γ2022
BARCELONA

Dark Matter Searches with Gamma Rays and Cosmic Rays

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7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy (γ-2022), Barcelona (Spain)
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Program

- Intro: what is dark matter and how we look for it
- Indirect WIMP searches
  - [Charged] cosmic rays
  - Gamma rays
  - Neutrinos
- Axion-like particles

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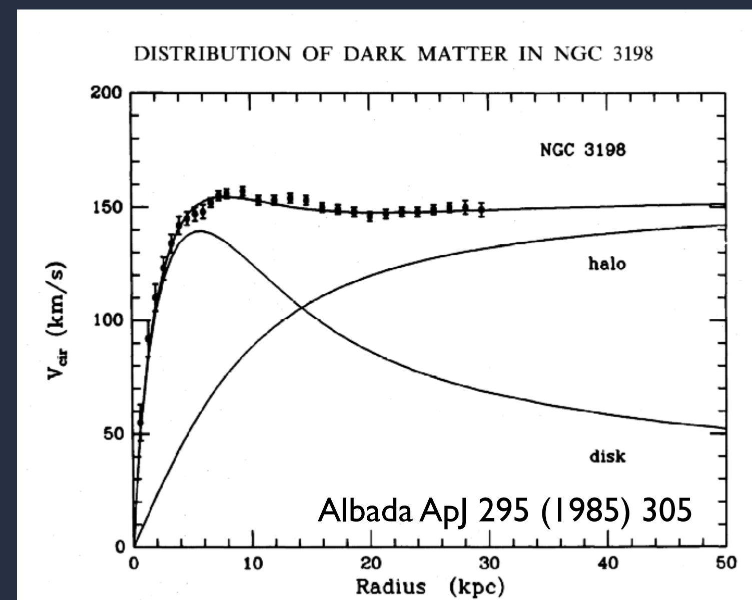
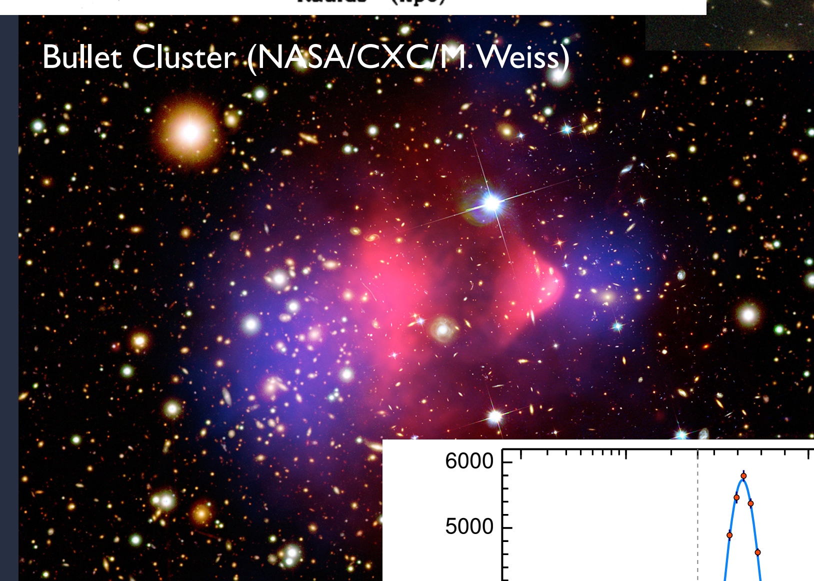
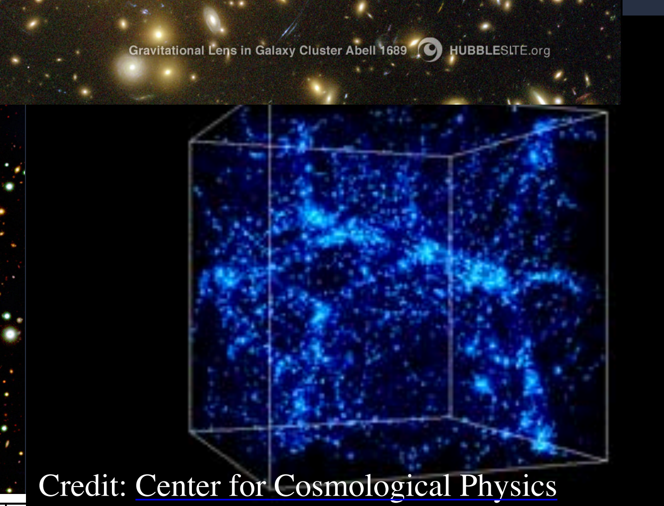
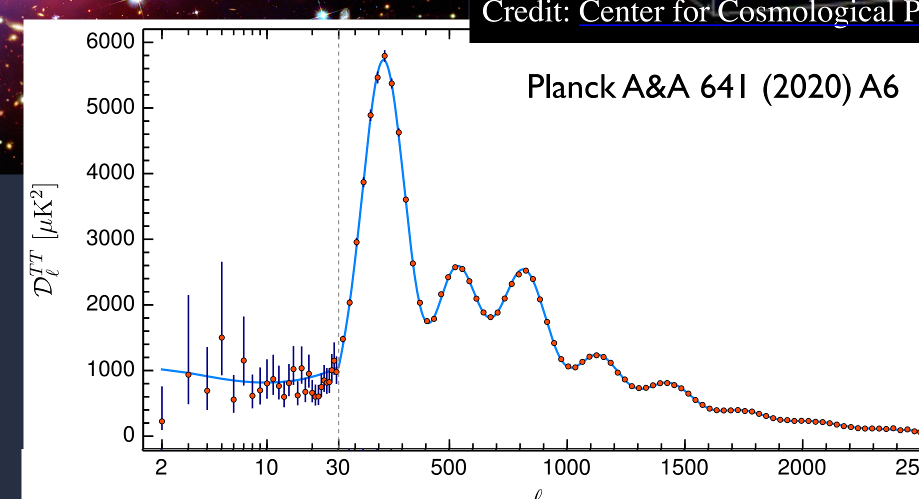
Evidence for dark matter

- Evidence:
  - Rotation of stars in galaxies
  - Rotation of galaxies in galaxy clusters
  - Lensing
  - Bullet cluster
  - Power spectrum of cosmic microwave background
  - Large structure formation









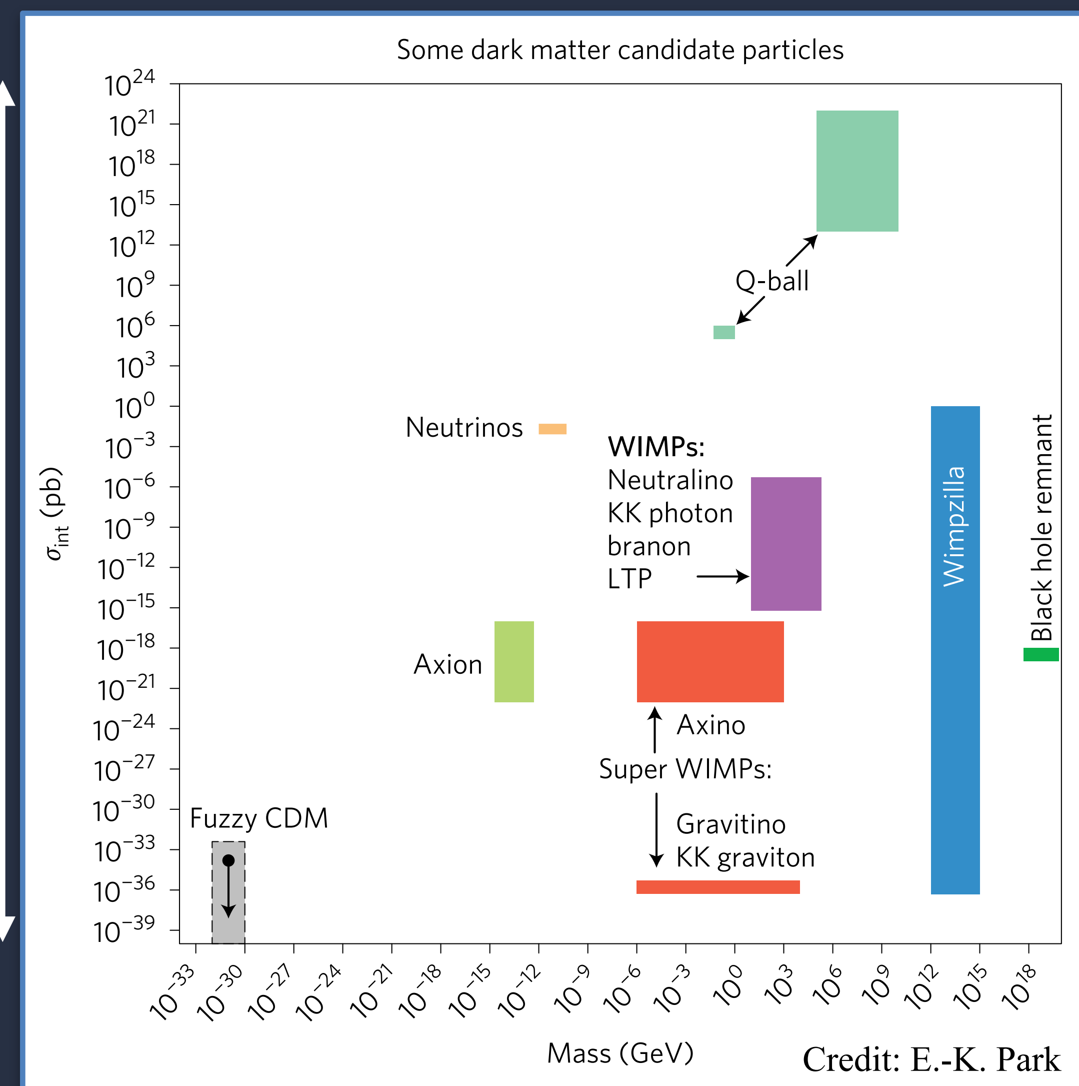
The Cold Dark Matter Paradigm

- Dark matter (DM) is a particle beyond Standard Model:
  - Electrically neutral
  - Non baryonic
  - Non-relativistic or cold at freeze-out
  - Stable at cosmological scales
- DM Discovery = revolution in Physics:
  - Physics beyond the Standard Model
    - → New particle [sector] constituting ~80% of total mass;
    - → New interaction[s?]
    - → Elucidation of other standing problems of Particle Physics
  - DM distribution in galaxies and clusters → improve our understanding on formation, evolution and dynamics of large structures
  - If a thermal relic, probably the earliest one at reach → insight in early epochs of the Universe prior to nucleosynthesis

Cold dark matter candidates

- Weakly Interacting Massive Particles (WIMPs):
  - Mass and interaction cross section in the weak scale provides correct (thermal) relic density
  - Different candidates arise in theories Beyond the Standard Model addressing the hierarchy problem
- Axion-like particles
  - Very light ($10^{-10} – 10^{-2}$ eV), neutral particle
  - Produced non-thermally
  - Can convert to photons (and back)
- Sterile neutrinos
  - Natural ingredient of mechanism for generating neutrino masses
  - Interact only through mixing with ordinary neutrinos
- Primordial black holes
  - Being found by Gravitational Waves detectors?
- …

~65 orders of magnitude in cross section



~50 orders of magnitude in mass

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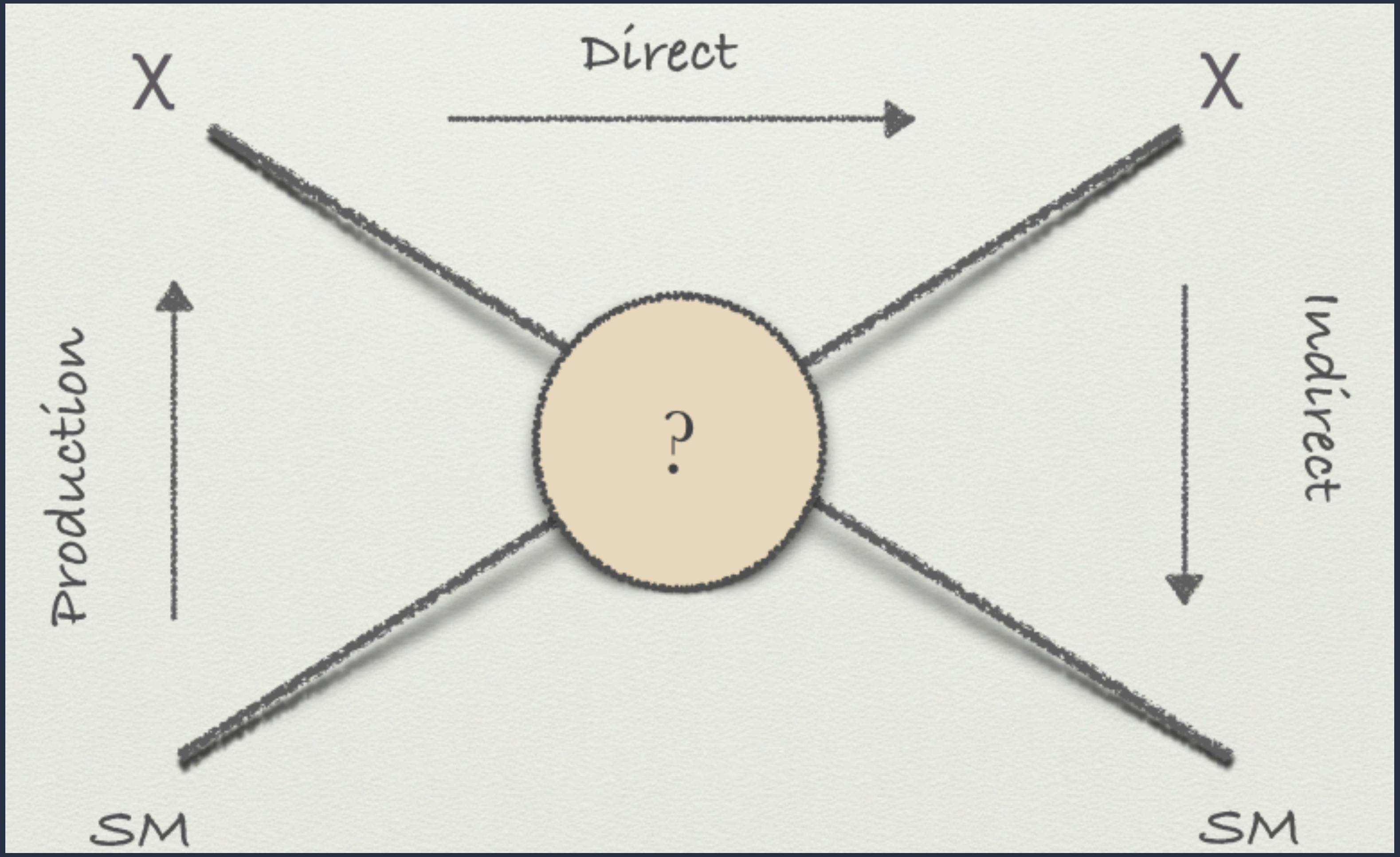
Searches for WIMP dark matter



Production

SM + SM $\rightarrow \chi + \chi$

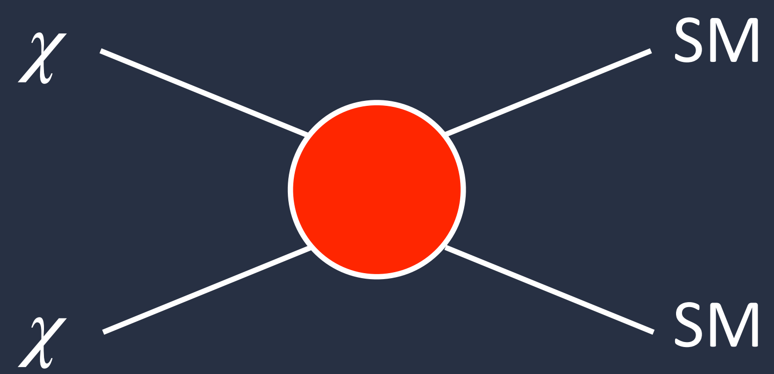
Direct

χ + SM $\rightarrow \chi$ + SM

Indirect

$\chi + \chi \rightarrow$ SM + SM

Indirect searches



Primary channels: $b\bar{b}$, W^-W^+, ZZ, $\tau^-\tau^+$,…

Hadronization, decay, radiation →

Final states γ, $e^\pm$, $p^\pm$, ν,…

- **Indirect searches**: looking for spectral and spatial signatures of dark matter in the extra-terrestrial fluxes of stable SM particles
- **HE Messangers:**
  - Gamma-rays
  - Neutrinos
  - Electron/positrons
  - Antiprotons, Antideuterium, Anti-nuclei
- **Characteristic spectral features**:
  - Separation from background
  - Can measure basic physical properties: mass, cross-section / lifetime
- **Gamma-rays or neutrinos do not suffer from propagation effects**:
  - Exploit spatial features known from simulations
  - Can determine DM abundance and distribution in the Universe

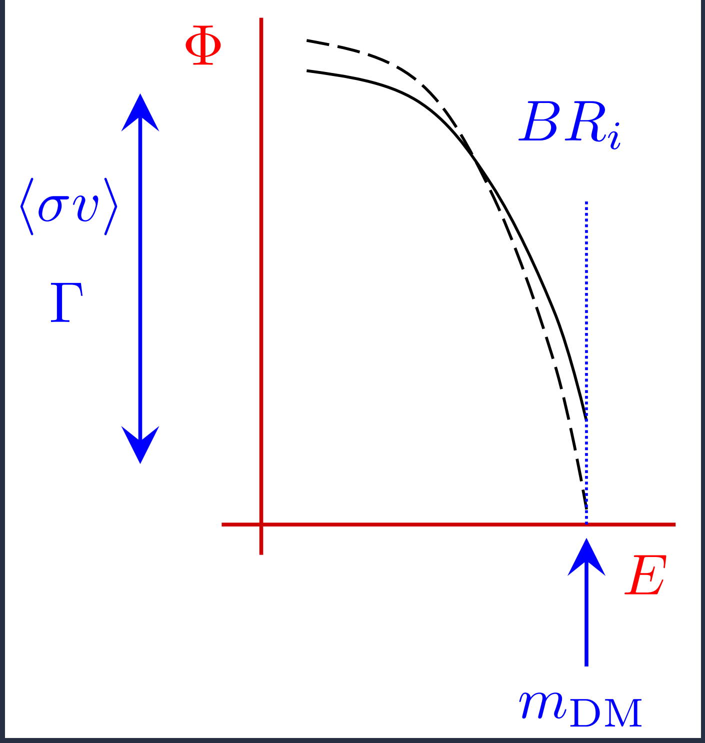
Features of signals

★ **Production**:

$$\Phi_x \sim \int \left(\frac{\rho_{\rm DM}}{m_{\rm DM}}\right)^{2,1} \mathrm{dV} \times \{\langle\sigma v\rangle, 1/\tau\} \times \sum_i BR_i \times \left(\frac{dN_x}{dE}\right)_i$$

flux — DM abundance — reaction probability — channel weight — spectrum per channel reaction

- Signal intensity:
  → Total observed mass and/or concentration
  → Annihilation cross section or lifetime
  → Mass
- Spectral features:
  → Branching ratio of different final states
  → Mass



