Constraining neutrino-DM interactions with Milky Way dwarf spheroidals and supernova neutrinos

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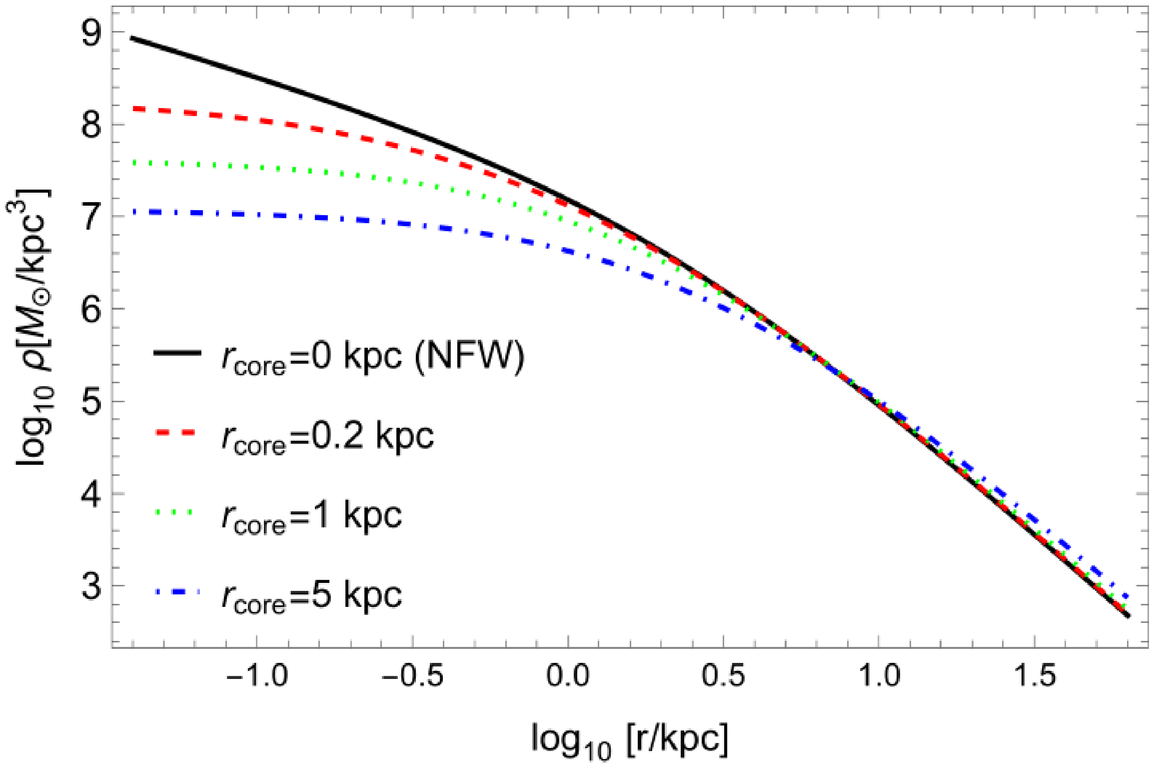
Why use dwarf spheroidals?

- DM-only simulations show cuspy DM profiles for small halos [*Navarro, Frenk, White (1996)*]
  - These small halos host dwarf spheroidals (dSph)
- Observations suggest cored halos [*Spergel and Steinhardt (2000)*]
- Need DM self-interactions or feedback from SM processes
  - Supernovae, star formation, etc.



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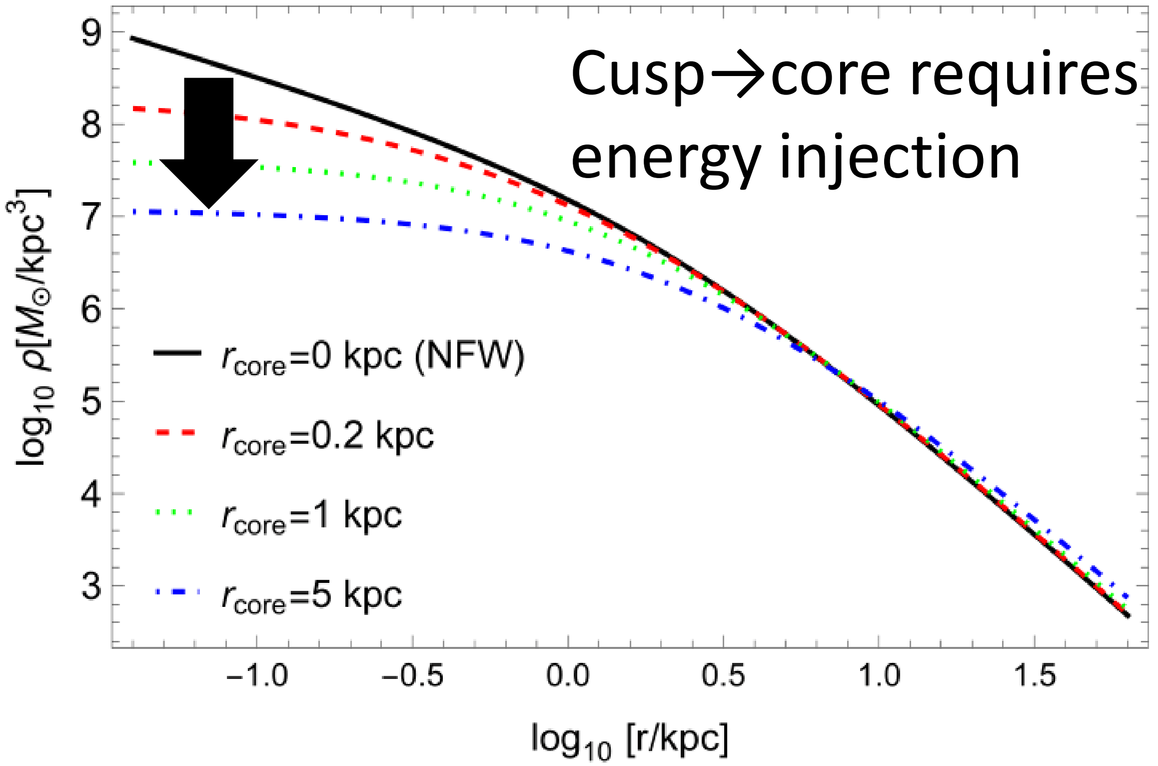


