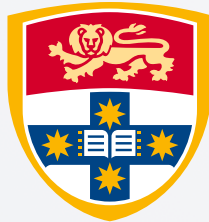


ARC CENTRE OF EXCELLENCE FOR
DARK
MATTER
PARTICLE PHYSICS



Australian Government



The University of Melbourne | The University of Adelaide | The University of Sydney | The University of Western Australia | The Australian National University | Swinburne University

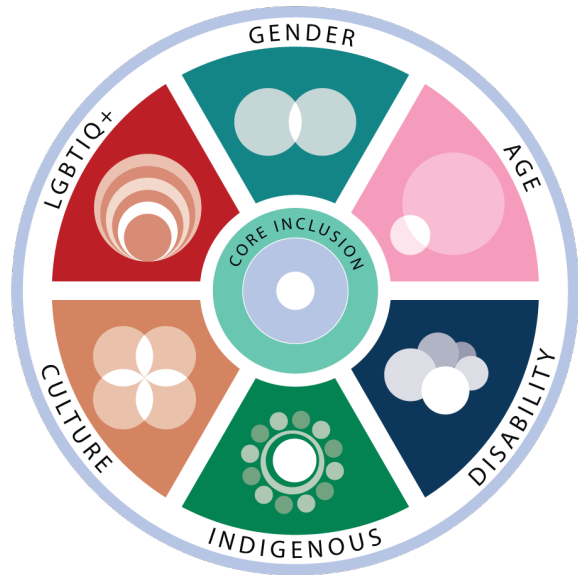
ARC FEEDBACK ON ANNUAL REPORT



We are excited to read that the Centre has identified many objectives, from hiring policies to carer support, fellowships, and training to ensure the best working environment for all members.

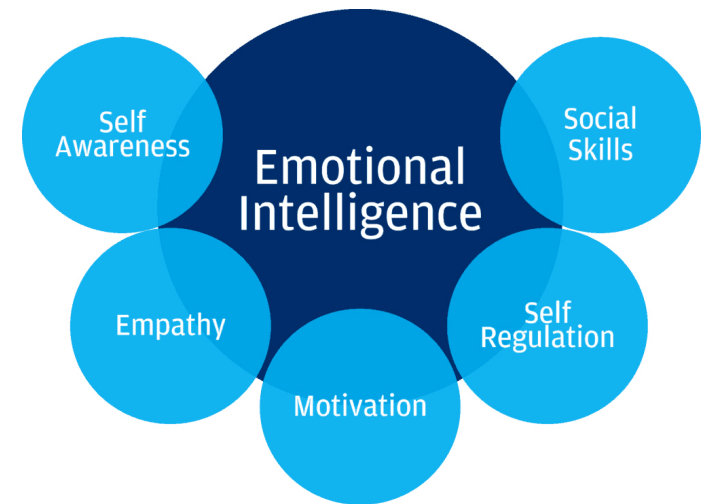
Illustration by Sandbox Studio, Chicago

INCLUSION AND DIVERSITY



**SBS inclusion program: two courses
(Core inclusion and Gender) for all
centre members**

**Emotional Intelligence module from
enmass for all centre members**





2021 Outreach and Impact Award



Michael Baker



Raghda Abdel Khaleq



2021 Collaboration & Centre Values Award



Ciaran O'Hare



Madeleine Zurowski

Congratulations!





Ben McAlester, UWA Rising Stars 2021 competition

Navneet Krishnan John Carver Physics Prize

Theo Motta, Alexander von Humbolt Fellowship.

Anna Mullin, Gates Scholarship

Mike Tobar IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society Distinguished Lecturer for 2021/2022

Catriona Thompson EFTF-IFCS 2021 Best Student Paper Award

Maximillian Amerl Silver Bragg Medal

COLLABORATIONS]



Artist in residence partnership and DM exhibition in 2023 (with CERN if Covid allows)

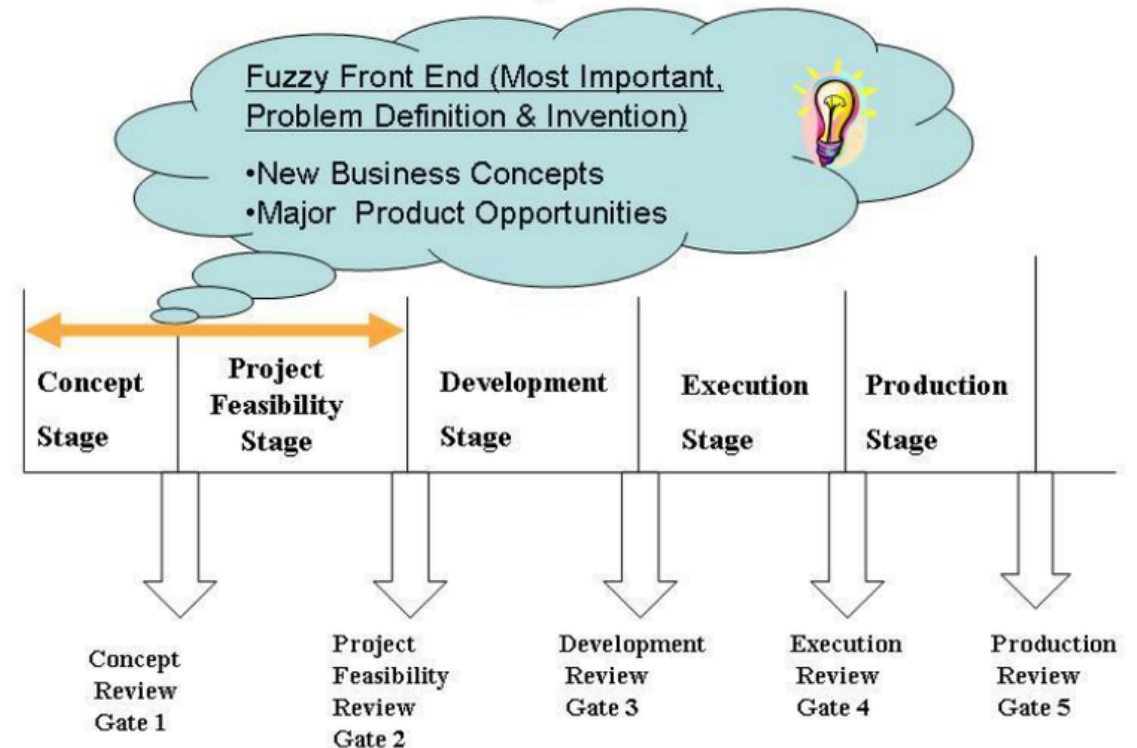
Graduate Melbourne School of Education: Jan van Driel, Victoria Millar and Maurizio Toscano, they funded 2 PhD scholarships to research STEM uptake in schools in partnership with our outreach program

COLLABORATIONS

Swinburne Design

Factory: Christine Thong
at the “fuzzy frontend”
of translation


Classical Product Development Process with Fuzzy Front End



FUTURE PLANS

Ideas suggested by ECRs:

- Media training
- Writing workshop
- Science communication
- Resume writing
- Networking with international partners
(esp. for people on or soon to be on the job market)
- Professional skills



