Light Dark Matter Accumulating in Terrestrial Planets: Nuclear Scattering

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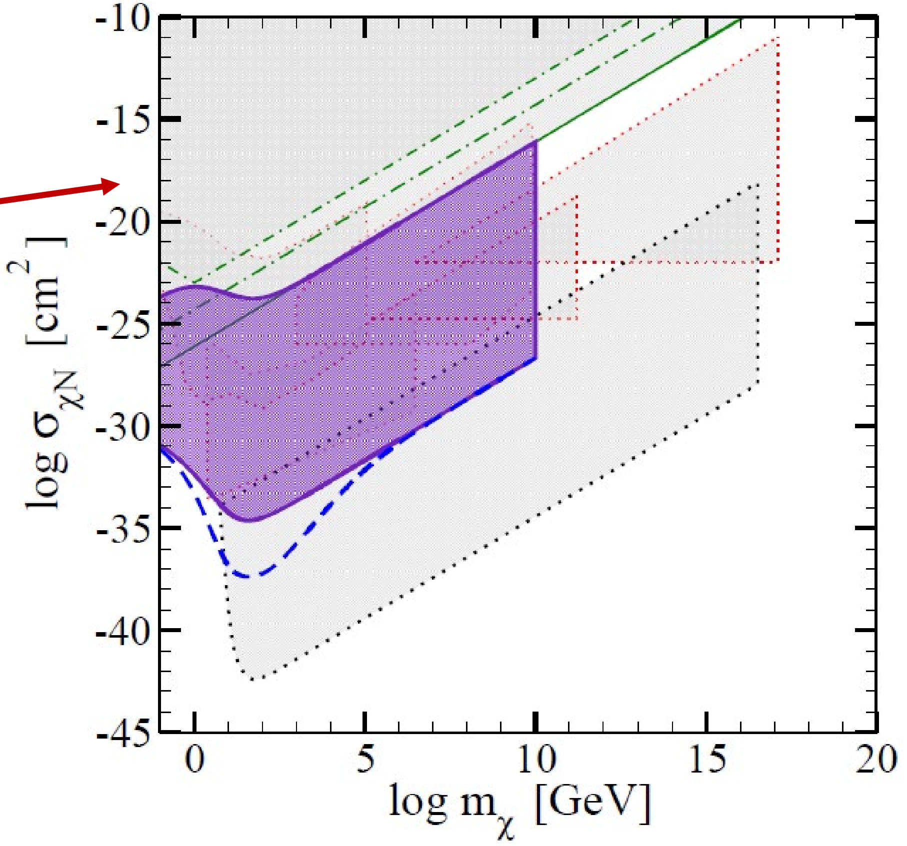
dark matter accumulation in the Earth

- why do we care?
- leads to several search strategies
    - DM annihilation constrained by anomalous Earth heating …
    - … and neutrino flux
    - low-threshold direct detection may probe captured DM (RKL, JS 2209.09834; AD, NK, RKL 2210.09313)
- most studies focus on optically thin regime
- we focus on optically thick regime

Mack, Beacom, Bertone 0705.4298



optically thick regime

- dark matter can scatter many times as it passes through Earth
- opportunities for studying otherwise unconstrained parameter space
  - deep-underground direct detection experiments shielded, so need another way to close parameter space at large $\sigma_{\chi N}$
  - evaporation calculation more tricky, affecting constraints at low mass
- new aspects to the analysis
  - low-mass dark matter can bounce off the Earth ("ping-pong effect")
  - must deal with three-body gravitational effects

- some studies use analytic treatments
- we use a numerical simulation using modified DaMaSCUS code
  - can address some more complicated features

pathway to DM accumulation

- dark matter scatters, loses energy, and is gravitationally captured by Earth
- continues scattering and thermalizes with SM matter
- thermal dark matter distribution can annihilate or evaporate
- total number accumulated (N) determined by equilibrium of capture (C), annihilation (A) and evaporation (E) rates

$$\frac{dN}{dt} = C - \left(\frac{E}{N}\right) N - AN^2$$

outline

- dark matter capture in the optically-thick regime
- density profile
- evaporation
- annihilation
- application to bounds on dark matter annihilation via anomalous Earth heating

DM capture – our basic approach

- assume a Maxwell-Boltzmann distribution (boosted) for DM far from Sun
- particles incident on Earth after including acceleration due to Earth and Sun gravitational potential
- propagate with DaMaSCUS until particles drop below Earth escape speed
  - captured
  - 3D Earth model includes atmosphere, crust, mantle, core
- if particle leaves Earth with $v > v_e$ (Earth escape speed) → gone

- determine the fraction of incident particles which are captured, and will eventually thermalize
- numerical simulation is computationally intensive, but worth it ….

