Direct Detection
Dark Matter Searches

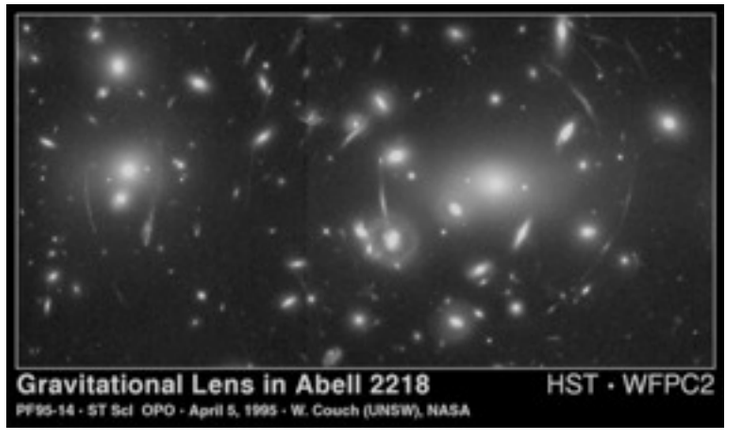
Reina Maruyama
Yale University

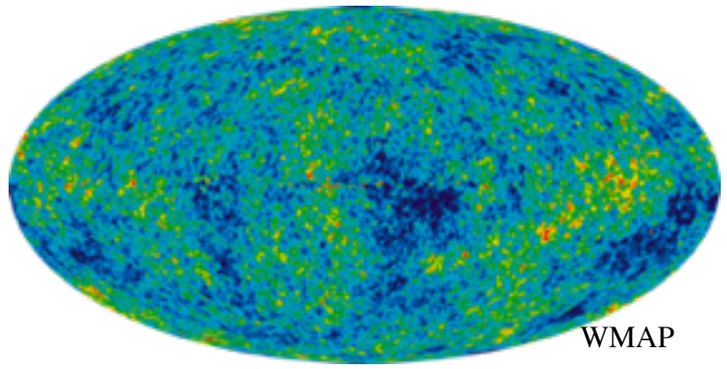
4th Uppsala workshop on Particle Physics with Neutrino Telescopes (PPNT19)
7 - 9 October 2019

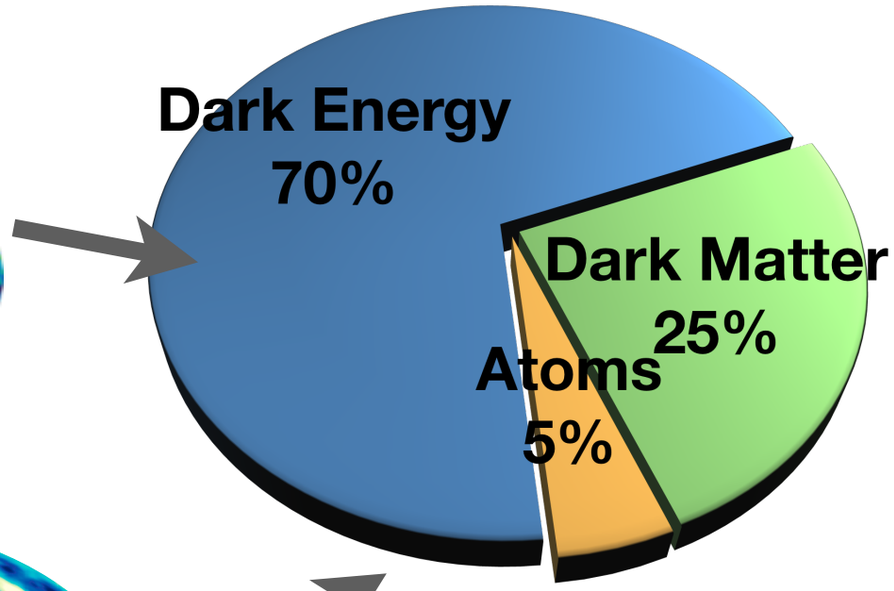
Yale

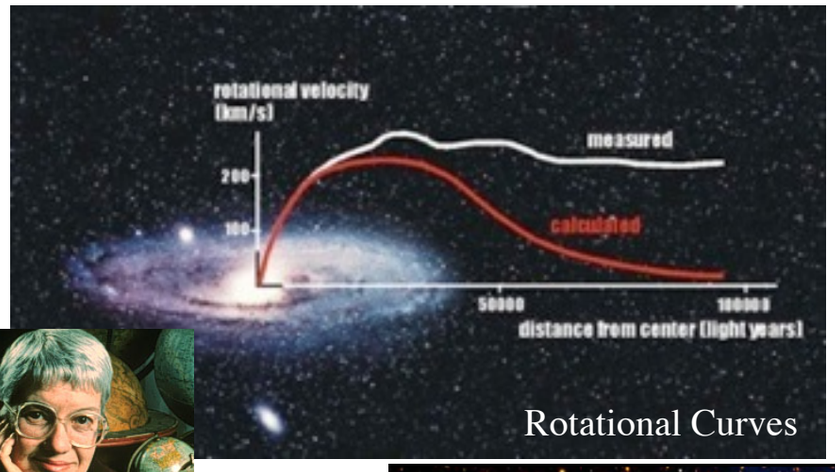
Wright Laboratory

Evidence for Dark Matter

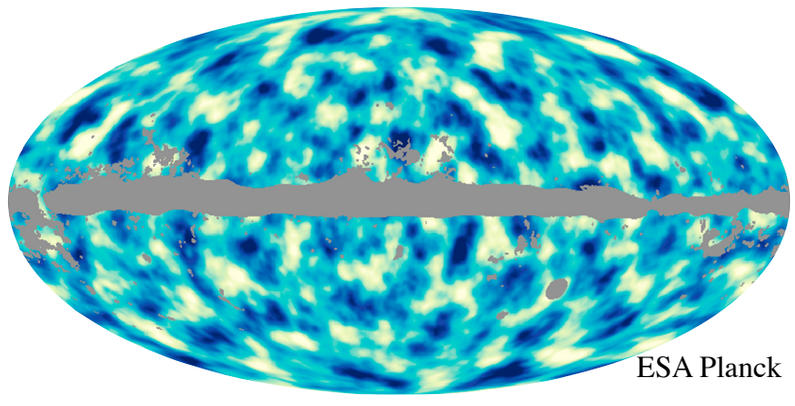



WMAP



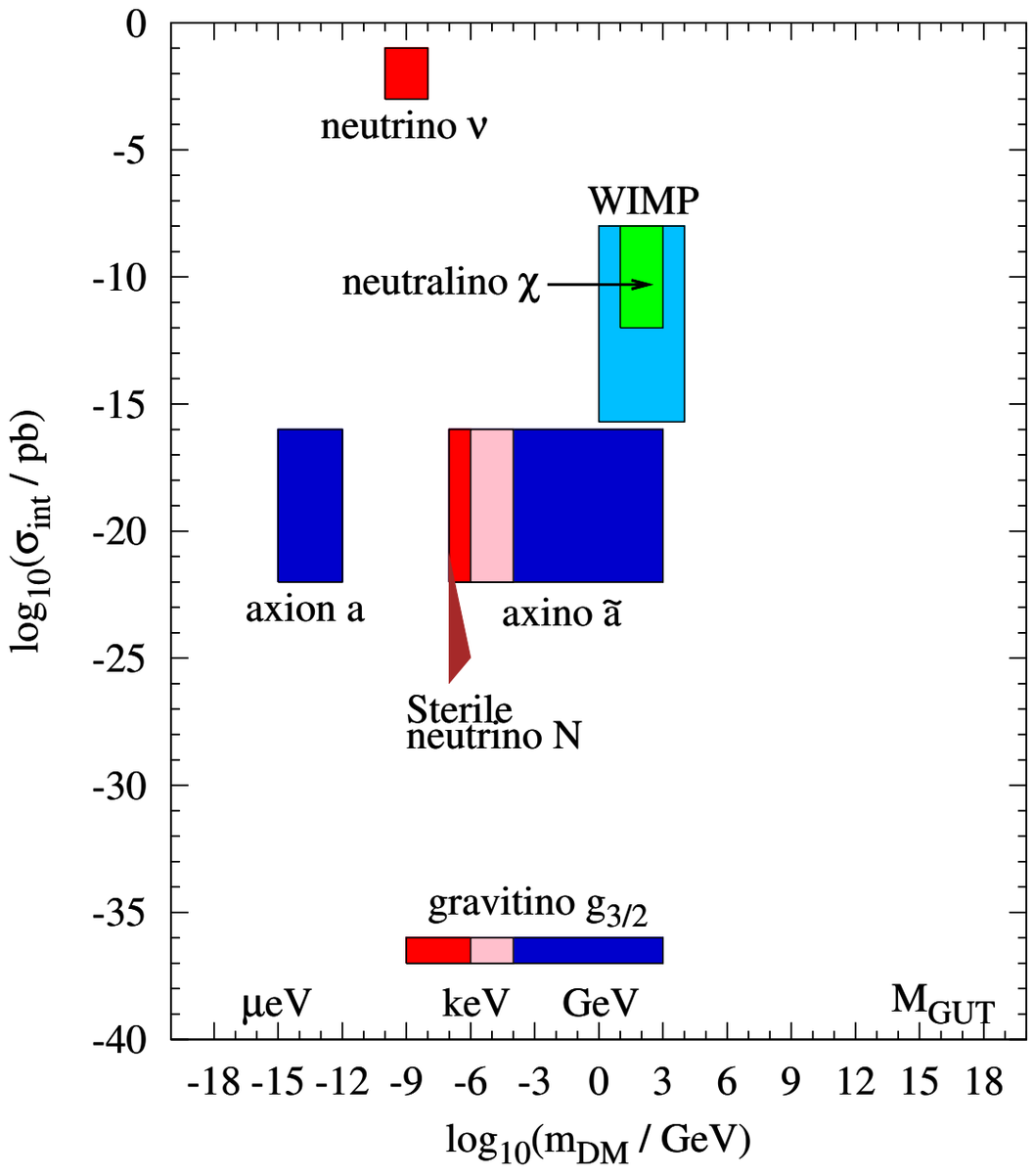


Rotational Curves


ESA Planck

All consistent with ~25% dark matter

Strongly Motivated Dark Matter Candidates



Roszkowski, Sessolo & Trojanowski
Rep. Prog. Phys. **81** (2018) 066201

Leading Search Candidates:

WIMPs: Weakly Interacting Massive Particles

- mass of 1 GeV – 10 TeV
- weak scale cross sections results in observed abundance
- DAMA, CDMS, LUX/LZ, XENON, PICO, DarkSide, PandaX, …
- Recent developments for low-mass …

Axions

- mass ~10^{-3} – 10^{-6} eV
- Arises in the Peccei-Quinn solution to the strong-CP problem
- ADMX, HAYSTAC, Radio-DM, ABRA, CASPEr, …

First publication on an underground experimental search for cold dark matter

Volume 195, number 4 PHYSICS LETTERS B 17 September 1987

LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

S.P. AHLEN [a], F.T. AVIGNONE III [b], R.L. BRODZINSKI [c], A.K. DRUKIER [d,e], G. GELMINI [f,g,1] and D.N. SPERGEL [d,h]

[a] *Department of Physics, Boston University, Boston, MA 02215, USA*
[b] *Department of Physics, University of South Carolina, Columbia, SC 29208, USA*
[c] *Pacific Northwest Laboratory, Richland, WA 99352, USA*
[d] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
[e] *Applied Research Corp., 8201 Corporate Dr , Landover MD 20785, USA*
[f] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[g] *The Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[h] *Institute for Advanced Study, Princeton, NJ 08540, USA*

Received 5 May 1987

An ultralow background spectrometer is used as a detector of cold dark matter candidates from the halo of our galaxy Using a realistic model for the galactic halo, large regions of the mass–cross section space are excluded for important halo component particles. In particular, a halo dominated by heavy standard Dirac neutrinos (taken as an example of particles with spin-independent Z^0 exchange interactions) with masses between 20 GeV and 1 TeV is excluded. The local density of heavy standard Dirac neutrinos is <0.4 GeV/cm^3 for masses between 17.5 GeV and 2 5 TeV, at the 68% confidence level.

