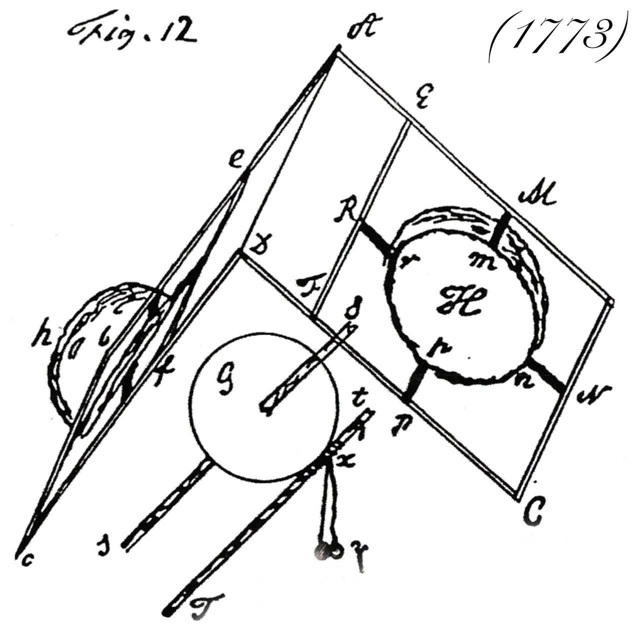
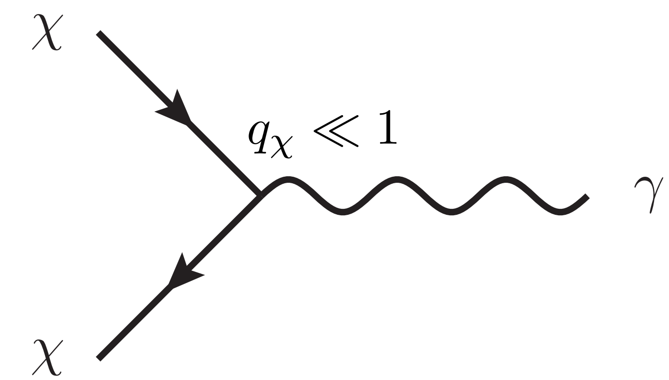
Cavendish Tests of Millicharged Relics





Asher Berlin (Fermilab)

University of Wisconsin–Madison, March 3, 2025

AB, Zach Bogorad, Peter Graham, Hari Ramani (in progress)

AB, Hongwan Liu, Maxim Pospelov, Hari Ramani (arXiv:2302.06619)

Cosmological Subcomponents

$$\Omega_\chi \equiv \rho_\chi/\rho_{\rm cr}\Big|_0 \ll 1$$

<u>Dark Matter Subcomponent</u>

$$\left(\Omega_\chi = f_{\rm DM}\,\Omega_{\rm DM} \sim 0.25 \times f_{\rm DM}\right)$$

Why a subcomponent?

$f_{\rm DM} \sim 1$ is special , $f_{\rm DM} \neq \mathcal{O}(1)$ is generic , $f_{\rm DM} \ll 1$ is generic **and** viable

$\Omega_{\rm DM} \sim \Omega_b$

Cosmological Subcomponents

$$\Omega_\chi \equiv \rho_\chi/\rho_{\rm cr}\,\Big|_0 \ll 1$$

Dark Matter Subcomponent

$$\left(\Omega_\chi = f_{\rm DM}\,\Omega_{\rm DM} \sim 0.25 \times f_{\rm DM}\right)$$

- Thermal Relic

$$f_{\rm DM} \gtrsim 10^{-10} \times (m_\chi/{\rm GeV})^2 \qquad \text{(perturbative unitarity)}$$

Griest, Kamionkowski, Phys. Rev. Lett. (1990)

- Low Reheat

$$f_{\rm DM} \propto e^{-2m_\chi/T_{\rm RH}} \qquad (m_\chi \gg T_{\rm RH})$$

Berlin, Liu, Pospelov, Ramani, arXiv:2110.06217

+ model-dependent modifications from the local environment

Cosmological Subcomponents

Gaps in Coverage

Dark Matter Subcomponent

- Properties are unconstrained for $f_{\rm DM} \lesssim 10^{-2}$
- E.g., strong interaction with normal matter.

  large couplings ~ small abundances

  $f_{\rm DM} \propto (m_{\rm DM}/\alpha_{\rm DM})^2$
- Local population tracks ambient temperature,

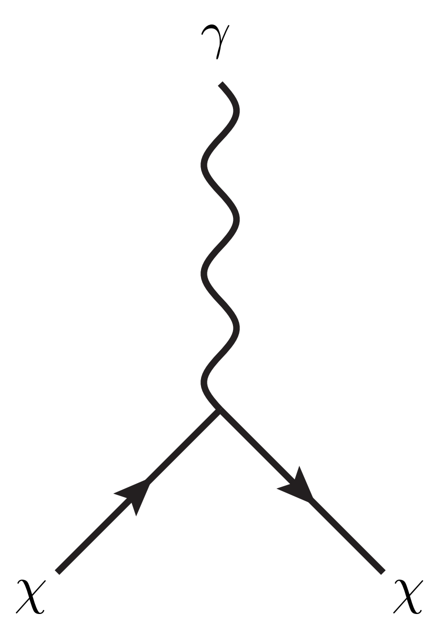
  $E_\chi \sim 300$ K ~ 25 meV $\ll$ typical thresholds

a detectable example = new particles with small effective charge (millicharge)

Outline

Cavendish Tests of Millicharged Relics

1. Overview of Millicharges
2. Terrestrial Density
3. Cavendish

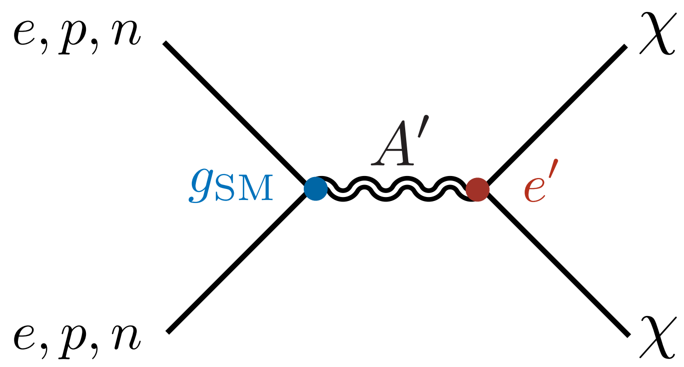


Millicharges

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

Analogous long-ranged force that couples to dark matter?

Do they also couple to normal matter?



equivalence principle tests: $g_{\mathrm{SM}} \lesssim 10^{-2} \times \dfrac{m_e}{m_{\mathrm{pl}}} \sim 10^{-24}$

Millicharges

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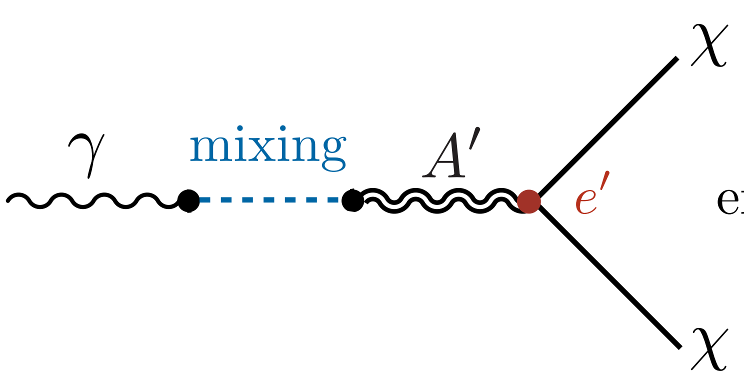


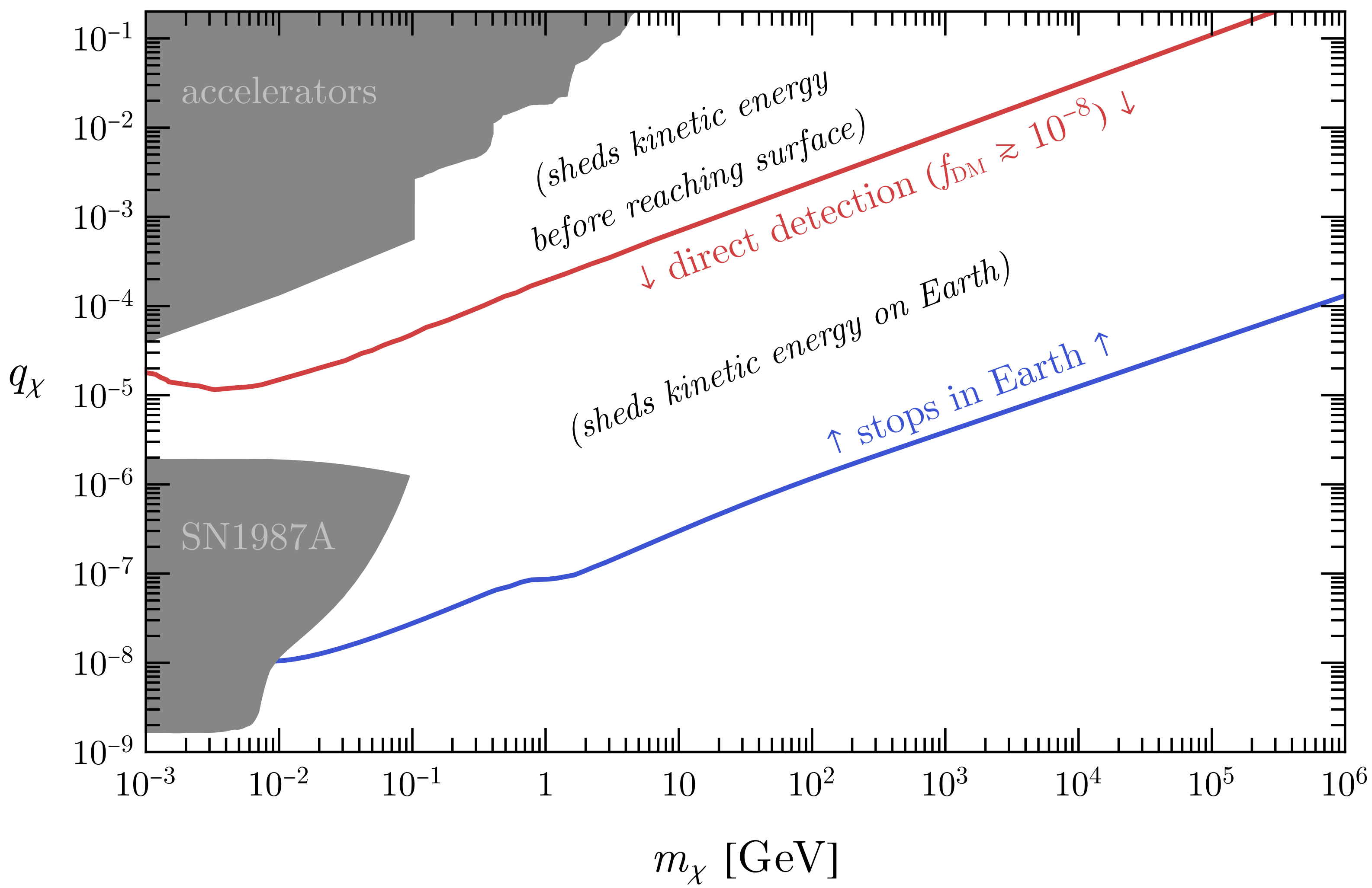
effective charge ~ mixing × dark charge

$$e\,q_\chi = \epsilon \times e'$$

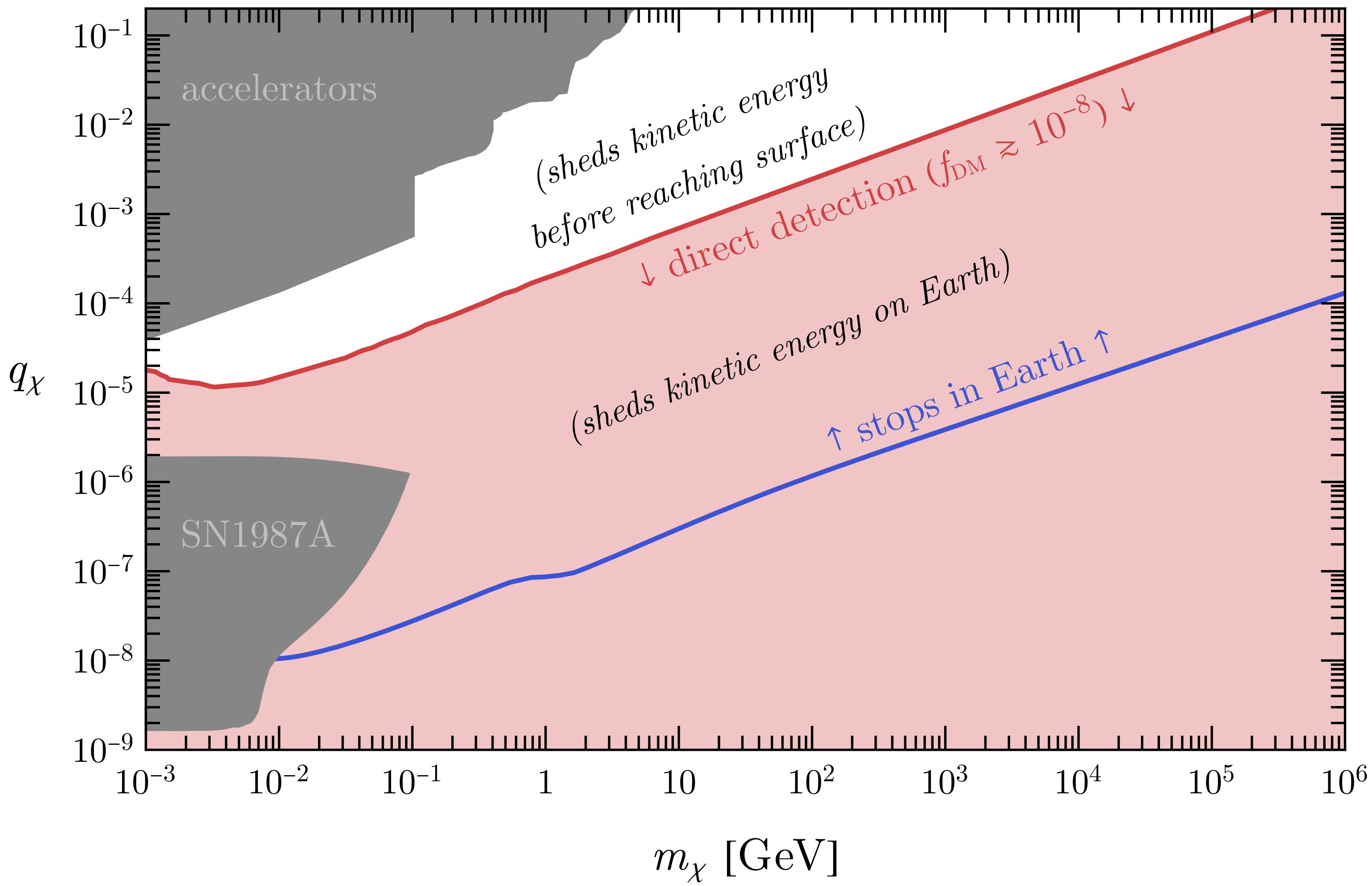
$$\mathscr{L} \sim \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu} - j^\mu_\chi A'_\mu - j^\mu_{\rm em} A_\mu \xrightarrow{A' \to A' + \epsilon A} \mathscr{L} \sim -j^\mu_\chi \left(A'_\mu + \epsilon A^\mu\right) - j^\mu_{\rm em} A_\mu$$

couples through known long-ranged force $\Longrightarrow$ relatively unconstrained

Millicharges

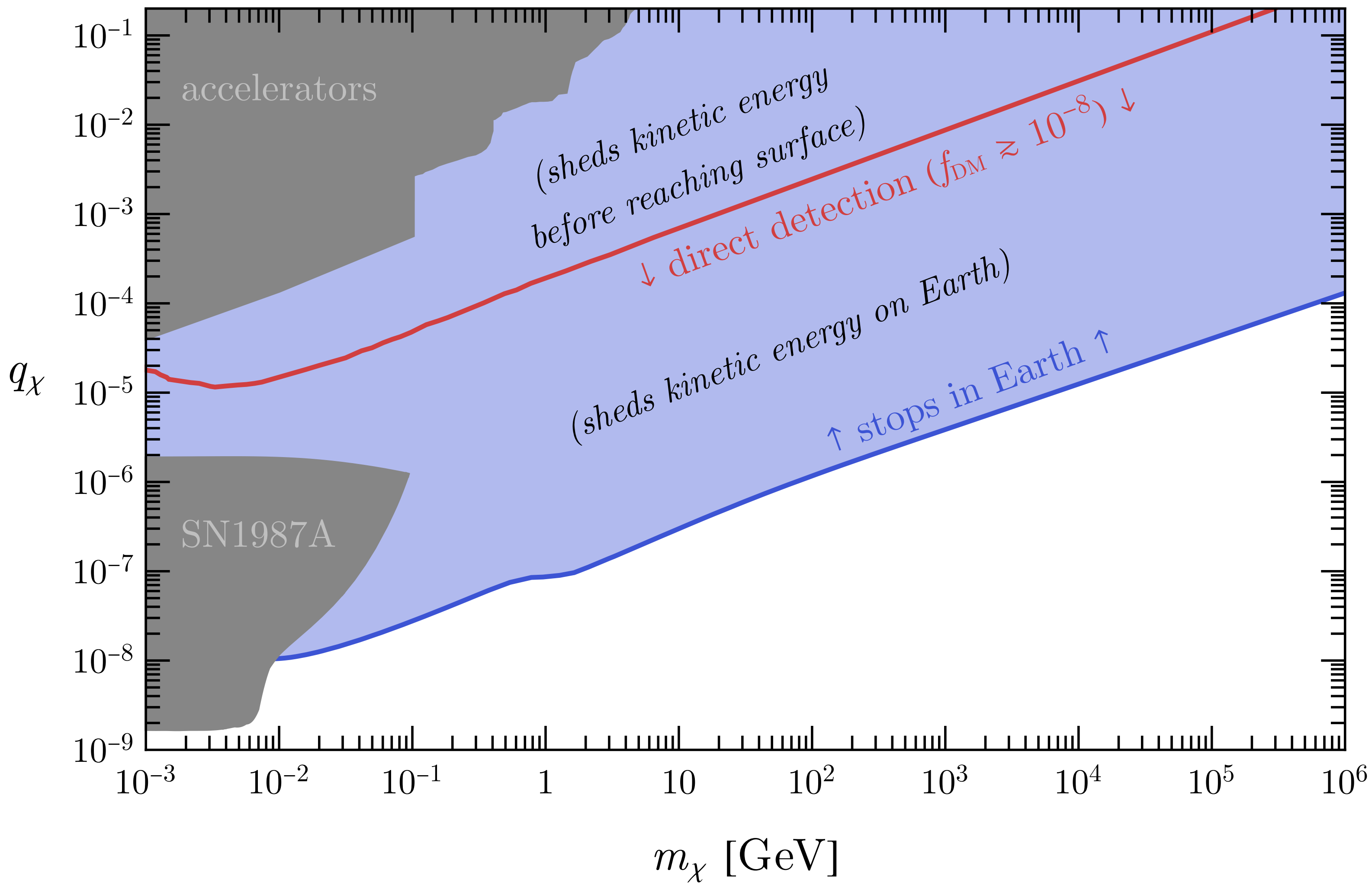


Millicharges



surface/underground direct detection sensitive to DM subcomponents $f_{DM} > 10^{-8}$

