Accelerating Earth-bound dark matter

DM+nu Forum at TDLI & SJTU

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Physics

Fonds de recherche Nature et technologies Québec

NSERC CRSNG

UBC

Outline

- Dark matter & strongly interacting dark matter
- Dark matter accumulation
- Dark matter acceleration and detection
  - Underground nuclear accelerators
  - Thermal sources
- Summary

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19th century

everything that could not be seen with optical instruments: planets, black holes, neutron stars, white dwarfs, cold gas clouds...

1950s

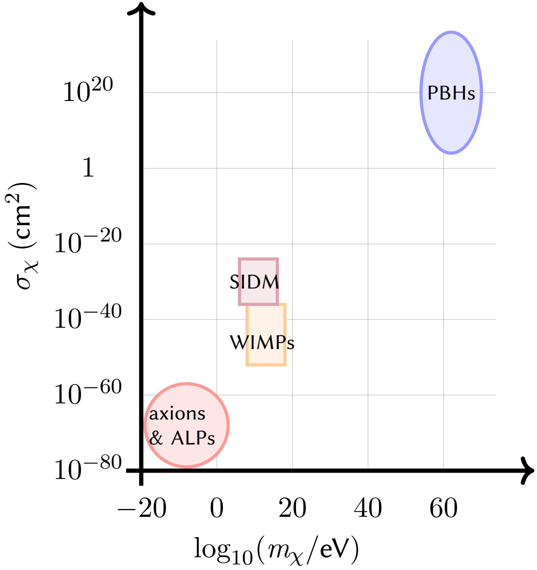
start of the use of X-rays, gamma rays, infrared instruments, improved precision of instruments

NASA, ESA, and Johan Richard

1980s

only non-baryonic matter which is not seen directly by tele-scopes

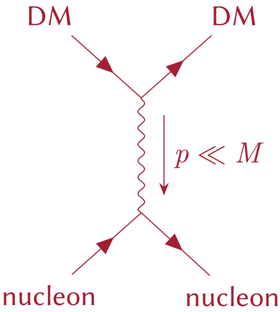
timeline



$Q = 0$

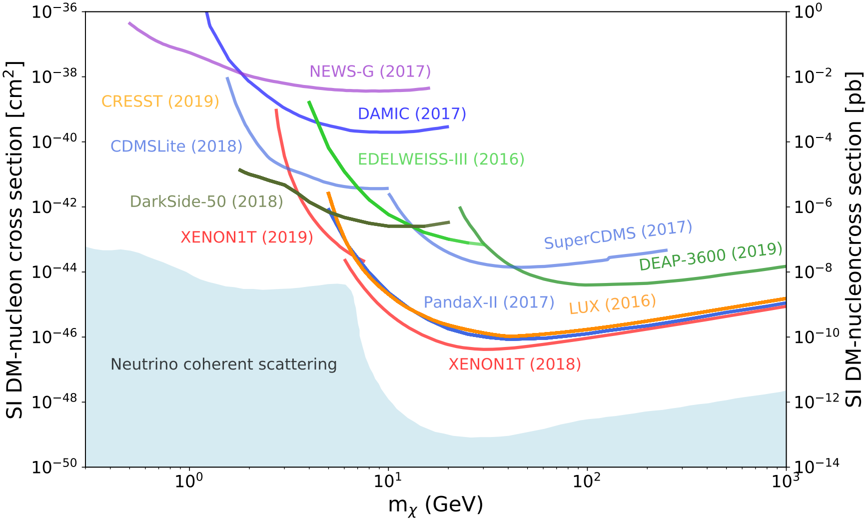
collision time $\in [10^{10}, 10^{22}]$ years in the interstellar medium

Spin-independent contact interaction



no annihilation or very little at the present epoch ($\bar{\chi}\chi \not\to NN$)

Similar analysis done with a dark photon ($m_{A'} = 15, 50$ MeV).



there are also bounds on DM-electron scattering, SD-proton and SD-neutron scattering

PDG 2020

Particle Detectors are Blind to Strongly Interacting Dark Matter

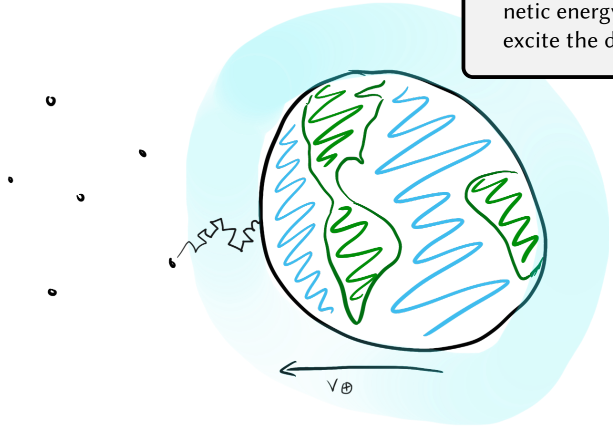
Scatters many times in the atmosphere and slows down

