Inelastic Dark Matter-Nucleus Scattering in Stopped-pion Experiments using Transition Photons

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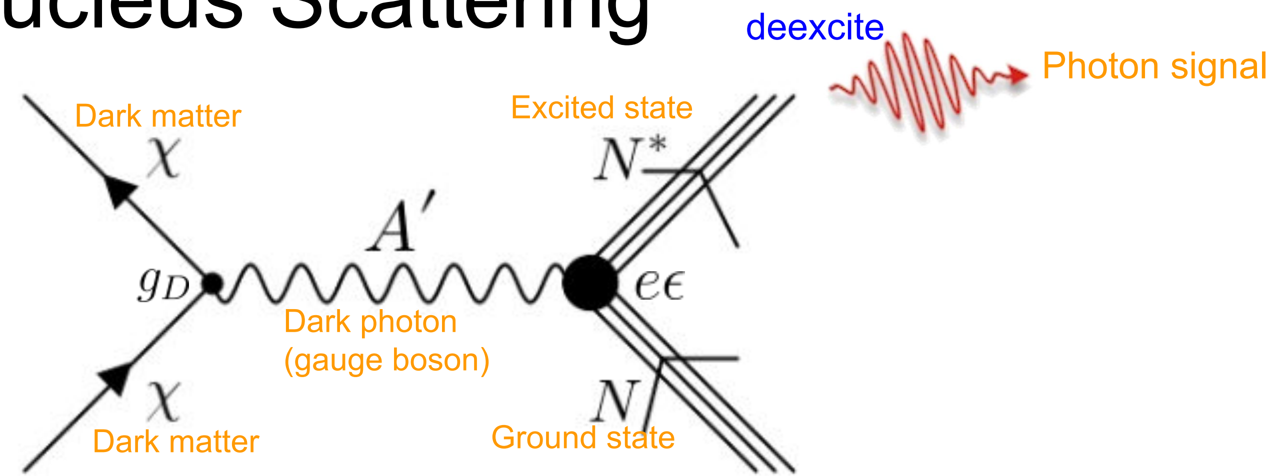
Outline

1. Theories and models
2. Experiments
3. Results

Ref: 2206.08590 ongoing work

Inelastic DM-Nucleus Scattering



$$\mathcal{L} \supset g_D A'_\mu \bar{\chi}\gamma^\mu\chi + e\epsilon Q_q A'_\mu \bar{q}\gamma^\mu q$$

$$\mathcal{L}_s = |D_\mu \phi|^2 \qquad g_D = \sqrt{2\pi} \qquad m_{A'}/m_\chi = 3$$

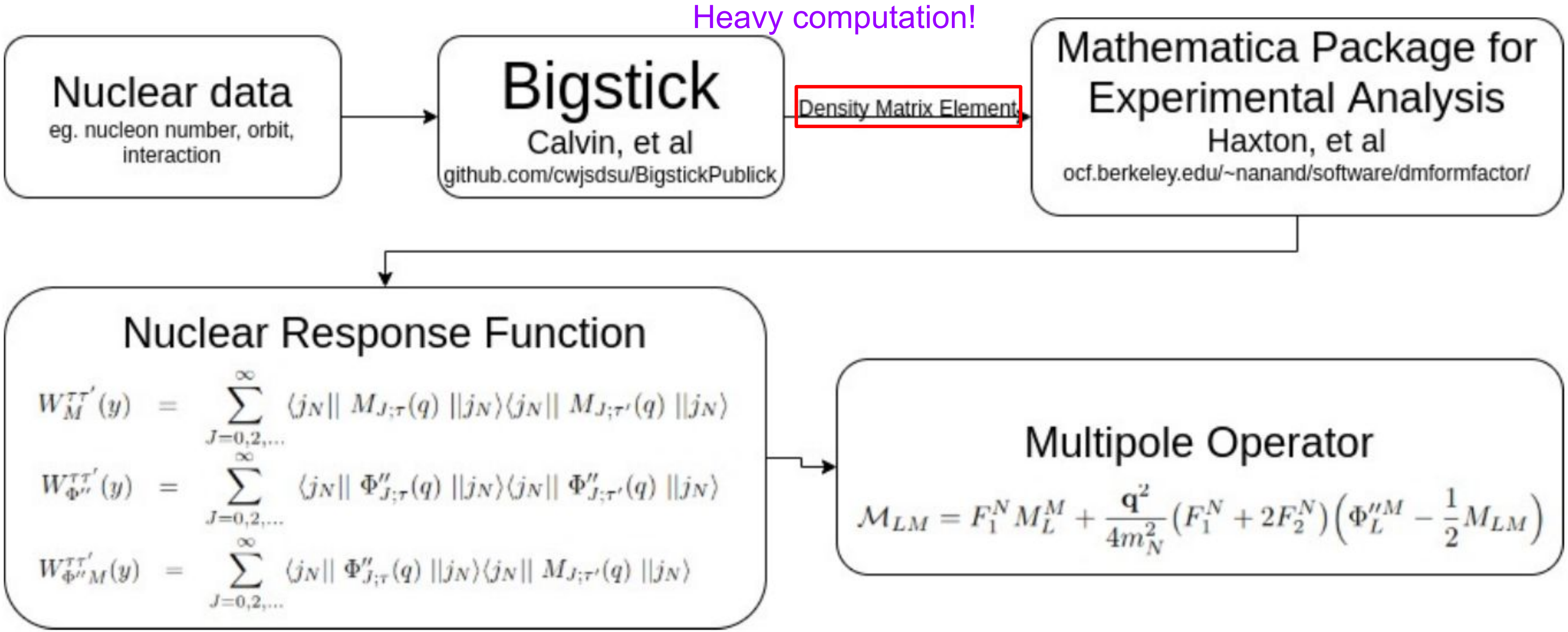
Why not elastic?

Elastic has high signals but also high background

Multipole expansion

$$\frac{d\sigma^{DM}_{\text{inel}}}{dE_r} = \frac{2e^2\epsilon^2 g_D^2 E'^2_\chi}{p_\chi p'_\chi (2m_N E_r + m^2_{A'})^2}\frac{m_N}{2\pi}\frac{4\pi}{2J+1}\Bigg\{\sum_{J\geqslant 1, spin}\left[\frac{1}{2}(\vec{l}\cdot\vec{l}^* - l_3 l_3^*)\left(|\langle J_f||\hat{\mathcal{T}}_J^{mag}||J_i\rangle|^2 + |\langle J_f||\hat{\mathcal{T}}_J^{el}||J_i\rangle|^2\right)\right]$$
$$+ \sum_{J\geqslant 0, spin}\left[l_0 l_0^*\,|\langle J_f||\hat{\mathcal{M}}_J||J_i\rangle|^2 + l_3 l_3^*\,|\langle J_f||\hat{\mathcal{L}}_J||J_i\rangle|^2 - 2\,l_3 l_0^* Re\left(\langle J_f||\hat{\mathcal{L}}_J||J_i\rangle\langle J_f||\hat{\mathcal{M}}_J||J_i\rangle^*\right)\right]\Bigg\}$$

Nuclear Shell Model Code: BIGSTICK



It takes a long time and needs tons of RAM and CPU

Is there a shortcut?

Long Wavelength Limit

$$\hat{\mathcal{M}}_{JM}(q) = \frac{q^J}{(2J+1)!!}\int d^3x x^J Y_{JM}\hat{\mathcal{J}}_0(\mathbf{x})$$

$$\hat{\mathcal{L}}_{JM}(q) = \frac{-iq^{J-1}}{(2J+1)!!}\int d^3x x^J Y_{JM}\nabla\cdot\hat{\mathcal{J}}(\mathbf{x})$$

$$\hat{\mathcal{T}}^{el}_{JM}(q) = -i\frac{q^{J-1}}{(2J+1)!!}\left(\frac{J+1}{J}\right)^{1/2}\int d^3x x^J Y_{JM}\nabla\cdot\hat{\mathcal{J}}(\mathbf{x})$$

$$\hat{\mathcal{T}}^{mag}_{JM}(q) = i\frac{q^J}{(2J+1)!!}\left(\frac{J+1}{J}\right)^{1/2}\int d^3x\left[\frac{1}{J+1}\mathbf{r}\times\hat{\mathcal{J}}(\mathbf{x})\right]\cdot\nabla x^J Y_{JM}$$

The surviving multipoles are $\hat{\mathcal{M}}_{00}, \hat{\mathcal{L}}_{1M}, \hat{\mathcal{T}}^{el}_{1M}$.

$$\hat{\mathcal{M}}_{00} = \frac{1}{\sqrt{4\pi}}F_1\sum_{i=1}^{A}\hat{FT}\,(\sim\hat{\tau})$$

Fermi doesn't contribute to inelastic scattering because it's even-even operator. It only exists in elastic scattering

$$\hat{\mathcal{T}}^{el}_{1M} = \sqrt{2}\hat{\mathcal{L}}_{1M} = \frac{i}{\sqrt{6\pi}}G_A\sum_{i=1}^{A}\hat{GT}\,(\sim\hat{\sigma}\hat{\tau})$$

Is GT (Gamow Teller) the shortcut?

Strength and Multipole in BIGSTICK

BIGSTICK can calculate the strength of a given operator

$$B(\mathcal{O} : i \rightarrow f) = \frac{1}{2J_i + 1} \left| (\Psi_f : J_f || \hat{O}_J || \Psi_i J_i) \right|^2$$

	Strength	Multipole
Time	Short	Long
RAM & CPU	Light	Heavy
Output	Less detailed The strength and energy	Comprehensive Density matrix -> strength

Multipole has energy, spin, isospin, and density matrix
Strength only has energy, strength

GT Strength Lines

GT strength = $|\langle J_f || \sum_{i=1}^{A} \frac{1}{2} \hat{\sigma}_i \hat{\tau}_0 || J_i \rangle|^2$