Core-Collapse Supernovae

- Occurs for stars with $\mathrm{M} > 8\ \mathrm{M}_{\odot}$
- Collapse when Fe core reaches Chandrasekhar mass ($\sim 1.4\ \mathrm{M}_{\odot}$)
- Release of $\sim 10^{58}$ neutrinos, total energy of 3×10^{53} erg
- Typical neutrino energies around $10 - 15$ MeV

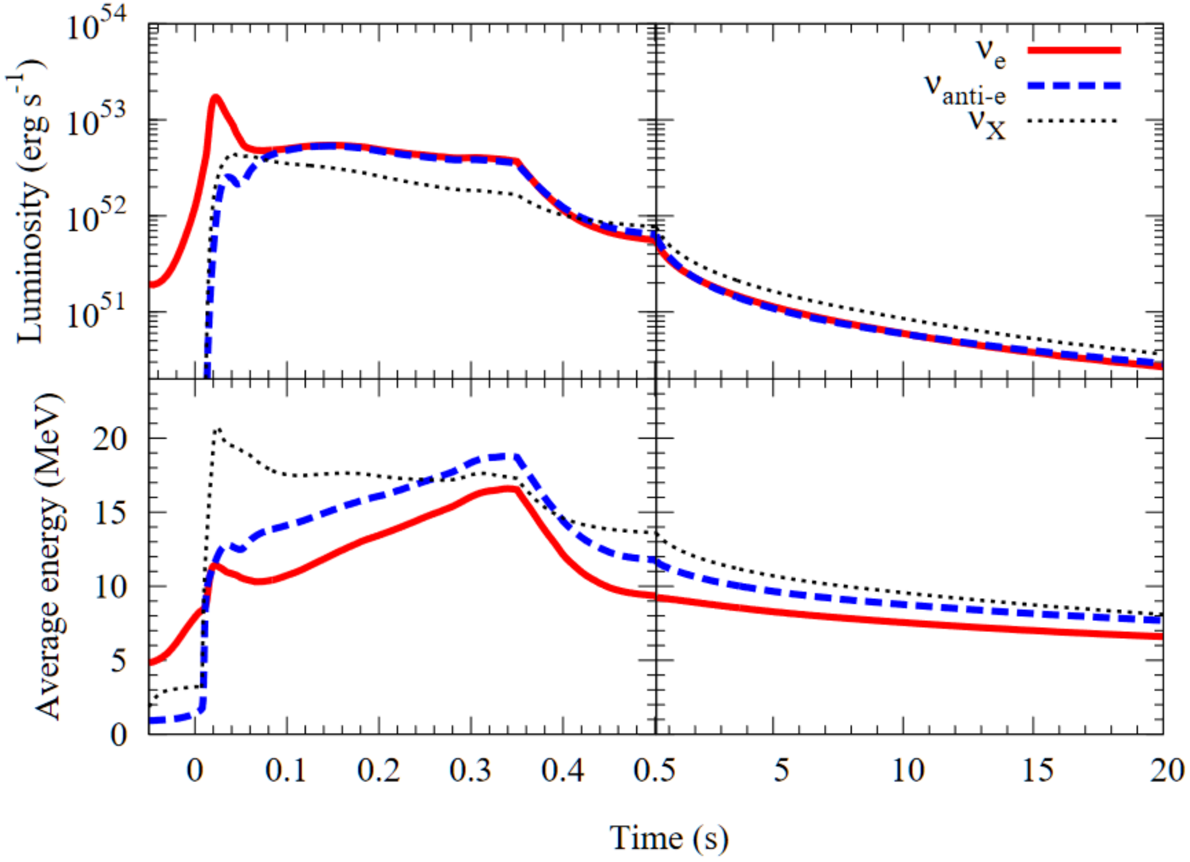


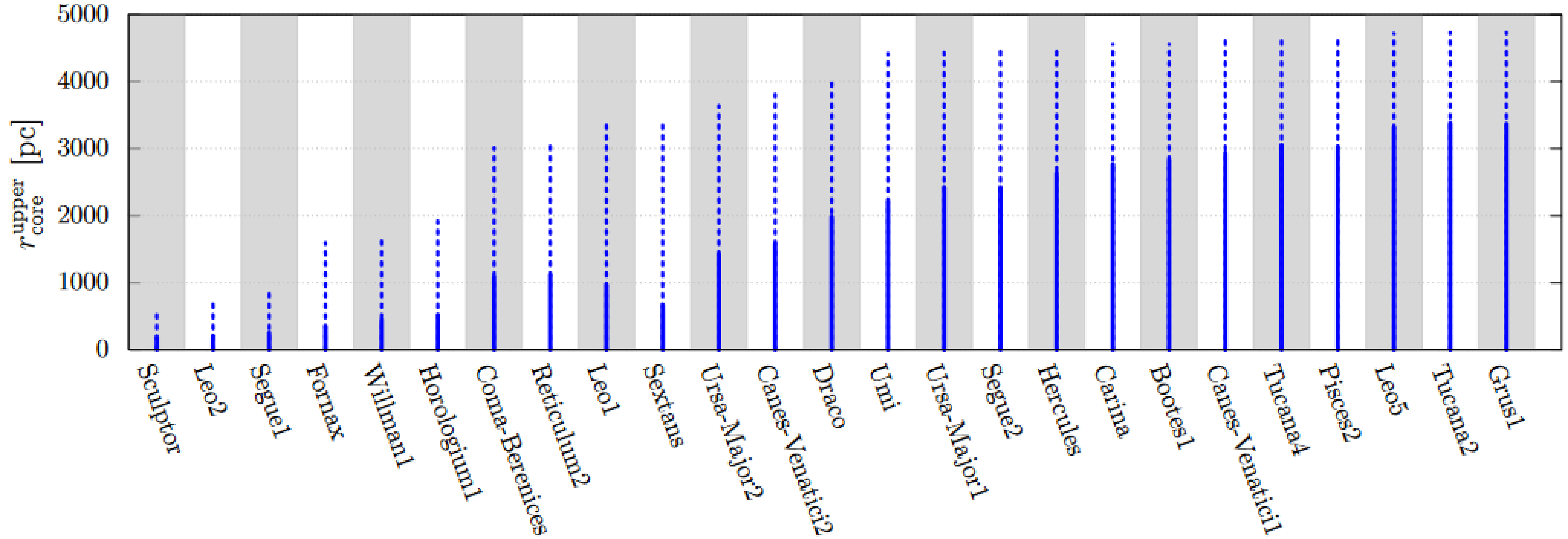
Fig. from Suwa et. al (2019)

Overview of the Idea

1. DM halos initially form with cusped profiles
   - Assume ΛCDM, no DM self-interactions, ignore baryonic feedback
