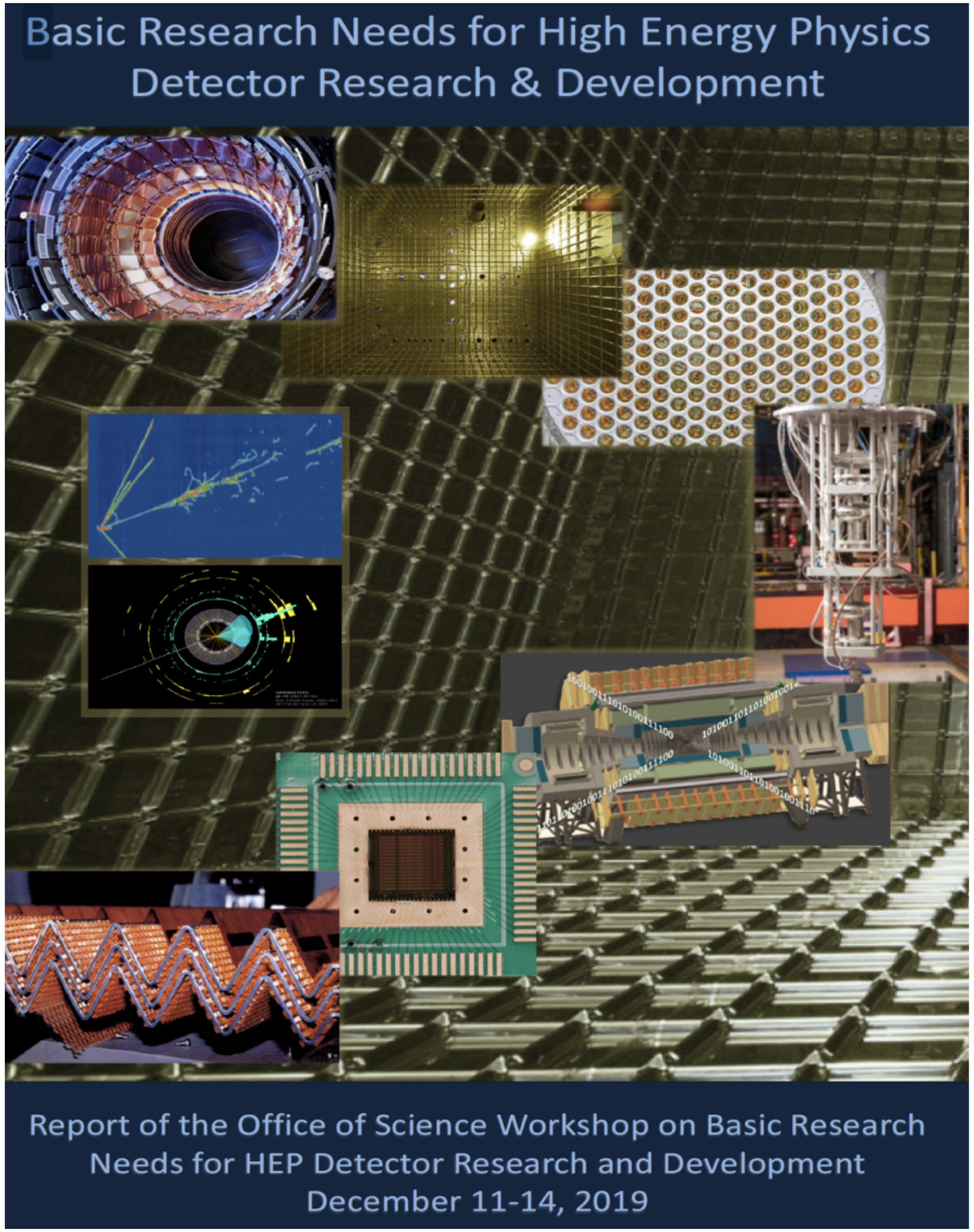

Dark Matter

(as described in the Basic Research Needs for High Energy Physics Detector Research and Development report)

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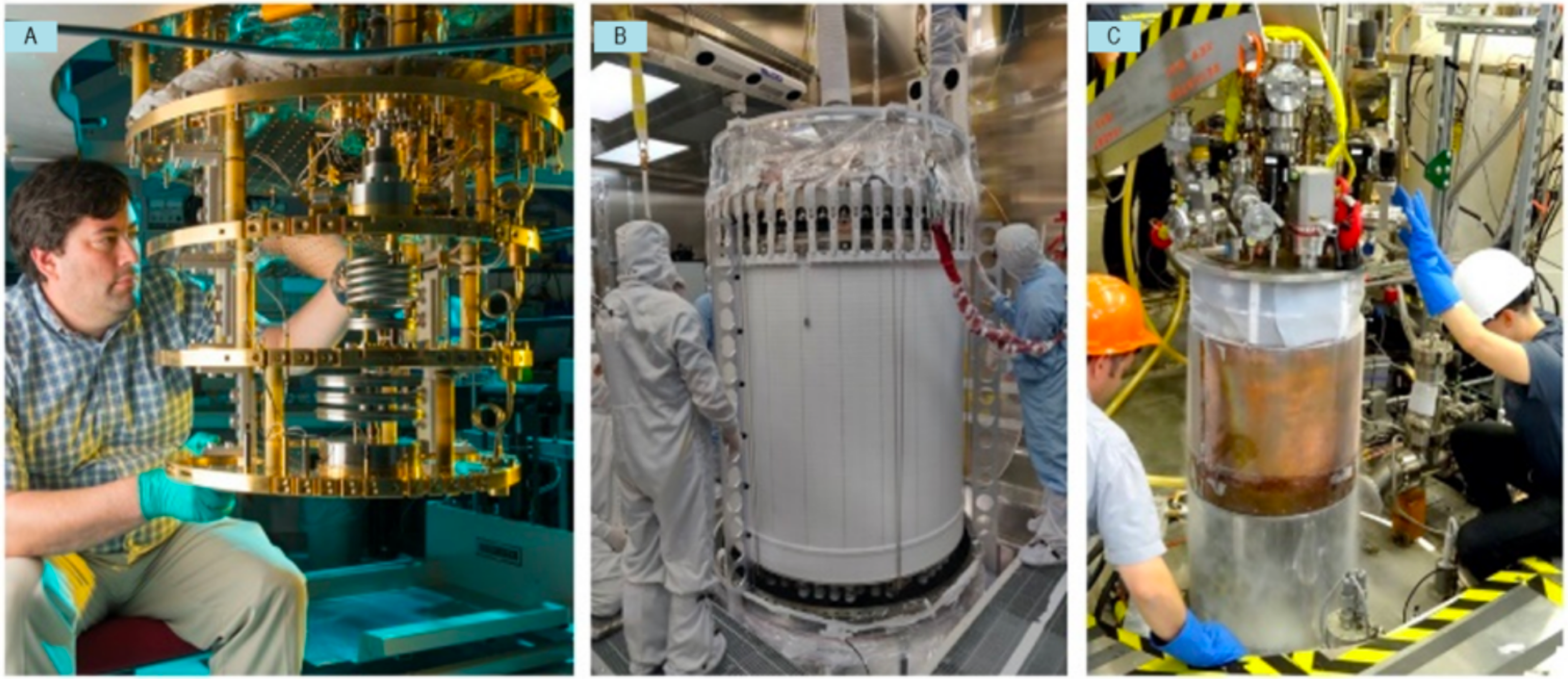
P5 identified the new physics of dark matter as one of six science drivers in its most recent report.

