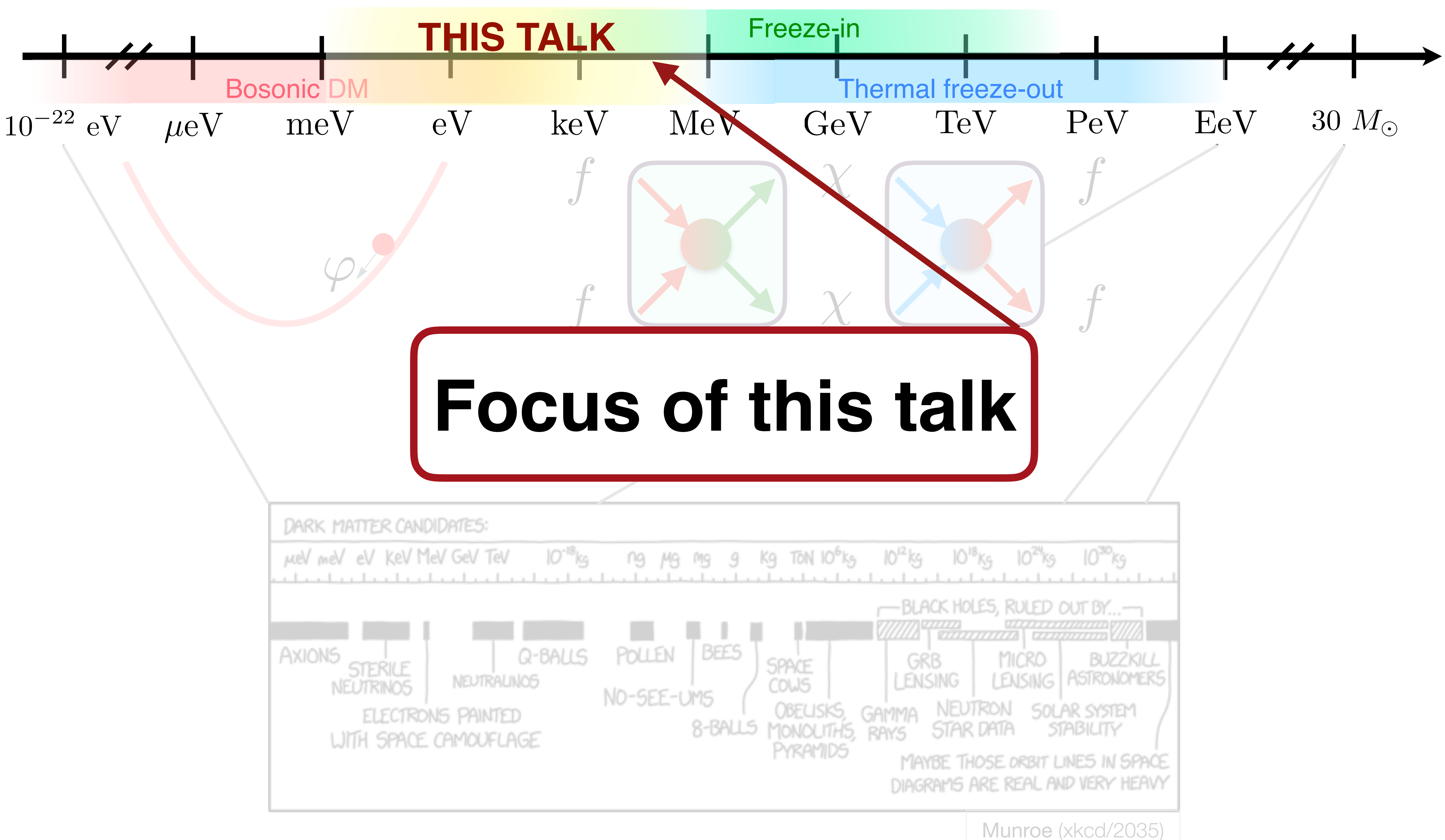
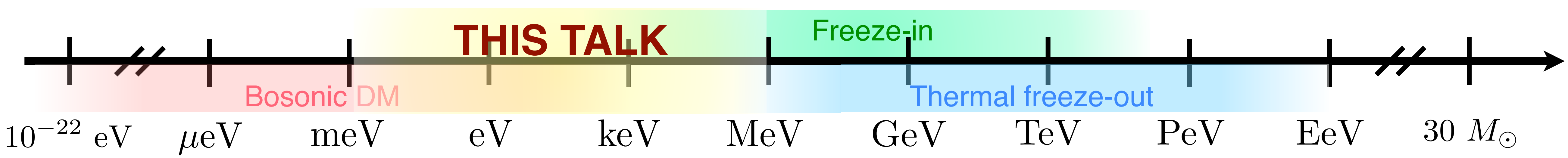
The Dark Matter Landscape



The experimental landscape



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

Collective Effects

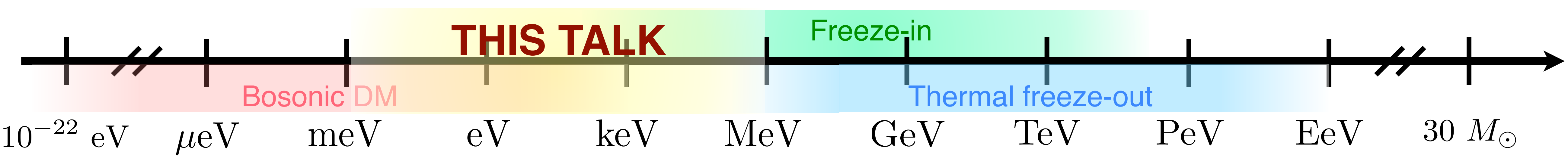
- Direct Detection
- Beam Dumps
- LLP Searches (e.g. FASER and others)
- Direct LHC production

Particle Effects

- Astronomy

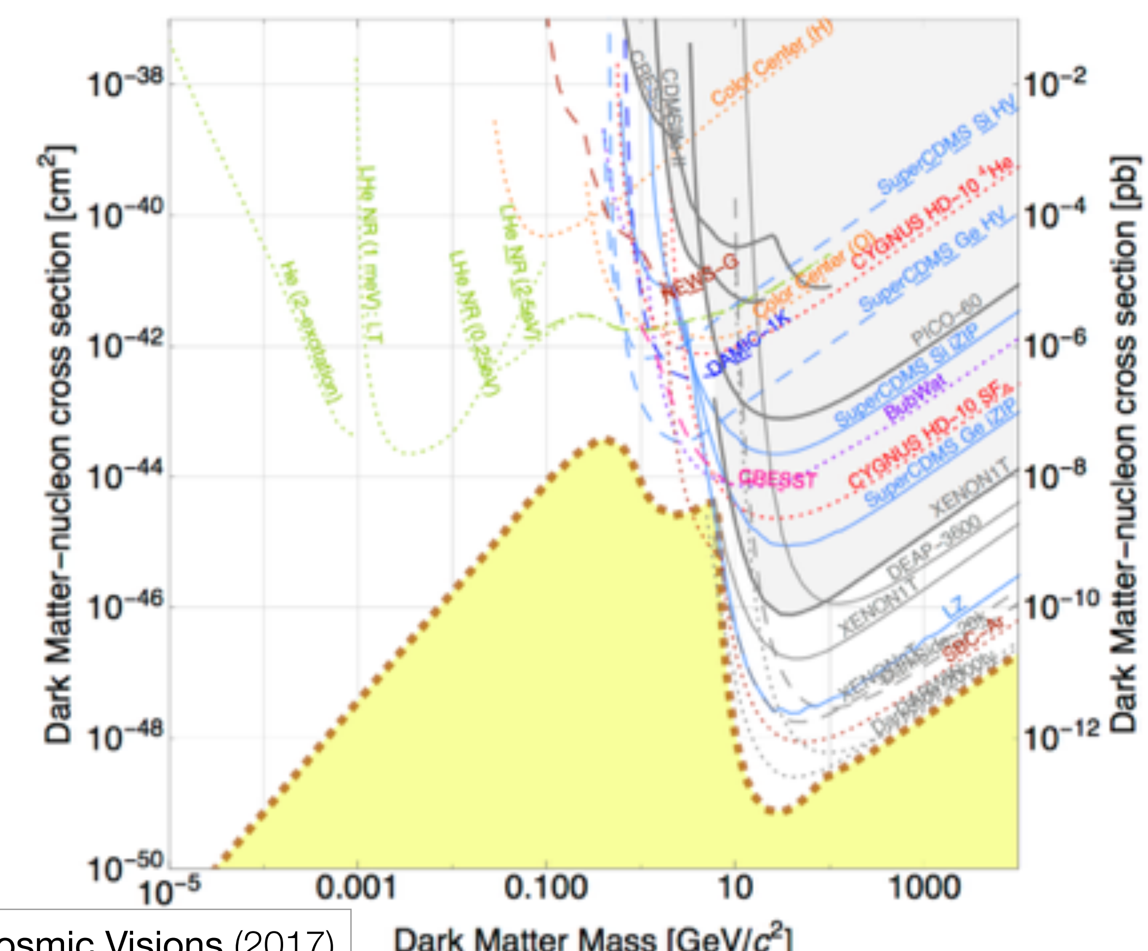
Macroscopic

Experimental techniques > keV: *particle effects*



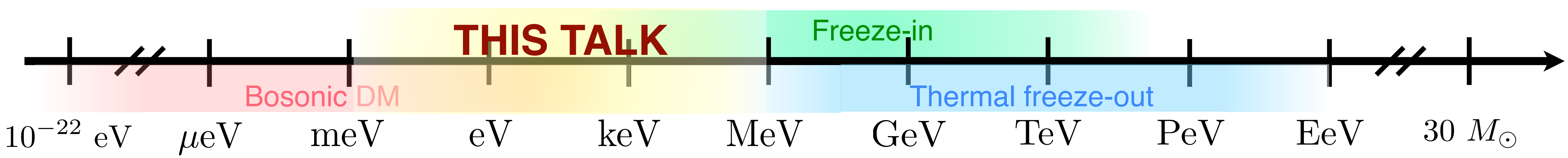
- **Nuclear recoils:** $E_\mathrm{N} = \dfrac{q^2}{2m_N} \lesssim 800\ \mathrm{eV}\left(\dfrac{m_\chi}{1\ \mathrm{GeV}}\right)^2\left(\dfrac{16\ \mathrm{GeV}}{m_N}\right)$

quickly drops below threshold below GeV DM mass



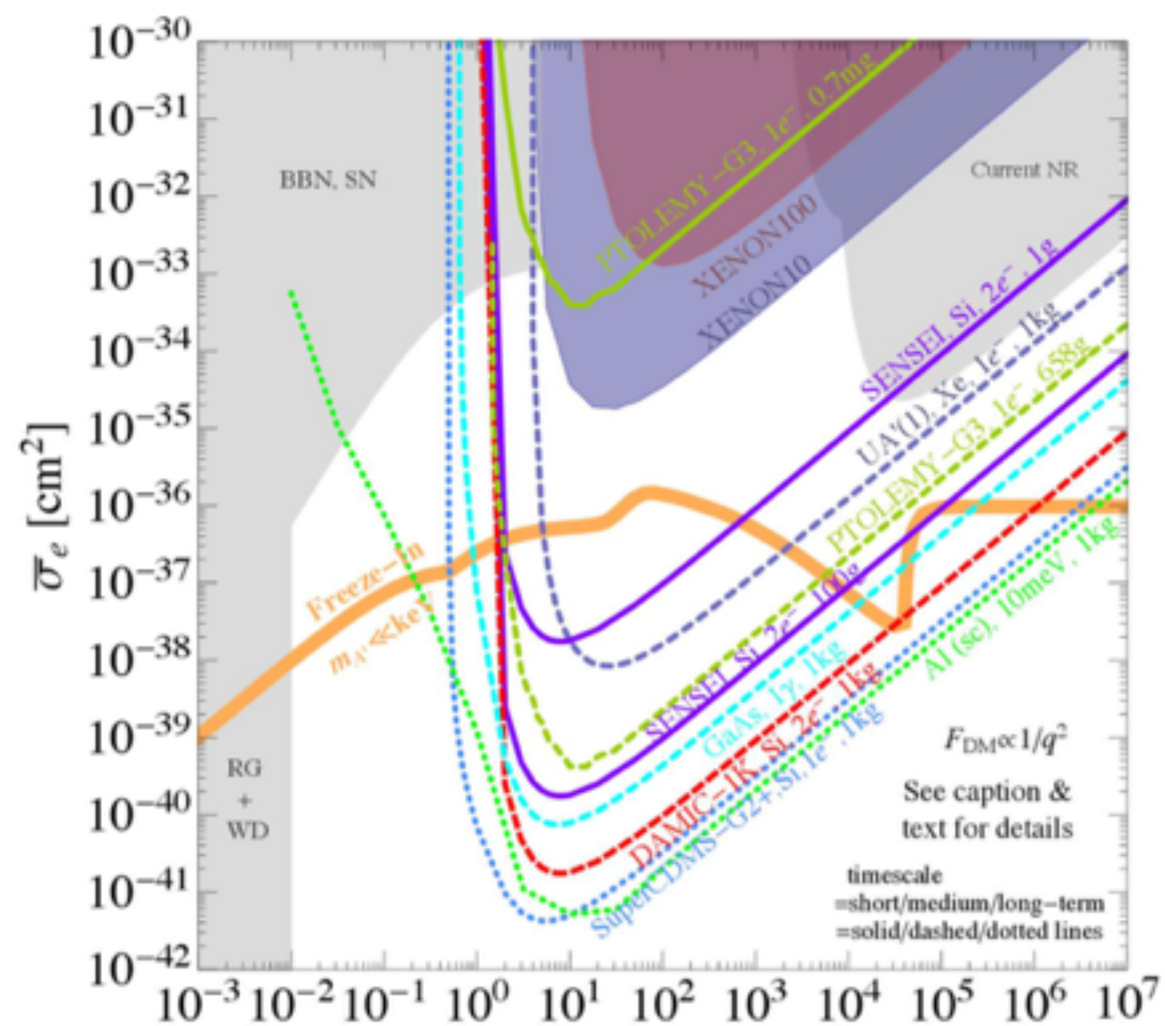
Cosmic Visions (2017)

Experimental techniques > keV: *particle effects*



- **Electron Scattering:**

  prospects for MeV sensitivity



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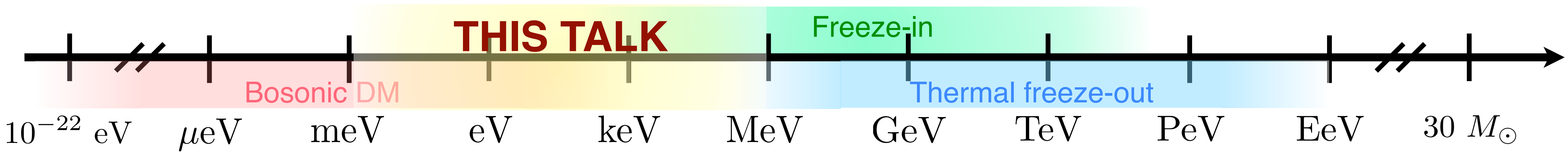
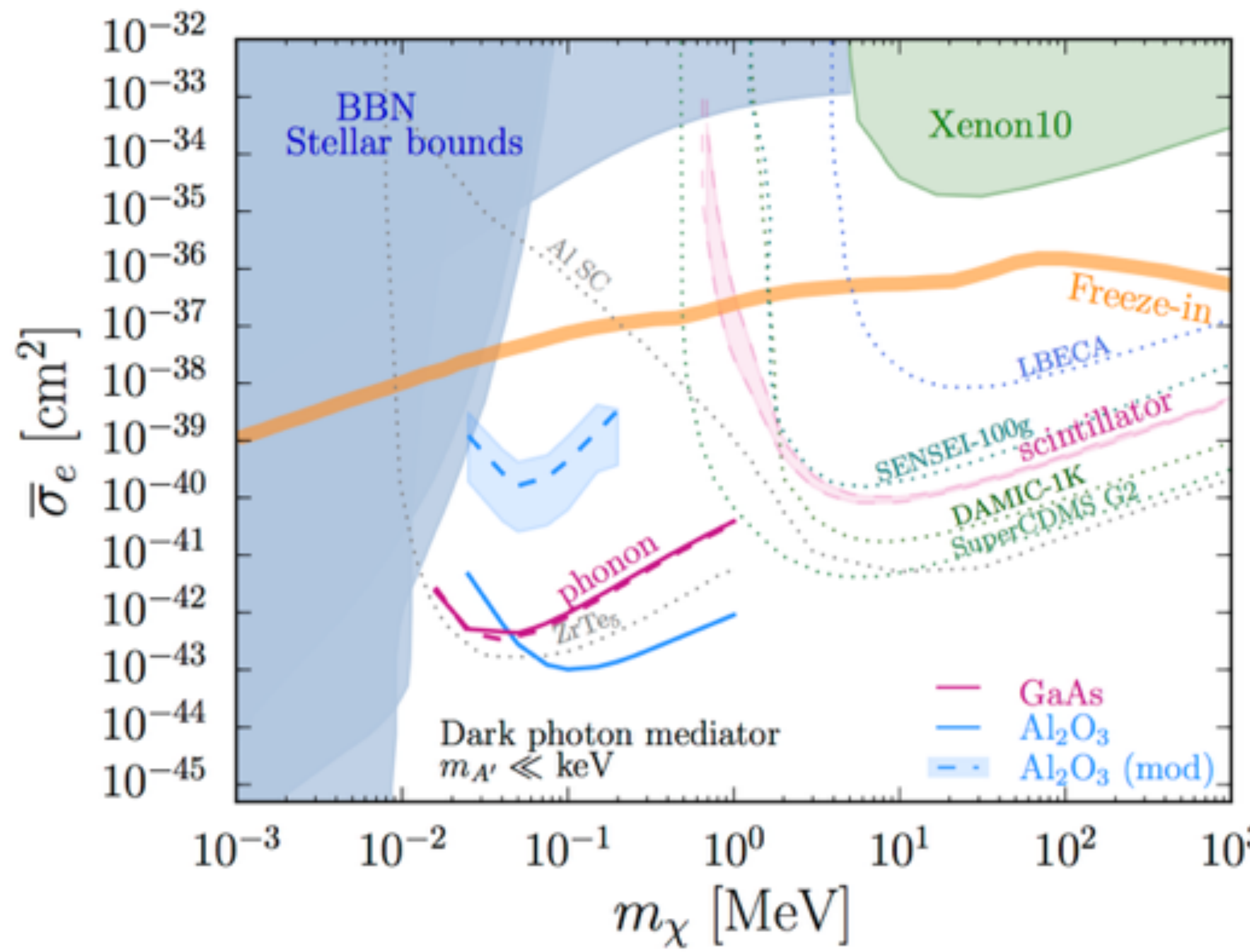
Experimental techniques > keV: *particle effects*



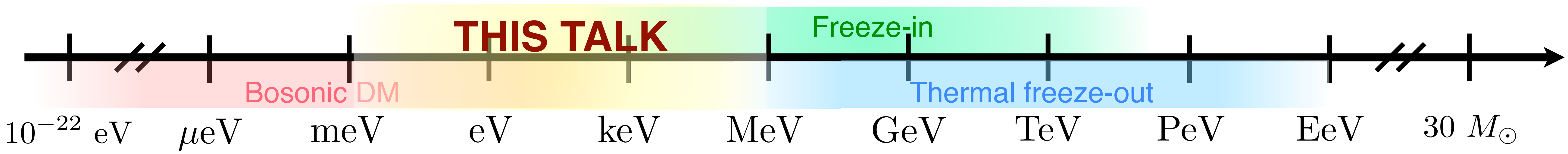
- **Phonon excitation**

  coupling to optical phonons has ~10 keV potential



Knapen, Lin, Pyle, Zurek (2017)
Griffin, Knapen, Lin, Zurek (2018)

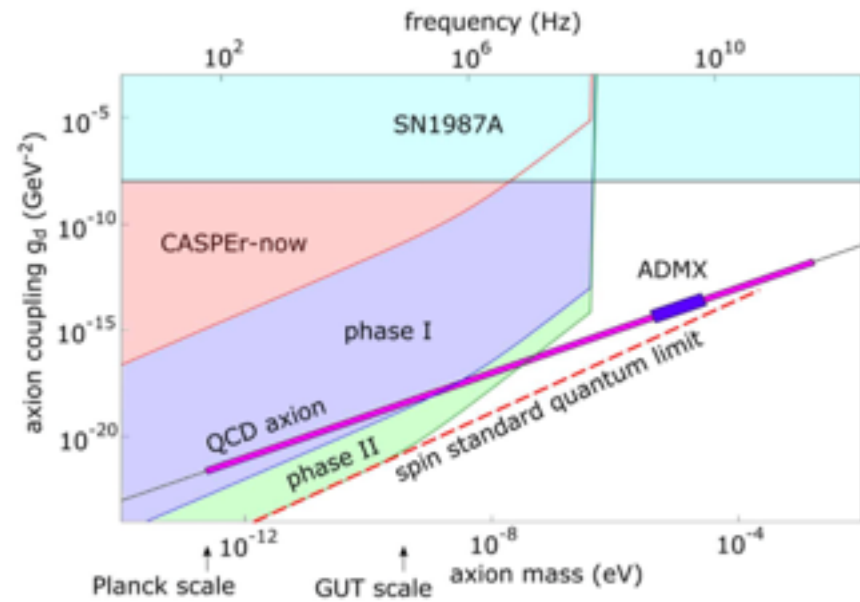
Experimental techniques « keV: *collective effects*



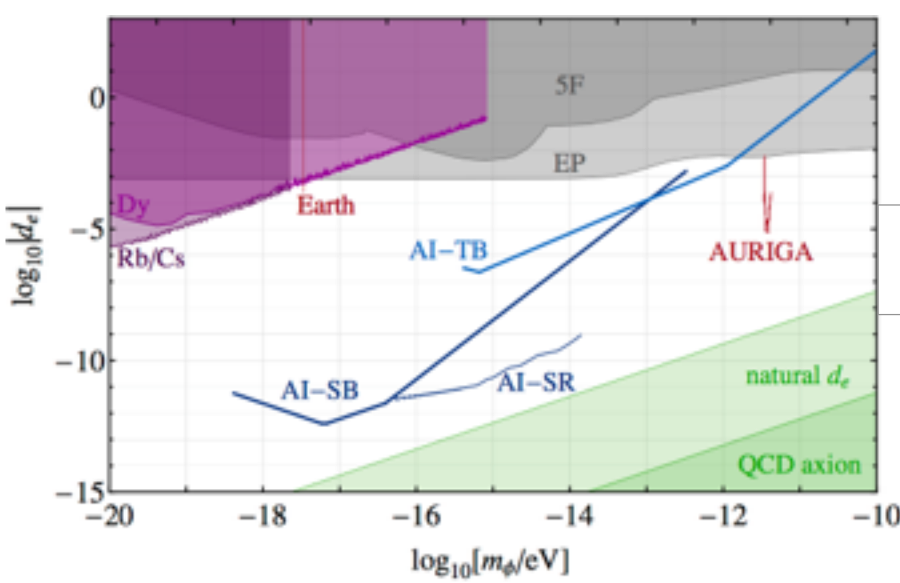
- **Coupling to spin:**

  E.g. CASPEr

- **Scalar coupling:**

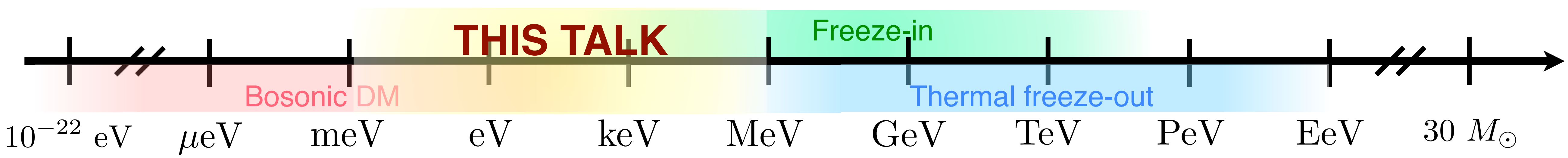


Budker, Graham, Ledbetter, Rajendran, Sushkov (2013)



