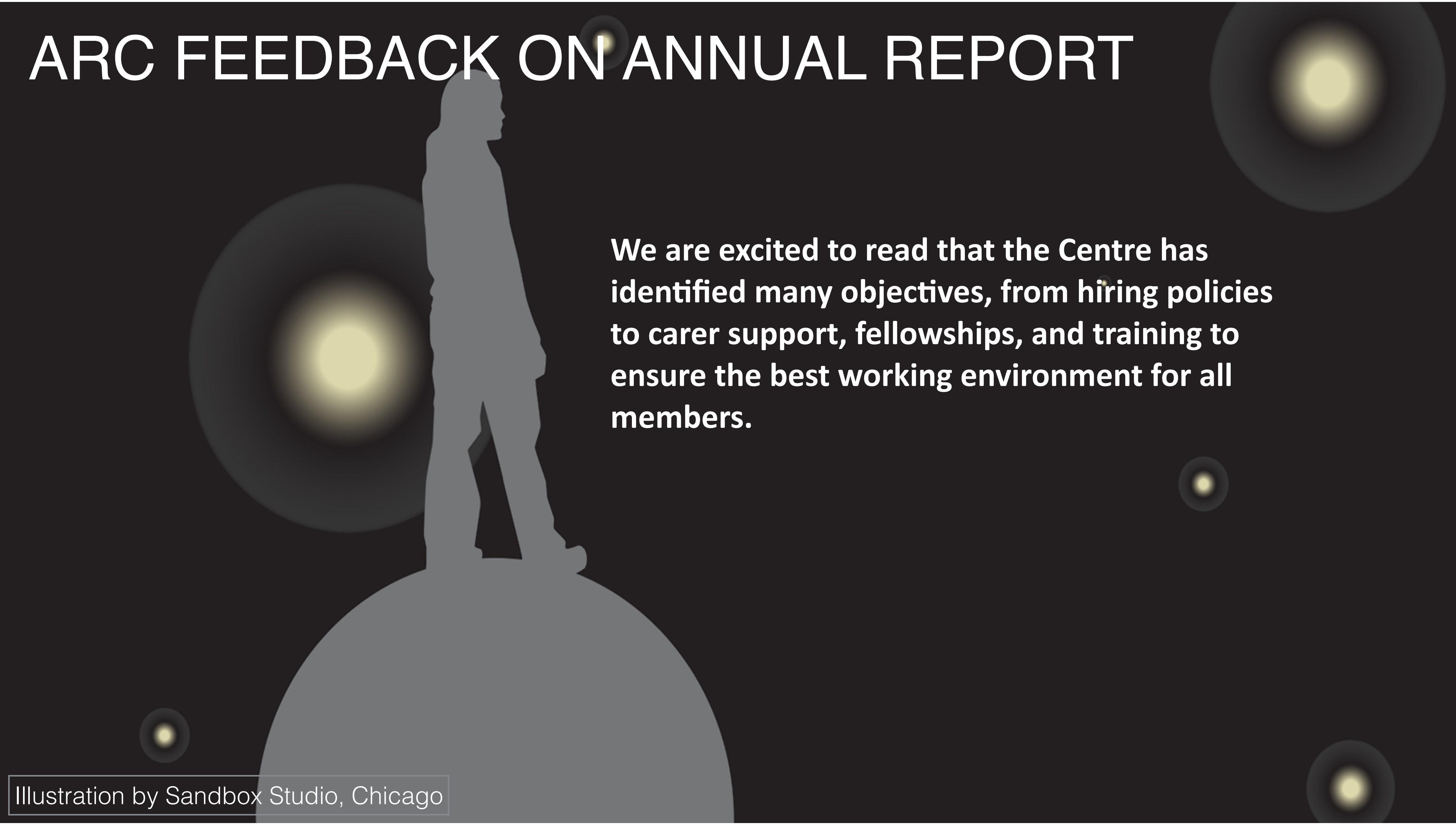
ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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

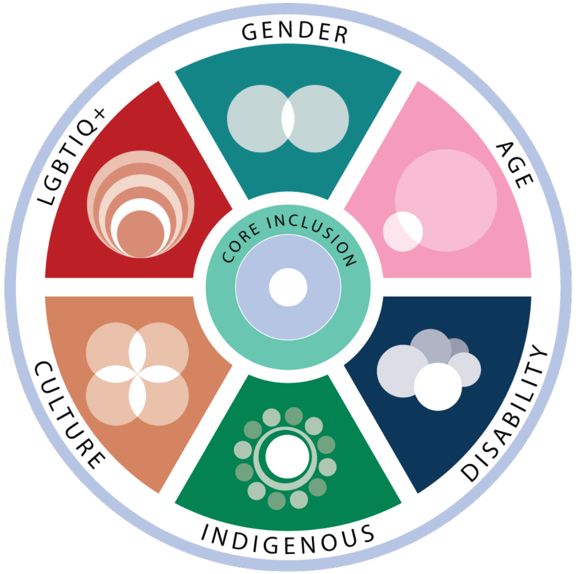
ARC FEEDBACK ON ANNUAL REPORT



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.

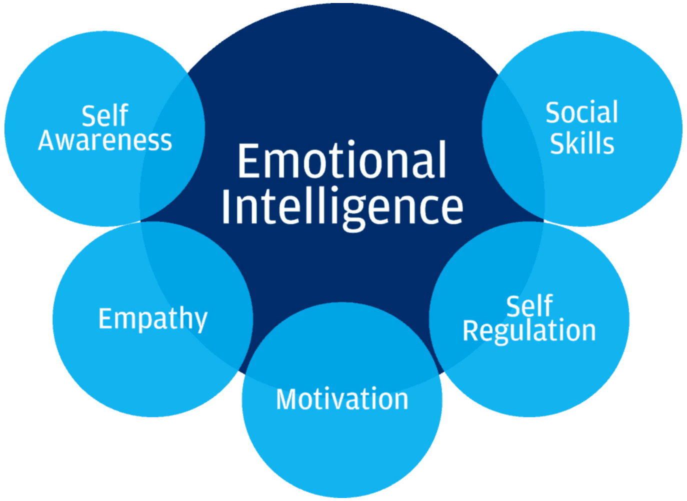
Illustration by Sandbox Studio, Chicago

INCLUSION AND DIVERSITY



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

Emotional Intelligence module from enmasse for all centre members



2021 Collaboration & Centre Values Award

Ciaran O’Hare

Madeleine Zurowski

2021 Outreach and Impact Award

Michael Baker

Raghda Abdel Khaleq

Congratulations!

Ben McAllister, 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

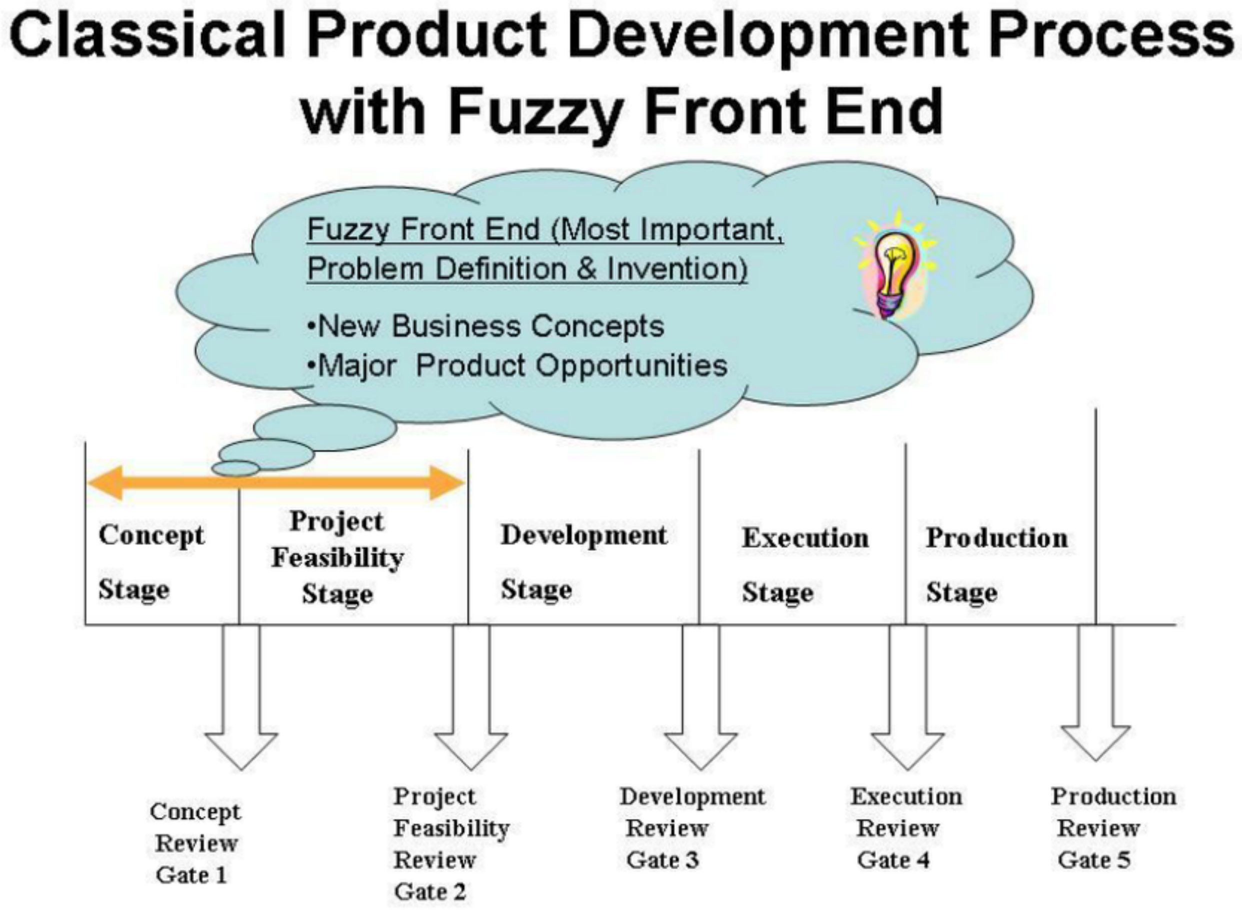
SCIENCE GALLERY

Artist in residence partnership from 2022 and DM exhibition in 2023 (with CERN if Covid allows)

