Direct Dark Matter Searches

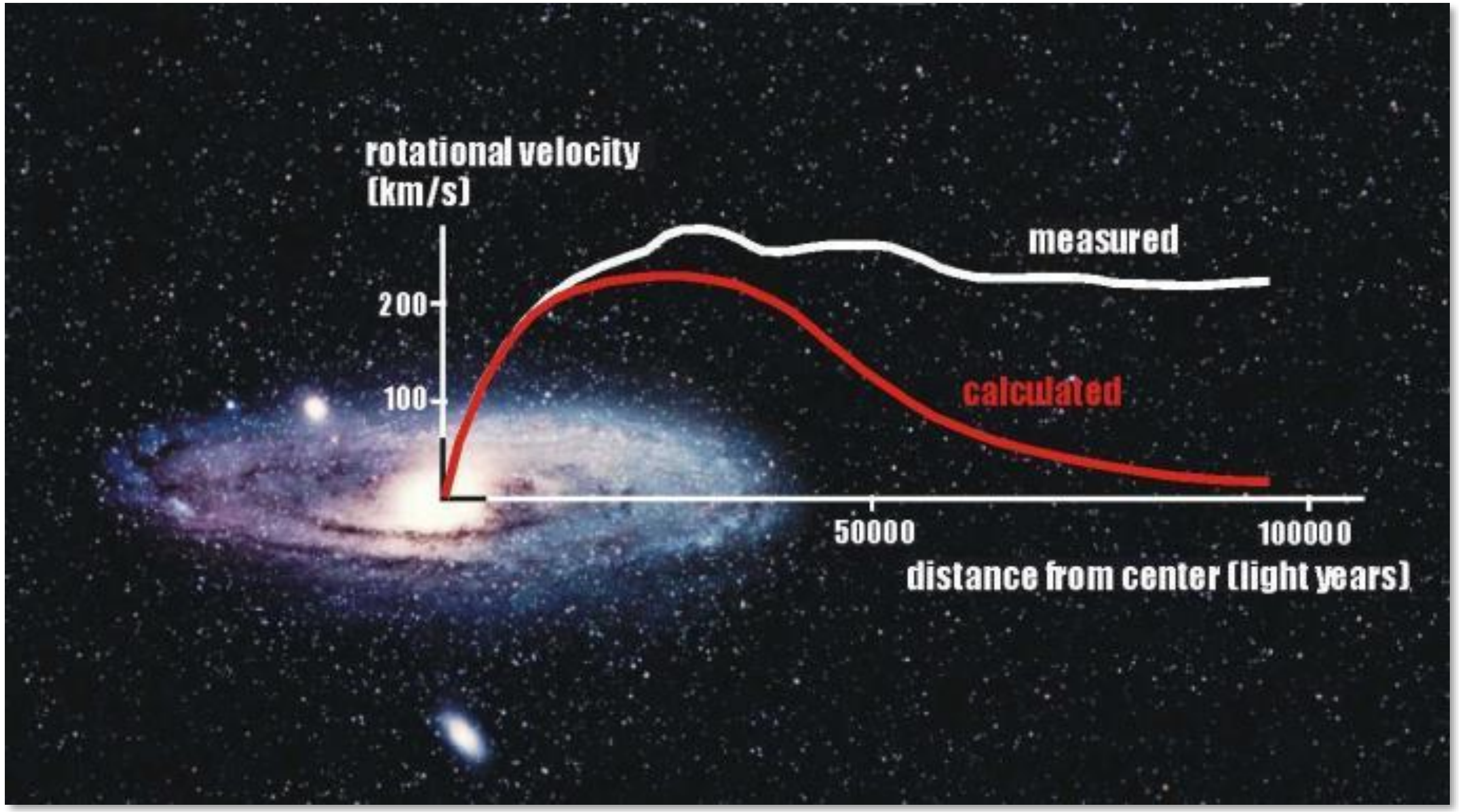
Wolfgang Rau, TRIUMF

Overview

- Evidence for Dark Matter
- Dark Matter Candidates
- Ways to detect Dark Matter
- Direct Detection of Dark Matter
- Conclusions

Evidence for Dark Matter

Galactic scale: Rotation curves



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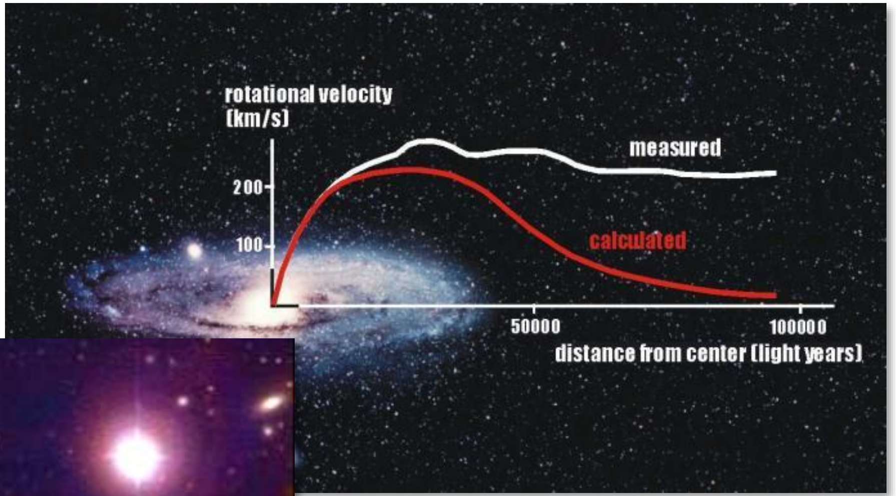
- Peculiar motion



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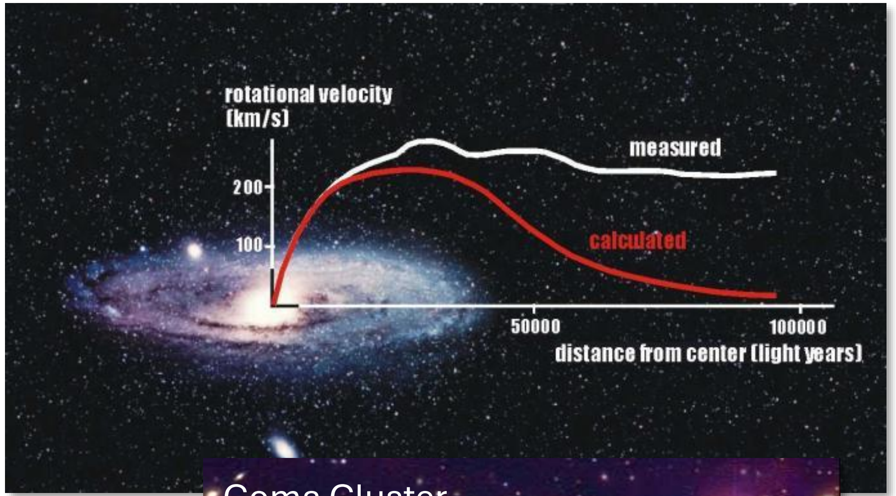

Cluster scale:
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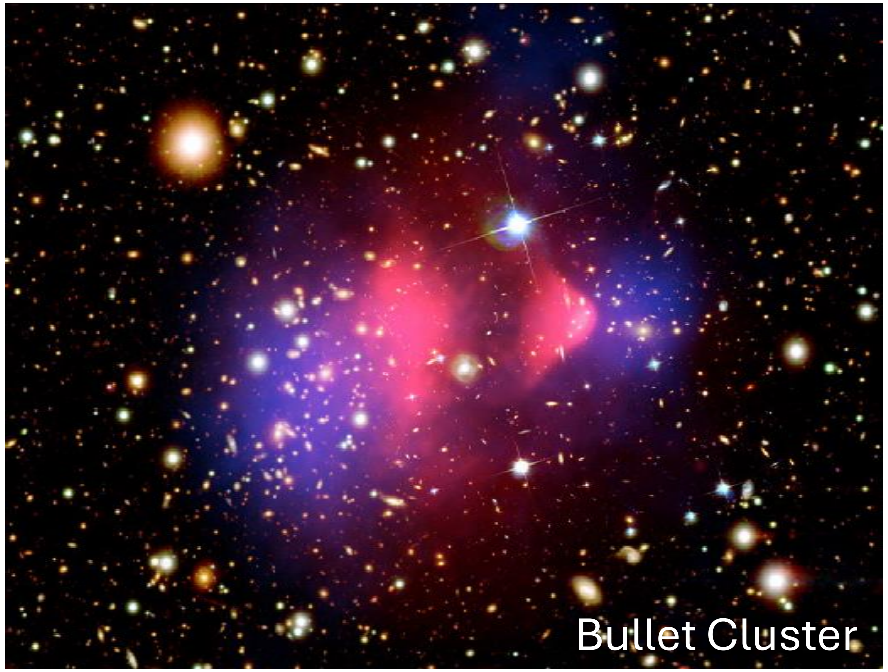
- Centre of gravity offset from centre of visible mass


Coma Cluster


Bullet Cluster

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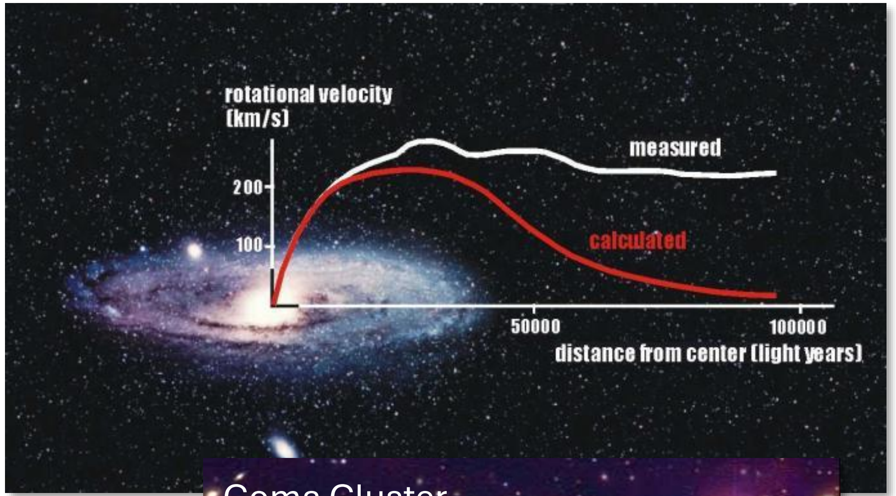

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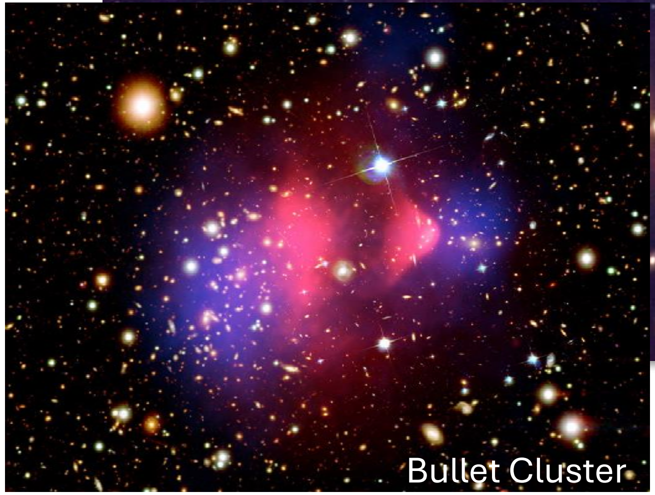
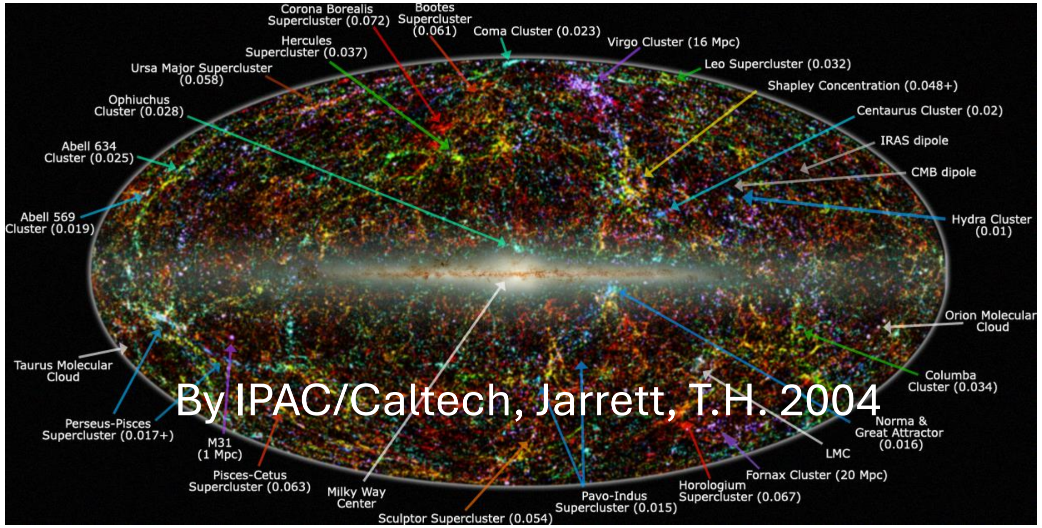


Large scale structure



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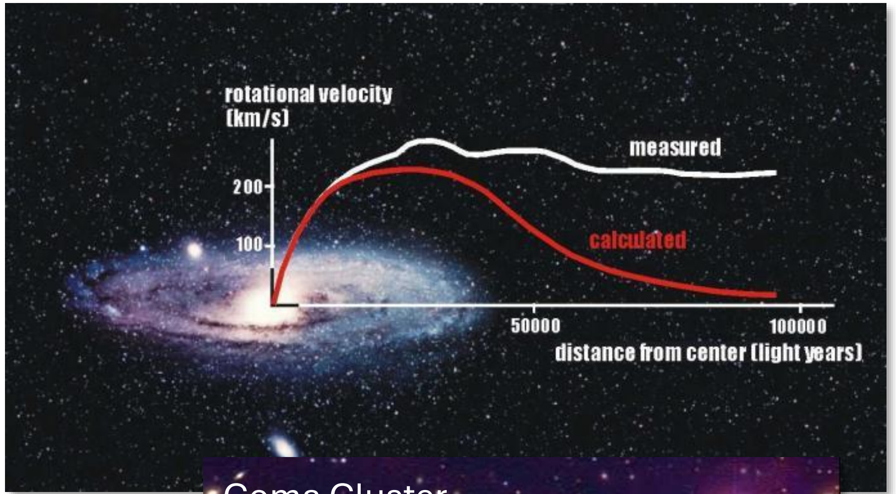

