SNOWMASS 2021:
INDIRECT DETECTION OF DARK MATTER

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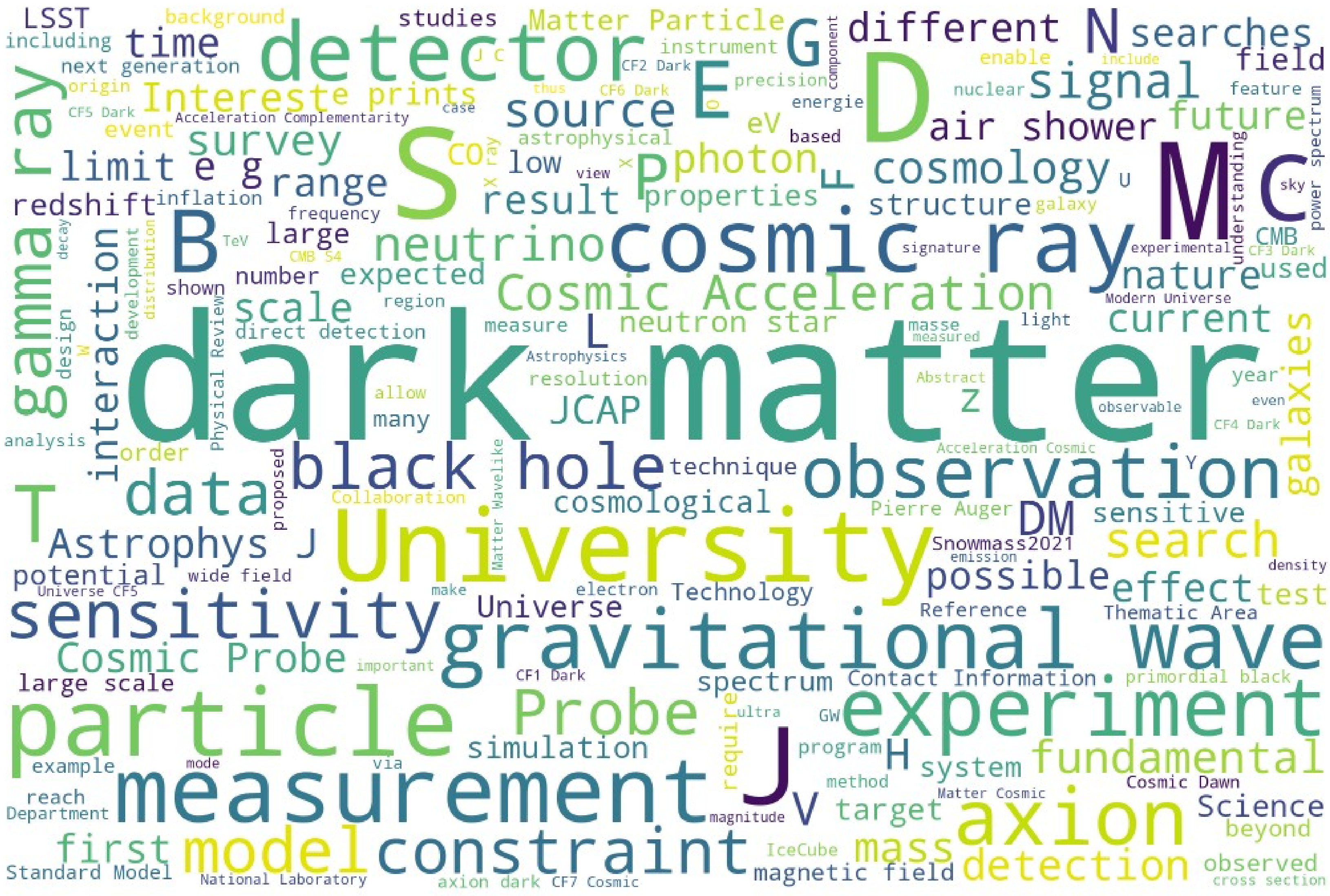
HOT TOPICS ON THE COSMIC FRONTIER
JUNE 17TH 2022

Discovering dark matter

- Steady evidence for its existence across many length scales
- One of the most pressing physics problems of our time
- In 2014, the Particle Physics Project Prioritization Panel (P5) identified DM as one of the five priority science drivers for the HEP Program
- In 2022, where do we sit now?

Cosmic Frontier



https://gordonwatts.github.io/snowmass-loi-words/wordcloud.html

All LOI's

https://gordonwatts.github.io/snowmass-loi-words/wordcloud.html

How do we find dark matter?

- Multi-pronged search strategy to study all its potential non-gravitational interactions:

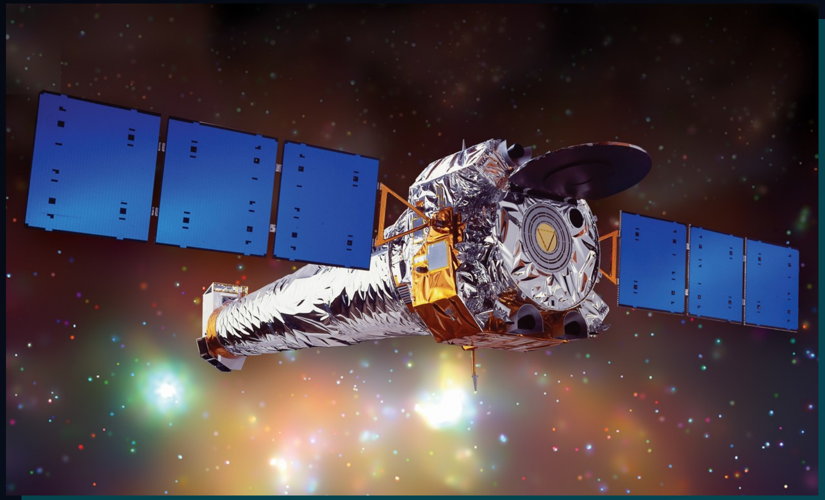
- Terrestrial probes
  - Direct detection
  - Colliders
  - New detectors

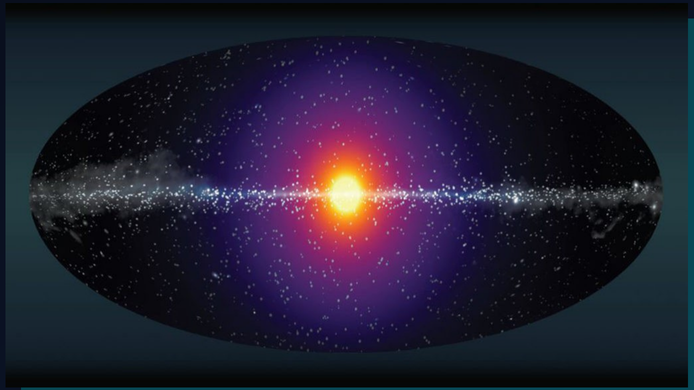
- Cosmic probes (Risa's talk next)

- Astrophysical probes
  - Indirect detection (this talk)

Outline

- Ingredients for Searches
- Targets and environments
  - Theory targets
  - Systems to use
- Instruments
  - Current and future reach
- Path Forward to Discovery
  - Modeling improvements (diffuse, CRs)
  - Complementarity of multi-wavelength data



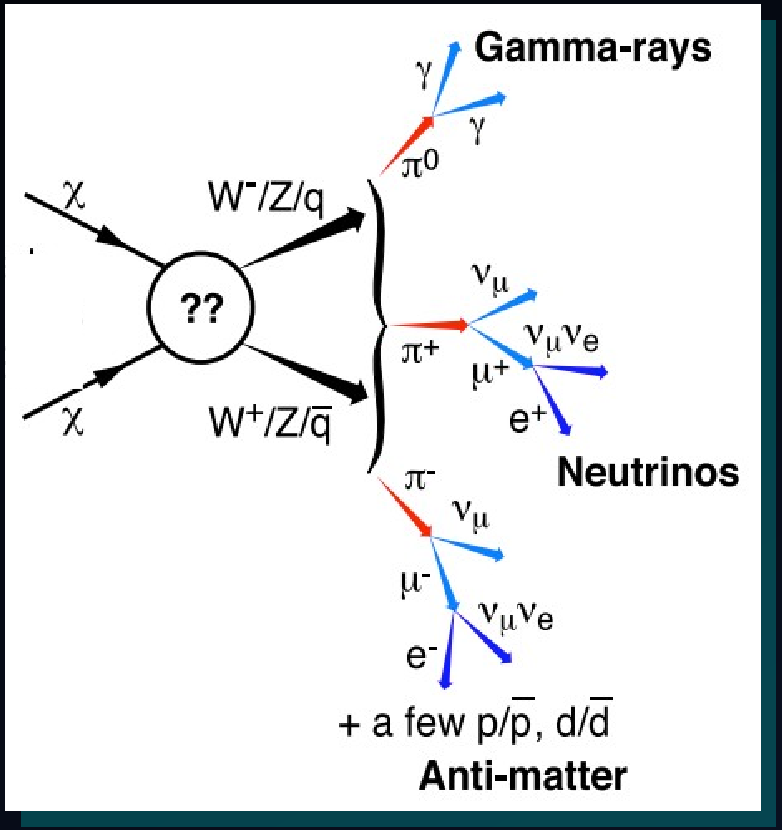


Ingredients for Indirect Searches

Rebecca Leane

What are indirect DM searches?

Any search looking for DM annihilation or decay products.

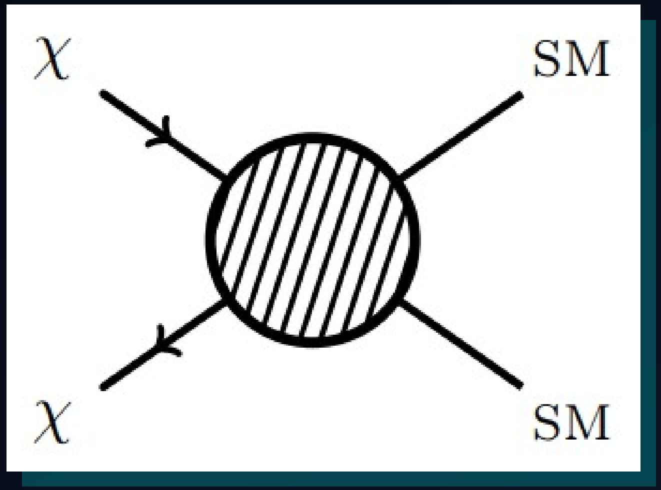


Baltz et al 0806.2911

Search for SM flux in astrophysical systems, or *effects* of the SM flux

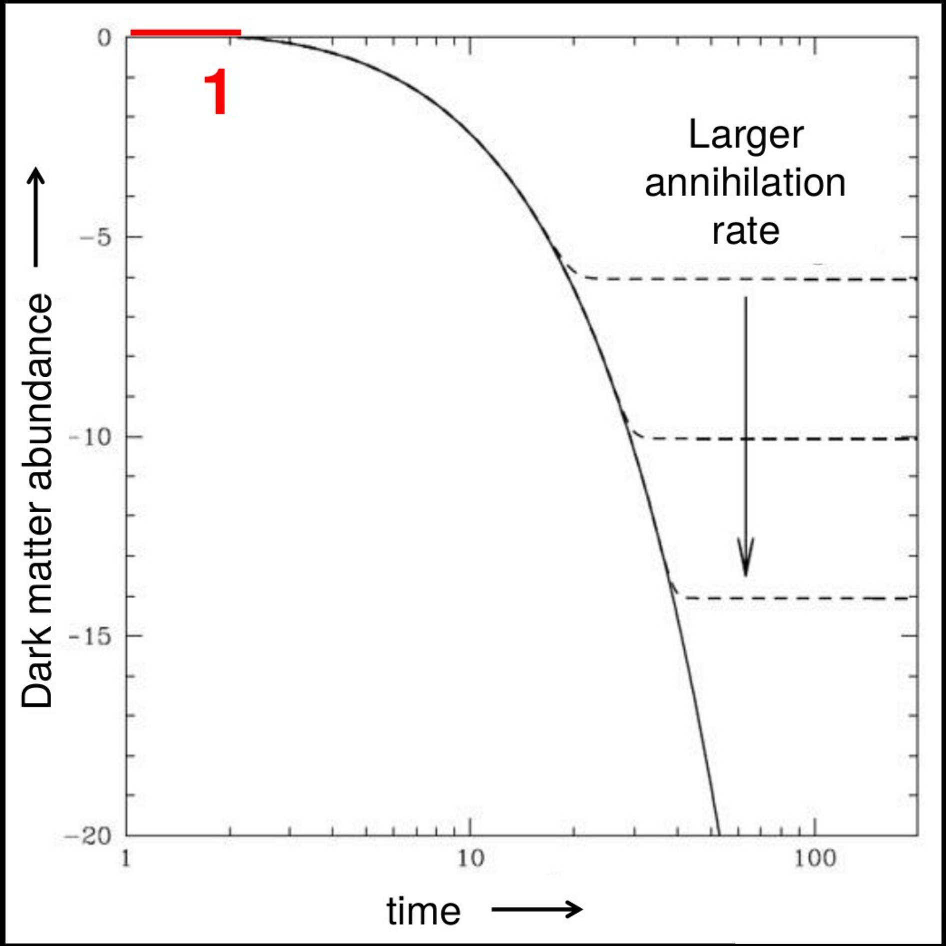
Ingredient #1: DM Interaction Rate

- DM annihilation or decay rate
- Particle model dependent, usually fixed by relic abundance



Ingredient #1: DM Interaction Rate

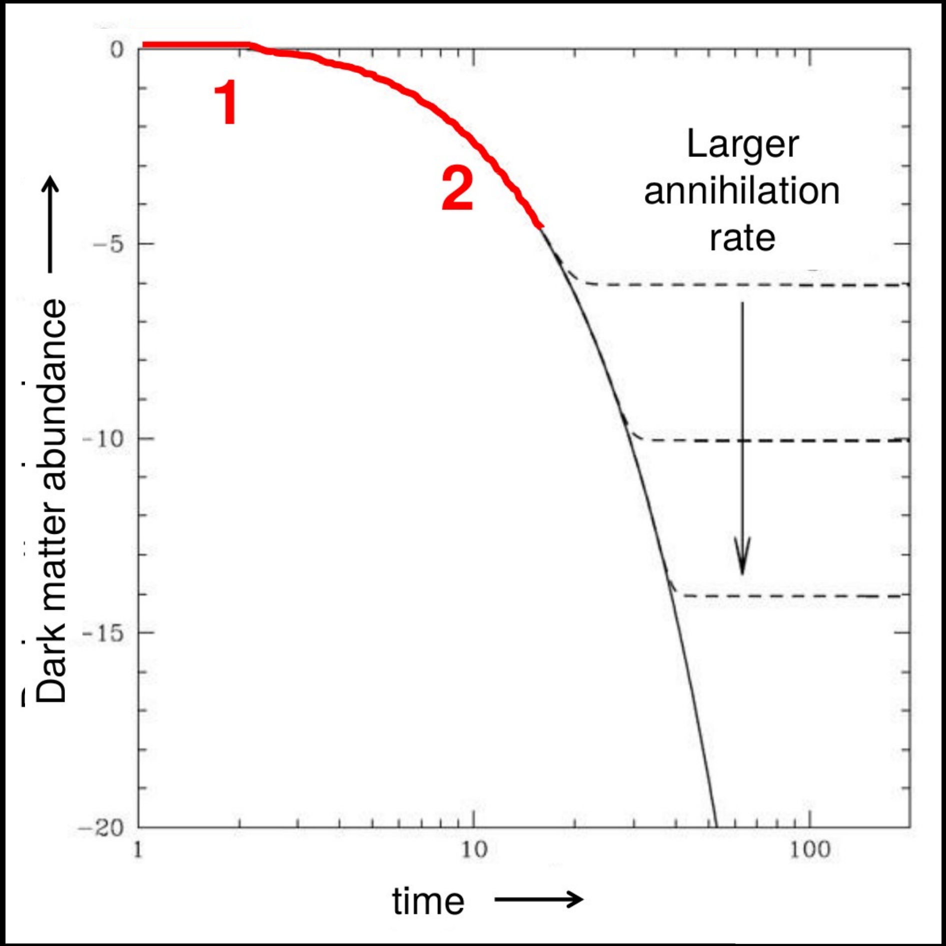
1) Thermal equilibrium:
DM + DM ⇒ visible particles
Visible particles ⇒ DM + DM



