The Path to Dark Matter

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Cosmic Frontier
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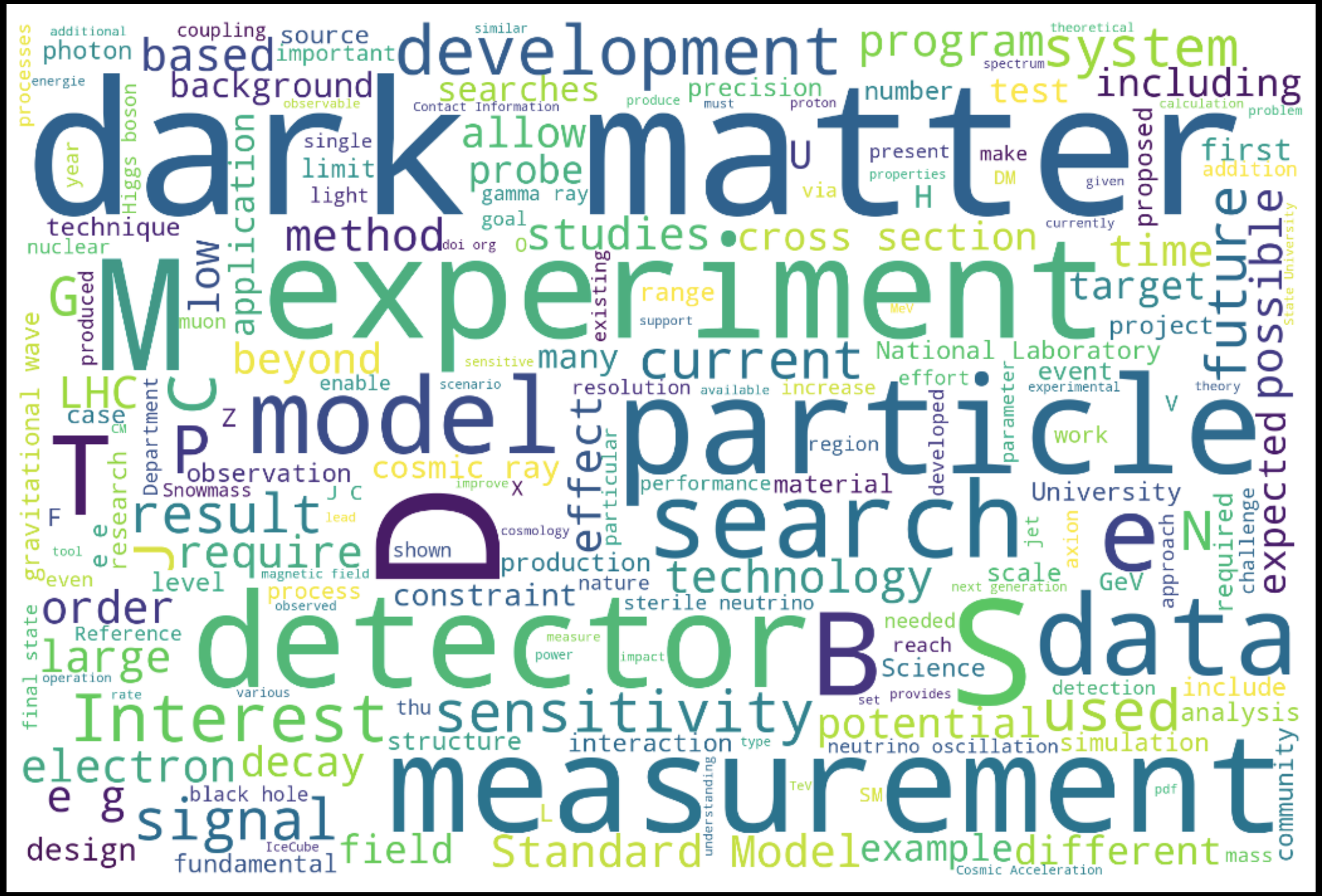
Thanks to everyone who gave feedback and made suggestions, in particular Luis Anchordoqui, Aaron Chou, Jodi Cooley, Philip von Doetinchem, Alex Drlica-Wagner, Hugh Lippincott, Kerstin Perez, Gray Rybka, Bangalore Sathyaprakash, Marcelle Soares-Santos, Tim Tait, Lindley Winslow, Risa Wechsler & Tien-Tien Yu



- The nature of dark matter (DM) is an outstanding puzzle of fundamental physics
- DM is a challenge that crosses many Frontiers, but our current knowledge of its properties and our hopes for establishing its identity rely on Cosmic Frontier searches

A path to discovery at the Cosmic Frontier

- The coming decade will be an exciting time for searches aiming to characterize dark matter. A non-exhaustive list of examples:
  - For the first time, axion searches will have sensitivity to the QCD axion across a vast mass range
  - Mature direct-detection technologies will probe orders of magnitude of new parameter space, into the neutrino fog, covering a range of highly-motivated and parsimonious scenarios
  - New technologies allowing detection of very low-energy recoils will test entirely new physical regimes and scenarios for DM production
  - Photon and cosmic-ray telescopes will have the capability to test thermal relic dark matter up to masses comparable to the unitarity bound, and seek signals in new background-free channels
- This talk: explore <u>one</u> (optimistic) scenario for the discoveries these advances could unlock, over the next 10-15 years