The existence of dark matter is one of the most striking pieces of evidence we have for new physics beyond the Standard Model. Astrophysical observations imply that the known particles of the Standard Model make up only about one-sixth of the total matter in the Universe. The rest is dark matter, presumed to be particles that are all around us and are passing through the Earth. Dark matter represents a bizarre shadow world of fundamental particles that are both omnipresent and largely imperceptible. Discovery of the identity of dark matter would transform the field of particle physics, advancing the understanding of the basic building blocks of the Universe.

Determination of its particle physics properties (mass, interactions) would not only elucidate the nature of the dominant form of matter in our universe, but would likely provide critical clues leading to additional new physics, as well as a deeper understanding of the principles that underpin the workings of our universe.

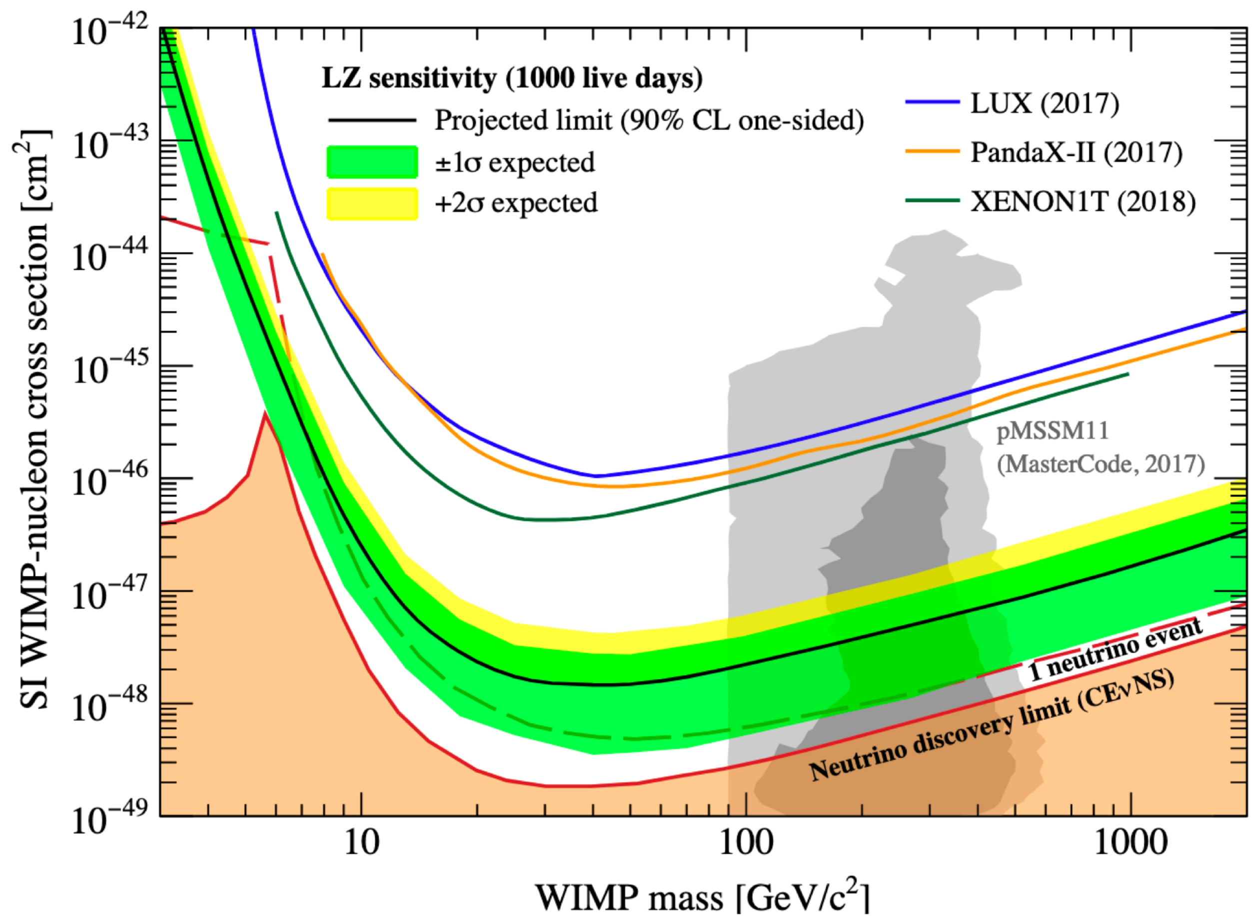
The G2 Experiments



The current generation (G2) experiments include A) SuperCDMS, B) LZ, and C) ADMX
The next generation of experiments (G3) will build upon these technologies.
In addition, there are a large variety of novel detectors currently under development to search for dark matter with mass less than the proton.

