University of BRISTOL

Direct Dark Matter Detection

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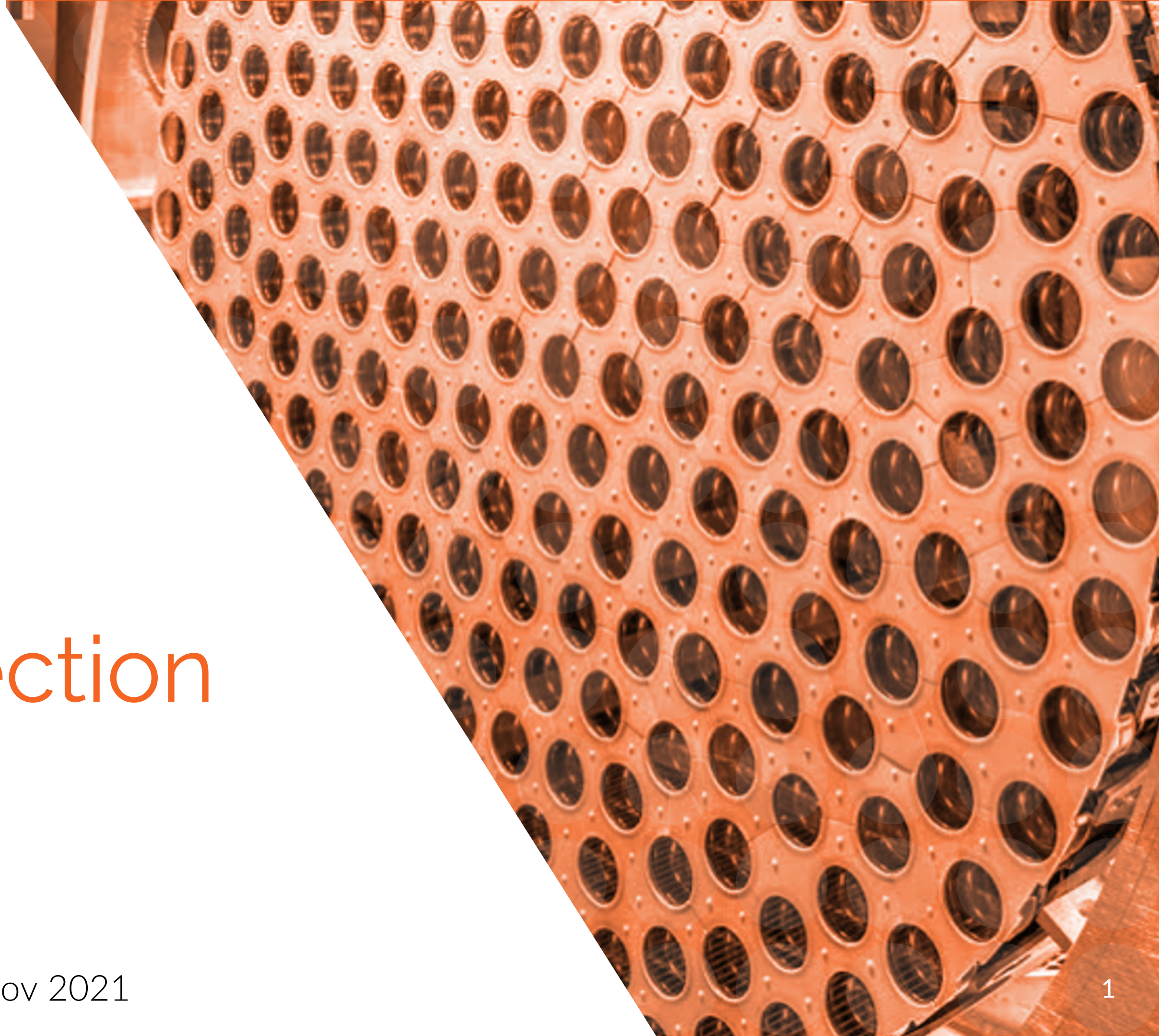
HUNTING SUSY @ HL-LHC, 25 Nov 2021



Starting point

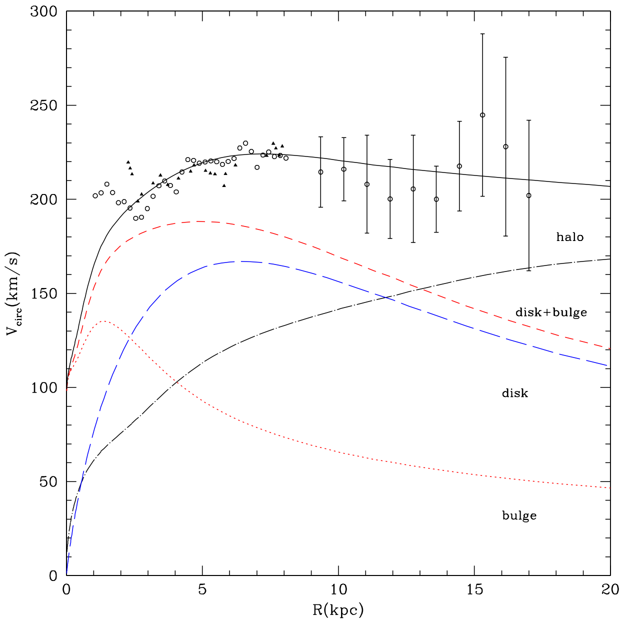
- How much dark matter is there? How is it distributed?
- How can dark matter interact?
  - Nuclei and electrons
- How large are these signals?

- How can we hope to detect such interactions?
  - Noble liquid detectors (LZ, XENONnT, PandaX-4T, Darkside-20k,...)
  - Solid state cryogenic detectors (CRESST, EDELWEISS, SuperCDMS,...)
  - Superheated liquids (PICO, MOSCAB)
  - Room temperature ionization detectors (DAMIC, SENSEI,...)
  - Room temperature scintillators (DAMA\LIBRA, COSINE,...)
  - ... and many more

Dark Matter velocity distribution

The Standard Halo Model (SHM)

Rotation curve of Milky Way



arXiv:astro-ph/0110390

The Dark Matter halo

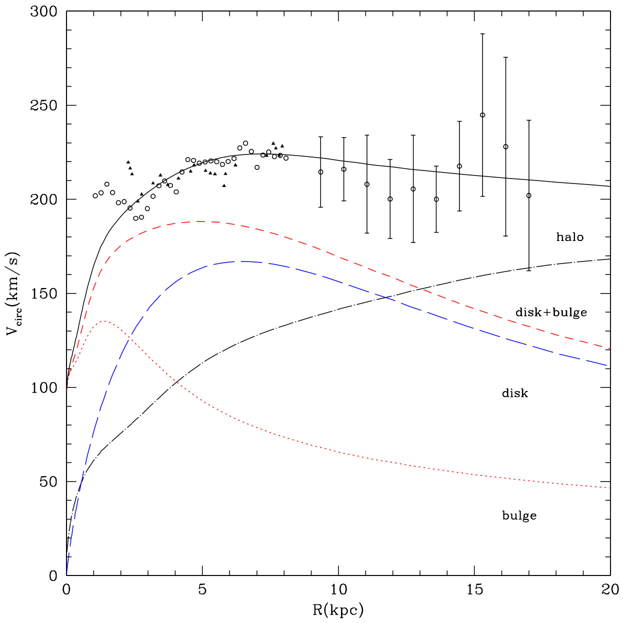
Not to scale!
Halo around
10 x size of
Milky Way

Luminous matter exists in a disc rotating at around 200 km/s.

Dark Matter velocity distribution

The Standard Halo Model (SHM)

Rotation curve of Milky Way



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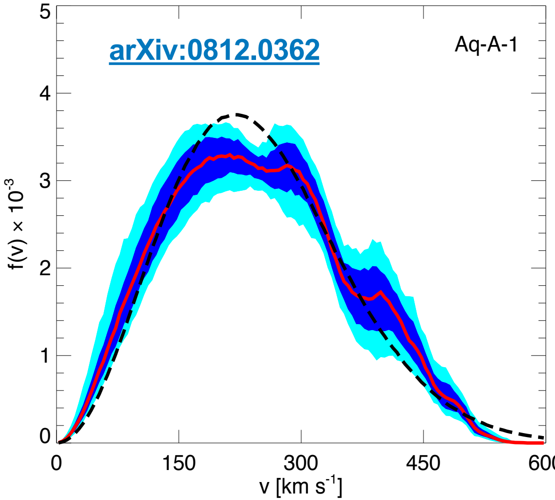
Local DM velocity distribution



- The standard parameter values used for the SHM are the following:

- local density

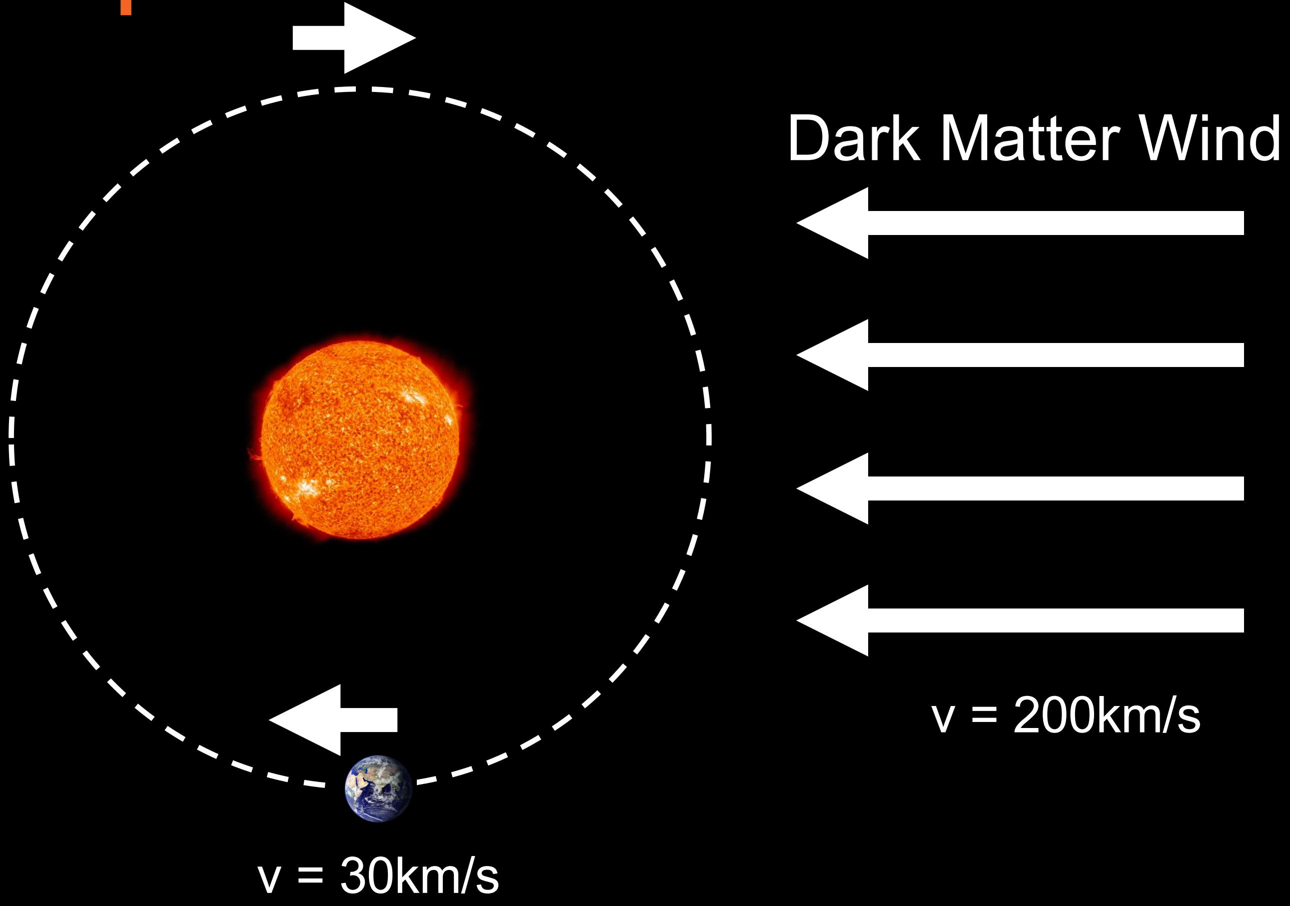
$$\rho_0 \equiv \rho(R_0) = 0.3\,\mathrm{GeV\,cm^{-3}}$$

$$\rho_0 = 0.008 M_\odot \mathrm{pc}^{-3} = 5 \times 10^{-25} \mathrm{g\,cm^{-3}}$$

- local circular speed

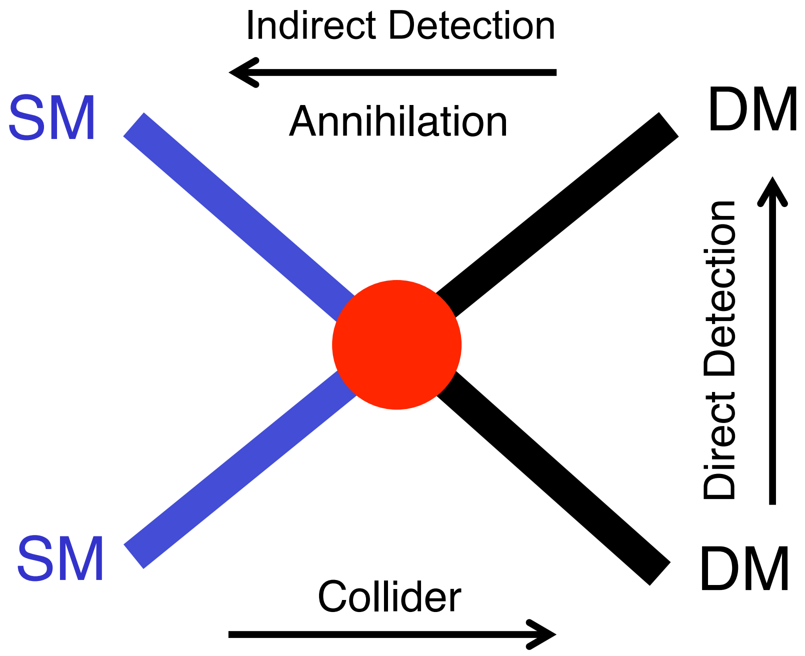
$$v_c = 220\,\mathrm{km\,s^{-1}}$$

From our point of view – a Dark Matter flux



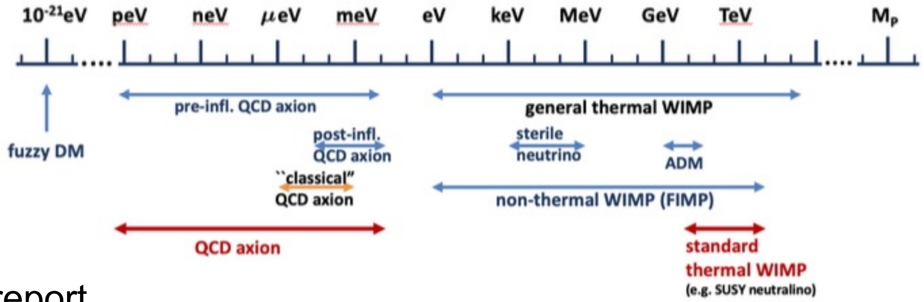
How to search for dark matter

- Scattering
  - Direct detection
- Annihilation
  - Indirect detection
- Production
  - Colliders

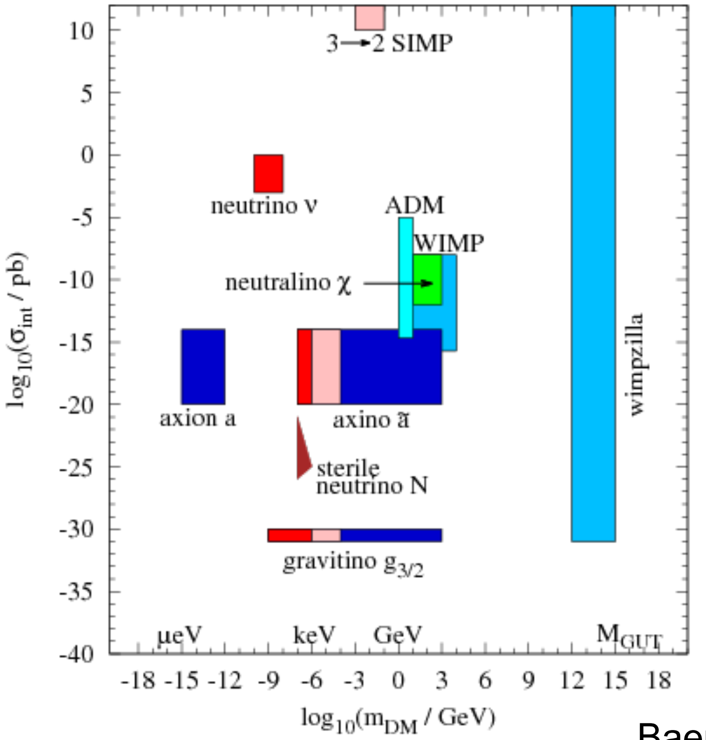


Proposed dark matter candidates

- WIMPs
- Axions and axion-like particles (ALPs)
- Dark Photons
- Sterile Neutrinos
- And many more (FIMP, SIMP, GIMP, PBH, etc. etc.)
- Spanning many many orders of magnitude in mass and interaction strength



APPEC report

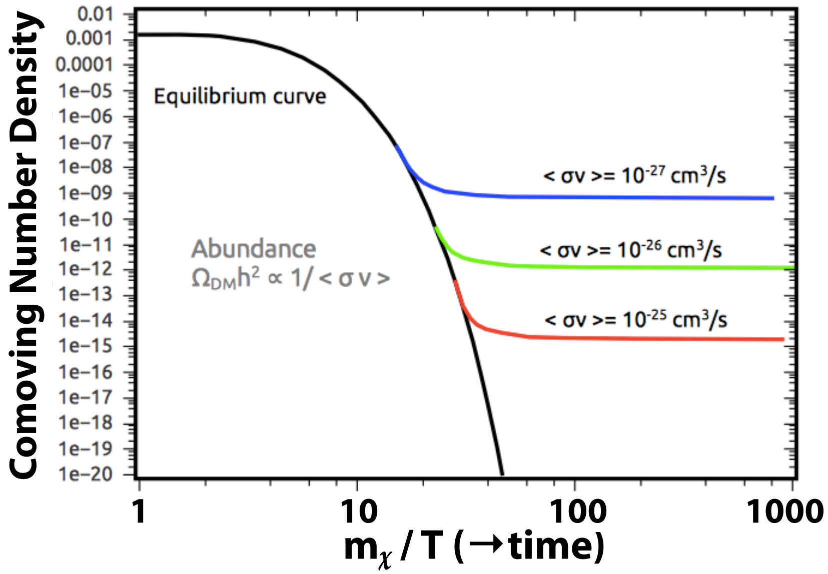


Baer

Let's focus on WIMPs

- Why WIMPs?
  - It's what you get in SUSY ;-)

- Assumption that in early universe DM was in thermal equilibrium with SM matter
  → some interaction with SM matter
- As universe expands and cools down, DM decouples
- DM abundance determined by annihilation cross section at freeze-out
- A particle with weak scale interactions and mass of O(100 GeV) gives relic density in agreement with our measurements
  → "WIMP miracle"



$$\Omega_\chi h^2 \simeq 0.1 \times \left(\frac{3\times10^{-26}cm^3s^{-1}}{\langle\sigma v\rangle}\right)$$

$$\langle\sigma v\rangle \sim 3\times10^{-26}cm^3s^{-1}$$
$$\sim \pi\alpha^2/(100\ \mathrm{GeV})^2$$

How much Dark Matter?

