Dark matter annihilation signatures from the possible faintest dwarf satellite galaxy

Peng-Fei Yin

Key laboratory of particle astrophysics,
Institute of High Energy Physics, CAS

XuYi， 2025. 10. 25

In collaboration with Y. Zhao, X. J. Bi, S. J. Lin, P. L. Zhang, and Q. Chang
arXiv: 2406.16769, 2409.12414

Outline

- *Indirect detection based on observations of dwarf satellite galaxies*
- *The properties of Ursa Major III (UMa III)*
- *Set constraints on DM annihilation cross section based on the Fermi-LAT gamma-ray observation*
- *Investigate the SKA sensitivities to the radio signals*

Photon signals from WIMP

- *Preserve the information of the nature and distribution of the DM*
- *Primary signal flux of DM annihilation*

$$\left(\frac{dN}{dE}\right)^A = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_\chi^2}\left(\frac{dN}{dE}\right)_i^A \times \boxed{\int d\Omega \int_{\text{l.o.s.}} dl \ \ \rho^2[r(l,\psi)]}$$

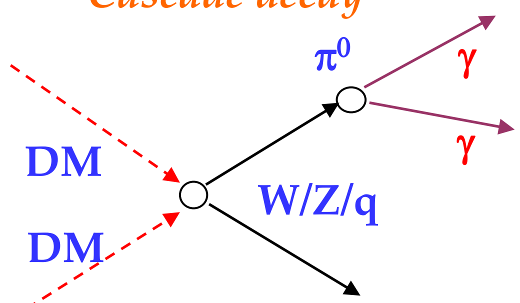
J factor: astrophysical factor depending on the DM distribution of source

- *Primary signal flux of DM decay*

$$\left(\frac{dN}{dE}\right)^D = \frac{1}{4\pi}\frac{1}{\tau_\chi m_\chi}\left(\frac{dN}{dE}\right)_i^D \times \boxed{\int d\Omega \int_{\text{l.o.s.}} dl \ \ \rho[r(l,\psi)]}$$ ← D factor

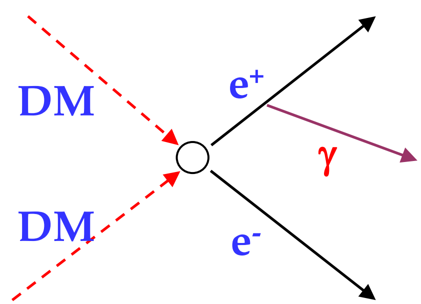
- *Primary processes. We focus on gamma-ray signals from WIMP*

Cascade decay



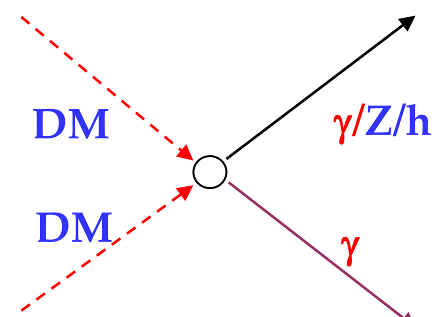
soft spectrum

Final state radiation



hard spectrum

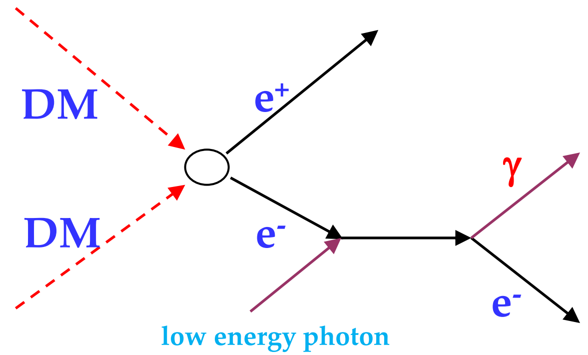
Monochromatic line



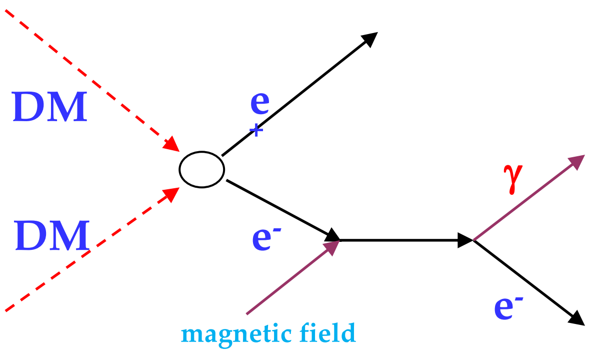
line spectrum

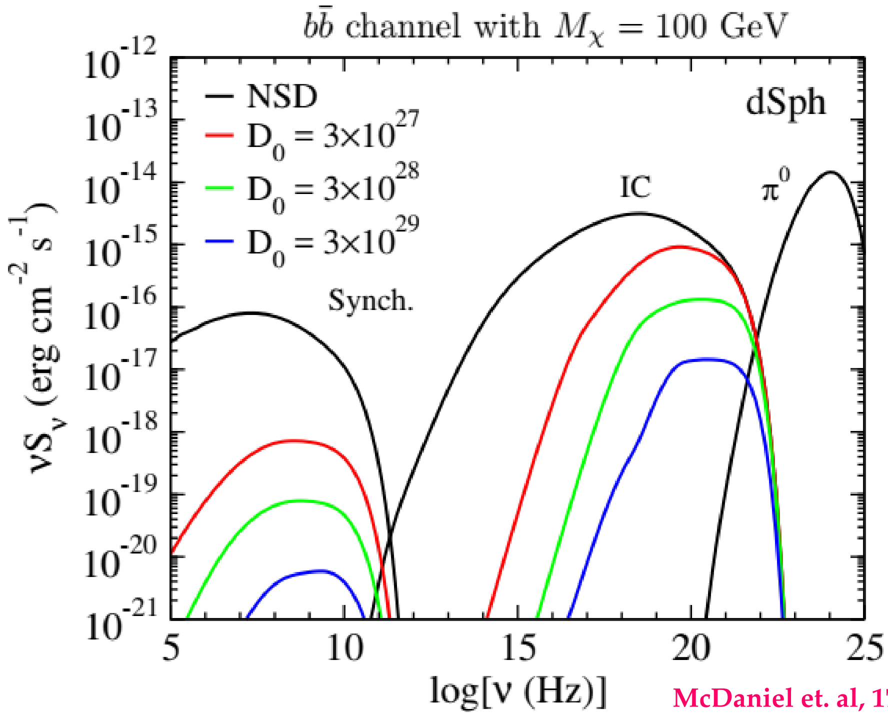
Multi-wavelength signals

Inverse Compton scattering



Synchrotron radiation

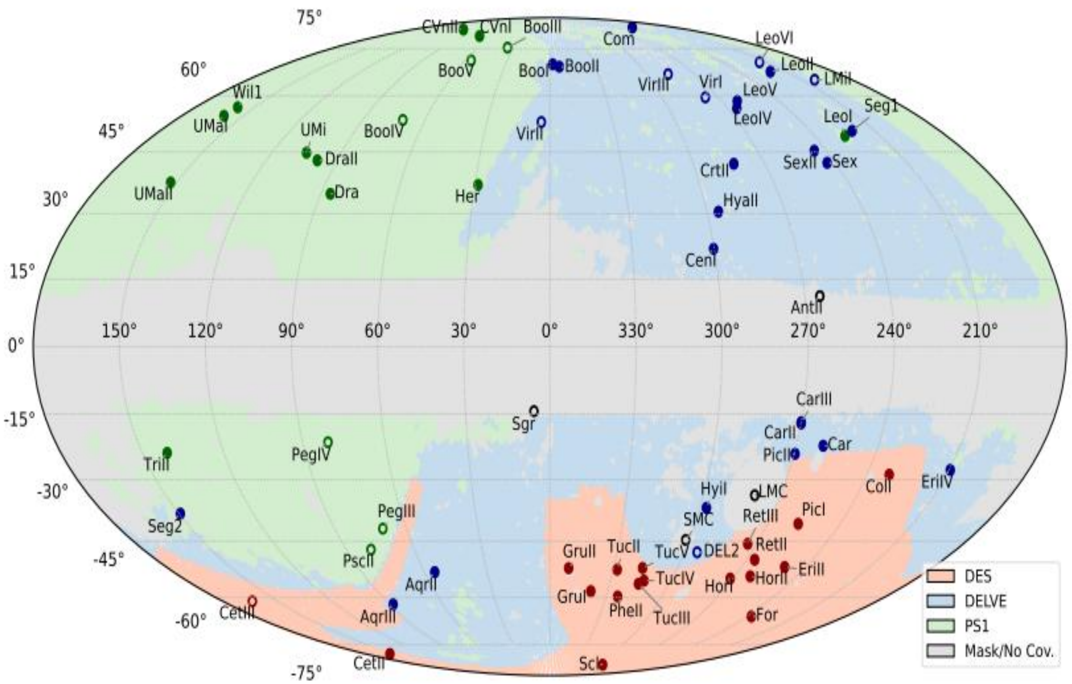




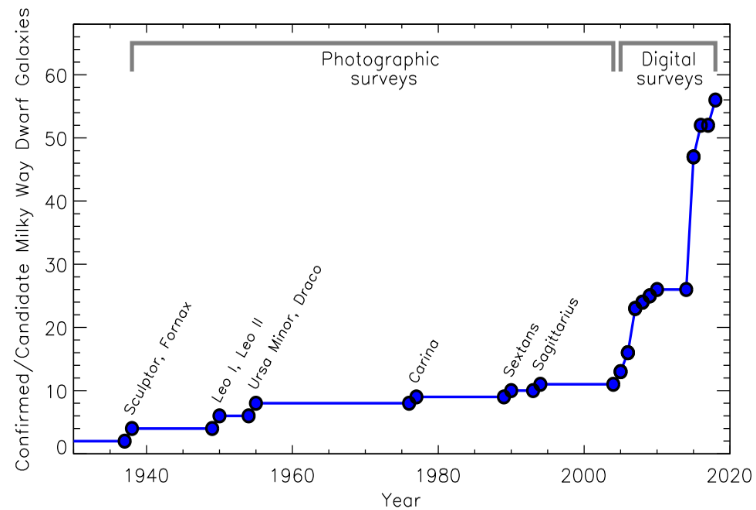
McDaniel et. al, 1705.09384

- *Secondary emission processes. primary $e^\pm$ from DM annihilation/decay interact with other matter during propagation. They produce photons at lower energies.*
- *Include inverse Compton scattering, synchrotron, bremsstrahlung, and Coulomb energy loss.*
- *Signals from radio to X-ray. High resolution.*
- *Flux depends on the environment of astrophysical systems. Uncertainties!*

Dwarf satellites are ideal probe



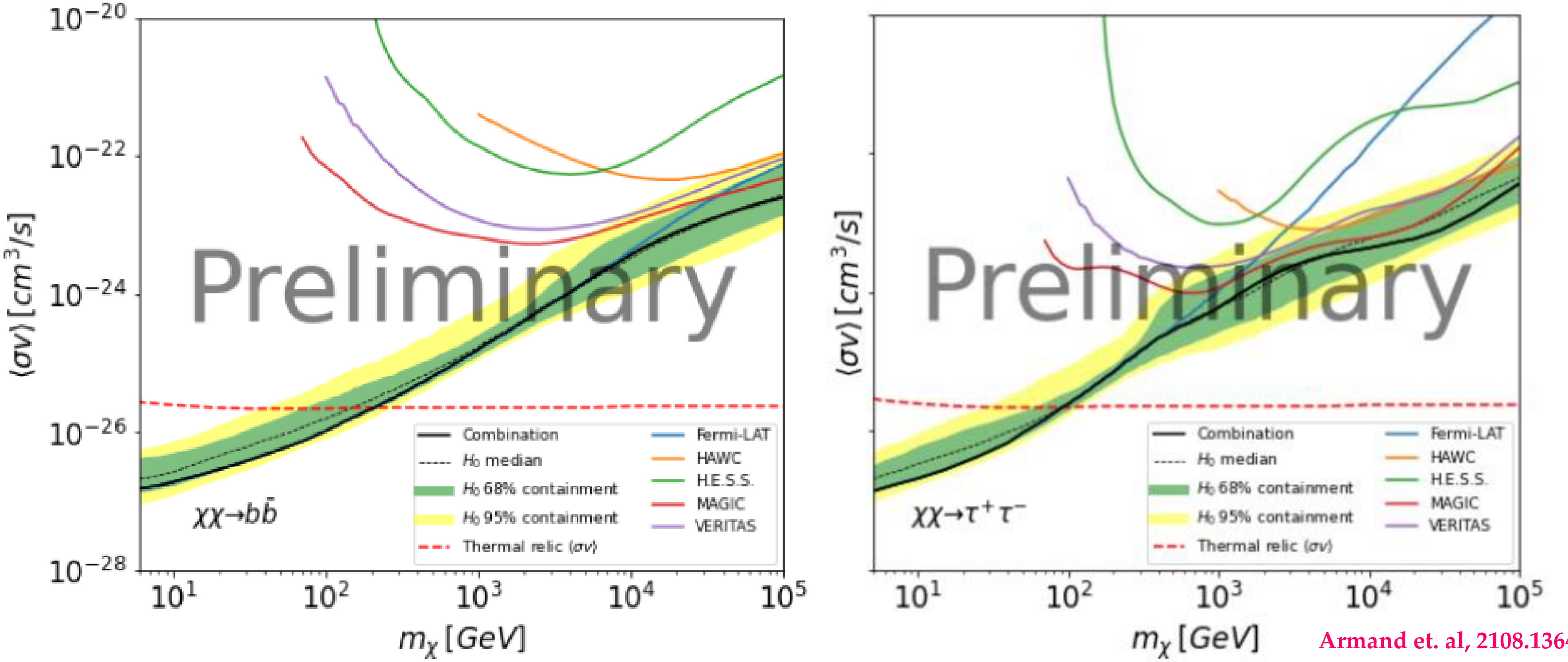
DELVE, DES, 2509.12313



Simon, 1901.05465

- *Dwarfs are ideal probe for DM indirect detection*
- *Nearby sources; large mass-luminosity ratio (DM dominant); small backgrounds*
- *Current 60+ sources. Increasing discoveries*