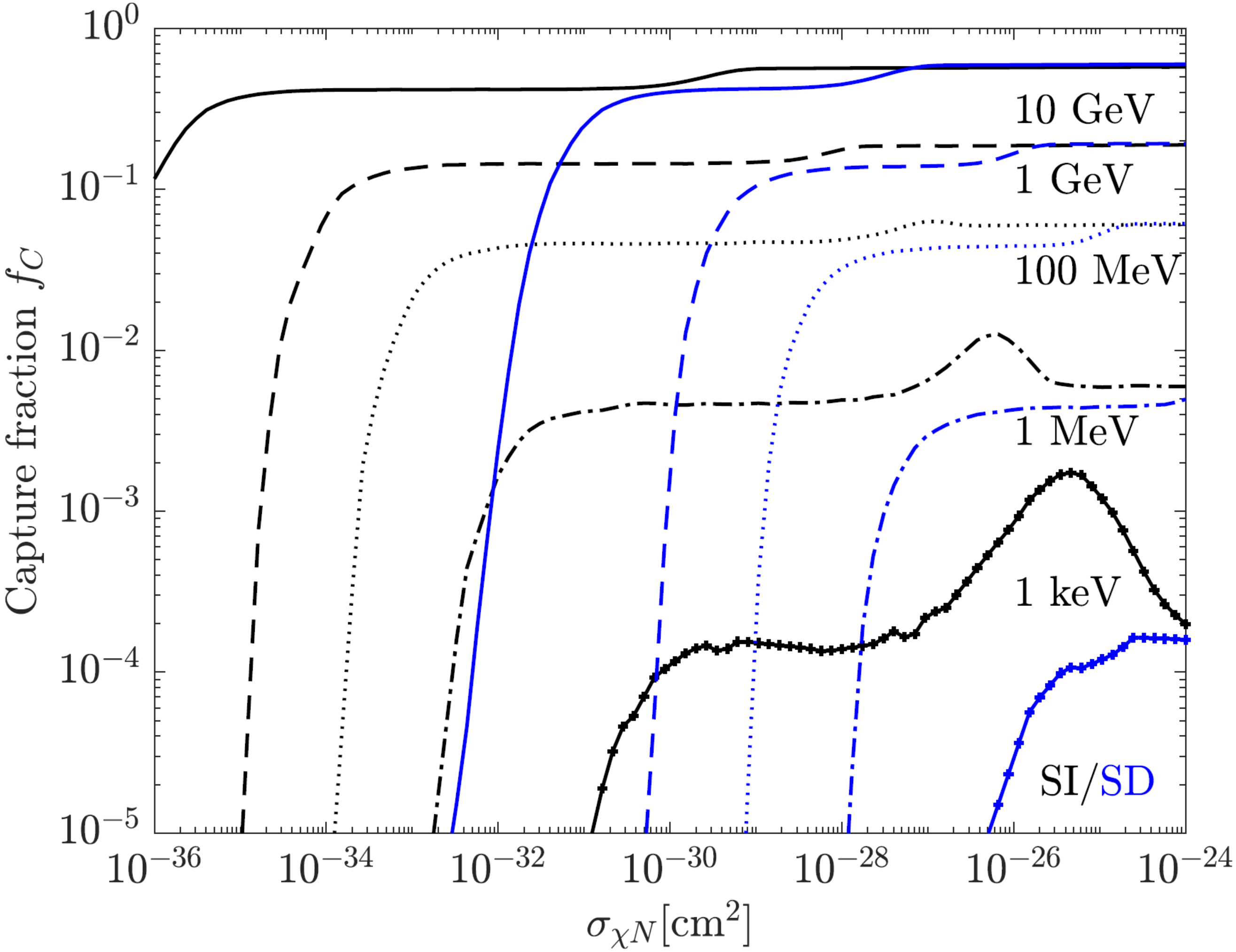
fraction of DM captured

$f_C = C / C_{geom}$
$C_{geom} \sim 10^{25}\ s^{-1}\ (GeV/m_\chi)$

f_C saturates at large $\sigma_{\chi N}$, but not to 1 (for this mass range)

smaller m_χ → smaller f_C at saturation

"resonant" bump

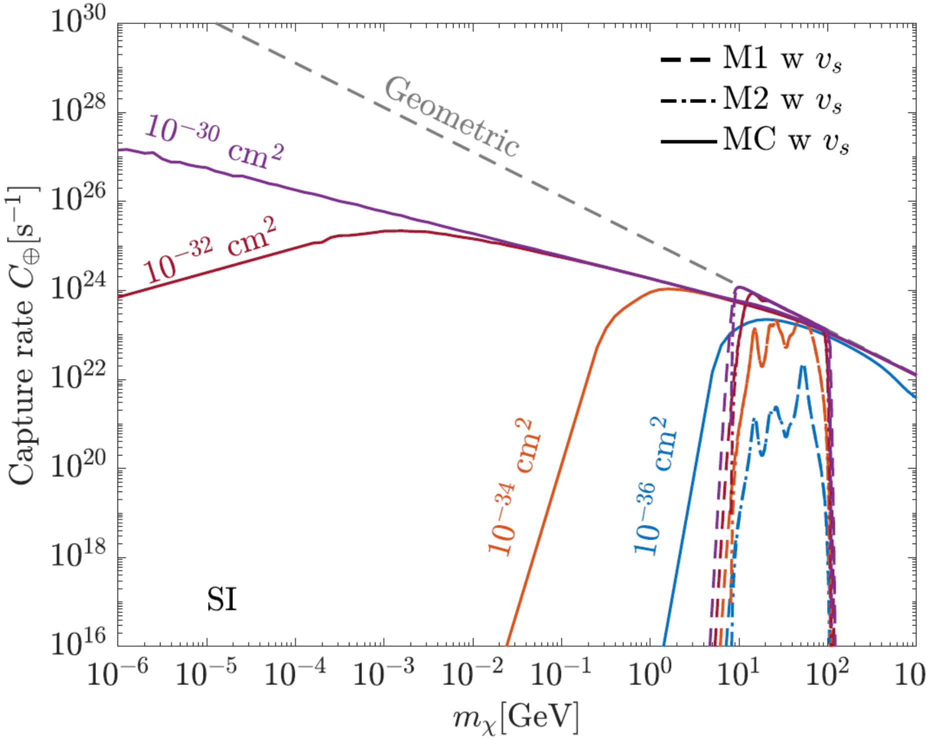


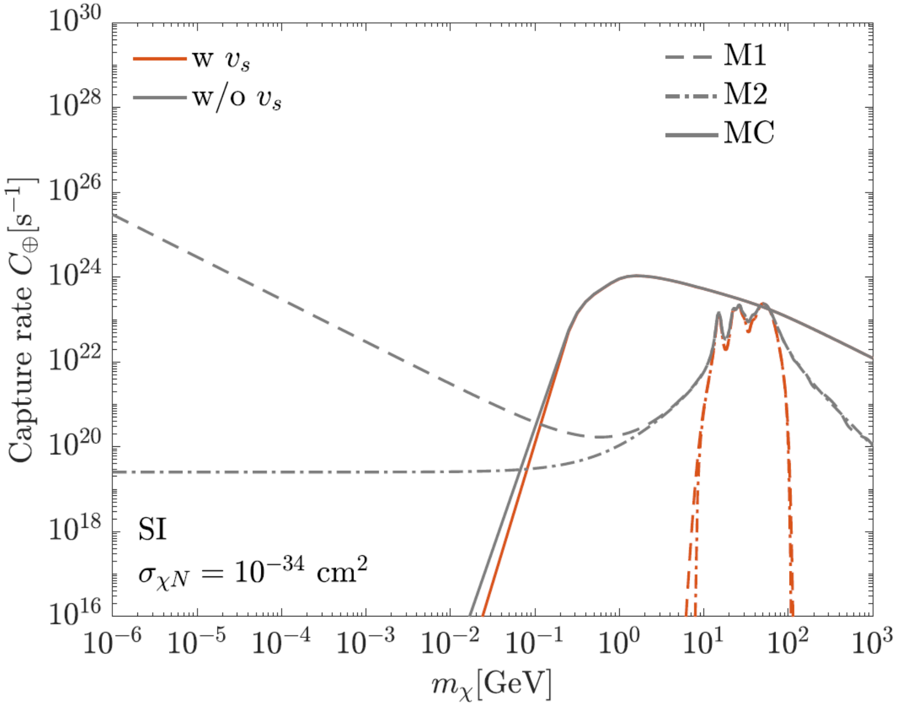
approaches to optically-thick regime

- several works use analytic approximations, but can miss some features which matter in optically-thick regime