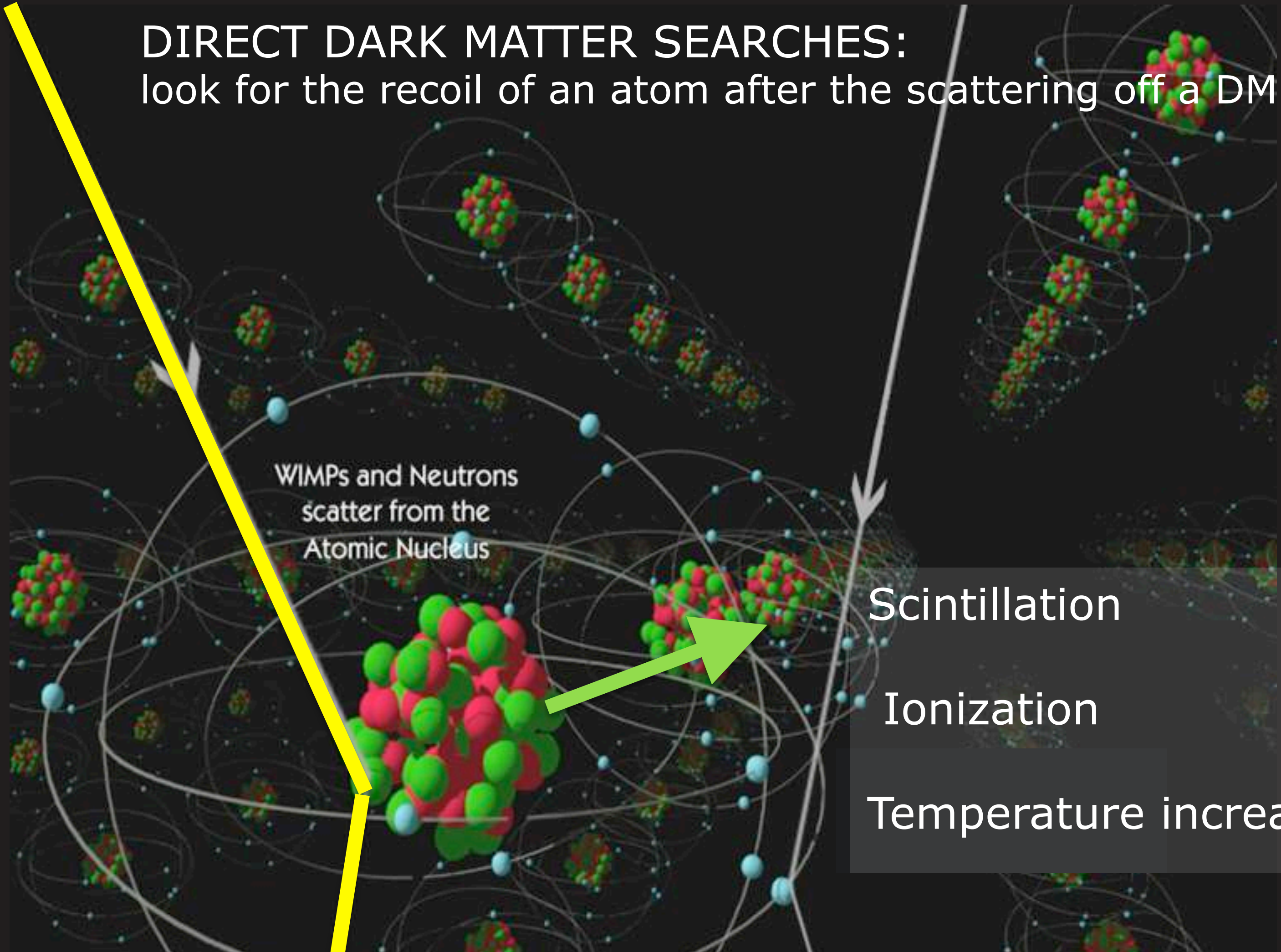
- Dark matter density is 0.3 GeV/cm^3
- i.e., if dark matter particle has mass of 100 GeV then

1 dark matter particle in every can of

Direct detection of Dark Matter

- If DM is a particle with a finite probability to scatter of SM particles...
- ... we are searching for interactions with nuclei (nuclear recoils) and electrons (electron recoils)
- Good sensitivity generally requires:
  - Large mass detector
  - Excellent suppression of similar signals from background sources

DIRECT DARK MATTER SEARCHES:
look for the recoil of an atom after the scattering off a DM particle

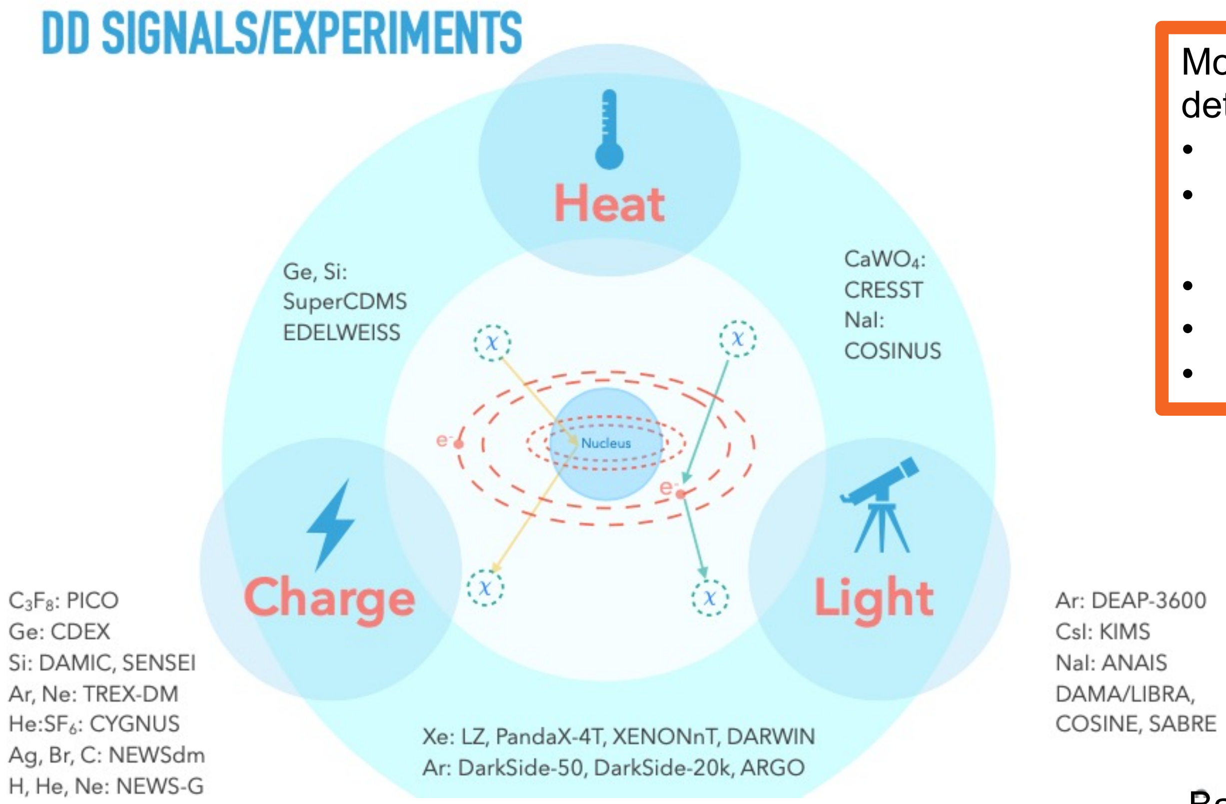


Scintillation

Ionization

Temperature increase

Experimental detection signals



Modern experiments are based on detecting two of these signals, e.g.:

- Liquid Nobel Gases:
- Scintillation & Ionization

- Cryogenic solid state detectors:
- Ionization and phonons
- Scintillation and phonons

Baudis

Experimental detection methods

- Scintillation light
- Ionization
- Phonons

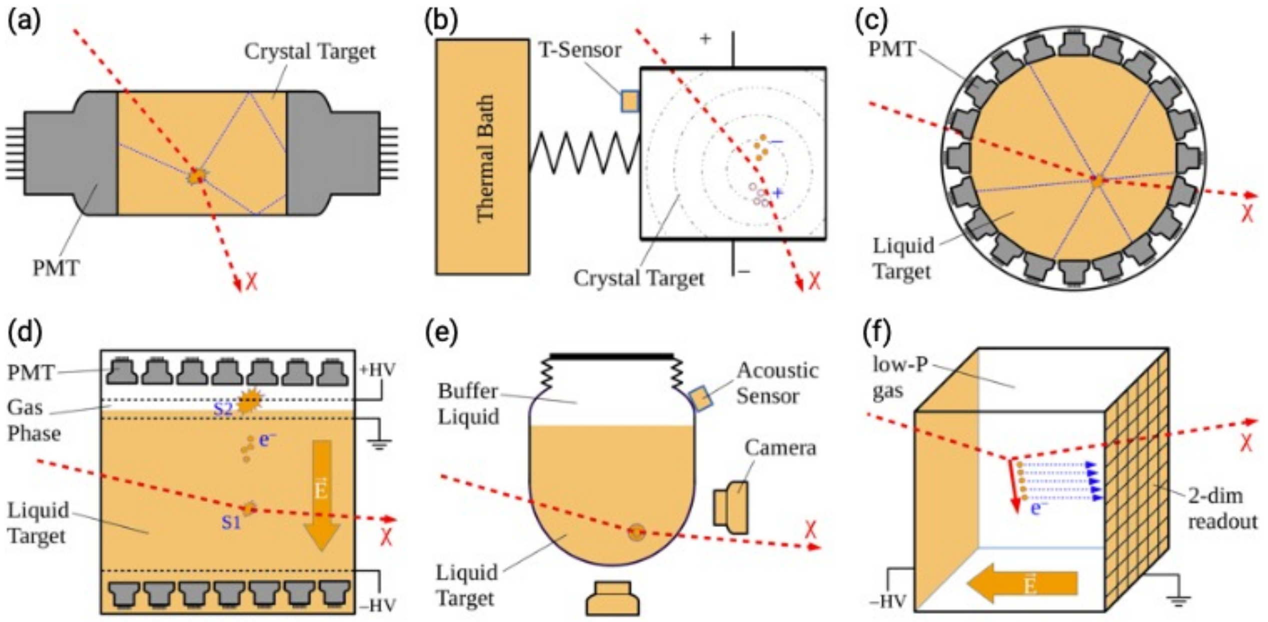
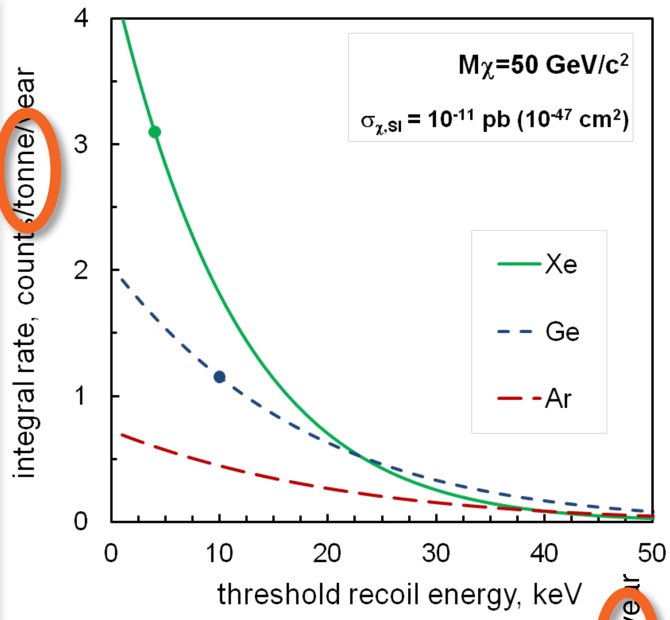


Figure 2: Working principle of common detector types for the direct WIMP search: (a) scintillating crystal, (b) bolometer (here with additional charge-readout), (c) single-phase and (d) dual-phase liquid noble gas detectors, (e) bubble chamber, (e) directional detector. Images adapted from [113].

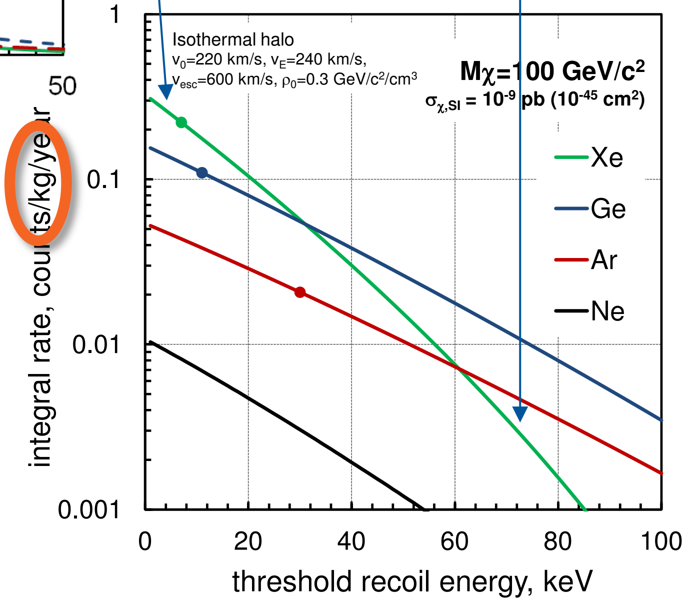
Energy transfer in scattering

- Signal rate strongly depends on achievable threshold recoil energy (and WIMP mass)
- Recoil of nucleus will result in ionisation
- These curves assume velocity distribution according to SHM



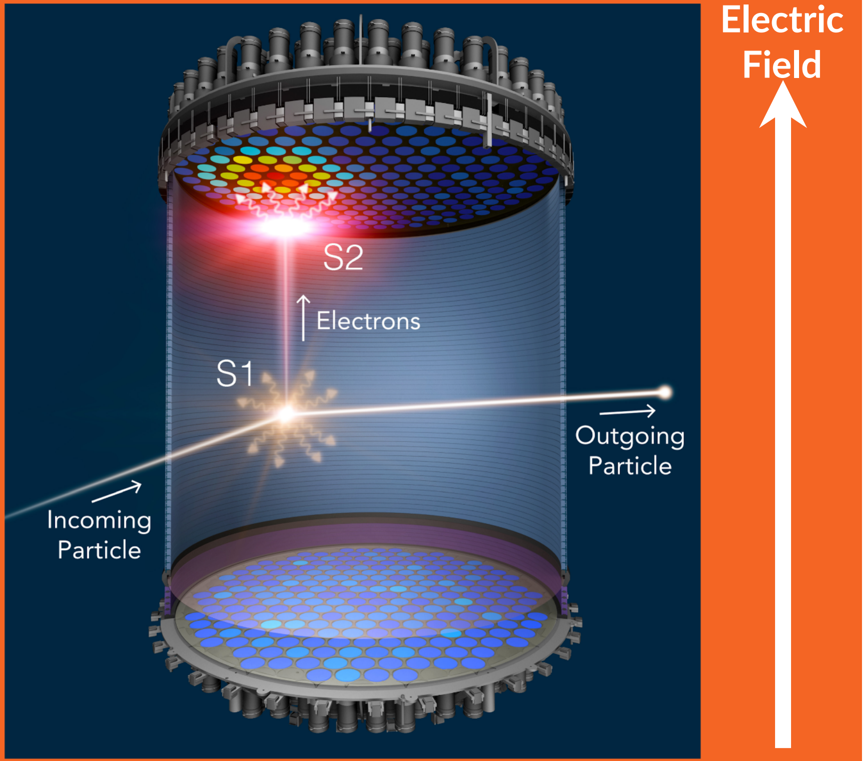
Rate increases with A^2

for large nuclei rate decreases at higher energies due to form factor suppression



