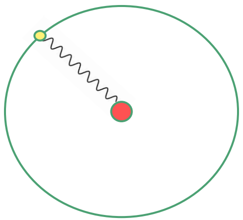
Atomic Dark Matter Capture in the Earth - GUINEAPIG 2024

Speaker: Keegan Humphrey - University of Toronto
Ongoing work in Collaboration With: David Curtin, Zackaria Chacko, Ina Flood, Michael Geller, Yuhsin Tsai

Atomic Dark Matter (aDM) is a model of DM with rich and complicated dynamics

$$\mathcal{L}_{aDM} = -\frac{1}{4}F_{D\mu\nu}F_D^{\mu\nu} + \bar{\psi}_{p_D}(i\partial\!\!\!/ + q_D A\!\!\!/_D - m_{p_D})\psi_{p_D} + \bar{\psi}_{e_D}(i\partial\!\!\!/ - q_D A\!\!\!/_D - m_{e_D})\psi_{e_D}$$

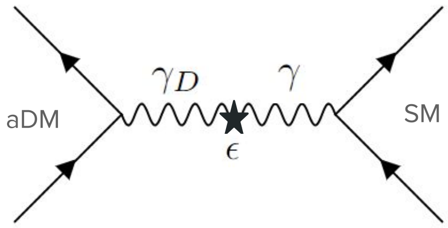
- What is aDM?
  - aDM is a class of DM models where a component of DM consists of a dark proton, dark electron, and a massless dark photon + CDM
    - $m_{e_D} < m_{p_D}$, e_D and $p_D$have opposite dark charge
- Why should we be interested in aDM?
  - It seems very plausible that there a version of EM that makes up some component of DM given that it already exists in the SM
  - It is simple model, but it’s dynamics are complicated and extremely rich



aDM Interacts with the SM and can be discovered in DM searches

- The minimal interaction of aDM with the SM is a kinetic mixing between the SM and dark photons
    - This gives aDM an effective millicharge
- There are a variety of experiments looking to discover DM which are sensitive to aDM. We will focus on **Direct Detection** experiments
    - These are VERY sensitive to incoming DM velocity distribution. Electrostatic effects have the potential to significantly alter exclusion bounds or discovery potential of DD experiments

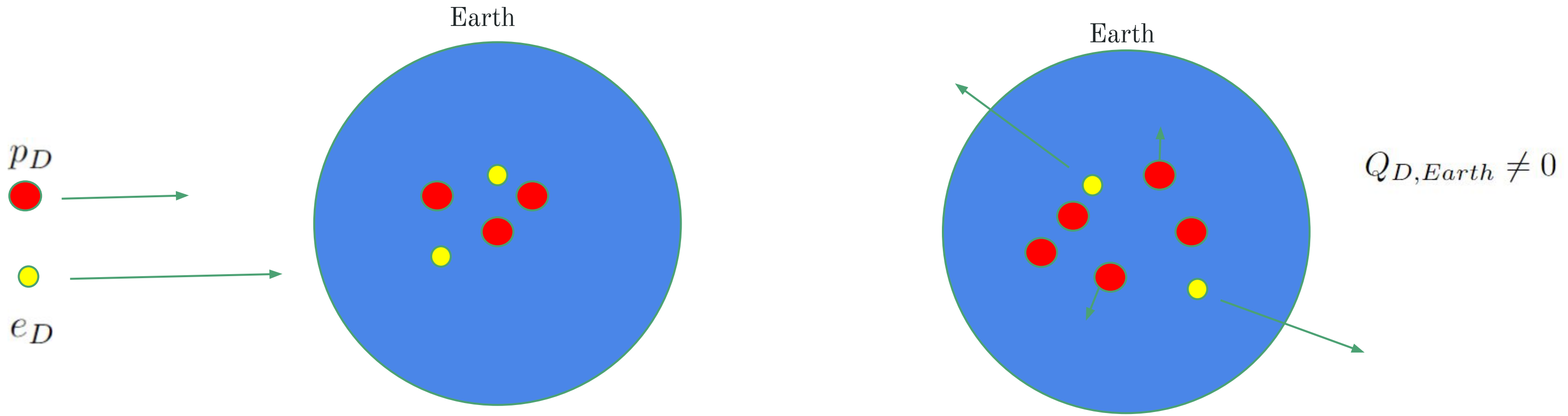
$$\mathcal{L}_{mix} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F_{D\mu\nu}F_D^{\mu\nu} - \frac{\epsilon}{2}F_{\mu\nu}F_D^{\mu\nu}$$