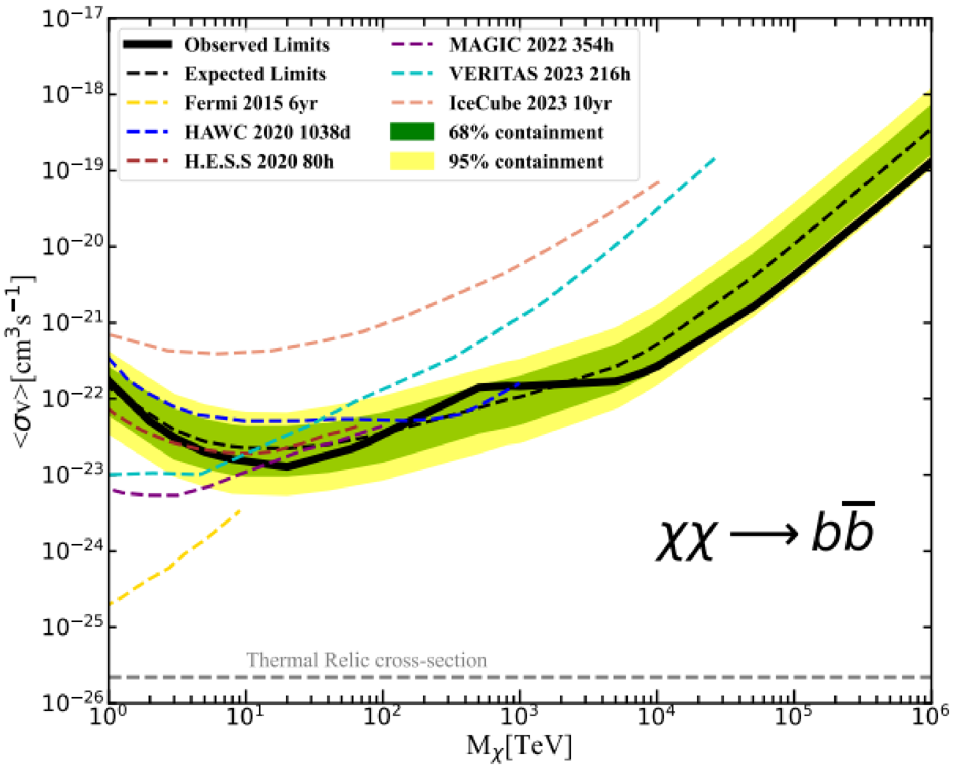
Limits from dSphs

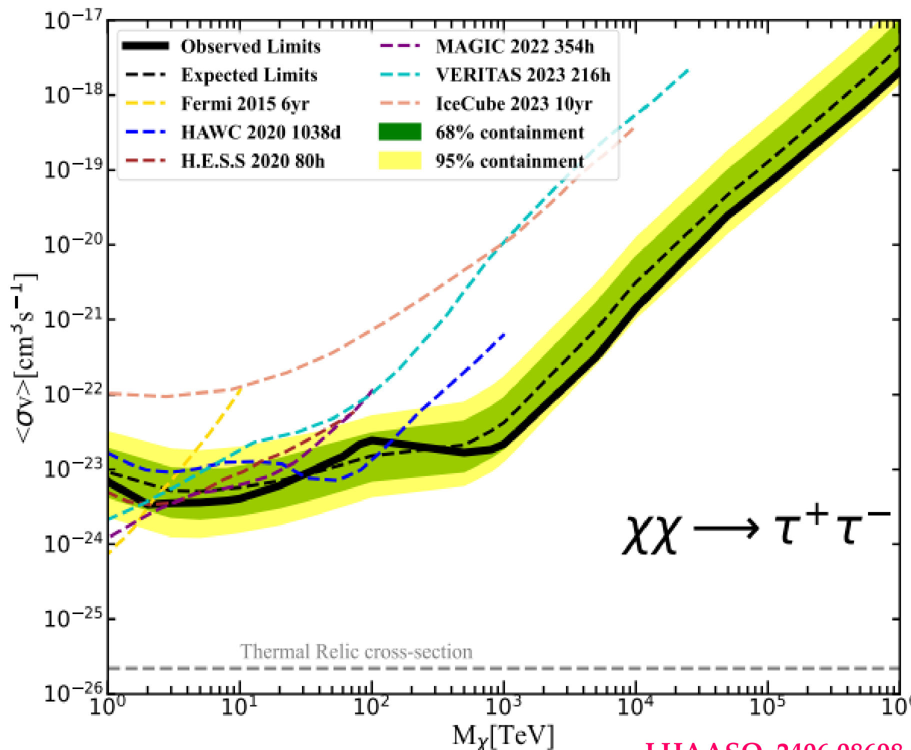


Armand et. al, 2108.13646

- *limits base on the observations of Fermi-LAT, HWAC, H.E.S.S., MAGIC, and VERITAS*
  Observations of 20 dSphs are considered in the combined analysis
- *Ground-based gamma-ray experiments investigate very high energy gamma-ray*
  Set constraints for very heavy DM
- *Uncertainties of the J-factor should be considered*

Limits from dSphs





LHAASO, 2406.08698

- *Latest LHAASO limits (from 16 dSphs)*
- *Most stringent limits on heavy DM*

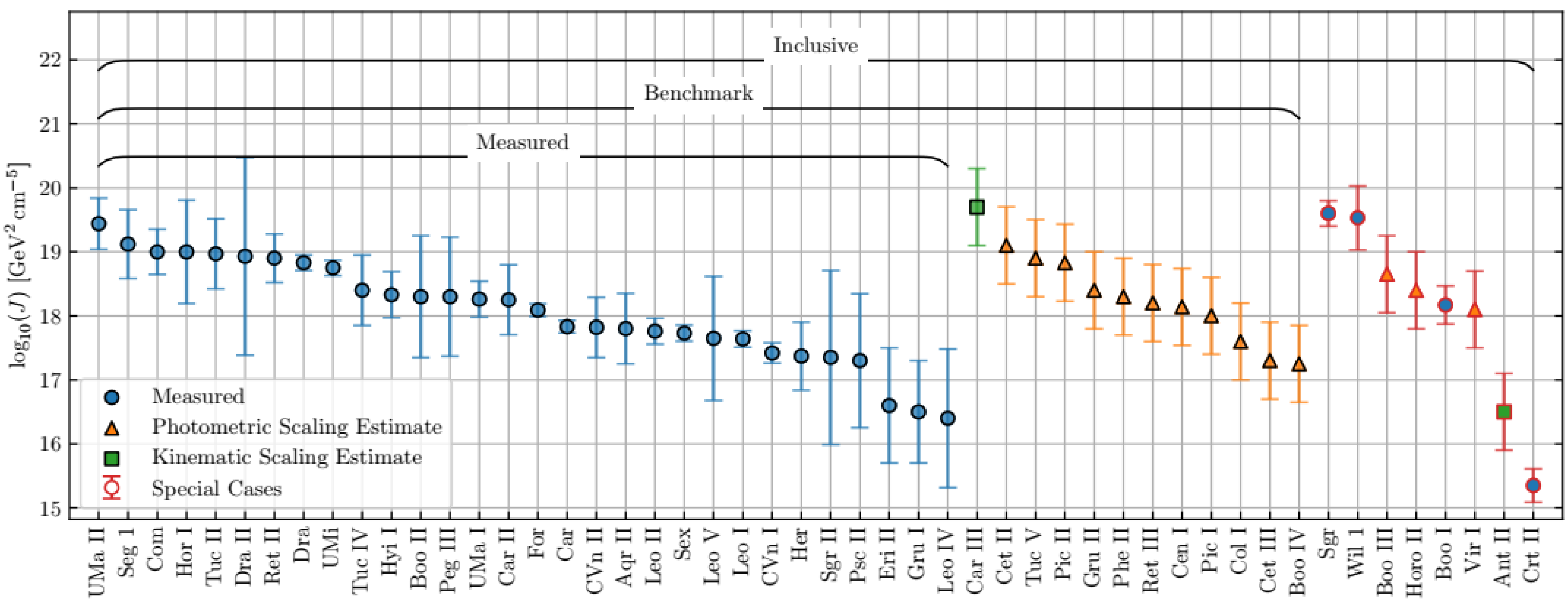
J factors

- *J factor is very important for these studies*
- *Can be derived from Jeans analysis or scaling relation*

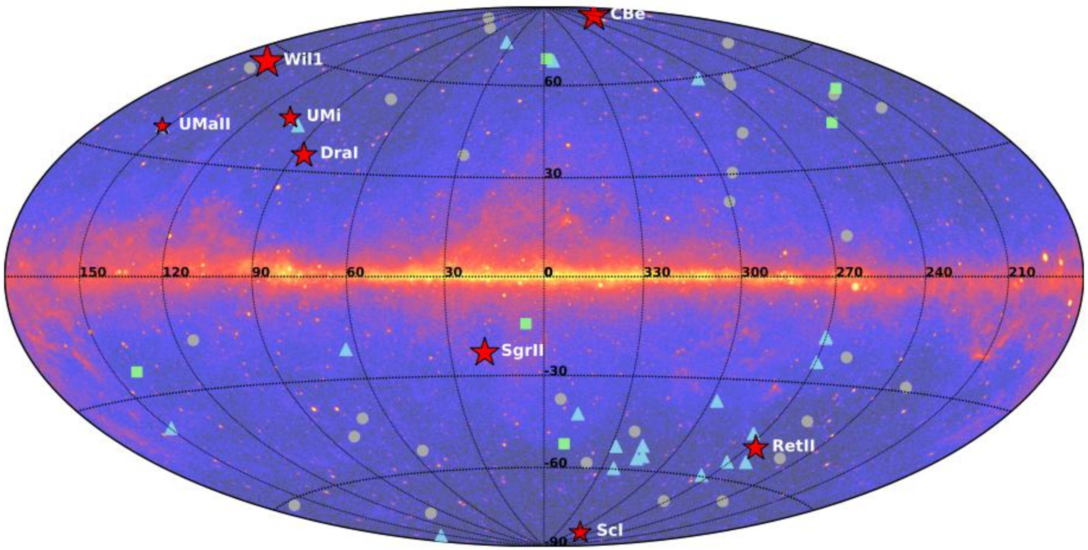
$$\frac{J(0.5°)}{\mathrm{GeV^2 cm^{-5}}} = 10^{17.87}\left(\frac{\sigma_{\mathrm{l.o.s}}}{5\,\mathrm{kms^{-1}}}\right)^{4}\left(\frac{d}{100\,\mathrm{kpc}}\right)^{-2}\left(\frac{r_{1/2}}{100\,\mathrm{pc}}\right)^{-1}$$

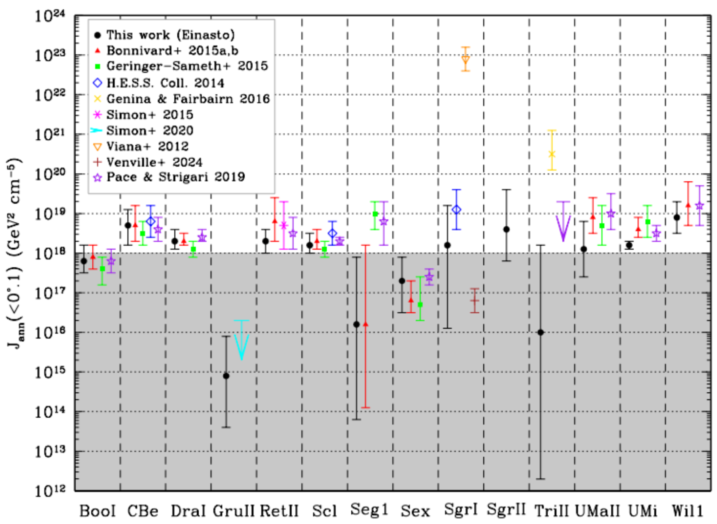
$$\frac{J(0.5°)}{\mathrm{GeV^2 cm^{-5}}} = 10^{18.17}\left(\frac{L_V}{10^4 L_\odot}\right)^{0.23}\left(\frac{d}{100\,\mathrm{kpc}}\right)^{-2}\left(\frac{r_{1/2}}{100\,\mathrm{pc}}\right)^{-0.5}$$

