SAC Cosmic Working Group Summary

Bradford Benson, Liz Buckley-Geer, Andrew Sonnenschein

All-Scientists Retreat

May 4, 2017

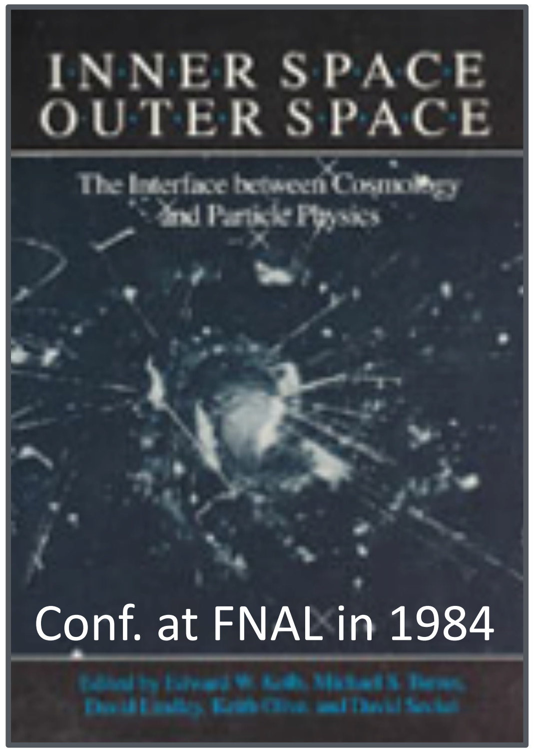
Cosmic Program at Fermilab

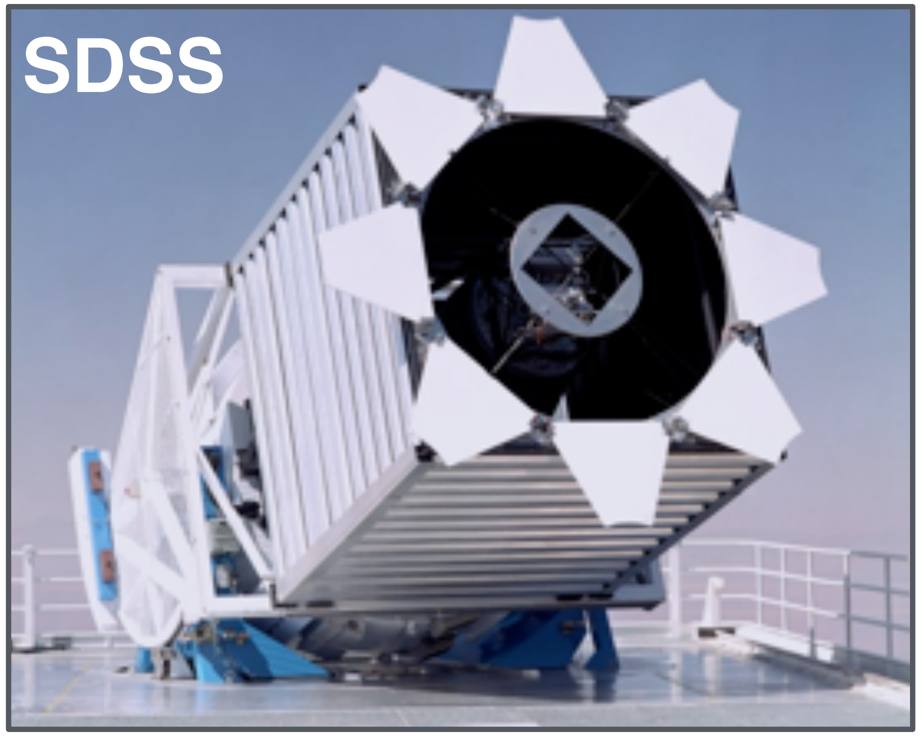
- Grew out of connection of particle physics and cosmology, and close ties between theory groups at Fermilab and Chicago.

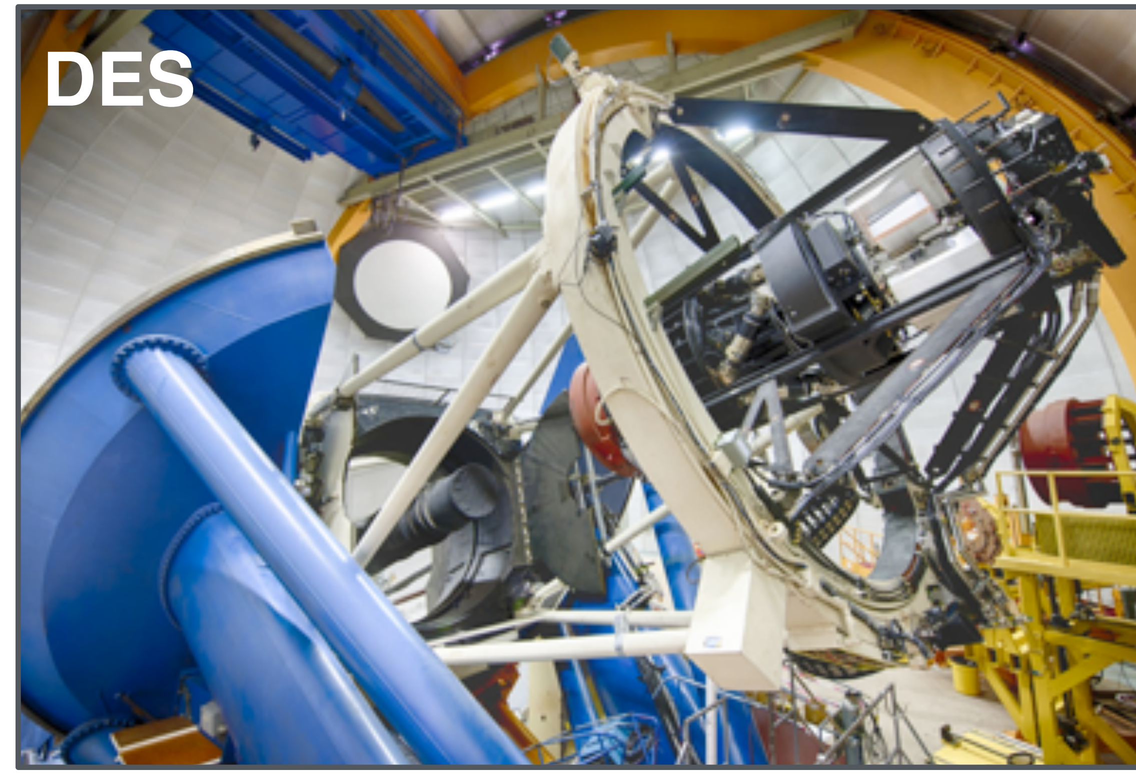
- Capitalizes on scientific expertise, technical skills, and facilities developed for particle physics by applying them to cosmology projects:
  - Data handling, analysis and quality control
  - Silicon detectors: assembly, testing, characterization, integration
  - Cryogenic engineering
  - Light detection
  - Bubble chambers
  - RF engineering

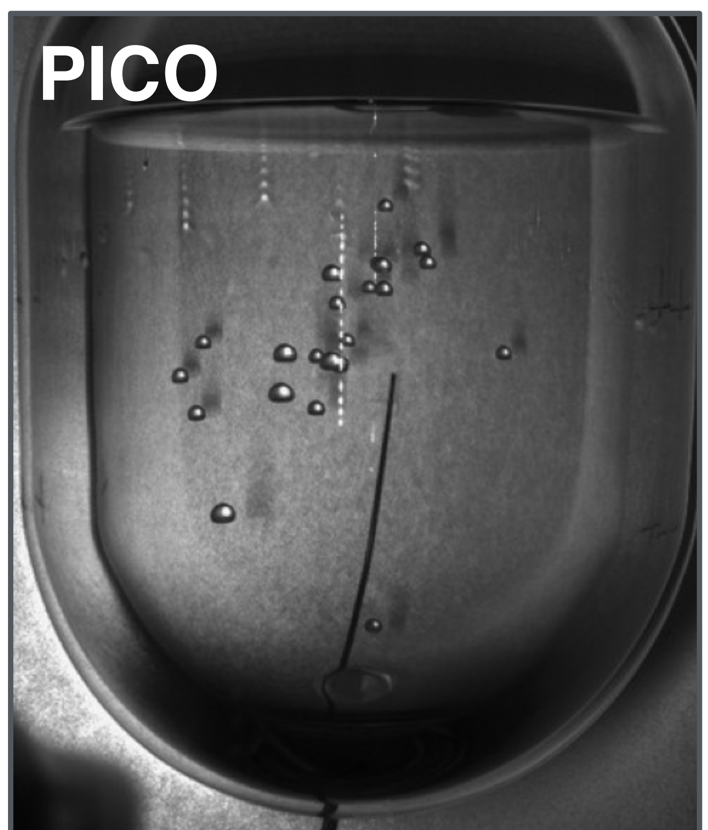
- Fermilab's expertise is unique and in demand by cosmology community.