Dark Charge Accumulation can alter aDM flux on Earth's Surface

arxiv: 2104.02074

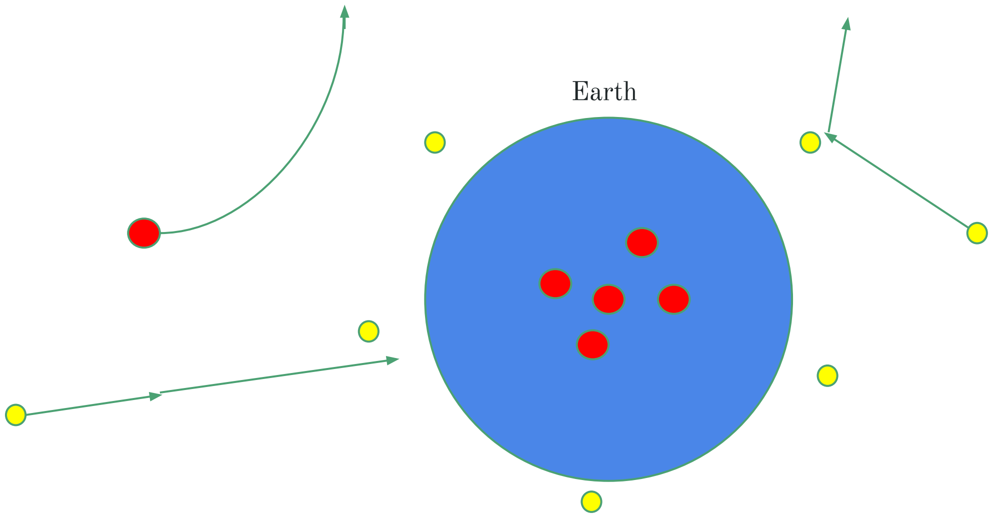
- Kinetic Mixing leads to small interactions with the Earth and hence energy loss
- Occasionally aDM can be slowed enough to be captured by Earth's Gravity
    - Dark Electrons will be moving faster, making them harder to capture
- Captured aDM thermalizes with the Earth, the lighter species (dark electron) is more likely to be evaporated, this can lead to a net Dark charge accumulated in the earth and generate a dark Electric field



Dark Charge Accumulation can alter aDM flux on Earth's Surface - Continued

arxiv: 2104.02074

- Due to the presence of the ambient dark plasma, this dark charged Earth acts as a Debeye probe, screening the Dark Electric field and altering the incoming flux of aDM (through resultant yukawa potential and collisional shielding)
- Highly non-linear nature of the accumulation and plasma effects may make this effect very significant in some regions of parameter space or negligible in others, altering the sensitivity of direct detection experiments



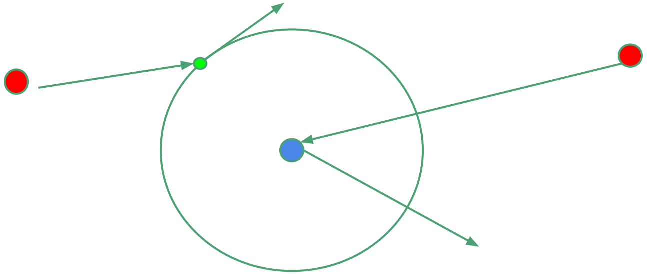
How to Determine the effect of capture on aDM flux

1. Given an aDM distribution far from Earth, **propagate it to the surface**
2. Find the **interaction cross-section** with the material in the Earth
    - From electronic and nuclear scatters
3. Compute the **Capture Probability Distribution** (as a function of impact parameter and velocity)
    - Consider both hard scatters and multiple soft scatters
4. Compute the **Capture and Evaporation rates** for each dark species
5. Determine the equilibrium distribution of the aDM plasma at Earth's Surface (WORK IN PROGRESS!)
    - Eventually we will simulate the full evolution of the aDM plasma over the lifetime of the Earth
    - For now we simply try to identify where in parameter space we get the largest amount of charge accumulation ignoring dark electrostatics and the behaviour of the plasma

aDM Interactions in the Earth

aDM interacts with both Nuclei and Electrons in Earth

- Capture in celestial bodies has been considered before, however unlike others in the literature, aDM interacts with both Electrons and Nuclei.
  - Further, while in stars where the species are ionized (2404.10066), in the Earth we must properly treat scattering of a solid
  - We want to determine the captured population over a wide range of aDM parameters, so our motto is to be accurate at O(1) throughout parameter space



The Dynamical Structure Function

2101.08275
https://doi.org/10.1103/PhysRev.113.1254

- The interaction rate of a charged probe with a material is computed in NR QM with the **Dynamical Structure Function**

$$dP(\omega) = d\omega \int \frac{d^3q}{\hbar(2\pi)^3} \delta\left(\omega - \boldsymbol{q}\cdot\boldsymbol{v} + \frac{\hbar q^2}{2m_\chi}\right) \kappa^2 V^2(q) S(\boldsymbol{q},\omega)$$
$$S(\boldsymbol{q},\omega) \equiv \frac{2\pi}{V} \sum_{m,n} P_m |\langle n|\rho_{-\boldsymbol{q}}|m\rangle|^2 \delta(E_n - E_m - \hbar\omega)$$

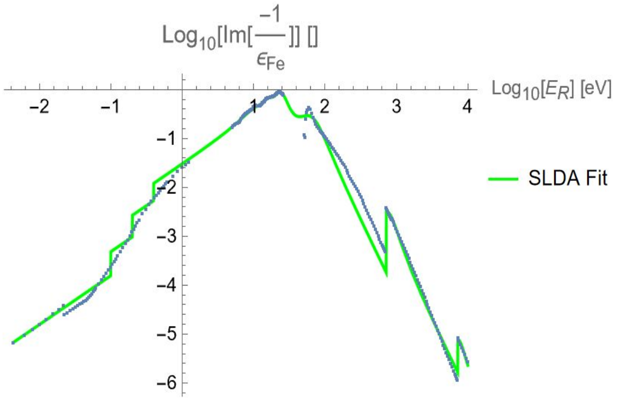
- Through the fluctuation dissipation theorem, we can relate the dynamical structure function to the imaginary part of the polarization (dielectric) tensor
  - We use this expression for **electronic scattering**

