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THE UNIVERSITY OF
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HIDDEN DEPENDENCIES IN MODEL INDEPENDENT TESTS OF DAMA

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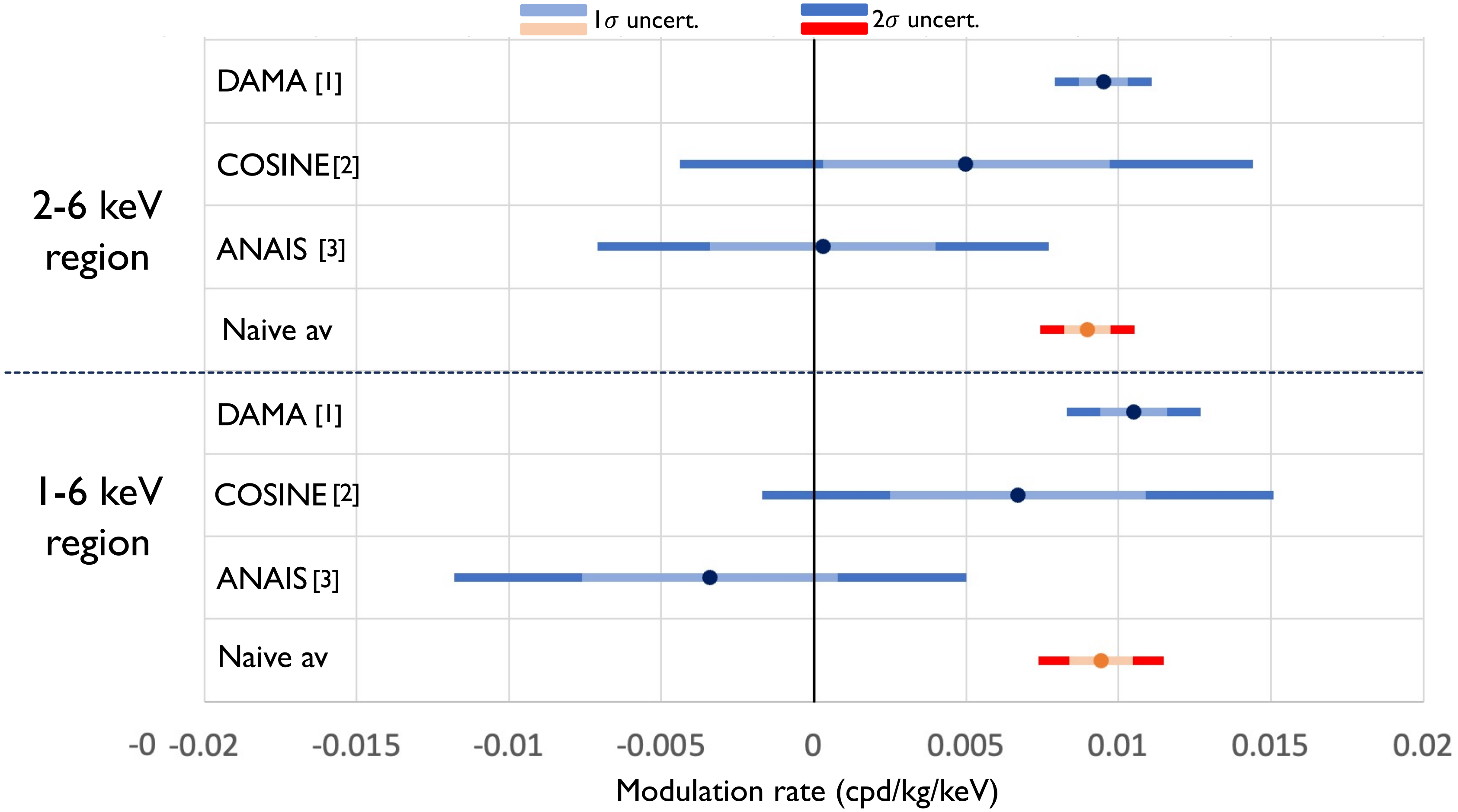
ARC CENTRE OF EXCELLENCE FOR
DARK
MATTER

RECENT RESULTS

[1] Bernabei et al. PPNP114 103810 (2020)
[2] Adhikari et al. arxiv:2111.08863
[3] Amare et al. PRD 103, 102005 (2021)

For modulation searches, both COSINE and ANAIS are beginning to reach strong sensitivity, but at present both have large uncertainties compared to DAMA



Naïve average = weighted average assuming no correlation

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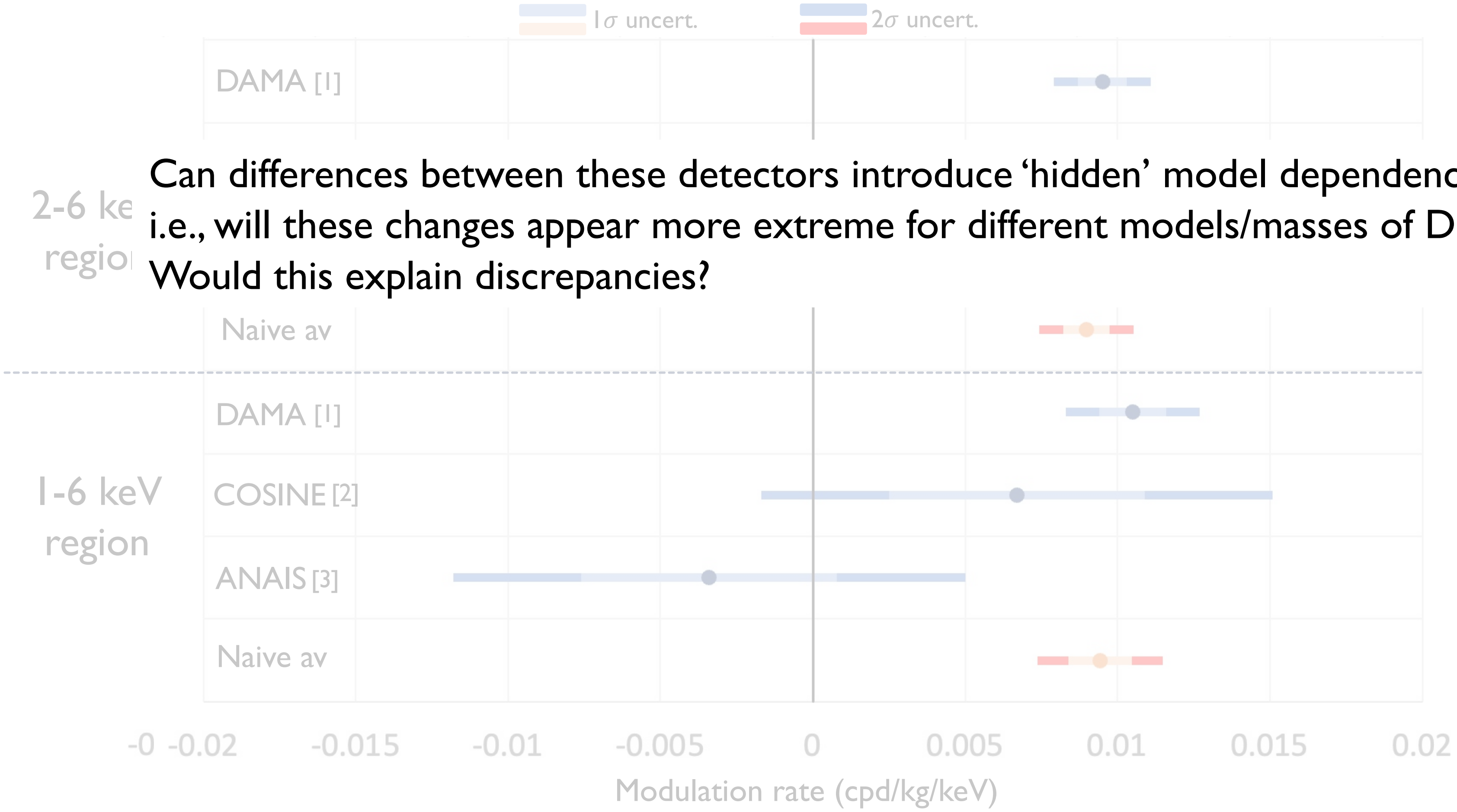