2. Massive stars form in dSph, eventually undergo core collapse and release neutrinos
3. SN neutrinos interact with DM, energy injection into DM
4. Energy injection causes transition from cusped to cored profile, **this is what we directly constrain**
5. Turn energy constraint into cross section constraint

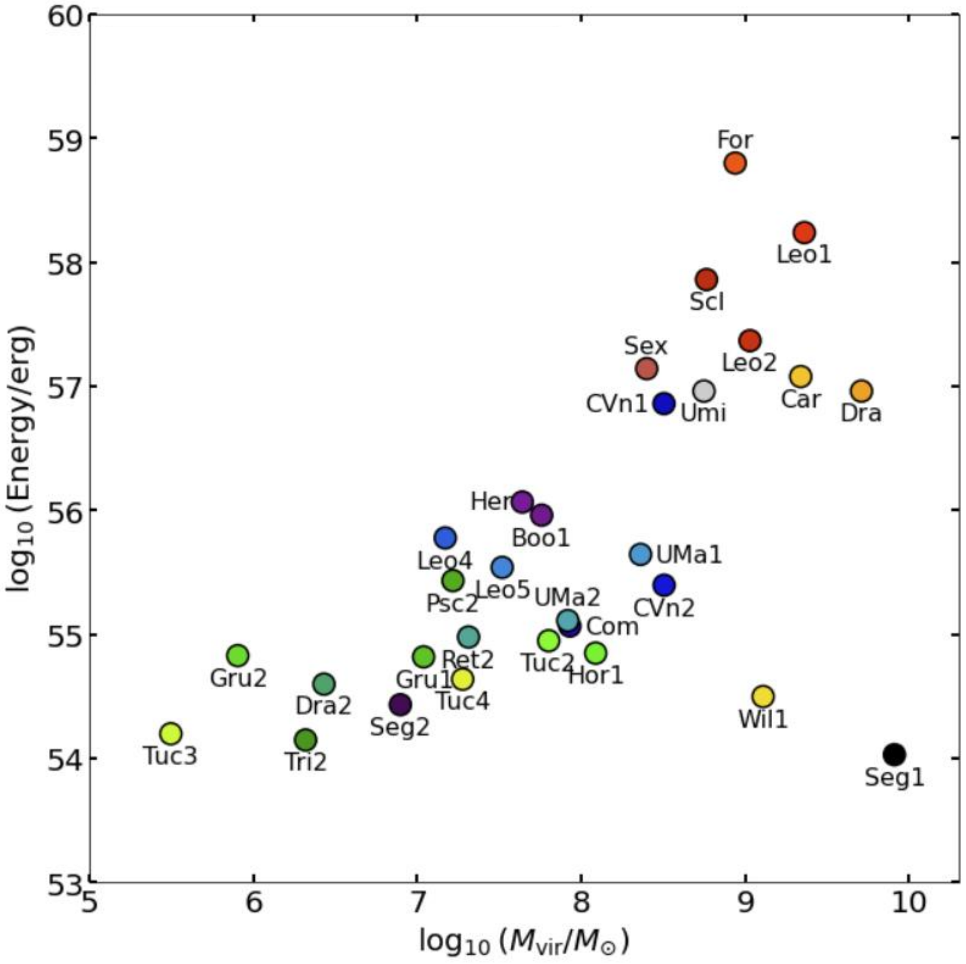
Finding Energy for Cusp→Core

- Use the virial theorem $\Delta E = \frac{W_{\rm core} - W_{\rm cusp}}{2}$
- Depends on sub-halo DM params, found with stellar kinematic data