Arvanitaki, Graham, Hogan, Rajendran, Van Tilburg (2016)

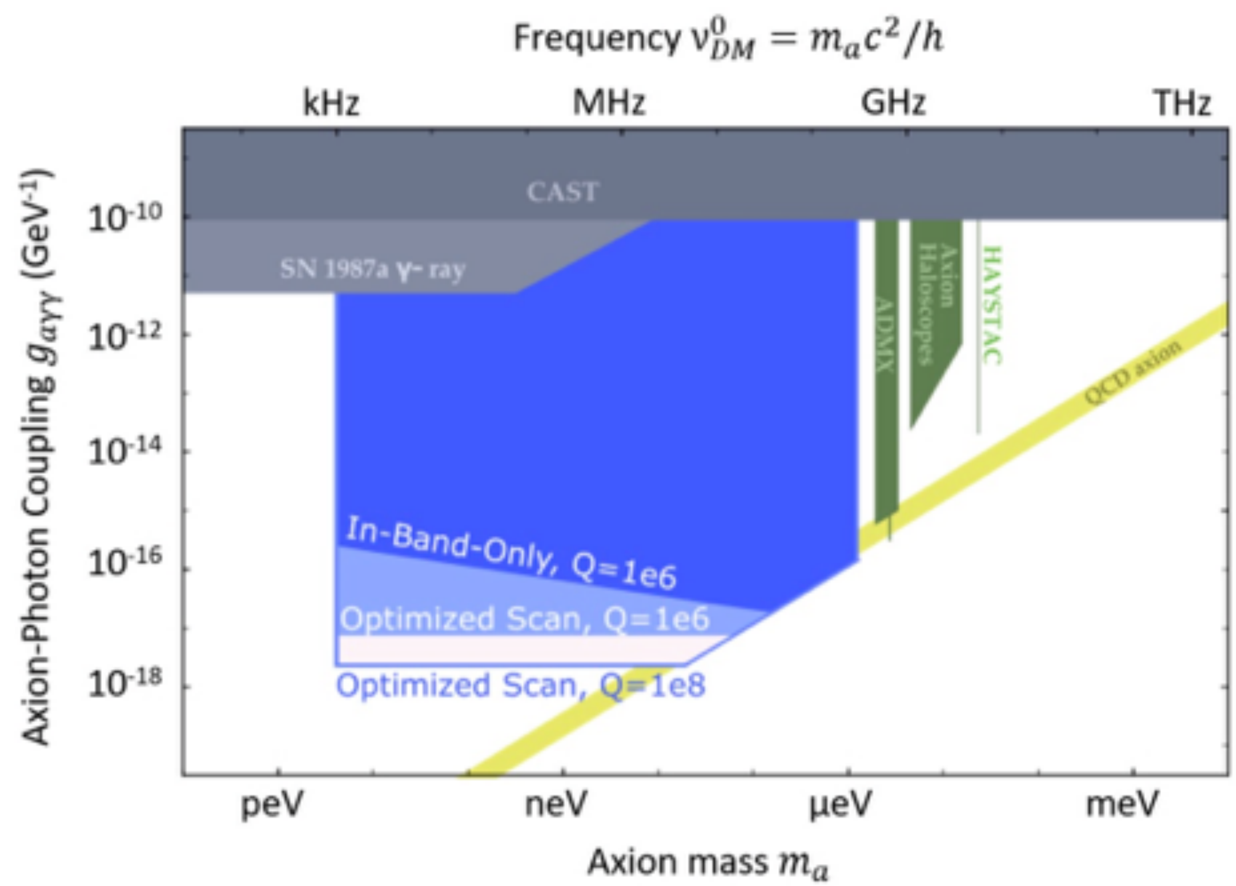
Experimental techniques « keV: *collective effects*



- **Coupling to EM:**

  E.g. ADMX, DM Radio, ABRACADABRA

Sikivie (1983, 1984)
Chaudhuri, Graham, Irwin, Mardon, Rajendran, Zhao (2015)
Kahn, Safdi, Thaler (2016)
Chaudhuri, Graham, Irwin, Mardon (2019)



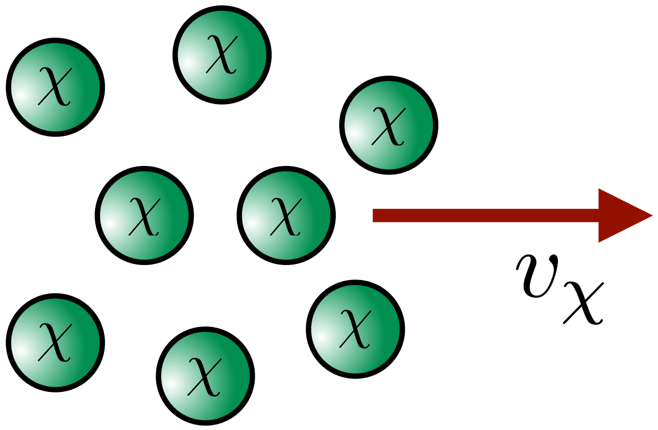
Chaudhuri, Graham, Irwin, Mardon (2019)

Bridging the gap

A General Approach

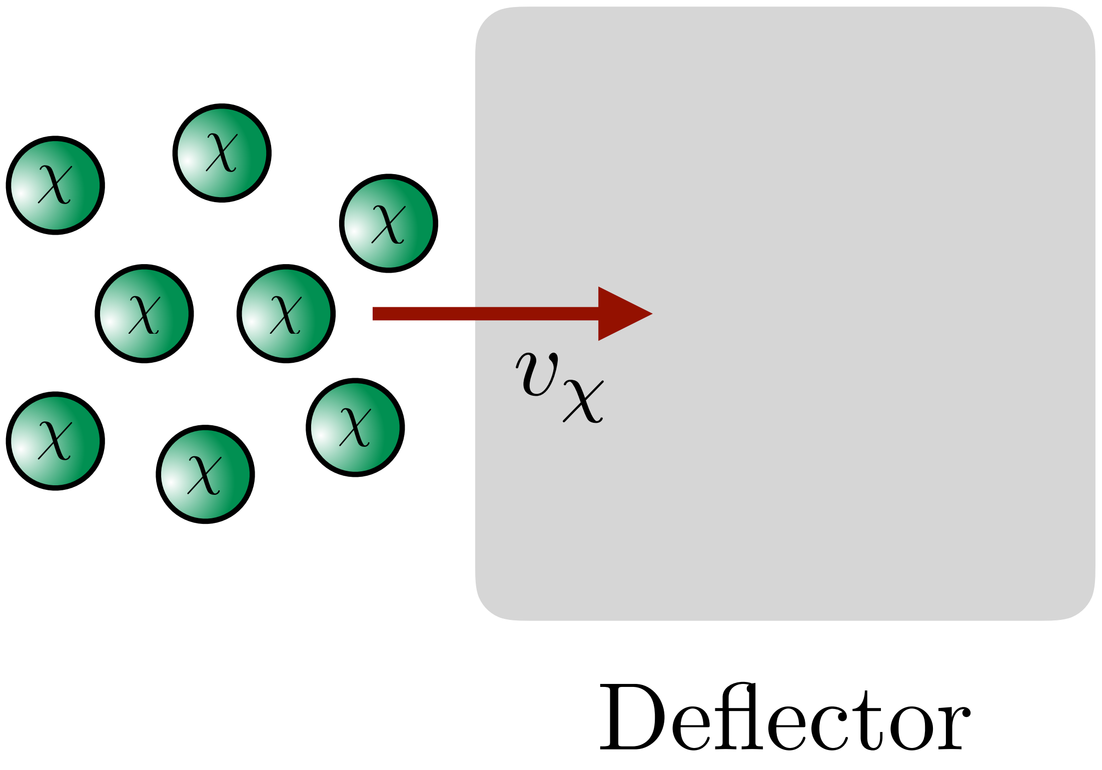
Sub-keV particle DM — low recoil

Assume interacts via long-range mediator



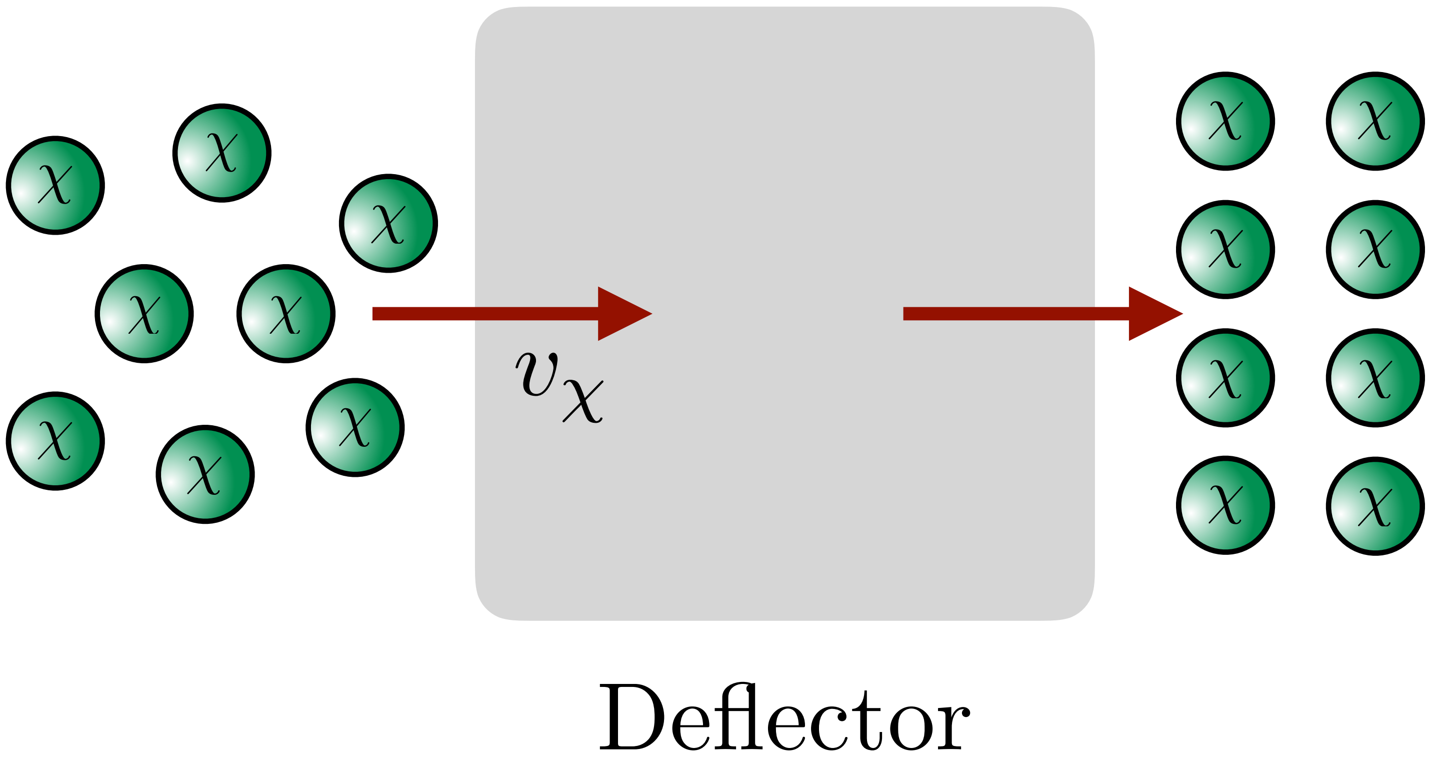
A General Approach

Interaction-dependent



A General Approach

Coherent effect induced



A General Approach

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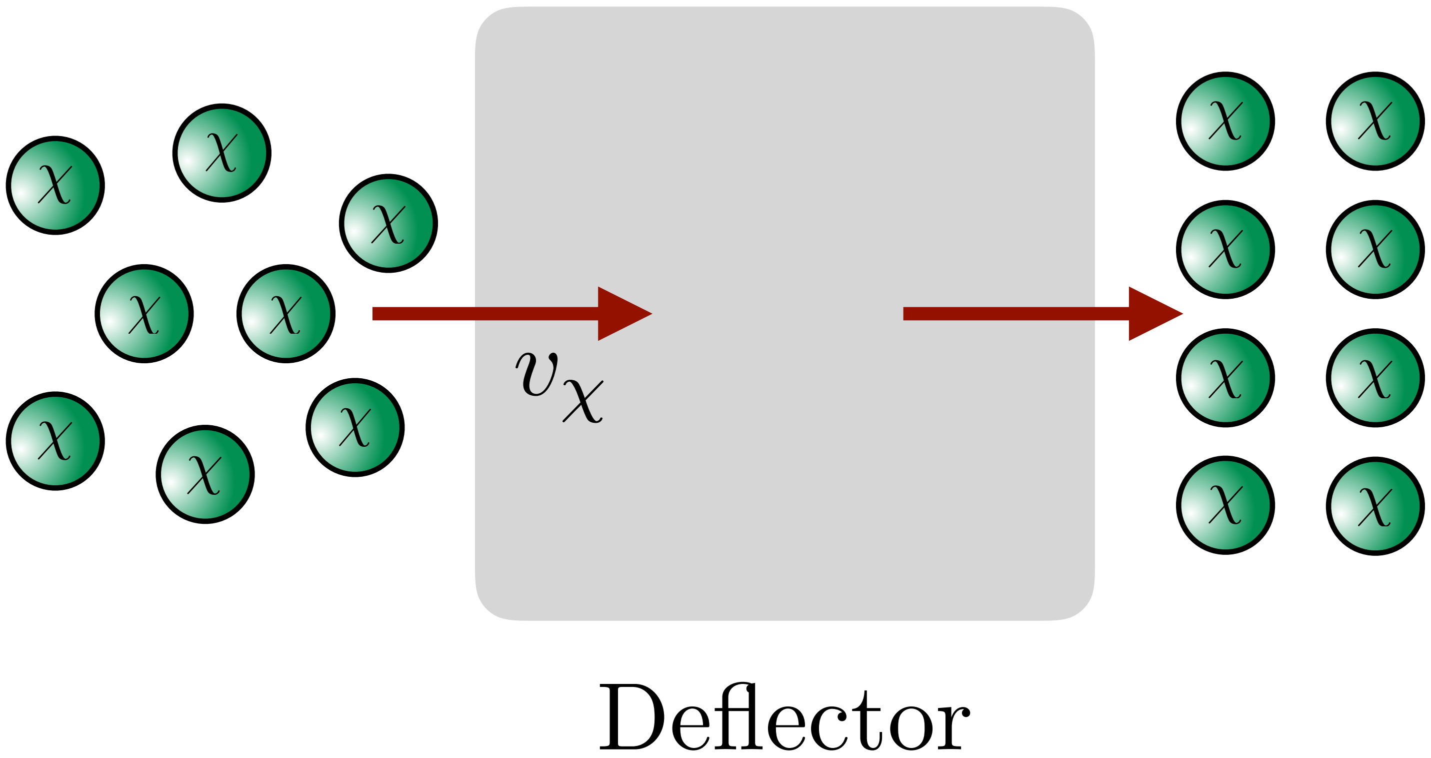
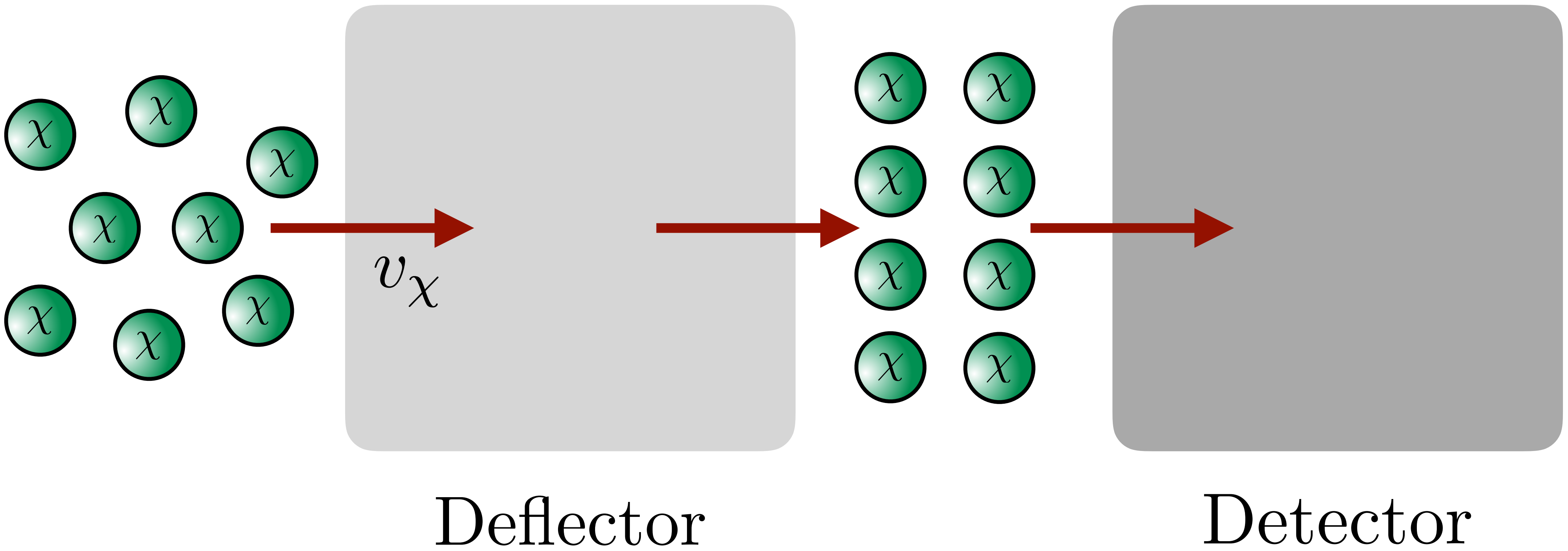