Two-phase xenon TPC

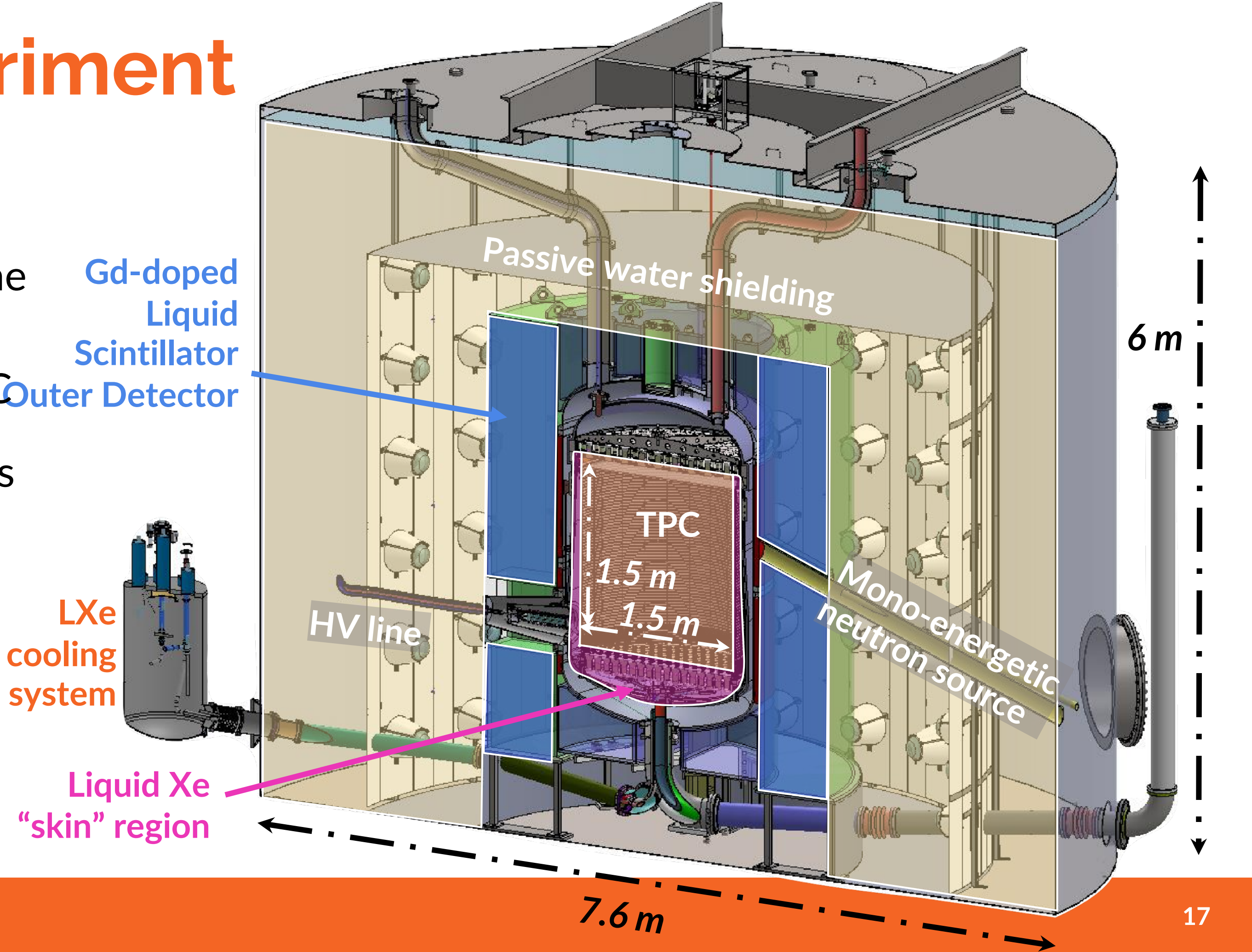
(LZ, XENONnT, PandaX)



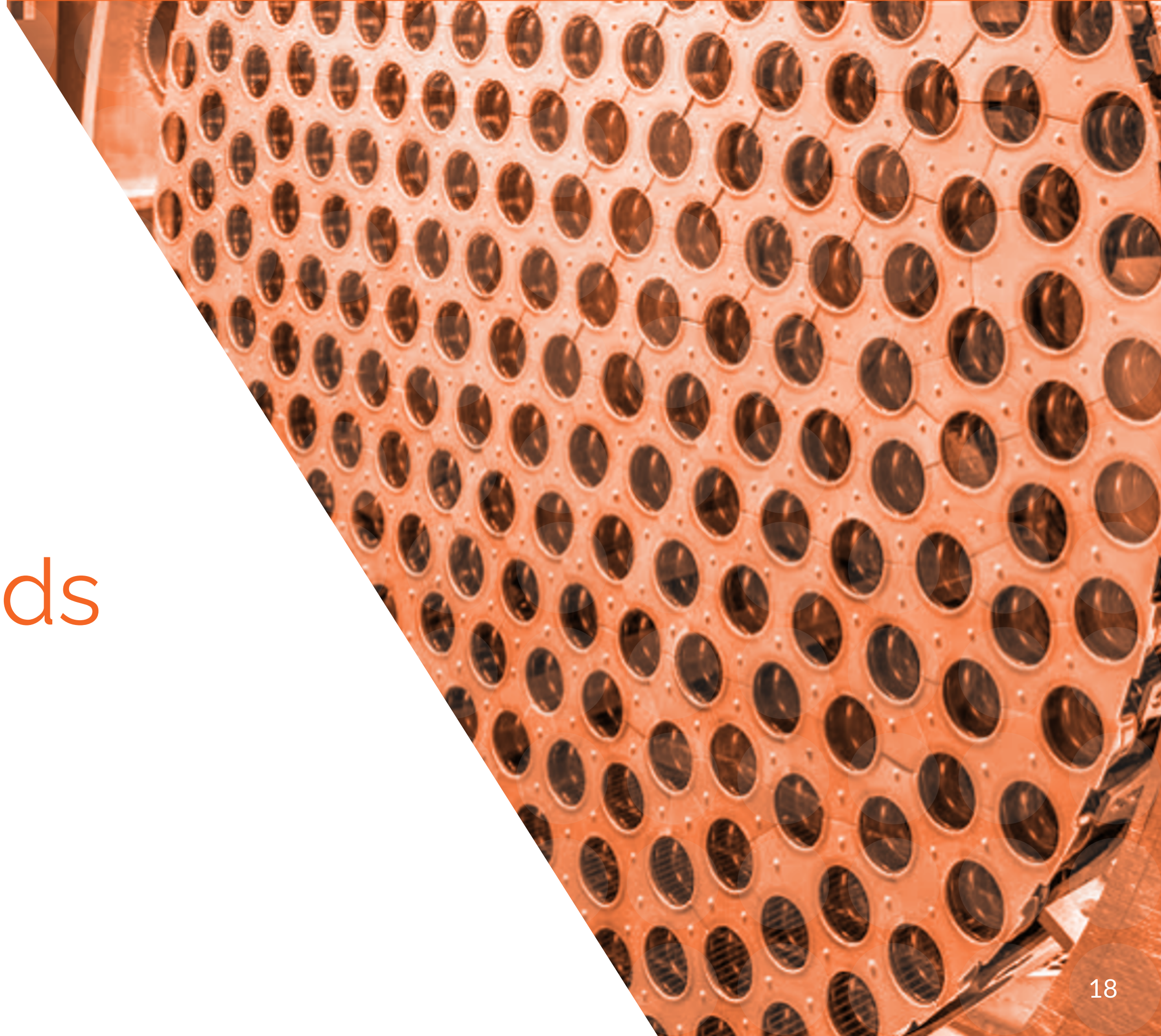
- Scattering off atom in liquid xenon
    - Recoil from nucleus (NR) or atomic electrons (ER)
- Produces light and free electrons / ions
    - Prompt light detected: "S1"
    - Electric field drifts electrons
- Charge reaches gas xenon
    - Amplification
    - Second delayed light: "S2"
- From S1 and S2:
    - Relative time: depth in detector
    - Transverse position
    - Type of interaction: ER vs NR
- Xenon naturally radio-pure

The LZ experiment

- Two-phase xenon TPC:
  - 7 tons liquid xenon
  - 5.6 t of fiducial volume
  - 50 kV cathode
  - 494 x 3” PMTs in TPC
- Veto and shield systems
  - LXe skin
  - Gd doped liquid scintillator in Outer Detector
  - Water Tank
- ~1.6km underground



Backgrounds and Sensitivity



Sources of Background

- External sources
  - Cosmogenics
  - Radiation from experiment cavern
  - Other new physics (e.g. neutrinos)
- Internal sources
  - Radioactive materials in detector components
  - Emanation of Radon from detector components
  - Radioactive dust on surfaces
  - Contaminants in the xenon

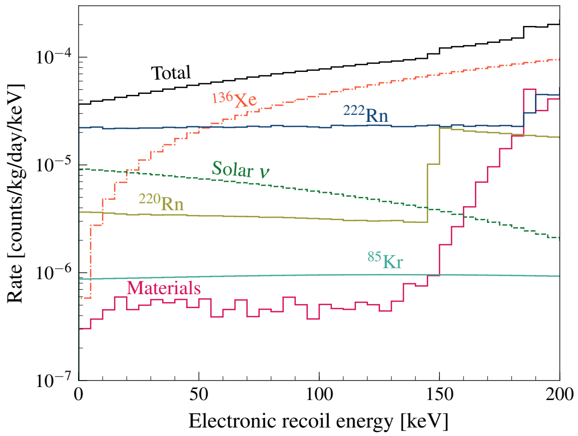
Backgrounds, backgrounds, backgrounds...

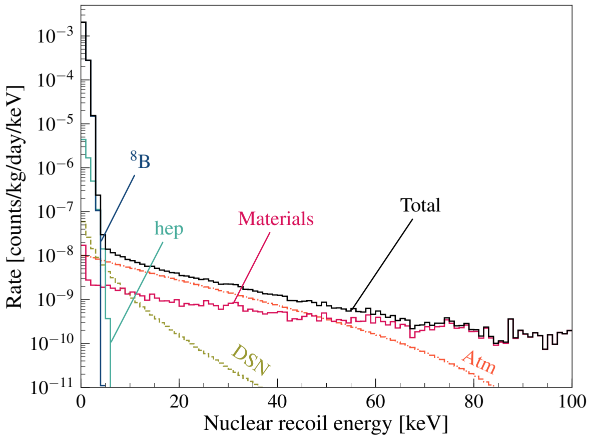
- External backgrounds mainly gammas and neutrons but also some neutrinos

- Intrinsic radioactivity in LXe (beta decay of ^{214}Pb, ^{212}Pb, ^{85}Kr)
    - Xenon filtering: 1 Krypton atom per 100 trillion Xenon atoms

- Solar neutrino scattering off atomic electrons
- Solar and atmospheric neutrino coherent nuclear scattering

- Veto detectors:
    - LXe skin region to reject gammas
    - Outer detector (GdLS) for tagging neutrons
    - Water tank to suppress natural radiation from surrounding rocks





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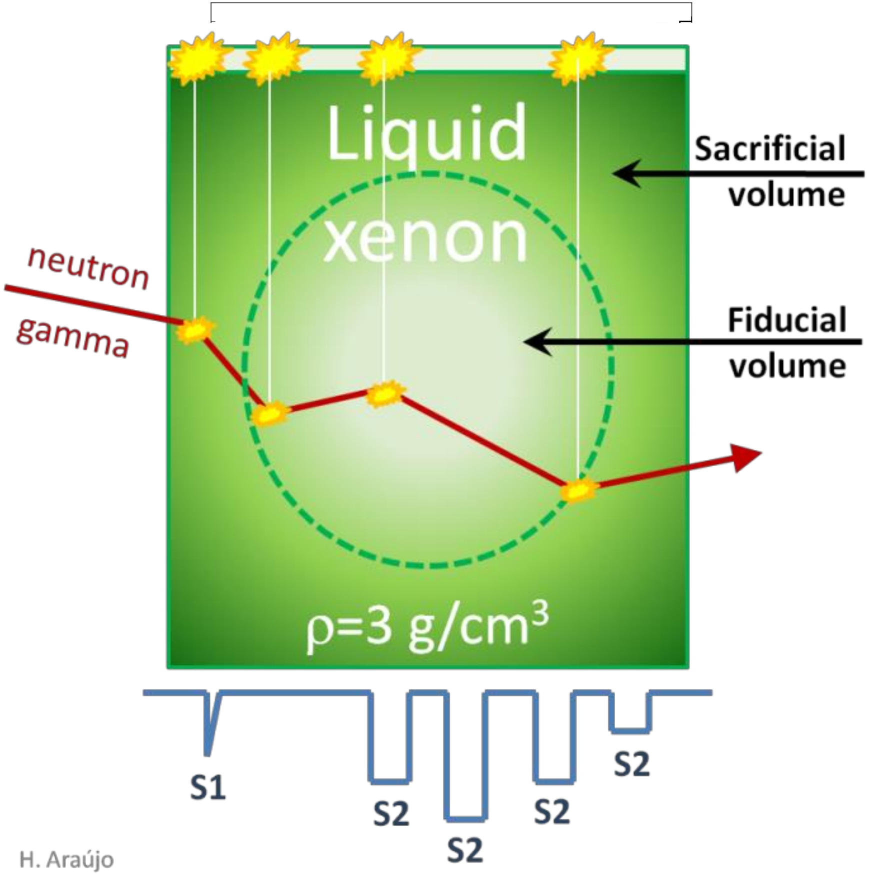
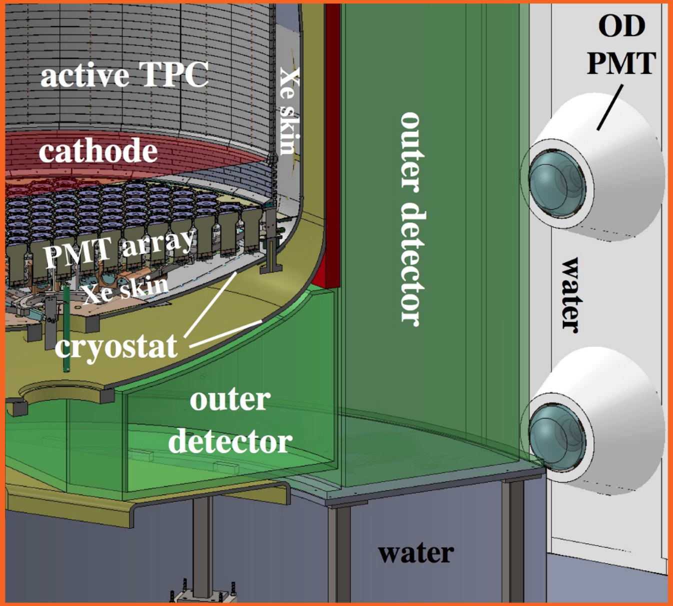
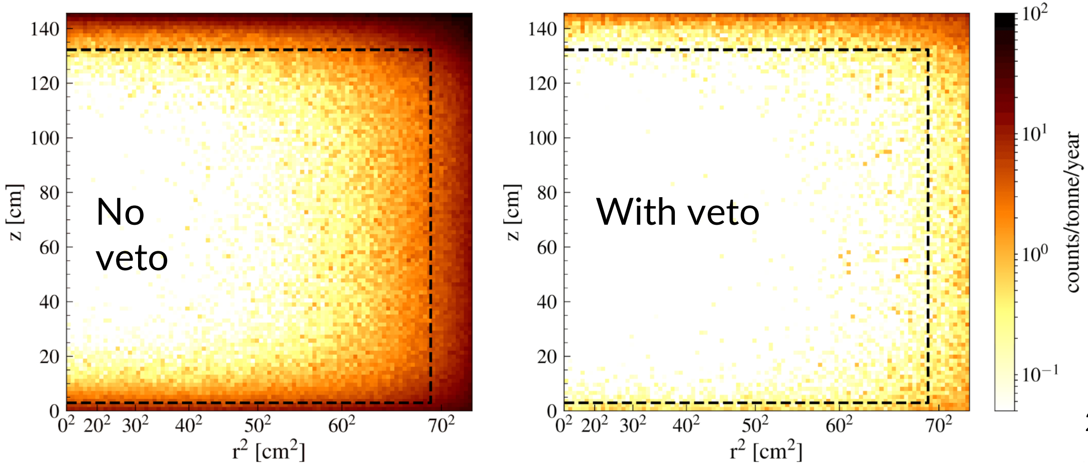


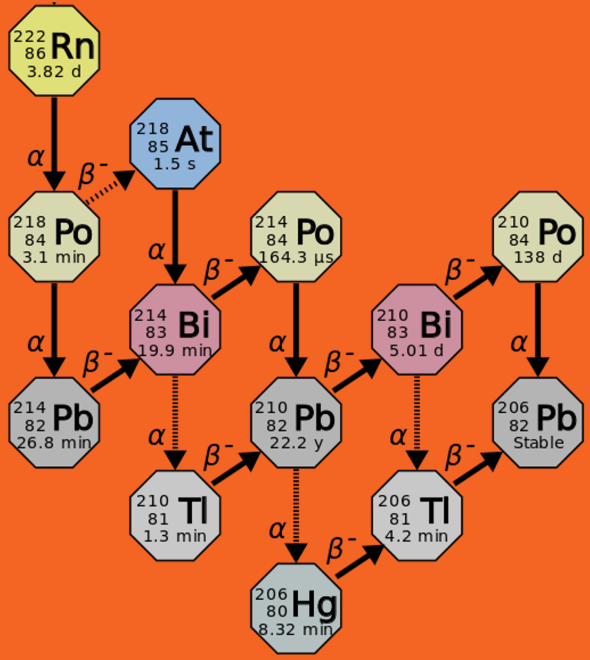
Mitigating External Backgrounds



- Go deep underground
  - 4300 m.w.e. underground at SURF in Lead, SD
  - Measure rock backgrounds: [ArXiv:1904.02112](https://arxiv.org/abs/1904.02112)
- Add three layers of outer shields:
  - Instrumented xenon skin around TPC
    ⇒ gamma ray scatters
  - Gadolinium-doped liquid scintillator tank
    ⇒ neutron tagging
  - Passive high-purity water



Mitigating Internal Backgrounds



- **Detector materials**
  - Radio-assay campaign
  - Gamma-screening, ICPMS, NAA
  - Screening Gd-LS: ArXiv: 1808.05595
- **Radon emanation**
  - Four screening sites and two portable assays
  - Target Rn activity: 2 µBq/kg
  - Rn removal system: reduces Rn from warm components by > x10: doi:10.1016/j.nima.2018.06.076
- **Radon daughters and dust on surfaces**
  - TPC assembly in Rn-reduced cleanroom
  - Dust < 500 ng/cm^3 on all LXe wetted surfaces
  - Rn-daughter plate-out on TPC walls < 0.5 mBq/m^2
- **Xenon contaminants – ^{85}Kr, ^{39}Ar**
  - Charcoal chromatography @ SLAC
  - Final ^{nat}Kr/Xe 0.015 ppt

Total backgrounds

- Assumes 1000 live days (full LZ run)
- Radon in the xenon dominates ER counts
- Coherent atmospheric neutrino scattering dominates NR
- Sub-dominant NR backgrounds
  - Alpha-n on PTFE from Pb-210
  - Ions reconstructed in fiducial volume

Background source	ER counts	NR counts
Detector Components	9	0.07
Surface contamination	40	0.39
Xenon Contamination	819	0
Laboratory and cosmogenics	5	0.06
Physics	322	0.51
Total	1195	1.03
Total after 99.5% ER rejection and 50% NR efficiency	5.97	0.52

