QUEST-DMC: Direct Detection of Low Mass Dark Matter

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QTFP School, Cambridge

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ROYAL HOLLOWAY UNIVERSITY OF LONDON

QUEST-DMC

QUantum Enhanced Superfluid Technologies for Dark Matter and Cosmology

WP1: Detection of sub GeV dark matter with a quantum amplified ^{3}He calorimeter.

Use superfluid 3He detector as a **quantum calorimeter,** reading out energy depositions using **quantum sensors**. Very low threshold will allow low mass dark matter searches. Search for a range of well motivated sub GeV dark matter candidates.

WP2: Phase transitions in extreme matter.

Phase transitions between distinct quantum vacua in superfluid 3He will be studied as a **quantum simulator** to test nucleation theory, which critically informs predictions of gravitational wave production

See second QUEST lecture on Thursday

Outline

- Dark matter introduction – why, what, how?
- Dark matter search strategies – complimentary methods
- Direct detection of dark matter – idea, challenges, landscape
- Sub GeV dark matter - motivation, searches
- QUEST - new technique for sub GeV dark matter search

Dark matter introduction

Dark universe

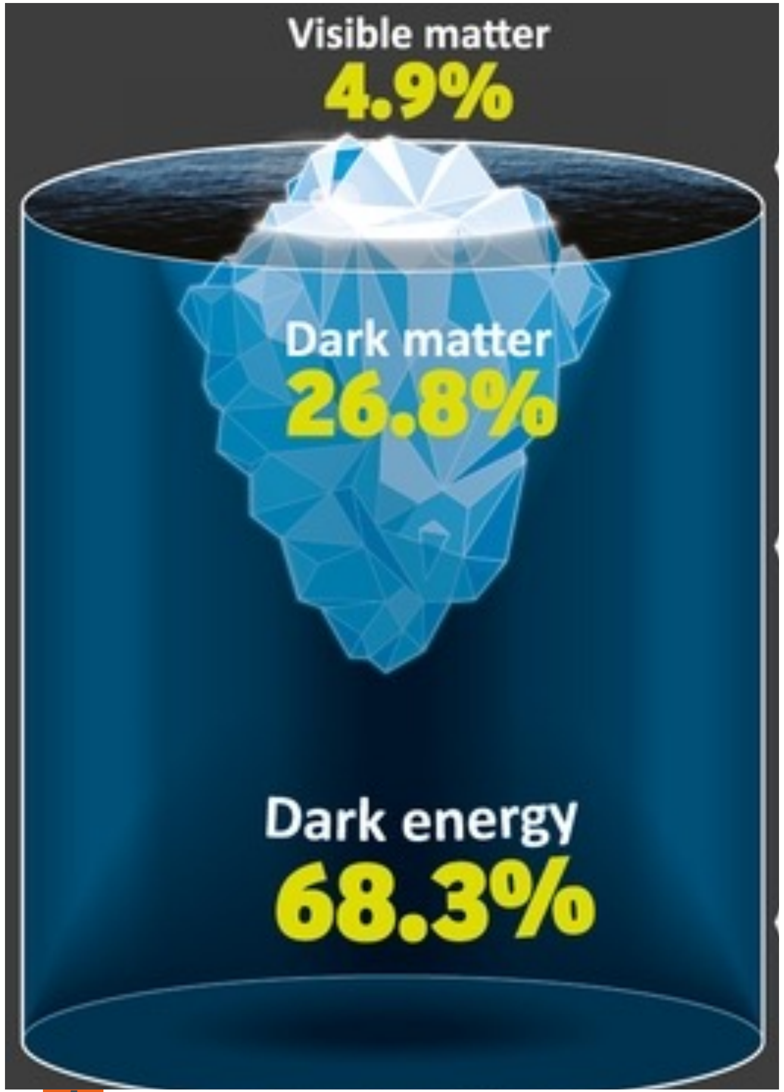


Image: STFC Dark Matter Day

<5% understood

27% dark matter (DM)

68% dark energy

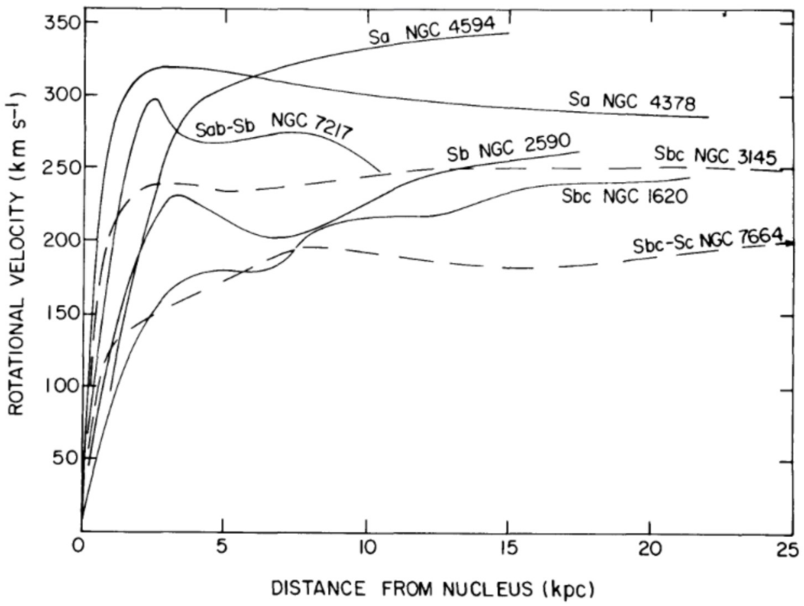
N. Aghanim et al. Planck 2018 results.
Astron. Astrophys., 641, Sep 2020

Dark matter evidence

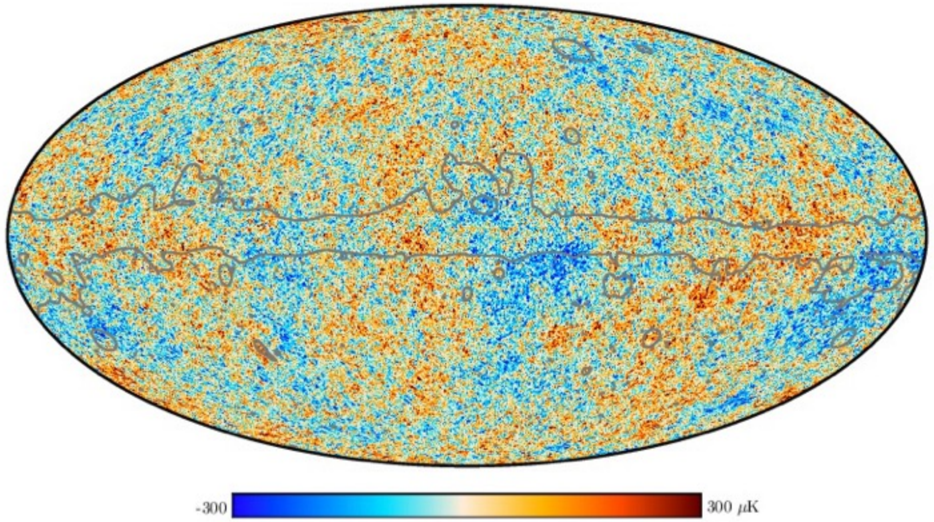
On a range of astrophysical scales:

- Galaxy rotation curves (Rubin)
- Velocity dispersion of galaxies in a cluster (Zwicky)
- X-ray emission from gas in clusters
- Gravitational lensing
- CMB power spectra

See first few sections of Bertone, Hooper, Silk (2004) for a good review



J. Ford V. Rubin and N. Thonnars. Extended rotation curves of high-luminosity spiral galaxies. Astrophys. J., 225:107–111, 1978



N. Aghanim et al. Planck 2018 results. Astron. Astrophys., 641, Sep 2020.

Properties

What do we know?

Dark

- No observable emission or absorption of light
- Any electromagnetic coupling must be very small

Stable

- or has a lifetime much longer than the age of the universe

Mostly dissipation less

- no radiative heat loss and collapse to galactic disk structure

Cold or warm

- required for structure formation

No candidates in the Standard Model (SM).
Particle dark matter requires physics beyond the SM.

Dark matter mass range

Only constrained within ~80 orders of magnitude…

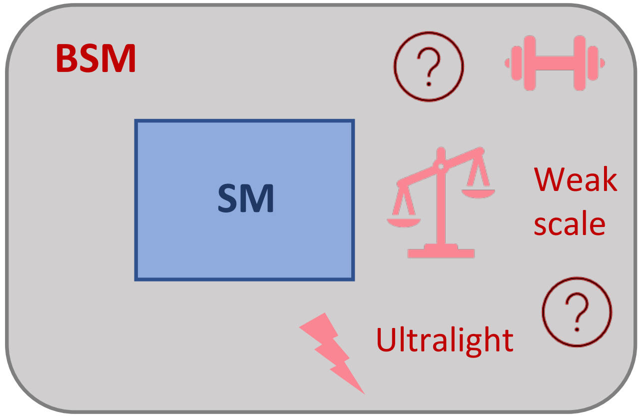
For particle dark matter limits can be derived by considering the particle type:

- Fermions constrained by Pauli exclusion, filling states whilst requiring the velocity to be below the halo escape velocity gives: $m_{DM} > 400$eV
- Bosons constrained by the de Broglie wavelength being smaller than the halo size gives: $m_{DM} > 10^{-22}$ eV

