Searching for the Particle Nature of Dark Matter

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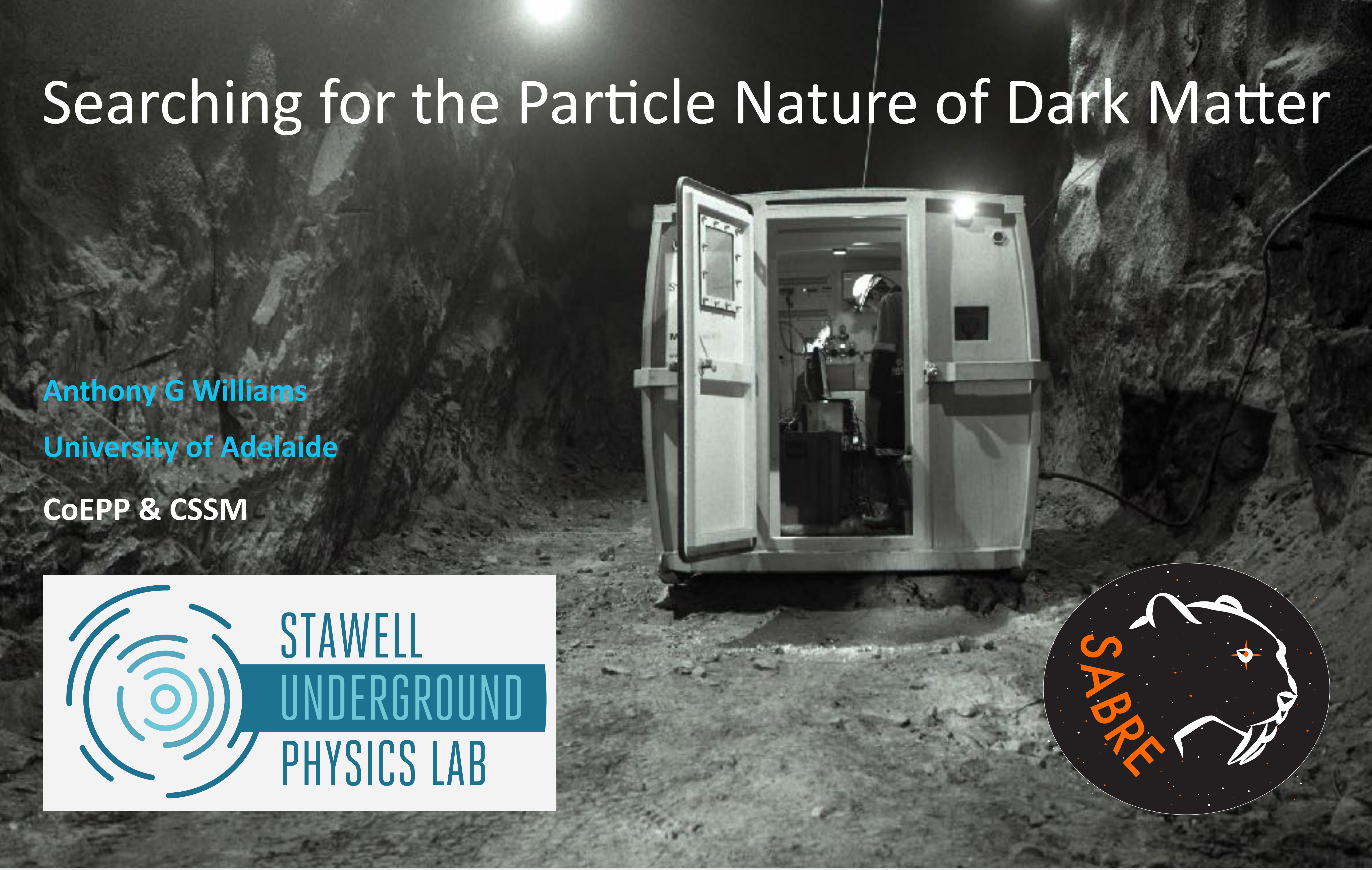
CoEPP & CSSM



STAWELL UNDERGROUND PHYSICS LAB

SABRE

Australian Government
Australian Research Council

Special Research Centre for the Subatomic Structure of Matter

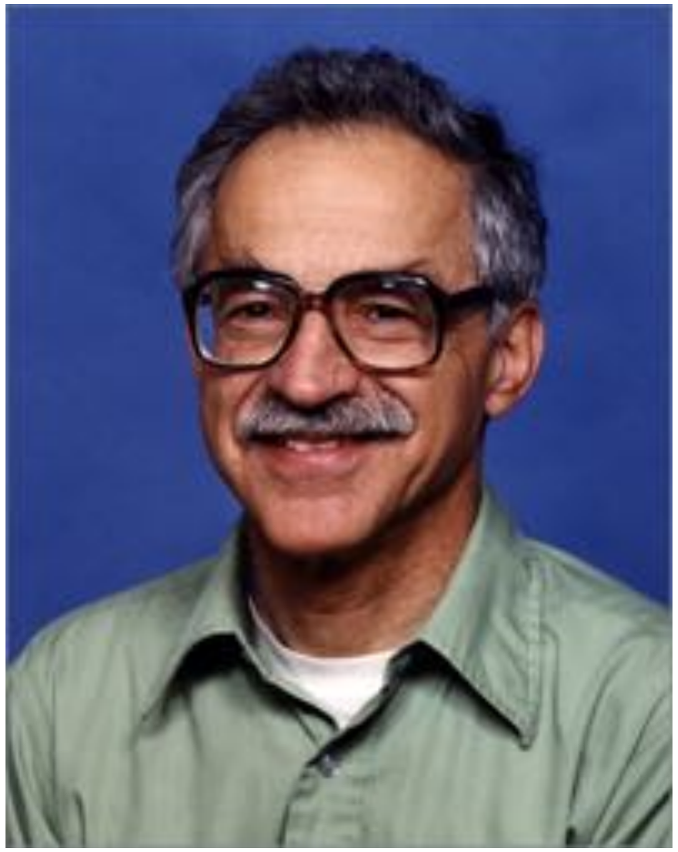
The University of Adelaide

Sub Cruce Lumen

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

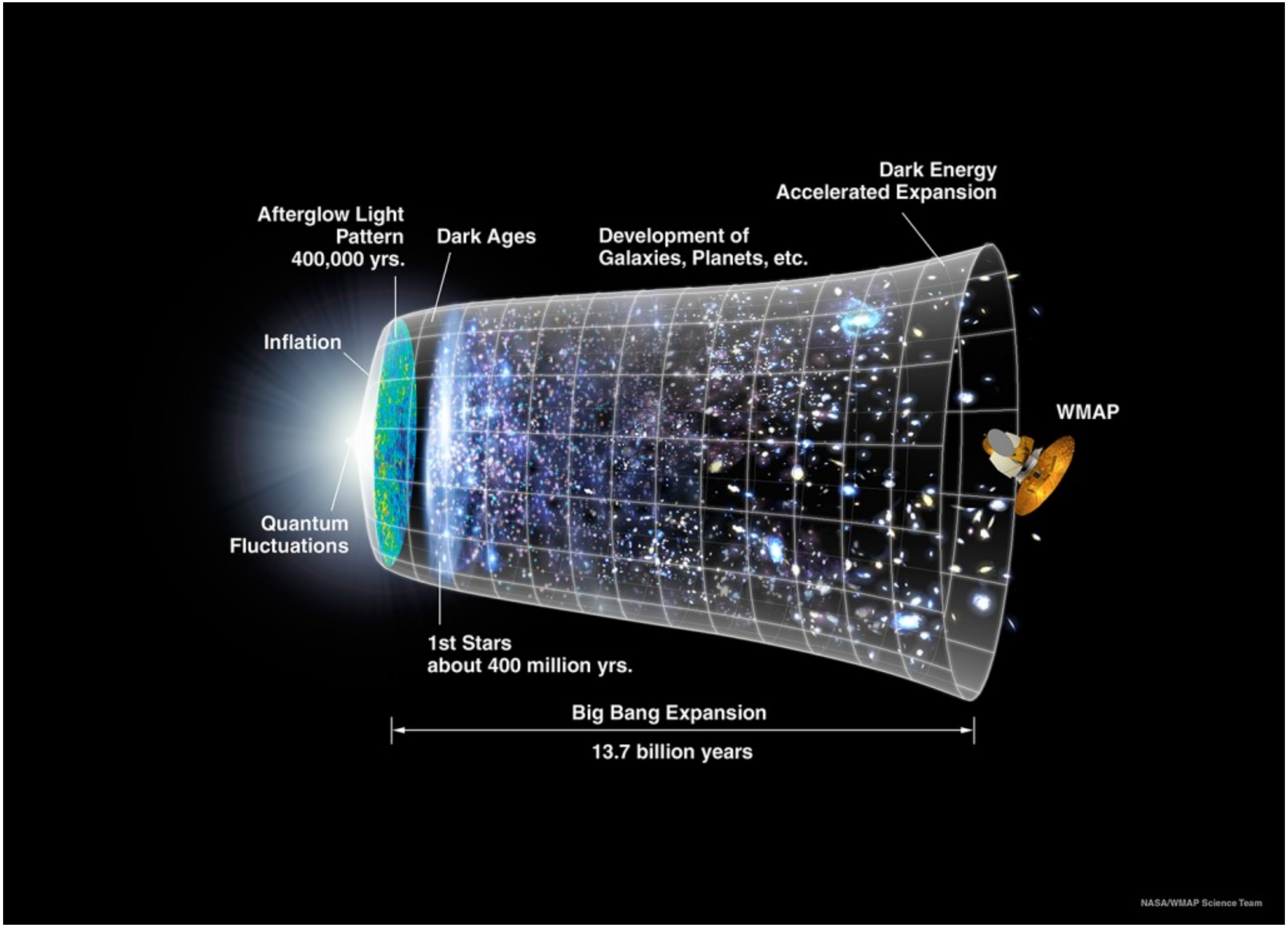
Ernest Henley - Memories and Influence

- Reception at Ernie & Elaine's home 1986 - warm and welcoming
- Symmetry as a tool - intelligent and insightful
  - Isospin;
  - Charge symmetry breaking (CSB);
  - Chiral symmetry;
  - Parity;
  - Time reversal, CP violation;