A multitude of well-motivated possibilities

- I will focus here on probing DM through its possible (non-gravitational) interactions with visible particles

- Even in the absence of such interactions, there are powerful cosmic probes of the DM mass, spin, velocity, self-interactions, and distribution throughout the universe, which complement the search channels I will discuss

- Additionally, there are currently a number of interesting excesses/anomalies in indirect/direct detection

  - For the purposes of this talk I will assume <u>all</u> of them are telling us about systematics/backgrounds rather than DM

  - Not necessarily true - but there is already plenty of interesting literature on discovery paths if one or more is a DM signature

- In one hypothetical cosmos, let's take a tour of the next decade+…

HYPOTHETICAL FUTURE TIMELINE

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SENSEI-100g finds a small near-threshold excess

GAPS finds a single antideuteron event in their first flight

Associated efforts/ questions/ inferences

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Associated efforts/ questions/ inferences

- SENSEI signal consistent with ~eV DM absorption or few-MeV DM scattering on electrons
- First detection of low-energy antideuterons from any source - if DM origin, suggests higher mass scale (> few GeV)

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Associated efforts/ questions/ inferences

- Accelerator studies of cosmic-ray cross sections, and better modeling of propagation through Galaxy, reduce theory uncertainties for AMS-02
- Intensive study of neutrino and other possible backgrounds in xenon experiments

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Associated efforts/ questions/ inferences

- Intensive effort to study backgrounds & threshold effects in SENSEI & DAMIC
- Null results from accelerator experiments exclude parameter space for SENSEI signal
- New models developed for high-energy Galactic gamma-ray emission using multiwavelength data, ahead of CTA/SWGO

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Associated efforts/ questions/ inferences

- Is the signal actually a QCD axion?
- If so, suggests new physics at ~10^{14} GeV scale - possible new states to search for?
- Such a QCD axion would be created pre-inflation: immediately sets upper bound on scale of inflation

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Associated efforts/ questions/ inferences

- Simultaneous fit to AMS-02 + CTA + GAPS data suggests multi-TeV DM annihilating primarily to quarks (needed to get antideuterons)
- Cross section is >> thermal benchmark - implies non-thermal origin or late-time enhancement

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Associated efforts/ questions/ inferences

- COSI and AMEGO-X set stringent upper limits on MeV-band gamma ray signals from DM, ruling out parameter space for SENSEI+ excess
- Cosmological searches for eV-scale light relics constrain absorption explanation

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Associated efforts/ questions/ inferences

- Once axion signal is detected, discovery instrument can function as a "DM telescope"
- Enables possible tests of axion fraction by comparison to cosmic probes of DM structure

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Associated efforts/ questions/ inferences

- Spectrum consistent with heavy DM > TeV
- How does the DM candidate couple to the SM?
- Combined fits to xenon + argon + indirect detection + lack of spin-dependent signal constrain operators/ couplings

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SWGO measures TeV+ morphology - consistent with cored DM halo

CTA detects a faint gamma-ray line at 7.5 TeV

Associated efforts/ questions/ inferences

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Associated efforts/ questions/ inferences

- Mass of 7.5 TeV
- Combined data breaks cross-section/density profile degeneracy
- Improved background models + multimessenger spectrum measurements allow detection of subdominant branching ratios (into gauge bosons, leptons, etc)

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Associated efforts/ questions/ inferences

- Multiple detections with different methods allow testing for systematics
- Detections at different experiments can permit directionality studies by comparing signal phase - measure full 3D velocity distribution

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Associated efforts/ questions/ inferences

- Low-energy spectrum is sensitive to the velocity-dependence of the scattering
- Rules out absorption hypothesis
- Favors very light mediator
- Signal consistent with freeze-in of subdominant component

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- First direct measurement of velocity distribution of heavy DM component
- Improved mass constraints from XLZD + DarkSide-20k still consistent with TeV+ DM

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GAPS finds a single antideuteron event in their first flight

AMS-02 reports first antideuteron candidate + antiproton results extending above 500 GeV

LZ and Xenon-nT report full-run results; handful of events detected, weakening limits at high DM mass

DAMIC-M confirms SENSEI signal with higher statistics

In-depth study of modulation over time

DMRadio-m^3 detects signal consistent with 100 neV axion with ~QCD coupling

3rd GAPS flight finds more antideuterons

First CTA study of the Galactic Center reveals excess TeV+ diffuse emission

SuperCDMS & OSCURA independently measure recoil spectrum at eV+ scale

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CTA detects a faint gamma-ray line at 7.5 TeV

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Directionality study using multiple experimen

TESSERACT achieves 0.01 eV threshold & measures low-energy spectrum

Darwin/ XLZD measures recoil spectrum precisely

CASPEr detects defining EDM coupling

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Associated efforts/ questions/ inferences

- Consistency check on QCD axion explanation, although still degenerate with axion DM fraction
- Combined coupling measurements constrain model parameter space, potentially pointing to new collider signatures (e.g. expanded Higgs sector for DFSZ axion)

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Associated efforts/ questions/ inferences

- Could suggest additional DM components, or substructure in 7.5 TeV particle - DM spectroscopy!
- Velocity dependence of cross section tested by searches in dwarfs, clusters - can reveal dark forces, test consistency with thermal freezeout

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Associated efforts/ questions/ inferences

- New high-scale physics? Could it be connected to the axion?

