

Direct Dark Matter Searches: Recent Results and Prospects



Shengchao Li
Westlake University
2024/10/24

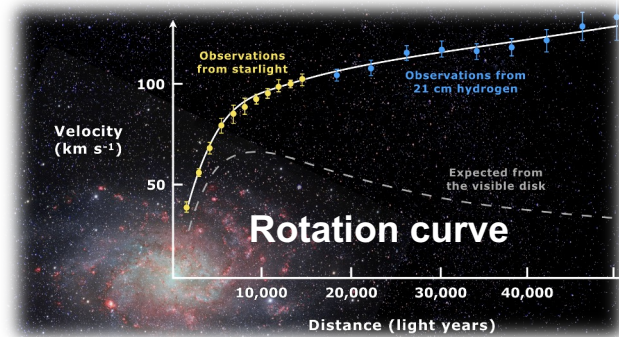
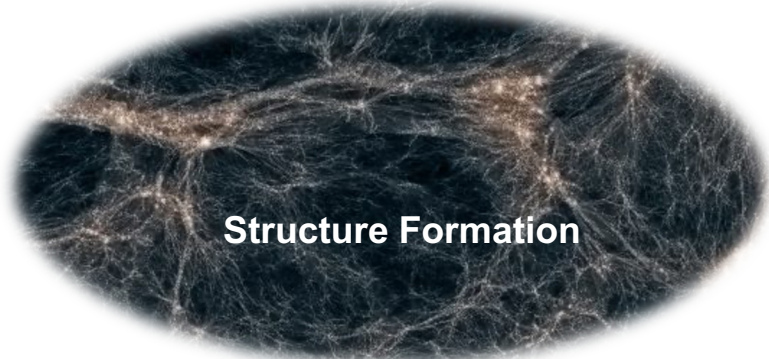
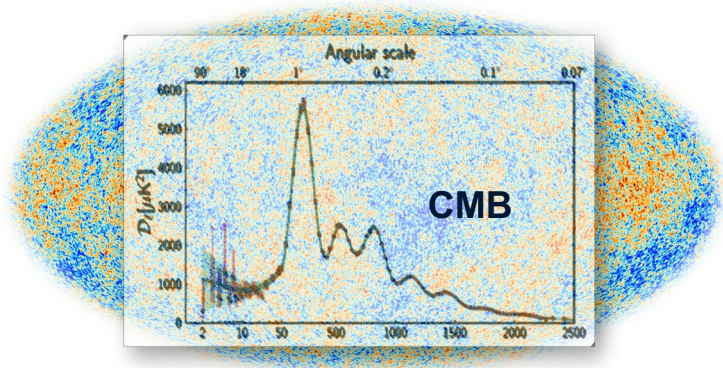


PIC2024@Athens

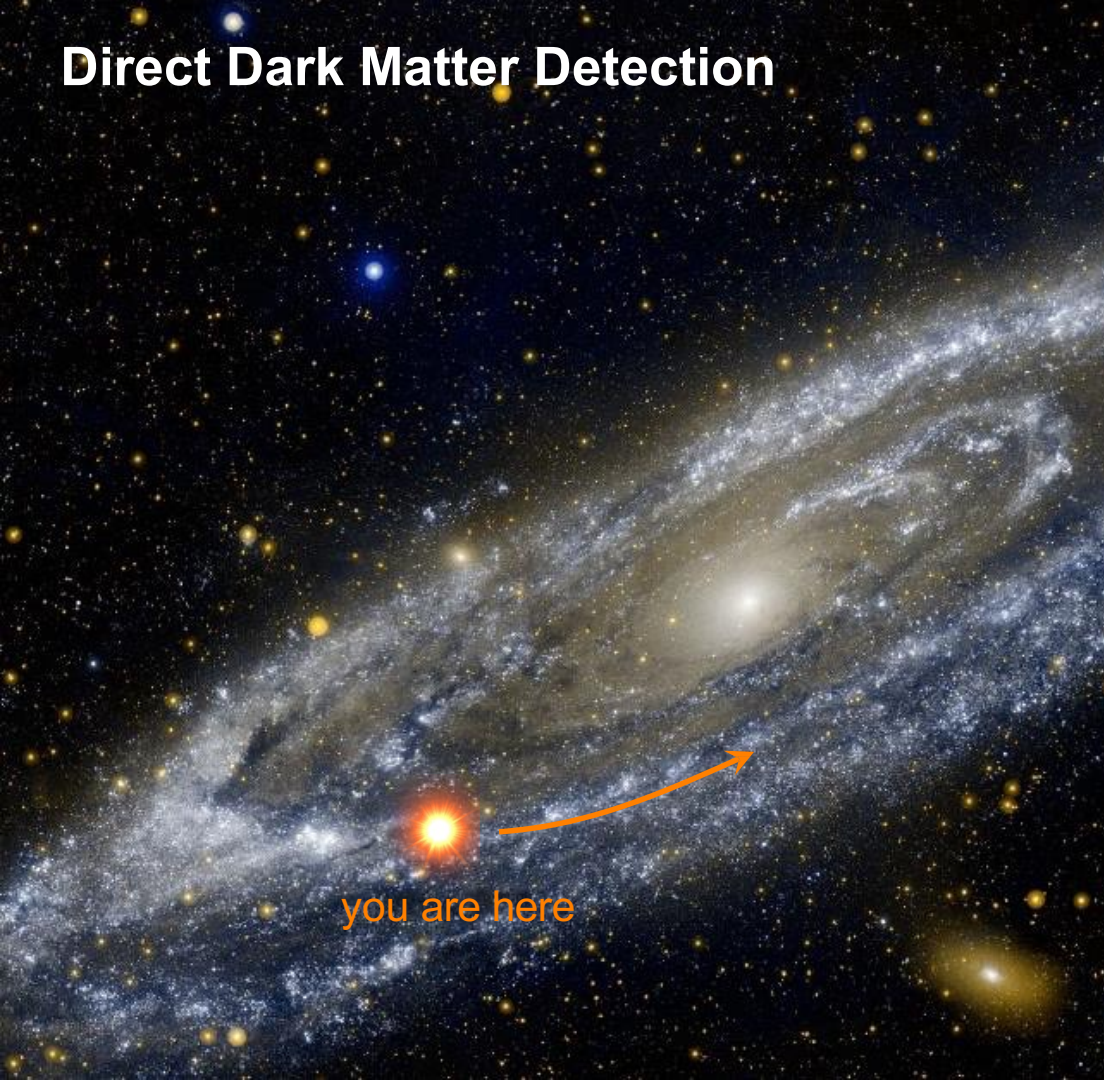
Dark Matter exists

Cosmology

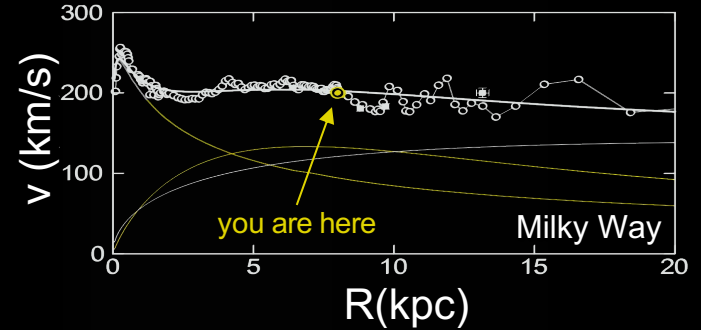
Astronomy



Direct Dark Matter Detection



you are here



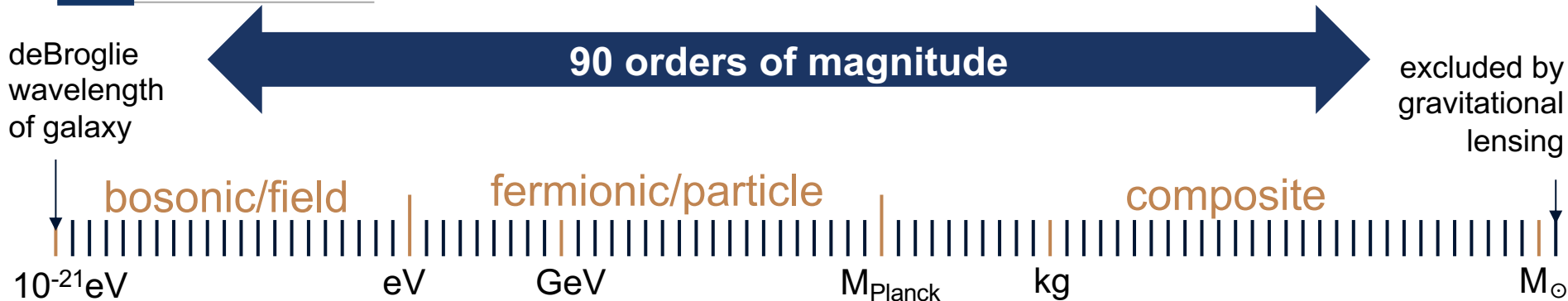
Local DM mass density:

