IMPACT OF QUENCHING FACTOR MODEL ON TESTS OF DAMA

The Dark Side of the Universe – DSU2022

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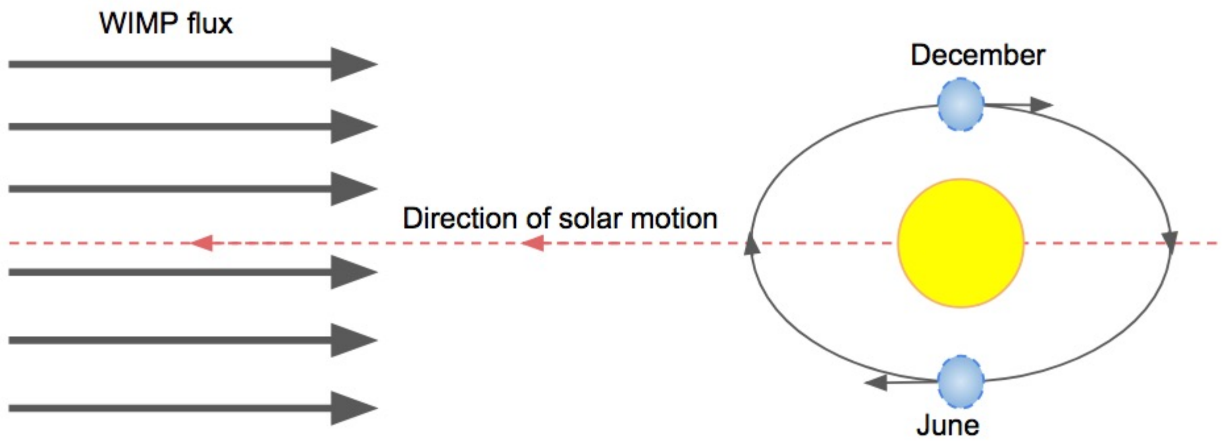
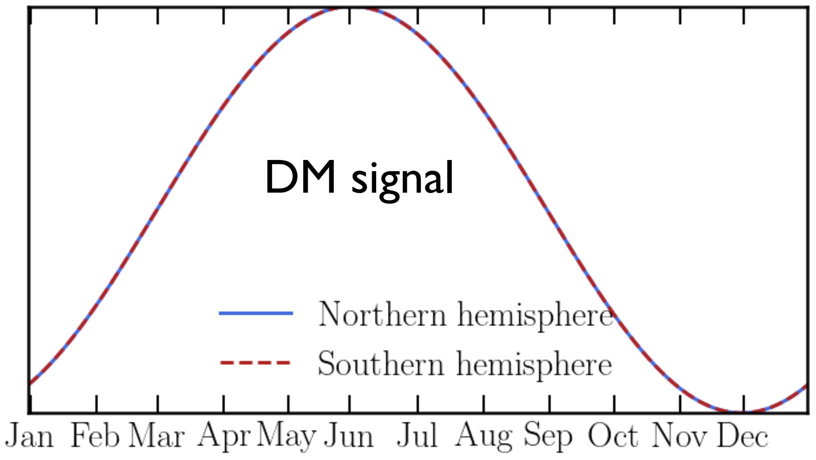
MODULATING SIGNAL

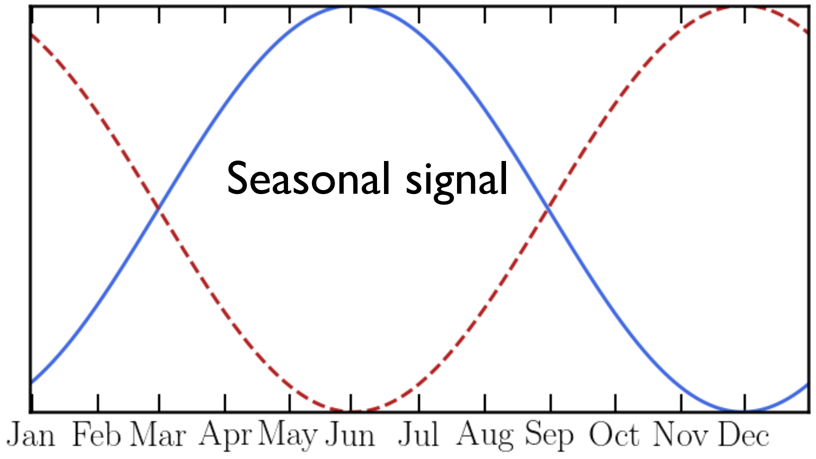
Astrophysical predictions of DM distribution imply a modulating signal due to Earth's rotation around the Sun.

$$R(E) = R_0(E) + R_m \cos(\omega(t - t_0))$$

- Period should be 1 year
- Phase should produce a peak in June
- Signal should appear in low energy range
- Events should be single hit
- Signal should be identical in north and south hemispheres





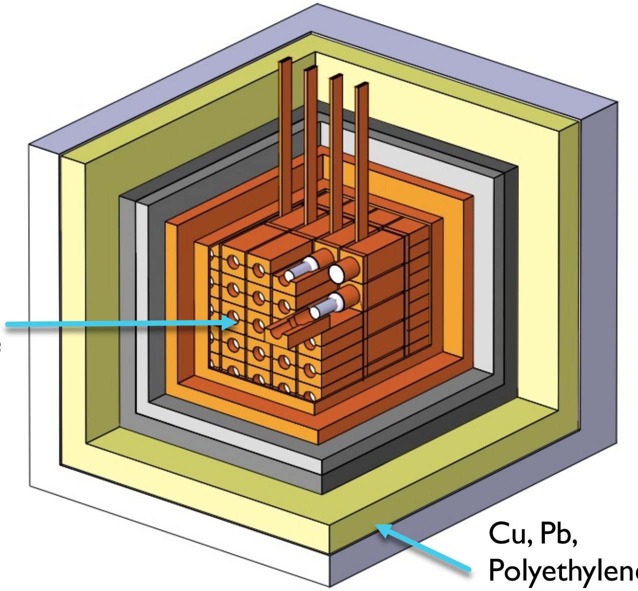


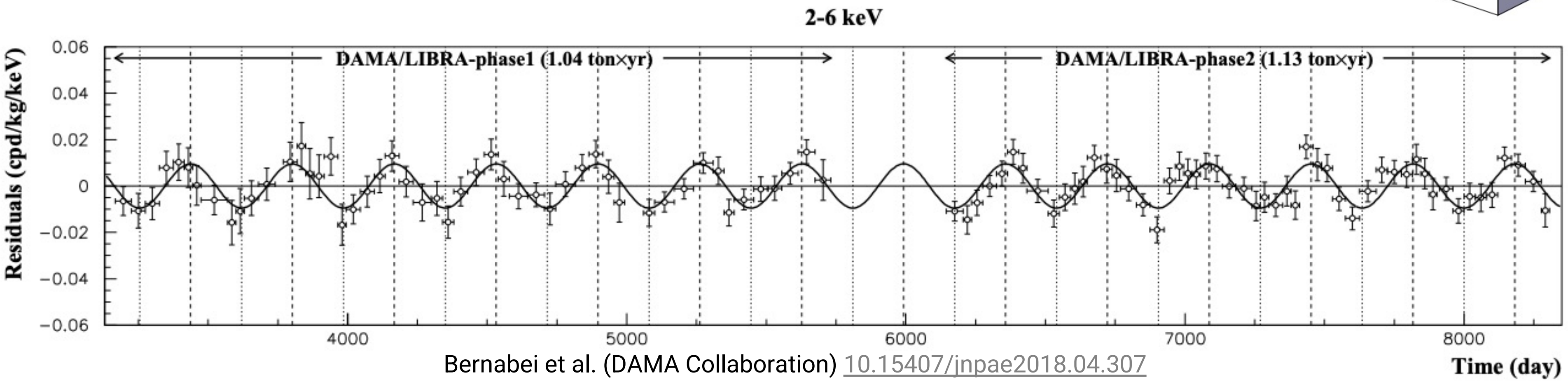
DAMA RESULTS

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

<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

MODEL DEPENDENT TEST

DM and target properties

DM interaction model

DM velocity distribution

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

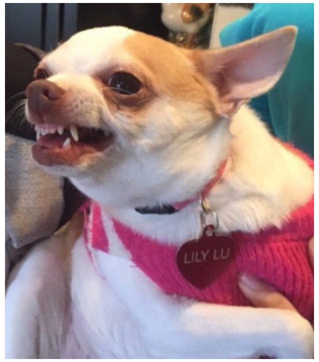
$$\frac{dR}{dE'} = \epsilon(E')\frac{1}{(2\pi)^{1/2}}\int_0^\infty \frac{dR}{dE_R}\frac{dE_R}{dE_{ee}}\frac{1}{\Delta E_{ee}}\exp\left[\frac{-(E'-E_{ee})^2}{2(\Delta E_{ee})^2}\right]dE_{ee}$$