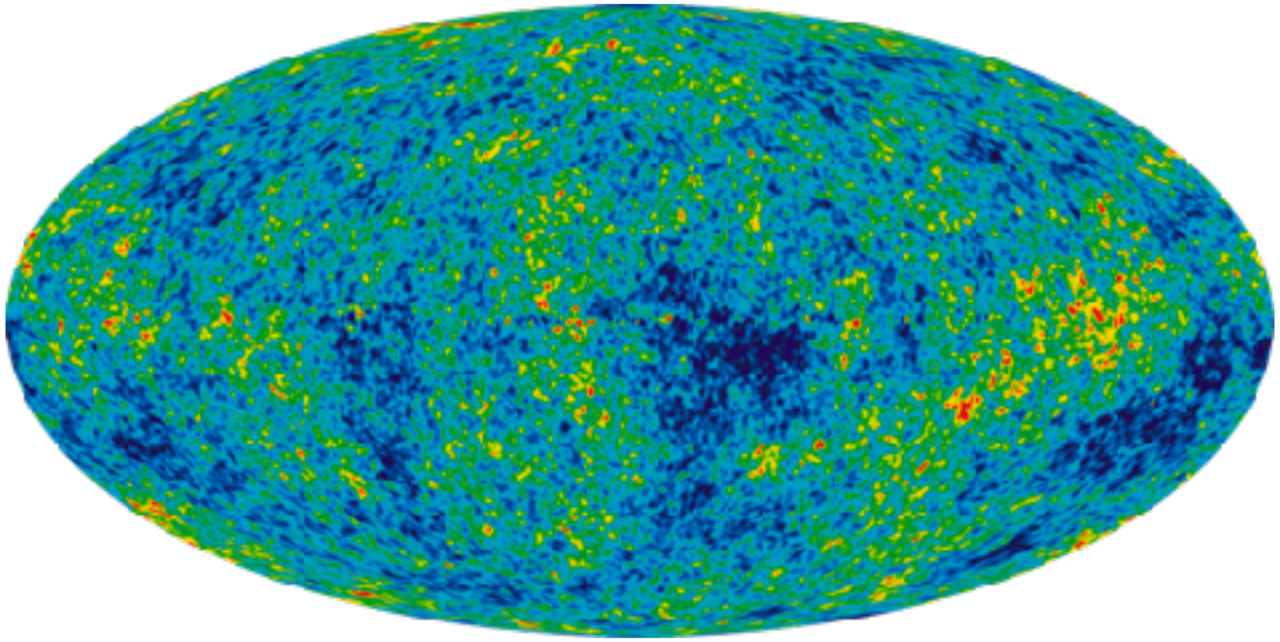


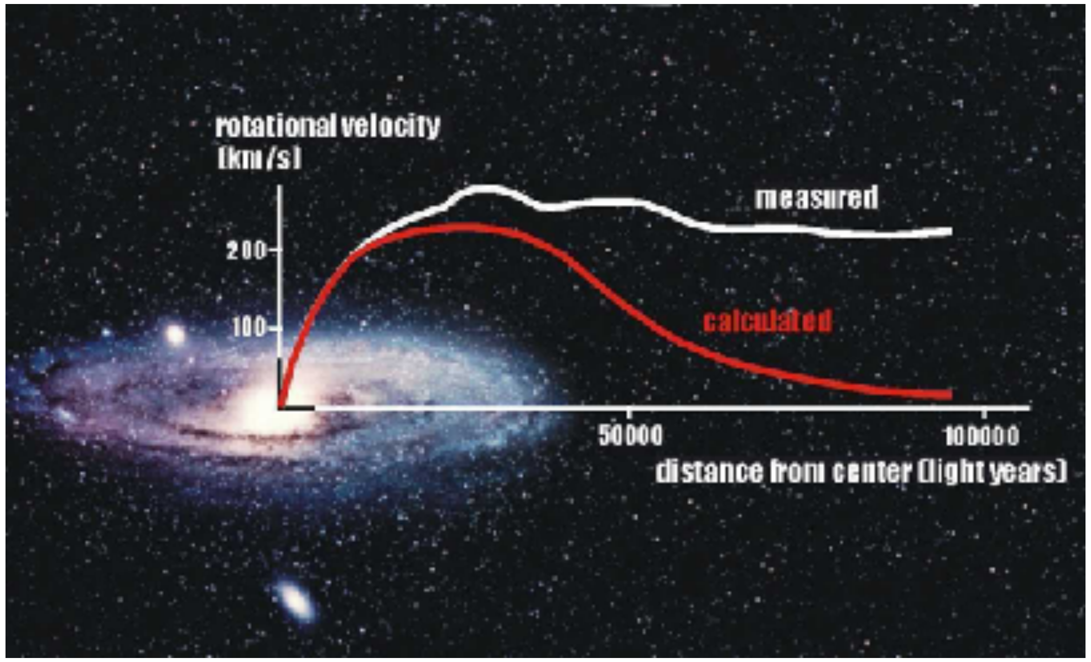
- Influence on physics research
  - CSB, chiral symmetry, NSA, strangeness in proton;
  - Lorentz invariance - Dyson Schwinger Equations, Bethe-Salpeter equations;
  - Gauge invariance - Lattice gauge theory, lattice QCD
  - Symmetry & model building - physics Beyond the Standard Model (BSM) and Dark matter - how do we extend the SM?
  - Major symmetry question today: What is the particle mature of DM?
  - Where does DM fit? $(SU(3)_c \times SU(2)_L \times U(1)_Y)$ with DM $\subseteq$???

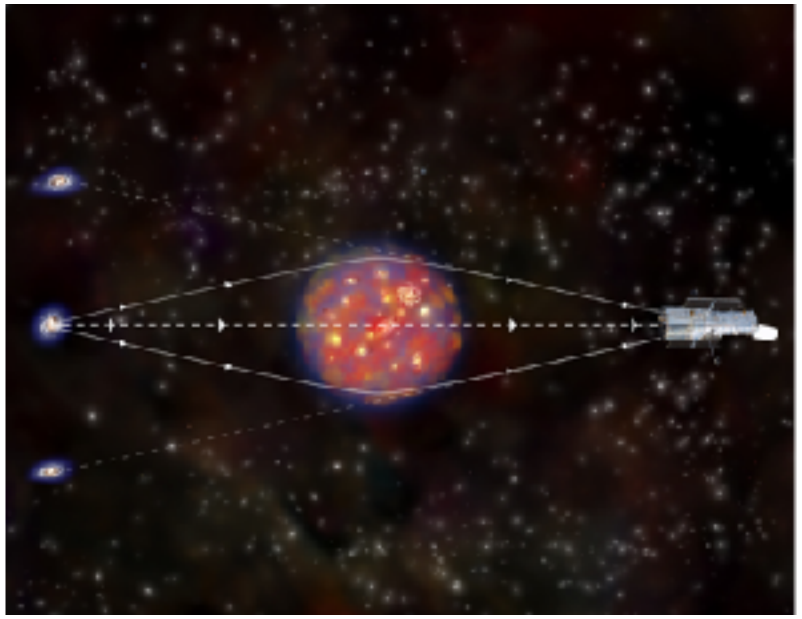
Evolution of the Universe



Evidence for Dark Matter (DM)