Melbourne Graduate 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 front end” of translation



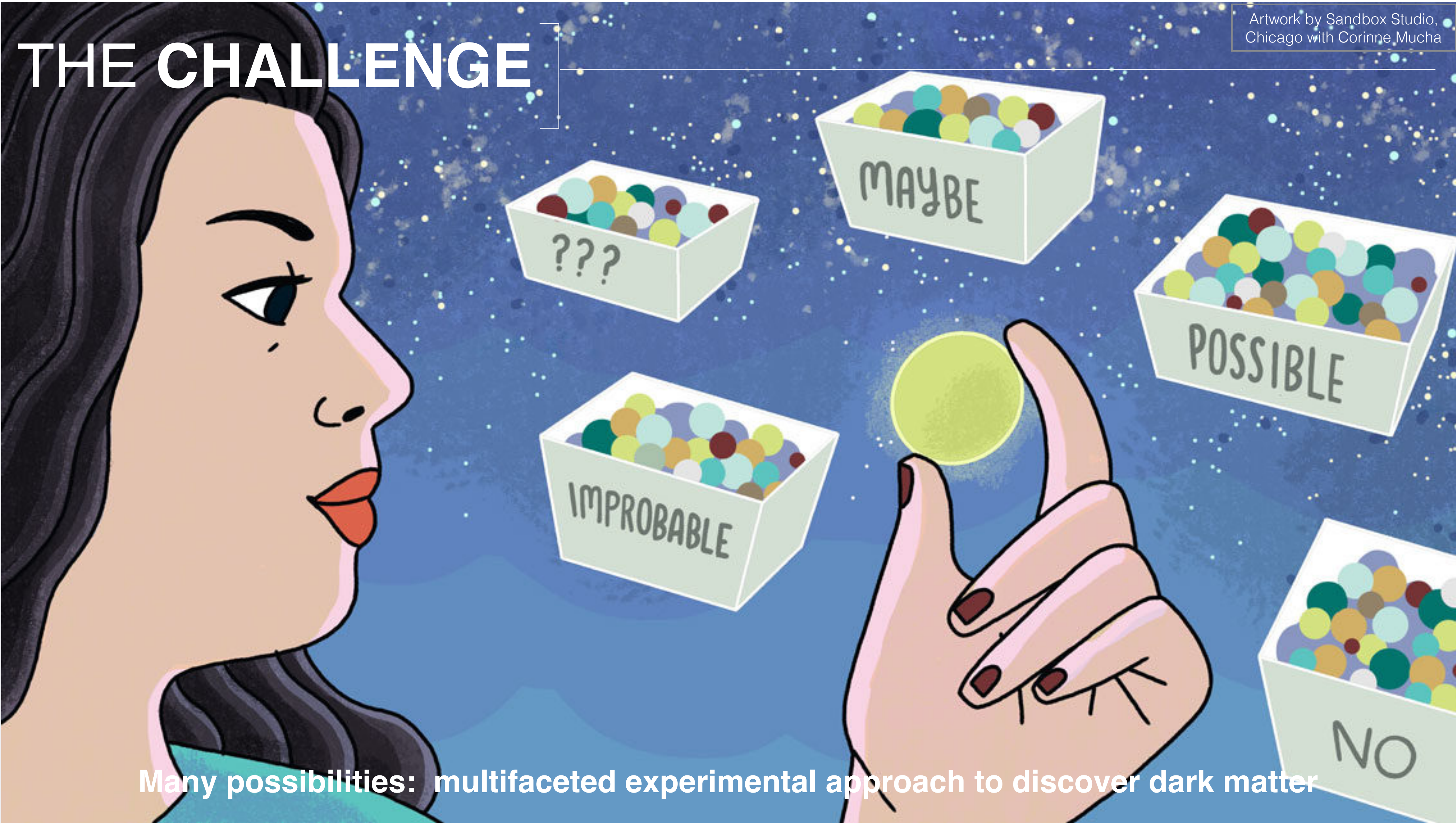
FUTURE PLANS

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

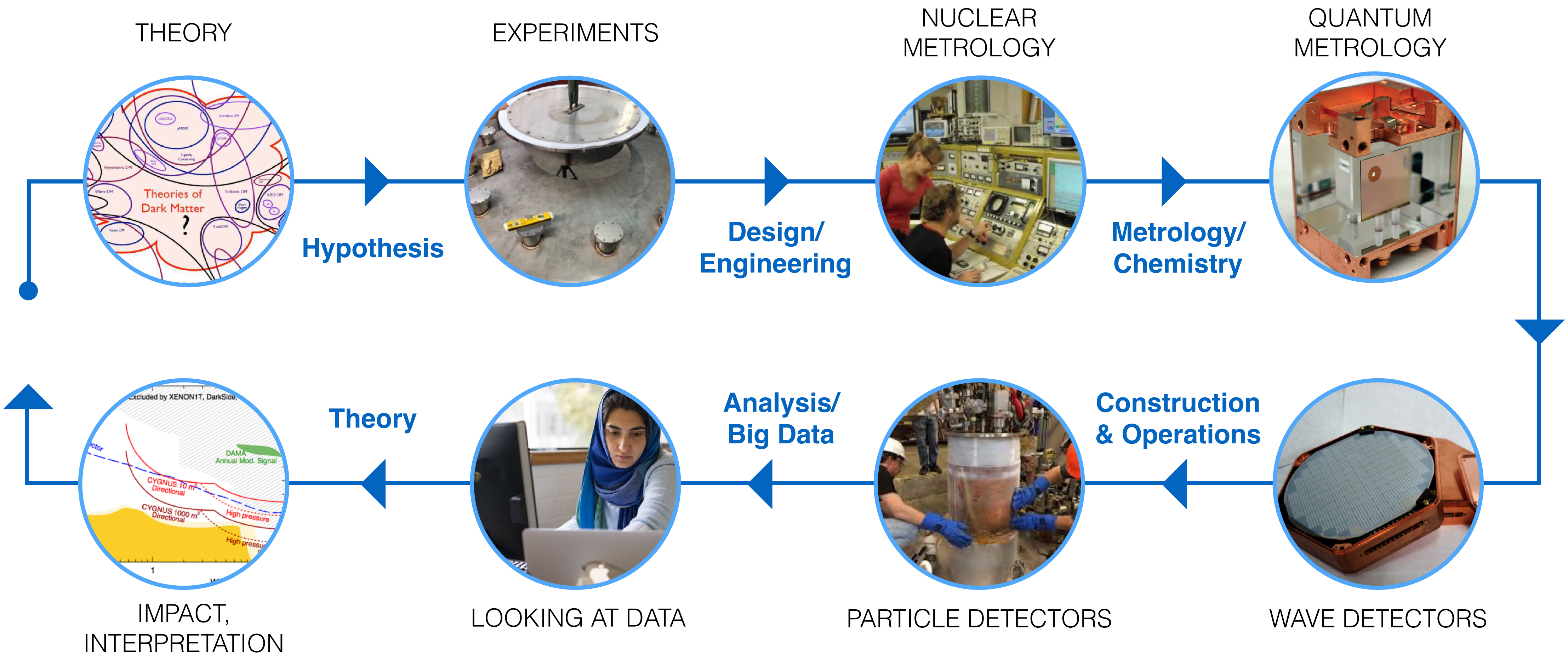
THE CHALLENGE



Artwork by Sandbox Studio, Chicago with Corinne Mucha

Many possibilities: multifaceted experimental approach to discover dark matter

DARK MATTER SEARCHES



THEORY

Hypothesis

EXPERIMENTS

Design/ Engineering

NUCLEAR METROLOGY

Metrology/ Chemistry

QUANTUM METROLOGY

WAVE DETECTORS

Construction & Operations