$$\rho_{\text{DM},\oplus} \approx 0.3 \text{ GeV}/\text{cm}^3$$

$$v_{\text{DM}} \approx 220 \text{ km/s}$$

Non-relativistic wind of Dark Matter **waves** or **particles**

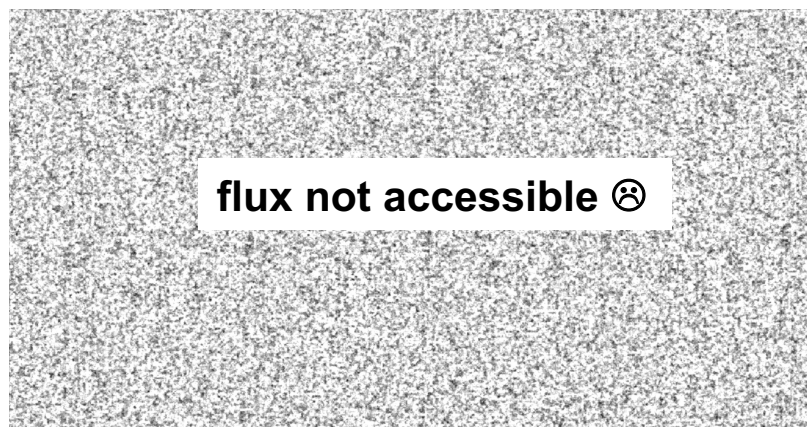
Dark Matter candidates



DM wave resonators

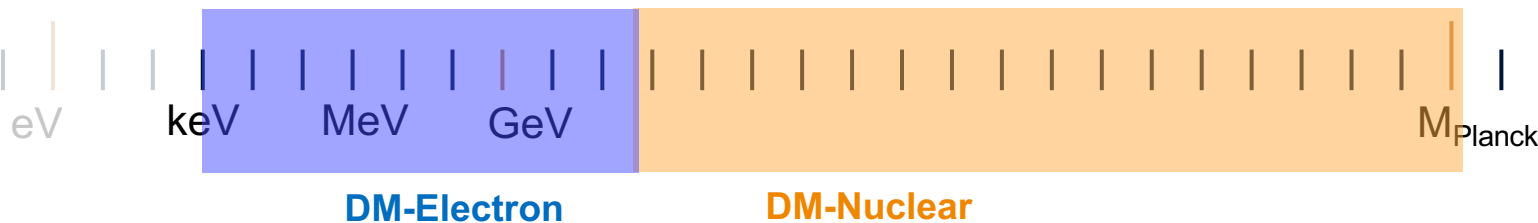
electronic recoil detectors

nuclear recoil detectors



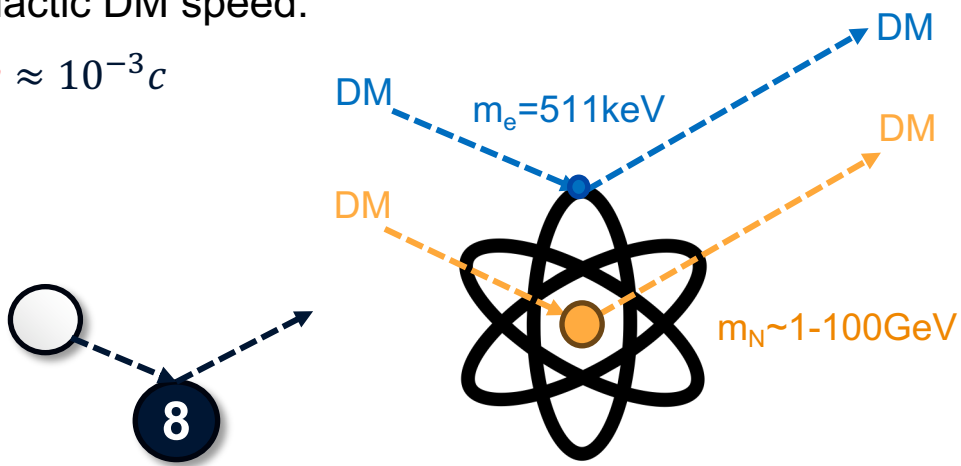
Particle Dark Matter: “physics in collision”

non-relativistic



- Galactic DM speed:

$$v \approx 10^{-3}c$$



- Elastic scatter:**

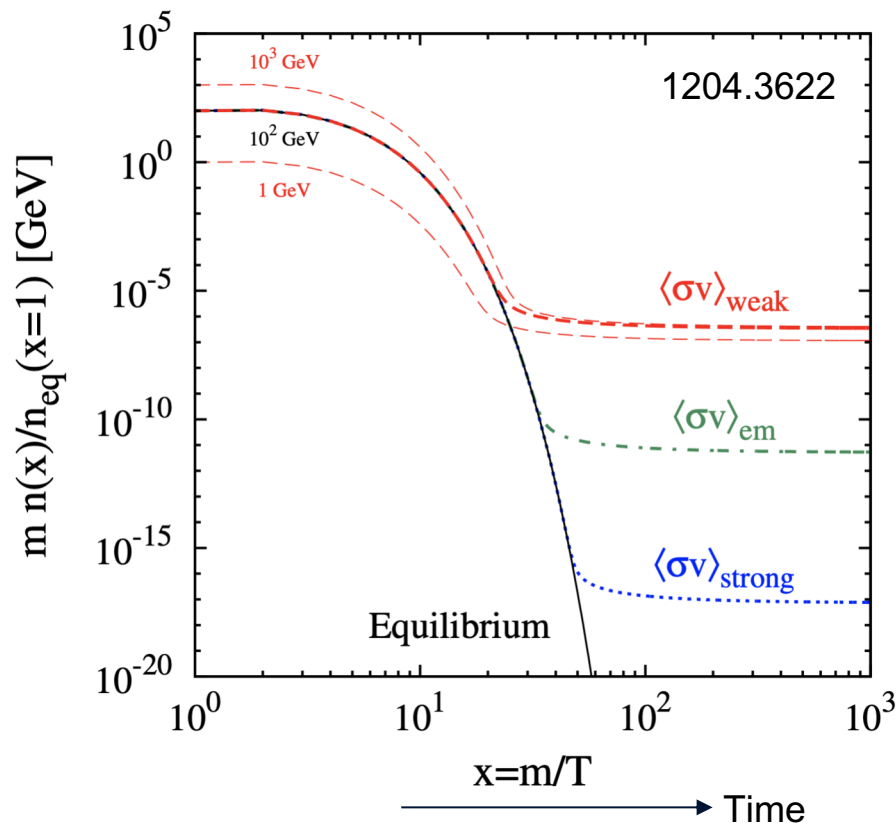
$$E_R^{max} = 2 \frac{\mu_{\chi T}^2 v^2}{m_T}$$

- Kinetic-matching is key:**

$$\mu_{\chi T} = \frac{m_{\chi} m_T}{m_{\chi} + m_T} \sim m_{\chi} \text{ if } m_{\chi} \lesssim m_T$$

$$\sim m_T \text{ if } m_{\chi} \gg m_T$$

WIMP (Weakly Interacting Massive Particle)



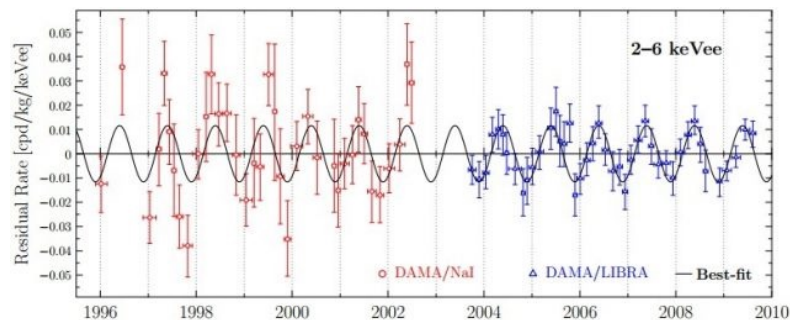
Thermal relic: direct baryon/photon coupling in primordial thermal bath

WIMP miracle: weak DM pair annihilation cross section predicts correct relic abundance

$$\langle\sigma v\rangle = 2.2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

May solve the naturalness and hierarchy problem.

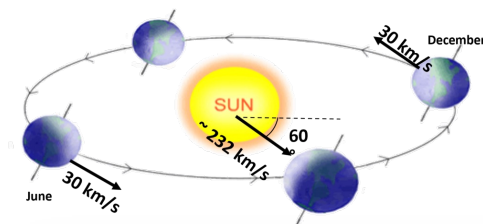
DAMA results



Sinusoidal modulation from DAMA data, DM signal?

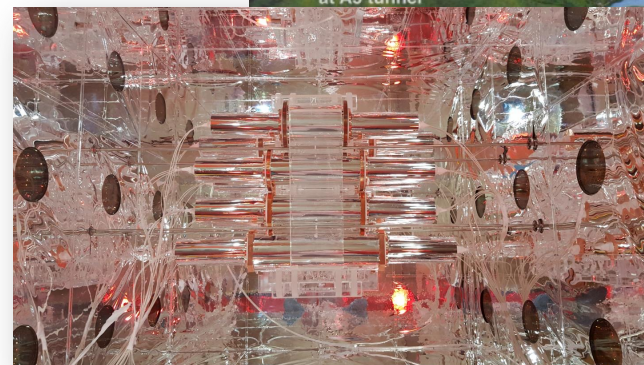


25 NaI(Tl) scintillators



Annual modulations from secular variations: relaxing DAMA?

Dario Buttazzo^a, Paolo Panci^{a,b}, Nicola Rossi^c, Alessandro Strumia^b



Independent crosschecks:

COSINE, ANAIS, SABRE, PICO-LON, DM-ICE...