Millicharges



local phase space is significantly modified

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AB, Hongwan Liu, Maxim Pospelov, Hari Ramani (arXiv:2302.06619)

Terrestrial Population

incoming galactic wind
of strongly-coupled relics

large fraction thermalizes
to ~ 300 K ~ 25 meV

outgoing evaporation flux
above escape velocity

(virial)

buildup in density

accumulation	*traffic jam*
Accumulated equilibrium density of bound particles	Out of equilibrium density of recently thermalized particles

Terrestrial Population

incoming galactic wind
of strongly-coupled relics

large fraction thermalizes
to ~ 300 K ~ 25 meV

χ

$v_{\rm th}(T_\oplus)/v_{\rm esc} \sim 10^{-1} \times \left(1\ {\rm GeV}/m_\chi\right)^{1/2}$

(gravitationally bound)

(virial)

buildup in density

accumulation

Accumulated equilibrium density of bound particles

traffic jam

Out of equilibrium density of recently thermalized particles

Accumulating Population

incoming galactic wind
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(gravitationally bound)

(virial)

buildup in density

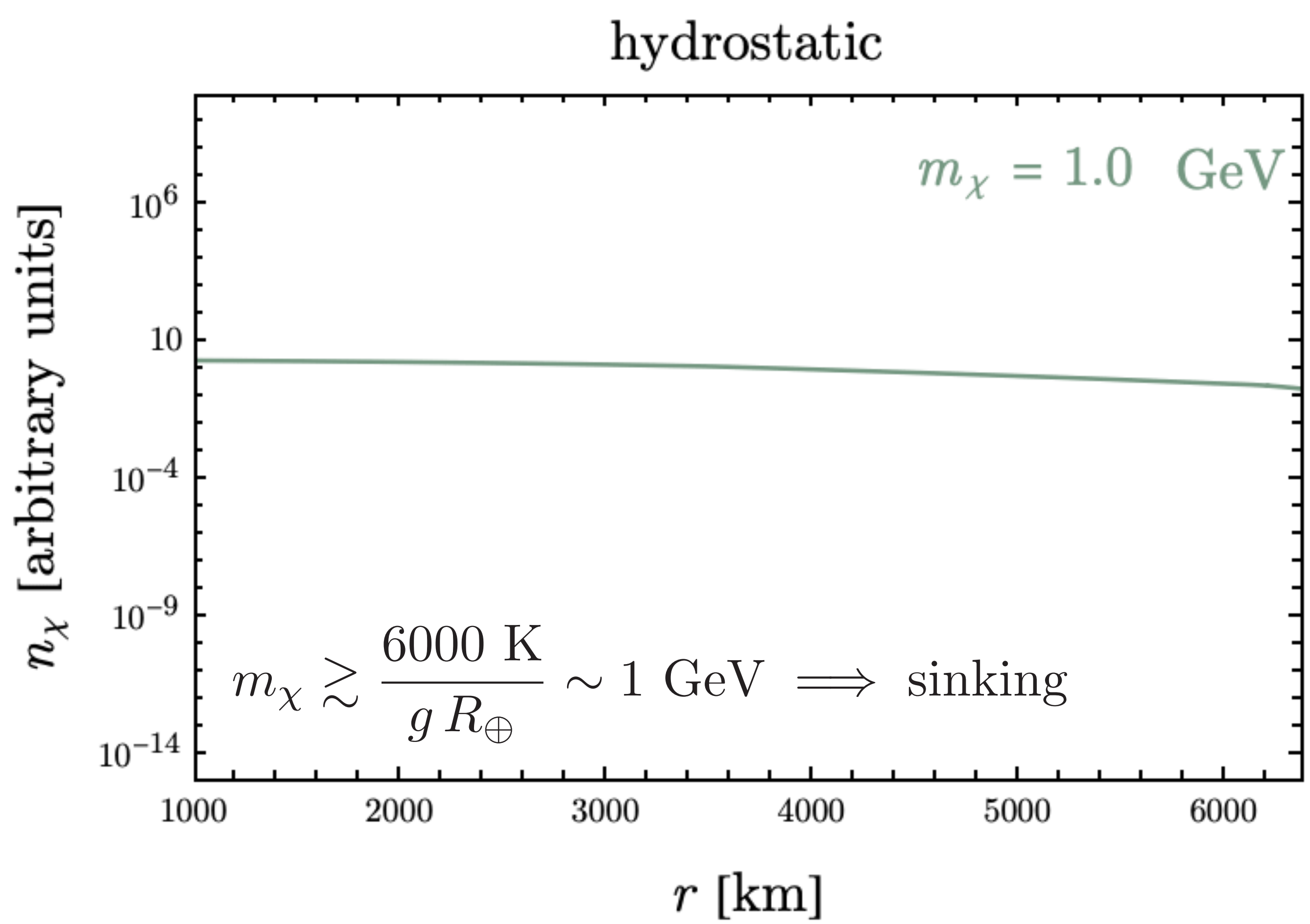
$$\langle n_\chi \rangle_\oplus \sim 10^{15}~{\rm cm}^{-3} \times f_{\rm DM} \left(\frac{1~{\rm GeV}}{m_\chi}\right)$$

(average density)

Accumulating Population

After diffusing throughout the Earth, particles settle into hydrostatic equilibrium

$$\boldsymbol{g} = \frac{\nabla P_\chi}{m_\chi\, n_\chi} \simeq T_\oplus \frac{\nabla n_\chi}{m_\chi\, n_\chi} \qquad \text{(static limit)}$$



Heavier particles are pulled towards Earth's center.

*Relevant near surface for **small** range of masses*

Terrestrial Population

incoming galactic wind
of strongly-coupled relics

large fraction thermalizes
to ~ 300 K ~ 25 meV

outgoing evaporation flux
above escape velocity

(virial)

buildup in density

---

accumulation

Accumulated equilibrium
density of bound particles

traffic jam

Out of equilibrium density of
recently thermalized particles

Traffic Jam

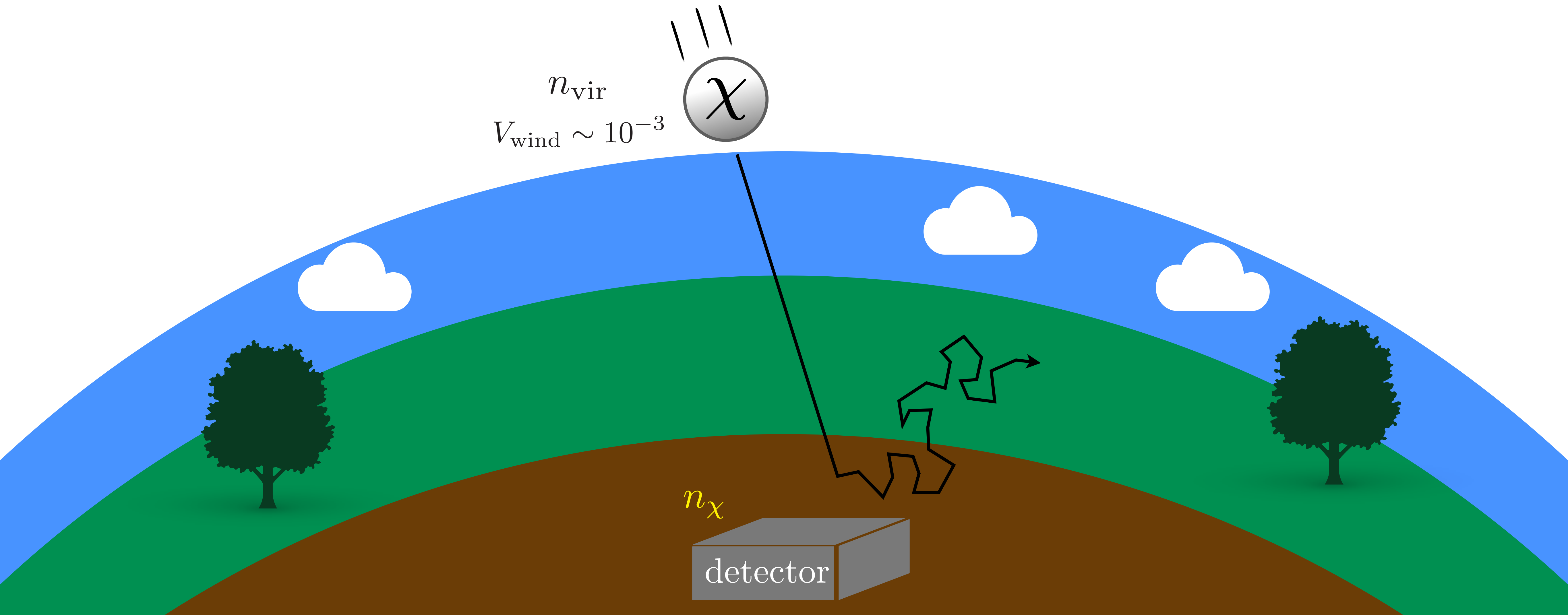
Fluid Dynamics

(continuity) $\partial_t n_\chi + \nabla \cdot (n_\chi \boldsymbol{V}_\chi) = 0$

(Euler) $\partial_t \boldsymbol{V}_\chi + (\boldsymbol{V}_\chi \cdot \nabla)\, \boldsymbol{V}_\chi + \Gamma_{\text{coll.}} \boldsymbol{V}_\chi = \boldsymbol{g} + \frac{e q_\chi \boldsymbol{E}}{m_\chi} - \frac{\nabla P_\chi}{m_\chi\, n_\chi}$

collisional "drag" rate

$\Gamma_{\text{coll.}} \sim \frac{\mu}{m_\chi}\, n_{\text{SM}}\, \sigma_T\, v_{\text{rel}}$



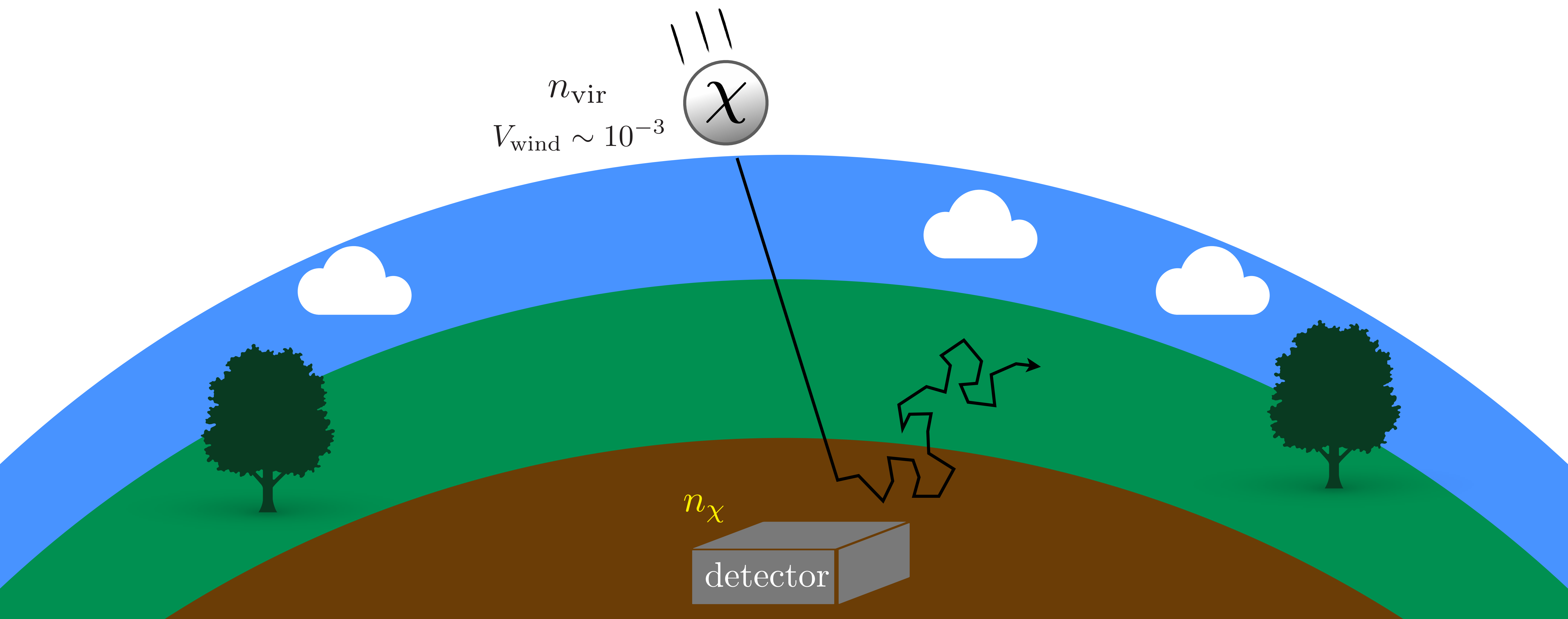
Traffic Jam

Fluid Dynamics

(diffusion) $$\partial_t n_\chi + \nabla \cdot \boldsymbol{j}_\chi = 0 \ , \ \boldsymbol{j}_\chi \simeq n_\chi \boldsymbol{V}_{\rm drift} - D_\chi \nabla n_\chi$$

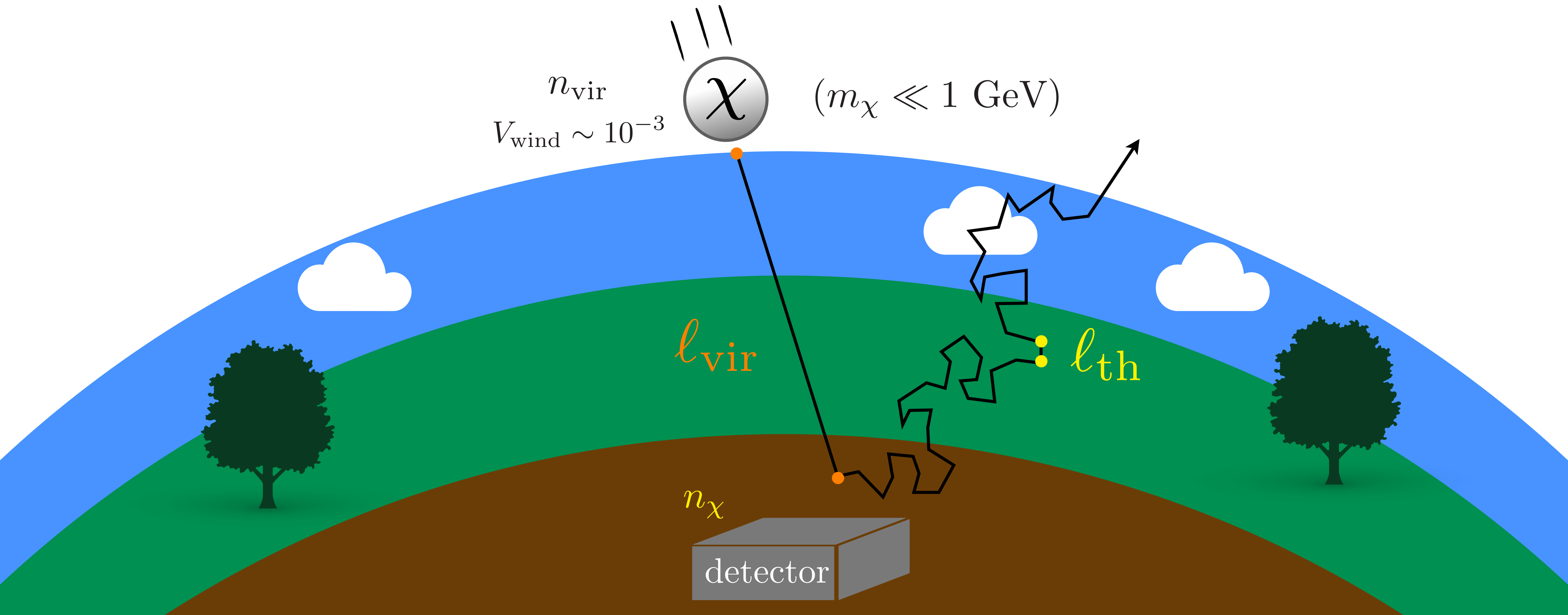
(drift-velocity) $$\boldsymbol{V}_{\rm drift} = \frac{\boldsymbol{g} + (eq_\chi/m_\chi)\,\boldsymbol{E}}{\Gamma_{\rm coll.}}$$ (equivalent to a biased random walk)

(diffusion coefficient) $$D_\chi = \frac{T_\chi}{\Gamma_{\rm coll.}\, m_\chi} \sim \frac{m_\chi}{\mu}\,\ell_{\rm mfp}\, v_{\rm th}$$



Traffic Jam (<< 1 GeV)

light mediator $\Longrightarrow$ enhanced interactions at smaller temperatures



Traffic Jam (<< 1 GeV)

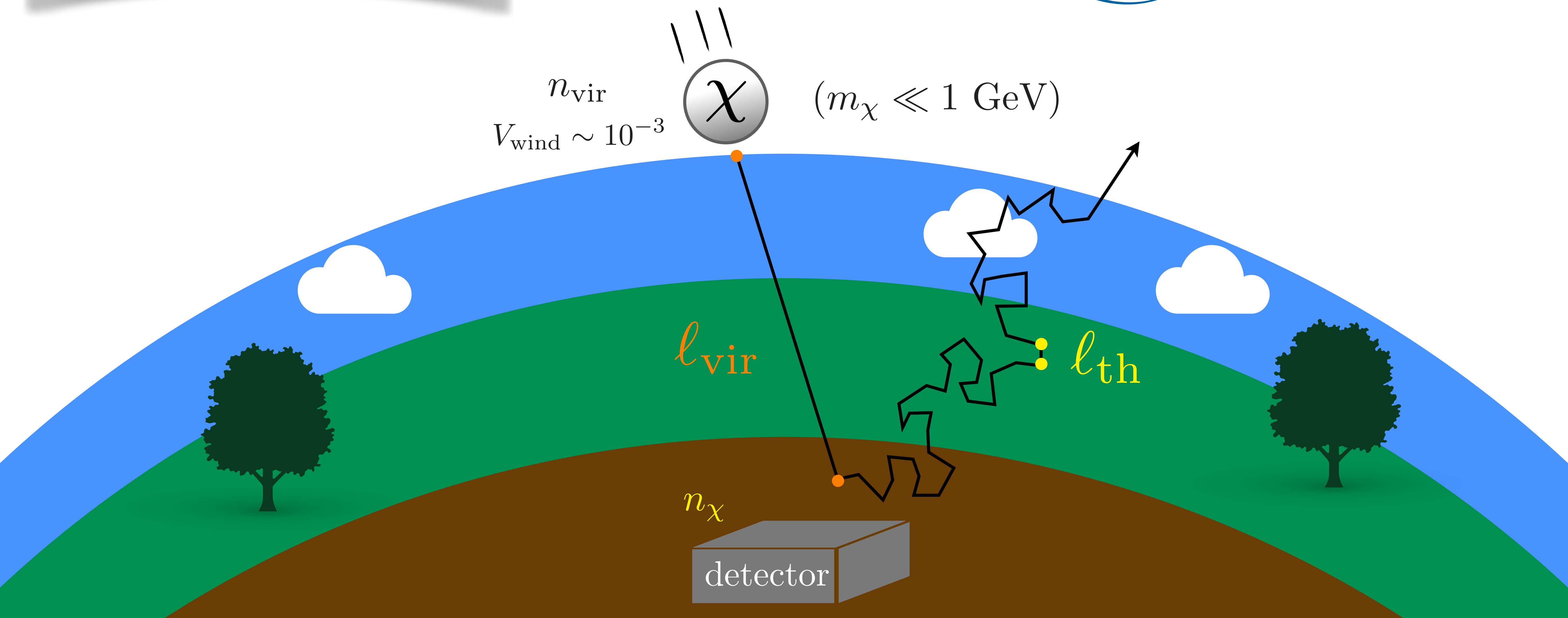
Enter	Exit
$j_{\rm in} \sim n_{\rm vir}\, V_{\rm wind}$	$j_{\rm out} \sim n_\chi\, D_\chi/\ell_{\rm vir} \sim n_\chi\, v_{\rm th}\, (\ell_{\rm th}/\ell_{\rm vir})$

