DARK MATTER AT ICRC2023

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Disclaimer! I am not all knowing – if I've misinterpreted your work please send me an email and I will fix it for the proceedings

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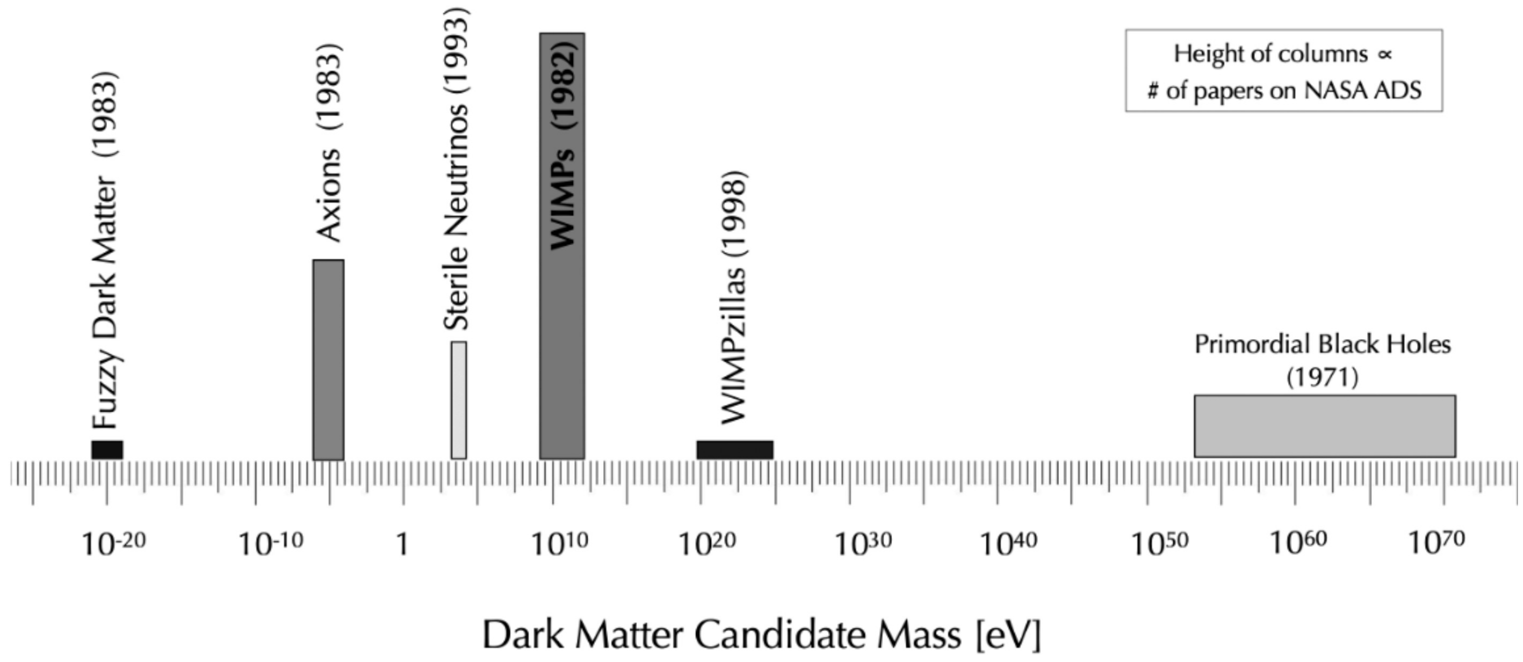
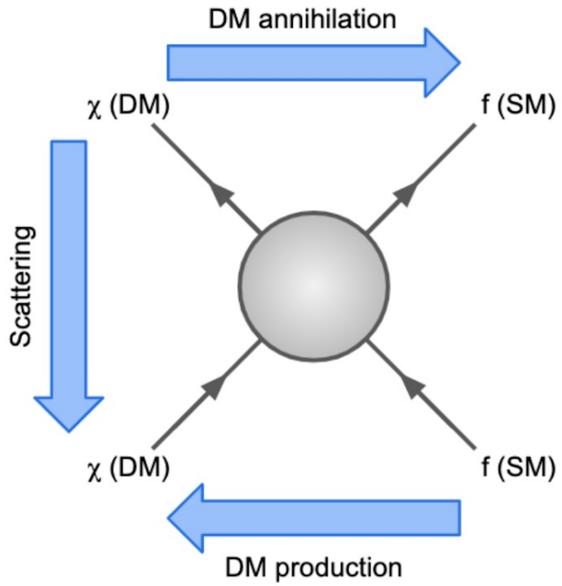
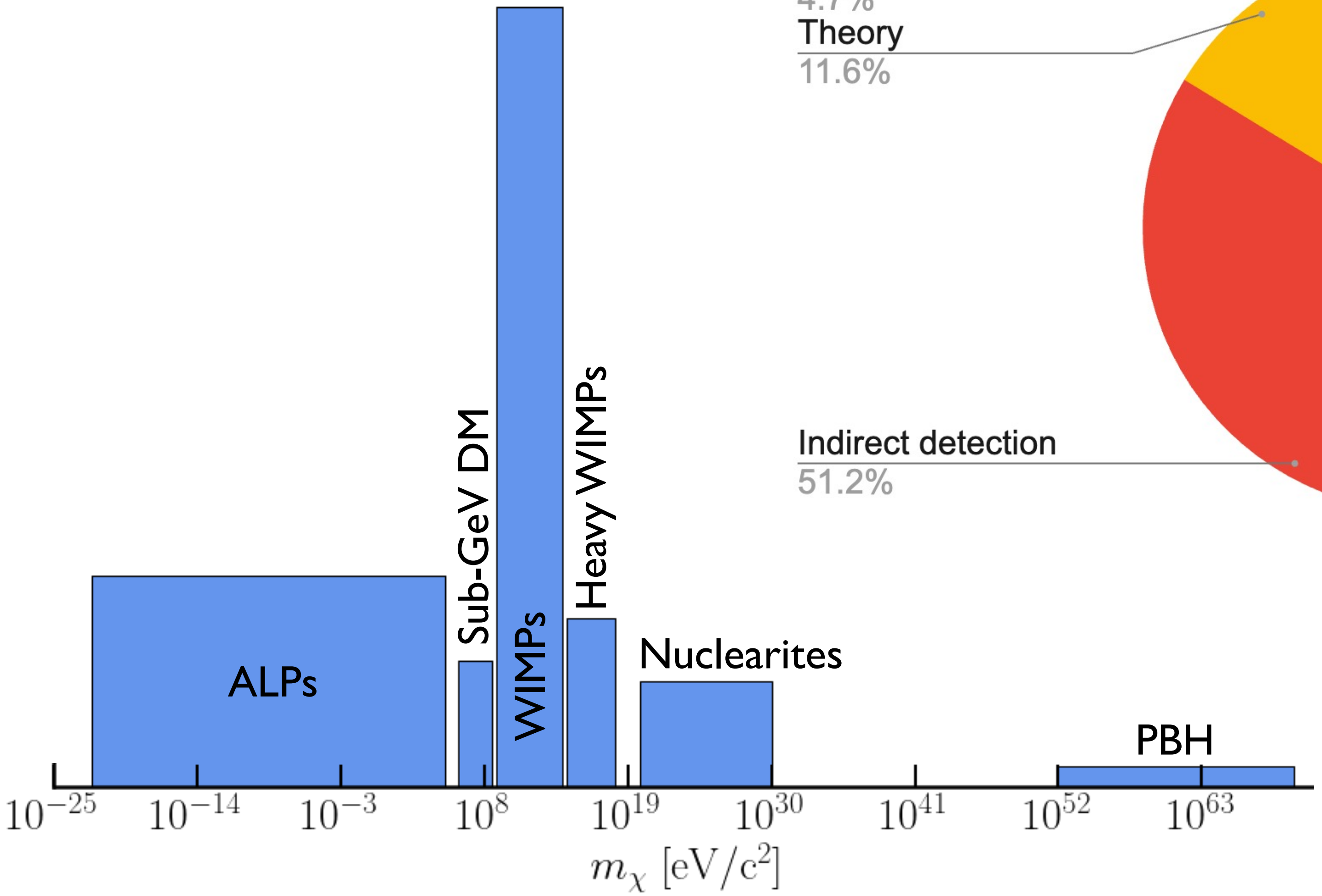
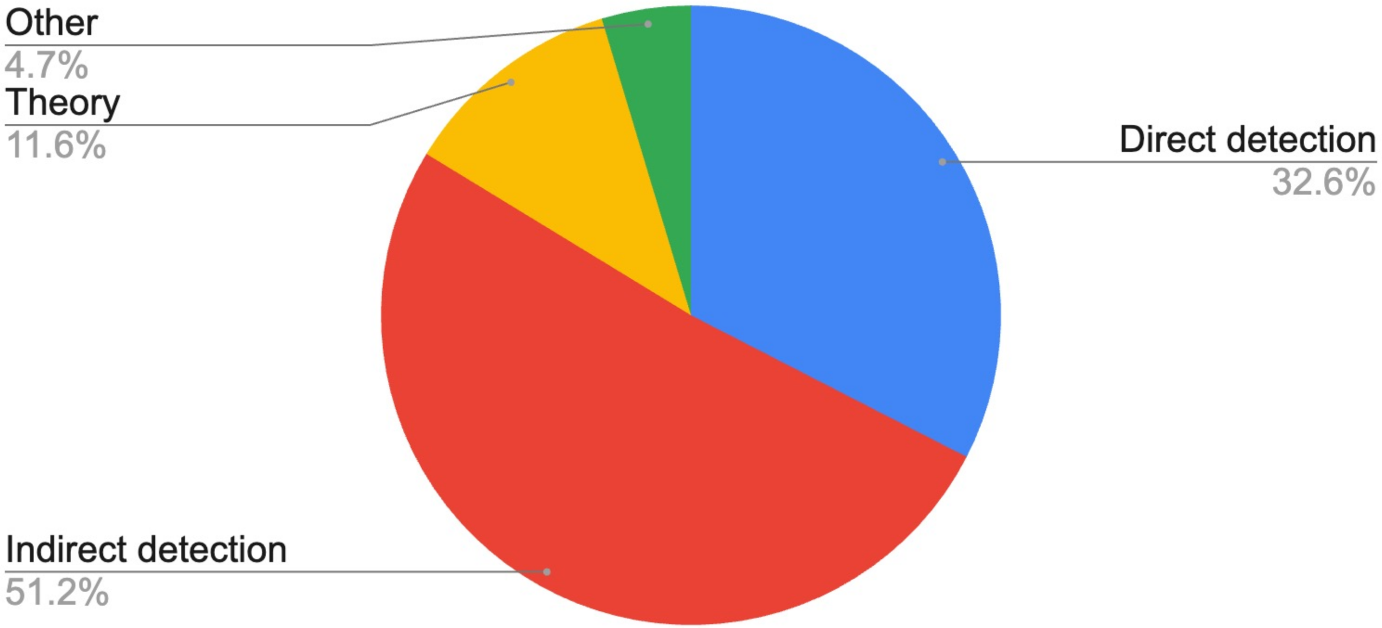
DM OVERVIEW


Fuzzy Dark Matter (1983)
Axions (1983)
Sterile Neutrinos (1993)
WIMPs (1982)
WIMPzillas (1998)
Height of columns ∝
# of papers on NASA ADS
Primordial Black Holes
(1971)
10^{-20}
10^{-10}
1
10^{10}
10^{20}
10^{30}
10^{40}
10^{50}
10^{60}
10^{70}
Dark Matter Candidate Mass [eV]


DM annihilation
χ (DM)
f (SM)
Scattering
χ (DM)
f (SM)
DM production

DM AT ICRC


ALPs
Sub-GeV DM
WIMPs
Heavy WIMPs
Nuclearites
PBH
10^{-25}
10^{-14}
10^{-3}
10^{8}
10^{19}
10^{30}
10^{41}
10^{52}
10^{63}
m_χ [eV/c^2]


Other
4.7%
Theory
11.6%
Direct detection
32.6%
Indirect detection
51.2%

DM: WHAT ARE WE LOOKING FOR?