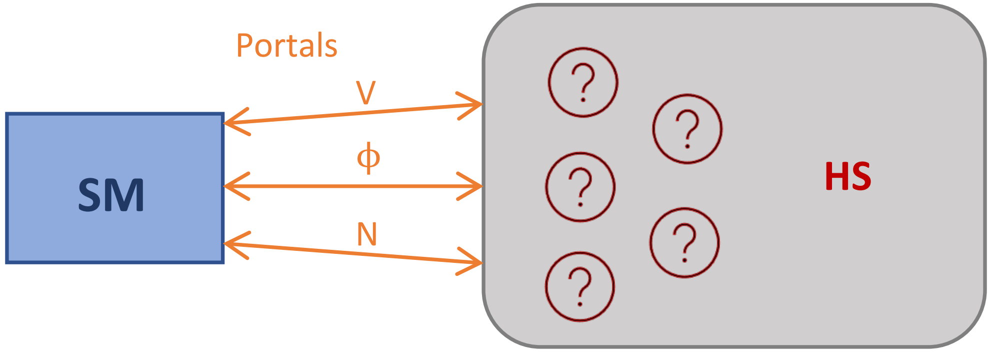
Upper limit Planck scale 10^{28} eV

Model building approaches

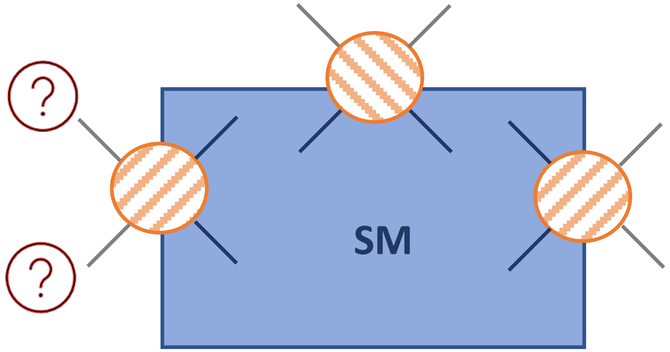
1. Standard Model Extension



2. Hidden Sector



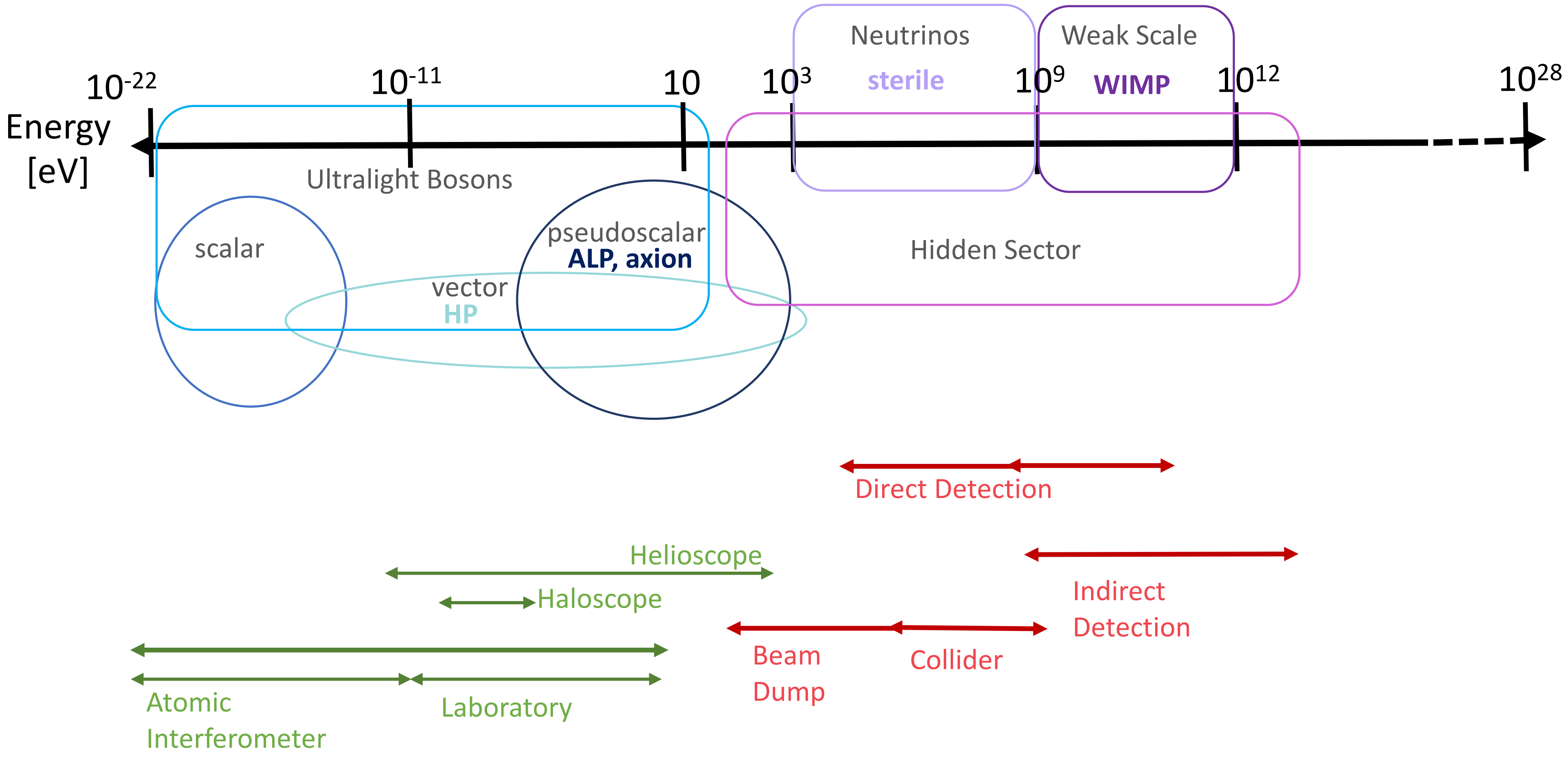
3. Effective Field Theory



Dark matter parameter space

Wide mass range, allows for many different models

Different search strategies best suited for each.
Wavelike <30eV (separation >> de Broglie wavelength)



Freeze out production

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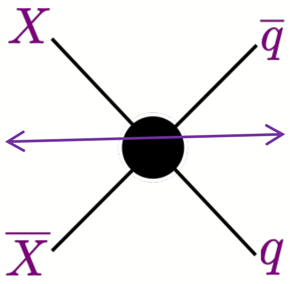
Assume single species of dark matter which has 2 point interaction with SM:

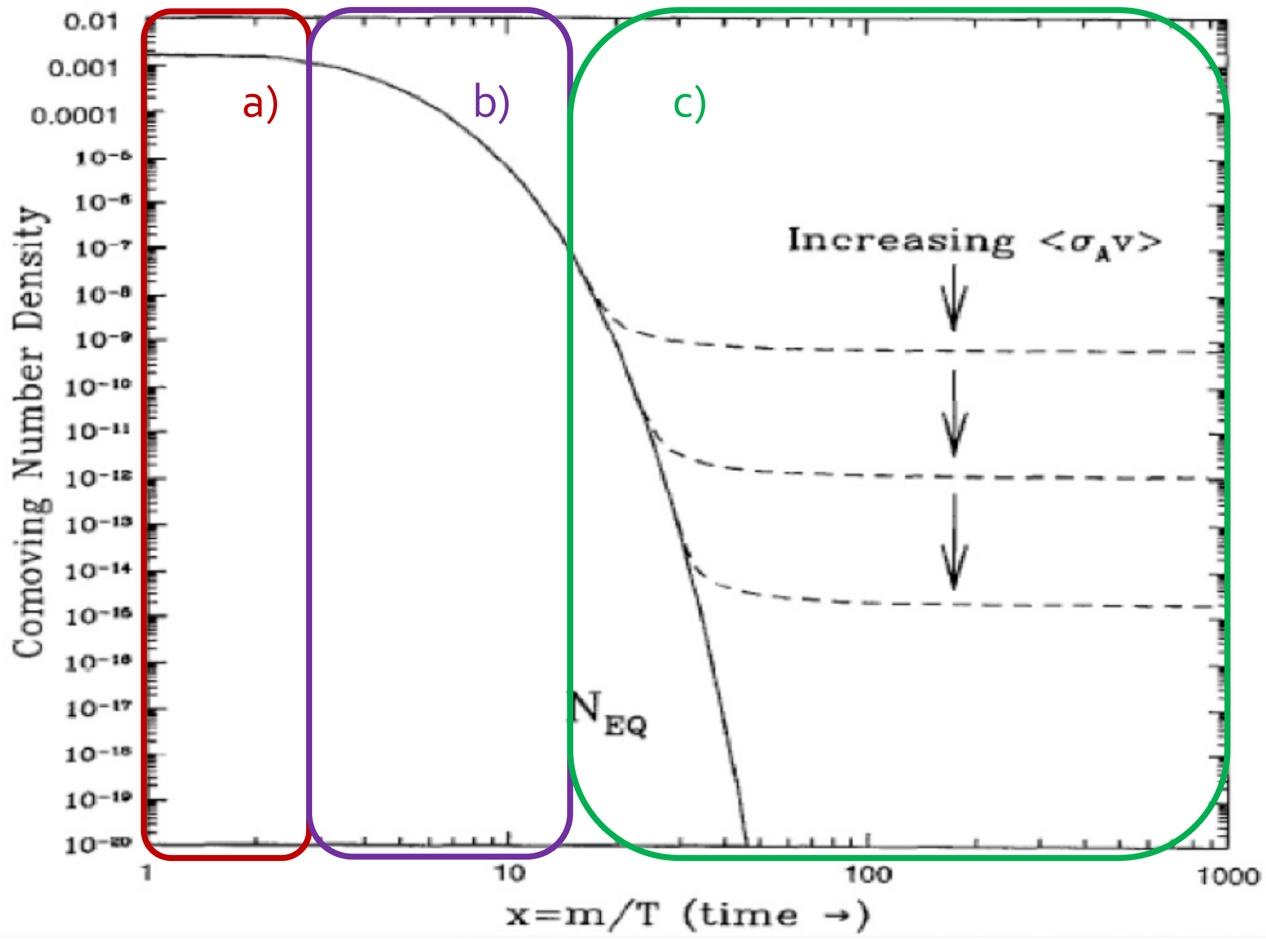


a) Hot early universe – particles in thermal equilibrium, high production T>m_X and annihilation $\Gamma = n\sigma v > H$ (exceeds expansion)

b) Temperature decreases T<m_X production supressed, annihilation continues

c) Expansion exceeds annihilation, number density freezes out at time when $n\langle\sigma_A v\rangle = H$

Kolb and Turner The Early Universe



Relic density

Boltzmann equation:

$$\frac{dn}{dt} = -3Hn - \langle\sigma_A v\rangle\left(n^2 - n_{eq}^2\right)$$

expansion annihilation production

Freeze out abundance depends on annihilation cross section.

Solution gives:

$$\Omega h^2 \sim 0.1 \frac{3\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma_A v\rangle}$$

Cross section $\langle\sigma_A v\rangle \sim 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ gives abundance observed today – weak scale couplings and GeV-TeV mass.

Motivates WIMP (weakly interacting massive particle) dark matter.

Sub GeV dark matter

How about lower masses?

Alternatives to standard freeze out:

- Modify freeze out – new mediator, DM asymmetry
- Freeze in (Hall, Jedamzik, March-Russell, West (2009))
- Non-thermal production

Sub GeV dark matter models:

- Asymmetric dark matter – see review Zurek (2013) arxiv:1308.0338
- Hidden sectors (P Barnes Phys.Rev.D **102,** 075019 (2020))
- SIMP (Y Hochberg Phys. Rev. Lett. 113, 171301 (2014))
- Axions/ALPs (keV scale - M Pospelov Phys.Rev.D 78,115012(2008))
- Dark photons (review - J. Jaeckel (2013) arxiv:1303.1821)

Dark matter search strategies

Search strategies

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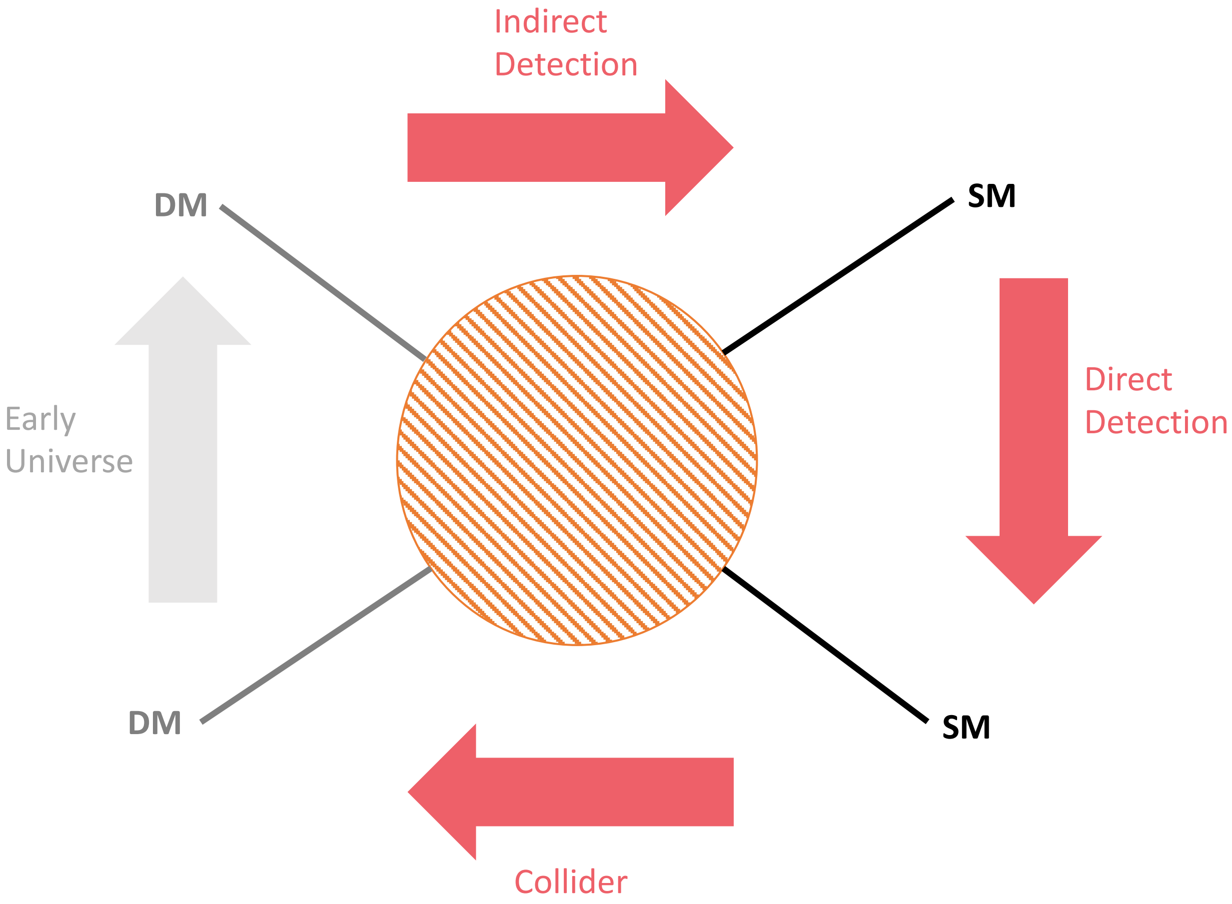
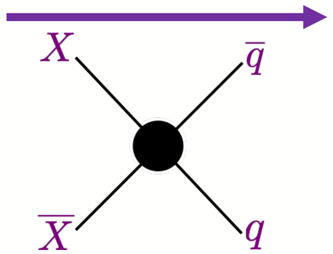
Three complimentary search strategies:

- **Indirect detection** – annihilation of DM particles, implied by early universe annihilation
- **Collider production** – DM created from SM particles (also fixed target/beam dump)
- **Direct detection** – scattering of DM off SM particles in a terrestrial detector



Indirect searches



- DM annihilation today can produce photons, neutrinos or cosmic rays
- Detect using gamma ray/x-ray/neutrino telescopes
- Sources from higher DM density astrophysical environments e.g. Galactic Centre, Dwarf Spheroidal galaxy, Sun, other stars, white dwarfs, neutron stars
- Many astrophysical backgrounds
- Model dependent annihilation signature

