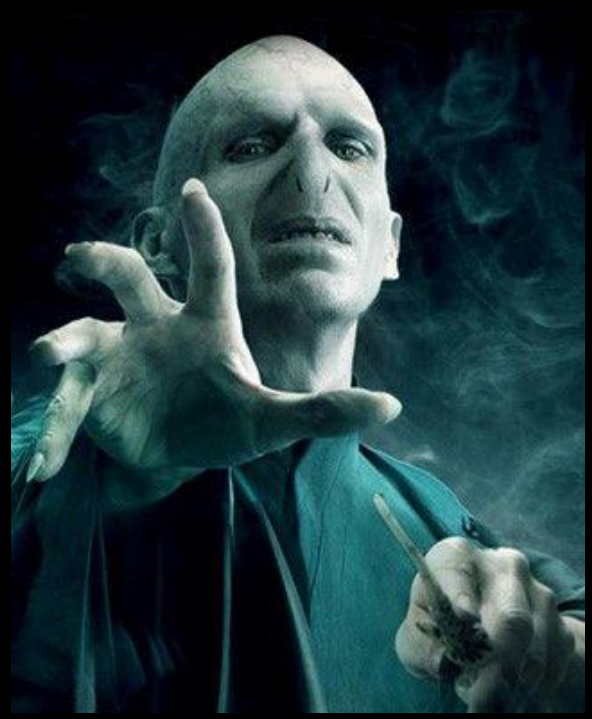
Direct Detection Dark Matter Searches



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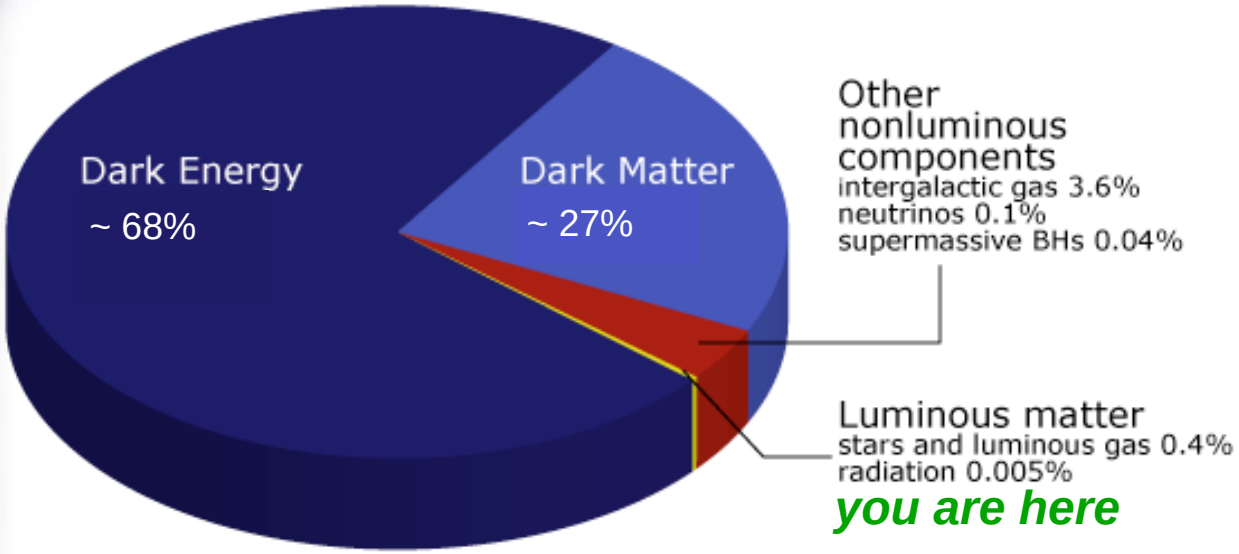
Arthur B. McDonald Canadian Astroparticle Physics Research Institute
University of Toronto

Feb 15 2019

What is Dark Matter?



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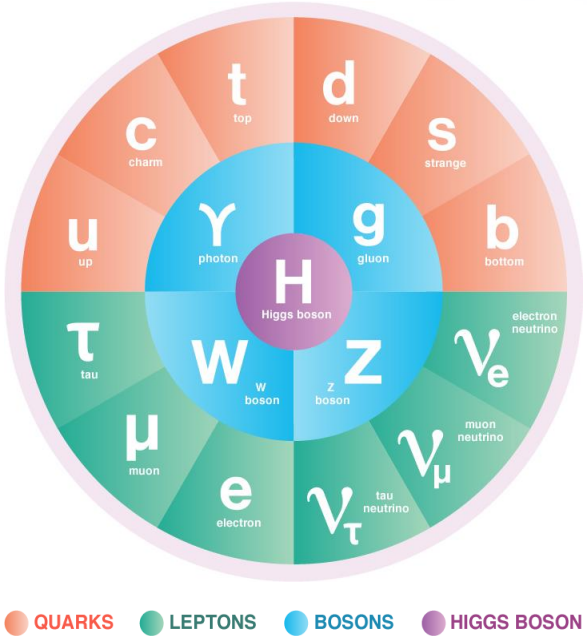

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More questions …

What mechanism(s) set the amount of dark matter?

And its ratio to regular matter?

How did this amount change over cosmic timescales?

Dark Outline

- Thermal WIMPs?
- Direct Detection Strategy
- Search Status
- Lower-mass DM?
- Next-Generation DD Experiments
  - Technologies: bubble chambers, noble liquid/gas, cryogenic solid-state, charge-coupled devices, …
  - Inelastic & electron recoils
- Near-Future Outlook

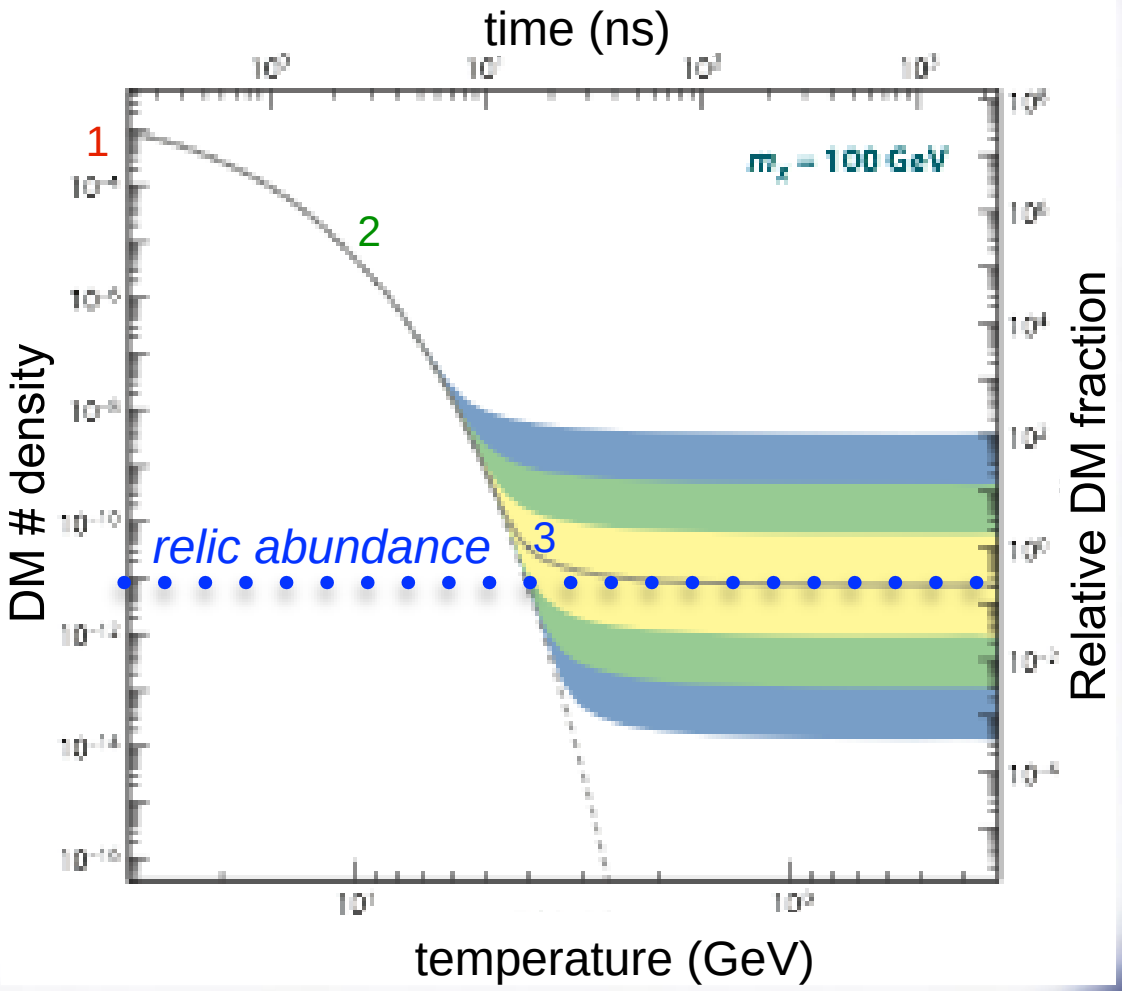
Thermal Production

General, simple mechanism for DM production in early universe:

1. DM initially in thermal equilibrium with SM, in hot "soup"
   $\chi\bar{\chi} \leftrightharpoons f\bar{f}$

2. Universe cools, SM no longer energetic enough to produce DM pairs, DM begins annihilating away
   $\chi\bar{\chi} \leftharpoondown f\bar{f}$

3. Universe expands, DM stops annihilating ("freeze-out")
   $\chi\bar{\chi} \not\leftrightharpoons f\bar{f}$



WIMP Miracle?

"relic abundance" of DM particle χ

$$\Omega_\chi h^2 \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma v \rangle}$$

cross section

$$\Omega_\chi h^2 \approx 0.1 \Longrightarrow \langle \sigma v \rangle \approx 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

$$\langle \sigma v \rangle \propto \frac{m_\chi^2}{m_Z^4} \Longrightarrow m_\chi \approx 100 \text{ GeV}$$

weak scale

"Weakly Interacting Massive Particles" (WIMPs)

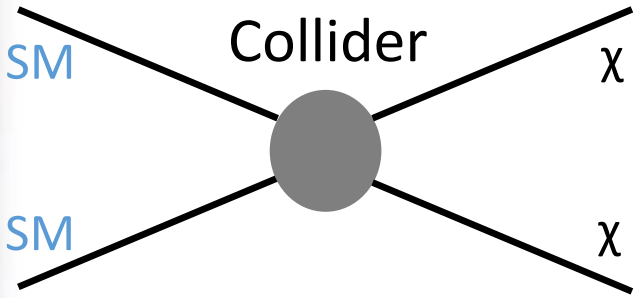
Other DM Possibilities:

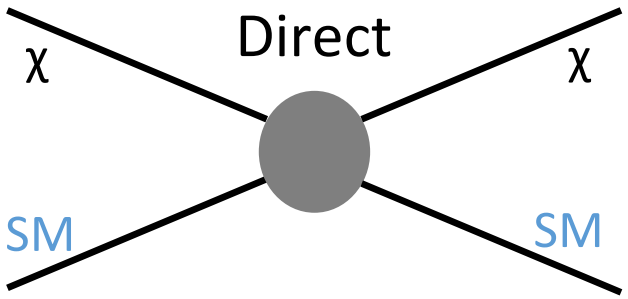
- Only gravitational interactions and/or self-interactions
- Axion-like (sub-eV masses), behaving like waves
- MACHOs
- Only modified [quantum / super-] gravity
- …

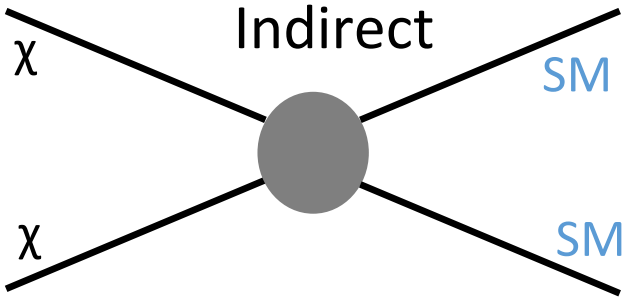
But these would be other talks!

WIMP-y Search Strategies

Complementarity between different types of experiments

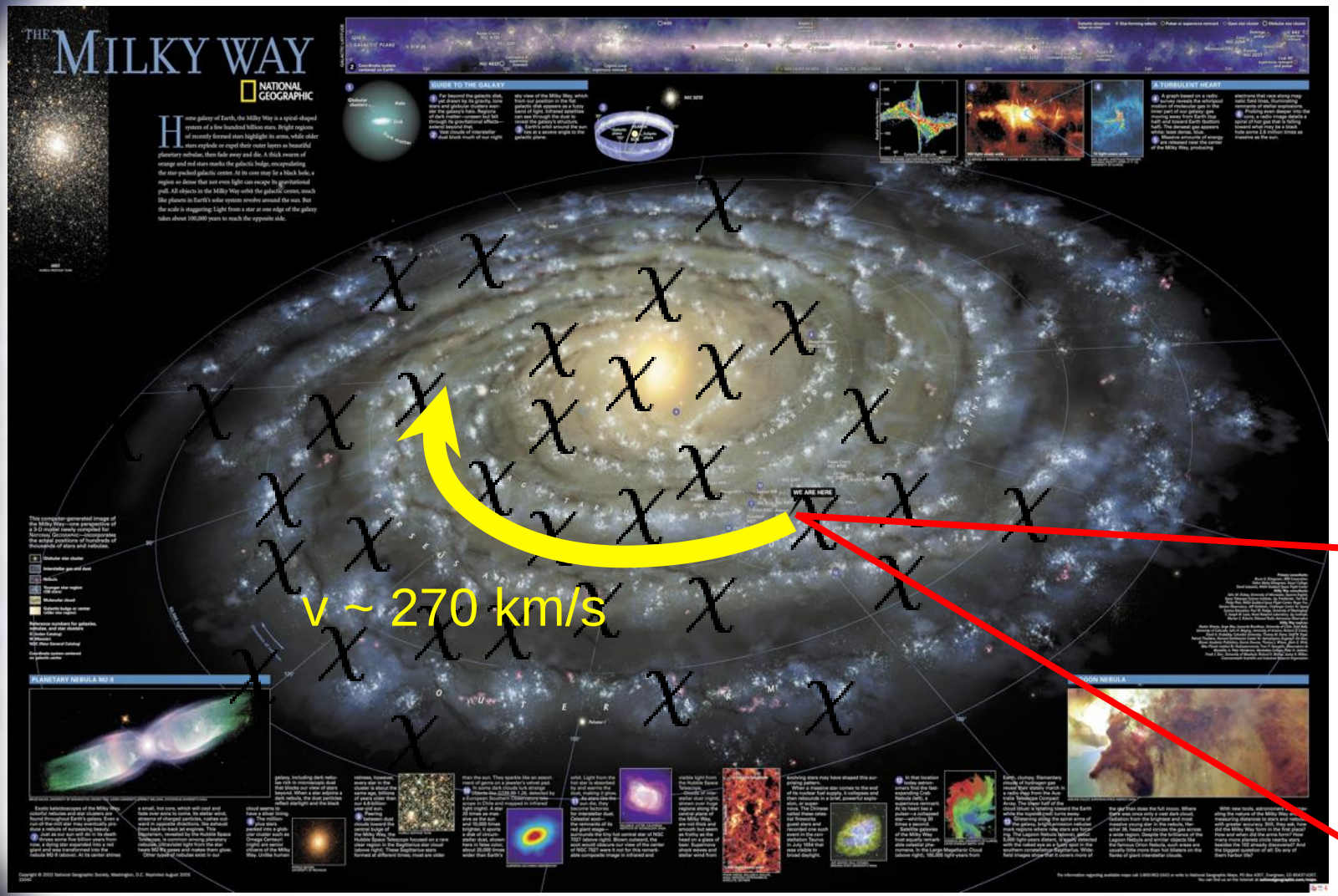






Sometimes, but not always, formulated in the context of SUSY models

Direct Detection



Collisions of galactic DM with SM particles in detector on Earth

Direct Detection

particle theory | nuclear structure | local properties of DM halo

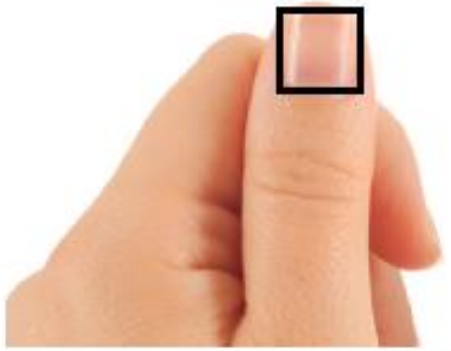
$$\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o T(E_R)}{v_o \sqrt{\pi}}$$