★ **Transport** (for charged particles):

$$\frac{dn}{dt} = \nabla[D\nabla n] + \frac{\partial}{\partial E}[b(E)n] + Q(E,r)$$

time evolution — diffusion — energy-loss — injection

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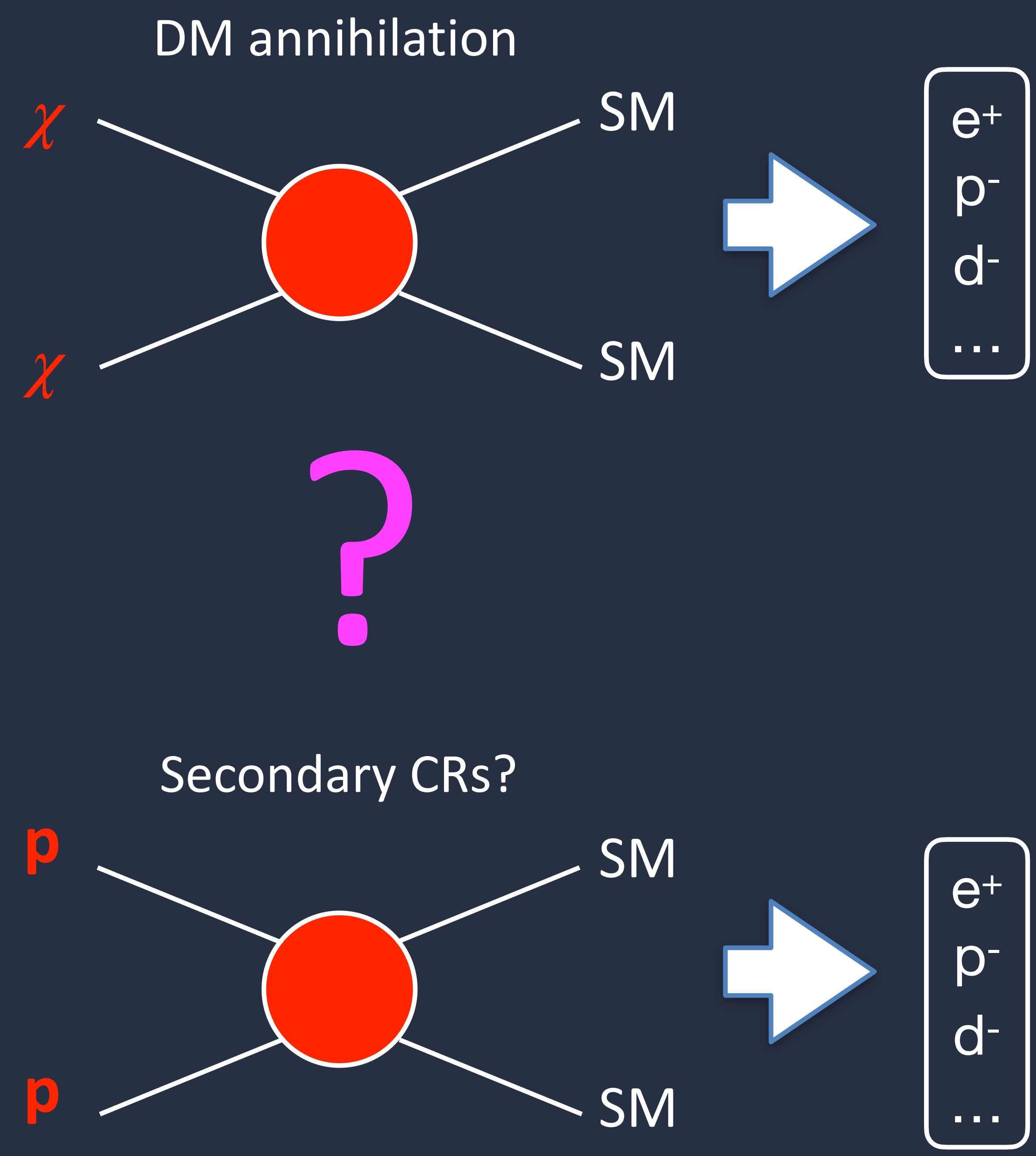
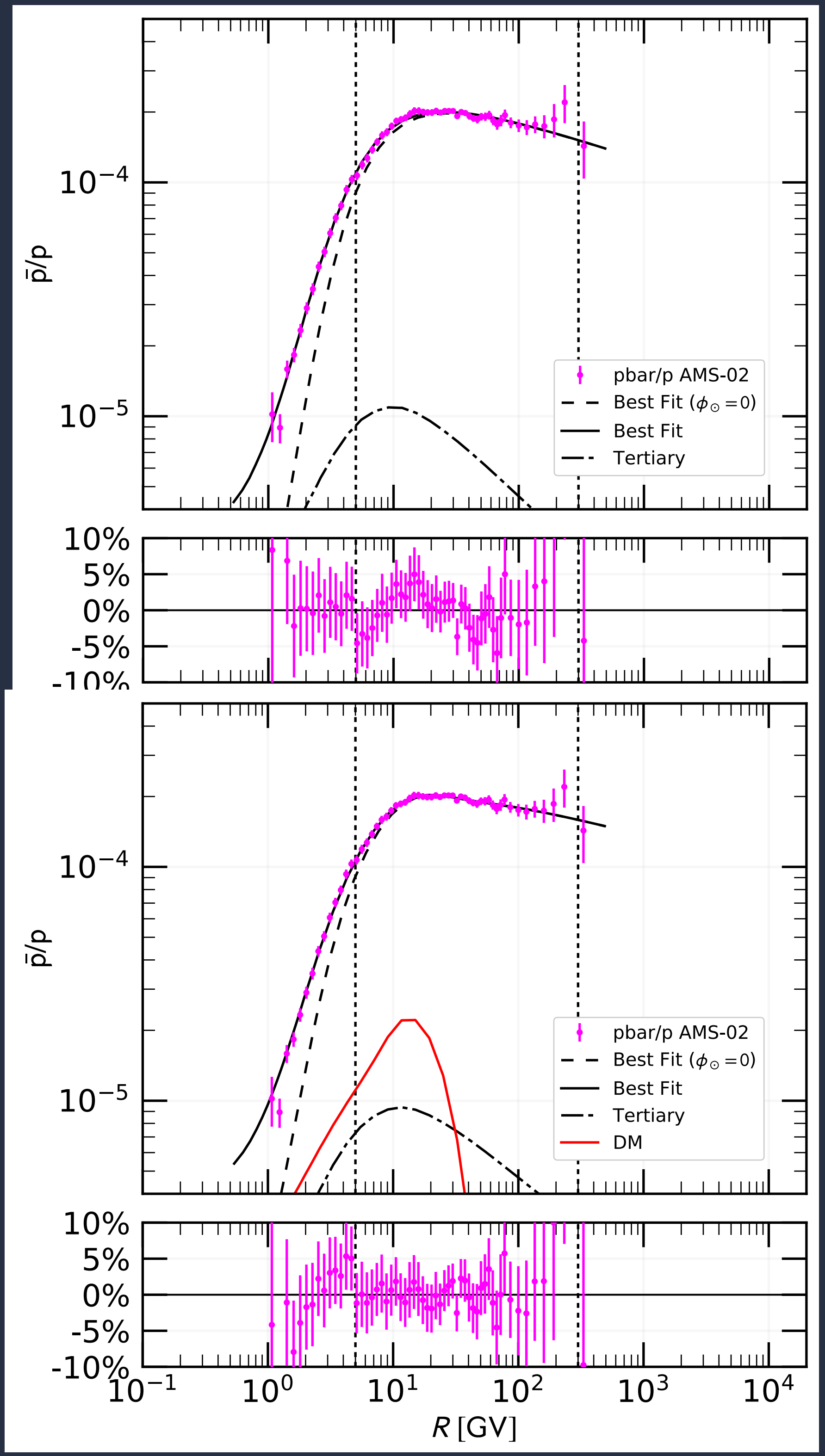
Charged cosmic rays

- Main strategy:
  - look for **anomalies in spectra** of cosmic ray (CR) anti-particles (anti-protons, positrons, anti-nuclei)
  - May be produced in annihilation or decay of DM particles into pairs of SM particles,
  - Background: secondary CRs by interaction of primary CRs in interstellar medium, eg in pulsars, PWN, SNR…
  - Uncertainties: distance-, time- and energy- dependence of CR sources and propagation.
- Also look for **anisotropies** in the CR flux
- Because of energy losses, we only detect local charged CRs



Anti-proton/proton ratio

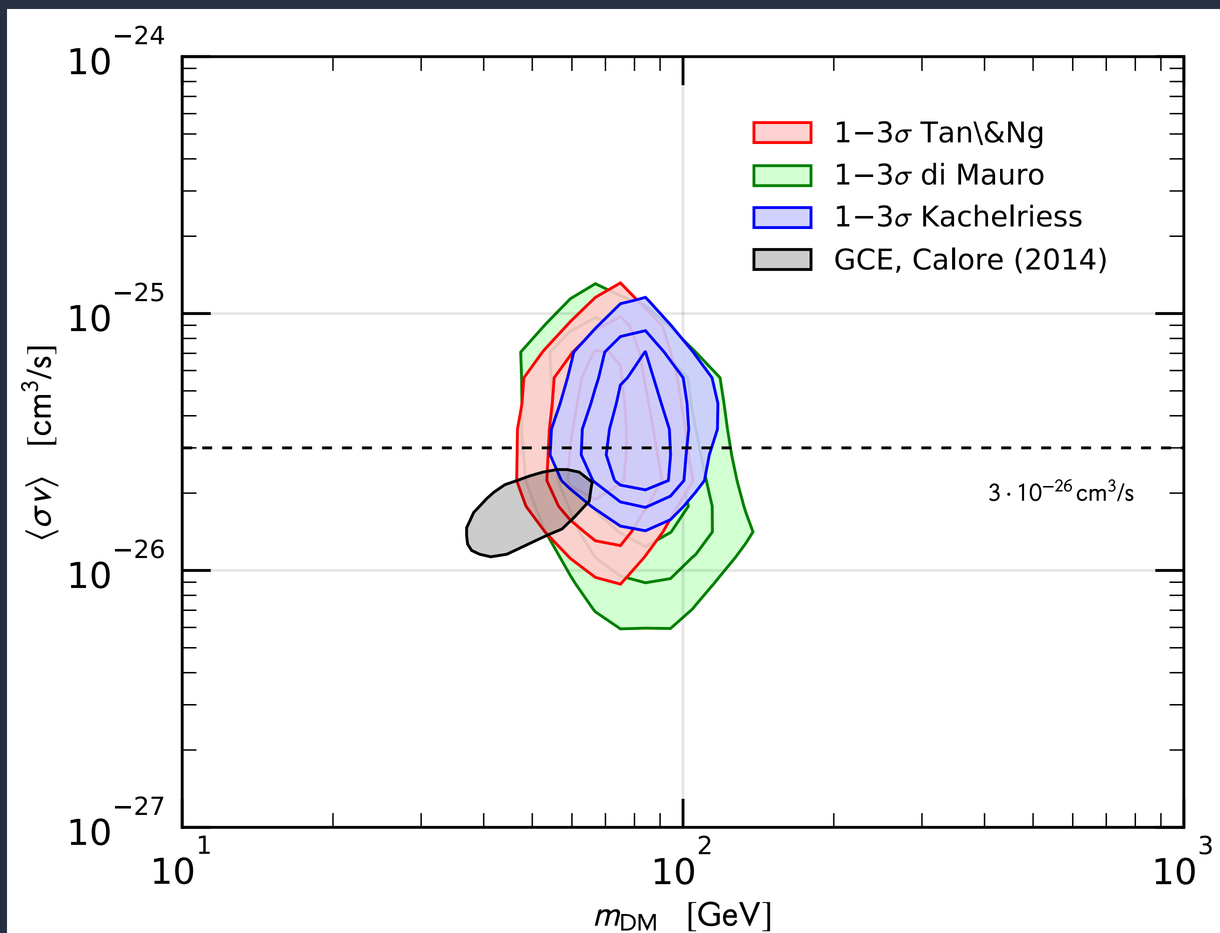
Cuoco et al. Phys. Rev. D99 (2019) 103014

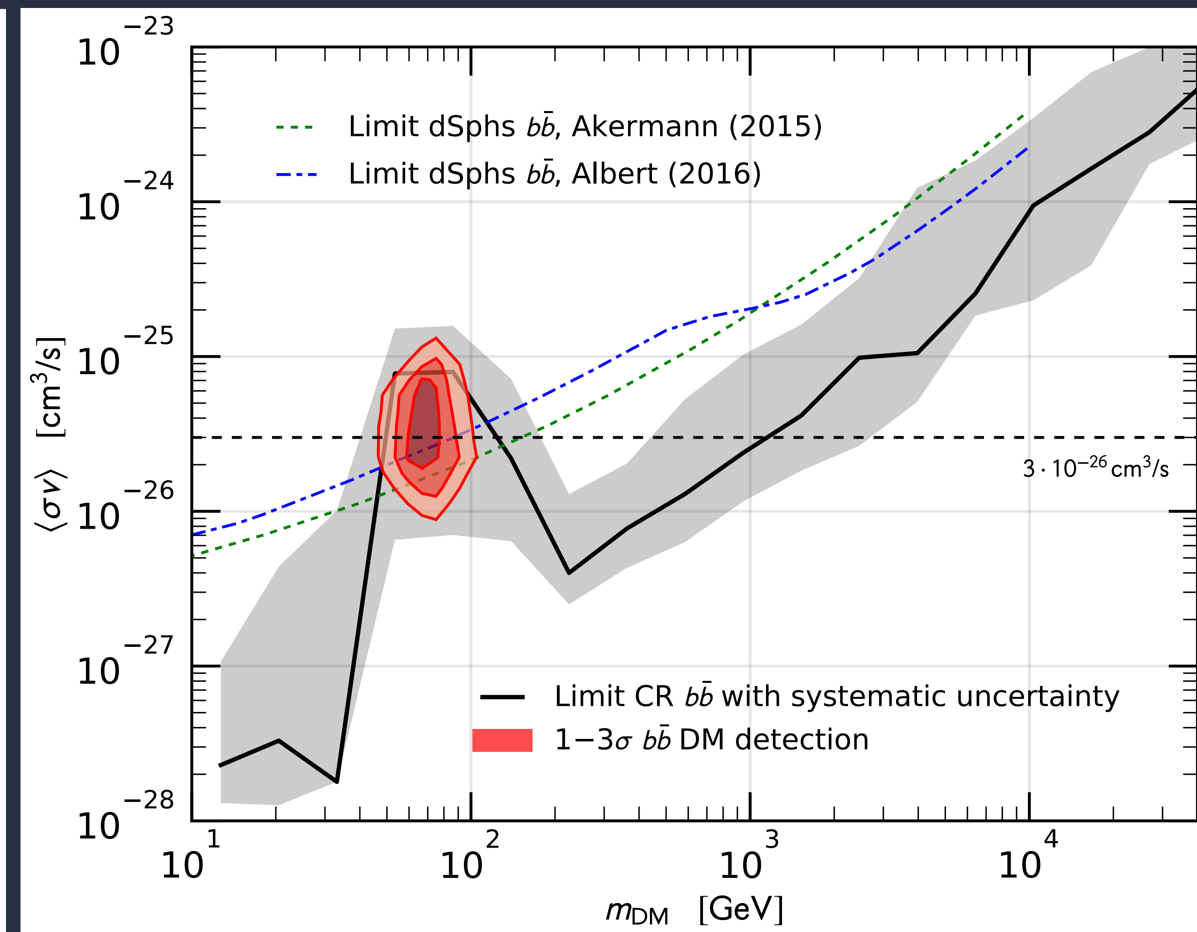


- ★ Data from AMS-02 on board the ISS [Phys. Rev. Lett. 117 (2016) 091103]
- ★ Solar modulation and tertiary CR component needed to fit the data
- ★ Authors claim: “DM component has distinct shape and improves the fit (3σ level effect)”, but trials have not been taken into account…
- ★ Also, several uncertainties affect the modeling:
  - the primary proton and Helium spectra
  - the antiproton spallation production cross section
  - CR propagation schemes

Bounds from anti-protons

Cuoco et al. PRL 118 (2017) 191102



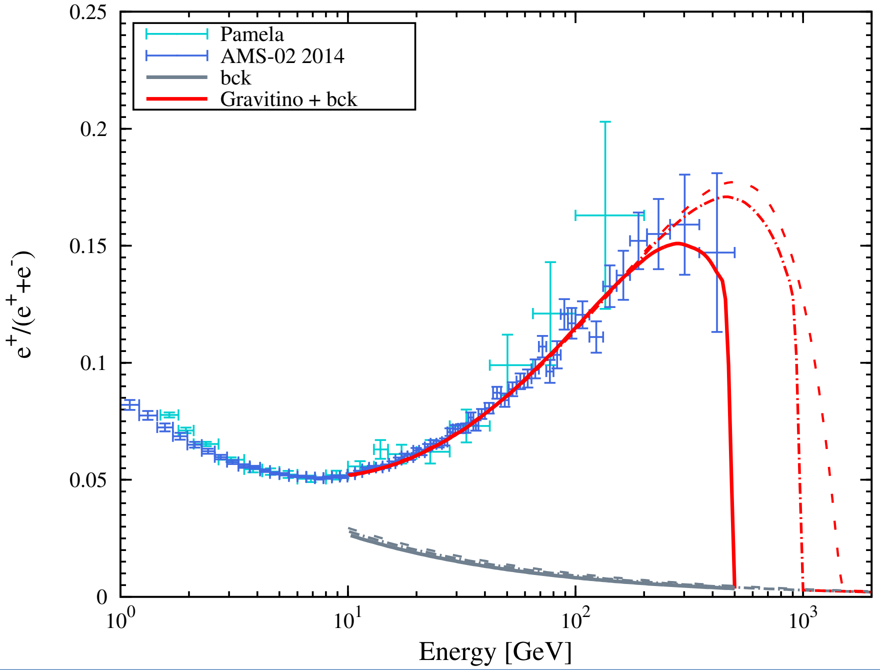


- ★ Excess best fitted by DM particle with m_{DM} ~70 GeV and about the thermal relic density
- ★ Limits for other masses exclude relic density
- ★ Remember: affected by large uncertainties

Positron fraction

- Clear feature in the $e^+/(e^+ + e^-)$ ratio for E>10 GeV, detected by Pamela (2009) and later confirmed by Fermi-LAT (2012) and AMS-02 (2014)
- Signs of flattening/cutoff above 300 GeV measured by AMS-02
- Possible explanations:
  - Dark matter annihilation or decay, implying m_{DM}>O(TeV) and $\langle\sigma v\rangle \simeq 10^{-23}$ $cm^3 s^{-1}$ cross section
    - Huge cross section, why other channels or gammas from bremsstrahlung not detected?
  - Nearby astrophysical source(s), e.g. pulsar-wind-nebulae
- Measuring anisotropy as a function of the E would provide extra clues

Carquin et al. Phys. Dark Univ. 11 (2016) 1



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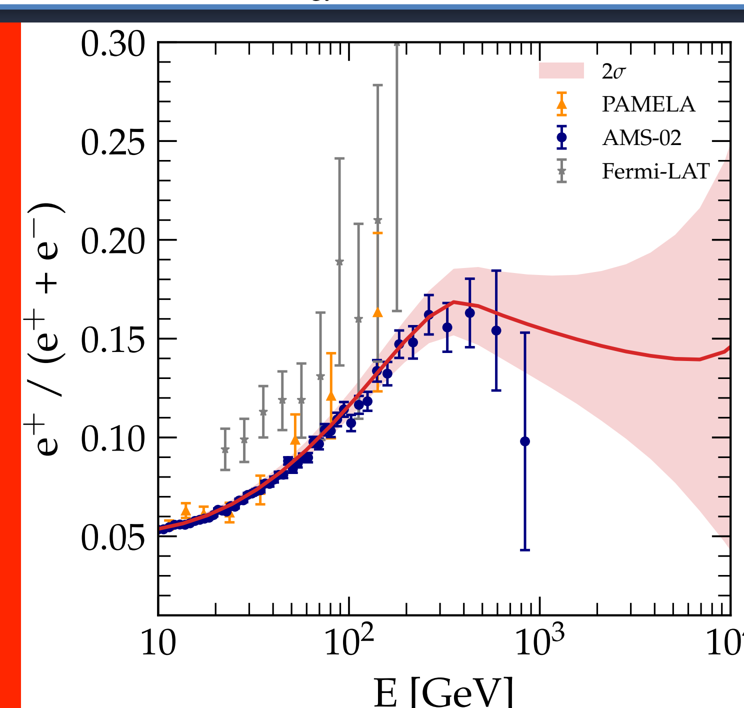
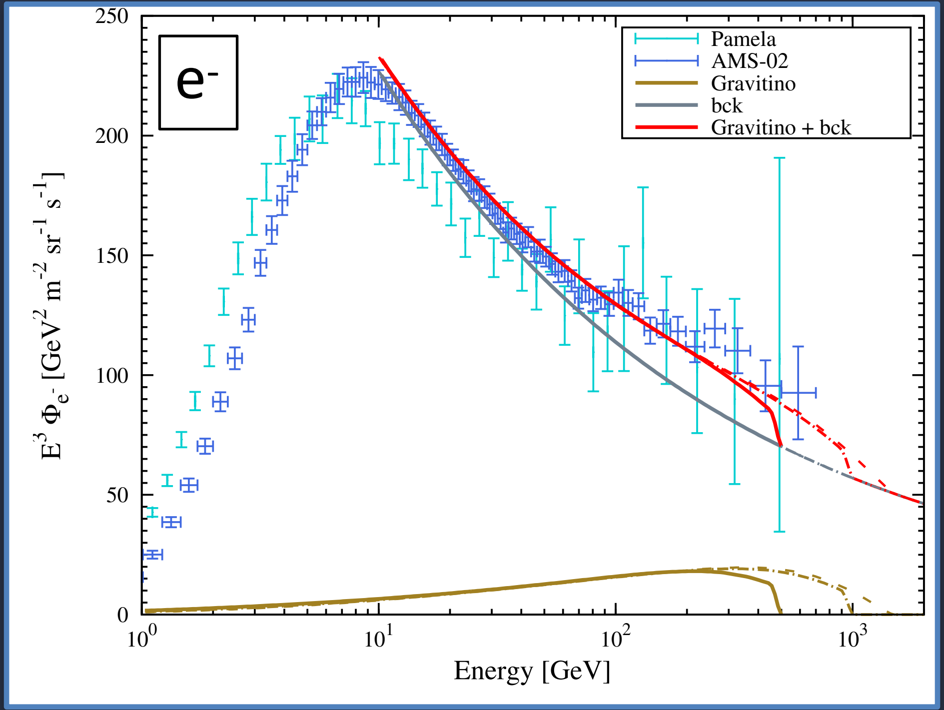


