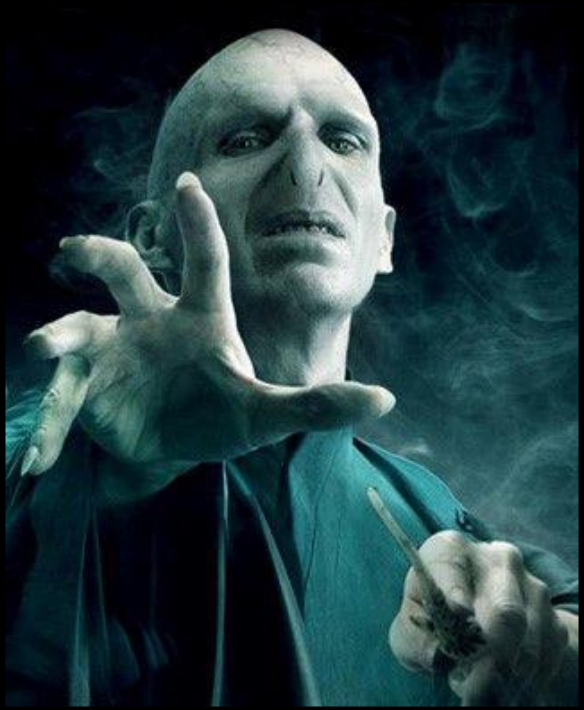
Come To The Dark Side



Miriam Diamond

Assistant Professor, University of Toronto

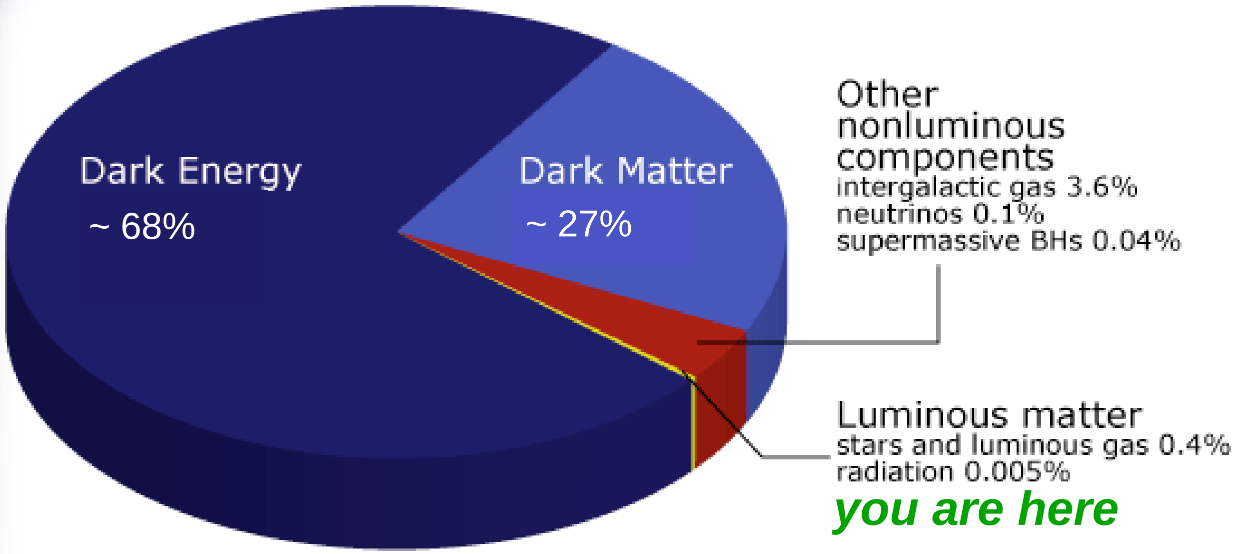
Faculty, Arthur B. McDonald Canadian Astroparticle Physics Research Institute

TRISEP, July 2022

Dark Outline

- **Experimental Evidence from Astrophysics**
- **DM Candidates**
- **Detection Strategies: <u>Direct</u>, Indirect, Collider**
- **Examples of Current & Next-Generation Experiments**
- **Summary of Recent Experimental Results & Near-Future Outlook**

The Dark Matter Question



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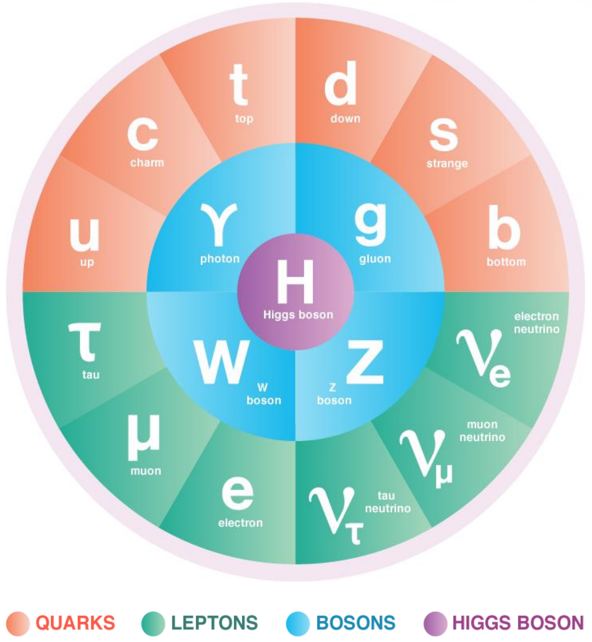

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So far, evidence for existence of DM comes from astrophysics

How to look for it in particle physics experiments?

The Idea of Dark Matter Started in Astrophysics

The Early History of Dark Matter

SIDNEY VAN DEN BERGH

The discovery by Zwicky (1933) that visible matter accounts for only a tiny fraction of all of the mass in the universe may turn out to have been one of the most profound new insights produced by scientific exploration during the 20th century. From observations of the radial velocities of eight galaxies in the Coma Cluster, Zwicky found an unexpectedly large velocity dispersion, … Zwicky concluded from these observations that, for a velocity dispersion of 1000 km s^{-1}, the mean density of the Coma Cluster would have to be 400 times greater than that which is derived from luminous matter. Zwicky overestimated the mass-to-light ratio … His value for the overdensity of the Coma Cluster should therefore be reduced from 400 to ~50.[1] Zwicky writes (my translation): "If this [overdensity] is confirmed we would arrive at the astonishing conclusion that dark matter is present [in Coma] with a much greater density than luminous matter." He continues: "From these considerations it follows that the large velocity dispersion in Coma (and in other clusters of galaxies) represents an unsolved problem."

Fritz Zwicky estimated total mass of a galaxy cluster via two different methods:

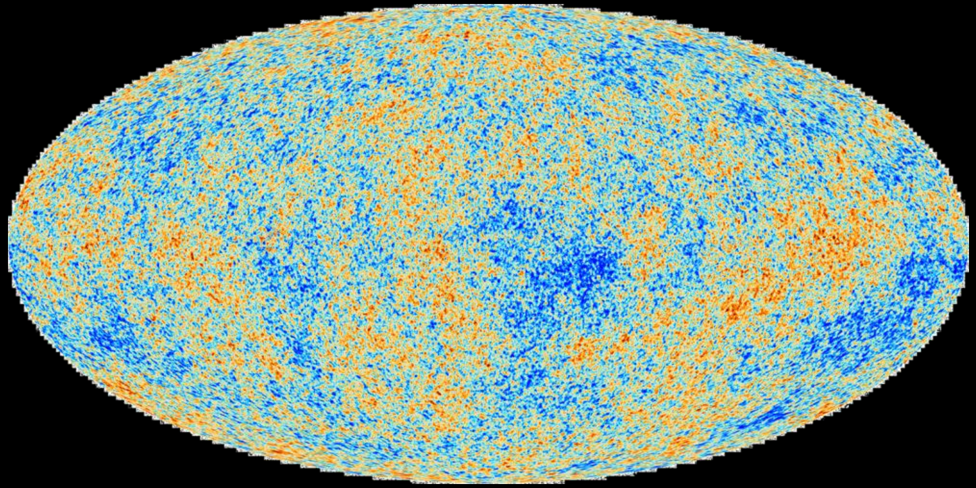
1. **Observed brightness**
2. **Virial theorem (using velocities of the bodies)**

After a mismatch between the results, Zwicky proposed another method to settle the disagreement:

3. **Gravitational lensing**

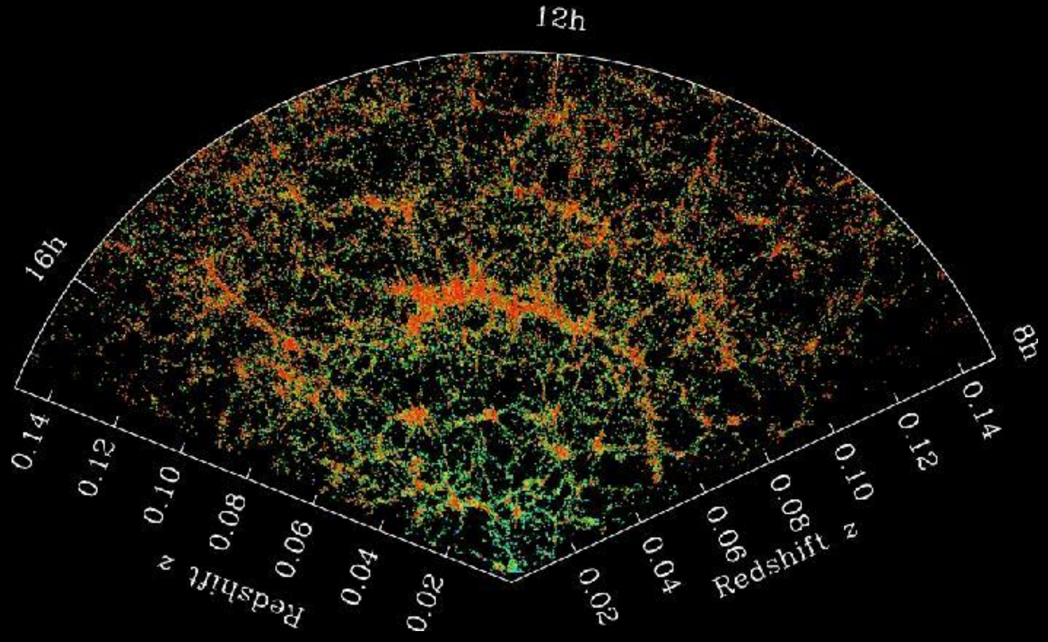
Zwicky hypothesized non-luminous "dark matter", but in the form of previously-overlooked gas, dust, and very faint dwarf stars for which he spent ~20 years looking!

Cosmic Microwave Background



Galactic Rotation Curves

Large-Scale Structure



Collisions between galaxy clusters

Galaxy Cluster Collisions

Once upon a time, at the far end of the universe, two galaxy clusters collided. Their head-on encounter tore apart the galaxies and left behind two reconfigured heaps of stars and gas, separating again and moving apart from each other, destiny unknown.

…

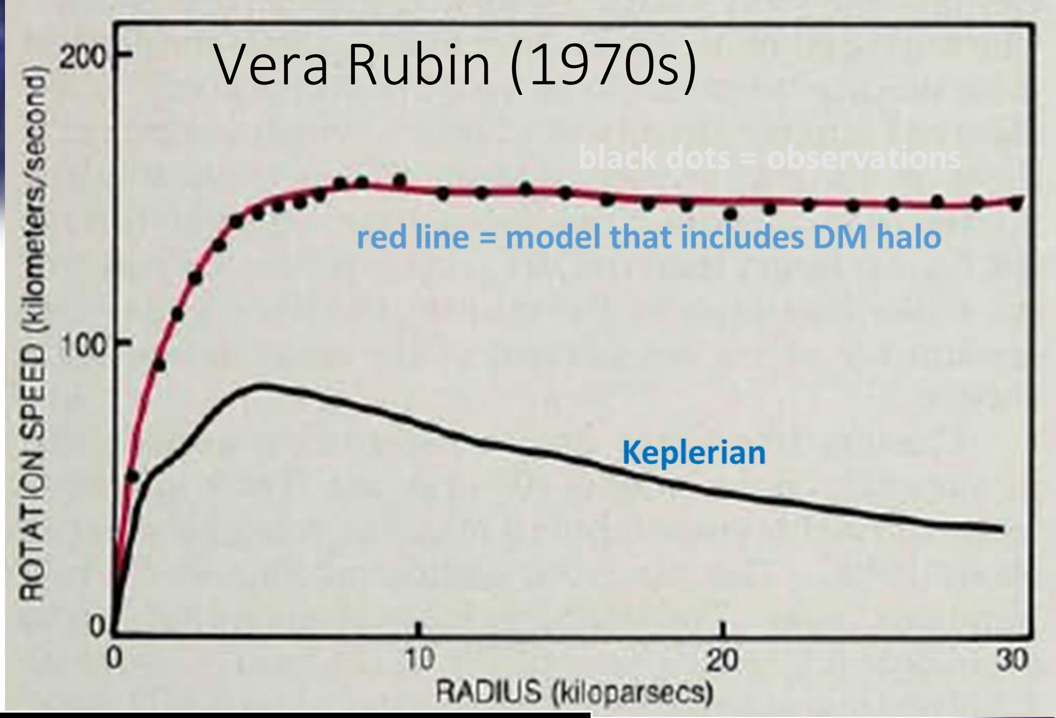
In the below image of the Bullet Cluster you see three types of data overlaid. First, there are the stars and galaxies in the optical regime. (Can you spot the two foreground objects?) Then there are the regions colored red which show the distribution of hot gas, inferred from X-ray measurements. And the blue-colored regions show the space-time curvature, inferred from gravitational lensing which deforms the shape of galaxies behind the cluster.

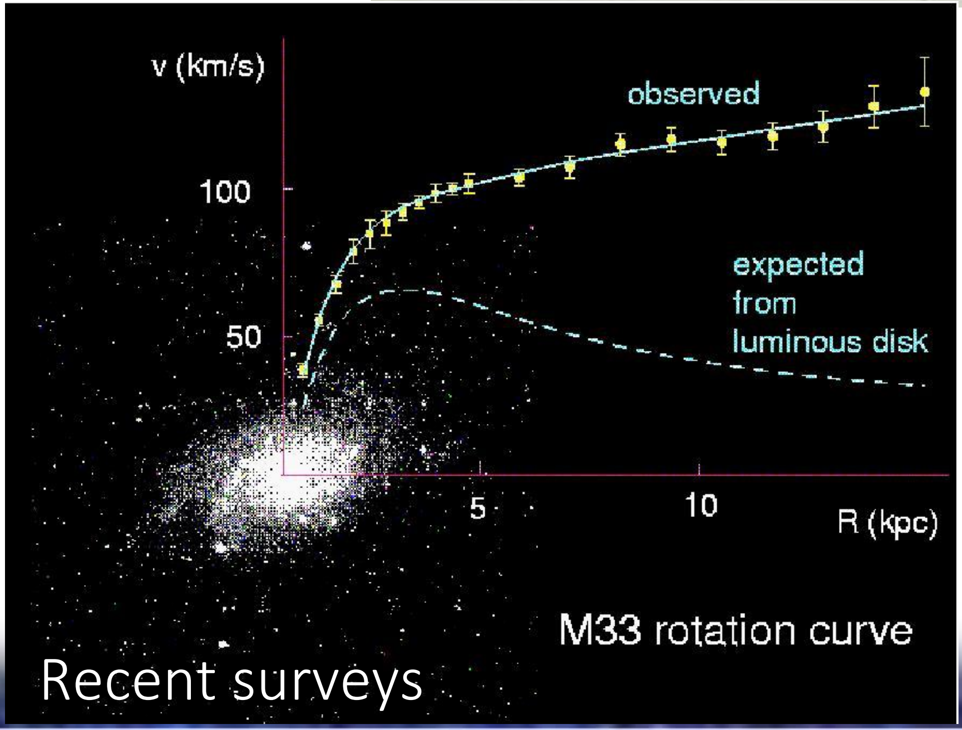
- Sabine Hossenfelder, BackRe(action)

Explanation requires feebly-interacting non-luminous matter, or modified gravity

Galactic rotation curves

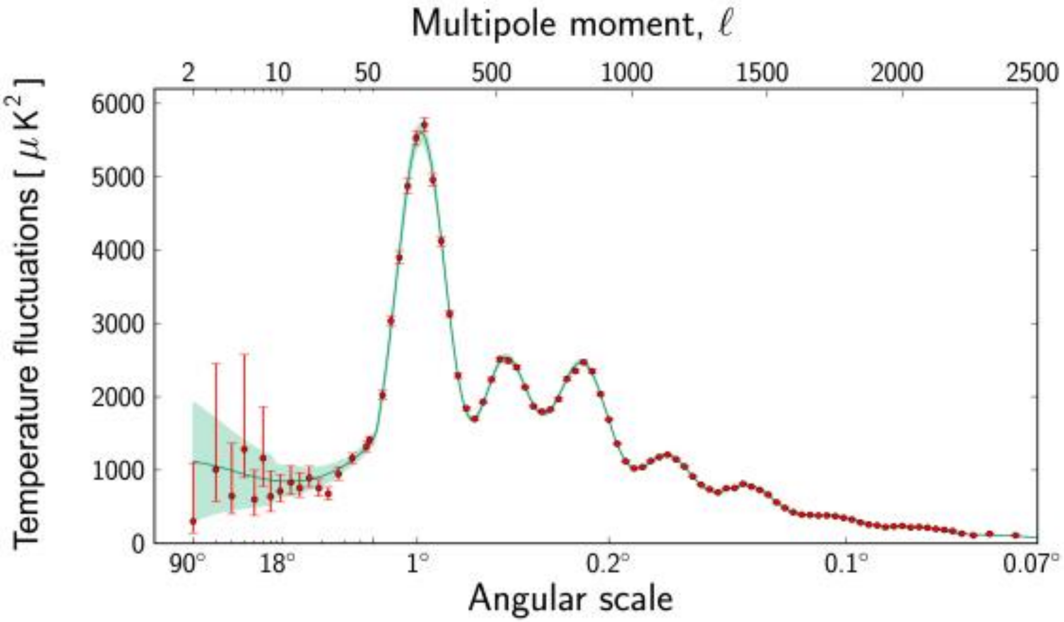
- **Rotation curve: for stars in a galaxy, plot of stellar circular speed v_c as a function of radial distance from galactic centre R**
- **"Keplerian behaviour": predicted by Kepler's (Newton's) classical laws of gravity & motion, based on the mass of observed visible matter**
- ***Rubin calculated gravitational field from the disk is too small by a factor of ~10 to account for the observed rotation***



