# Searches for Dark Matter with the MAGIC and CTA gamma-ray telescopes: Latest results and a glimpse into the future

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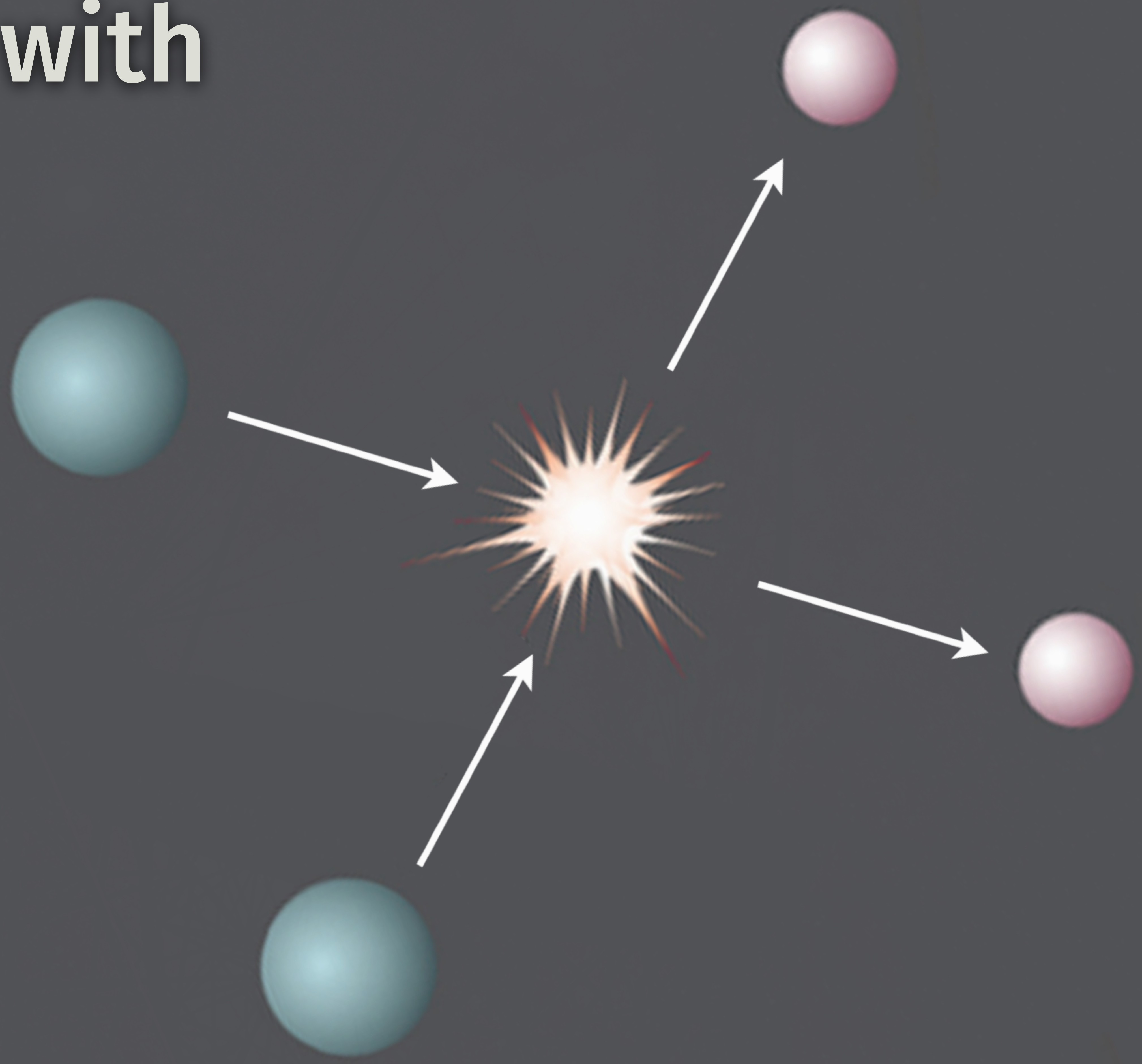
ICRR Seminar
December 8, 2021

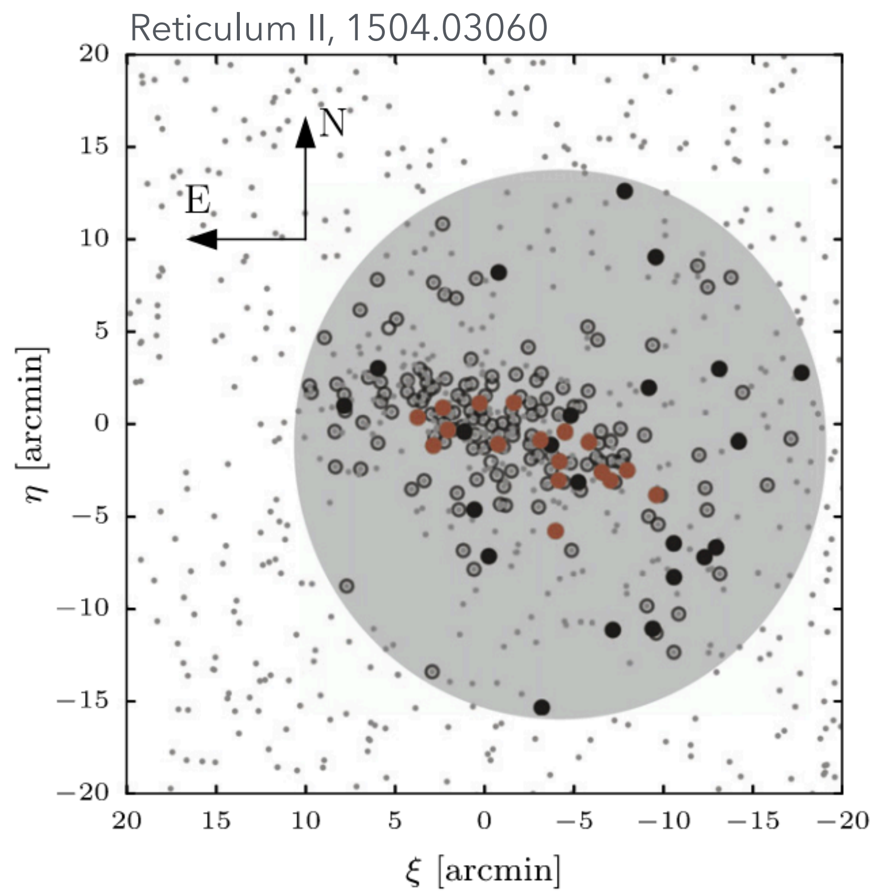

# Introduction: Searching for Dark Matter with gamma rays



# The compelling evidence for Dark Matter

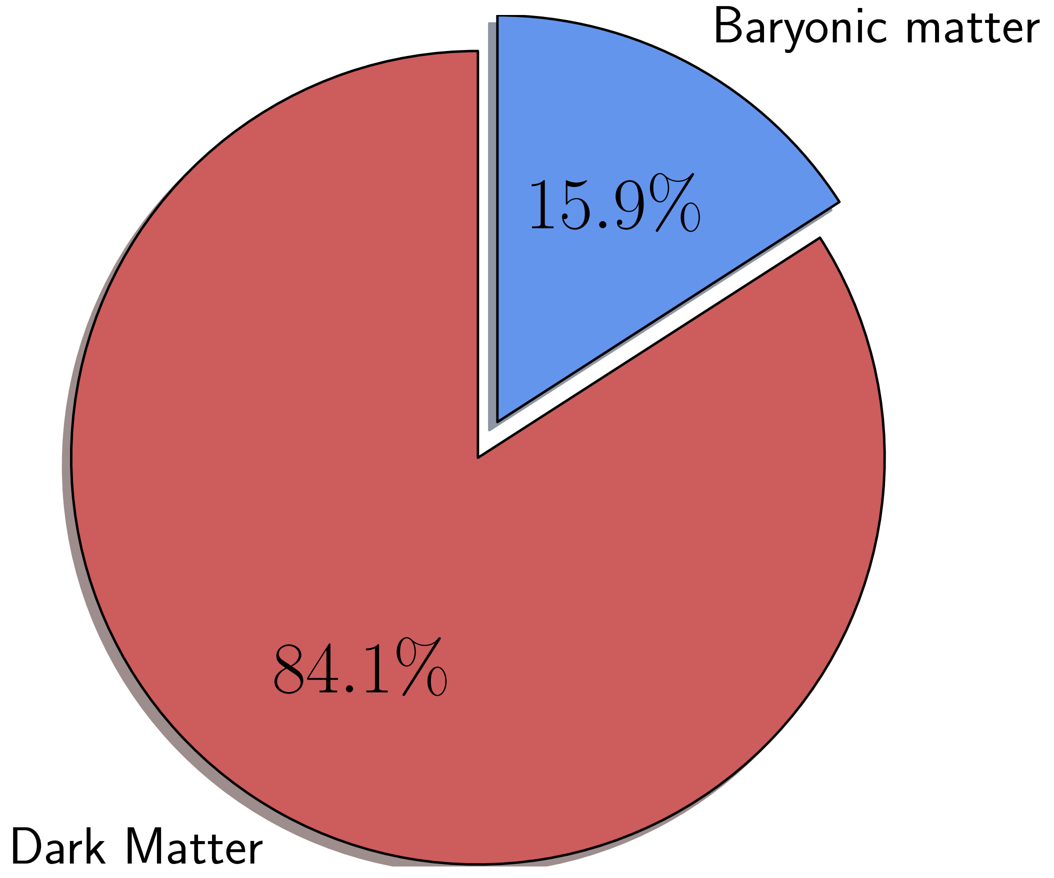
All evidence is gravitational

Reticulum II, 1504.03060



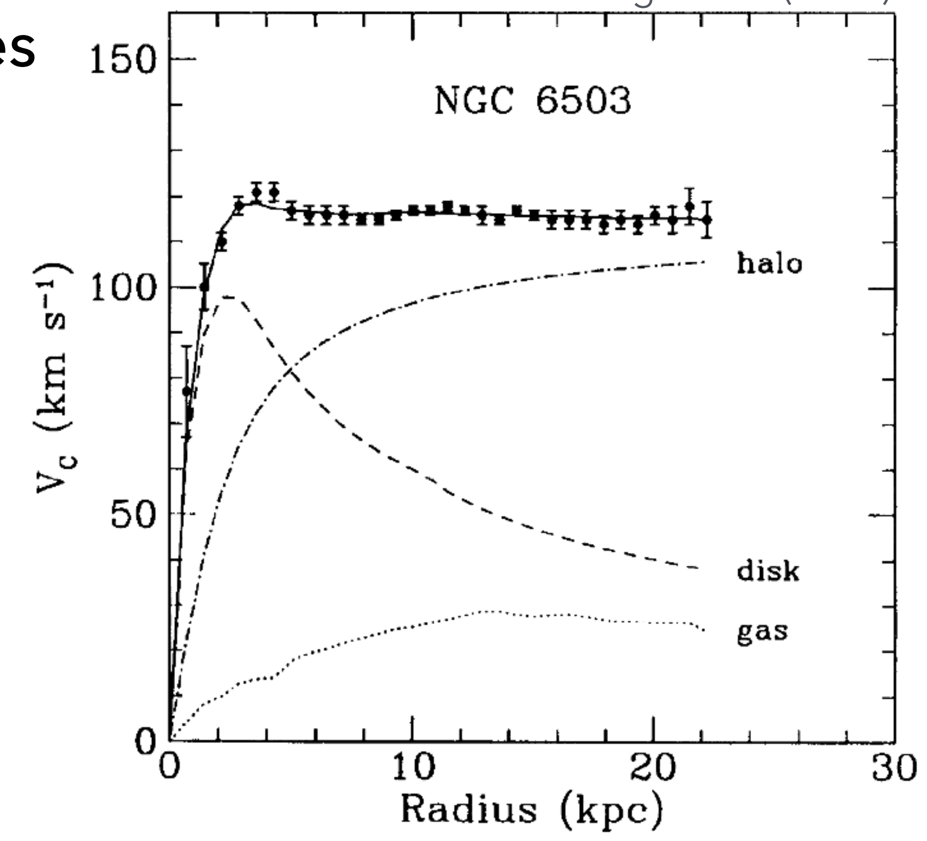

Dwarf spheroidal galaxies

exhaustive review: 1001.0316

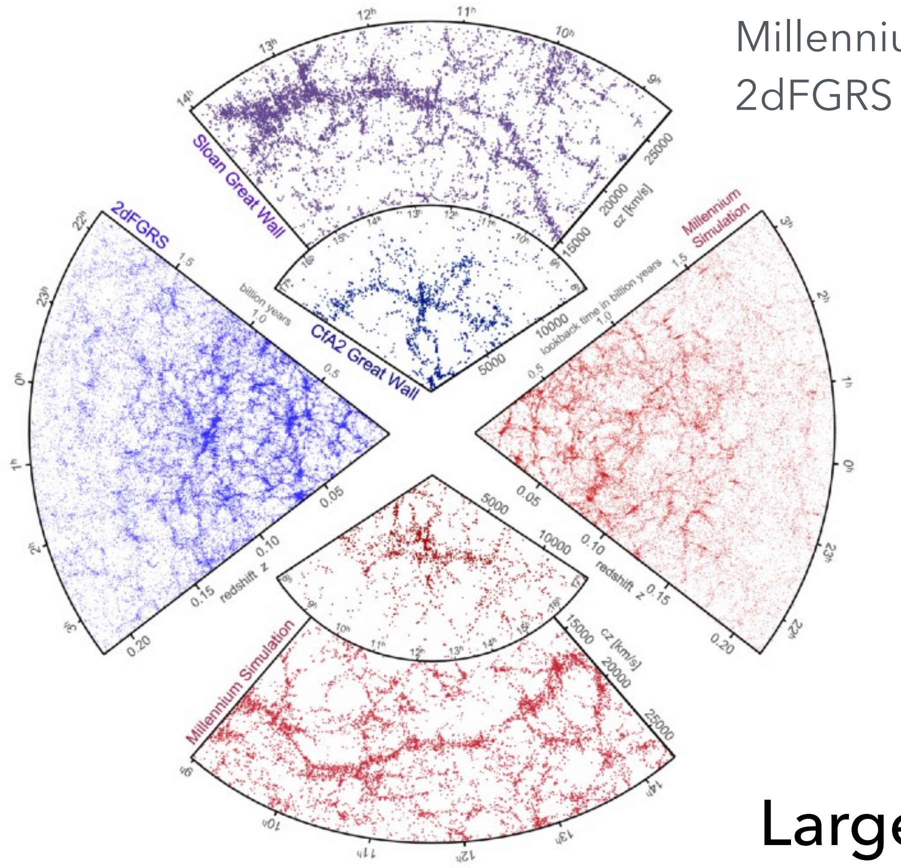



Spiral galaxies

Begemann (1991)

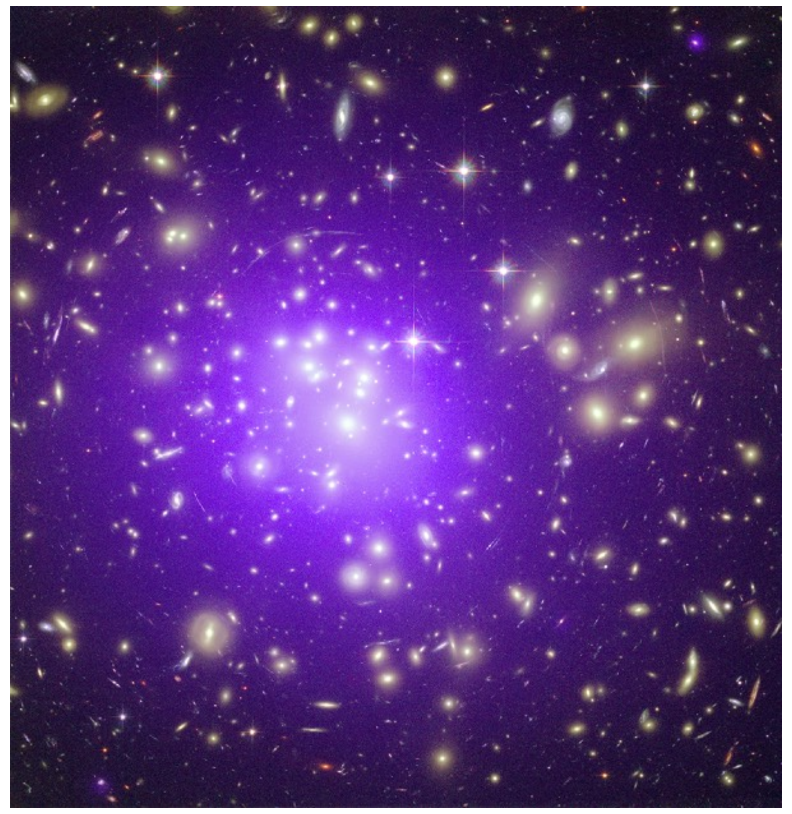



Millennium ΛCDM simulation vs. 2dFGRS survey



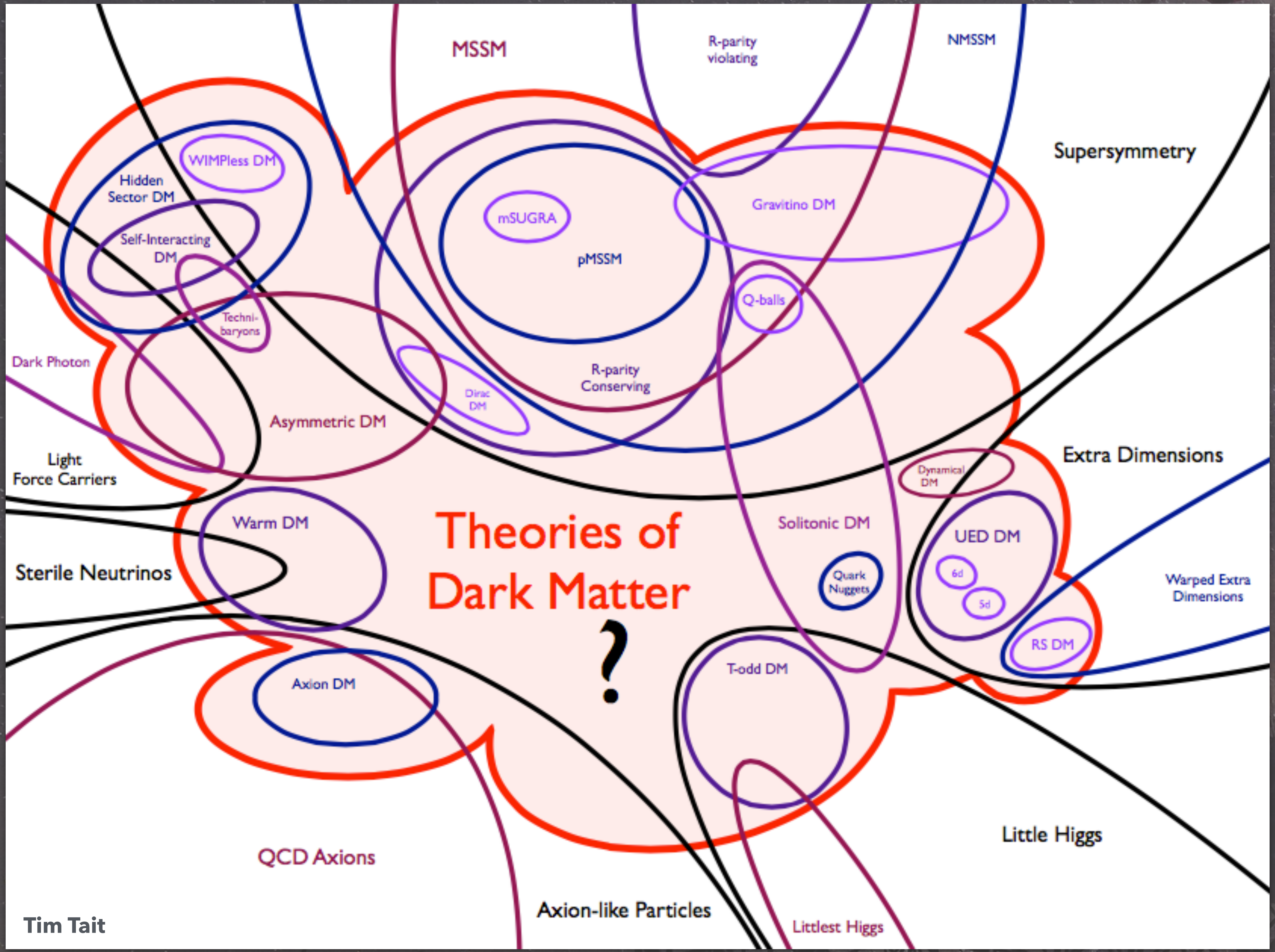

Large Scale Structure

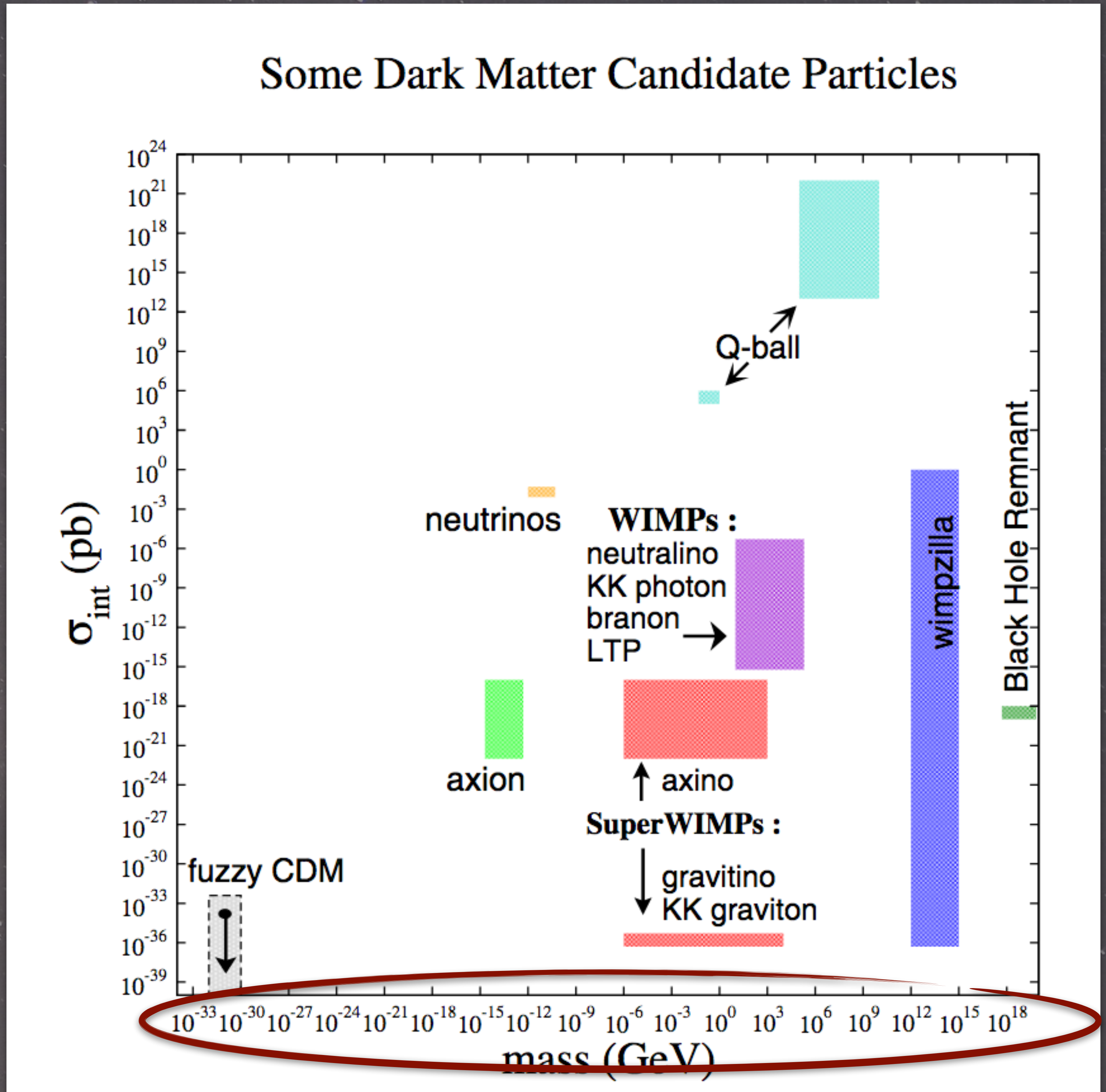
Chandra/HST image of Abell 1689



Galaxy clusters

# The Dark Matter theory jungle



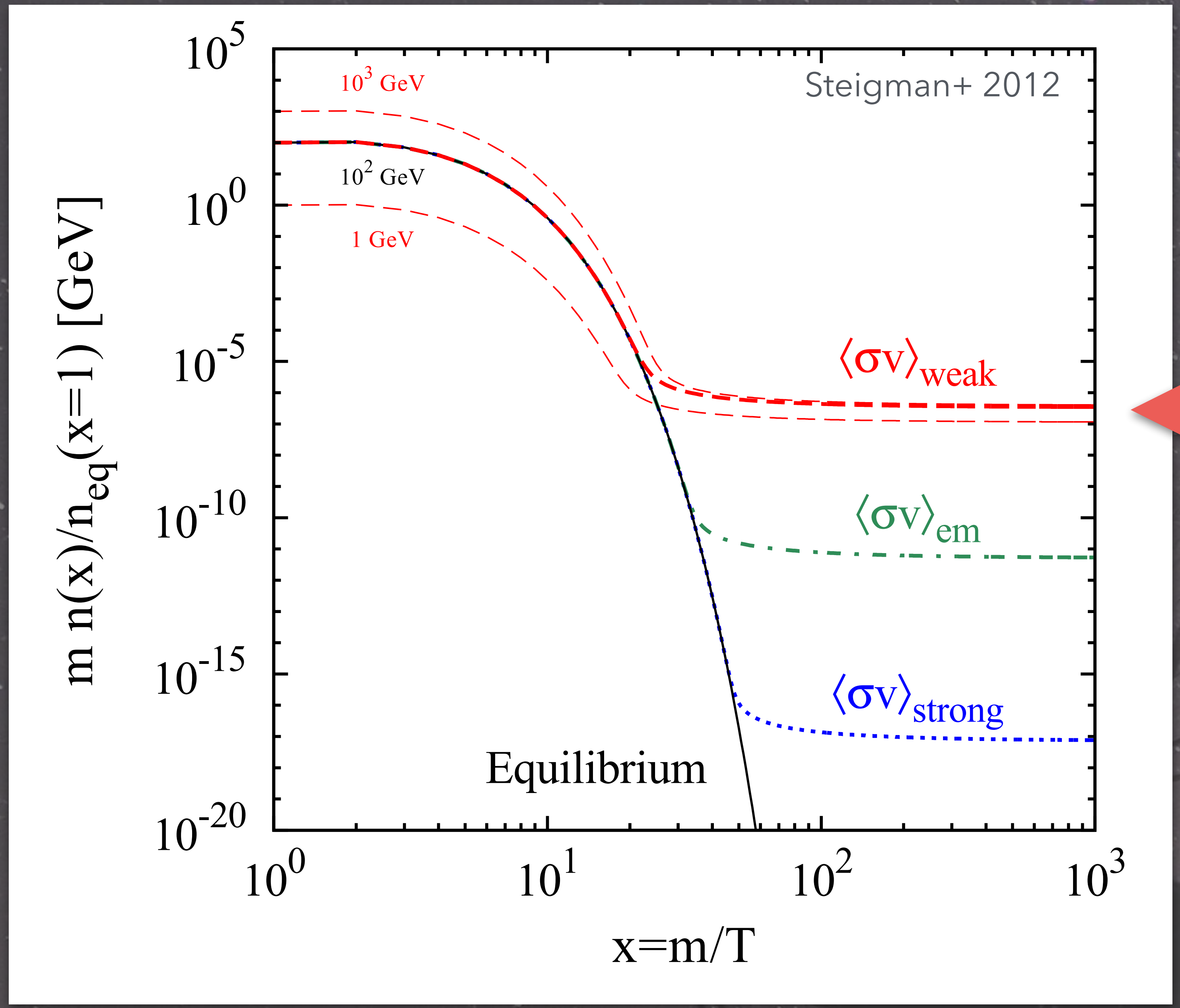



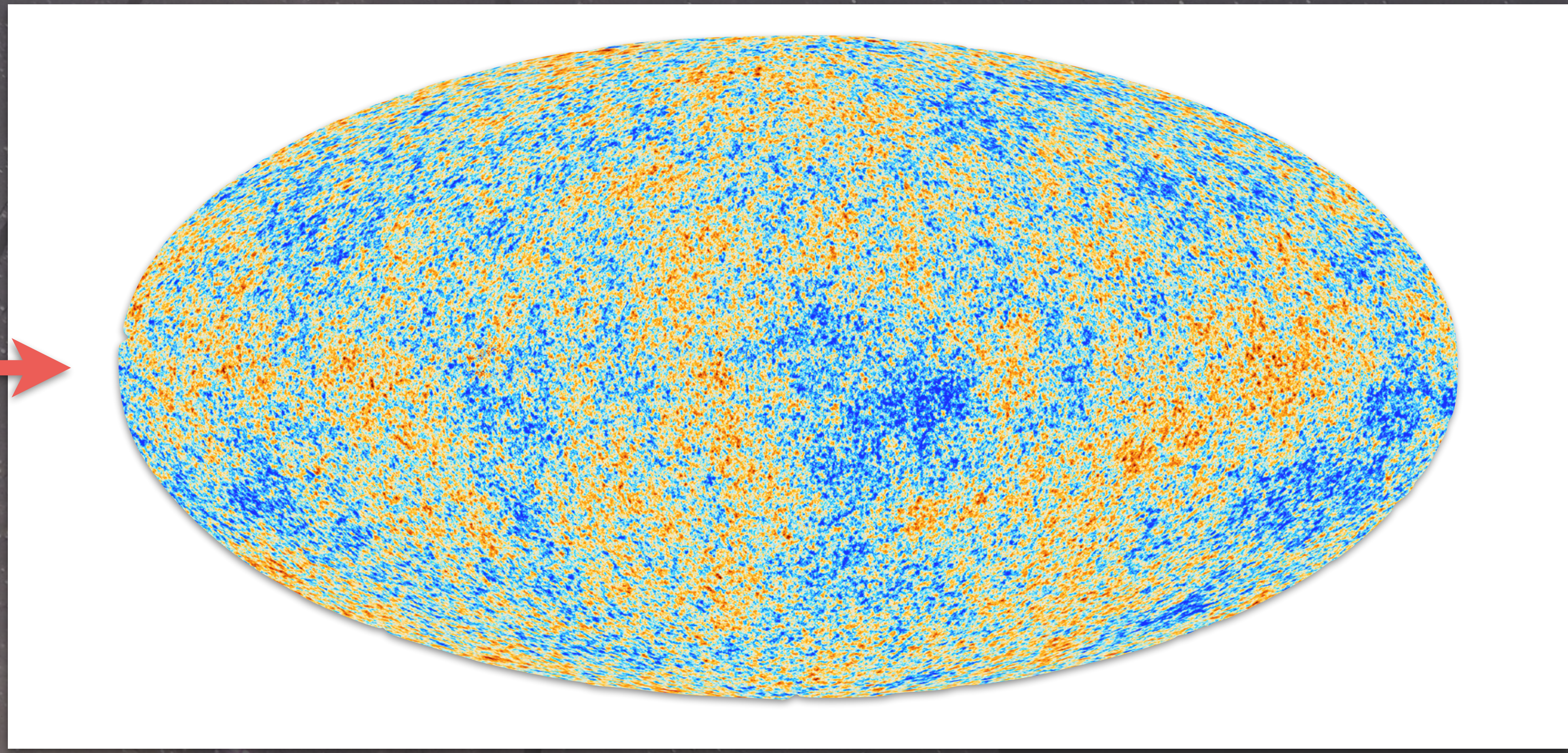

E. Park, DMSAG Report on the Direct Detection … (2007)

51 orders of magnitude

# Appeal of the WIMP paradigm

"Weakly interacting massive particle" (WIMP) miracle:

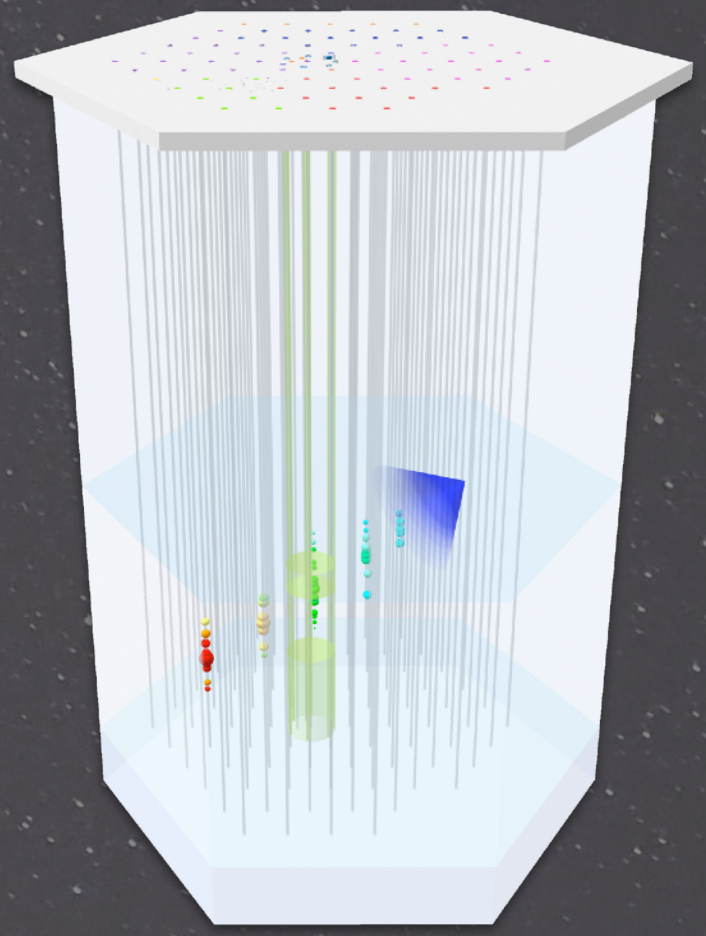


$$\rho_\chi h^2 \simeq 0.12 \rho_{crit} \left(\frac{80}{g^*}\right)^{1/2} \left(\frac{m_\chi}{25\,T_F}\right) \left(\frac{2.2\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle}\right)$$

