SLACmass Dark Sectors

Conveners: Maria Elena Monzani, Peter Graham, Philip Schuster
Slides contributions: Tim Nelson, Natalia Toro, Yun-Tse Tsai, Eric Charles, Alden Fan and the entire LZ group

U.S. DEPARTMENT OF ENERGY | Stanford University

SLAC NATIONAL ACCELERATOR LABORATORY

Kickoff Workshop, February 27, 2020

Time	Talk	Location	Speaker	Slot
10:00	**Kickoff Workshop Goals**	*51/3-305 - Kavli 3rd Floor, SLAC*	*Maria Elena Monzani*	10:00 - 10:05
	Dark Matter Searches at Colliders	*51/3-305 - Kavli 3rd Floor, SLAC*	*Timothy Nelson*	10:05 - 10:55
11:00	**WIMP-like Dark Matter**	*51/3-305 - Kavli 3rd Floor, SLAC*	*Alden Fan*	10:55 - 11:45
12:00	**Lunch break**	*51/3-305 - Kavli 3rd Floor, SLAC*		11:45 - 12:15
	Ultralight Dark Matter	*51/3-305 - Kavli 3rd Floor, SLAC*	*Peter Graham*	12:15 - 13:05
13:00	**Astrophysical Searches for Dark Matter**	*51/3-305 - Kavli 3rd Floor, SLAC*	*Eric Charles*	13:05 - 13:55

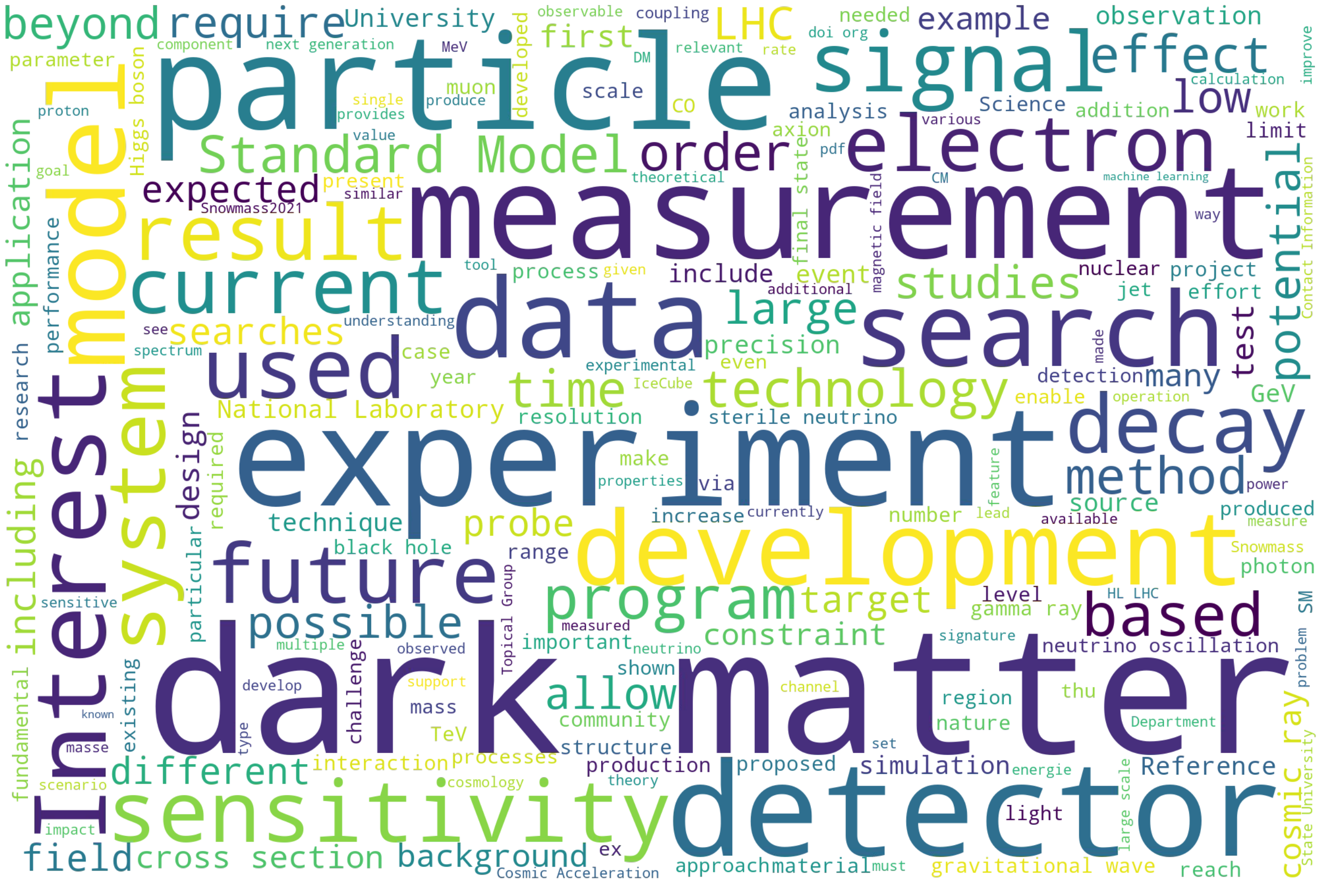
- Part tutorial, part workshop
- See full agenda on Indico
- All talks and materials collected at the indico site as well
- Notes are linked from the main workshop page

Notes
- Astrophysical searches for Dark M...
- Dark Matter Searches at Colliders
- Ultralight Dark Matter
- WIMP-like Dark Matter

Workshop follow-up and outcome

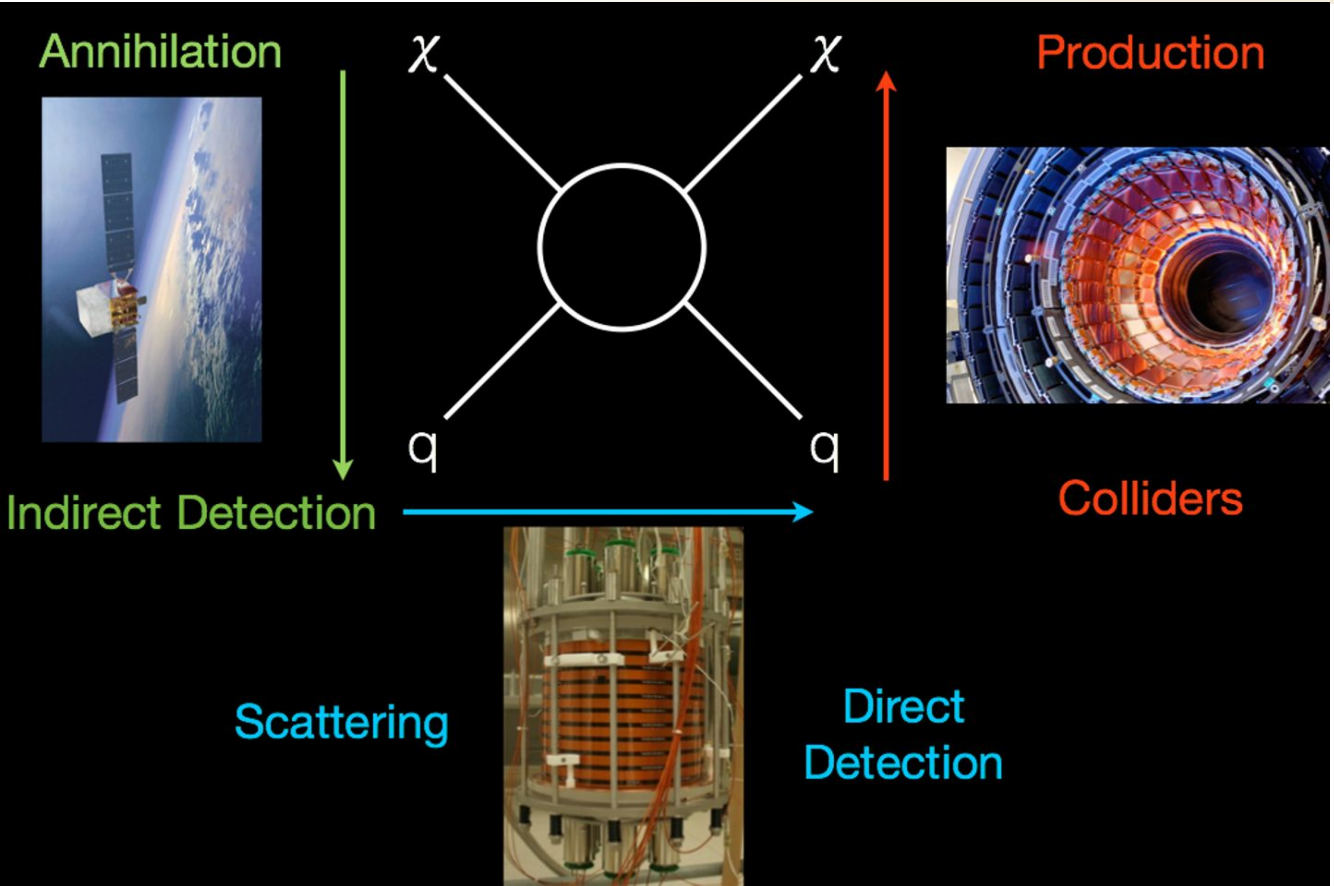
- After the workshop, a list of potential LOIs was identified
- People followed up with their respective collaborations/networks
- Folks involved in SLACmass ended up writing a bunch of LOIs
- Notably, several of us took on leading roles in “collaboration” LOIs
  - LOIs teams: anywhere between 1 and 250 authors!
- It was **extremely helpful** that we started thinking about this early
  - Example: LZ submitted 8 collaboration LOIs, 4 had SLAC leads
  - I found 41 “Dark Sector” LOIs submitted by/with SLAC staff

Snowmass Word Cloud - All LOIs



- Credit: here
- “Dark Matter” highlighted across all frontiers
- Top word for cosmic frontier
- In the top ~5 words for neutrino, theory and instrumentation

Searching for dark matter: overview



Outline for today:

- DM searches at Accelerators
- Direct Detection: WIMP-like
- Direct Detection: ultralight DM
- Astrophysical searches for DM
- Misc: computing, R&D, community