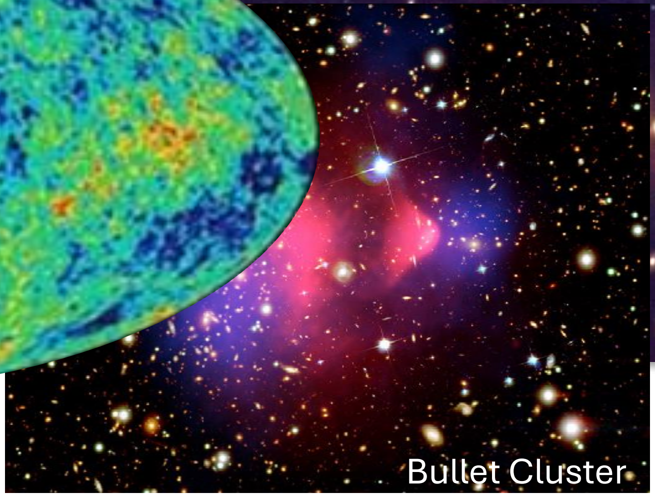

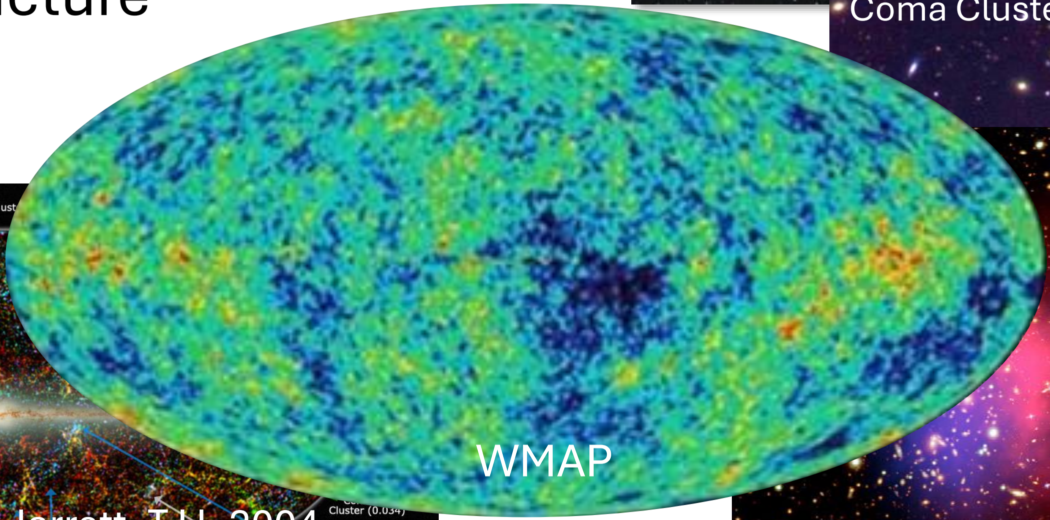

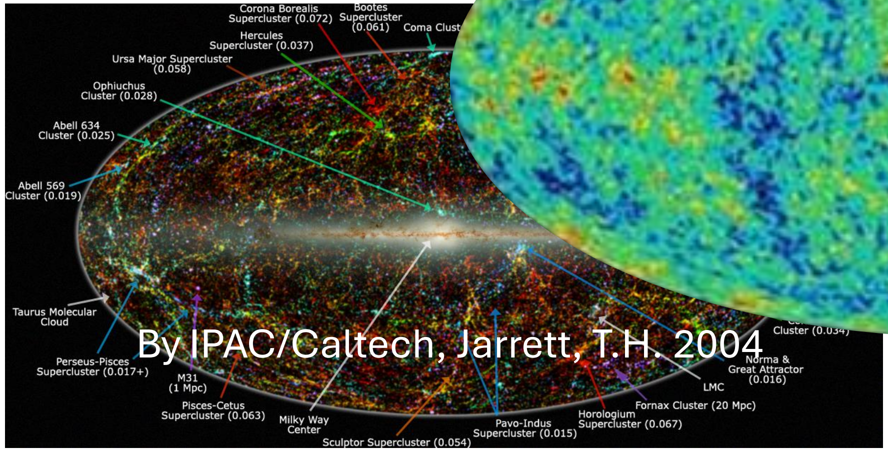

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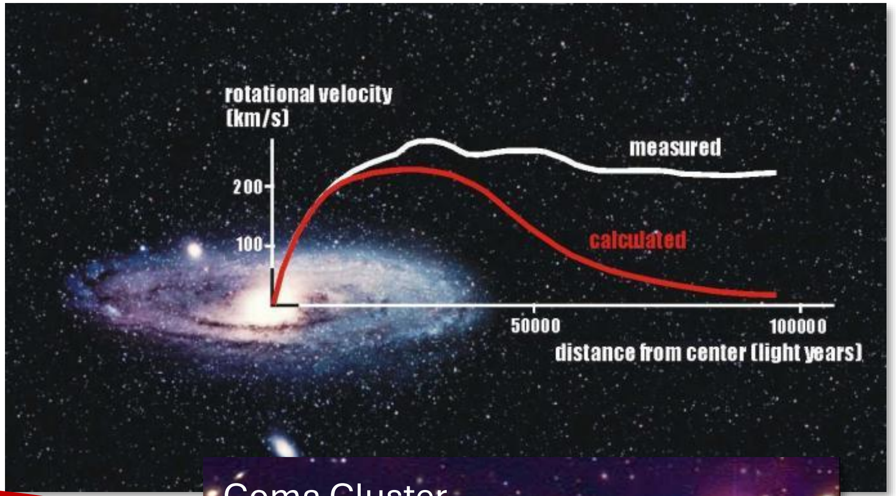
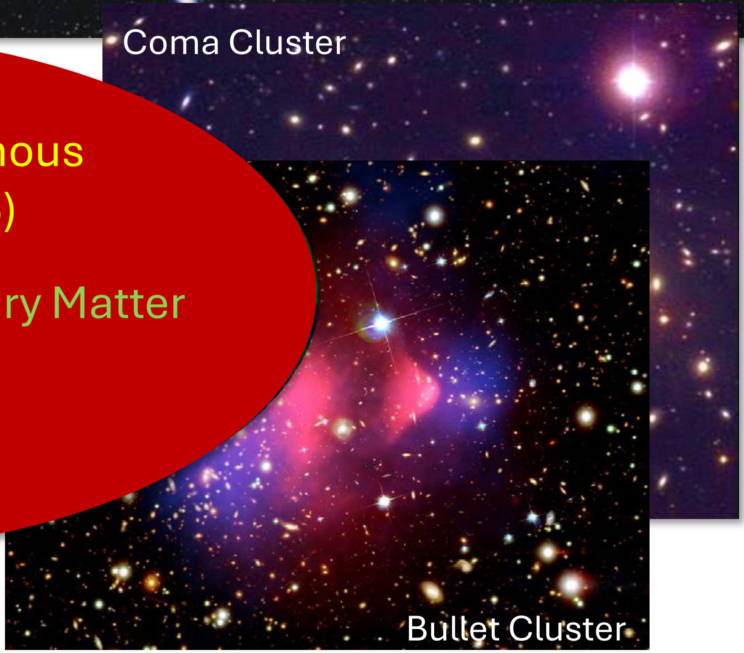
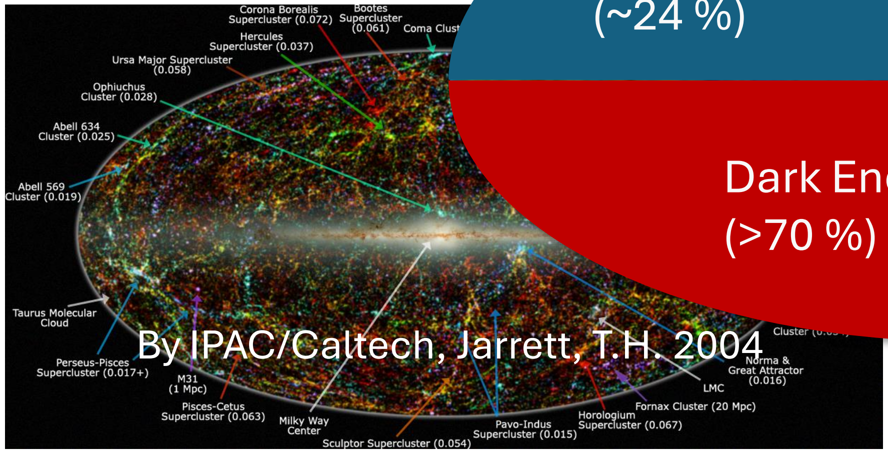
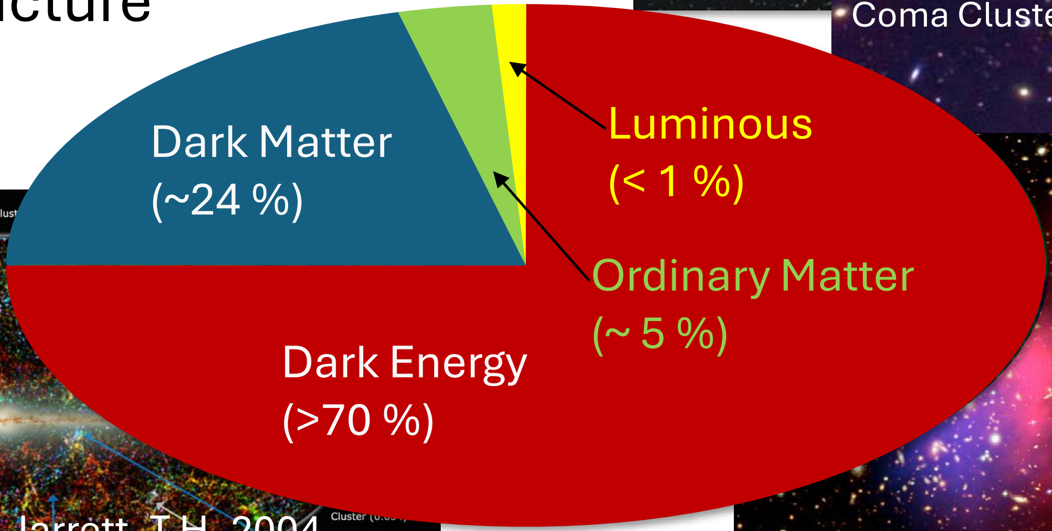






By IPAC/Caltech, Jarrett, T.H. 2004



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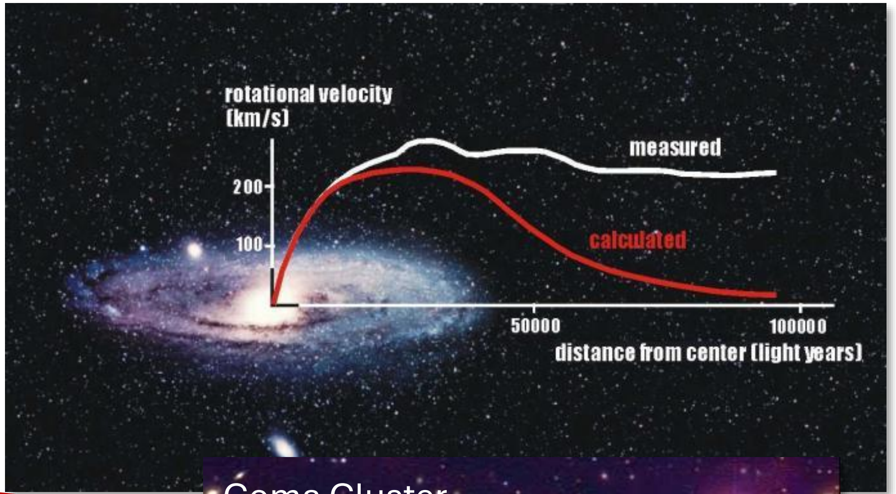
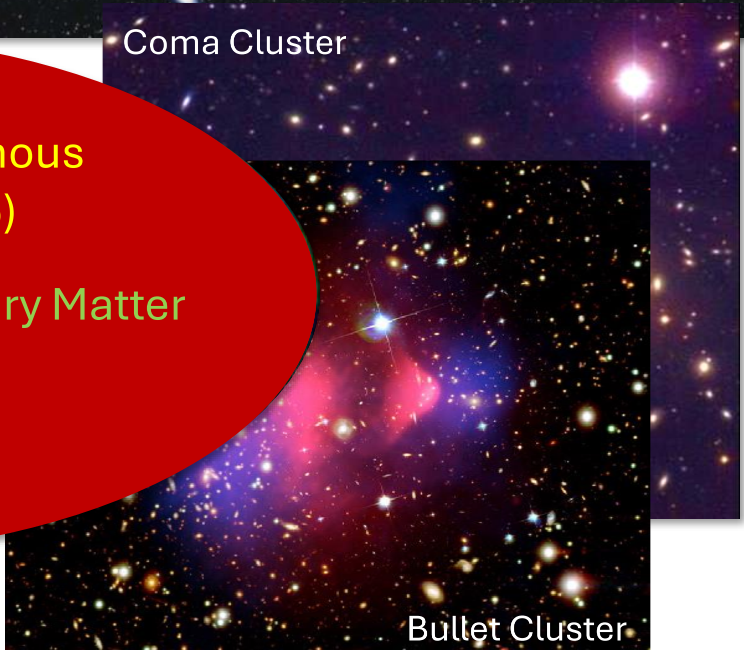
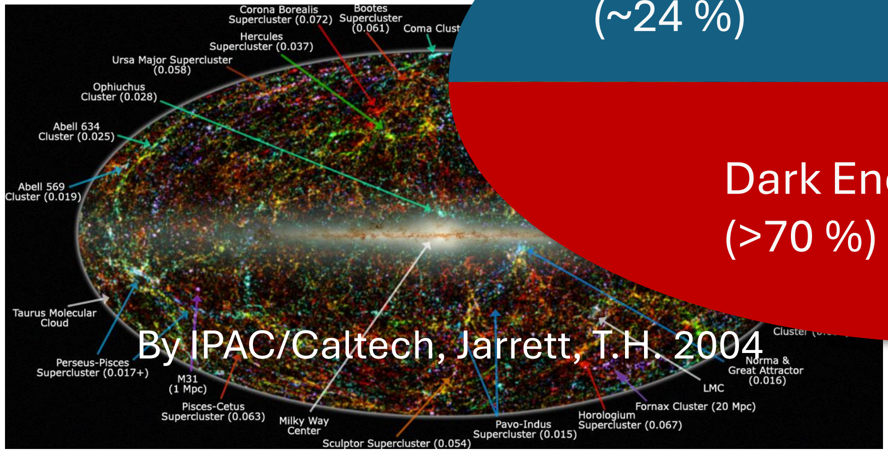
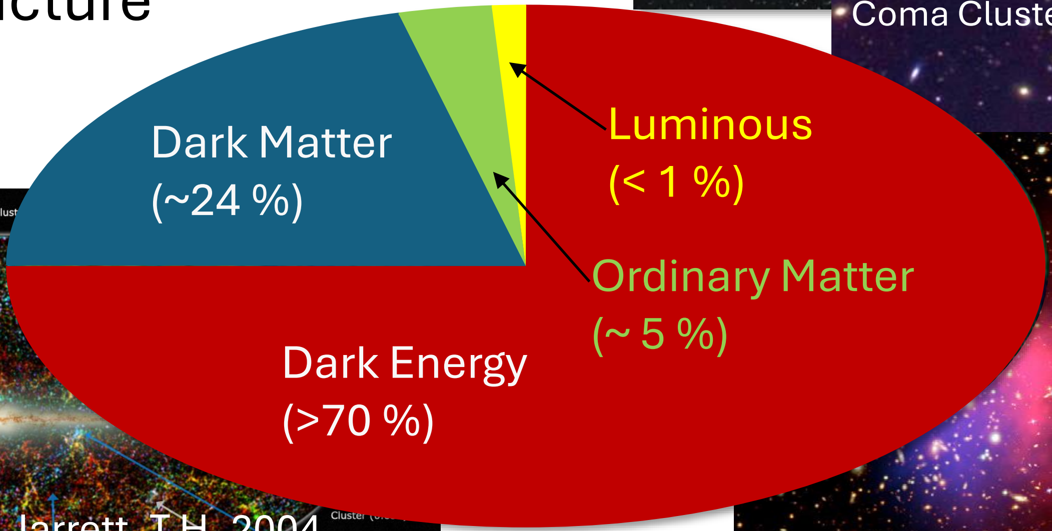






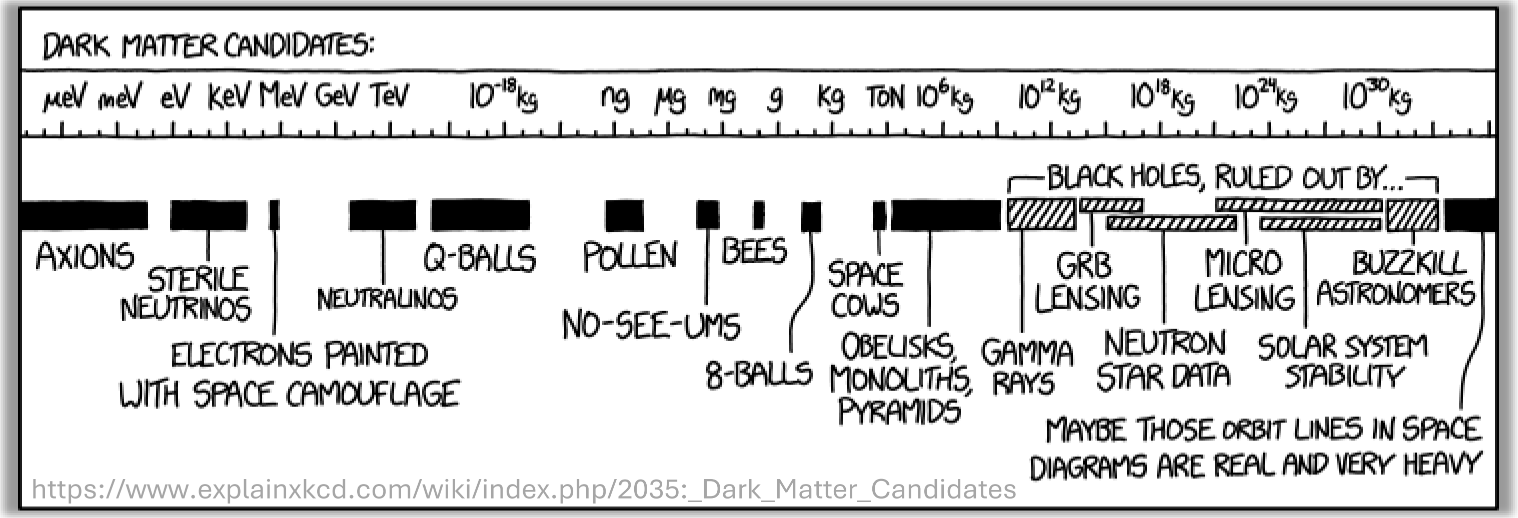


Only ~16% of matter is understood

Rest is unknown Dark Matter

Dark Matter Candidates

The Wannabe Scientist



Dark Matter Candidates

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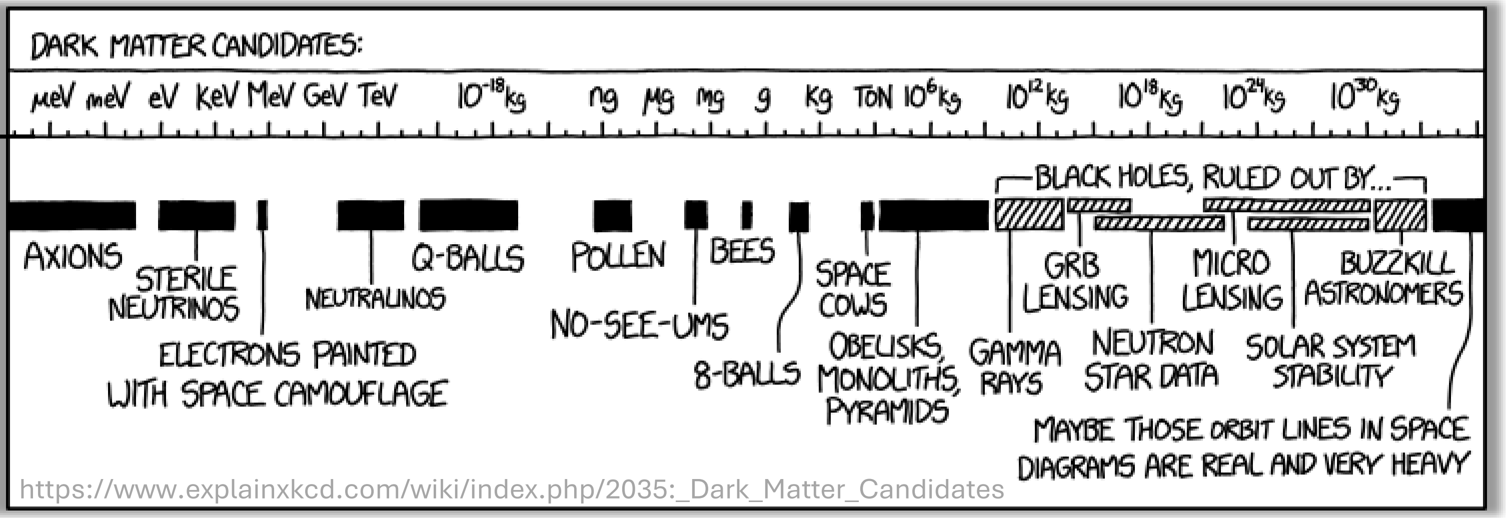
10^{-22} eV

fuzzy DM



https://www.explainxkcd.com/wiki/index.php/2035:_Dark_Matter_Candidates

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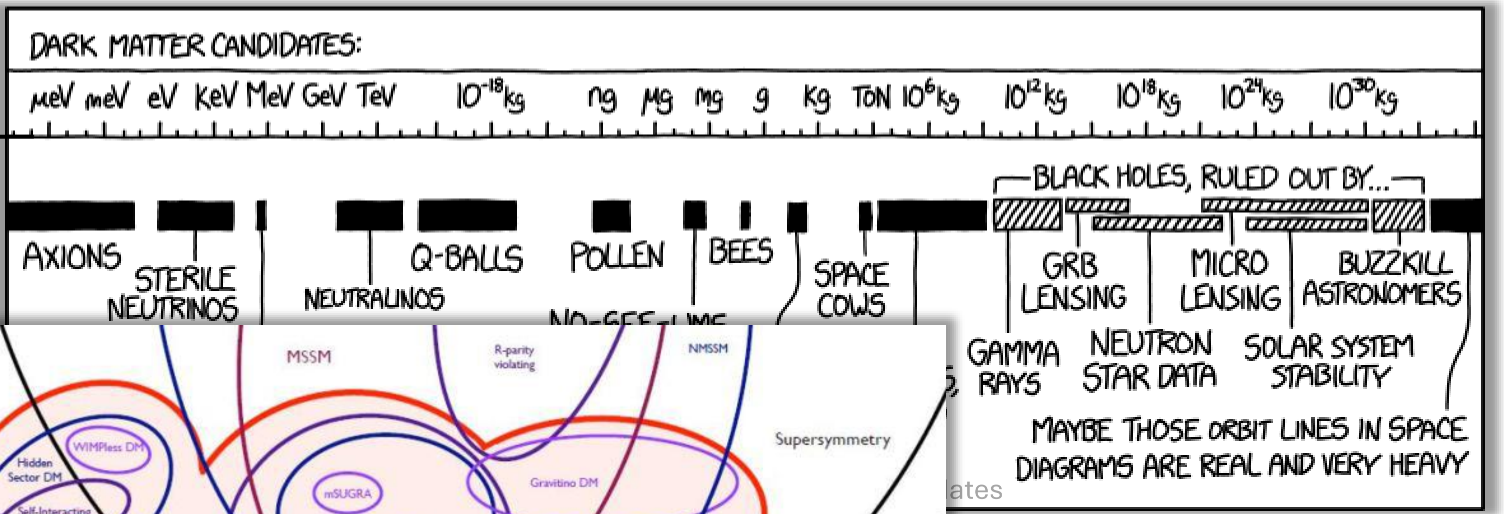

