Search for heavy dark matter with Fermi LAT

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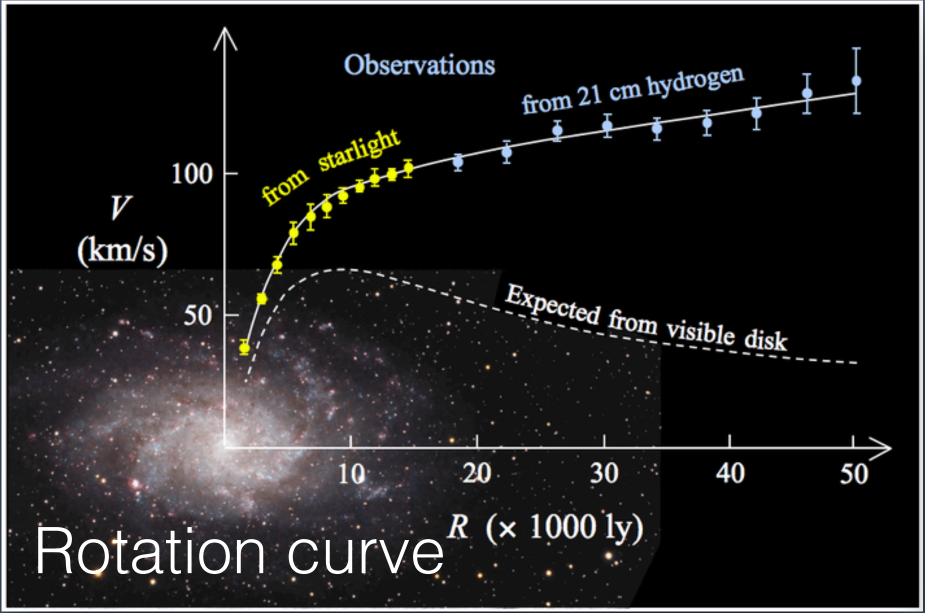
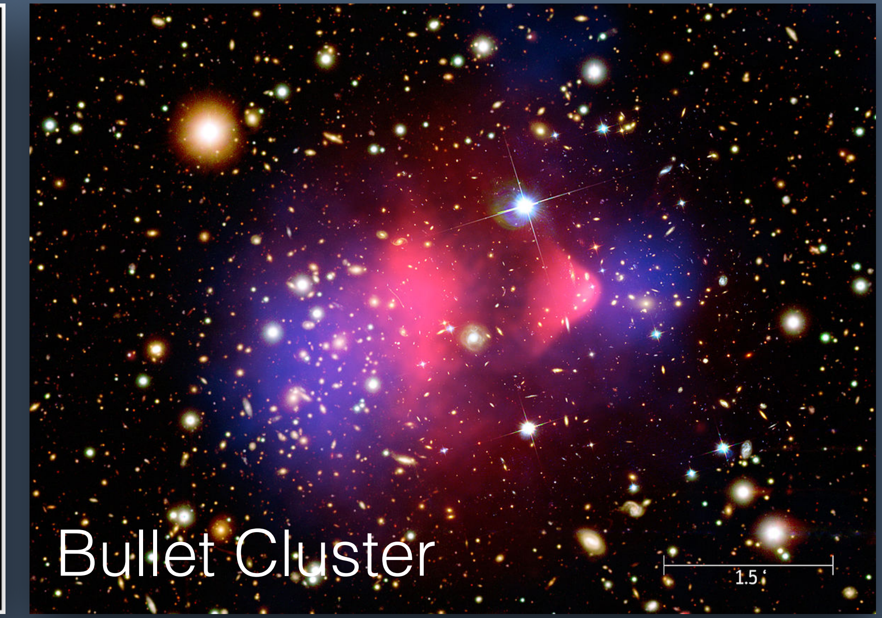
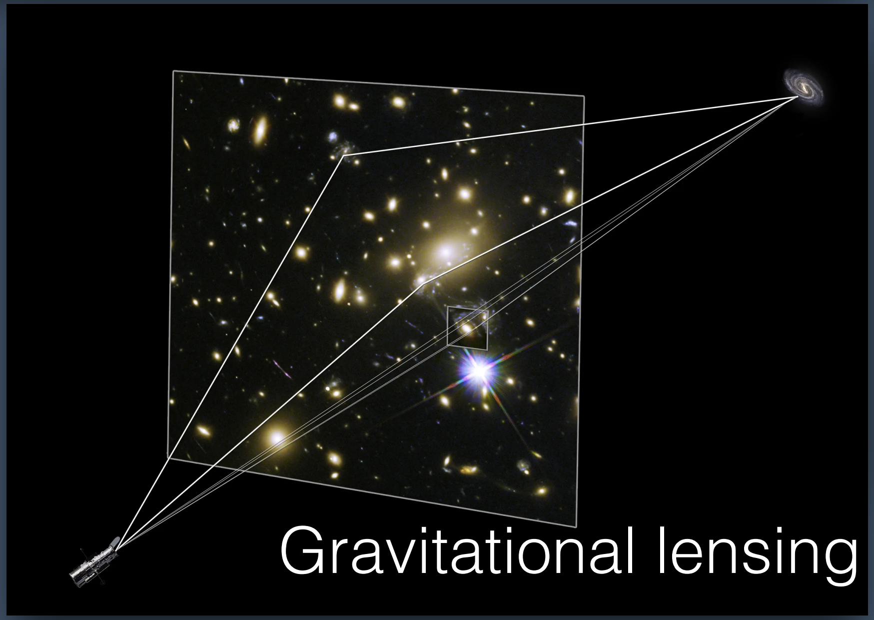
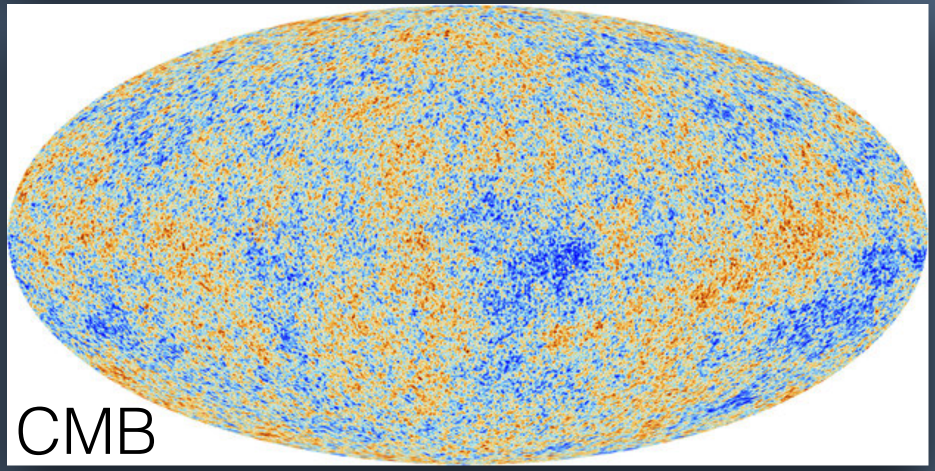
Based on Song, Murase, Kheirandish JCAP 03 (2024) 024 (arXiv 2308.00589)
and Song, Hiroshima, Murase JCAP 05 (2024) 087 (arXiv 2401.15606)