PARTICLE DETECTORS

Analysis/ Big Data

LOOKING AT DATA

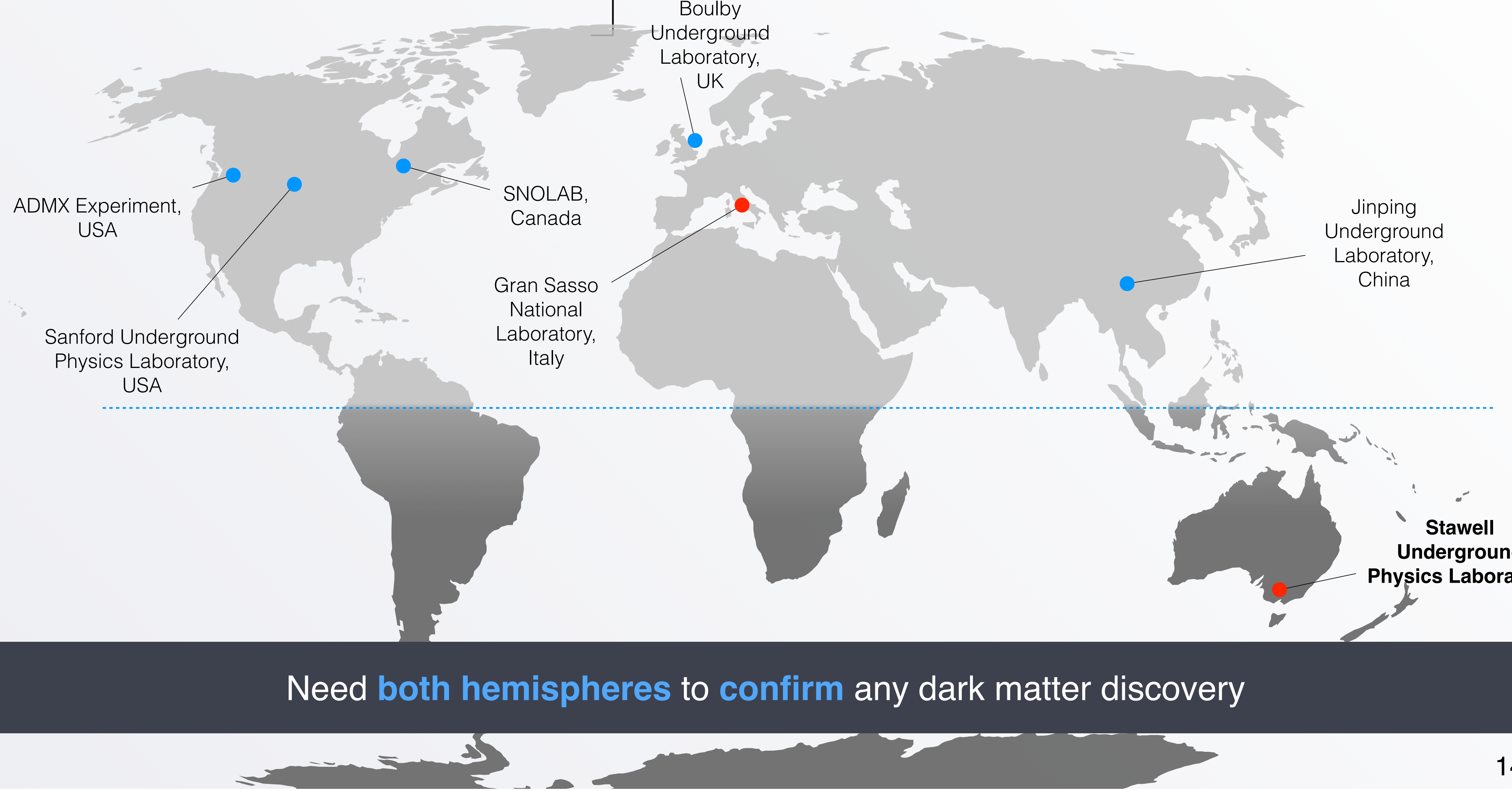
Theory

IMPACT, INTERPRETATION

Illustration by Sandbox Studio, Chicago

NEXT BIG DECISIONS

THE **ADVANTAGE**

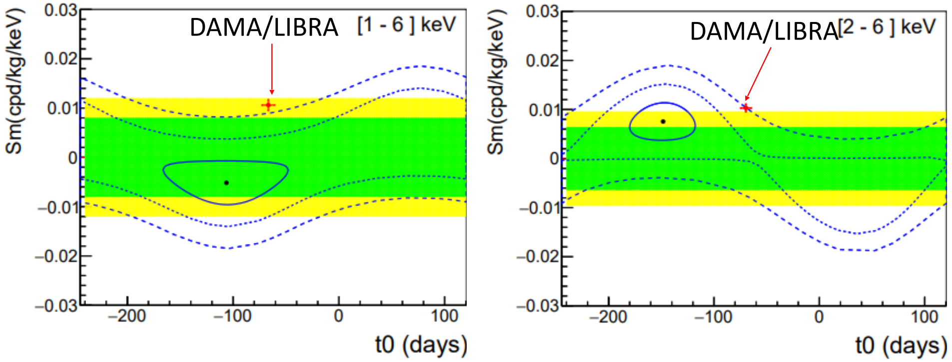


Need **both hemispheres** to **confirm** any dark matter discovery

Physical Review D 103.10 (2021): 102005.

ANAIS

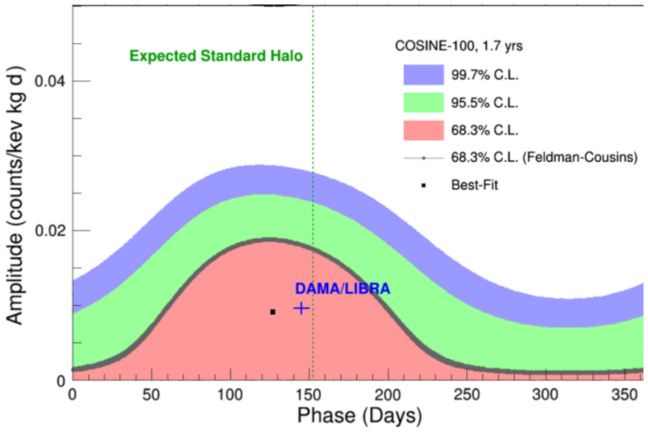
314 kg x yr exposure with no evidence of DAMA/LIBRA modulation at $\approx 3\sigma$ significance



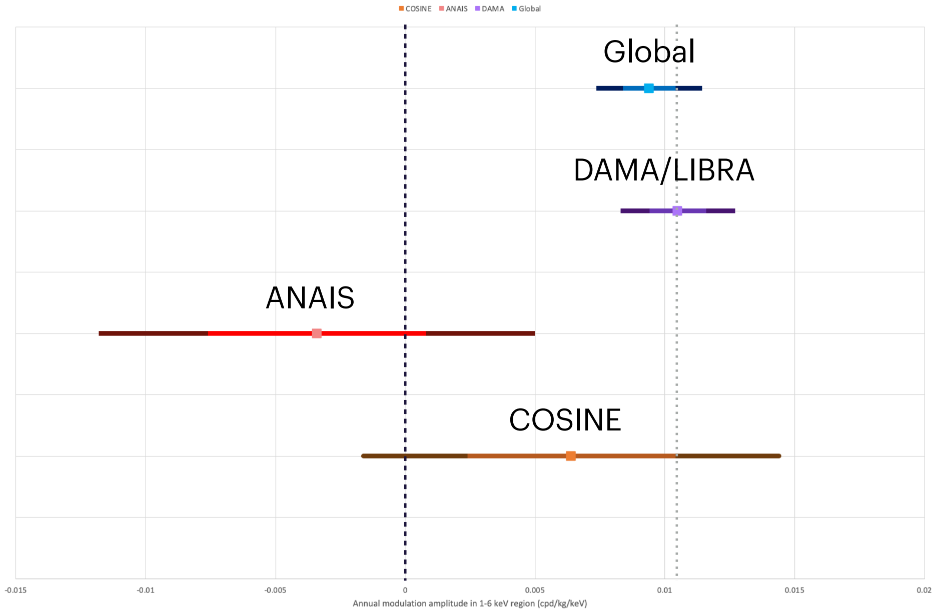
Physical review letters 123.3 (2019): 031302.