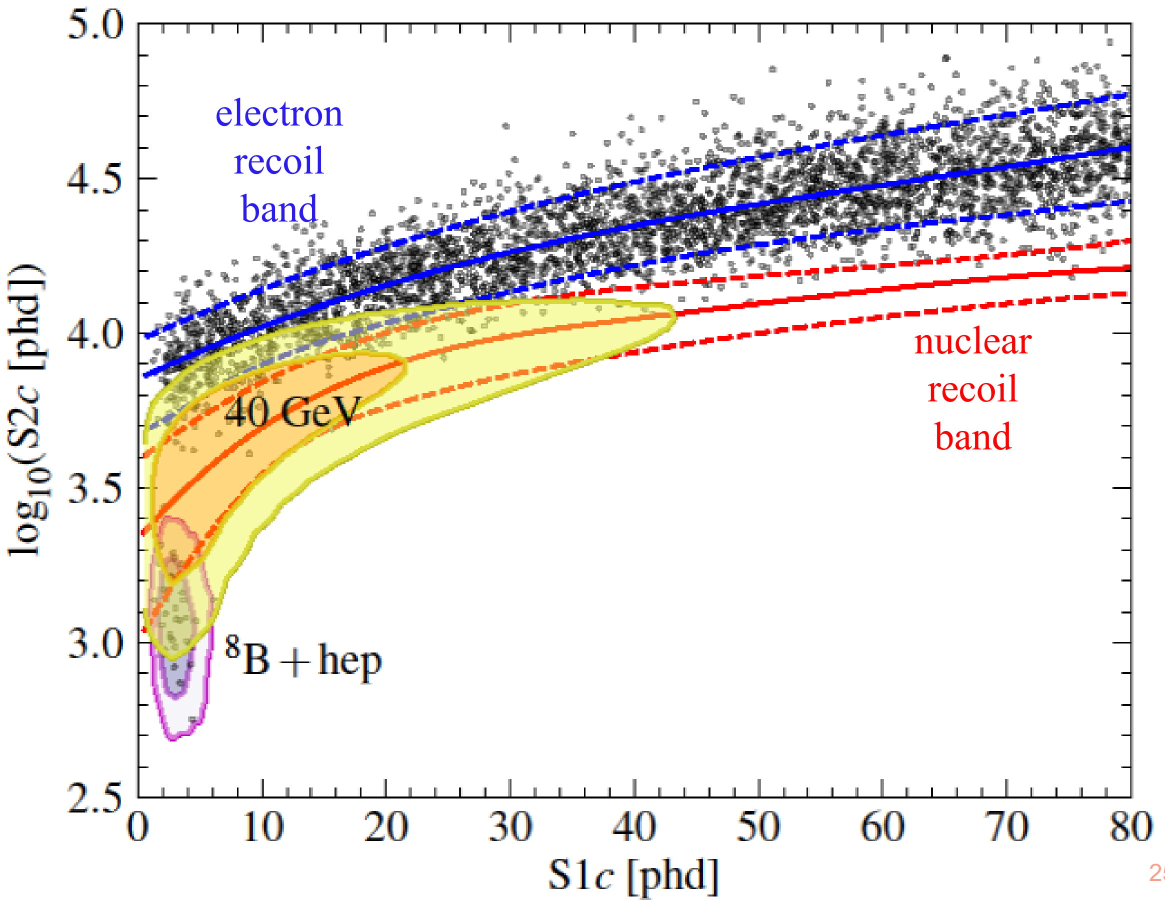
From “Projected WIMP sensitivity of the LUX-ZEPLIN (LZ) dark matter experiment” ArXiv:1802.06039

Simulated full LZ exposure

- 40 GeV/c² WIMP

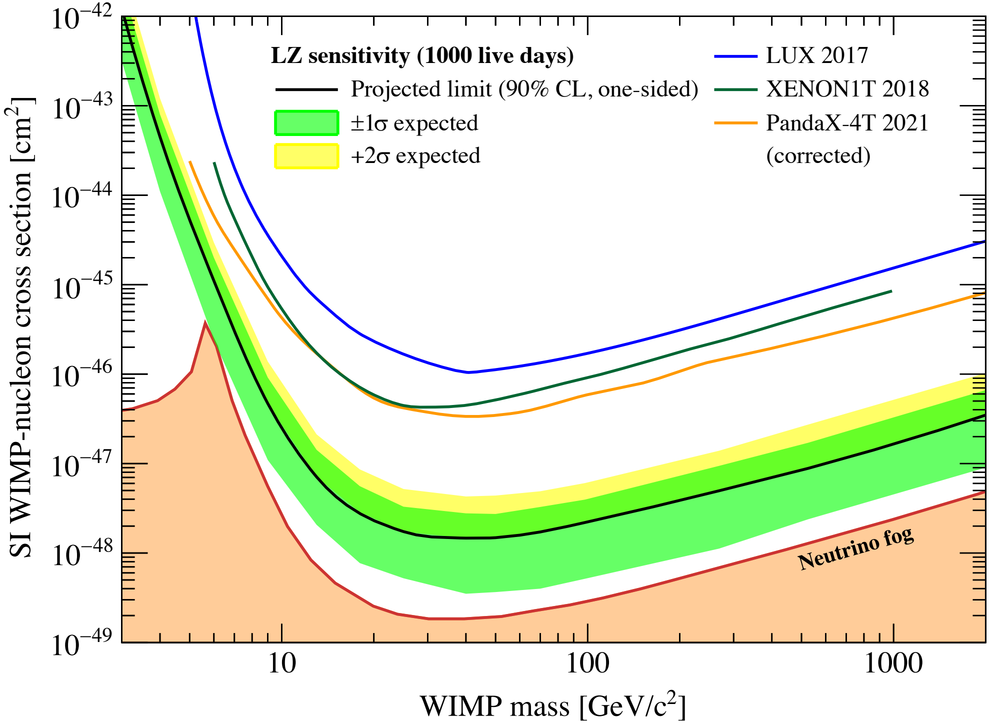
  1000 days

  5.6 Tons



Current direct detection WIMP limits

- Current limits for 40 GeV WIMP, spin-independent at $3x10^{-47}cm^2$ by PandaX-4T

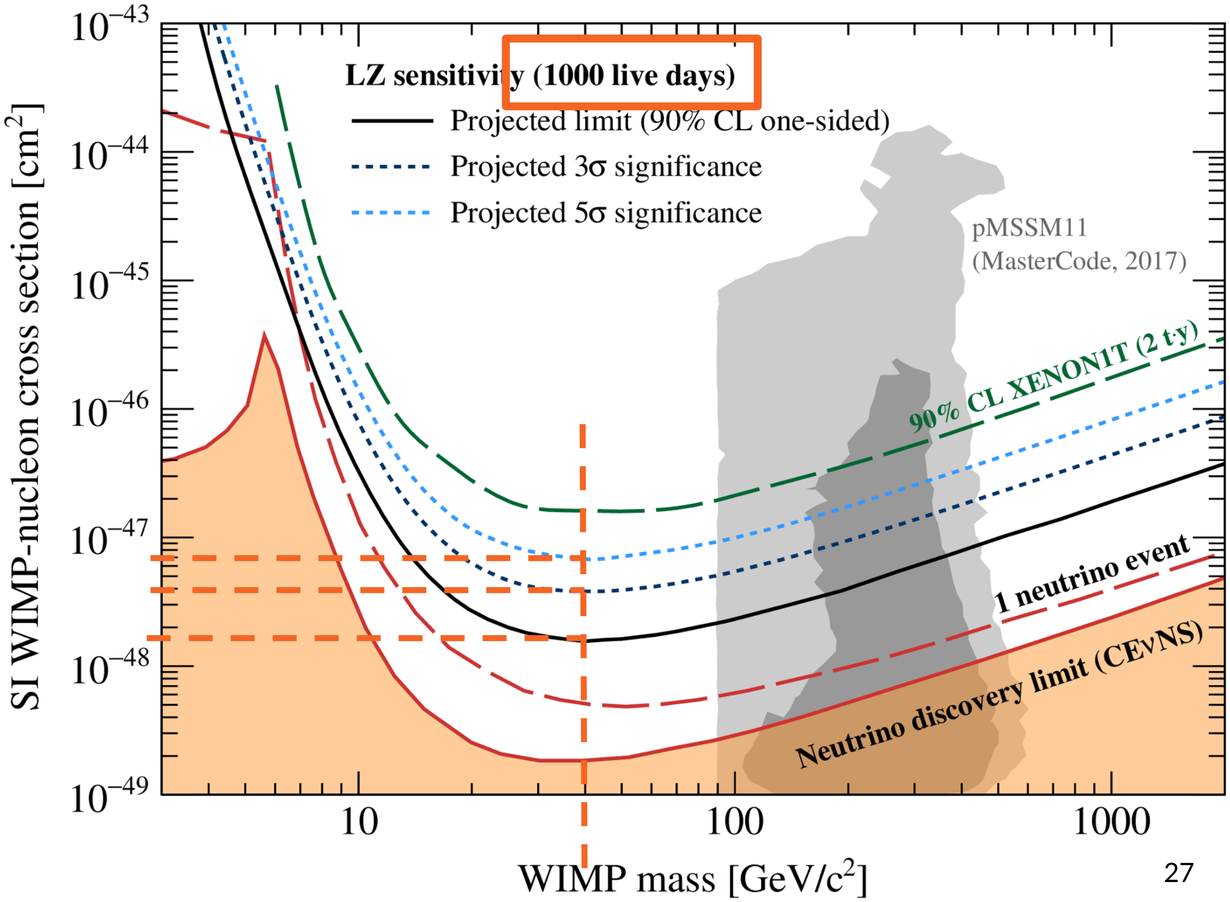


Sensitivity estimates

For WIMP of 40 GeV/c²

- Excluded at 90% C.L.: 1.6×10^{-48} cm²
- 3σ discovery: 3.8×10^{-48} cm²
- 5σ discovery: 6.7×10^{-48} cm²

From “Projected WIMP sensitivity of the LUX-ZEPLIN (LZ) dark matter experiment” ArXiv:1802.06039



Spin dependent couplings

- So far only looked at spin-independent scattering
  - Because of its large de Broglie wavelength, the WIMP interacts coherently with all nucleons in the target nucleus

- In spin-dependent interactions, WIMP is assumed to be a (Majorana or Dirac) fermion coupling to **unpaired** nuclear spins
  - Nuclei without unpaired spins are blind to spin-dependent scattering
  - Nuclei with unpaired spins, e.g. $^{19}_{9}F,\ ^{73}_{32}Ge,\ ^{131}_{54}Xe,\ ^{129}_{54}Xe$ are sensitive to spin-dependent WIMP scattering

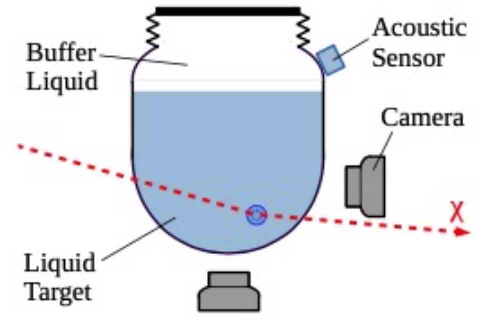
- Neutrons and protons typically contribute differently to the total spin of the target such that the SD-results are commonly quoted assuming that WIMPs couple either only to neutrons or protons

Bubble chambers - PICO

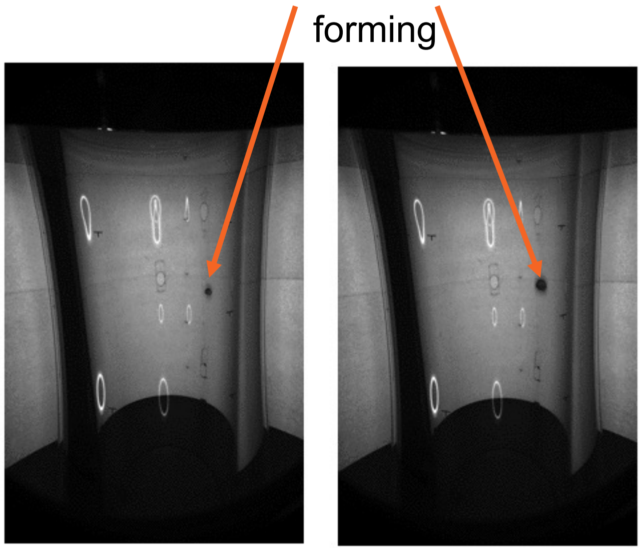
- Use superheated liquids, usually refrigerants such as CF_3I, C_3F_8, C_4F_{10}, C_2ClF_5 or C_3ClF_8 as WIMP target
  - ^{19}F enhances sensitivity to spin-dependent scattering (WIMP-**proton**)

- Temperature kept just below boiling point. A sufficient energy deposition into a micro-volume will lead to a local phase transition of the superheated liquid and start the formation of a bubble.

- PICO: superheated liquid C_3F_8, octafluoropropane
  ⊙ Acoustic + visual readout for background rejection
  ⊙ PICO-500 at SNOLAB: under design, installation/data in 2022/23



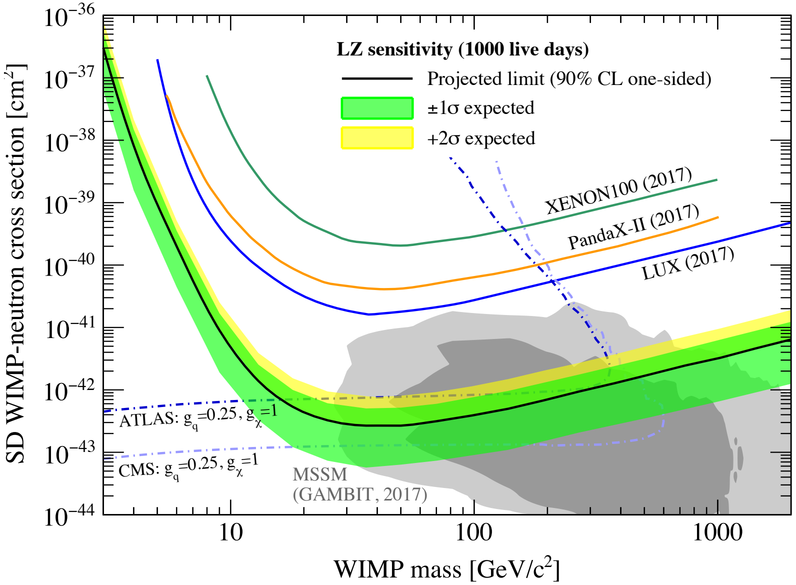
Bubble forming



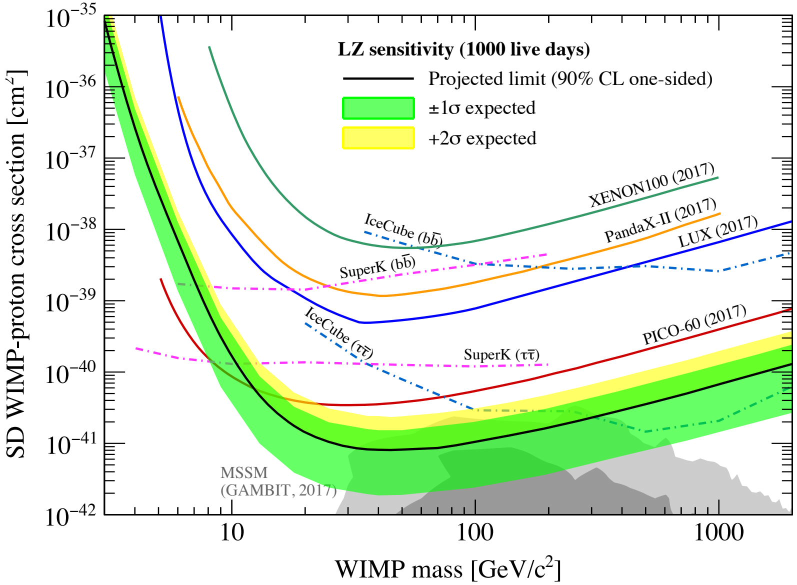
Spin-dependent scattering

- Naturally occurring Xenon has around 50% odd-neutron isotopes
  - 26.4% ^{129}Xe and 21.2% ^{131}Xe by mass

SD WIMP-neutron



SD WIMP-proton



Cryogenic Solid State detectors/ Bolometers

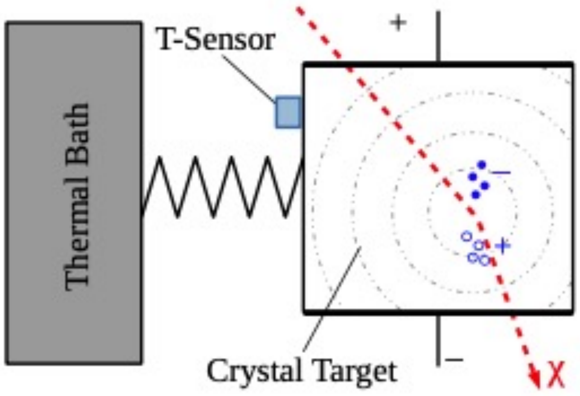
- Crystalline detectors allow for detection of a heat signal in form of phonons by measuring the temperature increase following a particle interaction
  - E.g. with transition edge sensors (TES) operated at the transition temperature between their super-conducting and the normal-conducting state
- In addition measure ionization (e.g. SuperCDMS, EDELWEISS) or scintillation (CRESST) signals
- Best suited to probe light dark matter (lighter target nuclei)

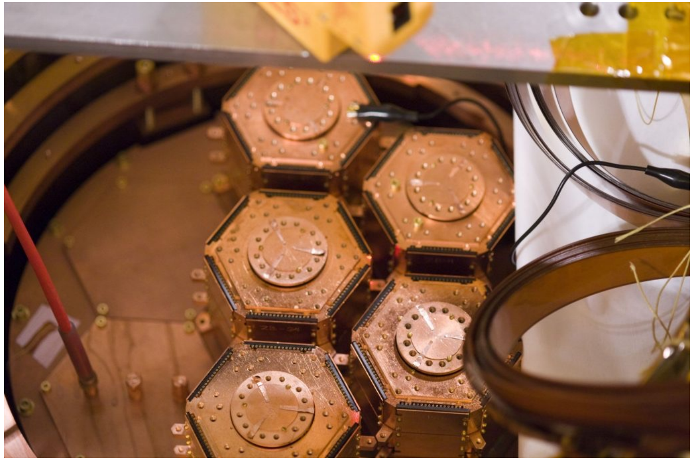
SuperCDMS

- Uses Silicon and Germanium crystals to detect DM

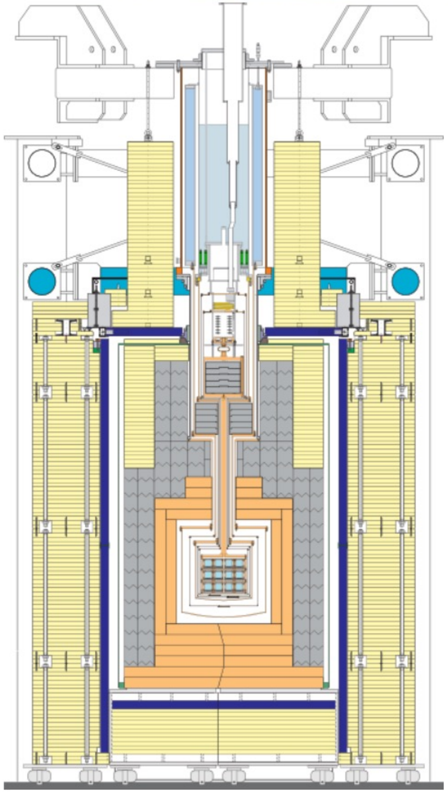
- Cooled to 15 mK to reduce thermal noise
- Vibration isolation