Evidence for dark matter



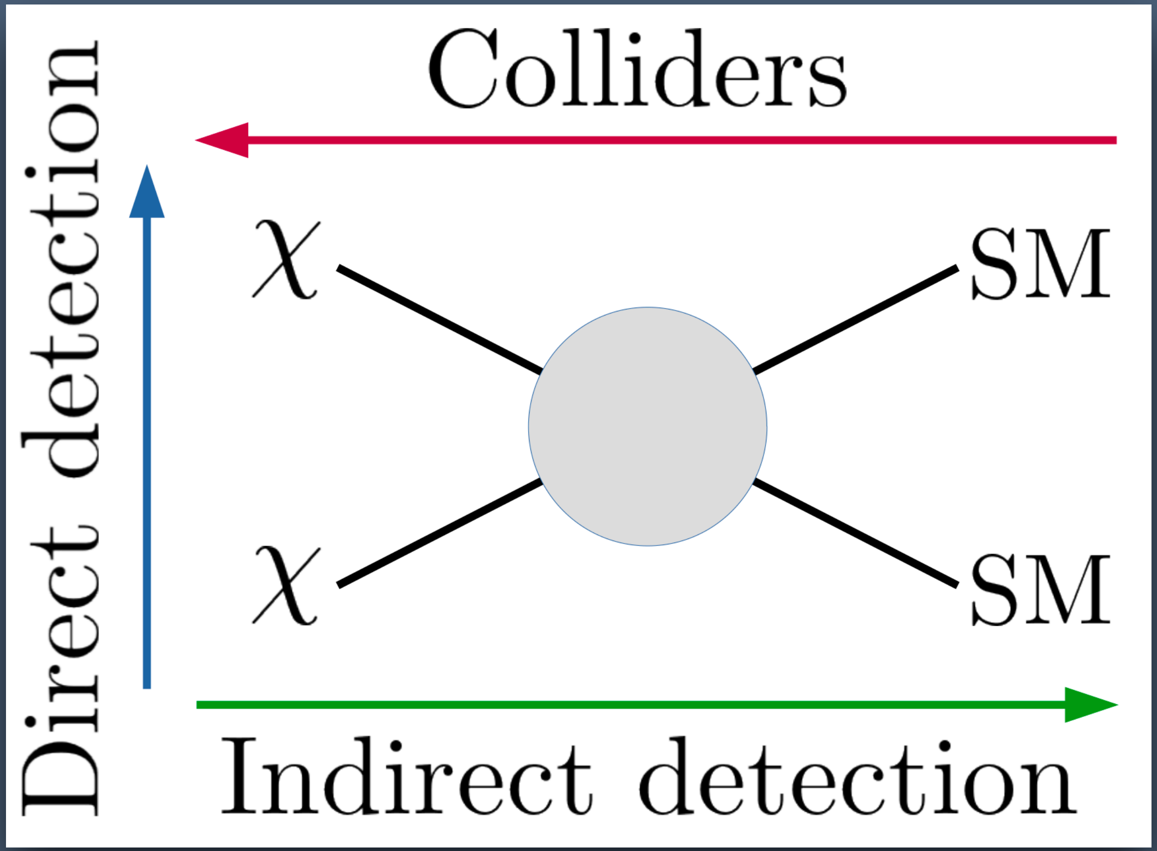


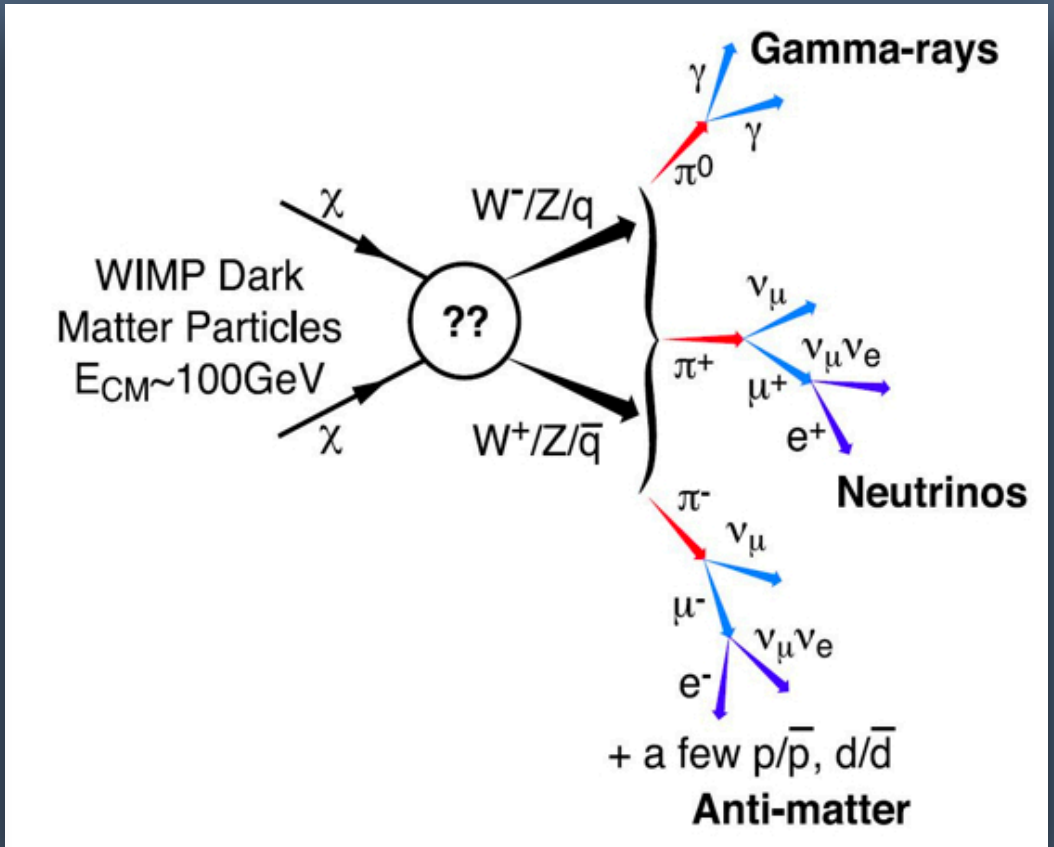




Indirect detection

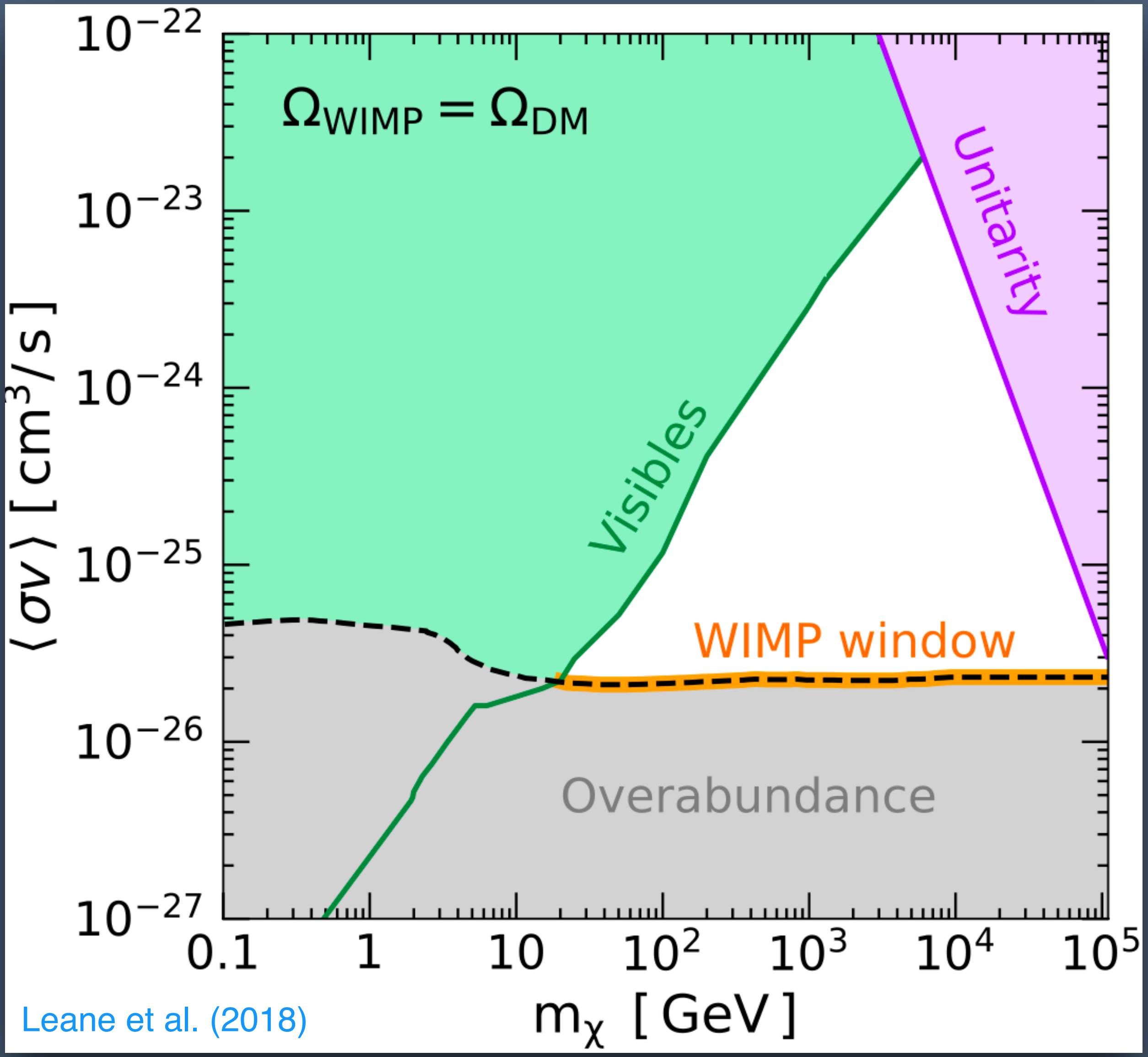
- Dark matter annihilation/decay in the Universe
- Sequential photons, neutrinos, cosmic rays could be detectable on Earth





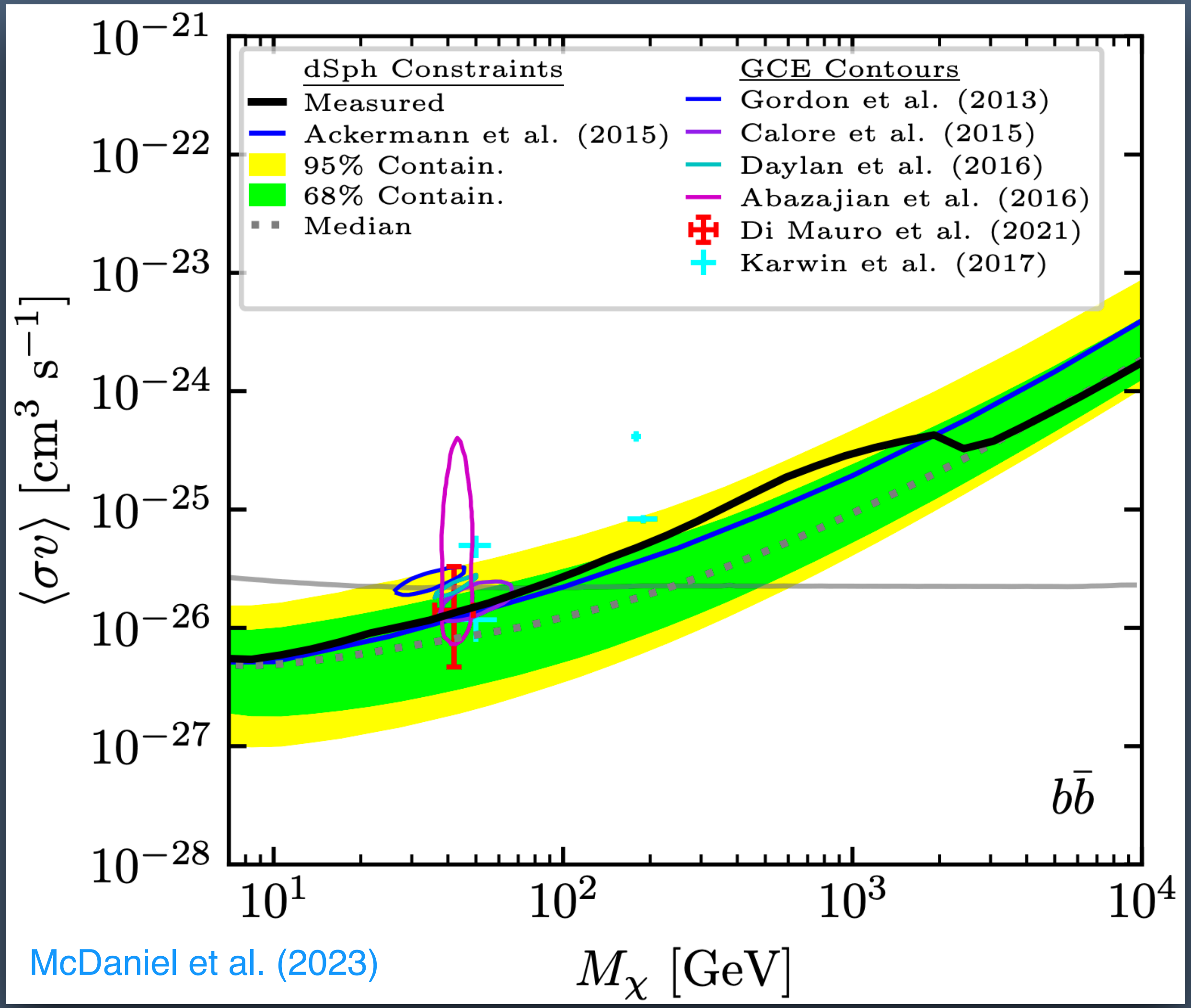
The WIMP window

- Thermally produced WIMP dark matter is not (yet) ruled out, but the window is getting smaller



