Astrophysical Searches for Dark Matter

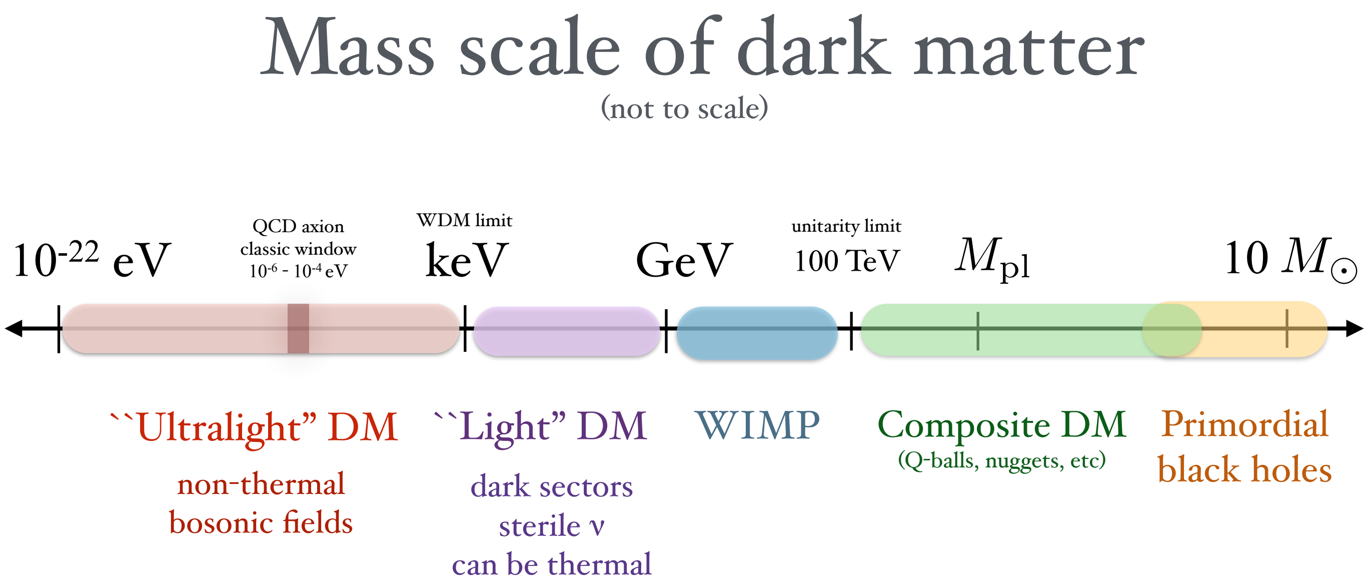
Elisa Pueschel

ISAPP School "Neutrinos and Dark Matter"

24 September 2024

RUHR UNIVERSITÄT BOCHUM

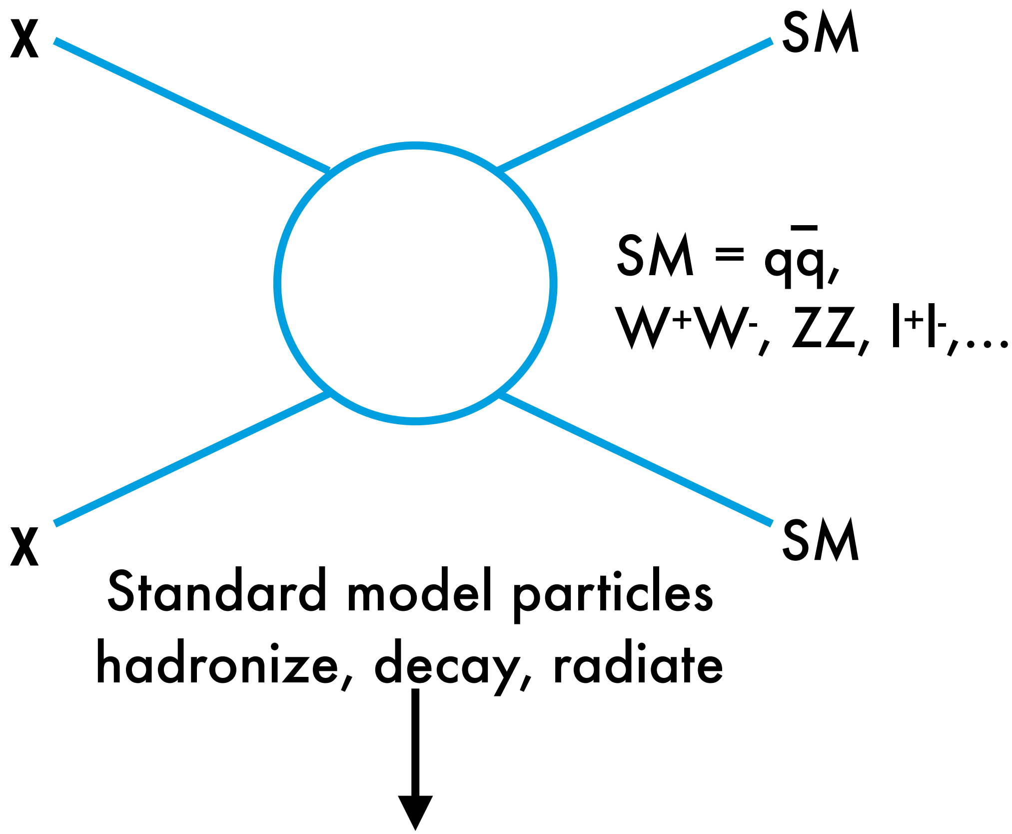
Dark Matter: Where to Look



Lin 2019 arXiv:1904.07915

Astrophysical searches probe across different mass scales

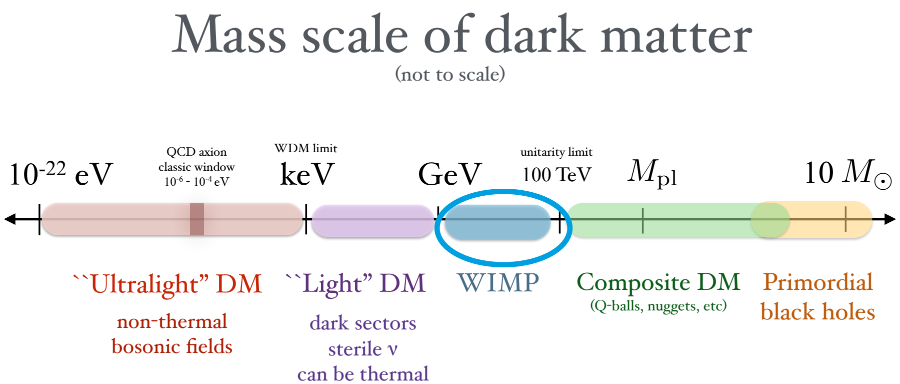
Indirect Searches for Dark Matter



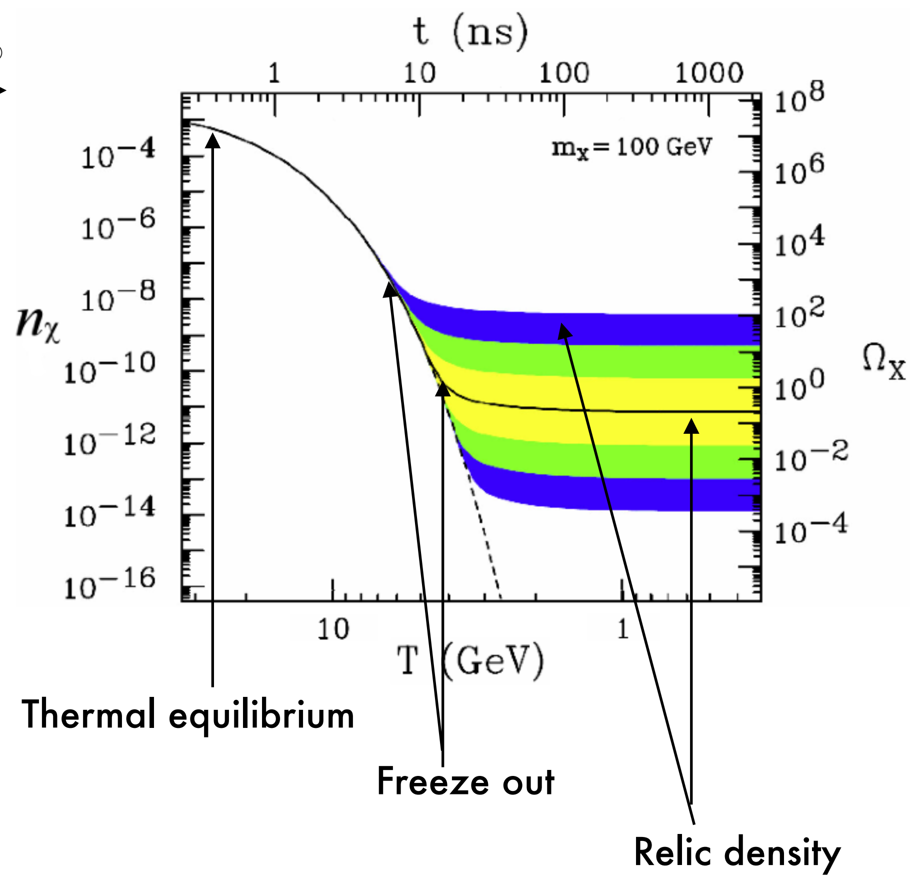
Gamma rays, neutrinos, p^+/p^-, e^+/e^-

Astrophysical signal from annihilation or decay to standard model particles

Weakly Interacting Massive Particles



Feng 2010 arXiv:1003.0904

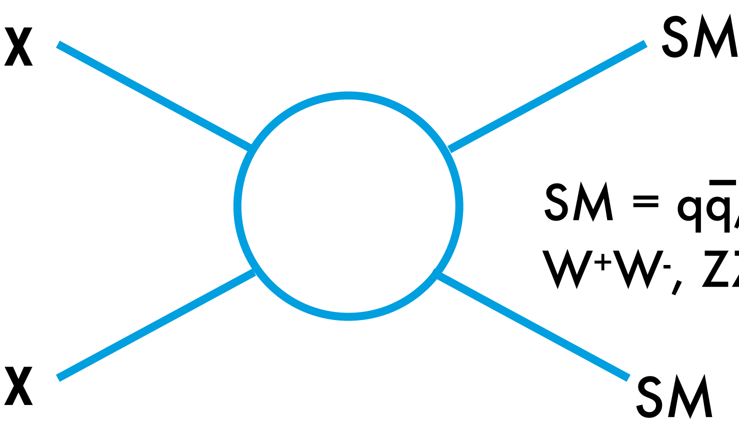


Appealing to consider **GeV-TeV mass, weakly-interacting** particle

"WIMP Miracle"

$\langle \sigma v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}$

Indirect Searches with Gamma Rays and Neutrinos

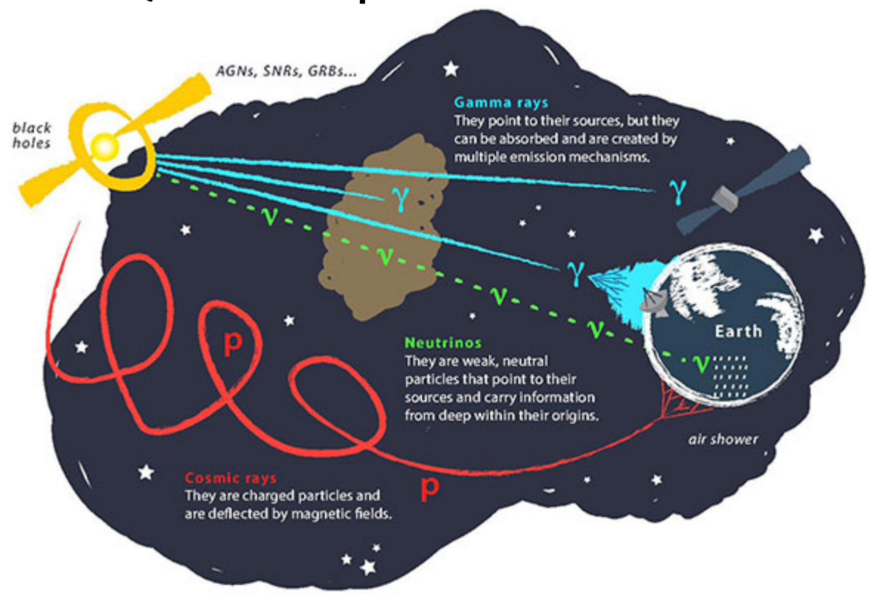


SM = $q\bar{q}$,
W^+W^-, ZZ, l^+l^-,…

Standard model particles
hadronize, decay, radiate

Gamma rays, neutrinos, p^+/p^-, e^+/e^-

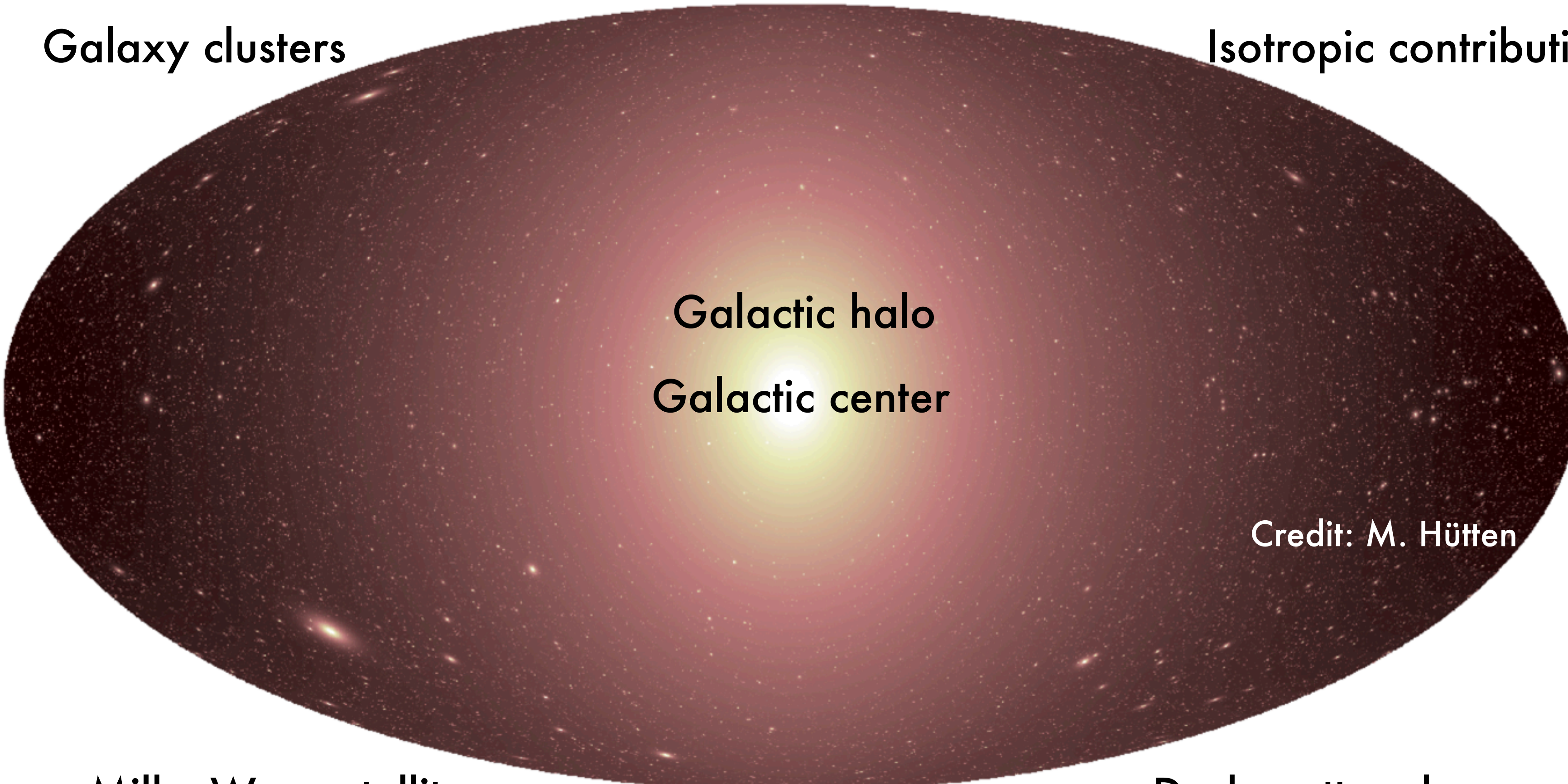
γs and νs point back to sources



IceCube Collaboration

Look for an excess above astrophysical backgrounds

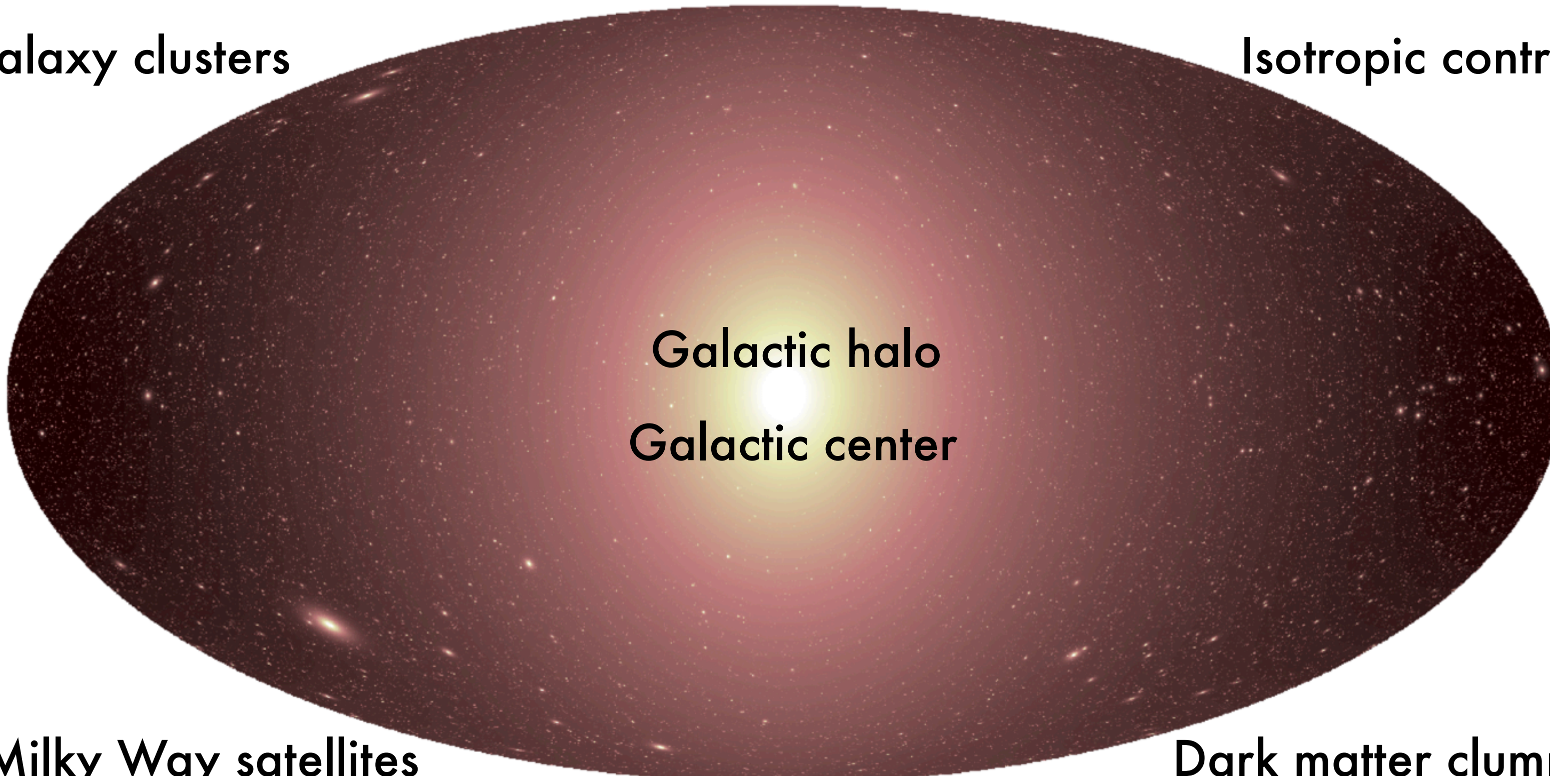
Gamma-ray Targets



Neutrino Targets

Galaxy clusters

Isotropic contributions



Milky Way satellites

Dark matter clumps

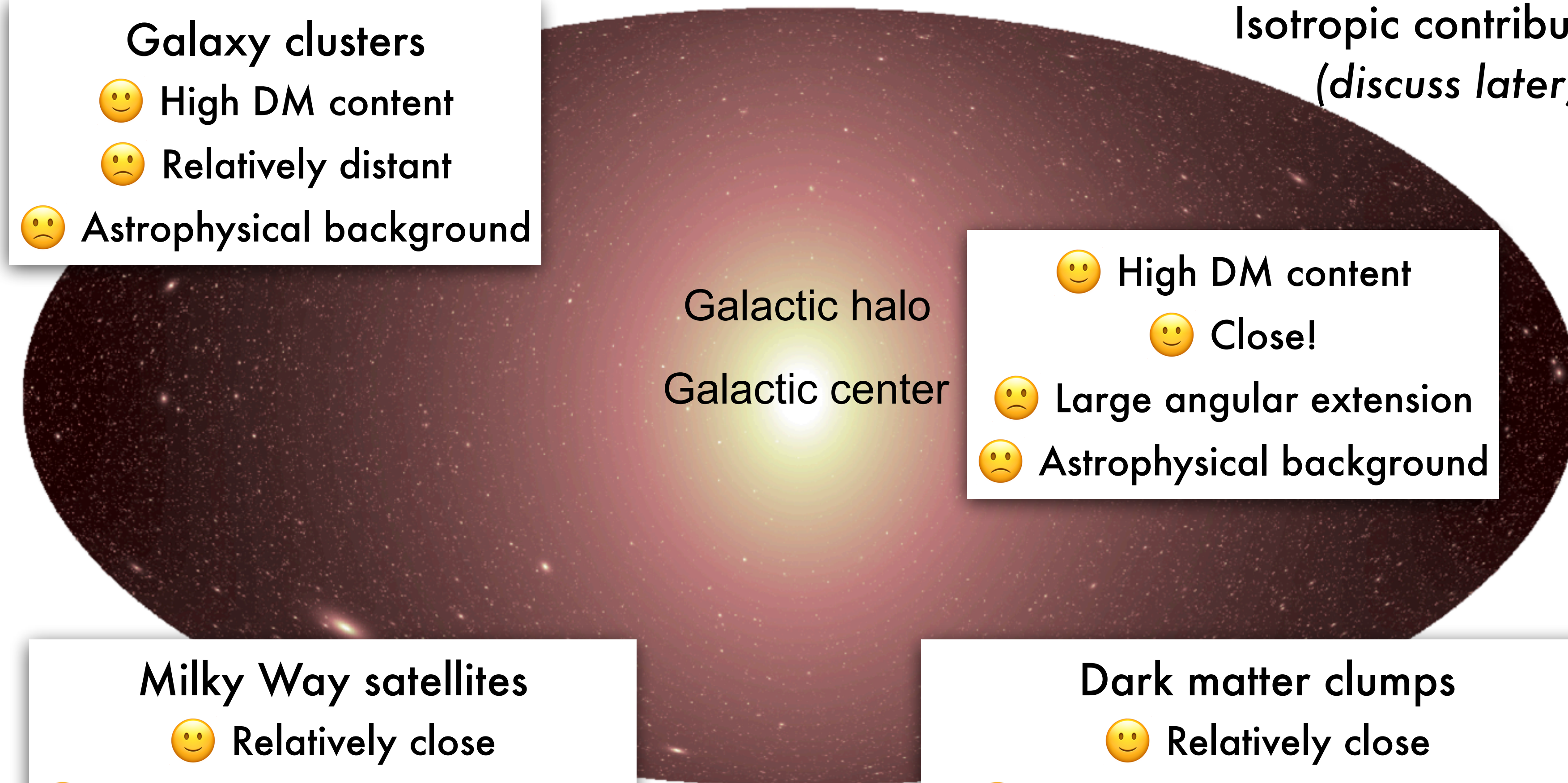
+ Sun

+ Earth

Targets: Advantages and Disadvantages

Galaxy clusters
🙂 High DM content
🙁 Relatively distant
🙁 Astrophysical background

Isotropic contributions
(discuss later)

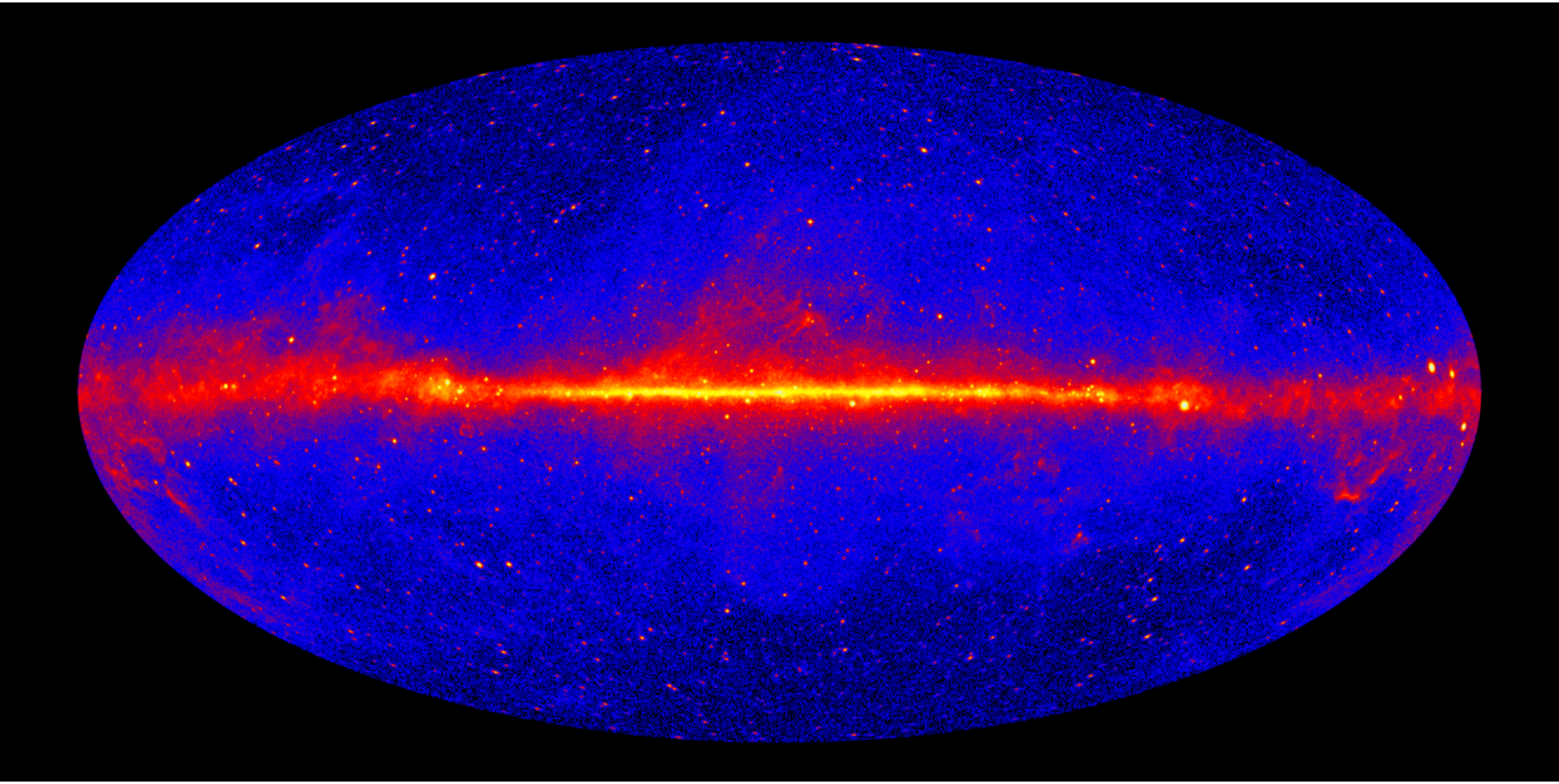


🙂 High DM content
🙂 Close!
🙁 Large angular extension
🙁 Astrophysical background

Milky Way satellites
🙂 Relatively close
🙂 Low astrophysical background
🙂 Modest angular extension
🙁 Modestly high DM content

