Dark Matter at the DOE Cosmic Frontier

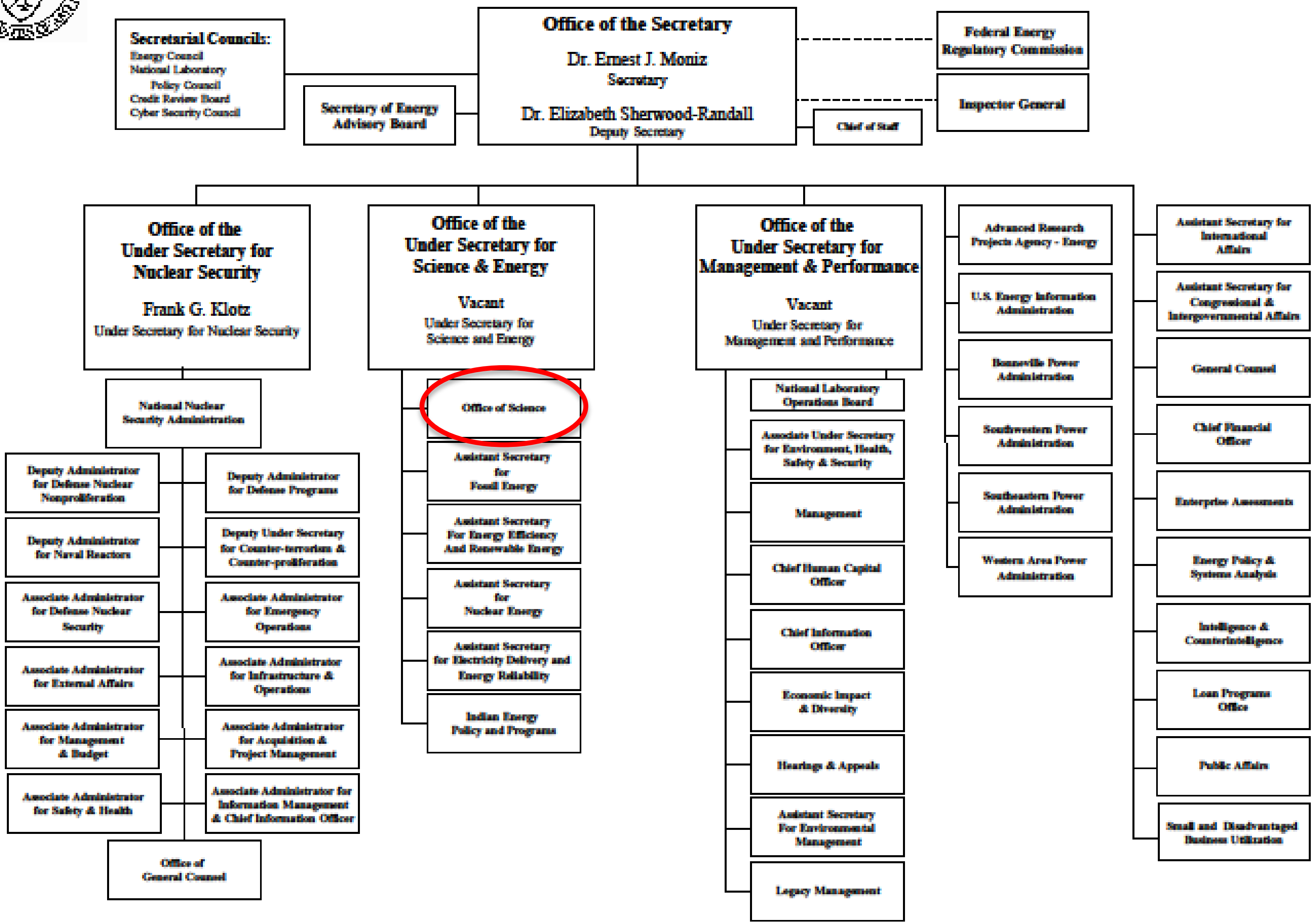
AMS Days at CERN

April 15-17, 2015

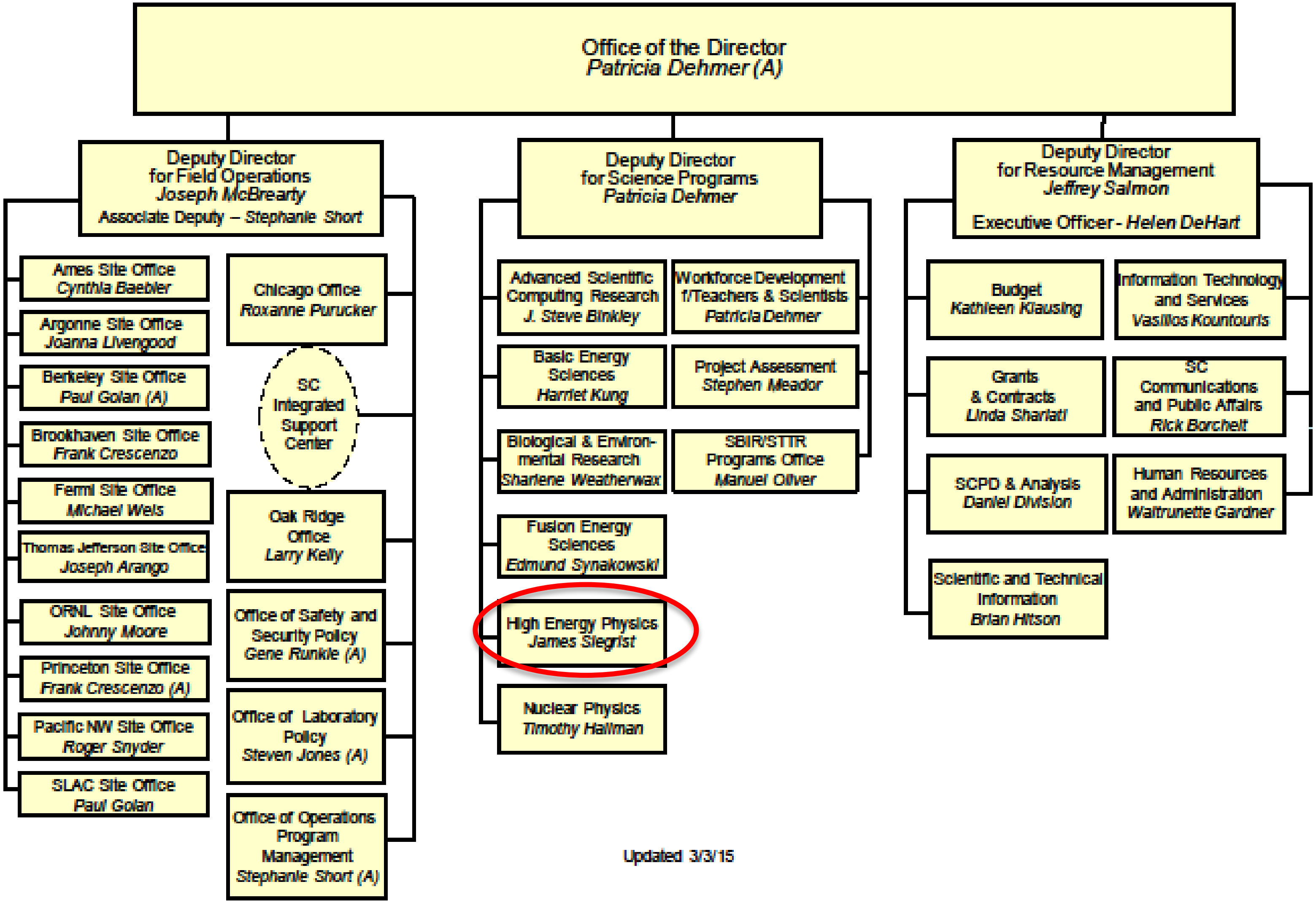
Michael Salamon
Office of High Energy Physics
Office of Science, U.S. Department of Energy

Where Dark Matter resides in DOE

DEPARTMENT OF ENERGY



06 Oct 2014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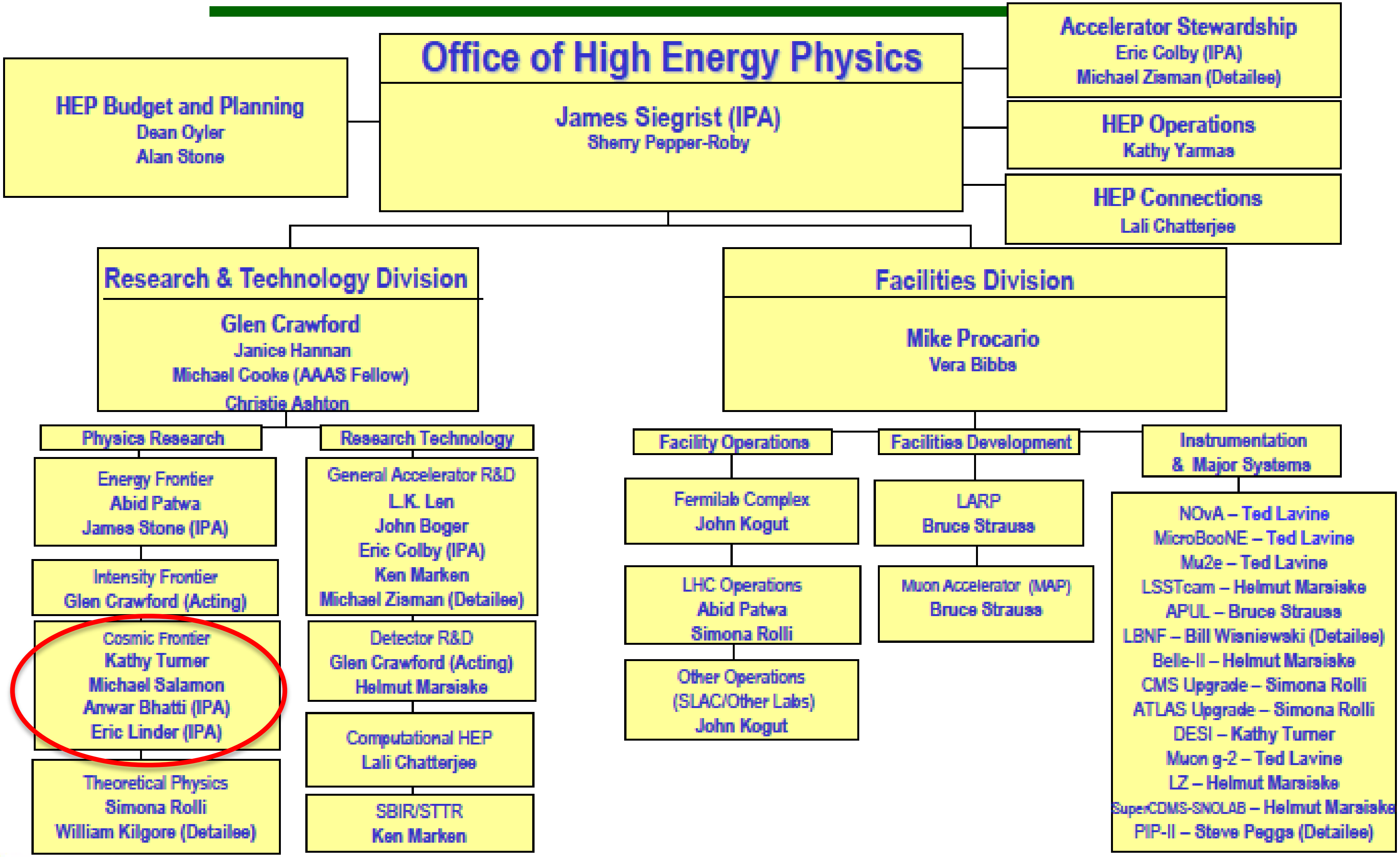
HEP Organization Chart



U.S. DEPARTMENT OF ENERGY

Office of Science

Cosmic Frontier Program

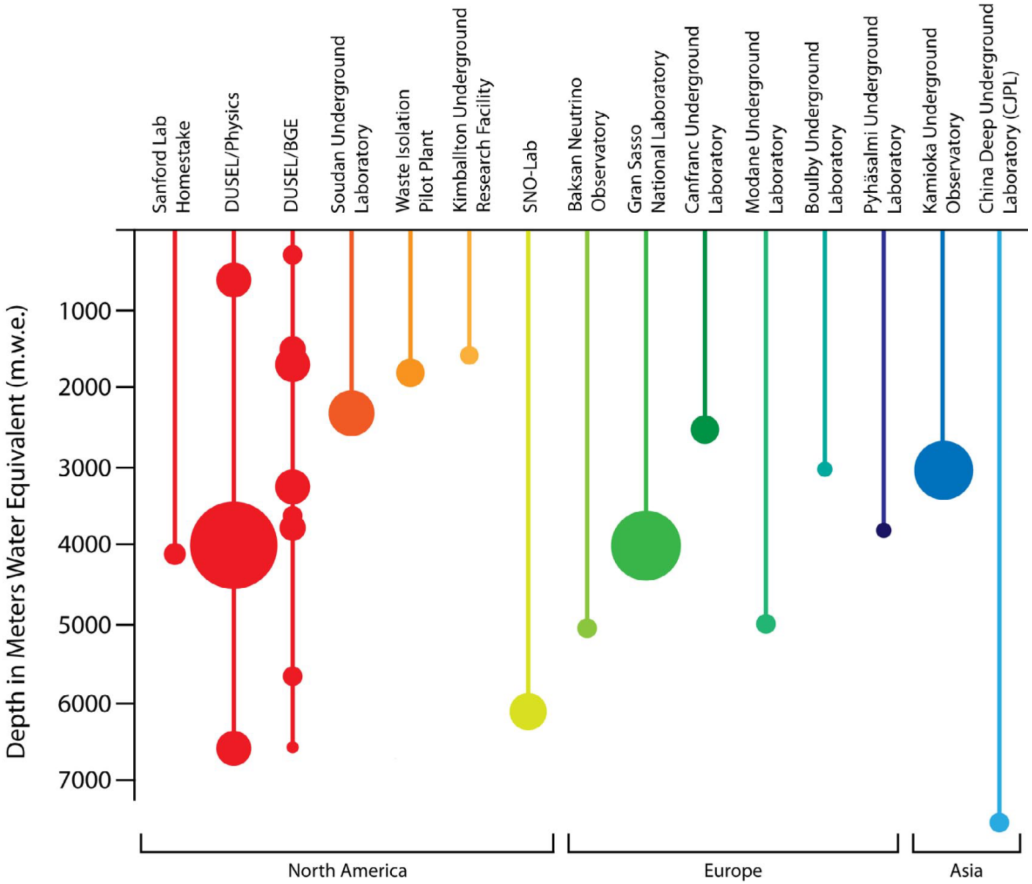
- Studies of the nature of **Dark Energy** using imaging and spectroscopic surveys
- Direct detection searches for **Dark Matter** particles
- Study of the high energy universe and indirect dark matter searches using **Cosmic-ray, Gamma-ray** experiments
- **CMB** experiments to study the nature of inflation, neutrino properties, and dark energy
- **Other** efforts, including
  - Computational cosmology efforts
  - Other experiments