Evoli et al Phys. Rev. D103 (2021) 083010

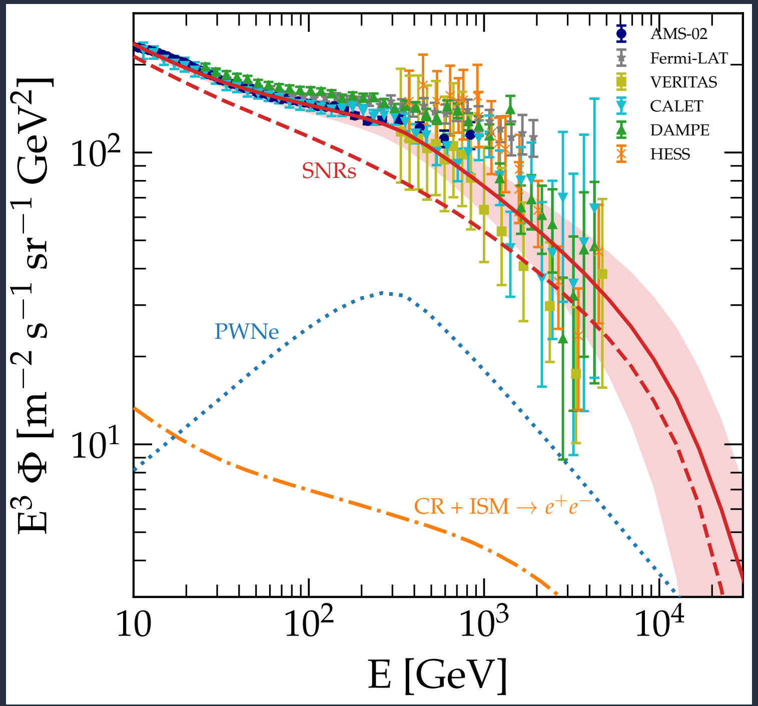
Electron flux

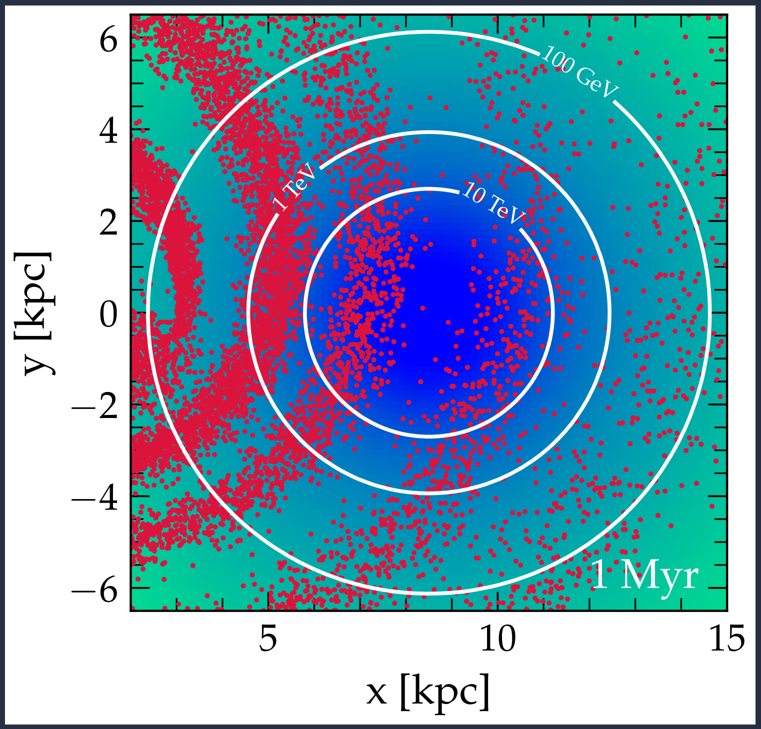
- Overall flux dominated by primaries (SNRs, PWNe) and secondaries CR interactions
- Spectral features:
  - Hardening at ~40 GeV → transition from Thomson to KN regimes in IC of electrons with UV background light
  - Cutoff at ~1 TeV due to spiral-arm distribution of sources (SNR) and energy-dependent horizon due to radiative losses

Carquin et al. Phys. Dark Univ. 11 (2016) 1

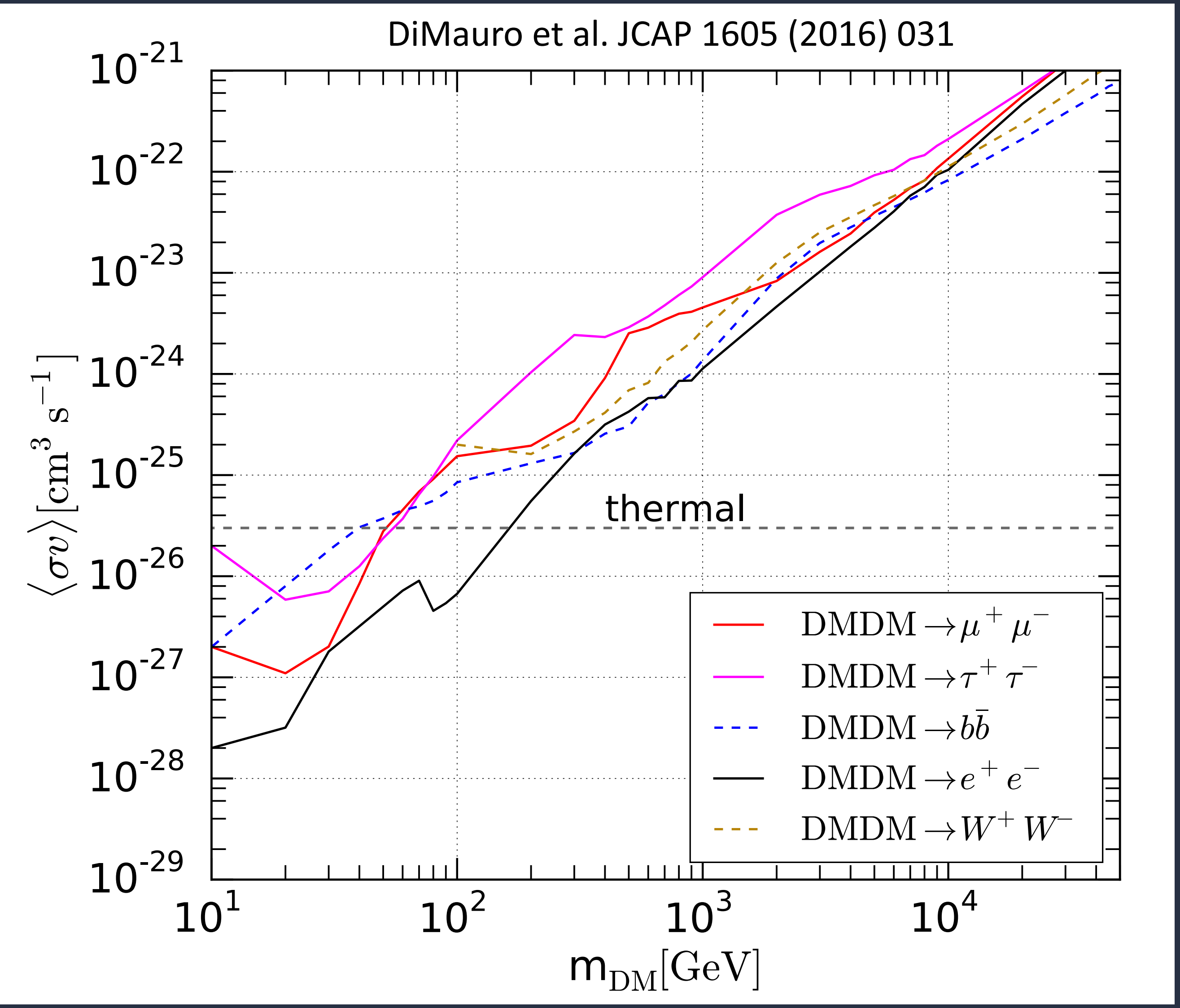


Evoli et al Phys. Rev. D103 (2021) 083010





Bounds on DM from positron fraction

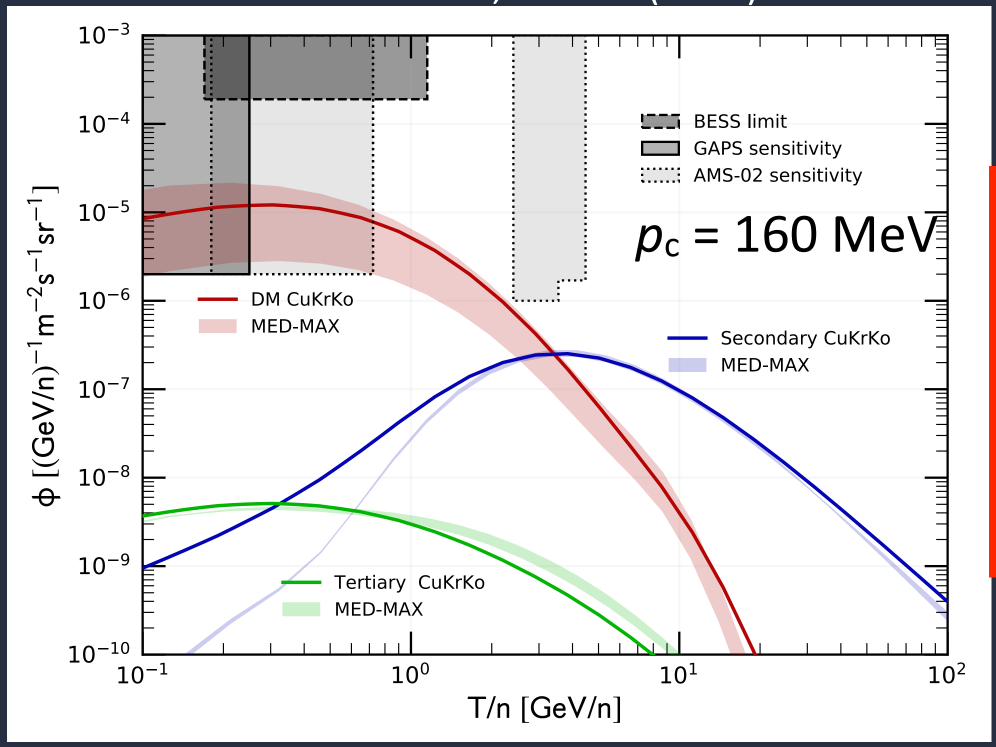


- ★ Even if features assumed to be produced by DM, limits can be set
- ★ Both prompt and secondary e^+ are possible
- ★ In general, the thermal cross section is excluded for DM particle with $m_{DM} \lesssim$ 100 GeV

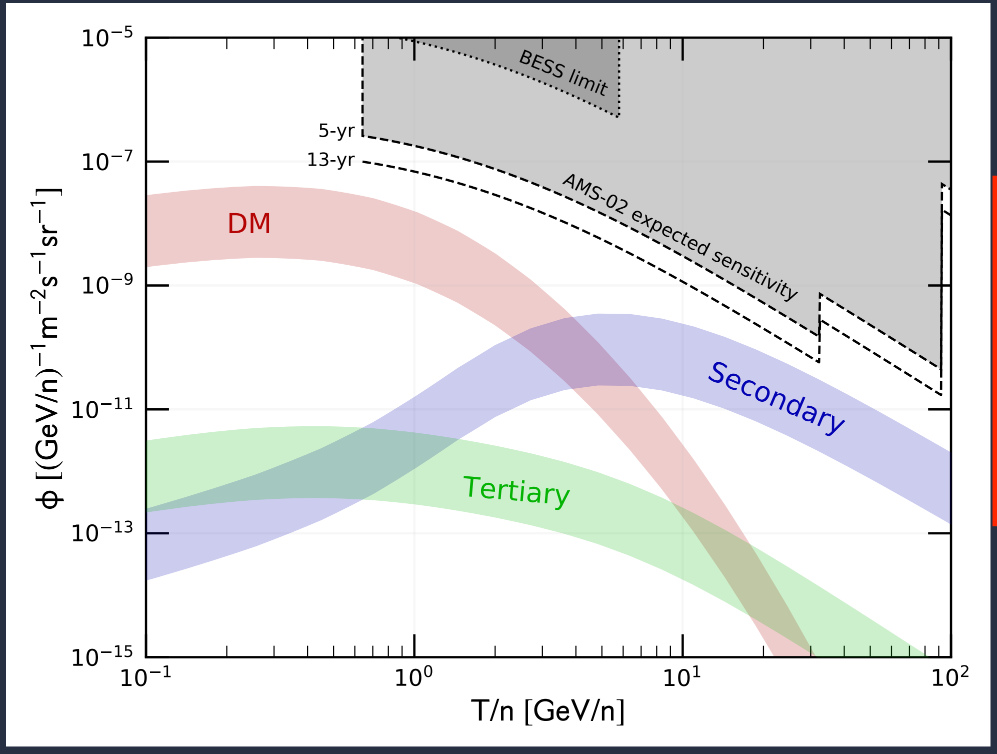
Anti-deuteron and anti-helium

- ★ Anti-nuclei can be produced in DM annihilation/decay or CR interactions
- ★ Coalescence of anti-nucleons with small relative momenta ($p<p_c$, O(100MeV))
  - Very small expected fluxes
  - DM and CR produce very different spectra (DM peaks at fraction of GeV) → One event would be smoking gun!
- ★ Present limits by BESS ~2 orders of magnitude above most optimistic DM predictions
- ★ AMS-02 and GAPS have potential for discovery

Korsmeier et al, PRD 97 (2018) 103011



Anti-Deuteron



Anti-Helium

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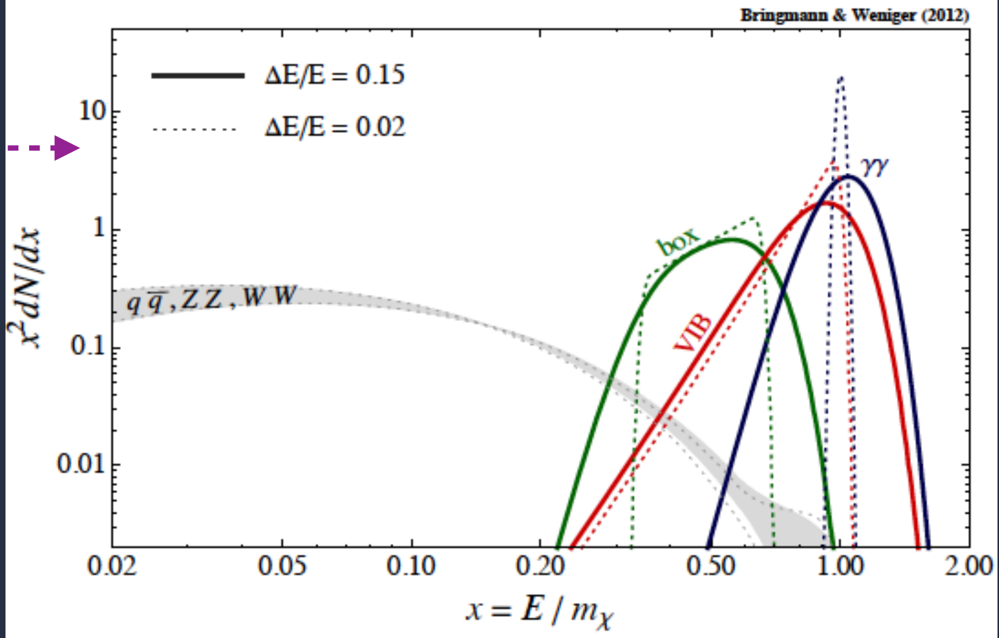
Searches in gamma rays

- Gammas do not interact from nearby production sites to Earth:
  - Keep direction information: allow measure DM distribution
  - No need to use complicate transport equations
- Expected fluxes:

Pythia

$$\frac{d^2\Phi}{dEd\Omega}(E,\hat{\boldsymbol{p}}) = \frac{1}{4\pi}\frac{dN_\gamma}{dE}(E)\int_{\mathrm{los}(\hat{\boldsymbol{p}})} dl\, n_\chi(\hat{\boldsymbol{p}},l)\,\Gamma_\chi$$



Annihilation:

$$\Gamma_\chi = \frac{1}{k} n_\chi \langle\sigma v\rangle$$

Decay:

$$\Gamma_\chi = \frac{1}{\tau_\chi}$$

$$\frac{d^2\Phi_{\mathrm{ann}}}{d\Omega\, dE}(E,\hat{\boldsymbol{p}}) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{k\, m_\chi^2}\frac{dJ_{\mathrm{ann}}}{d\Omega}(\hat{\boldsymbol{p}})\frac{dN_\gamma}{dE}(E)$$

$$\frac{dJ_{\mathrm{ann}}}{d\Omega}(\hat{\boldsymbol{p}}) = \int_{\mathrm{los}(\hat{\boldsymbol{p}})} dl \rho^2(\hat{\boldsymbol{p}},l)$$ ∝ mass & concentration

$$\frac{d^2\Phi_{\mathrm{dec}}}{d\Omega\, dE}(E,\hat{\boldsymbol{p}}) = \frac{1}{4\pi}\frac{1}{\tau_\chi m_\chi}\frac{dJ_{\mathrm{dec}}}{d\Omega}(\hat{\boldsymbol{p}})\frac{dN_\gamma}{dE}(E)$$

$$\frac{dJ_{\mathrm{dec}}}{d\Omega}(\hat{\boldsymbol{p}}) = \int_{\mathrm{los}(\hat{\boldsymbol{p}})} dl \rho(\hat{\boldsymbol{p}},l)$$ ∝ mass

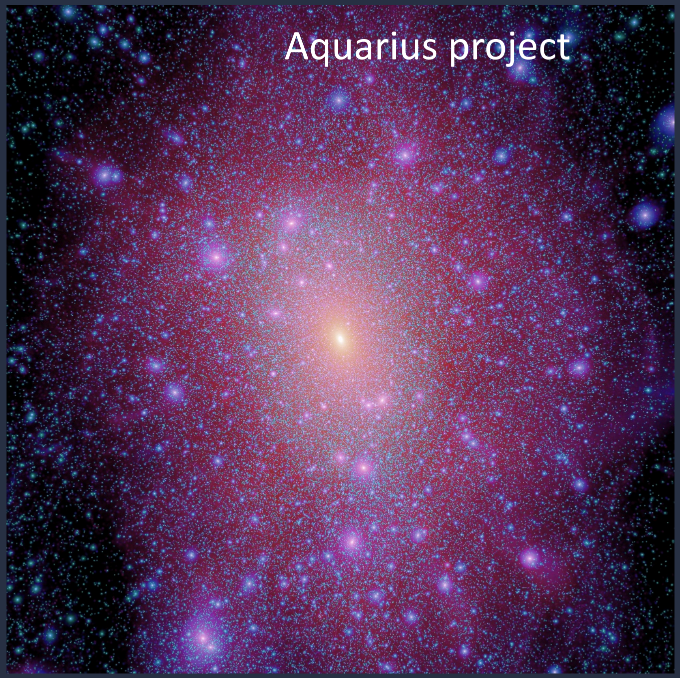
Density profiles

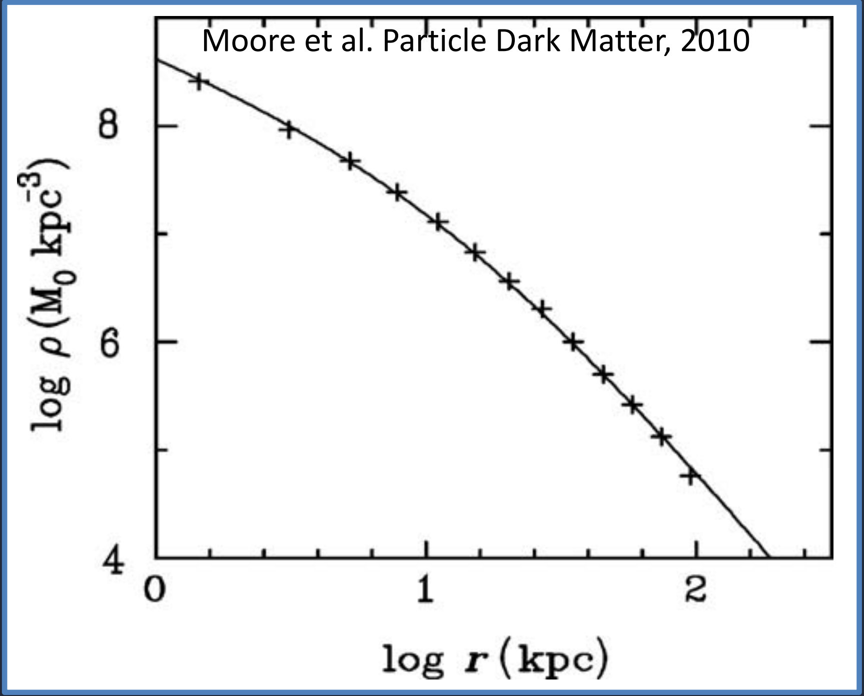
- DM distributes in quasi-spherical halos of gravitationally bound matter
- From N-body simulations we know:
  - Hierarchical: DM halos contain sub-halos
  - Density profile for all halo size described by:

$$\rho(r) = \frac{\rho_\mathrm{s}}{(r/r_\mathrm{s})^\gamma (1 + r/r_\mathrm{s})^{3-\gamma}}$$