**Good suggestions
but base off a few
responses**

NEXT STEP

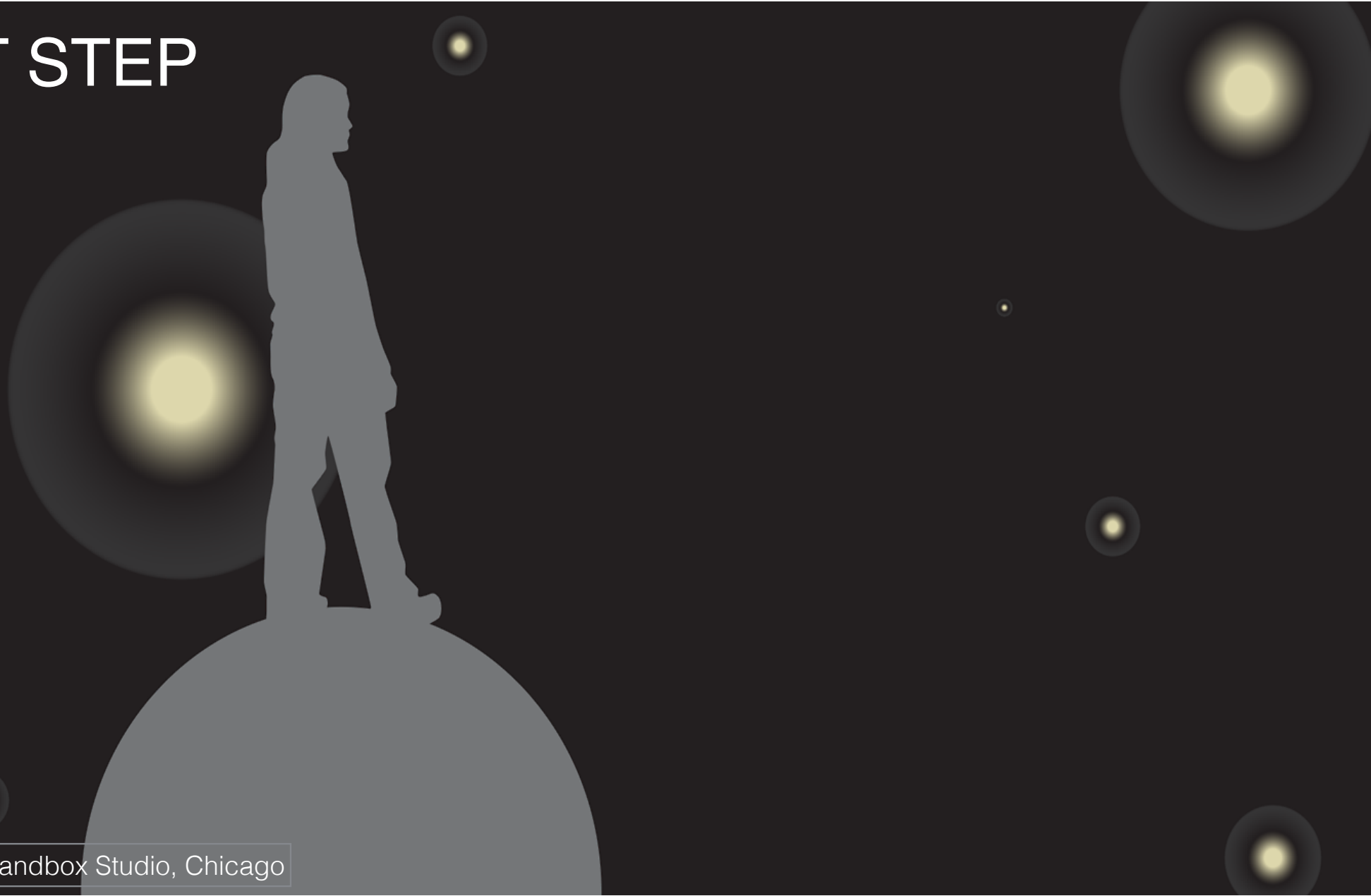
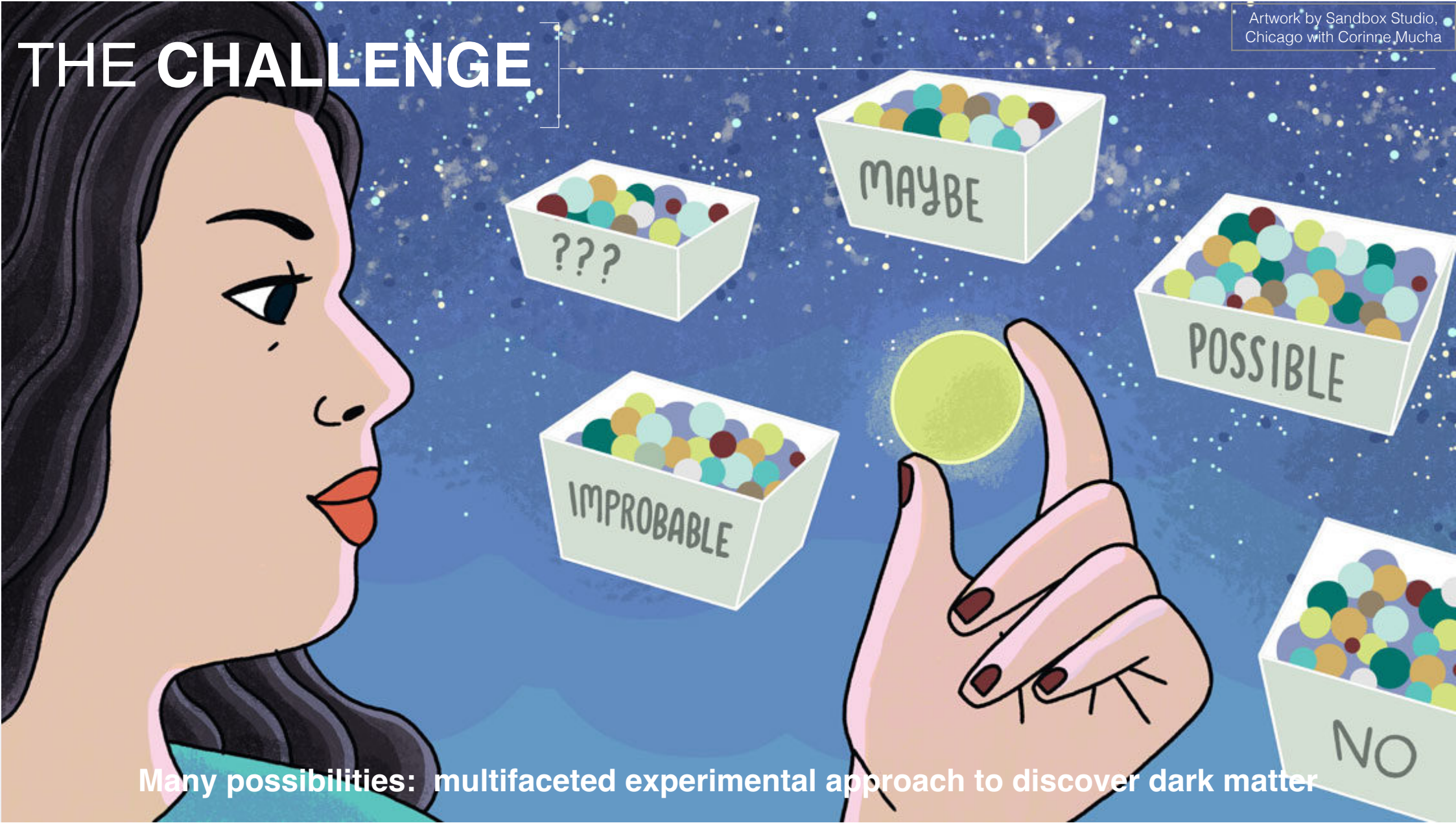


Illustration by Sandbox Studio, Chicago

THE CHALLENGE



Many possibilities: multifaceted experimental approach to discover dark matter

THE ADVANTAGE

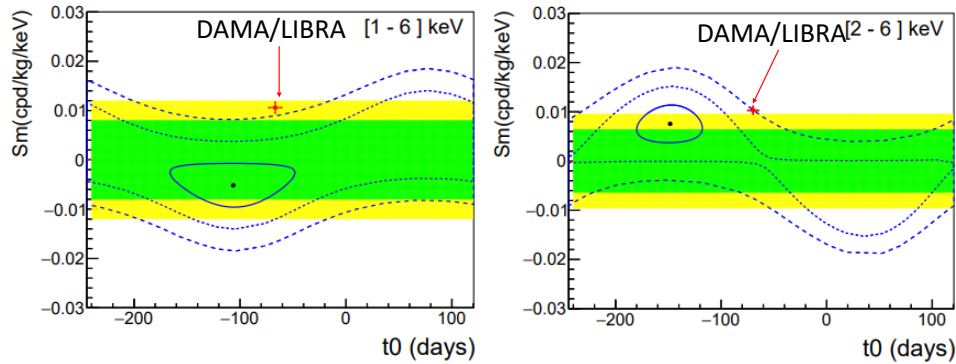


Need **both hemispheres** to **confirm** any dark matter discovery

Physical Review D 103.10 (2021): 102005.