DM field has always been diverse, this conference is no different with a wide range of models being discussed (see Calore for a much more in-depth motivation and review)

Direct detection probes scattering of DM with protons, neutrons, and (sometimes) electrons

$$\frac{dR}{dE} = N_T \frac{\rho}{m_\chi} \int_{v_{min}}^{v_{esc}} v f(v) \frac{d\sigma}{dE} d^3 v$$

which produce excess in the energy spectrum of a detector.

Indirect detection probes annihilation

$$\frac{d\Phi_s}{dE} = \frac{1}{4\pi} \frac{\langle \sigma_a v \rangle}{2m_\chi^2} \frac{dN_s}{dE} \int_{los} \rho^2(\vec{r}) ds$$

and/or decay of DM

$$\frac{d\Phi_s}{dE} = \frac{1}{4\pi} \frac{1}{m_\chi \tau} \frac{dN_s}{dE} \int_{los} \rho(\vec{r}) ds$$

that produces a flux of observed particles s, typically neutrinos or gammas.

Both searches have dependencies on particle physics interactions, and astrophysical parameters, as well as detector specific performance (not shown). In general, we make assumptions about these to constrain σ and m_χ.

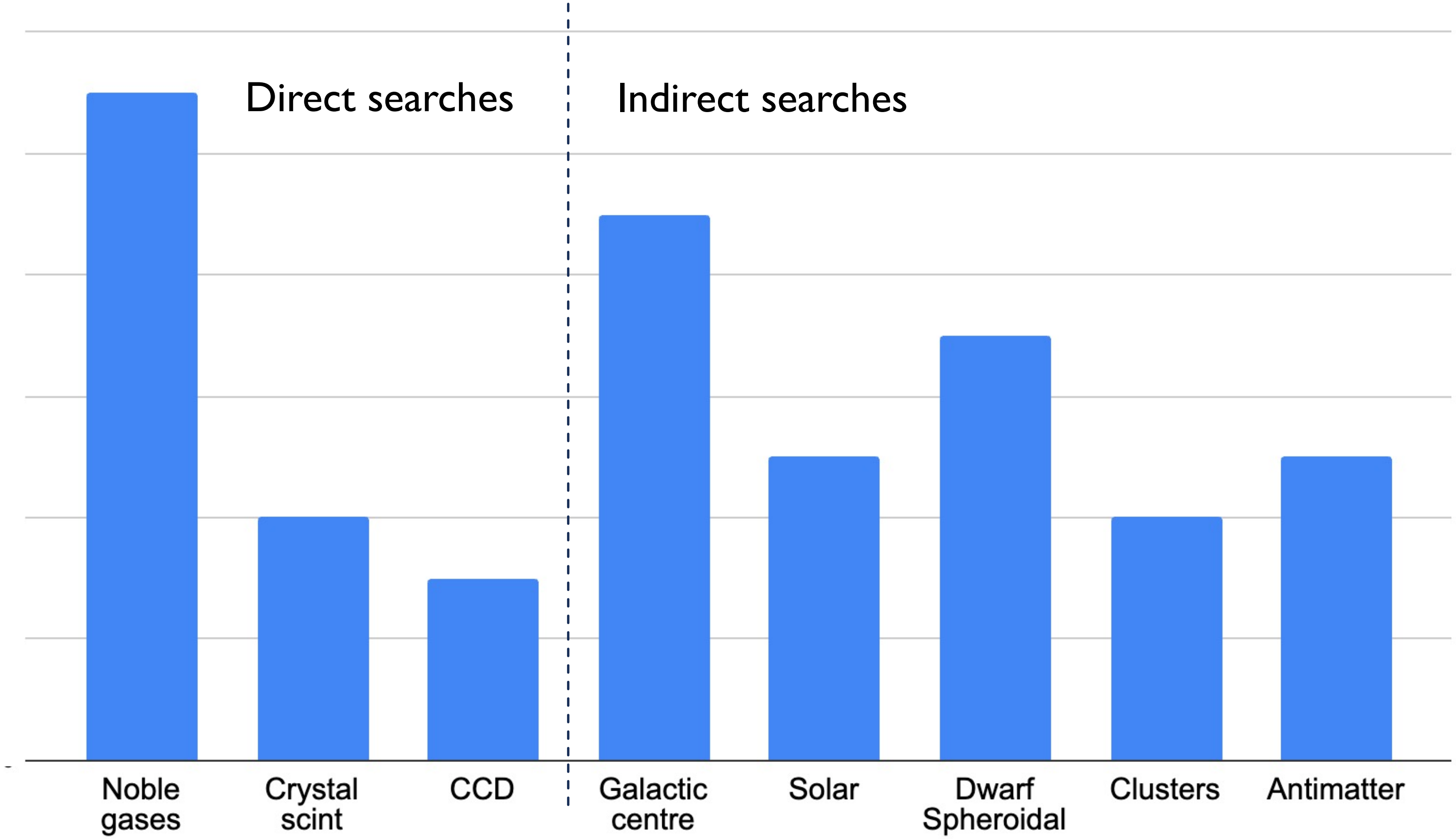
DM THEORIES: ASSUMPTIONS

Lots of model building and assumptions needs to go into test of DM. Have we been making the appropriate ones?

- Removing assumptions about velocity distribution in direct detection relaxes constraints significantly, are we being too aggressive if SHM isn't the way to go? (S. Kang)
- Recent J-factor modelling can change the results for indirect detection by factors 2-6, which is the correct model to use? (McGrath, Kerszberg)
- Can we say something more conclusive about the Galactic Centre Excess with corrections to models with ML? (Eckner)
- Can we improve our simulations of electromagnetic cascades for photon-ALP conversion? (Batista)
- Could DM/MOND be responsible for the Hubble tension? (De Simone)
- Are there other scalar DM models that can be probed by HL-LHC or indirect detection? (Avila)
- How does DM subhalo survival impact gamma-ray DM searches? (Aguirre Santaella)
- How can we appropriately constrain neutrino DM annihilation given their intrinsic model dependence? (Ng)
- Can using the polarization of microwave radiation from DM annihilation improve constraints? (Manconi)

DM: WHERE TO LOOK?

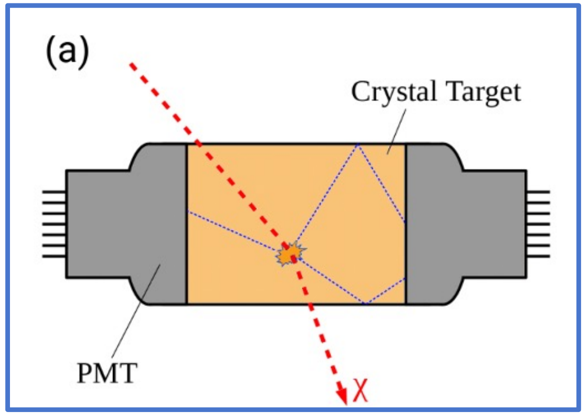
Most searches for DM involve pointing our equipment at something and staring at it. What have we focused on?

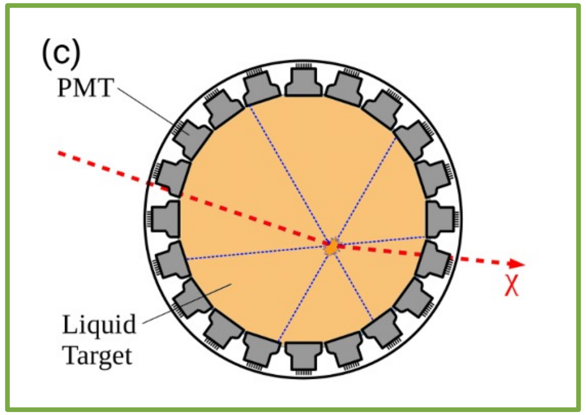


DIRECT DETECTION AT ICRC

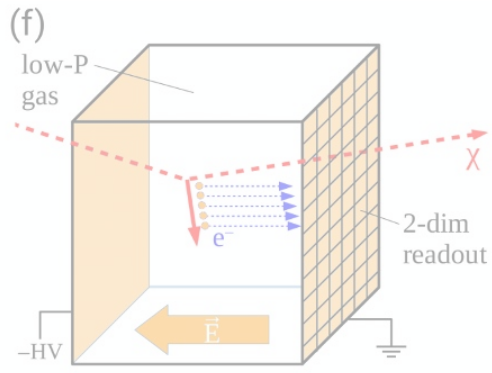
Probing direct scattering of DM with nuclei or atoms. This can produce scintillation, ionization, or phonon signals.