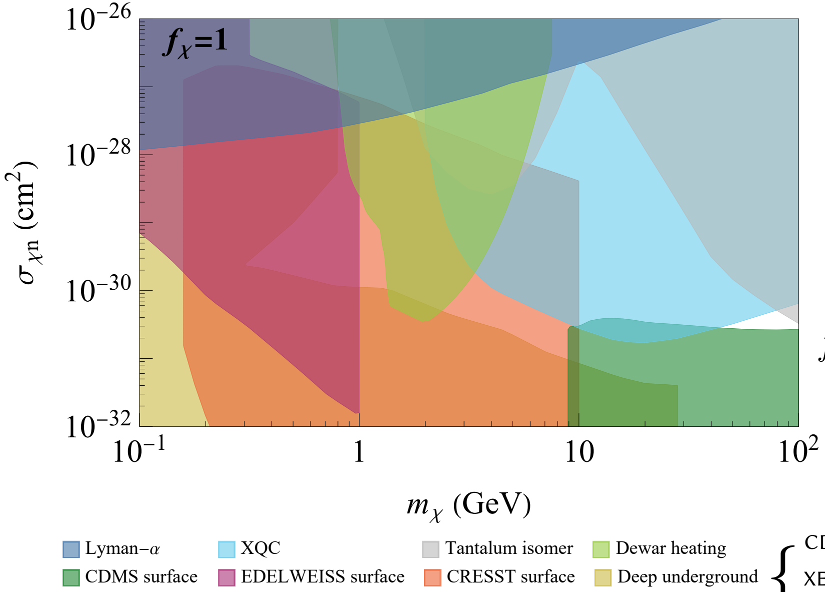
velocity $\sim \sqrt{\frac{kT}{m_\chi}}$, kinetic energy ~ 0.03 eV

Current nuclear detection thresholds: $\mathcal{O}$(keV)

Goodman & Witten

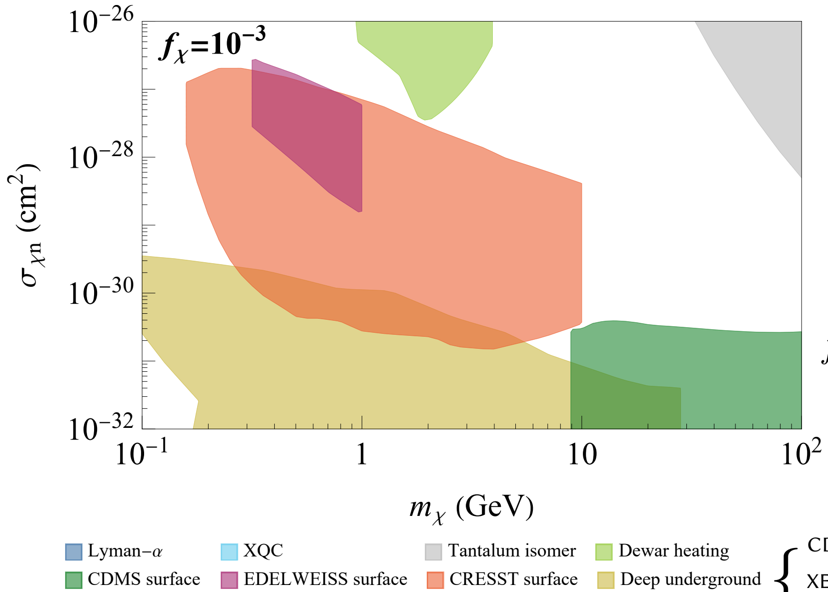
For values of $M_\chi \lesssim 100$ GeV, the stopping power of the atmosphere becomes important, and the χ particle probably could not be detected at sea level. Their kinetic energy would be too low to excite the detector [...] (1985)





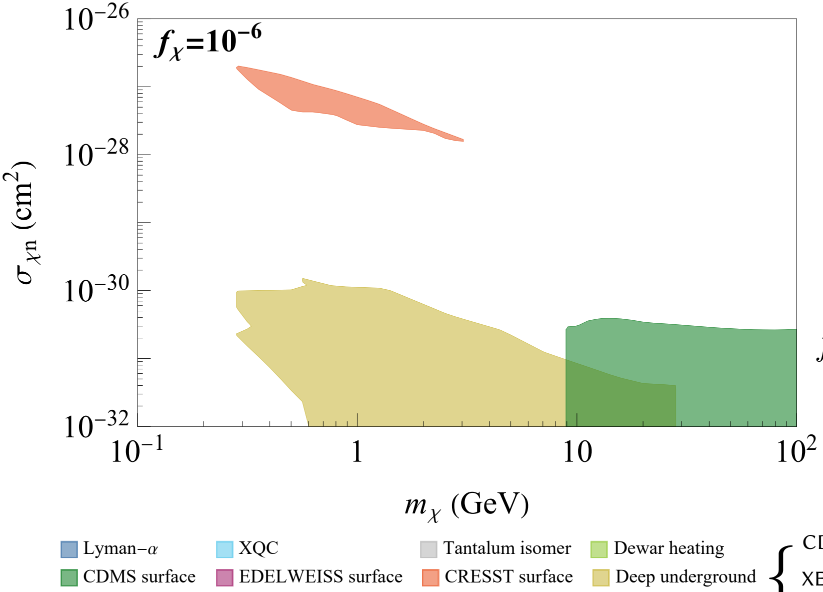
$$f_\chi = \frac{\Omega_\chi}{\Omega_{DM}}$$

Deep underground: CDEX, CRESST-III, XENON1T, PandaX-II, DarkSide-50



$$f_\chi = \frac{\Omega_\chi}{\Omega_{DM}}$$

$\Big\{$ CDEX, CRESST-III, XENON1T, PandaX-II, DarkSide-50



$$f_\chi = \frac{\Omega_\chi}{\Omega_{DM}}$$

$\left\{\begin{array}{l}\text{CDEX, CRESST-III,} \\ \text{XENON1T, PandaX-II,} \\ \text{DarkSide-50}\end{array}\right.$

Should we care about strongly interacting dark matter?

