MAPPING THE NEUTRINO FLOOR FOR LOW MASS DARK MATTER

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OUTLINE

- MOTIVATION
- SIGNAL – DARK MATTER
  - Nuclear Scattering Rates
  - Electron Scattering Rates
- BACKGROUND – SOLAR NEUTRINOS
  - Solar-ν Flux
  - Nuclear Scattering Rates
  - Electron Scattering Rates
- CONVERSION OF RECOIL ENERGY TO DETECTOR SIGNAL
  - Ionization from Electron Scattering
  - Ionization from Nuclear Scattering
- STATISTICAL ANALYSIS
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- DISCOVERY LIMITS
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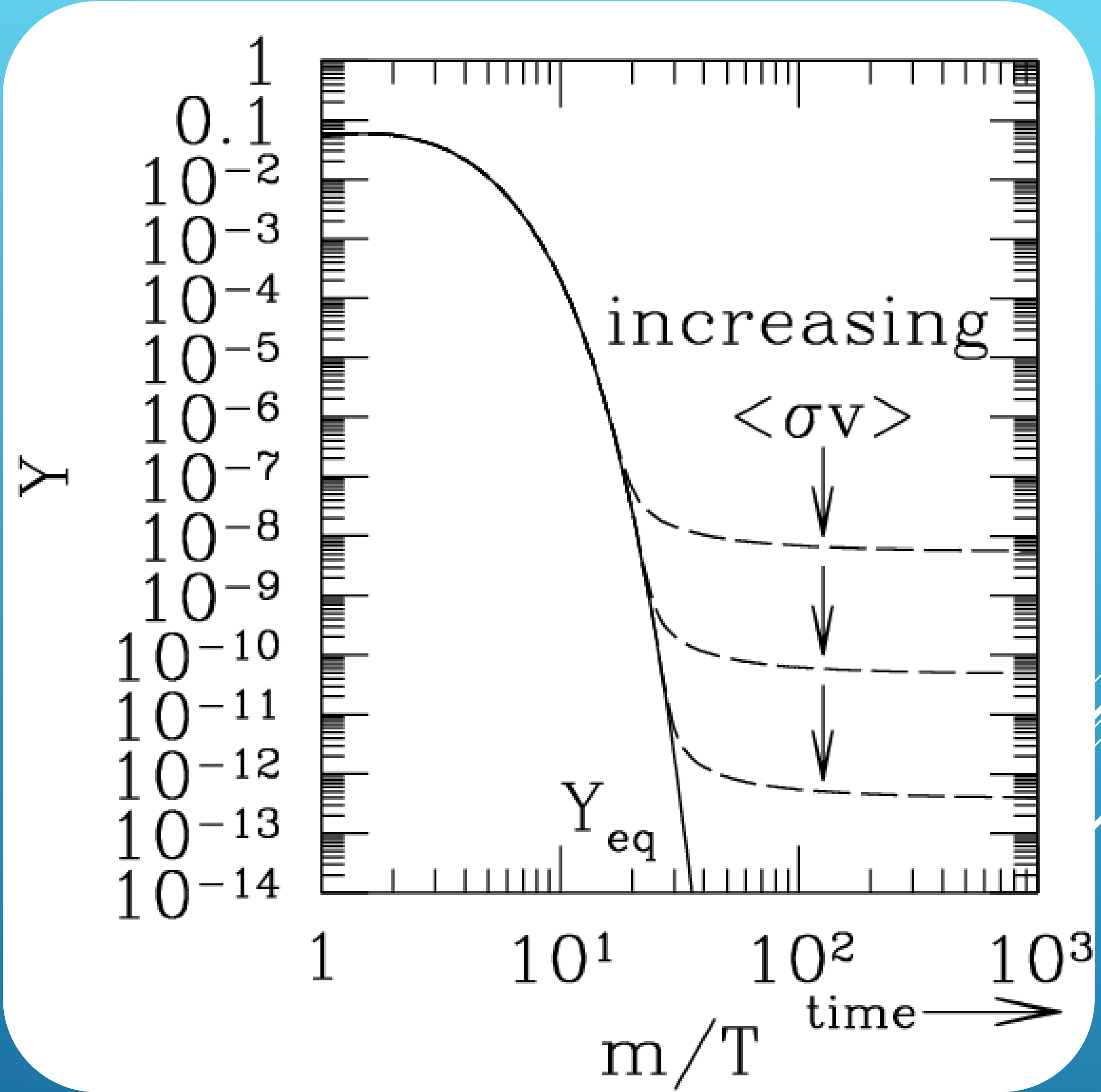
  - Theoretical “floor” for Cross Section
- CONCLUSION / QUESTIONS

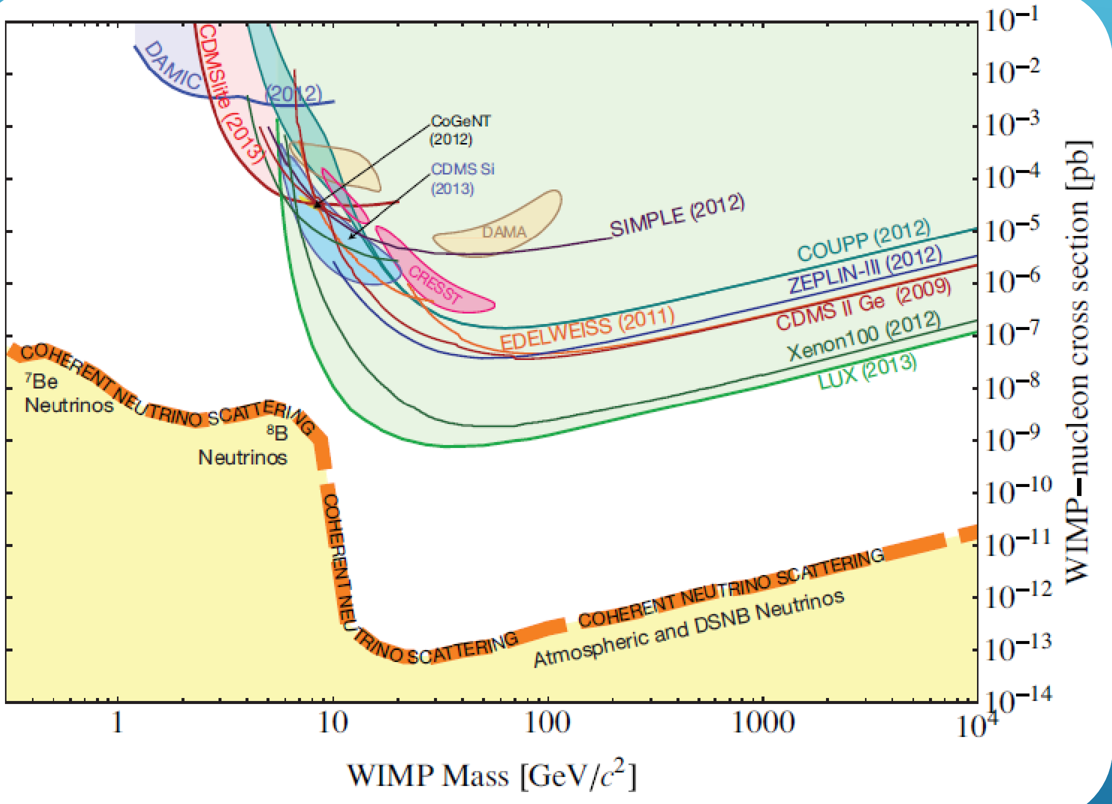
MOTIVATION

- THEORETICALLY MOTIVATED BY "WIMP MIRACLE"