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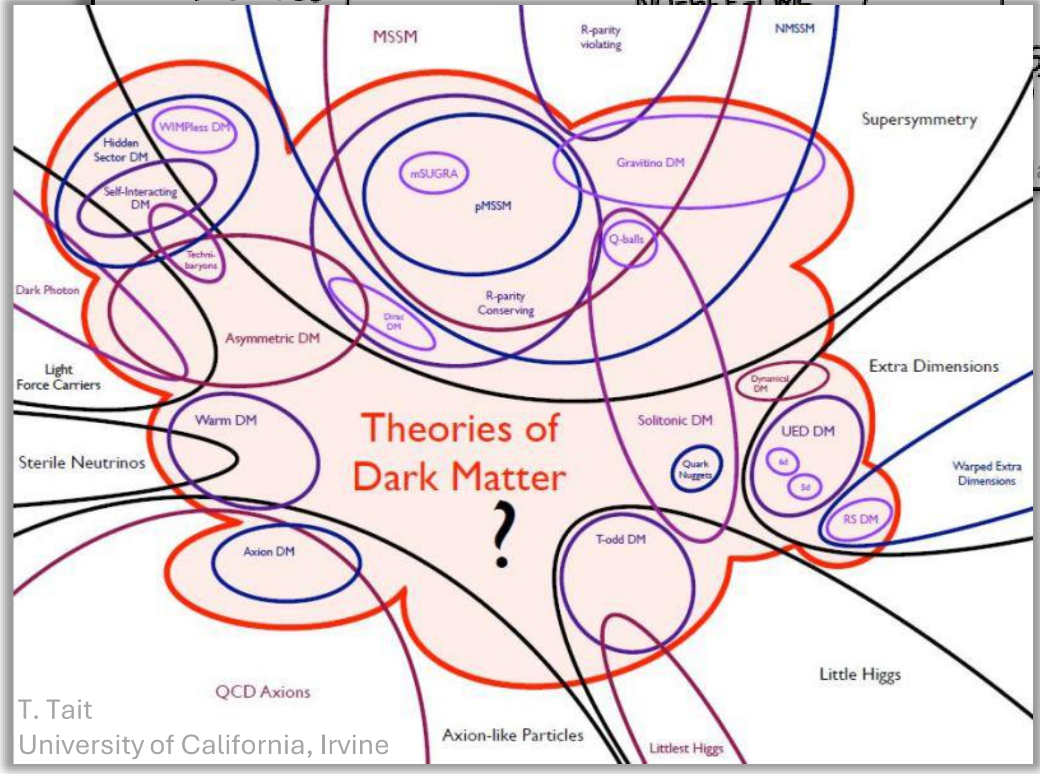

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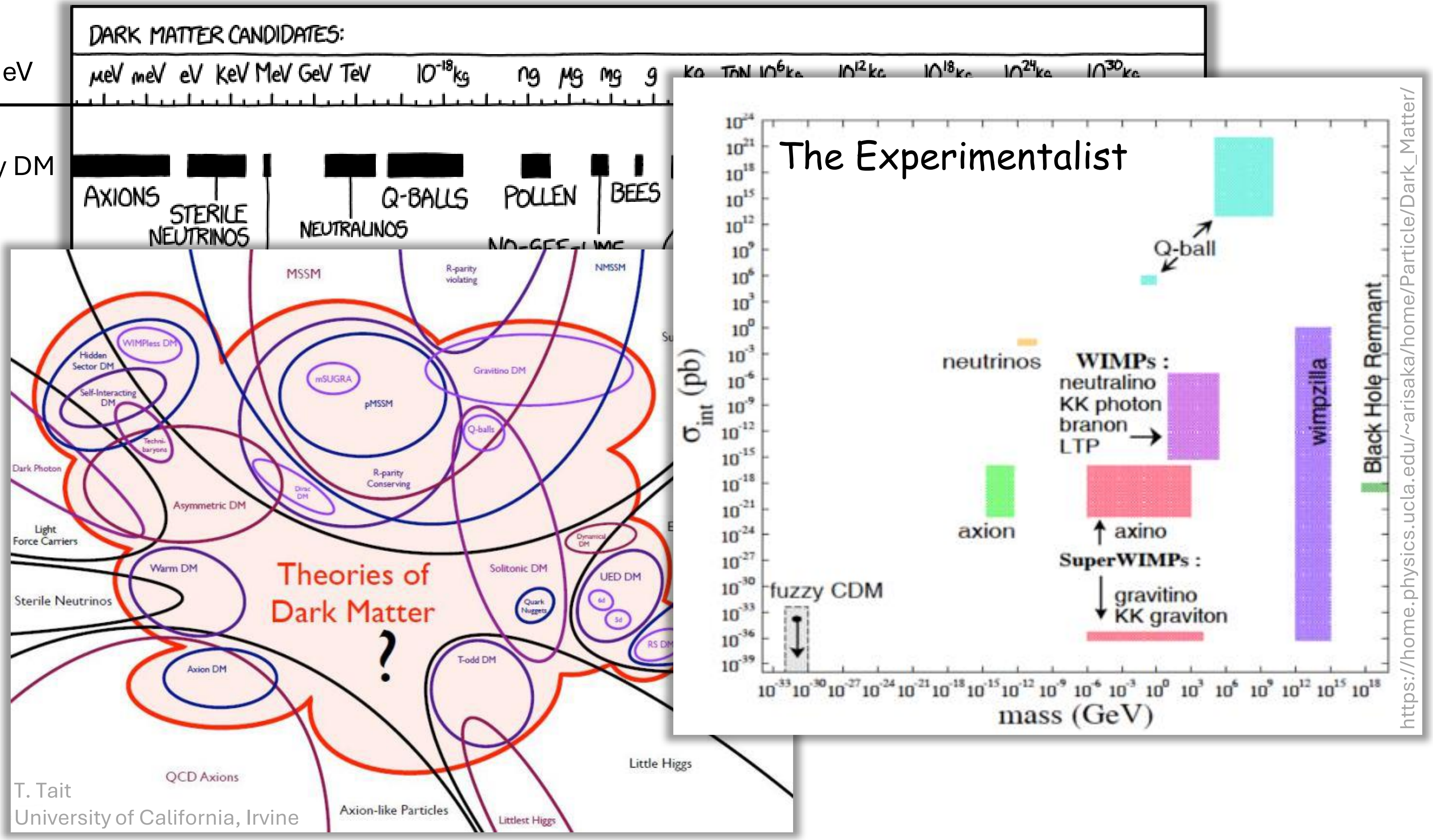

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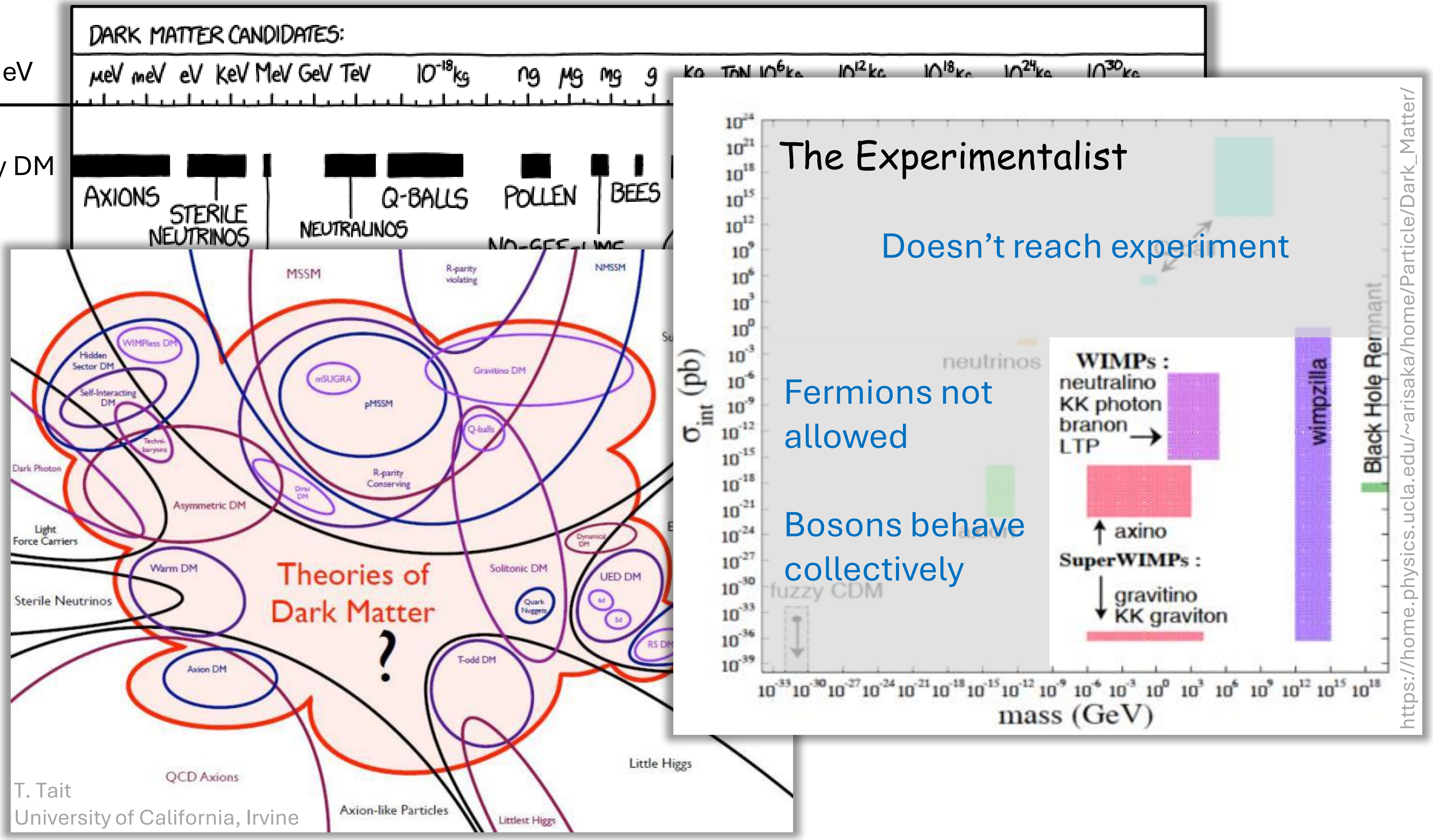

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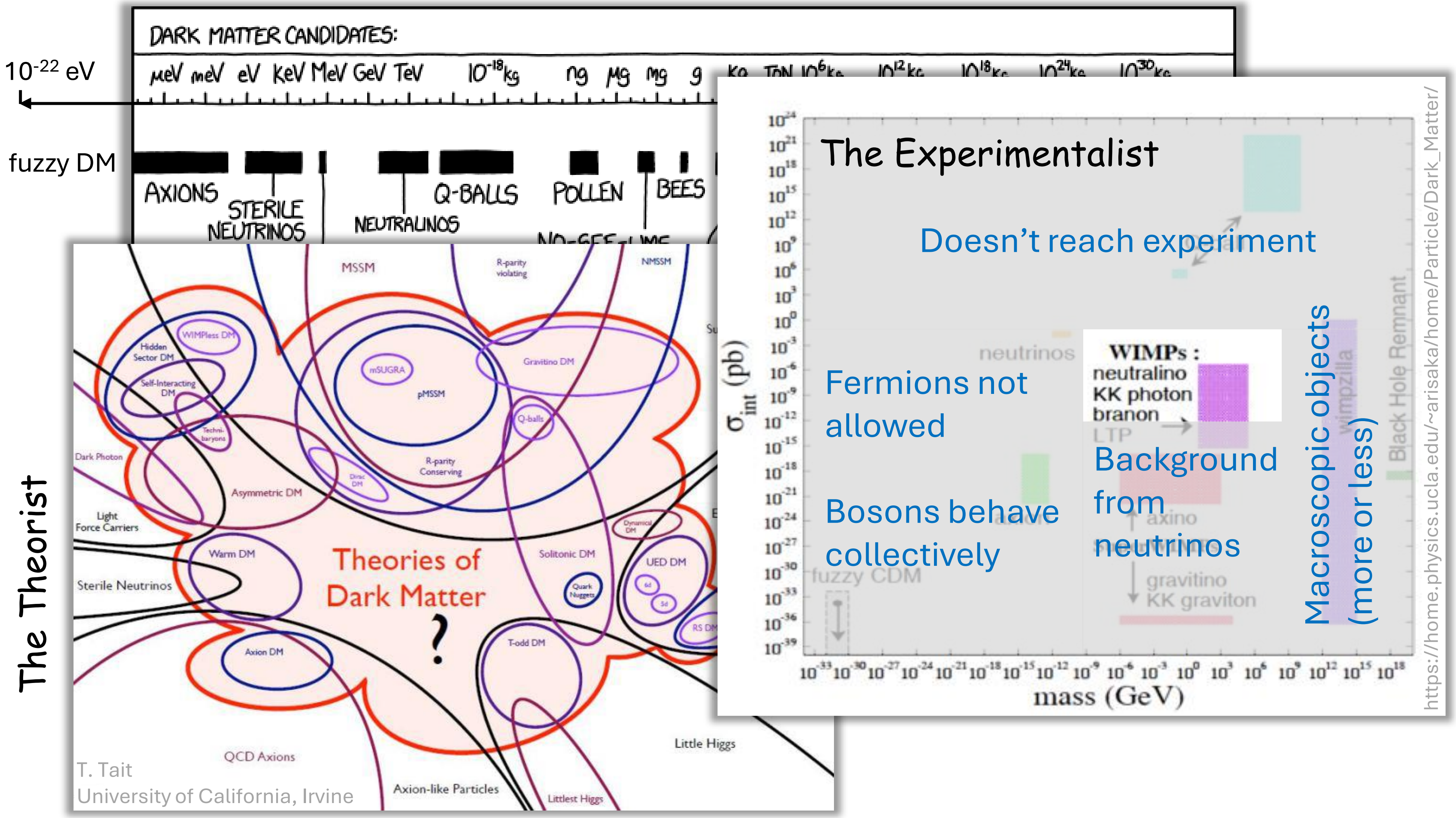

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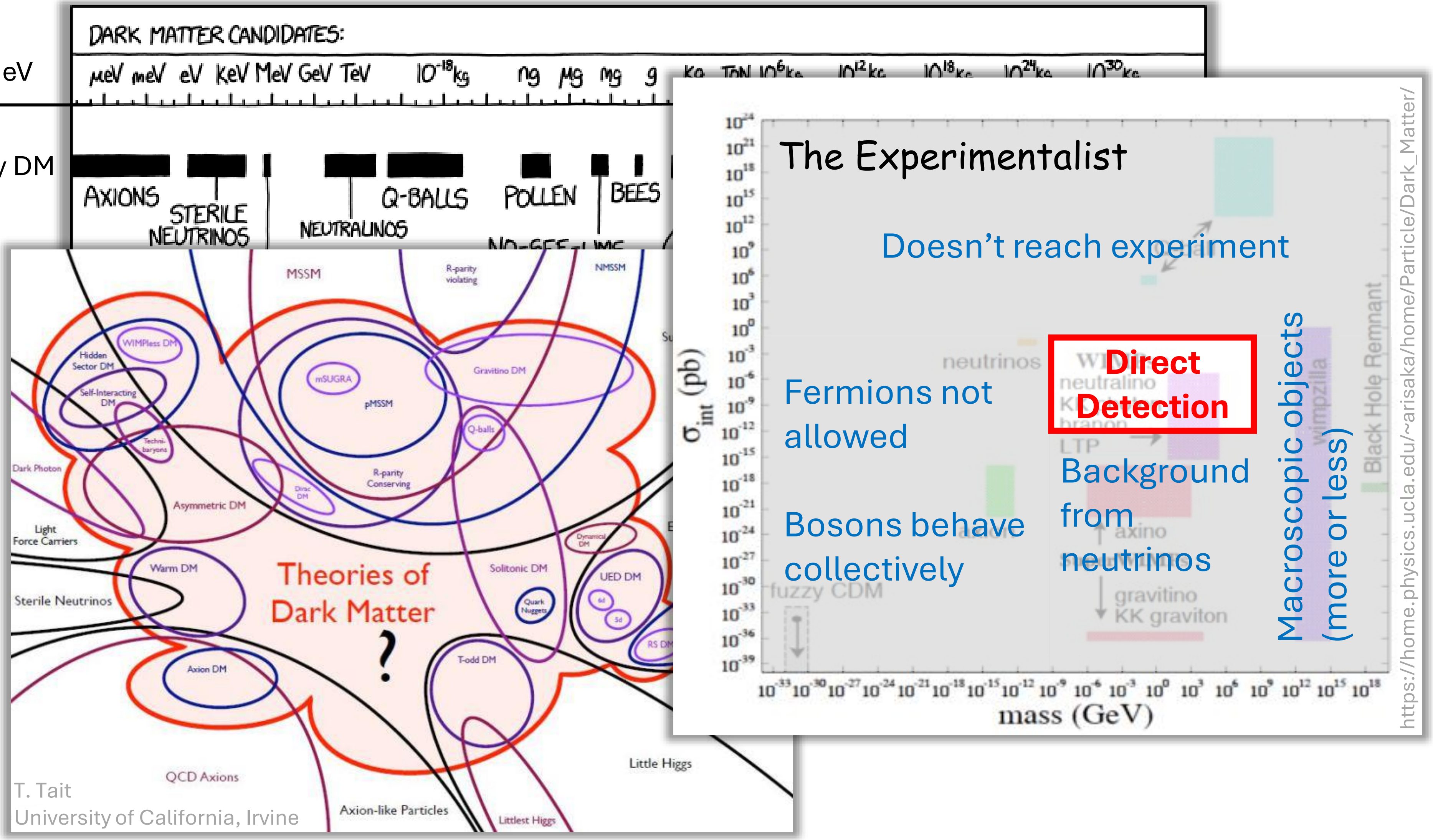
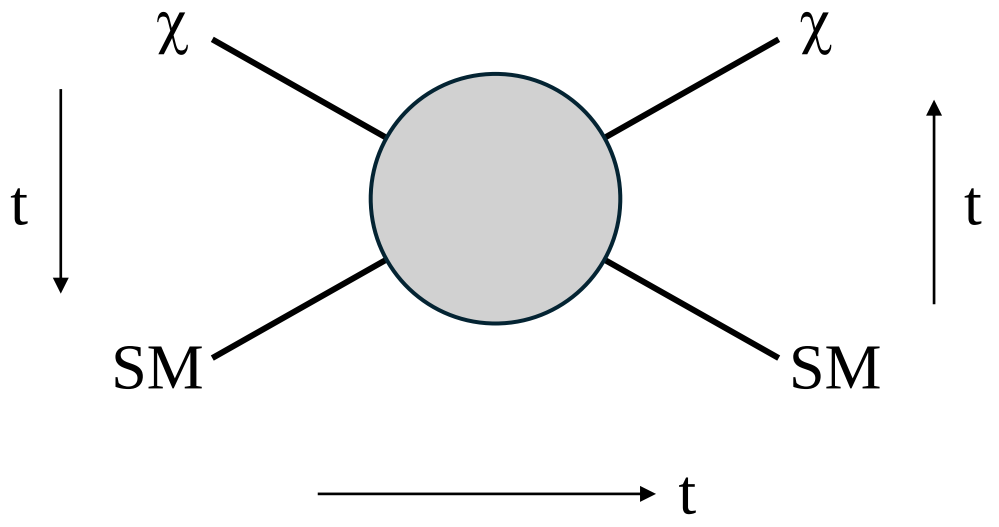