Probably!

How can we detect it?

- Too sparse ($f_\chi \sim 10^{-6}$, $\rho \sim 0.3$ GeV/cm^3, $m_\chi \sim 1$ GeV)
- Too slow (not energetic enough to be detected)

$\Rightarrow$

- accumulate in the Earth over its lifetime
- accelerate with nuclear accelerators and thermal sources

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Thermal Population of Dark Matter in the Earth

$$\frac{\mathrm{d}N_{\text{DM}}}{\mathrm{d}t} = \frac{\rho_{\text{DM}}}{m_{\text{DM}}} v_{\oplus} \pi R_{\oplus}^2 \, f_{\text{cap}} - N_{\text{DM}} \, f_{\text{loss}}$$

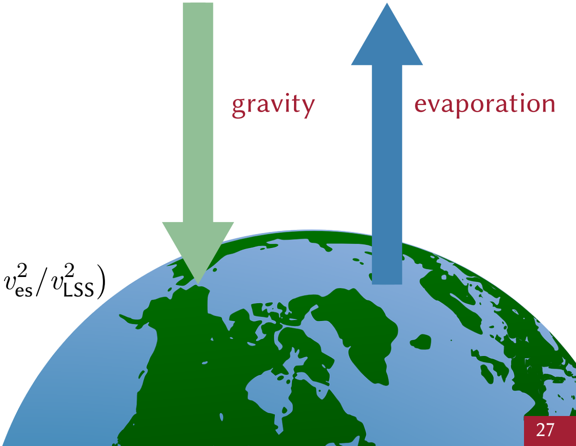
# of DM intercepted by Earth

fraction of DM captured by gravity

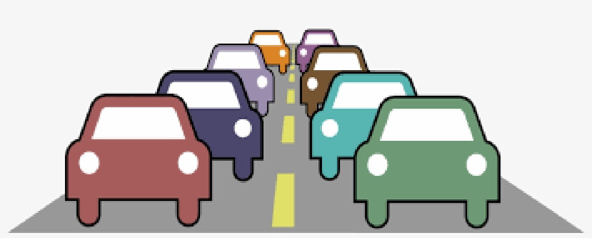
$$f_{\text{cap}} = \frac{2(\ln[1-\bar{f}_{\text{KE}}])^{1/2}}{\left(\pi \ln[v_{\text{es}}^2/v_{\oplus}^2]\right)^{1/2}}$$

fraction of DM lost by Jeans escape

$$f_{\text{loss}} = \frac{3}{R_{\oplus}\bar{n}_{\text{DM}}} \frac{n_{\text{LSS}} v_{\text{LSS}}}{2\pi^{1/2}} \left(1 + \frac{v_{\text{es}}^2}{v_{\text{LSS}}^2}\right) \exp\left(-v_{\text{es}}^2/v_{\text{LSS}}^2\right)$$



ApJ **866** 111 (2018), ApJ **321** 560 & 571 (1987)

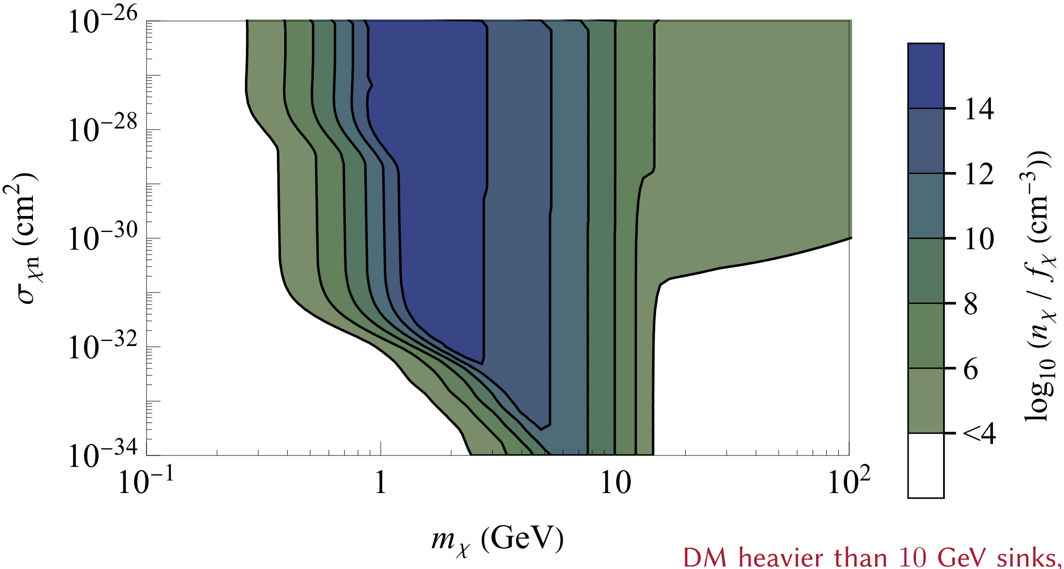


infalling dark matter that has not yet reached the equilibrium distribution

$$v_z \, \frac{\mathrm{d}v}{\mathrm{d}z} \propto -n_N \, \sigma_{\chi n} \, \frac{v_N^3}{v}$$