Crystal scintillator
COSINE-100
SABRE
PICOLON

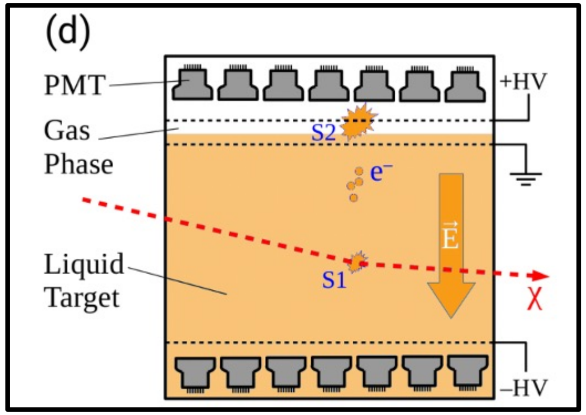


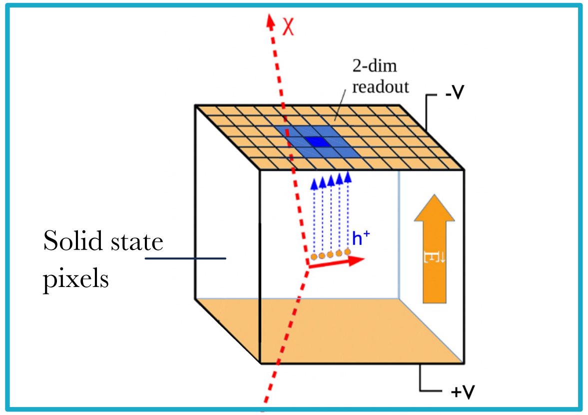


Noble scintillator
DEAP-3600



Dual phase TPC
LZ
XENONnT
DarkSide
DARWIN





CCD
SENSEI
DAMIC
OSCURA

Future: directional TPCs
NEWAGE
Cygnus

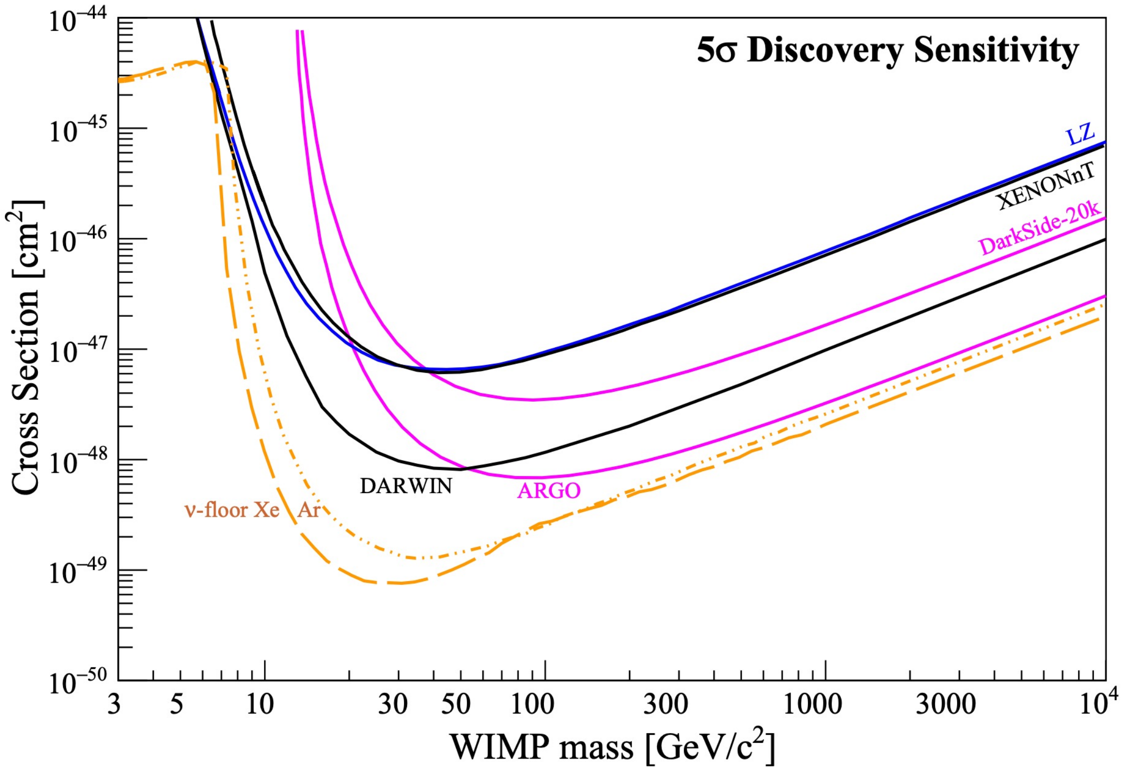
NOBLE GASES

Leading exposure getters for standard WIMP models due to high mass.

LZ (Wang)
- Current world record holders for sensitivity
- Broad physics program planned beyond WIMPs/DM

DEAP-3600 (Tardif, Walczak)
- New results probing WIMP DM, Heavy DM, EFT and velocity substructure
- Using PSD to ID possible events vs background

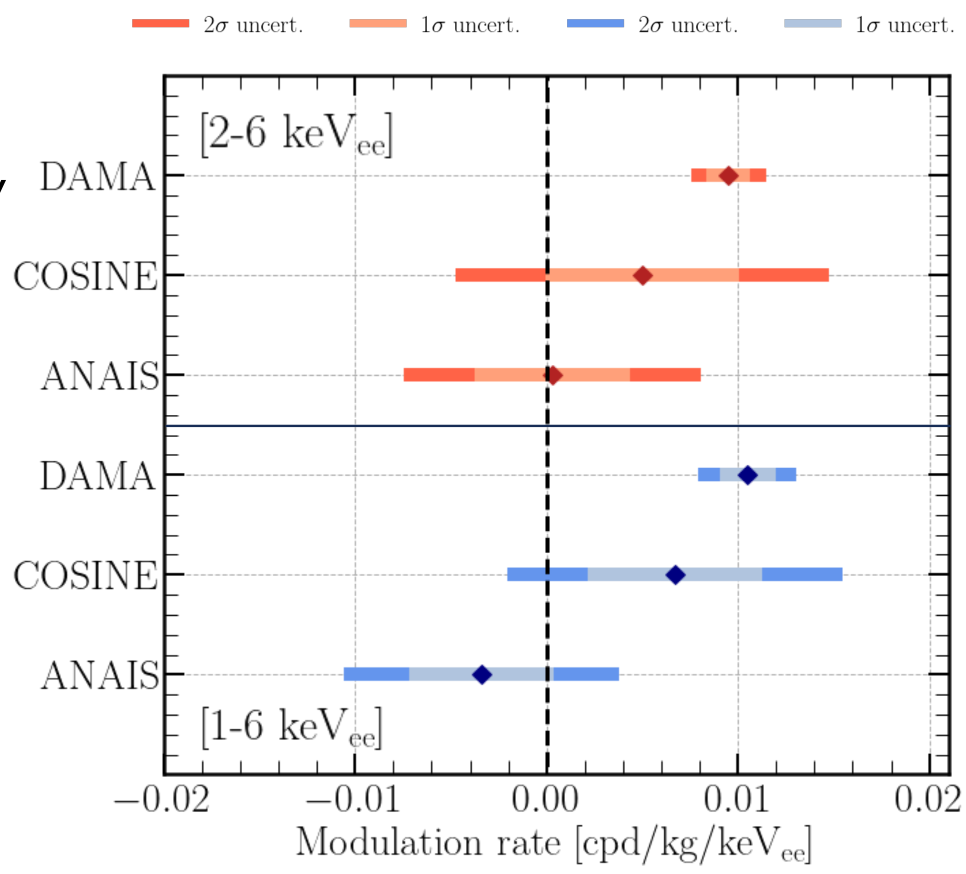
DarkSide (Walczak)
- On track for 2027 data with upgrade, projected to produce limits 10x stronger



XENONnT (Brown)
- Upgrades from X1T with neutron veto + Rn distillation to reduce background
- A few WIMP-y events, but totally consistent with background model
- Use a more conservative statistical approach from limits than LZ

CRYSTAL SCINTILLATORS

NaI(Tl) experiments focused on understanding DAMA modulation.



<u>COSINE</u> (Yu)

- Observed positive modulation with three years of data, but compatible with both null and DAMA hypothesis
- Demonstrated "induced modulation" caused by DAMA analysis strategy can explain the modulation only if their background is increasing
- Run finished, upgrading to larger crystals with lower background and energy threshold

<u>SABRE</u> (Mews)

- Testing modulation in the Southern hemisphere: key to knowing origin
- Lowest background large crystals developed, production starting Q3 2023

<u>PICOLON</u> (Fushimi, Kotera)

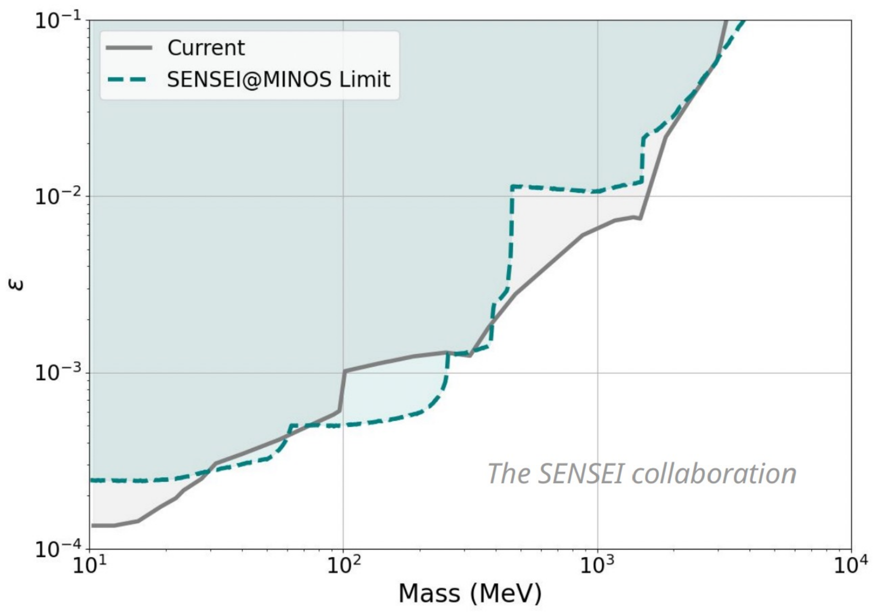
- Ultra-low background results for small crystals with new purification techniques (<0.1 cpd/kg/keV)
- Plan to run with 52 kg in 2025