MOTIVATION

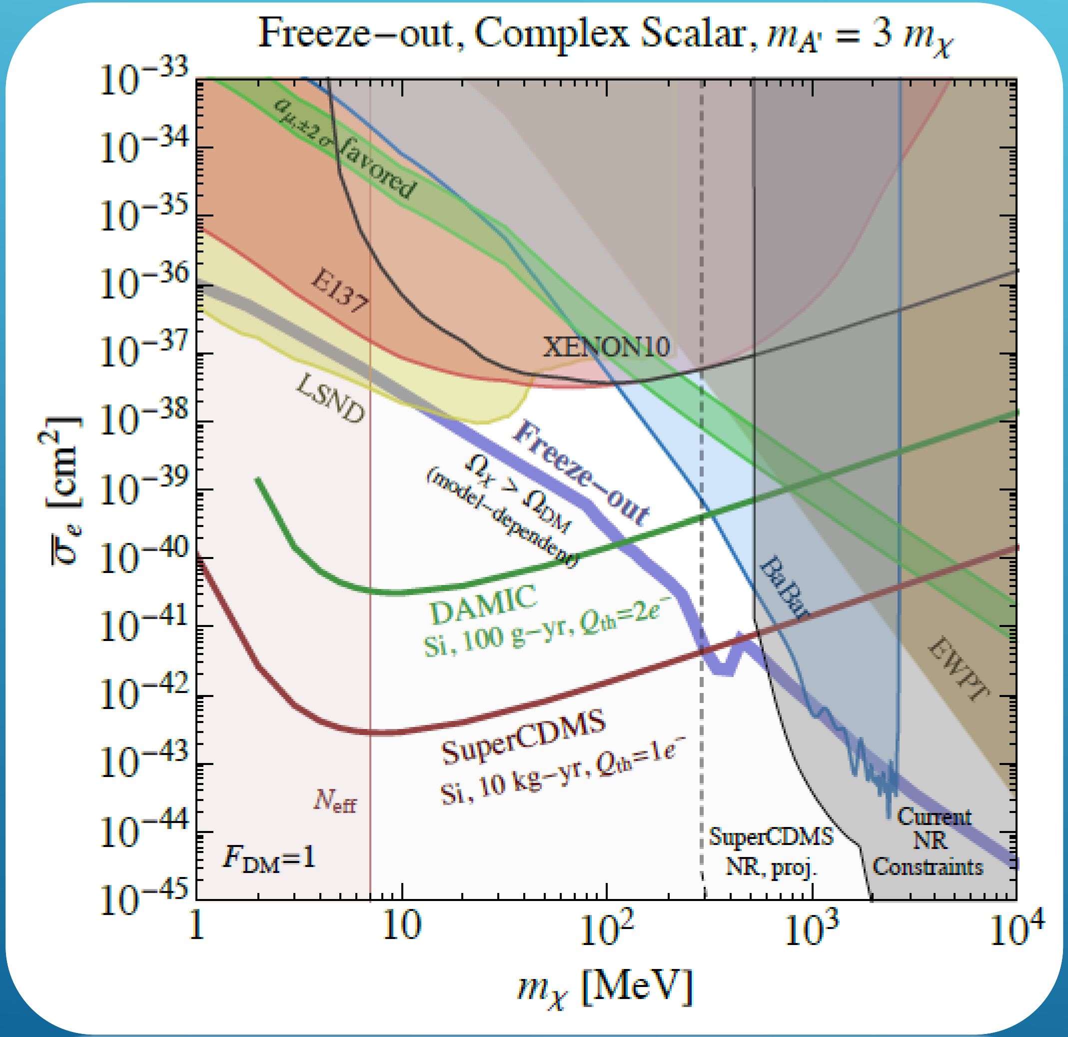
- THEORETICALLY MOTIVATED BY "WIMP MIRACLE"
- UNEXPLORED PARAMETER SPACE
  - Traditional Direct Detection on nuclei – limitations at low DM Mass (< ~100 MeV)