(Navarro-Frenck-White profile)

  - Free parameters determined by fitting to measured kinematics of visible mass probes (stars and galaxies) - Jeans equation
- This does not include baryon-DM interplay, relevant at the centre of halos, normally baryon dominated
  - Disagreements at the smaller scales





Estimating measured DM fluxes

- Gamma-ray instruments measure number of counts coming from promising DM targets, as a function of measured energy and direction, and compare with background expectations, with a likelihood function:

$$\mathcal{L}_\gamma\ (\alpha\bar{J};\boldsymbol{\mu}|\boldsymbol{\mathcal{D}}_\gamma) = \prod_{i=1}^{N_{E'}}\prod_{j=1}^{N_{\hat{p}'}} P\left(s_{ij}(\alpha\bar{J};\boldsymbol{\mu}) + b_{ij}(\boldsymbol{\mu})|N_{ij}\right) \cdot \mathcal{L}_\mu(\boldsymbol{\mu}|\boldsymbol{\mathcal{D}}_\mu)$$

α = $\langle\sigma v\rangle$ or τ^{-1} | s_{ij} = expected # of gamma events | $\bar{J} = J(\Delta\Omega_{\text{tot}})$

$\boldsymbol{D}_\gamma$ = data | b_{ij} = expected # of background events | $J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \frac{dJ}{d\Omega}$

$\boldsymbol{\mu}$ = nuisance parameters | N_{ij} = observed counts

- The number of expected measured gamma-ray counts is:

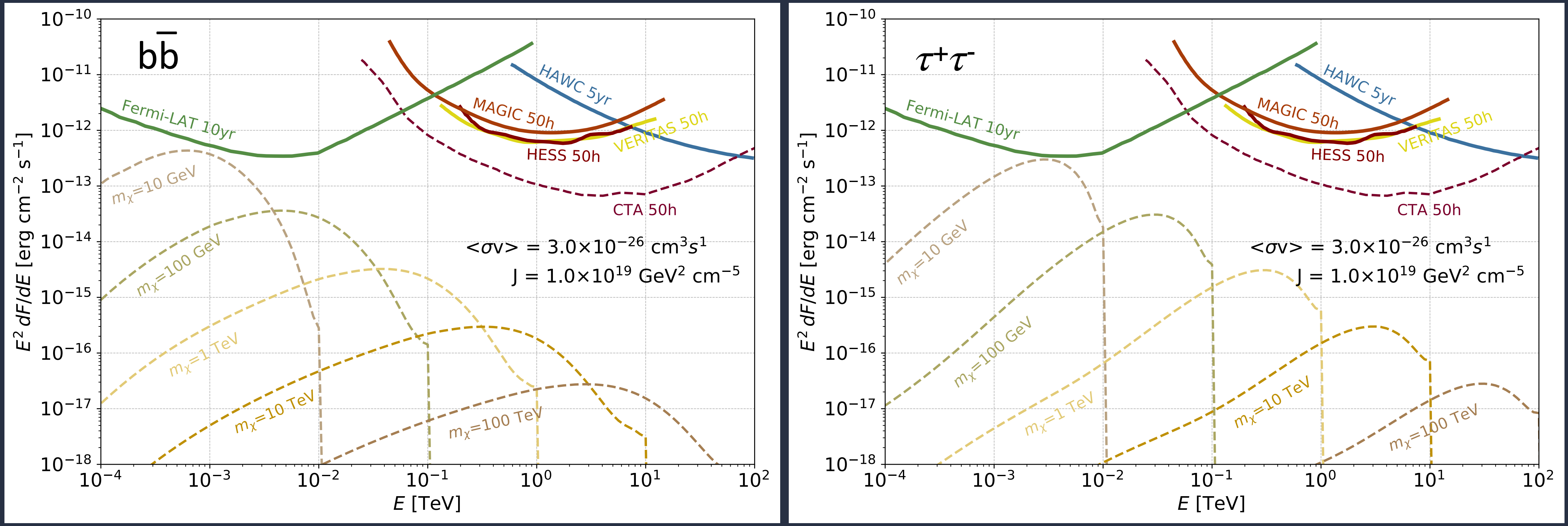
$$s_{ij}(\alpha\bar{J}) = \int_{\Delta E'_i} dE' \int_{\Delta\hat{p}'_j} d\Omega' \int_0^\infty dE \int_{\Delta\Omega_{\text{tot}}} d\Omega \int_0^{T_{\text{obs}}} dt\, \frac{d^2\Phi(\alpha\bar{J})}{dE\, d\Omega}\, \text{IRF}(E',\hat{\boldsymbol{p}}'|E,\hat{\boldsymbol{p}},t)$$

with IRF the Instrument Response Function, which can be factored in effective area times PDFs for energy and direction estimators

$$\text{IRF}(E',\hat{\boldsymbol{p}}'|E,\hat{\boldsymbol{p}},t) = A_{\text{eff}}(E,\hat{\boldsymbol{p}},t)\cdot f_E(E'|E,t)\cdot f_{\hat{p}}(\hat{\boldsymbol{p}}'|E,\hat{\boldsymbol{p}},t)$$

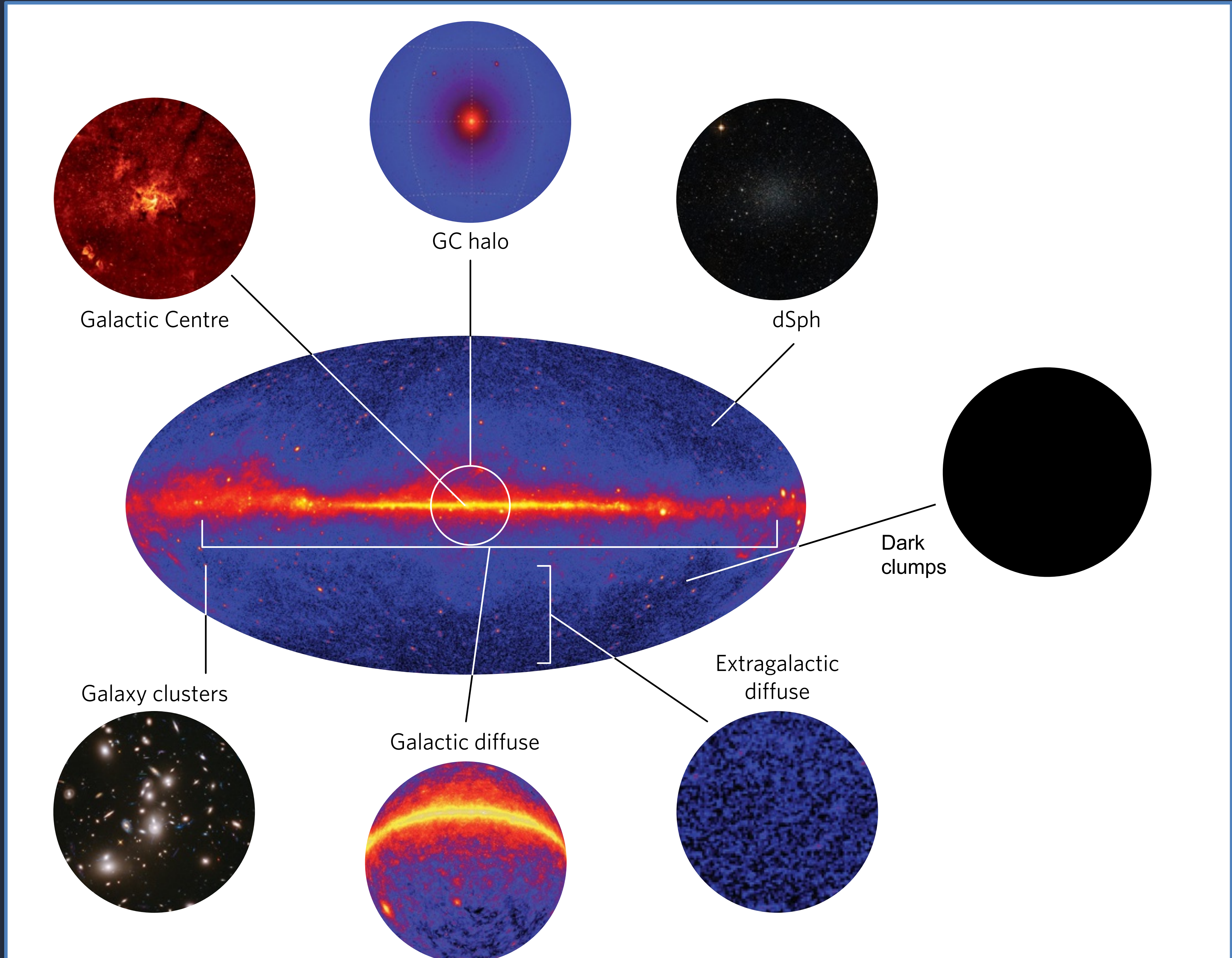
Fluxes vs sensitivity

Rico, Galaxies 8 (2020) 25



- ★ Fermi-LAT dominates searches up to m_{DM} ~1 TeV (100 GeV) for $b\bar{b}$ ($\tau^+\tau^-$) channel
- ★ Fermi-LAT is sensitive to the thermal relic density for m_{DM} ~10 GeV and the typical DM-dominated dSph (see later)
- ★ For higher masses sensitivity of Cherenkov telescopes and HAWC still not enough

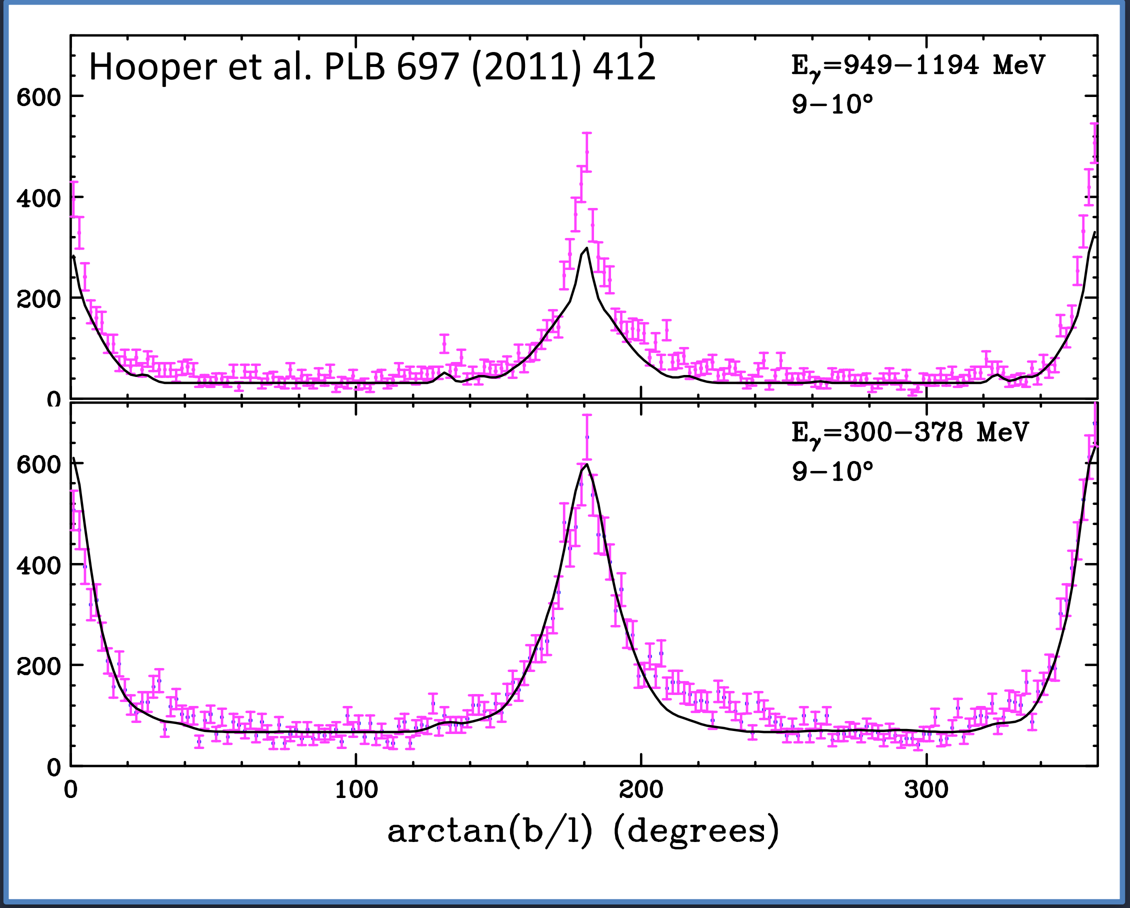
Posible DM gamma-ray sources

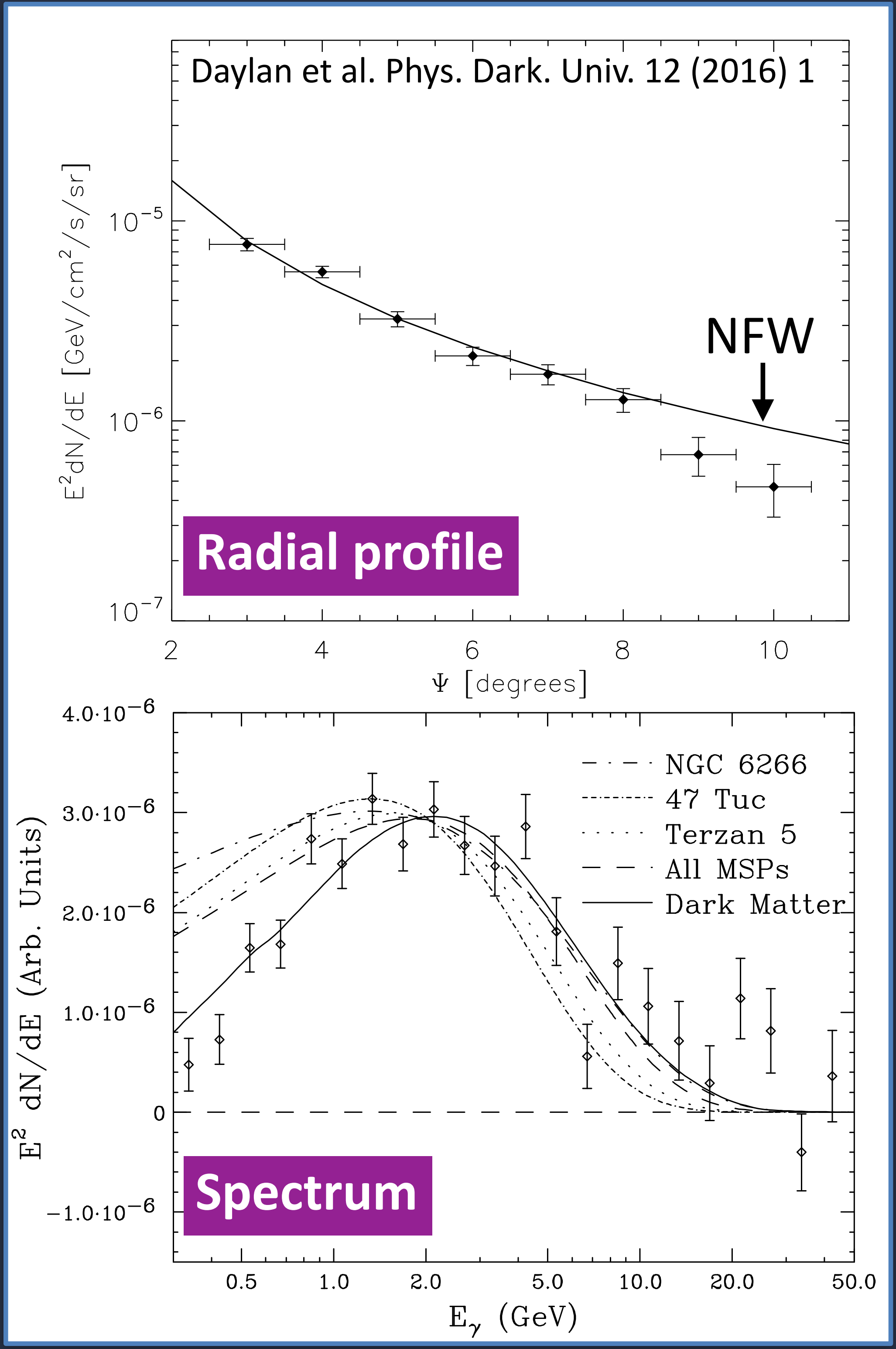


Conrad & Reimer, Nature Phys. 13 (2017) 224

GeV Galactic Center excess

- In Fermi-LAT: once contributions from known point-like sources and diffuse secondary emission are removed, residuals between 0.3 and 30 GeV have some of the DM predicted properties