Science Driver 1: Sensitivity approaching the neutrino floor to interaction of galactic dark matter particles (1 GeV - 100 TeV)

- Detectors at the 100 kg to 100 tonne scale
- Experiments thrive with some combination of low threshold, low background, and high mass
- Detectors with both spin-independent (SI) and spin-dependent (SD) sensitivity are desired
- Also divided into experiments focused in the > 10 GeV range versus experiments focused on the 1-10 GeV range



From Phys. Rev. D 101, 052002 (2020)

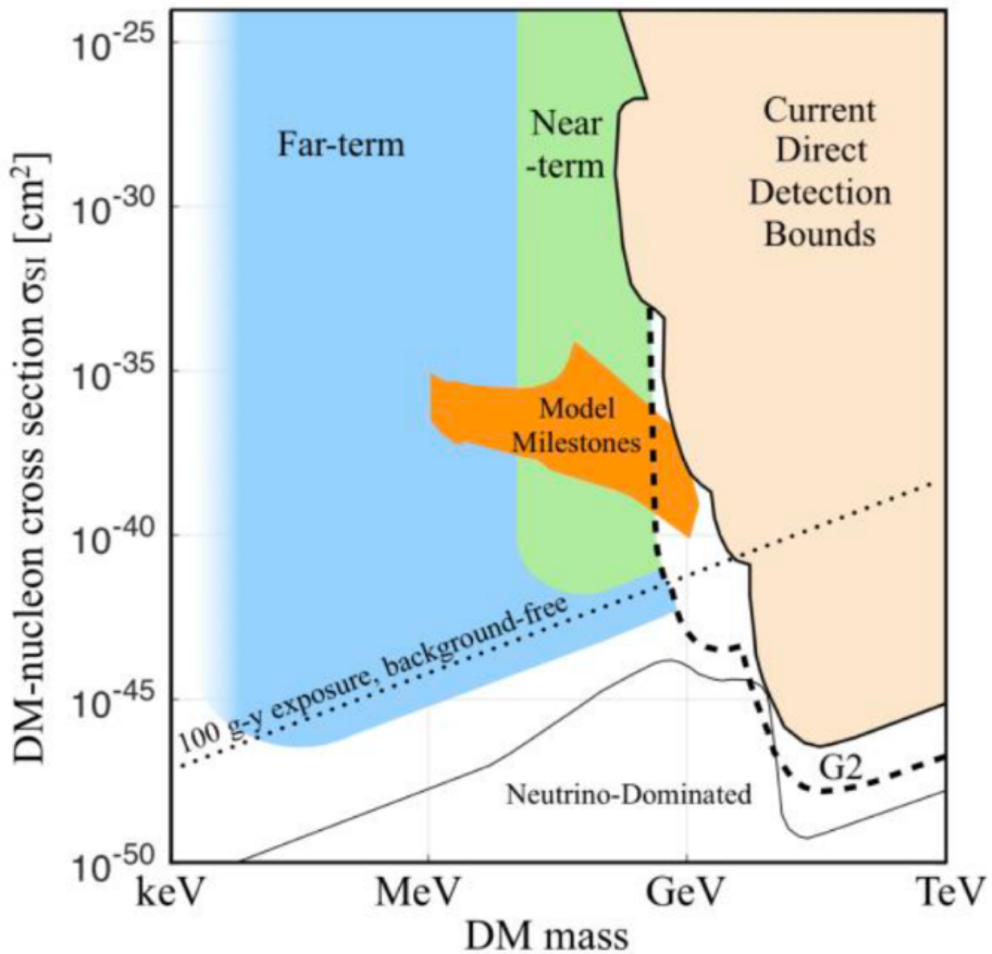
Science Driver 1: Sensitivity approaching the neutrino floor to interaction of galactic dark matter particles (1 GeV - 100 TeV)

Science	**Measurement**	**Technical Requirement (TR)**	**PRD**
Test for dark matter particles with mass >1 GeV	Search for nuclear recoils arising from scattering of >1 GeV dark matter with normal matter via spin-independent and spin-dependent couplings to nucleons	**Mass 1 - 10 GeV** TR 3.1(SI),TR 3.7(SD): Background rate < coherent scattering rate of solar neutrinos TR 3.2(SI), TR 3.8(SD): Target mass ∼100 kg TR 3.3(SI), TR 3.9(SD): Energy Threshold: ∼100 eV	**5**, **6**, **24**, **25**
		Mass > 10 GeV TR 3.4(SI), TR 3.10(SD): Background rate < coherent scattering rate of atmospheric neutrinos TR 3.5(SI), TR 3.11(SD): Target mass ∼100 tonnes TR 3.6(SI), TR 3.12(SD): Energy Threshold: ∼10 keV	**6**, **7**, **9**, **11**, **25**, **26**

