KING'S College LONDON

Pitfalls, challenges and frustrations interpreting direct detection data

Christopher McCabe

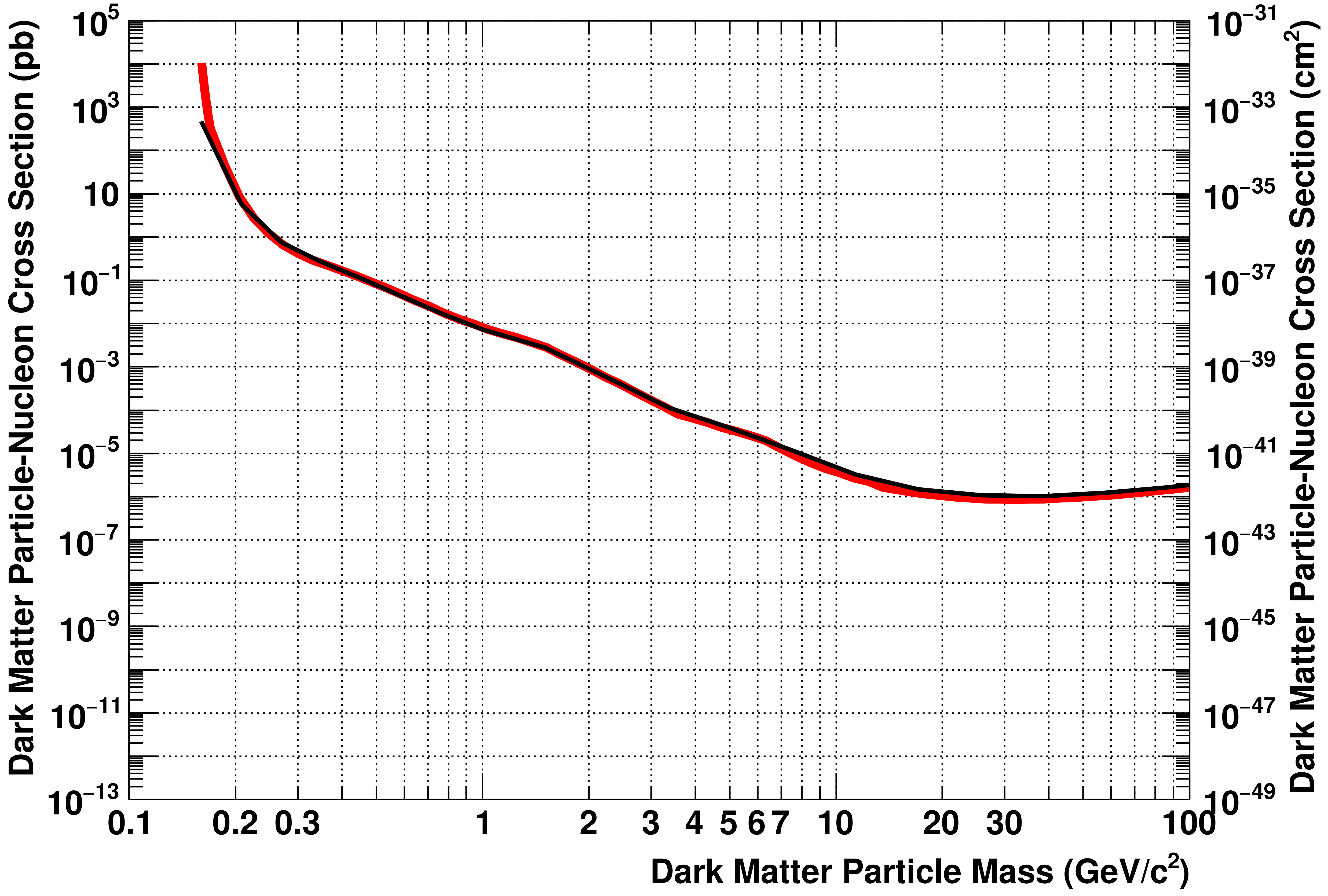
(Re)interpreting the results of new physics searches at the LHC (online) - 17th February 2021

What is in this talk?

This is a personal account of issues I have faced over the past 5 years on various direct detection projects

Pitfall

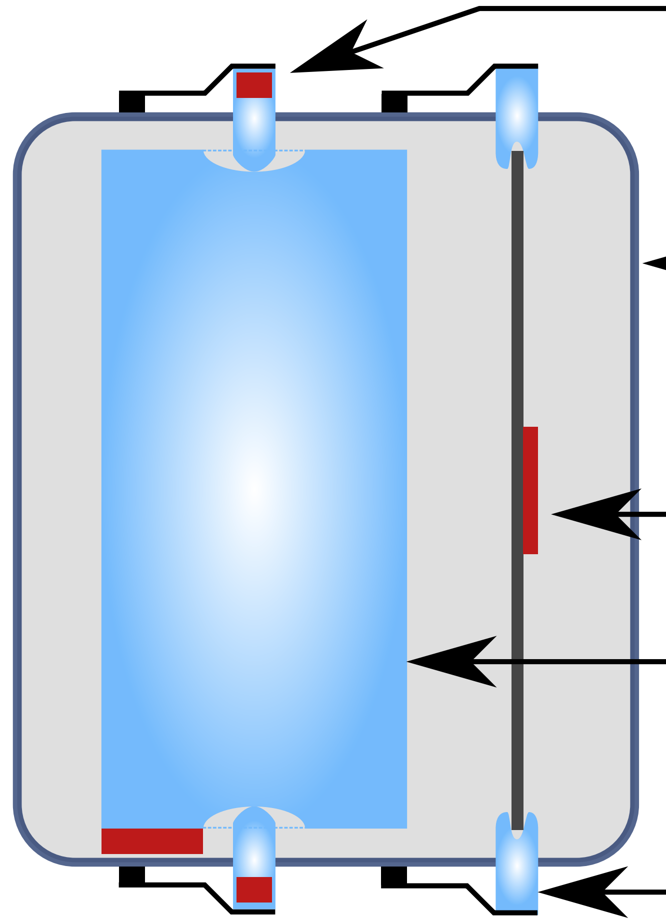
CRESST-II and -III



Small detector

Very low threshold

Optimised for low-mass searches



Good things: public data

Since 2017, the CRESST Collaboration have released their data on the arXiv and notes explaining how to use it

Description of CRESST-II data

G. Angloher[1], P. Bauer[1], A. Bento[1,a], C. Bucci[2], L. Canonica[2,b], X. Defay[3], A. Erb[3,c], F. v. Feilitzsch[3], N. Ferreiro Iachellini[1], P. Gorla[2], A. Gütlein[*4,5], D. Hauff[1], J. Jochum[6], M. Kiefer[1], C. Kistner[1], H. Kluck[4,5], H. Kraus[7], J.-C. Lanfranchi[3], J. Loebell[6], M. Mancuso[1], A. Münster[3], C. Pagliarone[2], F. Petricca[1], W. Potzel[3], F. Pröbst[1], R. Puig[4,5], F. Reindl[†1], S. Roth[3], K. Rottler[6], C. Sailer[6], K. Schäffner[2,d], J. Schieck[4,5], J. Schmaler[1], S. Scholl[6], S. Schönert[3], W. Seidel[1], M.v. Sivers[3], L. Stodolsky[1], C. Strandhagen[6], R. Strauss[1], A. Tanzke[1], H.H. Trinh Thi[3], C. Türkoğlu[4,5], M. Uffinger[6], A. Ulrich[3], I. Usherov[6], S. Wawoczny[3], M. Willers[3], M. Wüstrich[1] and A. Zöller[3]

Description of CRESST-III Data

A. H. Abdelhameed,[1] G. Angloher,[1] P. Bauer,[1,*] A. Bento,[1,8] E. Bertoldo,[1] C. Bucci,[2] L. Canonica,[1] A. D'Addabbo,[2,9] X. Defay,[3] S. Di Lorenzo,[2,9] A. Erb,[3,10] F. v. Feilitzsch,[3] S. Fichtinger,[4] N. Ferreiro Iachellini,[1] A. Fuss,[4,5] P. Gorla,[2] D. Hauff,[1] J. Jochum,[6] A. Kinast,[3] H. Kluck,[4,5] H. Kraus,[7] A. Langenkämper,[3] M. Mancuso,[1] V. Mokina,[4] E. Mondragon,[3] A. Münster,[3] M. Olmi,[2,9] T. Ortmann,[3] C. Pagliarone,[2,11] L. Pattavina,[3,9] F. Petricca,[1] W. Potzel,[3] F. Pröbst,[1] F. Reindl,[4,5] J. Rothe,[1] K. Schäffner,[2,9] J. Schieck,[4,5] V. Schipperges,[6] D. Schmiedmayer,[4,5] S. Schönert,[3] C. Schwertner,[4,5] M. Stahlberg,[4,5] L. Stodolsky,[1] C. Strandhagen,[6] R. Strauss,[3] C. Türkoğlu,[4,5] I. Usherov,[6] M. Willers,[3] and V. Zema[2,9,12]
(CRESST Collaboration)

CRESST data

The data required to reproduce their results is relatively small

```
#Energies (keV) for all events in the acceptance region for the CRESST-III dark matter search
0.1229
0.0546
0.0638
0.0316
0.0314
0.0384
0.0369
0.0433
0.0466
0.0833
0.0504
0.0440
0.1345
0.1216
0.0401
0.6268
0.0520
0.0533
0.0552
0.0326
0.0349
0.0545
0.0600
0.0315
0.0422
0.0423
0.0450
0.0519
0.0375
0.0324
0.0682
0.0354
0.0462
0.0583
0.0324
0.0453
0.0367
0.0356
0.0375
```

```
#analytically calculated fraction of events from the oxygen (O) band at a given reconstructed energy that is expected in the region of interest
for the CRESST-III dark matter search
#Energy(keV) Surviving Fraction
0.030   0.495
0.032   0.495
0.033   0.495
0.035   0.495
0.036   0.495
0.038   0.495
0.040   0.495
0.041   0.495
0.043   0.495
0.044   0.495
0.046   0.495
0.048   0.494
0.049   0.494
0.051   0.494
0.052   0.494
0.054   0.494
0.056   0.494
0.057   0.494
0.059   0.494
0.060   0.494
0.062   0.494
0.064   0.494
0.065   0.494
0.067   0.494
0.068   0.494
0.070   0.494
0.072   0.494
0.073   0.494
0.075   0.494
0.076   0.494
0.078   0.494
0.080   0.494
0.081   0.494
0.083   0.494
0.084   0.494
0.086   0.494
```

Ancillary files (details):

- C3P1_DetA_AR.dat
- C3P1_DetA_DataRelease_SD.xy
- C3P1_DetA_DataRelease_SI.xy
- C3P1_DetA_cuteff.dat
- C3P1_DetA_eff_AR_Ca.dat
- C3P1_DetA_eff_AR_O.dat
- C3P1_DetA_eff_AR_W.dat
- C3P1_DetA_full.dat

(collapse list)