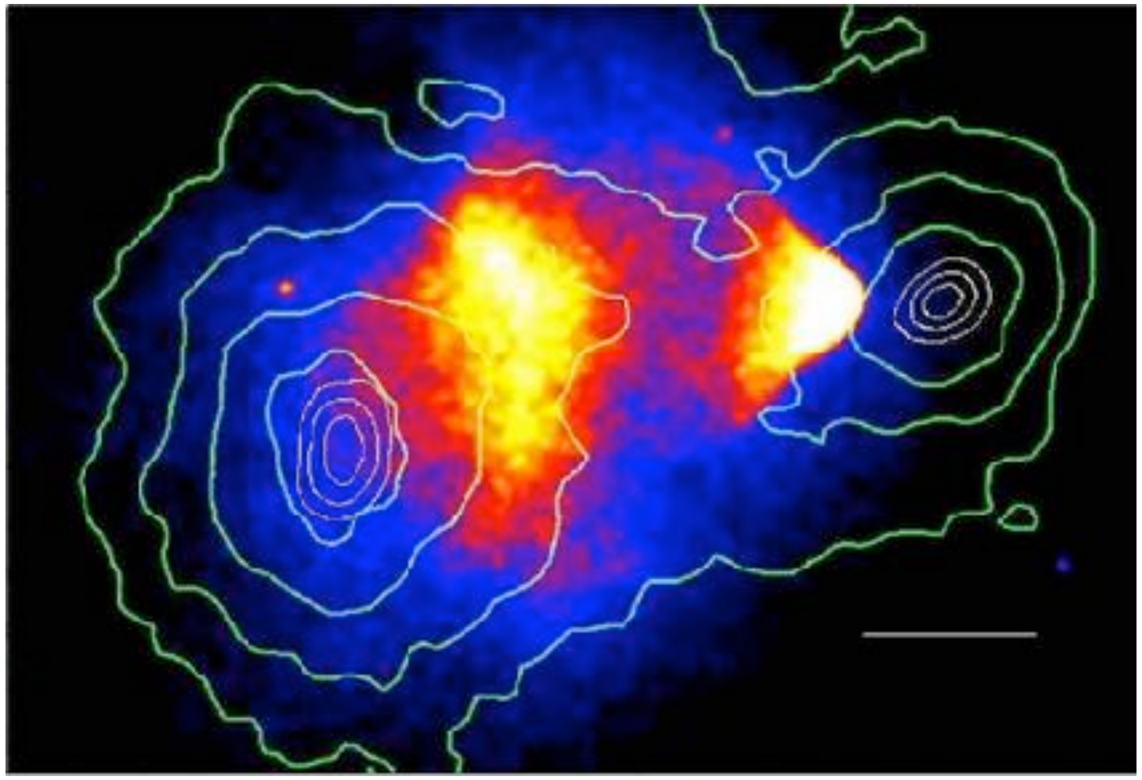






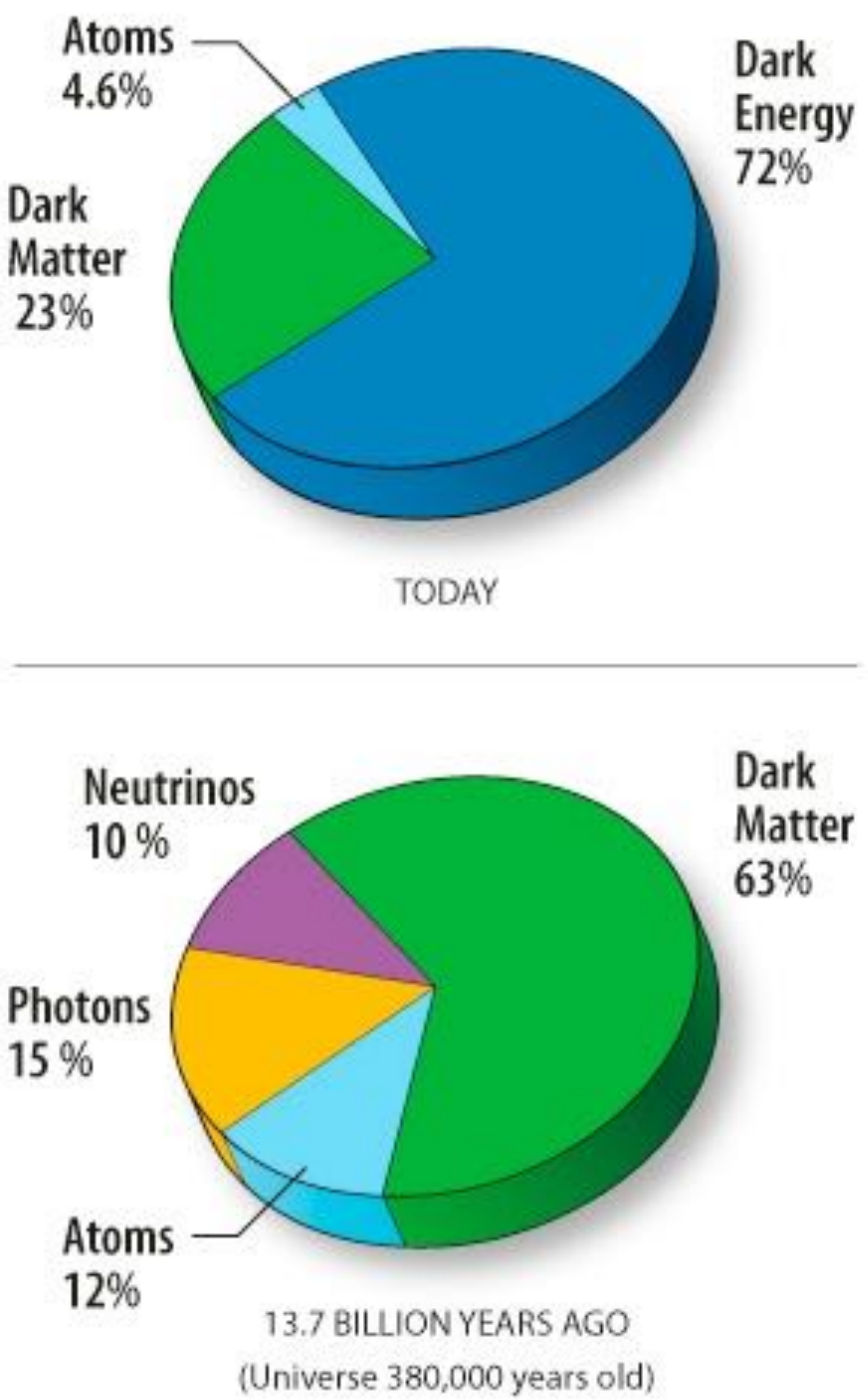
- DM consistent with: Cosmic Microwave Background (CMB) structure; large scale structure formation in the early universe; structure of galactic clusters; spiral galaxy rotation curves; why we see more gravitational lensing than the observed visible matter can explain; the understanding of the Bullet cluster; etc.

Evidence for Dark Matter from Bullet Cluster



- Two clusters of galaxies moving apart after collision (smaller is to the right of larger) - bow-shaped shock wave in smaller cluster;
- Strictly speaking the smaller right-hand cluster is the Bullet Cluster;
- The two clusters contain:
  - Visible stars: moved through each other largely unaffected;
  - Gas and dust: is most of the ordinary (hadronic) matter in clusters, interacted through e.m. $\Longrightarrow$ heated and slowed (visible in X-rays);
  - Dark Matter: weak lensing contour map shows most mass moved straight through and much more mass than due to stars $\Longrightarrow$ most mass invisible and weakly interacting;
- Best evidence to date of Dark Matter interacting weakly with itself (8σ significance).

Content of the Universe



- Dark energy increasingly dominates over time;
- Compare universe today at age approximately 14 billion years after Big Bang vs universe at age of 380,000 years.

Lambda-CDM Model

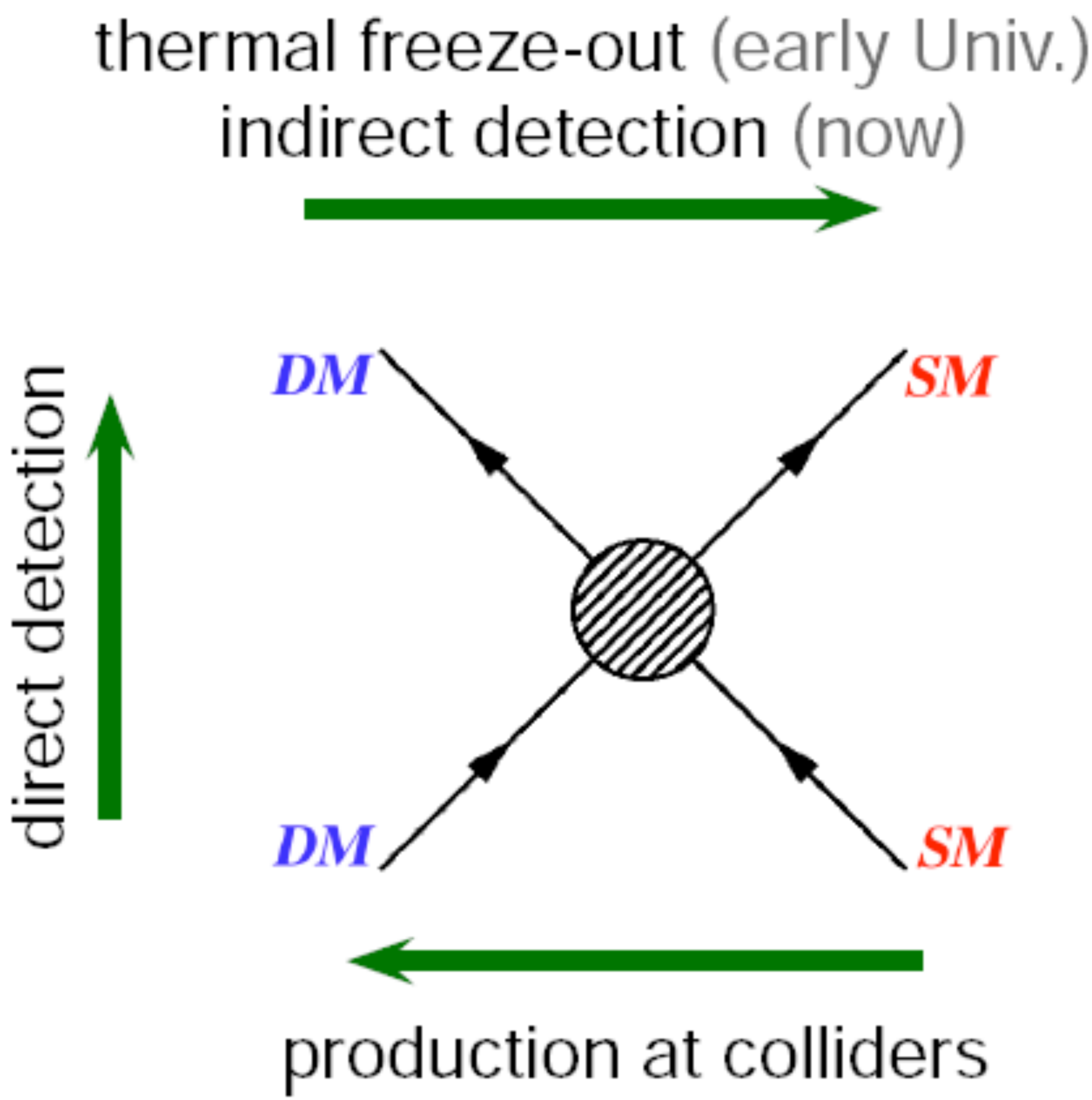
- The ΛCDM model parameterizes the Big Bang model where:
  - General relativity is assumed correct for cosmological scales;
  - There is a cosmological constant "Λ";
  - Dark Matter included and is cold in the present day (CDM):
    - Cold: most Dark Matter particles moving slowly c.f. light speed;
    - Dark: interacts via e.m. *very* weakly or not at all;
    - Matter: physical substance since it interacts gravitationally;
- ΛCDM is the simplest model that appears consistent with:
  - The Cosmic Microwave Background;
  - Large scale structure of galaxy distribution;
  - H, Deuterium, He, Li abundances;
  - Accelerating expansion of the universe as determined from distant galaxies and supernovae;
- Hot Dark Matter would smear out large scale structure of galaxies $\Longrightarrow$ not considered viable at this time.