Ahlen et al. Phys. Lett. B **195**, 603 (1987)

First publication on an underground experimental search for cold dark matter

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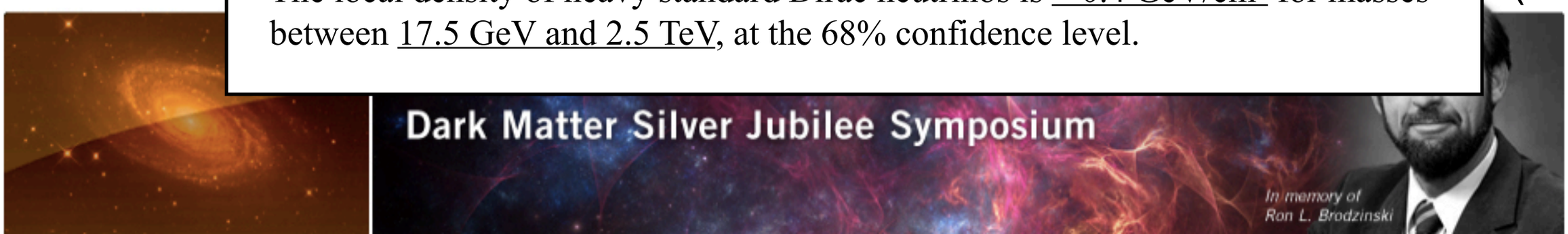
3 (1987)

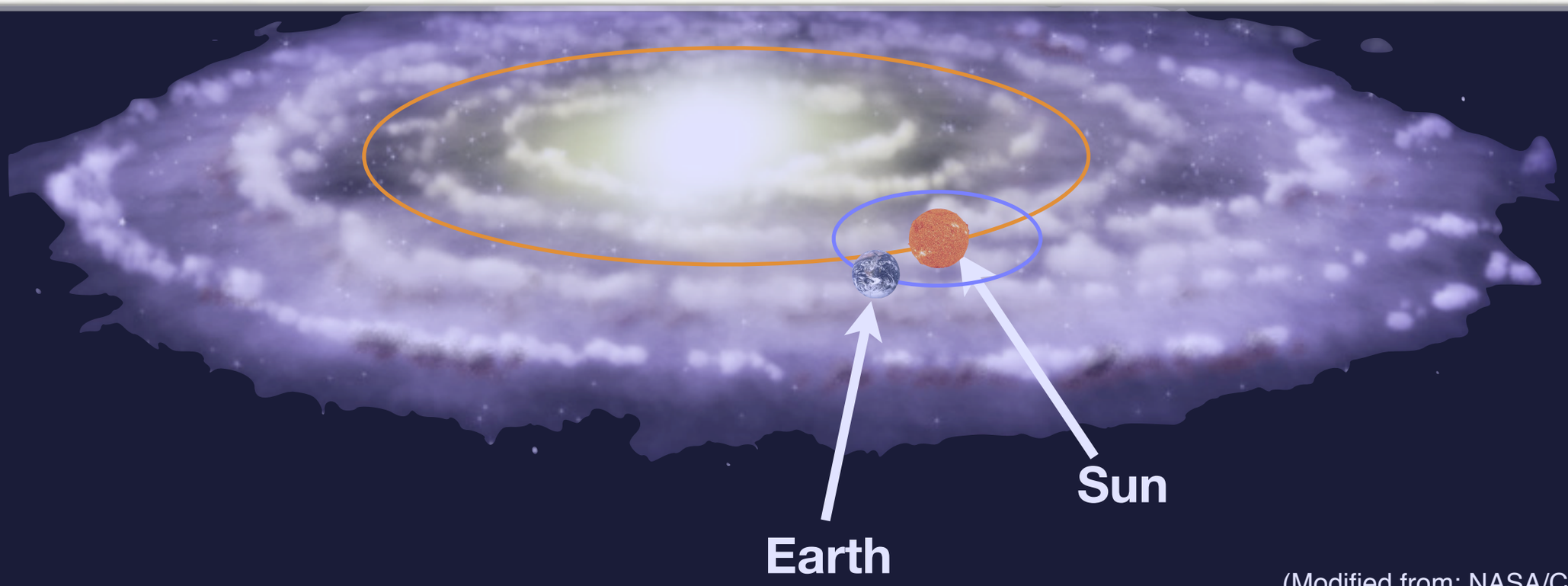


Direct Detection Dark Matter Search Strategies

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)



(Modified from: NASA/CXC/M.Weiss)

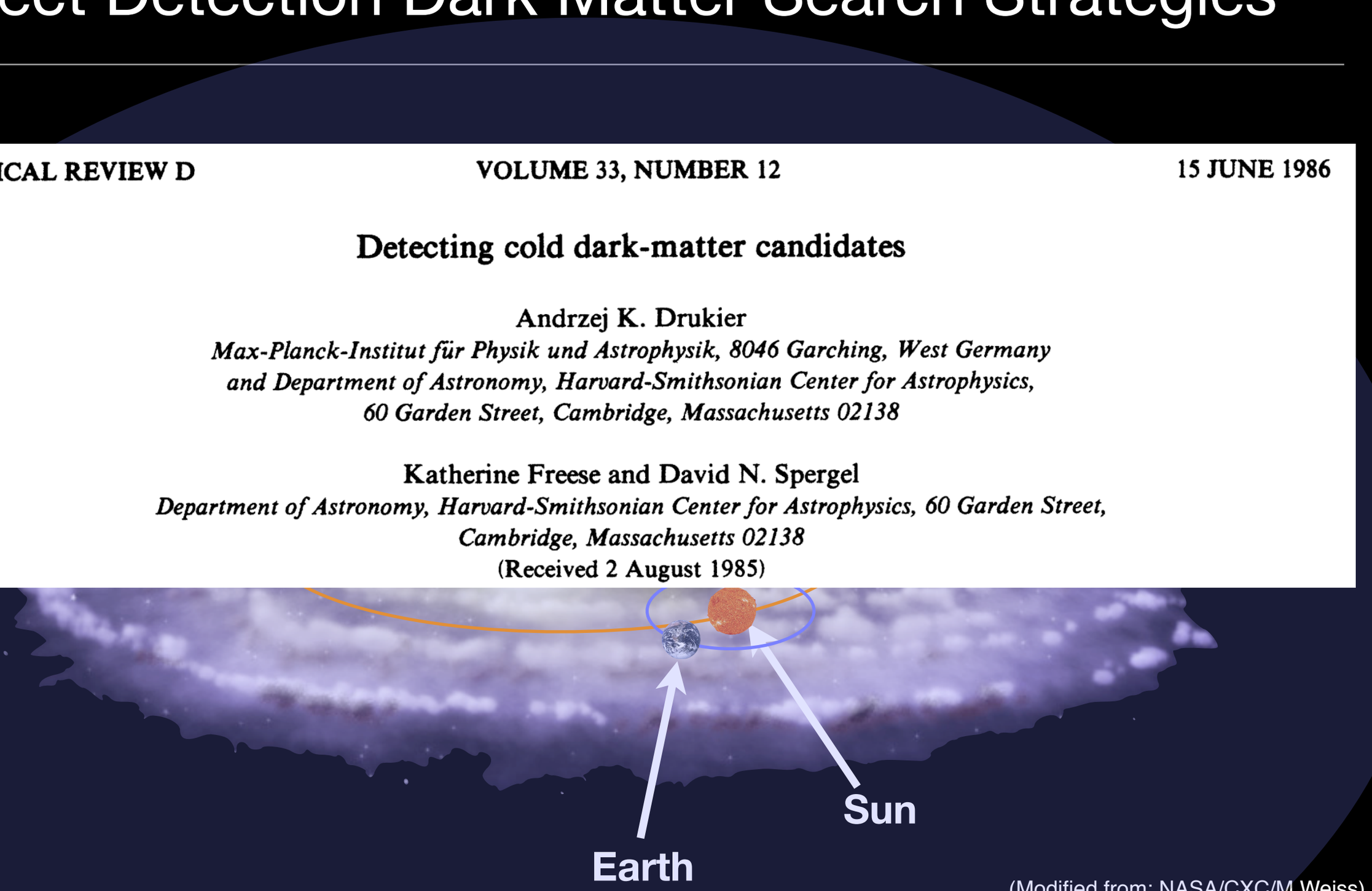
Direct Detection Dark Matter Search Strategies

PHYSICAL REVIEW D VOLUME 33, NUMBER 12 15 JUNE 1986

Detecting cold dark-matter candidates

Andrzej K. Drukier
Max-Planck-Institut für Physik und Astrophysik, 8046 Garching, West Germany
and Department of Astronomy, Harvard-Smithsonian Center for Astrophysics,
60 Garden Street, Cambridge, Massachusetts 02138

Katherine Freese and David N. Spergel
Department of Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street,
Cambridge, Massachusetts 02138
(Received 2 August 1985)



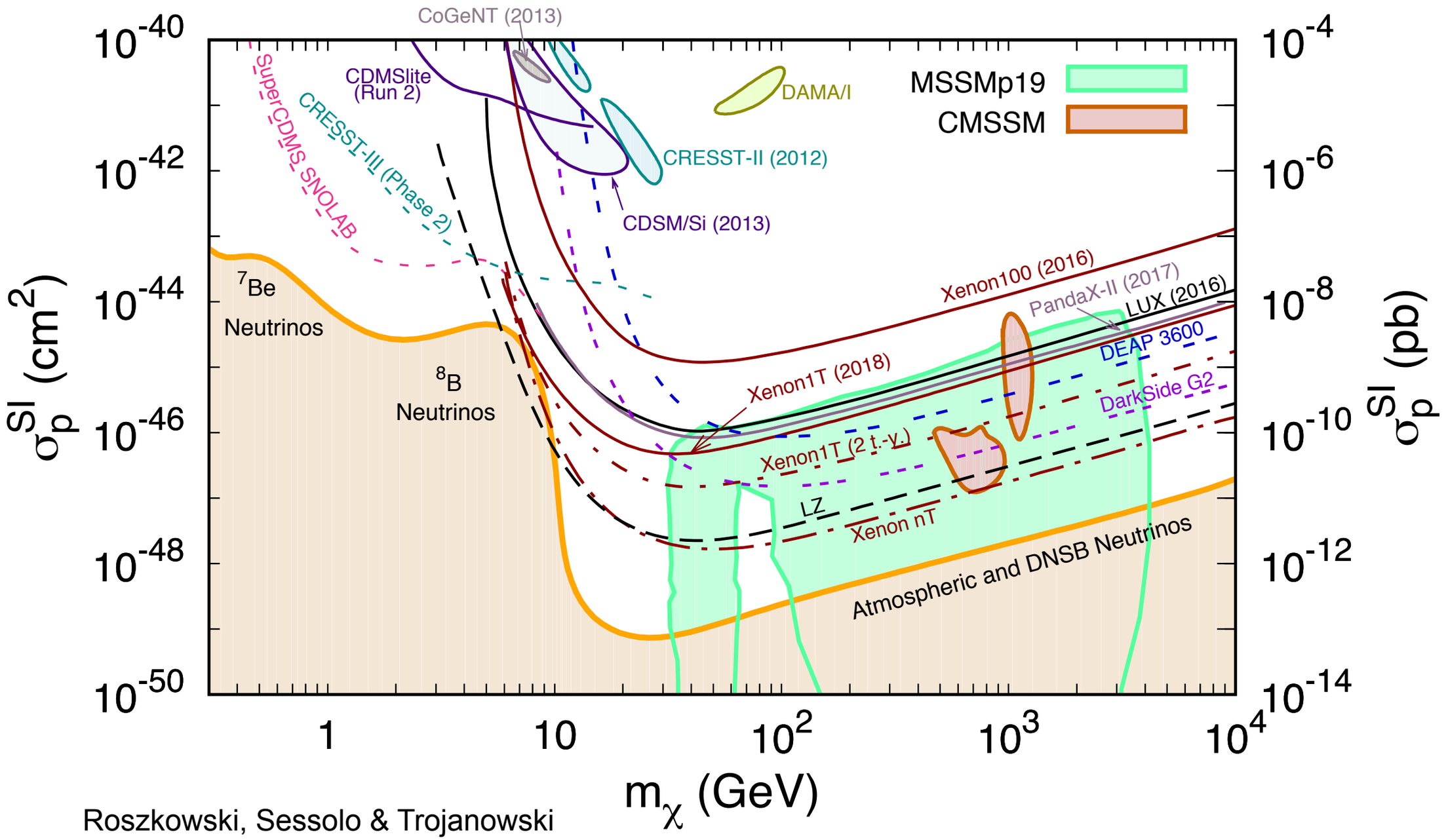
(Modified from: NASA/CXC/M.Weiss)

Drukier, Freese & Spergel PRD**33** 3495 (1986)

WIMP Searches Around the World

Yamashita, TAUP 2019

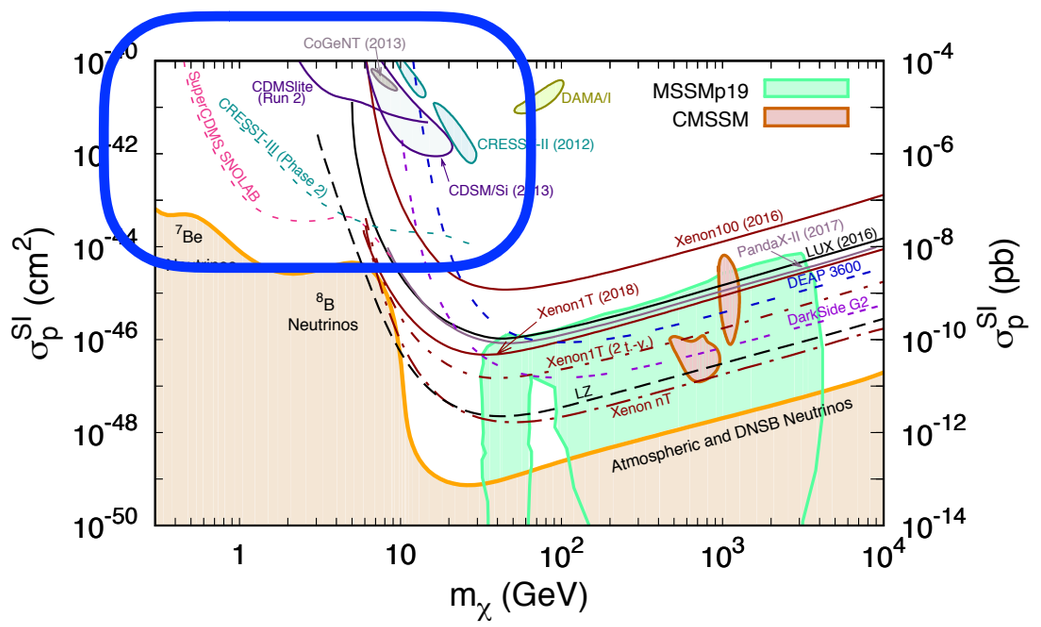
Current and Upcoming Experimental Limits