Can differences between these detectors introduce ‘hidden’ model dependence – i.e., will these changes appear more extreme for different models/masses of DM? Would this explain discrepancies?

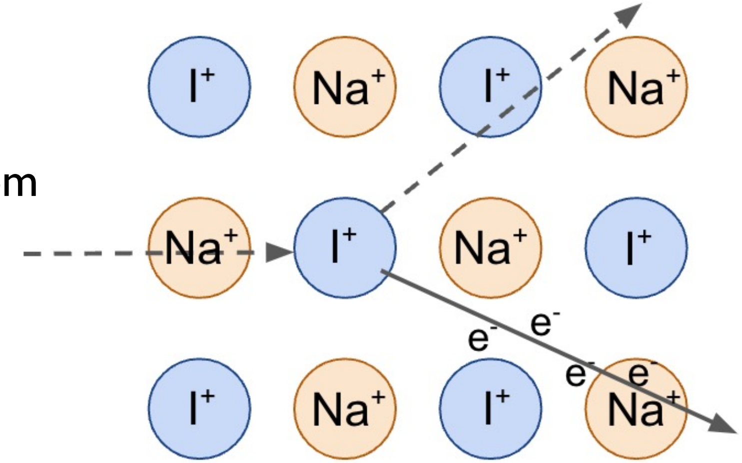
Naïve average = weighted average assuming no correlation

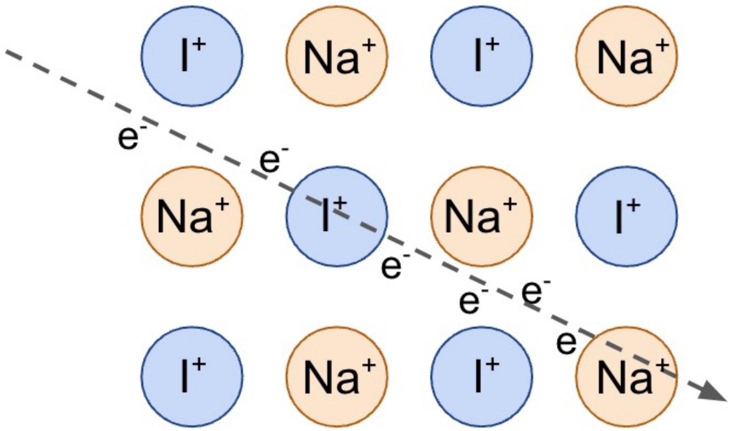
QUENCHING FACTOR

Purpose is to converts nuclear recoil energy (signal) into electron equivalent energy (used to calibrate detector).

$$E_{ee} = Q(E_{NR})E_{NR}$$

Ionisation from recoiling nucleus





Ionisation from external particle

Possible that this effect depends strongly on optical properties of crystal so different growth methods can impact results. Interesting to think about as:

- Differences observed in QF measurements by different groups
- Would change both amplitude and position of signal
- Depends on the nucleus DM interacts with so impacts different masses in different ways