Even in the absence of gravity, large residence time leads to an enhanced terrestrial abundance.

$$j_{\rm in} \sim j_{\rm out} \implies \frac{n_\chi}{n_{\rm vir}} \sim \frac{V_{\rm wind}}{v_{\rm th}} \frac{\ell_{\rm vir}}{\ell_{\rm th}}$$

$\frac{V_{\rm wind}}{v_{\rm th}} \gg 1$ for $m_\chi \gg 10$ keV

$\frac{\ell_{\rm vir}}{\ell_{\rm th}} \gg 1$ for $m_\chi \gg 10$ MeV



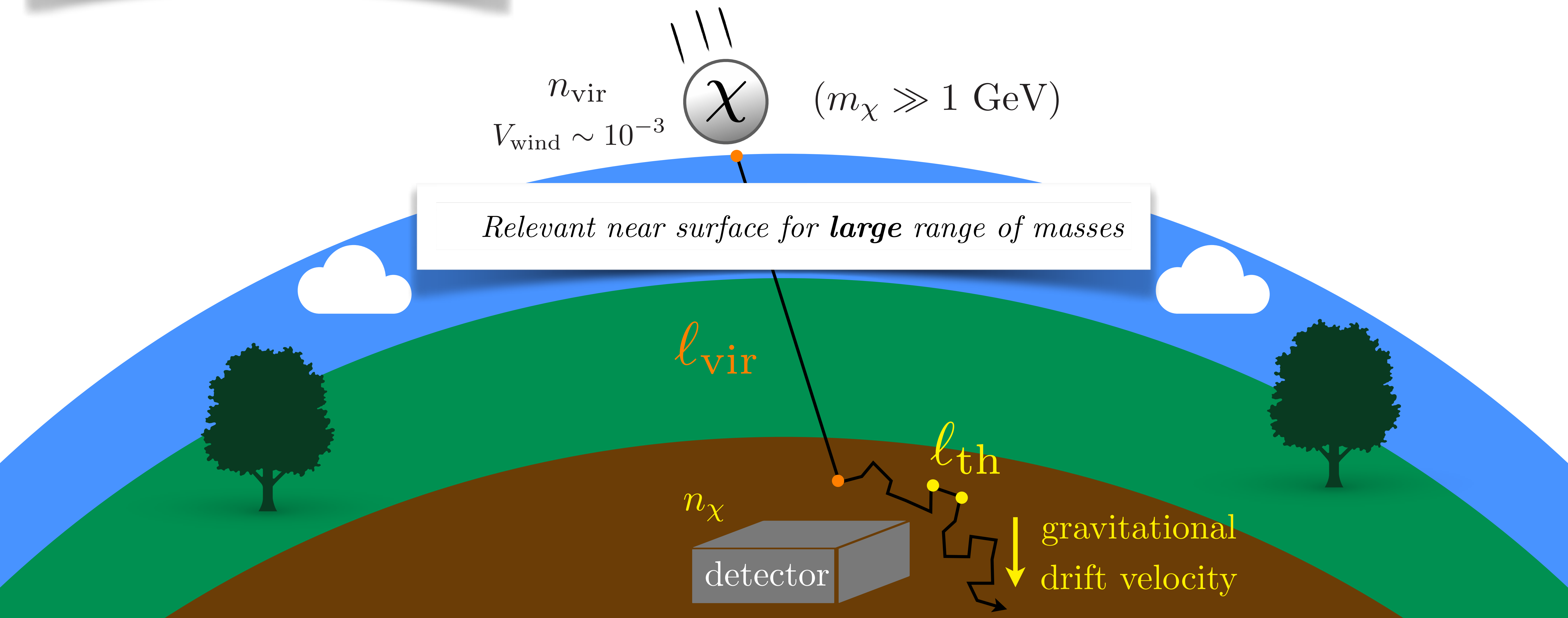
Traffic Jam (>> 1 GeV)

Enter	Exit
$j_{\text{in}} \sim n_{\text{vir}} V_{\text{wind}}$	$j_{\text{out}} \sim n_\chi V_{\text{drift}}$

Slow drift from collisional friction leads to an enhanced terrestrial abundance.

$$j_{\text{in}} \sim j_{\text{out}} \implies \frac{n_\chi}{n_{\text{vir}}} \sim \frac{V_{\text{wind}}}{V_{\text{drift}}}$$

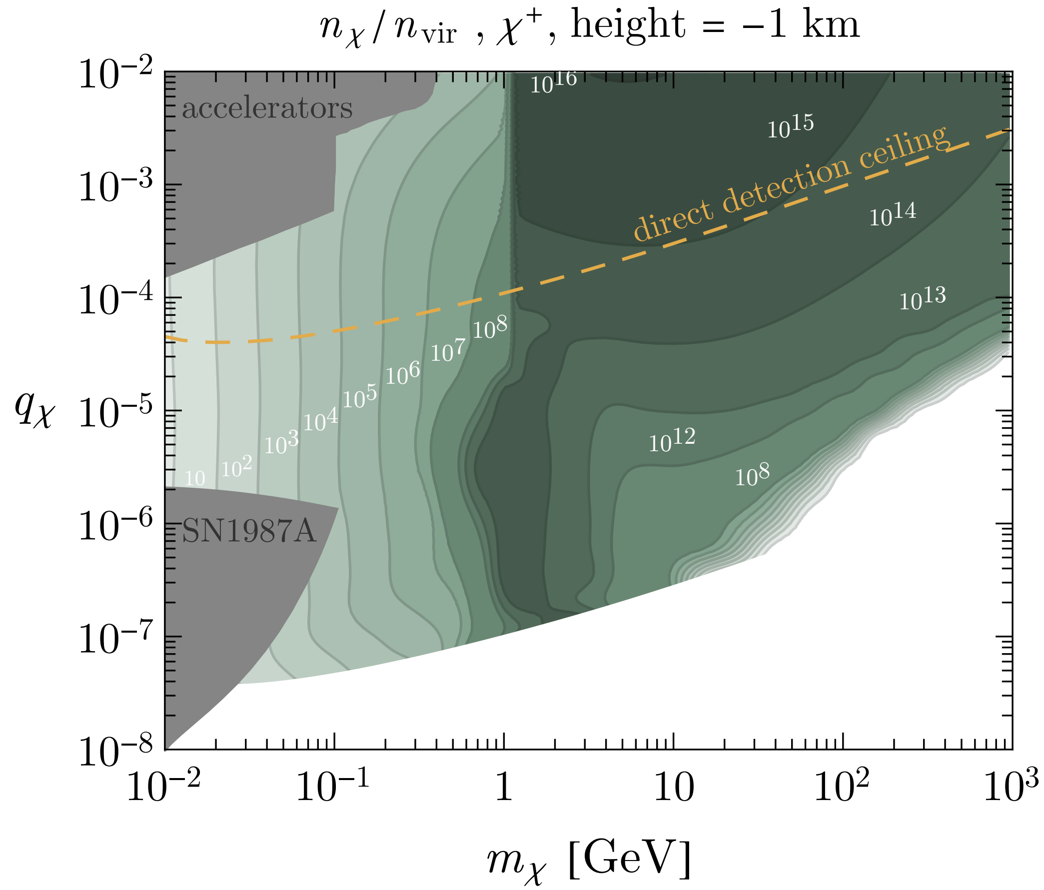
$\gg 1$



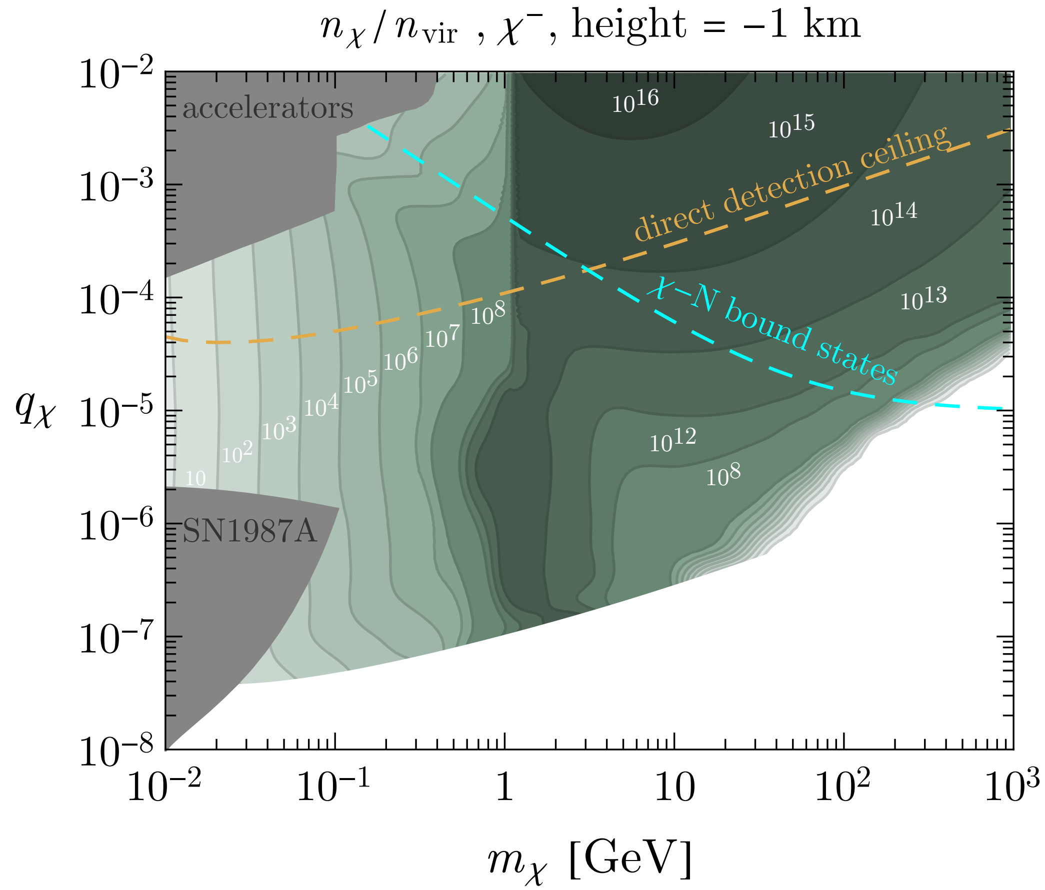
*Relevant near surface for **large** range of masses*

Terrestrial Overdensity

positively-charged



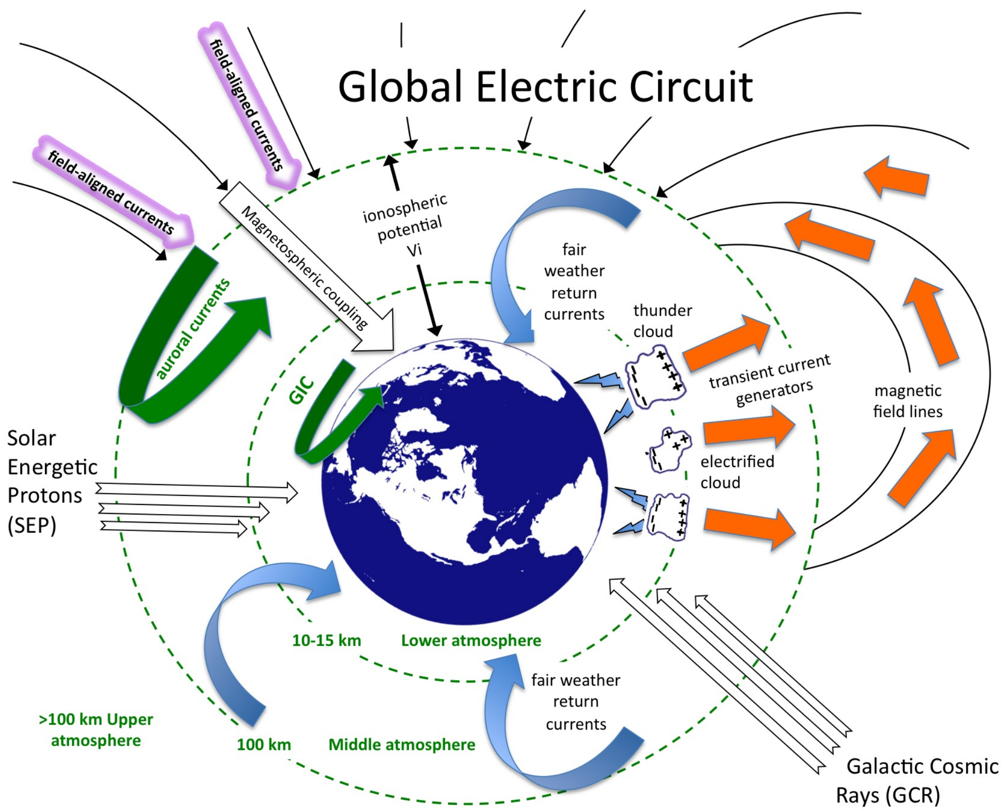
negatively-charged



large terrestrial overdensities (compared to galactic) across a broad range of masses

Terrestrial Overdensity

Local densities can be reduced or enhanced if interaction (set by dark photon's mass) is sufficiently long-ranged



Earth's magnetic and electric fields relevant if:

$(B_\oplus \sim 0.5\ \mathrm{G}\ ,\ \Delta V_\oplus \sim 0.5\ \mathrm{MV})$

$$r_{\mathrm{gyro}} \sim \frac{m_\chi\, v_{\mathrm{vir}}}{e q_\chi\, B_\oplus} \lesssim R_\oplus \implies q_\chi \gtrsim 10^{-8} \times (m_\chi/\mathrm{MeV})$$

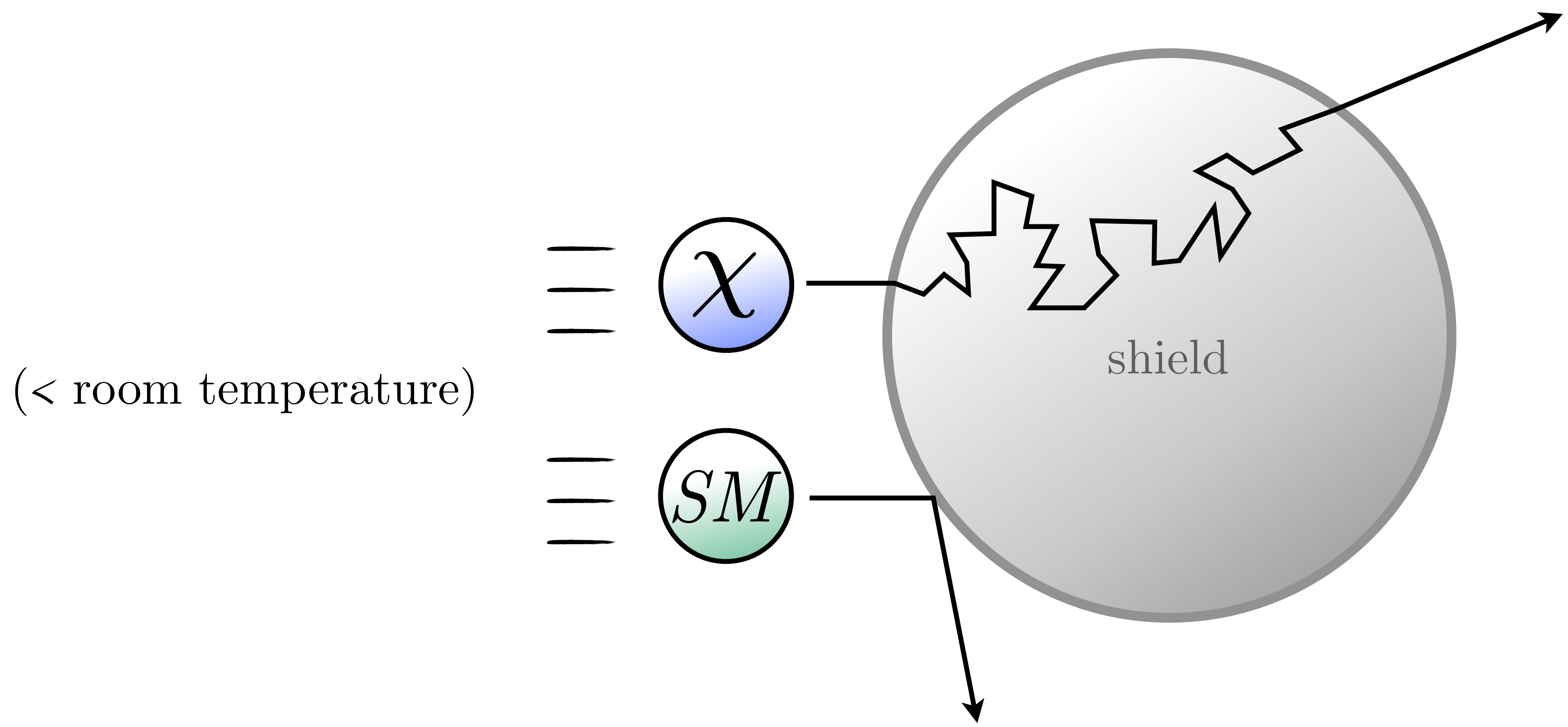
$$300\ \mathrm{K} \sim e q_\chi \times \Delta V_\oplus \implies q_\chi \gtrsim 10^{-7}$$

Parametrize ignorance by focusing on sensitivity to local density, n_χ

Terrestrial Detection

How do you detect this terrestrial population?