Dark matter clumps
🙂 Relatively close
🙂 Low astrophysical background
🙂 Modest angular extension
🙁 Very modest/uncertain DM content

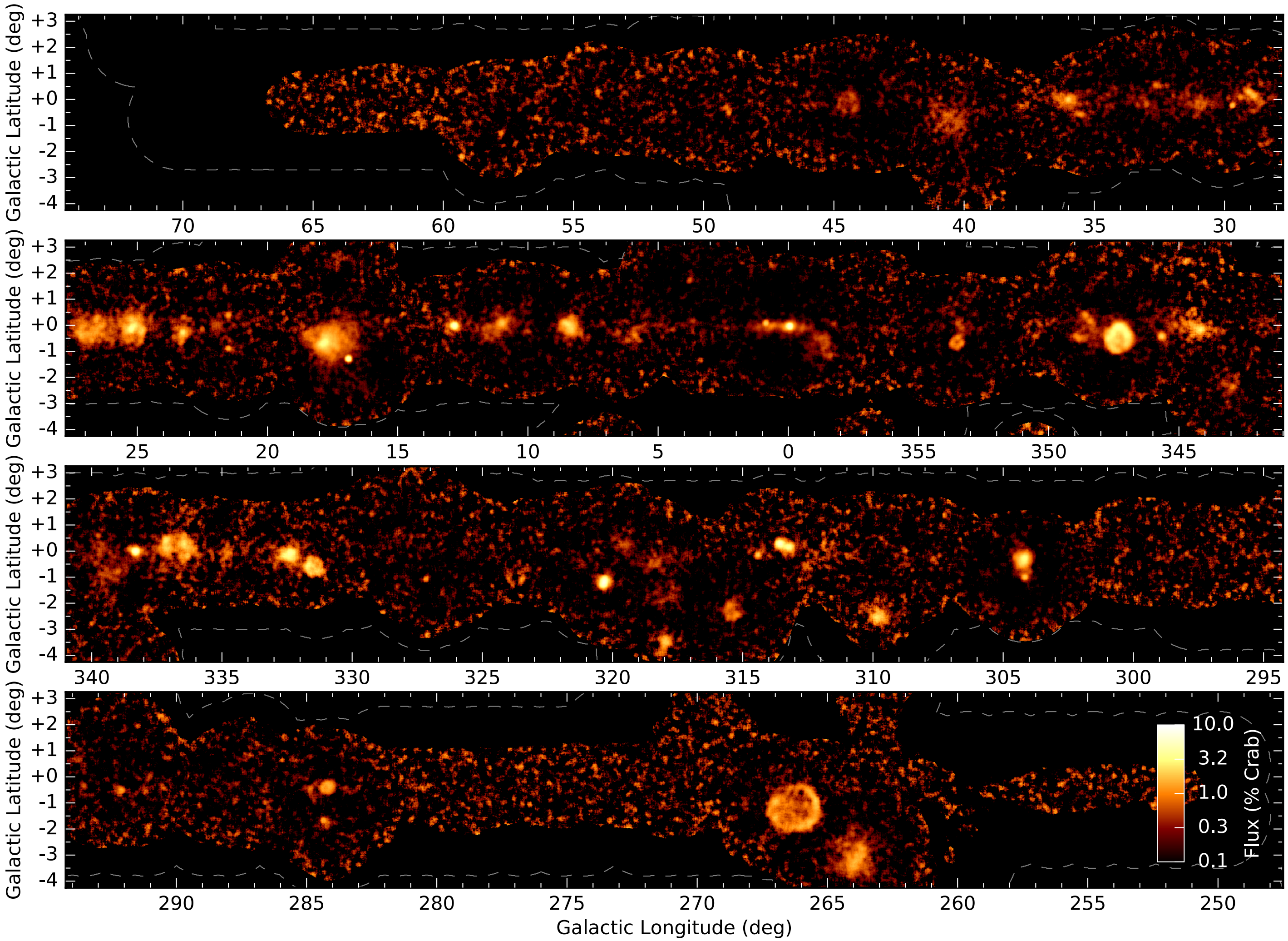
More on Galactic Center



Bright in gamma rays!

12 years of Fermi-LAT data, >1 GeV

More on Galactic Center

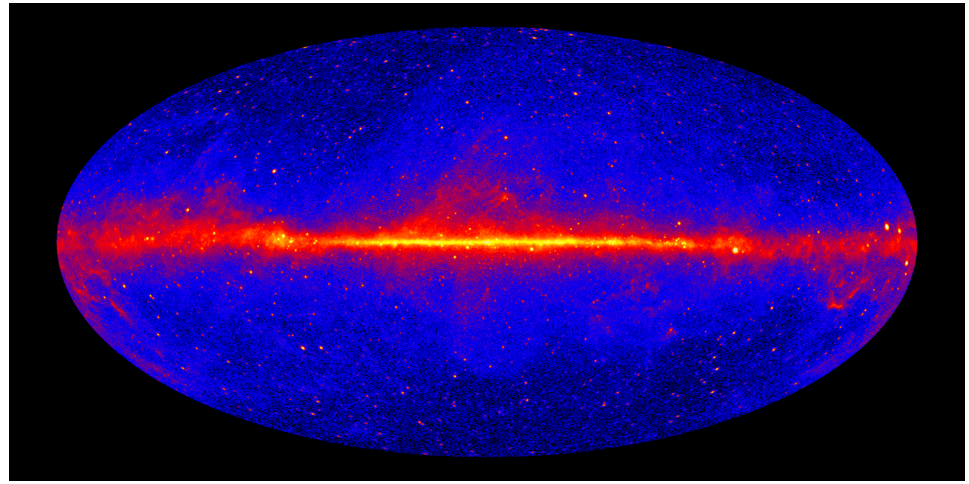


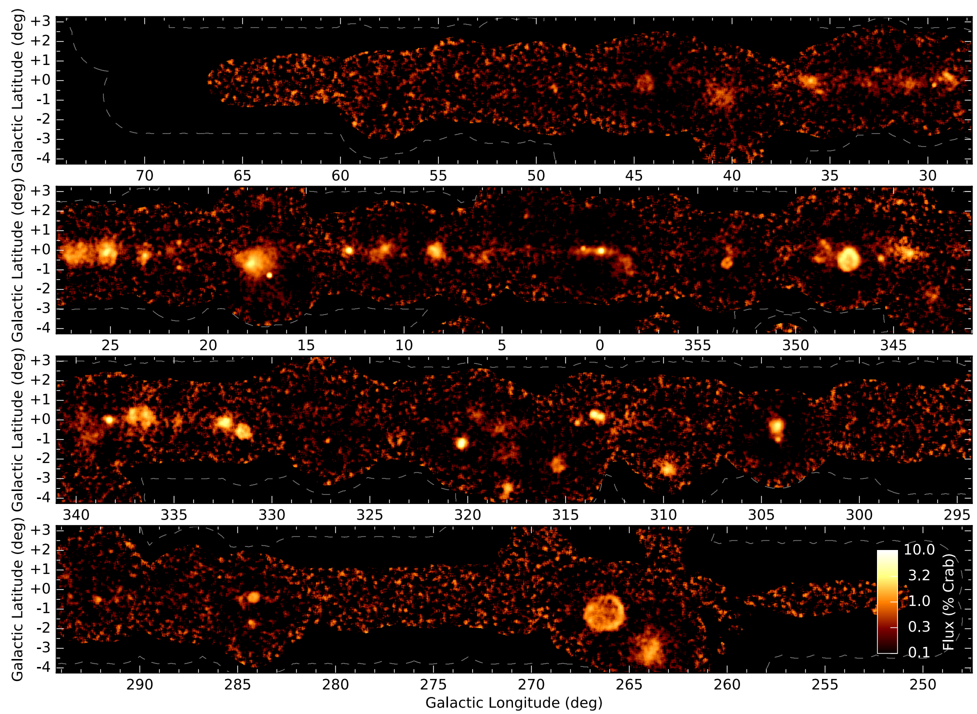
Bright in gamma rays!

9 years of H.E.S.S. data, >1 TeV

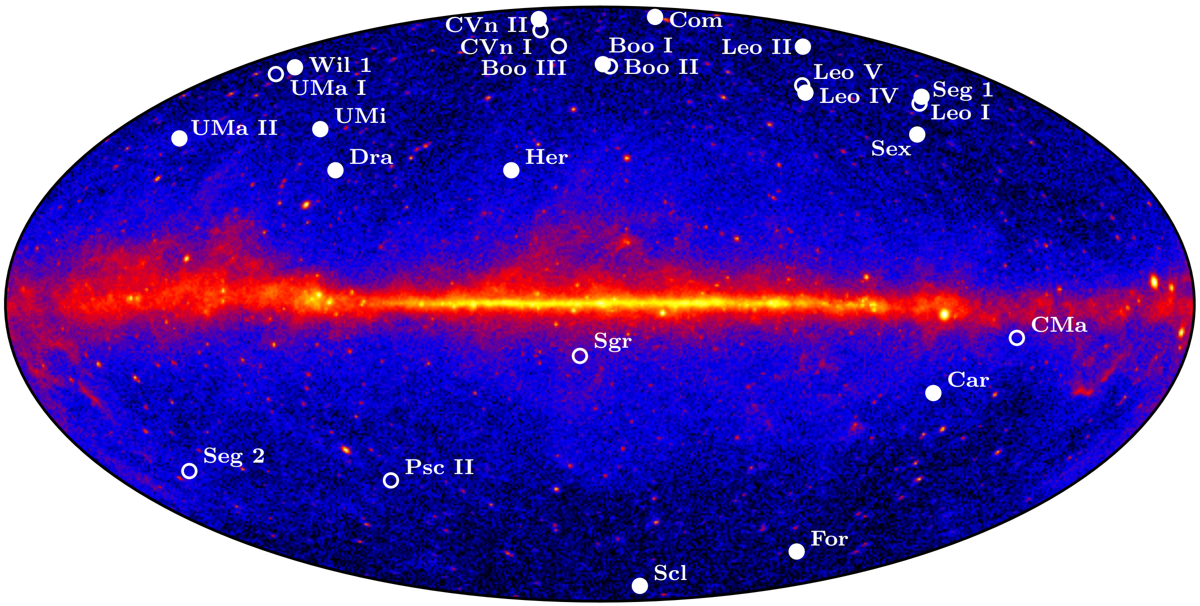
More on Galactic Center

- Resolved sources of gamma rays
  - Pulsar wind nebulae
  - Gamma-ray binaries
  - Supernova remnants/molecular clouds
  - Pulsars
  - Fermi bubbles
  - TeV halos
- Diffuse/isotropic emission
  - Cosmic ray/gas hadronic interactions
  - Interaction of cosmic rays with CMB & infrared/optical light via inverse Compton





More on Dwarf (Spheroidal) Galaxies



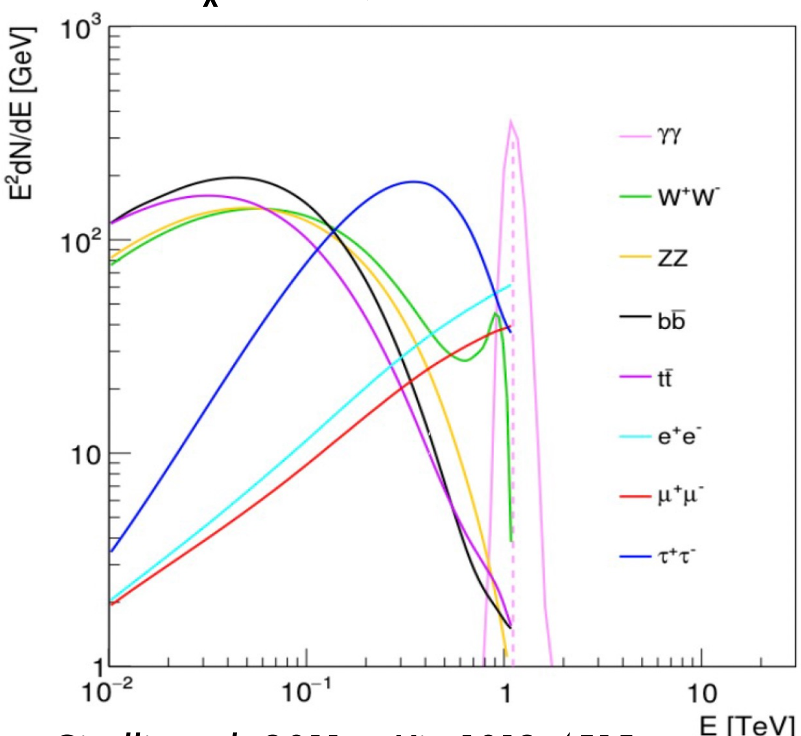
- Milky Way satellites: nearby (~20-200 kpc)
- Classic (thousands of bright stars) and Ultrafaint (tens of bright stars)
    - Multiple objects = less sensitivity to mis-modeling of single object
    - Many more expected with Vera Rubin Observatory
- Large mass to light ratios: ~O(1000) $M_\odot/L_\odot$
- Low astrophysical background (no known gamma-ray emitters)
- Modest angular extension

Predicted Signal (Annihilation)

"Particle physics term"

$$\frac{\mathrm{d}^2\Phi\left(\langle\sigma v\rangle, J\right)}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1}{4\pi}\boxed{\frac{\langle\sigma v\rangle}{2M_\chi^2}\sum_f \mathrm{BR}_f \frac{\mathrm{d}N_f}{\mathrm{d}E}}\int_{\mathrm{l.o.s.}} \rho^2_{\mathrm{DM}}(r(s,\theta))\, ds$$

M_χ = 1 TeV



Cirelli et al. 2011 arXiv:1012.4515

- Assuming branching ratio of 1 to a given final state
- Spectral shape is a key input!
  - Continuum emission from **χχ** → quark pairs, lepton pairs, W^+W^-, ZZ
    - Cut-off at M_χ (assuming annihilation)
  - "Line" emission from **χχ** → **γ**X, X = h, Z, **γ**

Predicted Signal (Annihilation)

"Astrophysics term"

$$\frac{\mathrm{d}^2\Phi\left(\langle\sigma v\rangle, J\right)}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2M_\chi^2}\sum_f \mathrm{BR}_f \frac{\mathrm{d}N_f}{\mathrm{d}E}\boxed{\int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}^2(r(s,\theta))\, ds}$$

J-factor

- J-factor depends on
  - Dark matter distribution in target
  - Distance to target
  - Instrument response (point spread function)
- Significant source of uncertainty in extracted limits on ⟨**σv**⟩

Predicted Signal (Decay)

$$\frac{\mathrm{d}^2\Phi(J)}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1}{4\pi}\frac{1}{\tau_\chi M_\chi}\sum_f \mathrm{BR}_f \frac{dN_f}{dE}\int_{l.o.s.} dl\rho_{DM}(r(s,\theta))ds$$

Note differences from flux for annihilation

$$\frac{\mathrm{d}^2\Phi\left(\langle\sigma v\rangle, J\right)}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2M_\chi^2}\sum_f \mathrm{BR}_f \frac{\mathrm{d}N_f}{\mathrm{d}E}\int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}^2(r(s,\theta))\,ds$$

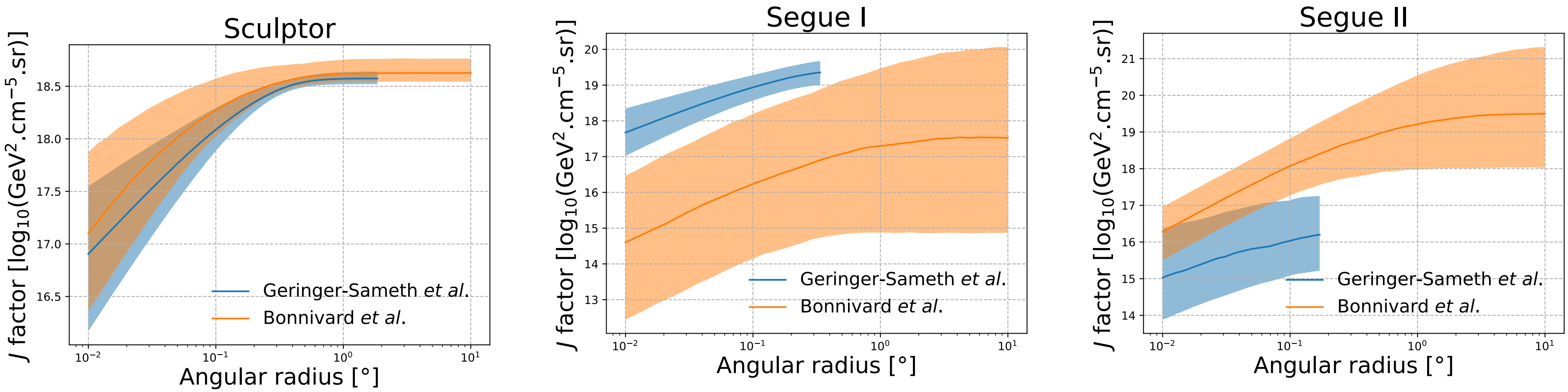
Order of ρ_{DM} affects target choice:
galaxy clusters good targets for decay searches

J-factor Calculations: Highly Non-Trivial

Example: dwarf spheroidal galaxies (Milky Way satellites)

- Different choices for DM density profile, velocity anisotropy, light profile, consideration of systematics
- Choice of stars to include has significant impact
  - Particularly for ultra faint systems with tens of stars

Kerszberg et al., in prep

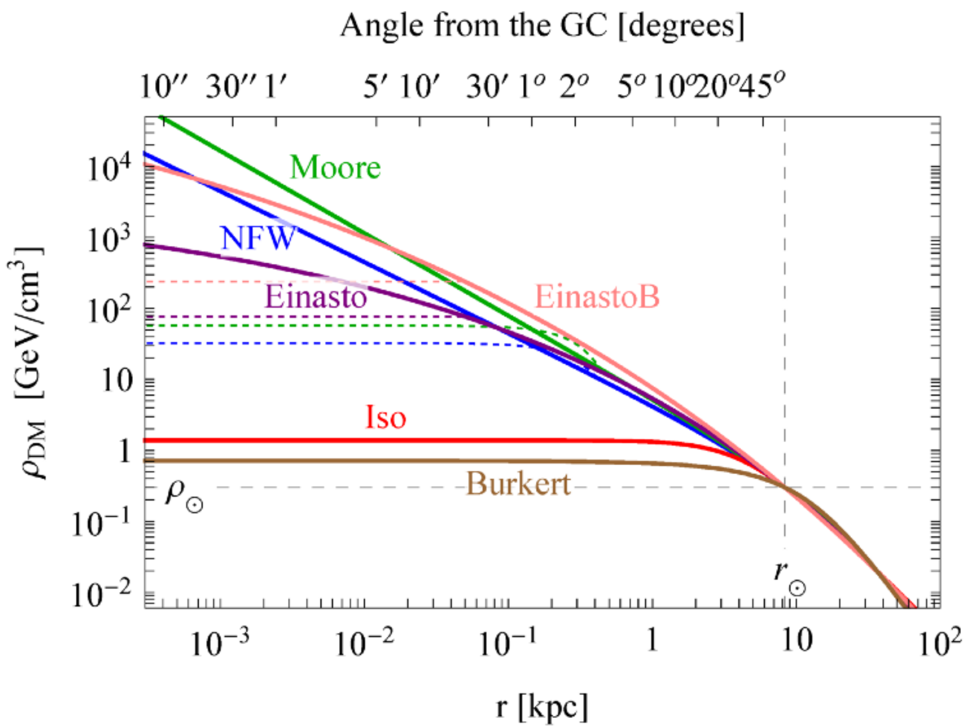


Different calculations can yield very different results!

J-factor Calculations: Highly Non-Trivial

Example: Galactic Center/Halo

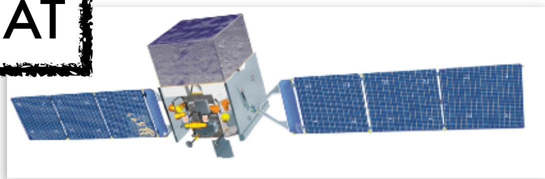
- Profiles motivated by N-body simulations
- Attempts to use observations of tidal streams to probe profiles
- Assumed dark matter density profile strongly affects extracted upper limits on dark matter annihilation cross section



Cirelli et al. 2011 arXiv:1012.4515

Detecting Gamma Rays

Fermi-LAT



- Energy range: 20 MeV to 1 TeV
- Large duty-cycle
- Full-sky coverage

- Imaging Atmospheric Cherenkov Telescopes (IACTs)
  - E ~100 GeV to > 30 TeV
  - Precise energy & angular reconstruction
  - High sensitivity
  - Limited duty-cycle/FOV

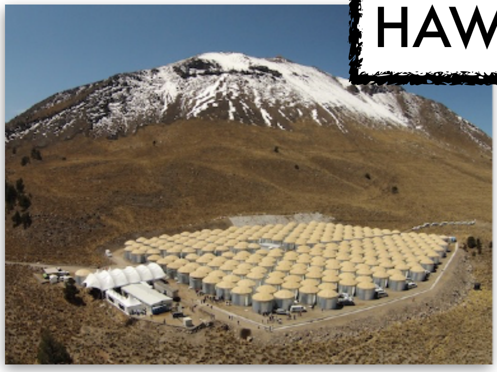
MAGIC

VERITAS

H.E.S.S.

- Water Cherenkov Technique
  - E ~1 - 100 TeV
  - Large duty-cycle
  - Large field of view

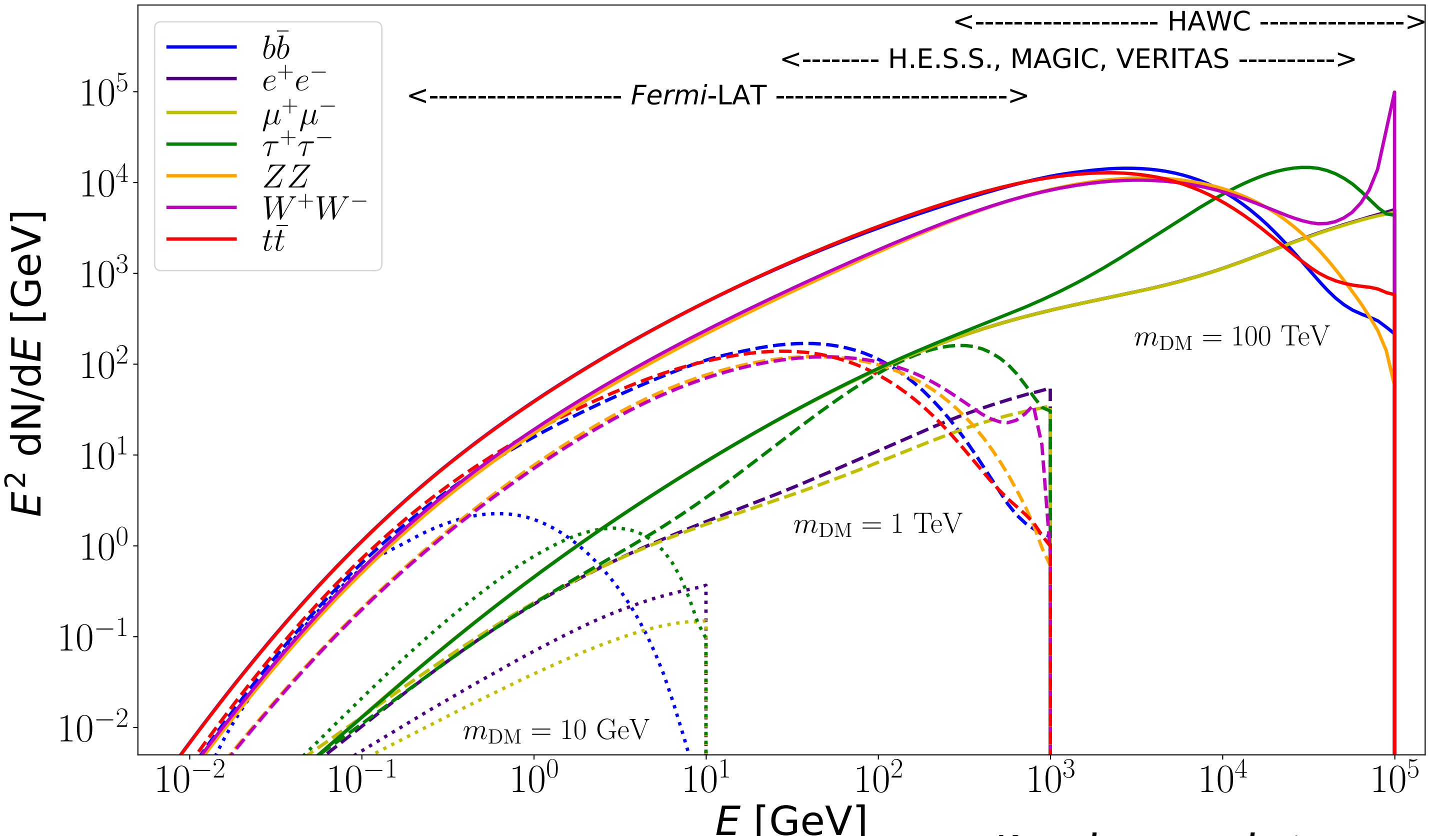
HAWC



- Multiple detection methods
  - E ~ < 1 TeV - 1 PeV
  - Large duty-cycle
  - Large field of view