FY 2016 High Energy Physics Budget

HEP Funding Category ($ in K)	FY 2014 Current	FY 2015 Enacted	FY 2016 Request	Explanation of Changes (FY16 vs. FY15)
Energy Frontier	152,386	147,584	154,555	*LHC detector upgrade fabrication; R&D for high-luminosity LHC upgrades*
Intensity Frontier	250,987	264,224	247,196	*Operations and upgrade of NuMI for NOvA and MicroBooNE; R&D for LBNF and SBN*
Cosmic Frontier	96,927	106,870	119,325	*Planned ramp-up of LSSTcam; support of DESI and 2nd generation dark matter experiments*
Theoretical and Comp.	64,275	59,274	60,317	*Planned increase in Lattice QCD project; slight reduction in theory research efforts*
Advanced Technology R&D	150,270	120,254	115,369	*Reductions reflect shift to P5 priority areas; MAP reduction continues in response to P5*
Accelerator Stewardship	9,075	10,000	14,000	*Increase supports new research topic areas and expands open test facility efforts*
Construction (Line Item)	51,000	37,000	56,100	*Planned profile for Mu2e; engineering and design for LBNF*
SBIR/STTR	21,601*	20,794	21,138	
Total	**796,521***	**766,000**	**788,000**	

**** SBIR/STTR added to FY 2014 for comparison to FY 2015/2016***

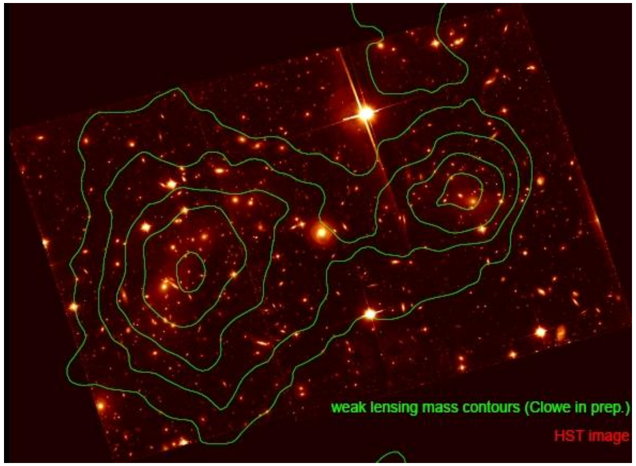
Dark Matter Program within the Cosmic Frontier



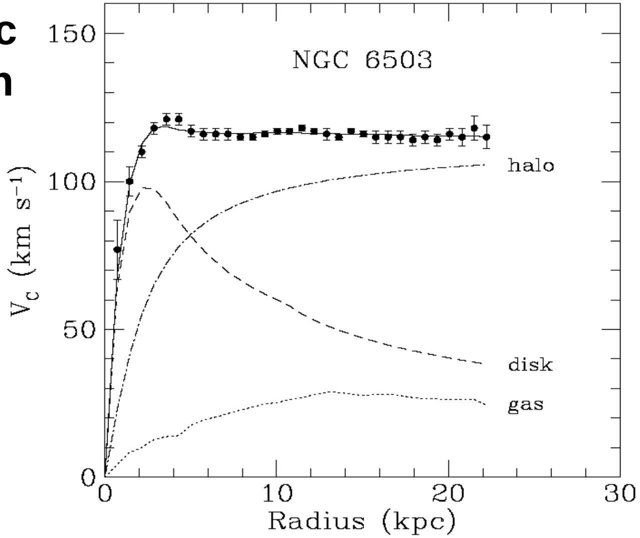
(NAS Board of Physics and Astronomy report, 2011)

Evidence for Dark Matter

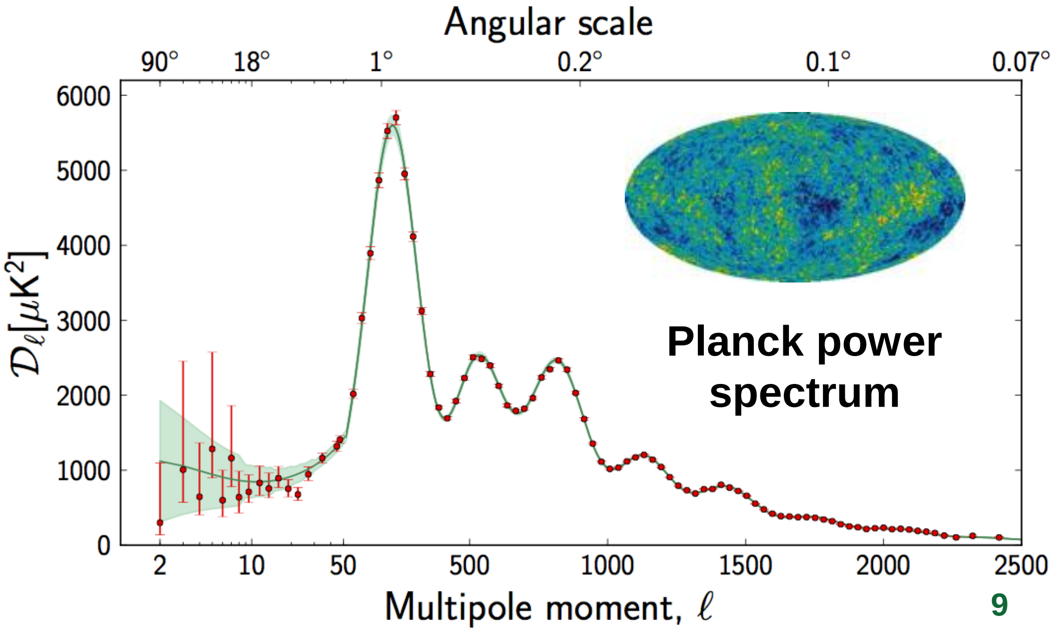
Weak lensing (Bullet Cluster)



Galactic rotation



But what is it? And how do we search for it?



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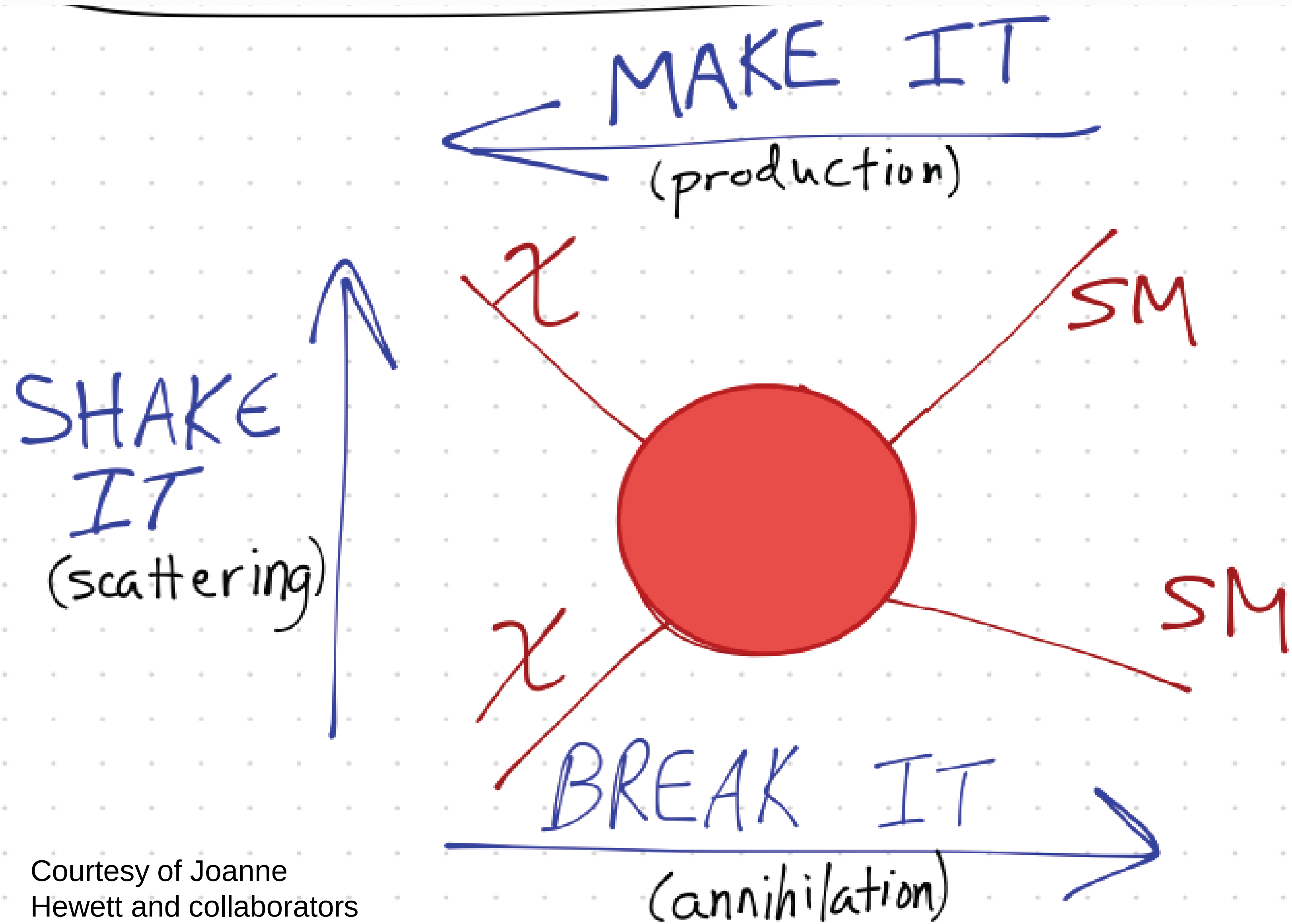
WIMP Dark Matter Complementarity

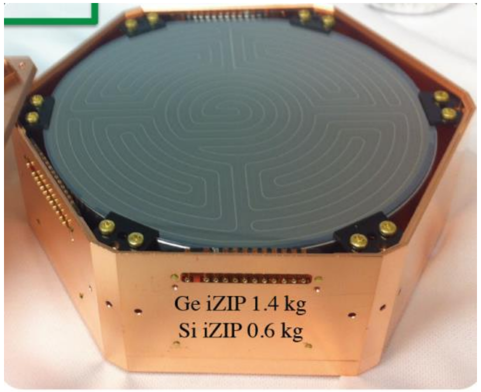


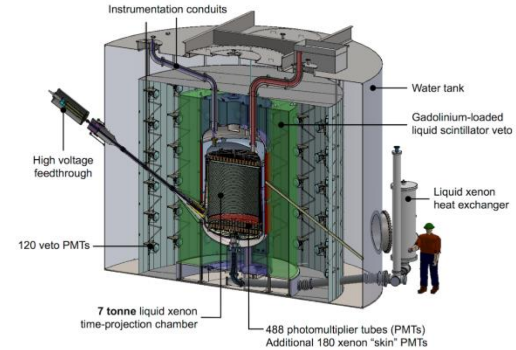
Courtesy of Joanne
Hewett and collaborators

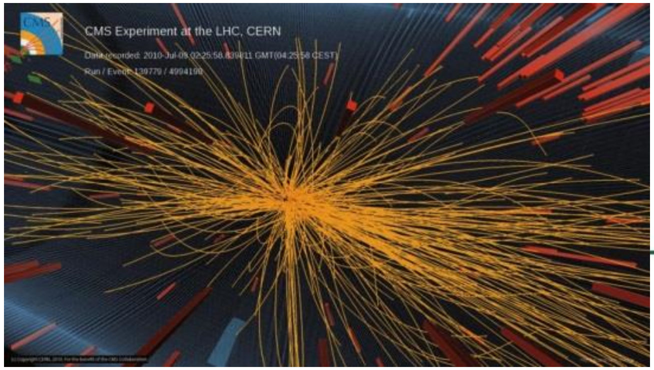
Complementary Techniques for DM Detection