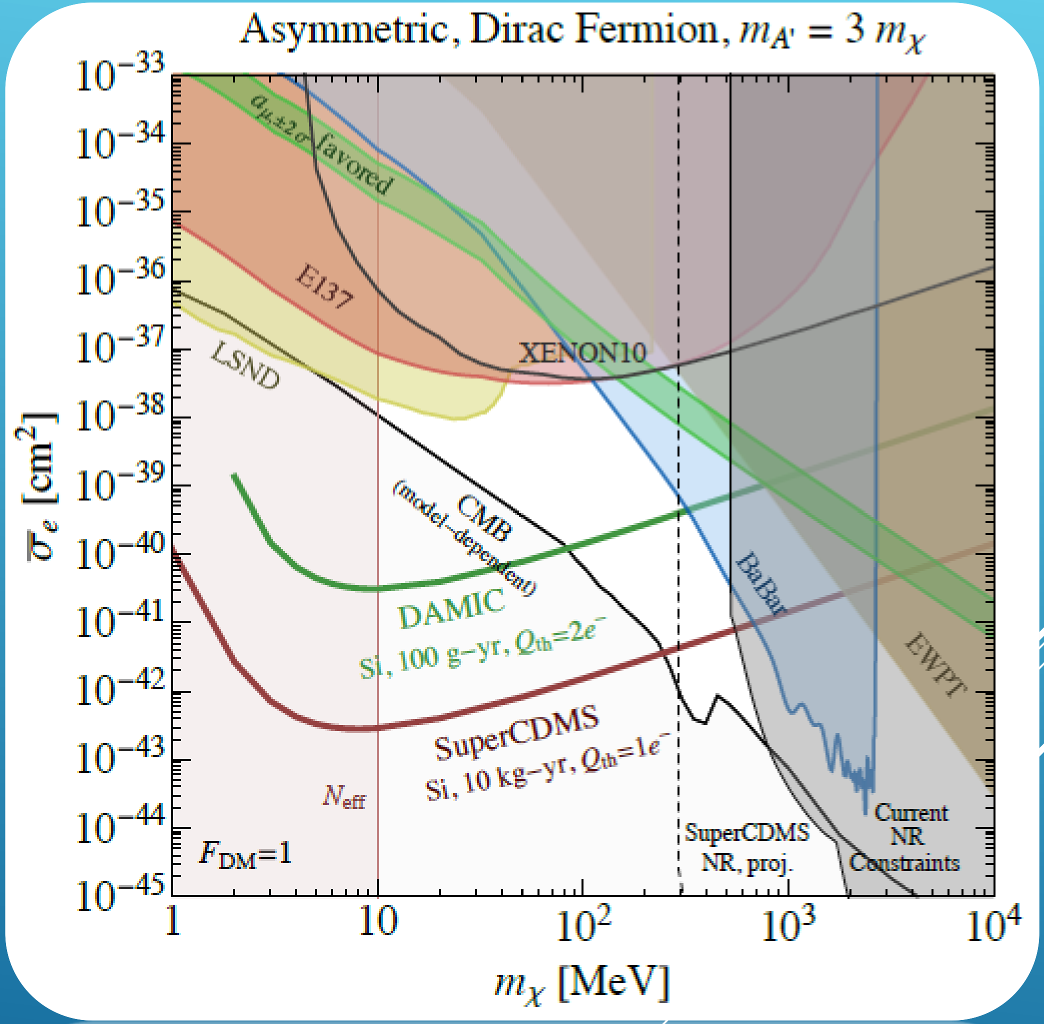
MOTIVATION

- THEORETICALLY MOTIVATED BY “WIMP MIRACLE”
- UNEXPLORED PARAMETER SPACE
  - Traditional Direct Detection on nuclei – limitations at low DM Mass (< ~100 MeV)
  - Well-motivated theory to probe this parameter space (below 100 MeV)

MOTIVATION



Freeze−out, Complex Scalar, $m_{A'} = 3\, m_\chi$
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]
$a_\mu \pm 2\sigma$ favored
E137
LSND
XENON10
Freeze−out
$\Omega_\chi > \Omega_{DM}$ (model−dependent)
BaBar
EWPT
DAMIC
Si, 100 g−yr, Q_{th}=2e^-
SuperCDMS
Si, 10 kg−yr, Q_{th}=1e^-
N_{eff}
F_{DM}=1
SuperCDMS NR, proj.
Current NR Constraints



Asymmetric, Dirac Fermion, $m_{A'} = 3\, m_\chi$
$\overline{\sigma}_e$ [cm^2]
m_χ [MeV]
$a_\mu \pm 2\sigma$ favored
E137
LSND
XENON10
CMB (model−dependent)
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Si, 100 g−yr, Q_{th}=2e^-
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Current NR Constraints

SIGNAL – DARK MATTER

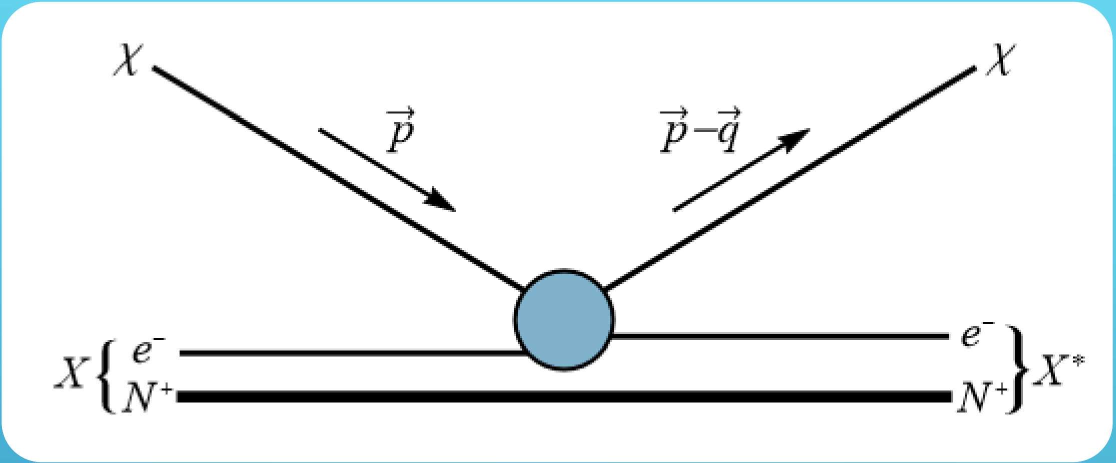
- NUCLEAR SCATTERING RATES
  - $F(E_r)$ is the Helm form factor, affects recoil energies > ~10 keV
  - σ_0 is the normalized to nucleus form factor, which scales as A^2
  - v_{min} is set by the kinematics of the collision and is equal to the minimum velocity necessary for recoil energy E_r

$$f(\vec{v}) = \begin{cases} \frac{1}{N_{\text{esc}}(2\pi\sigma_v^2)^{3/2}} \exp\left[-\frac{\left(\vec{v}+\vec{V}_{\text{lab}}\right)^2}{2\sigma_v^2}\right] & \text{if } |\vec{v}+\vec{V}_{\text{lab}}| < v_{\text{esc}} \\ 0 & \text{if } |\vec{v}+\vec{V}_{\text{lab}}| \geq v_{\text{esc}} \end{cases}$$

$$\frac{dR}{dE_r} = MT \times \frac{\rho_0\sigma_0}{2m_\chi m_r^2} F^2(E_r) \int_{v_{\text{min}}} \frac{f(\vec{v})}{v} d^3v$$

SIGNAL – DARK MATTER

- NUCLEAR SCATTERING RATES
- ELECTRON SCATTERING RATES
  - QE dark model used to simulate Ge electron wavefunctions
  - F_{ion} encodes the wavefunction information of the Ge atomic structure
    - How likely it is that an incoming velocity will ionize electron to energy E_r