- one approach is to only consider capture after a single scatter, but account for attenuation of flux (G,P-R 1702.02768; B, M-A, P-R 1208.0824 – for Sun)
  - interpolates between optically-thin and geometric capture rates
  - $C = C_{thin} [1 - \exp(-C_{geom}/C_{thin})]$
  - only accounts for capture after multiple scatters through "reprocessing"
- another approach → analytic approximation to multiple scattering (RKL, JS 2209.09834)
  - actual evolution of kinetic energy
  - may not fully account for varying composition of Earth, detailed DM trajectory (except in limiting cases) (but see Chris' talk for recent progress ….)

comparison to single scatter treatment





left → include effect of solar potential
right → compare with or without solar potential

M1 → target nucleus at rest
(G,P-R 1702.02768)
M2 → thermal motion for target
(BVFS 1611.09665)

comparison to single scatter treatment

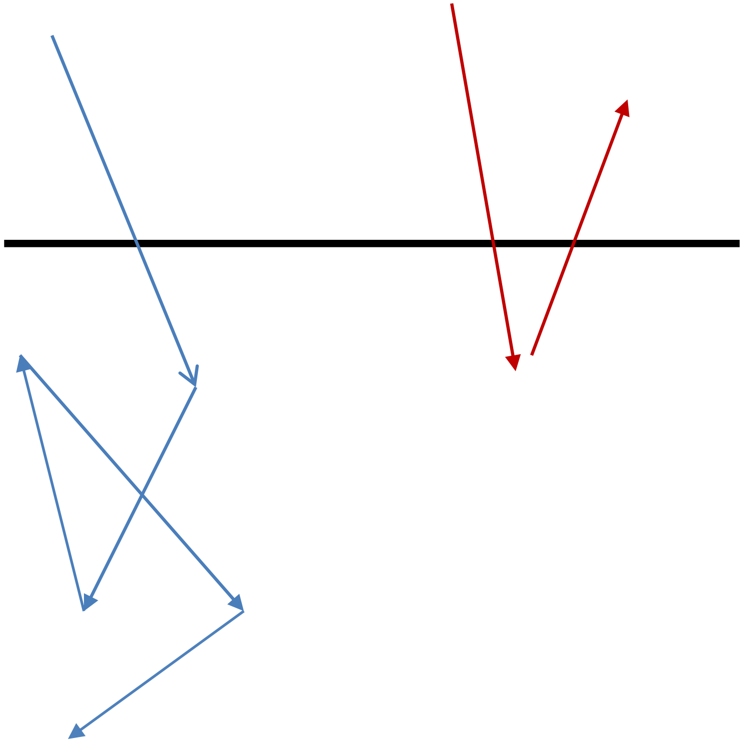
- including multiple scatters washes out the effect of kinematic resonances

- impact from solar potential on extrapolation from single scatter
  - need $\Delta E_{max}/E \sim m_A m_\chi / (m_A + m_\chi)^2 > (v^2 + v_s^2) / (v^2 + v_e^2 + v_s^2)$
  - if you ignore solar potential ($v_s=0$), then for any m_χ, some particles ($v \sim 0$) can be captured with a single scatter
  - if you assume reprocessing, reach geometric cross section for large $\sigma_{\chi N}$
  - but if you include solar potential, then for heavy or light χ, can never capture with a single scatter, so not captured at all

- but solar potential has little impact on MC result, even though $v_s > v_e$
  - related to slope of the low mass regime

ping-pong effect

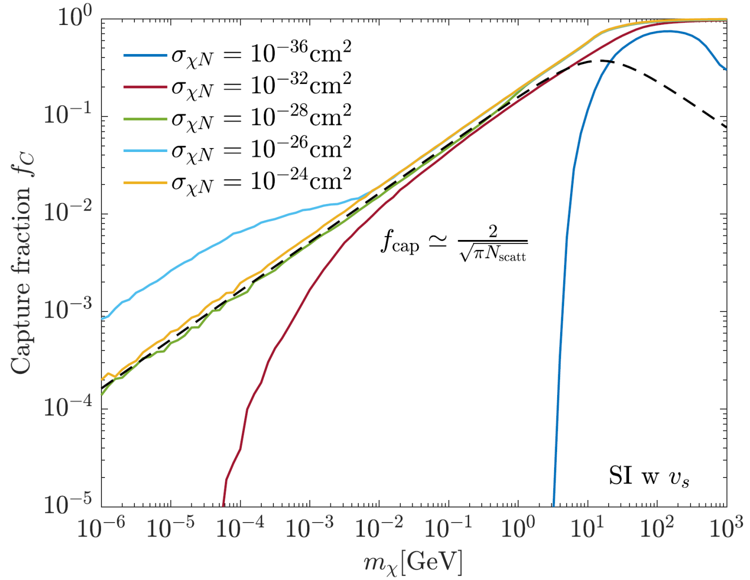
- for $m_\chi \ll m_A$, scattering is nearly isotropic
  - DM random walks through Earth until dropping below escape vel.
  - if it leaves Earth, it is gone
  - $N_{scat} \sim 2\,(m_A/m_\chi)\,\ln(v_i/v_f)$
  - fraction captured ~ $N_{scat}^{-1/2}$ (NFM, 1805.08794)
  - so f_c scales as $m_\chi^{1/2}$, but only logarithmically with v_s
- but for low mass, $f_c \ll 1$
- what about details?