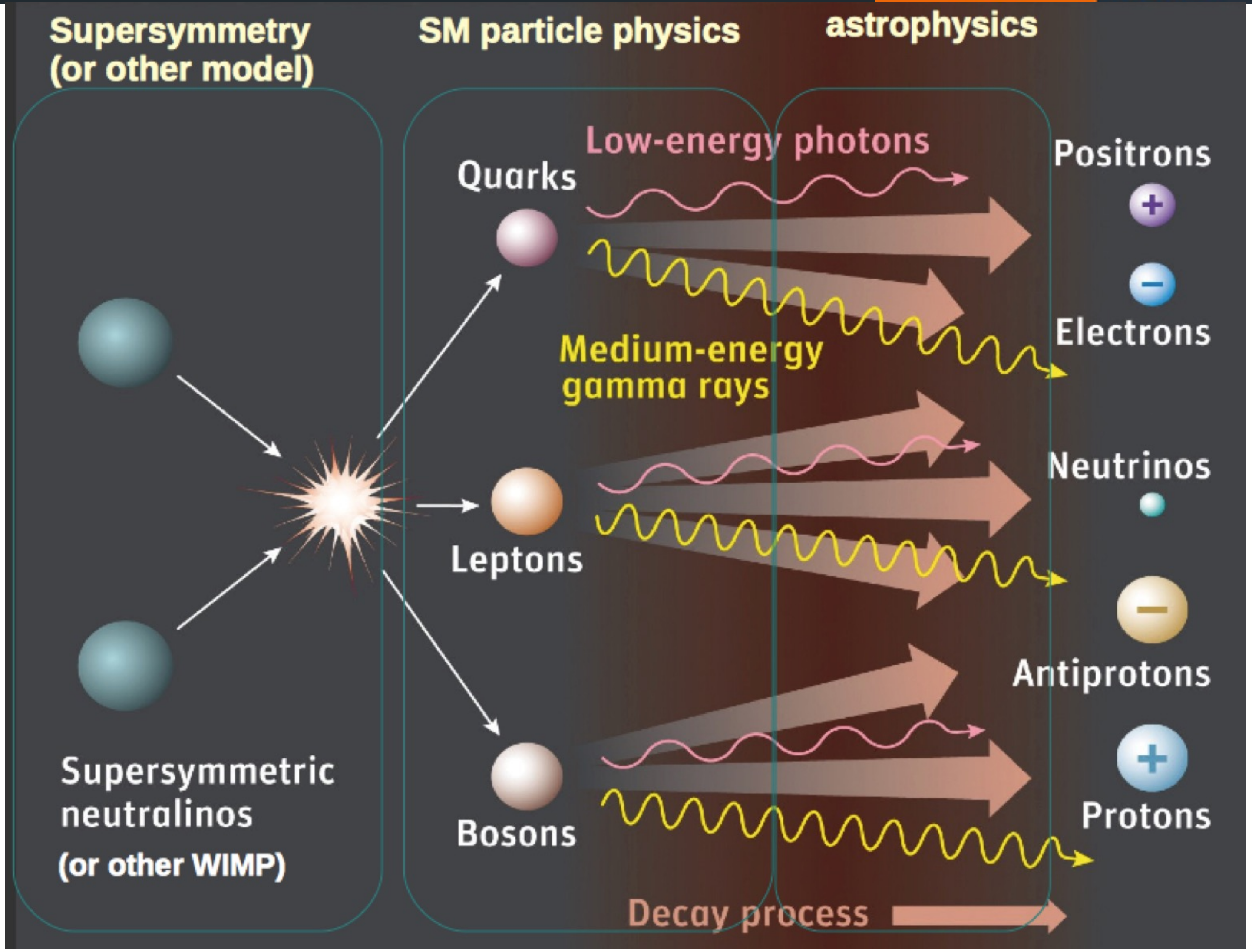
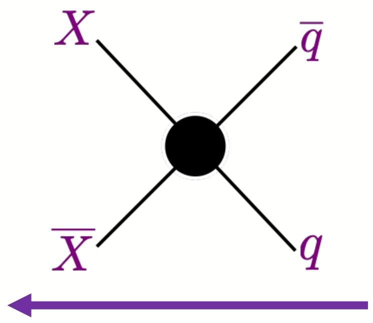


Image credit: de los Heros (2011)

Collider and accelerator searches



- Rotating the diagram allows SM -> DM production
- Stable DM produced would leave the detector
- Search for missing energy/momentum or heavy mediator
- Full, simplified model and EFT analyses
- Choice of model and couplings important
- No guarantee of stability on astrophysical timescales

- LHC review: Kahlhoefer (2017)

Beyond colliders

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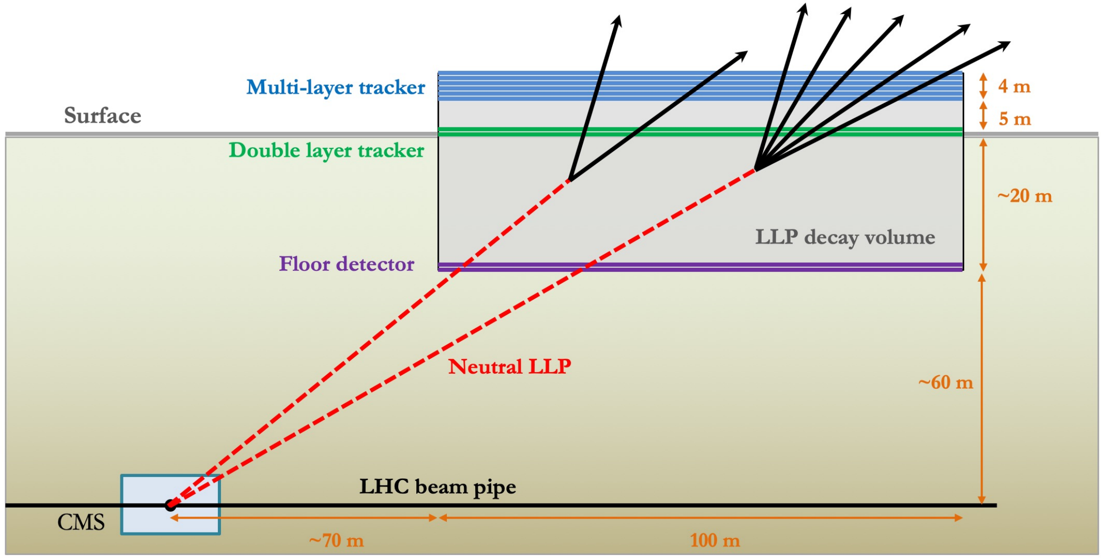
Physics beyond colliders report (2019)

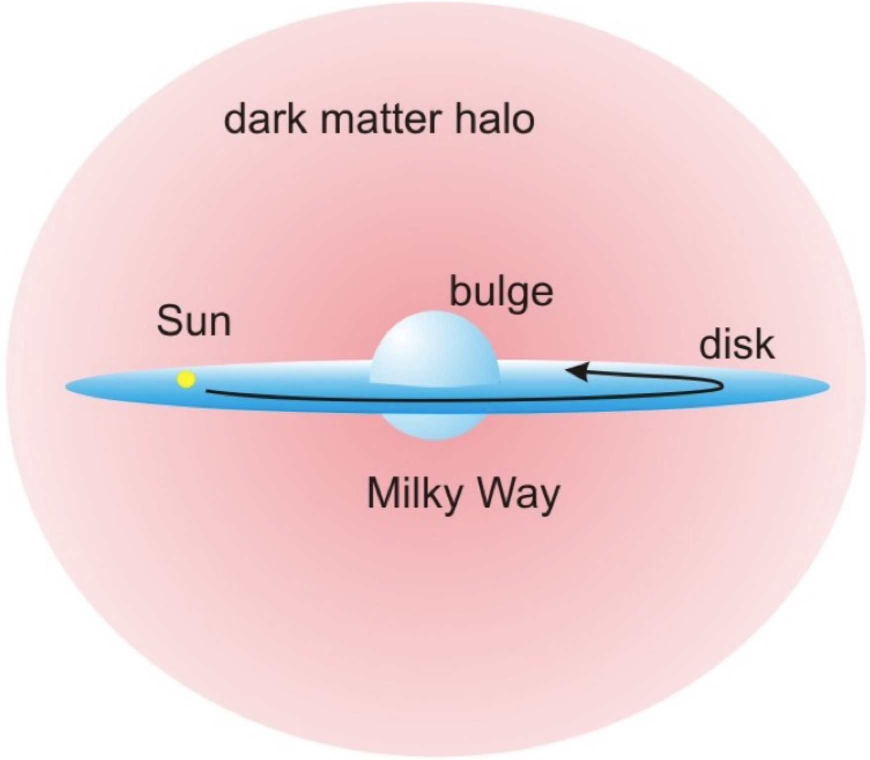
- Search for light long lived particles with additional detectors further from interaction points e.g. MATHUSLA and FASER at the LHC
- Fixed target and beam dump searches using extracted beams (proton or electron) for lower mass DM or hidden sector searches
- DM production via Bremsstrahlung or particle decay, missing energy searches e.g NA64, BDX, PADME

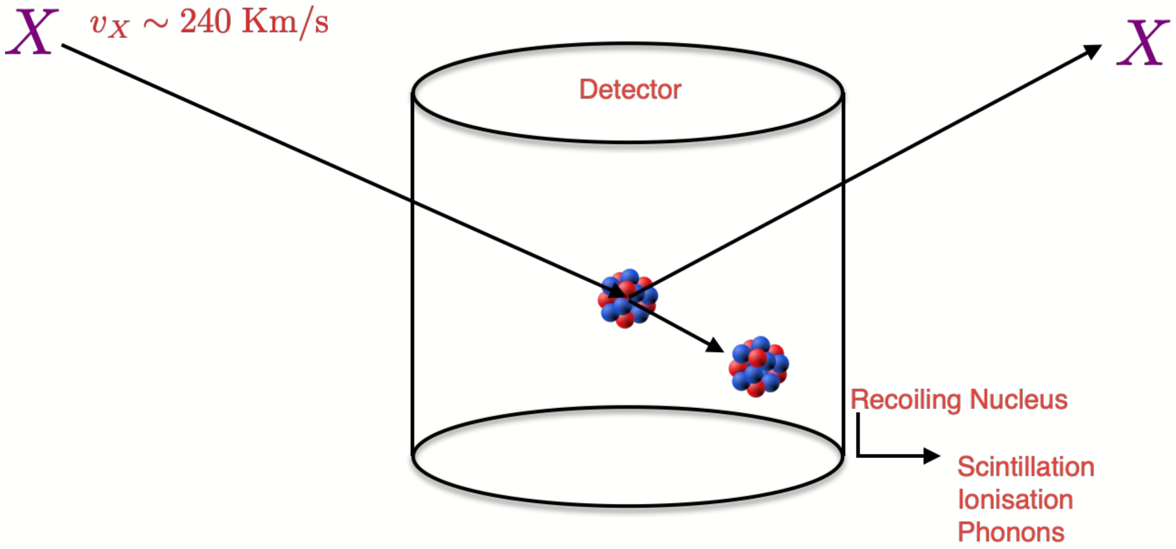


MATHUSLA schematic: from https://mathusla-experiment.web.cern.ch

Direct detection of dark matter

Direct detection





Earth moves through galactic dark matter halo

Search for interaction of DM particles with SM particles in terrestrial target

Direct detection review: M. Schuman (2019)

Direct detection rate

Galactic DM with SM interactions, in a terrestrial detector:

number of events = flux × cross section × exposure

flux	cross section	exposure
how much DM arriving at Earth	how likely it is to interact	how big the target and long you look

WIMP rate calculation

Rate of scattering events (per kg per unit times) for a given:

- detector material
- dark matter density and velocity distribution in the Milky Way
- scattering cross section of dark matter

Expected rate in an experiment:

$$\frac{dR}{dE_R}(t) = N_T \frac{\rho_\chi}{m_\chi} \int_{v_{min}} d^3v \, f(\bar{v}, t) v \frac{d\sigma}{dE_R}$$

Target atom density
$N_T = 1000 \times N_A / m_N$ per kg

Astro physics input:
ρ_χ local WIMP density
$f(\bar{v}, t)v$ velocity distribution integrated over all WIMP velocities

Particle physics input:
Differential cross section
$$\frac{d\sigma}{dE_R}$$
For WIMP nucleus scattering

Interaction

Different interactions can be constructed.