‘Easy’ to use

We used in the initial CRESST-II data release in our likelihood scans…

Identifying WIMP dark matter from particle and astroparticle data

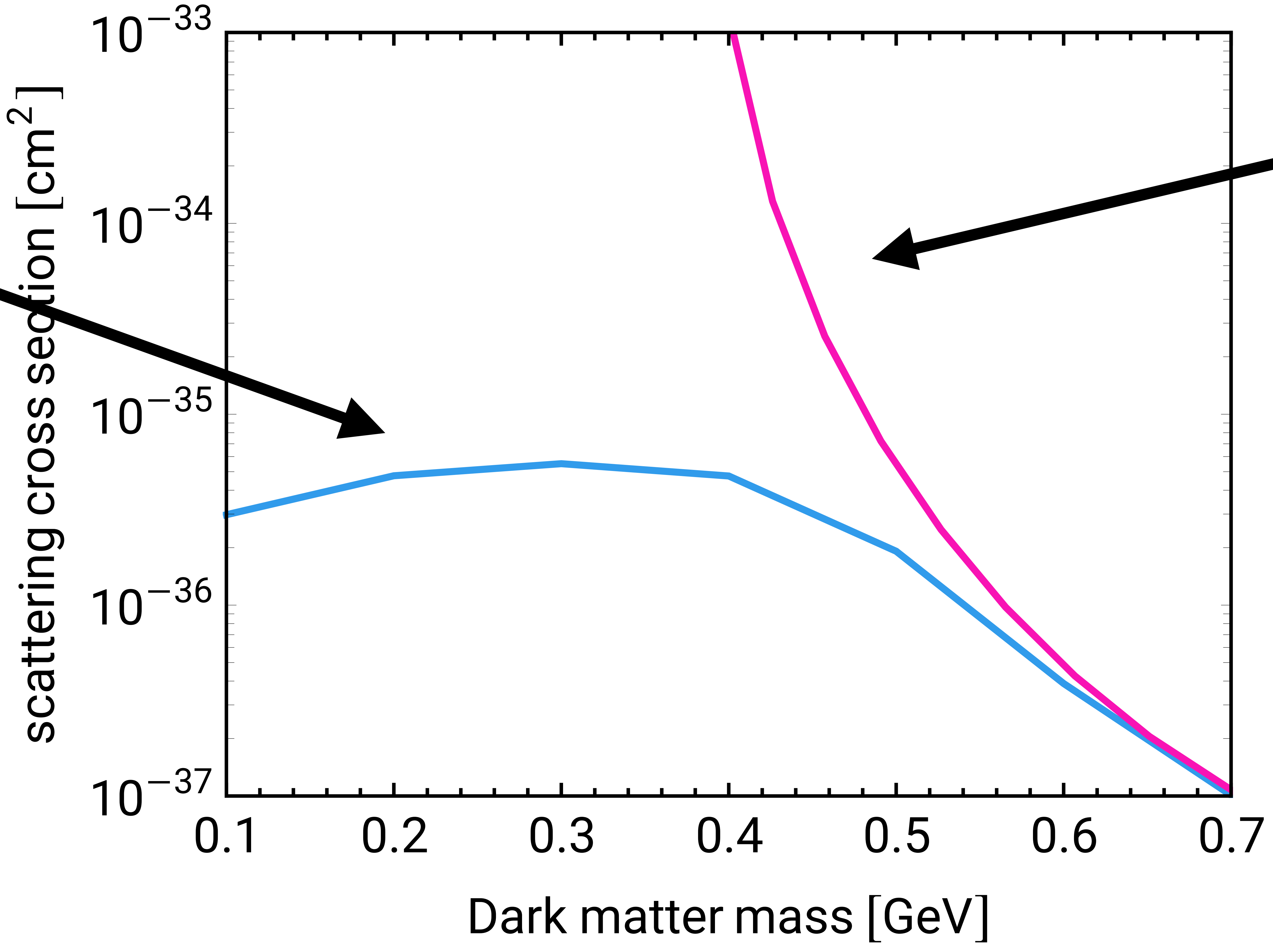
Gianfranco Bertone,[a] Nassim Bozorgnia,[a,b] Jong Soo Kim,[c] Sebastian Liem,[a] Christopher McCabe,[d] Sydney Otten[e] and Roberto Ruiz de Austri[f]

arXiv:1712.04793

…but we realised you have to be careful when dealing with the events very close to the threshold

Pitfall…using the data incorrectly

What we naively obtained
(which great if true)



What we should have obtained

Pitfall…using the data incorrectly

We got the wrong behaviour because our treatment of the detector resolution was too naive

The detector resolution is modelled with a Normal distribution:

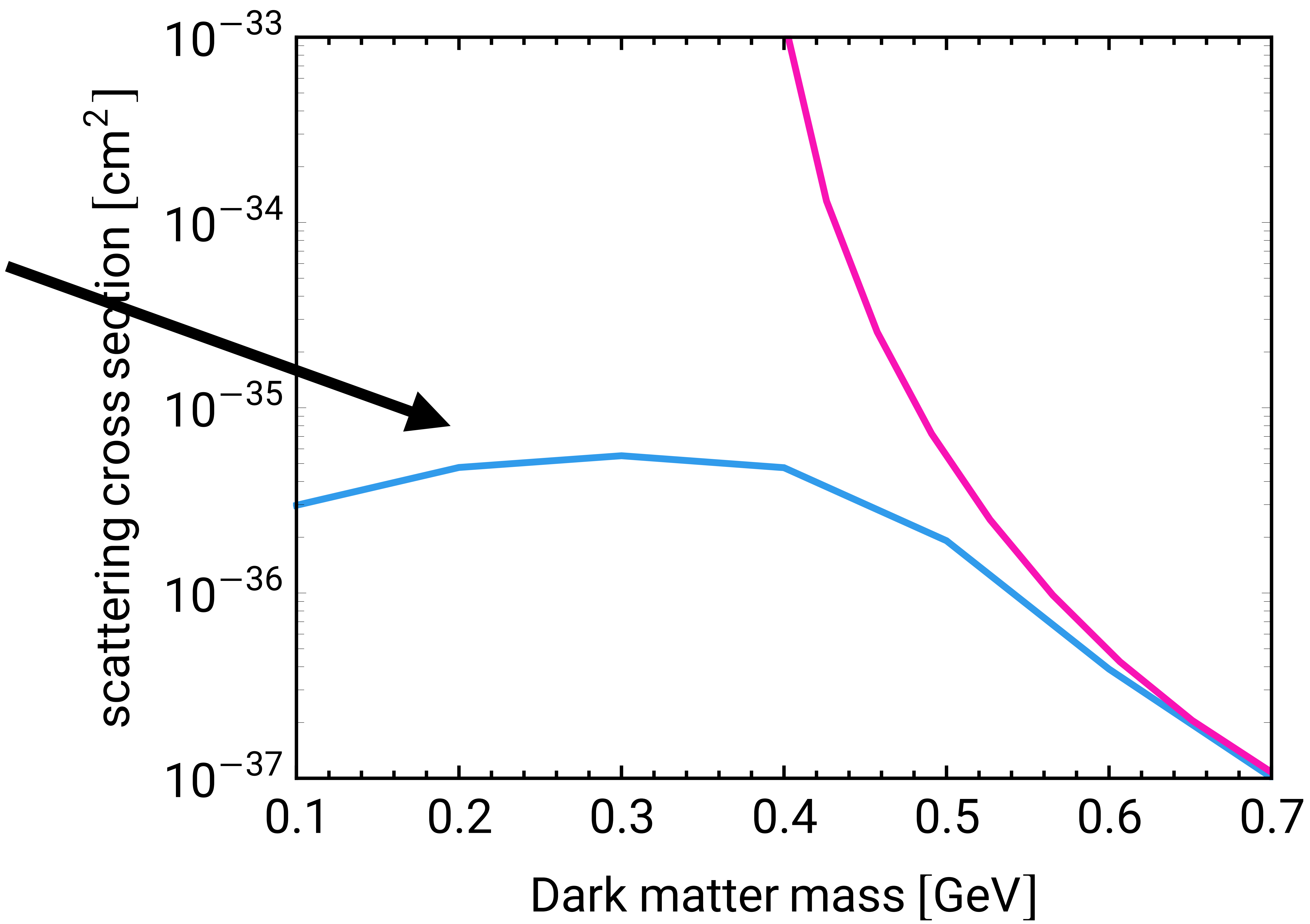
$$p(E) = \Theta(E - E_{\text{thr}}) \cdot \epsilon_x(E) \cdot \int_0^\infty p_{\text{model}}(E') \cdot \mathcal{N}(E - E', \sigma_p^2) dE' \quad (1)$$

Equation (1) is a simplification which is perfectly valid for energies well above of the energy threshold. For energies not exceeding a distance of one to two times the baseline resolution below the threshold ($\sim 0.45\,\text{keV}$ for TUM40 and $\sim 0.2\,\text{keV}$ for Lise) equation (1) is still a very good approximation. The simplification of the correct handling of detector resolutions and survival probabilities allows studies of a variety of models with different energy distributions while introducing only a small inaccuracy for very low recoil energies.

Pitfall…using the data incorrectly

We were allowing arbitrarily small energy depositions to fluctuate upwards

We needed to put a cut off on fluctuations 2-sigma below threshold to remove spurious events



Pitfall…using the data incorrectly

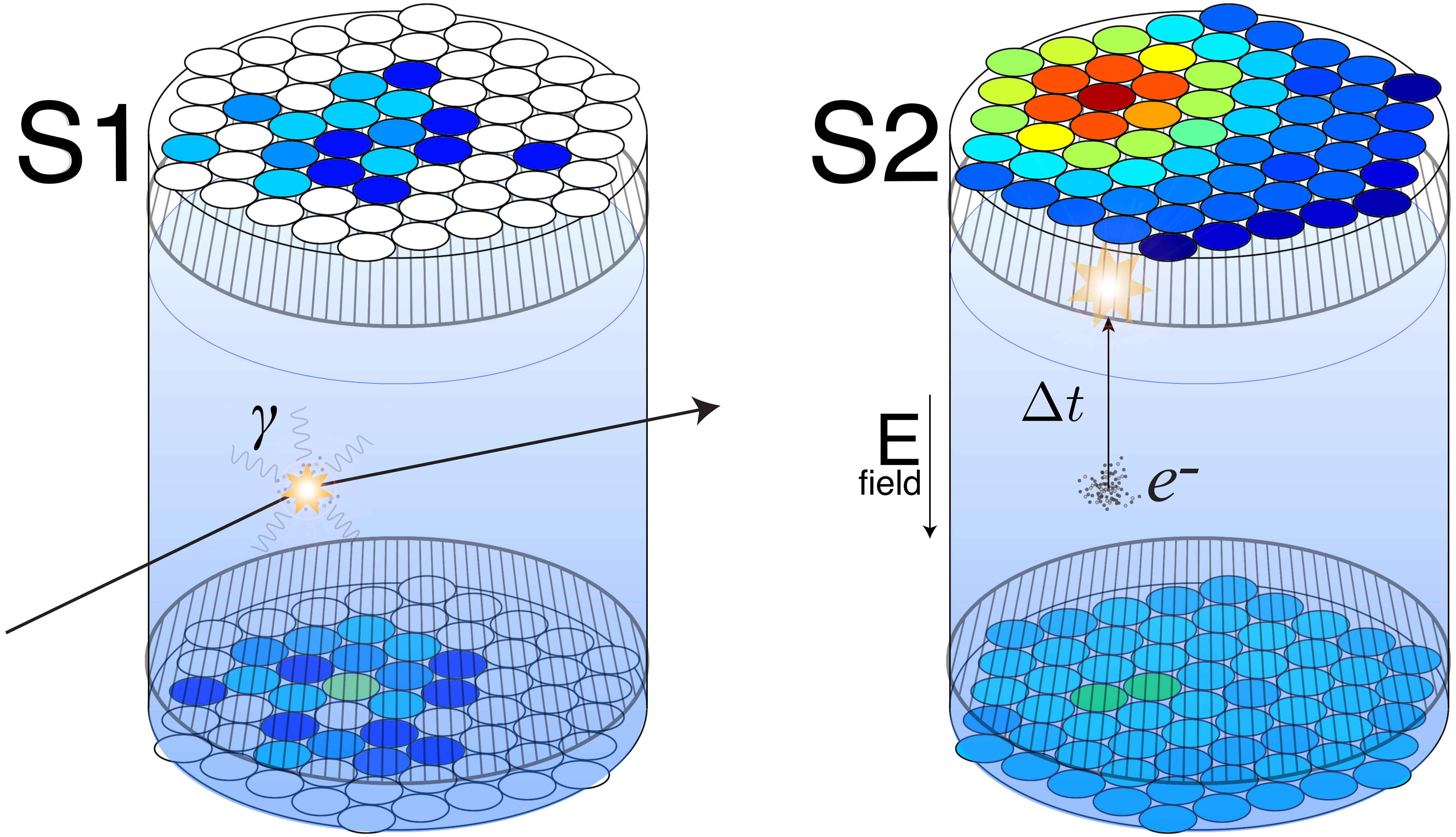
Lesson: read (and understand) the documentation that accompanies the data very carefully

(… I have seen other papers make the same error we did)

Challenge

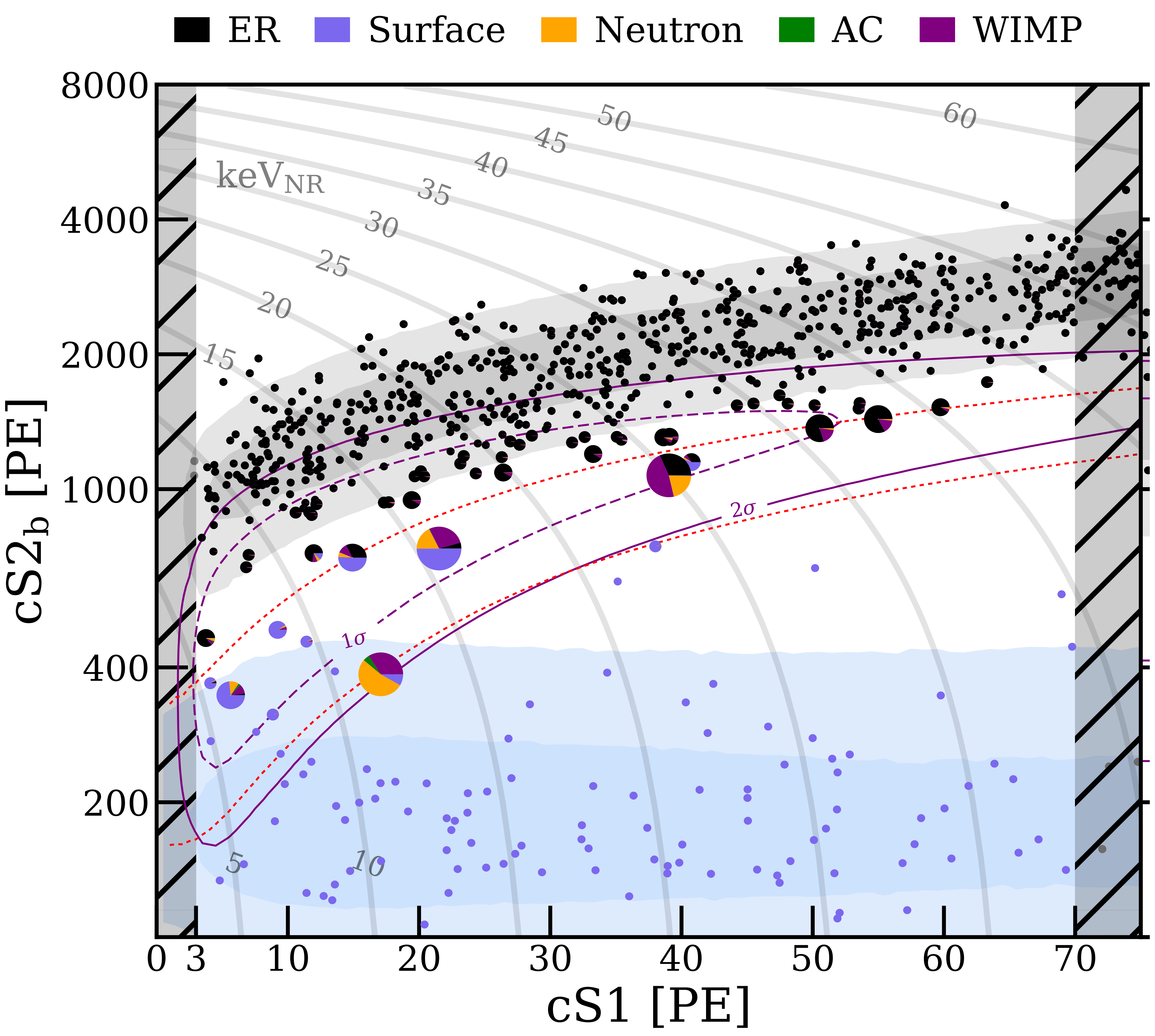
Challenges: simulating signals in two phase xenon