Expected properties of DM

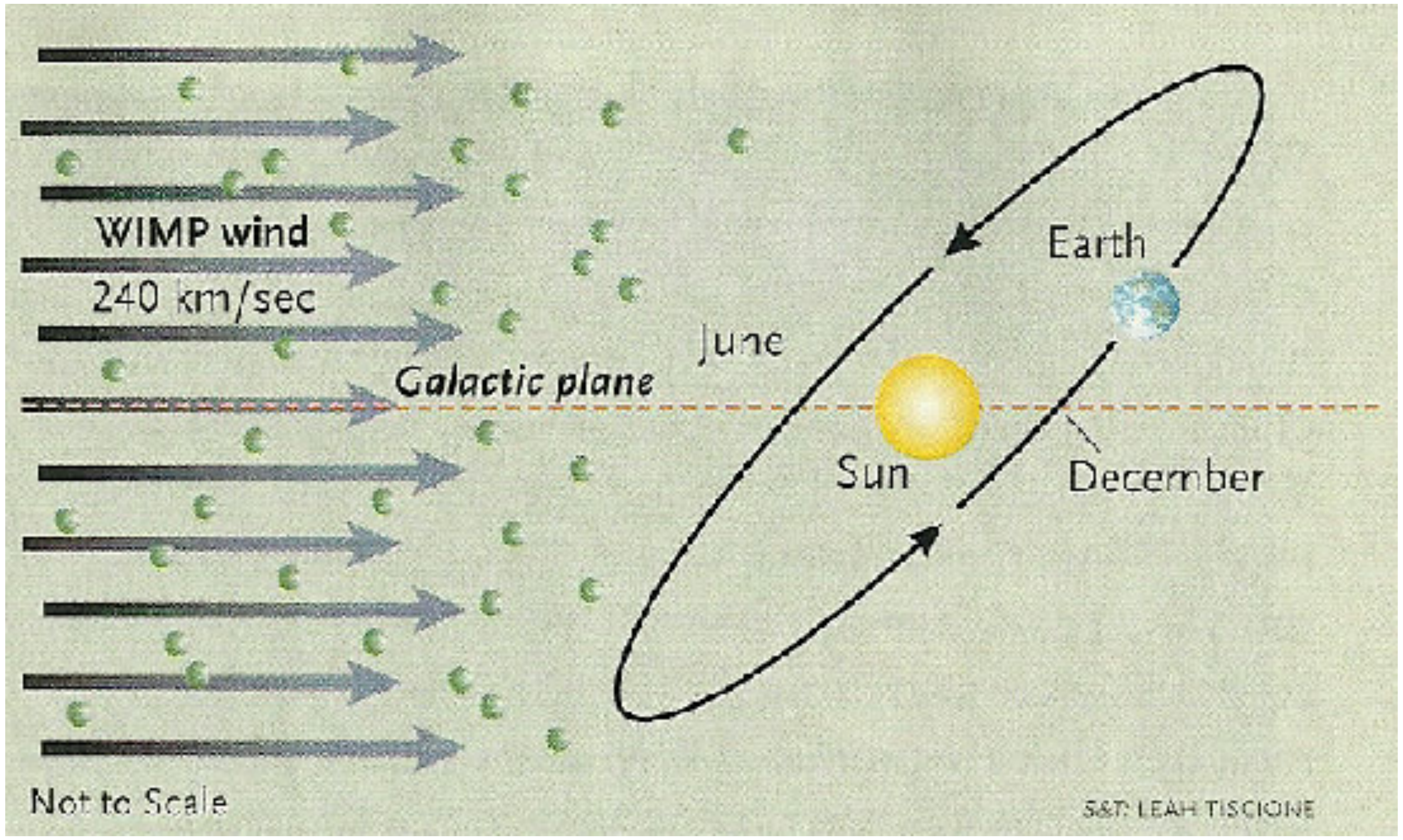
- what do we think we know?
  - long-lived
    - survived from CMB scales to now, with very little loss in density
  - not baryonic
    - BBN and ΛCDM
  - dark
    - haven't seen it!
    - tight constraints on electromagnetic coupling from structure formation
  - not charged under QCD
    - otherwise, would bind with nuclei to form heavy isotopes
    - tight bounds
  - 80% of all matter
    - rotation curves, CMB, BBN
  - $\rho \sim 0.3$ GeV/cm^3 near earth (from rotation curve of Milky Way)
  - cold (non-relativistic)
    - from structure formation, rotation curves

Searches for Dark Matter

Our focus here is on **direct detection** of Dark Matter deep underground to minimize the cosmic ray background



Dark Matter Wind

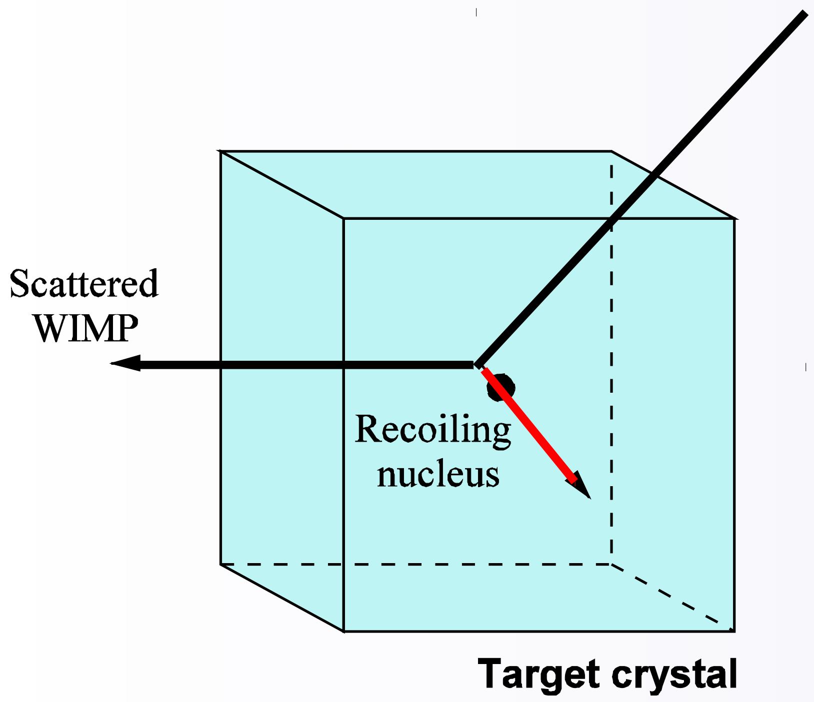


- Dark Matter (e.g., Weakly Interacting Massive Particles - WIMPs) are expected to form an approximately static halo around the galaxy (shown in blue); Is there small scale structure, turbulence?
- As the spiral galaxy rotates, the Sun experiences a wind of DM particles (aprpoximate direction is from the direction of Cygnus);
- As the earth rotates around the sun, the velocity of the Dark Matter wind passing through the earth changes accordingly.

Direct detection strategies

For typical low-energy scattering, DM scatters coherently from entire nucleus

- The direct detection of Dark Matter can take place through their interaction with nuclei inside a detector



The nuclear recoiling energy is measured

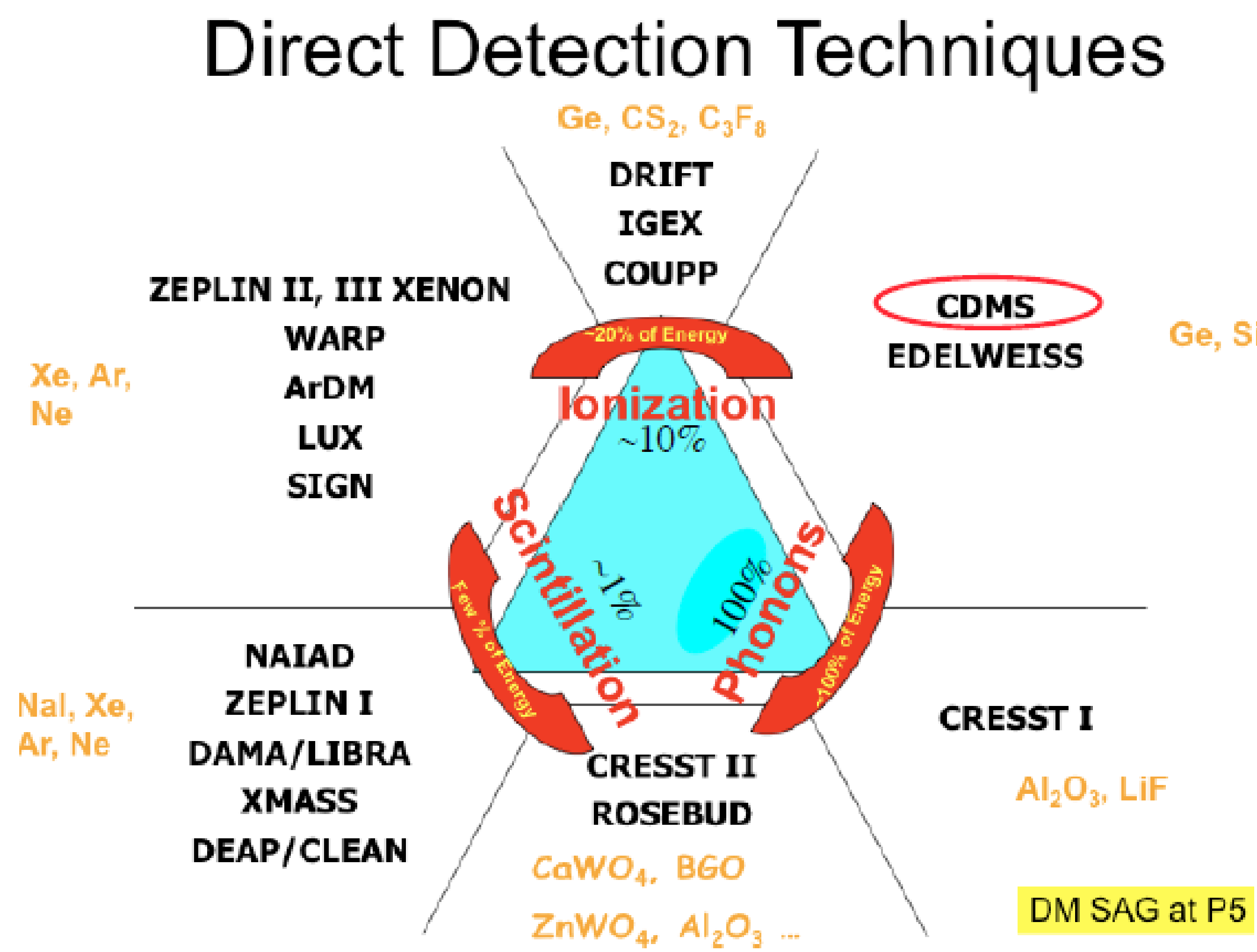
- Ionization on solids
- Ionization in scintillators (measured by the emmited photons)
- Temperature increase (measured by the released phonons)

Problems

- Very small interaction rate
- Large backgrounds (experiments must be deep underground)
- Uncertainties in the DM properties in our galaxy