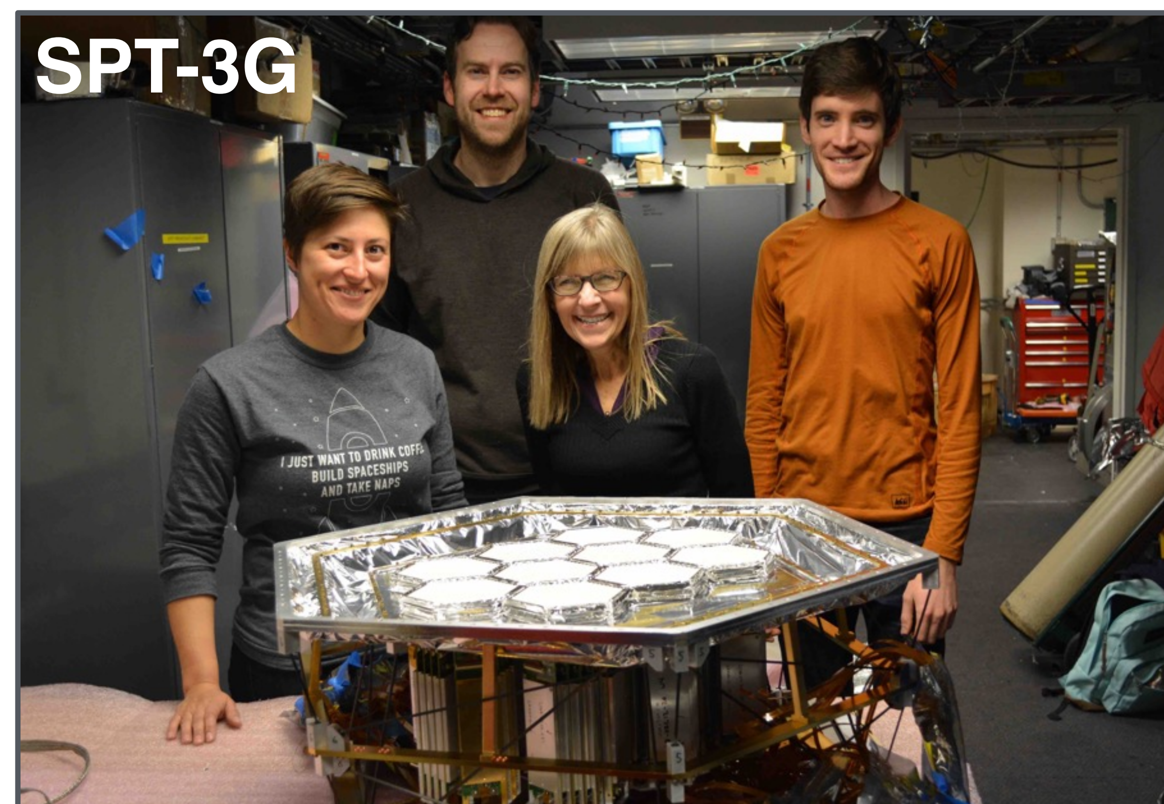
Strong Theory and Instrumentation Capabilities Drive FNAL's Cosmic Frontier Program







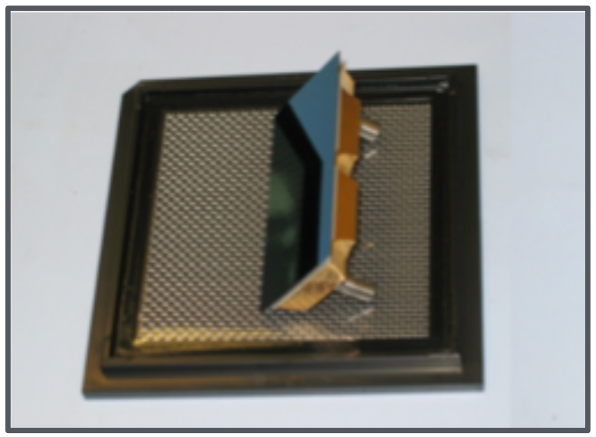


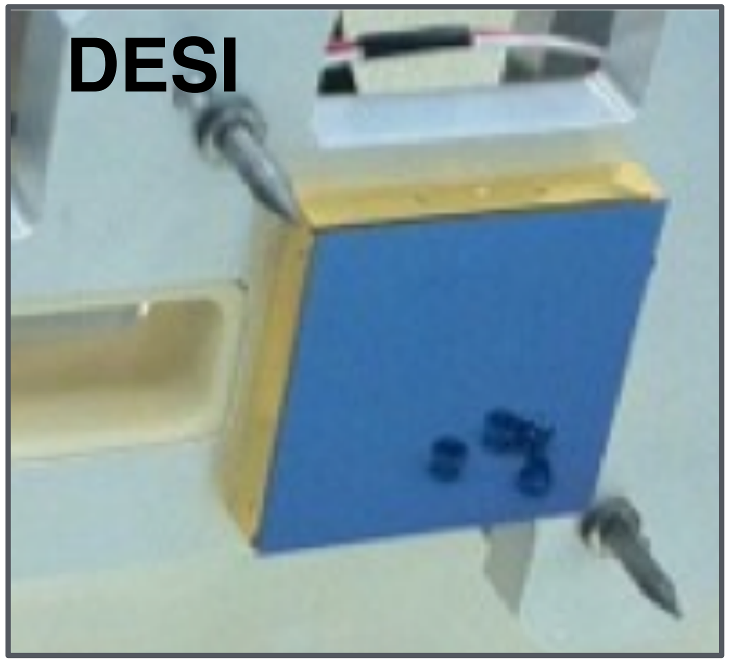


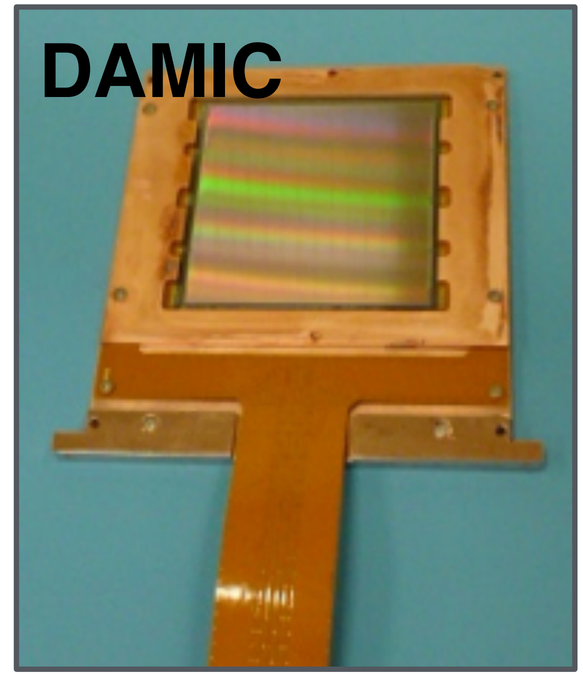
Fermilab

Unique Expertise at SiDet:
Precision Assembly and Detector Characterization

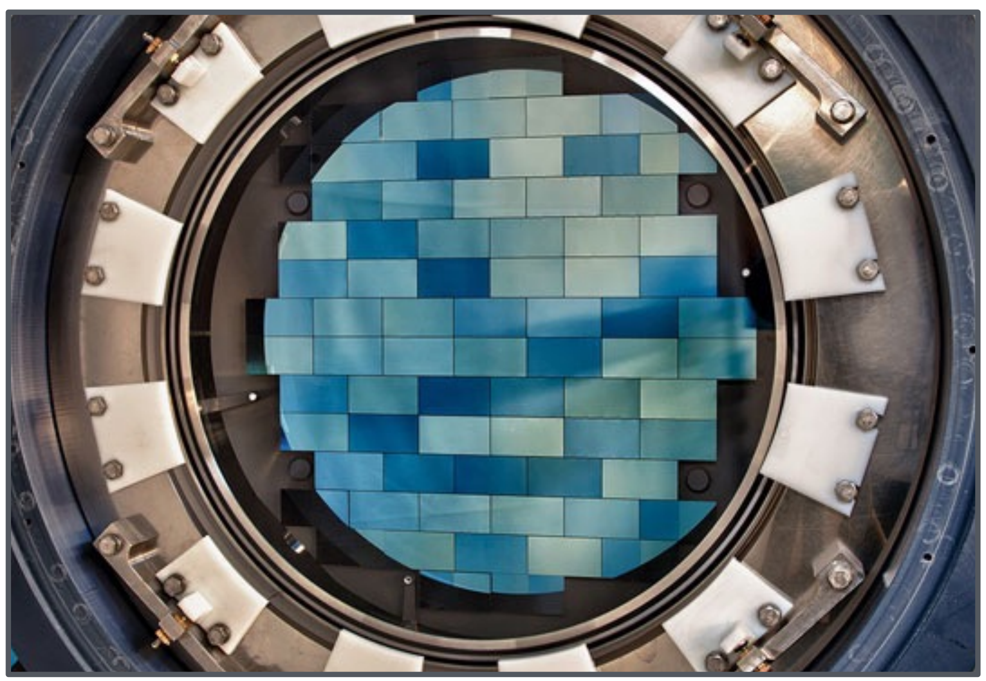
DECam CCDs and Imager

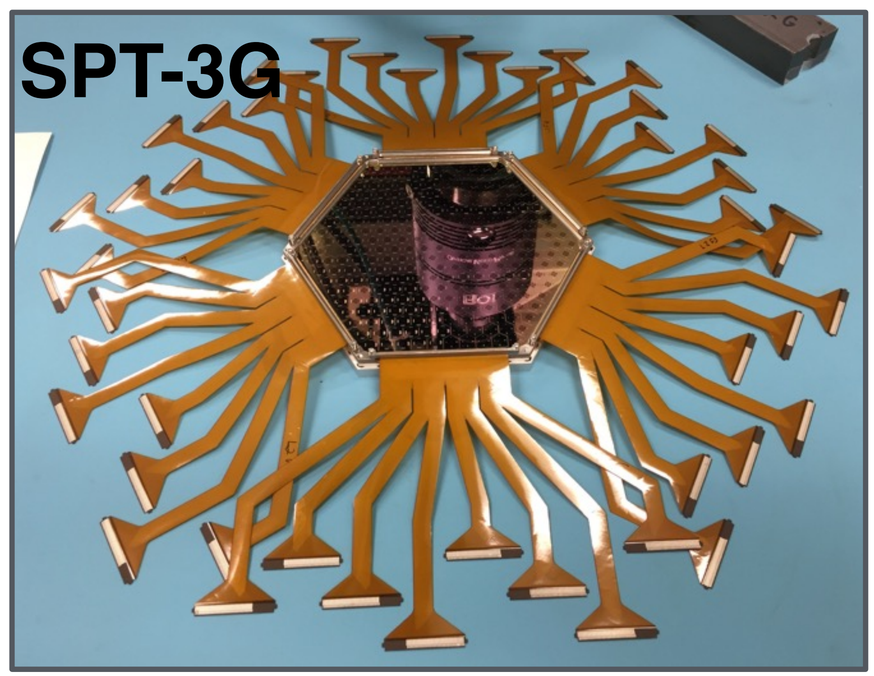






- Developed for Tevatron collider program: CDF, Dzero, CMS
- Dark Energy Camera for DES
- Now being used for: DAMIC, CDMS, DESI, SPT-3G, and R&D





Silicon detectors delivered by LBNL (CCDs) and ANL (TES's). FNAL builds detector package, tests, and integrates them into full systems.

