SABRE South: not just a modulation hunter

Francesco Nuti

The University of Melbourne

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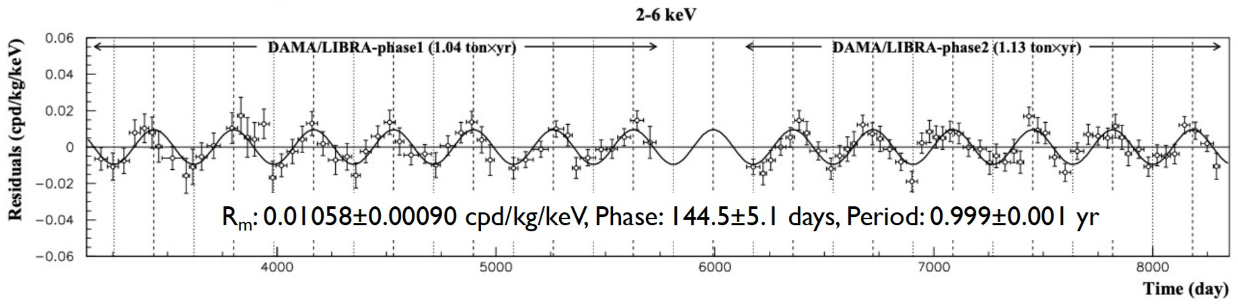
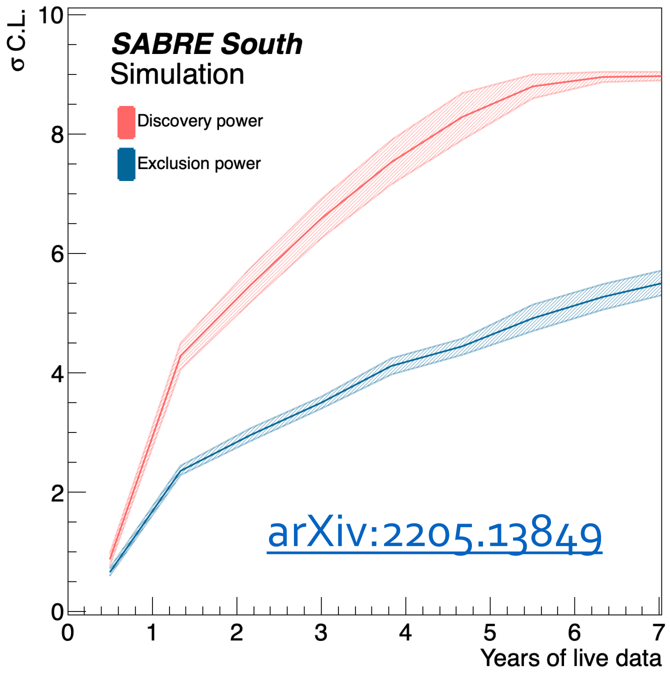
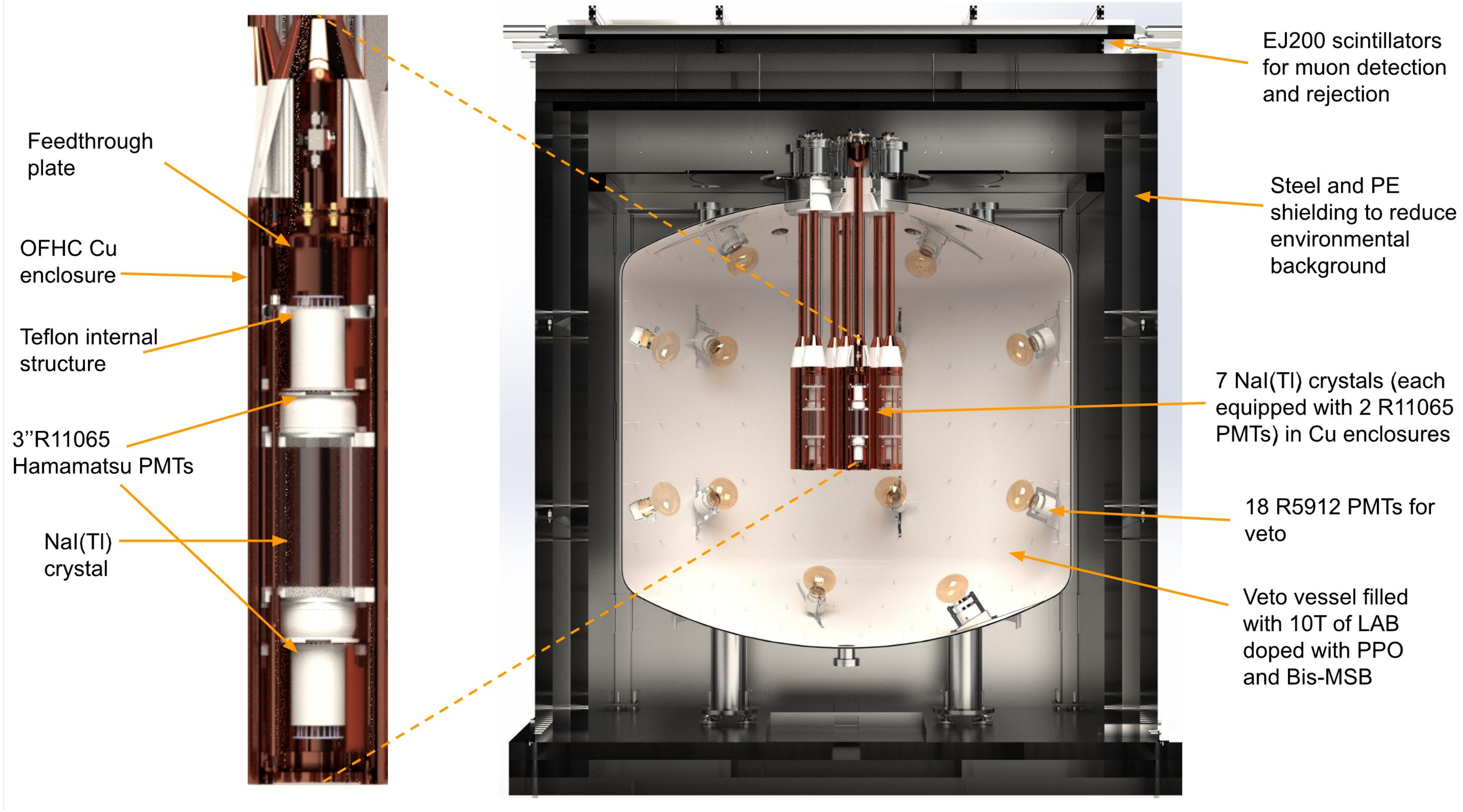
SABRE South

- SABRE South has been designed with the intent of testing DAMA/LIBRA long-standing annual modulation
- It uses 50 kg of the lowest background NaI(Tl) crystals
- Can exclude (observe the DAMA/LIBRA modulation at 3σ (5σ) in about two years





SABRE South is a complex and unique apparatus



- 3 types of high-performance detectors capable of measuring a variety of signatures
- Uniquely positioned in the Southern Hemisphere

Detailed detector features in backup

What else can SABRE measure?

What else can SABRE measure?