1.Dark Matter searches at Accelerators

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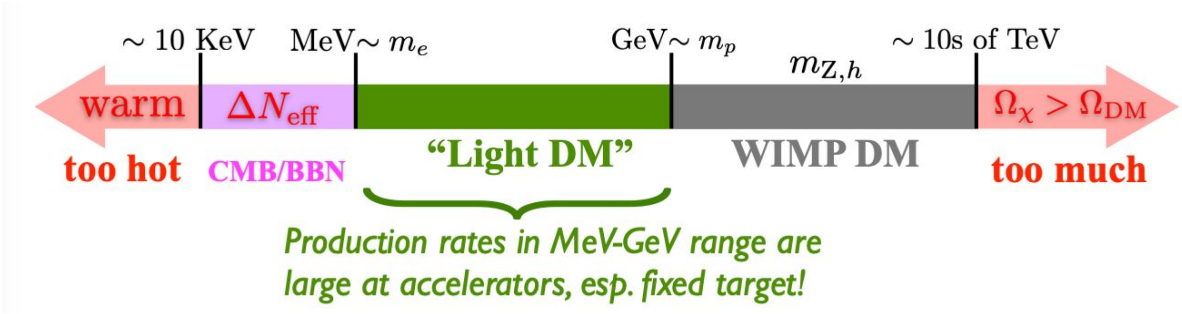
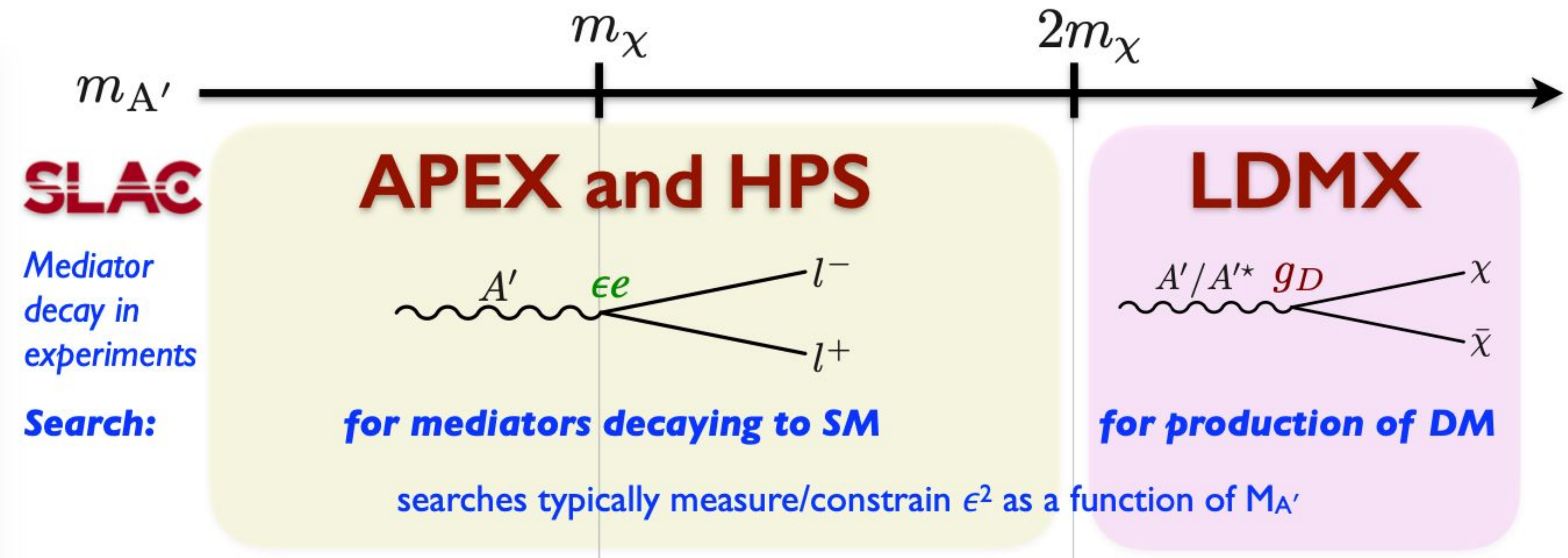
Dark Photon Searches: Motivation and Strategy

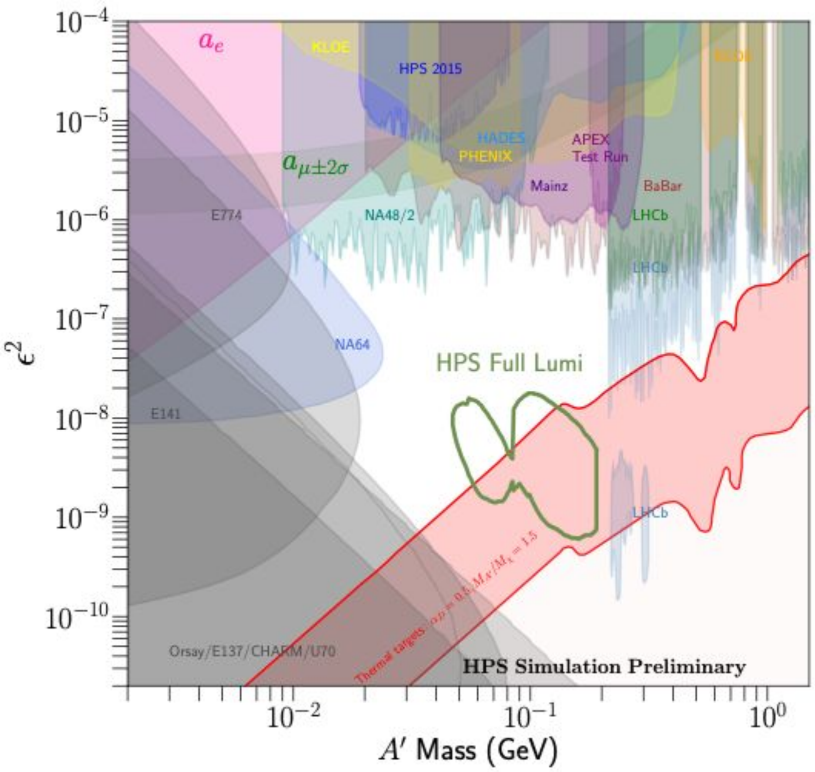


MeV-GeV thermal relic DM requires new, comparably light mediators to achieve required annihilation cross-section for thermal freeze-out



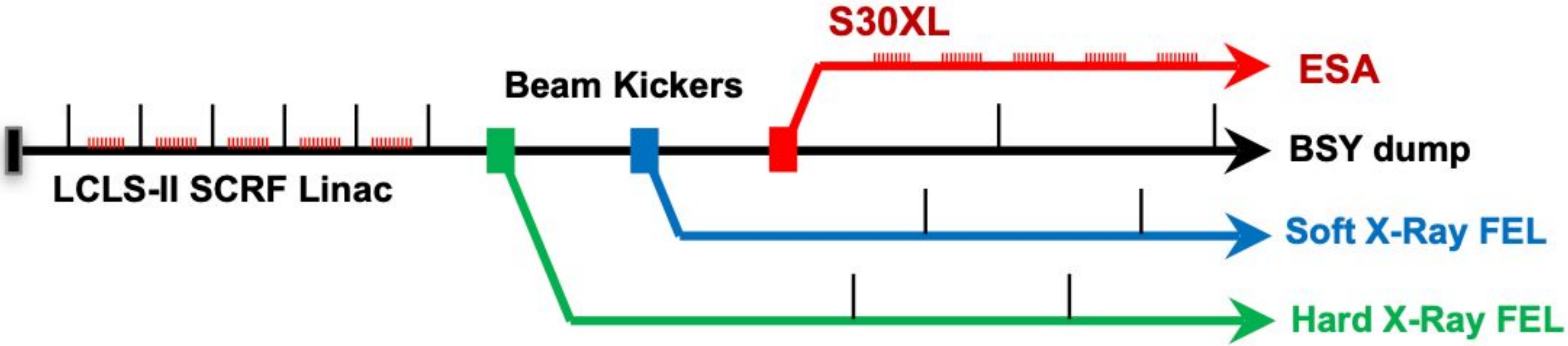
Heavy Photon Search experiment @ JLab

- Compact e+e- spectrometer, immediately downstream of thin target in multi-GeV beam
- Engineering runs in 2015 and 2016:
  - see blue shaded region in plot for 2015
  - 2016 publication is being written
- First physics run in 2019:
  - Collected ~2 weeks of data at 4.55 GeV
  - Calibration, reconstruction, and analysis of the latest dataset is ongoing
- LOI (led by Tim N.) highlights extended run:
  - HPS is scheduled for 4 weeks in 2021
  - still approved for ~4 months of operation



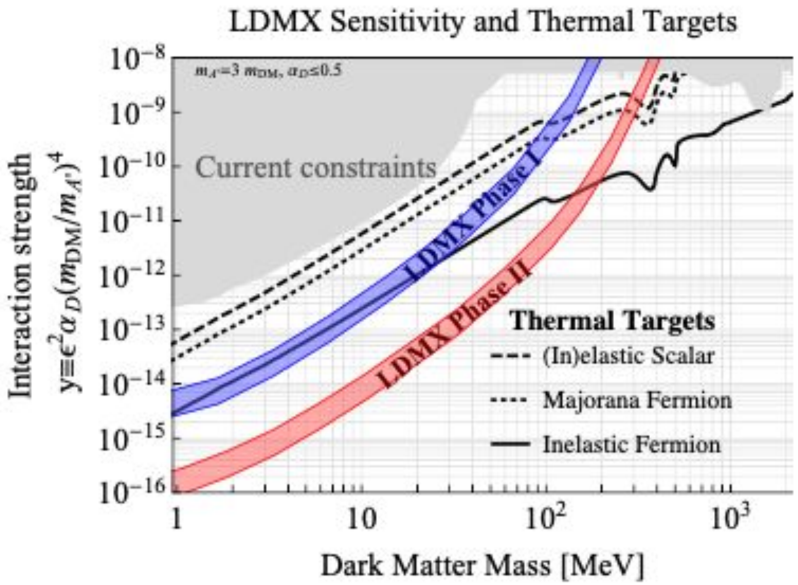
Linac to End-Station-A (LESA)