Ways to detect Dark Matter

Break it

DM annihilation



Make it

DM production

Shake it

DM scattering

Indirect detection
(SM particles from
dense regions)

Direct detection
(Energy deposition
in detectors)

Accelerators
(missing
transverse $\vec{p}$)

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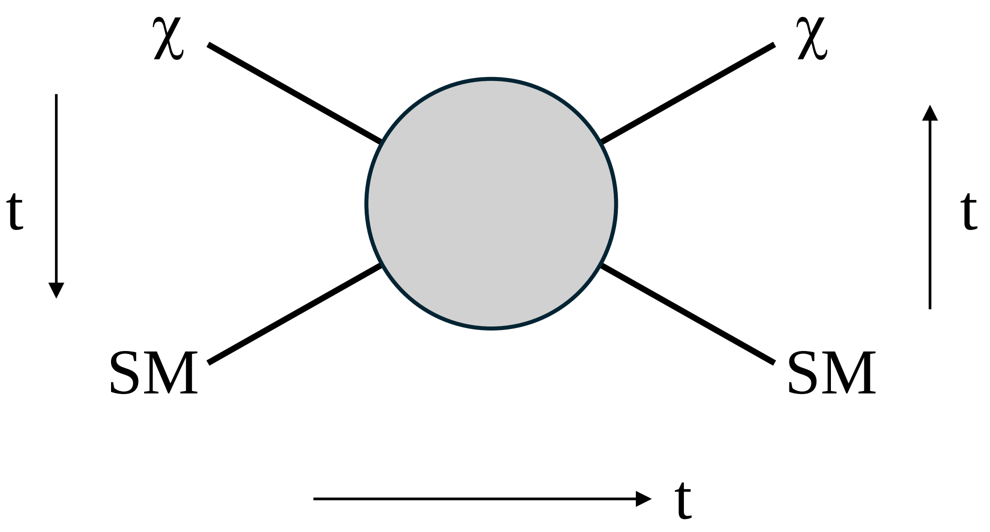

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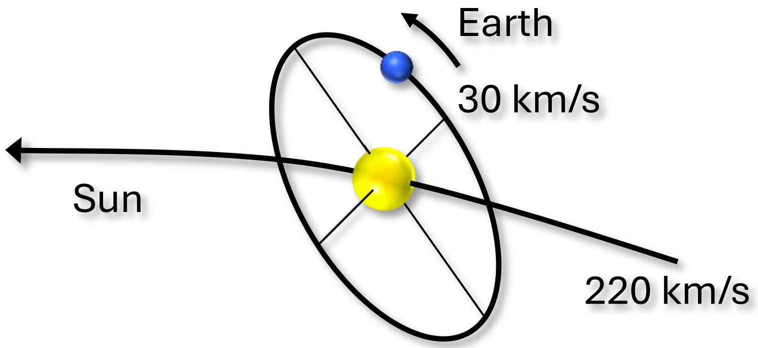
Fermionic DM

In Direct Detection, bosonic DM can also be absorbed in an inelastic process similar to the Photoelectric effect

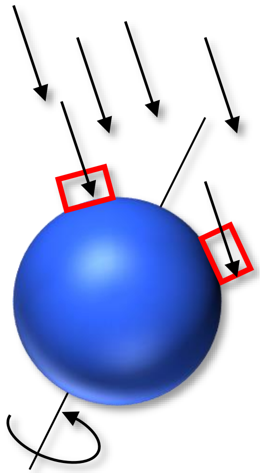
Dark Matter Signatures

- DM gravitationally bound to the Milky Way
  $\rightarrow v_{DM} \leq v_{esc} \approx 600\ km/s\ =\ 2\ x\ 10^{-3}\ c$
  (typical: $v_{DM} \approx 300\ km/s =\ 10^{-3}\ c$)
  Elastic scattering (heavy DM, basic kinematics):
  - Energy transfer to nuclei ("NR") up to 10s of keV
  - Energy transfer to electrons ("ER"): order of eV

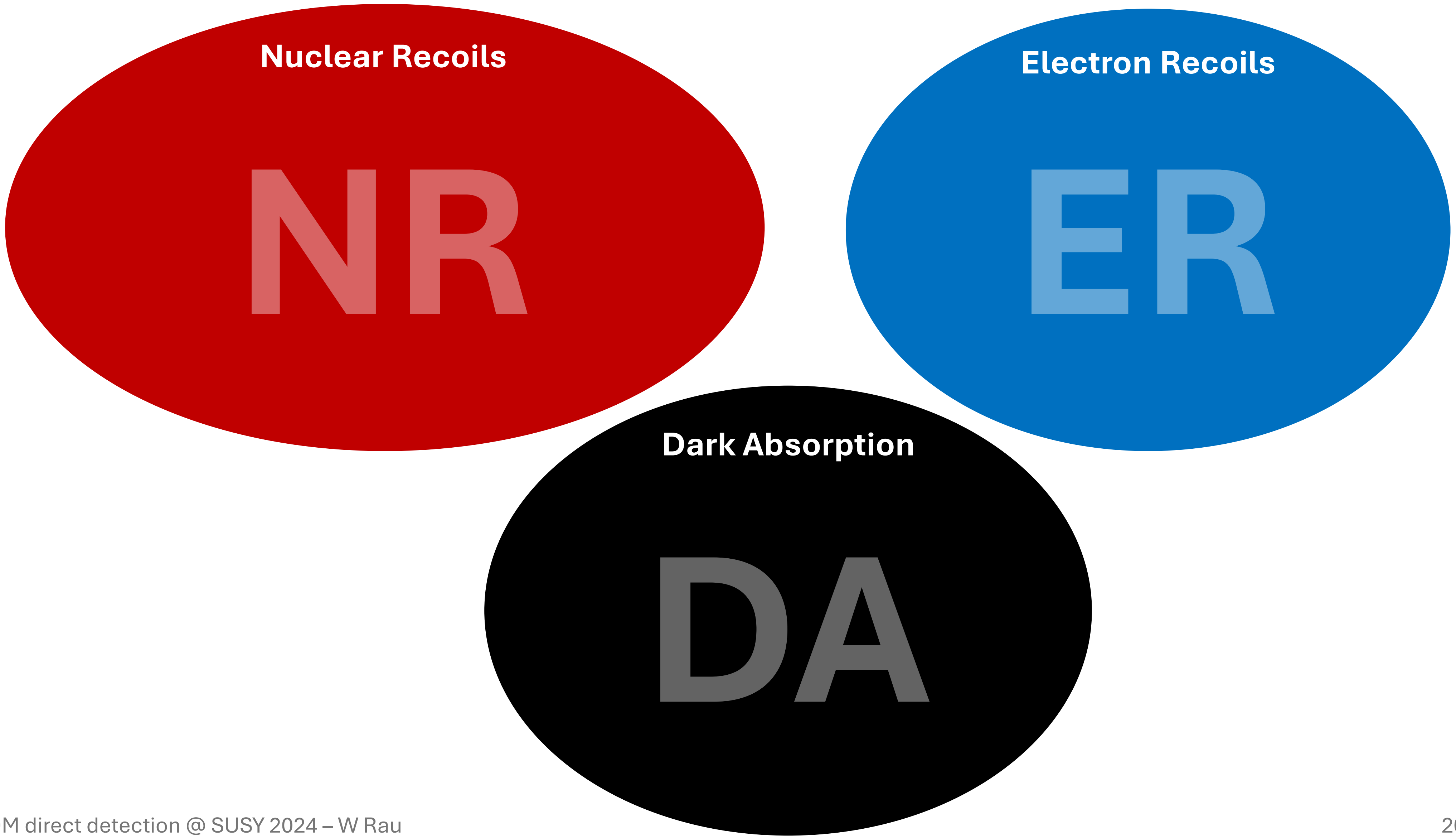
  Lower energies for lower-mass particles



- DM density at location of Earth: 0.3 GeV/c^2/cm^3
  $\rightarrow$ ~150 g/earth; 150,000 /cm^2/s for 60 GeV particle
- Main challenges:
  - Medium-/high-mass particles: background (BG)
  - Low-mass particles: detection threshold
- DM signatures:
  - Medium-/high-mass particles: NR signal with ER BG
  - Scattering: ~exponential spectrum, target mass dependent
  - Absorption: peak at DM particle mass (non-relativistic!)
  - Annual modulation
  - Directionality / diurnal modulation



Direct Detection Channels



Direct Detection Channels

Nuclear Recoils

- Low momentum transfer: nuclear coherence (rate $\propto A^2$)
- Low-mass DM: higher E-transfer for low A
- Migdal effect – E-transfer via nucleus to e^-: improves kinematic match at low mass

DM mass range:
few hundred MeV to TeV+

Electron Recoils

- Kinematic estimate with e^- at rest: max. E-transfer is a few eV
- High atomic e^- momentum: E-transfer of hundreds of eV possible

DM mass range:
~e^--mass up to > GeV

Dark Absorption

- Bosons: Dark Photons, Axion-like particles (ALPs)
- Like Photo-electric Effect
- Kinetic E small (non-rel.): measured E = DM particle mass

DM mass range:
band gap (eV) to ~2x e^--mass

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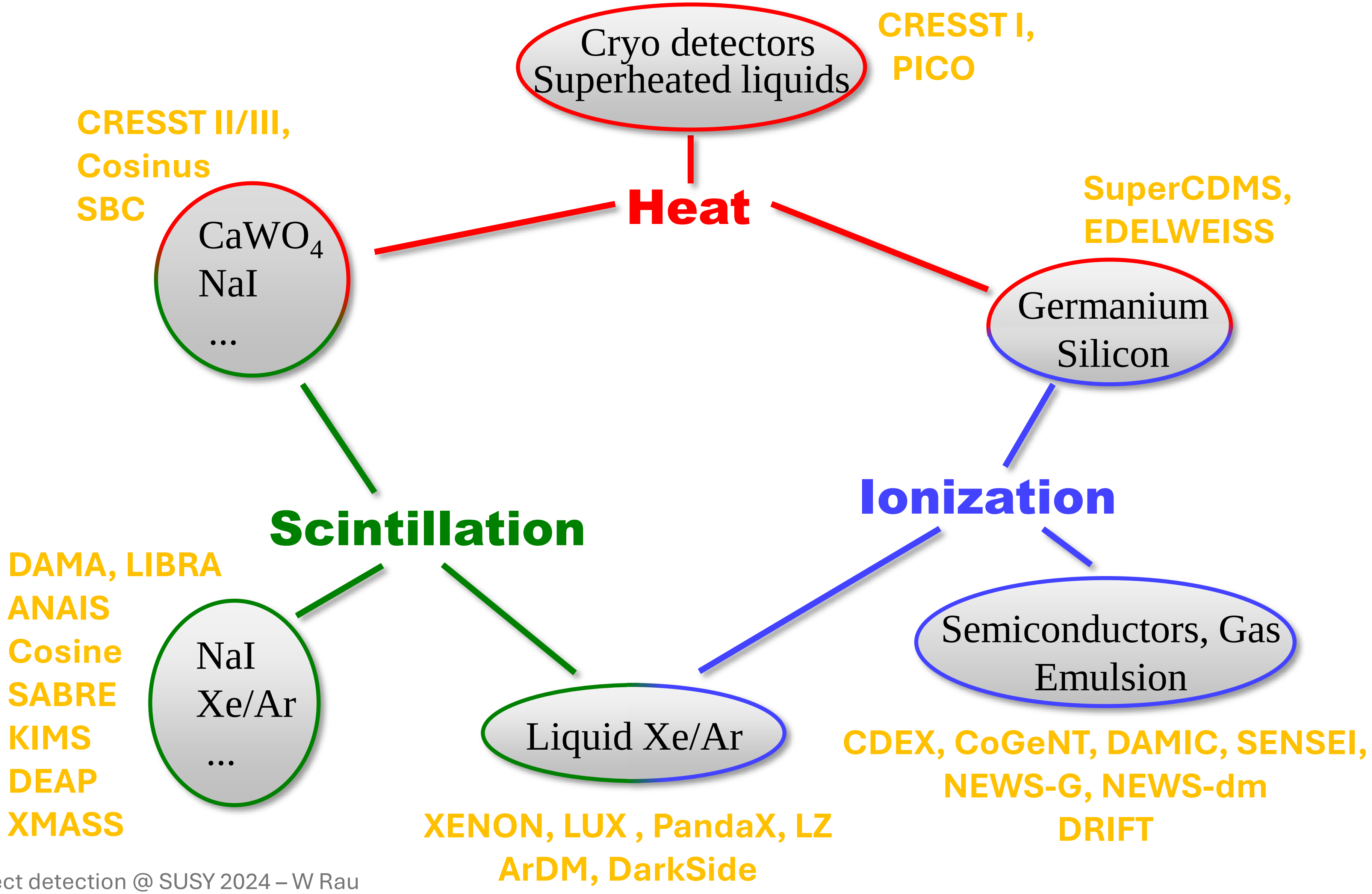
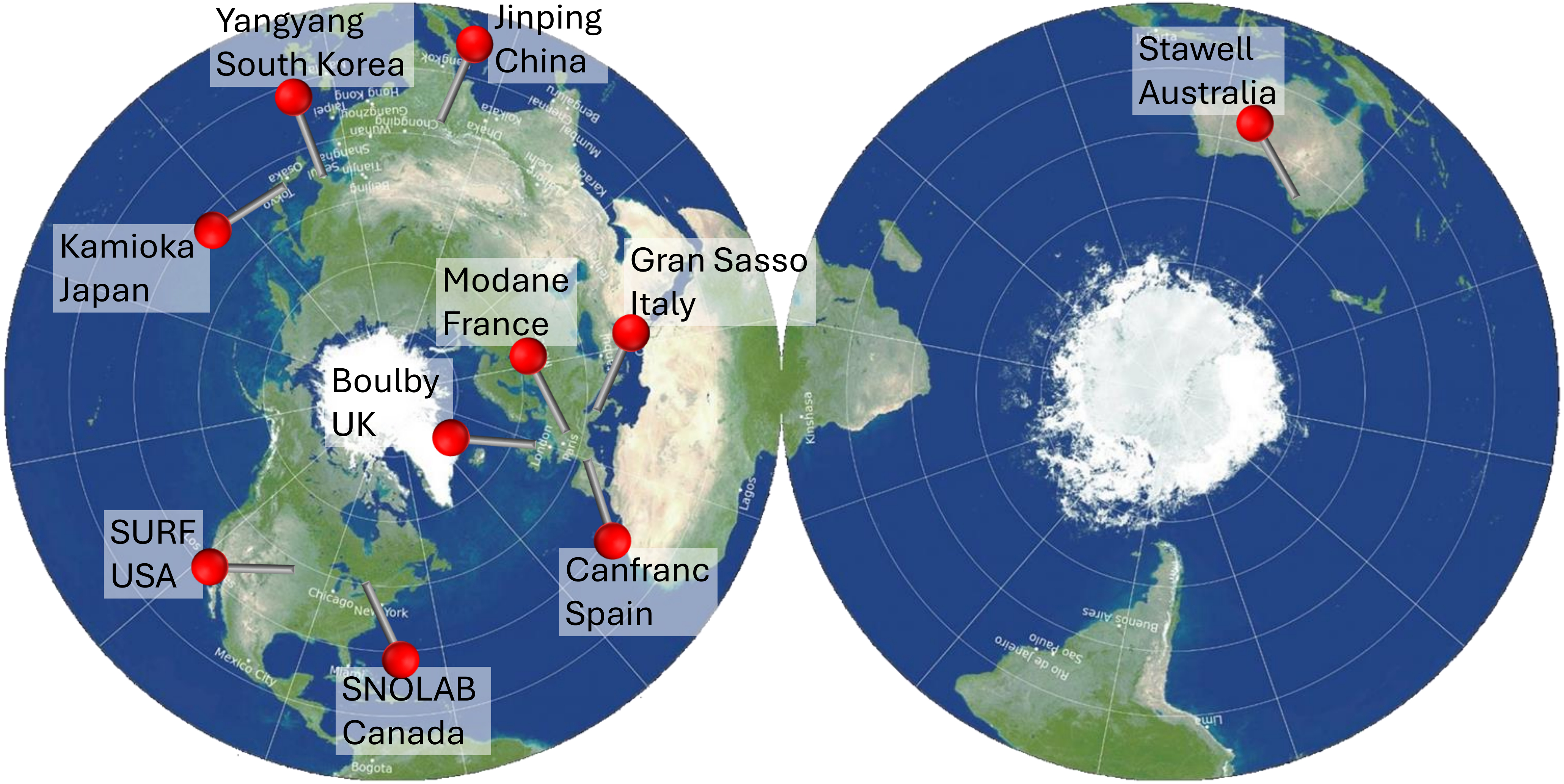
Alternative channels/models:

- Spin dependent
- Other operators (EFT)
- Lightly Ionizing Particles (LIPs)
- Supermassive strongly interacting particles
- …