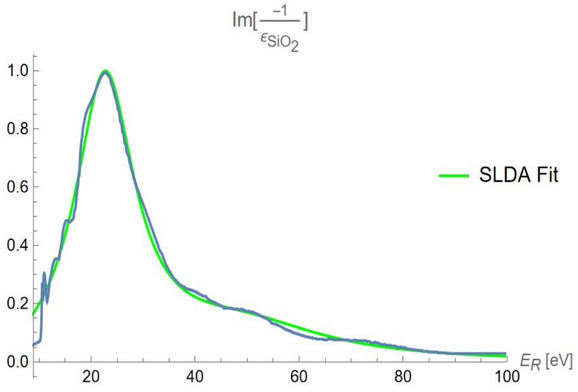
$$S(q,\omega) = \frac{2}{1-e^{-\beta\hbar\omega}} \frac{1}{V(q)} \mathrm{Im}\left(\frac{-1}{\epsilon(q,\omega)}\right)$$

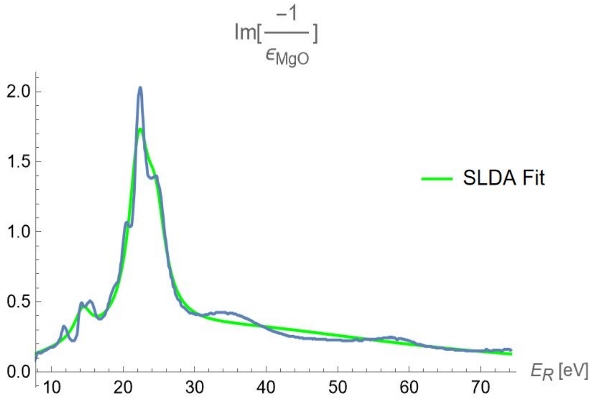
We use a Data Driven Dielectric Model of the Electron Interactions to treat both conductors and insulators

2101.08263
2101.08275
2108.03239
(Chen et al., 1993)

- We match to optical data using the Mermin Dielectric Shell Wise Local Density Approximation
    - Accounts for screening, collective effects, and the shell structure of the atoms







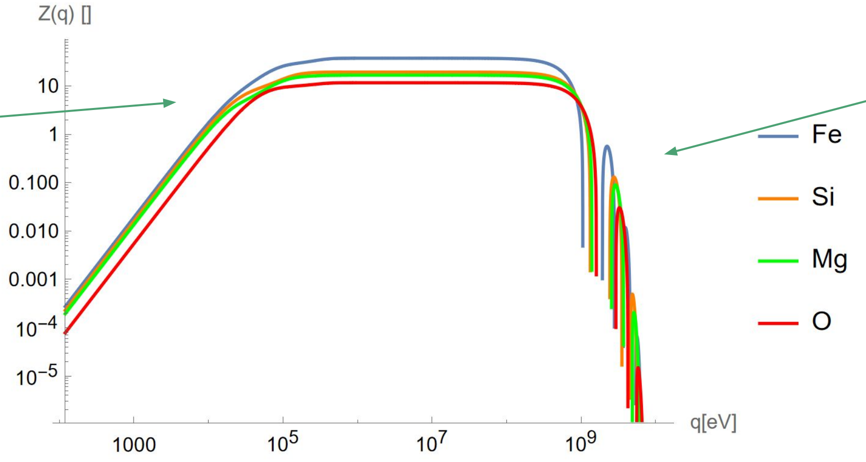
Preliminary

We use both Atomic and Nuclear form factors for scattering off Nuclei

$$S(q,\omega) = 2\pi n_N Z_{eff}^2(q)\delta\left(\frac{\hbar^2 q^2}{2m_N} - \hbar\omega\right)$$

- At lower momentum transfers, the Electrons screen the Nuclear Charge
  - We use atomic form factors for this (eg. 2012.02508)
- For large momentum transfers, aDM scatters off individual protons rather than coherently scattering off the whole nucleus
  - We characterize this using the Helm Nuclear Form Factor (arxiv:0608035)

Atomic FF turns on below a 100 keV



Nuclear FF turns on around a GeV

Preliminary

Accumulation of aDM in the Earth

We look for parts of parameter space where aDM flux may be significantly affected

- Working out the equilibrium distribution of a plasma is a **work in progress**
- We begin by ignoring electrostatics, aDM plasma effects and self capture
    - We simply look to identify parts of parameter space where accumulation will be most significant
- We make the local assumptions about aDM that:
    - There is an asymmetric component of aDM
    - There is an ionized fraction aDM
    - aDM is thermalized with itself near Earth