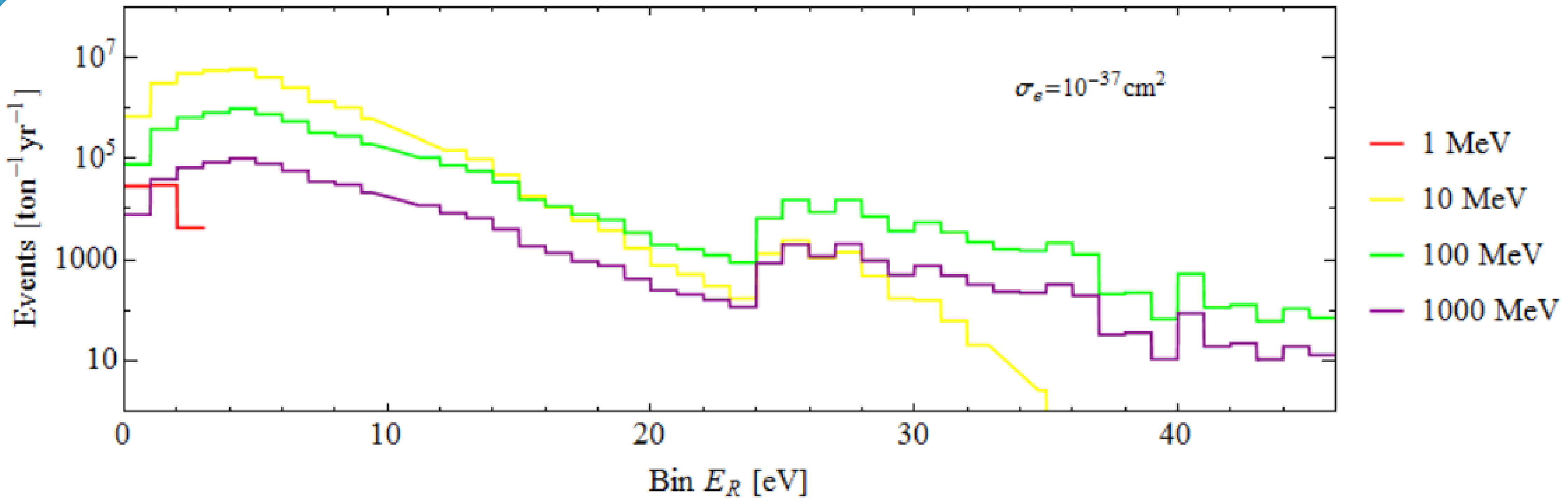


$$\frac{d\langle\sigma^i_{ion}v\rangle}{d\ln E_r} = \frac{\sigma_e}{8\mu^2_{\chi e}}\int q\,dq|f^i_{ion}(k',q)|^2|F_{DM}(q)|^2\eta(v_{min}),$$

$$\frac{dR}{dT} = \frac{\rho_\chi}{M_\chi}\frac{M_{det}}{M_{Ge}}\frac{\sigma_e}{8\mu^2_{\chi e}E_r}\sum_{i=1}^{32}\int q\,dq|f^i_{ion}(k',q)|^2|F_{DM}(q)|^2\eta(v_{min})$$

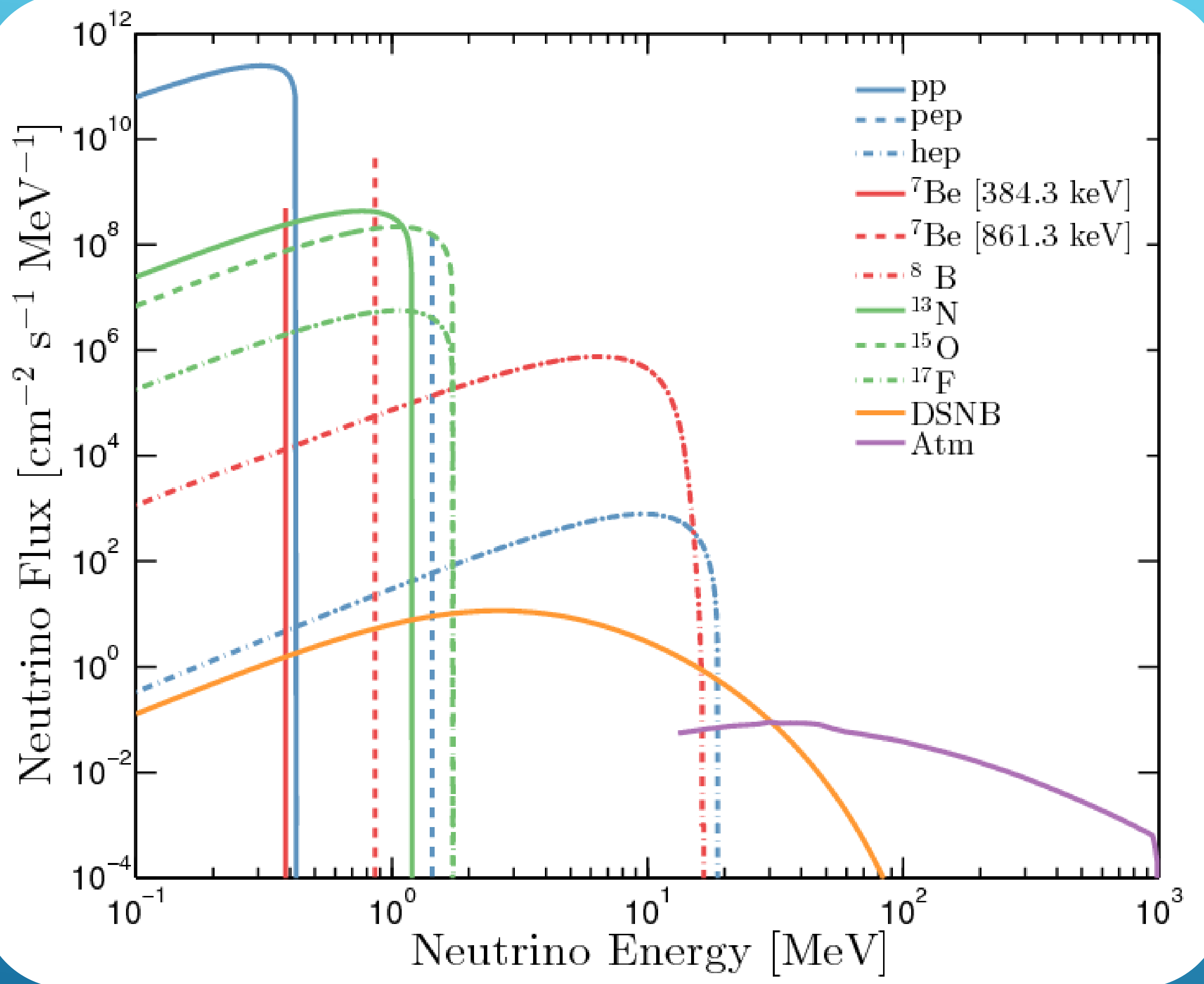
SIGNAL – DARK MATTER

- NUCLEAR SCATTERING RATES
- ELECTRON SCATTERING RATES



BACKGROUND – SOLAR NEUTRINOS

- SOLAR-NEUTRINO FLUX
  - Relevant energy levels



BACKGROUND – SOLAR NEUTRINOS

- SOLAR-NEUTRINO FLUX
- EVENT RATES
  - Nuclear Scattering

$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2}{4\pi} Q_w^2 m_N \left(1 - \frac{m_N E_r}{2E_\nu^2}\right) F^2(E_r)$$