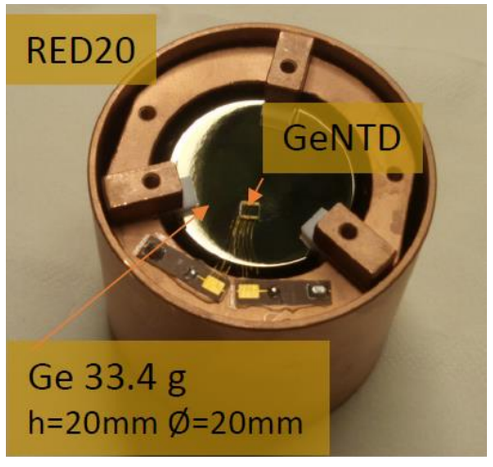
Roszkowski, Sessolo & Trojanowski
Rep. Prog. Phys. **81** (2018) 066201

Cryogenic Detectors: Low Mass Searches

- Precision instrument
- great energy resolution & threshold
- Hard to scale up, grams -> ~30 kg
- Most sensitive to low-masses

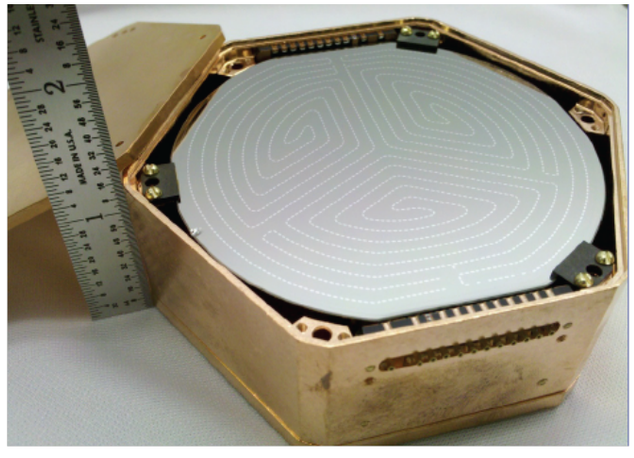


EDELWEISS



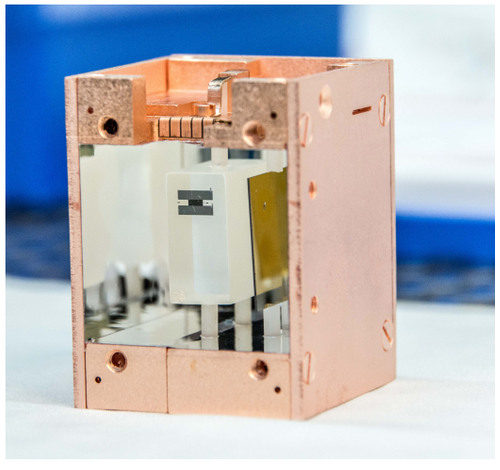
arXiv:1901.03588

SuperCDMS



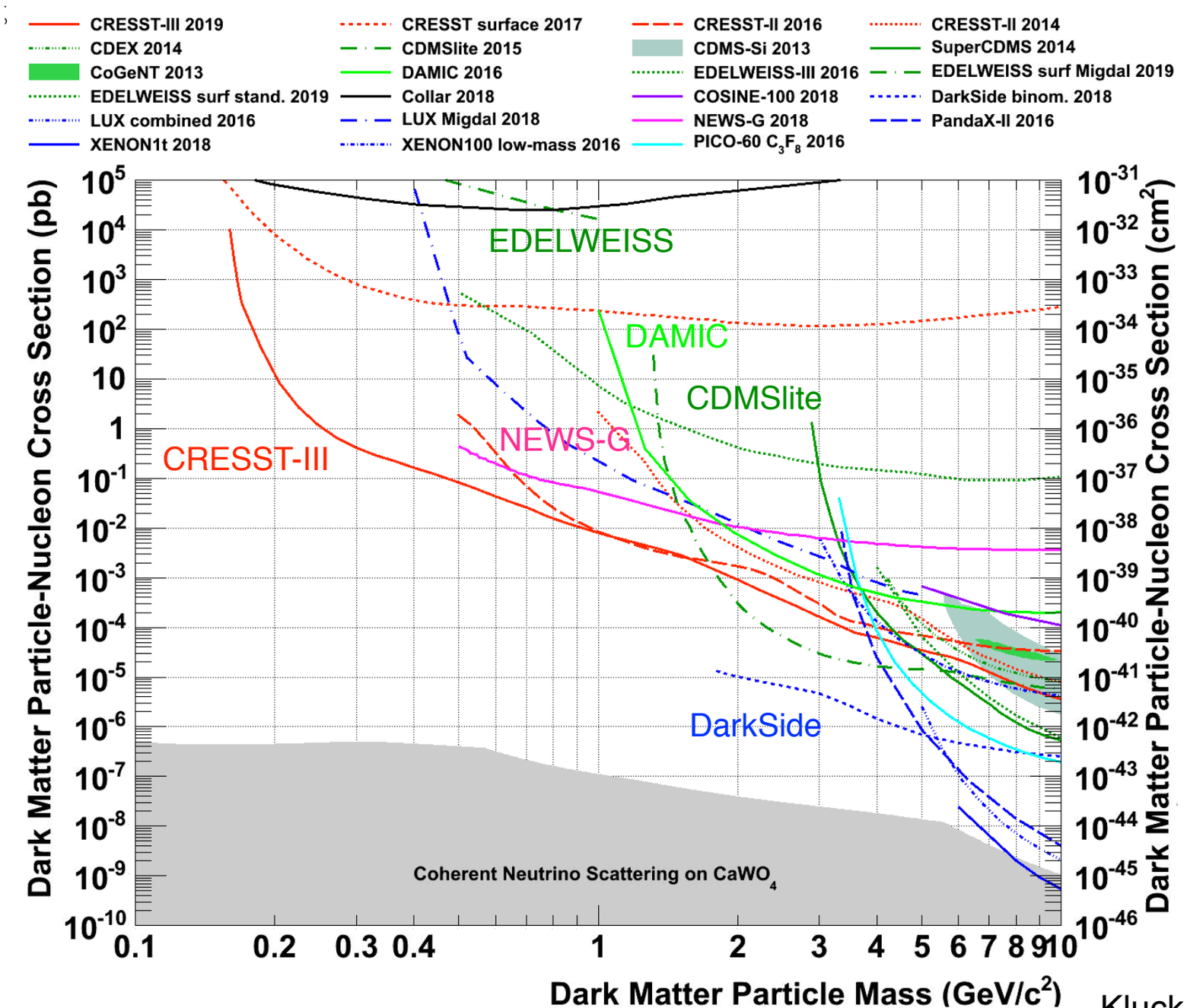
PRD **99** 062001

CRESST-III



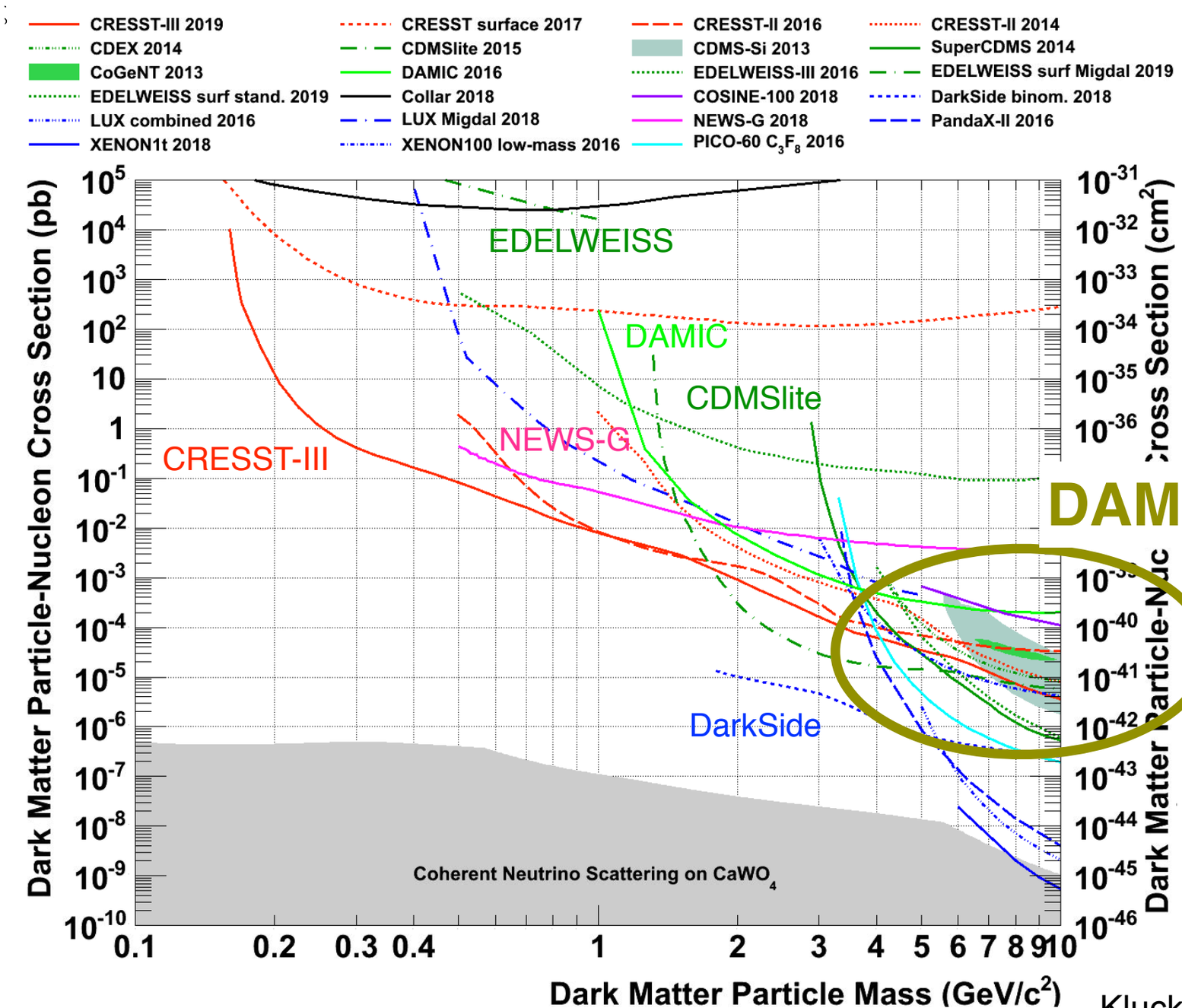
arXiv:1711.07692

Spin-Independent Limits < 10 GeV



Kluck, CRESST-III TAUP 2019

Spin-Independent Limits < 10 GeV



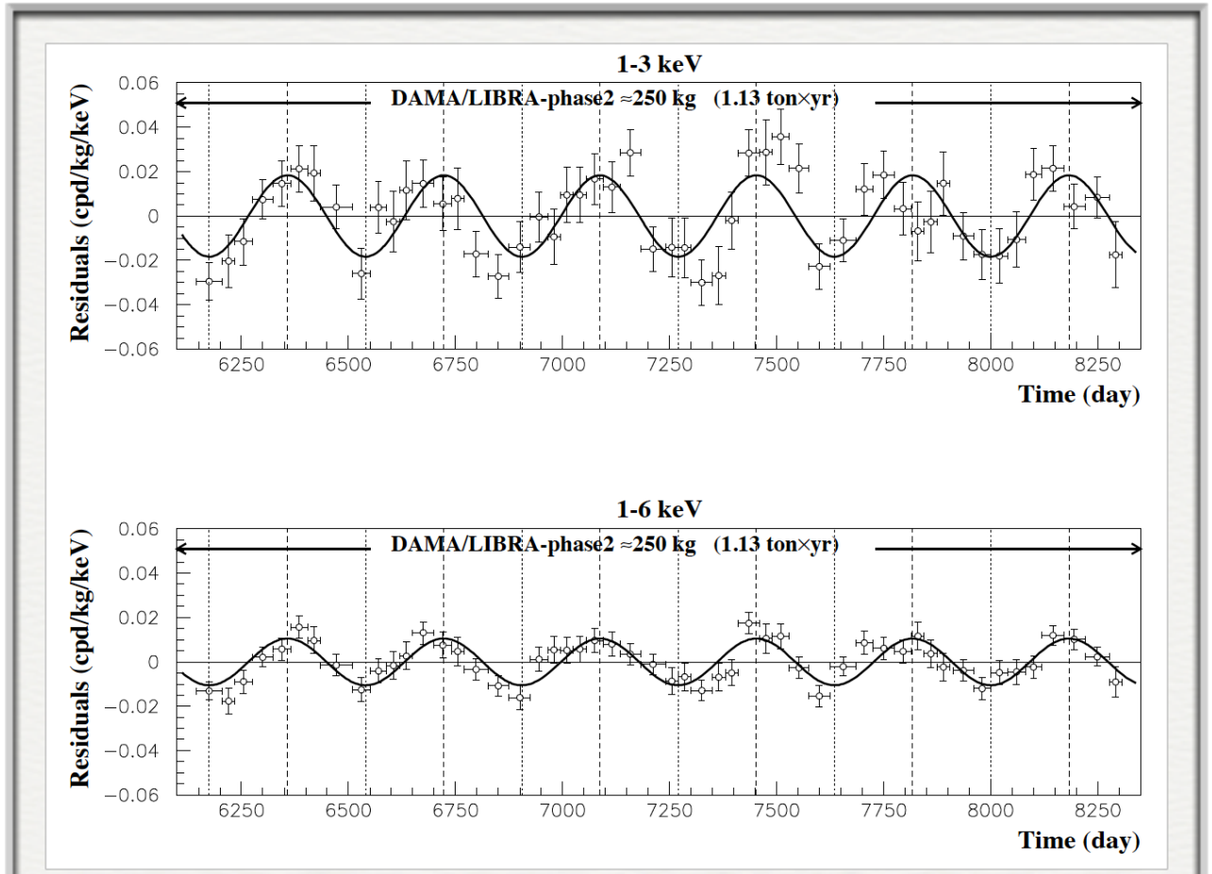
DAMA Anomaly

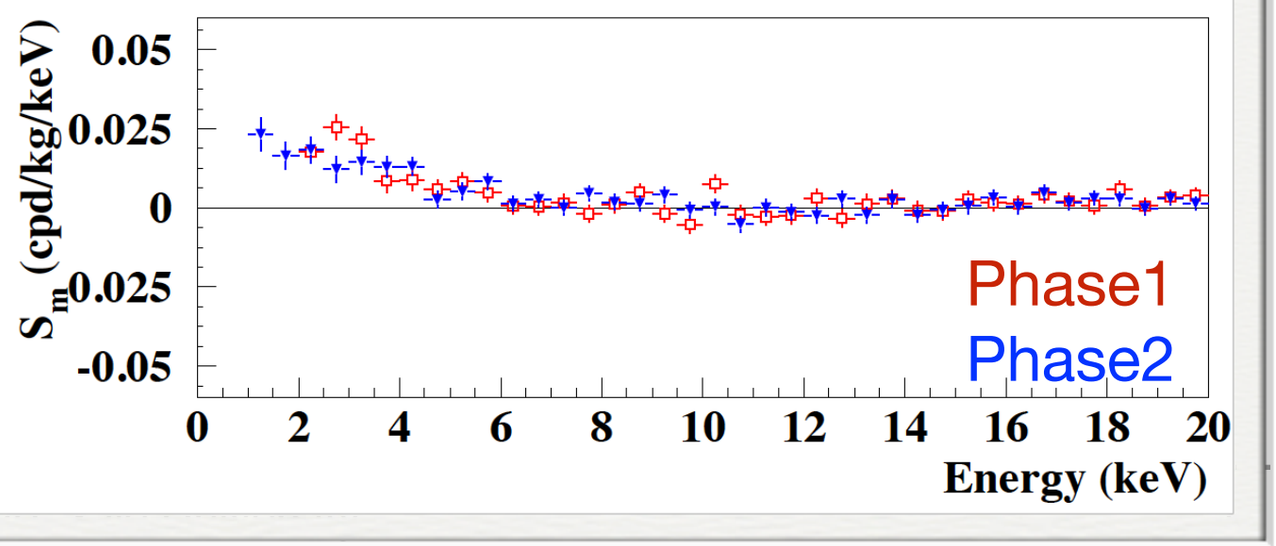
Kluck, CRESST-III TAUP 2019

DAMA's annual modulation

Nucl. Phys. At. Energy 19 (2018) 307
arXiv:1805.10486

- Modulation persists in Phase 2