Direct detection techniques

- many experiments with different targets, measurement strategies
- basic points
  - dark matter scatters off nuclei
    - looks similar to neutron scattering
  - would like to distinguish nuclear recoils from electron recoils
    - can try to use multiple signals from detector
  - event spectrum determines mass, event rate determines cross-section
  - background often comes from surface



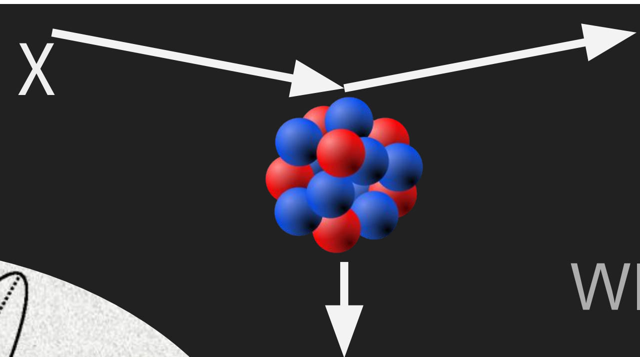
Blas Cabrera

Experimental issues

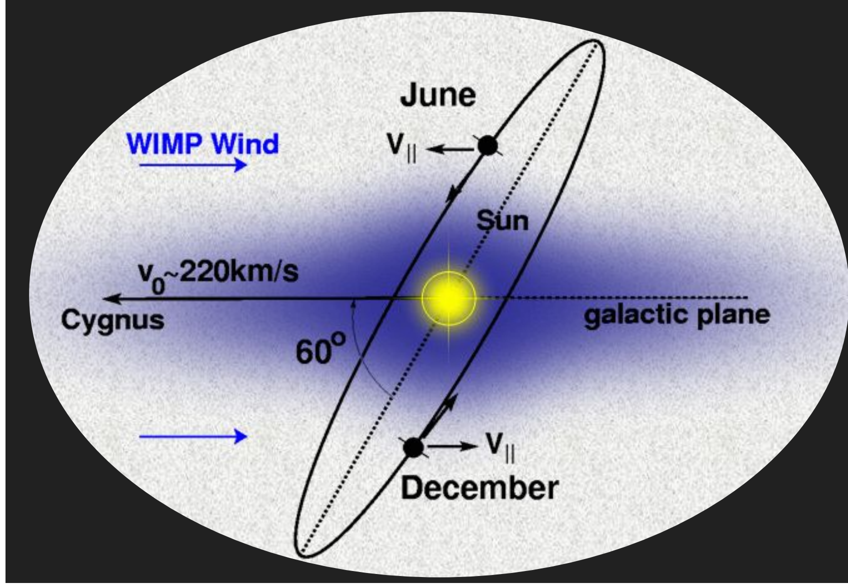
- all detectors will have a recoil energy threshold
  - where you can cut out bgd
  - if using multiple signals, where they're each large enough
  - makes low-mass difficult
- need to scale from the signal you measure to the recoil energy
  - quenching factor
  - uncertainty affects mass determination
- form factor uncertainties
  - especially important when comparing to collider, indirect

- spectrum depends on m_X only through reduced mass
  - comes in through E_{max}
    - for $m_X \gg m_A$, reduced mass independent of m_X
    - if $F_A(E_{max}) \ll 1$, can't "see" E_{max}
  - can't read off m_X from spectrum
- velocity distribution uncertainties
  - recoil energies depend on v
  - events above threshold may be at the tail of f(v)
    - deviations can have a big effect on rate
  - important for comparing to collider, indirect

DAMA/LIBRA enigma



Annual Modulation

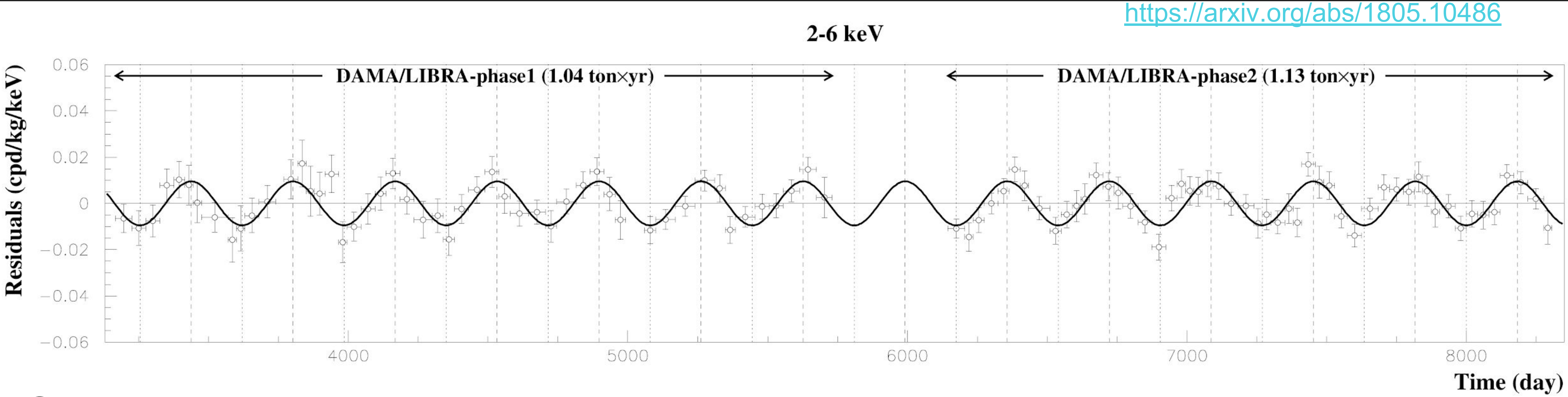


WIMP dark matter detection: elastic scattering.

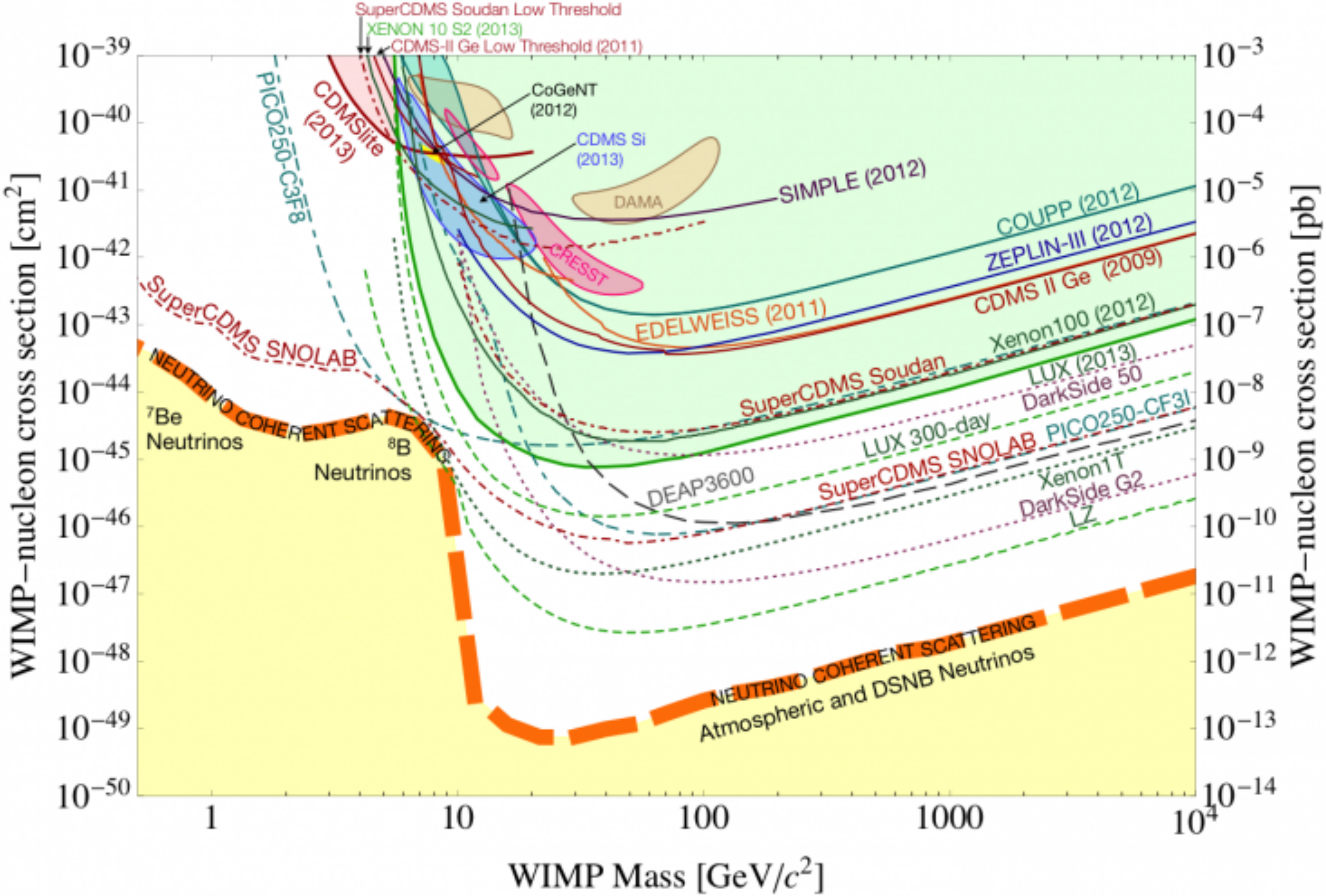
Flux (scatter rate) of dark matter modulates through the year

DAMA: reports a highly significant (11.9 σ) modulation signal consistent with dark matter.