Non-relativistic **GeV to TeV particle** with weak-scale cross section gives relic abundance matching observed cosmic DM density

# How many relic interactions do we expect?



## Relic annihilation @ Earth (in a detector):

A few kg of DM inside Earth volume

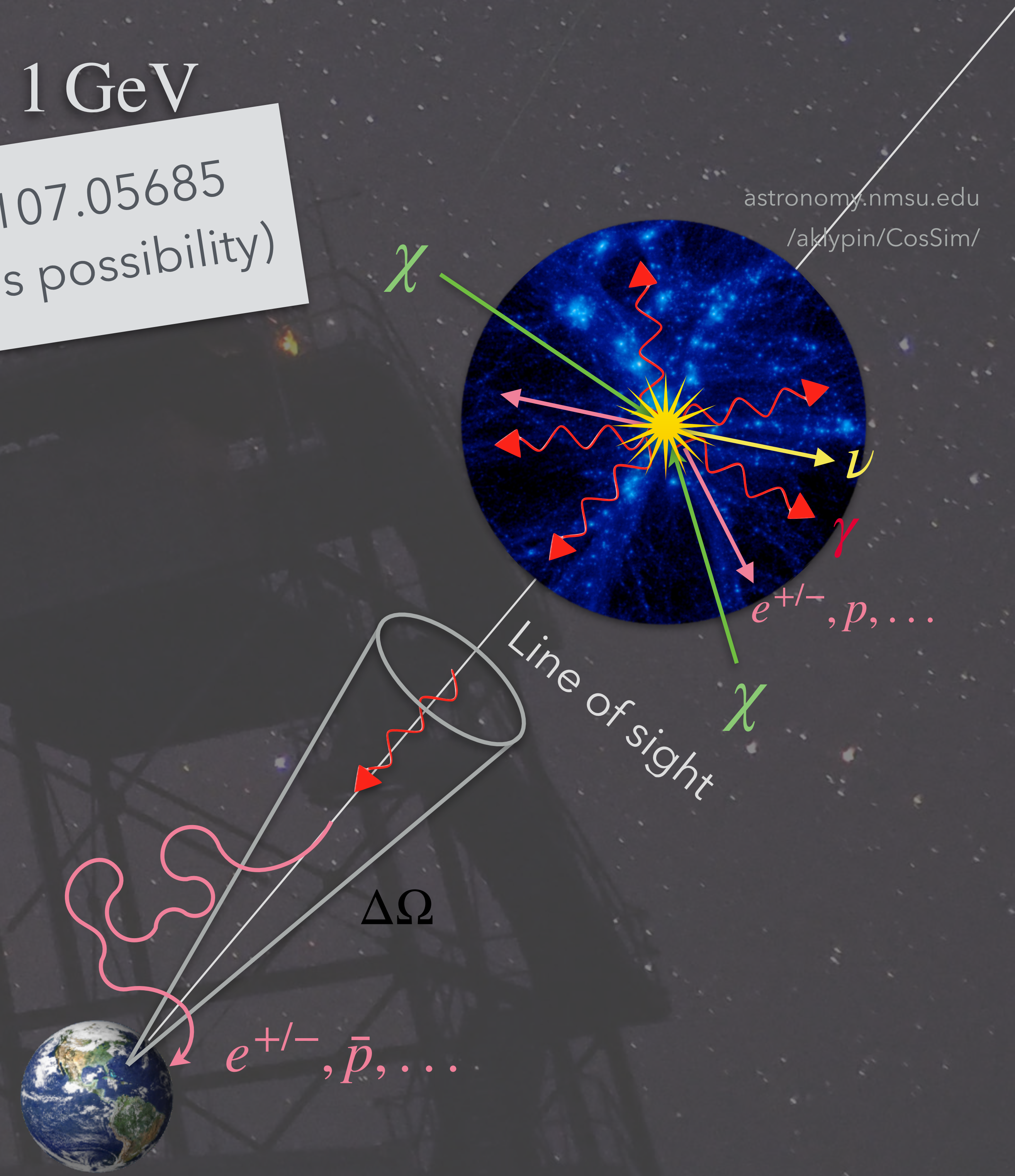
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}V} = \frac{\rho_\chi^2}{\delta\, m_\chi^2}\langle\sigma v\rangle \quad \text{with} \quad \delta = \begin{cases} 4, \chi \neq \bar{\chi} & \text{Dirac DM} \\ 2, \chi = \bar{\chi} & \text{Majorana DM} \end{cases}$$

$$< \frac{1\ \text{interaction}}{\mathrm{km}^3\ 1000\ \mathrm{years}} \quad \text{for} \quad \rho_\chi = \frac{1\,\mathrm{GeV}}{\mathrm{cm}^3},\ \langle\sigma v\rangle = 10^{-26}\,\frac{\mathrm{cm}^3}{\mathrm{s}},\ m_\chi = 1\,\mathrm{GeV}$$

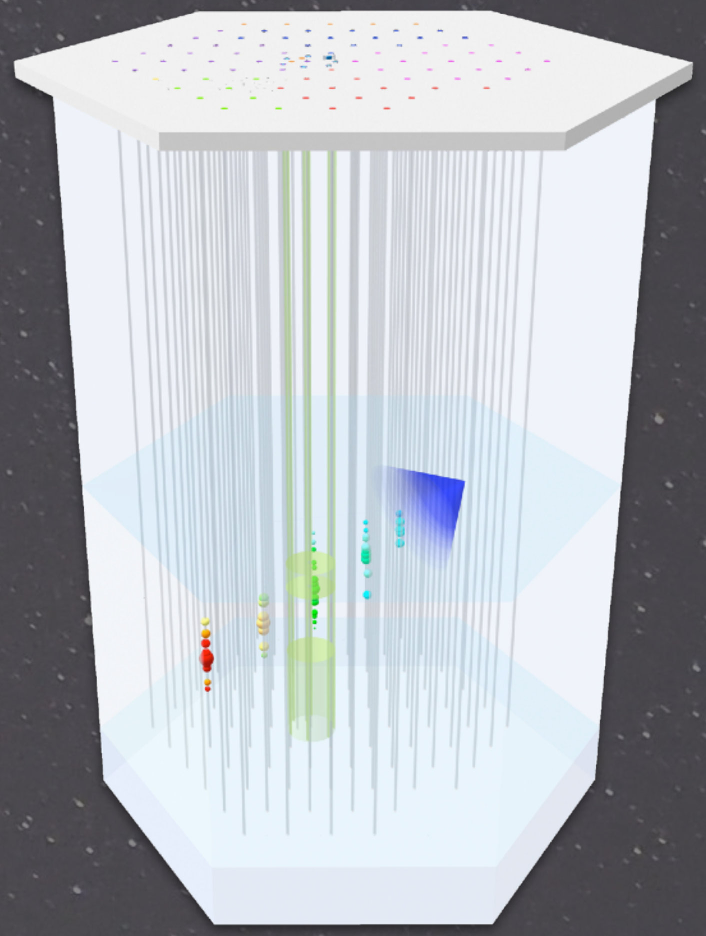
(However: 2107.05685 investigate this possibility)

## Relic annihilation in space:

$$\frac{\mathrm{d}N_{\gamma,\nu,e,\ldots}}{\mathrm{d}A\mathrm{d}t} = \frac{1}{4\pi}\,\frac{\langle\sigma v\rangle}{\delta\, m_\chi^2} \times \int \frac{\mathrm{d}N^{\text{per interact.}}_{\gamma,\nu,e,\ldots}}{\mathrm{d}E}\,\mathrm{d}E \times \int_{\Delta\Omega}\int_{l.o.s.} \rho_\chi^2\, \mathrm{d}l\mathrm{d}\Omega$$



# How many relic interactions do we expect?



## Relic annihilation @ Earth (in a detector):

A few kg of DM inside Earth volume

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}V} = \frac{\rho_\chi^2}{\delta\, m_\chi^2}\langle\sigma v\rangle \quad \text{with} \quad \delta = \begin{cases} 4, \chi \neq \bar{\chi} & \text{Dirac DM} \\ 2, \chi = \bar{\chi} & \text{Majorana DM} \end{cases}$$

$$< \frac{1 \text{ interaction}}{\mathrm{km}^3\ 1000\ \mathrm{years}} \quad \text{for} \quad \rho_\chi = \frac{1\,\mathrm{GeV}}{\mathrm{cm}^3},\ \langle\sigma v\rangle = 10^{-26}\,\frac{\mathrm{cm}^3}{\mathrm{s}},\ m_\chi = 1\,\mathrm{GeV}$$

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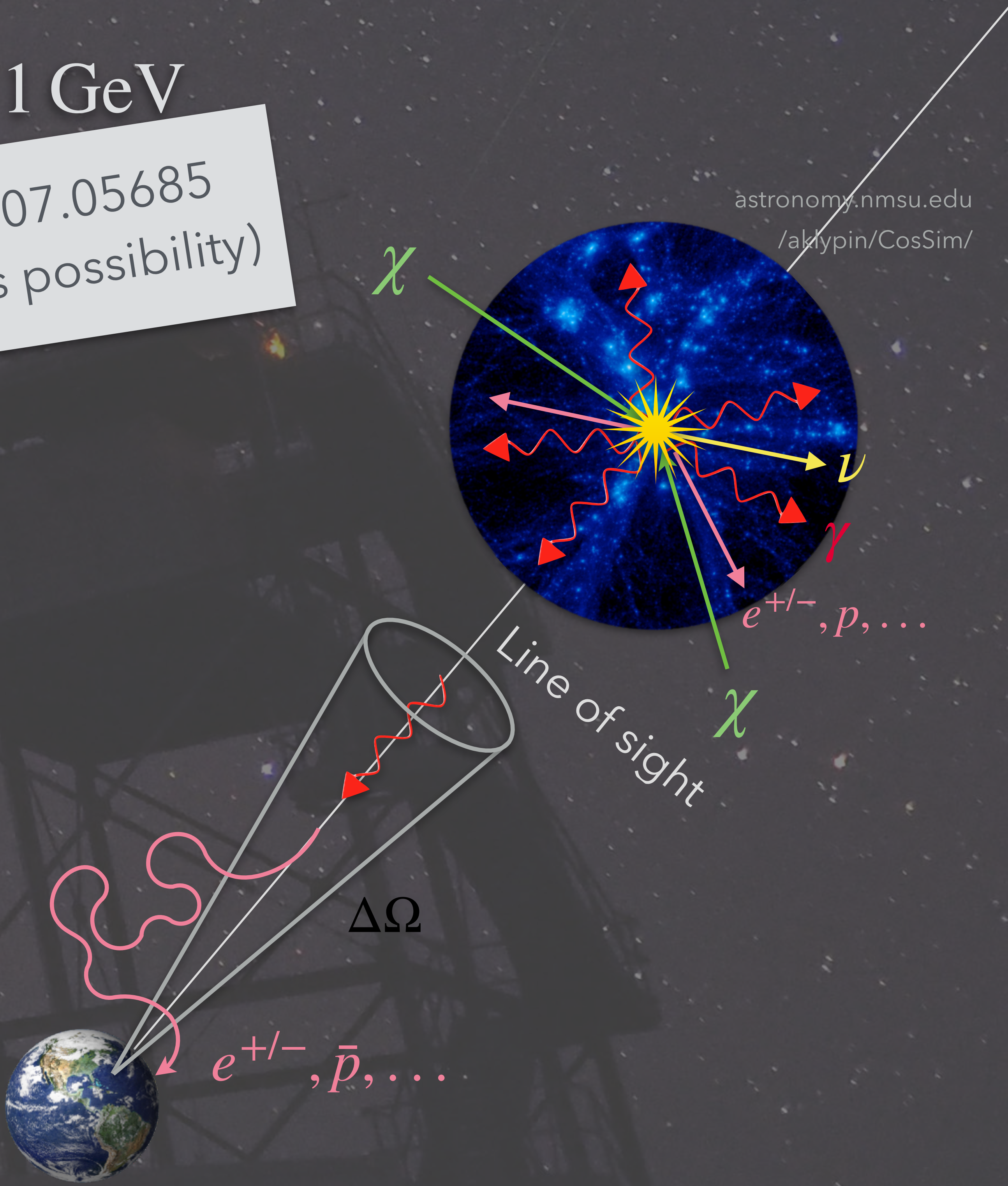
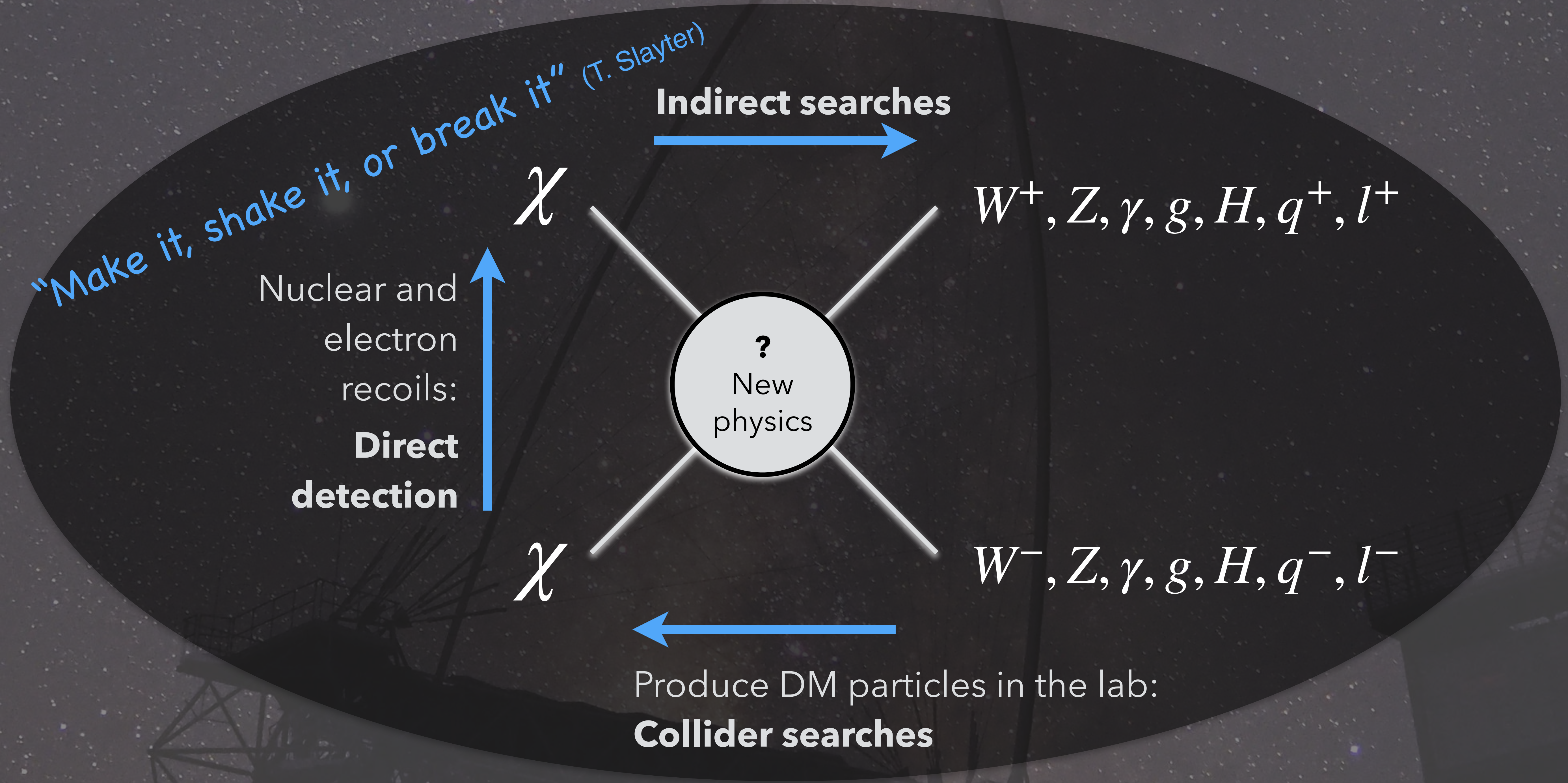



**Detectable fluxes!**

# Appeal of indirect dark matter searches



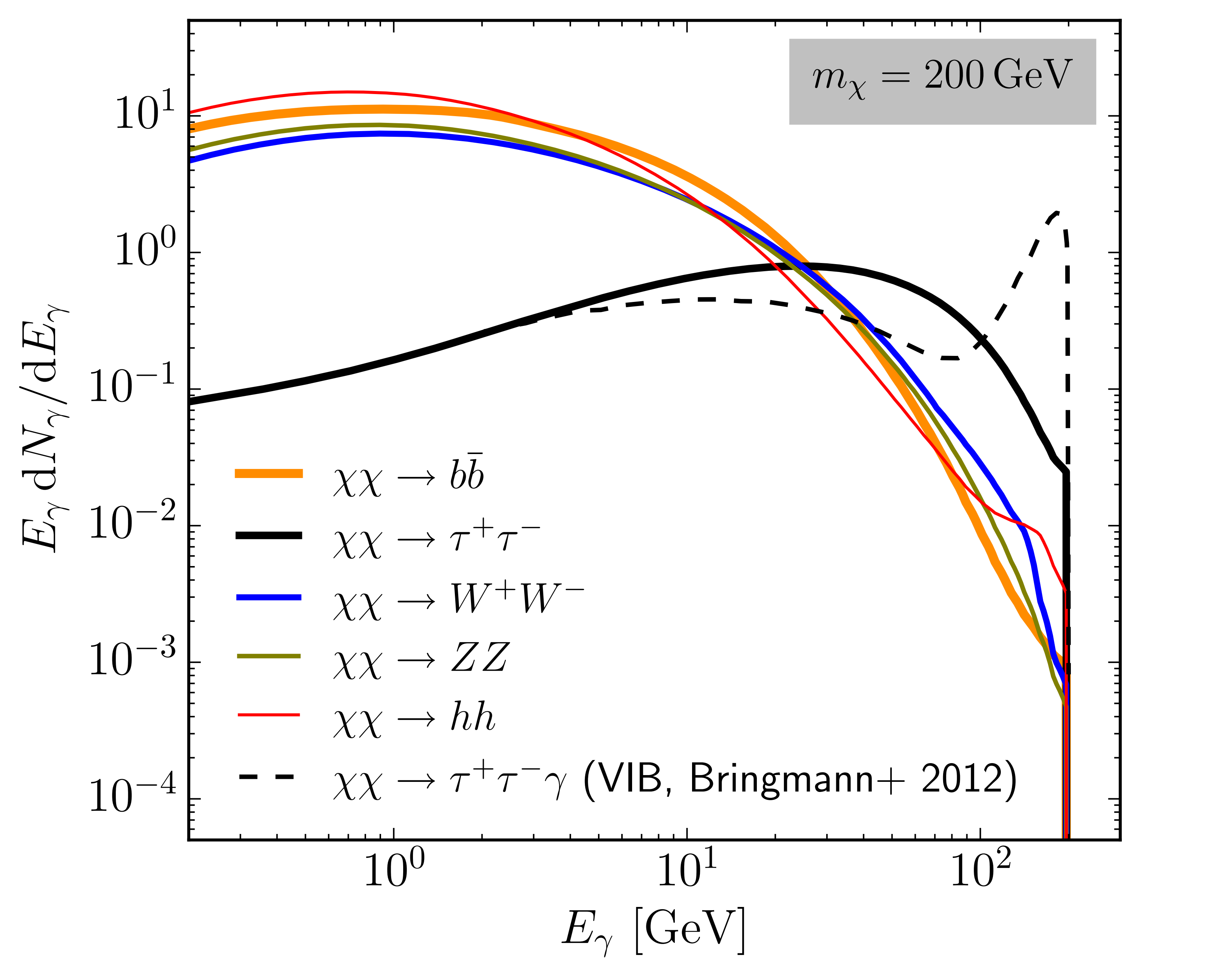

Indirect WIMP searches:

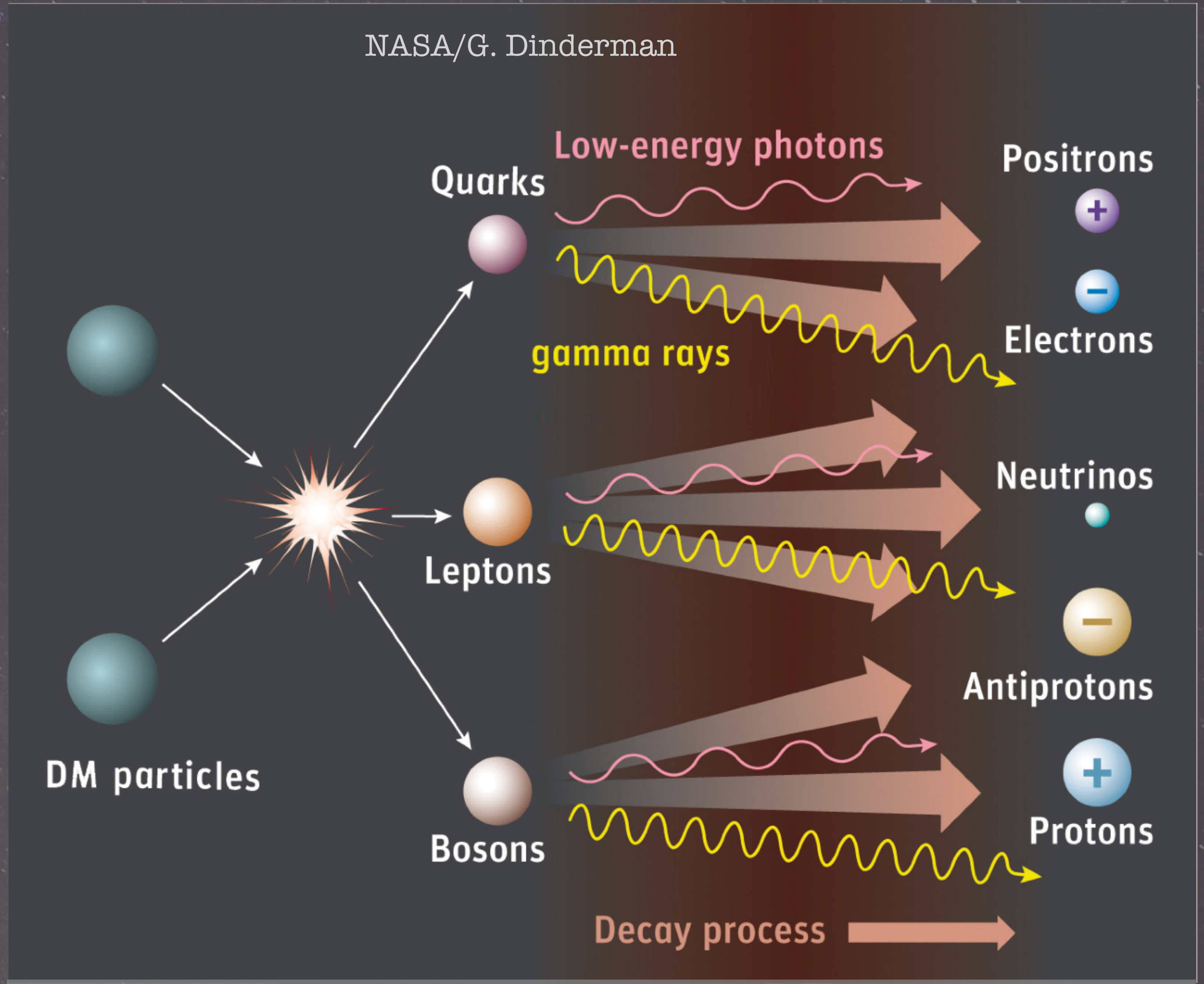
- Probing the **same mass budgets** which provide DM gravitational evidence
- Probing the **same interaction** (annihilation) explaining DM thermal relic abundance

# Indirect detection ingredients: Spectra

1. Secondary spectra ("particle physics term")

$$\frac{\mathrm{d}N_{\gamma,\nu,e,\ldots}}{\mathrm{d}A\mathrm{d}t} = \frac{1}{4\pi}\,\frac{\langle\sigma v\rangle}{\delta\, m_\chi^2} \times \int \frac{\mathrm{d}N^{\text{per interact.}}_{\gamma,\nu,e,\ldots}}{\mathrm{d}E}\,\mathrm{d}E \times \int_{\Delta\Omega}\int_{l.o.s.} \rho_\chi^2\, \mathrm{d}l\mathrm{d}\Omega$$




Role of thumb:

TeV DM particles: most energy deposited in GeV-TeV final state particles:

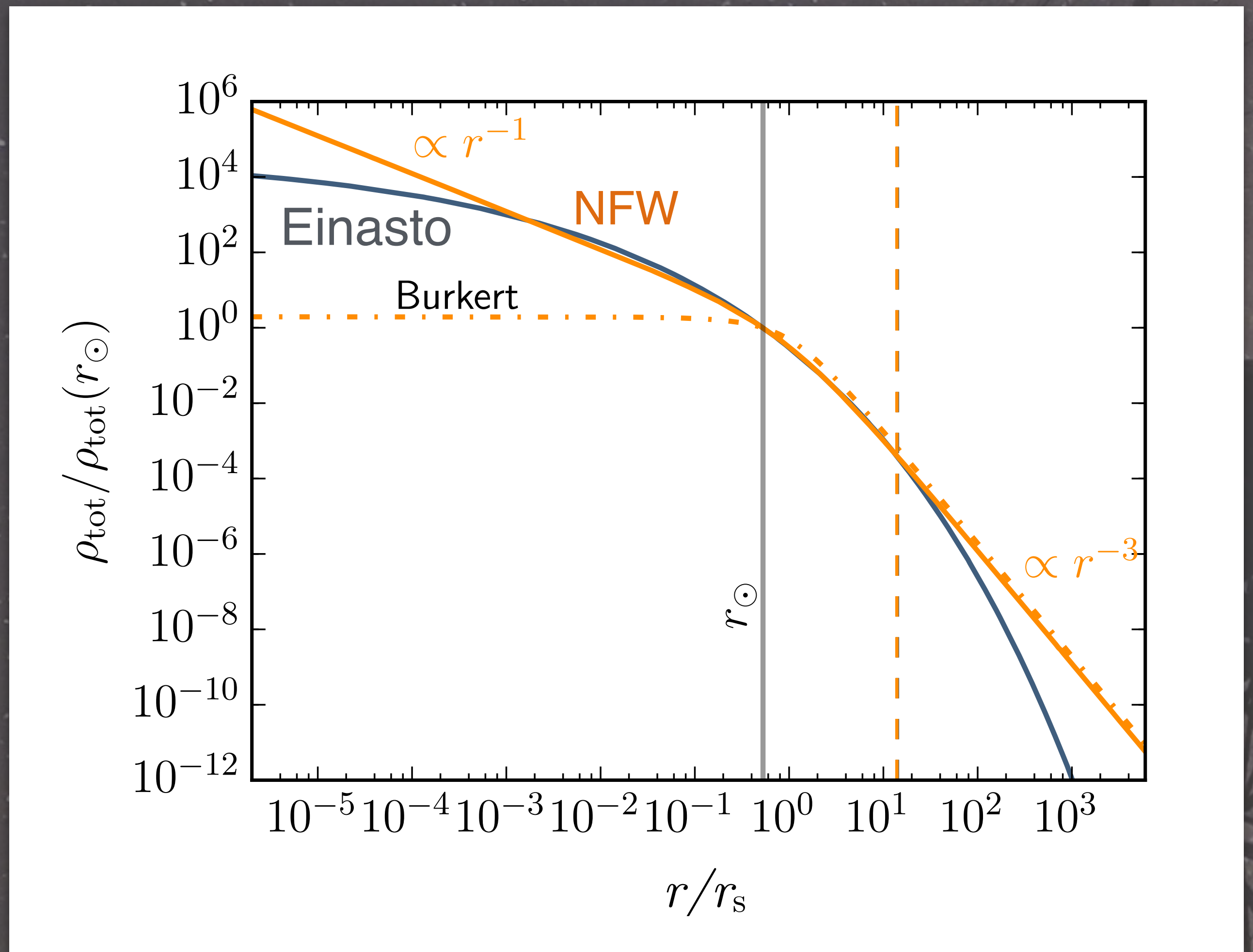
**High energy astronomy**

# Indirect detection ingredients: Dark Matter densities

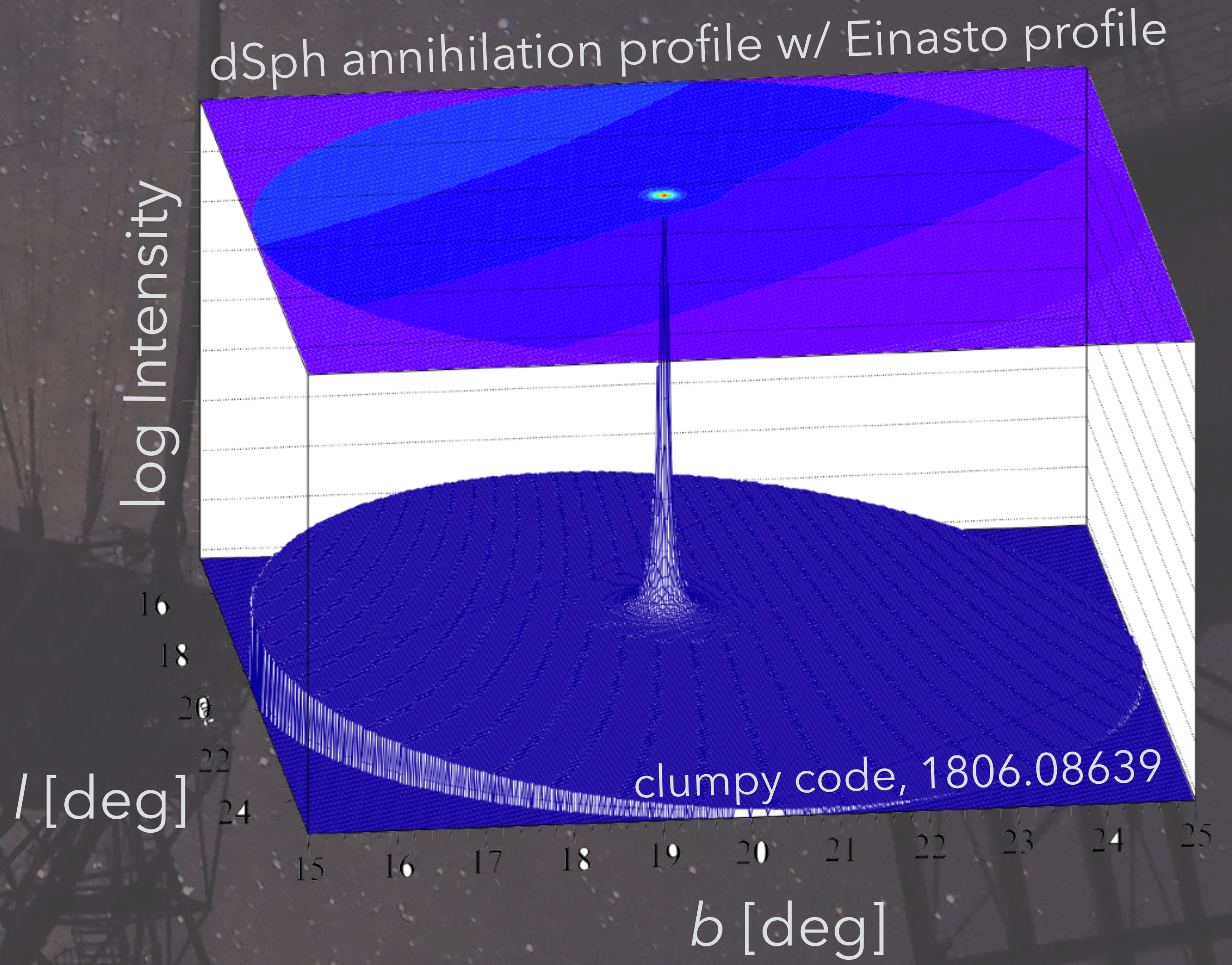
2. *J*-factor ("astrophysical term")

$$\frac{\mathrm{d}N_{\gamma,\nu,e,\dots}}{\mathrm{d}A\mathrm{d}t} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{\delta\, m_\chi^2} \times \int \frac{\mathrm{d}N^{\text{per interact.}}_{\gamma,\nu,e,\dots}}{\mathrm{d}E}\mathrm{d}E \times \int_{\Delta\Omega}\int_{l.o.s.} \rho_\chi^2 \, dl d\Omega$$