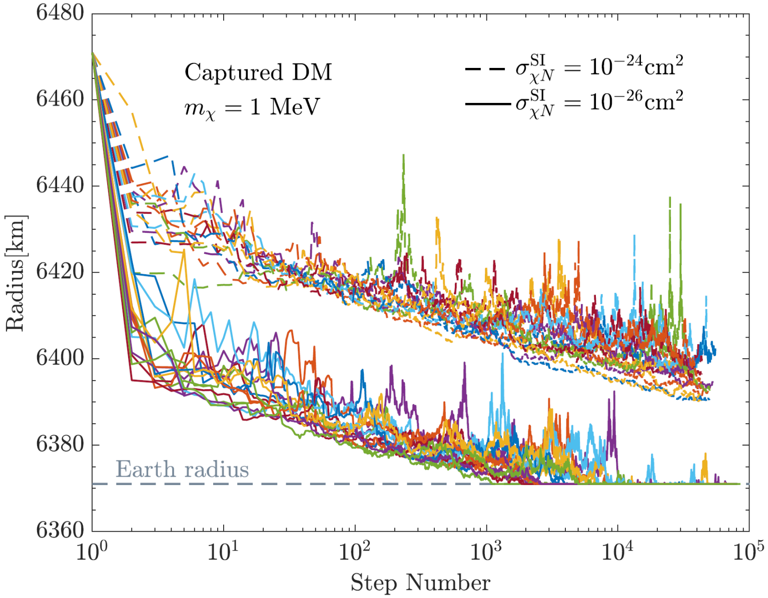


“greenhouse” resonance

- MC shows a peak in capture fraction near $\sigma_{\chi N} \sim 10^{-26}$ cm^2
  - for larger $\sigma_{\chi N}$ capture/reflection in atmosphere
  - for smaller $\sigma_{\chi N}$, atm. transparent, capture/reflection off crust

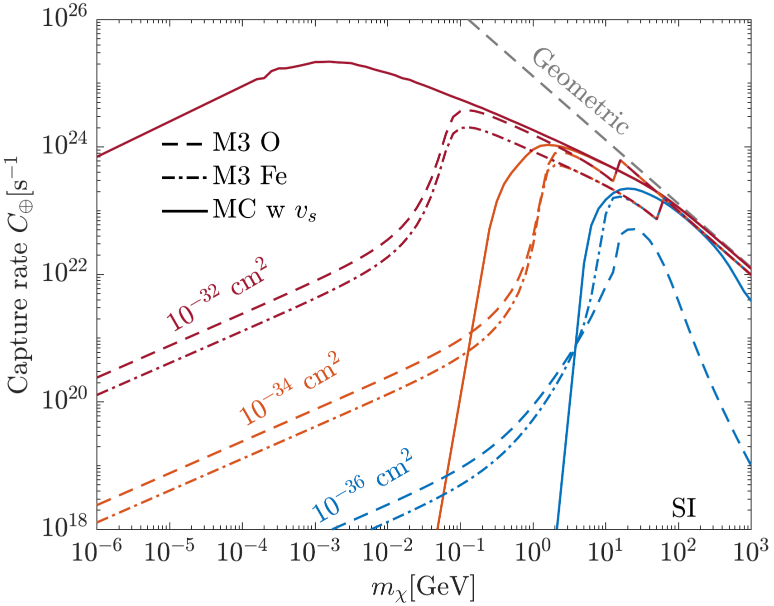
- in between, some DM reflected off Earth reflects back off atmosphere

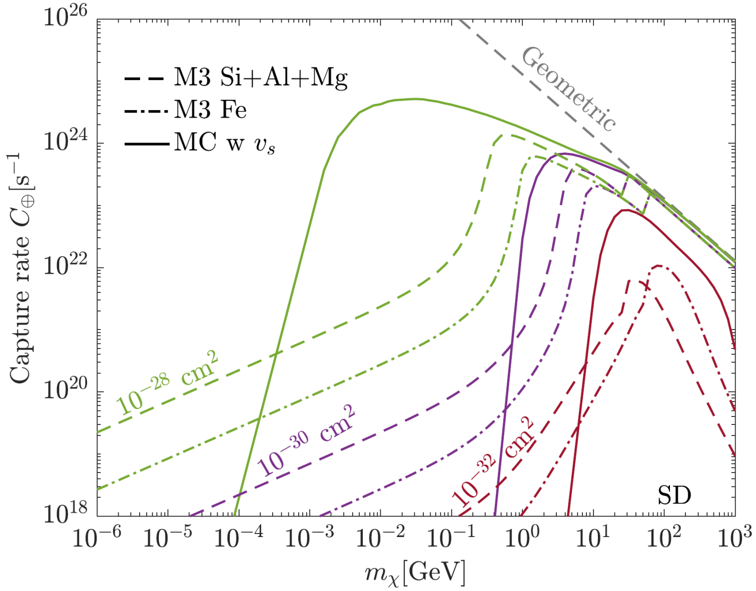




comparison to multi-scatter treatment

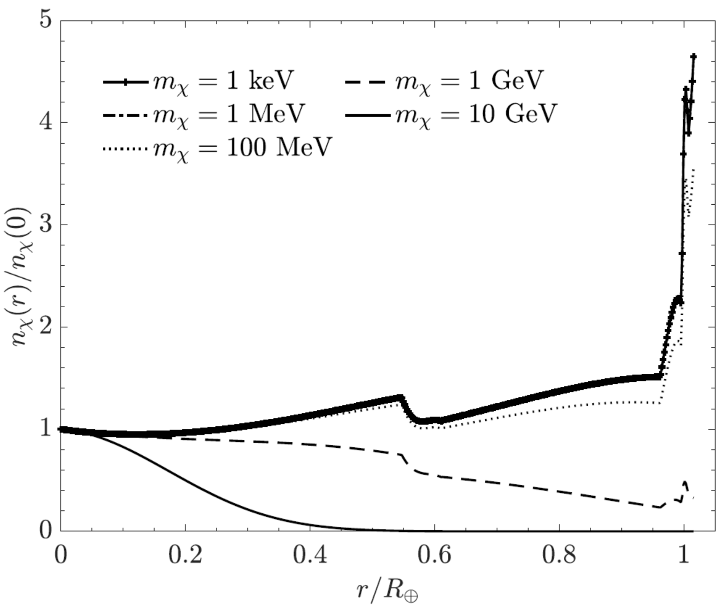
- multi-scatter analytic (M3) result (RKL, JS 2209.09834)
  - $N_{scat}^{-1/2}$ scaling at small m_χ
  - straight line trajectory at large m_χ
  - assume one element
- match geometric at large $\sigma_{\chi N}$, m_χ
- M3 overestimates capture at low mass, but not so relevant
  - will evaporate away anyway
- M3 underestimates capture at large m_χ





density distribution

- DM in local thermodynamic equilibrium (LTE)(see Aaron's talk)
  - like ideal gas in thermal equi. with SM (Earth)
  - grav. potential as μ_{ext}
- given N, determines $n_\chi(r)$
  - heavier DM sinks
- density distribution affects
  - evaporation
    - rate depends on T(r), $n_\chi(r)$
  - annihilation rate within Earth
    - annihilation in atmosphere not constrained by Earth heating