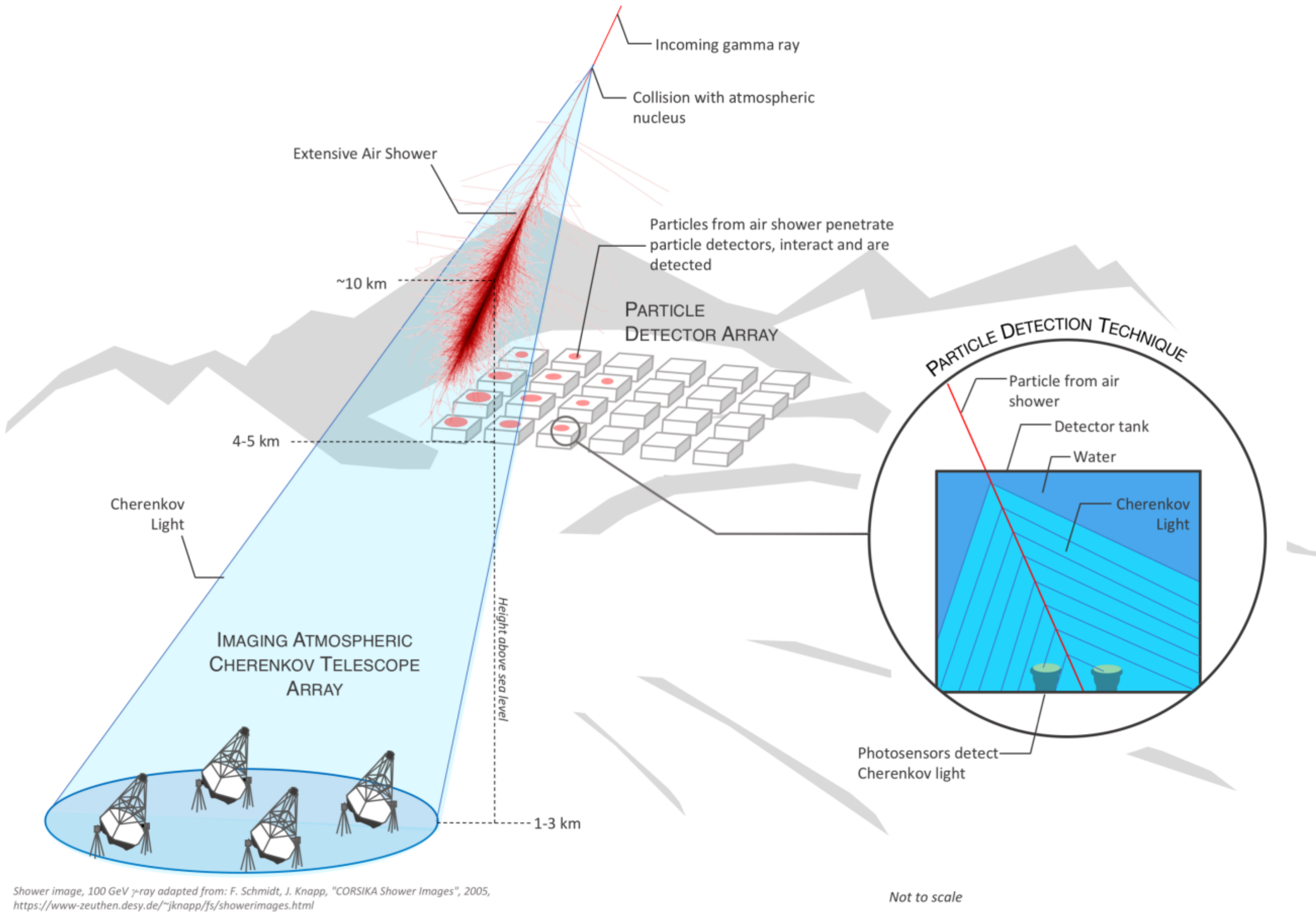
LHAASO

Impact of differing sensitive energy ranges



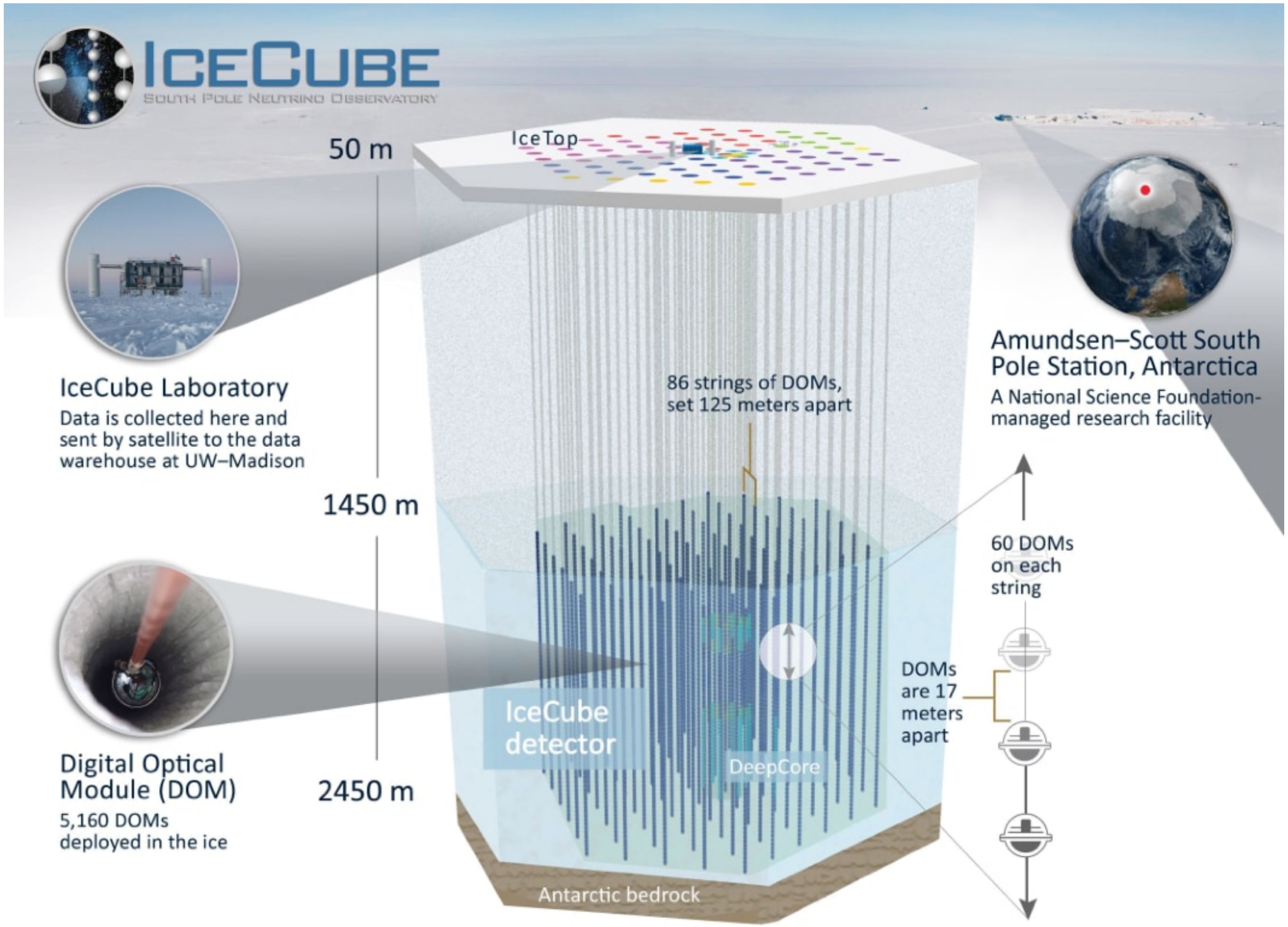
Kerszberg et al., in prep

Detecting Gamma Rays



PoS(ICRC2019)785

Detecting Neutrinos

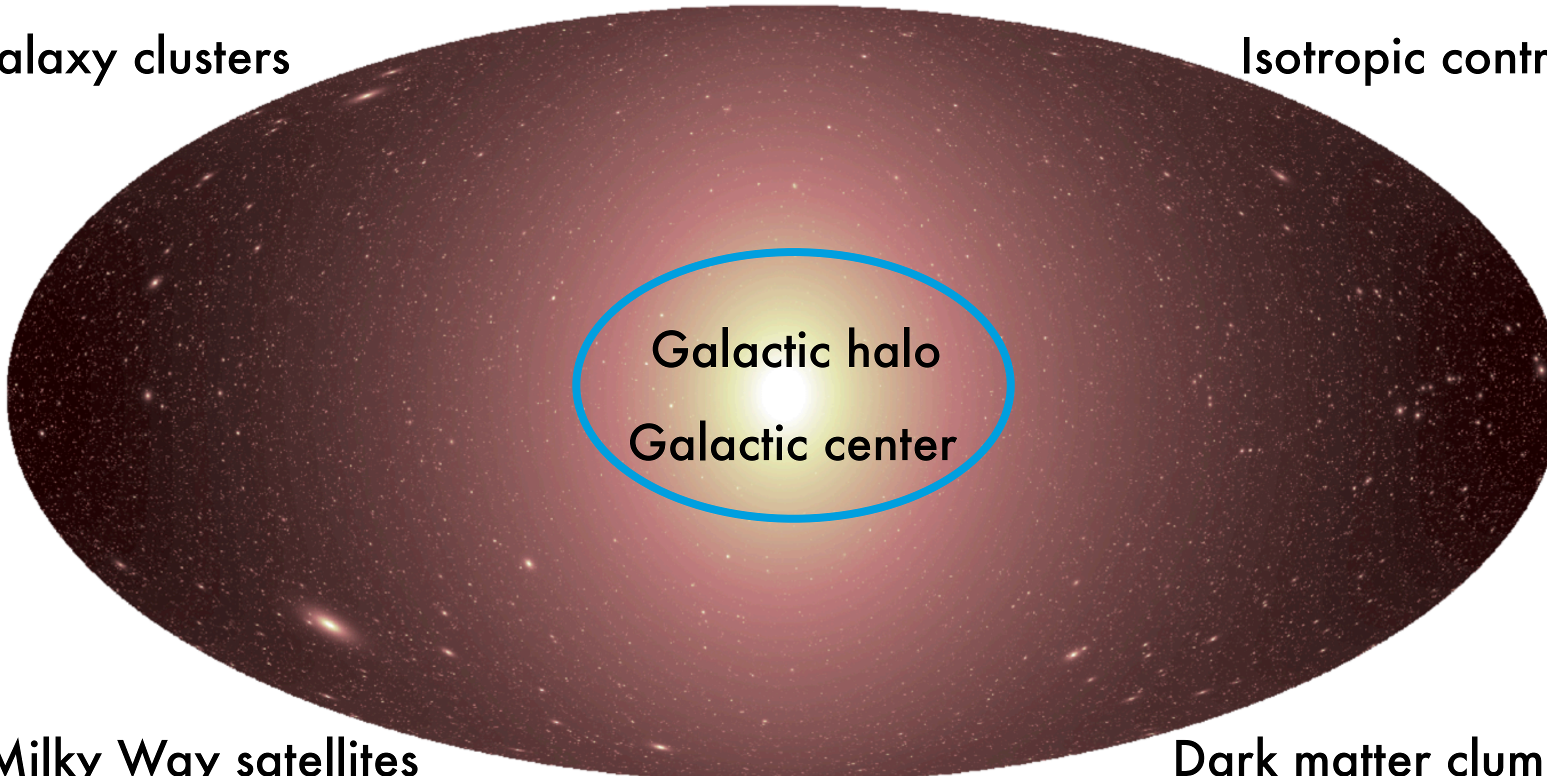


See Anna Franckowiak's lectures last week!

Targets

Galaxy clusters

Isotropic contributions



Milky Way satellites

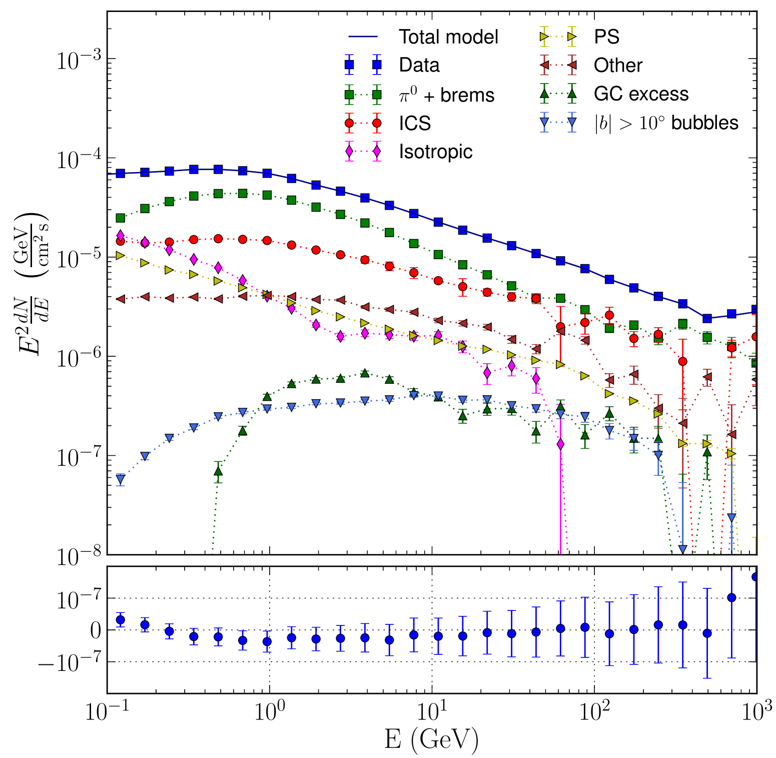
Dark matter clumps

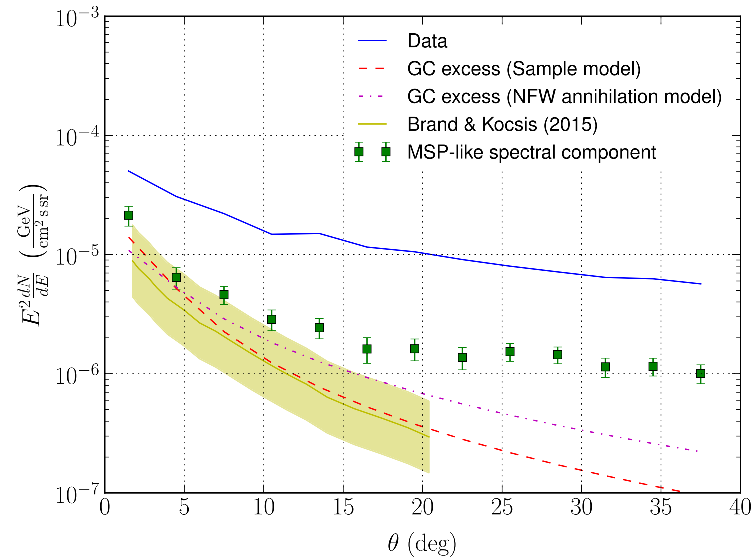
+ Sun

+ Earth

Galactic Center Excess

- Excess observed at high significance in Fermi-LAT diffuse emission towards Galactic Center
- Significant backgrounds: dominated by hadronic interactions + bremsstrahlung, inverse Compton scattering
- Spectrum and morphology have been studied by many groups

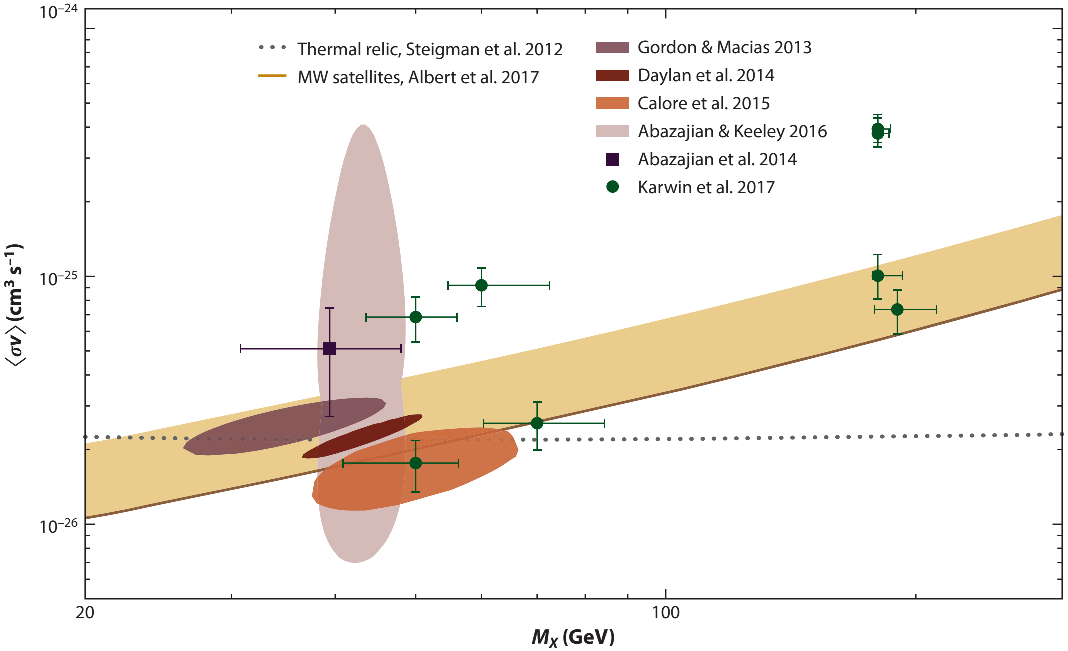




γ

arXiv:1704.03910

Galactic Center Excess

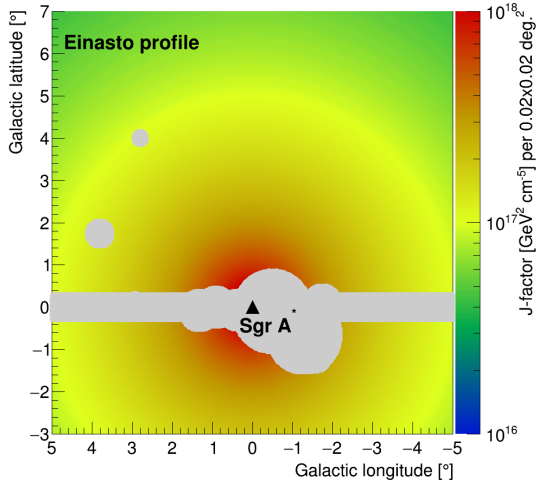


https://doi.org/10.1146/annurev-nucl-101916-123029

- Galactic Center excess consistent with a dark matter signal
  - In mild tension with limits from other dark matter searches
- Modeling of interstellar emission has large uncertainties
- Signal consistent with other explanations
  - Population of millisecond pulsars

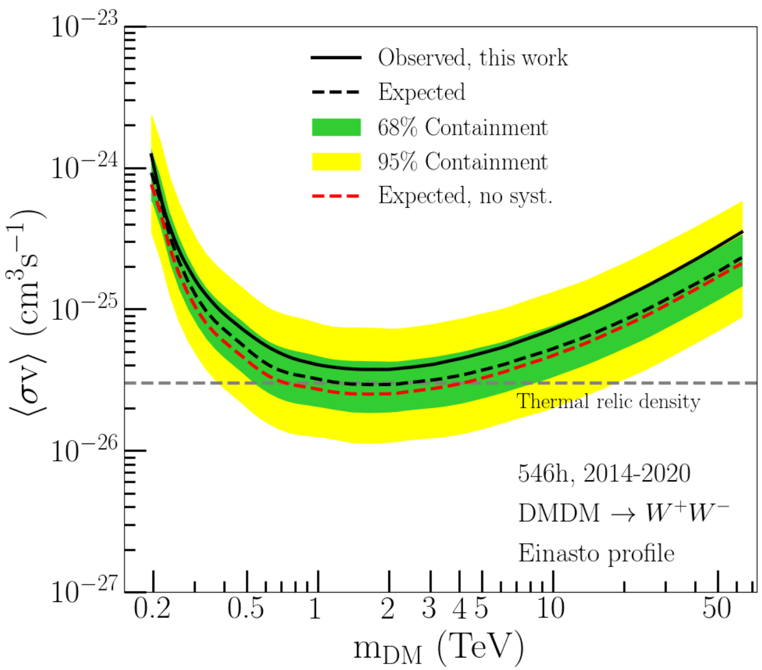
γ

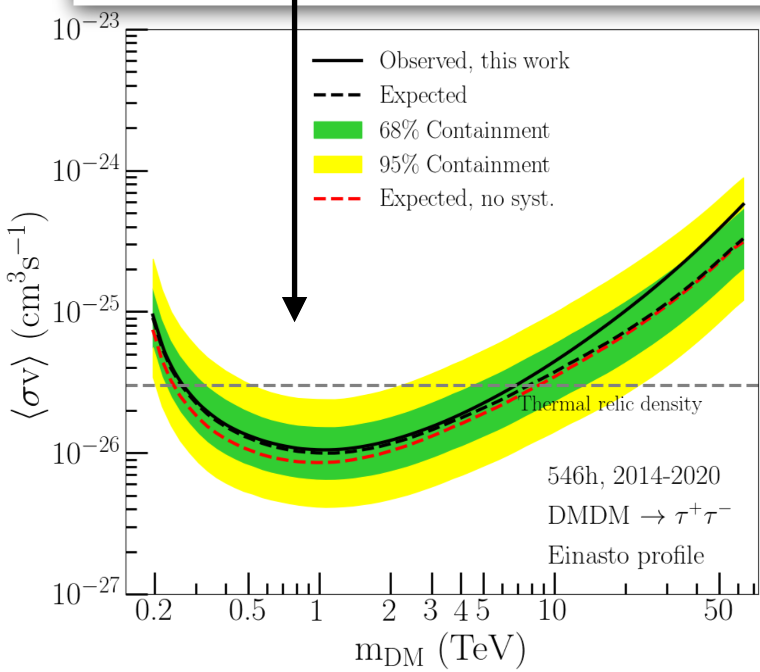
Annihilation in the Galactic Center: Continuum Emission



- H.E.S.S. location → good visibility for Galactic Center
- Deep survey observations of inner region of Galactic halo (546 hours, 5 telescopes)
- Exclude Galactic plane and known gamma-ray emitters

Probe below thermal relic density for annihilation to $\tau^+\tau^-$





arXiv:2207.10471

γ

Annihilation in the Galactic Center: Continuum Emission

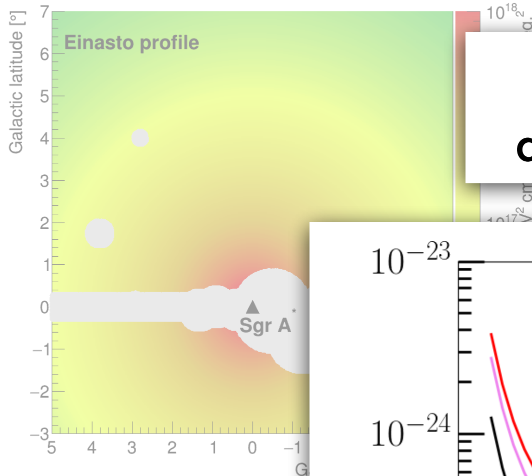
Strong dependence on assumed dark matter profile

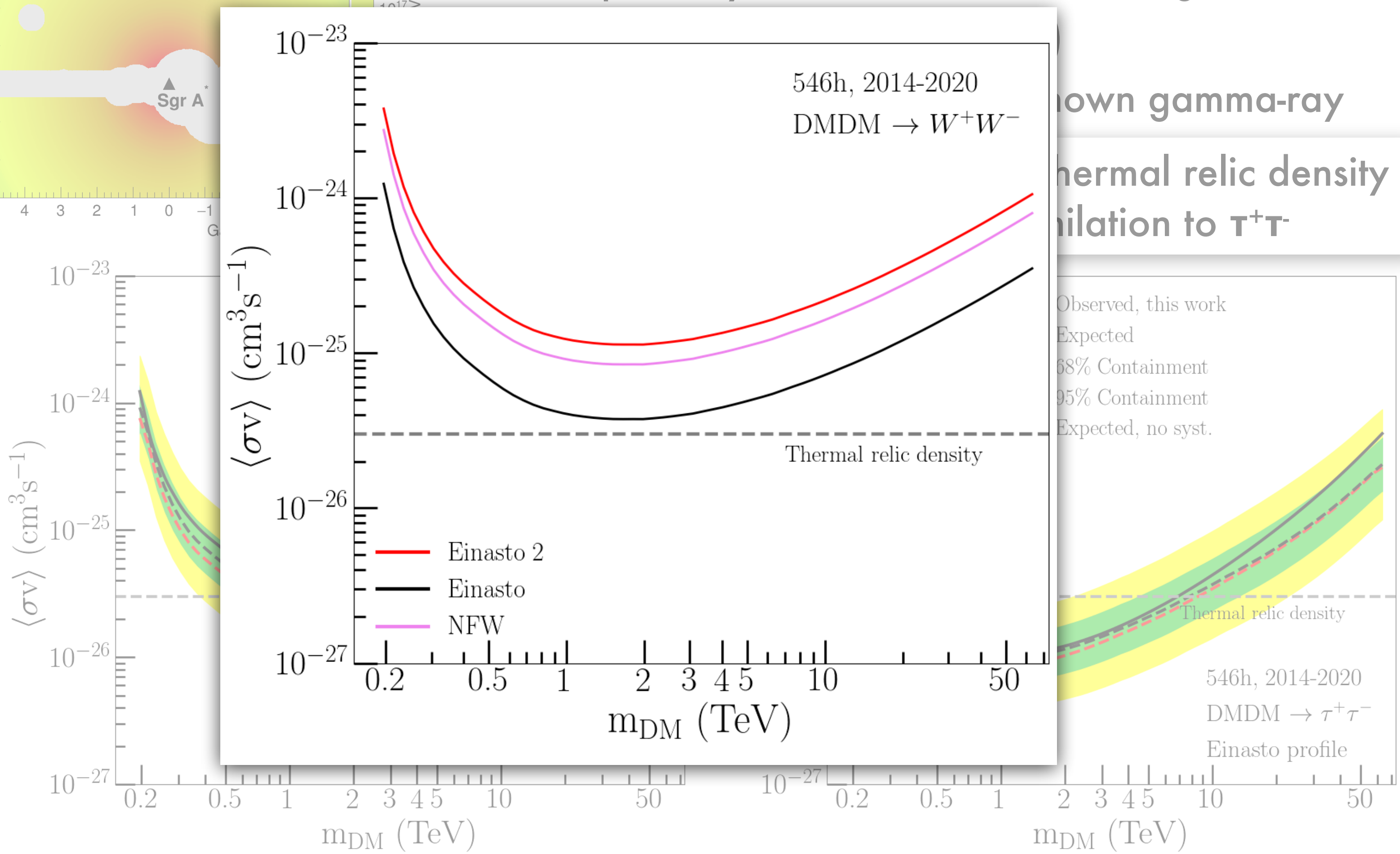
visibility for Galactic

- Deep survey observations of inner region of Galactic

own gamma-ray

hermal relic density
ilation to $\tau^+\tau^-$





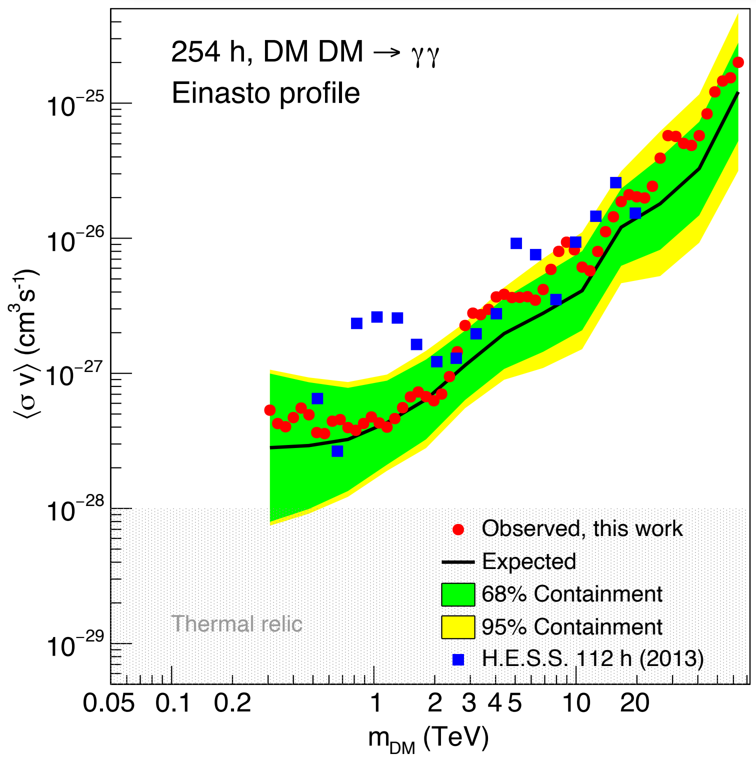
arXiv:2207.10471

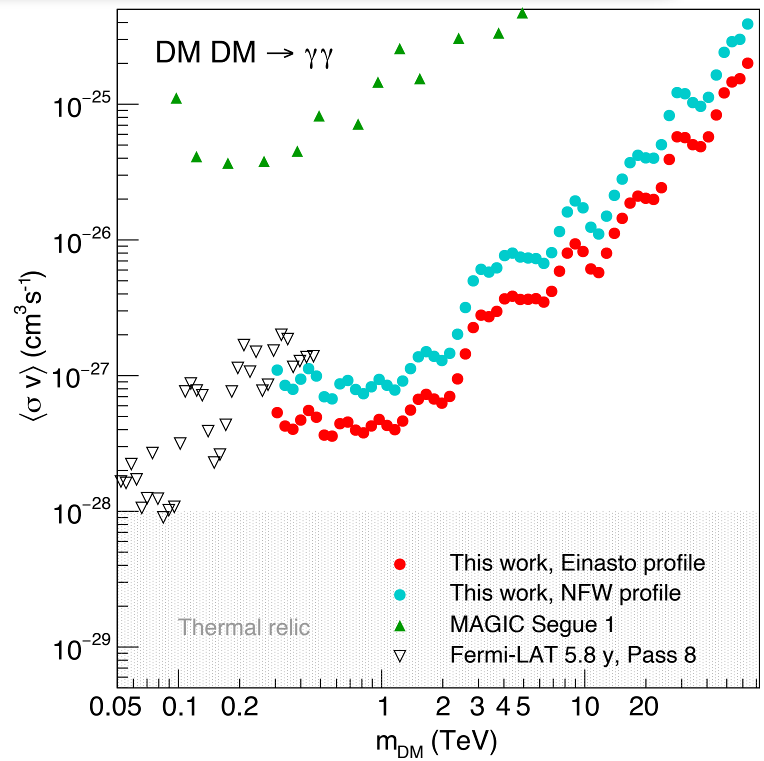
γ

Annihilation in the Galactic Center: Line Emission

- H.E.S.S. location → good visibility for Galactic Center
- Earlier survey observations of inner region of Galactic halo (254 hours, 4 telescopes)
- Gaussian "line" at $E_\gamma = M_\chi$ with width set by H.E.S.S. energy resolution @ E_γ