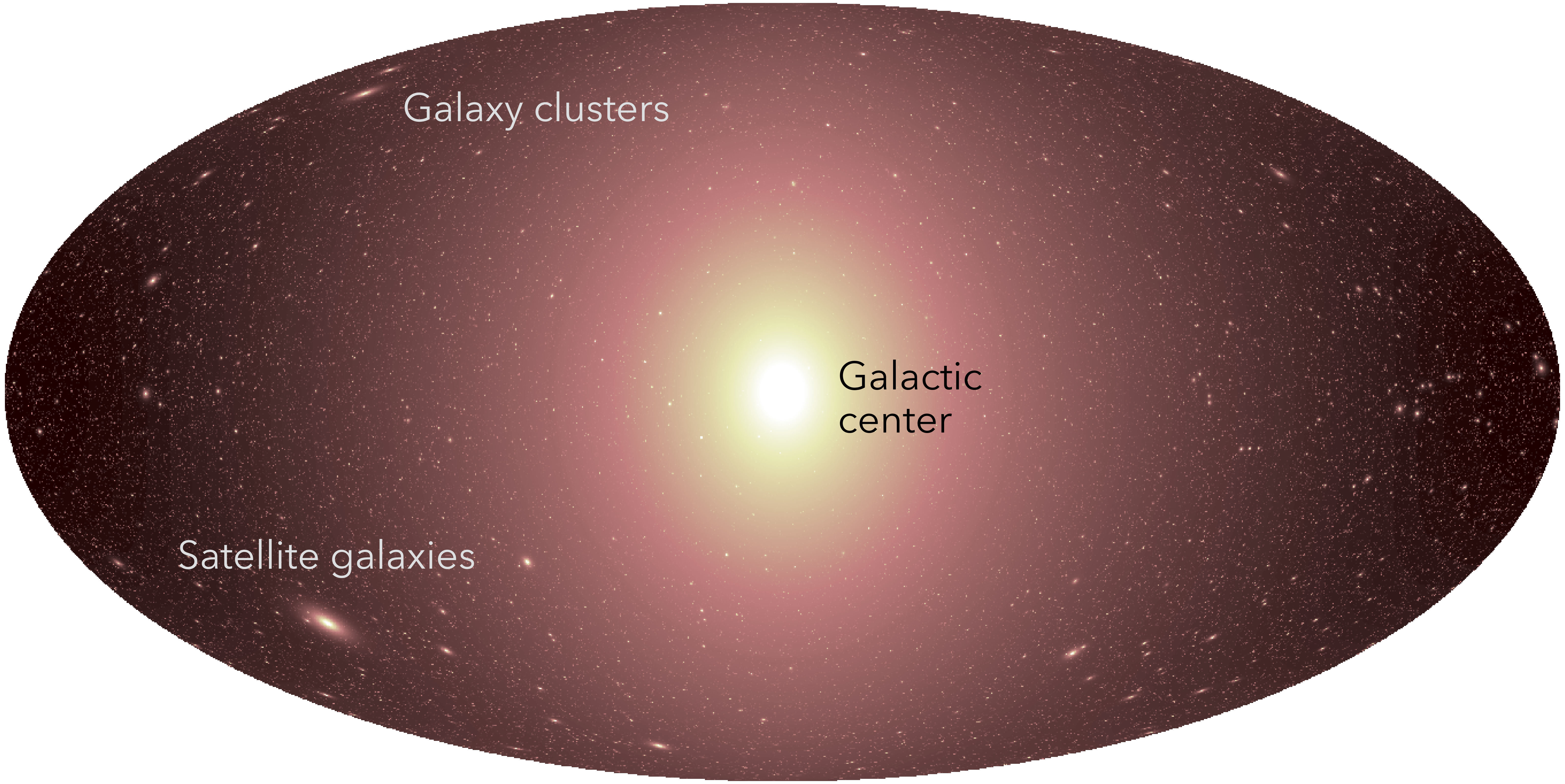
Annihilation boost: Increased signal, but also increased uncertainty:




$$\int_{l.o.s.} \rho^2 \, \mathrm{d}l$$



# Where to search? Dark matter structures at all scales

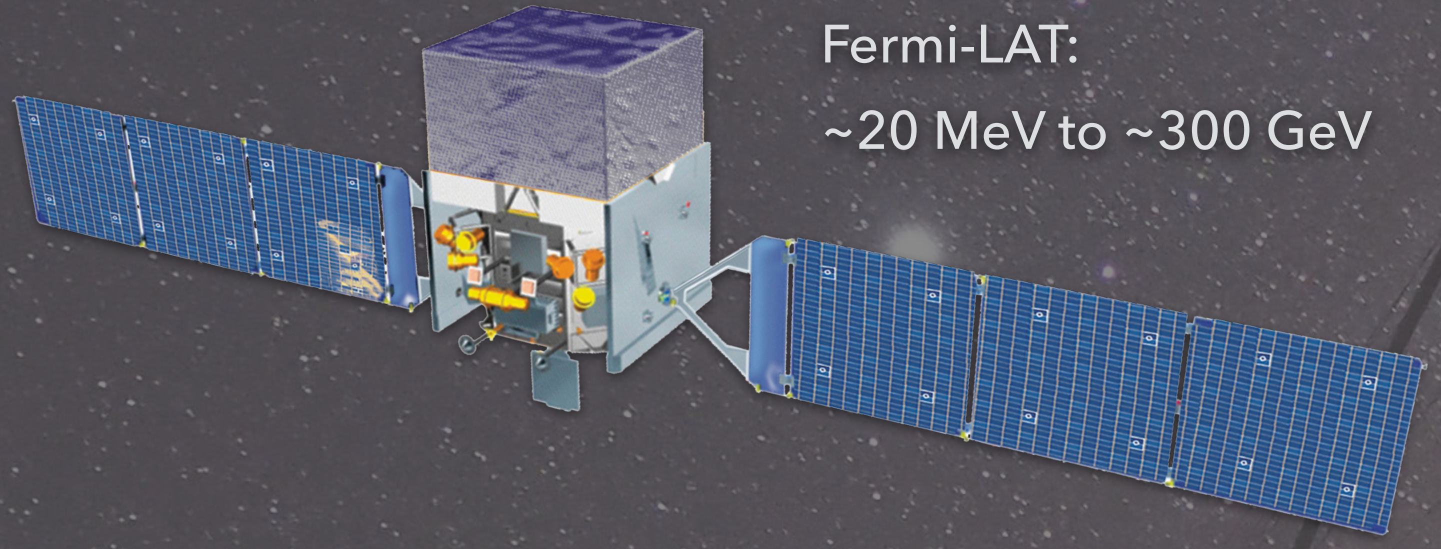



log (γ-ray intensity from DM annihilation), **MH** et al., 1806.08639

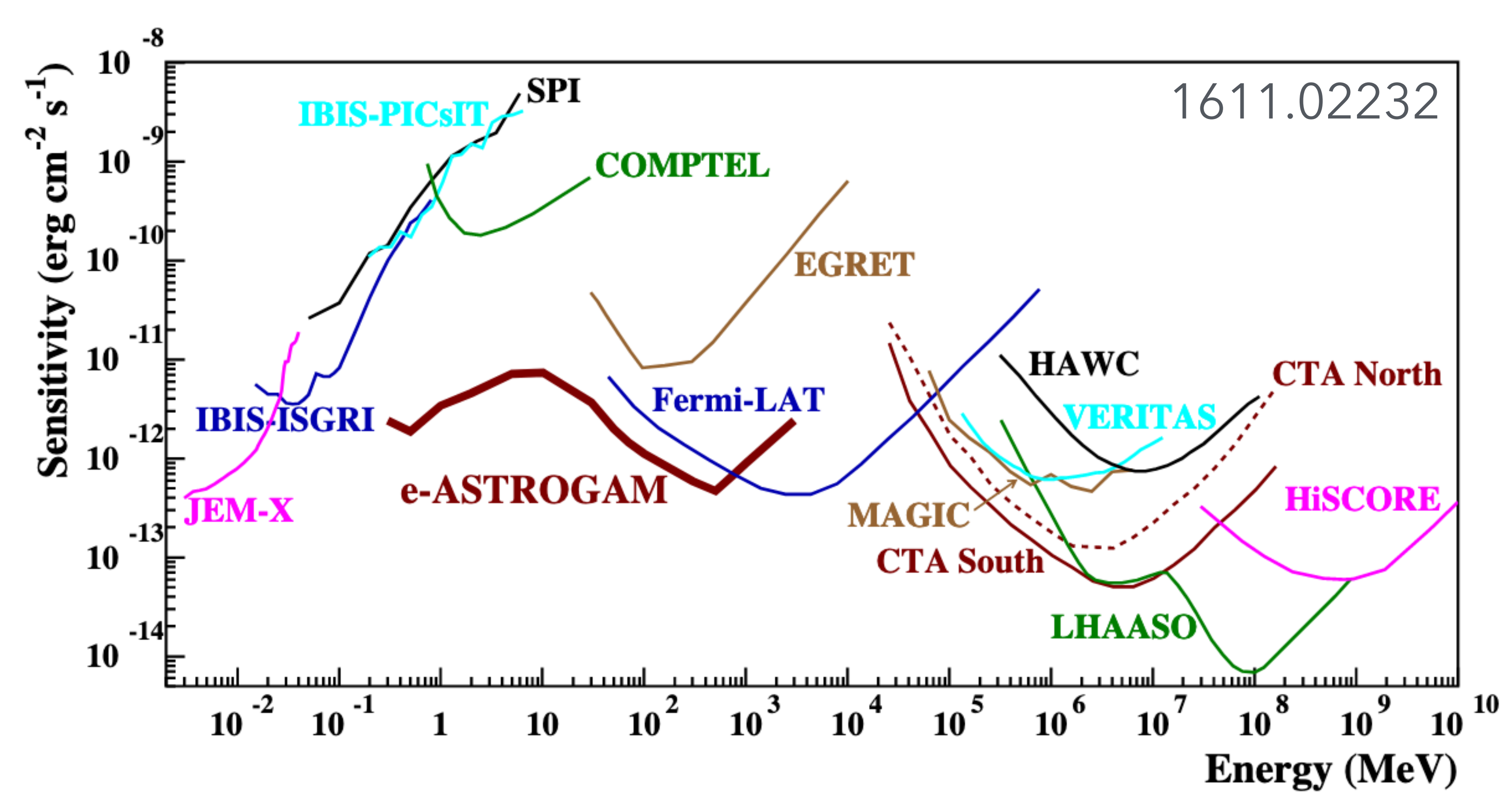
# The searches with MAGIC and CTA

# Indirect detection instruments

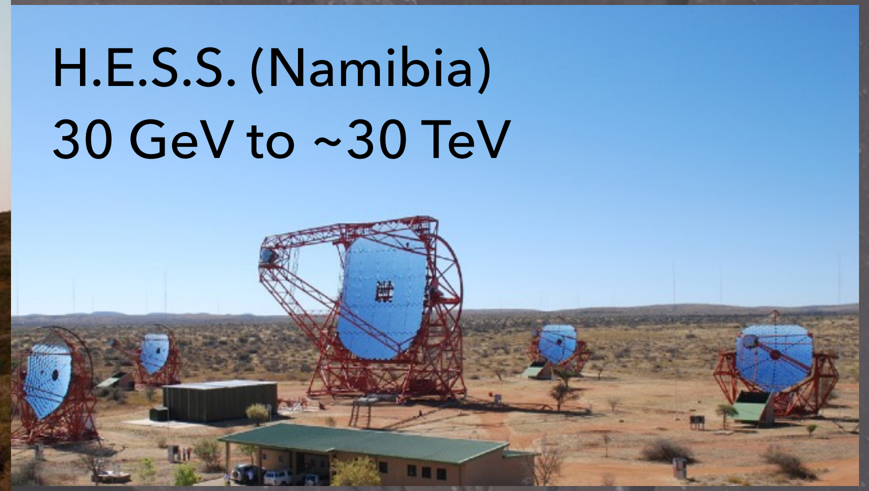
To detect energetic gamma rays from space

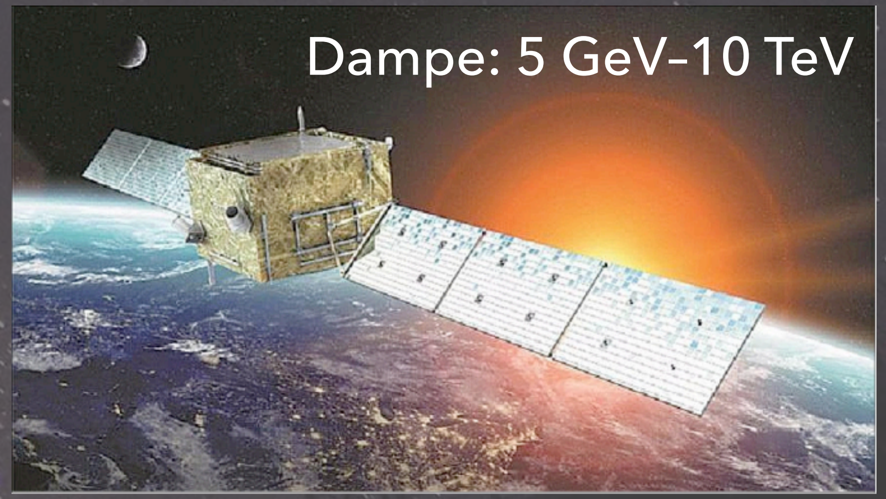


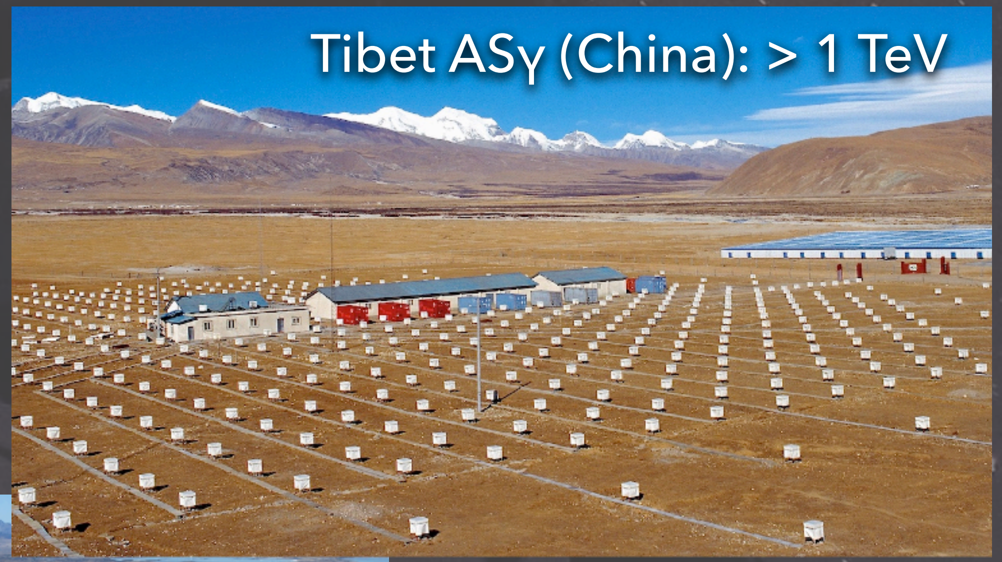
Fermi-LAT:
~20 MeV to ~300 GeV

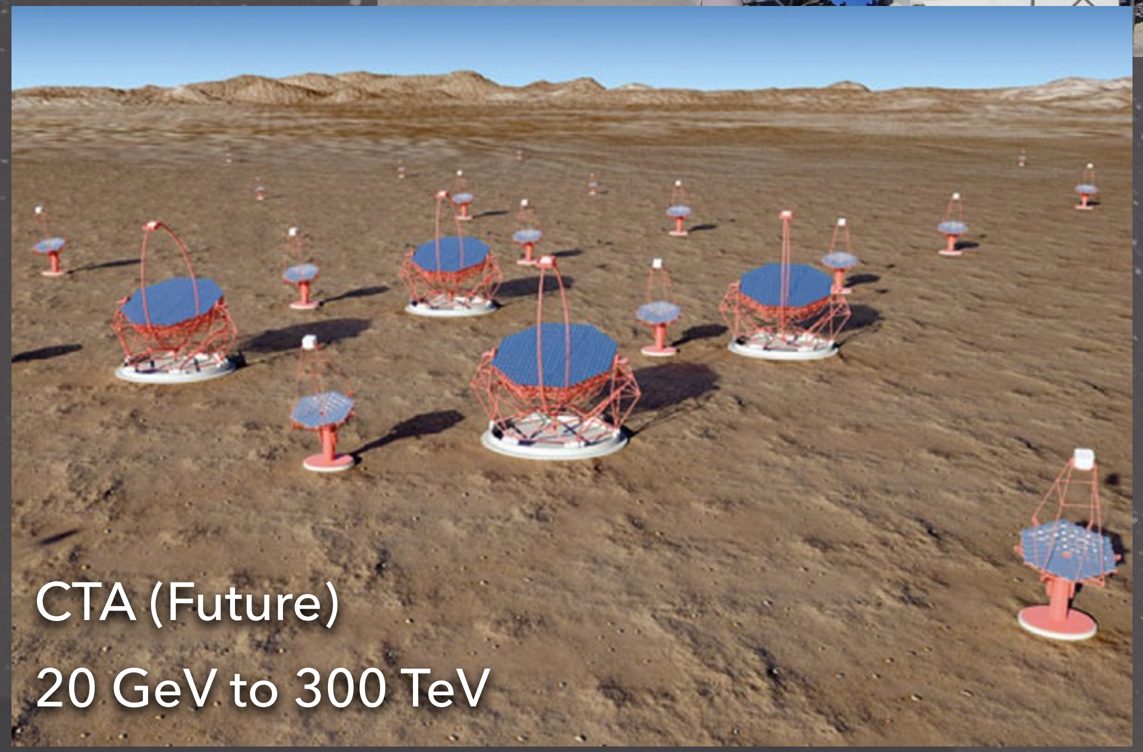




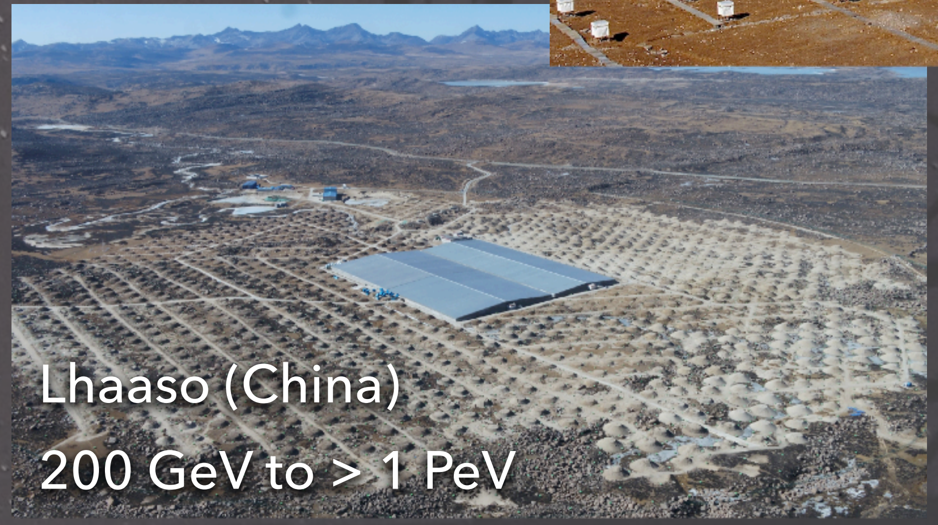








Energy

# Imaging Air Cherenkov Telescopes (IACTs): MAGIC


System of two **M**ajor **A**tmospheric **G**amma-ray **I**maging **C**herenkov telescopes

In operation for 18 years (12 years in stereo)

# Imaging Air Cherenkov Telescopes (IACTs): MAGIC

# Imaging Air Cherenkov Telescopes (IACTs): MAGIC

very-high energy (VHE, >GeV) γ-ray


- Mirror diameter: 17 m
- Camera field of view: 3.5°
- Energy range: 50 GeV – 50 TeV (Low zenith ~20°)
- Energy resolution: 15% – 25%
- Angular resolution: 0.05° – 0.10°

# So far: No detection after 20+ years

M. Doro, M. Sánchez-Conde, **MH** (2111.01198): all DM searches with IACTS:

- MAGIC alone: almost 1000h
- dSph: > 1500 h

| Target | Year | Time [h] | IACT | Limit | Ref. |
|---|---|---|---|---|---|
| **The Milky Way central region & halo** | | | | | |
| MW Centre | 2004 | (48.7) | H.E.S.S. | Ann. | Aharonian et al. (2006) |
| MW Inner Halo | 2004 – 2008 | (112) | H.E.S.S. | Ann. | Abramowski et al. (2011) |
| | 2010 | 9.1 | | Ann. | Abramowski et al. (2015) |
| | 2004 – 2014 | 254 | | Ann. | Abdallah et al. (2016) |
| | 2014 – 2020 | 546 | H.E.S.S.† | Ann. | Montanari et al. (2021) |
| MW Outer Halo | 2018 | 10 | MAGIC | Decay | Ninci et al. (2019) |
| **Dwarf Satellite Galaxies** | | | | | |
| Draco | 2003 | 7.4 | Whipple | Ann. | Wood et al. (2008) |
| | 2007 | 7.8 | MAGIC‡ | Ann. | Albert et al. (2008b) |
| | 2007 | (18.4) | VERITAS | Ann. | Acciari et al. (2010) |
| | 2007 – 2013 | (49.8) | | Ann. | Archambault et al. (2017) |
| | 2007 – 2018 | 114 | | – | Kelley-Hoskins (2018) |
| | 2018 | 52.6 | MAGIC | Ann. | Maggio et al. (2021) |
| Ursa Minor | 2003 | 7.9 | Whipple | Ann. | Wood et al. (2008) |
| | 2007 | (18.9) | VERITAS | Ann. | Acciari et al. (2010) |
| | 2007 – 2013 | (60.4) | | Ann. | Archambault et al. (2017) |
| | 2007 – 2018 | 161 | | – | Kelley-Hoskins (2018) |
| Sagittarius | 2006 | (11.0) | H.E.S.S. | Ann. | Aharonian et al. (2008) |
| | 2006 – 2012 | 90 | | Ann. | Abramowski et al. (2014) |
| | 2006 – 2012 | (85.5) | | Ann. | Abdalla et al. (2018a) |
| Canis Major | 2006 | 9.6 | H.E.S.S. | Ann. | Aharonian et al. (2009a) |
| Willman 1 | 2007 – 2008 | 13.7 | VERITAS | Ann. | Acciari et al. (2010) |
| | | (13.6) | | Ann. | Archambault et al. (2017) |
| | 2008 | 15.5 | MAGIC‡ | Ann. | Aliu et al. (2009) |
| Sculptor | 2008 | (11.8) | H.E.S.S. | Ann. | Abramowski et al. (2011) |
| | | | | Ann. | Abdalla et al. (2018a) |
| | 2008 – 2009 | 12.5 | | Ann. | Abramowski et al. (2014) |
| Carina | 2008 – 2009 | (14.8) | H.E.S.S. | Ann. | Abramowski et al. (2011) |
| | 2008 – 2009 | (12.7) | | Ann. | Abramowski et al. (2014) |
| | 2008 – 2010 | 22.9 | | Ann. | Abdalla et al. (2018a) |

Table 8.1 – Continued on next page

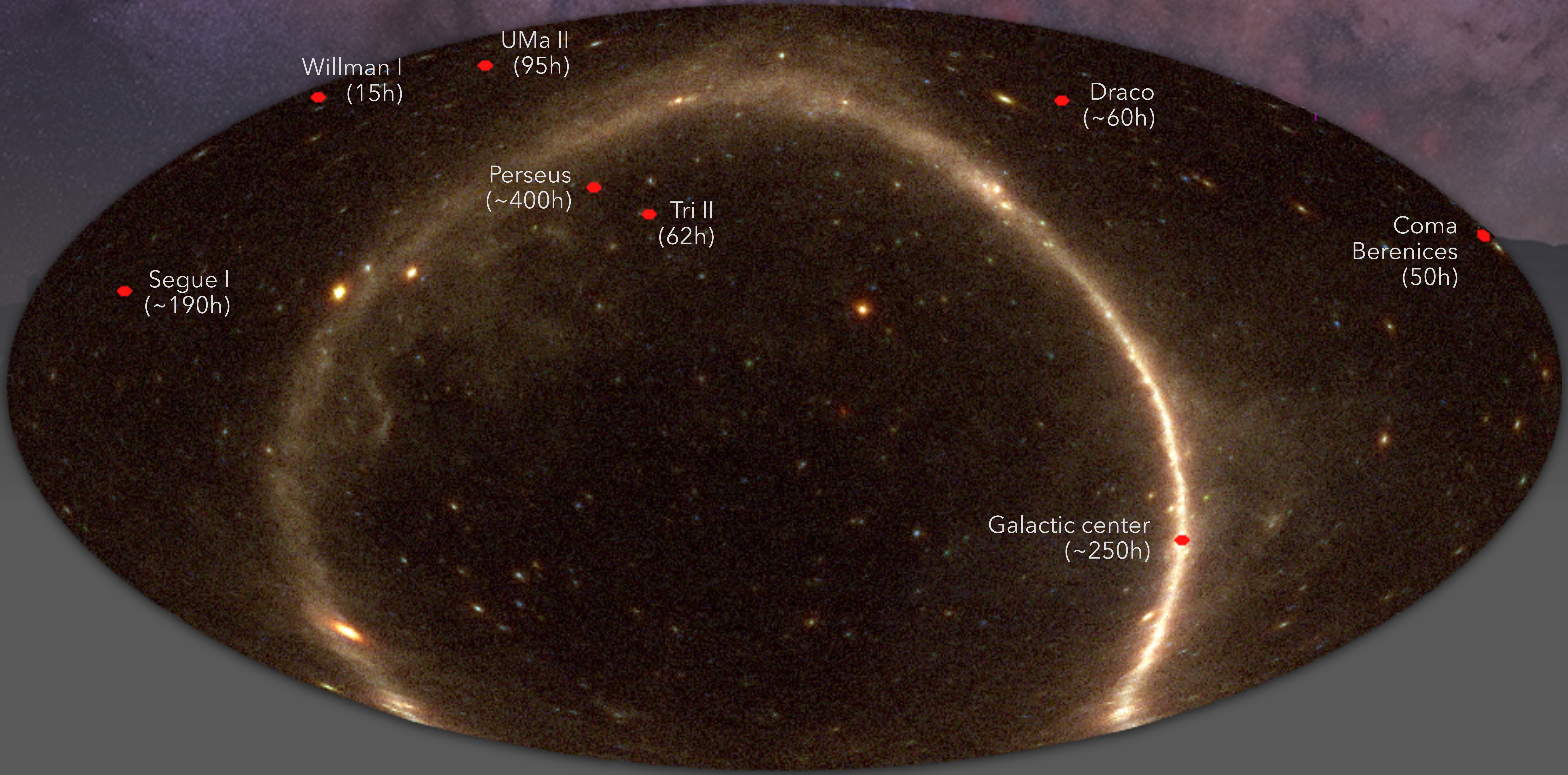
| Target | Year | Time [h] | IACT | Limit | Ref. |
|---|---|---|---|---|---|
| Segue 1 | 2008 – 2009 | 29.4 | MAGIC‡ | Ann. | Aleksić et al. (2011) |
| | 2010 – 2011 | (47.8) | VERITAS | A.+D. | Aliu et al. (2012) |
| | 2010 – 2013 | (92.0) | | Ann. | Archambault et al. (2017) |
| | 2010 – 2013 | 157.9 | MAGIC | A.+D. | Aleksić et al. (2014) |
| | | | | Ann. | Ahnen et al. (2016b) |
| | 2010 – 2018 | 184 | VERITAS | – | Kelley-Hoskins (2018) |
| Boötes 1 | 2009 | 14.3 | VERITAS | Ann. | Acciari et al. (2010) |
| | | (14.0) | | Ann. | Archambault et al. (2017) |
| Coma Berenices | 2010 – 2013 | (8.6) | H.E.S.S. | Ann. | Abramowski et al. (2014) |
| | 2010 – 2013 | 10.9 | | Ann. | Abdalla et al. (2018a) |
| | < 2018 | 37 | VERITAS | – | Kelley-Hoskins (2018) |
| | 2018 | 50.2 | MAGIC | Ann. | Maggio et al. (2021) |
| Fornax | 2010 | 6.0 | H.E.S.S. | Ann. | Abramowski et al. (2014) |
| | | | | Ann. | Abdalla et al. (2018a) |
| Ursa Major II | 2014 – 2016 | 94.8 | MAGIC | Ann. | Ahnen et al. (2018a) |
| Triangulum II* | 2014 – 2016 | 62.4 | MAGIC | Ann. | Acciari et al. (2020) |
| | < 2018 | 181 | VERITAS | – | Kelley-Hoskins (2018) |
| Segue II | < 2018 | 19 | VERITAS | – | Kelley-Hoskins (2018) |
| Canes Ven I | < 2018 | 14 | VERITAS | – | Kelley-Hoskins (2018) |
| Canes Ven II | < 2018 | 14 | VERITAS | – | Kelley-Hoskins (2018) |
| Hercules | < 2018 | 13 | VERITAS | – | Kelley-Hoskins (2018) |
| Sextans | < 2018 | 13 | VERITAS | – | Kelley-Hoskins (2018) |
| Draco II | < 2018 | 10 | VERITAS | – | Kelley-Hoskins (2018) |
| Leo I | < 2018 | 7 | VERITAS | – | Kelley-Hoskins (2018) |
| Leo II | < 2018 | 16 | VERITAS | – | Kelley-Hoskins (2018) |
| Leo IV | < 2018 | 3 | VERITAS | – | Kelley-Hoskins (2018) |
| Leo V | < 2018 | 3 | VERITAS | – | Kelley-Hoskins (2018) |
| Reticulum II | 2017 – 2018 | 18.3 | H.E.S.S.† | Ann. | Abdalla et al. (2020) |
| Tucana II | 2017 – 2018 | 16.4 | H.E.S.S.† | Ann. | Abdalla et al. (2020) |
| Tucana III* | 2017 – 2018 | 23.6 | H.E.S.S.† | Ann. | Abdalla et al. (2020) |
| Tucana IV* | 2017 – 2018 | 12.4 | H.E.S.S.† | Ann. | Abdalla et al. (2020) |
| Grus II* | 2018 | 11.3 | H.E.S.S.† | Ann. | Abdalla et al. (2020) |
| **Dark satellites** | | | | | |
| 1FGL J2347.3+0710 | 2010 | 8.3 | MAGIC | – | Nieto et al. (2011a) |
| 1FGL J0338.8+1313 | 2010-2011 | 10.7 | MAGIC | – | Nieto et al. (2011a) |
| 2FGL J0545.6+6018 | 2013-2015 | 8.5 | VERITAS | Ann. | Nieto (2015) |
| 2FGL J1115.0-0701 | 2013-2015 | 13.8 | VERITAS | Ann. | Nieto (2015) |
| H3FHL J0929.2-4110 | 2018-2019 | 7.8 | H.E.S.S.† | Ann. | Abdallah et al. (2021a) |
| 3FHL J1915.2-1323 | 2018 – 2019 | 3.0 | H.E.S.S.† | Ann. | Abdallah et al. (2021a) |
| 3FHL J2030.2-5037 | 2018 – 2019 | 8.8 | H.E.S.S.† | Ann. | Abdallah et al. (2021a) |
| 3FHL J2104.5+2117 | 2018 – 2019 | 5.5 | H.E.S.S.† | Ann. | Abdallah et al. (2021a) |

Table 8.1 – Continued on next page

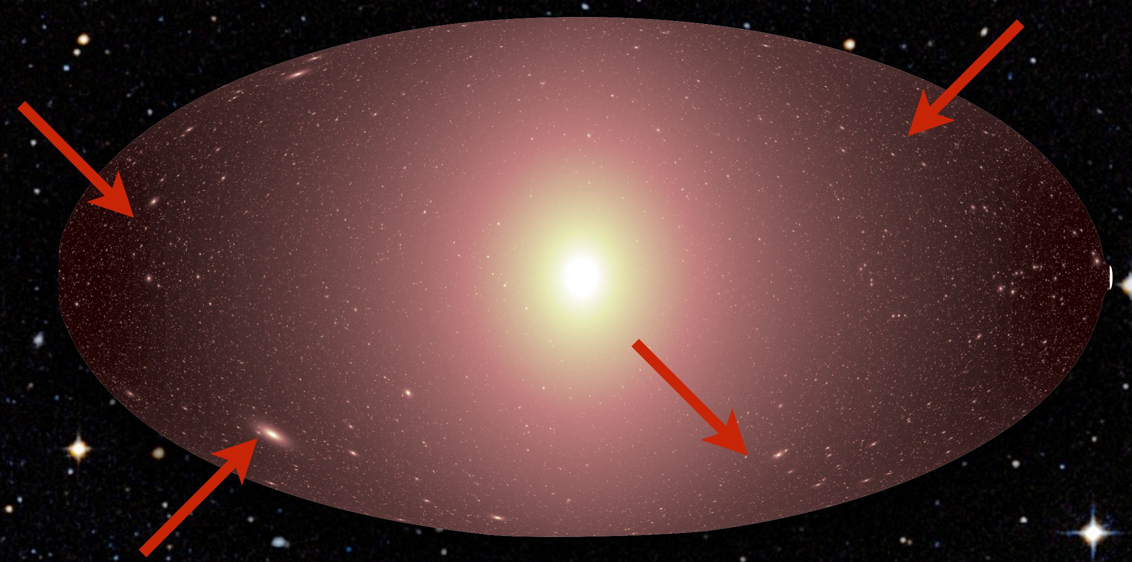
| Target | Year | Time [h] | IACT | Limit | Ref. |
|---|---|---|---|---|---|
| **Intermediate Mass Black Holes** | | | | | |
| Galactic Plane Survey | 2004 – 2007 | 400 | H.E.S.S. | Ann. | Aharonian et al. (2008a) |
| | 2005 – 2006 | 25 | MAGIC‡ | Ann. | Doro et al. (2007) |
| **Globular Clusters** | | | | | |
| M15 | 2002 | 0.2 | Whipple | Ann. | Wood et al. (2008) |
| | 2006 – 2007 | 15.2 | H.E.S.S. | Ann. | Abramowski et al. (2011) |
| NGC 6388 | 2008 – 2009 | 27.2 | H.E.S.S. | Ann. | Abramowski et al. (2011) |
| **Other galaxies** | | | | | |
| M33 | 2002 – 2004 | 7.9 | Whipple | Ann. | Wood et al. (2008) |
| M32 | 2004 | 6.9 | Whipple | Ann. | Wood et al. (2008) |
| WLM | 2018 | 18.2 | H.E.S.S.† | Ann. | Abdallah et al. (2021b) |
| **Galaxy Clusters** | | | | | |
| Abell 2029 | 2003 – 2004 | 6.1 | Whipple | – | Perkins et al. (2006) |
| Perseus (Abell 426) | 2004 – 2005 | 13.5 | Whipple | – | Perkins et al. (2006) |
| | 2008 | 24.4 | MAGIC‡ | Ann. | Aleksić et al. (2010) |
| | 2009 – 2017 | 202.2 | MAGIC | Decay | Acciari et al. (2018) |
| Fornax (Abell S0373) | 2005 | 14.5 | H.E.S.S. | Ann. | Abramowski et al. (2012) |
| Coma (Abell 1656) | 2008 | 18.6 | VERITAS | Ann. | Arlen et al. (2012) |
| **Line searches** | | | | | |
| MW Inner Halo | 2004 – 2008 | (112) | H.E.S.S. | Ann. | Abramowski et al. (2013c) |
| | 2014 | 15.2 | H.E.S.S.† | Ann. | Abdalla et al. (2016) |
| | 2004 – 2014 | (254) | H.E.S.S. | Ann. | Abdalla et al. (2018b) |
| | 2013 – 2019 | 204 | MAGIC | Ann. | Inada et al. (2021) |
| Segue 1 dSph | 2010 – 2013 | (157.9) | MAGIC | A.+D. | Aleksić et al. (2014) |
| Five dSph galaxies | 2006 – 2012 | (137.1) | H.E.S.S. | Ann. | Abdalla et al. (2018a) |
| Five dSph galaxies | 2007 – 2013 | (229.8) | VERITAS | Ann. | Archambault et al. (2017) |
| WLM | 2018 | (18.2) | H.E.S.S.† | Ann. | Abdallah et al. (2021b) |
| **Charged particles** | | | | | |
| All-electron | 2004 – 2007 | 239 | H.E.S.S. | – | Aharonian et al. (2008b, 2009b) |
| | 2009 – 2012 | 296 | VERITAS | – | Archer et al. (2018) |
| | 2009 – 2010 | 14 | MAGIC | – | Borla Tridon et al. (2011) |
| Moon shadow | 2010 – 2011 | 20 | MAGIC | – | Colin et al. (2011) |
| | 2014 | 1.2 | VERITAS | – | Bird et al. (2016) |