ANAIS

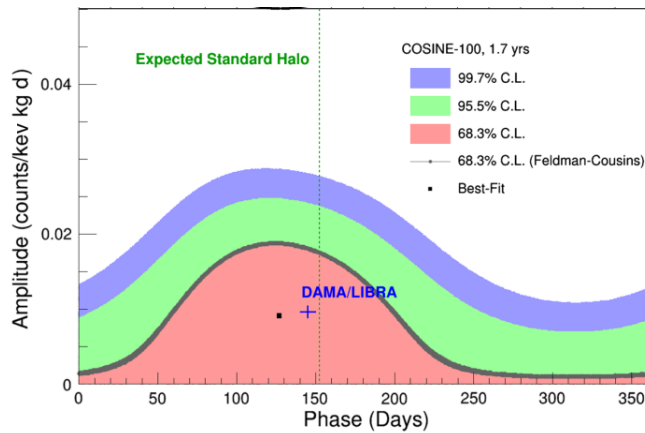
314 kg x yr exposure with no evidence of DAMA/
 LIBRA modulation at $\approx 3\sigma$ significance



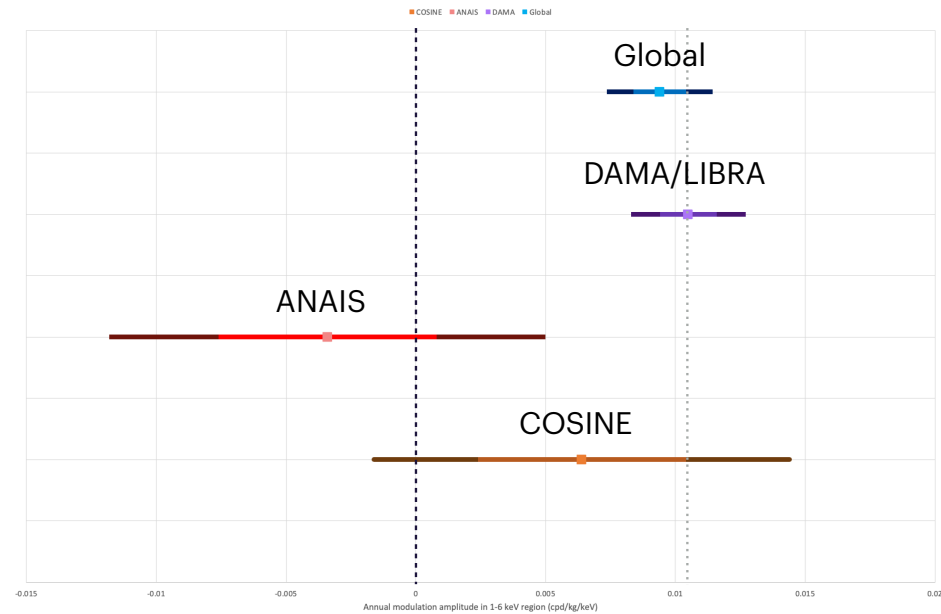
Physical review letters 123.3 (2019): 031302.

COSINE-100

97.7 kg x yr
 exposure
 compatible with
 the DAMA/LIBRA
 result



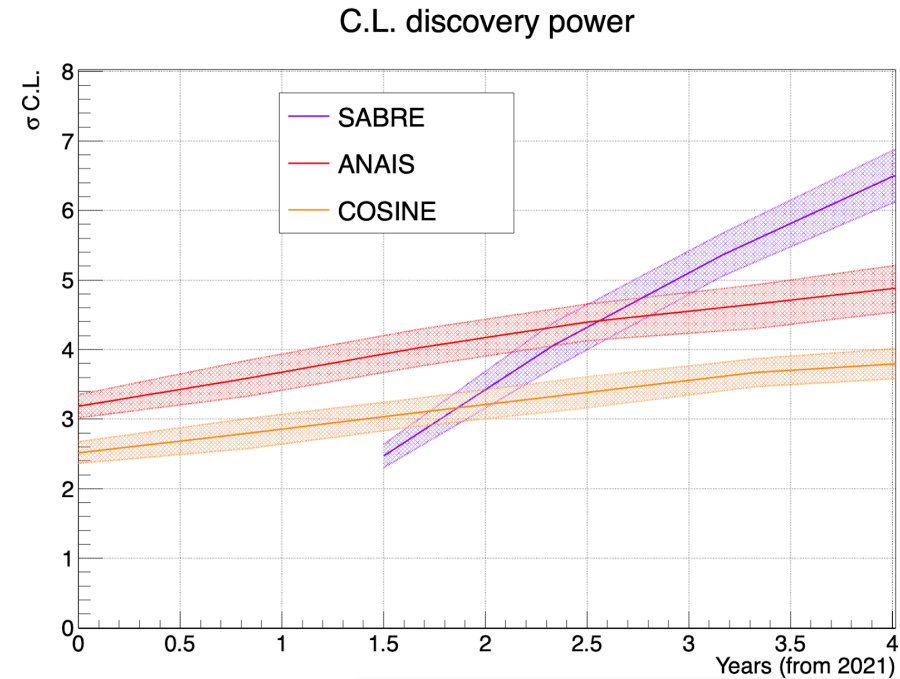
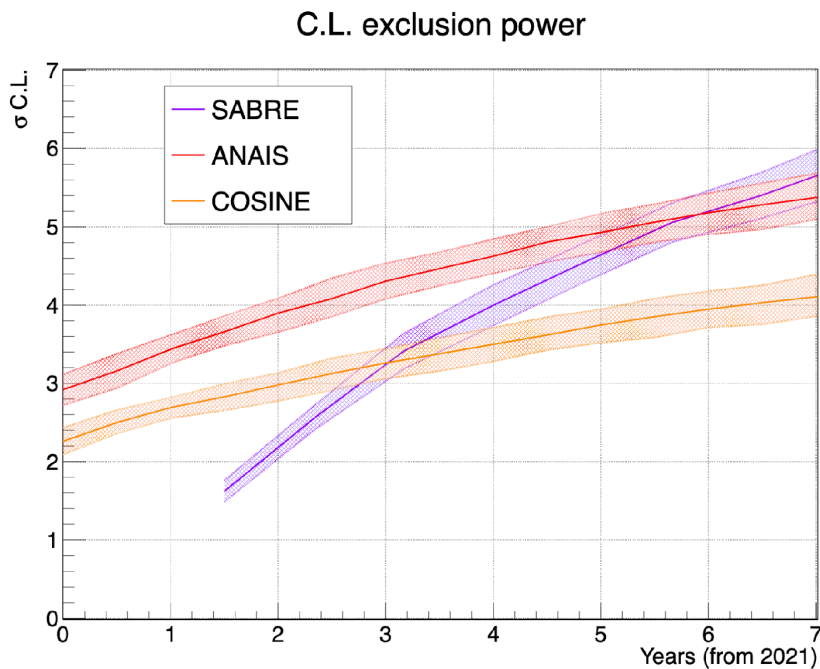
Naive S_m Combination (depends on QF)