Direct Detection of Dark Matter

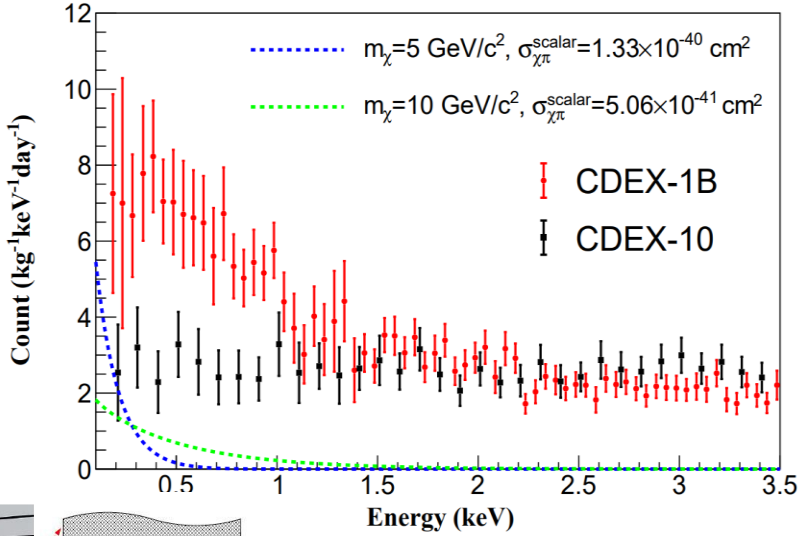


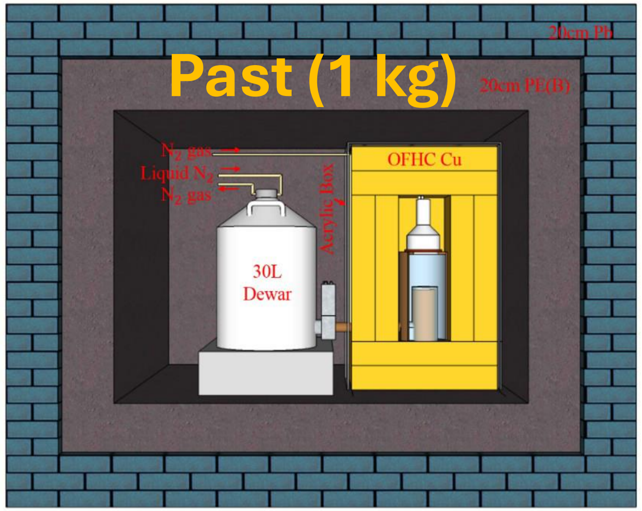
Experiment Locations



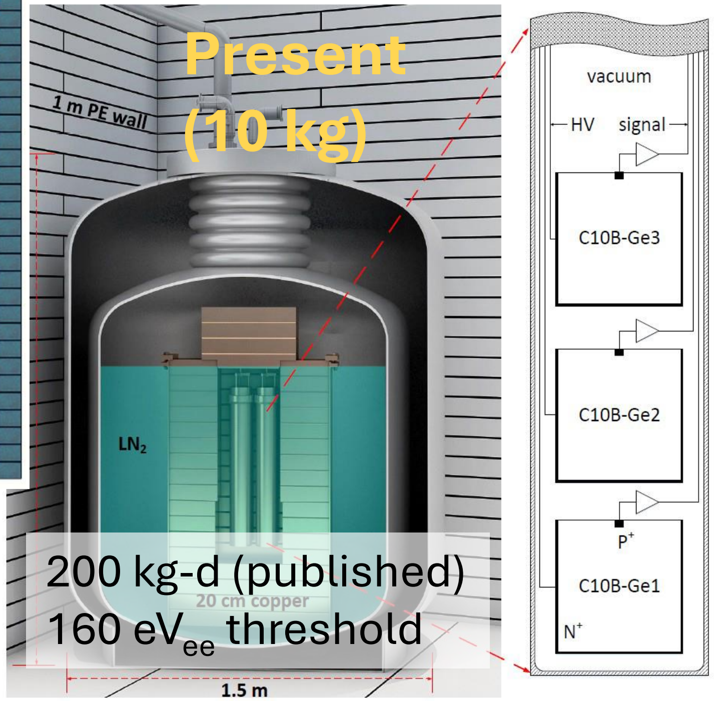
Experiments – Ionization Detectors

Germanium Detectors (70 K)
- Historically: first DM DD experiments
- Present day: CDEX @ Jinping
  - Point-contact (low threshold)
  - Minimize background
- Looking for a variety of DM models

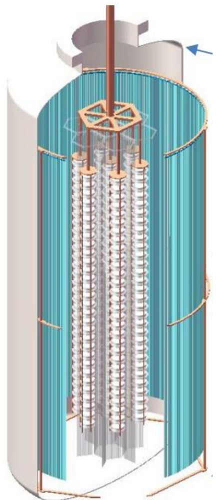




700 kg-d,
~200 eV_{ee} threshold



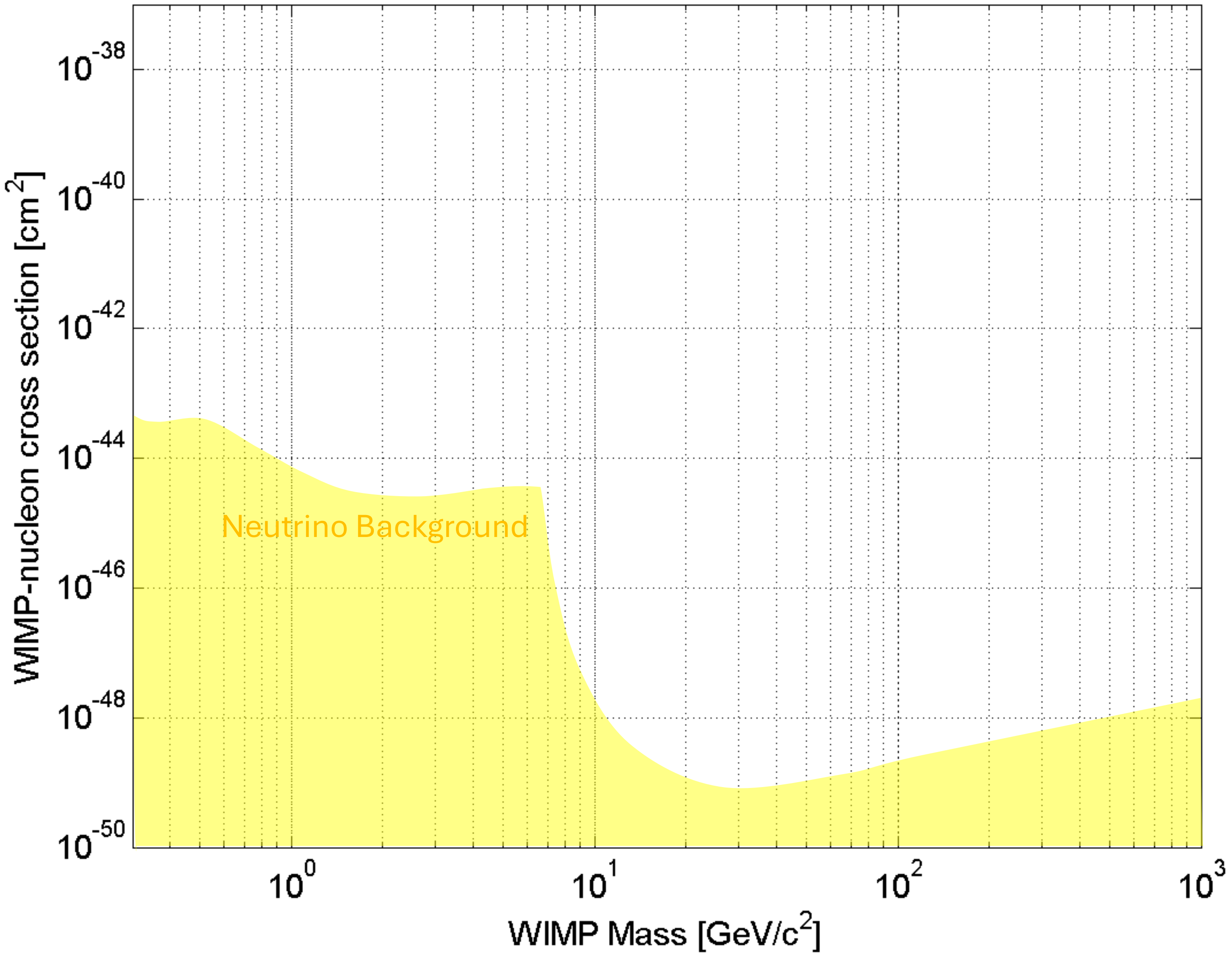
200 kg-d (published)
160 eV_{ee} threshold



Future (50-300 kg)

Immersed in LAr
Inside big (13 m)
LN dewar

Results – Spin-independent Interaction



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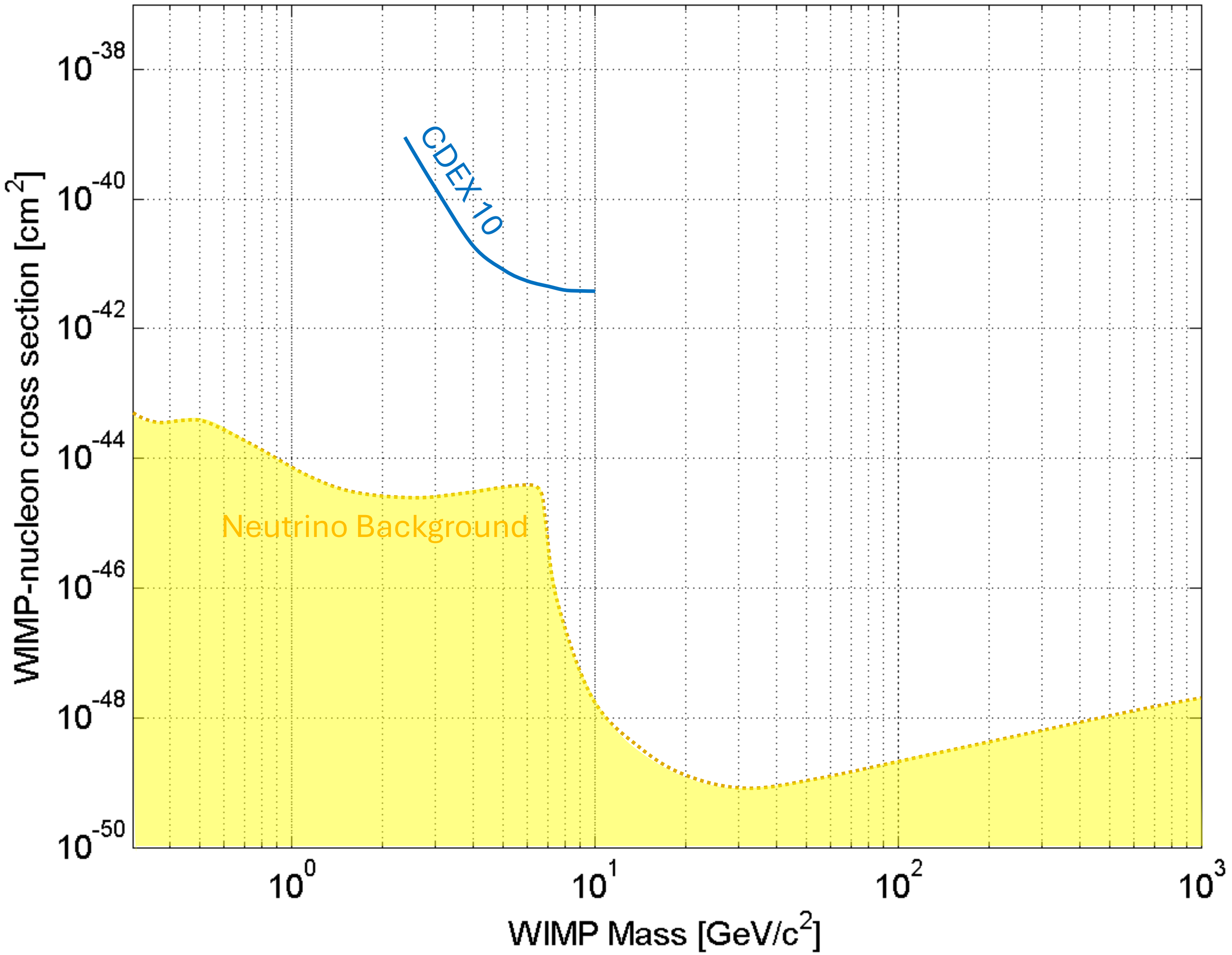
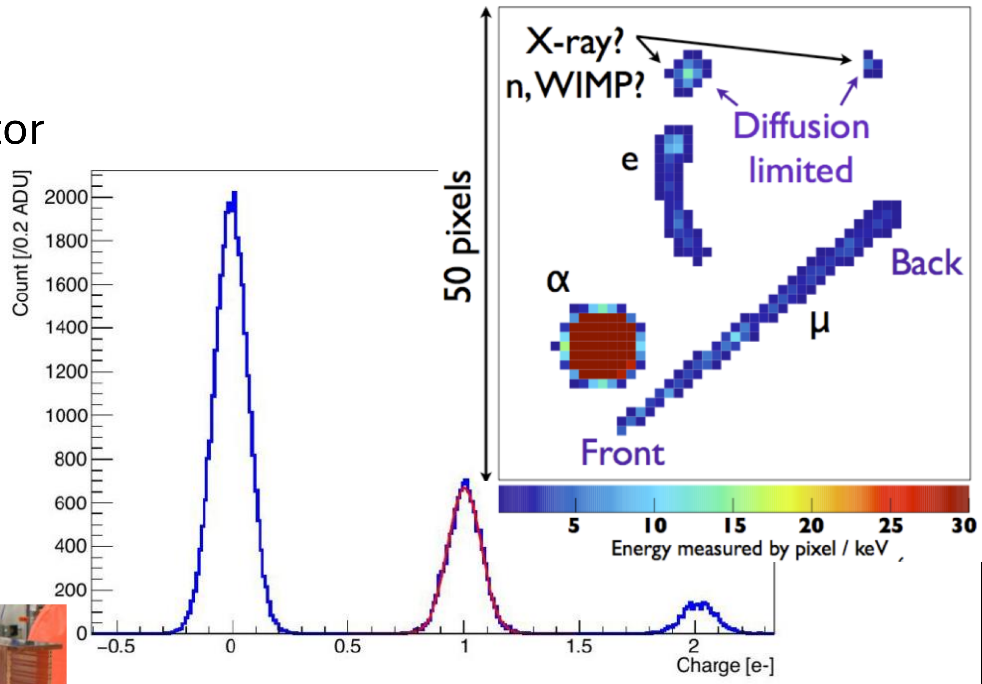
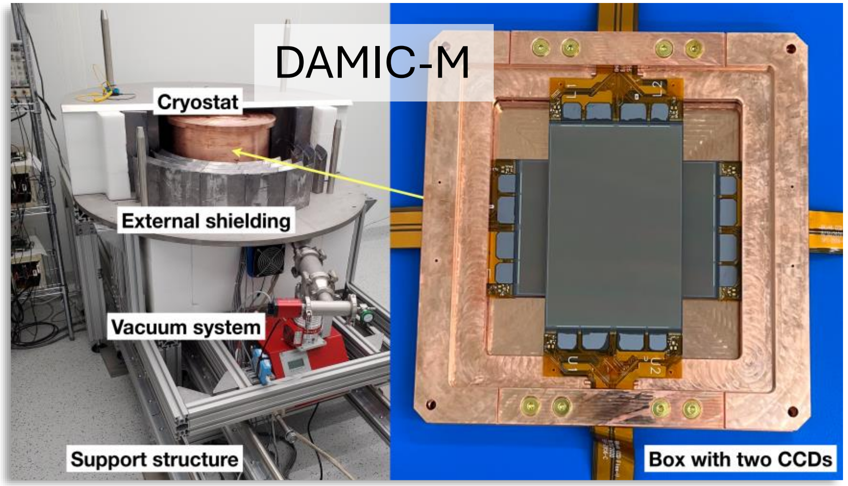


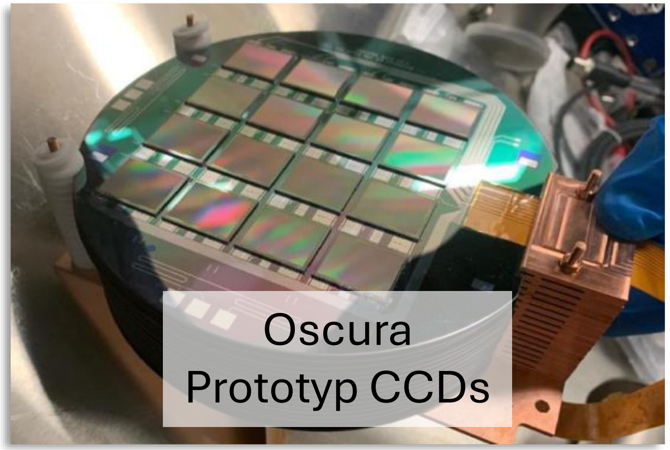
Experiments – Ionization Detectors

Silicon CCDs: DAMIC-M / SENSEI / Oscura

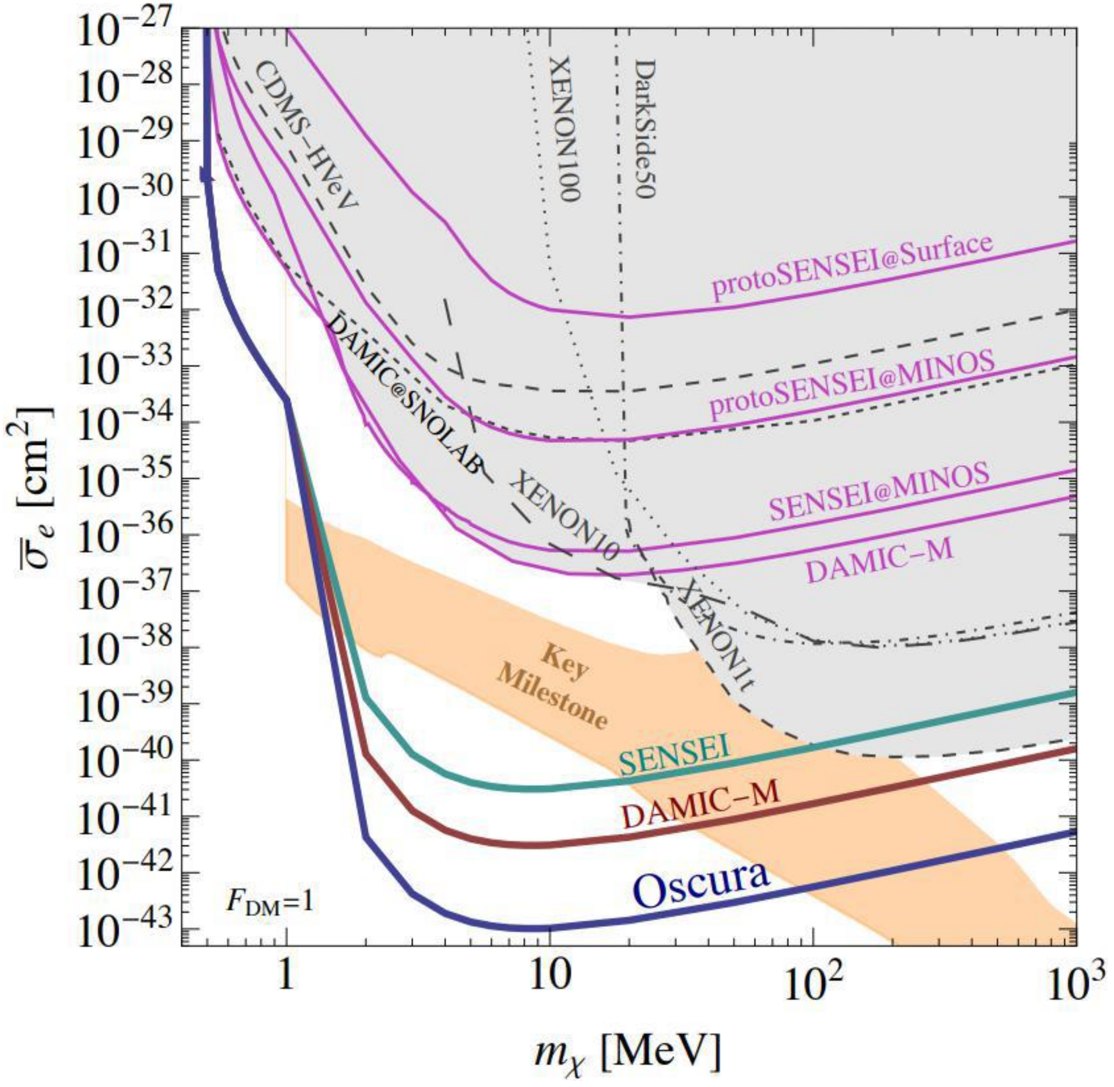
- Good position resolution; low mass per detector
- Repeated readout of each pixel: resolution better than single e^-
- DAMIC-M (2x9 g)/ SENSEI (6+1 x ~2 g)
- Exposure: 85 (D) / 35 (S) g-d
- Focus on Electron-interacting DM
- Future: 100 g (S) / 700 g (D) / 10 kg (Oscura)