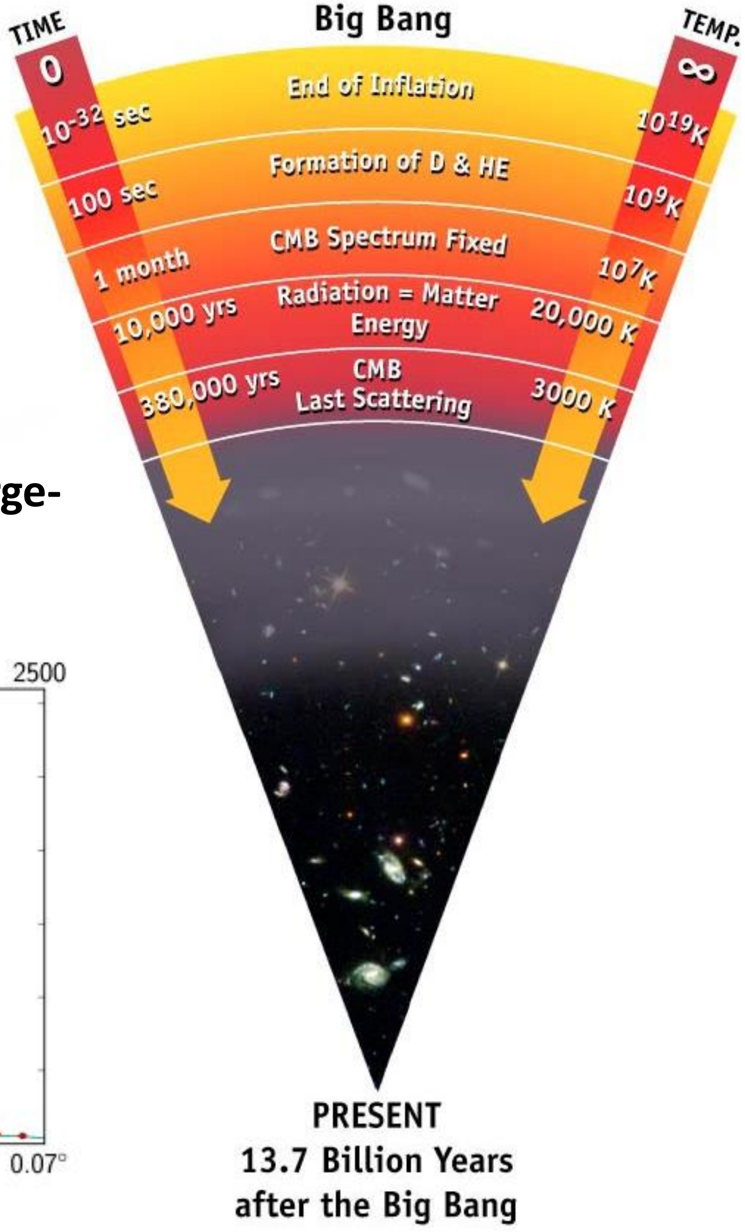


CMB

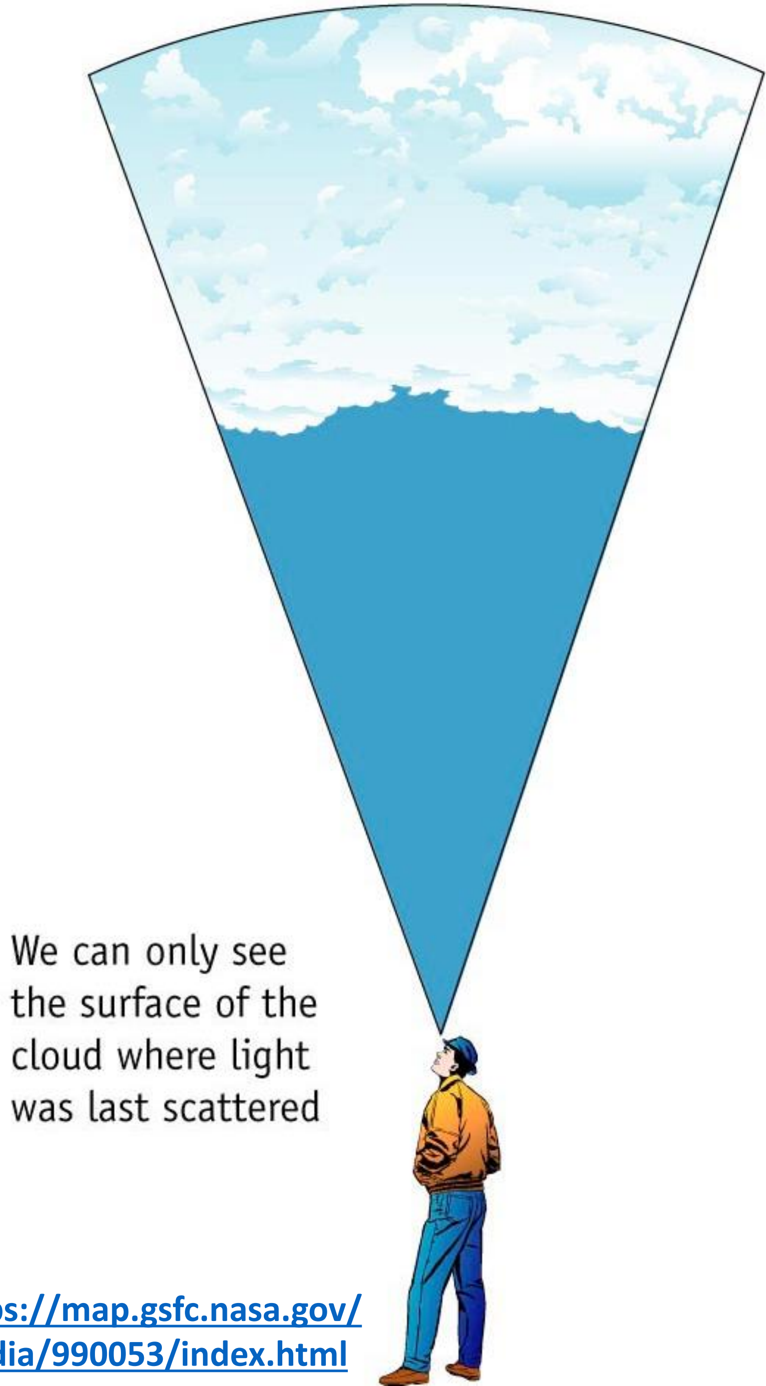
Anisotropy (< 1/10,000) indicates very small fluctuations at CMB emission time, when SM matter started clustering …
How could these clusters have turned into large-scale structures in the time since then?



https://sci.esa.int/web/planck/-/51555-planck-power-spectrum-of-temperature-fluctuations-in-the-cosmic-microwave-background



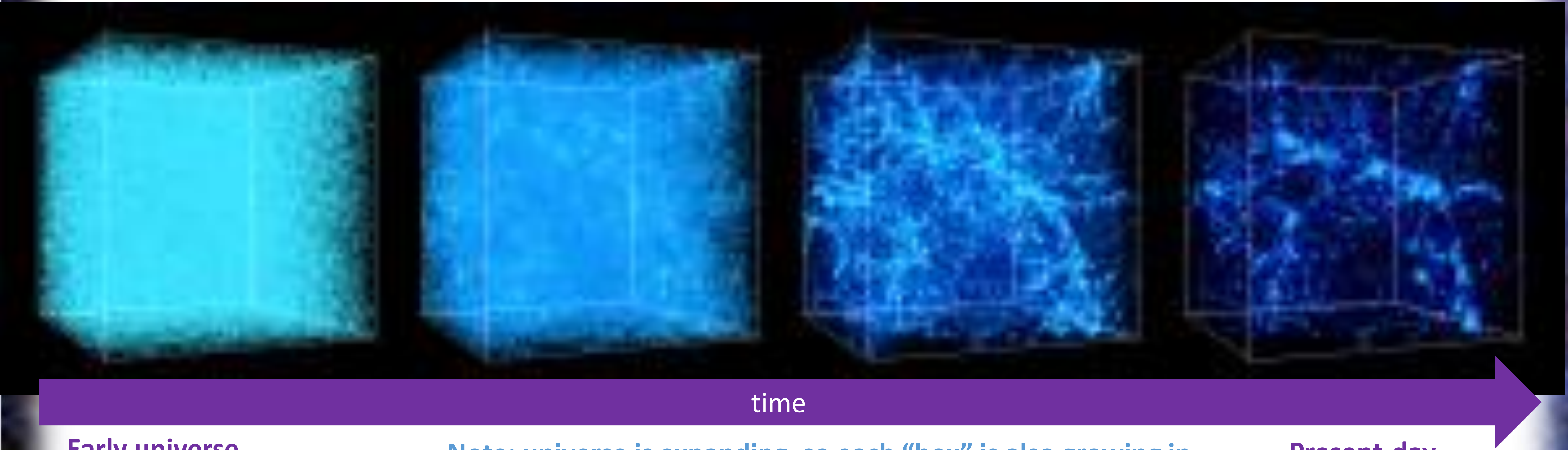
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



https://map.gsfc.nasa.gov/media/990053/index.html

Large-scale structure formation

DM model must give correct degree of large-scale structure formation (right amount of clumping) when we compare cosmological simulations to observations from sky surveys



Early universe
(more diffuse)

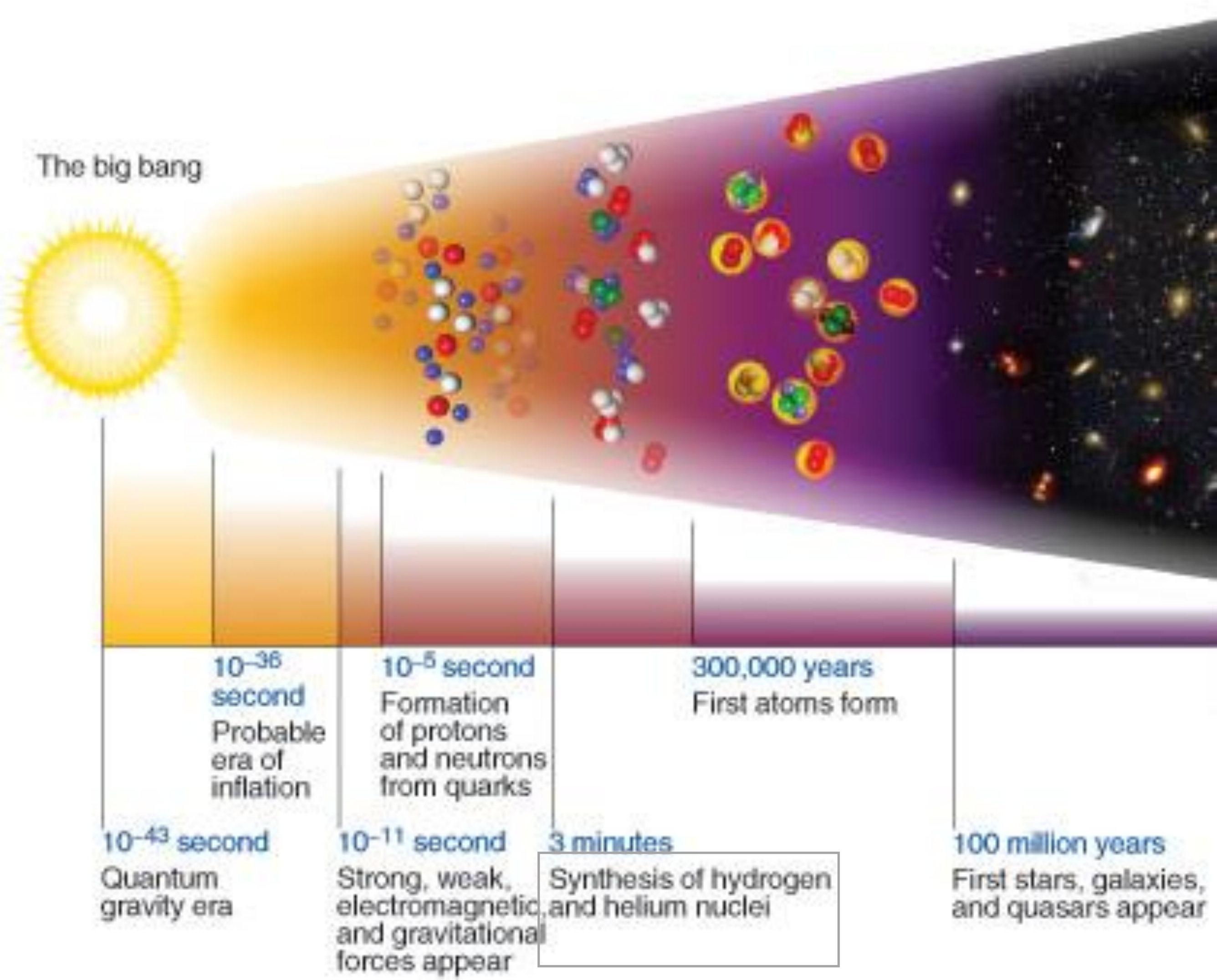
Note: universe is expanding, so each "box" is also growing in size, much more than can be shown

Present-day
(more clustered)

Simulation Images: Andrey Kravtsov & Anatoly Klypin, National Center for Supercomputer Applications

Other Astrophysical Constraints on DM

- **Prior to CMB was "Big Bang nucleosynthesis", when H and He were formed**
  - **Extra baryonic matter upsets H : He ratio, providing evidence DM is non-baryonic**
- **Then came star formation**
  - **DM accreting in stellar cores must not cause stars to collapse too much, prevent stars from igniting, nor prevent supernovas from exploding**



DM Candidates

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Targeting "Beyond the Standard Model" Searches

DM searches → looking for BSM particle(s) with the following properties:

- Cold (non-relativistic)
- Stable on cosmological timescales
- Gravitationally interacting
- Feeble, if any, non-gravitational self-interactions
- Feeble, if any, non-gravitational interactions with luminous matter

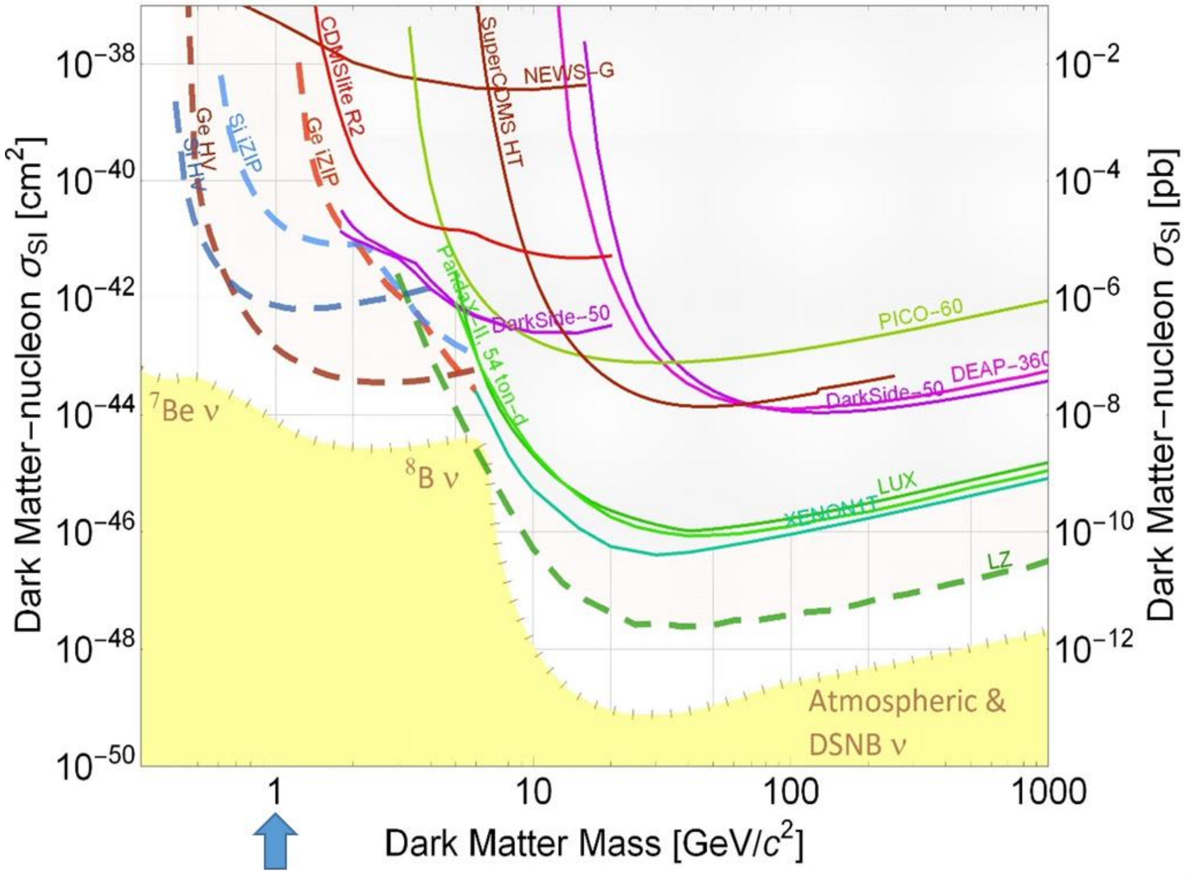
What mass scale?
What interactions with SM?
Are there "dark forces"?
How many new particle species?

WIMPing out?