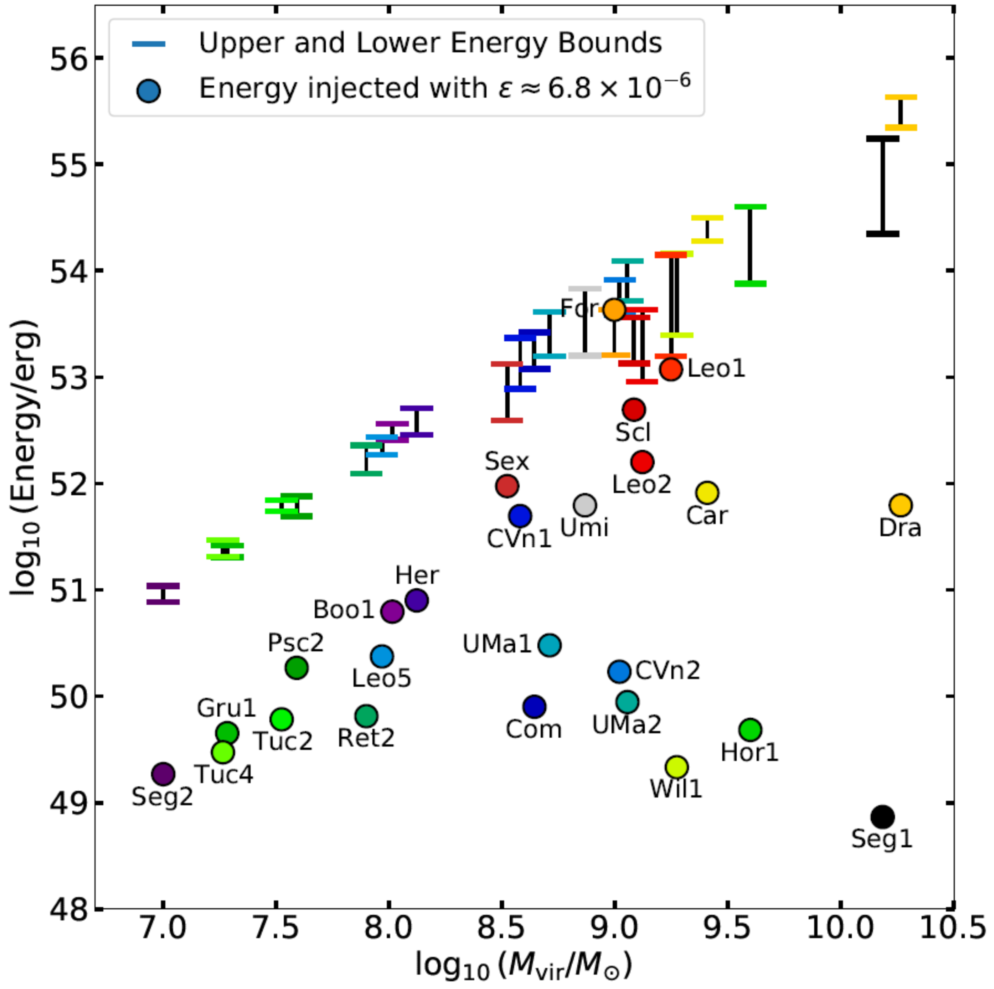
CCSNe Neutrino Energy Budget

- Estimate number of CCSNe in each dSph
  - Find stellar mass from luminosity $M_\odot/L_\odot=1$
  - Get number of massive stars from stellar initial mass function
- Each CCSNe emits 3×10^{53} erg in neutrinos
- Combining these gives total energy budget, want $E_{budget} \gg E_{transformation}$



Energy Constraint Example: Fornax

- Limit fraction of CCSN neutrino energy injected, $\varepsilon = E_{\text{inj}}/E_{\text{budget}}$
- Assume this is the only form of energy injection
  - Allows for conservative constraint
- Each dSph has a different constraint
  - Fornax has smallest $\varepsilon \sim 6.8 \times 10^{-6}$