recoil energy of nucleus

$m_r = \frac{m_\chi m_N}{m_\chi + m_N}$ reduced mass of DM-nucleon system

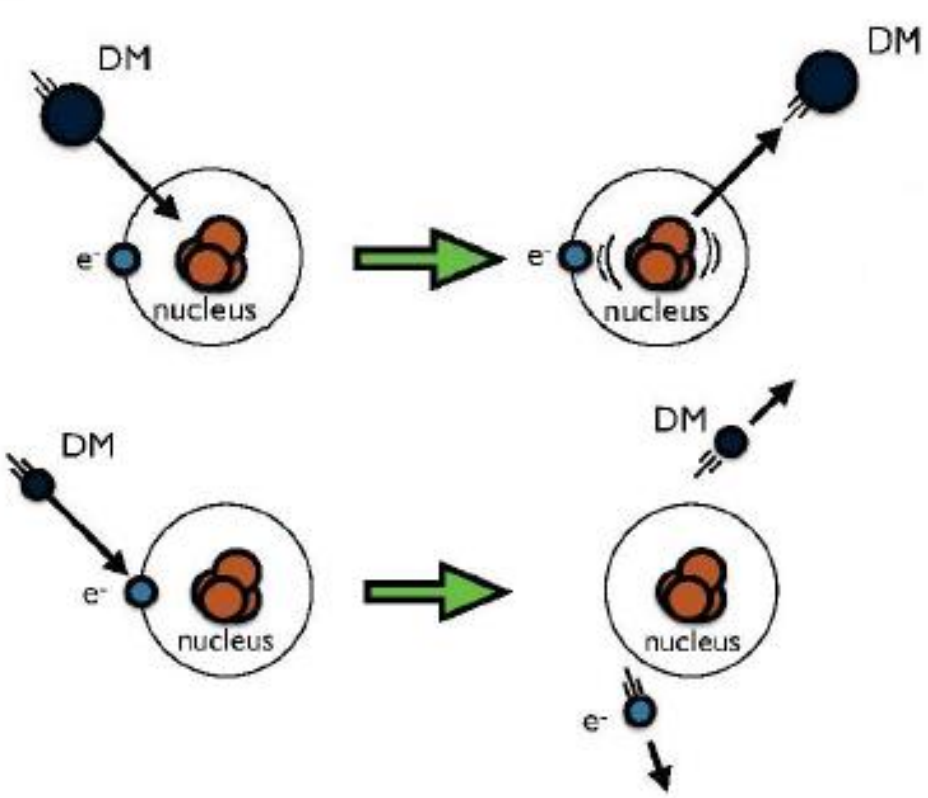
Local $\rho_{DM} \approx 0.4$ GeV/cm^3
$v_{DM} \approx 220$ km/s (non-relativistic)

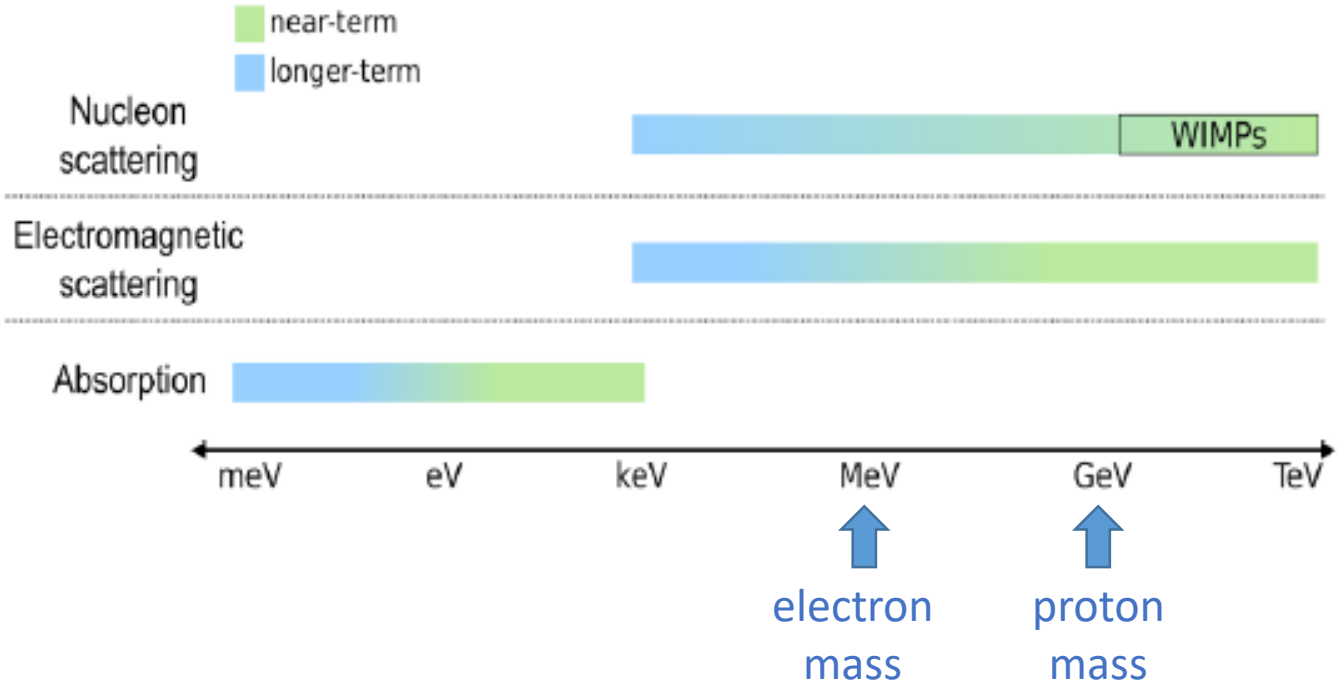
For $m_{DM} \approx 1$ GeV:
$\text{flux}_{DM} \approx 10$ million / cm^{2}s



Direct Detection

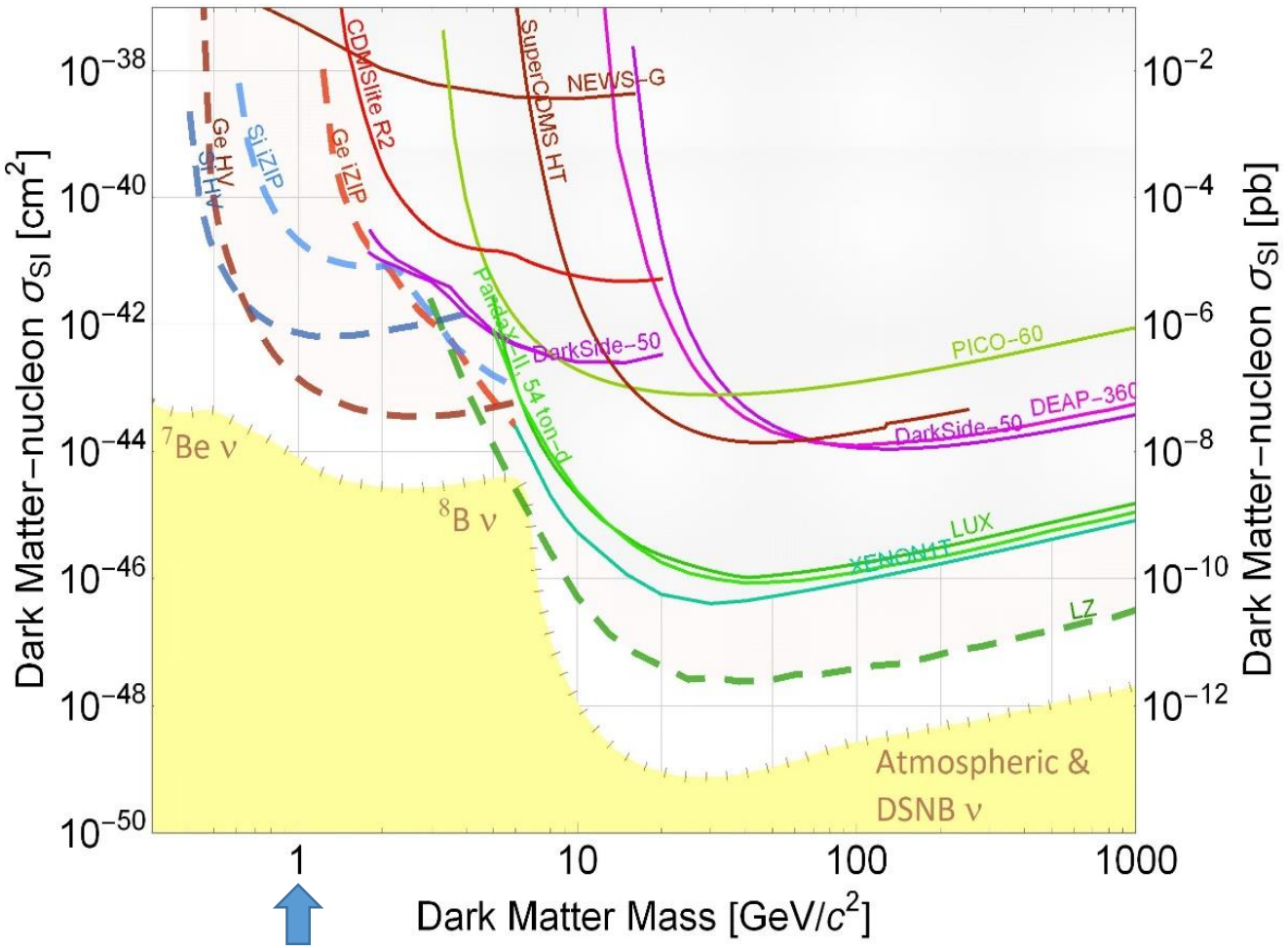
DM particles collide with SM particles in detector “target” and are absorbed, or cause nuclear and/or electronic recoils





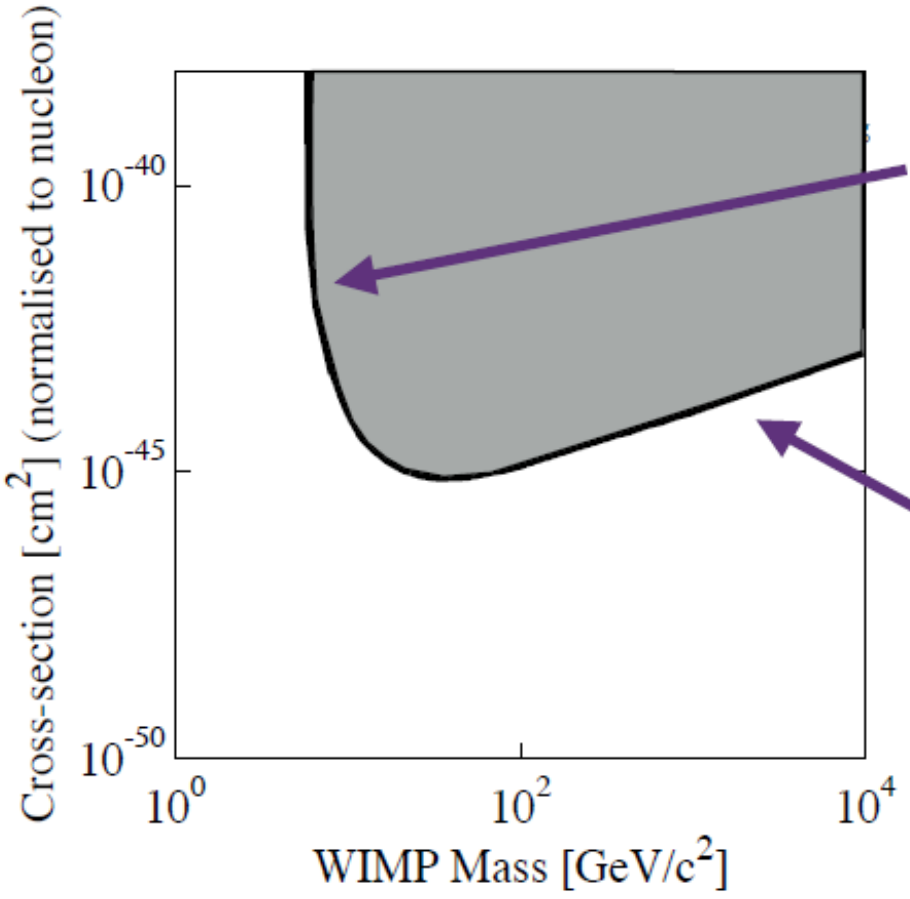
Search Status

Searches *where we most expected to find WIMPs* haven't found them!



