Atomic Dark Matter Capture in the Earth

Speaker: Keegan Humphrey - University of Toronto

Ongoing work in Collaboration With: David Curtin, Zackaria Chacko, Ina Flood, Michael Geller, Yuhsin Tsai

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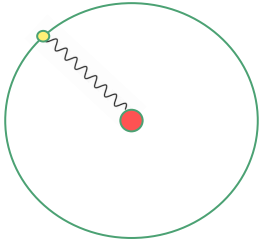
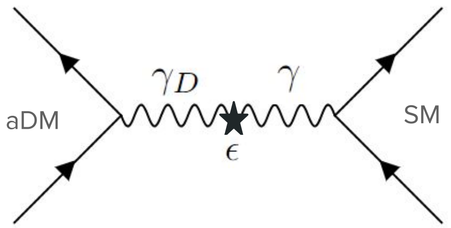
Atomic Dark Matter (aDM) is a simple model with rich and complicated dynamics

$$\mathcal{L}_{aDM} = -\frac{1}{4}F_{D\mu\nu}F^{\mu\nu} + \bar{e}_D\gamma_\mu(i\partial^\mu + q_D A^\mu_D - m_{e_D})e_D + \bar{p}_D\gamma_\mu(i\partial^\mu - q_D A^\mu_D - m_{p_D})p_D$$

- 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 is extremely simple! 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’s dynamics are complicated even though theory is simple (see other talks!)



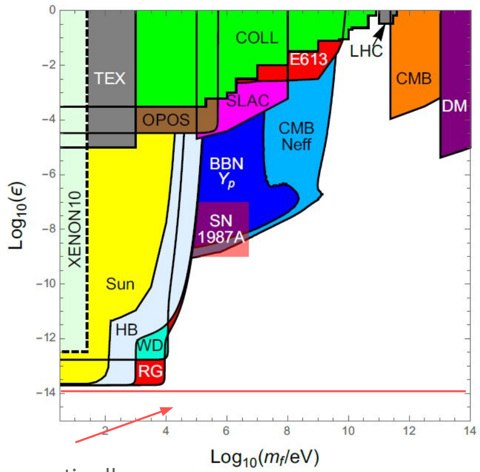
aDM has a Wide Range of Potential Discovery Channels



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

- The minimal interaction of aDM with the SM is a kinetic mixing between the SM and dark photons
  - This gives aDM an effective millicharge
  - The kinetic mixing parameter (ϵ) is constrained by a variety of experiments and expected to be $\gtrsim 10^{-14} - 10^{-13}$ based on theory considerations (1909.00696)
- There are a variety of experiments 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

arxiv: 1511.01122

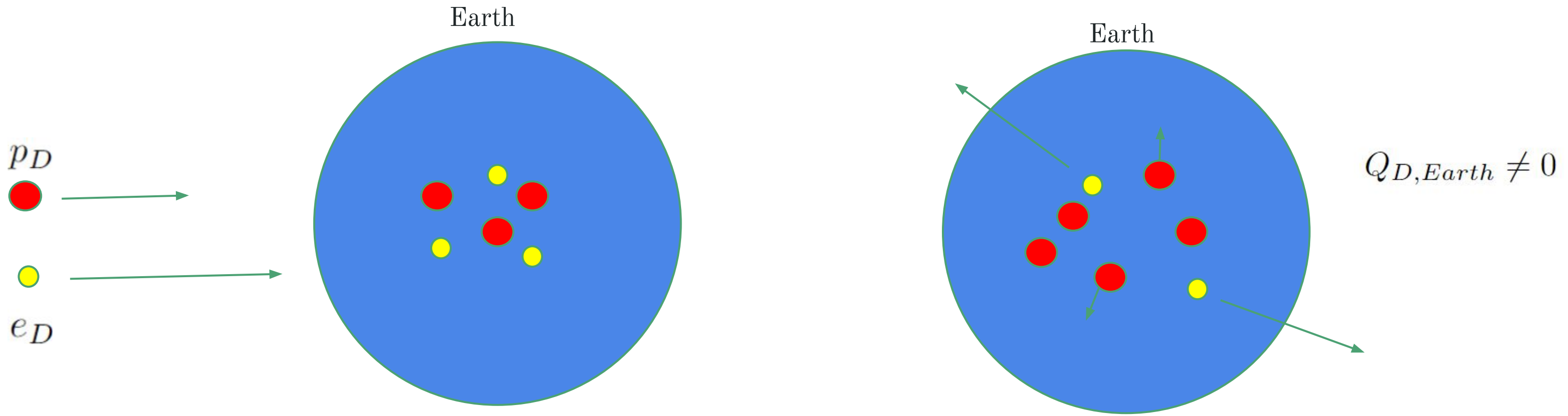


Theoretically disfavoured

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

arxiv: 2104.02074

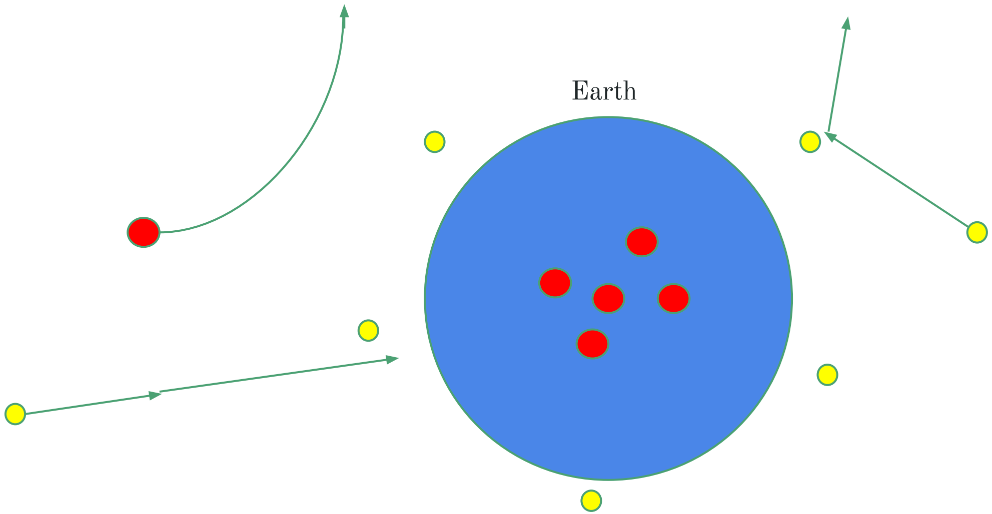
- Long range interactions of aDM make it's dynamics very different from the WIMP
  - Kinetic Mixing leads to small interactions with the Earth and hence energy loss
  - Occasionally aDM can be slowed enough to be captured by Earth's Gravity
  - Captured aDM thermalizes with the Earth, the lighter species (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 electrostatic effects 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, altering the sensitivity of direct detection experiments