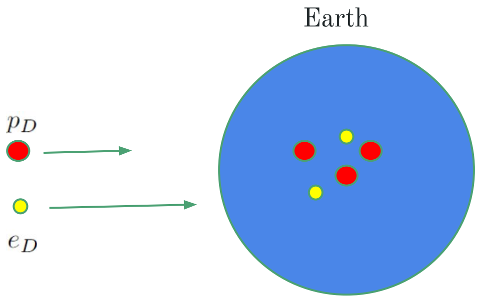
Galactic simulations are required to understand these assumptions

2311.02148

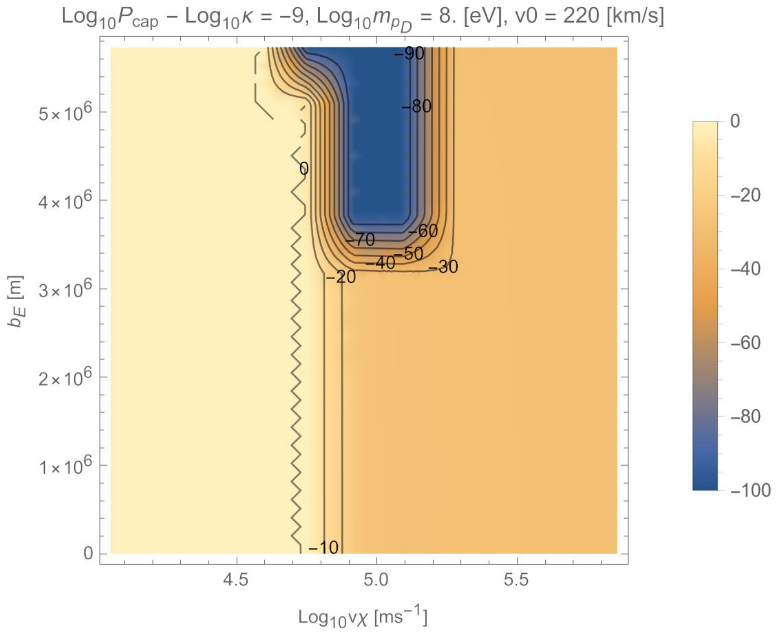
We estimate aDM capture Probability, ignoring Dark Electrostatics

Preliminary

- For the capture probability we treat the Earth as either optically thick (captured by multiple soft scatters) or optically thin (captured by a single hard scatter)



Impact parameter



aDM velocity at the Surface

Captured aDM can be evaporated

Preliminary

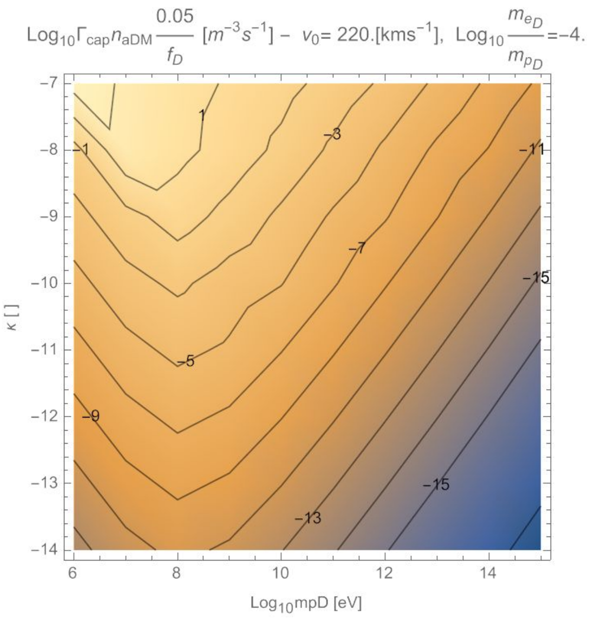
- Captured aDM can scatter off the nuclei and be evaporated
- Where Evaporation is significant, equality of the rates then determines the total captured population

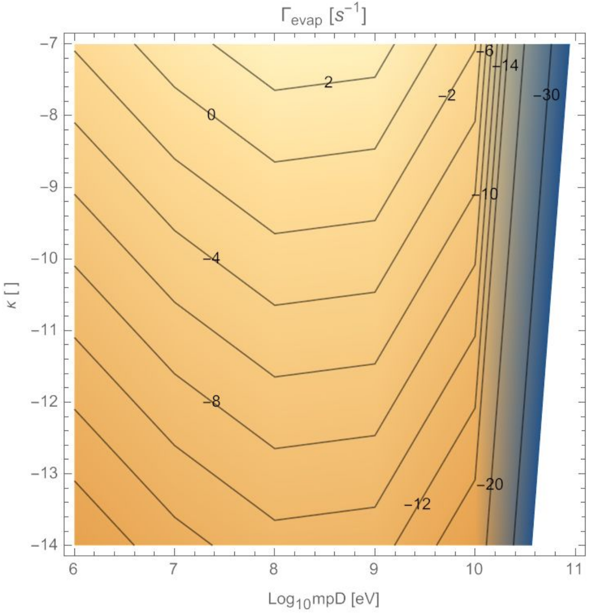
$$\Gamma_{evap} n_{cap} = \Gamma_{cap} n_{aDM,local}$$