See Hyun Su Lee's poster

Dual-phase Time Projection Chamber (TPC)

XENONnT@LNGS

LZ@SURF



<xihu>

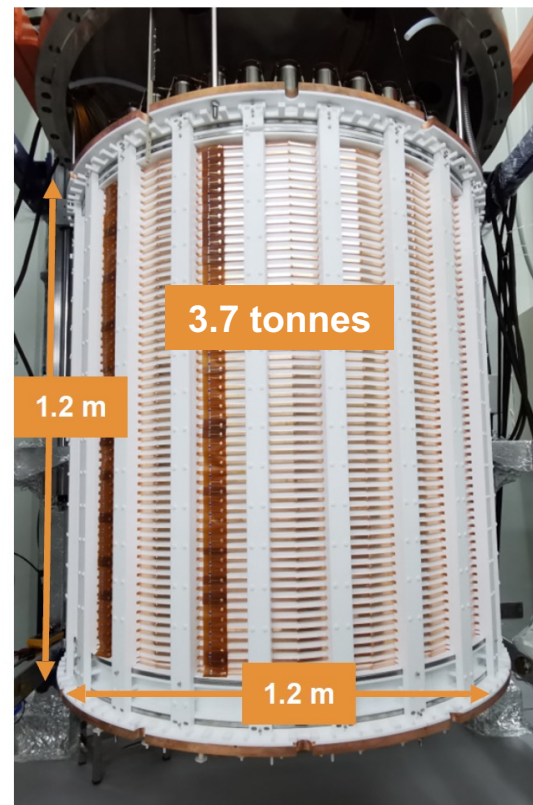
7

Westlake University | DM and neutrino lab

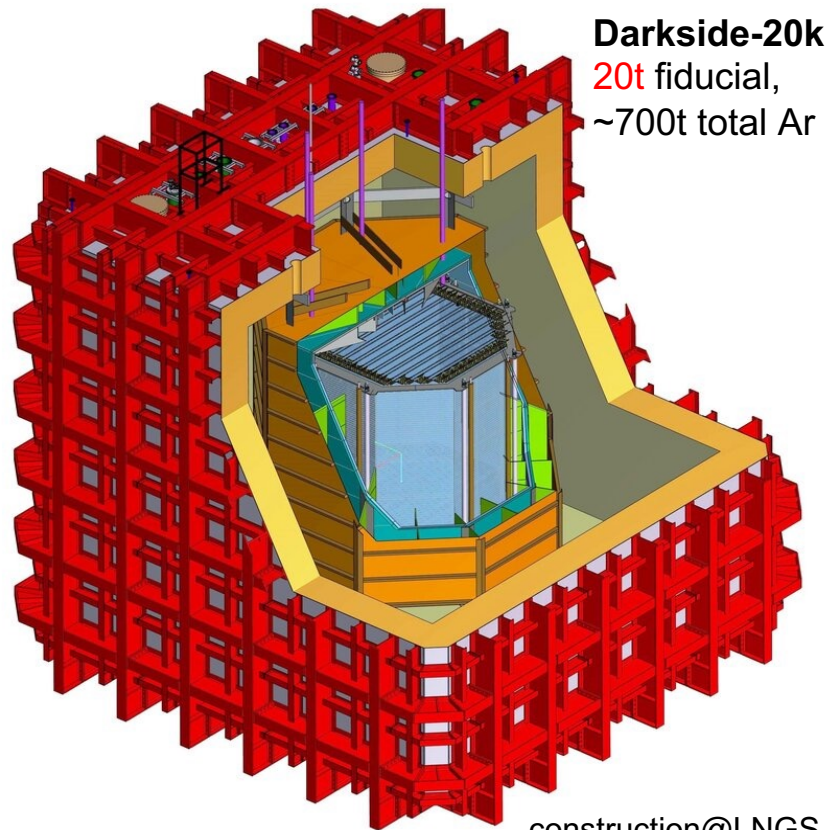
PandaX-4T@JinPing



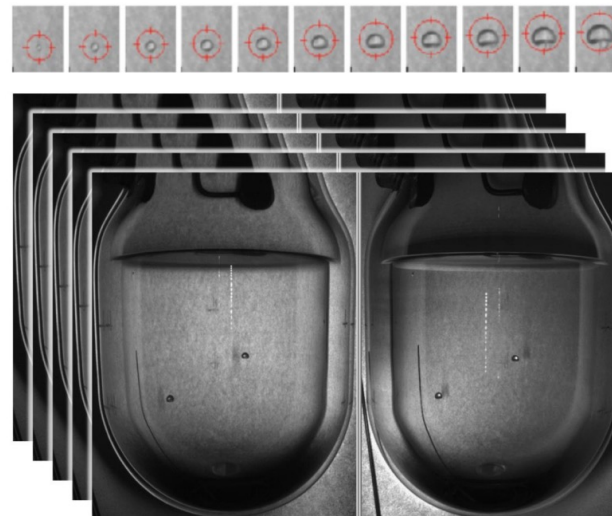
E. Aprile, UCLA DM23



Other “Big Bucket” WIMP detectors



PICO Bubble Chambers (superheated C_3F_8 fluid)



PICO-60 leading WIMP-proton limits (^{19}F)
PICO-40L running now
PICO-500 under construction



XENON

muon 99.5% ↓
neutron 65%-87% ↓

H₂O

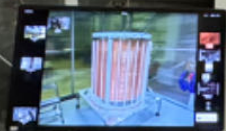
H₂O+Gd

Xe

5.9 t

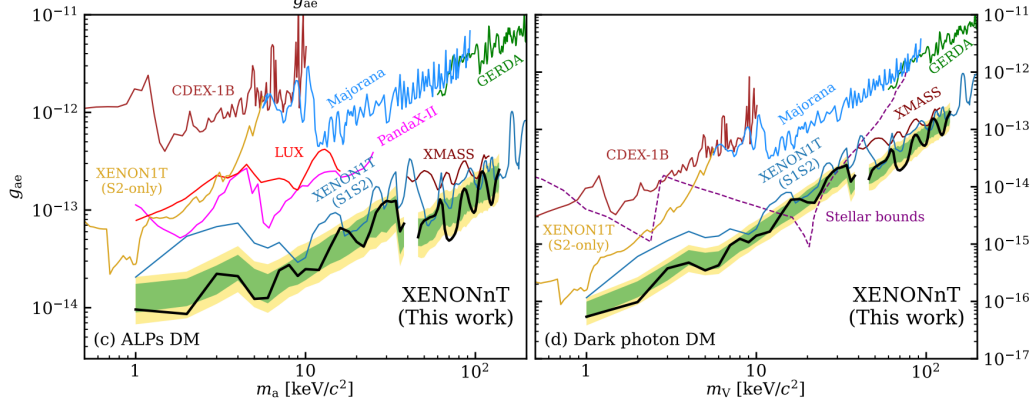
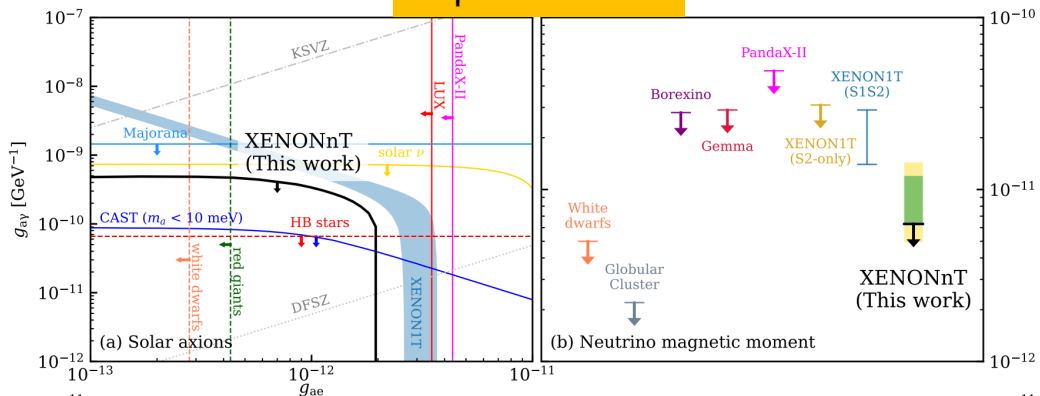
Online distillation
²²²Rn 0.9 μBq/kg
Lowest, 15-fold ↓