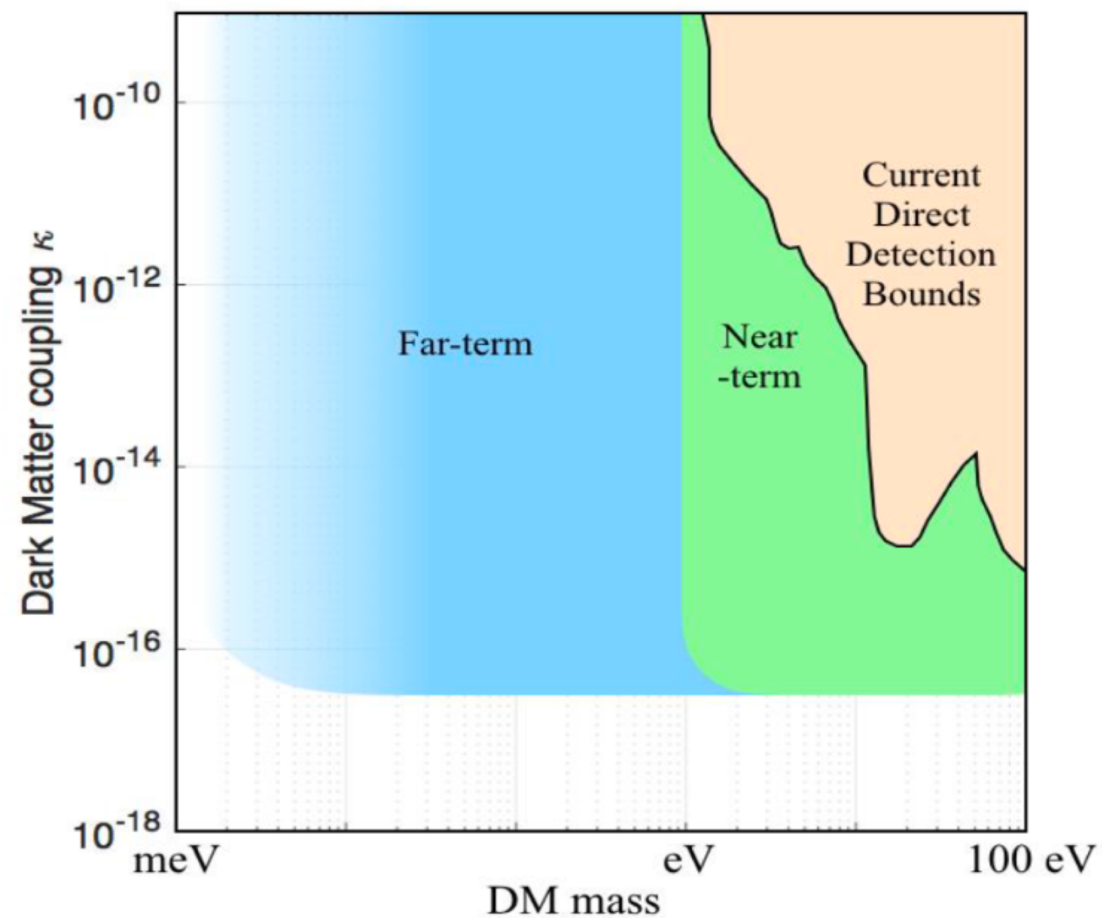
Science Driver 2: Detection of sub-GeV galactic dark matter particles (1 meV – 1 GeV

- Considerable open parameter space; an area of much new theoretical study, technical ferment & innovation
- Detectors at the 1 g to 1 kg scale in the near term, up to 100 kg scale in longer term
- Interactions of interest include DM-nuclear recoils, DM electronic recoils, and DM absorption
- An important technical driver is energy threshold, varying from the eV scale in the short term, down to the meV scale in the longer term.
- Backgrounds are still important, with increasing emphasis on:
  - Instrumental backgrounds such as dark current, slow chemical processes, solid-state relaxation processes, vibration, electromagnetic interference, background light, …
  - Backgrounds from radioactivity entering new regime that includes Thomson and Delbruck scattering from gamma rays, x-ray-material scattering, epithermal neutrons,….