"Weakly Interacting Massive Particles" (WIMP) candidates:

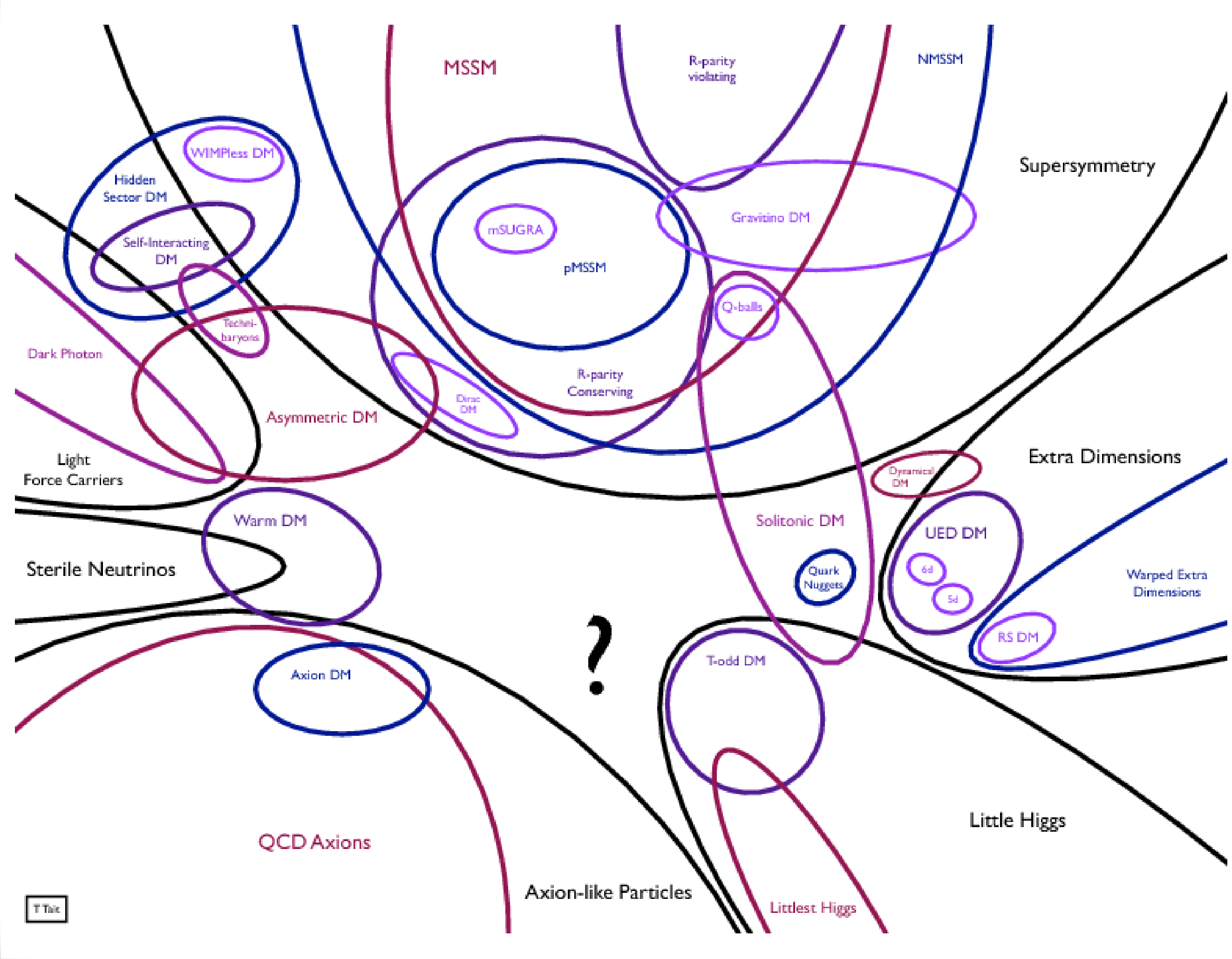
- *Supersymmetric partners*
- *Additional Higgs bosons*
- *"Mirror universe" / "Hidden Valley" particles*
- *Kaluza-Klein particles*
- *Sterile neutrinos*
- *… etc*

But… searches *where we most expected to find WIMPs* haven't found them!



proton mass

Particle Zoo!

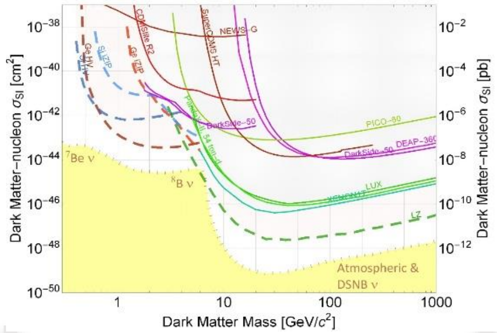


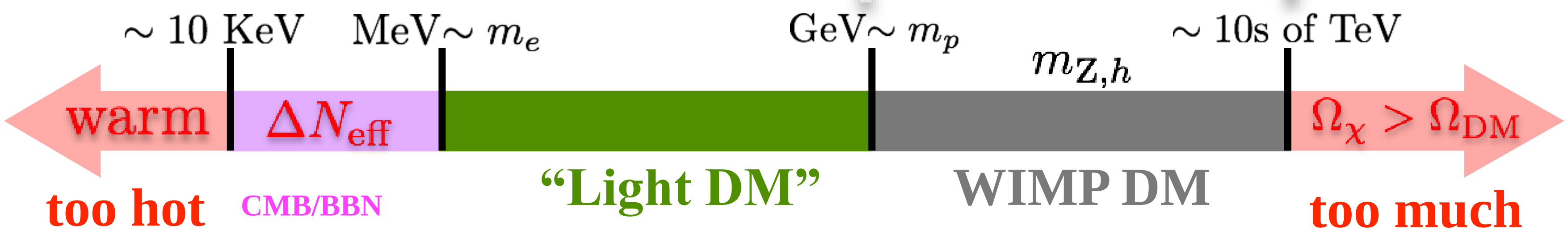
"Zoo" of possibilities

Non-WIMP candidates

- FIMPs (Feebly Interacting), WIMPzillas (> 1000 TeV), SIMPs (Self-Interacting), ELDERs (Elastically Decoupling Relics), …
- Low-mass dark photons (sub-GeV)
- Lightly-ionizing / millicharged particles (sub-GeV)
- Axion-like particles (sub-eV)
- Massive gravitons
- Particles with only gravitational interactions and/or self-interactions
- MACHOs (Massive Compact Halo Objects), e.g. primordial black holes
- Modified [quantum / super-] gravity

Lower-mass Thermal Relics?





- Thermal relic dark matter works fine (theoretically) at least down to $2m_e$
- But “light WIMP-like DM” requires new, comparably low-mass “dark mediators” (dark force carriers, e.g. dark photons)
- Experimental challenges: look for the mediators, as well as sub-GeV DM?

Search Strategies

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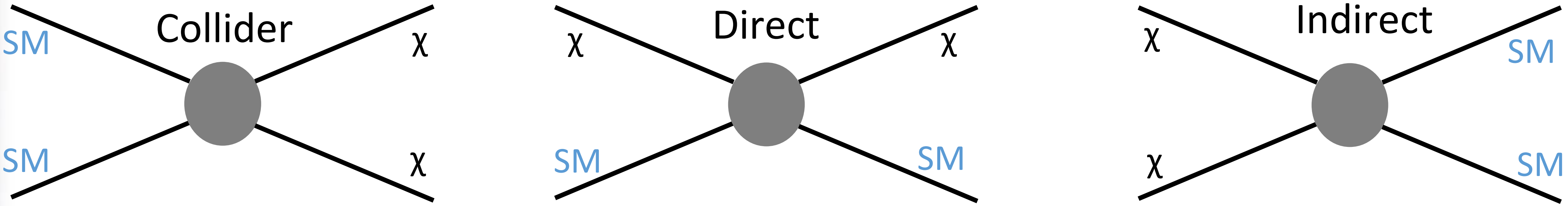
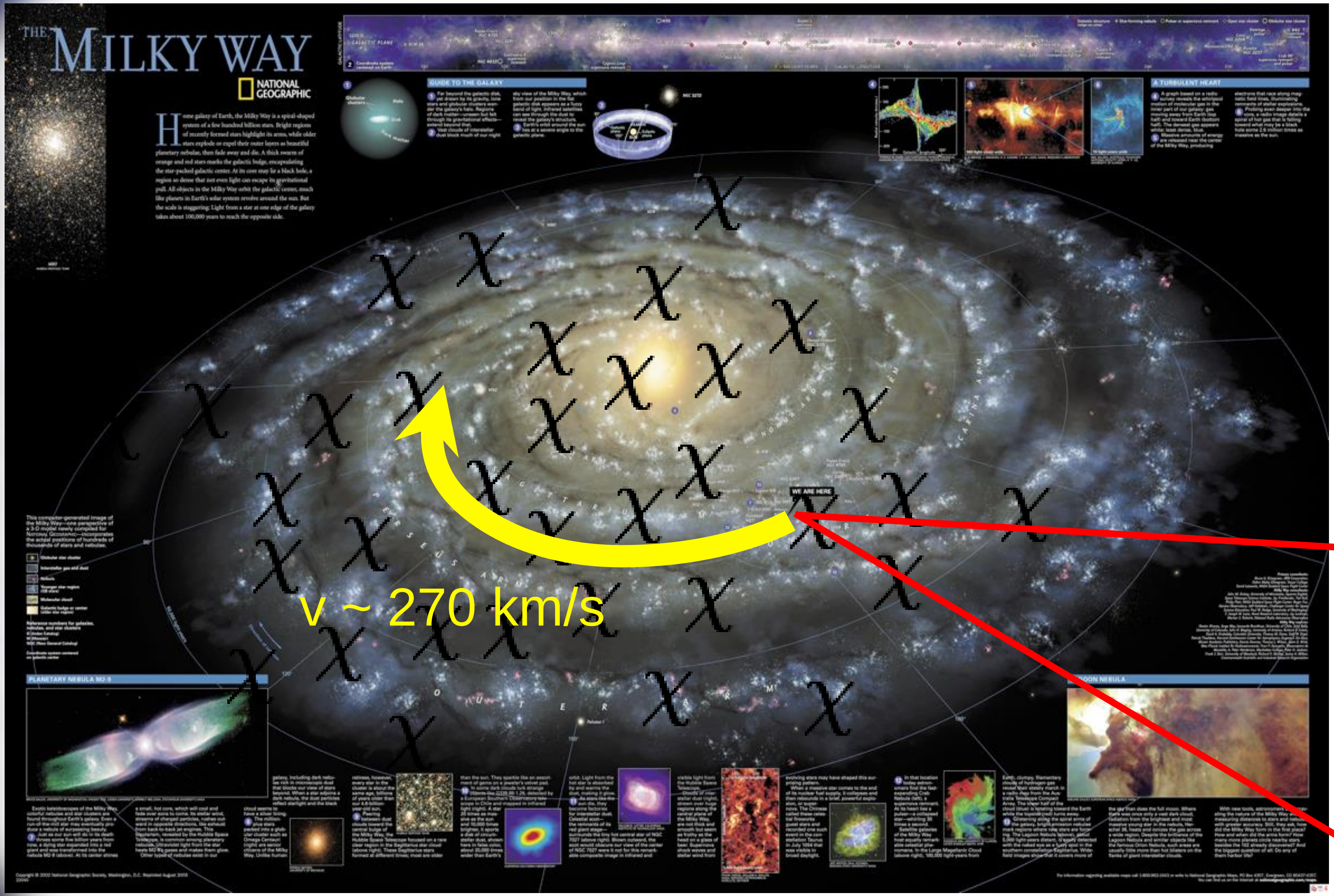
Search Strategies