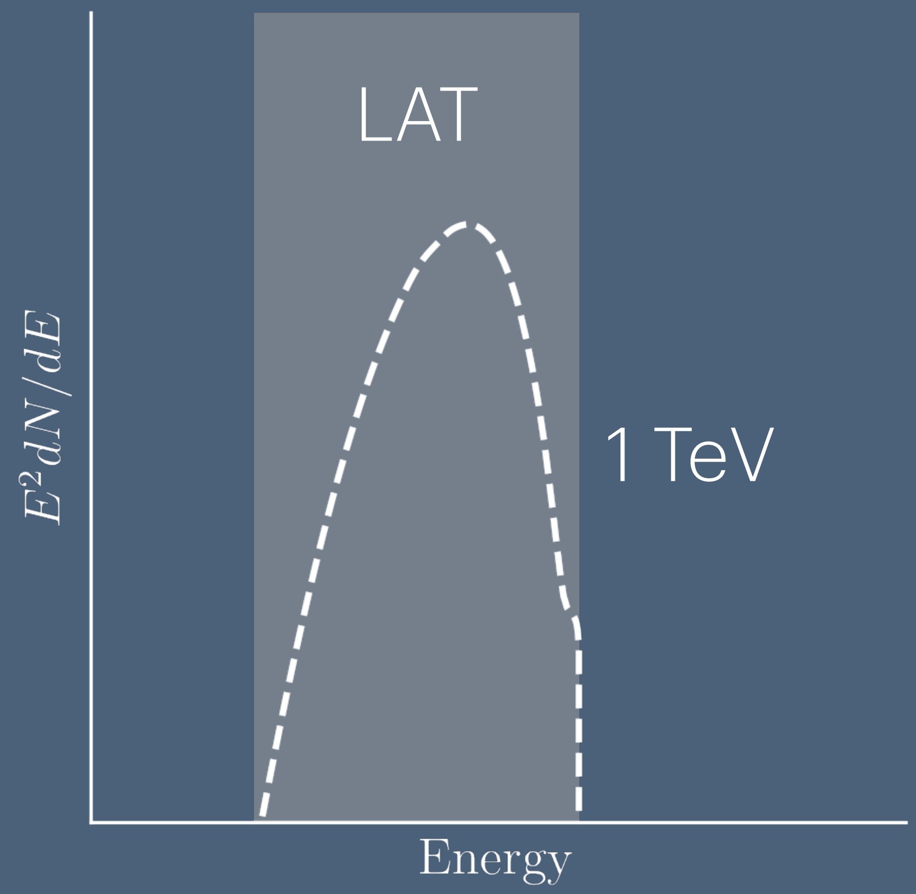
Fermi LAT search for WIMP

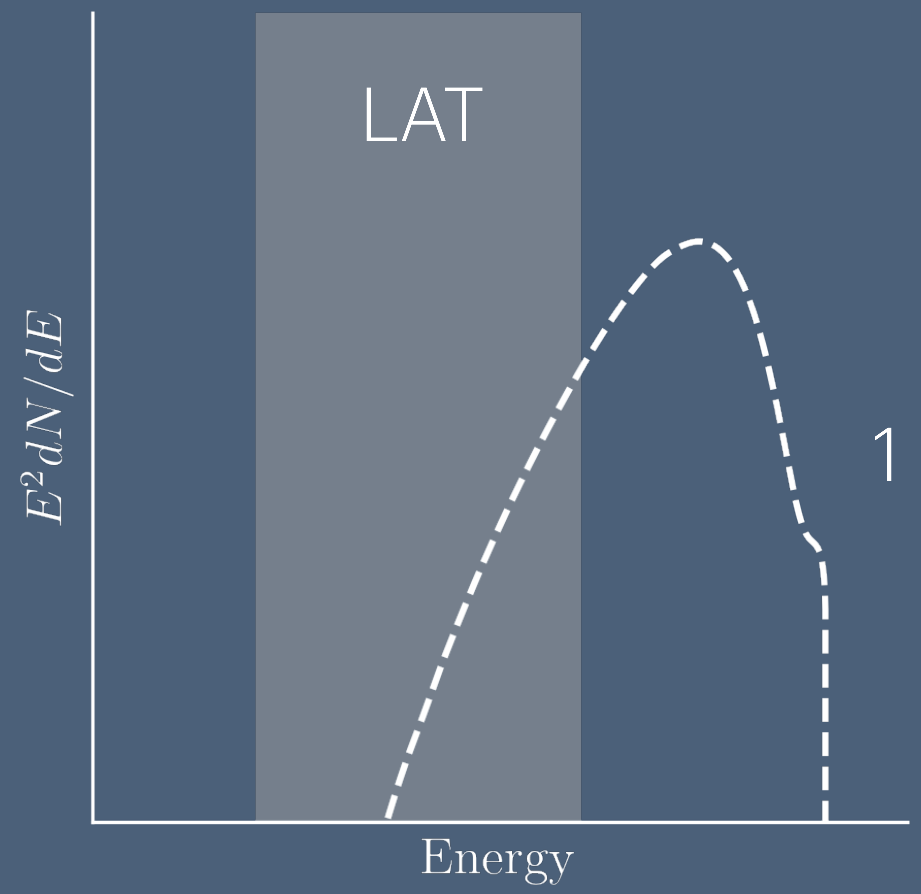
- LAT is a pivotal tool to search for WIMP DM thanks to its exceptional sensitivity in the GeV range
- Recent stacking analysis of dwarfs is ruling out thermal WIMP parameter space



Fermi LAT search beyond WIMP

- Fermi LAT is sensitive in GeV energies, so usually not used for heavy dark matter beyond the WIMP mass range

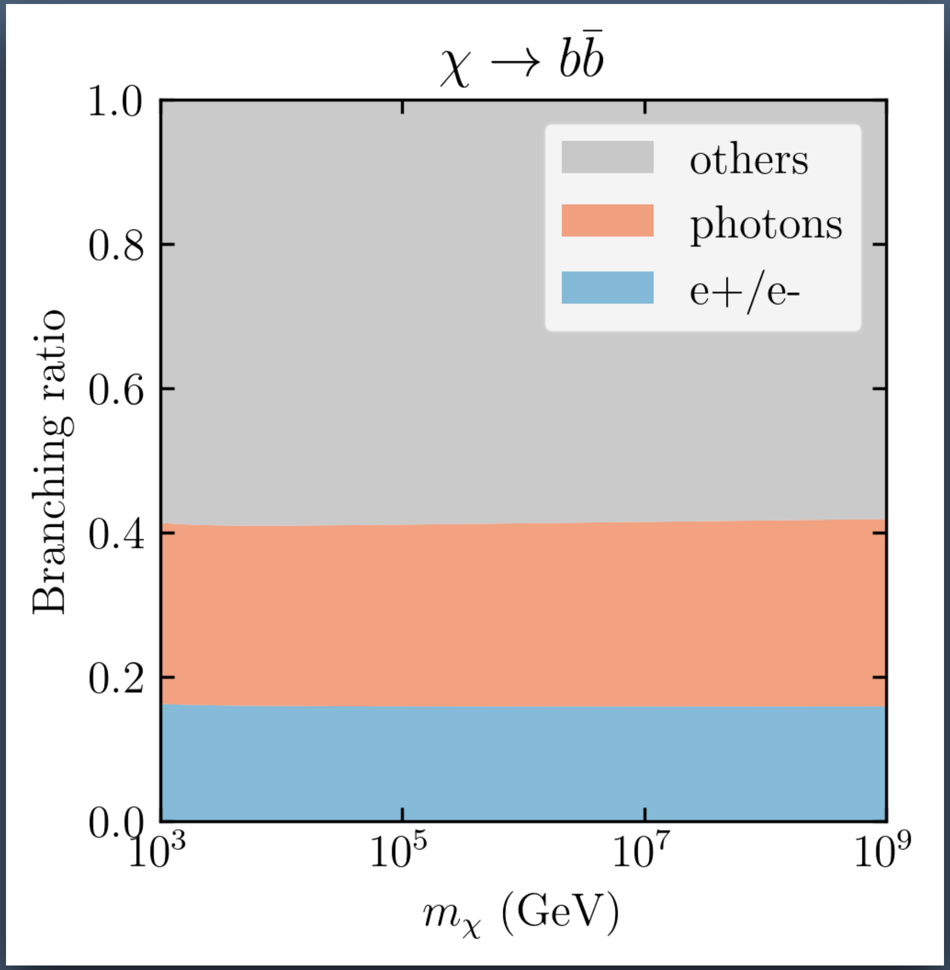


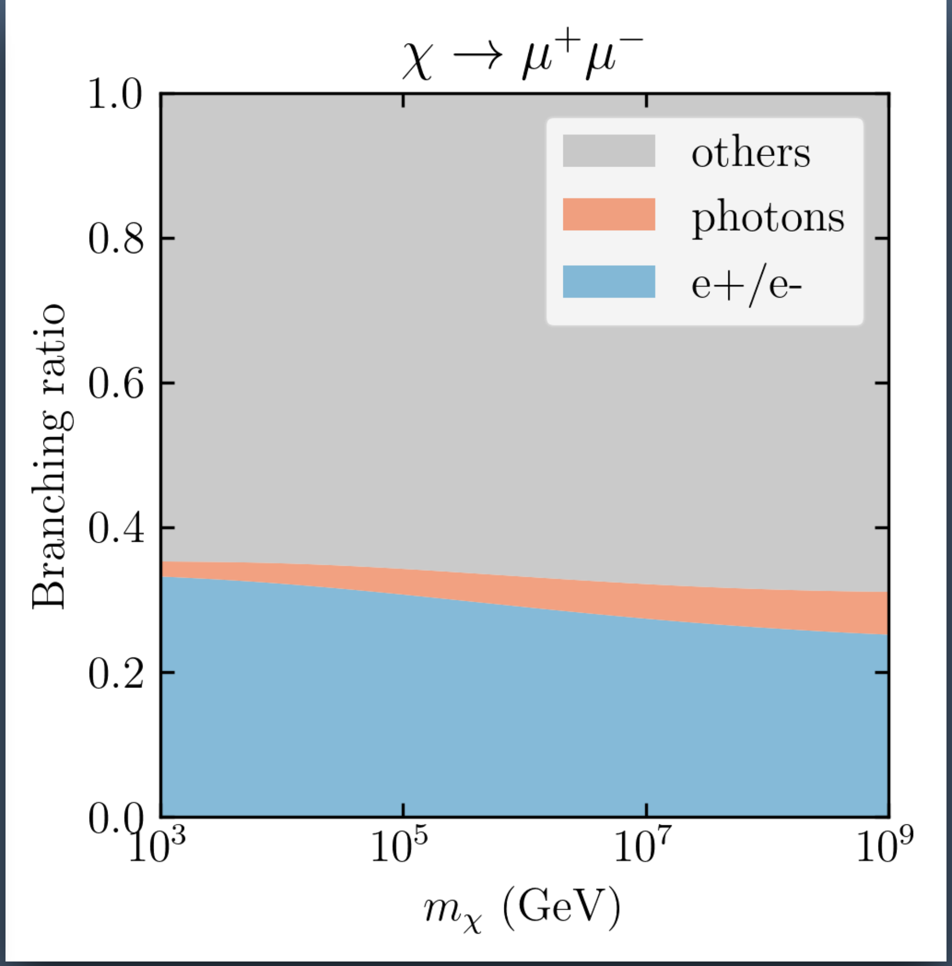


*$b\bar{b}$ channel

High-energy e+/e- from heavy dark matter

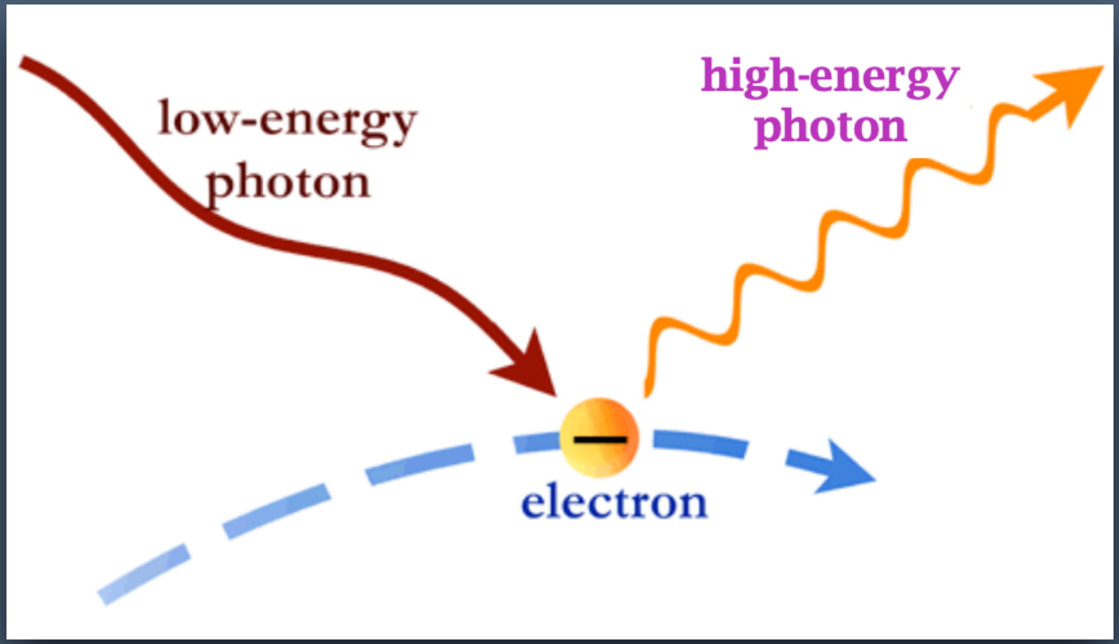
- For WIMP-like dark matter, a substantial portion of its energy budget is annihilated/decayed into electrons and positrons (depending on the channels)
- These high-energy e+/e- from DM are often overlooked in conventional DM searches using gamma rays