Dark matter – nucleon scattering



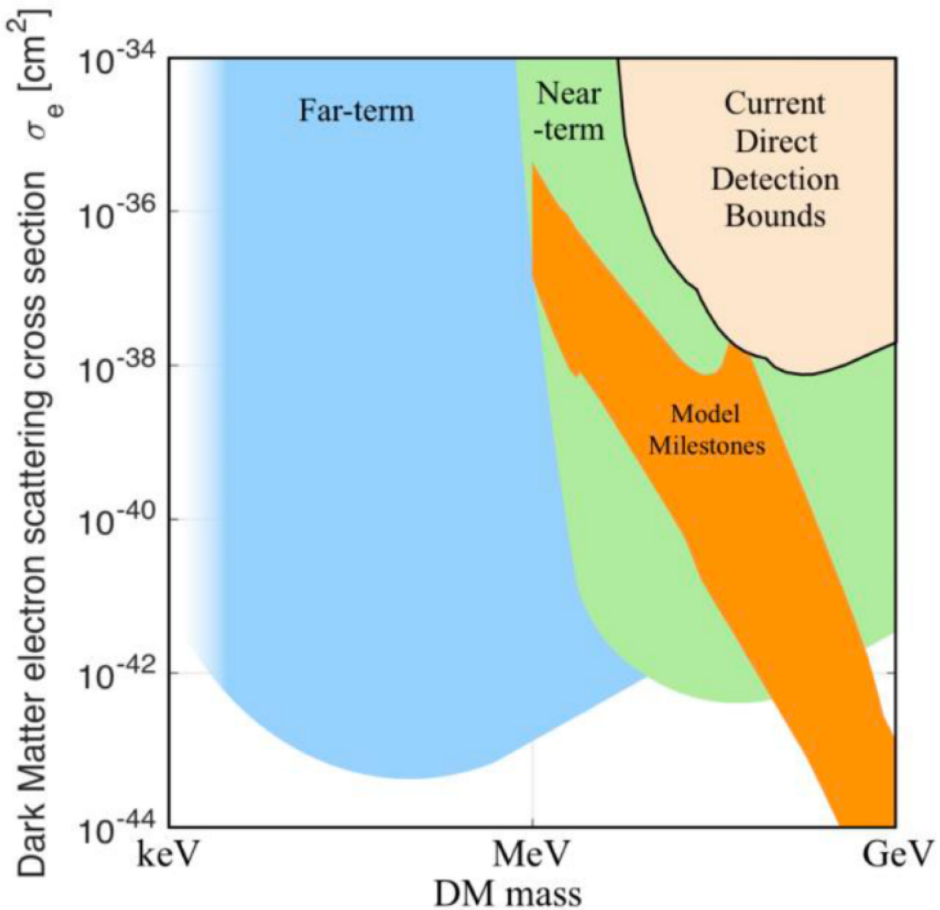
Dark matter absorption



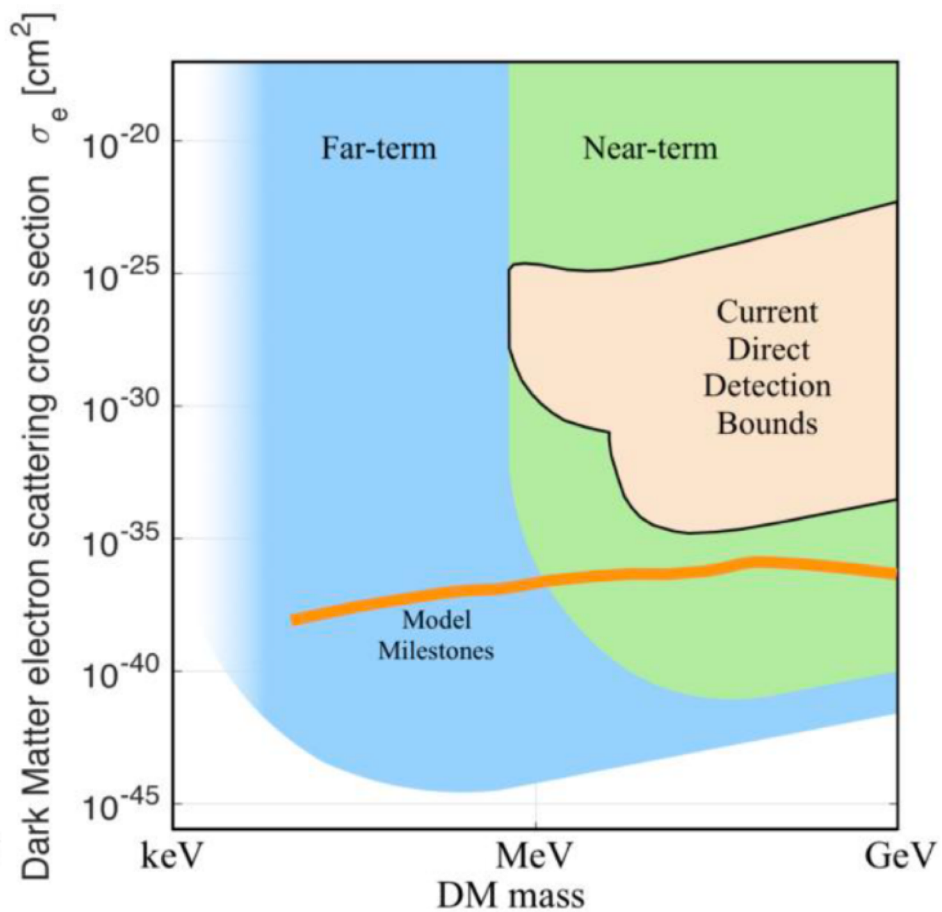
Office of High Energy Physics (HEP) Department of Energy Office of Science. Basic research needs for dark matter small projects new initiatives. Technical report, Dec 2018.

Dark matter – electron scattering

HEAVY MEDIATOR



ULTRALIGHT MEDIATOR



Office of High Energy Physics (HEP) Department of Energy Office of Science. Basic research needs for dark matter small projects new initiatives. Technical report, Dec 2018.

Science Driver 2: Detection of sub-GeV galactic dark matter particles (1 meV – 1 GeV

Science	Measurement	Technical Requirement (TR)	PRD
Test for meV–GeV mass dark matter particles	Search for scattering or absorption of meV–GeV dark matter via coupling to nucleons	**Near Term:** TR 3.13 Threshold ∼1 eV TR 3.14 Target Mass ∼1 kg with negligible background **Long Term:** TR 3.15 Threshold ∼1 meV TR 3.16 Target Mass ∼100 kg with negligible background	**5**, **6**, **11**, **14**, **24**, **25**, **26** **5**, **6**, **14**, **25**, **26**
Test for meV–GeV mass dark matter particles	Search for scattering of meV–GeV dark matter with normal matter via coupling to electrons	**Near Term:** TR 3.17 Threshold ∼1 eV TR 3.18 Target Mass ∼1 kg with negligible background **Long Term:** TR 3.19 Threshold ∼1 meV TR 3.20 Target Mass ∼100 kg with negligible background	**5**, **6**, **11**, **14**, **24**, **25**, **26** **6**, **14**, **25**, **26**

Science Driver 3:
Detection of galactic dark matter waves (10^{-22} to 10^{-1} eV)

- Considerable open parameter space; an area of much new theoretical study, technical ferment & innovation
- Focus on the QCD axion, which is very strongly theoretically motivated, but also sensitive to a broad range of bosonic dark matter candidates.
- Technologies include microwave cavities, lumped circuits, magnetic resonance, and atom interferometers.
- Tremendous technical connection with quantum information methods, AMO.
- Technologies can be imported from these communities, and developments from the high energy physics may be useful to these communities in turn, and training the quantum information workforce.