SABRE

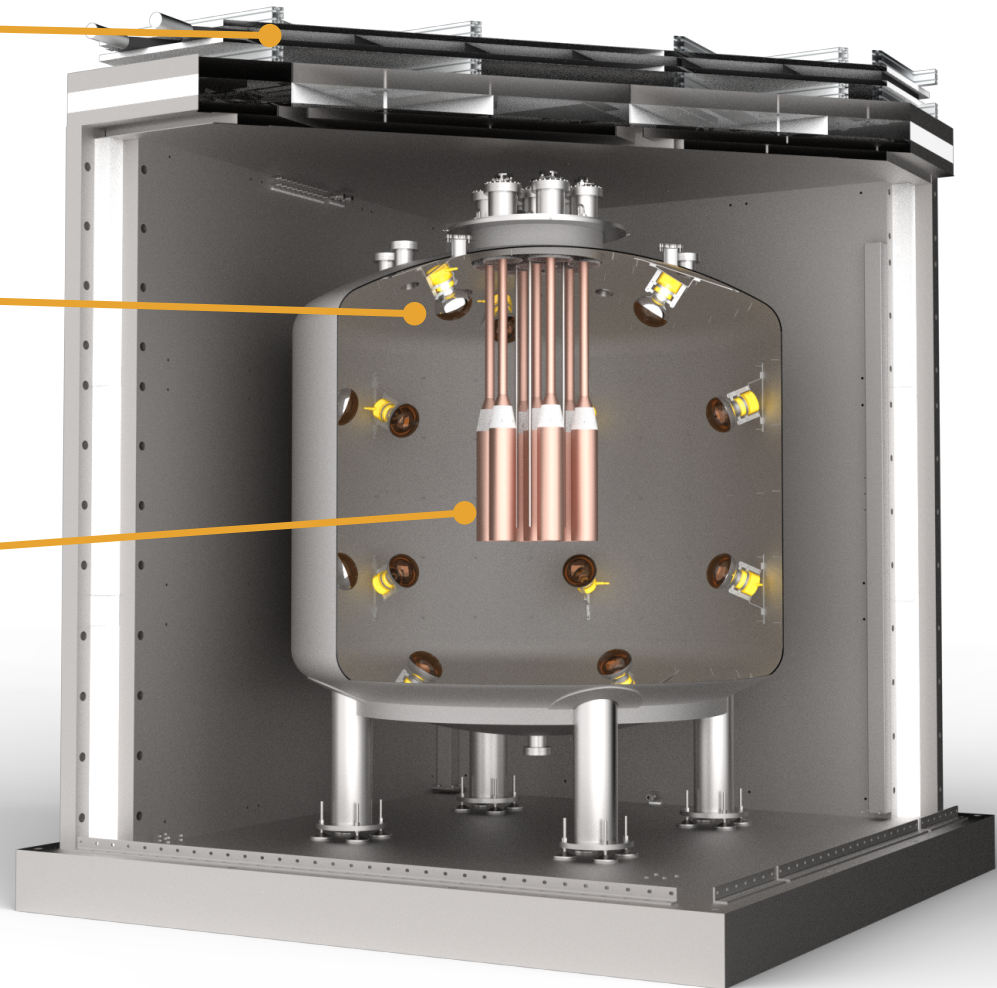
SABRE Projected performance

To compare the exclusion/discovery power of currently operating NaI detectors, want to test how well they can observe the DAMA modulation with their setup, accounting for present live time (NB: typical benchmark values are 3σ for exclusion and 5σ for discovery)



SABRE South @ SUPL

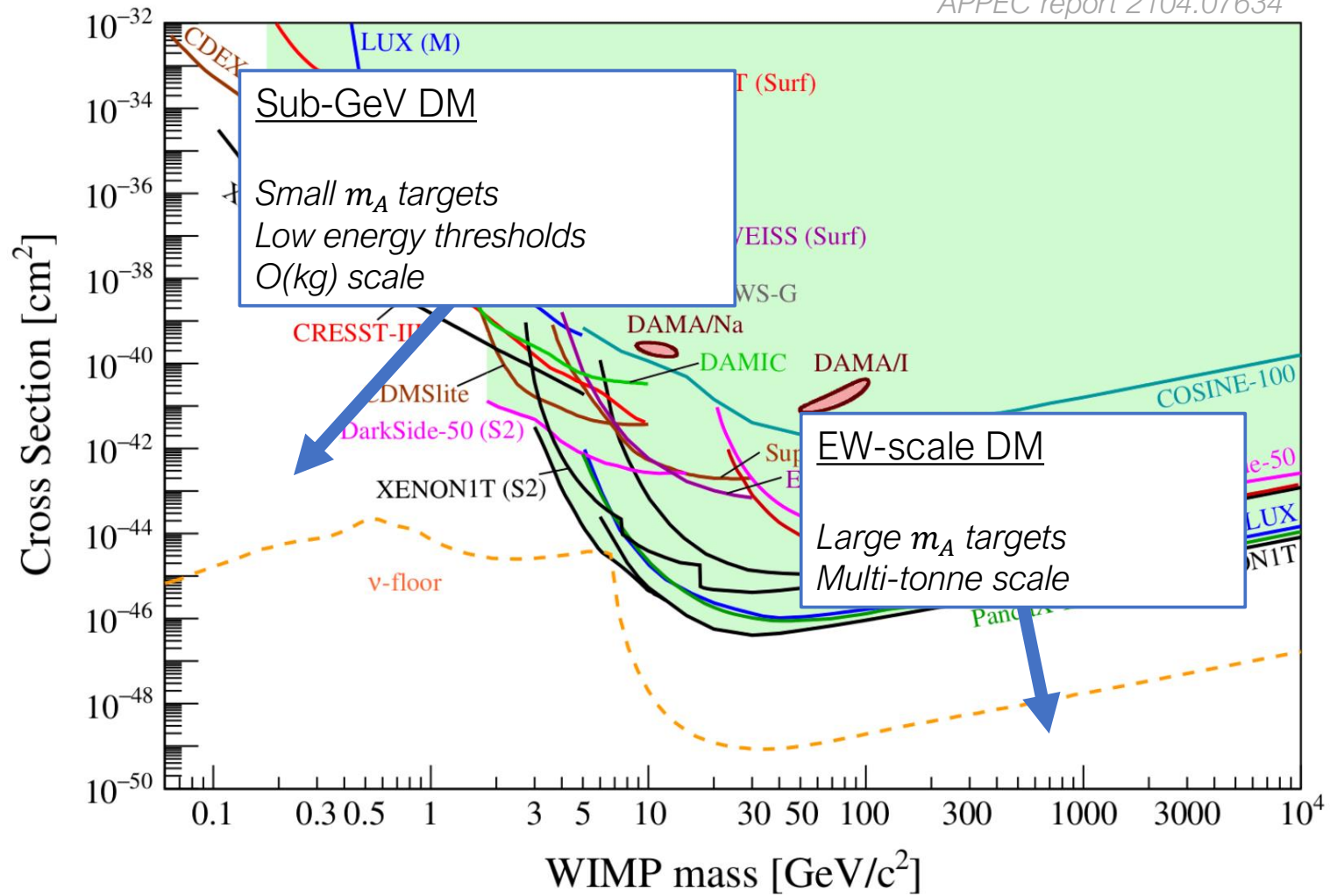
- **ToF Muon System**
9.6 m² x 5 cm EJ200
R13089 PMT x 16 @ 3.2 GS/s
- **Veto System**
12k litres Linear Alkyl Benzene + PPO & Bis-MSB
Stainless steel, non-thoriated welds, lumirror coating
Oil-proof base R5912 PMT x 18 @ 500 MS/s
- **DM Target Detector**
NaI(Tl) Crystals
R11065 low radioactivity PMT x ~14 @ 500 MS/s
- Key requirement to understand modulation in background contributions - requires particle ID. e.g. $\mu/\gamma/n$.