Ingredient #1: DM Interaction Rate

1) Thermal equilibrium:
DM + DM ⇒ visible particles
Visible particles ⇒ DM + DM

2) Universe cools, only
DM + DM ⇒ visible particles

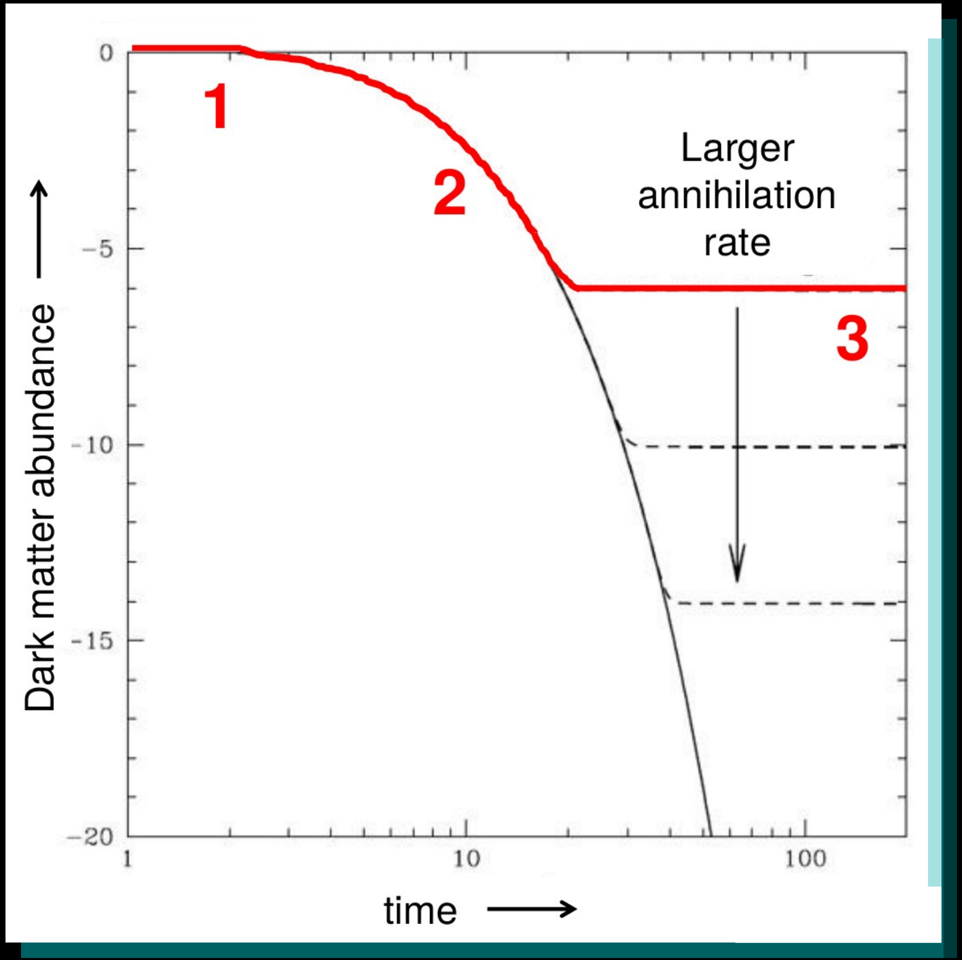


Ingredient #1: DM Interaction Rate

1) Thermal equilibrium:
DM + DM ⇒ visible particles
Visible particles ⇒ DM + DM

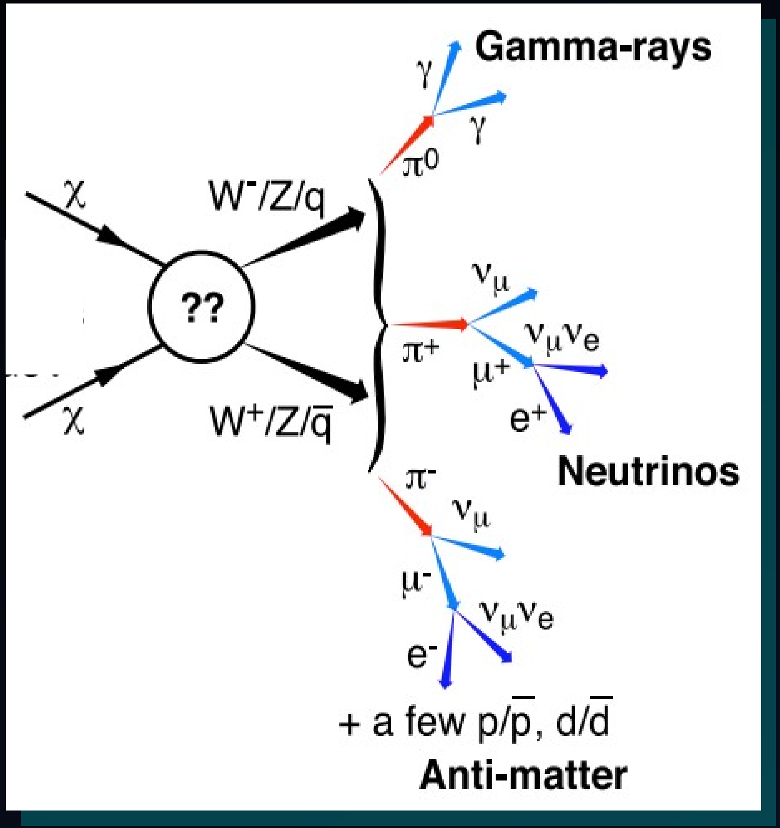
2) Universe cools, only
DM + DM ⇒ visible particles

3) Universe expands too fast.
No more annihilations.
DM abundance is set.



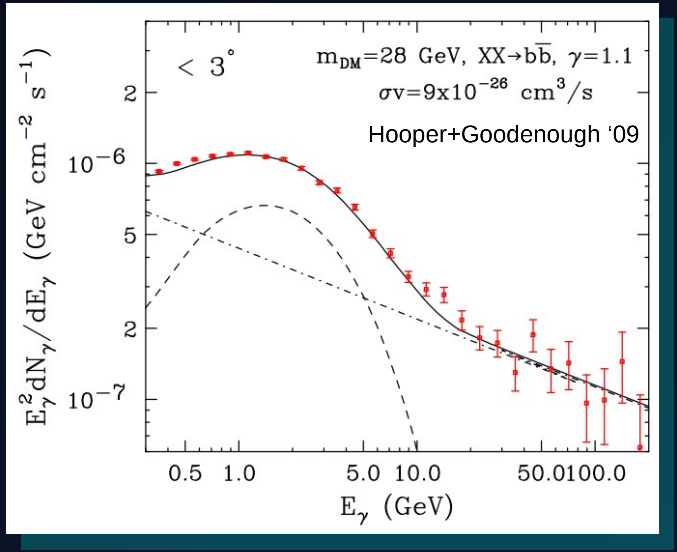
Predicts a particular annihilation rate for dark matter.

Ingredient #2: Energy Spectrum



Baltz et al 0806.2911

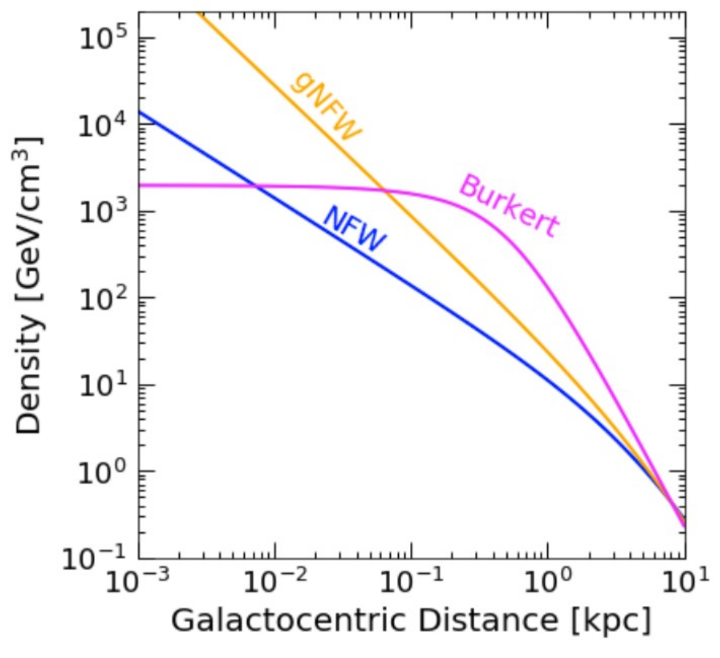
- Also driven by particle physics model
- Shape depends on:
  - branching ratios to final SM states
  - boosts of particles



Ingredient #3: DM Density+Distribution

- Line of sight integral over DM density
  - J-factor (annihilation)
  - D-factor (decay)

- DM density profiles not well-known
  - large uncertainties

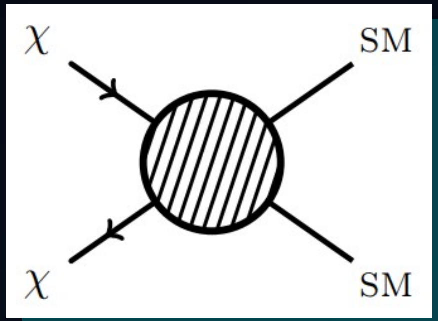


Indirect Detection Ingredients

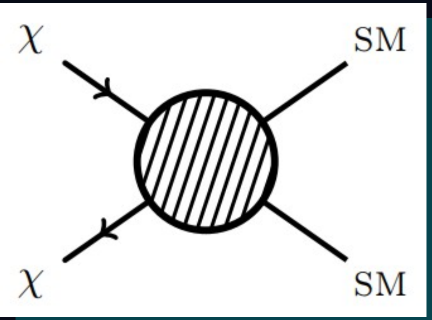
Particle Physics — Astrophysics

(Neutral particles)

$$\Phi(E,\phi) = \frac{\Gamma}{4\pi m_\chi^a}\frac{dN}{dE}\int \rho[r,(\ell,\phi)]^a\, d\ell.$$



Indirect Detection Ingredients



Particle Physics Astrophysics

(Neutral particles)

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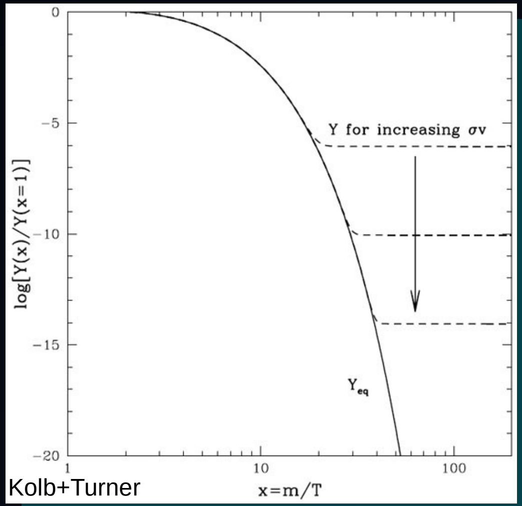
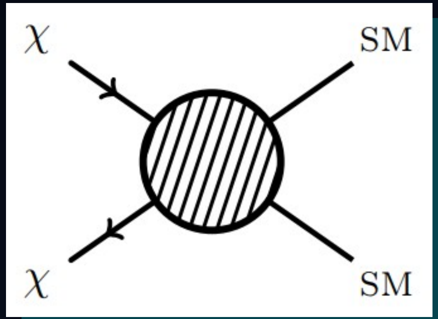
Annihilation cross section



Kolb+Turner

Indirect Detection Ingredients



(Neutral particles)

Particle Physics   Astrophysics

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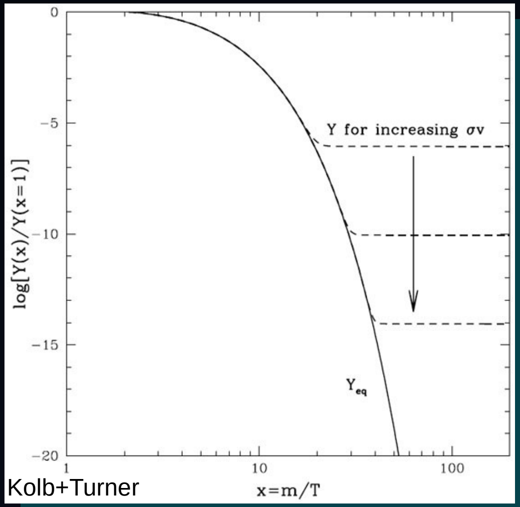
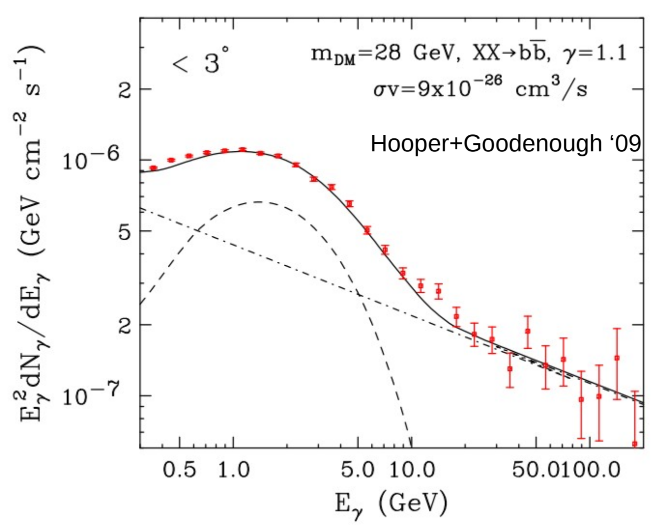


Energy spectrum



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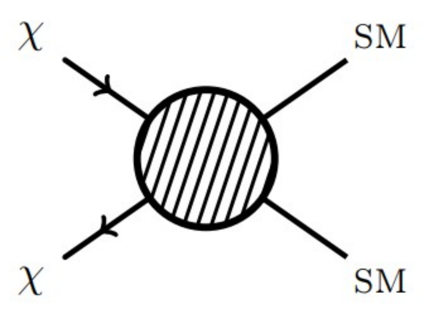

Particle Physics

Astrophysics

(Neutral particles)