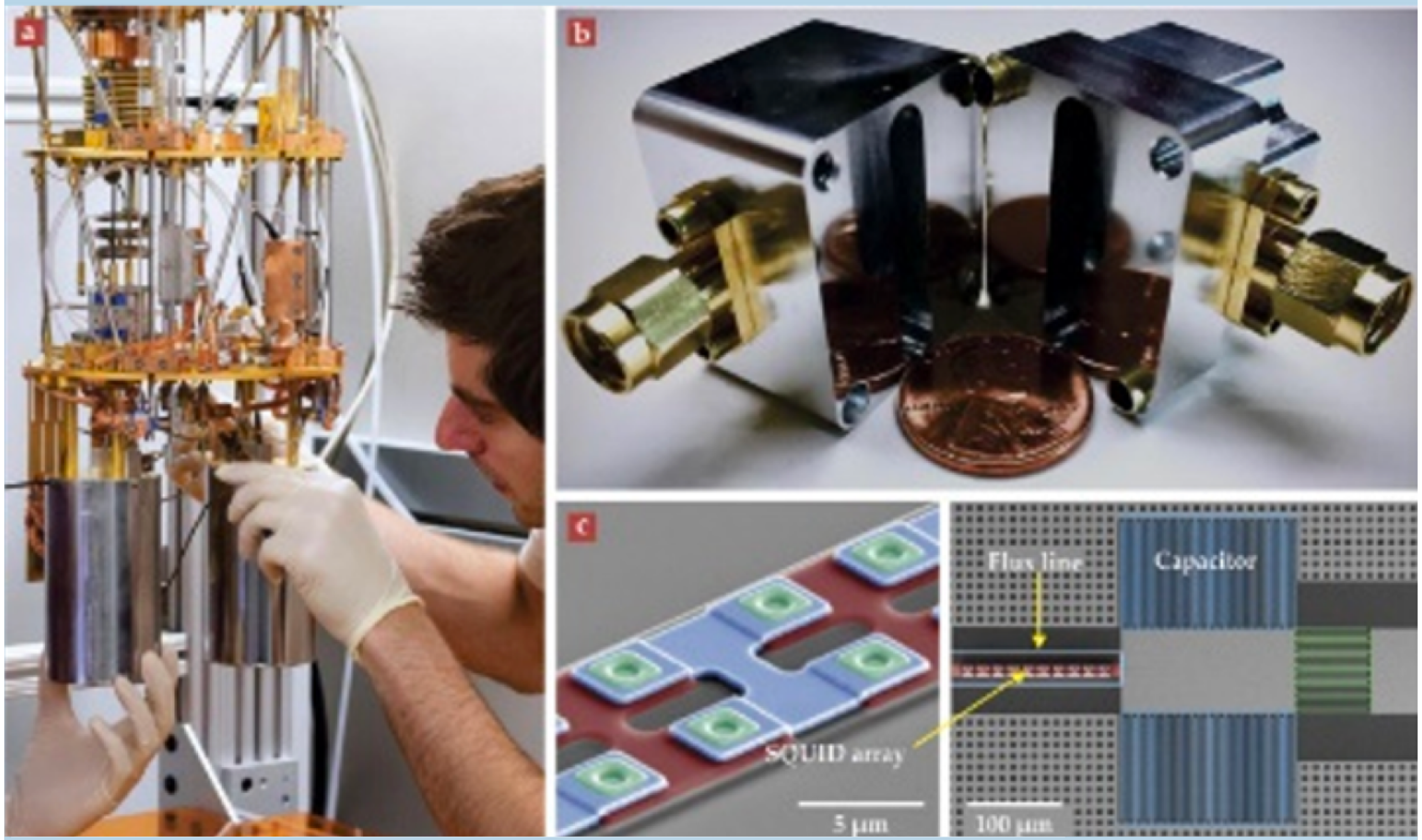
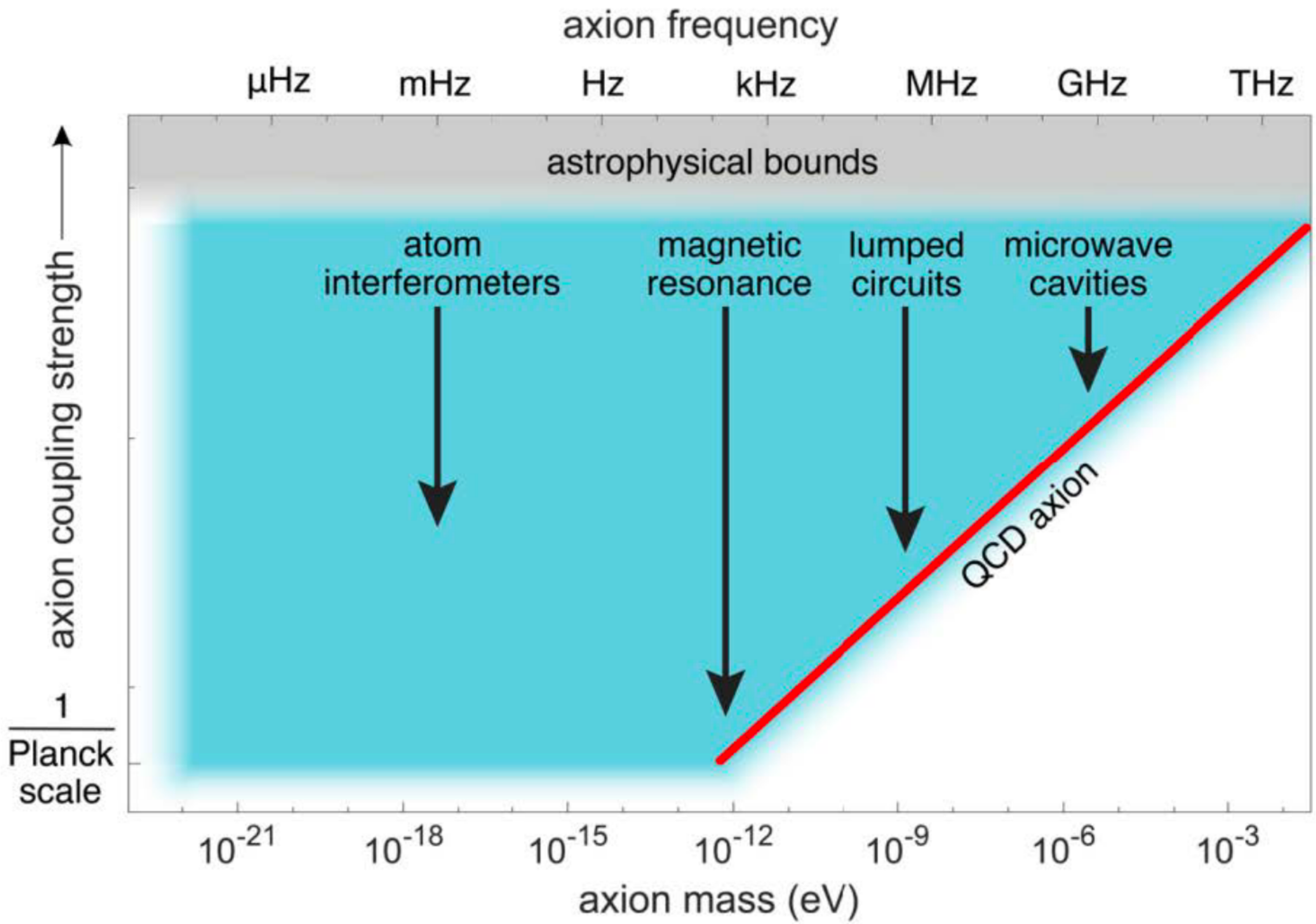