Approaching thermal relic cross section (note loop suppression)

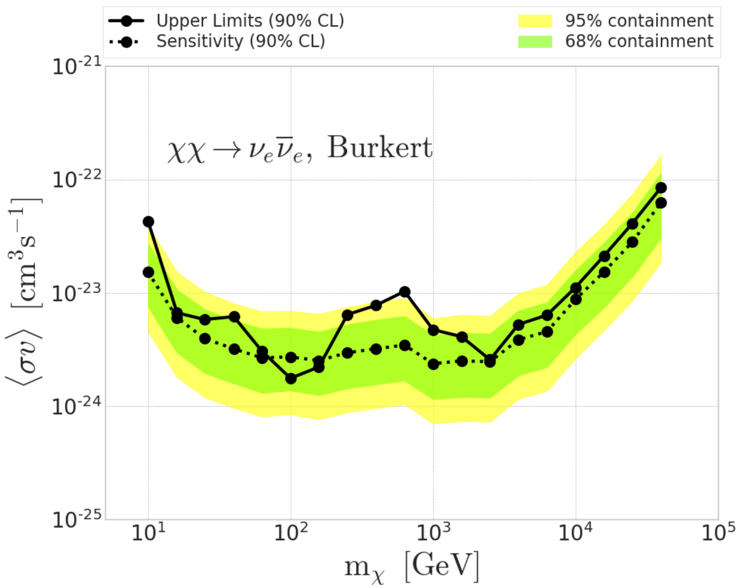




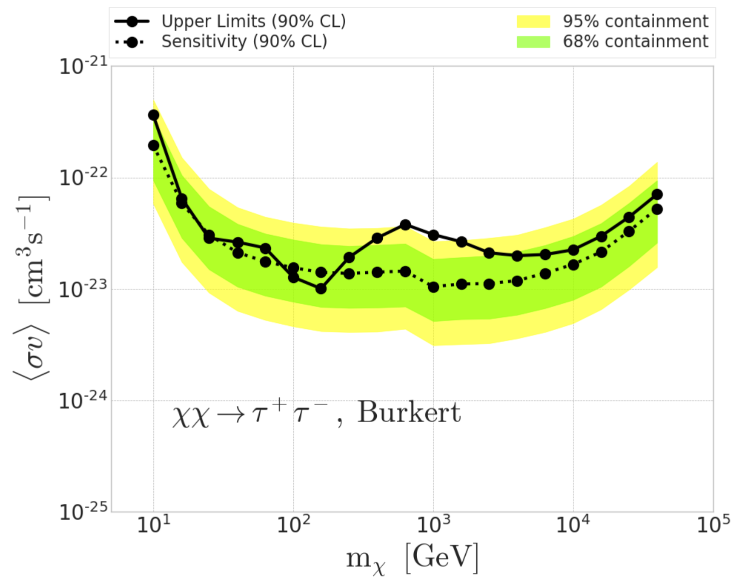
γ

arXiv:1805.05741

Annihilation in the Galactic Center: Neutrino Channel



Line search
Annihilation to 2 neutrinos



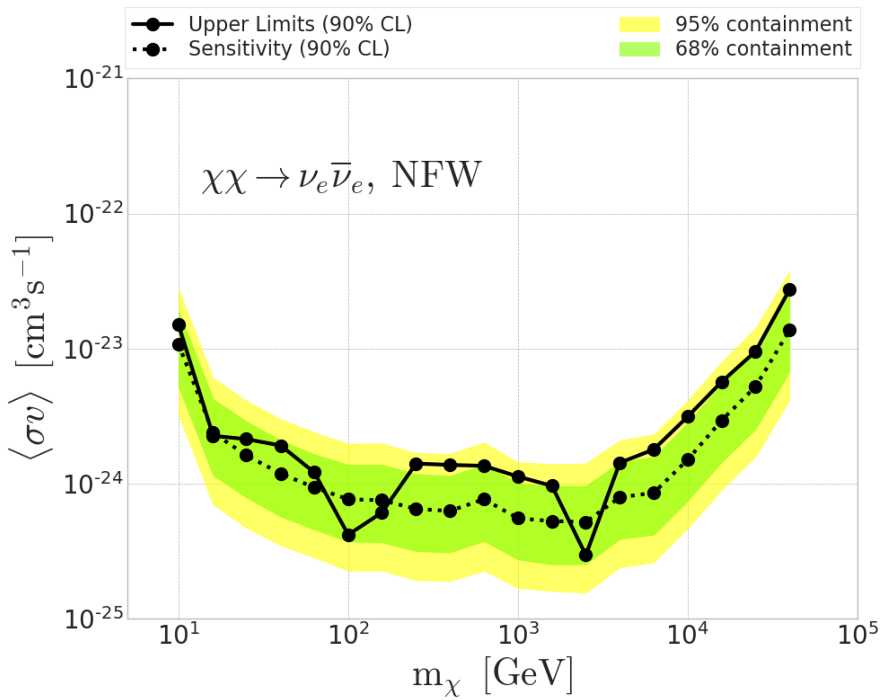
Continuum search
Search for secondary neutrinos

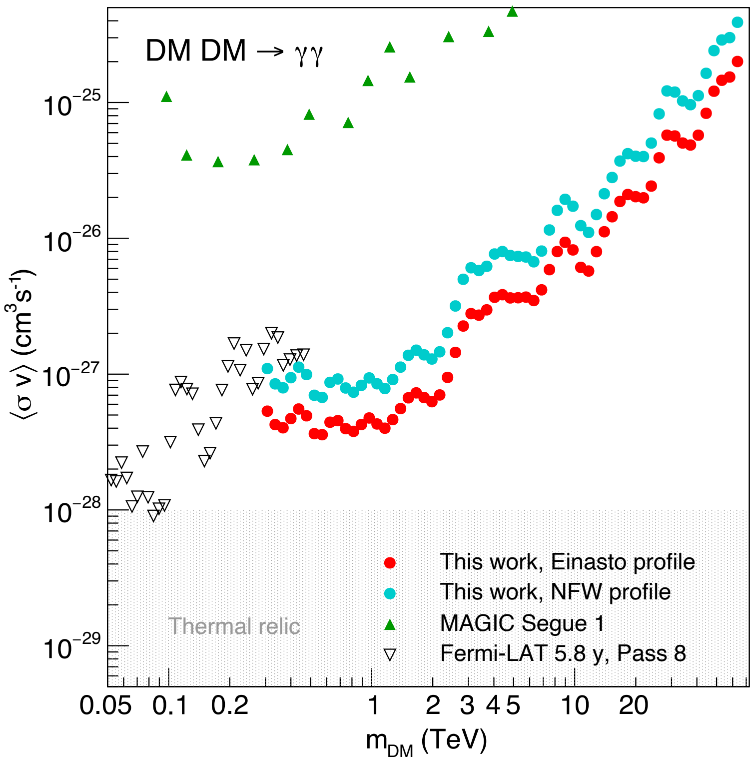
Strong sensitivity to assumed dark matter profile

ν

arXiv:2303.13663

Line Searches in GC: Gamma/Neutrino Comparison





Gamma-ray searches currently achieve better sensitivity

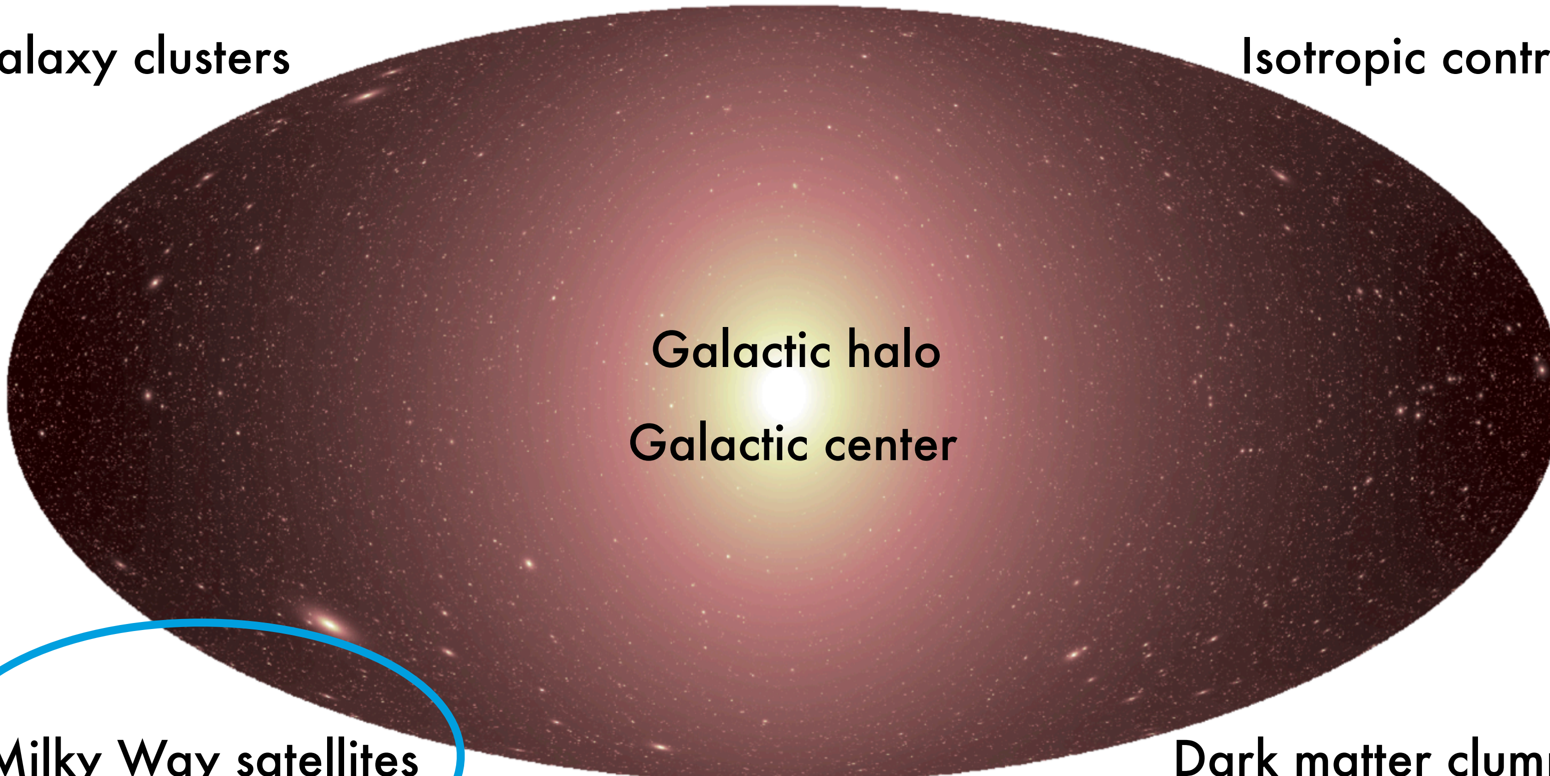
arXiv:2303.13663

γ,ν

Targets

Galaxy clusters

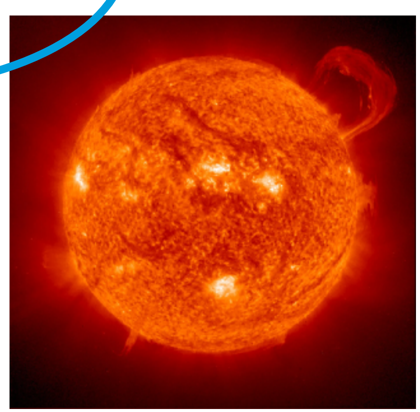
Isotropic contributions



Milky Way satellites

Dark matter clumps

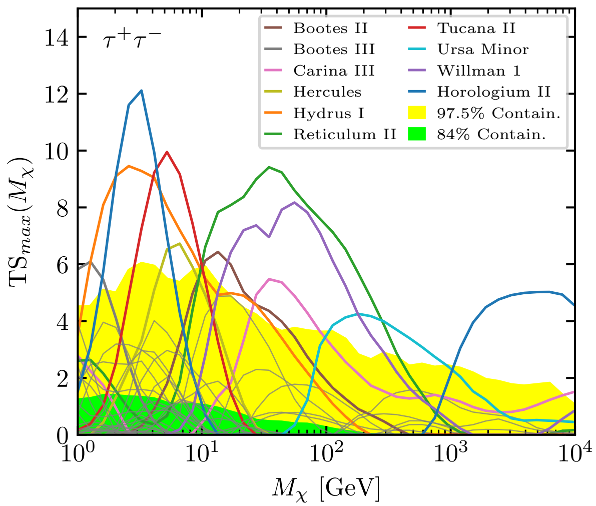
+ Sun

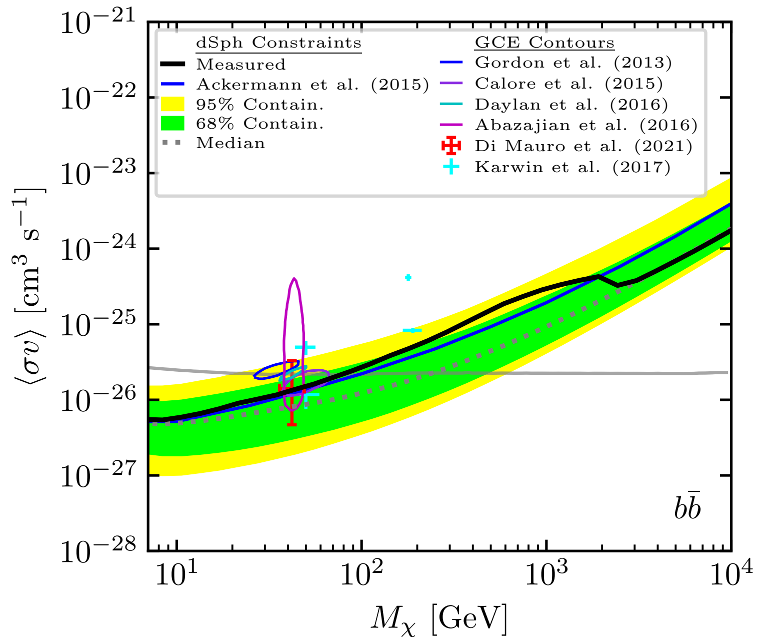


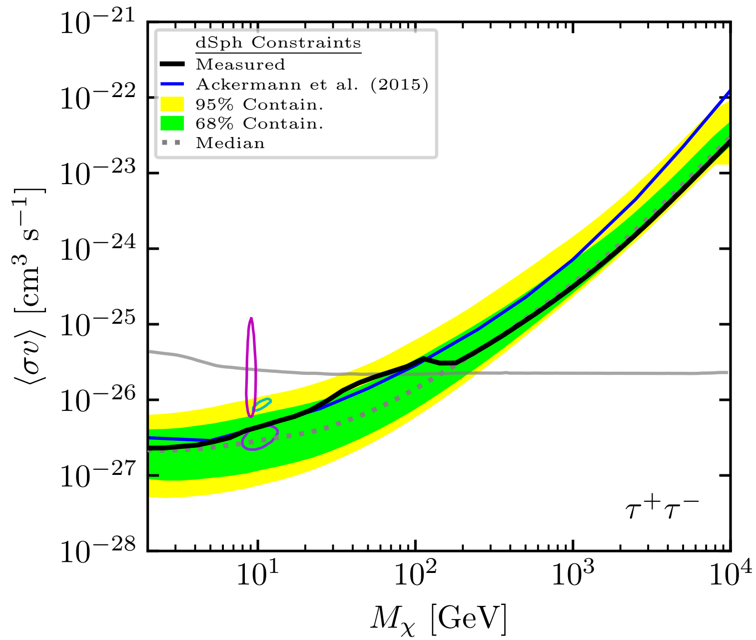
+ Earth

Annihilation in Dwarf Spheroidal Galaxies

- Fermi-LAT archival search
- 14 years of data
- ~40 dwarf spheroidal galaxies
- Probe below thermal relic cross section <~100 GeV



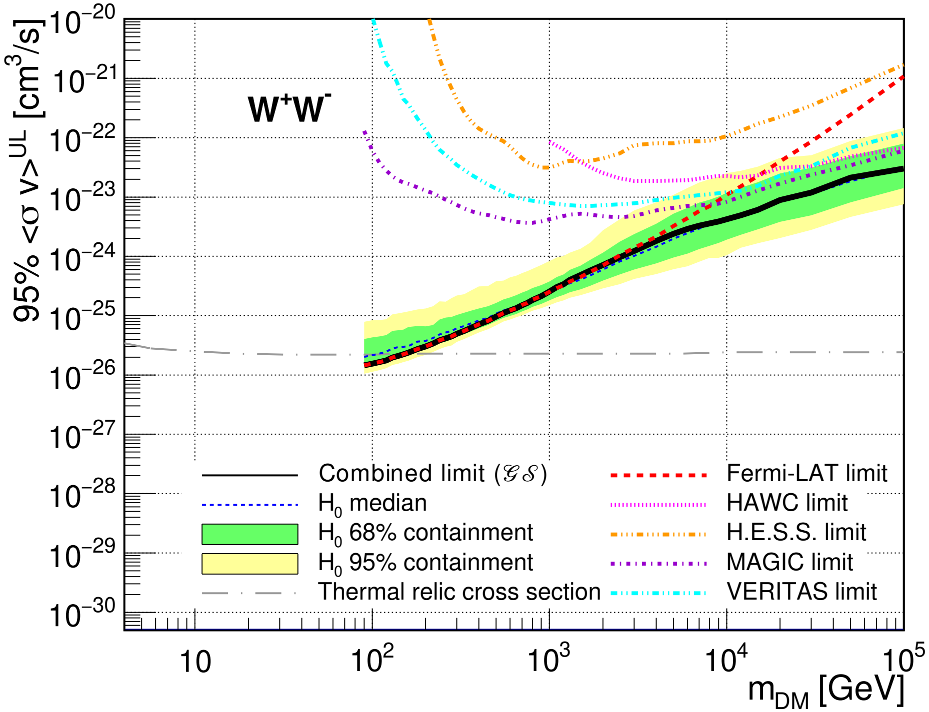


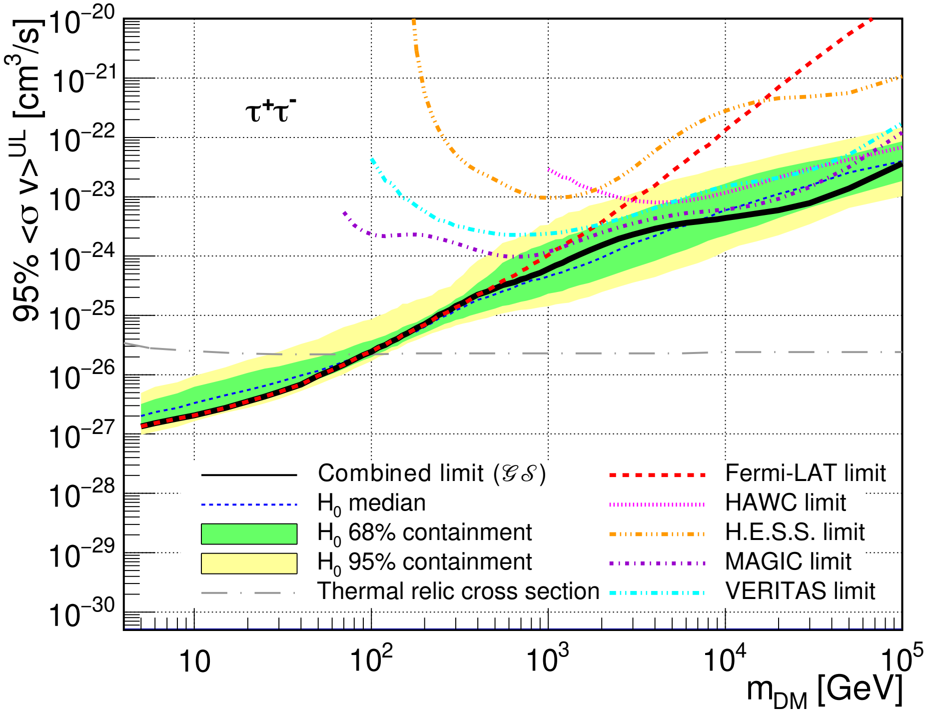


γ

arXiv:2311.04982

Annihilation in Dwarf Spheroidal Galaxies





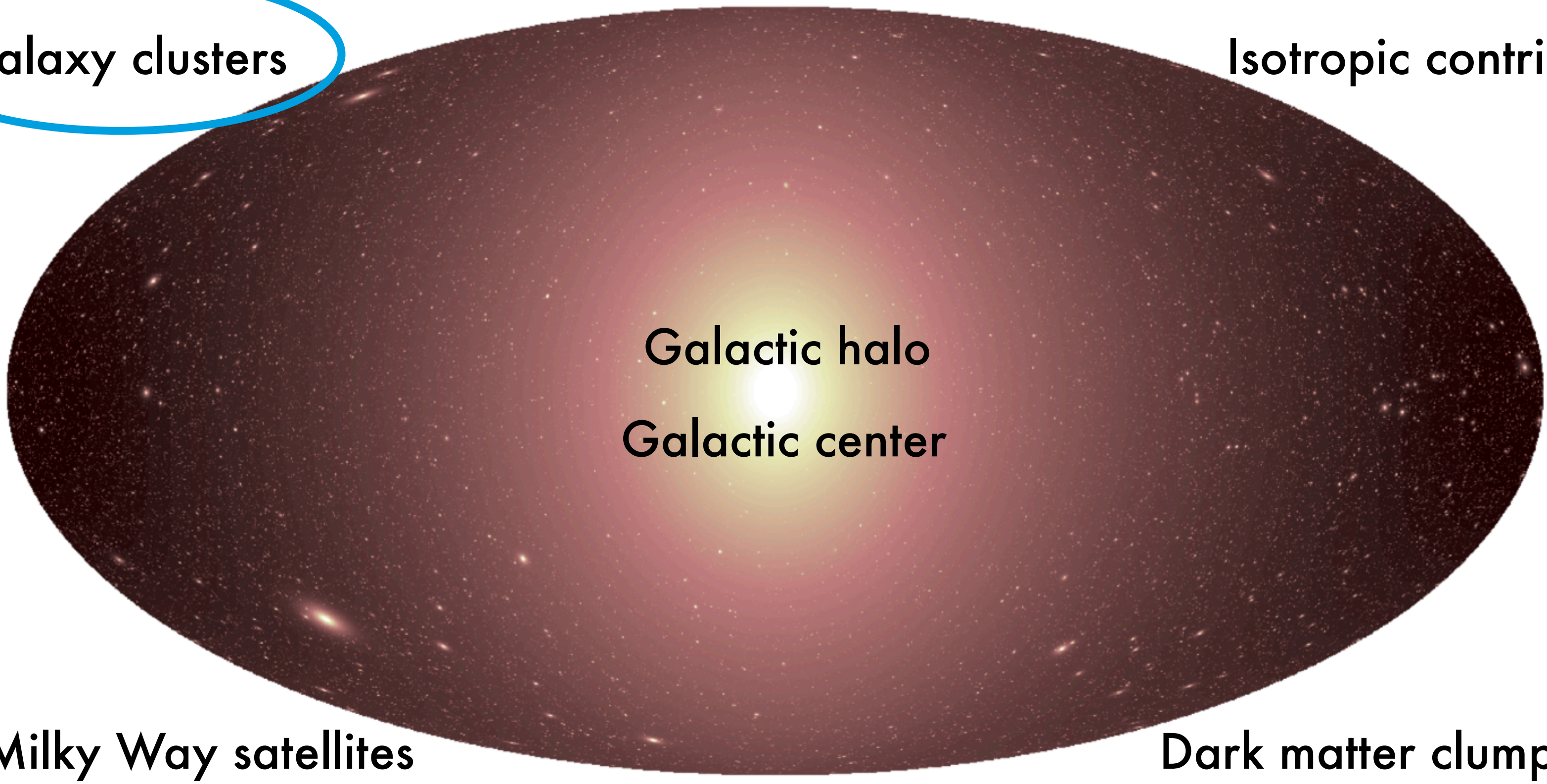
- Joint search from 5 current generation gamma-ray instruments
- Combined limits from 5 GeV to 100 TeV
- Factor than 2-3 more constraining than individual limits