Overview

- aDM Interactions in the Earth
  - Electronic
  - Nuclear
- Accumulation of aDM in the Earth
  - Capture Rate
  - Evaporation Rate
- Where in aDM parameter space could incoming flux be affected?
  - Escape velocity in the absence of electrostatic or plasma effects
  - How to determine the equilibrium flux of aDM at Earth
- Conclusions and Next Steps

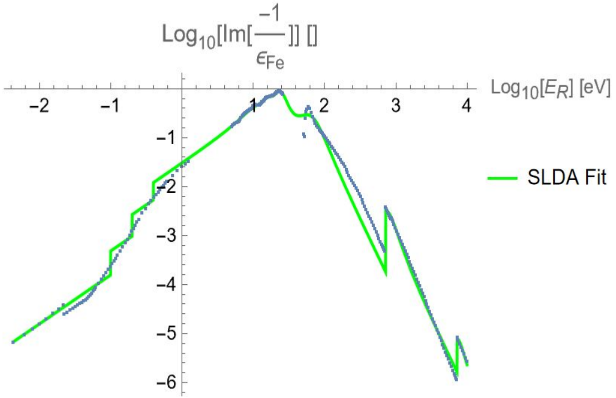
aDM Interactions in the Earth

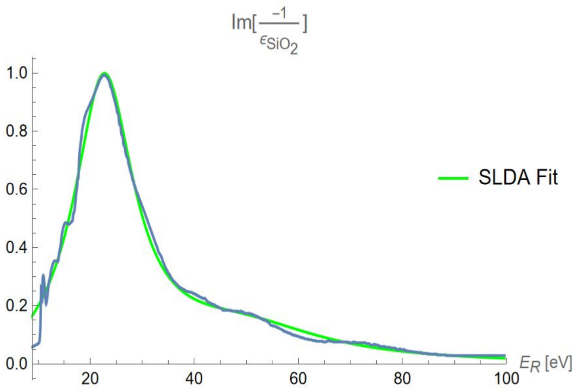
We use a Data Driven Mermin Model of the Electron Interactions to treat both conductors and insulators

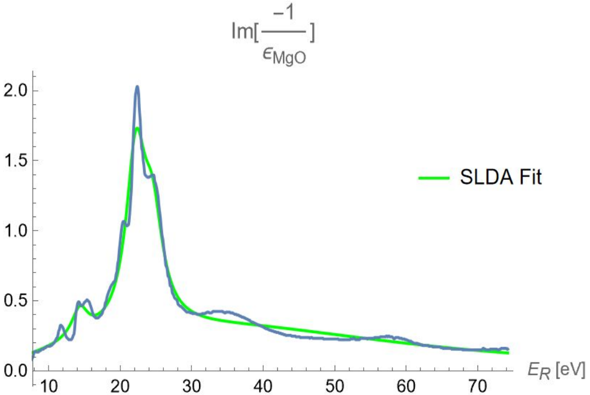
arxiv: 2101.08275
arxiv: 2108.03239
(Chen et al., 1993)

- The response of electrons in a solid to a non-relativistic probe are completely characterized by the Longitudinal Dielectric Function (in medium photon polarization)
  - This can be measured directly using optical experiments (2101.08263)
- 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

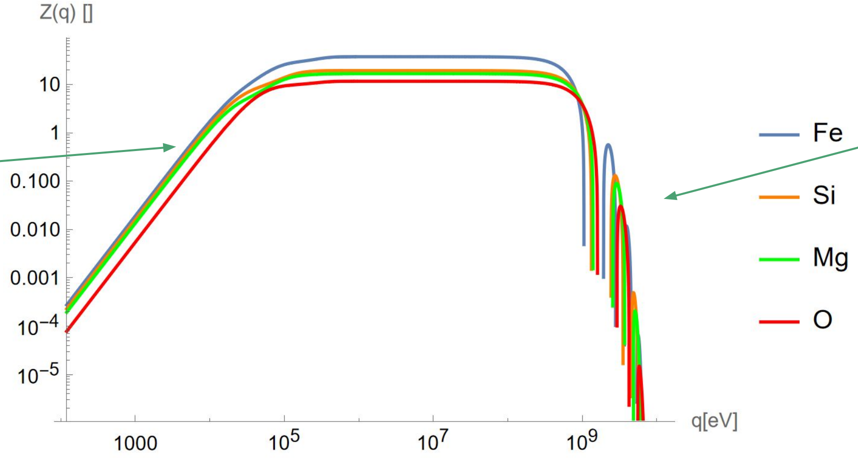






We use both Atomic and Nuclear form factors for scattering off Nuclei

- At lower momentum transfers, the Electrons screen the Nuclear Charge
  - We use atomic form factors from fit to data from X-ray scattering experiments (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