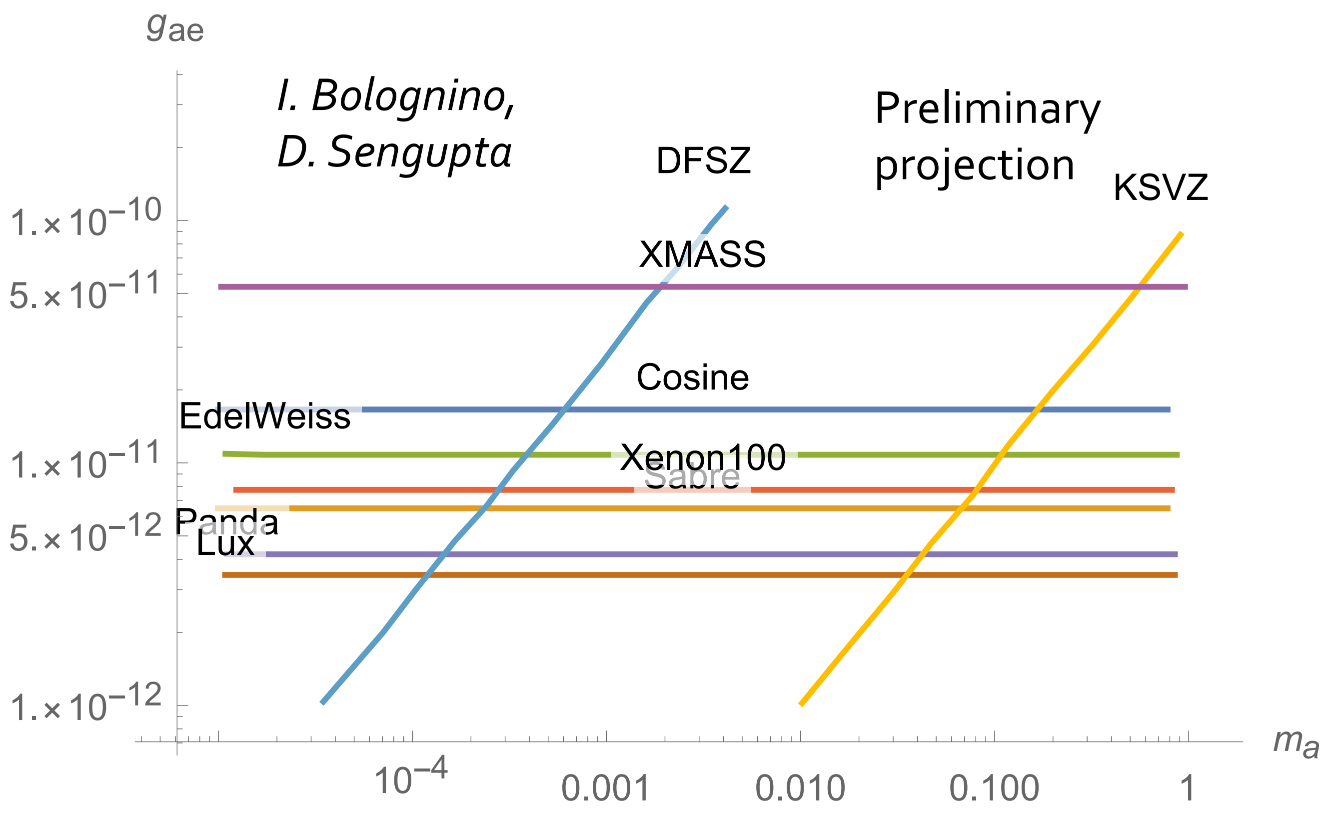
- We created experimental+theory working groups to explore a variety of research topics
- More info at: https://darkmatteraustralia.atlassian.net/wiki/spaces/CDMPublic/pages/1254653955/SABRE+White+Paper

Topics	Coordinators
Dark Matter Halo	Ciaran O'Hare (Theo) Madeleine Zurowski (SABRE)
Low velocity Dark Matter Single Interaction Multiply-interacting	Dipan Sengupta (Theo) Matthew Dolan (Theo) Irene Bolognino (SABRE) Lindsey Bignell (SABRE)
Boosted Dark Matter	Jayden Newstead (Theo) Matthew Gerathy (SABRE)
Quantum Mechanics	Raymond Volkas (Theo) Francesco Nuti (SABRE)
Supernova neutrinos	Ciaran O'Hare (Theo) Madeleine Zurowski (SABRE)

Low-energy single-interaction signals

- SABRE South is pound-for-pound the best NaI(Tl) detector
- Should DAMA/LIBRA signal be ruled out, SABRE South can still test DM hypotheses more strongly than other NaI(Tl) experiments given enough time
- Plenty of models test but other target experiments expected to have generally higher sensitivity

solar axion induced signals



Solar Axion arXiv:1904.06860

NaI favorable models?

Looking for inputs from theory for models which favor NaI targets so that SABRE can set strong limits:

- Inelastic DM - relaxes low mass constraints (F, Ne)
- Proto-philic DM - relaxes neutron heavy targets (Xe, Ge)
- Spin dependent DM - relaxes spin-less targets (Ar)

Target	A	Spin nucleon
F	19	p
Ne	20	-
Na	23	p
Ar	40	-
Ge	73	n
I	127	p
Xe	131	n

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Comprehensive sensitivity calculation tool

Tool to calculate rates and consistently test DM theories considering:

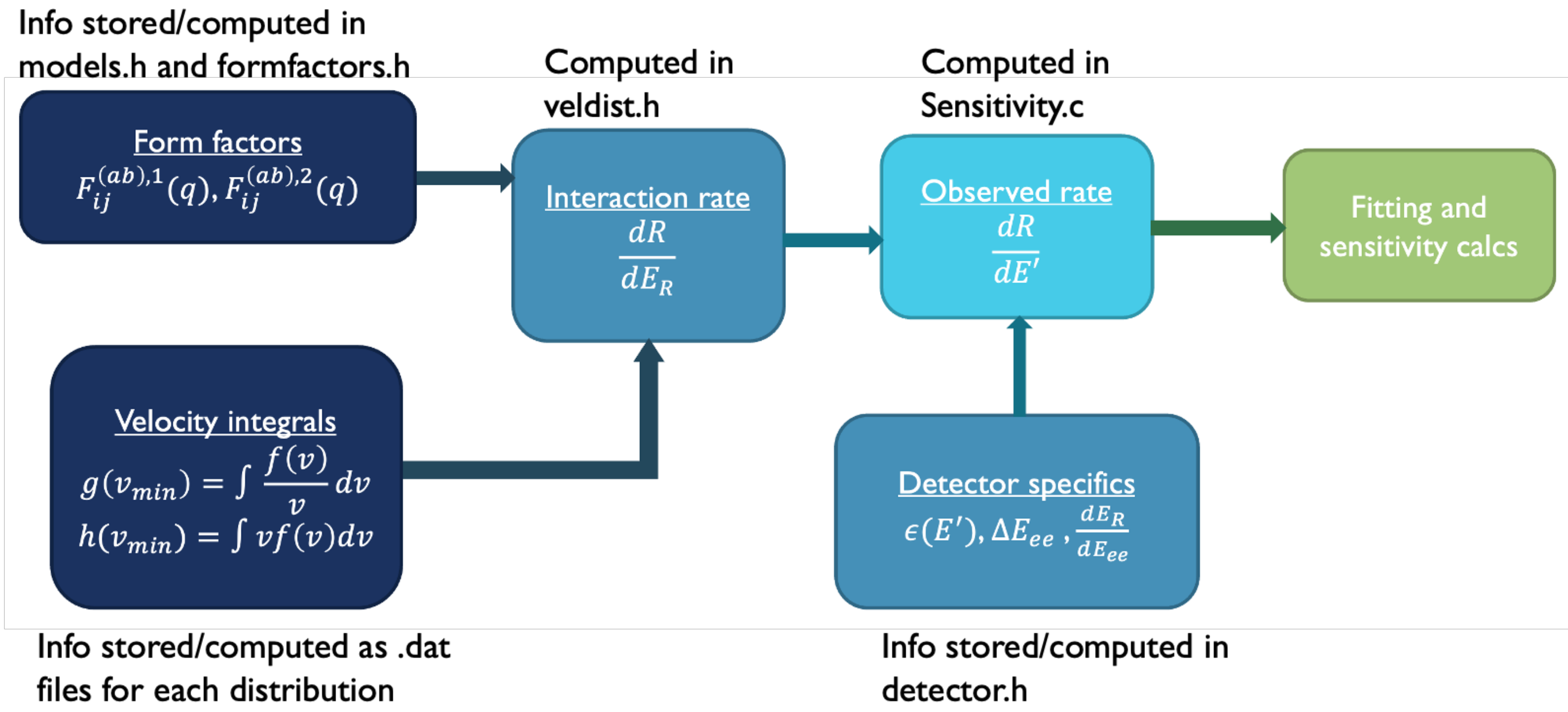
- DM velocity distributions
- Form factors
- Experimental factors: efficiency, resolution, quenching factors

Looking for contributors:

- improve sensitivity calculations (add time-dependent background)
- expand applicability