γ

Targets

Galaxy clusters

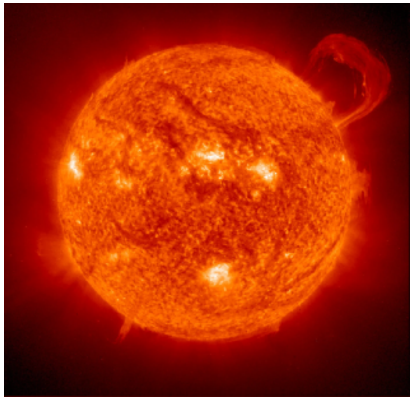
Isotropic contributions



Milky Way satellites

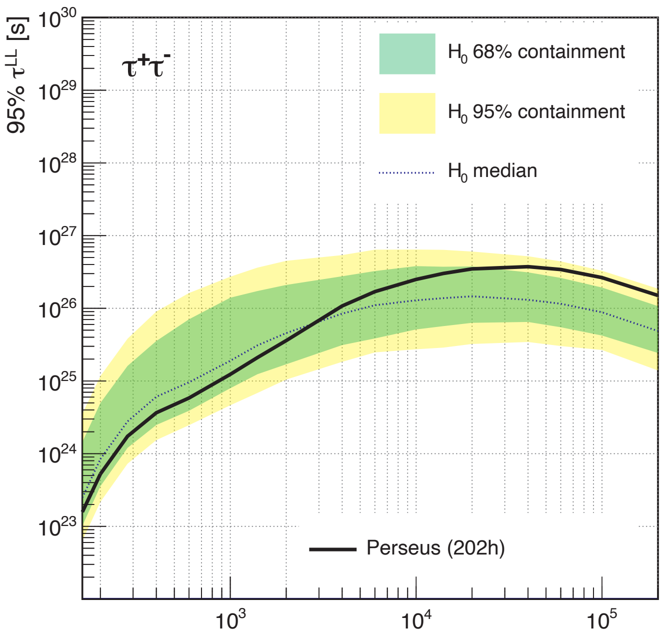
Dark matter clumps

+ Sun

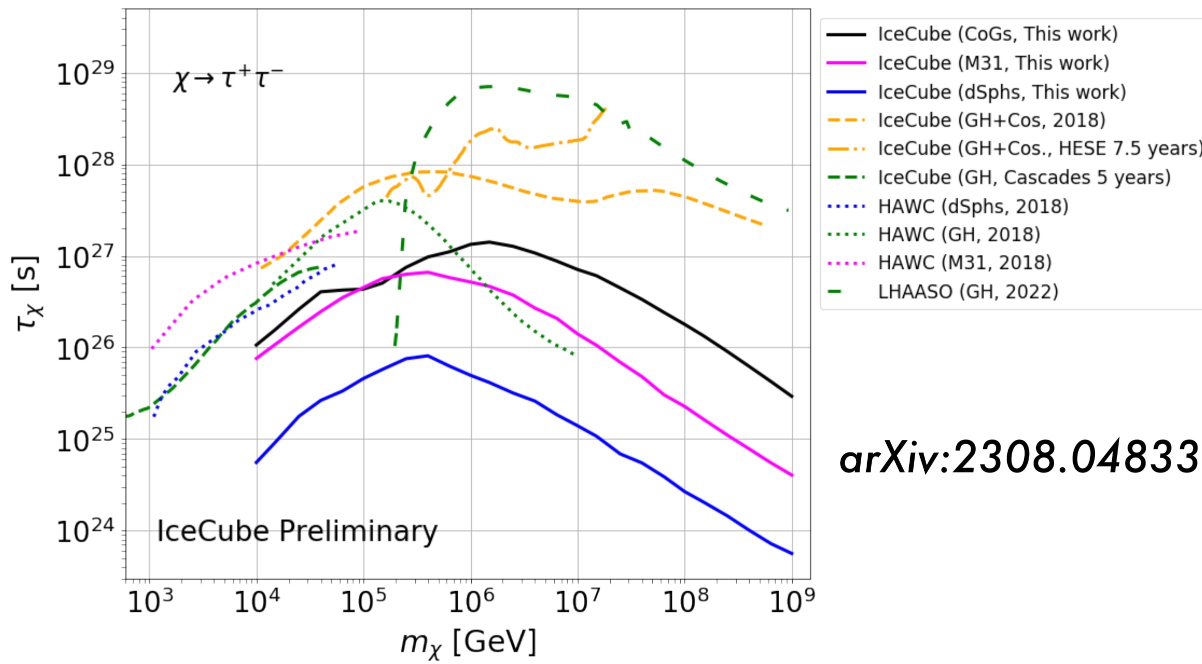


+ Earth

Galaxy Clusters



arXiv:1806.11063



arXiv:2308.04833

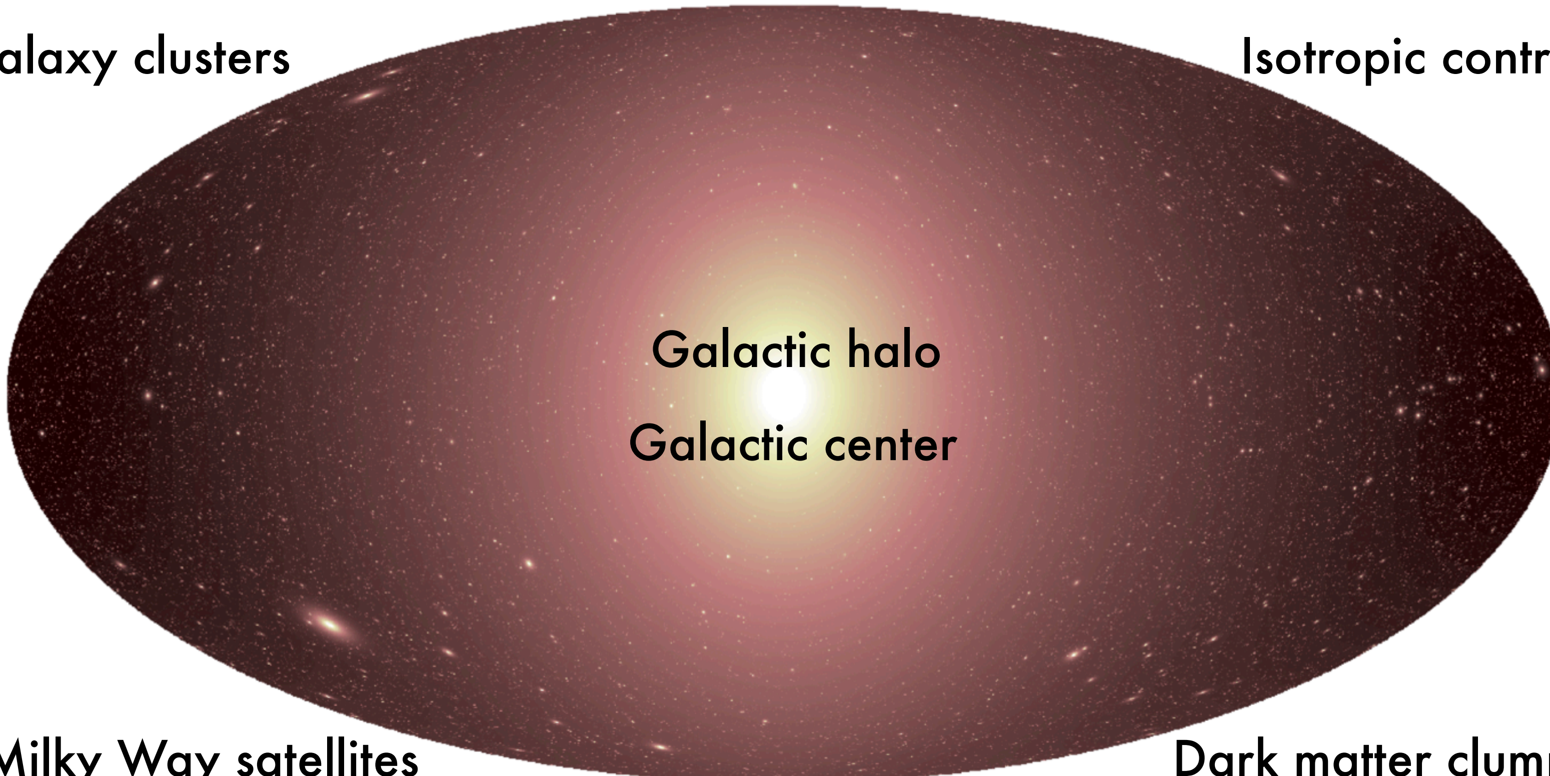
- Particularly interesting for decaying dark matter searches
- Dark matter lifetime must be >> age of the universe (10^{17} sec) to be viable
- Gamma-ray search using observations of Perseus cluster (MAGIC)
- Neutrino stacked analysis using several galaxy clusters and dwarf spheroidal galaxies

γ,ν

Targets

Galaxy clusters

Isotropic contributions



Milky Way satellites

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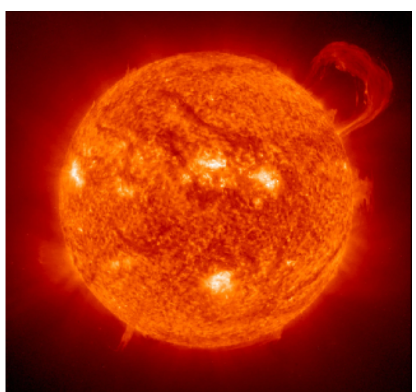
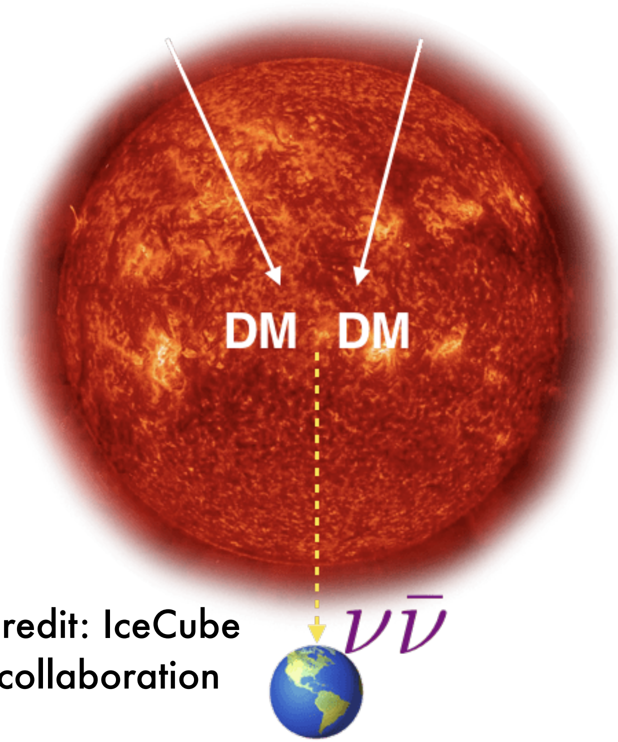


+ Earth

Dark Matter Capture in the Sun or Earth



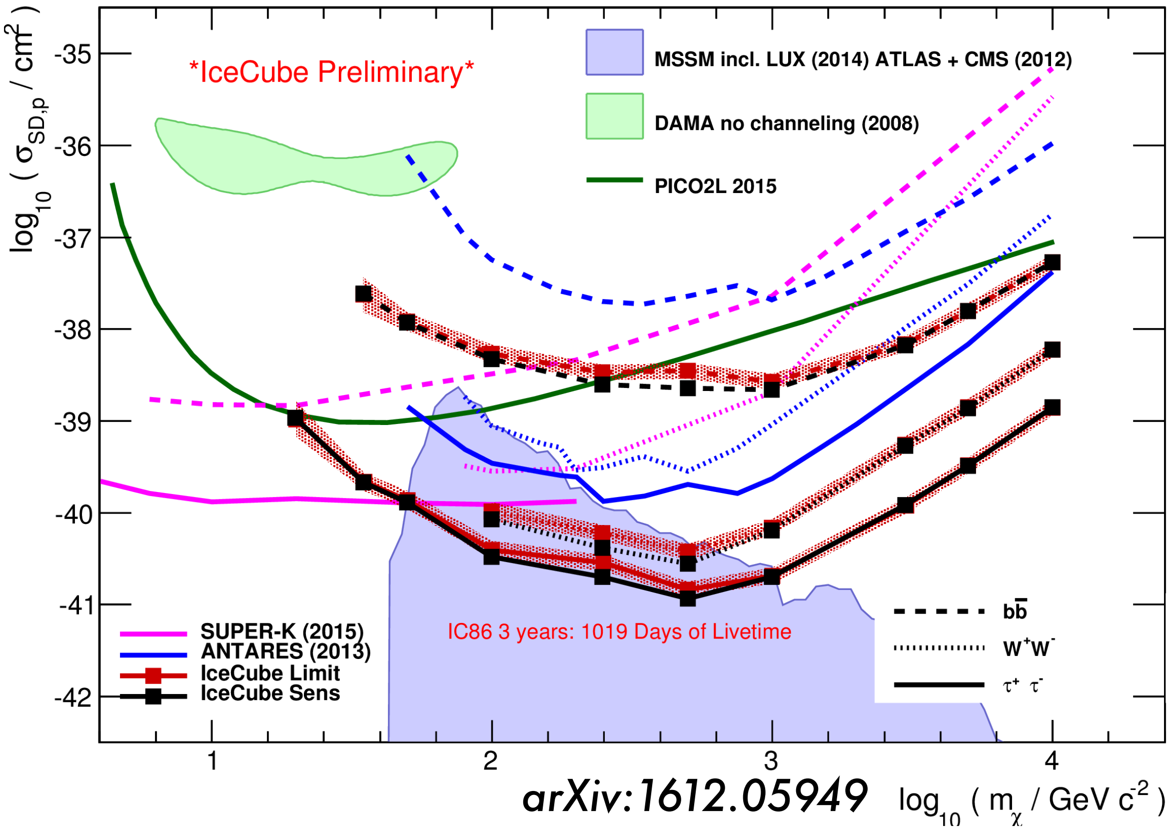
Credit: IceCube collaboration

- Dark matter particles scatter on nuclei of Sun/Earth/star
- Energy loss → some fraction gravitationally bound to object
- Further scattering can occur
- Dark-matter overdensity at object's core
  - Sufficient for dark matter self-annihilation or decay
  - Search for excess neutrinos

ν

Neutrino Capture in the Sun

F. Halzen UCLA DM 2023



arXiv:1612.05949

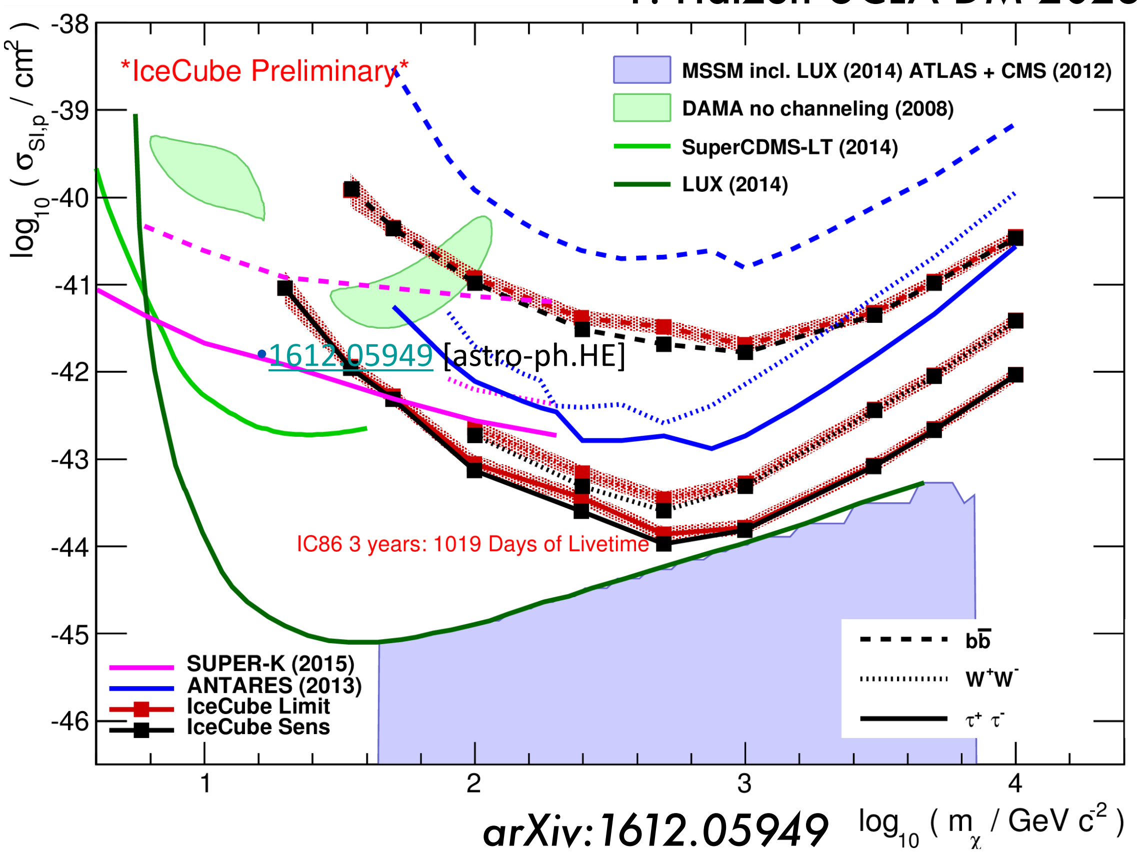
Spin-dependent DM/proton scattering cross section

Can be compared to direct detection limits

ν

Neutrino Capture in the Sun

F. Halzen UCLA DM 2023



arXiv:1612.05949

Spin-independent DM/proton scattering cross section

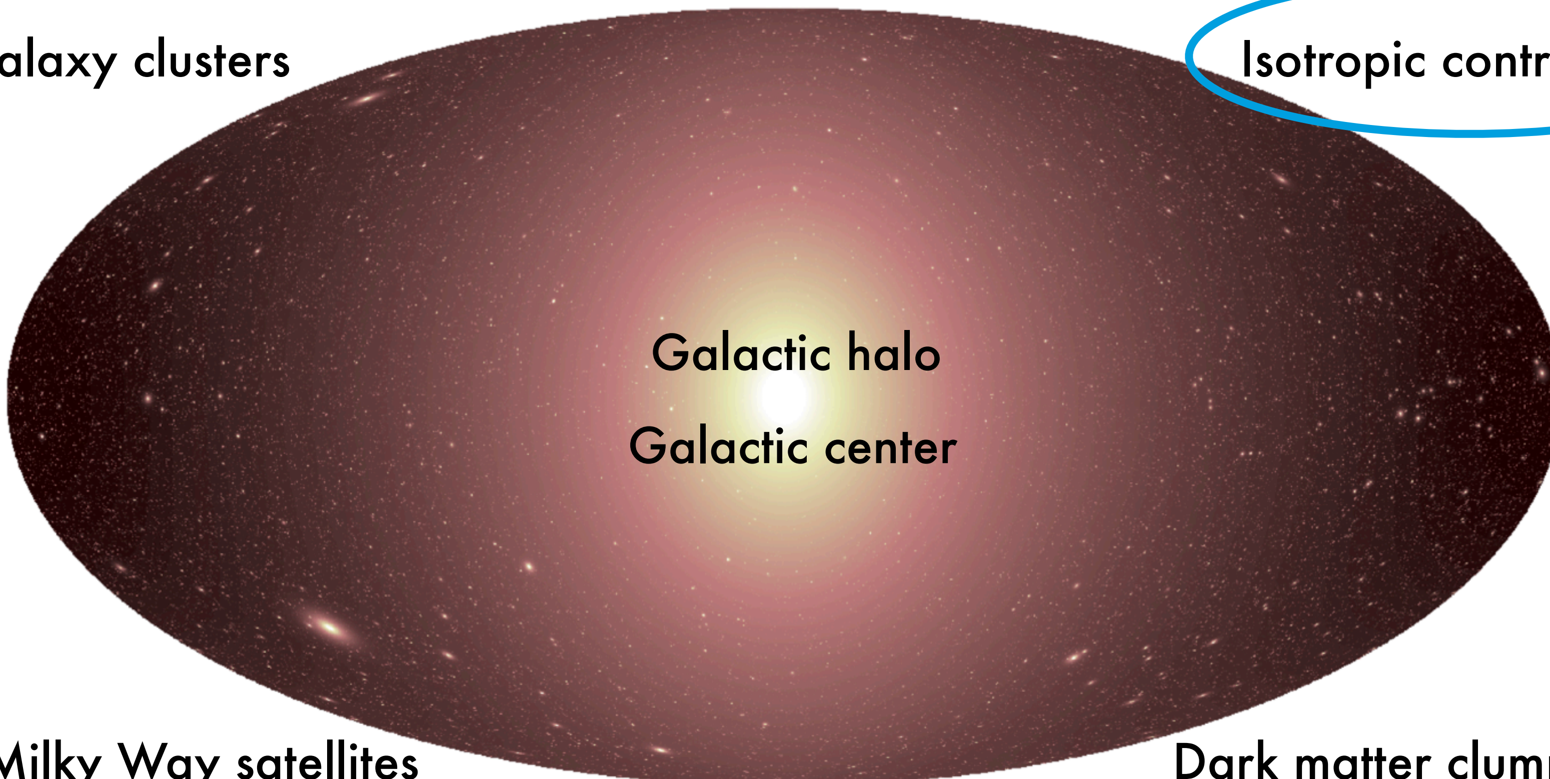
Can be compared to direct detection limits

ν

Targets

Galaxy clusters

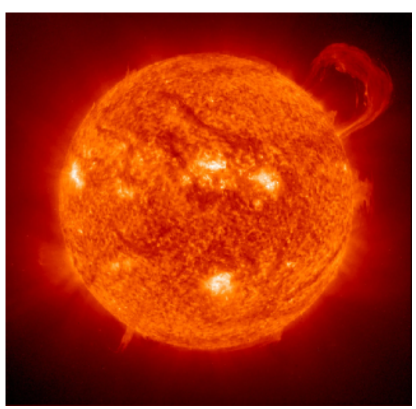
Isotropic contributions



Milky Way satellites

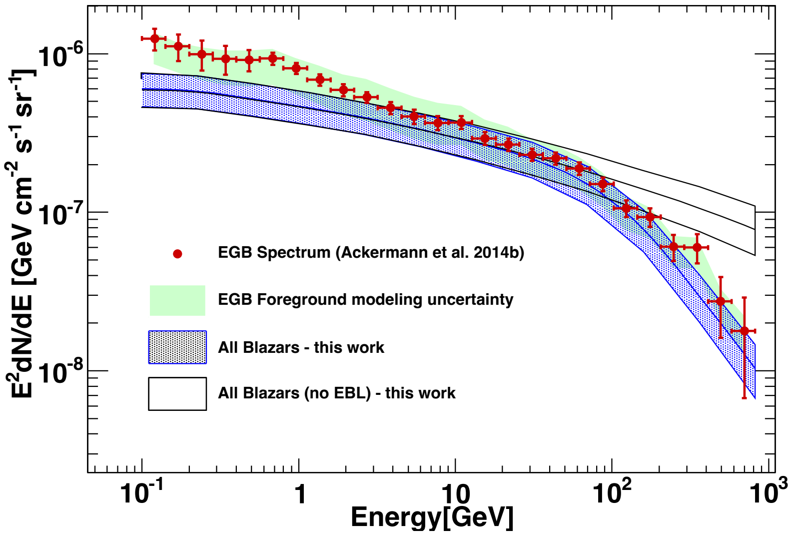
Dark matter clumps

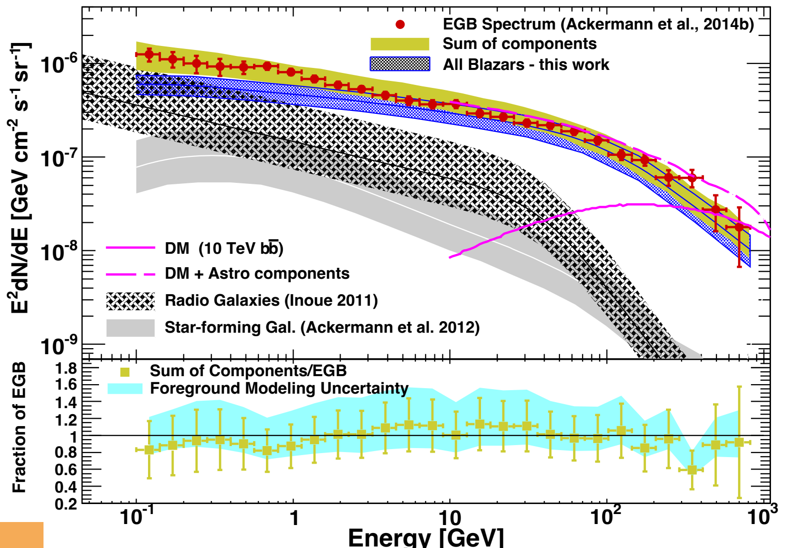
+ Sun



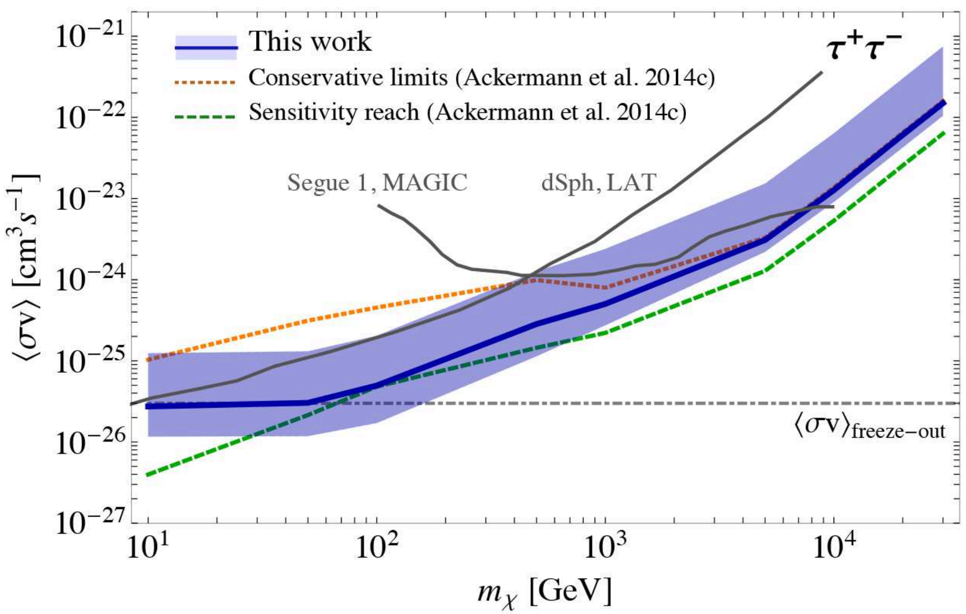
+ Earth

Extragalactic Gamma-ray Background



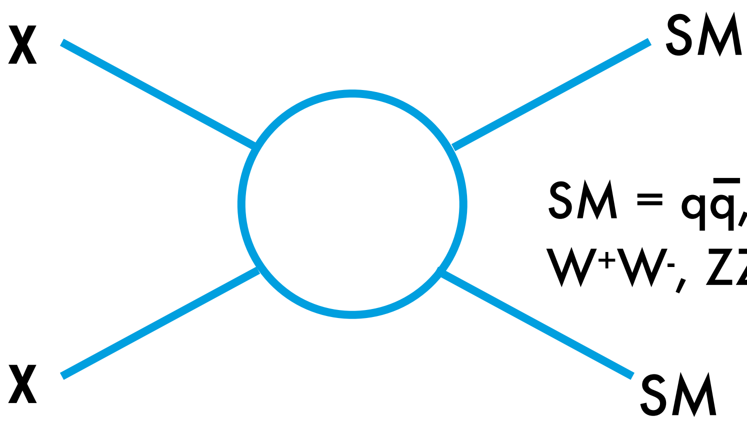


- Diffuse gamma rays from resolved and unresolved extragalactic gamma-ray populations, diffuse contributions (e.g. dark matter annihilation)
  - Mostly blazars
- Limited budget for additional contributions



arXiv:1501.05301

Indirect Searches with Cosmic Rays

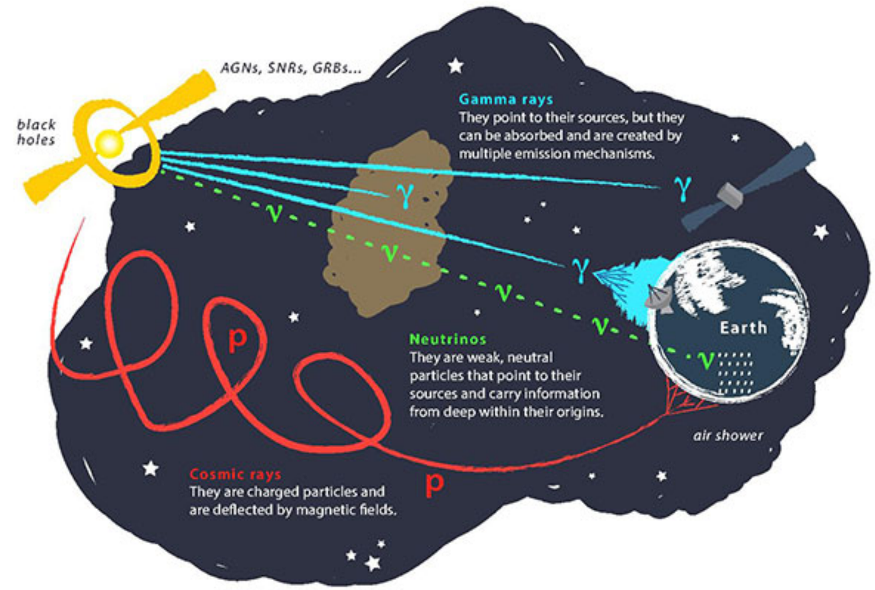


SM = $q\bar{q}$,
W^+W^-, ZZ, l^+l^-,...