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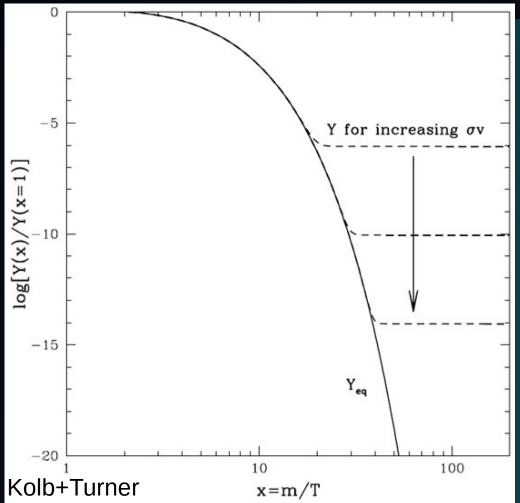
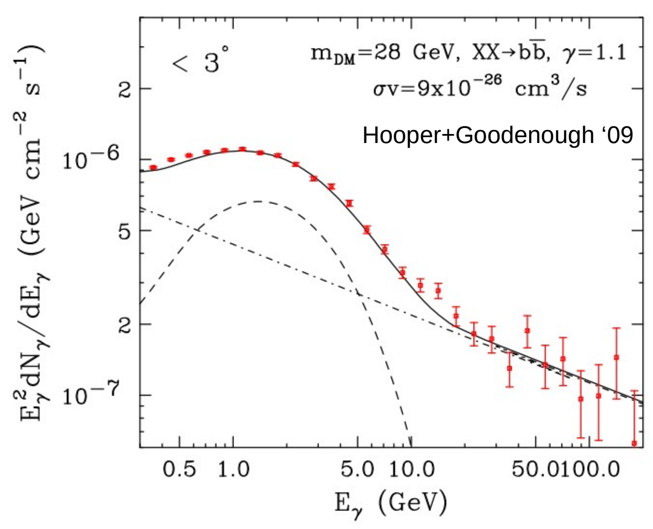
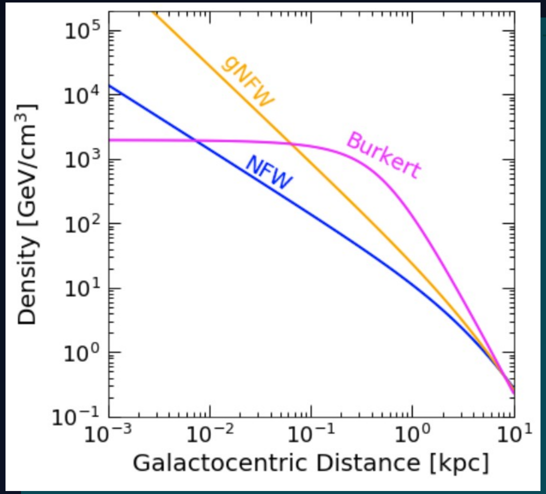
Annihilation cross section

Energy spectrum

"J factor", DM density







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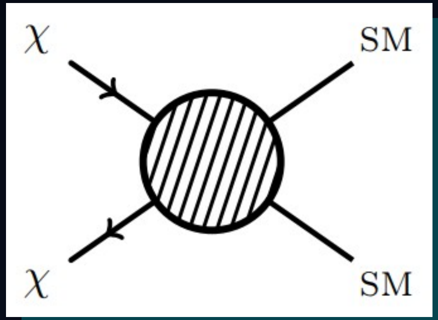

Particle Physics   Astrophysics

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Annihilation cross section

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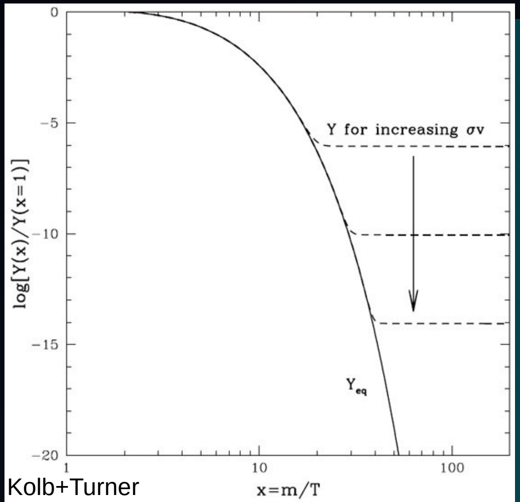

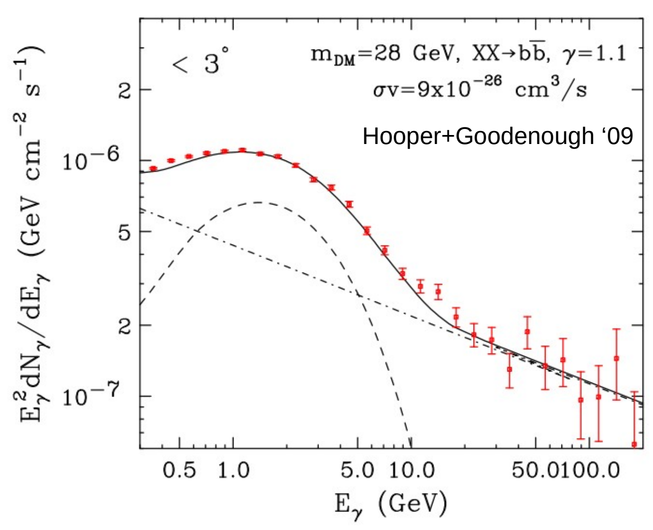

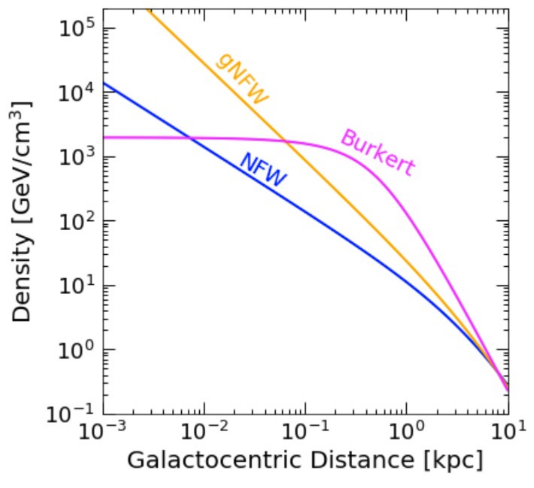

Look where this is large!

Indirect Detection Ingredients

Particle Physics　　Astrophysics

(Neutral particles)

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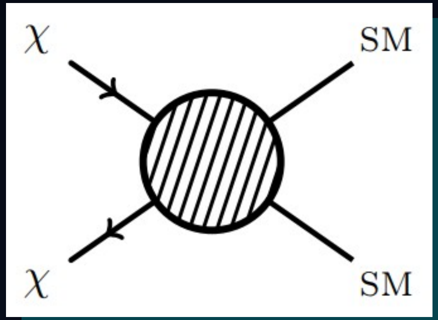
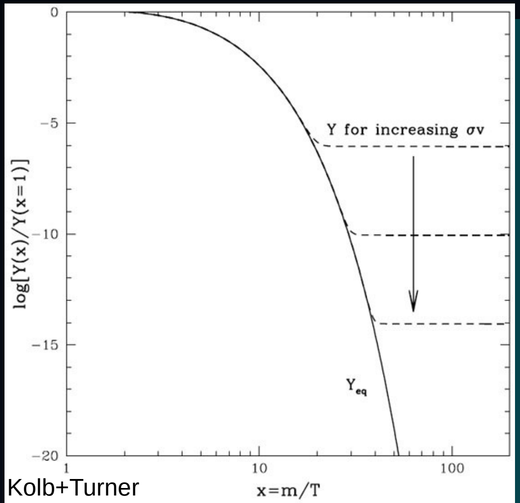
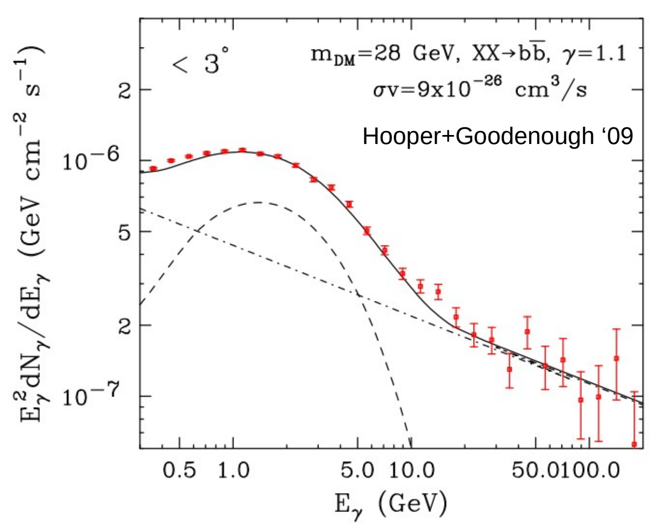


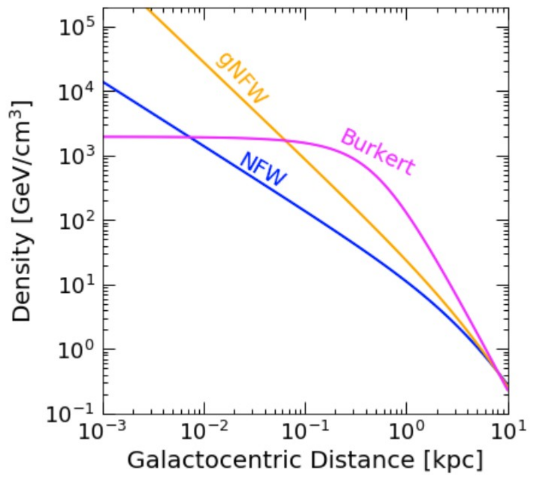
Annihilation cross section

Energy spectrum

"J factor", DM density







Look where this is large!

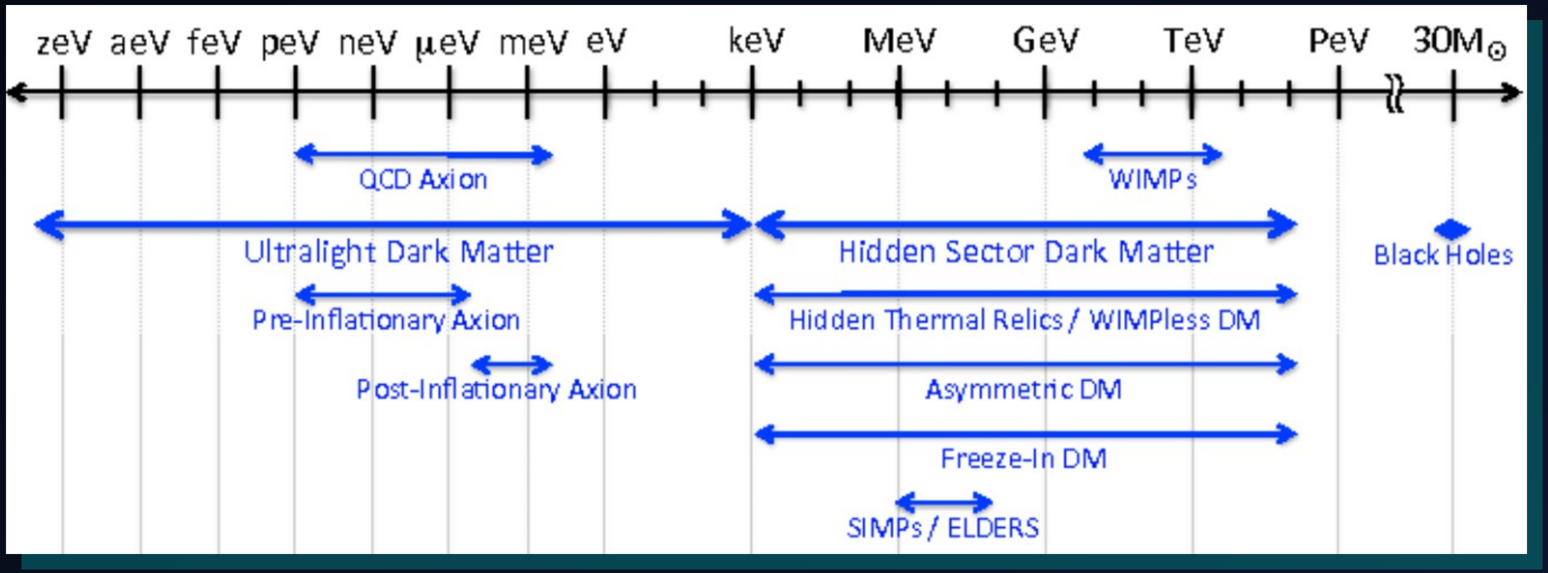
...or places with low background!

Targets and Environments

Rebecca Leane

Indirect Detection Across Scales

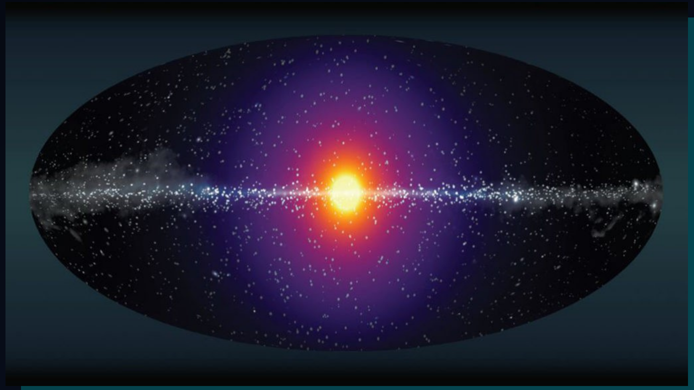
- Universe has been running experiments <u>for us</u> over very long time scales
- Can uniquely access specific scales: long decay lengths, smaller couplings, high energies
- *Allows us to probe DM candidates over many orders of magnitude in mass*

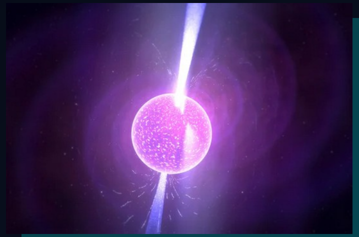


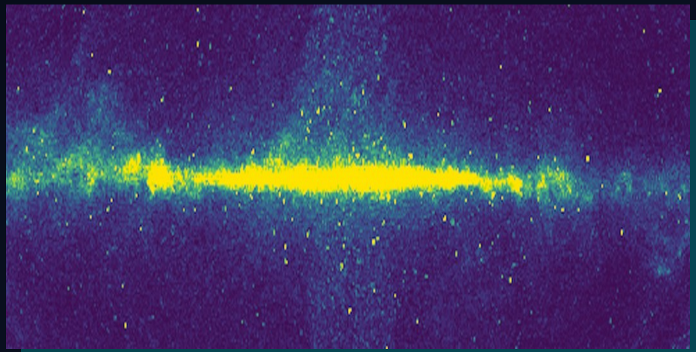
Cosmic Visions 2017

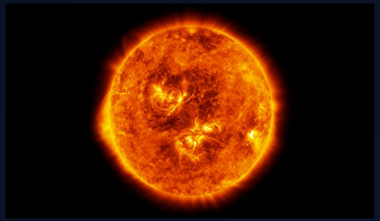
Diverse systems + types of searches!