PRD **101** 055001 (2020)

A Large Density Near the Earth Surface can be Obtained



DM heavier than 10 GeV sinks,
lighter than 1 GeV evaporates

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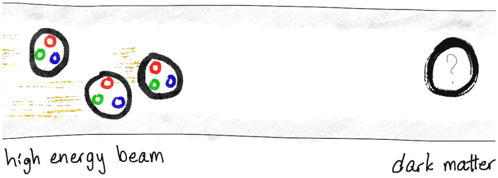
We need to give energy to the dark matter:

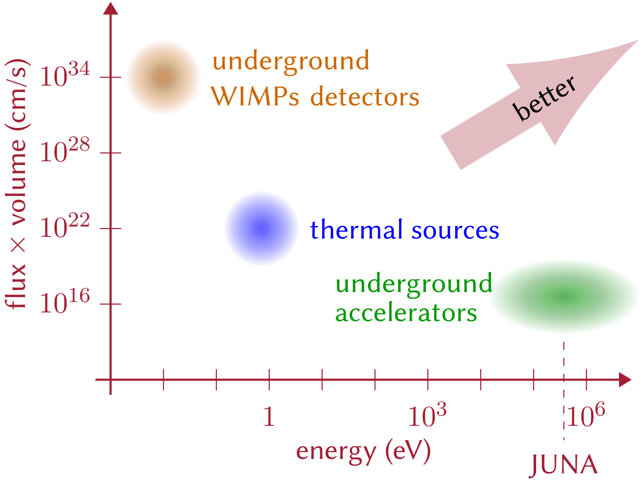
Beams

1. Particle accelerators (~ 1 TeV)
2. **Nuclear accelerators ($\sim$ 1 MeV)**

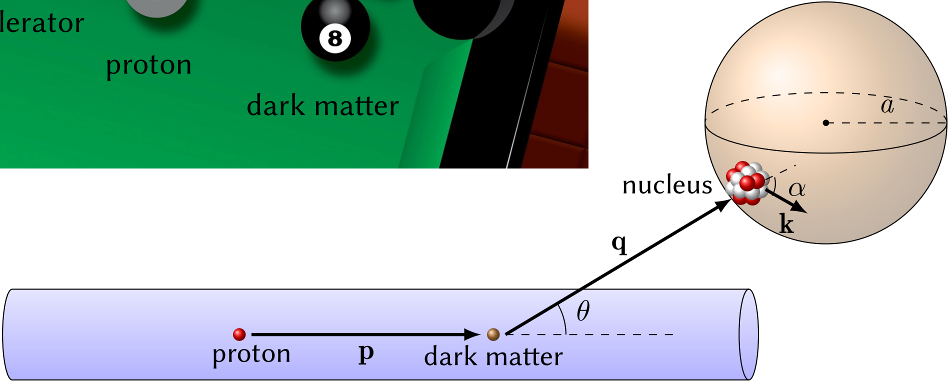


Heat

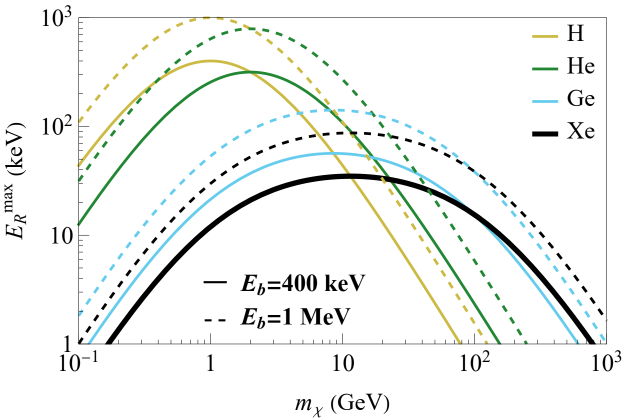
1. **Light bulbs (~ 3000 K ~ 0.3 eV)**
2. Tokamak ($\sim 10^8$ K ~ 10 keV)

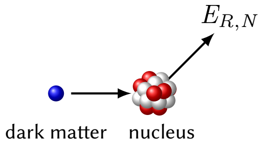

flux × volume (cm/s)
10^{34}
10^{28}
10^{22}
10^{16}
underground
WIMPs detectors
better
thermal sources
underground
accelerators
1
10^3
10^6
energy (eV)
JUNA