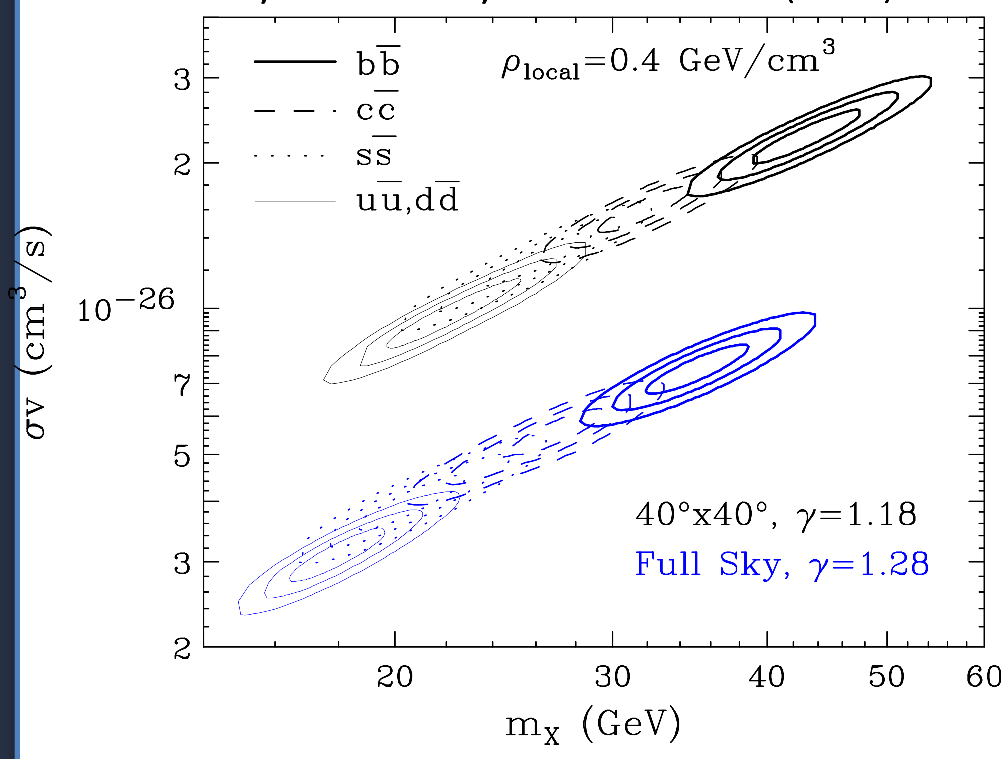


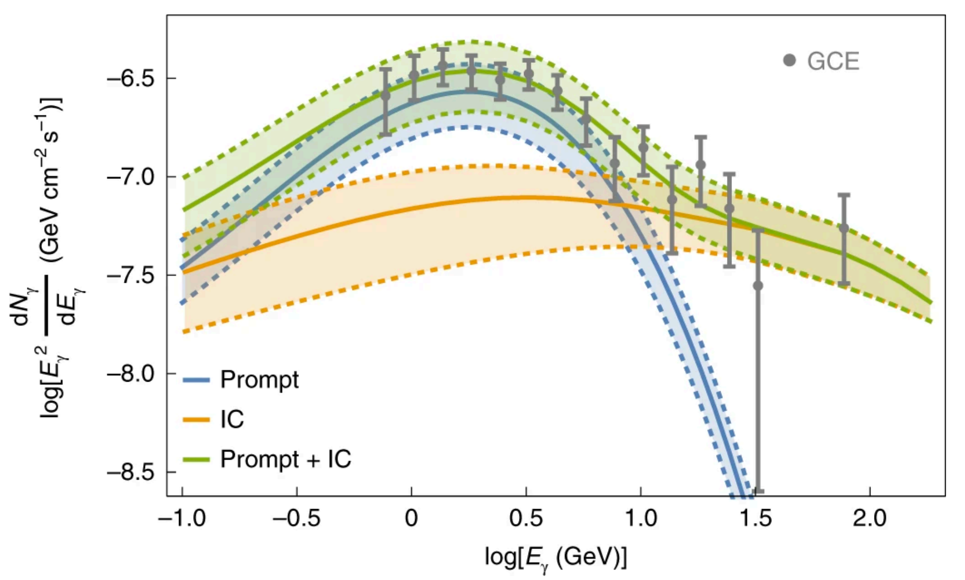


Explanations of GC excess

- Interpretation as annihilation of DM particles with m_{DM} ~ few 10 GeV with close to relic cross-section
- Favored astrophysical interpretation: unresolved population of millisecond pulsars:
  - Spectrum compatible with prompt emission by interacting e^-/e^+ pairs within magnetosphere + IC of escaping/reaccelerated pairs
  - Bulge-like spatial distribution preferred over spherical
  - Clustering analysis favors unresolved point-like sources over diffuse emission
- Still an open question

Daylan et al. Phys. Dark. Univ. 12 (2016) 1



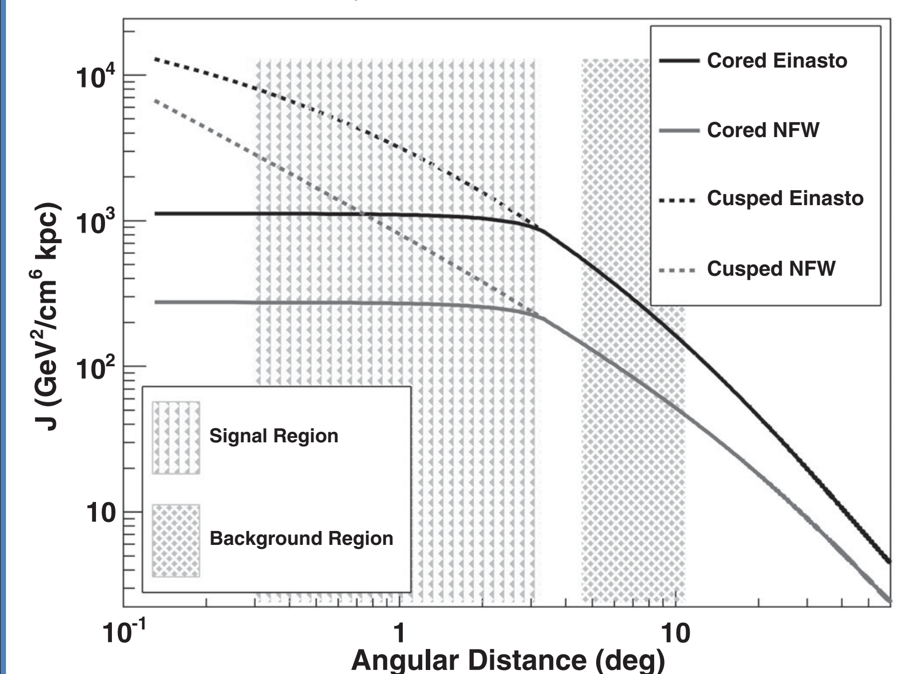


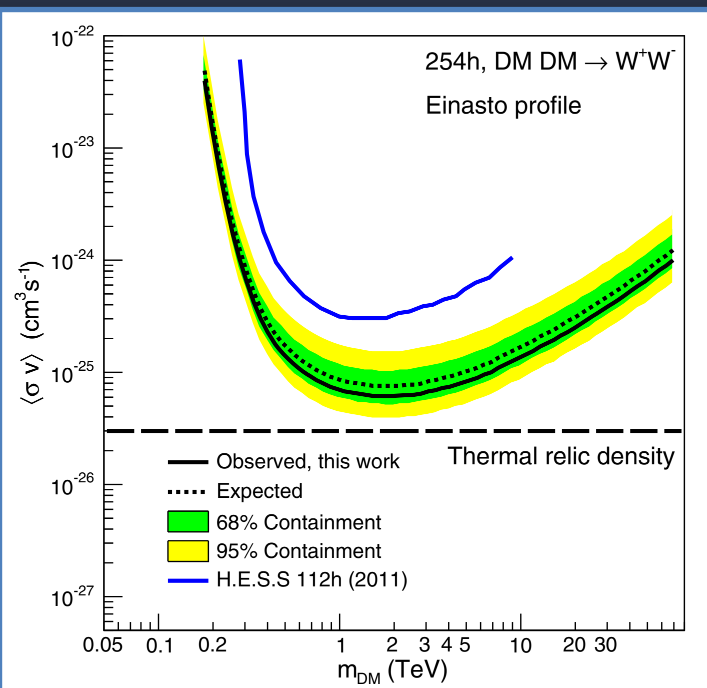
Gautam et al. Nat. Astron. 6 (2022) 703

Galactic Center at Very High Energy

- HESS (254h), MAGIC (223h)
- J-factor ~ 10^{21} GeV^2 cm^{-5}
- Most constraining limits of cross section: $\langle\sigma v\rangle < 6\times10^{-26}$ cm^{3}s^{-1} for m_{DM} ~1 TeV
- Caveat: assuming a cored density profile limit is ~100 times worse

Abramowski et al. Phys. Rev. Lett. 114 (2015) 081301





Abdallah et al. Phys. Rev. Lett. 117 (2016) 111301

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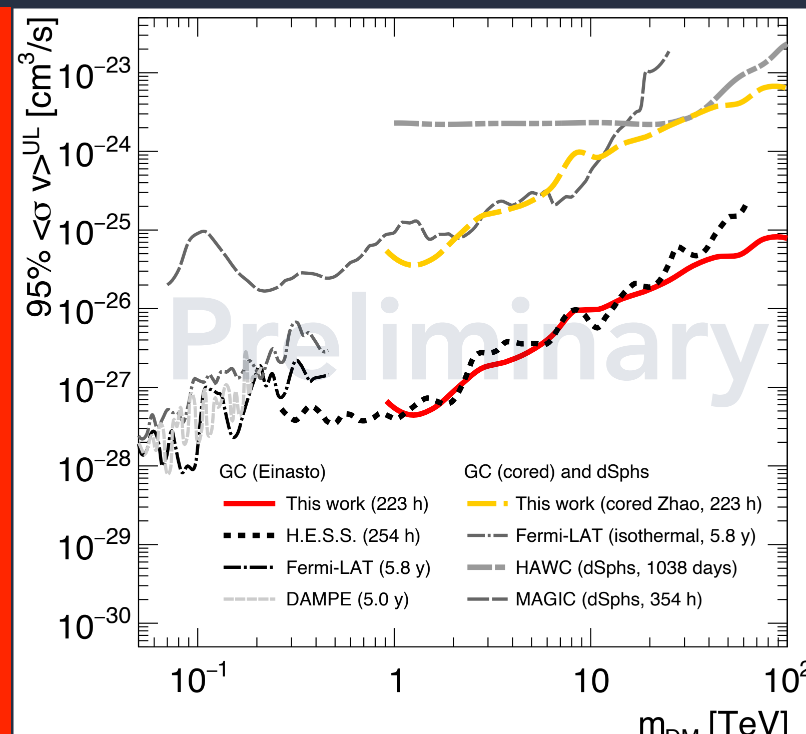
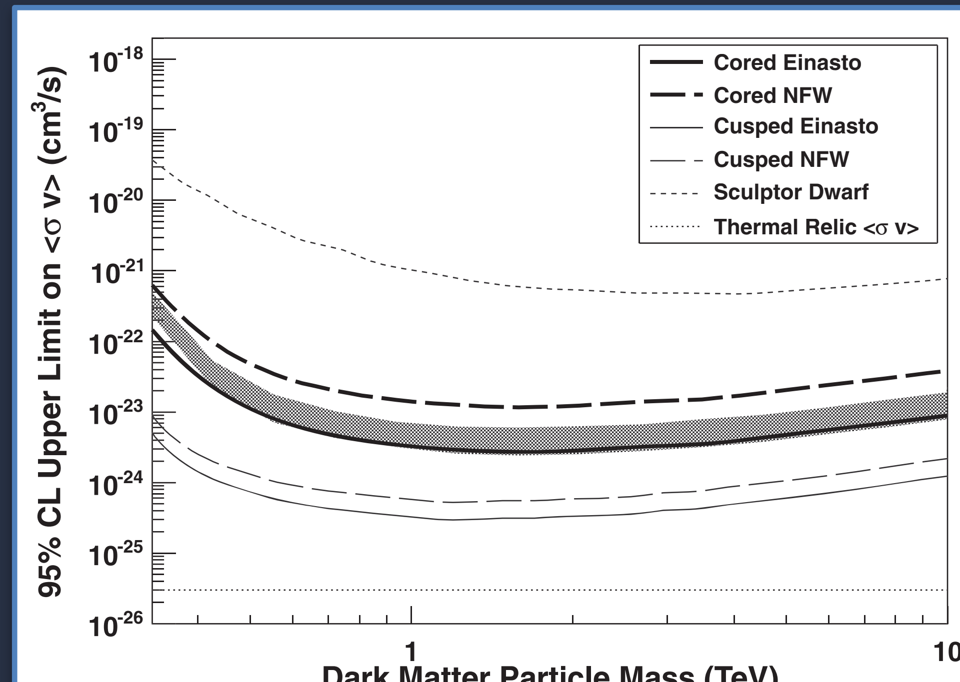


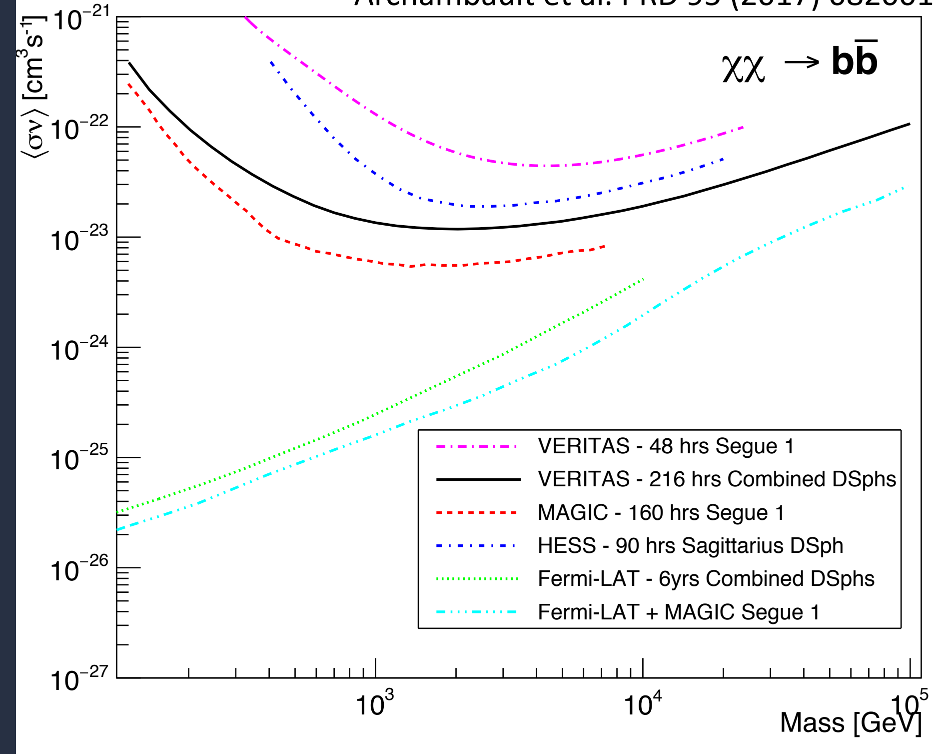


Abramowski et al. Phys. Rev. Lett. 114 (2015) 081301

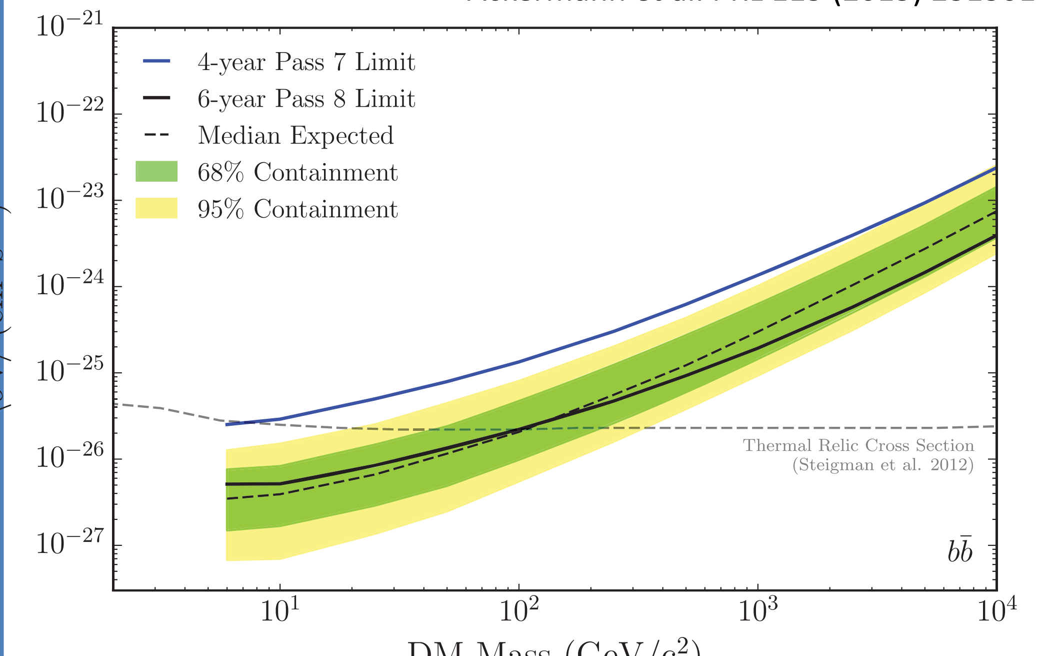
Observations of dSphs

- ★ Low luminosity galaxies orbiting the Milky Way
- ★ Kinematics dominated by DM: M/L ~ O(1000) $M_\odot/L_\odot$
- ★ Moderate J-factors ~ O(10^{18}-10^{19} GeV^2 cm^{-5}), with relatively low uncertainties
- ★ Fermi excludes the thermal relic cross section for DM particles of mass m_{DM} < 100 GeV
- ★ Cherenkov telescopes most constraining for m_{DM} ~ 1 TeV
- ★ HAWC most sensitive for m_{DM} ~ 100 TeV

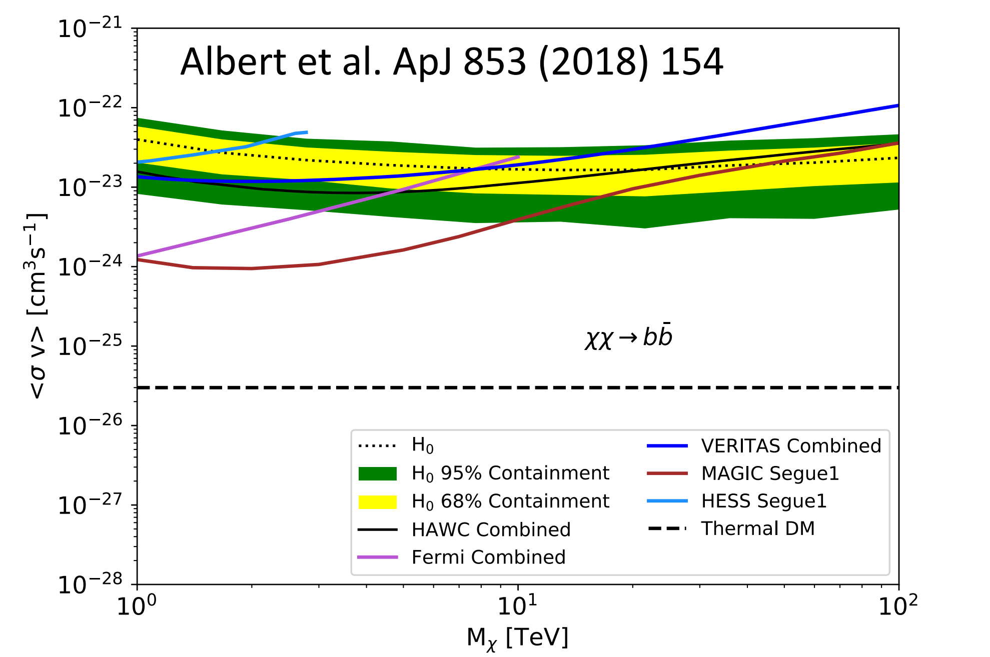
Archambault et al. PRD 95 (2017) 082001



Ackermann et al. PRL 115 (2015) 231301



Albert et al. ApJ 853 (2018) 154



Combining dSph results

- Stack the likelihoods (no the data!), of different dSphs:
  - with different uncertainties in J-factor

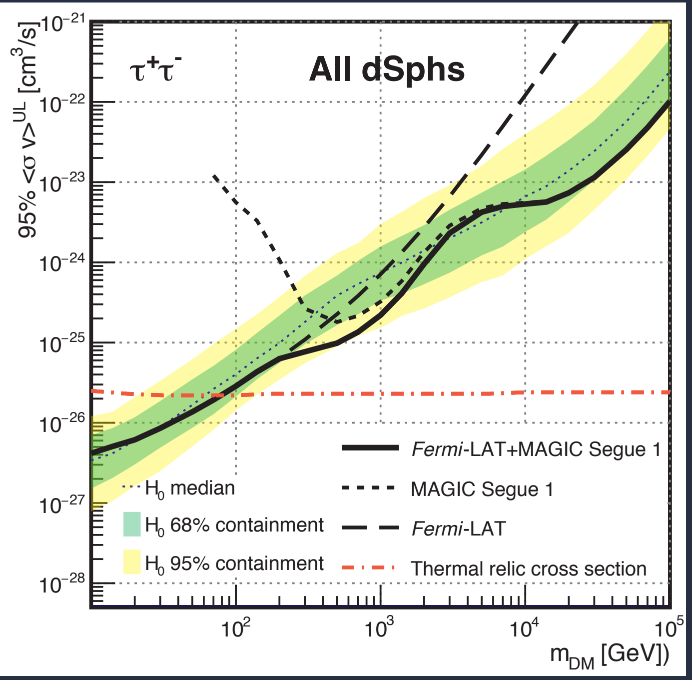
$$\mathcal{L}(\alpha;\boldsymbol{\nu}|\boldsymbol{\mathcal{D}}) = \prod_{l=1}^{N_{\mathrm{dSph}}} \mathcal{L}_\gamma(\alpha \bar{J}_l;\boldsymbol{\mu}_l|\boldsymbol{\mathcal{D}}_{\gamma_l}) \cdot \mathcal{L}_J(\bar{J}_l|\boldsymbol{\mathcal{D}}_{J_l})$$

$$\mathcal{L}_J(\bar{J}\,|\,\bar{J}_{\mathrm{obs}},\sigma_J) = \frac{1}{\ln(10)\bar{J}_{\mathrm{obs}}\sqrt{2\pi}\sigma_J}\, e^{-\left(\log_{10}(\bar{J})-\log_{10}(\bar{J}_{\mathrm{obs}})\right)^2/2\sigma_J^2}$$