COSINE-100

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

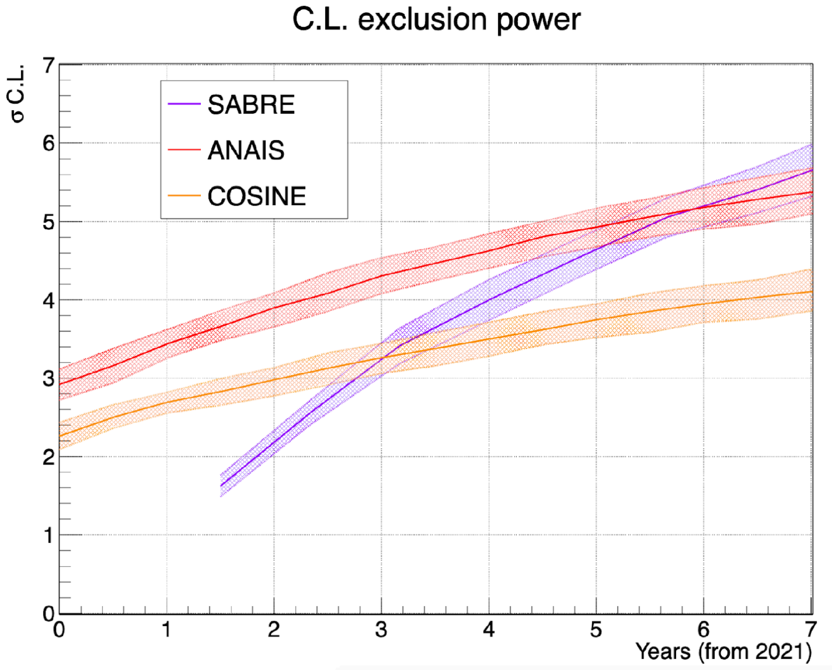


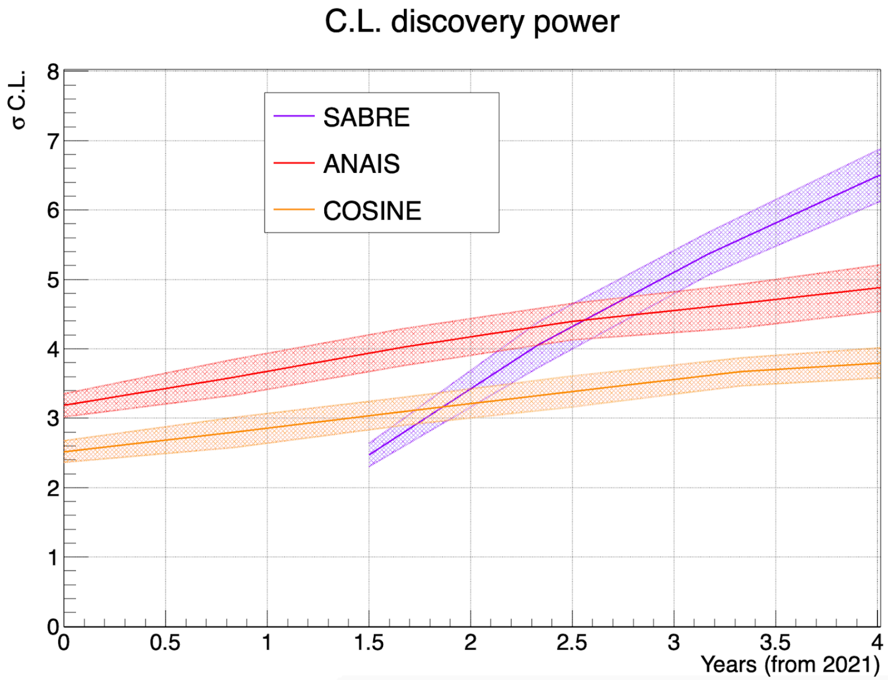
Naive S_m Combination (depends on QF)



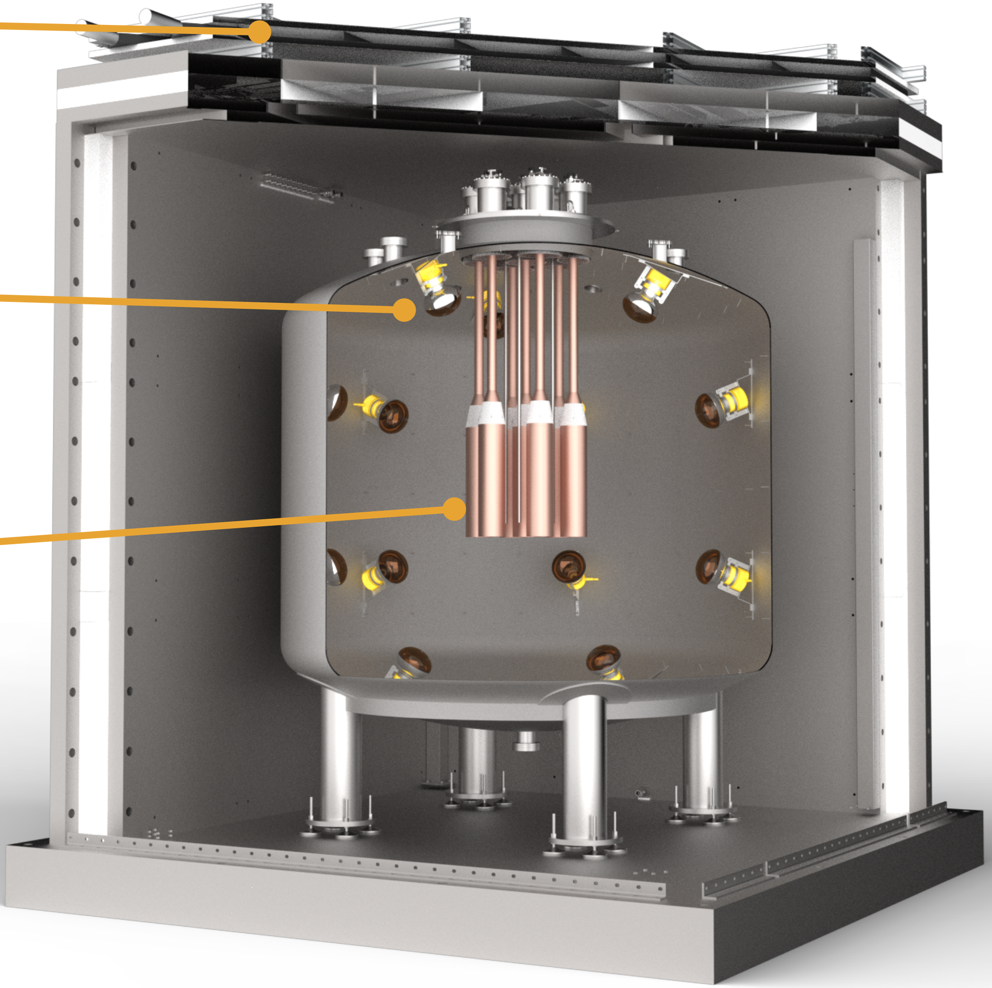
SABRE Projected performance

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

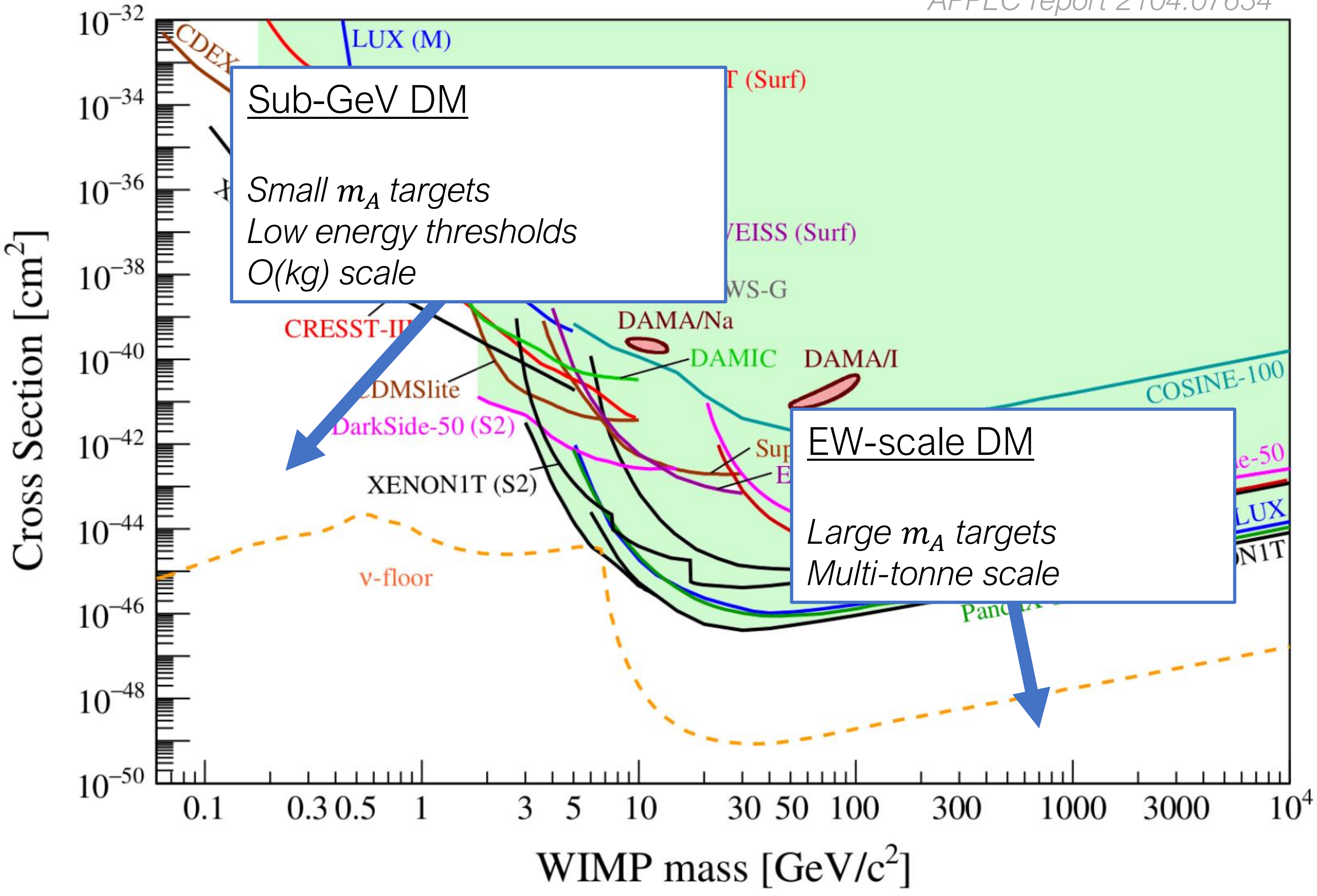


- **ToF Muon System**
  9.6 m^2 x 5 cm EJ200
  R13089 PMT x 16 @ 3.2 GS/s
- **Veto System**
  12k litres Linear Alkyl Benzene + PPO & Bis-MSB
  Stainless steel, non-thoriated welds, lumirror coating
  Oil-proof base R5912 PMT x 18 @ 500 MS/s
- **DM Target Detector**
  NaI(Tl) Crystals
  R11065 low radioactivity PMT x ~14 @ 500 MS/s
- Key requirement to understand modulation in background contributions - requires particle ID. e.g. ***μ***/γ/n.