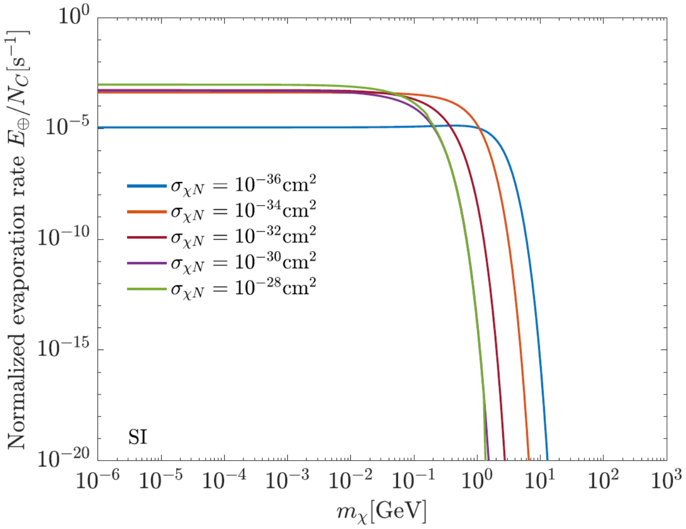
$$\frac{\eta_\chi(r)}{\eta_\chi(0)} = \left(\frac{T_\oplus(r)}{T_\oplus(0)}\right)^{3/2} \exp\left(-\int_0^r \left[\alpha \frac{dT_\oplus}{dr'} + m_\chi \frac{d\phi}{dr'}\right] T_\oplus^{-1}\, dr'\right)$$

$\alpha(r)$ = thermal diffusivity parameter

Nauenberg PRD**36** (1987) 1080
Gould, Raffelt, ApJ**352** (1990) 654

evaporation

- evaporation rate given by likelihood that DM at r is scattered above escape vel, and doesn't scatter back down
  - if it scatters down on way out, rethermalizes
  - effect of atm. is important, since it is cooler and can block evap.
  - use G,P-R 1702.02768
- evaporation rate per particle (E/N) depends only on m_χ, $\sigma_{\chi N}$
- saturates for $m_\chi \lesssim 100$ MeV
- for larger $\sigma_{\chi N}$, evaporation saturates at smaller m_χ



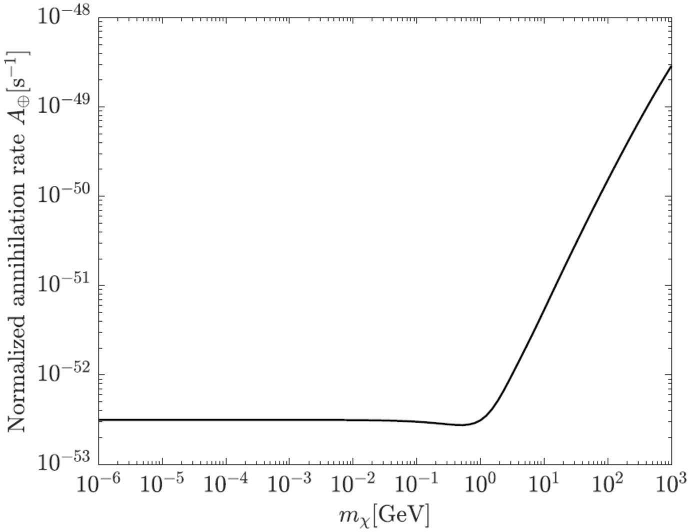
annihilation

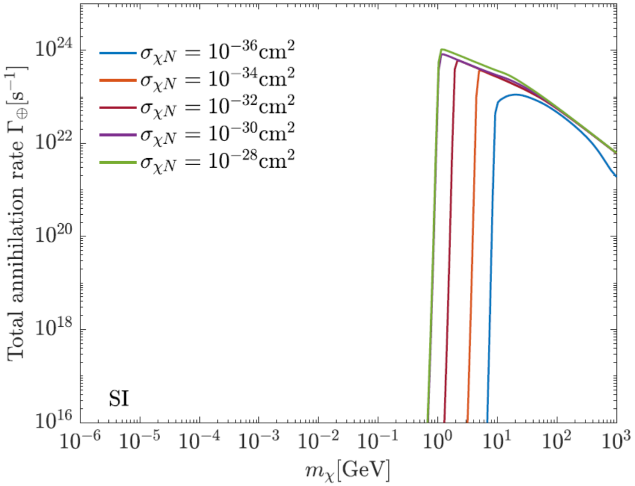
- solve for N(t) at age of earth
  - assume s-wave thermal
  - A depends on m_χ
  - annih. negligible for $m_\chi \lesssim 1$ GeV