# So far: No detection after 20+ years

MAGIC Dark Matter searches:



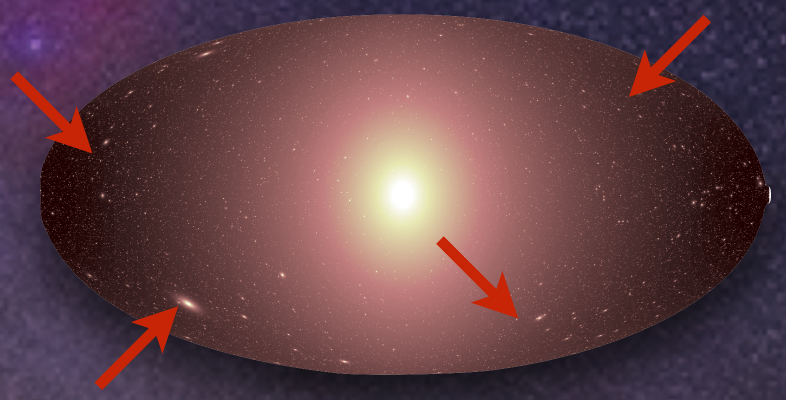
# MAGIC searches in dwarf spheroidal galaxies



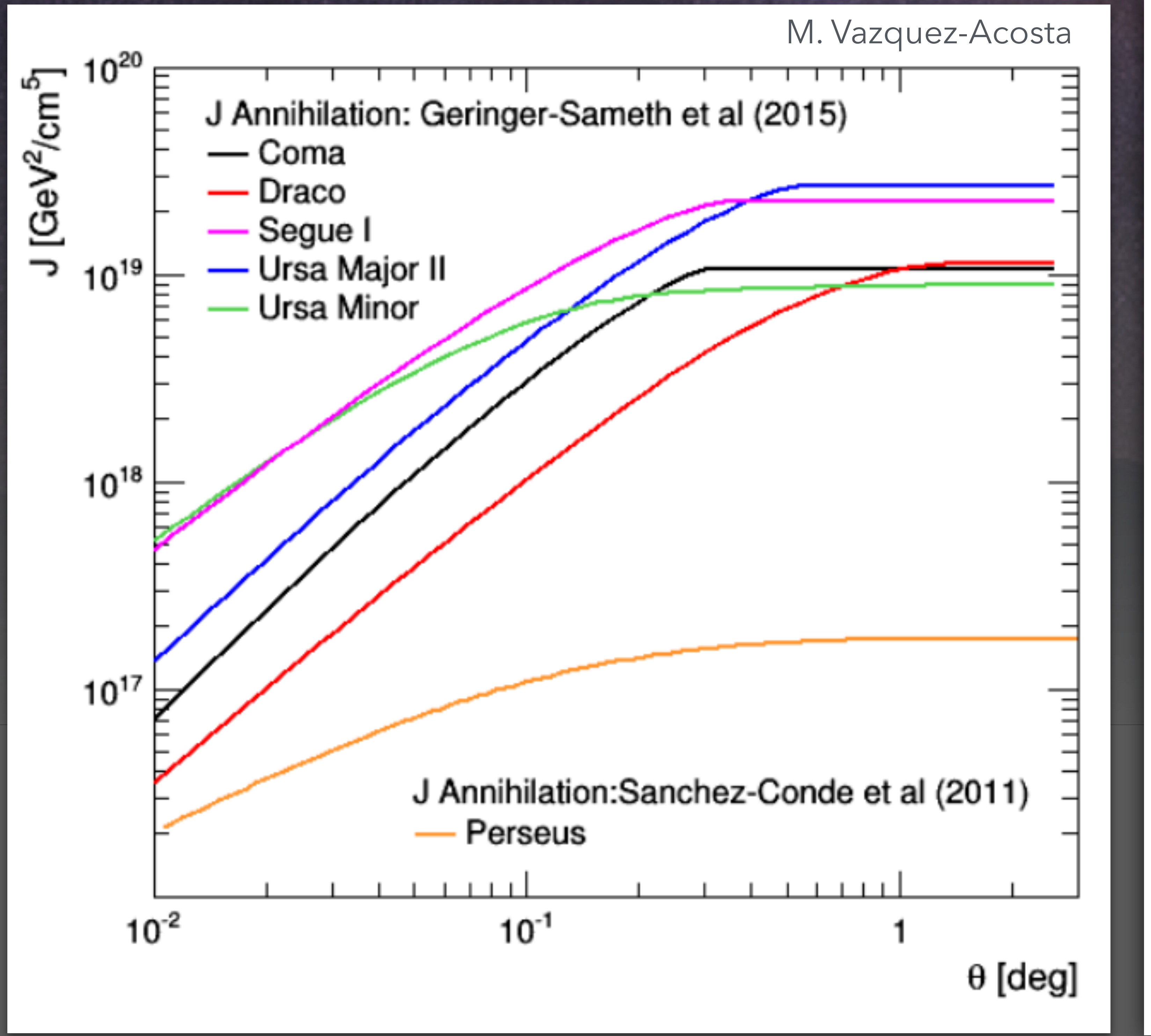
| + | - |
|---|---|
| no astrophysical background: clean targets | lower fluxes than from GC region |
| Relatively robust *J*-factor constraints | Systematic *J*-factor uncertainties in ultrafaint dSphG (stellar interlopers + bias) |

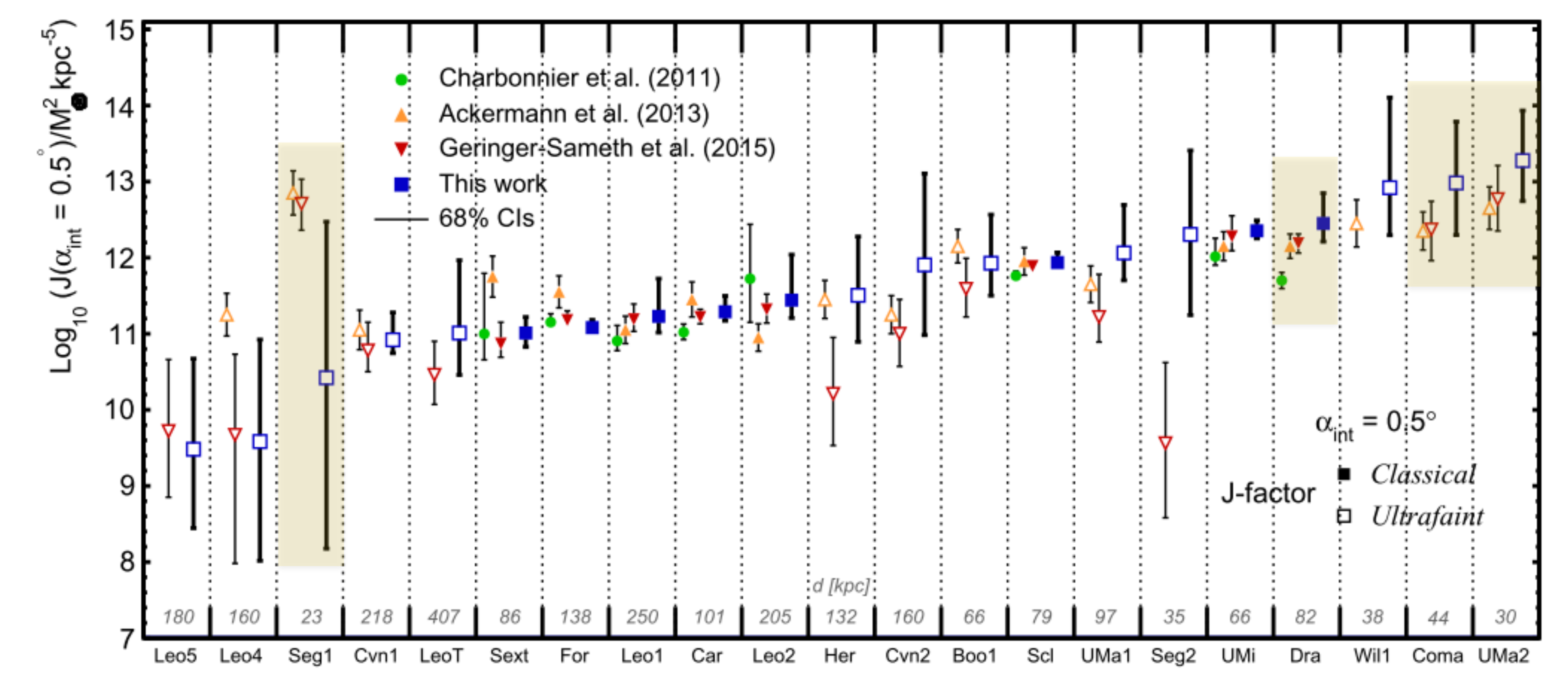
Picture credit: ESO/DSS2

# dSph Galaxies: Limits by MAGIC



Pointed observations: Choose the best target(s)



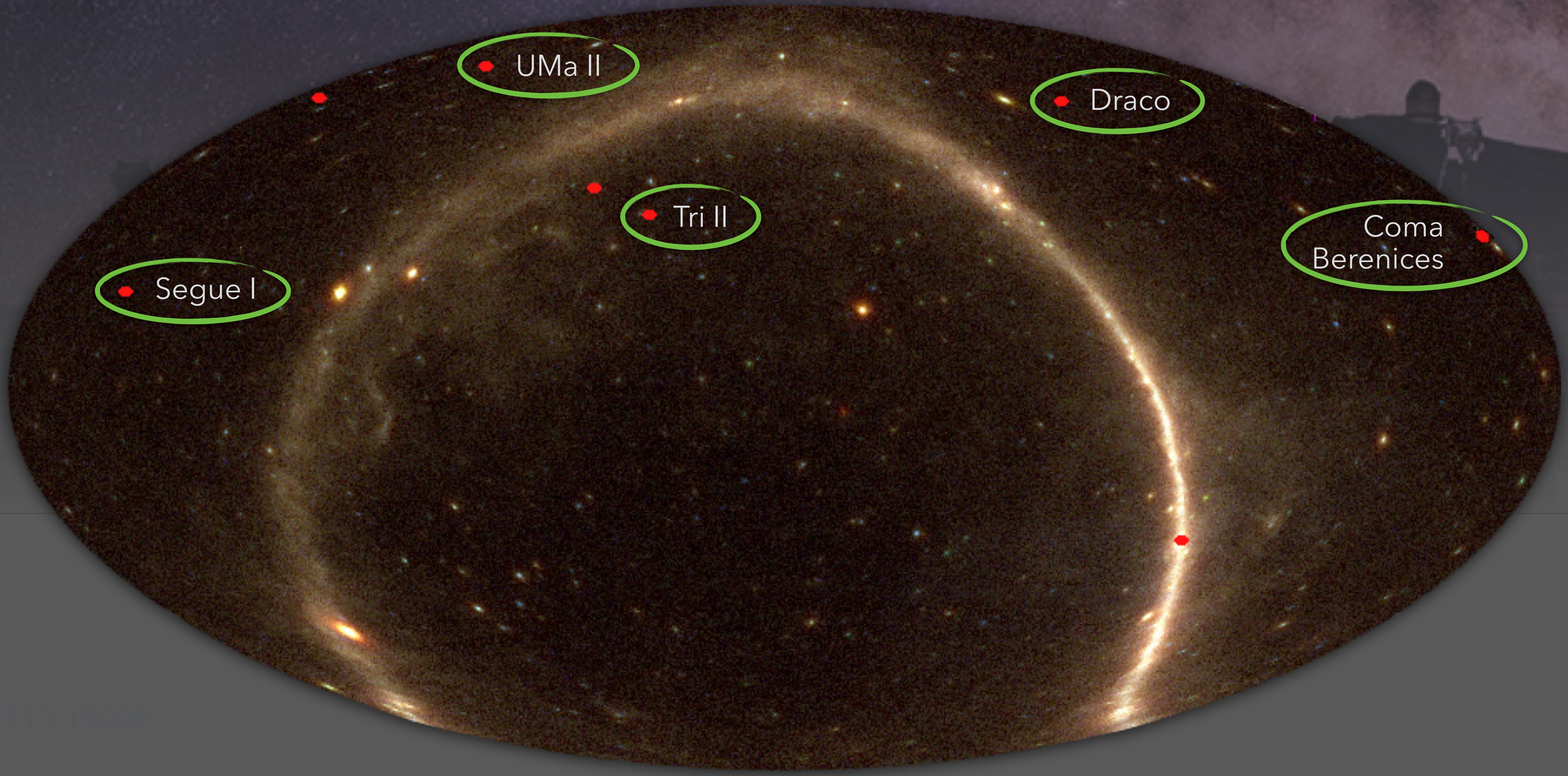




Bonnivard et al., 1504.02048

Due to *J*-factor uncertainties, diversify targets to increase chance of discovery + obtain more robust limits

# dSph Galaxies: Combined limits by MAGIC

Combined analysis of more than 350h of MAGIC dSph observations




| Target | Obs. time | ***J***-factor log[GeV$^2$cm$^{-5}$ |
|---|---|---|
| **Segue 1** | 158h | 19.36±0.35 |
| **Ursa Major II** | 95h | 19.42±0.42 |
| **Draco** | 52h | 19.05±0.21 |
| **Coma Berenices** | 50h | 19.02±0.41 |

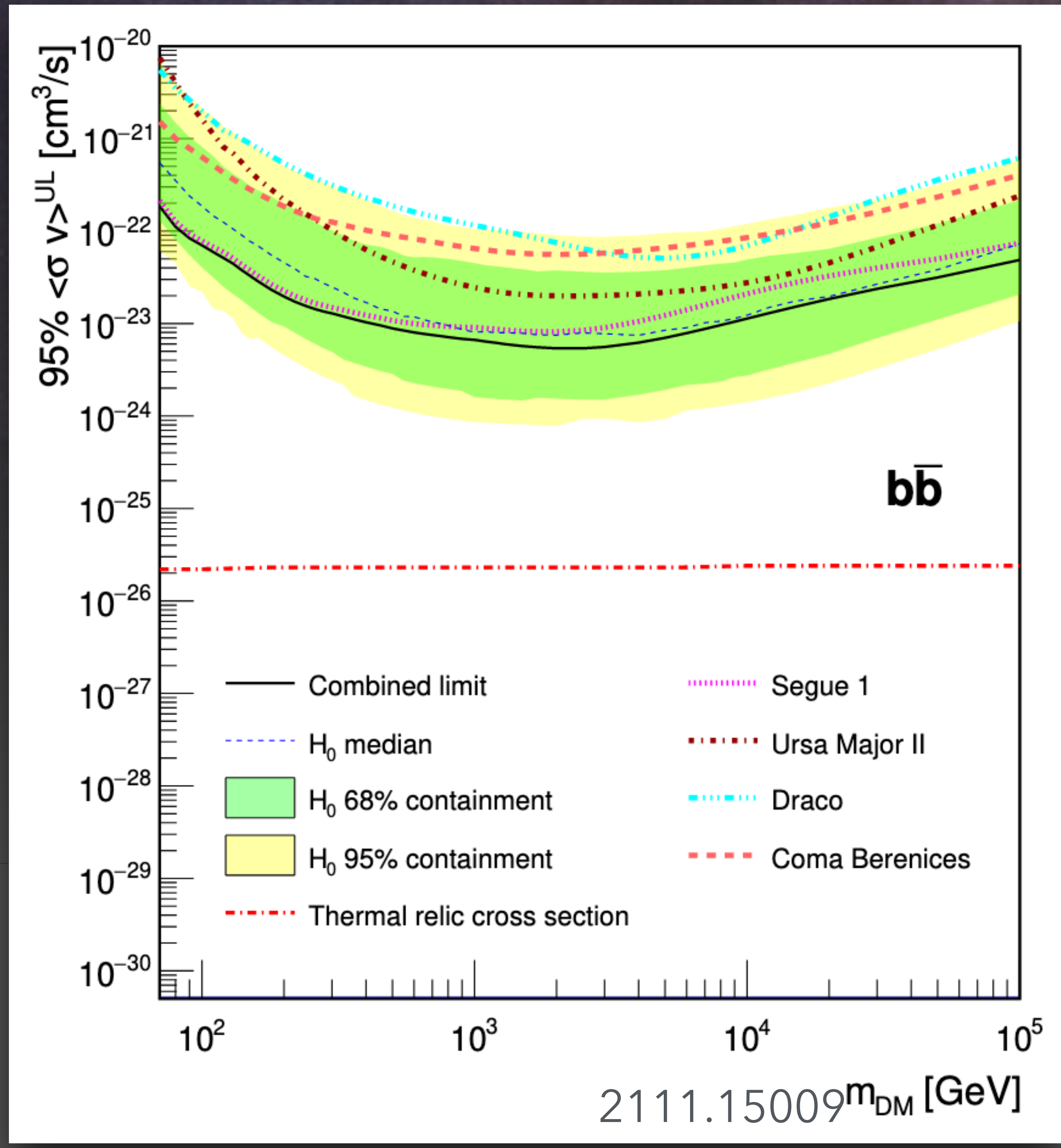
Total observation time: 354h

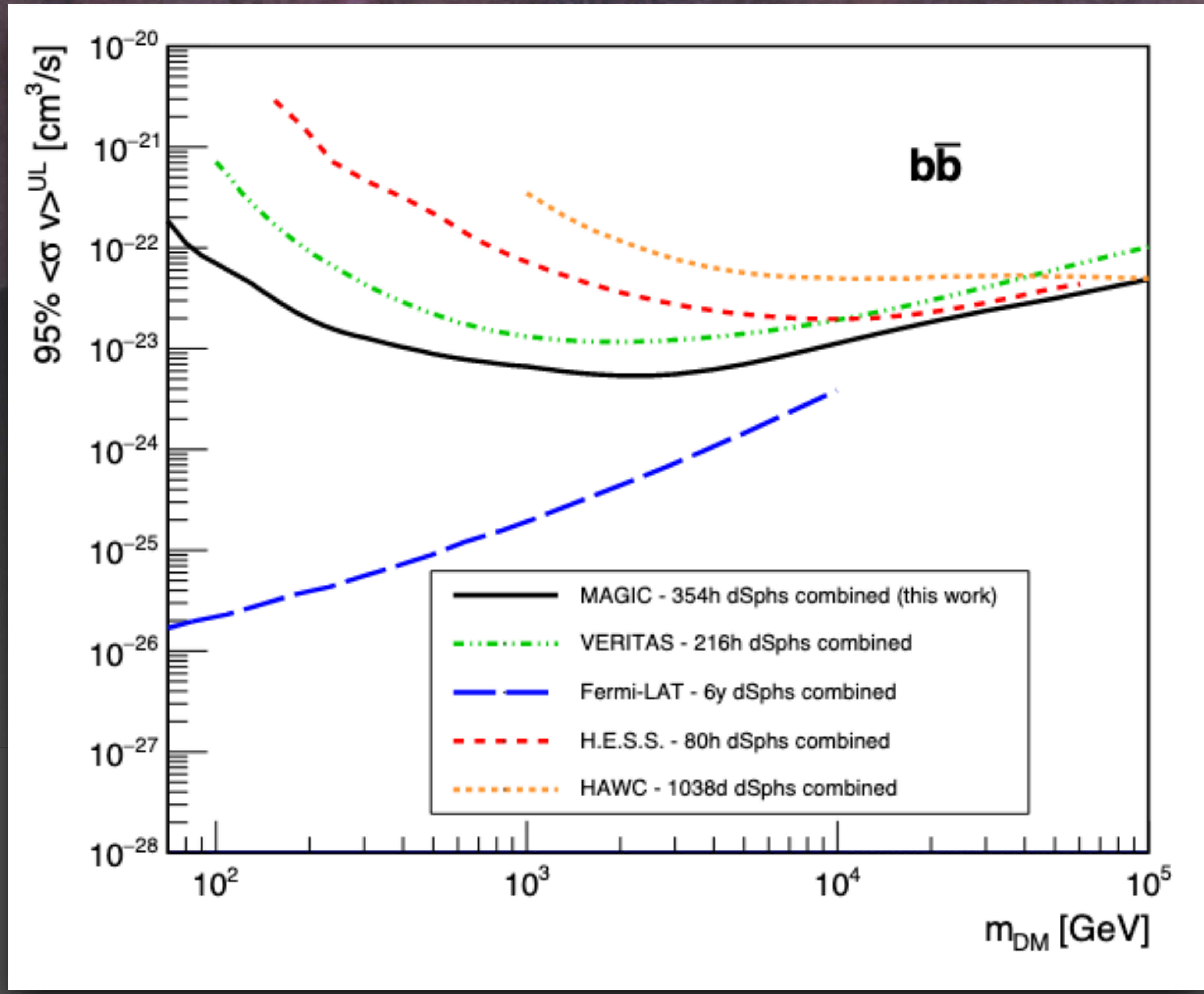
| | | |
|---|---|---|
| Tri II | 62h | 19.35±0.37 |

Separately: Acciari et. al., 2020.100529

# dSph Galaxies: Combined limits by MAGIC

No signal neither in Segue 1, UMa II, Draco, Coma, Tri II, nor after combination:




Accepted for publication in PDU two weeks ago and now on arXiv:
https://arxiv.org/abs/2111.15009

# dSph Galaxies: Combined limits by MAGIC + others

## Add data from 4 more telescopes and 16 additional targets

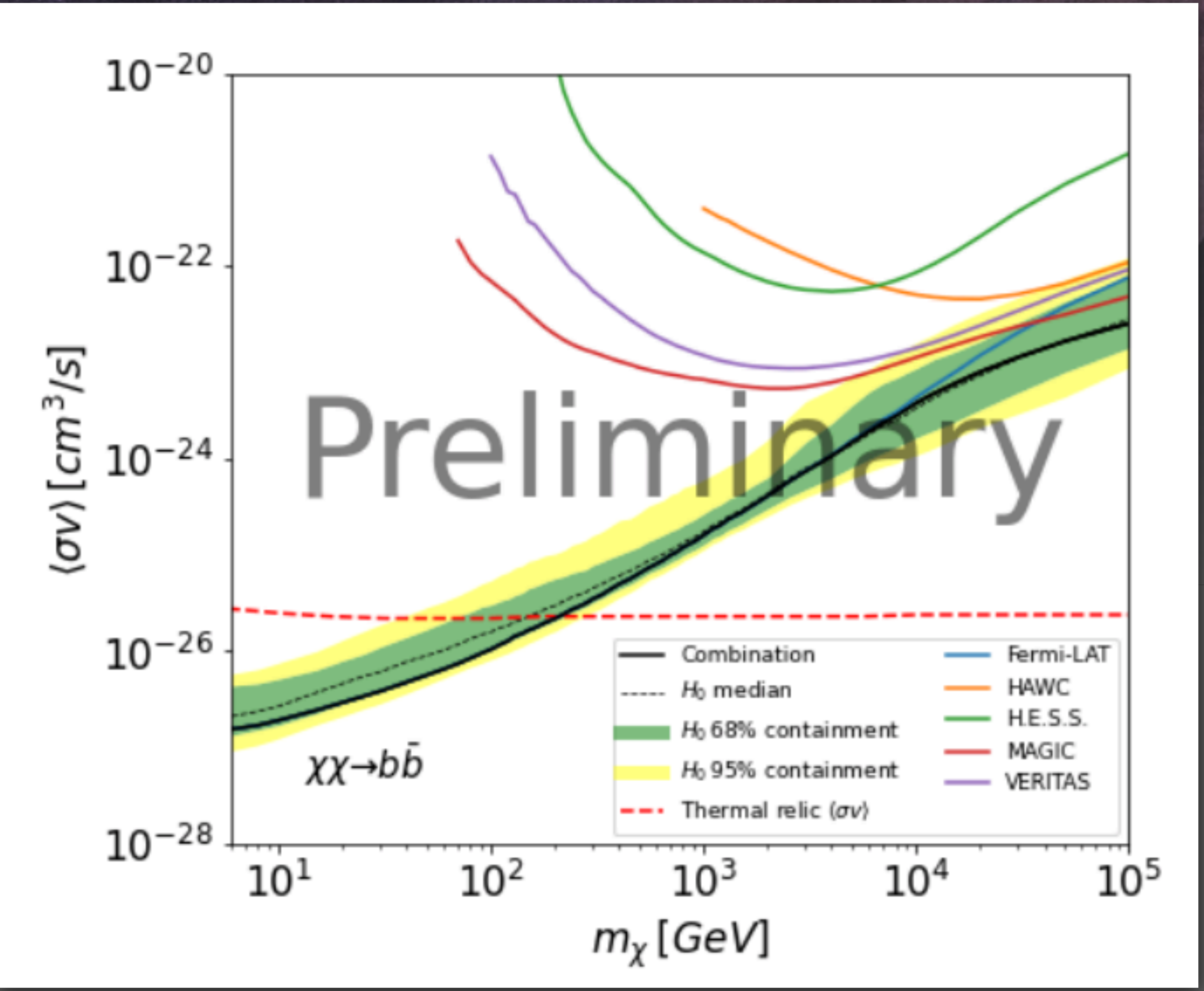
| Source name | Experiments | Distance (kpc) | $\log_{10} J$ $\log_{10}(\mathrm{GeV^2 cm^{-5} sr})$ |
|---|---|---|---|
| Bootes I | *Fermi*-LAT, HAWC, VERITAS | 66 | $18.24^{+0.40}_{-0.37}$ |
| Canes Venatici I | *Fermi*-LAT | 218 | $17.44^{+0.37}_{-0.28}$ |
| Canes Venatici II | *Fermi*-LAT, HAWC | 160 | $17.65^{+0.45}_{-0.43}$ |
| Carina | *Fermi*-LAT, H.E.S.S. | 105 | $17.92^{+0.19}_{-0.11}$ |
| Coma Berenices | *Fermi*-LAT, HAWC, H.E.S.S., MAGIC | 44 | $19.02^{+0.37}_{-0.41}$ |
| Draco | *Fermi*-LAT, HAWC, MAGIC, VERITAS | 76 | $19.05^{+0.22}_{-0.21}$ |
| Fornax | *Fermi*-LAT, H.E.S.S. | 147 | $17.84^{+0.11}_{-0.06}$ |
| Hercules | *Fermi*-LAT, HAWC | 132 | $16.86^{+0.74}_{-0.68}$ |
| Leo I | *Fermi*-LAT, HAWC | 254 | $17.84^{+0.20}_{-0.16}$ |
| Leo II | *Fermi*-LAT, HAWC | 233 | $17.97^{+0.20}_{-0.18}$ |
| Leo IV | *Fermi*-LAT, HAWC | 154 | $16.32^{+1.06}_{-1.70}$ |
| Leo T | *Fermi*-LAT | 417 | $17.11^{+0.44}_{-0.39}$ |
| Leo V | *Fermi*-LAT | 178 | $16.37^{+0.94}_{-0.87}$ |
| Sculptor | *Fermi*-LAT, H.E.S.S. | 86 | $18.57^{+0.07}_{-0.05}$ |
| Segue I | *Fermi*-LAT, HAWC, MAGIC, VERITAS | 23 | $19.36^{+0.32}_{-0.35}$ |
| Segue II | *Fermi*-LAT | 35 | $16.21^{+1.06}_{-0.98}$ |
| Sextans | *Fermi*-LAT, HAWC | 86 | $17.92^{+0.35}_{-0.29}$ |
| Ursa Major I | *Fermi*-LAT, HAWC | 97 | $17.87^{+0.56}_{-0.33}$ |
| Ursa Major II | *Fermi*-LAT, HAWC, MAGIC | 32 | $19.42^{+0.44}_{-0.42}$ |
| Ursa Minor | *Fermi*-LAT, VERITAS | 76 | $18.95^{+0.26}_{-0.18}$ |

2108.13646

- more than 500h of IACT data on 9 dSphs
- 10 years Fermi-LAT integrated time on 20 dSphs
- 1038 days of HAWC exposure on 12 dSphs

# dSph Galaxies: Combined limits by MAGIC + others

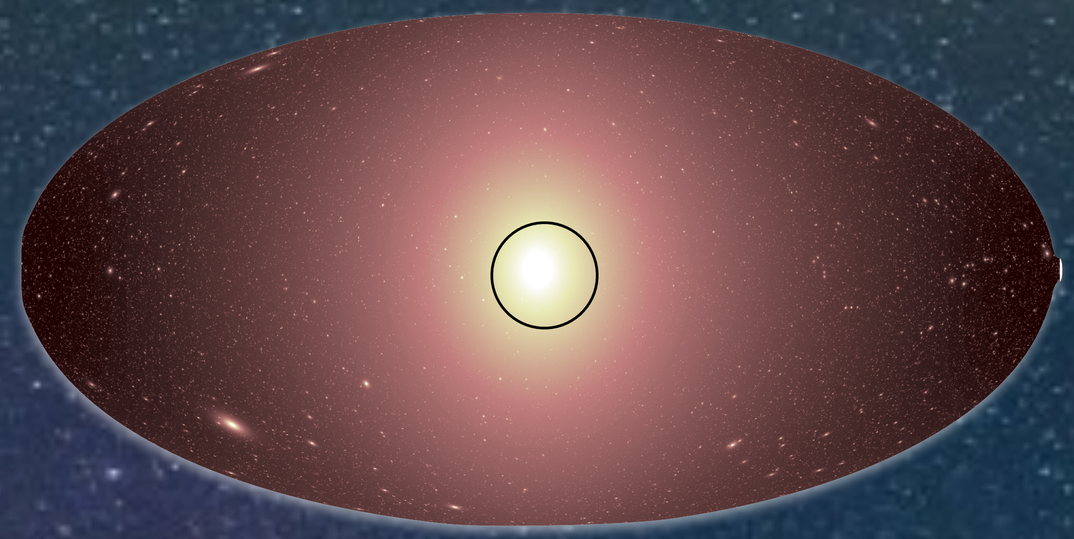
Add data from 4 more telescopes and 16 additional targets




2108.13646

- more than 500h of IACT data on 9 dSphs
- 10 years Fermi-LAT integrated time on 20 dSphs
- 1038 days of HAWC exposure on 12 dSphs

# MAGIC searches at the Galactic center

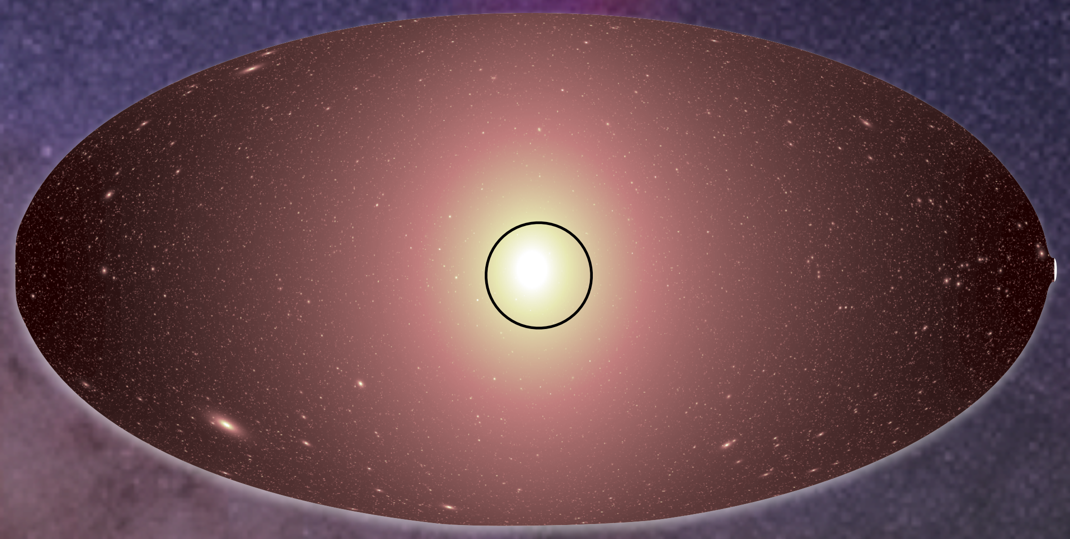


| + | - |
|---|---|
| By far strongest signal for all DM models | Limits: Uncertainty on cusp/ core |
| Large solid angle with high intensity | Astrophysical γ-ray backgrounds |
| | Cosmic-ray background for Earth-bound instruments |