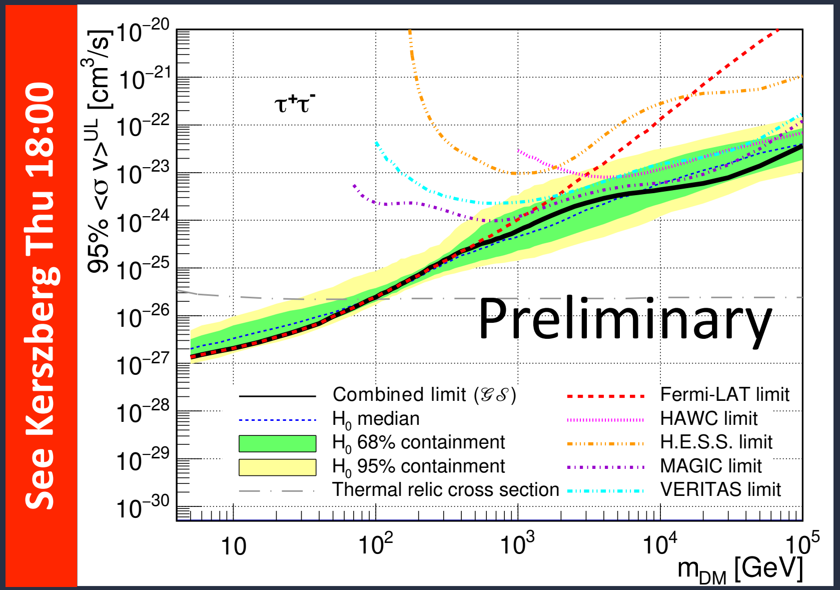
  - observed by different instruments

$$\mathcal{L}_\gamma(\alpha\bar{J};\boldsymbol{\mu}|\boldsymbol{\mathcal{D}}_\gamma) = \prod_{k=1}^{N_{\mathrm{meas}}} \mathcal{L}_{\gamma,k}(\alpha\bar{J};\boldsymbol{\mu}_k|\boldsymbol{\mathcal{D}}_{\gamma,k})$$

Fermi-LAT+MAGIC: Ahnen et al. JCAP 1602 (2016) 39



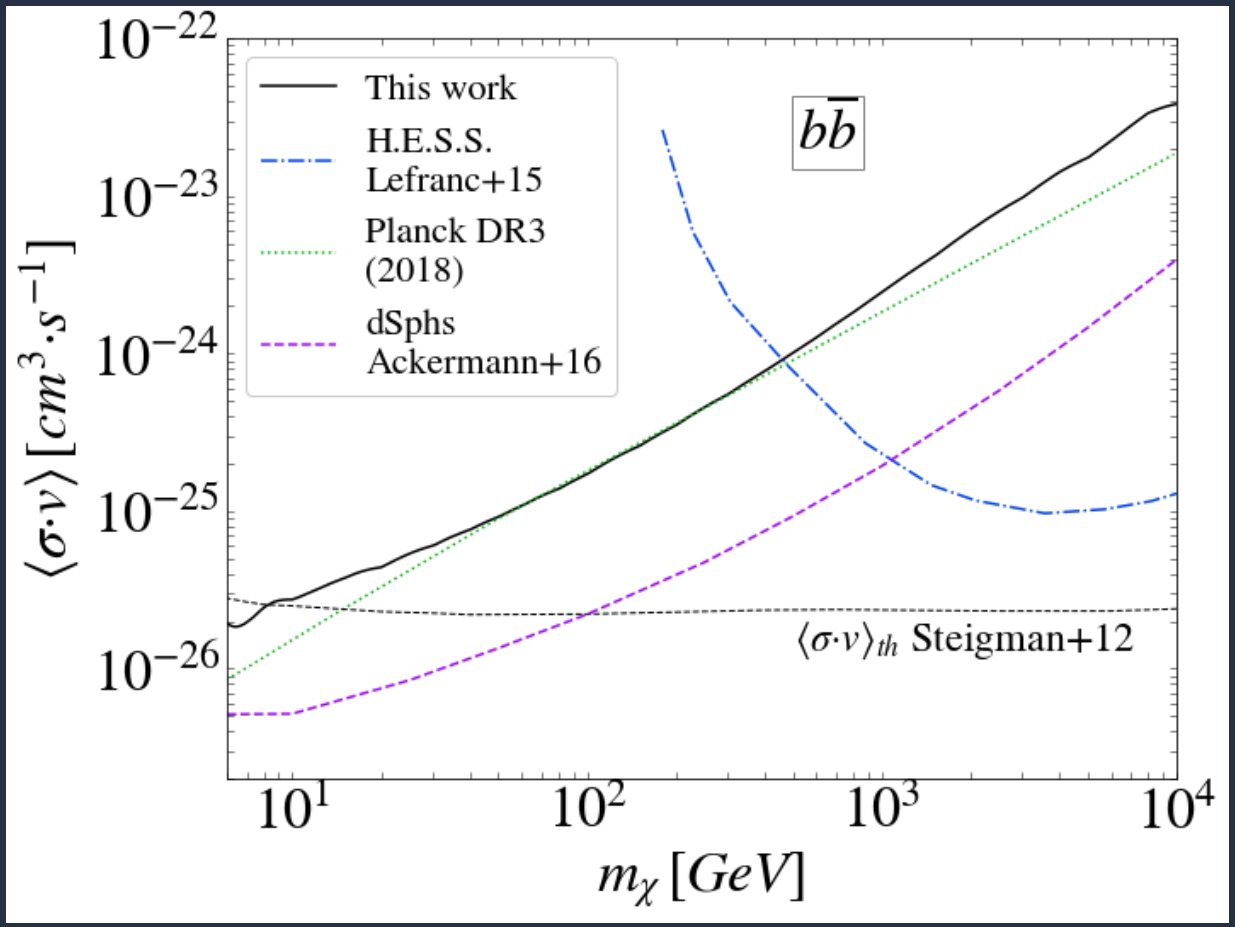
Fermi-LAT+HAWC+HESS+MAGIC+VERITAS in prep.



Dark matter clumps

- DM galactic satellites (sub-halos) that have not triggered any stellar activity (they shine only in DM-related signals)
- Can only be found serendipitously or in unbiased surveys (Fermi-LAT, HAWC)
- DM clump selection criteria generally based on:
  - No association with astrophysical source/ no emission in other wavelengths
  - Steady sources
  - Spectrum compatible with DM emission
- Selection:
  - 1235 unidentified sources in Fermi-LAT catalogue
  - 44 survive criteria but no preference of DM spectrum over other astrophysical explanations

Coronado-Blázquez et al. JCAP 07 (2019) 020

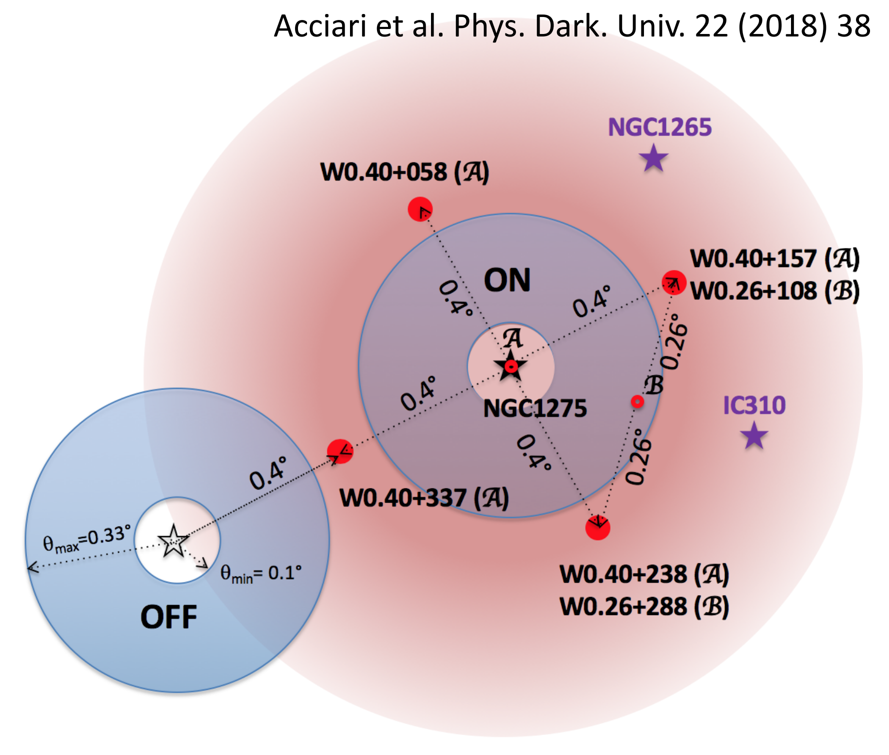


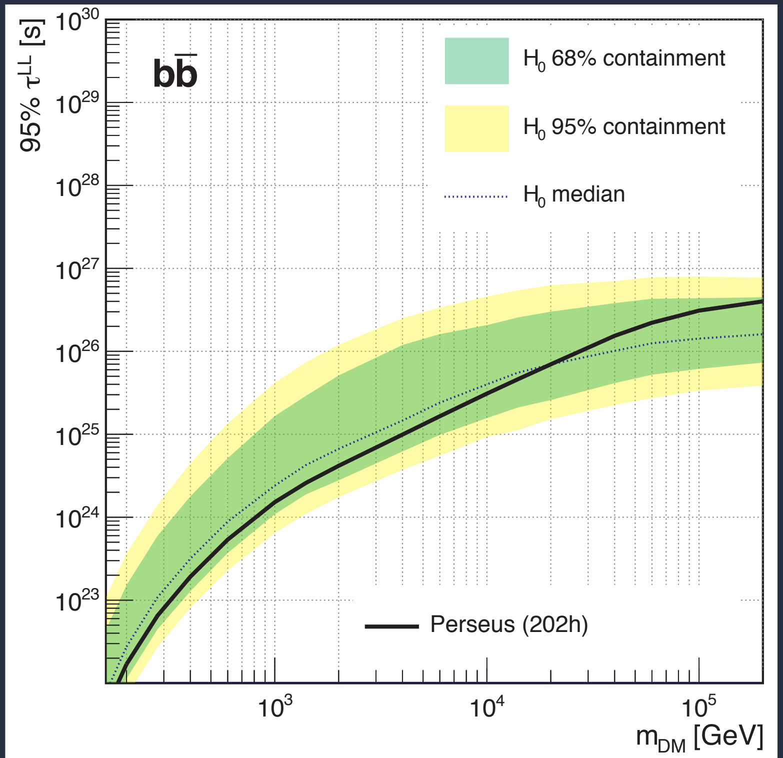
- Limits obtained assuming survivors are actually DM clumps and comparing with clumps from N-body simulations

Galaxy clusters

- ★ Group of gravitationally bound galaxies
- ★ Largest and youngest (i.e. closest) structures in the Universe
- ★ Huge amounts of dark matter ($M \sim 10^{15}\ M_\odot$), but not highly concentrated (except for sub-halos)
  - ✦ good candidates to look for DM decay
  - ✦ (only hard constraint: DM lifetime should be larger than Hubble time: 10^{17}s)
- ★ Complex fields of view with possible foregrounds
- ★ Limits from Perseus cluster (MAGIC, 220h): $\tau_{DM} > 10^{26} - 10^{27}$ s
- ★ Other investigated clusters: Fornax (HESS), Coma (VERITAS+Fermi-LAT), Virgo (Fermi-LAT)

Acciari et al. Phys. Dark. Univ. 22 (2018) 38

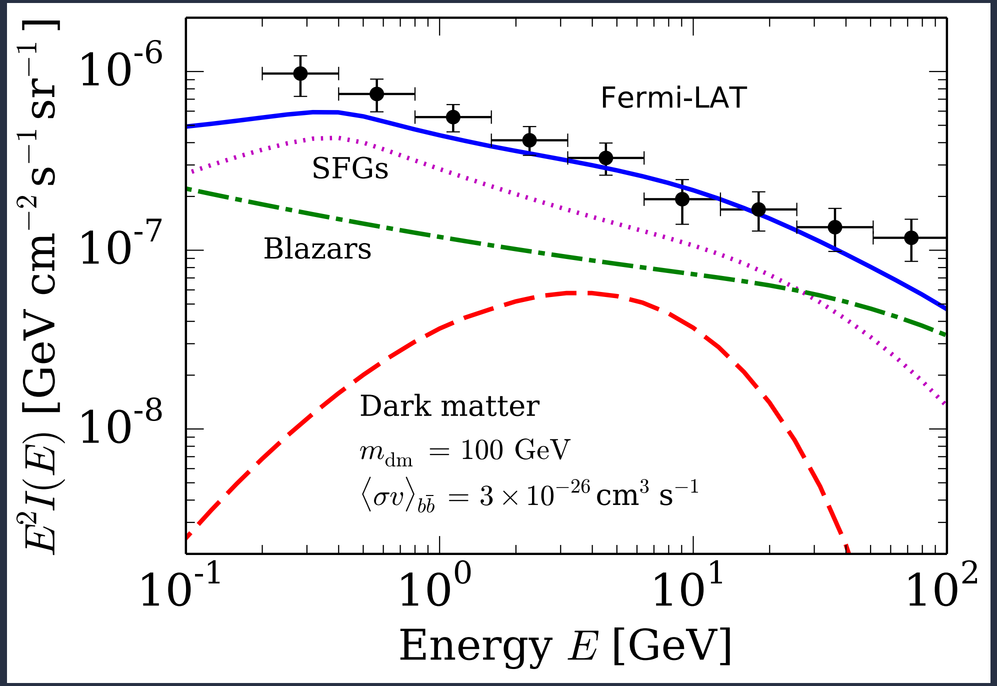


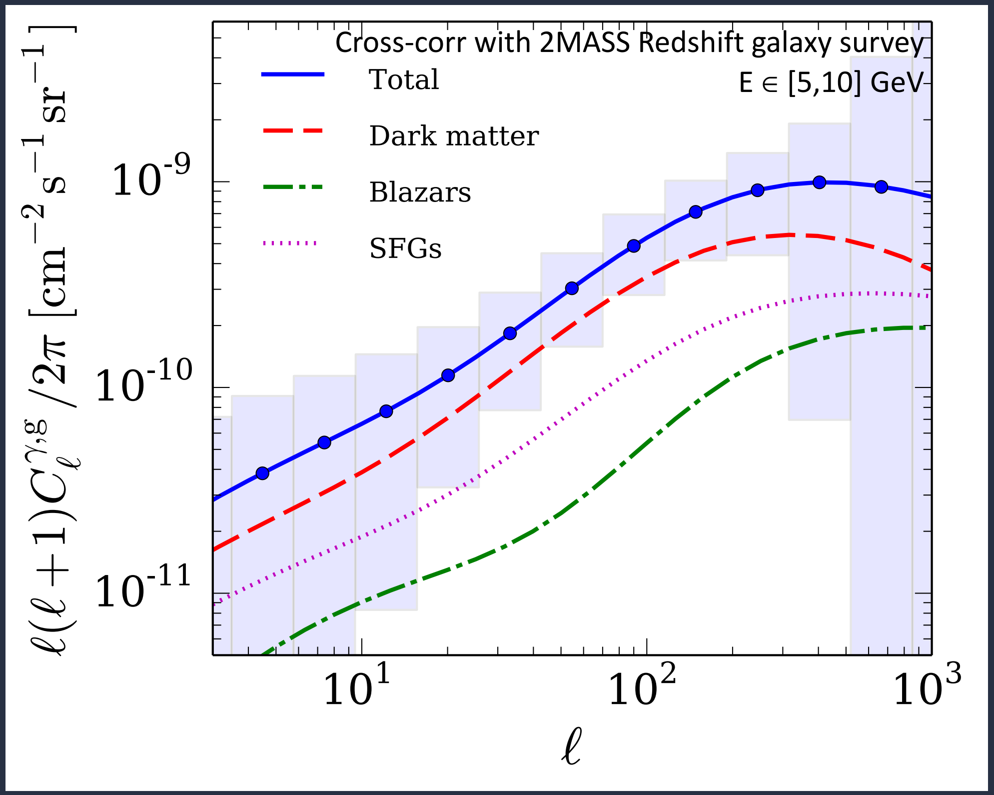


Isotropic gamma-ray background

- All-sky diffuse gamma-ray emission measured by EGRET, Fermi-LAT
- Sources:
  - Unresolved members of extragalactic/high-latitude galactic sources:
    - AGNs
    - Star-forming galaxies
    - Millisecond pulsars
  - Dark matter?
- DM signal searched for in the auto-correlation power spectrum or cross-correlation with catalogues of astronomical objects
  - DM leaves imprints at different angular scales than other sources
  - Degeneracies broken by investigating in different energy windows and different catalogues

Ando et al. PRD 90 (2014) 023514



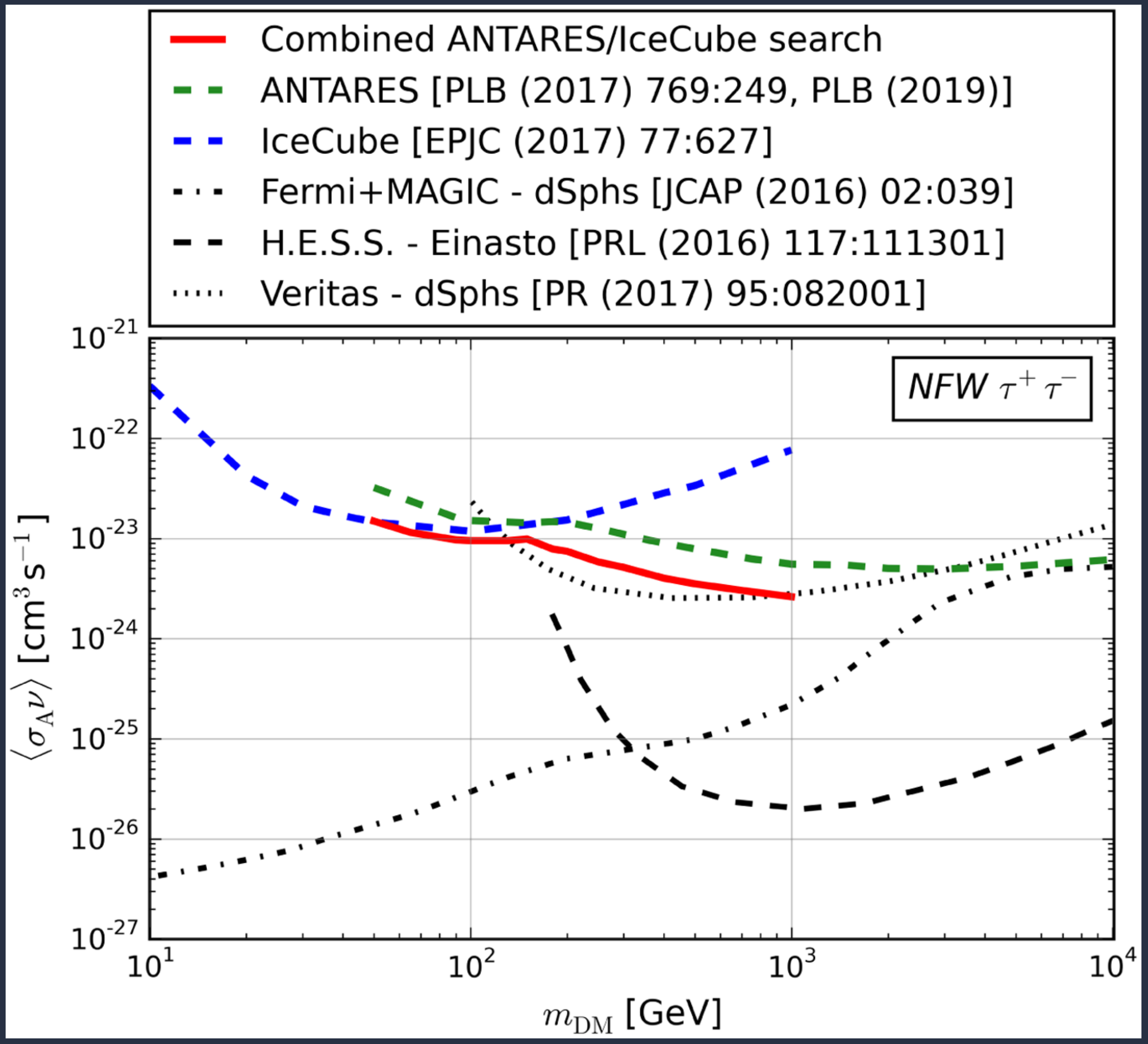


Program

- Intro: what is dark matter and how we look for it
- Indirect WIMP searches
  - [Charged] cosmic rays
  - Gamma rays
  - Neutrinos
- Axion-like particles