Efficiency/threshold

Number of nuclear recoils

Quenching factor

Resolution



MODEL INDEPENDENT TEST

Same target = same nuclear recoil rate. Use measured values and avoid making assumptions about DM

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

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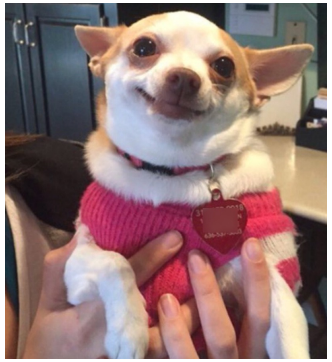
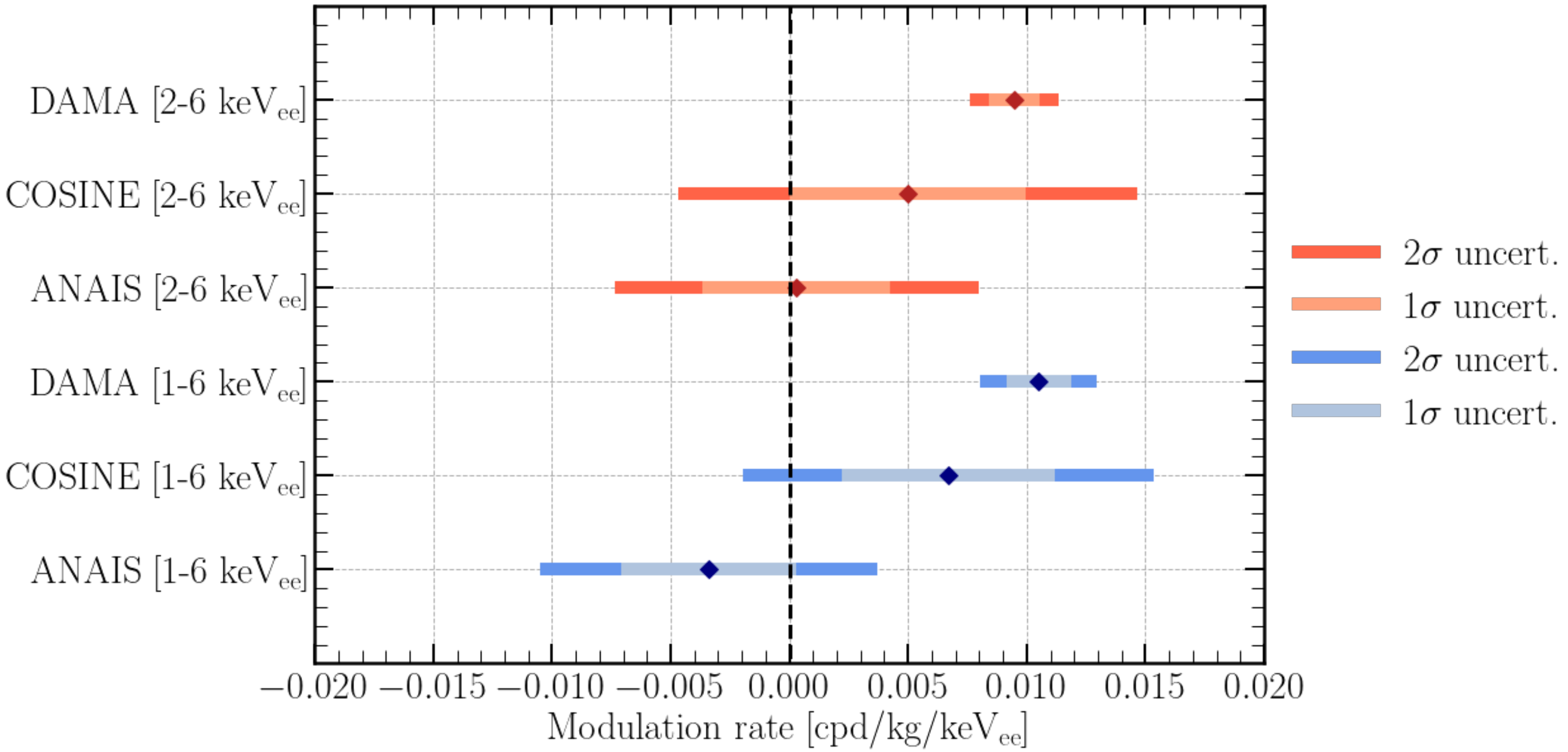


RECENT RESULTS

Bernabei et al. PPNP114 103810 (2020)
Adhikari et al. PRD 105, 052005 (2022)
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



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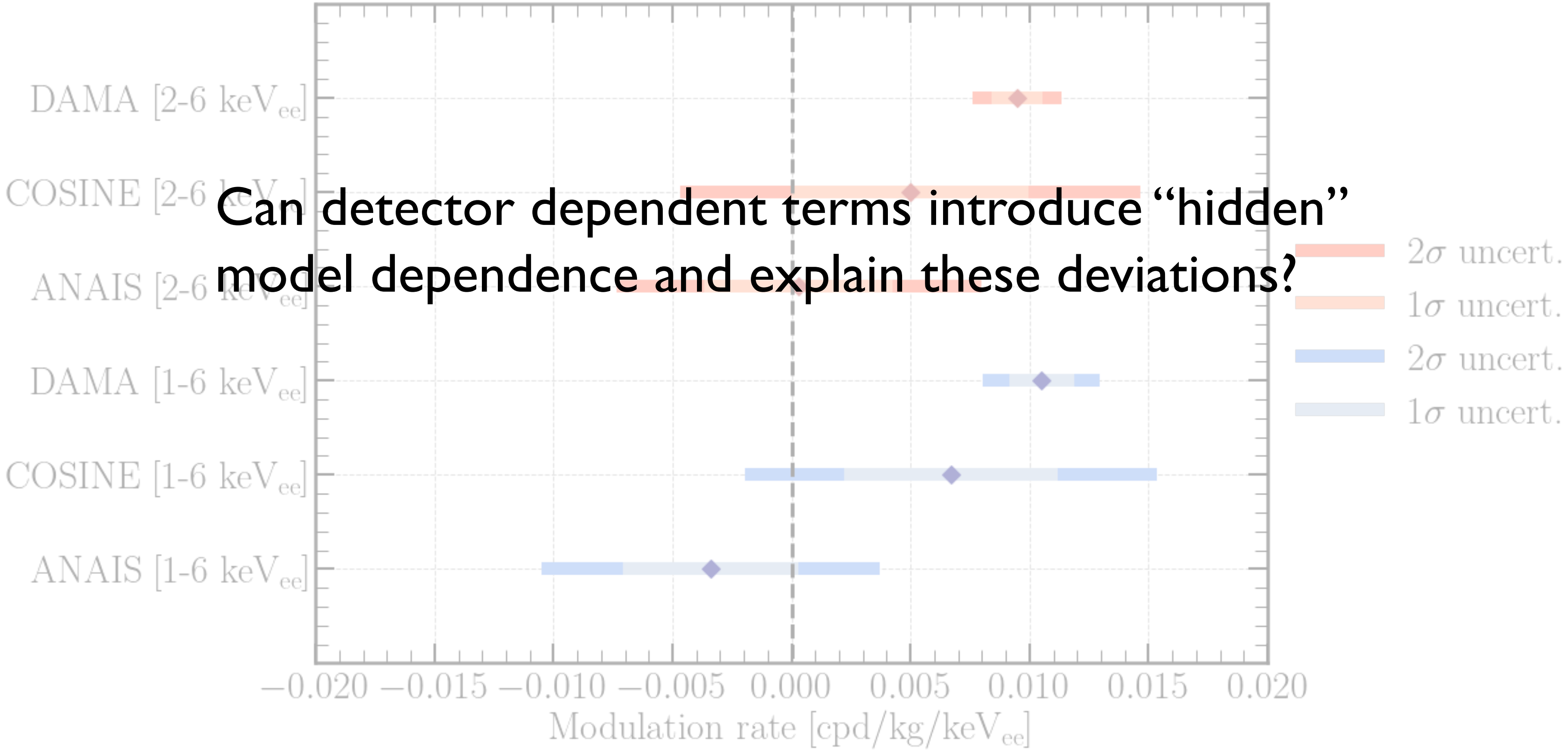