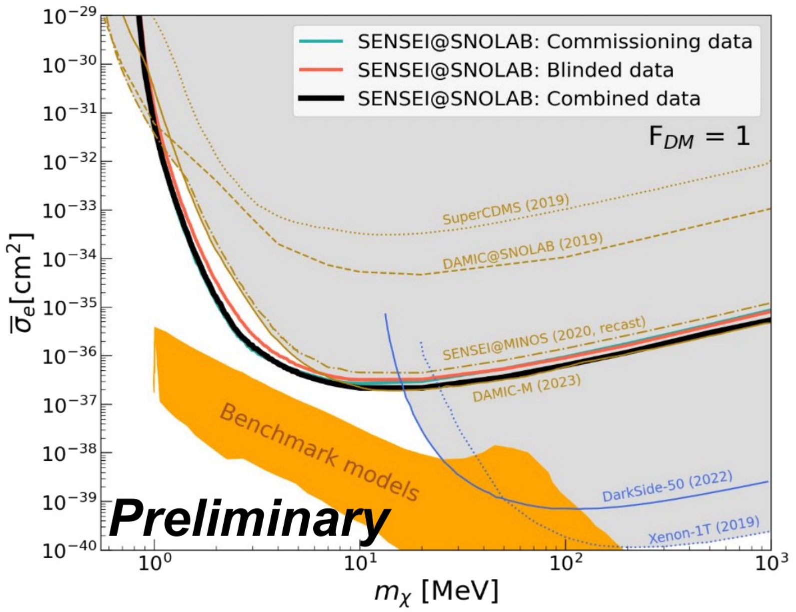
CHARGE COUPLED DEVICES

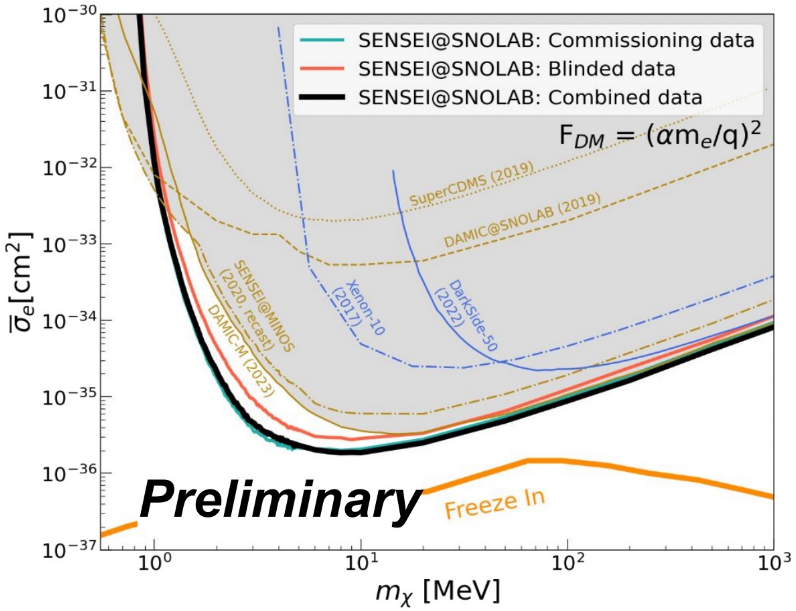
Moving from CCD's to Skipper CCD's has significantly improved sub-GeV detector reach by reducing detector noise.

SENSEI (Botti)
- Searching for DM-e scattering as well as millicharged DM from proton beam
- Possible pilot tech for neutrino searches

DAMIC-M (Gaior)
- Main detector background is dark current – benchmark levels of 4.5E-3 electrons/pix/day
- Skipper CCD setup allows you to trade resolution for read out time
- Installation planned for 2024

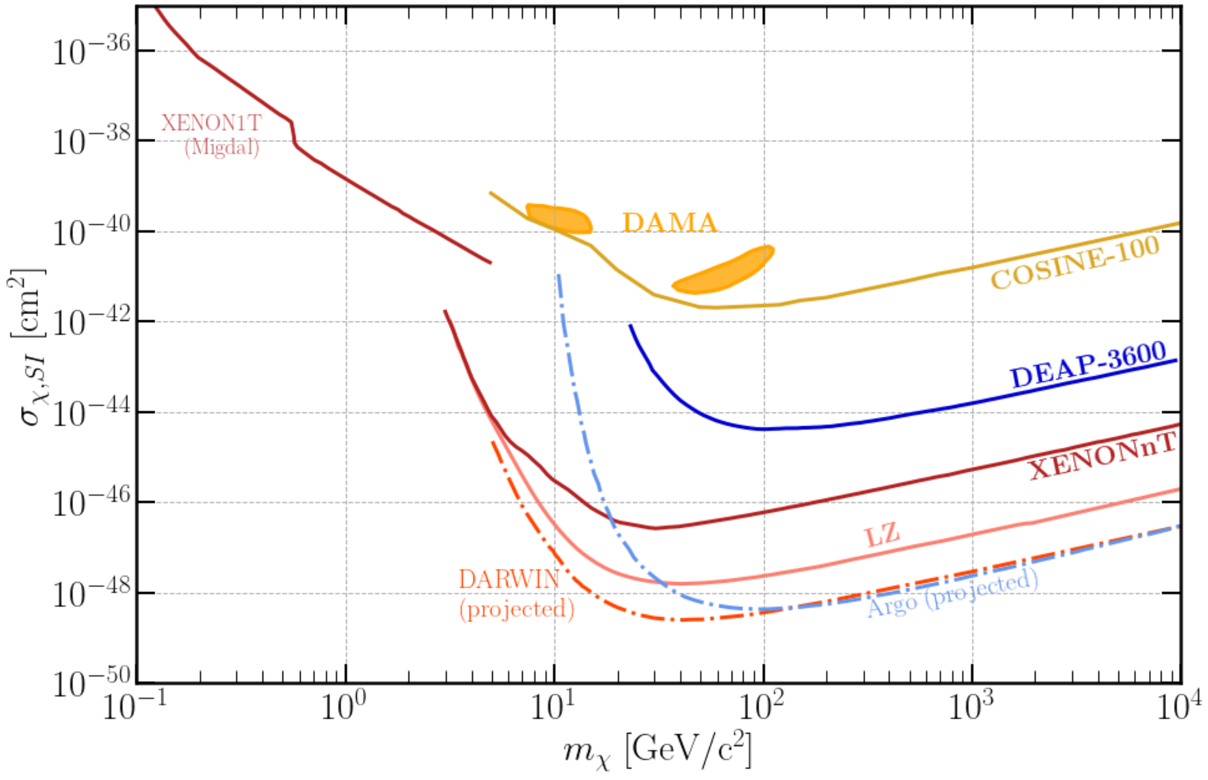




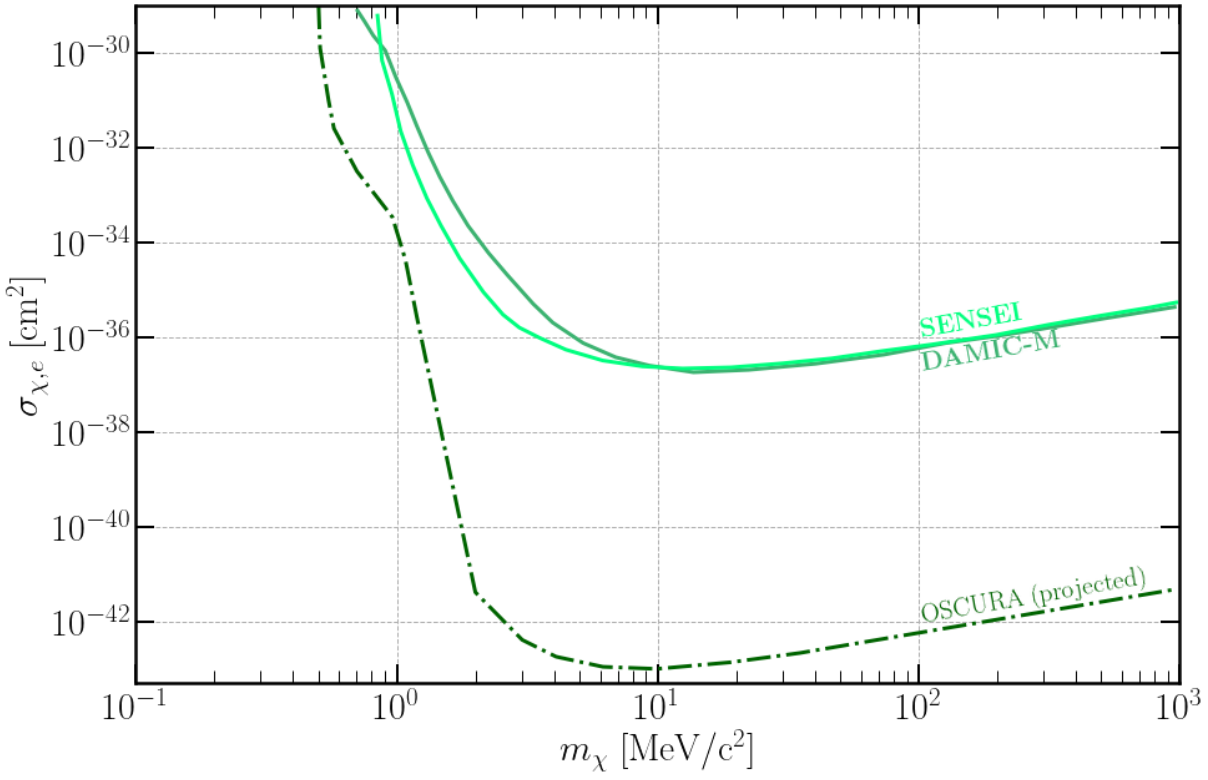


ICRC PRESENT LIMITS

Spin independent nuclear scattering



Electron scattering (F=1)



EXPERIMENTAL R&D

No positive identification of DM announced from direct detection at ICRC. So, how do we improve our experiments?

Scale up!

- Improved Xe purification for XENONnT (Kobayashi)
- Multi channel skipper CCD's (Botti)
- Global Xe collaboration XLZD for next gen (Wang)
- Global Ar collaboration ARGO for next gen (Walczak)
- OSCURA (SENSEI+DAMIC) planned with order of magnitude mass increase (Botti)
- XeLab testing new equipment needed for large scale Xe detectors (Gaior)

Scale down!

- Cryogenic radon reduction for XENONnT (Eising)
- Calibration of nuclear recoils to lower energies (100 eV) to lower thresholds (Erhart)
- Recrystallisation, resin purification, and zone refining developed for low background NaI(Tl) detectors (Fushimi, Mews)
- New low background photo-sensor technology for DARWIN (Hasegawa, Sakamoto)
- Ultra low backgrounds need new inventive ways to measure them, and a possibility it TPCs (Ito)

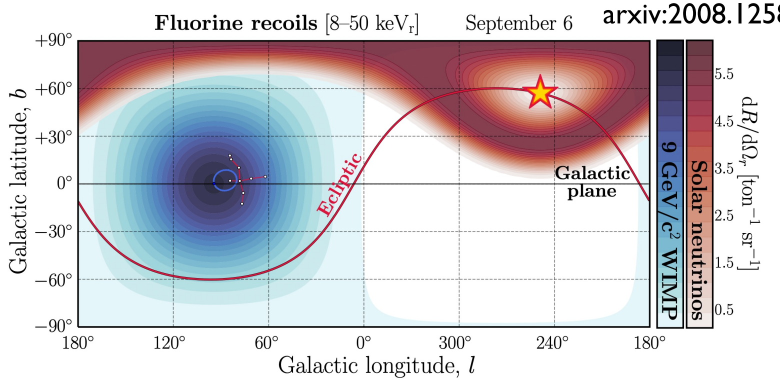
Or go looking somewhere else!