excited state

ground state

Experiment data

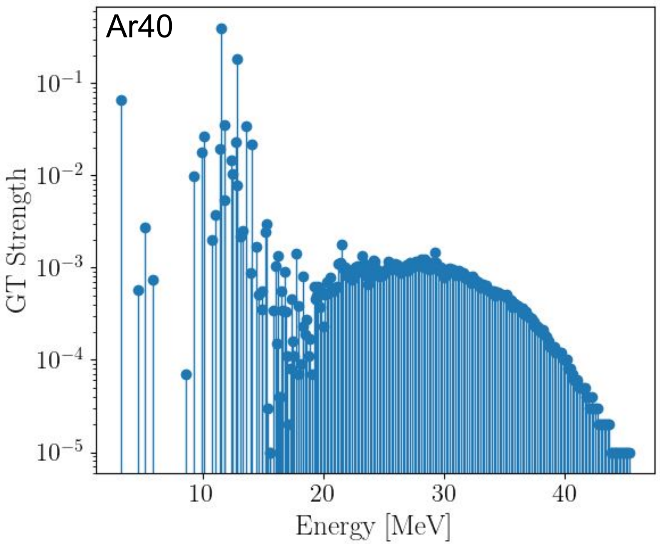
$$\Delta J = |J_f - J_i| = 1$$

$$\chi + N \rightarrow \chi + N^*$$

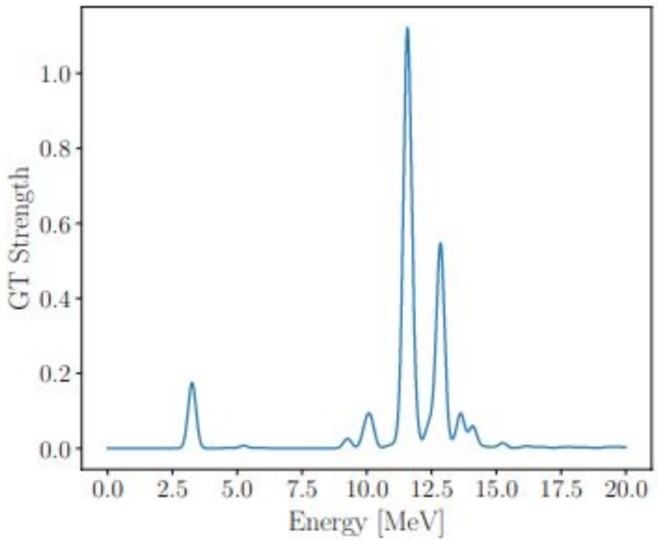
$$N^* \rightarrow N + \gamma$$

Signal

one line = one transition = one excited state

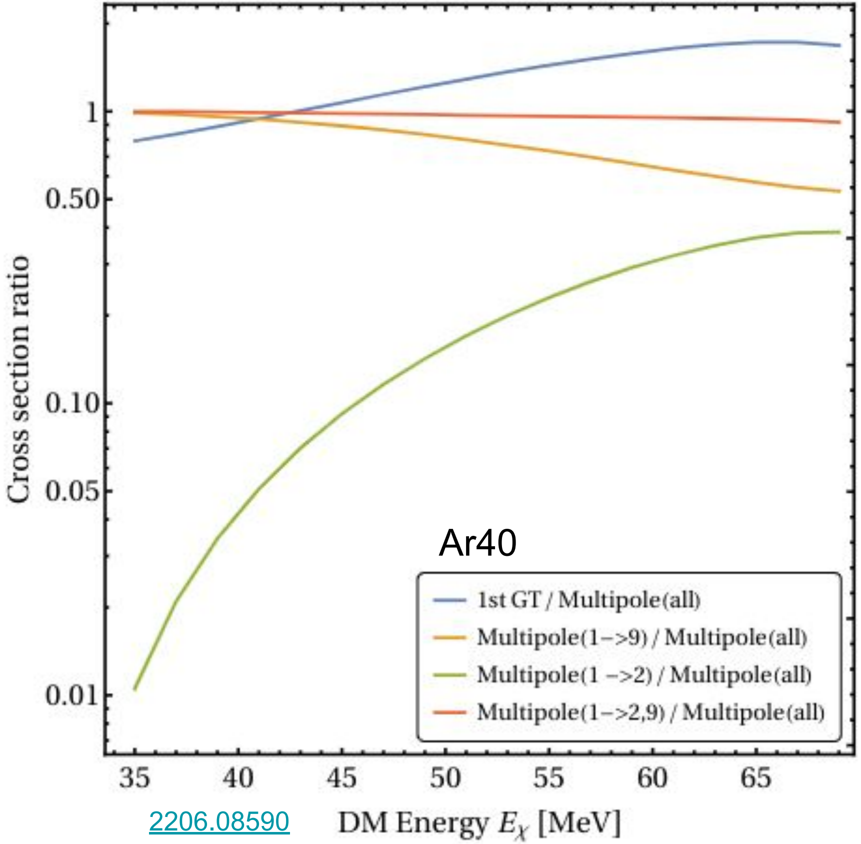


convoluted with 150 keV width Gaussian



E^* [keV]	J^π
0.0[a]	0^+
1460.851(6)[a]	2^+
2120.8(3)[b]	0^+
2524.1(2)[b]	2^+
2892.6(1)[a]	4^+
3208.0(6)	2^+
3464.5(1)[a]	6^+
3511.3(5)	2^+
3515(1)[b]	4^+
3680.8(2)	3^-
3918.8(2)	2^+
3941.7(3)*	
4041(1)	N
4082.5(2)	3^-
4178.9(3)*	
4226(1)	4^-
4229(1)	$1^+,2^-,3^+$
4300.8(3)	$\langle 1,3\rangle^-$
4324.5(3)	2^+
4358.0(3)	N
4420(1)	$\langle 0^+–4^+\rangle$
4427(1)	$\langle 4^+\rangle$
4473(1)	1
4481.0(3)	1^-
4494(1)[c]	5^-
4562.3(2)	$\langle 1,3\rangle^-$
4578(1)	$\langle 2^+,3^-\rangle$
4602(1)	$\langle 0^+–4^+\rangle$
4674(1)	$1^+,2^-,3^+$
4737.8(4)*	
4769.0(3)	1^-

Cross Section in Long Wavelength Limit



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Er -> 0

$$\frac{d\sigma^{DM}_{inel}}{d\cos\theta} = \frac{2e^2\epsilon^2 g_D^2 E'^2_\chi}{(2m_N E_r + m_{A'}^2)^2}\frac{1}{2\pi}\frac{4\pi}{2J+1} \times \sum_{s_i,s_f} \vec{l}\cdot\vec{l}^*\frac{g_A^2}{12\pi}|\langle J_f||\sum_{i=1}^{A}\frac{1}{2}\hat{\sigma}_i\hat{\tau}_0||J_i\rangle|^2$$

Gamow-Teller (GT) operator

GT dominates the cross section!

GT strength is the shortcut!

DM-Nucleus Scattering: Elastic vs Inelastic (GT)

$$\frac{d\sigma_{\rm el}^{DM}}{dE_r} = \frac{e^2\epsilon^2 g_D^2 Z^2}{4\pi(E_\chi^2-m_\chi^2)(2m_N E_r+m_{A'}^2)^2}F^2(E_r) \times \left[2E_\chi^2 m_N\left(1-\frac{E_r}{E_\chi}-\frac{m_N E_r}{2E_\chi^2}\right)+E_r^2 m_N\right]$$

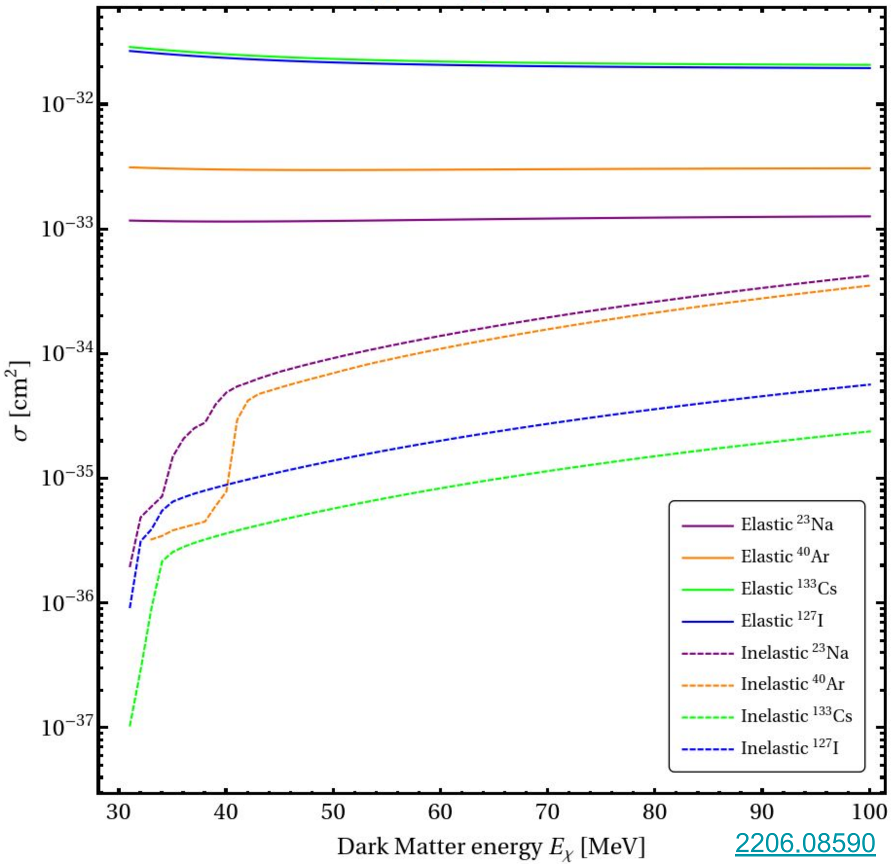
$$\frac{d\sigma_{inel}^{DM}}{d\cos\theta} = \frac{2e^2\epsilon^2 g_D^2 E_\chi'^2}{(2m_N E_r+m_{A'}^2)^2}\frac{1}{2\pi}\frac{4\pi}{2J+1} \times \sum_{s_i,s_f}\vec{l}\cdot\vec{l}^*\frac{g_A^2}{12\pi}|\langle J_f||\sum_{i=1}^{A}\frac{1}{2}\hat{\sigma}_i\hat{\tau}_0||J_i\rangle|^2$$

$$\left(\frac{Inelastic}{Elastic}\right)_{signal} = 10^{-2}-10^{-1}$$

$$\left(\frac{Inelastic}{Elastic}\right)_{bkg} = 10^{-4}-10^{-3}$$

Inelastic search can be better

$\epsilon = 10^{-4}$ $m_\chi = 30$ MeV.



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Inelastic DM-Nucleus Scattering (GT)

Cross section has the same form for fermion and scalar DM, only difference is the current

Fermion DM ~ 2 * scalar DM

$$\frac{d\sigma_{inel}^{DM}}{d\cos\theta} = \frac{2e^2\epsilon^2 g_D^2 E'^2_\chi}{(2m_N E_r + m_{A'}^2)^2}\frac{1}{2\pi}\frac{4\pi}{2J+1}$$

$$\times \sum_{s_i,s_f} \vec{l}\cdot\vec{l}^* \frac{g_A^2}{12\pi}|\langle J_f||\sum_{i=1}^{A}\frac{1}{2}\hat{\sigma}_i\hat{\tau}_0||J_i\rangle|^2$$

Fermion

$$\mathcal{L} \supset g_D A'_\mu \bar{\chi}\gamma^\mu\chi + e\epsilon Q_q A'_\mu \bar{q}\gamma^\mu q$$

$$\sum_{s_i,s_f} \vec{l}\cdot\vec{l}^* = 3 - \frac{1}{E_\chi E'_\chi}\left[\frac{1}{2}\left(p_\chi^2 + p'^2_\chi - 2m_N E_r\right) + \frac{3m_\chi^2}{4}\right]$$

Scalar

$$\mathcal{L}_s = |D_\mu\phi|^2$$

$$\vec{l}\cdot\vec{l}^* = \frac{1}{2E_\chi E'_\chi}\left(p_\chi^2 + p'^2_\chi - 2m_N E_r\right)$$

DM Flux

$A' \rightarrow \chi\bar{\chi}$ Decay in < O(-10) ns

$\pi^- + p \rightarrow n + A'$ pion absorption

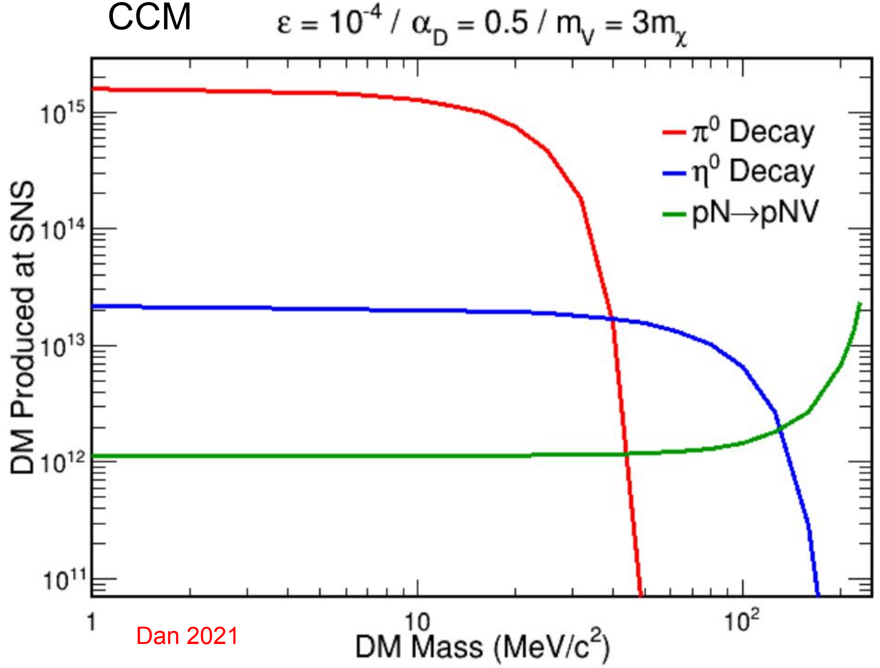
$\pi^+ + n \rightarrow p + A'$ pion absorption