McDaniel et. al, 2311.04982



Few sources are more important





CTAO, 2508.19120

- *Only a fraction of dSphs are needed to be used in indirect DM detection*
- *For instance, in the CTAO analysis*
  - *29 of total 64 dSphs are too far (with d> 100 kpc)*
  - *Considering the quality of photometric and spectroscopic data, only 14 dSphs are selected*
  - *8 dSphs are optimal with large J factors*

Properties of Ursa Major III

- *Ursa Major III/UNIONS I is a stellar system discovered by a search for faint Local Group systems in the deep wide-field Ultraviolet Near Infrared Optical Northern Survey (UNIONS) in 2023.*

Smith et. al, 2311.10147

- *This system is very close to the Earth.*
  Distance to the Sun is ~10 kpc; distance to the Galactic Center is ~14 kpc

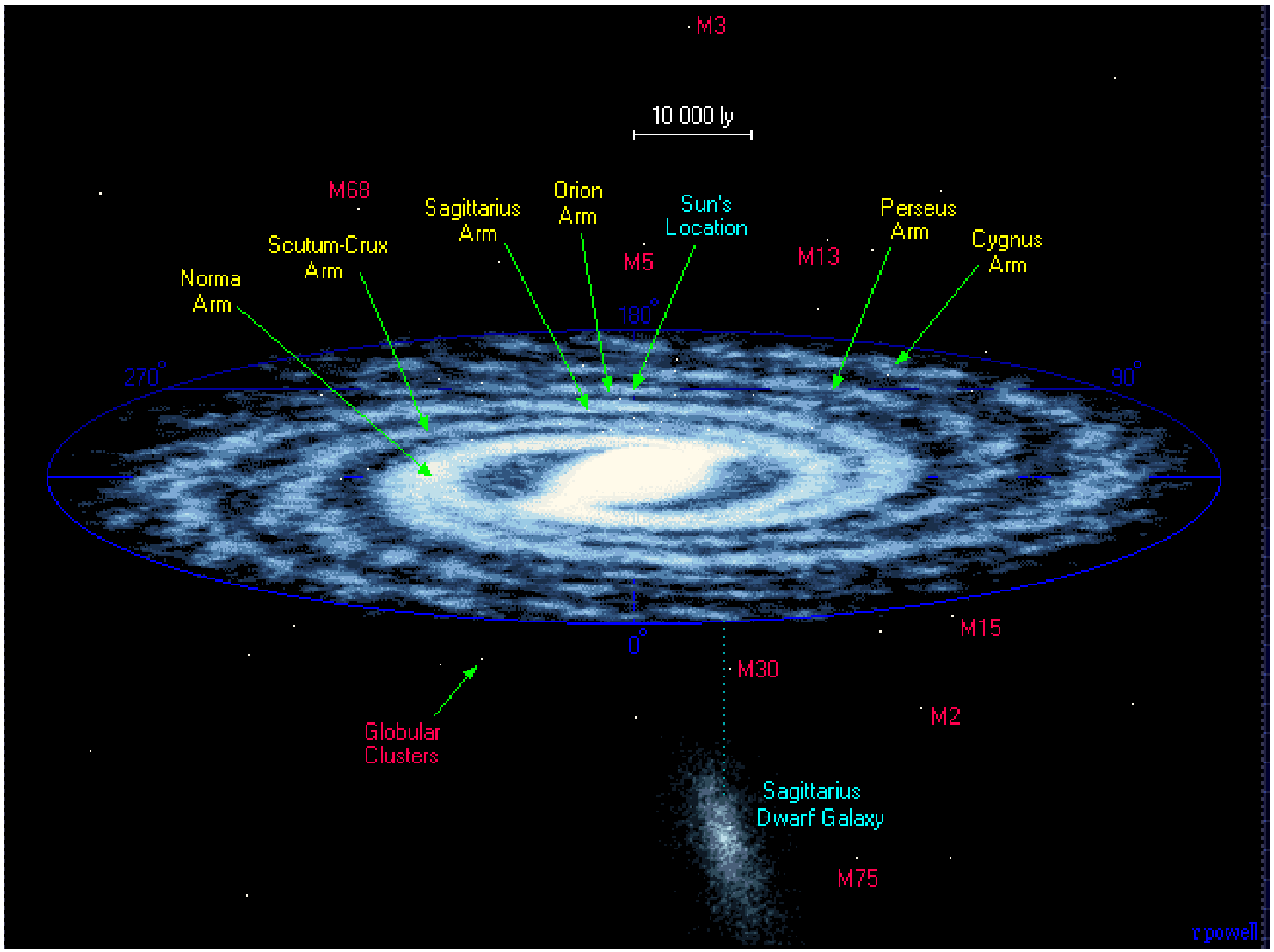
- *An old $\tau > 11$ Gyr and metal-poor [Fe/H]~-2.2 stellar population.*

- *Very small half-light radius ~3 pc. Stellar mass ~ 16 M_s. Absolute M_V~+2.2.*

- *A dwarf spheroidal galaxy (dSph) or a star cluster.*

UMa III is very close

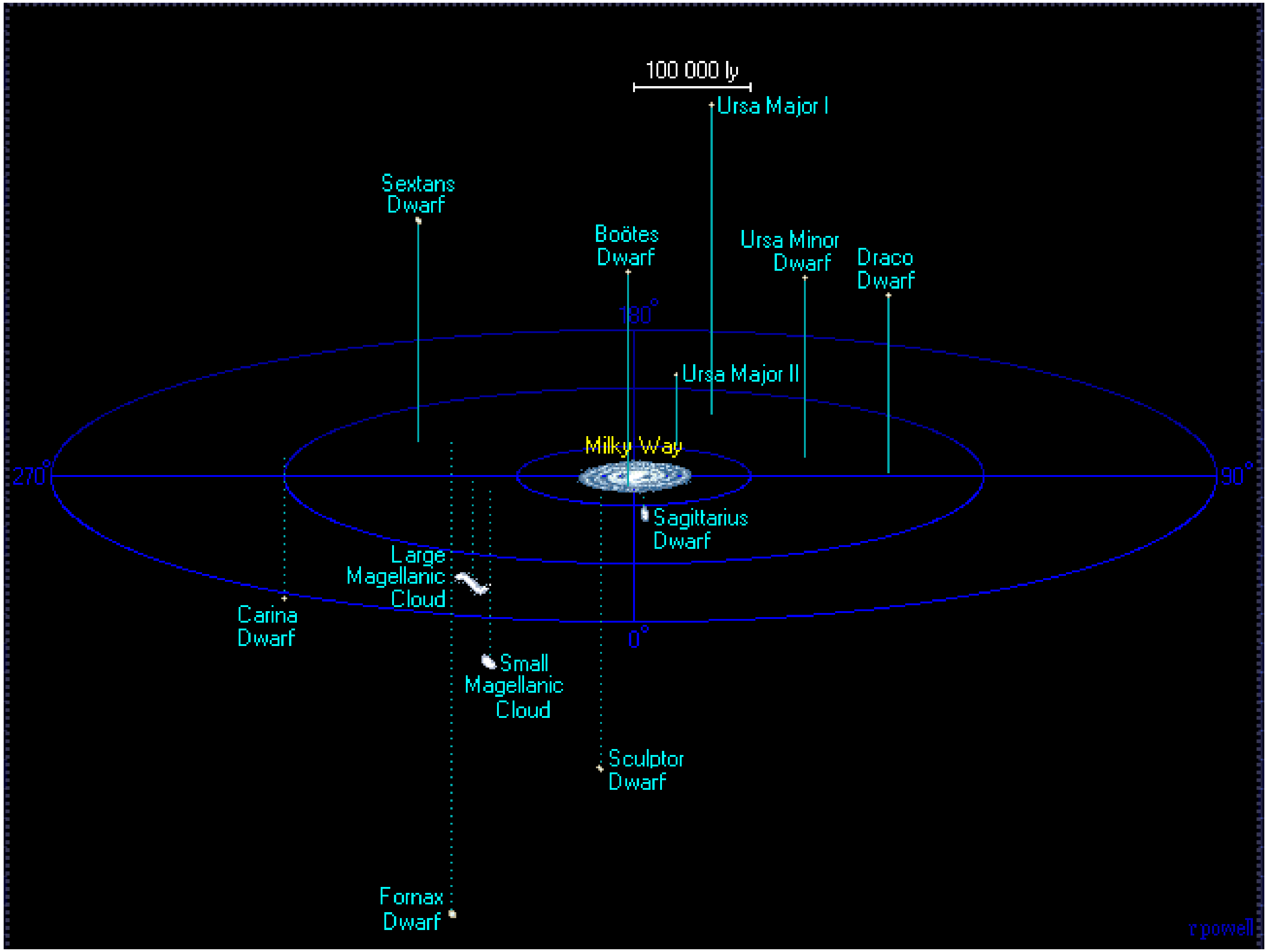
- *UMa III is very close to the Earth with d~10 kpc (l=194°, b=74°)*



http://www.atlasoftheuniverse.com/galaxy.html

UMa III is very close

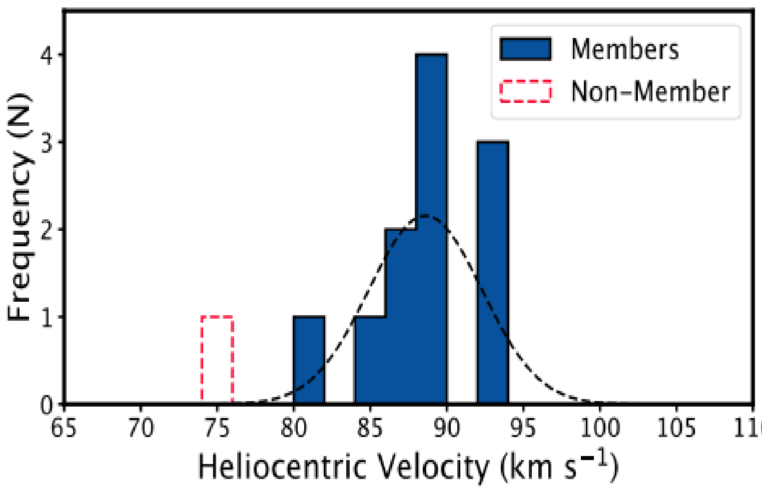
- *UMa III is very close to the Earth with d~10 kpc (l=194°, b=74°)*



http://www.atlasoftheuniverse.com/sattelit.html

Velocity distribution

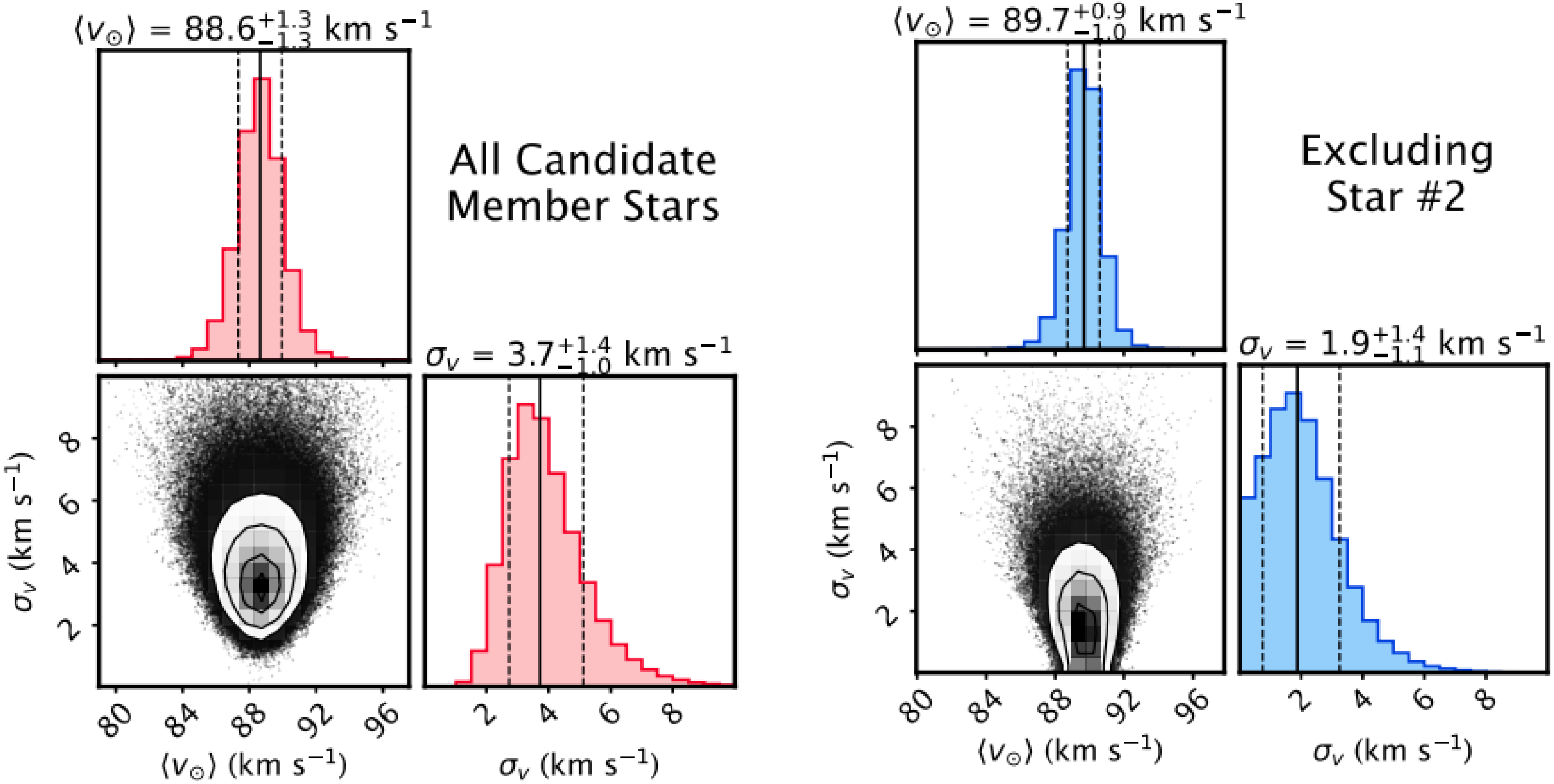
Object	Gaia Source ID	$v_{\odot}$ (km s^{-1})	P_{sat}	Member?
1	4024083571202406912	89.3 ± 1.3	0.99	Y
2	4024177442007708672	81.4 ± 1.5	1.0	Y
3	4024177648166139904	89.9 ± 1.5	1.0	Y
4	4024178472800038016	92.6 ± 1.6	0.99	Y
5	4024179297433597056	n/a[a]	0.10	N
6	4024177648166141184	88.9 ± 2.0	0.99	Y
7	4024178472800038144	86.7 ± 2.5	0.99	Y
8	4024036262137953536	74.4 ± 1.9	0.02	N
9	4024177442007709440	93.7 ± 2.5	0.75	Y
10	4024177751245359744	84.4 ± 2.6	0.99	Y
11	4024177682525881344	93.6 ± 2.5	n/a[b]	Y
12	4024177442007706752	86.3 ± 2.8	n/a[b]	Y
13	4024177648166141312	88.6 ± 3.3	n/a[b]	Y



