DAMA confronts null searches in the effective theory of dark matter-nucleon interactions

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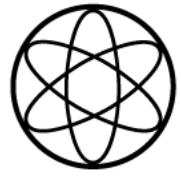
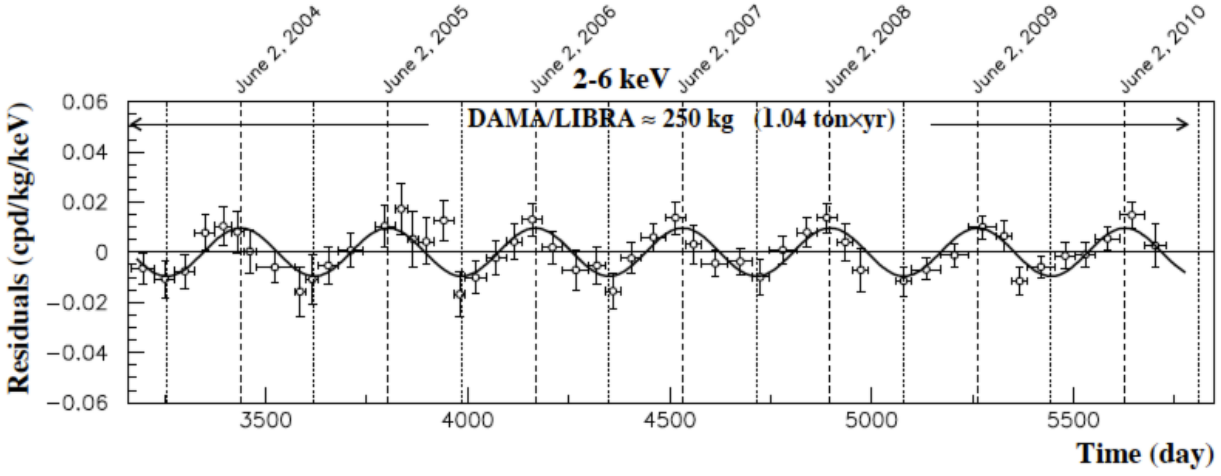


DSU 2016, Bergen

Based on 1602.04074 by **Riccardo Catena, Alejandro Ibarra, SW**

+ a little bit of 1607.04418 by **Felix Kahlhoefer, SW**

DAMA vs. the rest of the world



Bernabei et. al.
[1308.5109]

- DAMA: 9.3σ observation of **annually modulating event rate**
- Puzzling situation:
  1) (SI or SD dark matter scattering) $\times$ Maxwell-Boltzmann: ruled out e.g. by LUX and PICO
  2) But also no generally accepted explanation in terms of backgrounds

Is there **any** dark matter model leading to compatibility?

This work: consider "all" possible models for DM-nucleon scattering

(for fixed astrophysics, i.e. assuming Maxwell-Boltzmann)

Non-relativistic effective theory of DM-nucl. interactions

Fan et. al. [1008.1591], Fitzpatrick et. al. [1203.3542]
see also the talks by Paolo Gondolo and Nicolao Fornengo