git@bitbucket.org:darkmatteraustralia/sensitivity_studies.git

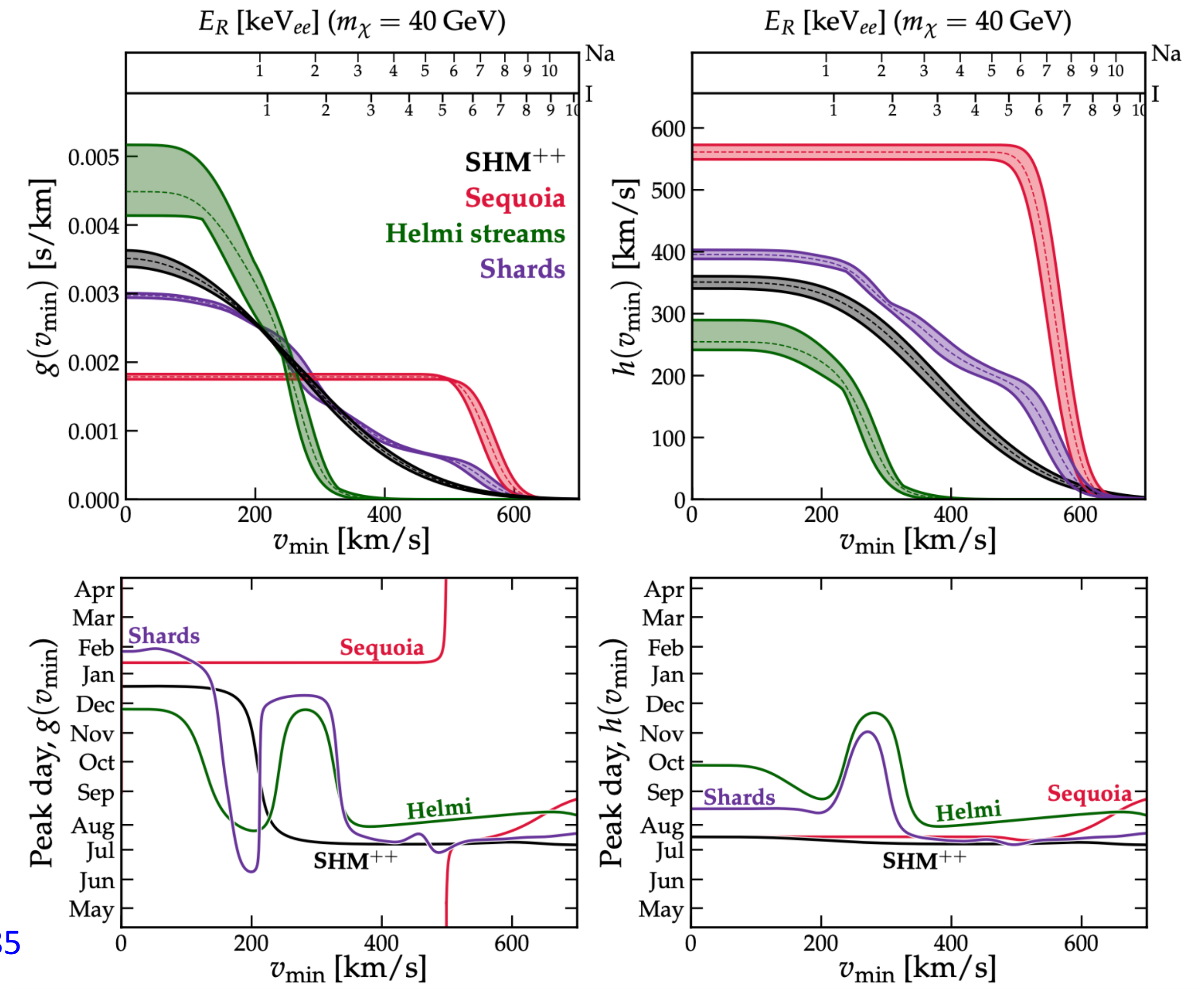
M. Zurowski



Testing local DM distribution

M. Zurowski
C. O'Hare

- Modulation searches typically assume Standard Halo Model (SHM) → isotropic Gaussian velocity distribution
- Local substructures such as Sequoia, Helmi streams and the Shards have been observed
- These are expected to have associated underlying DM halo substructures which change overall velocity and density distributions
- More rapid modulation amplitude and peak position changes with v_{min}, i.e. type of target → experiments can observe significantly different modulations



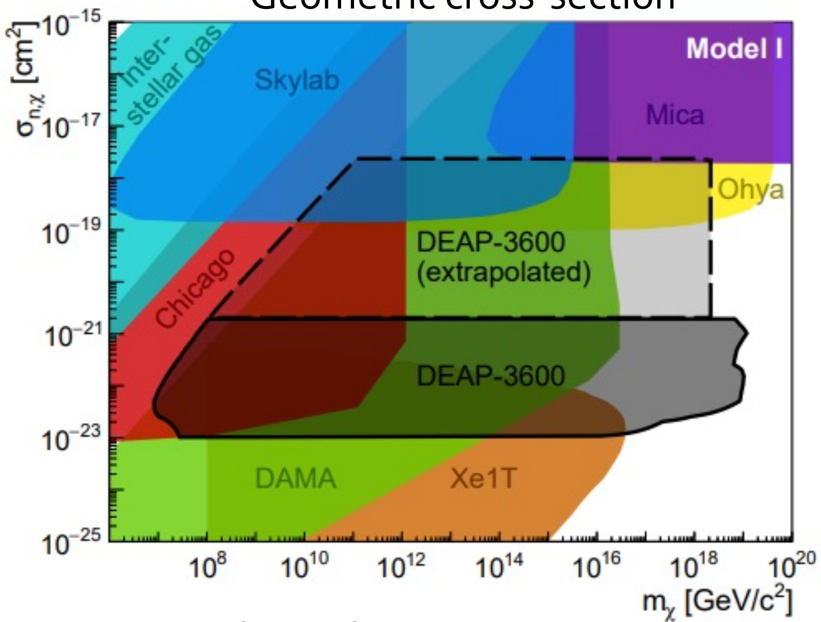
Sequoia arXiv:1904.03185
Helmi arXiv:1611.00222
Shards arXiv:1909.04684]

Multiply-interacting dark matter

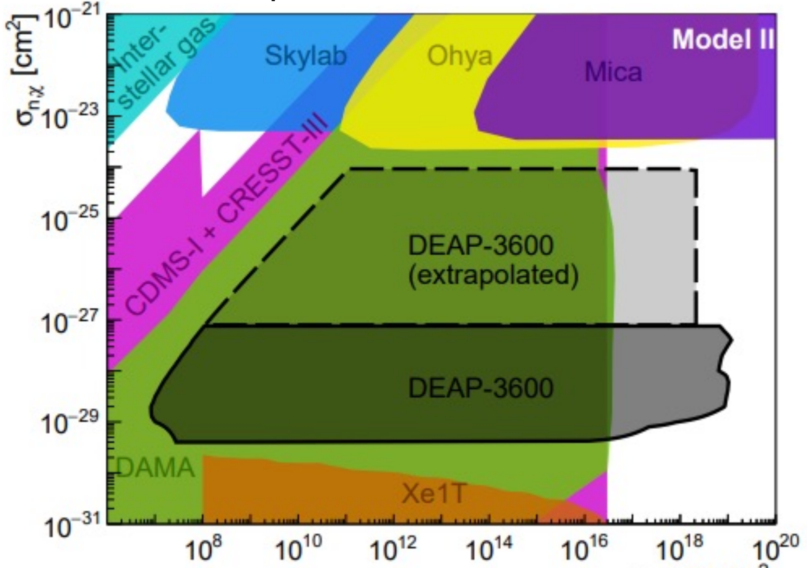
- Plank scale mass DM candidates expected to produce multiple keV energy interactions in liquid scintillator in the span of μs
- Requires dedicated trigger
- Background from PMT dark rate → determine minimum number of coincidences → E threshold
- Sensitive to cross-sections down to $5\text{x}10^{-24}$ (E_th/500keV) cm^2 and 10^{-28} (E_th/500keV) cm^2 and masses up to $m\chi < 10^{19}$ GeV after 3 years
- To improve estimate:
  - Model of incident direction, scattering energy distribution (theo)
  - Dark rate characterisation (exp)
  - Assess other background sources (exp)

L. Bignell
P. cox

Geometric cross-section



A⁴ dependent cross-section



arxiv:2108.09405

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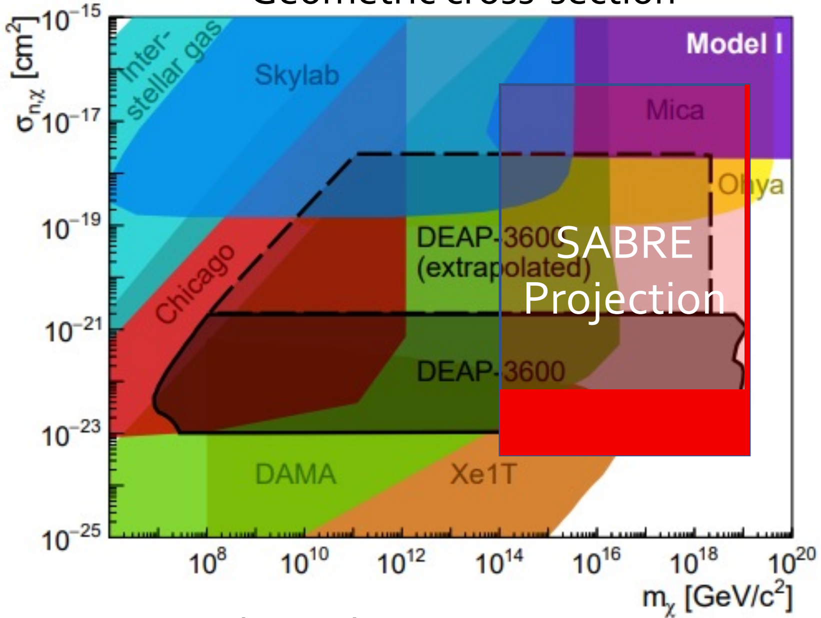
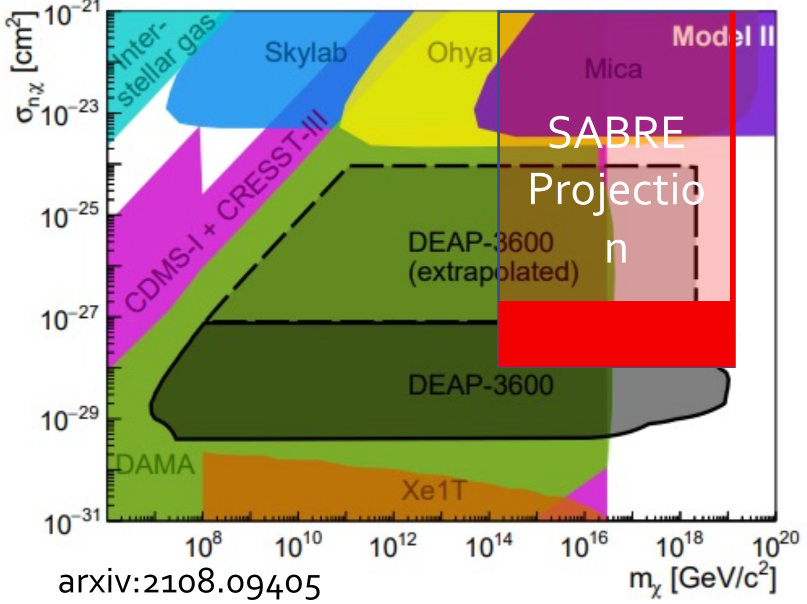