Figure IV: Experimental prototypes. (a) Researchers assemble the two Josephson parametric amplifiers in this squeezed-state receiver for the HAYSTAC experiment. (b) The 7.1 GHz aluminum cavity for the squeezed-state receiver is split open. (c) This microphotograph shows a Josephson parametric amplifier composed of an array of superconducting quantum interference devices (SQUIDs). (Photographs courtesy of Dan Palken.) Published in: Karl van Bibber; Konrad Lehnert; Aaron Chou; *Physics Today* **72,** 48-55 (2019), DOI: 10.1063/PT.3.4227 Copyright © 2019 American Institute of Physics


axion frequency
μHz
mHz
Hz
kHz
MHz
GHz
THz
astrophysical bounds
atom interferometers
magnetic resonance
lumped circuits
microwave cavities
QCD axion
axion coupling strength
1 / Planck scale
10^-21
10^-18
10^-15
10^-12
10^-9
10^-6
10^-3
axion mass (eV)

Science Driver 3:
Detection of galactic dark matter waves (10^{-22} to 10^{-1} eV)

Science	Measurement	Technical Requirement (TR)	PRD
Test for peV–neV QCD axion dark matter	Search for peV–neV QCD axion dark matter via axion-nucleon coupling with nuclear magnetic resonance	**Near Term:** TR 3.21 $P \geq 0.05$ TR 3.23 $N\tau = 10^{24}$ sec.	**12, 13, 15**
		Long Term: TR 3.22 $P \geq 0.3$ TR 3.24 $N\tau = 10^{25}$ sec.	**12, 13, 15**
Test for neV–μeV QCD axion dark matter	Search for neV–μeV QCD axion dark matter using axion-photon conversion in lumped-element electromagnetic resonators	**Near Term:** TR 3.25 $Q_L \geq 10^6$ GeV TR 3.27 $\eta \leq 20$ TR 3.29 $BV \geq 4\,\mathrm{T}\cdot\mathrm{m}^3$	**12, 15**
		Long Term: TR 3.26 $Q_L \geq 10^8$ TR 3.28 $\eta \leq 0.1$ TR 3.30 $BV \geq 10\,\mathrm{T}\cdot\mathrm{m}^3$	**12, 15**
Test for μeV–meV QCD axion dark matter	Search for μeV–meV QCD axion dark matter using axion-photon conversion in cavity electromagnetic resonators	**Near Term:** TR 3.31 $Q_C \geq 10^5$ TR 3.33 $\eta \leq 1$ TR 3.35 $B \geq 10\,\mathrm{T}$, $V \geq 100l$	**12, 15**
		Long Term: TR 3.32 $Q_C \geq 10^6$ TR 3.34 $\eta \leq 10^{-6}$ TR 3.36 $B \geq 30\,\mathrm{T}$, $V \geq 1l$	**12, 15**

Science Driver 3:
Detection of galactic dark matter waves (10^{-22} to 10^{-1} eV)

Science	**Measurement**	**Technical Requirement (TR)**	**PRD**
Search for 10 μeV–10 meV QCD axions and ALPs (not necessarily dark matter)	Test for fifth forces via nuclear magnetic resonance	**Near Term:** TR 3.37 $P \geq 0.5$ TR 3.39 $n\tau = 10^{24}$ sec.cm^{-3} TR 3.41 $V = 10^3\,\lambda_a$	**12**, **13**, **15**
		Long Term: TR 3.38 $P \geq 0.7$ TR 3.40 $n\tau = 10^{27}$ sec.cm^{-3} TR 3.42 $V = 10^4\,\lambda_a$	**12**, **13**, **15**
Search for hidden photons (not necessarily dark matter) 10^{-12} eV - 10^{-4} eV	"Light shining through walls" experiments with electromagnetic resonators	**Near Term:** TR 3.43 $Q \geq 10^{11}$	**12**, **15**
		Long Term: TR 3.44 $Q \geq 10^{13}$	**12**, **15**

Science Driver 4:
Detection of dark matter particle annihilations and decays

- If the dark matter particle has mass above the TeV scale, indirect detection techniques, where the gamma rays, antiprotons, positrons, neutrinos, and other particles that are produced in the annihilations or decays of dark matter particles can be detected,
- An important target is to reach the canonical thermally-averaged cross-section expected for WIMP dark matter, all the way up to the 100 TeV scale.
- Substantial overlap with detector technologies from collider-based particle physics. Tracking,
- Strong need for cheap photodetectors with sufficiently high quantum efficiency.