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7.5 TeV thermal relic (?) interacting directly with SM

MeV dark sector populated via freeze-in (?) with a light mediator

100 neV QCD axion

Do they interact with each other? What (if any) is the associated spectrum of non-DM particles? Are they part of a single dark sector / is there a unified theory of dark matter?

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Where next? Many new opportunities…

Search for new high-scale physics - cosmology, UHE CRs/gammas/neutrinos, gravitational waves, ultraheavy DM direct searches?

Search for light particles associated with MeV-and-lighter dark sector - cosmology? wavelike scalar/vector DM searches?

Directional detection and paleodetectors to map the halo now and in the past?

Antideuterons/antihelium as a new cosmic probe with next-gen cosmic-ray experiments?

Neutrino counterparts with KM3NeT or successors?

Possibility of muon-collider detection of multi-TeV dark matter/sector?

precisely

defining EDM coupling

spatially correlated with high-energy emission

Galactic center by GCOS or POEMMA

Sensitive high-energy-resolution MeV-band telescopes find even lower-energy counterparts

2035

2036

Paths not taken (today)

- Many of these discoveries would be made by different experiments given slightly different underlying physics, e.g:
  - Heavier QCD axions could be probed by other experiments (in particular ADMX-EFR), and could have striking cosmological signatures (CMB B-modes, DM substructure, even gravitational waves from the PQ phase transition)
  - A GeV-scale dark matter candidate scattering on nucleons would likely be first detected by SuperCDMS (and other mass scale / mediator / channel combinations could provide other paths to discovery)
- If the thermal WIMP was an order of magnitude heavier, or the DM density profile was different than assumed here, the relative sensitivity of different high-energy gamma-ray experiments (and neutrino and cosmic-ray experiments) would be modified
- And many more examples…

The proposed programs are <u>versatile</u> and cover a great deal of ground

General lessons

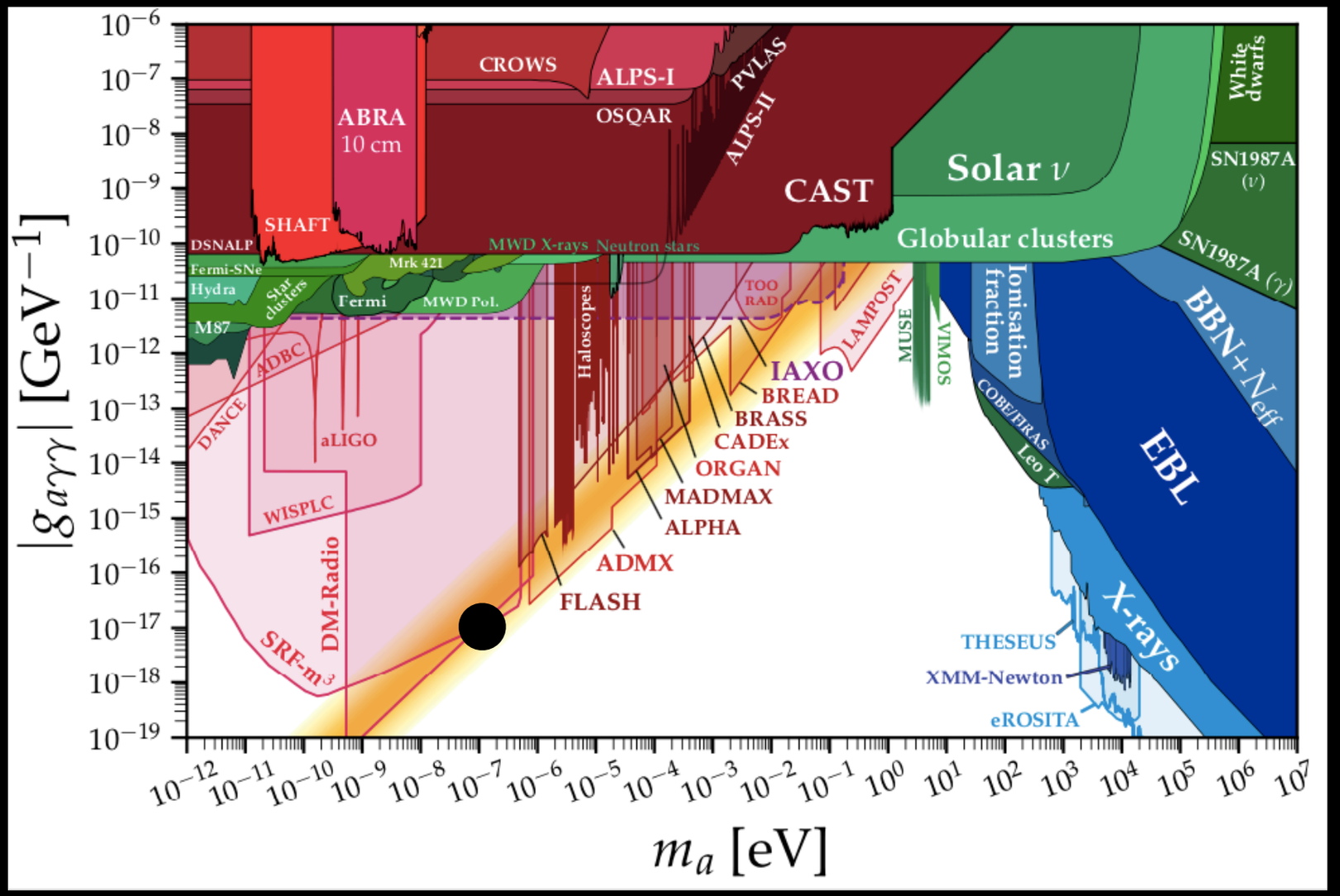
- This decade will see great advances in sensitivity across an enormous range of models and detection channels
- Two forms of complementarity, and both are valuable:
  - A broad, multi-scale experimental program allows us to test many different scenarios
  - In the event of a detection, such a program also enables us to cross-check our results and triangulate the properties of the dark matter
- Support for theory and study of systematics, backgrounds, and calibration are essential to understand what these sensitive experiments will tell us
- With regard to specific scenario classes (the ones I picked as examples):
  - Thermal relic dark matter remains well-motivated; even minimal classic WIMP models remain viable
  - Multiwavelength and multimessenger indirect signals are natural and would be very powerful
  - Low-threshold direct detection has unique capabilities and many avenues to follow up a first detection
  - Axion searches are well-positioned to probe the QCD axion (& beyond) from multiple directions
- A discovery in Cosmic Frontier search channels has the potential to teach us about the composition, distribution, and velocity of dark matter throughout our Galaxy and beyond with unprecedented precision