$\pi^0 \rightarrow \gamma + A'$ pion decay *dominant

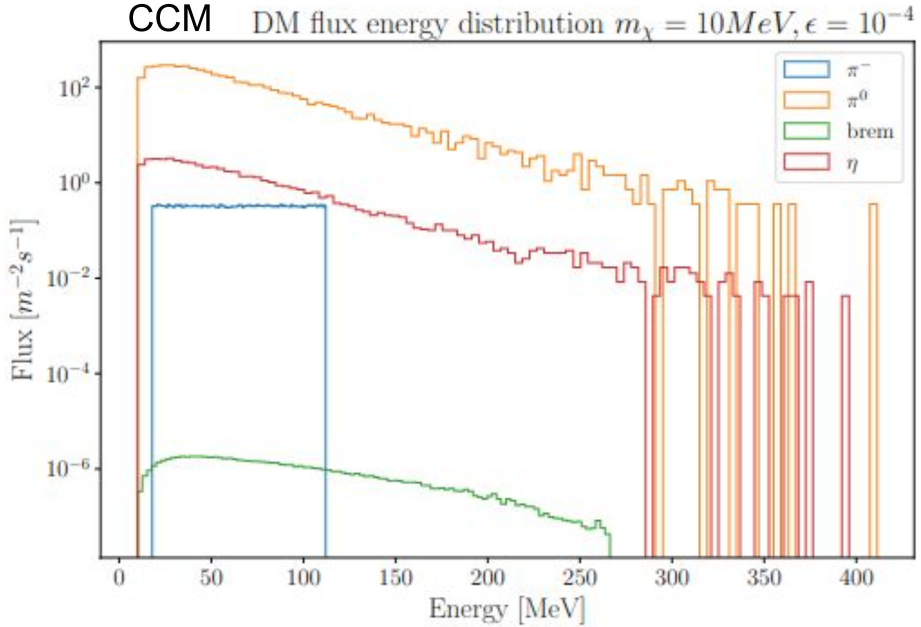
$\eta^0 \rightarrow \gamma + A'$ eta decay

$e^{\pm *} \rightarrow e^{\pm} + A'$ bremsstrahlung

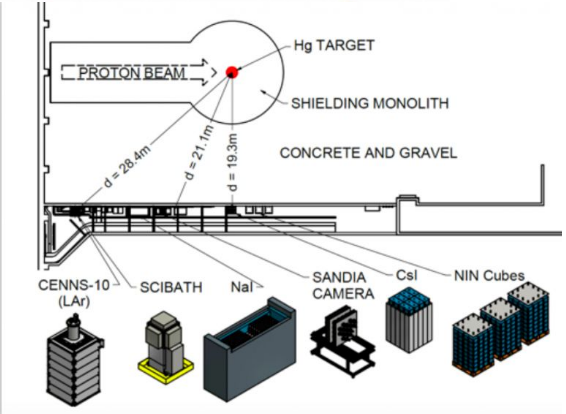
CCM

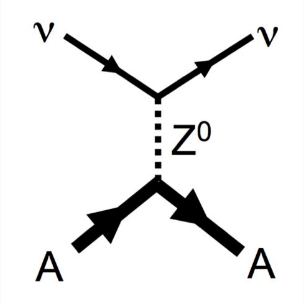


CCM



Experiments and Detectors





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CAPTAIN = "Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos"

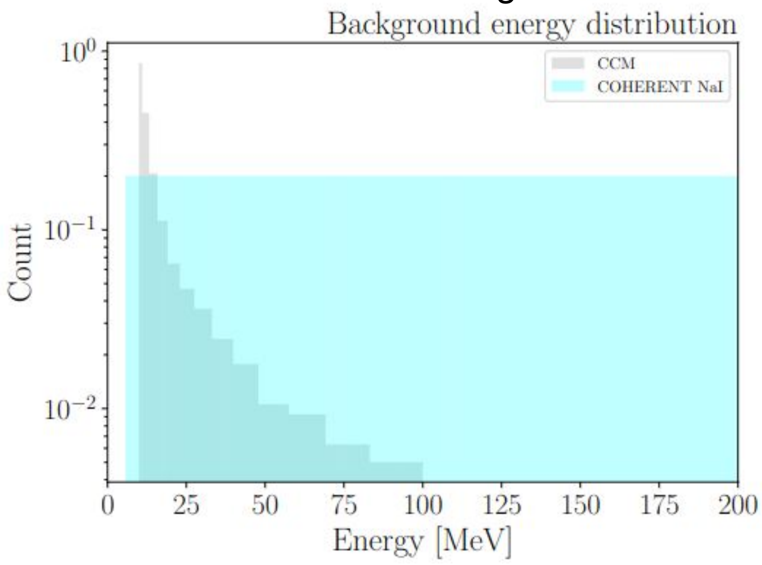
Why NaI and CCM?
They have large mass and low background

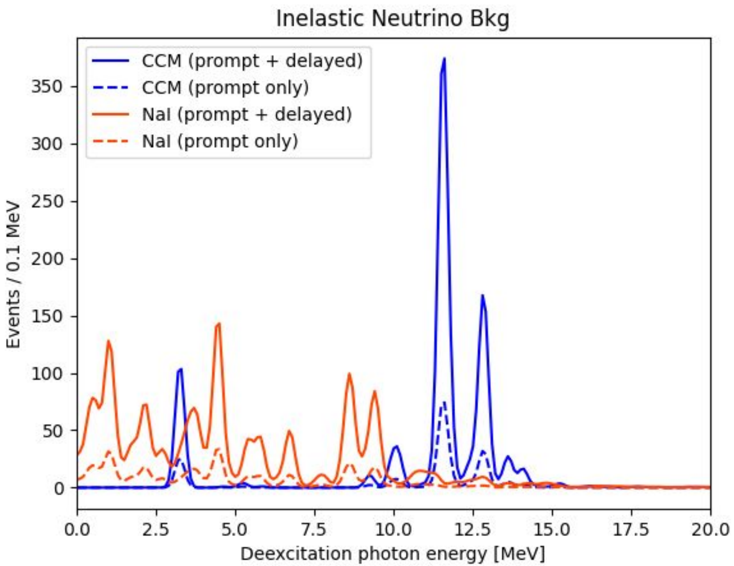
Experiment	E_{beam} [GeV]	POT [yr^{-1}]	Target	Detector: target	mass	distance	angle	E_r^{th}
COHERENT	1	1.5×10^{23}	Hg	CsI[Na]	14.6 kg	19.3 m	90°	6.5 keV
				NaI[Tl]	185 kg	22 m	120°	900 keV
				NaI[Tl]	3500 kg	22 m	120°	~few keV
CCM	0.8	1.0×10^{22}	W	Ar	7 t	20 m	90°	25 keV

Detector Background

Detector	Bkg reduction	Bkg (after reduction)
COHERENT NaI	5 (ones-like bkg)	~1
CCM	100	~100

Reduced detector bkg





We also include inelastic nu as bkg

Prompt Window

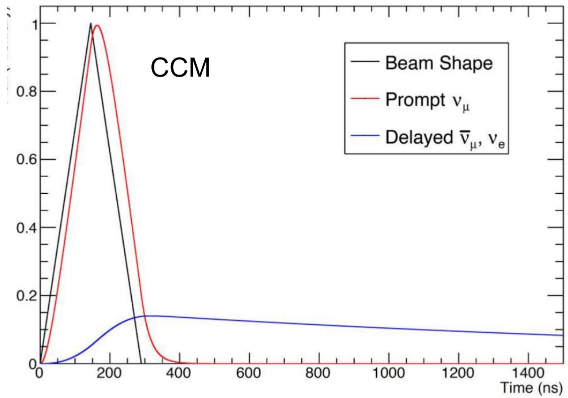
Signal = inelastic DM from pion and eta decay
Bkg = inelastic prompt neutrino → Remove ν_e → No bkg due to charge current

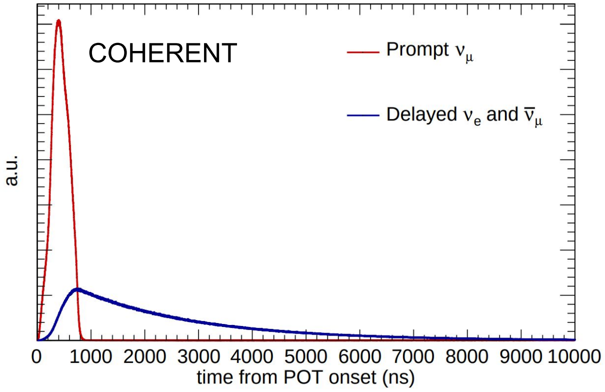
$$\tau_\eta \sim 10^{-10} ns$$

$$\tau_{\pi^0} \sim 10^{-7} ns$$

Timing cut (upper cut)

- COHERENT NaI: 1 mus
- CCM: 0.3 mus





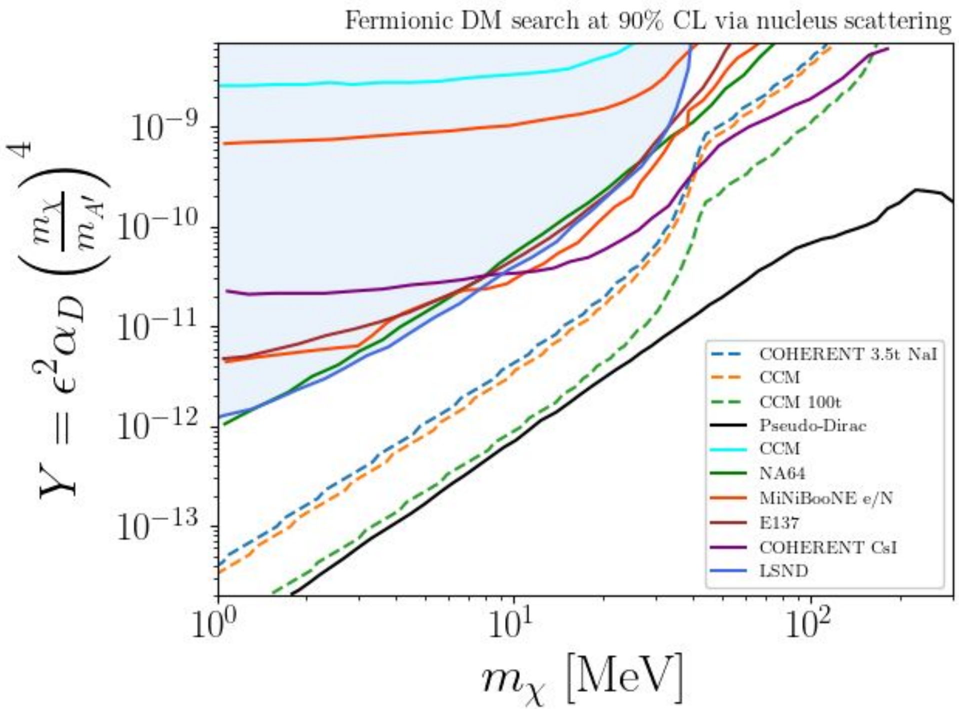
Inel ν bkg

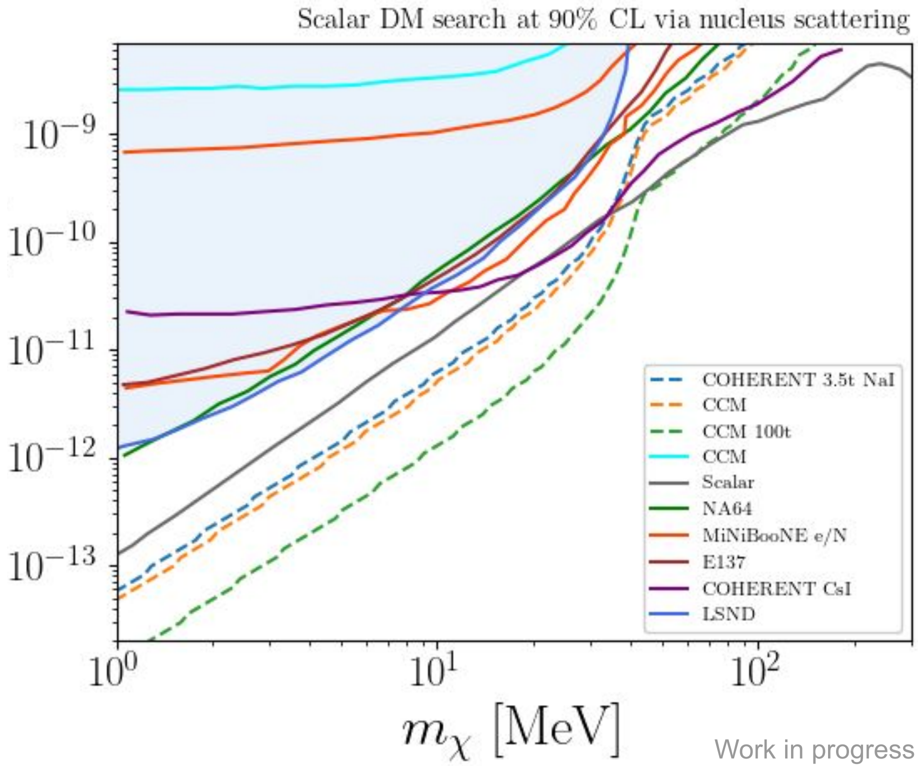
Detector	CCM	NaI
Bkg (w/o t cuts)	327	462
Bkg (w/ t cuts)	64.8	106