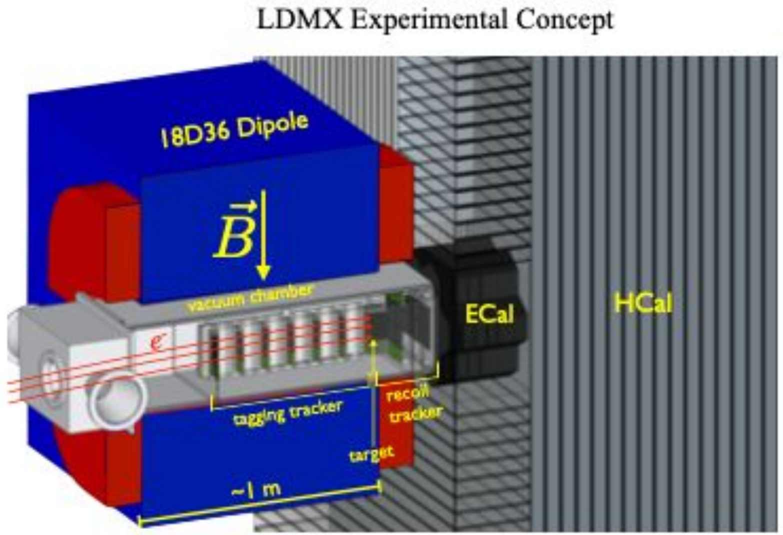
- For low mass (i.e. < few GeV), SLAC can directly host discovery experiments (in End Station A) with world leading sensitivity! (LOIs led by Tor and Natalia)
  - S30XL@SLAC can provide electron beam to end station A: multi-purpose particle physics program (including neutrino physics, test-beam physics, etc.) hosted here at SLAC!
  - (dark matter) SLAC can host the Light Dark Matter eXperiment (LDMX) with S30XL
  - (dark forces) SLAC can host "HPS-like" experiments with S30XL, among others
  - Covers broad range of low mass relic DM, new vector or axion like particles, other BSM



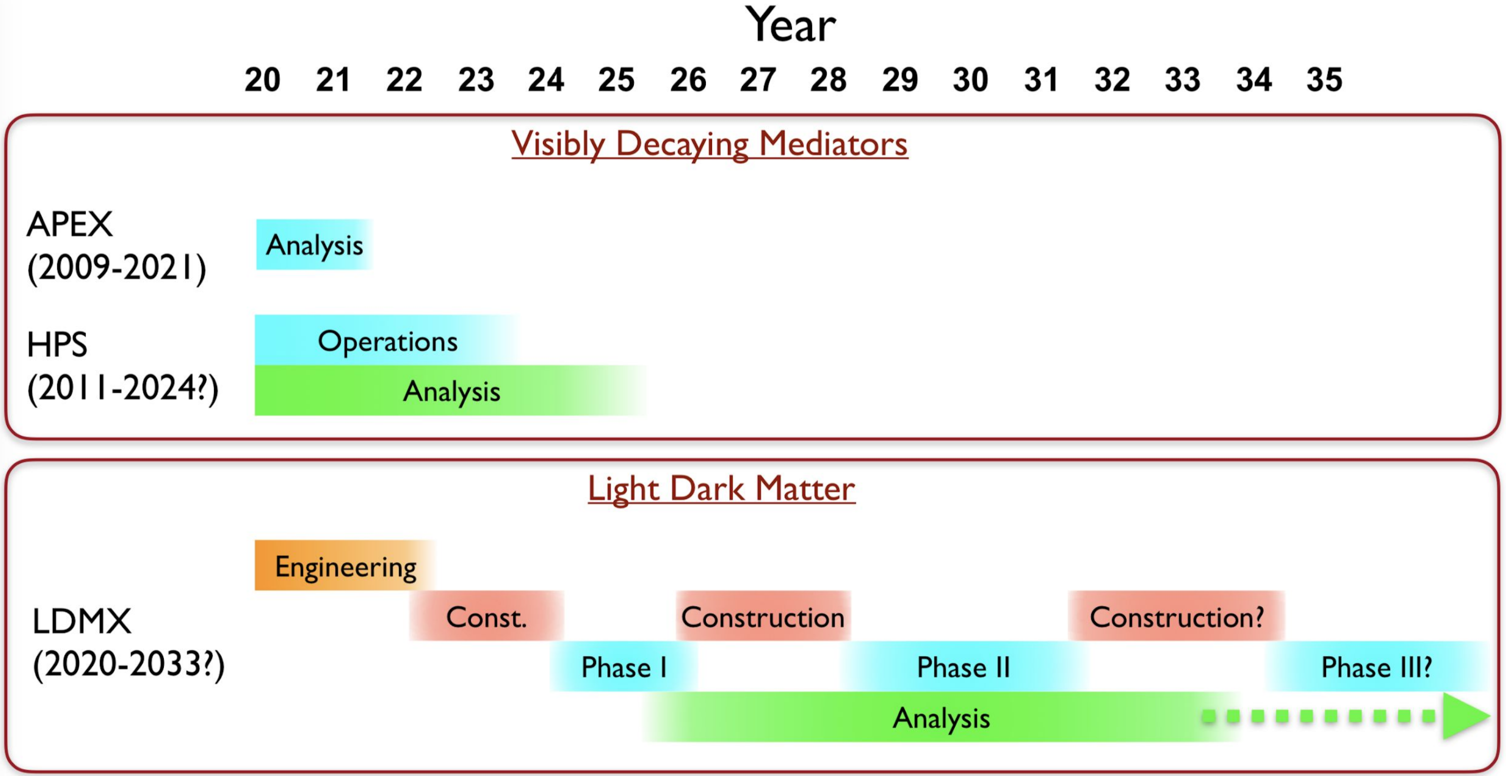
The Light Dark Matter eXperiment (LDMX)

- Missing momentum experiment for $\gtrsim 10^{16}$ *e-*
  - beam delivered through the Sector 30 Transfer Line (LESA)
  - detector technology: tracking and magnet are patterned on HPS
  - 2 years of operation with 4 GeV beam, then LCLS-II upgrade to 8 GeV





Dark Matter Searches at Accelerators: Timeline



The usual caveats apply, especially for LDMX (not yet approved)

Neutrino beams and Neutrino detectors

- Dark Sector Studies With Neutrino Beams (Yun-Tse/Gianluca + theorists)

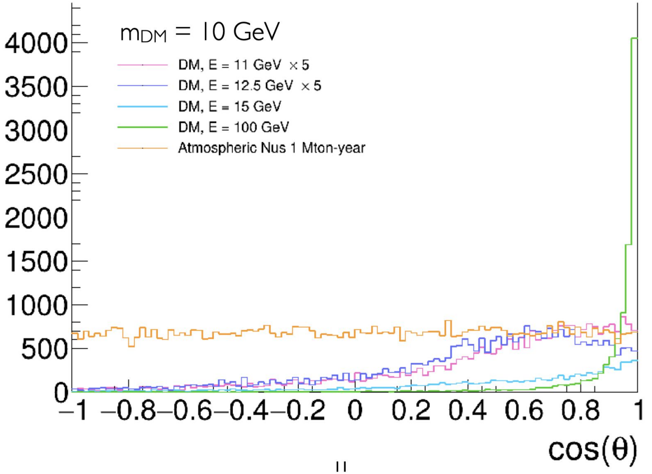
Model	Production	Detection
Higgs Portal	K, B decay	Decay ($\ell^+\ell^-$)
Vector Portal	π^0, η Decay Proton Bremmstrahlung Drell-Yan	Scattering (χe^-, χX, Dark Tridents) Decay ($\ell^+\ell^-$, $\pi^+\pi^-$) Inelastic Decay ($\chi \to \chi' \ell^+\ell^-$)
Neutrino Portal	π, K, $D_{(s)}$, B decay	Decay (many final states)
ALP Portal (γ-coupling dominant)	Meson Decay Photon Fusion Primakoff Process	Decay ($\gamma\gamma$) Inverse Primakoff process
Dark Neutrinos Dipole Portal	SM Neutrino Dalitz Decay	Upscattering + Decay ($\nu \to \nu_D$, $\nu_D \to \nu\ell^+\ell^-$) Decay ($\nu_D \to \nu\gamma$)
νphilic Mediators	SM Neutrino	Scattering (Missing $\not{p}_T$, SM Tridents)

Table 1: A selection of models that can be probed by neutrino beam experiments.

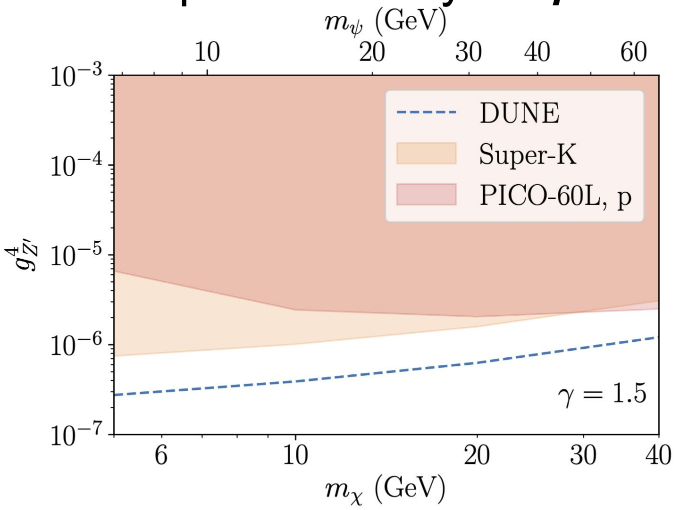
Neutrino beams and Neutrino detectors

- Search for Boosted Dark Matter in DUNE-like experiments (Yun-Tse/Gianluca)
  - cold dark matter captured by dense object, like the Sun or Galaxy Center
  - lighter, boosted dark matter produced via annihilation or decay
  - boosted dark matter interacts with electrons or nucleons in detectors