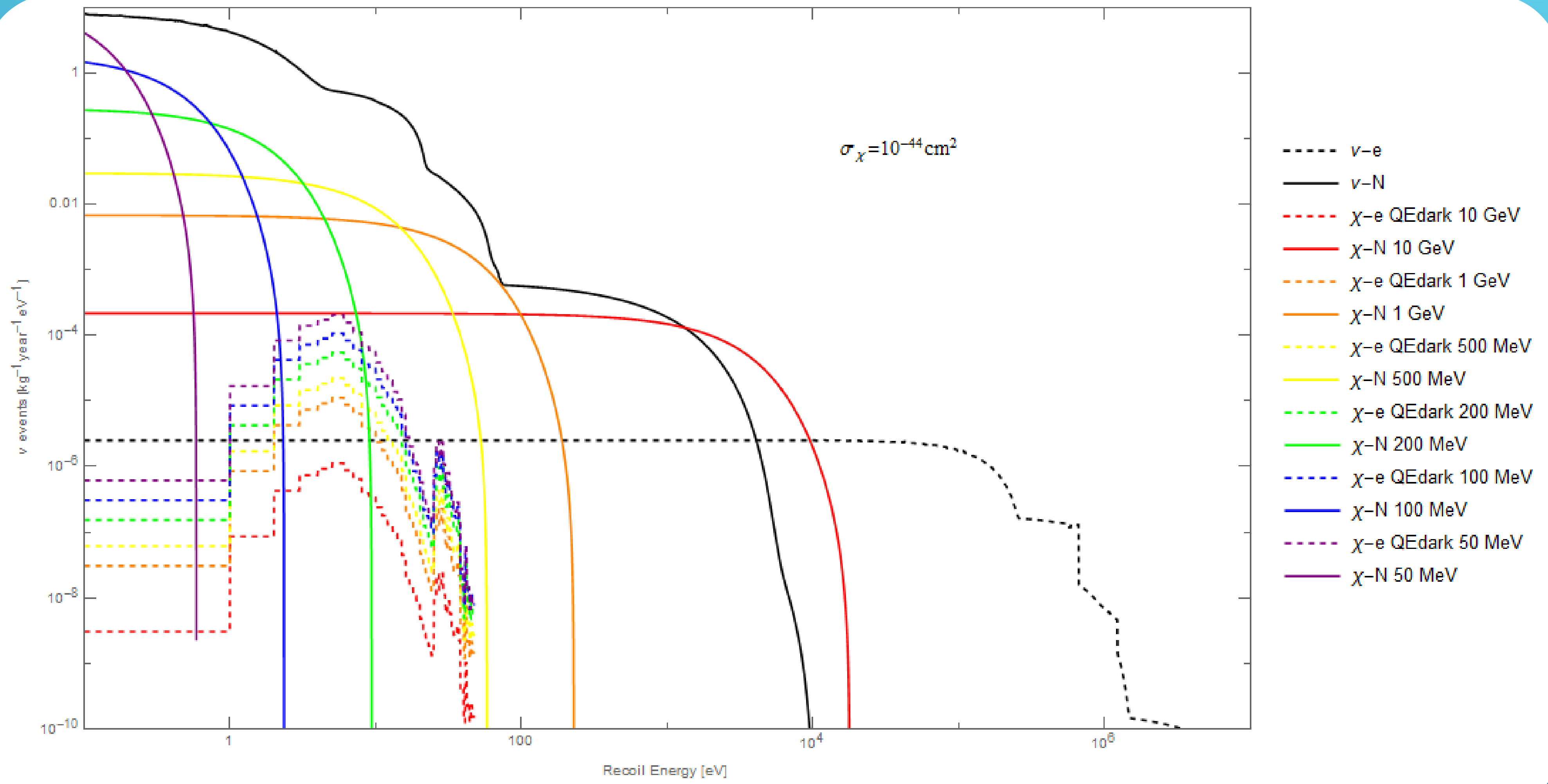
BACKGROUND – SOLAR NEUTRINOS

- SOLAR-NEUTRINO FLUX
- EVENT RATES
  - Nuclear Scattering
  - Electron Scattering

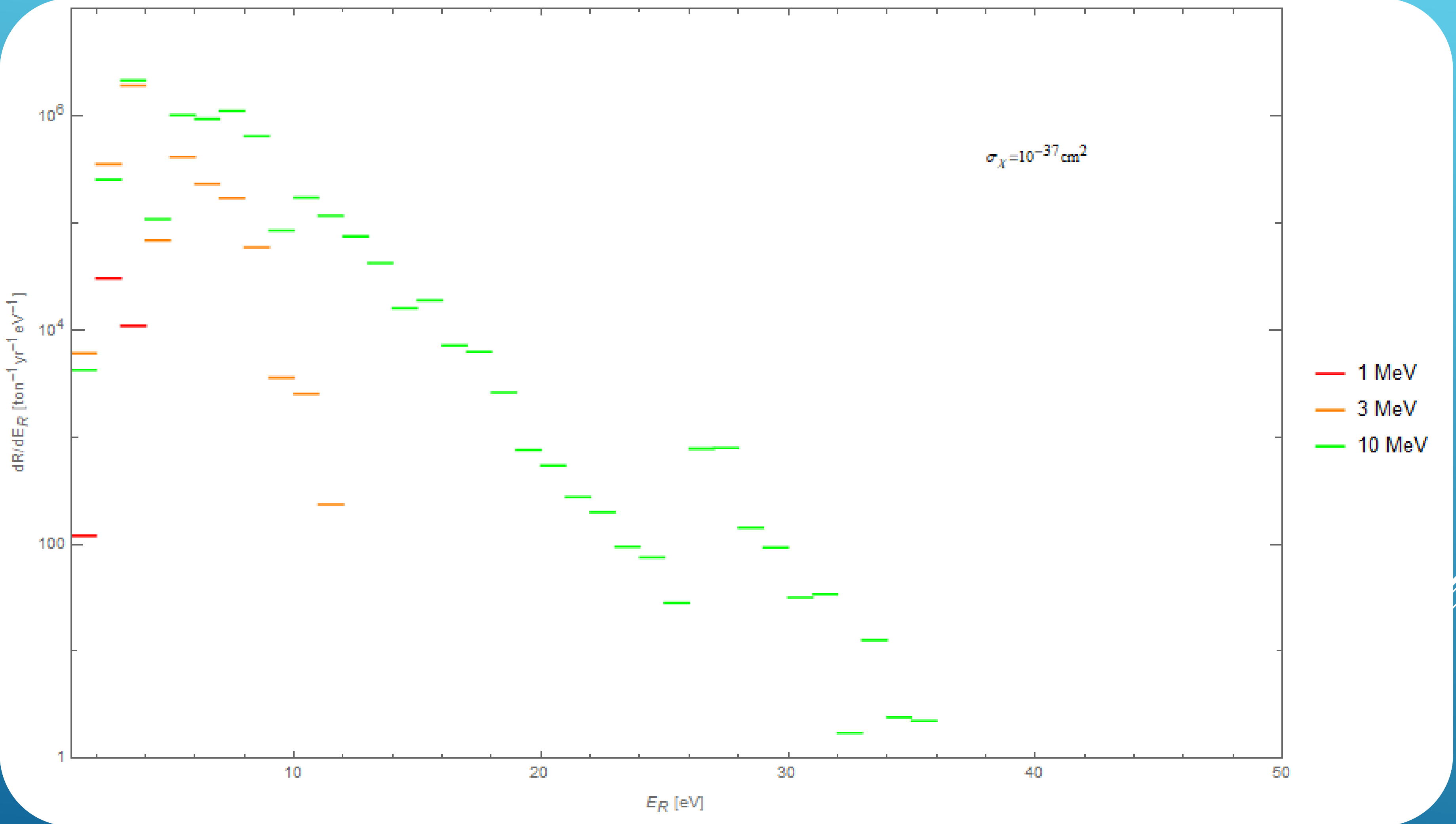
$$\frac{d\sigma(E_\nu, E_r)}{dE_r} = \frac{G_f^2 m_e}{2\pi}\left[(g_\nu + g_a)^2 + (g_\nu - g_a)^2\left(1 - \frac{E_r}{E_\nu}\right)^2 + (g_a^2 - g_\nu^2)\frac{m_e E_r}{E_\nu^2}\right]$$