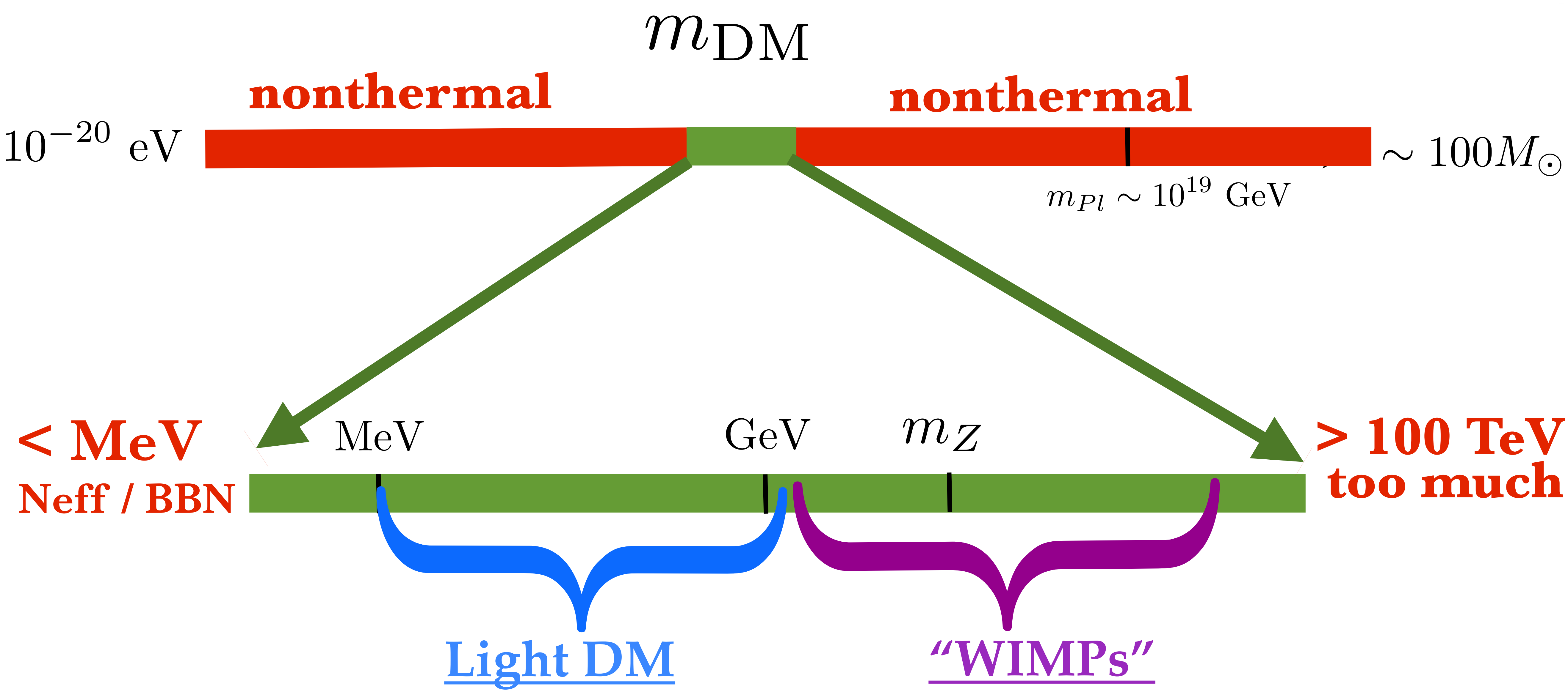
Program Evolution: Projects Making Way for Future

- Dark Matter
  - Leading in Axions
  - Critical contributions to WIMPS: LZ, SuperCDMS, DAMIC, PICO
  - Exciting opportunities enabled by LDRD:
    - Quantum Sensor Initiative; Axions, SENSEI.

- Dark Energy
  - DES successfully completed 4th year of observations
  - Critical role in DESI and strong engagement in LSST operations
  - DES effort will transition to LSST-Dark Energy Science Collaboration

- CMB
  - Group jump-started by LDRD on CMB detector development.
  - SPT-3G camera design and construction led by FNAL, installed at South Pole in January 2017.
  - Planning for FNAL role in next-generation CMB-S4

Dark Matter Landscape



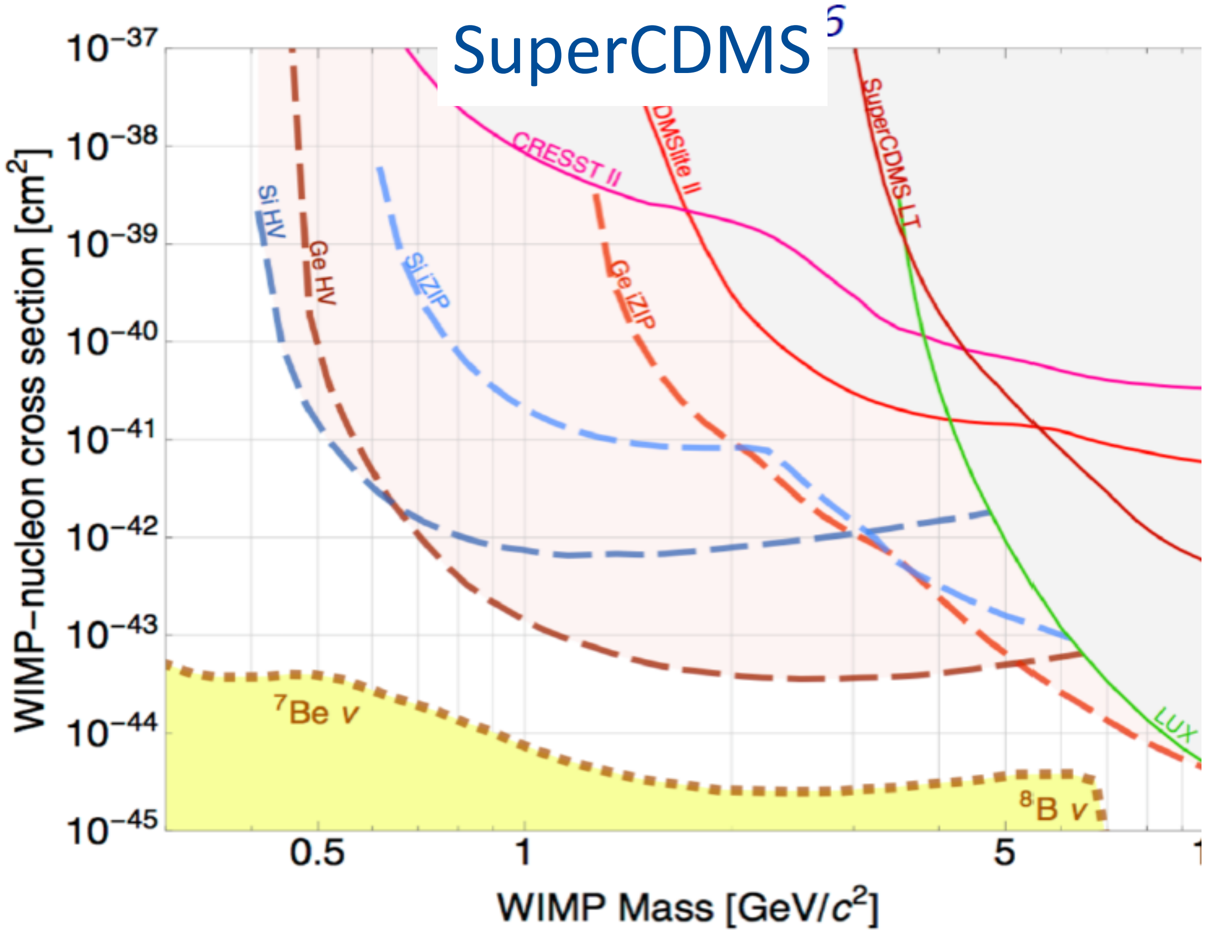
Prob.$(<$ GeV thermal$) \approx 10^{-2} - 10^{-3}$
Need new forces / richer pheno