$$\hat{\mathcal{O}}_1 = 1_{\chi N} \qquad \hat{\mathcal{O}}_9 = i\hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \frac{\hat{\mathbf{q}}}{m_N}\right)$$
$$\hat{\mathcal{O}}_3 = i\hat{\mathbf{S}}_N \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right) \qquad \hat{\mathcal{O}}_{10} = i\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}$$
$$\hat{\mathcal{O}}_4 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{S}}_N \qquad \hat{\mathcal{O}}_{11} = i\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}$$
$$\hat{\mathcal{O}}_5 = i\hat{\mathbf{S}}_\chi \cdot \left(\frac{\hat{\mathbf{q}}}{m_N} \times \hat{\mathbf{v}}^\perp\right) \qquad \hat{\mathcal{O}}_{12} = \hat{\mathbf{S}}_\chi \cdot \left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right)$$
$$\hat{\mathcal{O}}_6 = \left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right) \qquad \hat{\mathcal{O}}_{13} = i\left(\hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp\right)\left(\hat{\mathbf{S}}_N \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)$$
$$\hat{\mathcal{O}}_7 = \hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp \qquad \hat{\mathcal{O}}_{14} = i\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left(\hat{\mathbf{S}}_N \cdot \hat{\mathbf{v}}^\perp\right)$$
$$\hat{\mathcal{O}}_8 = \hat{\mathbf{S}}_\chi \cdot \hat{\mathbf{v}}^\perp \qquad \hat{\mathcal{O}}_{15} = -\left(\hat{\mathbf{S}}_\chi \cdot \frac{\hat{\mathbf{q}}}{m_N}\right)\left[\left(\hat{\mathbf{S}}_N \times \hat{\mathbf{v}}^\perp\right) \cdot \frac{\hat{\mathbf{q}}}{m_N}\right]$$

$$\hat{\mathcal{H}}_{\rm N}(\mathbf{r}) = \sum_{\tau=0,1} \sum_k c_k^\tau \hat{\mathcal{O}}_k(\mathbf{r})\, t^\tau$$

- Most general theory of DM with spin 0 or 1/2 interacting via heavy mediators
- 28 + 1 free parameters: $\mathbf{c} \equiv \left(c_1^{(0)}, c_1^{(1)}, c_3^{(0)}, c_3^{(1)}, ..., c_{15}^{(0)}, c_{15}^{(1)}\right)^T$, $m_{\rm DM}$
  ↪ e.g.: SI → $c_1^{(0)}, c_1^{(1)}$, SD → $c_4^{(0)}, c_4^{(1)}$, pseudoscalar exchange → $c_6^{(0)}, c_6^{(1)}$, ...

Is there **any** 28-dim. $\mathbf{c}$ leading to compatibility of DAMA with all null searches?

Event rates as quadratic forms

$$\hat{\mathcal{H}}_{\rm N}(\mathbf{r}) = \sum_{\tau=0,1} \sum_{k} c_k^\tau \, \hat{O}_k(\mathbf{r}) \, t^\tau$$

Is there **any** 28-dim. $\mathbf{c}$ leading to compatibility of DAMA with all null searches?

↪ extremely hard to answer by just scanning the parameter space
↪ considering one operator at a time is **not enough**! → **Interferences**

We have developed a **semi-analytical approach** for comparing experimental results in this high-dimensional parameter space:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_R} = \sum_{k,k'} \sum_{\tau,\tau'} c_k^\tau c_{k'}^{\tau'} \, \widetilde{W}_{kk'}^{\tau\tau'}(q^2, v^2)$$