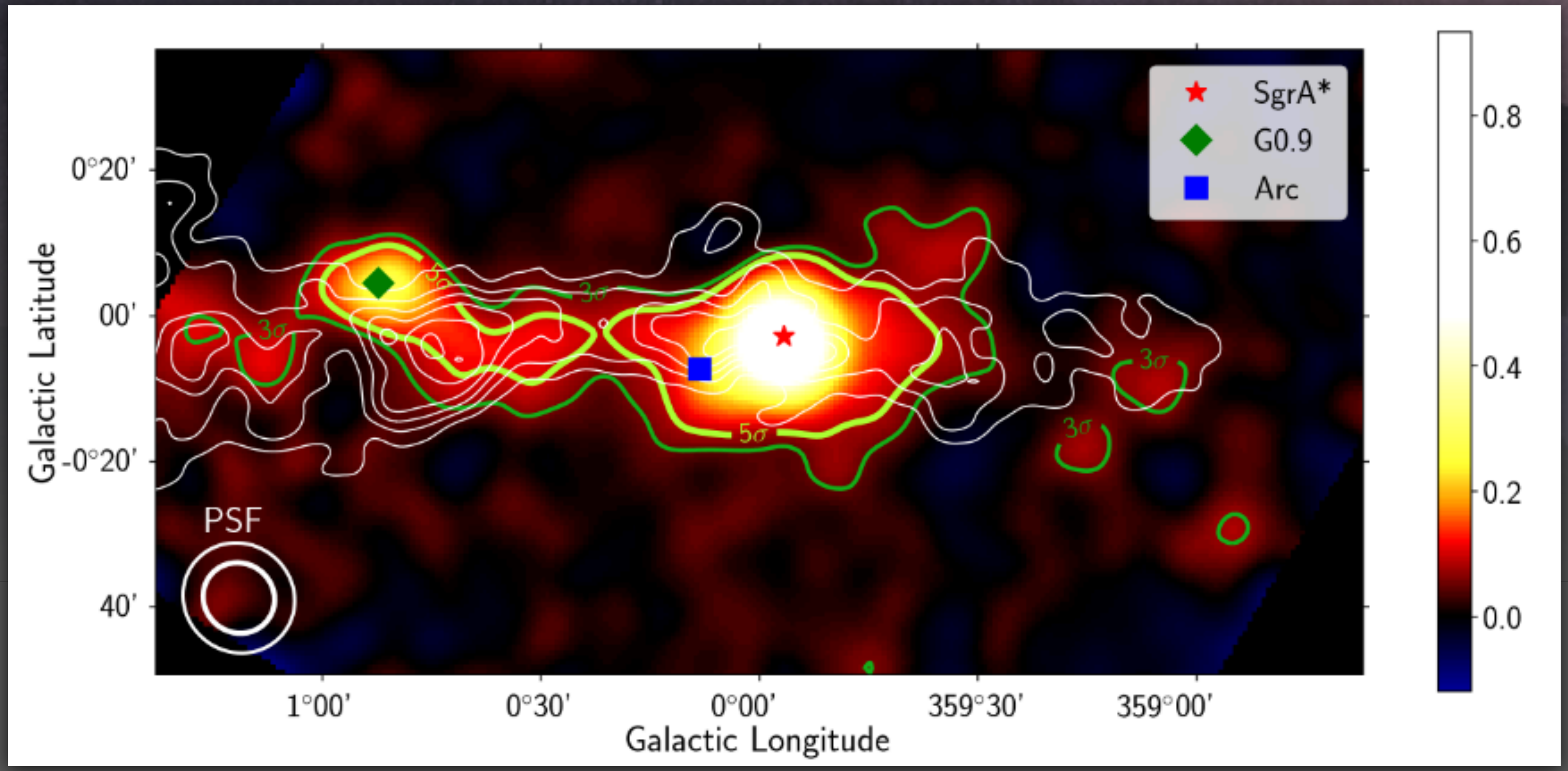
Galactic Center rises only 32° above horizon for MAGIC

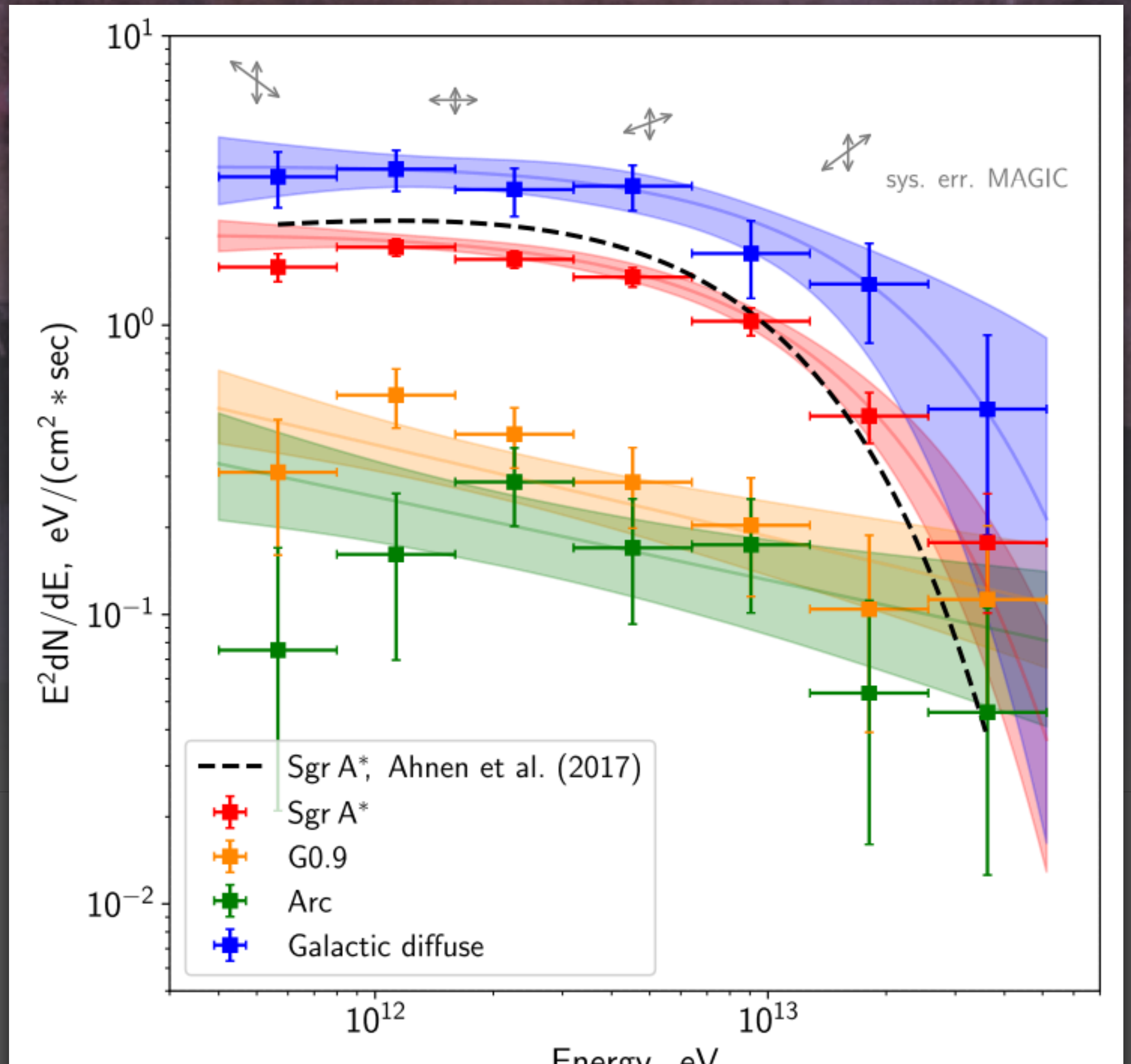
Picture credit: D. López

# MAGIC searches at the Galactic center



MAGIC, 2006.00623



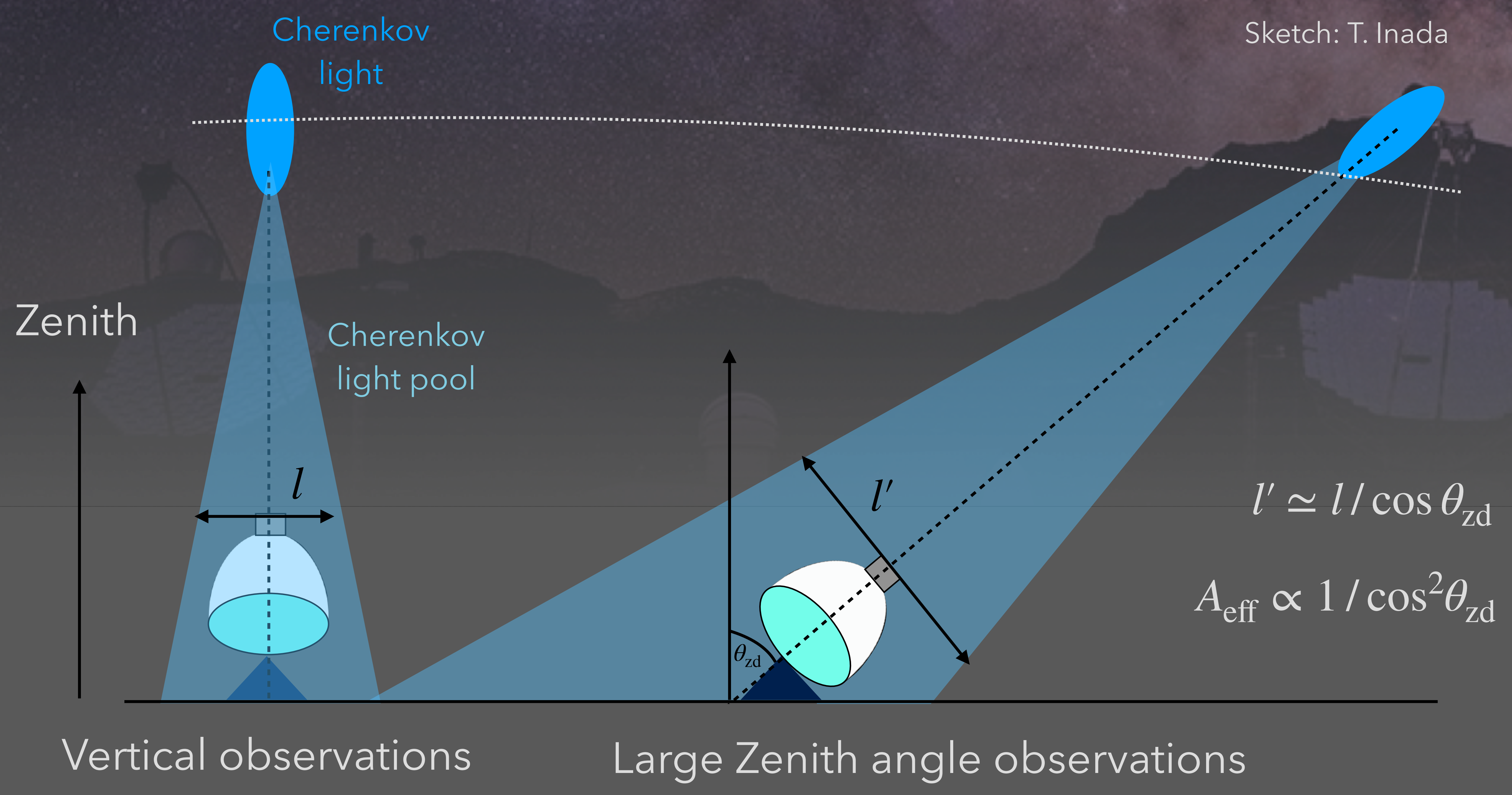




MAGIC, 2006.00623

Galactic center active region with diverse known γ-ray emitters

# MAGIC searches at the Galactic center

58° - 70° distance from zenith: large zenith angle observation (LZA)

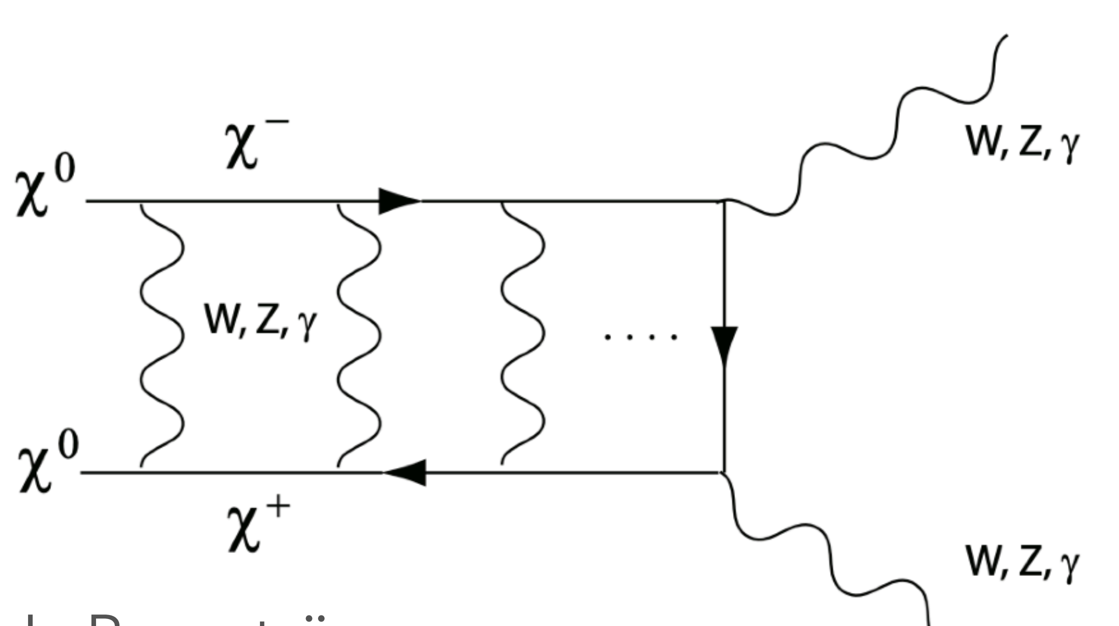



| | |
|---|---|
| + | Increased γ-ray detection area: larger statistics at TeV energies |
| - | Increased energy threshold |

LZA observations of the GC suitable for TeV DM line searches

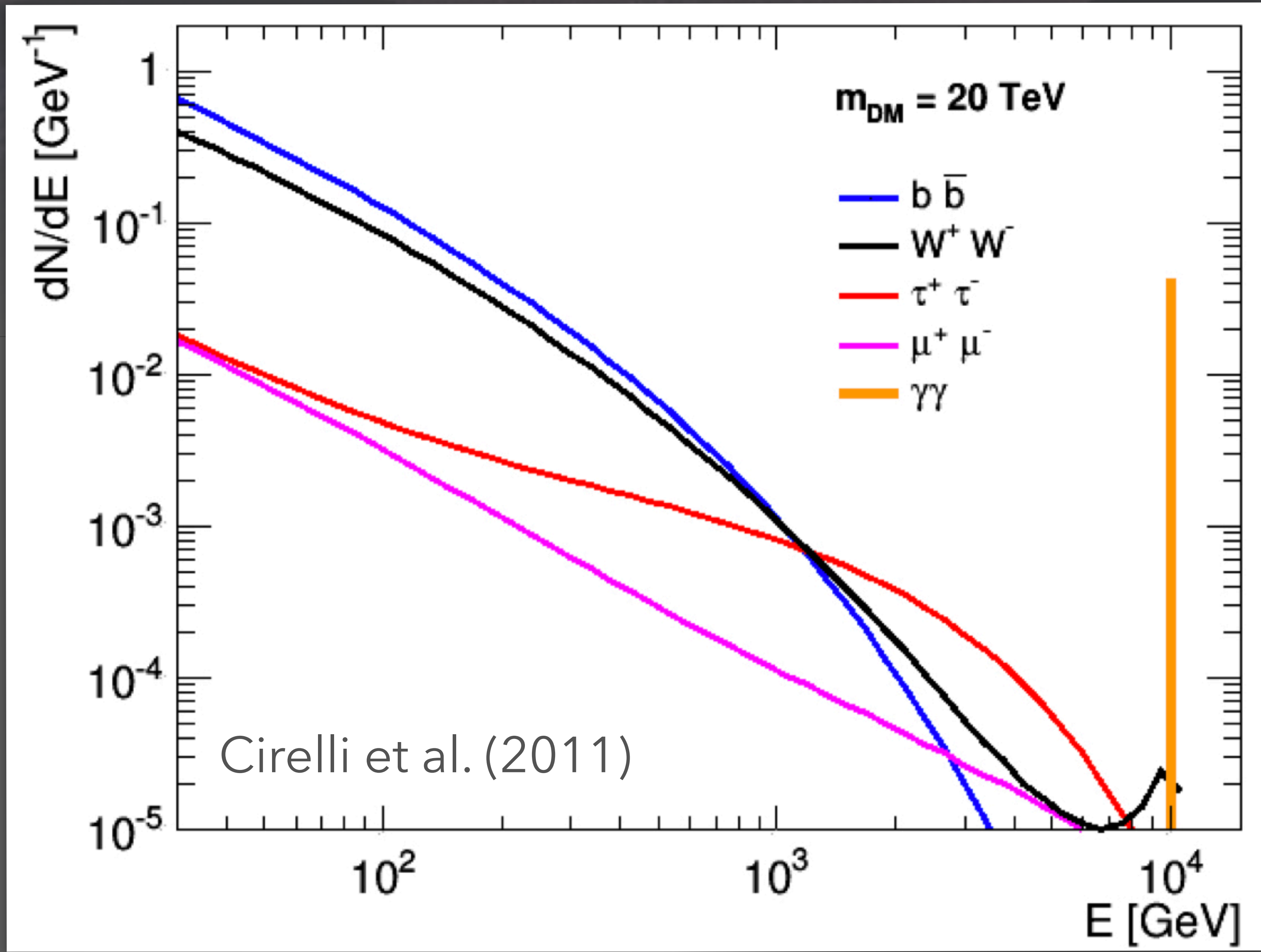
# Search for DM line emission

Ongoing project: T. Inada (ICRR), D. Kerszberg (IFAE), **MH**

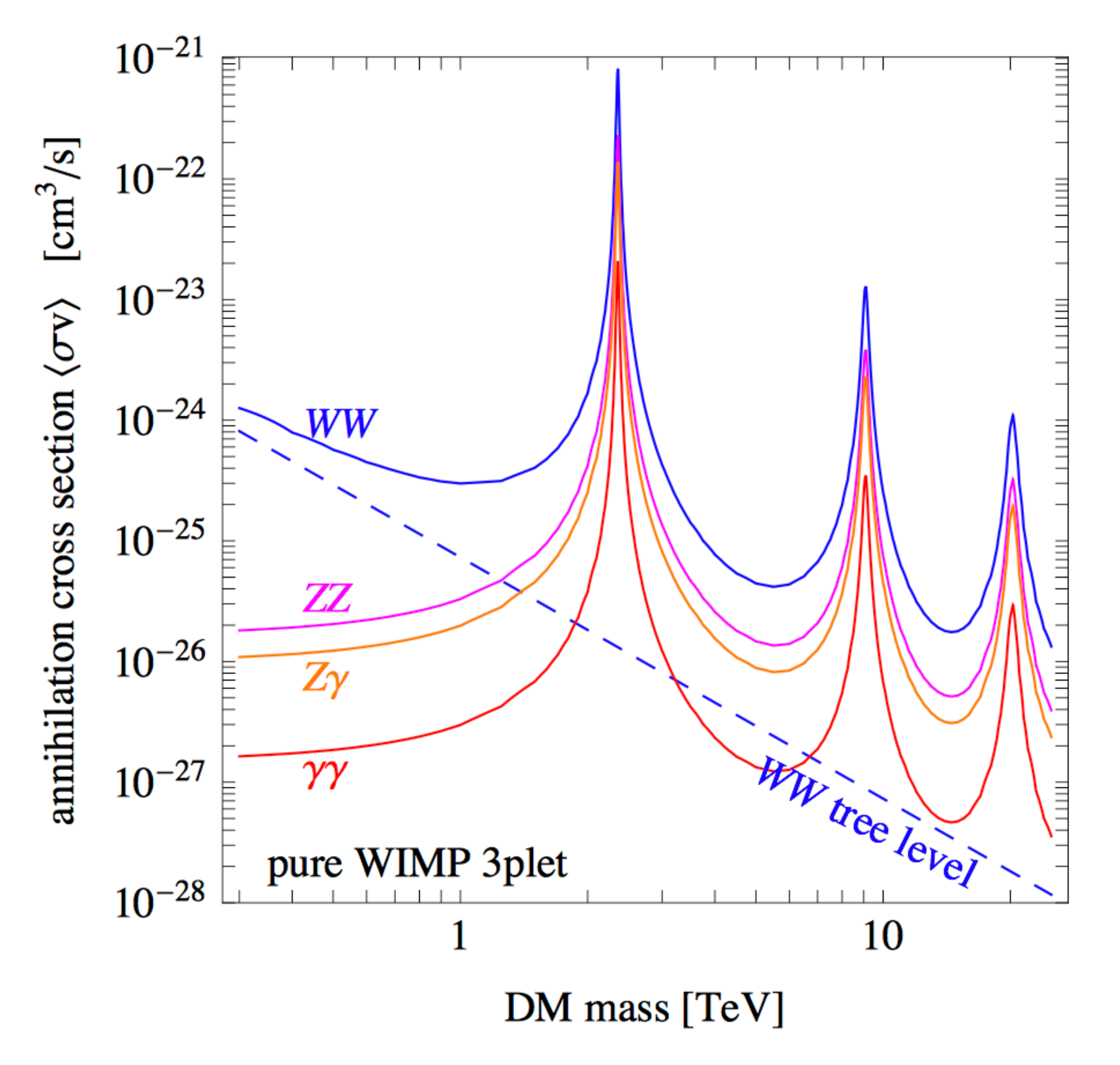


L. Bergström

- Sharp peak at DM mass
- $\chi\chi \rightarrow \gamma\gamma$ channel loop-suppressed by $\alpha^2$ (Some TeV DM models expected with Sommerfeld enhanced $\sigma v$)
- Line-like features also by three-body annihilations (virtual internal bremsstrahlung)

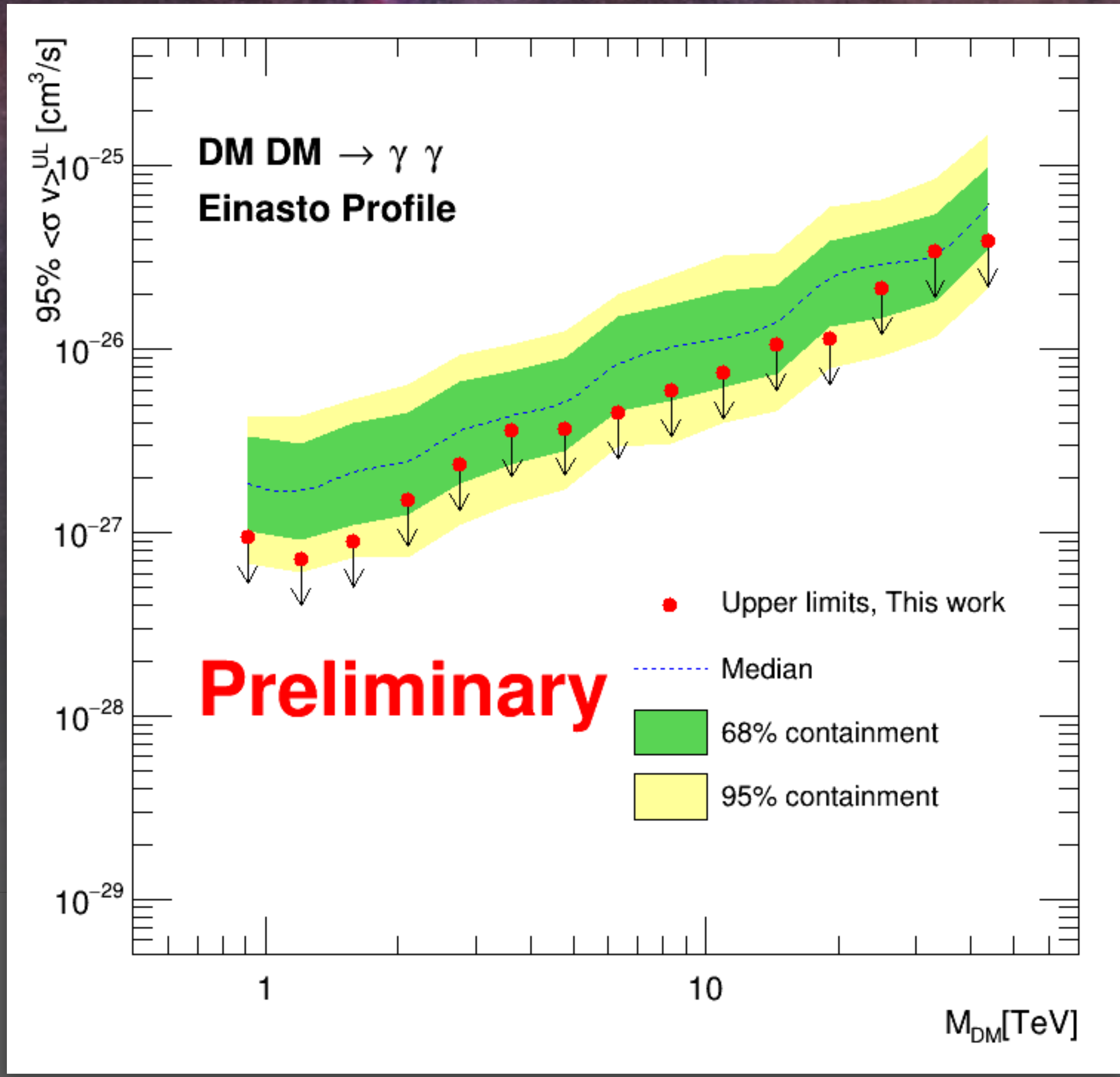


Cirelli et al. (2011)



H.E.S.S. collaboration JCAP11(2018)

# GC line search: Results

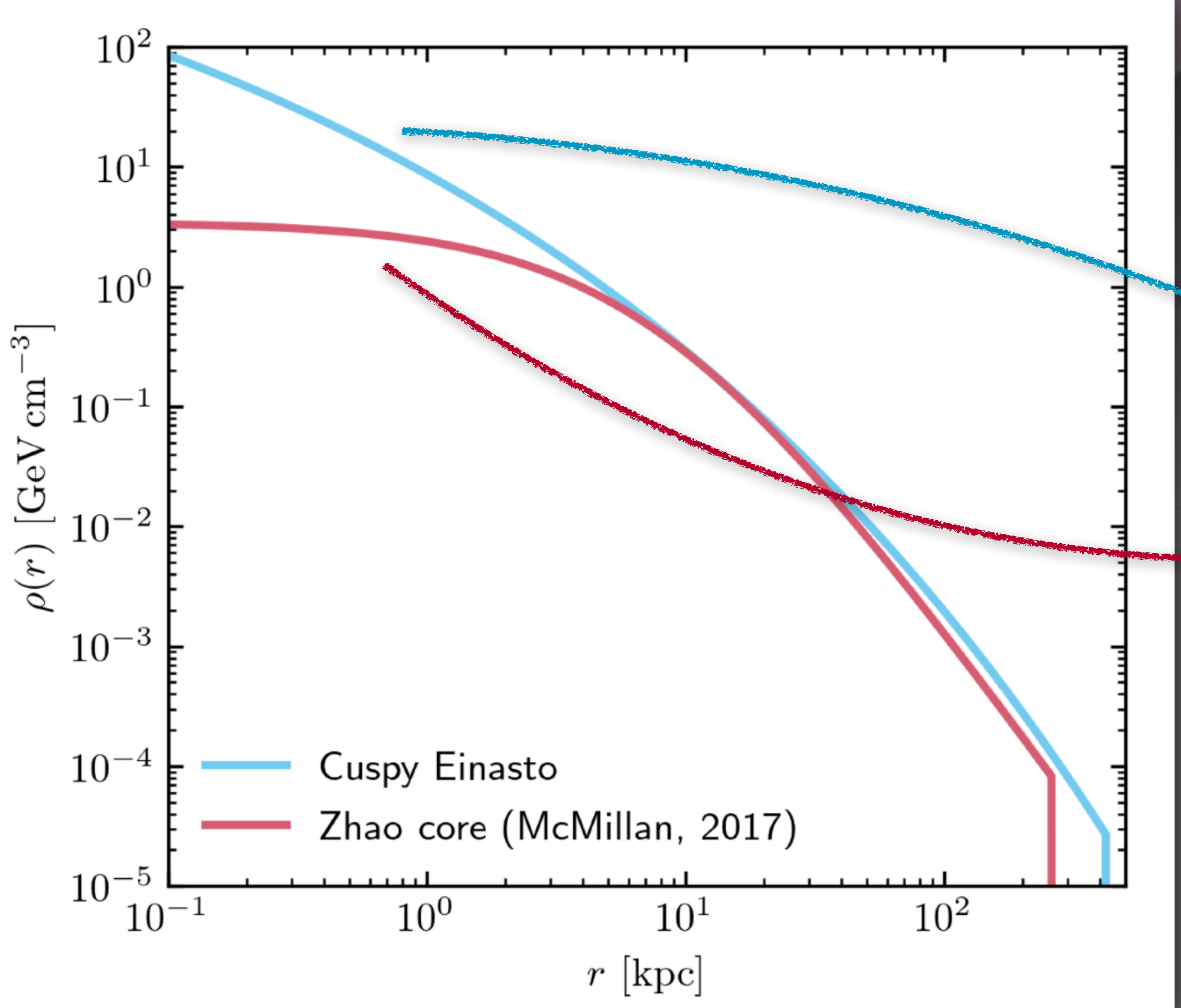


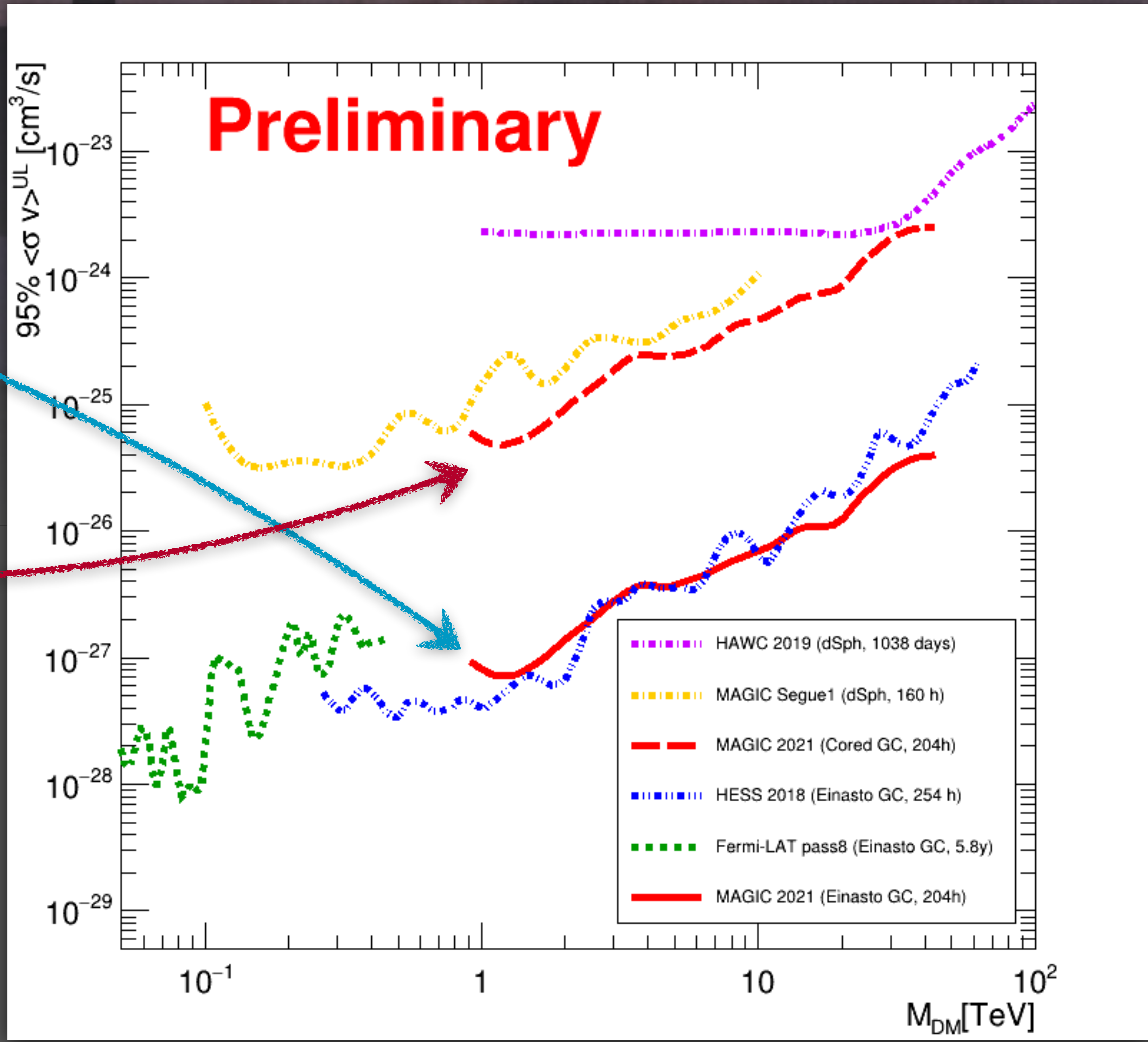

- No significant line-like excess found
- Set upper limits at 95% C.L. on 15 masses between 912 GeV - 43 TeV