Sensitivities Plot

Energy cut: No
Timing cut: Yes

Dashed is our calculation
No nu bkg
Detector bkg rescale to 10 total



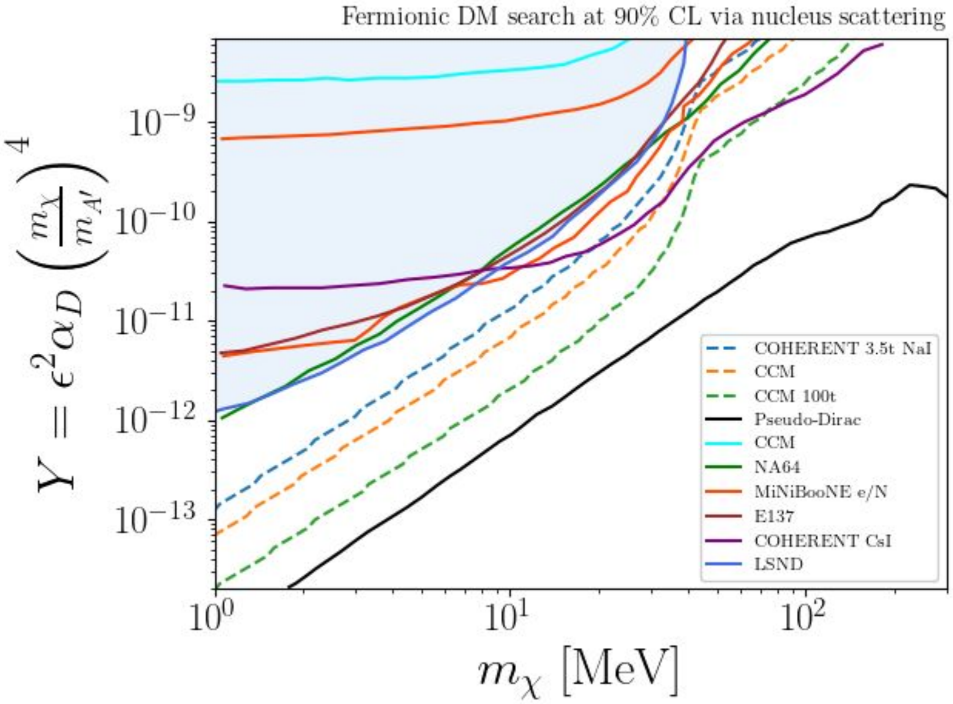


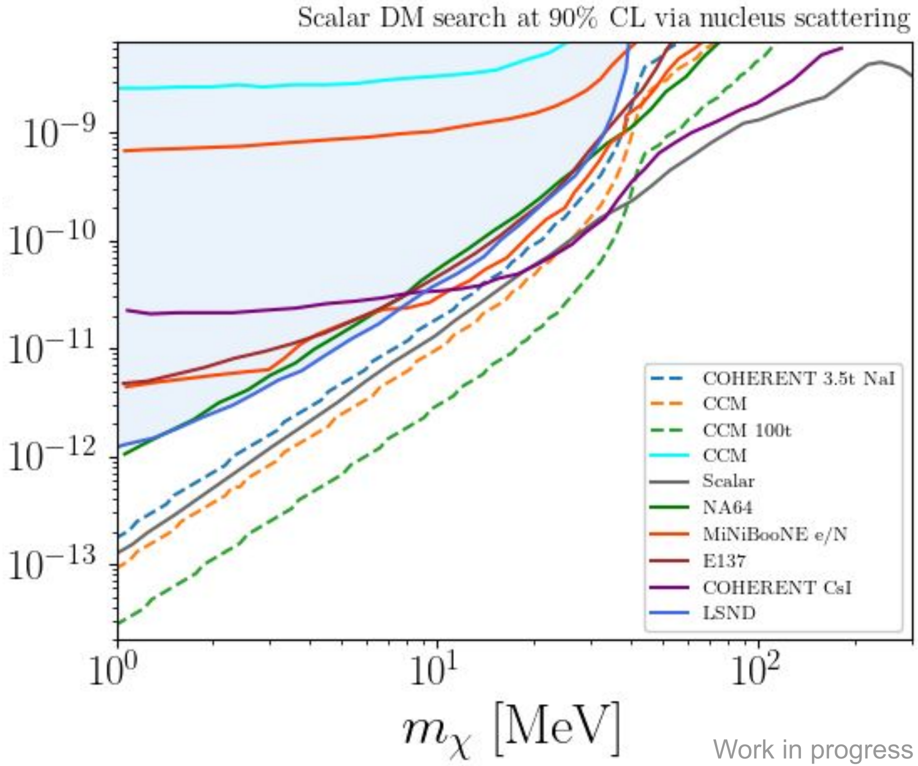
Work in progress

Sensitivities Plot

Energy cut: No
Timing cut: Yes

Dashed is our calculation
Inel prompt nu bkg included





Work in progress

Conclusion

- We calculate the inelastic cross-section and event rates ratio for DM nucleus scattering.
- Gamow-Teller transitions (long wavelength limit) dominate the cross section.
- With inelastic DM, we have better probe on the parameter space.
- We can remove most of the neutrino background efficiently with prompt timing cut.

Backup slides

Inel DM scattering cross section

$$\frac{d\sigma^{DM}_{inel}}{dE_r} = \frac{2e^2\epsilon^2 g_D^2 E'^2_\chi}{p_\chi p'_\chi (2m_N E_r + m^2_{A'})^2} \frac{m_N}{2\pi} \frac{4\pi}{2J+1}$$

$$\times \sum_{s_i, s_f} \vec{l} \cdot \vec{l}^* \frac{g_A^2}{12\pi} |\langle J_f || \sum_{i=1}^{A} \frac{1}{2} \hat{\sigma}_i \hat{\tau}_0 || J_i \rangle|^2$$

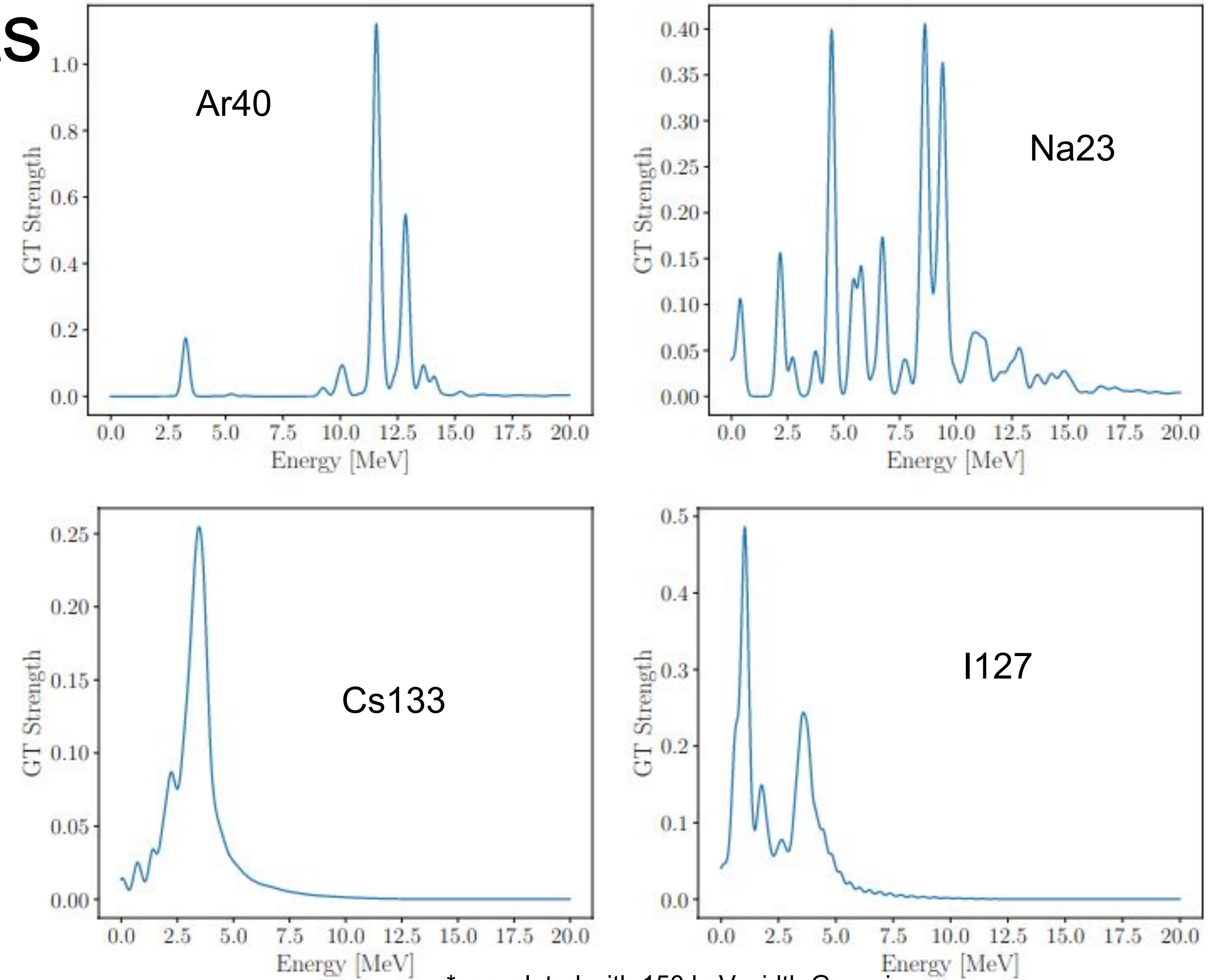
Rewrite in scattering angle with

$$\frac{d\sigma}{dE_r} = \frac{d\sigma}{d\Omega}\frac{d\Omega}{dE_r} = 2\pi \frac{d\sigma}{d\Omega}\frac{m_N}{p_\chi p'_\chi} = \frac{d\sigma}{d\cos\theta}\frac{m_N}{p_\chi p'_\chi}$$

$$\frac{d\sigma^{DM}_{inel}}{d\cos\theta} = \frac{2e^2\epsilon^2 g_D^2 E'^2_\chi}{(2m_N E_r + m^2_{A'})^2} \frac{1}{2\pi} \frac{4\pi}{2J+1}$$