Prob.(WIMP) $\sim 10^{-1} - 10^{-2}$
SM charged, more bounds

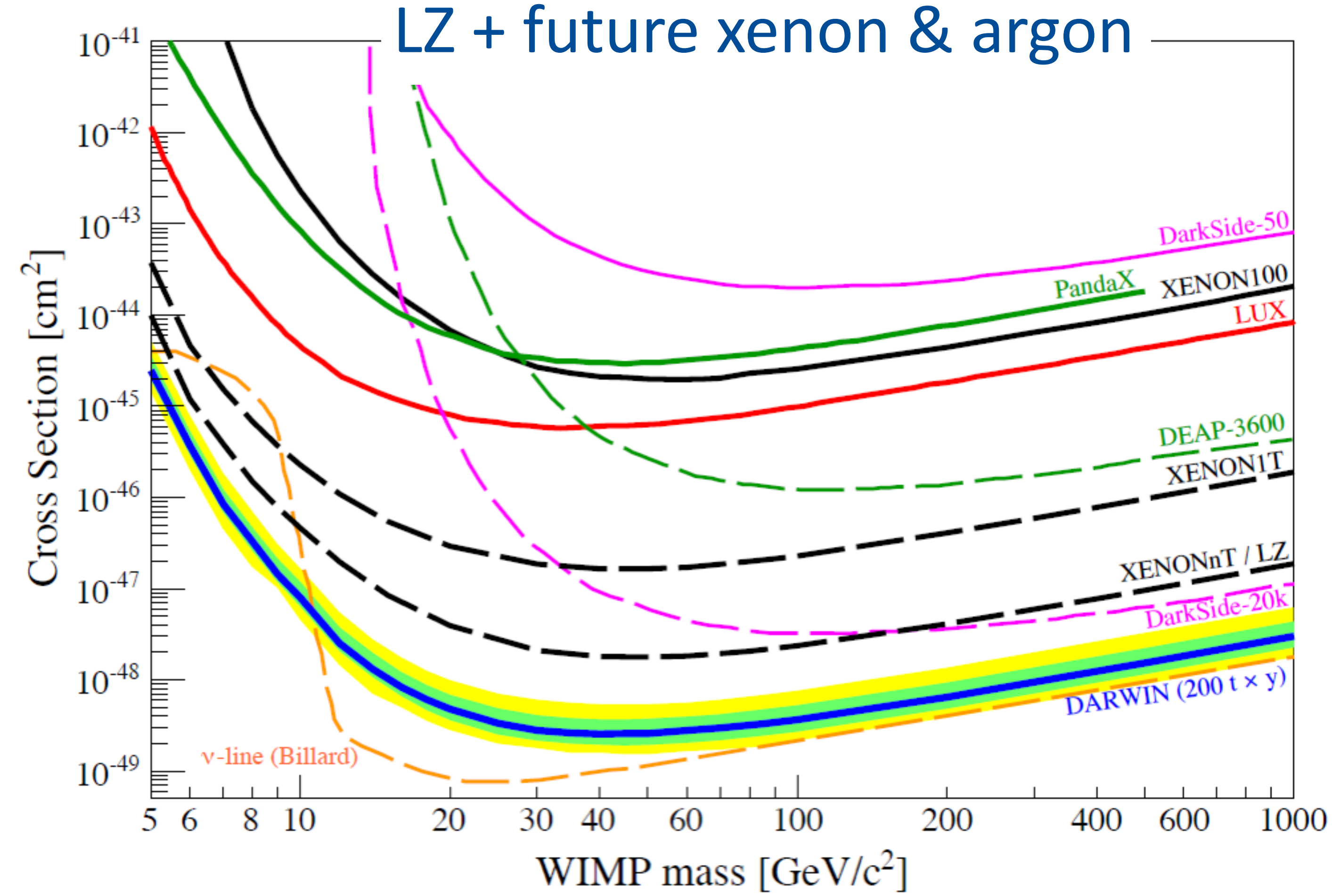
Searches for WIMPs and WIMP-like particles

- **SuperCDMS** (now-2025) and follow-on projects will search for "light WIMPs" ~1-10 GeV down to level of neutrino background ~ 10^{-44} cm² using high voltage cryogenic detectors.
- **LZ** (now-2023) liquid-xenon TPC experiment will probe dark matter particles with weak-scale masses and couplings down to 10^{-48} cm². A follow-on project such as **DARWIN** or **ARGO** may improve by one order of magnitude.

SuperCDMS



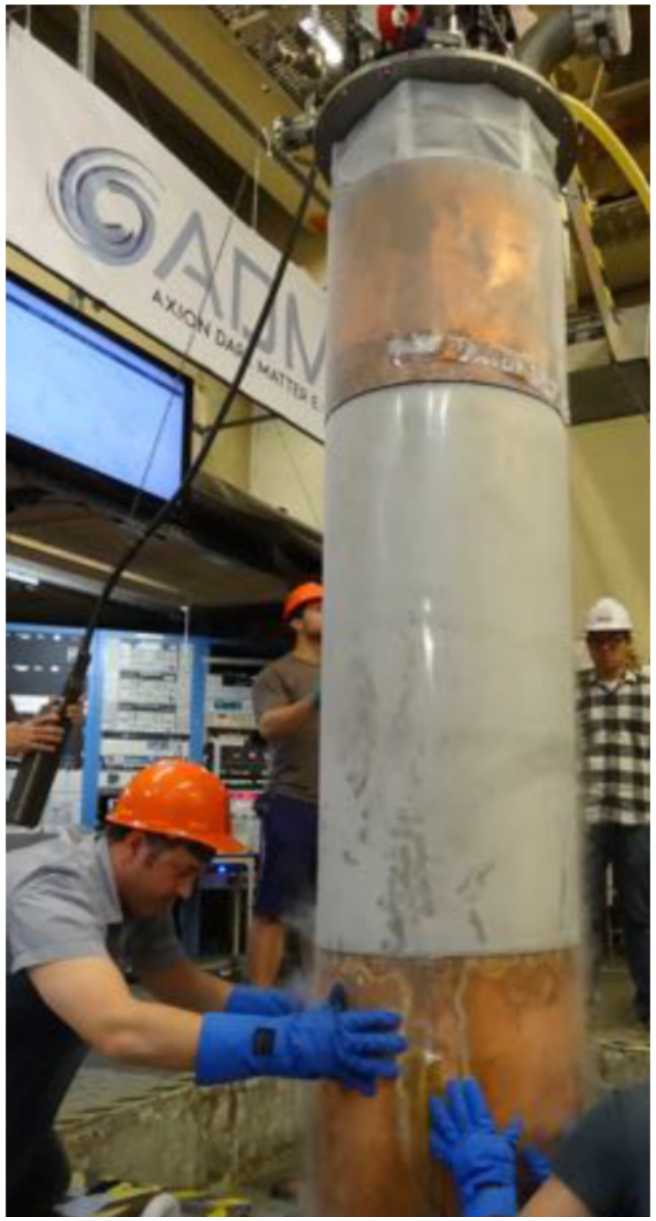
LZ + future xenon & argon

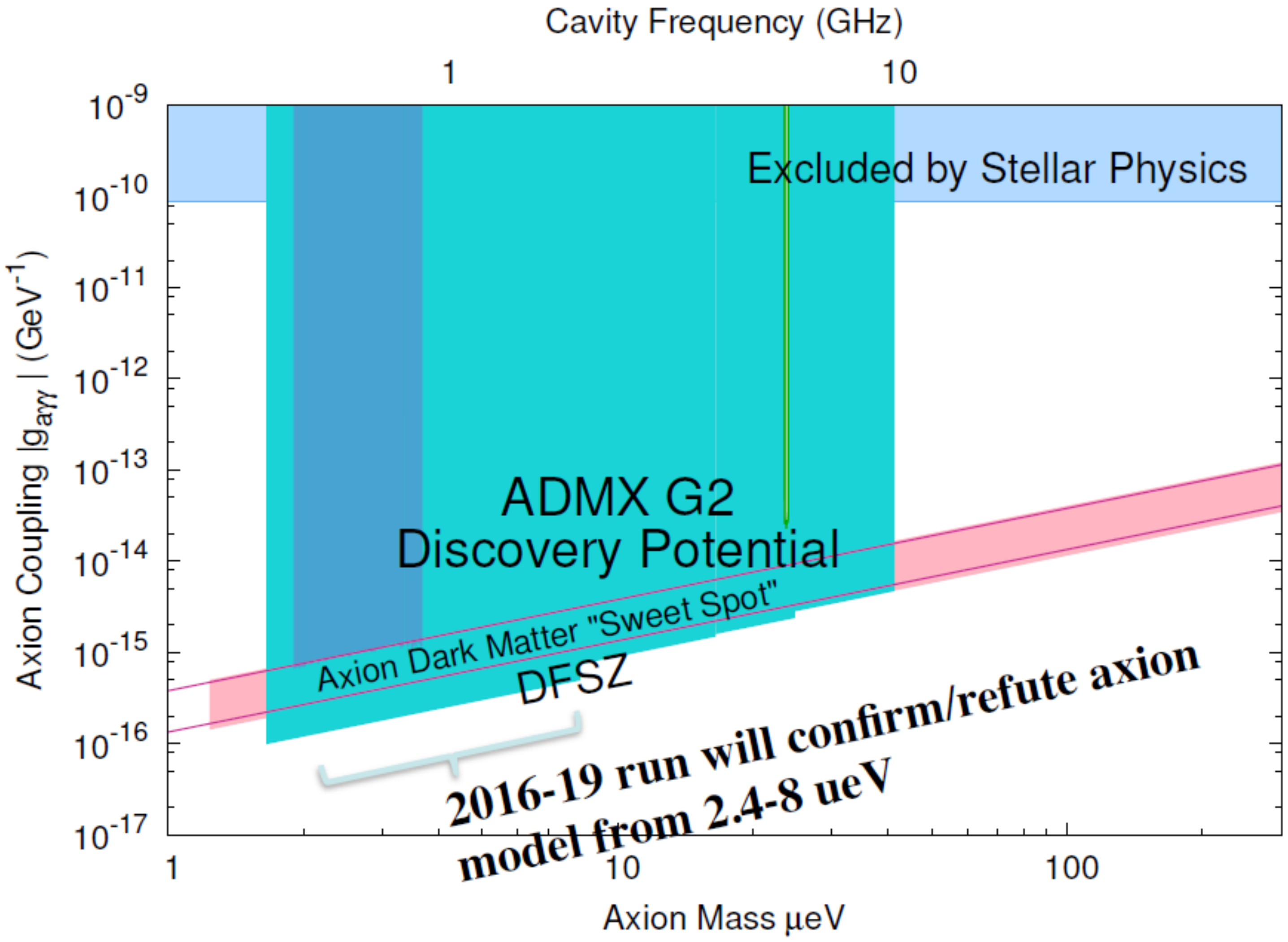


Talks by Lauren Hsu, Hugh Lippincott
https://indico.fnal.gov/conferenceDisplay.py?confId=14299

Searches for the QCD Axion

- Currently we are lead lab for **ADMX-G2** search for QCD axions (now- > ~2020). FNAL is working towards hosting the next generation experiment on site in a dedicated high-field magnet facility. The 20-year goal is to discover the QCD axion as dark matter.