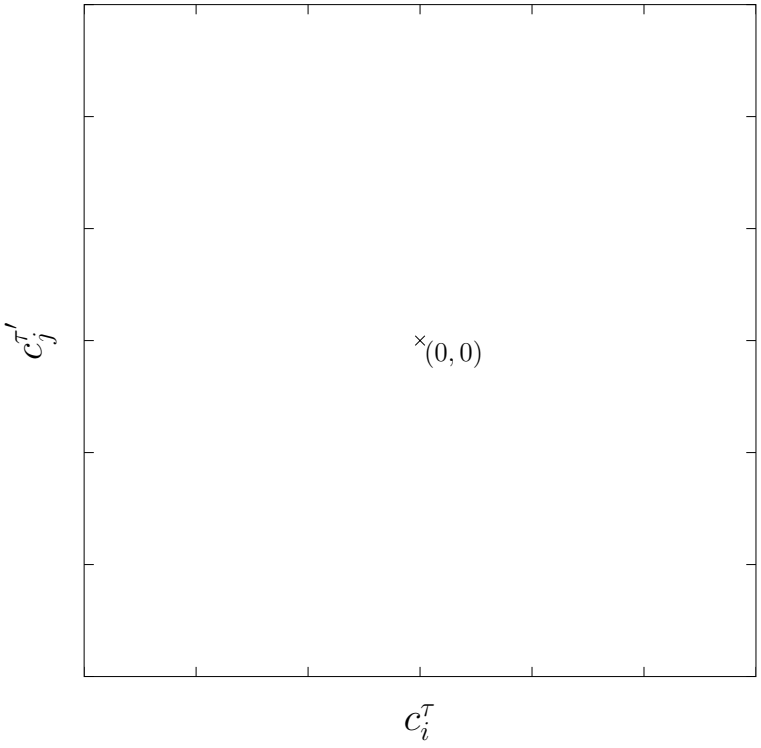
↖ contains nuclear response functions

$$\Rightarrow \text{ event rate } \equiv \mathbf{c}^T \mathbb{X} \, \mathbf{c}$$

For each $m_{\rm DM}$ and each experiment, there is one real symmetric 28×28 matrix $\mathbb{X}$
↪ $\mathbb{X}$ is independent of $\mathbf{c}$, and is straightforward to calculate

Intersecting ellipsoids in two dimensions

Illustration with only **two** operators (instead of 28), not based on real data



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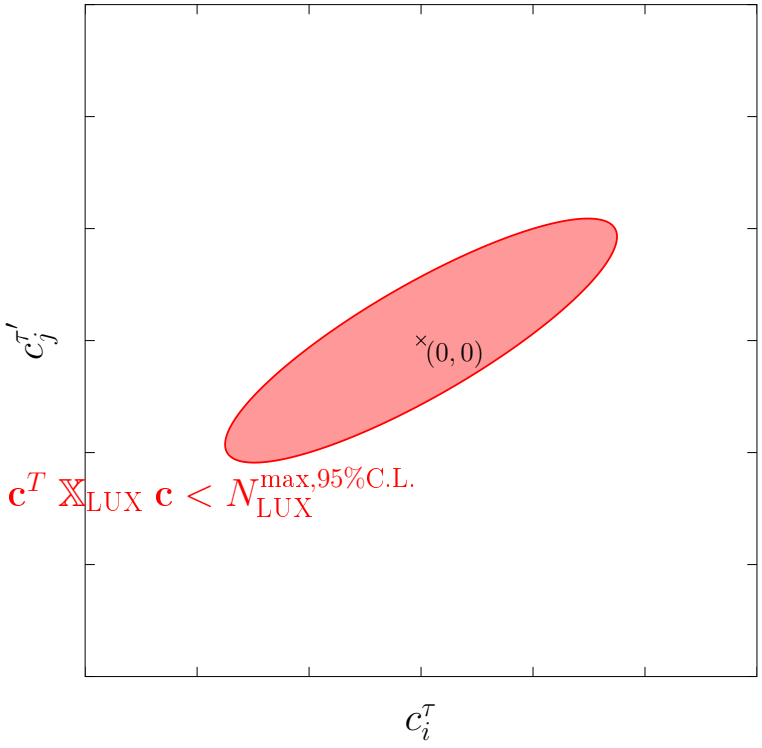

- Parameter space **allowed** by e.g. LUX at 95% C.L.: interior of an **ellipsoid**
  $\hookrightarrow$ size given by $N_{\rm LUX}^{\rm max,95\%C.L.} = 4.74$