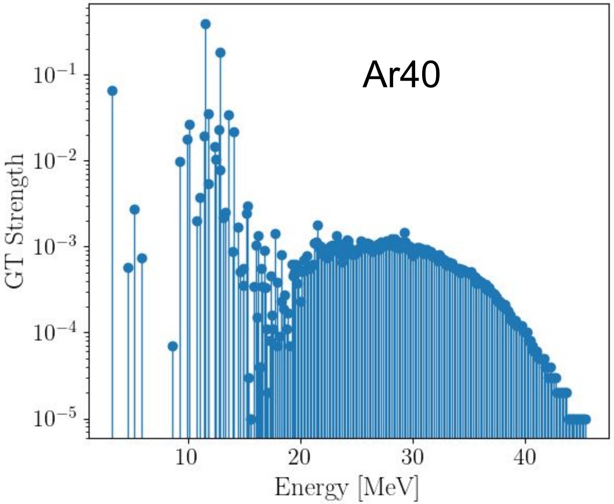
$$\times \sum_{s_i, s_f} \vec{l} \cdot \vec{l}^* \frac{g_A^2}{12\pi} |\langle J_f || \sum_{i=1}^{A} \frac{1}{2} \hat{\sigma}_i \hat{\tau}_0 || J_i \rangle|^2$$

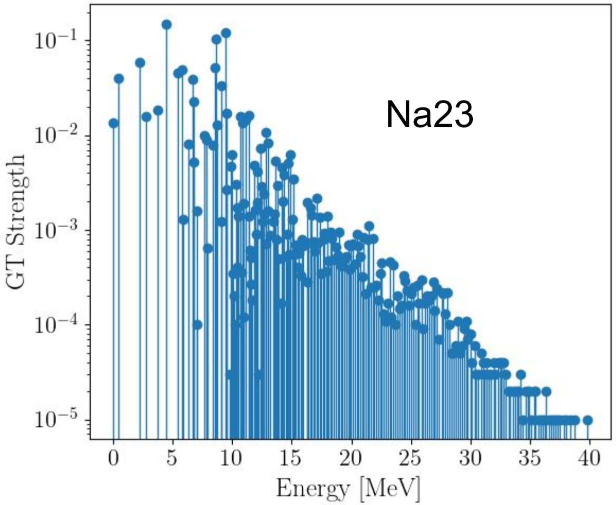
Convolution Plots

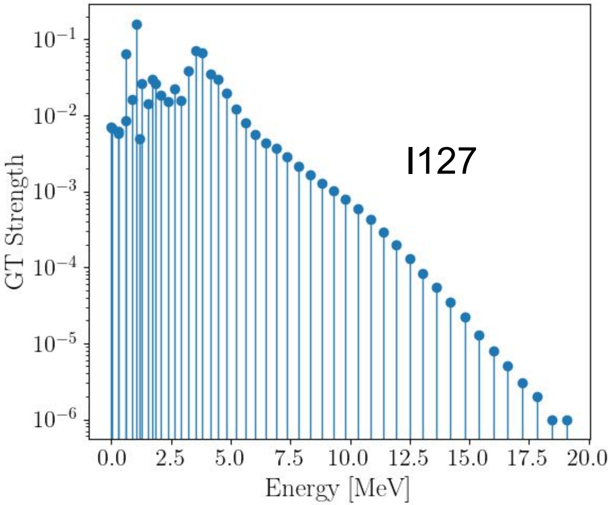


*convoluted with 150 keV width Gaussian

Raw Discrete Strength Lines







Other Cuts

Energy cut

(lower cut)

Set 1

- COHERENT NaI: 12MeV
- CCM: 16MeV

Set 2

- COHERENT NaI: 5MeV
- CCM: 10MeV

Timing cut:

(upper cut)

- COHERENT NaI: 1 mus
- CCM: 0.3 mus

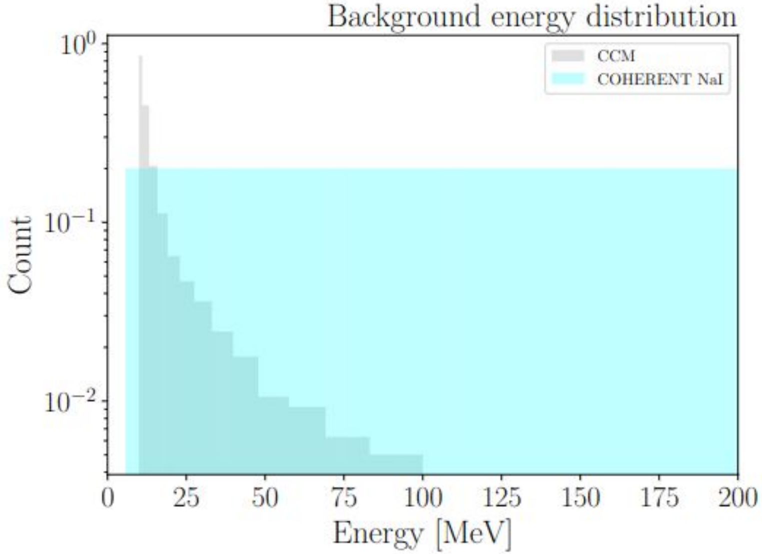
Inel nu bkg CCM / NaI

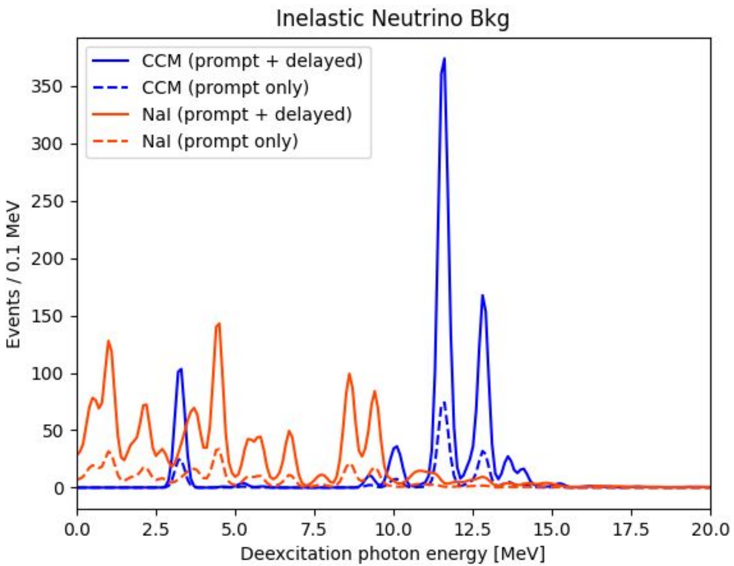
	Energy cut Set 1	Energy cut Set 2	No energy cut
Timing cut	0.74/3.16	52.7/39.5	64.8/106
No timing cut	9.32/18.25	275.4/185.3	327/462

Detector Background with Energy Cut

Detector	Bkg reduction	Energy cut (lower)	Total bkg (after energy cut)
COHERENT NaI	5 (ones-like bkg)	5MeV	2.8
CCM	100	10MeV	2.84