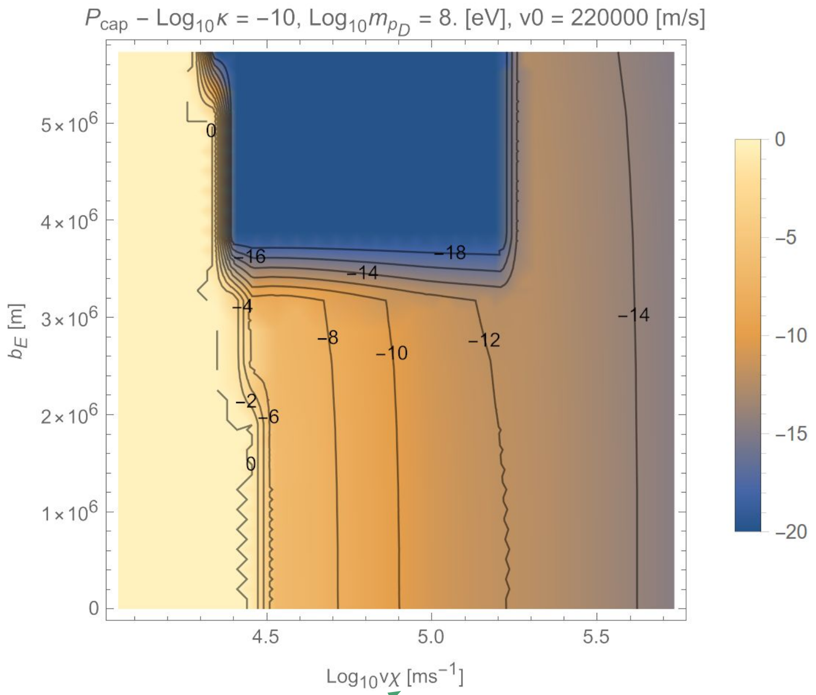
Accumulation of aDM in the Earth

We estimate aDM capture, ignoring Dark Electrostatics

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

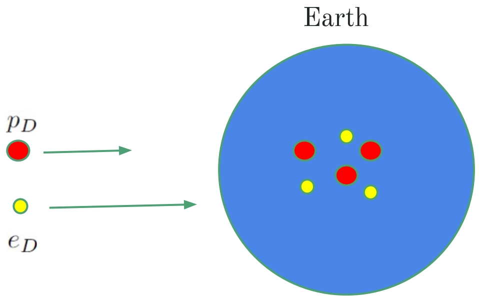
Galactic simulations are required to understand these assumptions

Preliminary



Impact parameter

aDM velocity at the Surface



Captured aDM can be evaporated

Preliminary

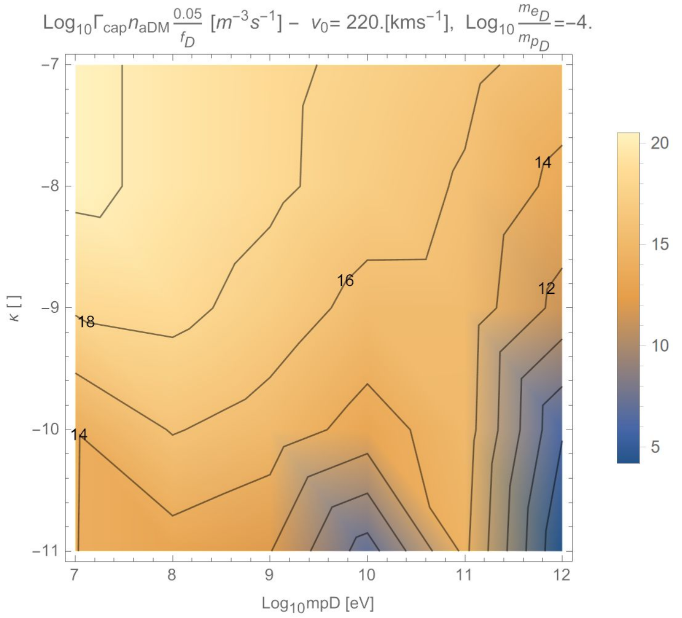
- Captured aDM can scatter off the nuclei and be evaporated
- Evaporation and capture rates quickly equilibrate.
    - Equality of the rates then determines the total captured population

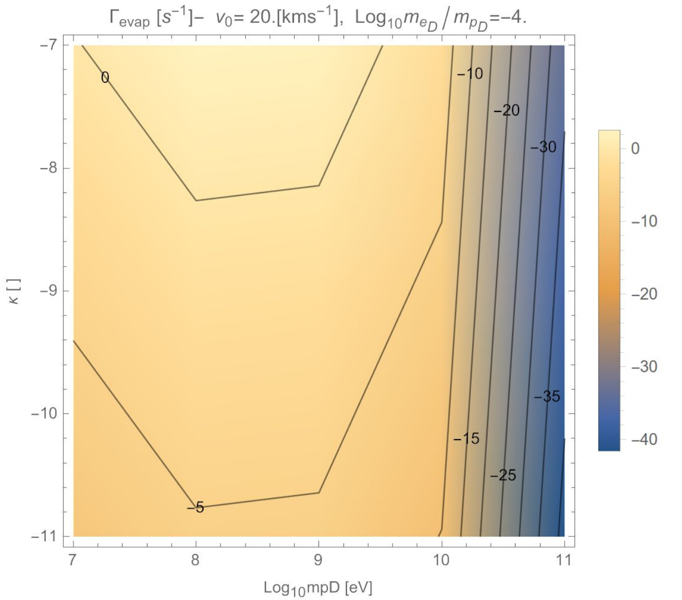
$$\Gamma_{evap} n_{cap} = \Gamma_{cap} n_{aDM,local}$$