- phonon sensors consist of array of tiny superconducting transition edge sensors
  - they themselves consist of microscopic strips of tungsten coupled to aluminium "fins" to collect phonon energy from the crystal.
  - Energy threshold of ~70eV
- Voltage applied across crystals to collect ionization signals

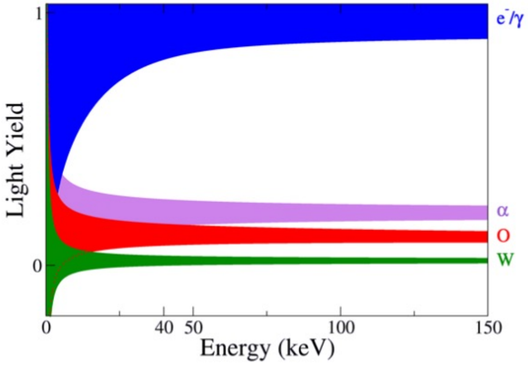


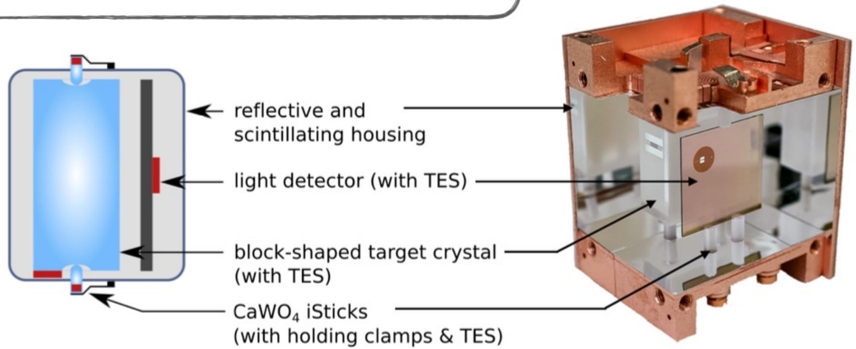


CRESST- scintillating crystal



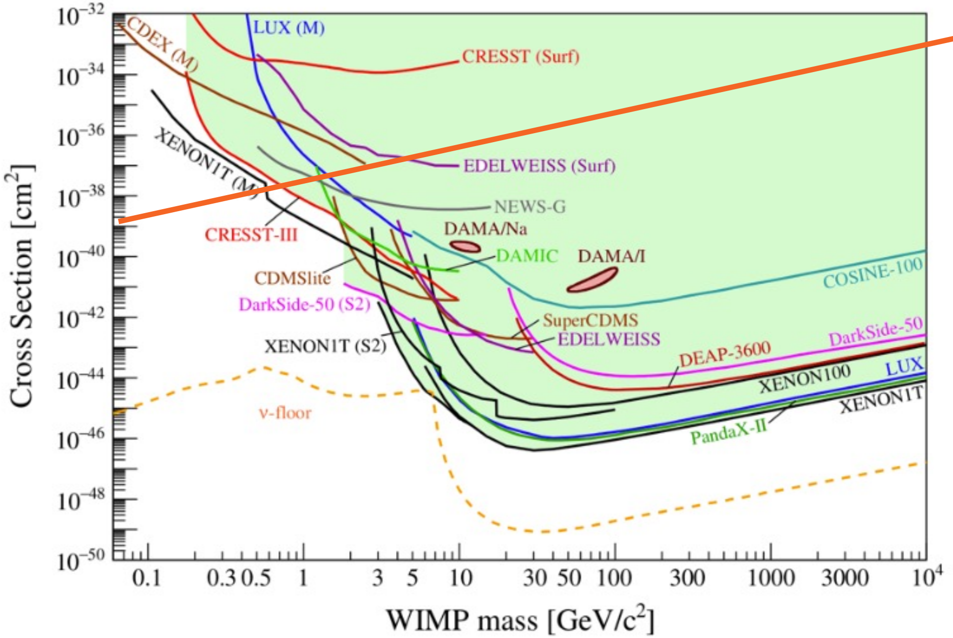
- Search of light DM direct interactions with $CaWO_4$ cryogenic detectors
- Operating temperature ~15 mK
- Second cryogenic detector to collect emitted scintillation light: particle identification
- Single detector mass ~24 g
- Energy Threshold: 30 eV



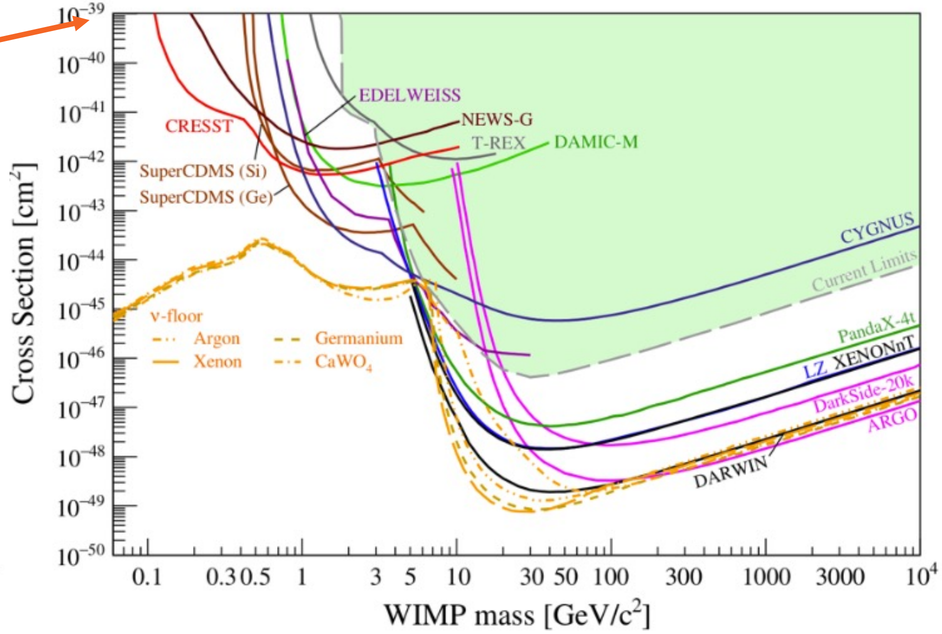


Sensitivity to low mass WIMPs

Current experiments



Future experiments

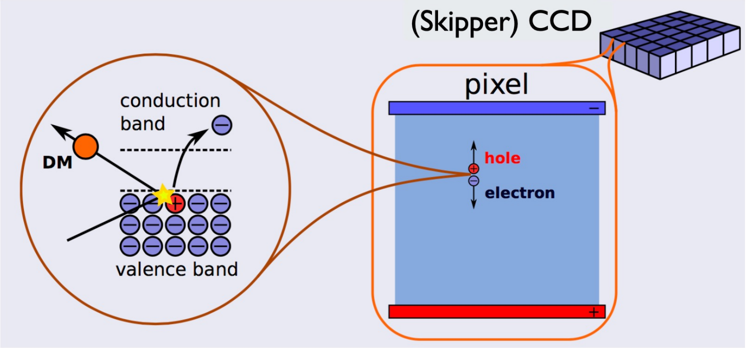


Note: neutrino “floor/fog” is target dependent

SENSEI

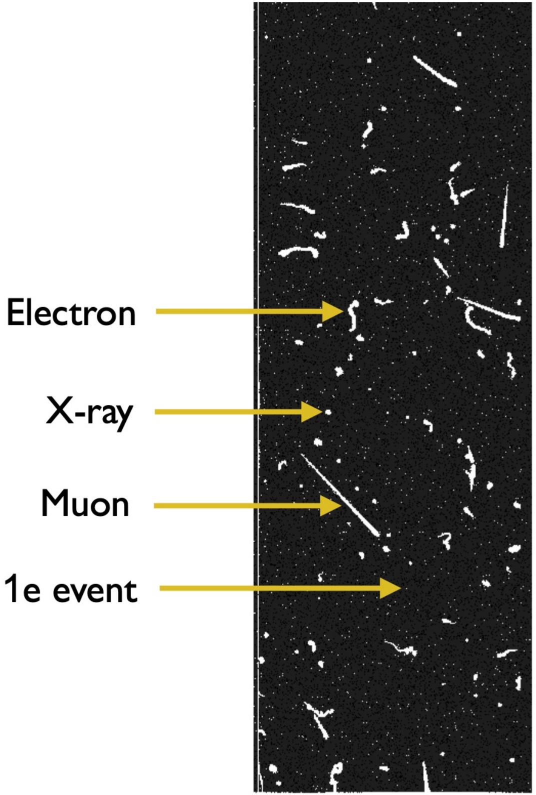
- Skipper-CCD, mass of ~2g

- DM scatter creates one (or possibly a few) electron in a pixel.



- Si band gap is 1.2 eV. Sensitivity to small DM masses

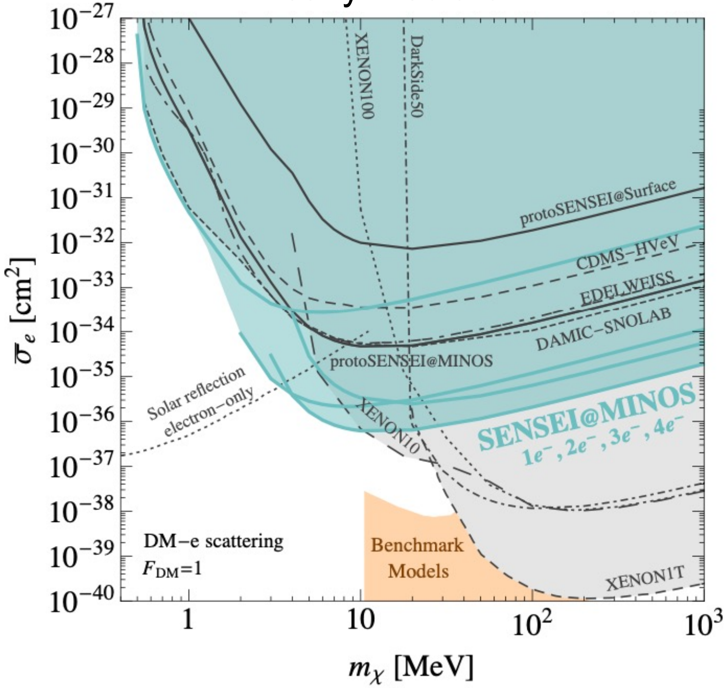
Example image



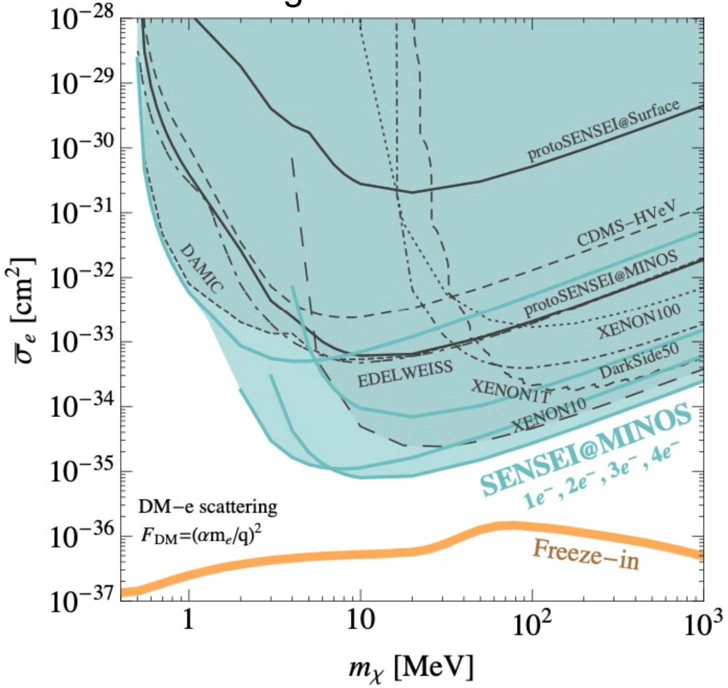
Current sensitivity

- Scattering off electrons

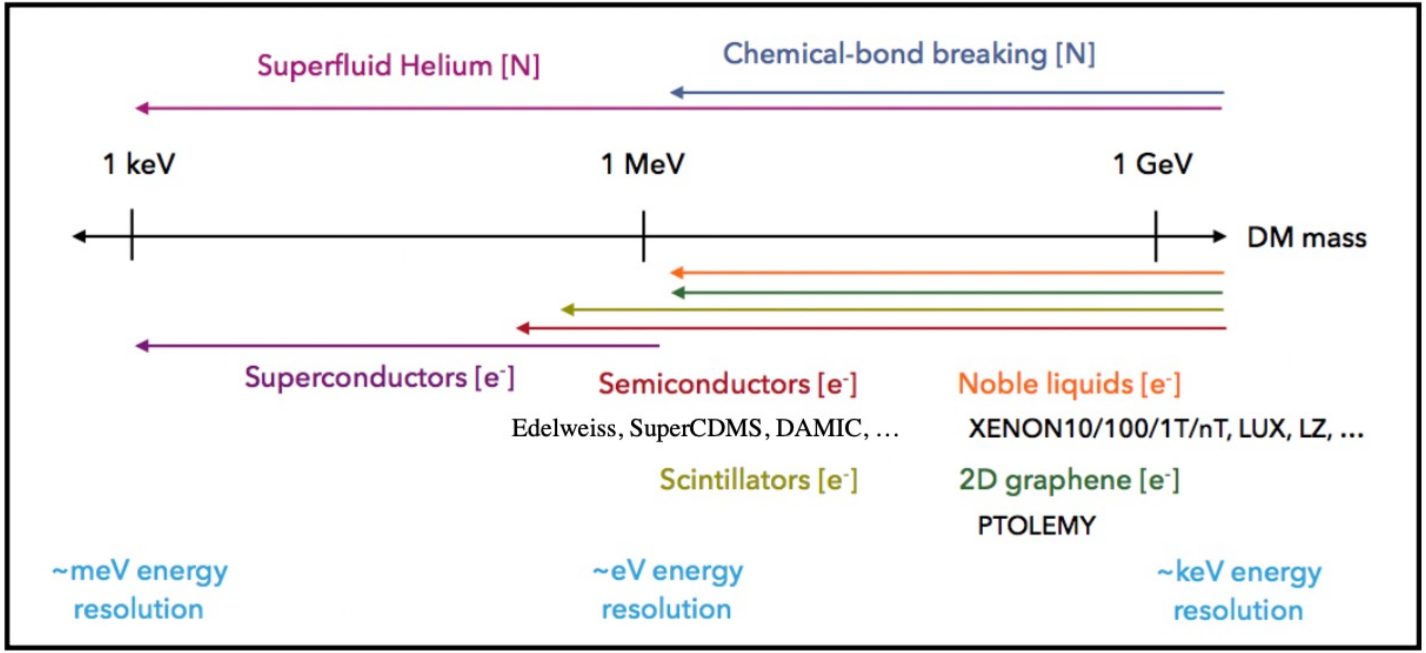
heavy mediator



light mediator



As we try to probe lighter and lighter DM...