A^4 dependent cross-section

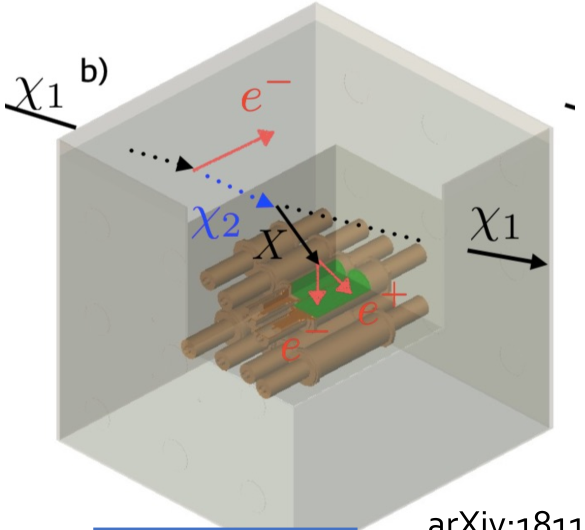


arxiv:2108.09405

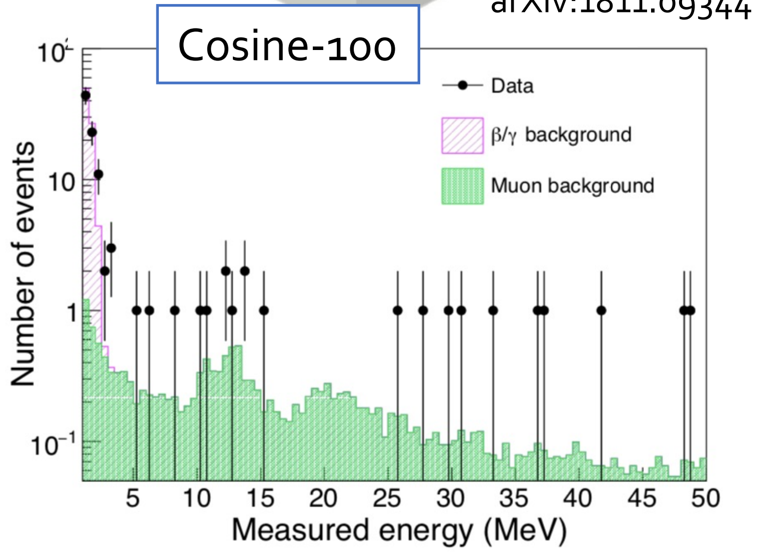
Boosted Dark Matter

M. Gerathy
J. Newstead
X. Wang

- Cosmic-ray upscattered DM (arXiv:2108.00583)
- Inelastic Boosted DM (arXiv:1811.09344, see Xuan-Gong Wang talk at ECR)
- Multiple MeV scale interactions
- To assess SABRE sensitivity:
  - Model of incident direction, scattering energy distribution (theo)
  - Study how attenuation through Earth and detector position affect signal detection (theo)
  - Cosmogenic muon background characterisation (exp)
  - Study resolution on spatial and time reconstruction of individual interactions (exp)



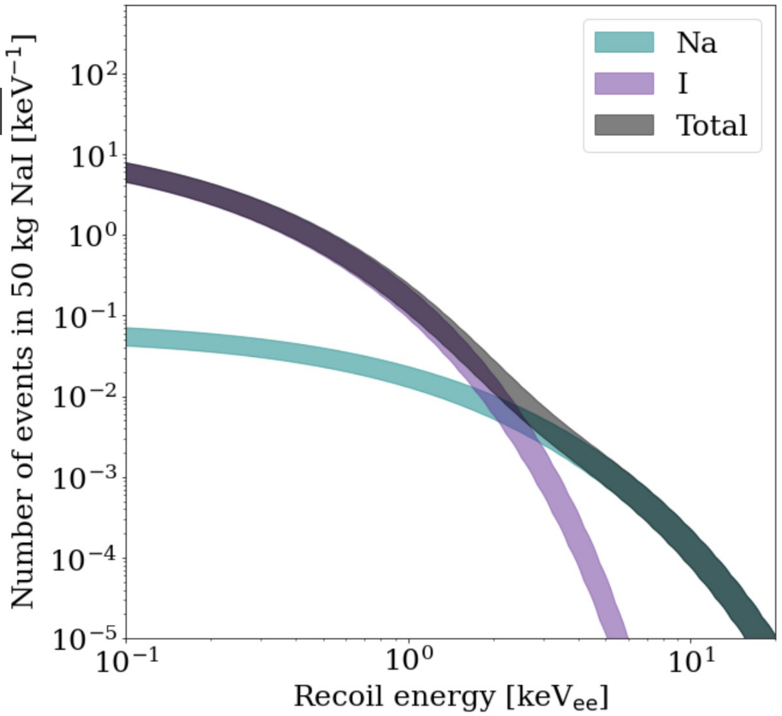
arXiv:1811.09344

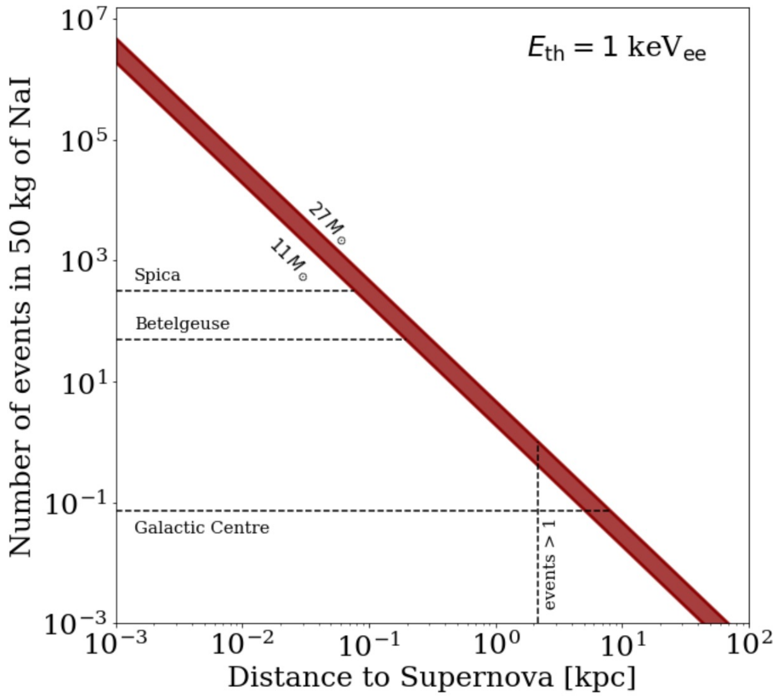


Rare events detection

- SABRE could also observe supernova neutrinos via coherent elastic neutrino-nucleus scattering
- Handful of events in a 10 second burst
- Max distance ~2 kpc with 1 keVee threshold and 50 kg detector
- Can this contribute to supernova characterisation?
    - Time accuracy requirements
    - Is position of detector in Southern Hemisphere advantageous?