Where we are now

WIMPS

APPEC report 2104.07634



The future (high mass)

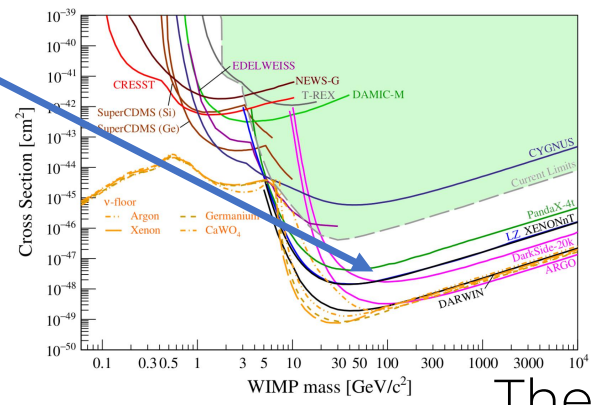
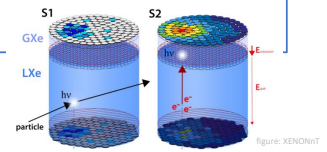
Current generation

PandaX-4t, LZ, XENON-nT ~5t Xe commissioning/data taking

Future

DarkSide-20k 46t Ar (2025)

DARWIN ~40t Xe
ARGO ~300t Ar



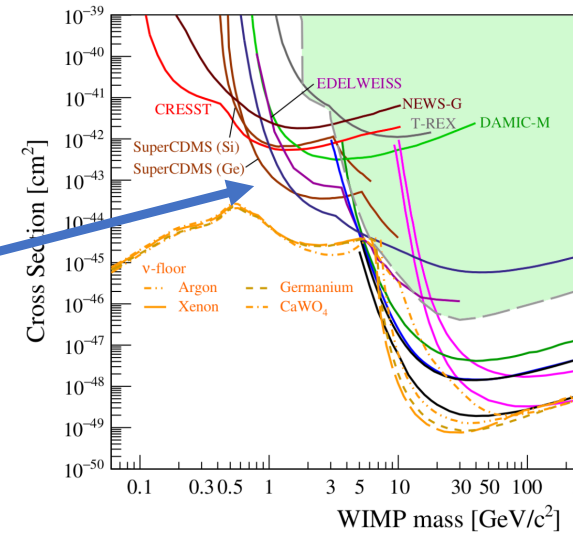
The future (low mass)

Significant progress expected in the next ~5 years

Cryogenic bolometers (phonons)
CRESST-III, COSINUS (+ scintillation)
EDELWEISS, SuperCDMS (+ ionisation)

Ionisation detectors
SENSEI, DAMIC-M (skipper CCD)
NEWS-G (SPC)

Ar/Xe TPCs
Migdal effect
Dedicated *DarkSide-LM*



The next frontier: $m_{DM} < 100$ MeV

(see Wednesday's session)

Many ideas/proposals in this space...

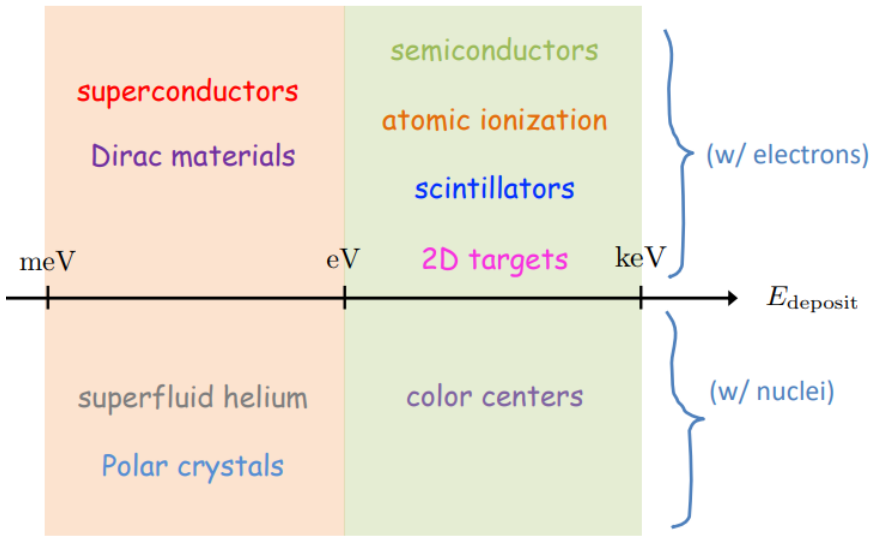
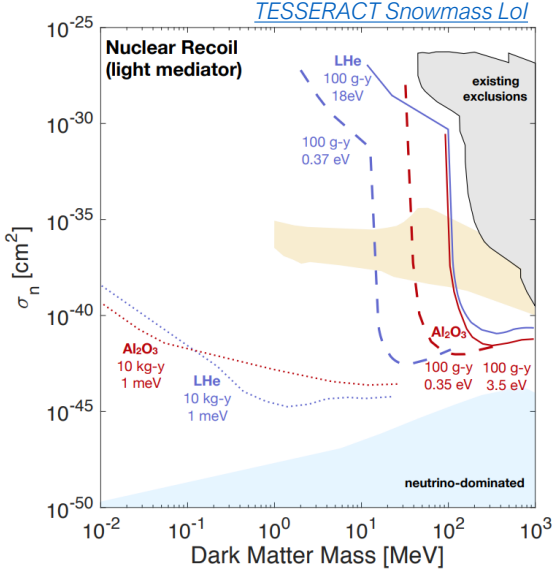
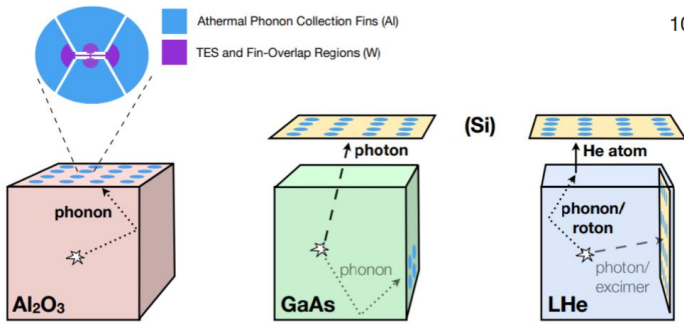