distinguishing feature = penetrates shields



Terrestrial Detection

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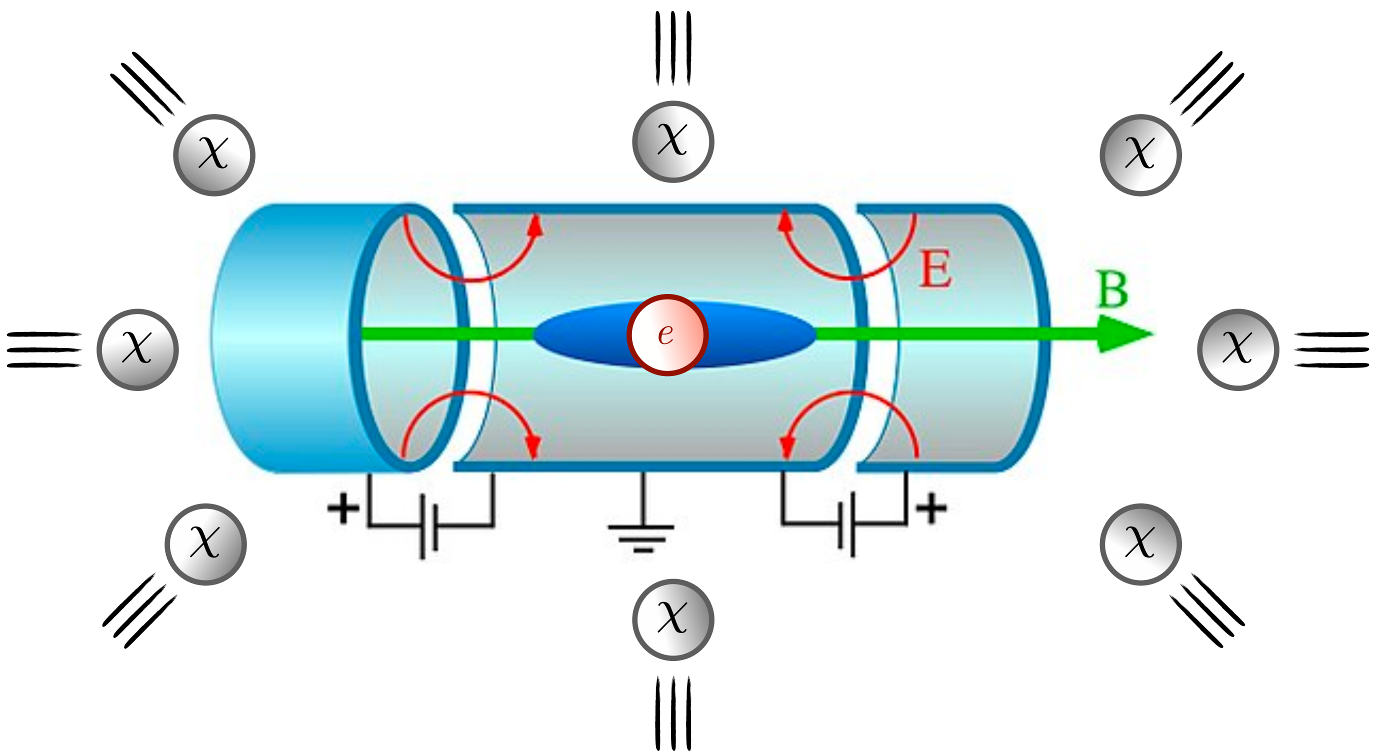
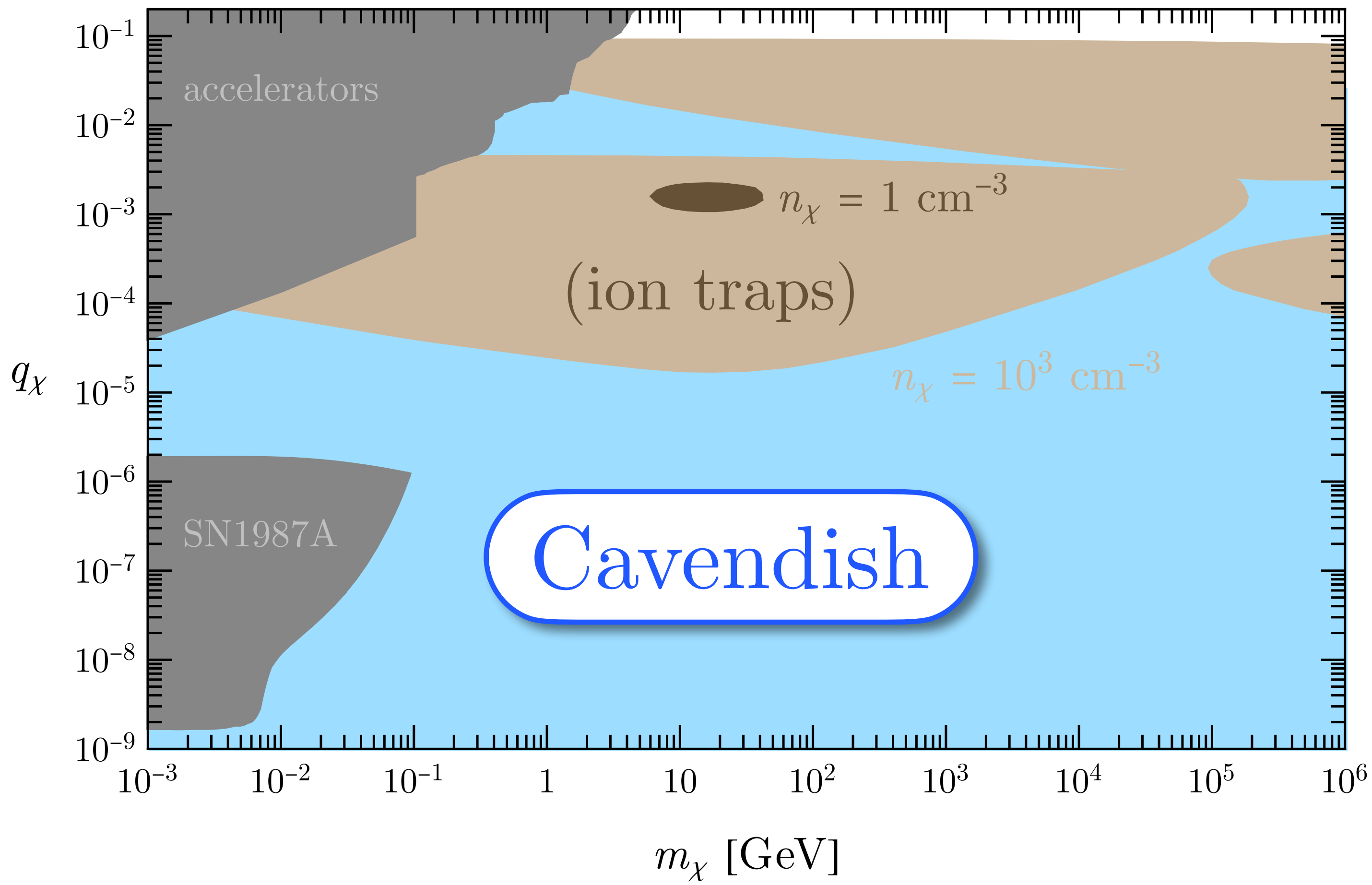


e.g., anomalous heating of cold ions

Carney, Häffner, Moore, Taylor, arXiv:2104.05737
Budker, Graham, Ramani, Schmidt-Kaler, Smorra, Ulmer, arXiv:2108.05283

Terrestrial Detection



collective effects

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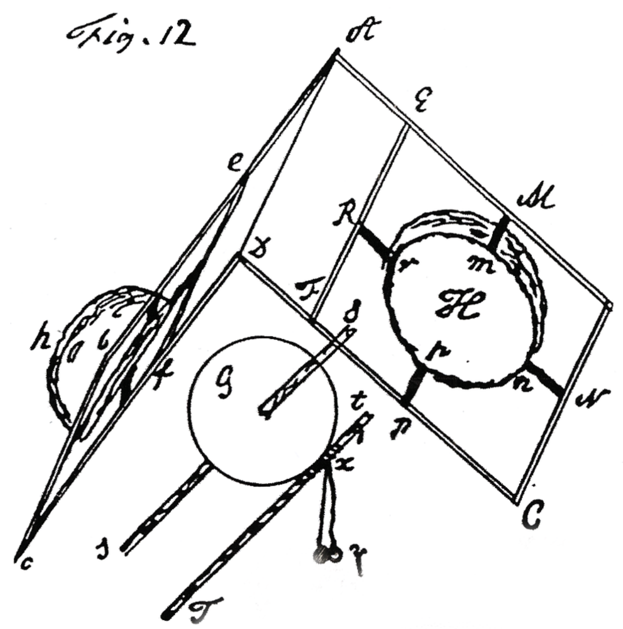
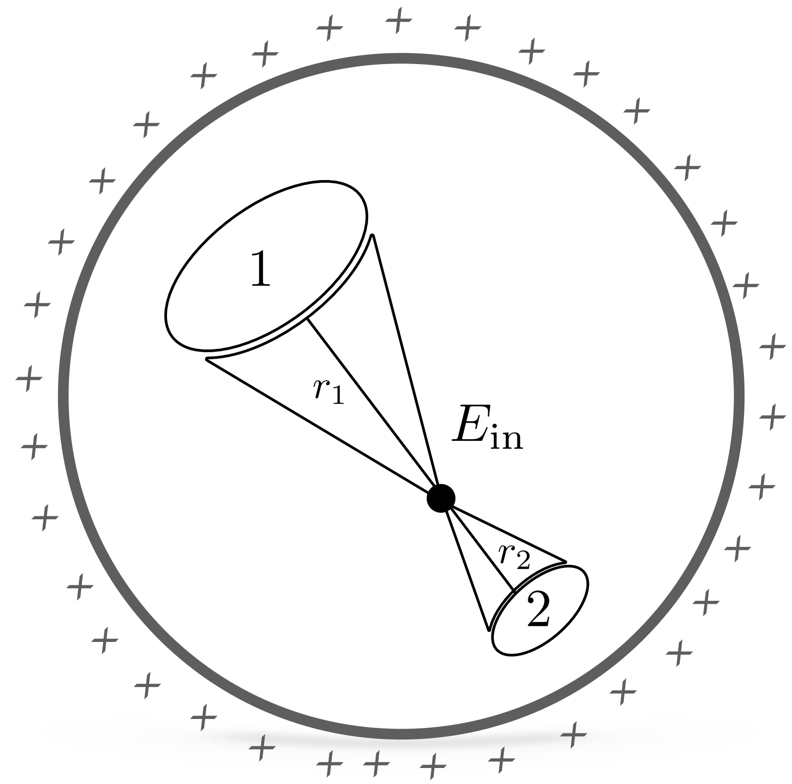


AB, Zach Bogorad, Peter Graham, Hari Ramani (in progress)

Coulomb's Law

Coulomb's Law ⟹ zero field inside charged shell

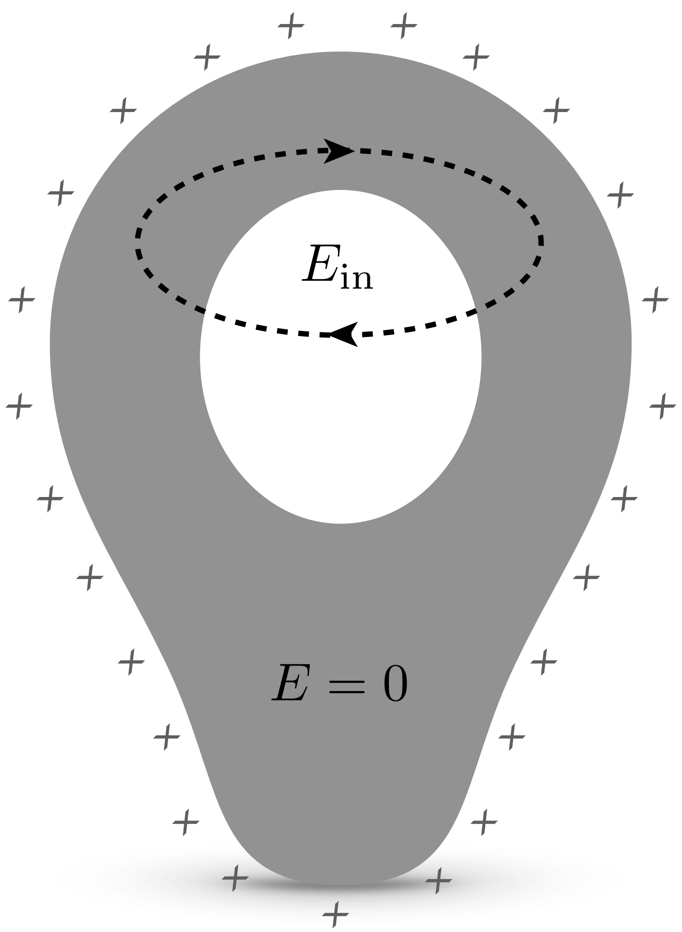


empty shell of uniform surface charge

$$\frac{q_1}{q_2} = \frac{A_1}{A_2} = \frac{r_1^2}{r_2^2} \implies \frac{E_1}{E_2} = \frac{q_1/r_1^2}{q_2/r_2^2} = 1 \implies E_{\text{in}} = 0$$