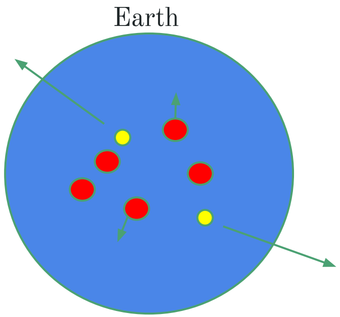
Per particle evaporation rate

Captured density in Earth

Per particle capture rate

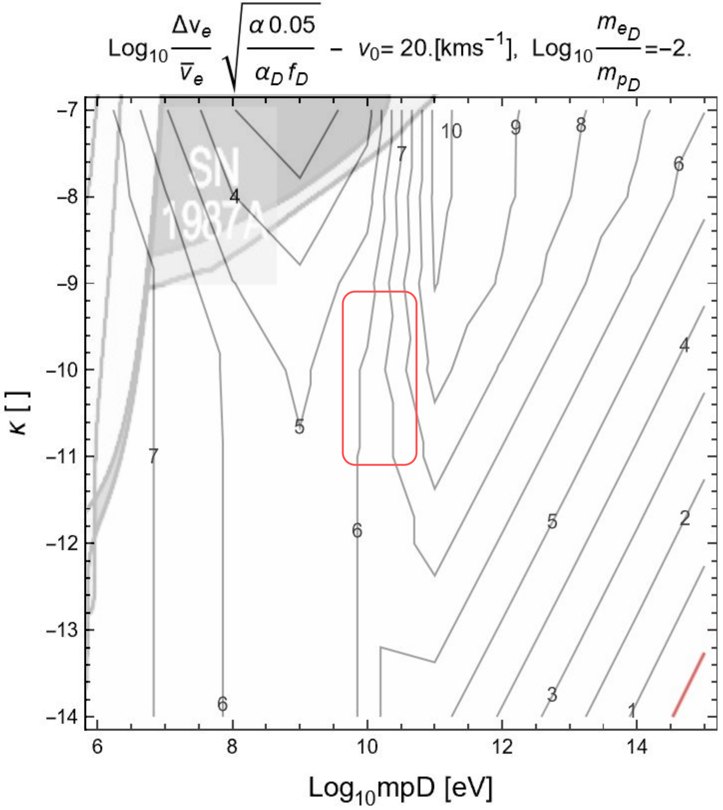


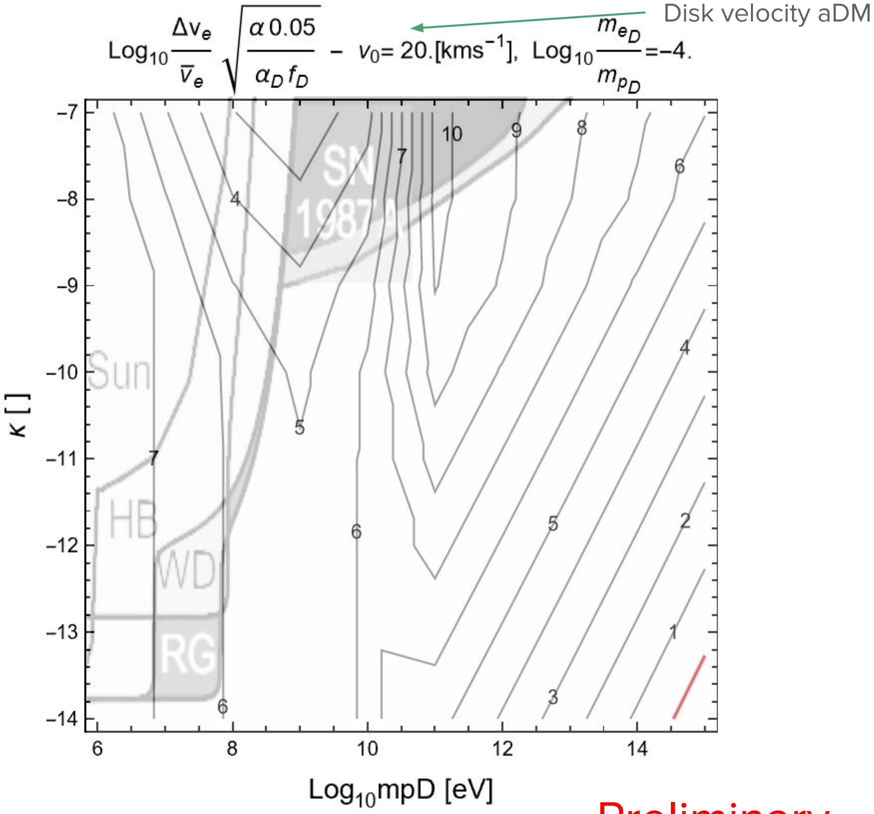




Where in aDM parameter space will accumulation be most significant?