C. O'Hare





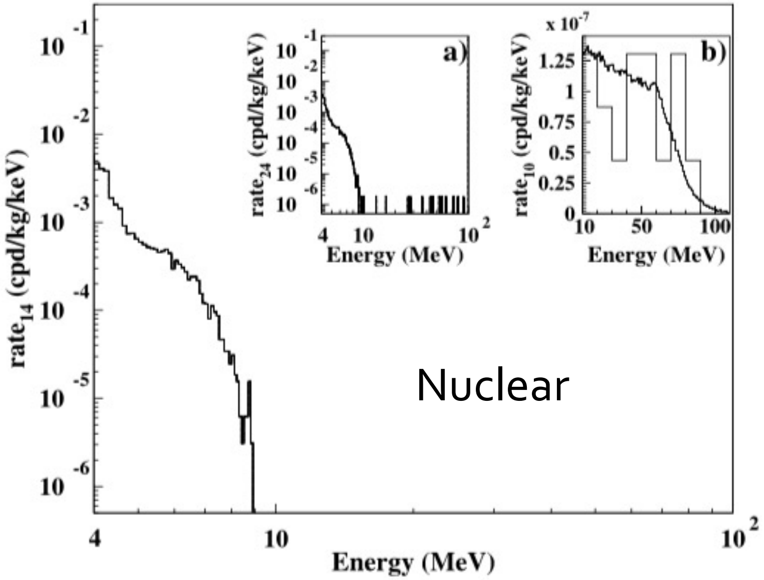
Quantum Mechanic tests

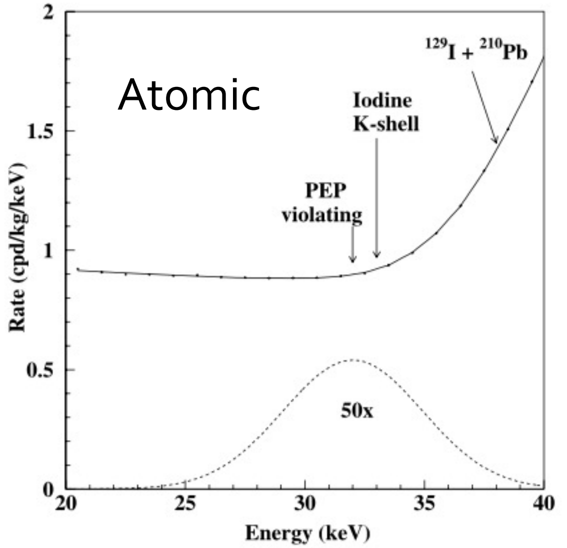
PEP Violating Transitions

- Quantum mechanics extensions have been hypothesized to address fundamental questions (wave function collapse as result of measurement and transition to non-QM macroscopic systems) or introduce quantum gravity
- QM extension can allow new radiation producing processes that can be measured by low background detector

1. Atomic and Nuclear transitions in Pauli Exclusion Principle (PeP) violating processes
   - SABRE sensitivity to be investigated
   - Nuclear transitions could potentially be measured without shielding
2. Spontaneous radiation emission from charged particles

R. Volkas
F. Nuti





R. Bernabei, Eur. Phys. J. C (2009) 62: 327–332

The CSL models

- The Continuous Spontaneous Localization (CSL) models address the measurement problem with the introduction of a stochastic non-linear noise field in the Schrödinger Equation

Mass density operator → $\hat{M}(\mathbf{x})$; Noise field → $w_t(\mathbf{x})$

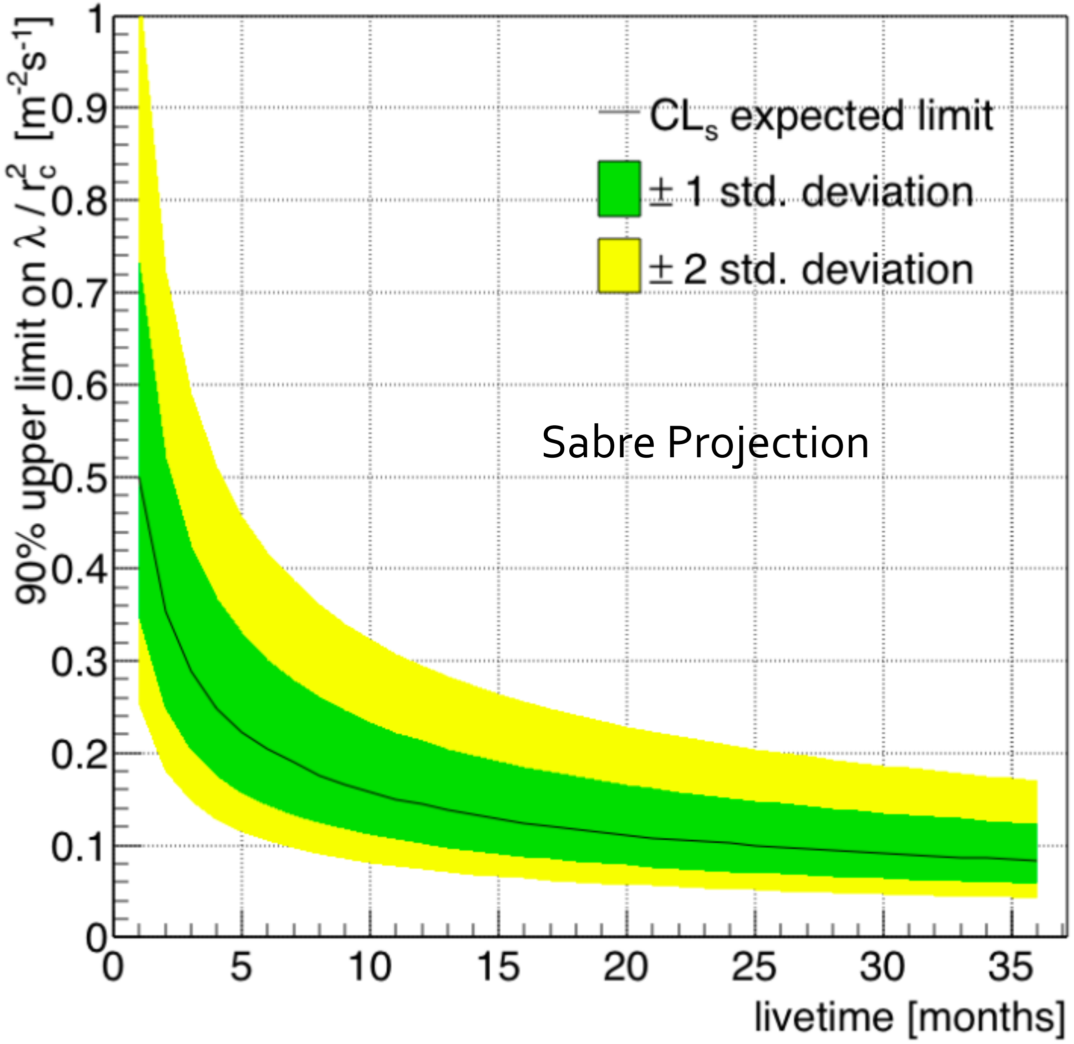
$$i\hbar \frac{\mathrm{d}|\psi(t)\rangle}{\mathrm{d}t} = \hat{H}|\psi(t)\rangle \longrightarrow i\hbar \frac{\mathrm{d}|\psi_t\rangle}{\mathrm{d}t} = \left[\hat{H} - \frac{\hbar\sqrt{\lambda}}{m_0}\int \mathrm{d}\mathbf{x}\, \hat{M}(\mathbf{x}) w_t(\mathbf{x})\right]|\psi_t\rangle$$

- Fundamental parameters of the theory: the collapse rate λ, the correlation length of the noise r_C
- Origin of noise field can be bounded to gravitational models
- Lead to spontaneous radiation emission rate from nuclei and electrons with $10<E<10^5$ keV

$$\frac{d\Gamma}{dE} = N_{atoms} \times \left(N_A^2 + N_A\right) \times \frac{\lambda\hbar e^2}{4\pi^2\varepsilon_0 m_0^2 r_C^2 c^3 E}$$

Spontaneous radiation limits

- Assessed sensitivity of SABRE to spontaneous radiation
- Background from SABRE simulation model with 10% uncertainty on overall rate (0.72 dru)
- Target mass 50 kg of target
- Expected to reach $\lambda/r_C < 0.1$ in about 2 years