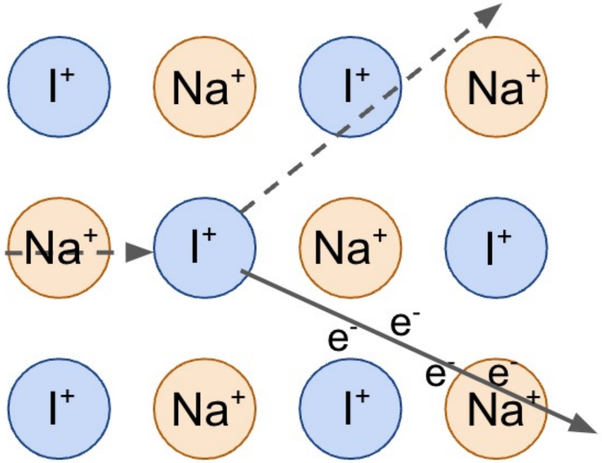
Can detector dependent terms introduce "hidden" model dependence and explain these deviations?

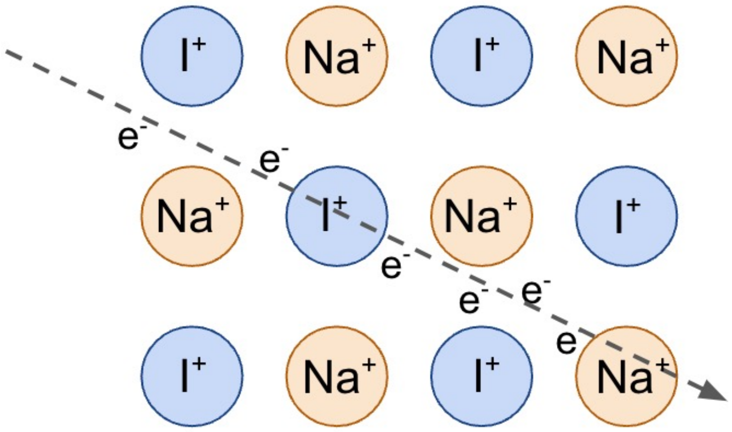
QUENCHING FACTOR

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

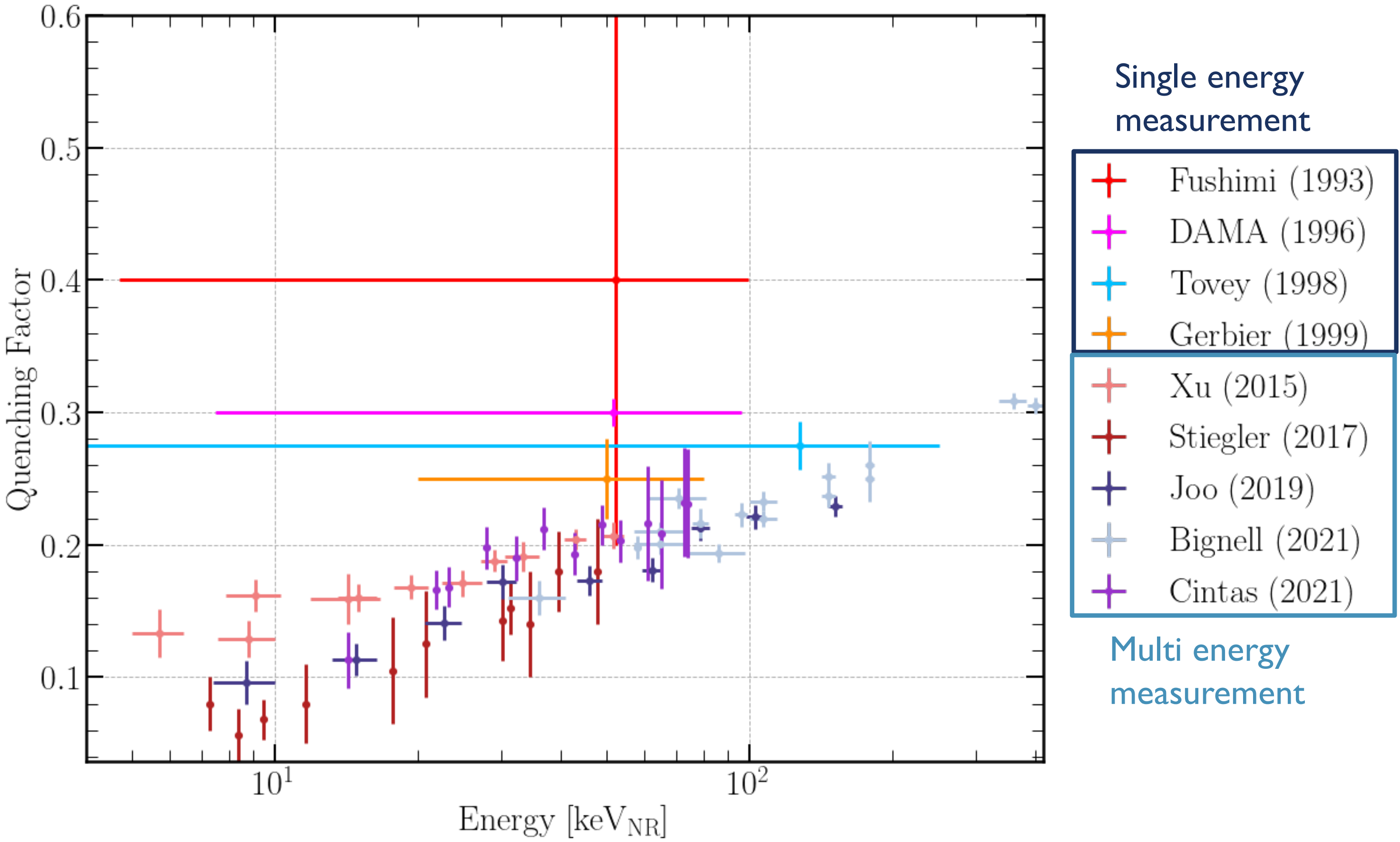
Why are the DAMA quenching factors different to those measured since?
Possible solutions:

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.

Possible that (1) and (2) are both true - still inconsistencies at low energy.

Also the question of energy dependence – is this a feature of calibration? (See Cintas et al.)



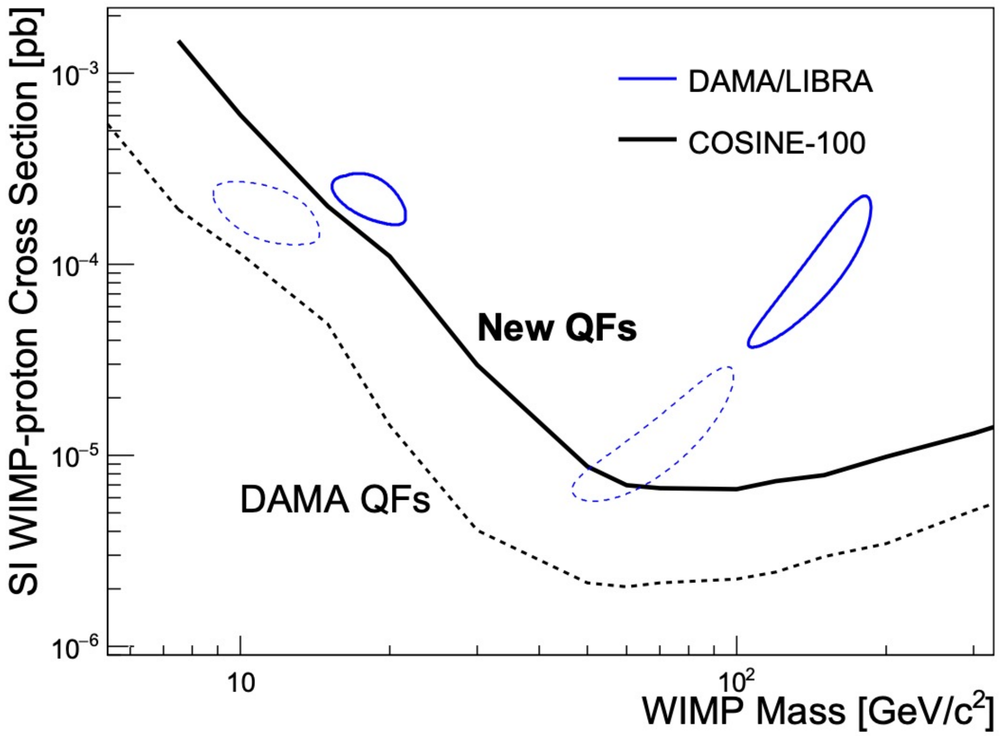
K. Fushimi et al. PRC 47 425 (1993)
R. Bernabei et al. Riv Nuovo Cim 26 (2003)
D. R. Tovey et al. PLB 433.1 (1998)
G. Gerbier et al. Astropart. Phys. 11.3 (1999)