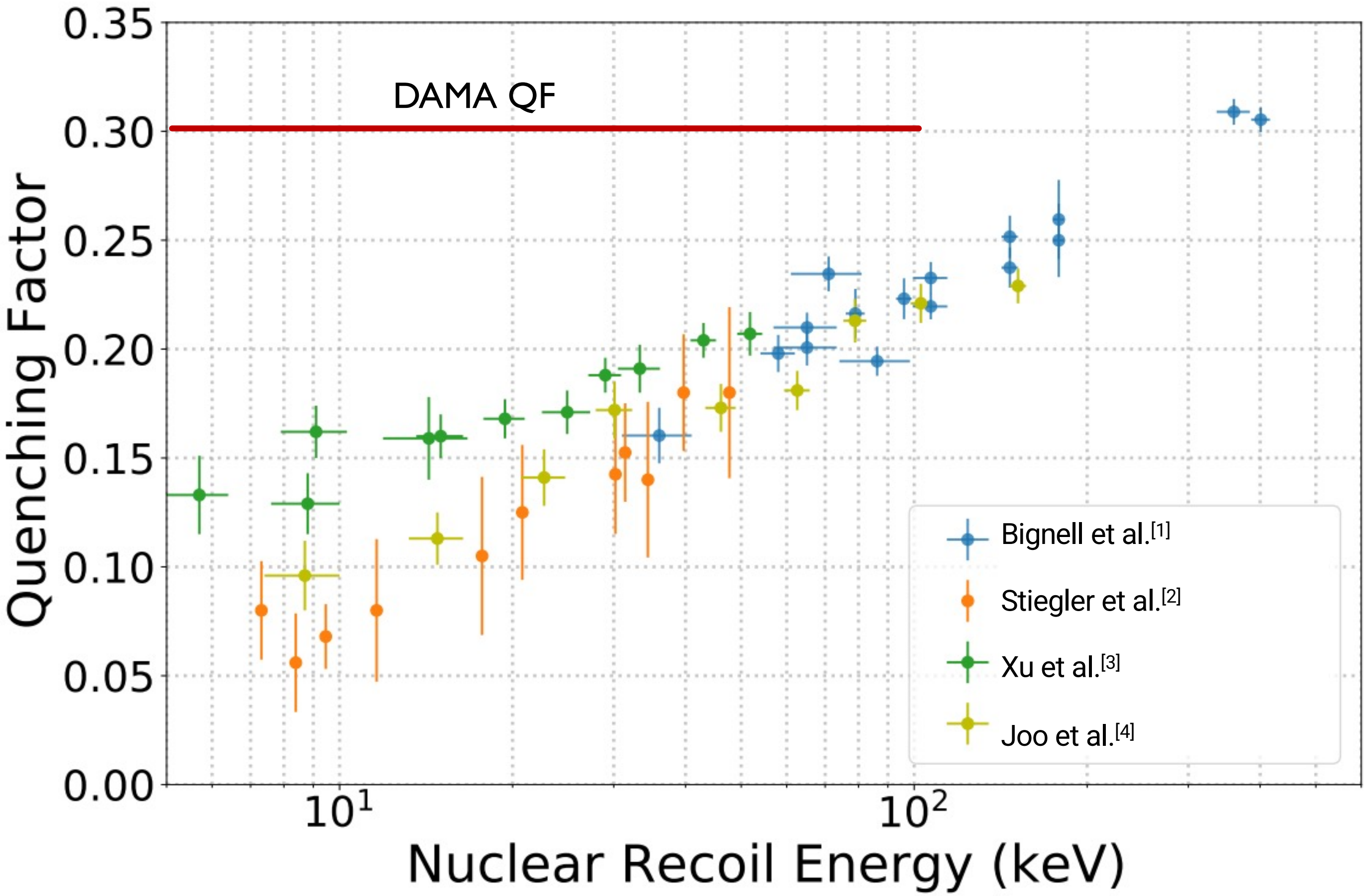
QUENCHING FACTOR MEASUREMENTS

Why are the DAMA quenching factors different to those measured since?
Possible solutions:

1. Differences in measurement method
2. QF is something that changes crystal to crystal

Particular solution will influence how data should be interpreted and compared.

Also possibility that (1) and (2) are both true - still inconsistencies at low energy

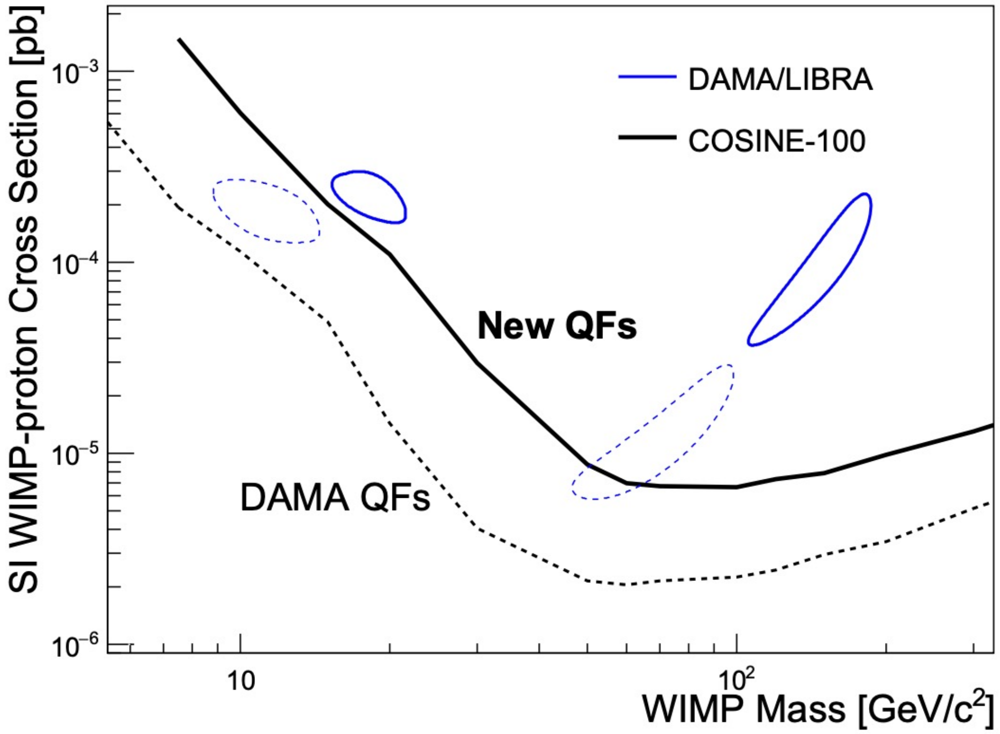


[1] L.J. Bignell et al 2021 JINST 16 P07034
[2] T. Stiegler et al. 2017 arxiv:1706.07494
[3] J. Xu et al. 2015 10.1103/physrevc.92.015807
[4] H. Joo et al. 2019 10.1016/j.astropartphys.2019.01.001

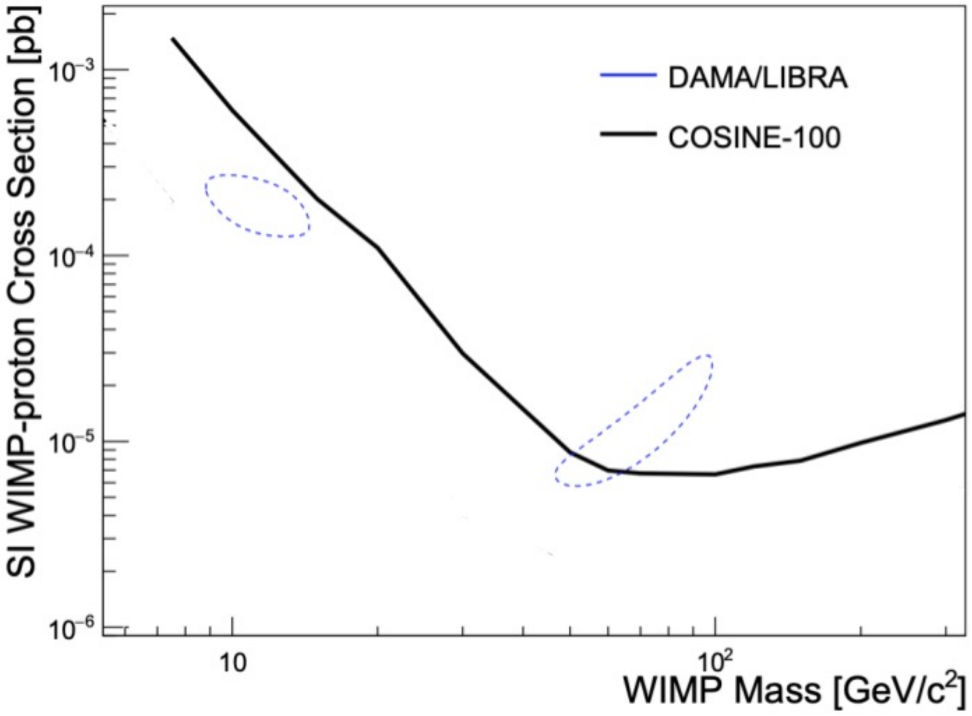
QUENCHING FACTOR IMPACT

[1] Adhikari et al. JCAP 11 (2019)