Effect magnitude set by deflector, not DM

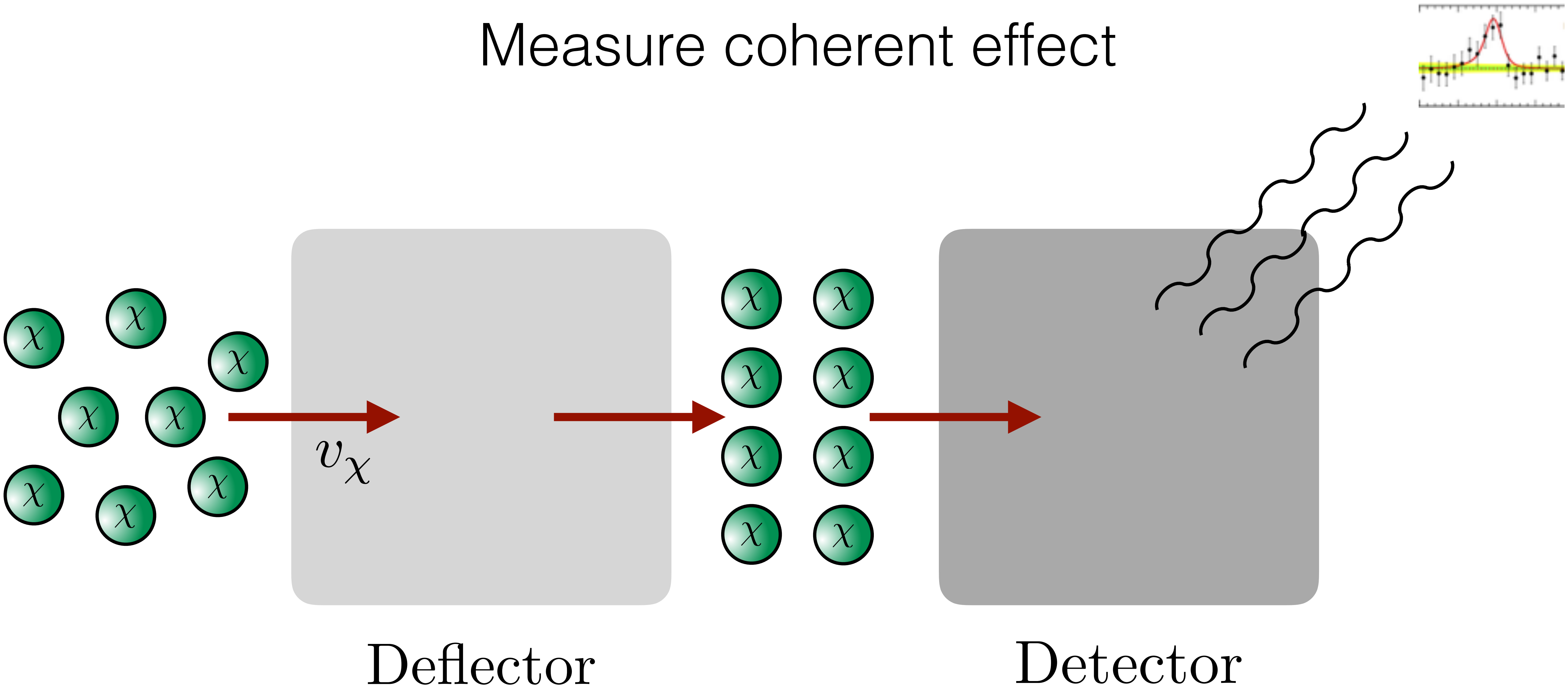
A General Approach

Coherent flow into detector

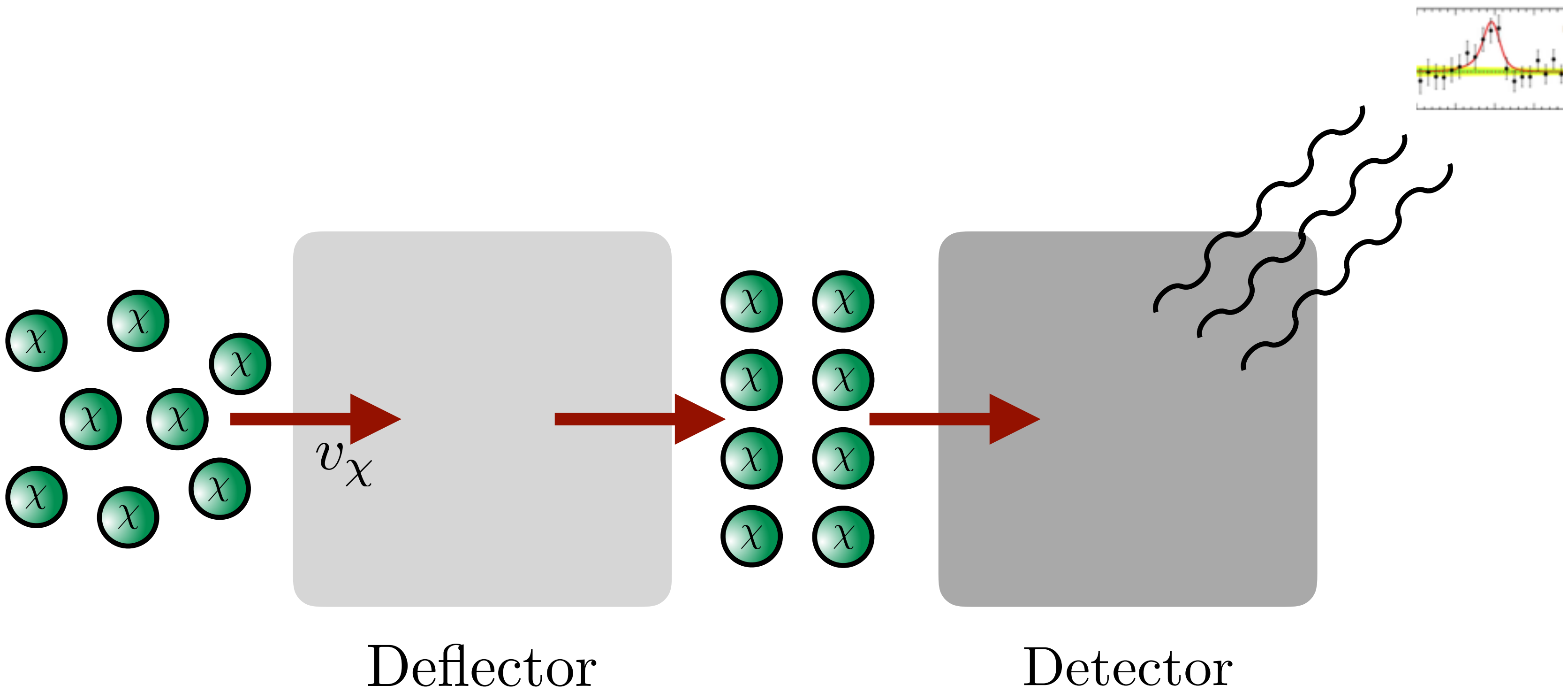


A General Approach

Measure coherent effect



A General Approach

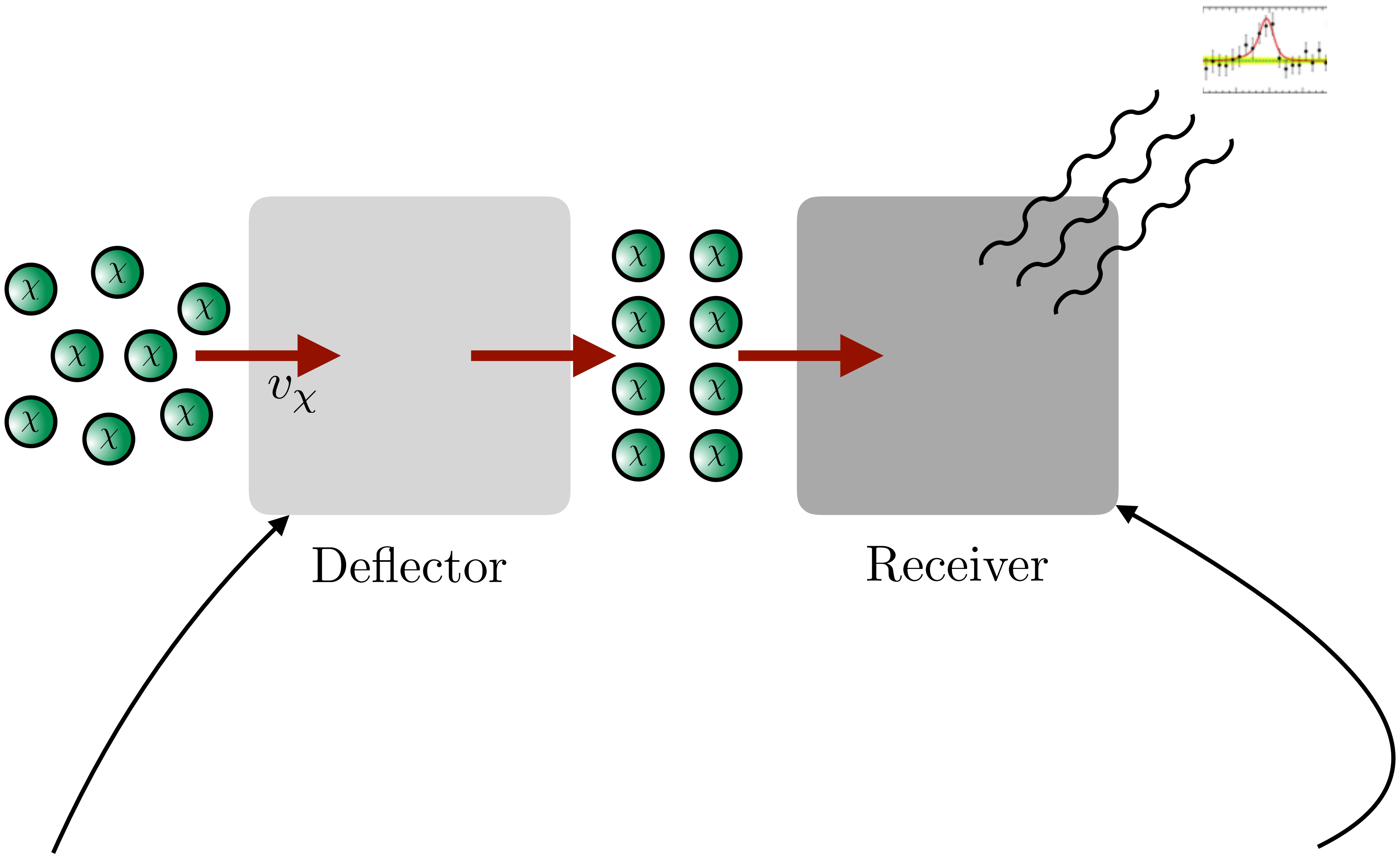


Makes use of large number density at low DM mass

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

Health warning: requires low-mass mediator

A Concrete Example: (Effectively) Millicharged DM



EM field region

Magnetometer/Voltmeter

Millicharges & pseudo-millicharges

Violin & Candlestick,
Georges Braque (1910),
SFMOMA

Dark Matter coupled to a Dark Photon

- Kinetically mixed Dark Photon

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

- Dark Current:

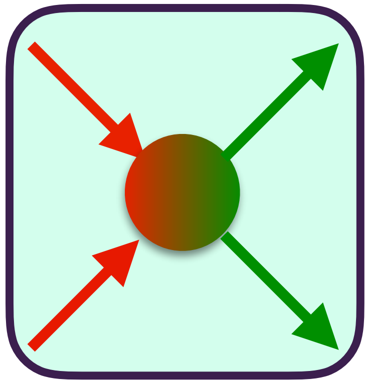
$$J^\mu_{\rm D} = \quad \bar{\chi}\gamma^\mu\chi, \quad (\varphi^\dagger\partial^\mu\varphi - (\partial^\mu\varphi)^\dagger\varphi)$$

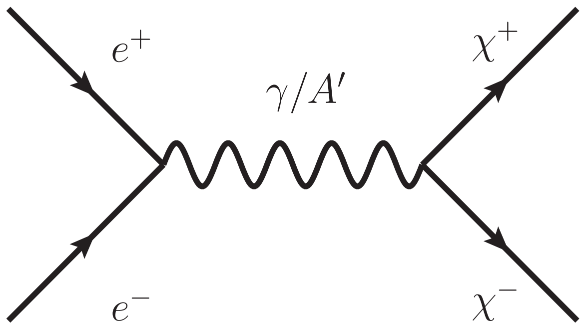
Fermion **Scalar**

Freeze-In Sub-MeV

McDonald (2001)
Hall, Jedamzik, March-Russell, West (2009)

- DM never in thermal equilibrium
- Slow leakage into dark sector
- At low masses, frozen in by electron annihilation (and plasmon decay — see 1902.08623 — Dvorkin, Lin & Schutz)

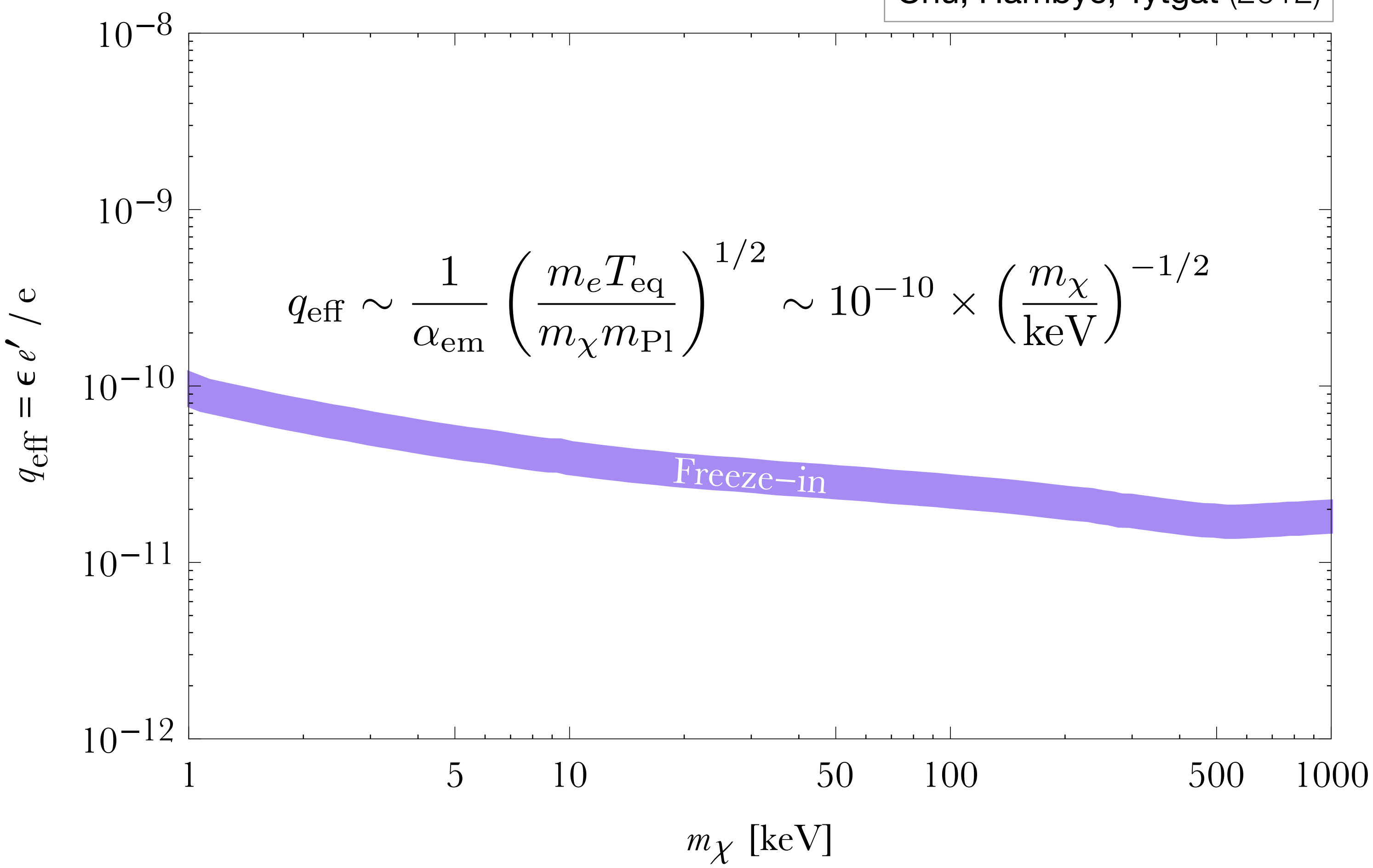




$$Y_{\rm DM} \simeq \left. \frac{n^2_{\rm SM,\,eq.} \langle \sigma v \rangle}{sH} \right|_{T_{\rm FI}}$$

$$\langle \sigma v \rangle \sim \left(\frac{e_D \epsilon e}{4\pi T} \right)^2$$

Chu, Hambye, Tytgat (2012)



Self-Interactions via a Light Mediator

- Ellipticity Constraints:

Peter, Rocha, Bullock, Kaplinghat (2012)

$$\frac{\sigma}{m_\chi} \lesssim \frac{1\ \text{cm}^2}{\text{g}}$$

Carnegie-Irvine Galaxy Survey

- Substructure mergers:

Harvey et al (2015)
Wittman, Golovich, Dawson (2017)

$$\frac{\sigma}{m_\chi} \lesssim \frac{2\ \text{cm}^2}{\text{g}}$$

- Bullet cluster:

Randall, Markevitch, Clowe, Gonzalez, Bradac (2007)

$$\frac{\sigma}{m_\chi} \lesssim \frac{0.7\ \text{cm}^2}{\text{g}}$$


Chandra X-Ray Observatory

$$\alpha_D \lesssim 10^{-10} \left(\frac{m_\chi}{\text{MeV}}\right)^{3/2}$$

Feng, Kaplinghat, Tu, Yu (2009)
Agrawal, Cyr-Racine, Randall, Scholtz (2016)

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Chandra X-Ray Observatory

Review
Tulin & Yu (2017)

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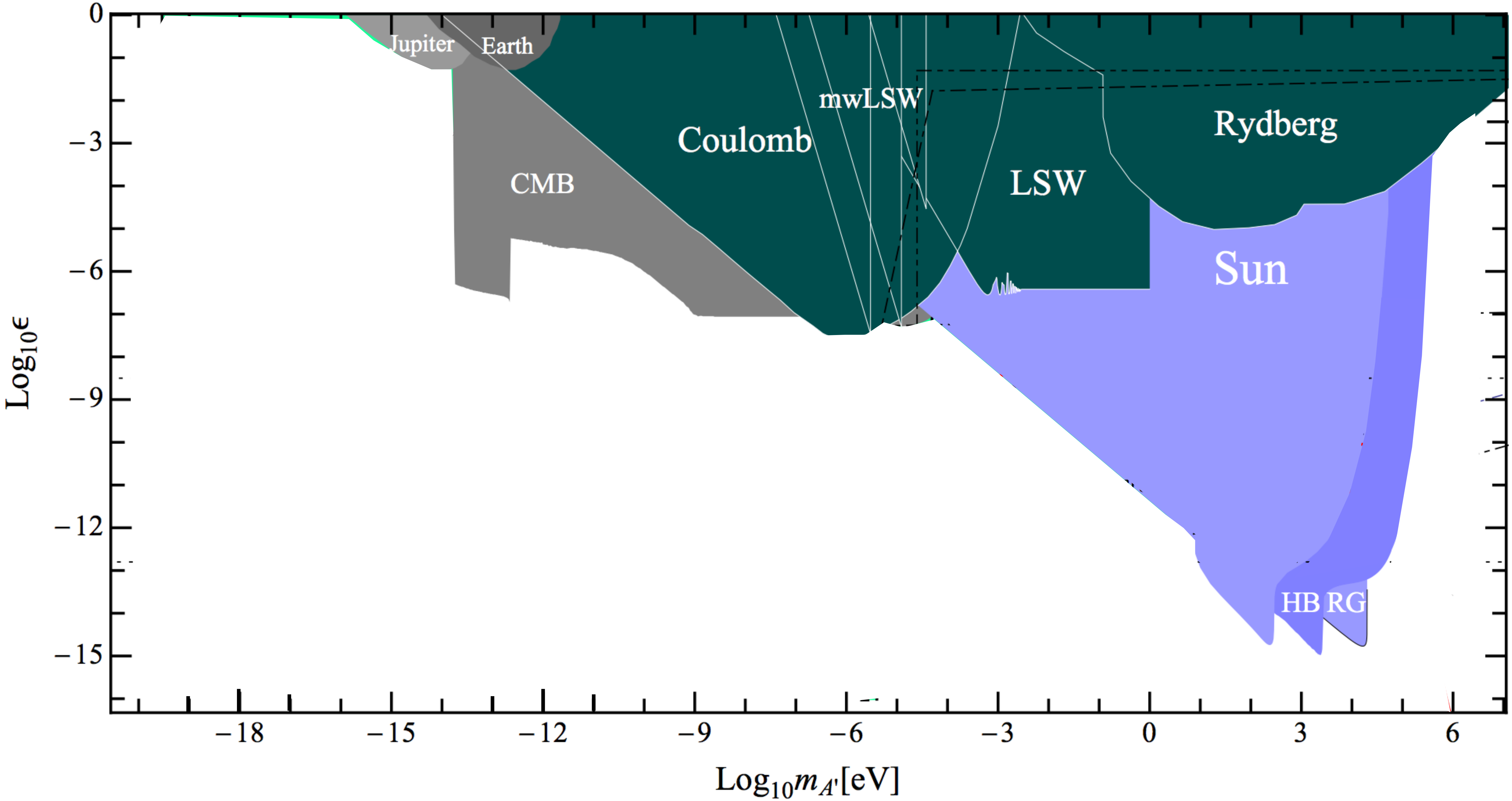
Allowed range for Dark Photon Mediator



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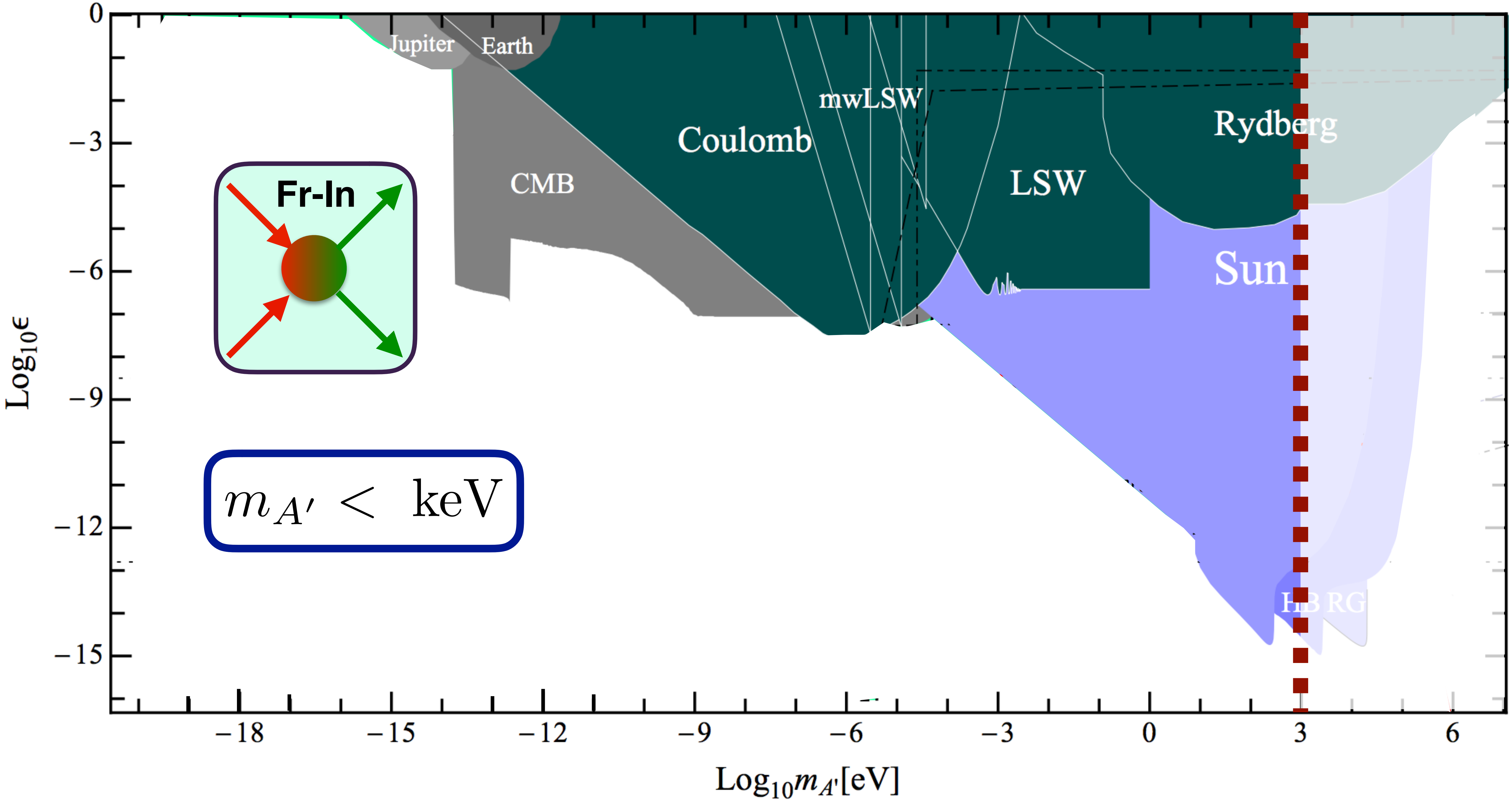