Reminder: two-phase xenon detectors measure light (S1) and charge (S2) signals



Challenges: simulating signals in two phase xenon

Reminder: two-phase xenon detectors measure light (S1) and charge (S2) signals

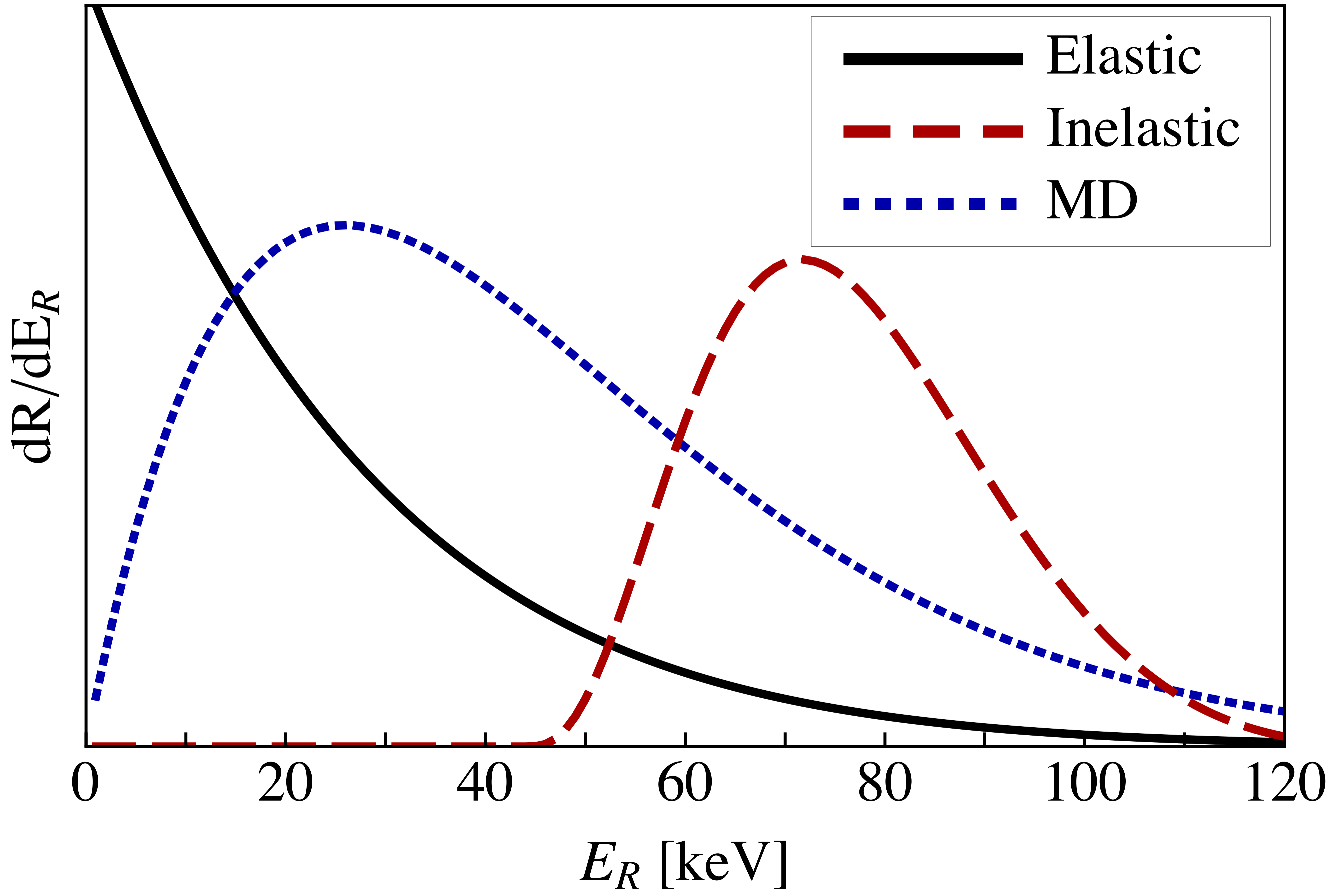


Challenges: simulating signals in two phase xenon

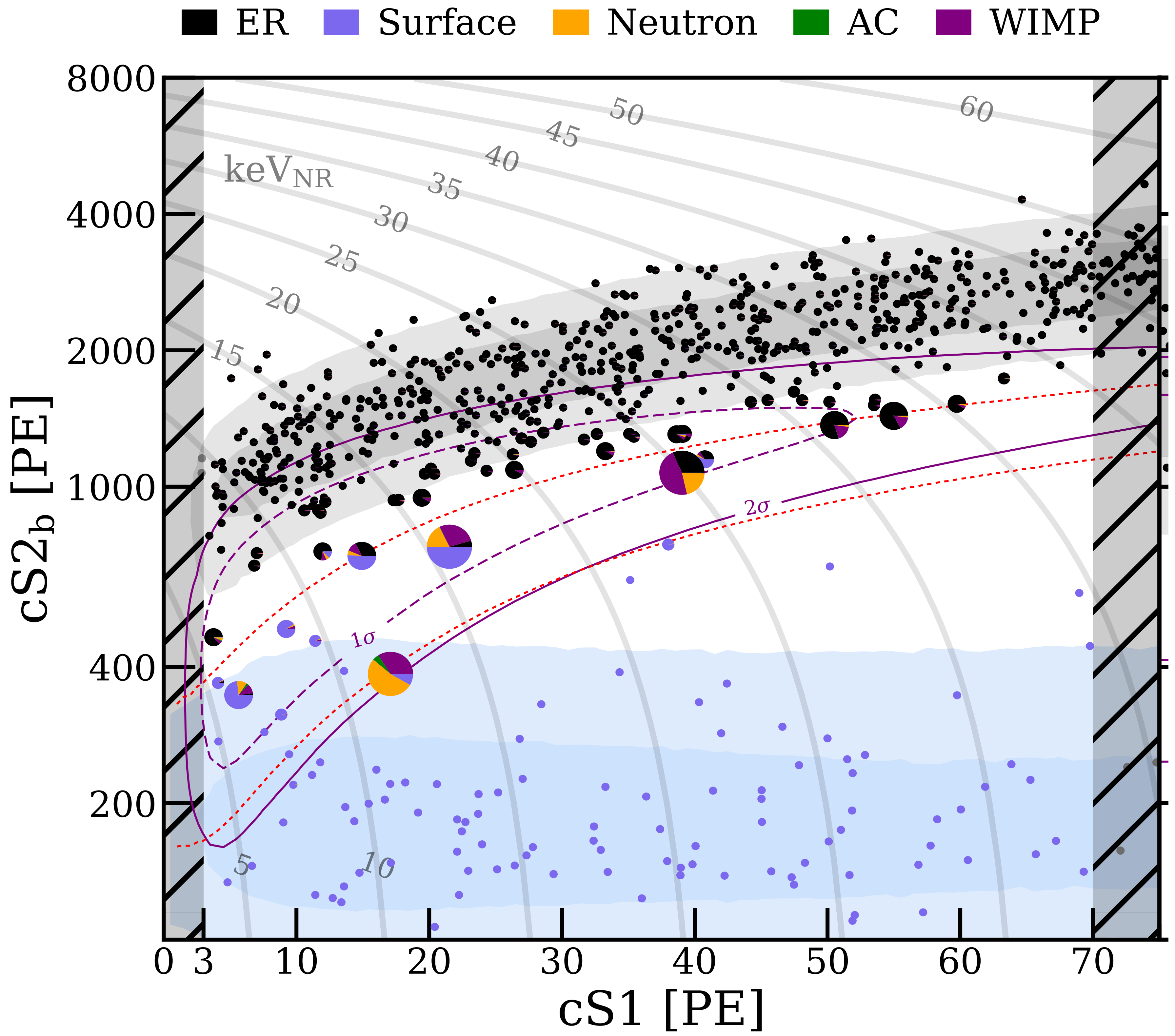
The ‘theory’ input is typically a recoil spectrum

→

Translate to the measured parameters



→

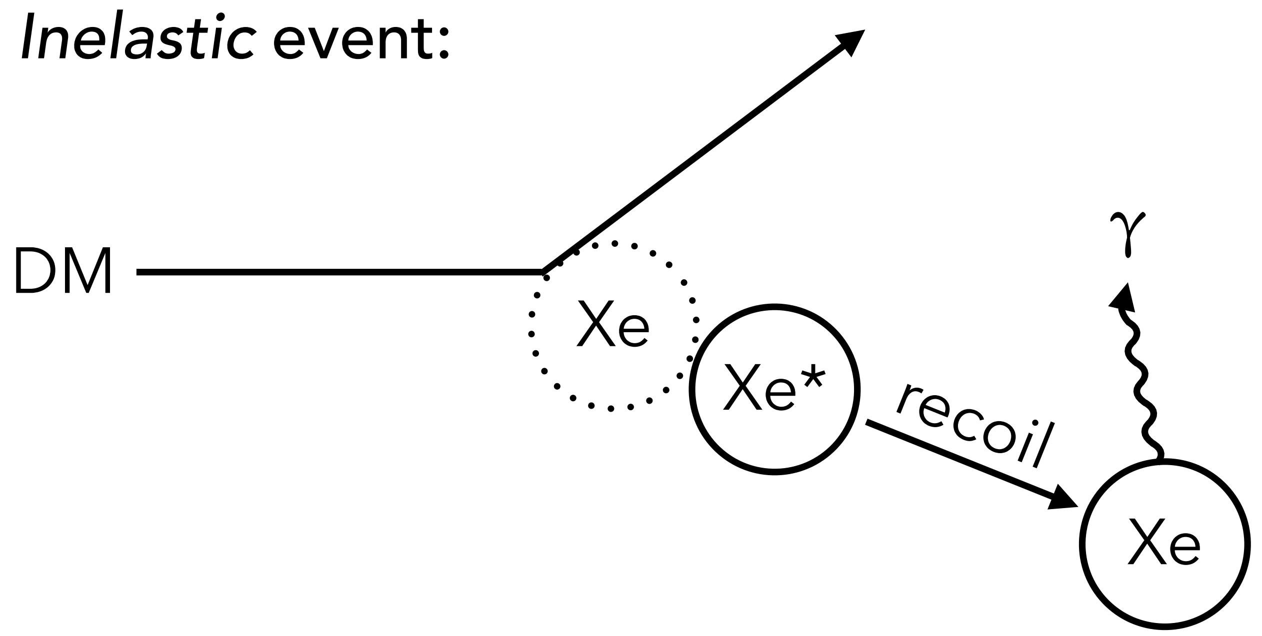


Do we need to do this translation?