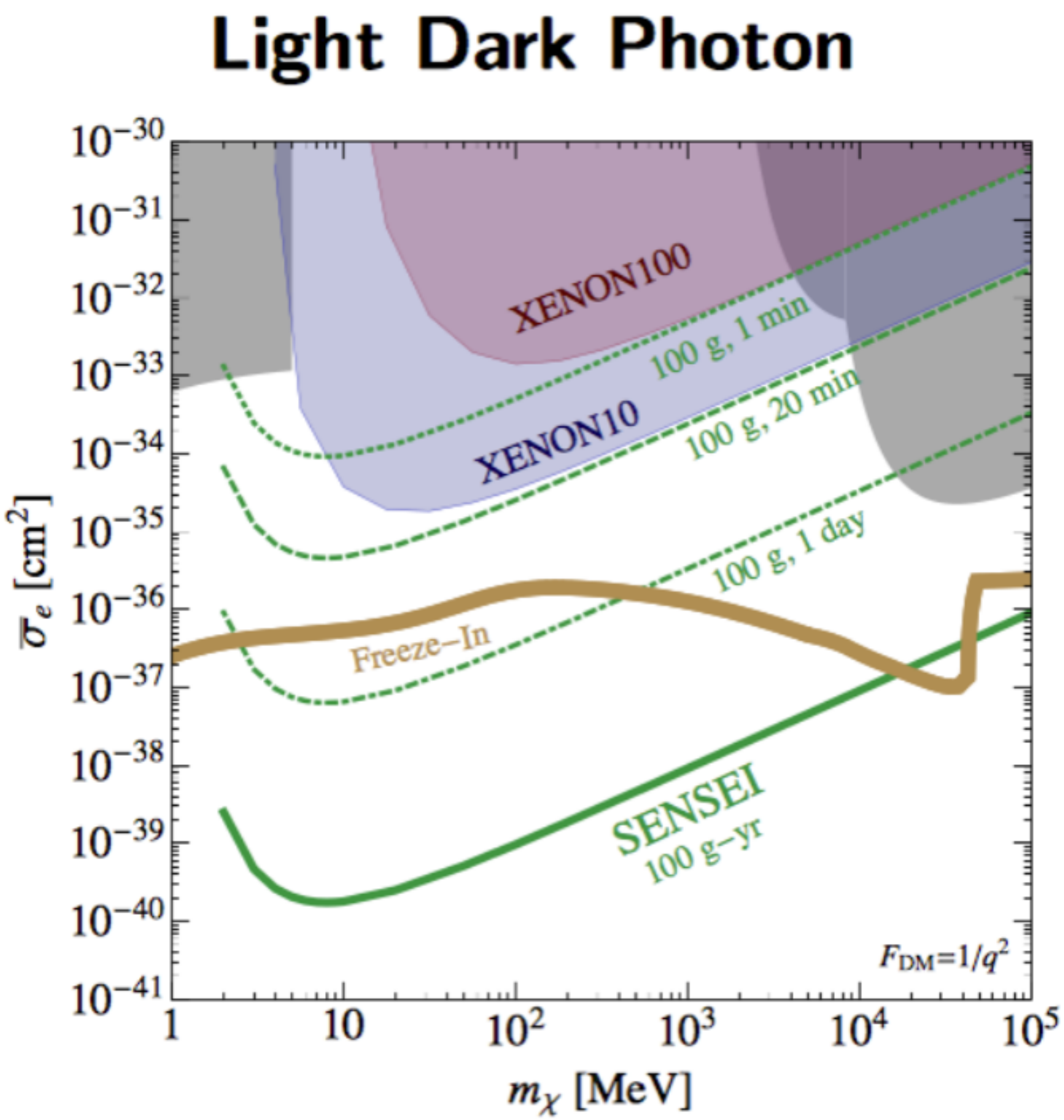
See talk by Aaron Chou:
https://indico.fnal.gov/conferenceDisplay.py?confId=14299

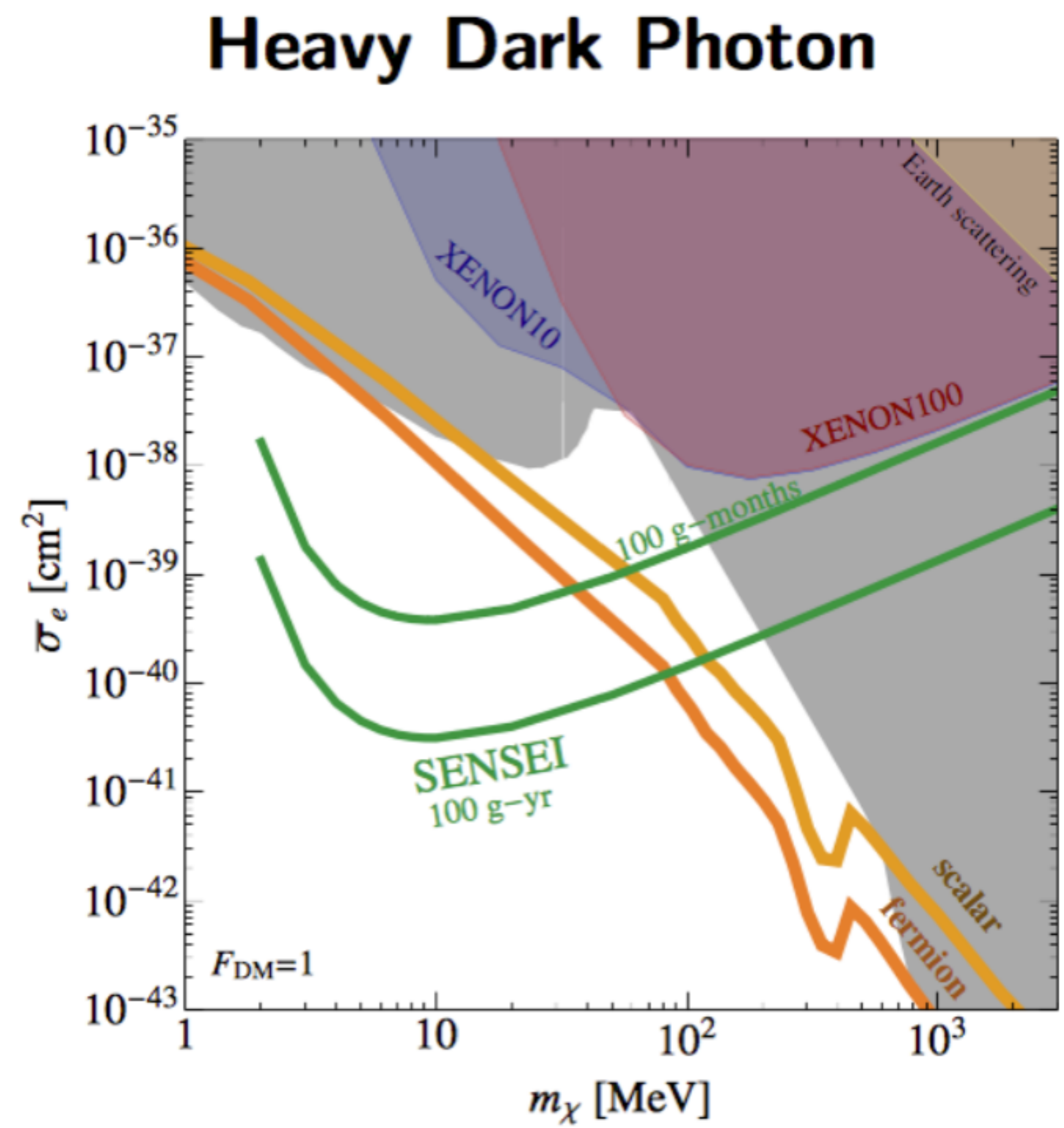
Goals for Dark Matter Detection, continued:

- **Quantum Sensors for Cosmic Science:**
  - Search for dark matter interactions with electrons using CCDs (SENSEI).
  - Development of novel cryogenic dark matter detectors using special Fermilab facilities and expertise. Examples: search for light WIMP interactions with cryogenic photon / phonon sensors or excitations in superfluid helium, novel quantum devices for axion detection.

- **Synergy Between Frontiers:**
  - New interest from DOE to add small projects to their portfolio
  - Leverage existing accelerator and detector facilities at Fermilab and SLAC to search for light dark matter:
    - BNB at Fermilab and LDMX at SLAC.