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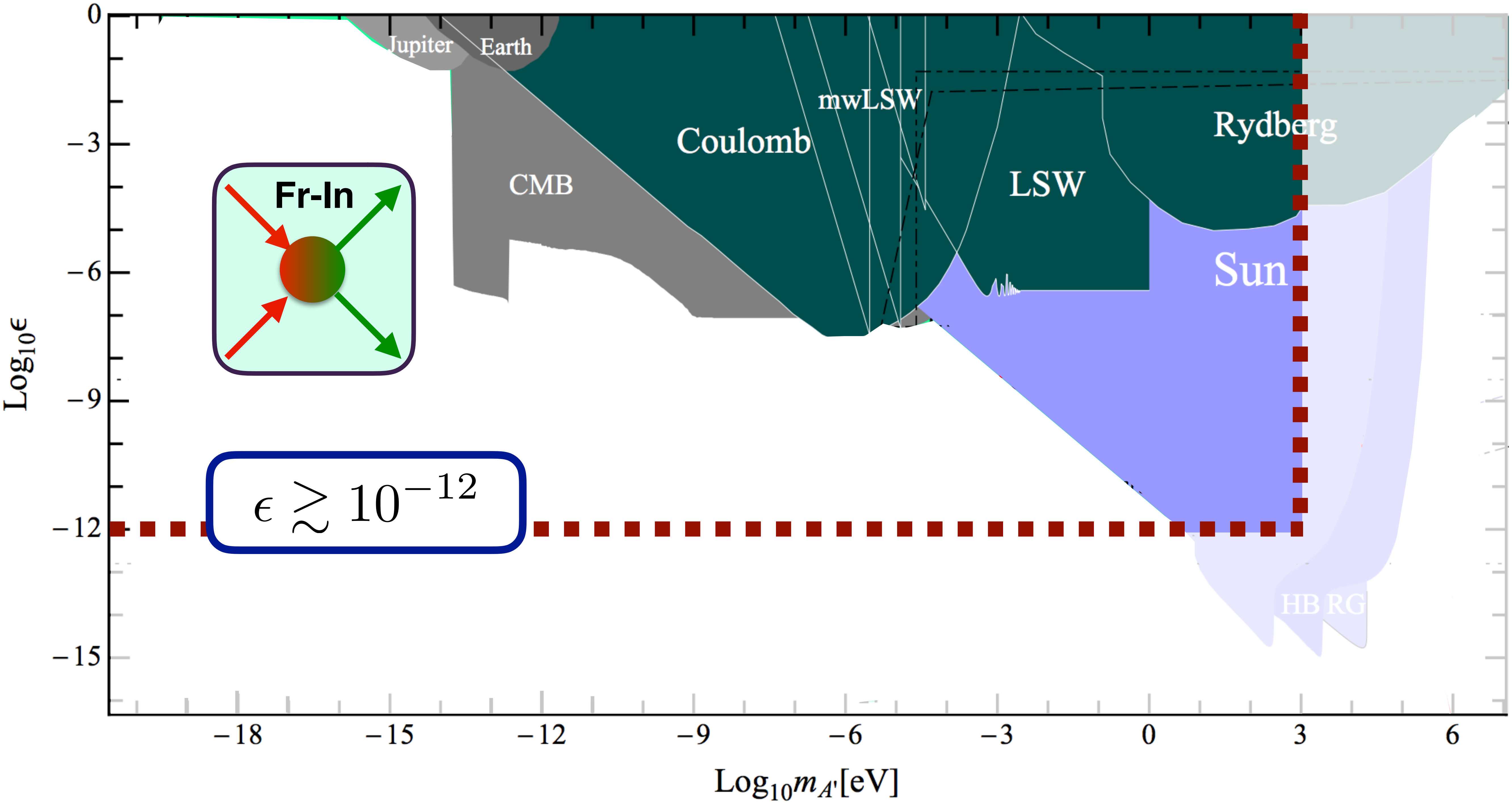

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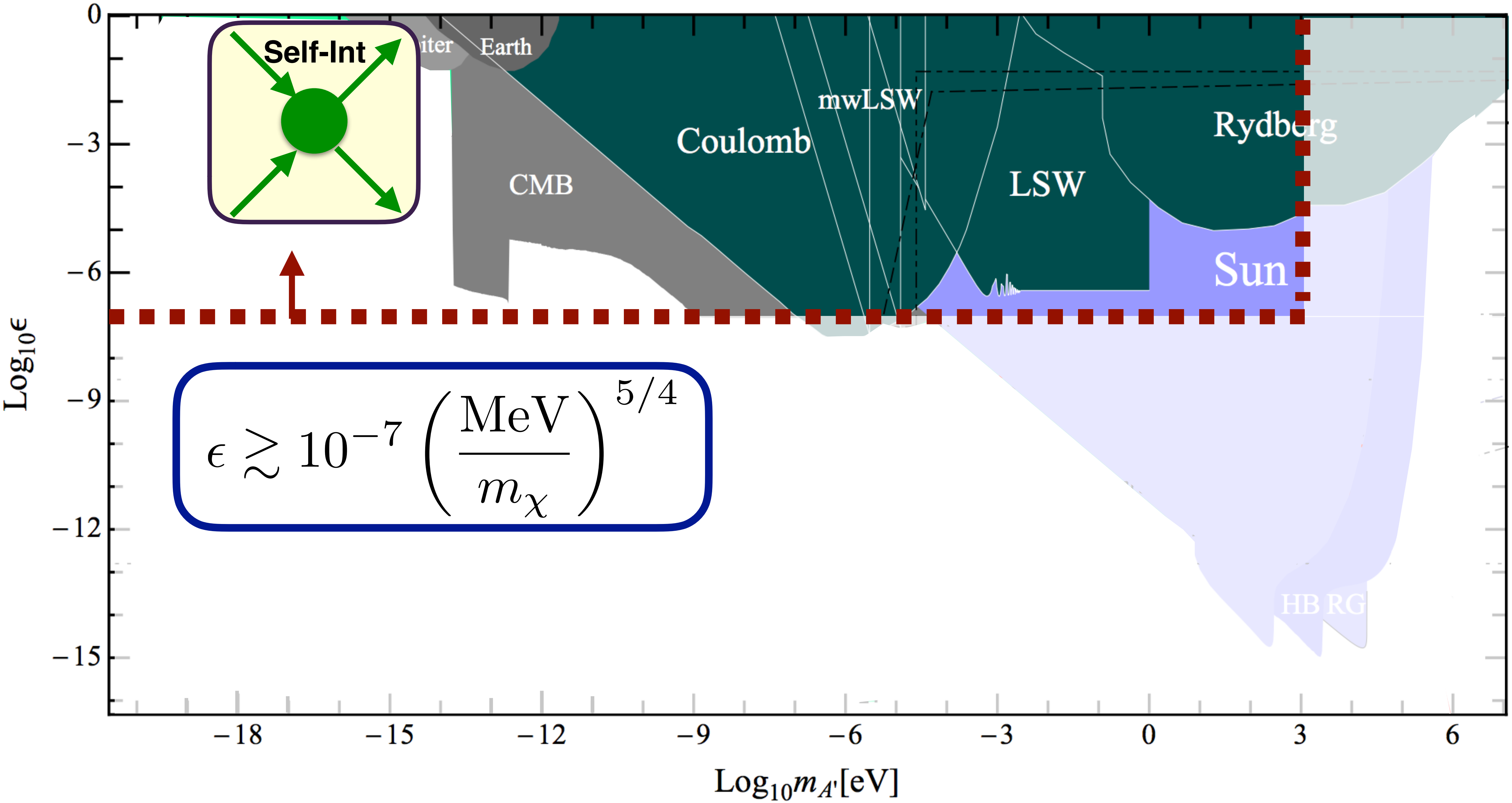
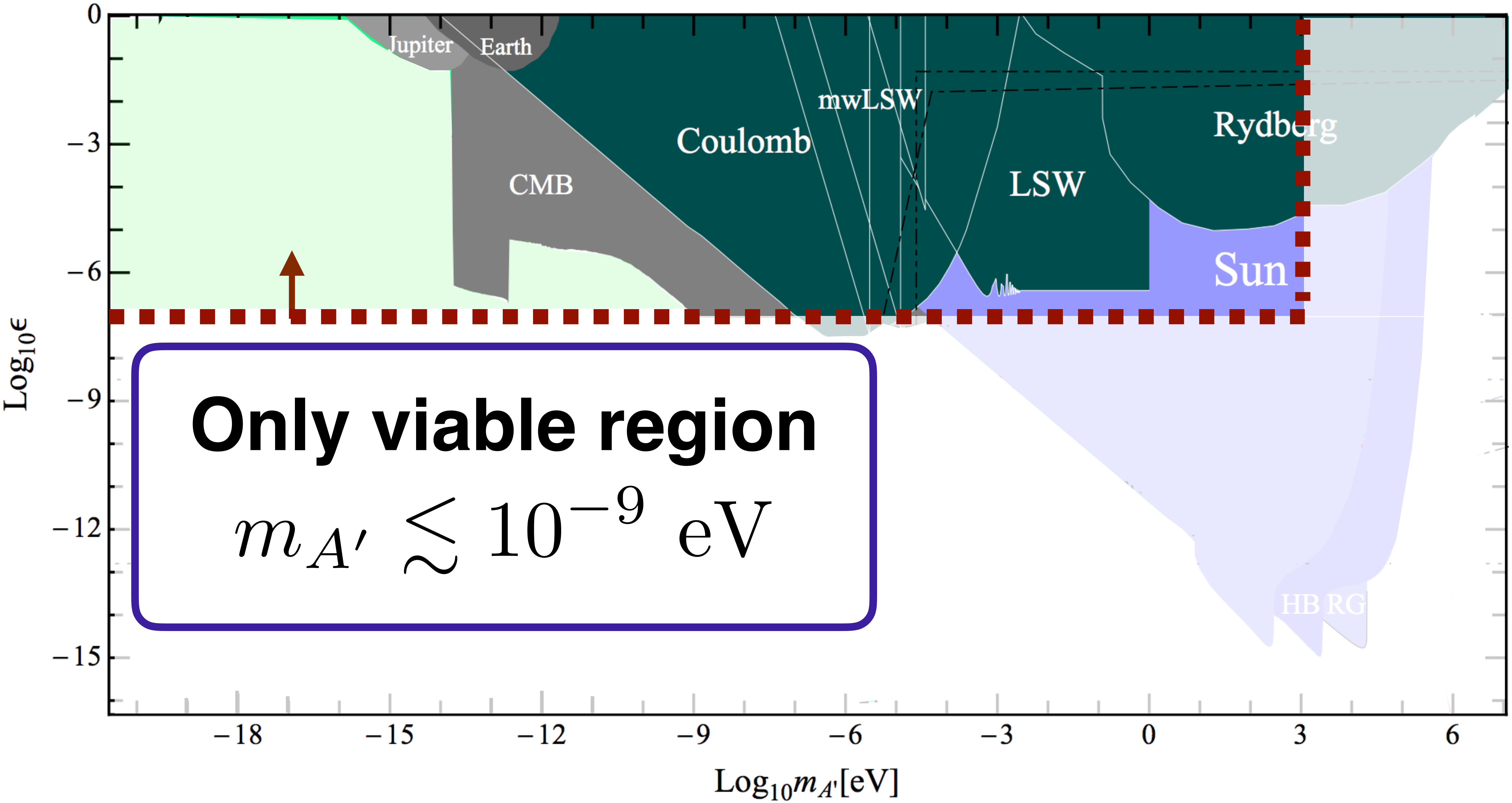


$$\epsilon \gtrsim 10^{-7} \left(\frac{\text{MeV}}{m_\chi}\right)^{5/4}$$

Allowed range for Dark Photon Mediator



Only viable region

$$m_{A'} \lesssim 10^{-9}\ \mathrm{eV}$$

Quo pseudo-millicharge:

Kinetically mixed A'

Self-interaction constraints

Requirements for Freeze-In

Quo pseudo-millicharge:

Kinetically mixed A’

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Requirements for Freeze-In

Quo pseudo-millicharge:

Kinetically mixed A’

Self-interaction constraints

Requirements for Freeze-In

$$1/m_{A'} \gg 1 \text{ m}$$

$$V(r) \sim \frac{e^{-m_{A'} r}}{r} \longrightarrow \frac{1}{r}$$

DM effectively MQ on experimental scales!

Key Implication

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

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

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

Key Implication

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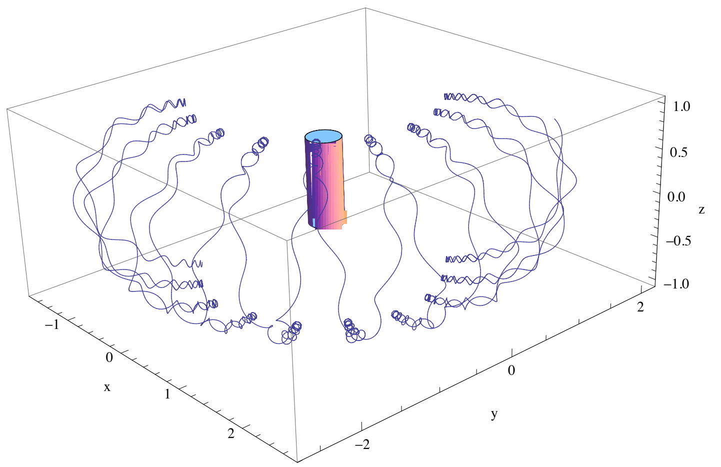
$$+ e\left(A_\mu + \epsilon A'_\mu\right) J^\mu_{\rm EM} + \frac{e_D}{\sqrt{1-\epsilon^2}} A'_\mu J^\mu_{\rm D}$$

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

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

New Observables

Bend/Trap Dark Matter $r_g = \frac{m_\chi v_\chi}{qB} \longrightarrow \frac{m_\chi v_\chi e}{\epsilon e_D B}$



$$r_g \sim \text{meter} \times \left(\frac{m_\chi}{\text{keV}}\right)^{3/2} \left(\frac{10\text{ T}}{B}\right)$$

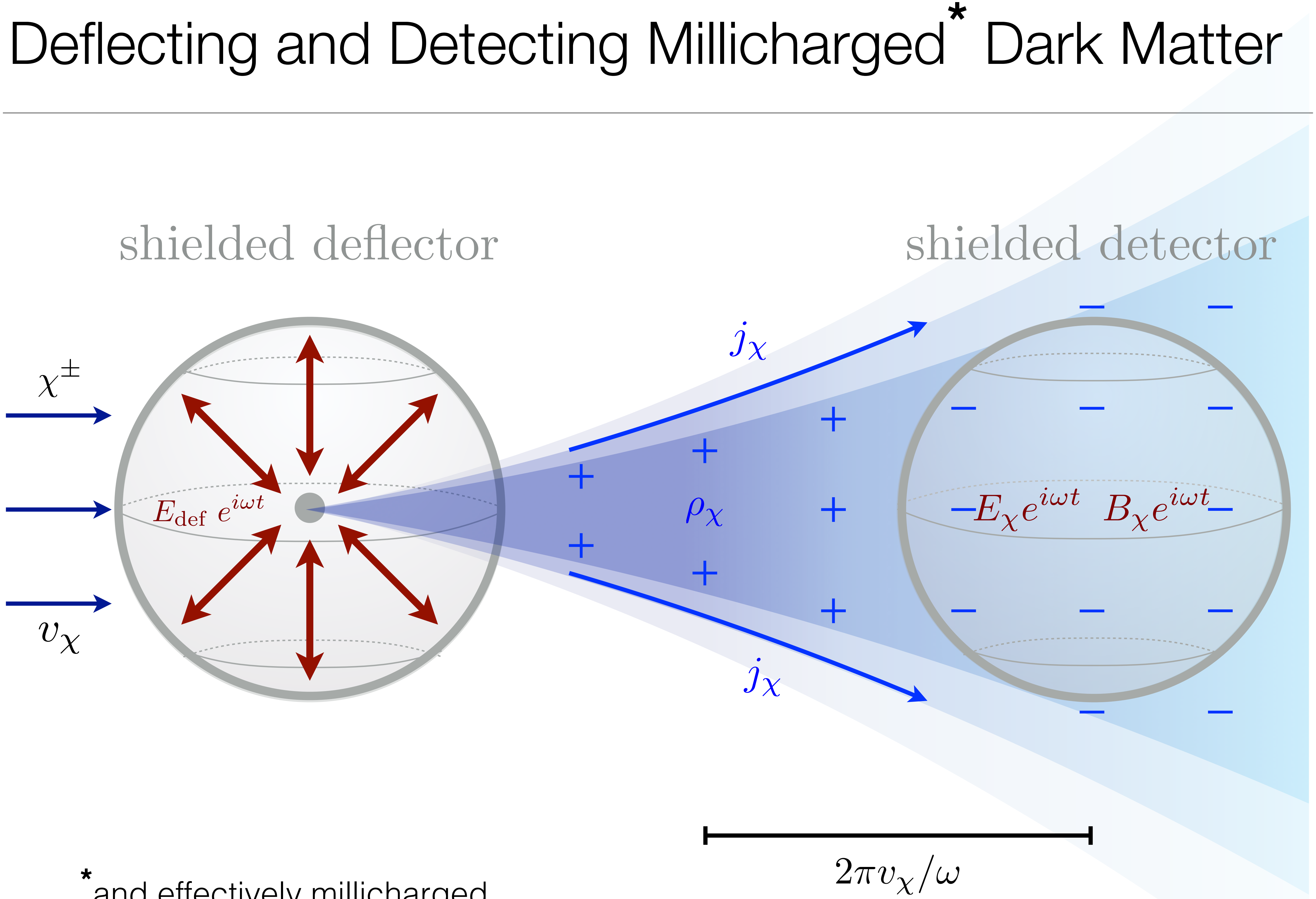
Accelerate/Stop Dark Matter

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

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

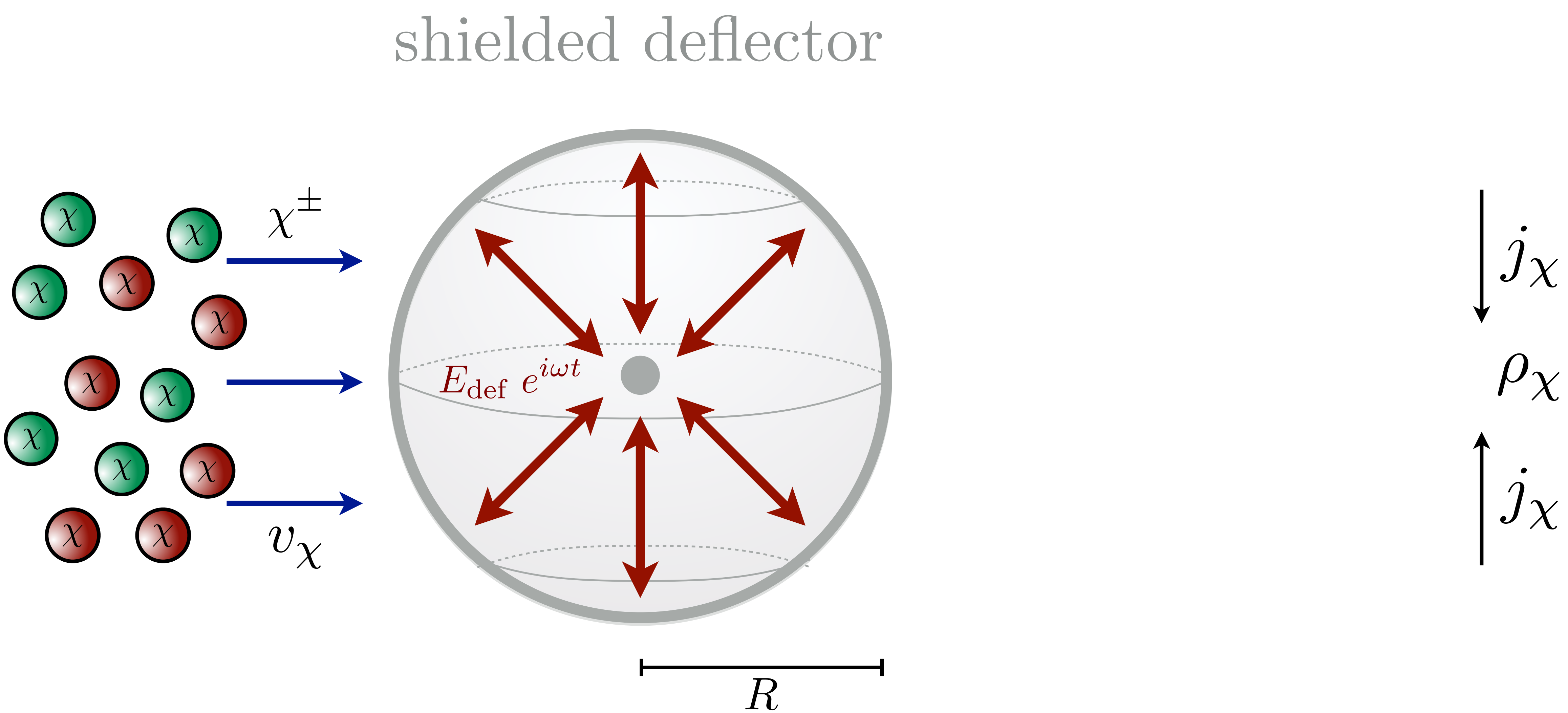
An Experimental Concept

Deflecting and Detecting Millicharged* Dark Matter



*and effectively millicharged

Inducing Dark Matter Waves



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

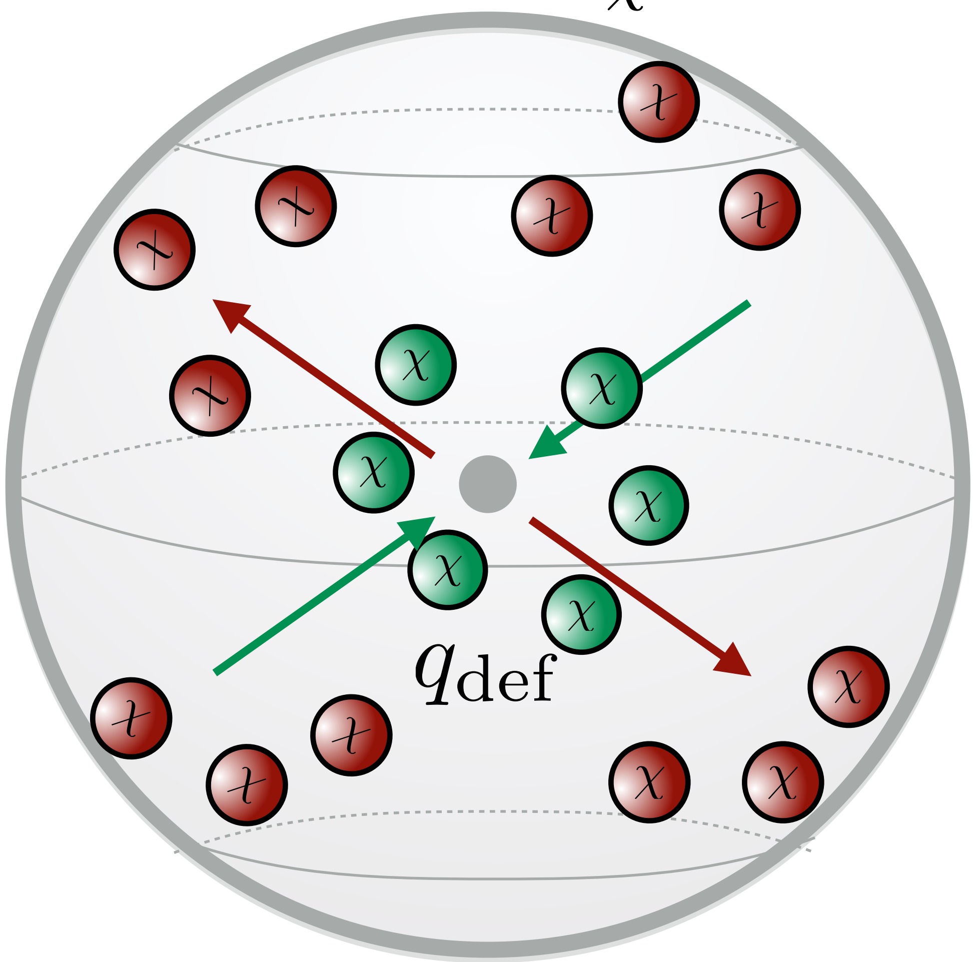
quasi-static limit

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



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

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

No backreaction

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

Charge Density Calculation w/ Shield

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*

Charge Density Calculation w/ Shield

Resultant charge density:

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

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

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

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

Comparison w/ Debye estimate

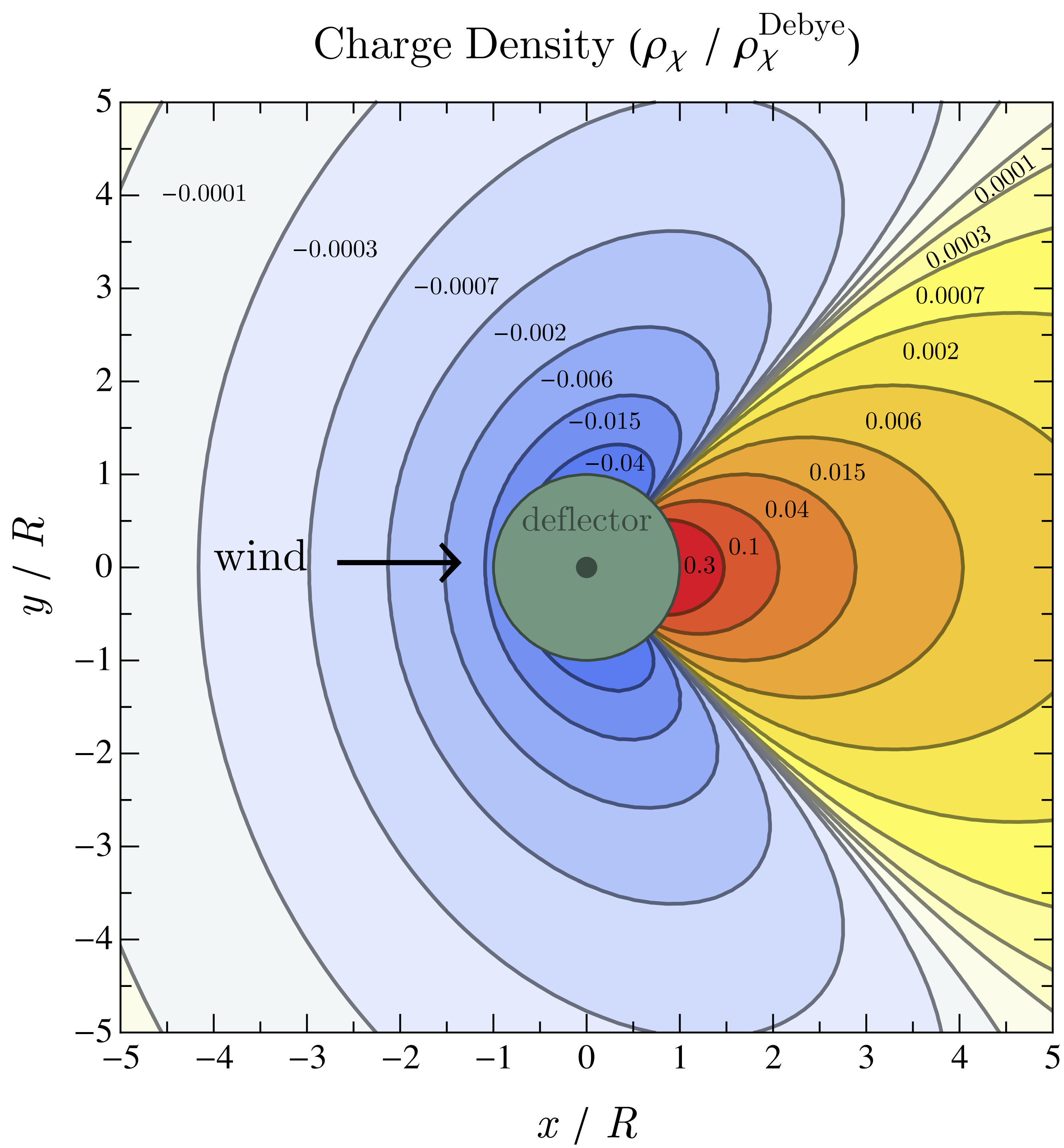
$$\rho_\chi^{\rm Debye}(\mathbf{x}) \sim -\frac{(eq_{\rm eff})^2\,\rho_{\rm DM}}{m_\chi^2\,v_0^2}\,\frac{eq_{\rm def}(\mathbf{x})}{|\mathbf{x}|}$$

Suppression due to charge radius: further x^2 suppressed:

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

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

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



Current density

Calculation proceeds in same manner as for charge density

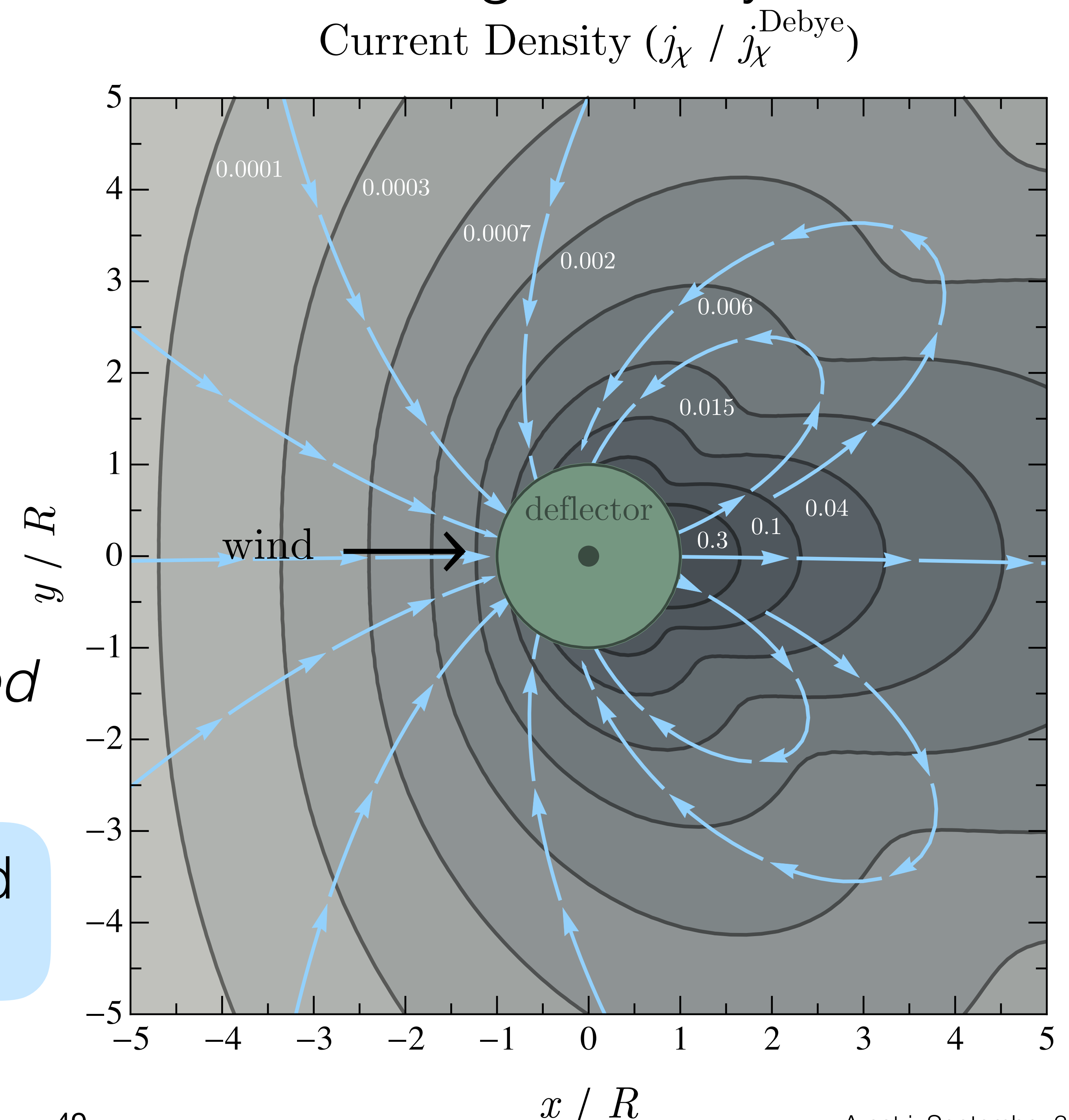
$$j_\chi(\mathbf{x}) \sim \rho_\chi(\mathbf{x})\, v_{\mathrm{wind}}$$

Compare with Debye estimate:

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

Current density velocity-*suppressed*

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

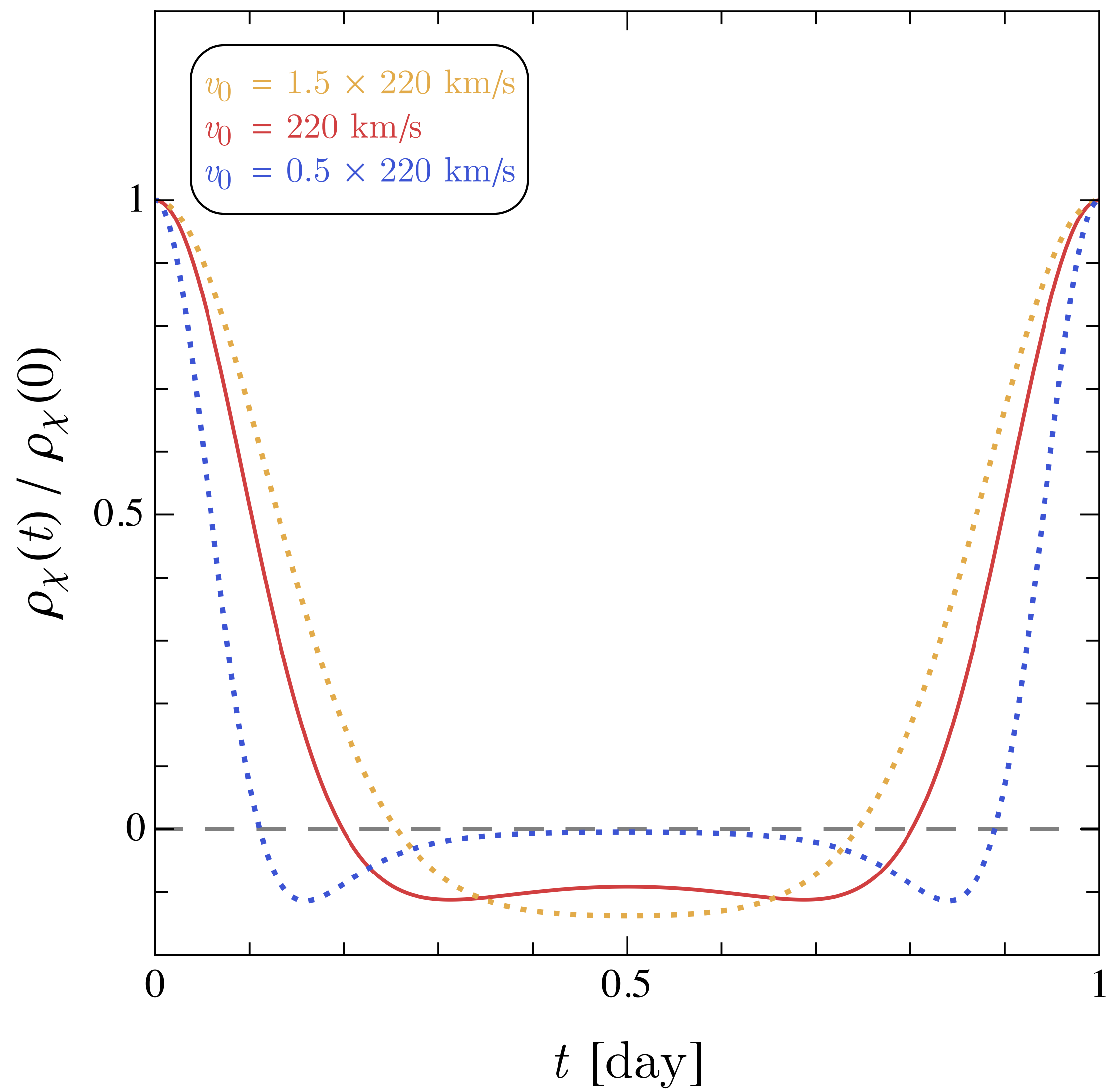


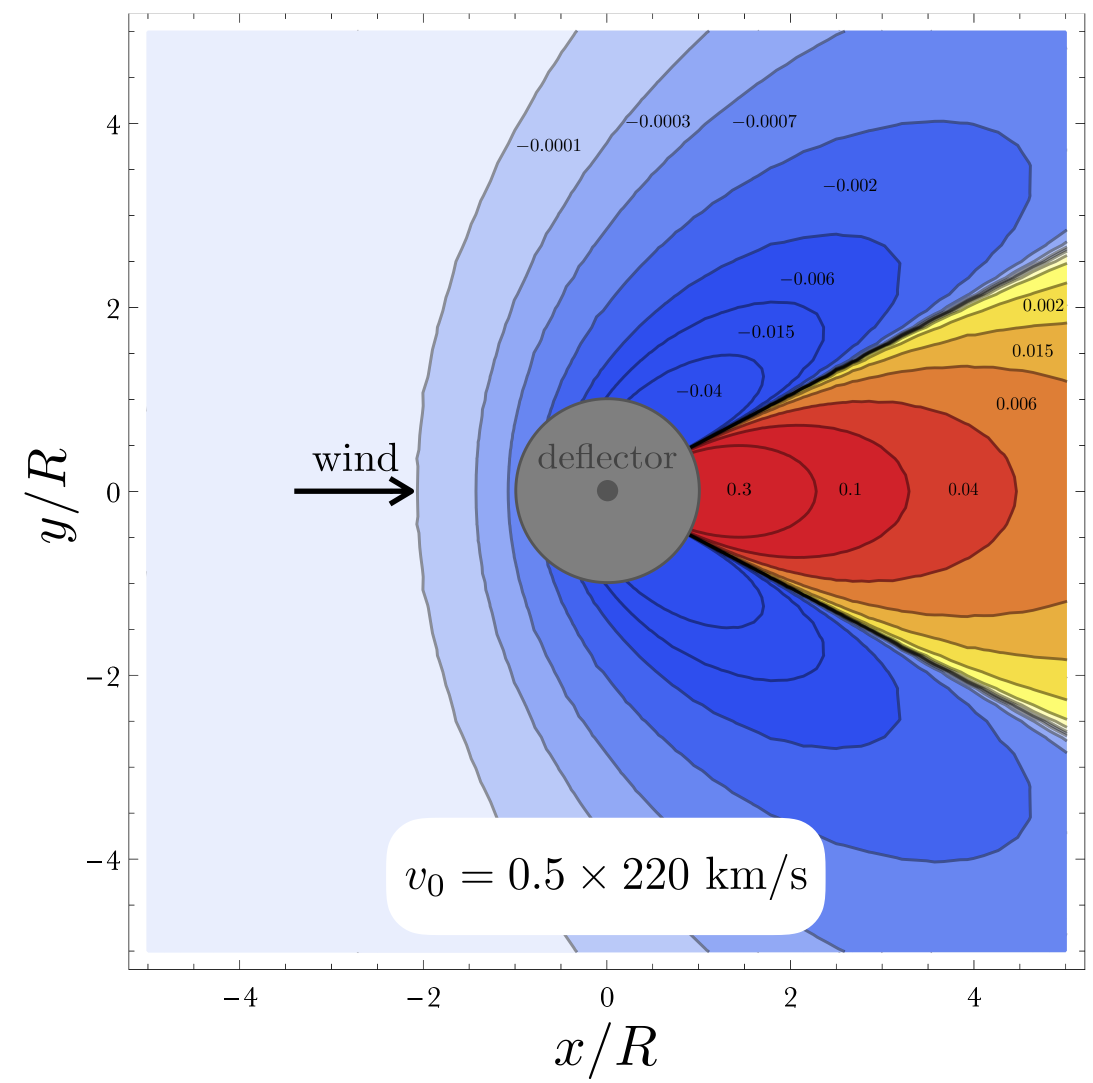
Effect of the Dark Matter Wind

Recall that charge and current density zero without wind $\quad \xi \equiv \left(\frac{v_{\rm wind}}{v_0}\right)$

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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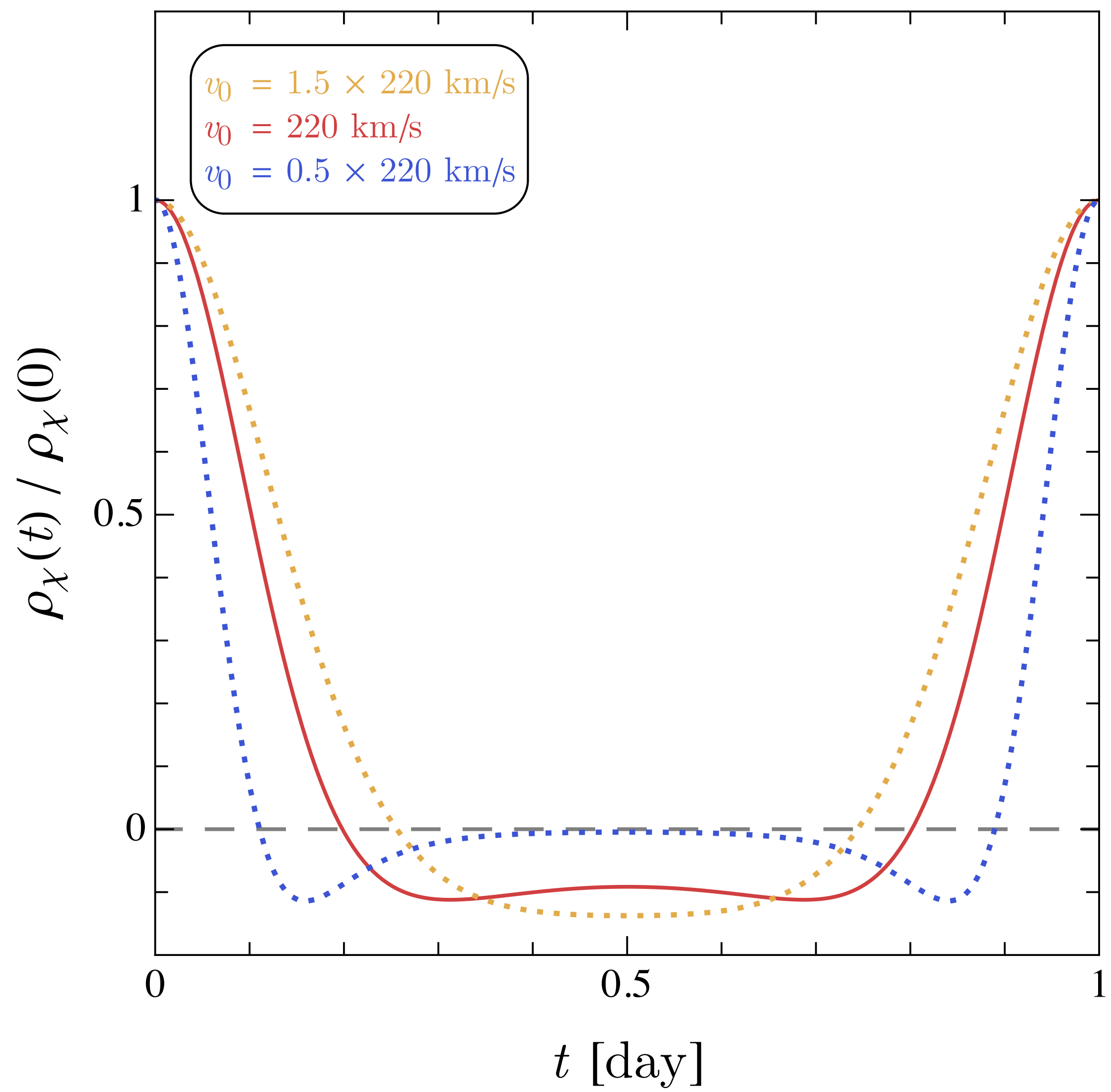