Yes, particularly when looking at 'non-standard' signals

Example 1:
inelastic nucleus scattering

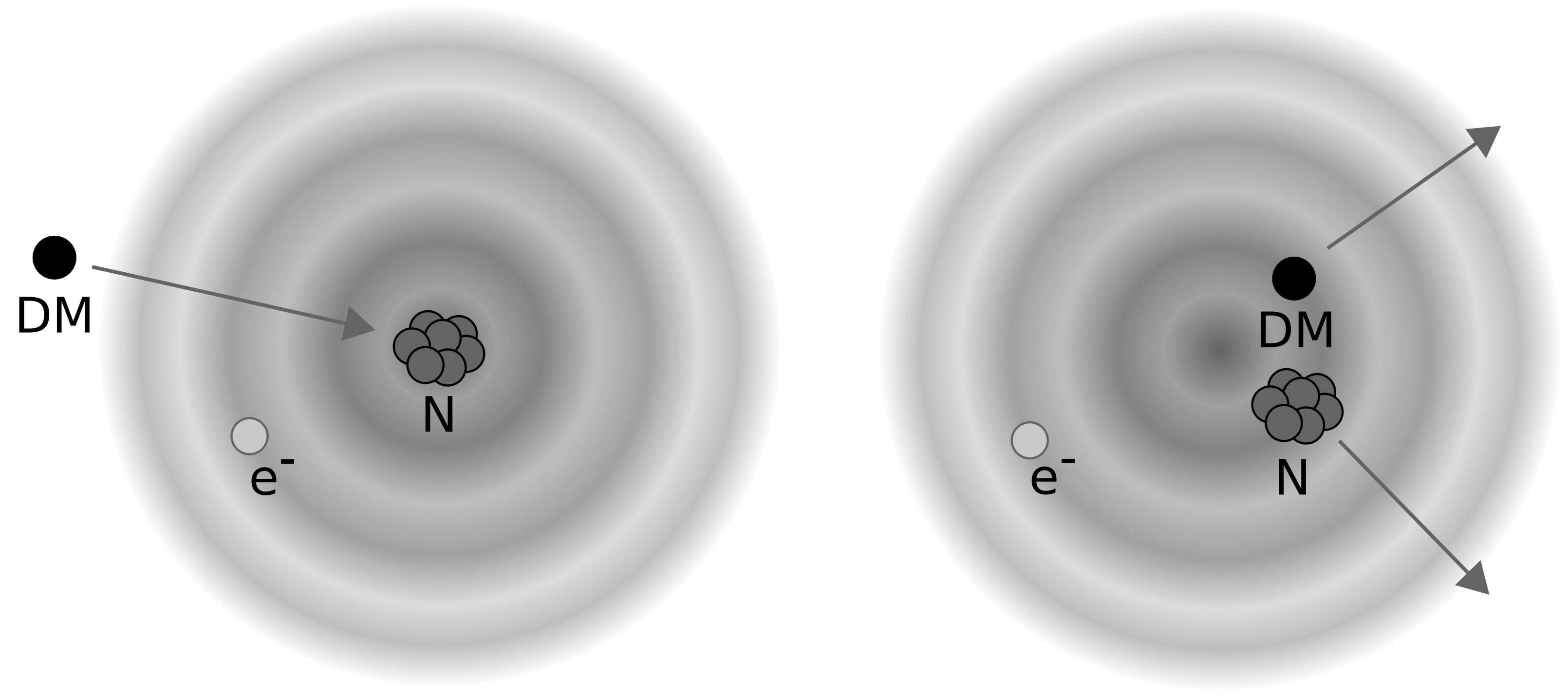
CM, arXiv:1512.00460



Signal is nuclear recoil energy + gamma-ray from nucleus

Example 2:
Migdal effect

Dolan, Kahlhoefer, CM arXiv:1711.09906



Signal is low-energy atomic electron (+ very small nuclear recoil)

In principle, this is a solved problem

A tool was/is available:

NEST **Noble Element Simulation Technique**
a symphony of scintillation

…but in the past, the barrier to utilising it was too high for theorists

It ran on top of a GEANT4 simulation of the detector (!)

What I did in the past

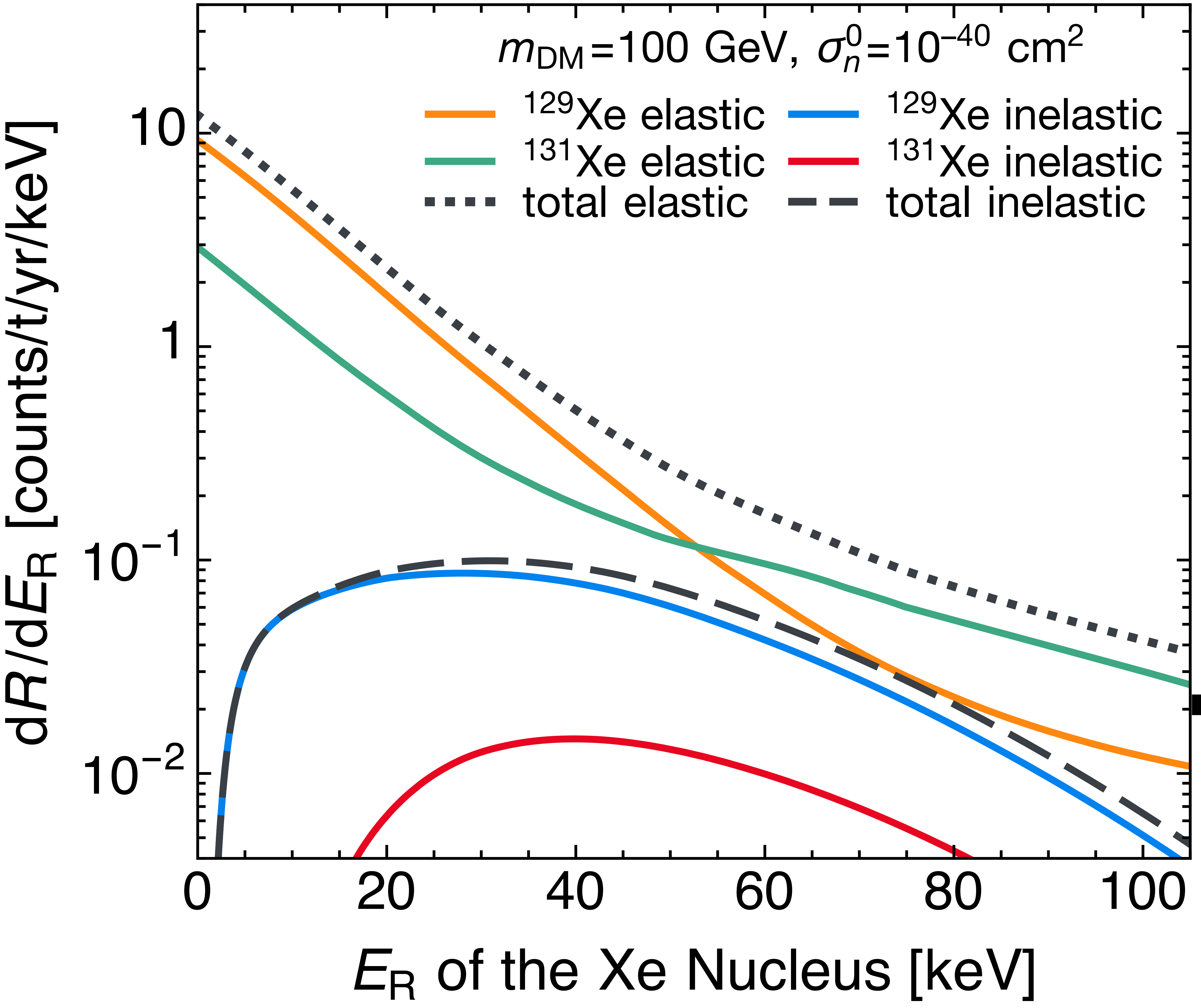
Various parts of NEST where described in papers, PhD thesis, online talks

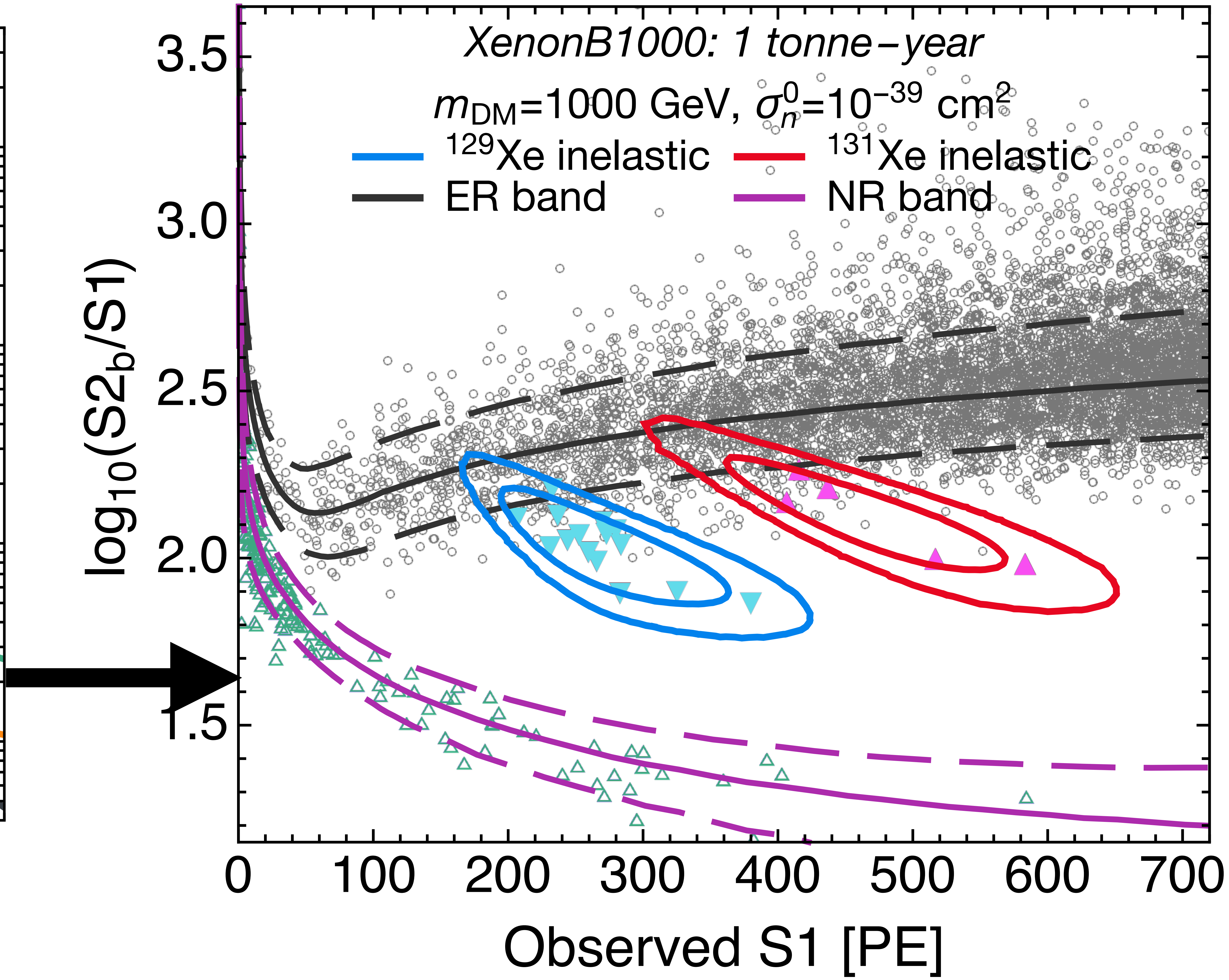
Hunting out this material, and talking to various experimentalists, I was able to write my own simplified version to do some analysis

This took a long time (even though the final code is relatively short)