Quantum Sensors for Dark Matter: SENSEI





See talk by Juan Estrada (Javier Tiffenberg, LDRD PI):
https://indico.fnal.gov/conferenceDisplay.py?confId=14299

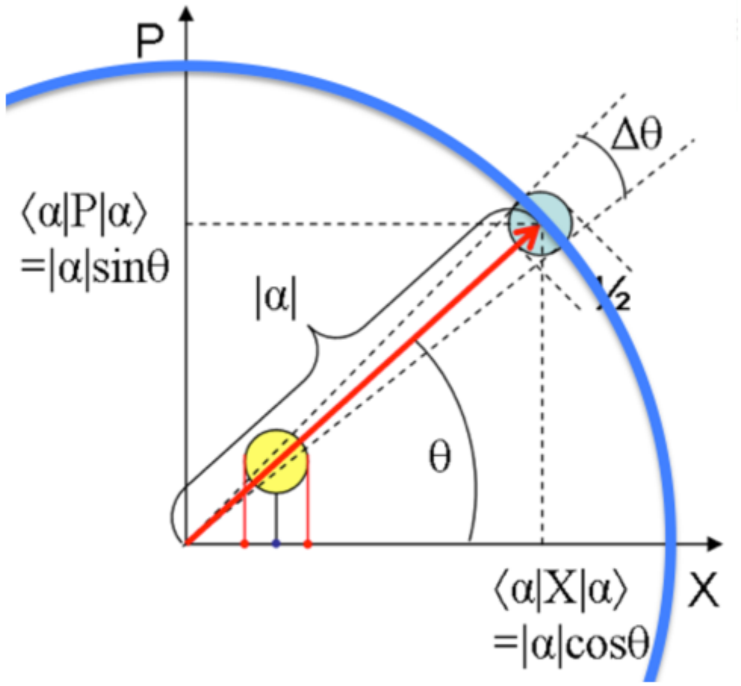
Quantum Sensors for Dark Matter: Axions

Superconducting single microwave photon detector based on qubits from quantum computing

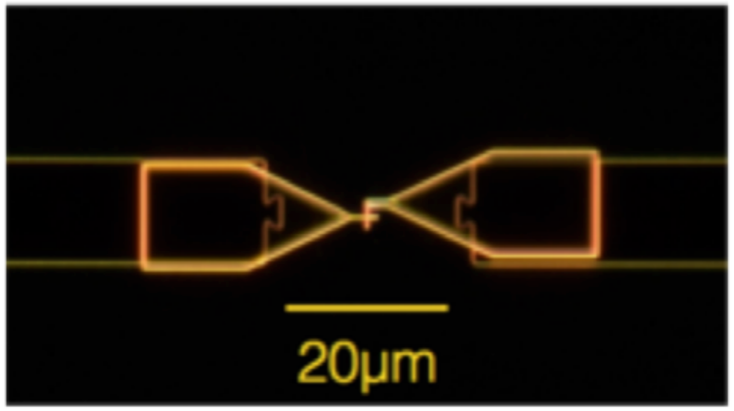
See talk by Aaron Chou: https://indico.fnal.gov/conferenceDisplay.py?confId=14299

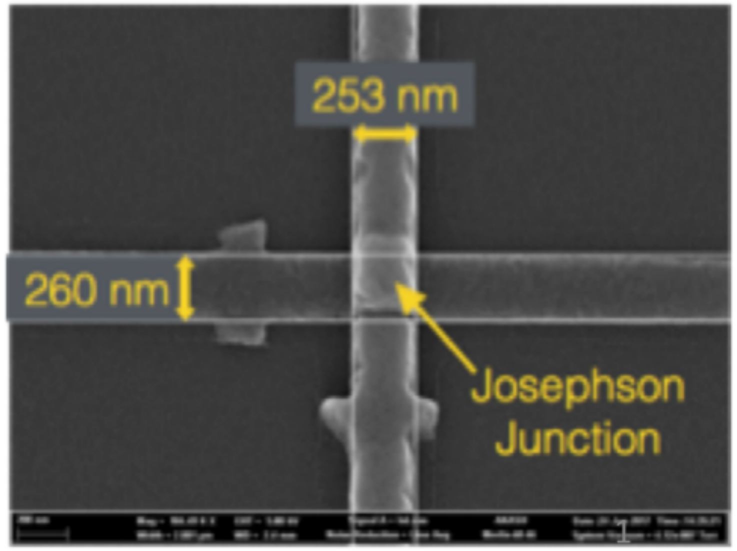
Enables next generation axion search by squeezing the quantum-limited amplitude noise.

Quantum non-demolition detector (2012 Nobel Prize)



$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

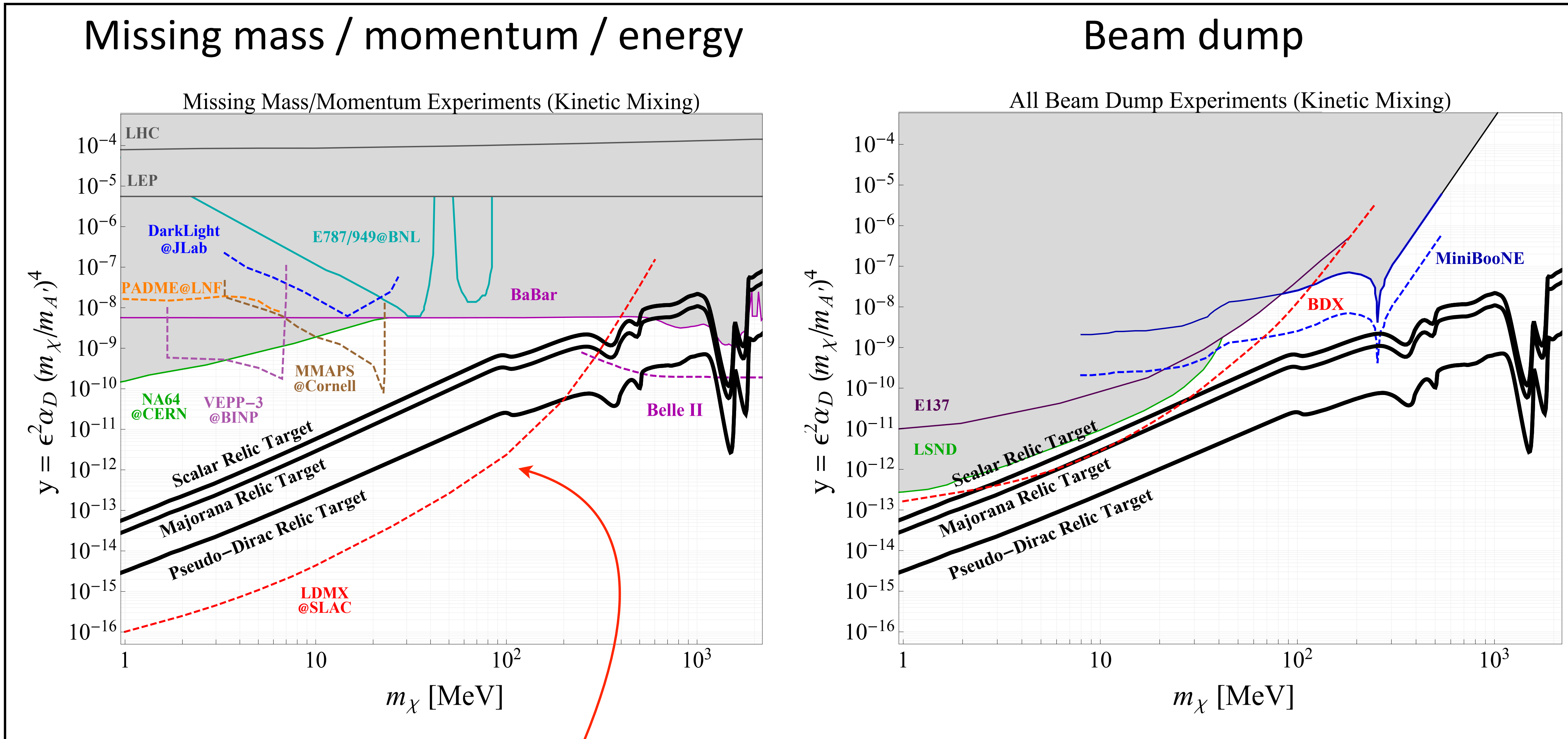




Collaboration with UChicago quantum computing group funded by Heising-Simons Foundation.

2017 LDRD funds new 10 mK cryo-magnetic test stand for cryogenic sensor development at FNAL.
Part of new FNAL-ANL-UChicago Quantum Sensors / Quantum Computing Initiative.

Synergy Between Frontiers: LDMX



electron fixed target missing momentum (LDMX) a strong candidate for achieving light thermal dark matter targets

(based on 10^{16} EOT)

See talk by Nhan Tran

https://indico.fnal.gov/conferenceDisplay.py?confId=14299

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Cosmic Surveys (Optical, CMB) in last P5

- **DESI** at CD3 (2019-2024)
  - Optical spectroscopy survey to probe late-time acceleration
- **LSST** at CD3 (2022-2031)
  - Optical photometric survey to probe late-time acceleration
- **CMB-S4** (~2023-2029)
  - Aiming for CD0 in 2019
  - Optimized to probe early universe acceleration (i.e., inflation, neutrino number density)

Cosmic Surveys: What Physics Will We Learn?

- **By next P5 (~2021)**
  - Stage-3: DES, SPT-3G producing results
  - Stage-4: Only DESI will have started
  - Stage-5: Planning beginning
- **By end of FNAL 10-year plan (~2026)**
  - Stage-4: LSST+CMB-S4 ~few years into surveys, DESI complete
  - Factors of ~5-10 improvements in key parameters

Year	Stage	Tensor/ Scalar **$r_{u.lim}$**	Eff.Num. Rel.Spec. **$\sigma(N_{eff})$**	Sum of ν mass **$\sigma(\Sigma m_\nu)$**	Dark energy Fig of Merit **D.E. F.O.M**
2015	Stage 2				
2016		r ≲ 0.1	0.14	150 meV	~180
2017	Stage 3				
2018					
2019					
2020					
2021		r ≲ 0.01	0.06	60 meV	~300-600
2022	Stage 4				
2023					
2024					
2025					
2026+		**r ≲ 0.001**	**0.02**	**15 meV**	**~1200**

Fermilab

Cosmic Surveys: What Physics Will We Learn?