$$\frac{dR}{dT} = \frac{M_{det}}{M_{Ge}}\sum_i \int_{E_\nu^{min}} \frac{d\Phi_\nu^i}{dE_\nu}\frac{d\sigma(E_\nu, E_r)}{dE_r} dE_\nu$$

BACKGROUND – SOLAR NEUTRINOS



BACKGROUND – SOLAR NEUTRINOS



RECOIL ENERGY TO DETECTOR SIGNAL

- IONIZATION FROM ELECTRON SCATTERING

$$Q(E_r) = 1 + \lfloor (E_r - E_{gap})/\varepsilon \rfloor$$

$$\varepsilon = 2.9\, eV, \quad E_{gap} = 0.67\, eV$$

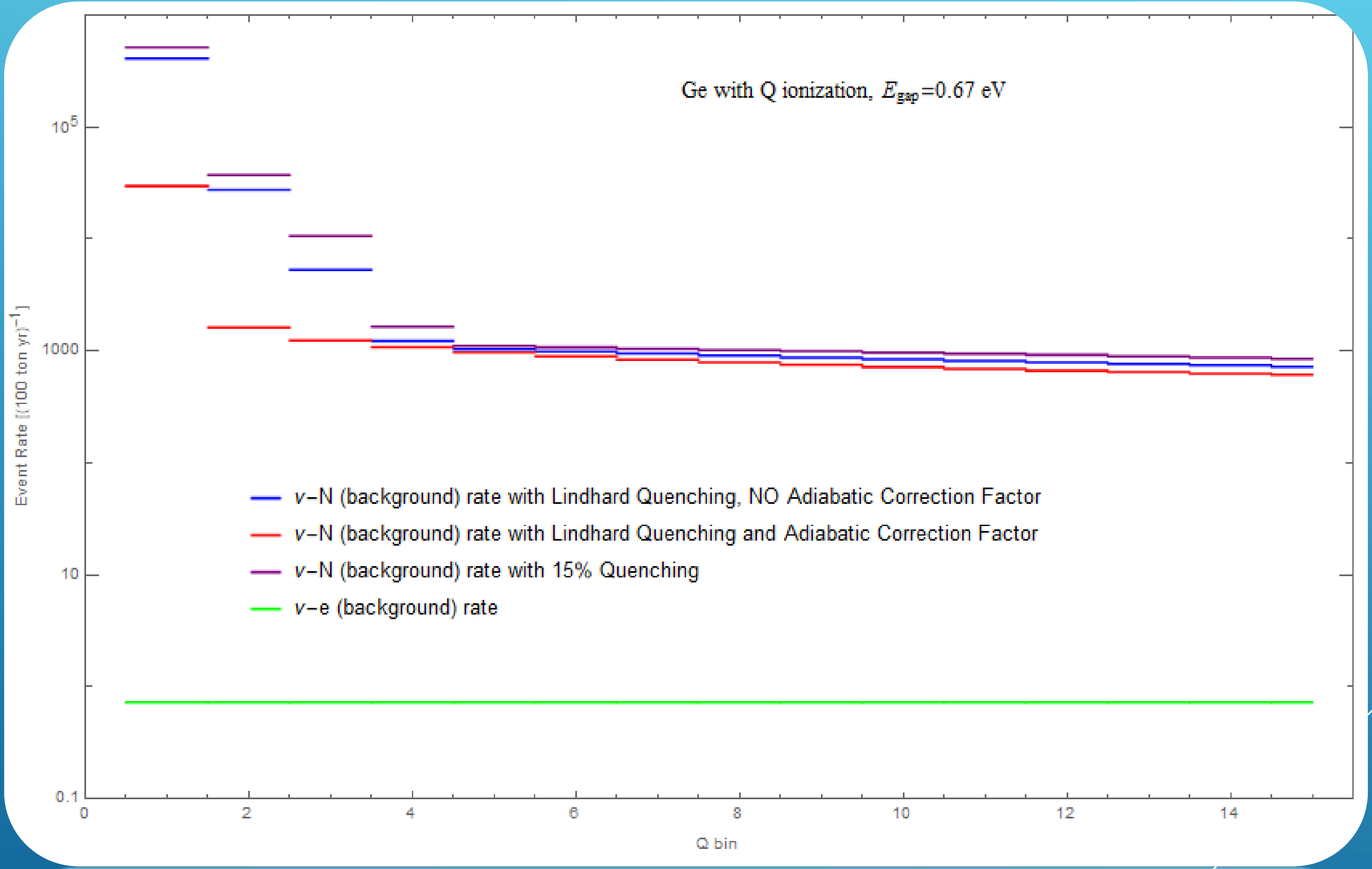
RECOIL ENERGY TO DETECTOR SIGNAL

- IONIZATION FROM ELECTRON SCATTERING
- IONIZATION AFTER NEUTRON SCATTERING
  - Lindhard "Quenching" model
  - Adiabatic Correction Factor (FAC)