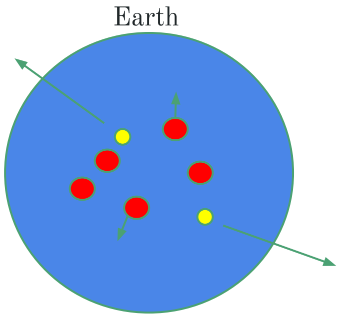
Per particle evaporation rate

Captured density in Earth

Per particle capture rate

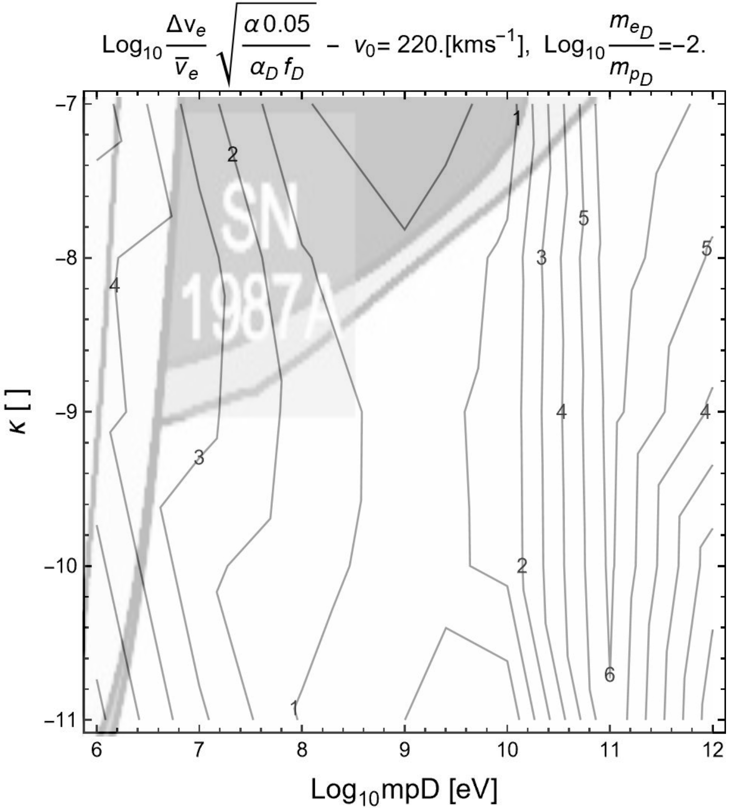

$\mathrm{Log}_{10}\Gamma_{cap} n_{aDM} \frac{0.05}{f_D}$ $[m^{-3}s^{-1}]$ – v_0= 220.[kms^{-1}], $\mathrm{Log}_{10}\frac{m_{e_D}}{m_{p_D}}$=−4.

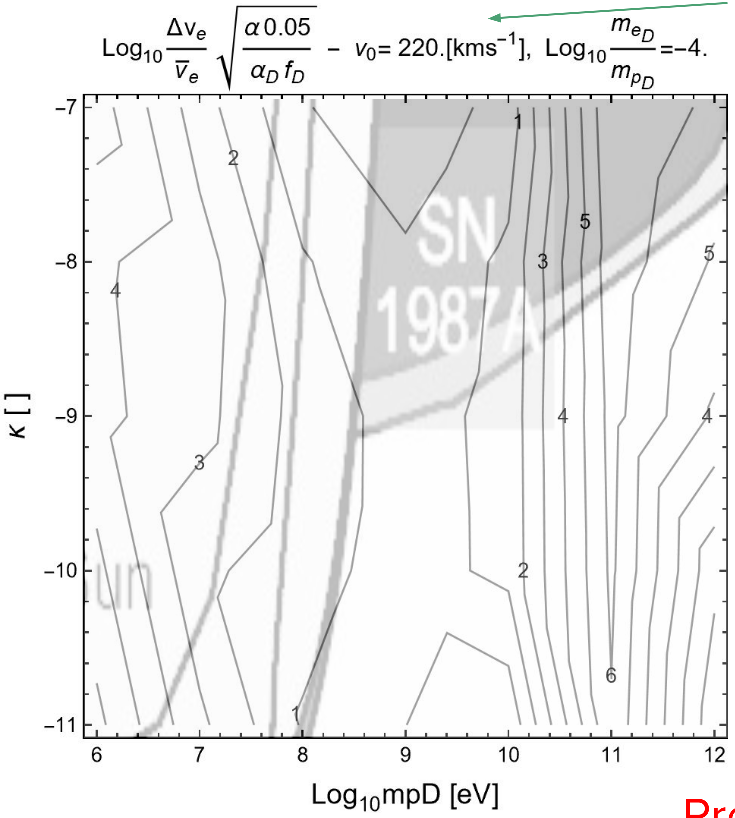

Γ_{evap} $[s^{-1}]$– v_0= 20.[kms^{-1}], $\mathrm{Log}_{10} m_{e_D} / m_{p_D}$=−4.



Where in aDM parameter space could the incoming flux be affected?