Signature: angular distribution

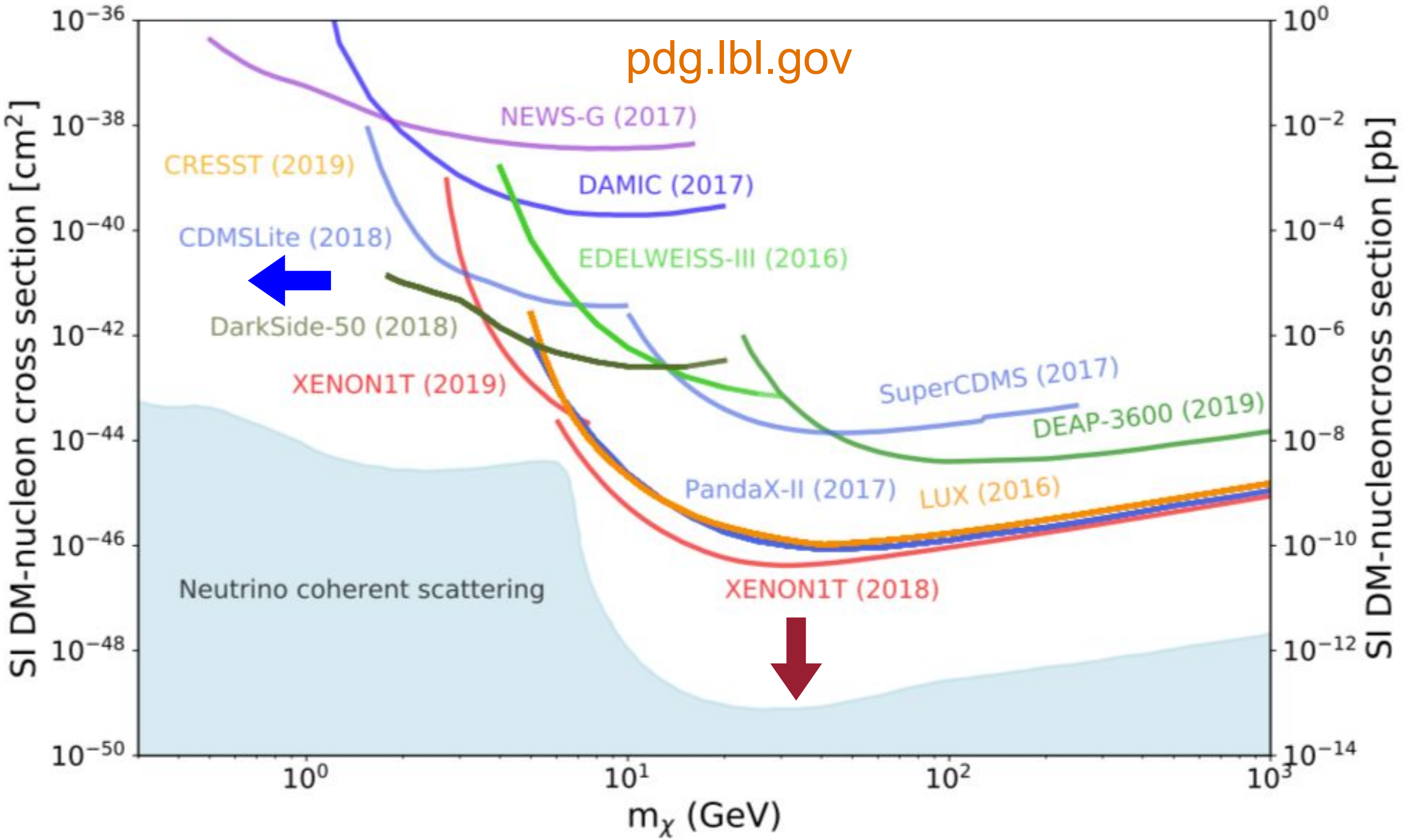


Example sensitivity for ***γ*** =1.5



2. Direct Detection: WIMP-like Dark Matter

WIMP-like Dark Matter

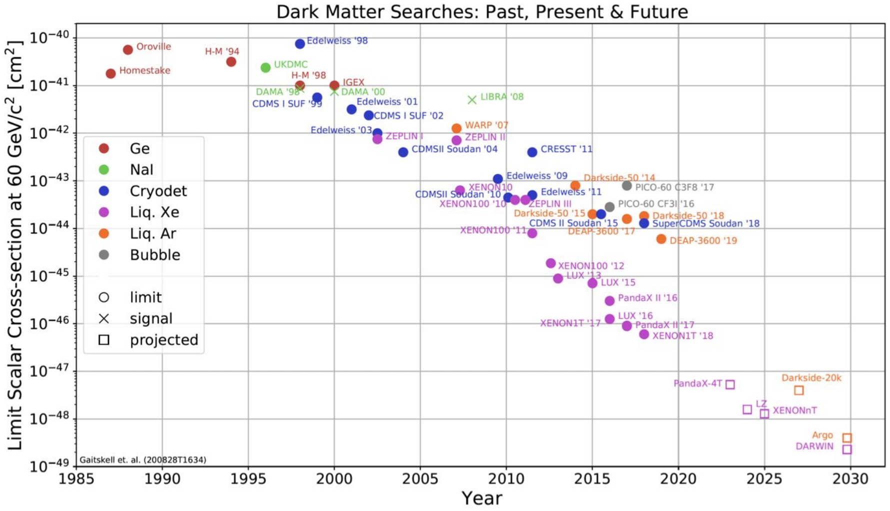


Main Thrusts:

- Enhance Sensitivity
- Expand the mass range
- New detector technologies

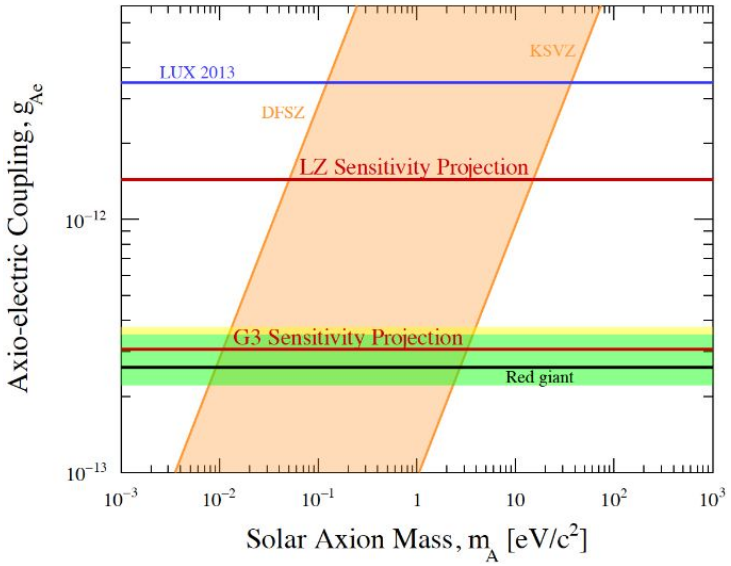
Noble Liquid Detectors: the case for G3

- LXe TPCs have led WIMP searches steadily for the last 15-20 yrs
- WIMPs are still well motivated and LXe G3 detector (scale of 40-100 tonnes) can probe remaining parameter space, to the neutrino floor
- LOI led by Alden Fan (SLAC) & LZ'ers. Multiple signatories from XENON
- Sensitivity to a multitude of particle DM candidates
  - e.g. inelastic DM, self-interacting DM, dark photons, ALPs, MIMPs, etc
- Dominant background will be electron recoils from pp solar neutrinos
  - assume improvement in control of terrestrial BGs (radon, seel later slides)

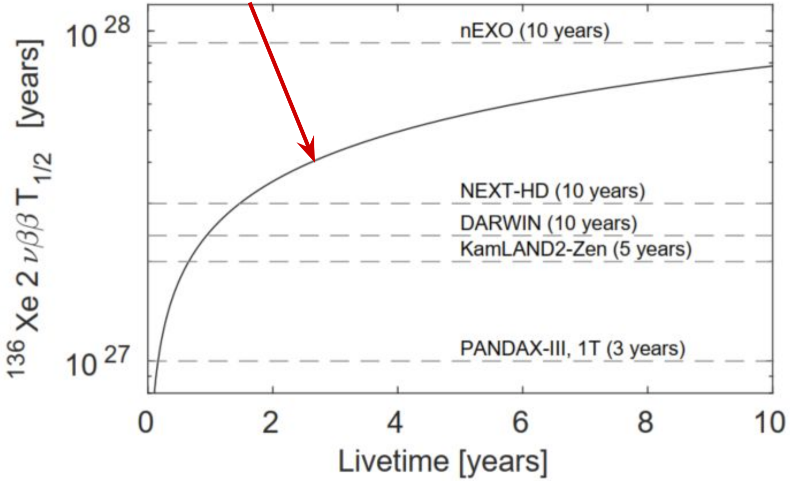


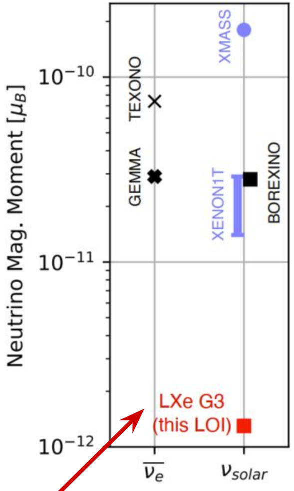
Liquid Xenon-G3 as a “multi-physics” observatory

Axion sensitivity (75 tons, 10 years)



Neutrinoless ββ decay (75 tons)



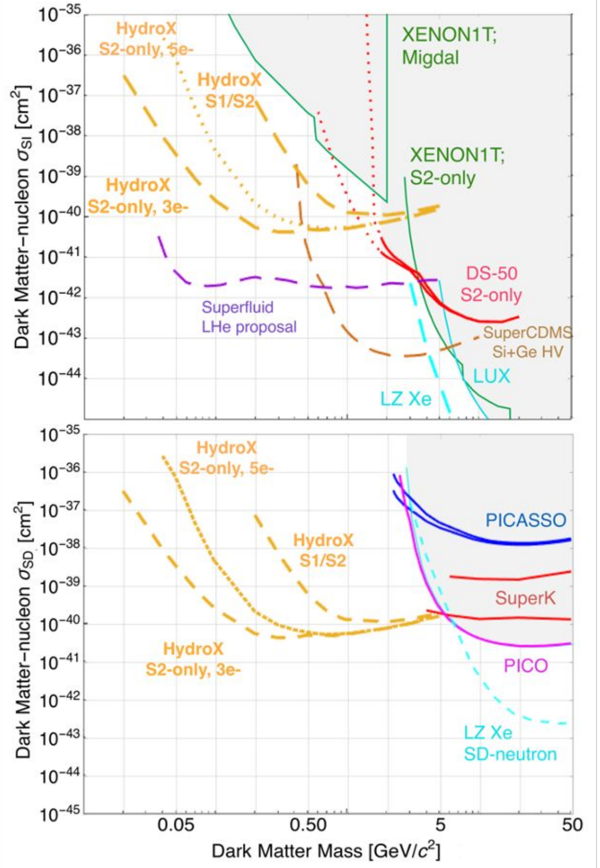


Neutrino magnetic moment (75 tons)

- Not pictured: solar, supernova, and atmospheric neutrinos

What else is fun that we could do with LXe?