  - 6 more years, 1.13 ton-year
  - Threshold now 1 keV
- **(1 – 6) keV: 9.5σ from 1.13 ton- year**
- **(2 – 6) keV: 12.9σ from 2.46 ton-year**





NaI(Tl) Experiments

DAMA

SABRE COSINUS

★ Gran Sasso + Australia

KIMS (+ DM-Ice)

COSINE-100

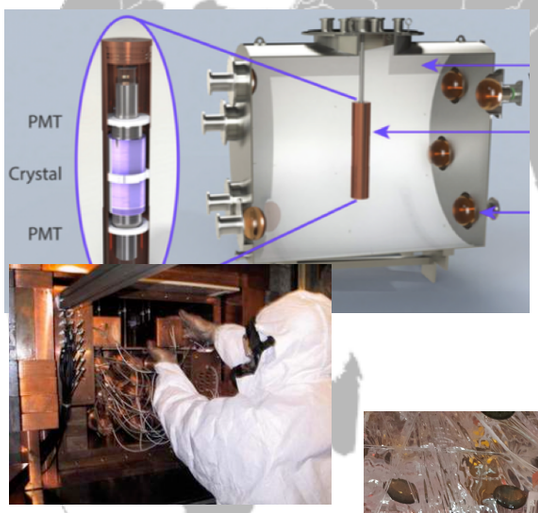
★ Yangyang ★ Kamioka

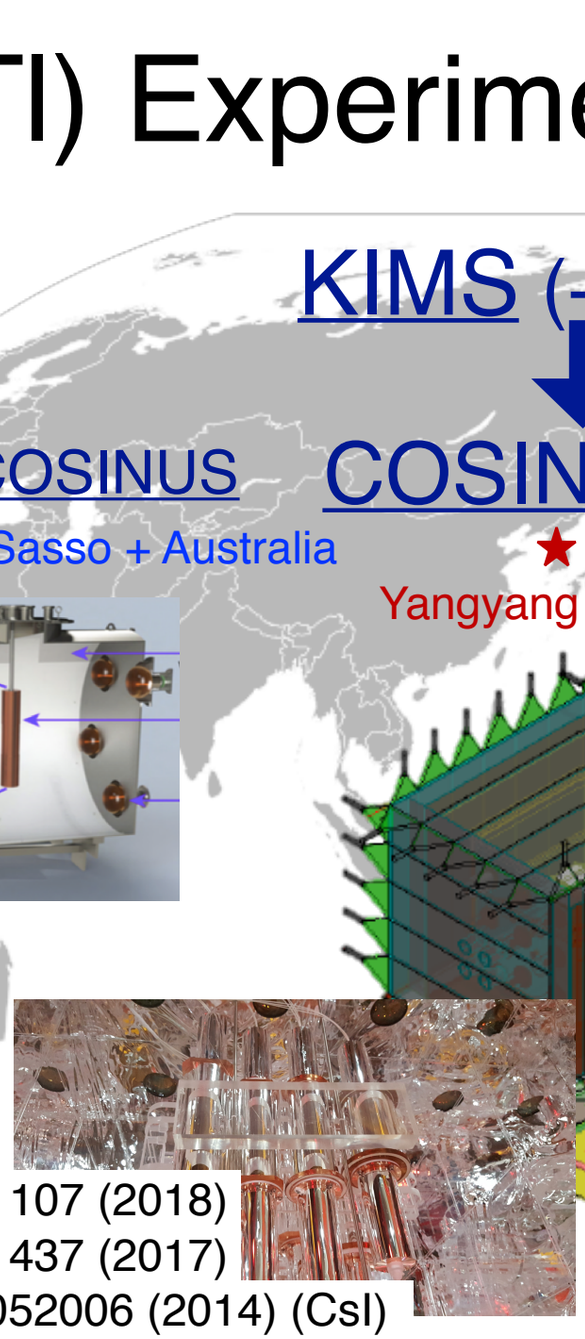
PICOLON

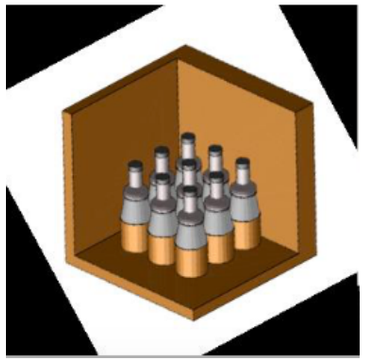
ANAIS

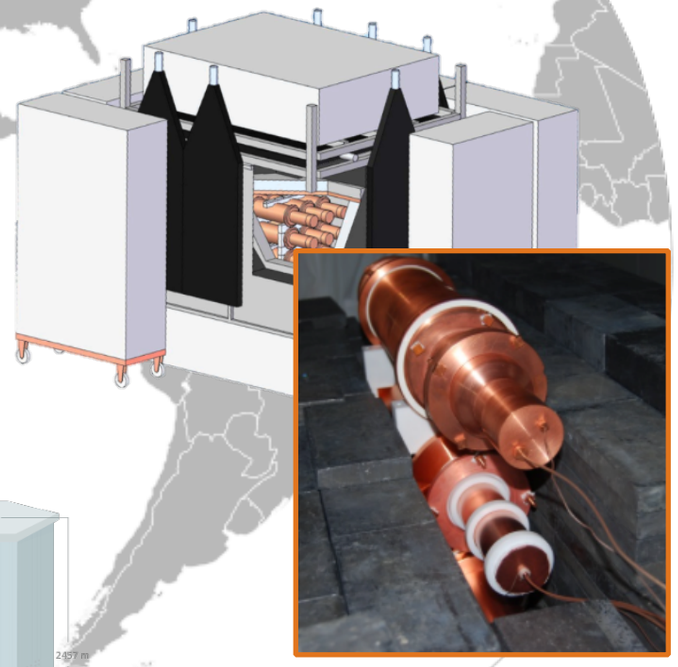
★ Boulby

★ Canfran

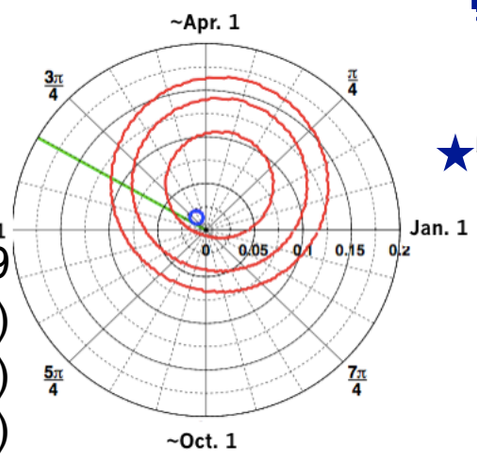








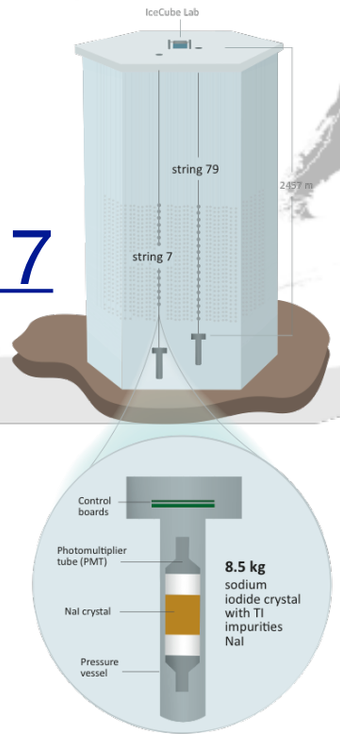
Eur.Phys.J. C **78** 107 (2018)
Eur.Phys.J. C **77** 437 (2017)
Phys.Rev. D **90** 052006 (2014) (CsI)
Nature **564** 83-86 (2018)
arXiv:1903.10098 (2019) -> PRL

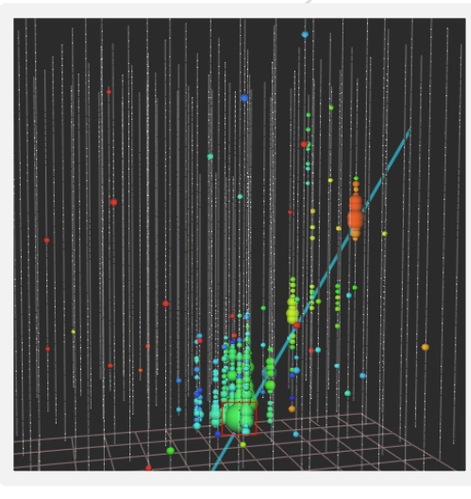


Astropart. Phys. **35** (2012) 749
Phys. Rev. D **90** 092005 (2014)
Phys. Rev. D **93** 042001 (2016)
Phys. Rev. D **95** 032006 (2017)