- So far, DM has been tested using, e.g.:
  - galaxy clusters,
  - dwarf galaxies,
  - the Andromeda galaxy,
  - the Magellanic clouds,
  - the Sun,
  - the extragalactic background light,
  - and the Milky Way Galactic Center









Wide range of plausible DM scenarios: important to pursue a broad program of searches w/ sensitivity to different energy scales and cosmic messengers

Instruments: Reach and Future Goals

Rebecca Leane

High energy gamma rays: now

Fermi

Space based

~10 MeV – 1 TeV

Data recording
~13 years elapsed

HAWC,
LHAASO

Water Cherenkov

~100 GeV-100 TeV

Data recording
~5 years elapsed

VERITAS,
HESS, MAGIC

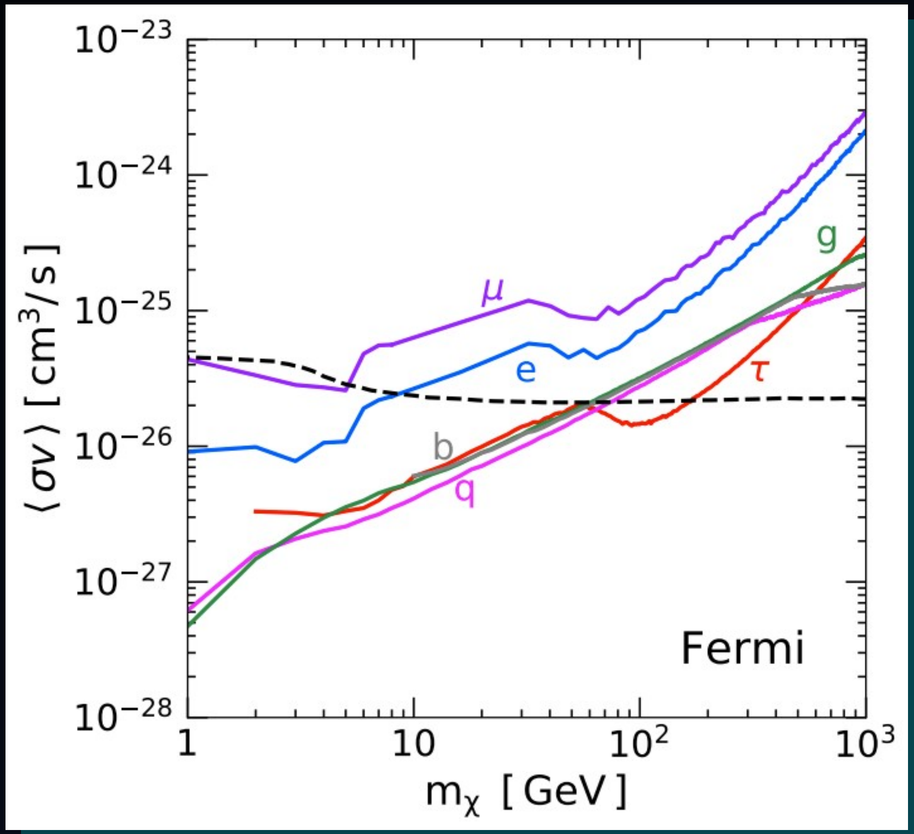
Imaging atmospheric
Cherenkov telescopes

~10 GeV–100 TeV

Data recording
~17 years elapsed

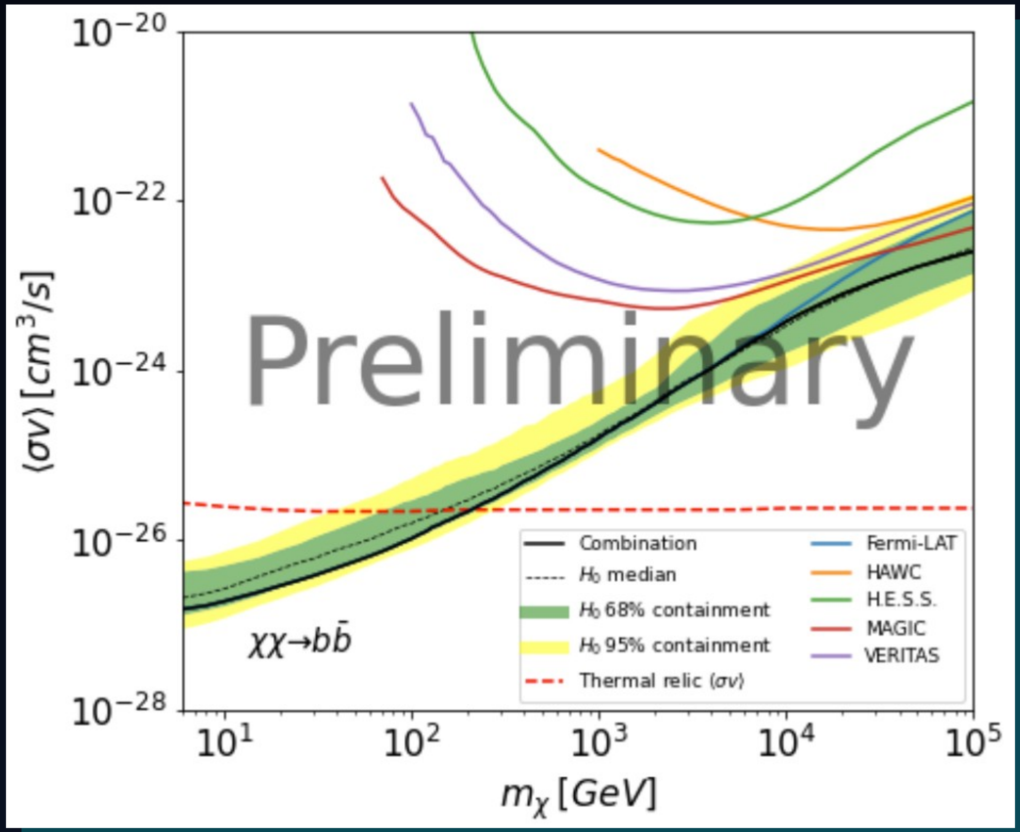
High energy gamma rays: now

Fermi



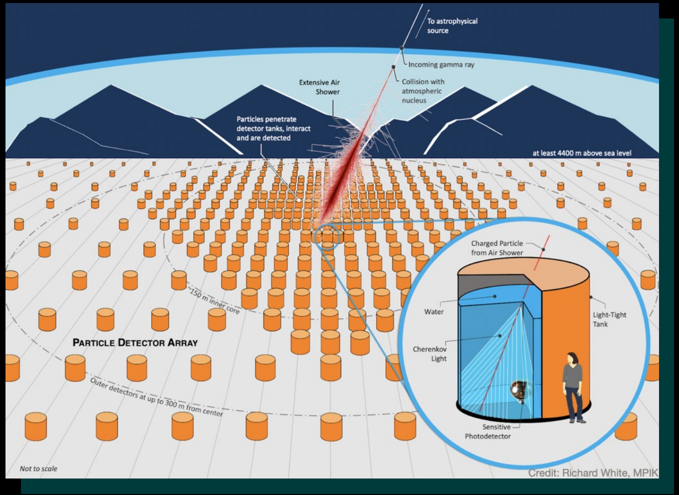
RL et al, 2018
(See also Fermi Collab 2016)

Fermi + HAWC + HESS + MAGIC + VERITAS



Armand et al, Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS Collaborations (2021)

High energy gamma rays: future



SWGO

Water Cherenkov

~100 GeV-1 PeV

In R&D

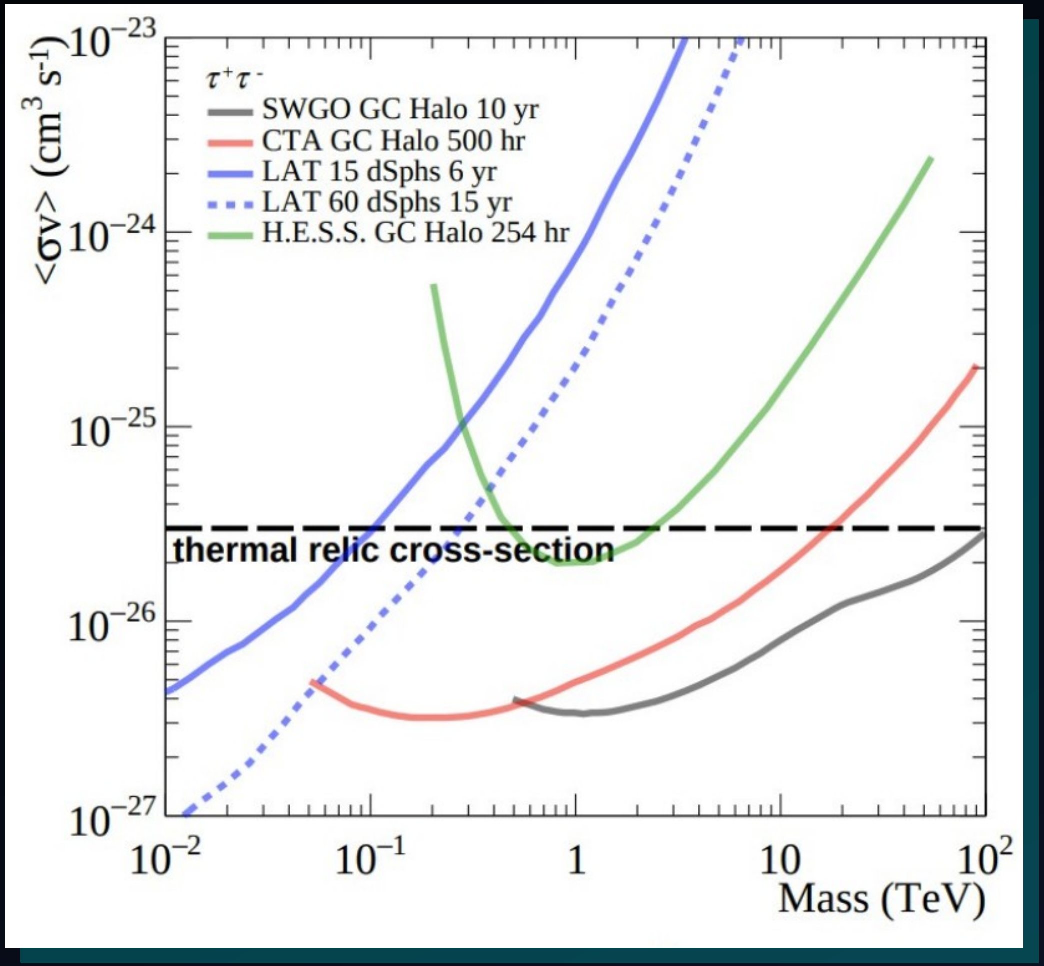
Cherenkov Telescope Array (CTA)