Deriving Cross Section Bound

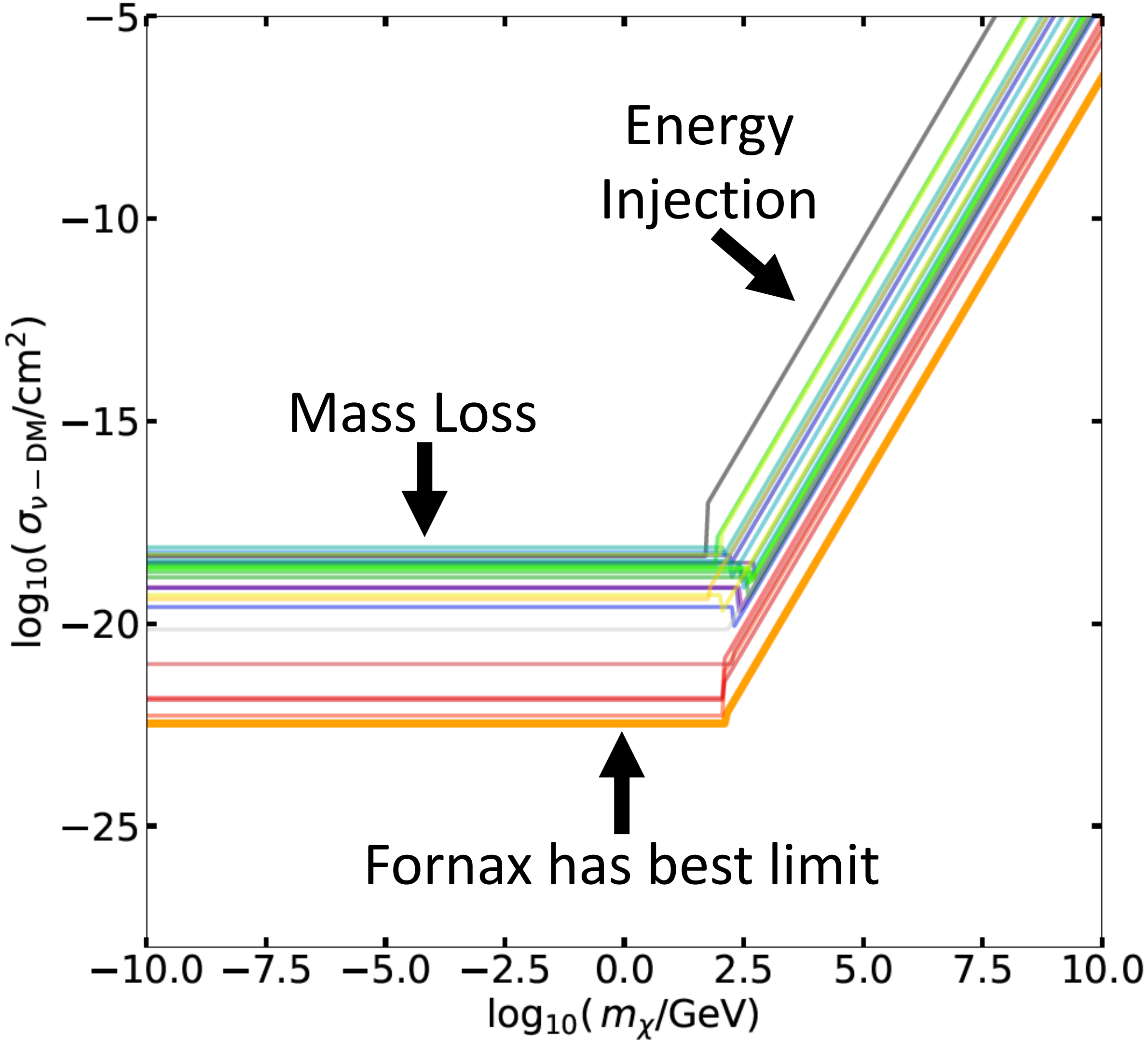
- Assume maximal energy transfer per interaction $\Delta E_{\text{int}} = \frac{2E_\nu^2}{2E_\nu + m_{\text{DM}}}$
  - Small escape velocities, Fornax is $\sim$50 km/s
- Interaction fraction $\eta = N_{\text{int}}/N_\nu$, DM column number density Σ_{DM}
- Cross section $\sigma = \eta/\Sigma_{\text{DM}}$, for Fornax the bounds are as follows