Can use results presented by COSINE [1] to understand how different QF combinations impact exclusion of DAMA



Assuming detectors have the same QF
(either the solid or dotted lines)



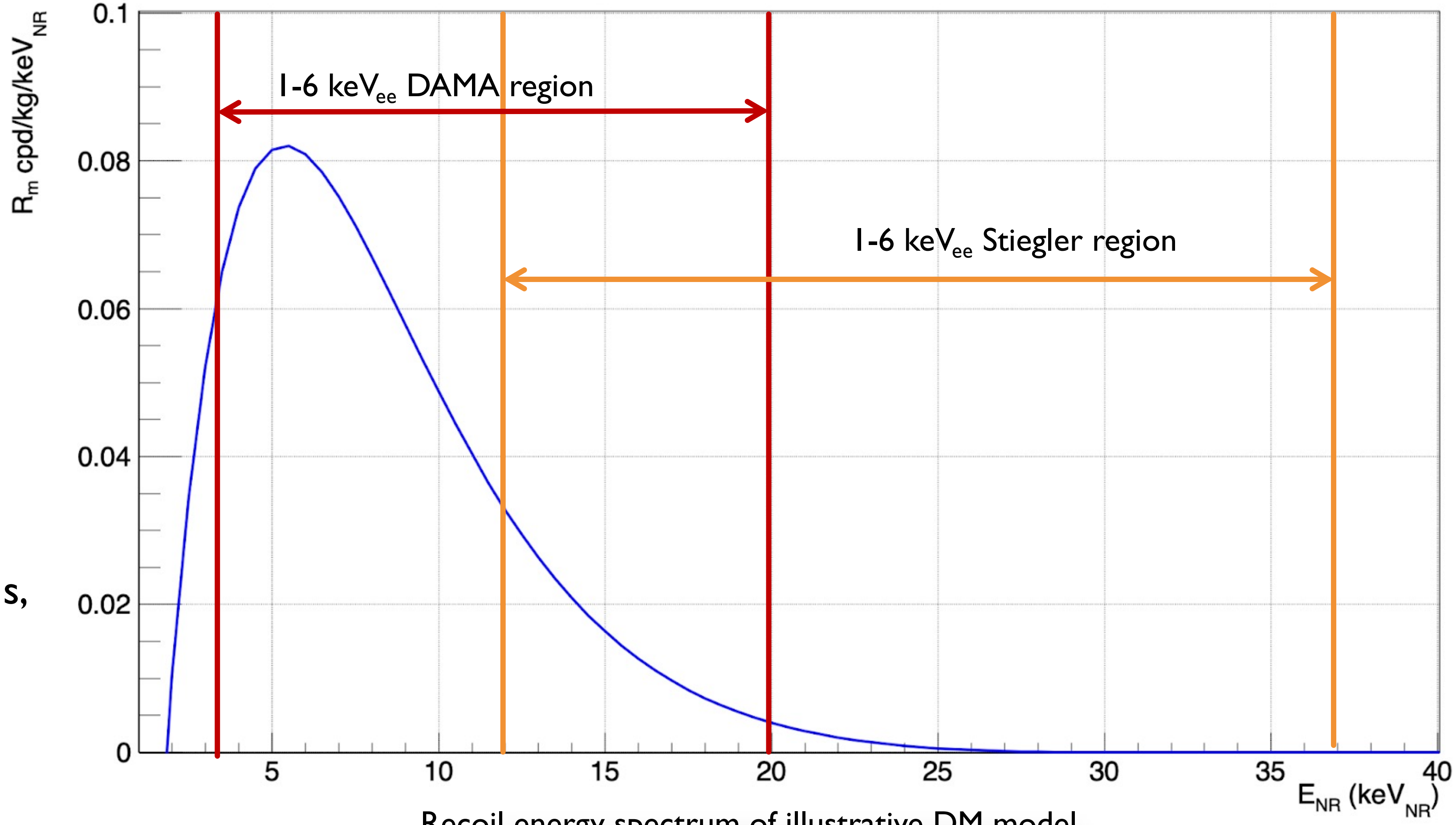
Assuming detectors have different QFs

QUENCHING FACTOR IMPACT

Change of QF has a strong influence on observable rate.

Changing relationship between NR and observed energy means the 1-6 keV_{ee} observable region of interest is "accessing" different parts of the recoil energy spectrum.

This will effect all DM interaction models, where the degree of extremity is dictated by the shape of the recoil spectrum



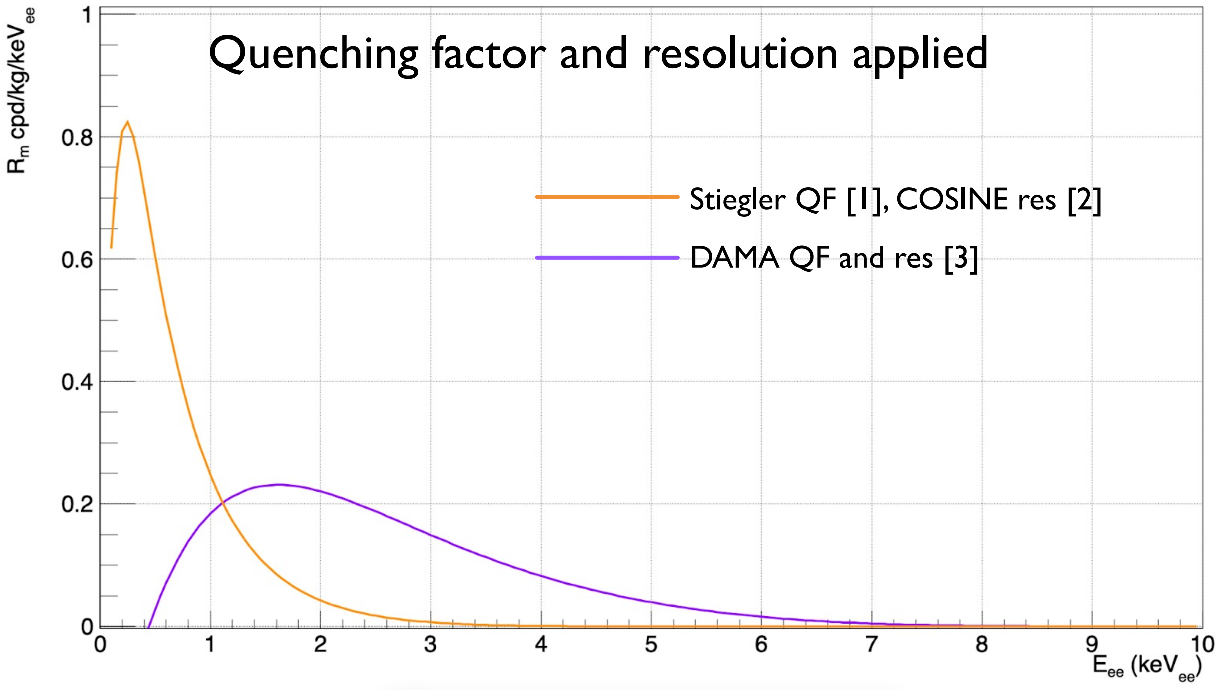
Recoil energy spectrum of illustrative DM model