Xe purification
e⁻ lifetime = 15ms
86% bottom e⁻ survive

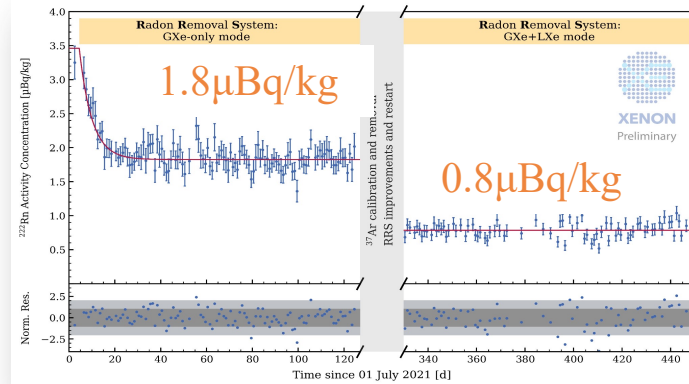


Electronic recoil background

Improved limits

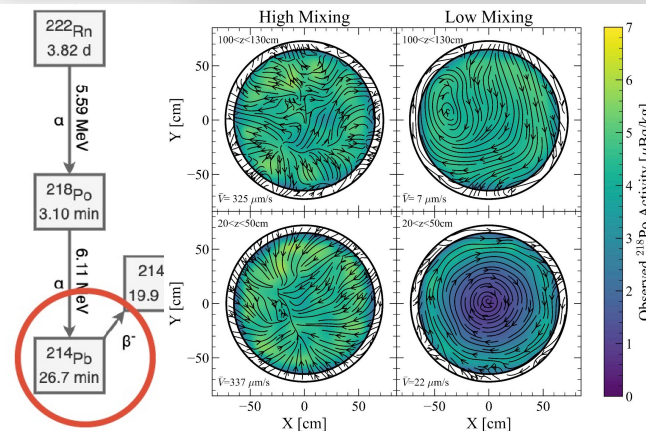


XENONnT



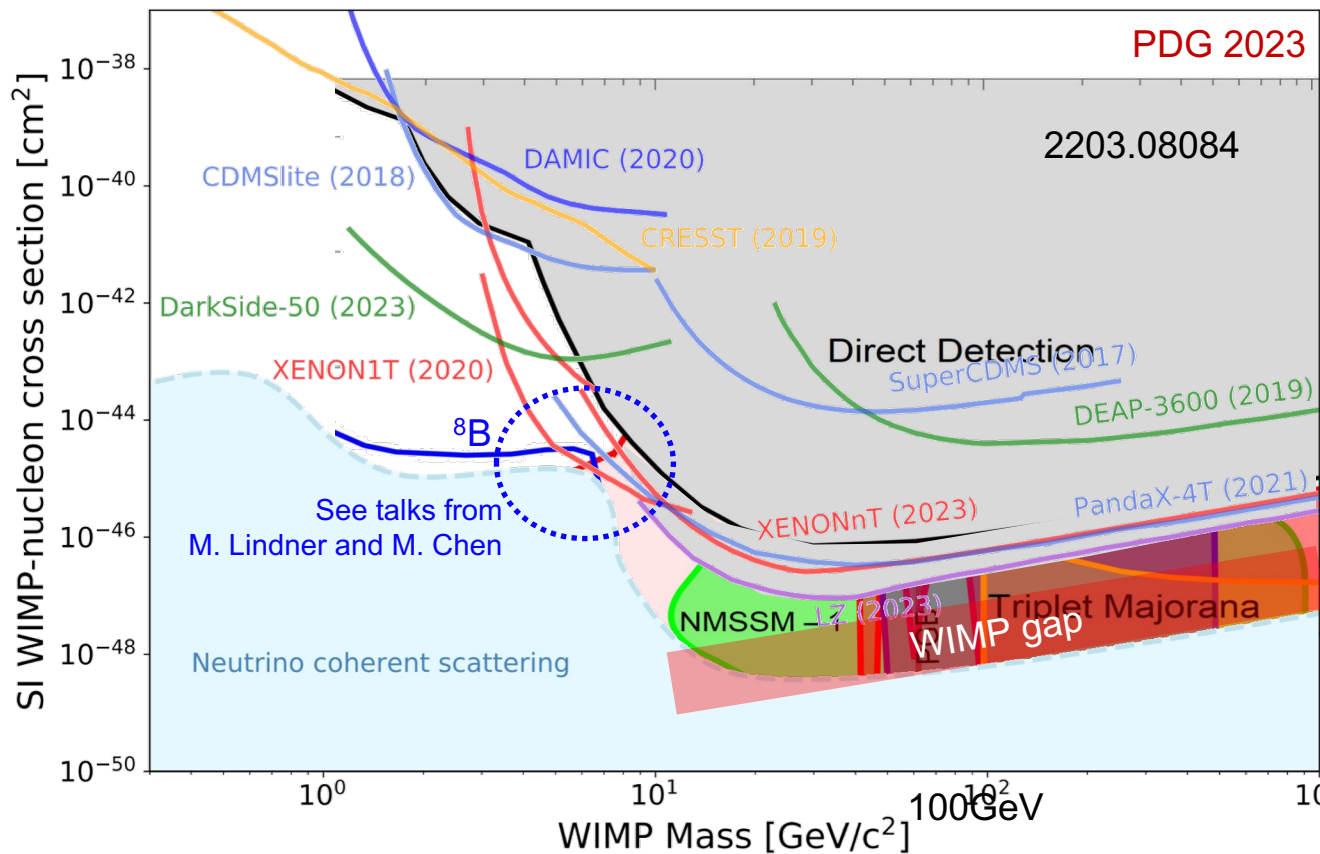
XENON 2205.11492

LZ



Haselschwardt, TeV/PA24

WIMP search results



Shengchao Li: DM Direct Detection

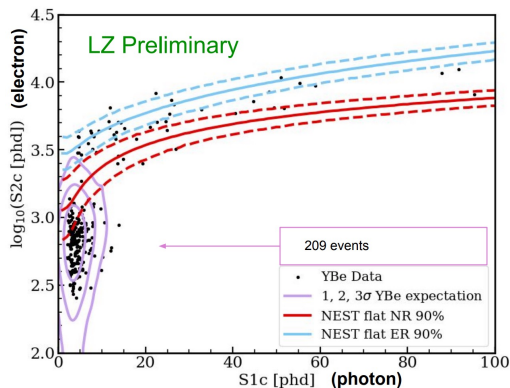
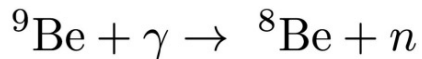
Factor of 10 every 3.3 years,
Z-boson, Higgs interacting:
NMSSM-1 (2102.08986)
NMSSM-2 (2011.12848)
Triplet Majorana (1801.08551)
Pseudo-Goldstone (2008.09605)

Neutrinos (solar, atm)
degenerate in momentum --
“neutrino fog”

Now sees ~ 10 MeV ^8B solar
neutrino via coherent elastic
v-N scattering (CEvNS)

Current program leaves a
WIMP gap: final push with
Gen-3 detectors (e.g., XLZD)

2024 milestone: ^8B neutrino signal

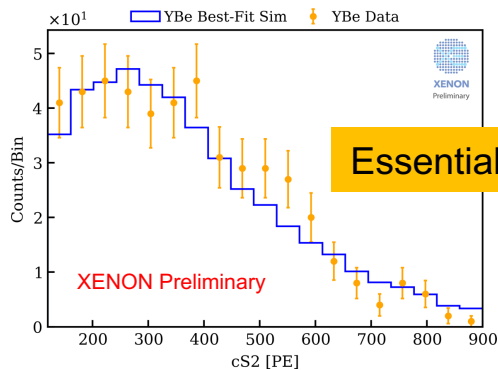


$$E_n = 152 \text{ keV}$$

$$E_{NR} < 4.6 \text{ keV}$$

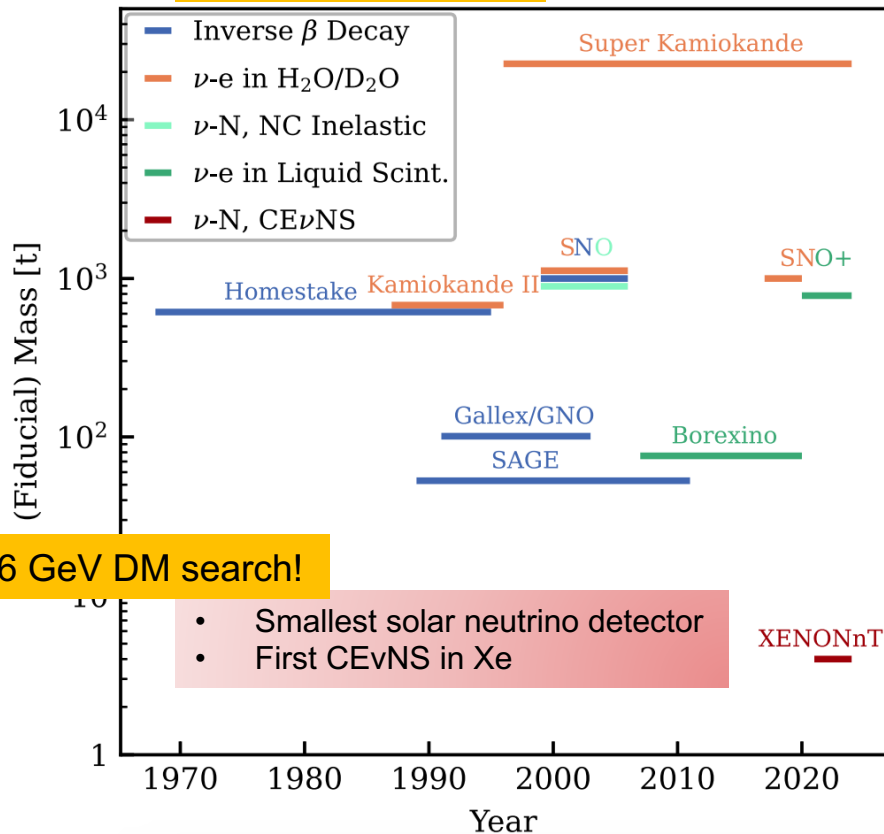


precise modeling
enables discovery



Essential step for future ~ 6 GeV DM search!