Challenge 1 : Simulating inelastic signals

CM, arXiv:1512.00460

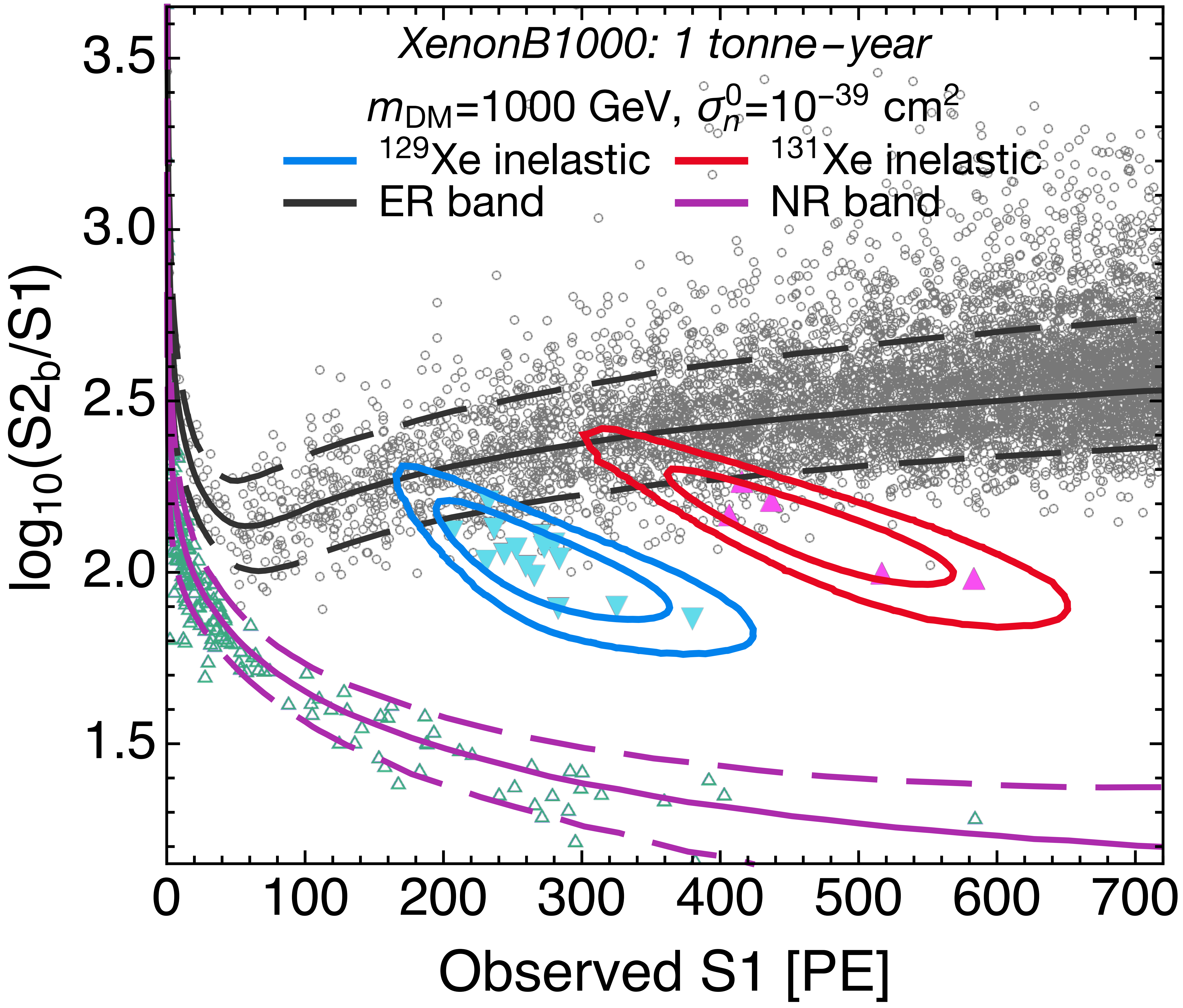




Challenge 1 : Simulating inelastic signals

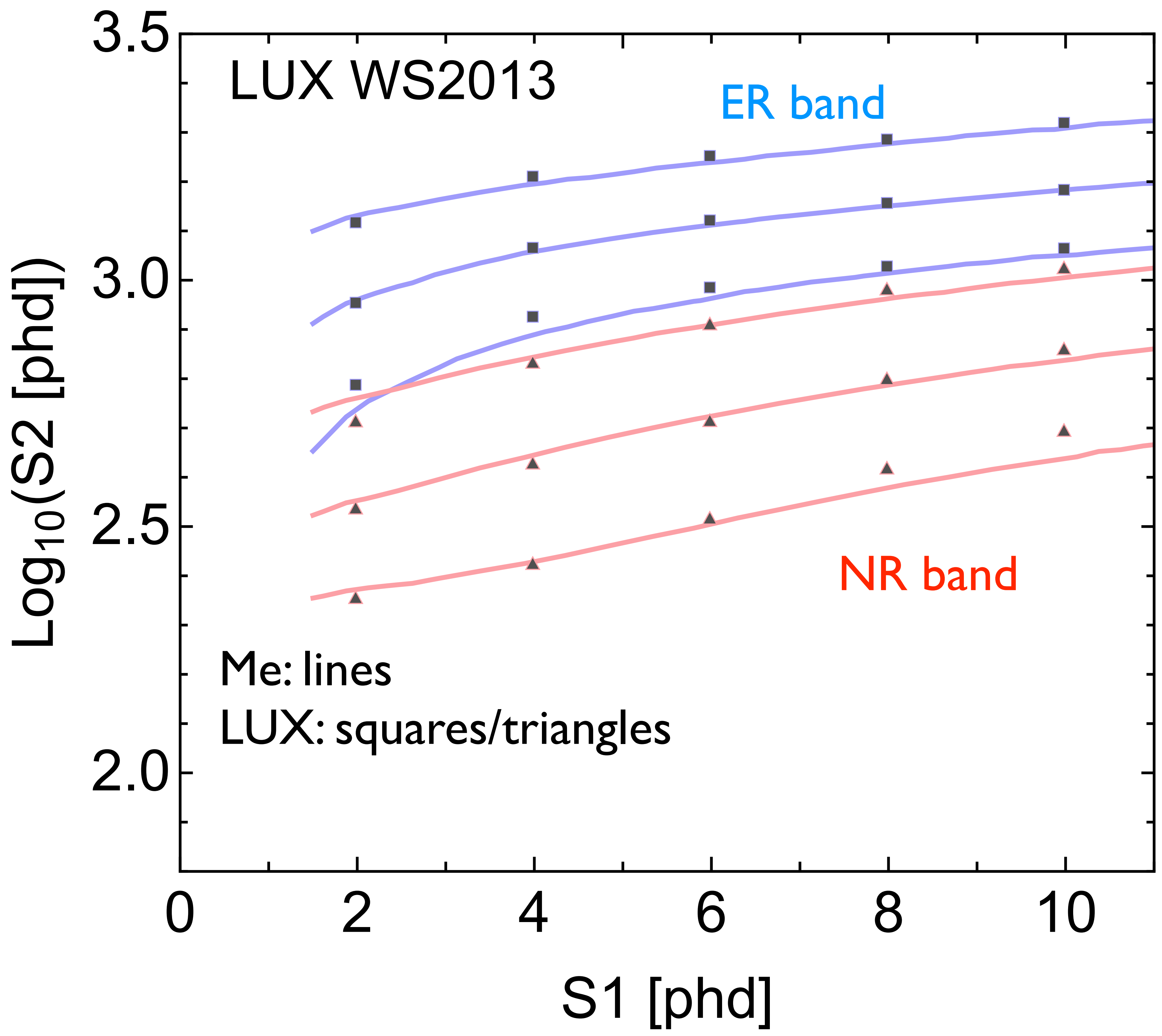
It took me around one year to develop a working simulation for the nuclear inelastic paper

(…perhaps it would have been faster to learn GEANT4)

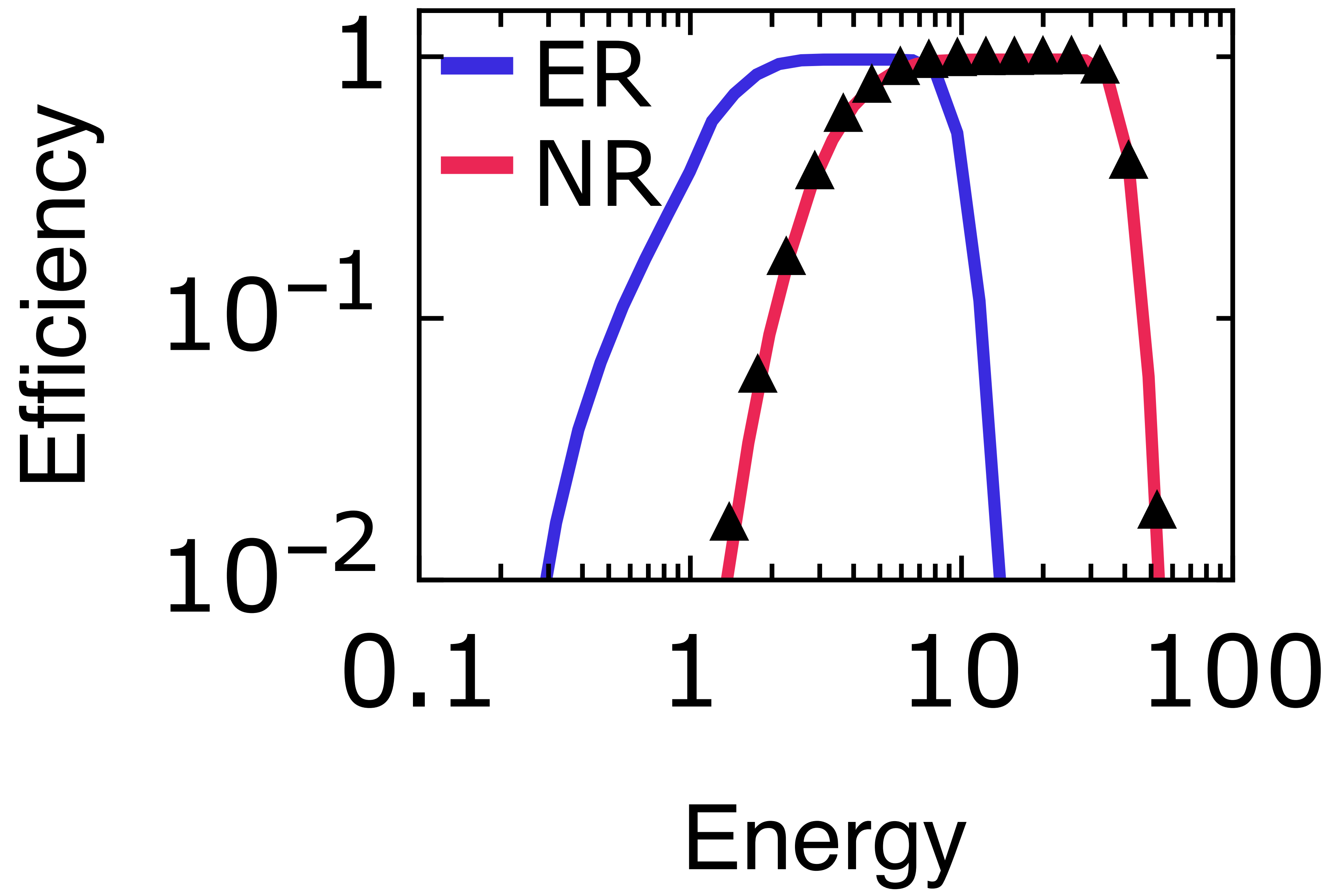


Challenge 2 : Re-Simulating LUX (for Migdal)