Reduced detector bkg

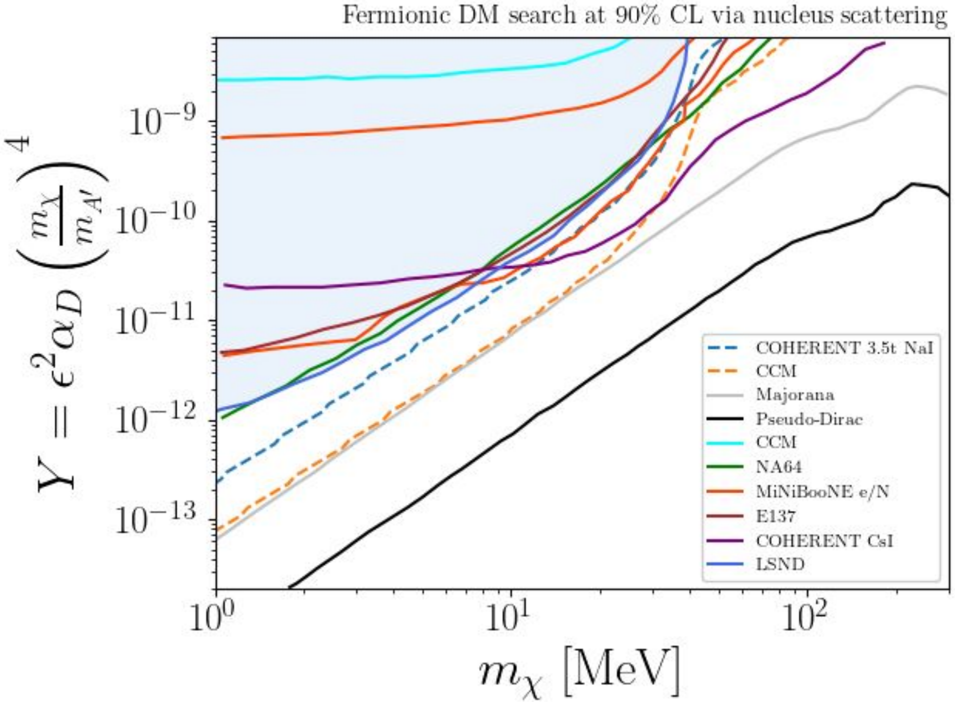


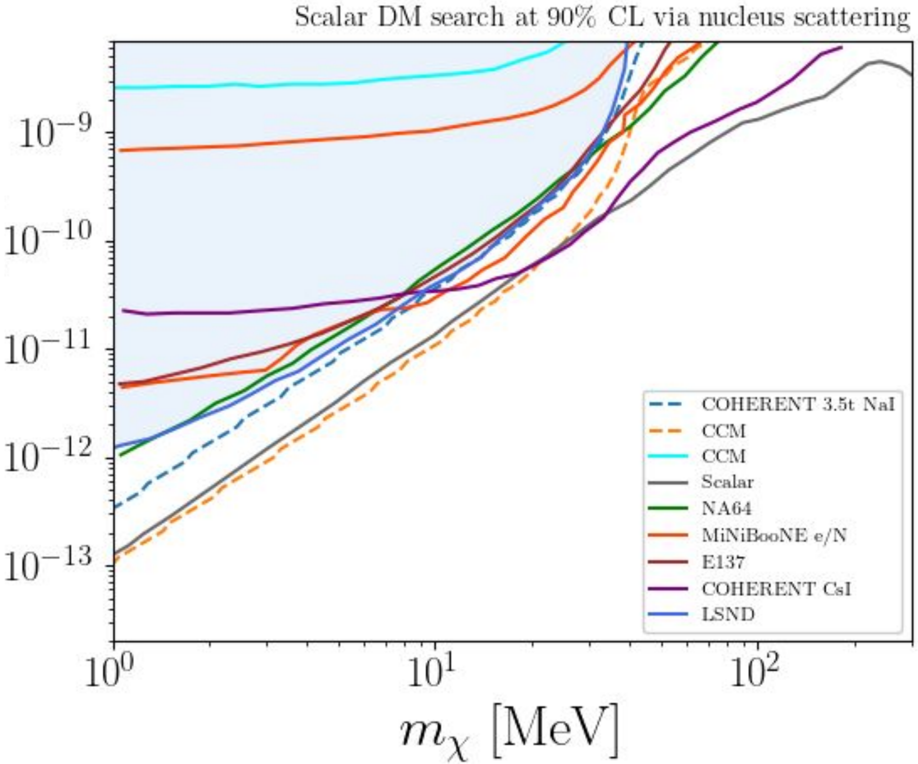


We include inelastic nu as bkg

Sensitivities Plot

Energy cut: set2
Timing cut: Yes

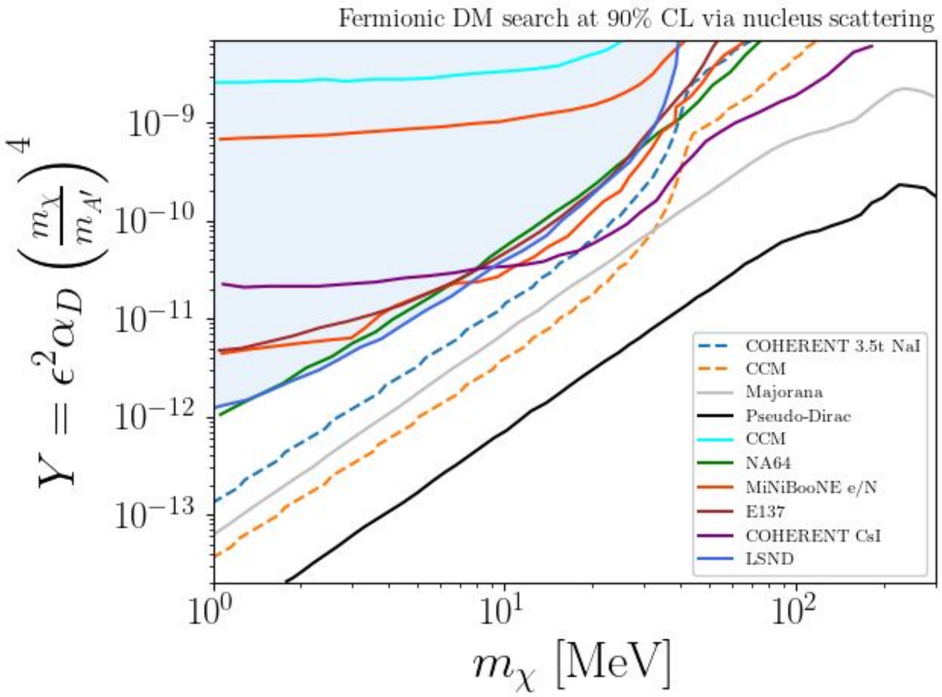


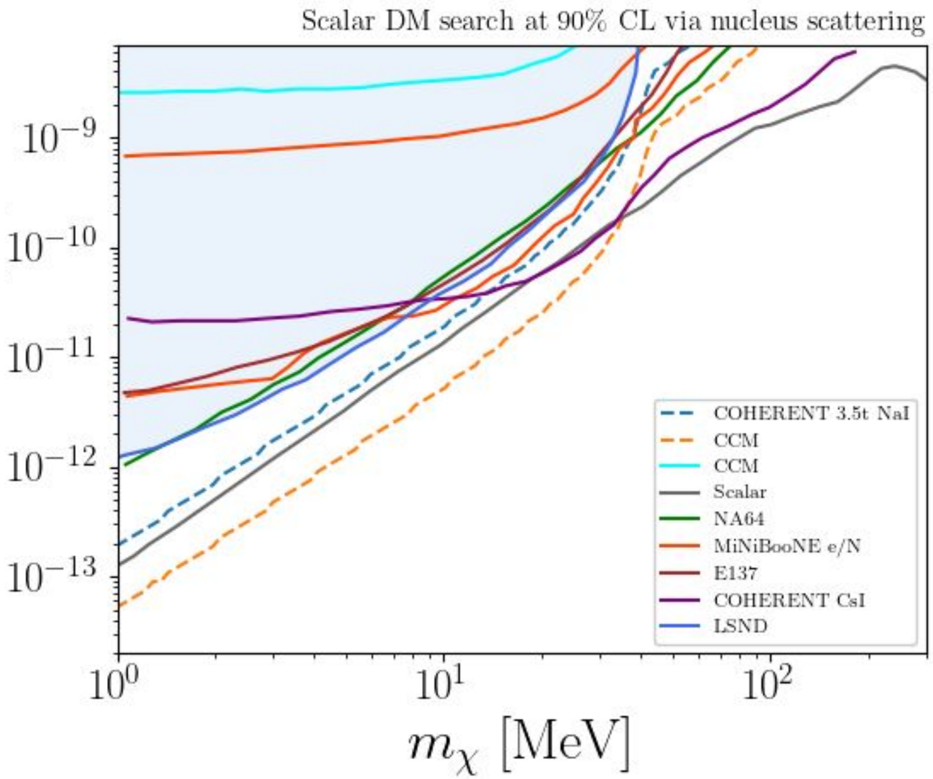


Sensitivities Plot

Energy cut: set2
Timing cut: Yes

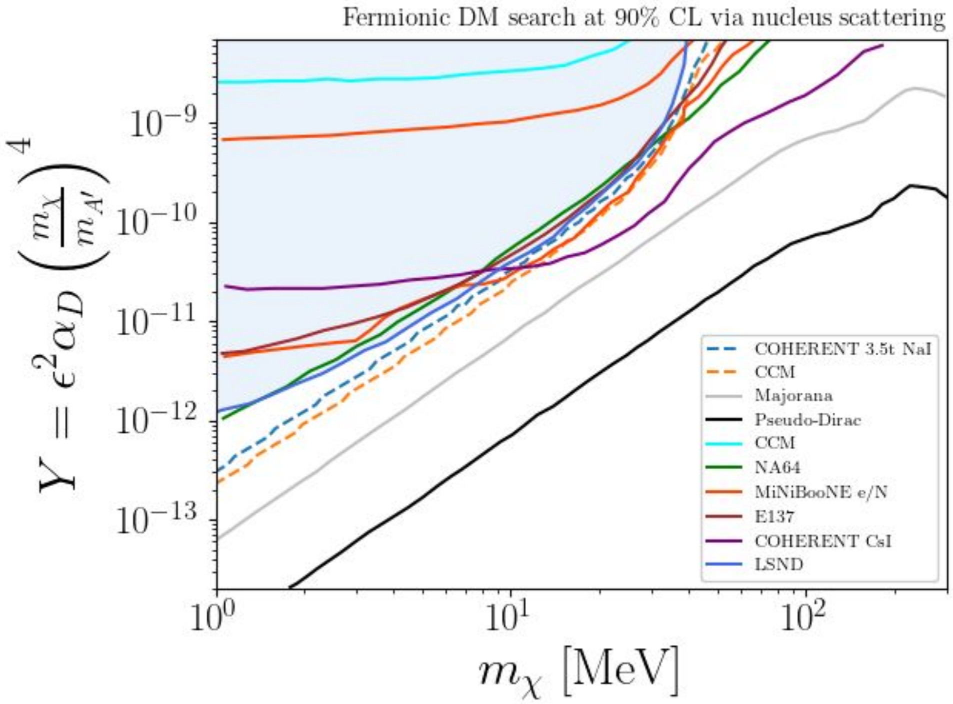
No nu bkg
Detector bkg rescale to 10 total