Where we are now

WIMPS

APPEC report 2104.07634



Sub-GeV DM

Small m_A targets
Low energy thresholds
O(kg) scale

EW-scale DM

Large m_A targets
Multi-tonne scale

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

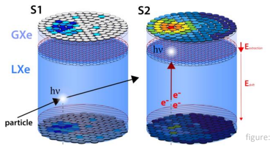
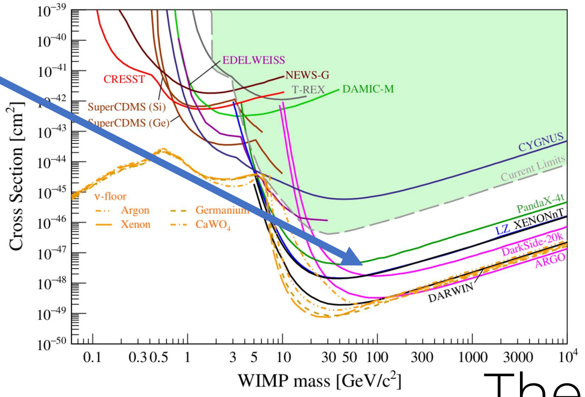


figure: XENONnT



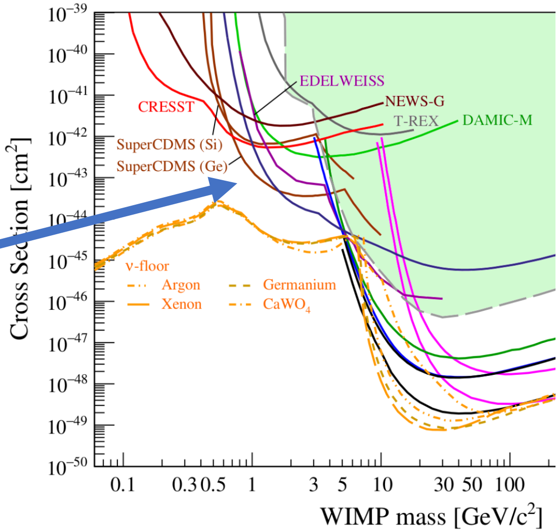
The future (low mass)

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: $m_{DM} < 100\ \mathrm{MeV}$

(see Wednesday's session)

Many ideas/proposals in this space…

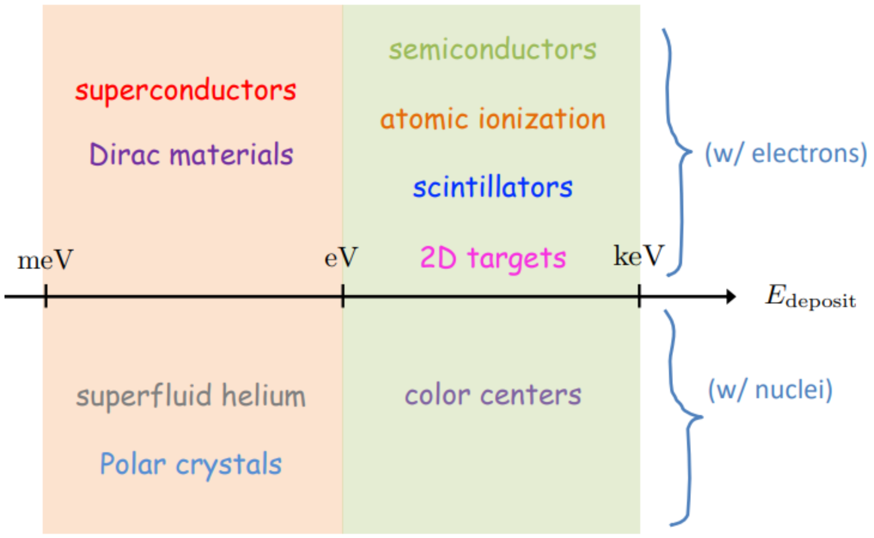
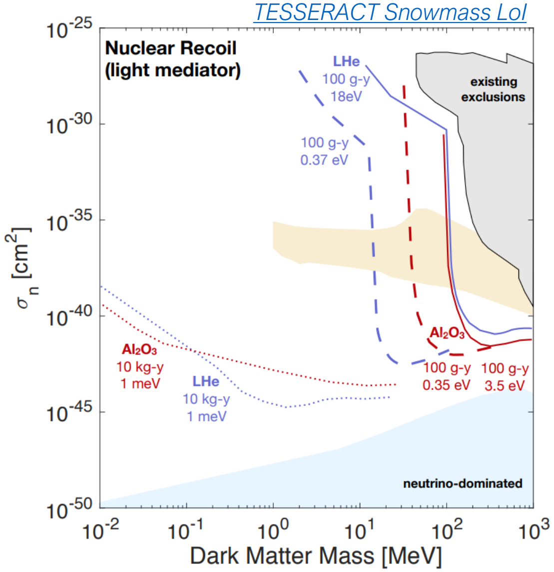