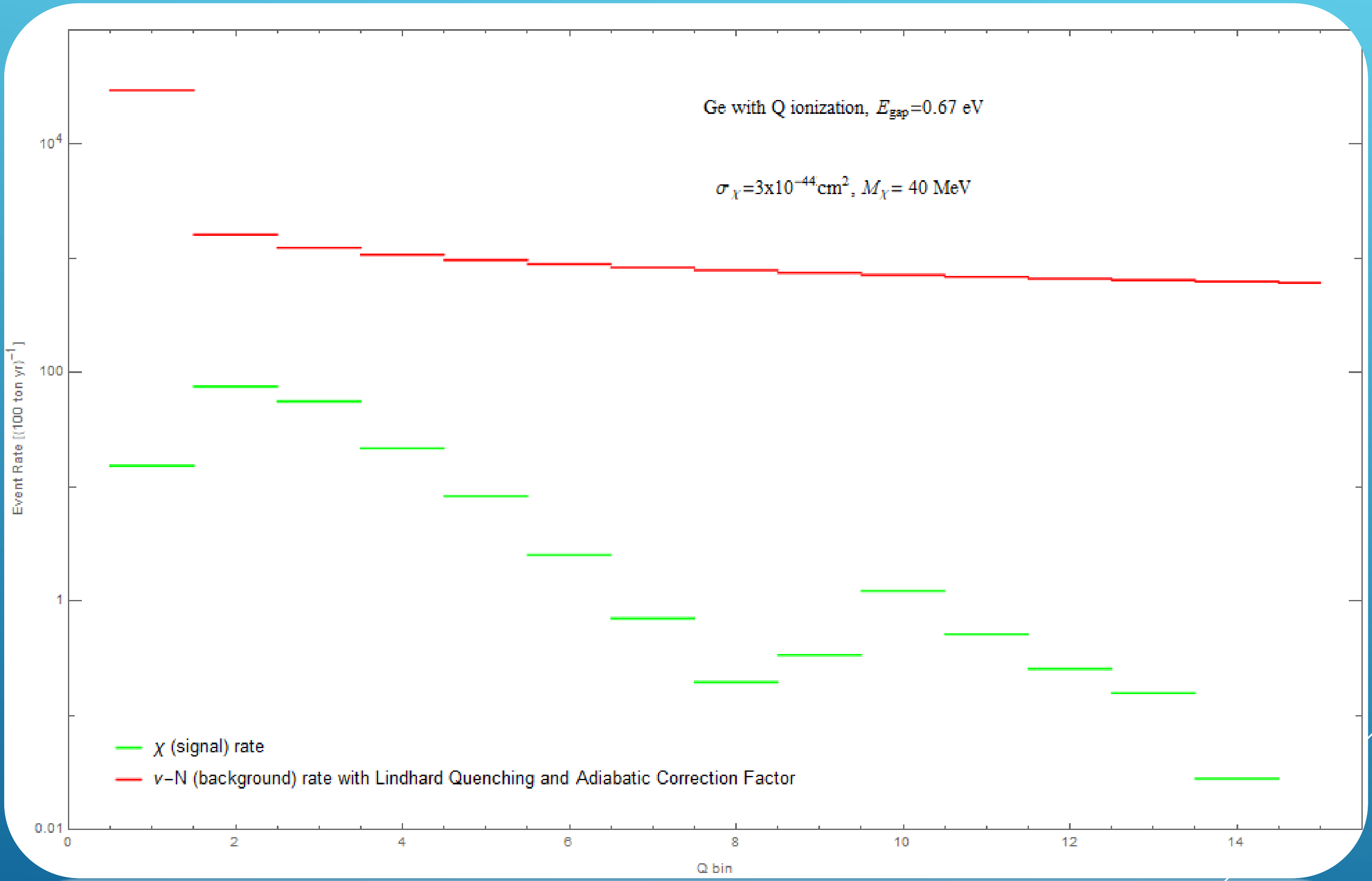
$$Q(E_r) = \frac{kg(\varepsilon)}{1+kg(\varepsilon)}, \quad g(\varepsilon) = 3\varepsilon^{0.15} + 0.7\varepsilon^{0.6} + \varepsilon, \quad \varepsilon = 11.5Z^{-7/3}E_r/keV$$

$$F_{AC}(E_r, \xi) = 1 - \exp[-E_r/\xi]$$

RECOIL ENERGY TO DETECTOR SIGNAL



RECOIL ENERGY TO DETECTOR SIGNAL



STATISTICAL ANALYSIS

- LIKELIHOOD FUNCTIONS
  - Likelihood of the observed data with hypothesized model

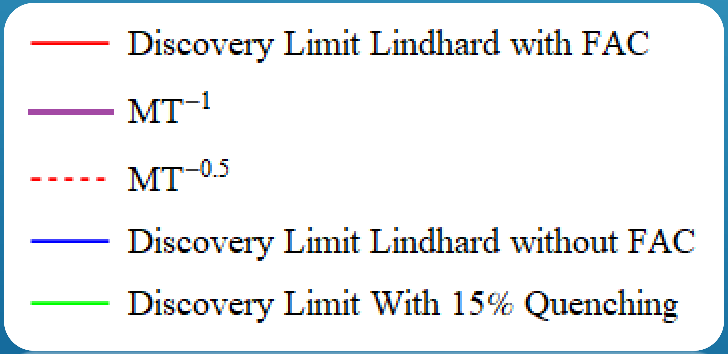
$$\mathcal{L}(\sigma_\chi, \vec{\phi}) = \frac{e^{-(\mu_\chi + \sum_{j=1}^{n_\nu} \mu_\nu^j)}}{N!} \prod_{i=1}^{N} \left[\mu_\chi f_\chi(E_{r_i}) + \sum_{j=1}^{n_\nu} \mu_\nu^j f_\nu^j(E_{r_i}) \right] \prod_{i=1}^{n_\nu} \mathcal{L}_i(\phi_i)$$

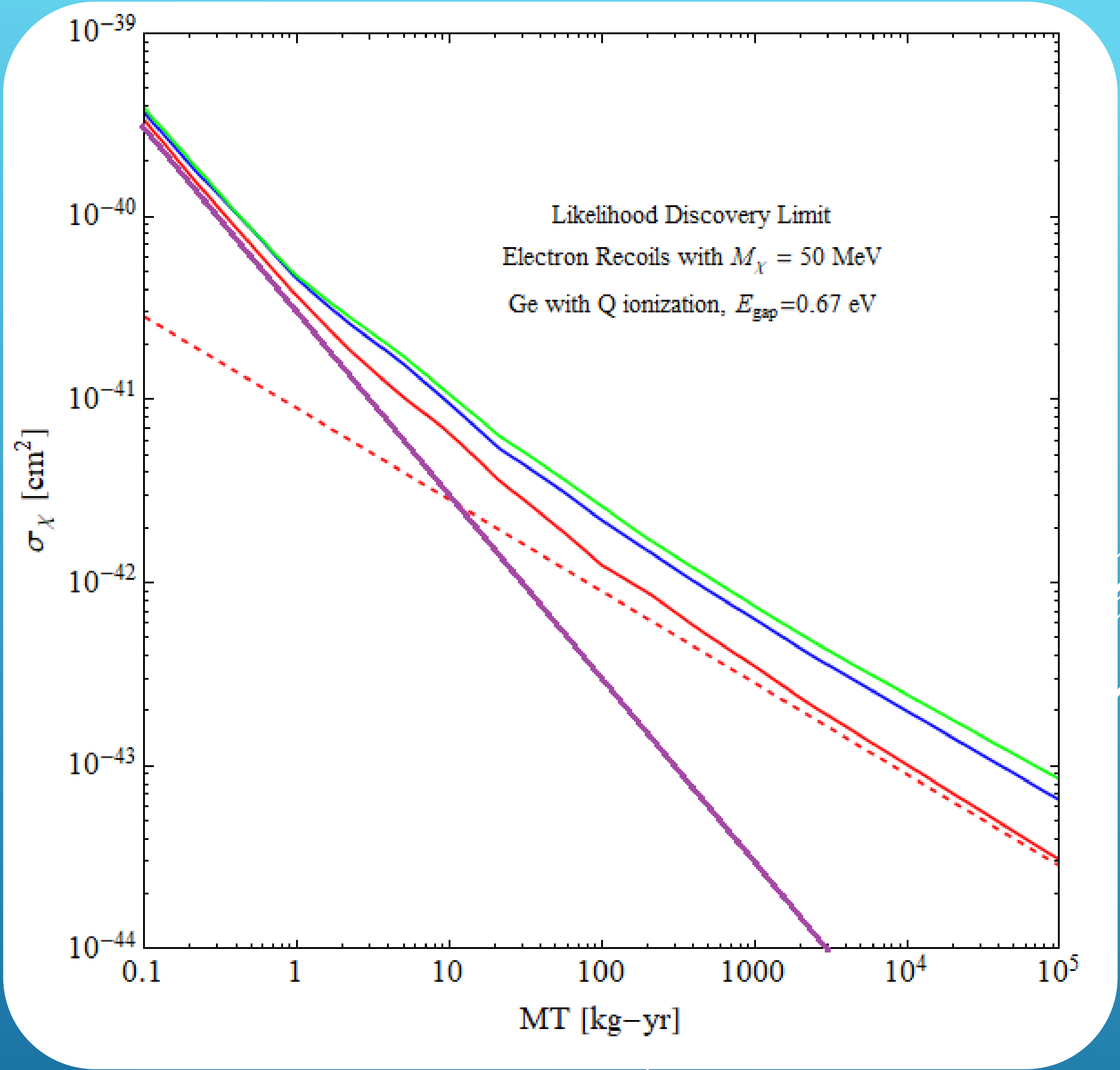
$$\lambda(0) = \frac{\mathcal{L}(\sigma_\chi = 0, \hat{\hat{\vec{\phi}}})}{\mathcal{L}(\hat{\sigma}_\chi, \hat{\vec{\phi}})}$$