DM-Ice17

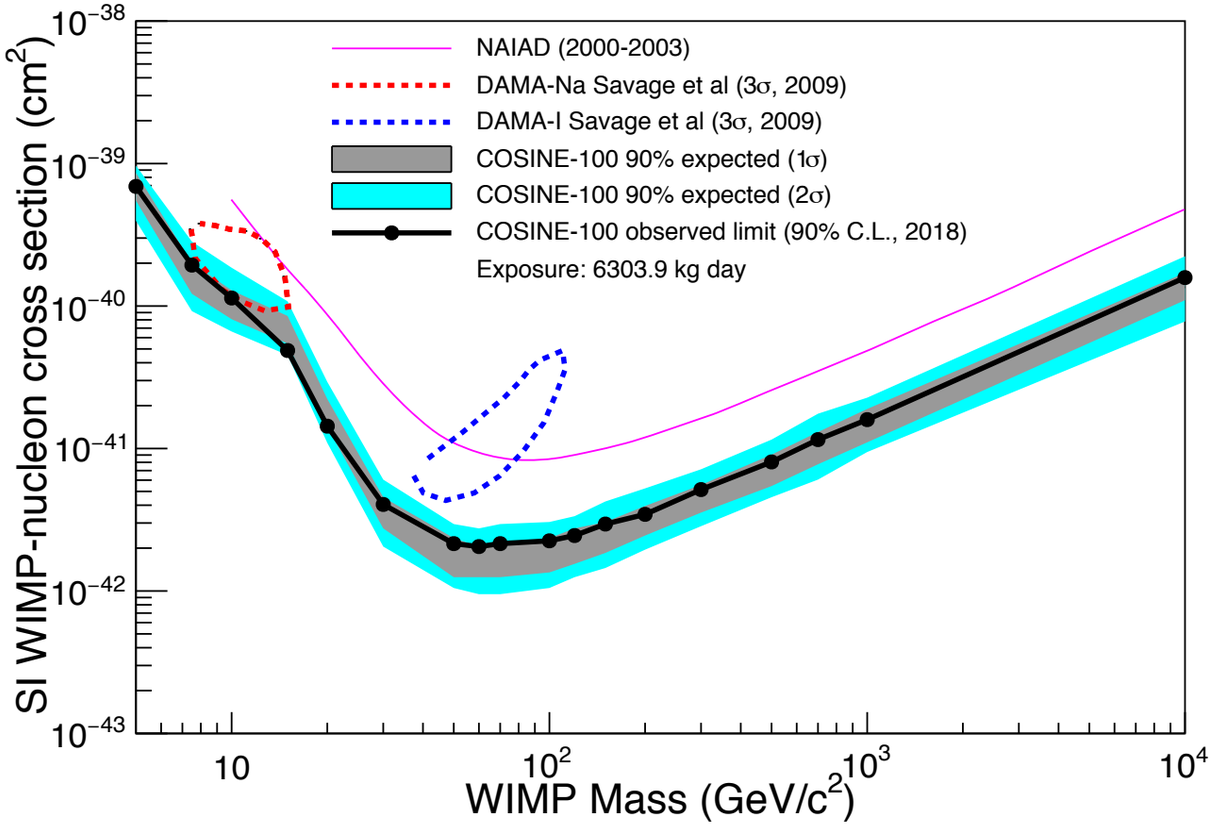
★ South Pole

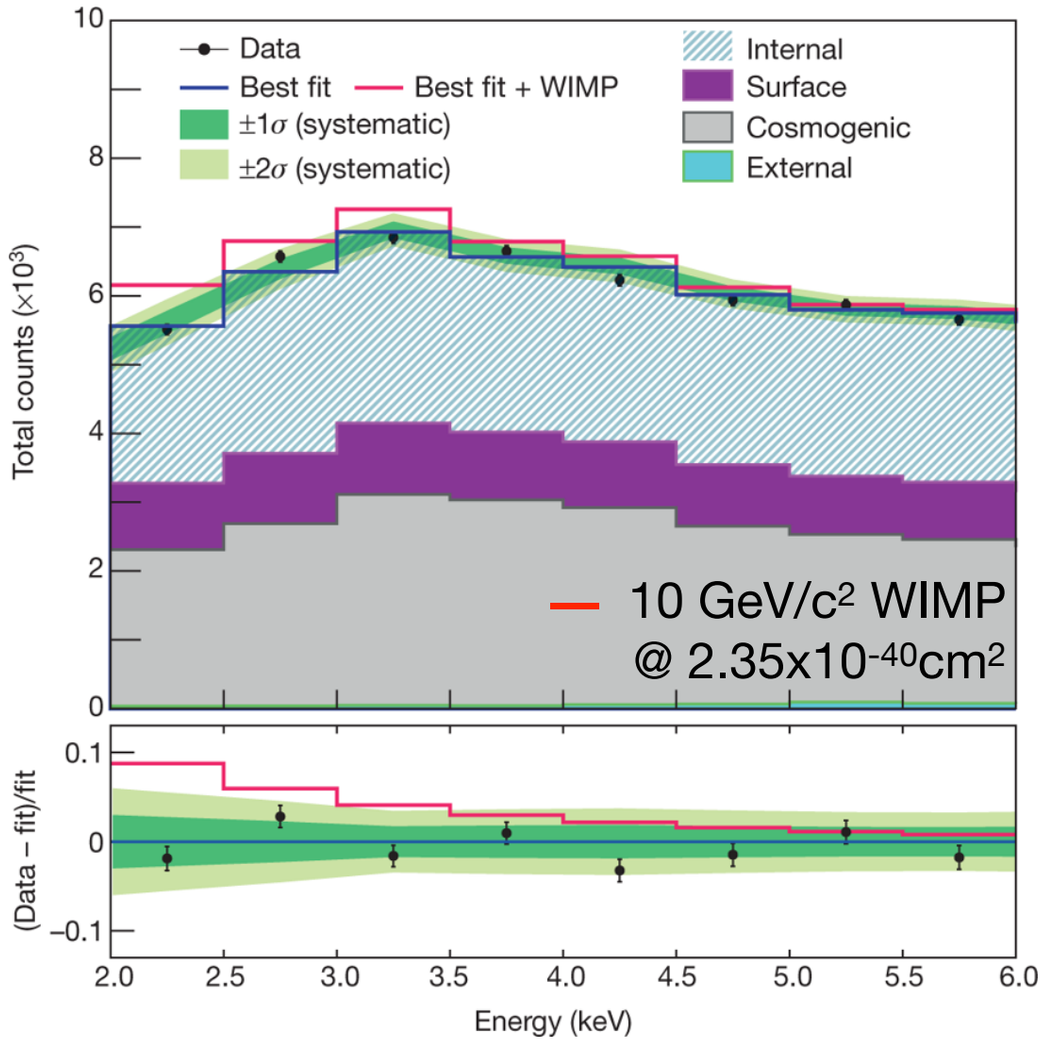




COSINE: Spin-Independent WIMP Search

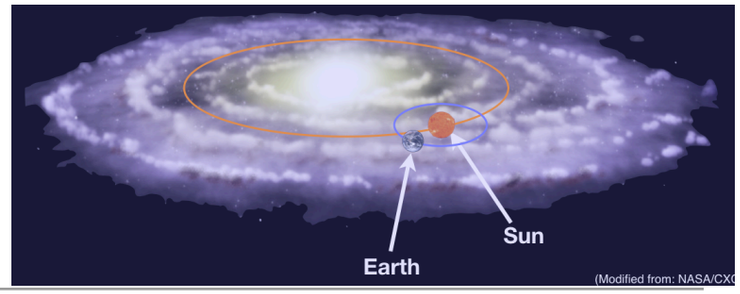
Nature **564** 83-86 (2018)





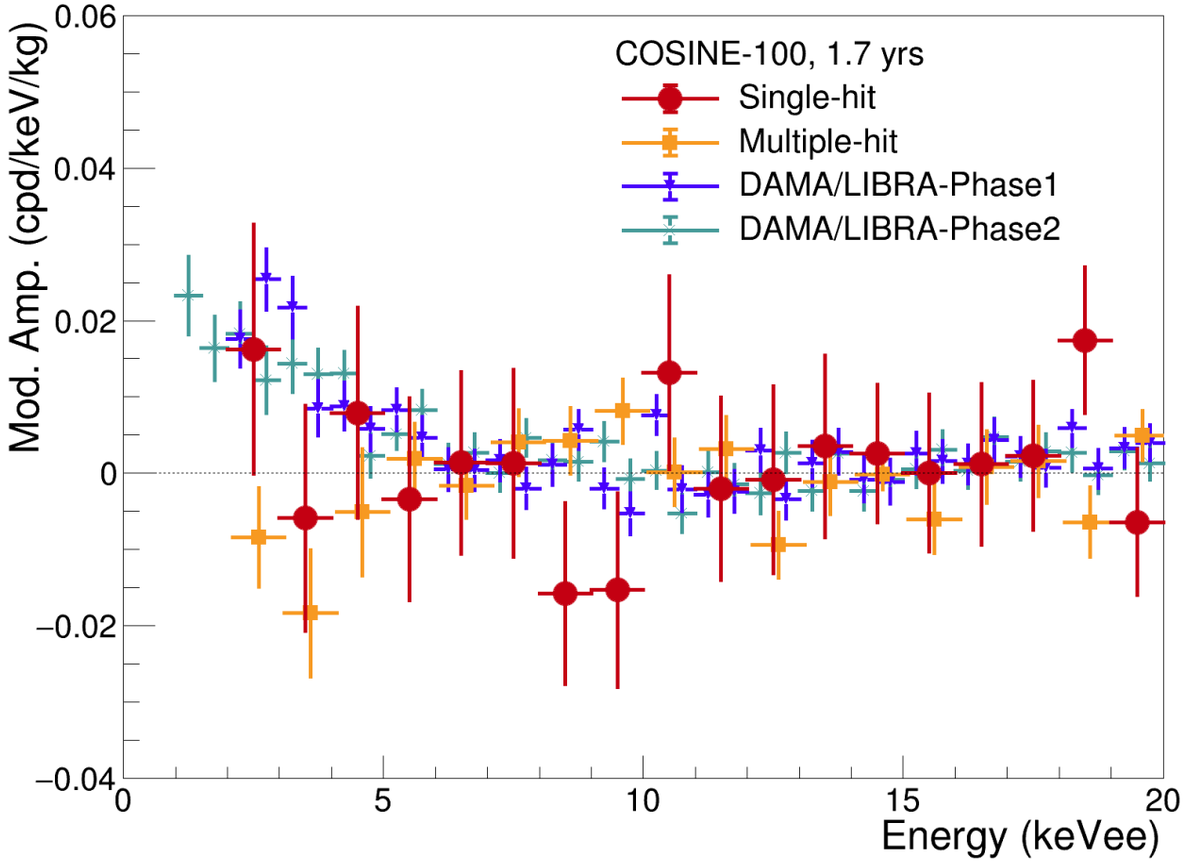
- **Exclude DAMA/LIBRA's signal as spin-independent WIMP with NaI(Tl)**
- **Confirms null results from other direct detect experiments with different target medium**

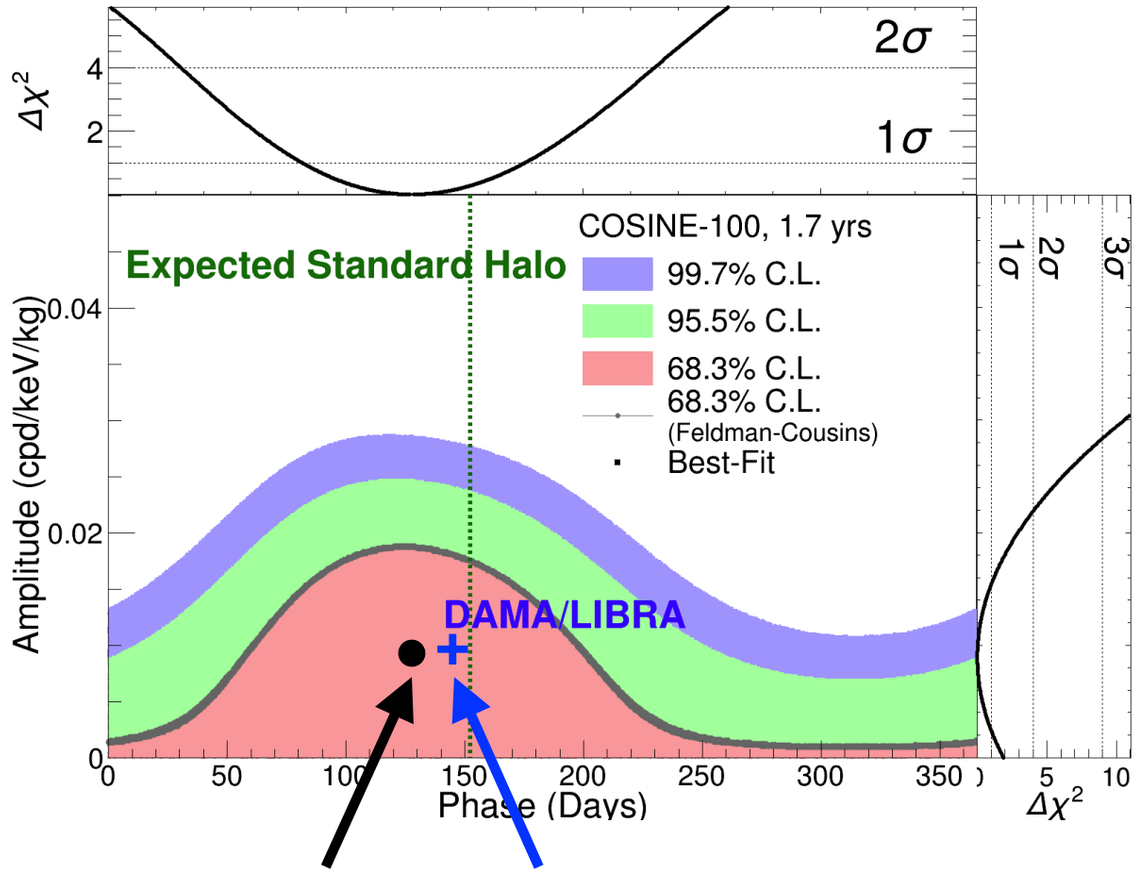
Annual Modulation Search



PRL **123**, 031302 (2019)

COSINE-100 (1.7 years)