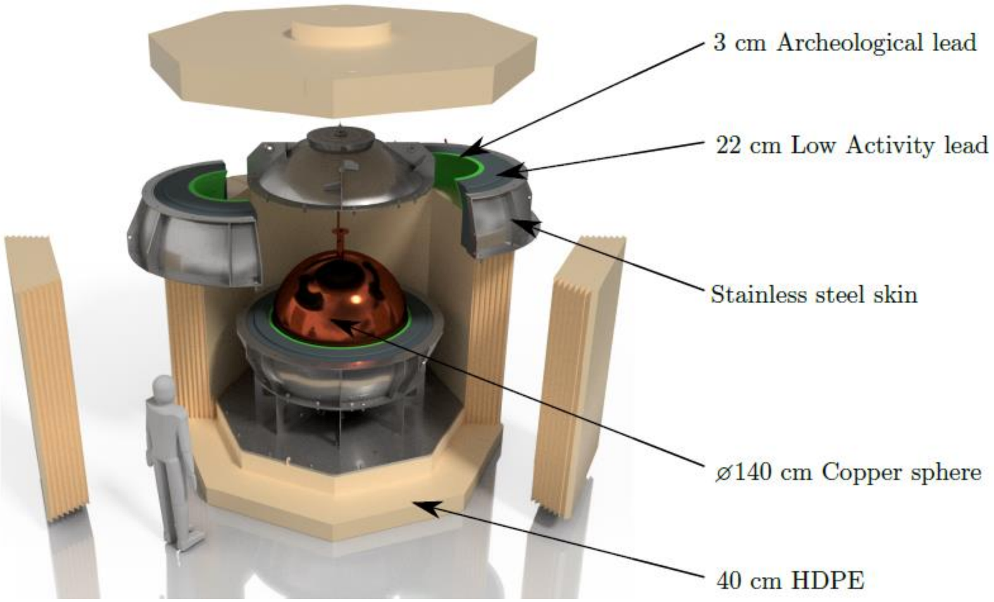
Results – Electron Recoil

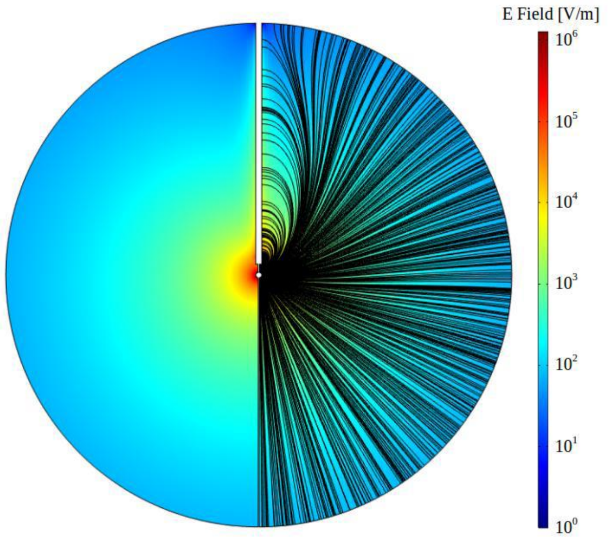


Experiments – Ionization Detectors

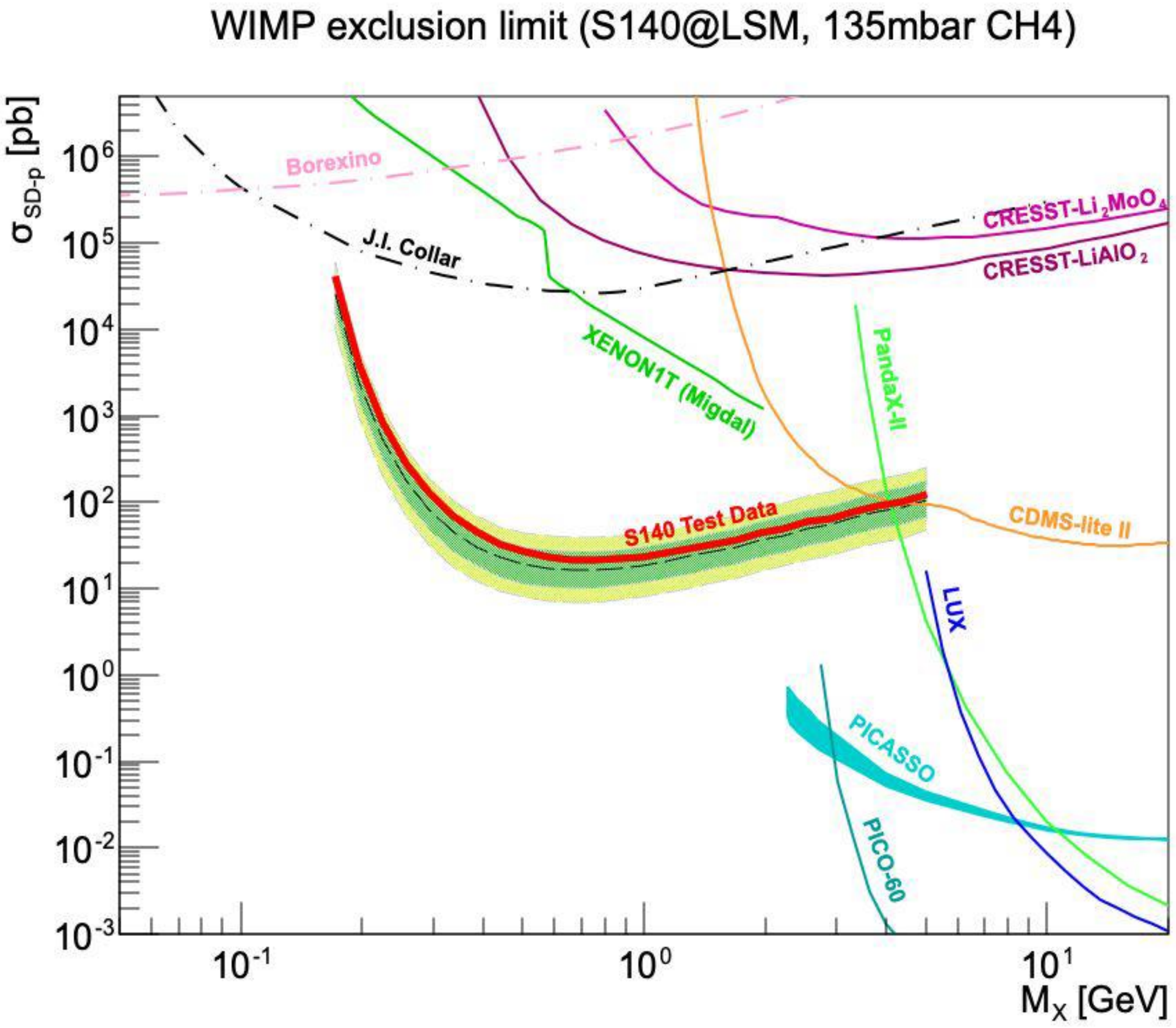
Gas – NEWS-G (SNOLAB)

- Spherical proportional counter
- Innovative electrode design: small spheres (avalanche field), distributed (drift field)
- 2 sensors (top/bottom): discard distorted field region
- Pulse shape discriminates surface events
- Different target gas mixtures (incl. CH_4 for low-mass DM)





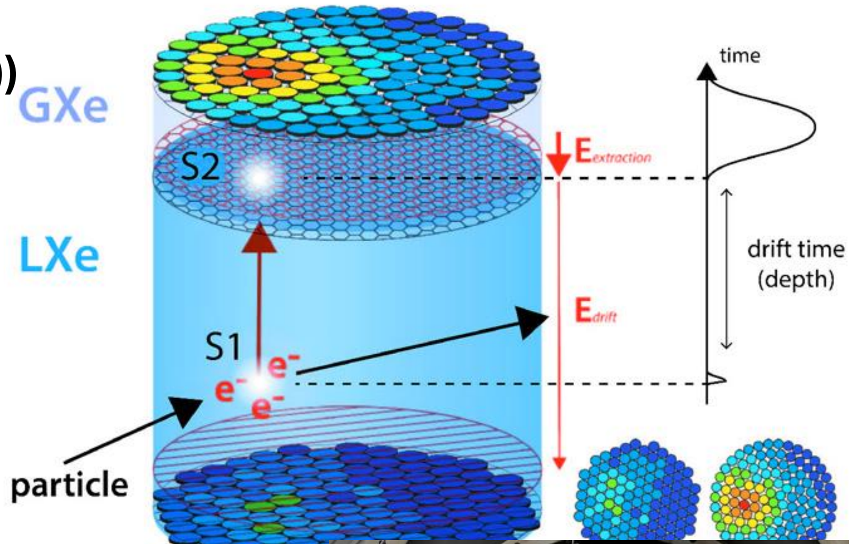
Results – Spin dependent Interaction

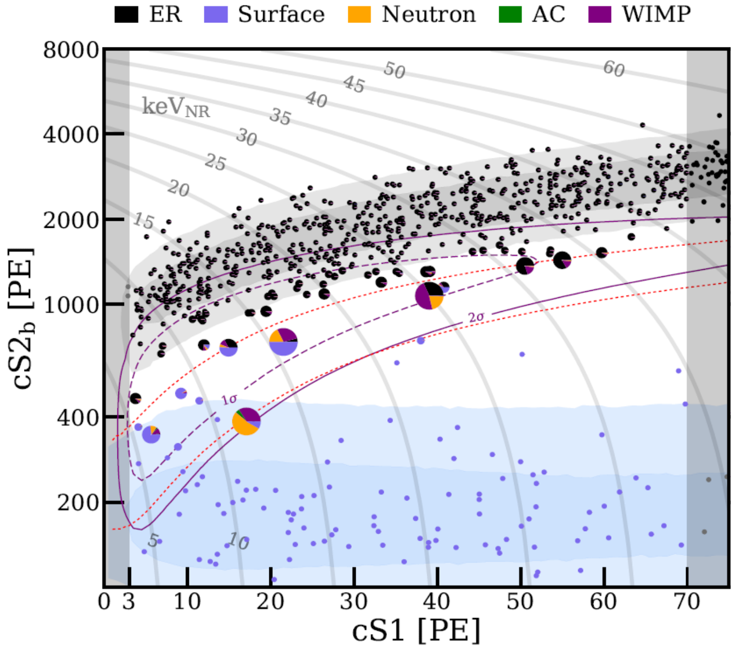


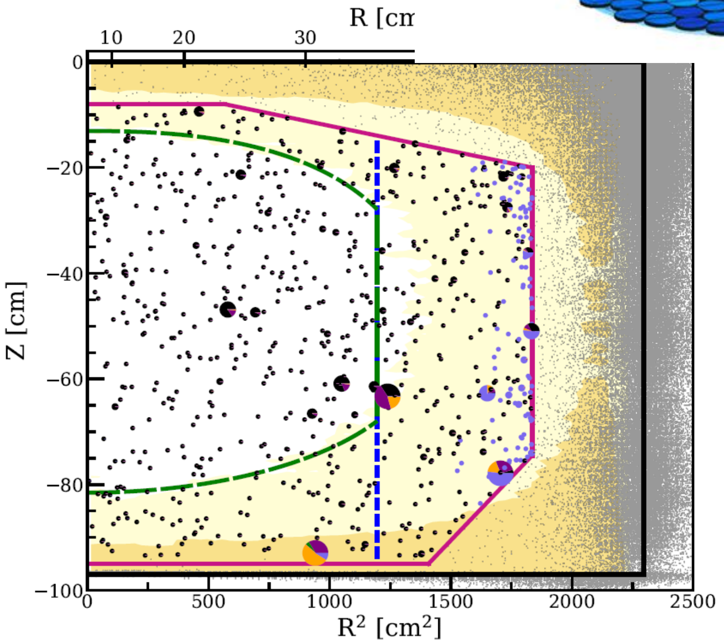
Experiments – Noble Liquids

Xe dual-phase TPCs (XENON (6t), LZ (7t), PandaX (4t))

- Noble liquids are excellent scintillators
- Inert atoms: charge transport possible
- 2 Signals for ER/NR discrimination:
  - S1: scintillation, “weak”
  - S2: drifted charge+gas ampl., “strong”
- High density: self-shielding
- Future: DARWIN / PandaX-Xt (50-t scale)



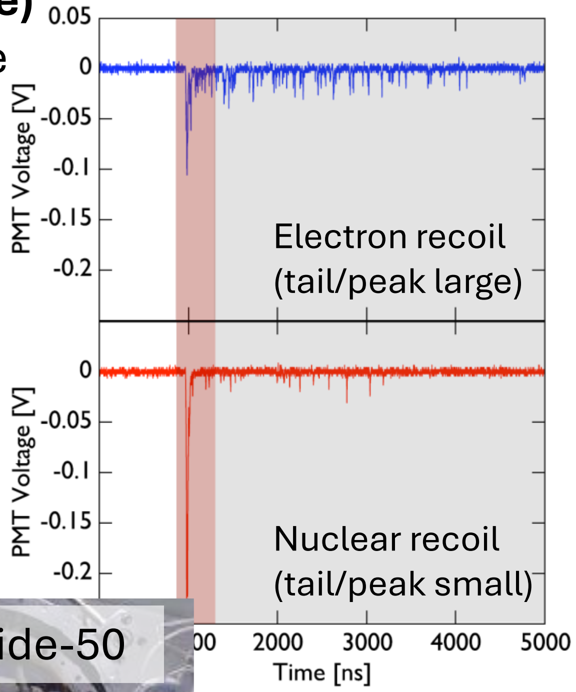


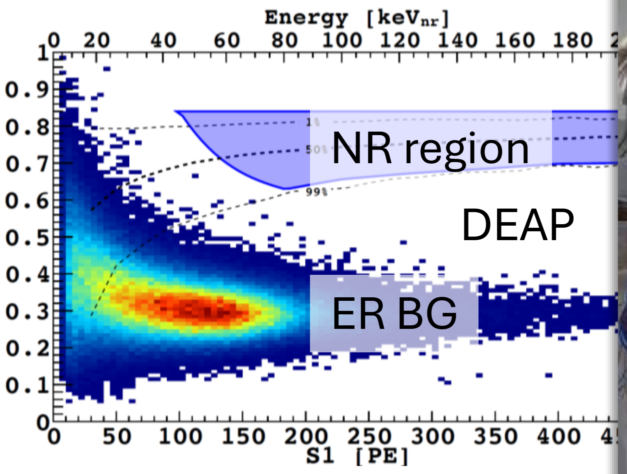


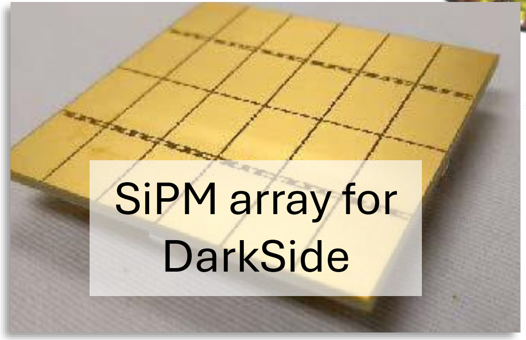
Experiments – Noble Liquids

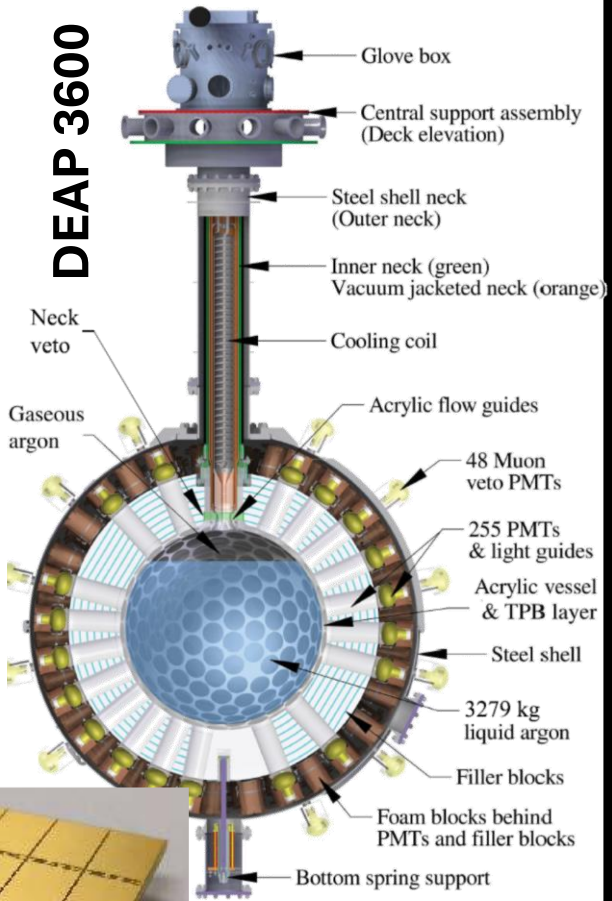
Ar single / dual-phase (DEAP, DarkSide)

- ER/NR discrimination by pulse shape
- Much cheaper than Xe
- Intrinsic radioactivity
  - Cosmogenic ^{37,40}Ar
  - Underground Ar, distillation
- DEAP: 3.3 t single phase
- DarkSide-50: 50 kg, dual phase
- Future: DS-20k (20 t), Argo (300 t), DS-LM (1 t, low threshold)
- Replace PMTs by SiPMs