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

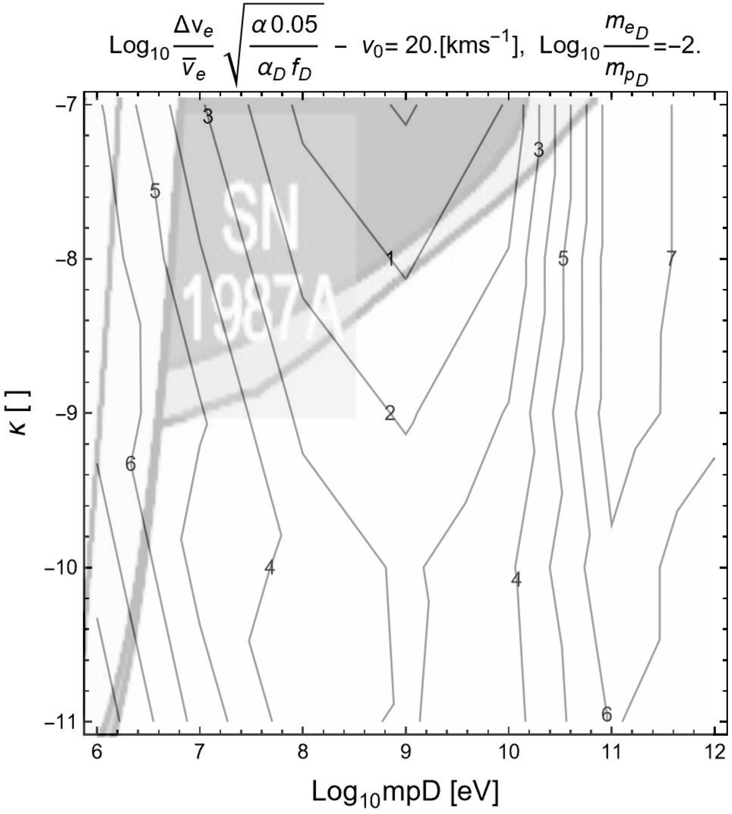


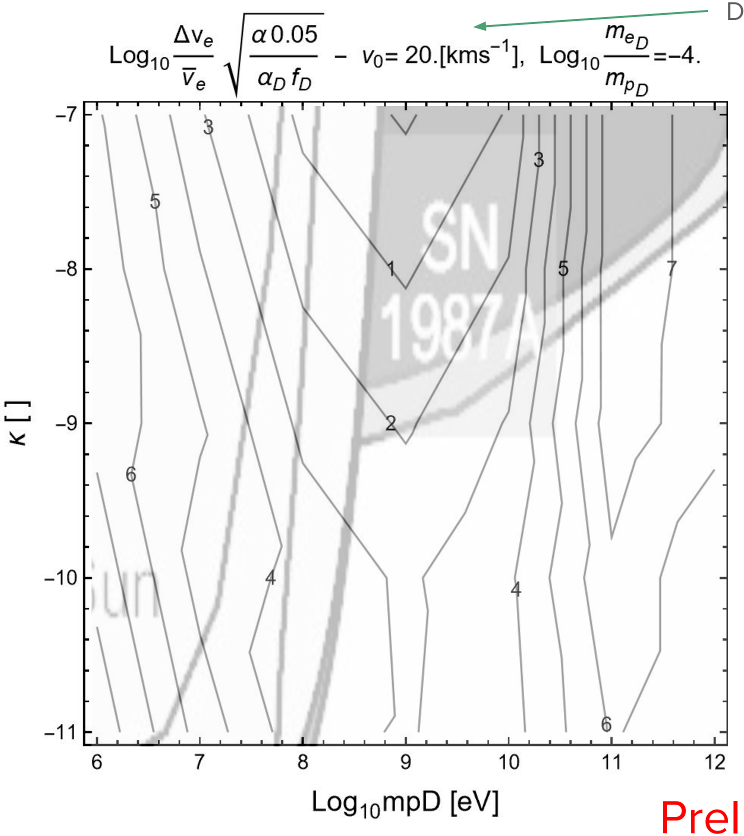


Halo Velocity aDM

Preliminary

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





Disk velocity aDM

Preliminary

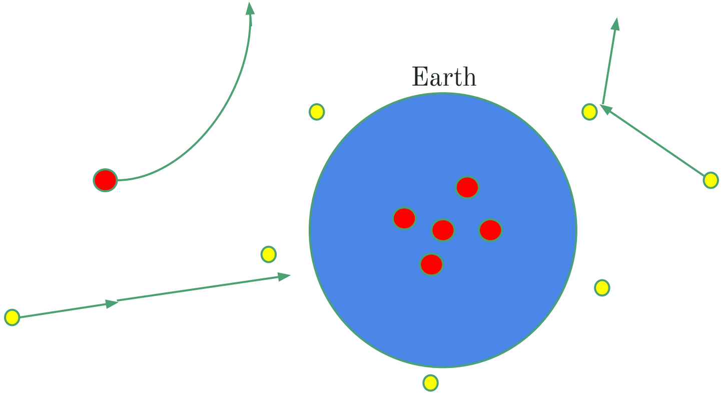
Complicated Plasma Physics is required to Understand Equilibration in the regime of significant Capture

- In reality, determining the effect of the captured dark charge on the incoming velocity distribution will not be so simple
  - The flux of aDM in the presence of the dark charged Earth is described by a Collision Full Vlasov Poisson equation (Boltzmann equation in the presence long range interactions), this is a non-linear PDE
  - In rare cases, this equation can be solved analytically, often one must resort to perturbative or numerical methods

$$\frac{\partial f_a}{\partial t} + v_i \frac{\partial f_a}{\partial x_i} + \frac{F_i}{m_a}\frac{\partial f_a}{\partial v_i} = \sum_b \mathcal{C}[f_a, f_b]$$

Gravitational and Electrostatic Forces

Non-linear collision term between species a and b



(Ng & Bhattacharjee, 2005)
(Hirschfelder et al., 2010)
(Vogman et al., 2019)

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
- Complicated Plasma Physics affects must be understood to disentangle the effect on DD experiments

References

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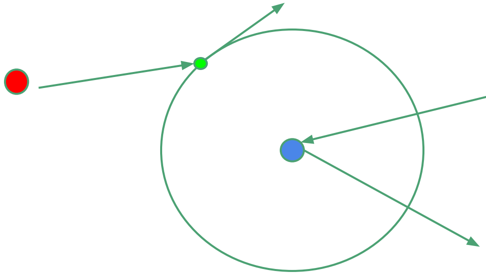
Backup Slides

aDM interacts with both Nuclei and Electrons in Earth

- Unlike scenarios considered by other capture codes (eg. 1706.02249 which considers only nuclear interactions), our DM interacts with both Electrons and Nuclei.
  - Further, unlike in stars where the species are ionized (2404.10066), in the Earth we must account for the complicated electronic structures of solids
- 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
  - Capturing the huge variations over the huge range of $\alpha_D,\ \kappa,\ m_{p_D},\ m_{e_D}$ is more important than eg. small differences between low abundance elements
  - As such we use a two component Earth model: SiO2 and MgO in the Mantle (the most abundant elements), and Fe in the core



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

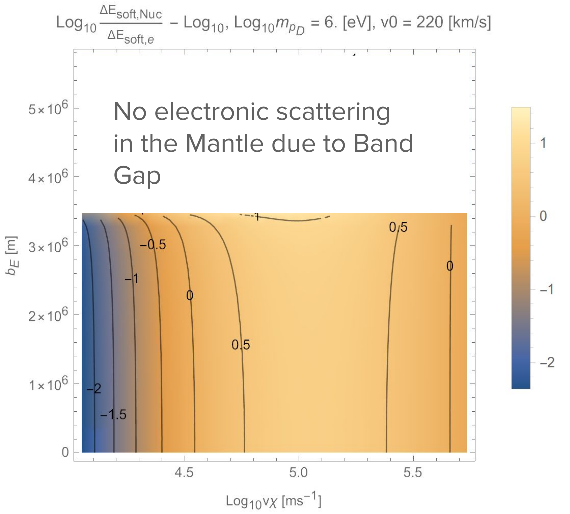
- Working out the equilibrium distribution of a plasma is difficult
- We begin by ignoring aDM plasma effects and self capture, estimating how much aDM could be accumulated, and determining how significantly the accumulated aDM affects the incoming aDM speed throughout parameter space.
    - Since p_D is less efficiently evaporated, we conservatively only consider their capture
- The accumulated charge depends on:

α_D	● Dark Coupling
$\kappa = \epsilon\sqrt{\alpha_D \alpha^{-1}}$	● Kinetic mixing with SM photon (constrained by DM searches)
$f_D = \frac{\rho_{aDM,local}}{\rho_{CDM}}$	● The Local aDM number density (this is not known apriori and must be determined from N-Body Galactic simulations!)
$v_0 = \sqrt{3T_D \bar{m}_D^{-1}}$	● The DS temperature (this is bounded by stellar speed, and the galactic escape velocity $(\sim 20,\ \sim 500)\mathrm{kms}^{-1}$)
$m_{p_D},\ m_{e_D}$	● The aDM masses