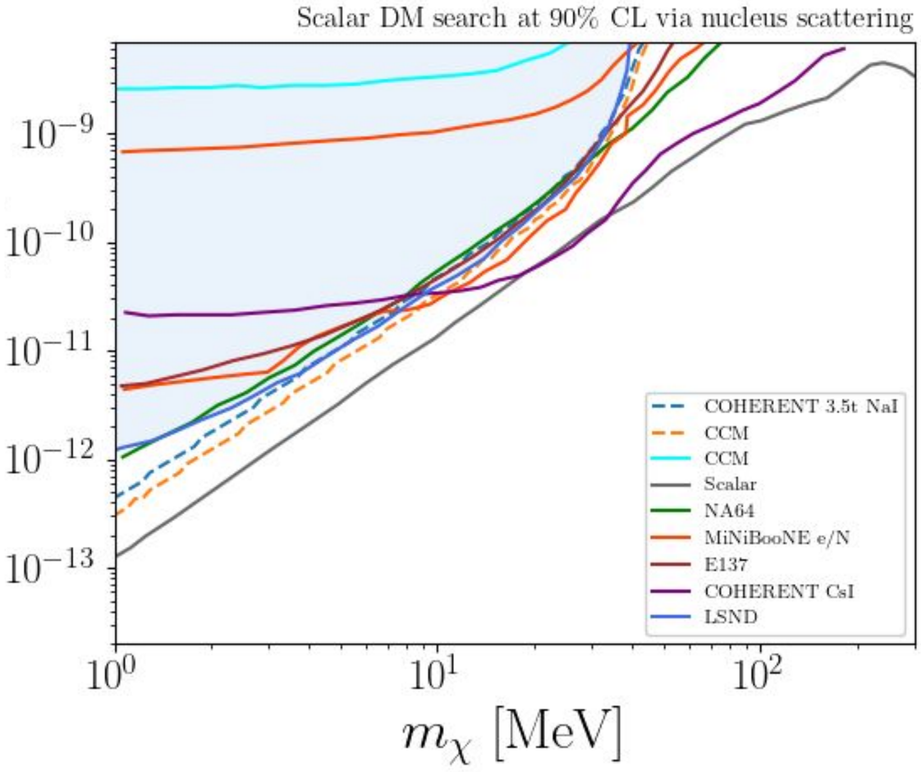




Sensitivities Plot

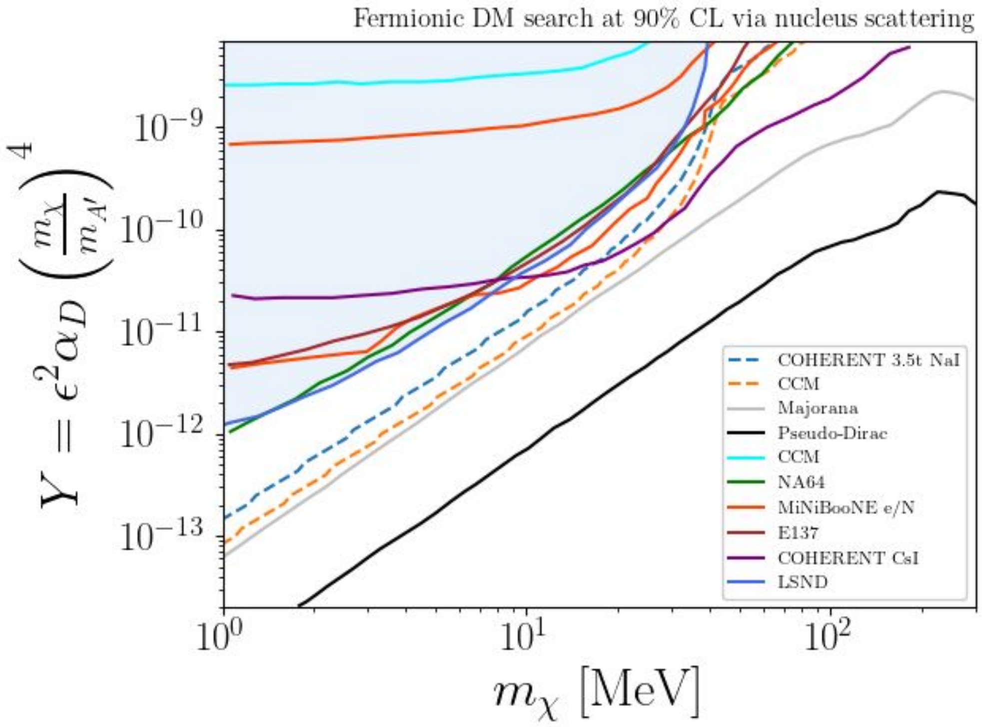
Energy cut: set1
Timing cut: No

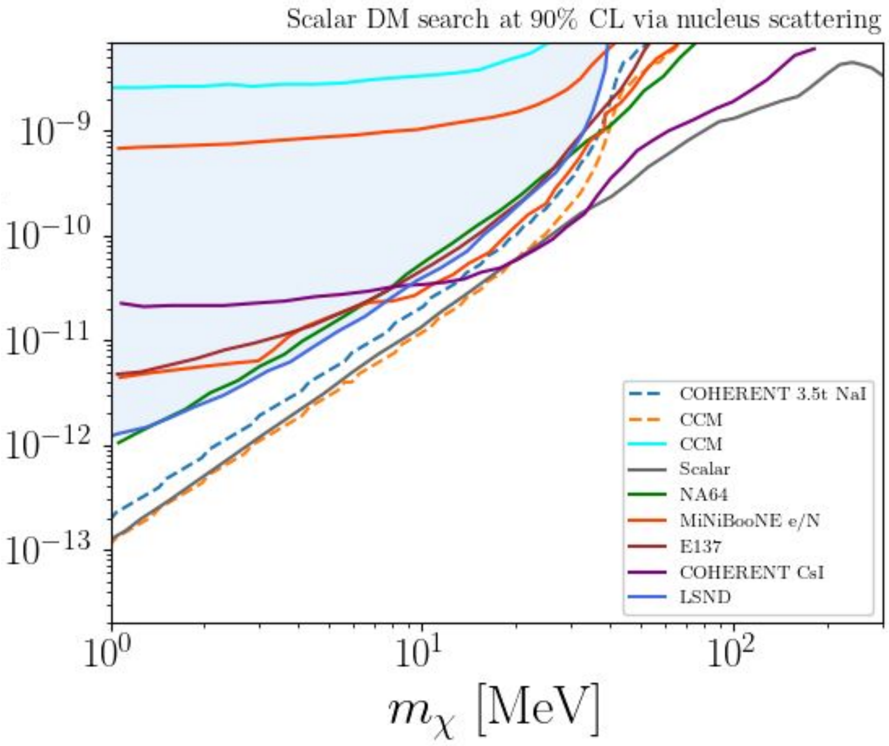




Sensitivities Plot

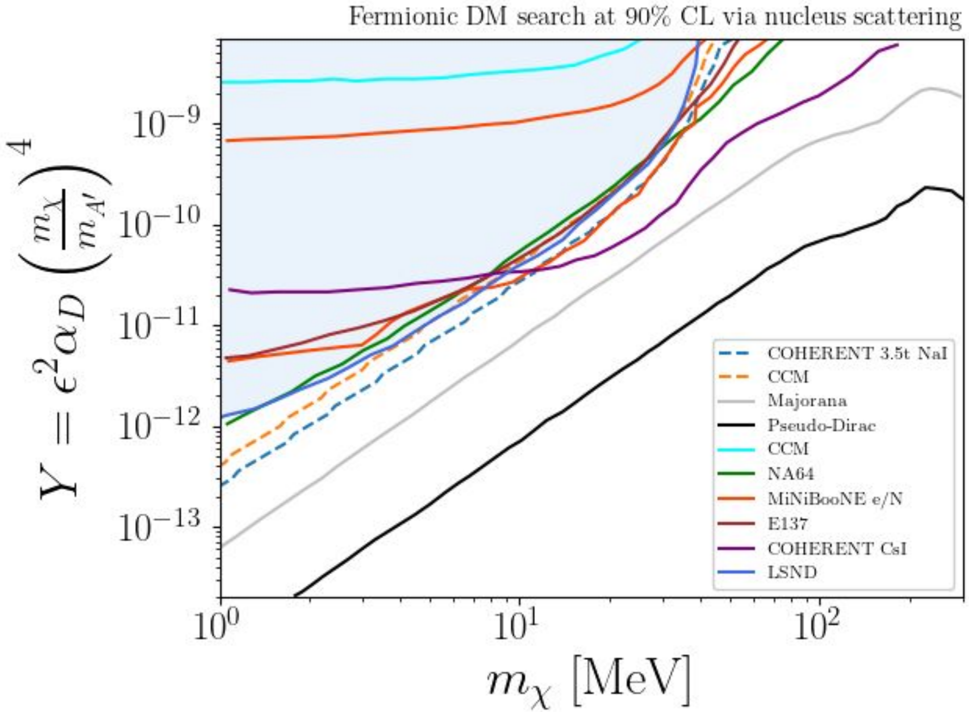
Energy cut: set1
Timing cut: Yes

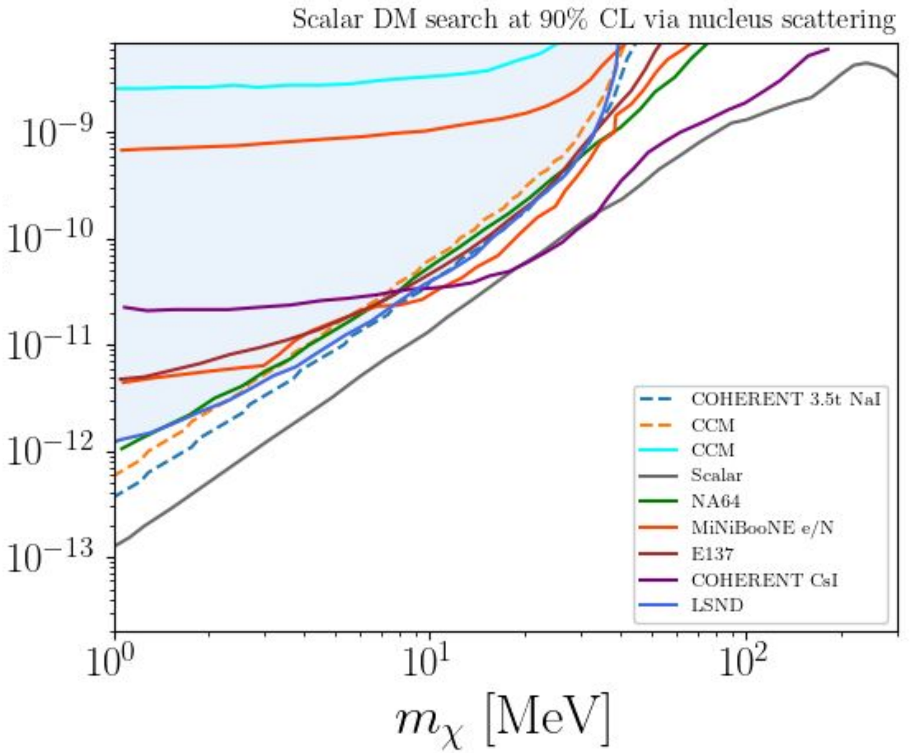




Sensitivities Plot

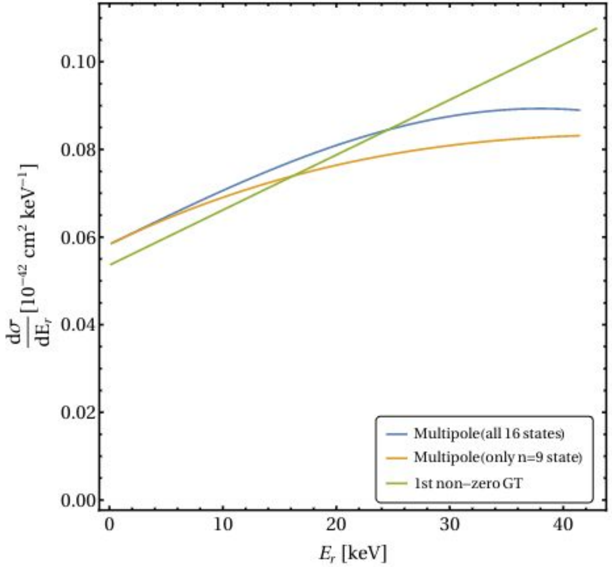
Energy cut: No
Timing cut: No



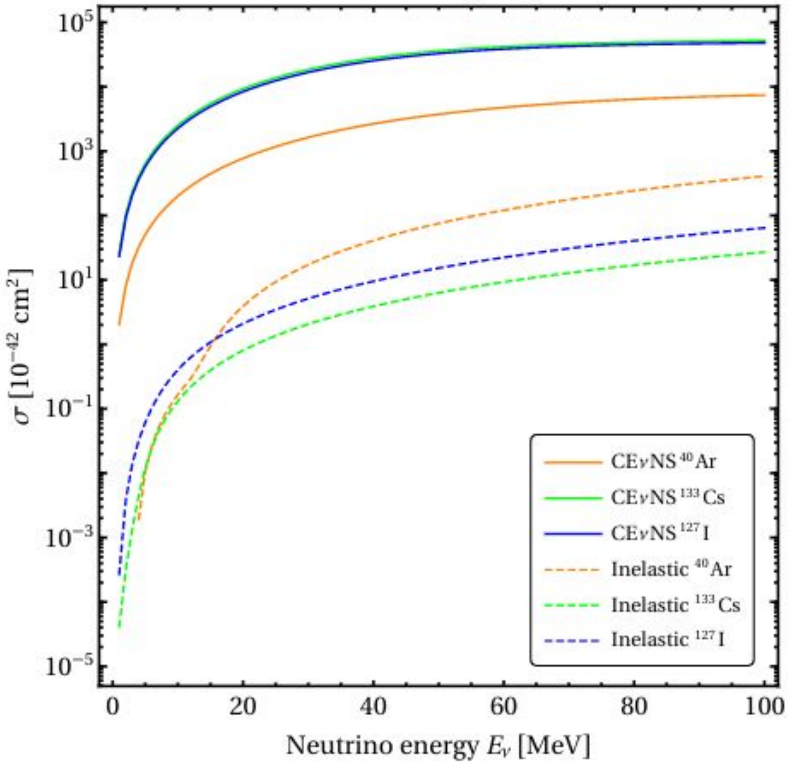


Inelastic neutrino-nucleus scattering

Similar to DM scattering, GT also dominates



$$\sigma_\nu^{GT} \approx \frac{G_f^2 g_A^2}{\pi(2J+1)}(E_\nu - \Delta E)^2 |\langle J_f || \sum_{i=1}^{A} \frac{1}{2}\hat{\sigma_i}\hat{\tau_0} || J_i \rangle|^2.$$

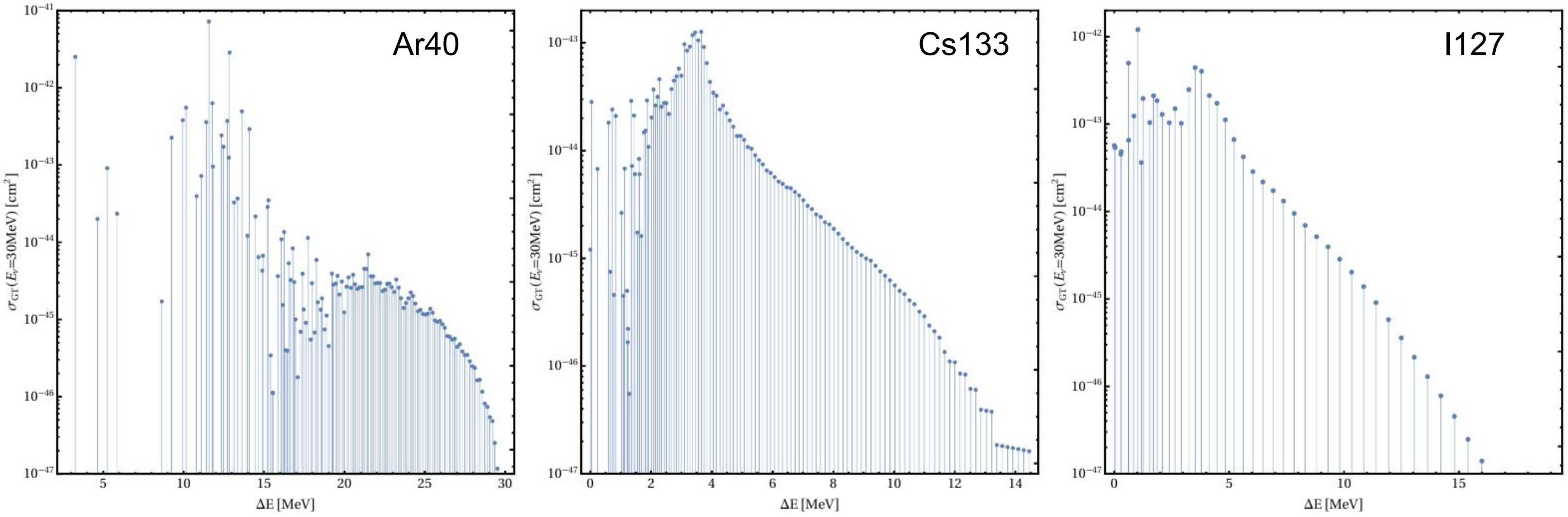


Events

Scattering	Experiment	Elastic	Inelastic	Ratio
ν-^{40}Ar	COHERENT	2.27×10^2	3.15	7.21×10
ν-^{40}Ar	CCM	1.91×10^4	2.65×10^2	7.21×10
ν-^{133}Cs	COHERENT	1.16×10^3	1.52×10^{-2}	7.65×10^3
ν-^{127}I	COHERENT	1.06×10^3	3.75×10^{-1}	2.81×10^3