Imaging atmospheric Cherenkov telescope

~20 GeV–300 TeV

Planned ~2024

High energy gamma rays: future



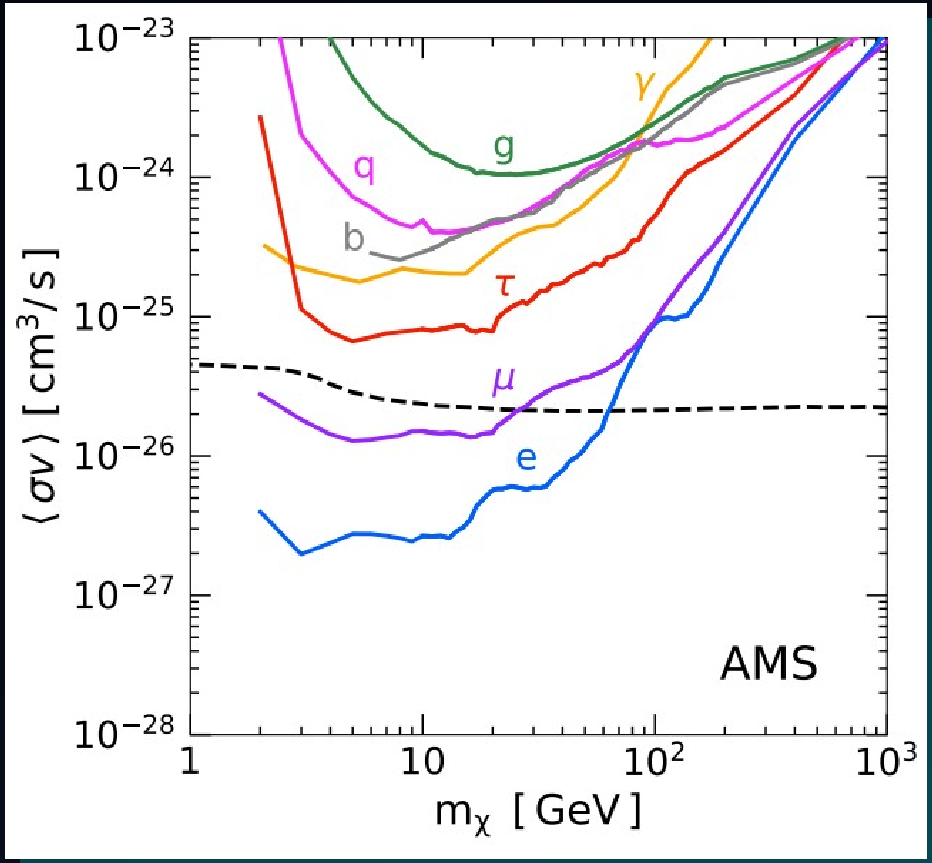
Viana+, 2019

Strong potential to probe much of thermal relic target

Solid probe of ultra-heavy DM

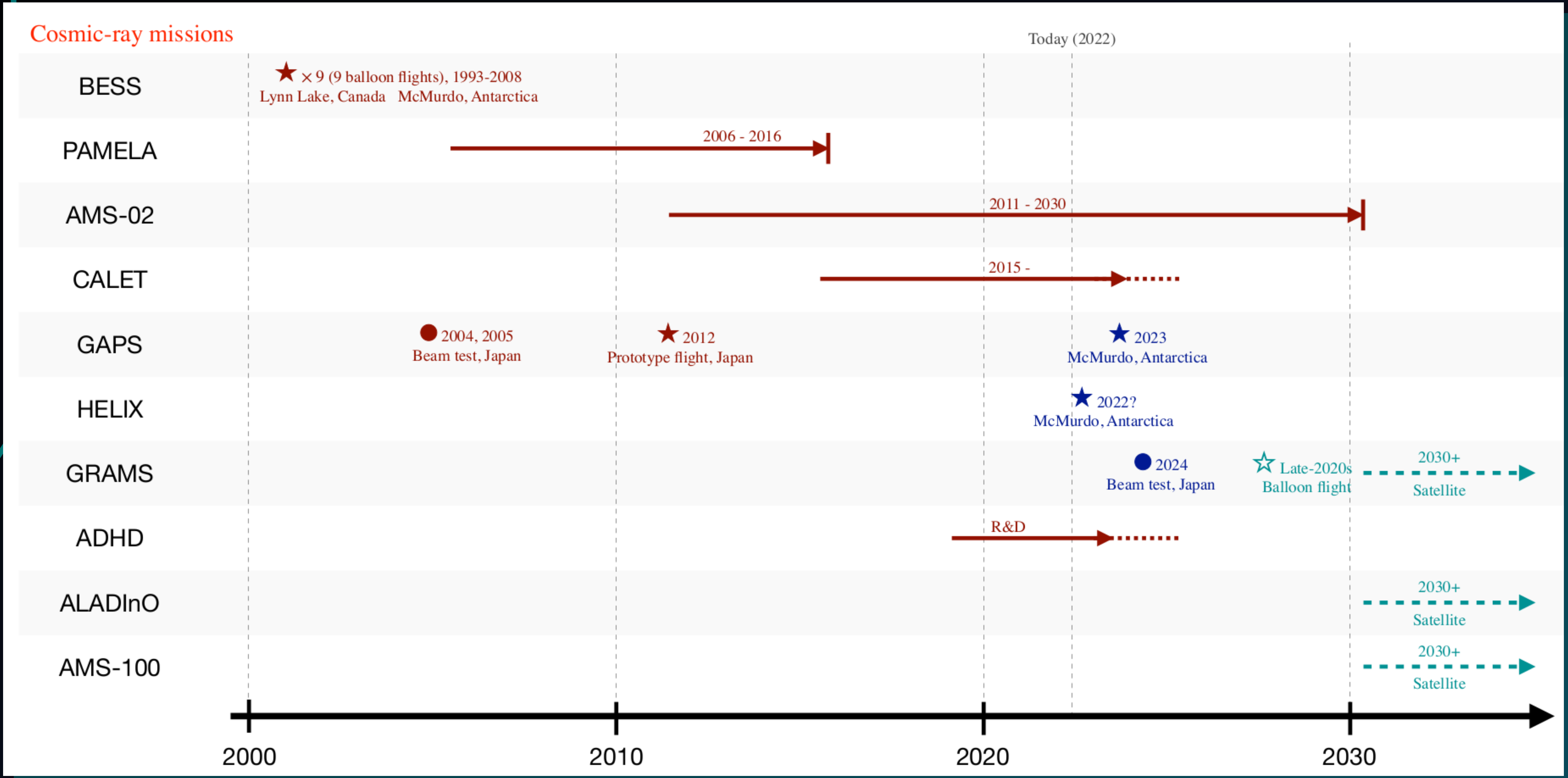
Cosmic Rays: now

AMS, positron data



RL et al ‘18
Also see AMS collab ‘14

Cosmic Rays

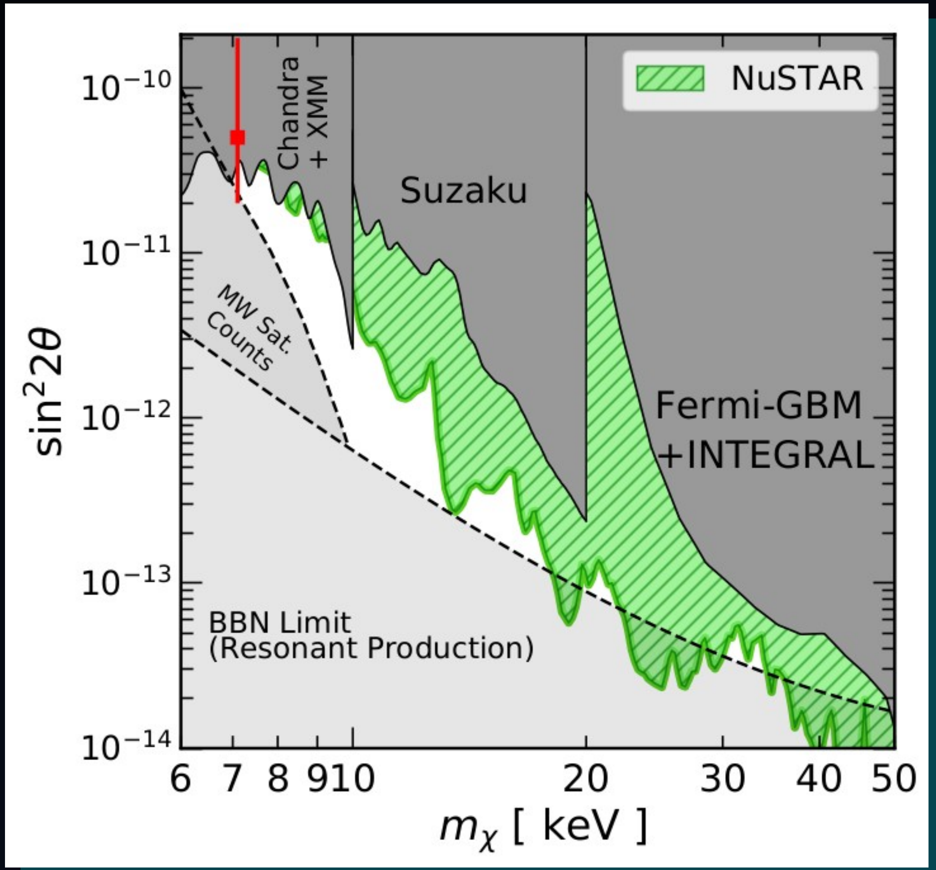


Rebecca Leane

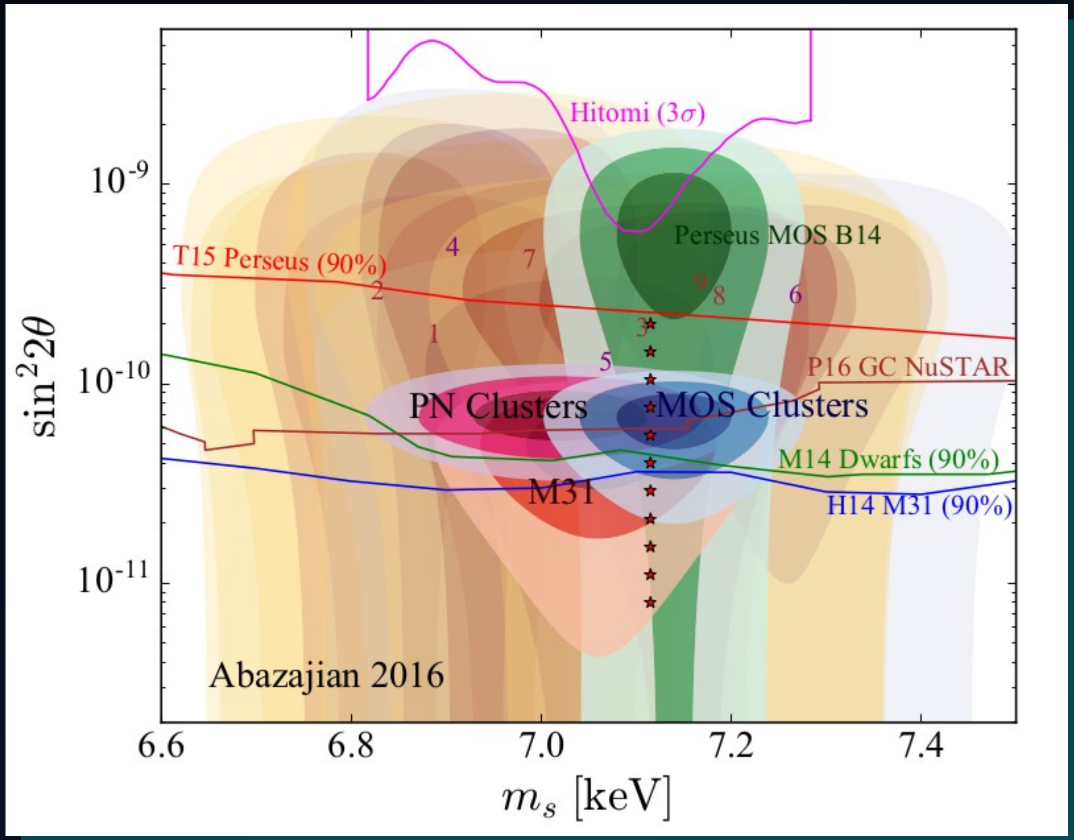
Aramaki et al, '22

X Rays: now

- Strong constraints on sterile neutrino candidate, tension for 3.5 keV

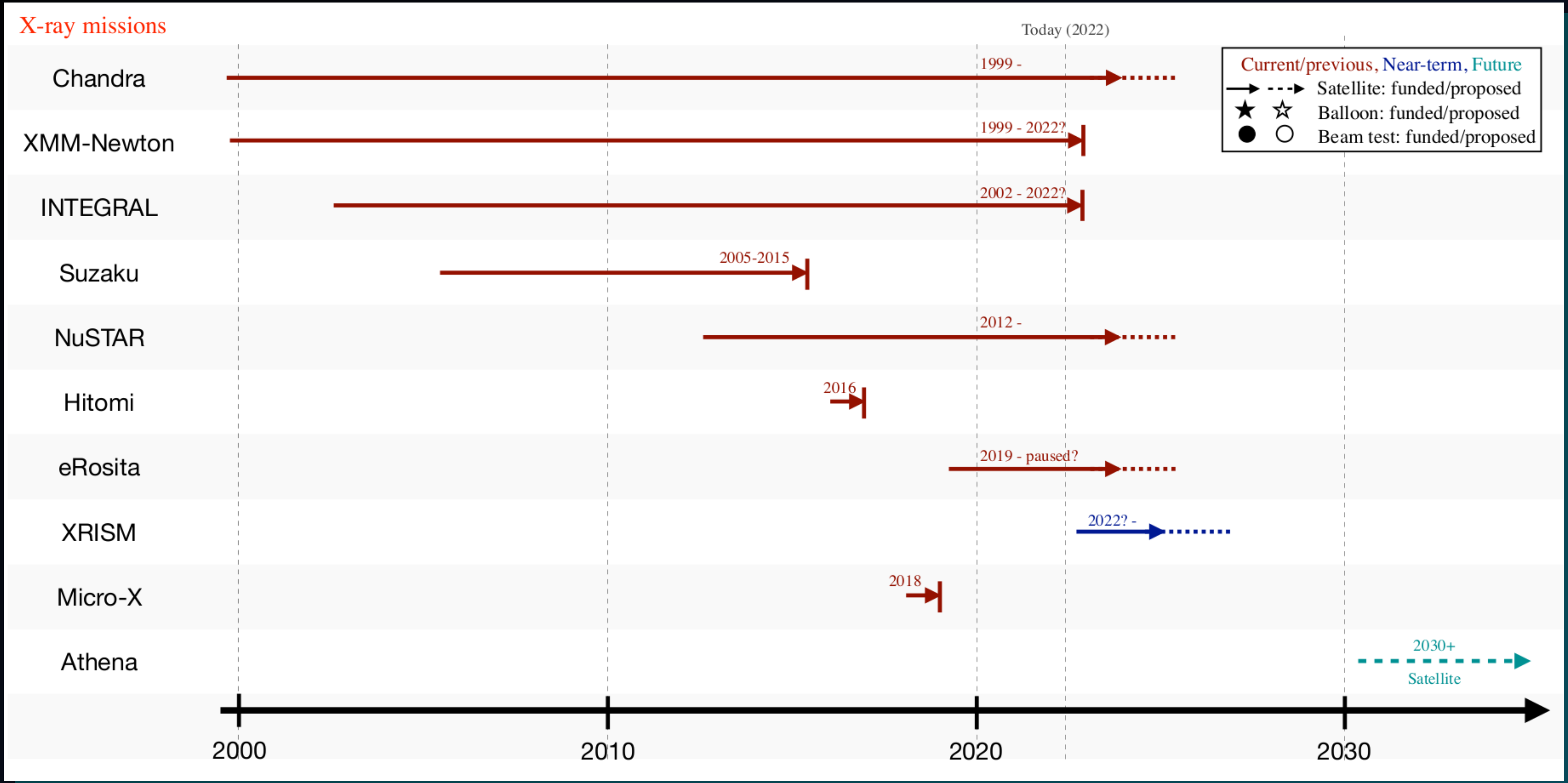


Roach et al '19



Abazajian '16,
Dessert et al adds down to ~10^-11-10^-12

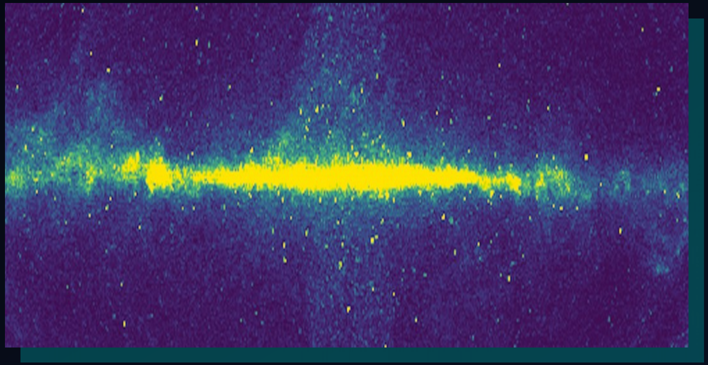
X Rays



Aramaki et al, '22

Path forward for discovery

Rebecca Leane

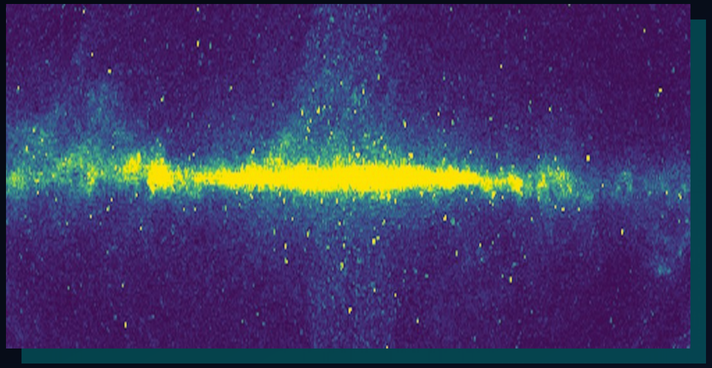


Improved modeling

Example 1: diffuse gamma-ray foreground

- Impedes our understanding of Galactic center excess!
- Need to understand e.g. the distribution of gas, cosmic rays, and radiation throughout the Milky Way, the Galactic magnetic field
- Input from astrophysics going forward:
  - Use of multiwavelength/multimessenger data, e.g. new maps of the interstellar dust, improved measurements of the magnetic field from upcoming radio telescopes
  - Development of improved tracers for components of the interstellar gas, particularly molecular hydrogen
  - Improved modeling techniques, e.g. accounting for non-steady-state behavior, incorporating insights from simulations, propagating systematic uncertainties