- assume DM annihilates entirely to visible states (heat)
  - Earth heating < 44 TW (WV-HAS, Geo. J Int. 38 (09, 1974) 587-608)

$$\Gamma = \frac{1}{2} A N^2$$

$$A = \frac{\langle \sigma v \rangle}{N^2} \int dV\, \eta_\chi^2(r)$$

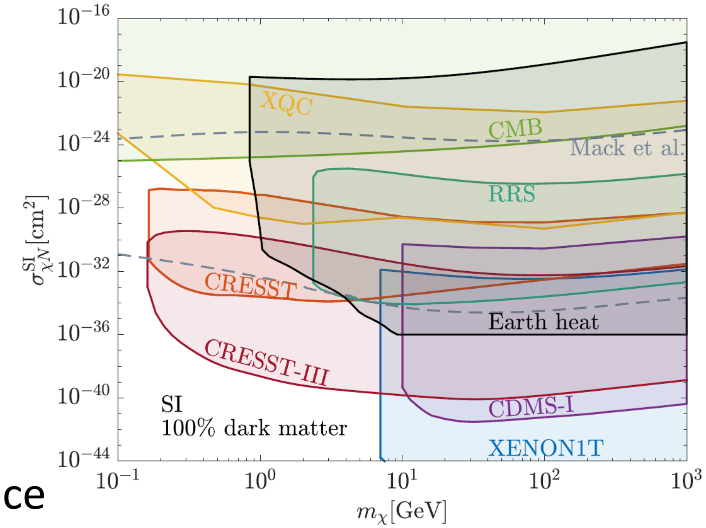


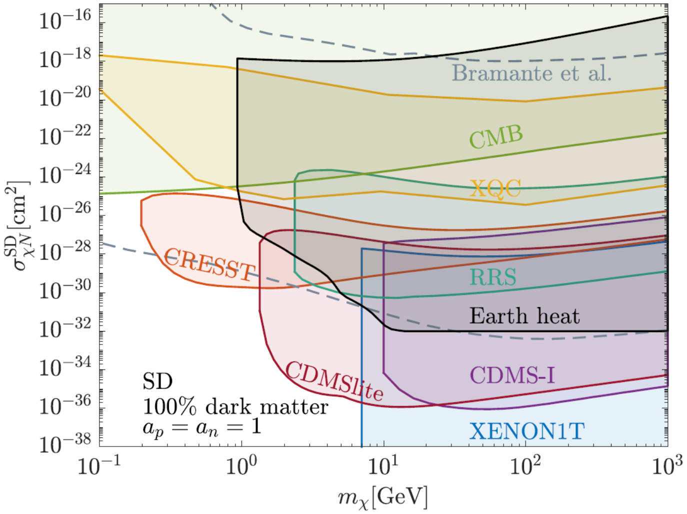


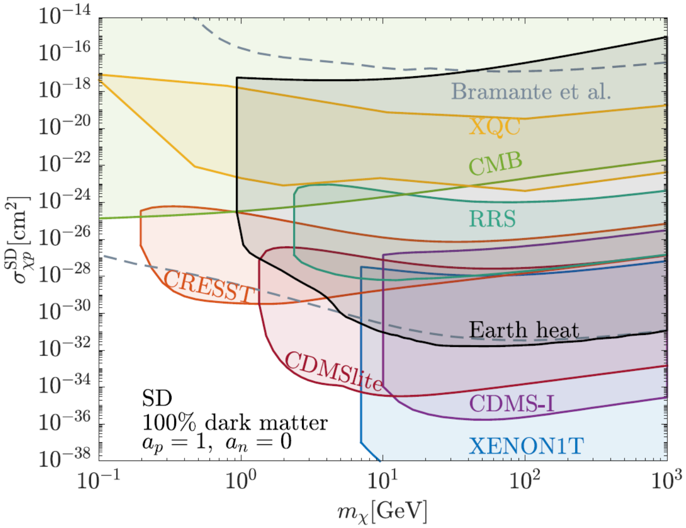
Earth heating bounds

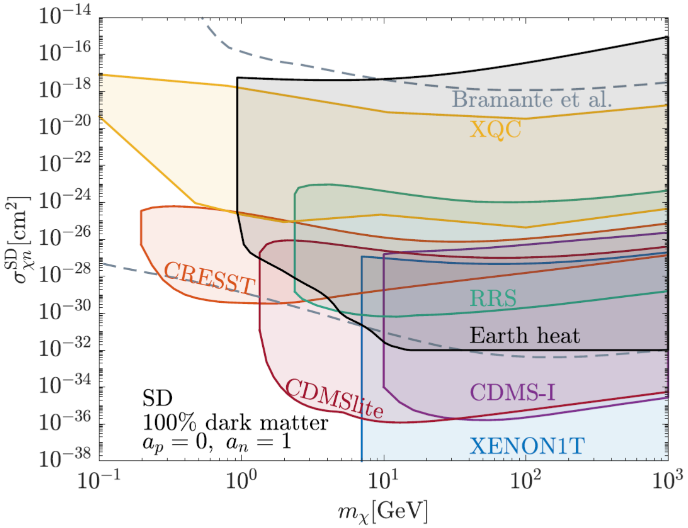
for SI/SD, some space opens up at low mass

for SD (a_p=0), some space closed off at large $\sigma_{\chi N}$









conclusion

- dark matter accumulation in the Earth in the optically-thick regime can lead to important constraints on the parameter space
- requires more detailed study of capture, density distribution, and evaporation
- we do so with Monte Carlo study

- new Earth heating bounds → some constraints strengthened, others weakened
- can apply these results to other search strategies and targets

Mahalo!