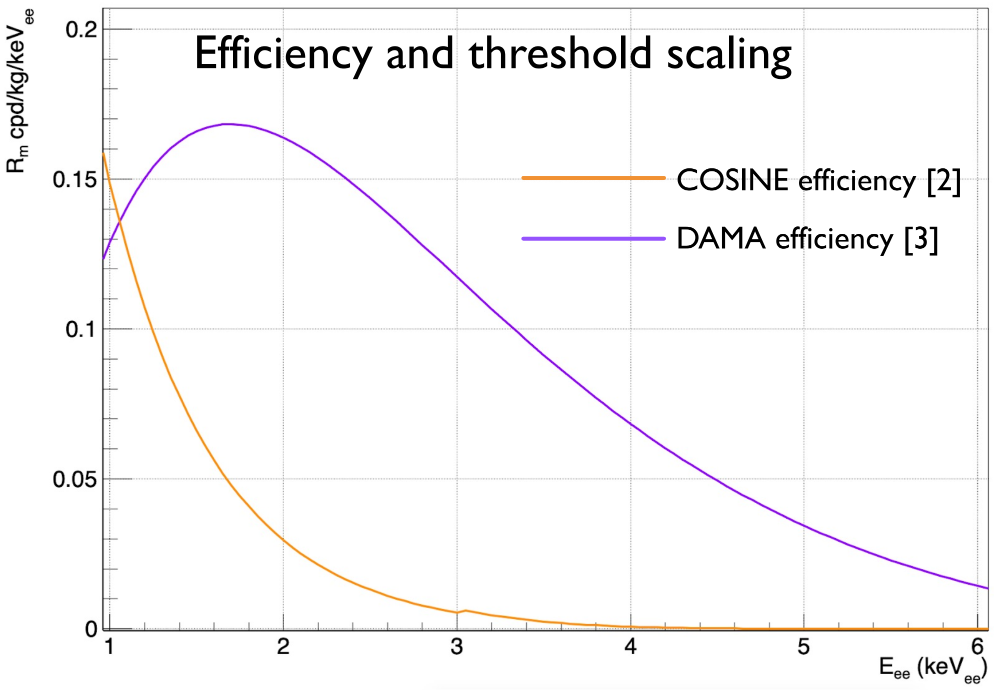
QUENCHING FACTOR IMPACT

[1] Stiegler et al. 2017 arxiv:1706.07494
[2] Adhikari et al. Astropart Phys 2021 102581
[3] Bernabei et al. JINST 2012

Detector differences can still change the observed modulation even if interaction rate is the same
e.g., for low mass spin independent DM, m_χ= 10 GeV/c^2, σ_χ=1.15x10^{-39} cm^2, change to QF drastically changes the observable signal, both in value and shape in region of interest.

⇒ Even for a same target test, no guarantee the modulation will look the same





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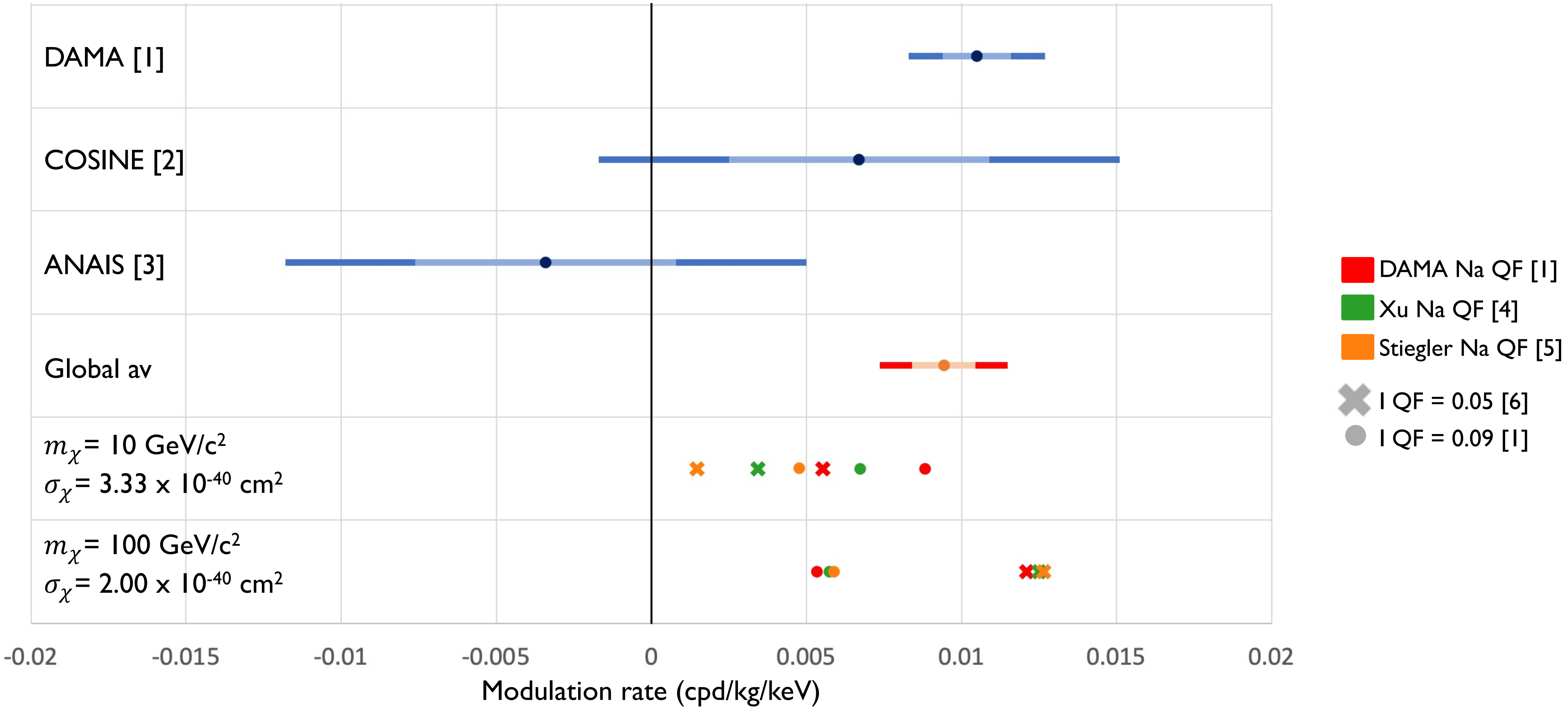
[5] Stiegler et al. 2017 arxiv:1706.07494
[6] Bignell et al 2021 JINST 16 P07034