J. Xu et al. PRC 92.1 (2015)
T. Stiegler et al. 2017 arxiv:1706.07494
H. Joo et al. Astropart. Phys. 108 (2019)
L. J. Bignell et al. JINST 16 P07034 (2021)
D. Cintas et al. JPCS 2156.1 (2021)

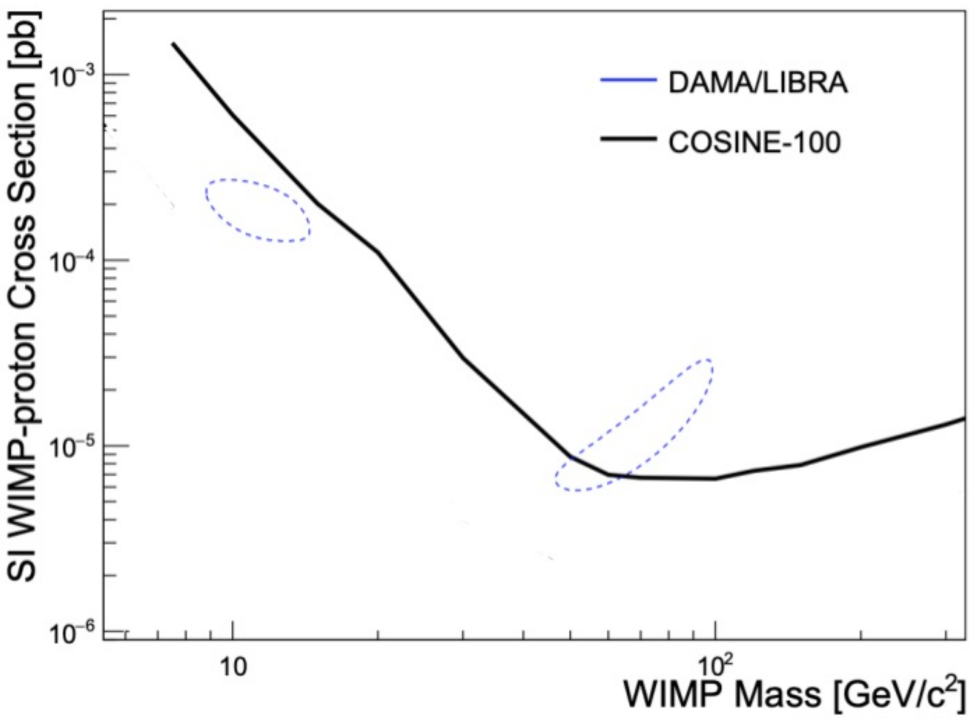
QUENCHING FACTOR IMPACT

Ko et al. JCAP 11 (2019)