NOVEL DETECTION STRATEGIES

<u>NEWAGE</u> (Higashino)

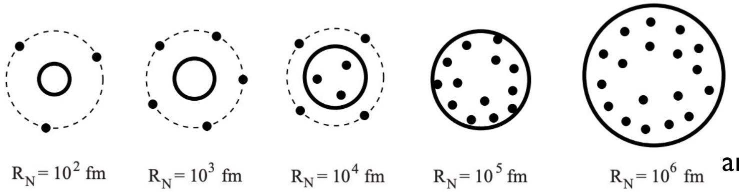
- Detectors able to distinguish direction of tracks can distinguish between neutrinos and DM and pierce the neutrino fog
- Large scale TPC's under development, working with Cygnus to troubleshoot tech

arxiv:2008.12587

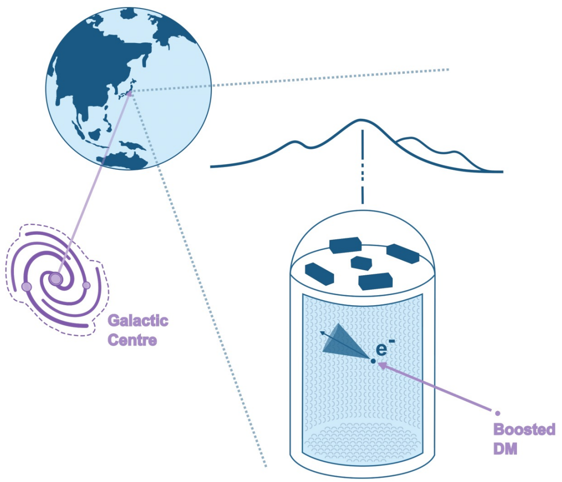


<u>Nuclearites</u>

Macro DM (~10^{30} eV) could be visible directly at neutrino observatories (Paun) or in the sky with Mini-EUSO DIMS (Kajino, Casolino, Mori, Shinozaki)



arxiv:0004019

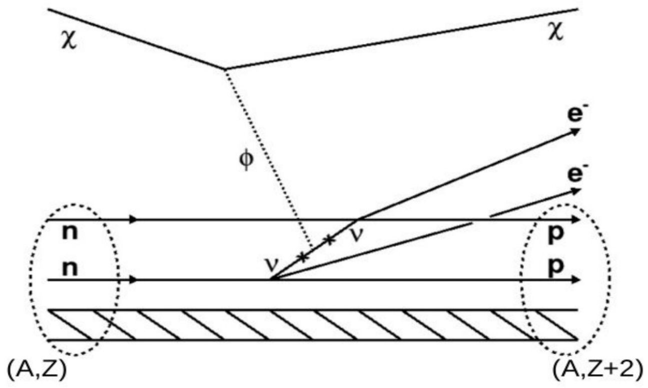


<u>Boosted DM</u> (Iovine)

Low mass, high speed DM can cause low energy electron recoils peaked towards the galactic centre that can be detected at SuperKamiokande

<u>$0\nu\beta\beta$</u> (Nozzoli)

Sterile neutrinos could form a light DM not detectable with typical DD experiment can produce results at $0\nu\beta\beta$ facilities



INDIRECT DETECTION

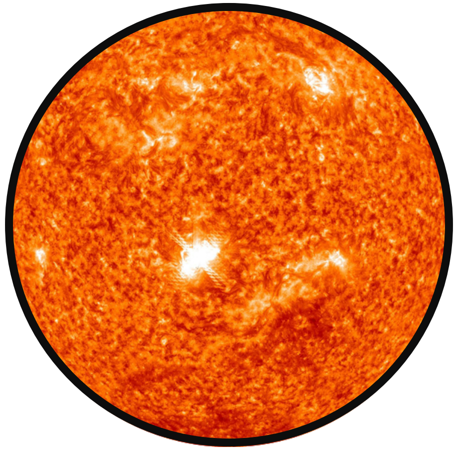
Probes products of DM; decay, annihilation, capture. These can be probed with final state neutrinos, gammas, or anti matter.

Galactic centre

Fermi-LAT
MAGIC
HESS
IceCube
KM3Net
ANTARES
SWGO
HAWC

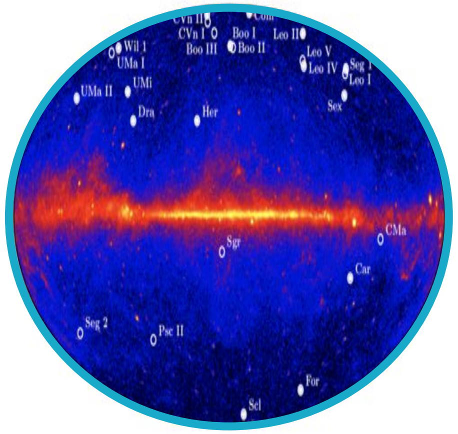
Galaxy clusters

CTA
IceCube
MAGIC



The Sun

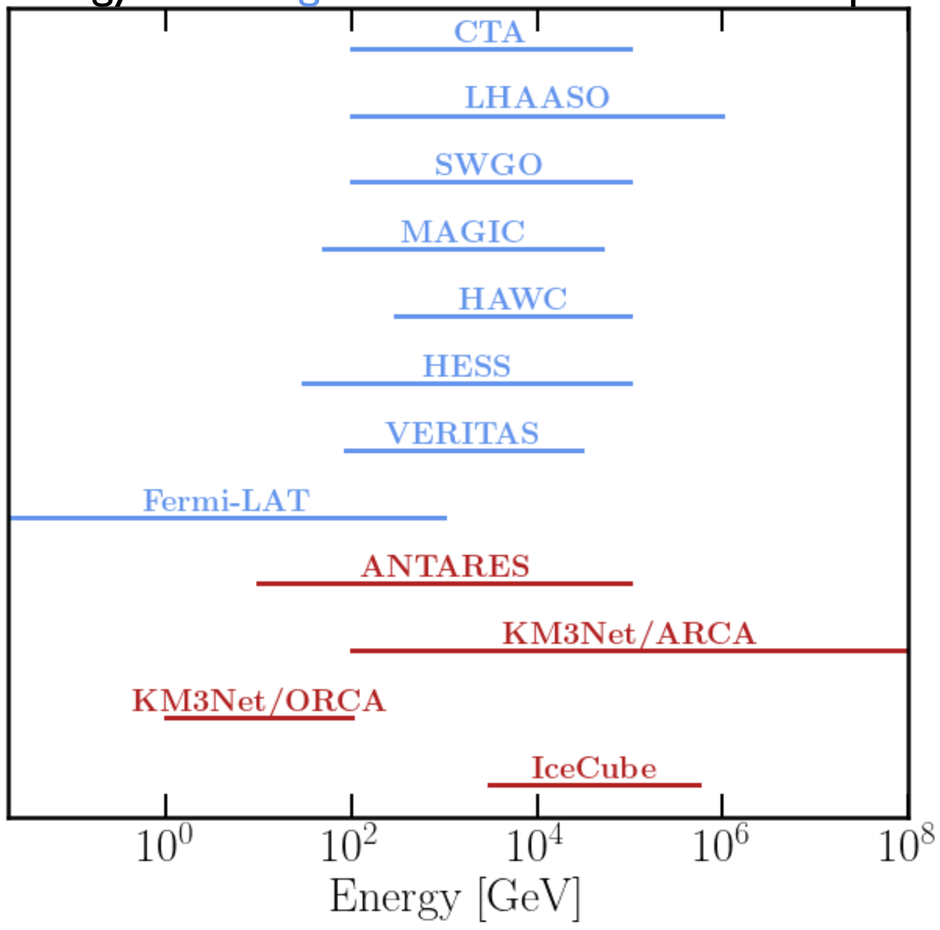
KM3Net
ANTARES
Fermi-LAT



Dwarf Spheroidal Galaxies

LHAASO
CTA
VERITAS
Fermi-LAT
HAWC
HESS
MAGIC
SWGO

Energy RoI for gamma and neutrino telescopes



DWARF SPHEROIDALS

Dwarf spheroidals have a high mass to light ratio and no background making them great for excess searches.

CTA (Saturni)

- 14 candidates analysed with MCMC Jeans analysis with CLUMPY (collisionless, steady state system with negligible rotational support and spherical symmetry).
- Limits on decay lifetime and annihilation cross section set assuming 100 h observation for each dwarf

VERITAS (McGrath)

- 17 candidates observed with no excess, but limits are set beyond the unitarity limit

HAWC (Harding)

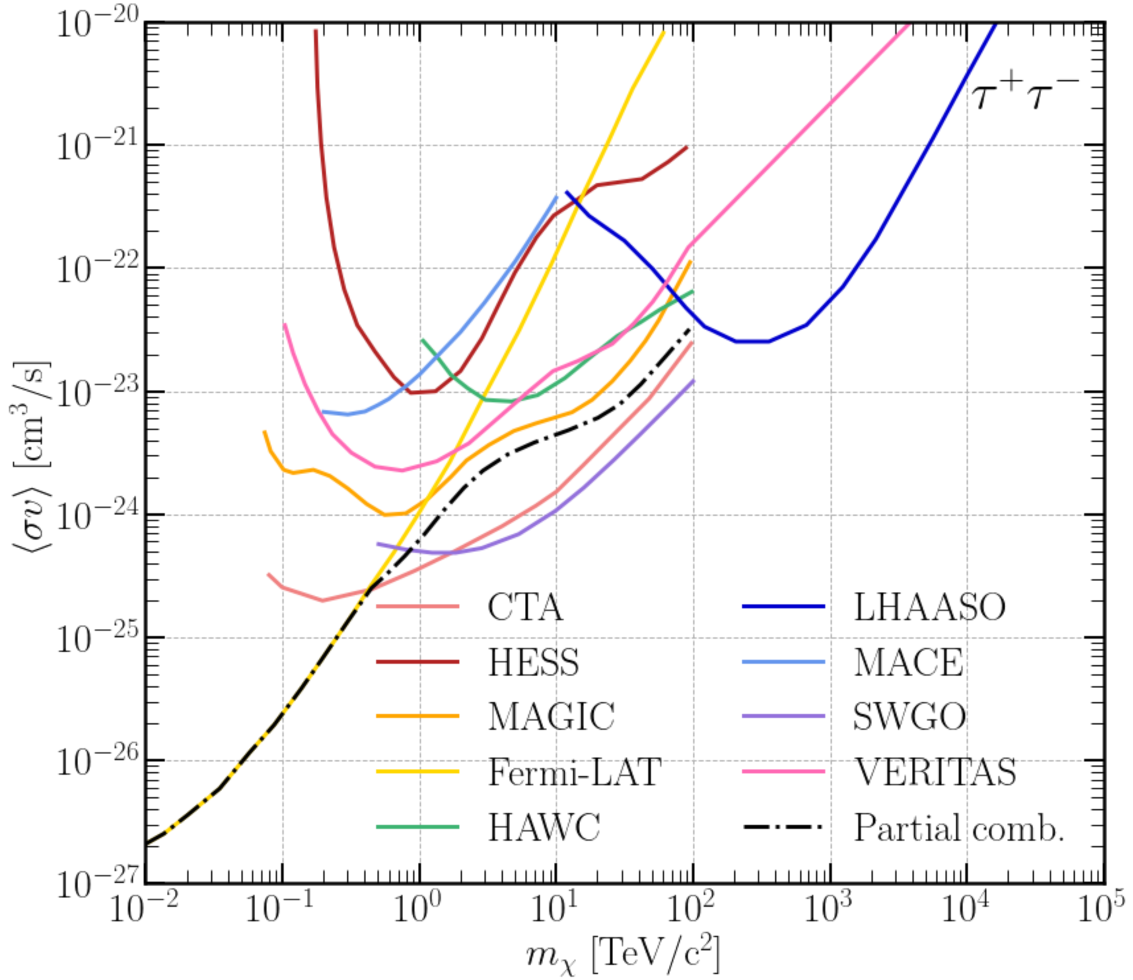
- Wide field of view means HAWC is excellent at detecting candidates, and can constrain at significantly higher energies