Indirect detection

Direct detection





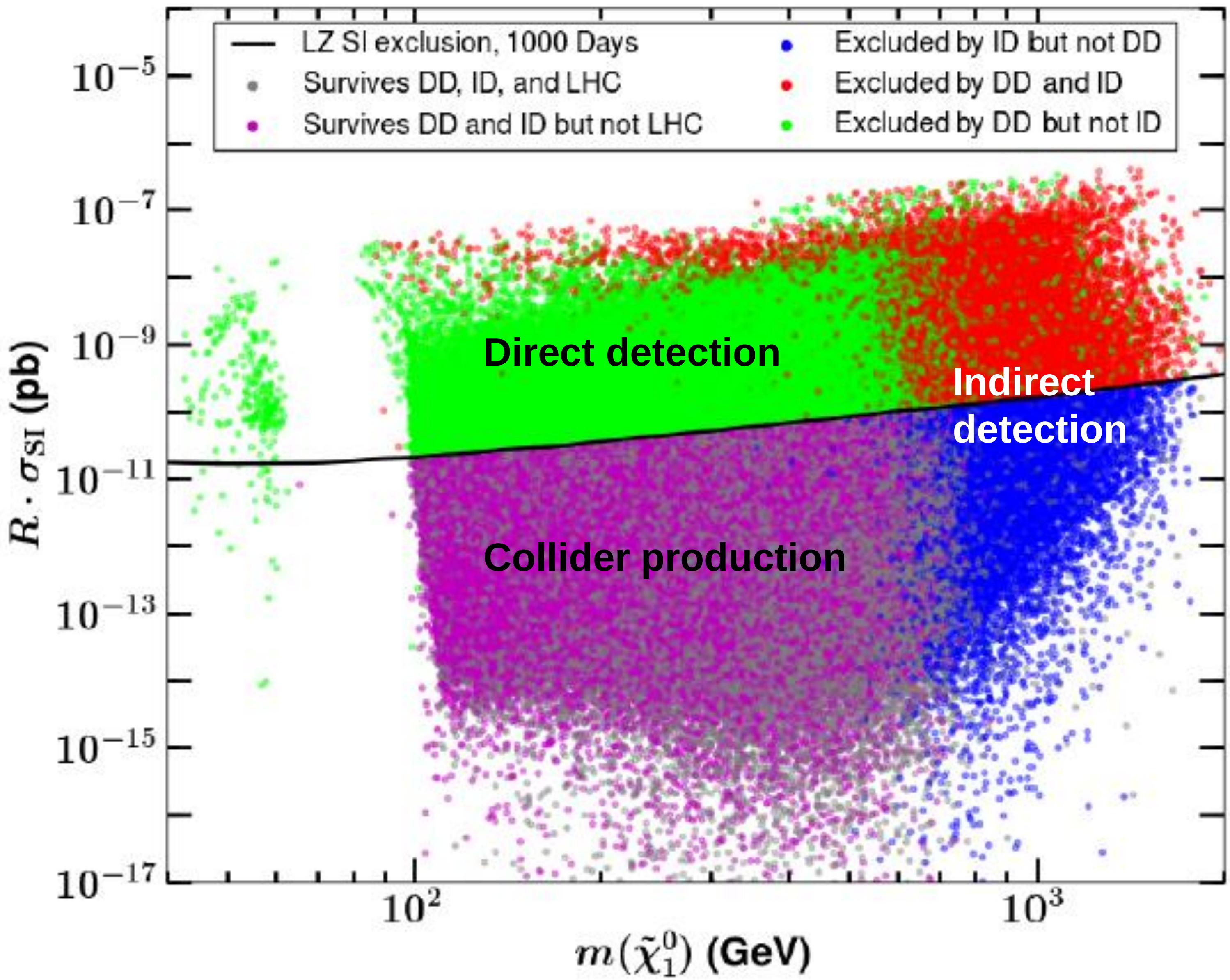


Collider production

Dark Matter Projects in the Cosmic Frontier

- Indirect Detection
  - Alpha Magnetic Spectrometer, in low Earth orbit
  - Fermi Gamma-ray Space Telescope (FGST), in low Earth orbit
  - High Altitude Water Čerenkov array (HAWC), in Mexico
  - VERITAS, in Arizona
- First-Generation (G1) Direct Detection
  - WIMPs
    - DarkSide-50: LAr TPC, in Gran Sasso
    - LUX: LXe TPC, in Sanford Underground Research Facility (SURF)
    - PICO: bubble chamber, 60 kg C_3F_8 target, in SNOLAB
    - SuperCDMS-Soudan: Cryo Ge crystals, in Soudan Mine
  - Axions
    - ADMX-IIa at the U. of Washington
- Second-Generation (G2) Direct Detection (>10x sensitivity than G1)
  - WIMPs
    - LUX-Zepplin (LZ): 7-tonne LXe TPC in SURF
    - SuperCDMS-SNOLAB: Cryo Ge and Si in SNOLAB
  - Axions
    - ADMX-Gen2 at the U. of Washington

Complementary Techniques: pMSSM parameter space

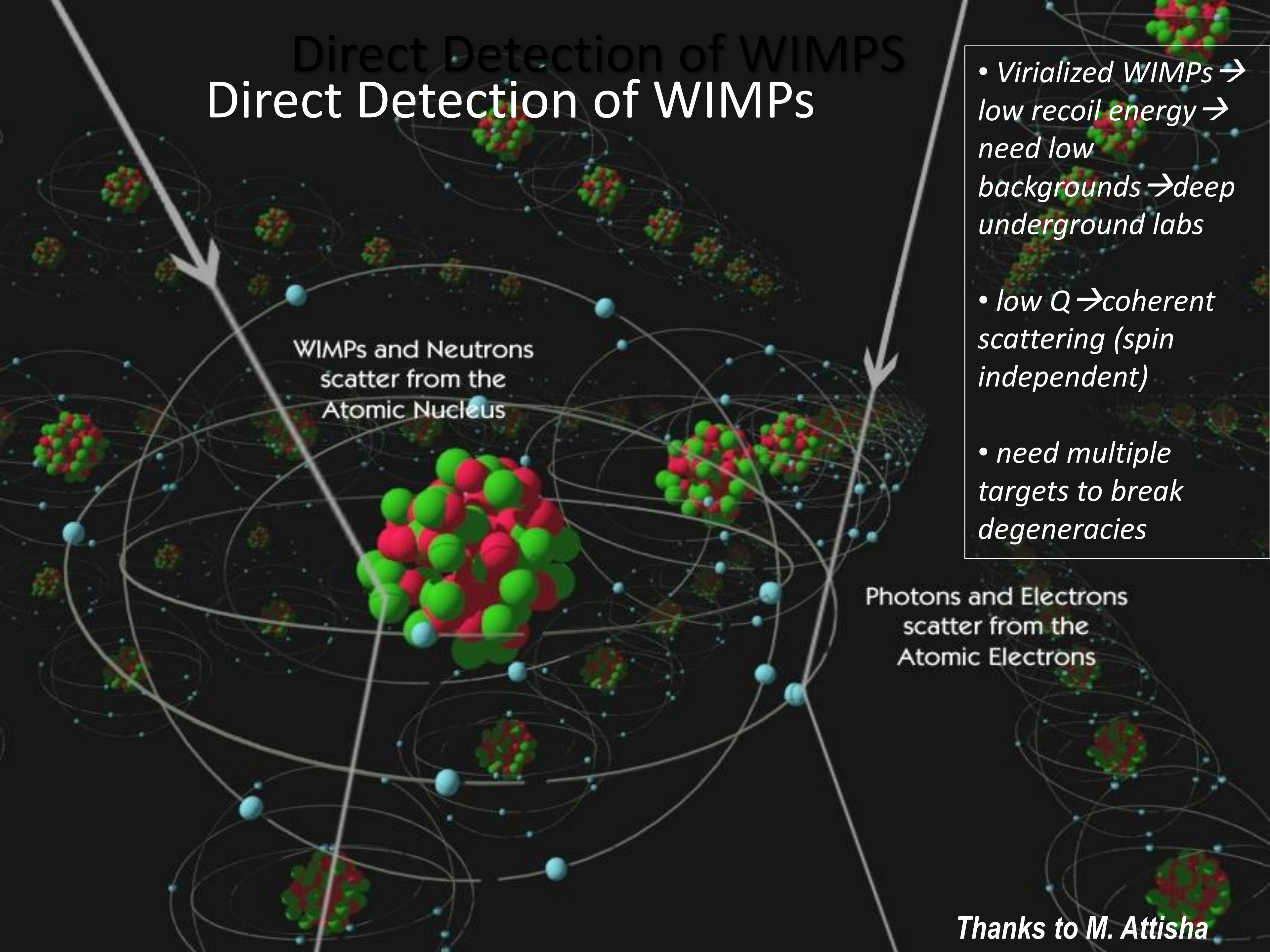


From Cahill-Rowley et al., arXiv:1405.6716 (May 2014)

Direct Detection of WIMPs

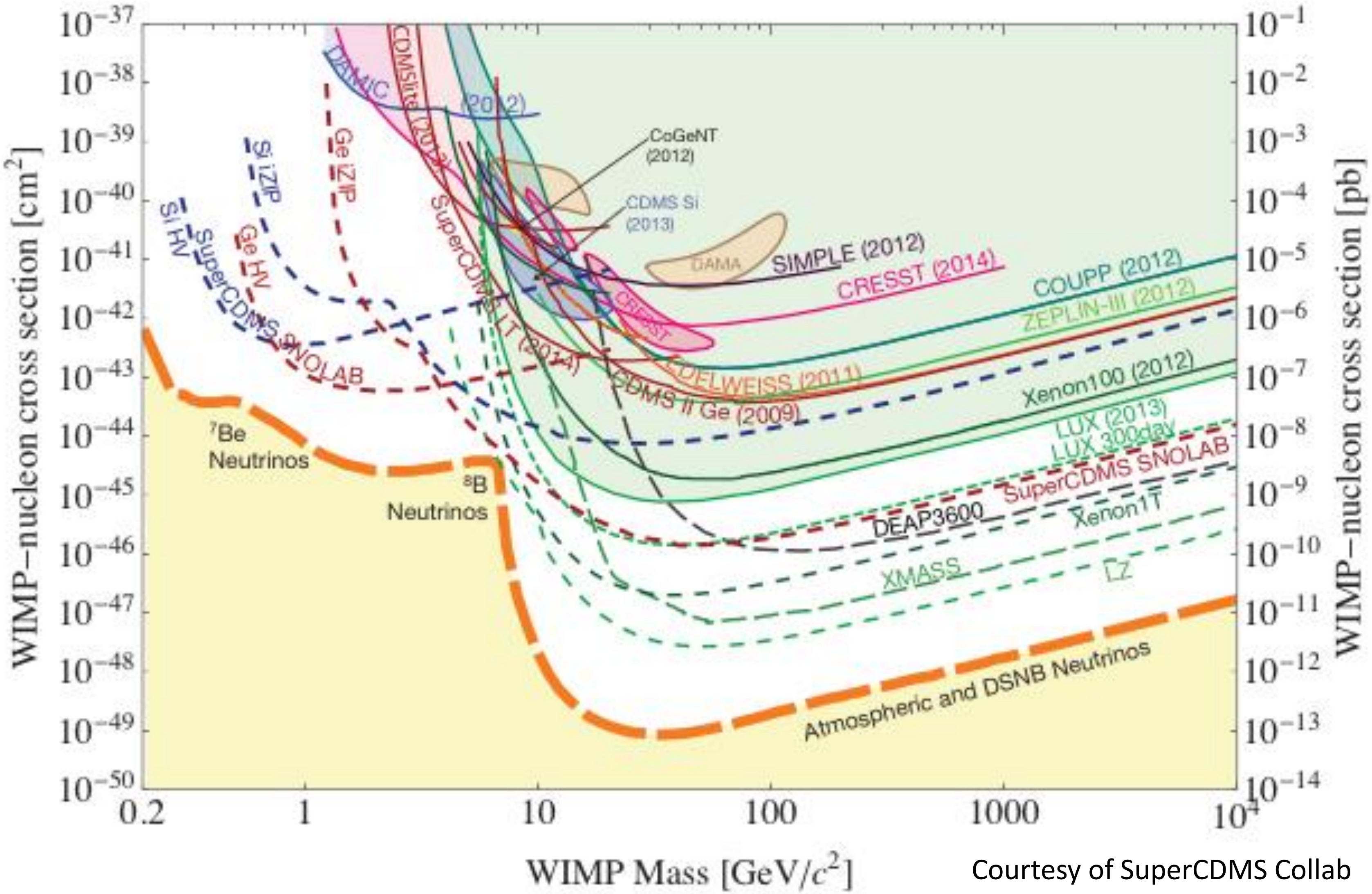
Direct Detection of WIMPS

- *Virialized WIMPs → low recoil energy → need low backgrounds → deep underground labs*
- *low Q → coherent scattering (spin independent)*
- *need multiple targets to break degeneracies*