Standard model particles
hadronize, decay, radiate

Gamma rays, neutrinos, p^+/p^-, e^+/e^-

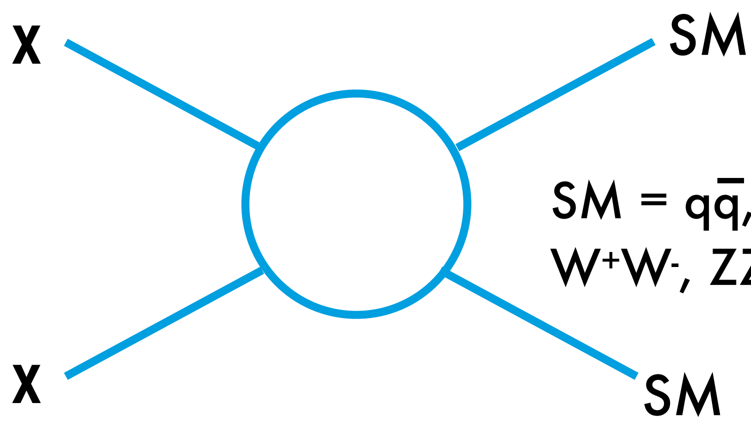
Charged cosmic rays do NOT point back to sources



IceCube Collaboration

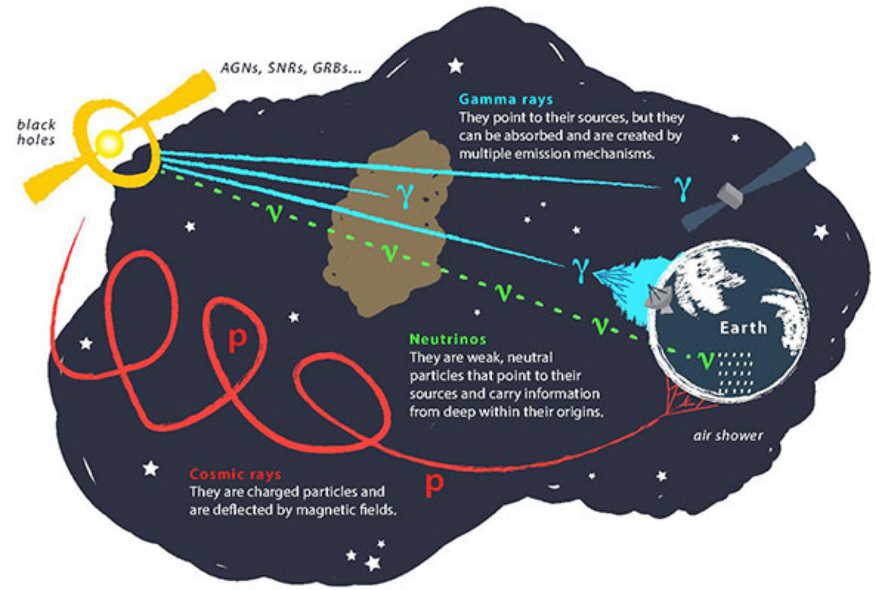
- Large astrophysical backgrounds for matter particles
- Search for anti-matter (e^+, p^+,...)
- Cosmic-ray transport models important to interpretation

Indirect Searches with Cosmic Rays



SM = $q\bar{q}$,
W^+W^-, ZZ, l^+l^-,...

Charged cosmic rays do NOT point back to sources



IceCube Collaboration

Standard model particles hadronize (jets)

Coalescence of $\bar{n}$ and $\bar{p}$ or $\bar{p}$ and $\bar{p}$

Antideuteron, Antihelium

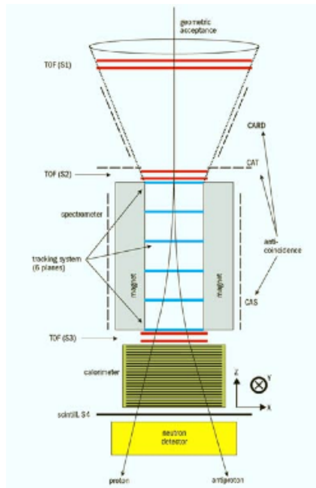
Particularly clean search channels

Detecting Cosmic Rays

Particle detectors: measure particle energy, momentum, species

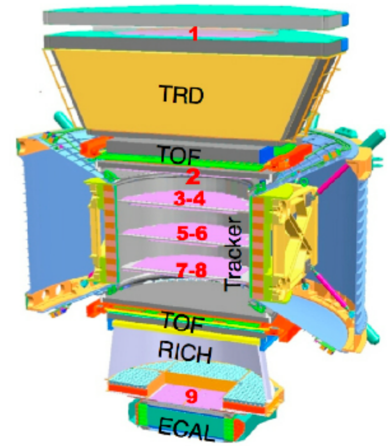
PAMELA

- Positrons



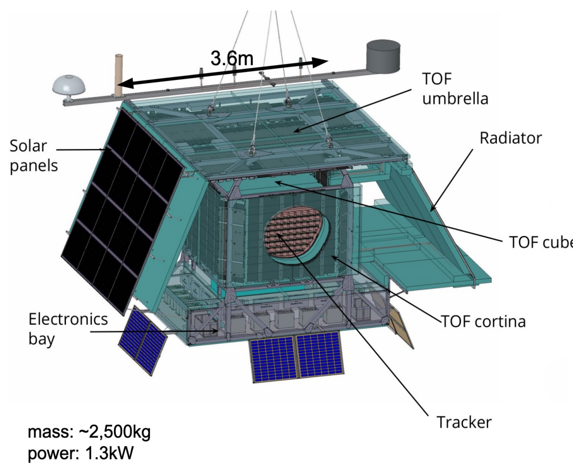
AMS-02

- <u>Positrons</u>
- <u>Antiprotons</u>
- Antideuterons
- Antihelium3



GAPS

- Positrons
- Antiprotons
- <u>Antideuterons</u>
- <u>Antihelium3?</u>



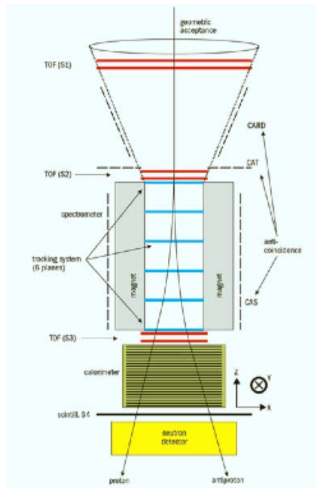
To name a few,
also CALET, HELIX,
GRAMS...

Detecting Cosmic Rays

Particle detectors: measure particle energy, momentum, species

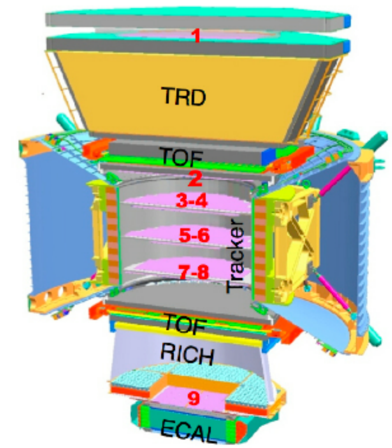
PAMELA

- Space-based
- Data-taking 2006-2016



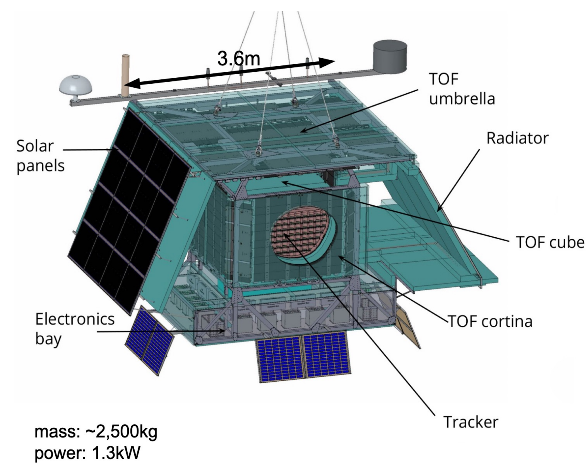
AMS-02

- Space-based (ISS)
- Data-taking since 2011



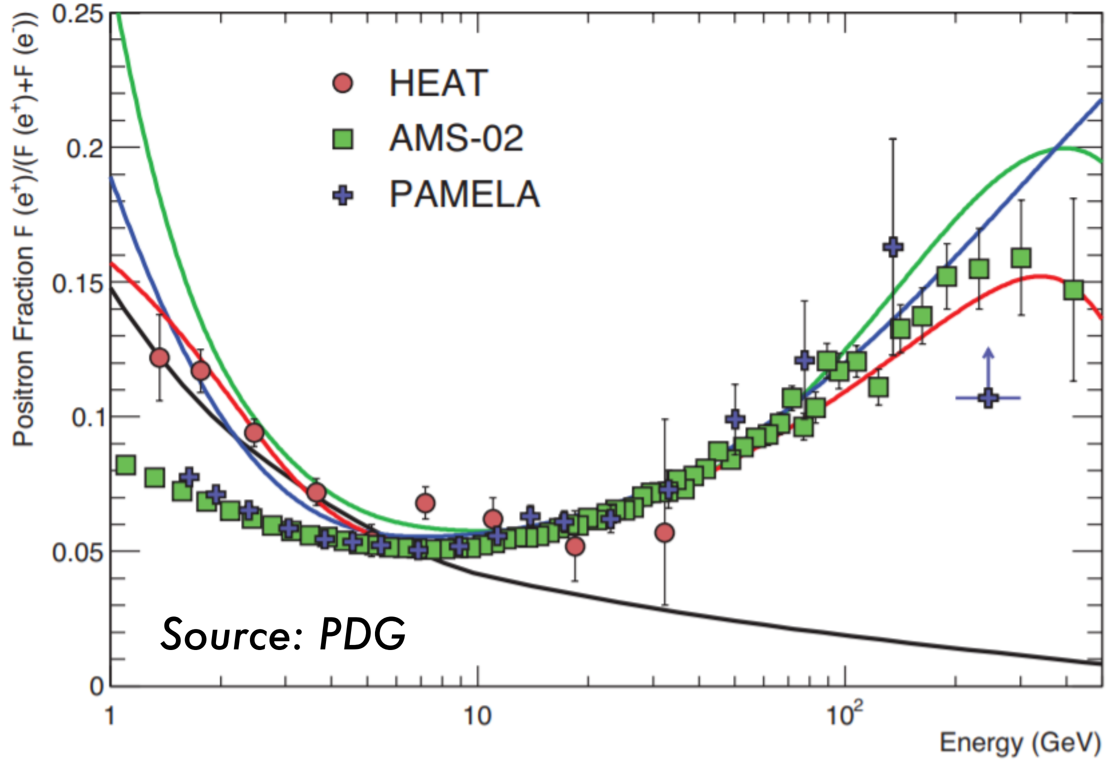
GAPS

- Balloon flight Antarctica planned for late 2024



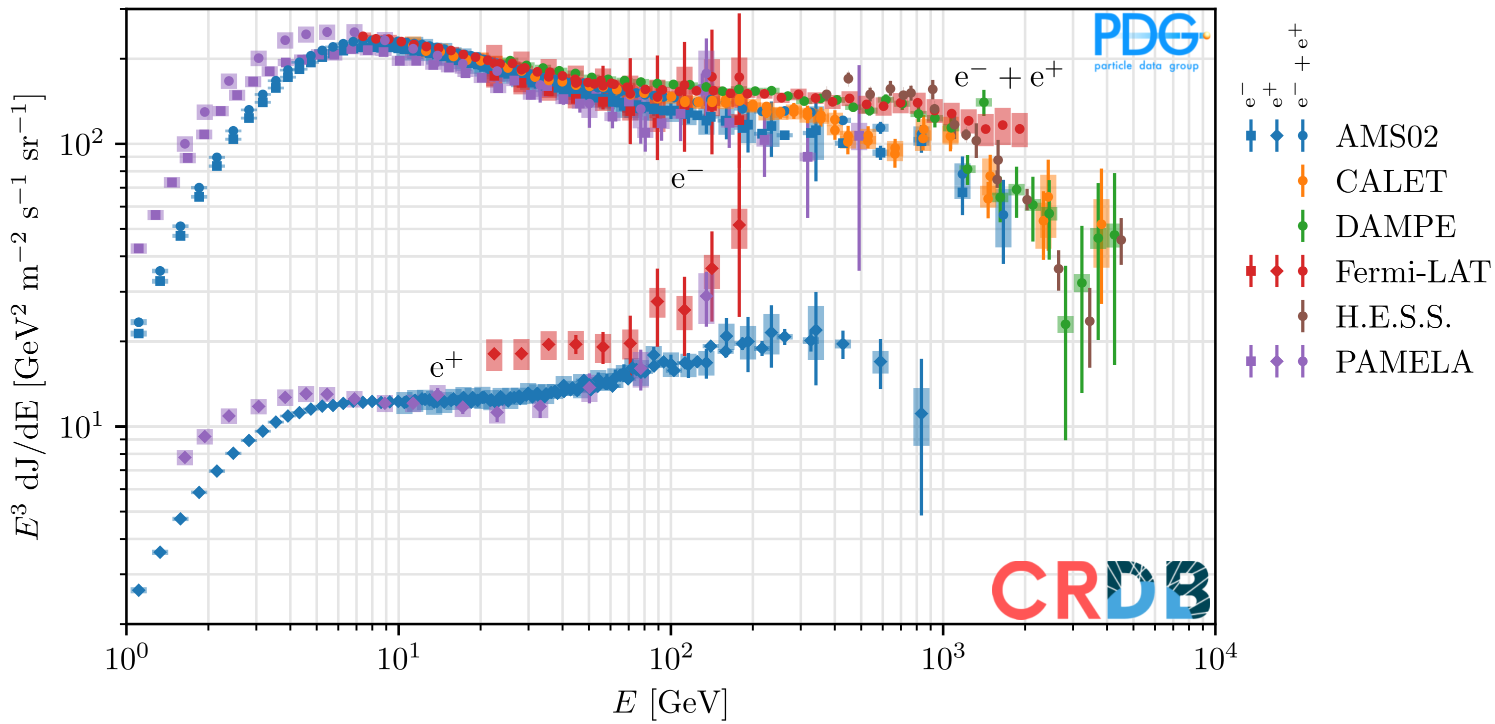
To name a few,
also CALET, HELIX,
GRAMS...

Positron spectrum/Positron fraction



- Rise observed in positron fraction, contrary to expectations
- Positron spectrum softer than electron spectrum for secondary positrons
- Advantage of fraction: less sensitive to instrument response

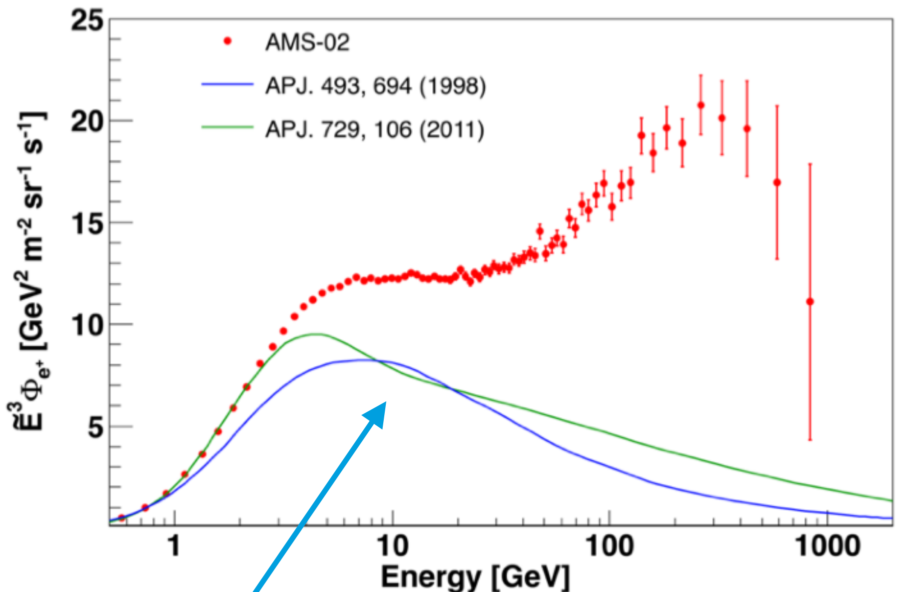
Positron spectrum/Positron fraction

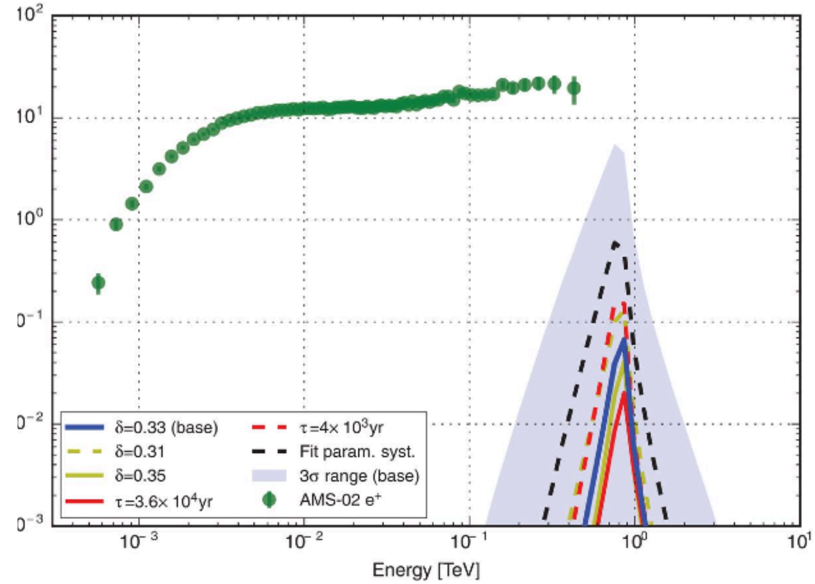


- Rising positron spectrum also observed
- Possible scenarios for producing high-energy positrons:
  - Dark matter annihilation
  - Positron acceleration in (local) sources
  - Secondary production from cosmic rays on interstellar gas

Positron spectrum/Positron fraction

arxiv:1711.06223



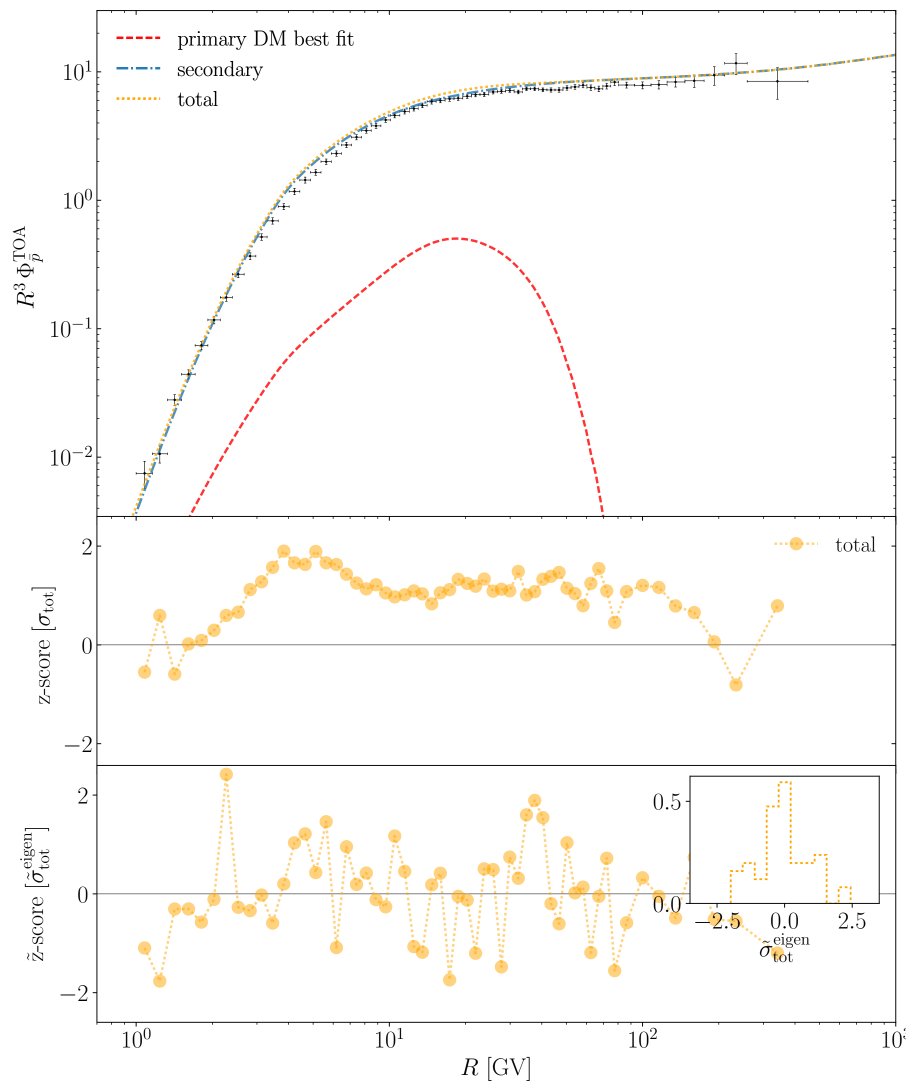


Hard to explain spectrum with secondary particles

- Local source? Diffusion constant in TeV halos around pulsars important
- Dark matter annihilation?
  - Not for a simple model - leptophilic?
  - Measurement of high-energy cutoff important

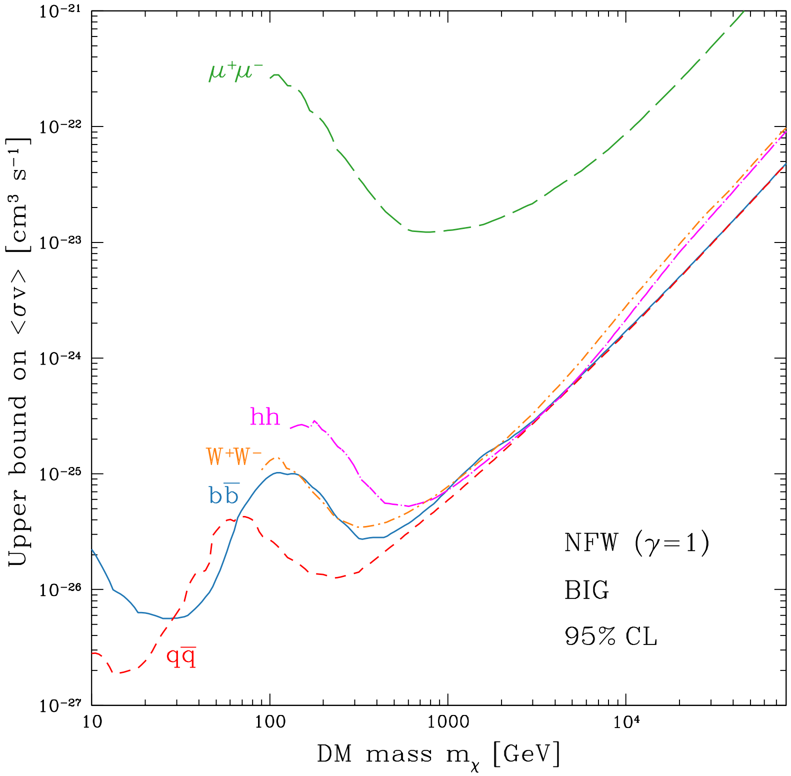
Antiproton spectrum

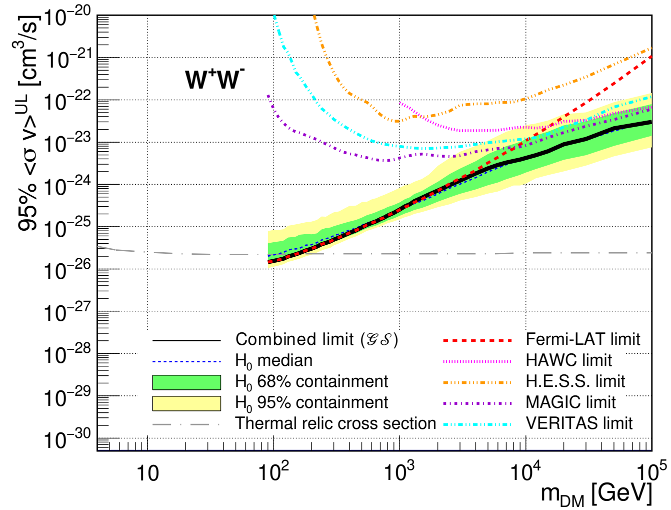
- Four years of AMS-02 data
- Fit antiproton spectrum
- Expected to be mainly due to secondaries
- Include contribution from dark matter annihilation



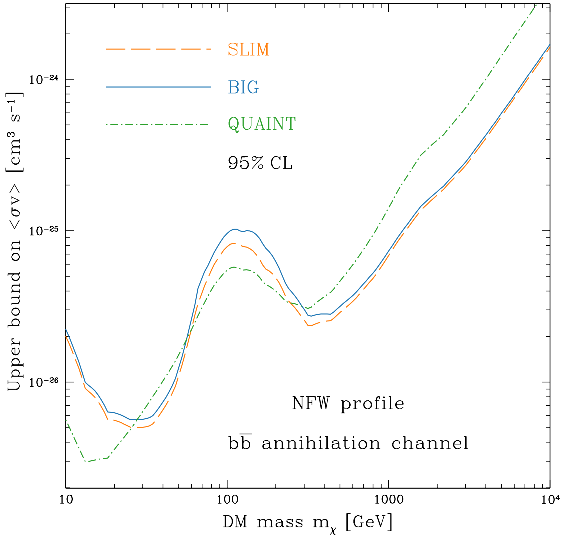
arXiv:2202.03076

Antiproton spectrum



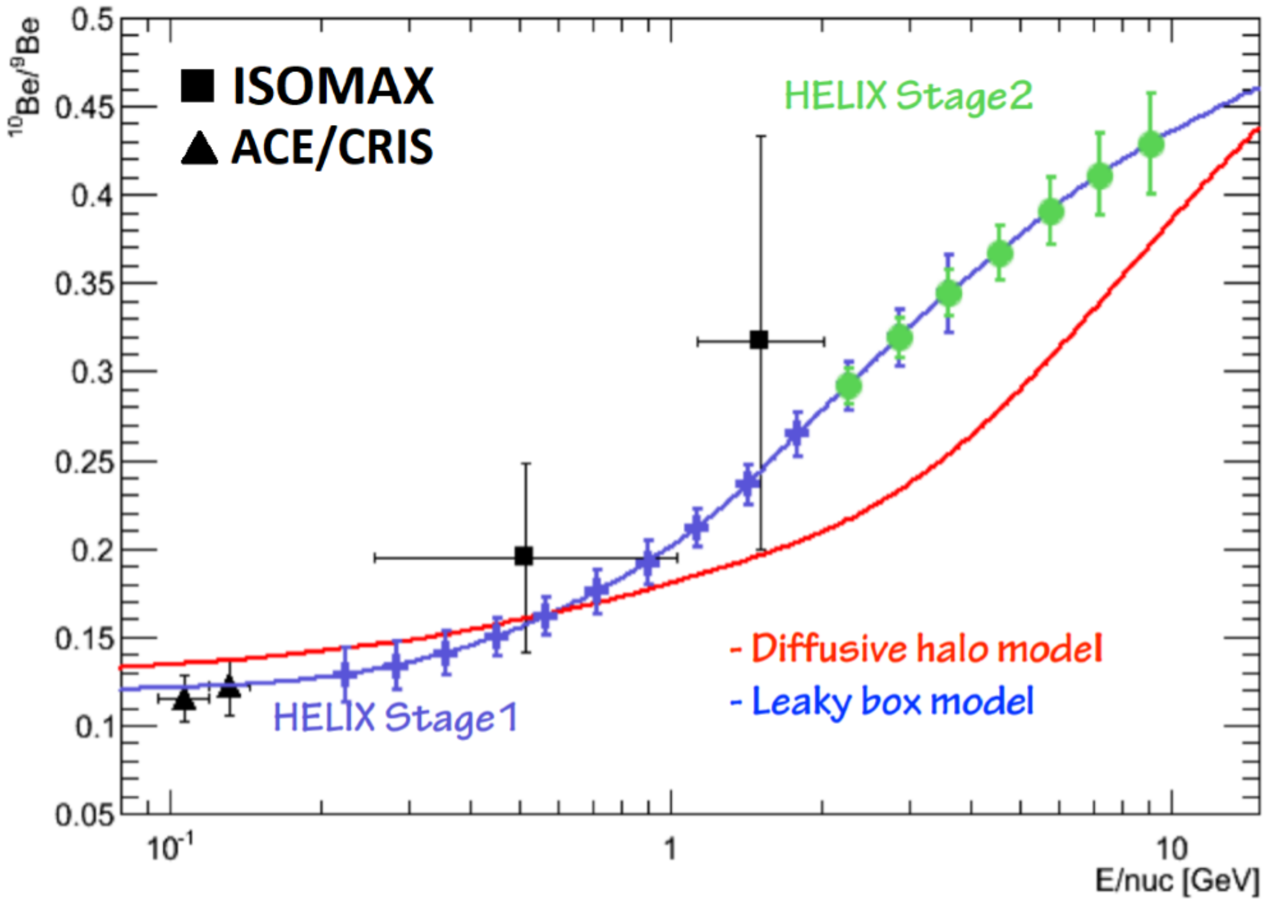


- Limits competitive with Fermi-LAT dSphs limits at 100 GeV
- Limits sensitive to propagation model



arXiv:2202.03076

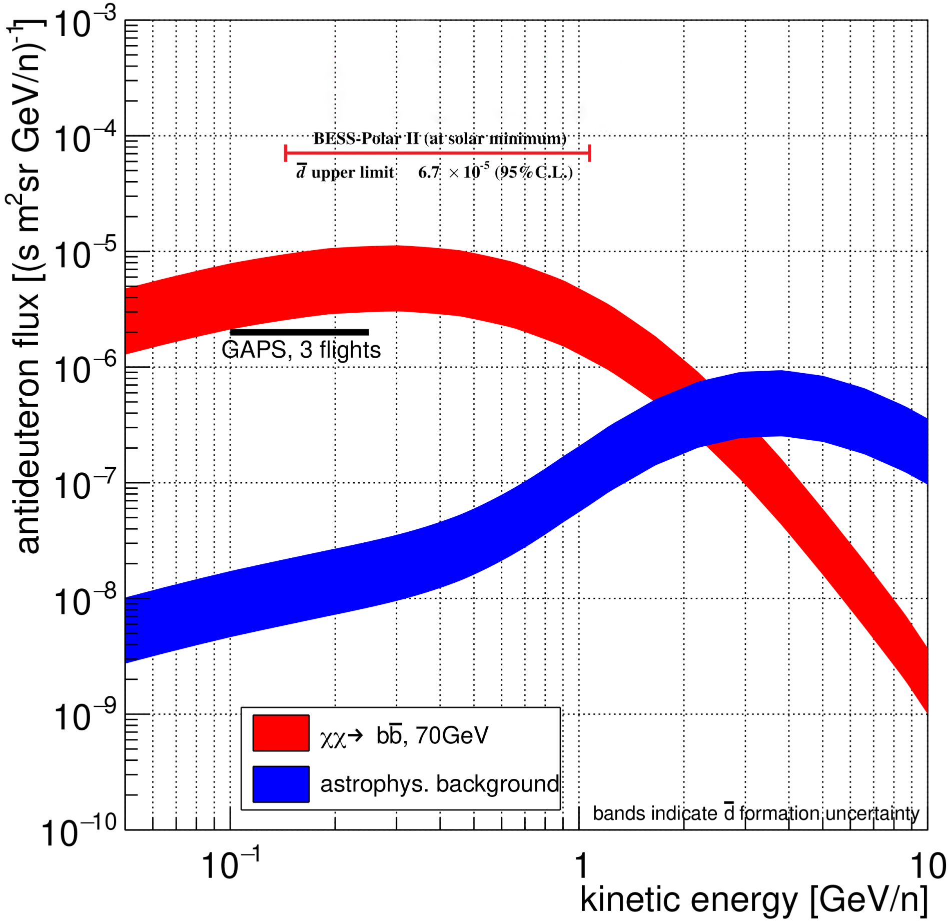
Cosmic Ray Propagation



HELIX balloon experiment: measure isotopic abundance ratios
→ distinguish between propagation models