Smith et. al, 2311.10147

- *Using the measurements of velocity distribution of stars to determine the mass and density of the system.*
- *Only 11 member stars are considered.*

Velocity dispersion



Smith et. al, 2311.10147

$$\ln L = -\frac{1}{2}\sum_{i=1}^{N}\ln\left(\sigma_i^2+\sigma_v^2\right) - \frac{1}{2}\sum_{i=1}^{N}\frac{(v_i-\langle v_\odot\rangle)^2}{\sigma_i^2+\sigma_v^2} - \frac{N}{2}\ln(2\pi)$$

- *11 member stars, velocity dispersion ~3.7 km/s*
- *10 member stars, velocity dispersion ~1.9 km/s*

What is the nature of UMa III

- *If UMa III is a star cluster* **Errani et. al, 2311.10134**

  Under the assumption of dynamical equilibrium, consider the virial theorem

$$\langle\sigma_{\rm los}^2\rangle = \frac{5}{96}\frac{GM_\star}{r_\star} \qquad \rho_\star(r) = \rho_0\ \exp(-r/r_\star)$$

Using the half-light radius and stellar mass, the velocity dispersion is

$$\sigma_{\rm los} \equiv \langle\sigma_{\rm los}^2\rangle^{1/2} = 49^{+14}_{-11}\,{\rm m\,s^{-1}}$$

This value is much smaller than previous measured value ***~O(1) km/s***

- *Controversy, given the measured value, the dynamical mass is estimated as*

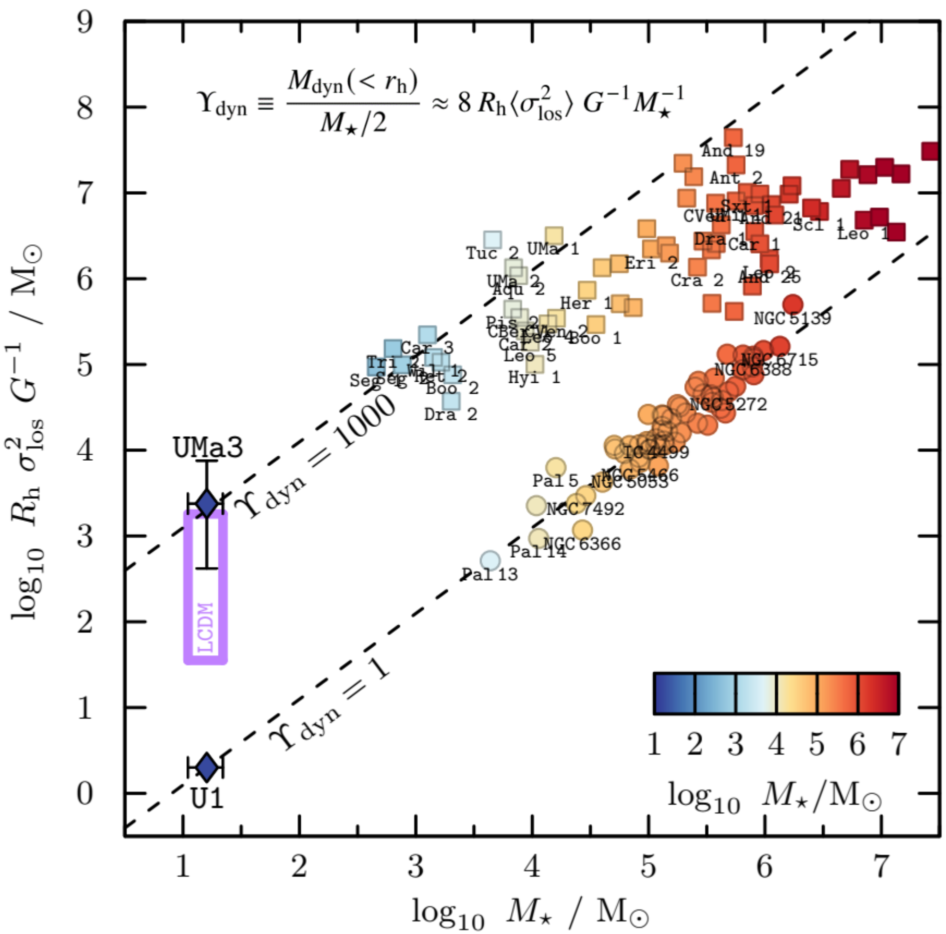
$$M_{\rm dyn}(<r_{\rm h}) \approx 4\,R_{\rm h}\langle\sigma_{\rm los}^2\rangle G^{-1} = \left(1.0^{+2.1}_{-0.8}\right)\times 10^4\,{\rm M_\odot}$$

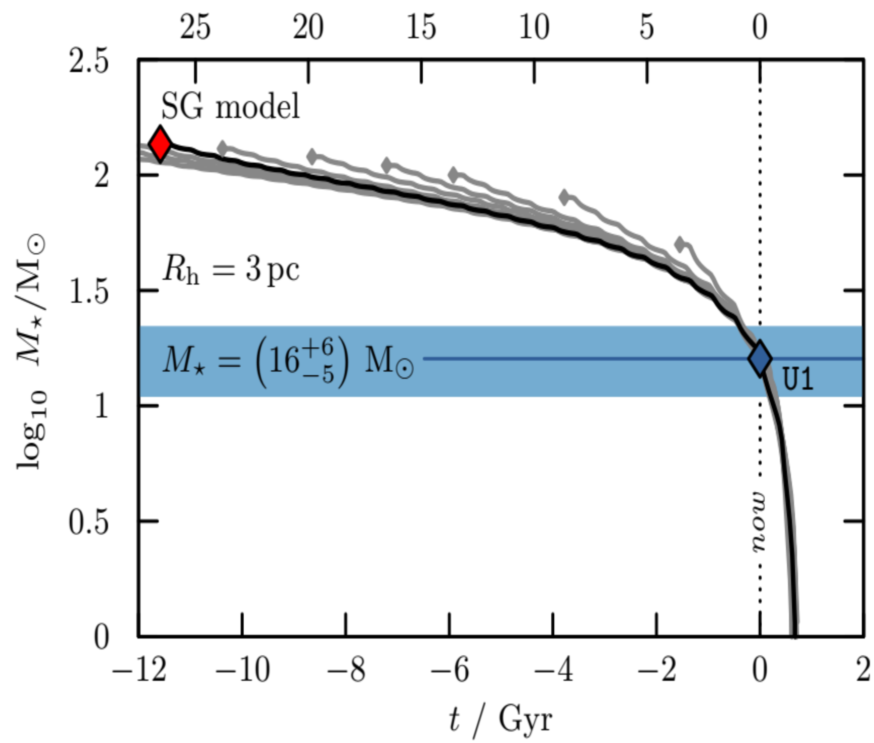
$$\bar{\rho}_{\rm h} = \left(4^{+11}_{-3}\right)\times 10^{10}\,{\rm M_\odot\,kpc^{-3}}$$

This system has large mass to light ratio and central density, thus it is a dwarf galaxy with substantial DM component.

It may be the faintest and densest dwarf galaxy in the Milky Way.

What is the nature of UMa III

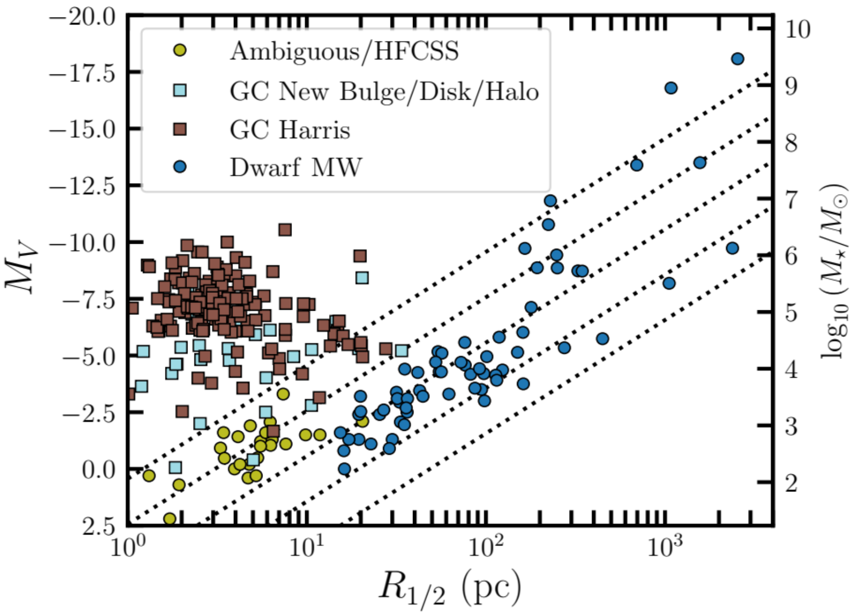


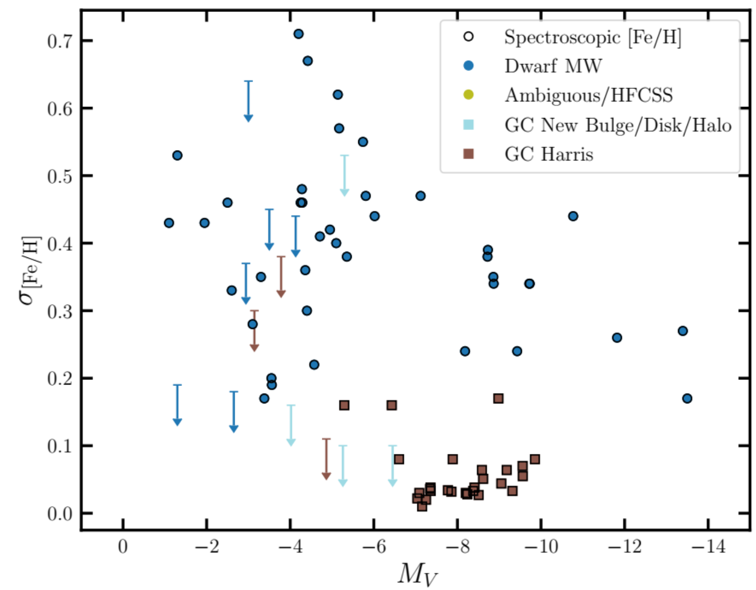


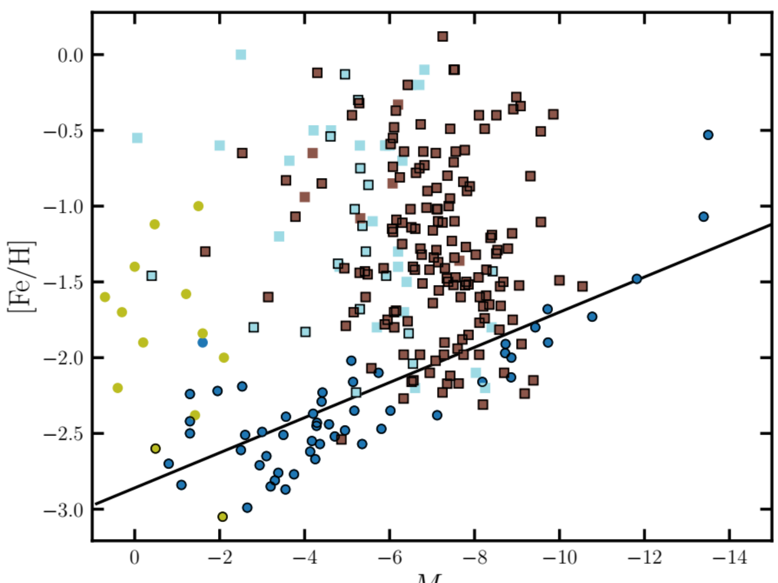
Errani et. al, 2311.10134

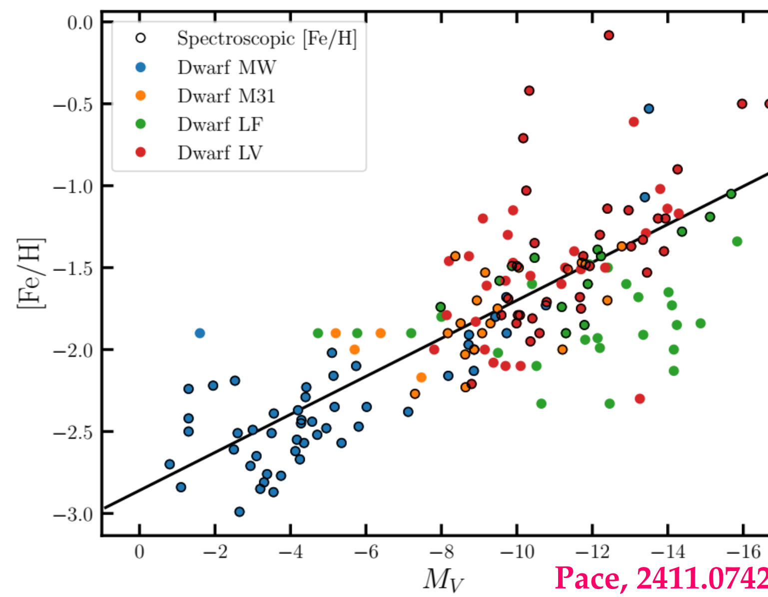
- *Dynamical to stellar mass ratio indicates UMa III is not a star cluster.*
- *Another argument: if UMa III is a star cluster, it will quickly disrupt within ~0.6 Gyr. This means that we accidentally observe it at a special point in its evolution.*