Spin independent:

Coherent scattering with all nucleons, from vector or scalar couplings

$$\sigma^{\mathrm{SI}}_{XN}(0) = A^2 \frac{\mu^2_{XN}}{\mu^2_{Xp}} \sigma^{\mathrm{SI}}_{Xp}$$

A = atomic mass number of target nucleus

Scales with target mass

Spin dependent:

Axial vector coupling depends on target spin

$$\sigma^{\mathrm{SD}}_{XN}(0) = \frac{4\mu^2_{XN}}{\pi} \frac{J+1}{J} \times |\langle S_p \rangle G^p_a + \langle S_n \rangle G^n_a|^2$$

$\langle S_p \rangle, \langle S_n \rangle$ = expectation value of spin of p and n in nucleus

J = nuclear spin

G^p_a, G^n_a = axial four-fermion couplings of the WIMP with point-like protons and neutrons

Kinematics

DM nucleon scattering gives recoil energy (*derivation in tutorial):*

DM-Nucleus Reduced mass

$$\mu = \frac{M_N M_X}{M_N + M_X}$$

Scattering angle - max recoil with $\theta = \pi$

$$E_{\rm recoil} = \frac{\mu_{XN}^2 v_X^2}{M_N}(1 - \cos\theta)$$

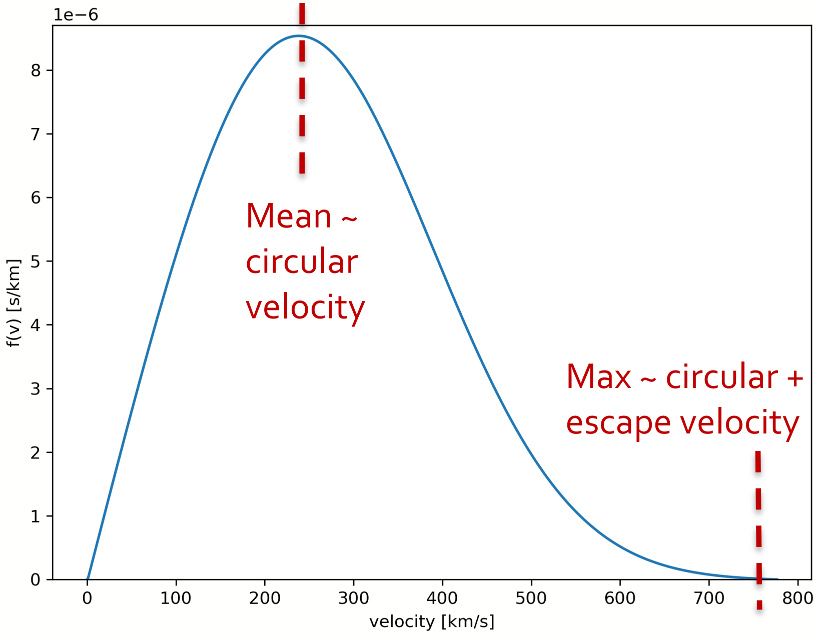
Nucleus mass

$v_X \sim 220\ \mathrm{km/s}$

Circular velocity at Earth radius

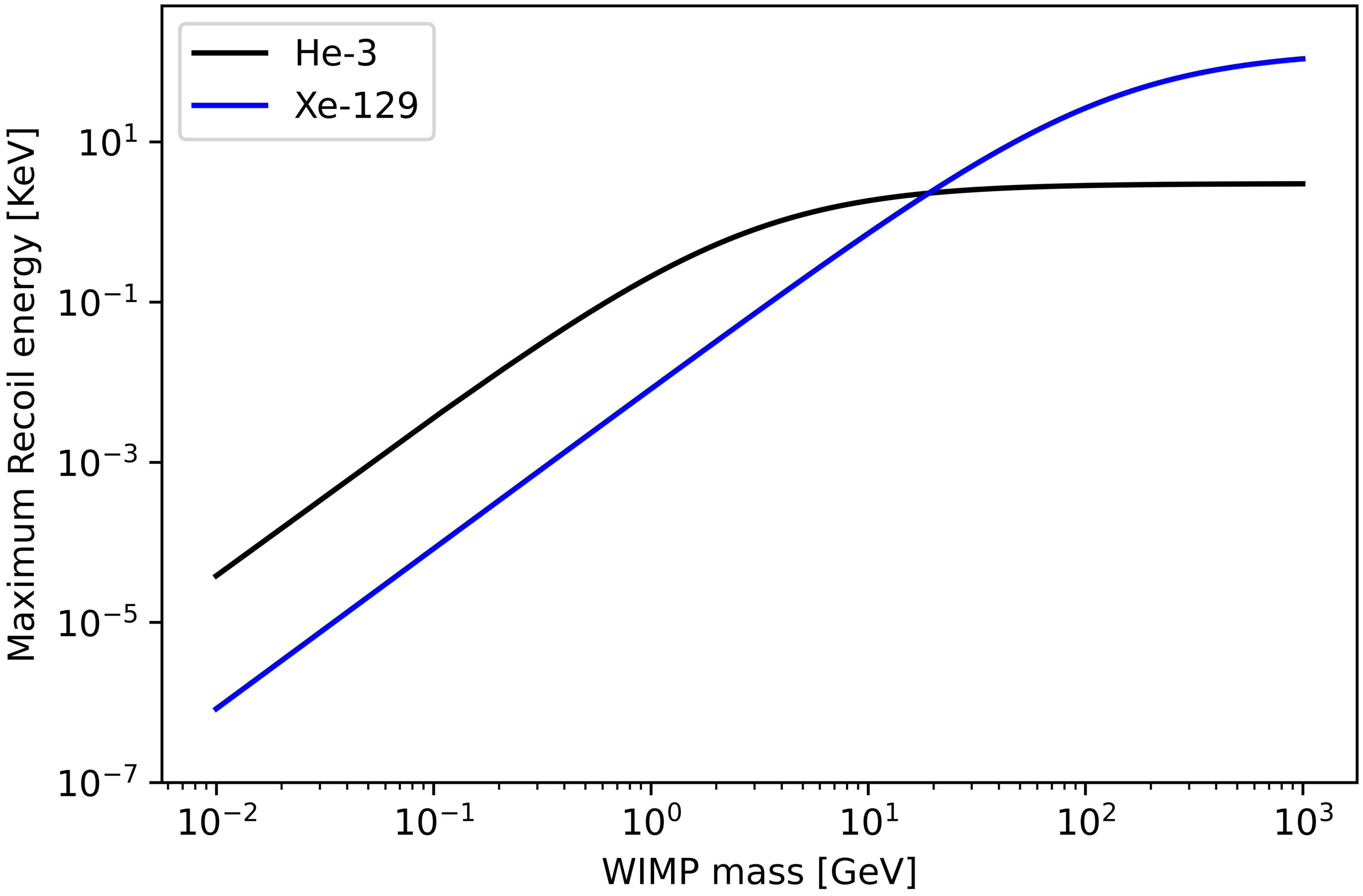
Typical recoil energies:

$$M_N \sim 100\mathrm{GeV} \begin{cases} E_R \sim 100 keV, & if\ \mu \sim M_N \\ E_R \sim 0.01\ keV, & if\ \mu \ll M_N \end{cases}$$



Velocity distribution for dark matter arriving at Earth ($v = v_{Earth} + v_{DM}$)

Target comparison



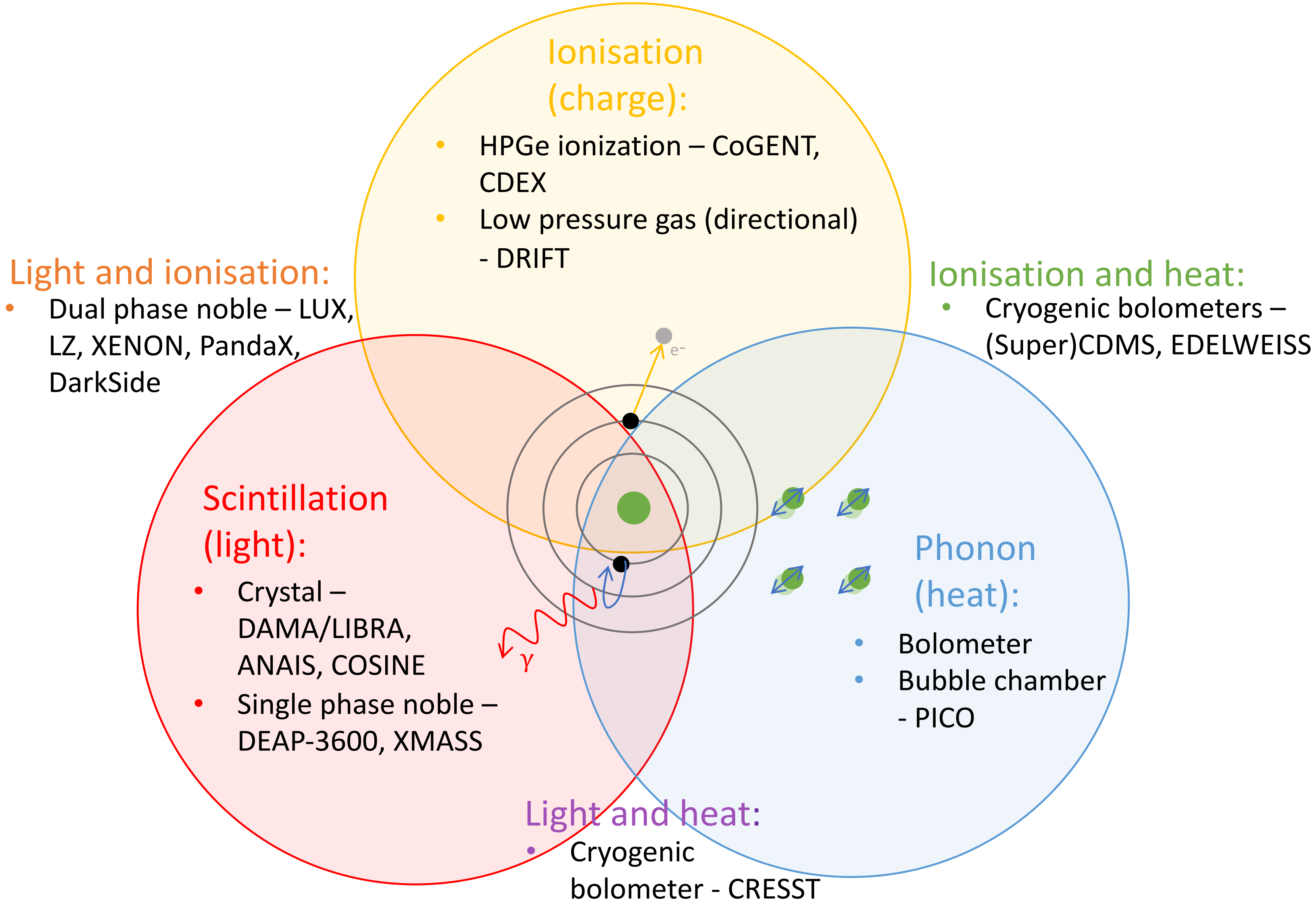
Maximum recoil energy for light and heavier target nuclei

Light nuclei can probe lower masses

If the detector threshold is low enough!

Tutorial exercise

Signal channels



Challenges

Backgrounds (*low and well understood*)

- Sources: surrounding radioisotopes, cosmic rays, solar neutrinos
- Mitigations: screen materials, clean, shield, put deep underground, discrimination techniques
- Scale: ~event/kg/day

Threshold (*low*)

- Scale: typically ~keV
- Determines minimum DM mass probed (*requirements – see tutorial problem*)

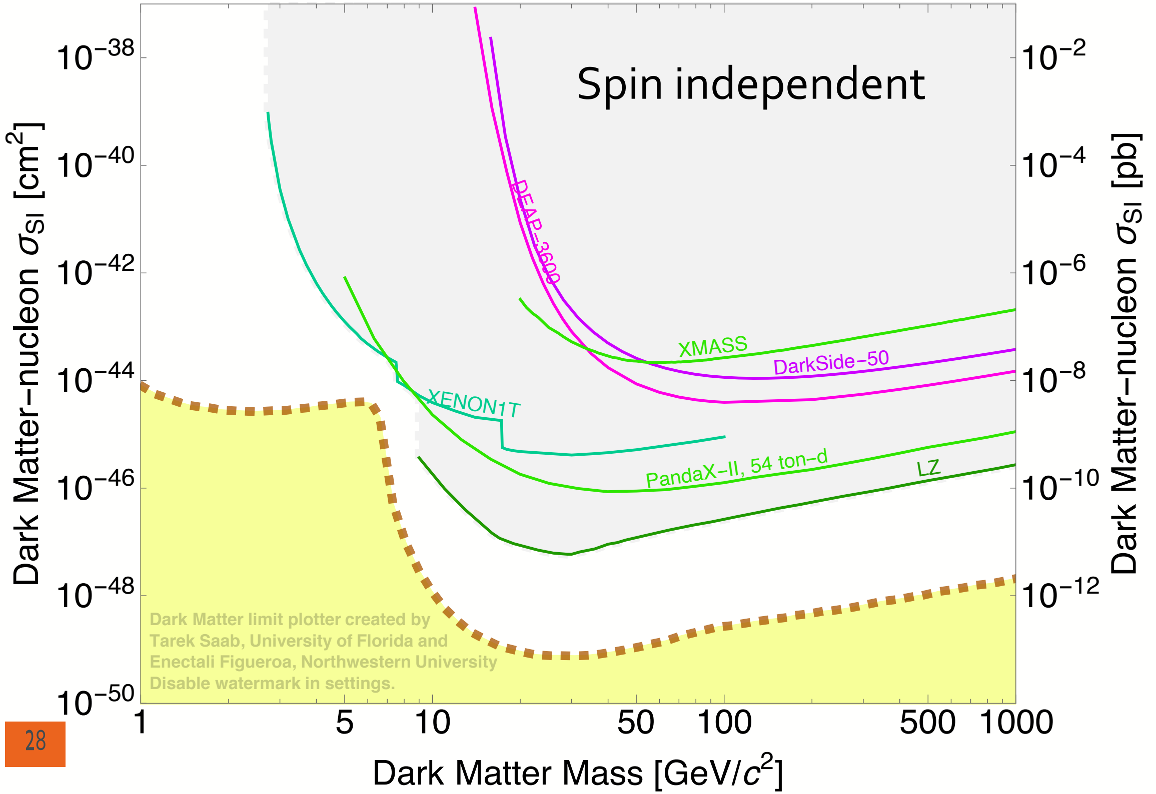
Exposure (*high*)

- Determines lowest cross section sensitive to

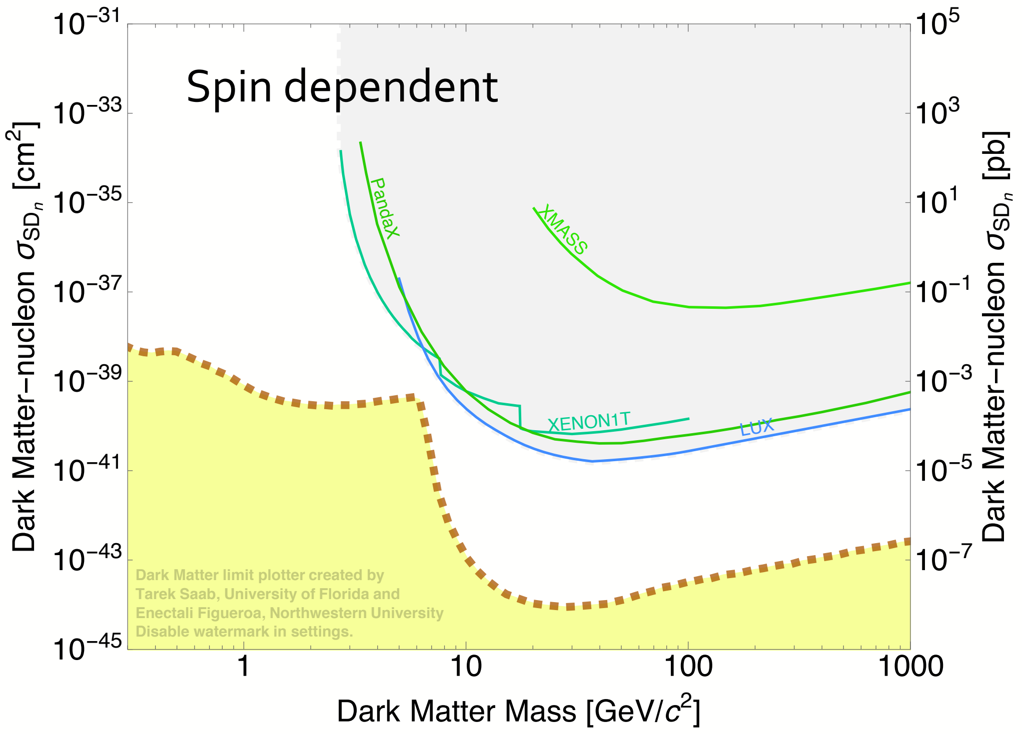
Direct detection landscape

Several decades focussed on 10-100 GeV WIMP dark matter. Noble liquids dominate.