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



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



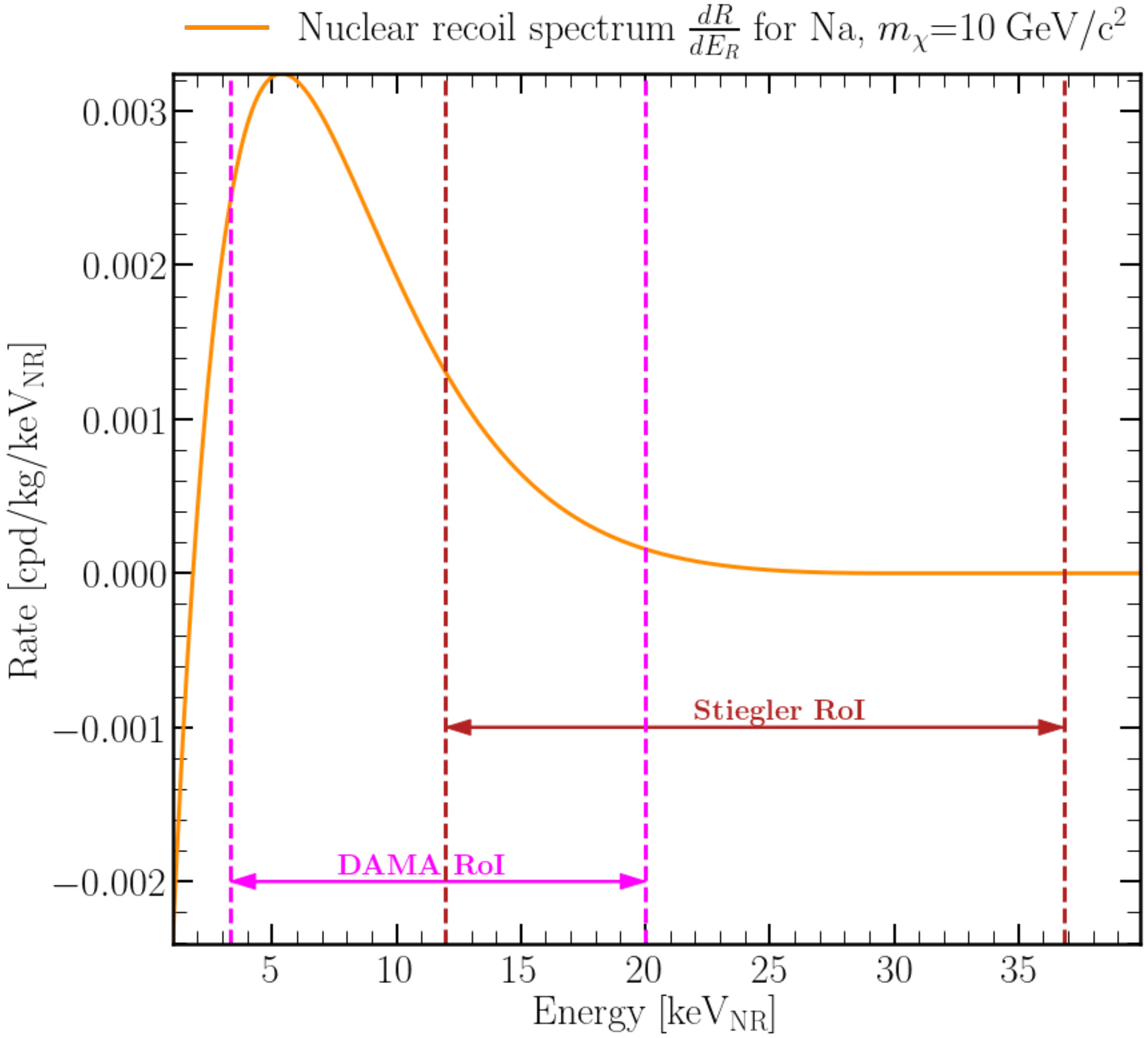
Assuming detectors have different QFs

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



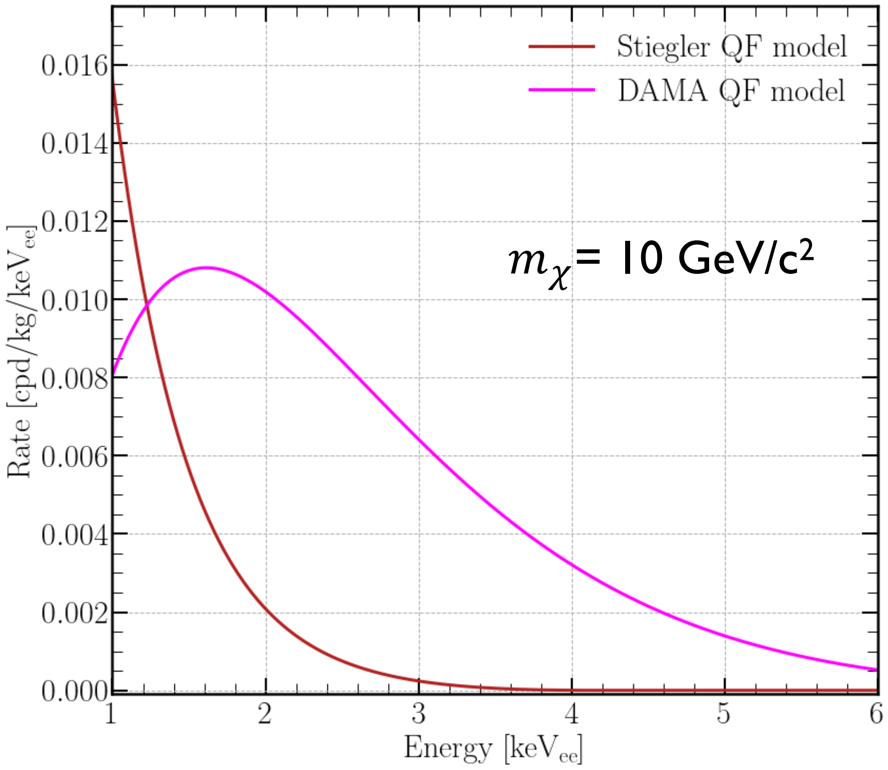
QUENCHING FACTOR IMPACT

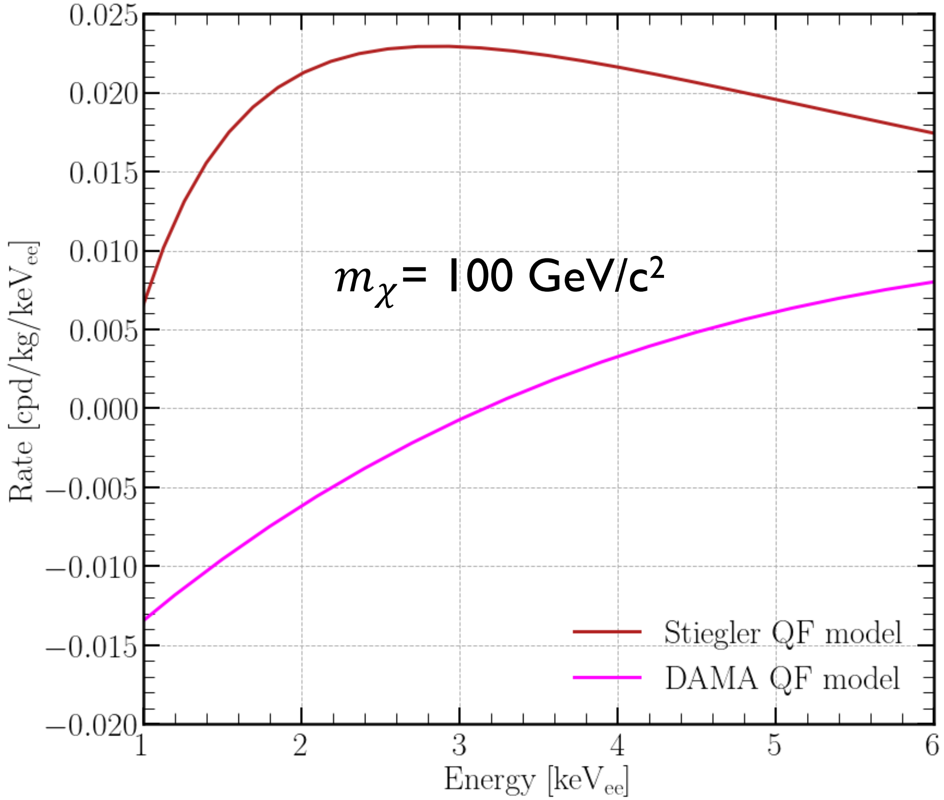
R. Bernabei et al. Riv Nuovo Cim 26 (2003)
T. Stiegler et al. 2017 arxiv:1706.07494

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, change to QF drastically changes the observable signal, both in value and shape in region of interest. Effect is more pronounced than for m_χ= 100 GeV/c^2