Improved modeling



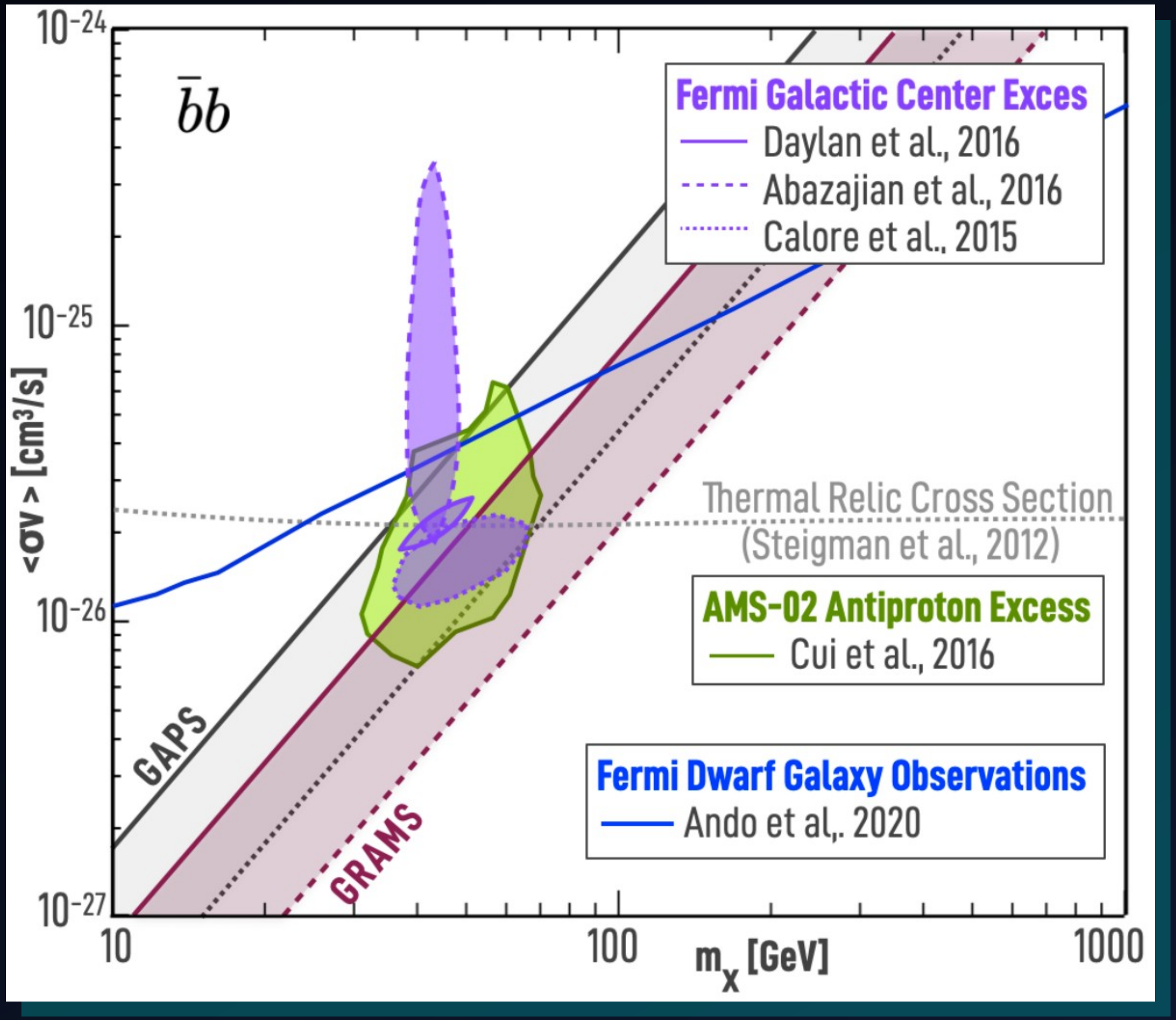
Example 2: cosmic-ray production + propagation

- Affects understanding of many DM indirect searches
- Production cross section uncertainties, +propagation

- Input going forward:
  - Ongoing cosmic-ray observations of multiple species
  - Correlation matrices from AMS, related to antiproton excess (DM?)
  - Data from fixed-target accelerator experiments, covering a range of energies, with the capacity to detect antiproton, antideuteron and anti-helium nuclei (e.g. NA61/SHINE, ALICE, and LHCb)

Anti-Nuclei?

- AMS-02 collaboration: observation of several candidate anti-deuterons and antihelium nuclei events
- Tentative, need verification or refutation w/ other experiments
- GAPS, GRAMS: Different identification techniques, reducing systematic uncertainties (2023 flight)
- Consistency of other excesses?

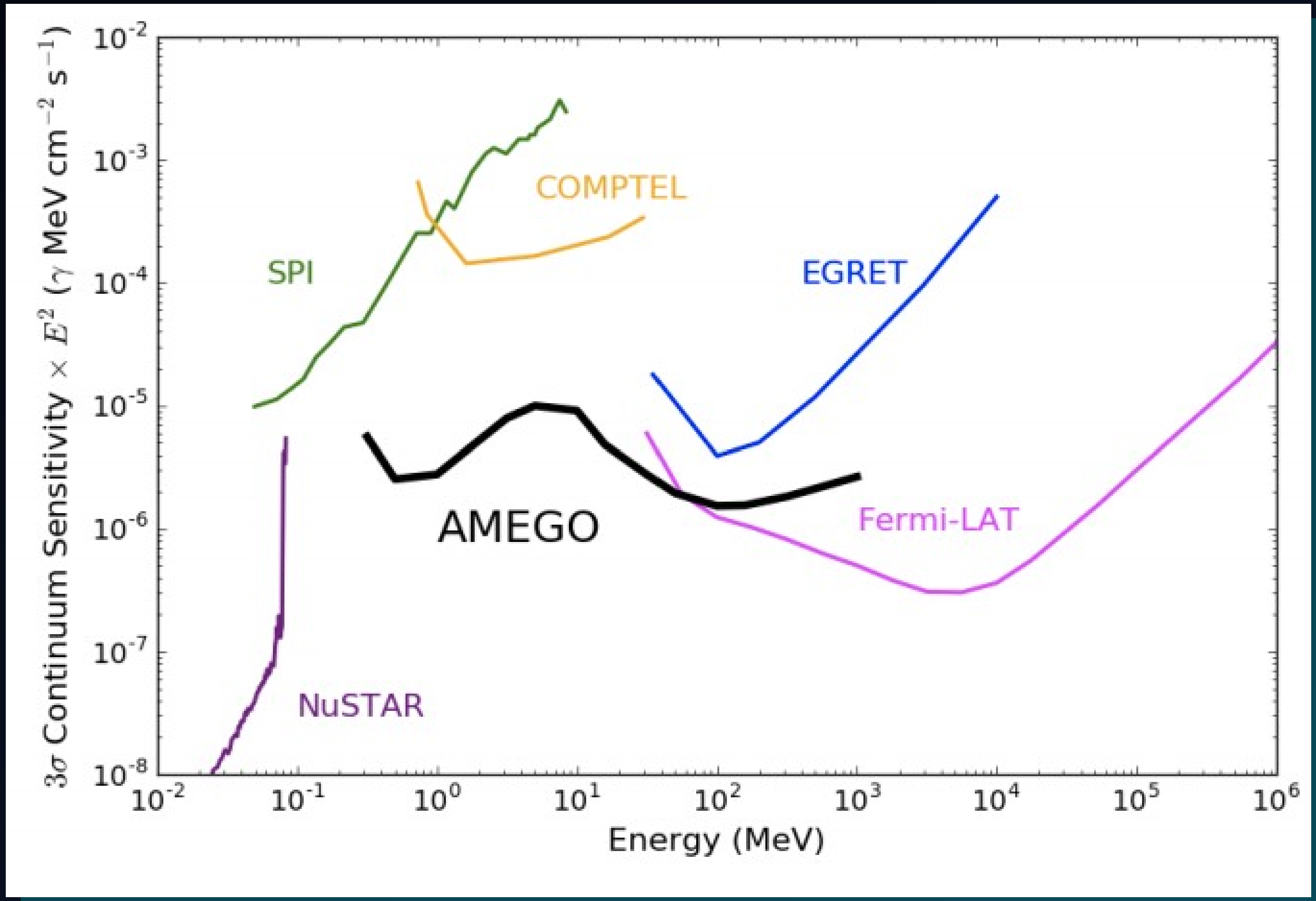


RL+, '22

Closing the MeV gap

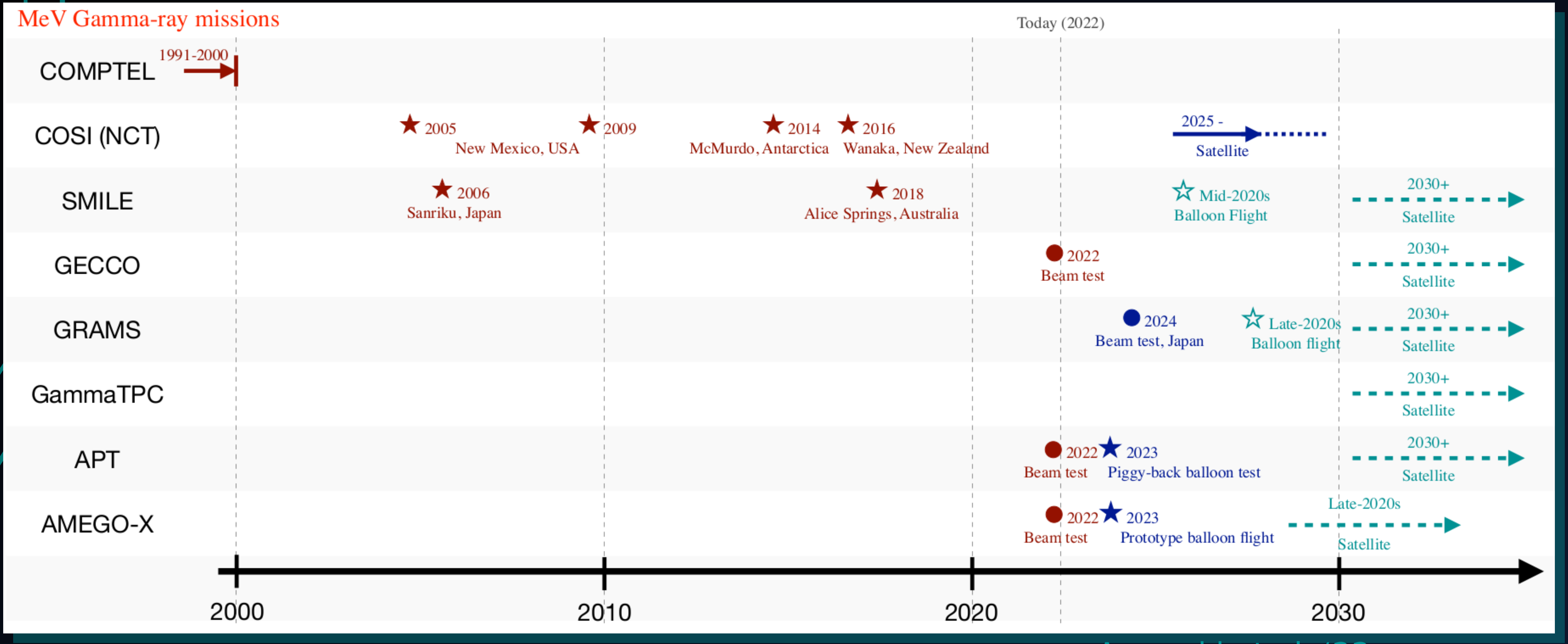
- Last major experiment in the ~MeV gamma-ray band was COMPTEL, 1991-2000

- Closing this gap is important for:
  - enabling data-driven studies of backgrounds at both lower and higher energies,
  - providing greater sensitivity to light DM in the MeV-GeV mass range.