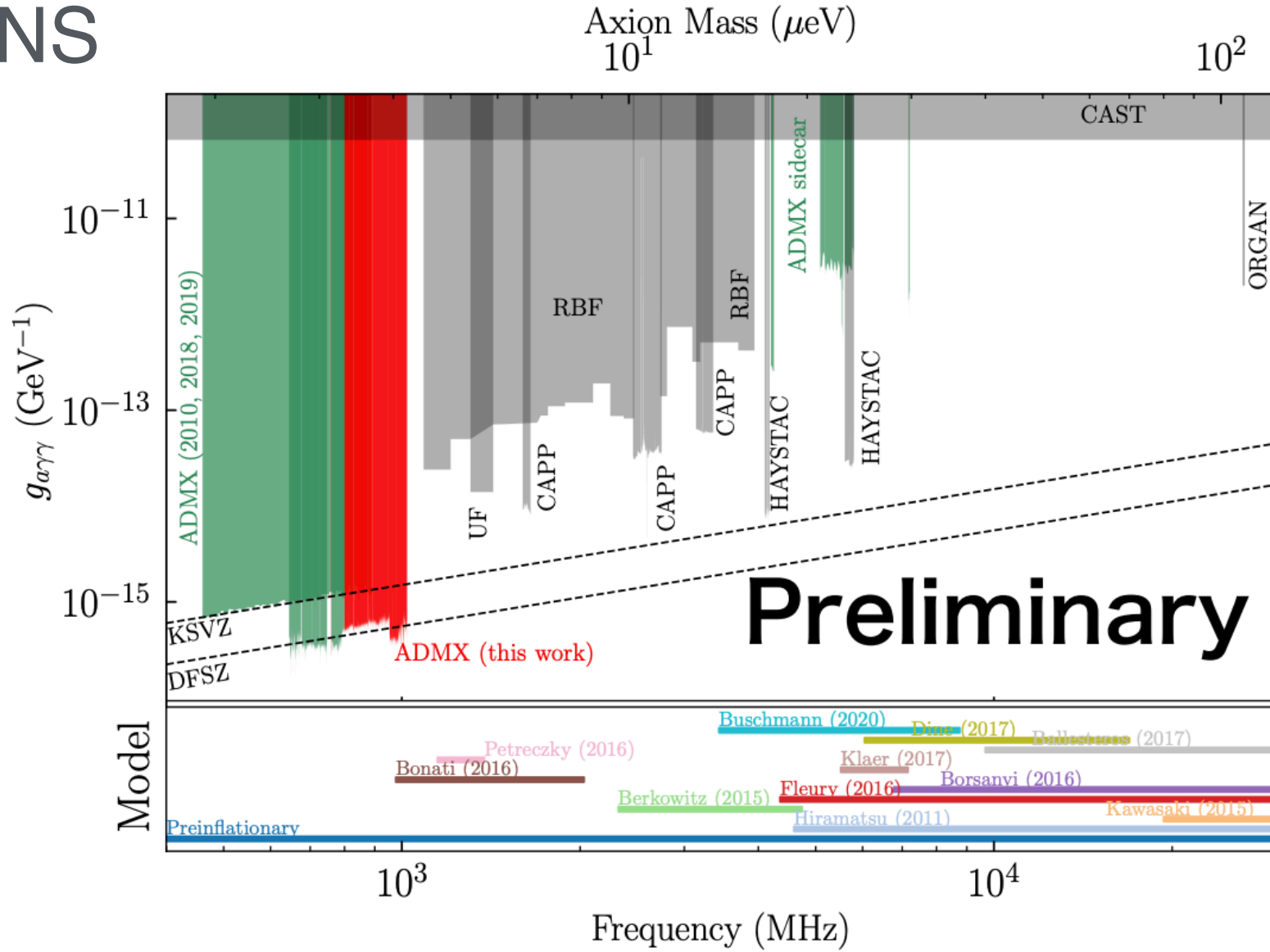
figure: Y. Hochberg

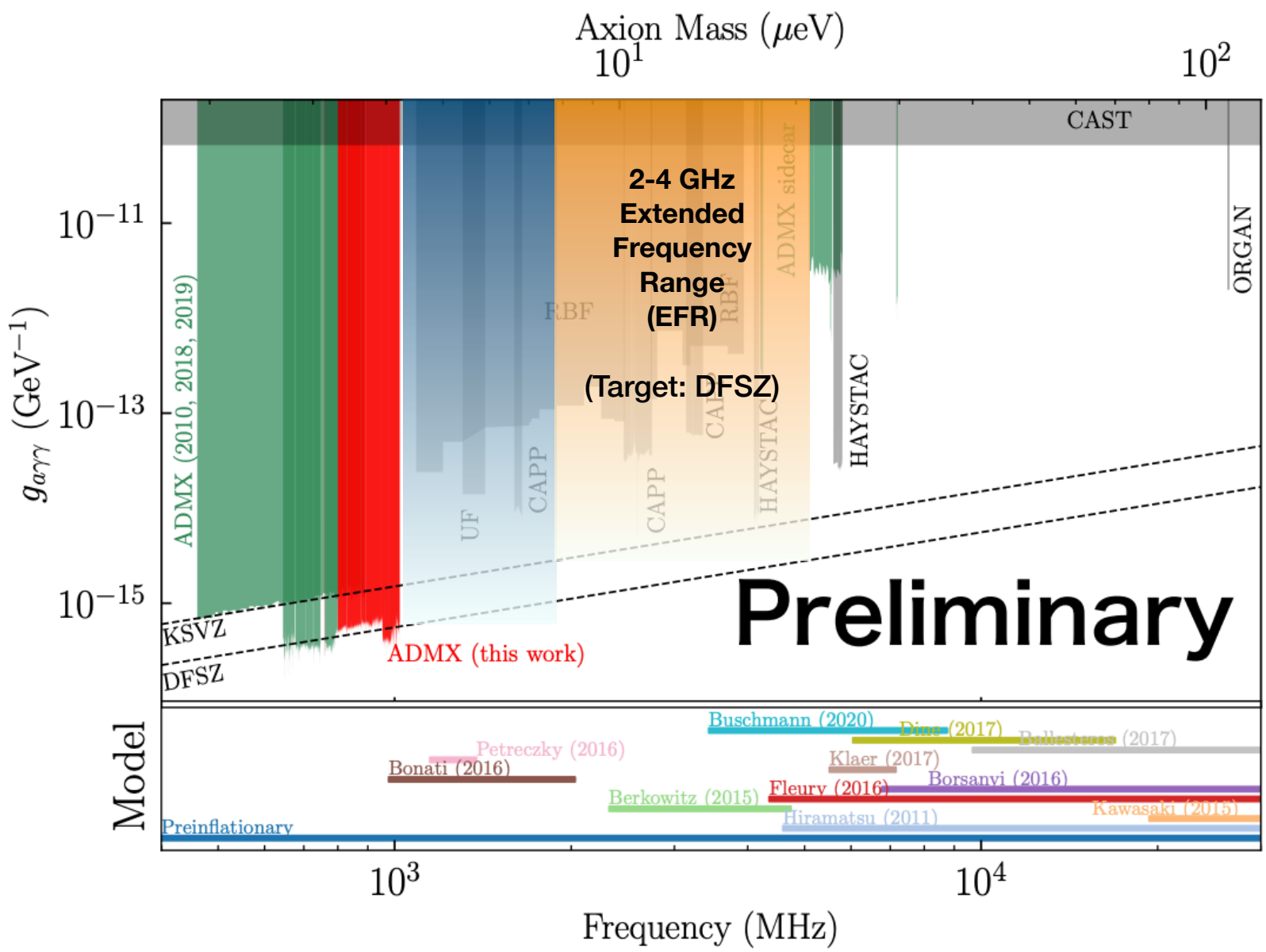
e.g. *TESSERACT* (*HeRALD*/*SPICE*)