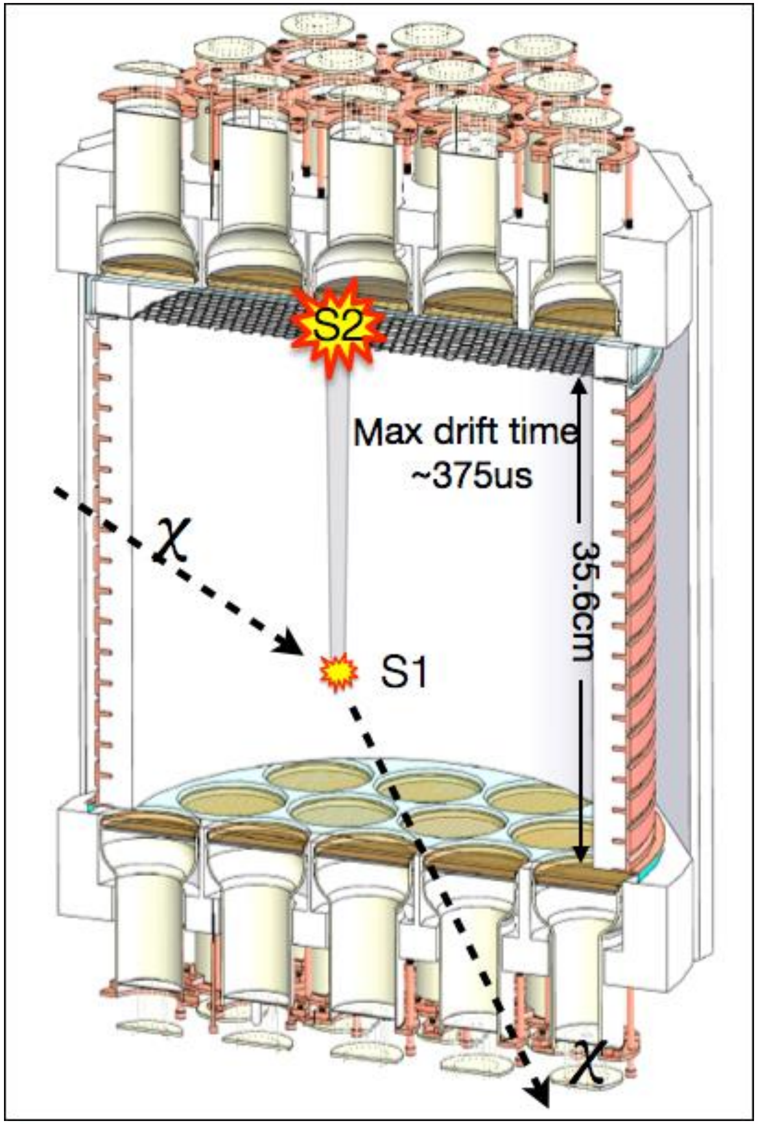
Thanks to M. Attisha

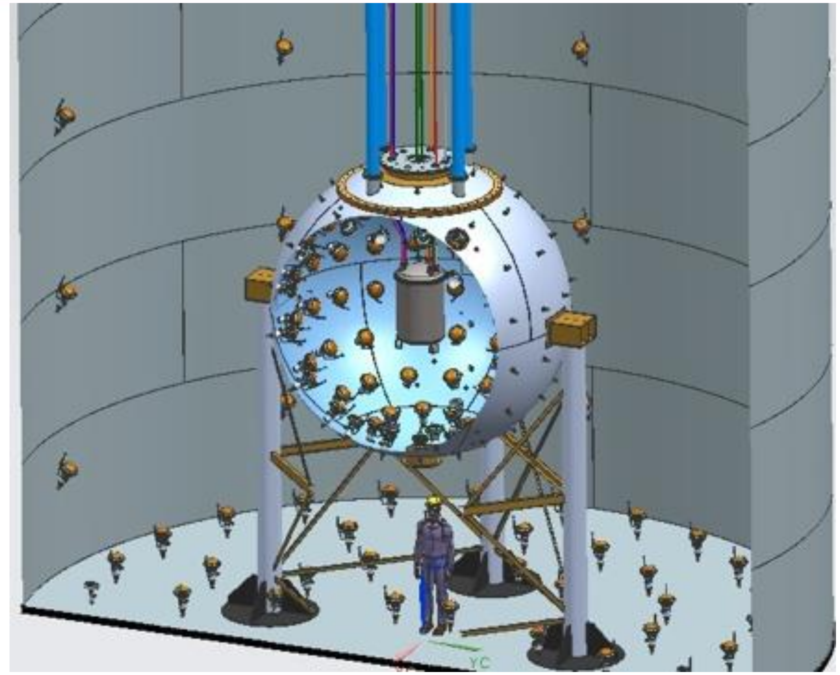
Direct Detection: the WIMP Neutrino Floor



Courtesy of SuperCDMS Collab

DarkSide-50 (G1)



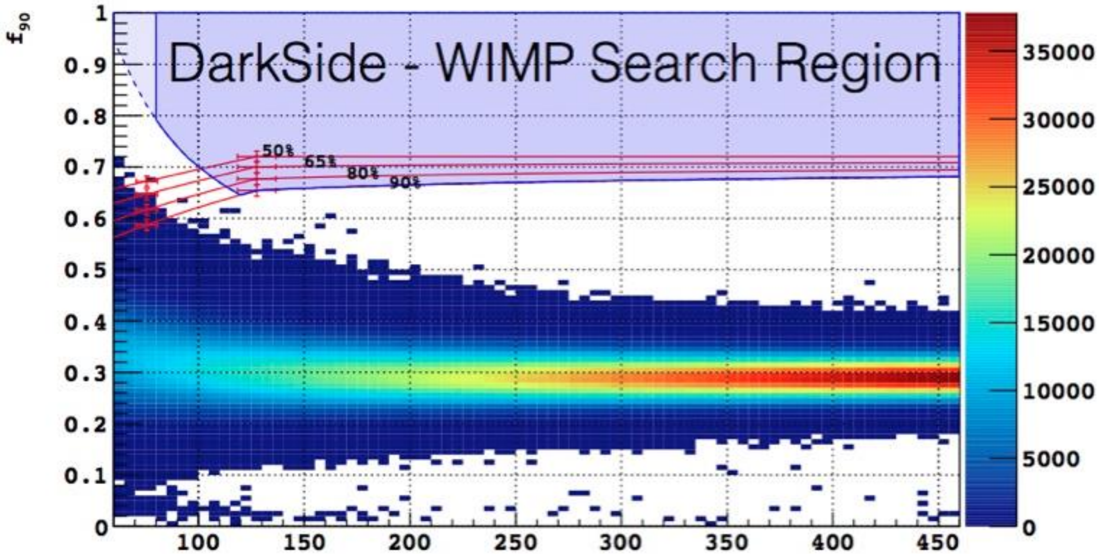


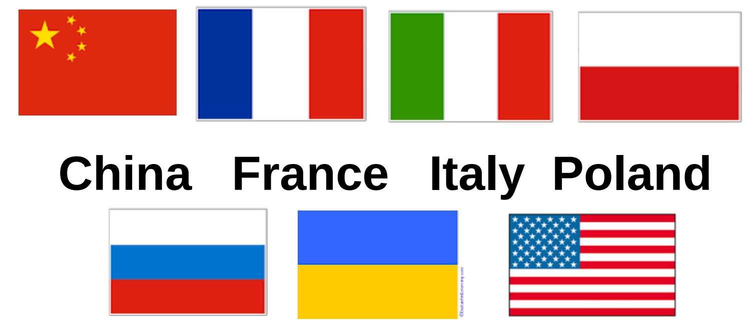
Dark Matter Search with 2-phase, liquid argon TPC as target (45kg) at LNGS

Sensitivity goal 2 x 10^{-45} cm^2

- low-radioactivity argon from underground (Co., U.S.A) (UAr)
- borated liquid scintillator veto
- water cerenkov veto

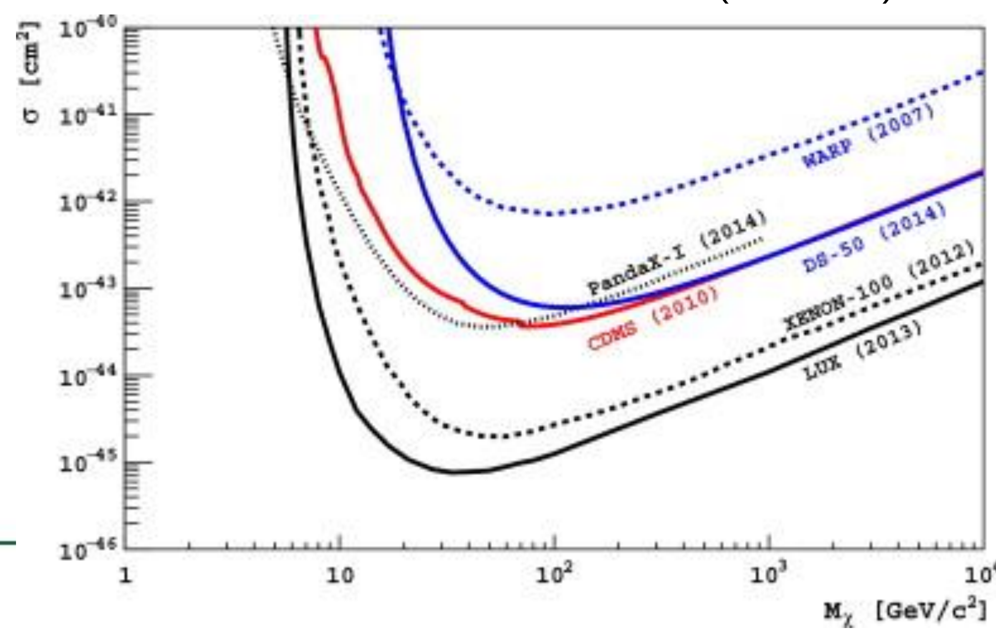
DarkSide-50





7 nations, 32 institutions

arXiv:1501.03541v1 (Jan 2015)



Discrimination:

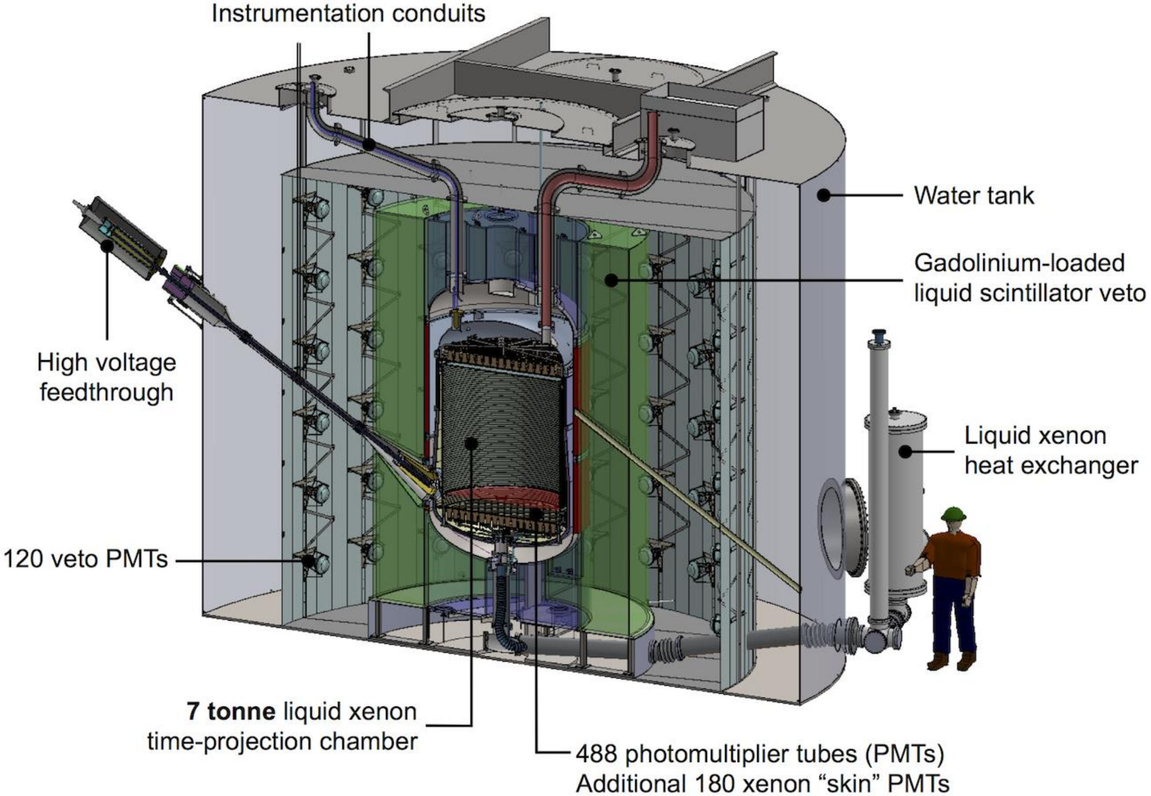
- Singlet to triplet scintillation ratio
- Electromagnetic recoil vs. nuclear recoil ionization yield
- Fiducial cuts with TPC.