detector
accelerator
proton
dark matter


a
nucleus
α
$\mathbf{k}$
$\mathbf{q}$
θ
proton
$\mathbf{p}$
dark matter

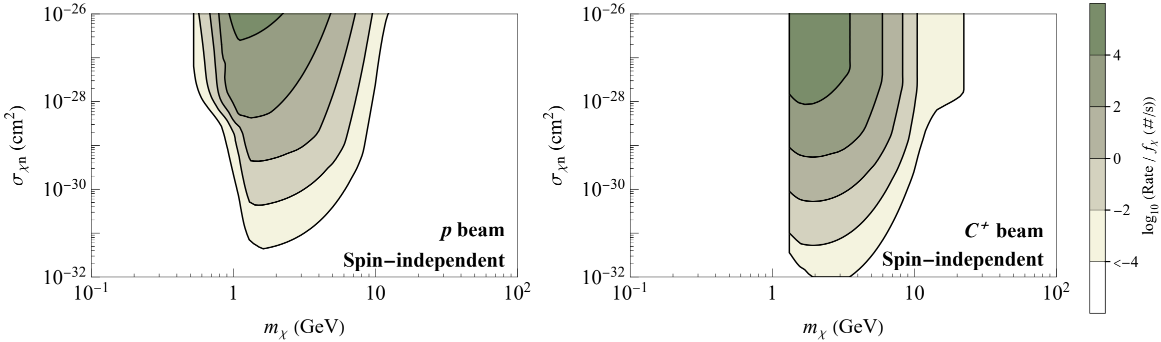
	LUNA-MV	JUNA	CASPAR
voltage (kV)	3500	400	1100
H current (mA)	1	10	0.25
He current (mA)	0.5	2	0.22
C current (mA)	0.15	–	–





The Rate is Measurable in a 10cm Diameter Xenon Detector

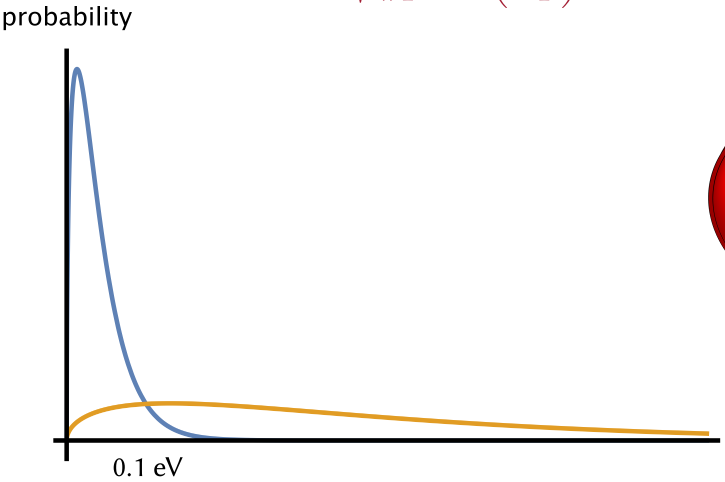
$$E_{\text{th}} = 5 \text{ keV} \qquad\qquad R \sim n_\chi \times \left(\underbrace{\frac{I_b}{Q_b}}_{\sim 10^{17}\ \text{cm/s}} L\ \sigma_{\chi b} \right) \times (\ell\ \sigma_{\chi N}\ n_N)\ P_{\text{sh}}\ P_{\text{th}}$$

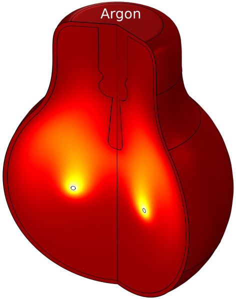


The Incandescent Light Bulb Setup

Dark matter gas @ 300 K   Argon gas @ 3000 K

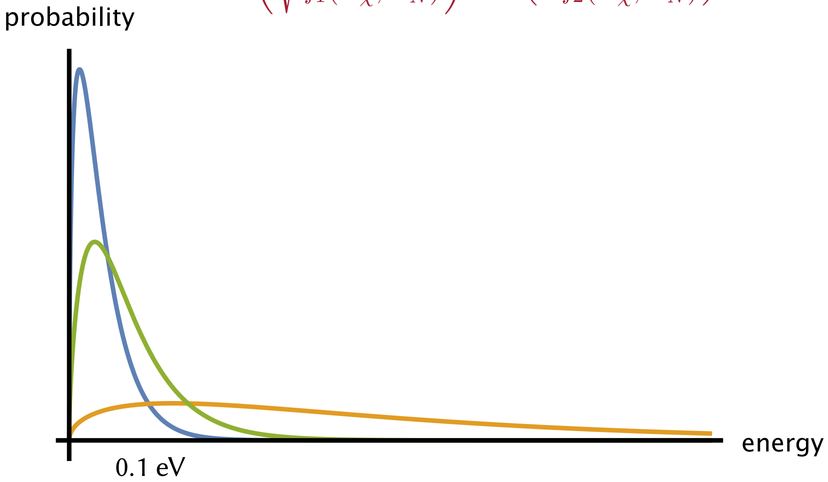
$$P(E)\,\mathrm{d}E = \sqrt{\frac{E}{\pi\,T^3}}\,\exp\left(-\frac{E}{T}\right)\mathrm{d}E$$