R&D, targeting experiment in ~2027



AXIONS





ORGAN

Predictions for axion couplings from ALP co-genesis

Axion Kinetic Misalignment Mechanism

Raymond T. Co¹, Lawrence J. Hall^{2,3} and Keisuke Harigaya⁴

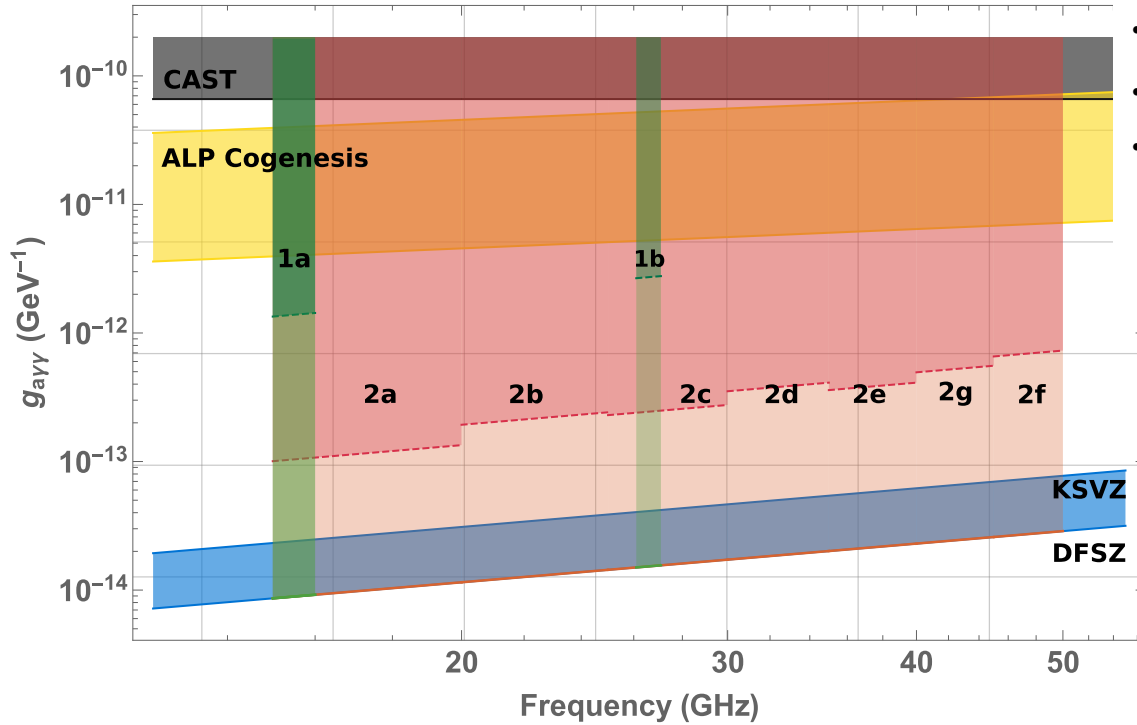
¹Leinweber Center for Theoretical Physics, University of Michigan, Ann Arbor, Michigan 48109, USA
²Department of Physics, University of California, Berkeley, California 94720, USA
³Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
⁴School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA

Raymond T. Co,^a Lawrence J. Hall^{b,c} and Keisuke Harigaya^d

^aLeinweber Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, MI 48109, U.S.A.
^bDepartment of Physics, University of California, Berkeley, CA 94720, U.S.A.
^cTheoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, U.S.A.
^dSchool of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, U.S.A.
 E-mail: rtco@umich.edu, ljhall@lbl.gov, keisukeharigaya@ias.edu

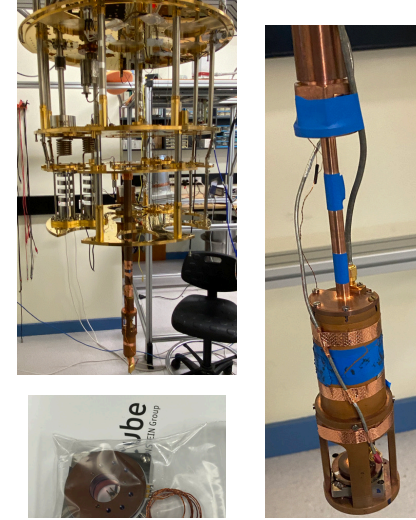
(Received 22 November 2019; revised manuscript received 6 April 2020; accepted 8 June 2020; published 26 June 2020)

In the conventional misalignment mechanism, the axion field has a constant initial field value in the early Universe and later begins to oscillate. We present an alternative scenario where the axion field has a nonzero initial velocity, allowing an axion decay constant much below the conventional prediction from axion dark matter. This axion velocity can be generated from explicit breaking of the axion shift symmetry in the early Universe, which may occur as this symmetry is approximate.



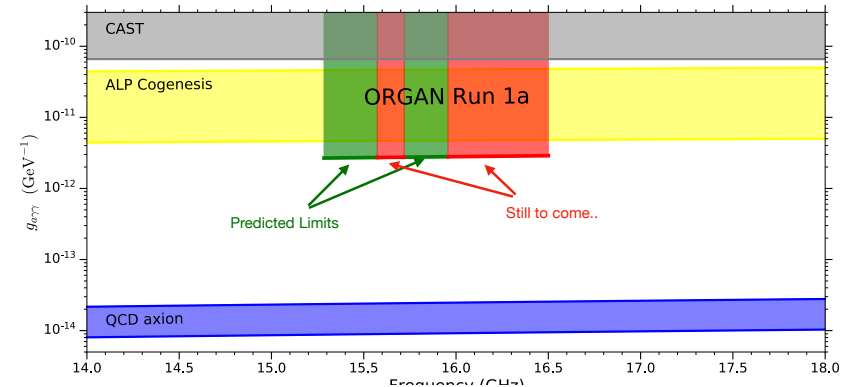
Phase 1a

- Targeting 15.3-16.5 GHz at $\sim 3 \times 10^{-12} g_{\gamma\gamma}$ (ALP co-genesis)
- Scan rate - How fast we can exclude axions at a given mass and coupling
- Scan rate $\propto \omega^{-14/3}$
- $\omega \propto R^{-1}$ and $V \propto R^3$ (small cavities)
- Small cavities = Small machining tolerances



Preliminary Limits

- Predicted limits using $Q_{ave} = 4000$, $T_{sys} = 10K$, $B_0 = 11.5T$
- Set to be place the most sensitive limits in this region



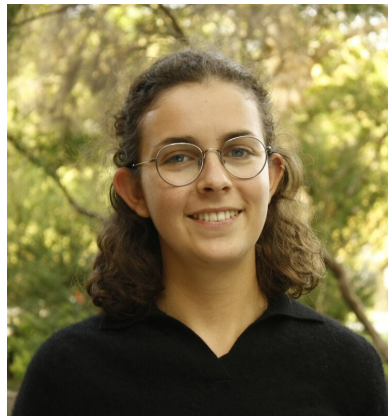


2021 CDM Poster Awards

Voted by panel:

Madeleine Zurowski

Influence of NaI background and mass on model independent tests of DAMA's modulation



Influence of NaI background and mass on model independent tests of DAMA's modulation
 arXiv:2107.07674
 Madeleine J. Zurowski, Elisabetta Barberio (School of Physics, University of Melbourne)
 madeleine.zurowski@unimelb.edu.au

NaI experiments should be sensitive to the same DM-DM interactions proposed to explain the observed DAMA modulation. As such, they are often called a 'model independent' test of the signal. While the same signal will be produced at all NaI detectors, the ability to observe it is strongly dependent on the experimental setup – in particular the mass and background of the target.

We present here a study on how changes to these values influence the ability of a detector to observe a dark-matter DM modulation. We consider a model-independent analysis assuming exactly the modulation signal observed by DAMA, i.e., making no assumptions about the particle interaction model postulating this signal, and find that in general a low background is favoured over a higher exposure mass (based on currently achievable levels).

Analysis procedure.
 Account for the fact that although we are comparing a modulating rate to a constant background, in some cases substantial uncertainties in constant rate on mask or energy signature modulation.
 Event rates at a detector are simulated by randomly sampling from a Poissonian on top of $N_{\text{sig}} = M_0 \Delta T \Delta E (R_s + R_b + R_m \cos \alpha)$ (for signal + background model) or
 or $N_b = M_0 \Delta T \Delta E (R_b)$ (for background only model),
 where
 M_0 = exposure mass (kg)
 ΔT = data taking time period (days)
 ΔE = energy bin of interest (keV)
 R_b = background rate (cpd/kg/keV)
 R_s = constant signal rate (cpd/kg/keV)
 R_m = modulating signal rate (cpd/kg/keV)

Experimental lifetime is simulated 100x times and fit to a cosine (Fig. 1) to find the probability function for modulation observation for each case (Fig. 2). Mean (μ) interpreted as observed modulation and standard deviation (σ) its uncertainty. These are used to construct the test statistics used for analysis.

Test statistics.
 Exclusion (or C.L.): how well a signal can be identified assuming signal + background hypothesis. Depends on signal + background uncertainty.

$$n = \frac{|R_{\text{sig}} - \mu_1|}{\sigma_1}$$

 Discovery (or C.L.): how well a signal can be identified assuming background only hypothesis. Depends on background uncertainty.

$$n = \frac{|R_{\text{sig}} - \mu_1|}{\sigma_1}$$

Model independent results.
 For model independent tests, instead of using different values of m_χ and σ_χ to compare, R_b and R_m we take the values observed by DAMA. This allows us to calculate the required time each detector takes to exclude (or discover) the signal with some confidence without assuming any particle interaction model. (Though as DAMA have not published their constant rate we assume the standard halo model distribution for dark matter to derive a value for $R_b = 0.002 R_{\text{DM}}$.)
 The results for each detector are shown in Figs. 3 and 4, with the table below giving experimental assumptions, and expected time frame for benchmark exclusion and discovery levels.