- Single or dual phase, Xe and Ar
- Standard NR search down to ~6GeV, best sensitivity ~30GeV



LZ – 2022 60 days x 5.5tonne fiducial volume (arxiv.:2207.03764) . Run 2 ongoing.
XENON – 2019 279 days x 1.3 tonne fiducial (arxiv:1805.12562). Run with 5.9t ongoing.
DarkSide – 2018 532 days x 46 kg fiducial volume (arxiv:1802.07198). Commissioning 20 tonne version.



Sub GeV dark matter direct detection

Sub GeV dark matter motivation

Streetlight effect

Lots of expertise in 10-1000GeV WIMP searches

Dark matter might be elsewhere in parameter space...

How to detect lower masses

Kinematic matching: lighter target – smaller atomic mass $E_R \propto \frac{M_X}{M_N + M_X}$.

1 GeV DM on a 3 GeV target: $E_R \sim 0.3$ keV

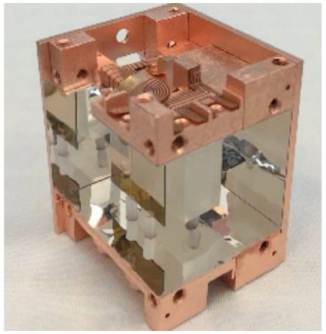
Lower energy **threshold** needed – main challenge

New analysis techniques and technologies:

- Ionisation only searches – liquid nobles, sub GeV search with NRs [e.g XENON1T, DarkSide50]
- Migdal effect – adds electromagnetic energy to event (due to instantaneous change in momentum of nucleus with respect to electron cloud) [Bernabei (2007)]
- Electron scattering – all materials
- New detector materials – use processes with low energy barrier
- Low noise readout – improve energy resolution

Current technology

CRESSTIII Phys. Rev. D 100, 102002 (2019)



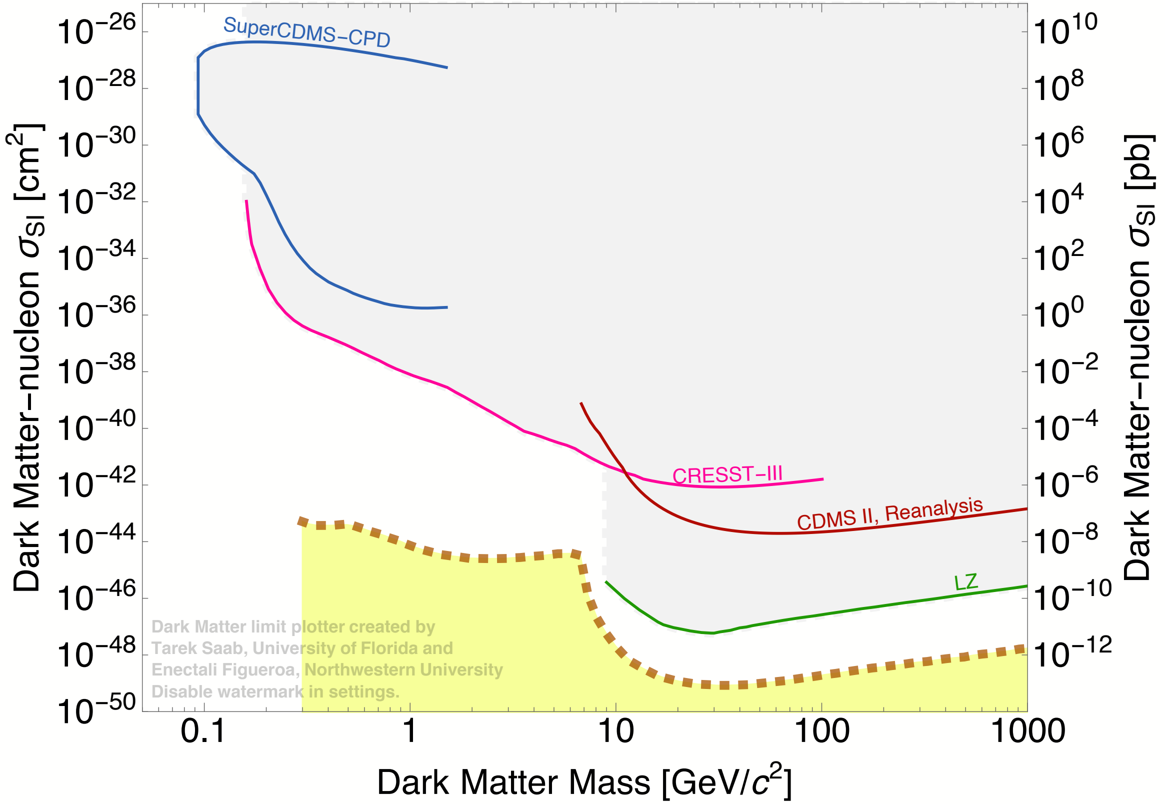
- Calcium tungstate scintillating bolometer (scintillation + phonon signal)
- 30 eV threshold

CDMSII Phys.Rev.Lett. 116 (2016) 071301

- Ge and Si crystals (ionisation + phonon signal)
- 5 keV threshold

SuperCDMS Phys. Rev. Lett. 127, 061801 (2021)

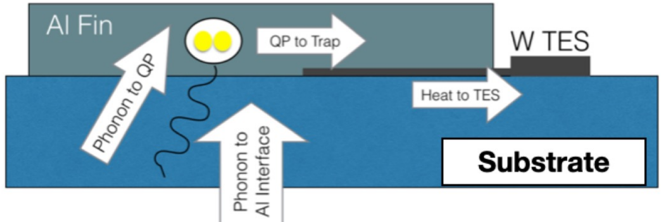
- Si crystal instrumented with QETs (Quasiparticle trap and TES)
- Short surface run 9.9 g days, 16.2 eV threshold



Recent developments: CDMS Phys. Rev. D 104, 032010 (2021)

- **9.2 eV threshold**

Lowest ever achieved for a macroscopic detector

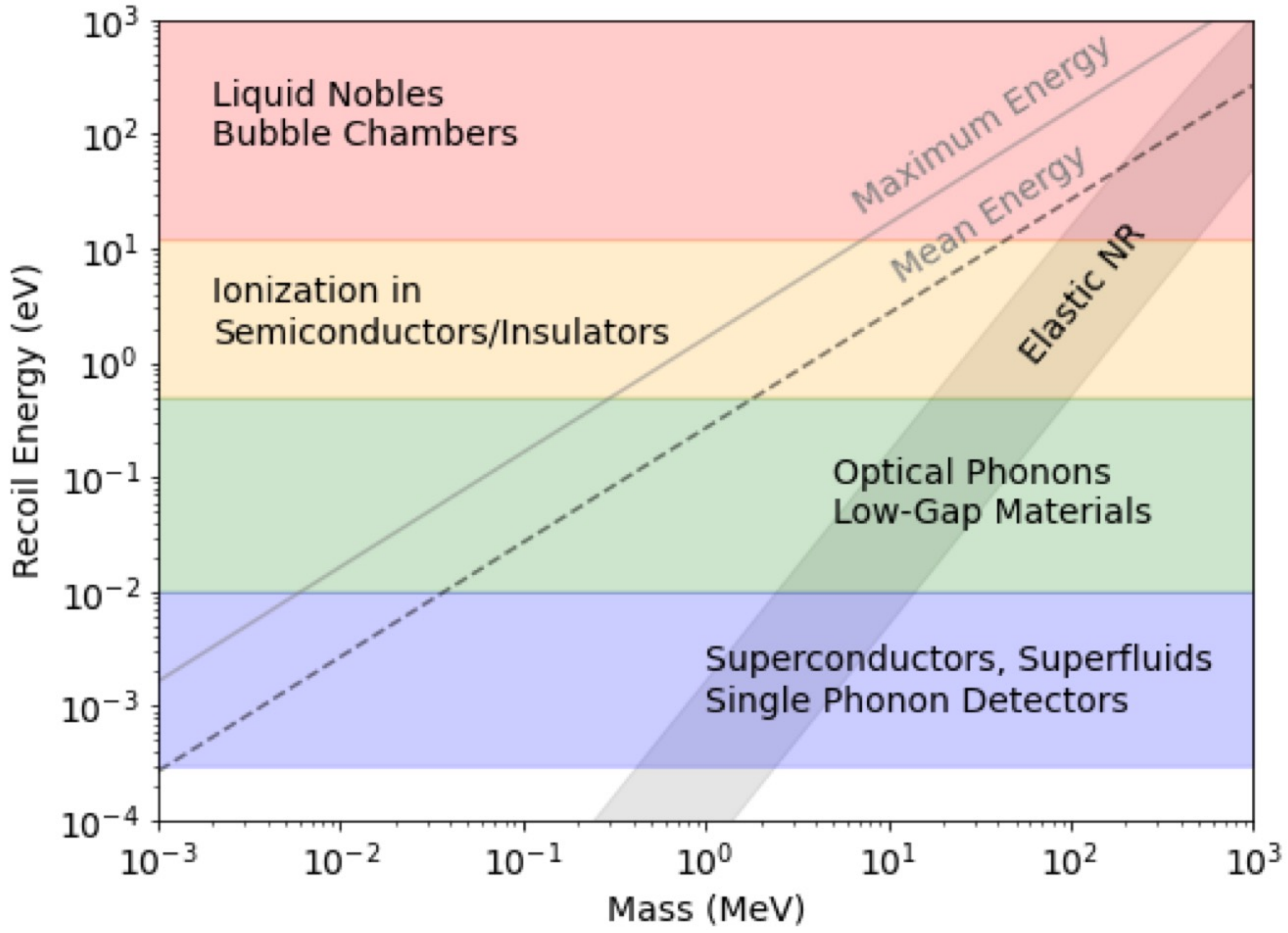


Going even lower

Fundamental threshold limits from physical process for quanta production:

- ~10eV Xe, Ar ionisation
- ~1eV semiconductor gap Ge, Si
- μeV – meV collective excitations doped semiconductors, superconductors, Dirac materials

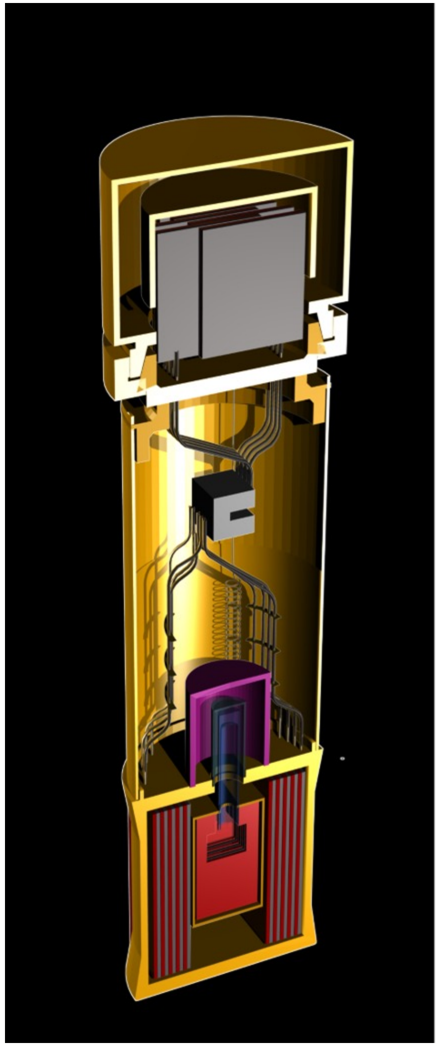
New proposals to bridge gap between DM scattering and resonant cavity experiments



Snowmass report 2022

QUEST-DMC

Low mass dark matter detector



Superfluid 3He bolometer – heat (quasiparticle) and scintillation light signals.