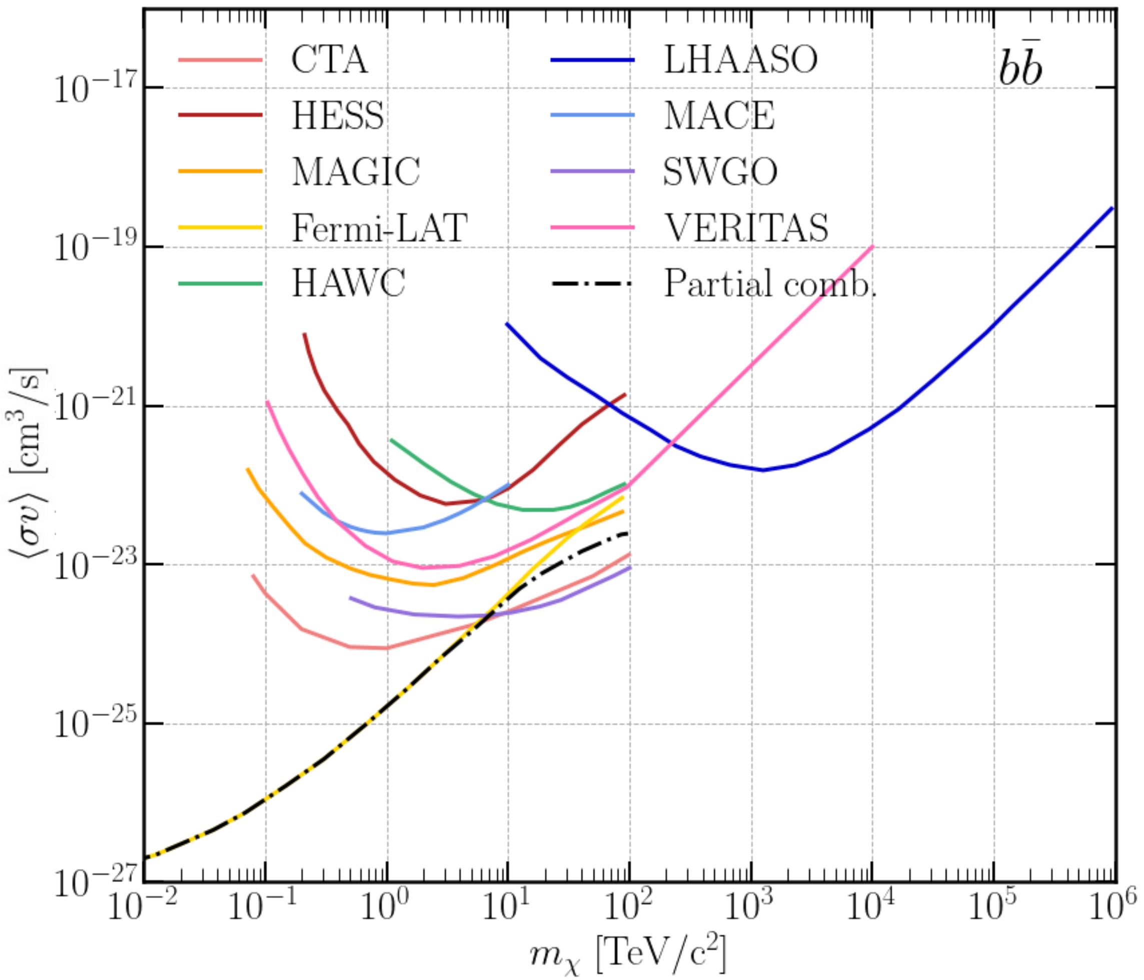
SWGO (Andrade): Projection for upcoming experiment in South America, improves on limits above 1 TeV
LHAASO (Li):16 candidates observed over 794 days and extends mass limits to the EeV region (10^{18} eV)
FAST (Guo): Radio searches for $\mu^+\mu^-$ from Coma Berenices in tension with the Galactic Centre Excess
MACE (Khurana): Feasibility study of 100 h examination of Segue 1

Combined analysis (Kerszberg)

- Combining data from Fermi-LAT, HAWC, HESS, MAGIC and VERITAS to increase statistics
- Uses 45 different data sets made up of 20 candidate galaxies, improves limits by a factor of 2-3

DWARF SPHEROIDALS





NB: some of this is approximate or from preliminary data sets, just want to compare reach of different searches

SOLAR SOURCES

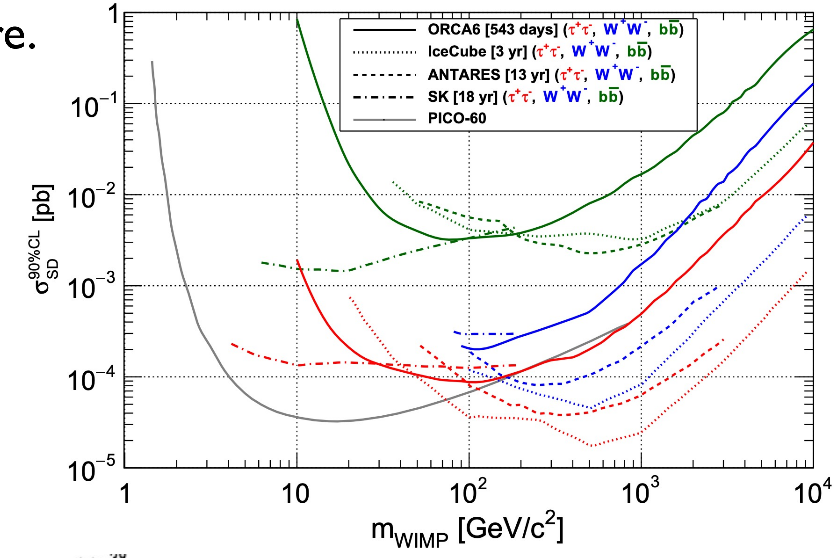
Close to Earth/large in the sky, and presents an ideal candidate for DM capture.

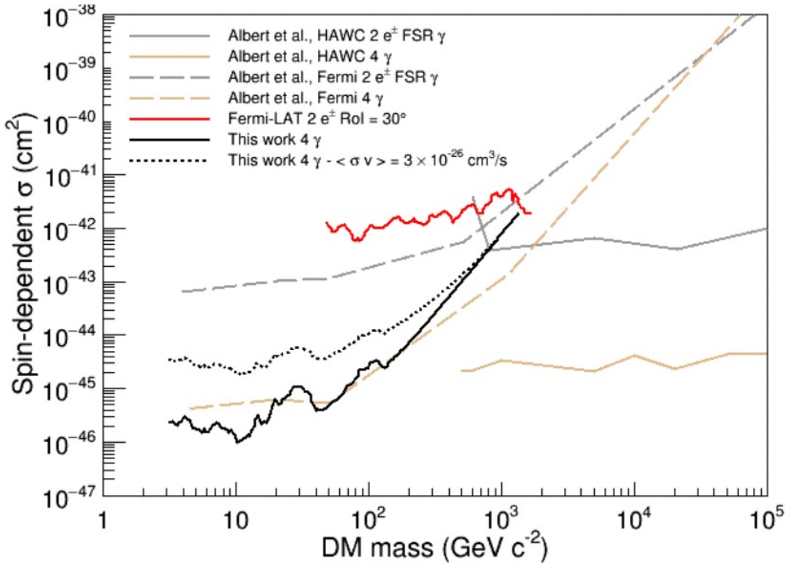
<u>KM3Net</u> (Šaina, Gutierrez)
- Solar analysis done with 534 days of ORCA neutrino data
- Results are competitive with other telescopes and PICO in spin dependent regime

<u>ANTARES</u> (Garcia-Mendez)
- To observe this solar neutrinos, excellent detector resolution is required
- This can be improved by using ML techniques

<u>Fermi-LAT</u> (Serini)
- Enhanced photon flux from either direct decay or decay with intermediaries.
- Shape of spectrum will depend on the exact process

<u>ISAI</u> (Onuki)
- Solar axions from Fe-57 cause distinct energy depositions that can be observed on Earth





GALACTIC CENTRE

Nearby with high dark matter content, but high backgrounds and uncertain background profile.

KM3Net (Šaina): GC analysis done with 300 days of ARCA data. Represents a small percentage of expected lifetime, and already comparable to other experimental results

HESS (Moulin): Provides visibility from the Southern hemisphere, looking for annihilation lines in the GC. None seen so limits set on TeV scale DM

Fermi-LAT (Mazziotta): Also looking for annihilation lines, but down to lower energies (GeV). No excess observed.

MAGIC (Inada): Energy reaches up to 100 TeV can probe TeV scale DM with gamma ray lines.