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

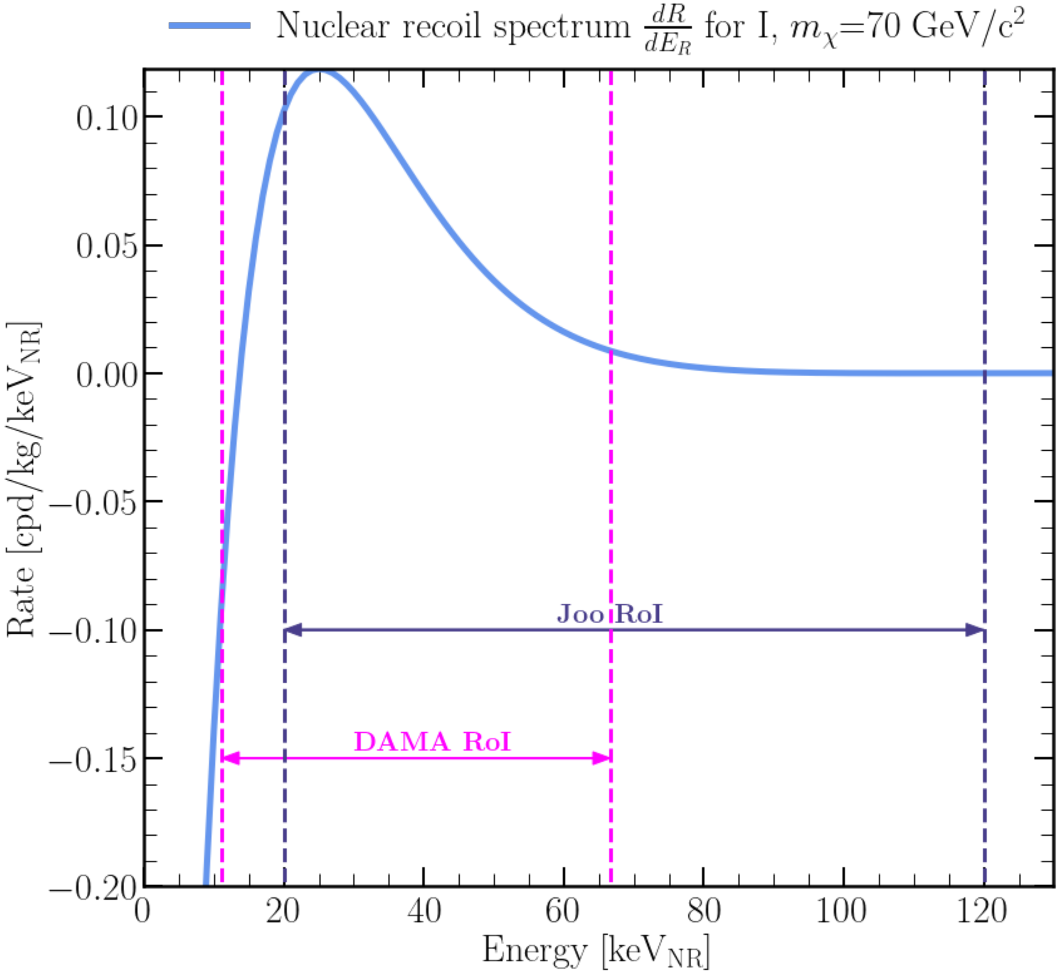


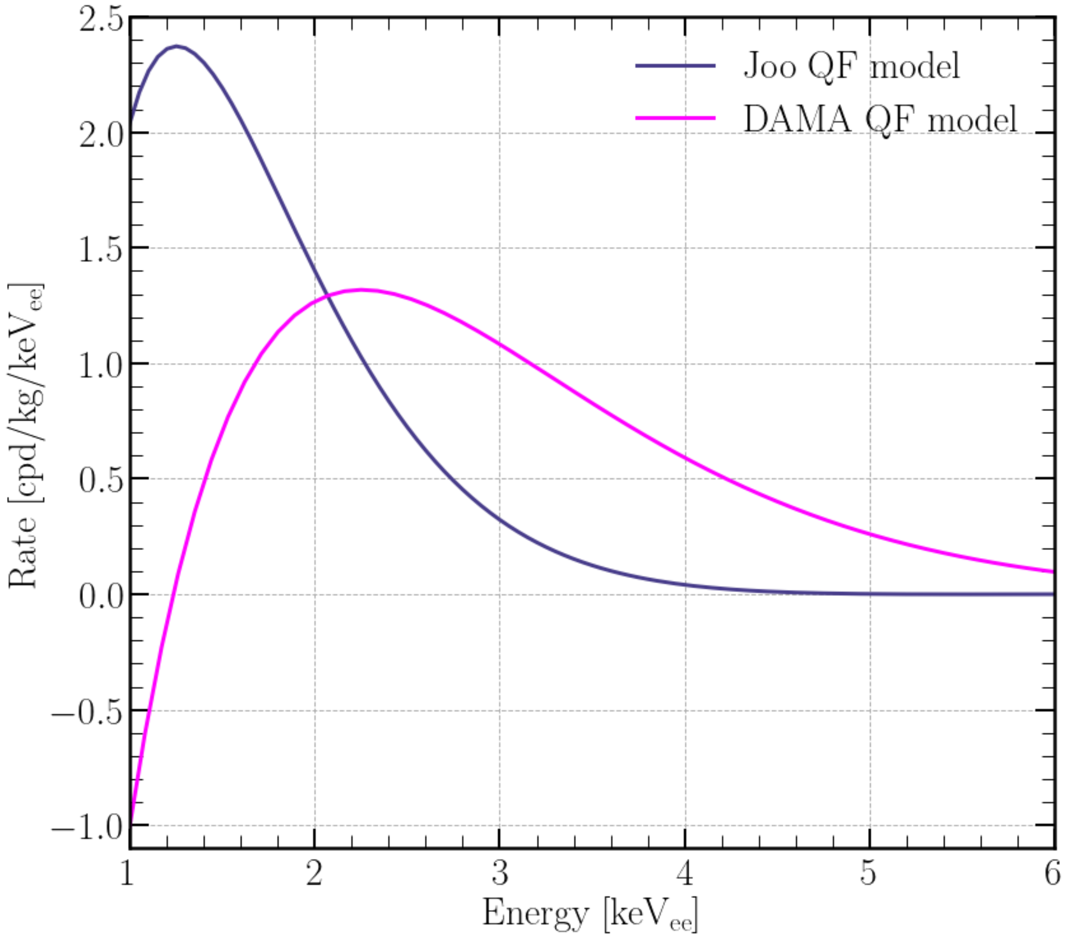


QUENCHING FACTOR IMPACT

R. Bernabei et al. Riv Nuovo Cim 26 (2003)
H. Joo et al. Astropart. Phys. 108 (2019)

Similar effect occurs for I scattering too, but only two 'models' to choose from (more difficult to measure than Na)