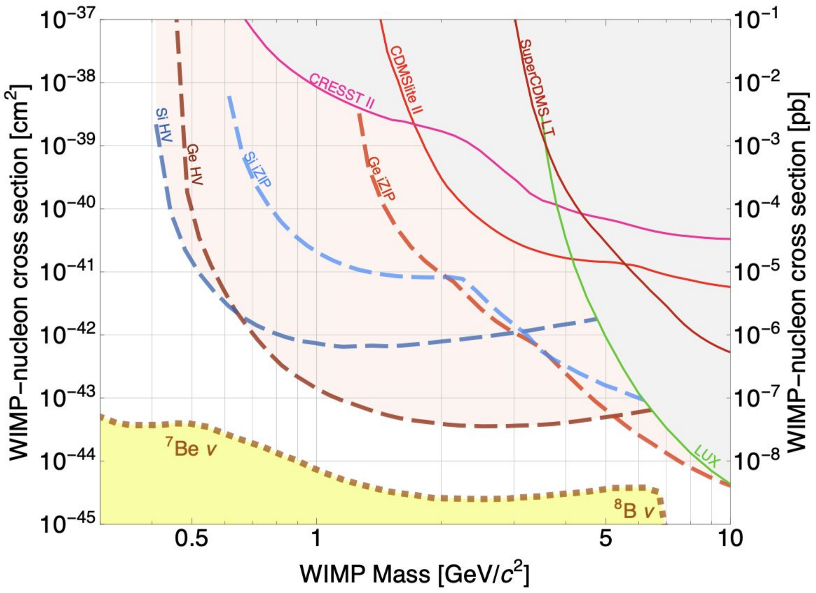
- Low mass DM search by dissolving hydrogen into a large LXe TPC, e.g. LZ or a G3 detector, at O(1%) level
  - Hydrogen is the DM target and LXe becomes the sensor (HydroX: "Hydrogen in Xenon")
  - Proton recoils: better kinematic match to low mass DM, more efficient observable signal
  - Sensitivity to <300 MeV dark matter particles, both SI and SD couplings
  - Backgrounds: Retain all of the BG control from G2 and G3 experiments, e.g. self-shielding, radiopurity
- Could be done as a "G2.5" or G3 experiment
- SLAC would host (most of) the R&D for this project
- R&D at SLAC starting ~now (LXe LDRD)



SuperCDMS: Phased Expansion

- Current detector (under construction):
  - 24 detectors of four types (iZIP and HV, Ge (1.4 kg) and Si (0.6 kg))
  - Oversized cryostat and infrastructure
- Proposed upgrade plan with milestones at 5, 10 and 15 years:
  - Mass reach down to ~0.05 GeV
  - Cross section reach to neutrino floor for masses 0.5-5 GeV
  - Cross section and mass reach to neutrino floor for masses 0.05-1 GeV

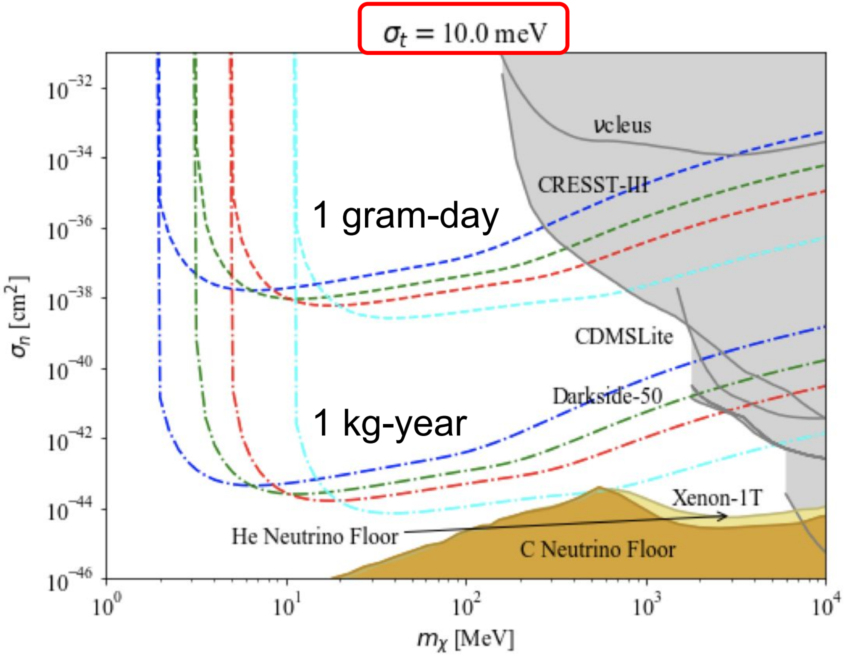
SuperCDMS SNOLAB sensitivity



- Explore synergies with other experiments (EDELWEISS, DAMIC, ADMX, etc.)

Cryogenic Carbon Detectors

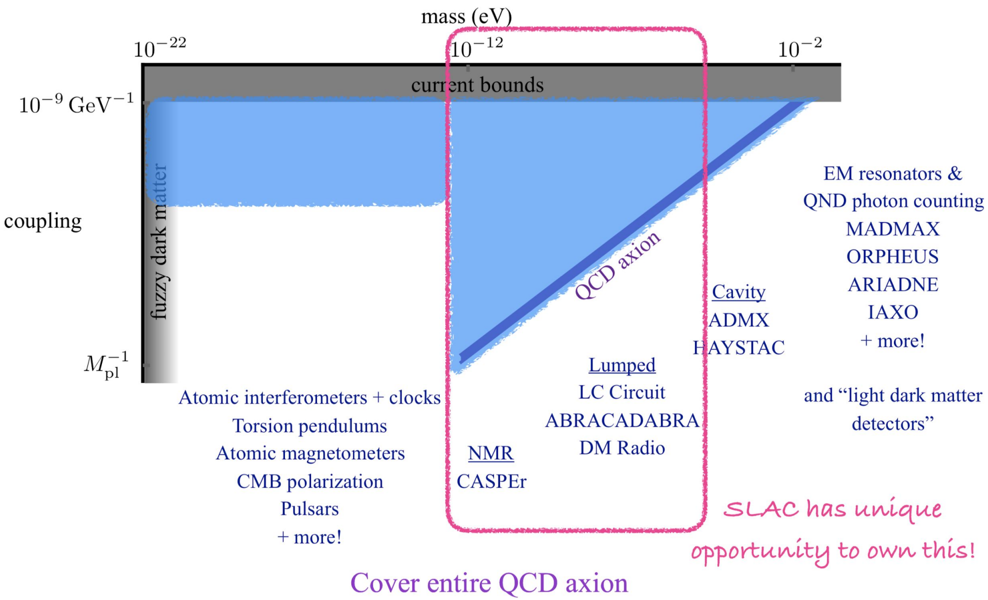
- Cryogenic Carbon (Diamond + Si C)
- Three 'modes' of detecting dark matter:
  - 'Conventional' Nuclear Recoil (NR) off nucleus
    - Low-mass (GeV) suggests light nuclei
  - Electron Recoil (ER) off electrons : 2 mass-scales for mediator
    - High electron-density targets
  - Dark photon (photoelectric) absorption
    - Coupling to available final states
    - Also available for axion-like particles



liquid helium (blue), diamond (green), silicon (red), xenon (cyan)

3. Direct Detection: Ultralight Dark Matter

Ultralight Dark Matter



Several techniques actively being explored at SLAC, plus many other new approaches: an excellent time to join the field!

Recent burst of activity in searching for axions and ultralight DM worldwide:

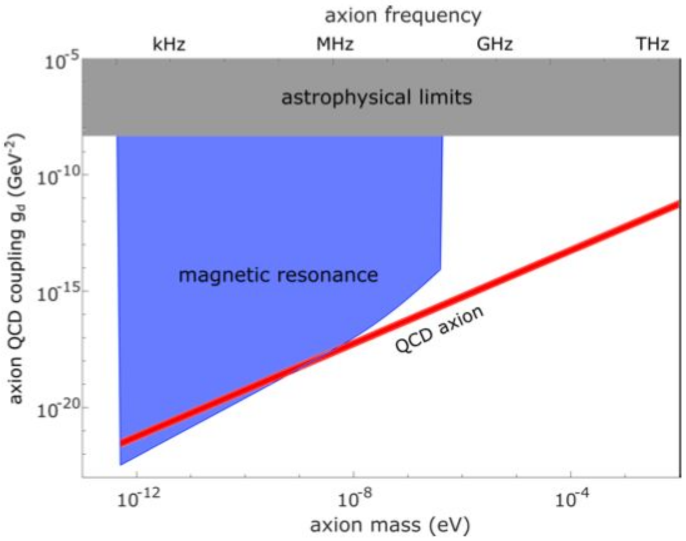
- Use of dark matter structure for ultralight (fuzzy) dark matter
- CMB polarization measurements for lightest axion
- Direct detection of QCD axion over majority of its parameter space: Lumped Element, NMR techniques (DM Radio & CASPEr)

SLAC likely to be a major site for ultralight dark matter detection!

QCD Axion Detection: 3 main techniques

NMR, Lumped Elements, and Microwave Cavities

nuclear coupling

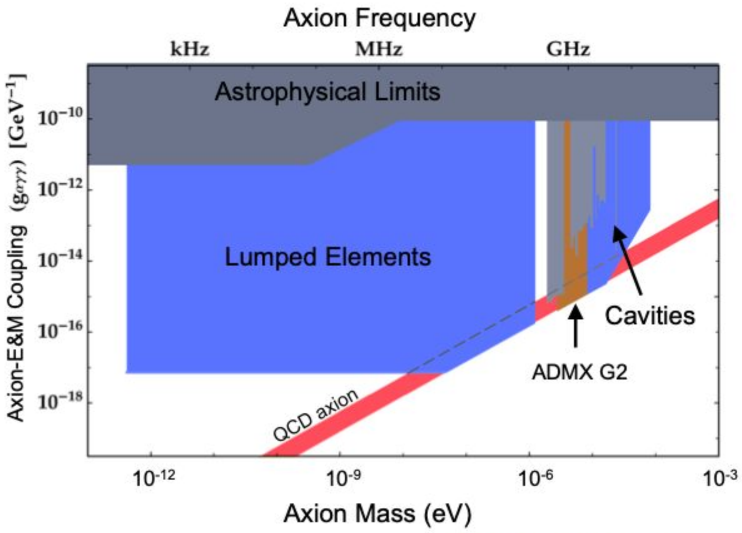


CASPEr

significant overlap/collaboration with DM Radio

needs a national lab "home"