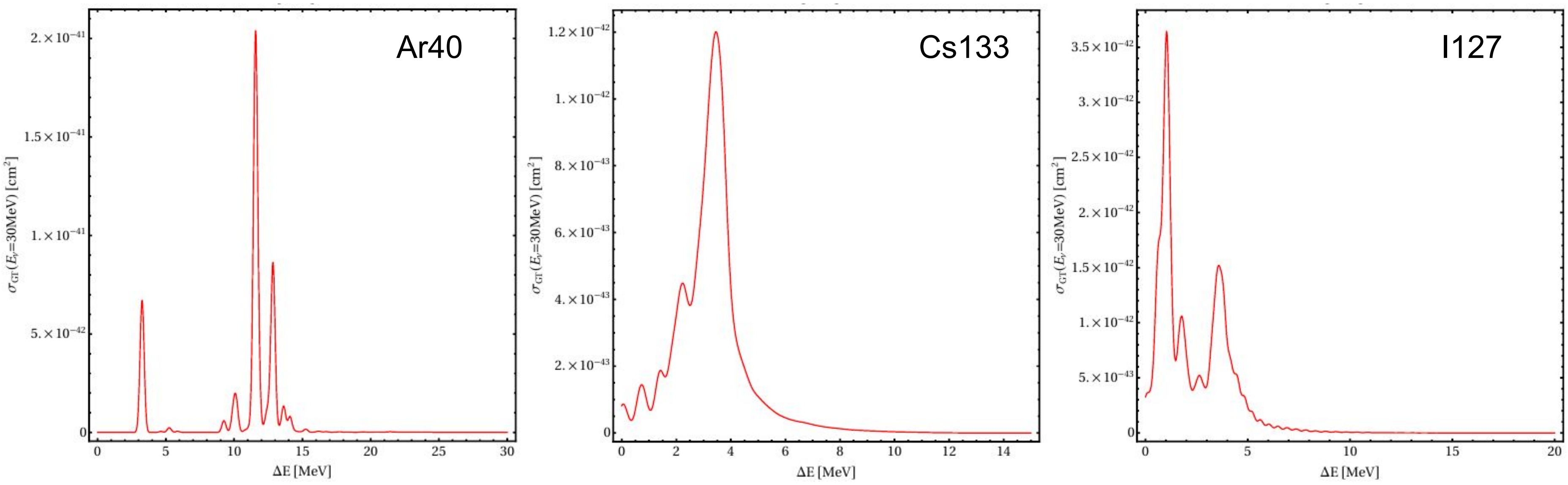
GT strength for neutrino scattering

30MeV nu energy



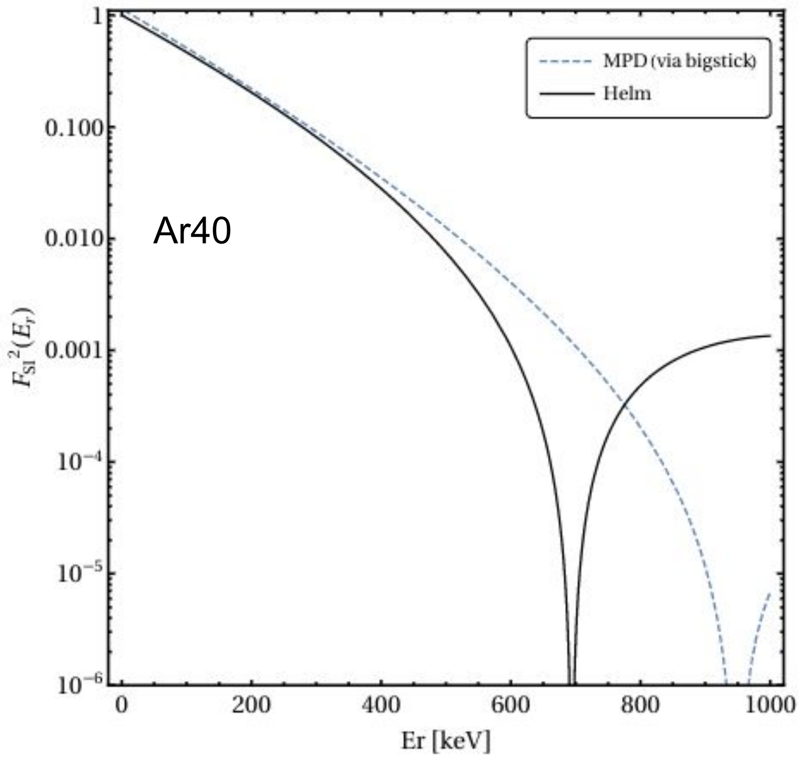
GT strength for neutrino scattering

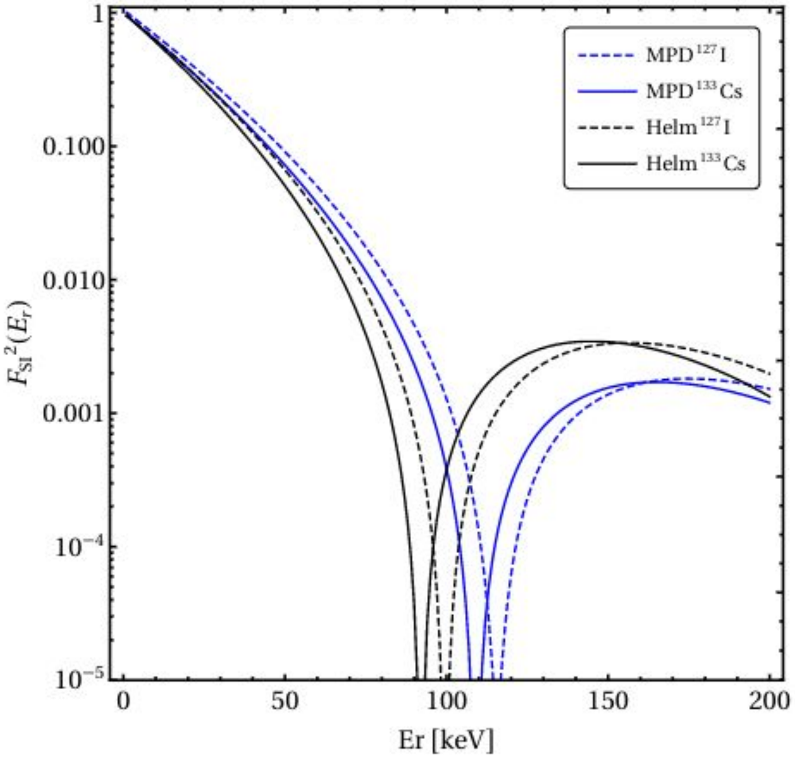
30MeV nu energy
150 keV width Gaussian



BIGSTICK ground state to ground state comparing to Helm form factor

MPD = multipole decomposition





Delta chi squared test

$$t \equiv \sum_{i=1}^{\nu} \frac{S_i^2}{B_i} = \mathrm{E}[\chi^2_{S+B}] - \nu \qquad \nu = \text{number of bins}$$

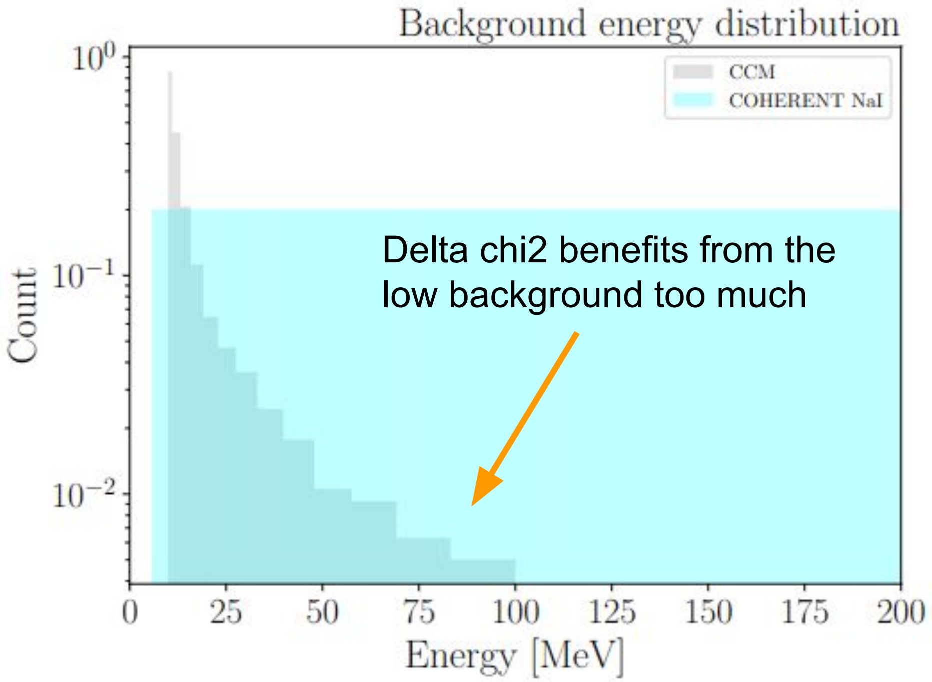
```
confidence_limit = 0.9
deltaChi2_limit = chi2.ppf(confidence_limit, len(bkg)) - len(bkg)
def deltaChi2(sig):
    return np.sum((sig)**2 / bkg)
```

Parameter space search

```
for idx, mass in enumerate(mass_array):
    for eps in epsilon_array:
        signals = dm_signal_gen(mass, eps)
        chi2 = deltaChi2(signals)

        if chi2 > deltaChi2_limit:
            lower_array[idx] = eps
            break
```

T test

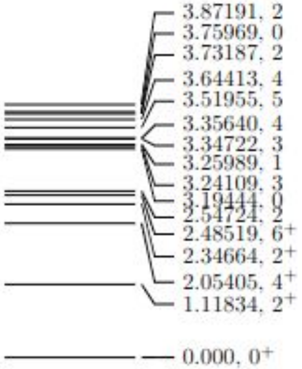


Confidence level	sig
68.3%	1
90%	1.645
95.5%	2
99.7%	3

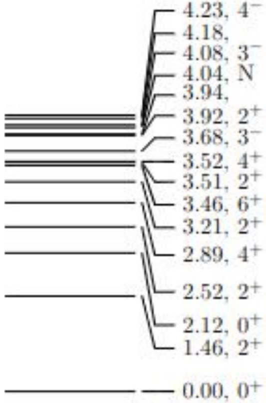
To make the inelastic nu more sensitive, we consider t test

$$\text{significance} = \frac{n_{\text{signal}} - n_{\text{bkg}}}{\sqrt{n_{\text{bkg}}}}$$

BIGSTICK energy level and spin

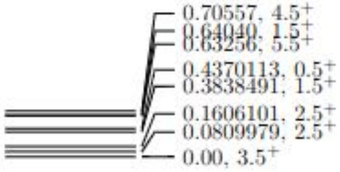


^{40}Ar (BIGSTICK)

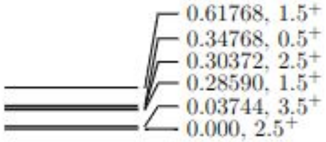


^{40}Ar (Exp)

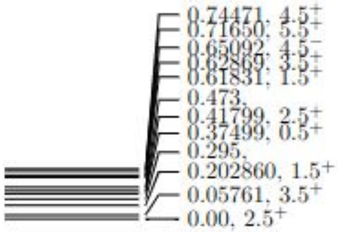
^{133}Cs (BIGSTICK)



^{133}Cs (Exp)



^{127}I (BIGSTICK)



^{127}I (Exp)

BIGSTICK nuclear magnetic moments

in keV

Nucleus	level n	J^π	μ	Expt.	E_x	Expt.
^{127}I	1	$5/2^+$	3.851	2.813	0	0
	2	$7/2^+$	3.007	2.54	37.44	57.61
	3	$3/2^+$	0.9155	0.97	285.9	202.86
^{133}Cs	1	$7/2^+$	3.007	2.582	0	0
	2	$5/2^+$	3.851	3.45	36.37	80.9979
	3	$5/2^+$	2.5849	2.0	235.36	160.6101
^{40}Ar	1	0^+	0	N/A	0	0
	2	2^+	0	-0.04	1118.33	1460.85