Search Status

Schematic view of typical direct-detection limit curve:



nuclear recoil energy too small

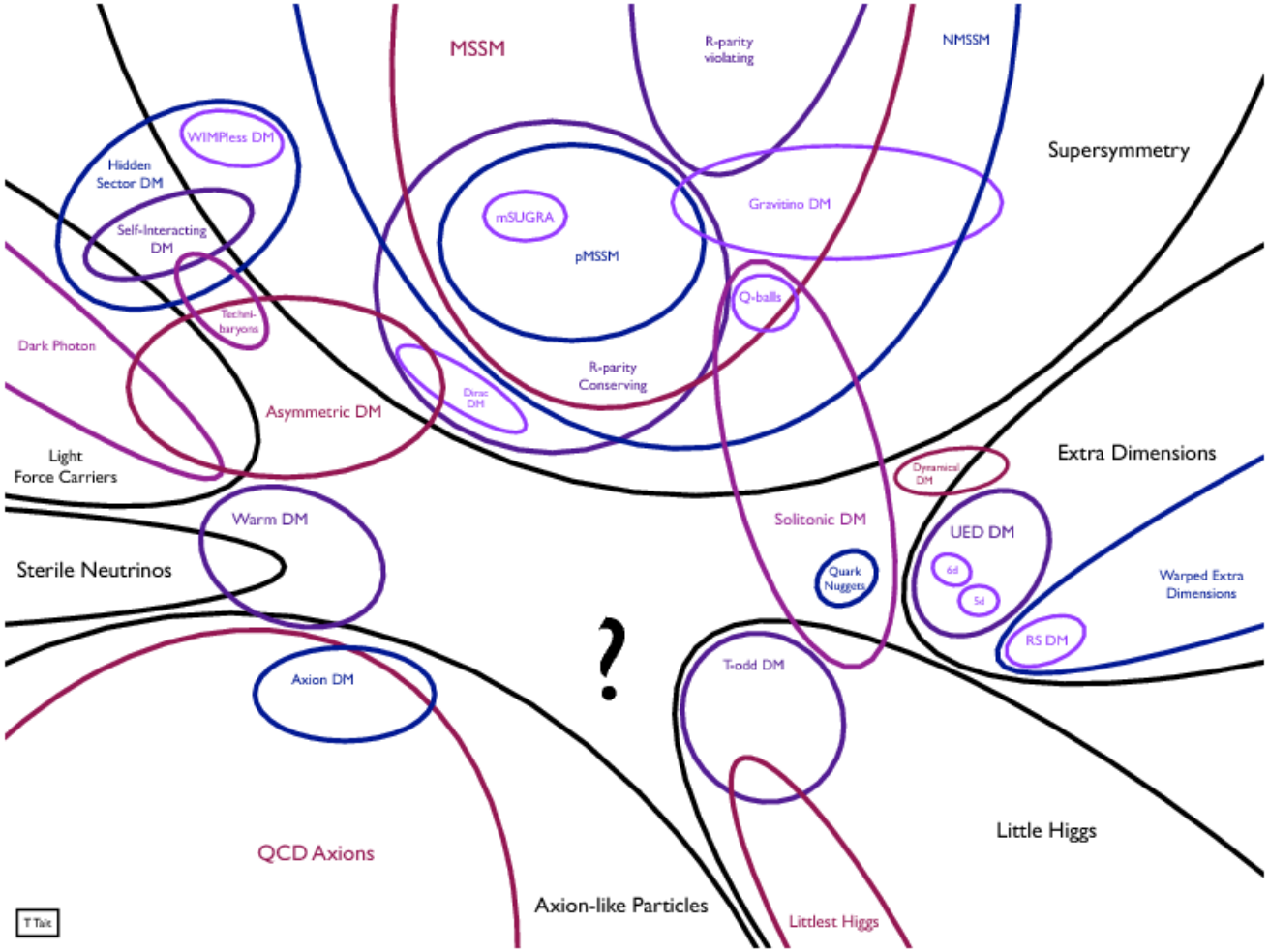
linear, since

$$\text{Rate} \propto n \propto \frac{\rho}{m}$$

$$\propto \frac{0.4\ \text{GeV/cm}^3}{m}$$

Search Status

What now?

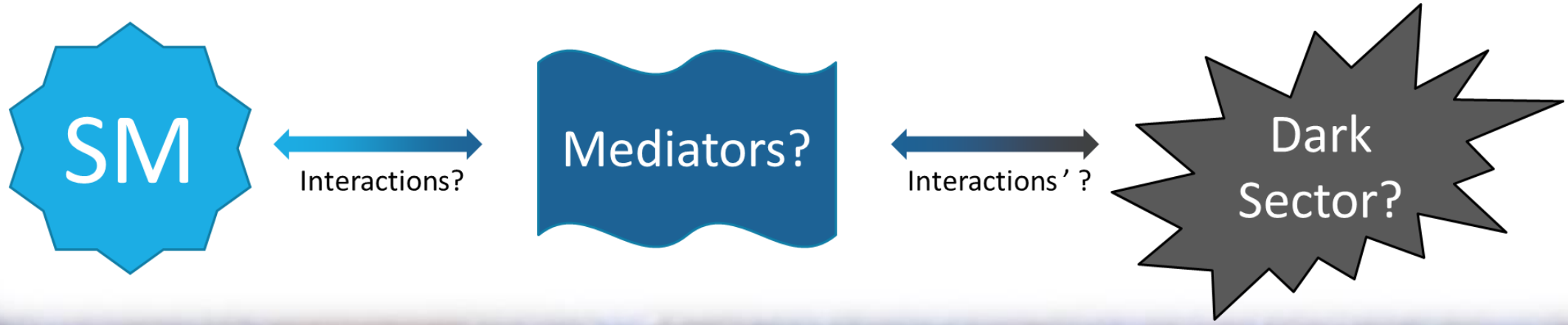

MSSM
R-parity violating
NMSSM
Supersymmetry
WIMPless DM
Hidden Sector DM
Self-Interacting DM
mSUGRA
pMSSM
Gravitino DM
Q-balls
Techni-baryons
Dark Photon
Asymmetric DM
Dirac DM
R-parity Conserving
Light Force Carriers
Extra Dimensions
Dynamical DM
Solitonic DM
Warm DM
UED DM
6d
5d
Sterile Neutrinos
Quark Nuggets
Warped Extra Dimensions
RS DM
?
Axion DM
T-odd DM
Little Higgs
QCD Axions
Axion-like Particles
Littlest Higgs
T Tait

Dark Sectors?

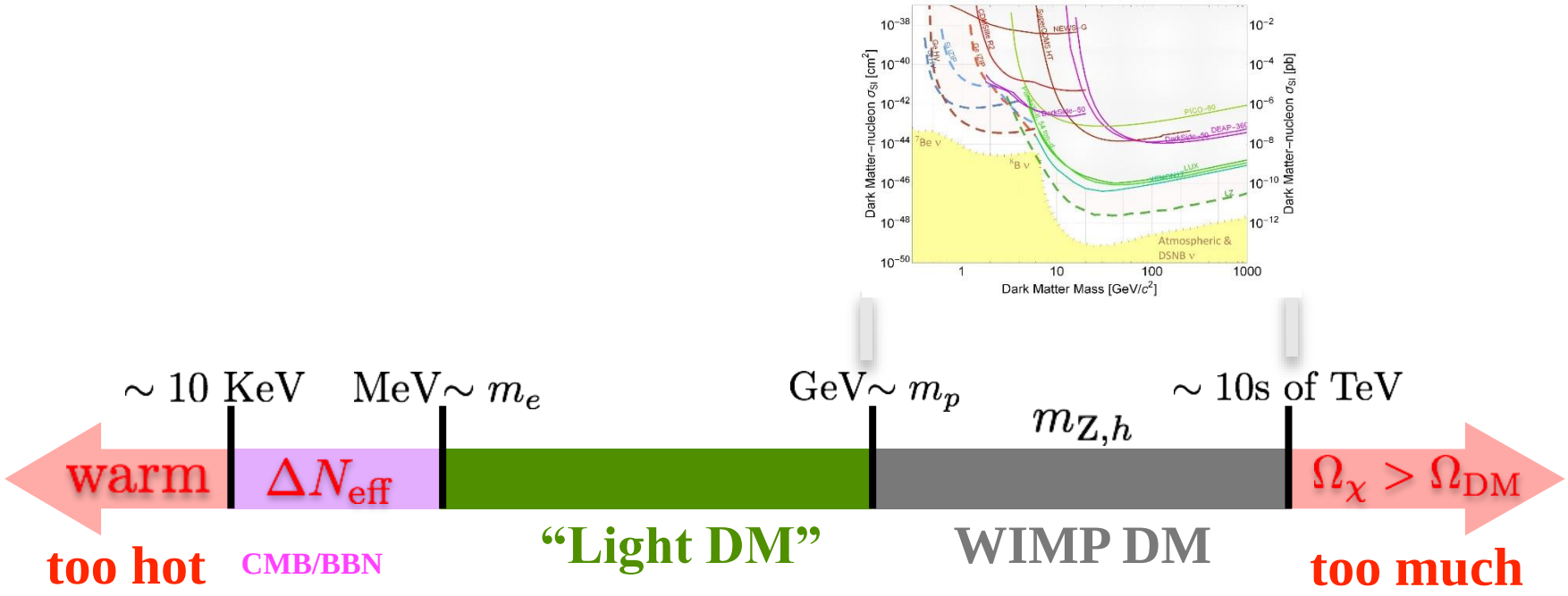
Standard Model is only ~5% of the universe.
It includes 3 forces.

Why should the ~25% that is Dark Matter be any simpler?
Dark Forces?

How would DM interact with the SM?
Mediator particles?



Lower-mass Thermal Relics?

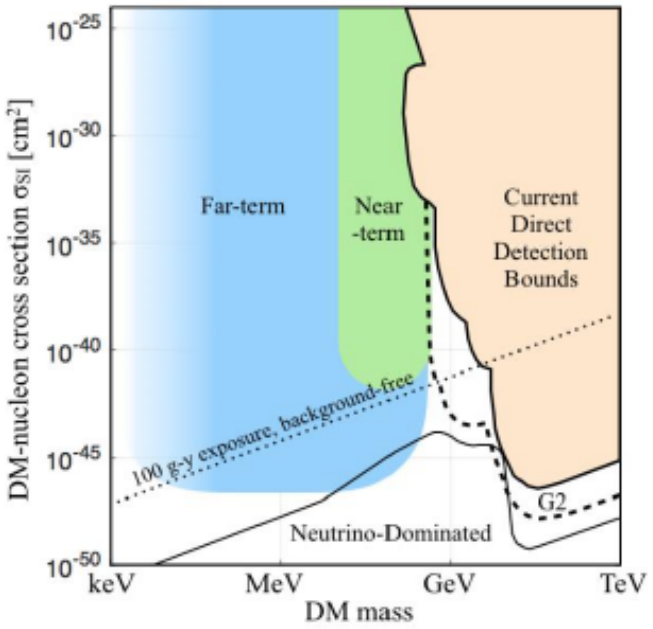


- Thermal relic dark matter works fine at least down to $2m_e$
- But "light WIMP-like DM" requires new, comparably low-mass "dark mediators" (dark force carriers)

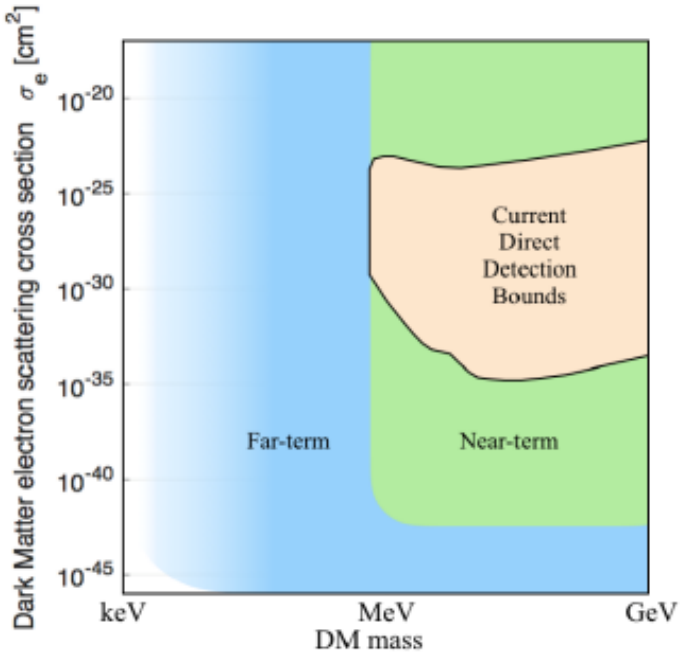
Moment of Truth

Next few years will either *find conventional WIMPs* or *rule them out.*

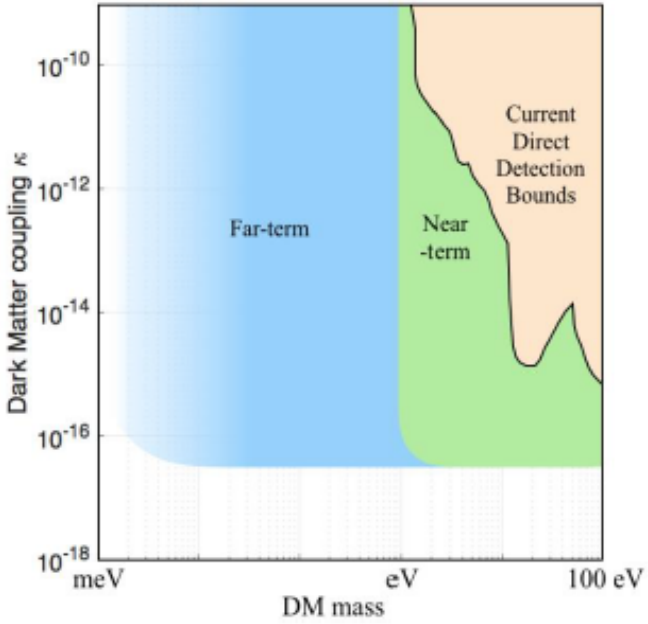
Lowering *mass* and/or *interaction* thresholds mean tougher backgrounds, and we will encounter "floor" where neutrinos drown out WIMP signal