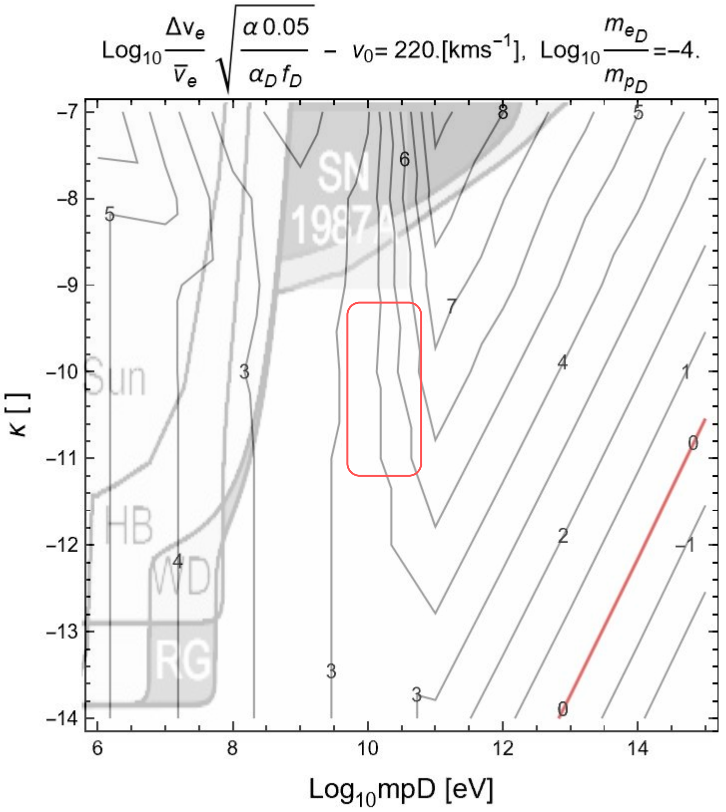
Electrostatic Repulsion and Screening are required to understand the flux in large regions of parameter space

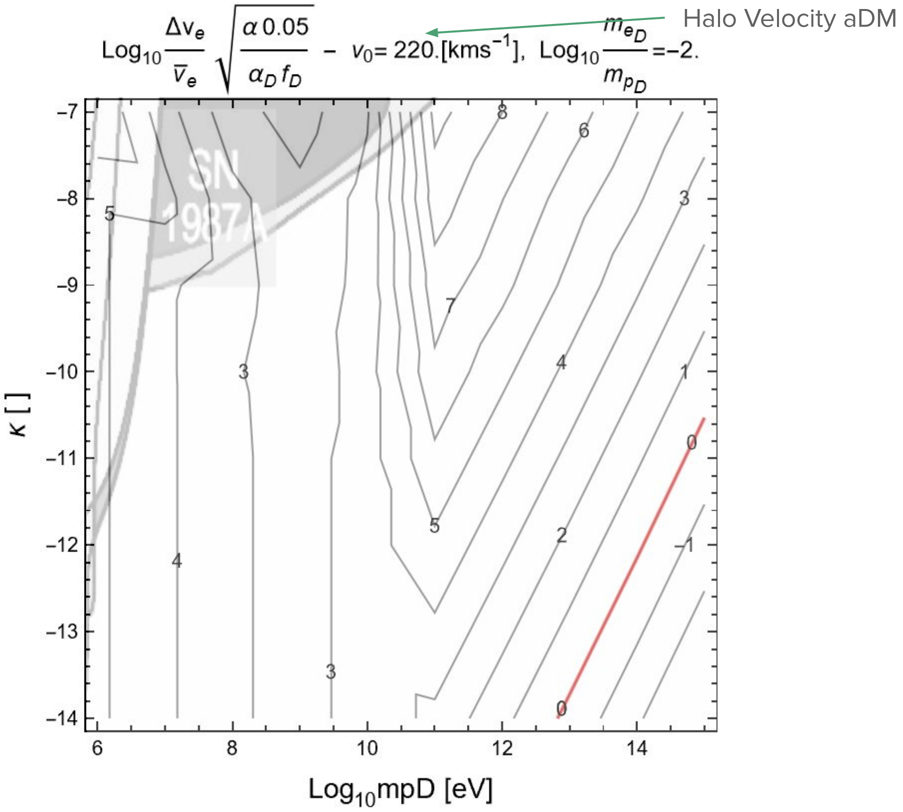




Preliminary

Electrostatic Repulsion and Screening are required to understand the flux in large regions of parameter space