First measurements



- Smallest solar neutrino detector
- First CE ν NS in Xe

Dark Matter

- Dark photons
- Axion-like particles
- Planck mass

WIMPs

- Spin-independent
- Spin-dependent
- Sub-GeV
- Inelastic

Sun

- pp neutrinos
- Solar metallicity
- ${}^7\text{Be}$, ${}^8\text{B}$, hep

Neutrino Nature

- Neutrinoless double beta decay
- Double electron capture
- Magnetic Moment

Underground Astro-particle Observatory

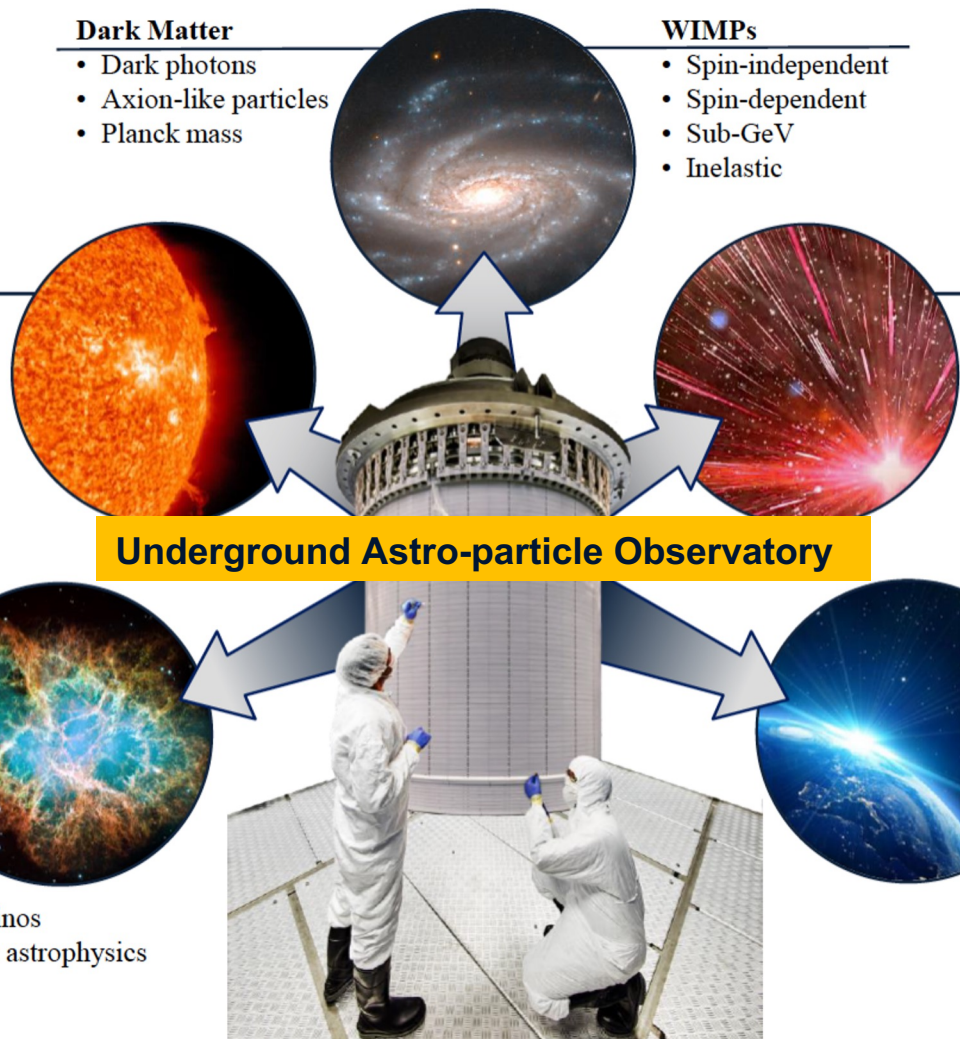
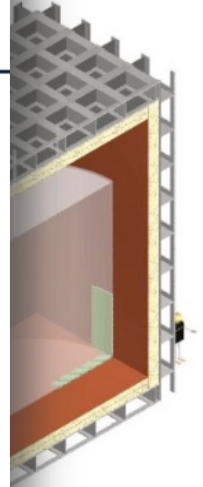
Supernova

- Early alert
- Supernova neutrinos
- Multi-messenger astrophysics

Cosmic Rays

- Atmospheric neutrinos

X
X
7
6

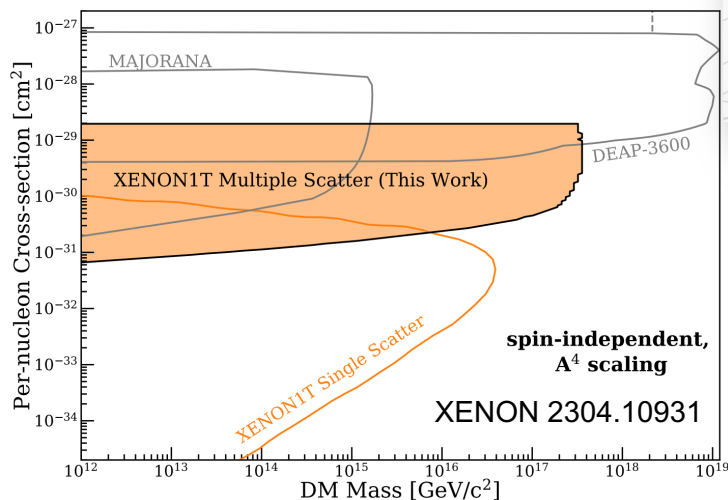
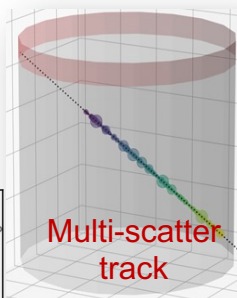


“Search wide” with existing detectors

Ultraheavy DM near Planck-scale (10^{19}GeV):
Well-motivated, low flux, clean signal

$$f(k, \theta) \approx -2\mu_A \int_0^{r_A} V(r') r'^2 dr' \quad \begin{matrix} \text{kinematic} \\ \text{coherence} \end{matrix}$$

$$\Rightarrow \sigma_{\chi A} \propto \frac{\mu_A^2}{\mu_N^2} A^2 \sigma_{\chi N} \sim A^4 \sigma_{\chi N}$$



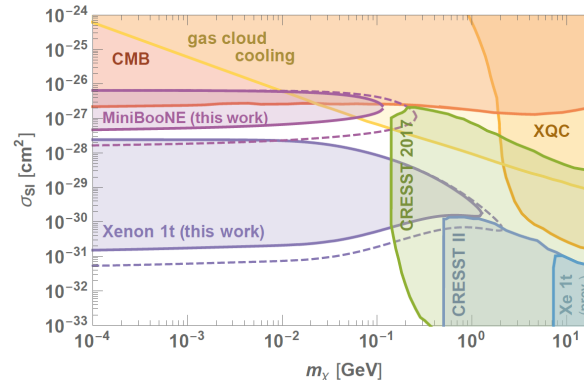
Also: DEAP 2108.09405, LZ 2402.08865

$p = mv$

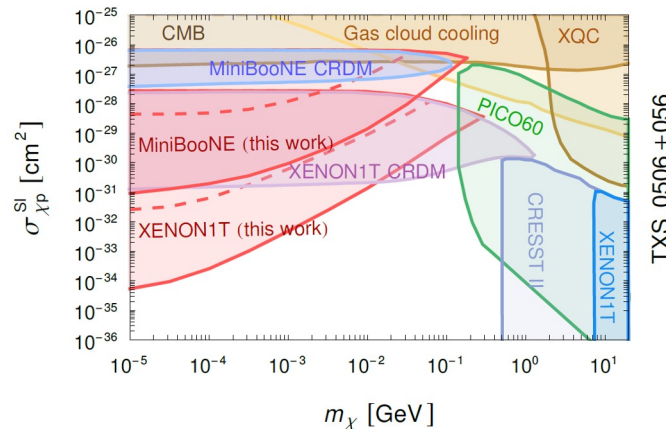
Large m ,
suppressed q in
C.O.M

Large v , large q ,
 $E_R > E_{th}$

Cosmic rays boosted DM 1810.10543

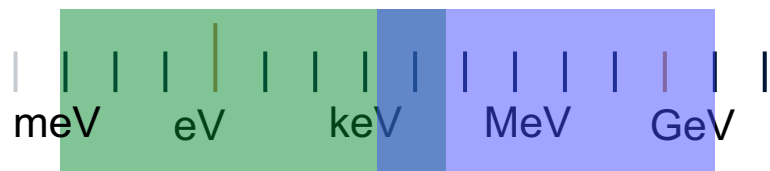


Blazar boosted DM 2111.13644



Check your neutrino detectors!

Sub-GeV DM: lowering detection threshold

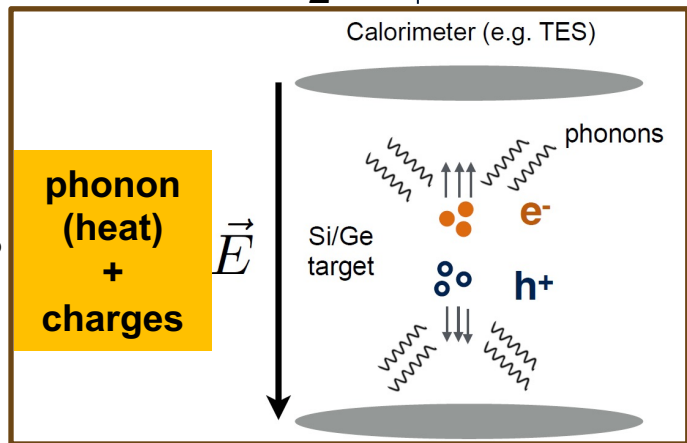


Absorption
(inelastic)