BONUS SLIDES

Paths not taken (today)

- Many of these discoveries would be made by different experiments given slightly different underlying physics, e.g:

O'Hare, https://cajohare.github.io/AxionLimits/



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- A somewhat heavier QCD axion (μeV+) could instead be found by ADMX-EFR

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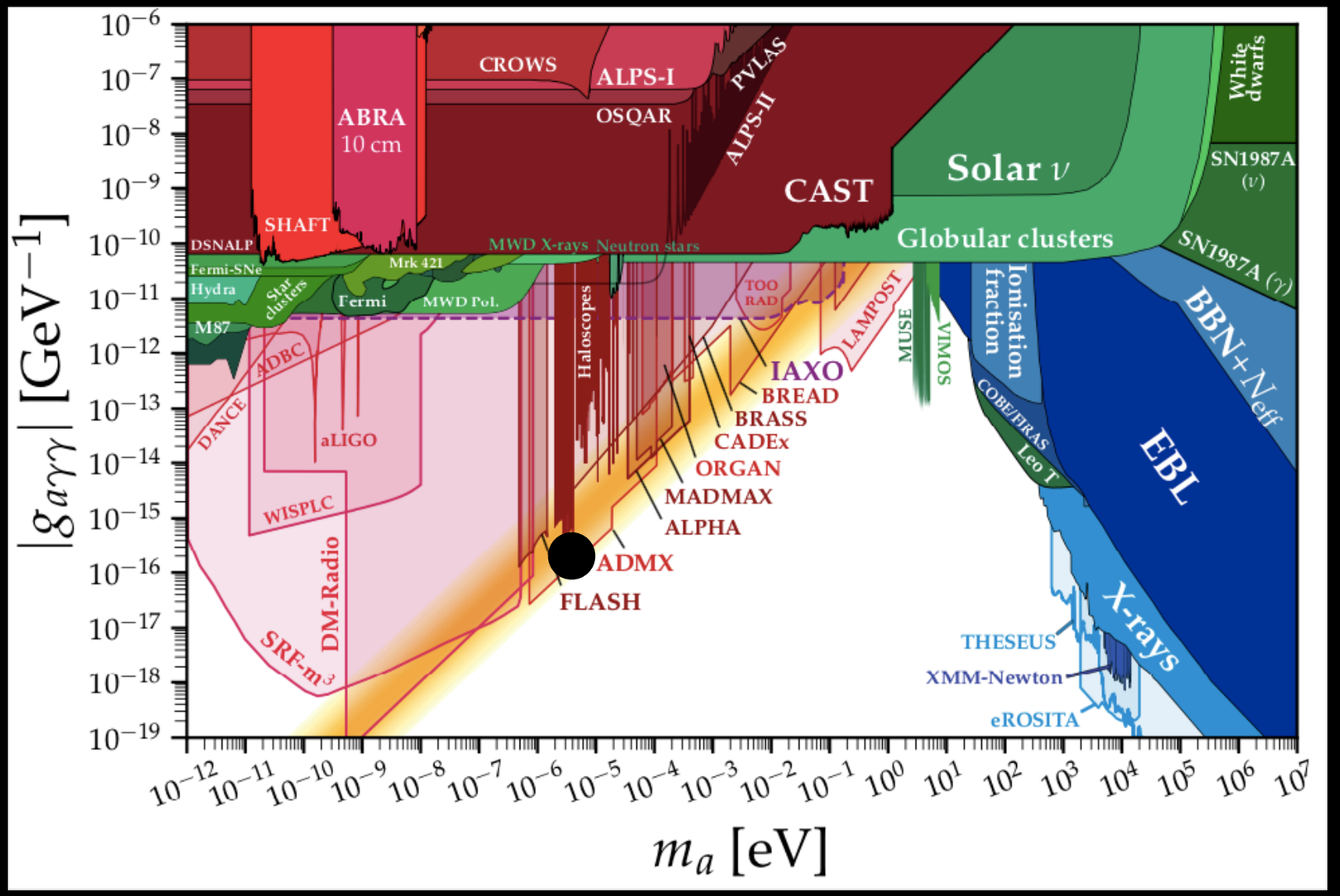