electromagnetic coupling



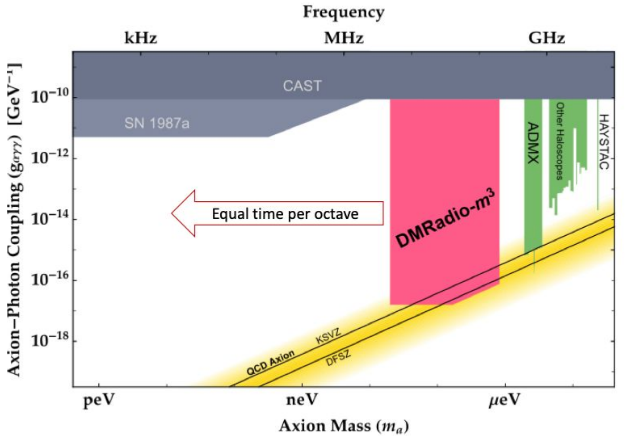
ADMX, HAYSTAC,…

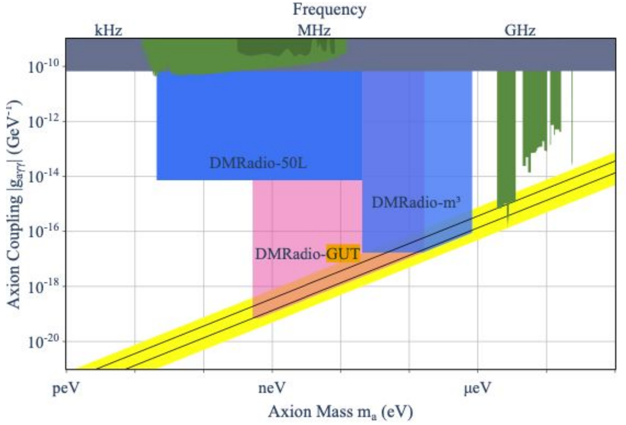
LC Circuit, ABRACADABRA, DM Radio

recently merged
based at SLAC

DM Radio Experiment

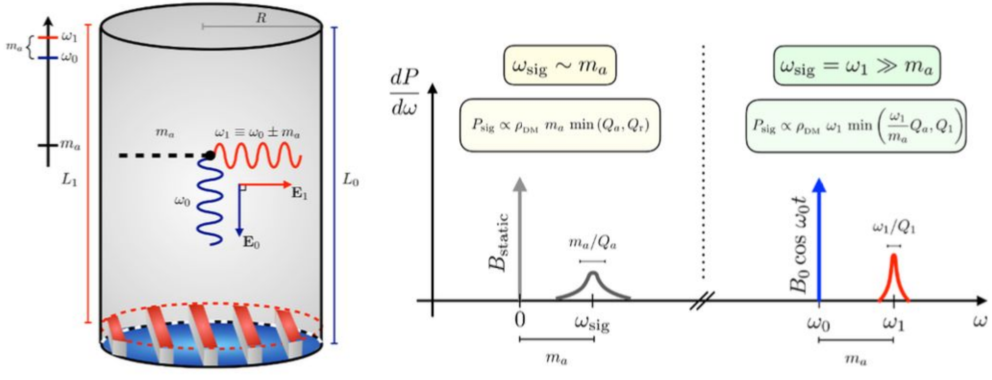
- Widely tunable, lumped element EM resonator
  - low dissipation/low noise resonator Q ~ 10^6
  - high precision magnetometry/amplifiers (SQUIDs)
  - pathfinder: 4 K 300 cm^3
  - 50L at <100 mK under construction
- Cubic meter experiment:
  - 20 mK temperature, Q=10^6, 4 T Magnetic Field
  - dc SQUID with 20x quantum limit
  - 5 MHz–200 MHz, 3 years of live scan
  - New Initiatives in Dark Matter R&D Selection
  - R&D: now-2022, construction: 2022-25
- DMRadio-GUT: more sensitive, next decade





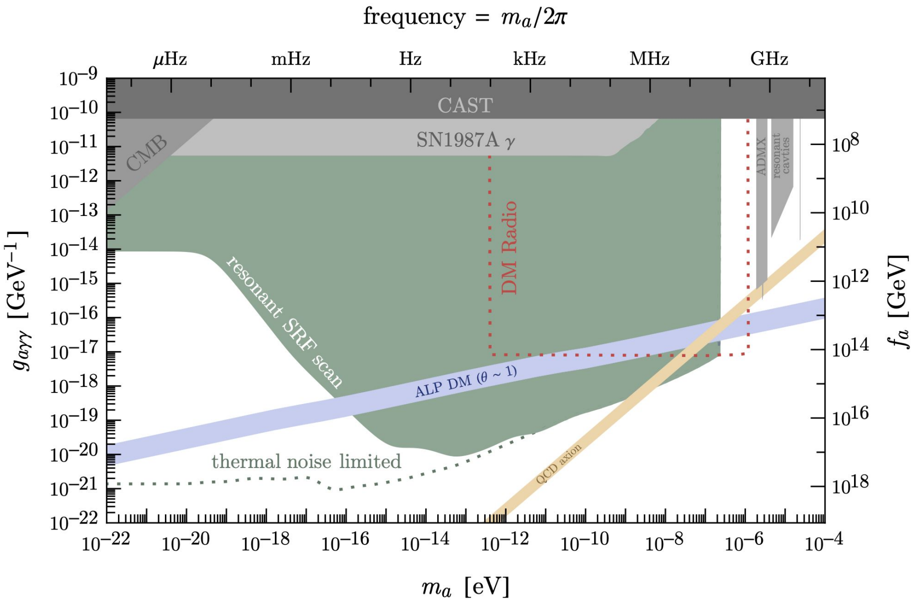
Superconducting cavities (resonant conversion)

- Idea: the superconducting cavity is prepared by driving a “pump” mode with frequency ω_0 ~ GHz
- The axion field causes frequency conversion, resonantly driving power into a “signal” mode with nearly degenerate frequency $\omega_1 = \omega_0 + m_a$
- Advantage: lower readout noise at low axion masses, since the signal is always at GHz frequencies



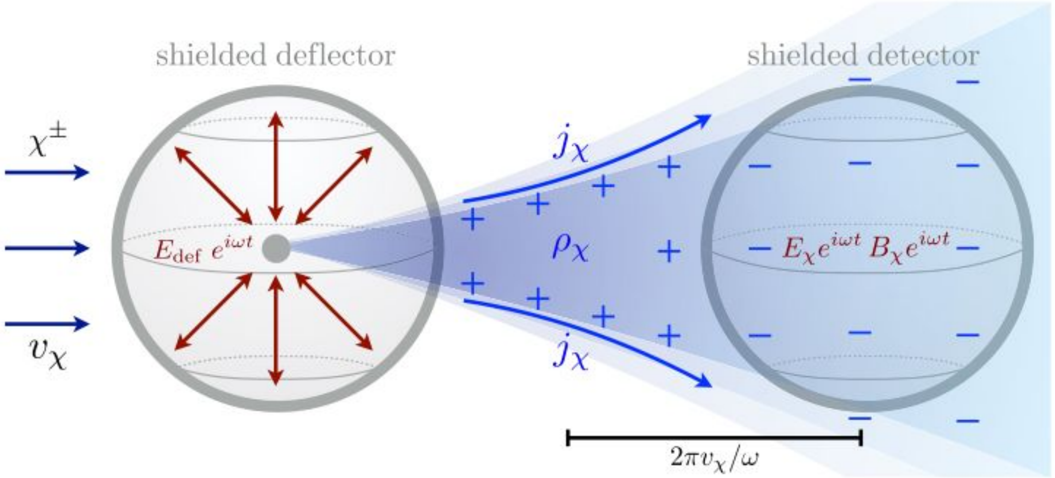
(a) Cartoon of cavity setup.

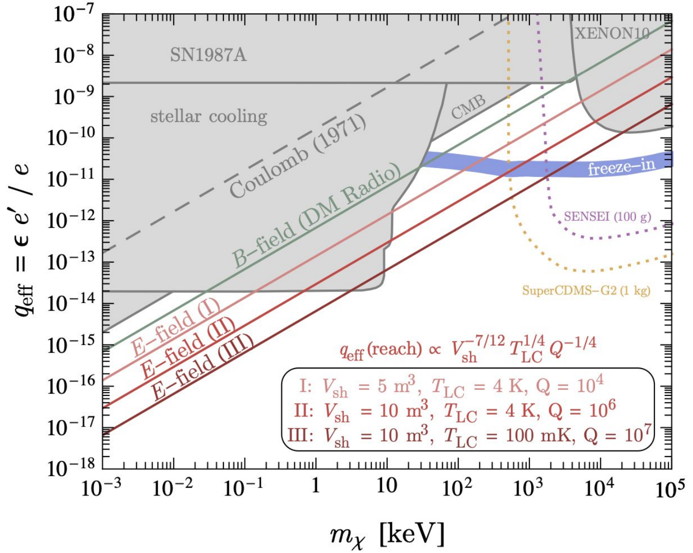
(b) Signal parametrics.



Direct *Deflection* of Dark Matter

- Detection principle: distort the local flow of dark matter with time-varying fields, and measure these distortions with shielded resonant detectors.
- Detection target: sub-MeV dark matter particles with very small electric charges or coupled to a light vector mediator. Example: “freeze-in” DM interacts with the SM through a dark photon of mass ~10^{-9} eV. It appears “millicharged” on □~100 m length-scales, allowing it to weakly couple to standard electromagnetic fields.

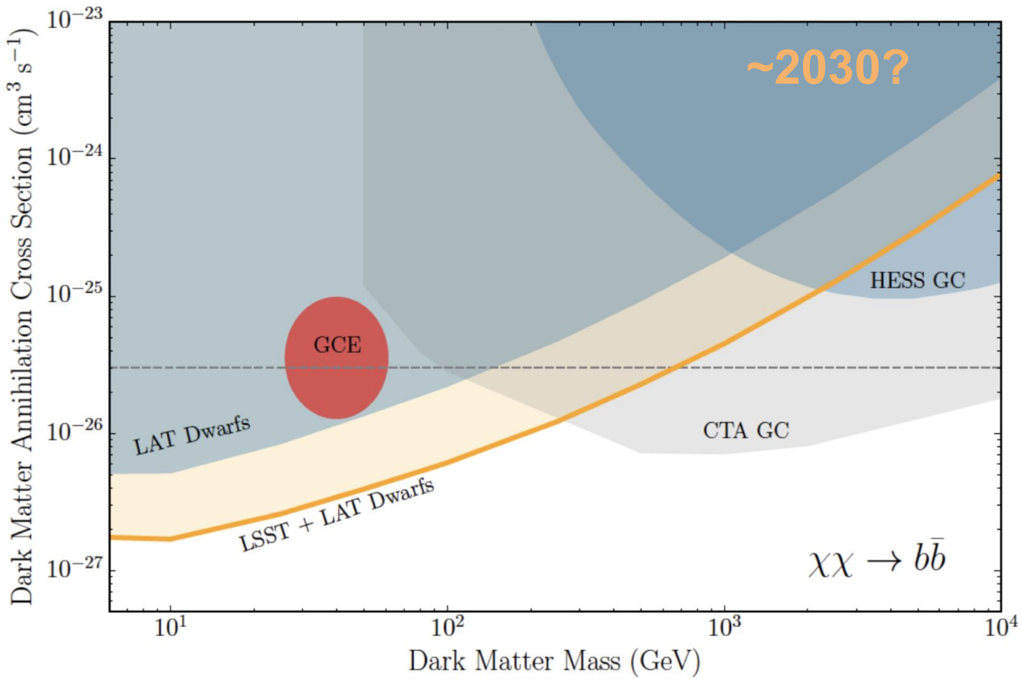




4. Astrophysical Searches for Dark Matter

Astrophysical probes for Dark Matter

WIMP sensitivity projections from indirect searches, circa 2030 (2019arXiv190201055D)