AMEGO collab, '19

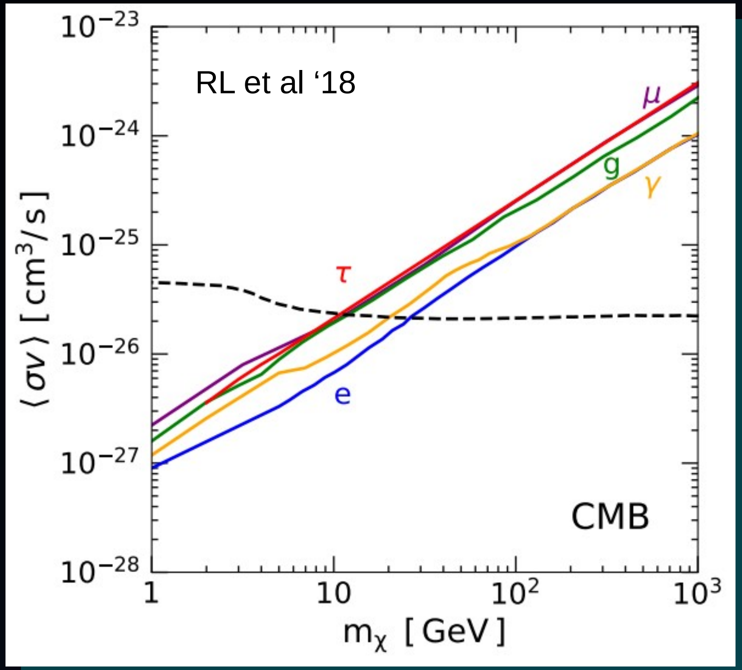
Closing the MeV gap



Aramaki et al, '22

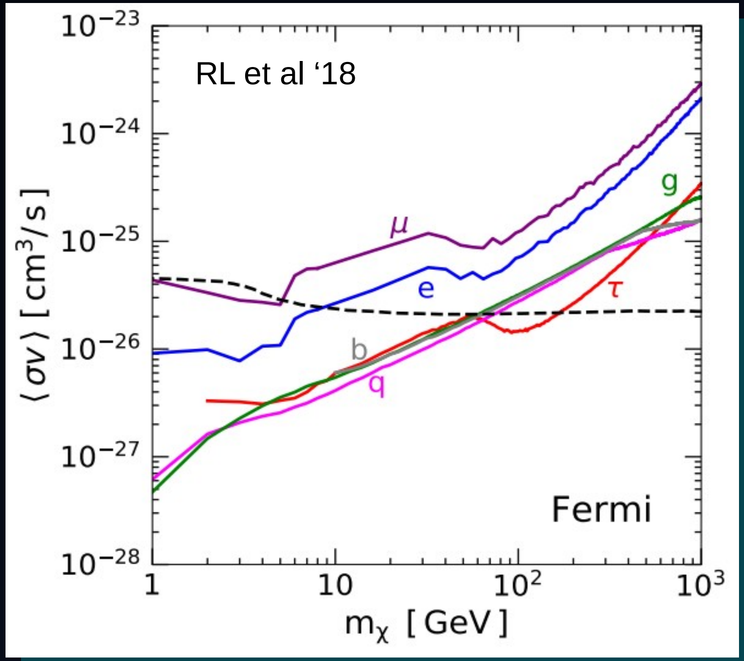
Complementarity: cornering WIMPs

Strongest low mass



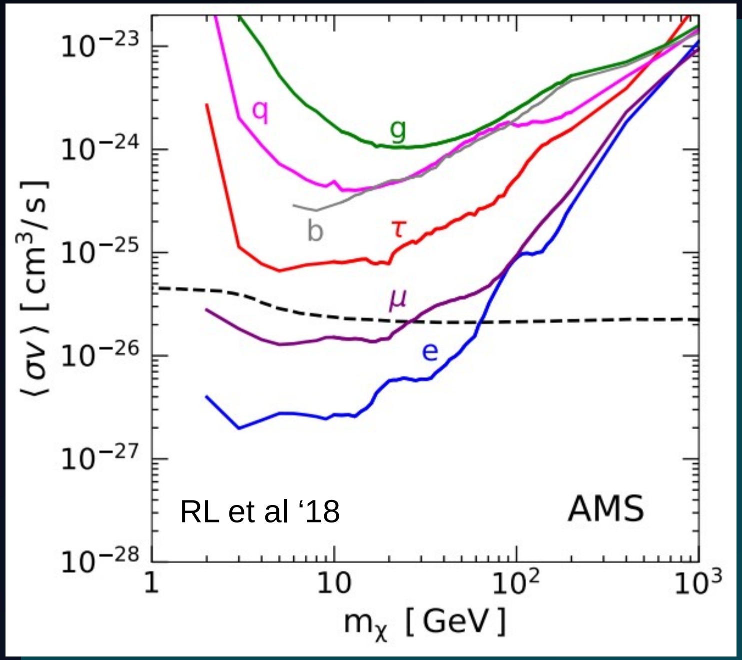
Also see Slatyer ‘15

Strongest for hadrons



Also see Fermi Collab ‘16

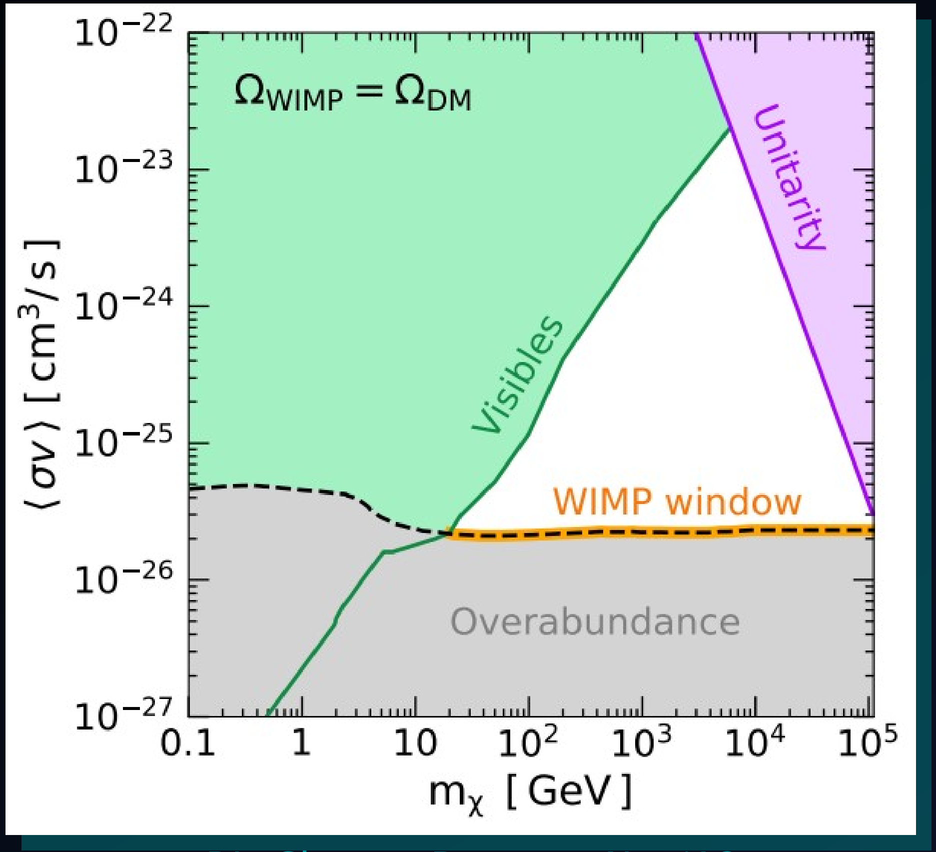
Strongest for leptons



Also see AMS collab ‘14

(strongest *and most robust* bounds)

Complementarity: cornering WIMPs



RL, Slatyer, Beacom, Ng, '18

WIMP is not dead!

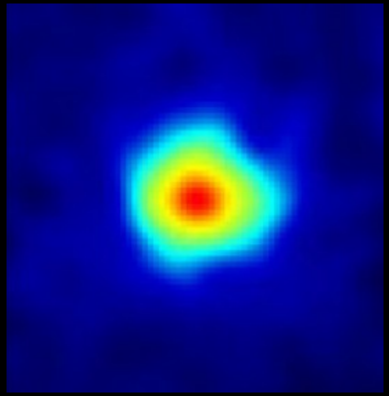
Use all possible final states, combine strongest limits

S-wave 2→2 thermal DM to visible states: mass greater than ~20 GeV

Vital to push through this window

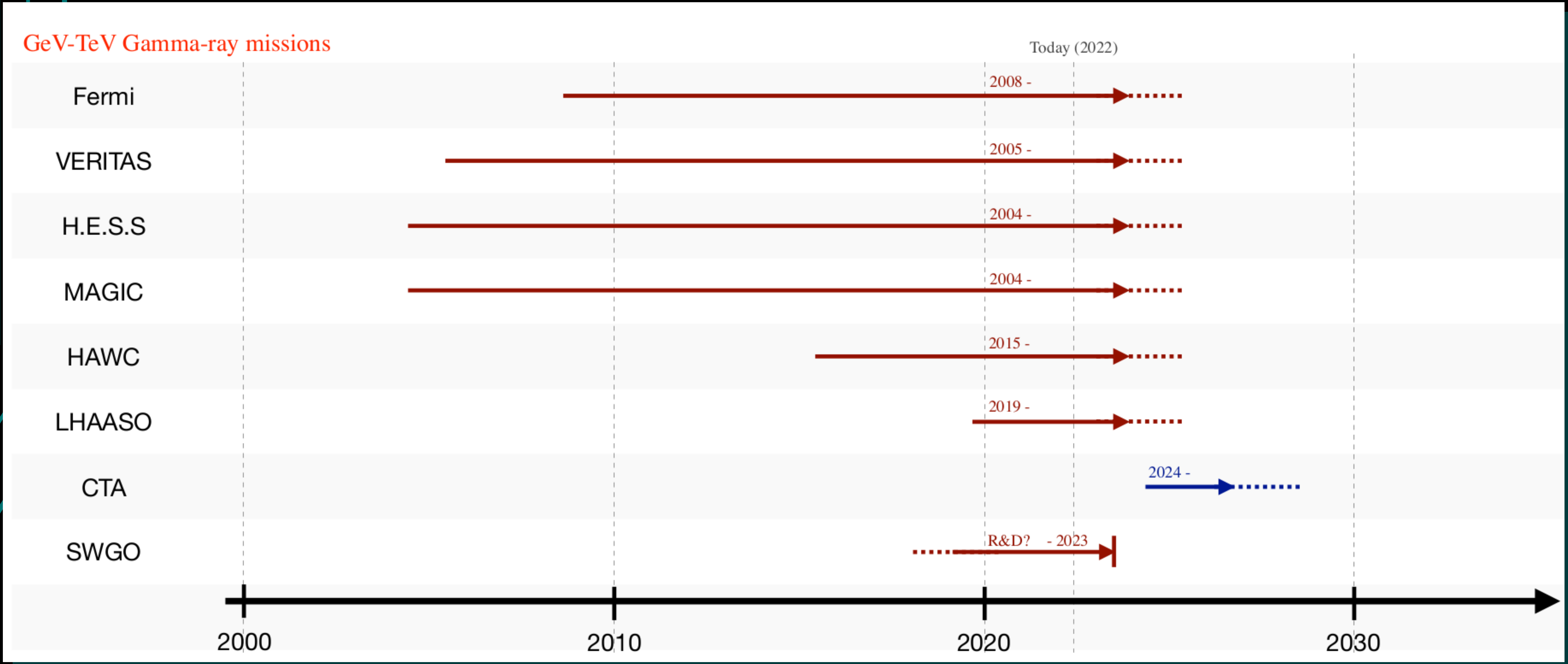
Summary

- Dark matter unknown, key goal of our community
- Indirect detection probes a wide range of wavelengths and multi-messenger data
  - Dark matter in its natural habitat



- Progress in modeling, backgrounds, and uncertainties, essential for a convincing discovery
- Ongoing development of open-source tools, data sharing, crucial to fully exploit the synergies between different wavelengths and astrophysical messengers

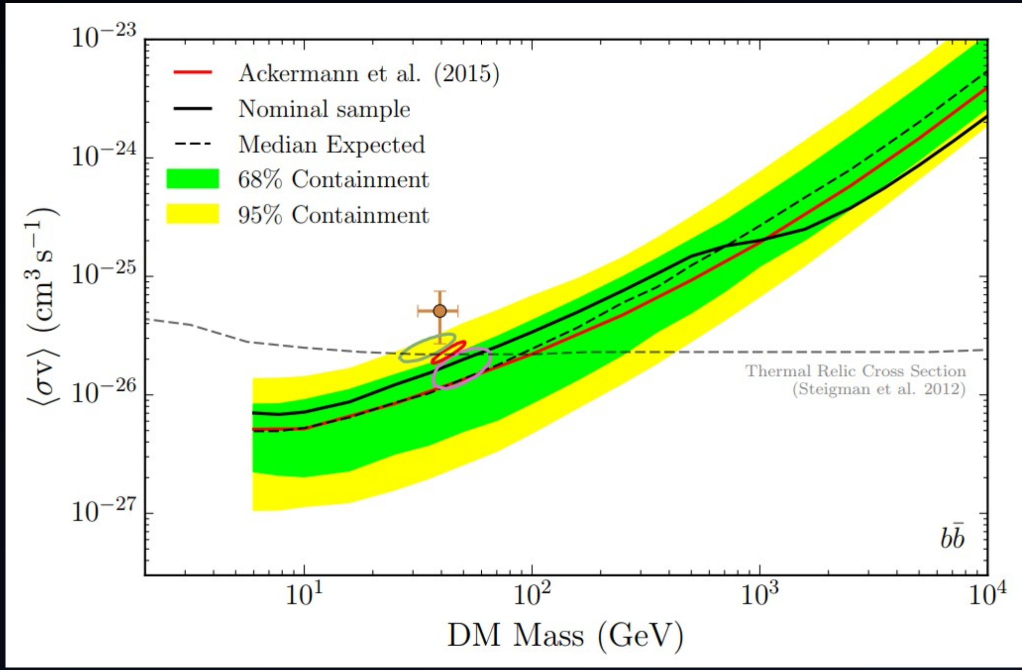
Extra Slides



Aramaki et al, ‘22

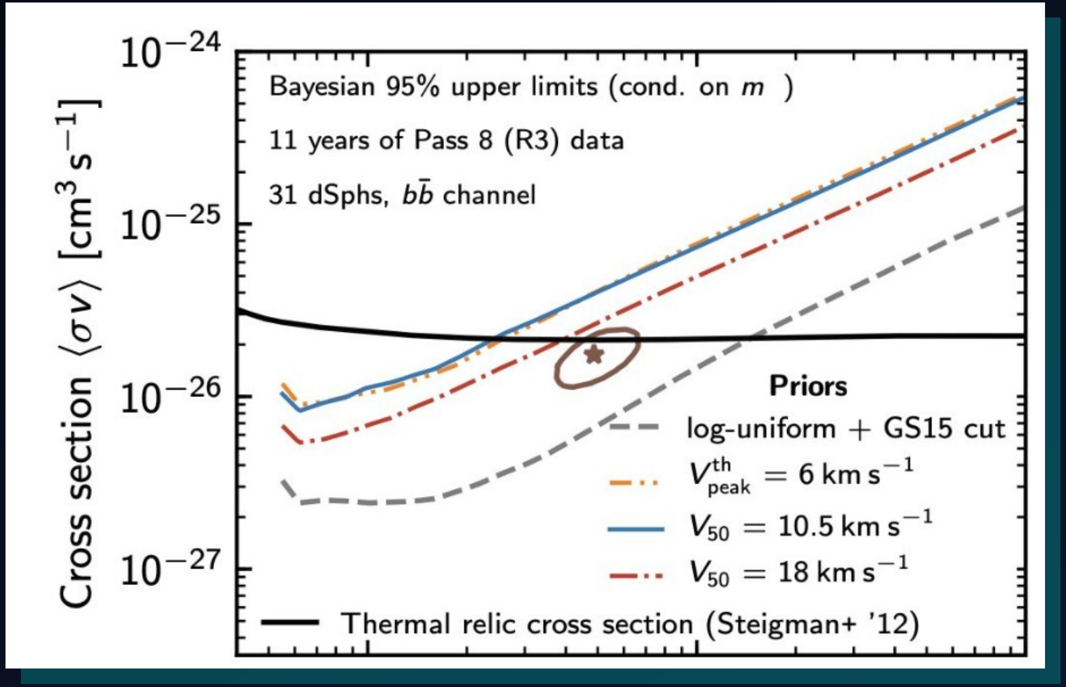
Signals from Dwarf Spheroidal Galaxies

- No strong tension with GCE at the moment, though if the GCE really is DM, signal might appear soon
- Keep in mind systematics here!



Ackermann+, '16

Ando+, '20



DM density uncertainties weaken limits further

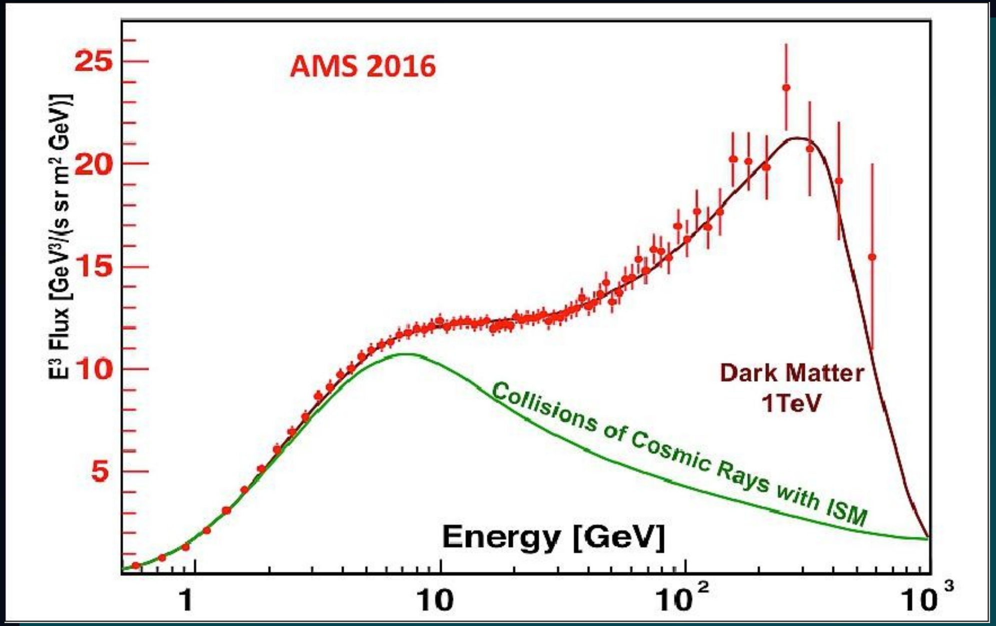
See also Chang, Necib '20

Positron Excess

Rebecca Leane

Positron Excess

- Observed by PAMELA, AMS-02, recently DAMPE
- If DM, needs to be ~TeV
- But, could be pulsars…