This toy model w/ different QFs can produce modulation amplitudes more consistent with other observations

Effect is strongly dependent on DM model and mass ⇒ <u>model independent test is impossible</u>



SUMMARY

* See Cintas at TAUP21, Bharadwaj at IDM22

- NaI detectors designed as model independent tests of DAMA seem to observing different modulation rates
- Crystal dependent quenching factors offer an explanation for this but introduce model dependence
  - Differences in QF appear to exist – but at present not clear if these are distinct optical differences/intrinsic property, or differences in method of measurement*
  - Not a simple scale factor correction – depends strongly on DM mass/cause of interaction
- If this is the case, truly model independent tests of DAMA become very, very difficult, if impossible
- We need to understand the quenching factors for the currently operating and planned experiments to begin to unpick what is going on

Unanswered questions? Contact me:
Email: madeleine.zurowski@unimelb.edu.au
Twitter: @mjzurowski
Or scan QR code for my details

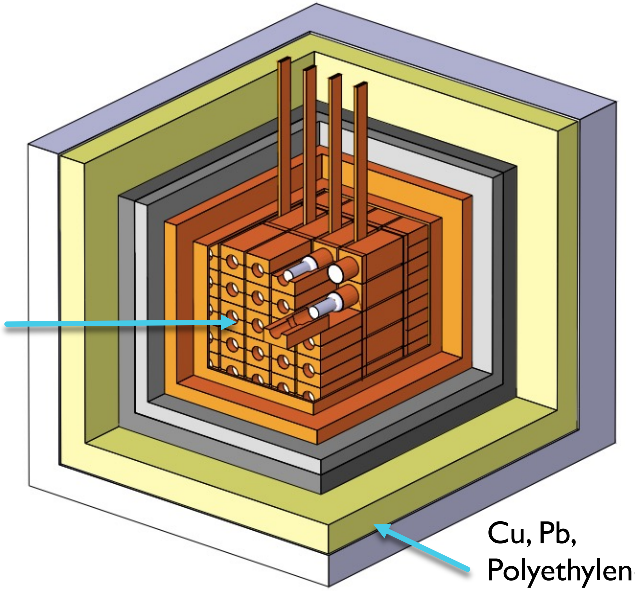
Scan for reference list as clickable links

BACK UP SLIDES

DAMA RESULTS

250 kg NaI(Tl) detector based in LNGS consistently observed modulation rate compatible with DM expectations for ~20 years w/ ~13σ CL

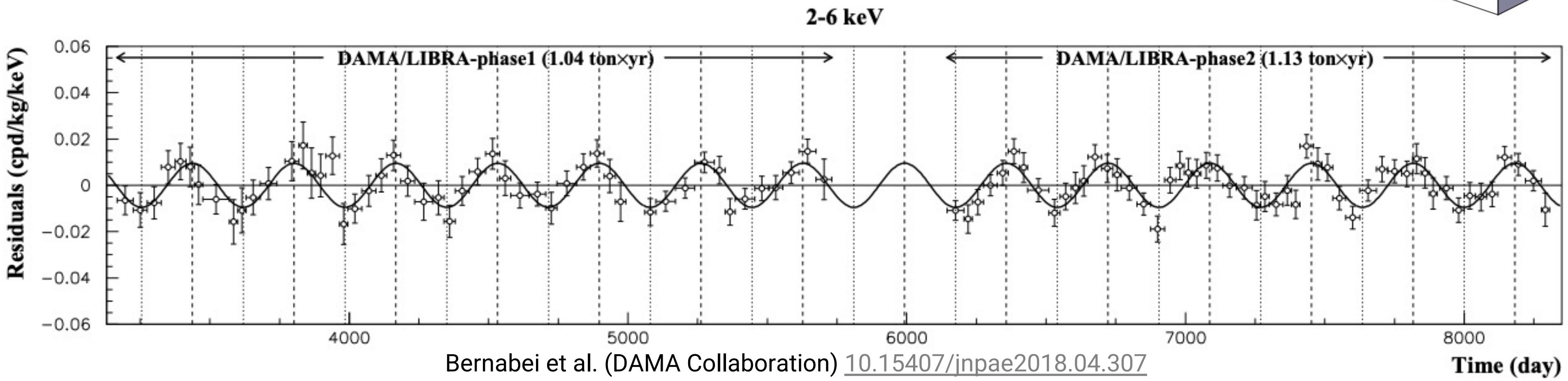
- R_m: 0.01058±0.00090 cpd/kg/keV
- Phase: 144.5±5.1 days
- Period: 0.999±0.001 yr
- Modulation present in 1-6 keV



25 NaI crystals in Cu enclosure

Cu, Pb, Polyethylene shielding

<u>No direct fitting to constant rate</u>, but upper limit given of ~0.8 cpd/kg/keV