1. Reproduce shape of signals:

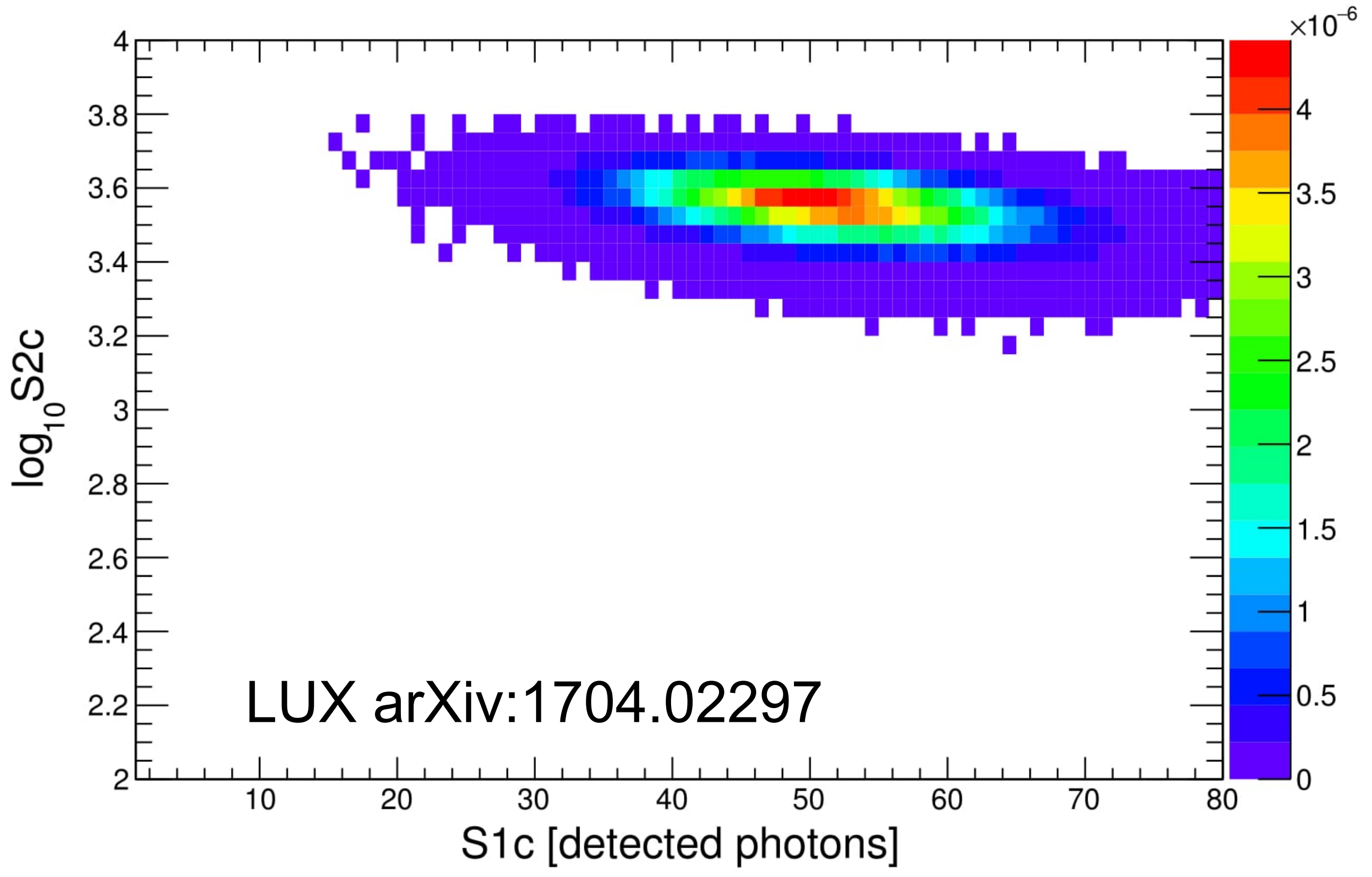


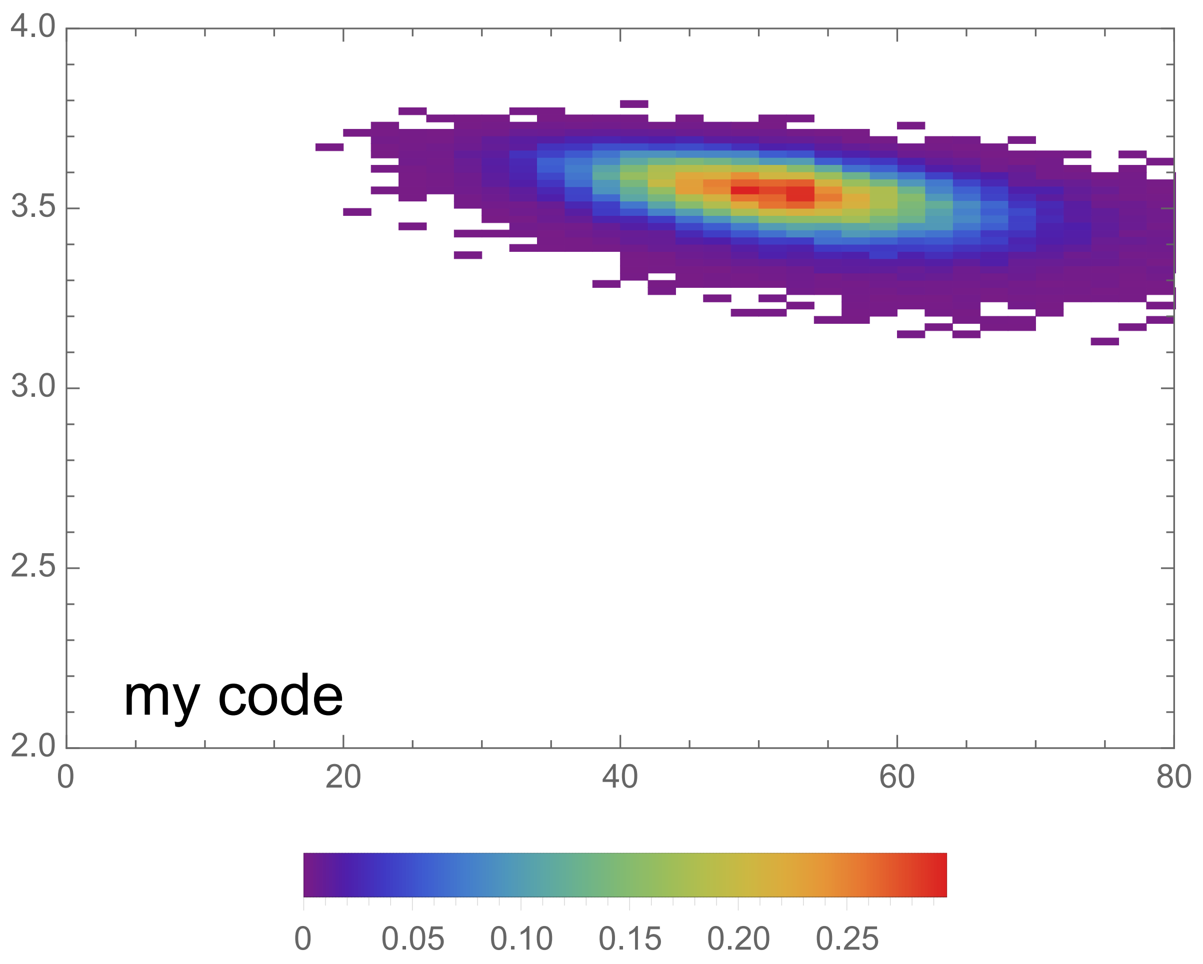
2. Reproduce detection efficiency:

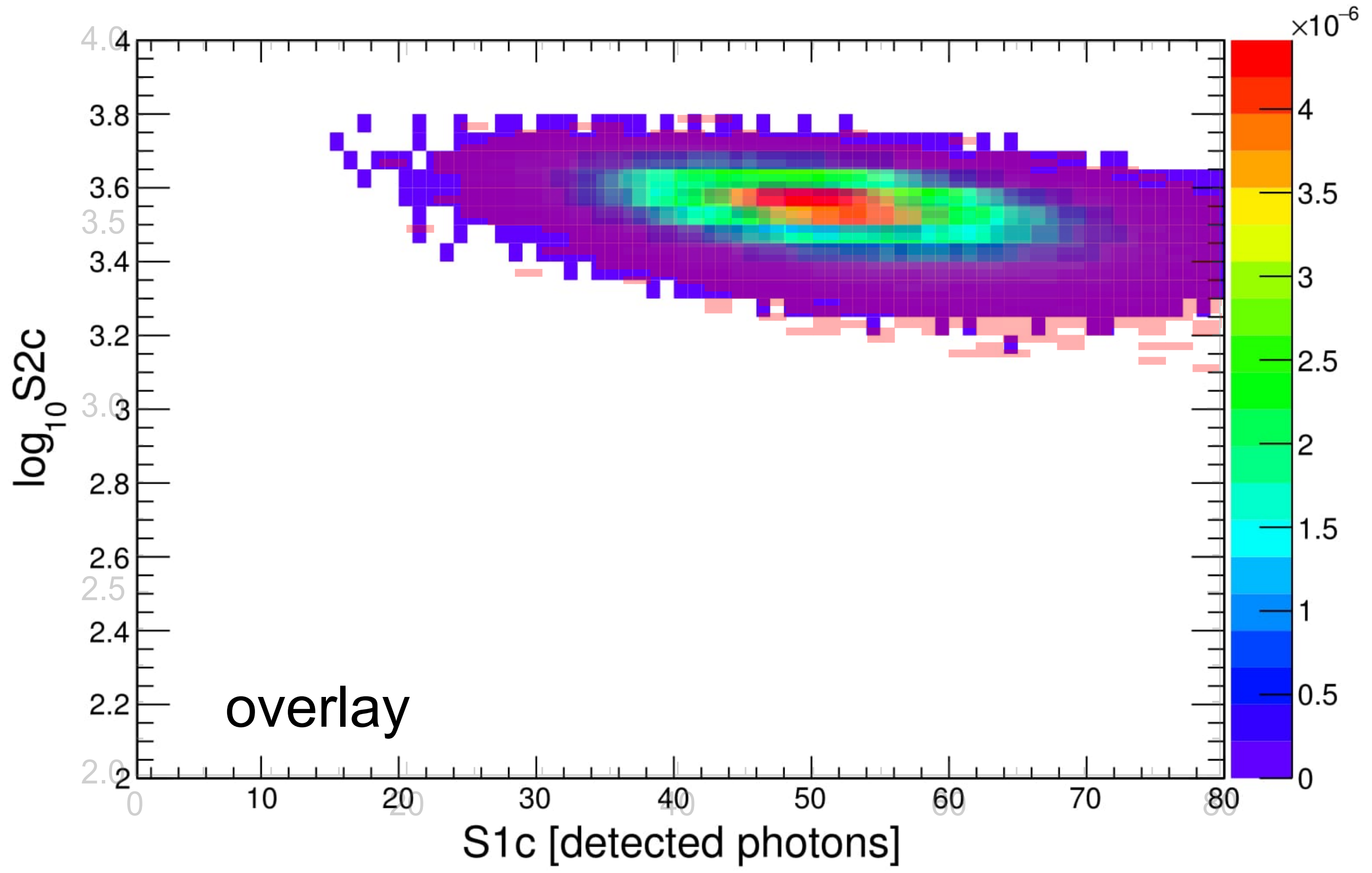


Challenge 2 : Re-Simulating LUX (for Migdal)