# GC line search: Results

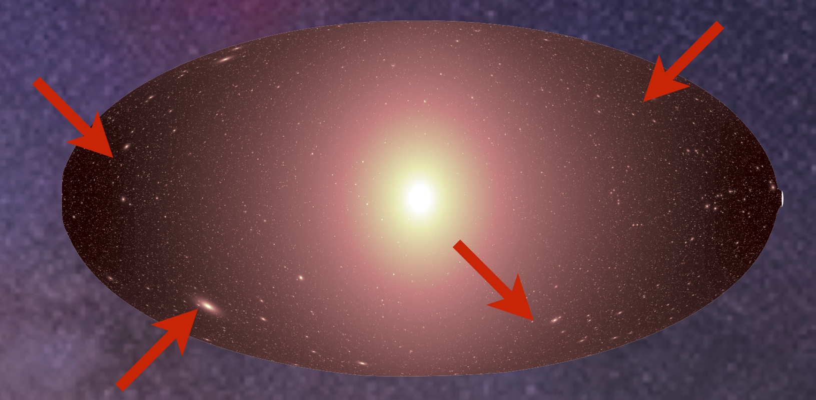
Limits obtained for Einasto (cuspy) and GC profile with ~500pc core (McMillan, 2017)

- For GC DM cusp: Competitive to most stringent limits to $\chi\chi \rightarrow \gamma\gamma$ at E > 10 TeV
- For GC DM core: Limit competitive to dSph results

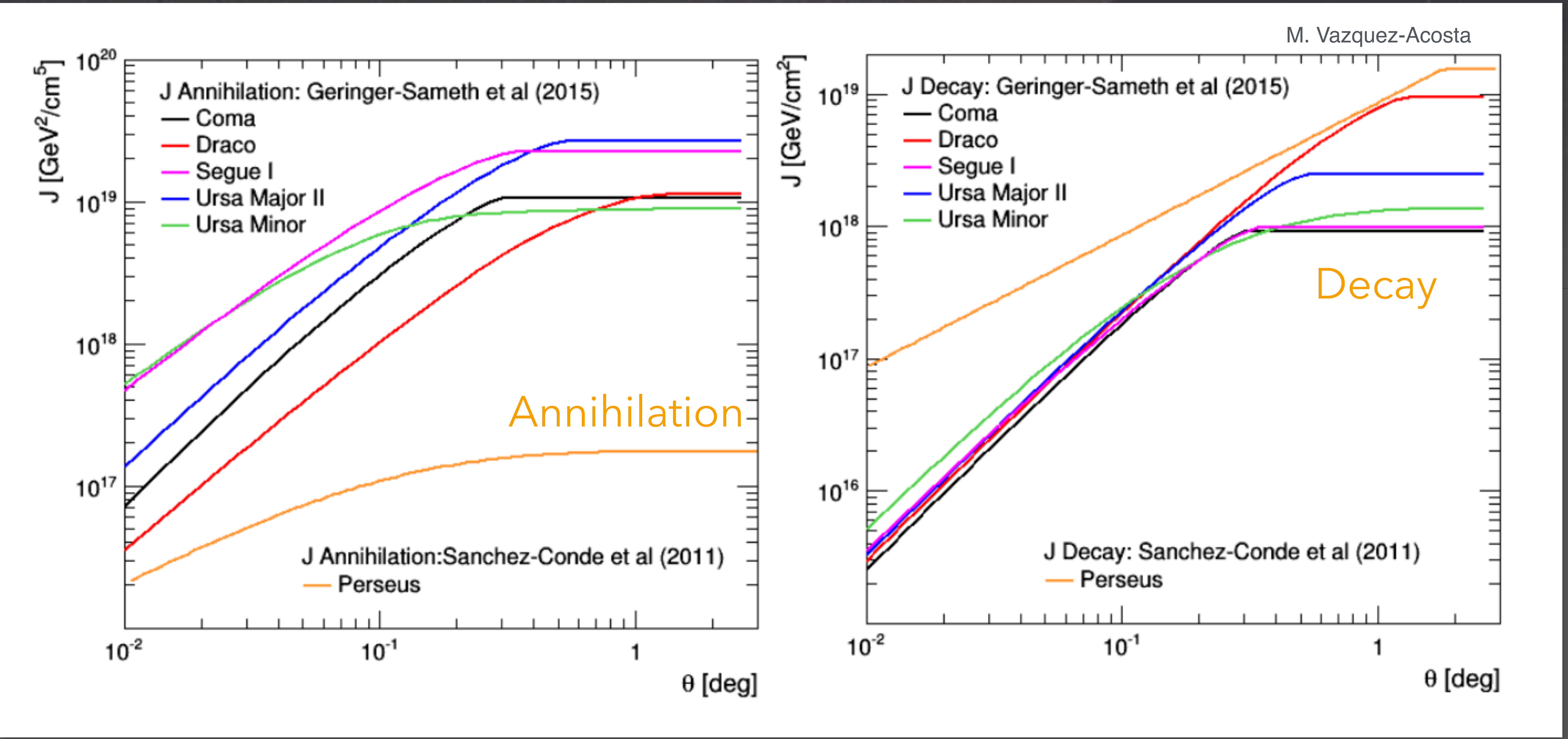


# Dark Matter decay searches in Galaxy clusters

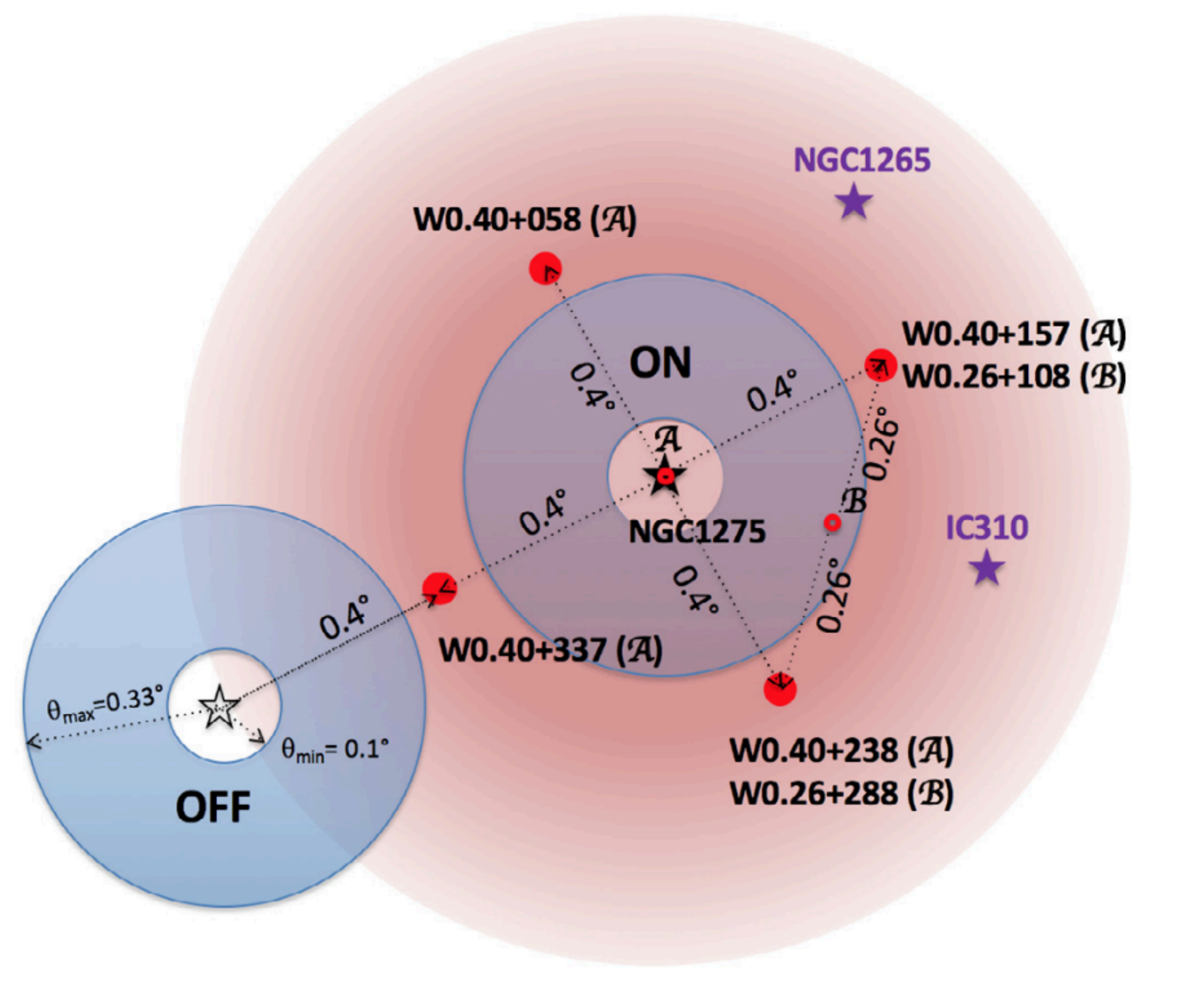


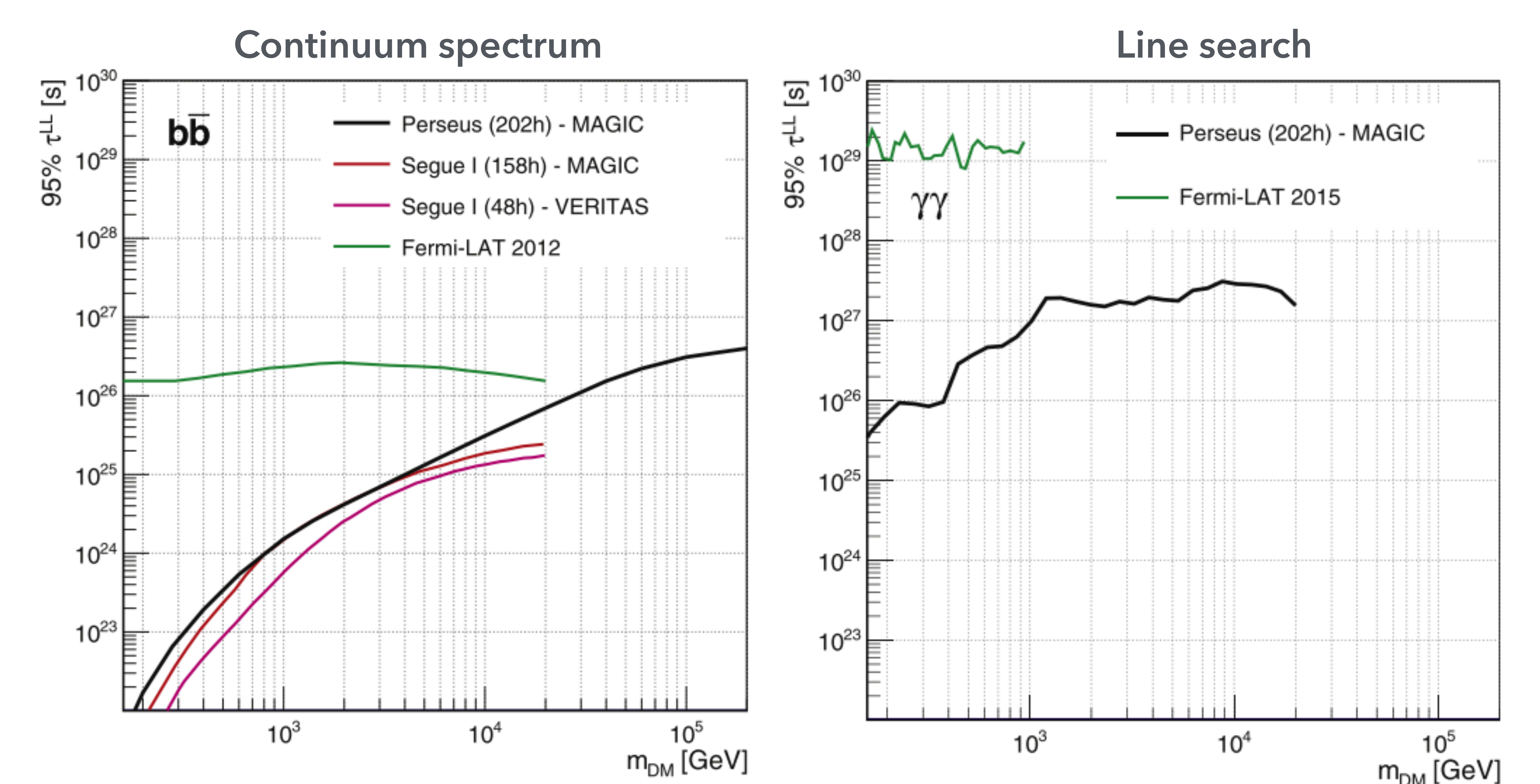
| + | - |
|---|---|
| Most massive DM targets | Dim because far away |
| Robust mass estimation (but less certain density boost) | Astrophysical backgrounds |




$$\frac{dN_{\gamma,\nu,e,...}}{dAdt} = \frac{1}{4\pi}\,\frac{\langle\sigma v\rangle}{\delta\, m_\chi^2} \times \int \frac{dN^{\text{per interact.}}_{\gamma,\nu,e,...}}{dE}\, dE \times \int_{\Delta\Omega}\int_{l.o.s.} \rho_\chi \, dl d\Omega$$

# MAGIC Dark Matter decay search in the Perseus cluster



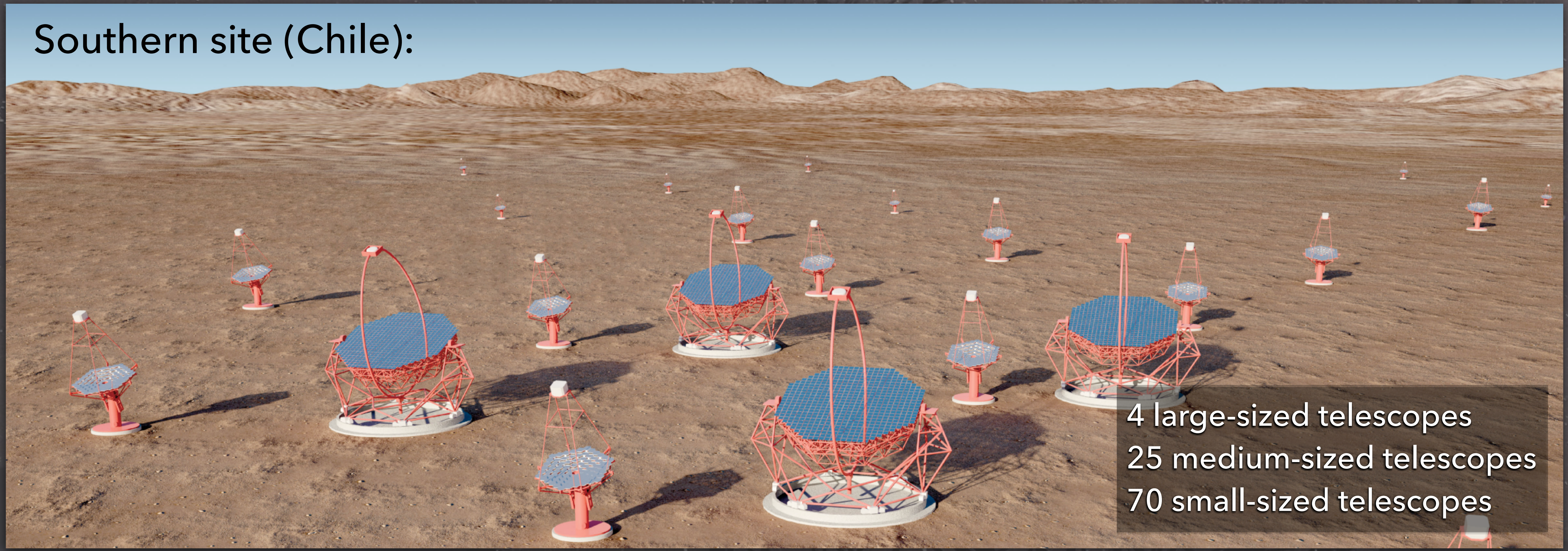




MAGIC, 1806.11063

- Optimal ON-region to set DM decay limits – yet only ~8% of the total *J*-factor
- *J*-factor largest uncertainty - proportional to cluster mass uncertainty

WIMP lifetime $> 10^{26}$ s in wide mass range

# The Cherenkov Telescope Array


cherenkov telescope array

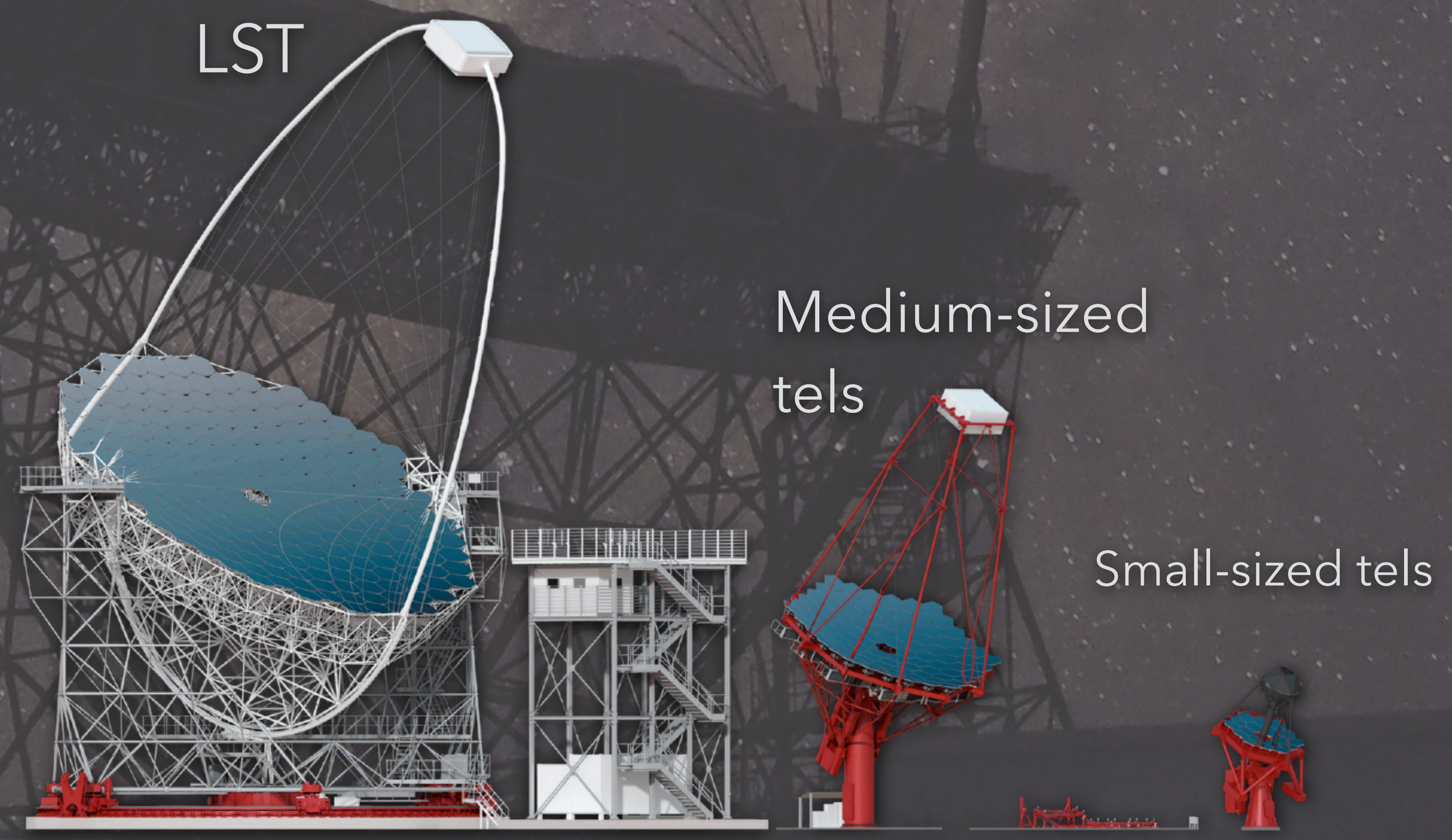
Next generation Earth-bound γ-ray telescope: Two arrays of Cherenkov telescopes in Chile/ La Palma

- Over 100 telescopes
- About 1500 scientists and engineers
- About 200 institutes
- 31 countries

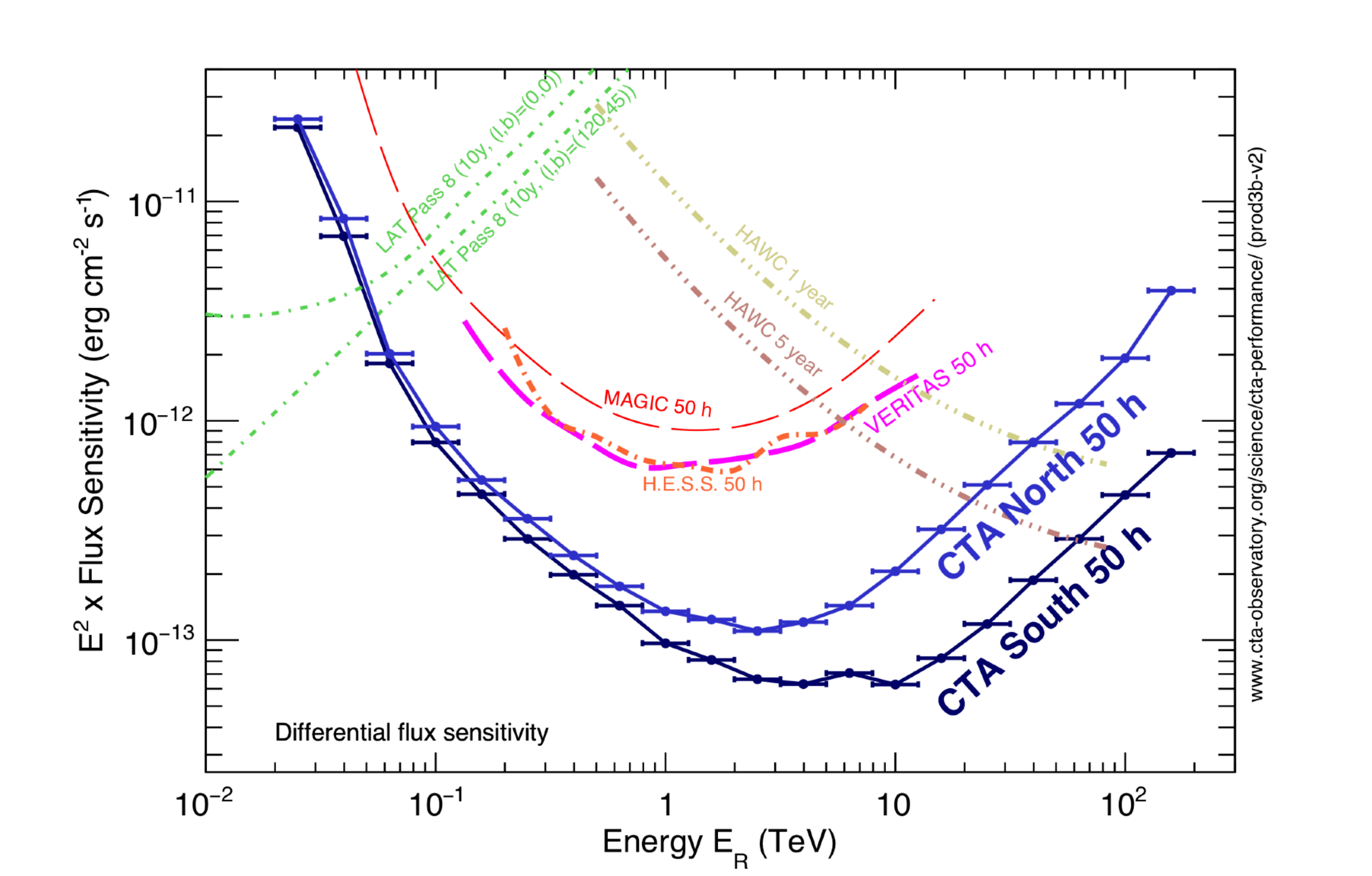
# The Large-Sized Telescope(s): CTA-LST

- Covers the lower energy range of CTA (> 20 GeV)
- On La Palma: First LST ("LST-1") under commissioning since 2018
- LST 2-4 are under way