Experiment	ANAS 1H	COSINE 1H	SABRE 1H
Mass (kg)	112	57.5	50
R_b (cpd/kg/keV)	3.2	2.7	0.36
Current excl.	2.5	2.3	0
For 3 σ excl.	3 yrs	5 yrs	2 yrs
For 5 σ disc.	7 yrs	>7 yrs	2 yrs

These results highlight the difference between the two test statistics – whether they depend on uncertainty of the background or signal + background modulation. Experiments with a lower background rate (like SABRE) naturally have a lower uncertainty (as this scales with $\sqrt{N_b}$), leading to the noticeably larger discovery level.

Conclusions.
 For both model-dependent and dependent limits the lowest background (SABRE) has performed the best of the three new experiments, despite having the lowest exposure mass. This makes clear how important a low background is for DM searches: in order to observe the small modulation at an already low interaction rate, further reducing the modulation and veto techniques presently explored by these collaborations.
 Based on this analysis, should the proposed exposure mass and backgrounds be achieved, and data taking commence in the next 18 months, SABRE will be positioned to provide statistically significant exclusion or discovery of the DAMA signal within 3–4 years.
 In this event (and even more so in the event of a positive DM-like signal), it will be beneficial to compare the results from the Northern and Southern hemispheres, to further elucidate clues as to nature of the modulating DAMA signal – DM or not.

Acknowledgements
 This work was supported by the ARC Centre of Excellence for Dark Matter Particle Physics through grant CE1100008. MZC is supported through the Australian Government Research Training Program Scholarship. Both authors are members of the SABRE Collaboration.

References
 [1] Aprile et al. (ANAS Collaboration) 10.1148/physmed.2020.046014
 [2] Aprile et al. (COSINE Collaboration) 10.1103/PhysRevLett.124.111301
 [3] Aprile et al. (SABRE Collaboration) 10.1103/PhysRevLett.124.111302





2021 CDM Poster Awards

Voted by CDM members:

Graeme Flower

Choosing Dissipative Models for Josephson Junction based Single Photon Counters



Choosing Dissipative Models for Josephson Junction based Single Photon Counters

Graeme Flower
 Supervisors: Michael Tobar, Maxim Goryachev, Ben McAllister
 Collaboration with Thomas Stace (UQ)

Motivation:

Beating the standard quantum limit is essential for searching for QCD axion dark matter above 50eV in a reasonable amount of time. A promising way to do this is with a current biased Josephson junction (JJ) as a single-photon counter (SPC). Something being in this area is a complete quantum model of the system, where in the past only phenomenological models have been used. The system is typically modelled as an RC circuit. Any correct quantum model should be able to reproduce the classical behaviour of the circuit entering a voltage state when the system's phase particle tunnels out of the well. This turns out to be non-trivial. This work needs to be done to ascertain the best model and the extent to which it is valid.

Aims:

The final aim is to find an appropriate complete quantum model of the a current biased Josephson junction as a photon counter. The aim for work shown here is to test some quantum models on an RC circuit to see if they can reproduce classical correspondence of the voltage state for the device.

Theory for the JJ based SPC

The current biased JJ has a well-known potential, where the system starts out in a metastable state and via the arrival of a photon can be excited to a higher metastable state where it can quickly escape. It is now rolling down the hill producing a measurable DC voltage that signals a photon arrive.

$H_{\text{app}} = E_C J^2 = E_J \cos(\phi) + E_C \phi + E_p \phi(a + a^\dagger) + h\omega_c a^\dagger a$

Test Model for the Voltage State

Generalised picture:

A current biased RC circuit is our test system to compare dissipation models. The state starts out as a Gaussian distribution with maximum equal to the steady state transmission predicted by ohm law for the resistor (which is proportional to voltage). The system should remain in the steady state transmission until it reaches the bottom of the well (an artificial bounding).

Master equations for different dissipative models

Block-Redfield equation:

$$\dot{\rho} = \frac{i}{\hbar} [H, \rho] + \sum_m \frac{\omega_m}{2\hbar} (\Phi_m \rho - \rho \Phi_m^\dagger) \Phi_m$$

Sum over transitions

Lindblad equation:

$$\dot{\rho} = \frac{i}{\hbar} [H, \rho] + \sum_k \frac{\omega_k}{\hbar} D_k \rho \sum_l \Phi_l^\dagger \rho \Phi_l \quad (\text{im} \gg \hbar)$$

Sum over degenerate subspaces Sum over degenerate transitions in each subspace

Why are Lindblad master equations usually standard

- They are completely positive and guaranteed to produce positive probabilities associated with measurements.
- Quantum trajectory theory for modelling quantum measurements is in Lindblad form.

But:

- They are obtained by making a rotating wave approximation of the Bloch-Redfield equations and are therefore less general.
- They can either reproduce detailed balance or have a transcendently incorrect dissipation but not both.

Simulation Results

Lindblad Master equation

Block-Redfield master equation

Dimensionless Momentum

Dimensionless Momentum

Dimensionless Velocity

Dimensionless Velocity

Clearly the Bloch-Redfield equations reproduce classical expectations set by ohm law for the resistor and the Lindblad equations don't. We also see the Lindblad results break the standard relation between velocity and momentum giving an ambiguous definition for voltage (as both should be related). This is related to transcendental ignorance of the dissipation.

But are the Block-Redfield results physical? No. States have significant negative eigenvalues manifesting in the standard observable bases as a violation of the uncertainty principle which is larger for more dissipation.

Neither equation is suitable for large dissipation inductive, as we trade correct kinematics for unphysical states. Small dissipations (large resistances) have more physical states and therefore may produce usable Bloch-Redfield equations for the real device.

Outlook and future work

Low-dissipation limit shows here seems to produce altered results and reproduces correct kinematics for the Bloch-Redfield equations. This may be the best option for modelling a Josephson junction although it limits the parameter space we can use the model. For large dissipations (small resistances) we may have to revert back to phenomenological models.

OUTLOOK



Thank you for all your effort this year

**Looking forward to the next years of
exiting research in an inclusive,
collaborative and safe environment**

Illustration by Sandbox Studio, Chicago

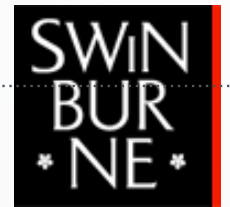
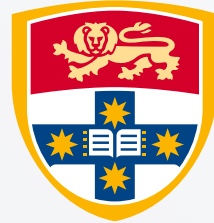
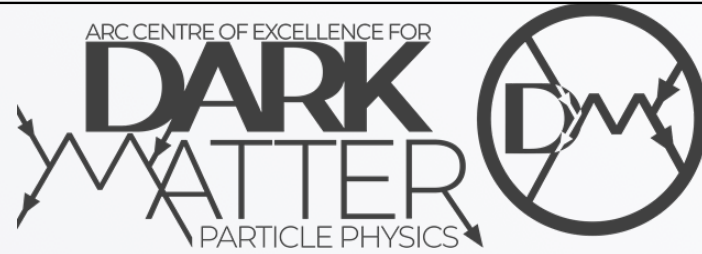
OUTLOOK



We are taking part in a scientific revolution that will transform how human beings see the universe.

Illustration by Sandbox Studio, Chicago

THE TEAM



The University of Melbourne | The University of Adelaide | The University of Sydney | The University of Western Australia | The Australian National University | Swinburne University

PARTNERS