Dwarf or Cluster









Pace, 2411.07424

Significant annihilation signals

- *The flux of DM annihilation signals is given by*

$$\Phi = \frac{1}{8\pi m_{\rm DM}^2} \int \frac{{\rm d}N_\gamma}{{\rm d}E_\gamma} {\rm d}E_\gamma \int_{\Delta\Omega} \int_{l.o.s.} \langle \sigma v \rangle \rho^2 {\rm d}l {\rm d}\Omega$$

- *The astrophysical factor* ***J-factor*** *is defined as*

$$J(\Delta\Omega) = \int_0^{\Delta\Omega} d\Omega \int_{l.o.s} dl \rho^2(l, \psi, \theta)$$

The J-factor of UMa III can be roughly estimated as

$$\mathcal{J}(0.5^\circ) = 10^{17.87} \left(\frac{\sigma_{\rm l.o.s.}}{5\ {\rm km\ s^{-1}}}\right)^4 \left(\frac{D}{100\ {\rm kpc}}\right)^{-2} \left(\frac{r_{1/2}}{100\ {\rm pc}}\right)^{-1}$$

$$\log_{10}\left(\frac{\mathcal{J}(0.5^\circ)}{{\rm GeV^2\ cm^{-5}}}\right) = 20.87^{+0.60}_{-0.58}$$

Crnogorcevixc, Linden, 2311.14611

A very large value, indicating ***significant*** *DM annihilation signals*

Jeans equation

- *In our study, we perform a Jeans analysis to determine the DM density profile within UMa III*

Zhao, Bi, Lin, Yin, 2406.16769

- *The dynamics of a stellar system in a gravitational field is determined by the Jeans equation (assuming a spherical symmetry and steady-state system)*

$$\frac{1}{\nu(r)}\frac{\mathrm{d}}{\mathrm{d}r}[\nu(r)\sigma_r^2] + 2\frac{\beta_{\mathrm{ani}}(r)\sigma_r^2}{r} = -\frac{GM(r)}{r^2}$$

$\nu(r)$: three-dimensional stellar number density

$M(r)$: enclosed mass at r, dominated by DM

$\beta(r)$: stellar velocity anisotropy $\beta_{\mathrm{ani}}(r) = 1 - \sigma_\theta^2/\sigma_r^2$

- *Solution*

$$\nu(r)\sigma_r^2 = \frac{1}{A(r)}\int_r^\infty A(s)\nu(s)\frac{GM(s)}{s^2}\mathrm{d}s \qquad A(r) \equiv A_{r_1}\exp[\int_{r_1}^{r} \tfrac{2}{t}\beta_{\mathrm{ani}}(t)\mathrm{d}t]$$

Jeans equation

- *Since only the two-dimensional projected stellar number density can be provided by observations, the solution is rewritten as*

$$\sigma_p^2(R) = \frac{2}{I(R)} \int_R^\infty \left[1 - \beta_{\rm ani}(r)\frac{R^2}{r^2}\right] \frac{\nu(r)\sigma_r^2 r}{\sqrt{r^2 - R^2}} \mathrm{d}r$$

$\sigma(R)$: projected velocity dispersion at projected radius R

$I(R)$: projected light profile

- *Consider NFW DM density profile*

$$\rho_{\rm DM} = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

- *Given three parameters r_s, ρ_s, β, $\sigma(R)$ can be obtained.*

Jeans analysis

- *Define likelihood function*

$$\mathcal{L}_{\text{unbin}} = \prod_{i=1}^{N_{\text{stars}}} \left(\frac{\exp\left(-\frac{1}{2} \frac{(v_i - \bar{v})^2}{\sigma_p^2(R_i) + \Delta_{v_i}^2} \right)}{\sqrt{2\pi \left[\sigma_p^2(R_i) + \Delta_{v_i}^2 \right]}} \right)^{P_i}$$

$\sigma(R)$: projected velocity dispersion at projected radius R
v: measured velocity of the member star
Δ_v: uncertainty of the velocity in the measurement
P: probability of the star as a member star

- *We use the package CLUMPY to perform an MCMC analysis.*

More than 6000 profiles with parameters following the posterior probability distribution are obtained

Velocity dependent annihilation

- *The general velocity-dependent DM annihilation cross section can be written as*

$$\sigma v_{\rm rel} = a \cdot F(v_{\rm rel}) \equiv a \cdot (v_{\rm rel}/c)^n$$

The average cross section at a specific position

$$\langle \sigma v \rangle = a \iint F(v_{\rm rel}) f(v_1, \mathbf{r}) f(v_2, \mathbf{r}) \mathrm{d}v_1^3 \mathrm{d}v_2^3$$

f(v, r): assume a standard isotropic Maxwell-Boltzmann distribution

$$\langle \sigma v \rangle = a \int \sqrt{\frac{2}{\pi}} \frac{1}{v_p^3} v_{\rm rel}^2 \mathrm{e}^{-\frac{v_{\rm rel}^2}{2v_p^2}} F(v_{\rm rel}) \mathrm{d}v_{\rm rel} \equiv a \cdot f(r)$$

- *We define an effective J factor*

$$J = \int_{\Delta\Omega} \int_{l.o.s.} \rho^2(r) f(r) \mathrm{d}l \mathrm{d}\Omega$$

$$\Phi = \frac{a \cdot J}{8\pi m_{\rm DM}^2} \int \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \mathrm{d}E_\gamma$$

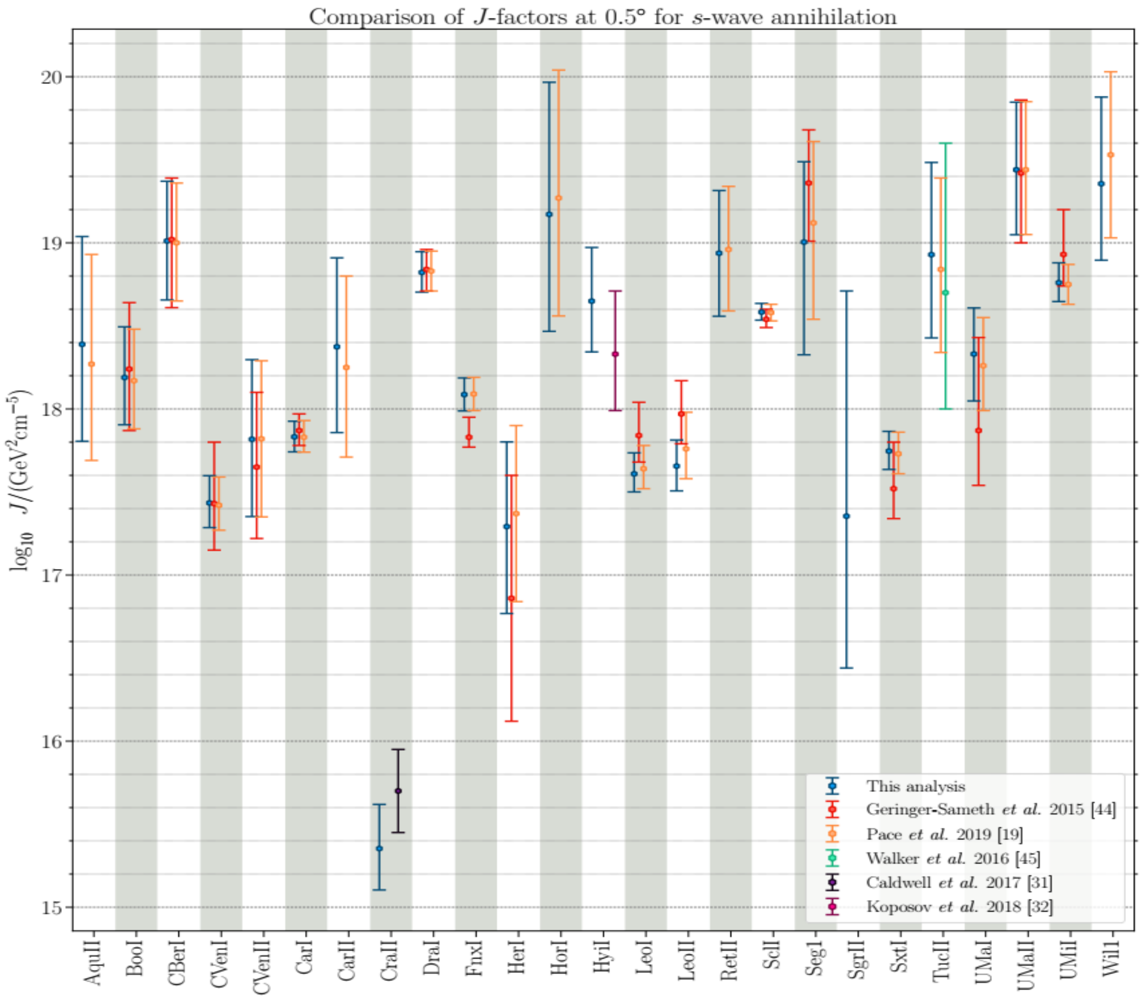
Large J factor of UMa III

- *We consider three scenarios, and obtain the large J factor and effective J factors for UMa III*

n	$\log_{10} J$ $(\log_{10}[\mathrm{GeV^2 cm^{-5}}])$
0 (*s*-wave)	$21.4^{+0.7}_{-0.7}$
2 (*p*-wave)	$13.6^{+1.4}_{-1.6}$
-1 (Sommerfeld-enhanced)	$25.3^{+0.5}_{-0.5}$

Zhao, Bi, Lin, Yin, 2406.16769

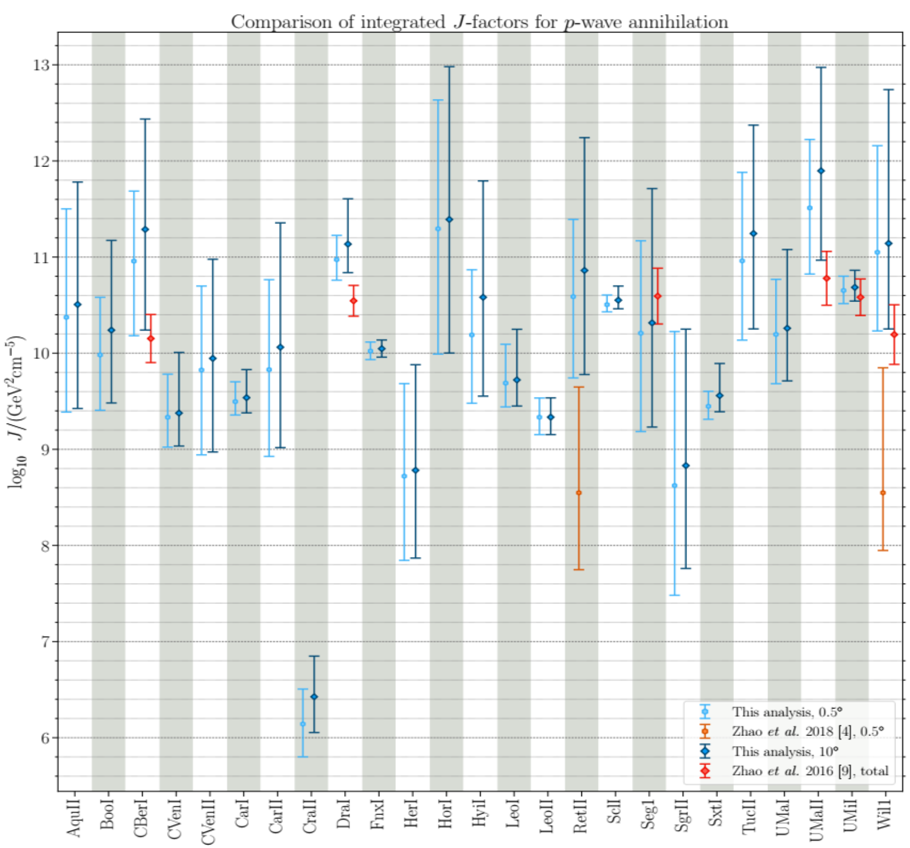
- *Compared with other dSphs, UMa III could provide more significant signatures*