COSINE-100
1.7 yr

DAMA/LIBRA

- **Not yet conclusive. More data being taken**

ANAIS-112

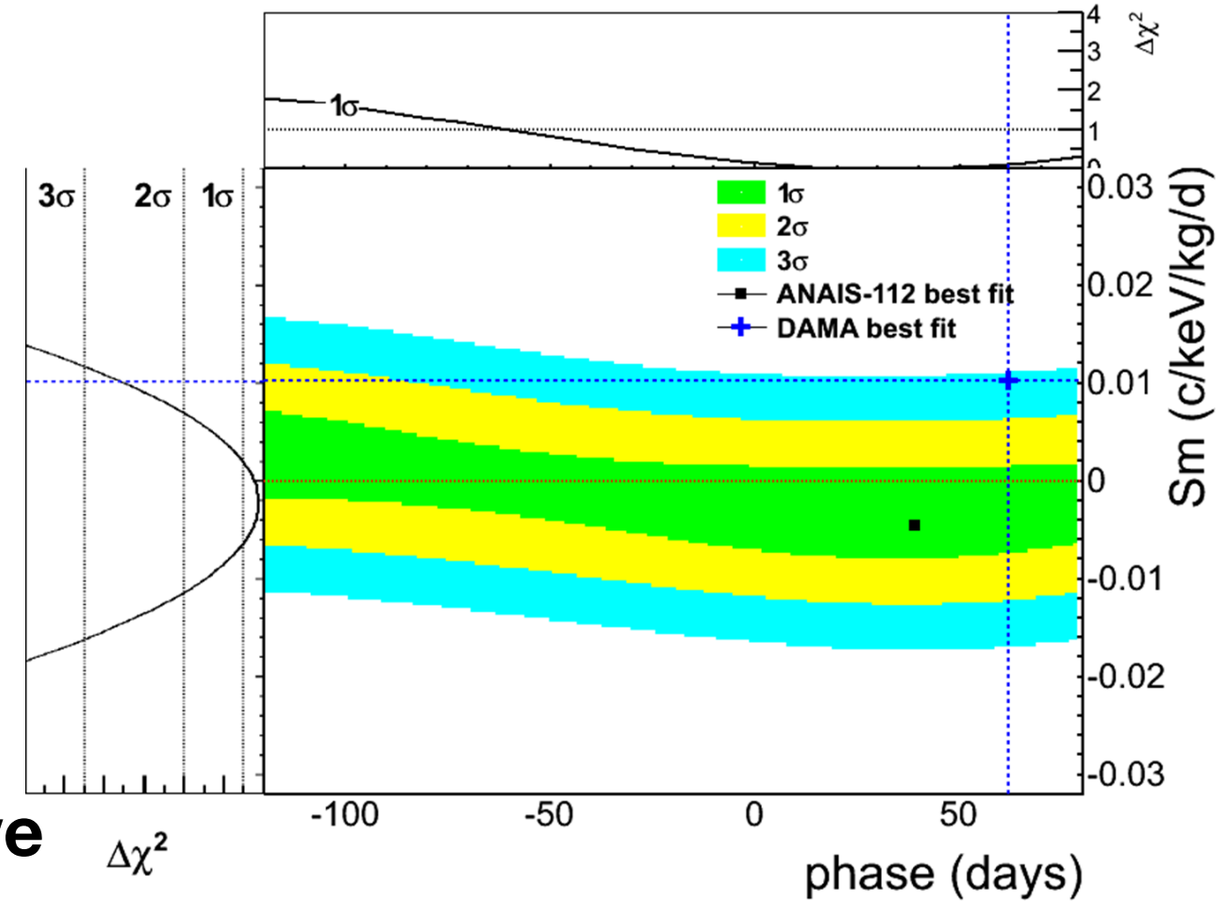
1.5 years data published in PRL **123** 031301 (2019)

Least squared fit of the ANAIS-112 time-binned data in 2-6 keV energy regions to:

$$R(t) = R_0 + R_1 \cdot exp(-t/\tau) + S_m \cdot cos(\omega \cdot (t + \phi)),$$

ω is fixed (1 year period)

NEW !!!
PRELIMINARY
ANAIS-112
2 years



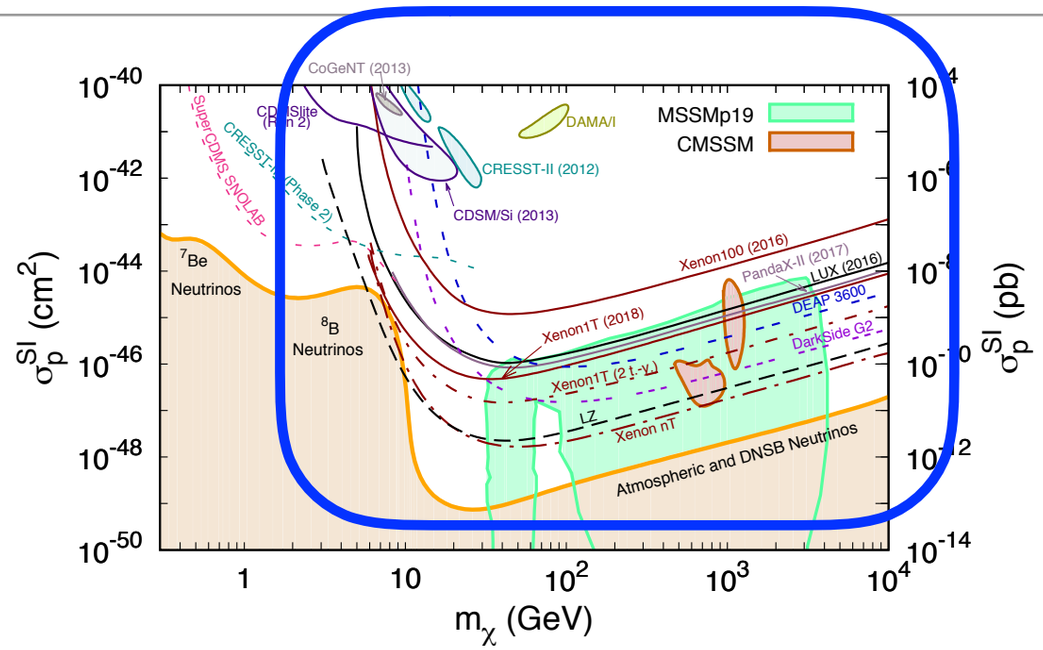
ANAIS-112 annual modulation

- **Also not yet conclusive**

Look for results from COSINE & ANAIS soon. Sarsa, TAUP 2019

Liquid Noble Gas Detectors: DM > 10 GeV

- Discovery instrument
- 300 - 1300 kg
- Single or dual phase
- Ar & Xe



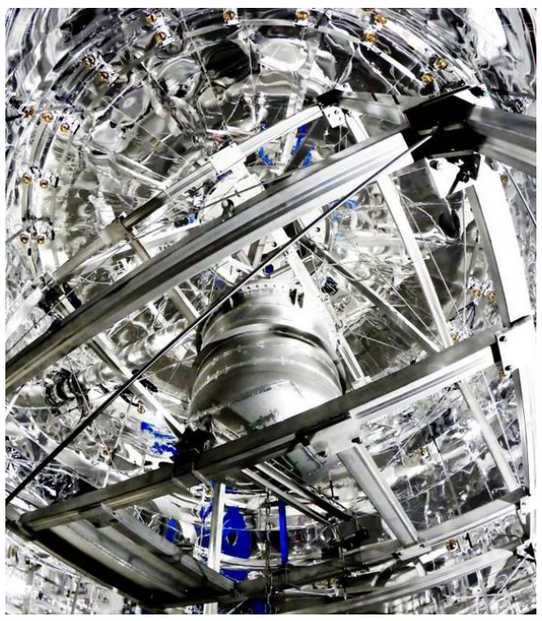
Darkside

XMASS

LUX

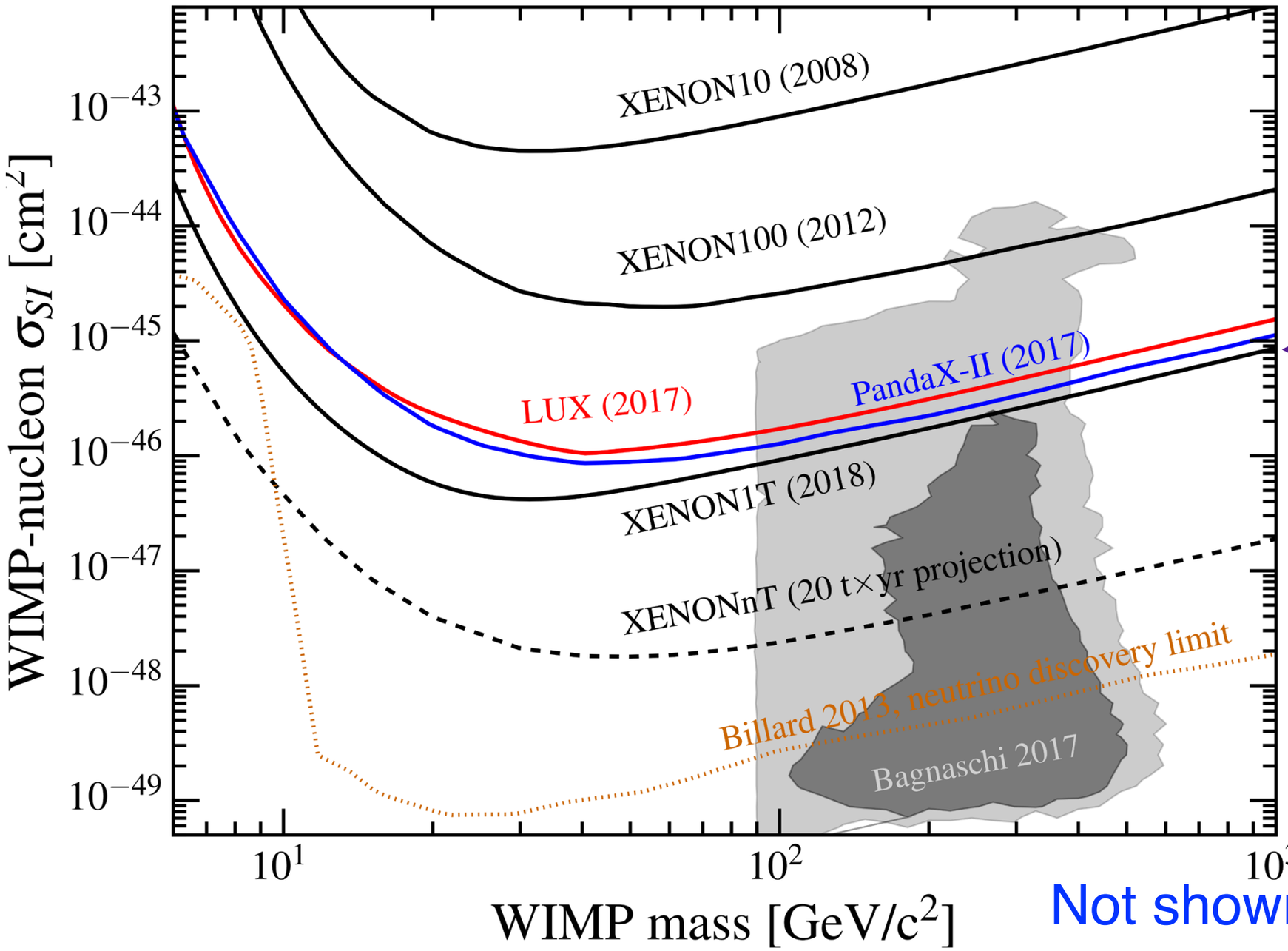
PANDA X

XENON 1T



PRL 121, 111302 (2018) 21, 111302 (2018)

Spin-Independent Limits > 10 GeV



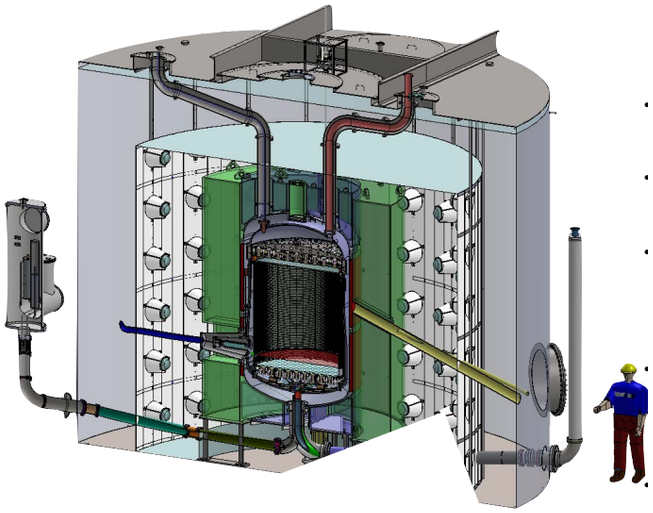
Nothing yet.