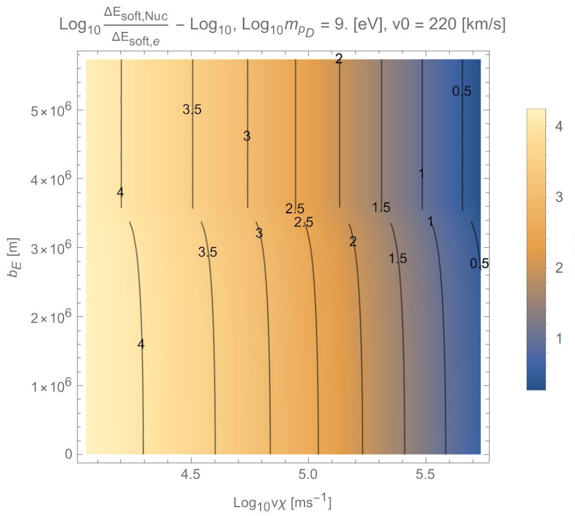
Backup - Capture in the Soft Scatter Regime

Preliminary

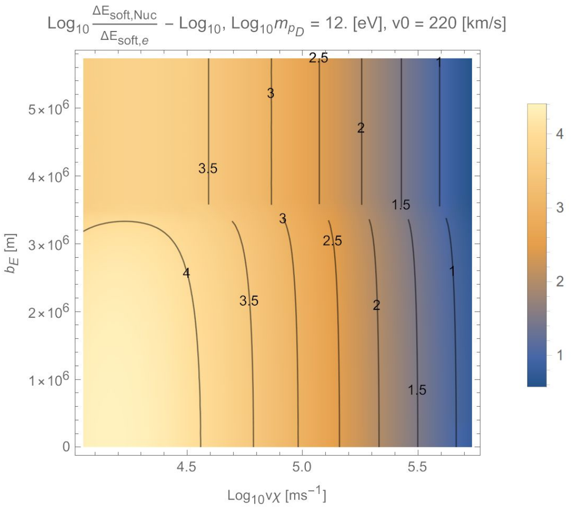
- We can compare Nuclear vs Electronic energy loss in the soft scattering regime (their ratio is independent of the kinetic mixing)
    - At intermediate and high masses, nuclear scattering always dominates the capture rate due to soft scatters
    - Only at low masses can electronic scattering with Iron in the core dominate the energy loss rate.
        - And as we see in the next slide, at such low masses aDM is not captured by soft scatters.



1 MeV



1 GeV

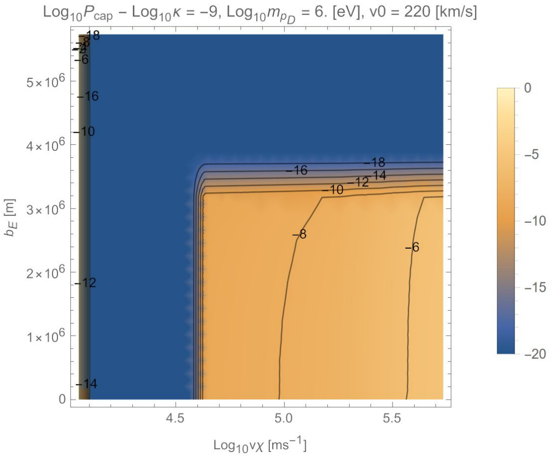


1 TeV

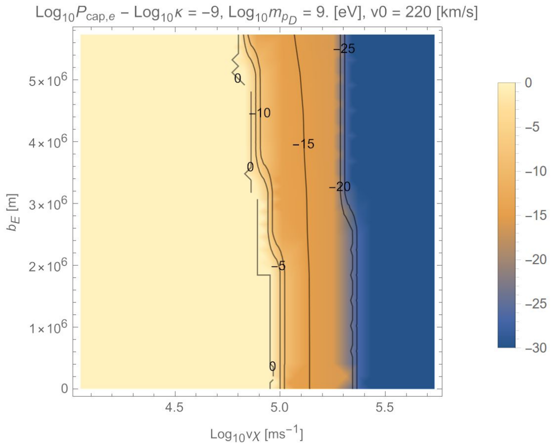
Backup - Capture in the Hard Scatter Regime

Preliminary

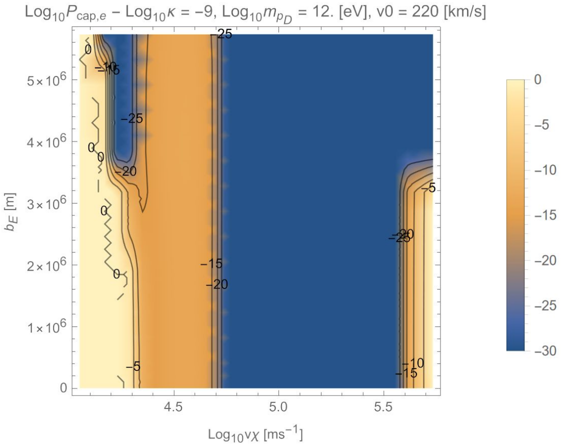
- A hard nuclear scatter is not able to capture aDM anywhere in the parameter space we consider
  - At low masses, only hard scatters off the electrons in Iron can lead to capture
  - At intermediate masses, we are above the band gap of the silicates, so hard scattering captures can occur in the mantle, however, we are dominated by soft scattering capture
  - At high masses the same applies, but now rare, fast moving, aDM can also be captured by scattering off inner core electrons in iron