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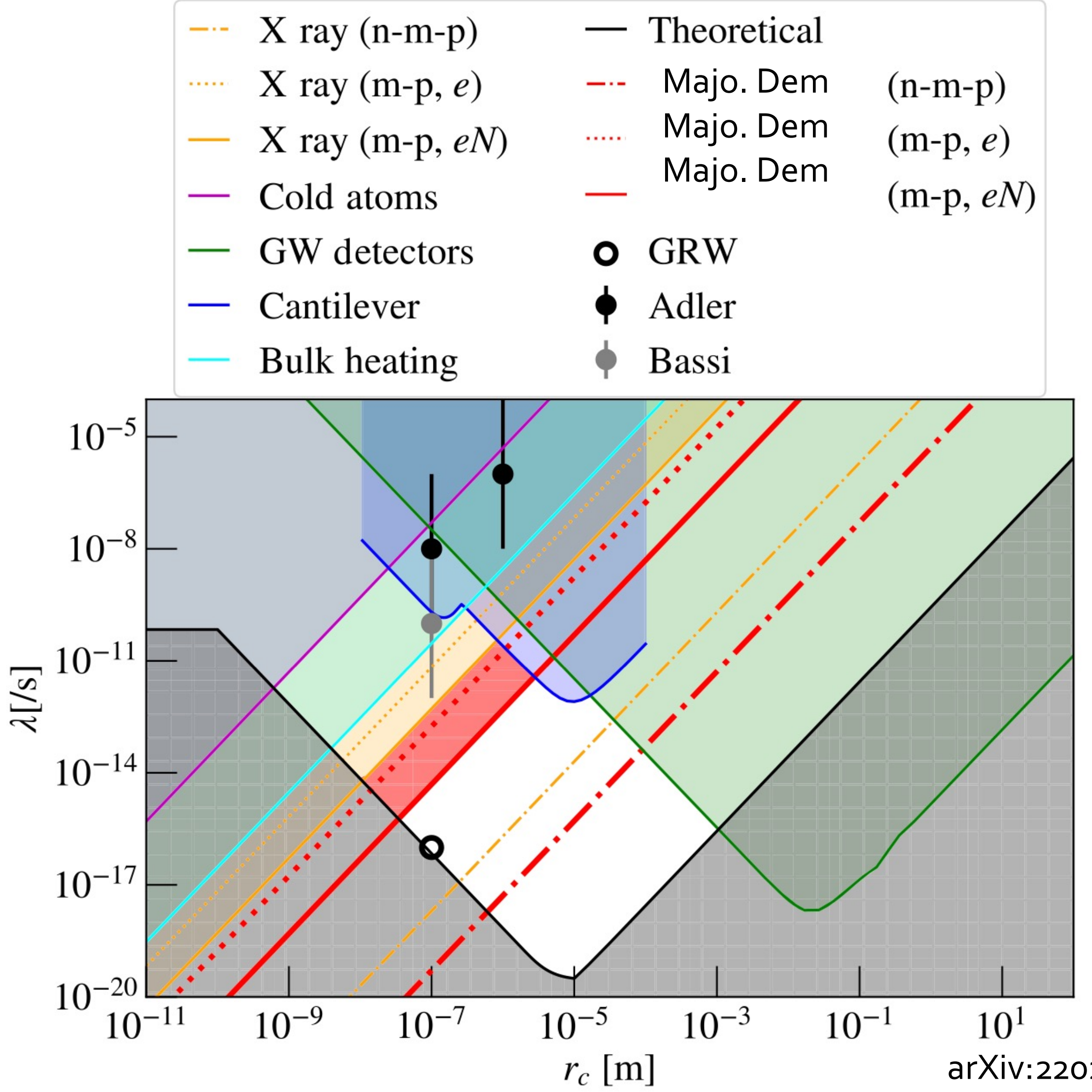

arXiv:2202.01343

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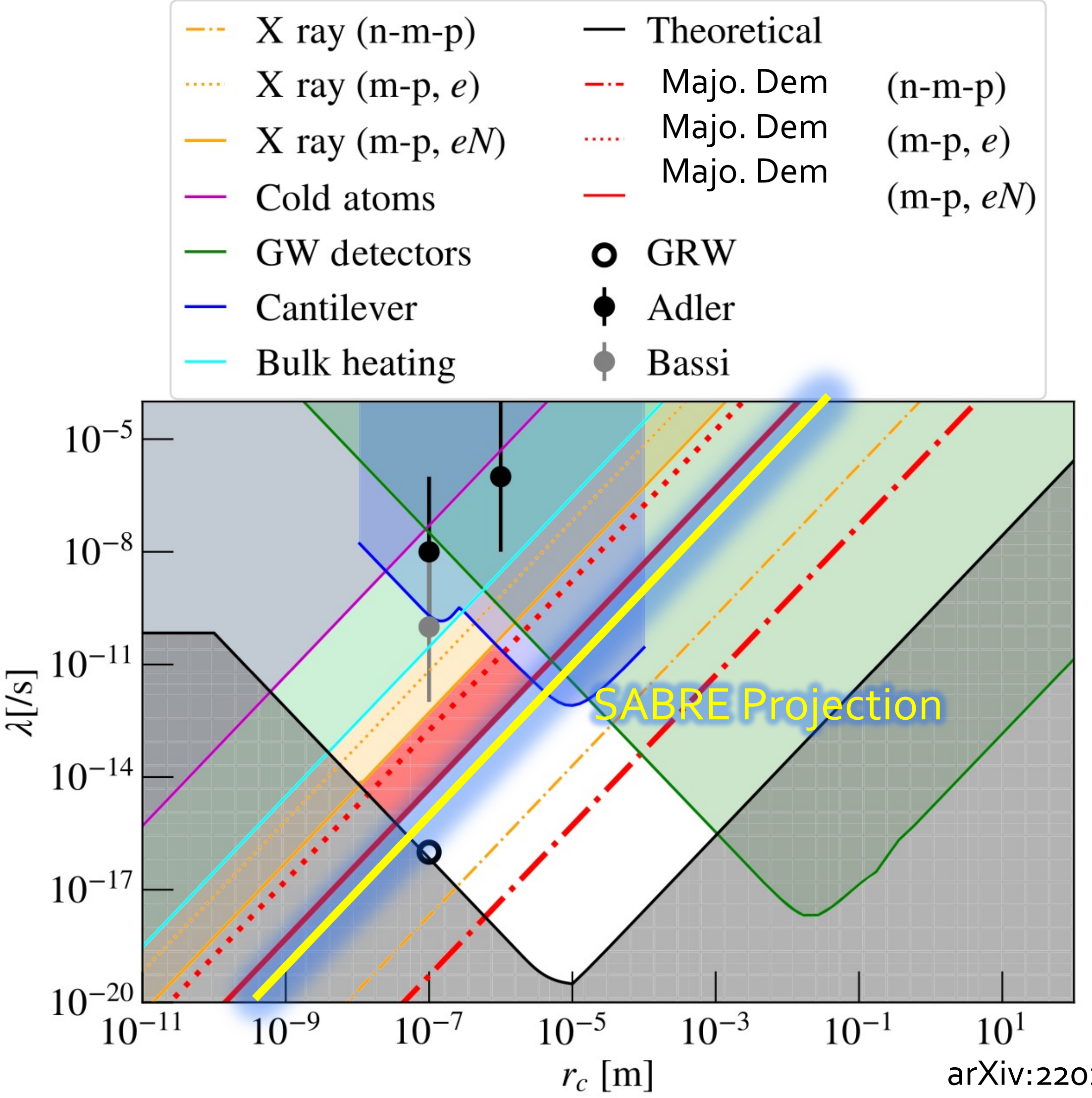
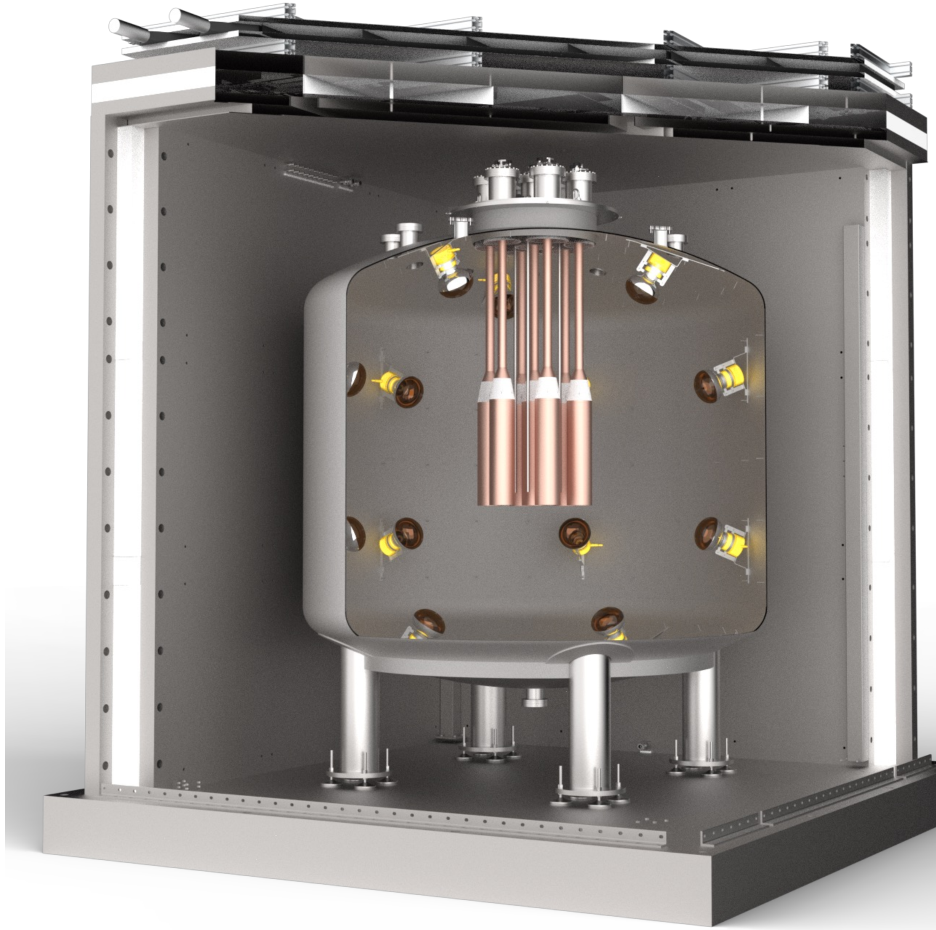