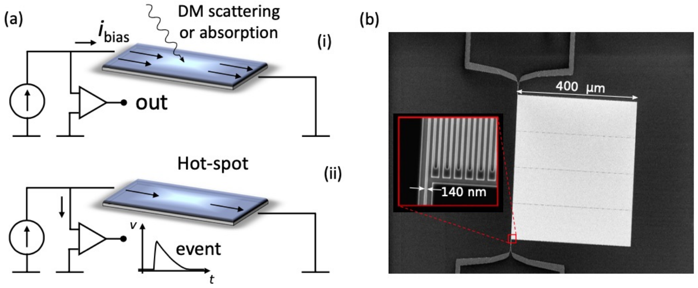


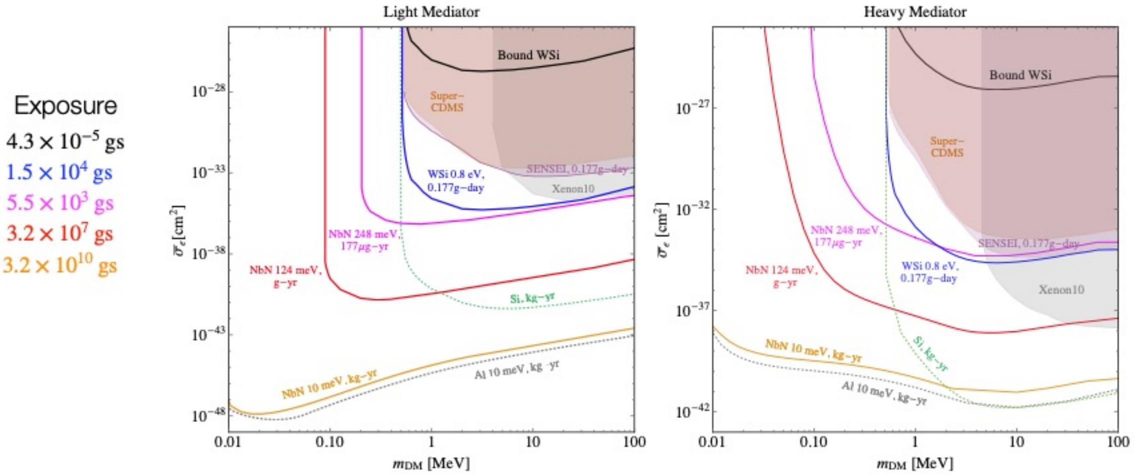
Noah Kurinsky

Single photon superconducting nanowires

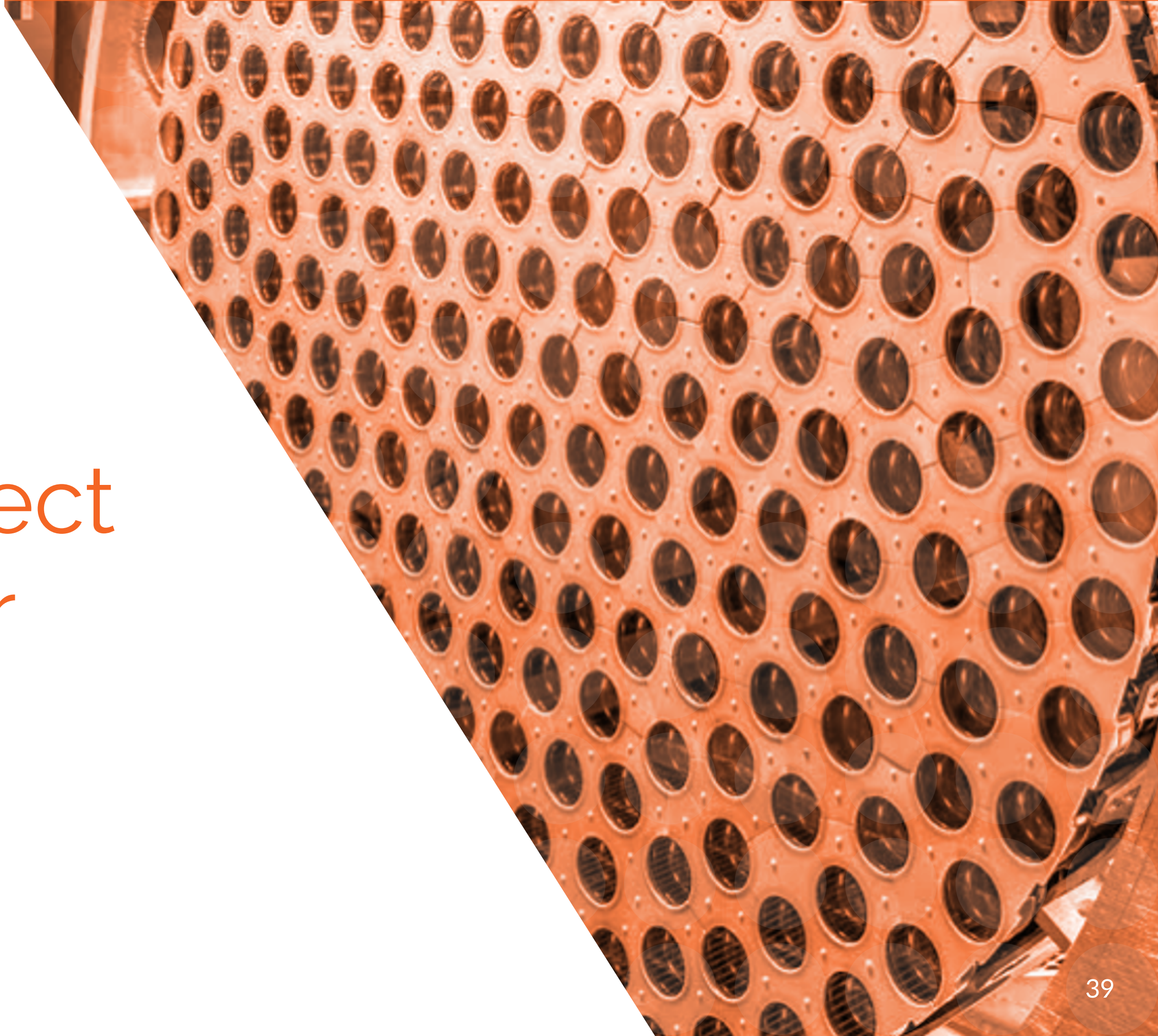
- Photon (or DM) interacts with electrons in Cooper pairs
- Breaking the Cooper pair results in normally conducting “hot spot”
- ~1mV pulse, ~10ns
- 0.8 eV threshold!

- Demonstrator:
  - 4.3ng active material
  - Run for 10000s
  - Exposure: 4.3x10^{-5} gs
  - Zero observed events





Indirect Direct Dark Matter Detection



Indirect dark matter detection

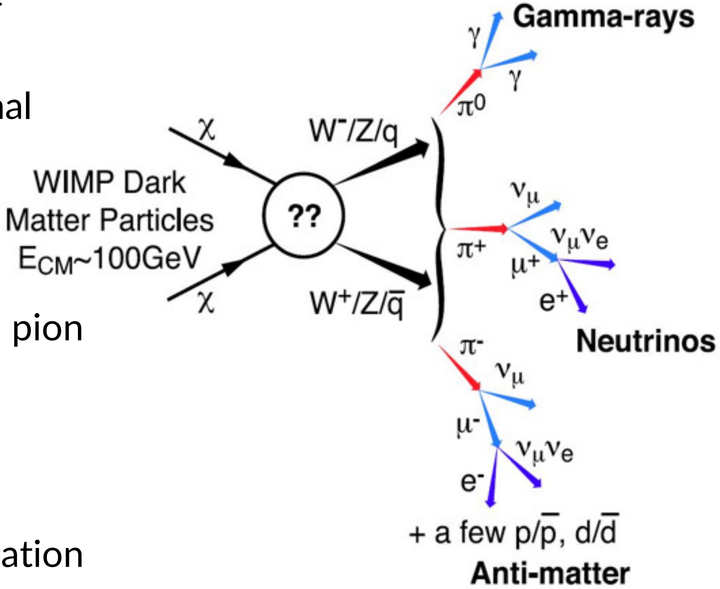
- Indirect searches are based on dark matter annihilation
- Can still happen today, as long as sufficiently large DM density is present
  - overdense regions are expected to arise due to gravitational collapse in the centre of gravitationally bound objects, like galaxies or clusters of galaxies, or more close by centre of sun or earth
- Final states generally include photons, neutrinos, light leptons and hadrons

- Good reach at large mass as signal becomes more evident over background.
- Can provide direct measurement of mass if annihilation into 2 (mono-chromatic) photons

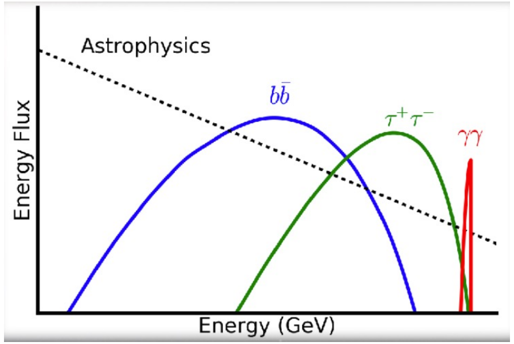
- Only possible to compare constraints from neutrino telescopes to direct detection constraints in a ~model independent way
- In general, direct and indirect searches probe different couplings in the dark sector

Dark Matter Annihilation to SM particles

- Photons:
  - DM annihilation to almost all final states will produce photons
  - Neutral pion decays, final state radiation, internal bremsstrahlung
- Neutrinos:
  - produced from charged pion decays and radiative processes
- Antinuclei:
  - can arise from hadronization of DM-initiated jets



- Dark matter makes a “bump”, not continuous spectrum.
- Cut-off at DM mass.

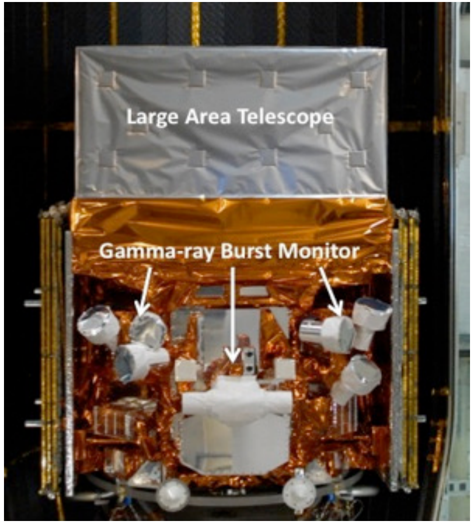


Gamma Flux

- Propagate without deflection
- Sources can be dwarf galaxies and central region of Milky Way
- Annihilation proportional to dark matter density squared
- Photons from internal bremsstrahlung, fragmentation or FSR give a continuous spectrum up to energies equal to DM mass
- Pairs of photons from direct annihilation generate monochromatic line at DM mass

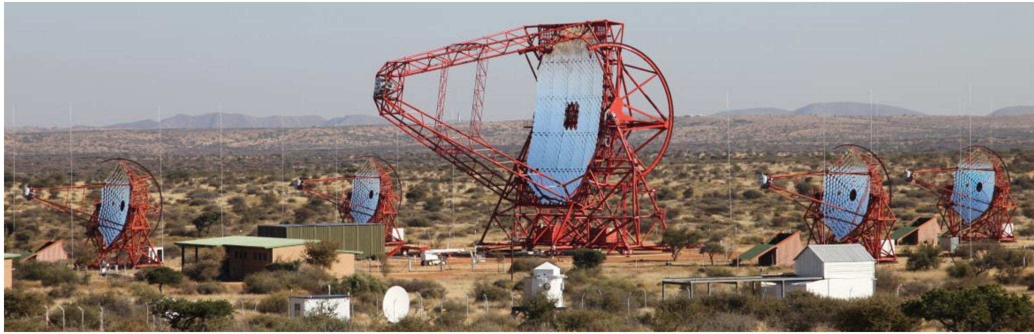
FERMI-LAT

- Fermi Gamma-ray Space Telescope: satellite observatory for photon energies from 8 keV to > 300 GeV
- Consists of Large Area Telescope and the Gamma-ray Burst Monitor



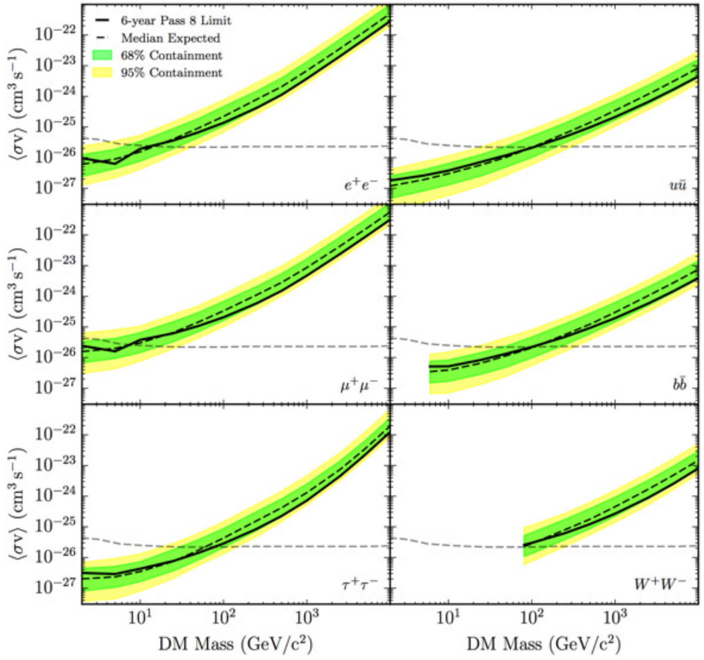
HESS - High Energy Stereoscopic System

- System of Imaging Atmospheric Cherenkov Telescopes in Namibia
- investigates cosmic gamma rays in the energy range O(10) GeV to O(10) TeV.



Dark Matter in gamma rays – FERMI-LAT

- Observation of **dwarf spheroidal galaxies** most promising as they do not emit any significant astrophysical background at gamma or X-ray frequencies

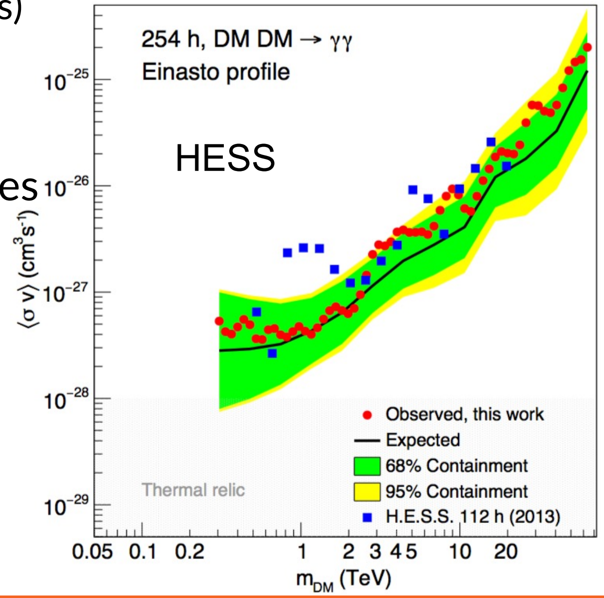


Limits on DM annihilation x-sec from dwarf galaxies by final state

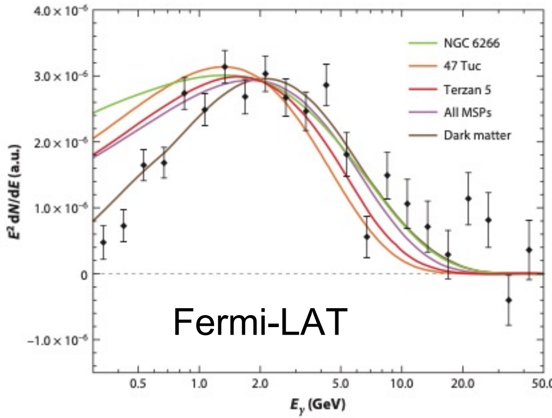
Additional uncertainties from DM density in dwarf galaxies

Dark Matter in gamma ray from galactic centre

- **Centre of Milky Way** good candidate for hosting large density of DM but large backgrounds at almost any wavelength
- FERMI-LAT observed excess but origin remains controversial
    - Contributions from unresolved point sources (Millisecond Pulsars)
    - Excess can also also be described by 43 GeV DM particle
- Limits from HESS on velocity-weighted annihilation cross-section for prompt annihilation into 2 photons at higher masses



S. Murgia

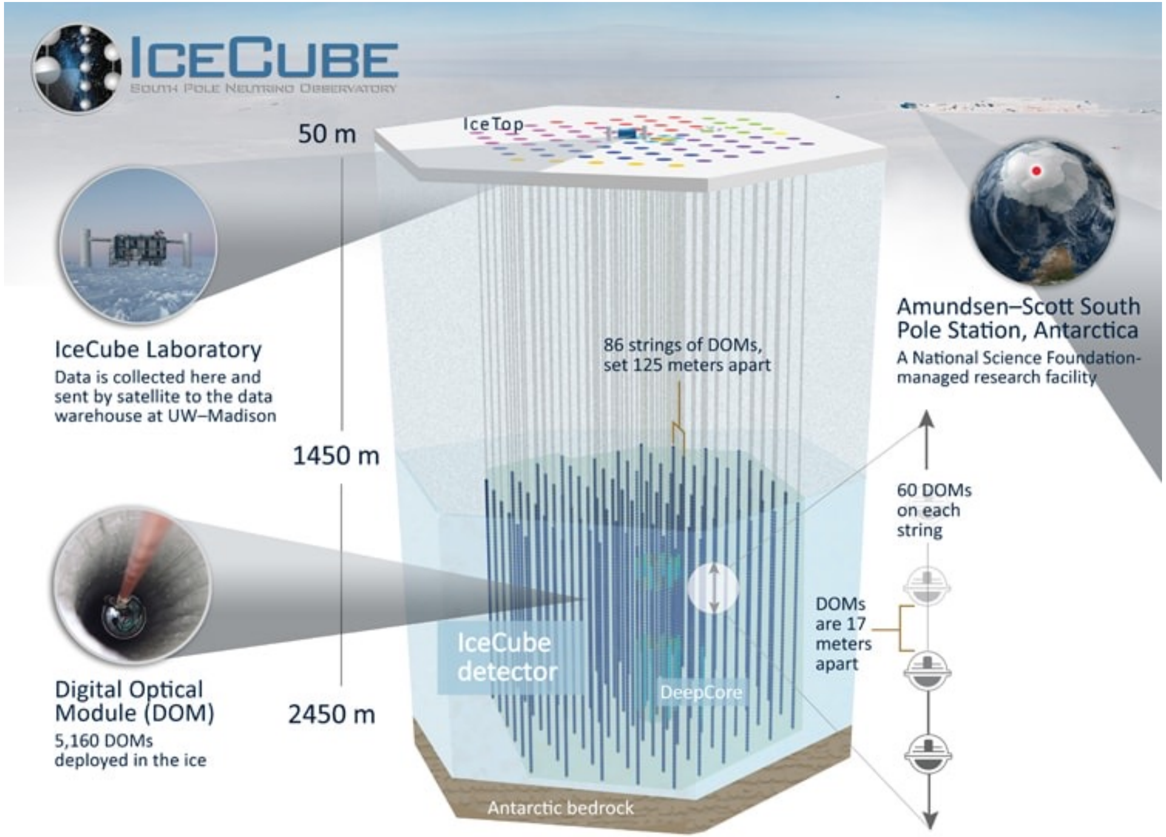


Neutrino Flux

- Neutrinos, like photons, propagate undeflected but more difficult to detect at low energies because of atmospheric neutrino background
- Sun and Earth are promising sources for neutrinos from WIMP annihilation
- SuperKamiokande, IceCube, Antares

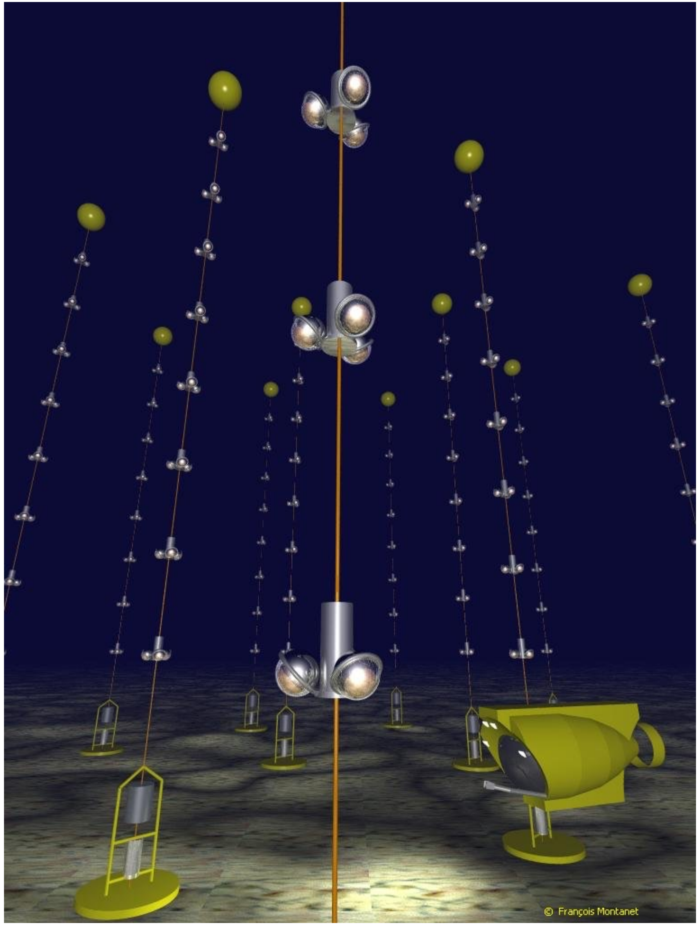
ICECUBE

- Gigaton neutrino detector in Antarctic
- Neutrino interactions in large ice volume create charged particles that emit Cherenkov radiation