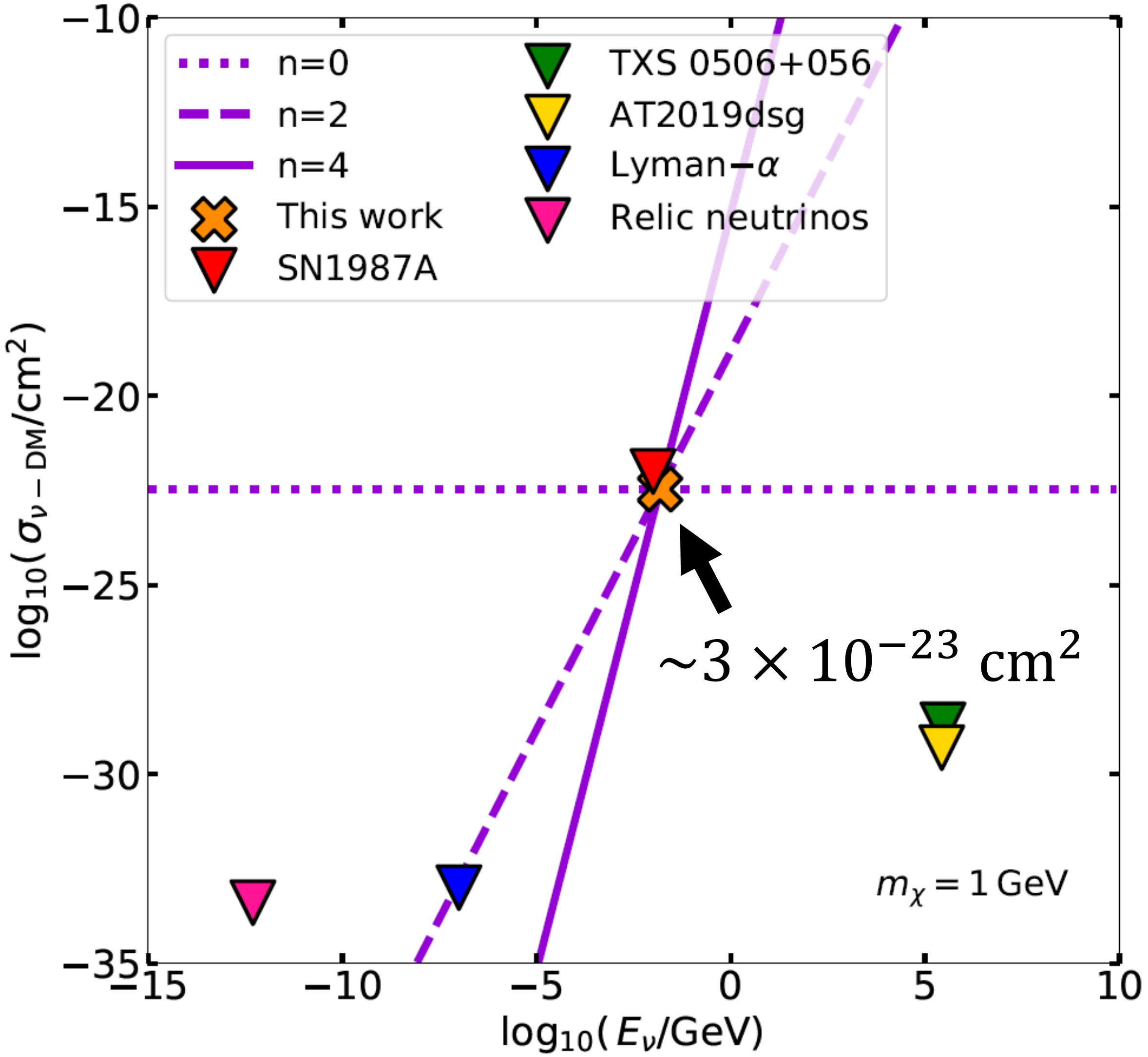
Mass Loss Bound

- $m_{\text{DM}} < 130$ GeV escapes sub-halo
- $N_{\text{int}} = \frac{\Delta M}{m_{\text{DM}}}$
- $\sigma \approx 3.4 \times 10^{-23}\ \text{cm}^2$

Energy Injection Bound

- $m_{\text{DM}} > 130$ GeV stays in sub-halo
- $N_{int} = \frac{E_{\text{inj}}}{\Delta E_{\text{int}}}$
- $\sigma \approx 3.2 \times 10^{-27} \left(\frac{m_{\text{DM}}}{1\ \text{GeV}}\right)^2\ \text{cm}^2$


Energy
Injection
Mass Loss
Fornax has best limit
$\log_{10}(\sigma_{\nu-\mathrm{DM}}/\mathrm{cm}^2)$
$\log_{10}(m_\chi/\mathrm{GeV})$
−5
−10
−15
−20
−25
−10.0 −7.5 −5.0 −2.5 0.0 2.5 5.0 7.5 10.0


n=0
n=2
n=4
This work
SN1987A
TXS 0506+056
AT2019dsg
Lyman−α
Relic neutrinos
$\sim 3 \times 10^{-23}\ \mathrm{cm}^2$
$m_\chi = 1\,\mathrm{GeV}$
$\log_{10}(\sigma_{\nu-\mathrm{DM}}/\mathrm{cm}^2)$
$\log_{10}(E_\nu/\mathrm{GeV})$
−10
−15
−20
−25
−30
−35
−15 −10 −5 0 5 10

Summary

- Constrain interaction by mass loss or energy injection
- Slightly stronger bound in SN neutrino energy range than SN1987A
- Many assumptions are made in this phenomenological model that can affect the upper limit we find
  - Maximal energy transfer, no host halo effects, ignoring other types of baryonic-induced feedback, etc.
- Future telescopes should be able to reduce uncertainties on dSph DM sub-halo parameters (e.g. Vera C. Rubin Observatory)

Thank you!

Backup Slides

Environments for SN ν Phenomenology

- Two important conditions
  1. CCSNe have occurred locally
  2. Large amount of DM present, but not a very deep potential
- Automatically, we can focus on dwarf spheroidals (dSphs)
  - Small dwarf galaxies with low luminosities and old stellar population
- dSPhs observations suggest cored DM profiles, ΛCDM predicts cuspy profiles (in DM-only simulations)
  - Need <u>energy injection</u> for cusp→core