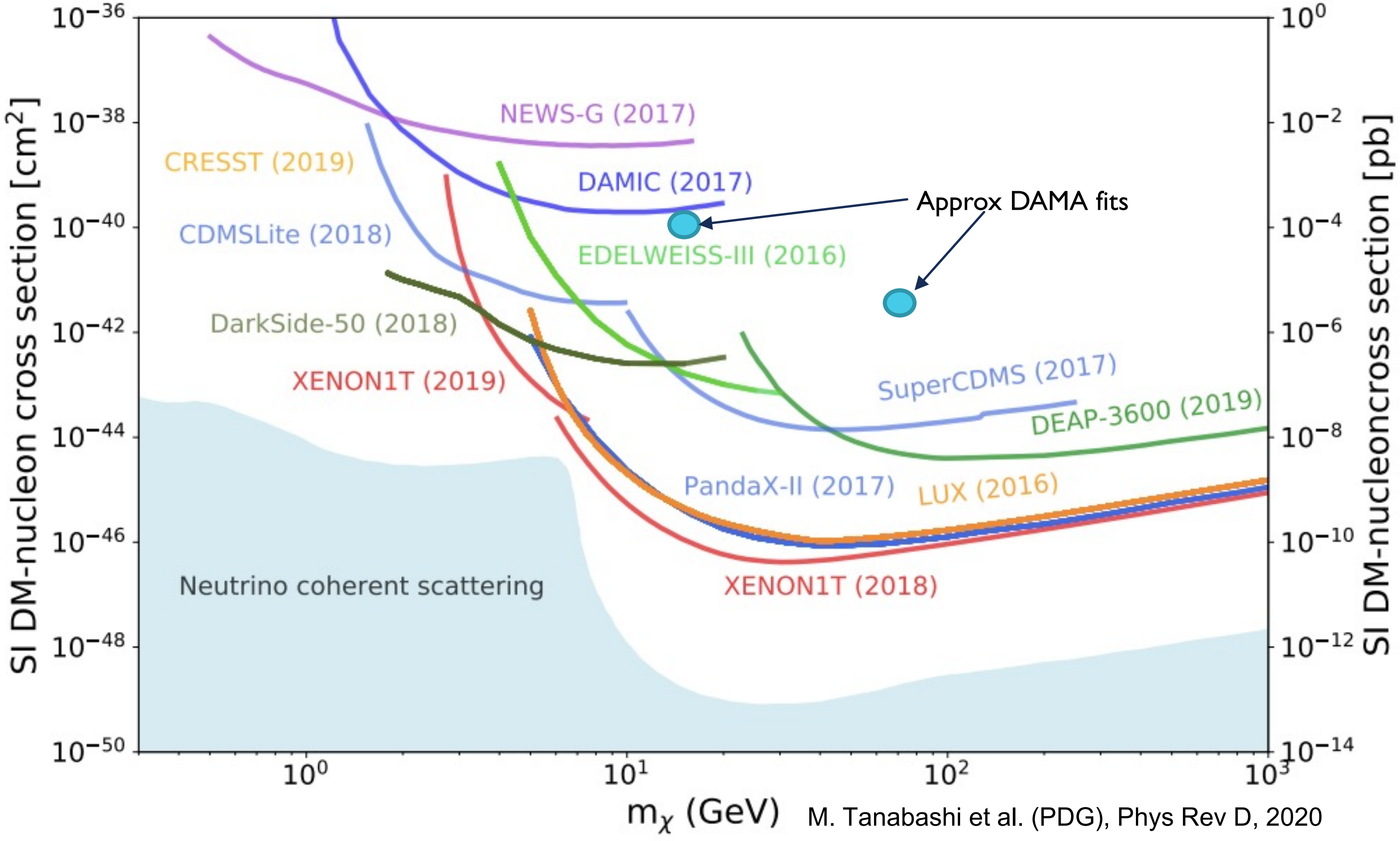


Bernabei et al. (DAMA Collaboration) 10.15407/jnpae2018.04.307

EXPERIMENTAL TENSION

Interpretation as DM is strongly constrained by null results from different targets

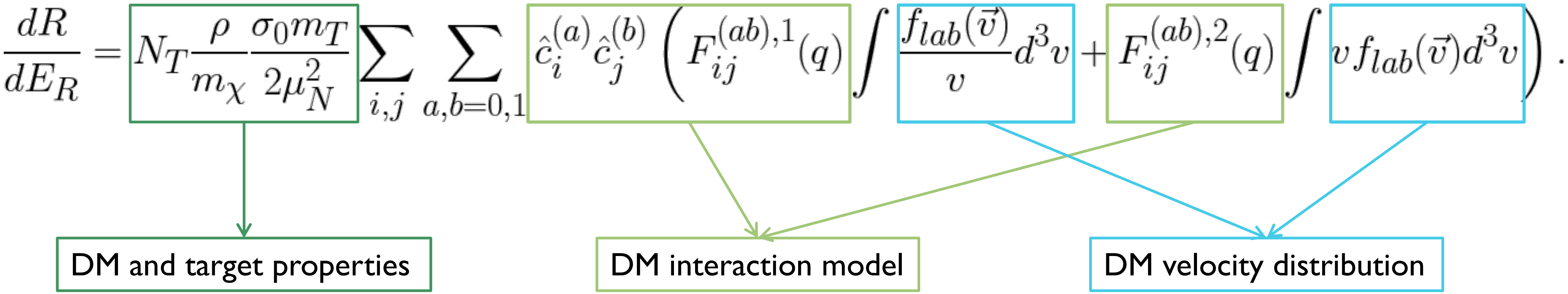
Target	Experiment/s
O	CRESST
F	PICO, PICASSO
Ne	NEWS-G
Na	DAMA
Si	DAMIC
Ar	DEAP, DarkSide
Ca	CRESST
Ge	CDMS, EDELWEISS
I	DAMA
Xe	XENON, LUX, PandaX
W	CRESST



M. Tanabashi et al. (PDG), Phys Rev D, 2020

INTERACTION RATE

Number of nuclear recoils as a function of nuclear recoil energy E_R



$$\frac{dR}{dE_R} = \boxed{N_T \frac{\rho}{m_\chi}\frac{\sigma_0 m_T}{2\mu_N^2}} \sum_{i,j}\sum_{a,b=0,1} \boxed{\hat{c}_i^{(a)}\hat{c}_j^{(b)} \Big(F_{ij}^{(ab),1}(q)} \int \boxed{\frac{f_{lab}(\vec{v})}{v}} d^3v + \boxed{F_{ij}^{(ab),2}(q)} \int \boxed{v f_{lab}(\vec{v}) d^3v} \Big) .$$

DM and target properties

- Target density
- Target mass
- DM density
- DM mass
- DM cross section

DM interaction model

- Coupling constants
- DM Form factors
- Nuclear response functions

DM velocity distribution

REQUIREMENTS FOR MODEL INDEPENDENCE

For model independent tests, don't need to assume a model: can just perform a Boolean check of interaction rate

$$\frac{dR}{dE'} = \boxed{\epsilon(E')}\frac{1}{(2\pi)^{1/2}}\int_0^\infty \boxed{\frac{dR}{dE_R}}\boxed{\frac{dE_R}{dE_{ee}}}\boxed{\frac{1}{\Delta E_{ee}}\exp\left[\frac{-(E'-E_{ee})^2}{2(\Delta E_{ee})^2}\right]}dE_{ee}$$