Complementarity between different types of experiments



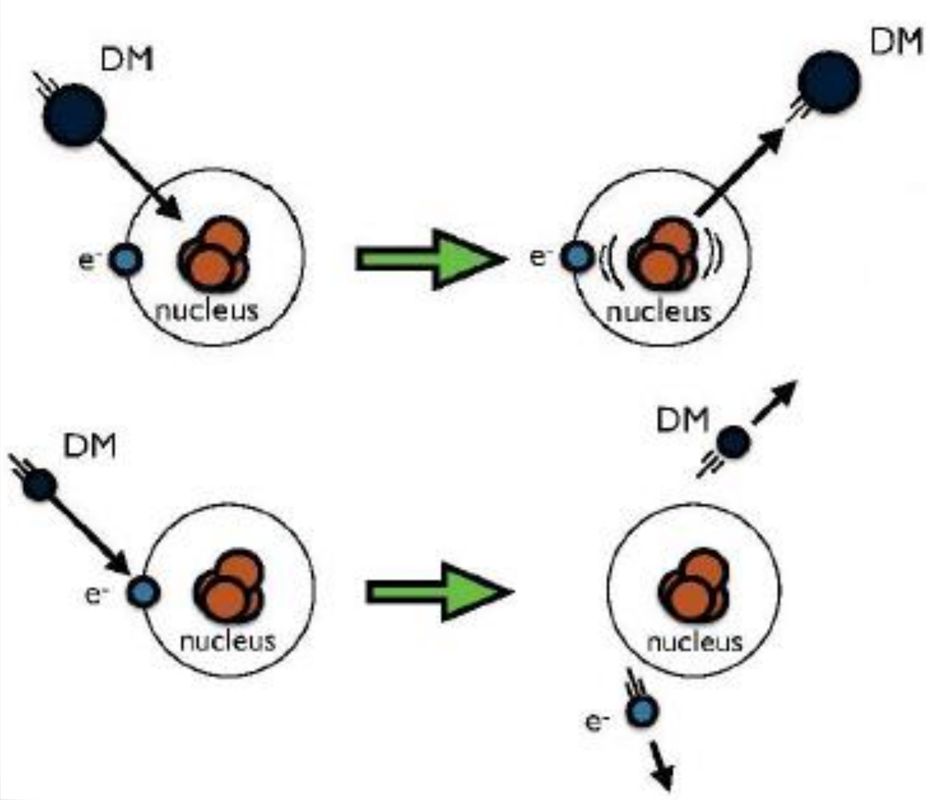
Direct Detection

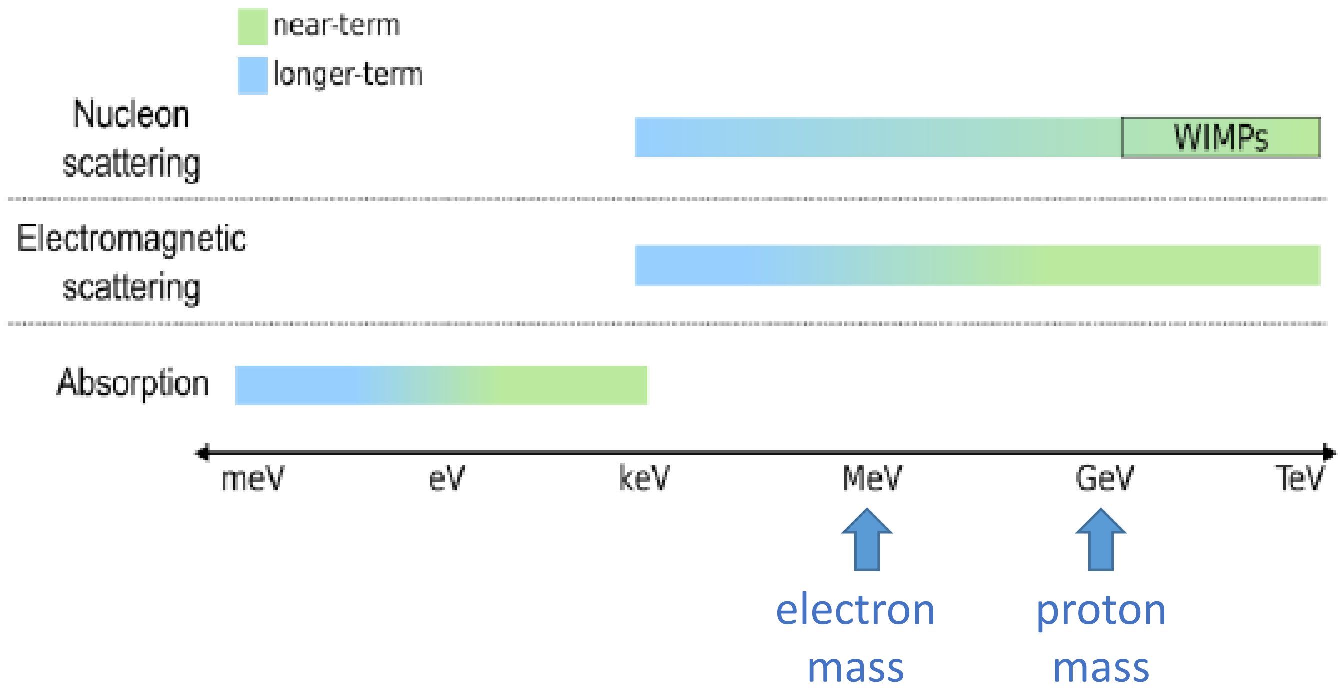


Collisions of galactic DM with SM particles in detector on Earth

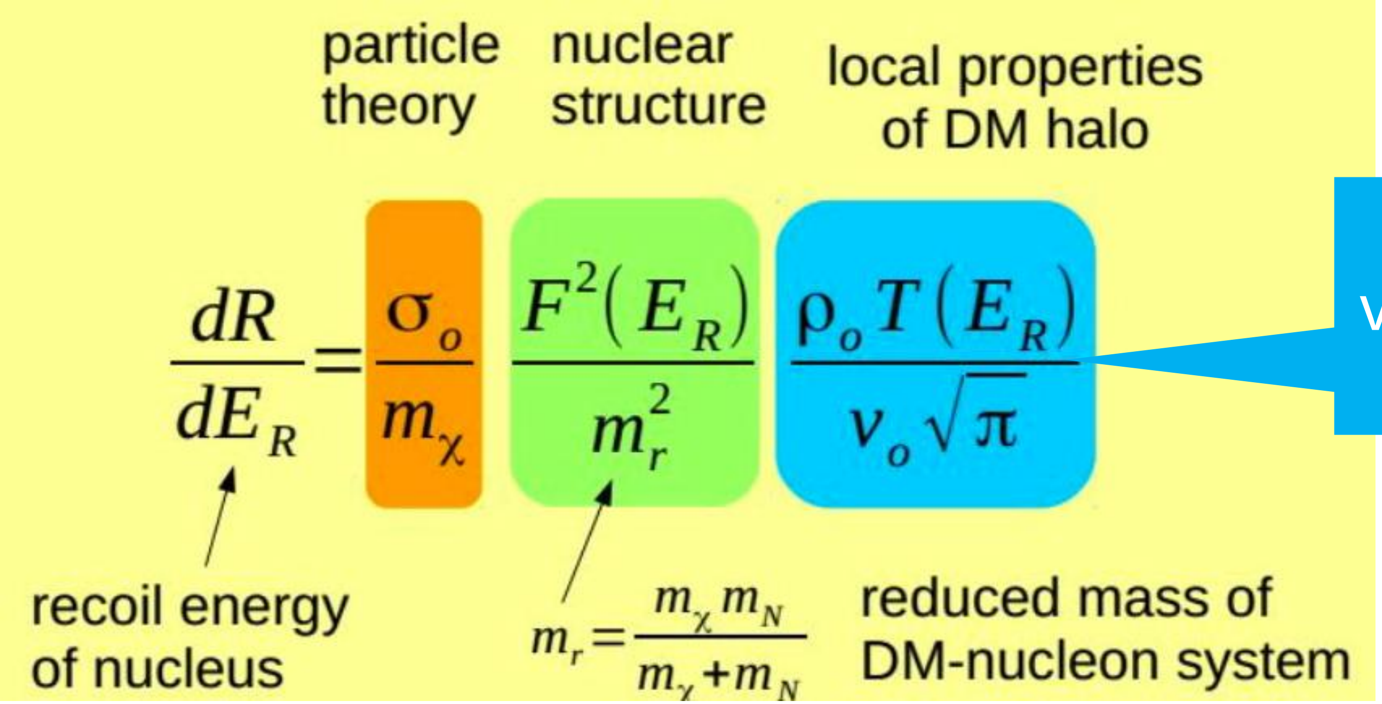
Direct Detection

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



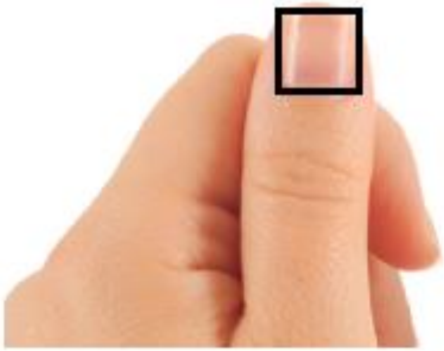


Direct Detection



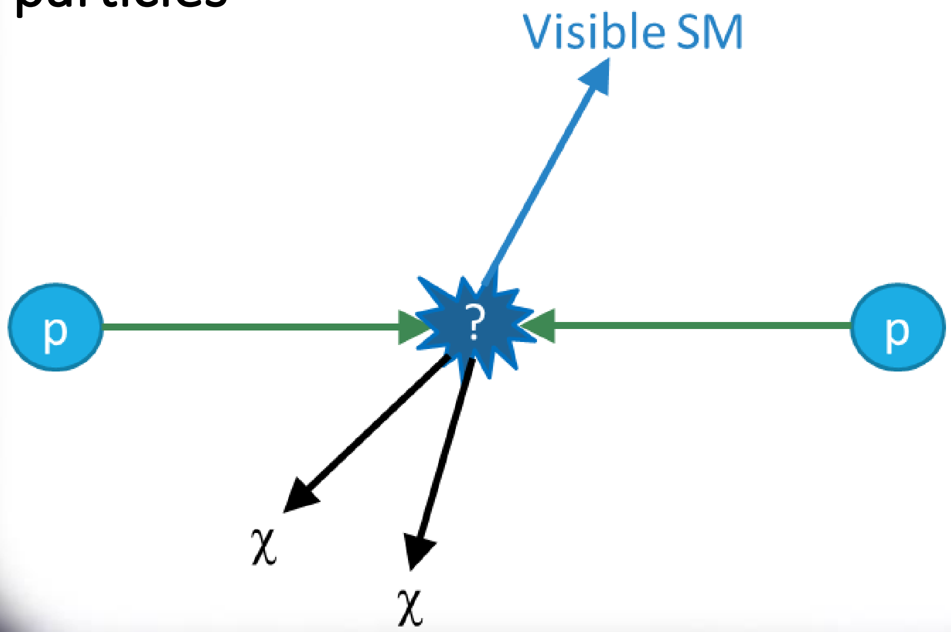
Local $\rho_{DM} \approx 0.4$ GeV/cm^3
$v_{DM} \approx 220$ km/s (non-relativistic)

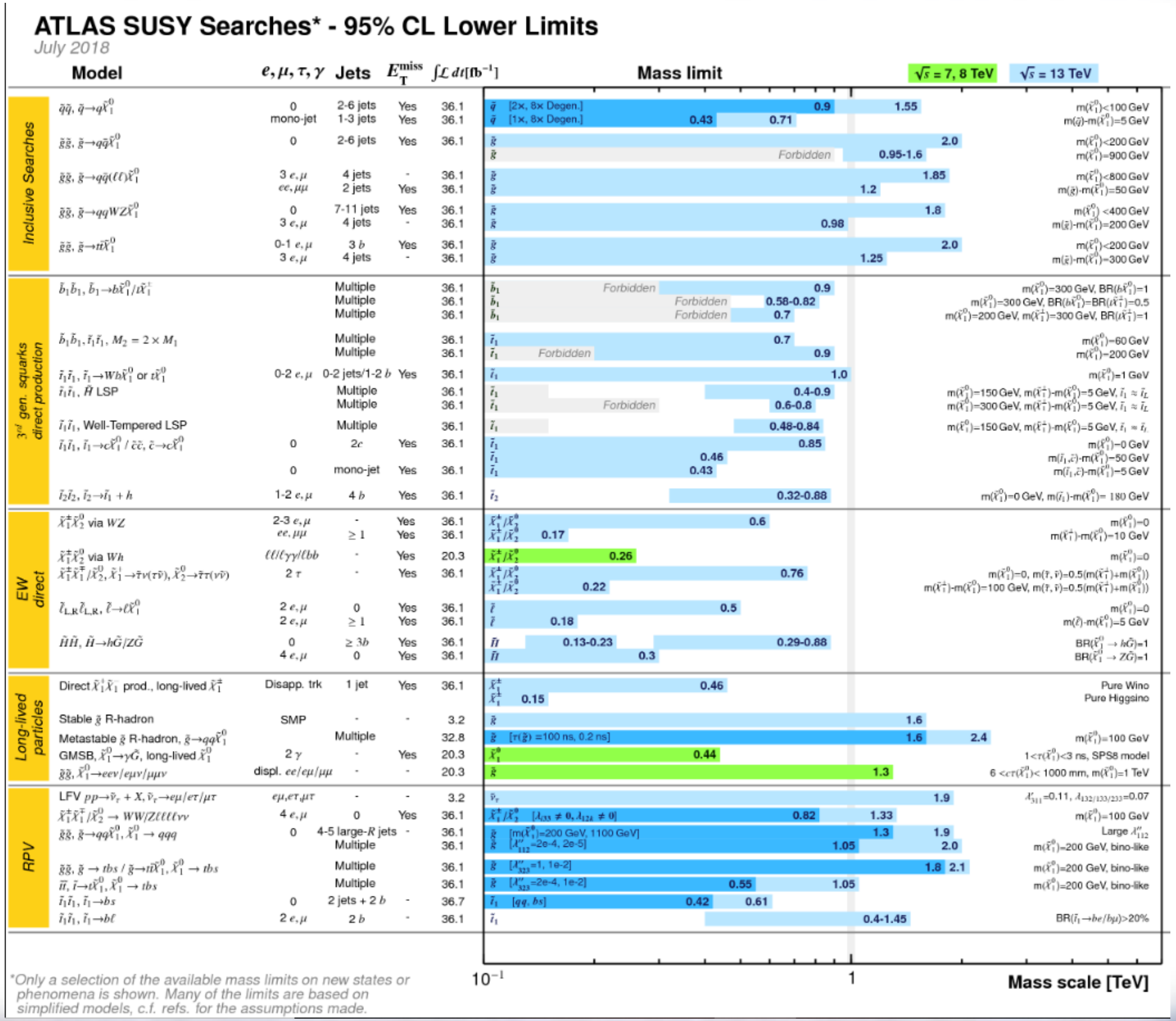
For $m_{DM} \approx 1$ GeV:
$flux_{DM} \approx 10$ million / cm^{2}s



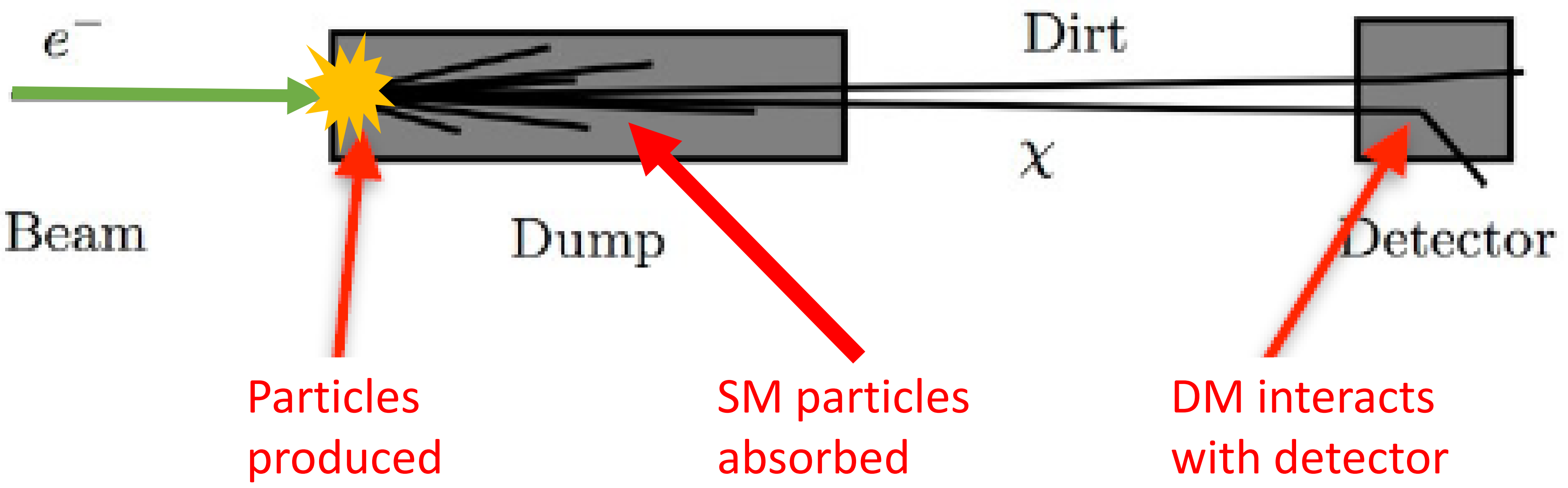
Collider Searches

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





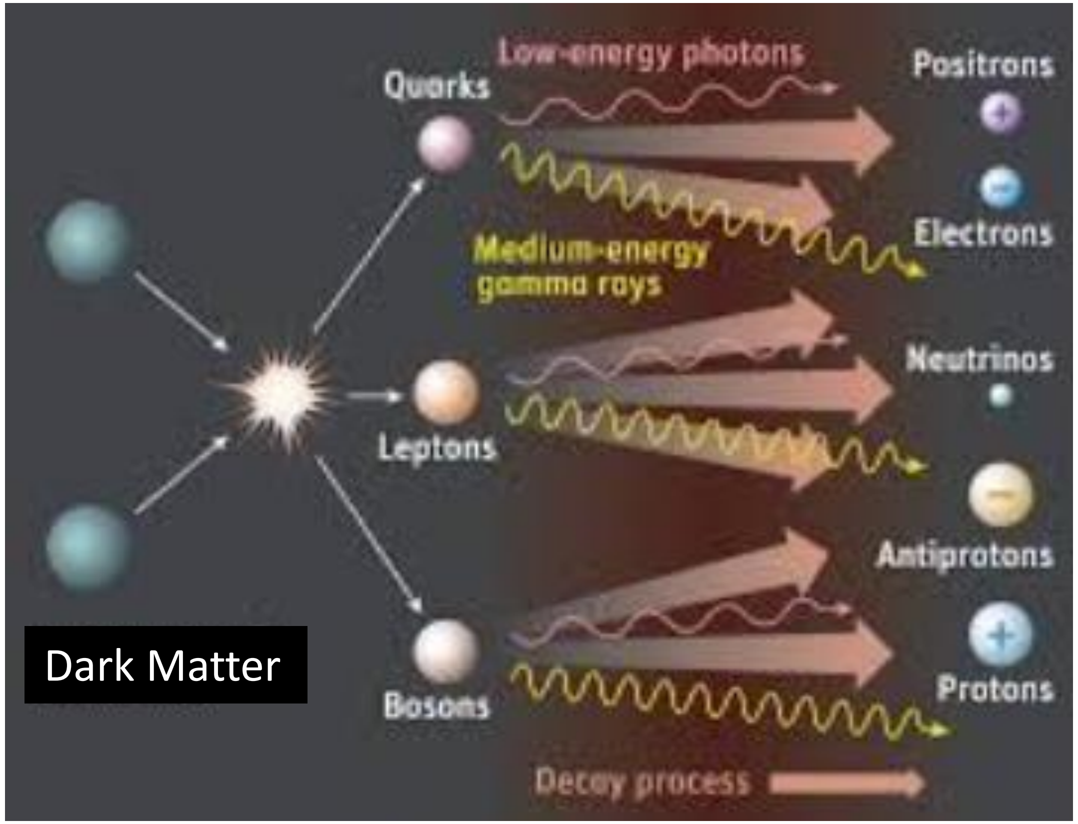
Fixed-Target Searches



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

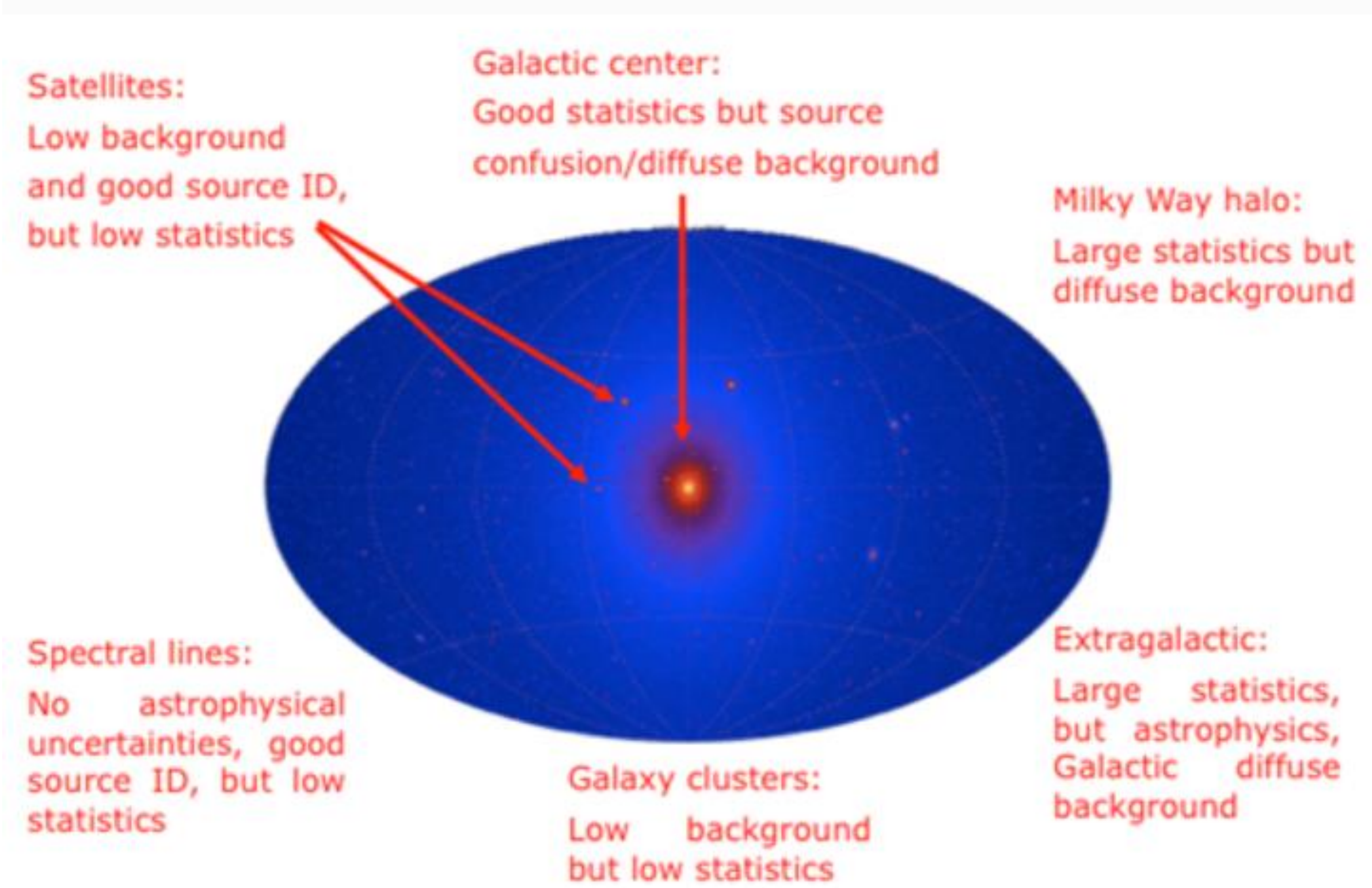
Indirect Detection



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

Direct Detection Experiments

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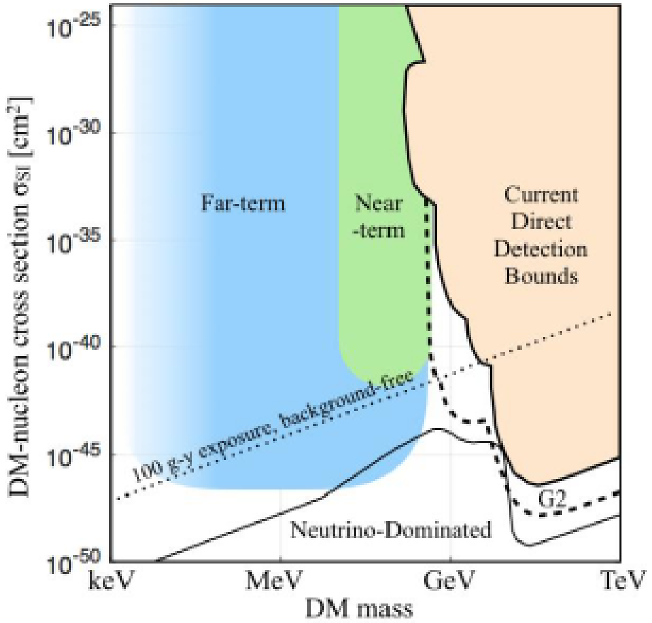
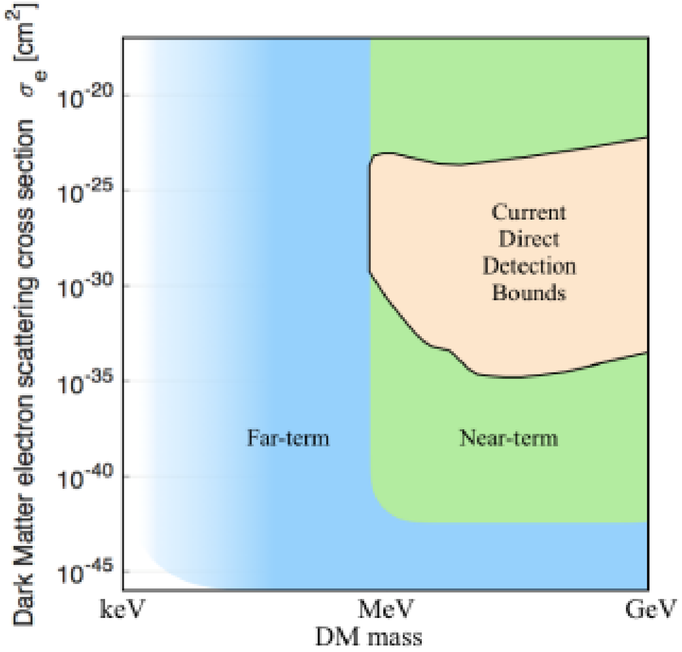
Moment of Truth