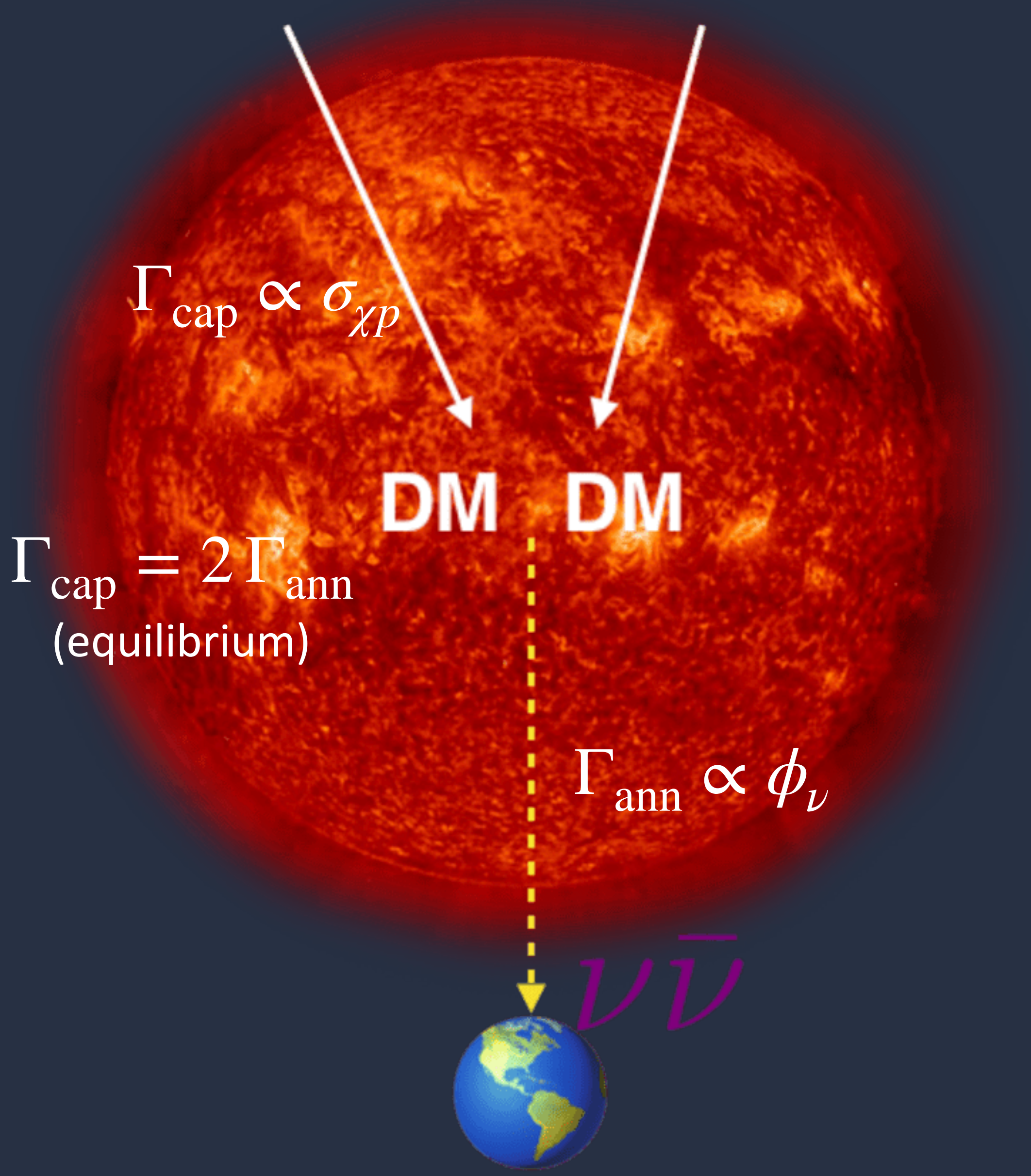
Neutrinos: observations of the Galactic Center

- WIMP searches with neutrino telescopes similar as for gamma-rays
  - Slight modification of flux formula to accommodate oscillations
  - Detection of neutrinos is more difficult and therefore sensitivity in principle degrades
- Joined analysis also possible as for gammas:
  - ANTARES (~2000 days)
  - IceCube (~1000 days)

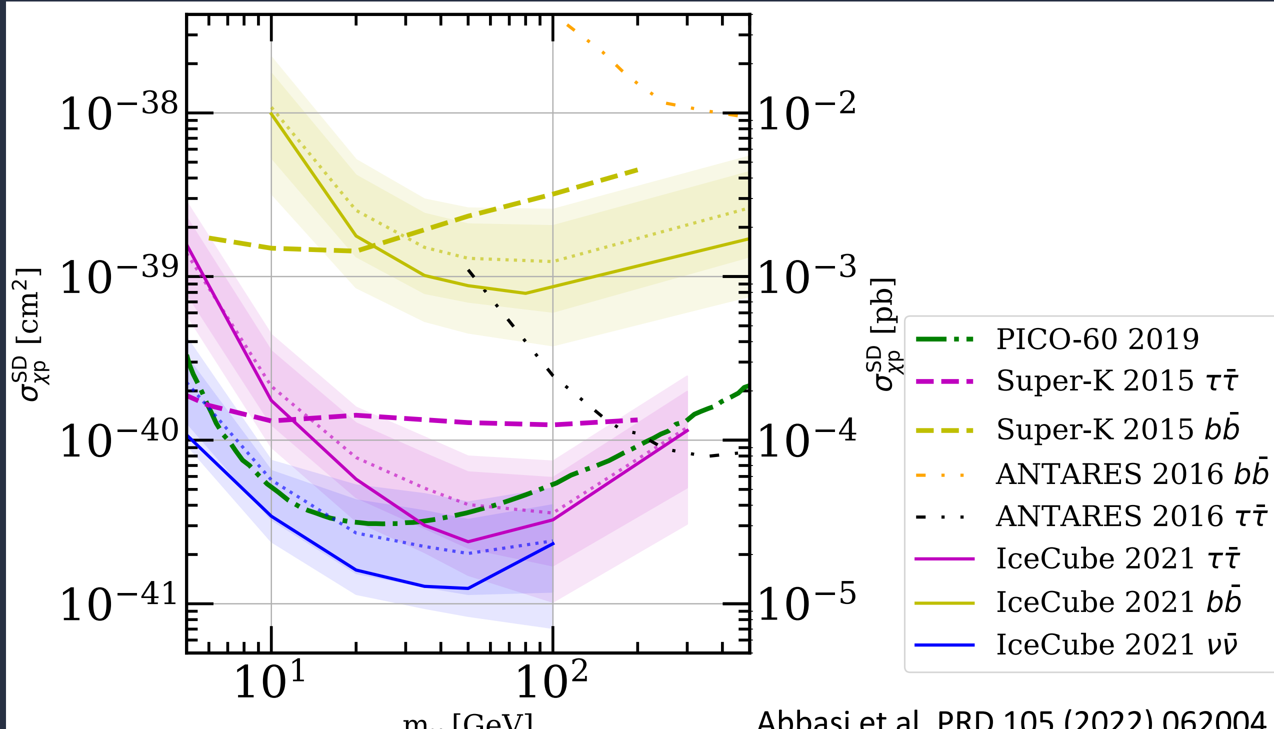


Albert et al. PRD 102 (2020) 082002

Searches for DM annihilation in the Sun



- WIMPs get trapped in the Sun's gravitational potential and annihilate
  - Resulting primary or secondary neutrinos escape
- IceCube 7 years
  - Most sensitive search for spin-dependent cross section for m~ O(10GeV)



Abbasi et al. PRD 105 (2022) 062004

Program

- Intro: what is dark matter and how we look for it
- Indirect WIMP searches
  - [Charged] cosmic rays
  - Gamma rays
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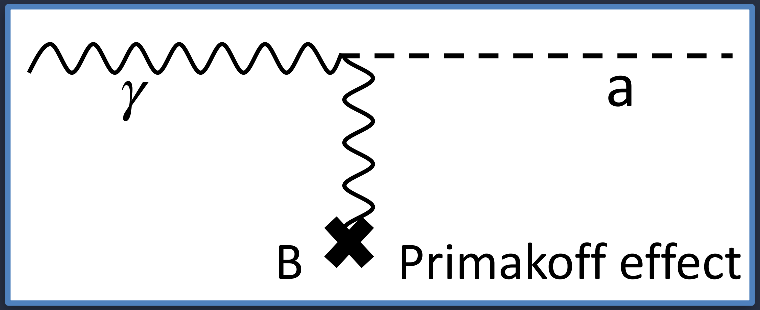
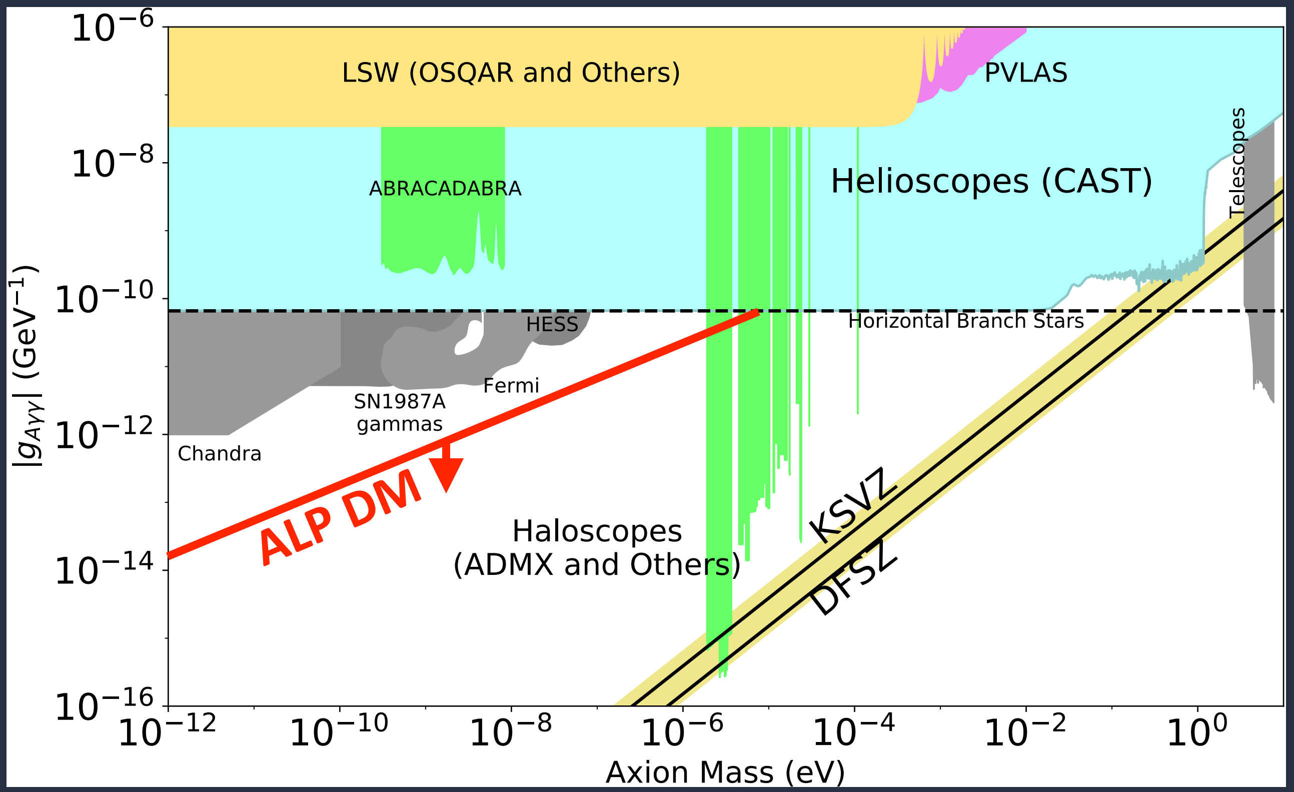
- Axion-like particles

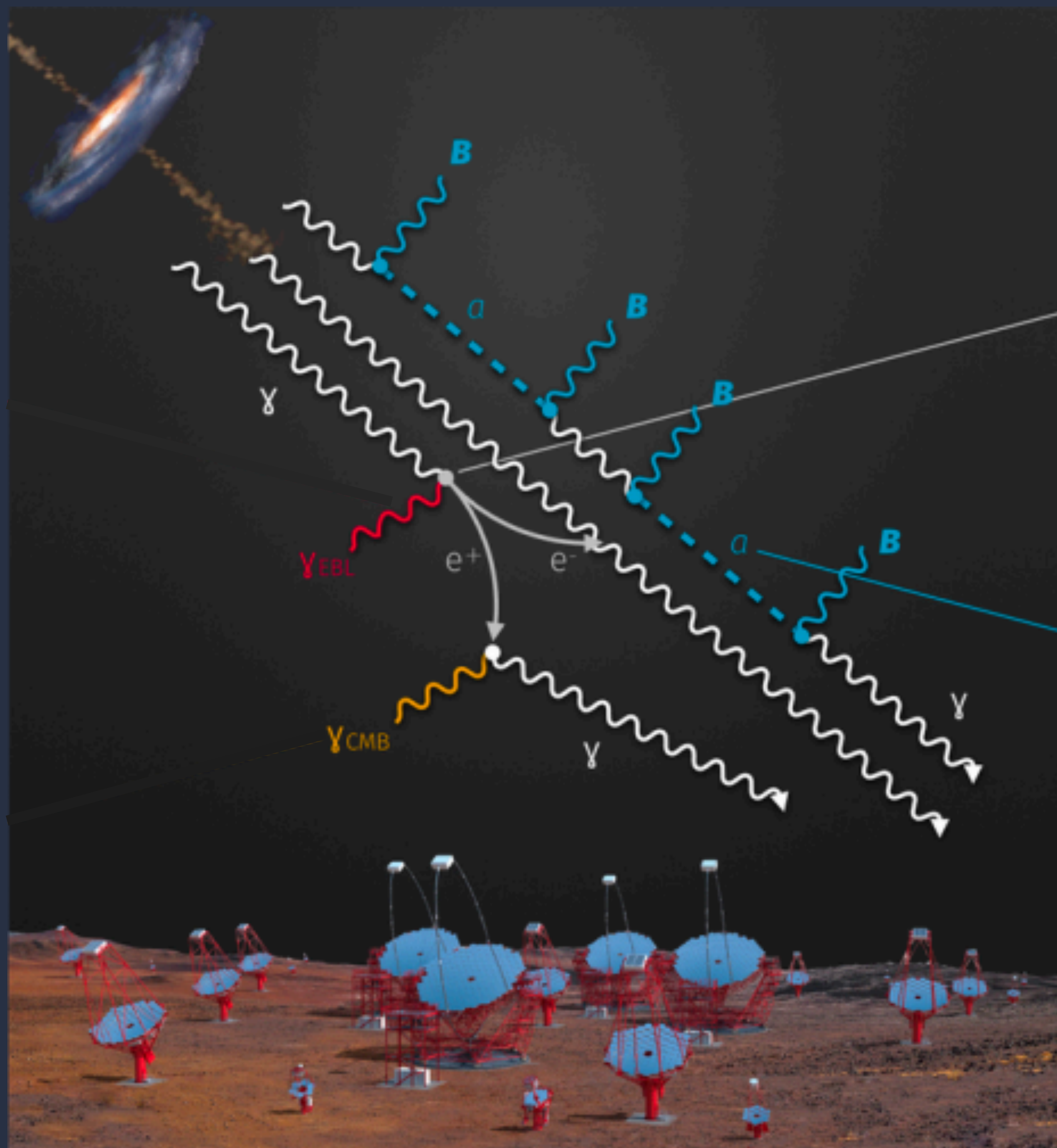
Axion and axion-like particle

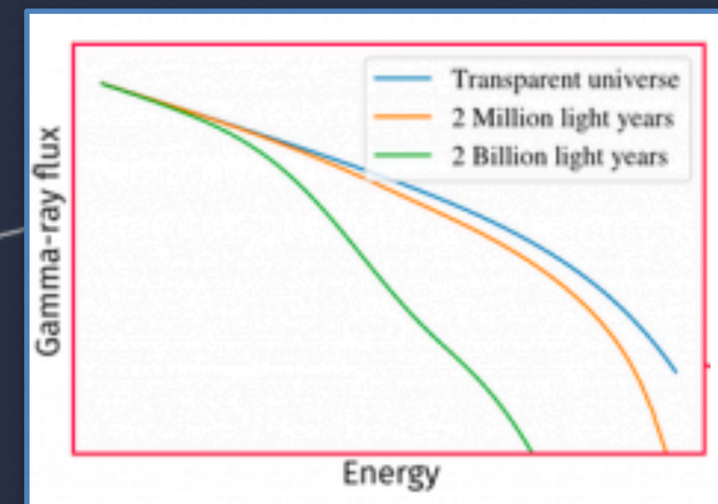
- **<u>Axion</u>**: Hypothetical spin-0 boson produced by spontaneous breaking of new symmetry introduced in the QCD Lagrangian to solve the "strong CP problem"
  - 2-photon vertex with weak coupling, proportional to their mass
- Generalized to **<u>Axion-like particles</u>** (**ALPs**): hypothetical spin-0 particles with 2-photon vertex
  - ALPs are very light and are not viable as <u>thermal relic</u>
  - Produced as a zero-momentum Bose-Einstein condensate when the temperature falls below the QCD scale → **<u>Cold</u>** dark matter!