LZ (LUX-ZEPPLIN) (G2)

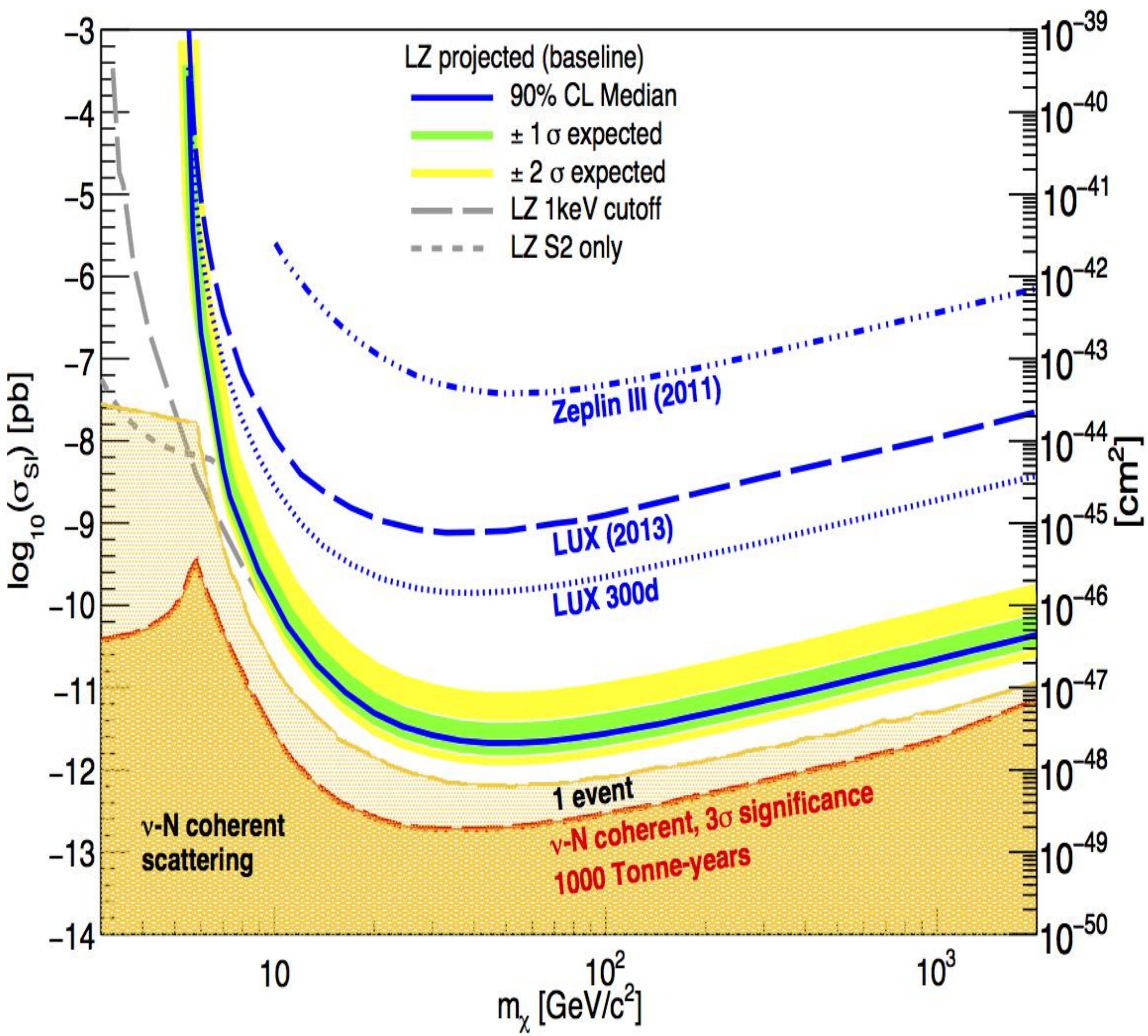
- LXe TPC detector
- Coherent WIMP scattering scales as ~A^2, giving Xe an advantage in sensitivity reach
- Located at the Sanford Underground Research Facility (SURF) in South Dakota, USA
- G1 version (LUX), 250 kg LXe active mass is now in middle of 300-day run.

Generation 2 experiment

- 10 total tonnes of LXe, 7 active tonnes with extensive background veto systems to maximize useful mass
- U.S. – UK – Portugal – Russia
- Currently 29 institutions and 160 people, continuing to grow
- Start operation ~ 2019



LZ Spin Independent Sensitivity for 1,000 Days



- LUX (2013) limit from 1000 kg-day operation (arXiv 1310.8214)
- LUX-300 day result in 2016, after which operations cease in preparation for LZ.
- LZ result with 1000 days livetime

PICO (PICASSO + COUPP): Bubble Chamber DM Search (G1)

- Superheated fluid in bubble chamber.
- Energy deposition > E_{th} in radius < r_c from particle interaction will result in expanding bubble. A smaller or more diffuse energy deposit will not.
- Thermodynamic parameters are chosen for sensitivity to nuclear recoils but not to electron recoils.
- Better than 10^{-10} reject of electron recoils (β and Υ)!

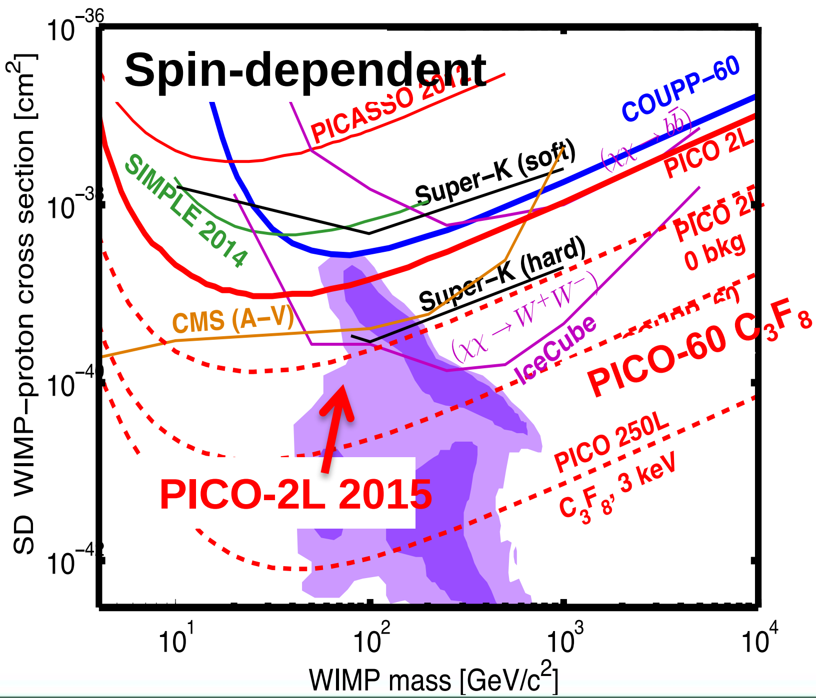
- PICO collaboration operates two bubble chambers at SNOLAB: PICO-2L (2 liters C_3F_8 target) and PICO-60 (20 liters CF_3I target in 2013-2014 Run).
- Comparison of rates on different targets allows unique tests of signal, background models.
- Thermodynamic conditions tuned to reject backgrounds according to specific energy loss (dE/dX).
- Acoustic signals from bubble growth provide additional background discrimination.

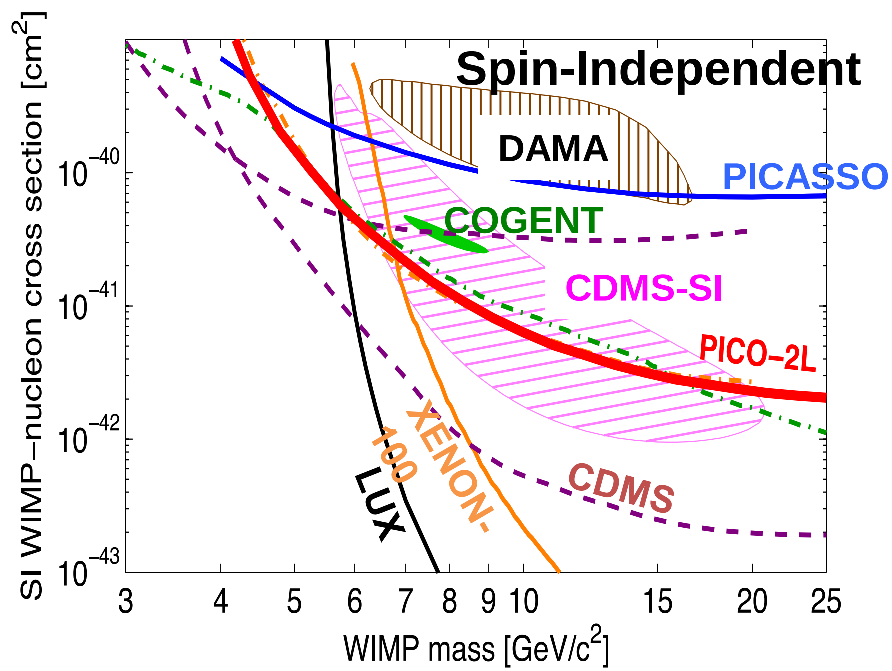
PICO 2015 Results (Preliminary)

- Competitive sensitivity for both spin-dependent and independent WIMP couplings.
- Leading experiment for WIMP-proton spin dependent sensitivity: ArXiv:1503.0008.
- Transition from CF_3I target liquid to C_3F_8 extends sensitivity to lower masses.

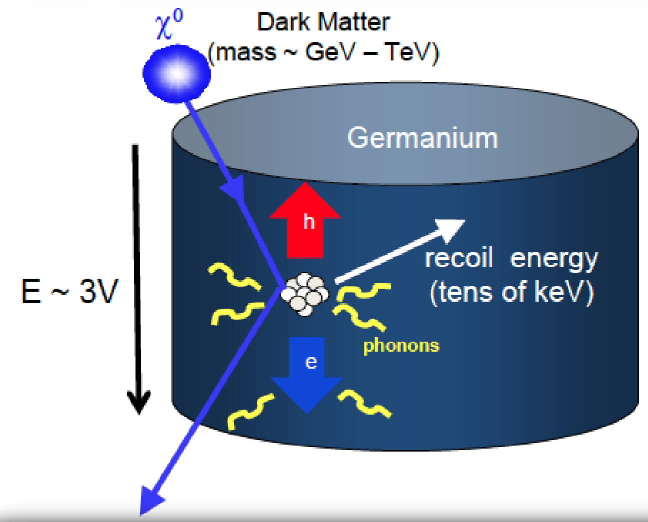
Collaboration:

- 5 nations: Canada, Czech Republic, India, Spain, U.S.A.
- 15 institutions



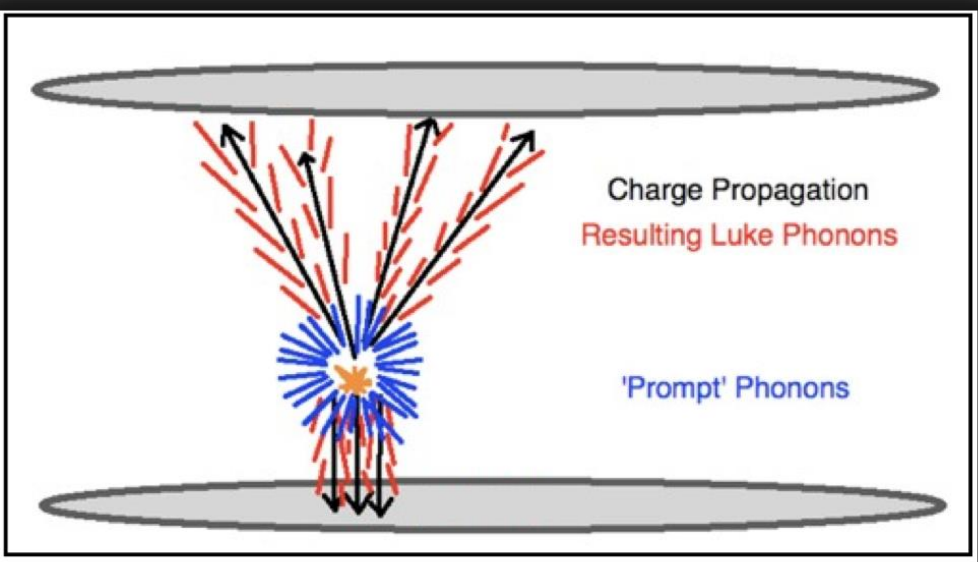


SuperCDMS (Cryogenic Dark Matter Search)



Standard CDMS mode for DM detection:

- Cryogenic Ge detectors operating at ~15 mK
- WIMP interaction creates phonons and electron-hole pairs
- Phonons measured with transition edge sensors
- Ionization charge drifts to amplifiers
- Charge/phonon ratio discriminates against electron recoil

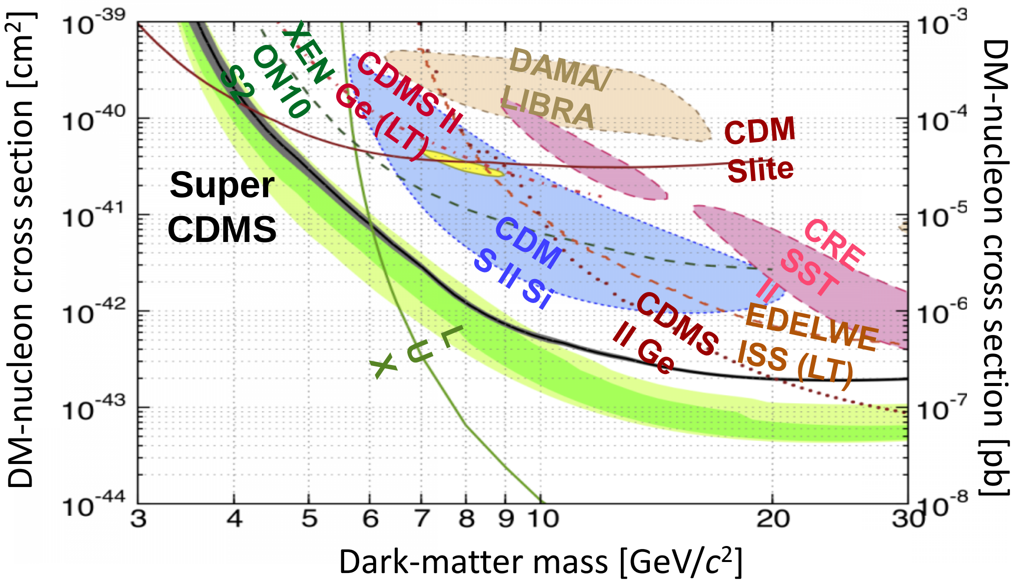


HV mode: Luke-Neganov phonon amplification:

- Increase voltage, phonons produced by drifting pairs dominate phonon signal
- Ability to count at the few electron charge level, allows for detection at <keV recoil energies → can reach to lower WIMP masses;
- Loss of background discrimination → far less sensitivity; much higher cross section limits

SuperCDMS-Soudan (G1) + SNOLAB (G2)

arXiv: 1402.7137v2 (Mar 2014)