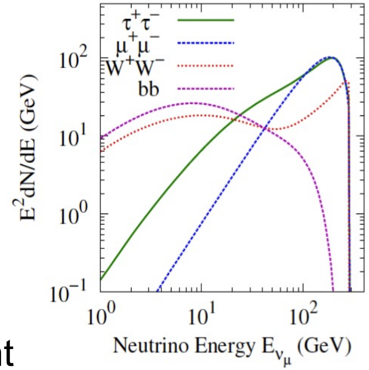
ANTARES

- large area water Cherenkov detector in the deep Mediterranean Sea, optimised for the detection of muons from high-energy astrophysical neutrinos



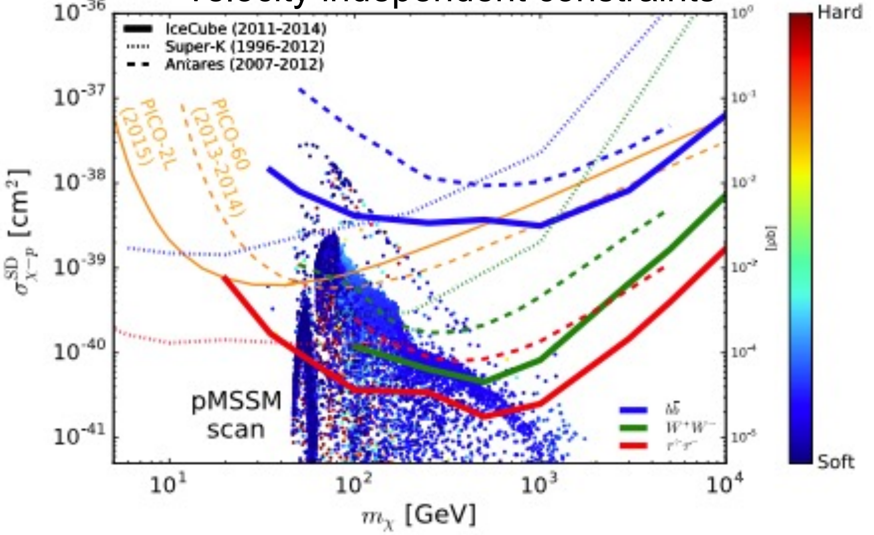
- Also SuperKamiokande

Constraints on DM from neutrinos

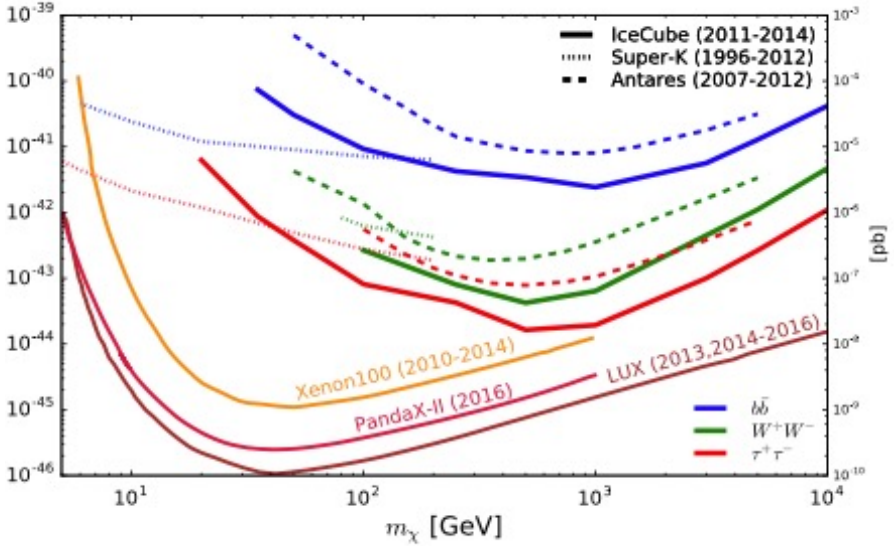


- WIMP annihilation in the sun

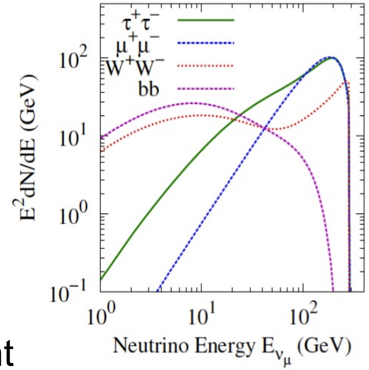
Spin dependent
velocity independent constraints



Spin independent

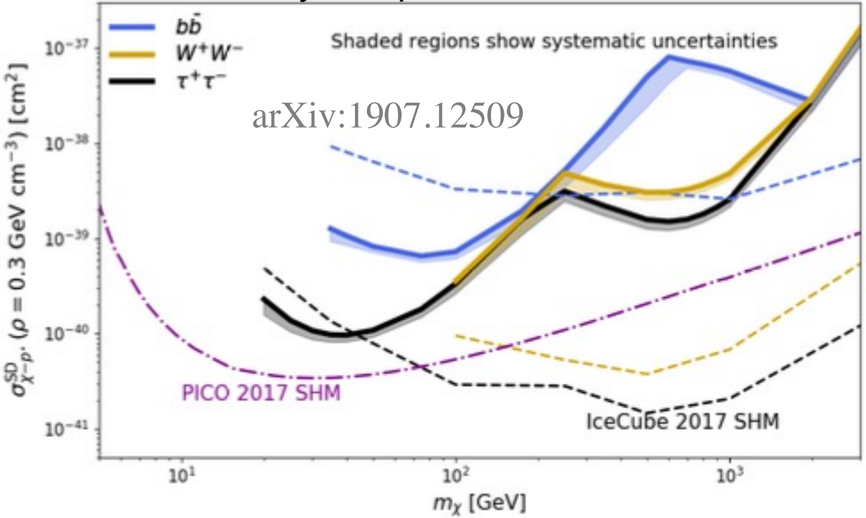


Constraints on DM from neutrinos

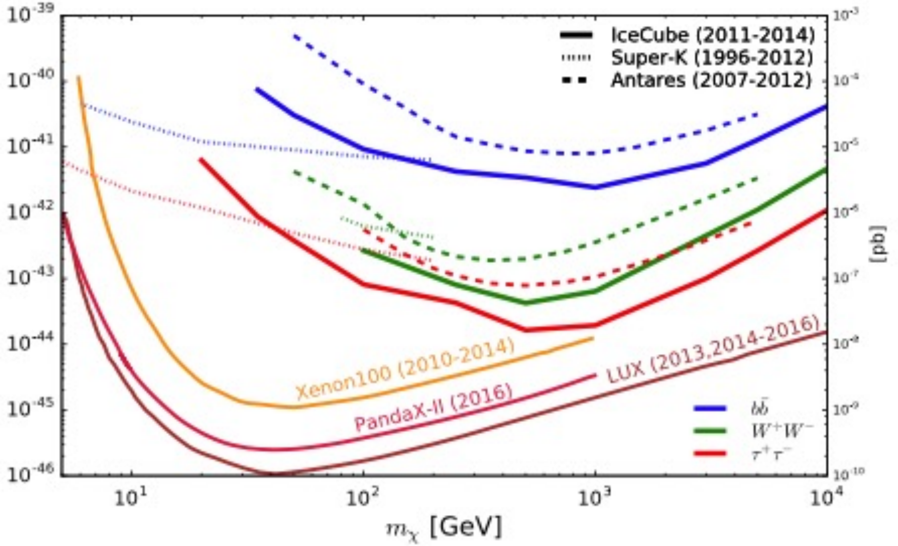


- WIMP annihilation in the sun

Spin dependent
velocity independent constraints



Spin independent



Charged Cosmic Rays

- Charged SM particles are deflected by magnetic fields, can only reach Earth when produced within a few kpc
- Search for excesses in flux of positrons, anti-protons, anti-deuterons.
- Extracting DM properties from spectra comes with challenges as modified during propagation

AMS – a particle physics detector in space

Precision magnetic spectrometer

- Tracking
- Calorimeters
- Particle ID

- Measurement of momentum, charge and mass

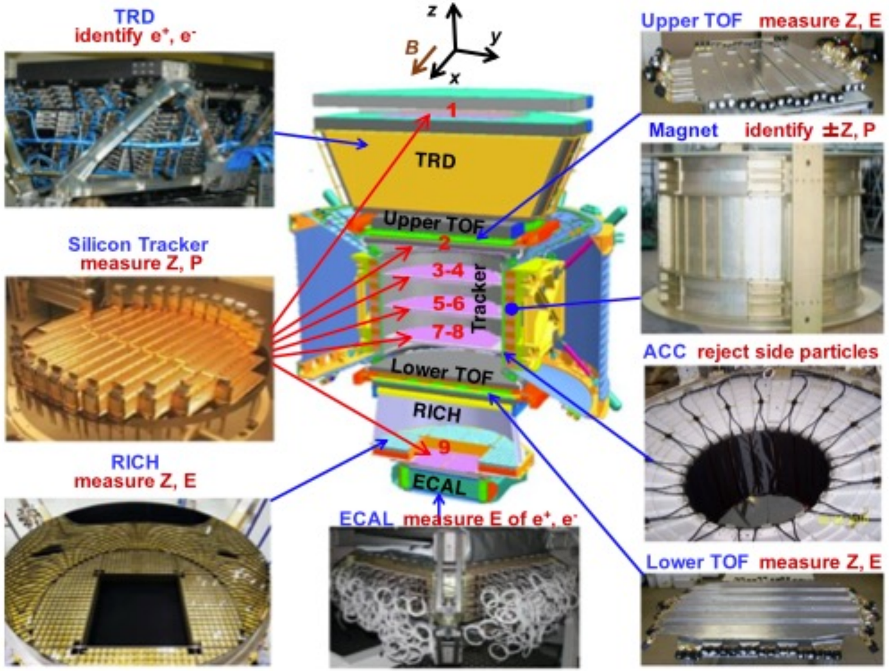


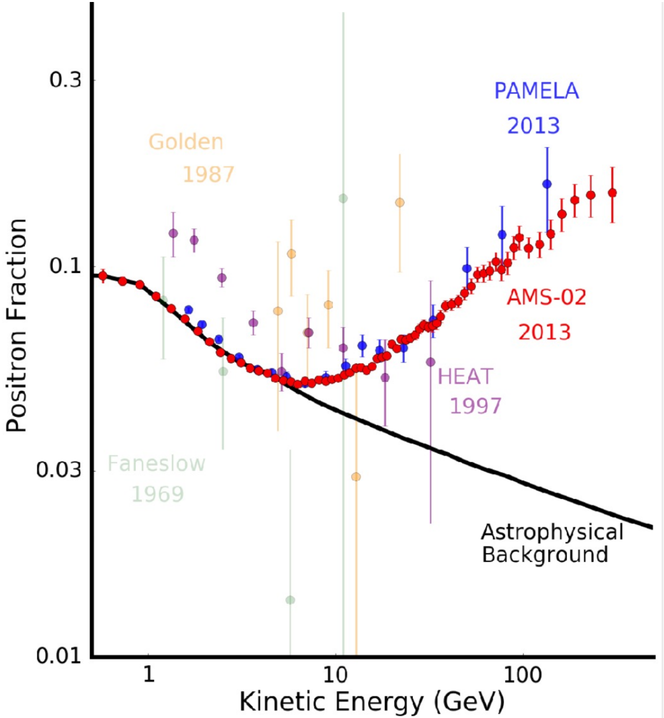
Fig. 2. The AMS detector showing the main elements and their functions. AMS is a TeV precision, multipurpose particle physics magnetic spectrometer. It identifies particles and nuclei by their charge (Z), energy (E) and momentum (P) or rigidity ($R = P/Z$), which are measured independently by the Tracker, TOF, RICH and ECAL. The ACC counters, located in the magnet bore, are used to reject particles entering AMS from the side. The AMS coordinate system, concentric with the magnet, is also shown. The x axis is parallel to the main component of the magnetic field and the z axis is pointing vertically.

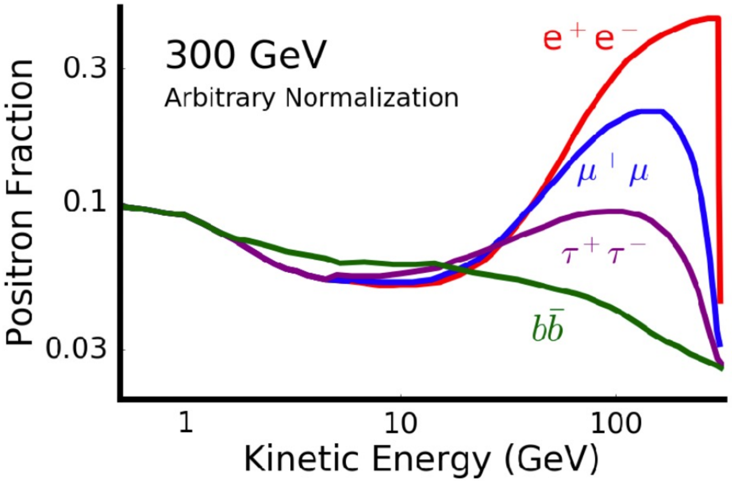
AMS

Fig. 1. AMS is a unique precision magnetic spectrometer on the ISS. AMS will operate on the ISS for the Station's lifetime. It is mounted on the ISS with a 12 degree angle to the zenith to prevent that the rotating ISS solar arrays are in the AMS field of view.

Positron excess

- First seen by PAMELA, later confirmed by AMS-02, caused a lot of excitement,... (see next page)



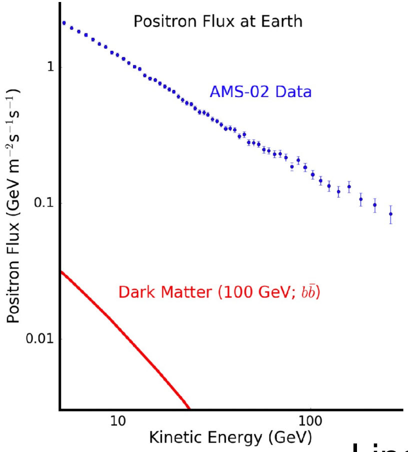


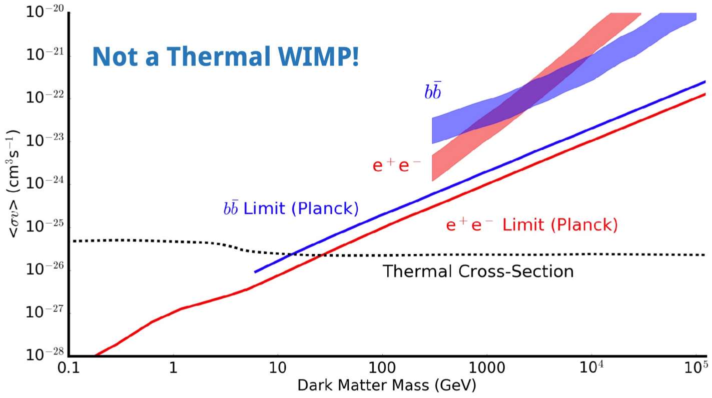
Linden, IDM2020

Positron excess

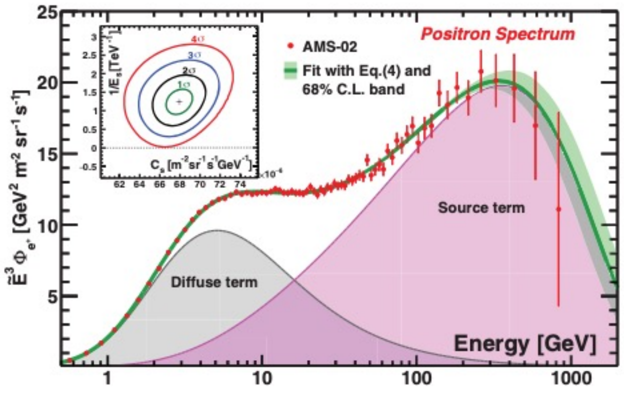
- But: Rate of excess much too large for any final state and in conflict with annihilation cross-section constraints from Planck (CMB)
- Additional data sees drop at high energies

AMS, PRL 122, 041102 (2019)