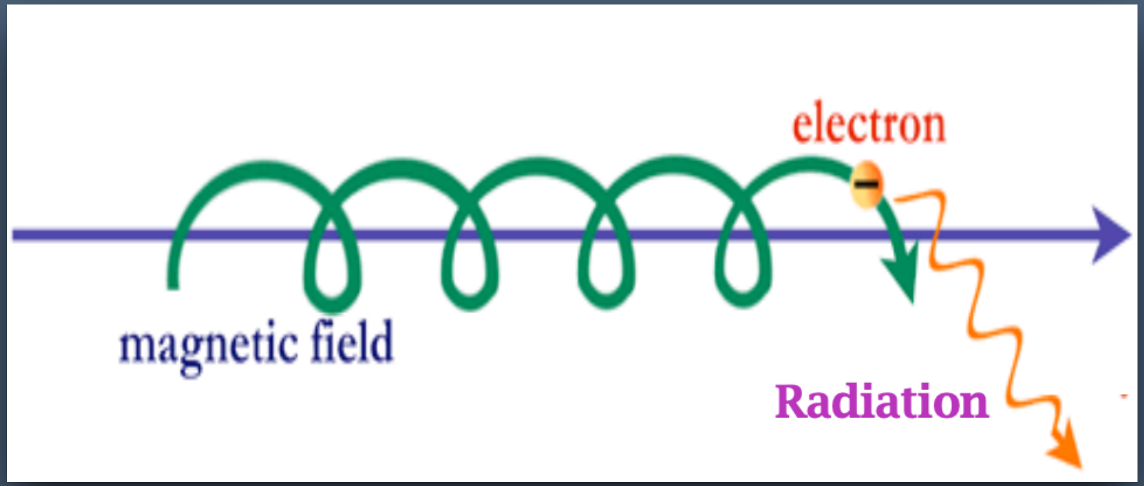




Secondary emissions from HDM e+/e-

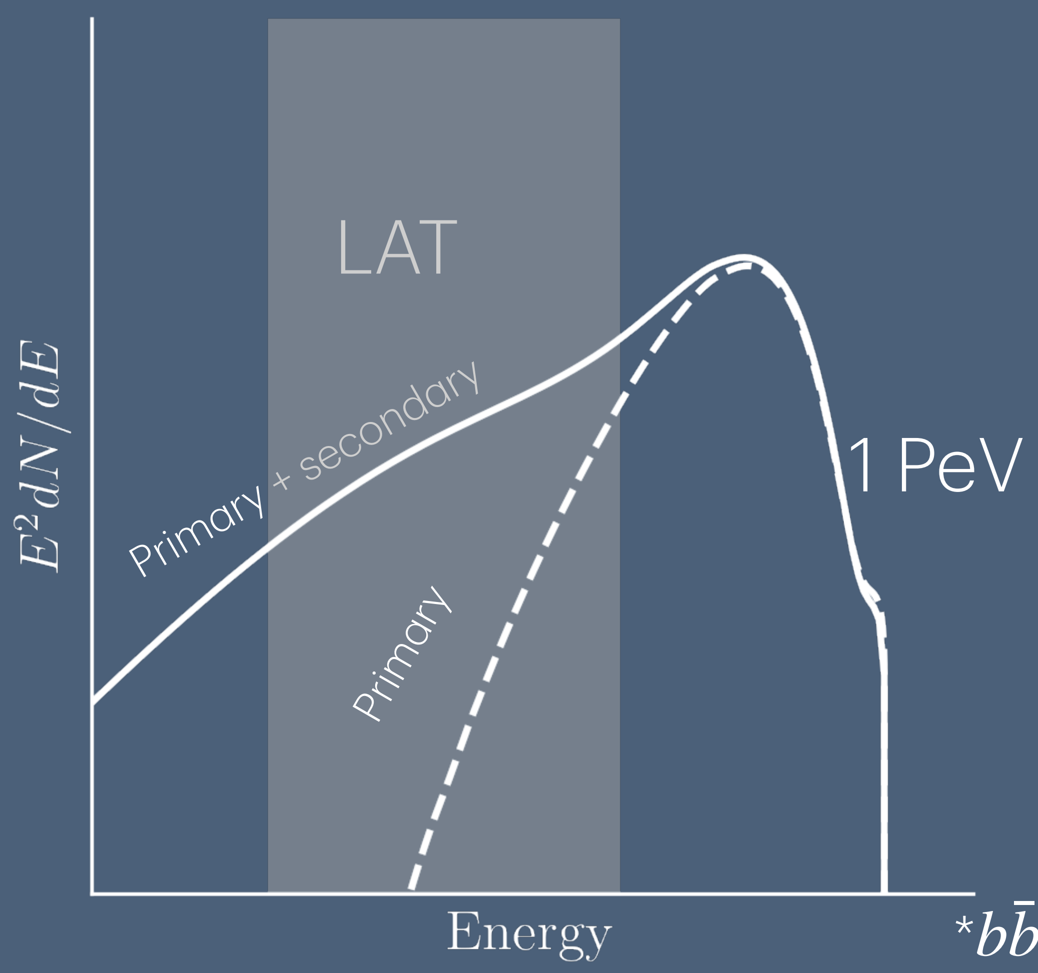
- High-energy e+/e- inevitably lose energies in interstellar medium and generate secondary gamma rays
  - Inverse Compton scattering
  - Synchrotron radiation





Power of the secondary

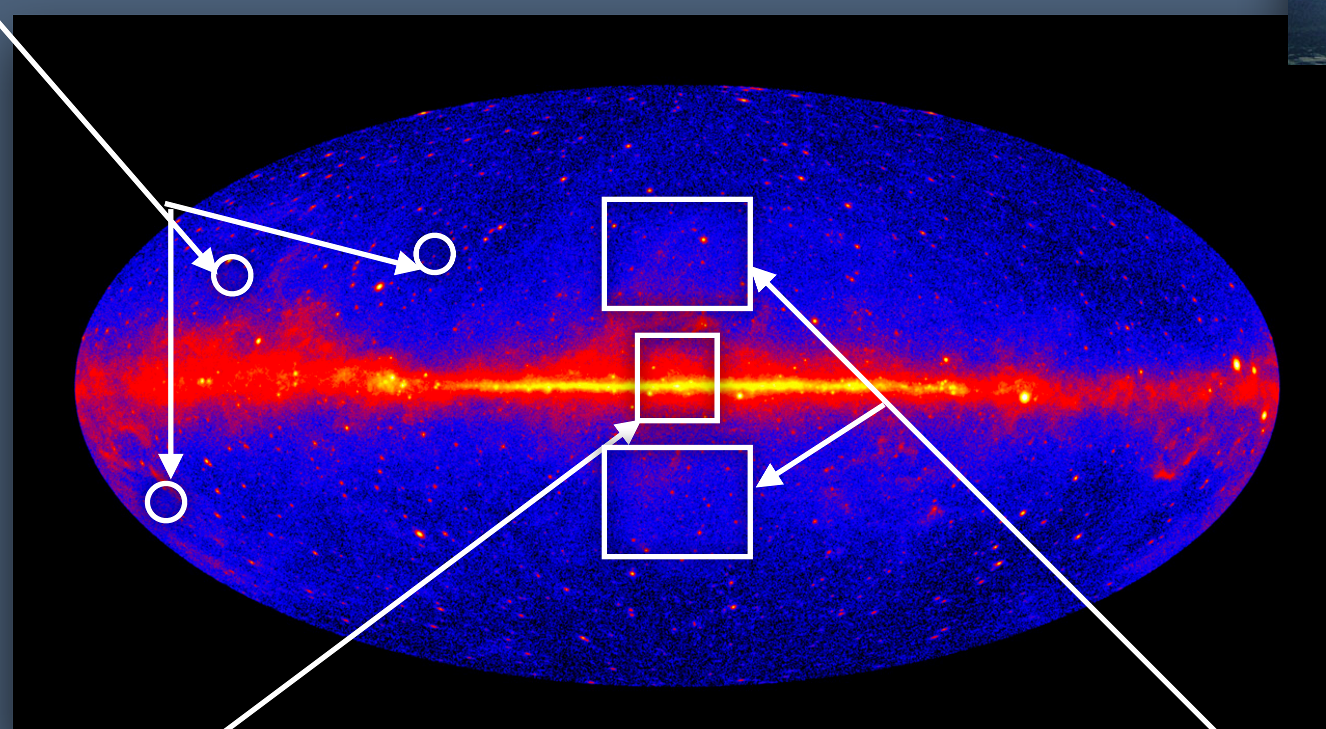
- By including secondary emission from DM e+/e-, we can broaden the LAT's DM search to include heavy candidates beyond WIMP



*$b\bar{b}$ channel
Draco dwarf

Where to find dark matter

Nearby dwarfs/galaxy
clusters
(Localized)