Dark matter gas @ 300 K   Argon gas @ 3000 K   Dark matter gas scattering

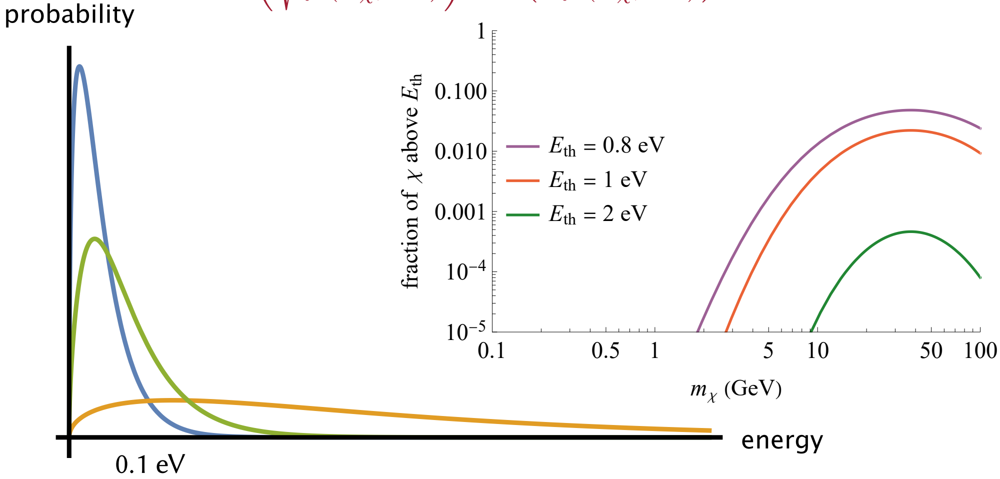
$$P(E)\,\mathrm{d}E \propto \operatorname{erf}\left(\sqrt{\frac{E}{f_1(T_\chi, T_N)}}\right)\exp\left(-\frac{E}{f_2(T_\chi, T_N)}\right)\mathrm{d}E$$



Energy Achievable by Up-Scattered Dark Matter

Dark matter gas @ 300 K Argon gas @ 3000 K Dark matter gas scattering

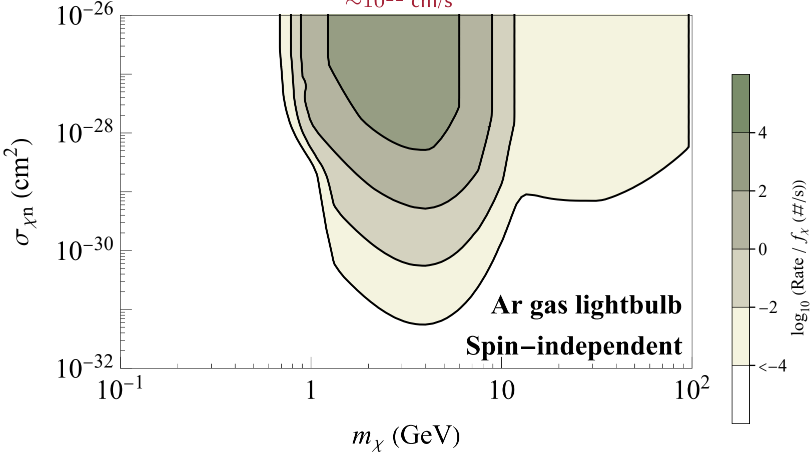
$$P(E)\,\mathrm{d}E \propto \mathrm{erf}\left(\sqrt{\frac{E}{f_1(T_\chi, T_N)}}\right)\exp\left(-\frac{E}{f_2(T_\chi, T_N)}\right)\mathrm{d}E$$



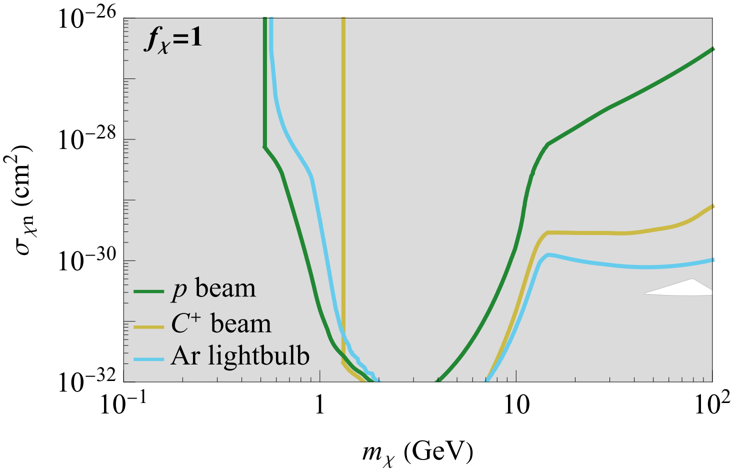
The Rate is Measurable in a 1g CO Detector

$E_{\rm th} = 0.8$ eV

$$R \sim n_\chi \Big(\underbrace{N_g \sqrt{\frac{T_g}{m_g}}}_{\sim 10^{22}\ \text{cm/s}} \sigma_{\chi g} \Big) \times \Big(\frac{1}{4\pi d^2} \sigma_{\chi N} N_N \Big) P_{\rm sh} P_{\rm th}$$