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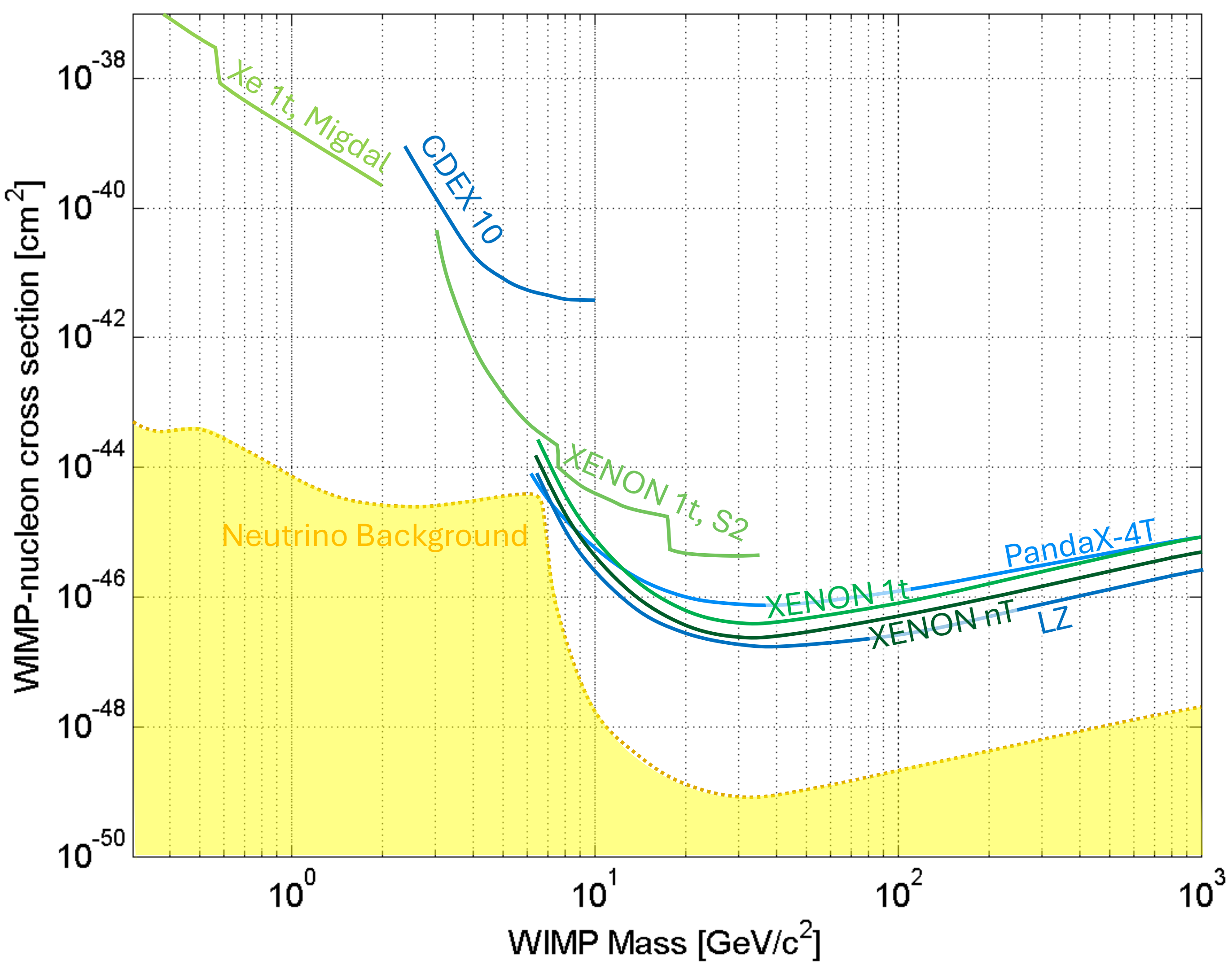

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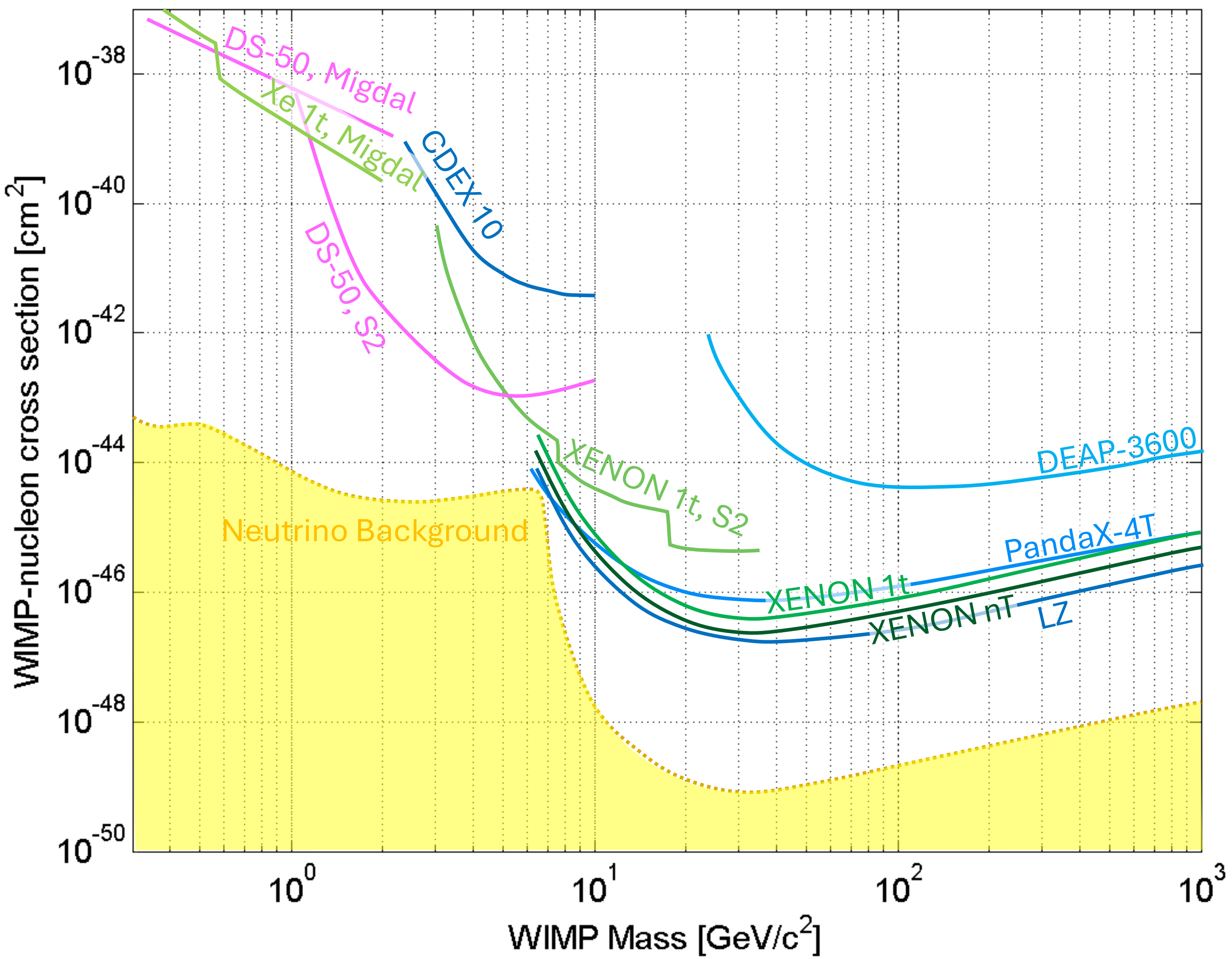
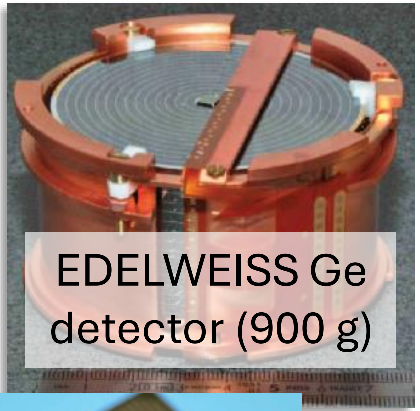


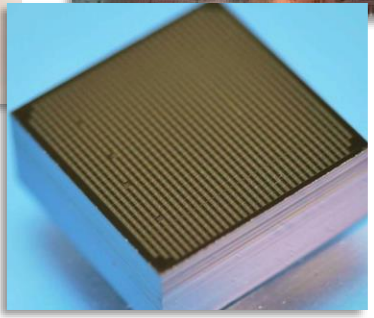
Experiments – Cryogenic Detectors

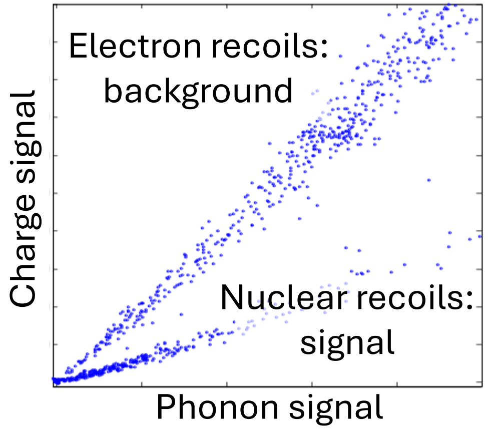
Cryogenic Ionization Detectors

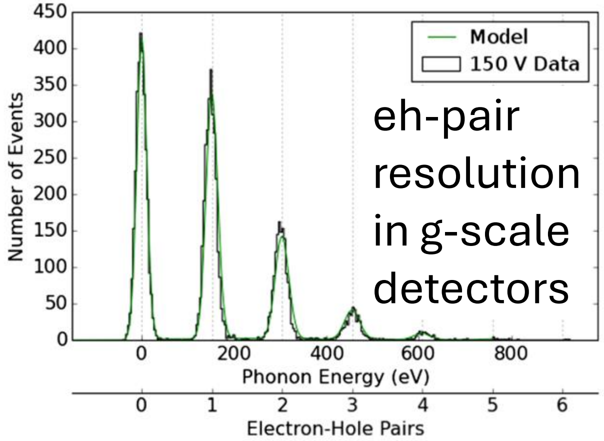
- Phonons: good resolution ($\mathcal{O}$(eV) in kg det.)
- Charge: ER/NR discrimination
- NTL effect (HV, electric potential energy $\rightarrow$ phonon energy): low threshold charge meas. with phonons
- Different technologies for readout
- EDELWEISS: Ge, thermal sensors
- SuperCDMS: Ge, Si, athermal sensors
- Target mass small compared to Xe/Ar
- Focus on low-mass DM (NR and ER/DA)
- Future: push even lower in threshold / DM mass



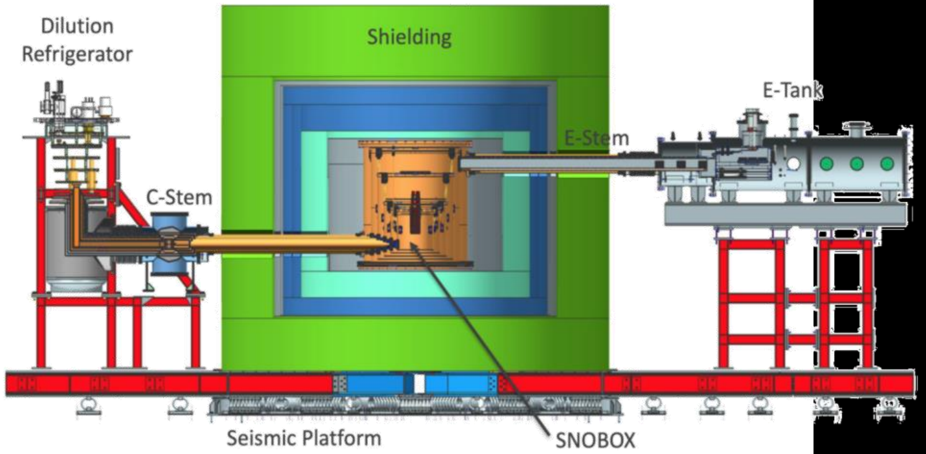
SuperCDMS Si detector (1 g)







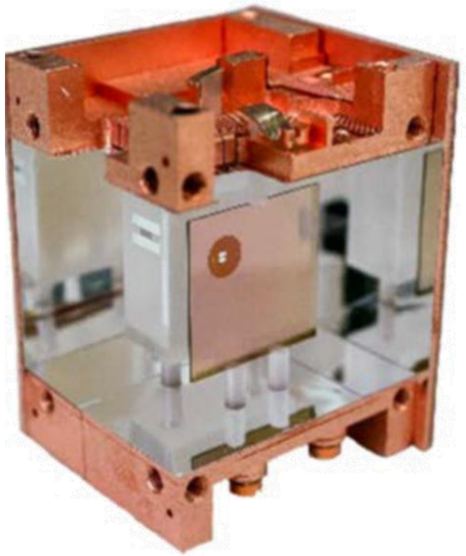
eh-pair resolution in g-scale detectors



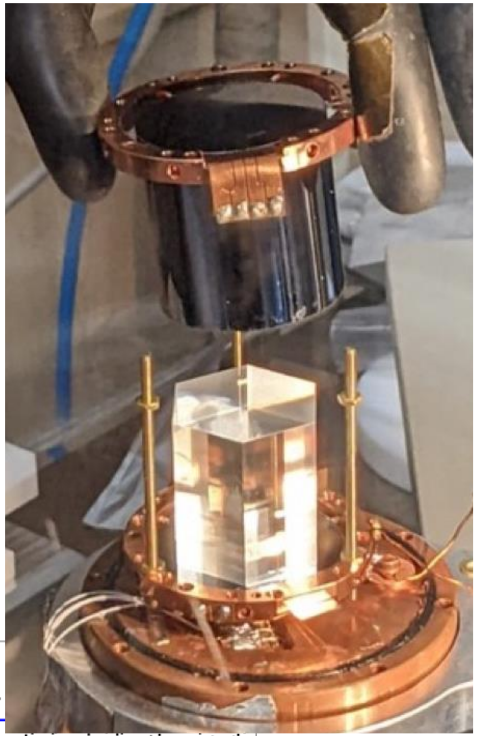
SuperCDMS SNOLAB Coming Soon!

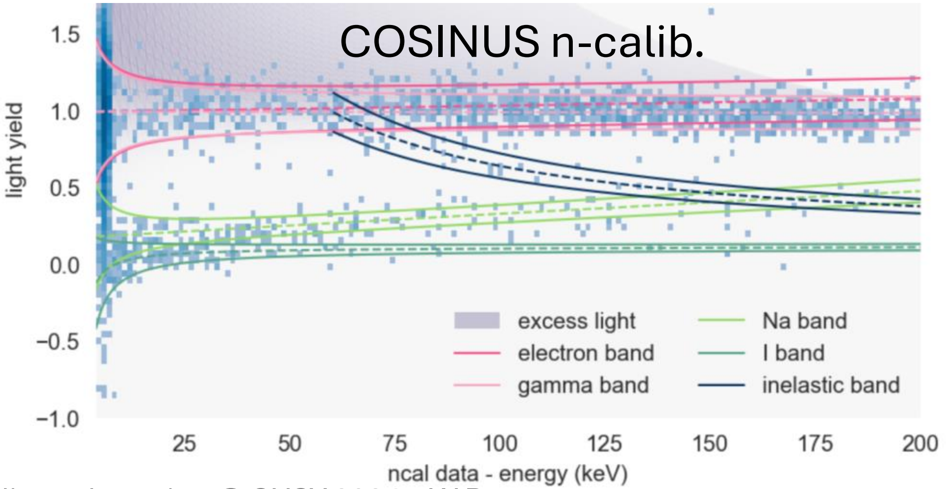
Experiments – Cryogenic Detectors

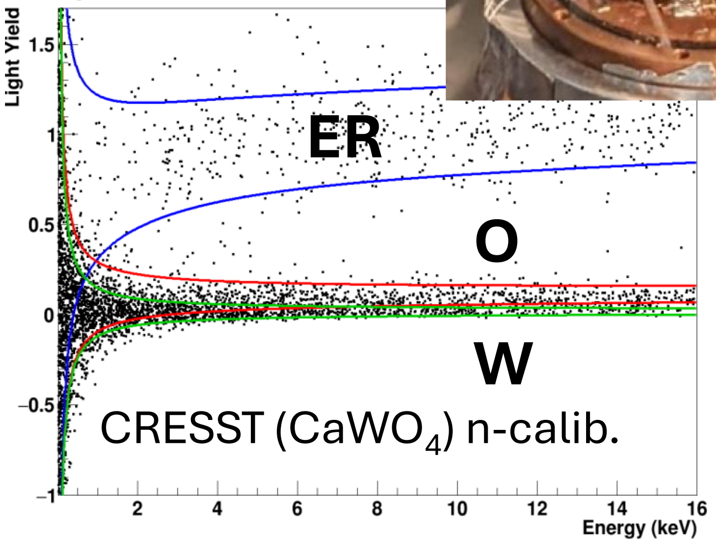
Cryogenic Scintillators
- Scintillation for ER/NR discrimination
- Light: separate cryogenic detector
- Multiple materials/targets available
- CRESST: Long-running, mainly $CaWO_4$
- Recently:
  - ~20 g detectors, few eV resol.
  - $LiAlO_2$ for spin-dependent search
- COSINUS:
  - NaI (another DAMA check)
  - Under construction