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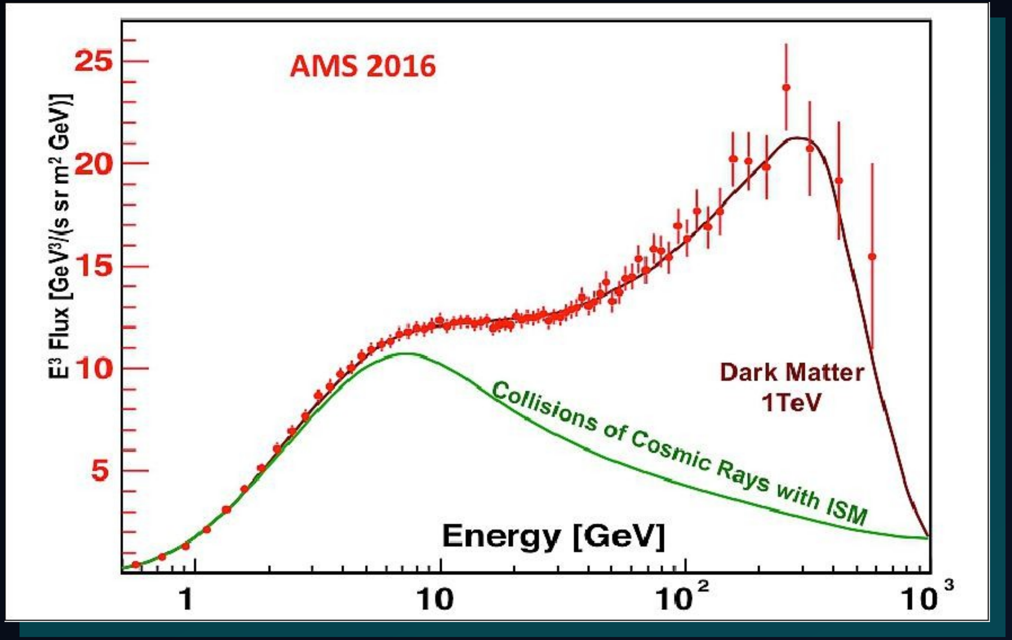
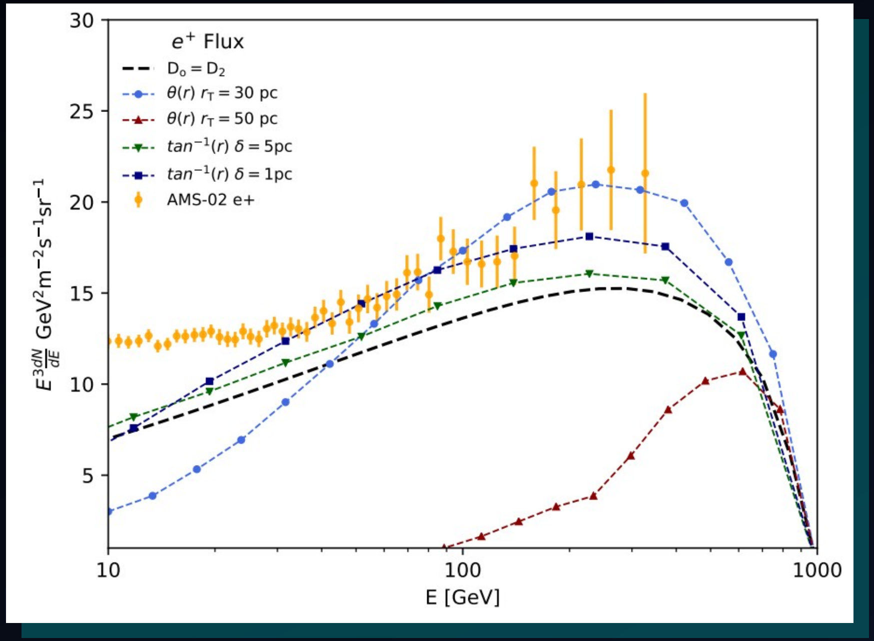




Excess cannot be due to main pulsar candidates if Galactic diffusion similar to diffusion in regions of nearby pulsars

HAWC Collab, ‘17

Implies diffusion coefficient is not uniform

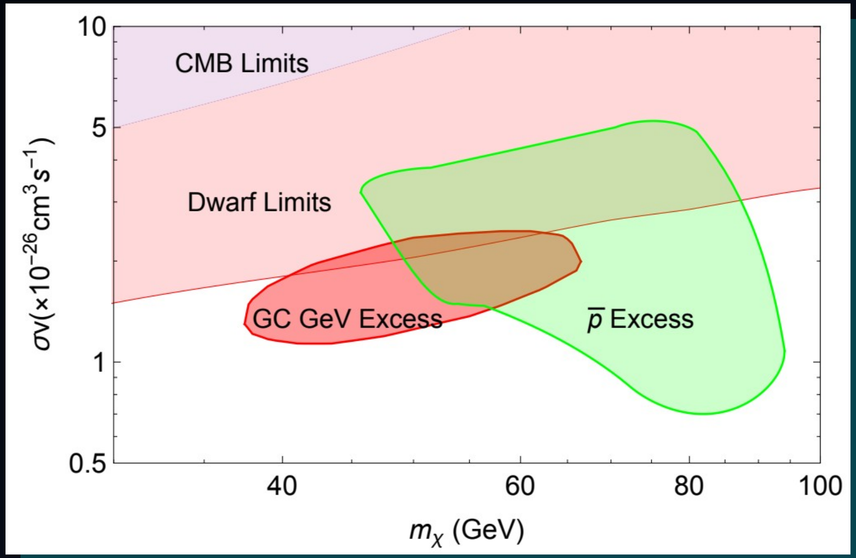
Profumo et al ‘18
Hooper+Linden ‘17

Antiproton Excess

Rebecca Leane

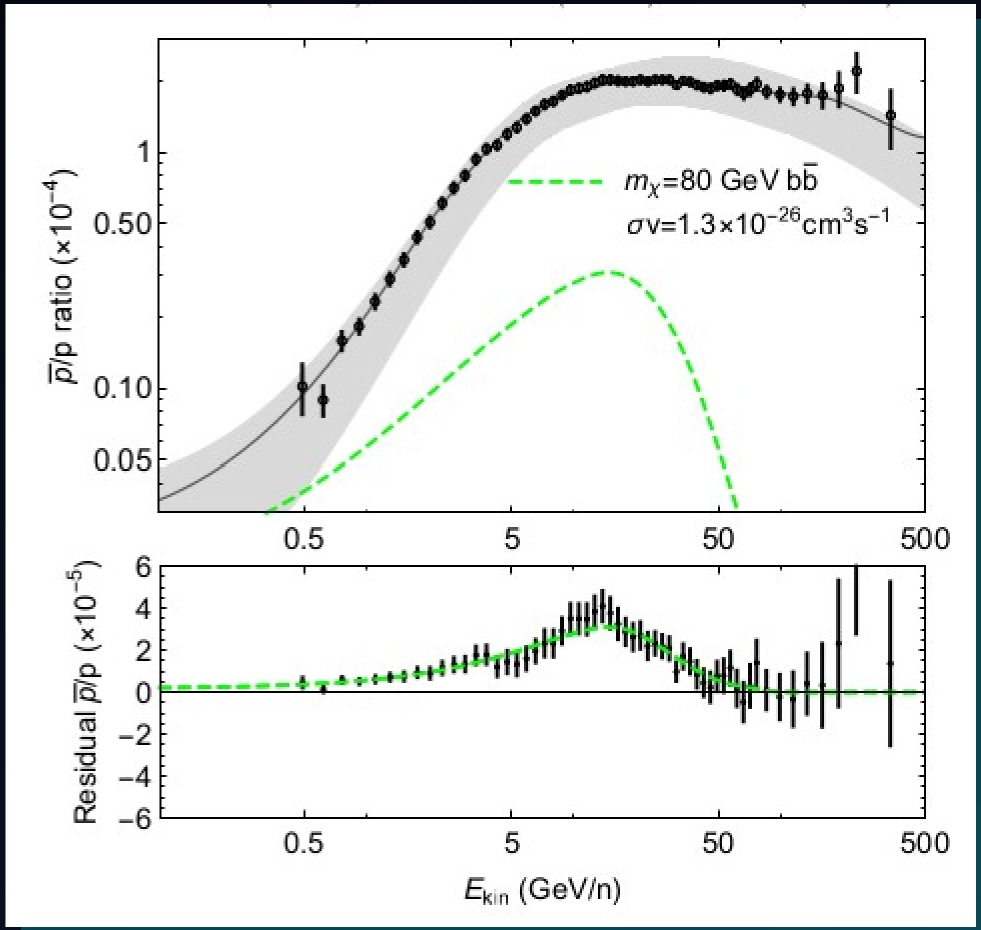
Antiproton Excess

- Excess in antiprotons, AMS
- AMS correlated uncertainties?
  - Quantifying systematics
- Link to GCE?

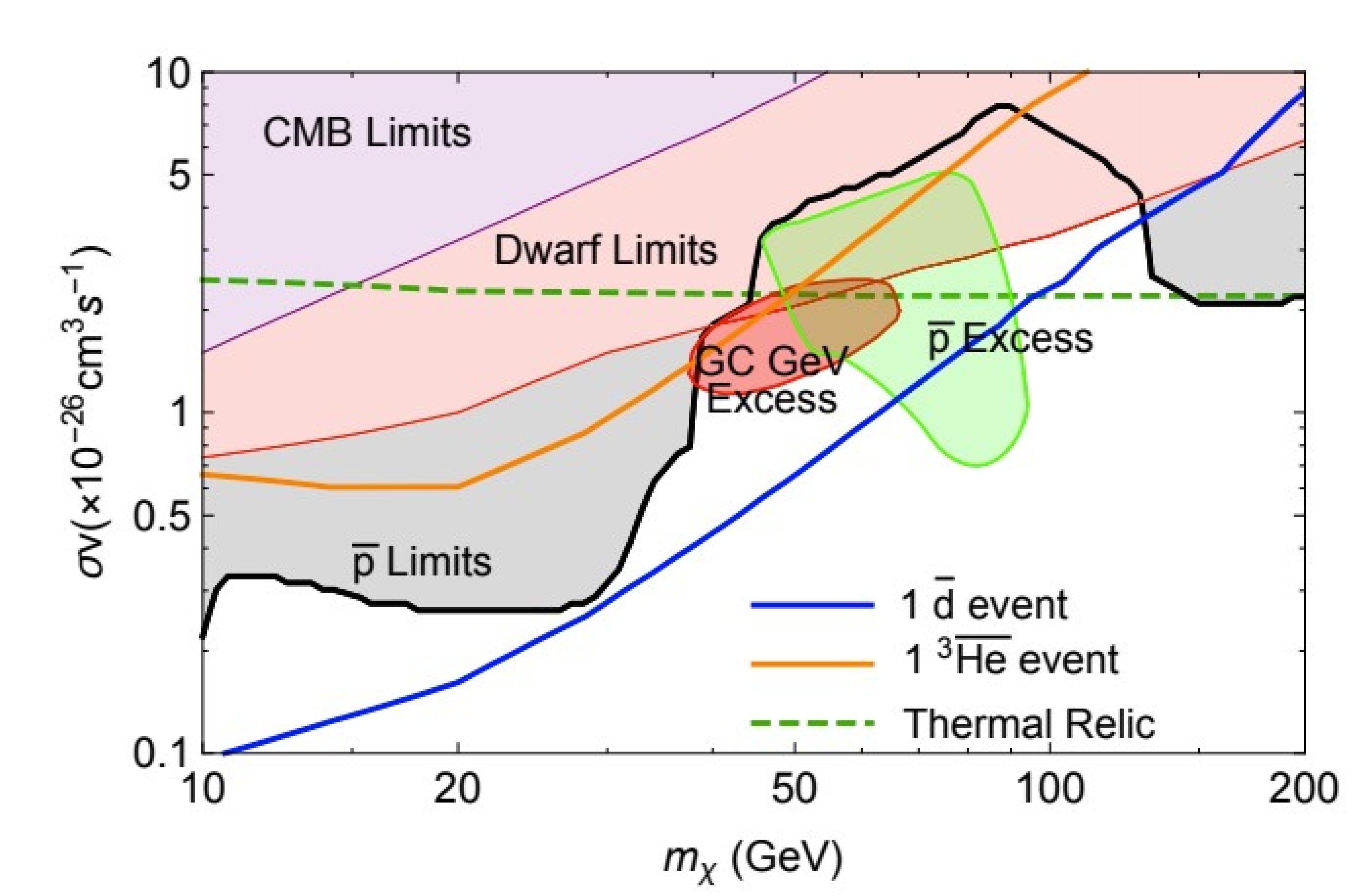


Cholis et al ‘19

See also Hooper, RKL, Tsai, Wegsman, Witte ‘19

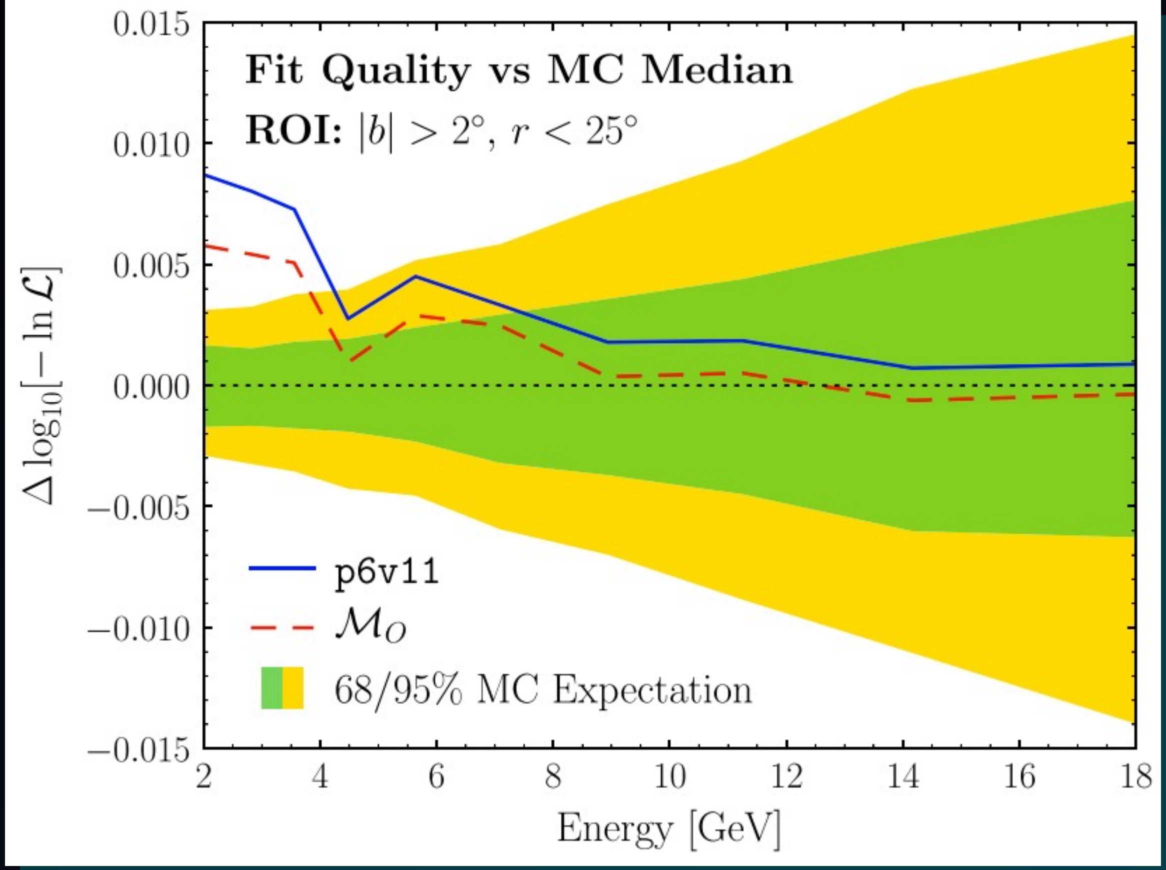


Cuoco et al ‘16 and ‘19, Cui et al ‘16 and ‘19,
Cholis et al ‘19
Boudaud ‘19
Heisig ‘20
Calore et al, ‘22



CMB Limits
Dwarf Limits
GC GeV Excess
p̄ Excess
p̄ Limits
1 d̄ event
1 ³He̅ event
Thermal Relic
σv(×10⁻²⁶cm³s⁻¹)
m_χ (GeV)
10
5
1
0.5
0.1
10
20
50
100
200

Key Point: All diffuse models are not good



Buschmann+, '20

- Even the best diffuse models are far from good fits to the data
- Fitting to real data, and simulating based on best-fit parameters, does not return likelihoods expected within Poisson noise
- There is clearly a systematic here
- Better diffuse models are key to moving forward