$$q_0 = -2 \log \lambda(0)$$

DISCOVERY LIMITS

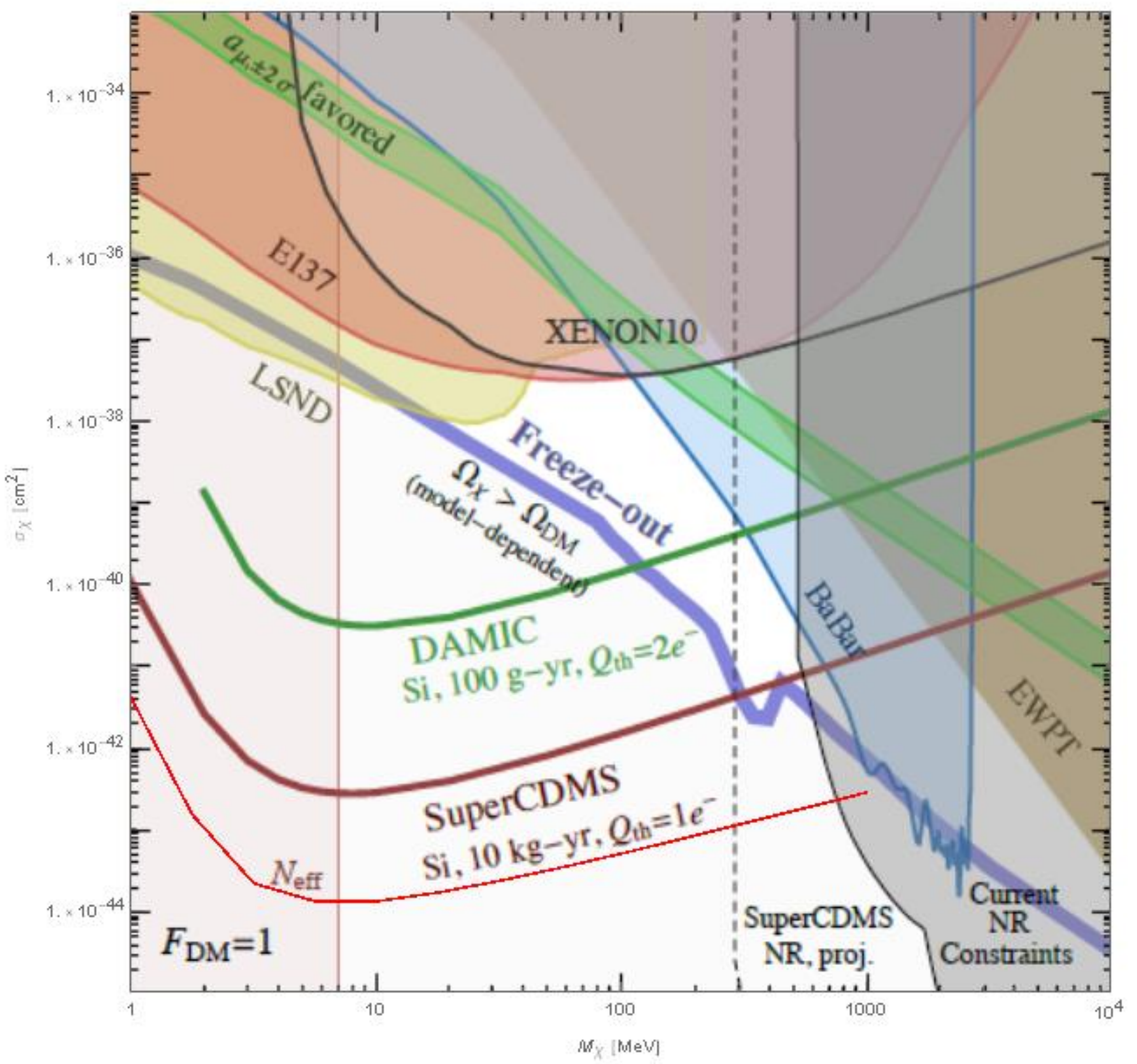
- EFFECT OF IONIZATION MODEL
- REGIMES OF DISCOVERY LIMIT VS EXPOSURES
  - 1/MT
  - 1/MT^0.5
  - Beyond (Extreme Exposures)





DISCOVERY LIMITS

- RED CURVE
  - 100 ton-yr exposure
  - DM-electron scattering signal
  - Neutrino-nuclear and electron scattering background.
    - Lindhard Quenching model with adiabatic correction factor for modeling of nuclear scattering to ionization



CONCLUSION

- FUTURE WORK
- REFERENCES

  - Essig, Mardon, Volansky. "Direct Detection of Sub-GeV Dark Matter". SLAC-PUB-14538.
  - Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu. "Direct Detection of sub-GeV Dark Matter with Semiconductor Targets". arXiv 1509.01598v2.
  - Billard, Figueroa-Feliciano, Strigari. "Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments". arXiv 1307.5458v3.

- QUESTIONS