https://arxiv.org/abs/1805.10486

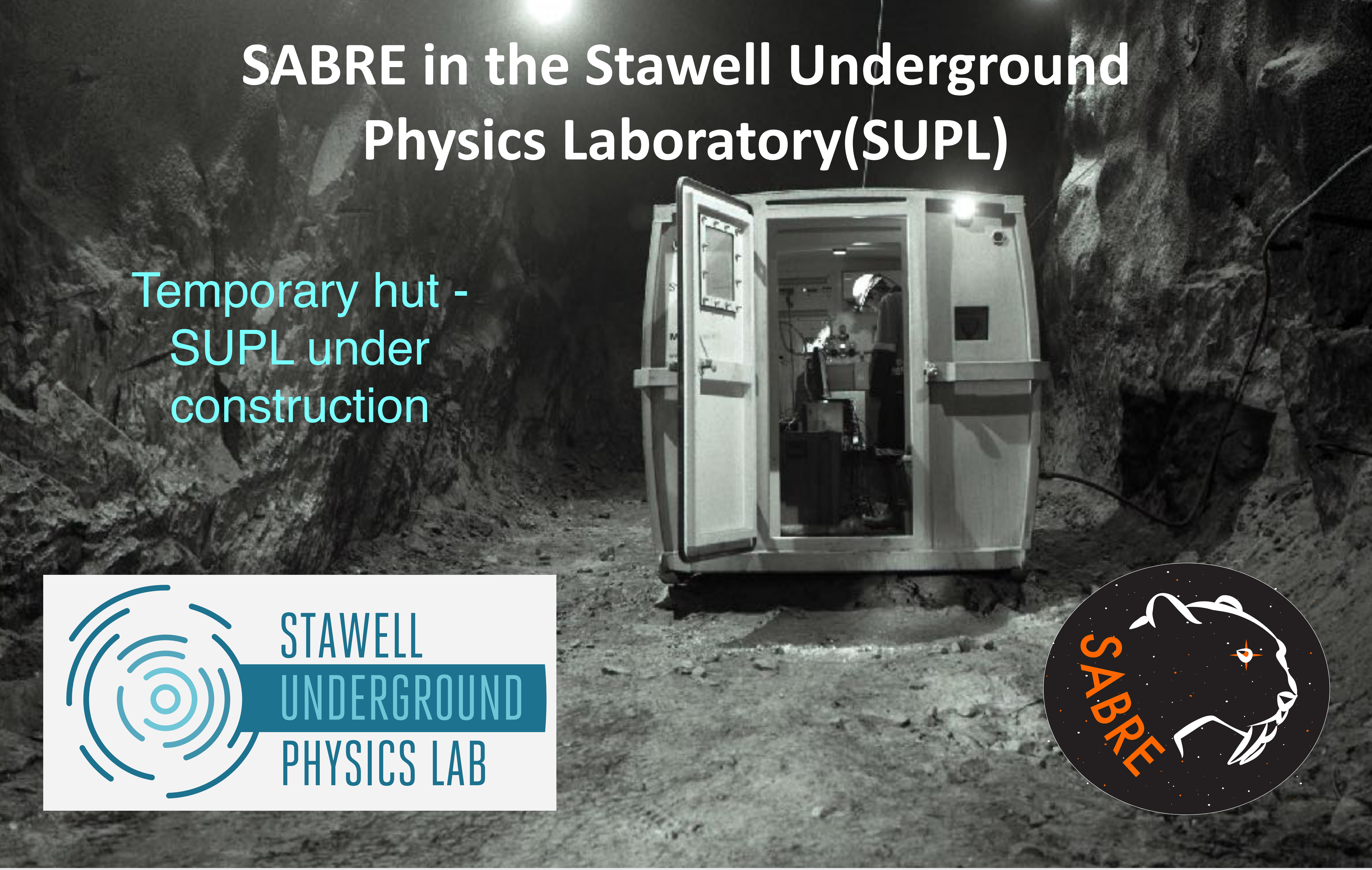


Simplest assumptions => inconsistent with all other experiments;
No known backgrounds appear to be able to explain it.



(Note: DSNB = Diffuse Supernova Neutrino Background)

SABRE in the Stawell Underground Physics Laboratory(SUPL)



Temporary hut - SUPL under construction

STAWELL UNDERGROUND PHYSICS LAB

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SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

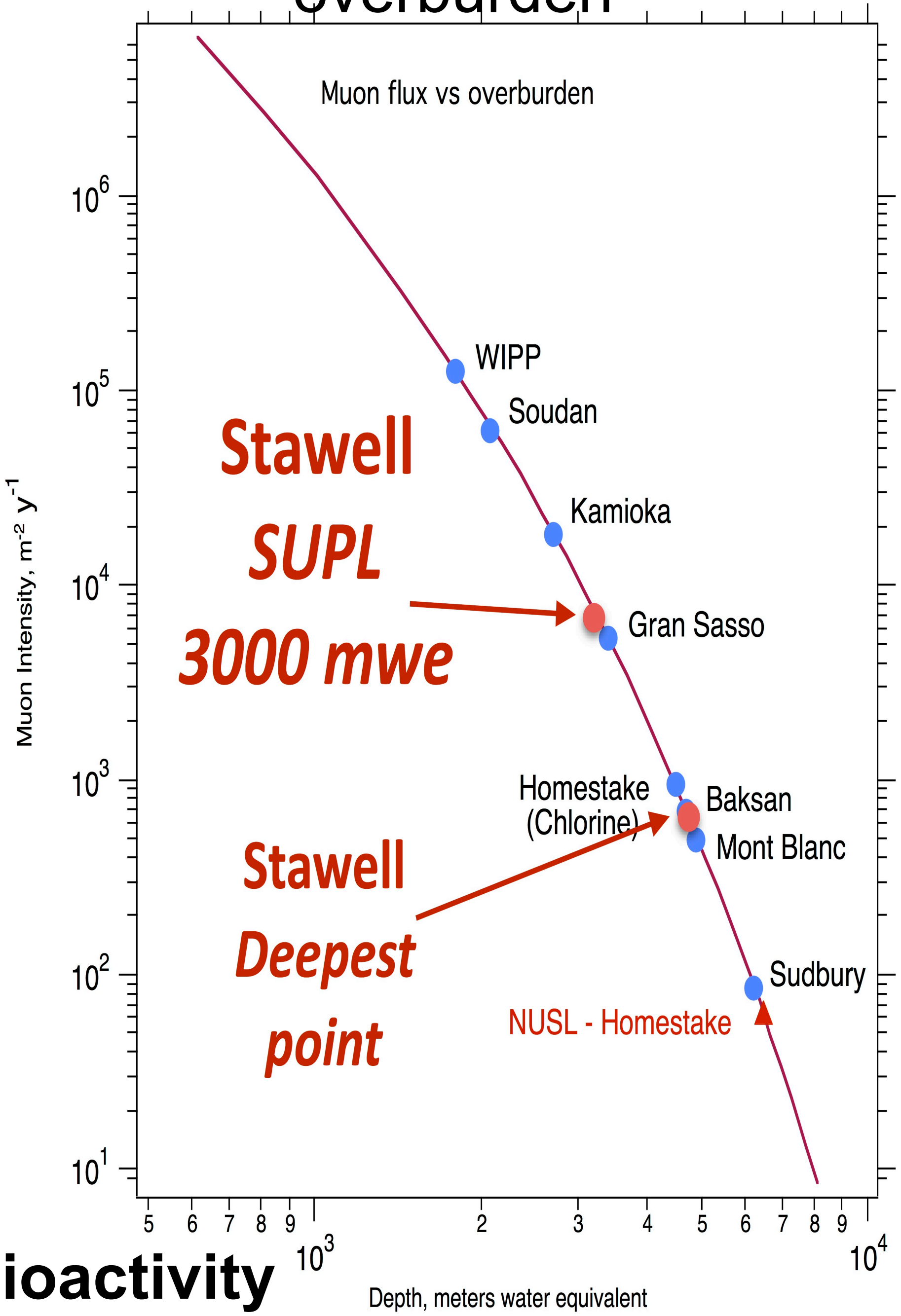
THE UNIVERSITY of ADELAIDE

SUB CRUCE LUMEN

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

SUPL - Stawell Underground Physics Laboratory

Gold mine with decline construction, accessible by car/truck, basalt rock, flat overburden