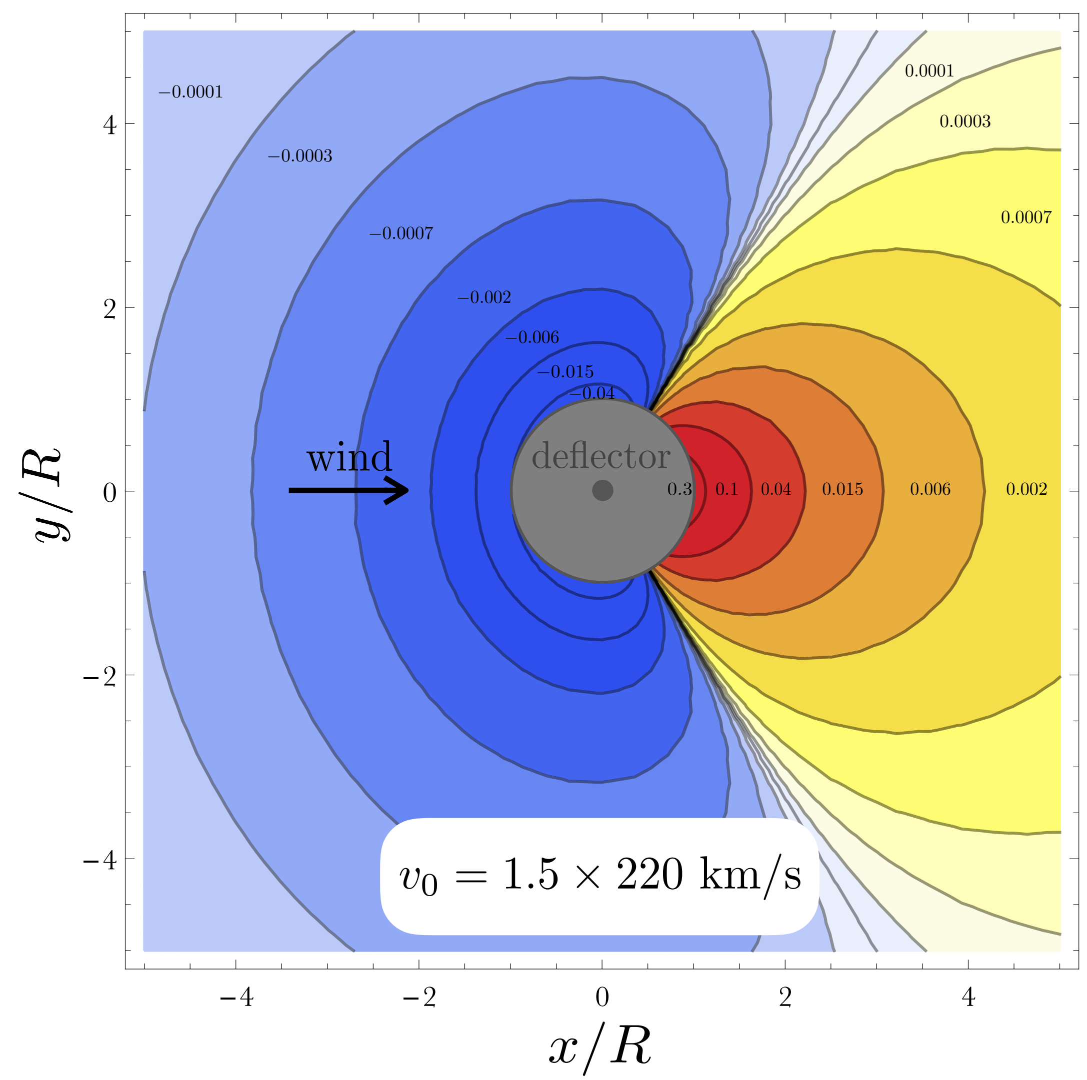

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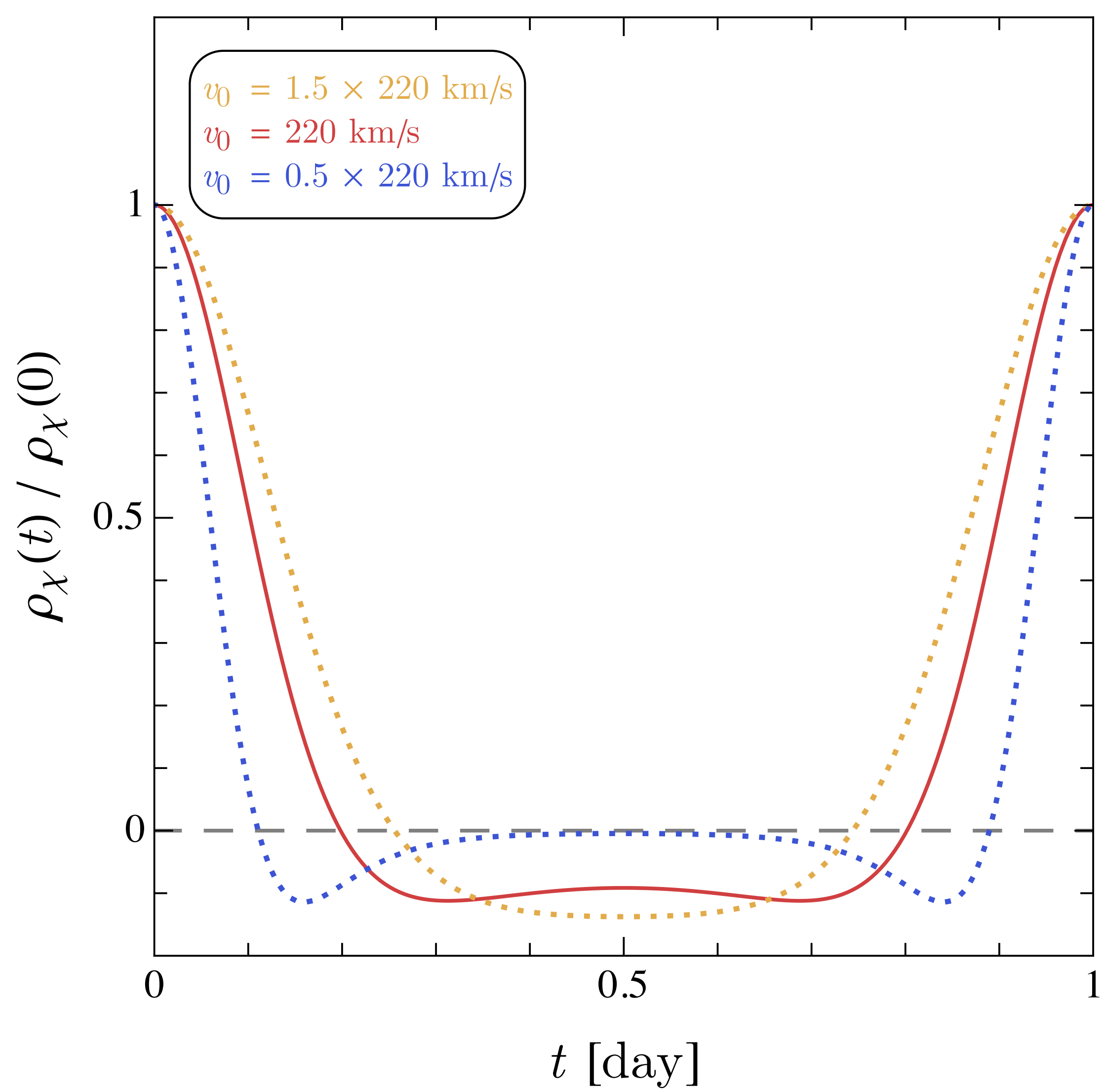


Sensitive to both wind and dispersion

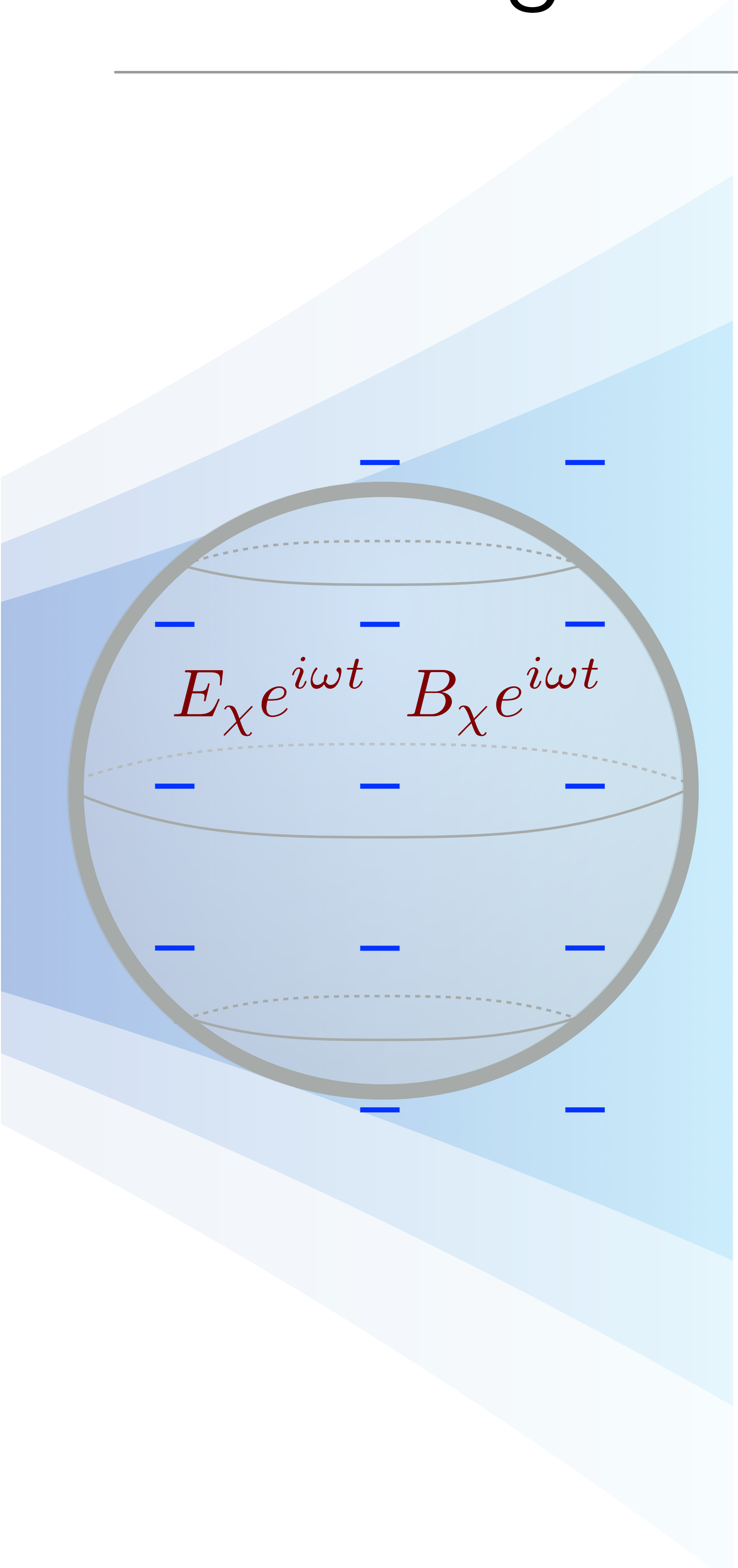
Daily modulation of signal:

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

deflector

sidereal

Detecting Dark Matter Waves



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

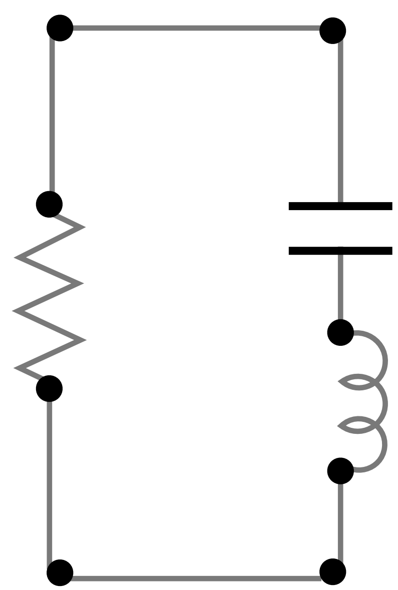
$$\rho_\chi(t) \simeq \rho_\chi\, e^{i\omega t}\ ,\ \boldsymbol{j}_\chi(t) \simeq \boldsymbol{j}_\chi\, e^{i\omega t}$$

Recall requirement

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

Solution: **Lumped LC Resonator**

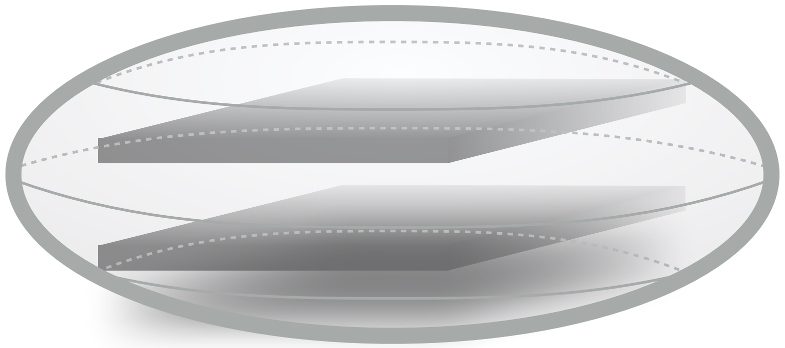
$$\omega_{\rm LC} = \frac{1}{\sqrt{LC}}$$



Ring up signal over Q cycles

Detecting Dark Matter Waves

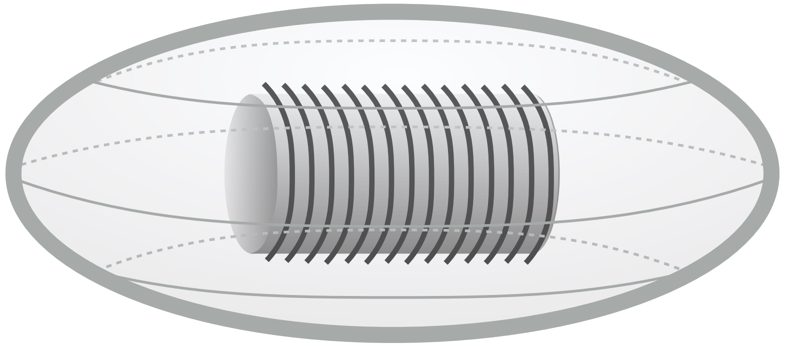
Since E-field signal dominant, capacitative pickup optimal



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

Effective volume of capacitor/antenna — bounded by shielded volume

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



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

Effective volume of inductor — many coils

Signal to Noise

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

Unpack this expression

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

Thermal (Johnson-Nyquist) noise limited power spectral density

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

Signal voltage power spectral density (E-field)

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

SNR is ratio of PSDs

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

Signal to Noise

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

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

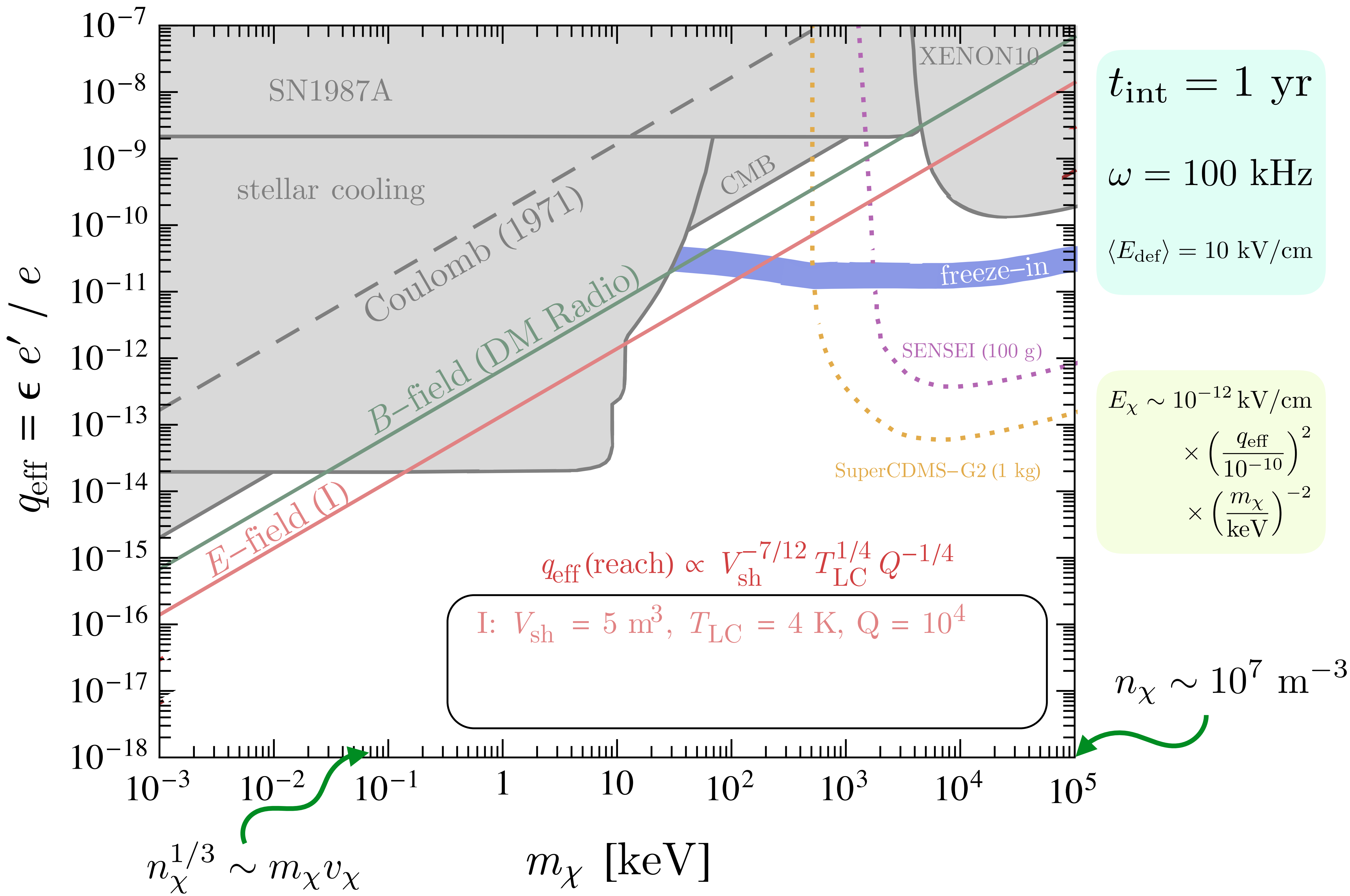
$\propto t_{\mathrm{int}}$ requires coherence time > integration time

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

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

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

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

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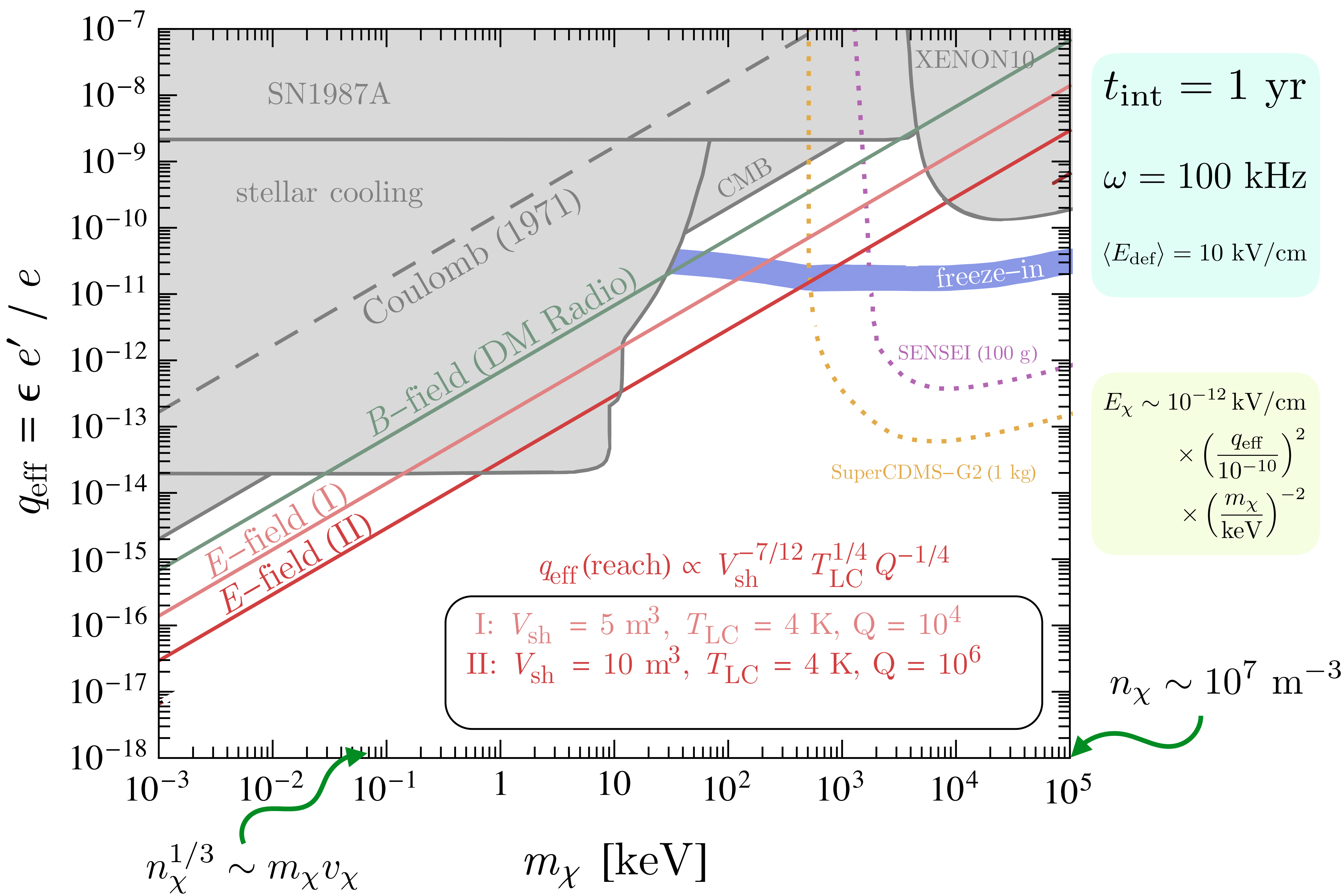

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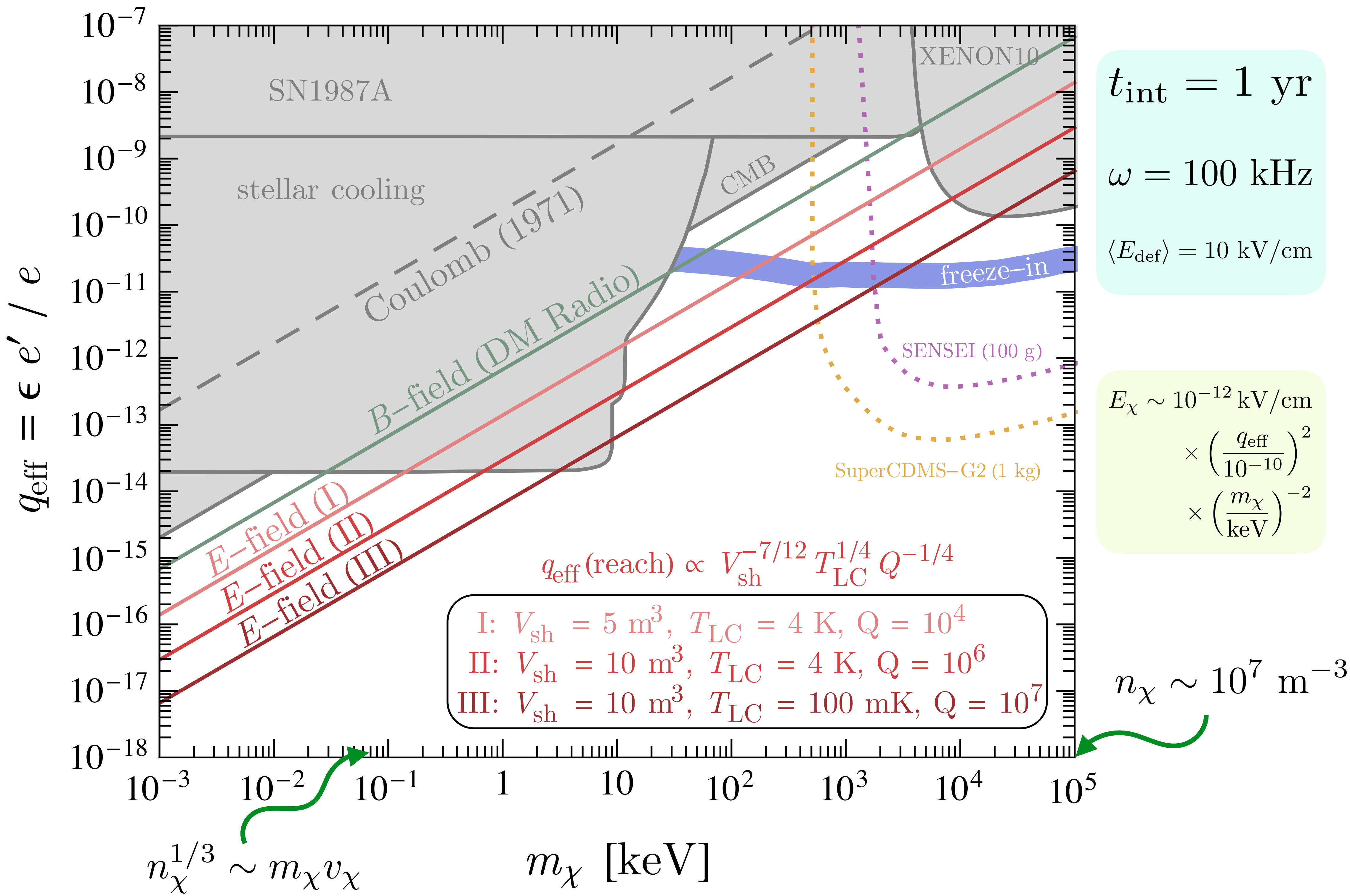