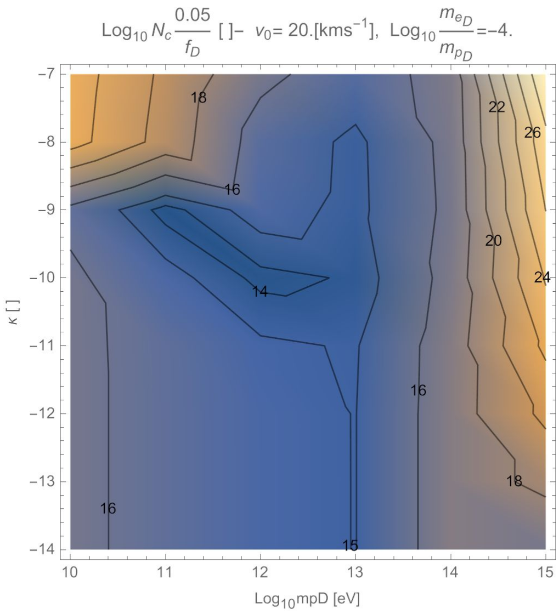


Preliminary

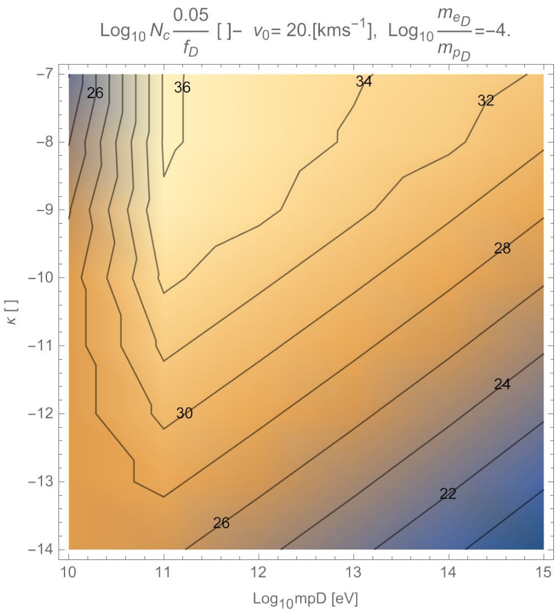
Dark Proton vs Dark Electron Total Captured Charge - Disk

- As outlined in the introduction, Dark Electron capture (ignoring electrostatics, self capture, and screening) is very subdominant to Dark Proton Capture

Dark Electrons



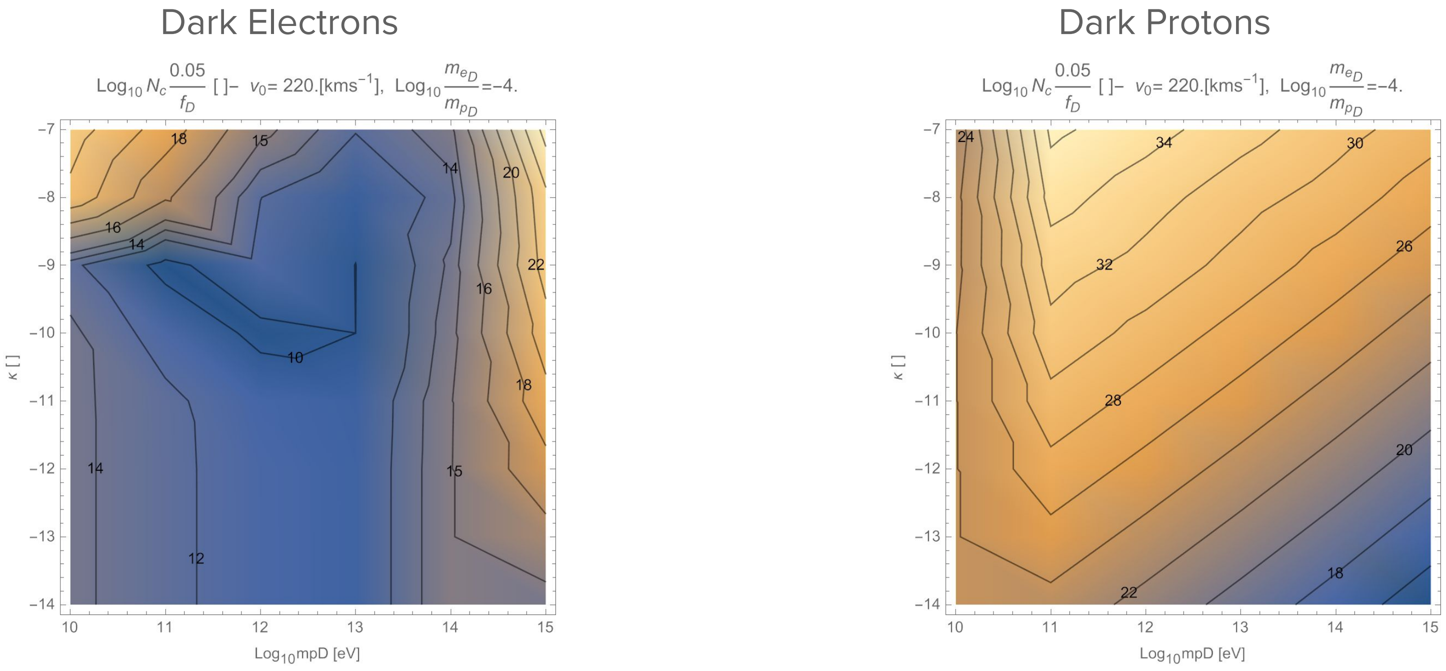
Dark Protons



Preliminary

Dark Proton vs Dark Electron Total Captured Charge - Halo

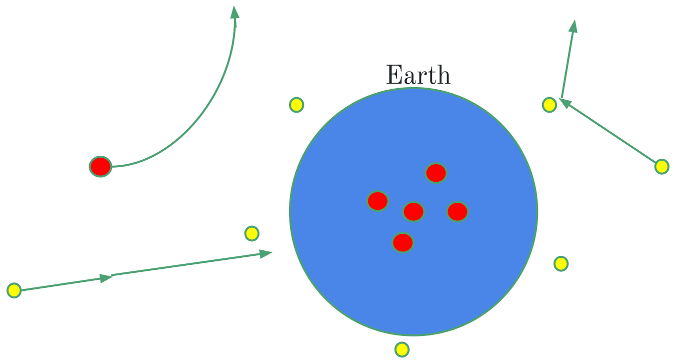
- As outlined in the introduction, Dark Electron capture (ignoring electrostatics, self capture, and screening) is very subdominant to Dark Proton Capture