Efficiency/threshold

Imperfect/realistic
detector setup
e.g., PMT QE ~30%

Interaction rate

Will be the same for same target detectors

Quenching factor

Transformation from nuclear recoil energy to observable energy

Resolution

Ability to resolve fine details in energy spectrum

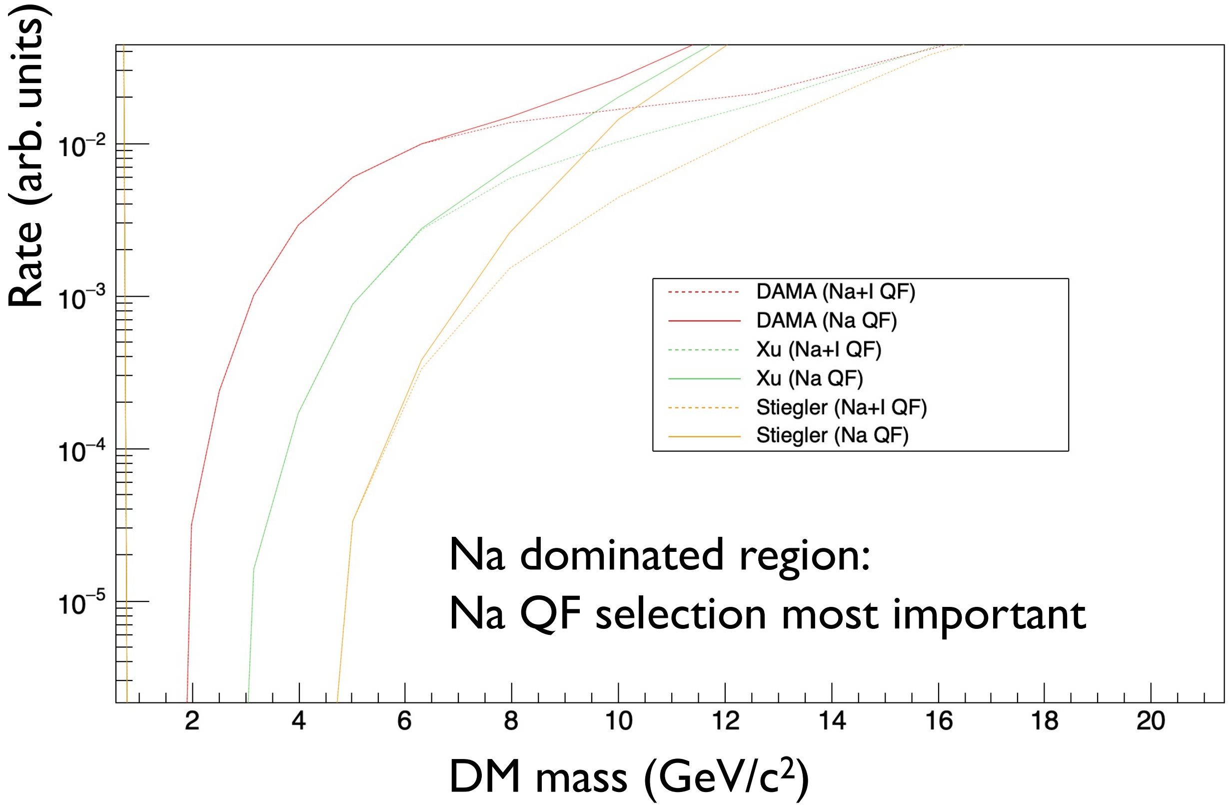
Test for a modulation that has the same ratio of R_m/R_0 as DAMA (exact value may change based on set up)

Cannot construct a true model independent test from constant constraints alone

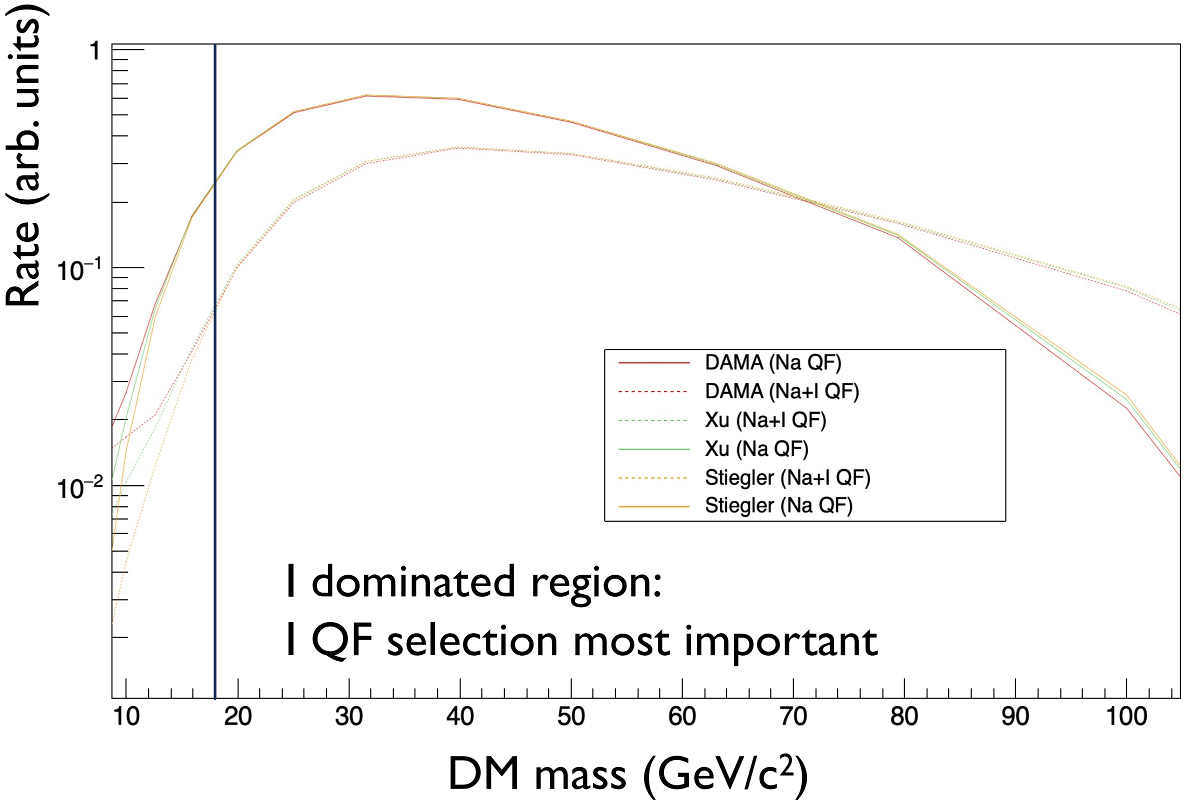
Need to assume a model to map DAMA modulation onto constrained parameter space

DM RATE

For composite target, need to add the rates for Na and I. They will contribute differently depending on DM interaction model, and particularly mass scale (c.f., traditional form factor with A^2 dependence)



Na dominated region:
Na QF selection most important



I dominated region:
I QF selection most important

PSIDM MODELS

[1] Kang, Scopel, Tomar, PRD 99, 103019 (2019)

Family of models presented to reduce experimental tension w/ DAMA

Case	Spin (j_χ)	m (GeV)	σ_0 (cm^2)	δ (keV)	Non zero $\hat{\mathbf{c}}_0$ components	
1	0	11.1	3.9×10^{-27}	22.8	$\hat{c}_7^0 = 0.68$	$\hat{c}_7^1 = 0.73$
2	1/2	11.6	4.7×10^{-28}	23.7	$\hat{c}_4^0 = -0.0014$ $\hat{c}_5^0 = -0.032$ $\hat{c}_6^0 = 0.692$	$\hat{c}_4^1 = -0.0015$ $\hat{c}_5^1 = -0.0166$ $\hat{c}_6^1 = 0.7217$
3	1	11.4	5.7×10^{-32}	23.4	$\hat{c}_4^0 = 0.0717$ $\hat{c}_5^0 = 0.1892$	$\hat{c}_4^1 = 0.0753$ $\hat{c}_5^1 = 0.9764$