Coulomb's Law

Coulomb's Law ⟹ zero field inside charged shell



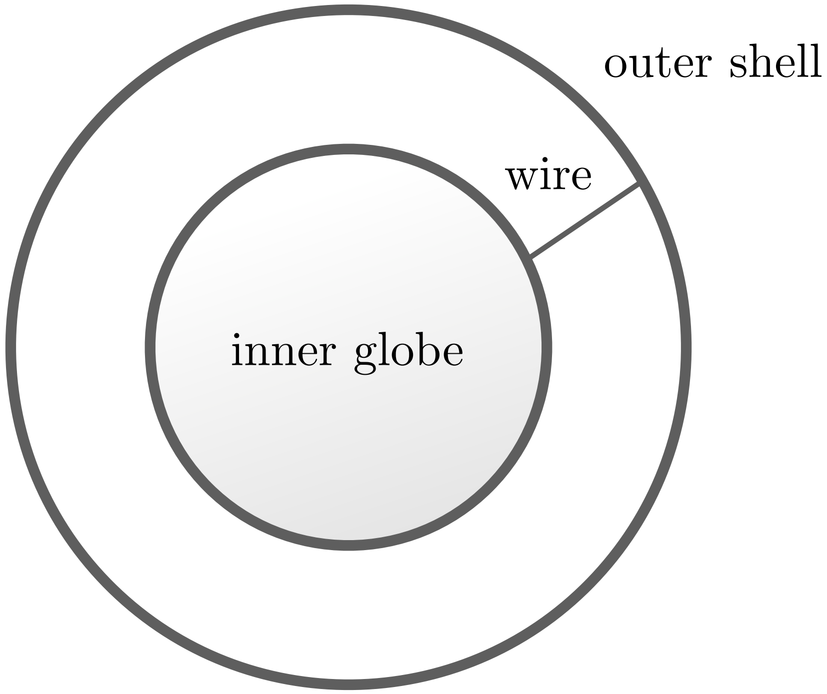
empty shell of any shape

$$\oint d\boldsymbol{\ell} \cdot \mathbf{E} = 0 \implies E_{\text{in}} = 0$$

systematics are reduced by comparing to zero

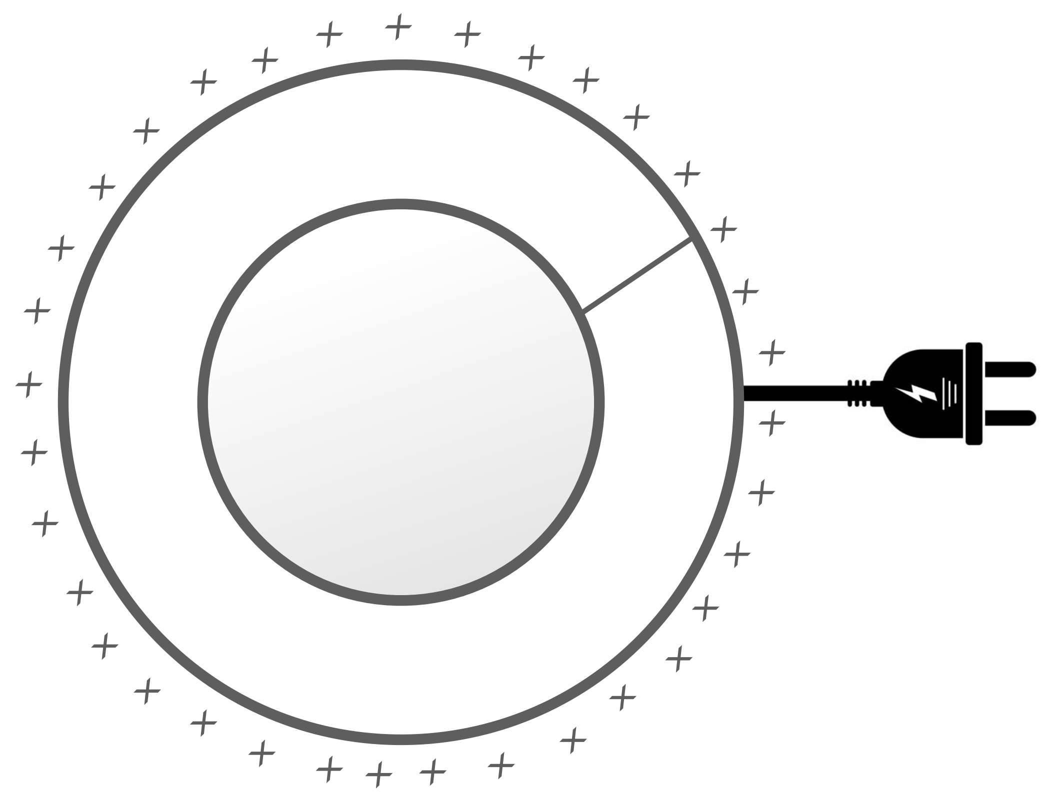
Cavendish

Cavendish ~1773



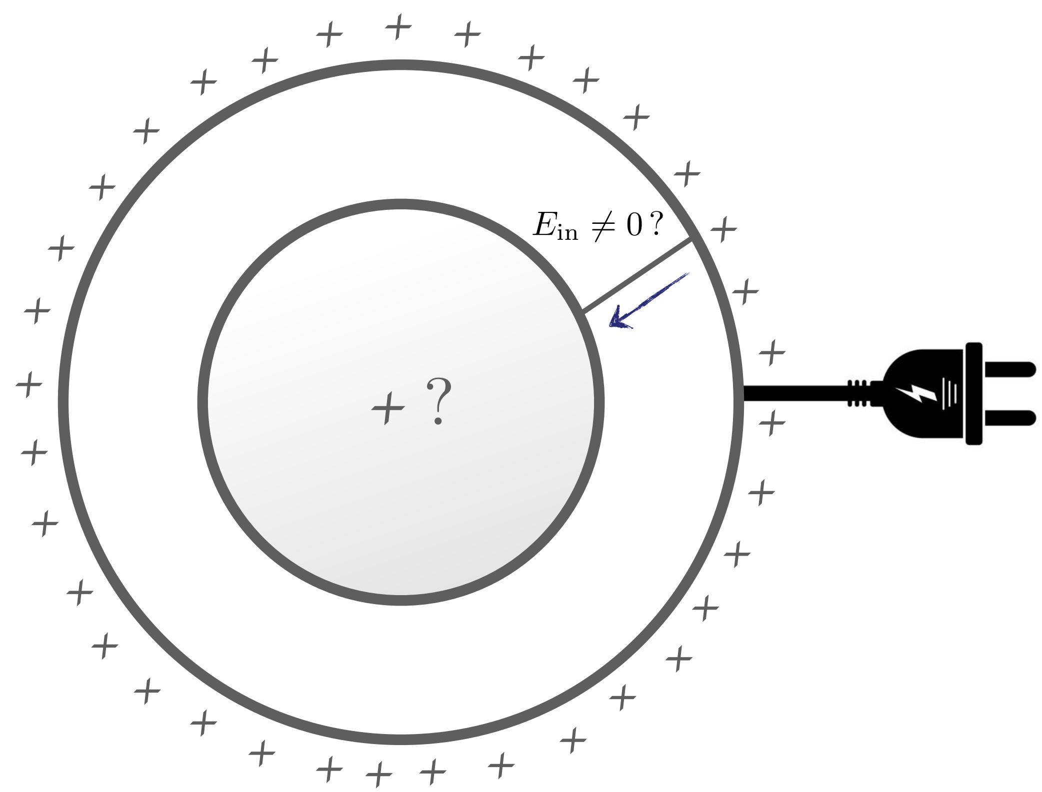
Cavendish

Cavendish ~1773



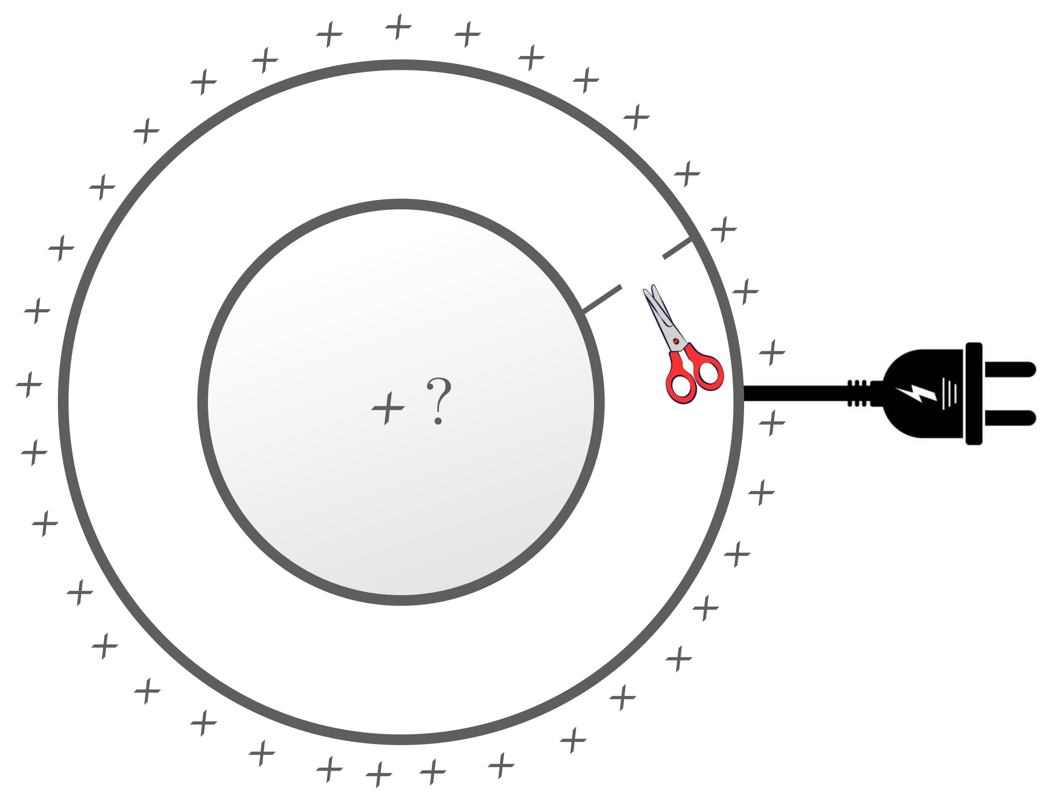
Cavendish

Cavendish ~1773



Cavendish

Cavendish ~1773



Cavendish

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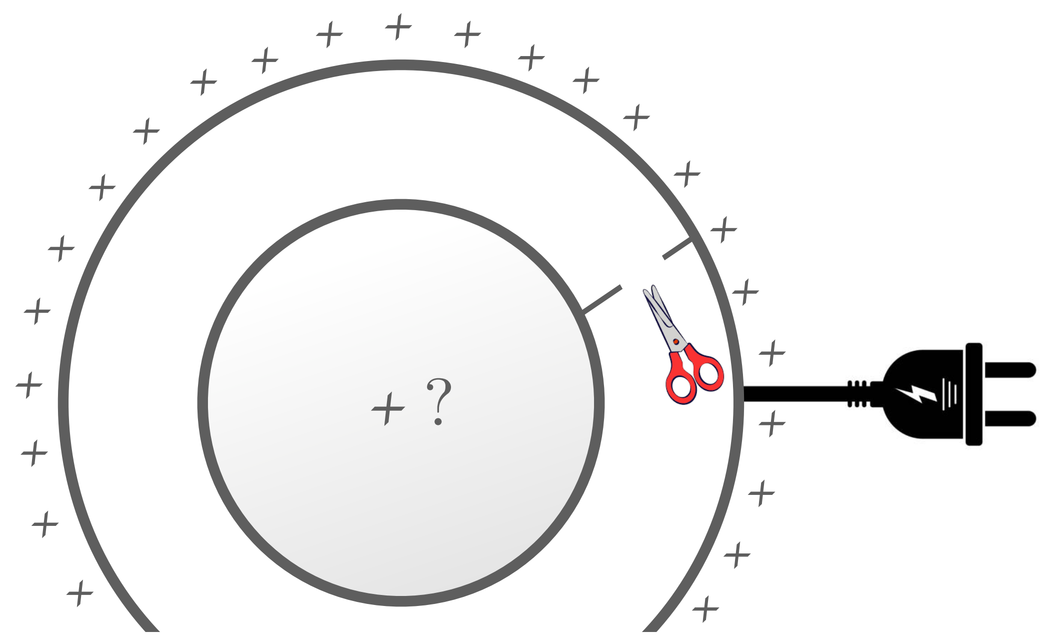

Cavendish

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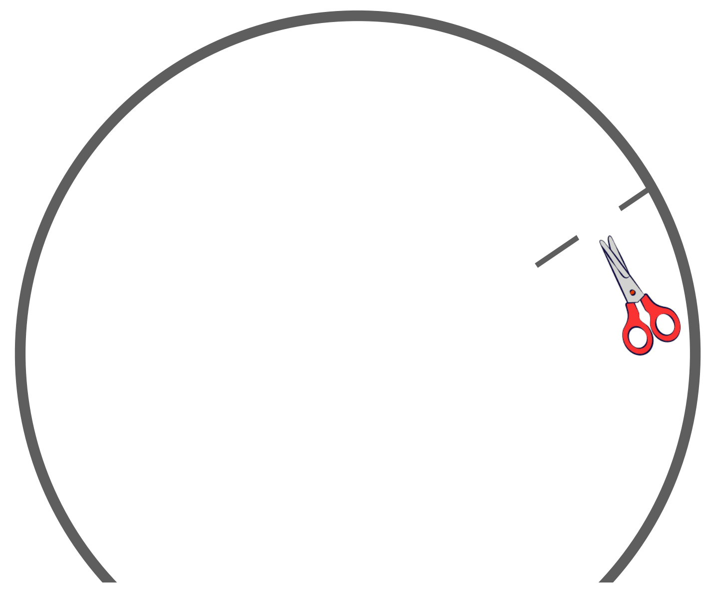
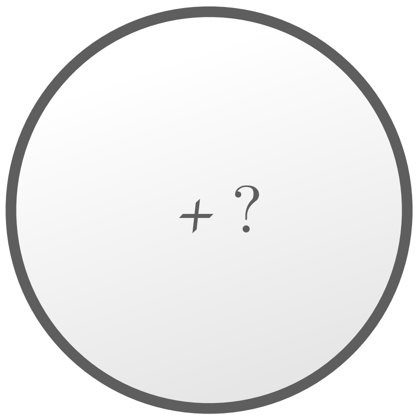
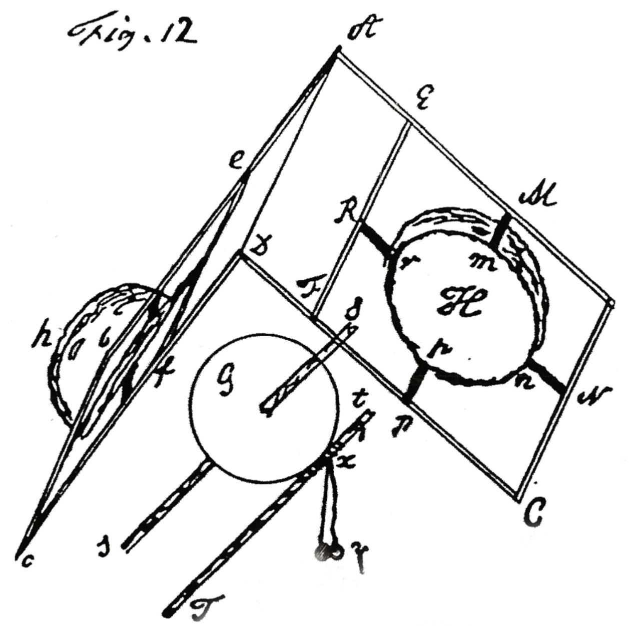




Cavendish

Cavendish ~1773

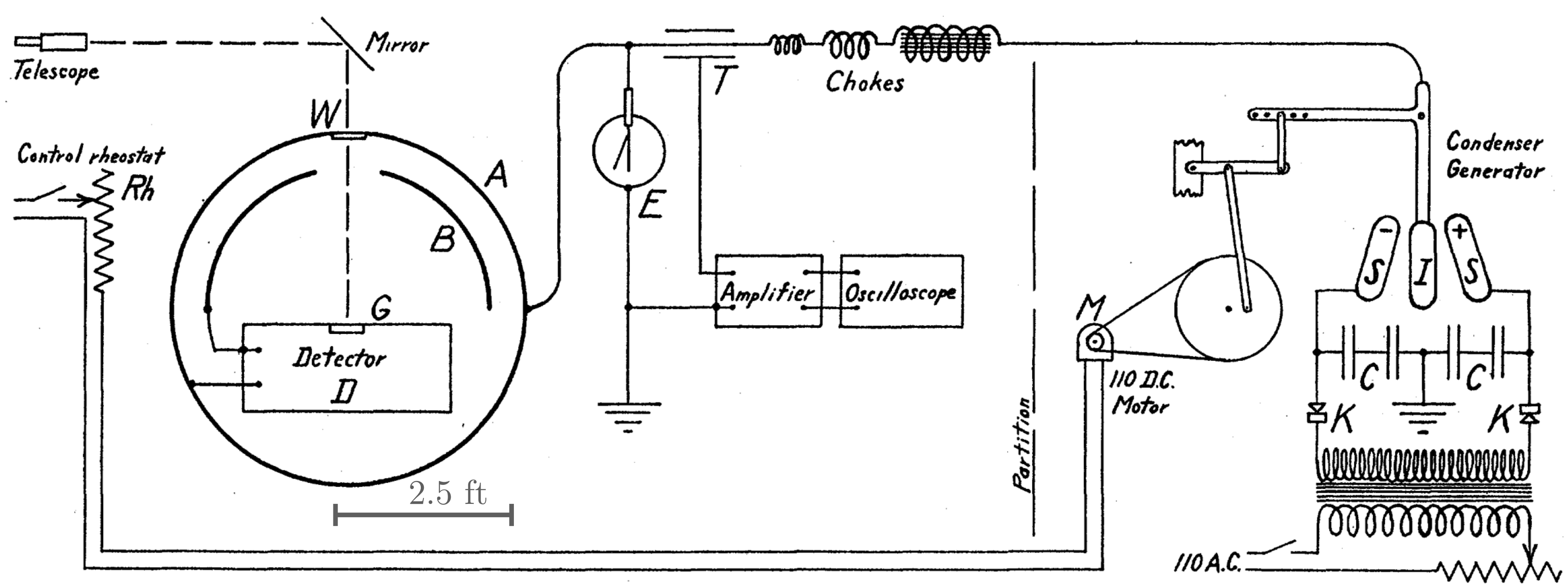


(limited by systematic noise)

$$E \propto r^{-2\,(1\pm 10^{-2})}$$

Plimpton and Lawton

Plimpton and Lawton ~1936

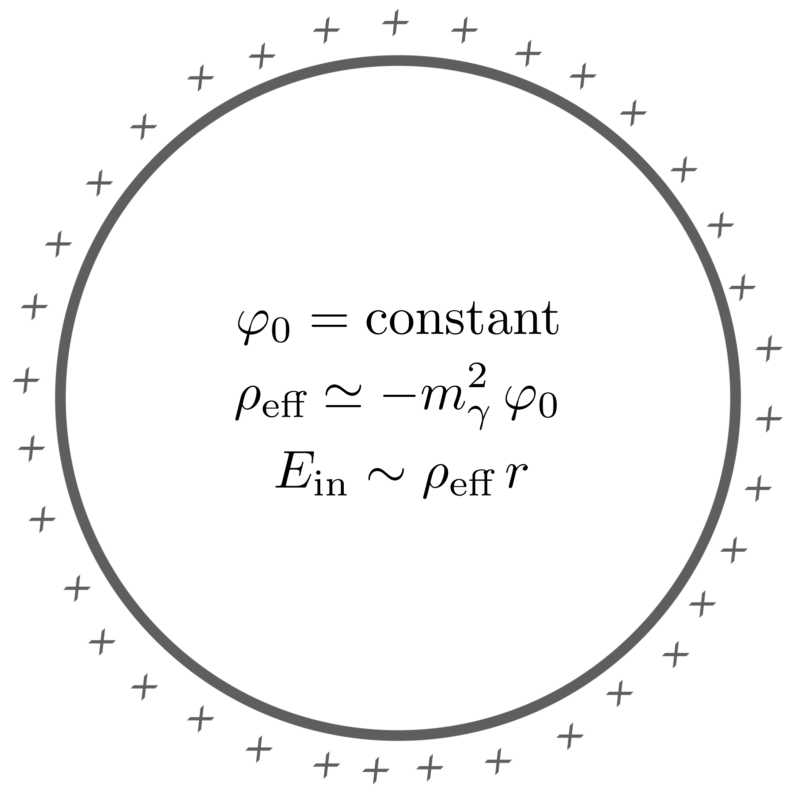


voltage $\varphi_0 \sim 3$ kV driven at frequency $\nu_0 \sim 2$ Hz

limited by thermal fluctuations $\Delta\varphi_{\rm shells} \sim 10^{-6}$ V

$$E \propto r^{-2\,(1 \pm 10^{-9})}$$

Photon Mass

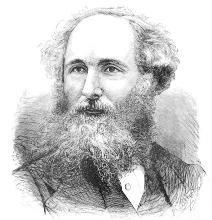


non-zero photon mass

$$\varphi \propto \frac{e^{-m_\gamma r}}{r} \quad , \quad \nabla \cdot \mathbf{E} = \rho - m_\gamma^2\, \varphi$$

Cavendish

Historical Summary



	1773	**1873**	**1936**	**1967**	**1971**
	Cavendish	Maxwell	Plimpton & Lawton	Cochran & Franken	Williams et al.
freq.	$\ll$ Hz	$\ll$ Hz	$\sim$ Hz	$\sim$ kHz	$\sim$ MHz
$\boldsymbol{r^{-2(1\pm n)}}$	$\sim 10^{-2}$	$\sim 10^{-4}$	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-16}$
$\boldsymbol{m_\gamma}$ **[eV]**	$\sim 10^{-7}$	$\sim 10^{-8}$	$\sim 10^{-11}$	$\sim 10^{-12}$	$\sim 10^{-14}$

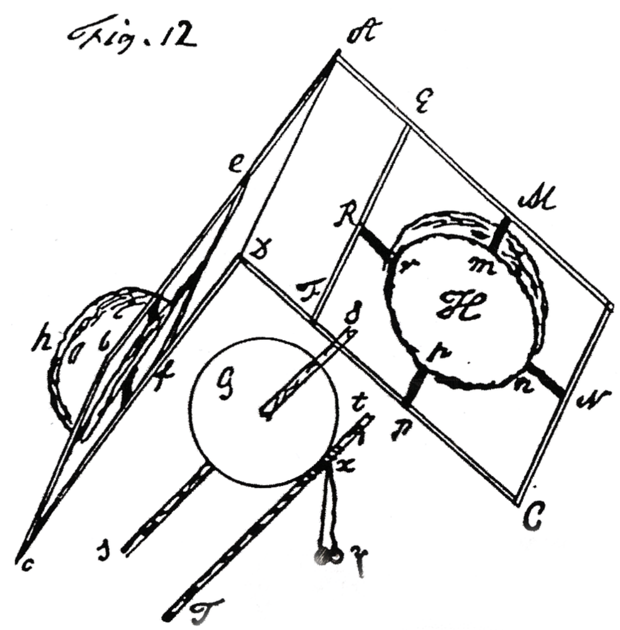
higher frequency/lower noise →

Ideal for slowly saturating signals (e.g., penetrating millicharges)