Effective depth and environmental radioactivity broadly comparable to Gran Sasso

SUPL Floor Plan - initial phase

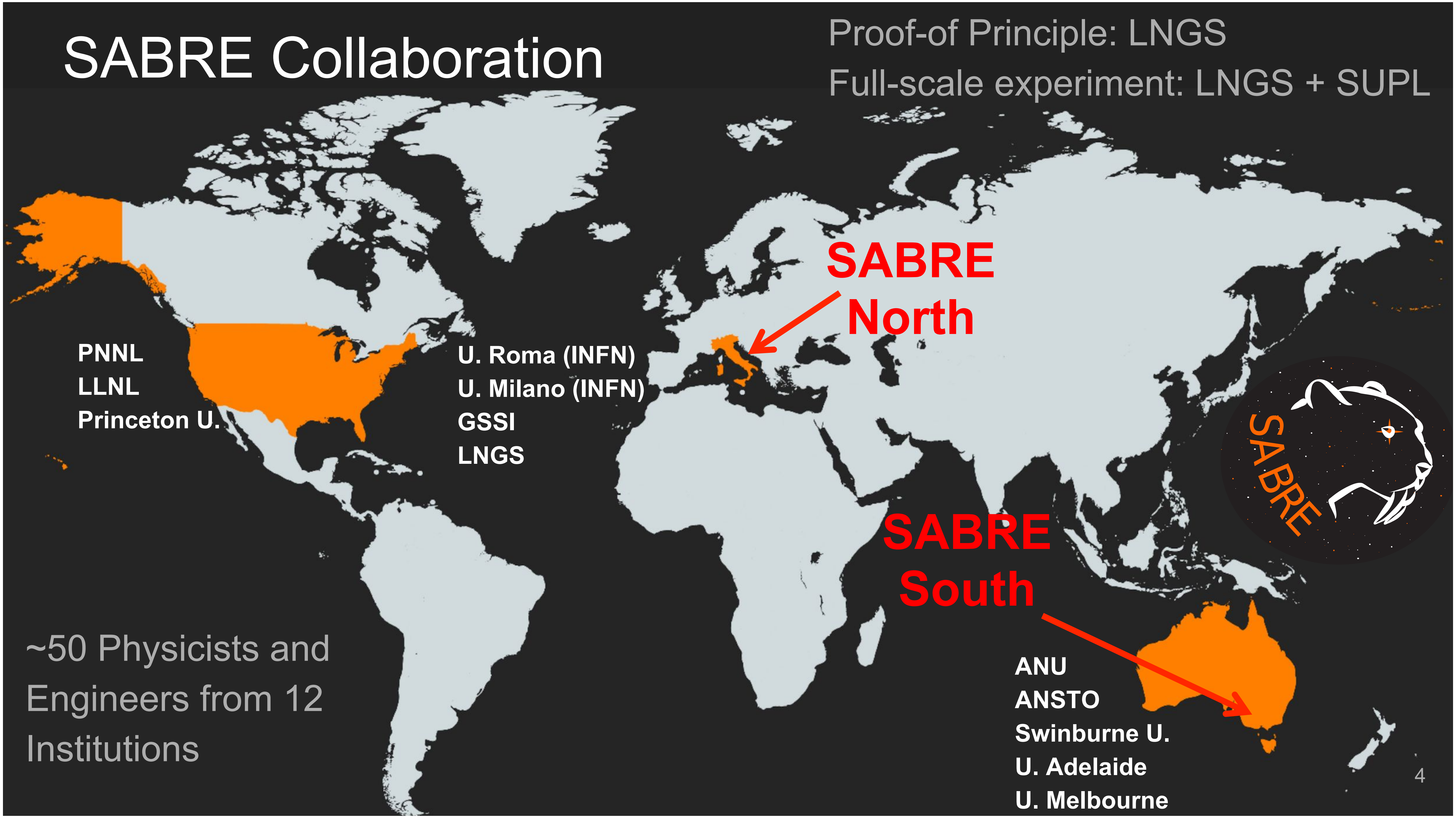
Future expansion allowed in design

Clean-room, low radon areas

Confirming or Refuting DAMA

- Is DAMA's signal some seasonally varying background or is it DM or does it interact differently with different detector materials or something else?
  - Need **Southern Hemisphere** perspective - **Seasonal background would be opposite phase; DM signal would be same phase.**
  - Need ultrapure NaI detectors; extremely low background;
  - Need similar conditions and experimental set up in North and South Labs.
- **Sodium-iodide with Active Background REjection (SABRE) experiment**: Same target as DAMA (i.e., Thallium doped NaI cystals), lower background via very high crystal purity and active rejection of background through placing the NaI(Tl) detector inside a liquid scintillator veto.
- **CYGNUS experiment:** If direct detection experiments hit the (isotropic) neutrino floor before DM detected, then in future may differentiate DM wind by directionality, e.g., a future CYGNUS experiment to study nuclear recoil direction using Time Projection Chambers (TPCs). CYGNUS experiment global R&D effort is ongoing.

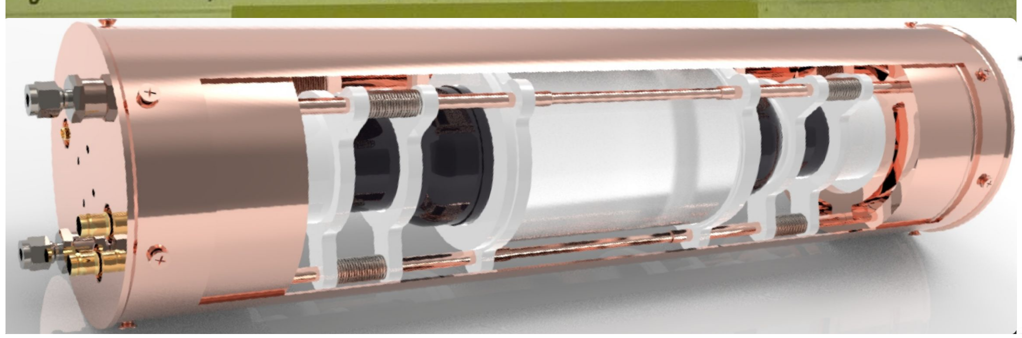
SABRE Collaboration



SABRE Strategy

- Lower Background
  - **NaI(Tl)** crystals with **higher purity** than DAMA/LIBRA
  - Lower-radioactivity enclosure & PMTs.
  - **Active scintillator veto** to reduce internal and external background events;
  - Use Pulse Shape Detection (PSD) to help identify and eliminate known background (non-DM) events.
- Lower energy threshold
  - **High QE** Hamamatsu PMTs **directly coupled** to NaI.
  - PSD based DAQ and data analysis, improved background measurements via AMS, improved quenching factors.

Ultra-pure NaI(Tl) Crystals- Frank Calaprice (Princeton)



Ultrapure NaI:Tl Target Detector

Intrinsic radioactivity limits WIMP sensitivity.
SABRE has made the most radiopure NaI:Tl to date.

- 'Astrograde' powder (Sigma Aldrich).
- Carefully-developed powder preparation and growth protocols (Princeton + RMD).

Lower radioimpurity than DAMA.
Production growth underway.
High QE + low background PMTs: 1 keV threshold design.

Element	DAMA powder [ppb]	DAMA crystals [ppb]	Astro-Grade [ppb]	SABRE crystal [ppb]
K	100	$\sim$13	9	9
Rb	n.a.	<0.35	<0.2	<0.1
U	$\sim$0.02	$0.5\text{-}7.5\times10^{-3}$	$<10^{-3}$	$<10^{-3}$
Th	$\sim$0.02	$0.7\text{-}10\times10^{-3}$	$<10^{-3}$	$<10^{-3}$

Liquid scintillator veto

Liquid Scintillator Veto

External background tagging

- Muons, spallation neutrons, etc.

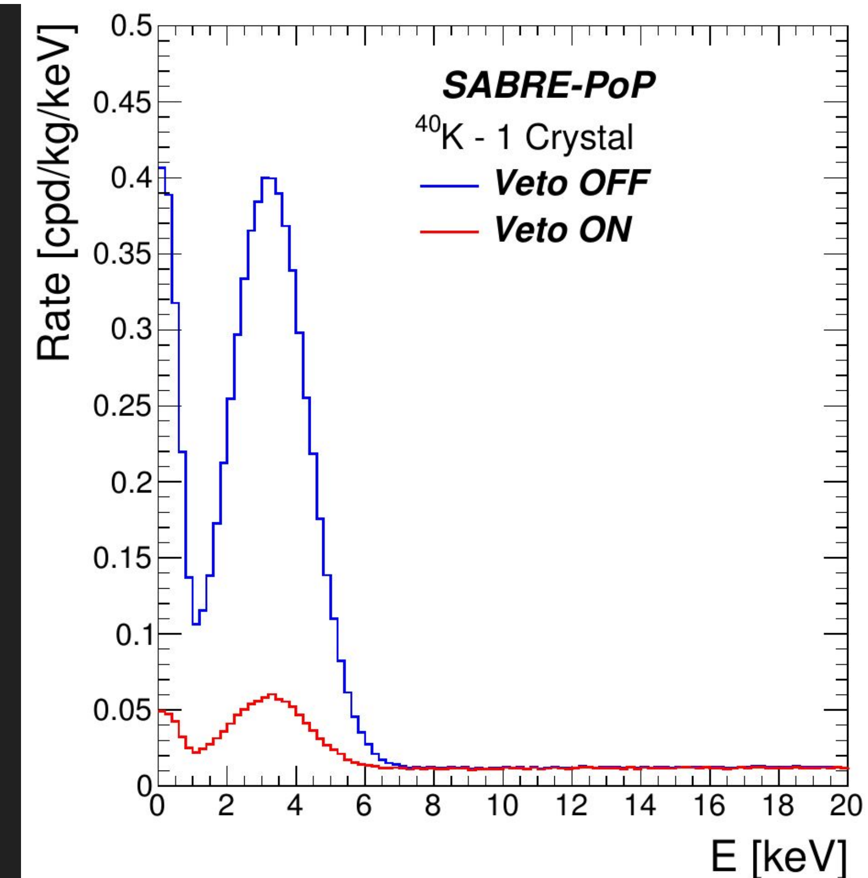
Intrinsic background tagging

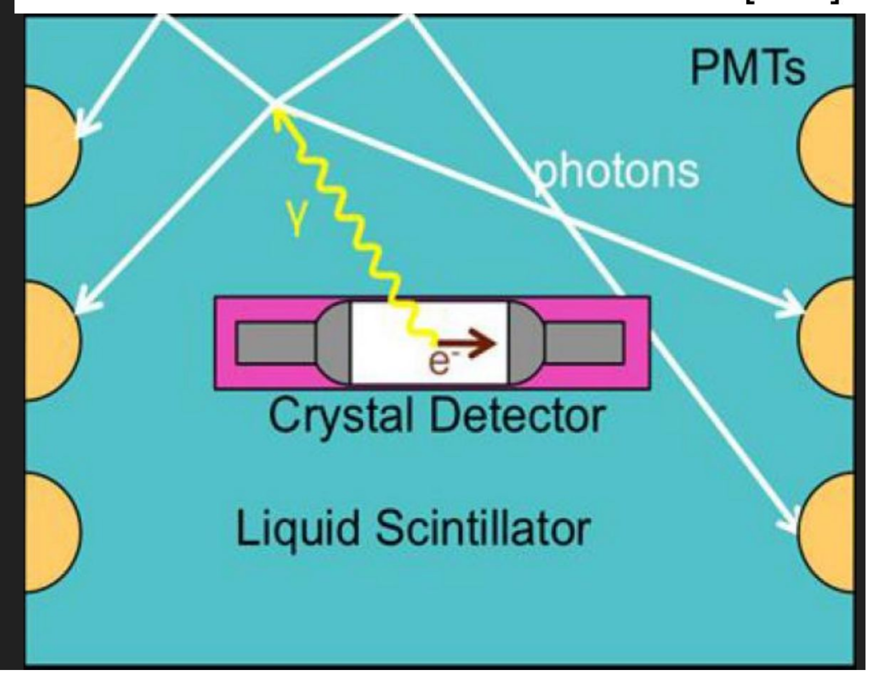
- Correlated gammas from decays
- ^{40}K is especially important

Radiopure Shielding

- SABRE North: Borexino's pseudocumene-based liquid scintillator
- SABRE South: Linear alkylbenzene-based LS, ex-CTF purification