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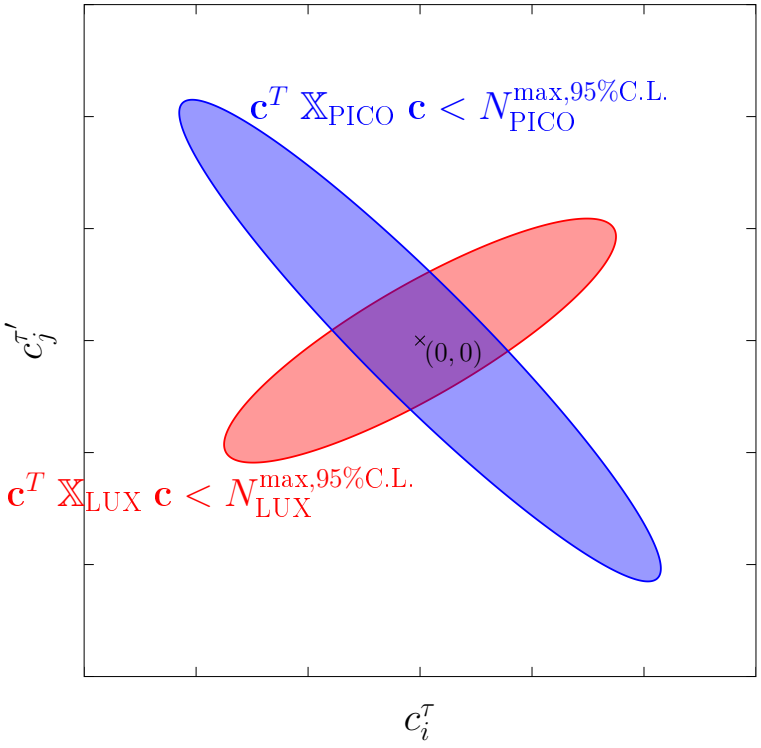

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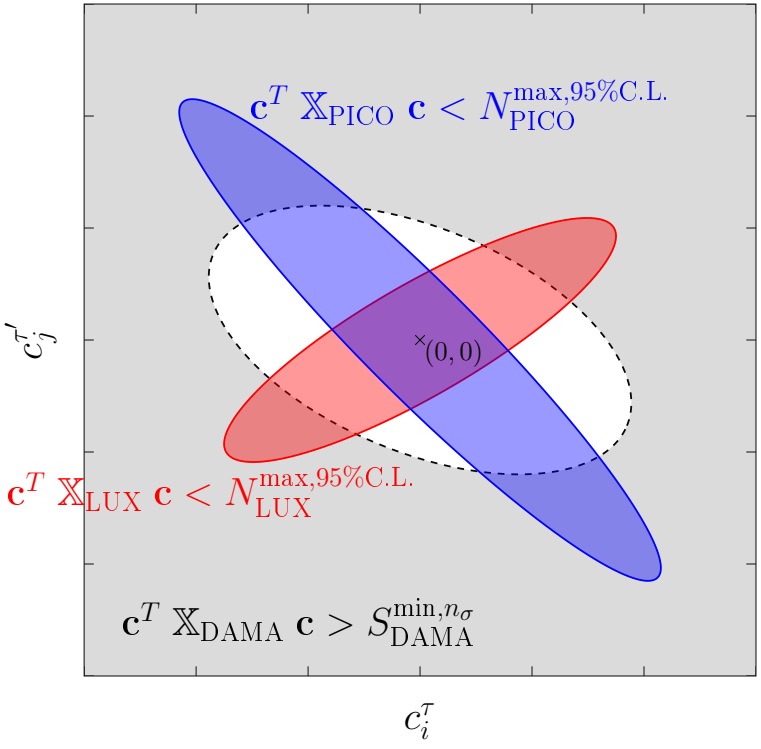