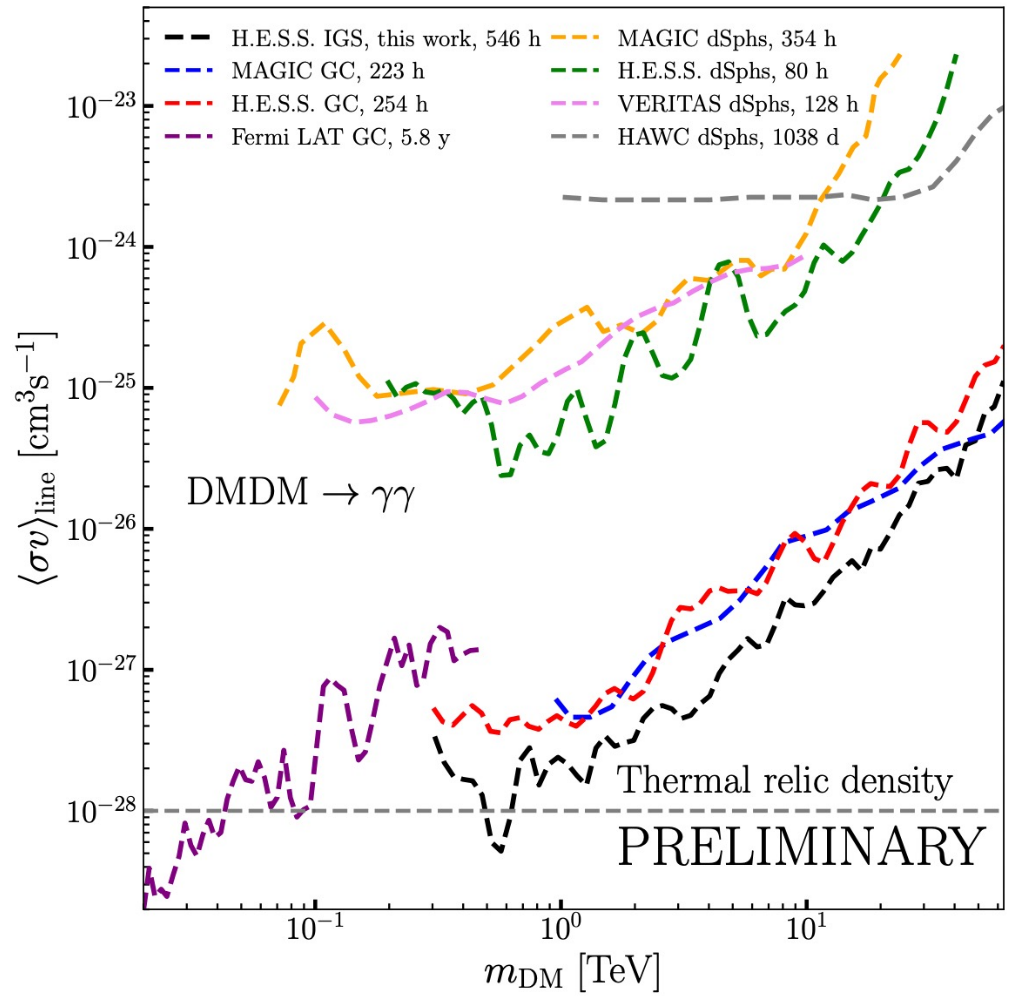
IceCube (Chau): Can constrain DM lifetime and/or annihilation cross section from neutrino spectrum. Large number of intermediate processes considered

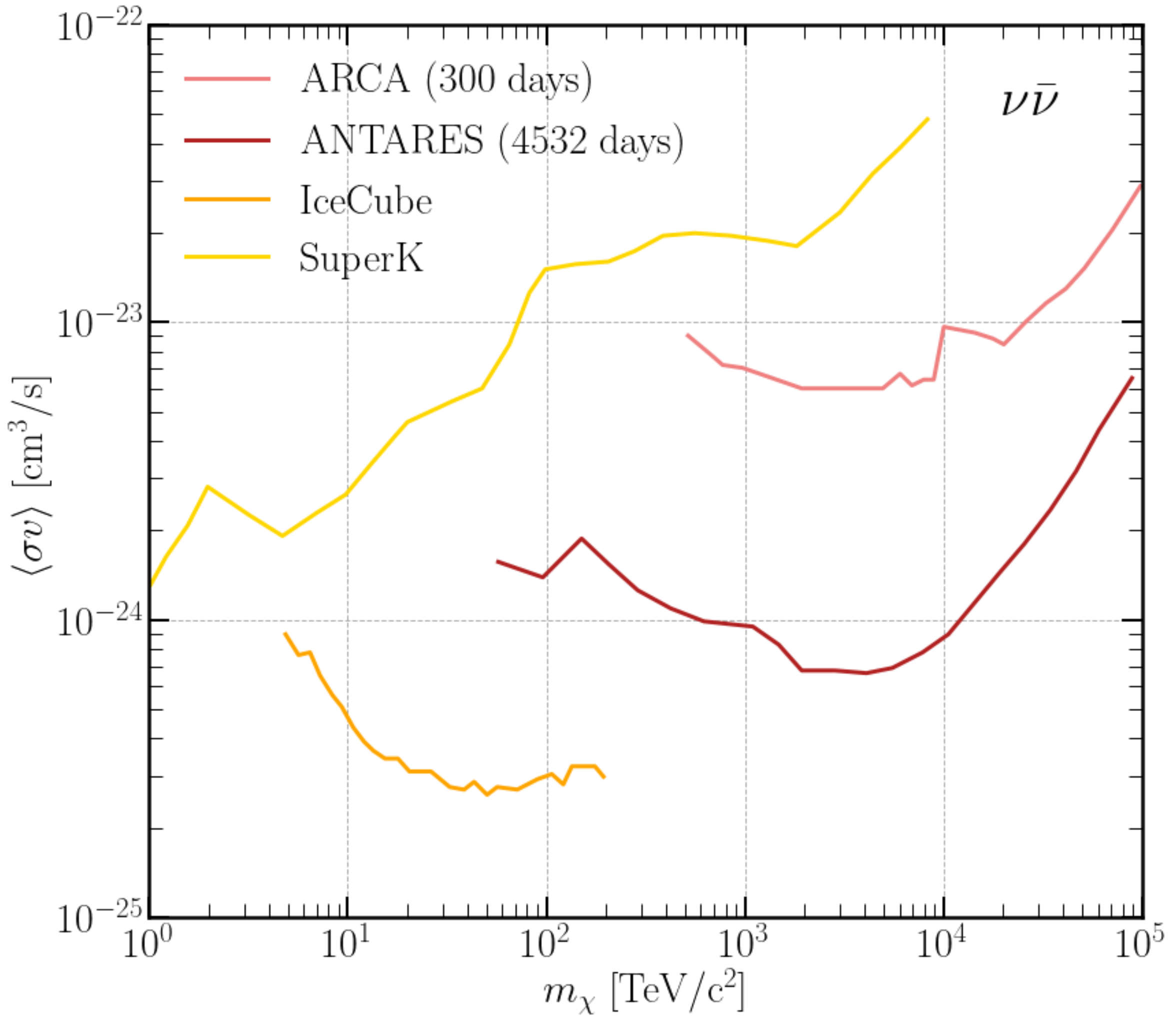
ANTARES (Gozzini): Pair annihilation and decays of WIMPs that can produce GeV-TeV neutrinos in the GC constrained

SWGO/CTA: Sub GeV scattering from cosmic rays with deep inelastic scattering causes deviations to the cosmic ray flux that can probe DM masses on the keV-MeV scale (Reis). SWGO can also place limits on PBH, ALPs, and WIMPs (Harding)

HAWC (Harding): Smooth component of Galactic dark matter covers the whole sky and peaks in the GC, which HAWC is very sensitive too. Can constrain PBH, ALPs, and WIMPs

GALACTIC CENTRE





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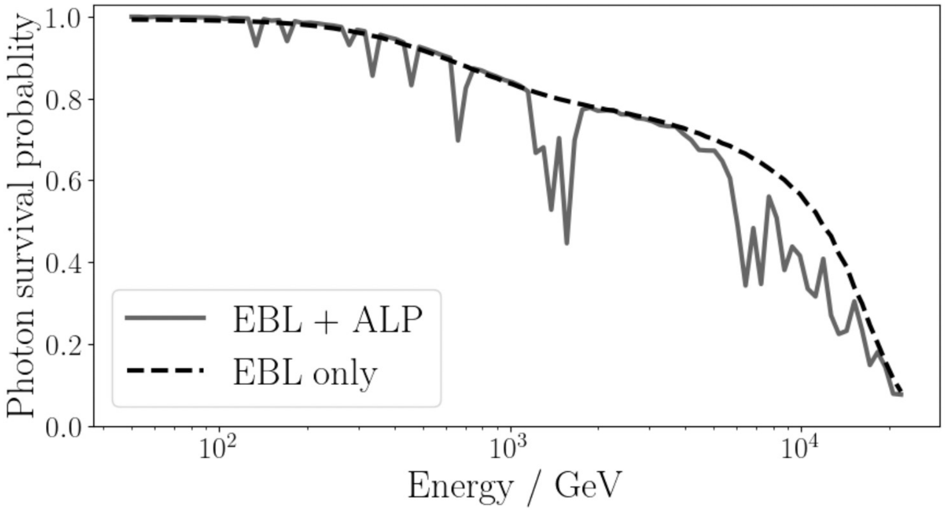
GALAXY CLUSTERS

High DM content, but far away and background contaminated.

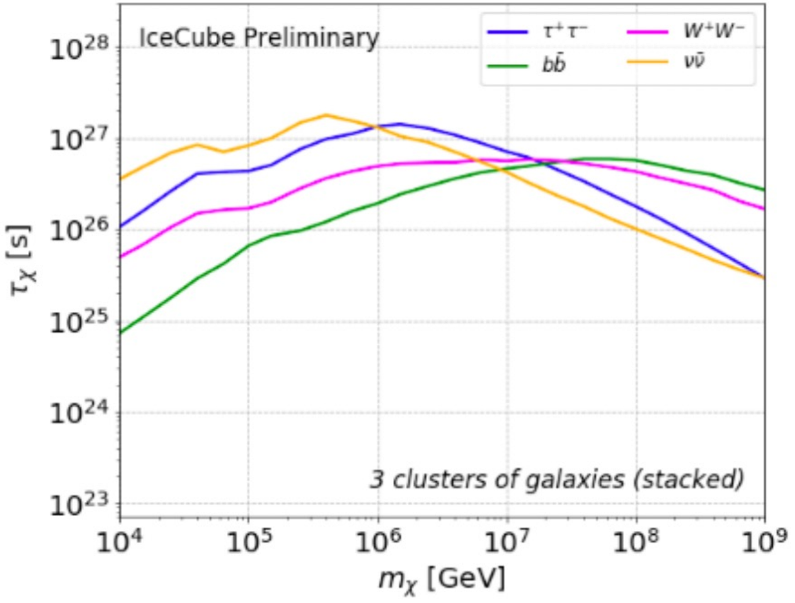


CTA (Hernandez-Cadena)

- Gamma ray excess from Perseus Cluster allows for annihilation and decay constraints on TeV scale DM

MAGIC (D'Amico)

- Search for deviations in expected photons observed from the Perseus Cluster that could be caused by conversion into ALPs
- Hints that there might be ALP impact, but not statistically significant and dependent on magnetic field modelling



IceCube (Jeong)

- High energy astro neutrinos observed at IceCube could be from heavy (TeV-PeV) scale WIMP.
- Can be used to put limits on lifetime

ANTIMATTER

Galactic DM decay or annihilation can produce various types of antimatter.