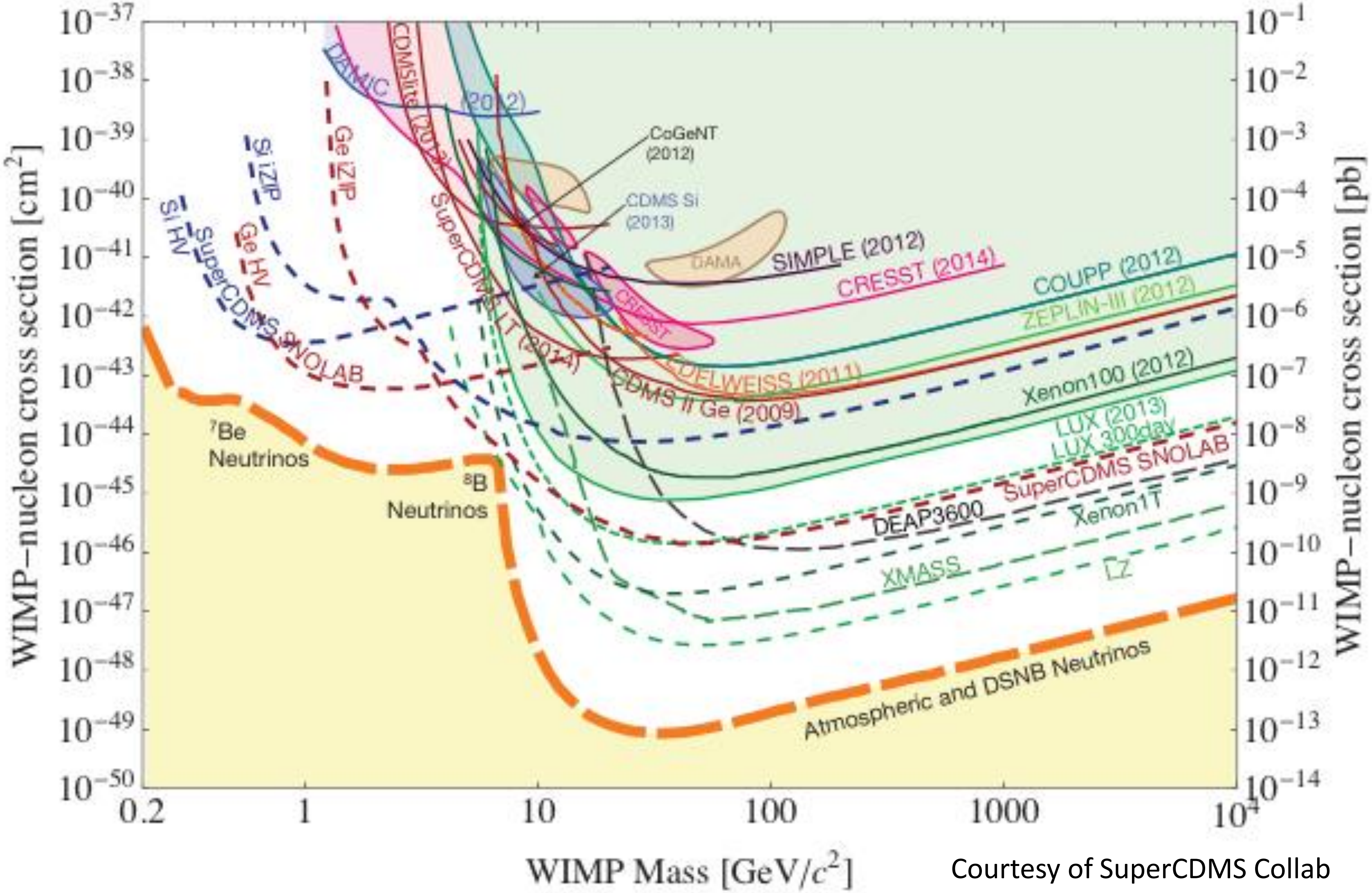
SuperCDMS-Soudan

- 15 Ge crystal detectors, 0.6kg each
- operating in the Soudan Underground Lab since 2012
- Published limits on WIMPs, axions, lightly ionizing matter
- operations coming to end to prepare for G2 version, SuperCDMS-SNOLAB
- latest (March 2014) limits from 557 kg-days exposure.

SuperCDMS-SNOLAB

- G2 version of SuperCDMS; to be located in SNOLAB (greater depth than Soudan)
- Both Ge and Si cryogenic crystals, Si for very low WIMP mass sensitivity
- Both standard and HV modes implemented; dedicated crystals for each mode.
- In potential partnership with Europe's EURECA collaboration, may have up to ~200 kg of Ge, smaller amount of Si.
- Canada, Spain, UK, US (+ France, Germany from EURECA)

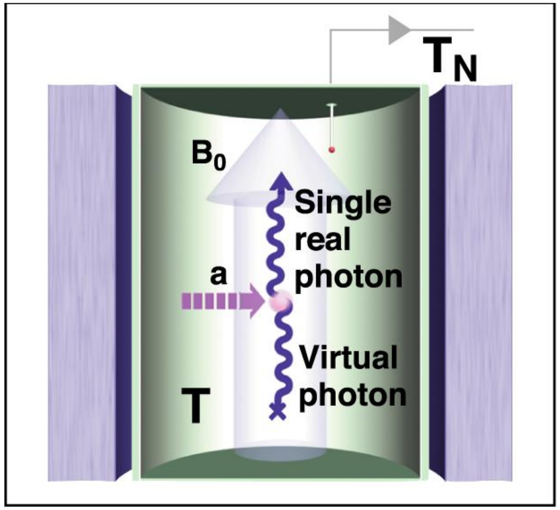
SuperCDMS-SNOLAB Expected Sensitivity Reach

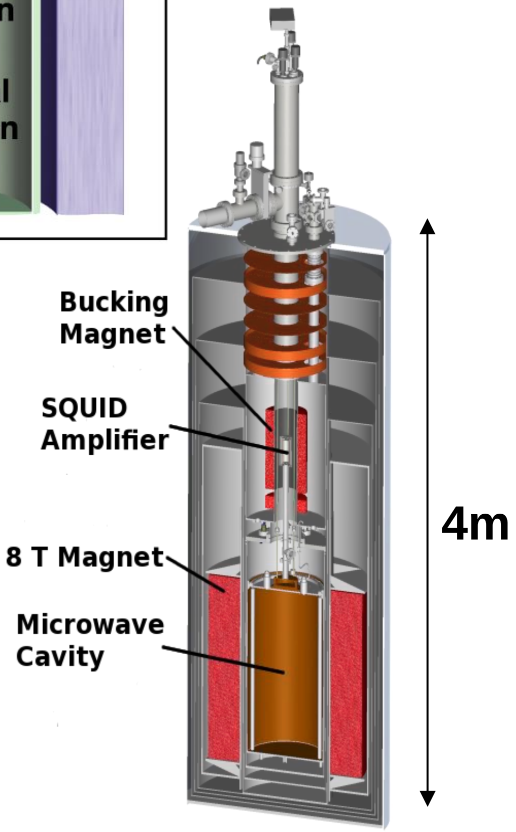


Courtesy of SuperCDMS Collab

ADMX (Axion Dark Matter Experiment) (G2)

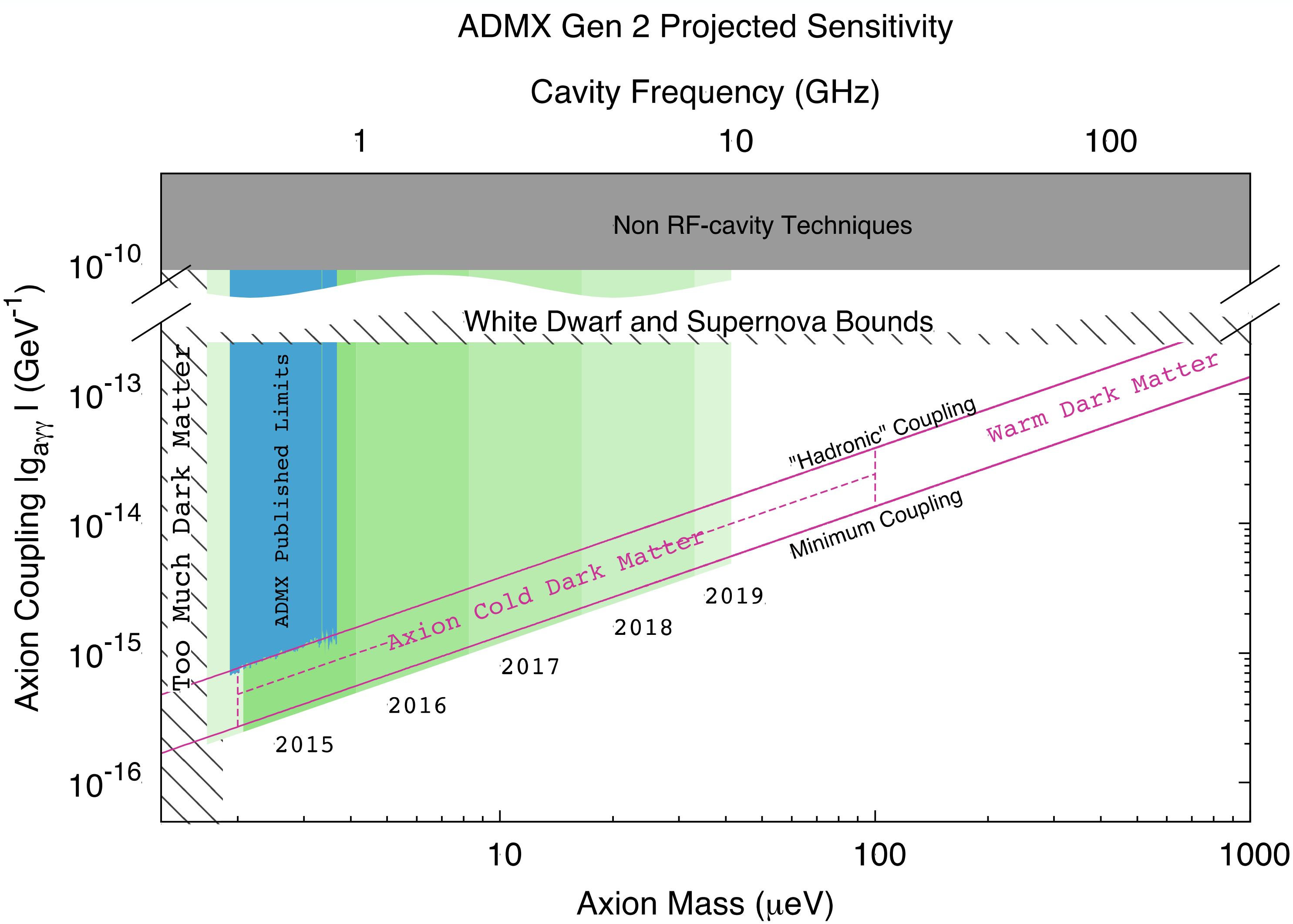
- Search for dark-matter axions; viable DM mass range is ~μeV to meV.
- Peccei-Quinn axion-photon coupling defines target sensitivity.
- Strong magnetic field in resonant cavity converts axions (from the dark matter Galactic halo) into photons via the Primakoff effect.
- Detector consists of a dilution-fridge cooled microwave cavity in a large superconducting 8 Tesla magnet. Microwave photons detected by an ultra-low-noise SQUID-based microwave .amplifier/receiver. These provide the sensitivity
- ADMX is sensitive to sub-yoctowatts of microwave power.
- 23 scientists from 2 countries.



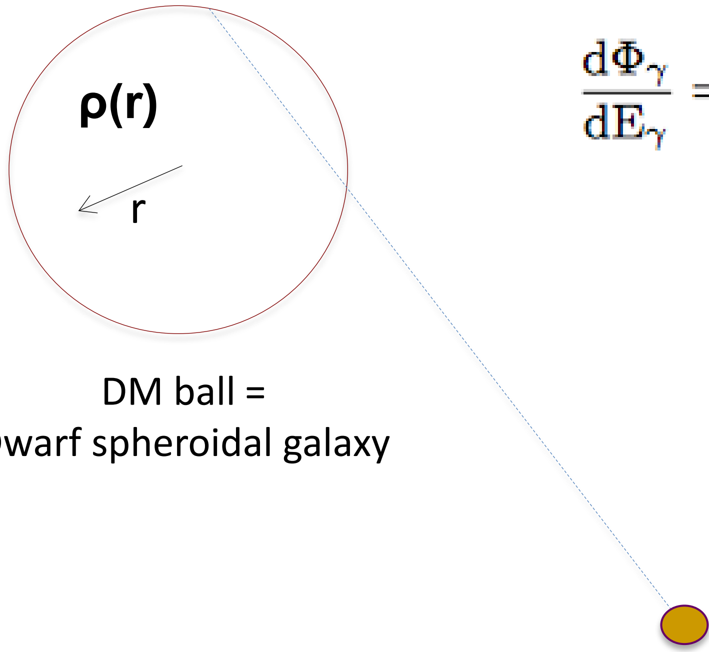


ADMX has the sensitivity to either detect the dark-matter QCD axion or reject the hypothesis at high confidence. This is called the "Definitive Search".