Science Driver 4:
Detection of dark matter particle annihilations and decays

Science	Measurement	Technical Requirement (TR)	PRD
Test for <1 TeV dark matter that annihilates or decays	Search for annihilation or decay products (gamma rays, antimatter) with space-based or balloon-based experiments	TR 3.45 Area ~30 m^2 str with all sky sensitivity TR 3.46 angular resolution ~few arcminutes	26 20
Test for 1–200 TeV dark matter that annihilates or decays	Search for dark matter annihilation or decay products with ground-based experiments	TR 3.47 Area ~221,000 m^2 with varying fill factors & wide field of view TR 3.48 SiPM QE > 40-50% in UV/optical TR 3.49 SiPM dark rate <1 KHz/mm^2 at 5° C TR 3.50 SiPM dynamic range from 1 PE to 100 PE / mm^2 TR 3.51 timing < 0.5 nsec TR 3.52 factor ~3 increase in scintillating light yield (1 PE for 6 MeV)	11, 26 7 7 7 7 11

Timeline: Dark Matter → Technologies to Discovery

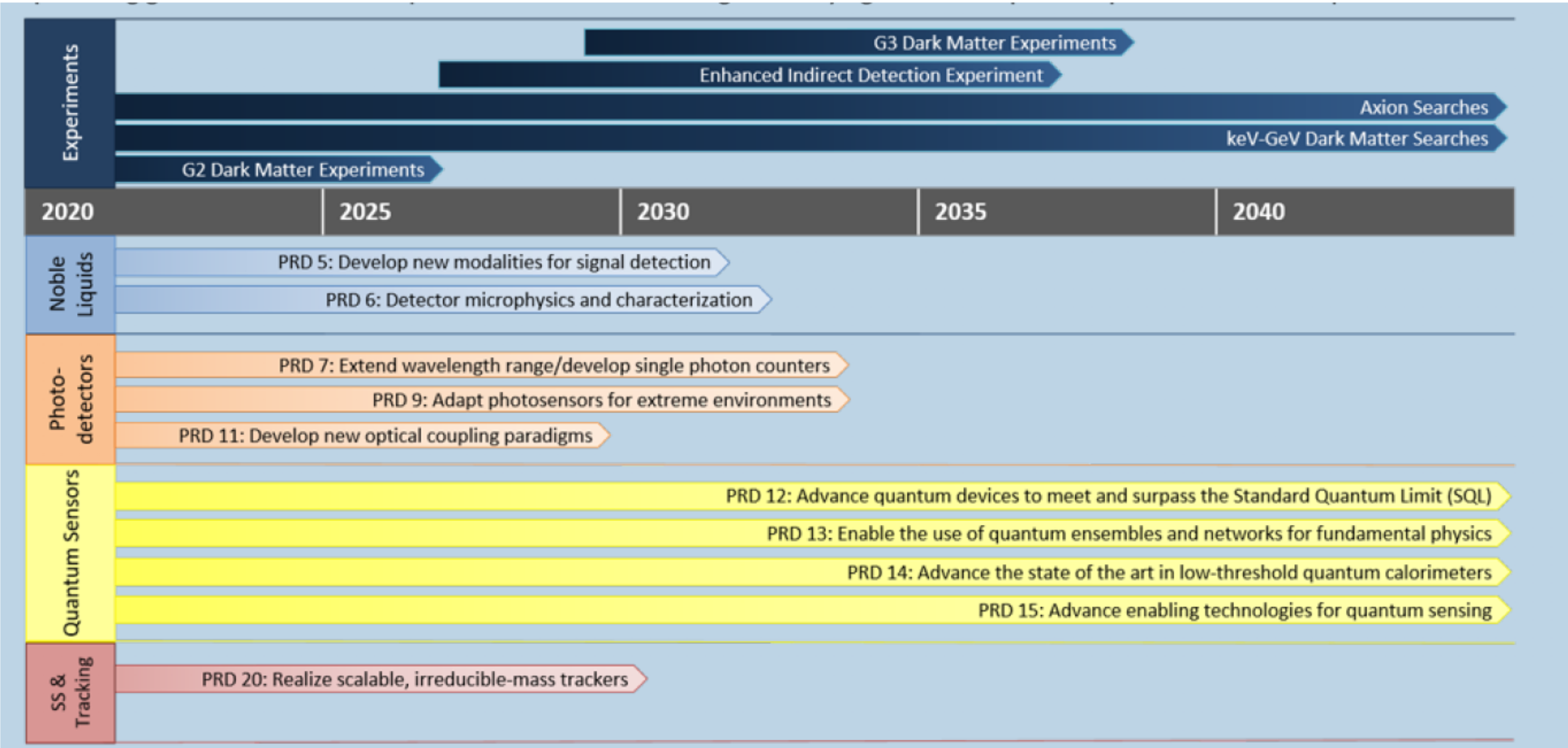


Figure II: Dark Matter Timeline

Dark Matter: Preparing for Discovery

Tremendous advances in technology have lead to significant progress in excluding large areas of dark matter parameter space. However, despite this progress, the constituents of dark matter remain unknown. We outlined an ambitious physics program along four major thrusts:

- Searching for WIMP dark matter towards the neutrino floor
- Searching for particle dark matter with low masses
- Searching for wave-like dark matter
- Searching for the annihilation or decay products of dark matter interactions

R&D into new technologies is required in order to achieve the science program outlined here.
With adequate support, each of these programs has the potential to lead to a major discovery in the coming decades.

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