**Big contribution of Japan and ICRR**

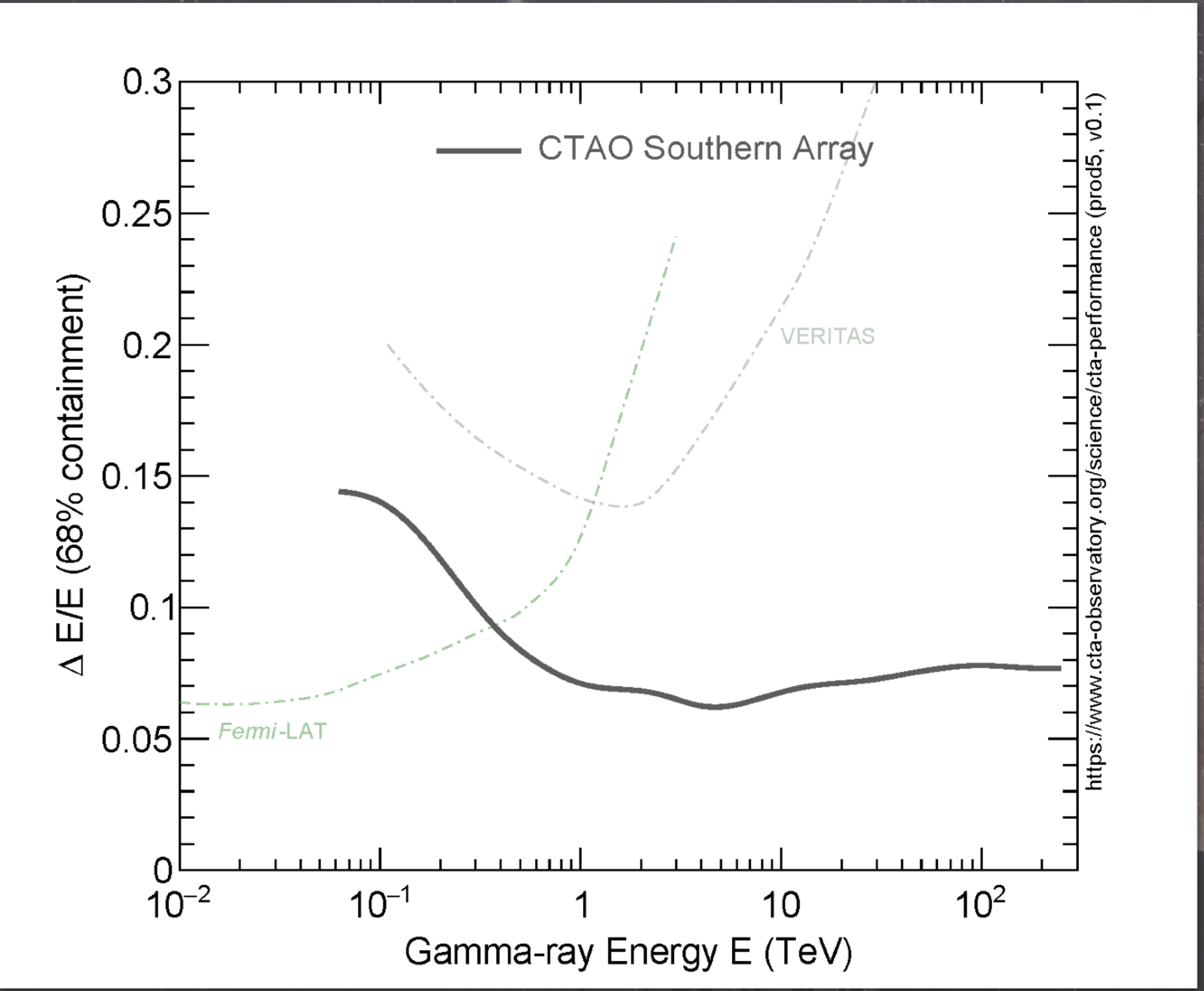


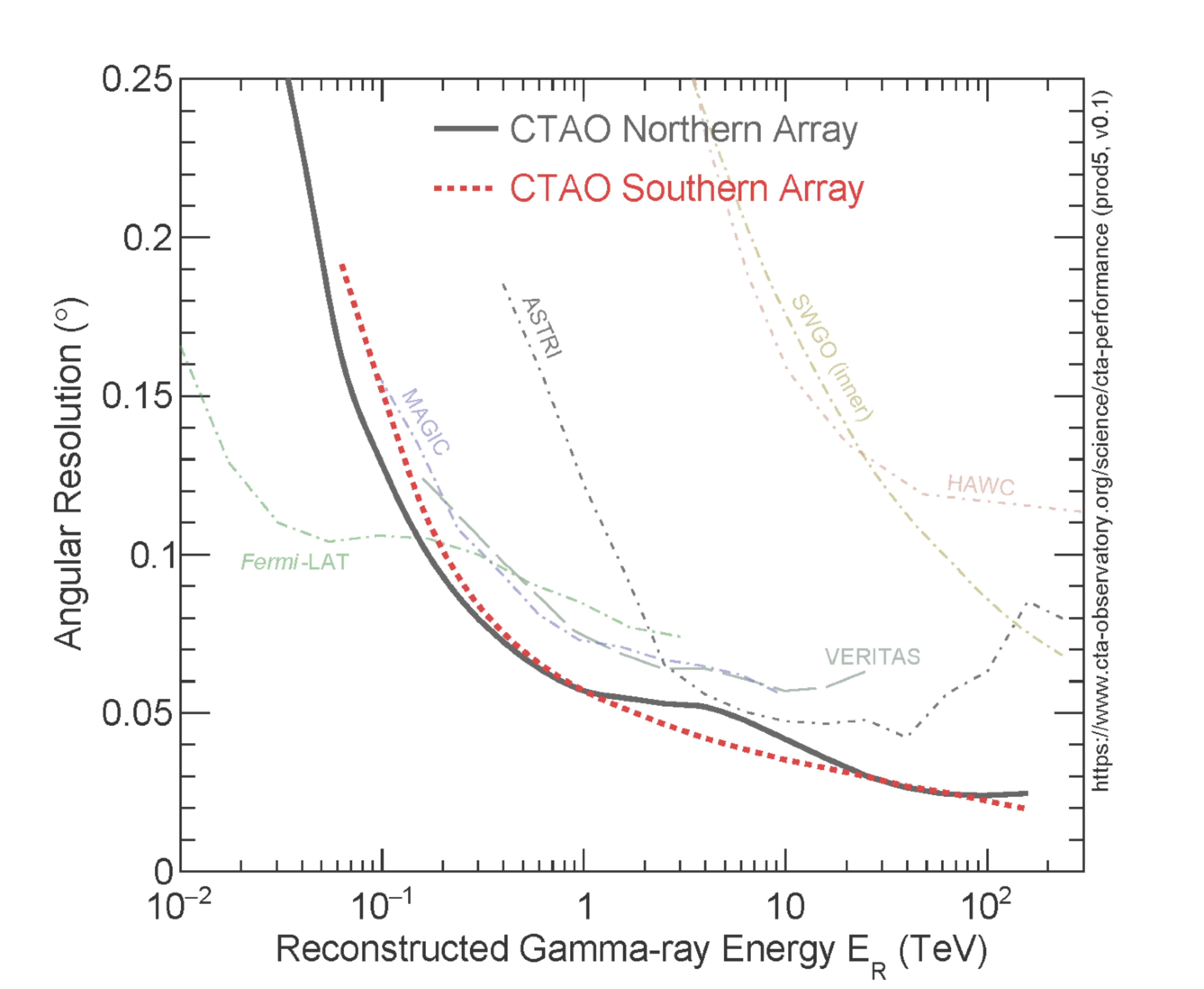

# CTA: Sensitivity




γ-ray energy range: 20 GeV – 300 TeV

# CTA: Angular and energy resolutions

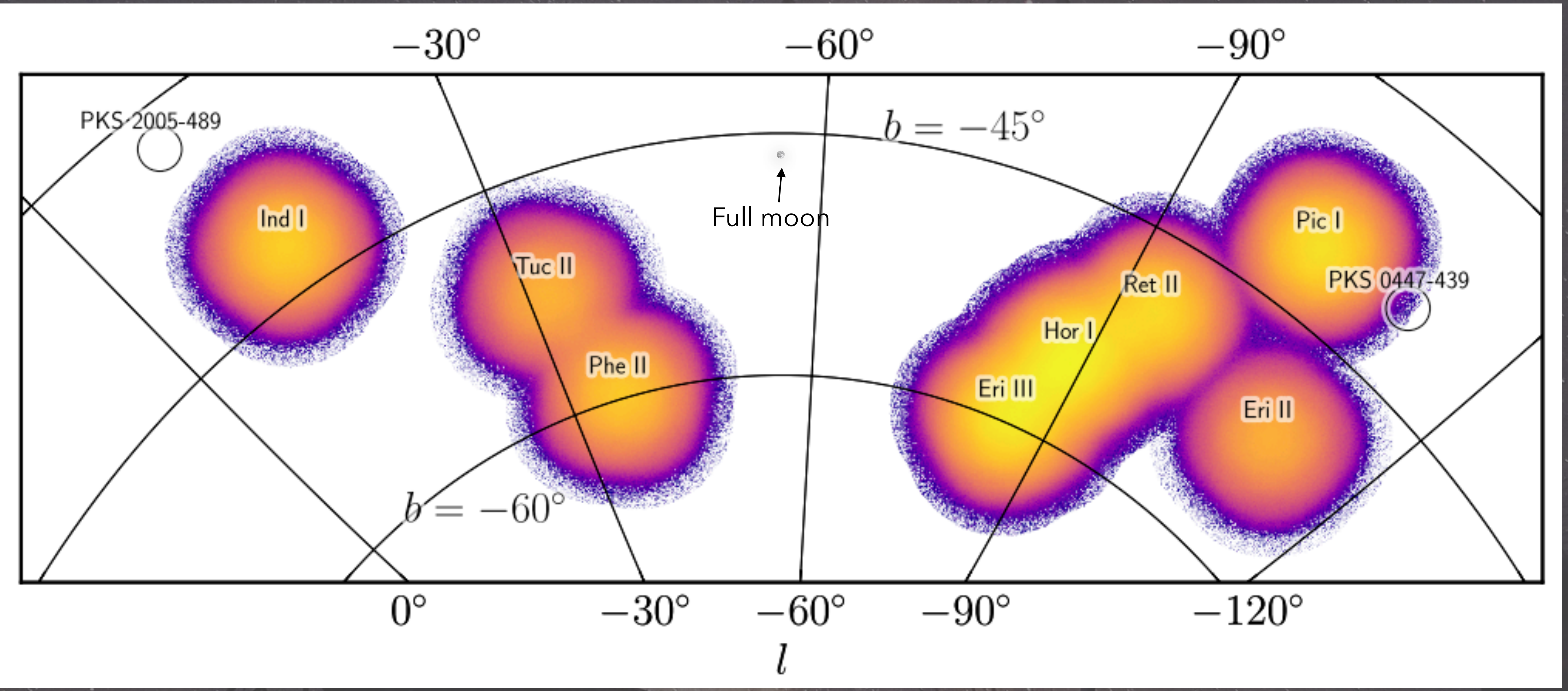



Energy resolution below 10%

Angular resolution: 0.03° – 0.10°

# CTA: Field of view



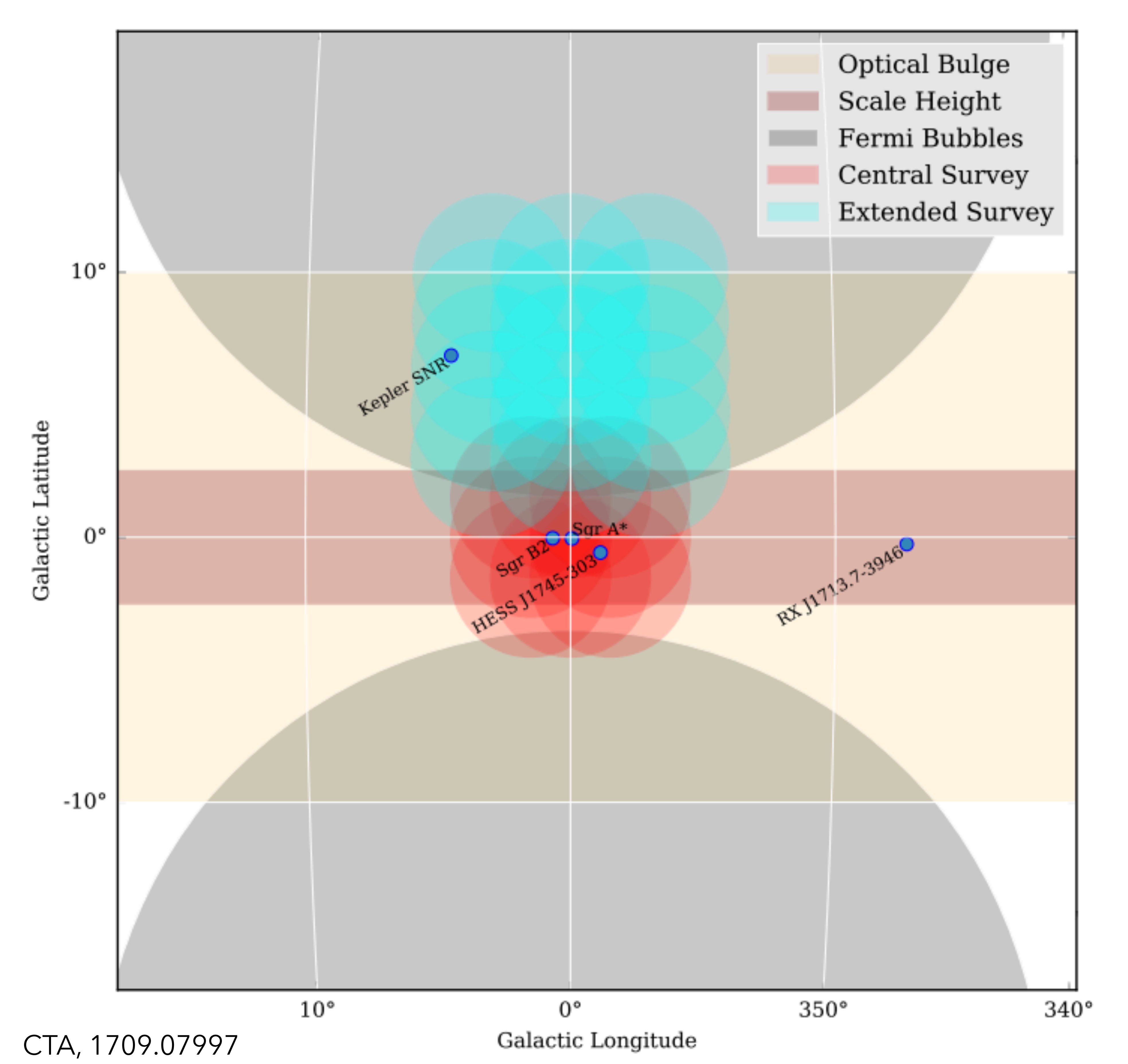

Observation of Southern dSph candidates from Bechtol+ (2015) with 1.5° wobbles

Field of view diameter: ~ 7°:

Large enough for large-sky surveys

# CTA: Sensitivity to DM signal from Galactic Center

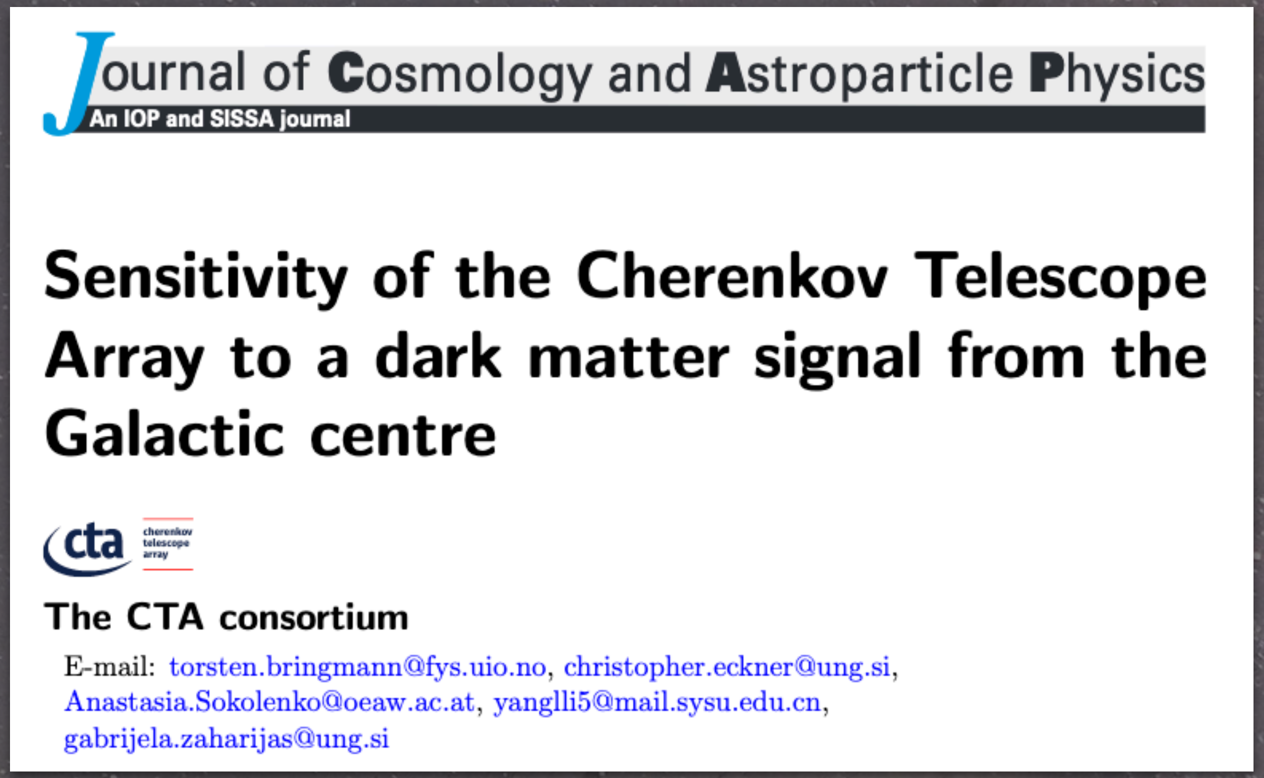
- Galactic Center survey: Key Science project with CTA: 525h + 300h in 1st decade
- Prime Dark Matter target with CTA




CTA, 1709.07997

# CTA: Sensitivity to DM signal from Galactic Center

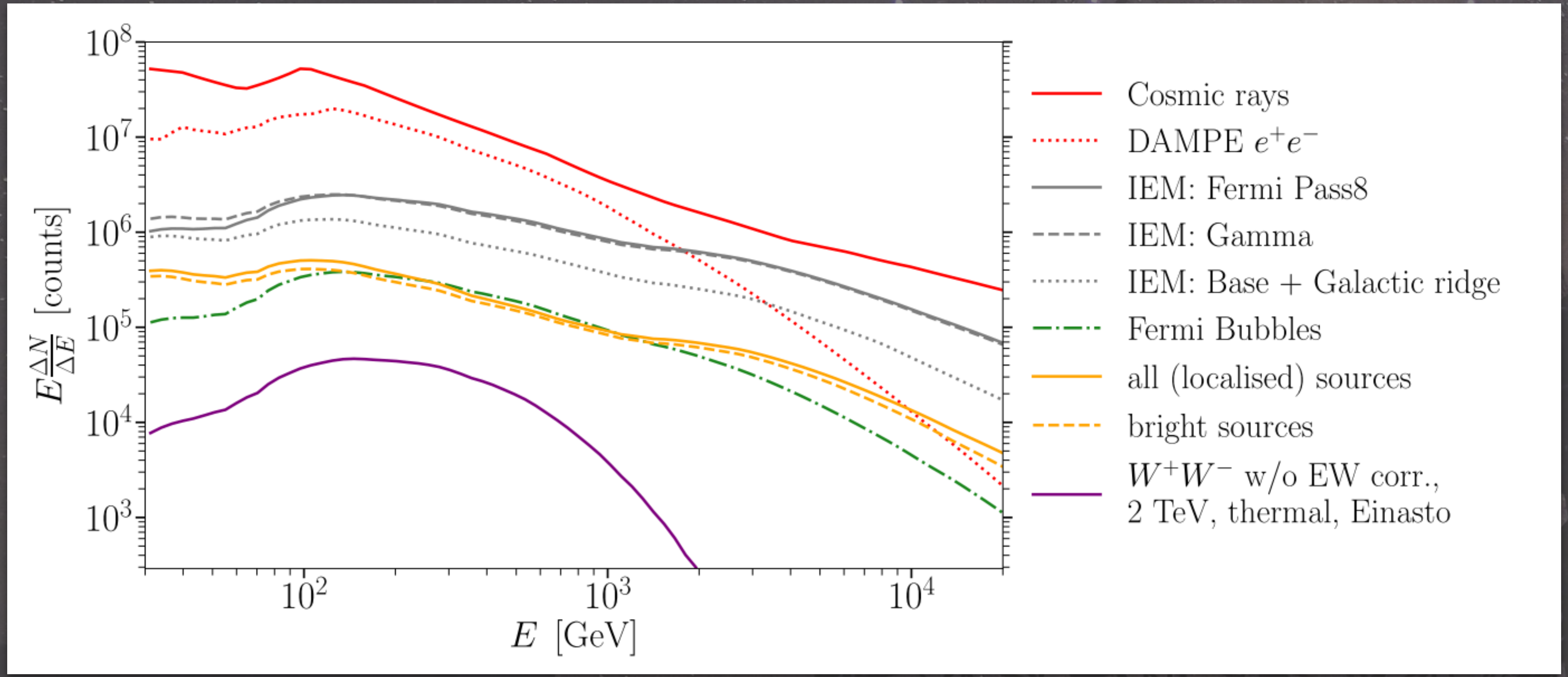
Detailed sensitivity study published (2007.16129)

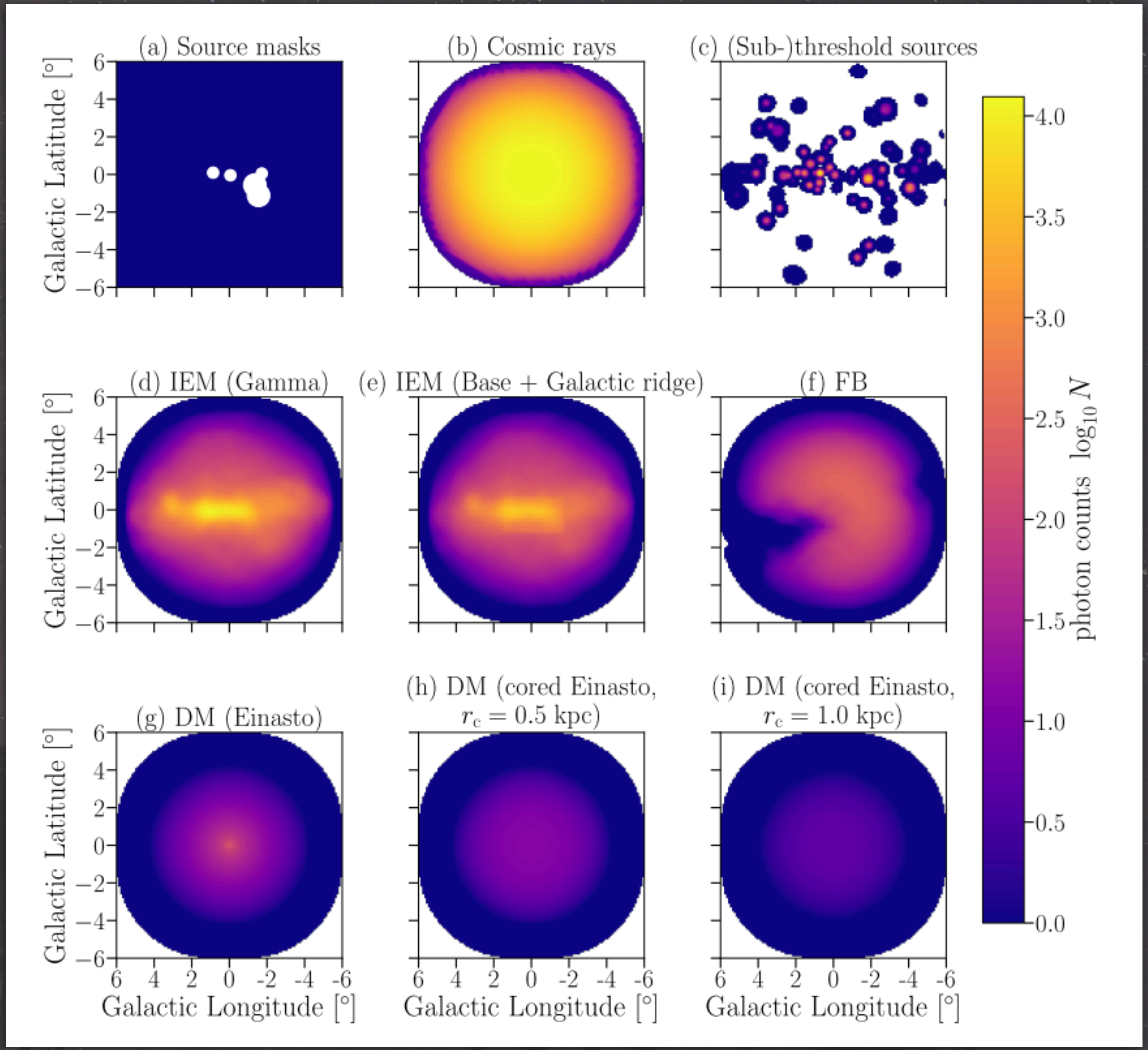

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

**Sensitivity of the Cherenkov Telescope Array to a dark matter signal from the Galactic centre**

**The CTA consortium**

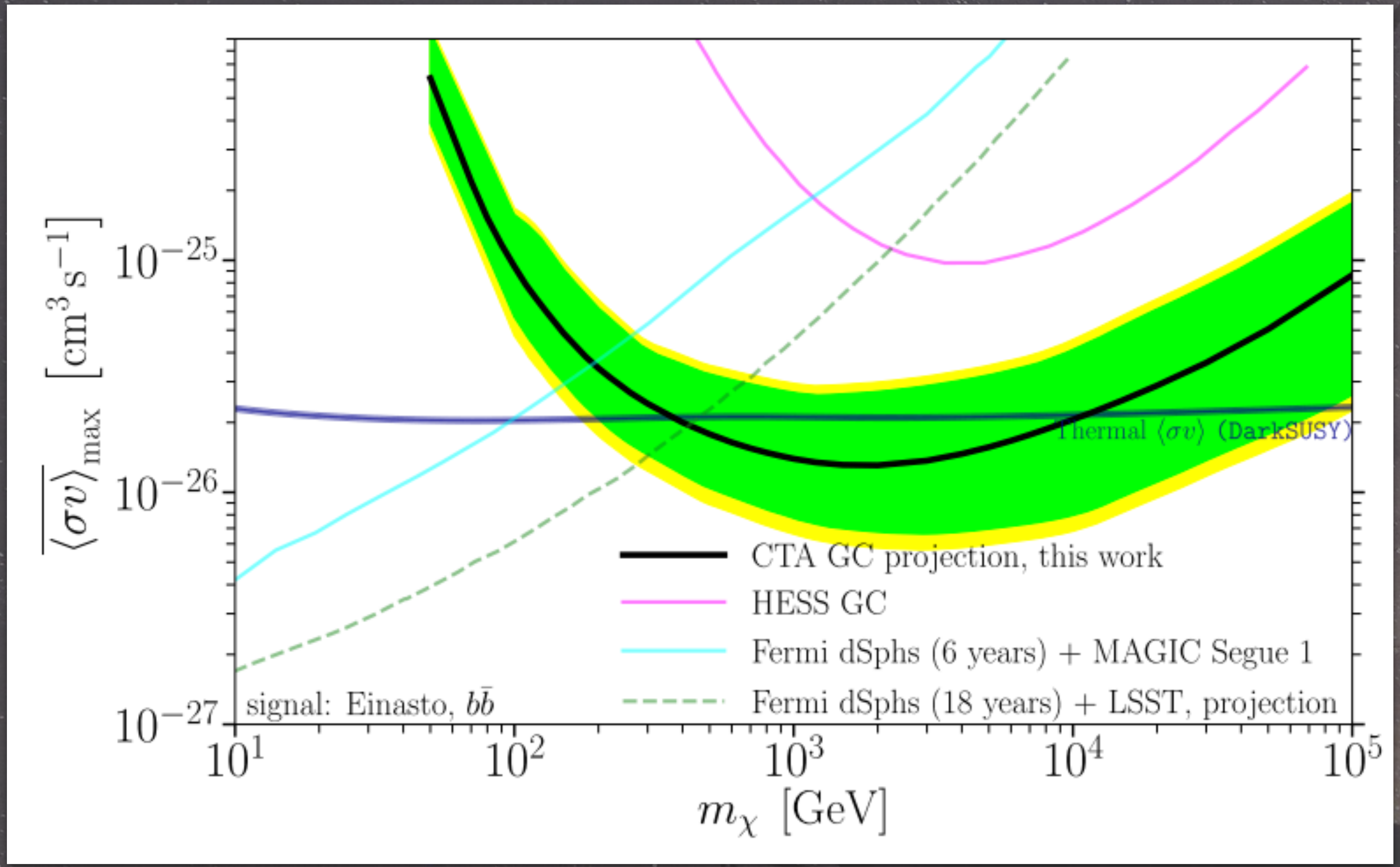
E-mail: torsten.bringmann@fys.uio.no, christopher.eckner@ung.si, Anastasia.Sokolenko@oeaw.ac.at, yanglli5@mail.sysu.edu.cn, gabrijela.zaharijas@ung.si

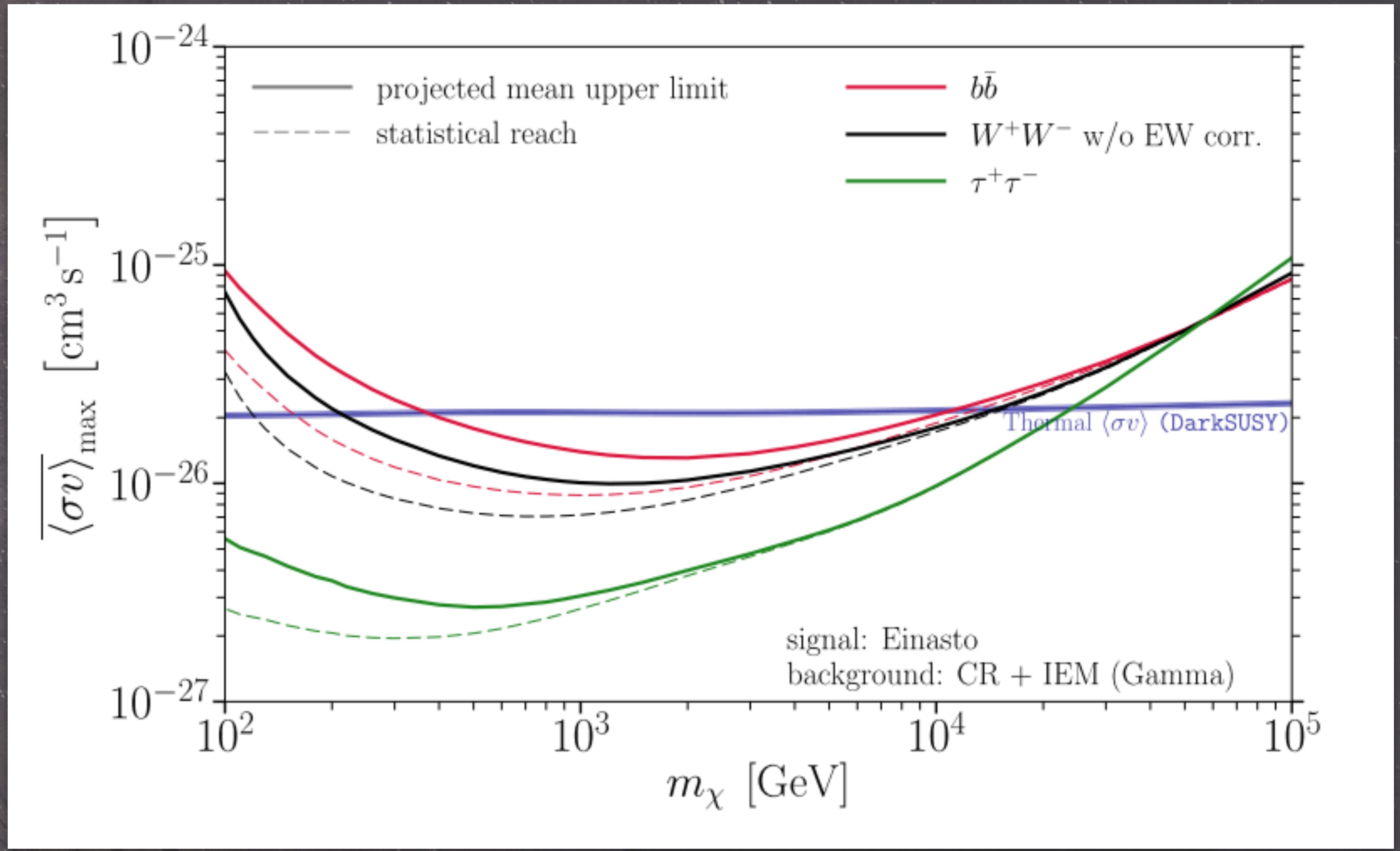


# CTA: Sensitivity to DM signal from Galactic Center

CTA, 2007.16129



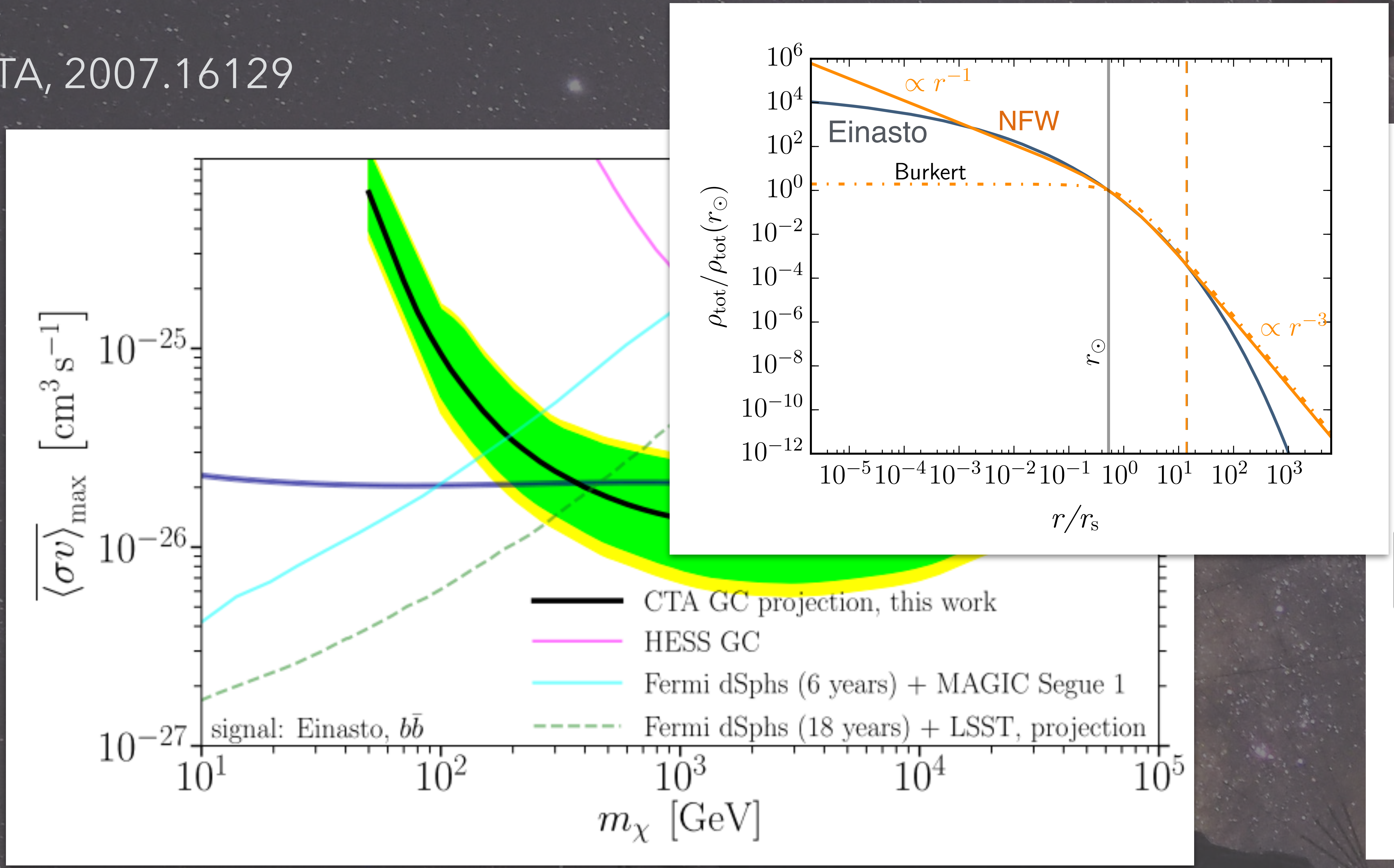



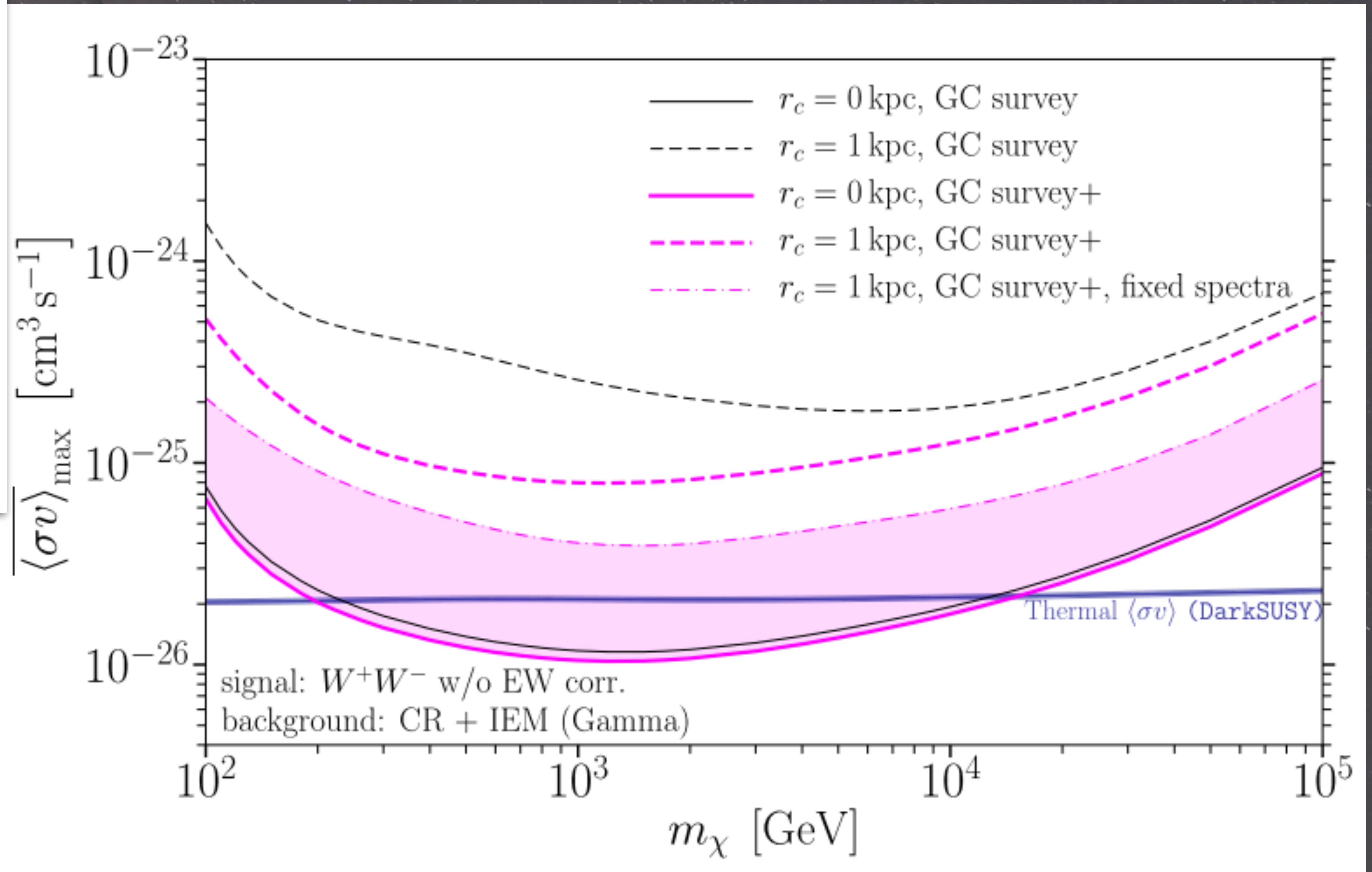

Uncertainties on limits: Background modelling

Galactic center observations with CTA can probe the thermal relic cross section of 500 GeV - 10 TeV WIMPs