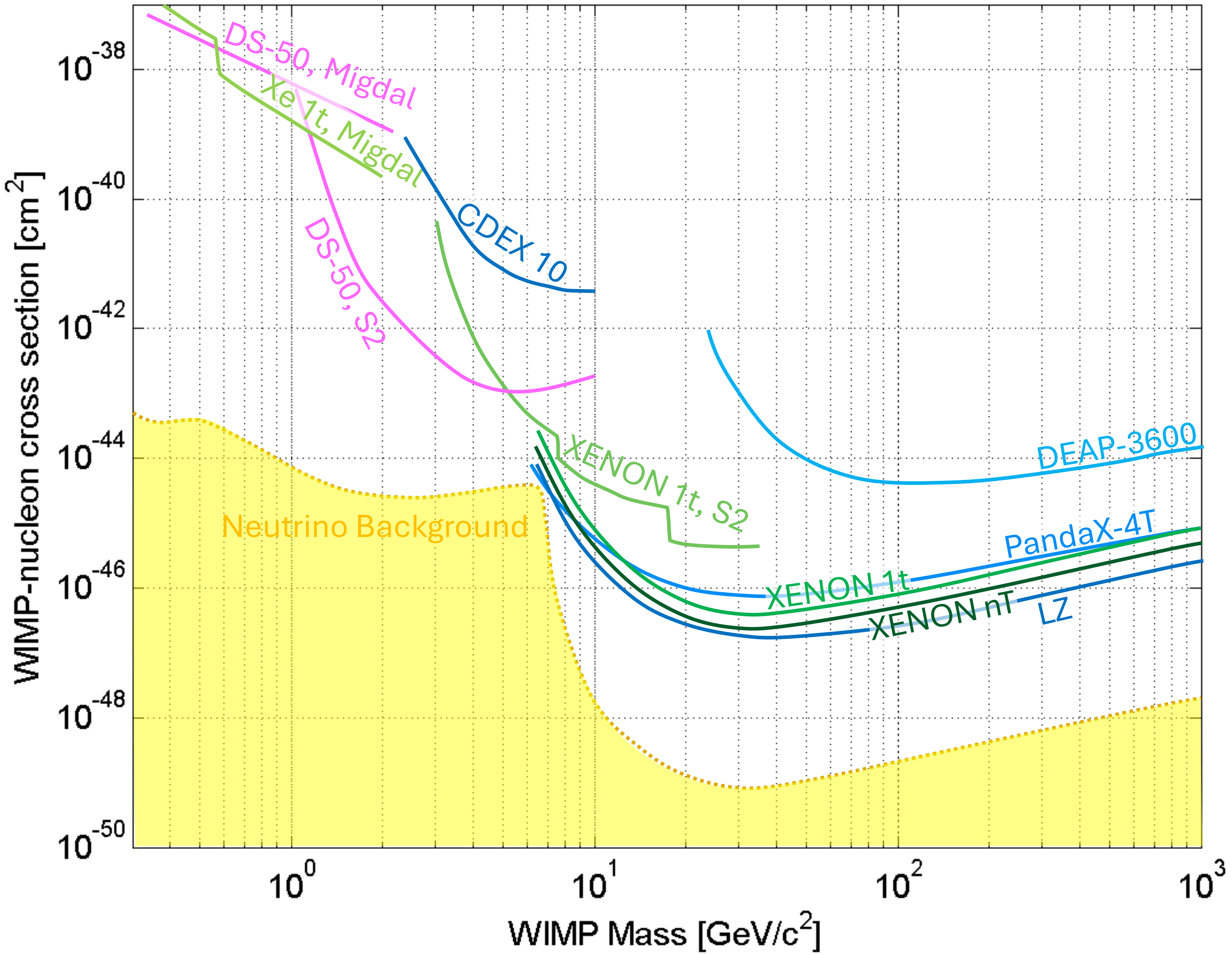
CRESST, $CaWO_4$
23 g detector



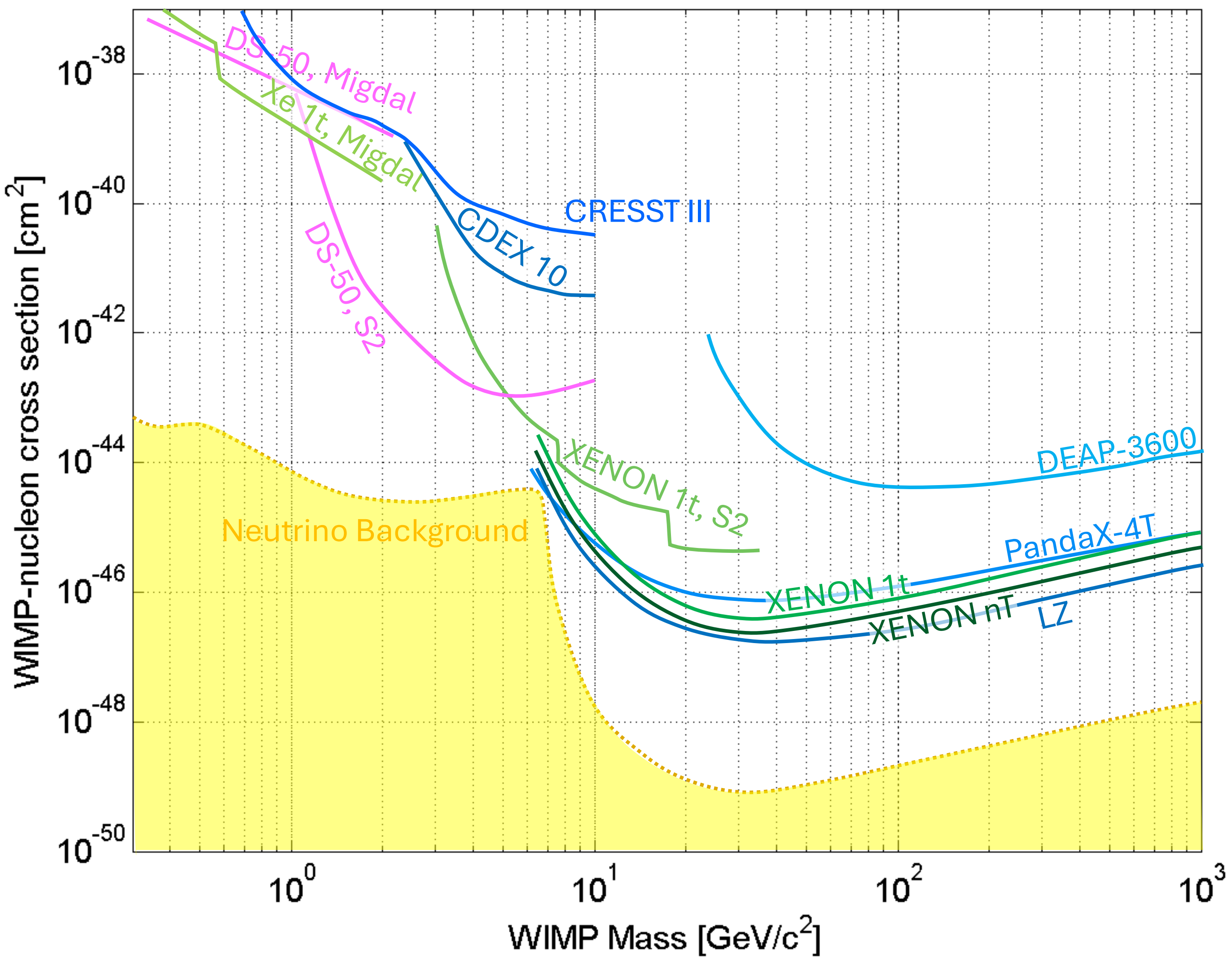




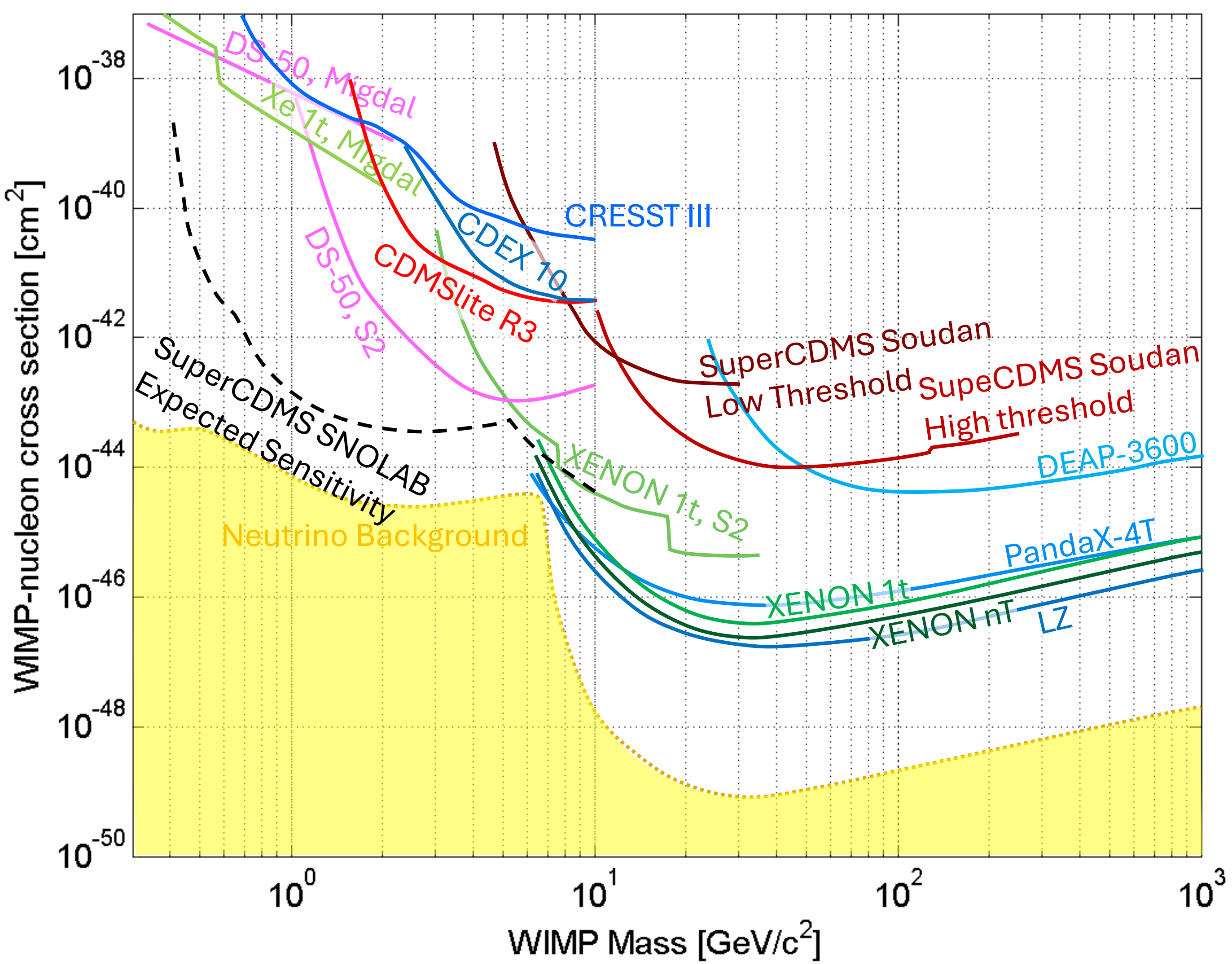
Results – Spin-independent Interaction



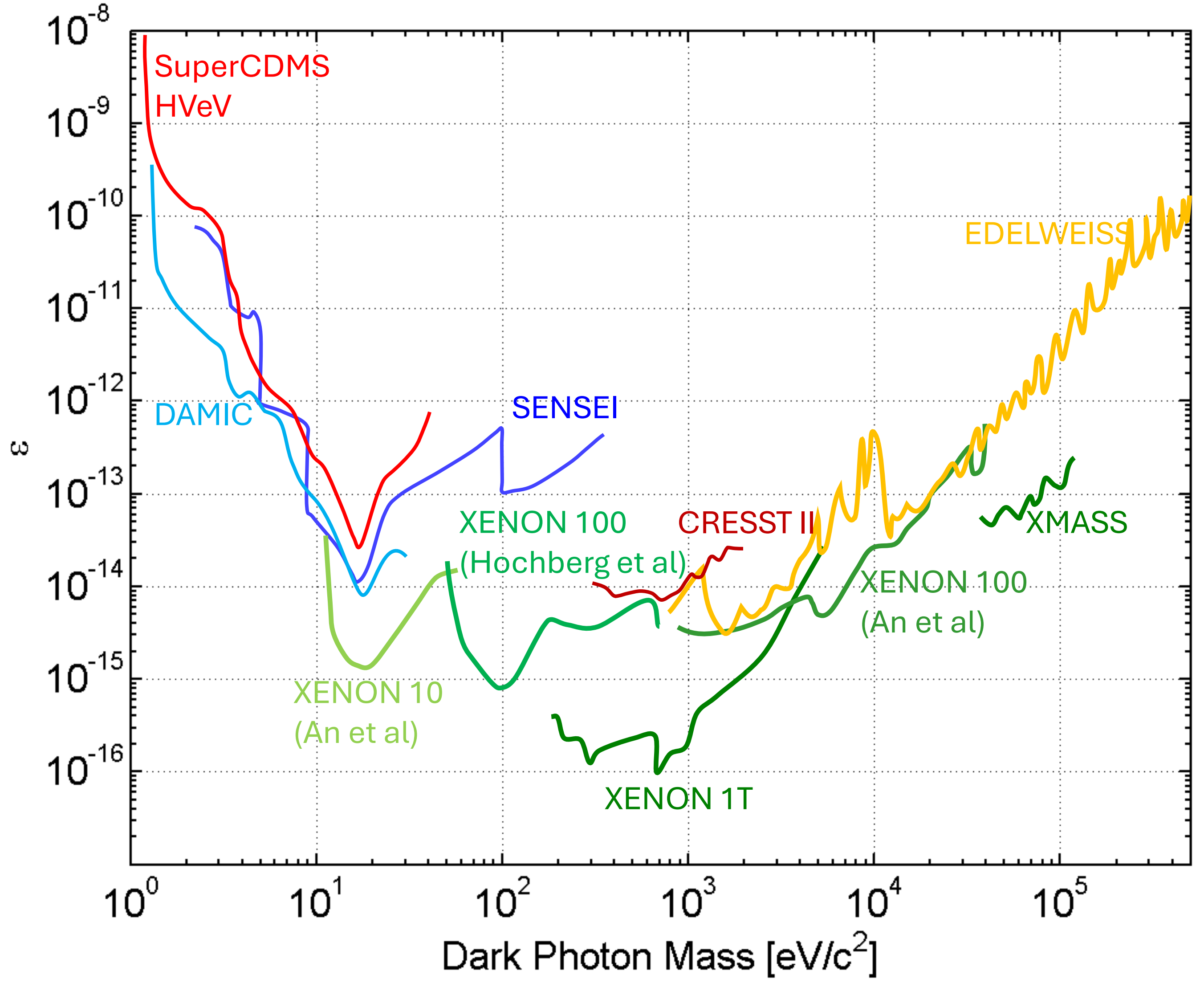
Results – Spin-independent Interaction



Results – Spin-independent Interaction



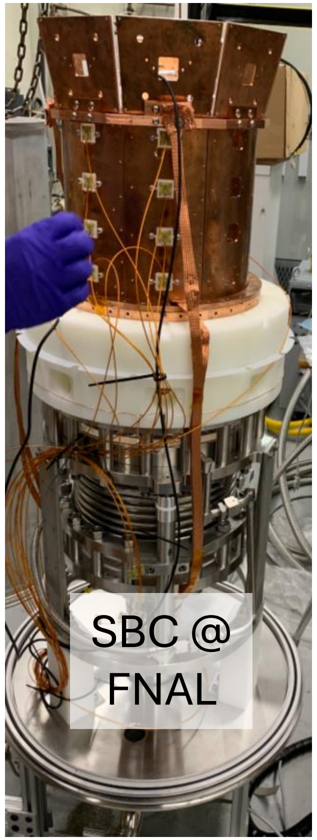
Results – Dark Photon Absorption

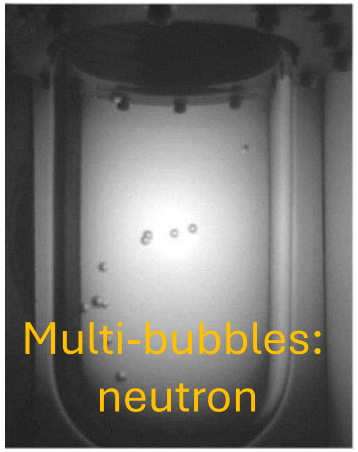


Experiments – Bubble Chambers

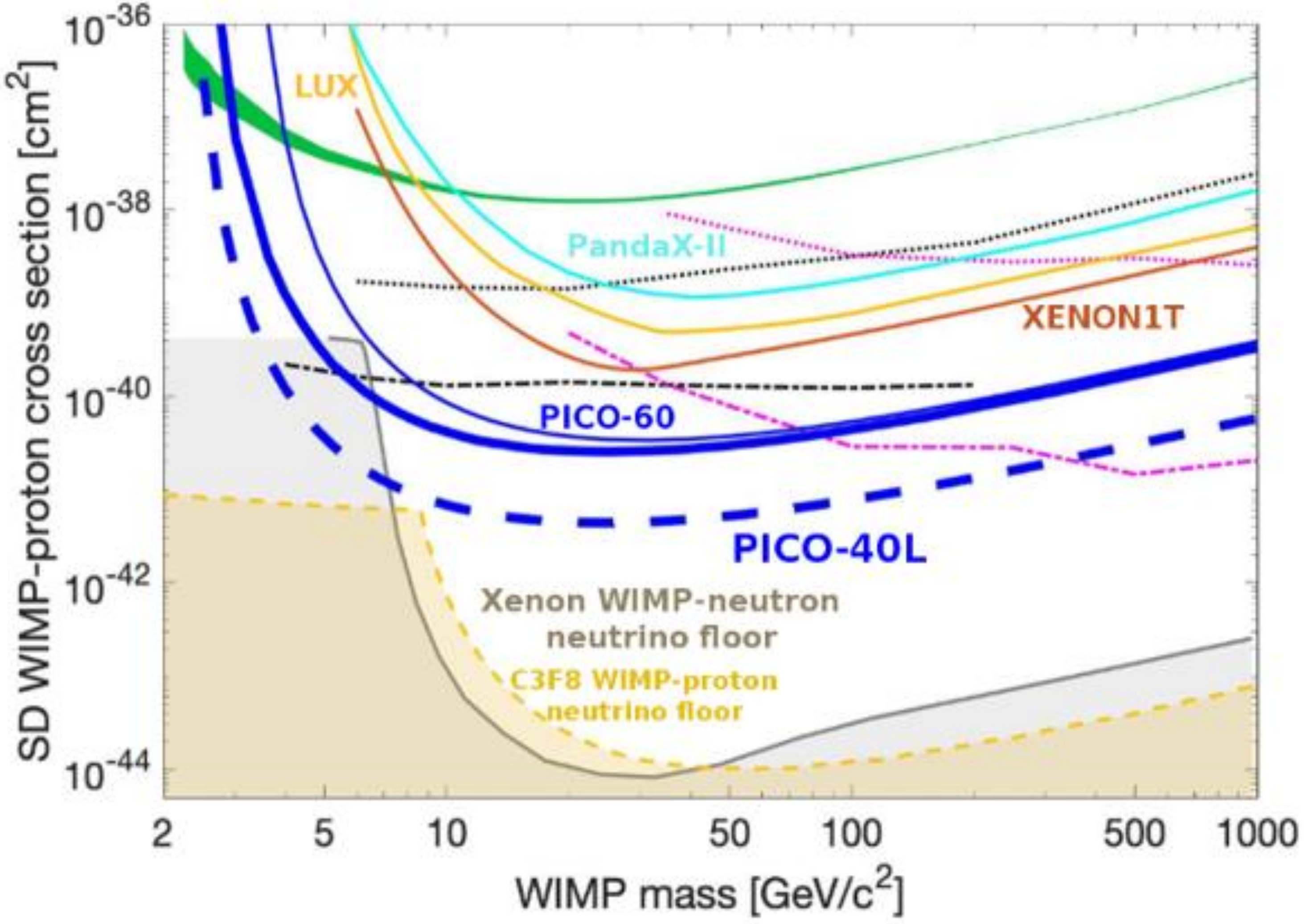
PICO (~room temp) / SBC (cryogenic)

- Superheated liquid; particles create bubbles
- Read out with cameras and piezzos (sound)
- Insensitive to ER (low energy density track) (becomes sensitive when threshold too low)
- Neutron discrimination (multiple bubbles)
- Alpha discrimination (more acoustic power)
- Threshold detector (no energy resolution)
- PICO: C_3F_8 – F is spin target (40 L, 250 L coming)
- SBC: scintillating bubble chamber (Xe or Ar)
- Scintillation removes energy from ER $\rightarrow$ lower threshold possible
- Under construction at SNOLAB; prototype running at FNAL





Results – Spin dependent Interaction



Experiments – Other

Various Projects and ideas

- Superfluid Helium:
  - Readout with cryo detectors
  - Low threshold (low-mass, NR)
  - Herald (US), DELight (Germany)
- Very low threshold cryogenic detectors
  technology improvements, new materials (meV band gap)
  (SPICE, Splendor)

- More distant future:
  Gravitational detection of Planck-mass particles

- And many more …

Conclusions

- Strong evidence for Dark Matter
- Direct Detection can test particle masses from meV to TeV+
- Different technologies focus on different ranges and interaction channels
- Many projects are coming online or expect new data soon
- The first detection might just be around the corner …