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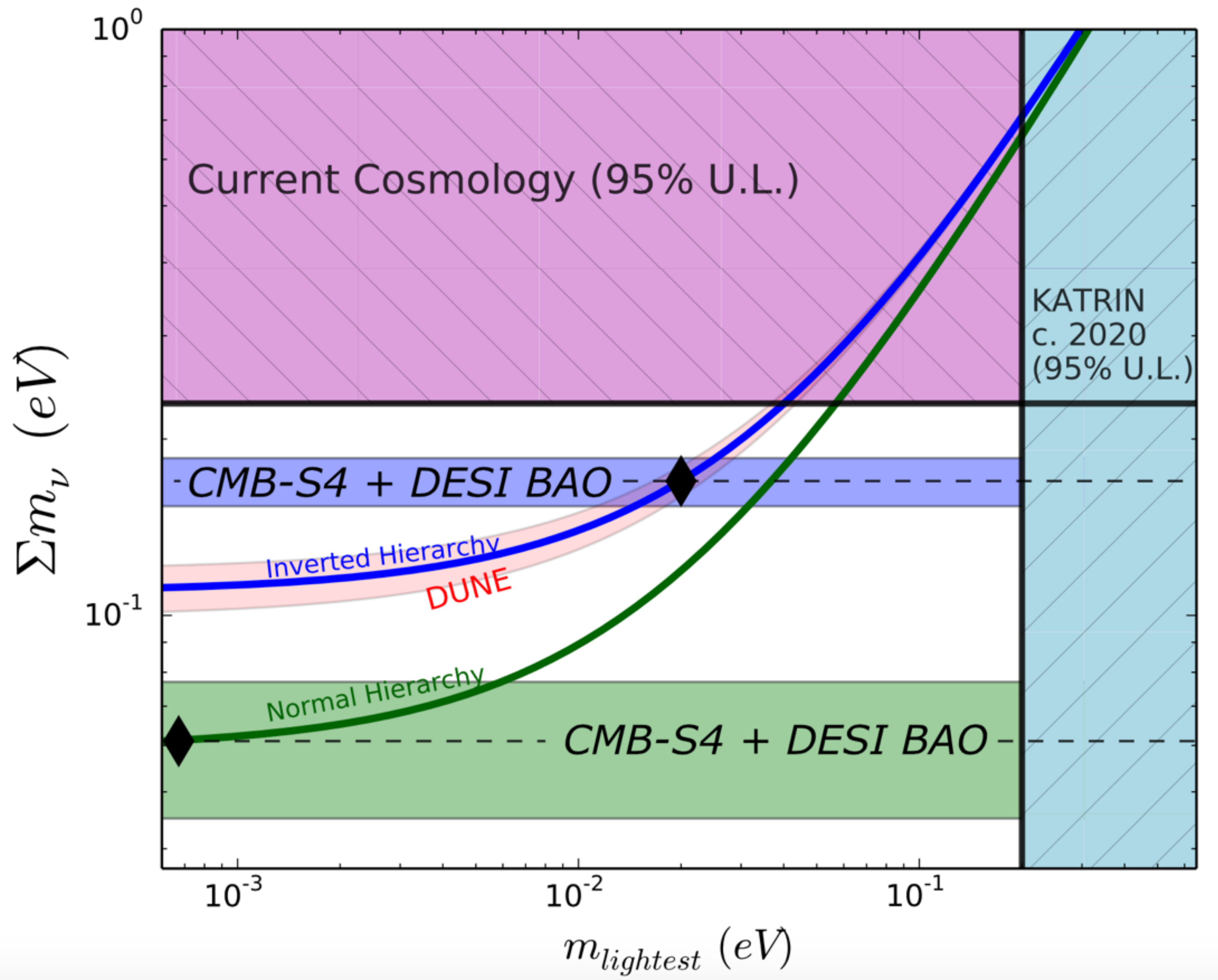
2025					
2026+		**$r \lesssim 0.001$**	**0.02**	**15 meV**	**~1200**

Fermilab

Cosmic Complementarity with HEP Neutrino Experiments



- **Synergy with DUNE:**
  - $\sigma(\Sigma m_\nu)$~15 meV gives 4-σ detection of neutrino mass for min. mass with normal hierarchy
  - With DUNE gives:
    - Sum of the neutrino masses
    - Neutrino hierarchy
    - Individual neutrino masses
- **Synergy with Short-Baseline Experiments:**
  - $\sigma(N_{eff})$~0.02 will rule out / confirm any significant sterile neutrino population, thermally generated in early Universe

Dodelson & Lykken (arXiv:1403.5173)
CMB-S4 Science Book (arXiv:1610.02743)

Cosmic Complementarity with Dark Matter Experiments

Snowmass: Cosmic Frontier (CF4)

https://arxiv.org/abs/1401.6085

Astrophysical probes are the only approach that show a "high confidence" positive signature of dark matter