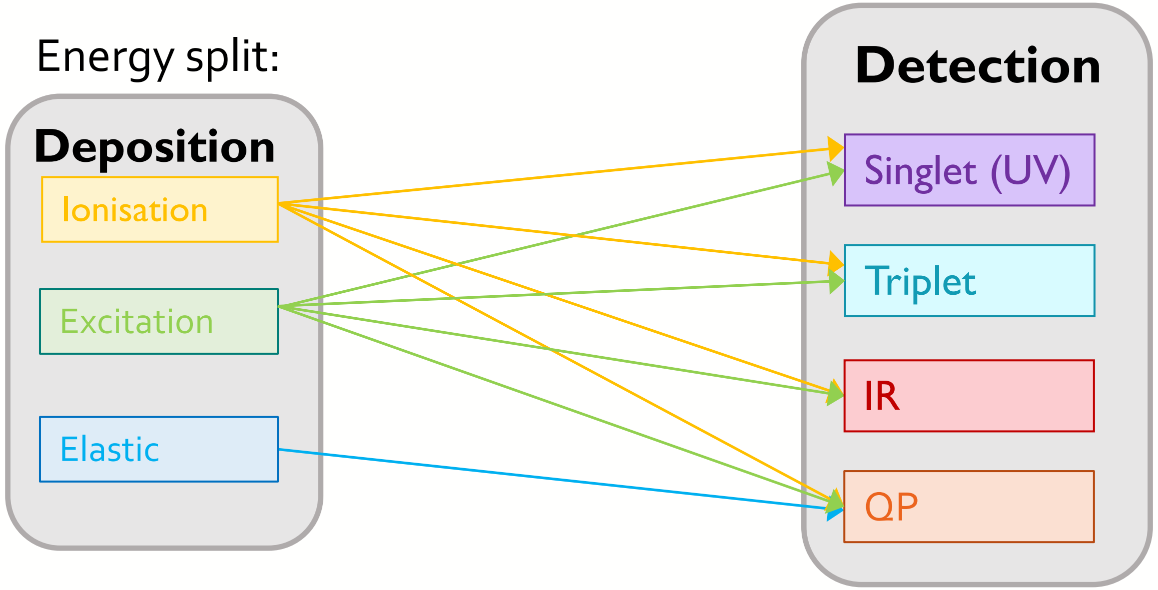
Advantages of 3He target:

- Light target
- Low threshold
- Unpaired nucleon – can do spin dependent search
- Intrinsically radiopure

See second QUEST lecture for more 3He physics…

Signal channels

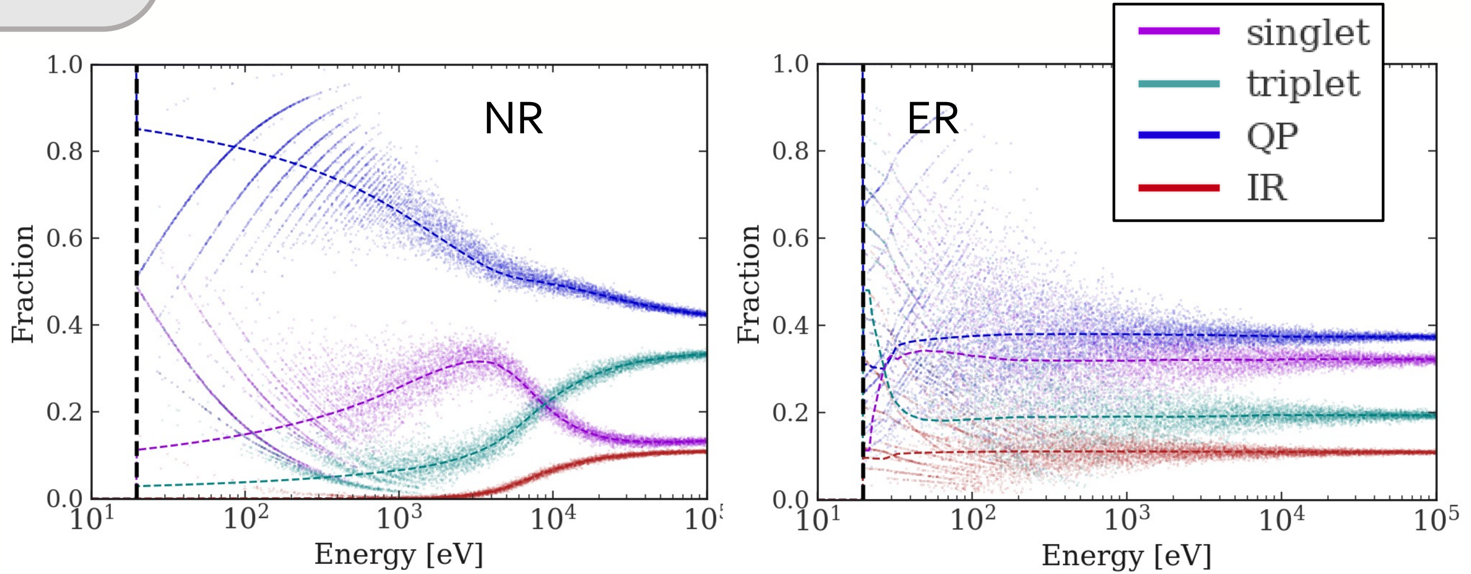
Energy split:



Photon detection –
SiPMs or PMTs

Quasiparticle detection – 3He bolometer O(100 uK) instrumented with vibrating nanowire resonators. Deposited energy determined from damping force on resonator.

Different ER/NR split allows discrimination.



Low threshold

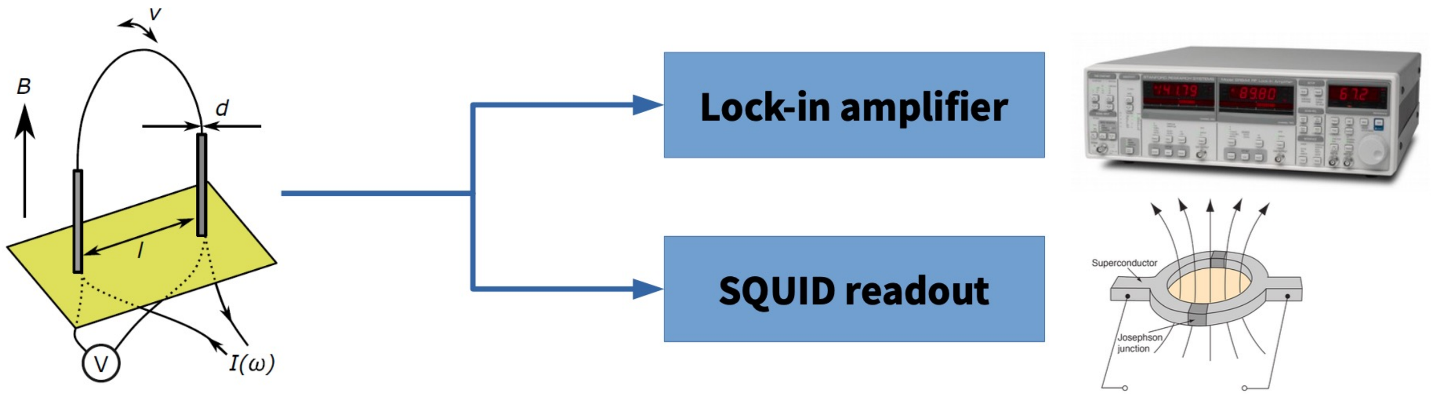
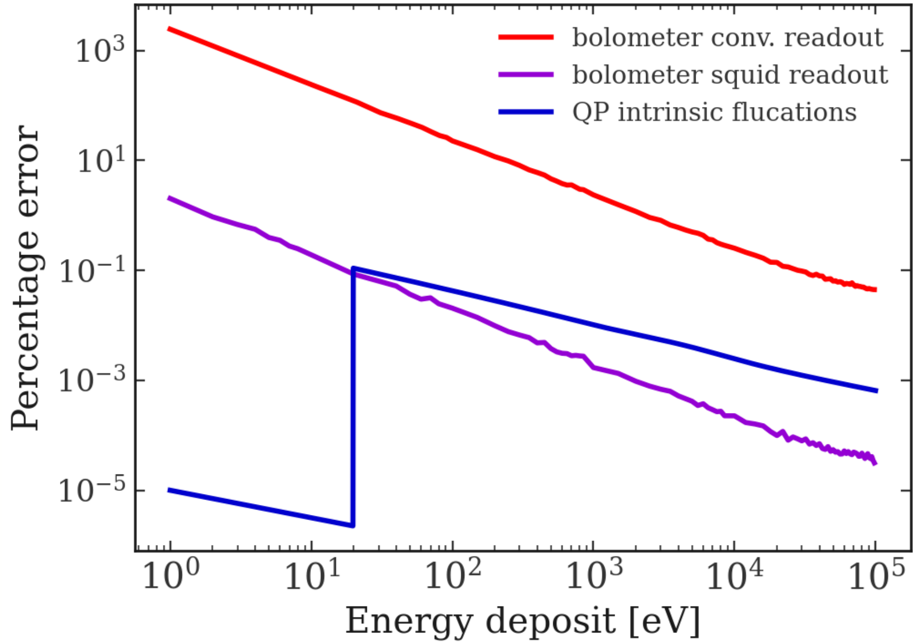


Image credit:
P Franchini

- Quasiparticle excitation energy all ~10^{-7} eV
- Threshold determined by detector resolution – intrinsic fluctuations in QP production and readout noise
- Nanowire readout using lockin amplifier or SQUID amplifier
- SQUID reduces energy uncertainty by factor ~10^{3}
- Allows sub eV threshold to be achieved (O(100)eV lockin and <1eV squid readout)