Cavendish + Millicharges

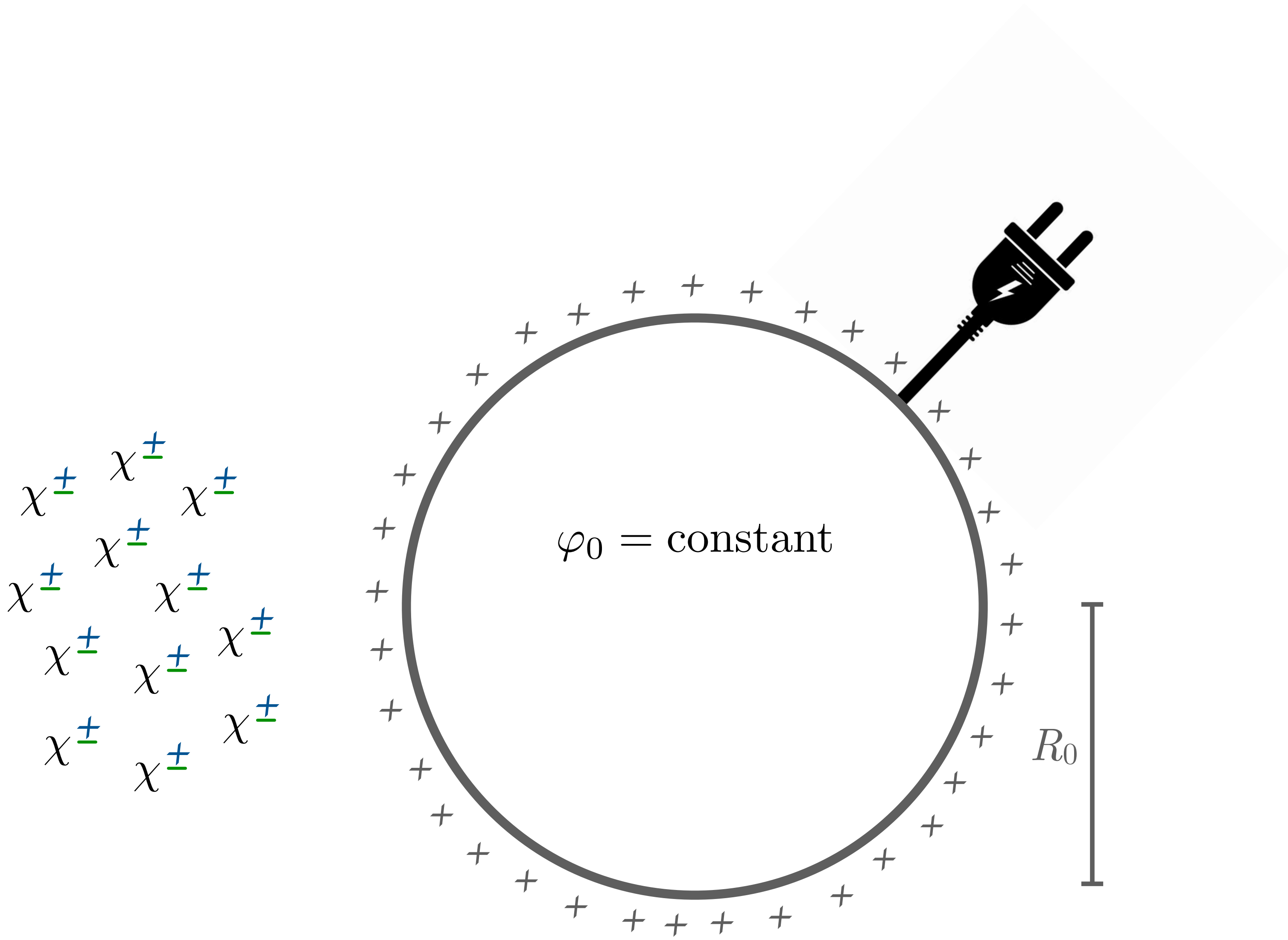
Recap

Large over terrestrial overdensity of cold (300 K) millicharges



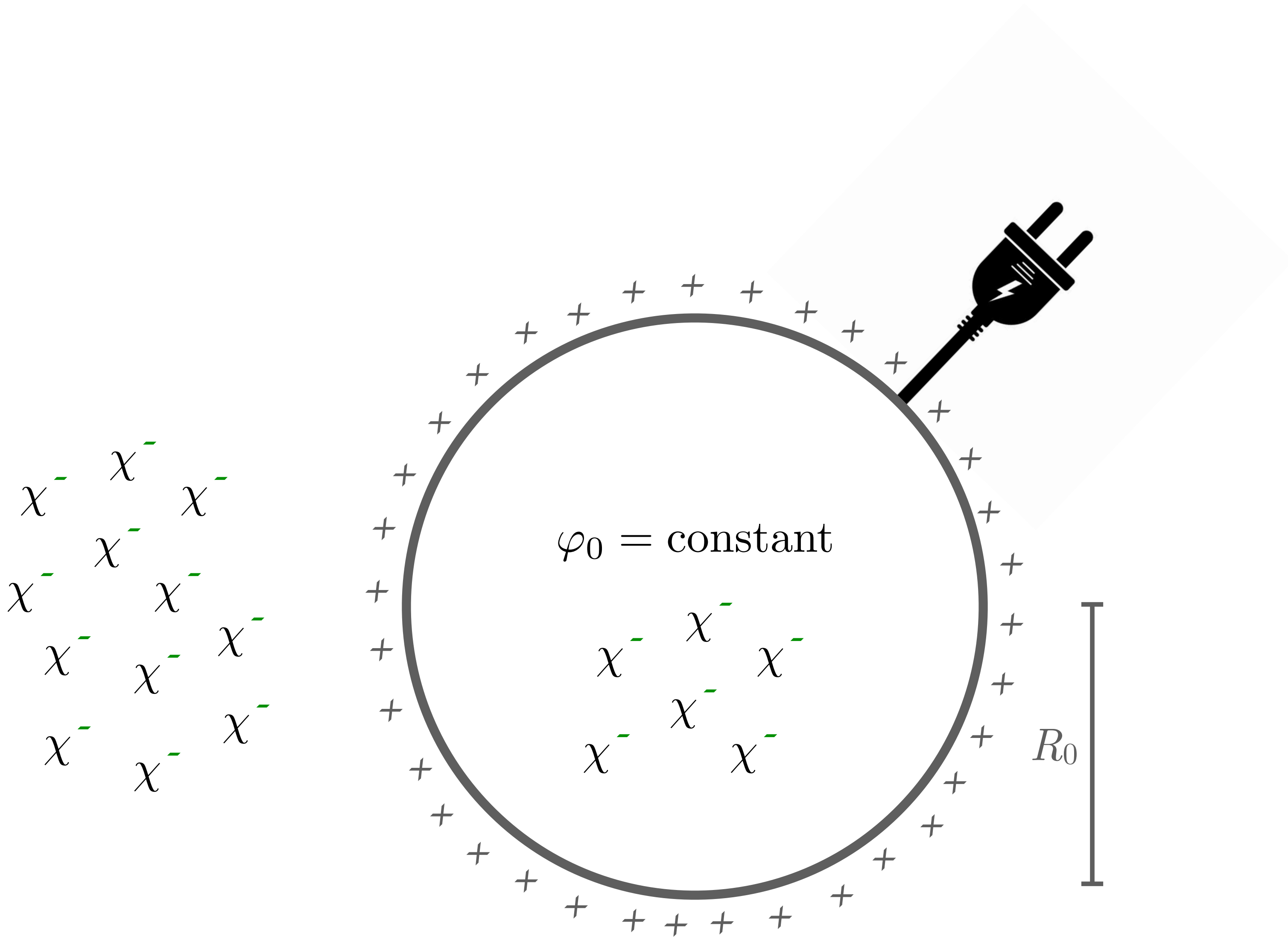
Precise tests of Coulomb's Law/ Gauss's Law/photon mass

Cavendish + Millicharges



permeating plasma

Cavendish + Millicharges



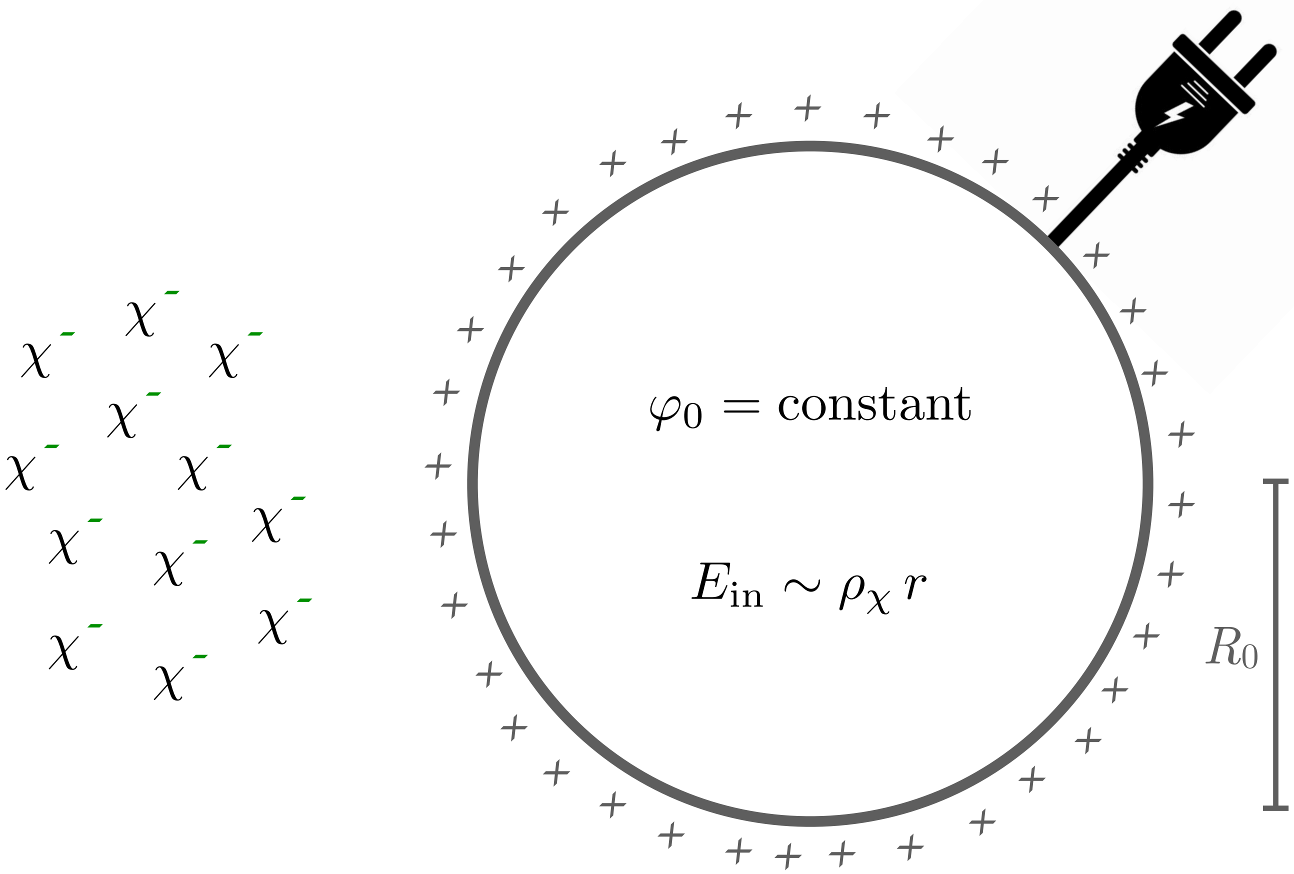
permeating plasma

millicharges discharge the shell

Cavendish + Millicharges

weak coupling

$eq_\chi \, \varphi_0 \ll T_\chi$



<u>permeating plasma</u>

(equilibrium)

$$\rho_\chi \simeq e q_\chi \, (n_\chi/2) \left(e^{-eq_\chi \varphi_0/T_\chi} - e^{eq_\chi \varphi_0/T_\chi} \right)$$

$$\rho_\chi \simeq -\frac{(eq_\chi)^2 \, n_\chi}{T_\chi} \, \varphi_0 \equiv -m_D^2 \, \varphi_0$$

(enhancement)

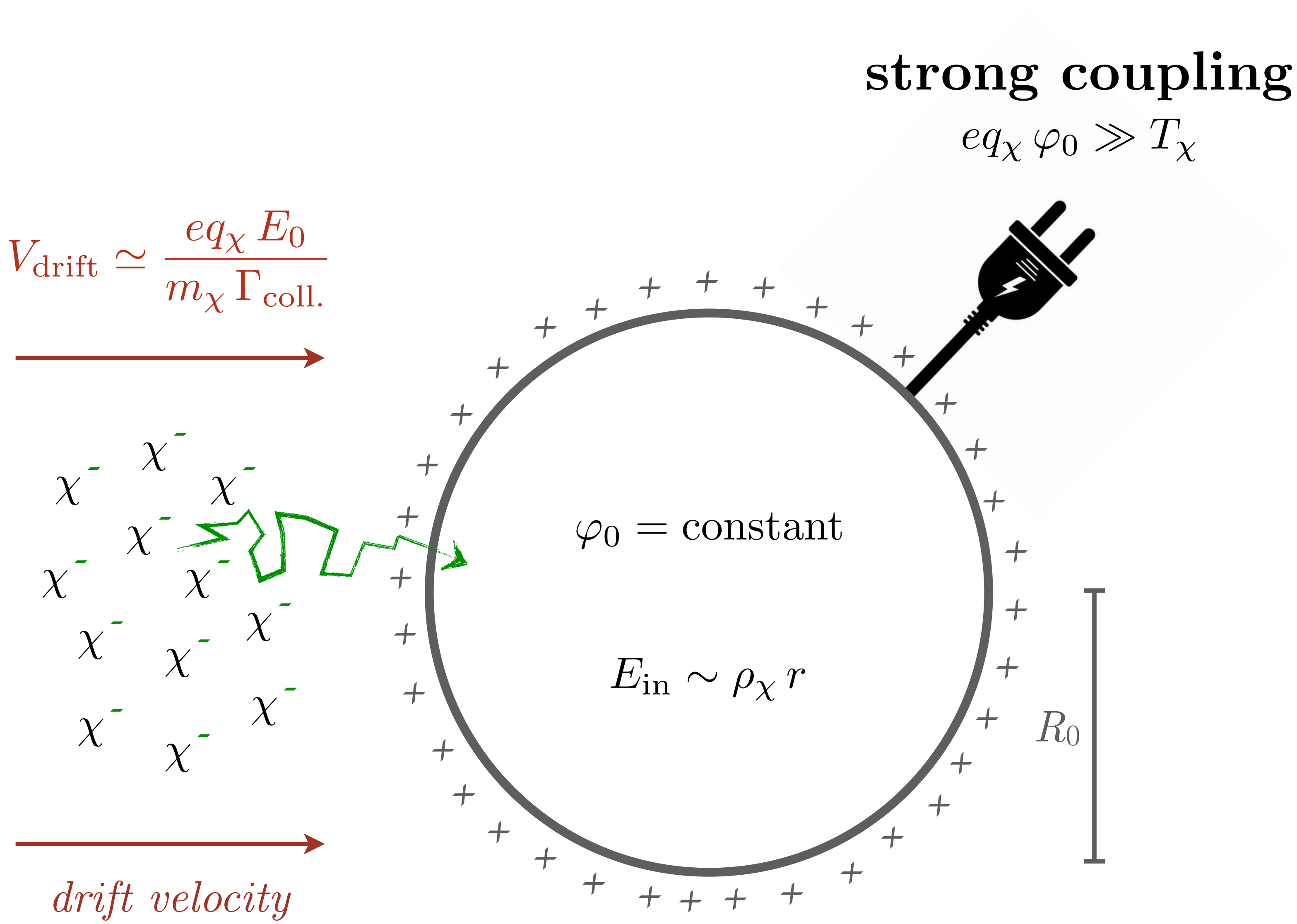
Debye mass

$m_\gamma \leftrightarrow m_D$

Analogous to photon mass

Generally holds for weakly-coupled plasma

Cavendish + Millicharges



permeating plasma

(accumulation)

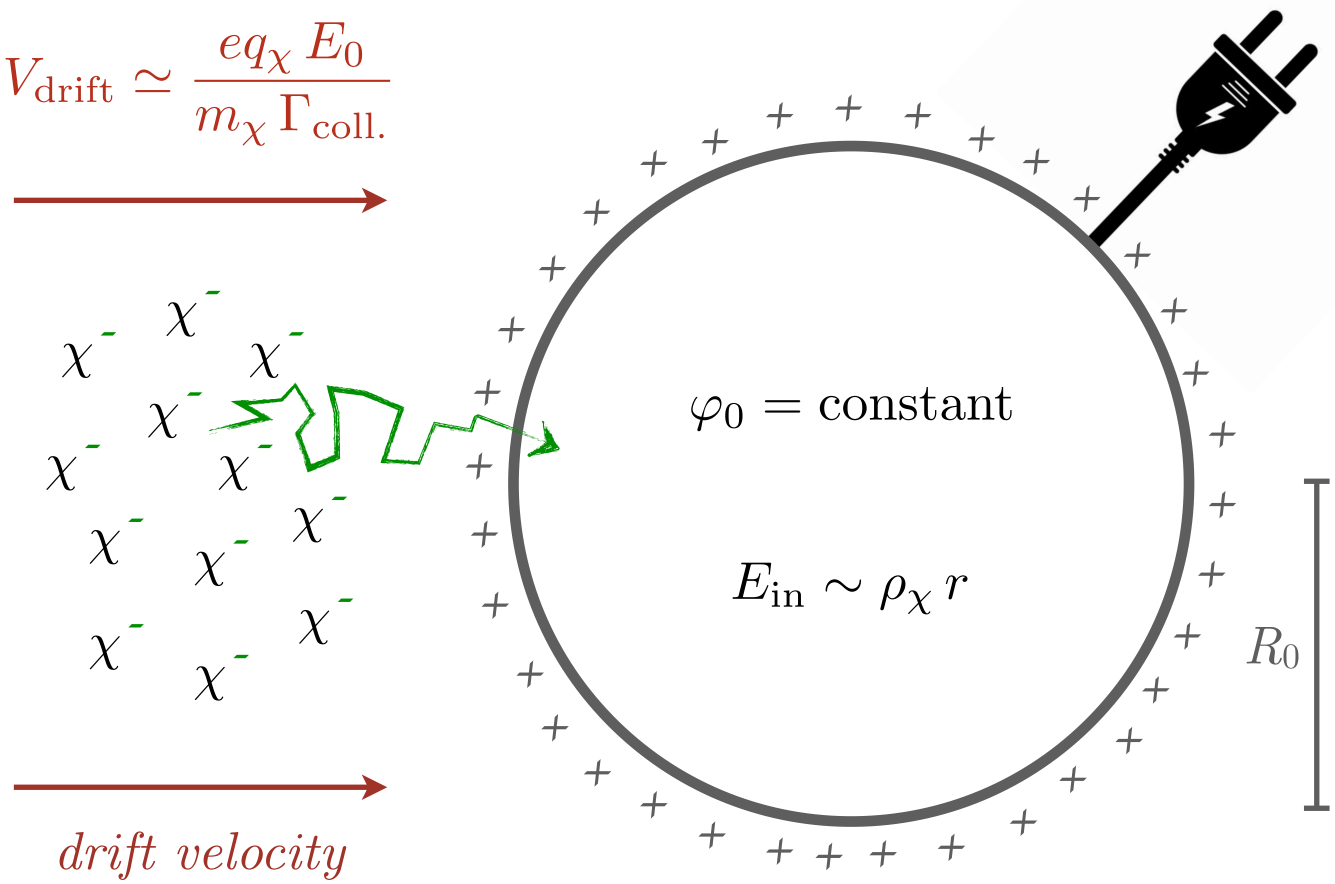
Millicharges "thermalize" and remain electrically bound

Cavendish + Millicharges

strong coupling

$e q_\chi \, \varphi_0 \gg T_\chi$

$$V_{\rm drift} \simeq \frac{e q_\chi \, E_0}{m_\chi \, \Gamma_{\rm coll.}}$$



<u>permeating plasma</u>

(accumulation)

$$\rho_\chi \sim -m_D^2 \, \varphi_0 \times \frac{t}{R_0^2 / D_\chi}$$

$$\text{diffusion coefficient } D_\chi \sim \frac{T_\chi}{m_\chi \, \Gamma_{\rm coll.}} \sim \ell_{\rm mfp} \, v_{\rm th}$$

what sets t ?