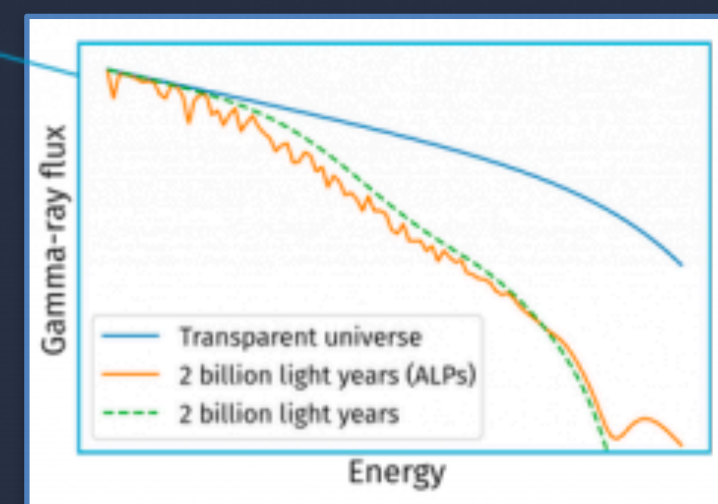


Gamma ray propagation with ALPs





EBL

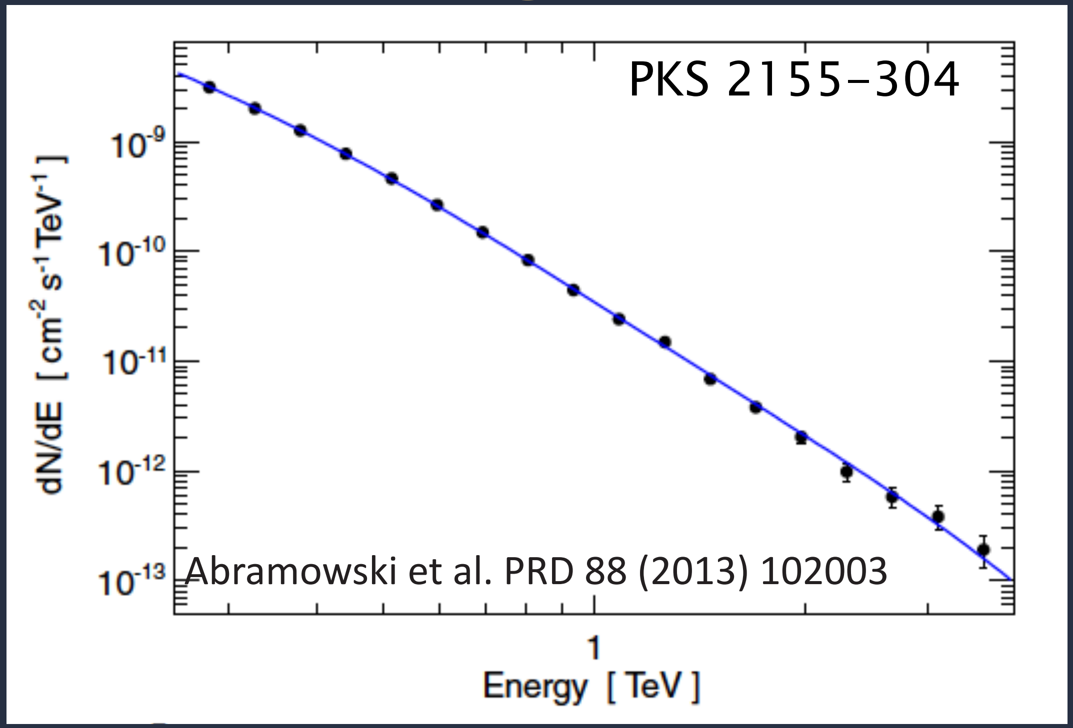


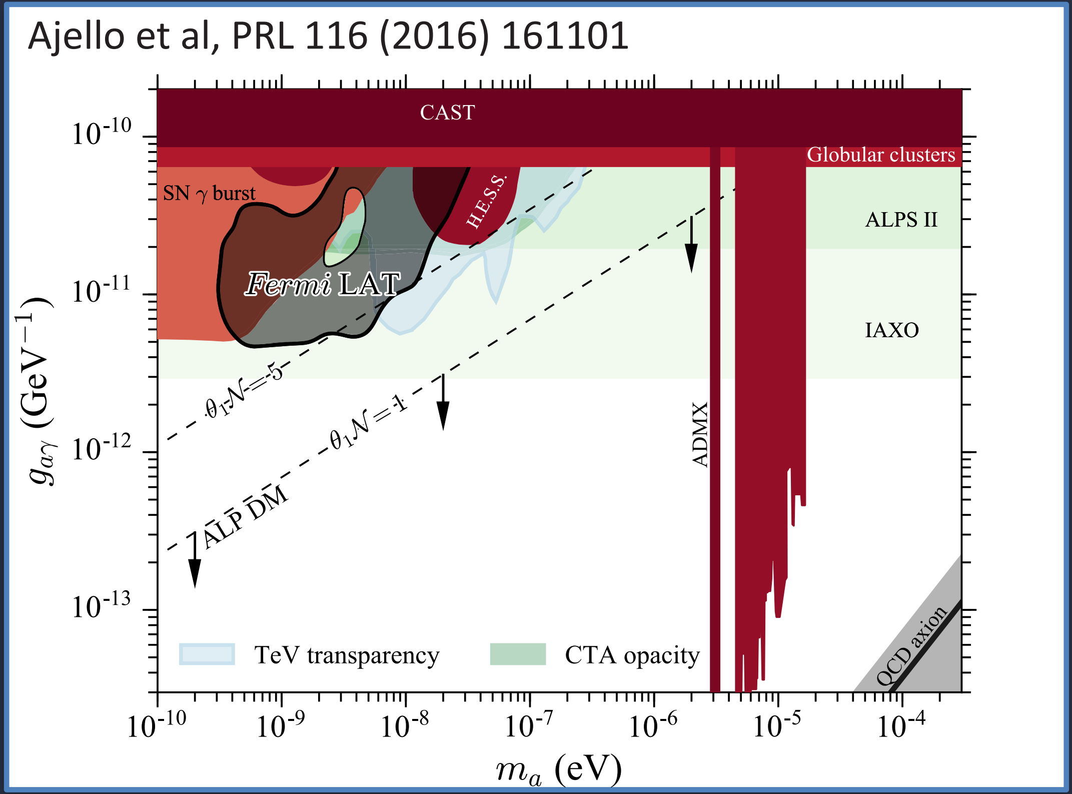
EBL+ALPs

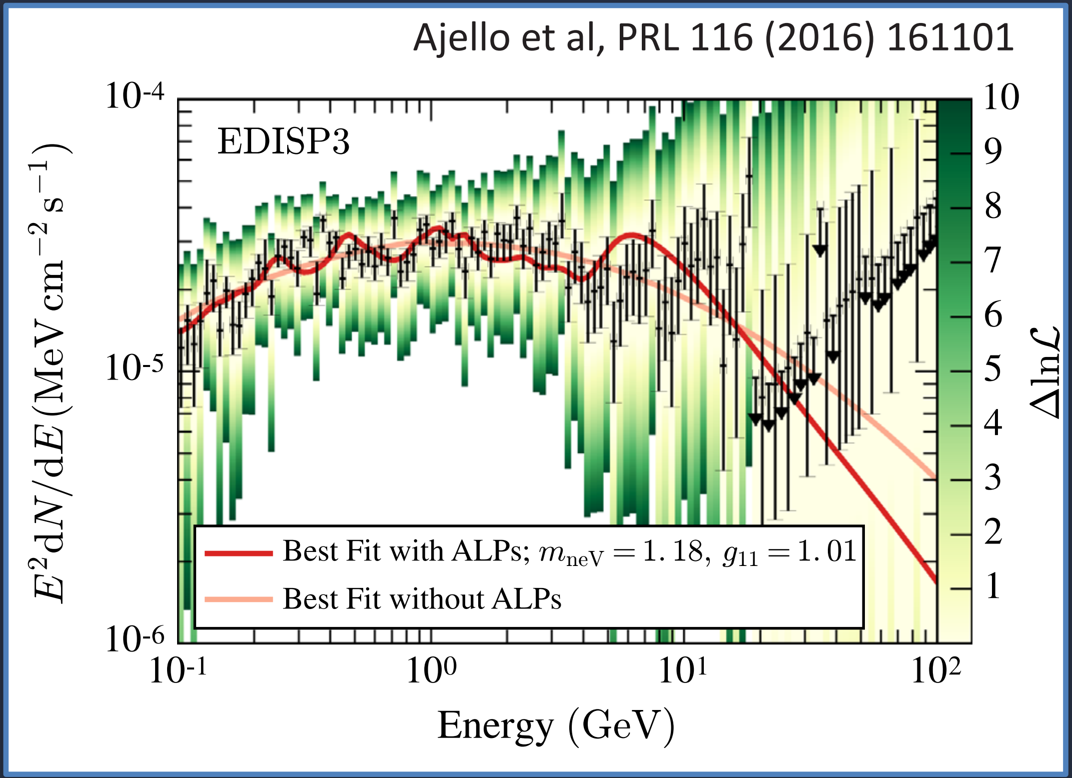
Adapted from Biteau & Meyer [https://www.cta-observatory.org/what-propogation-of-energetic-light-can-tell-us/]

Search for spectral irregularities

- Observations:
  - PKS2155-304 (13 h super flare with HESS)
  - NGC1275 (6 years with Fermi-LAT)
- No preference for ALP hypothesis found in the data
- Limits to irregularities translated into limits to $g_{a\gamma}$ under certain assumption of B-fields







Search for high energy boost in flux

Biteau & Williams, ApJ 812: No evidence of flux boost in a large compilation of HE+VHE spectra (106 blazars)

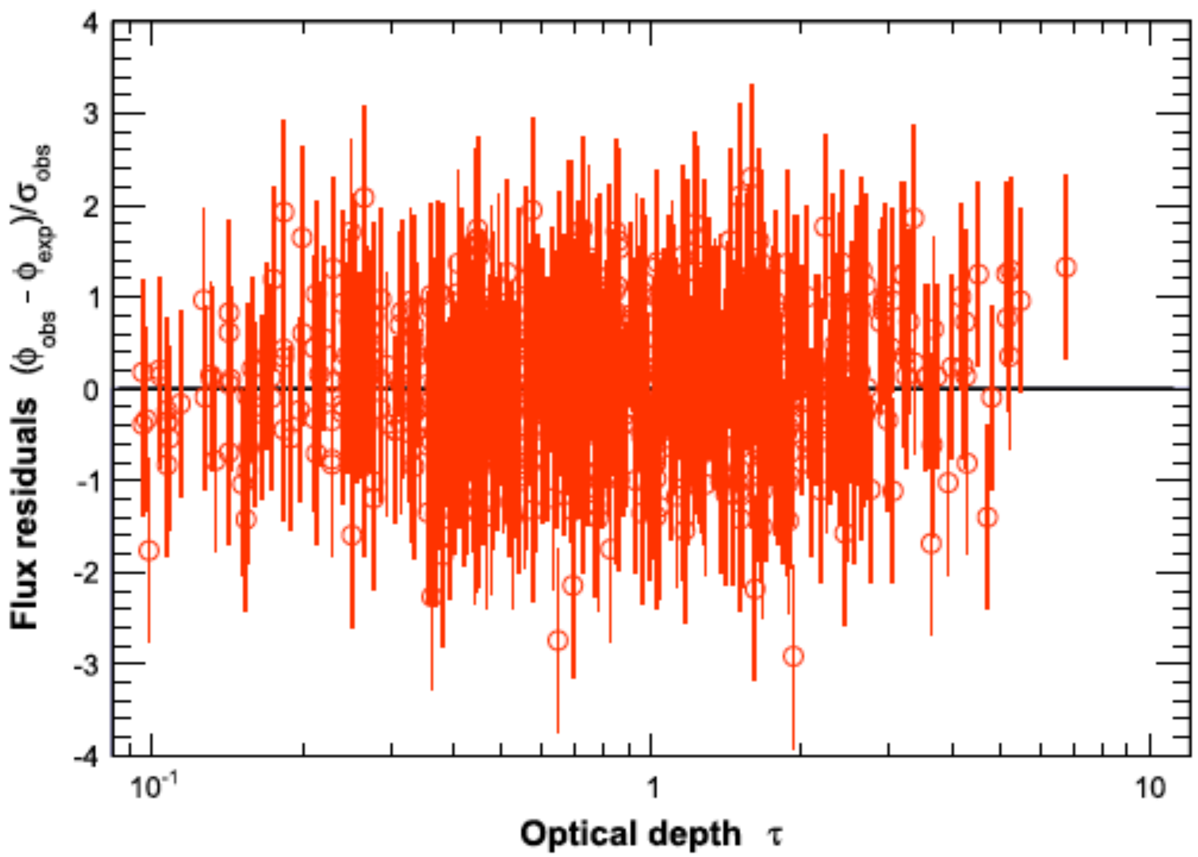


Figure 7. Residuals to the best-fit models for the 106 spectra (737 points) studied in this paper, as a function of optical depth.

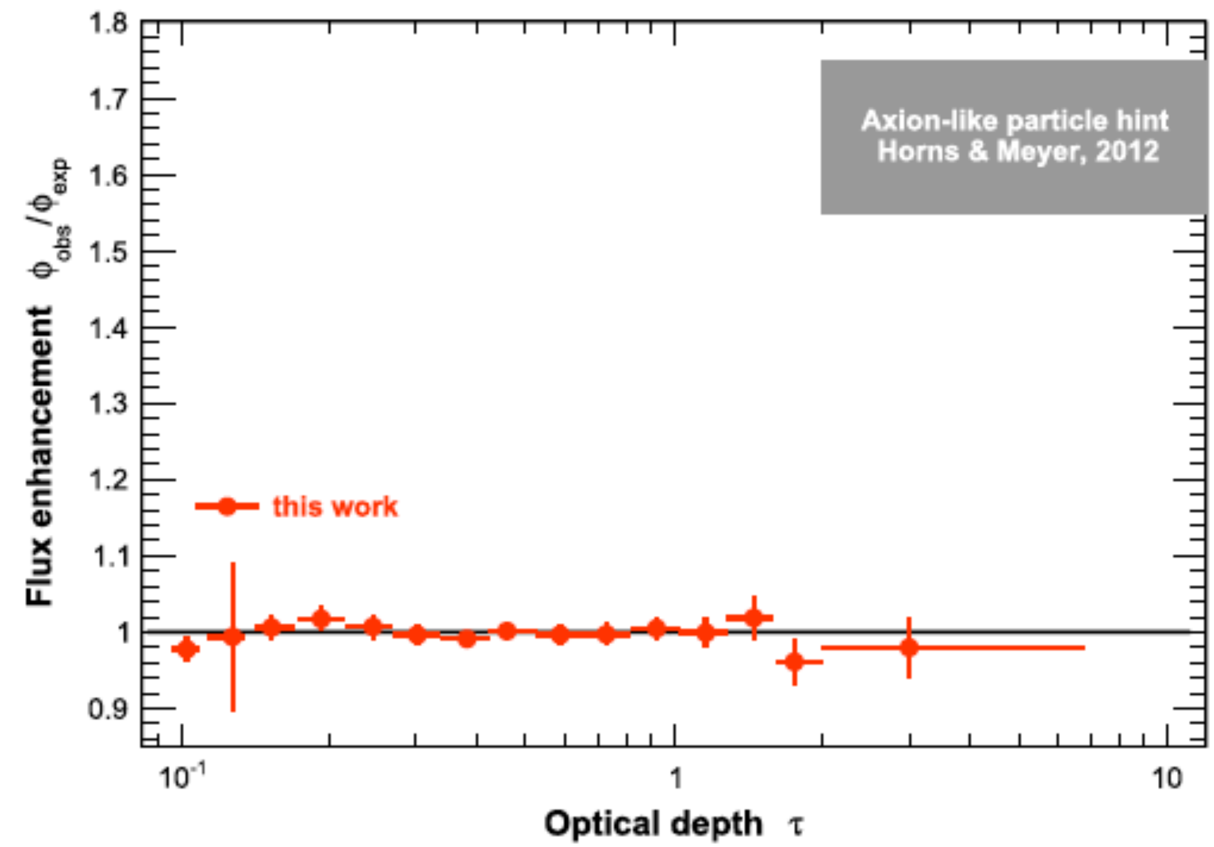
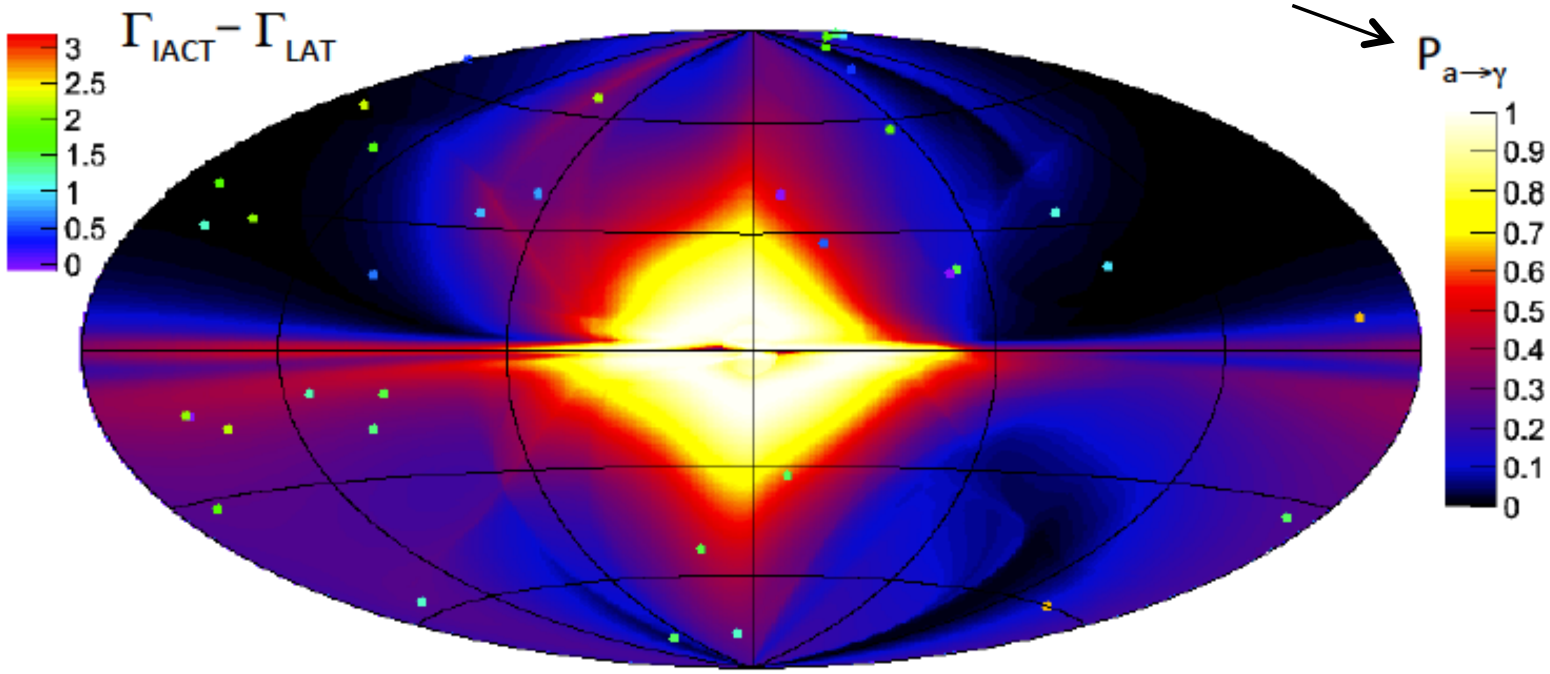


Figure 8. Flux enhancement, defined by the ratio of observed and expected fluxes, as a function optical depth. The shaded gray region is the flux enhancement implied by the results of Horns & Meyer (2012).

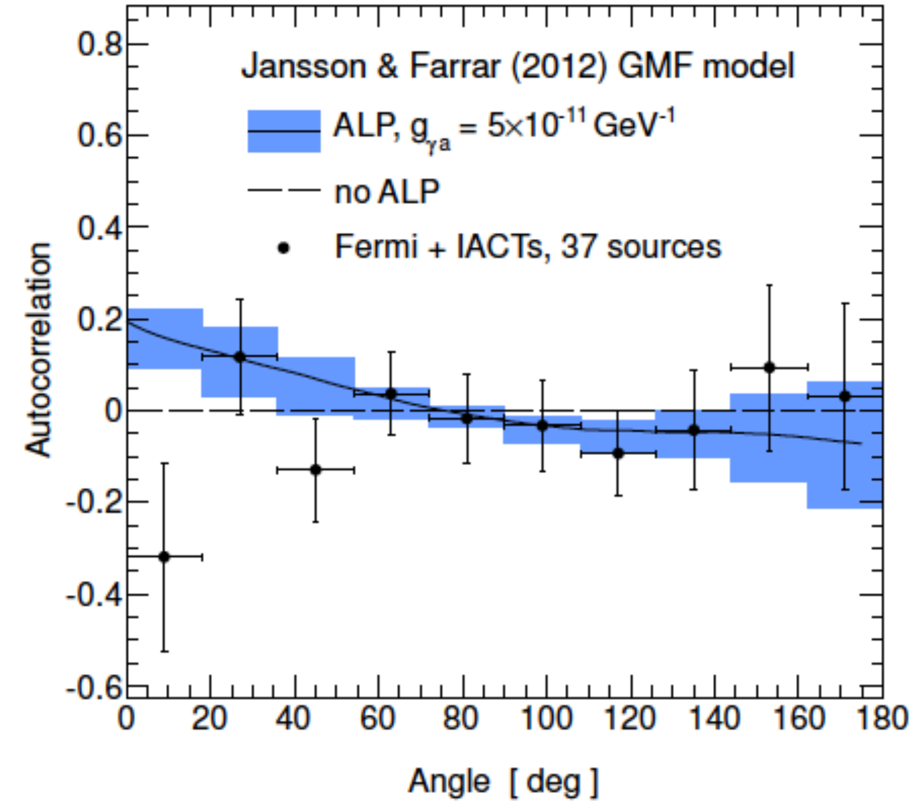
Correlation with magnetic fields

Wouters & Brun JCAP 01 (2014)

$P_{a\to\gamma}$ in the MW magnetic field



Example for $g_{11} = 5$ (close to CAST limit)
P=0.8 for no-autocorrelation hypothesis



- Assuming conversions only at the sources and in our galaxy
- Simple approach: compare HE (Fermi) and VHE photon indices, look for autocorrelations among sources. No correlation seen even assuming $g_{a\gamma}$ close to CAST limit

Conclusions

- Indirect WIMP searches look for spectral and/or morphological anomalies in cosmic-ray, gamma-ray and neutrinos extra-terrestrial fluxes
  - All possible messengers, signatures and sources explored
  - Results by Pamela, AMS-02, CALET, DAMPE, Fermi-LAT, MAGIC, VERITAS, HESS, HAWC, ANTARES, IceCube have been presented
- A few hints:
  - Anti-proton flux
  - Positron excess
  - Galactic center gamma-ray excess
  - All have plausible DM and astrophysical explanations
- WIMP limits start excluding the ~O(10 GeV) mass range
- Increasing activity in search for axion-like particles
- Next generation of instruments: HERD, GAPS, CTA, LHAASO, SWGO, Km3NeT,… will continue the search
- Checkout parallel session Thursday 17:30-18:30 for more details