NR energy resolution

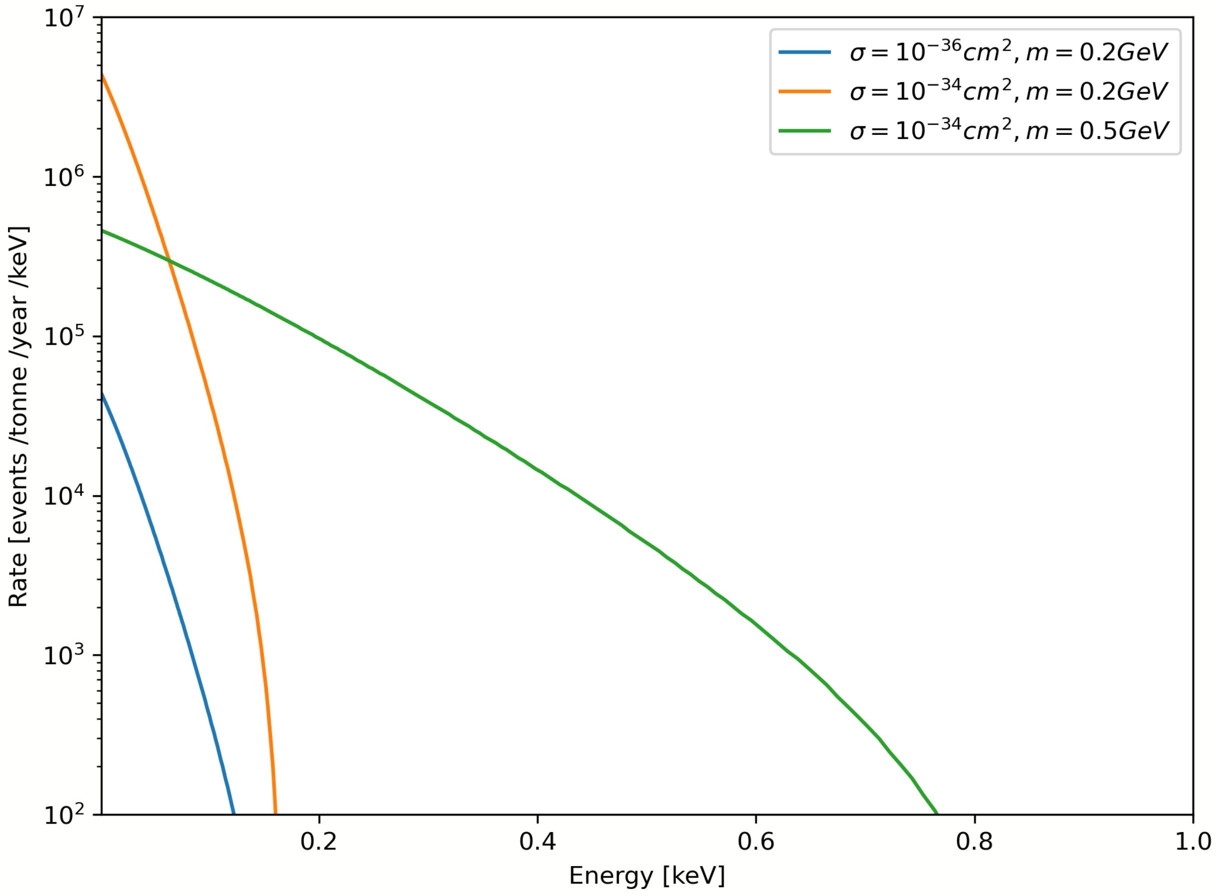


Dark matter signals

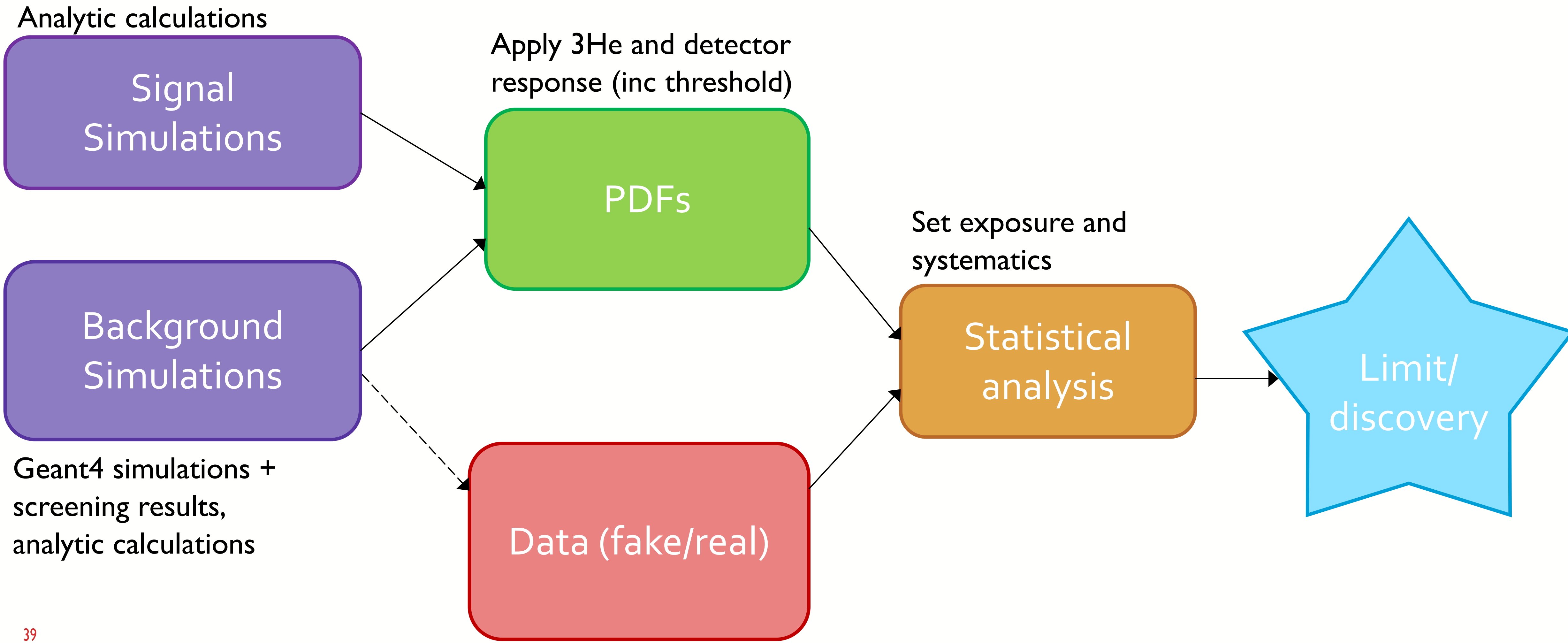
- Spin dependent WIMP
- Spin independent WIMP as a benchmark
- Electron absorption hidden photon and axion like particles
- Other possibilities later…

Signal spectra for SD WIMP interaction in 3He (with cross section

Compare to expected background rate of a few events/kg/day
(~10^5 events/tonne/year)



Limit setting



Future outlook

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Summary:

- Interest in dark matter searches beyond GeV scale WIMPs
- Need new technologies to bridge gap between GeV WIMP scattering and wavelike DM cavity searches.

- QUEST is on of many small scale experiments filling this gap, with a spin dependent advantage.
- Low threshold also means new parameter space can be probed for a range of interactions/models.
- World leading results possible with short exposures.

Useful references

TASI lecture series, feature DM each year: https://www.colorado.edu/physics/events/summer-intensive-programs/theoretical-advanced-study-institute-elementary-particle-physics (e.g. T. Lin 2019 https://arxiv.org/pdf/1904.07915.pdf)

T. Slatyer GGI Lectures Dark Matter: https://www.ggi.infn.it/ggilectures/ggilectures2018/program.html

STFC school, Diego Blas 2018:
https://conference.ippp.dur.ac.uk/event/785/attachments/3688/4159/Lectures_DM.pdf

J. Feng DM review: https://arxiv.org/pdf/1003.0904.pdf

M. Schuman direct detection review: https://arxiv.org/abs/1903.03026

J. Gascon cryogenic detectors talk:
https://indico.cern.ch/event/988708/contributions/4206747/attachments/2279028/3872048/ISAPP2021-CryogenicDetectors_compressed.pdf

Backup

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Freeze in production

Feebly interacting massive particles (FIMPs)

DM thermally decoupled and has negligible initial abundance

Rare interactions produce DM or a DM precursor (with abundance << equilibrium)

as T drops DM production increases

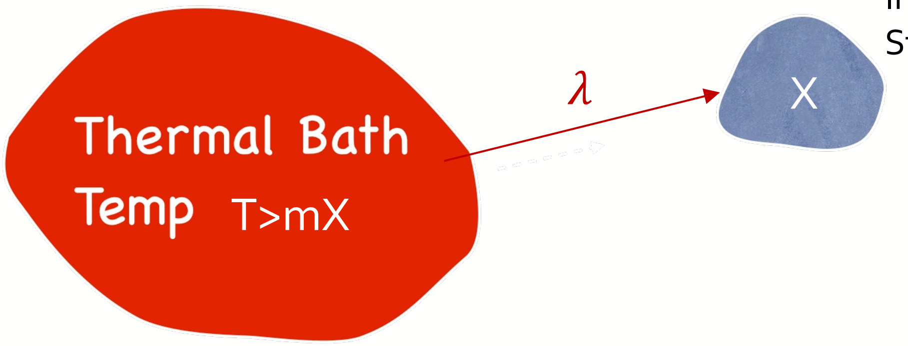
if the production rate rises with decreasing T, most DM will be produced by interactions occurring around T~m

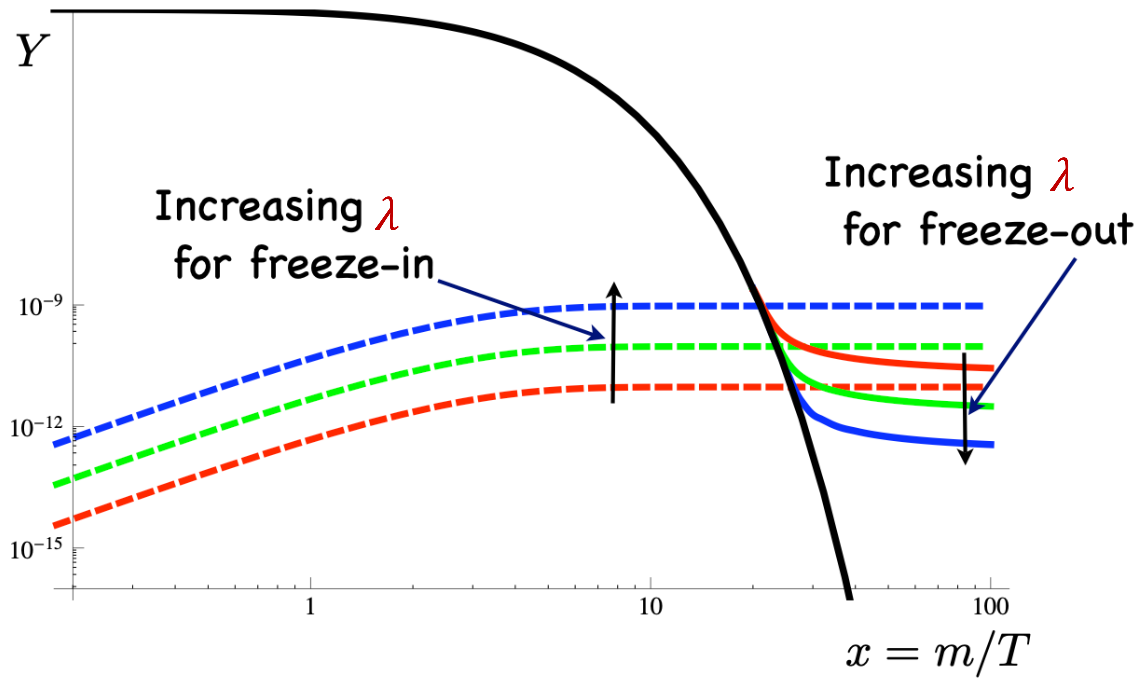
production cuts off when T < m, due to kinematic suppression

Higher interaction strength increases production from thermal bath (opposite to freeze out)

Hall, Jedamzik, March-Russell, West (2009)

Image credit: Stephen West





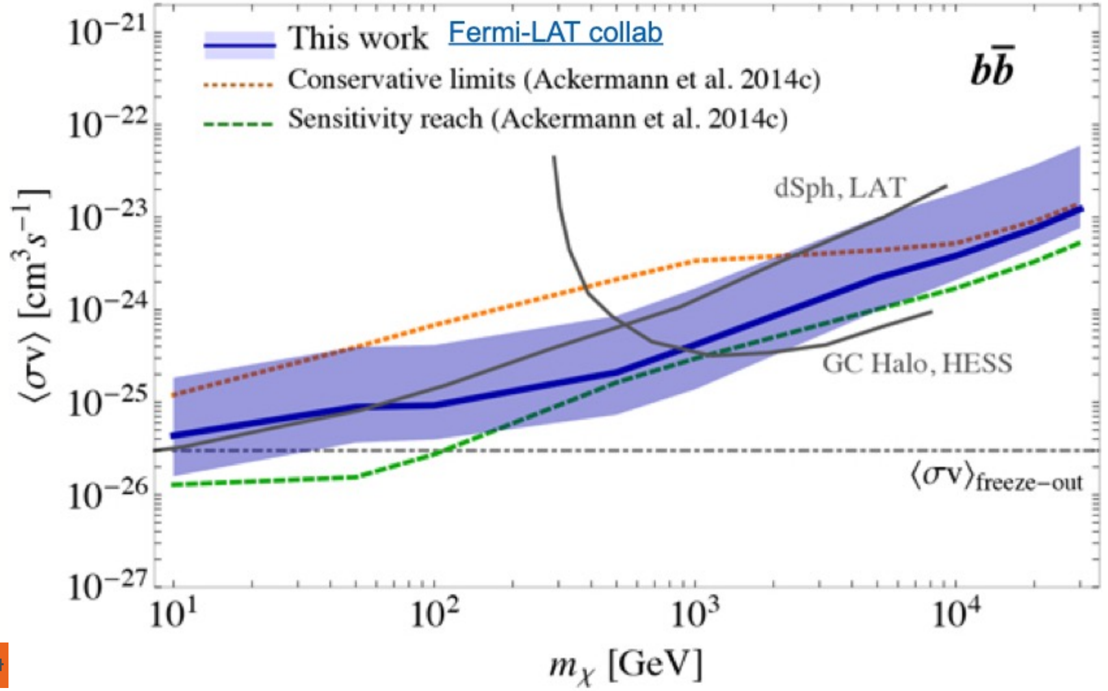
Indirect limits

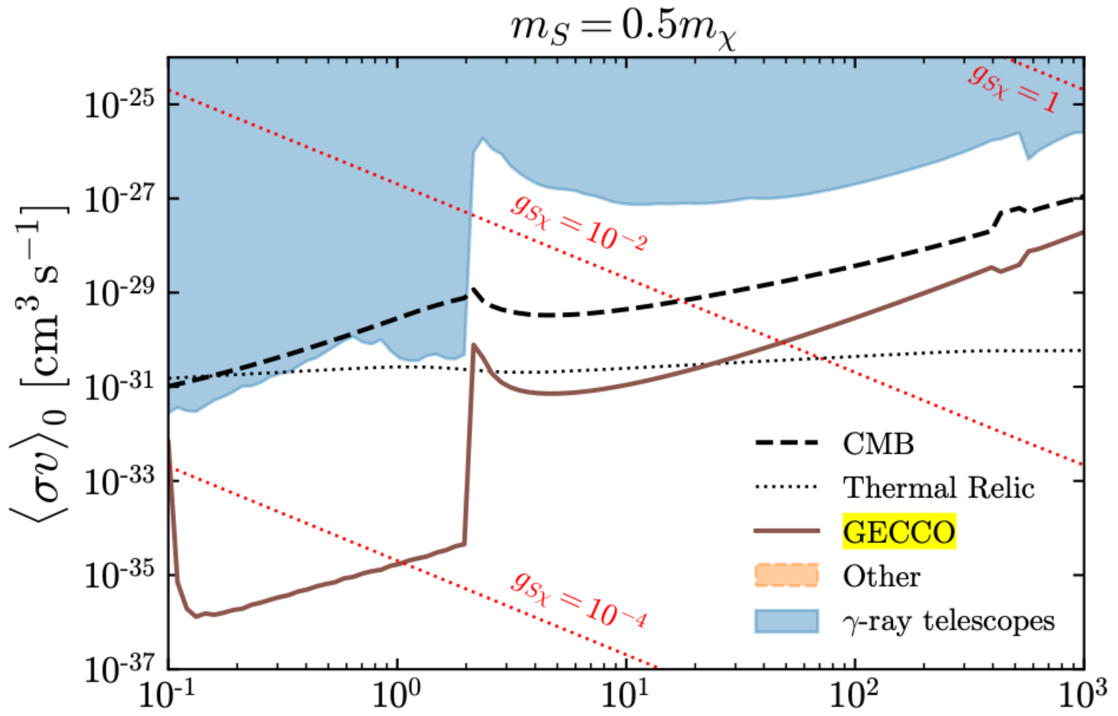
Use gamma ray/x-ray/neutrino telescopes to set limits