3. Check against published results: 10 keV

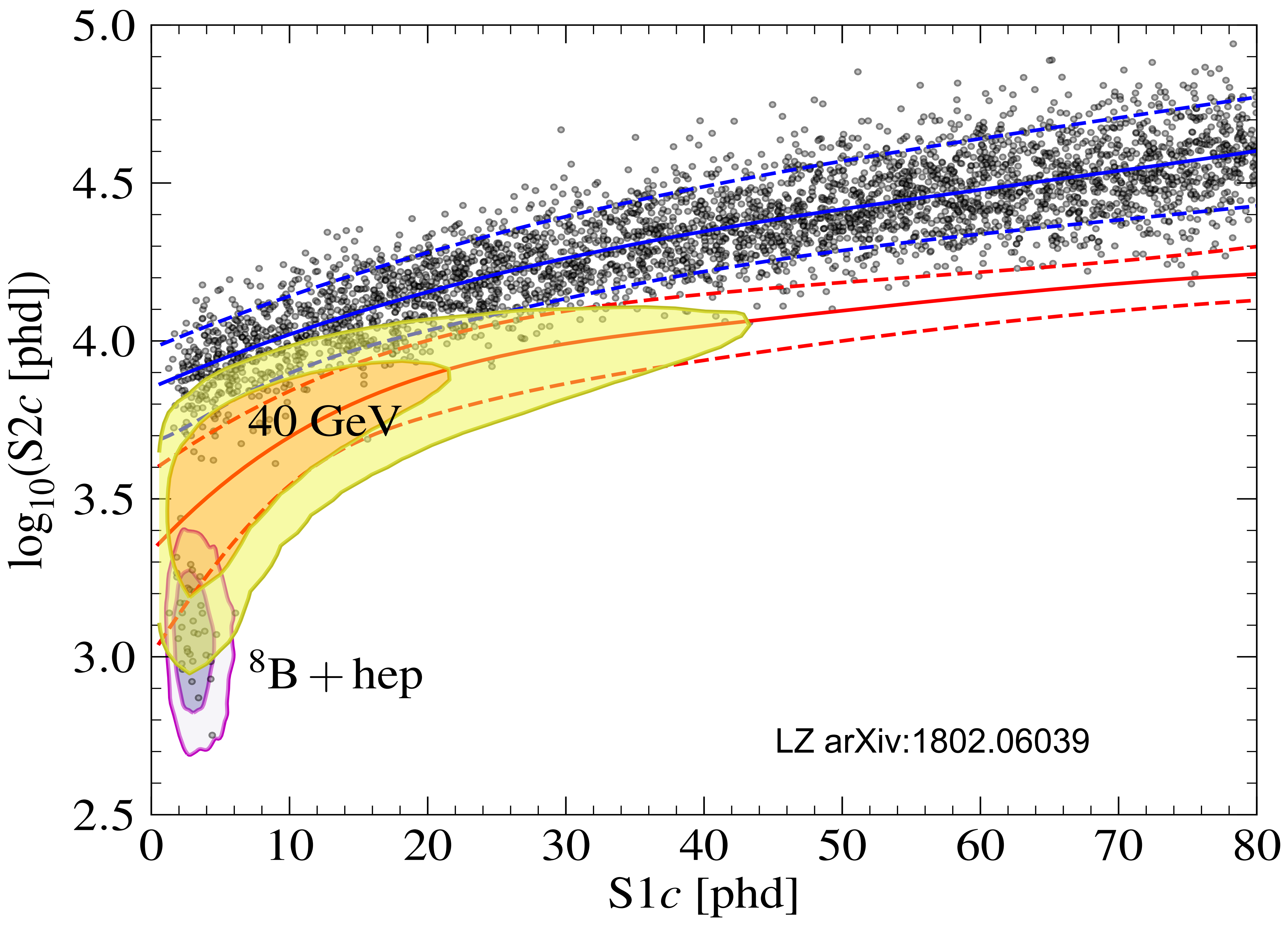


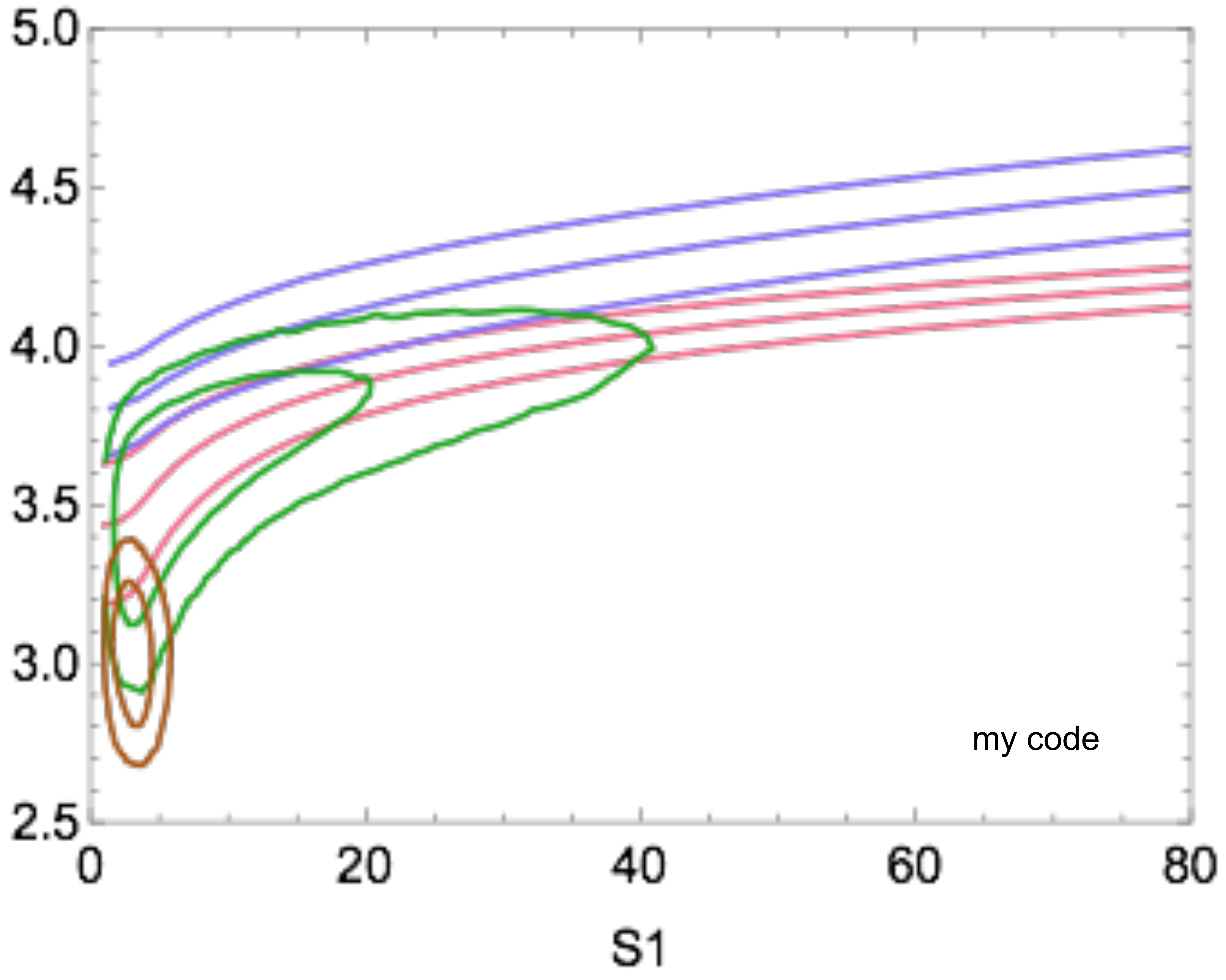




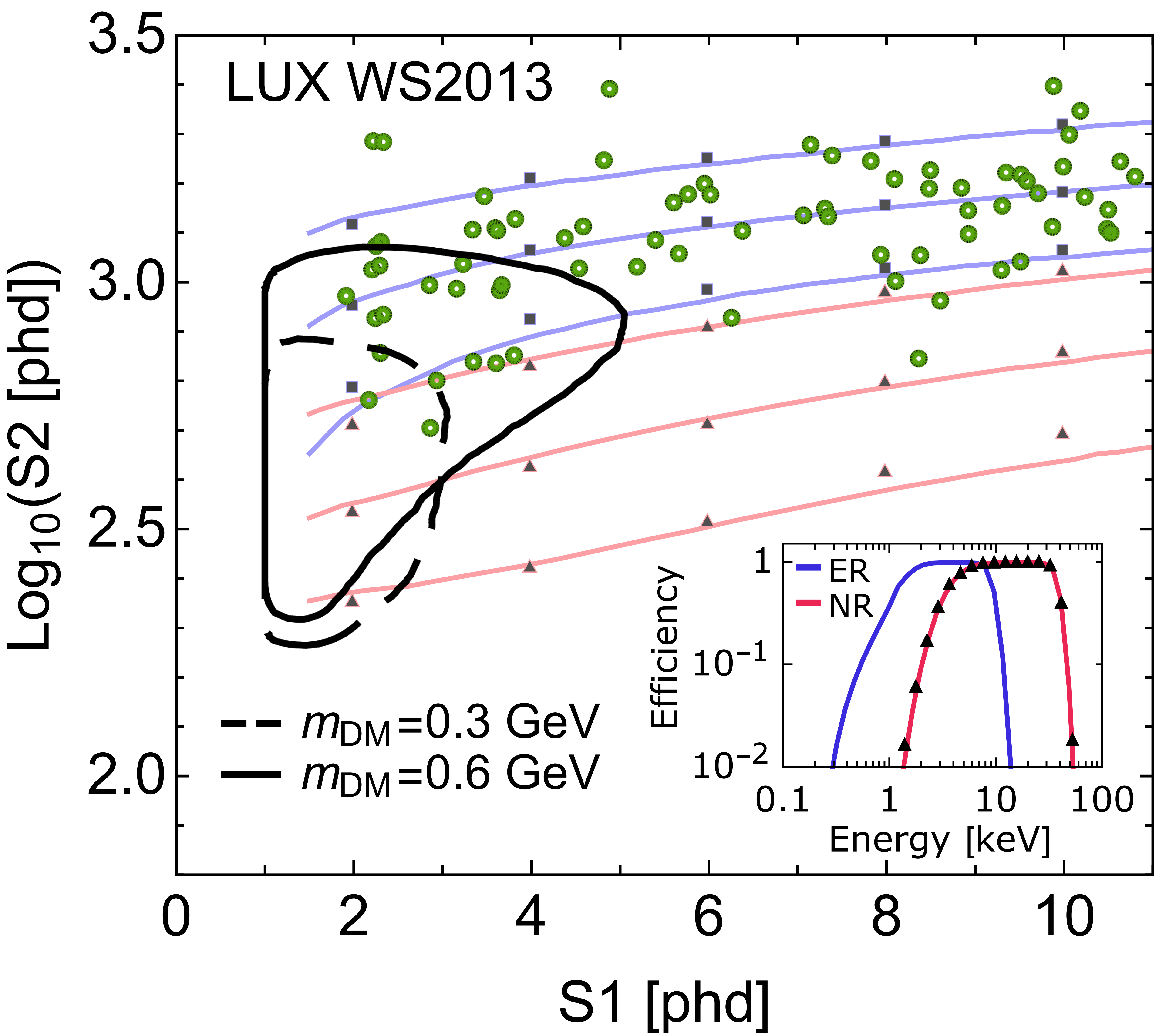
Challenge 2 : Re-Simulating LUX (for Migdal)

Check LZ simulation with LZ projected sensitivity paper





Challenge 2 : Re-Simulating LUX (for Migdal)



It took about 6 more months to tune it accurately to the LUX WS2013 data for Migdal studies

Triangles and Squares from collaboration

My results are the lines

Lines passing though points mean good agreement!

Today: the situation is improved!

NEST v2 promises to be much easier to use
Decoupled from GEANT4
Online calculator tools also available

Noble Element Simulation Technique, Version 2.0 July 18, 2018 (Major Refactor)

Fast C++ simulation of different particle types in liquid, gaseous, and solid xenon

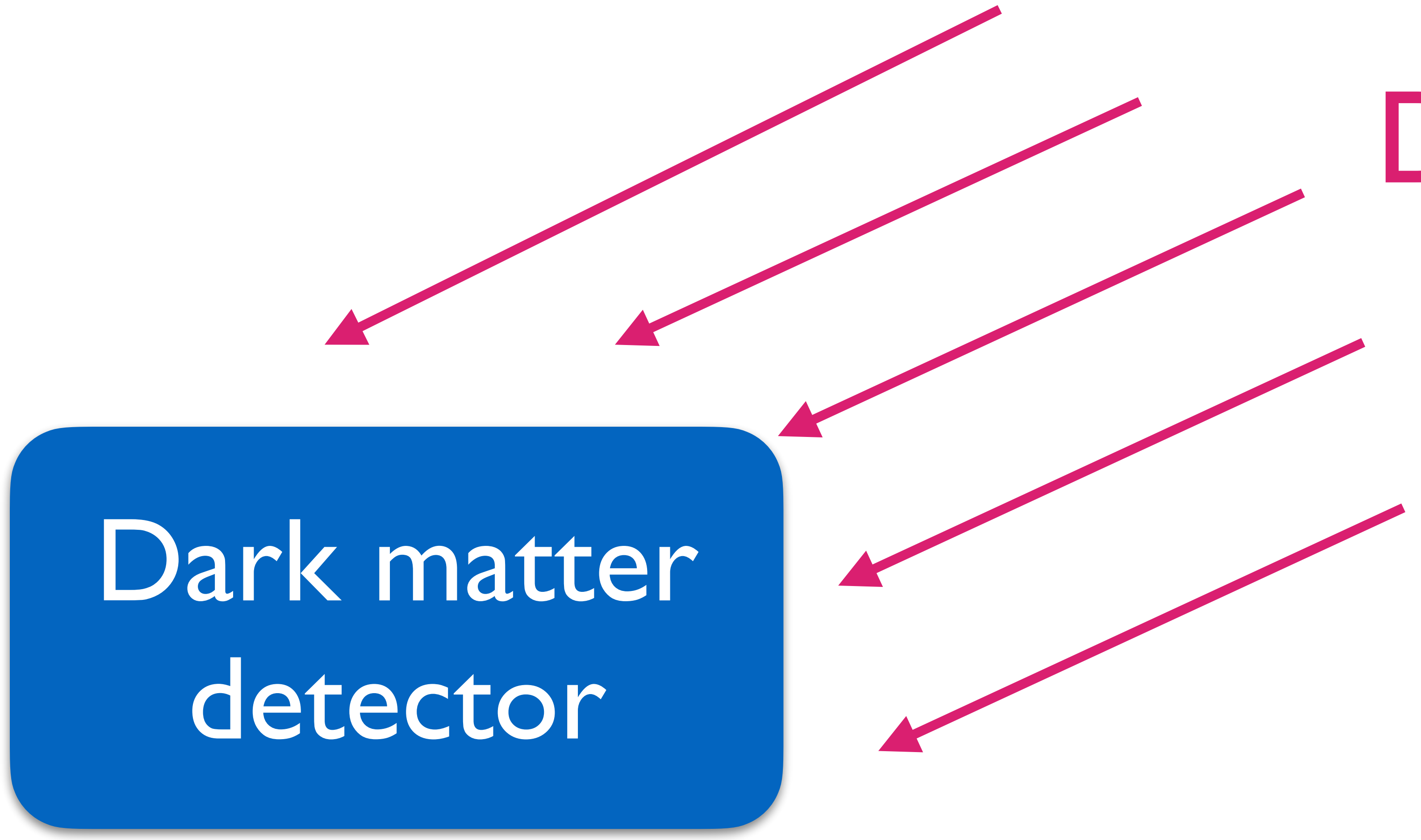
- Mean scintillation light and ionization charge yields
- Variation in total quanta, and recombination fluctuations
- Dependencies on energy, electric field strength, and density
- Pulse shape models for both S1 and S2, including e-trains
- Additional tools, for calculating leakage and limits

For "quick and dirty" results online, please see our web-based yields calculator sans fluctuations. Otherwise, please download the full C++ code above!

(I have to admit that I haven't had a project where I can utilise this yet)

Frustrations

Other issues: astrophysical parameters



Dark matter flux

$$\sim \rho_{\mathrm{DM}} \int d^3v \, f_{\mathrm{DM}}(\mathbf{v}) \, v$$

Event rate = DM flux $\times$ *particle physics*

Have to model the DM flux to extract the particle physics

Is there a Standard approach?