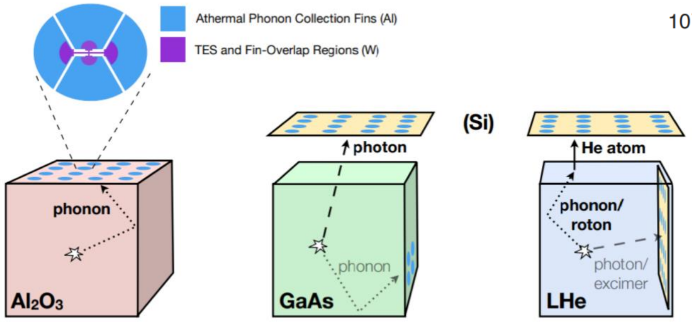
figure: Y. Hochberg

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

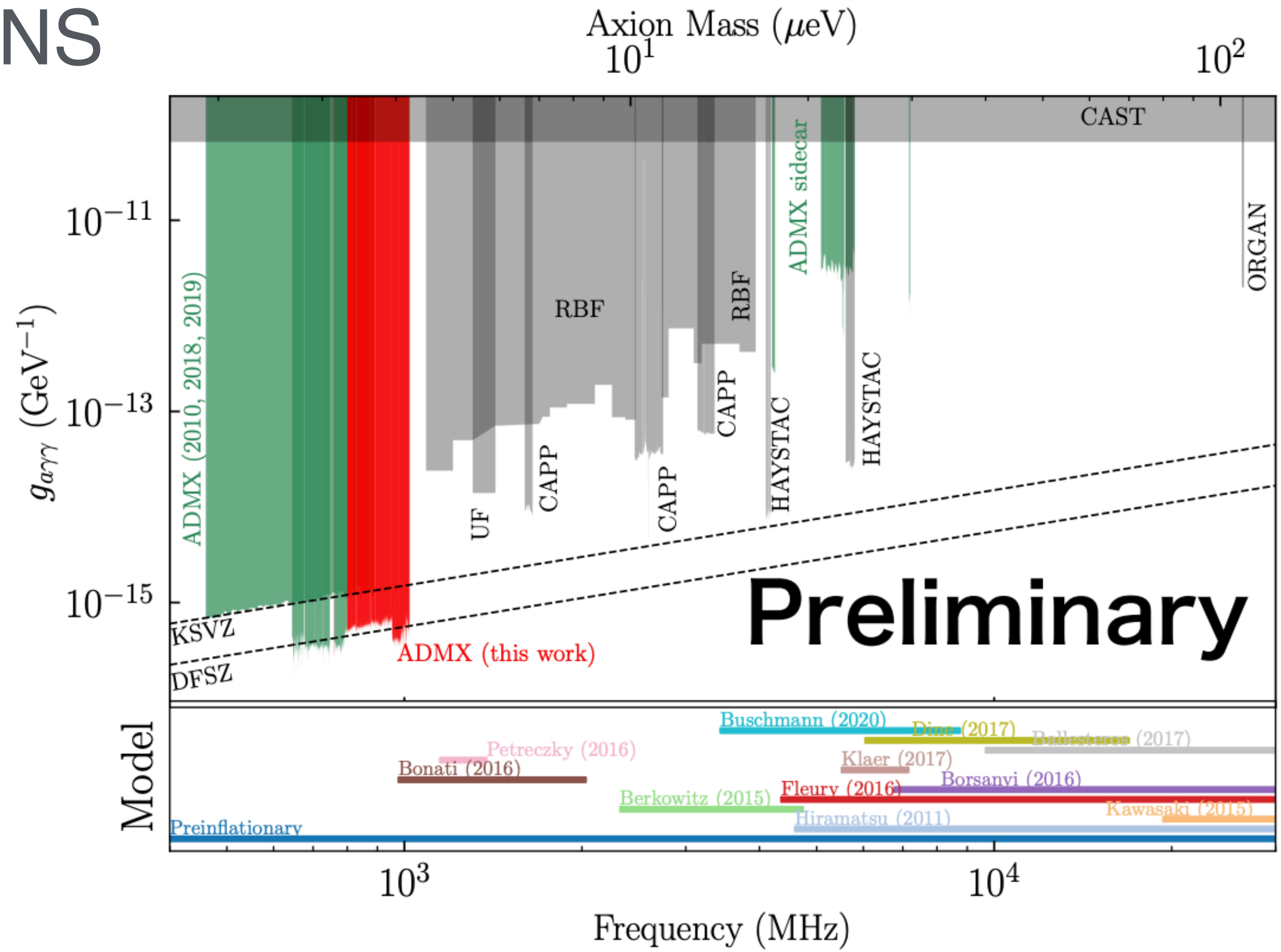
R&D, targeting experiment in ~2027

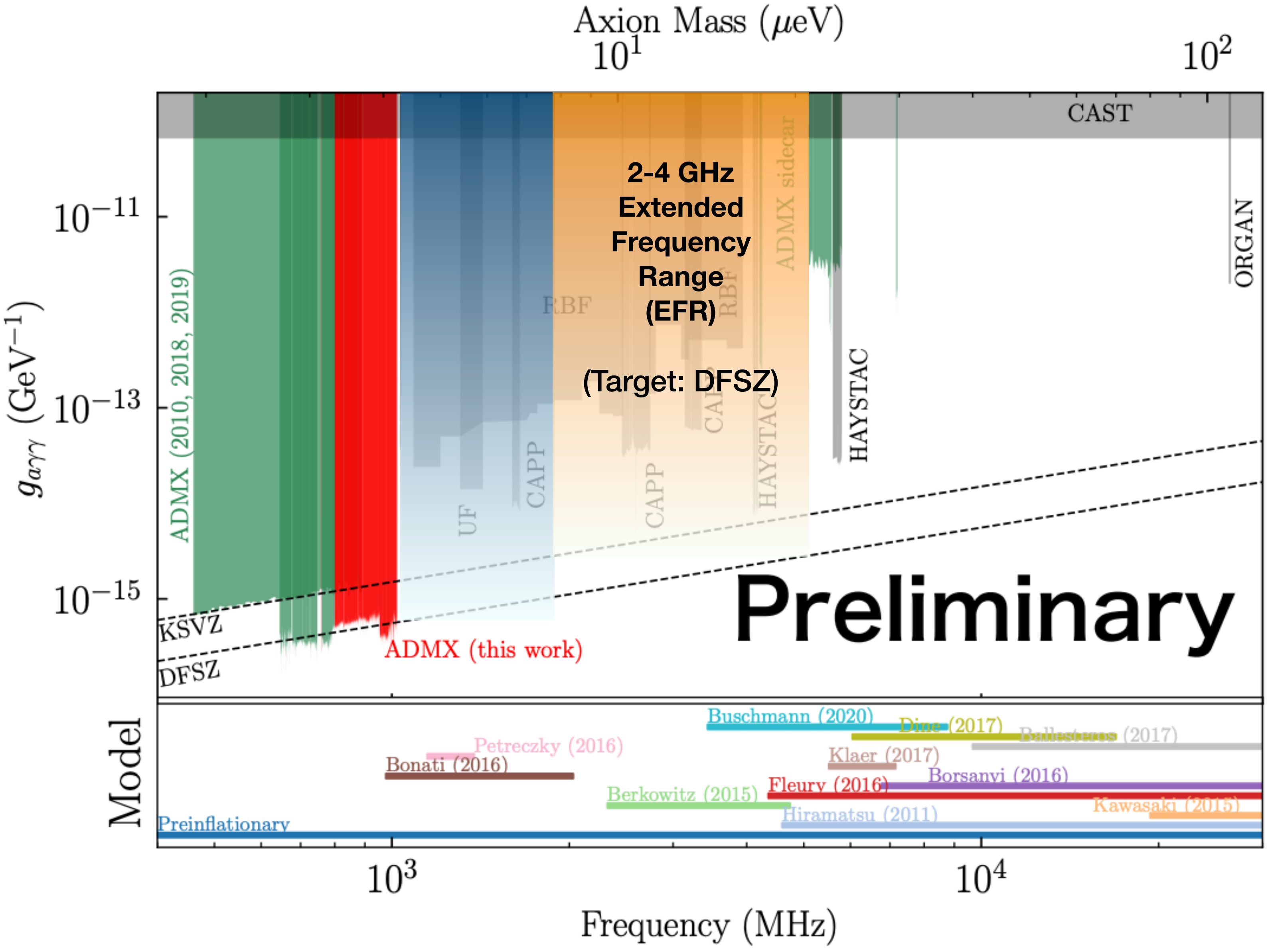
TESSERACT Snowmass LoI





AXIONS


Axion Mass (μeV)
10^1
10^2
CAST
ORGAN
ADMX sidecar
RBF
RBF
UF
CAPP
CAPP
CAPP
HAYSTAC
HAYSTAC
ADMX (2010, 2018, 2019)
ADMX (this work)
KSVZ
DFSZ
Preliminary
10^{-11}
10^{-13}
10^{-15}
$g_{a\gamma\gamma}$ (GeV^{-1})
Model
Buschmann (2020)
Dine (2017)
Ballesteros (2017)
Petreczky (2016)
Klaer (2017)
Bonati (2016)
Borsanyi (2016)
Fleury (2016)
Berkowitz (2015)
Kawasaki (2015)
Hiramatsu (2011)
Preinflationary
10^3
10^4
Frequency (MHz)

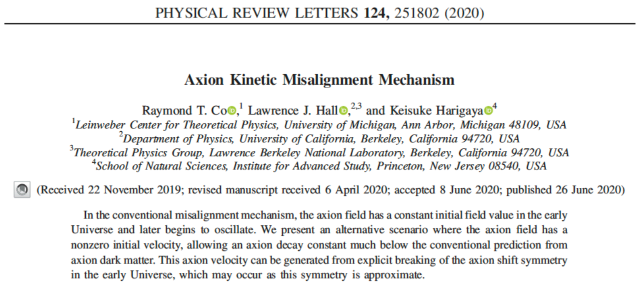


2-4 GHz Extended Frequency Range (EFR)

(Target: DFSZ)

Preliminary

ORGAN



PHYSICAL REVIEW LETTERS **124,** 251802 (2020)

Axion Kinetic Misalignment Mechanism

Raymond T. Co,[1] Lawrence J. Hall,[2,3] and Keisuke Harigaya[4]
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[2]*Department of Physics, University of California, Berkeley, California 94720, USA*
[3]*Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
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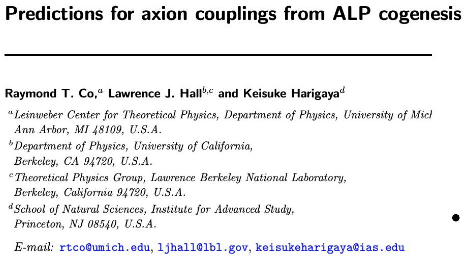
(Received 22 November 2019; revised manuscript received 6 April 2020; accepted 8 June 2020; published 26 June 2020)

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.



Predictions for axion couplings from ALP cogenesis

Raymond T. Co,[a] **Lawrence J. Hall**[b,c] **and Keisuke Harigaya**[d]

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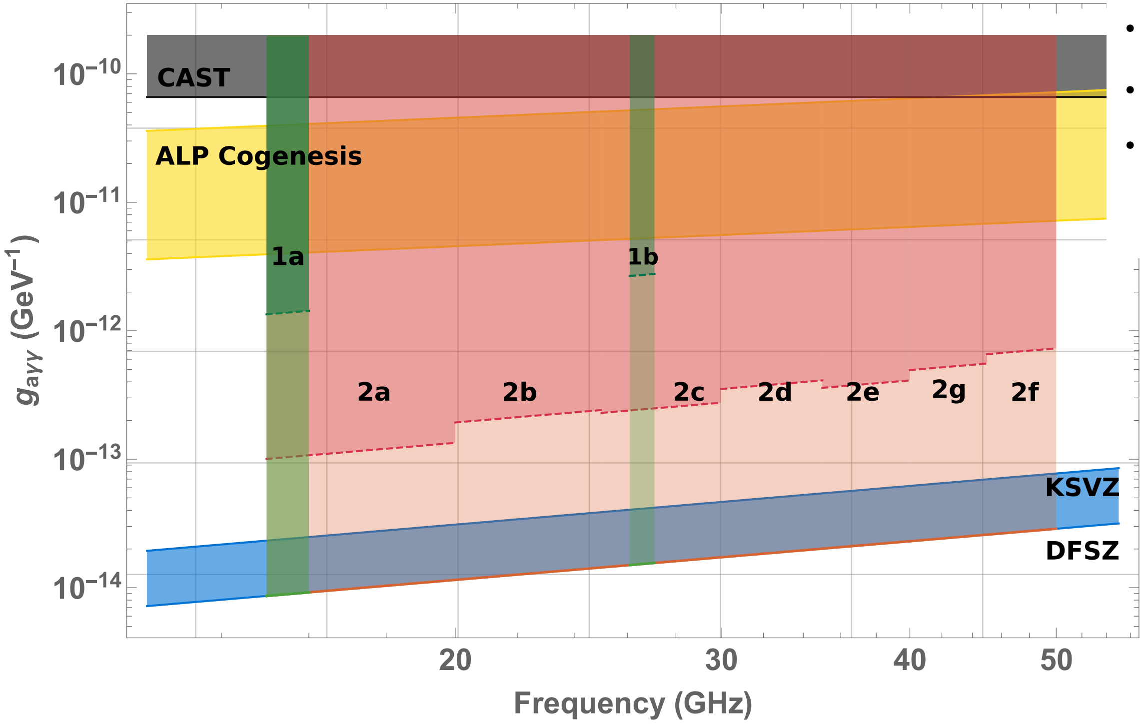
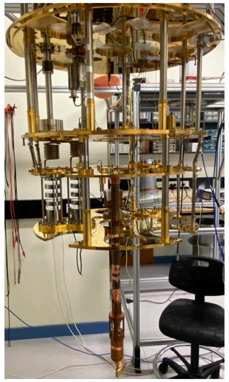
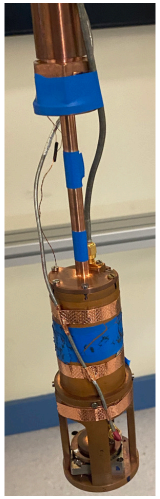