Preliminary

Complicated Plasma Physics is required to Understand Equilibration in the regime of significant Capture

- We have identified where in parameter space is most significant, now we must consider screening and electrodynamic effects
  - This is problem is highly non-linear, as any accumulated charge can affect both capture and evaporation
  - We look to solve for the equilibrium distribution by iteratively evolving and perturbing the 2 component accumulated charge over the lifetime of the earth.
- With the equilibrium distribution in hand we may find that the **expected recoil energies and fluxes** of aDM sensitive DD experiments **could be significantly altered** in some regions of parameter space



Dark Charge accumulation can affect aDM flux, it's effect on DD experiments is not yet understood

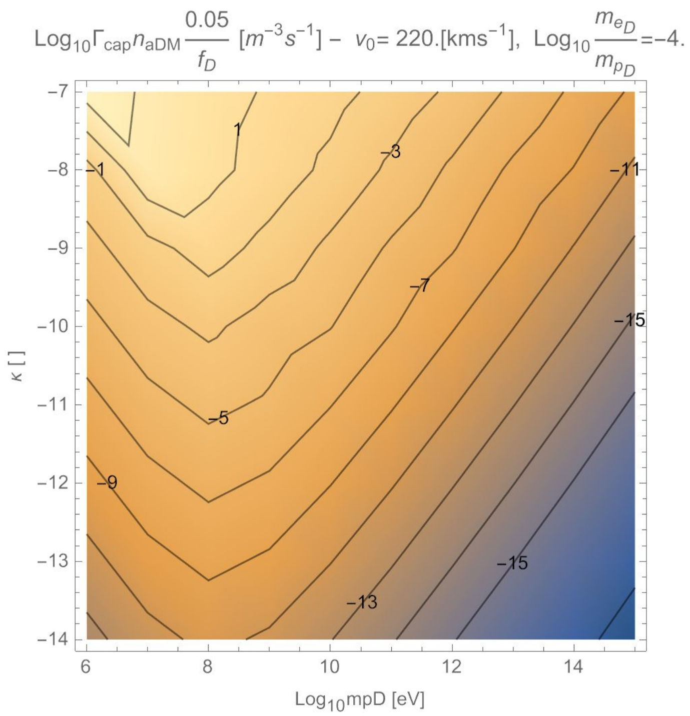
- aDM is a simple, well motivated class of models, with rich dynamics
- We can accurately model the interaction of aDM in the Earth throughout aDM parameter space
- There may be significant accumulation of aDM in the Earth, especially for dark proton masses around 100 GeV - 1 TeV
- Complicated Plasma Physics affects must be understood to disentangle the possibly very significant effect on DD experiments

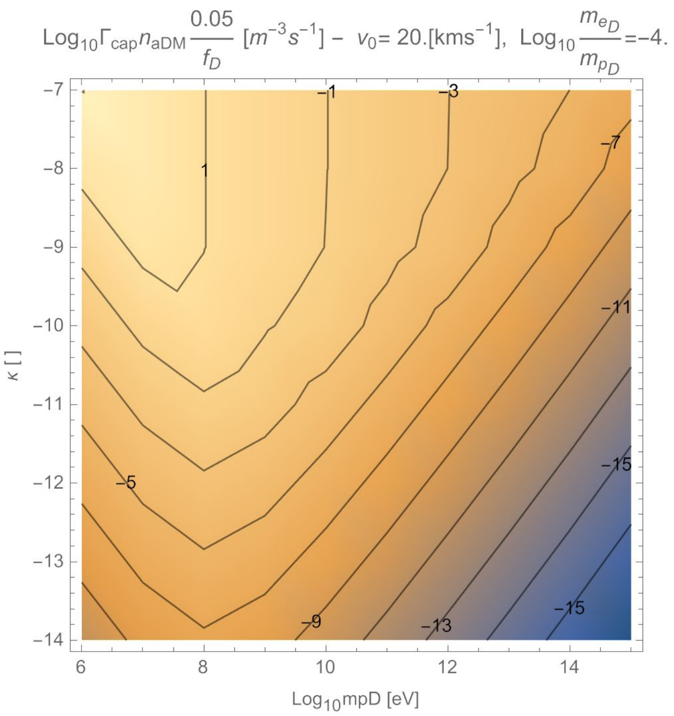
Backup Slides

Backup - Dark Proton Capture Rate

Preliminary

- Capture rates are higher for slower moving Dark Protons
  - Higher mass dark electron cases are similar





Backup - Dark Proton Total Captured Number

Preliminary

- The total captured number is largest in the neighborhood of a 100 GeV
  - Higher mass dark electron cases are similar