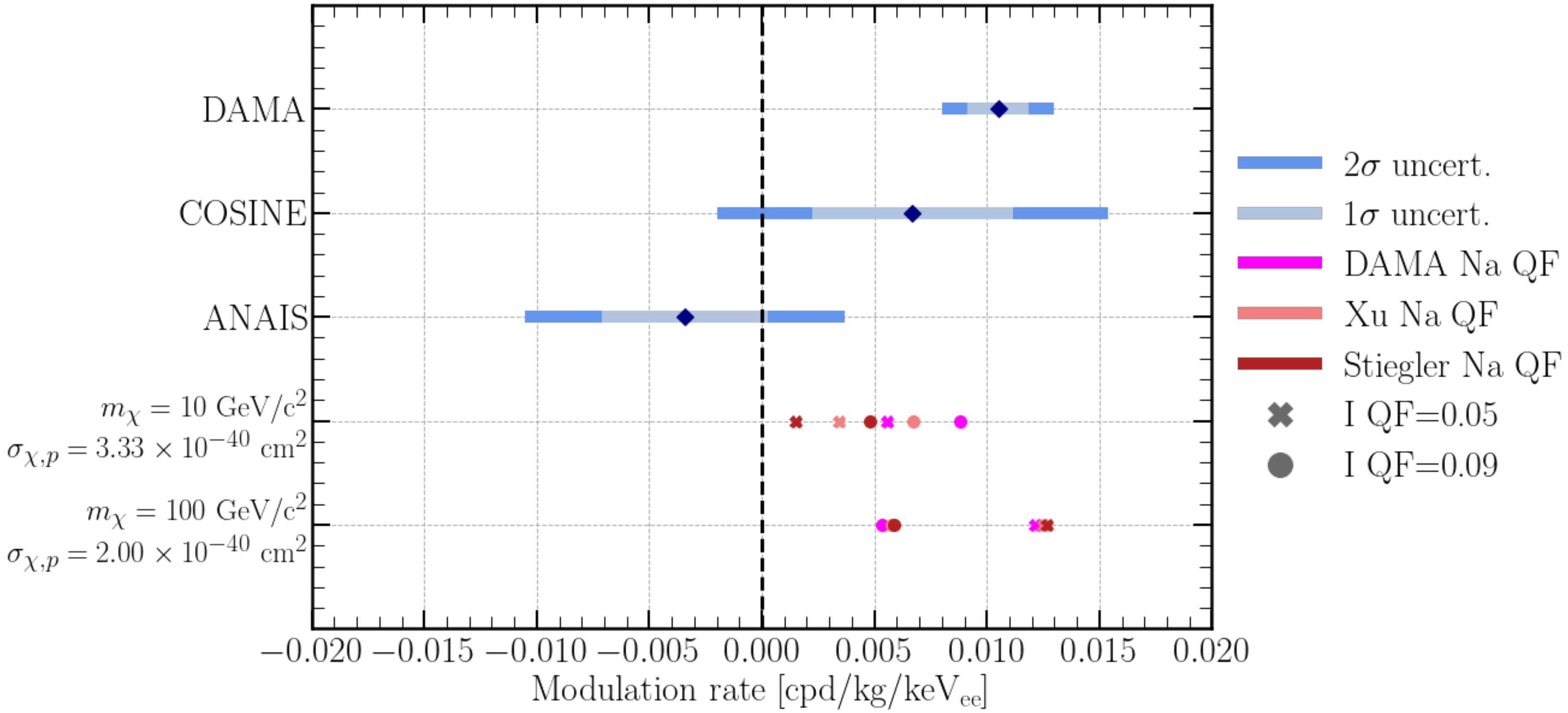




QUENCHING FACTOR IMPACT

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>



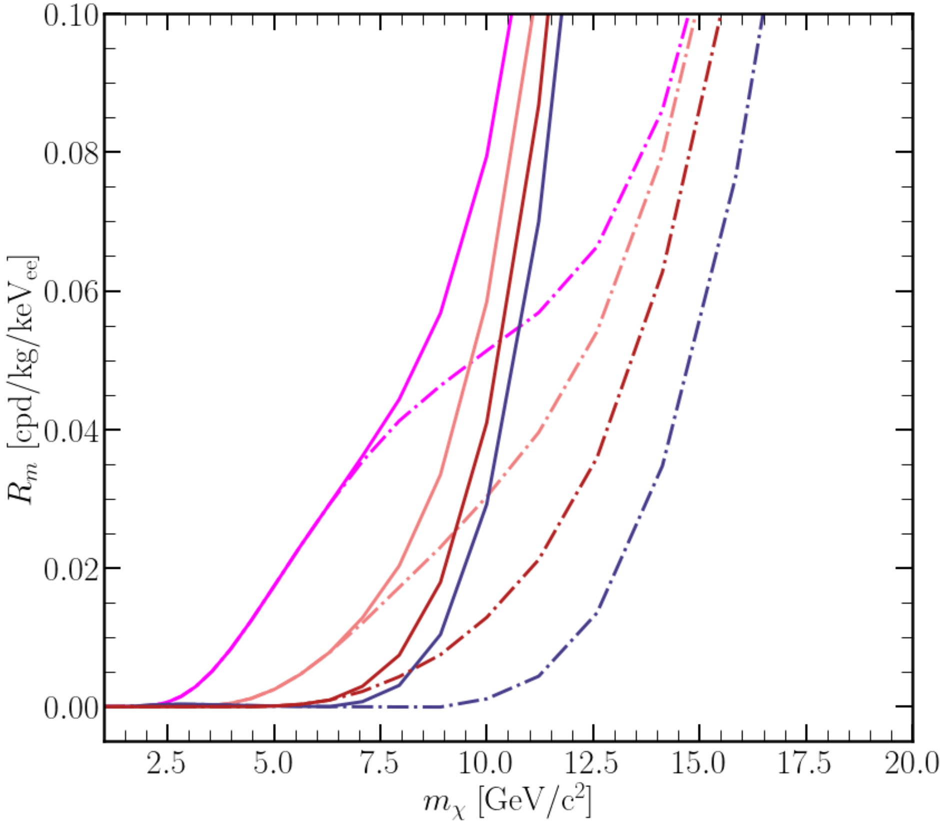
1-6 keV$_{ee}$ region

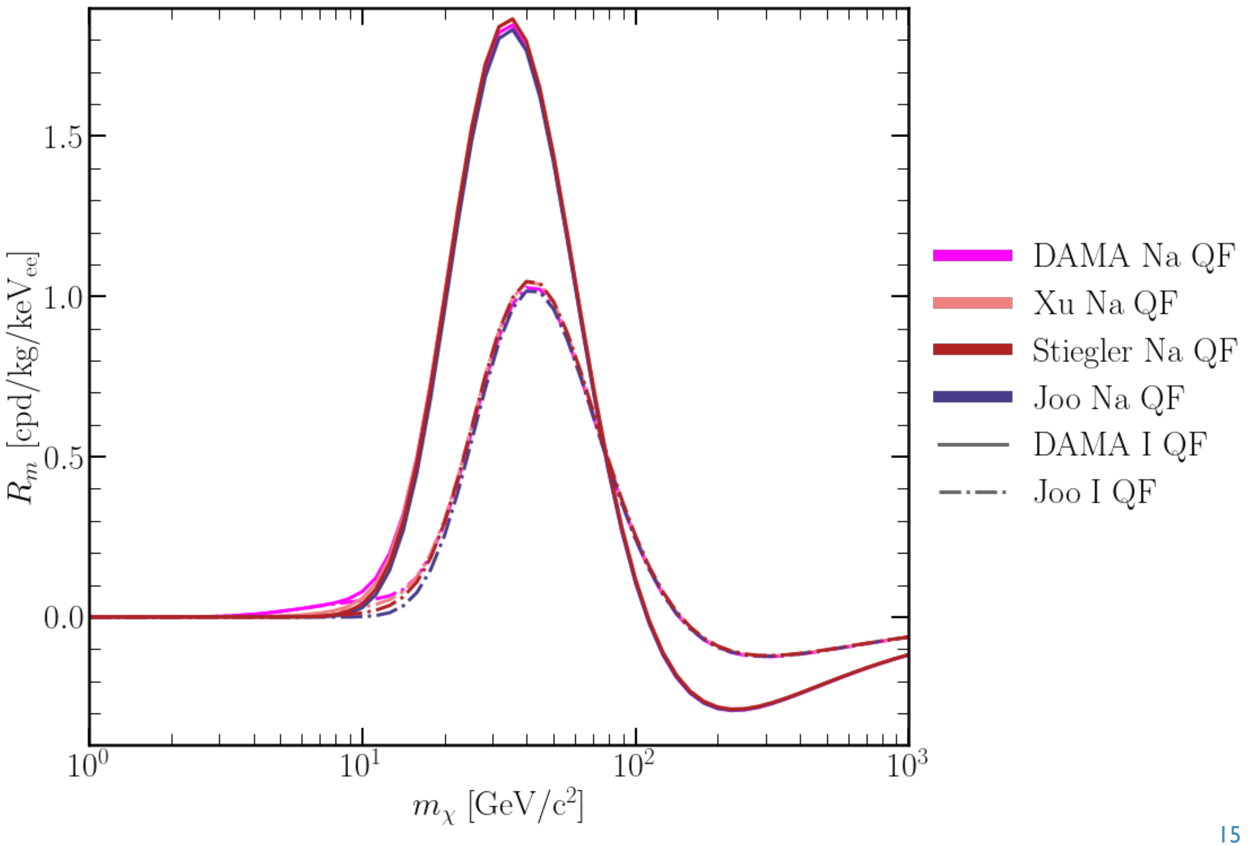
DM RATE

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)

I model dominates differences above ~15 GeV/c², Na model dominating below 7 GeV/c²

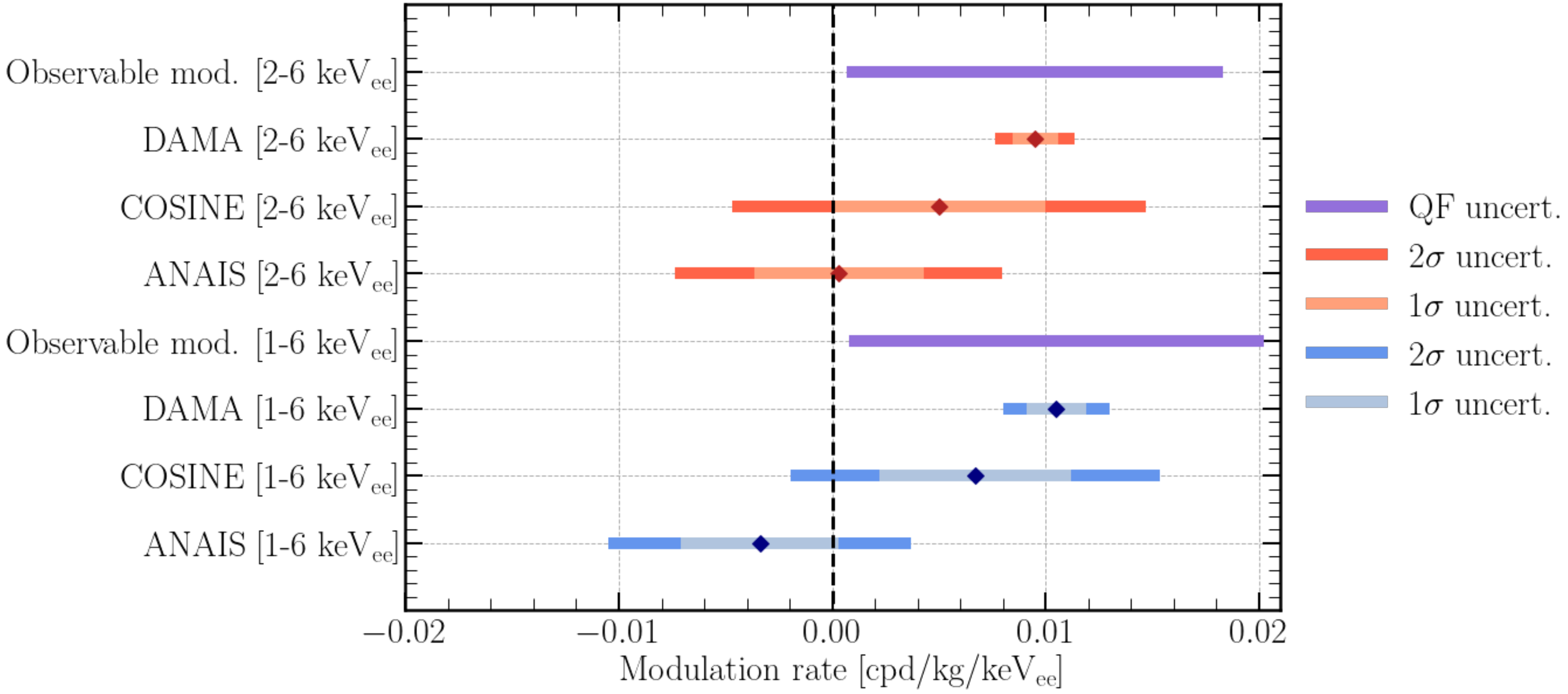
Between this region both QFs play a role – modulation rate can vary by an order of magnitude





RECASTING MODEL INDEPENDENT RESULTS

Assume nothing about the DAMA QF, but note that deviations in QF can produce rate changes ~ order of magnitude and plot a range of "observable modulation" DAMA could be recording - i.e., rates in this region are compatible with the central value assuming different QFs



SUMMARY

* See Cintas at TAUP21, Bharadwaj at IDM22

- NaI detectors designed as model independent tests of DAMA seem to be 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. Cross collaboration working group has been formed to do so.