ADMX-Gen2 Expected Sensitivity



Indirect Detection of WIMP Dark Matter

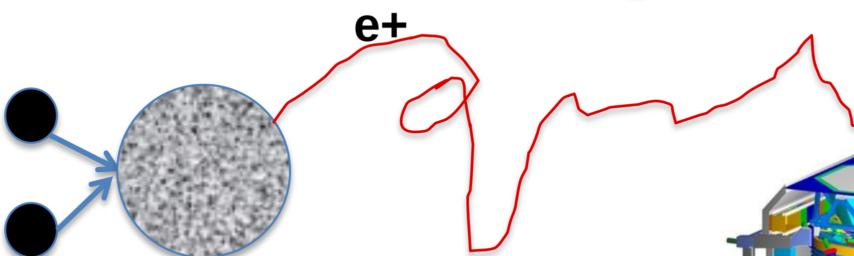


DM ball =
Dwarf spheroidal galaxy

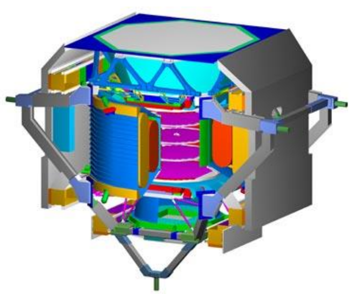
$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi}\underbrace{\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f}_{\text{'Particle Physics'}} \times \underbrace{\int_{\Delta\Omega} d\Omega' \int_{los}\rho^2 dl(r,\theta')}_{\text{'Astrophysics' or } J(E)}$$

ρ(r) = DM radial density

$$\Omega_\chi h^2 = 0.11\,\frac{3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{<\sigma_{ann}v>}$$

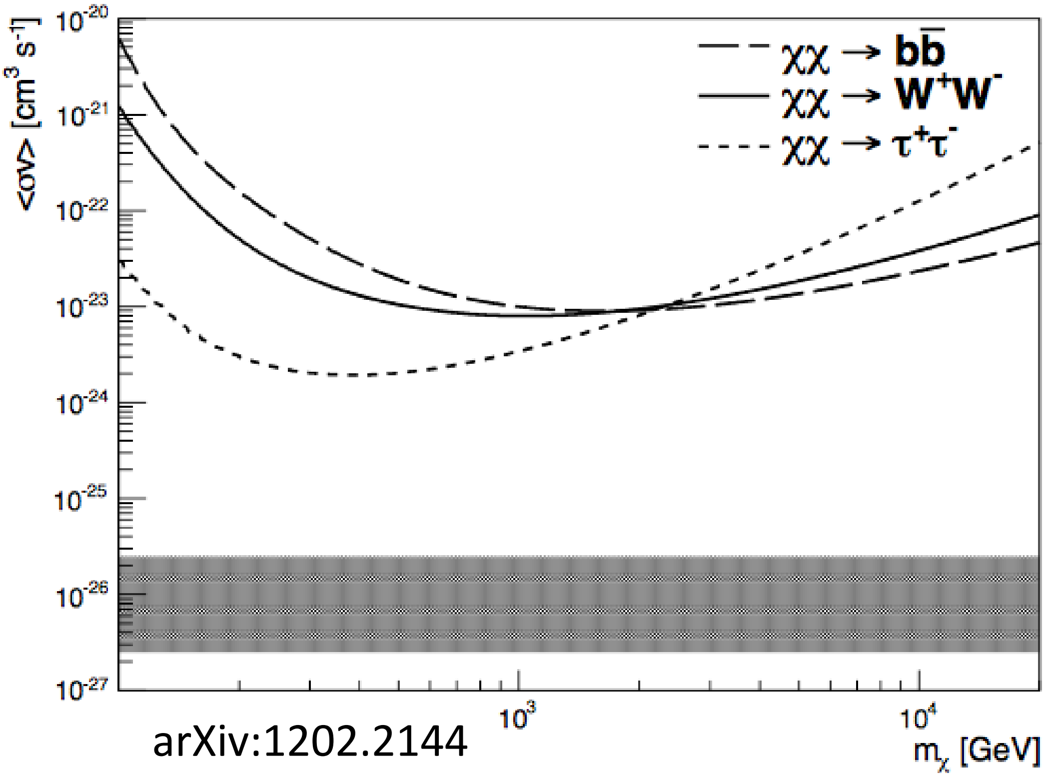


Local Galactic halo



VERITAS

Very Energetic Radiation Imaging Telescope Array



arXiv:1202.2144

- Imaging air Čerenkov telescope array in Arizona, pioneered by Trevor Weekes
- 50 GeV-50 TeV gamma-ray energy range
- complements FGST energy range
- Canada, Germany, Ireland, US: ~100 scientist
- 4 telescope operation started in 2007; continuing operation.

- Deep observation of DM-rich dwarf spheroidal galaxy Segue 1
- ~2 orders of magnitude above the relic <σv> of ~3 x 10^{-36} cm^3/s

Fermi Gamma-ray Space Telescope

Science Goals

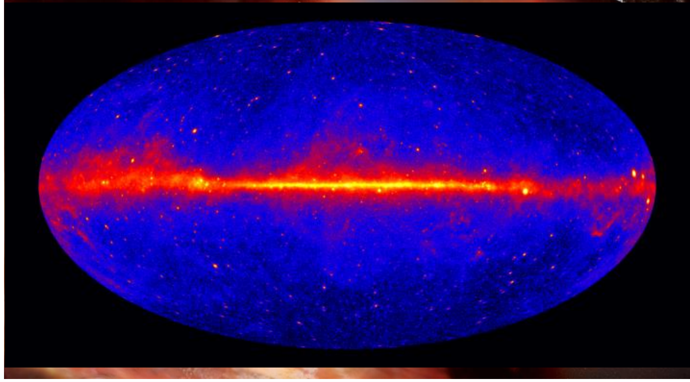
- Study high-energy (~20 MeV->300 GeV) γ rays using particle physics detector technology in space
- Indirect dark matter detection; high-energy acceleration mechanisms

Partnership

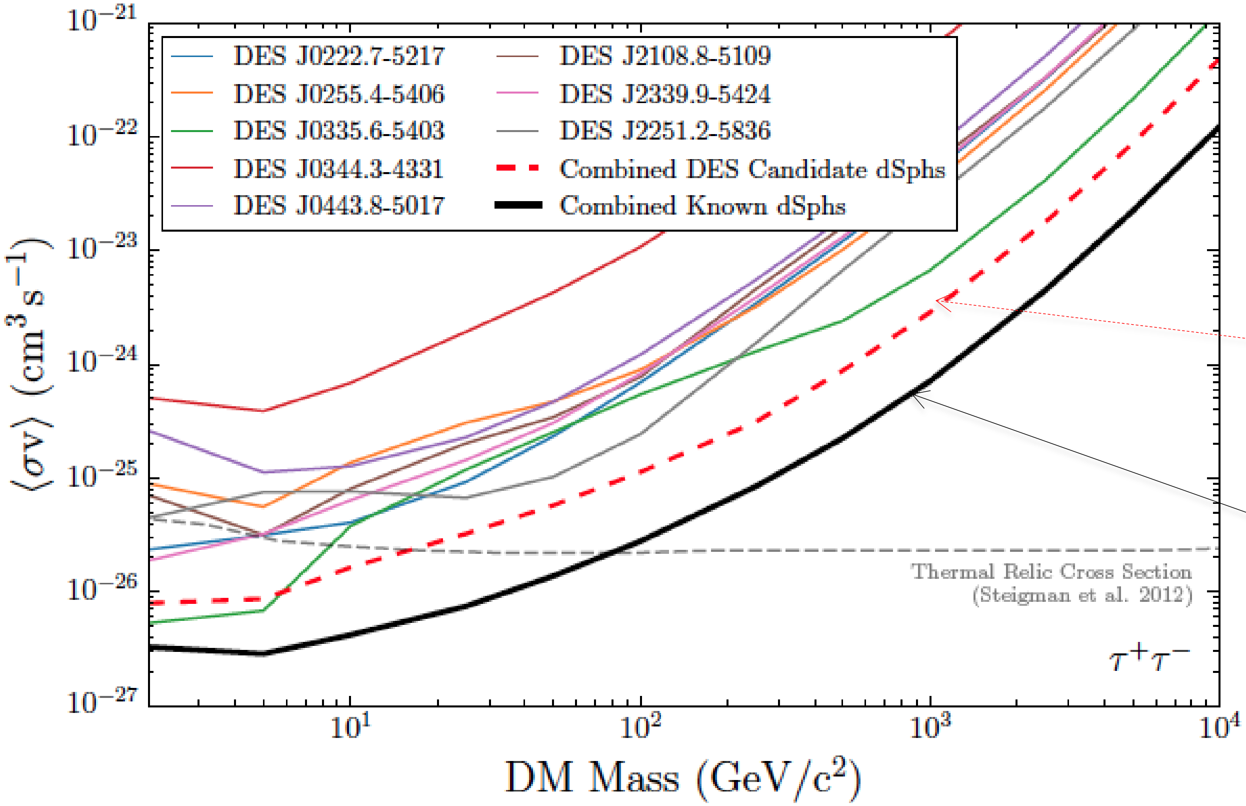
- DOE, NASA and 6 international agencies partnered on construction of the Large Area Telescope (LAT) on Fermi; NASA leads the mission, DOE supports LAT Instrument Science Operations Center at SLAC

Instrument

- Pair conversion telescope with tracker and calorimeter
- Field of view = 2.4 sr
- Effective area = 0.95 m2
- Point source sensitivity ~ 3 x 10^{-9} $cm^{-2}s^{-1}$
- Launched June 2008



FGST limits on relic <σv>



Dwarf spheriodal galaxies: nearly pure balls of DM orbiting Milky Way

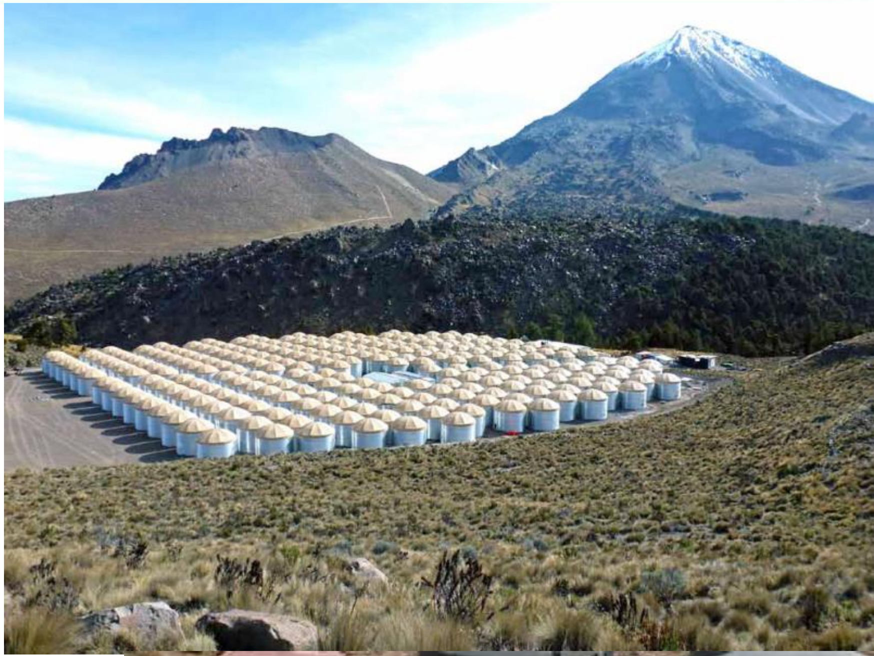
Combined DES dSph candidates

Combined known dSphs (Ackermann et al., arXiv:1503.02641)

"Search for Gamma-ray Emission from DES Dwarf Spheroidal Galaxy Candidates with Fermi-LAT Data" (March 2015) arXiv:1503.02632v2 (Fermi-LAT and DES Collaborations)

HAWC (High Altitude Water Čerenkov array)

Sky survey of ~100 GeV to >100 TeV gamma-rays



- Air Shower Detector with 300 Water Cherenkov Detector tanks covering 20,000 m^2 at 4100 m on Sierra Negra Volcano, Mexico. Exposure to half of the sky during a 24-hour period. Final tank was filled in January 2015.

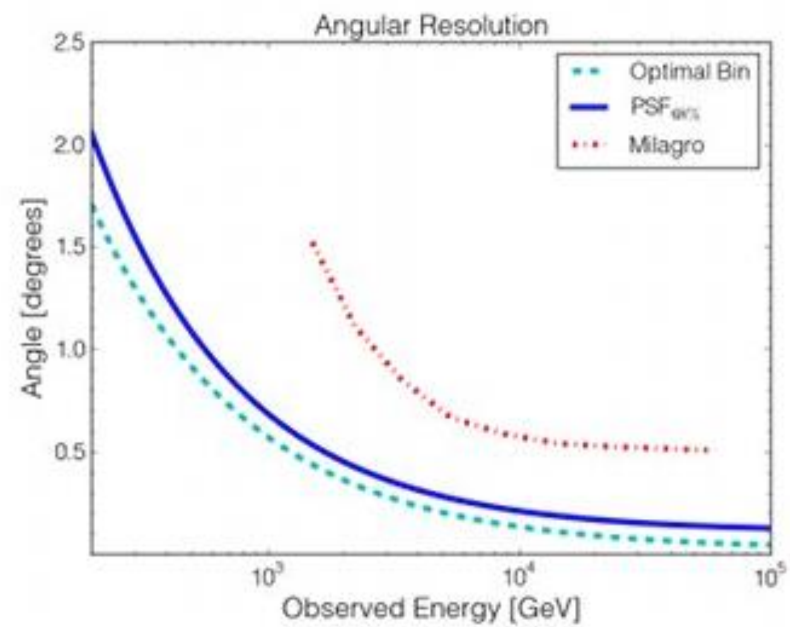
Science Goals

- Indirect dark matter search for gamma-rays from WIMP annihilation.
- Other astrophysical sources, e.g., supermassive black holes in active galactic nuclei and gamma ray bursts.