Neutrino floor

Not shown: other couplings

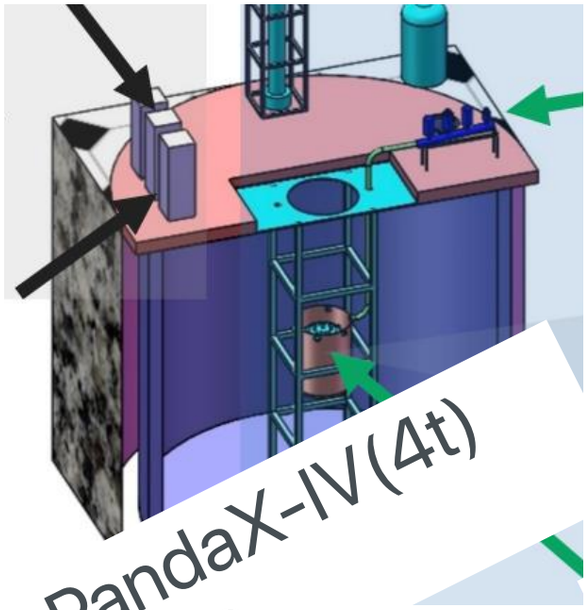
XENON Collaboration

Gen-2 experiments: next 5 years

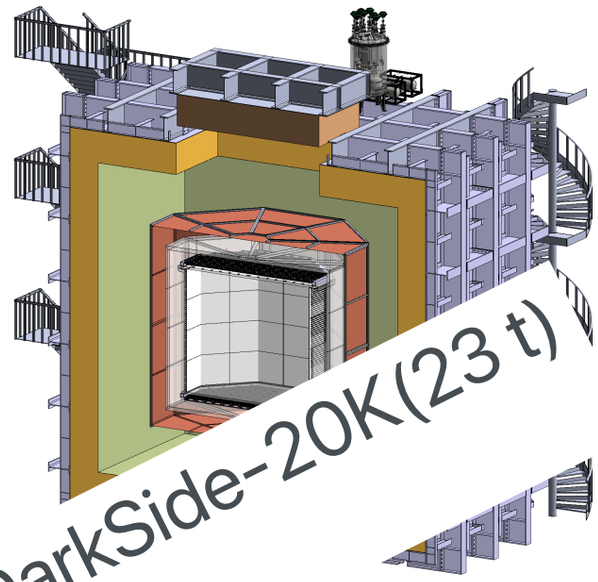


LZ(7t)
2020-

XENONnT (5.9t)
2019-



PandaX-IV(4t)
2020-

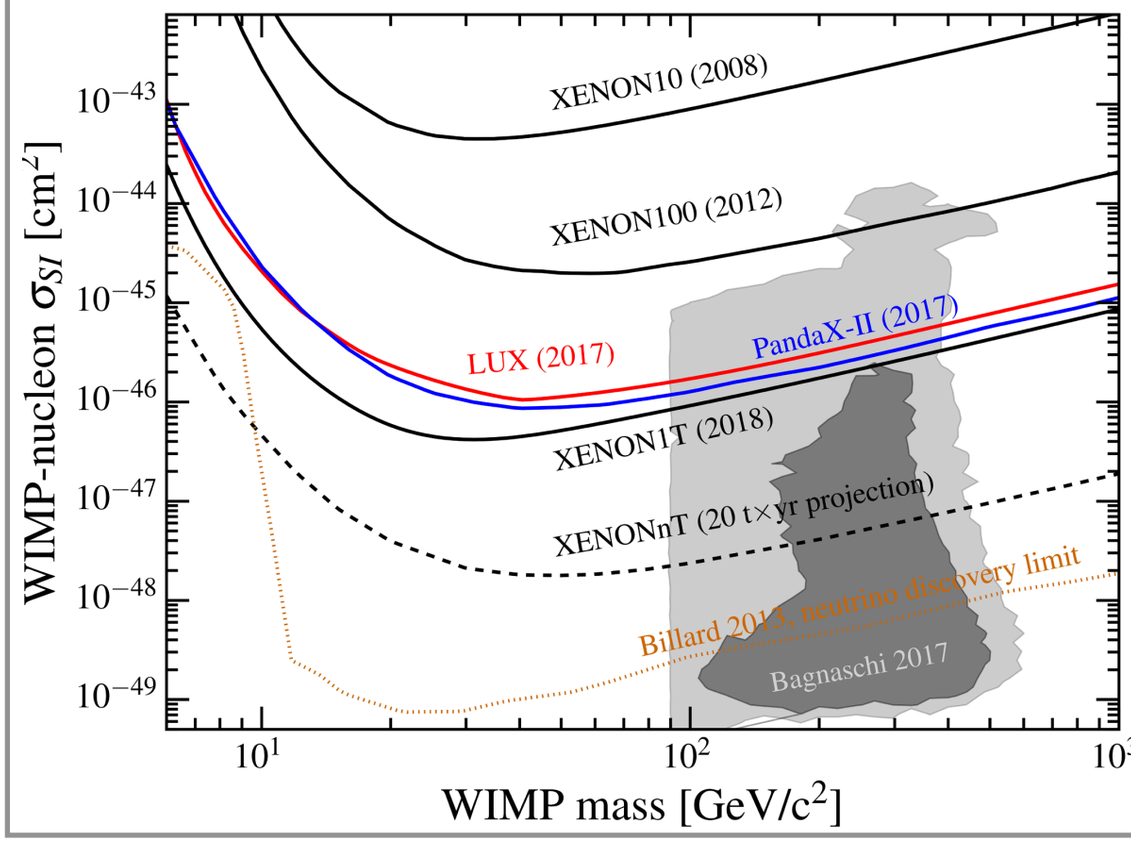


DarkSide-20K(23 t)
2022-

Yamashita, TAUP 2019

What might it look like in 2025?

- XENON 1T observes a few dark matter events
- Gen 2 solidifies discovery
- Start precision measurement with DARWIN



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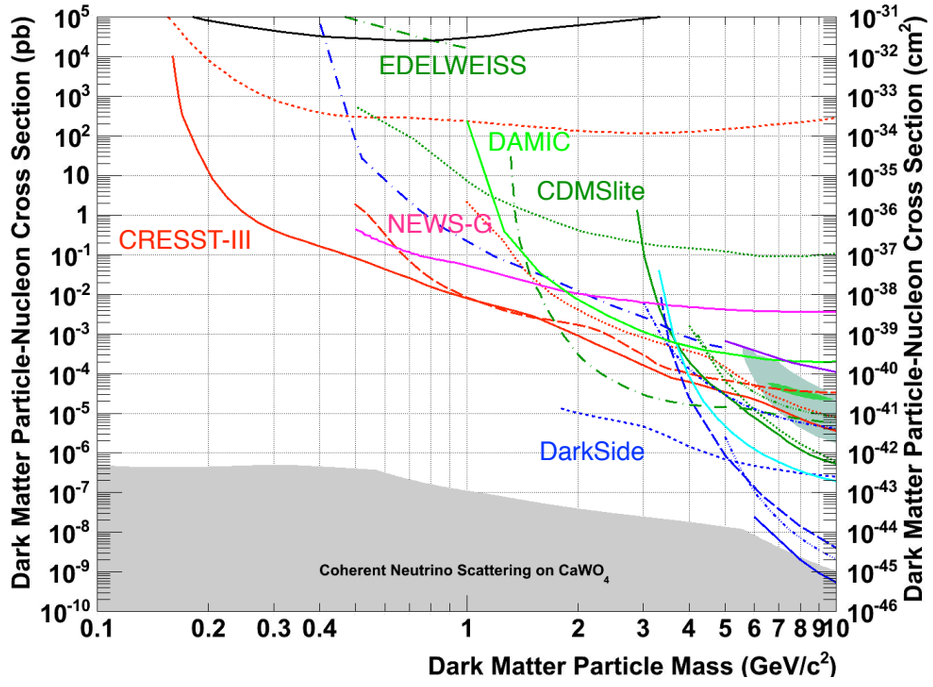
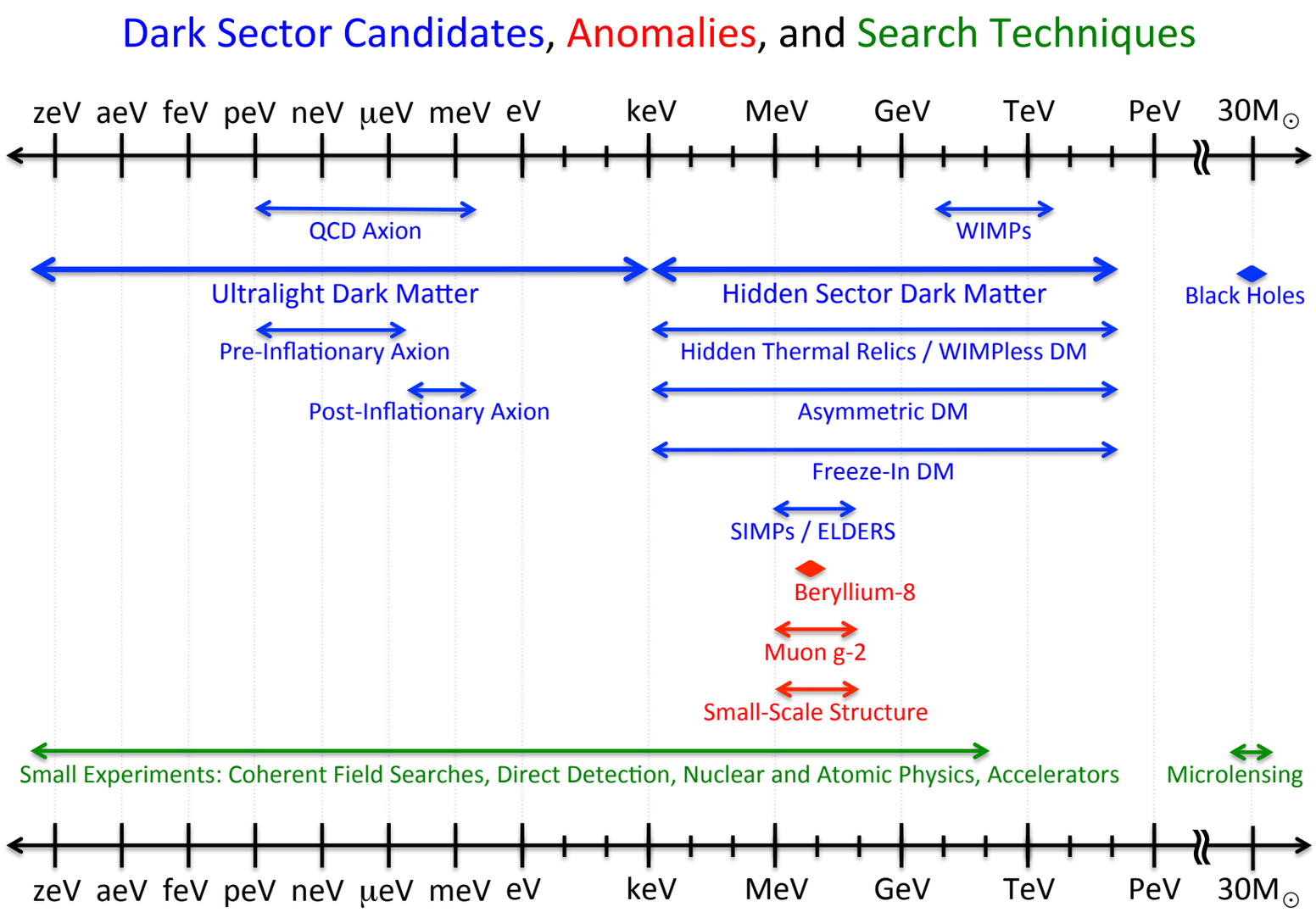


- we see dark matter events in low-mass searches
- consistent picture emerges out of different nuclear masses
- start precision measurement with larger detectors

???

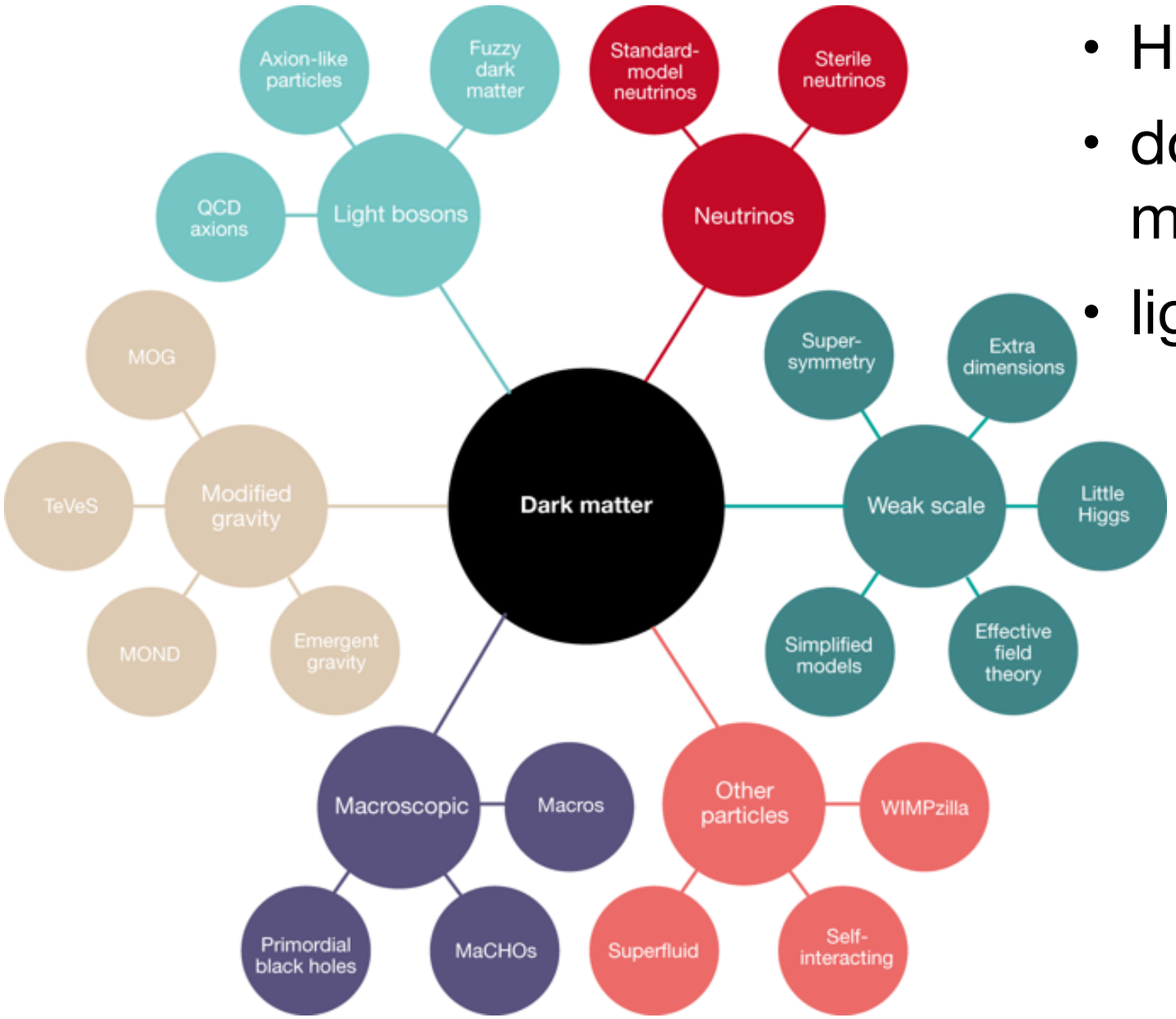
Soul searching for dark matter searchers