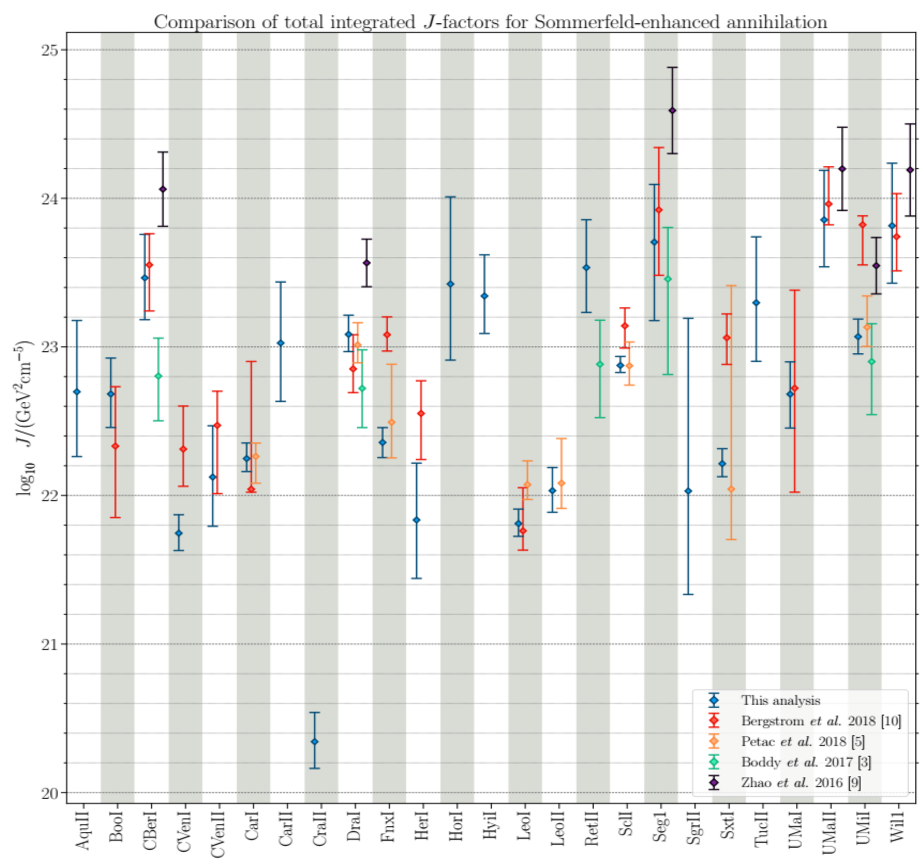


Boddy et. al, 1909.13197

Large J factor of UMa III

n	$\log_{10} J$ ($\log_{10}[\mathrm{GeV}^2\mathrm{cm}^{-5}]$)
0 (s-wave)	$21.4^{+0.7}_{-0.7}$
2 (p-wave)	$13.6^{+1.4}_{-1.6}$
-1 (Sommerfeld-enhanced)	$25.3^{+0.5}_{-0.5}$





Boddy et. al, 1909.13197

Strict constraints from Fermi-LAT

- *Given the close proximity and high DM density, UMa III is a very promising target for DM indirect detection.*

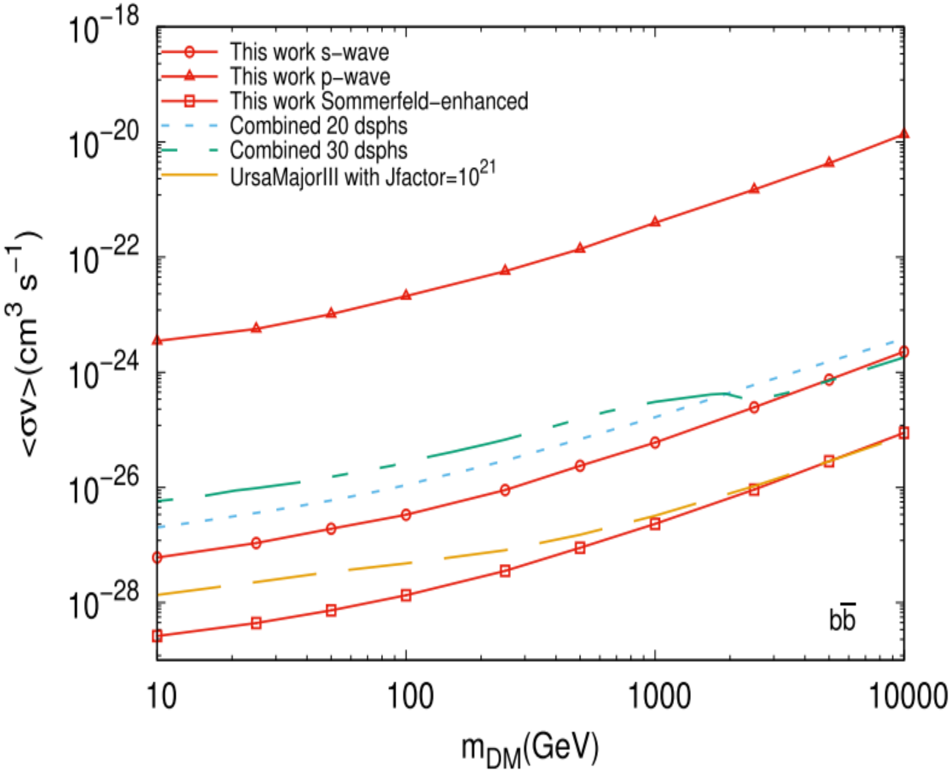
- *The location at high latitude implies there is no background from the Milky Way.*

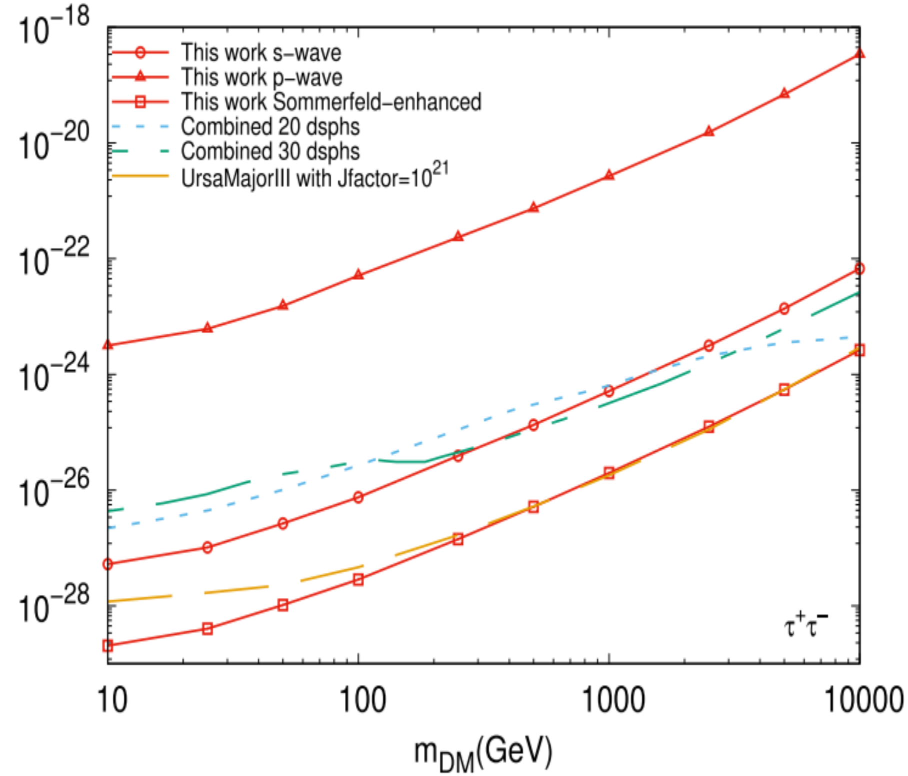
- *No gamma-ray excess from UMa III has been found in the Fermi-LAT data.*
  Crnogorcevixc, Linden, 2311.14611

- *We set constraints on the DM annihilation cross section, including the uncertainties from the J factor.*

$$\mathcal{L} = \prod_i \mathcal{L}_i(\Phi_i) \frac{e^{-[\log_{10}(J) - \log_{10}(J_{\rm med})]^2/2\sigma^2}}{\ln(10) J_{\rm med} \sqrt{2\pi}\sigma}$$

Strict constraints from Fermi-LAT

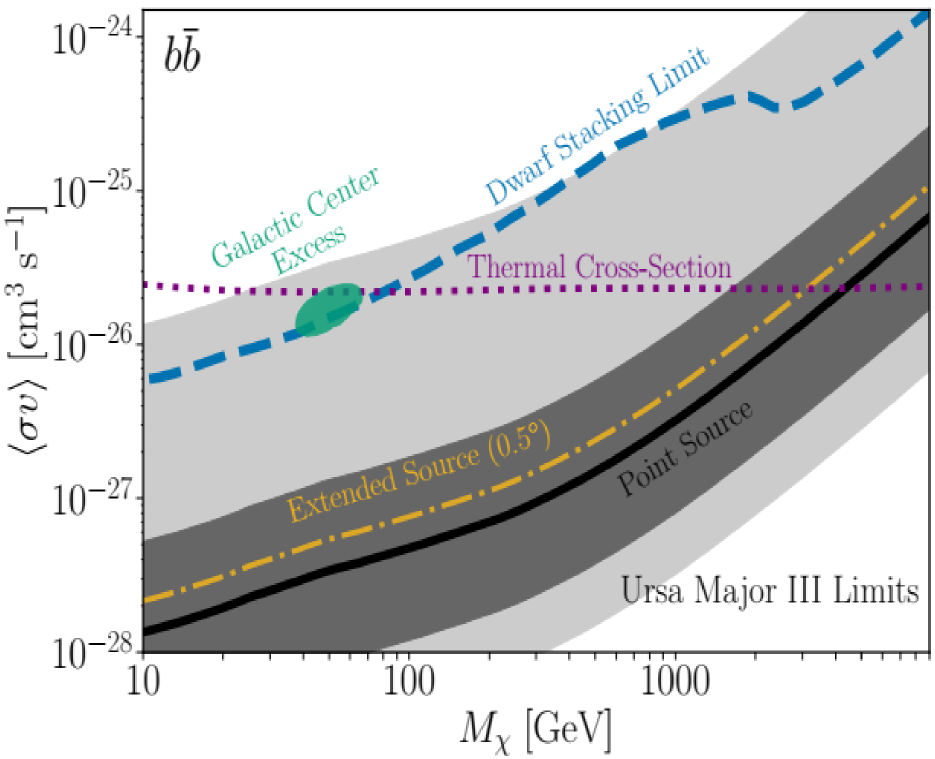


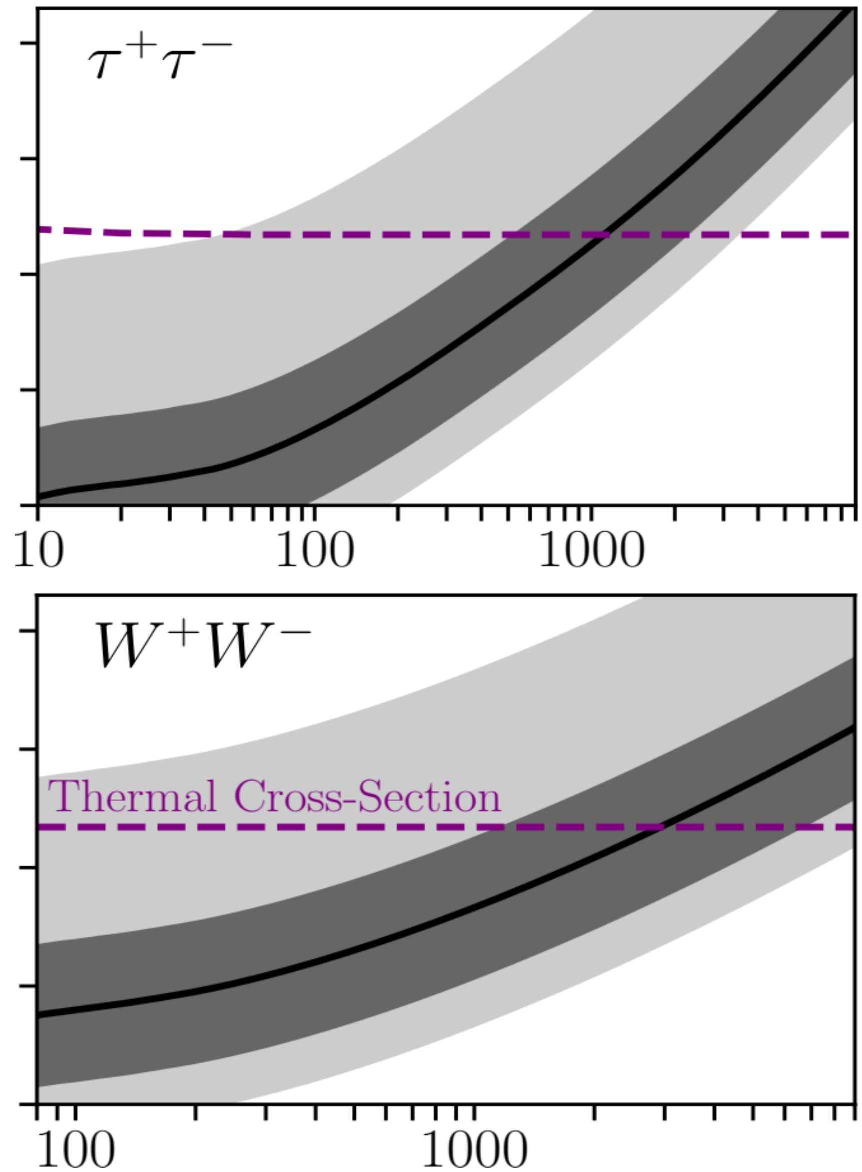


Zhao, Bi, Lin, Yin, 2406.16769

- *Compared with other experimental constraints, the observation of UMa III set very strict constraint on the DM annihilation cross section.*