Galactic dark matter scattering off nuclei

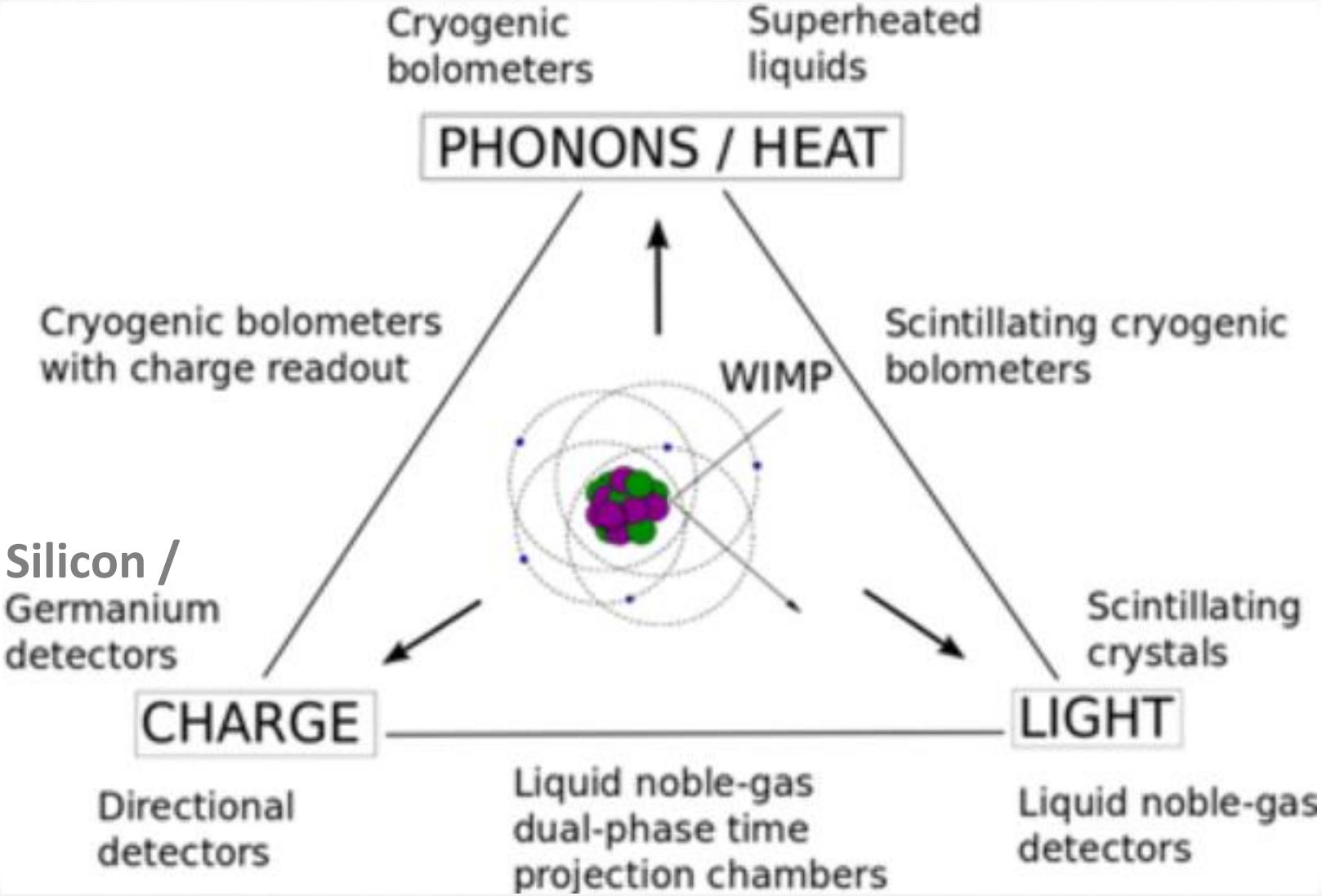


Galactic dark matter scattering off electrons



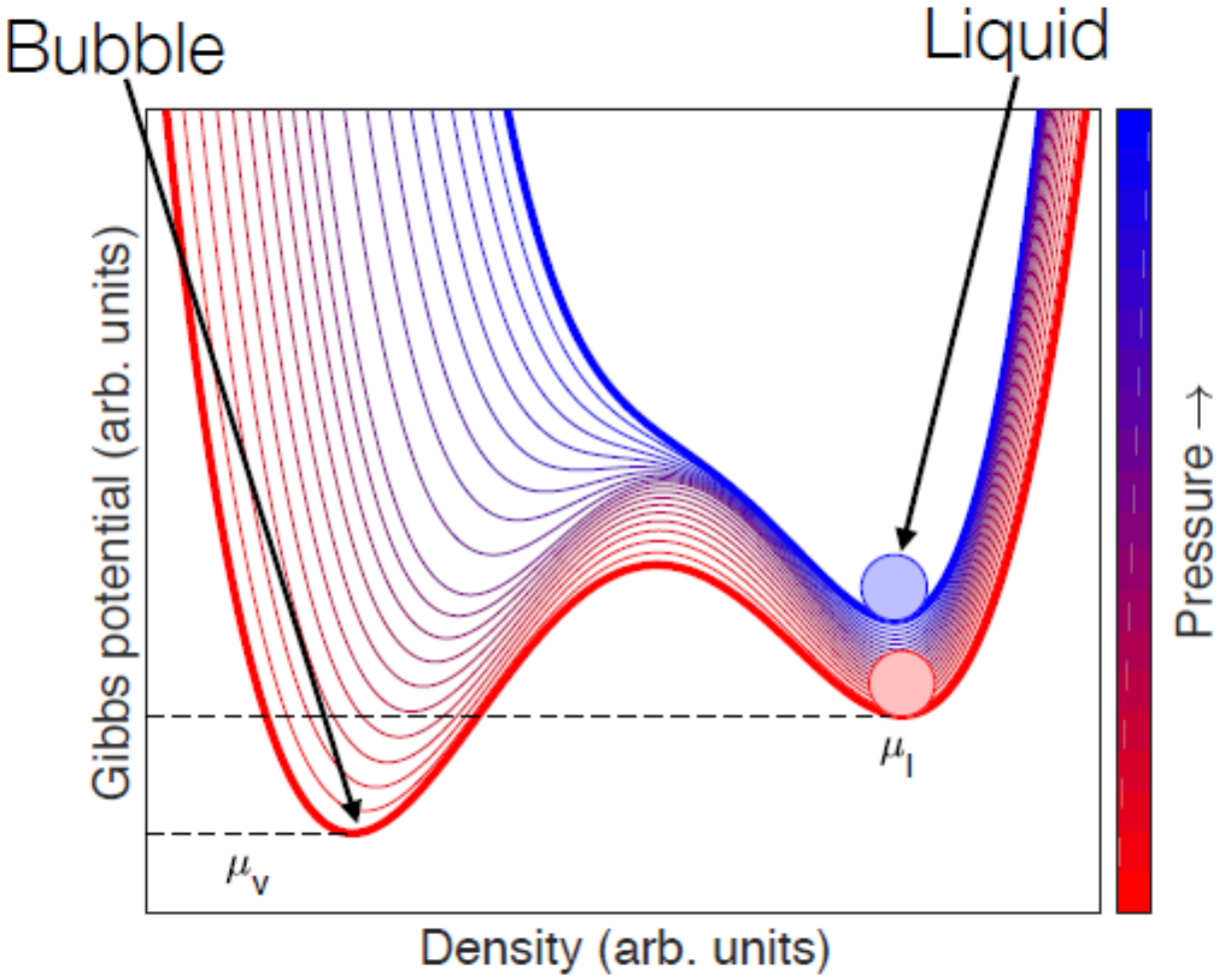
Galactic dark-photons absorbed by electrons

Next-Generation Direct Detection

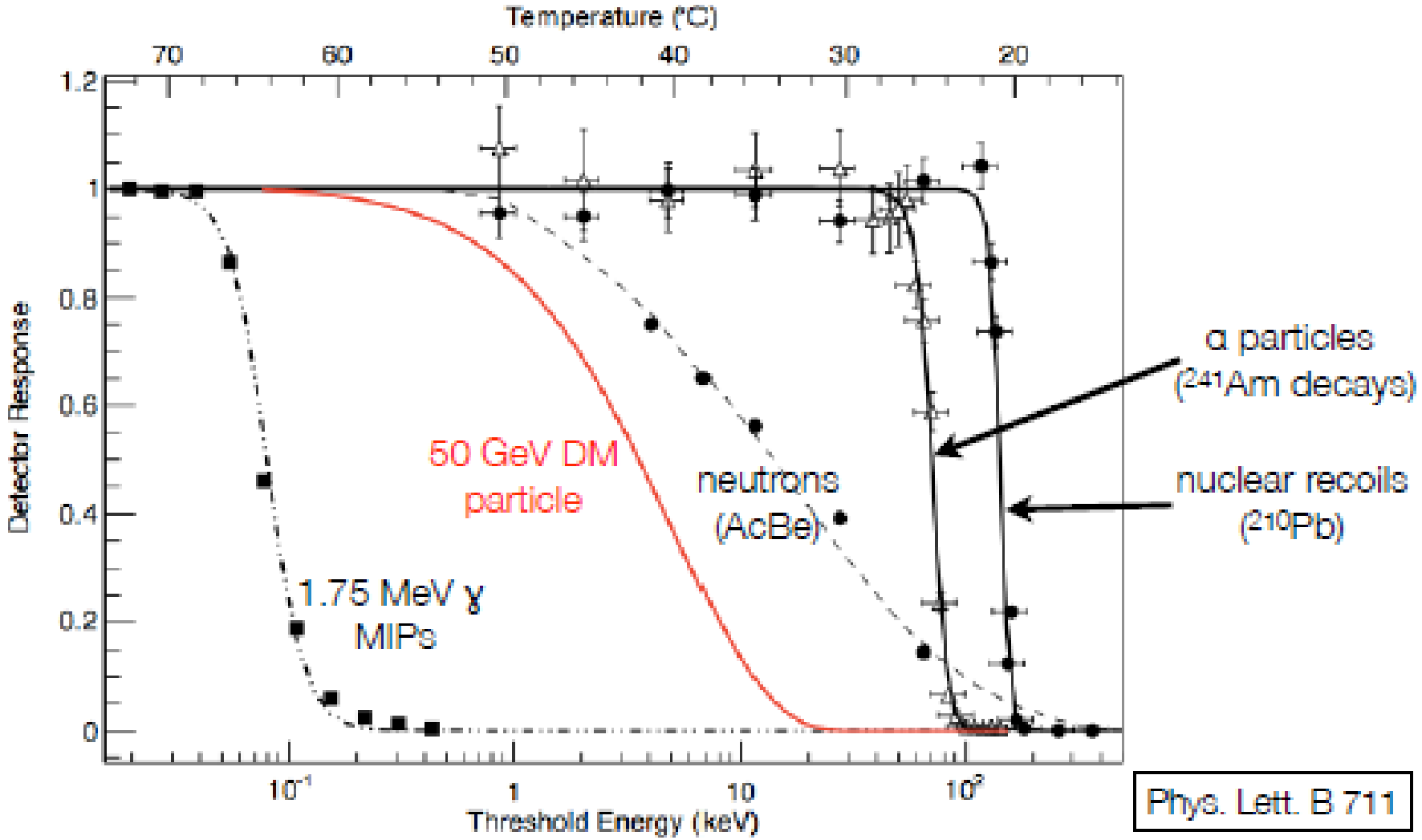


Bubble Chambers

- Jar of superheated liquid
- Incoming particle deposits energy, causing bubbles to nucleate
- Minimum deposition required to overcome surface tension: a few keV
- Cameras and/or acoustic sensors trigger on bubbles, then re-set chamber by pressurizing it
- e.g. PICO