US Cosmic Visions: New Ideas in Dark Matter 2017

arXiv:1707.04591

Soul searching for dark matter searchers

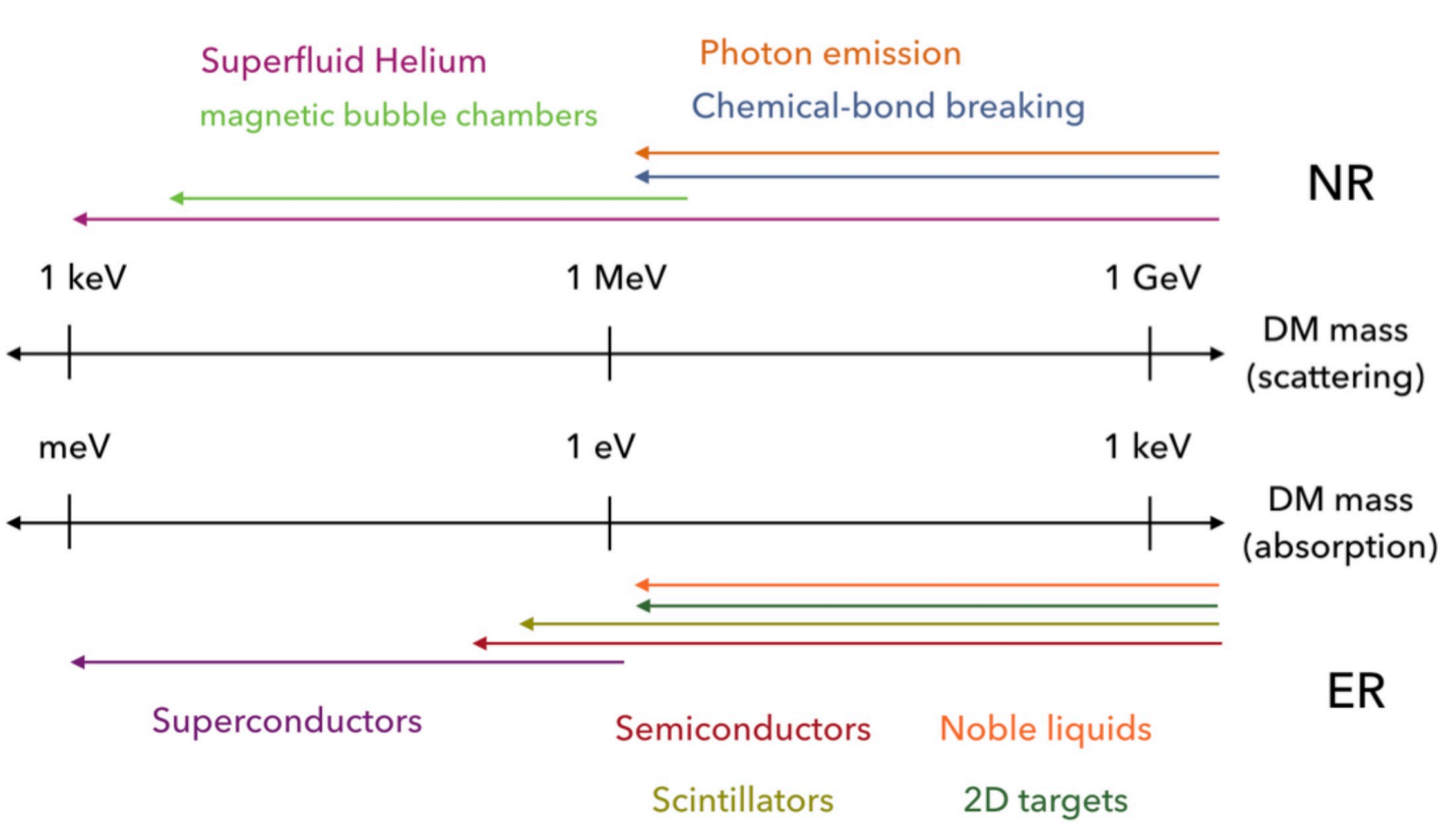


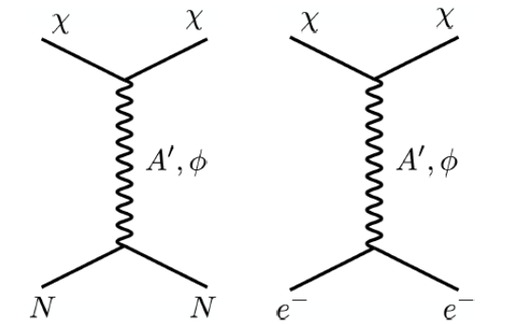
- Heavier? e.g. wino?
- do we need to explain dark matter on its own?
- lighter and weaker coupling?

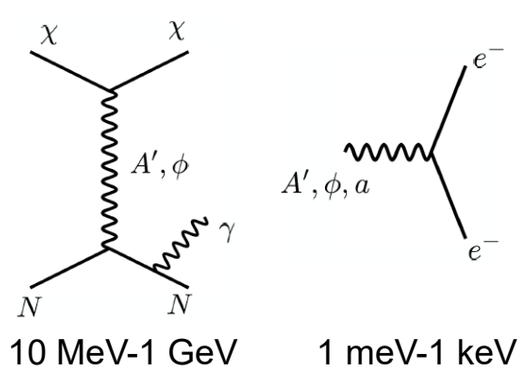
Bertone & Tait
Nature 562, 51–56 (2018)

Low mass detectors: meV — GeV

- Probe dark matter below proton mass
- lighter targets
- lower thresholds
- look for scattering or absorption by nuclei or electrons



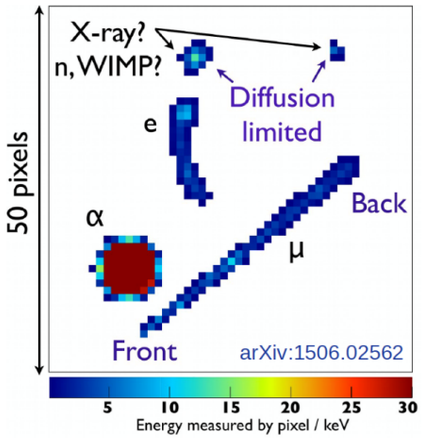


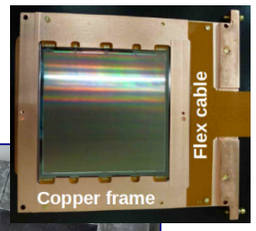


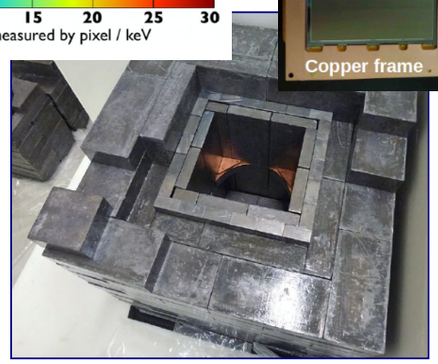
US Cosmic Visions, arXiv:1707.04591

Low mass searches: meV — GeV

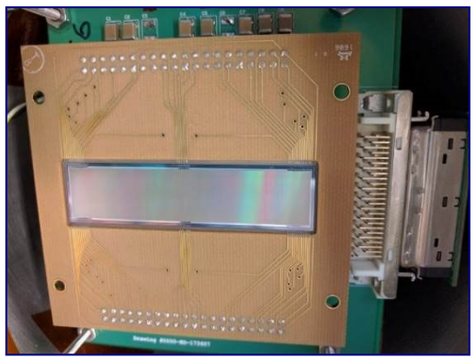
DAMIC
Si CCDs

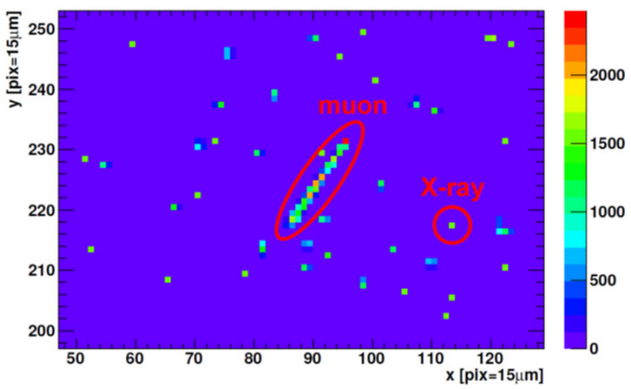


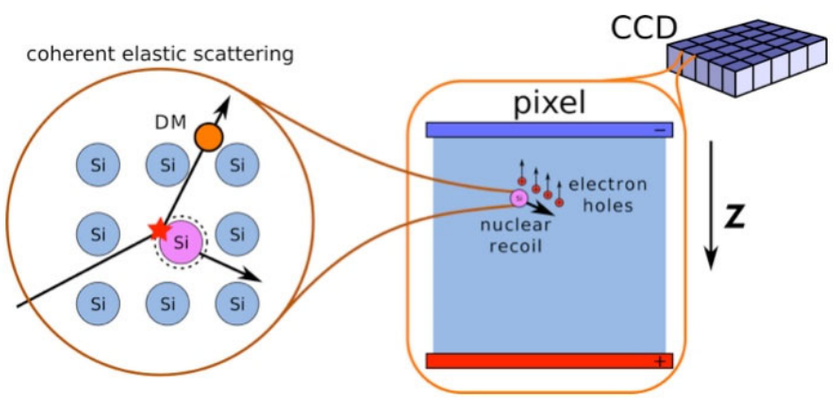




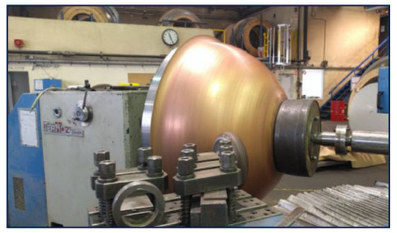
SENSEI
Skipper technology

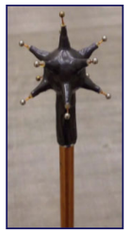




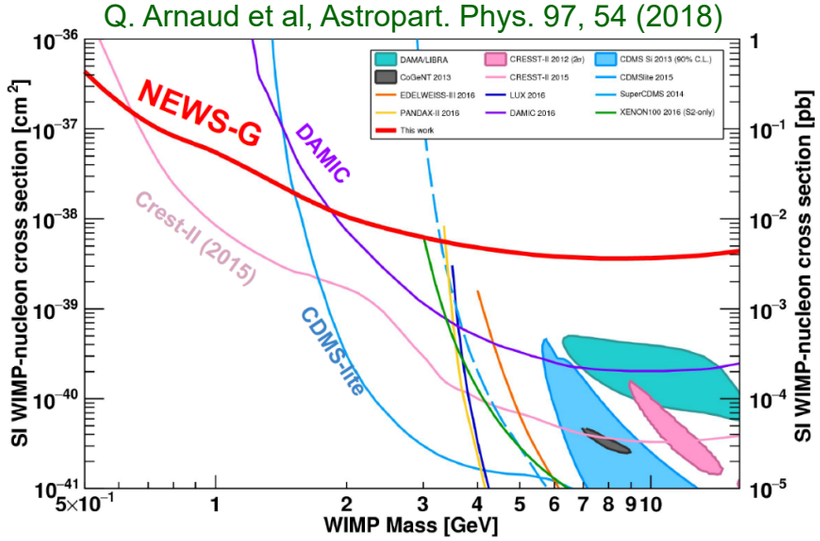


NEWS-G
Spherical proportional counter





Q. Arnaud et al, Astropart. Phys. 97, 54 (2018)



Summary

Where are we now?

- 30 years of Direct Detection WIMP Search
- DAMA vs. null-results
- Hints from indirect detection
- Upcoming “Gen2” experiments may yield signal
- Where to after “neutrino floor”?

Where to?

- New WIMP and axion experiments are coming online.
- WIMPs? Low mass? Warm? Other forms of DM?

When do we say “YES!” ?

- Consistent w/ astrophysics observations +
  - reproducible
  - targets, cross section, annual modulation, …