Model dependent annihilation signature

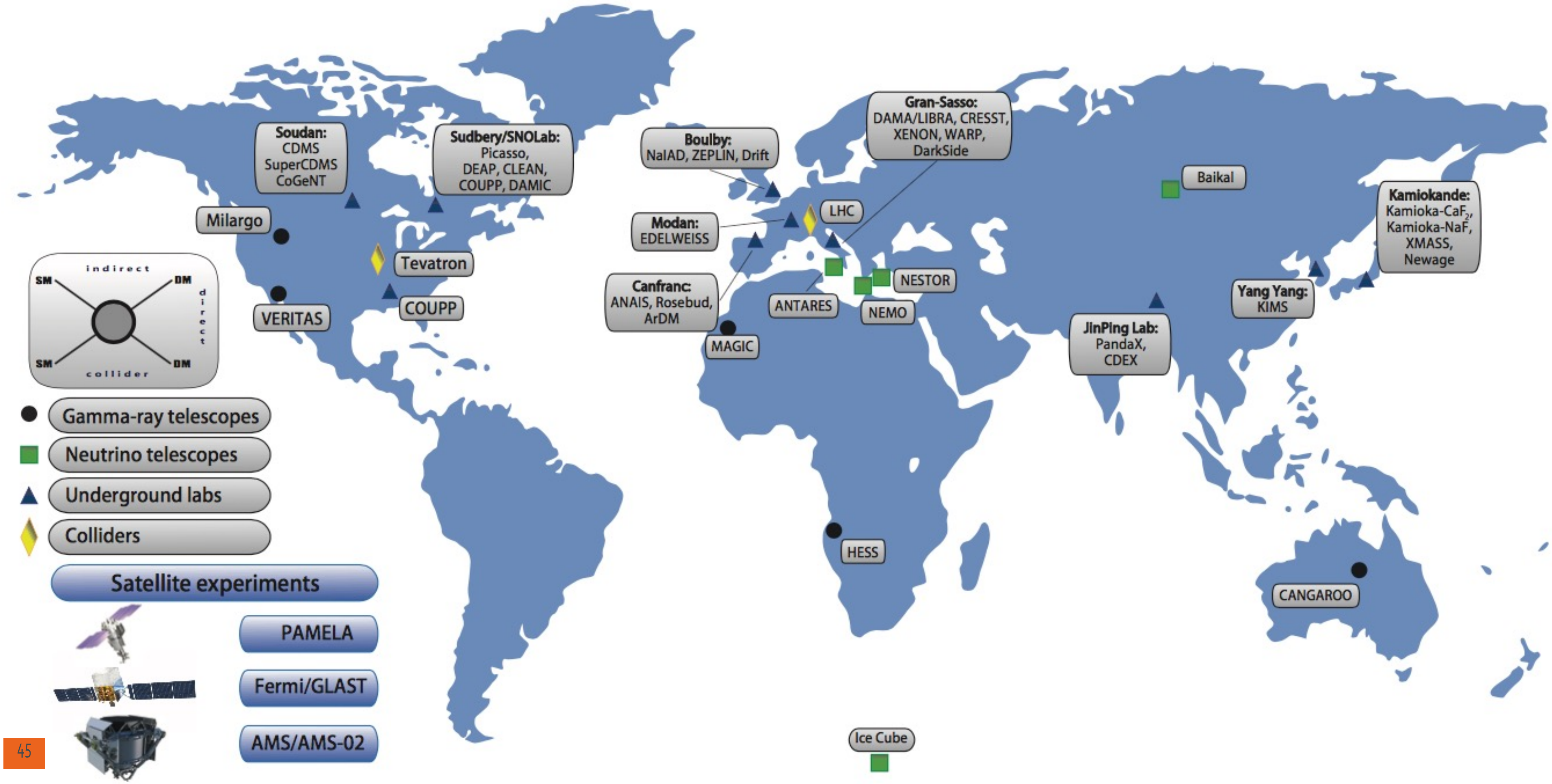
Many astrophysical backgrounds

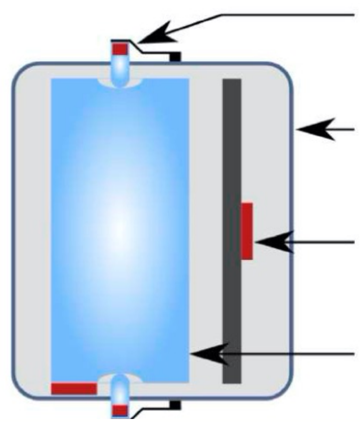
Fermi: https://arxiv.org/pdf/1503.02641.pdf





Global effort





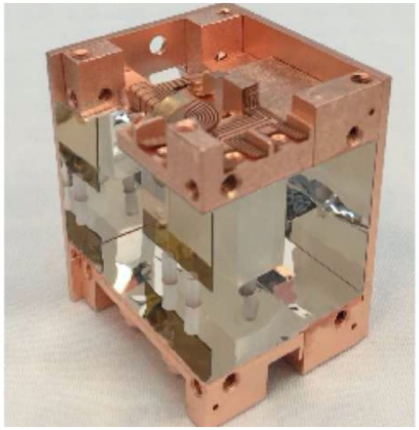
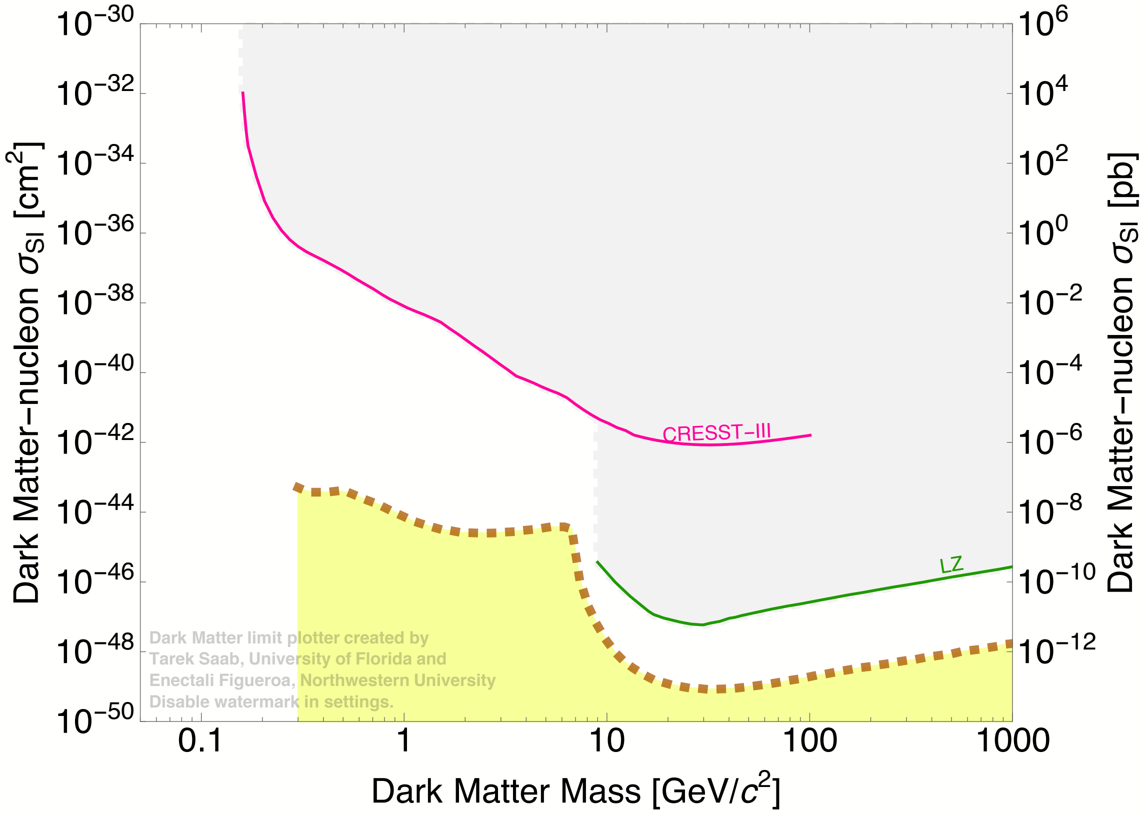


Image credit: Florian Reindl IDM 2018

CRESSTIII results: Phys. Rev. D 100, 102002 (2019)



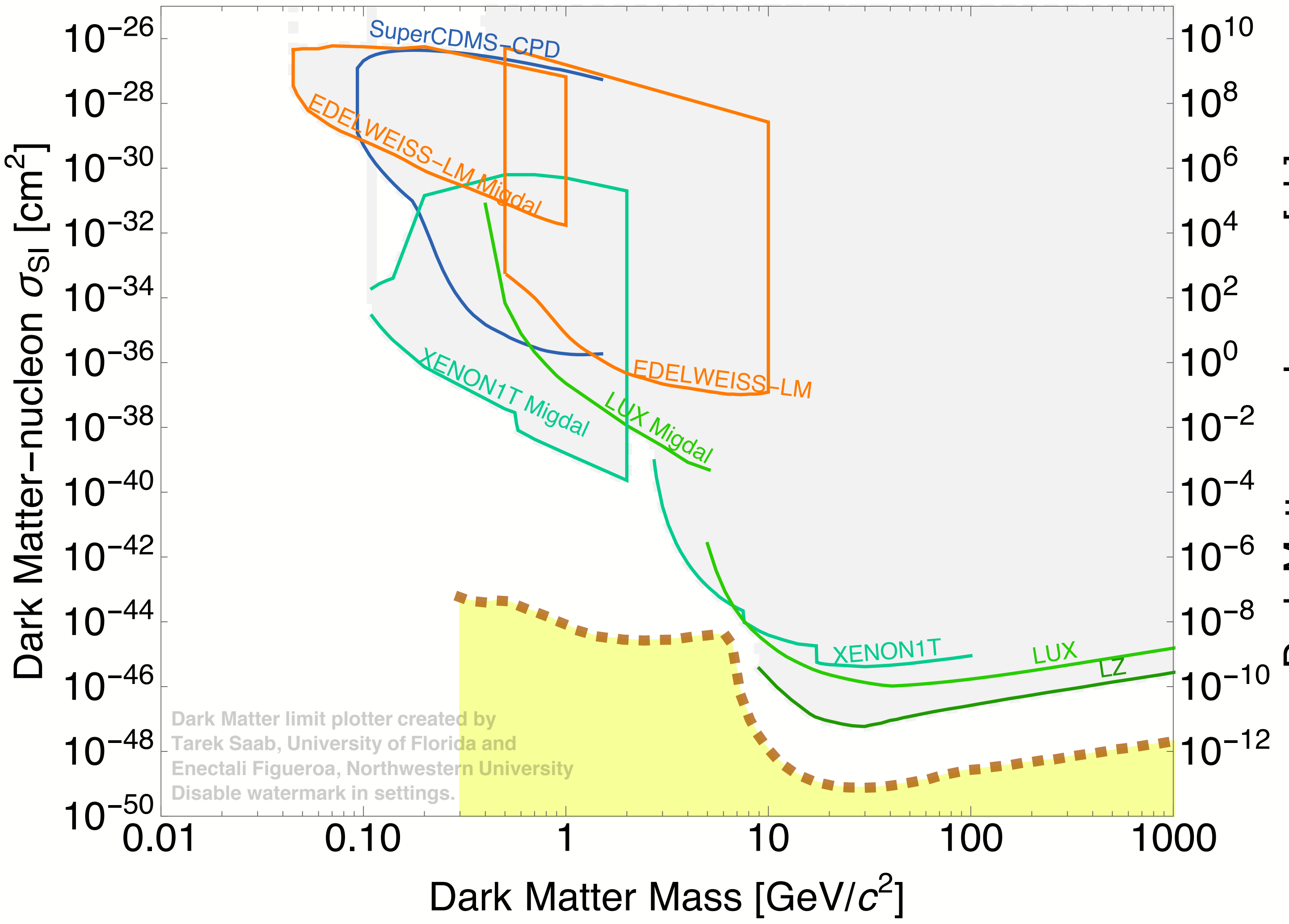
- Scintillating bolometers - calcium tungstate crystal operated at 15mK
- Phonon + scintillation signal acquired with TESs, readout using SQUID amplifiers
- 30 eV threshold
- 24g target x 152 live days (2016-18) -> 3.64 kg day exposure
- Probe DM masses down to 0.16 GeV

Migdal

Migdal effect adds electromagnetic energy to signal

- instantaneous change in momentum of nucleus with respect to electron cloud can cause ionisation/excitation of atomic electrons
- adds electromagnetic energy to the event
- pushes more events over threshold
- lower initial energy deposits (and therefore dark matter masses) can be detected

[references…]



Sub GeV spin dependent searches

- Ge: CDEX, EDELWEISS
- Bubble chamber: PICO