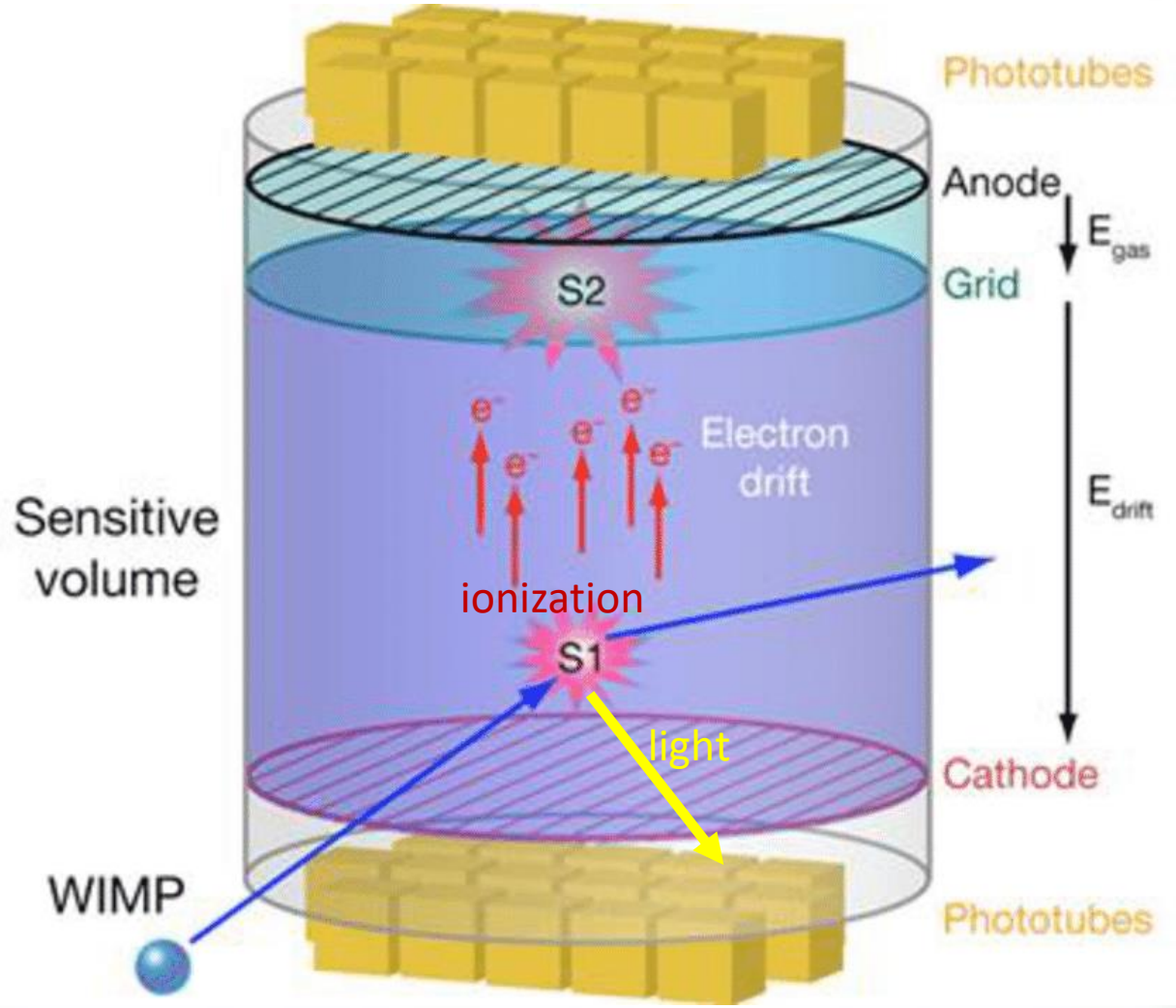
Bubble Chambers



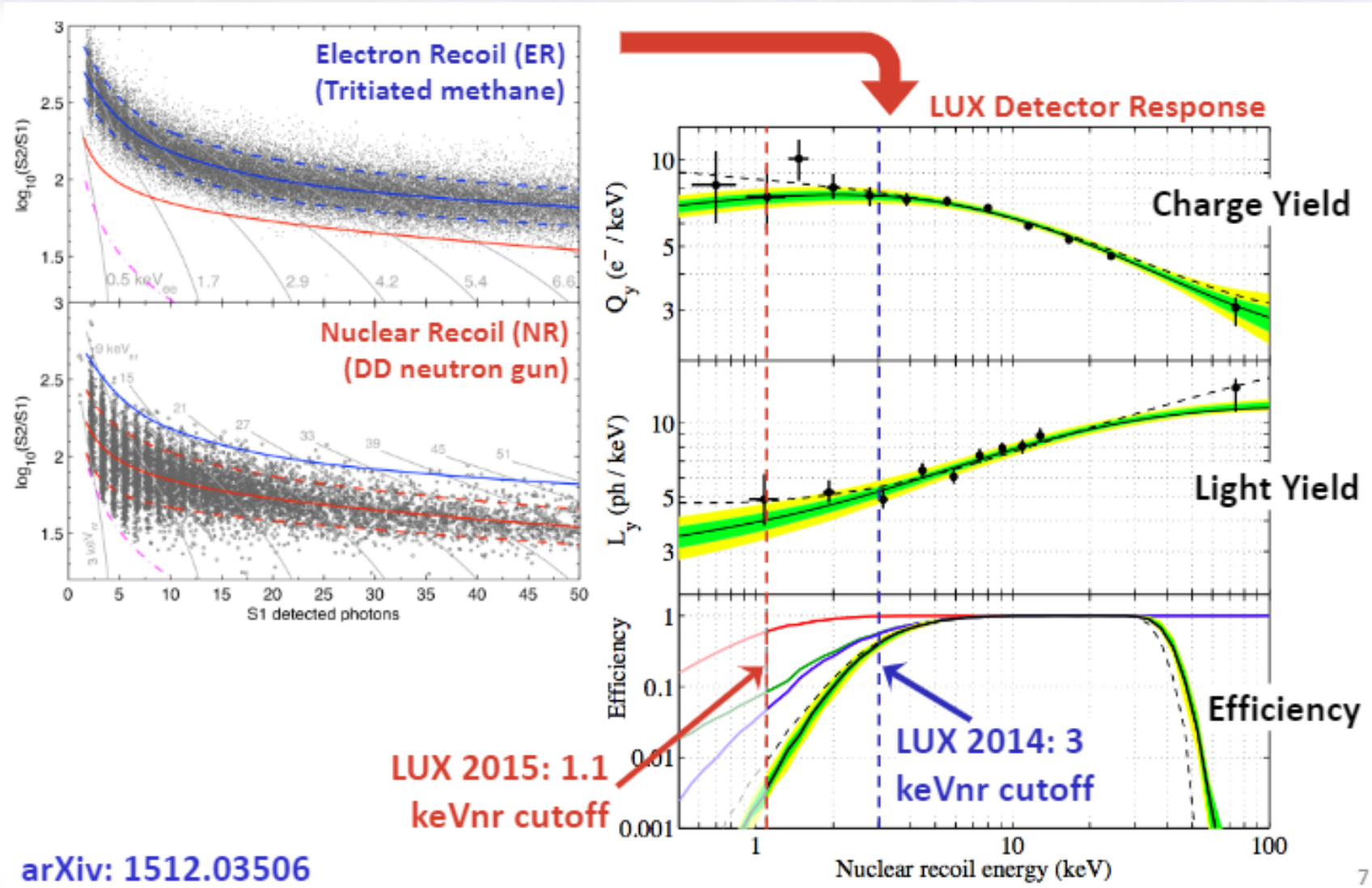
Phys. Lett. B 711

Noble Liquid/Gas Detectors

- Large tank of liquid noble element (xenon or argon) attached to sensors for light and ionization energy of particle interactions
- May also have gaseous layer
- Shielded, and often underground, to avoid interference from cosmic rays and ambient radiation
- e.g. XENON, LUX, LZ, PandaX, DarkSide, DEAP



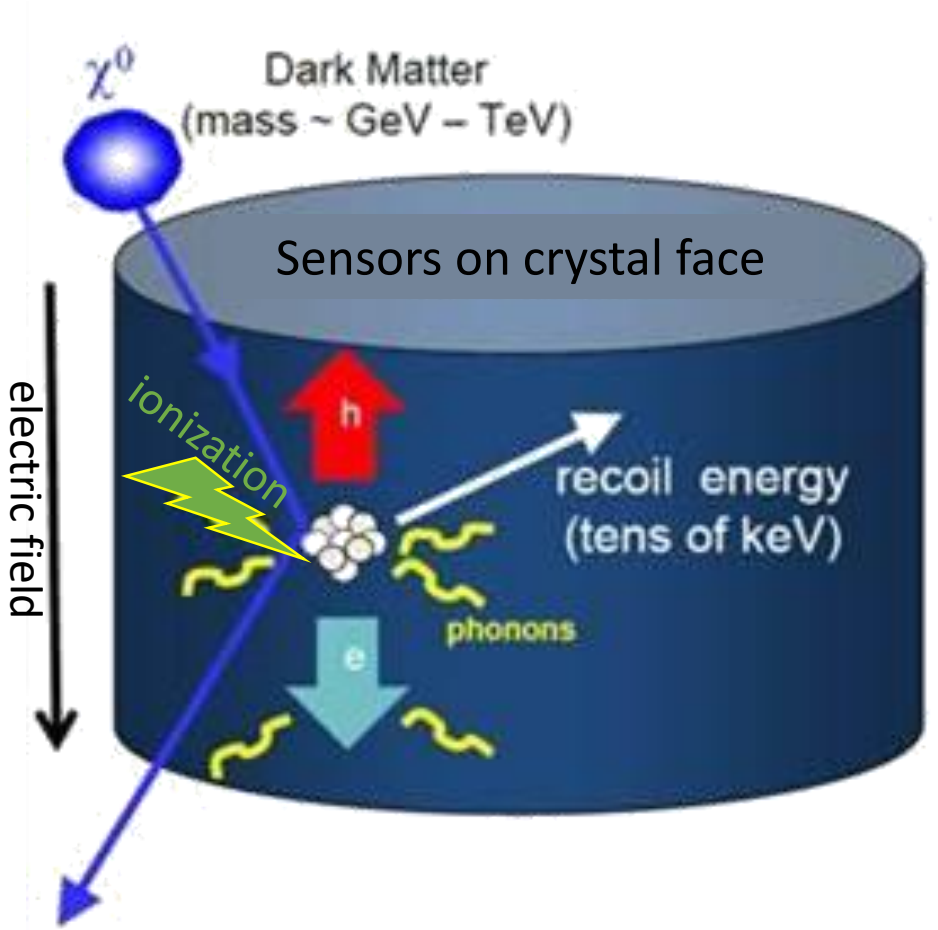
Noble Liquid/Gas Detectors



arXiv: 1512.03506

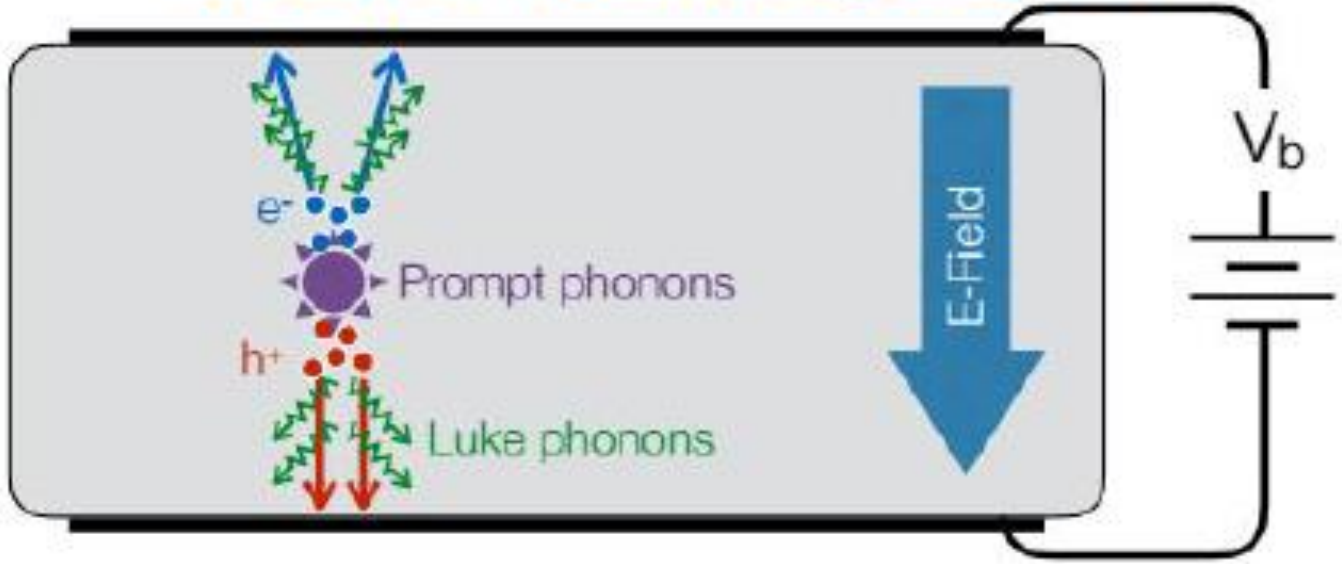
Cryogenic Solid-State Detectors

- Crystals, often semiconductors, attached to sensors for thermal and ionization energy of particle interactions
- Shielded, and often underground, to avoid interference from cosmic rays and ambient radiation
- Operated at very cold temperatures to avoid thermal noise
- e.g. EIDELWEISS, SuperCDMS



Cryogenic Solid-State Detectors

- **n_{eh} (# charges) measured, e.g. using high electron mobility transistors**
- **E_t (total phonon energy) measured, e.g. using transition edge sensors**
- **Drifting charges across a potential (V_b) generates Neganov-Trofimov-Luke phonons**
  - **Increasing V_b lowers recoil energy threshold**
  - **But NR vs ER discrimination lost**

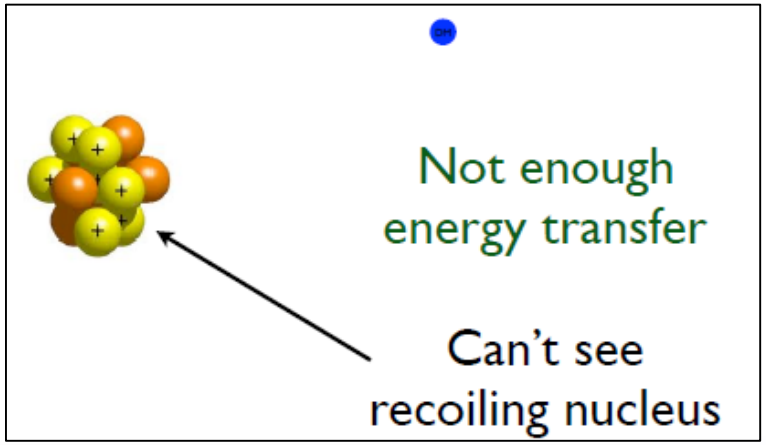


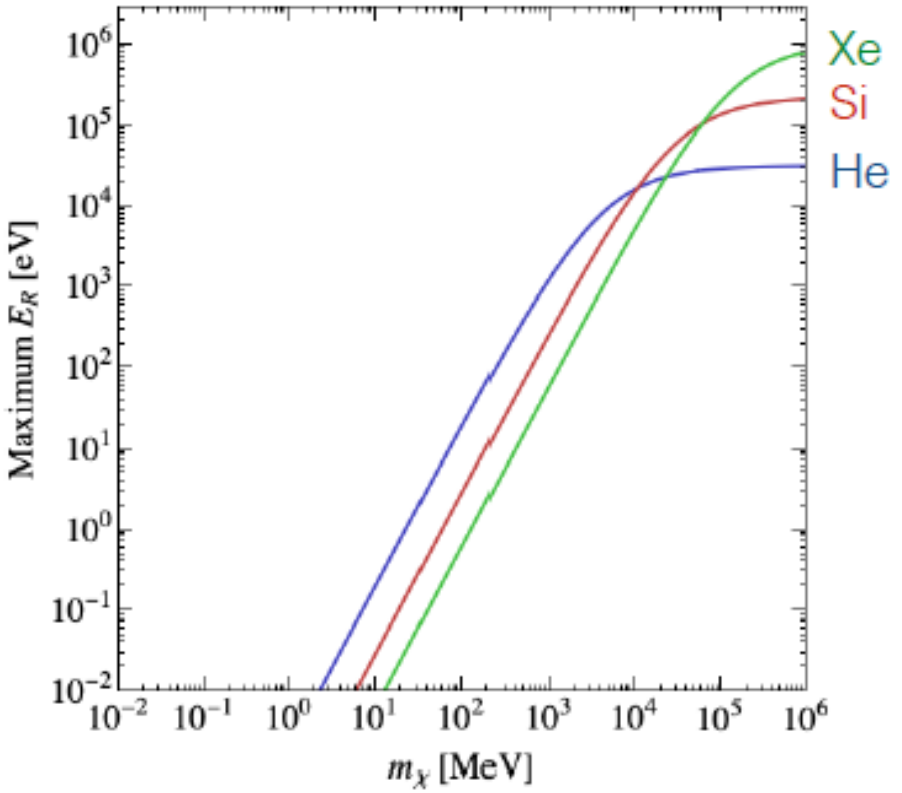
$$E_t = \underbrace{E_r}_{\text{Primary recoil energy}} + \underbrace{n_{eh} q V_b}_{\text{NTL phonon energy}}$$

The Sub-GeV Detection Challenge

- These detectors have traditionally relied on elastic NR signal
- But cannot use elastic NRs for sub-GeV DM: inefficient momentum & energy transfer
- Alternatives: inelastic processes, electron recoils

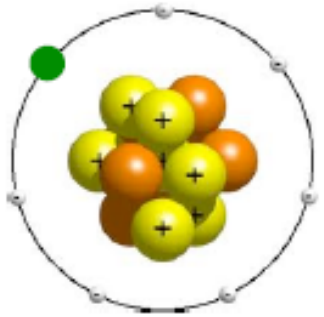
$$E_{\rm NR} = \frac{q^2}{2m_N} \leq \frac{2\mu_{\chi N}^2 v_\chi^2}{m_N} \simeq \frac{2m_\chi^2 v_\chi^2}{m_N}$$

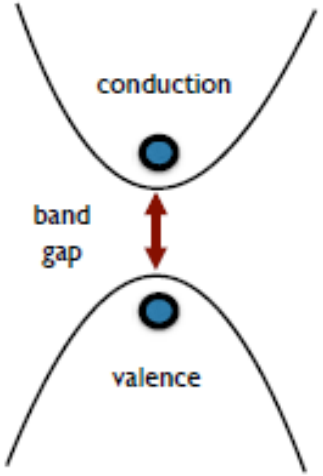


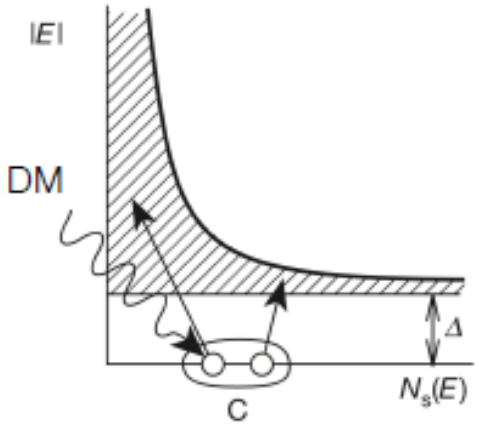


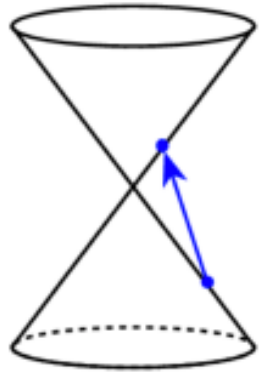
Electron Recoils

- Target materials include:









...

noble liquids

semiconductors
scintillators

superconductors

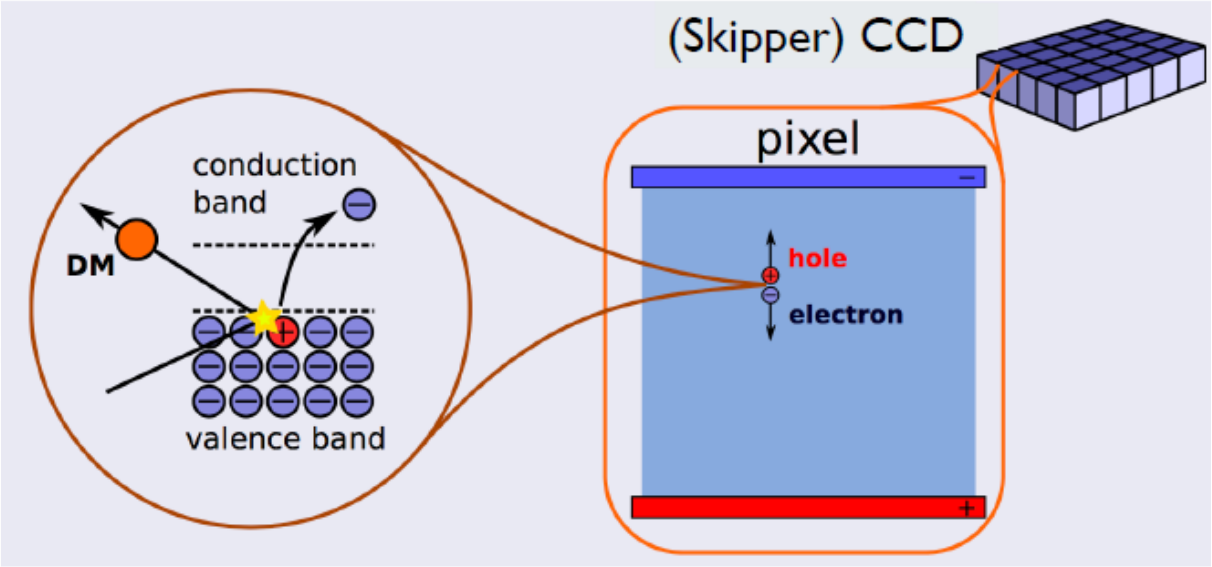
Dirac materials
(speculative “exotic”)

$\Delta E \sim 10$ eV
$m_{\rm DM} \sim 5$ MeV

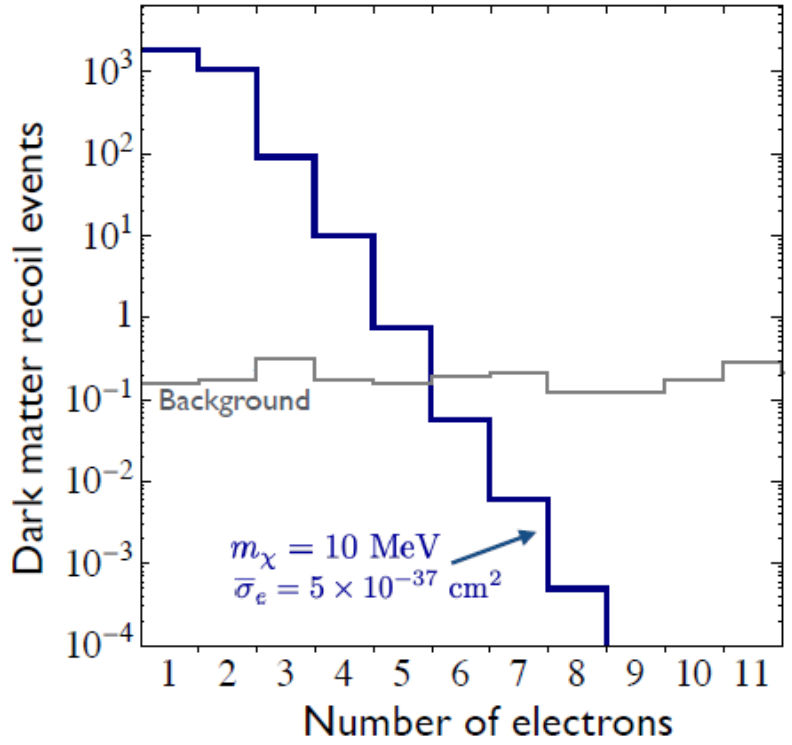
$\Delta E \sim 1$ eV
$m_{\rm DM} \sim 500$ keV

$\Delta E \sim$ few meV
$m_{\rm DM} \sim$ keV

Charge-Coupled Devices

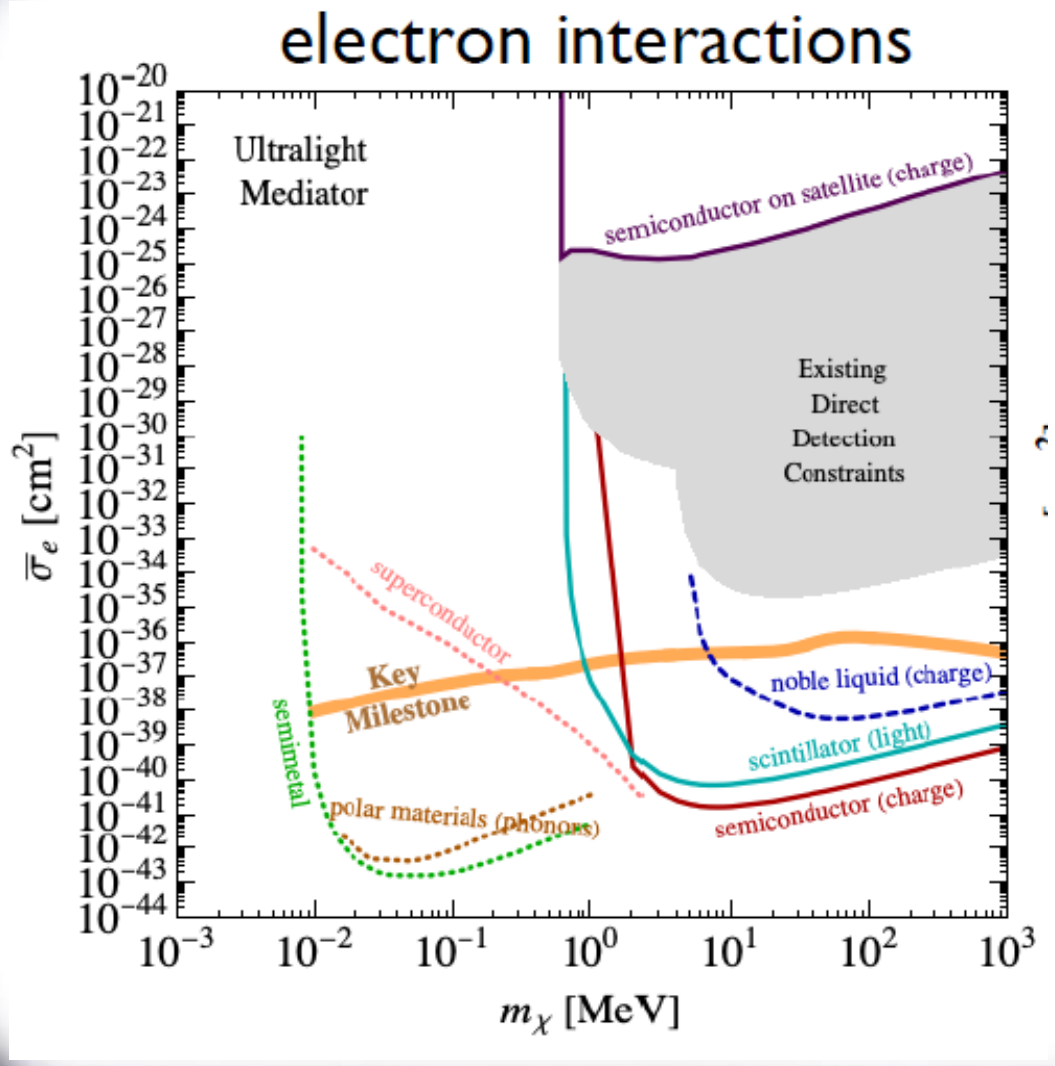


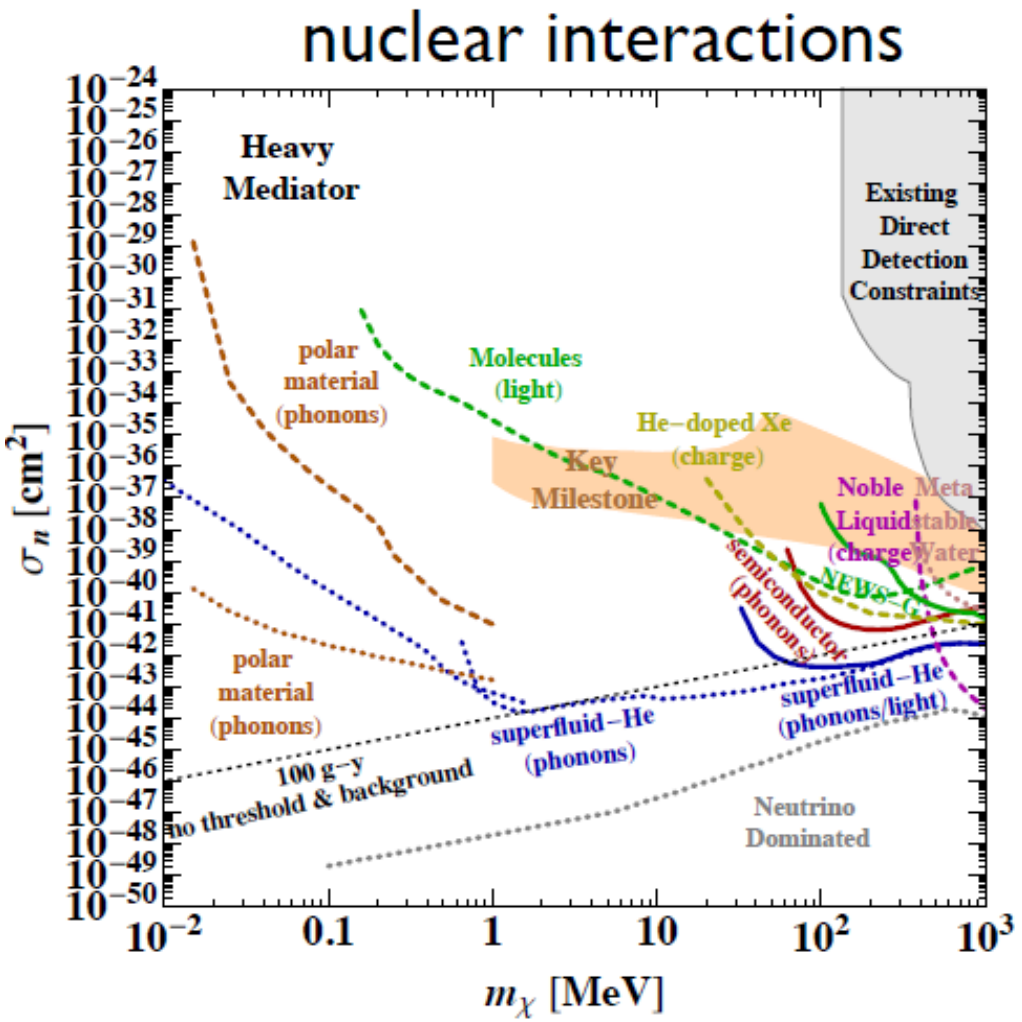
DM would create one or a few electrons in a pixel



- Single-electron sensitivity & readout with “skipper” technology
- E.g. DAMIC, SENSEI

Near-Future Prospects





Join the Dark Side

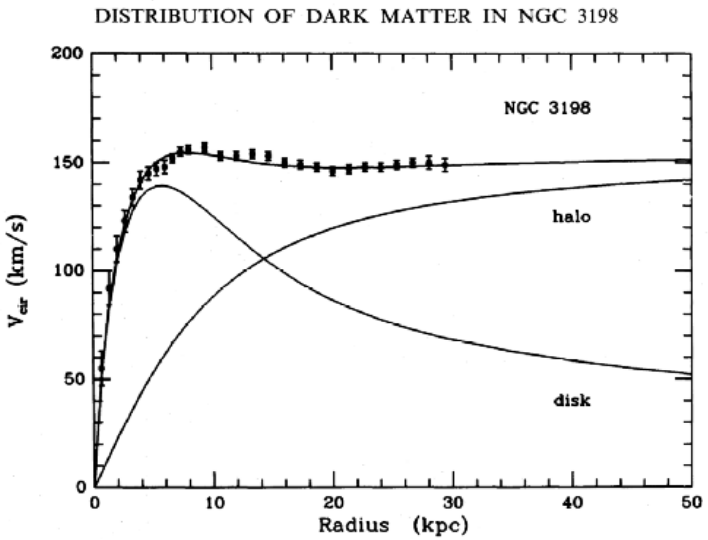
Beyond the Standard Model

Dark Matter (DM)

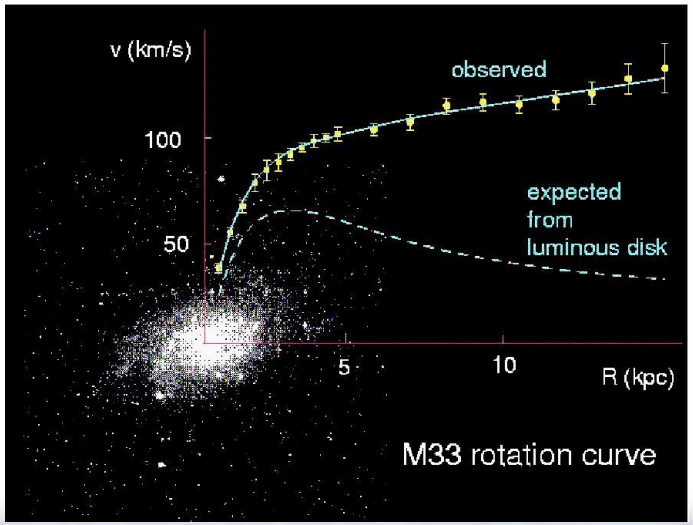
Jan Oort (1932)