arXiv:2202.01343

Conclusion

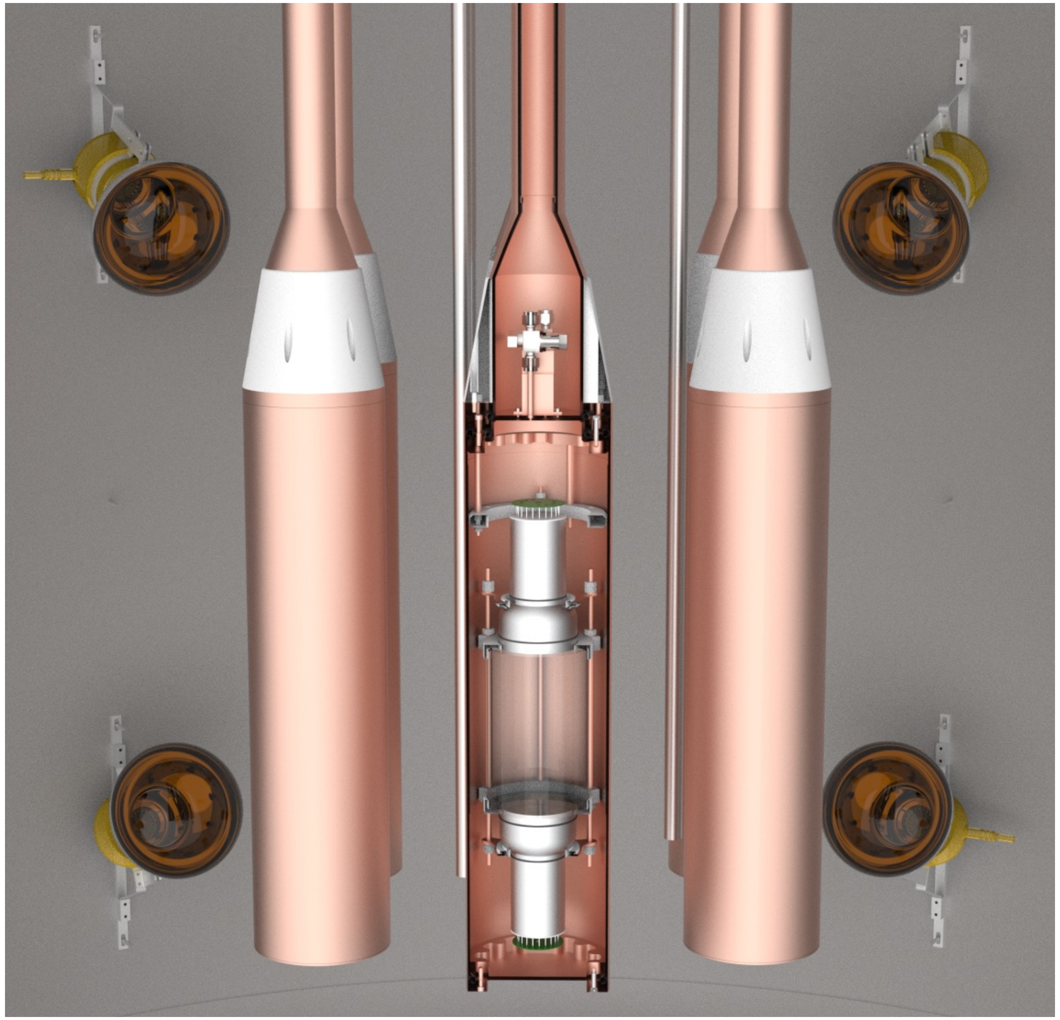
- SABRE South is a very complex and powerful particle detector
- There is potential to test physics beyond the DAMA/LIBRA modulation
- We have investigated single-interacting, multiply-interacting and boosted dark matter candidates and considered neutrino supernovae and quantum mechanics processes
- There is lots of phenomenological and experiential work to be done to improve the preliminary assessment
- Results of these investigations to be published in the SABRE South white paper
- Please get in touch if interested in participating



Backup

Crystal Detector

- Crystal size: 10 cm diameter, 15-25 cm length
- Double PMT readout
- Electromagnetic interaction threshold ~1 keV
- Nuclear recoil threshold ~10 keV
- Detectors positioned in a hexagonal configuration
- 26 cm distance between crystal (axis), 16 cm gap

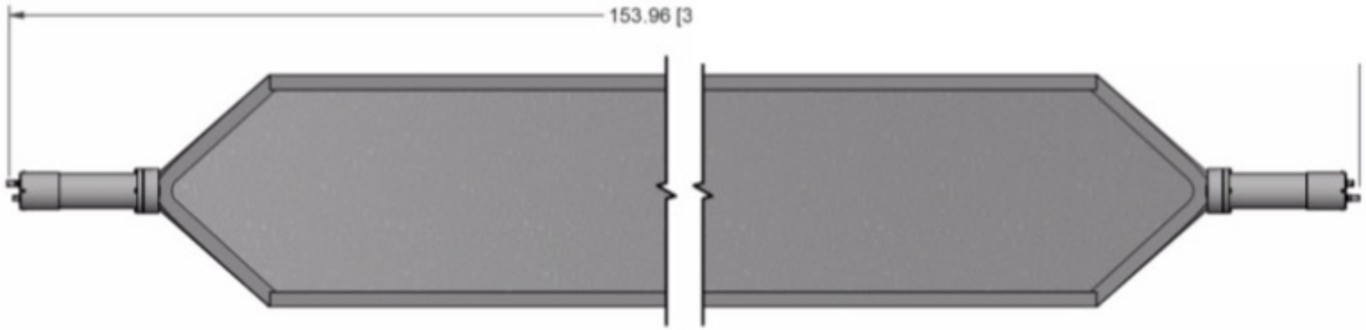


Liquid Scintillator Detector

- vessel size: ~2.6 m diameter, ~2.6 m height
- 10 tons of linear alkyl benzene scintillator
- electromagnetic interaction threshold ~50 keV
- nuclear recoil threshold ~500 keV
- Some spatial localization and directionality is possible

Muon Detector

- 8 panels: 3000 x 400 x 50 mm3
- Plastic Scintillator EJ200 (Polyvinyltoluene)
- Some spatial localization of interaction might be possible with limited resolution



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

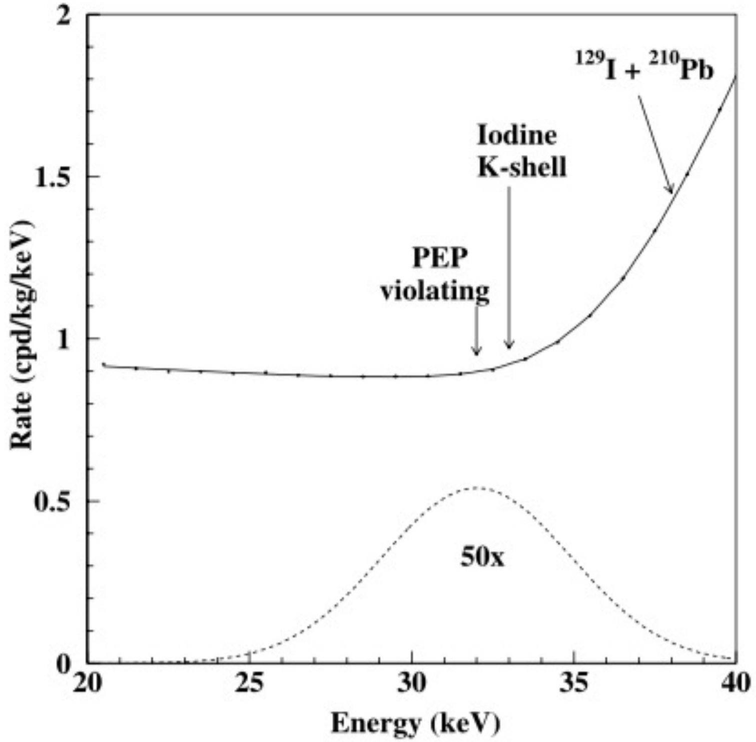
- Coupling constants
- DM Form factors
- Nuclear response functions