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

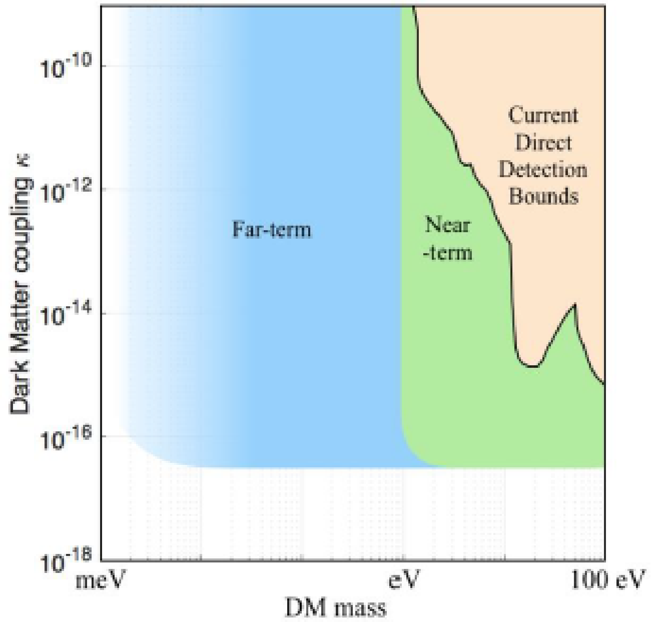
Lowering *mass* and/or *interaction* thresholds mean tougher backgrounds, and we will encounter "floor" where neutrinos drown out WIMP signal



Galactic dark matter scattering off nuclei

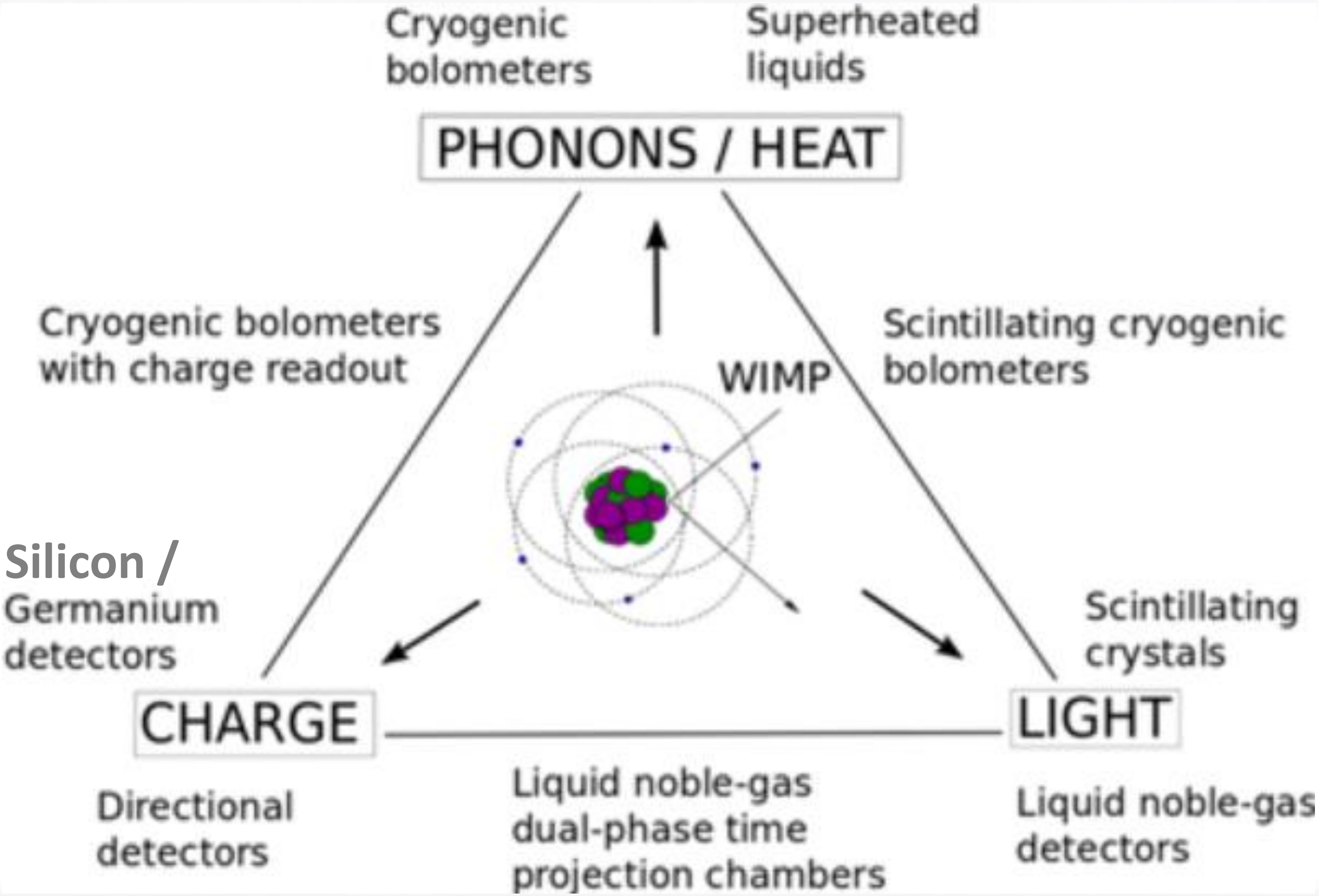


Galactic dark matter scattering off electrons



Galactic dark-photons absorbed by electrons

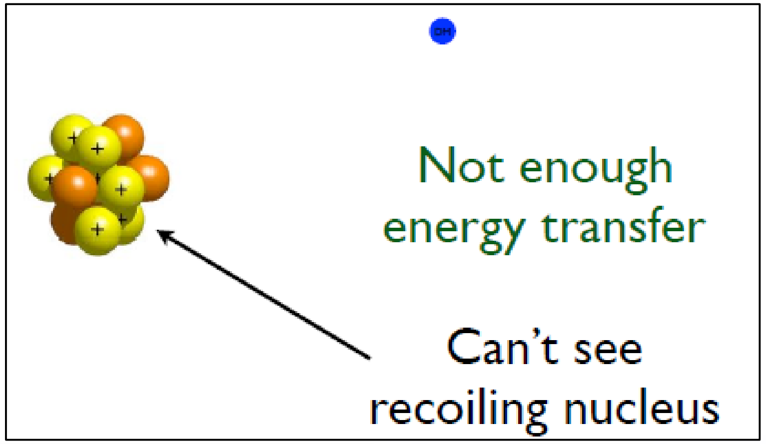
Next-Generation Direct Detection

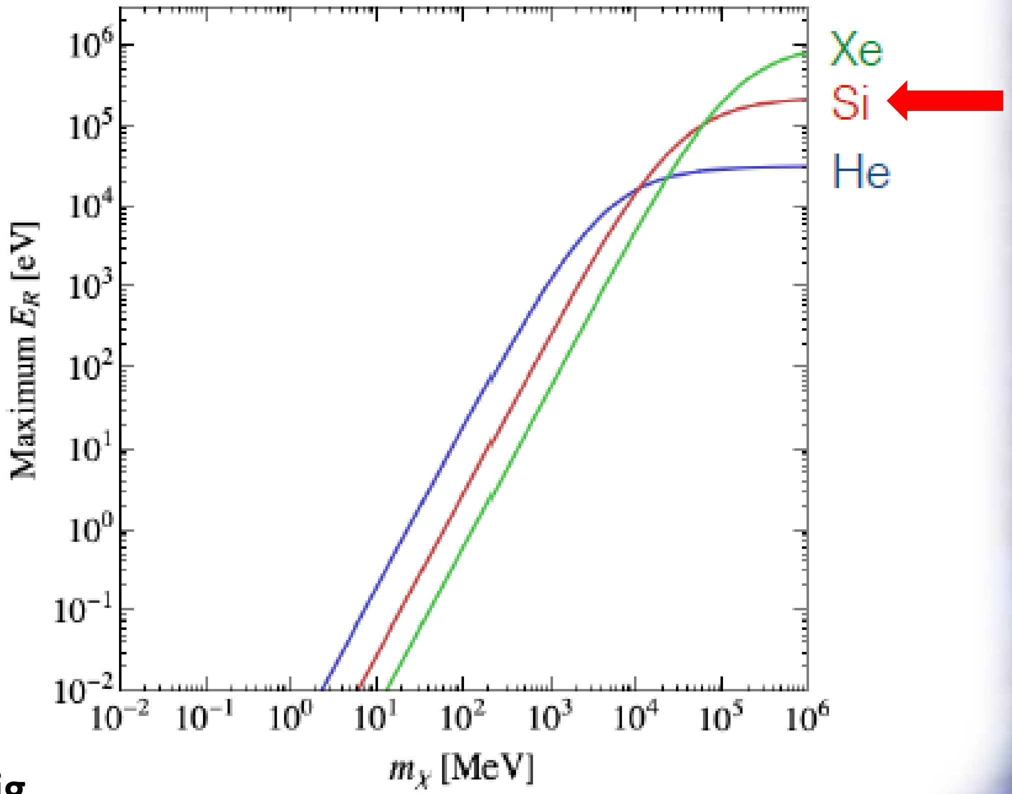


The Sub-GeV Detection Challenge

- **Can rely on elastic NR signal for DM masses down to ~ a few GeV**
- **But not for sub-GeV DM: inefficient momentum & energy transfer**
- **Alternatives: inelastic processes, electron recoils**

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





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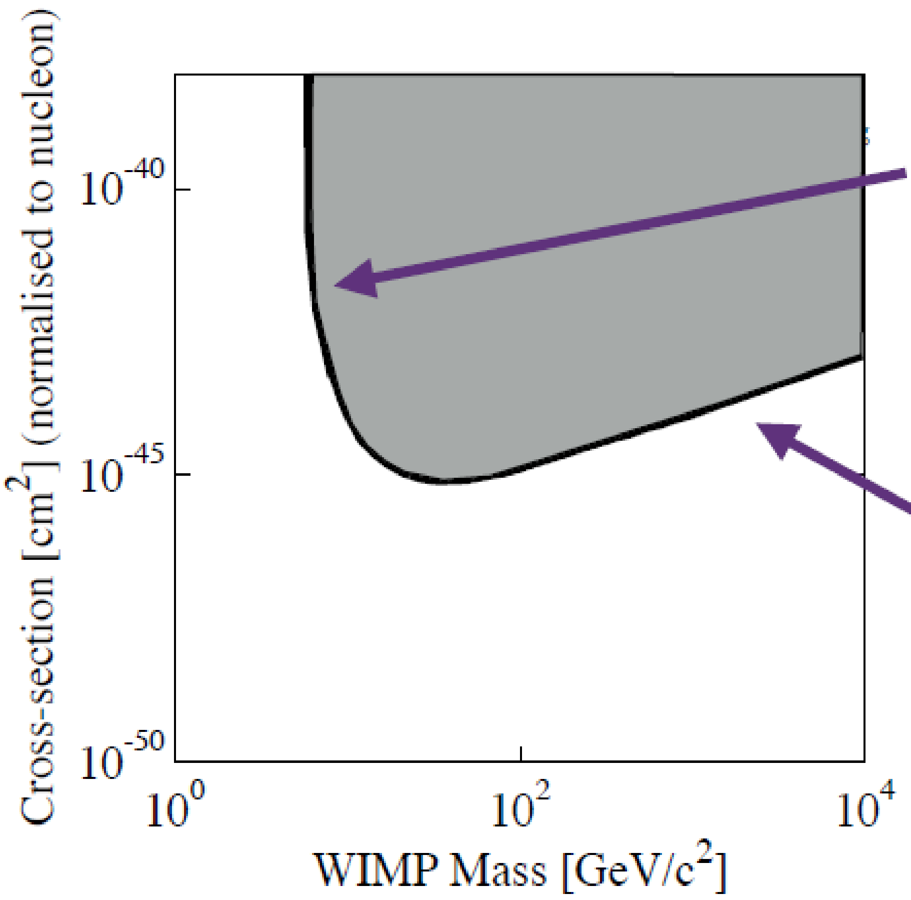
Search Status

Schematic view of typical direct-detection limit curve:



nuclear recoil energy too small

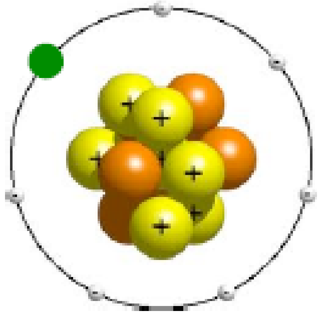
linear, since

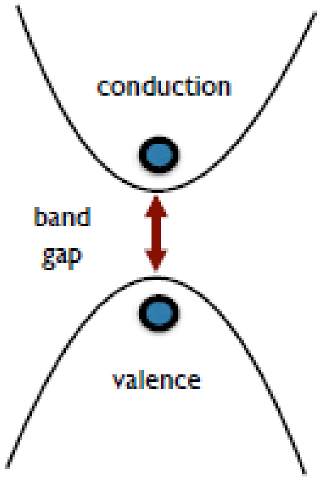
$$\text{Rate} \propto n \propto \frac{\rho}{m}$$

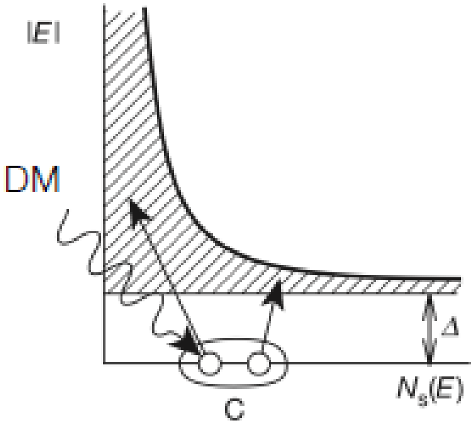
$$\propto \frac{0.4\ \text{GeV/cm}^3}{m}$$

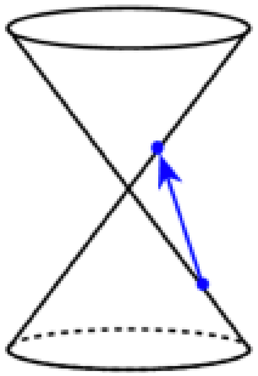
Various Options for ER & Dark Absorption

- **Detectable electron recoil energies and DM masses:**









...

noble liquids	semiconductors scintillators	superconductors **(R&D)**	Dirac materials **(speculative “exotic”)**
$\Delta E \sim 10$ eV	$\Delta E \sim 1$ eV	$\Delta E \sim$ few meV	
$m_{\rm DM} \sim 5$ MeV	$m_{\rm DM} \sim 500$ keV	$m_{\rm DM} \sim$ keV	