XENON1T	and a standard isothermal DM halo as in [5] are assumed, with $v_0 = 220\,\mathrm{km/s}$, $\rho_{\mathrm{DM}} = 0.3\ \mathrm{GeV}/(\mathrm{c}^2 \times \mathrm{cm}^3)$, $v_{\mathrm{esc}} = 544\,\mathrm{km/s}$, and Earth velocity of $v_{\mathrm{E}} = 232\,\mathrm{km/s}$.
LZ	The signal spectrum for WIMP recoils is calculated using the standard halo model following the formalism of [74], with $v_0 = 220$ km/s; $v_{esc} = 544$ km/s; $v_e = 230$ km/s and $\rho_0 = 0.3\ \mathrm{GeV}/c^2$.
LUX	derived from a standard Maxwellian velocity distribution with $v_0 = 220\,\mathrm{km/s}$, $v_{esc} = 544\,\mathrm{km/s}$, $\rho_0 = 0.3\,\mathrm{GeV/cm^3}$, average Earth velocity of 245 km/s,
DEAP-3600	assuming the standard halo dark matter model described in [49], with a Maxwell-Boltzmann velocity distribution below an escape velocity of 544 km/s and $v_0 = 220\,\mathrm{km/s}$, and a local density of $0.3\,\mathrm{GeV/cm^3}$.
SuperCDMS	The calculation uses the DM-particle and halo models summarized in [3, 17]. **?**

Is there a Standard approach? *Yes*

‘Standard Halo Model’

v0 = 220 km/s

vesc = 544 km/s

rho0 = 0.3 GeV/cm^3

vE = 230 - 245 km/s

Is there a Standard approach? *Yes-ish*

‘Standard Halo Model’
v0 = 220 km/s
vesc = 544 km/s
rho0 = 0.3 GeV/cm^3
vE = 230 - 245 km/s

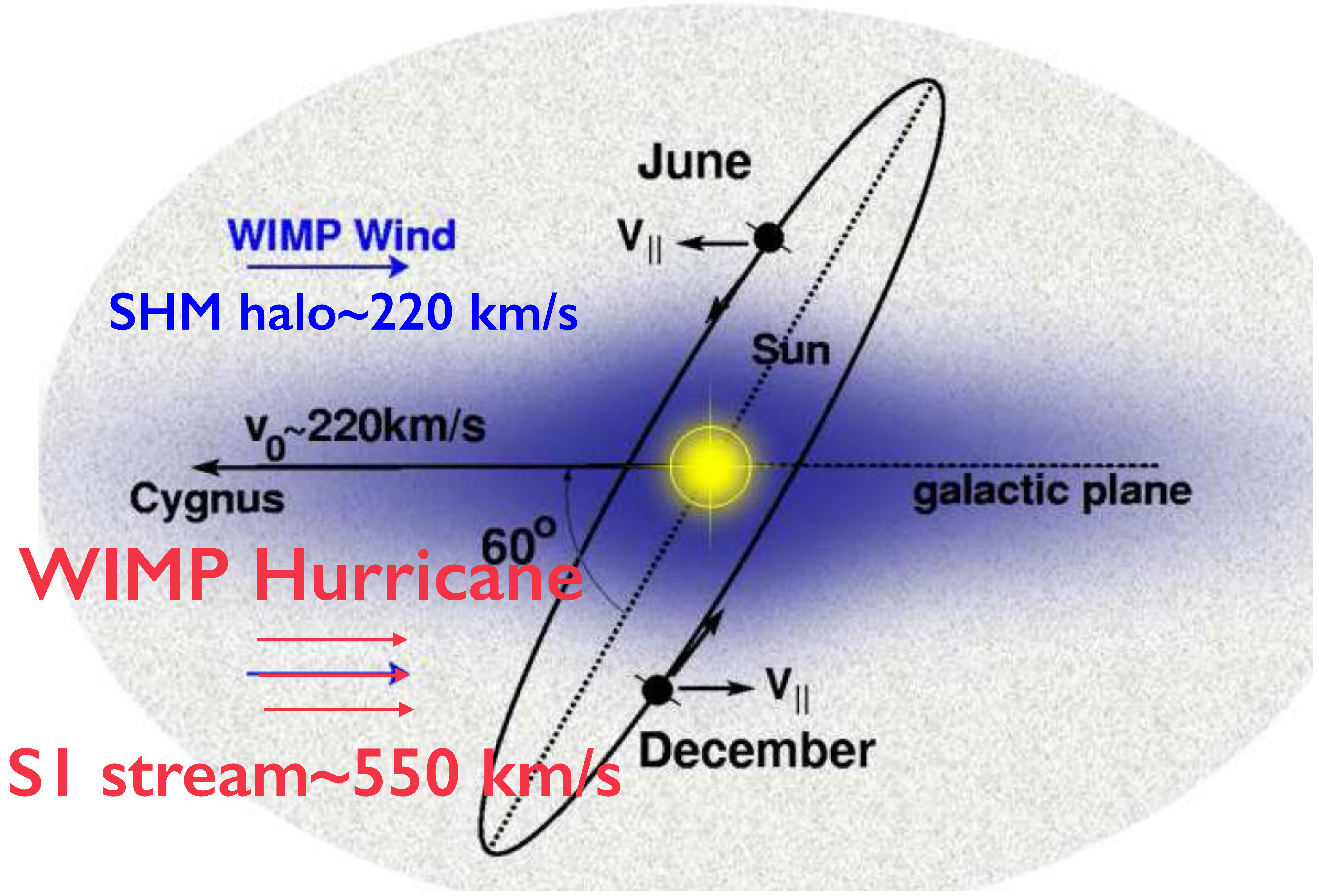
Not necessarily true across all dark matter searches…

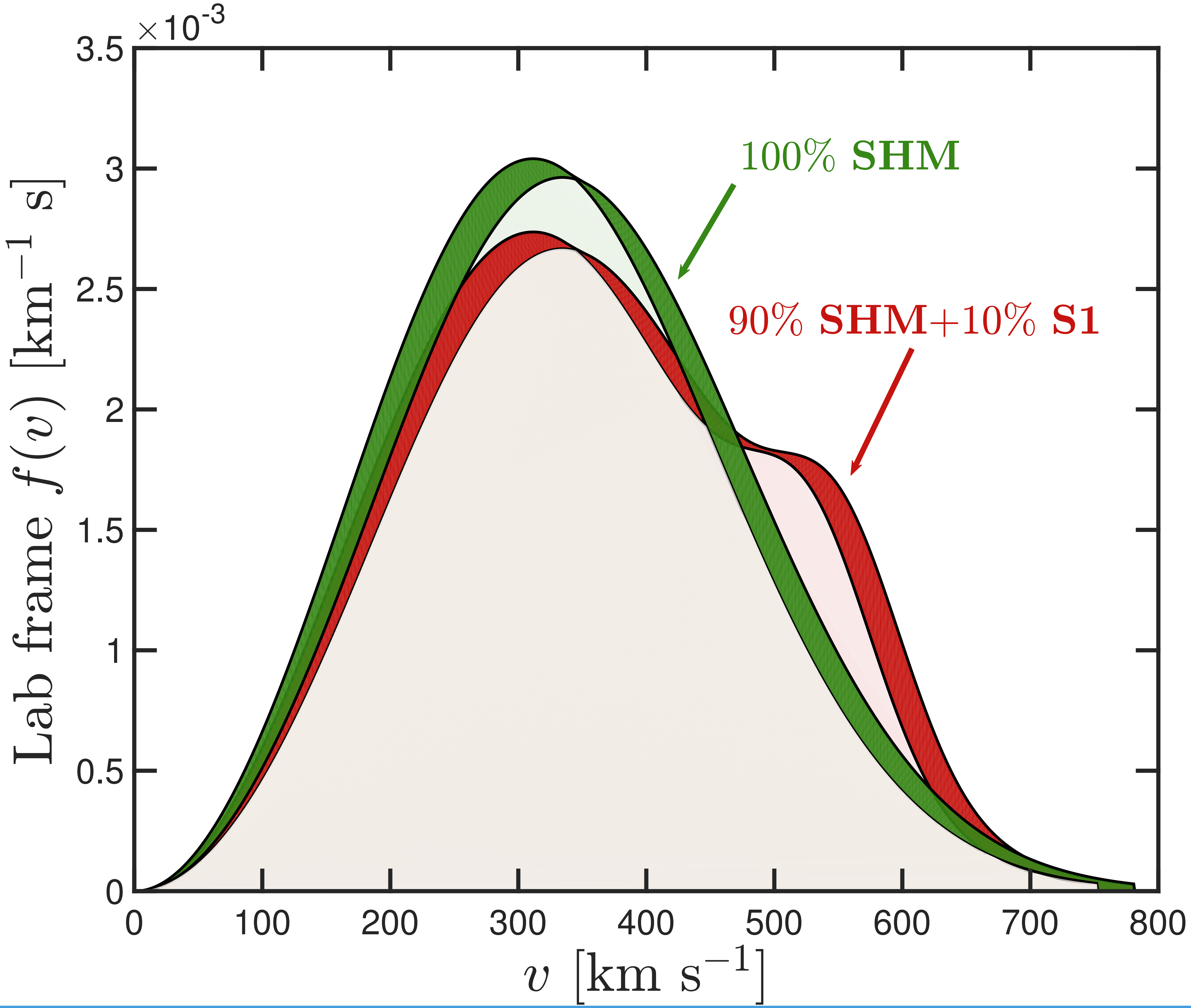
ADMX, HAYSTAC, ORGAN   **rho0 = 0.45 GeV/cm^3**

arXiv:1804.05750, 1801.00835, 1706.00209

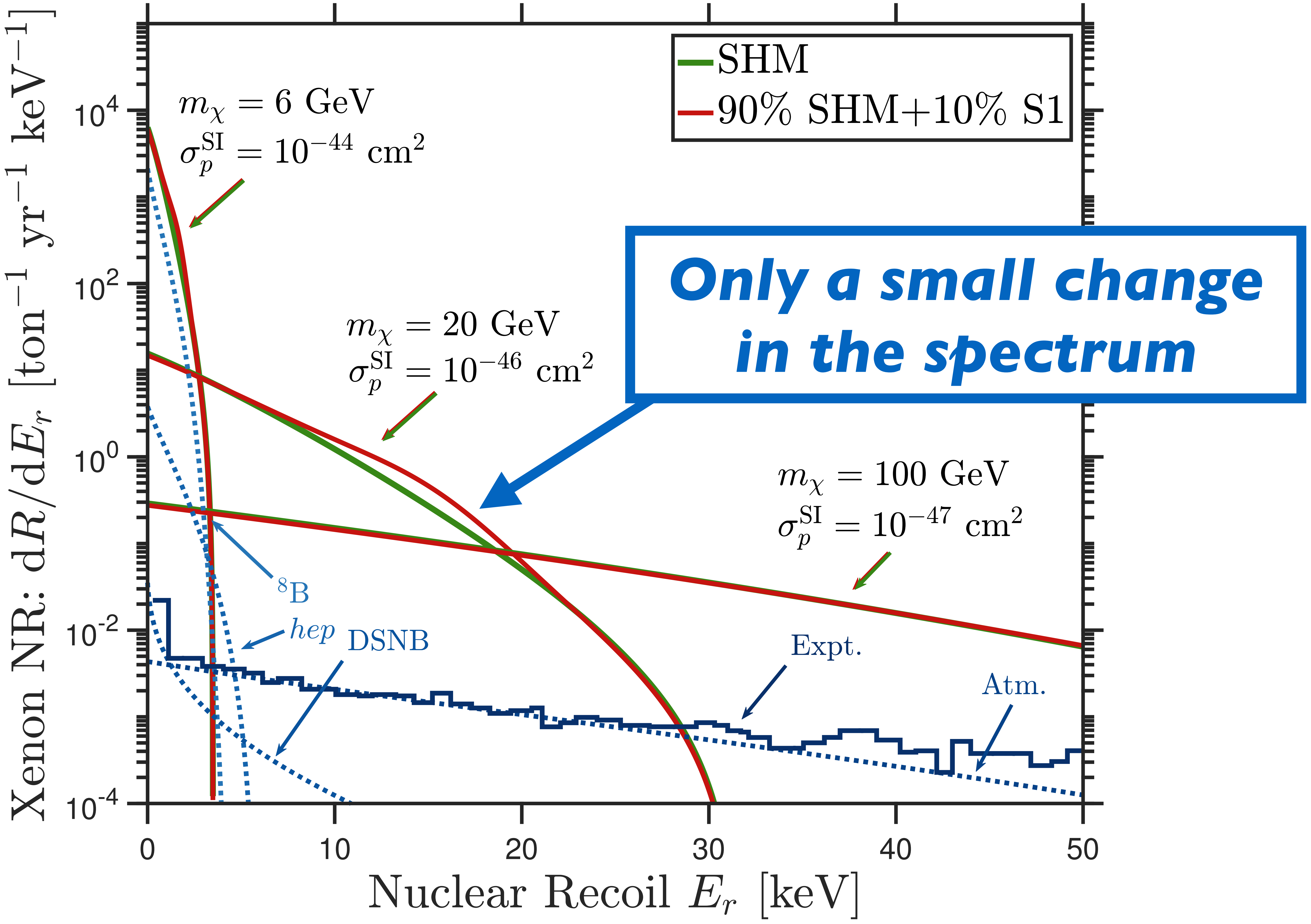
Extreme changes - S1: 'Dark matter hurricane'

O'Hare, CM et al.1807.09004
A dark matter hurricane…





Small effect for high mass searches



Spectrum is relatively featureless…

…except in a sweet spot around 20 GeV

The situation is improving

Collaborations are working together to agree on common statistical and astrophysical parameters in their analyses

White paper is being drafted

Conclusions

In my experience…

Pitfalls (based on CRESST): If you use the data blindly, you can derive strange conclusions

Challenges (bases on xenon): It is still challenging if you want to think about 'non-standard' signals eg with electronic and nuclear contributions

Frustrations: there is always the problem of figuring out what astrophysical parameters groups have used in their analysis

However, overall I am optimistic that things are improving!