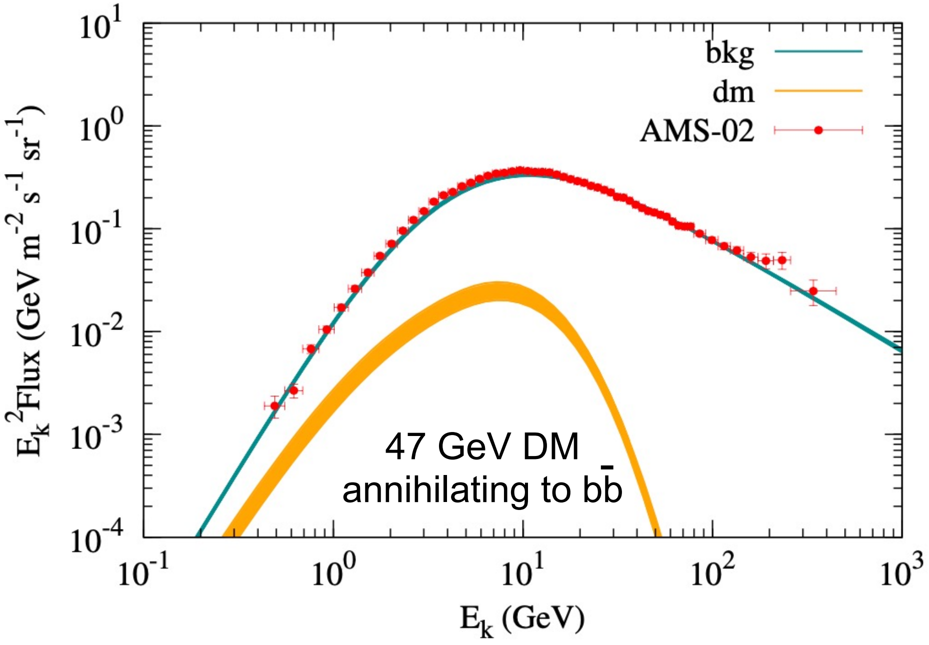
Linden, IDM2020



- Excess in positron fraction can be explained with emission from pulsars

Anti-proton spectrum

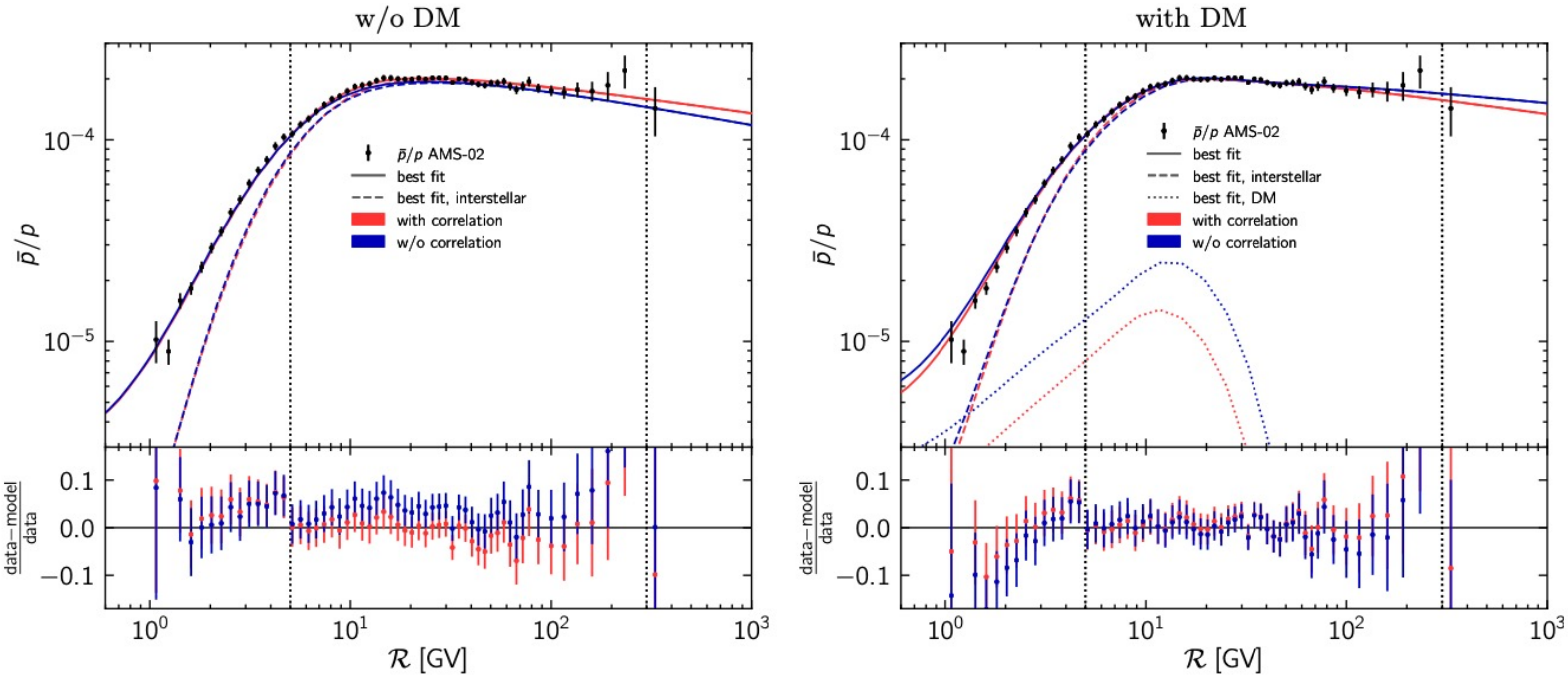
- Excess also observed in anti-proton spectrum of AMS-02
  - Dark Matter as an explanation
- But more likely background modelling inaccuracy
  - production, propagation, solar modulation, instrumental effects



arXiv:1610.03840

Anti-proton spectrum

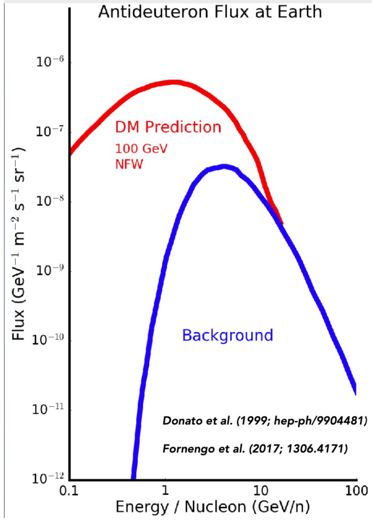
- Example: Fit considering correlations among AMS systematic uncertainties



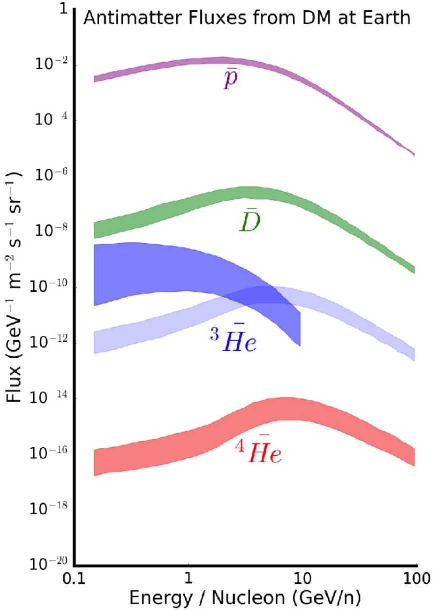
arXiv:2107.14606

Anti-deuteron/anti-helium spectrum

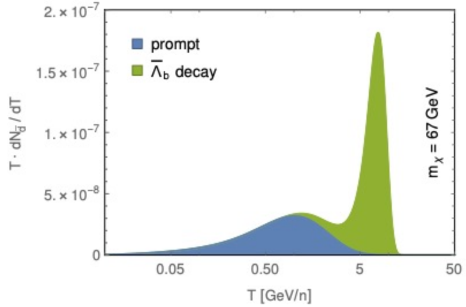
- Anti-nuclei can form as a result of DM annihilation
- "Easy" to detect, as low energetic compared to astrophysical background

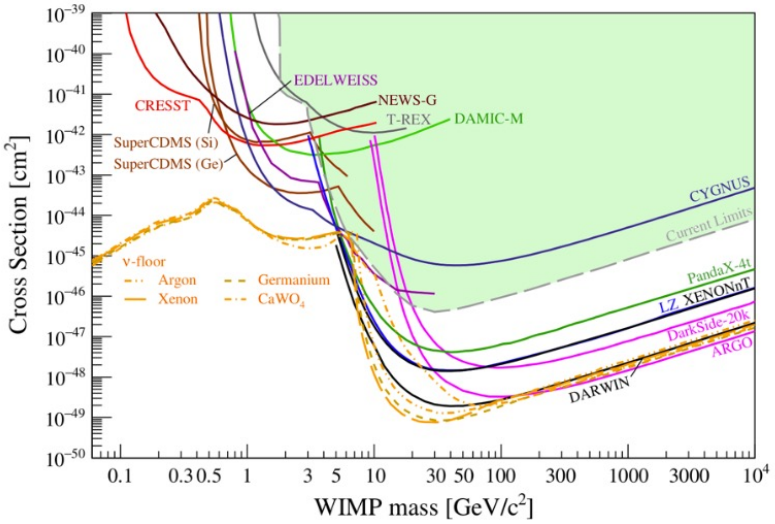


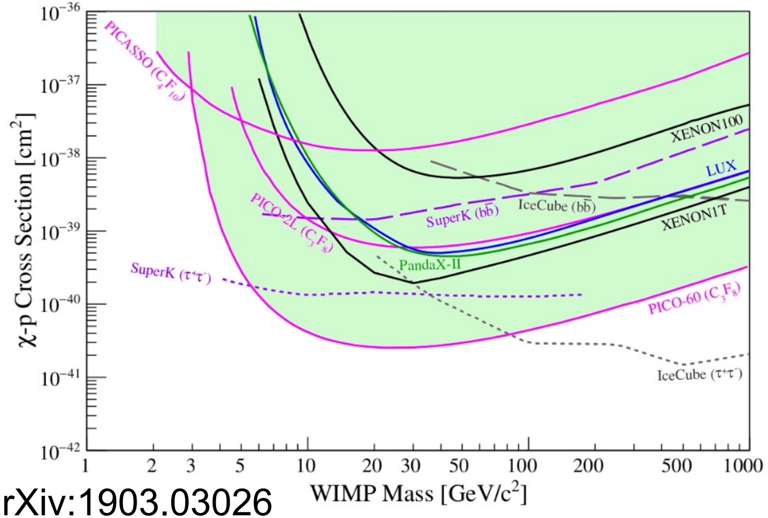
- However, strongly suppressed compared to anti-proton



- AMS-02 has recorded 8 candidates for $^3\overline{He}$
  - Too large a rate!
  - New possibility: production in DM annihilation via $\overline{\Lambda}_b$ rather than prompt
  - Most of these at high energies where AMS is sensitive
  - Might be able to explain observed rate







arXiv:1903.03026

Summary

- Direct dark matter detection is a very active field, with many new results expected in coming years
  - Exciting ideas for new experiments being developed
  - Established techniques complemented by new approaches, in particular when pushing towards lighter (MeV, keV) dark matter
- Indirect dark matter searches more difficult to interpret, still significant uncertainties on astrophysical models
  - Results from neutrino telescopes most relevant for comparison with collider and direct detection
  - But gamma excess from centre of Milky Way as well as positron, anti-proton and anti-helium excesses remain exciting

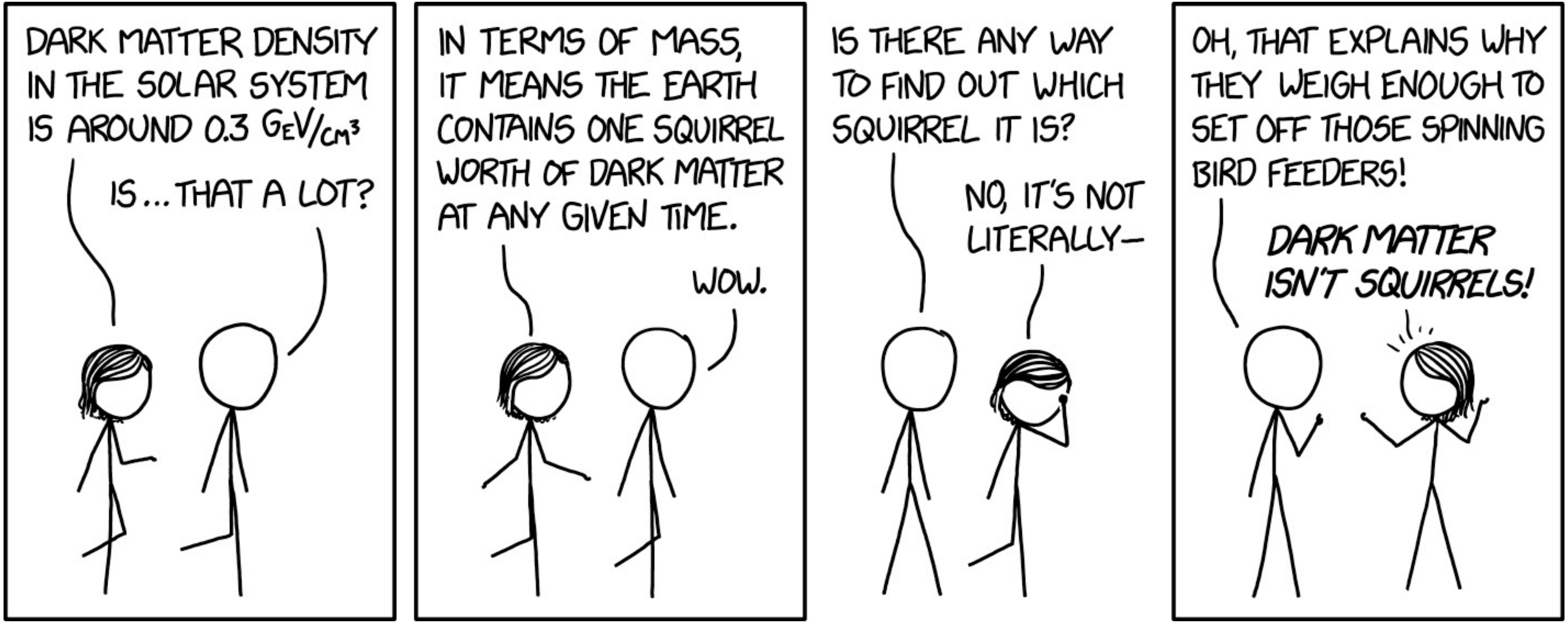
Useful resources/reviews

- Marc Schumann: Direct Detection of WIMP Dark Matter: Concepts and Status, arXiv:1903.03026

- J. Billard et al.: Direct Detection of Dark Matter -- APPEC Committee Report, arXiv:2104.07634

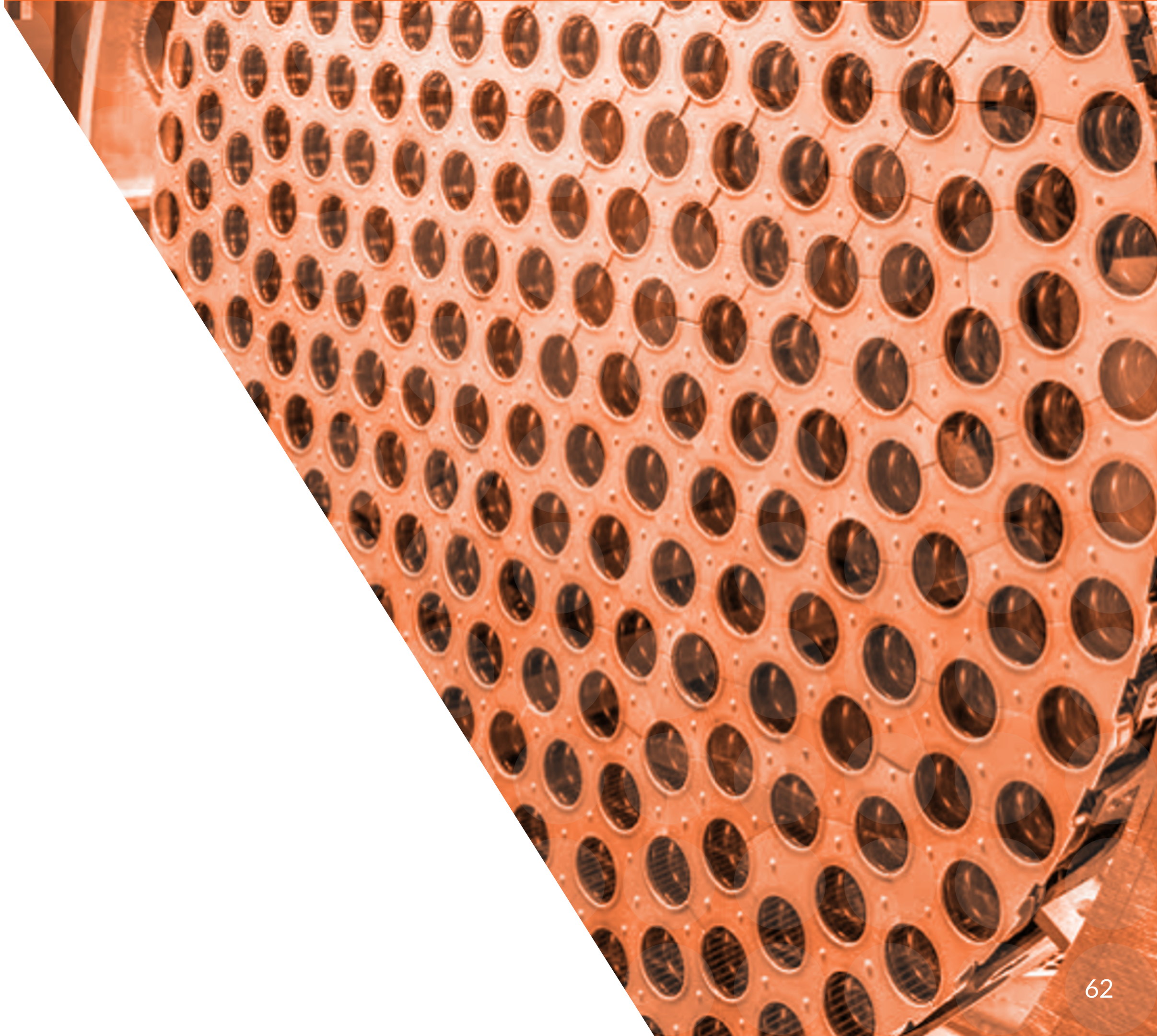
- PDG Dark Matter review: https://pdg.lbl.gov/2021/web/viewer.html?file=%2F2021/reviews/rpp2020-rev-dark-matter.pdf

How much Dark Matter?



https://xkcd.com/2186/

Thank you



Detailed background table

From “Projected WIMP sensitivity of the LUX-ZEPLIN (LZ) dark matter experiment”
ArXiv:1802.06039

Background Source	Mass (kg)	$^{238}U_e$	$^{238}U_l$	$^{232}Th_e$	$^{232}Th_l$	^{60}Co	^{40}K	n/yr	ER (cts)	NR (cts)
		mBq/kg								
Detector Components										
PMT systems	308	31.2	5.20	2.32	2.29	1.46	18.6	248	2.82	0.027
TPC systems	373	3.28	1.01	0.84	0.76	2.58	7.80	79.9	4.33	0.022
Cryostat	2778	2.88	0.63	0.48	0.51	0.31	2.62	323	1.27	0.018
Outer detector (OD)	22950	6.13	4.74	3.78	3.71	0.33	13.8	8061	0.62	0.001
All else	358	3.61	1.25	0.55	0.65	1.31	2.64	39.1	0.11	0.003
subtotal									**9**	**0.07**
Surface Contamination										
Dust (intrinsic activity, 500 ng/cm^2)									0.2	0.05
Plate-out (PTFE panels, 50 nBq/cm^2)									-	0.05
^{210}Bi mobility (0.1 µBq/kg LXe)									40.0	-
Ion misreconstruction (50 nBq/cm^2)									-	0.16
^{210}Pb (in bulk PTFE, 10 mBq/kg PTFE)									-	0.12
subtotal									**40**	**0.39**
Xenon contaminants										
^{222}Rn (1.81 µBq/kg)									681	-
^{220}Rn (0.09 µBq/kg)									111	-
^{nat}Kr (0.015 ppt g/g)									24.5	-
^{nat}Ar (0.45 ppb g/g)									2.5	-
subtotal									**819**	**0**
Laboratory and Cosmogenics										
Laboratory rock walls									4.6	0.00
Muon induced neutrons									-	0.06
Cosmogenic activation									0.2	-
subtotal									**5**	**0.06**
Physics										
^{136}Xe $2\nu\beta\beta$									67	-
Solar neutrinos: pp+^{7}Be+^{13}N									255	-
Diffuse supernova neutrinos (DSN)									-	0.05
Atmospheric neutrinos (Atm)									-	0.46
subtotal									**322**	**0.51**
Total									1195	1.03
Total (with 99.5% ER discrimination, 50% NR efficiency)									5.97	0.52
Sum of ER and NR in LZ for 1000 days, 5.6 tonne FV, with all analysis cuts									**6.49**	