Probe fundamental properties of DM using astrophysical data (mainly LSST). Examples:

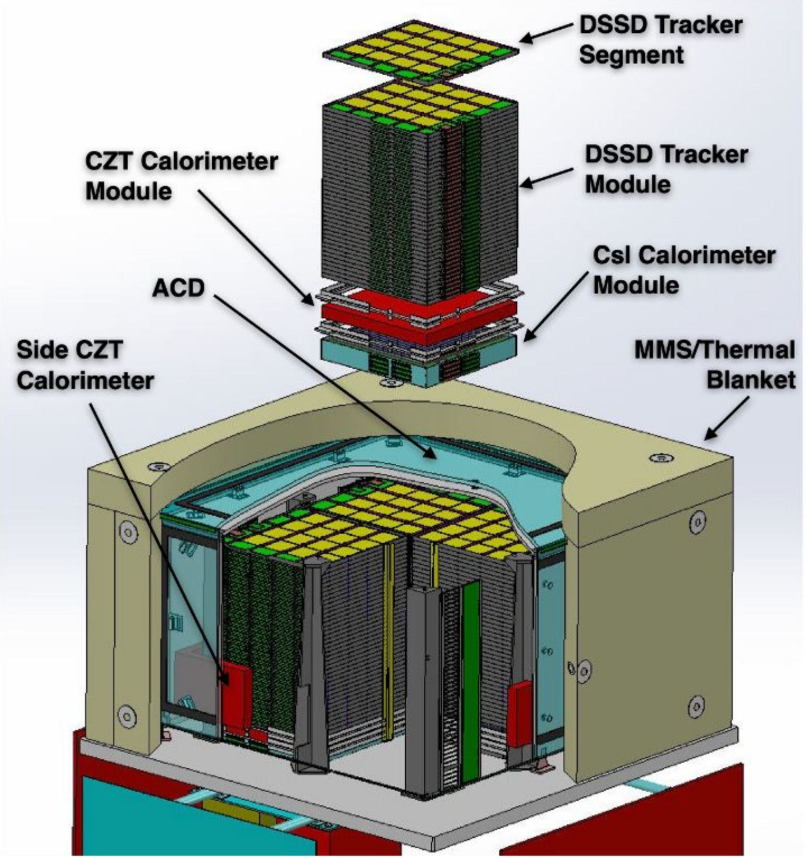
- Self-interaction cross section
- Mass for warm dark matter (from the minimum halo mass)

What else can we do?

- Fermi unlikely to be running in 2030s (survey data available)
- We lost the CTA argument
- Look in the MeV-GeV range?

AMEGO (All-sky Medium Energy Gamma-ray Observatory)

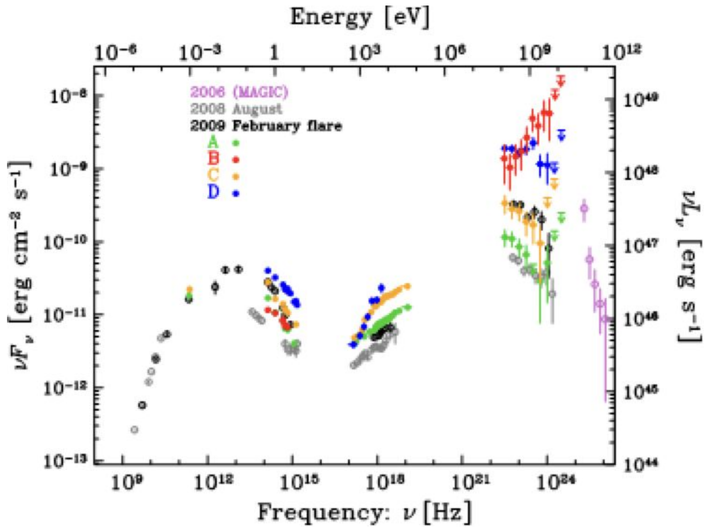
- NASA astrophysics probe mission concept:
  - Energy Range: (0.2 MeV - 10 GeV)
  - Compton + pair conversion regimes
  - Launch in 2029 (assuming 2022 approval)
- Explore a wide range of DM candidates:
  - WIMP annihilation with MeV signatures
  - explore models below thermal relic
  - improve handling of the diffuse emission
  - disentangling the nature of the GCE
  - WISP and Axion-like Particle Candidates
  - mass in the sub-eV range, non-thermally produced in the early Universe



GammaTPC Observatory

Idea: LAr TPC to measure MeV Gamma Rays. Energy range: ~0.2-100 MeV (LOI led by TomS)

- Essentially unexplored energy window:
  - Many broad sources peak in this region
  - Nuclear lines unique - SN, including SN1a
  - Multi-messenger, including NS-NS merger
- SLAC group started sensitivity studies with G4-based MEGALib, plus electron track reconstruction with ML
- Pixel readout with sparse triggering: significant development, excellent match to TID folks
- Other lab work: SiPM, light collection, etc. Close connection to local DUNE group

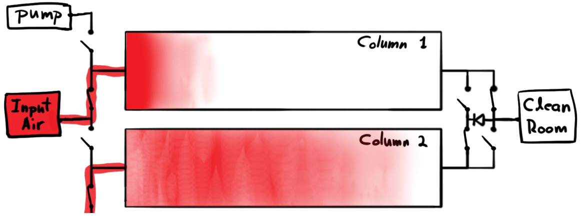


NASA APRA proposal this fall. Joint effort with AMEGO started, focused on reconstruction & sensitivity

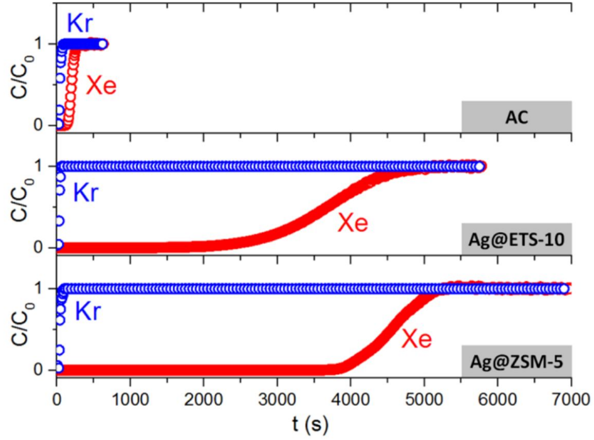
5. Miscellanea (R&D, computing, community)

Noble Liquid R&D: Radon Removal

- Current and next-generation LXe experiments will require online radon removal:
  - dominant background in LZ, XENONnT
  - also 2nd largest background for nEXO
- Current online radon removal technologies not capable/demonstrated at required high
- Michigan-SLAC (Eric Miller) LOI describes a cryogenic Vacuum Swing Absorption System
  - 2 charcoal columns (chromatography/regeneration)

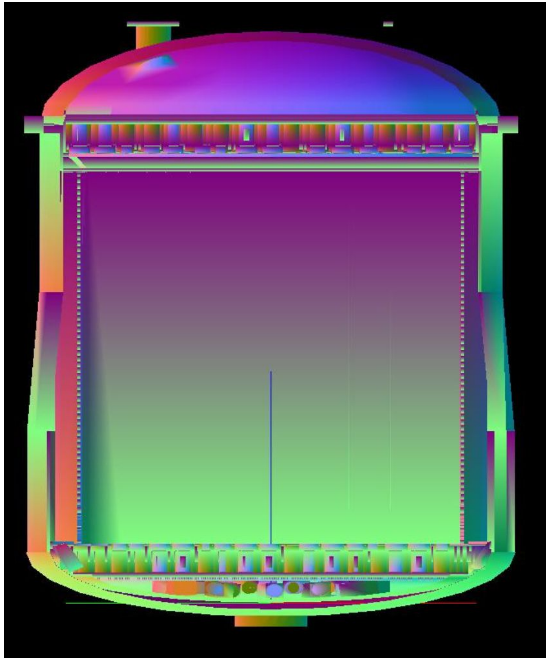


- SLAC LOI (Eric Miller, Brian Mong) proposes chromatography done with metal-oxyde frameworks (R&D also starting ~now, in LXe LDRD)
  - Very promising: 1,000's of articles already about MOFs and xenon with selectivity 100x better than charcoal

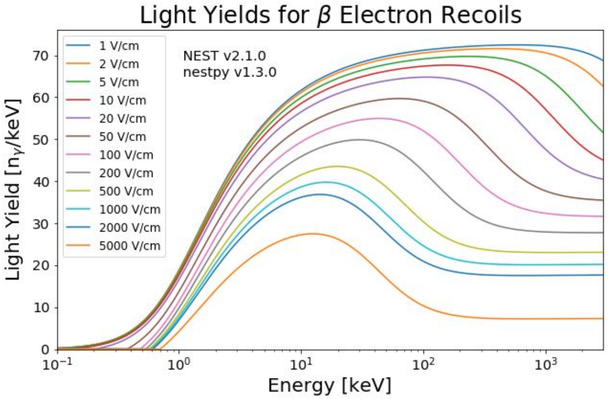


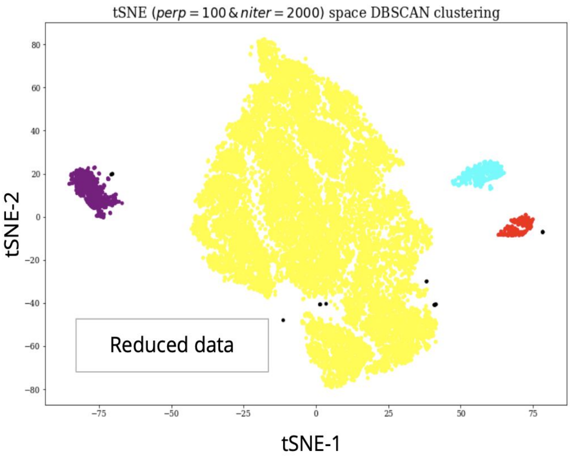
Joint Computing LOIs: LZ, XENON, DARWIN, etc.