$m_\gamma \leftrightarrow m_D \times$ enhancement

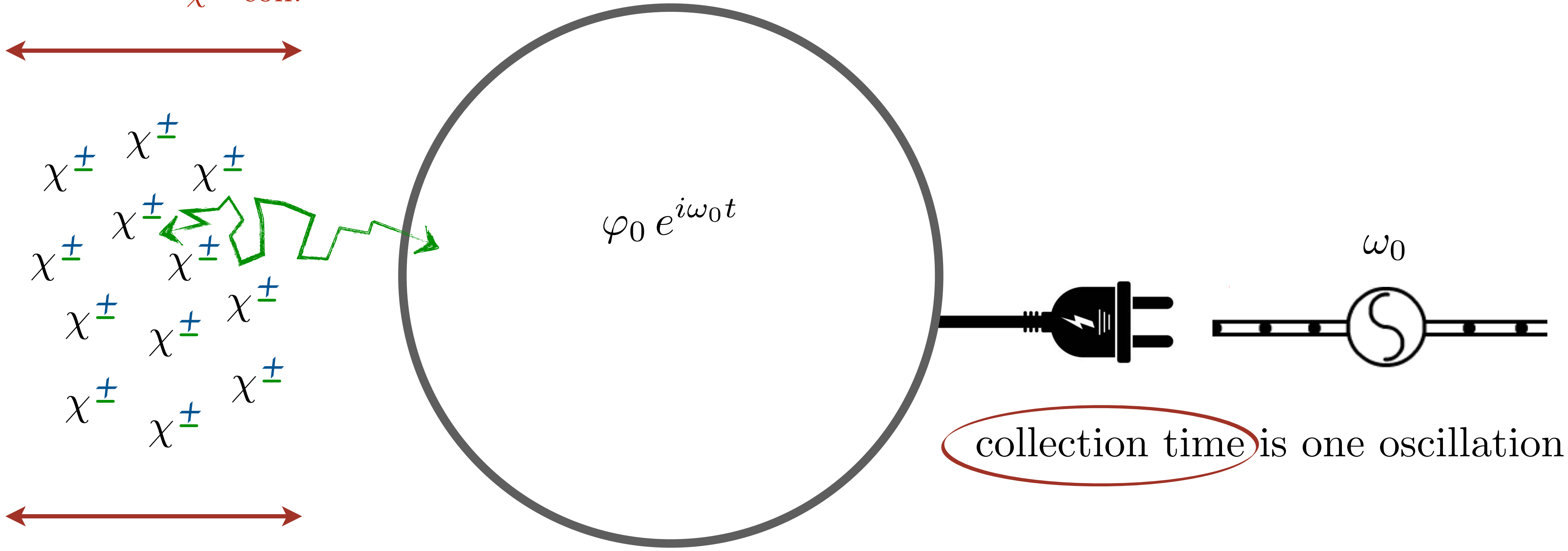
Analogous to photon mass,
but enhanced by (collection time / diffusion time)$^{1/2}$

Cavendish + Millicharges

strong coupling

$eq_\chi \varphi_0 \gg T_\chi$

$V_{\text{drift}} \simeq \dfrac{eq_\chi E_0}{m_\chi \Gamma_{\text{coll.}}}$

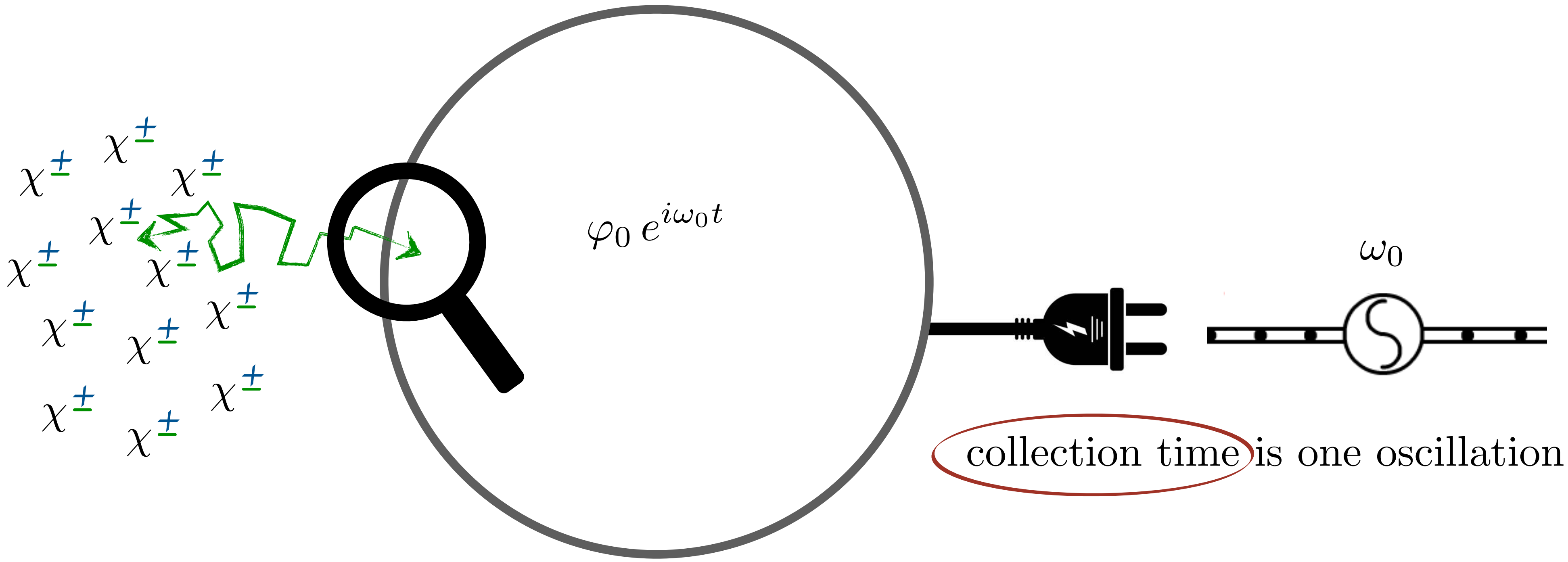


collection time is one oscillation time, $t \sim \omega_0^{-1}$

$m_\gamma \leftrightarrow m_D \times$ enhancement

Analogous to photon mass,
but enhanced by (collection time / diffusion time)$^{1/2}$

Cavendish + Millicharges



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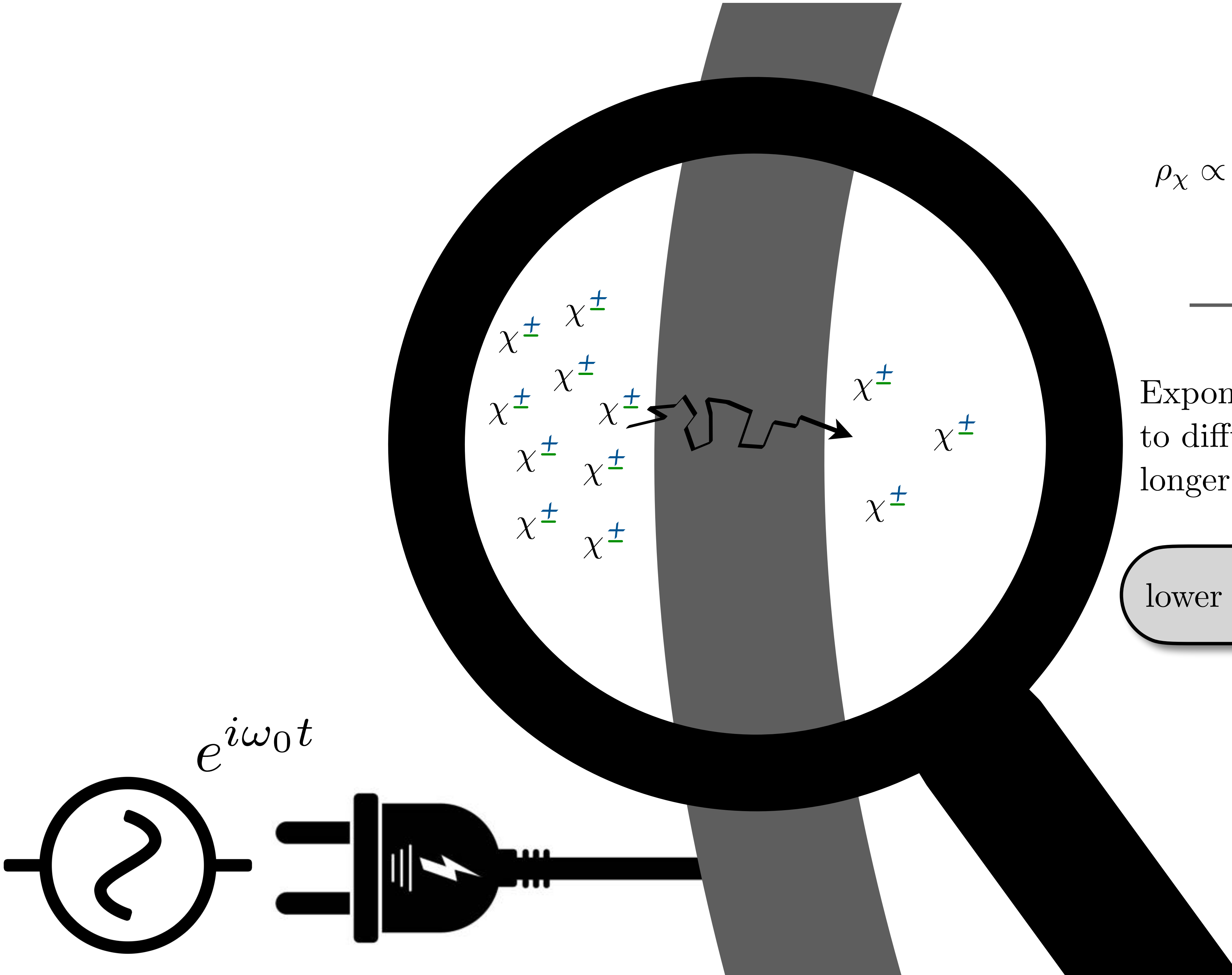


$$\rho_\chi \propto \exp\left(- \sqrt{\frac{x^2/2D_\chi}{\omega_0^{-1}}} \right)$$

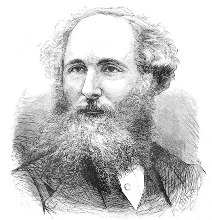
$\longrightarrow +x$

Exponentially suppressed if time to diffuse through experiment is longer than oscillation time

lower frequency preferred

Cavendish + Millicharges

Historical Summary



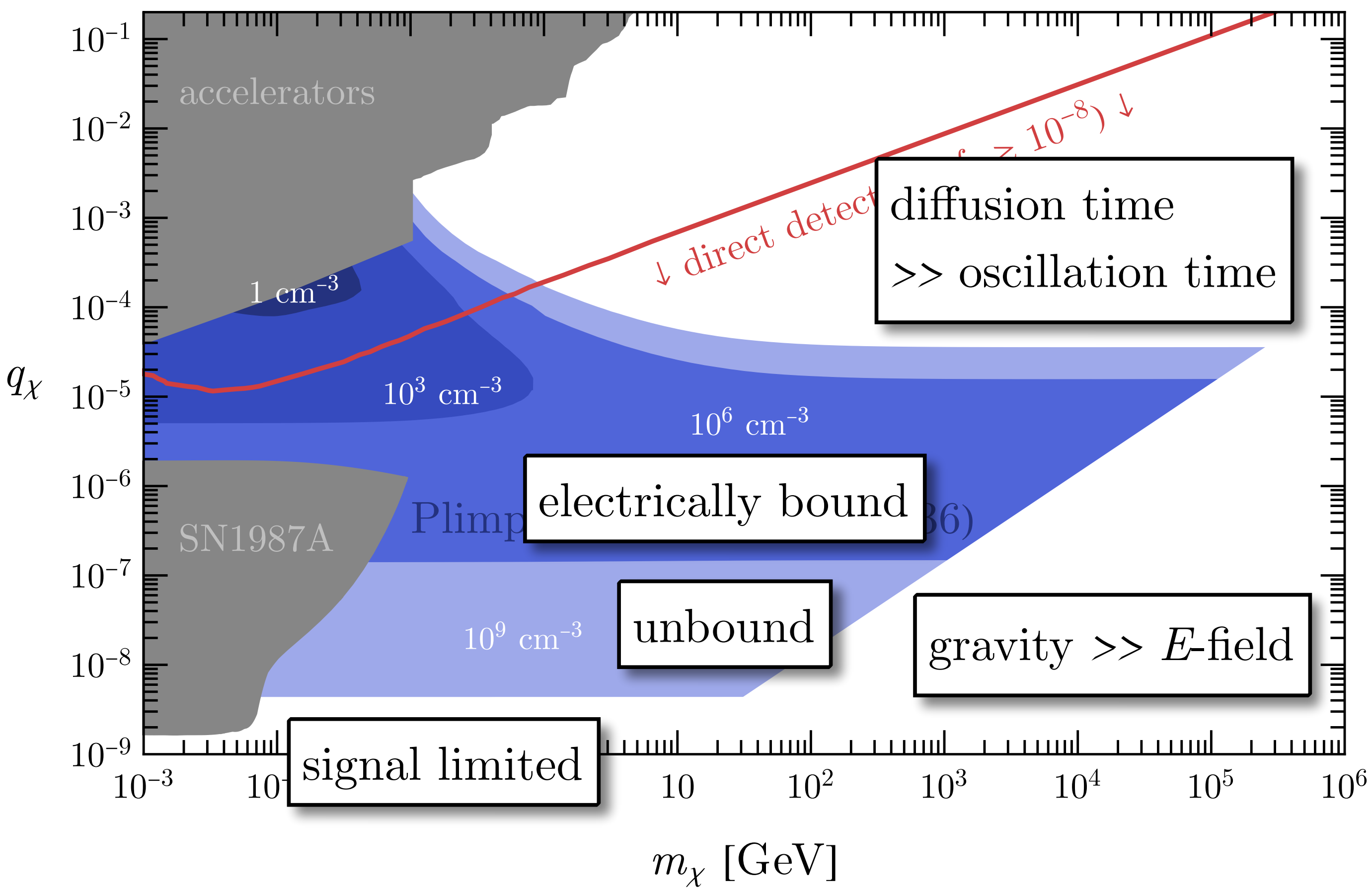
	1773	**1873**	**1936**	**1967**	**1971**
	Cavendish	Maxwell	Plimpton & Lawton	Cochran & Franken	Williams et al.
freq.	$\ll$ Hz	$\ll$ Hz	$\sim$ Hz	$\sim$ kHz	$\sim$ MHz
$\boldsymbol{r^{-2(1\pm n)}}$	$\sim 10^{-2}$	$\sim 10^{-4}$	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-16}$
$\boldsymbol{m_\gamma}$ **[eV]**	$\sim 10^{-7}$	$\sim 10^{-8}$	$\sim 10^{-11}$	$\sim 10^{-12}$	$\sim 10^{-14}$