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- DAMA signal in a given energy bin
  $\rightarrow$ **lower** limit on mod. amplitude $S_{\rm DAMA}$
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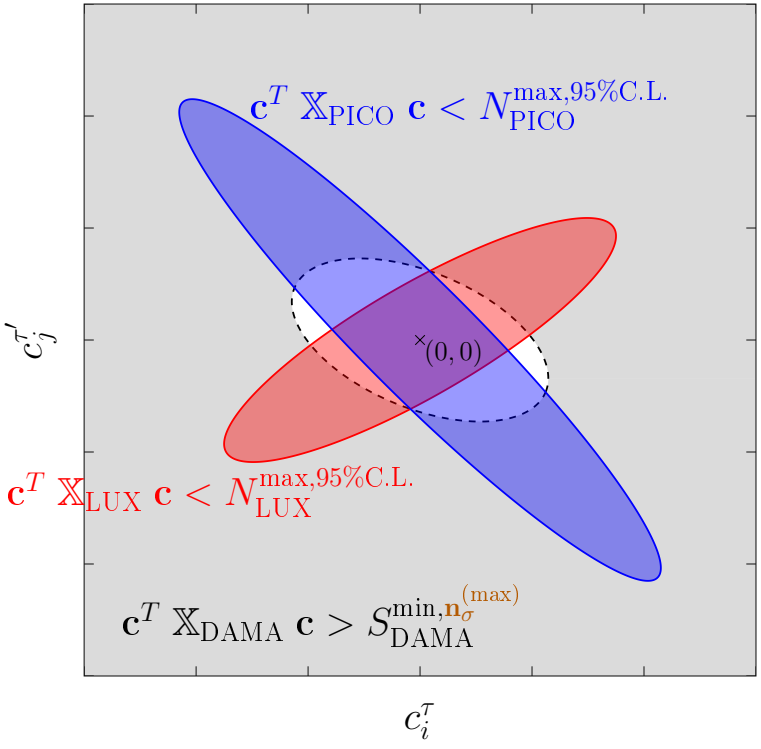

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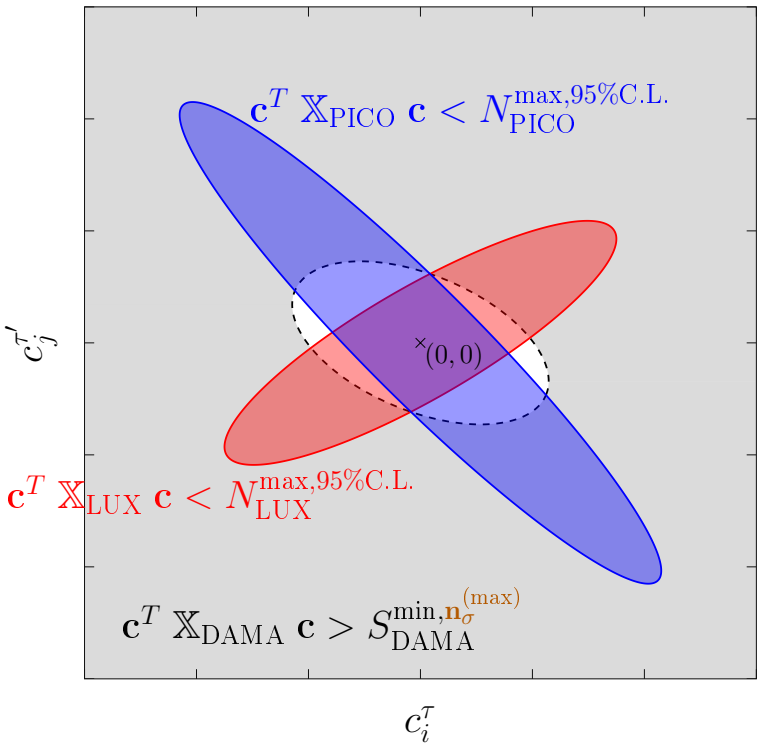
$n_\sigma^{(\rm max)} \equiv$ "critical" value of n_σ such that there is marginal compatibility

$N_\sigma^{(\rm max)} \equiv \max_{a=1,2,3} \left[n_\sigma^{(\rm max)}\right]_{\text{bin } a}$ $\rightarrow$ **measure of tension**