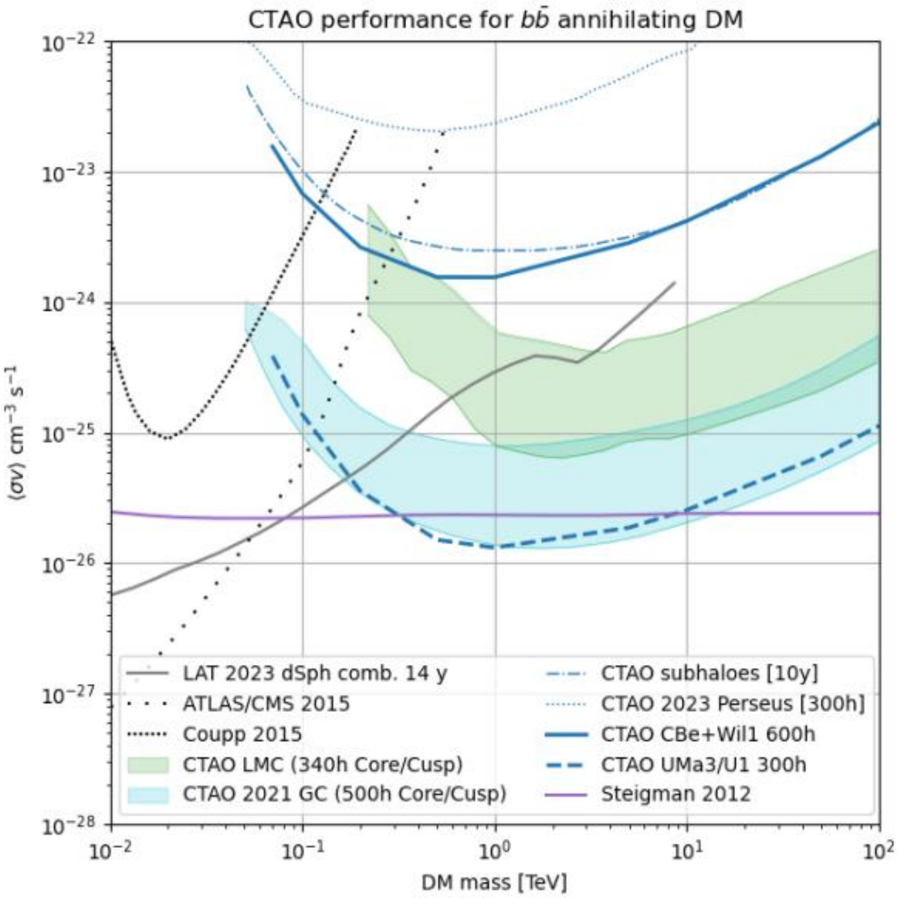
Strict constraints from Fermi-LAT

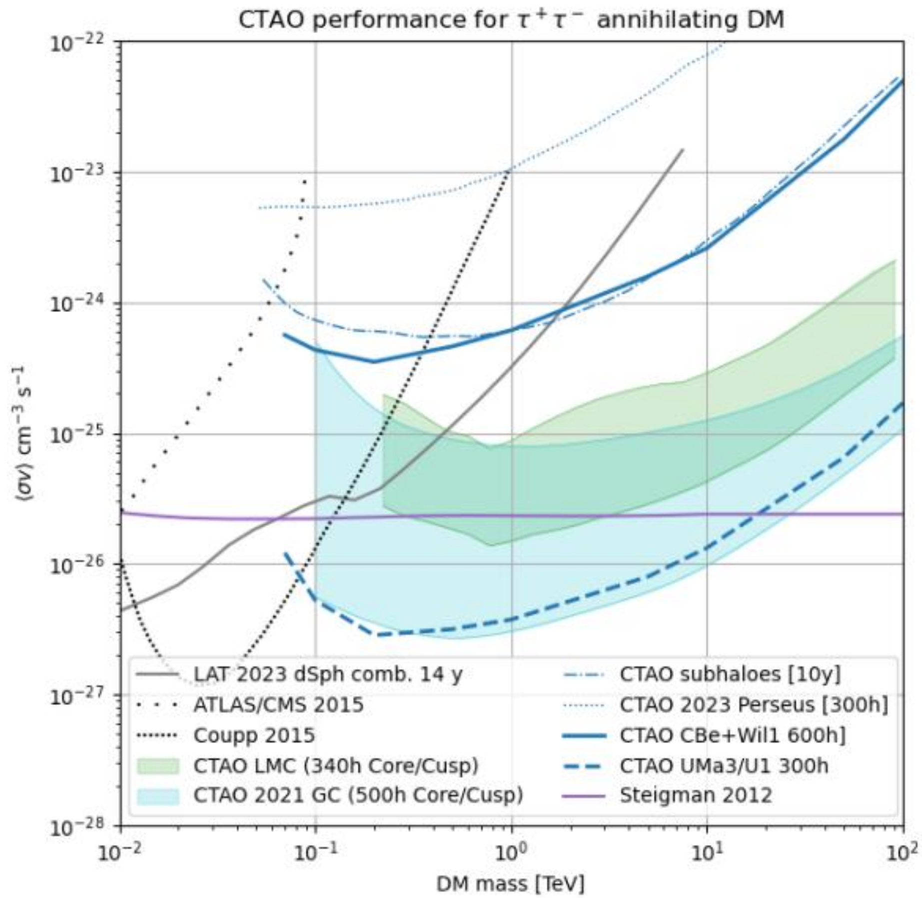




Crnogorcevic, Linden, 2311.14611

Expected limits from CTAO





CTAO, 2508.19120

Radio signals from DM in dSphs

- *Electrons and positrons from DM annihilation can generate a broad radio spectrum through the processes of synchrotron radiation and inverse Compton scattering.*

- *It is crucial to calculate the electron and positron spectrum by solving the **diffusion equation**.*

$$\frac{\partial}{\partial t}\frac{\partial n_e}{\partial E} = \nabla\left[D(E,\mathbf{r})\nabla\frac{\partial n_e}{\partial E}\right] + \frac{\partial}{\partial E}\left[b(E,\mathbf{r})\frac{\partial n_e}{\partial E}\right] + Q(E,\mathbf{r})$$

D(E): diffusion coefficient $D(E) = D_0(E/E_0)^\gamma$

b(E, r): energy loss term $b(E,\mathbf{r}) = b_{\rm IC}(E) + b_{\rm syn}(E,\mathbf{r}) + b_{\rm coul}(E) + b_{\rm brem}(E)$

Q(E, r): DM source term

$$Q(E,\mathbf{r}) = \frac{\rho(r)^2}{2m_\chi^2}\langle\sigma v\rangle\frac{dN_e}{dE}$$

Radio signals from DM in dSphs

- *The electron and positron spectrum is given by*

$$\frac{\partial n_e}{\partial E} = \frac{1}{b(E,\mathbf{r})} \int_E^{m_\chi} dE' G(\mathbf{r}, E, E') Q(E, \mathbf{r})$$

G(r, E, E′): Green function encompassing the diffusion and energy loss effects

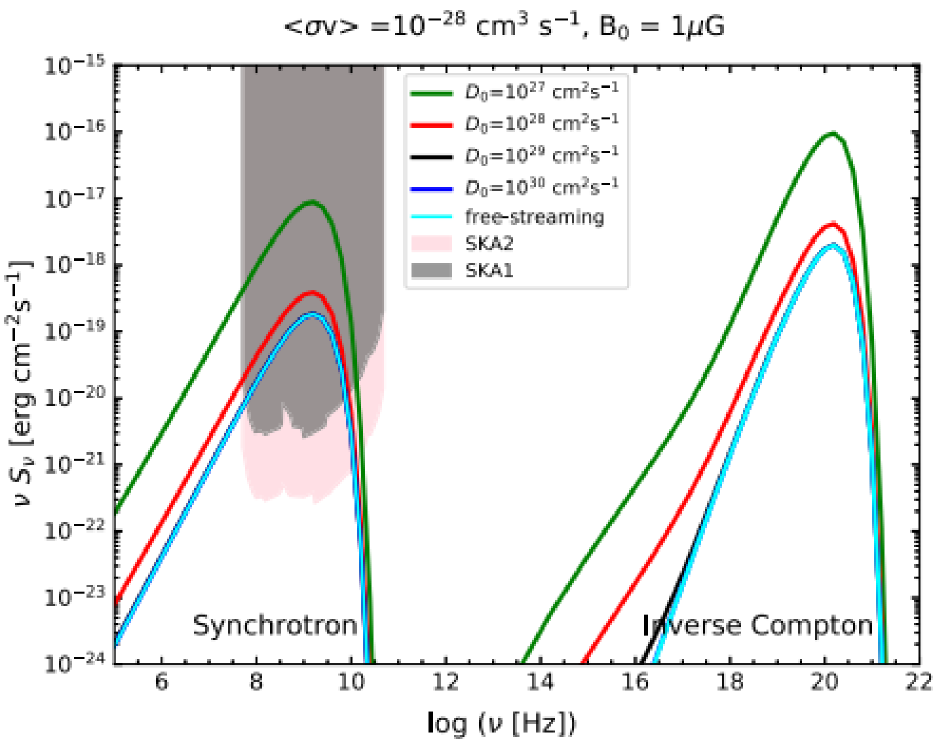
- *Radio flux density is given by (using package RX-DMFIT)*

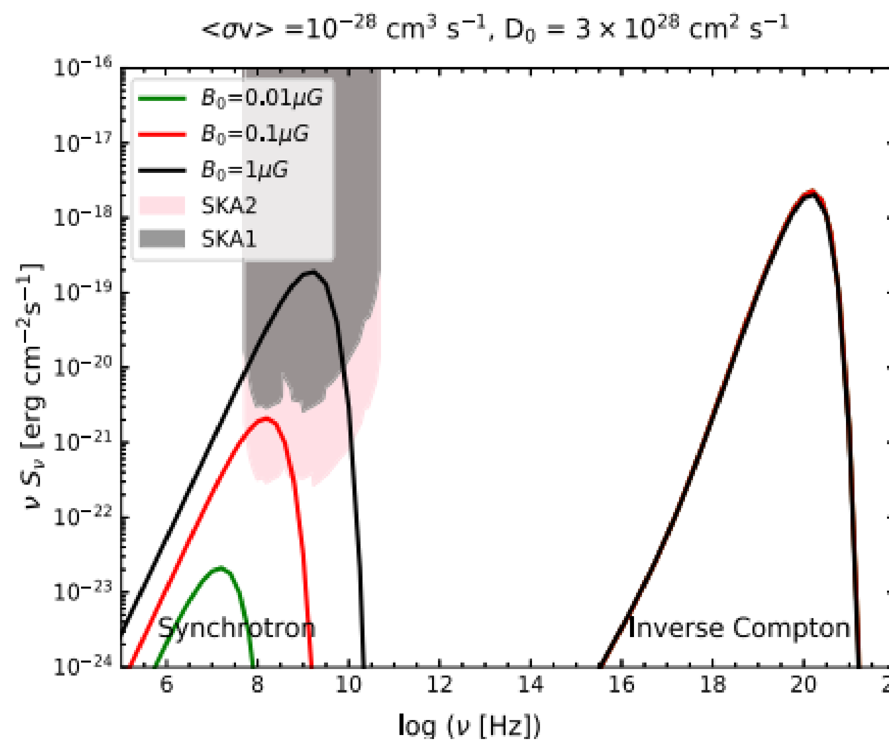
$$S(\nu) = \int_\Omega d\Omega \int_{\rm l.o.s.} \frac{dl}{4\pi} \int_{m_e}^{m_\chi} dE\, 2 \frac{dn_e}{dE}(E, r)(P_{syn}(\nu, E, r) + P_{IC}(\nu, E))$$

- *Predictions significantly depend on the magnetic field and diffusion model in astrophysical systems.*

These two factors are unclear in dSphs.