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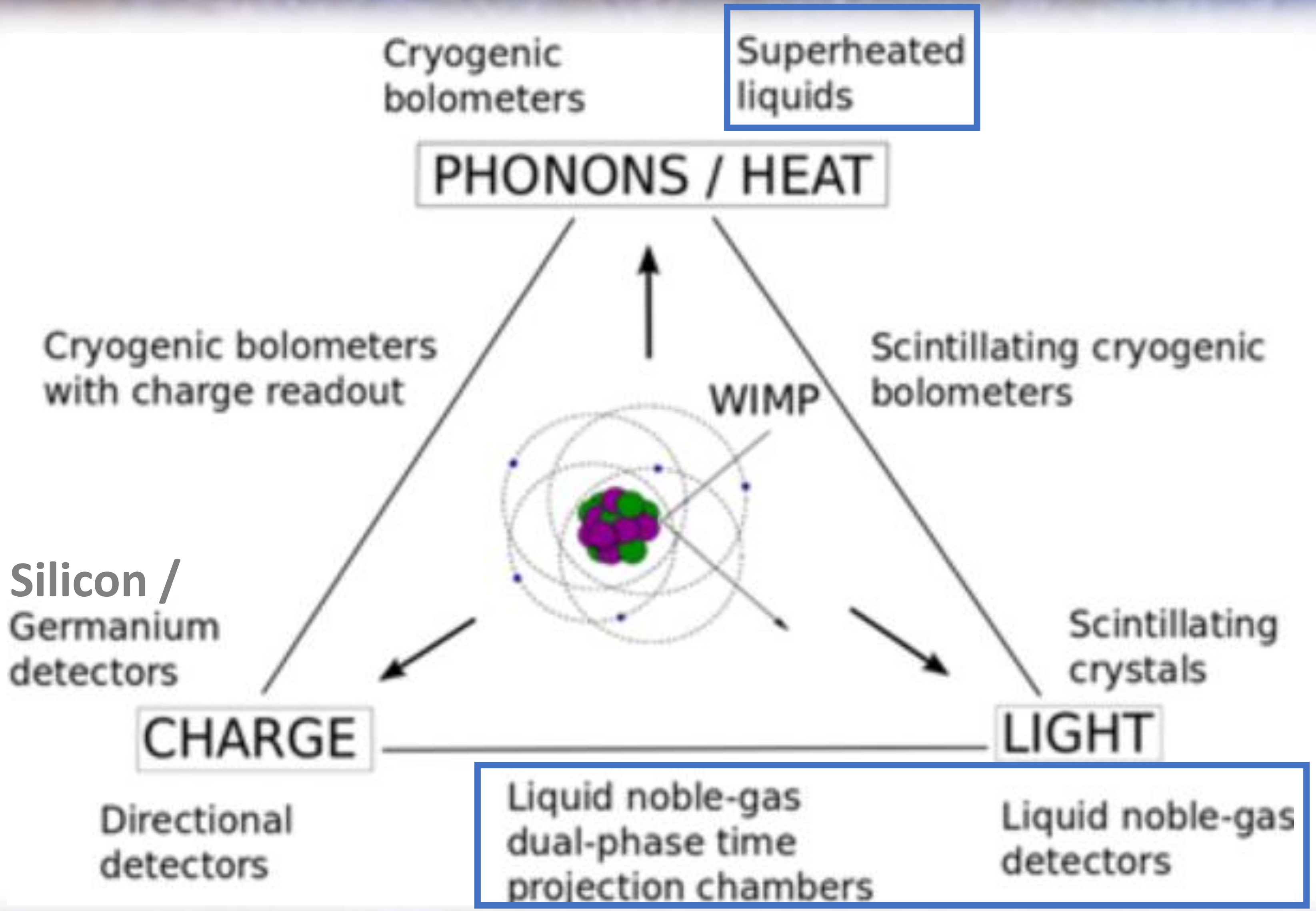
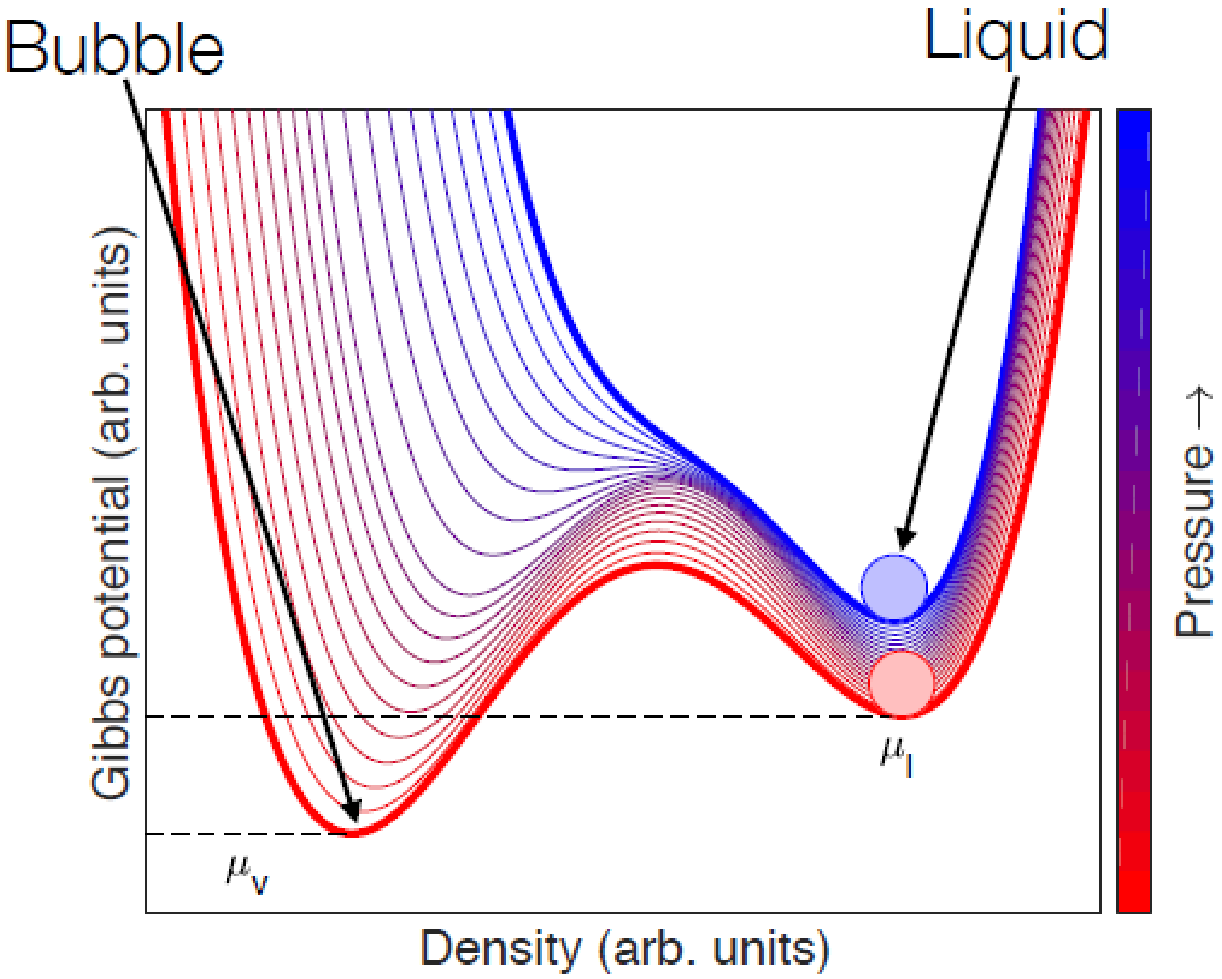
Next-Generation Direct Detection

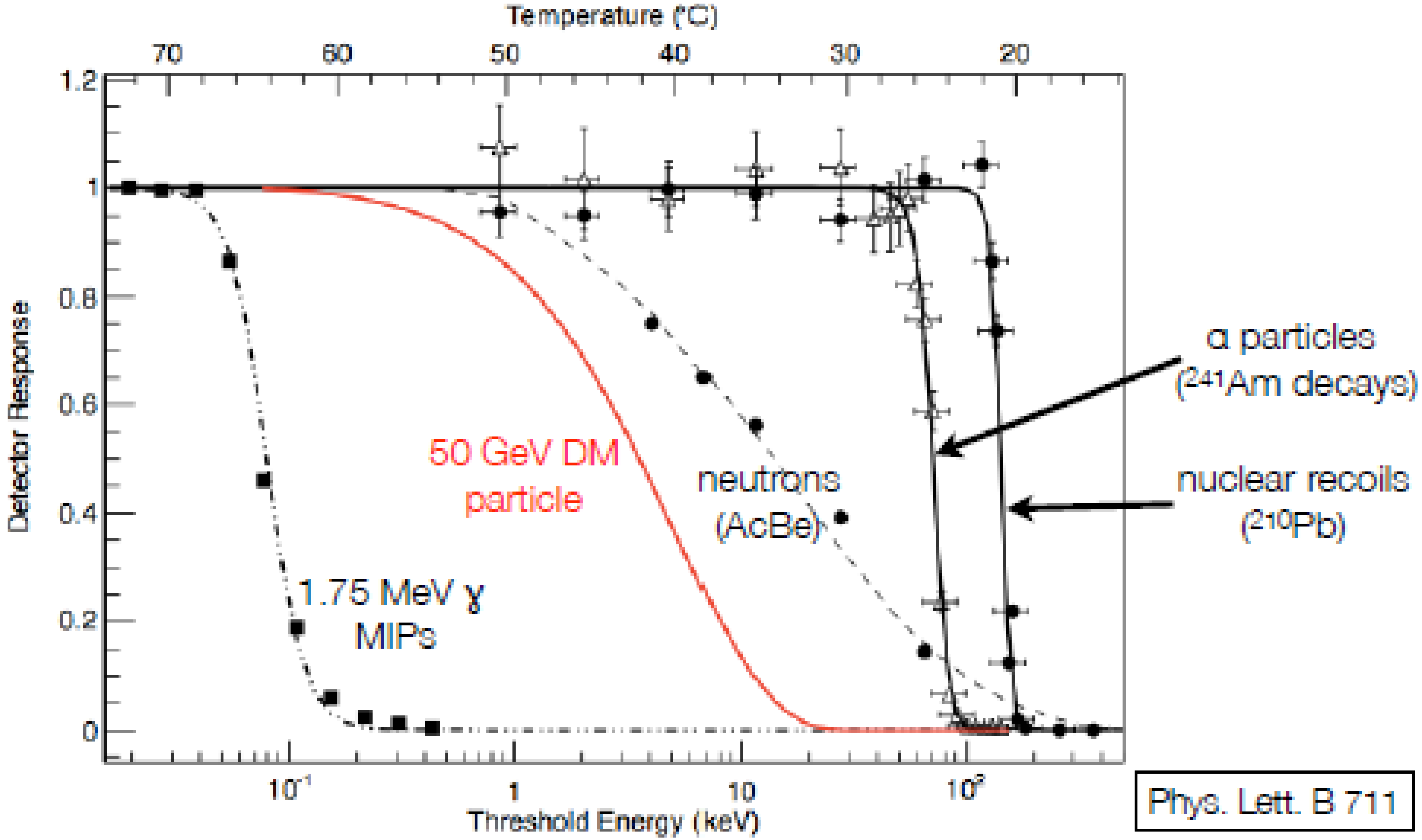


Bubble Chambers

- 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



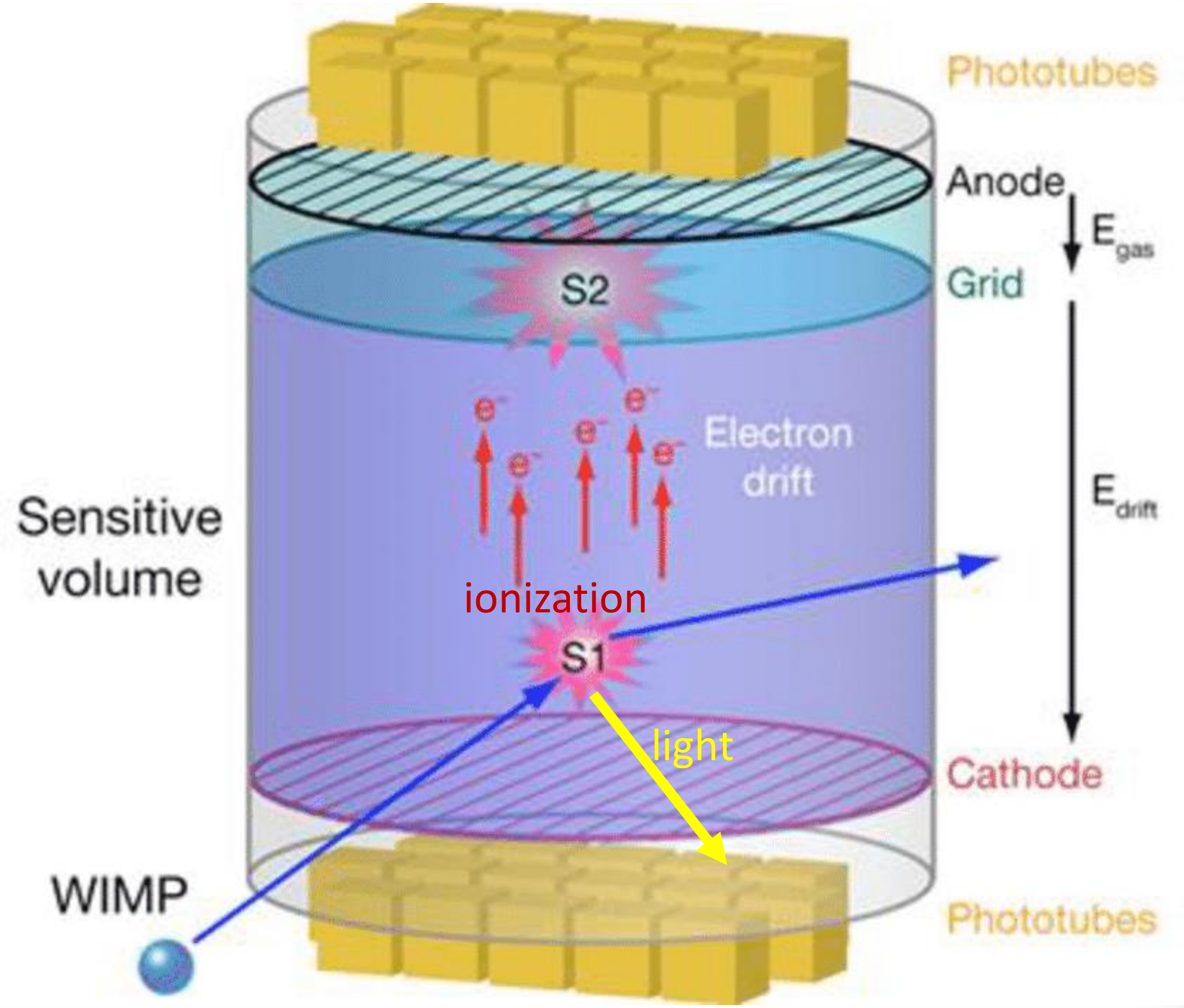
Bubble Chambers



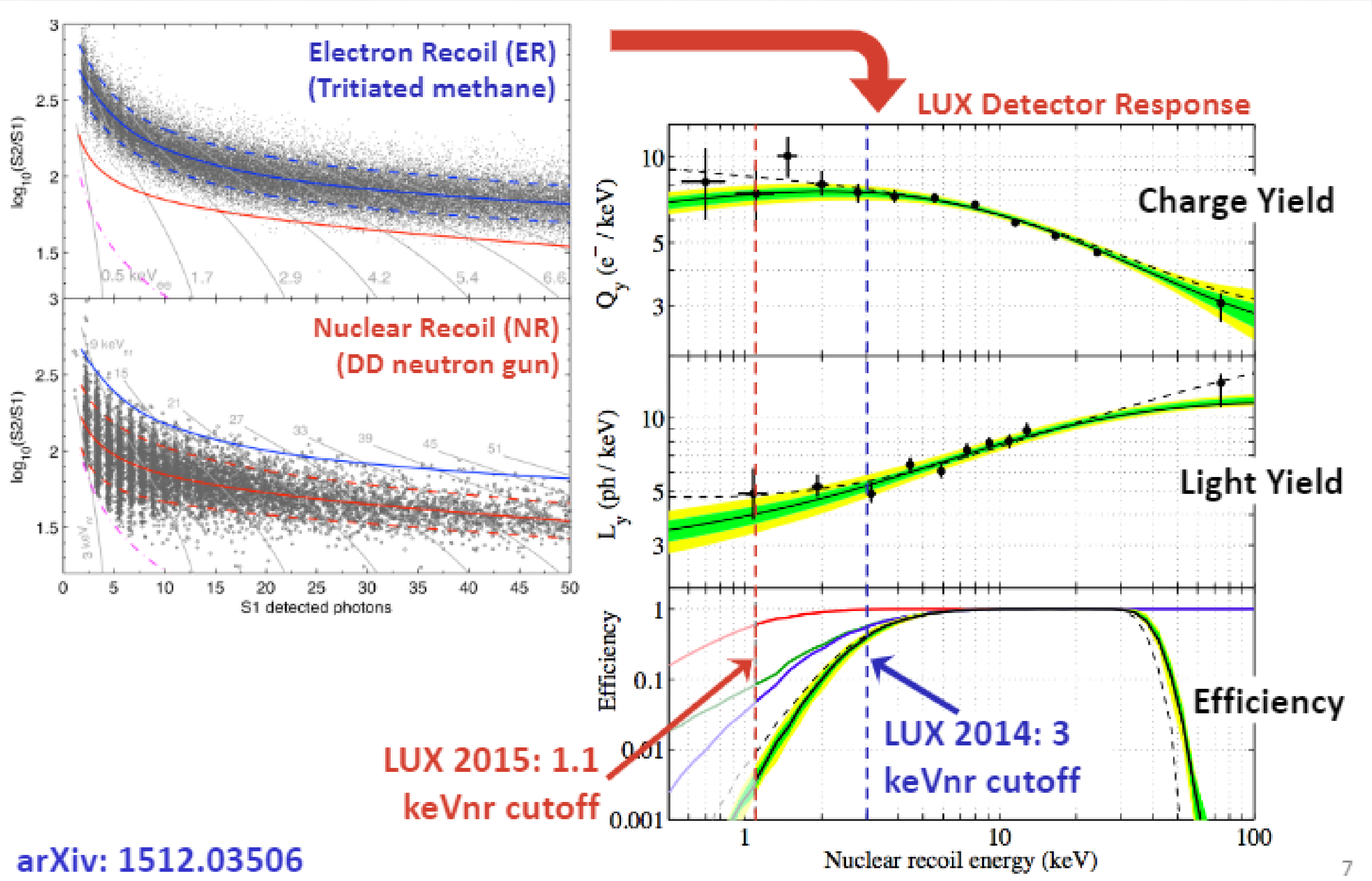
Phys. Lett. B 711

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

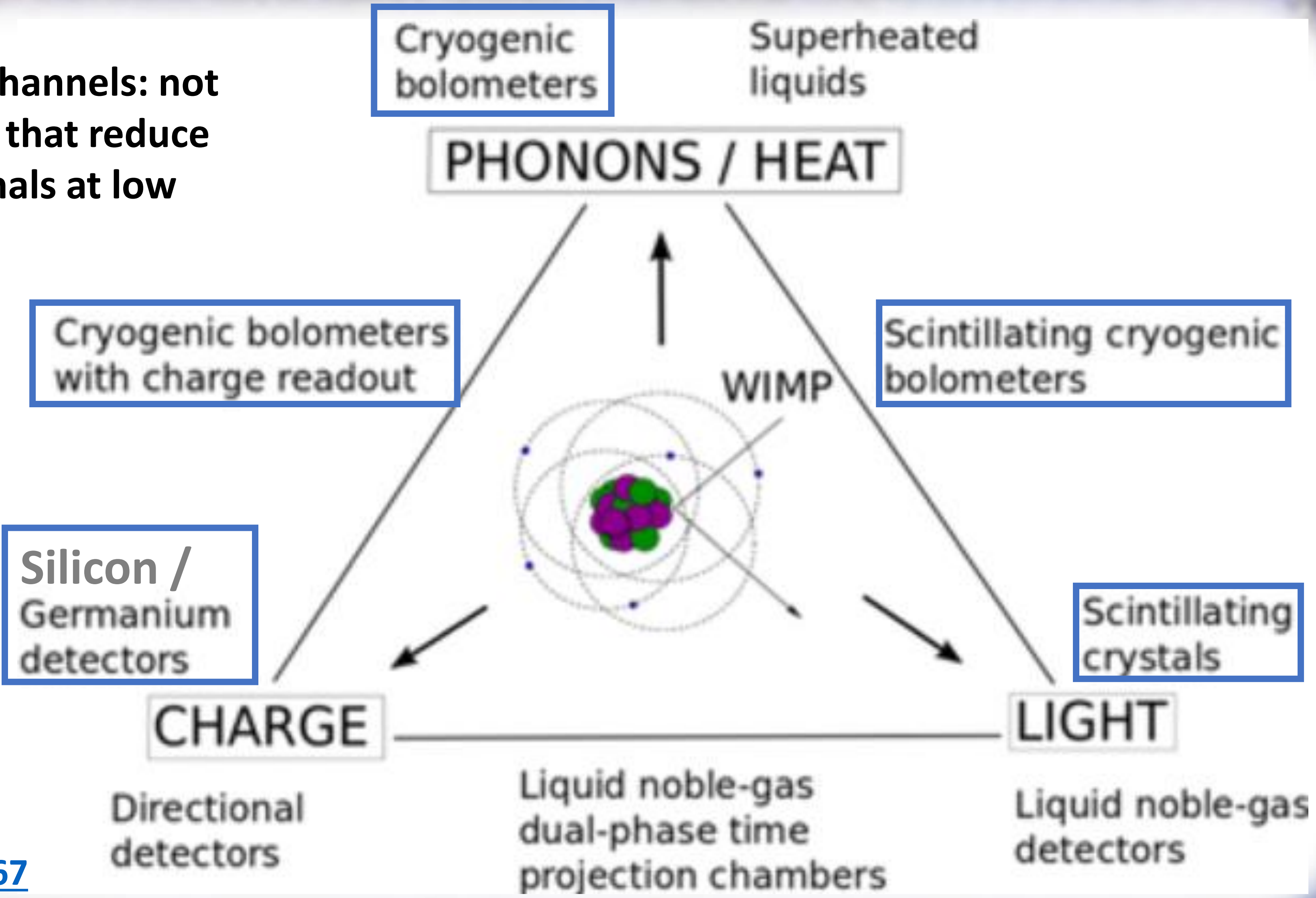


arXiv: 1512.03506

Many Next-Generation Detectors are Solid-State

Low thresholds on phonon channels: not subject to quenching effects that reduce ionization & scintillation signals at low energy