Intersecting ellipsoids in 28 dimensions

2D: graphical solution



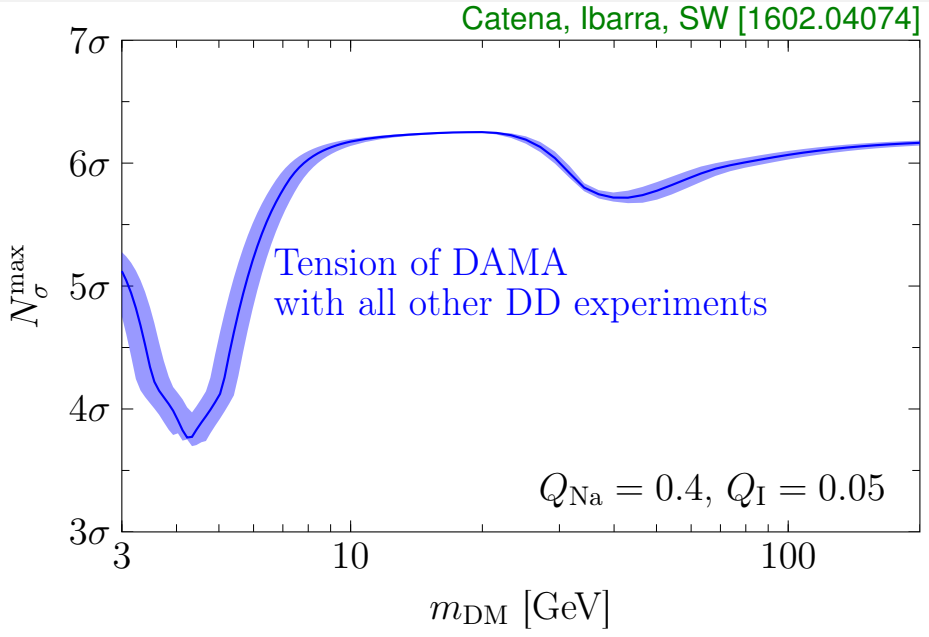
Generalization to **28 dimensions**

- Calculation of the tension $n_\sigma^{(\rm max)}$ becomes a **geometrical problem**:
  determine whether or not

$$\left(\mathcal{E}_{\rm LUX} \cap \mathcal{E}_{\rm PICO} \cap \ldots\right) \subset \mathcal{E}_{\rm DAMA}(n_\sigma^{(\rm max)})$$

- Non-trivial problem!
  - ↪ solved by B. Polyak in 1998
  - ↪ related to *linear matrix inequalities*: positive definiteness of certain linear combinations of the matrices $\mathbb{X}$
  - ↪ numerical solution in $\simeq 1$ sec

Results: tension of DAMA with the null searches



- We "intersect the ellipsoid" of DAMA with the ones from LUX, SuperCDMS, SIMPLE, PICO, COUPP and PICASSO
- Using *very* conservative quenching factors, we find $N_\sigma^{\max} \gtrsim 3.7\sigma$

$\Rightarrow$ **Strong tension** of DAMA with the null searches for **all** DM masses in **the complete parameter space** of the 28-dim. effective theory

- Using instead the more realistic value $Q_{\rm Na} = 0.3$, we even find $N_\sigma^{\max} \gtrsim 5.1\sigma$