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- Many of these discoveries would be made by different experiments given slightly different underlying physics, e.g:

- A somewhat heavier QCD axion (μeV+) could instead be found by ADMX-EFR

- At even higher masses (~15-50 μeV) multiple experiments have sensitivity; such an axion would be produced post-inflation and could have striking cosmological signatures (CMB B-modes, DM substructure, GW signals from the PQ phase transition)

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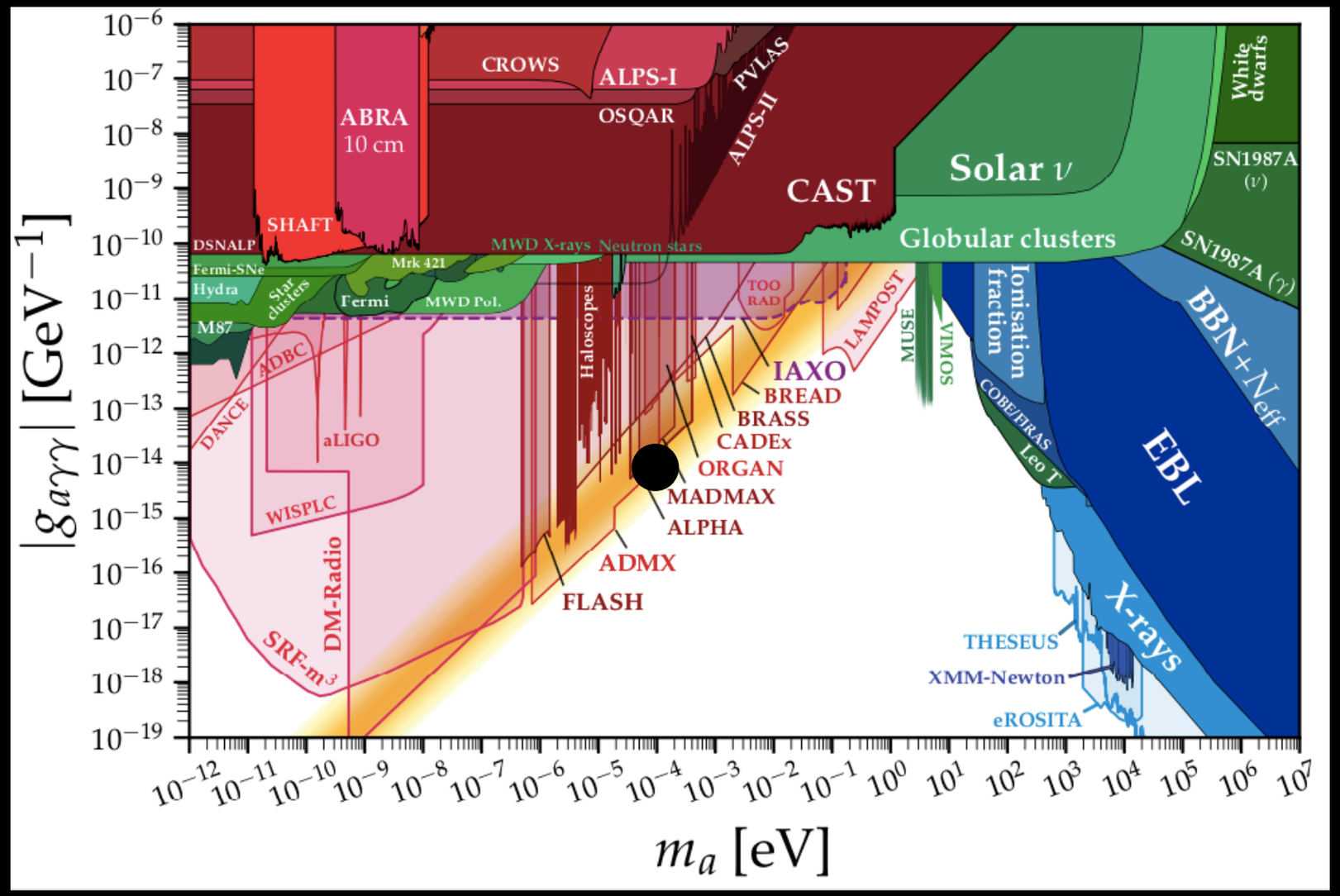
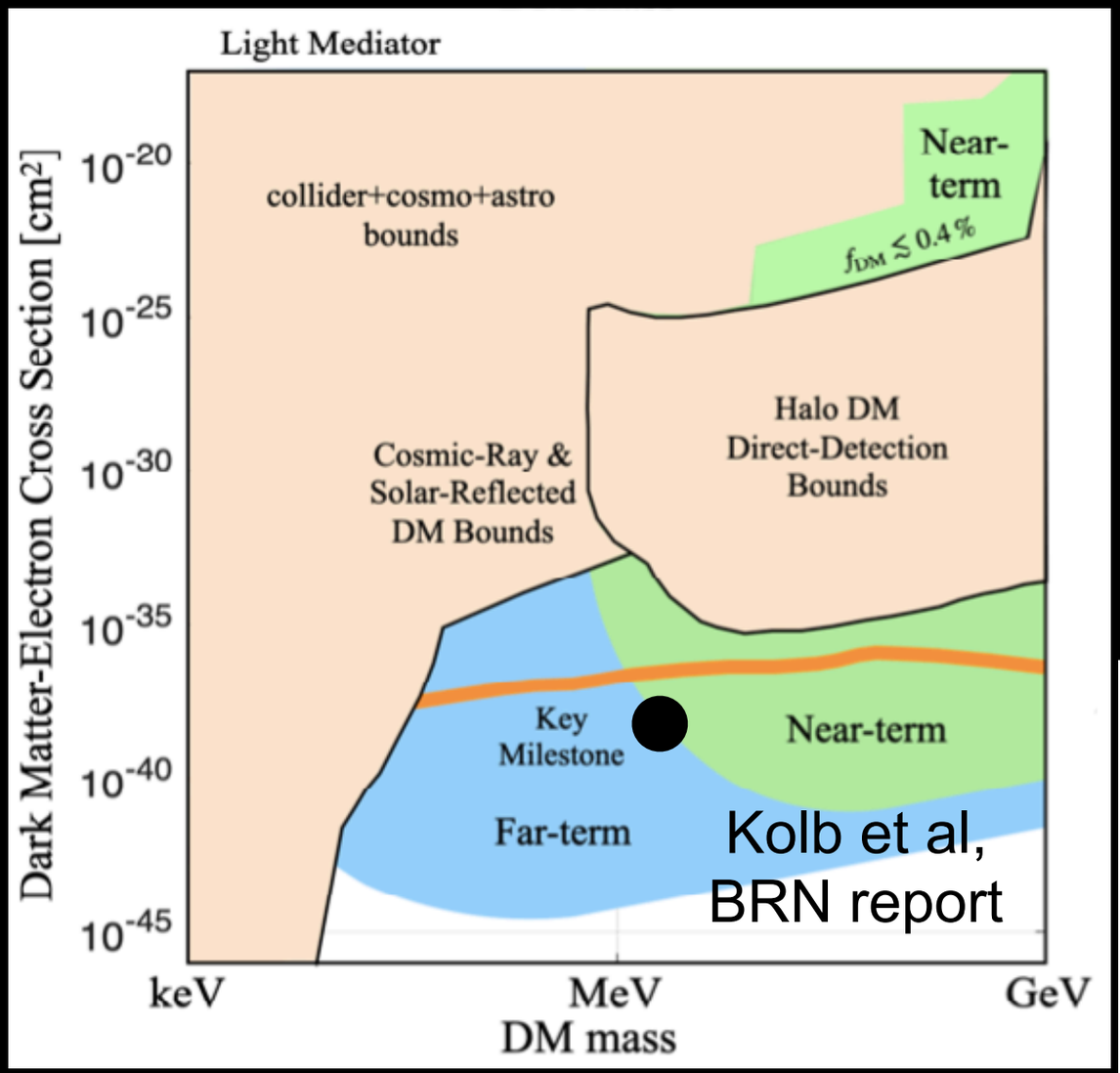
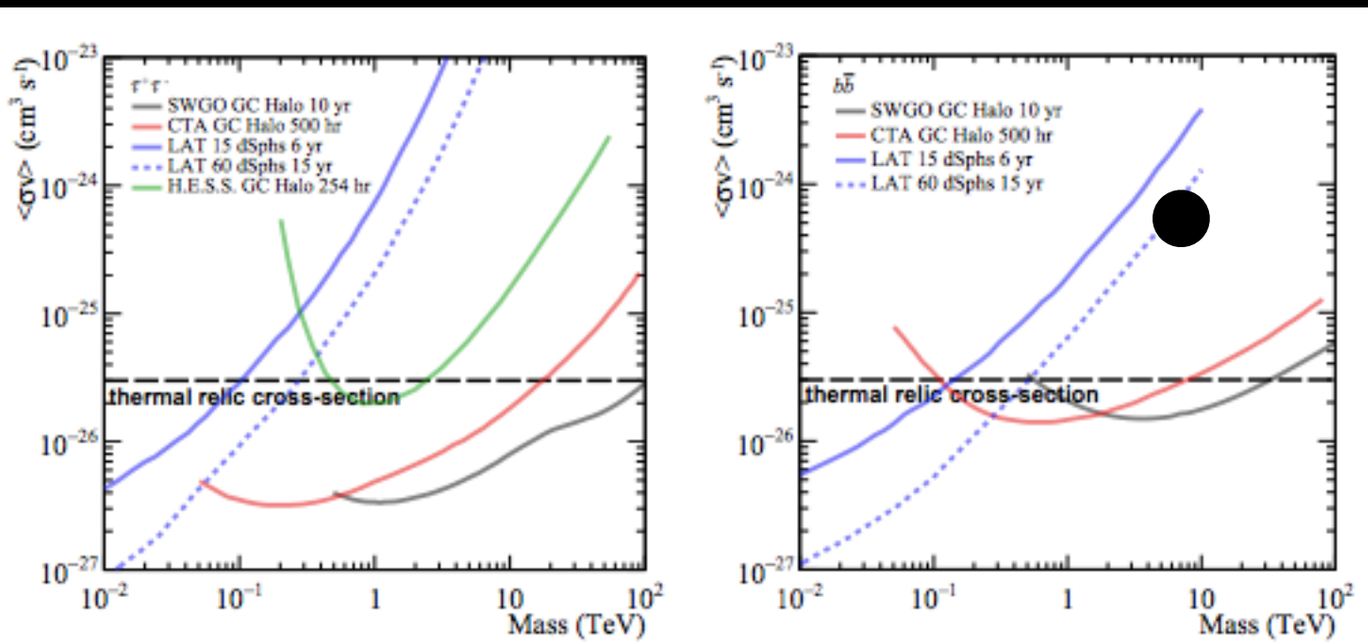
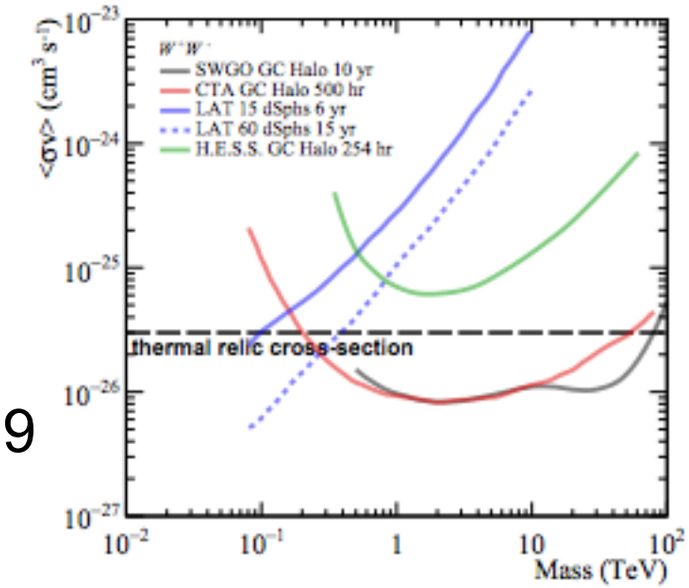
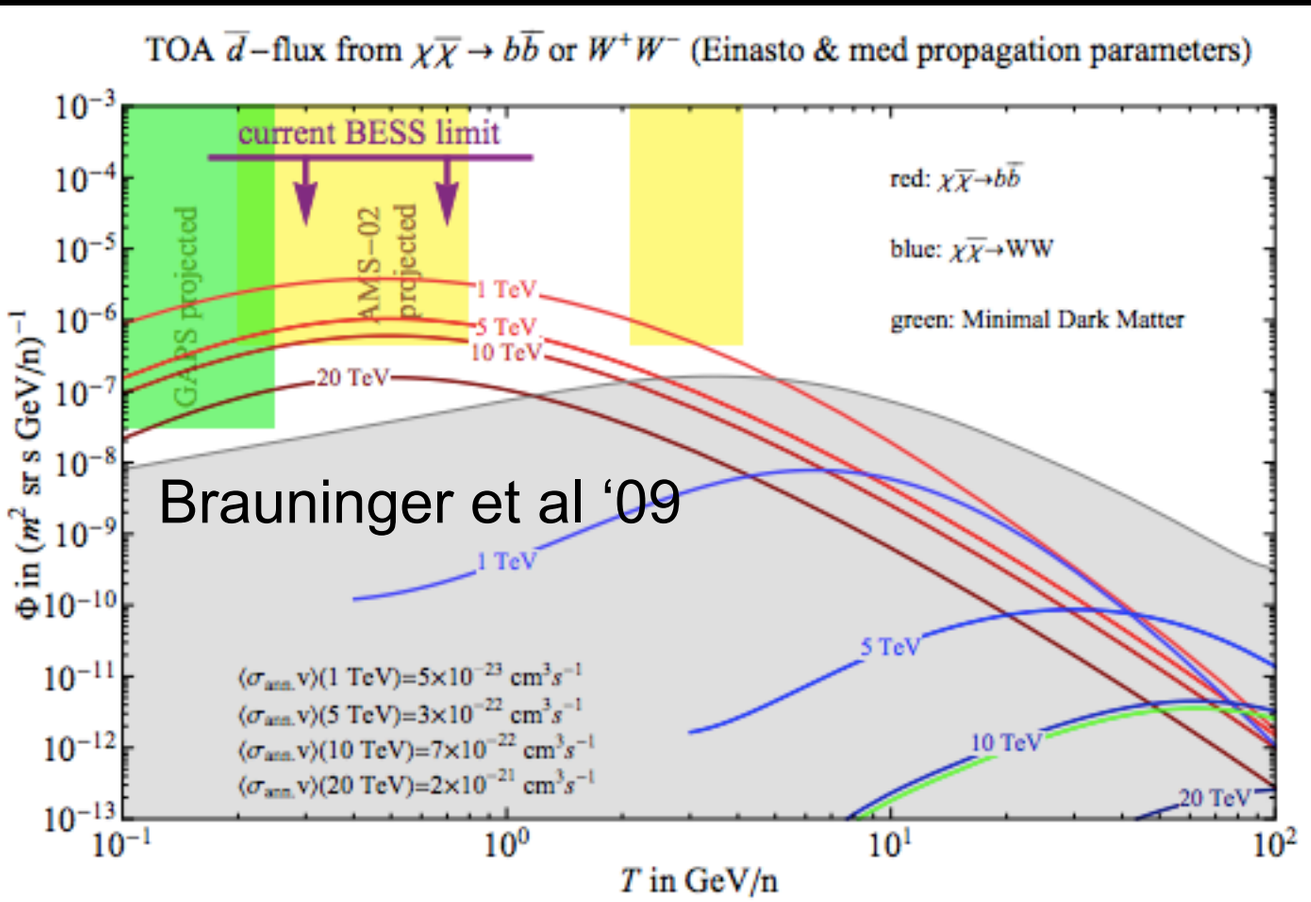