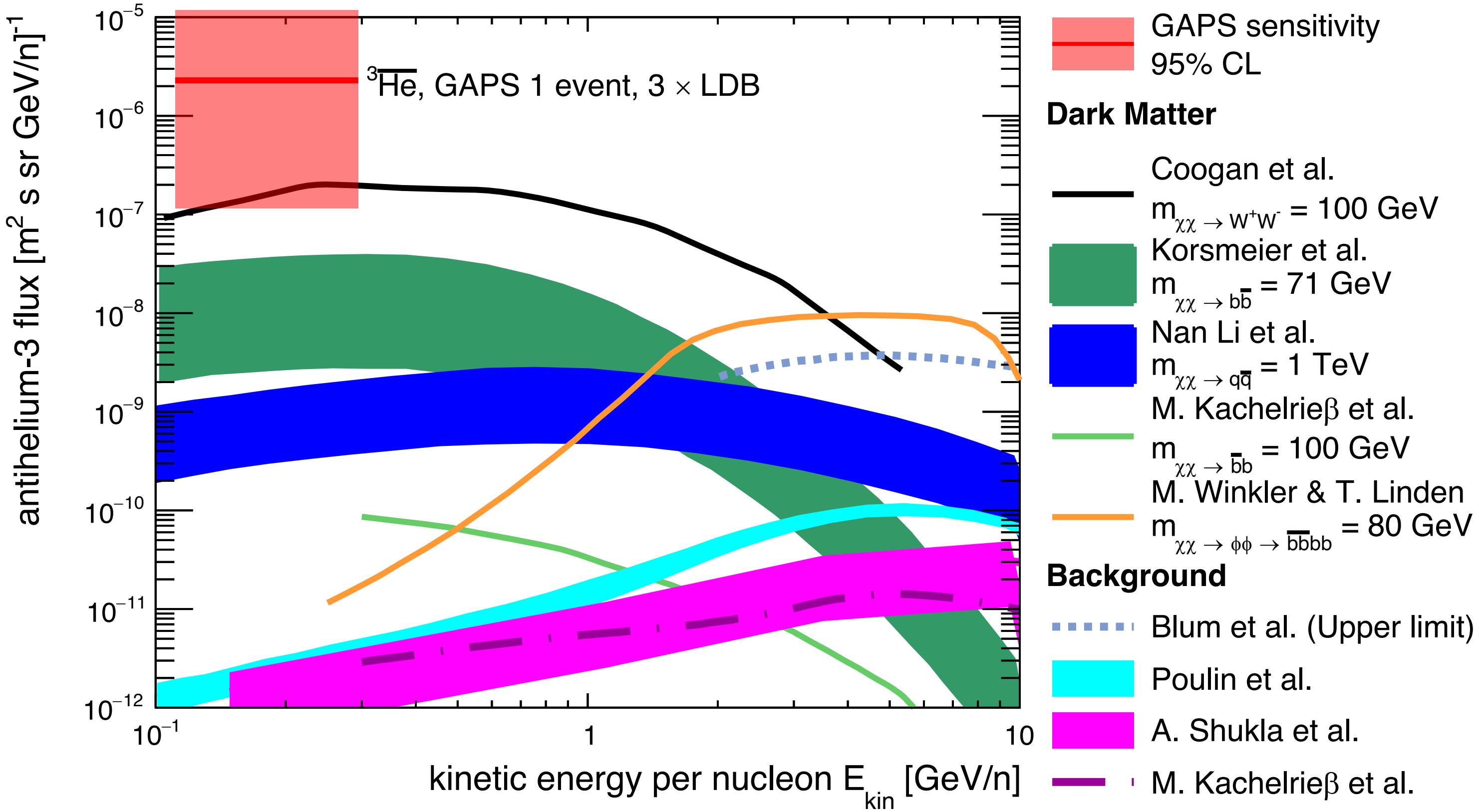
Antideuteron

GAPS: optimized for searches for low-energy antinuclei

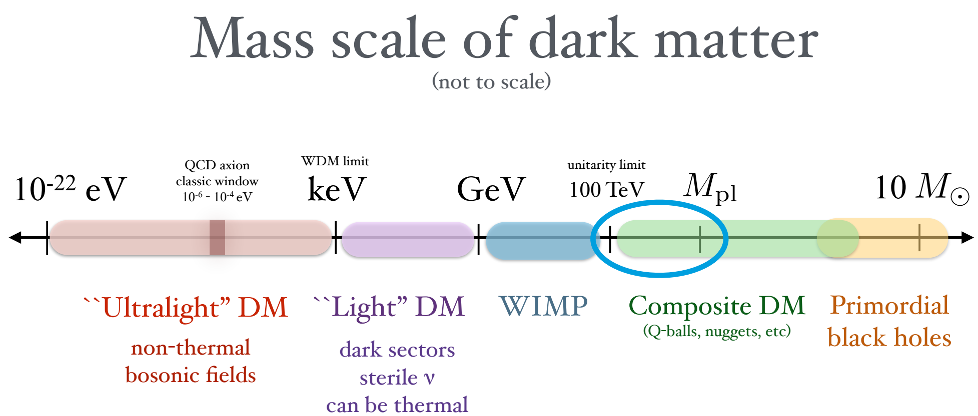


Antihelium

GAPS: optimized for searches for low-energy antinuclei



Beyond WIMPs



Thermal-relic scenario with point-like DM particle

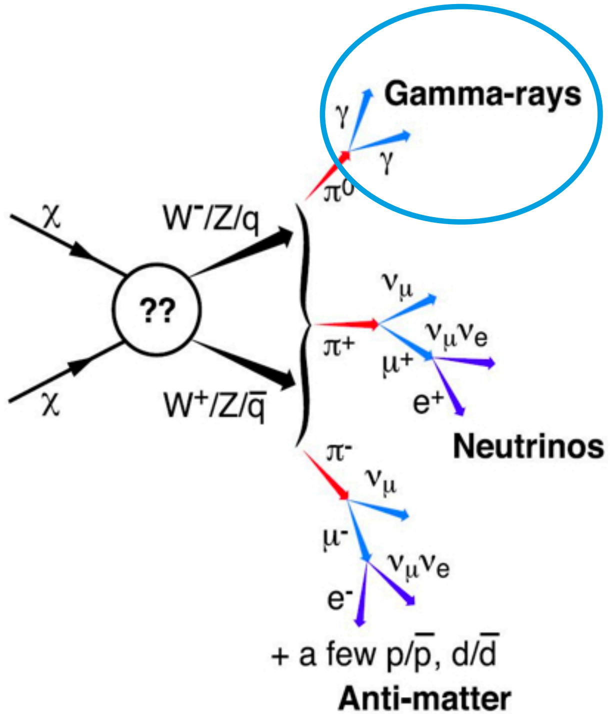
→ heavy DM (>~100-200 TeV) overproduced

$$\langle \sigma v \rangle_{max} \propto \frac{1}{M_\chi^2} \quad \text{(unitarity limit)}$$

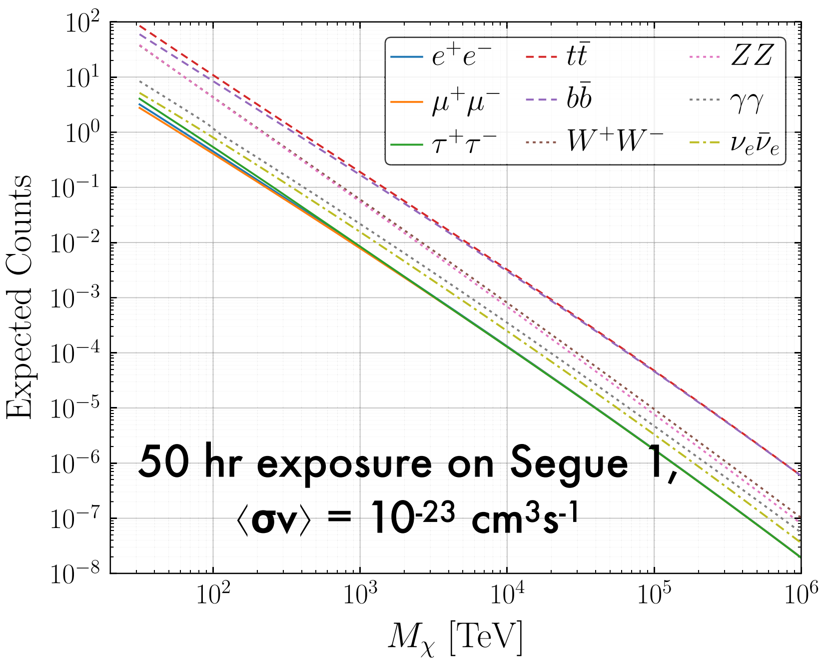
$$\text{and} \quad \Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \quad \text{(thermal relic density)}$$

- Unitarity bound can be evaded with various extensions
  - Dark sector: 1..., composite DM (with/without geometrical cross section): 1, 2, 3, capture to bound states: 1...

Accessing >100 TeV Dark Matter



arXiv:2208.11740



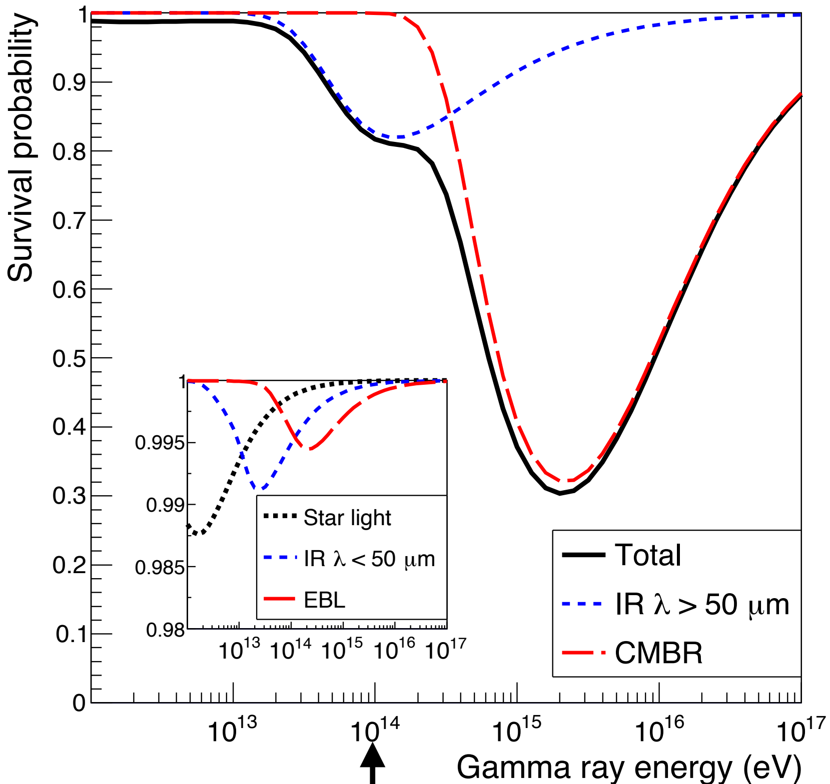
Final state gamma rays → only a small fraction of energy from heavy dark matter annihilation

>10% flux deposited in <100 TeV gamma rays for dark matter particles up to PeV masses

Absorption on Diffuse Photon Fields

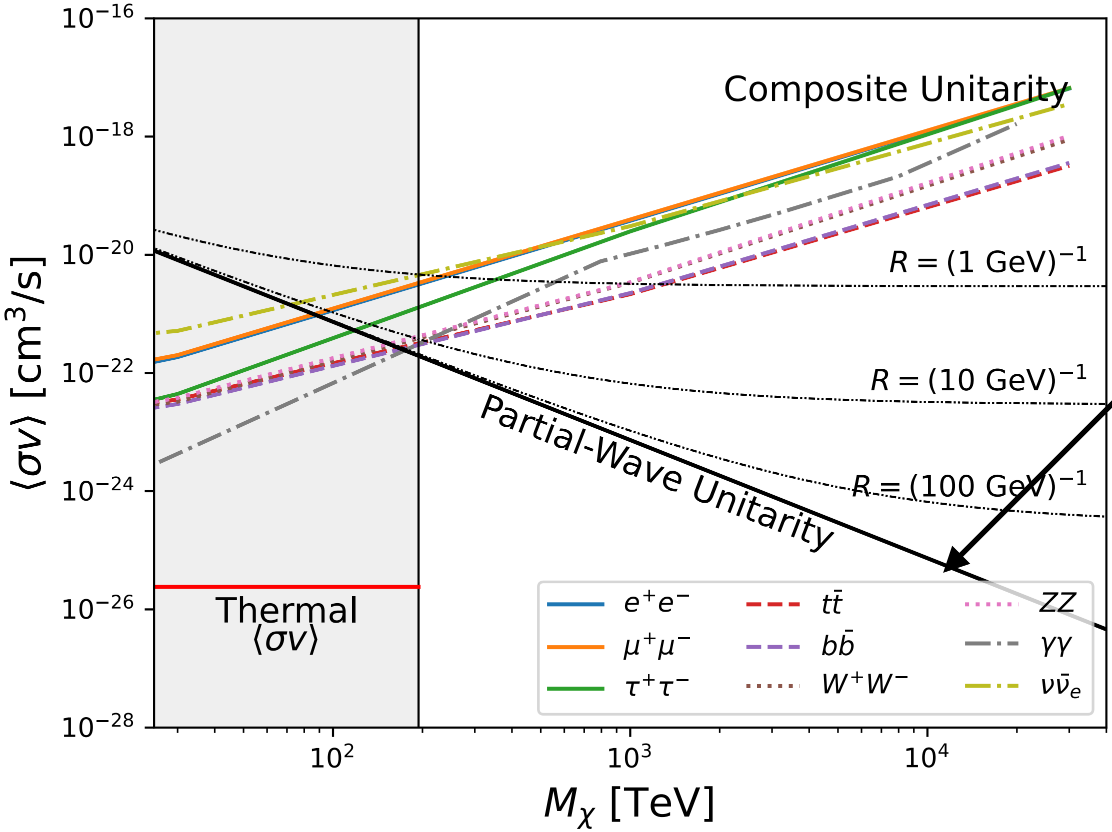
- Gamma rays undergo pair production on diffuse photon fields
- Galactic neighborhood
    - Cosmic microwave background radiation
    - Extragalactic background light
    - Starlight
    - Also can have absorption by dust

arXiv:1608.01587



>20% effect at 100 TeV

Gamma-ray Limits on Ultra-Heavy Dark Matter Annihilation

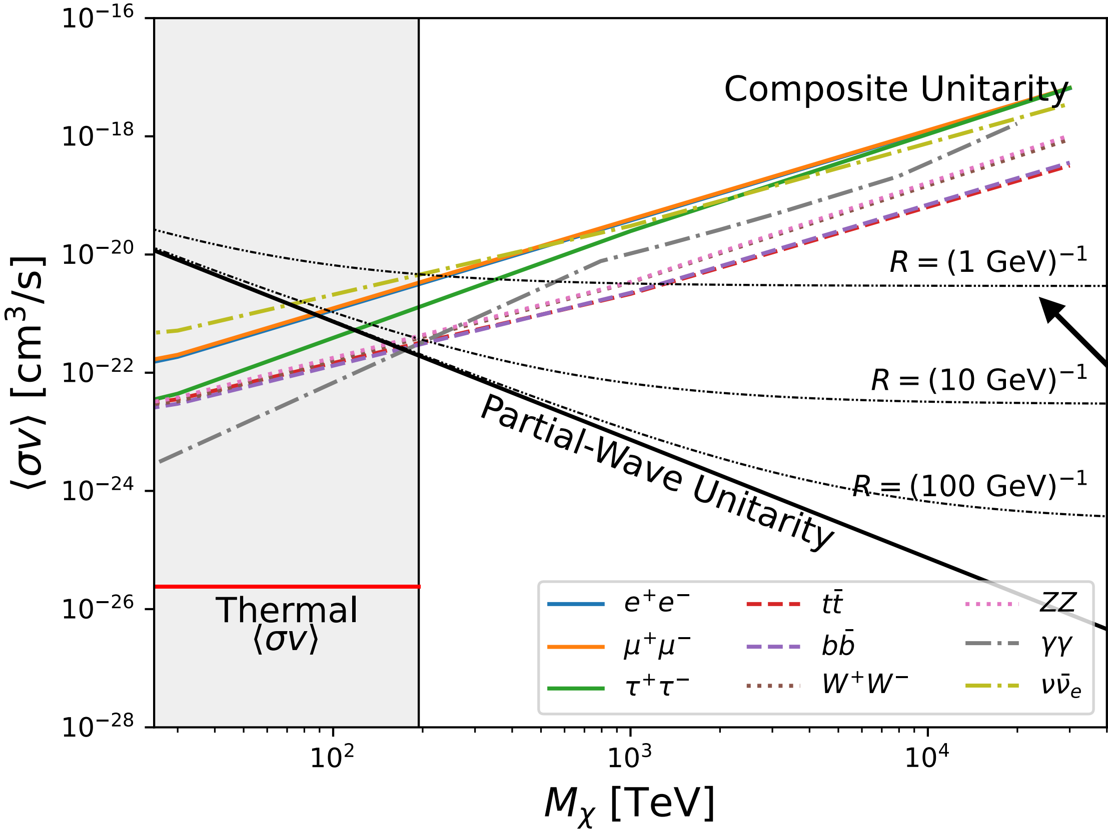


$$\langle \sigma v \rangle \leq 4\pi/(M_\chi^2 v_{\rm rel})$$

v_{rel} = between dark matter particles in target system

- VERITAS search using observations of dwarf spheroidal galaxies
- Benchmark 1: Partial-Wave Unitarity Bound
  - Point-like J=0 dark matter particle
  - VERITAS limits not constraining above unitarity bound

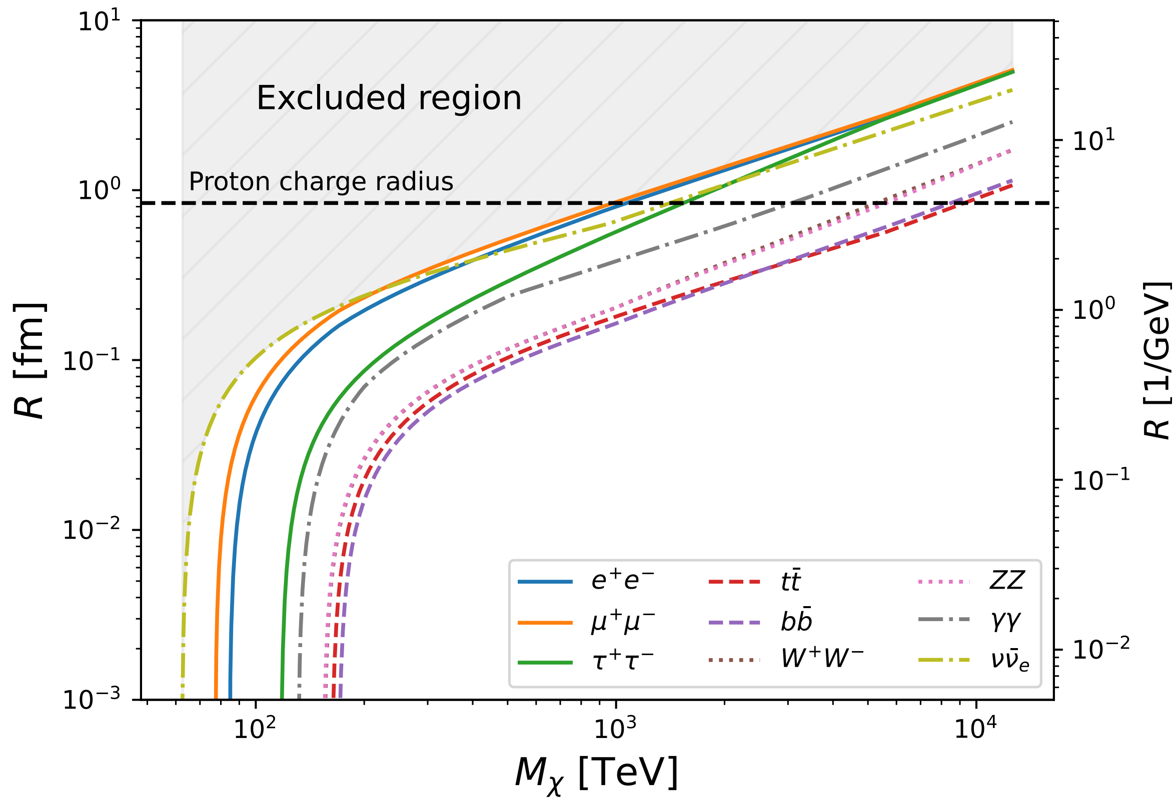
Gamma-ray Limits on Ultra-Heavy Dark Matter Annihilation



$$\langle \sigma v \rangle \leq 4\pi \frac{(1 + M_\chi v_{\mathrm{rel}} R)^2}{(M_\chi^2 v_{\mathrm{rel}})}$$

- Benchmark 2: Composite Unitarity Bounds
    - Composite dark matter particles; bound scales with particle radius
    - VERITAS able to constrain composite models

Gamma-ray Limits on Ultra-Heavy Dark Matter Annihilation

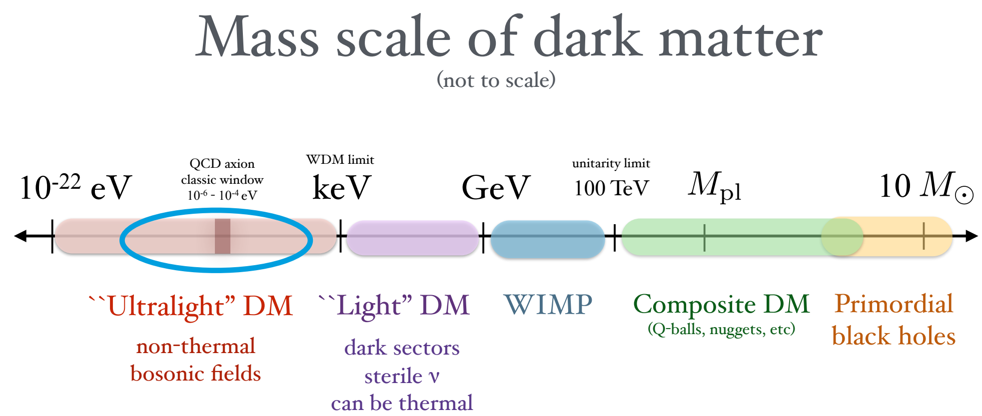


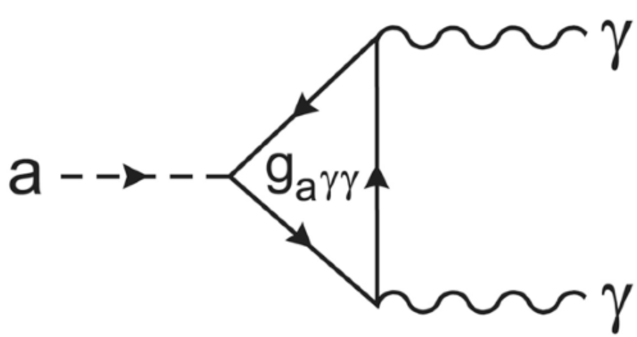
- Benchmark 2: Composite Unitarity Bounds
  - Composite dark matter particles; bound scales with particle radius
  - VERITAS able to constrain composite models

Axions and Axion-like Particles

Peccei-Quinn axion

- No observed CP violation in QCD
  - No reason theoretically to be zero
  - Violated in weak interaction
- CP-violating extension to QCD
  - New U(1) symmetry (globally broken) → new light particle