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

BACK UP SLIDES

INTERACTION RATE

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

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

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

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

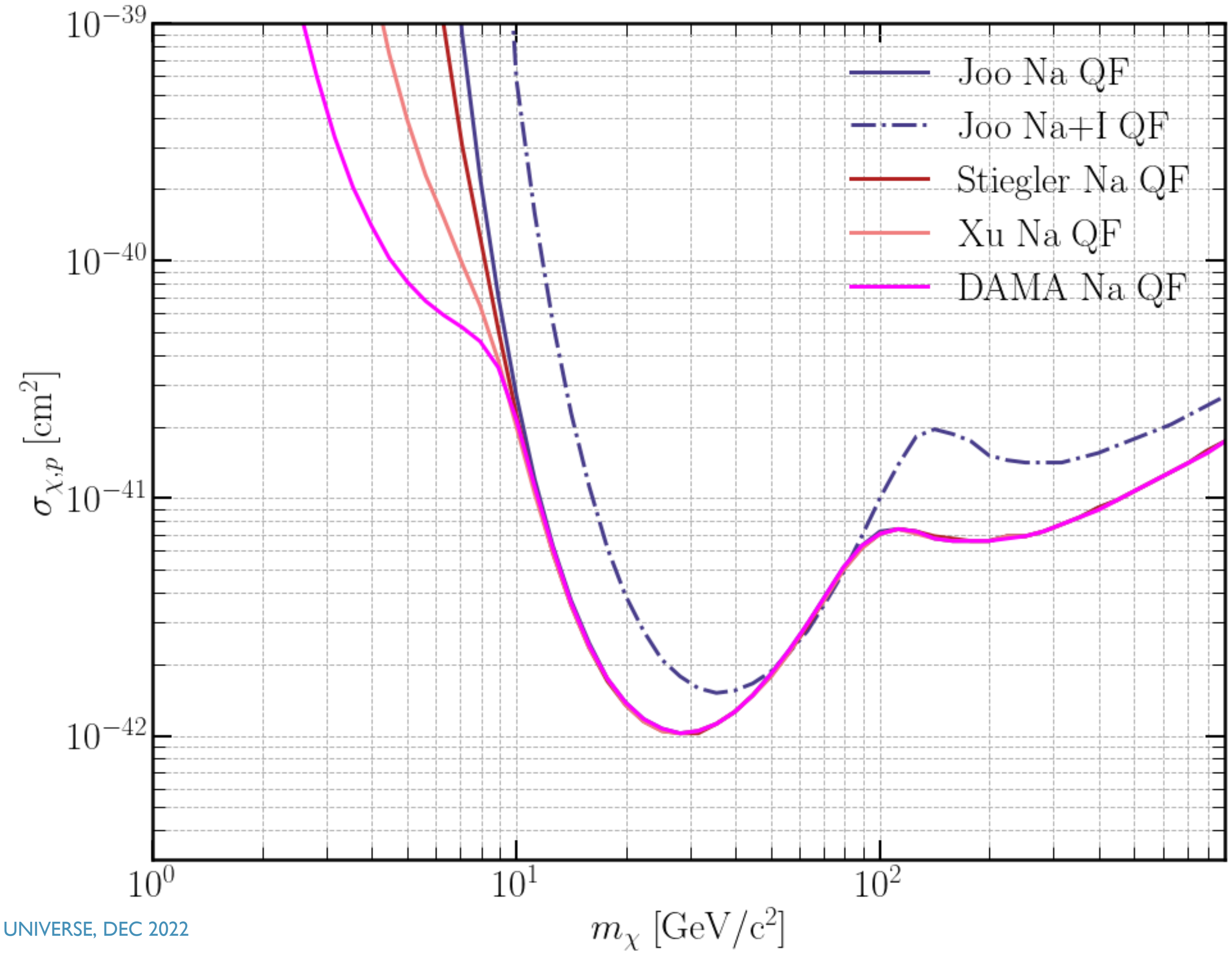
Resolution

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)
<u>Cannot construct a true model independent test from constant constraints alone</u>
Need to assume a model to map DAMA modulation onto constrained parameter space

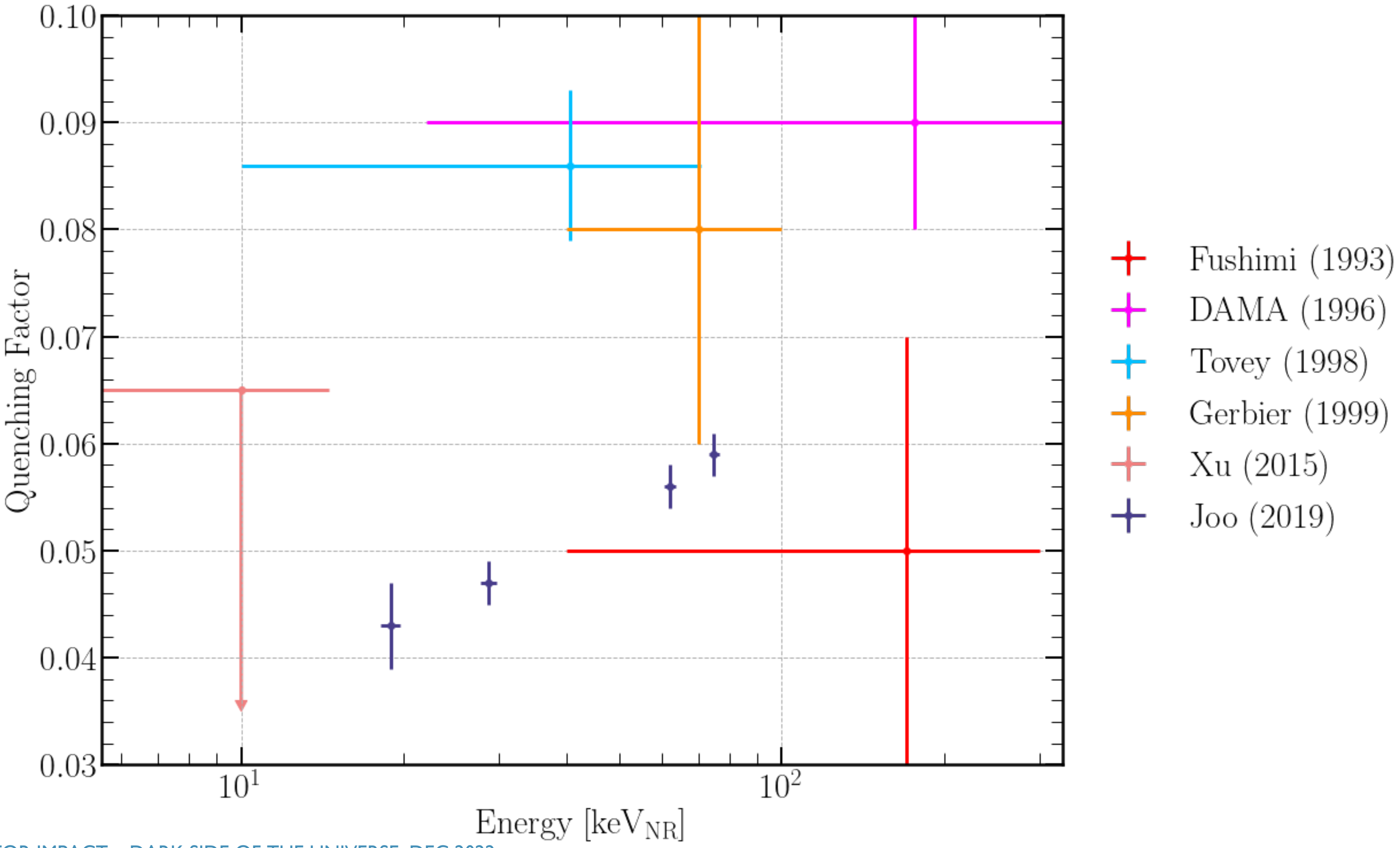
DM RATE

Can look at model dependent plots to get a baseline understanding of how it impacts sensitivity. Even here it is clear that is will be strongly dependent on mass ⇒ cannot use an arbitrary scale factor.



IODINE QF

Also appears to be differences in the I QF, but fewer measurements as more difficult to measure



MASS DEPENDENCE