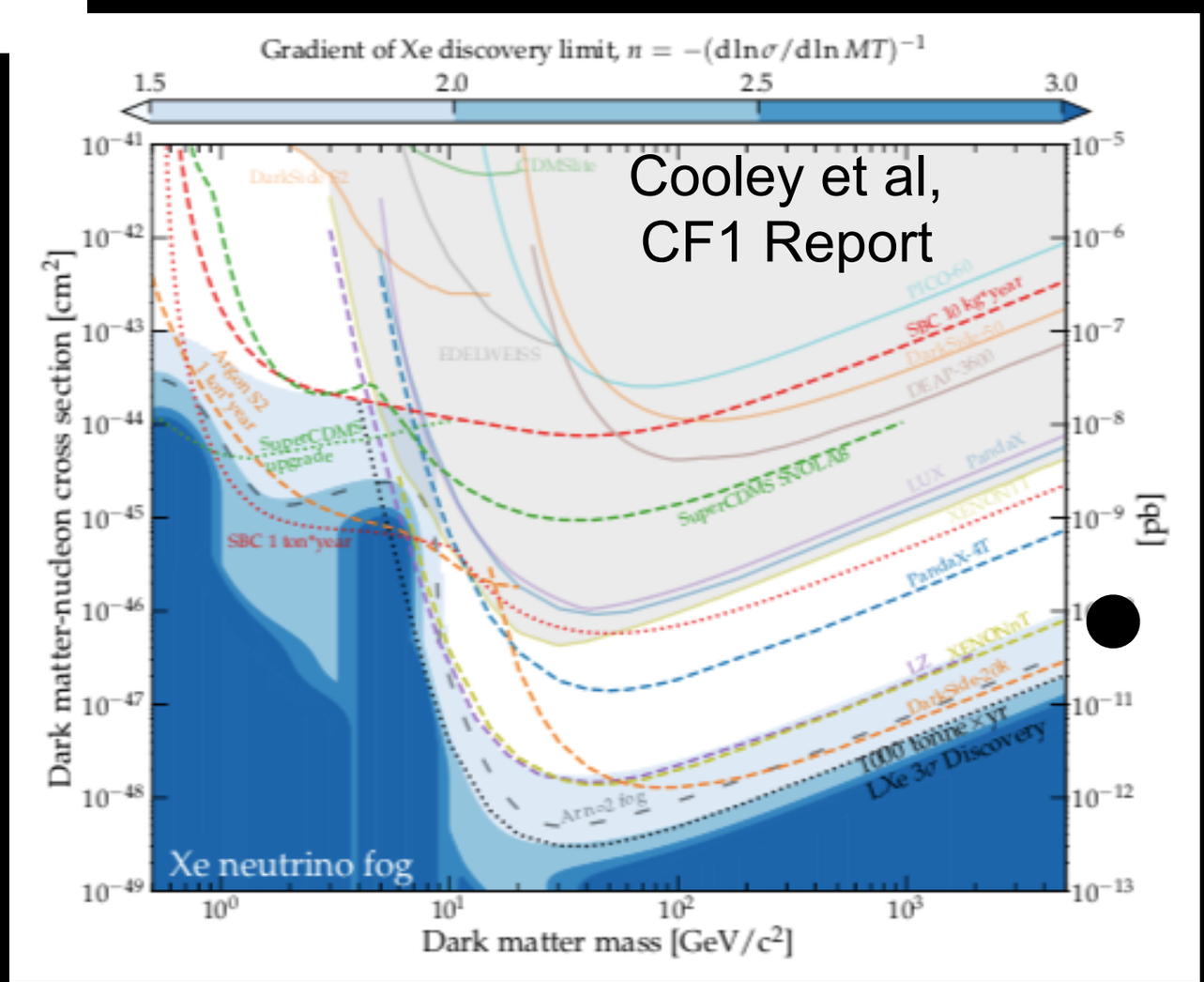






Viana et al ‘19


TOA $\overline{d}$ – flux from $\chi\overline{\chi} \to b\overline{b}$ or W^+W^- (Einasto & med propagation parameters)
current BESS limit
GAPS projected
AMS–02 projected
red: $\chi\overline{\chi}\to b\overline{b}$
blue: $\chi\overline{\chi}\to$WW
green: Minimal Dark Matter
1 TeV
5 TeV
10 TeV
20 TeV
Brauninger et al '09
$\langle\sigma_{ann.}v\rangle$(1 TeV)=5×10^{-23} cm^{3}s^{-1}
$\langle\sigma_{ann.}v\rangle$(5 TeV)=3×10^{-22} cm^{3}s^{-1}
$\langle\sigma_{ann.}v\rangle$(10 TeV)=7×10^{-22} cm^{3}s^{-1}
$\langle\sigma_{ann.}v\rangle$(20 TeV)=2×10^{-21} cm^{3}s^{-1}
Φ in (m^2 sr s GeV/n)$^{-1}$
T in GeV/n


Gradient of Xe discovery limit, $n = -(d\ln\sigma/d\ln MT)^{-1}$
Cooley et al,
CF1 Report
Xe neutrino fog
Dark matter-nucleon cross section [cm^2]
Dark matter mass [GeV/c^2]
[pb]