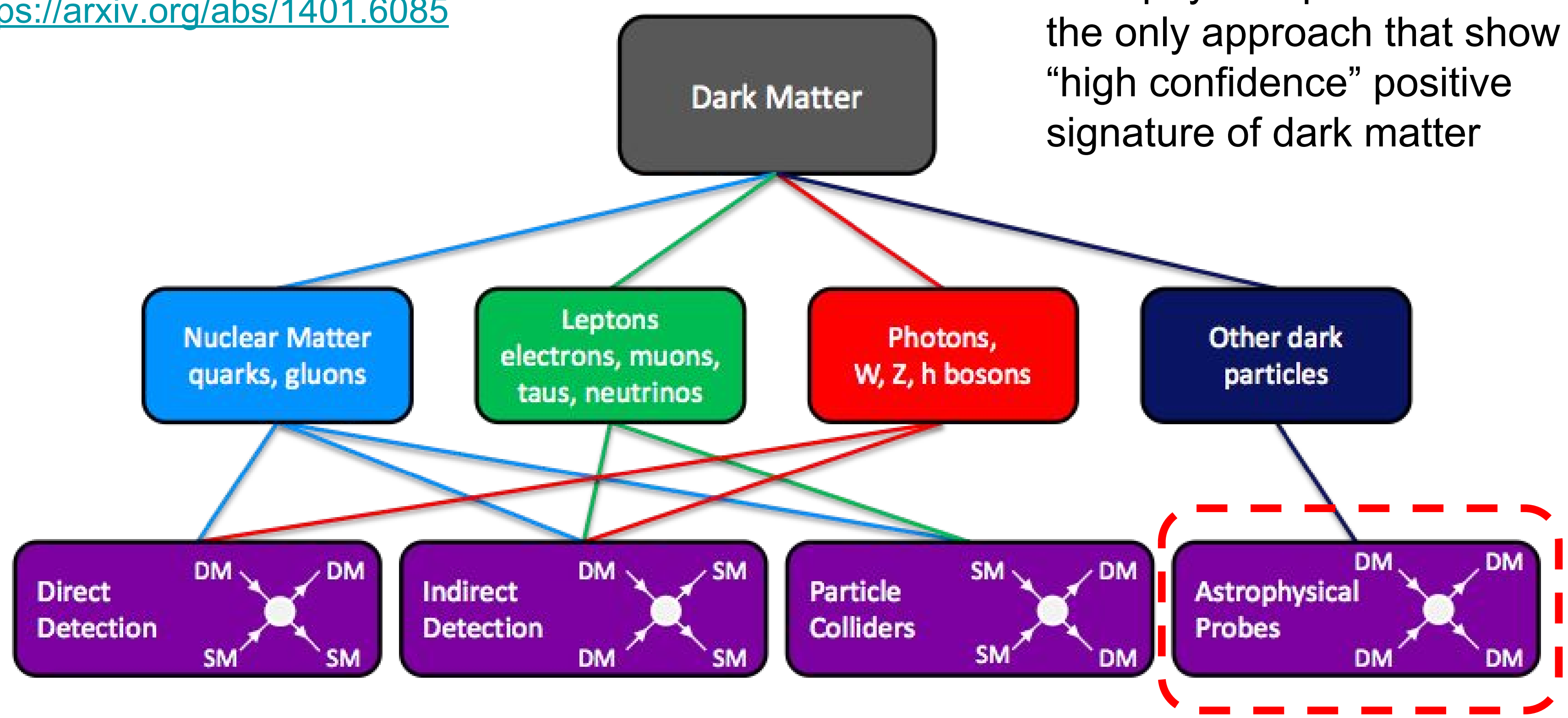


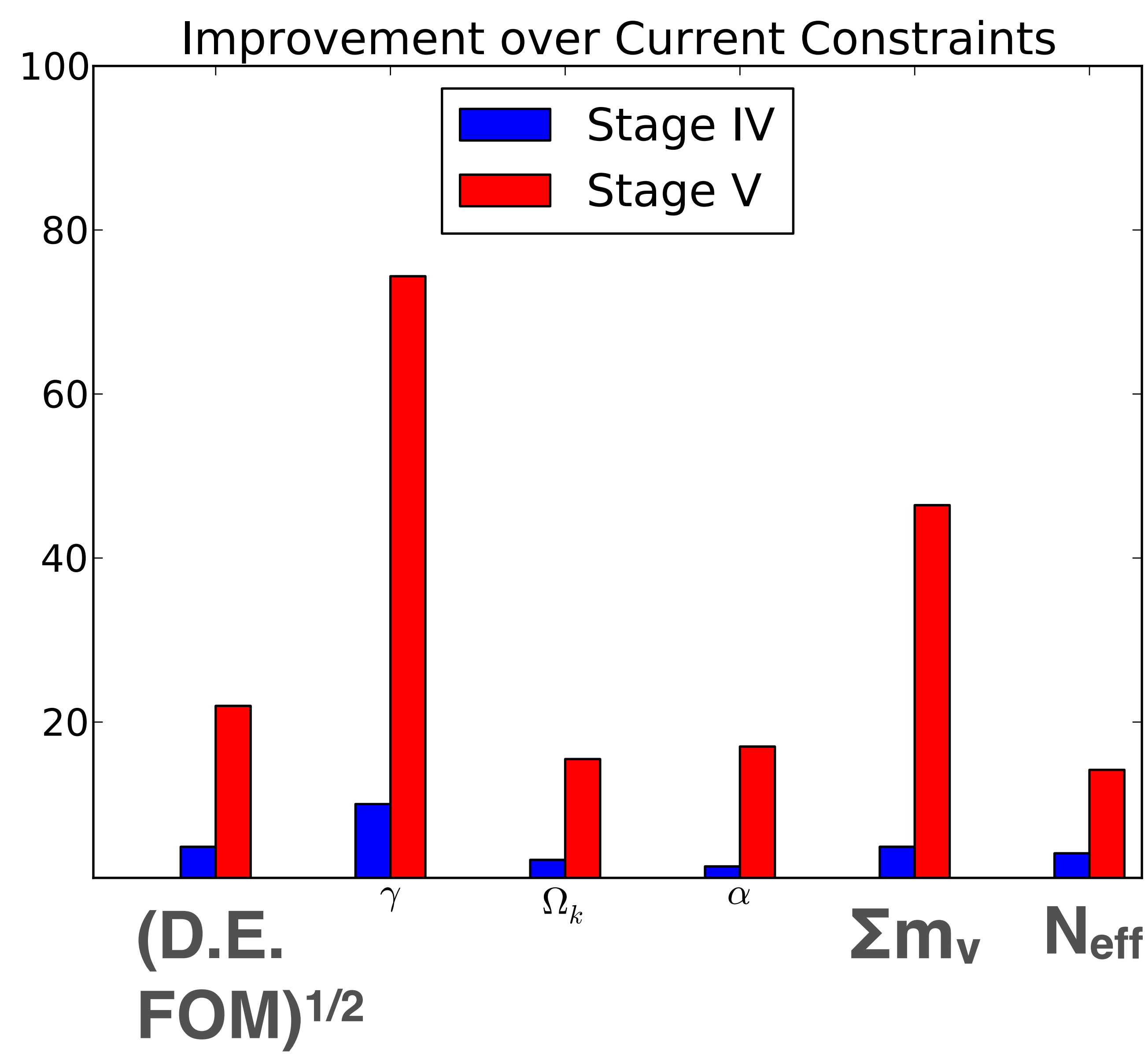
Figure 4-9. *Dark matter may have non-gravitational interactions with one or more of four categories of particles: nuclear matter, leptons, photons and other bosons, and other dark particles. These interactions may then be probed by four complementary approaches: direct detection, indirect detection, particle colliders, and astrophysical probes. The lines connect the experimental approaches with the categories of particles that they most stringently probe. The diagrams give example reactions of dark matter (DM) with Standard Model particles (SM) for each experimental approach. From Ref. [130].*

- LSST will make significant advances, with FNAL having important roles.
- Some examples:
  - **Dwarf Galaxies:** Searching for ~GeV annihilation signals
  - **MACHOs:** Limits on micro-lensing events from DES, LSST
  - **Strong Lensing:** Galaxy and cluster profiles from DES, LSST

Cosmic Surveys: What's Next?

- ***Leave no mode behind!***
  - Post-2026, a Stage-5 DE experiment can still make significant improvements. Possibilities:
    - ***Southern spectroscopic survey***
      - *Will happen in some form, technical expertise at FNAL can make significant contribution (e.g., DES-spec, Gigapix)*
    - 21 cm (e.g., Tianlai, HIRAX)
- New discoveries from Stage-3 surveys could stimulate new ideas, e.g.;
  - CMB spectral distortions, next-gen gamma-ray satellite, high-redshift surveys, etc.

Dark Energy Cosmic Visions Group (arXiv:1604.07626)



Cosmic WG: 10/20-year Goals

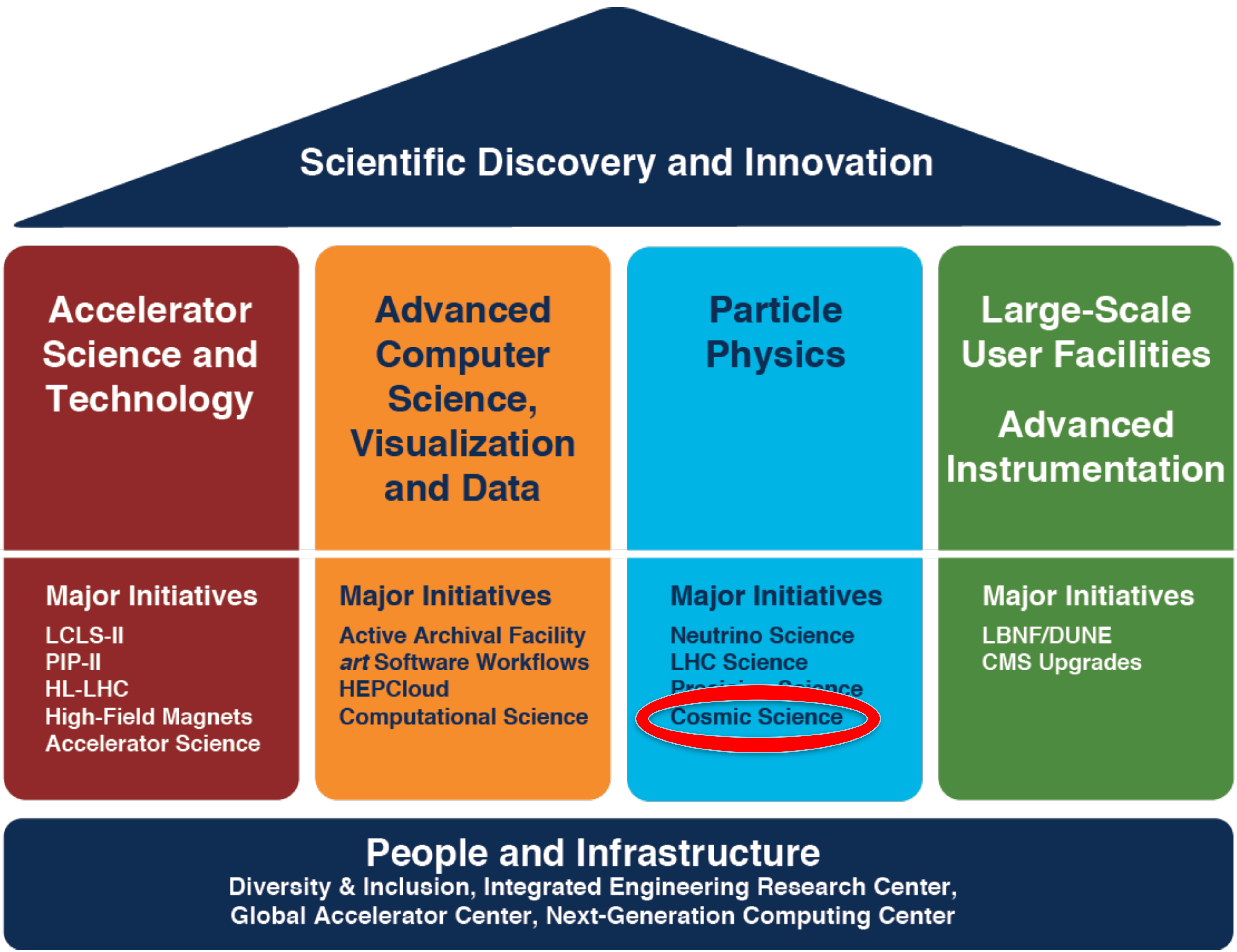
- **Build Current Generation of Experiments:** SuperCDMS, LZ, DESI, LSST, CMB-S4
- **Neutrinos:** Closer interaction between HEP+Cosmic, e.g., joint constraints, DUNE supernovae.
- **Southern Spectroscopic Survey:** Next big cosmic Dark Energy project, FNAL will have major role.
- **Axion Dark Matter Lab:** New frontier for DM searches, where FNAL can fill unique roles.
- **Quantum detectors:** Key technology for next-generation DM and CMB experiments. Major initiative at FNAL.

Extras

Discussion Generated During Meetings

- Many ideas discussed during meetings:
  - **Big Data:** build expertise / center at FNAL to exploit large surveys
  - **Cosmic Cross-Correlations:** Exploit optical + CMB joint analyses
  - **Cosmic DM:** build expertise at FNAL to search for signals in LSST
  - **LISA:** New satellite probe of gravity and cosmology (e.g., standard sirens), could be most transformative physics experiment in 20+ years.
  - **Icecube / PINGU:** Study astrophysical and atmospheric neutrino oscillations.
  - **Super-Fermi:** Next-generation gamma-ray satellite, to explore GeV-TeV scale dark matter in the form of thermal relic.
  - **WFIRST:** Dark energy and dark matter studies with WFIRST satellite, leveraging experience off other cosmic surveys (e.g., DES, DESI, LSST)
  - **Magis-100:** Atomic fountain to probe gravity waves, dark matter. Proposed pathfinder project in NuMI tunnel.
  - **PICO-500+:** Large bubble chamber experiment to search for spin-dependent WIMP interactions beyond the reach of xenon and argon experiments or perform a detailed study of WIMP nuclear couplings.

Cosmic Science is Part of the FNAL Strategic Plan



Cosmic Frontier Research at the lab funds ~8% of the scientists, and ~17% of the postdocs