1 MeV



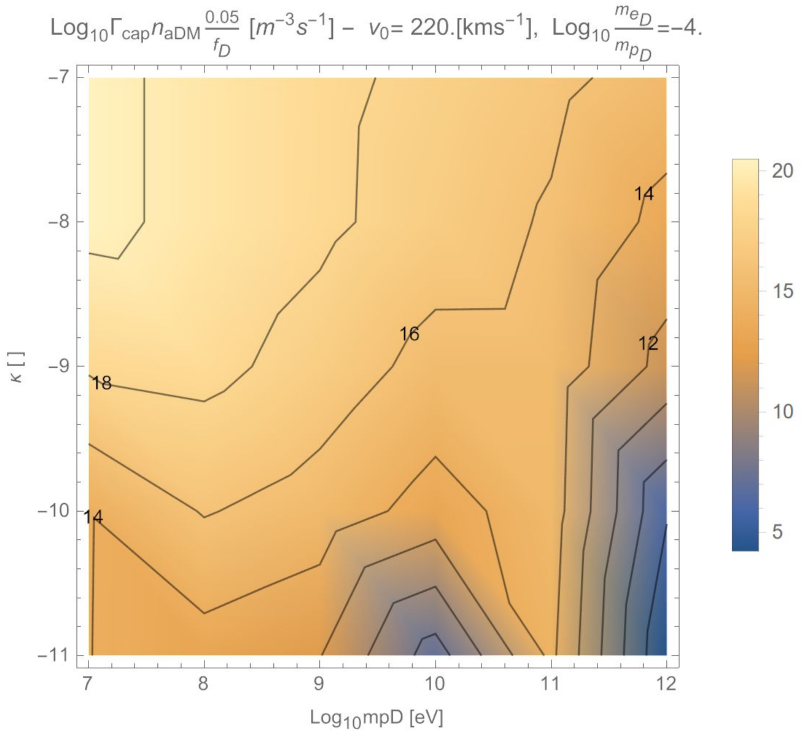
1 GeV

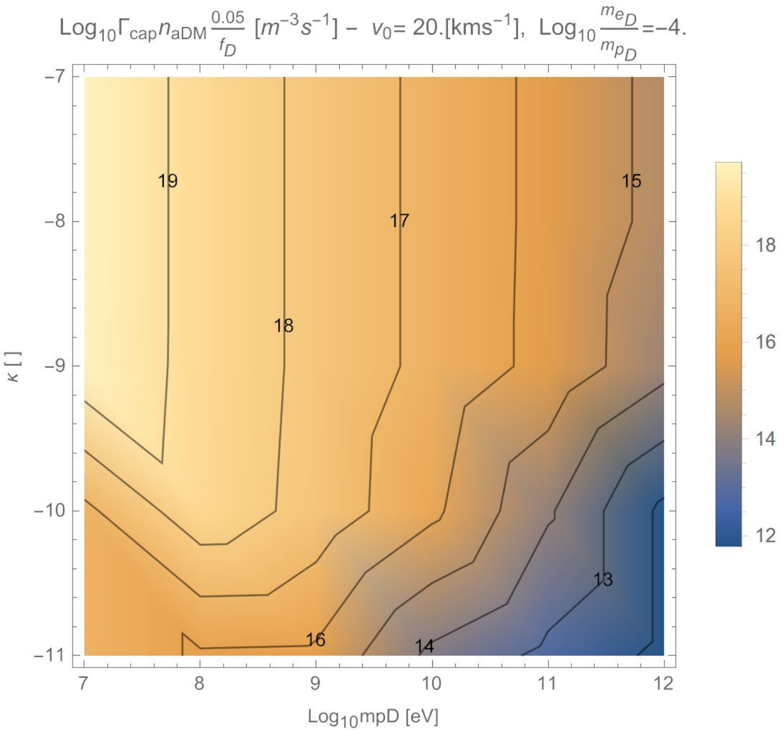


1 TeV

Backup - Capture Rates

Preliminary

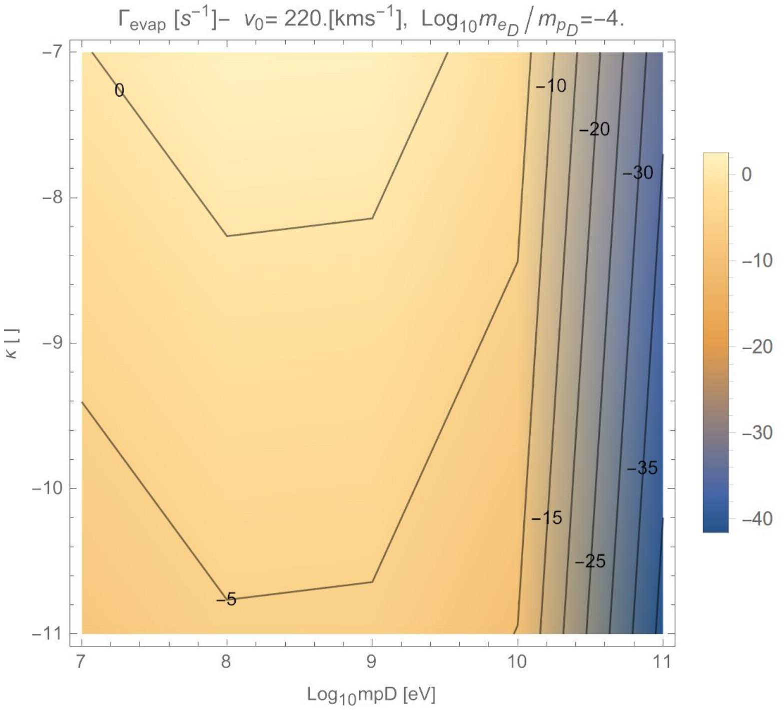


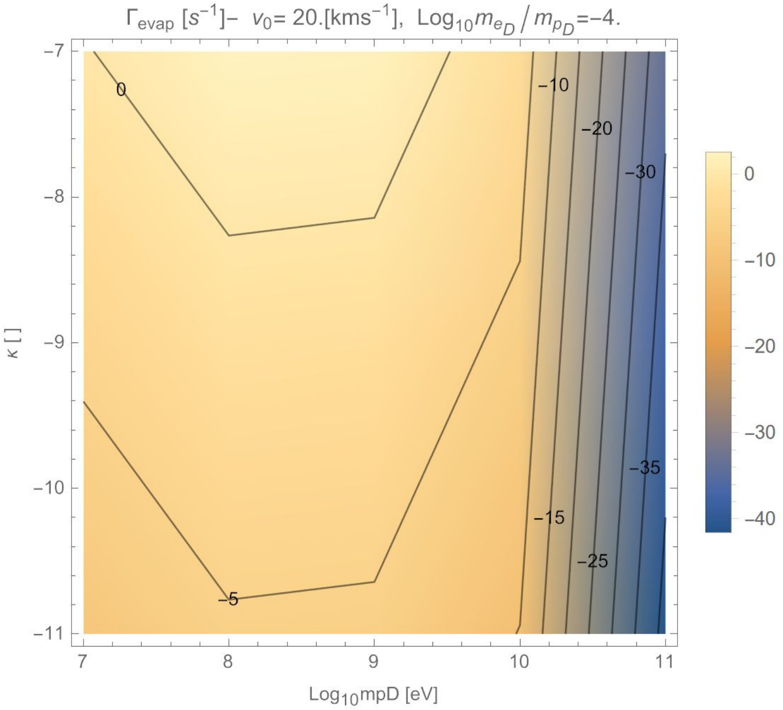


Backup - Evaporation Rates

Preliminary

- The evaporation rate drops off very quickly as the dark proton mass increases above the mass of the nuclei
    - It always scales as the kinetic mixing squared.