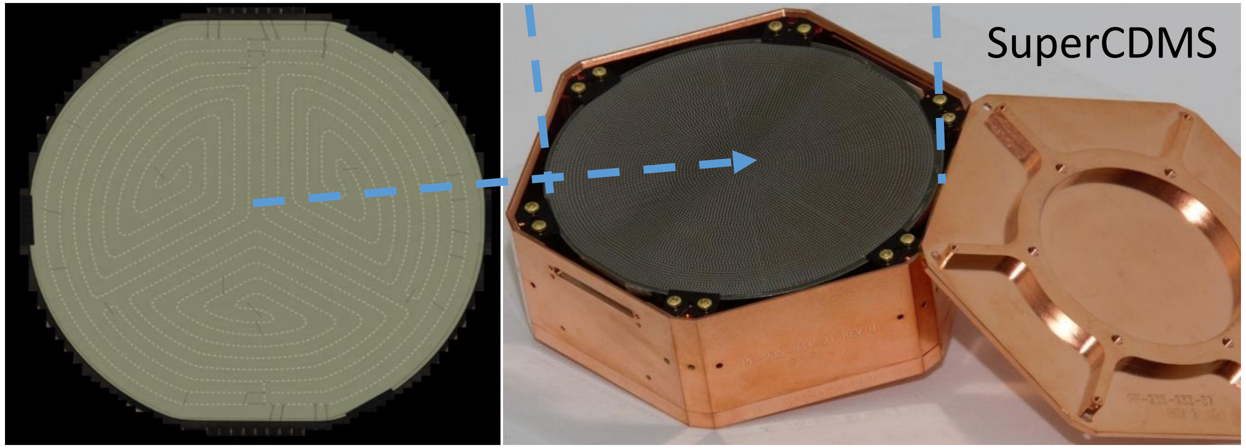
Phonon signal independent of particle interaction type, while ionization / scintillation can provide ER vs NR discrimination



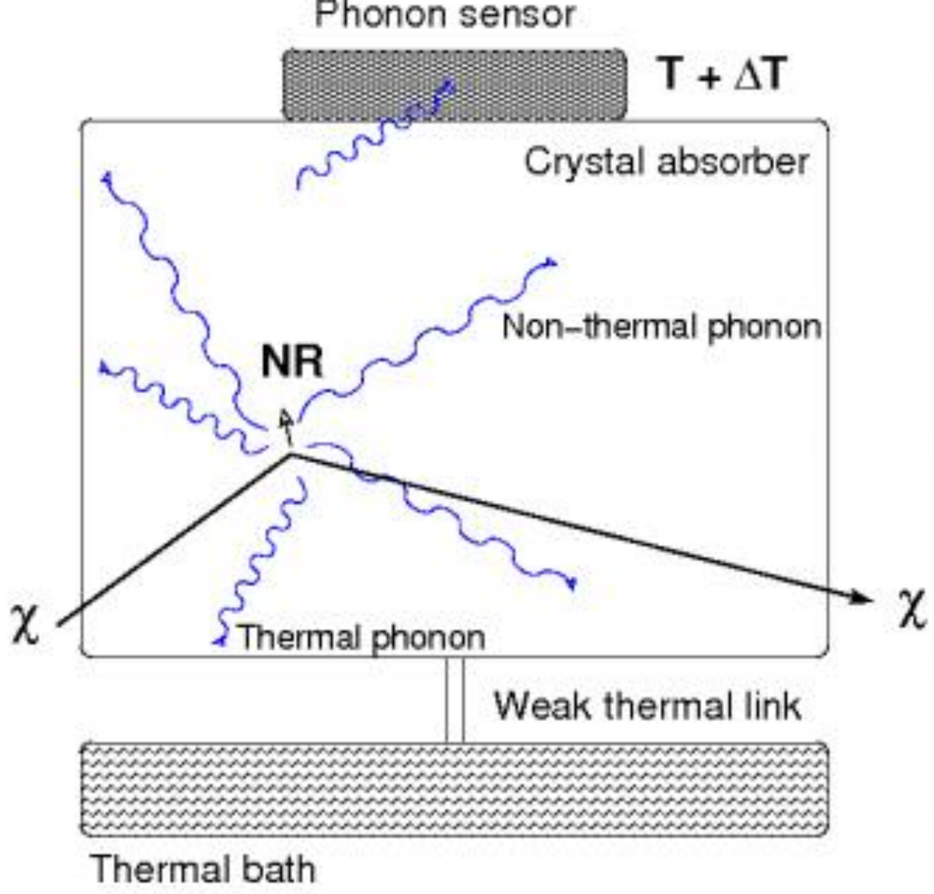
https://arxiv.org/abs/1509.08767

Cryogenic Semiconductor Crystals

- **Trigger & analysis thresholds tens of eV**
- **Tens of mK**
- **Tens of grams**



- **Shielding (lead, copper, polyethylene)**
- **Radiopure environment**

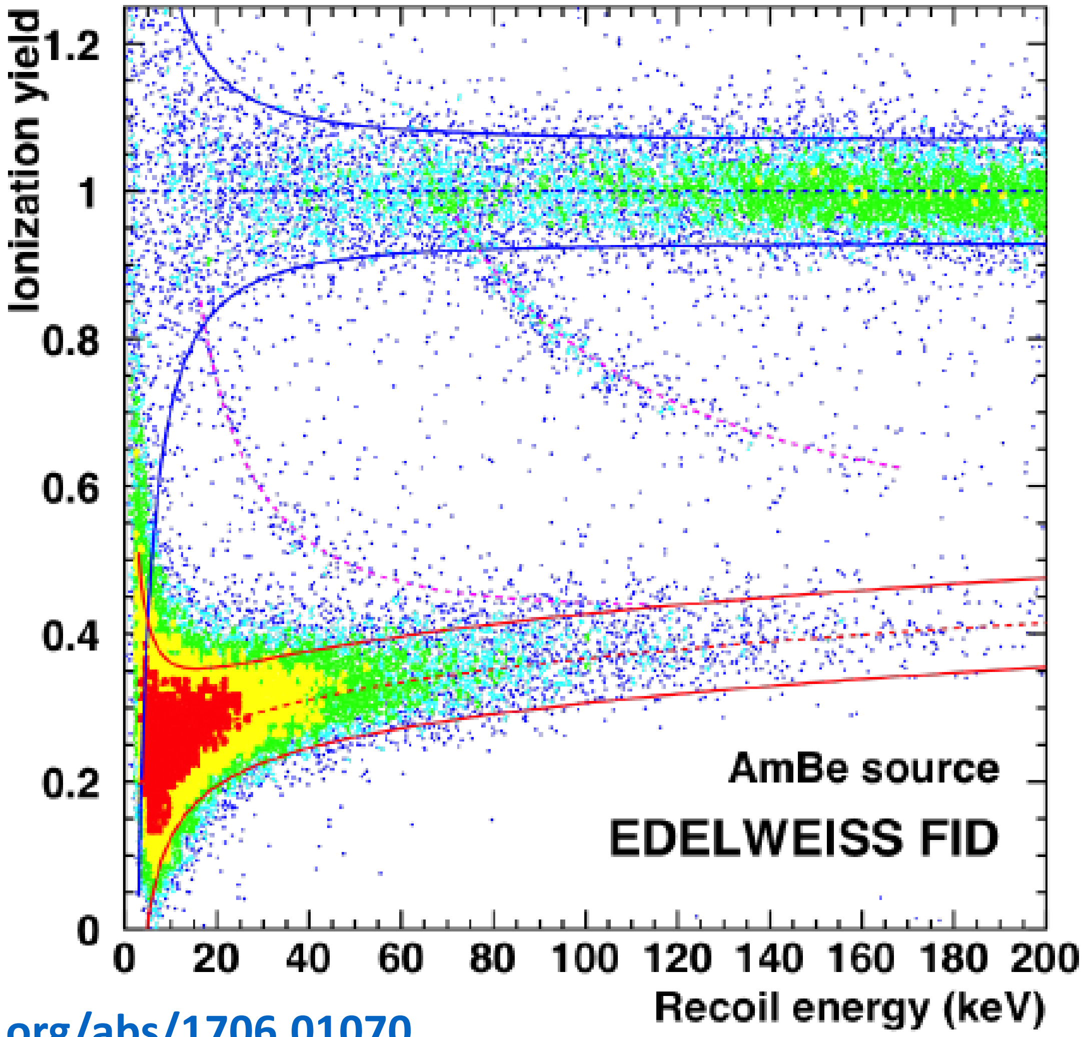


https://arxiv.org/abs/1509.08767

Cryogenic Semiconductor Crystals

EDELWEISS (Expérience pour Detecter Les WIMPs En Site Souterrain): neutron-transmutation-doped Ge

- **-III FD800 at Modane Underground Laboratory: combination of phonon and ionization channels allows NR vs ER discrimination**
- **-SURF at Institut de Physique Nucleaire de Lyon surface facility: phonon channel only**

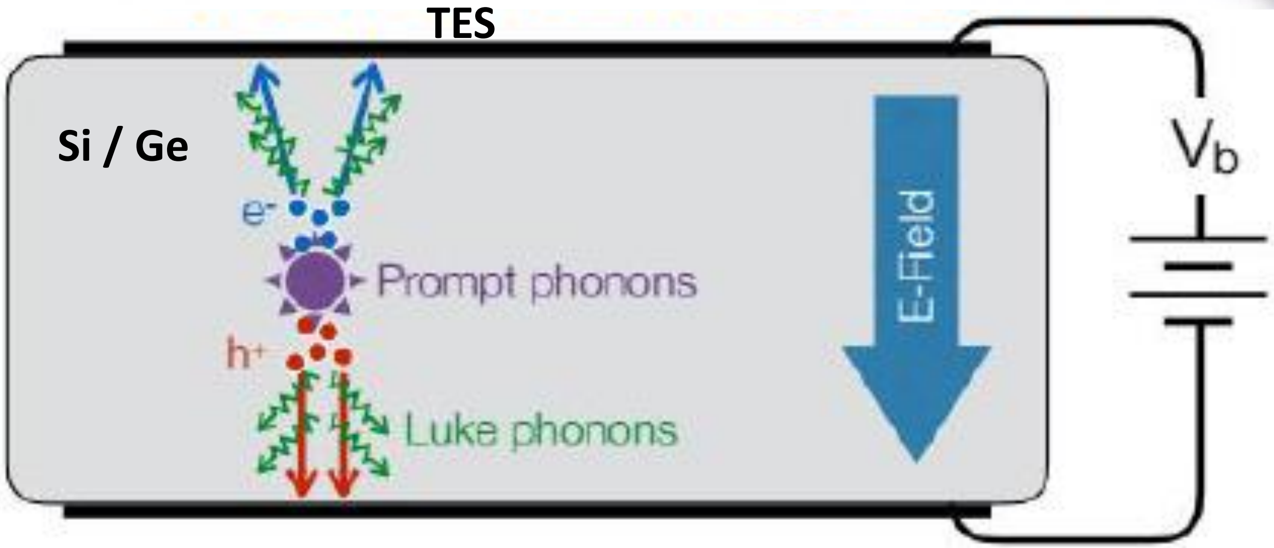


https://arxiv.org/abs/1706.01070

Cryogenic Semiconductor Crystals

SuperCDMS (Cryogenic Dark Matter Search) Soudan / SNOLAB:

- **Ge and Si crystals**
- **E_t measured using transition edge sensors (TESs) read out by SQUIDs**
- **n_{eh} measured using high electron mobility transistors ("iZIP" detectors)**
- **Drifting charges across a V_b generates Luke phonons ("HV" detectors)**
  - **Lowers recoil energy threshold**
  - **But "true calorimetry" and NR vs ER discrimination lost**

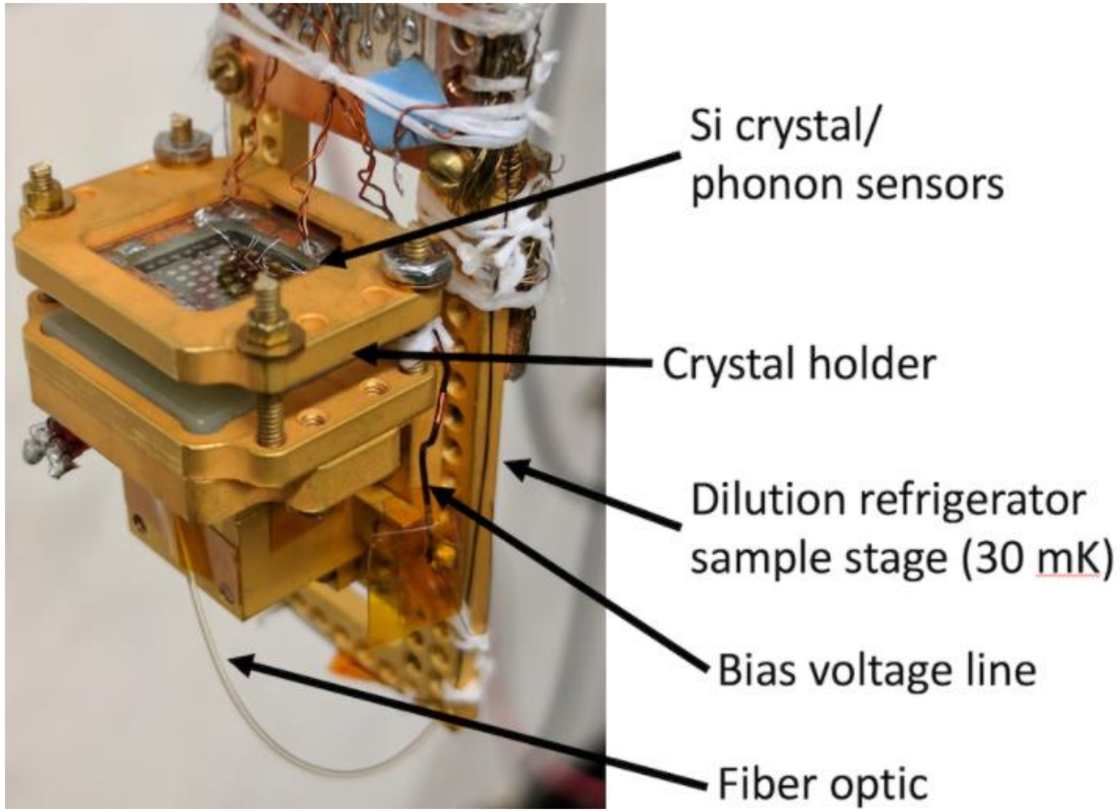


$$\underbrace{E_t}_{\text{Total phonon energy}} = \underbrace{E_r}_{\text{Primary recoil energy}} + \underbrace{n_{eh} q V_b}_{\text{Luke phonon energy}}$$

Total phonon energy | **Primary recoil energy** | **Luke phonon energy**

Cryogenic Semiconductor Crystals

- **SuperCDMS “HVeV”, “CPD” Si prototypes:**
  - **Gram-scale devices**
  - **Single electron-hole pair resolution**
  - **Few eV baseline phonon resolution**
  - **In runs at SLAC and Northwestern surface test facilities so far, just day(s) of live-time yielded near-world-leading DM limits**