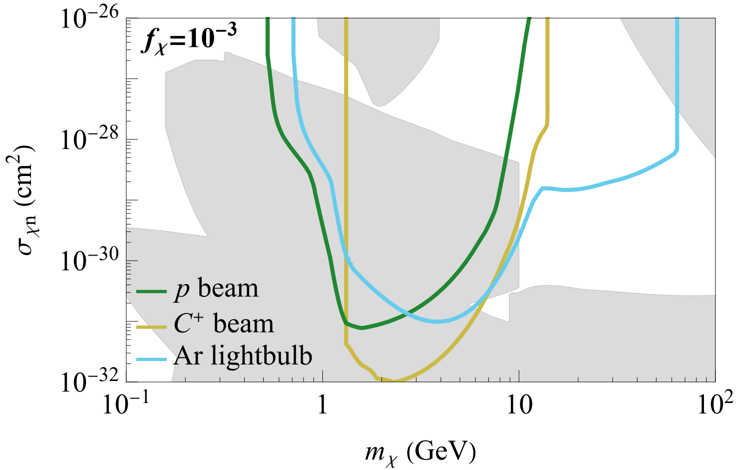


Rates in a Detector for $f_\chi = 1$



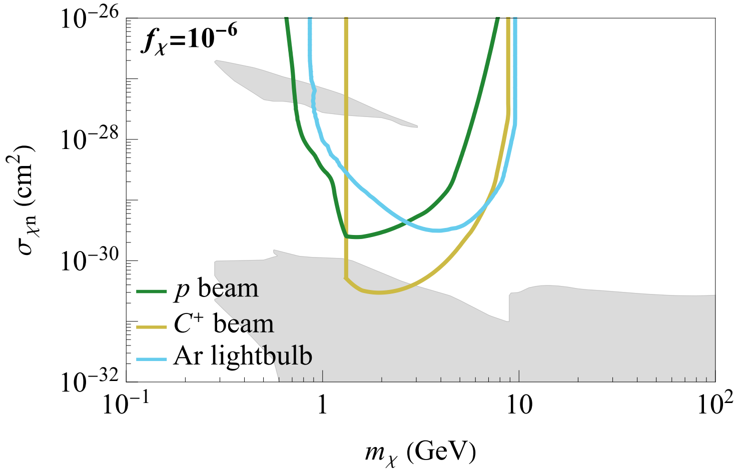
$$f_\chi = \frac{\Omega_\chi}{\Omega_{DM}}$$

10 events per year, rate $\propto \sigma_{\chi n}^2$



$$f_\chi = \frac{\Omega_\chi}{\Omega_{DM}}$$

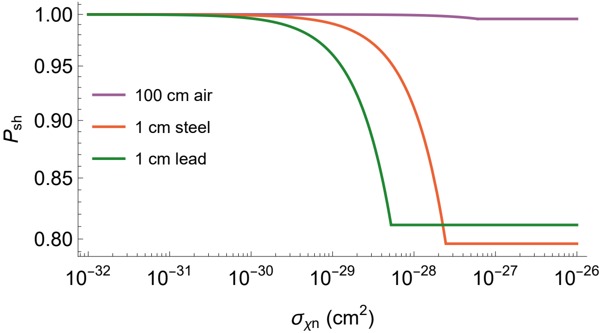
10 events per year, rate $\propto \sigma^2_{\chi n}$

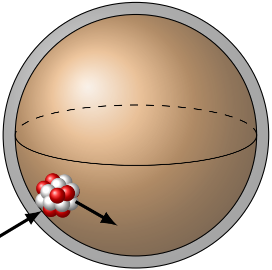


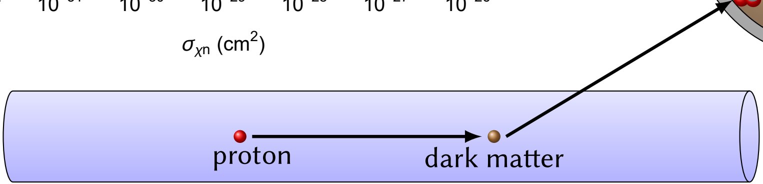
$$f_\chi = \frac{\Omega_\chi}{\Omega_{DM}}$$

10 events per year, rate $\propto \sigma_{\chi n}^2$

$$P_{\text{sh}} \sim P_{\text{sh, air}} \times P_{\text{sh, lead}} \times \ldots$$

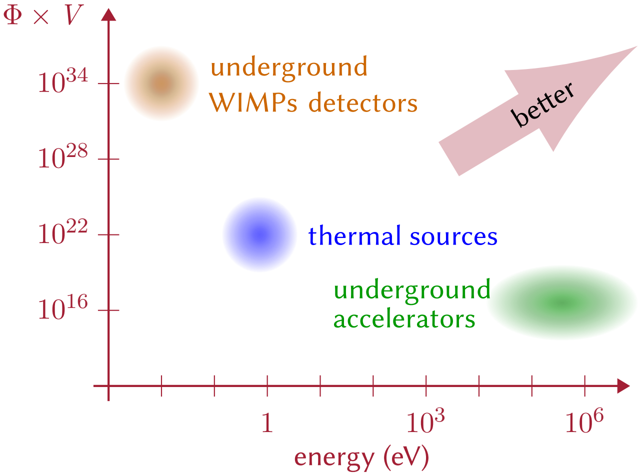






To be improved

elements to improve	effect on rate in detector
shielding analysis	$\downarrow$
collimation of the beam	$\uparrow$
V and T of gas	$\uparrow$



Summary

Strongly interacting dark matter:

- Could exist as a fraction of the total dark matter ✓
- Direct detection methods cannot probe sub-components ×
- Interacts with protons and neutrons ✓
- Overdense ✓
- Very slow ×

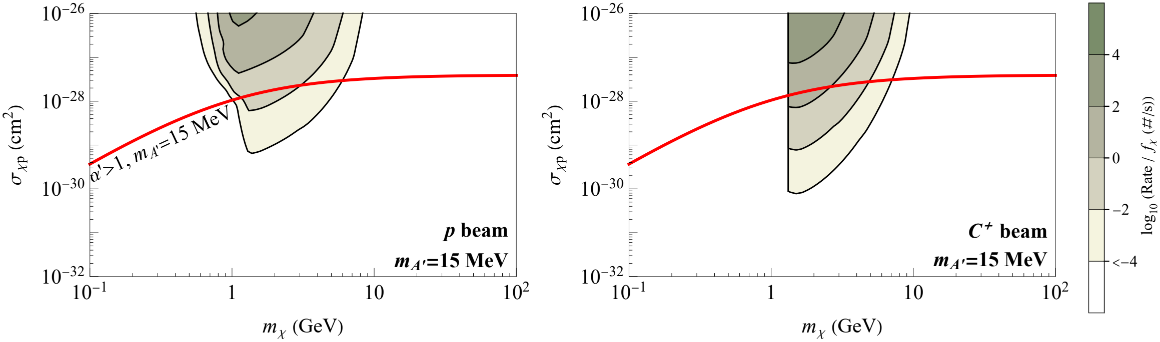
Accelerate it through up-scattering with nuclear accelerators (possible with current detector thresholds) or thermal sources, such as light bulbs (possible in the near future...?)

millicharge dark matter:
PRD **103** 115031 (2021)

Appendix

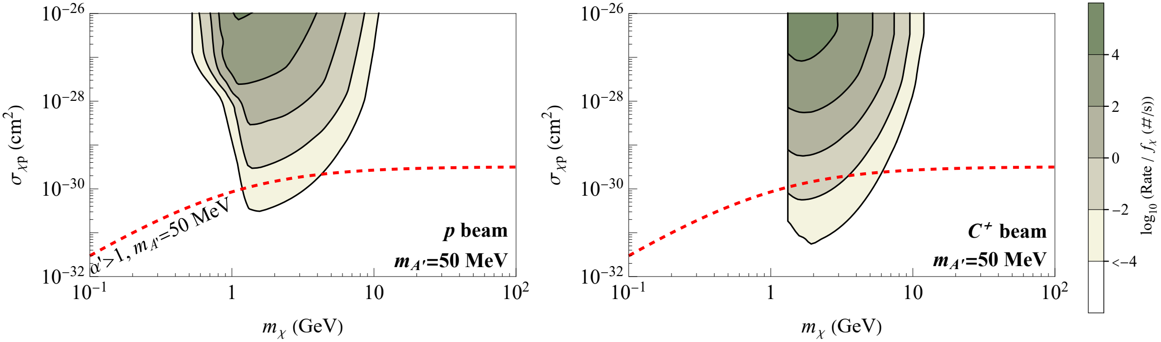
15 MeV Dark Photon

need $\alpha' \leq 1$ to maintain perturbative consistency



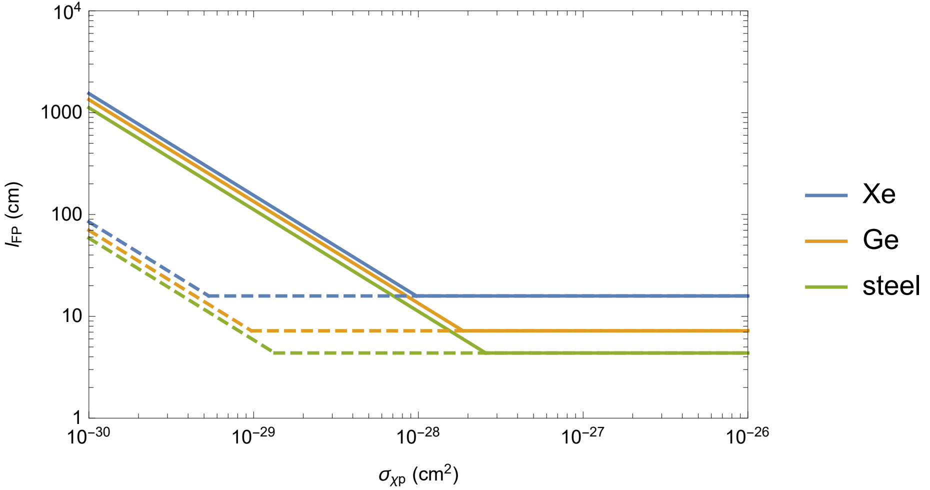
50 MeV Dark Photon

need $\alpha' \leq 1$ to maintain perturbative consistency



Mean Free Path of Dark Matter in Materials

$l_{FP} = (n_T\ \sigma_{\chi p})^{-1}$, saturates at the geometric cross-section $4\pi(1.2\ \mathrm{fm}\ A^{1/3})^2$



(for a particle of mass 1 GeV (full) and 10 GeV (dashed) up-scattered by a 400 keV beam)