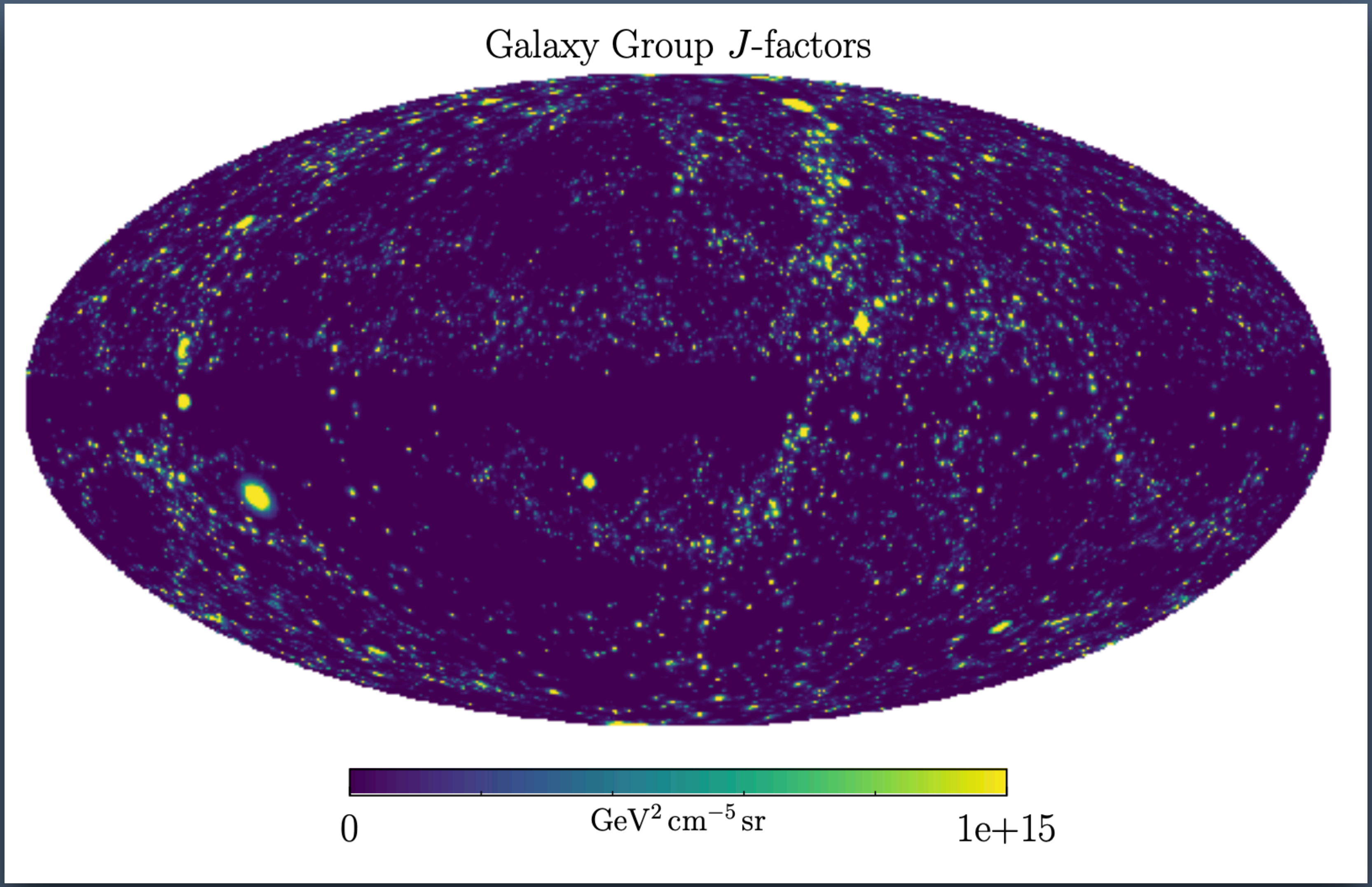


Fermi LAT

Galactic center
(Diffuse)

MW halo
(Diffuse)

Halo model of galaxy clusters

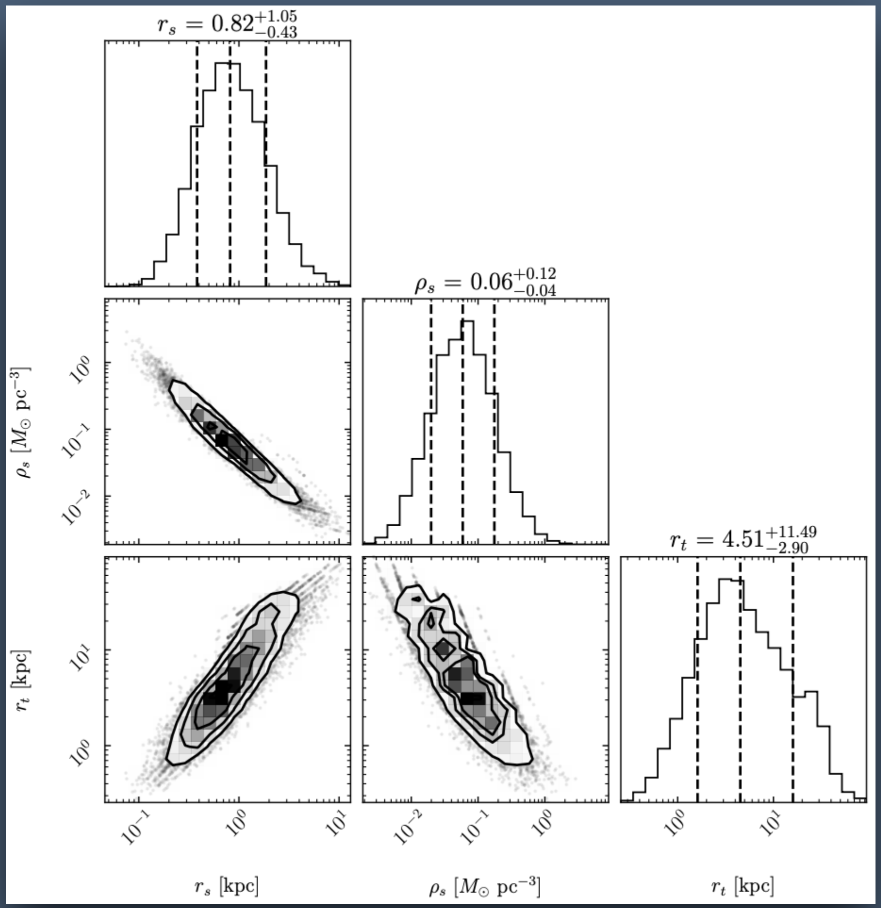


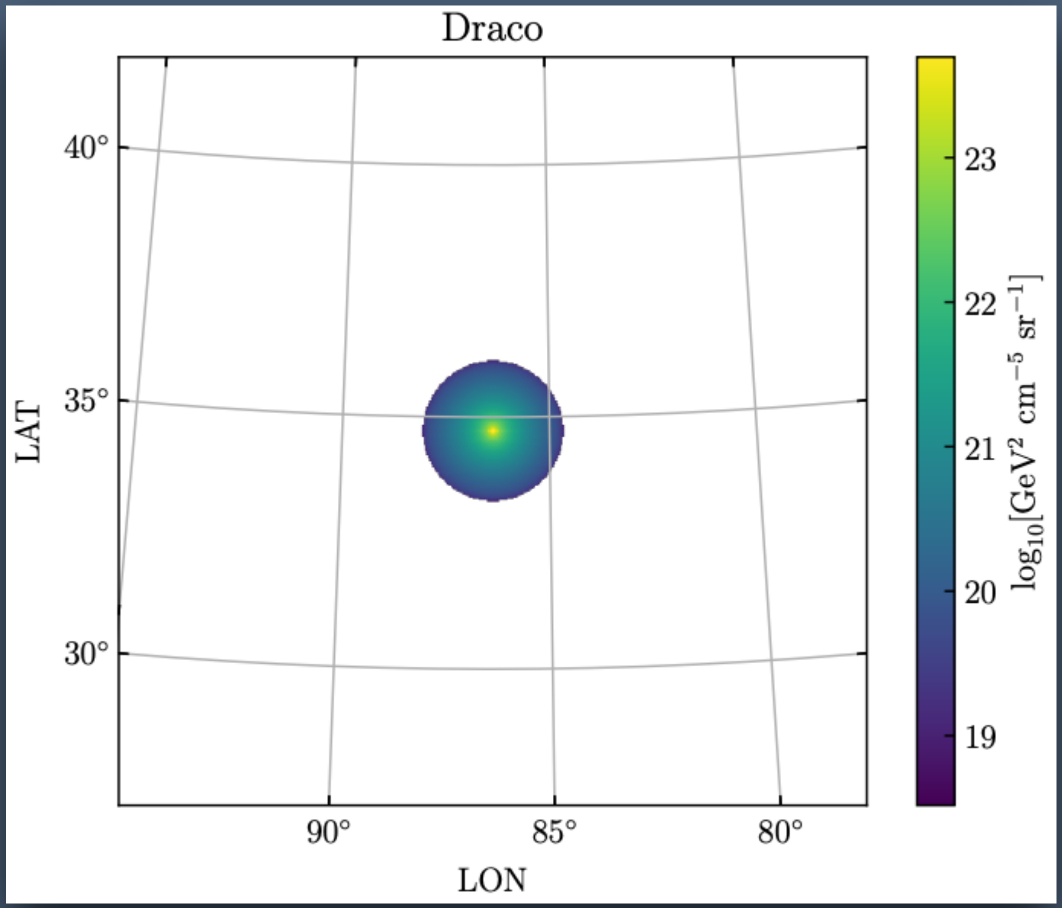
- Galaxy Group J-factors Lisanti et al. (2017)

Halo model of dwarf galaxies

- Dark matter distributions of dwarfs includes truncations (caused by tidal stripping from MW)
  - Use Extended Press-Schechter model to evaluate dSph halo profiles (ρ_s, r_s, r_t)

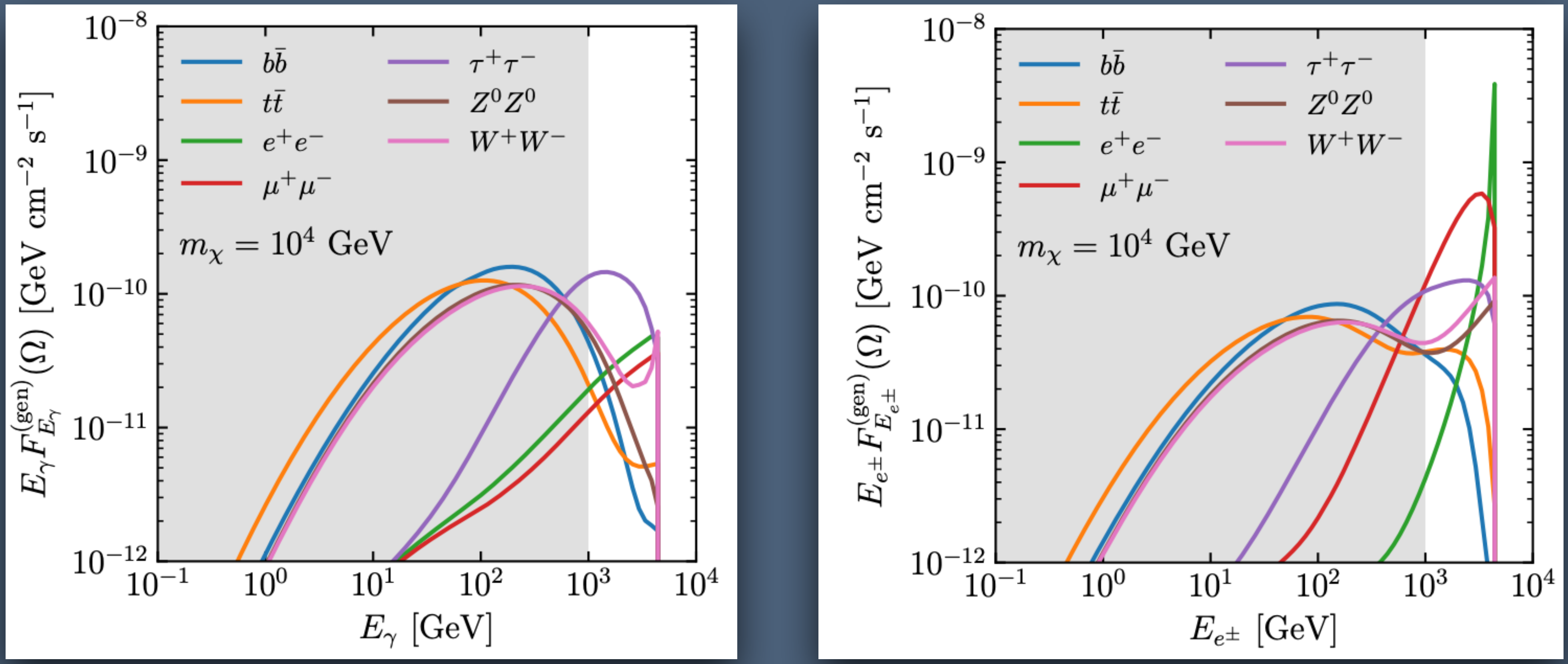
    Ando et al. (2020)
  - This in general yields a smaller J-factor