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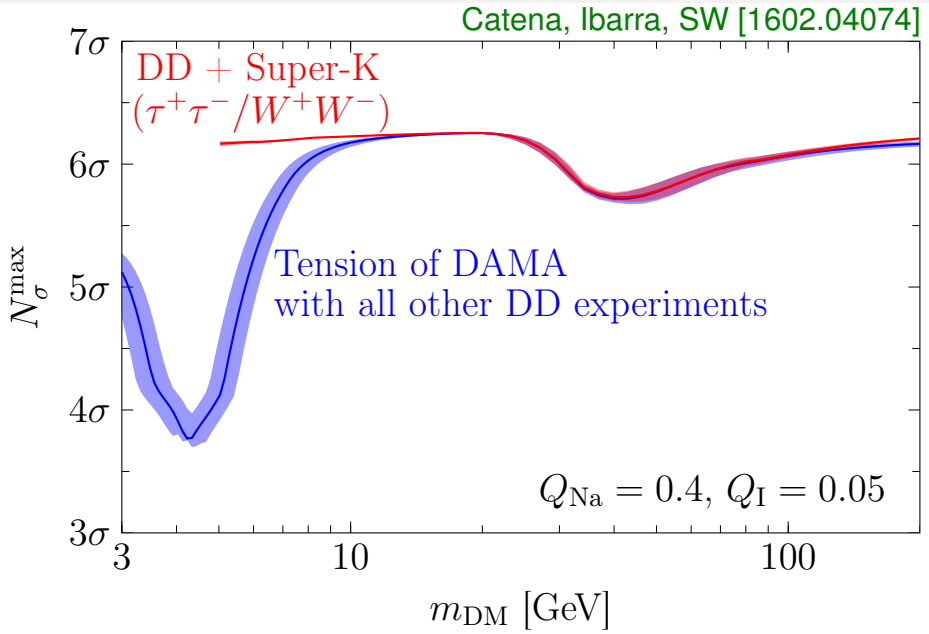