Processes for Neutrino Production

Processes	Formulae
Plasma	$\gamma^* \to \nu + \bar{\nu}$
$\nu\bar{\nu}$ annihilation	$\nu_a + \bar{\nu}_a \to \nu_b + \bar{\nu}_b$
Photoneutrino	$\gamma + e^{\pm} \to e^{\pm} + \nu + \bar{\nu}$
Nucleon-nucleon brehmsstrahlung	$NN' \to NN' + \nu\bar{\nu}$
Pair	$e^+ + e^- \to \nu + \bar{\nu}$
$\beta^{\pm}$ decay	$A(N,Z) \to A(N-1, Z+1) + e^- + \bar{\nu}_e$
	$A(N,Z) \to A(N+1, Z-1) + e^+ + \nu_e$
e^-/e^+ capture	$A(N,Z) + e^- \to A(N+1, Z-1) + \nu_e$
	$A(N,Z) + e^+ \to A(N-1, Z+1) + \bar{\nu}_e$

Langanke & Martínez-Pinedo 2003

Working Parts for Energy Constraint

- Density profile (Modified NFW) $\rho(r) = \frac{\rho_0 \, r_s^3}{(r_c + r)(r + r_s)^2}$
- Mass profile $\frac{M(r)}{M_0} = \begin{cases} \ln(1+\tilde{r}) - \frac{\tilde{r}\,(2+3\tilde{r})}{2(1+\tilde{r})^2}, \; x = 1 \\ \frac{x^2 \ln(1+\tilde{r}/x) + (1-2x)\ln(1+\tilde{r})}{(1-x)^2} - \frac{\tilde{r}}{(1+\tilde{r})(1-x)}, \; x = 0 \\ \text{with} \quad \tilde{r} \equiv r/r_\text{s} \quad \text{and} \quad x = r/r_\text{c} \end{cases}$
- Work (from virial theorem) $W = -4\pi \, G_N \int_0^{r_{200}} r \, \rho(r) \, M(r) \, dr$
- Energy required for transformation $\Delta E = \frac{W_\text{core} - W_\text{cusp}}{2}$

Dwarf Galaxy Properties

- Stellar mass from luminosity of the dwarf galaxy ($M_\odot/L_\odot=1$) [*McConnachie (2012) & Hayashi+ (2022)*]
- Estimate number of CCSNe from stellar mass assuming a Kroupa (2001) initial mass function

$$M_* \frac{\int_{8\,M_\odot}^{100\,M_\odot} \xi(m)\,dm}{\int_{0.1\,M_\odot}^{100\,M_\odot} m\,\xi(m)\,dm}$$

- Get virial radius as the distance at which the DM profile reaches 200 times the critical density, find virial mass then from integration

Name	ρ_s [a] $[M_\odot/\text{pc}]$	r_s [pc]	r_c Lower Bound [pc] [b]	r_c Upper Bound [pc]	Stellar Mass $[M_\odot]$	r_{200} [pc]	M_{200} $[M_\odot]$
Seg1	0.031587	2407.570	24	414	3.4×10^2	23538.093730	8.14×10^9
Seg2	0.114640	143.324	403	3354	8.6×10^2	2203.281263	7.87×10^6
Boo1	0.079187	320.852	739	3648	2.9×10^4	4335.833187	5.73×10^7
Her	0.053277	342.402	454	3617	3.7×10^4	4026.943038	4.37×10^7
Com	0.071163	381.789	218	1656	3.7×10^3	4970.113877	8.51×10^7

Supernova Neutrino Energetics

- Assume each CCSN gives off 3×10^{53} erg in neutrinos
- Assume some energy transfer fraction (ε), which is our initial constraint value
- Test over multiple values of ε until we begin to have too much energy such that the DM cores become too large

Name	# Massive Stars	DM-ν Energy Budget [erg]	Energy Injected [erg]	Lower Energy Bound (1σ) [erg]	Upper Energy Bound (1σ) [erg]
Seg1	3.56	1.07×10^{54}	2.67×10^{48}	1.05×10^{54}	1.11×10^{55}
Seg2	9.01	2.70×10^{54}	6.76×10^{48}	5.28×10^{50}	7.54×10^{50}
Boo1	303.91	9.12×10^{55}	2.28×10^{50}	1.25×10^{52}	1.74×10^{52}
Her	387.75	1.16×10^{56}	2.91×10^{50}	5.98×10^{51}	9.84×10^{51}
Com	38.77	1.16×10^{55}	2.91×10^{49}	1.34×10^{52}	2.77×10^{52}

Z’ model

- Simple model, assume exchange of a vector boson (Z')
  - Two couplings, g_ν which is the same for all flavors and g_χ for DM