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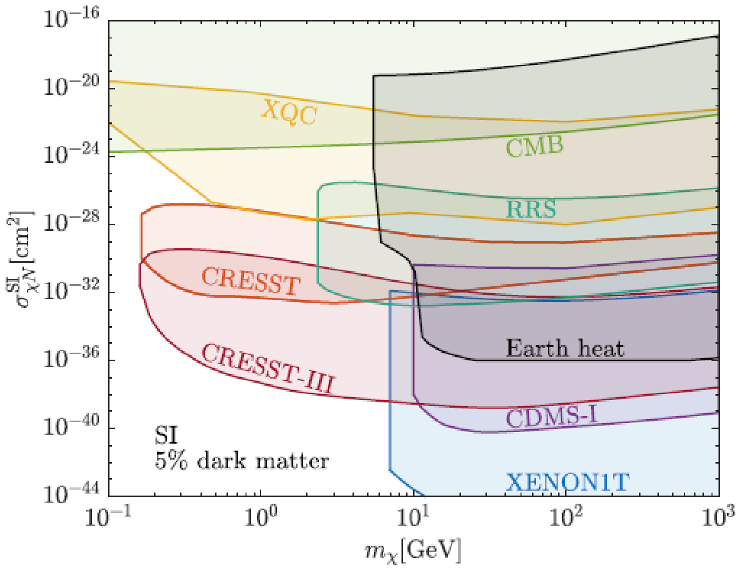
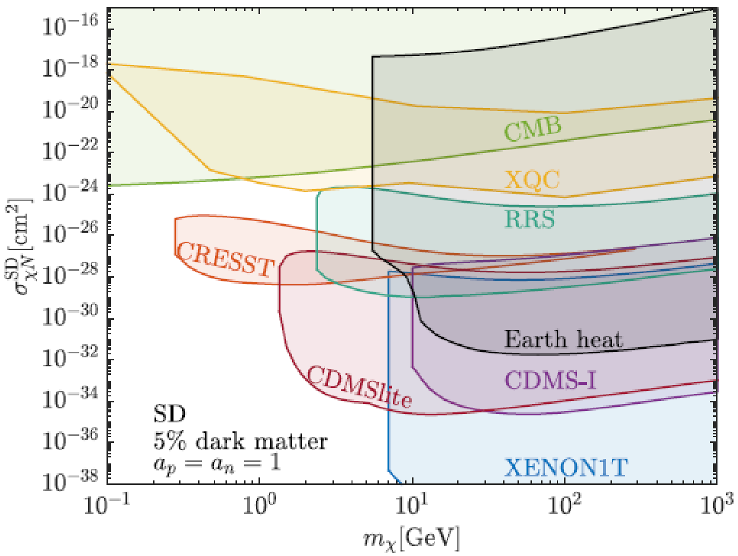
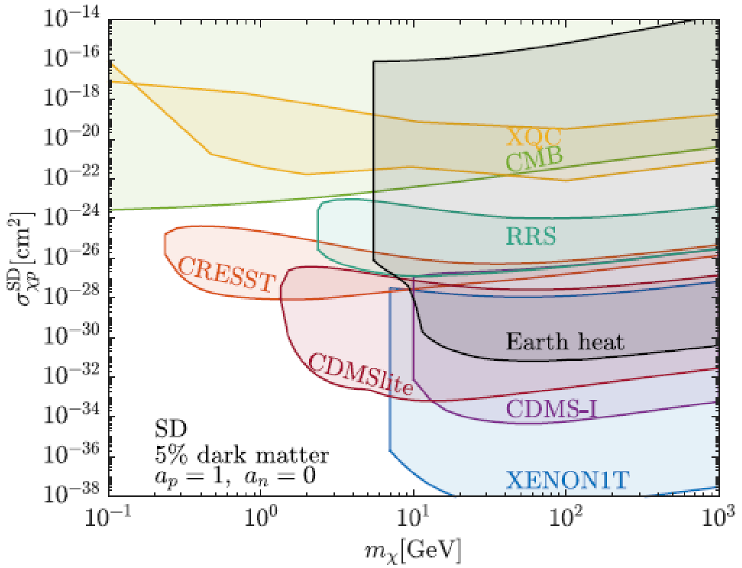
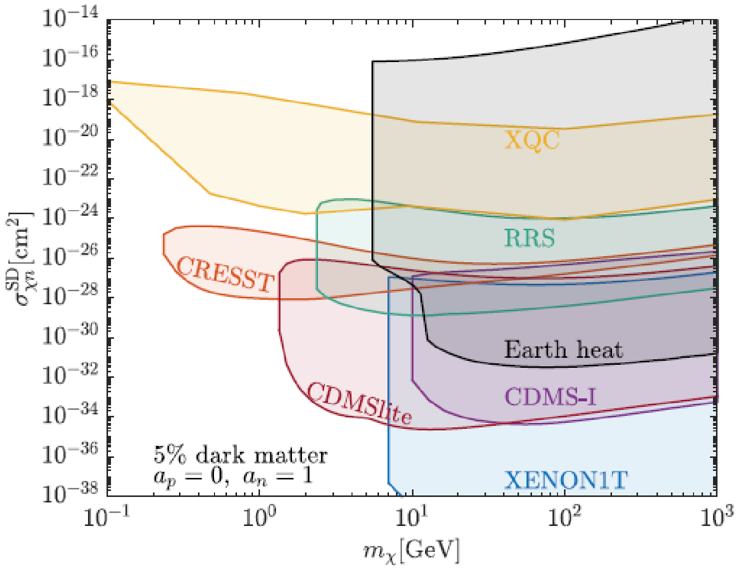
subdominant dark matter (5%)