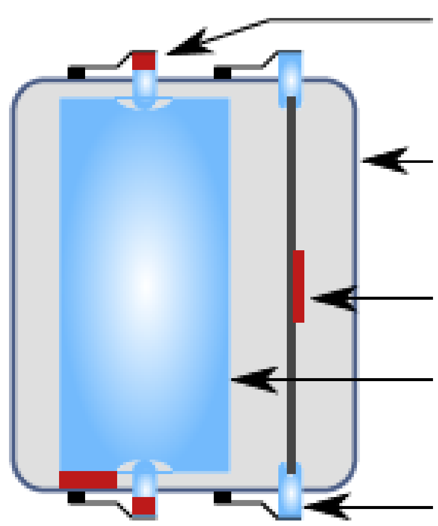
https://arxiv.org/abs/2005.14067

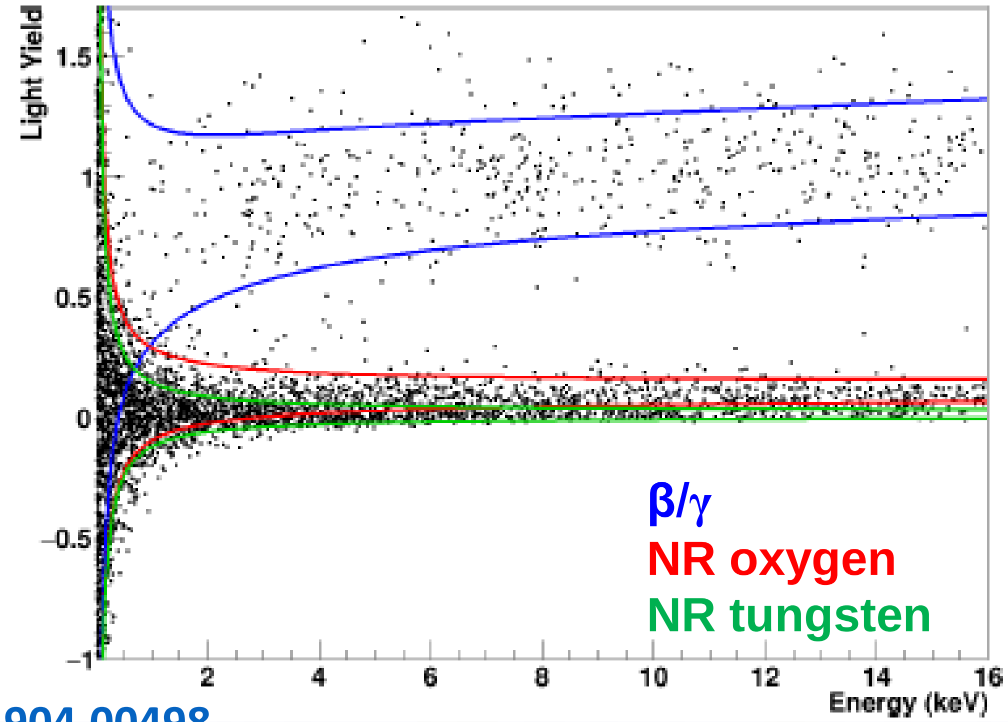
https://arxiv.org/abs/2007.14289

Cryogenic Scintillating Crystals

CRESST-III (Cryogenic Rare Event Search with Superconducting Thermometers) at Laboratori Nazionali del Gran Sasso: $CaWO_4$

- **TESs read out by SQUIDs**
- **Scintillation light emitted simultaneously with primary phonon signal**
  - **Collected in separate light absorber (e.g. silicon-on-sapphire)**
  - **Light yield (E_{light}/E_{phonon}) provides ER vs NR discrimination**
- **~5 mK**
- **Active muon veto**

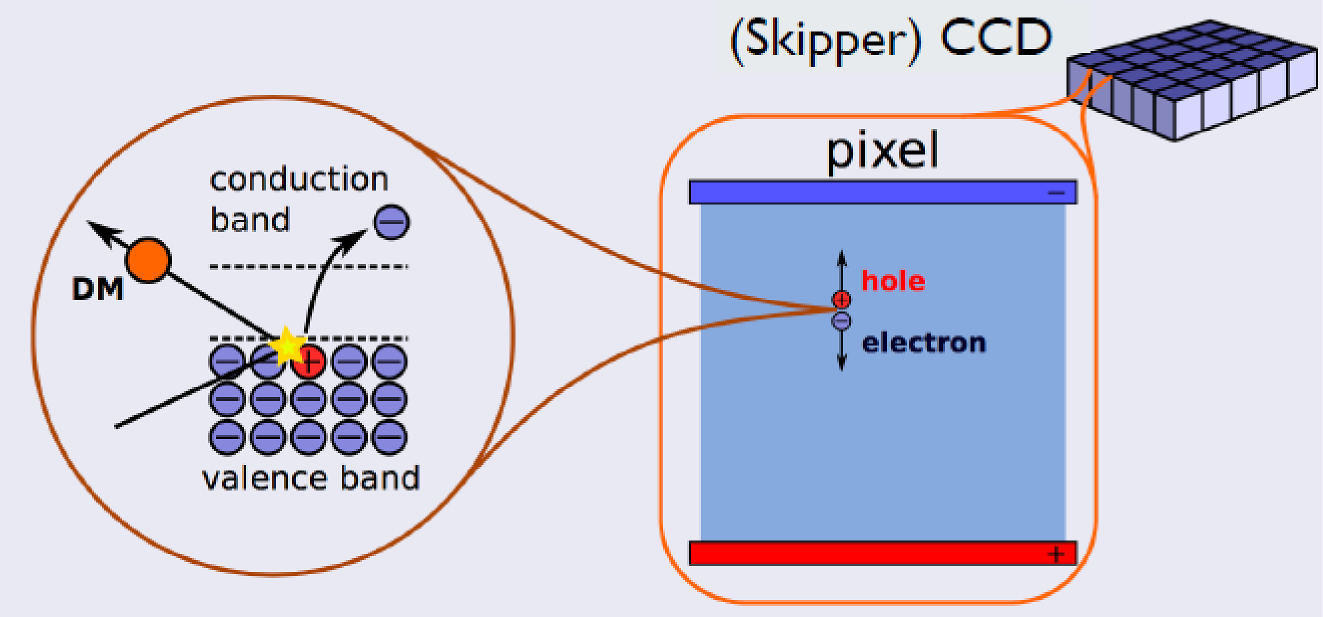




https://arxiv.org/abs/1904.00498

Charge-Coupled Devices

- **Ionization events induced in bulk Si of CCDs**
- **Underground in light-tight housing**
- **1 or 2 electron resolution**
- **~130-140 K**



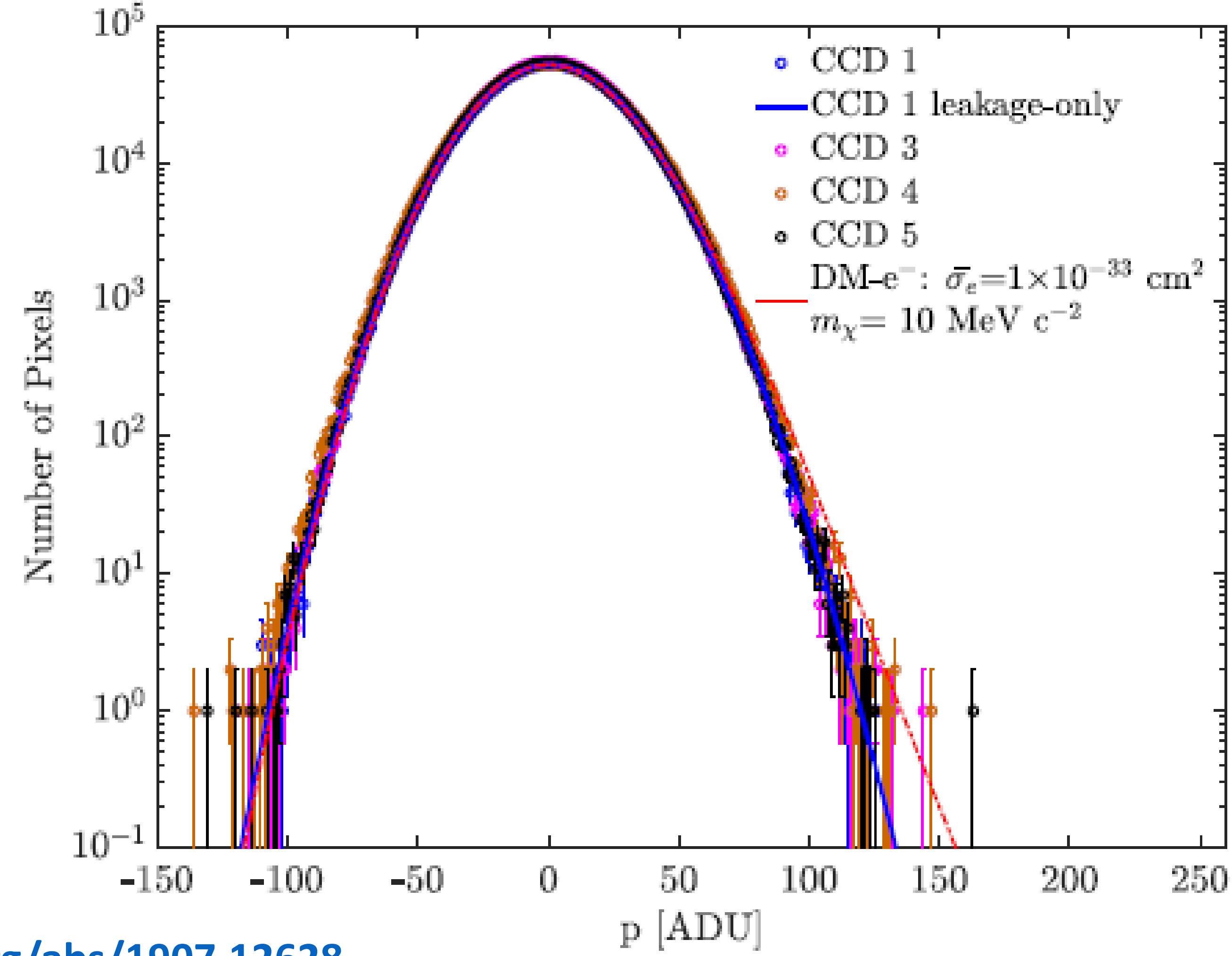
DM would create one or a few electrons in a pixel

R. Essig

Charge-Coupled Devices

DAMIC (Dark Matter In CCDs) at SNOLAB: thick, fully depleted CCDs with applied drift field

- **7 CCDs: each 6.0 g, 4k x 4k-pixels, 15 x 15 μm^2 pixel size, 675 μm thick**
- **Very low leakage current**
- **Operated in vacuum, with shielding**
- **"Image" formed by several hours of exposure followed by serial readout**



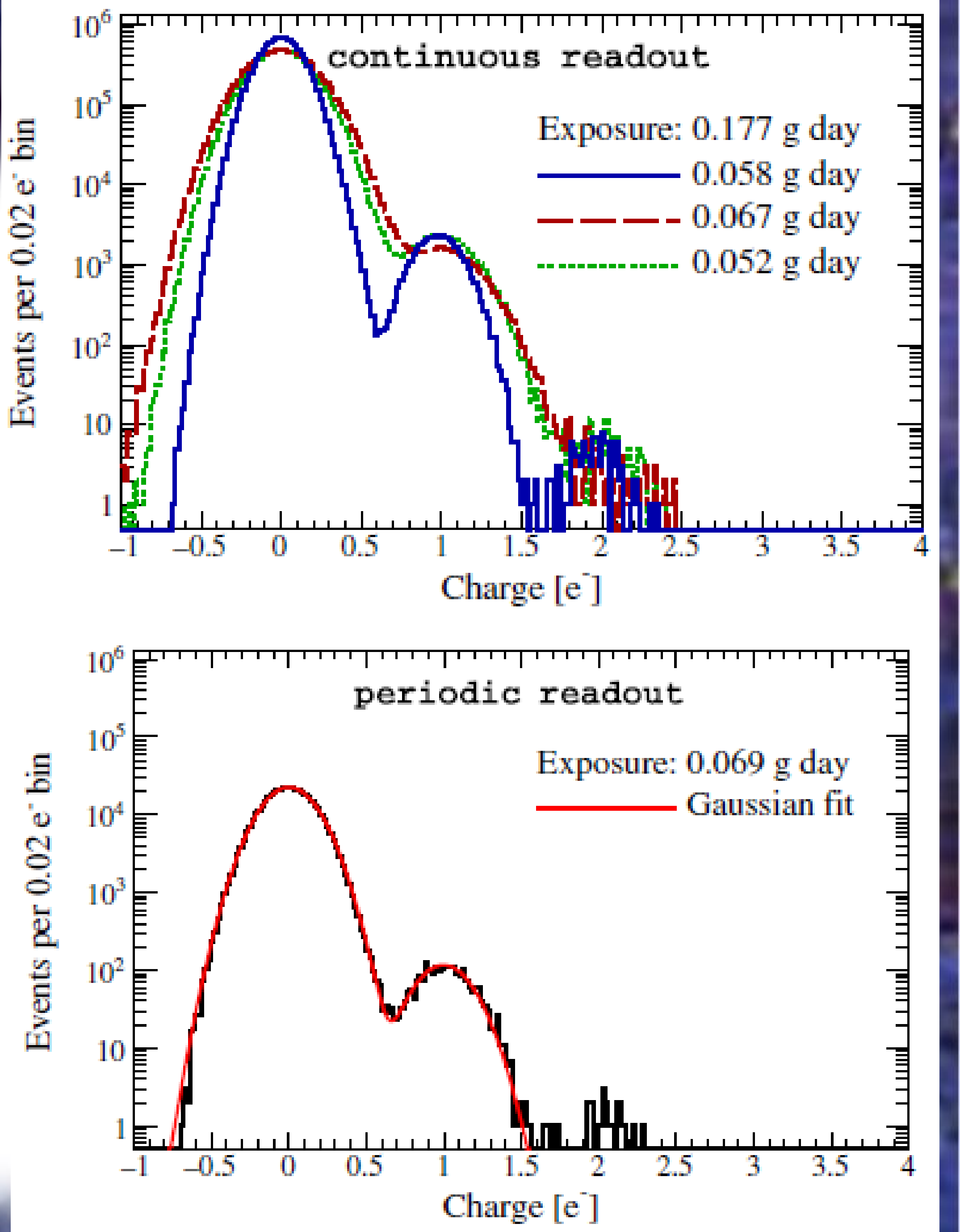
https://arxiv.org/abs/1907.12628

Charge-Coupled Devices

SENSEI (Sub-Electron-Noise Skipper-CCD Experimental Instrument) at Fermilab:

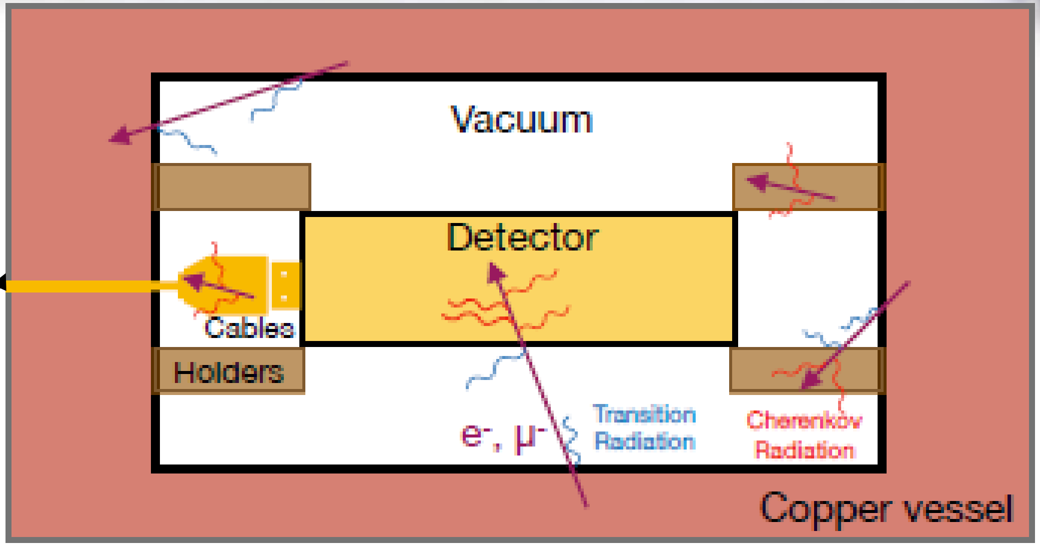
- **"Skipper" readout measures each pixel 800x**
- **Prototype: each quadrant ~0.025 g, 624 x 362 pixels, 15 x 15 μm^2 pixel size, 200 µm thick**
- **Continuous readout mode: ~1 hr exposure time per pixel (given by Skipper-CCD readout time)**
- **Periodic mode: several hours exposure followed by readout of all pixels**

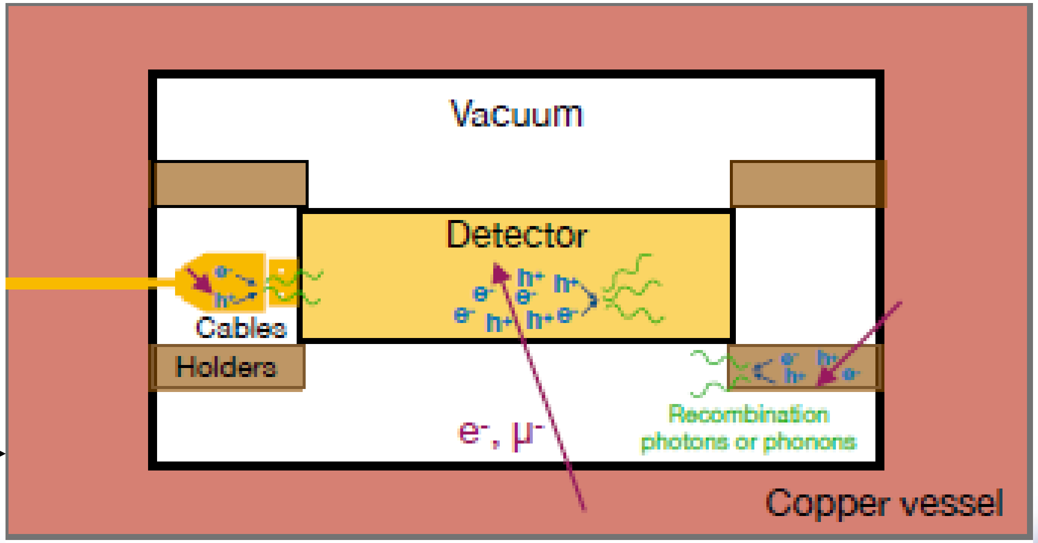
https://arxiv.org/abs/1901.10478



Shedding Light on Low-Energy Backgrounds

- **Low-energy background events, of unknown origin, observed in:**
  - **XENON1T, DarkSide-50 (liquid nobles)**
  - **SENSEI, DAMIC, SuperCDMS, EDELWEISS, CRESST-III (solid-state)**
- **Possible explanations in solid-state detectors include:**
  - **Cherenkov radiation**
  - **Transition radiation**
  - **Cracking/micro-fracturing of crystals or holders**
  - **Luminescence & phonons from recombination**





https://arxiv.org/abs/2011.13939