DM-Electron

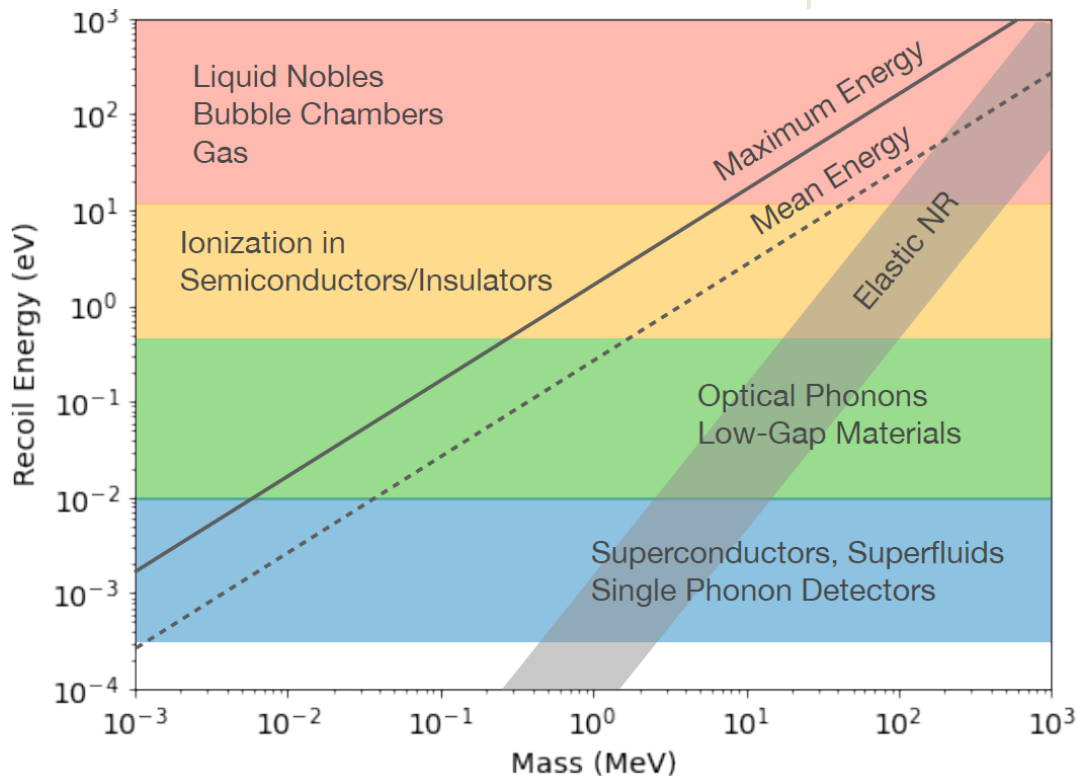
$$E_k = \frac{m_\chi v^2}{2}$$

$$E_R^{max} = 2 \frac{\mu_{\chi e}^2 v^2}{m_e}$$

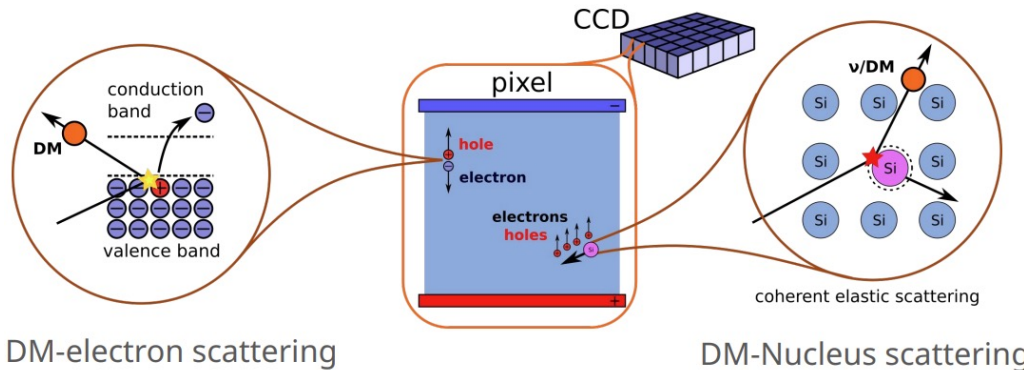


Shengchao Li: DM Direct Detection

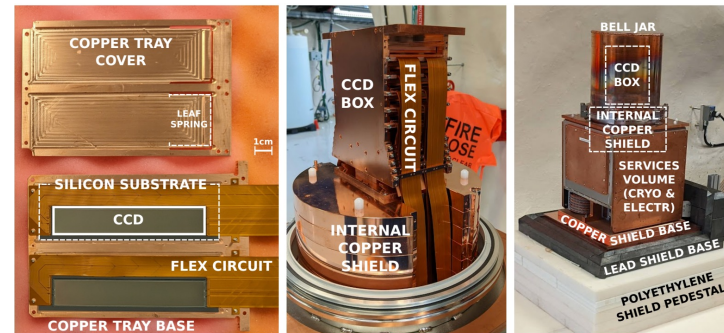
Snowmass 2021 2203.08297



SENSEI / DAMIC-M / Oscura: Skipper-CCDs

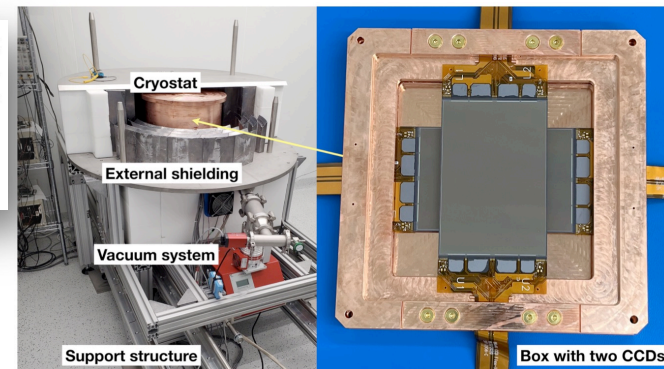


SENSEI



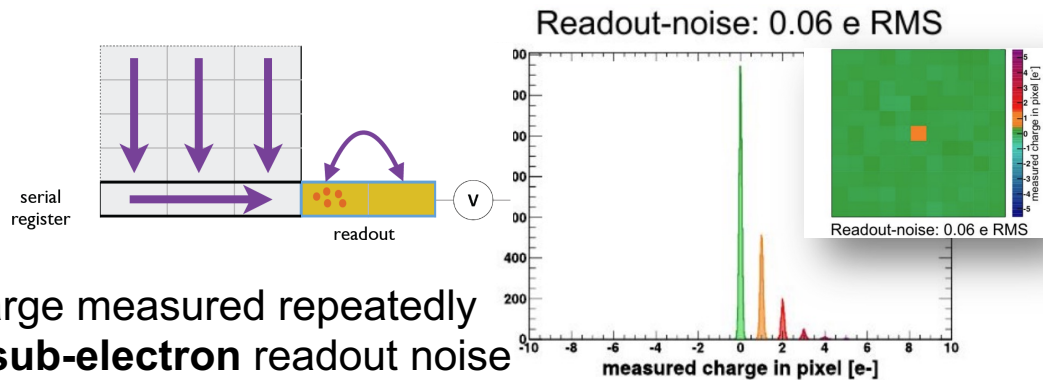
6k x 1k pixels, mass 2.19 g

DAMIC-M



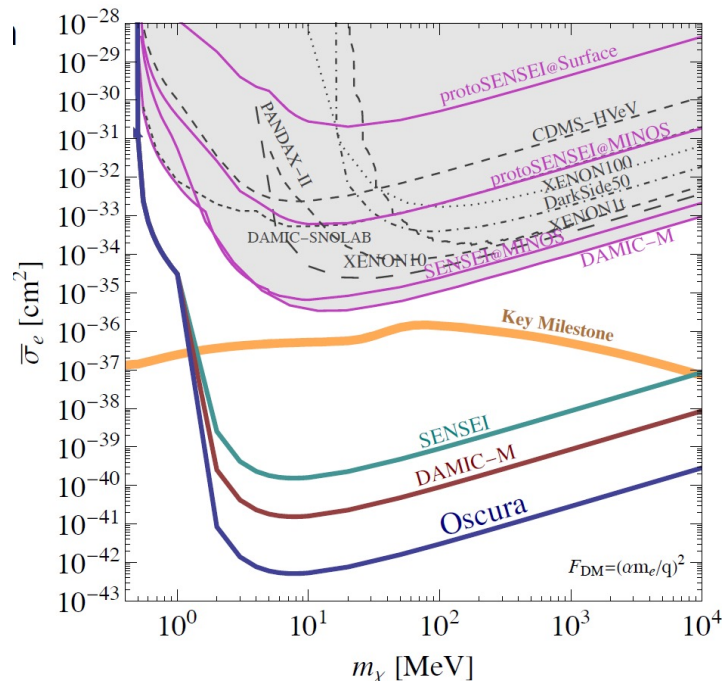
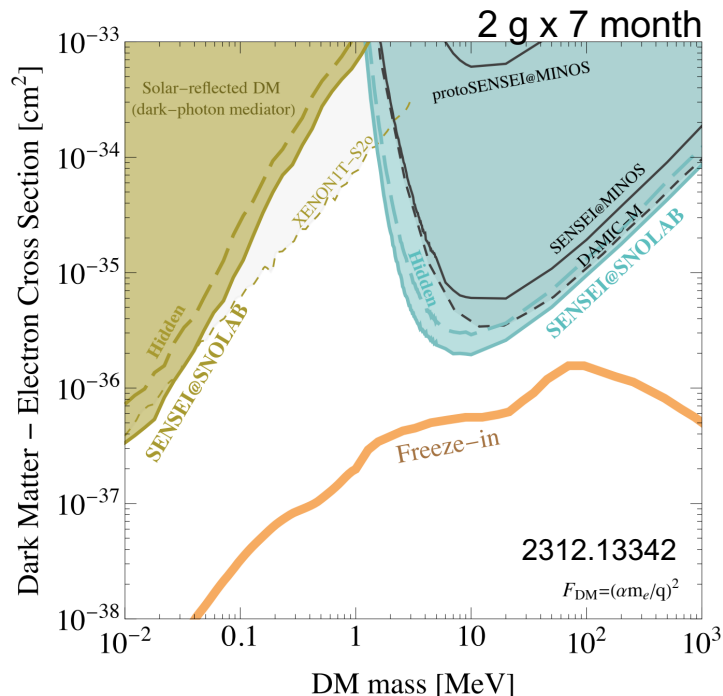
2 CCDs, 4k x 6k pixels