It may be of some interest to compare these numbers to some other estimates of the same quantity. From the rotational velocity of the galaxy we know approximately the total mass contained in the more central parts of the galactic system. It may be put at $1{\cdot}2.10^{11}$, if we take the mass of the sun as unit. We can also form an approximate estimate of the total luminosity contained in the same part of the system by computing from VAN RHIJN's star counts the total light which we receive from the region between, say, 280° and 10° galactic longitude and ± 20° latitude. The total luminosity estimated in this way is 10^{10} units. Thus, the average mass corresponding with a unit of light would be about 12 in this case, or about 7 times larger than the value derived above. It is not necessary to conclude from this that the absolutely bright stars are relatively less frequent near the centre, or that there is a greater percentage of nebulous or dark matter in this region: we might reverse the argument

Vera Rubin (1970)



Recent surveys

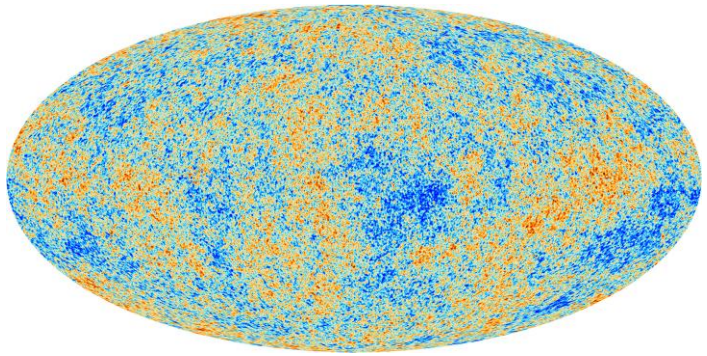


… a lot of it …

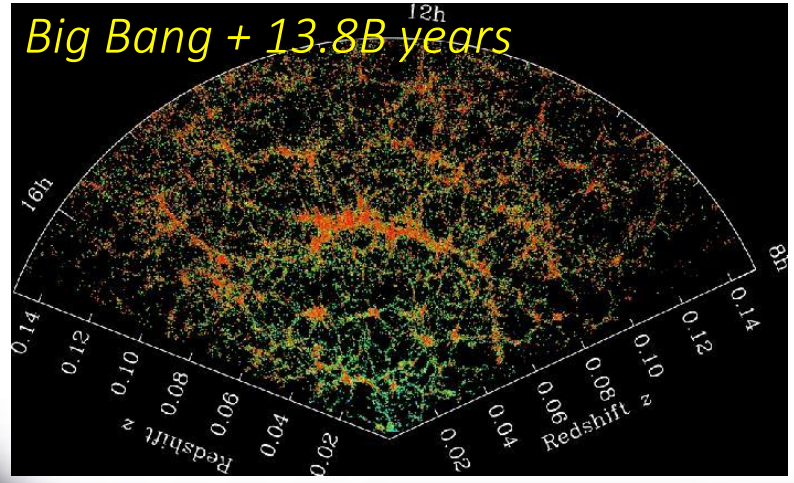
Dark Matter isn't in the Standard Model?!

Cosmic Microwave Background (Planck)

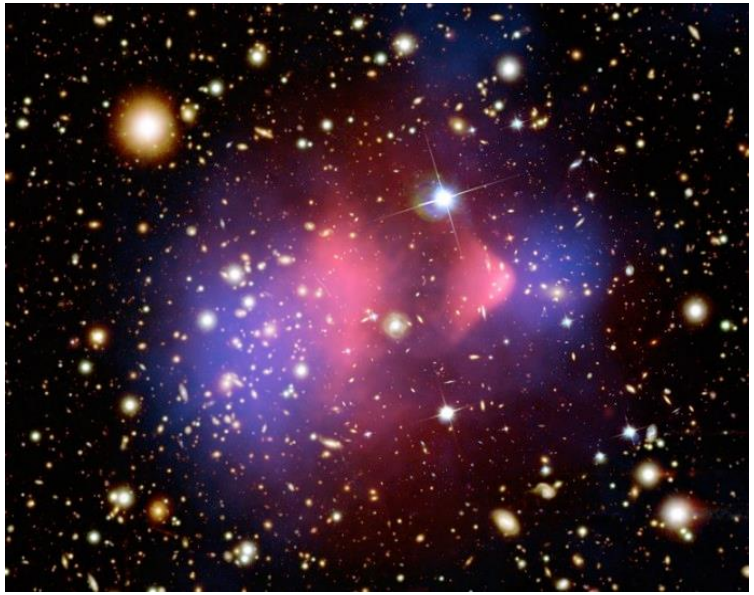
Big Bang + 380K years



Large-Scale Structure (SDSS)



Collisions between galaxy clusters

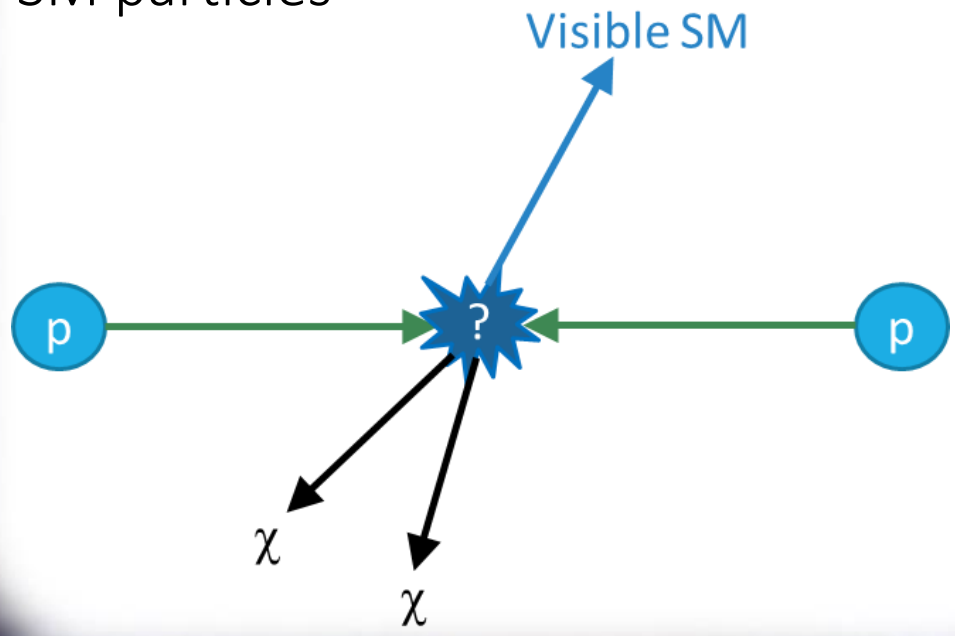


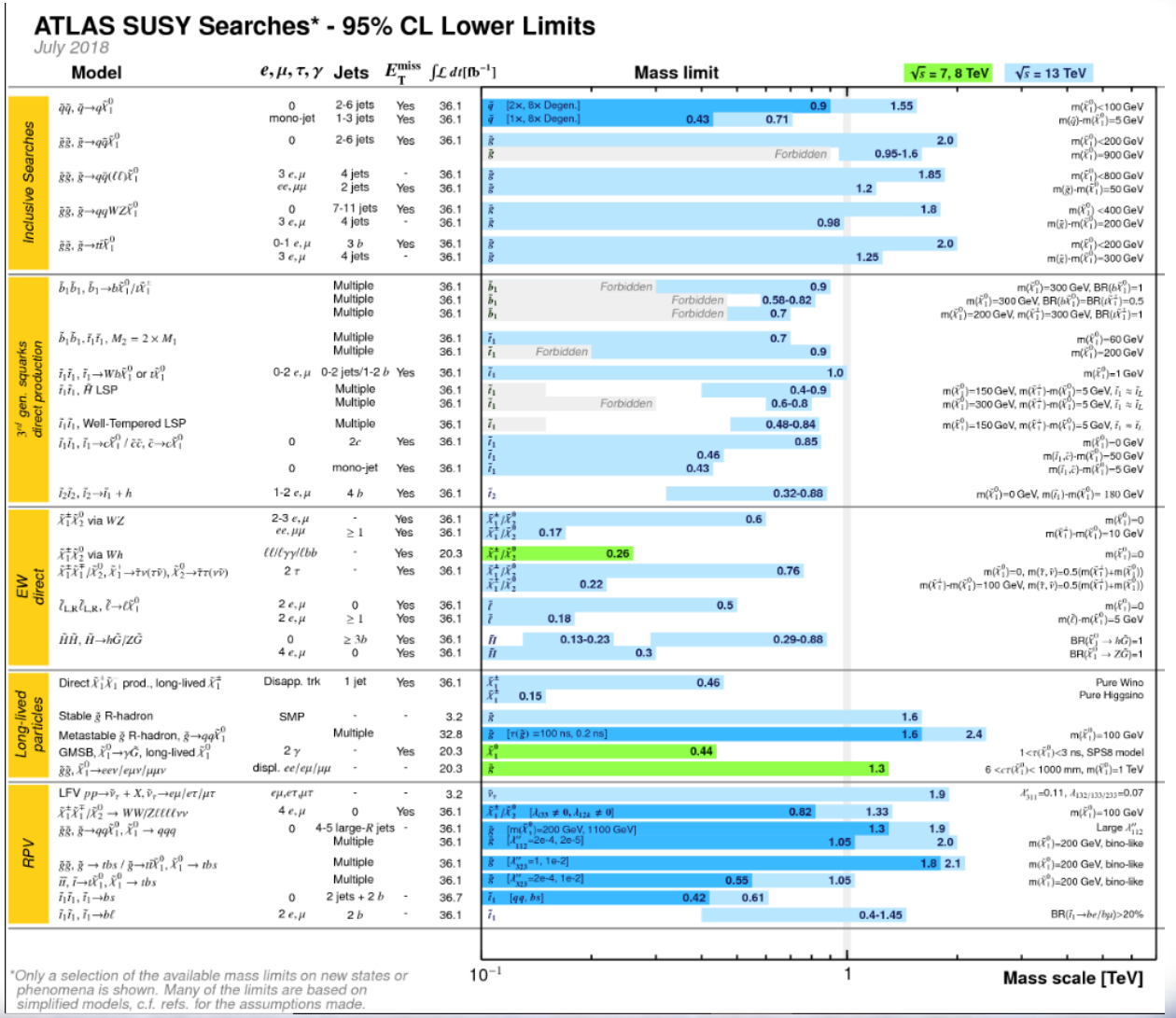
- Cold (non-relativistic)
- Little interaction with regular matter

DM seems to be some new kind of matter

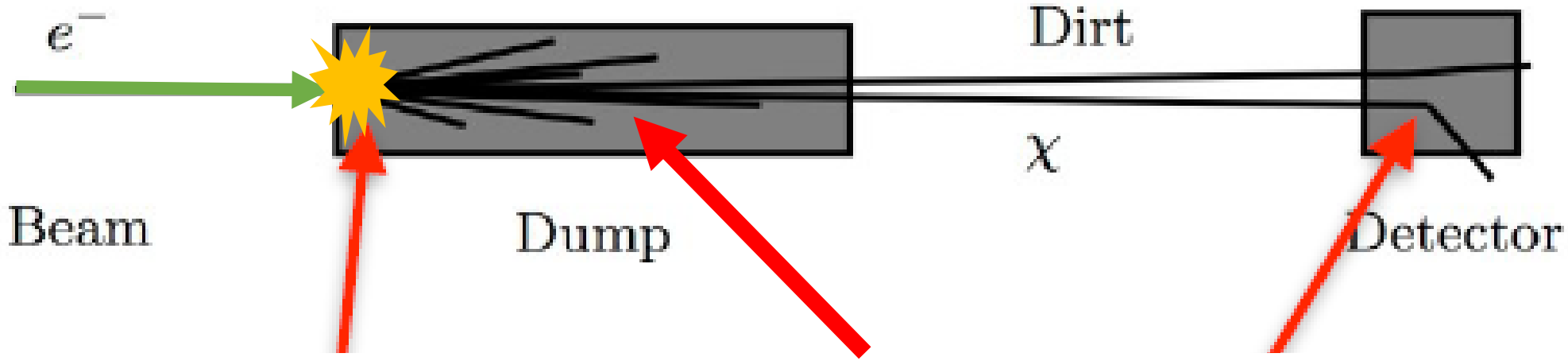
Collider Searches

- Most recent at Large Hadron Collider
- Often look for “missing transverse energy” carried off by WIMPs produced in association with visible SM particles





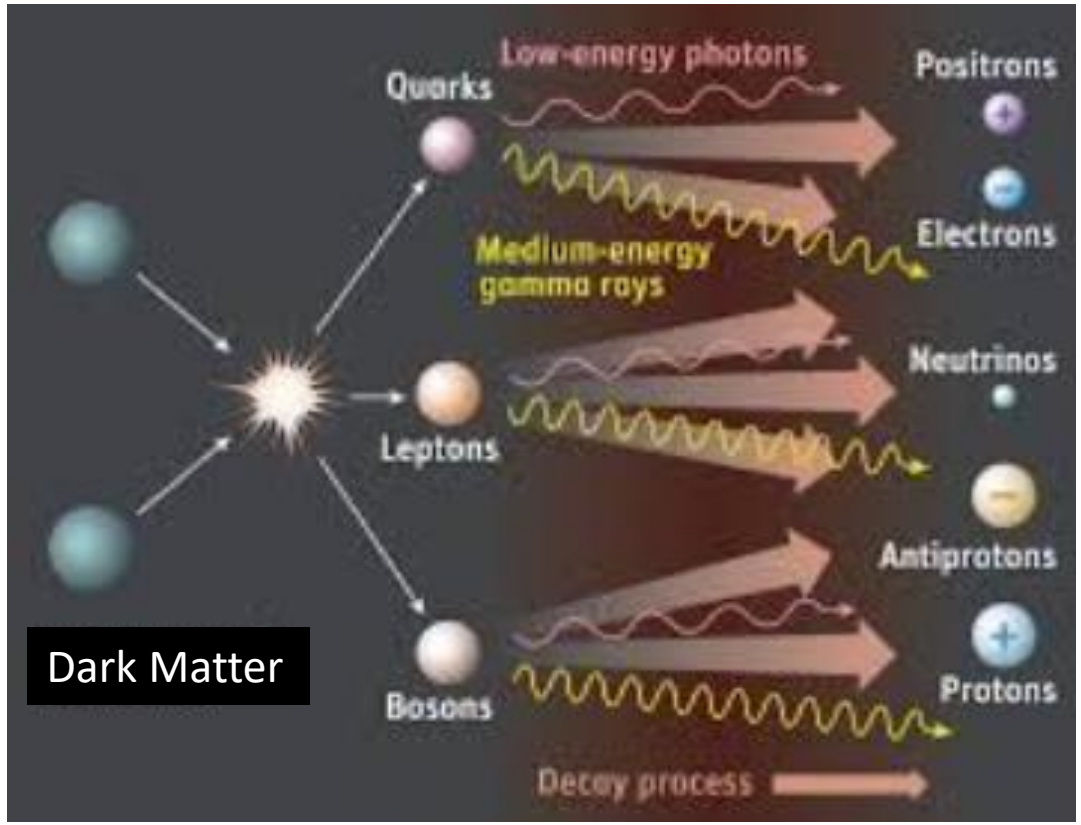
Fixed-Target Searches



When particle beam collides with fixed target, DM produced in association with visible SM particles