AMS (Lu)
- Searching for antideuteron in the GeV region
- A few candidate events seen, but nothing statistically significant

GAPS (Stößl)
- Searching for light cosmic ray anti-nuclei; a complicated search with difficult backgrounds
- GAPS has good sensitivity in the low energy (MeV) region, launching end of 2024

GRAMS (Zeng)
- Balloon measurement to look for MeV gamma ray excess and anti matter produced in DM interactions
- Low energy anti He-3 search can provide an almost background free channel

ALICE (Šerkšnytė)
- Need to understand anti He-3 survival, which requires knowledge about inelastic scattering
- ALICE can give us information about this using LHC antimatter production; ~50% survival

CALET (Motz)
- Previous assumptions about antimatter background model is that its smooth, but this isn't the case!
- Properly modelling all sources gives more reliable limits

*signal seen compatible with ALPs, but not statistically significant

OTHER ASTROPHYSICAL ODDITIES

Axion conversion

- Can produce deviations in the gamma flux observed by HAWC (Pratts, Harding)
- Can impact high energy (20 TeV) gamma ray bursts* (Rojas)

Neutrino point sources (W. Kang)

- Allow for constraints on generic DM-neutrino interactions that attenuate the neutrino flux

Heavy DM

- Various DM decay processes can produce a diffuse flux of very high energy gammas (Ng)
- Can cause cascaded gamma rays that could be detected by Fermi-LAT (Song)

PBH (Tan)

- Small window of mass for DM, can be tested with cross correlation with gamma rays and CMB shear

TeV blazars (Ghosh, Jacobsen)

- There are events we expect to see but don't, pointing towards the existence of ALPs with masses* 10^{-10} to 10^{-9} eV

Starburst nuclei (Ambrosone)

- DM-proton interactions can cause strange behaviour for cosmic ray transport

Omega Centauri (Beck)

- Recent modelling has suggested a dense DM core
- Due to its proximity to earth this could be a better probe than Dwarf Spheroidals

Earth capture (Aguilar Sanchez)

- Slow DM gravitationally trapped in the Earth can produce neutrinos

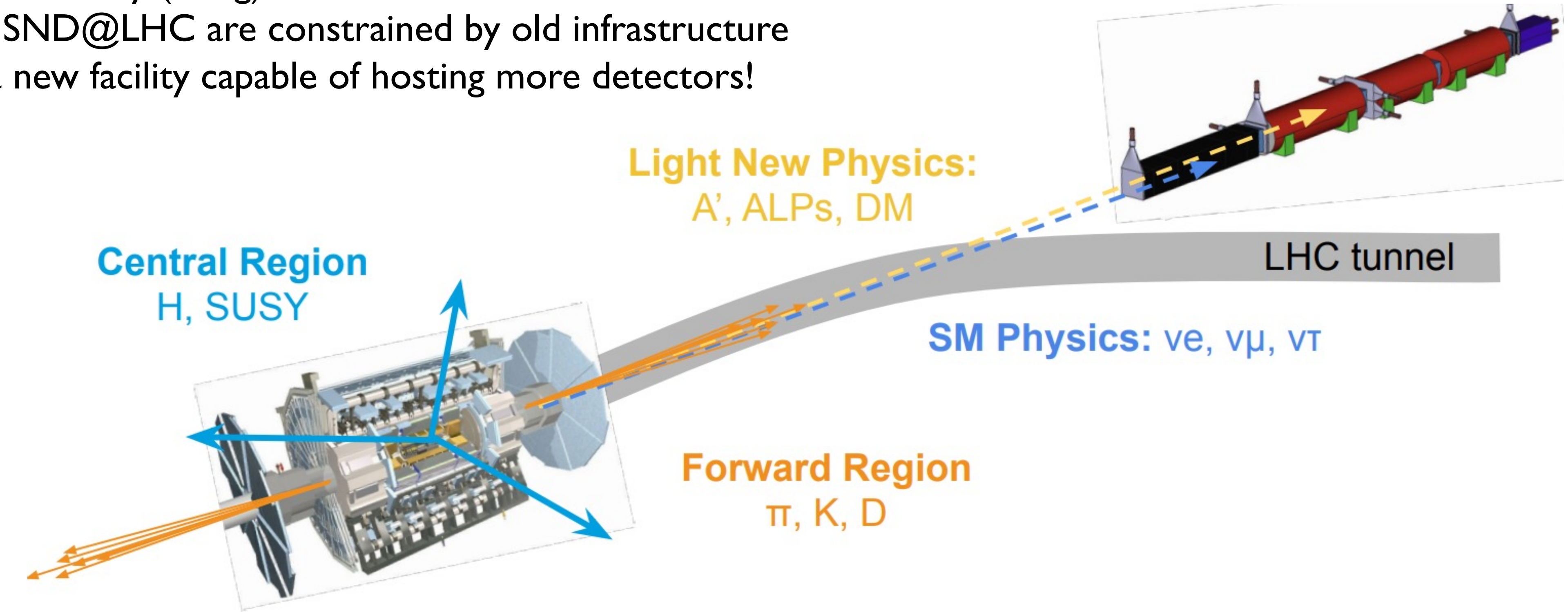
Neutrino flavour (Katori)

- Flavour ratio on Earth is well constrained, so astrophysical DM that interacts with ν_τ, changing this can be constrained

ADDITIONAL SEARCHES

FASER (Inada, Kling)
- Far forward experimental setup to probe neutrinos and long lived particles at the LHC
- New exclusion limits set on dark photon mediators

Forward Physics Facility (Kling)
- FASER and SND@LHC are constrained by old infrastructure
- Lets build a new facility capable of hosting more detectors!

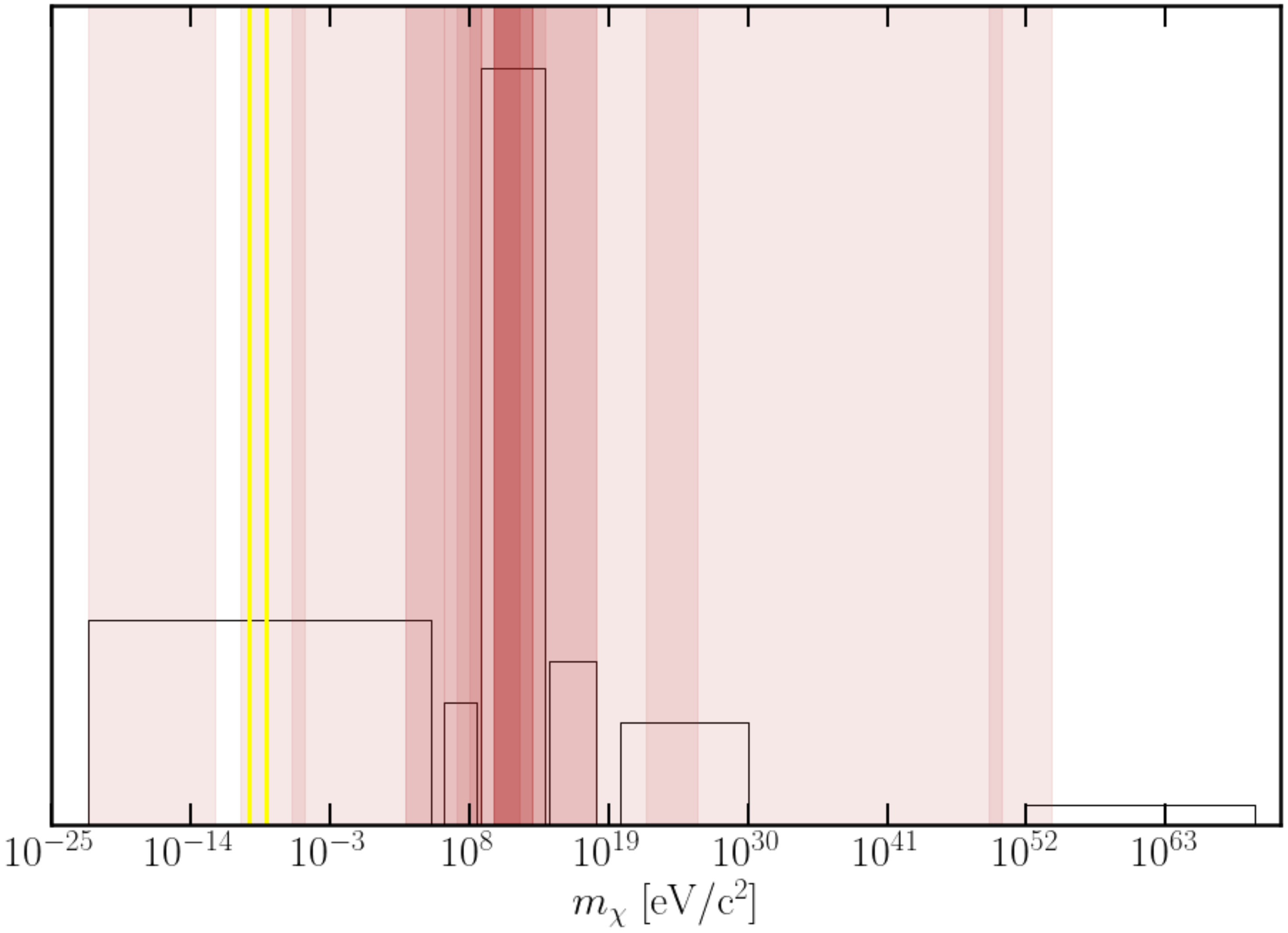


ICRC LIMITS

Difficult to construct a single plot that demonstrates the full reach of DM searches at ICRC.

Instead, show the mass reach of presented sensitivities to demonstrate the complementarity of methods.

Yellow lines indicate positive hints mentioned during talks!



FINAL THOUGHTS

One scientist's background is another scientist's signal. Conferences like ICRC allow us to compare identification methods and strengthen both cosmic ray and dark matter searches.

As detectors scale up in cost and personnel, it is important to squeeze out as much physics as we can. Particularly notable to me at ICRC that so many experiments are reporting results/limits for physics they were not originally designed for, especially neutrino detectors.

Although we haven't seen any conclusive DM, the presentations have demonstrated impressive results and projections, with significant and innovative R&D for detector design, construction, and analysis promising future upgrades across the DM mass space.

Personal highlight: emphasis on global collaboration, open data, and combined analysis. No matter how powerful the detector, there is no way for a single experiment to understand DM if (when!) we see a signal. Good to see the community moving towards a more inter-collaborative approach, and utilize complementarity of different detection methods