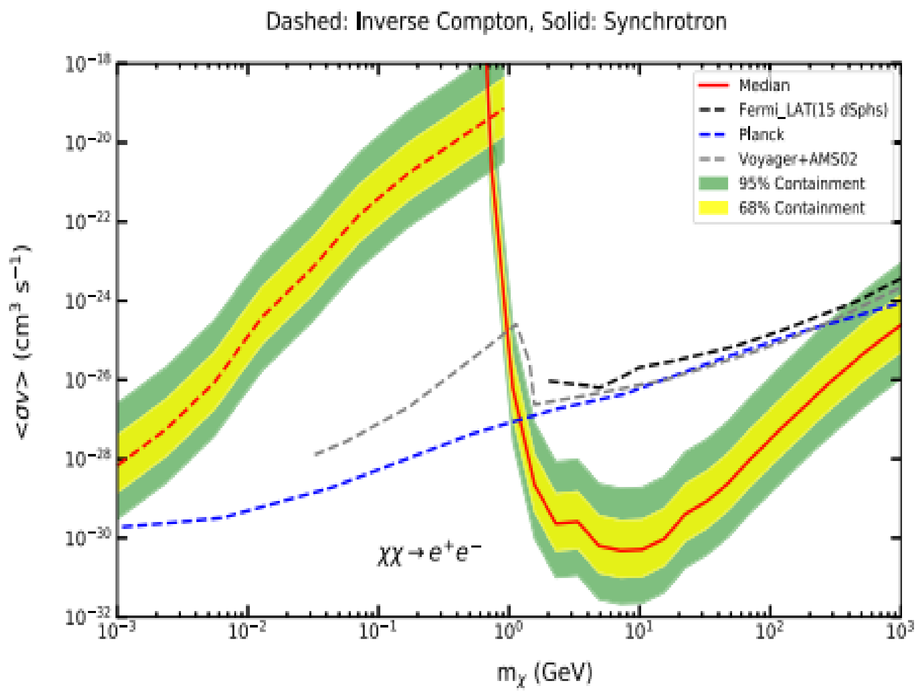
Impact of astrophysical factors

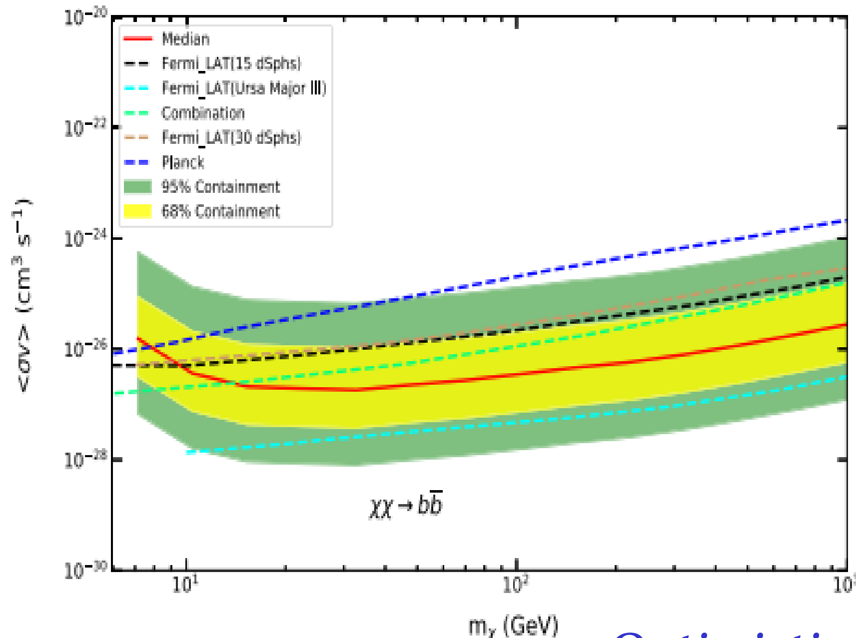




- *We consider two scenarios:*
  Optimistic: $B = 1\mu G$, $D_0 = 3*10^{28}$ cm^2/s
  Conservative: $B = 0.1\mu G$, $D_0 = 10^{30}$ cm^2/s
- *Diffusion radius is taken to be 0.03 pc*

SKA sensitivities



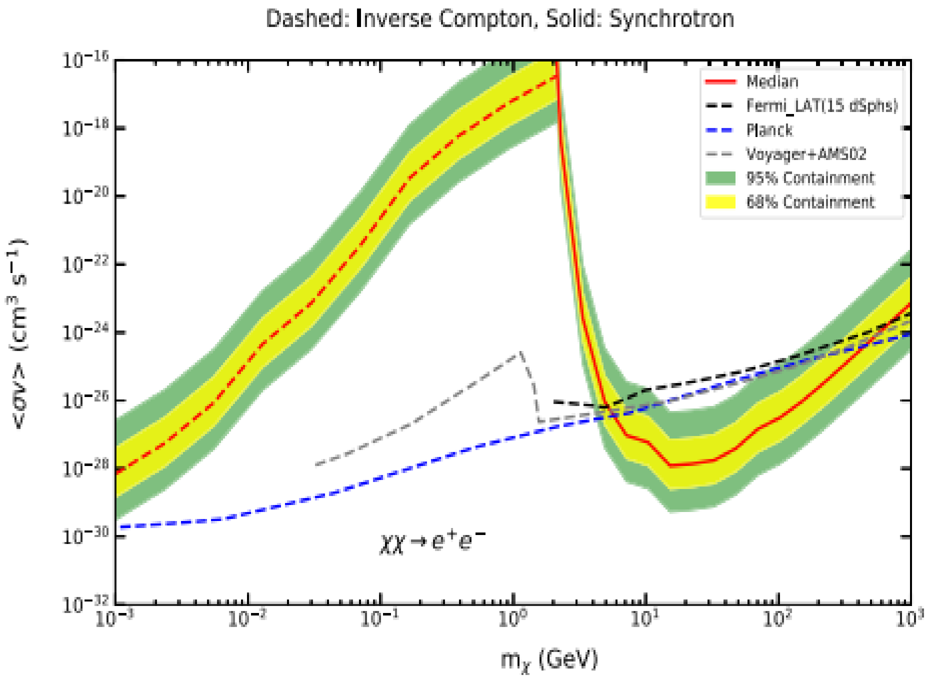


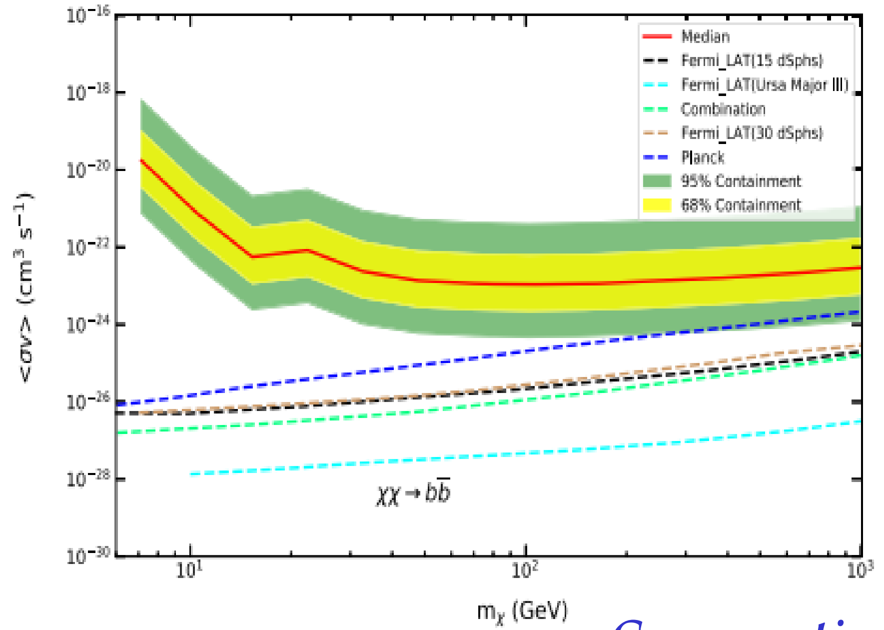
Optimistic

- *We consider 100 hour SKA observation at the low band and four mid bands.*
- *The uncertainties from the density profile are considered.*
- *The sensitivities to synchrotron signals can surpass the current constraints for the leptonic channels.*

Zhang, Bi, Chang, Yin, Zhao, 2409.12414

SKA sensitivities



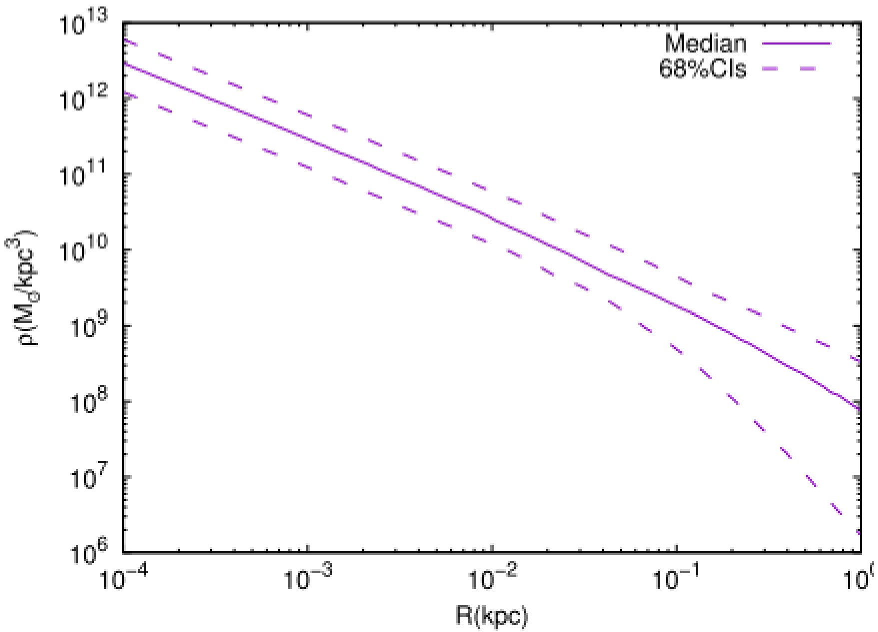


Conservative

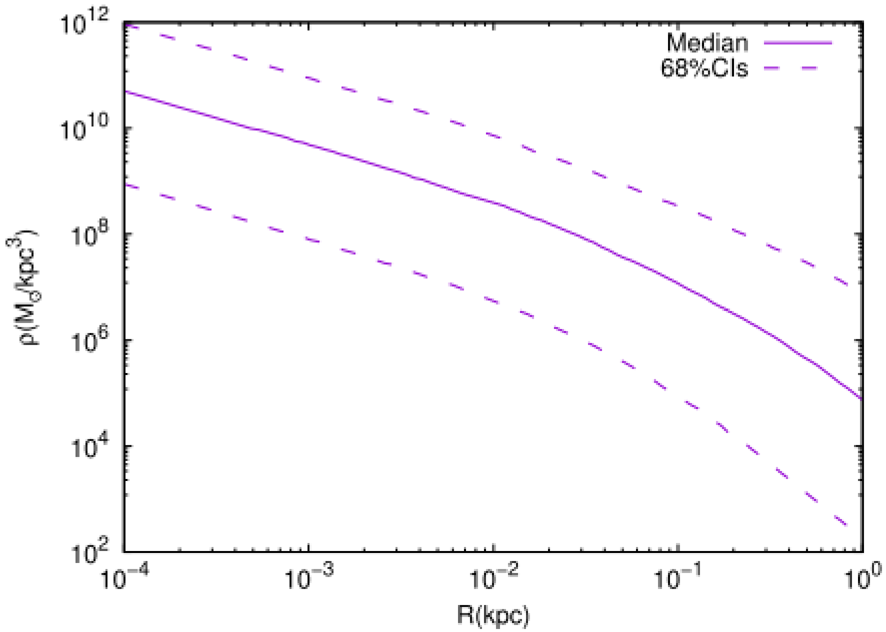
- *We consider 100 hour SKA observation at the low band and four mid bands.*
- *The uncertainties from the density profile are considered.*
- *The sensitivities to synchrotron signals can surpass the current constraints for the leptonic channels.*

Zhang, Bi, Chang, Yin, Zhao, 2409.12414

We should be cautious …



analysis with ***11*** *stars*



analysis with ***10*** *stars*

Zhao, Bi, Lin, Yin, 2406.16769

- *The sample of member stars used to determine DM density is very limited.*
- *If the star with largest velocity outlier is removed, the DM density profile is poorly determined. The corresponding J-factor has a much smaller median value and a very large uncertainty* $\log_{10} J = 17.7^{+2.5}_{-3.9}$.

Summary

- *The recently discovered system Ursa Major III may be the faintest and densest dwarf stellate galaxy in the Milky Way. It is a very promising target for DM indirect detection*

- *We determine the DM density profile in the UMa III through a Jeans analysis and obtain a large J-factor.*

- *We set strict constraints on the DM annihilation cross section based on the Fermi-LAT gamma-ray results, and investigate the SKA sensitivities to the radio signals.*

- *It is imperative to note that variations in kinematic data may lead to a significant reduction in the inferred DM content in UMa III. More observations are needed.*

Thank you