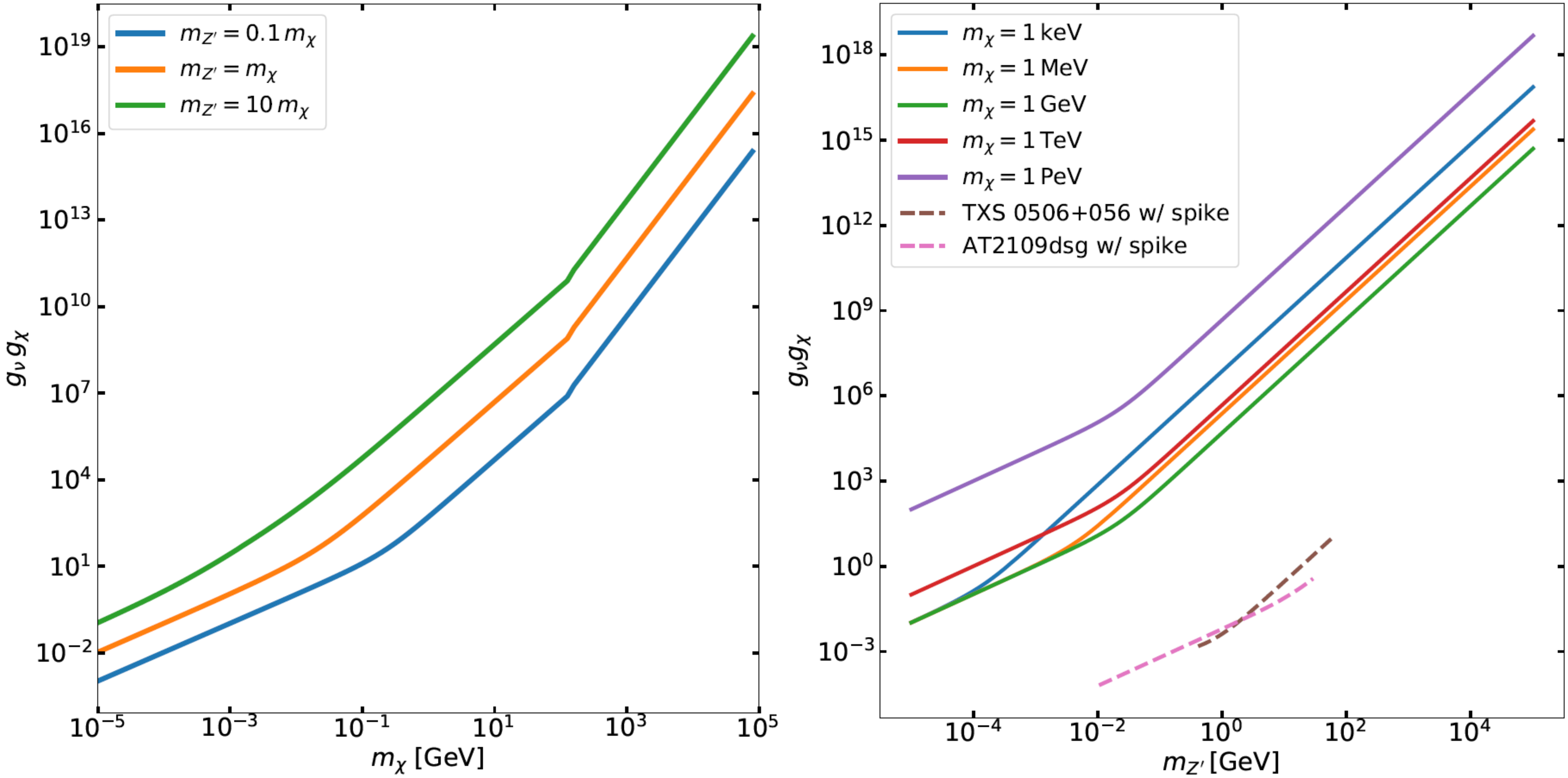
$$\sigma_{\nu-\mathrm{DM}} \approx \begin{cases} \frac{g_\nu^2 g_\chi^2}{4\pi m_{Z'}^4}\left[1 - \frac{m_{Z'}^2}{2m_\chi E_\nu}\ln\left(1 + \frac{2m_\chi E_\nu}{m_{Z'}^2}\right)\right], & E_\nu >> m_\chi, \\ \frac{g_\nu^2 g_\chi^2 m_\chi E_\nu}{4\pi m_{Z'}^4}, & E_\nu << m_\chi, \end{cases}$$

Full cross section for Z' model

$$\frac{d\sigma}{d\cos\theta} = \frac{g^2 g'^2 E_\nu^2 m_\chi^2((1-x^2)E_\nu m_\chi + (1-x)^2 E_\nu^2 + (1+x)m_\chi^2)}{4\pi\left((1-x)E_\nu + m_\chi\right)\left((1-x)E_\nu m_\phi^2 + m_\chi\left(m_\phi^2 - 2(x-1)E_\nu^2\right)\right)^2},$$

$$\sigma = \frac{g^2 g'^2}{16\pi E_\nu^2 m_\chi^2}\left[(m_\phi^2 + m_\chi^2 + 2E_\nu m_\chi)\log\left(\frac{m_\phi^2(2E_\nu + m_\chi)}{m_\chi(4E_\nu^2 + m_\phi^2) + 2E_\nu m_\phi^2}\right) + 4E_\nu^2\left(1 + \frac{m_\chi^2}{m_\phi^2} - \frac{2E_\nu(4E_\nu^2 m_\chi + E_\nu(m_\chi^2 + 2m_\phi^2) + m_\chi m_\phi^2)}{(2E_\nu + m_\chi)(m_\chi(4E_\nu^2 + m_\phi^2) + 2E_\nu m_\phi^2)}\right)\right]$$

Argüelles, Kheirandish, Vince (2017)



$m_{Z'} = 0.1\, m_\chi$
$m_{Z'} = m_\chi$
$m_{Z'} = 10\, m_\chi$
$g_\nu g_\chi$
m_χ [GeV]
$m_\chi = 1$ keV
$m_\chi = 1$ MeV
$m_\chi = 1$ GeV
$m_\chi = 1$ TeV
$m_\chi = 1$ PeV
TXS 0506+056 w/ spike
AT2109dsg w/ spike
$g_\nu g_\chi$
$m_{Z'}$ [GeV]