Fast Simulations for Noble Liquid Experiments (lead authors: MEM & LZ'ers)



The Noble Element Simulation Technique (NEST collaboration, incl.: XENON/DARWIN, LUX/LZ, (n)EXO, RED-100, DUNE, MicroBooNE, SBN)



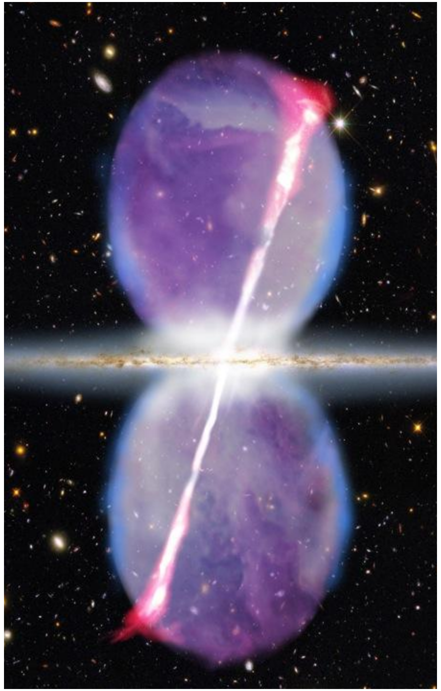


Clustered events in t-SNE space
Unexpected populations such as pulse finder issues are evident in this space but not in common analysis space

Machine learning in Rare Events Searches (lead authors: MEM & LZ/nEXO)

Data Preservation, public access to data

“Facilitating cosmic probes and dark matter searches with improved data access and software tools for multi-wavelength and multi-messenger analyses” (Eric Charles)



- Almost every science topic covered in the Cosmic Frontier will at some point require combined analysis of data from multiple instruments
- Successful precedent (i.e. Fermi): combination of publicly available data and high-quality publicly available software to analyze that data
  - Example: discovery of the “Fermi bubbles”
  - Joint Fermi/DES analyses of satellite galaxies
- Facilitating high-impact, cross-experiment data analysis in upcoming CF experiments should be a priority

Creating Inclusive Collaborations

- "Creating Inclusive Collaborations" (Comm. Front. LOI) - full LZ authorship, led by SLAC PD/GS (Micah Buuck, Kelly Stifter, plus Rachel Mannino, Alvine Kamaha)
- We as physicists have a moral obligation to ensure everyone in our field is enabled to do their best work - start by making our collaborations equitable spaces
- Highlighted strategies implemented in LZ:
  - Code of Conduct
  - Ombudspeople
  - Educating ourselves
  - Outreach
  - Good Citizenship awards
- Becomes increasingly important as new, larger collaborations are formed - want to work with other groups to define best strategies/practices moving forward

Backup slides

Please check out our notes from the Feb workshop!

SLAC

Topic	Speaker	Moderator	Scribe(s)	Notes
DM searches at accelerators	Tim Nelson	Philip Schuster	Kelly Stifter	gdoc
WIMP-like Dark Matter	Alden Fan	Micah Buuck	Natalia Toro	gdoc
Ultralight Dark Matter	Peter Graham	ME Monzani	Tom Shutt	gdoc
Astrophysical search for DM	Eric Charles	Peter Graham	ME Monzani	gdoc

Accelerator LOIs:

1. The Heavy Photon Search Experiment:
   https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF6_RF0_Nelson-078.pdf
2. Linac to End Station A (LESA): A Multi-GeV Source of near-CW e-*:
   https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF5_AF0-RF6_RF0_Raubenheimer-122.pdf
3. Linac to End Station A (LESA) as an Electron Test Beam:
   https://www.snowmass21.org/docs/files/summaries/IF/SNOWMASS21-IF9_IF0-AF5_AF0_Natalia_Toro-045.pdf
4. Electron-Nucleon Scattering at LDMX for DUNE:
   https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF6_NF0-RF6_RF0-TF11_TF0-091.pdf
5. Dark Sector Studies With Neutrino Beams:
   https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF3_NF0-RF6_RF0-CF1_CF3-TF9_TF11-148.pdf
6. Search for Boosted Dark Matter in DUNE-like experiments:
   https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF0-NF3_NF0-TF8_TF9_Yun-Tse_Tsai-261.pdf
7. Search for low mass dark matter at ICARUS detector using NuMI beam:
   https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF3_NF0-112.pdf

WIMP-like DM LOIs: LXe

8. The Exploitation of Xe Large Scale Detector Technology for a Range of Future Rare Event Physics Searches: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF2-NF5_NF4-IF8_IF0-CompF0_CompF0-UF2_UF3_Matthew_Szydagis-236.pdf
9. Particle dark matter searches with a G3 liquid-xenon detector: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF0_Matthew_Szydagis-174.pdf
10. Wave-like searches with a G3 liquid xenon detector: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF0_Matthew_Szydagis-200.pdf
11. A 3rd generation liquid xenon TPC dark matter experiment sensitivity to neutrino properties: magnetic moment and 0νββ decay of 136Xe: https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF5_NF0_Matthew_Szydagis-156.pdf
12. Extracting Physics from Natural Neutrinos with G3 Liquid Xenon Detector: https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF4_NF0_Matthew_Szydagis-163.pdf
13. HydroX - Using hydrogen doped in liquid xenon to search for dark matter: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF0_Hugh_Lippincott-106.pdf

WIMP-like solid state, Ultralight DM

14. A Strategy for Low-Mass Dark Matter Searches with Cryogenic Detectors in the SuperCDMS SNOLAB Facility: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF2-NF3_NF10-IF1_IF0-UF3_UF2_SuperCDMS-077.pdf
15. Cryogenic Carbon Detectors for Dark Matter Searches: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF2-NF10_NF0-IF2_IF3_Kurinsky-101.pdf
16. Probing the QCD Axion with DMRadio-m3: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF0-IF1_IF0_Ouellet-217.pdf
17. DMRadio-GUT: Probing GUT-scale QCD Axion Dark Matter: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF0-IF1_IF0_Saptarshi_Chaudhuri-219.pdf
18. Cosmic Axion Spin Precession Experiment (CASPEr-e): https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF0-IF1_IF0_Sushkov-100.pdf
19. DarkQuest and LongQuest at the 120 GeV Fermilab Main Injector: https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF6_RF0_Nhan_Tran-025.pdf
20. Heterodyne Detection of Axion Dark Matter via Superconducting Cavities: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF0-AF5_AF0_Kevin_Zhou-035.pdf

Astrophysical probes: DESI and LSST/Rubin

21. Direct Deflection of Dark Matter: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF2-TF9_TF10-IF1_IF0_Asher_Berlin-049.pdf
22. Next-generation Spectroscopic Surveys with DESI: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF6_CF4_Dawson-041.pdf
23. The Vera C. Rubin Observatory as a Dark Matter Experiment: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF3_CF1-TF9_TF8-CompF2_CompF0_Bechtol-115.pdf
24. The Vera C. Rubin Observatory as a Discovery Facility for Fundamental Physics: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF7_CF4_Chris_Walter-154.pdf
25. Rubin/LSST Black Hole Dark Matter Microlensing: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF3_CF7_Dawson-161.pdf
26. Potential Future Uses of the Rubin Observatory Facility After Completion of the Ten-Year Legacy Survey of Space and Time: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF4_CF0_Steven_Kahn-171.pdf
27. The Rubin/LSST Dark Energy Science Collaboration: Operations during the LSST Survey: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF4_CF3_Gawiser-221.pdf

Gamma-MeV astrophysics and Community LOIs

28. A next-generation LAr TPC-based MeV Gamma ray instrument: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF7_CF1-NF7_NF10-IF8_IF0_Shutt-224.pdf
29. WIMP Dark Matter Candidates with MeV gamma-ray signatures: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF3_CF1_Regina_Caputo-121.pdf
30. Light Dark Matter Candidates with MeV gamma-ray signatures: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF3_CF2_Regina_Caputo-122.pdf
31. Understanding the Galactic Center Gamma-Ray Excess: Observational Prospects: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF0-TF9_TF0_Rebecca_Leane-182.pdf
32. Understanding the Galactic Center Gamma-Ray Excess: Theory Prospects: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF0-TF9_TF0_Rebecca_Leane-183.pdf
33. Facilitating cosmic probes and dark matter searches with improved data access and software tools for multi-wavelength and multi-messenger analyses: https://www.snowmass21.org/docs/files/summaries/CompF/SNOWMASS21-CompF5_CompF7-CF7_CF1_Charles-054.pdf
34. Creating Inclusive Collaborations:

R&D/Computing LOIs

35. Scintillator Extrusions for Mega-detectors: MATHUSLA: https://www.snowmass21.org/docs/files/summaries/IF/SNOWMASS21-IF0_IF0_Jim_Freeman-111.pdf
36. Low-gap charge detection for fundamental physics searches: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF1_CF2-IF1_IF2_Kurinsky-029.pdf
37. Charcoal-based Radon Reduction Systems for Ultra-clean Rare-event Detectors: https://www.snowmass21.org/docs/files/summaries/IF/SNOWMASS21-IF8_IF0-CF1_CF0_Dongqing_Huang-152.pdf
38. Using Metal Organic Frameworks for Krypton and Radon Removal in Low-Background Xenon Detectors: https://www.snowmass21.org/docs/files/summaries/IF/SNOWMASS21-IF8_IF0-UF3_UF0_Brian_Mong-144.pdf
39. Fast Simulations for Noble Liquid Experiments: https://www.snowmass21.org/docs/files/summaries/CompF/SNOWMASS21-CompF2_CompF1-NF1_NF5-CF1_CF2-IF8_IF2_Monzani-085.pdf
40. NEST, The Noble Element Simulation Technique: https://www.snowmass21.org/docs/files/summaries/IF/SNOWMASS21-IF8_IF0-NF5_NF10-CF1_CF0-CompF5_CompF7_Matthew_Szydagis-104.pdf
41. The Future of Machine Learning in Rare Event Searches: https://www.snowmass21.org/docs/files/summaries/CompF/SNOWMASS21-CompF3_CompF2-NF1_NF5-CF1_CF2-IF8_IF3_Monzani-084.pdf

Appendix: non-SLAC axion LOIs

a. ARIADNE (Axion Resonant InterAction Detection Experiment): an NMR-based Axion Search: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF0-RF3_RF0_Andrew_Geraci-130.pdf

b. UP-conversion Loop Oscillator Axion Detectors (UPLOAD): https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF0-IF0_IF1_UPLOAD-067.pdf

c. HAYSTAC – Pioneering the Quantum Frontier: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF0-IF1_IF0_Reina_Maruyama-068.pdf

d. The International Axion Observatory (IAXO) and BabyIAXO Next Generation Helioscope Search for Axion and ALP Dark Matter: https://www.snowmass21.org/docs/files/summaries/CF/SNOWMASS21-CF2_CF0-AF5_AF0_Vogel-126.pdf

e. PASSAT Particle Accelerator helioScopes for Slim Axion-like-particle: https://www.snowmass21.org/docs/files/summaries/NF/SNOWMASS21-NF3_NF0-RF6_RF0-CF1_CF0_Doojin_Kim-016.pdf