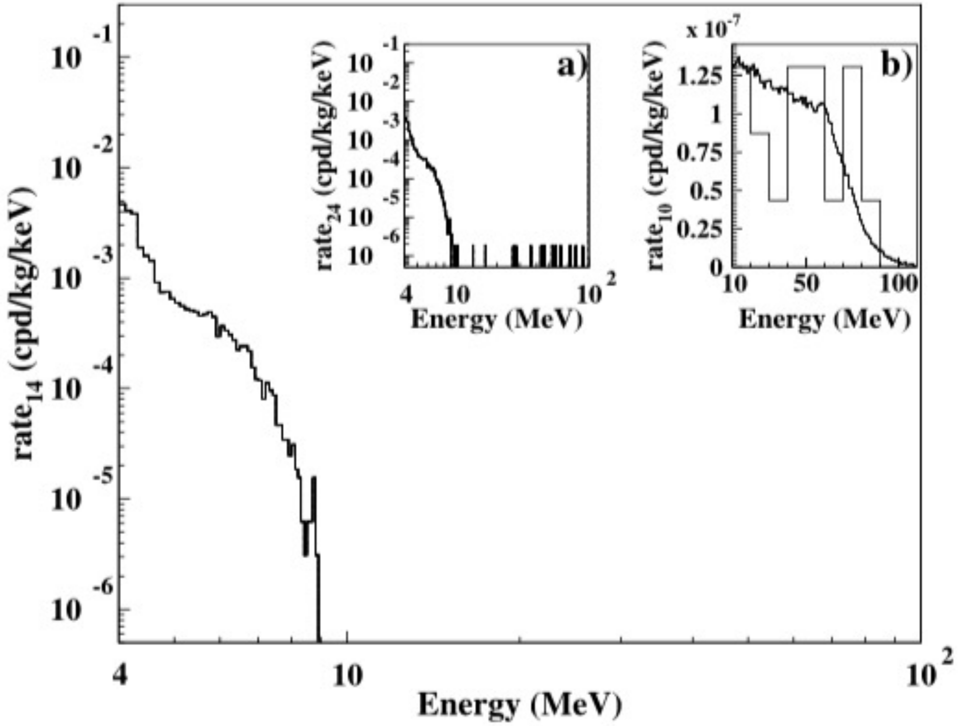
DM velocity distribution

Pauli Exclusion Principle Violation

R. Bernabei, Eur. Phys. J. C (2009) 62: 327–332

- PEP-violating K-shell electron transitions in iodine atoms
- Non-Paulian emissions of protons with Ep ≥ 10 MeV in ^{23}Na and in ^{127}I





PEP-violating transitions and spectra energy-shift

Piscicchia, Addazi, Marciano, Curceanu et al. PRL 129 13 131301 (2022)

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PEP-violation from Non-Commutative Quantum Gravity models

deformed transition rate $$W_\theta = W_0 \cdot \phi_{\mathrm{PEPV}}$$

"Electric" components

$$\phi_{\mathrm{PEPV}} = \delta^2 \simeq \frac{D}{2}\frac{E_N}{\Lambda}\frac{\Delta E}{\Lambda}$$

$$D = p_1^0 \tilde{\theta}_{0j} p_2^j + p_2^0 \tilde{\theta}_{0j} p_1^j$$

$$E_N \simeq m_N \simeq A m_p \qquad \Delta E = E_2 - E_1$$

"Magnetic" components

$$\phi_{\mathrm{PEPV}} = \delta^2 \simeq \frac{C}{2}\frac{\bar{E}_1}{\Lambda}\frac{\bar{E}_2}{\Lambda}$$

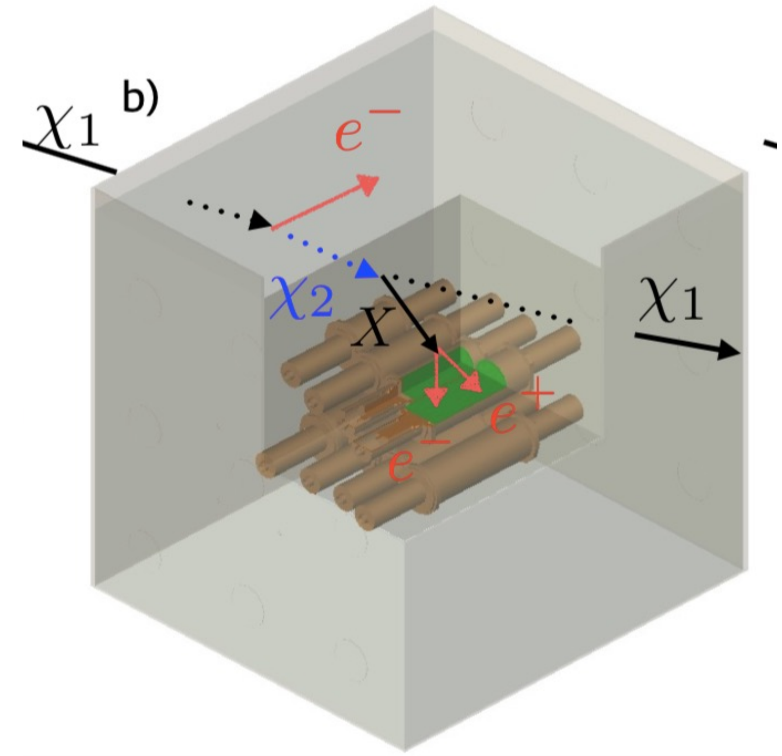
$$C = p_1^i \tilde{\theta}_{ij} p_2^j$$

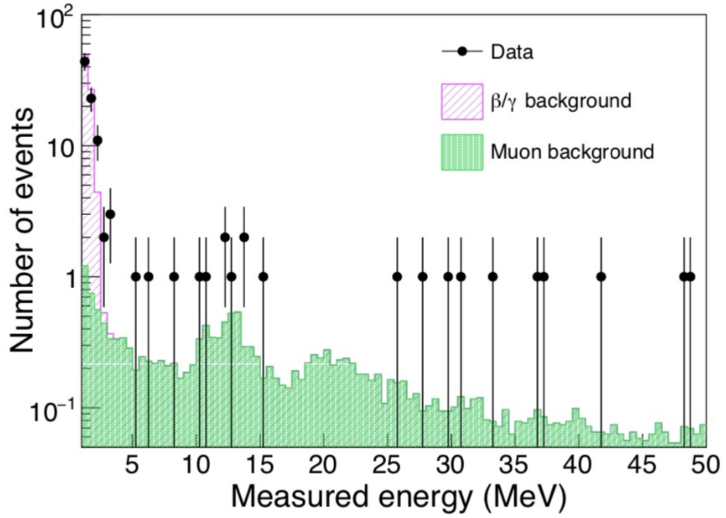
$E_{1,2}$ energy levels occupied by the initial and final electrons

Apply the same strategy as in DAMA, within MeV energy range, to distinguish with more precision PEP-violating lines at higher resolution

Boosted Dark Matter Results COSINE-100

C. Ha, arXiv:1811.09344





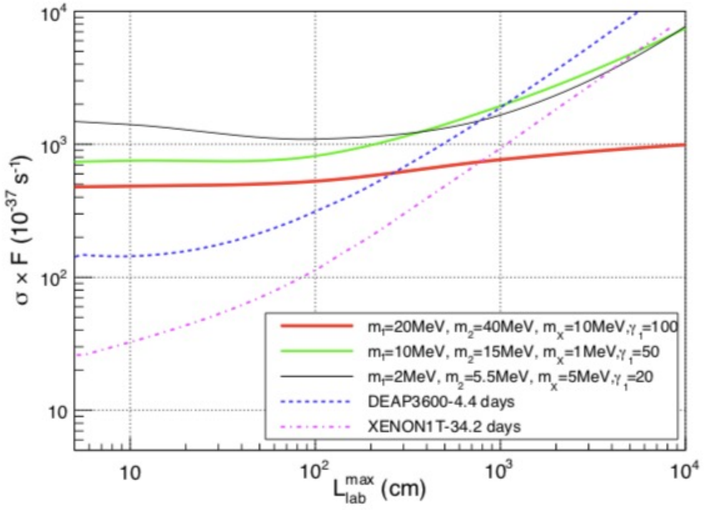


FIG. 5. Measured 90% CL upper limits from 59.5 days of COSINE-100 data in the L_{lab}^{max}-σ plane are presented for three different benchmark models. These results are compared with the experimental sensitivities of XENON1T with 34.2 days data [45] and DEAP-3600 with 4.4 days data [46] calculated in Ref. [22].