CR: A. Botti COSSURF22



charge measured repeatedly
-> **sub-electron** readout noise

Skipper-CCD results

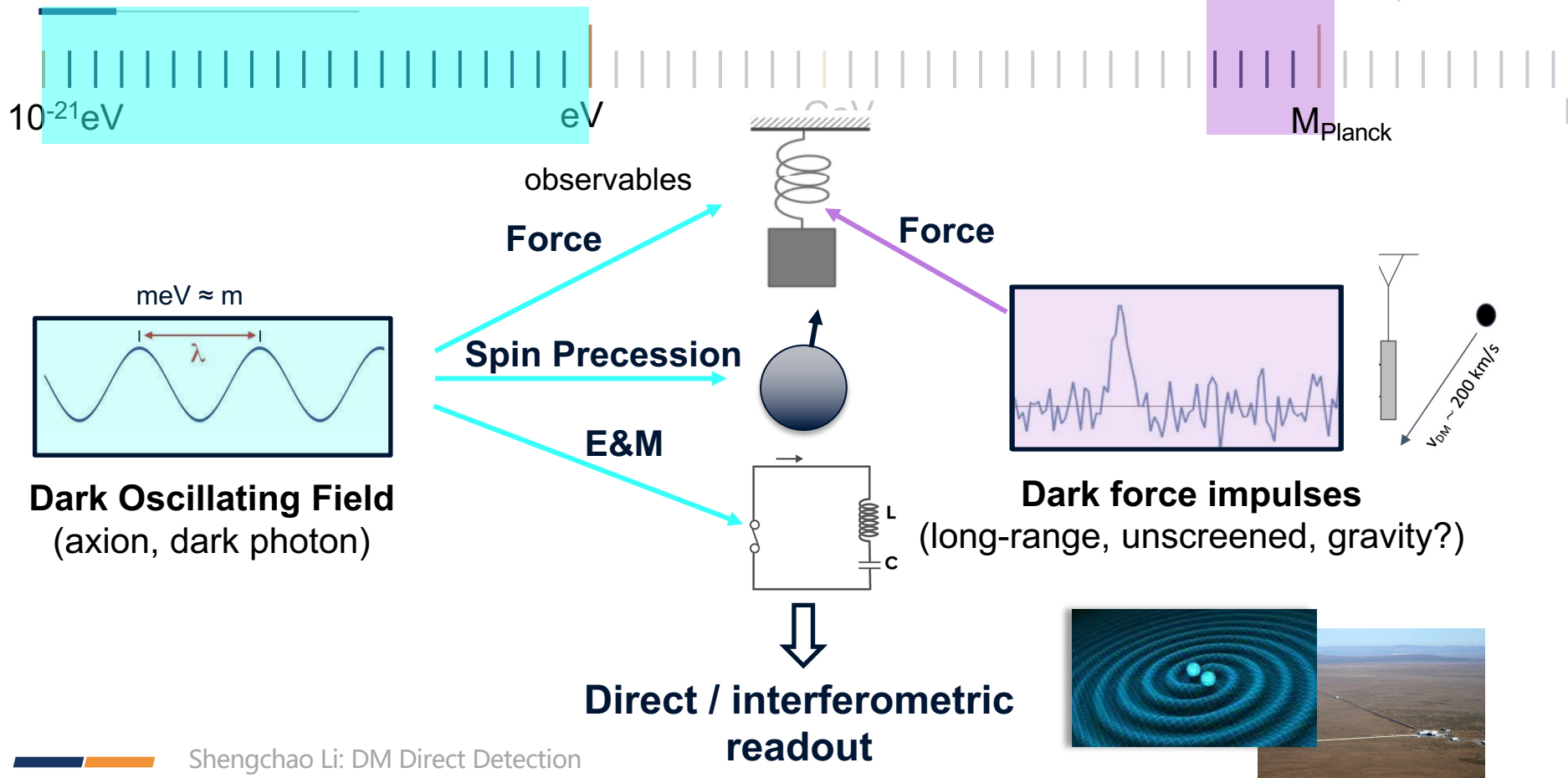


SENSEI 2023 SNOLAB result

Also, heavy mediator, Migdal, dark photon results

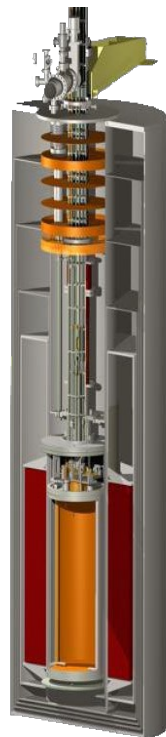
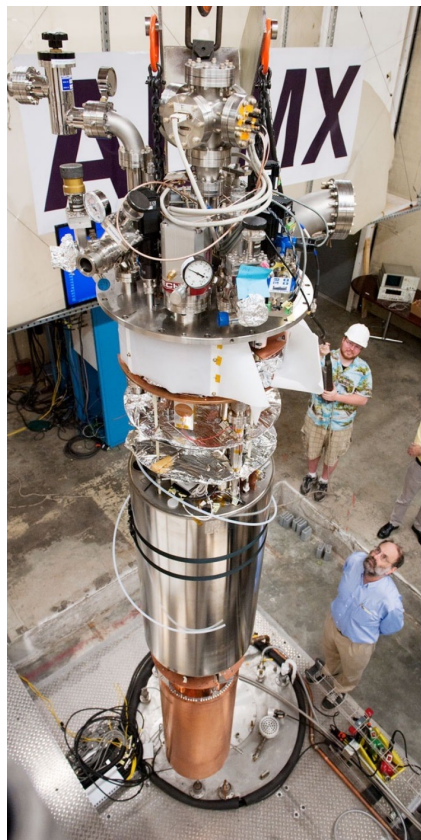
Push orders of magnitude into “freeze-in”
 SENSEI(100g) DAMIC-M(1kg) Oscura(10kg)
Need: understand low-energy “excess”

Wave Dark Matter: coherent resonance



ADMX haloscope: galactic axions search

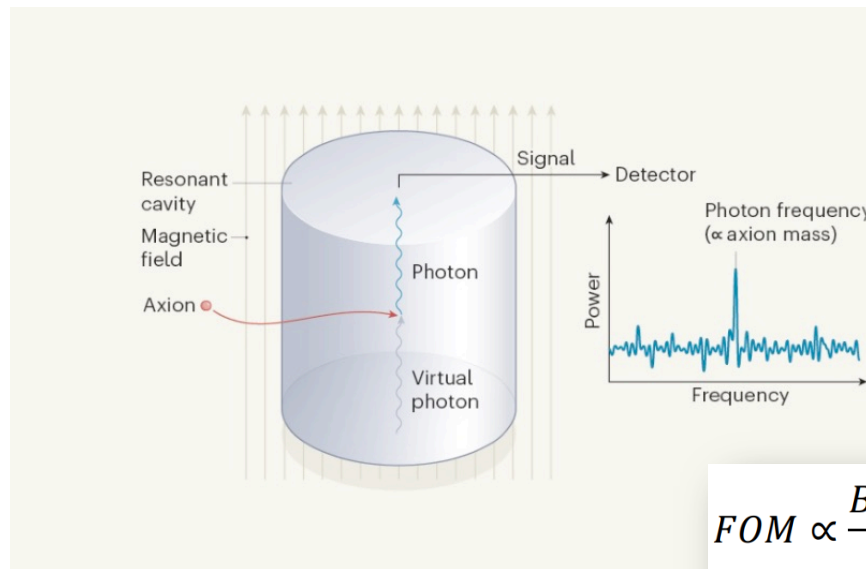
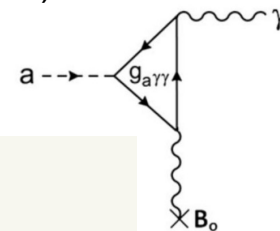
2410.09203



7T, 100mK

Primakov Effect (axion coupling with photons)

$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma}}{4} F_{\mu\nu} \tilde{F}_{\mu\nu} a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B} a$$



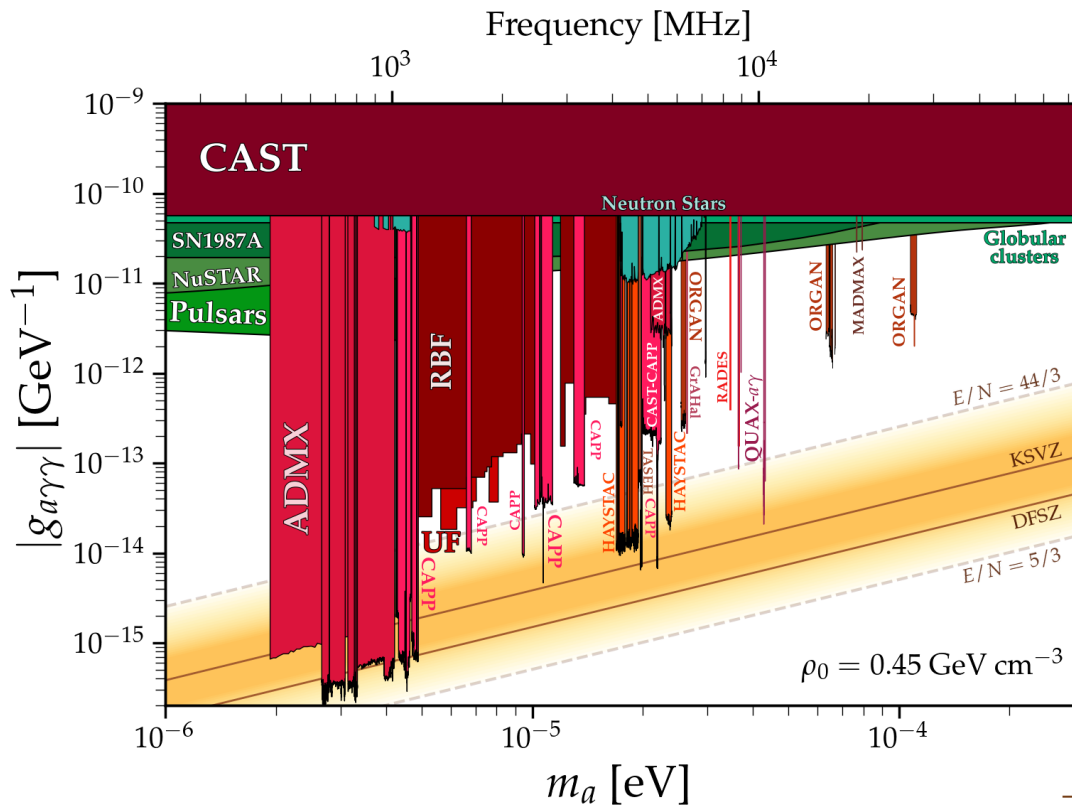
$$FOM \propto \frac{B^4 V^2 C^2 Q}{T_{SYS}}$$

Tunable resonant cavity

Scanning one frequency at a time, but can lock-in signal

Axion search results

<https://cajohare.github.io/AxionLimits/>



QCD axion:

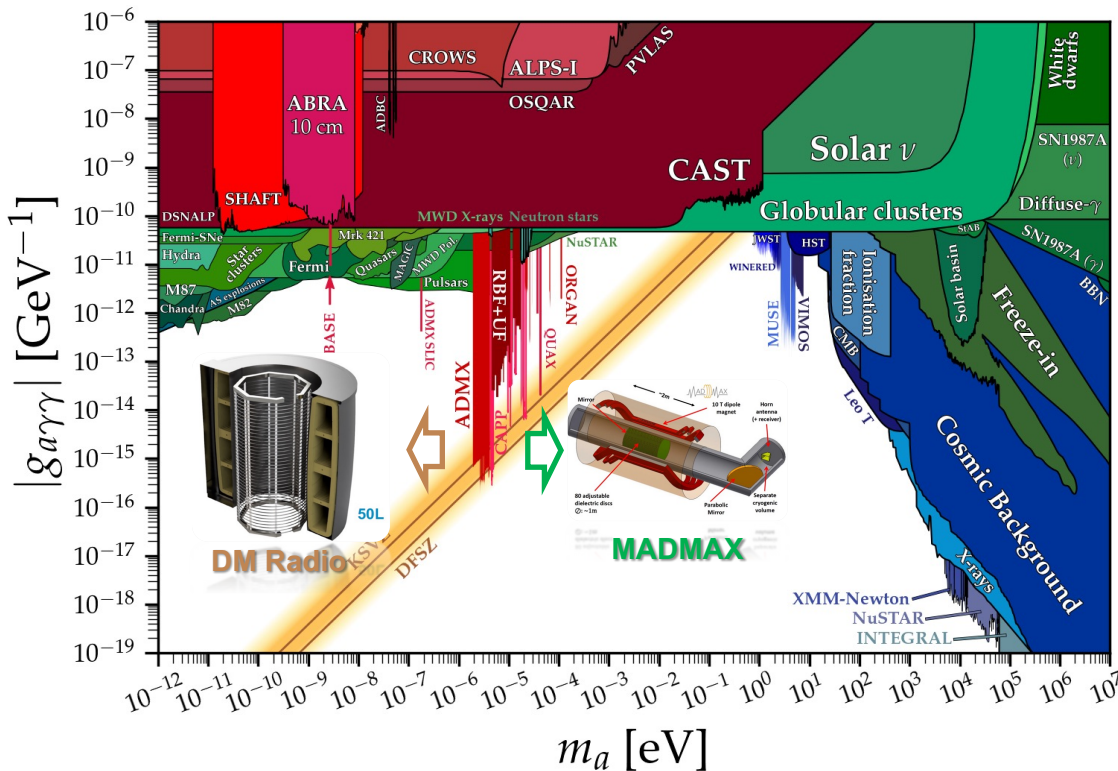
$$\mathcal{L} \supset \left(\theta + \frac{a(x)}{f_a} \right) \frac{g_s^2}{32\pi^2} G\tilde{G}$$

solves strong-CP problem

$$m_a \sim 10^{-6} - 10^{-4} \text{ eV}$$

Axion search results

<https://cajohare.github.io/AxionLimits/>



QCD axion:

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Axion-like particles:

generic scheme and wider parameter space

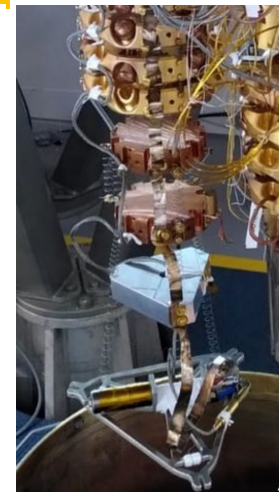
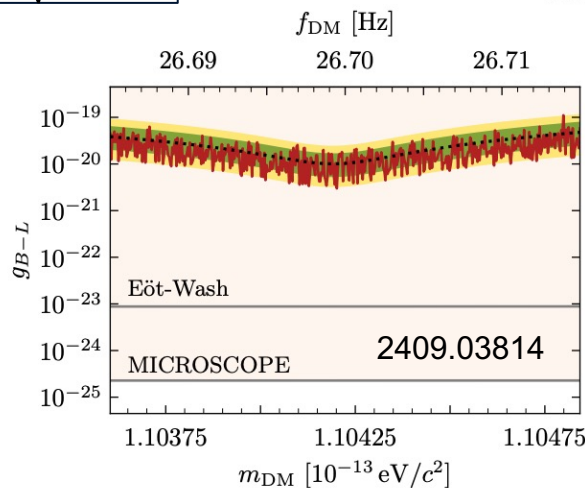
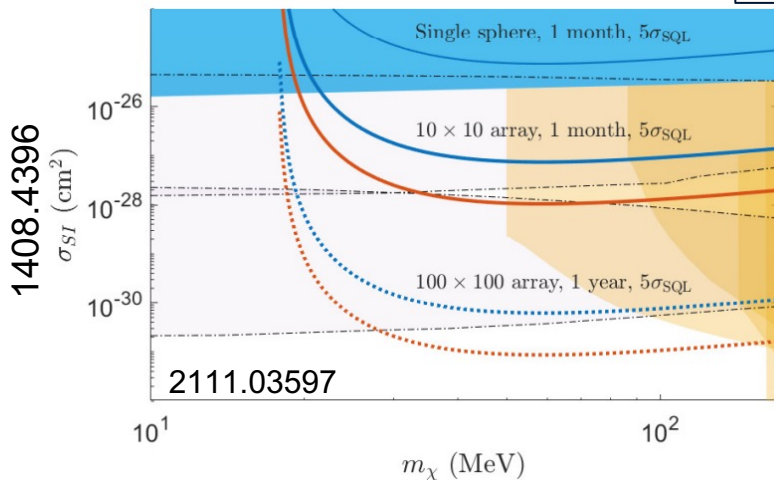
New search techniques to search **post-inflation** and **GUT-scale** axions

Quantum-enhanced DM force sensor

Optic

$$\omega_0 = \sqrt{k/m}$$

Magnetic



Macroscopic sensor measured:

- DM recoils
- DM force wave (axion, DP, B-L)

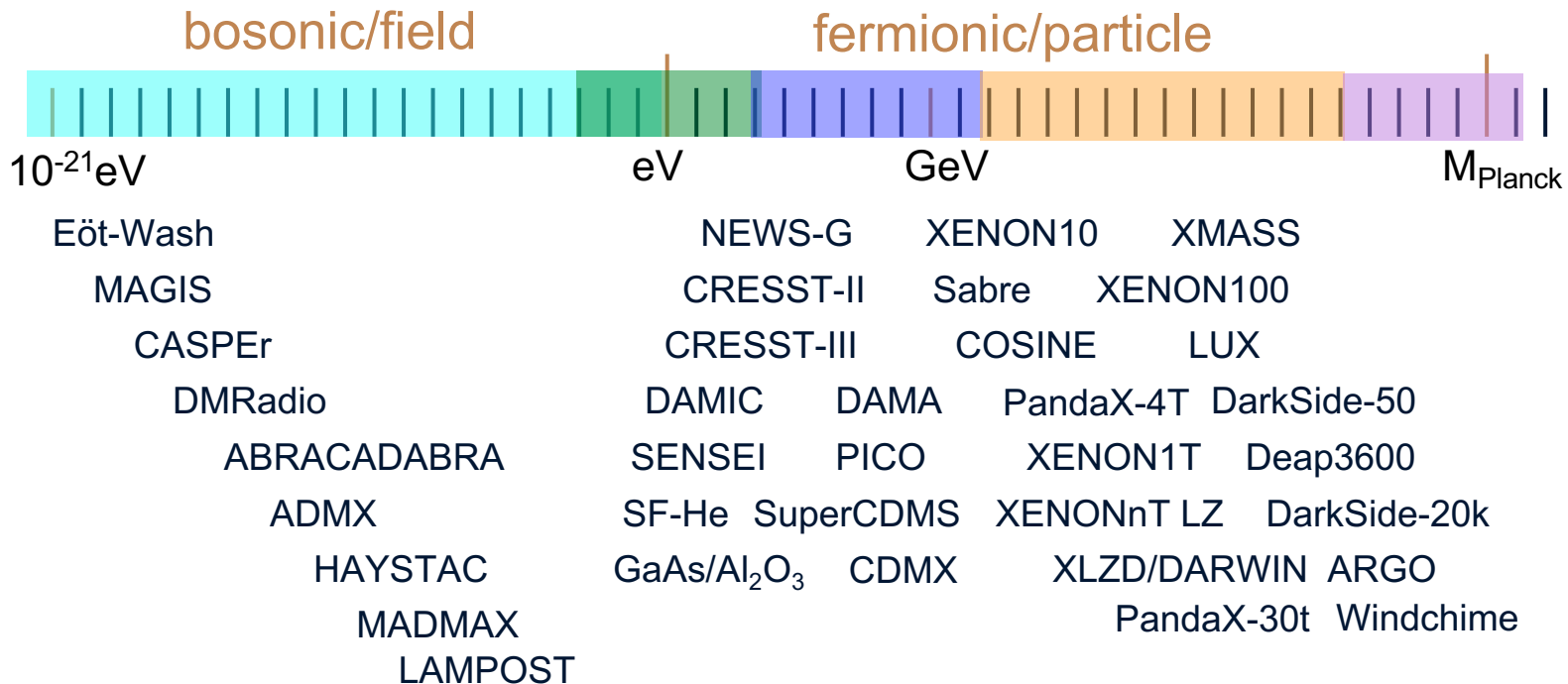
readout

beyond SQL

Vision: 10^9 array to probe
 ~6 orders better, even
 “**gravitational floor**”

Windchime: 2203.07242

Versatile DD programs



Delve Deep, Search Wide



Conclusions

- **Direct Detection** uses the *Physics in Collision* to understand **DM nature**
- By working principle, we look for “**nonrelativistic kicks**” or “**collective resonance**” in our DM detectors
- **Rapid progress** made for priority DM candidates (**WIMP**, **QCD axion**), next-gen experiments on the way
- **Wide spectrum** experimentally: **ton-scale** vs. **table-top**, many creative ideas turning into reality
- **Pre-Socratic period** for discovery



Artist: OpenAI