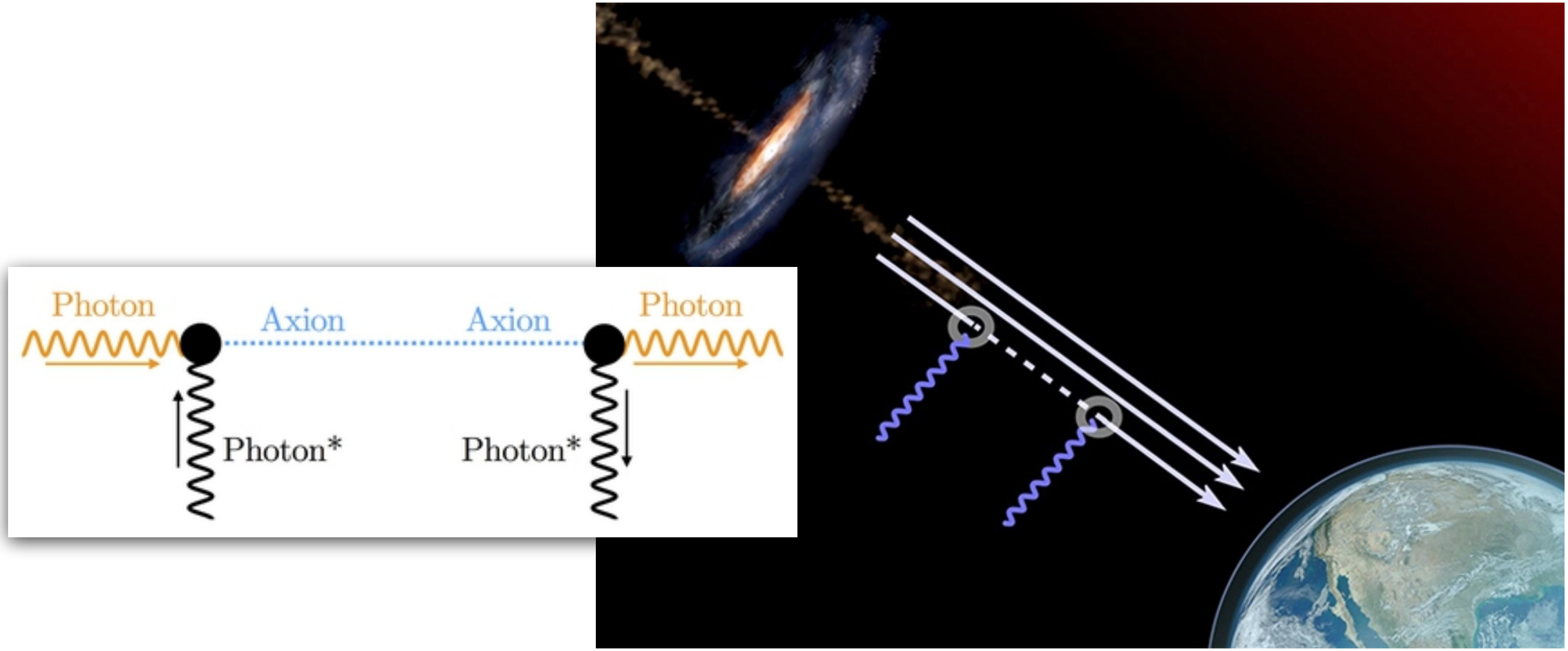




Axion-like particles

- Light particle mixing with photon predicted in several SM extensions
  - Does not necessarily solve strong CP-problem
  - Dark matter candidate

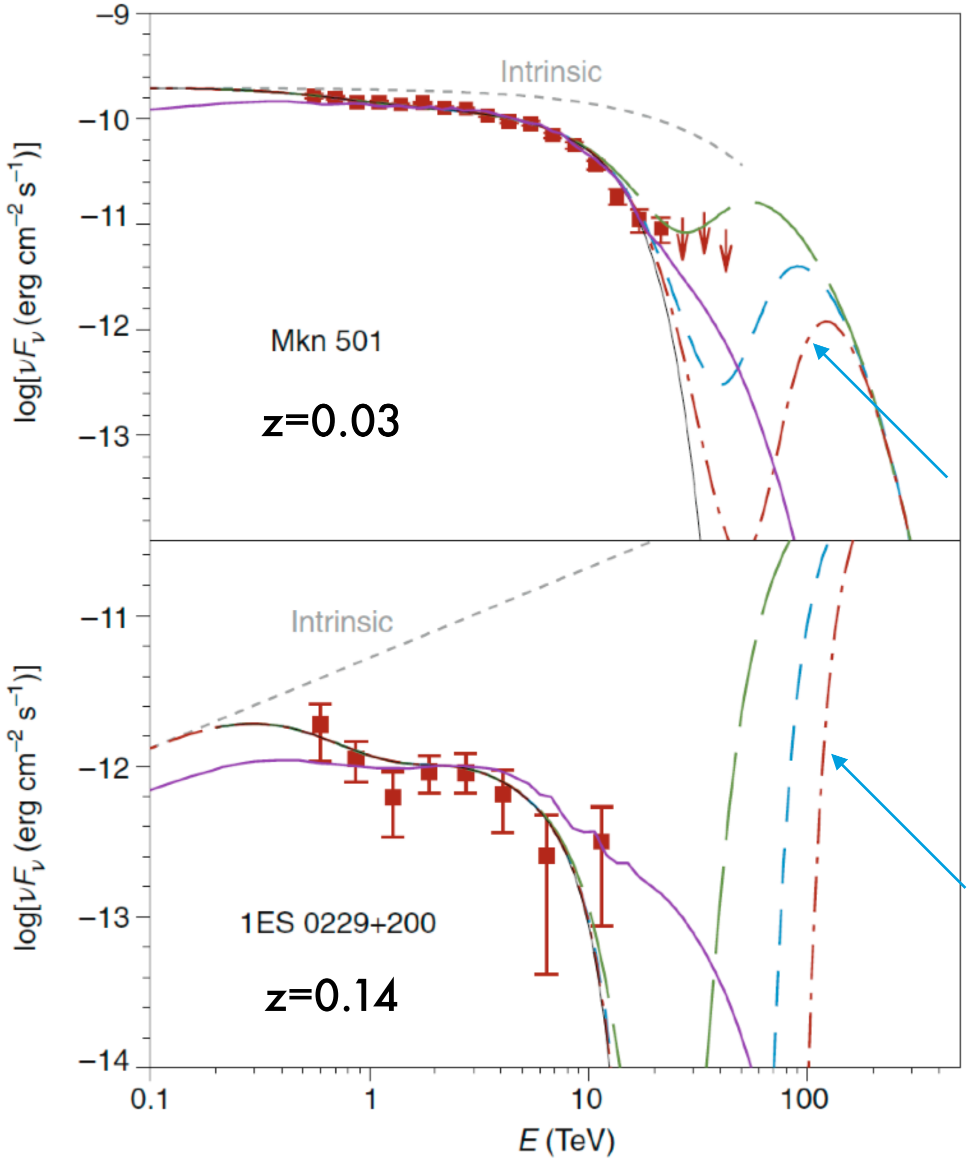
Axion-like Particles



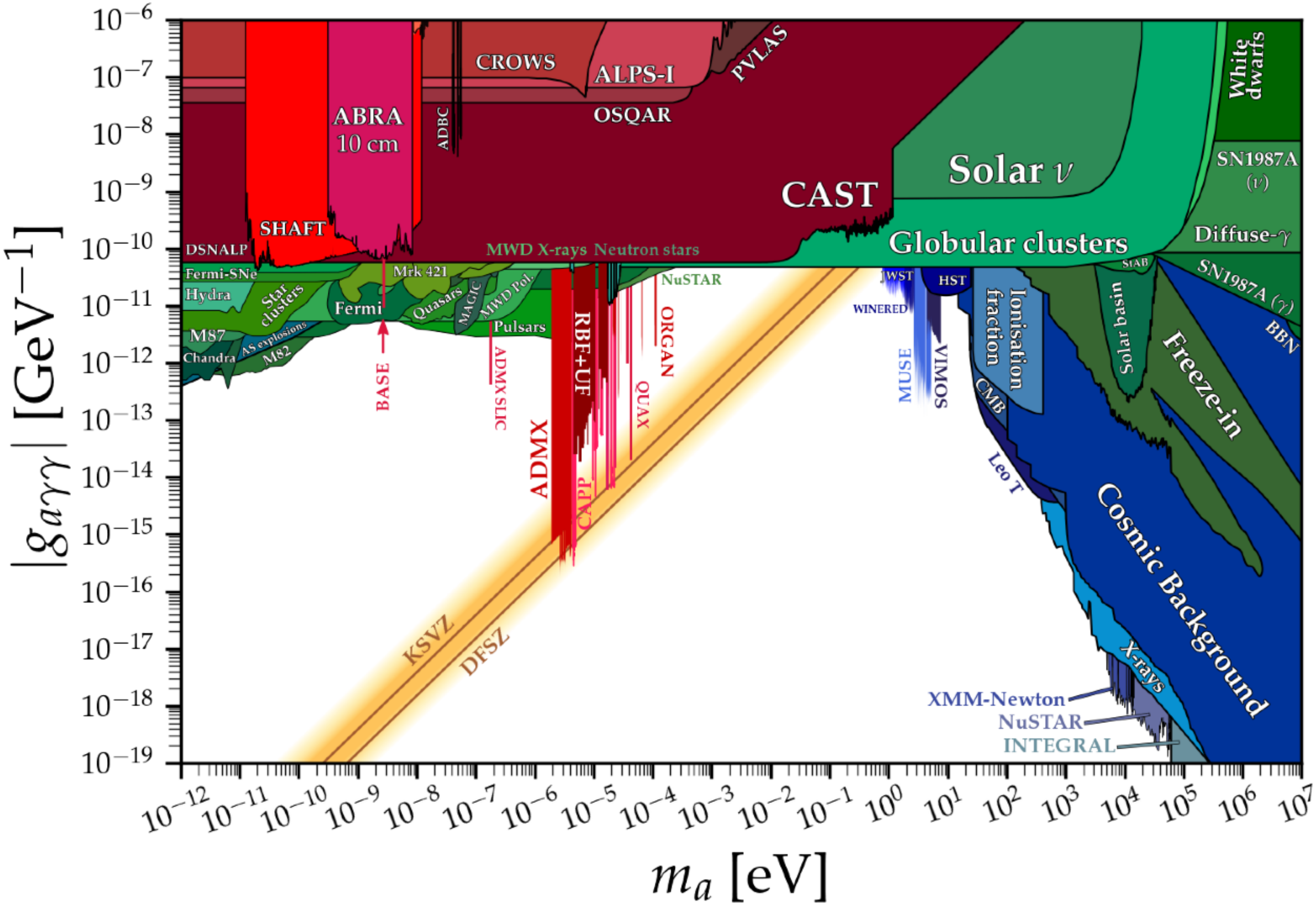
- Gamma rays traveling from distance sources could mix with ALPs en route to Earth
- Strong magnetic fields in e.g. galaxy clusters would induce mixing, or weak magnetic fields in intergalactic medium

Axion-like Particles

- Gamma-ray flux classically attenuated by interactions with diffuse photon fields (extragalactic background light)
- ALP-mixing reduces attenuation, introduces spectral features
- Non-detection used to set limits

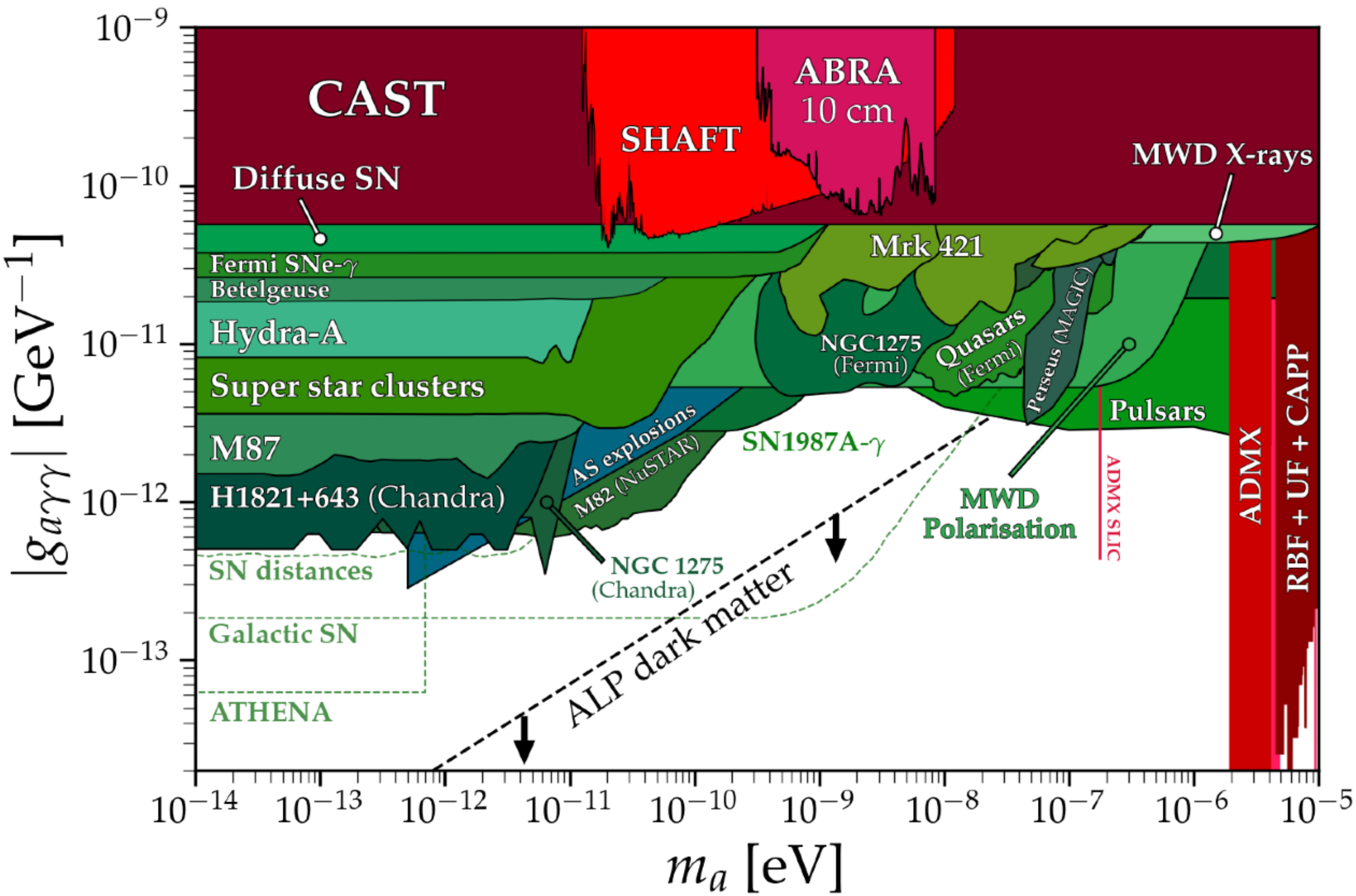


Limits on Axion-like Particles



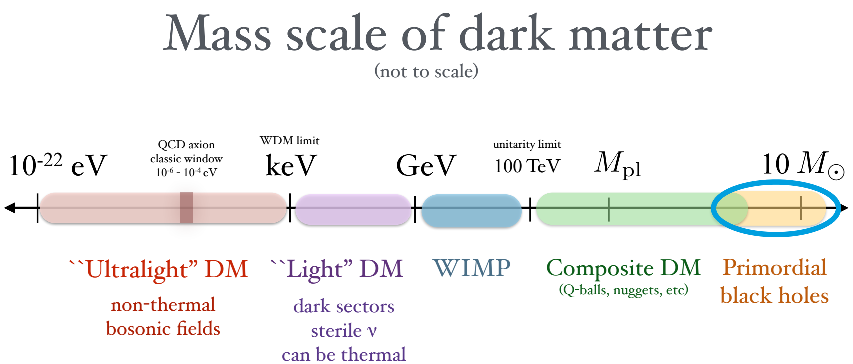
https://cajohare.github.io/AxionLimits/

Limits on Axion-like Particles



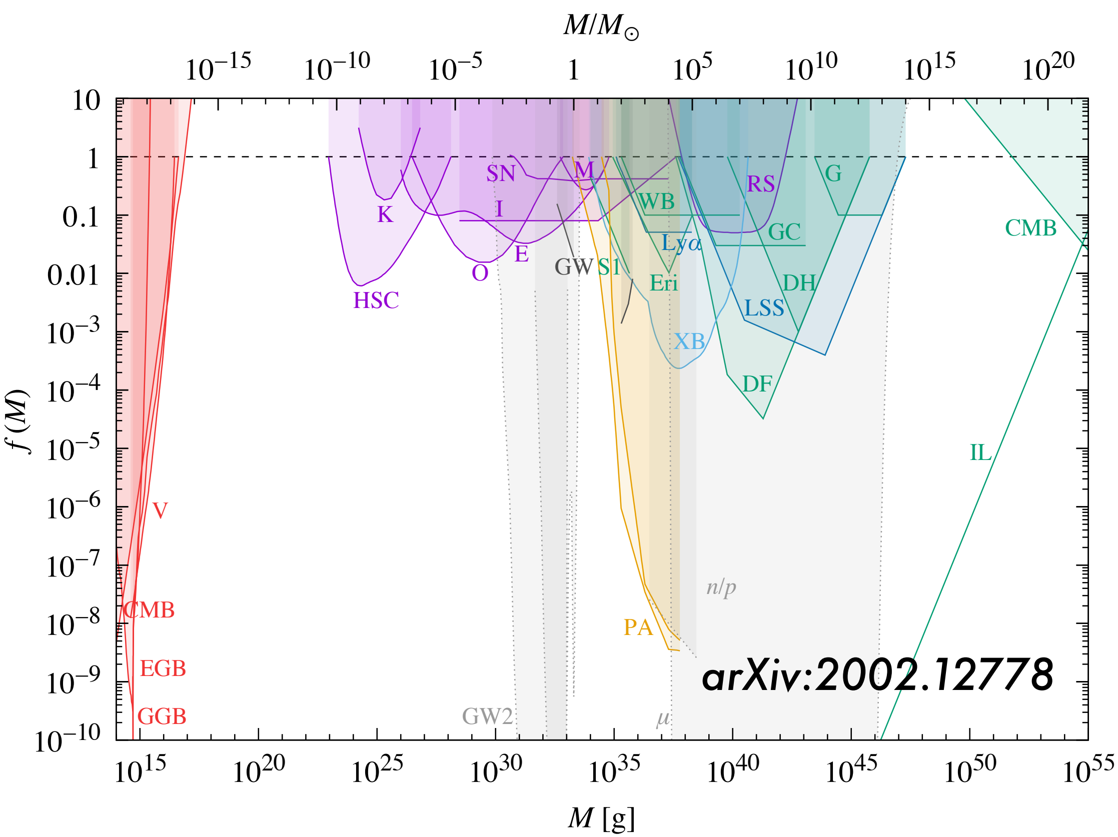
https://cajohare.github.io/AxionLimits/

Primordial Black Holes



- Form around matter overdensities in early Universe
- Possible contributor to dark matter content of Universe

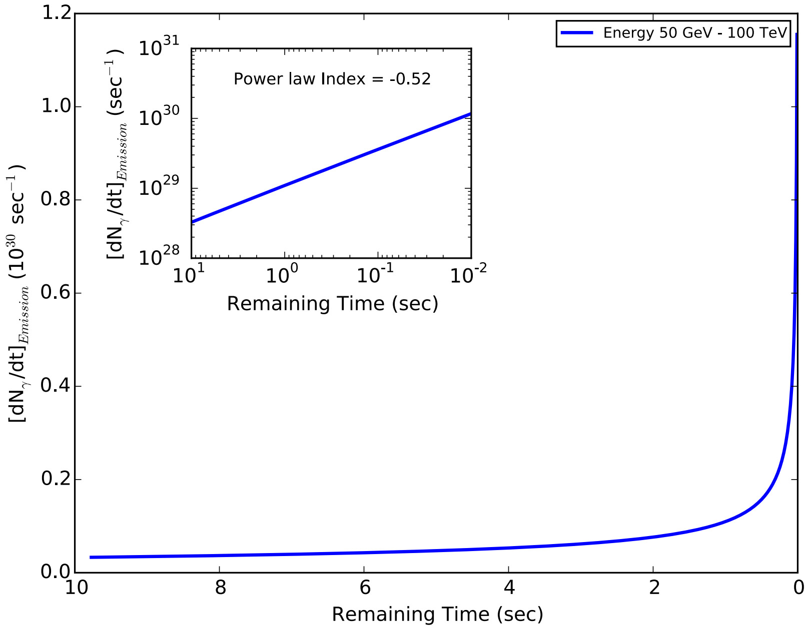
$$M \sim \frac{c^3 t}{G} \sim 10^{15}\left(\frac{t}{10^{-23}\ \mathrm{s}}\right)\ \mathrm{g}$$

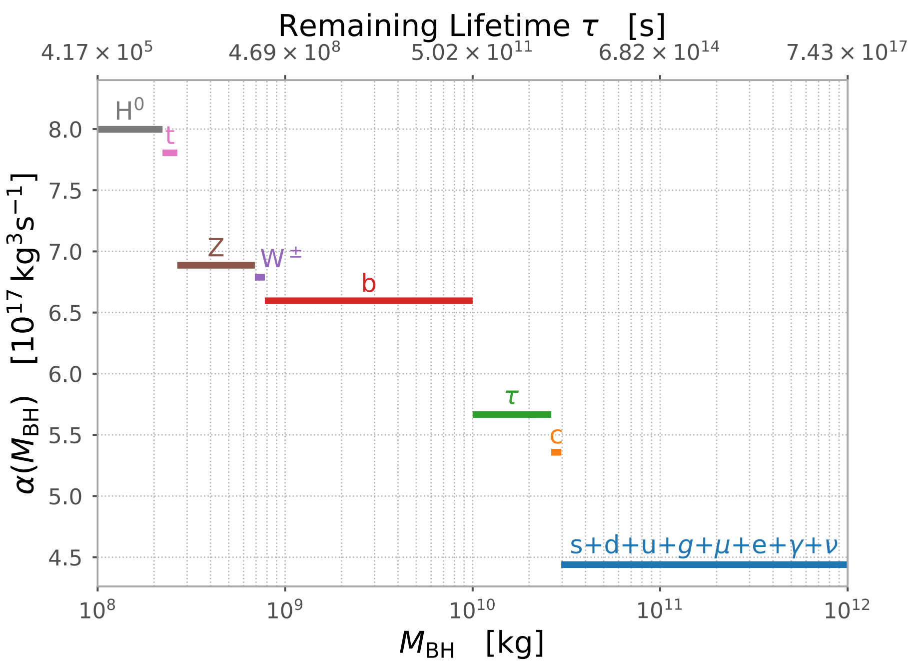


Mass related to time of formation

Primordial Black Hole Evaporation

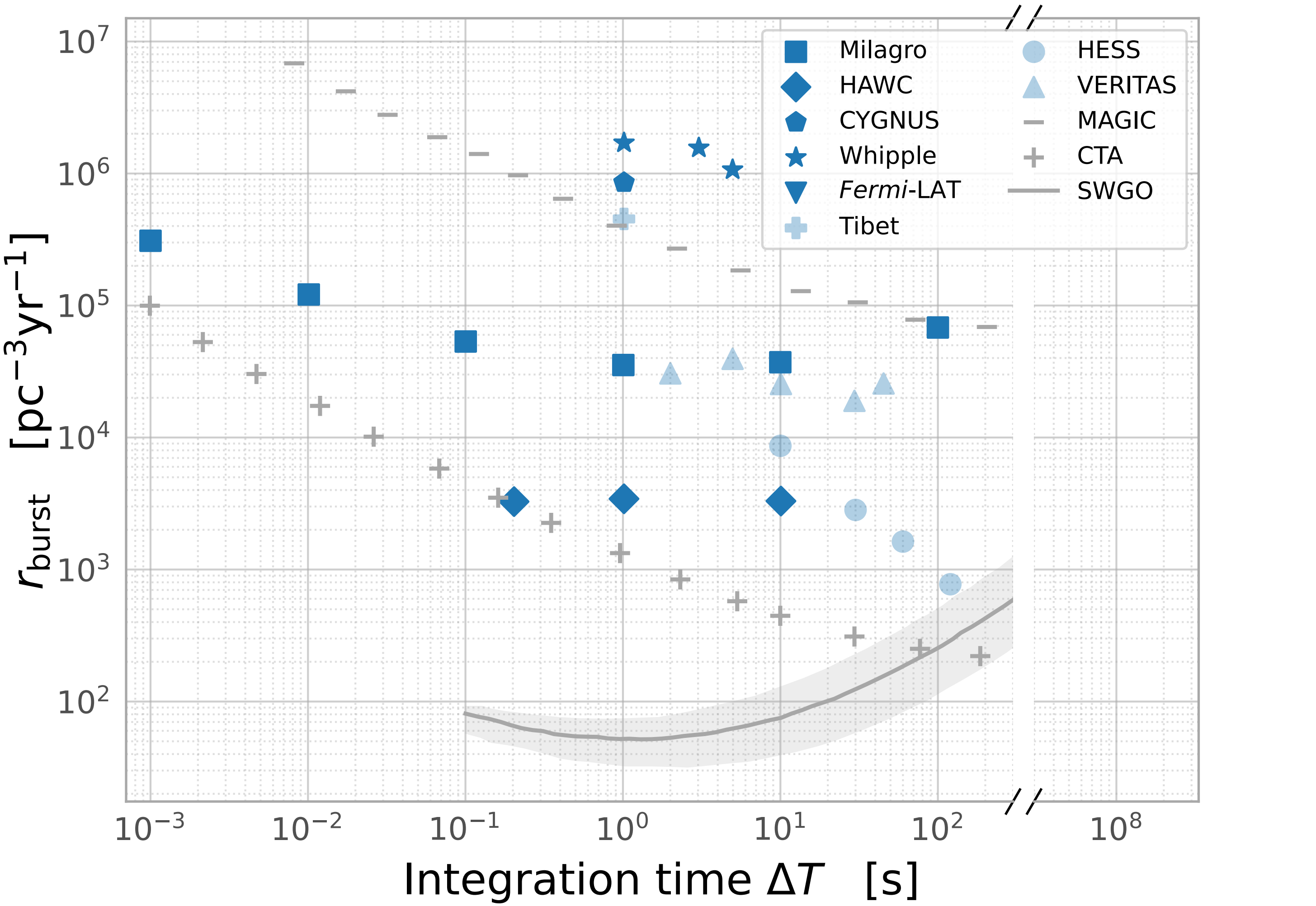
- PBH evaporation via Hawking radiation
- Heavier particle species produced at end of PBH lifetime
- PBHs with M = 10^{15} g would be evaporating now
- Expect gamma-ray burst with no counterpart or afterglow





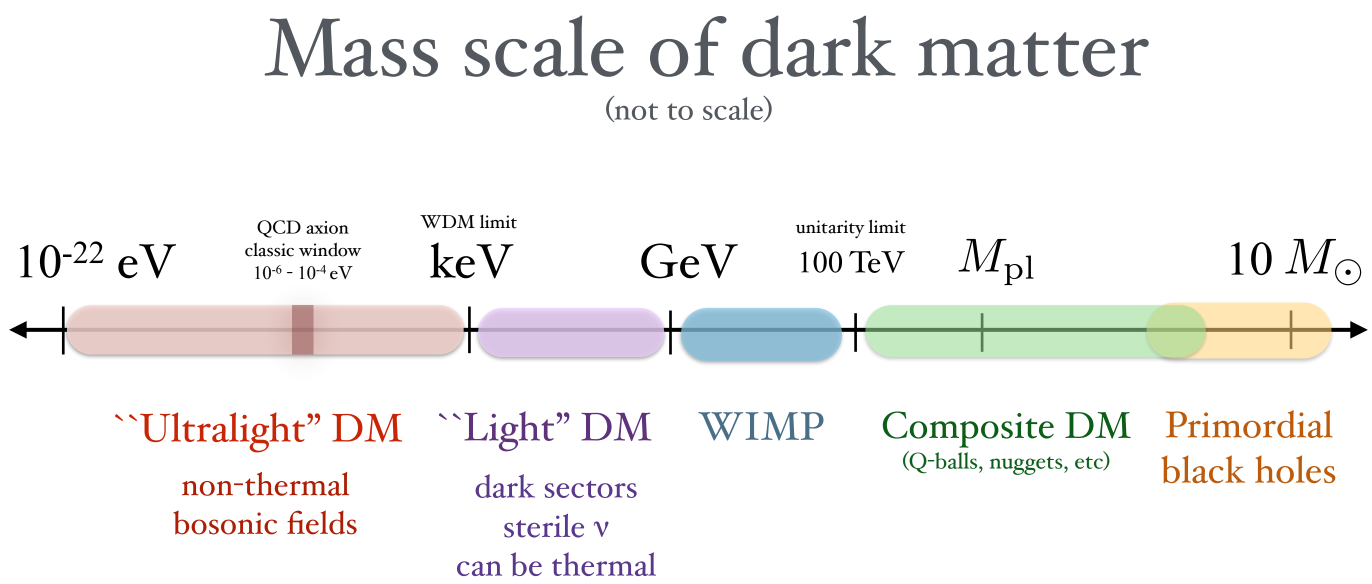
Limits on PBH burst rate

arXiv:2111.01198



- Survey instruments have a major advantage
- Competitive limits from upcoming Cherenkov Telescope Array Observatory

Astrophysical Searches for Dark Matter



Lin 2019 arXiv:1904.07915

Astrophysical searches diverse and capable of probing broad phase space

Including regions not discussed in this lecture!