Phase 1a

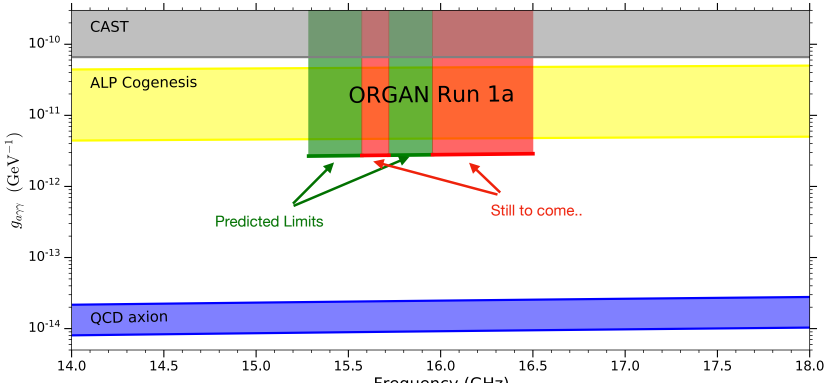




- Targeting 15.3-16.5 GHz at $\sim 3 \times 10^{-12} g_{a\gamma\gamma}$ (ALP co-genesis)
- Scan rate - How fast we can exclude axions at a given **mass** and **coupling**
- Scan rate $\propto \omega^{-14/3}$
- $\omega \propto R^{-1}$ and $V \propto R^3$ (small cavities)
- Small cavities = Small machining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

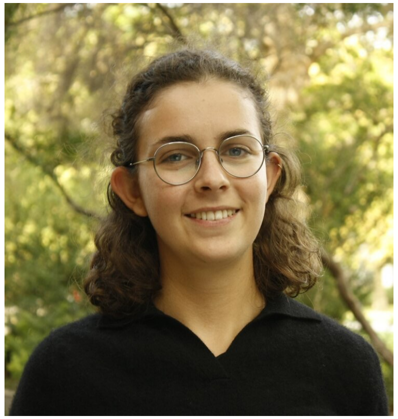


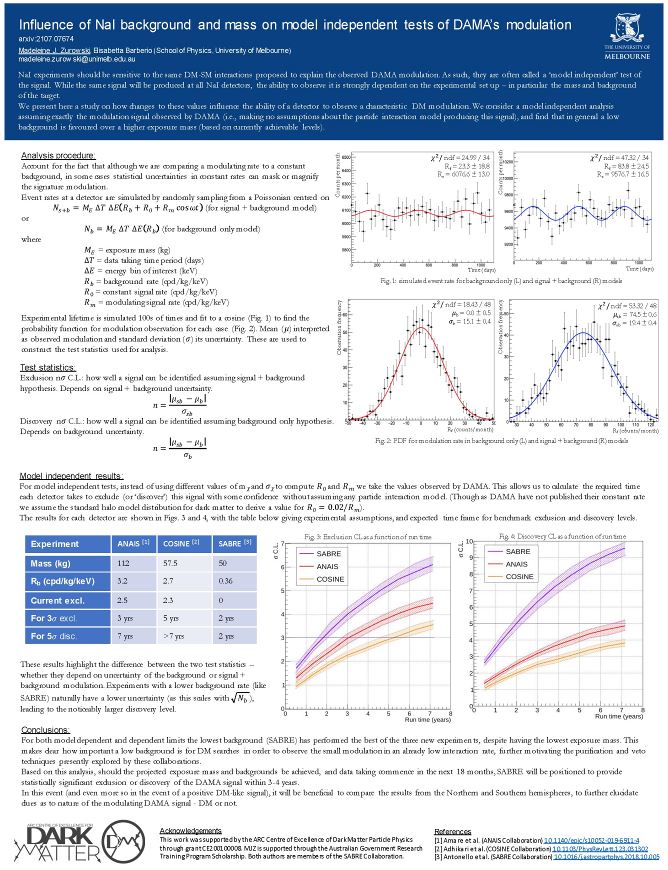
2021 CDM Poster Awards

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-SM 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 set up – 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 characteristic 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 producing 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 statistical uncertainties in constant rates can mask or magnify the signature modulation.

Event rates at a detector are simulated by randomly sampling from a Poissonian centred on

$$N_{s+b} = M_E\ \Delta T\ \Delta E(R_b + R_0 + R_m \cos\omega t) \text{ (for signal + background model)}$$

or

$$N_b = M_E\ \Delta T\ \Delta E(R_b) \text{ (for background only model)}$$

where

M_E = exposure mass (kg)
ΔT = data taking time period (days)
ΔE = energy bin of interest (keV)
R_b = background rate (cpd/kg/keV)
R_0 = constant signal rate (cpd/kg/keV)
R_m = modulating signal rate (cpd/kg/keV)

Experimental lifetime is simulated 100s of 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.

Fig. 1: simulated event rate for background only (L) and signal + background (R) models

Fig. 2: PDF for modulation rate in background only (L) and signal + background (R) models

Test statistics:

Exclusion nσ C.L.: how well a signal can be identified assuming signal + background hypothesis. Depends on signal + background uncertainty.

$$n = \frac{|\mu_{sb} - \mu_b|}{\sigma_{sb}}$$

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

$$n = \frac{|\mu_{sb} - \mu_b|}{\sigma_b}$$

Model independent results:

For model independent tests, instead of using different values of m_χ and σ_χ to compute R_0 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') this 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 $R_0 = 0.02/R_m$).

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	ANAIS [1]	COSINE [2]	SABRE [3]
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 3σ excl.	3 yrs	5 yrs	2 yrs
For 5σ disc.	7 yrs	>7 yrs	2 yrs

Fig. 3: Exclusion CL as a function of run time

Fig. 4: Discovery CL as a function of run time

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 in an already low interaction rate, further motivating the purification and veto techniques presently explored by these collaborations.

Based on this analysis, should the projected 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 of Dark Matter Particle Physics through grant CE200100008. MJZ is supported through the Australian Government Research Training Program Scholarship. Both authors are members of the SABRE Collaboration.

References

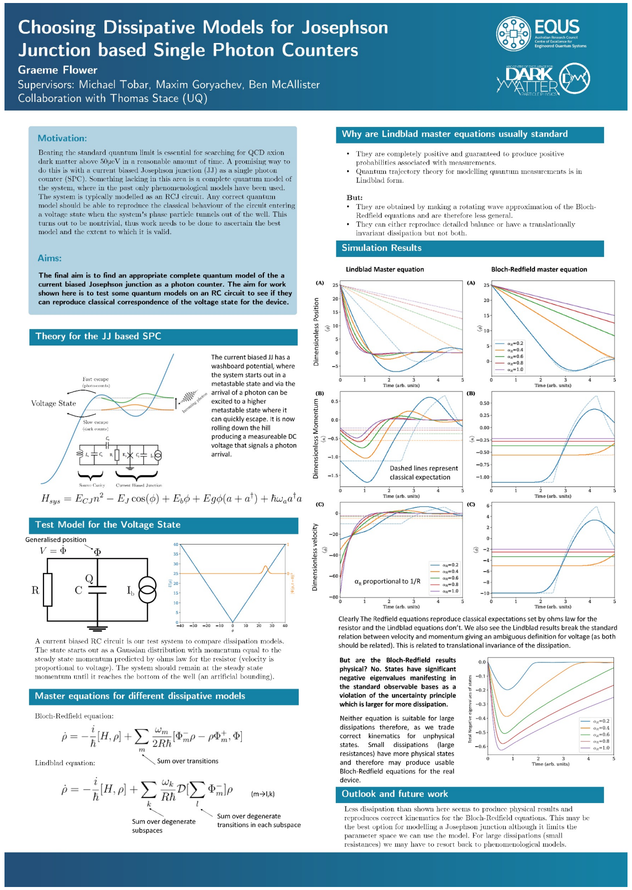
[1] Amare et al. (ANAIS Collaboration) 10.1140/epjc/s10052-019-6911-4
[2] Adhikari et al. (COSINE Collaboration) 10.1103/PhysRevLett.123.031302
[3] Antonello et al. (SABRE Collaboration) 10.1016/j.astropartphys.2018.10.005

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)

EQUS Australian Research Council Centre of Excellence for Engineered Quantum Systems
ARC Centre of Excellence for Dark Matter Particle Physics

Motivation:

Beating the standard quantum limit is essential for searching for QCD axion dark matter above 50μeV 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 lacking 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 RCJ 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 nontrivial, thus 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 washboard 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 measureable DC voltage that signals a photon arrival.

$$H_{sys} = E_{CJ}n^2 - E_J\cos(\phi) + E_b\phi + Eg\phi(a+a^\dagger) + \hbar\omega_a a^\dagger a$$

Test Model for the Voltage State

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

Master equations for different dissipative models

Bloch-Redfield equation:

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

Sum over transitions

Lindblad equation:

$$\dot{\rho} = -\frac{i}{\hbar}[H,\rho] + \sum_k \frac{\omega_k}{R\hbar}\mathcal{D}[\sum_l \Phi_m^-]\rho \quad (m\rightarrow l,k)$$

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 translationally invariant dissipation but not both.