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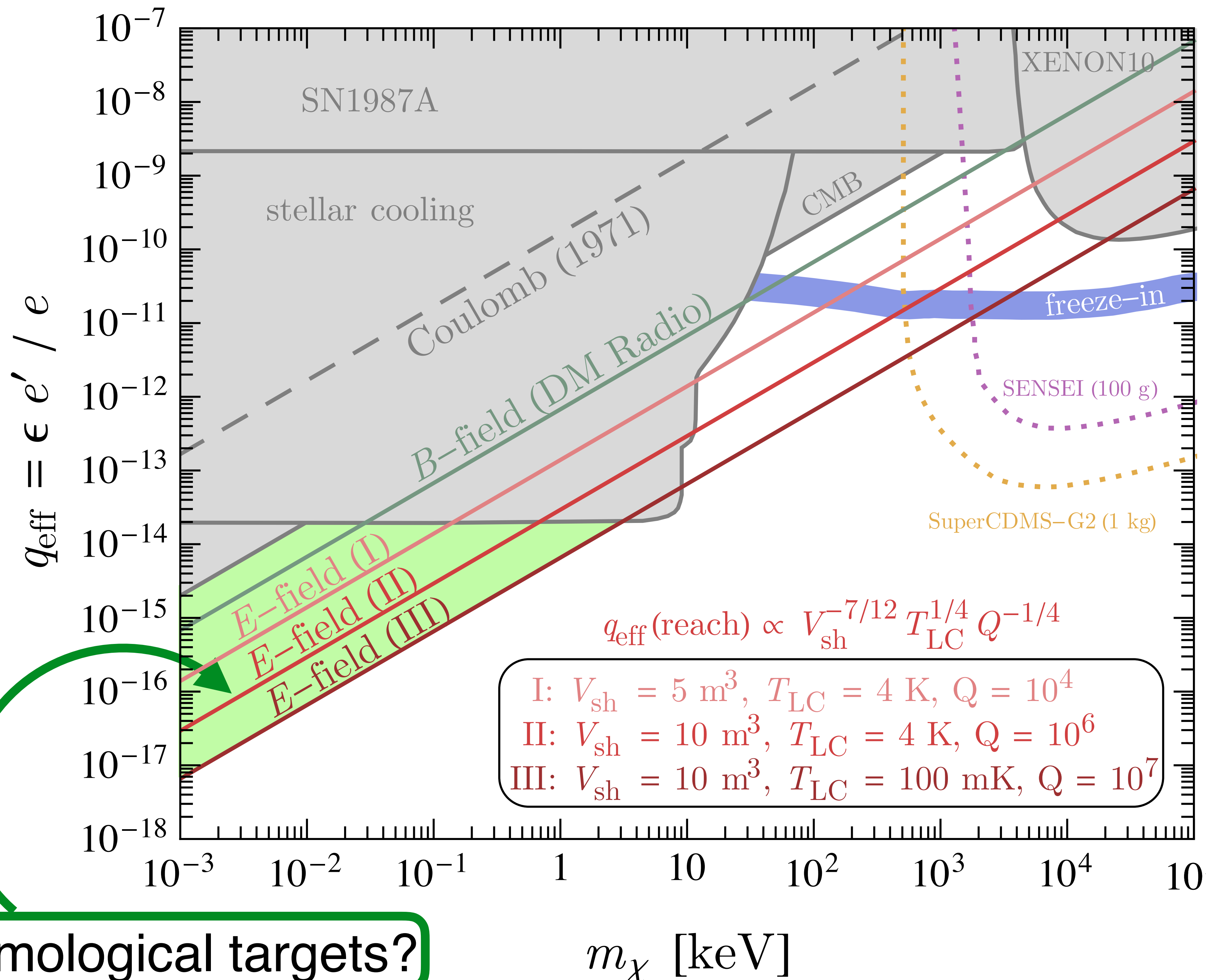

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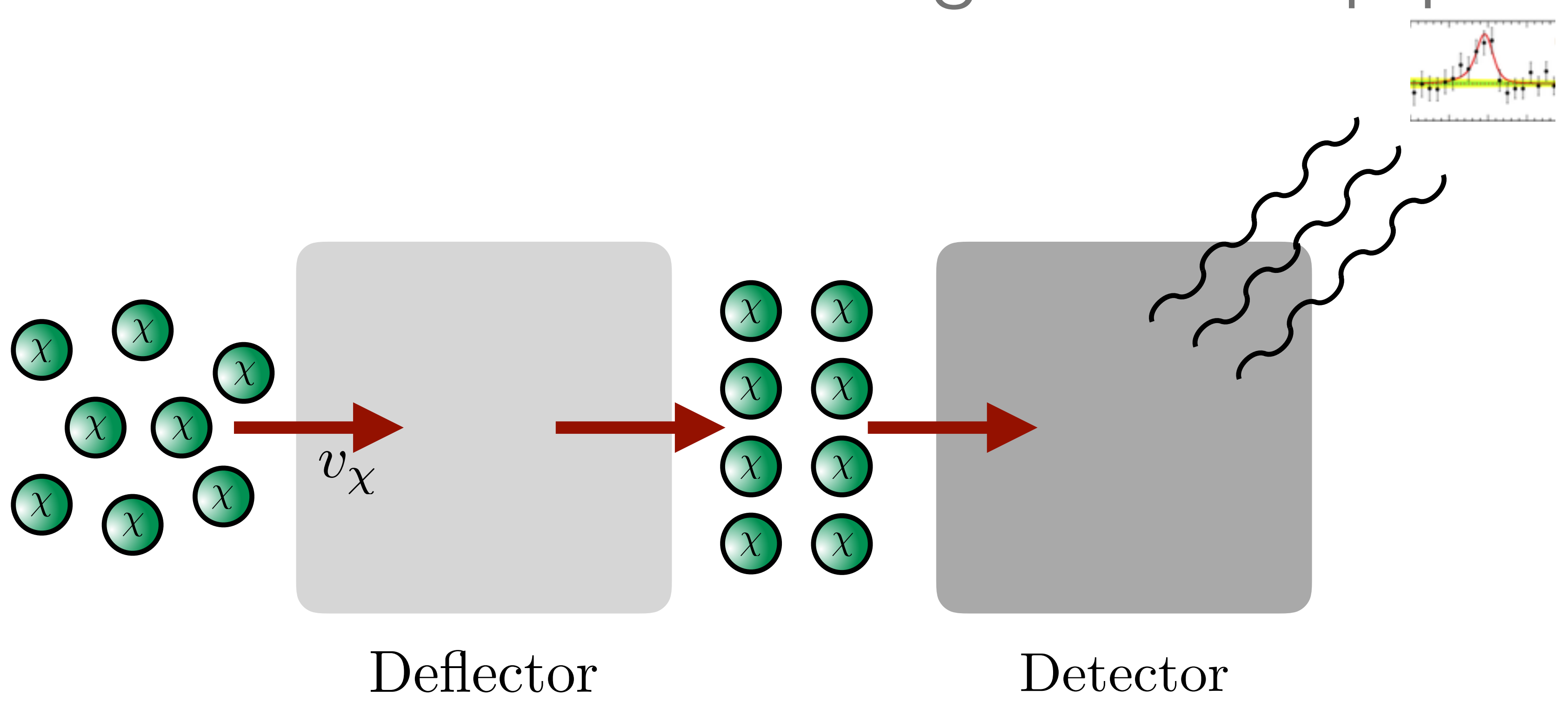
Any cosmological targets?

Outlook

- For DM masses < MeV — Non-Thermal History
- Such models may be accompanied by an ultralight mediator
- **Active Direct Detection** through two-step process:



Outlook

- An example model: (effectively) millicharged DM
- Detectable freeze-in for KeV — MeV requires ultralight A'

$$m_{A'} \lesssim 10^{-9}\ \mathrm{eV}$$

- Range of force: $1/m_{A'} \gtrsim 10^{3}\ \mathrm{m}$
- Borrow intuition from lower mass DM searches instead of extending WIMP-style searches
- Possible new signals at LSW experiments, Direct Detection

BACKUP

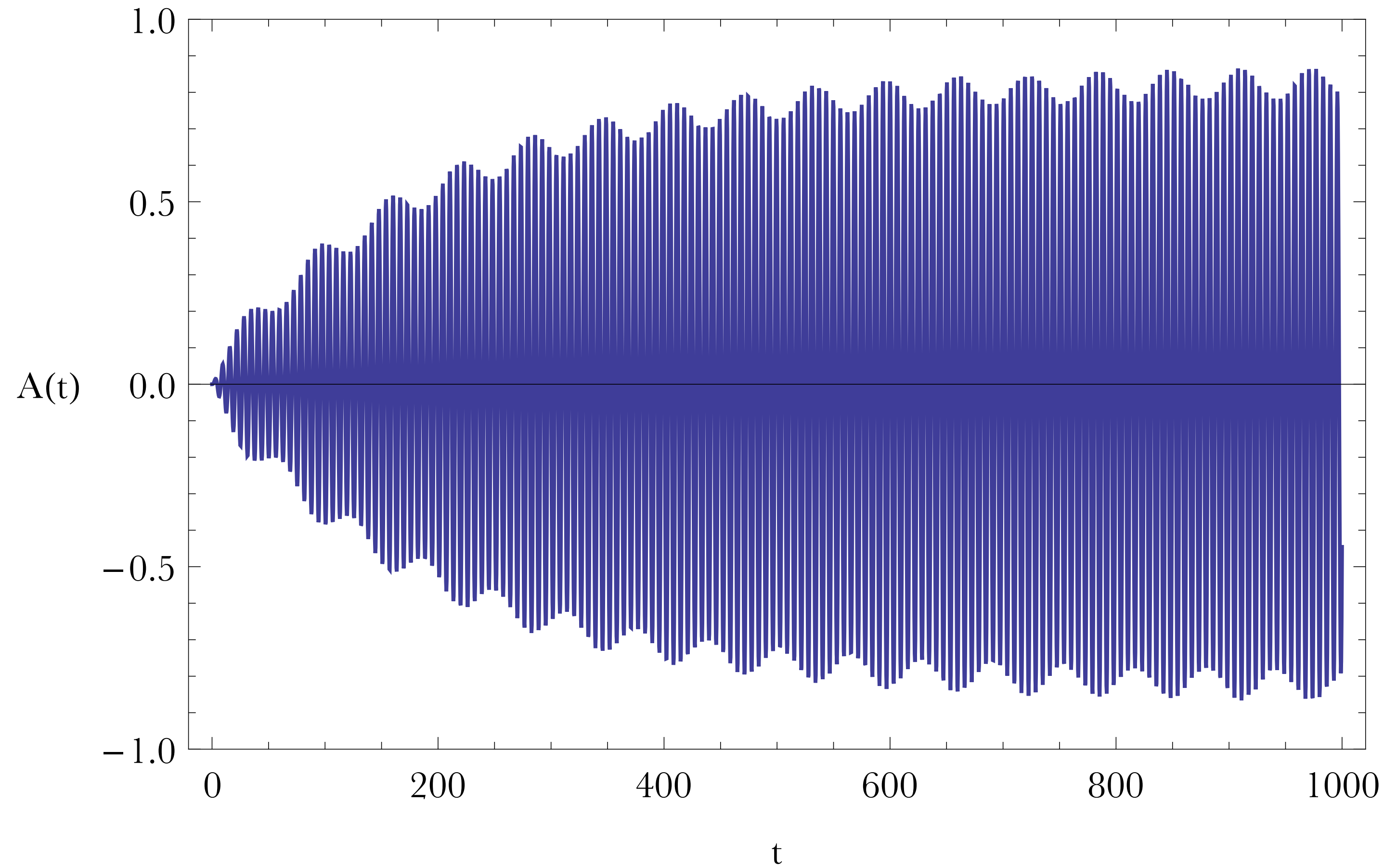
Poisson Fluctuations

Poisson variation of local DM number density

Leads to time-variation of amplitude of driving term:

$$\rho_\chi(t) \simeq \rho_\chi e^{i\omega t}$$

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

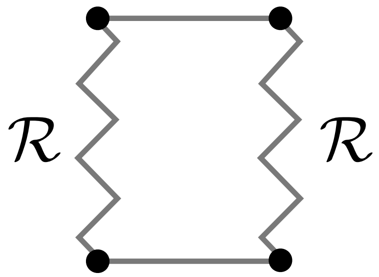


For $m_\chi \lesssim 1\ \mathrm{GeV}$, $\delta n_\chi \lesssim 10^{-3} n_\chi$

High-frequency fluctuations — effect averages to zero

Low-frequency fluctuations — negligible modulation of amplitude

Thermal Noise



$$dP = \langle E \rangle = k_B T d\omega = \frac{\bar{V}^2}{4R}$$

$$\bar{V}^2 = \lim_{t_{\rm int}\to\infty} \frac{1}{t_{\rm int}} \int_0^{t_{\rm int}} V(t) V^\star(t) dt$$

$$\tilde{\bar{V}}(\omega) = \frac{1}{\sqrt{t_{\rm int}}} \int_0^{t_{\rm int}} \bar{V}(t) e^{-i\omega t} dt$$

$$\int |\tilde{\bar{V}}(\omega)|^2 d\omega = \bar{V}^2$$

$$|\tilde{\bar{V}}(\omega)|^2 = 4 R k_B T$$

Noise Power Spectral Density

Phase knowledge

Measured:

$$B(t) = B_0 \sin\left(\omega_{\rm em} t + \varphi(t)\right) + B_n(t)$$

$$\tilde{B}(\omega) = \frac{1}{\sqrt{t_{\rm int}}} \int_0^{t_{\rm int}} B(t) \sin(\omega t) dt = \tilde{B}_0(\omega) + \tilde{B}_n(\omega)$$

$t_{\rm int} < \tau$ $\qquad |\tilde{B}_0(\omega)|^2 = B_0^2 t_{\rm int}$

$t_{\rm int} > \tau$ $\qquad |\tilde{B}_0(\omega)|^2 = \sqrt{N_{\rm meas}} B_0^2 \tau$ $\qquad N_{\rm meas} = t_{\rm int}/\tau$

Electric Field with Massive Dark Photon

EoM for scalar potential: $\left(\partial^2 + m_{A'}^2\right) \phi' = \rho' + \epsilon\rho$

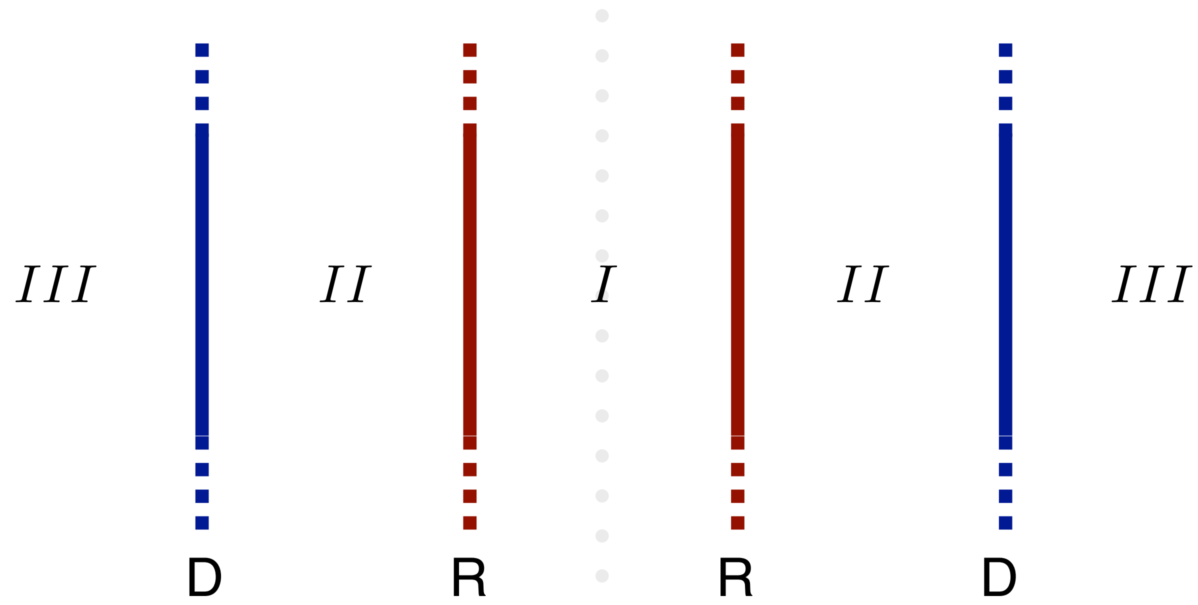
Potential sourced by SM charges: $\phi' = \frac{\epsilon e}{4\pi} \frac{e^{-m_{A'} r}}{r}$

Potential sourced by dark charges: $\phi' = \frac{e'}{4\pi} \frac{e^{-m_{A'} r}}{r}$

massless A' limit equivalent to r << 1/m

Dark Current With Massive Dark Photon

Region I:
— Inside conducting shield
— Inside dark current
Region II:
— Outside conducting shield
— Inside dark current
Region III:
— Outside conducting shield
— Outside dark current



Equations of motion:

$$\left(\nabla^2 - \partial_t^2\right) \mathbf{E} = \nabla \rho_{\rm SM} + \partial_t \mathbf{j_{SM}} \ ,$$

$$\left(\nabla^2 - \partial_t^2 - m_{A'}^2\right) \mathbf{E}' = \nabla \left(\rho_D + \epsilon \rho_{\rm SM}\right) + \partial_t \left(\mathbf{j_D} + \epsilon \mathbf{j_{SM}}\right)$$

Dark Current With Massive Dark Photon

Region I:
— Inside conducting shield
— Inside dark current
Region II:
— Outside conducting shield
— Inside dark current
Region III:
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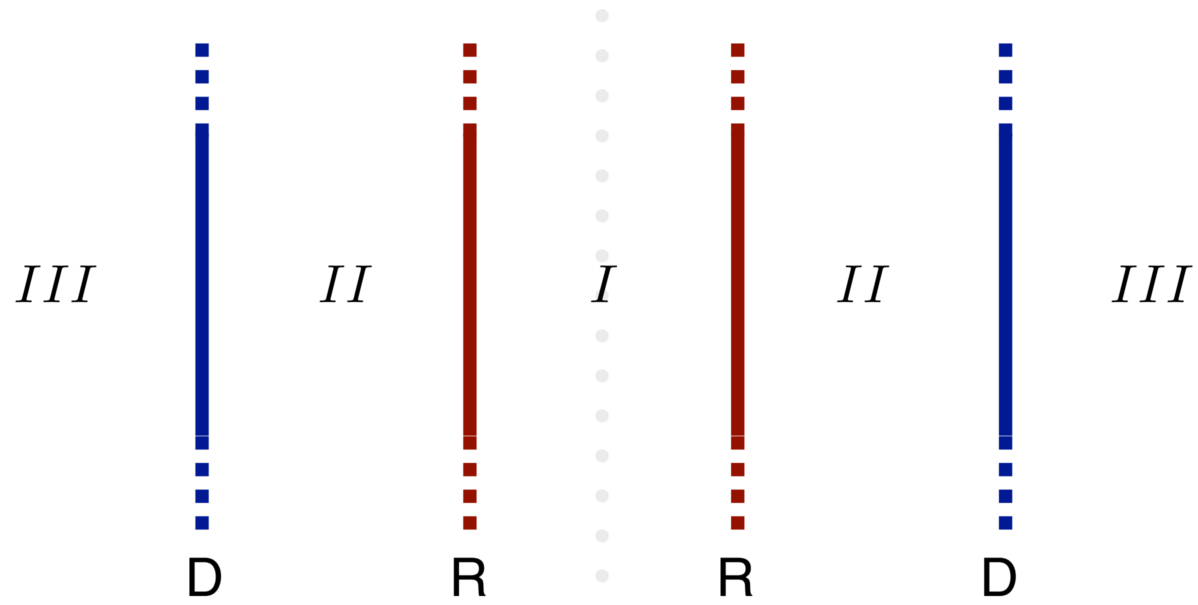

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$$\left(\nabla^2 - \partial_t^2 - m_{A'}^2\right)\mathbf{E}' = \nabla\left(\rho_D + \epsilon\rho_{\rm SM}\right) + \partial_t\left(\mathbf{j}_{\mathbf{D}} + \epsilon\mathbf{j}_{\mathbf{SM}}\right)$$

Solutions:

$$\mathbf{E}_{\mathbb{r}} = a_{\mathbb{r}} J_0(r\omega_{\rm em}) + b_{\mathbb{r}} Y_0(r\omega_{\rm em}) \ ,$$

$$\mathbf{E}'_{\mathbb{r}} = \frac{i\mathbf{j}_{\mathbf{D}}\omega_{\rm em}}{k^2}\theta(D-r) + c_{\mathbb{r}} J_0(rk) + d_{\mathbb{r}} Y_0(rk)$$

$$k = \sqrt{\omega_{\rm em}^2 - m_{A'}^2}$$

Receiving the Signal

Solutions:

$$\mathbf{E}_I = a_I J_0(r\omega_{\rm em}) + b_I Y_0(r\omega_{\rm em}) \ ,$$

$$\mathbf{E}'_I = \frac{i\mathbf{j_D}\omega_{\rm em}}{k^2}\theta(D-r) + c_I J_0(rk) + d_I Y_0(rk)$$

$$k = \sqrt{\omega_{\rm em}^2 - m_{A'}^2}$$

Basis:

$$E_{\rm vis} = E + \epsilon E' \qquad E_{\rm inv} = E' - \epsilon E$$

Boundary Conditions:

- *Well-behaved at r=0:* $b_I = d_I = 0$

Receiving the Signal

Solutions:

$$\mathbf{E}_{\mathbb{r}} = a_{\mathbb{r}} J_0(r\omega_{\rm em}) + b_{\mathbb{r}} Y_0(r\omega_{\rm em}) \ ,$$

$$\mathbf{E}'_{\mathbb{r}} = \frac{i\mathbf{j_D}\omega_{\rm em}}{k^2}\theta(D-r) + c_{\mathbb{r}} J_0(rk) + d_{\mathbb{r}} Y_0(rk)$$

$$k = \sqrt{\omega_{\rm em}^2 - m_{A'}^2}$$

Basis: $E_{\rm vis} = E + \epsilon E'$ $\quad E_{\rm inv} = E' - \epsilon E$

Boundary Conditions:

- *Well-behaved at r=0:* $b_I = d_I = 0$
- *Outgoing E_{vis} in region III:* $b_{III} = -ia_{III}$ $\quad d_{III} = -ic_{III}$

Receiving the Signal

Solutions:

$$\mathbf{E}_{\mathbb{r}} = a_{\mathbb{r}} J_0(r\omega_{\rm em}) + b_{\mathbb{r}} Y_0(r\omega_{\rm em}) \ ,$$

$$\mathbf{E}'_{\mathbb{r}} = \frac{i\mathbf{j_D}\omega_{\rm em}}{k^2}\theta(D-r) + c_{\mathbb{r}} J_0(rk) + d_{\mathbb{r}} Y_0(rk) \qquad k = \sqrt{\omega_{\rm em}^2 - m_{A'}^2}$$

Basis: $E_{\rm vis} = E + \epsilon E' \qquad E_{\rm inv} = E' - \epsilon E$

Boundary Conditions:

- *Well-behaved at r=0:* $b_I = d_I = 0$
- *Outgoing E_{vis} in region III:* $b_{III} = -i a_{III} \qquad d_{III} = -i c_{III}$
- *Conducting wall at r=R*

Receiving the Signal

Solutions:

$$\mathbf{E}_{\text{r}} = a_{\text{r}} J_0(r\omega_{\text{em}}) + b_{\text{r}} Y_0(r\omega_{\text{em}}) \ ,$$

$$\mathbf{E}'_{\text{r}} = \frac{i\mathbf{j}_{\mathbf{D}}\omega_{\text{em}}}{k^2}\theta(D-r) + c_{\text{r}} J_0(rk) + d_{\text{r}} Y_0(rk)$$

$$k = \sqrt{\omega_{\text{em}}^2 - m_{A'}^2}$$

Basis: $E_{\text{vis}} = E + \epsilon E'$ $E_{\text{inv}} = E' - \epsilon E$

Boundary Conditions:

- *Well-behaved at r=0:* $b_I = d_I = 0$
- *Outgoing E_{vis} in region III:* $b_{III} = -ia_{III}$ $d_{III} = -ic_{III}$
- *Conducting wall at r=R*
- *Continuity at r=D*

Receiving the Signal

Solutions:

$$\mathbf{E}_{\mathbb{r}} = a_{\mathbb{r}} J_0(r\omega_{\text{em}}) + b_{\mathbb{r}} Y_0(r\omega_{\text{em}}) \ ,$$

$$\mathbf{E}'_{\mathbb{r}} = \frac{i\mathbf{j_D}\omega_{\text{em}}}{k^2}\theta(D-r) + c_{\mathbb{r}} J_0(rk) + d_{\mathbb{r}} Y_0(rk)$$

$$k = \sqrt{\omega_{\text{em}}^2 - m_{A'}^2}$$

Basis:

$$E_{\text{vis}} = E + \epsilon E' \qquad E_{\text{inv}} = E' - \epsilon E$$

Boundary Conditions:

- *Well-behaved at r=0:* $b_I = d_I = 0$
- *Outgoing E_{vis} in region III:* $b_{III} = -ia_{III}$ $\quad d_{III} = -ic_{III}$
- *Conducting wall at r=R*
- *Continuity at r=D*
- *Continuity of derivative at r=D*

Receiving the Signal

Solutions:

$$\mathbf{E}_{\ulcorner} = a_{\ulcorner} J_0(r\omega_{\rm em}) + b_{\ulcorner} Y_0(r\omega_{\rm em}) \ ,$$

$$\mathbf{E}'_{\ulcorner} = \frac{i\mathbf{j_D}\omega_{\rm em}}{k^2}\theta(D-r) + c_{\ulcorner} J_0(rk) + d_{\ulcorner} Y_0(rk)$$

$$k = \sqrt{\omega_{\rm em}^2 - m_{A'}^2}$$

Basis:

$$E_{\rm vis} = E + \epsilon E' \qquad E_{\rm inv} = E' - \epsilon E$$

Boundary Conditions:

- *Well-behaved at r=0:* $b_I = d_I = 0$
- *Outgoing E_{vis} in region III:* $b_{III} = -ia_{III}$ $d_{III} = -ic_{III}$
- *Conducting wall at r=R*
- *Continuity at r=D*
- *Continuity of derivative at r=D*
- *Continuity of E_{inv} at r=R*

Receiving the Signal

Solutions:

$$\mathbf{E}_{\text{r}} = a_{\text{r}} J_0(r\omega_{\text{em}}) + b_{\text{r}} Y_0(r\omega_{\text{em}}) \ ,$$

$$\mathbf{E}'_{\text{r}} = \frac{i\mathbf{j}_{\mathbf{D}}\omega_{\text{em}}}{k^2}\theta(D-r) + c_{\text{r}} J_0(rk) + d_{\text{r}} Y_0(rk)$$

$$k = \sqrt{\omega_{\text{em}}^2 - m_{A'}^2}$$

Basis: $E_{\text{vis}} = E + \epsilon E'$ $\quad E_{\text{inv}} = E' - \epsilon E$

Boundary Conditions:

- *Well-behaved at r=0:* $b_I = d_I = 0$
- *Outgoing E_{vis} in region III:* $b_{III} = -ia_{III}$ $\quad d_{III} = -ic_{III}$
- *Conducting wall at r=R*
- *Continuity at r=D*
- *Continuity of derivative at r=D*
- *Continuity of E_{inv} at r=R*
- *Continuity of derivative of E_{inv} at r=R*

Received Signal

E-Field observed in Cavity:

$$\mathbf{E}_{\mathrm{vis}\,\mathbf{I}} = |\mathbf{j}_{\mathbf{D}}| \frac{\epsilon}{\omega_{\mathrm{em}}} \left(i - \frac{i J_0(r\omega_{\mathrm{em}})}{J_0(R\omega_{\mathrm{em}})} \right) e^{i\omega_{\mathrm{em}} t}\ \hat{\mathbf{x}}$$

Received Signal

E-Field observed in Cavity:

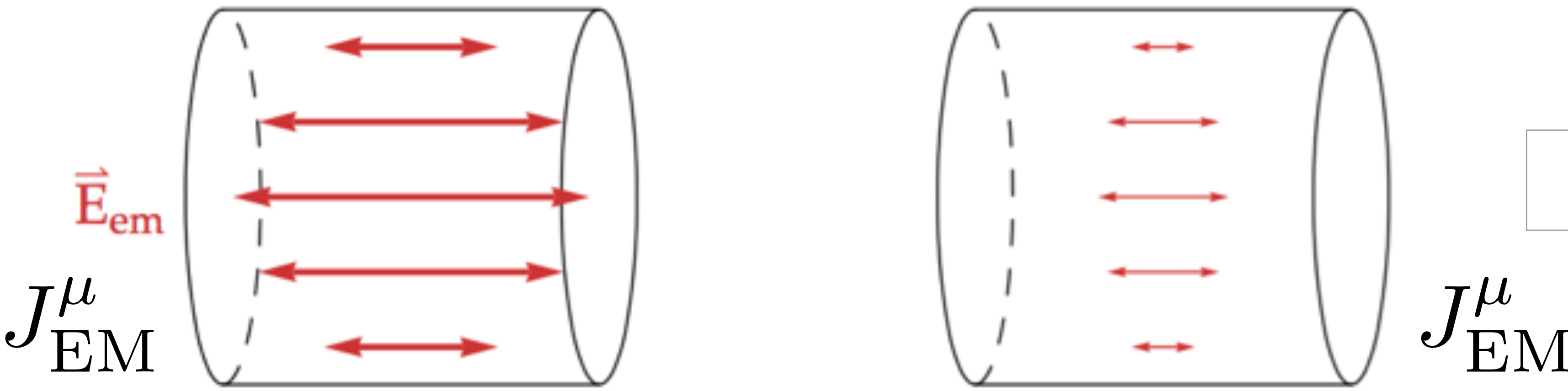
$$\mathbf{E}_{\mathrm{vis}\,\mathbf{I}} = |\mathbf{j}_\mathbf{D}| \frac{\epsilon}{\omega_{\mathrm{em}}} \left(i - \frac{i J_0(r\omega_{\mathrm{em}})}{J_0(R\omega_{\mathrm{em}})} \right) e^{i\omega_{\mathrm{em}} t} \, \hat{\mathbf{x}}$$

B-Field observed in Cavity:

$$\mathbf{B}_{\mathrm{vis}\,\mathbf{I}} = -|\mathbf{j}_\mathbf{D}| \frac{\epsilon}{\omega_{\mathrm{em}}} \frac{J_1(r\omega_{\mathrm{em}})}{J_0(R\omega_{\mathrm{em}})} e^{i\omega_{\mathrm{em}} t} \hat{\phi}$$

Additional Signals: Light Shining through Walls

Usual light shining through walls — jiggle SM charges to produce $A + \epsilon A'$:



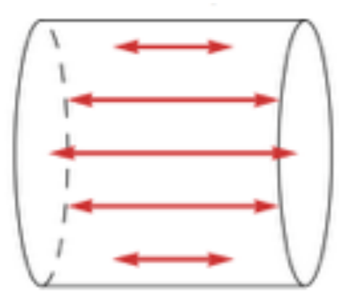
Graham, Mardon, Rajendran, Zhao (2014)

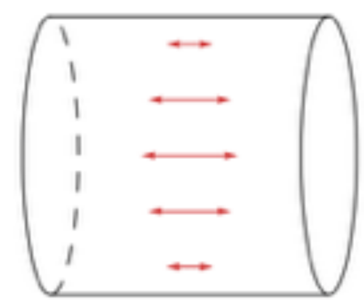
$$\left(\nabla^2 - \partial_t^2\right) \mathbf{E} = \nabla \rho_{\rm SM} + \partial_t \mathbf{j}_{\rm SM} \ ,$$

$$\left(\nabla^2 - \partial_t^2 - m_{A'}^2\right) \mathbf{E}' = \nabla \left(\rho_D + \epsilon \rho_{\rm SM}\right) + \partial_t \left(\mathbf{j}_{\rm D} + \epsilon \mathbf{j}_{\rm SM}\right)$$

Thinking collectively

$J^\mu_{\rm EM}$





$J^\mu_{\rm EM}$

Graham, Mardon, Rajendran, Zhao (2014)

Boundary conditions on conducting wall important:

$$E_{{\rm vis}\,T} = E_T + \epsilon E'_T$$ **Attenuated**

$$E_{{\rm vis}\,L} = \epsilon E'_L$$ **Unaffected**

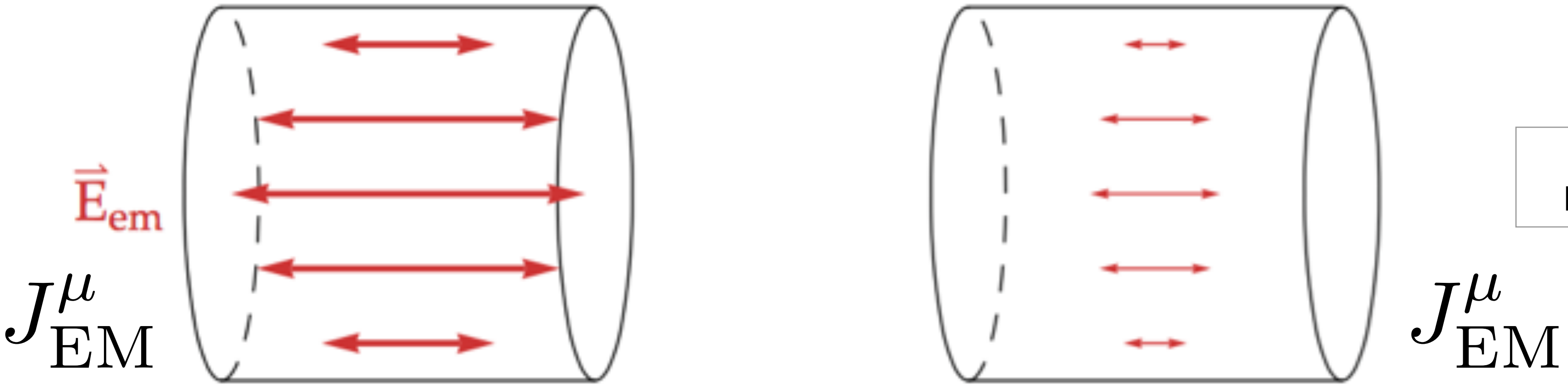
$$E_{{\rm inv}\,T,L} = E'_{T,L} - \epsilon E_T$$ **Unaffected**

$$E_{{\rm vis}\,T} \to \epsilon \left(\frac{m_{A'}}{\omega_{\rm em}}\right)^2 E_{{\rm inv}\,T} \to \epsilon^2 \left(\frac{m_{A'}}{\omega_{\rm em}}\right)^4 E_{{\rm vis}\,T}$$

$$E_{{\rm vis}\,L} \propto \left(\frac{m_{A'}}{\omega_{\rm em}}\right)^2 E_{\rm em}$$

Thinking collectively

Usual light shining through walls — jiggle SM charges to produce $A + \epsilon A'$:



Graham, Mardon, Rajendran, Zhao (2014)

$$B_{\mathrm{rec}} = Q\epsilon^2 \frac{m_{A'}^2}{\omega_{\mathrm{em}}^2} \frac{L}{d} \left(\frac{\sin kL/2}{kL/2} \right)^2 B_{\mathrm{em}}$$ Longitudinal

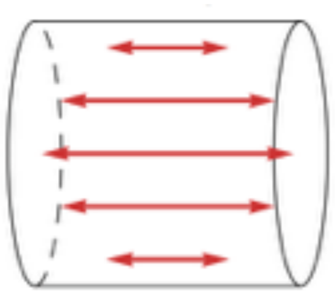
$$B_{\mathrm{rec}} = 0.39 Q\epsilon^2 \frac{m_{A'}^4}{\omega_{\mathrm{em}}^4} \frac{L}{d} B_{\mathrm{em}}$$ Transverse

Longitudinal dark photon emission wins

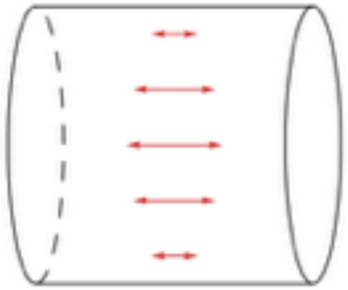
Thinking collectively

In the presence of DM, the story changes

Now, dark charges can be oscillated to generate E’ waves



J^{μ}_{EM}



J^{μ}_{D}

$\mathcal{O}(e_D^2 \epsilon^2 m_{A'}^2 \omega_{\mathrm{em}}^{-2})$ L, T

Thinking collectively

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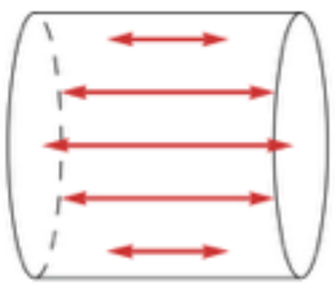
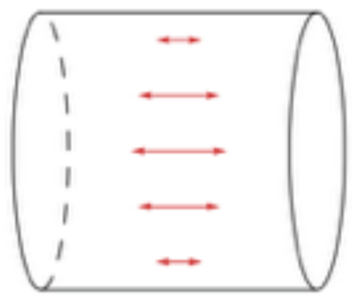
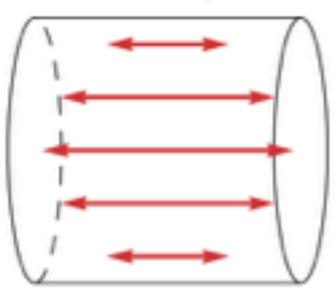


$J^{\mu}_{\rm EM}$

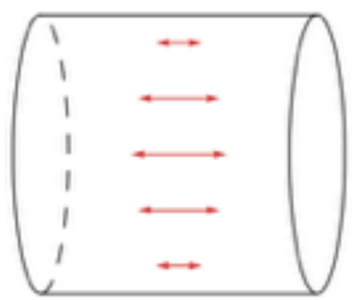


$J^{\mu}_{\rm D}$

$\mathcal{O}(e_D^2 \epsilon^2 m_{A'}^2 \omega_{\rm em}^{-2})$ L, T



$J^{\mu}_{\rm D}$



$J^{\mu}_{\rm EM}$

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Thinking collectively

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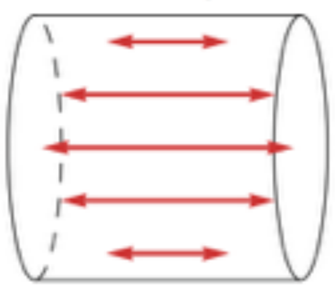
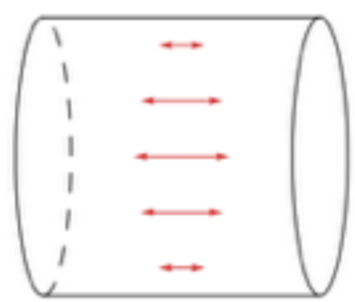
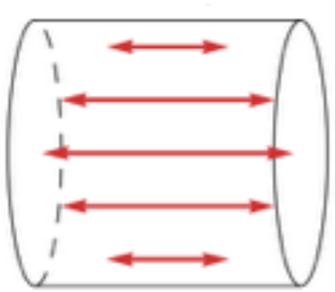
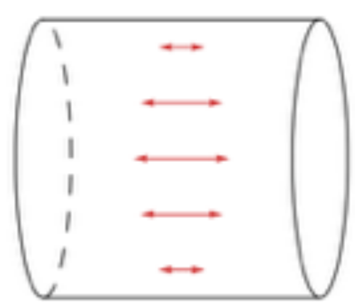
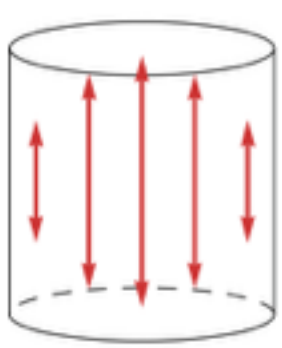
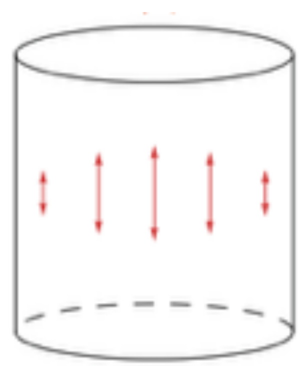
	J^{μ}_{EM}		J^{μ}_{D}	$\mathcal{O}(e_D^2\epsilon^2 m_{A'}^2\omega_{\mathrm{em}}^{-2})$	L, T
	J^{μ}_{D}		J^{μ}_{EM}	$\mathcal{O}(e_D^2\epsilon^2 m_{A'}^2\omega_{\mathrm{em}}^{-2})$	L, T
	J^{μ}_{D}		J^{μ}_{D}	$\mathcal{O}(e_D^4\epsilon^2 m_{A'}^2\omega_{\mathrm{em}}^{-2})$ $\mathcal{O}(e_D^4\epsilon^2)$	L T

Thinking collectively

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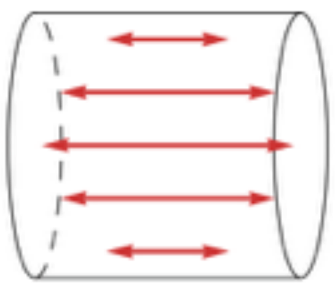
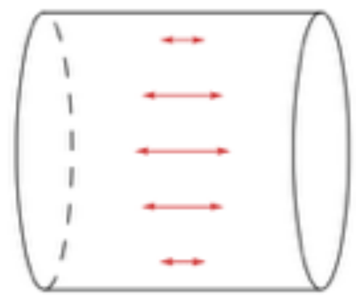
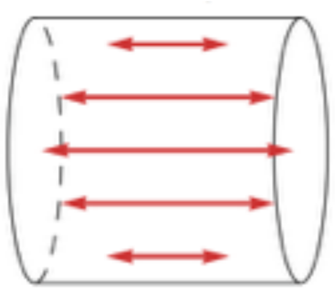
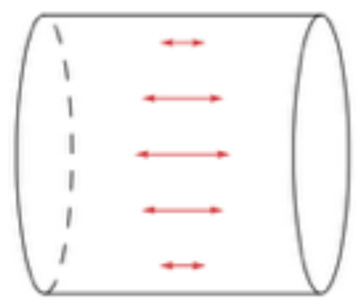
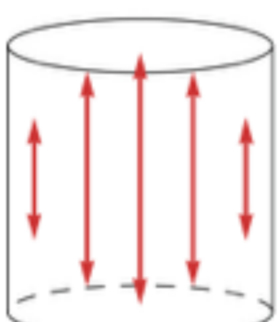
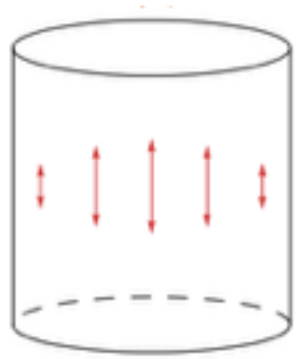

J^μ_{EM}

J^μ_{D}

$\mathcal{O}(e_D^2 \epsilon^2 m_{A'}^2 \omega_{\mathrm{em}}^{-2})$ L, T


J^μ_{D}

J^μ_{EM}

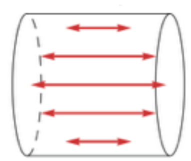
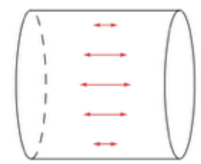
$\mathcal{O}(e_D^2 \epsilon^2 m_{A'}^2 \omega_{\mathrm{em}}^{-2})$ L, T

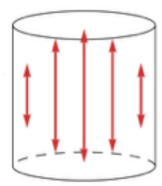
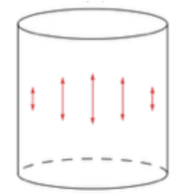

J^μ_{D}

J^μ_{D}

$\mathcal{O}(e_D^4 \epsilon^2 m_{A'}^2 \omega_{\mathrm{em}}^{-2})$ L

$\mathcal{O}(e_D^4 \epsilon^2)$ T

Thinking collectively

 J^μ_D  J^μ_EM $\mathcal{O}(e_D^2\epsilon^2 m_{A'}^2\omega_\mathrm{em}^{-2})$

 J^μ_D  J^μ_D $\mathcal{O}(e_D^4\epsilon^2 m_{A'}^2\omega_\mathrm{em}^{-2})$ L

$\mathcal{O}(e_D^4\epsilon^2)$ T