~100 scientists from US and Mexico. LANL, NASA/GSFC, 15 US universities, 11 Mexican institutions

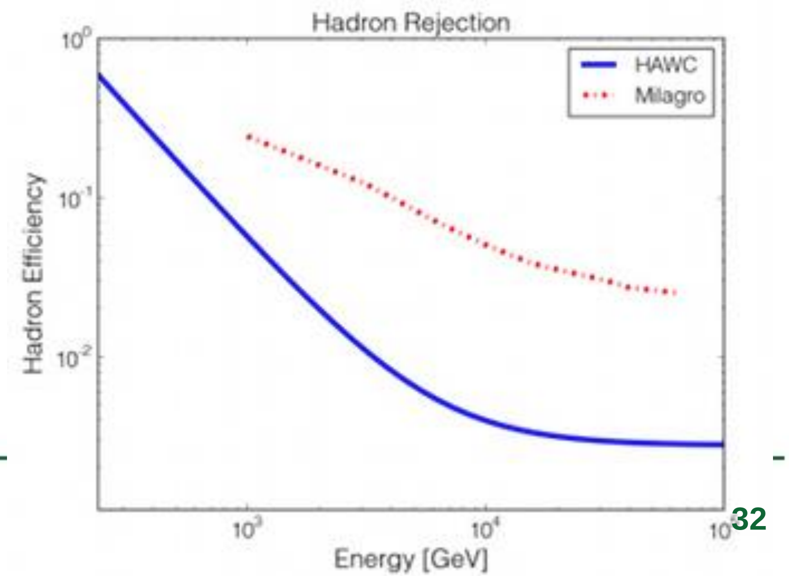
HAWC performance

Because the flux of gamma rays from all sources drops rapidly as a function of energy, observations of sources require a large effective area and long integration times, especially if the goal is to observe gamma rays above 10 TeV.



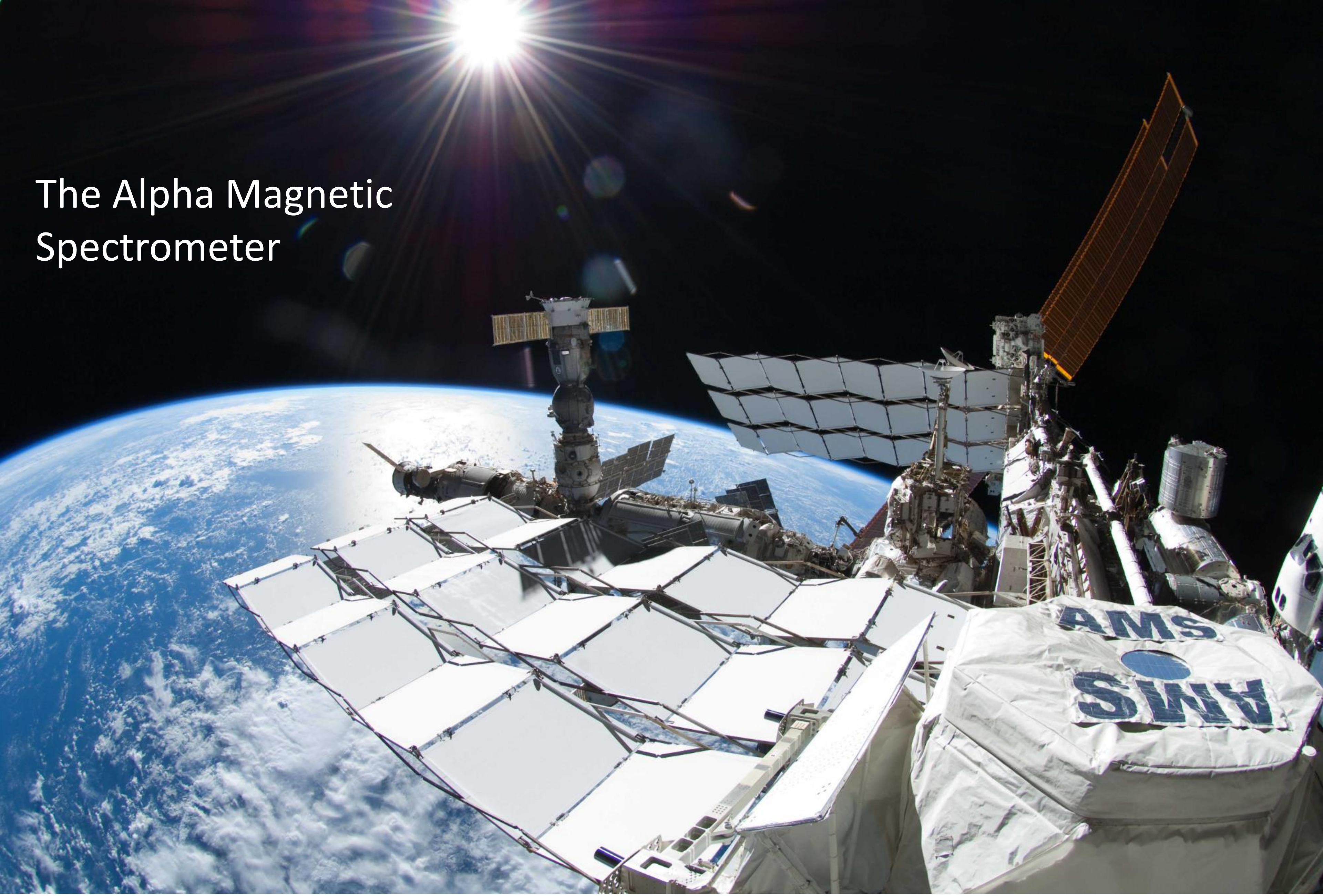
Specifications:

- Large FOV: out to 45° from zenith
- Duty cycle: >90% (insensitive to Sun or Moon)
- 1-year point source sensitivity (>2 TeV) ~ 3 x 10^{-13} $cm^{-2}s^{-1}$



Reference -- arXiv:1405.1730

The Alpha Magnetic Spectrometer



Selected Elements of AMS History

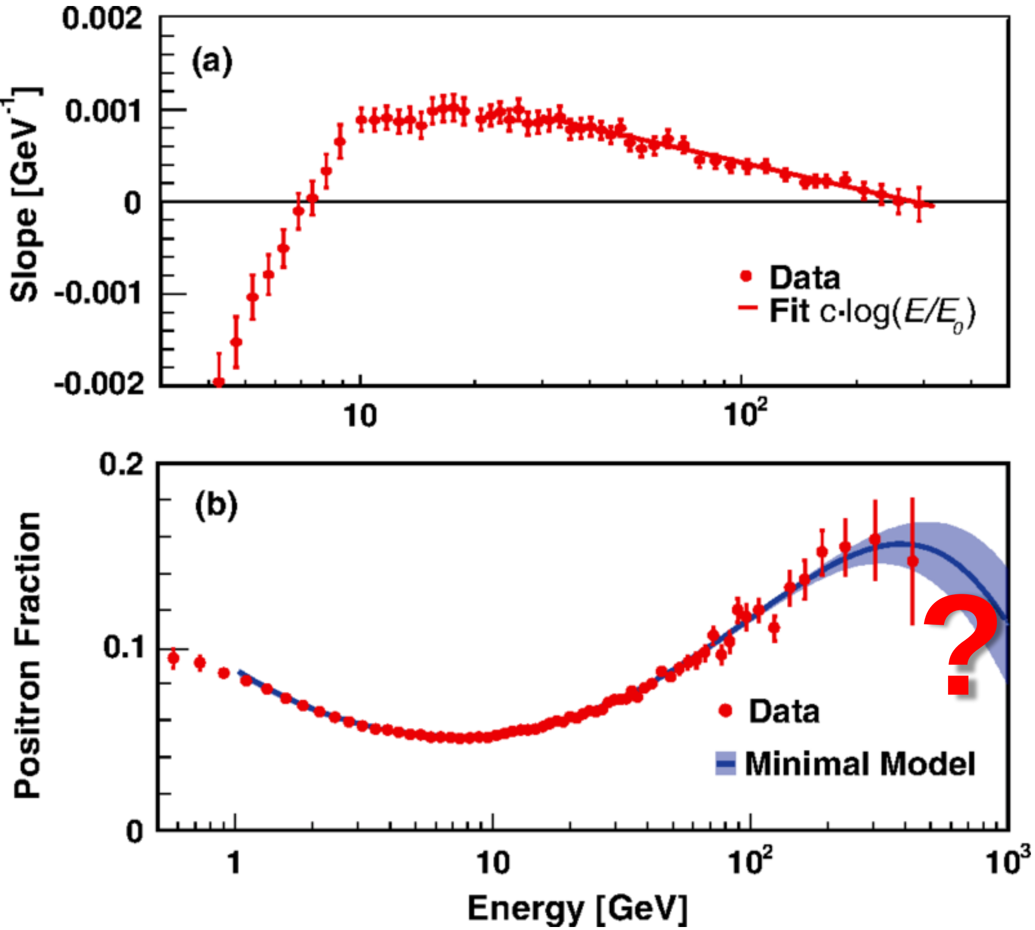
- 1994:
  - AMS concept development begins
  - Prof. Ting visits the NASA Administrator, (Dan Golden) to explore NASA interest in AMS
  - AMS first proposed to DOE
- April 1995: first DOE-AMS Committee Review ("Blue Ribbon Panel")
- 1997: AMS becomes a "recognized experiment" at CERN
- June 1998: AMS-01 "engineering test" Space Shuttle flight
- March 1999: second DOE-AMS Committee Review
- September 2006: third DOE-AMS Committee Review
- January 2010: NASA-DOE Implementing Arrangement signed: NASA delivers payload, provides ISS services; DOE responsible U.S. science effort.
- May 2011: AMS-02 arrives at ISS, is installed, taking data within 5 hours
- September 2013: fourth and most recent DOE-AMS Committee Review
  - Chair report endorses continued operation onboard the ISS at least to 2020, at which point statistical errors will be have been halved.
  - Next DOE-AMS Committee Review expected to be held in 2016-201

Great interest in AMS physics

- 1st paper (5 Apr 2013) - selected for VIEWPOINT in Physics. Also an Annual Highlight of 2013. “First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–350 GeV,” Phys. Rev. Lett. 110, 141102.
- 2nd paper (19 Sep 2014) - selected as Editor’s suggestion. “High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–500 GeV with the Alpha Magnetic Spectrometer on the International Space Station,” Phys. Rev. Lett. 113, 121101.
- 3rd paper (19 Sep 2014) - selected as Editor’s suggestion. “Electron and Positron Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station,” Phys. Rev. Lett. 113, 121102.
- 4th paper (28 Nov. 2014) “Precision Measurement of the (e+ + e−) Flux in Primary Cosmic Rays from 0.5 GeV to 1 TeV with the Alpha Magnetic Spectrometer on the International Space Station,” Phys. Rev. Lett. 113, 221102.
- 5th paper (coming soon) - selected as Editor’s suggestion. “Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station,” Phys. Rev. Lett.
  - *This conference!*

(My thanks to Mike Capell)

Example: the AMS Cosmic Ray Positron Fraction



L. Accardo et al., Phys. Rev. Lett. 113, 121101 (2014)

AMS-02 has provided us with *unprecedented precision and accuracy* in the measurement of cosmic rays.

These data are revolutionizing the field of cosmic ray physics. They already provide hints of new physics.

"AMS is a particle physics experiment in space." Uniquely capable, its discovery space is large. History tells us that new phenomena are revealed when new frontiers are opened.

Final Words on AMS

AMS is the product of a superb international collaboration. It is a poster child not only for "global physics," but also for collaboration in the U.S. between DOE and NASA.

> "AMS is a new space telescope, observing the cosmos not through photons but through charged particles. Discoveries come from opening new frontiers to scientific investigation."

Anonymous reviewer from the 2013 DOE AMS Committee Review

Summary

DOE's Cosmic Frontier has a vital and comprehensive program in dark matter research:

- *First generation WIMP direct detection experiments: several different target media and detection techniques*
- *Second generation WIMP direct detection experiments: multiple (two) target media, cover WIMP mass range of ~10^0 to 10^3 GeV, get close to the irreducible neutrino background.*
- *Indirect detection projects, both space-based and ground-based observatories, place limits on thermal relic cross section.*
- *Second generation axion detector, will provide definitive answer to whether PQ axions constitute the DM over most of the viable DM axion mass range*
- *DM R&D will continue to develop technologies for potential international G3 experiment.*

BACKUP

Particle Physics Project Prioritization Panel (P5)

The two U.S. high energy physics funding agencies, DOE/HEP and NSF/Physics, need a compelling & executable strategic plan, with full community support behind it.

- APS-DPF led a community planning process in 2013 (“Snowmass”)
- HEPAP P5 Subpanel in 2013/2014 (Steve Ritz, Chair) used Snowmass and other inputs to develop a strategic plan for the field
  - Plan to be executed over a ten year timescale in the context of a 20-year global vision for the field
  - P5 process was carried out in the context of realistic budget scenarios provided by the funding agencies in the charge

The P5 report “Strategic Plan for US Particle Physics in the Global Context” was delivered and approved by HEPAP in May 2014.

→***This report has been exceptionally well received in all parts of the U.S. Government***

Large community buy-in has been a very important factor.

Cosmic Frontier Strategy

P5 strategic plan: 5 science drivers

	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	●		
Neutrino Mass		●	●
Dark Matter	●	●	●
Cosmic Acceleration			●
Explore the Unknown	●	●	●

P5 report recommendations addressed several thrust areas of the Cosmic Frontier:

- **Dark Energy**
  - Build DESI as a major step forward in dark energy science
  - Complete LSST as planned
- **Dark Matter**
  - Proceed immediately with a broad second-generation (G2) dark matter direct detection program with at least two detector media, with WIMP mass range 1 GeV to 100 TeV.
    - Invest in this program at a level significantly above that called for in the 2012 joint agency announcement of opportunity
  - Support one or more third-generation (G3) direct detection experiments
    - Guide G3 by the results of the preceding (G1, G2) searches
    - Seek a globally complementary program and increased international partnership in G3 experiments
- **Cosmic Microwave Background (CMB)**
  - Support CMB experiments as part of the core particle physics program
  - The multidisciplinary nature of the science warrants continued multiagency support
- **Cosmic Rays and Gamma Rays**
  - Invest in CTA only if the critical NSF Astronomy funding can be obtained