Only the DM reaches detector behind “beam dump” and dirt

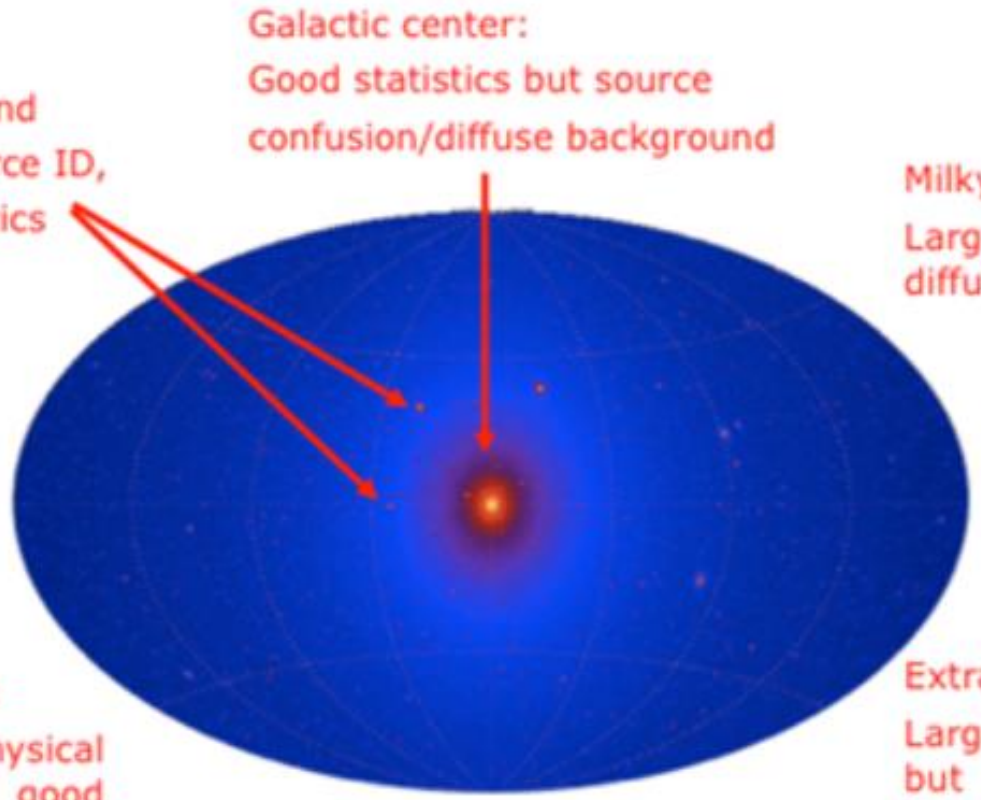
Indirect Detection



Collisions of WIMPs in outer space could produce SM particles that travel to Earth

"Signals" (e.g. excess photons of a certain frequency) detected by ground- or space-based telescopes

Indirect Detection

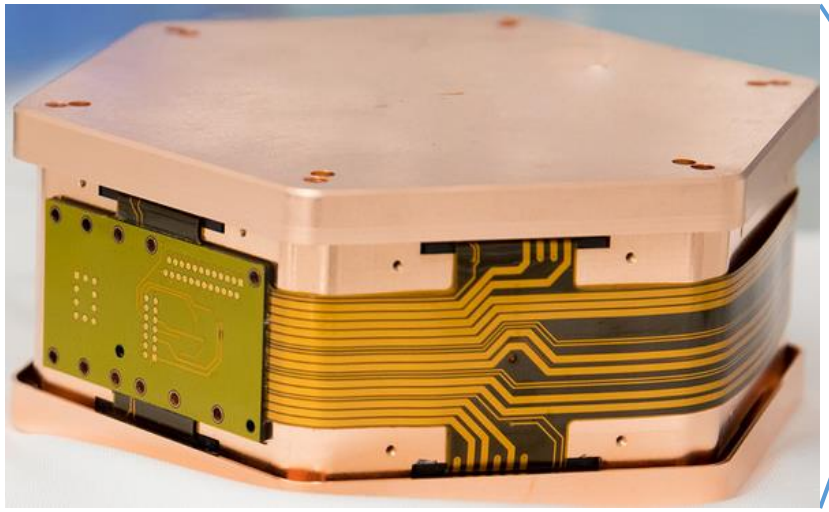


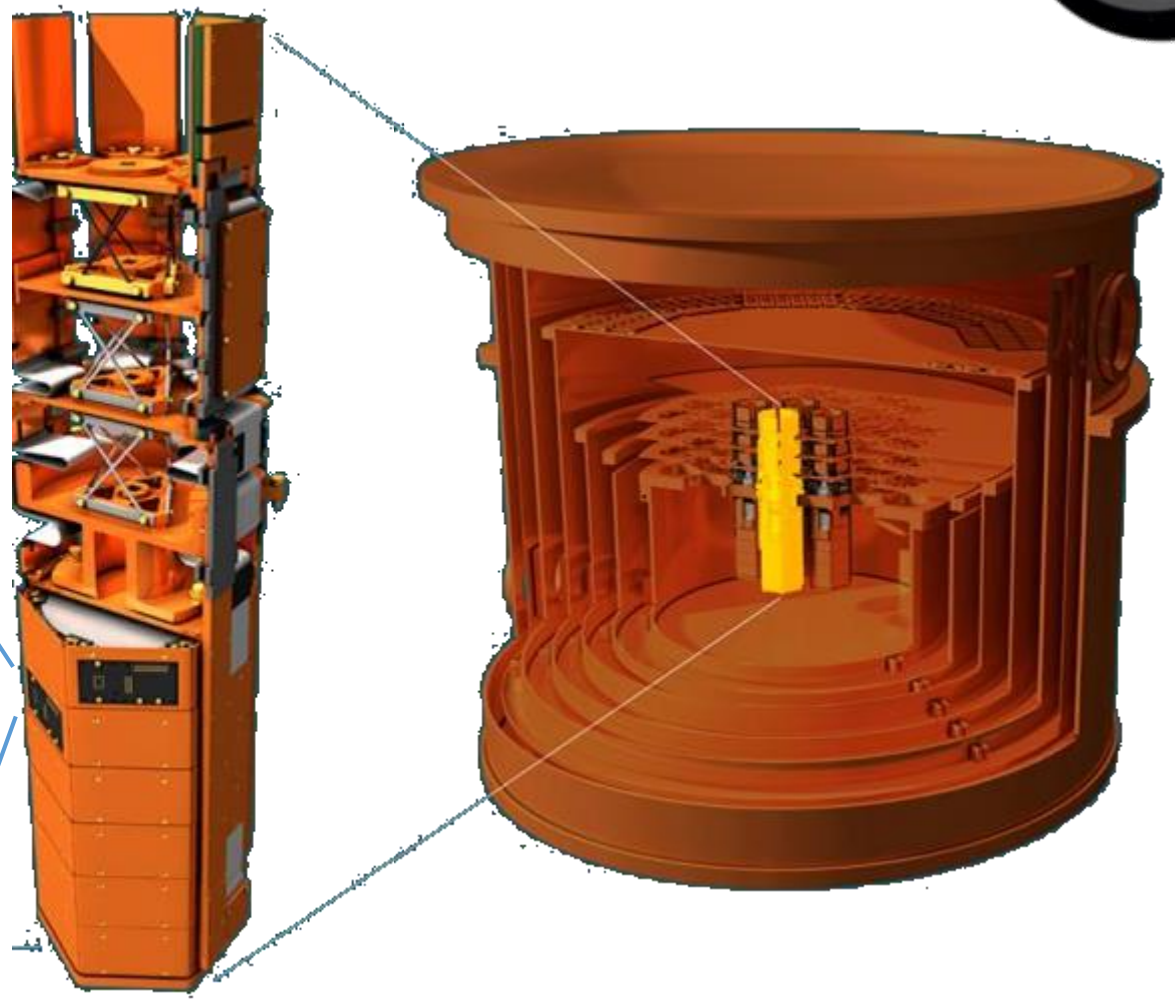
Expect some cosmic neighborhoods to have more DM than others

But some also give off more backgrounds

Super Cryogenic Dark Matter Search

- Silicon and germanium detectors
- Extremely low detection thresholds provide sensitivity to very feebly-interacting WIMPs, and lower-mass DM

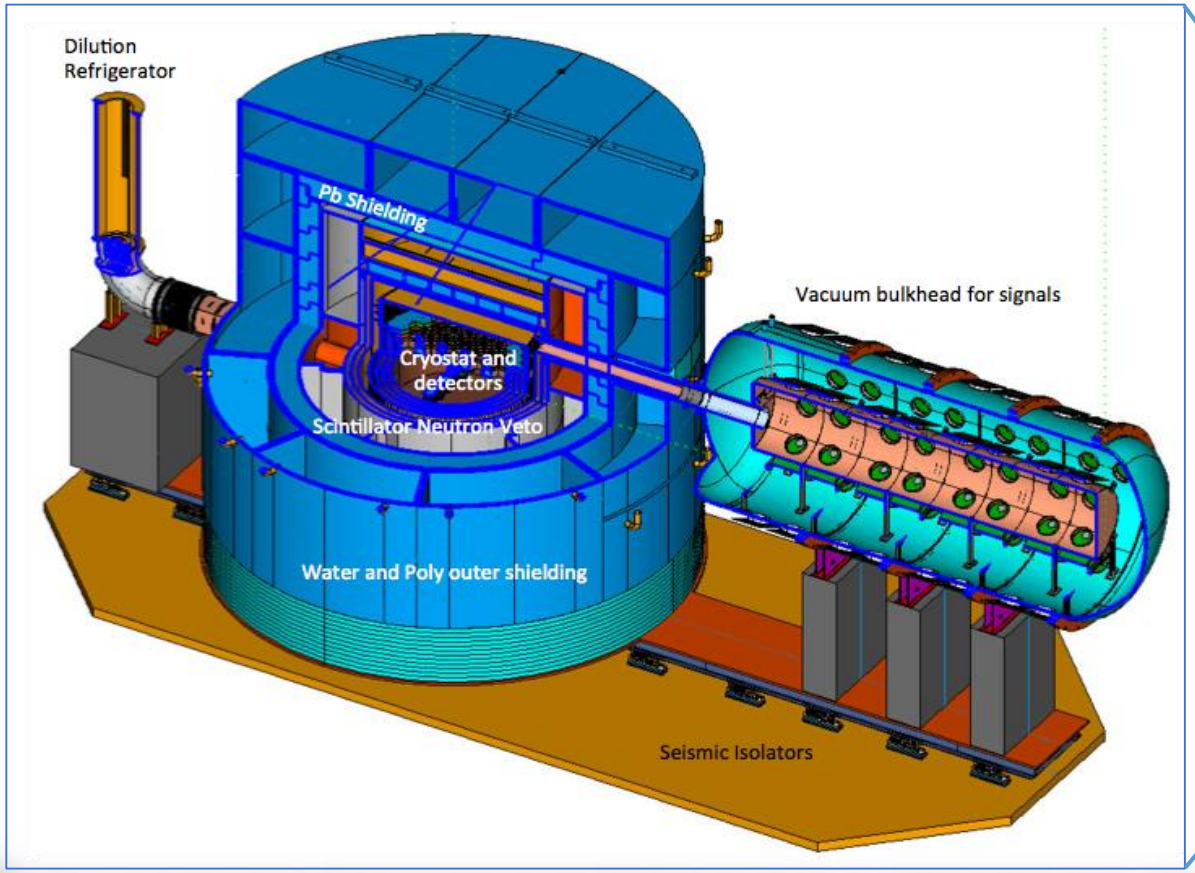


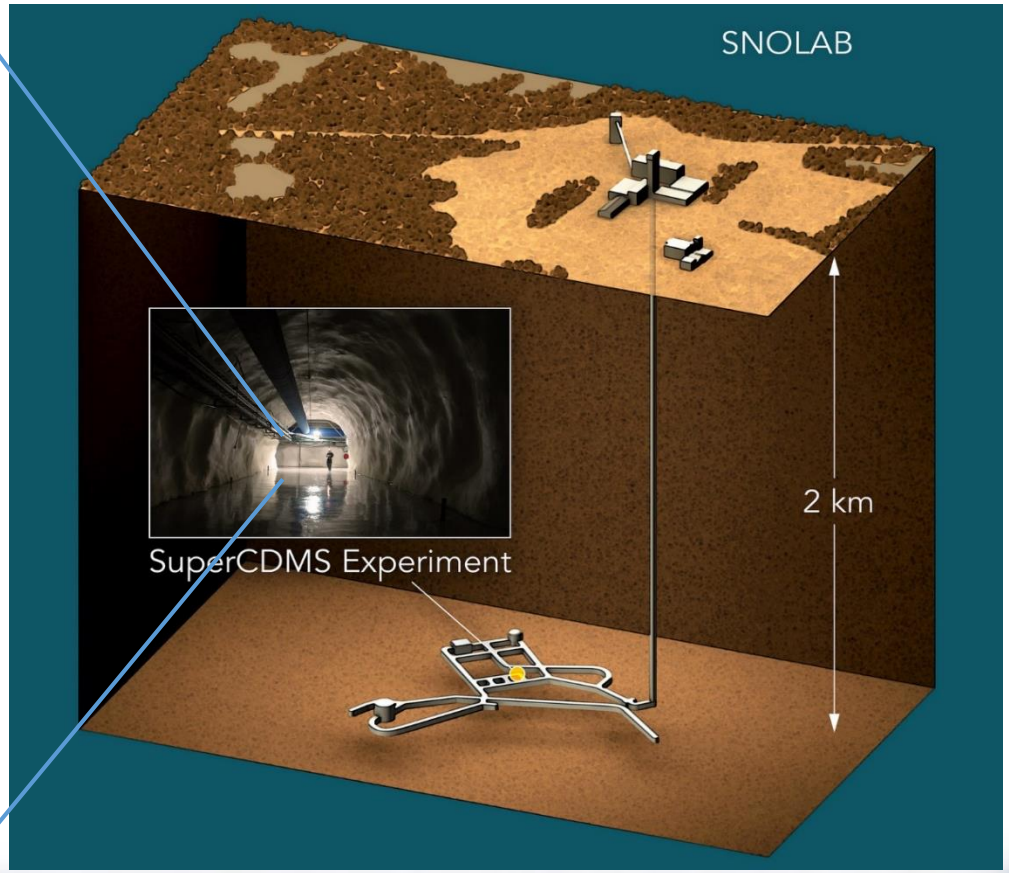


Super Cryogenic Dark Matter Search

Operated in a Soudan, Minnesota underground lab until 2015

More powerful version now being constructed in Canada's world-leading astroparticle physics facility, 2 km underground in the Vale Creighton Mine near Sudbury





Super Cryogenic Dark Matter Search at SNOLAB

- First operations expected in 2020