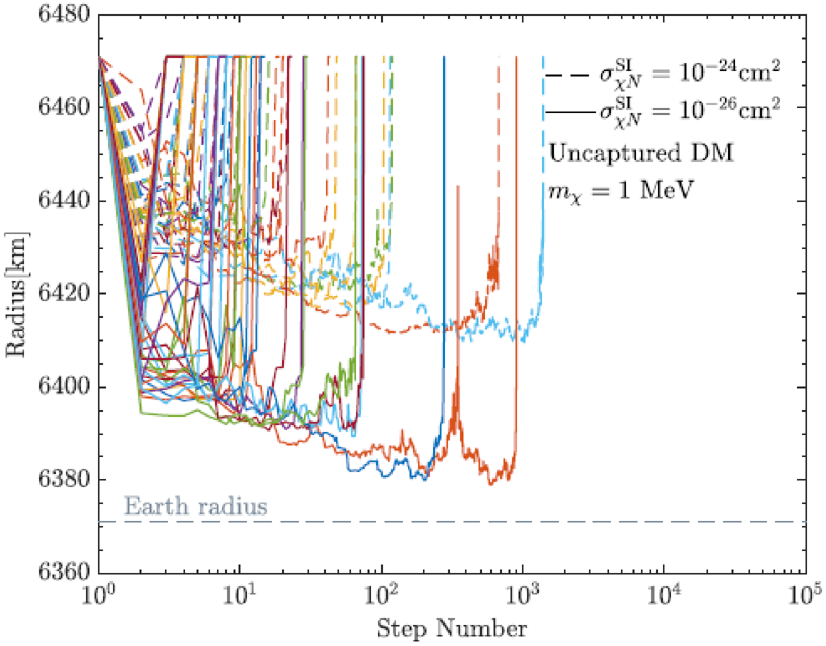


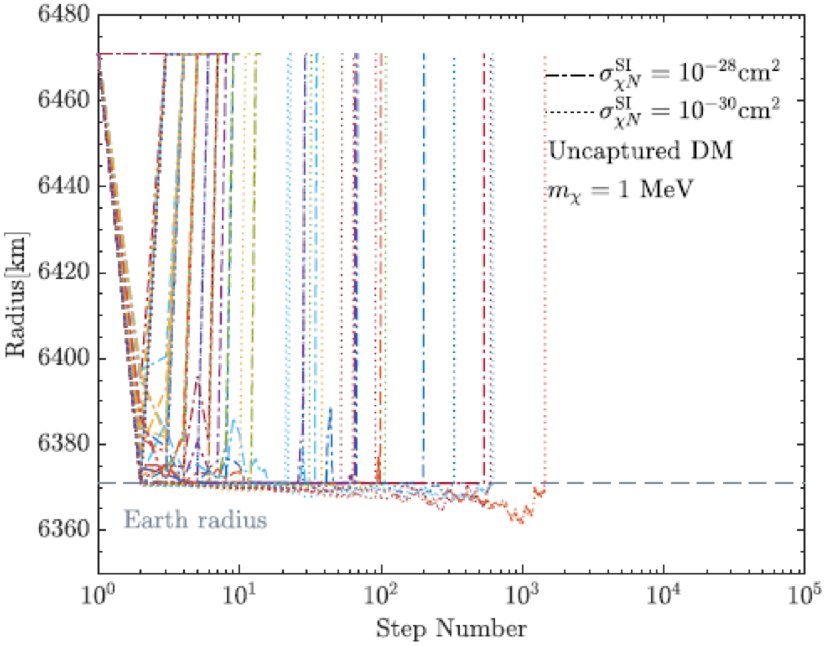






trajectories of particles not captured

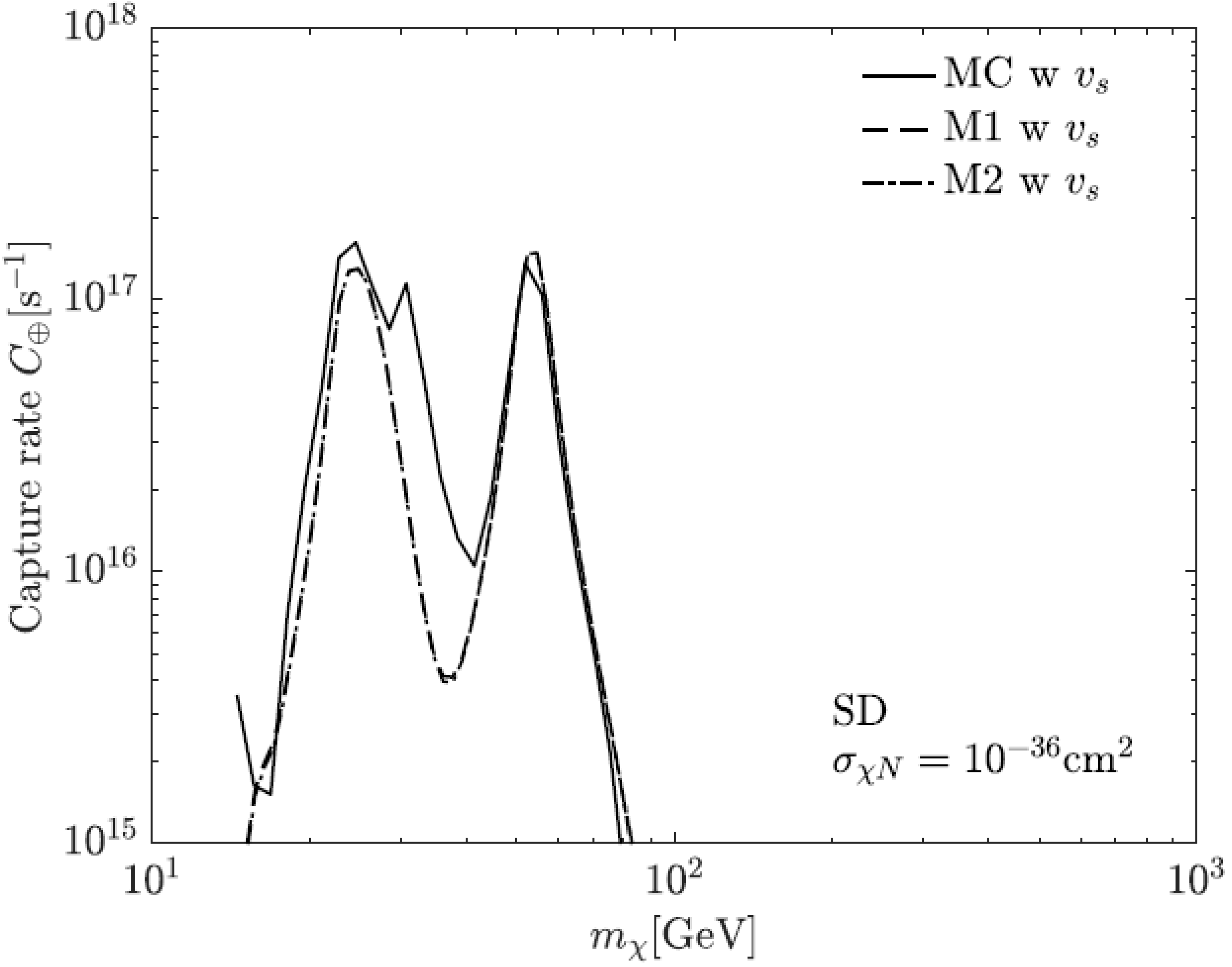




matching in the optically-thin regime

at small $\sigma_{\chi N}$, where single scatter should be a good approximation, MC matches the single scatter approach

also gets kinematic resonances



evaporation rate (G,P-R 1702.02768)

$$E_{\oplus} = \sum_j \int_0^{R_{\oplus}} 4\pi r^2 n_\chi(r) s(r) dr \times \int_0^{v_e(r)} 4\pi u_\chi^2 f_{\oplus} du_\chi \int_{v_e(r)}^{\infty} R_j^+(u_\chi \to v) dv \,.$$

$$s(r) = \eta_{\rm ang} \eta_{\rm mult} e^{-\tau(r)}$$

→ likelihood of getting out without scattering back below escape velocity

would be interesting to update with a Monte Carlo analysis for low mass regime

could affect s(r)