higher frequency/lower noise →

$Q_{\rm sig} \sim 10^3\, e$

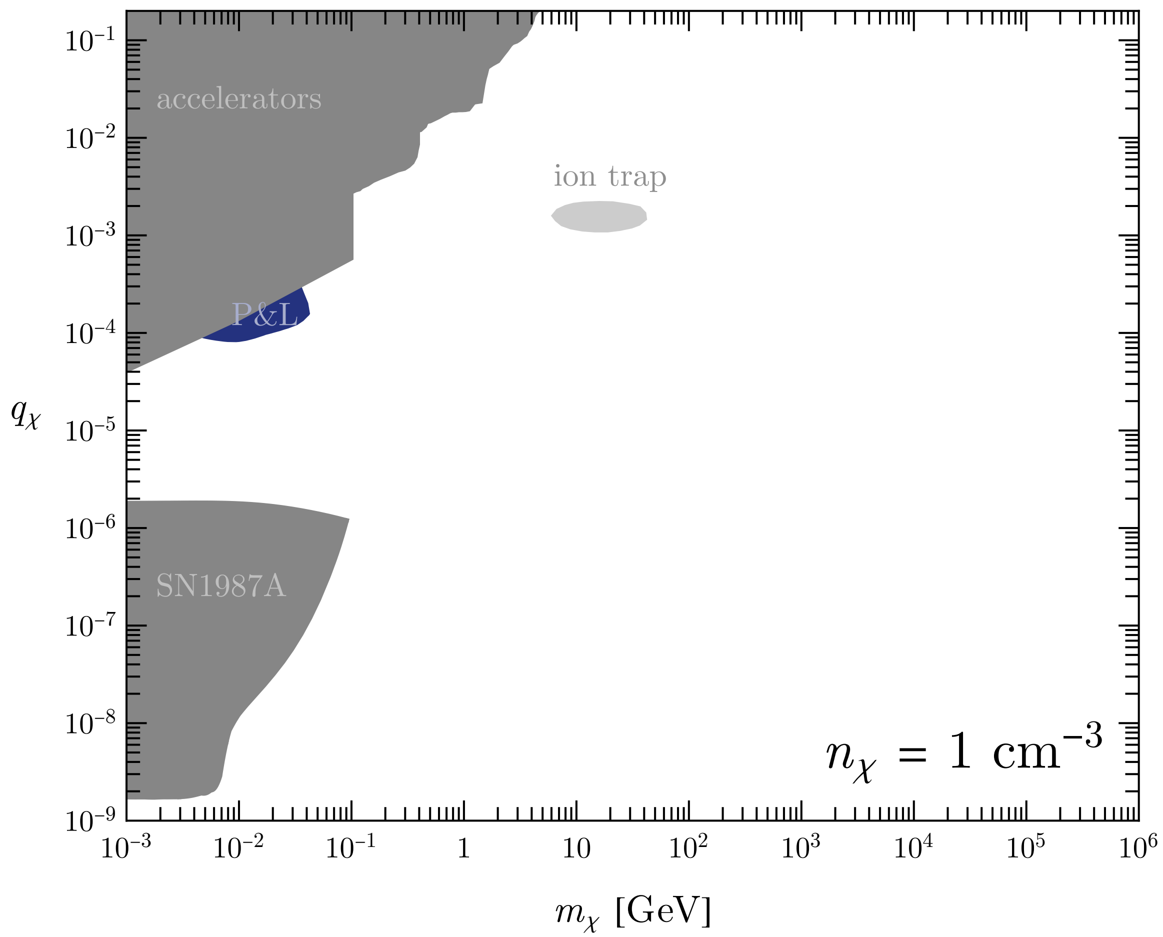
Plimpton and Lawton + Millicharges

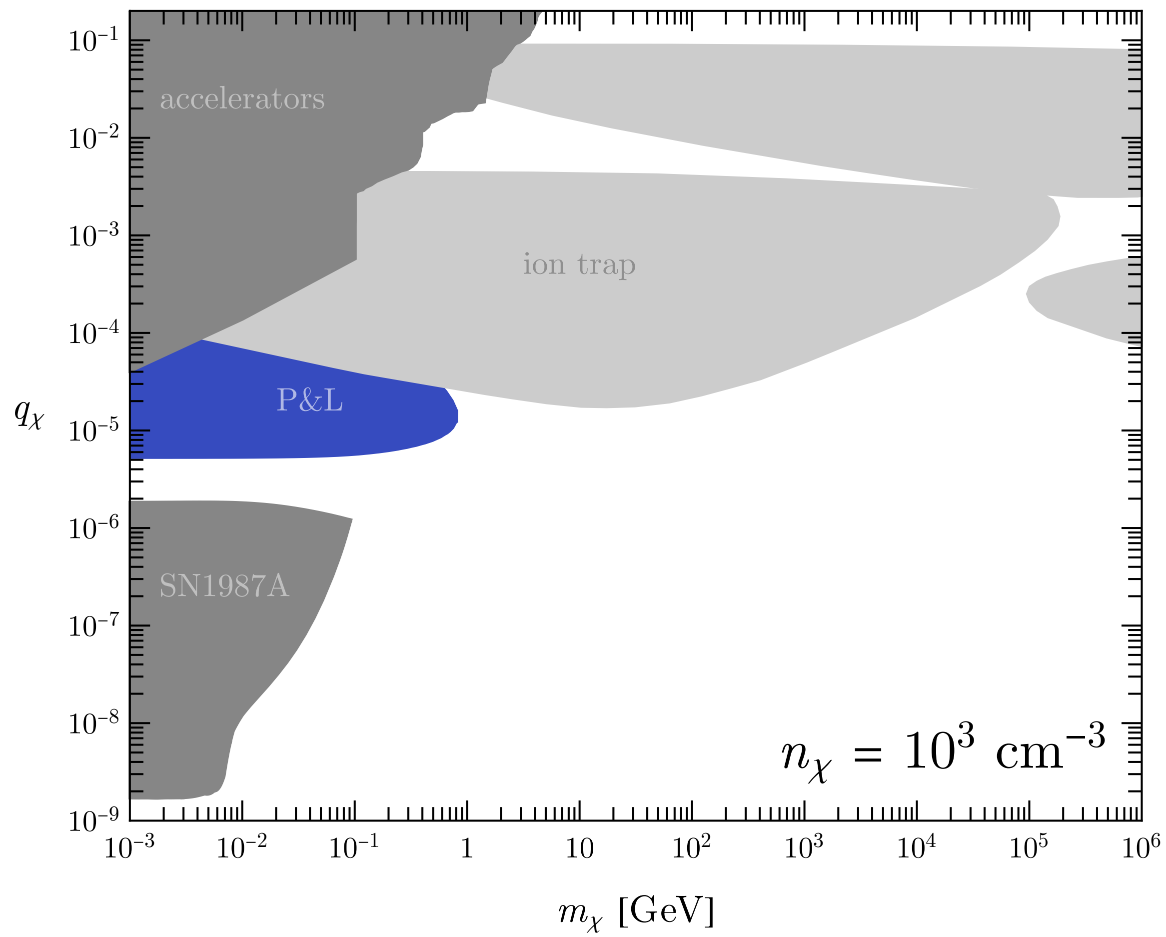
Recasted Limits



Plimpton and Lawton + Millicharges

Comparison to Ion Traps

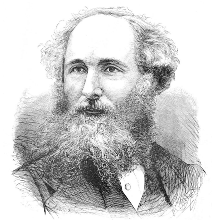




complementary sensitivity to modern ion traps

Cavendish + Millicharges

Historical Summary



	1773 Cavendish	**1873** Maxwell	**1936** Plimpton & Lawton	**1967** Cochran & Franken	**1971** Williams et al.	**2025** ?
freq.	$\ll$ Hz	$\ll$ Hz	$\sim$ Hz	$\sim$ kHz	$\sim$ MHz	
$\boldsymbol{r^{-2(1\pm n)}}$	$\sim 10^{-2}$	$\sim 10^{-4}$	$\sim 10^{-9}$	$\sim 10^{-11}$	$\sim 10^{-16}$	
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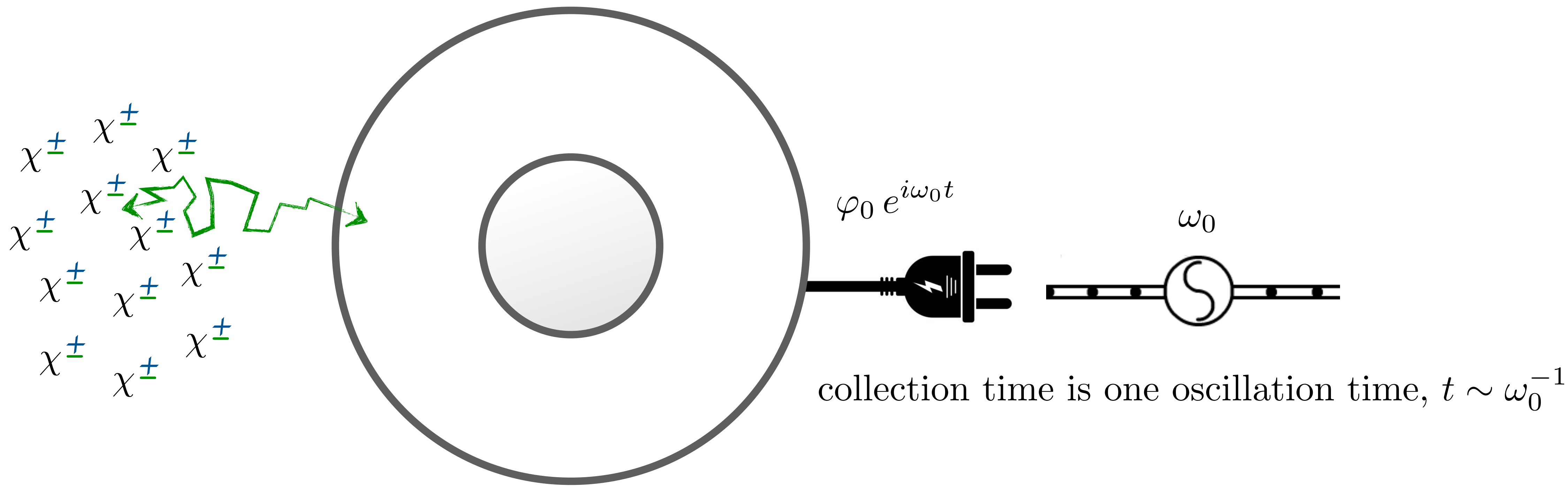
How to optimize with a dedicated setup?

(same noise levels as in 1936!)

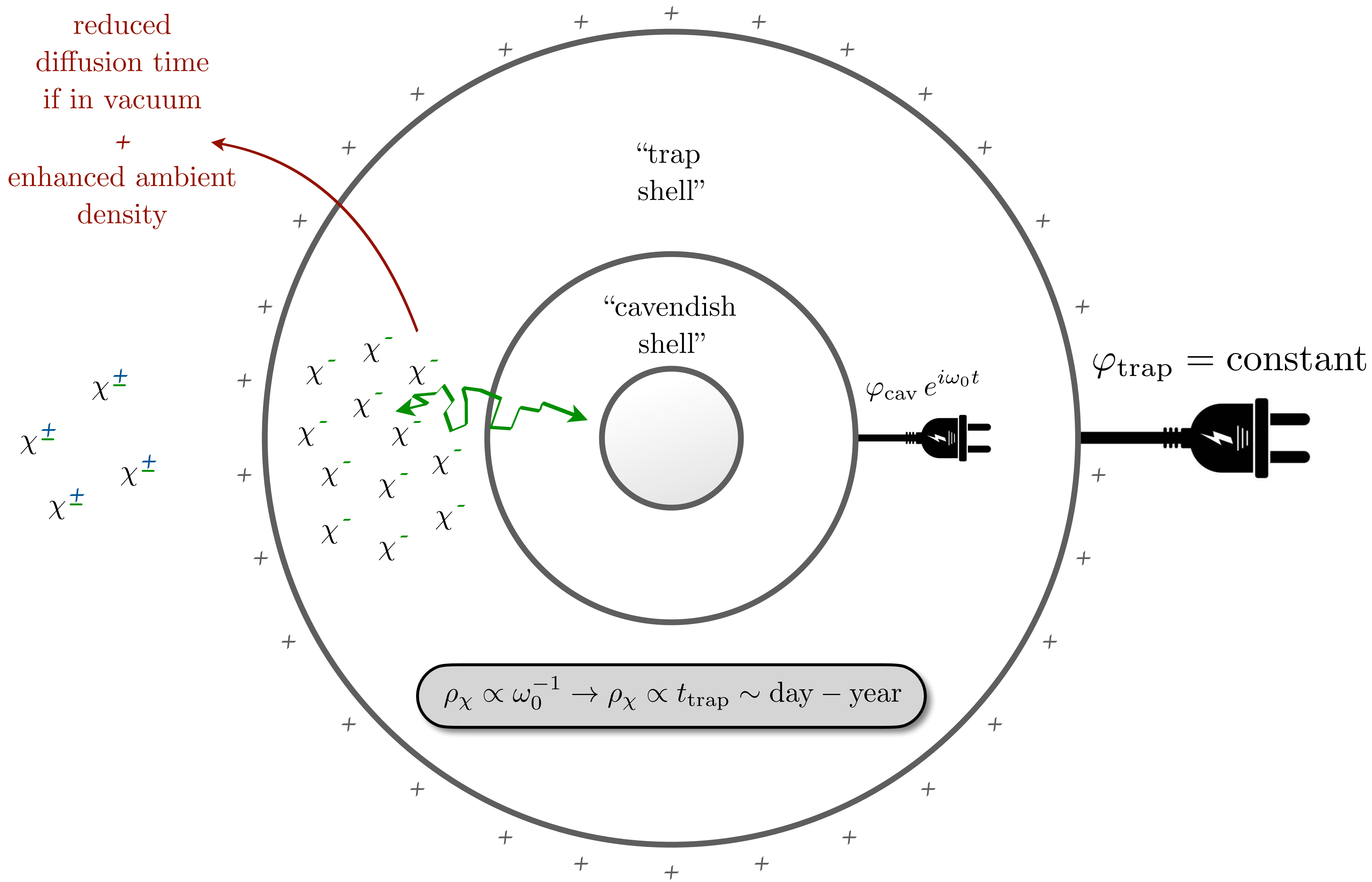
Cavendish + Millicharges



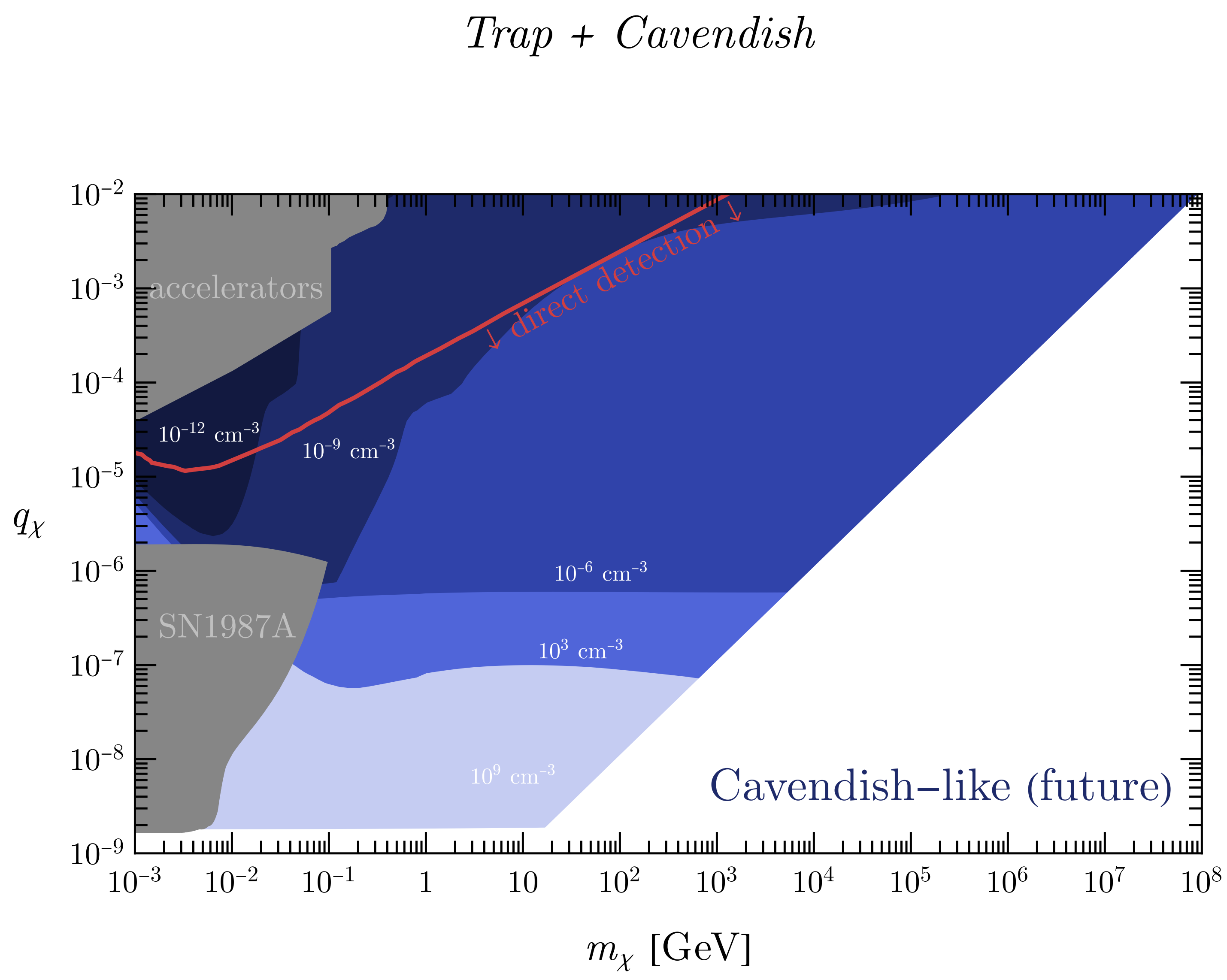
The Problem

lower frequency $\Longrightarrow$ greater collection time **but** increased noise

Cavendish + Trap + Millicharges



Cavendish + Trap + Millicharges

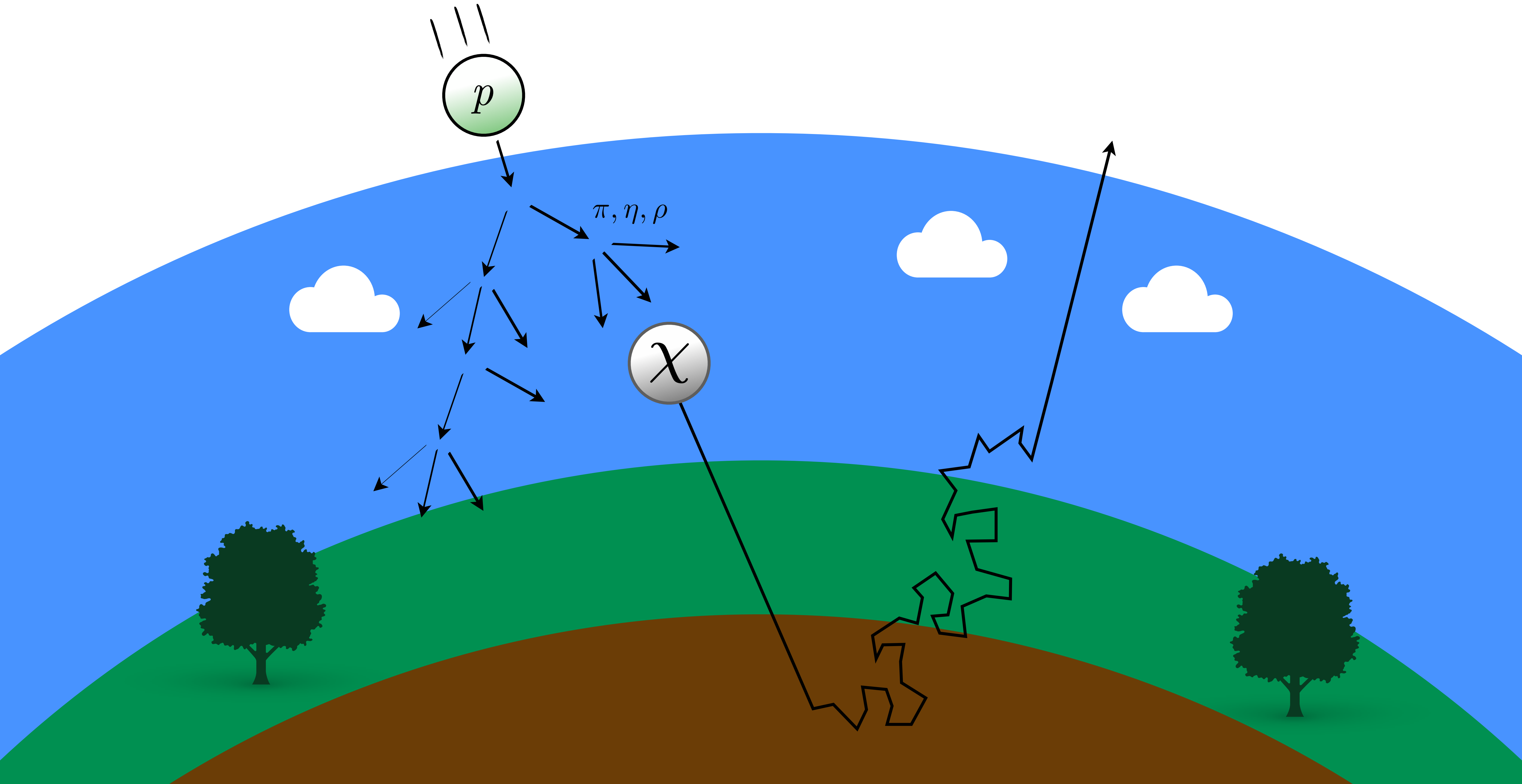


1936 setup
+ MV trap under high vacuum

Cosmic Rays + Millicharges

Cosmic Rays

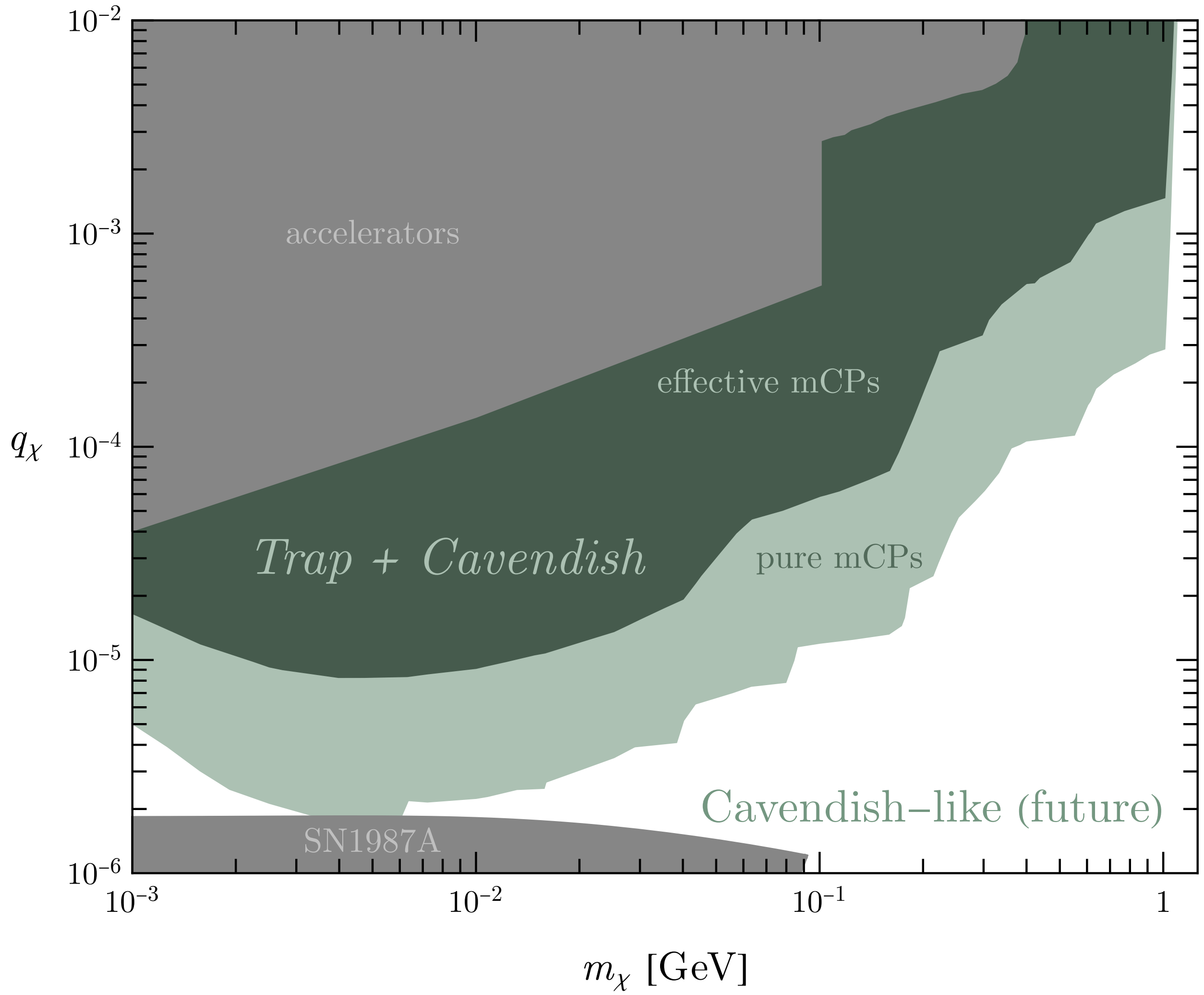
irreducible terrestrial population



Cosmic Rays + Millicharges

Cosmic Rays

irreducible terrestrial population



effective (kinetic mixing) = no-coupling to Earth's E-field

pure = trapped by Earth's E-field

Outlook

Cavendish Tests of Millicharged Relics

- Terrestrial overdensities of dark matter subcomponents.
- Large gaps in coverage motivate alternative detection strategies.
- Old experiments provide powerful limits.
- Simple dedicated setups can probe unexplored theory space.
- Application to other models? Better analogous tests?