Simulation Results

Clearly The Redfield equations reproduce classical expectations set by ohms 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 translational invariance of the dissipation.

But are the Bloch-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 dissipations therefore, 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

Less dissipation than shown here seems to produce physical 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 resort back to phenomenological models.

OUTLOOK

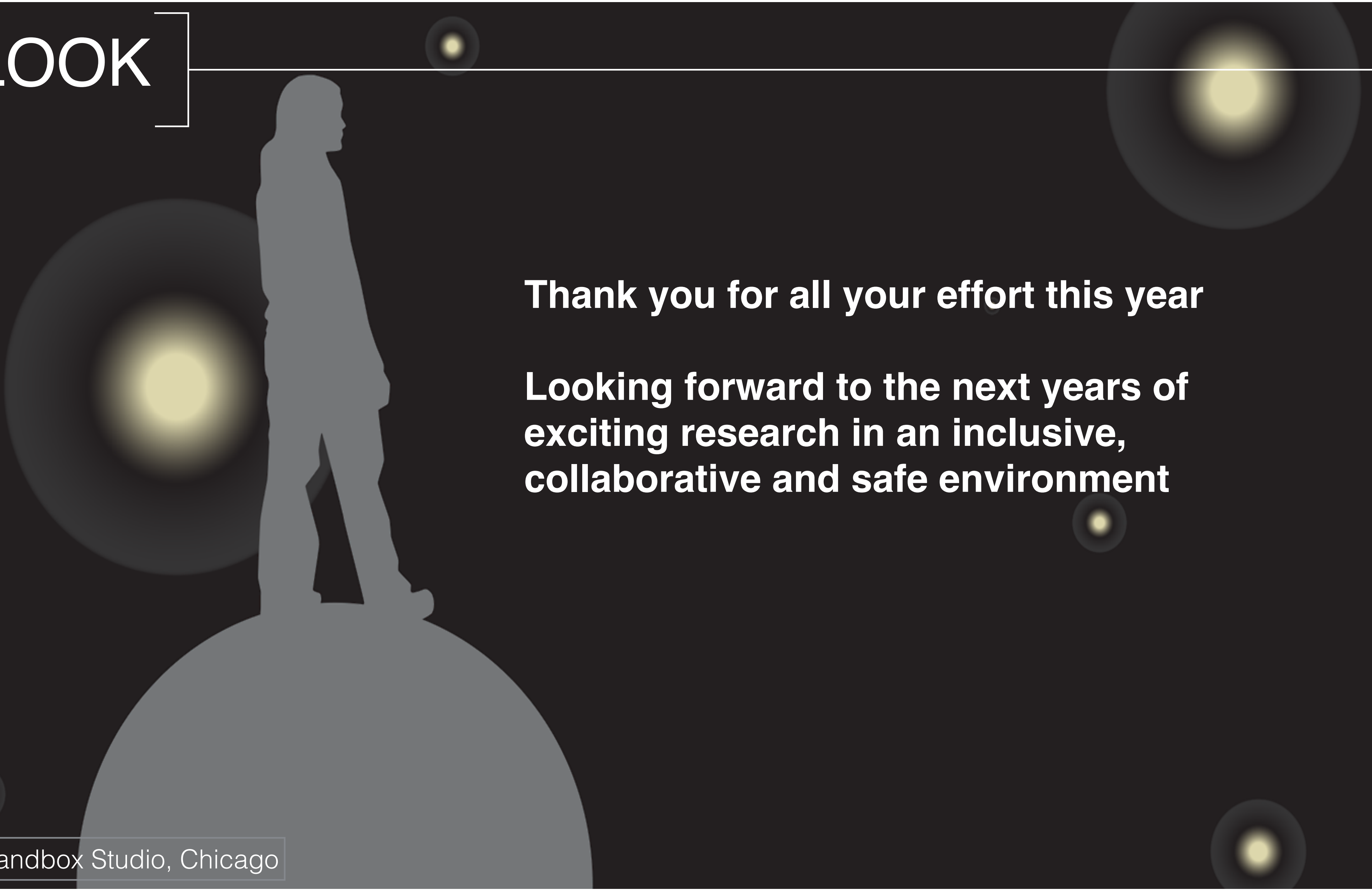
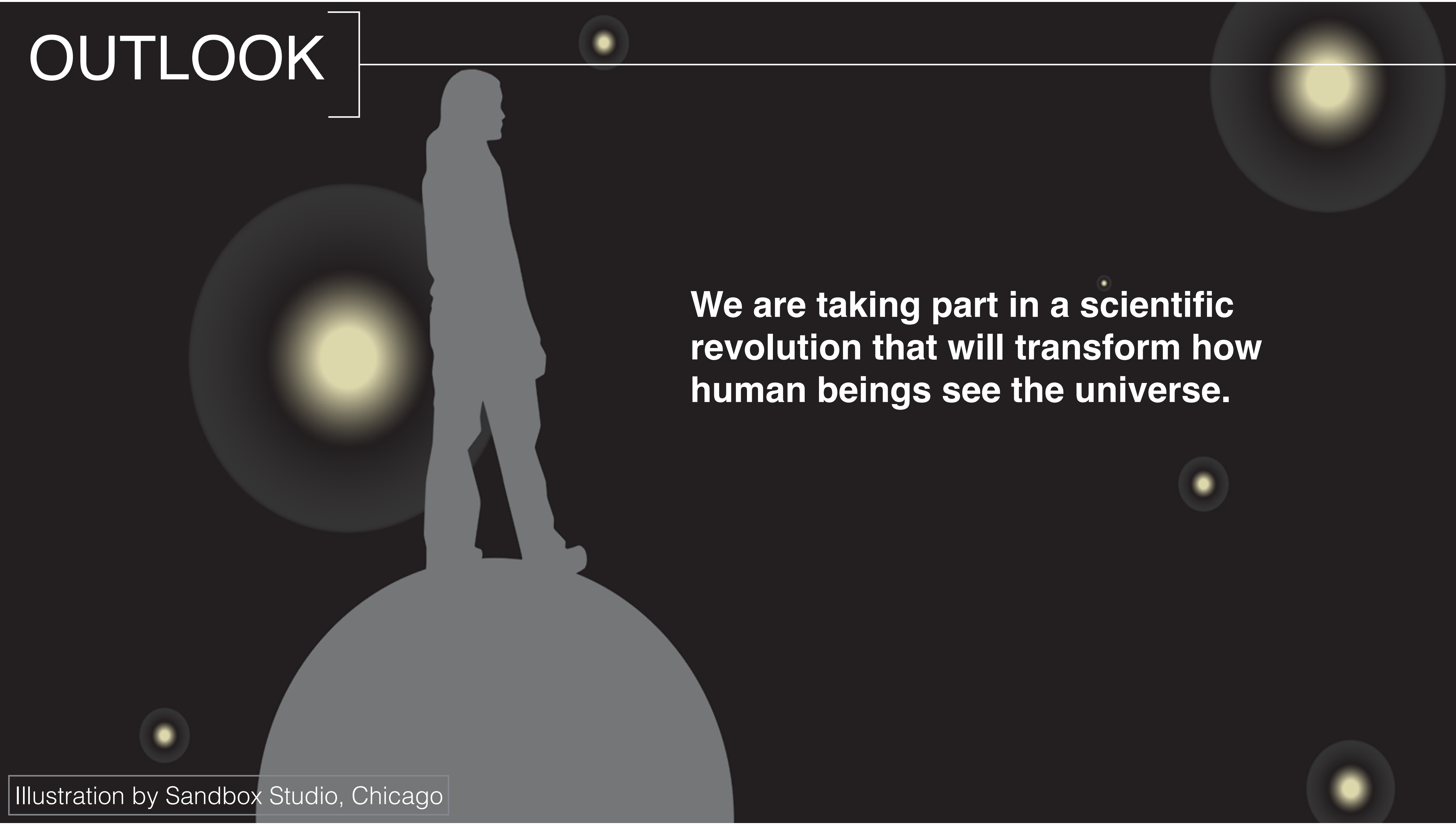


Illustration by Sandbox Studio, Chicago

Thank you for all your effort this year

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

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

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

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PRINCETON UNIVERSITY

The University Of Sheffield.

DST GROUP
Science and Technology for Safeguarding Australia