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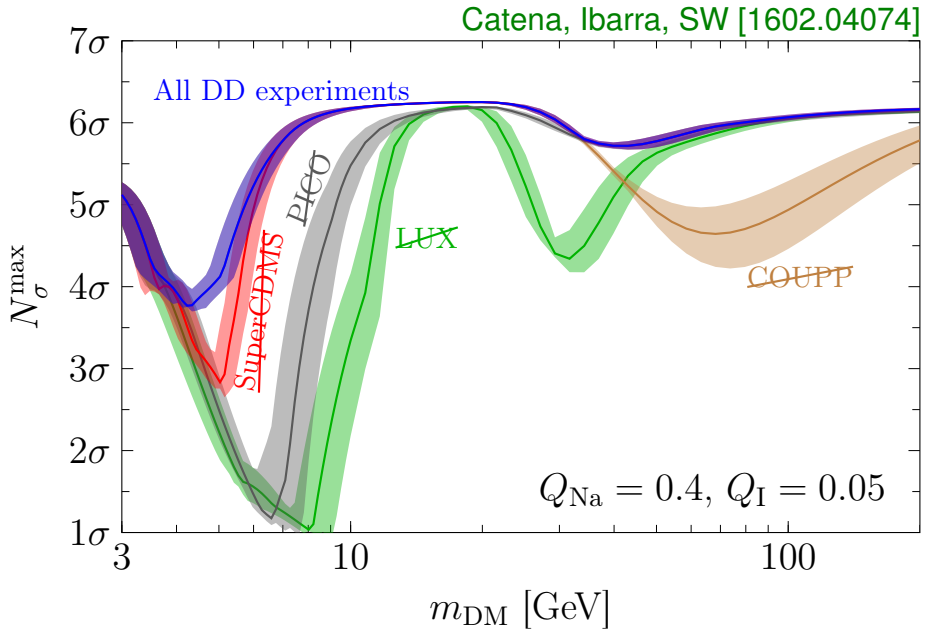
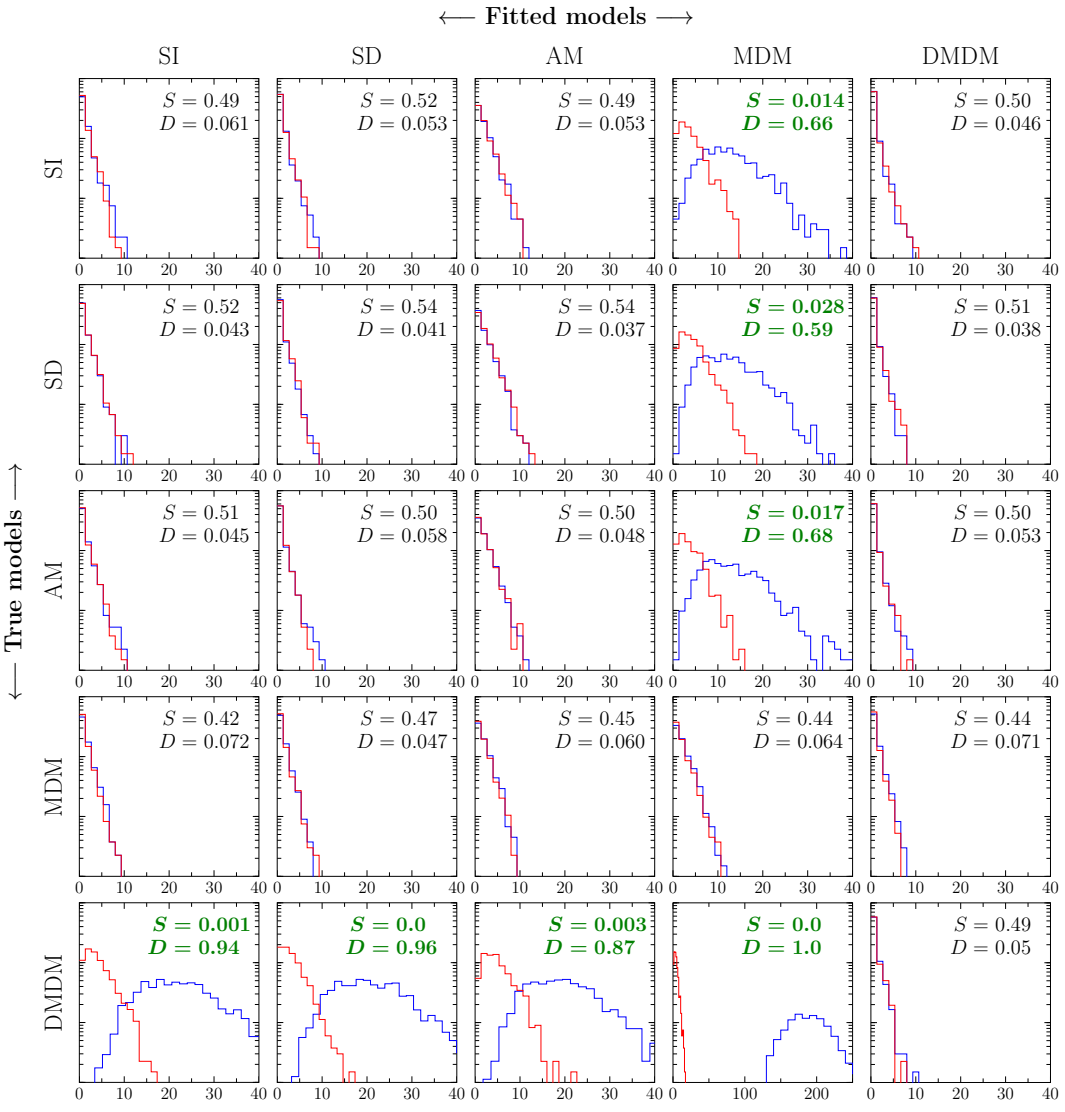
- Using instead the more realistic value $Q_{\rm Na} = 0.3$, we even find $N_\sigma^{\rm max} \gtrsim 5.1\sigma$
- Adding the information from SuperK (assuming ann. into $\tau^+\tau^-/W^+W-$) further increases the tension

Complementarity of direct detection experiments



- Different target nuclei are sensitive to different directions in the parameter space
  ↪ particularly important in view of the interferences!
- Experiments necessary for establishing the significant tension:
  LUX, PICO and SuperCDMS

Non-standard DM interactions in future experiments



Felix Kahlhoefer, SW [1607.04418]

see also Gluscevic, Zurek, ... [1506.04454]

- We have developed a framework to interpret **future DD data** in a **halo-independent** way, for any type of DM-nucleon interactions
- We investigate which interaction structures can be distinguished from each other, without referring to a specific $f(v)$