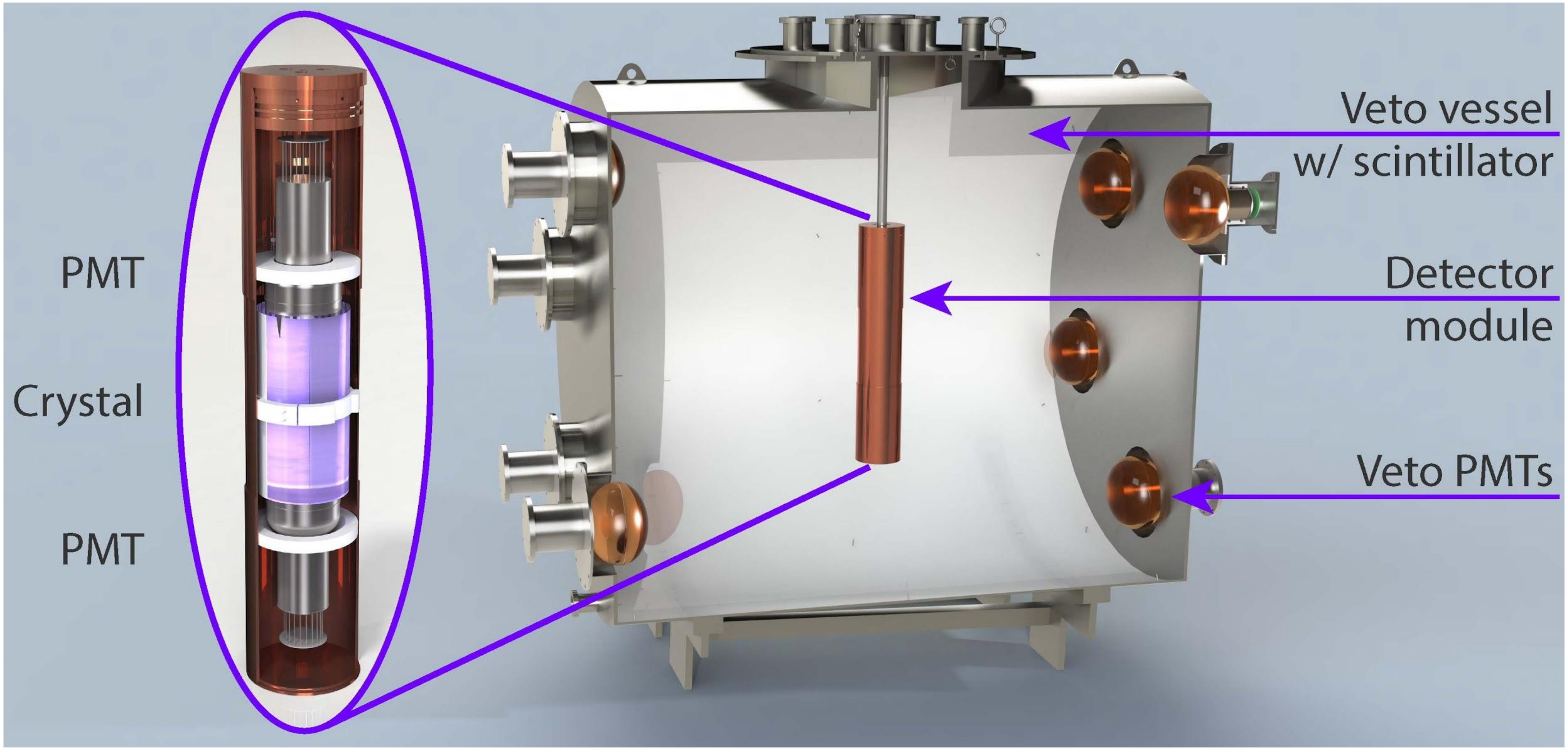
Proof-of-Principle veto 84% of ^{40}K in signal range.





SABRE PoP Design

- **Proof of principle** (LNGS): 5-kg ultra low background Na(Tl) crystals
  - LAB or pseudocumene scintillator veto (1.4m diameter, 1.5 length)
- **Full detector** (LNGS & SUPL): ~50kg @ each site



Conclusion

SABRE will confirm or refute the DAMA signal with high significance.

South detector will be housed in the first deep underground laboratory in the Southern Hemisphere.

Proof-of-Principle to start collecting data in Autumn 2018.

Full scale SABRE drawing.

First SABRE publications

The SABRE project and the SABRE Proof-of-Principle

M. Antonello[a], E. Barberio[b], T. Baroncelli[b], J. Benziger[c], L. J. Bignell[d], I. Bolognino[a,e], F. Calaprice[f], S. Copello[g,h], I. Dafinei[i], D. D'Angelo[a,e], G. Di Carlo[g], M. Diemoz[i], A. Di Ludovico[f], G. D'Imperio[i], W. Dix[b], A. R. Duffy[j,k], F. Froborg[l], G. K. Giovanetti[f], E. Hoppe[m], A. Ianni[g], L. Ioannucci[g], S. Krishnan[k], G. J. Lane[d], I. Mahmood[b], A. Mariani[h], M. Mastrodicasa[i,n], P. Montini ☆[i,n], J. Mould[j,k], F. Nuti[b], D. Orlandi[g], M. Paris[g], V. Pettinacci[i], L. Pietrofaccia[f], S. Rahatlou[i,n], N. Rossi[i], E. Shields[f], A. E. Stuchbery[d], B. Suerfu[f], C. Tomei[i], V. Toso[a,e], P. Urquijo[b], C. Vignoli[g], A. Wallner[d], M. Wada[f], A. G. Williams[o], J. Xu[f]

The SABRE Collaboration

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[n] *Dipartimento di Fisica, Sapienza Università di Roma, Roma I-00185, Italy*
[o] *The University of Adelaide, Adelaide, South Australia, 5005 Australia*

arXiv: 1806.09344

Both submitted to Astroparticle Physics

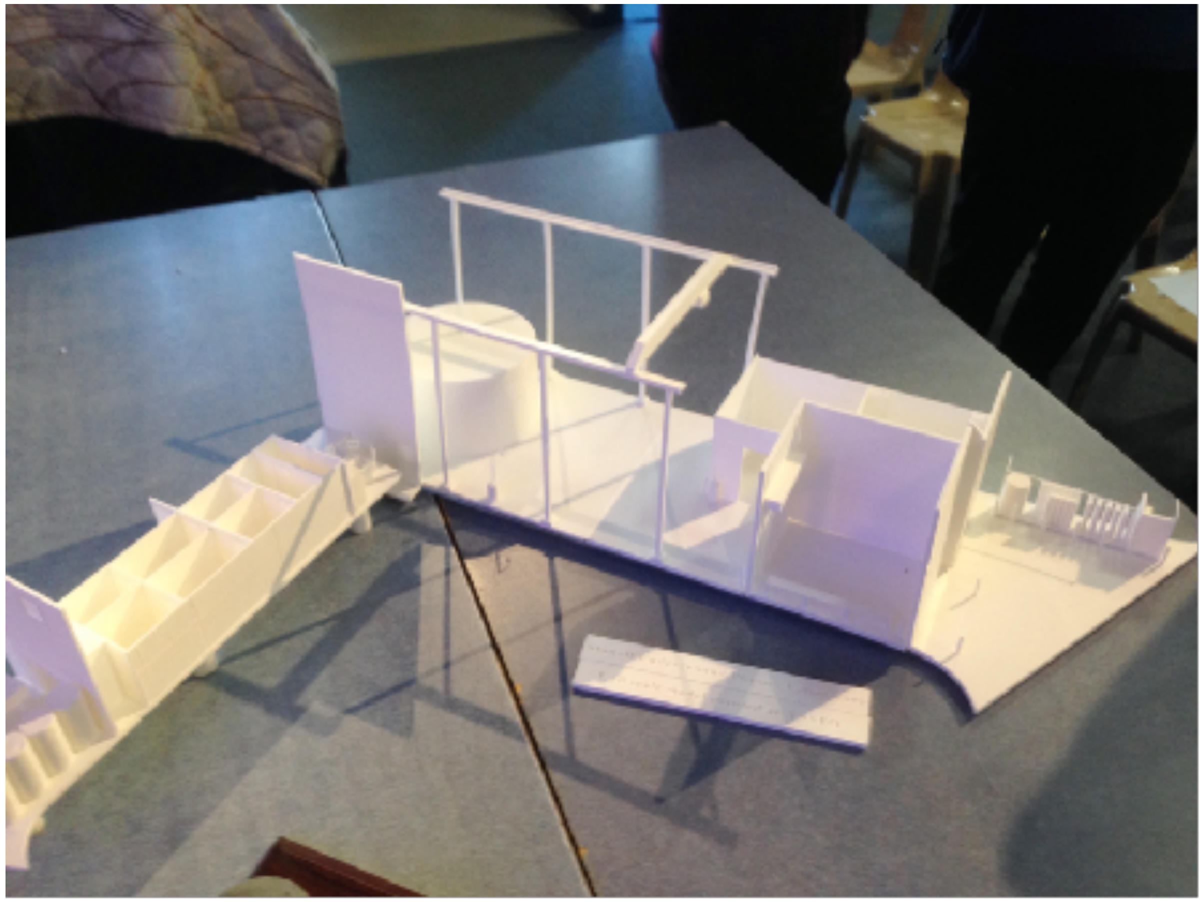
Monte Carlo simulation of the SABRE PoP background

M. Antonello[a], E. Barberio[b], T. Baroncelli[b], J. Benziger[c], L. J. Bignell[d], I. Bolognino[a,e], F. Calaprice[f], S. Copello[g,h], I. Dafinei[i], D. D'Angelo[a,e], G. Di Carlo[g], M. Diemoz[i], A. Di Ludovico[f], G. D'Imperio[i], A. R. Duffy[j,k], F. Froborg[l], G. K. Giovanetti[f], E. Hoppe[m], A. Ianni[g], L. Ioannucci[g], S. Krishnan[k], G. J. Lane[d], I. Mahmood[b], A. Mariani[h], P. McGee[n], P. Montini ☆[i,o], J. Mould[j,k], F. Nuti[b], D. Orlandi[g], M. Paris[g], V. Pettinacci[i], L. Pietrofaccia[f], S. Rahatlou[i,o], N. Rossi[i], E. Shields[f], A. E. Stuchbery[d], B. Suerfu[f], C. Tomei[i], P. Urquijo[b], C. Vignoli[g], A. Wallner[d], M. Wada[f], A. G. Williams[n], J. Xu[f], M. Zurowski[b]

The SABRE Collaboration

arXiv: 1806.09340

SUPL @ Stawell



Conclusions

- I am still a theorist 95% of the time, but we needed to get SABRE and SUPL happening in Australia;
- Ernie Henley was a warm, principled and deeply intelligent physicist and it was a privilege to know him;
- His influence on my research continues to this day;
- By pursuing symmetry as a way to better understand our universe.