Injection spectra

- Use HDMspectra to calculate the injection spectra of HDM Bauer et al. (2020)
  - Improved HDM spectra from TeV to the Planck scale
  - Includes full electroweak interactions



Secondary spectra

- Solve the Boltzmann equations of gamma rays and e+/e- electromagnetic cascades
  - Inverse Compton, Synchrotron, Pair production
  - Diffusion is ignored for such high energy e+/e-

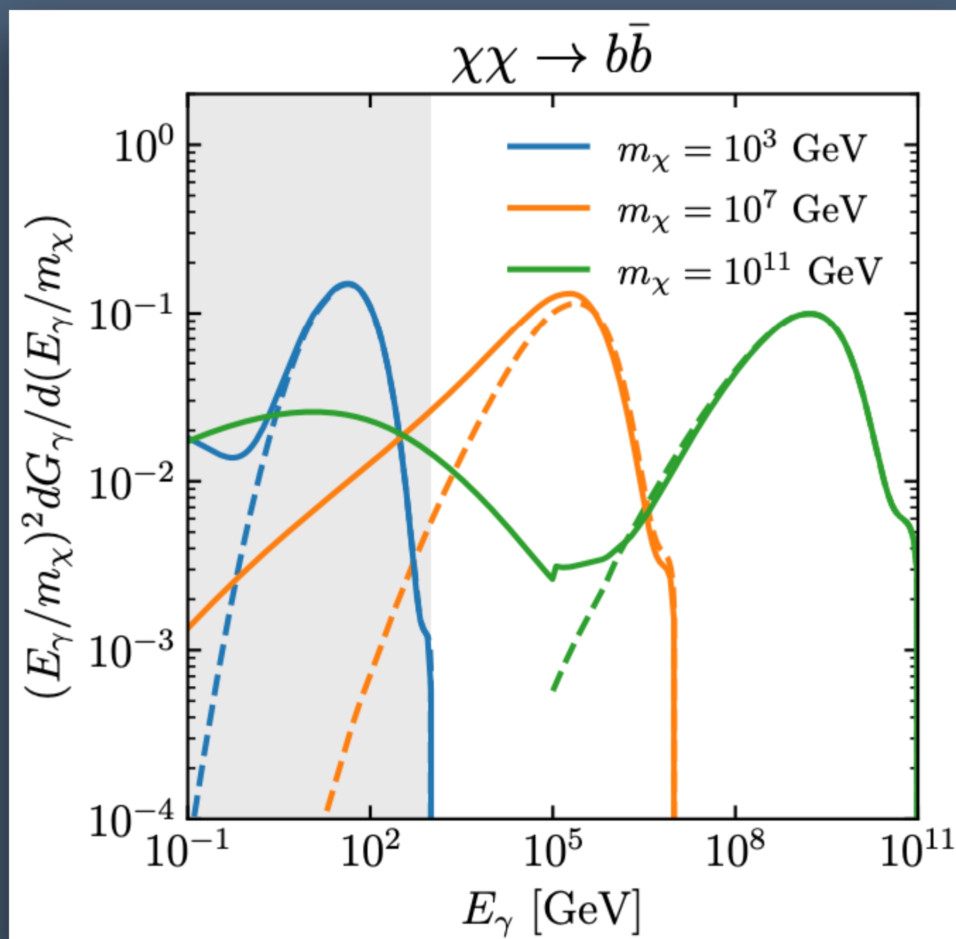
$$
\begin{aligned}
\frac{\partial N_\gamma(E_\gamma)}{\partial t} =& -N_\gamma \int d\varepsilon \frac{dn}{d\varepsilon} \int \frac{d\mu}{2}(1-\mu)c\sigma_{\gamma\gamma}(\varepsilon,\mu) - \frac{N_\gamma}{t_{\rm esc}} \\
&+ \int dE' N_e\left(E'\right) \int d\varepsilon \frac{dn}{d\varepsilon} \int \frac{d\mu}{2}(1-\mu)c\frac{d\sigma_{\rm IC}}{dE_\gamma}\left(\varepsilon,\mu,E'\right) \\
&+ \frac{\partial N_\gamma^{\rm syn}}{\partial t} + Q_\gamma^{\rm inj}, \\
\frac{\partial N_e(E_e)}{\partial t} =& -N_e \int d\varepsilon \frac{dn}{d\varepsilon} \int \frac{d\mu}{2}(1-\mu)c\sigma_{\rm IC}(\varepsilon,\mu) \\
&+ \int dE' N_\gamma\left(E'\right) \int d\varepsilon \frac{dn}{d\varepsilon} \int \frac{d\mu}{2}(1-\mu)c\frac{d\sigma_{\gamma\gamma}}{dE_e}\left(\varepsilon,\mu,E'\right) \\
&+ \int dE' N_e\left(E'\right) \int d\varepsilon \frac{dn}{d\varepsilon} \int \frac{d\mu}{2}(1-\mu)c\frac{d\sigma_{\rm IC}}{dE_e}\left(\varepsilon,\mu,E'\right) \\
&- \frac{\partial}{\partial E}\left[P_{\rm syn} N_e\right] + Q_e^{\rm inj}.
\end{aligned}
$$

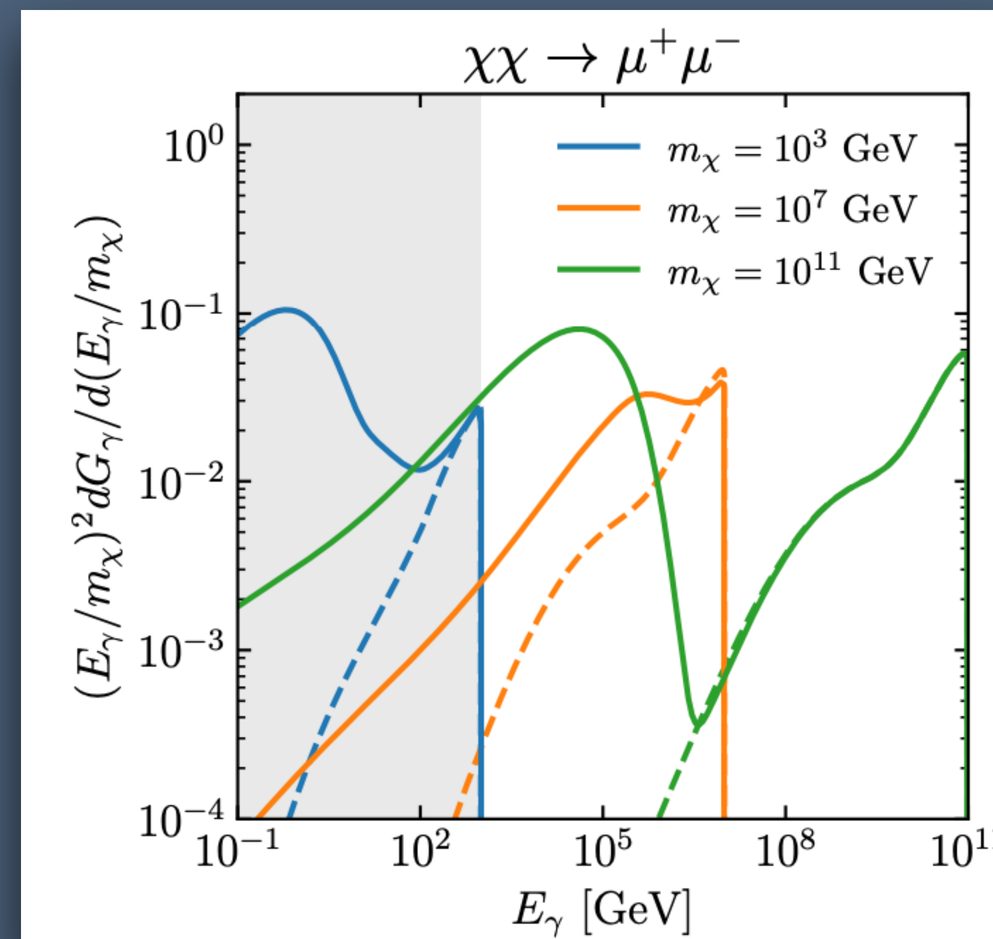
Magnetic fields:

Galaxy clusters: 0.1 — 1 μG

Dwarfs: 1 — 10 μG

Injection and secondary spectra



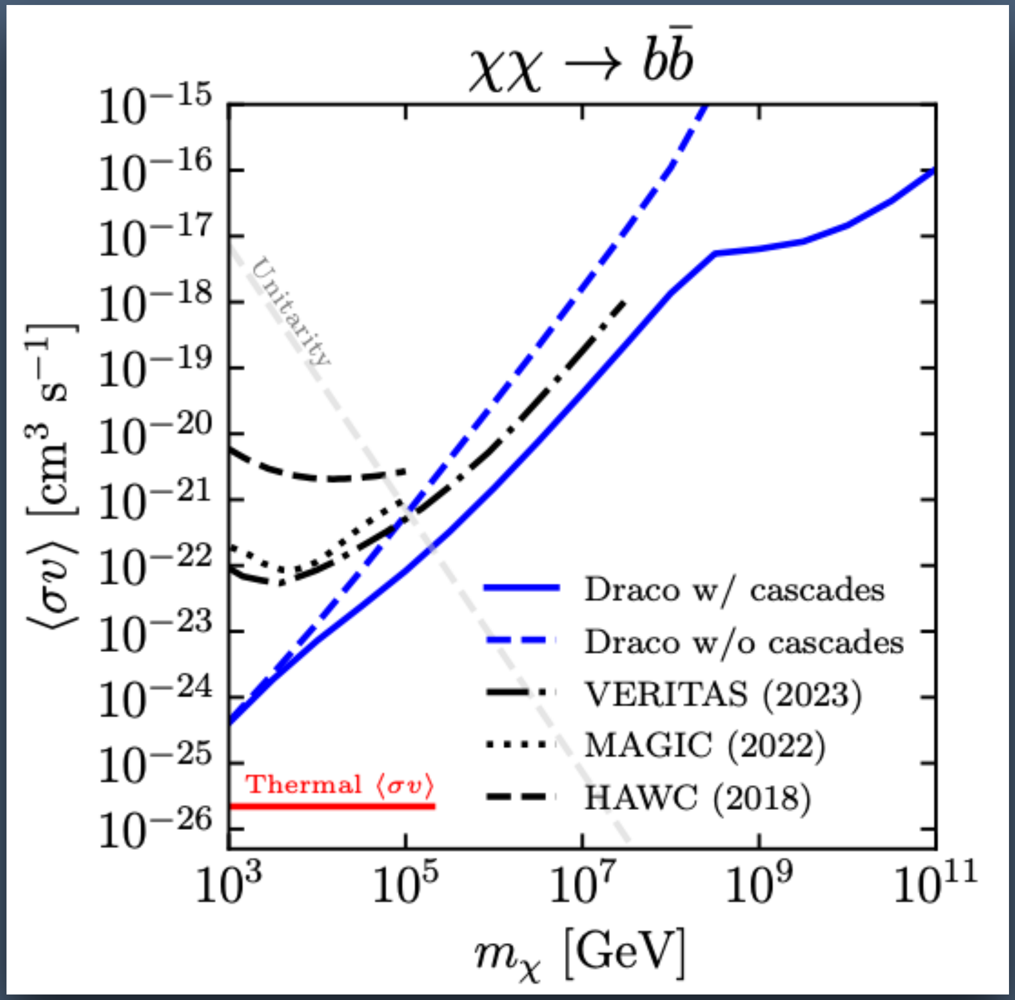


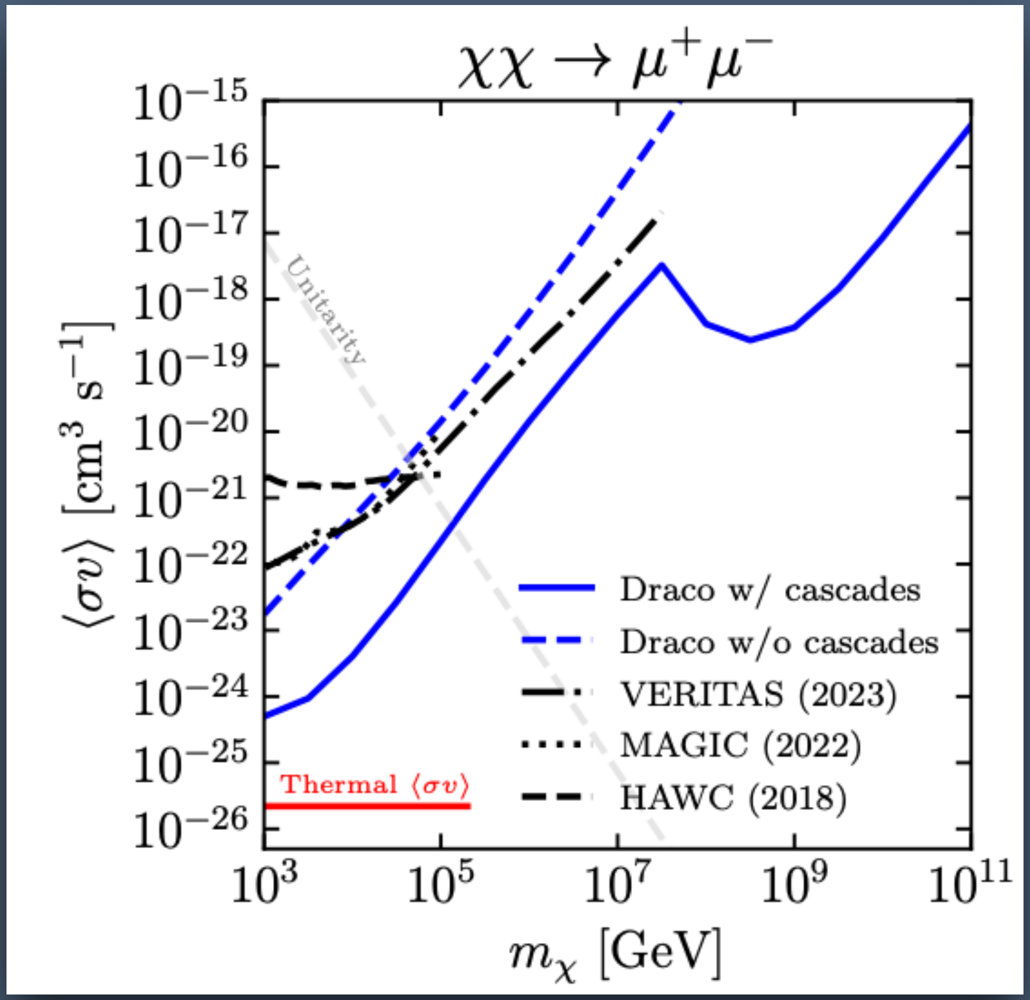
- Expected spectra at Earth
  - Draco dwarf, $B = 1\ \mu\mathrm{G}$

Fermi data analysis

- 14 years of Fermi data (100 MeV to 1 TeV)
  - ULTRACLEANVETO class for galaxy clusters
  - SOURCE class for dwarfs (for their smaller sizes)
- 7 nearby galaxy clusters:
  - Virgo, Centaurus, Norma, Persus, Coma, Hydra, Fornax
- 8 classical dwarf spheroidal galaxies (dSphs):
  - Carina, Draco, Fornax, Leo I, Leo II, Sculptor, Sextans, Ursa Minor
- Profile likelihood method to set 95% C.L. limits for DM annihilation cross section or decay lifetime

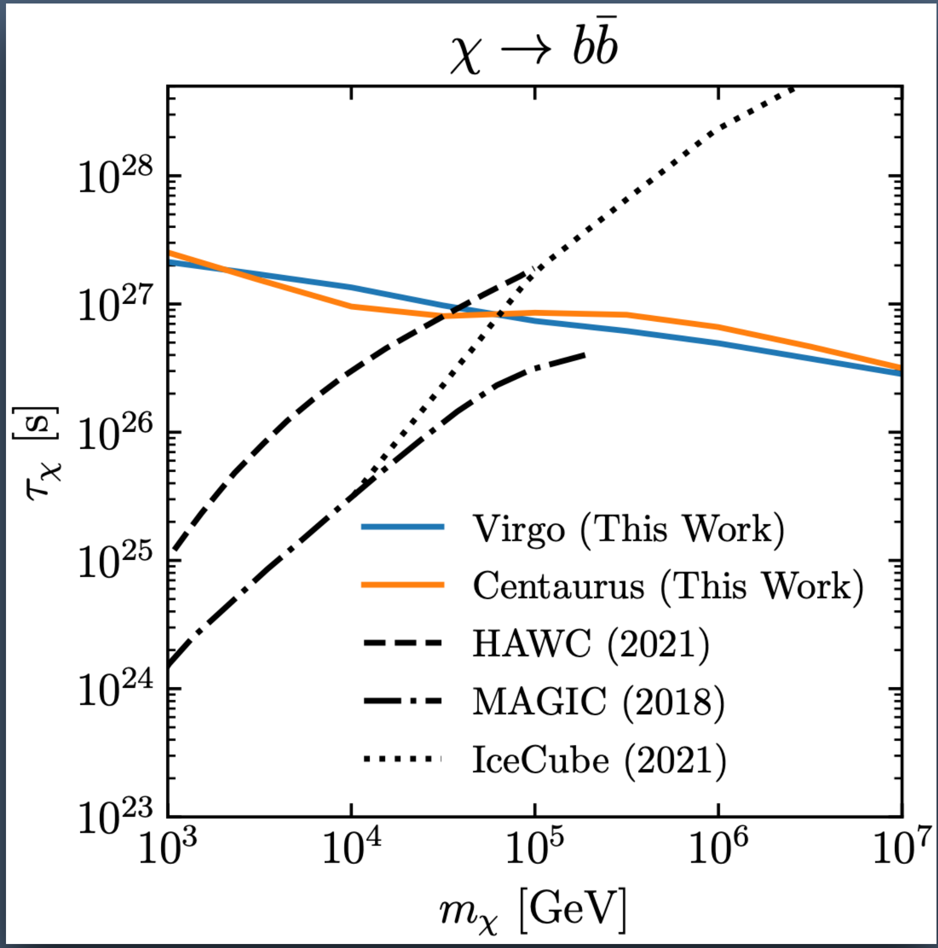
Constraints

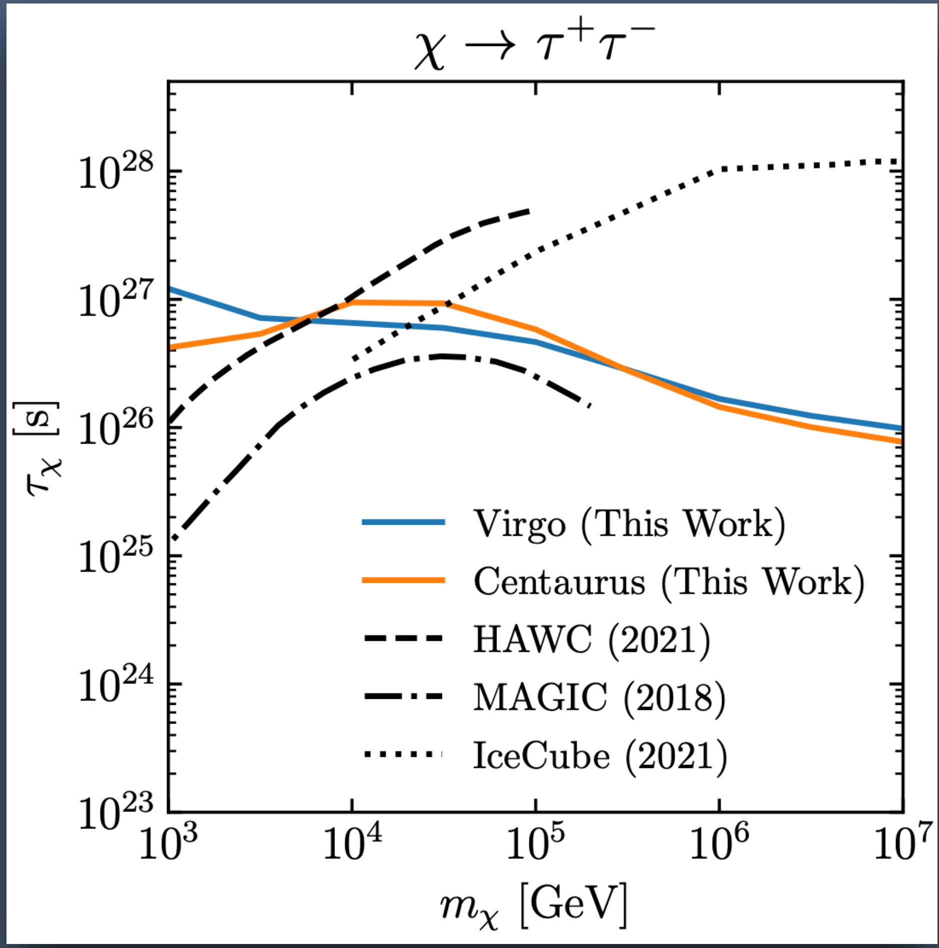




- Constraints on HDM annihilation from Draco dwarf
  - With secondary, Fermi limits are more stringent than other gamma-ray instruments