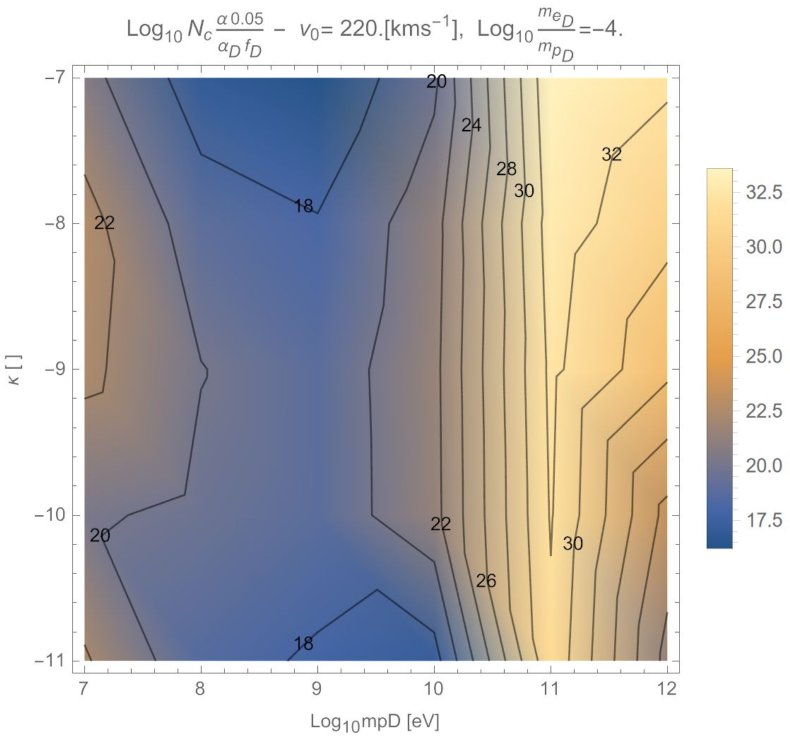


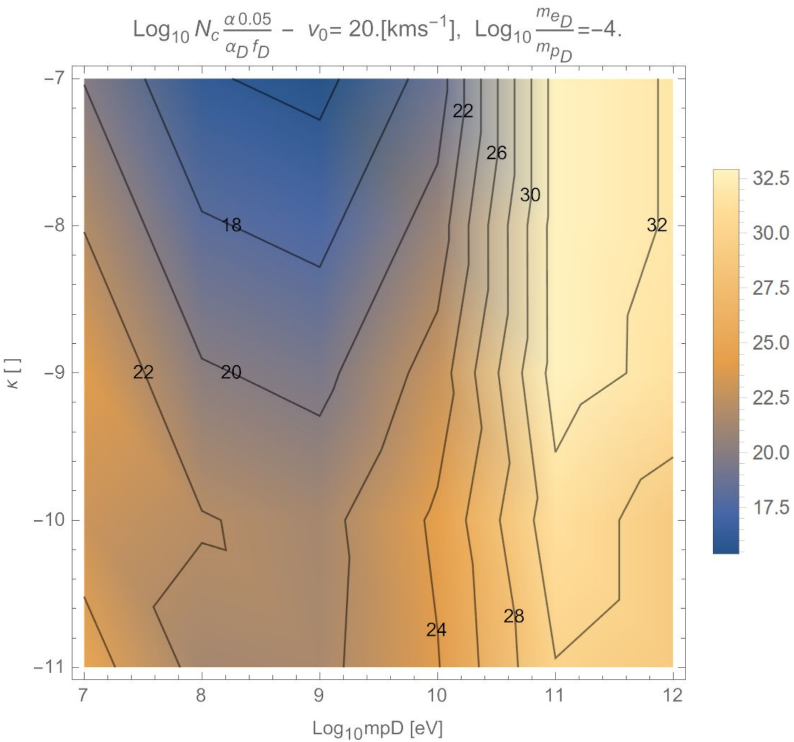


Backup - Total Captured Number

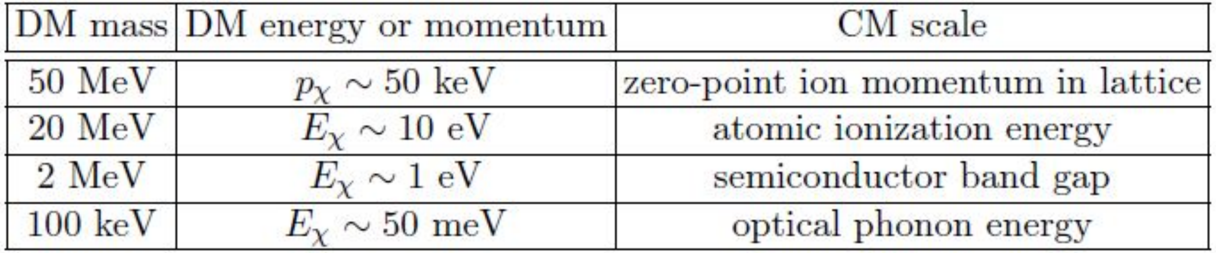
Preliminary

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





Backup - Relevant Scales for Scattering in CM Systems



DM mass	DM energy or momentum	CM scale
50 MeV	$p_\chi \sim 50$ keV	zero-point ion momentum in lattice
20 MeV	$E_\chi \sim 10$ eV	atomic ionization energy
2 MeV	$E_\chi \sim 1$ eV	semiconductor band gap
100 keV	$E_\chi \sim 50$ meV	optical phonon energy

TABLE I: Energy and momentum scales relevant for DM scattering in CM systems

Courtesy of: 2108.03239

$$\omega_p = \frac{3\pi e^2 n}{m}$$

$$D = \mu\beta \to E_F\beta = \frac{\hbar^2(3\pi^2 n)^{2/3}}{2m}\beta$$