Constraints

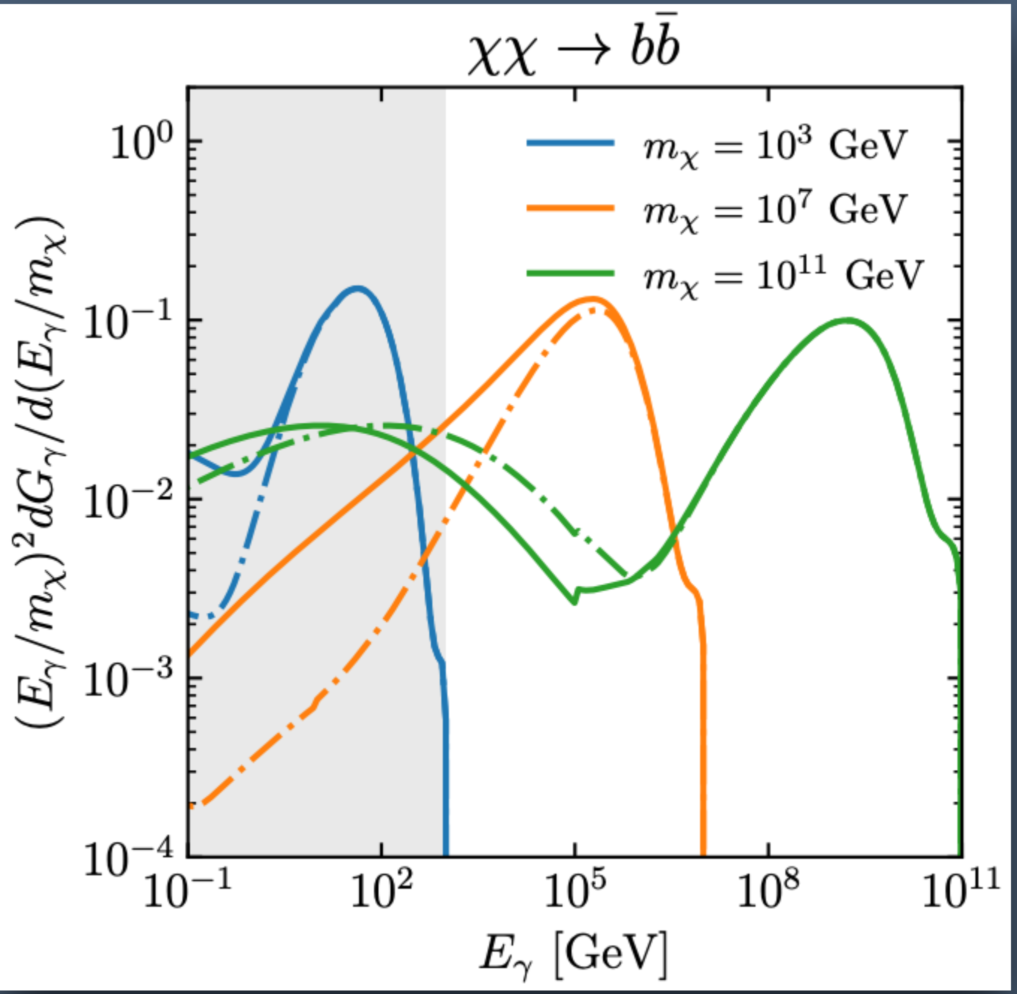


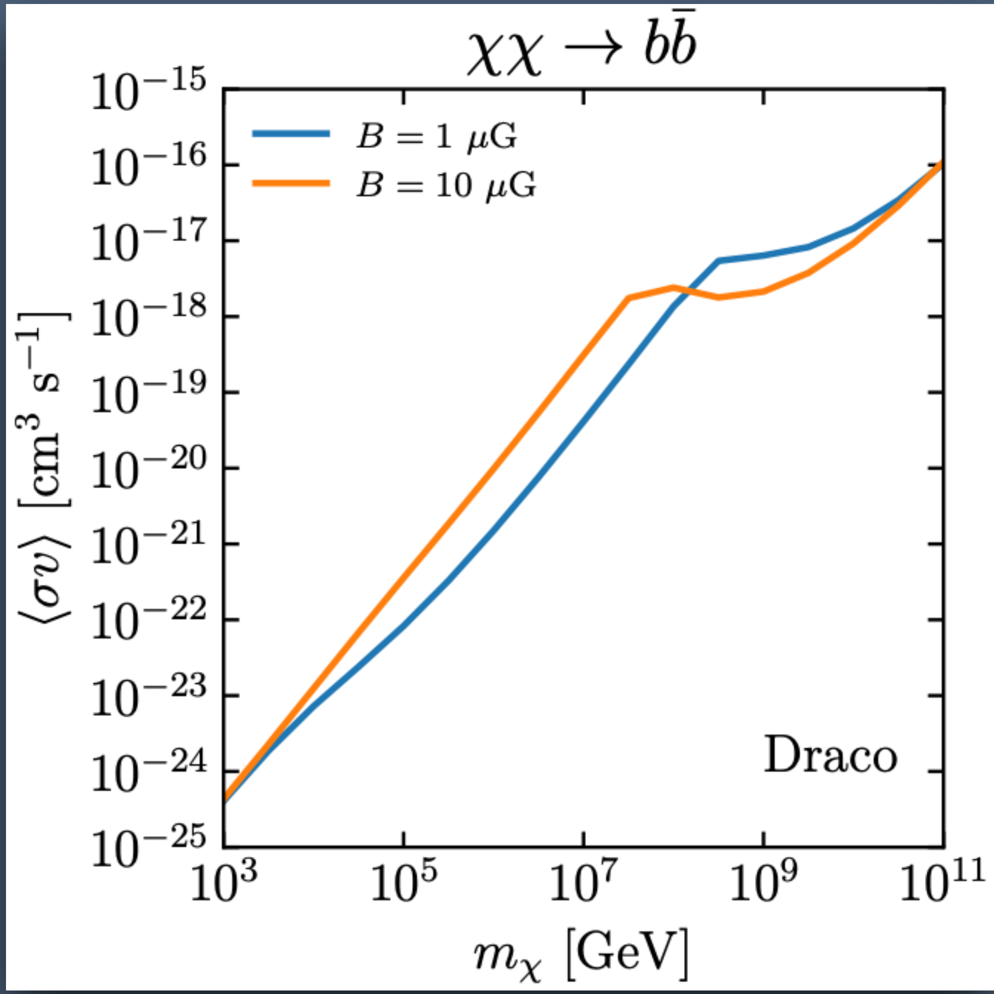


- Constraints on HDM decay from galaxy clusters (Virgo and Centaurus)
- Again, including secondary provides competitive limits

Please refer to our papers for all channels/targets
arXiv 2308.00589 & 2401.15606

Systematic uncertainty:
Varying magnetic field





- Varying magnetic field in the reasonable range alters the constraints by up to one order of magnitude

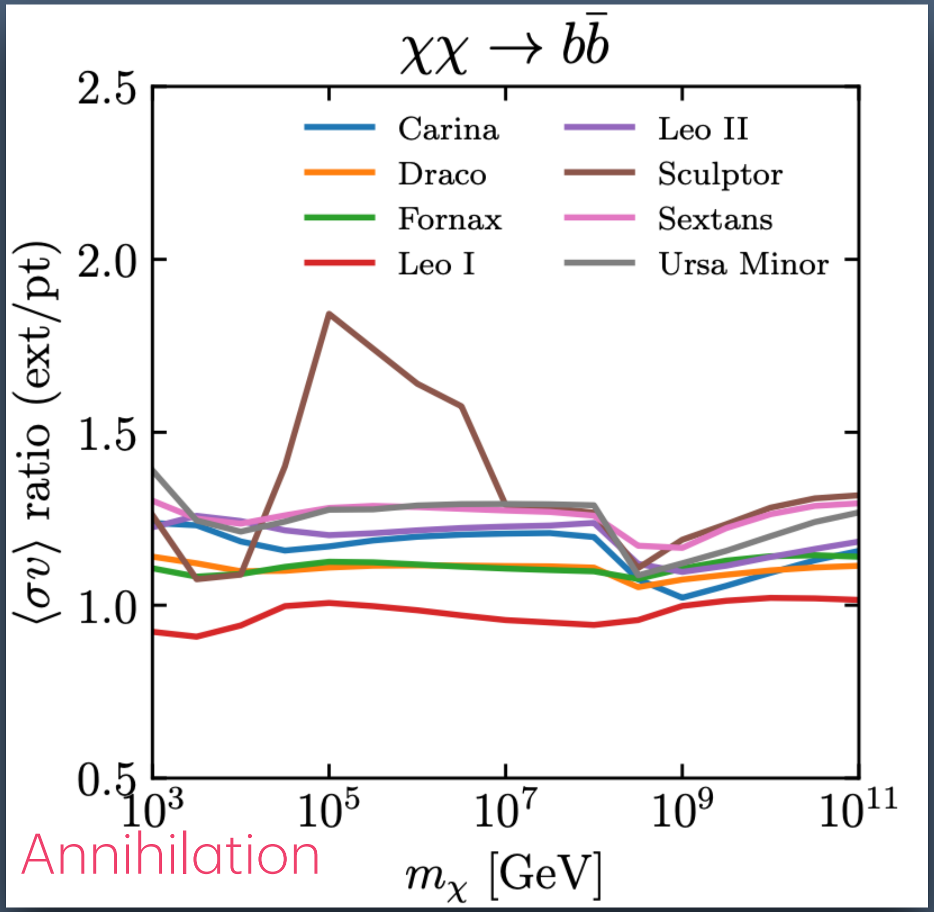
  - Draco dwarf, $B = 1 - 10\ \mu\mathrm{G}$

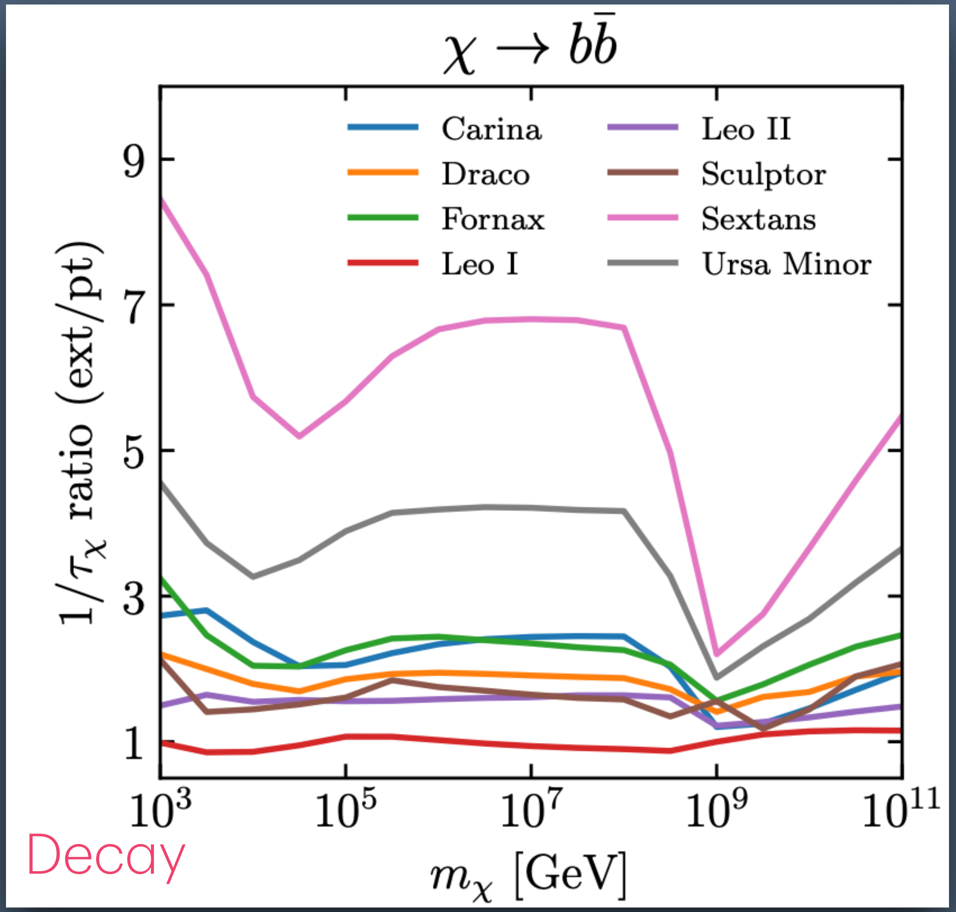
Systematic uncertainty:
Extended analysis vs point-source analysis

- We campare constraints by assuming the dwarfs as extended and point-like sources

- Extended analysis yields slightly weaker constraints

  - Consistent with previous work Di Mauro et al. (2022)





Summary

- We have set competitive constraints on heavy dark matter annihilation/decay using Fermi data by including secondary gamma rays caused by dark matter e+/e-.
- Our results are robust while considering different systematic uncetainties.
- Including secondary should be a norm
  - In case of non-detection, constraints are enhananced
  - In case of detection/excess, spectra are altered

Thank you!