# CTA: Sensitivity to DM signal from Galactic Center

CTA, 2007.16129

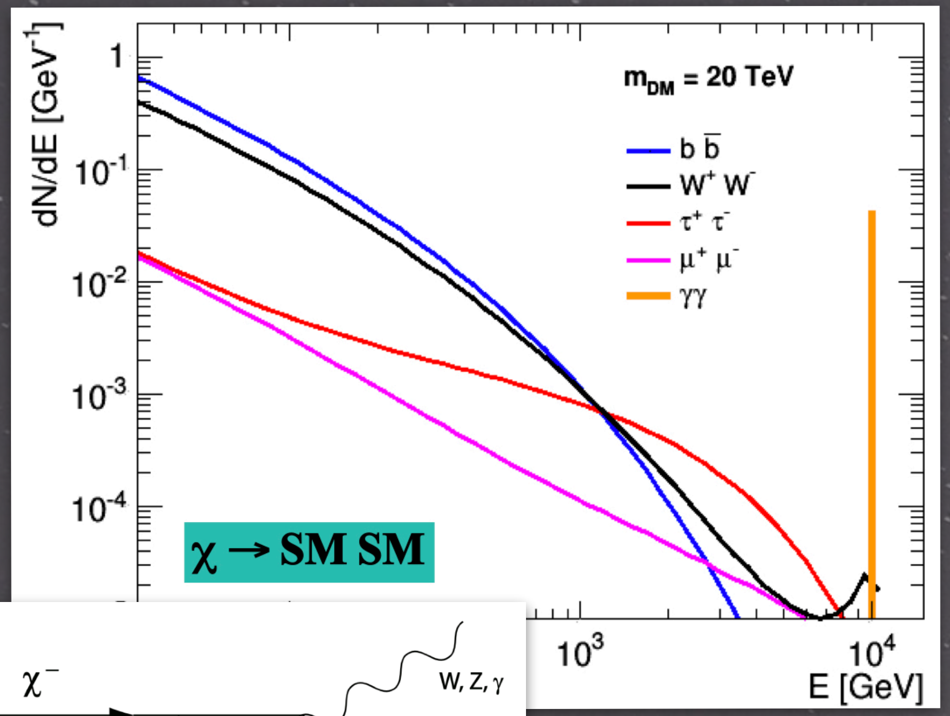


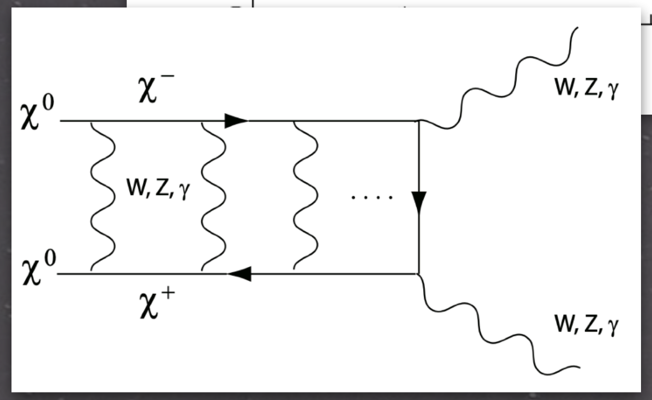



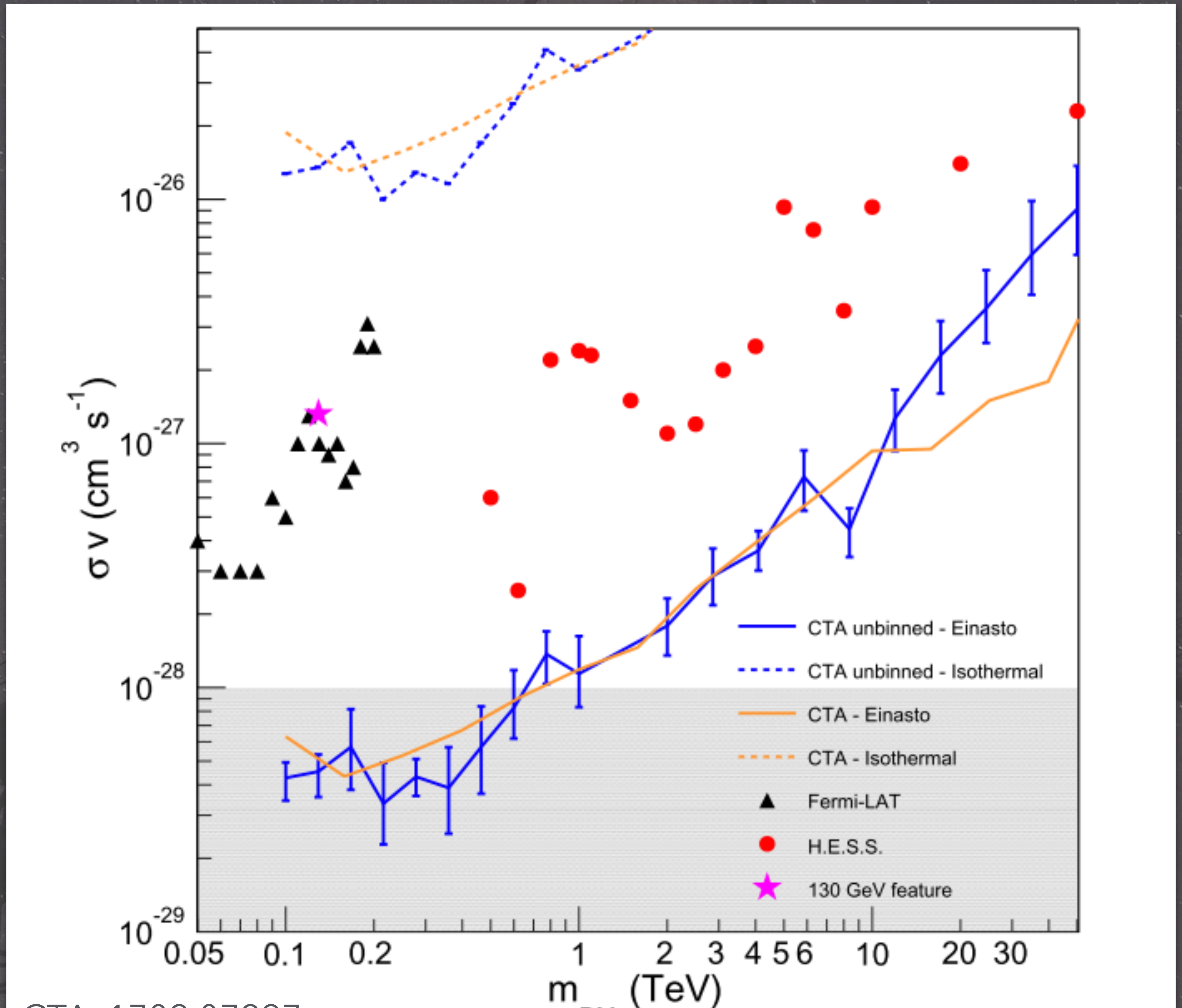

Uncertainties on limits: DM profile

Galactic center observations with CTA can probe the thermal relic cross section of 500 GeV - 10 TeV WIMPs

# CTA: Sensitivity to *Line* DM signal from Galactic Center



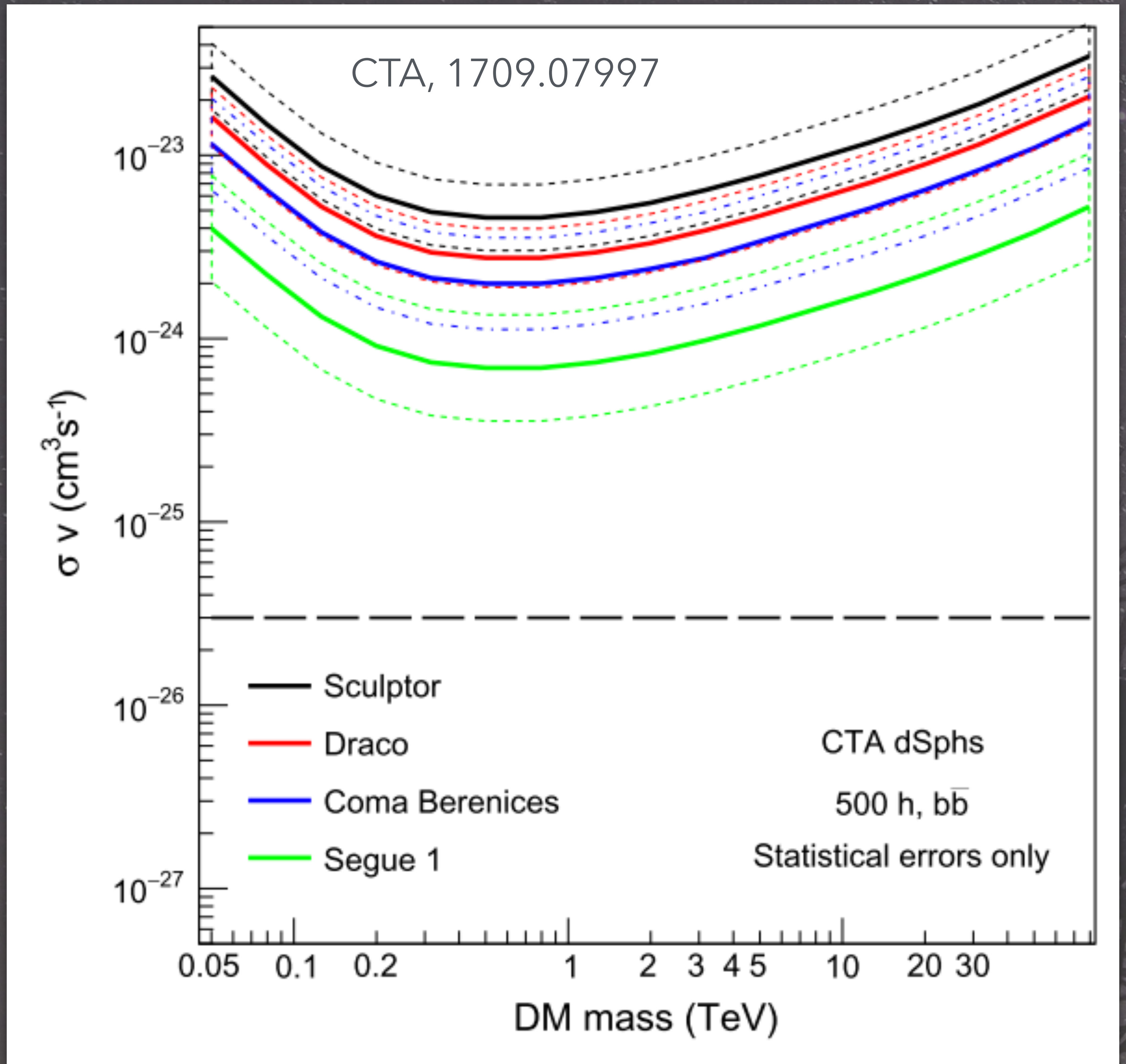




CTA, 1709.07997

Refined analysis ongoing (separate publication)

# CTA: What to reach with dSph Galaxies

CTA Key Science Project: 300h reserved for best dSph target at that time



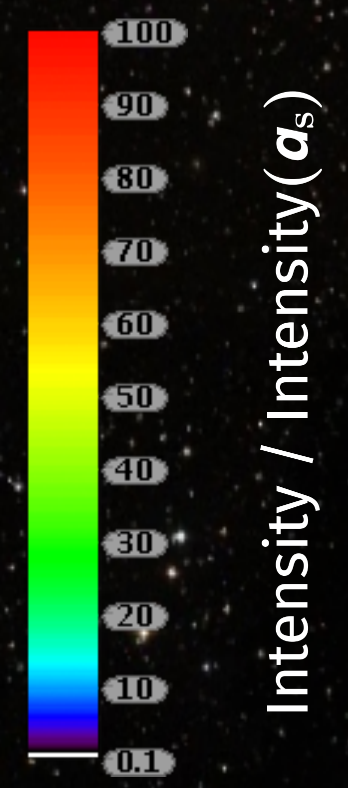

Use dSph observations to confirm DM origin of a signal detected at Galactic Center:

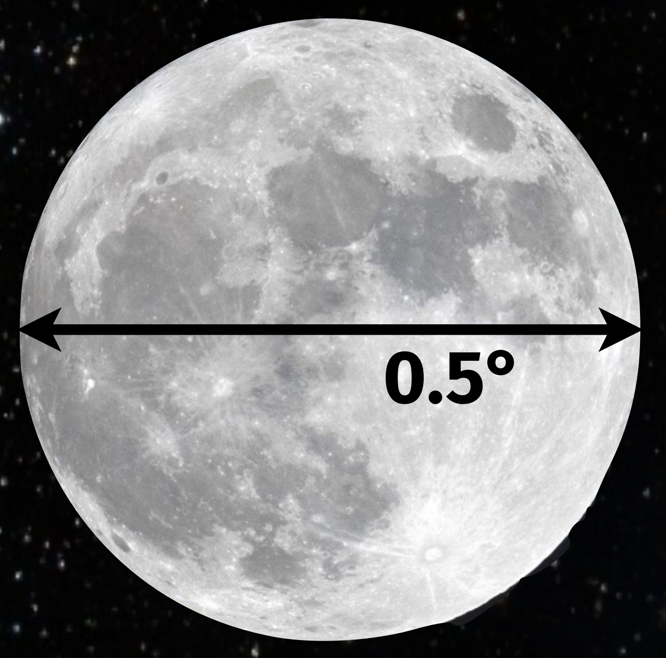
| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Galactic halo | 175 h | 175 h | 175 h | | | | | | | |
| Best dSph | 100 h | 100 h | 100 h | | | | | | | |
| *in case of detection at GC, large $\sigma v$* | | | | | | | | | | |
| Best dSph | | | | 150 h | 150 h | 150 h | 150 h | 150 h | 150 h | 150 h |
| Galactic halo | | | | 100 h | 100 h | 100 h | 100 h | 100 h | 100 h | 100 h |
| *in case of detection at GC, small $\sigma v$* | | | | | | | | | | |
| Galactic halo | | | | 100 h | 100 h | 100 h | 100 h | 100 h | 100 h | 100 h |
| *in case of no detection at GC* | | | | | | | | | | |
| *Best Target* | | | | 100 h | 100 h | 100 h | 100 h | 100 h | 100 h | 100 h |

CTA observation strategy (1709.07997)

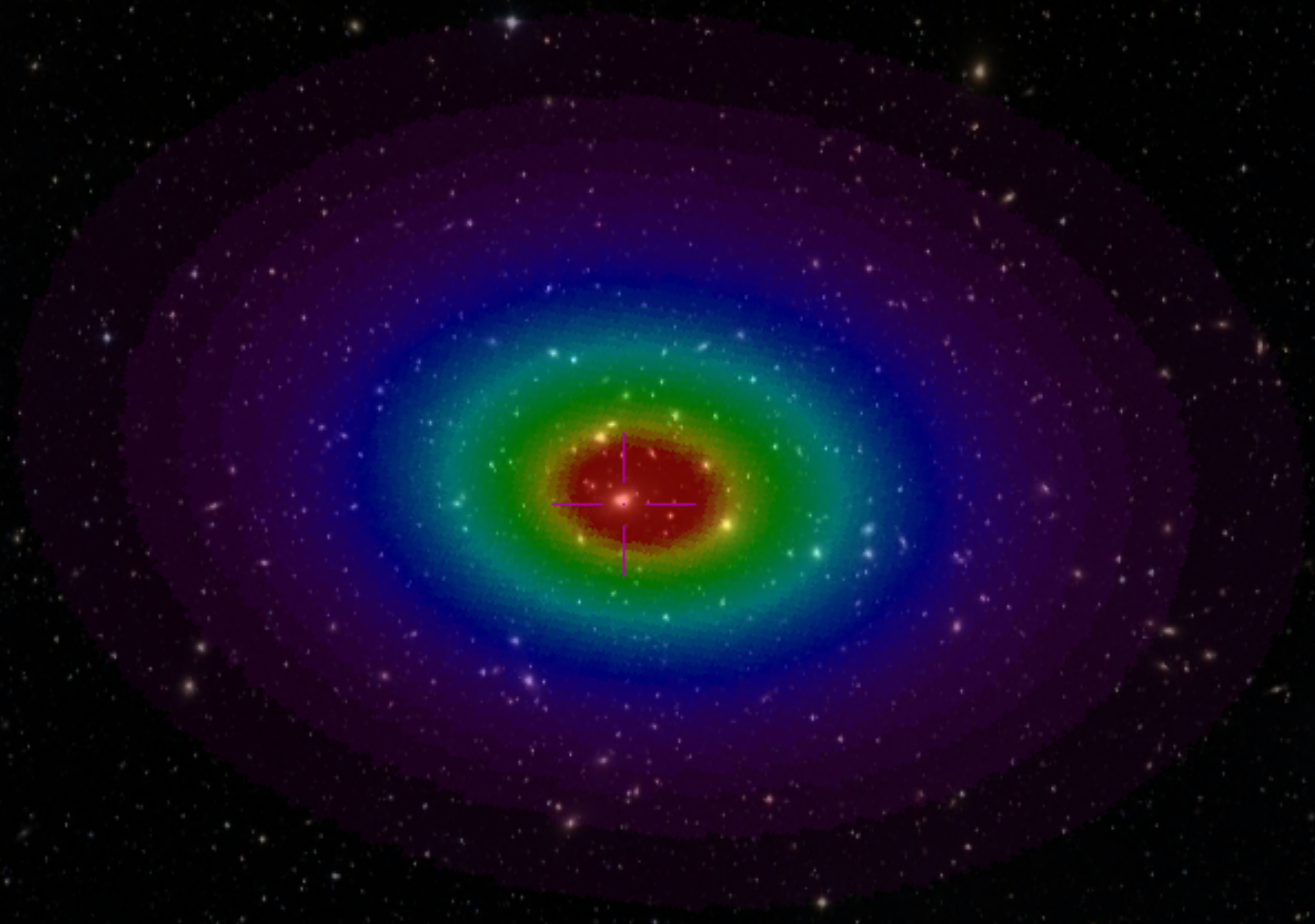
Refined analysis ongoing

# Galaxy cluster prospects with CTA




CTA resolution



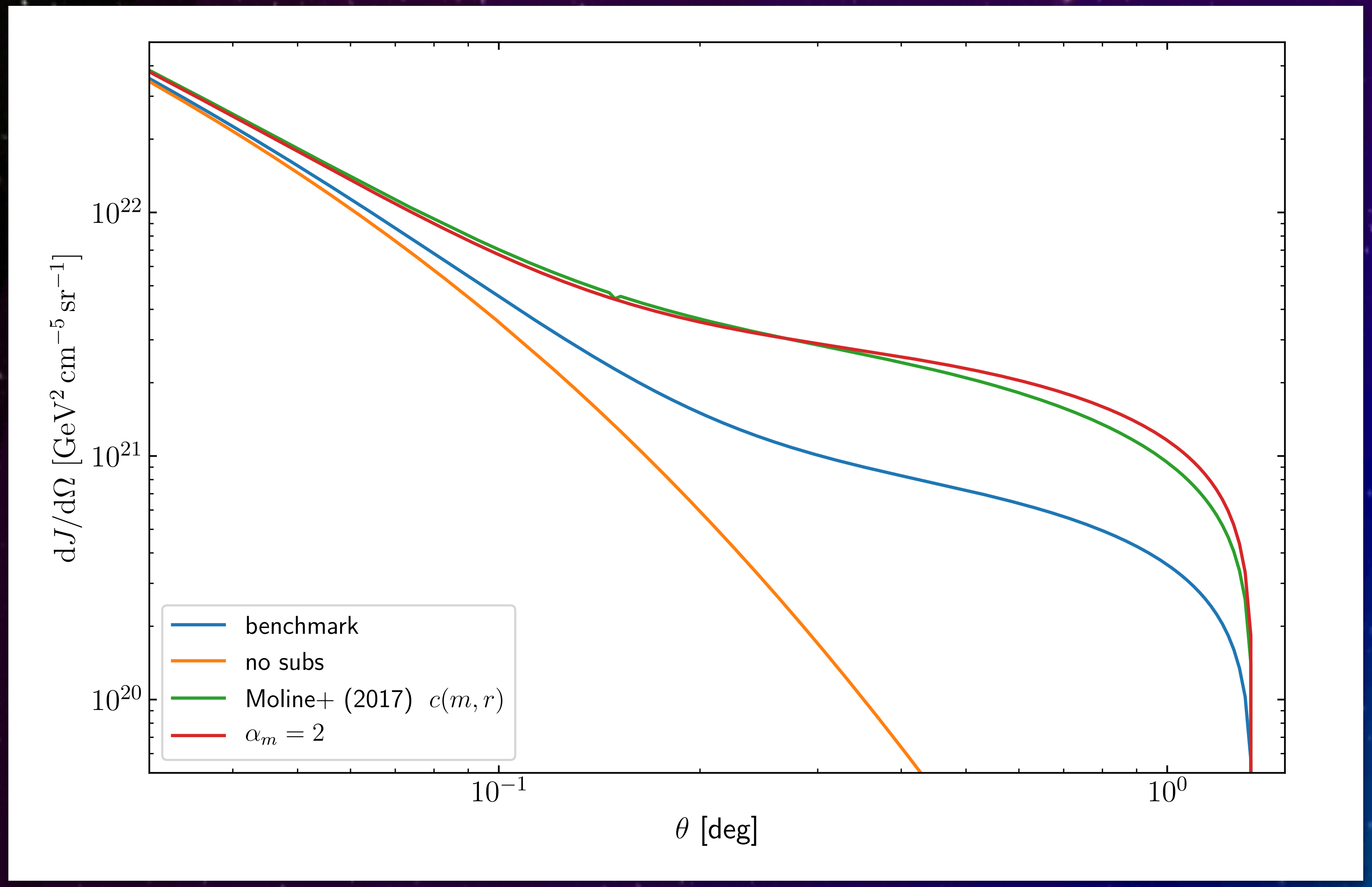

Perseus galaxy cluster DM halo model (random triaxiality)

DSS2 color

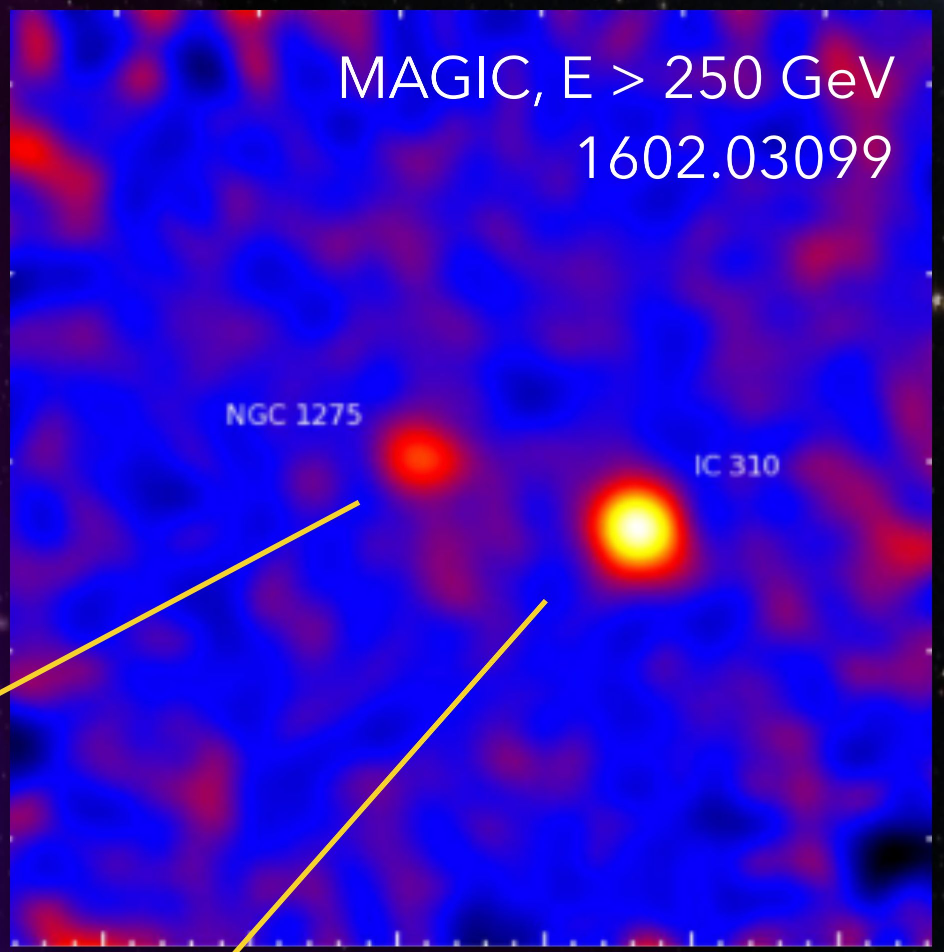
# Galaxy cluster prospects with CTA

100 90 80 70 60 50 40 30 20 10 0.1

Intensity / Intensity$_{\text{no subs}}(\alpha_s)$

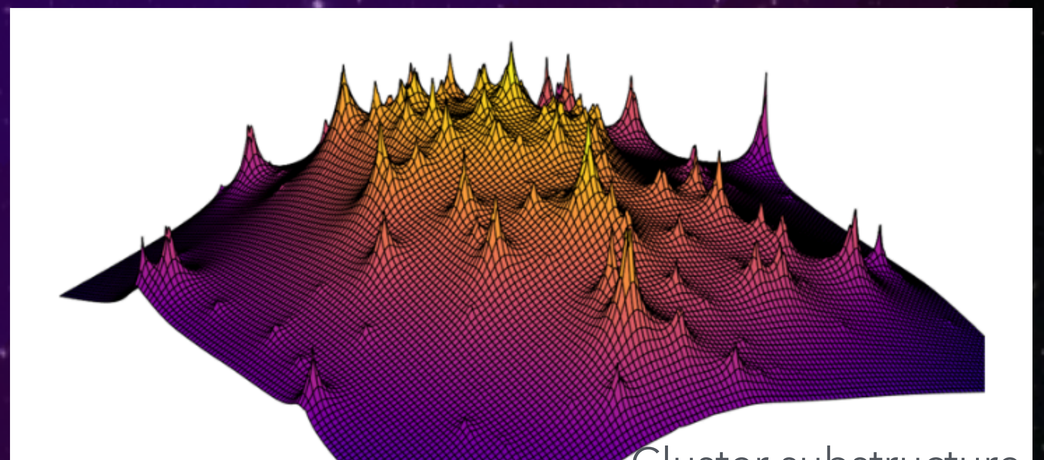



NCG 1275




IC 310

Perseus galaxy cluster DM halo model with substructure



Cluster substructure inferred from lensing
1702.04348

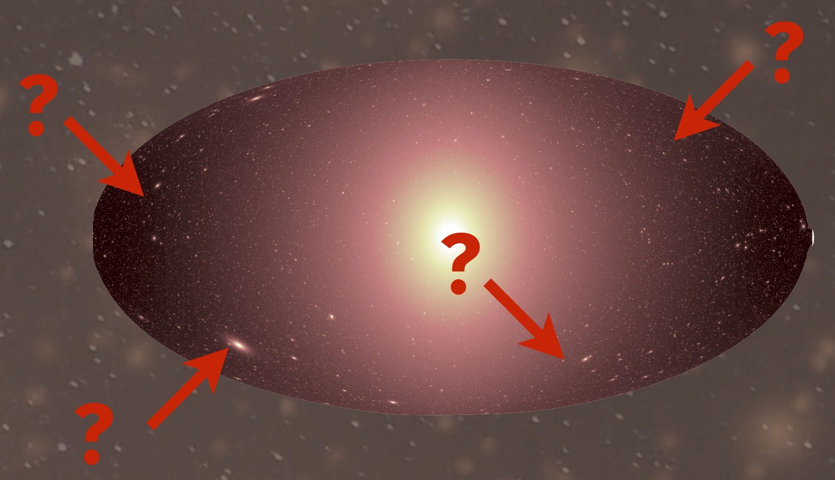
CTA resolution

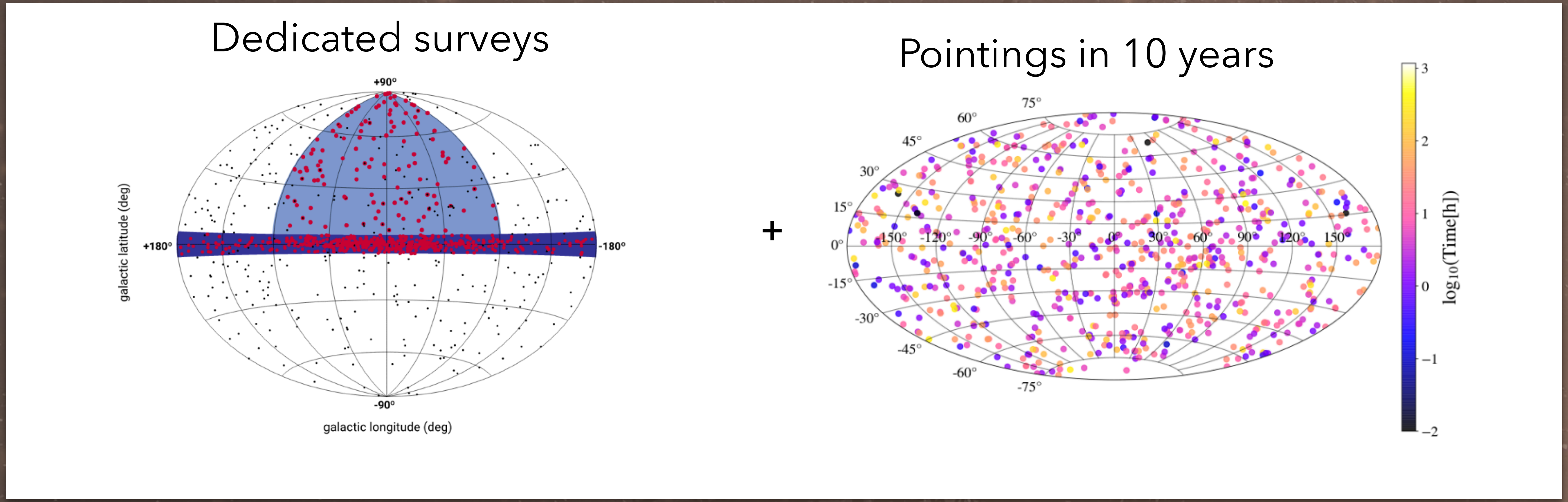
Analysis + publication ongoing

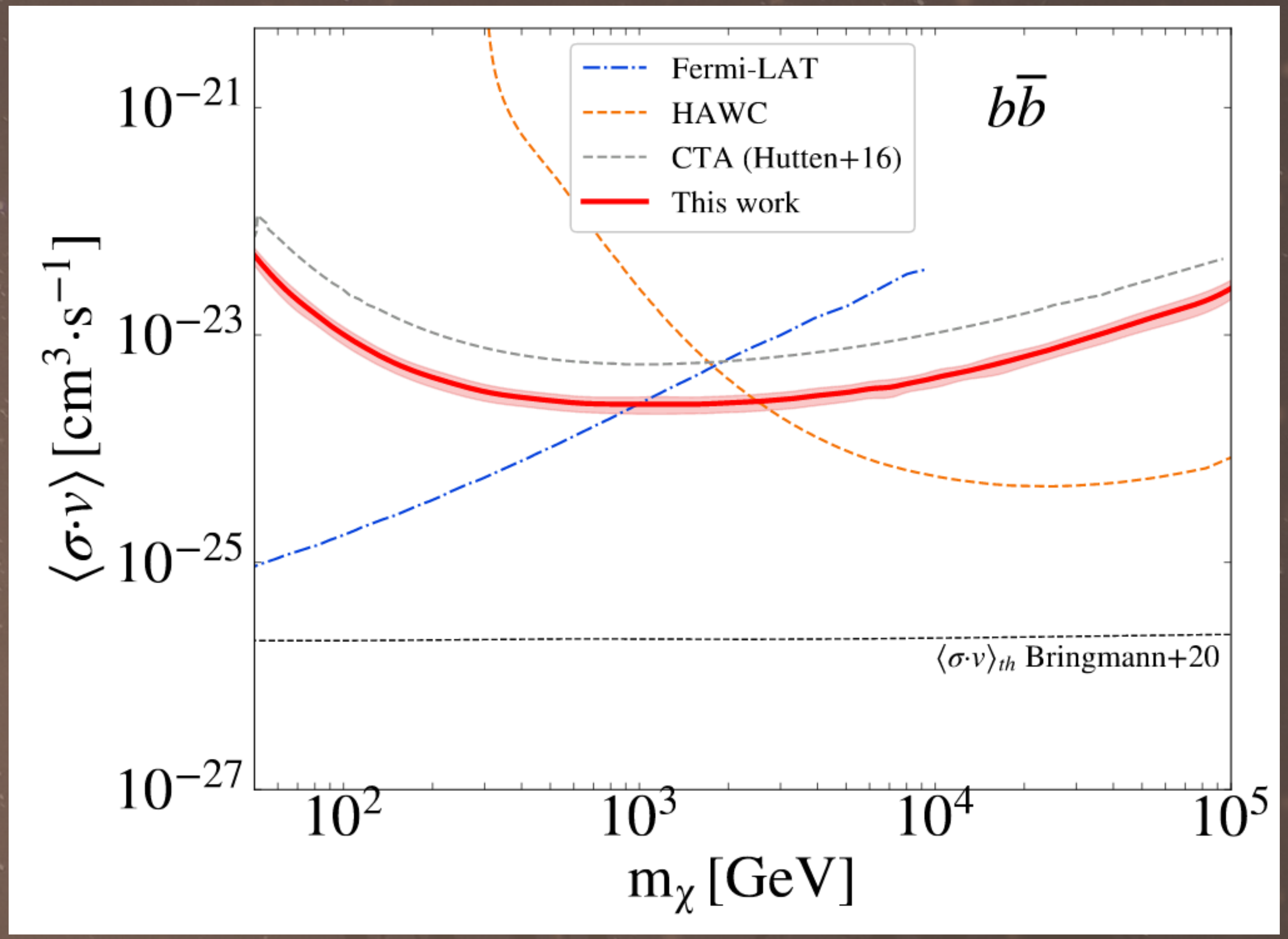
(R. Adam, G. Brunetti, H. Goksu, S. Hernández Cadena, **MH**, J. Pérez-Romero, M. Á. Sánchez-Conde for CTA) z=0.0

# CTA searches for Dark Galactic Subhalos

| + | - |
|---|---|
| No astrophysical background by definition | Unknown position |
| Possibly brighter *J*-factors than satellites | Only theoretical evidence for existence<br>Large modelling uncertainties |

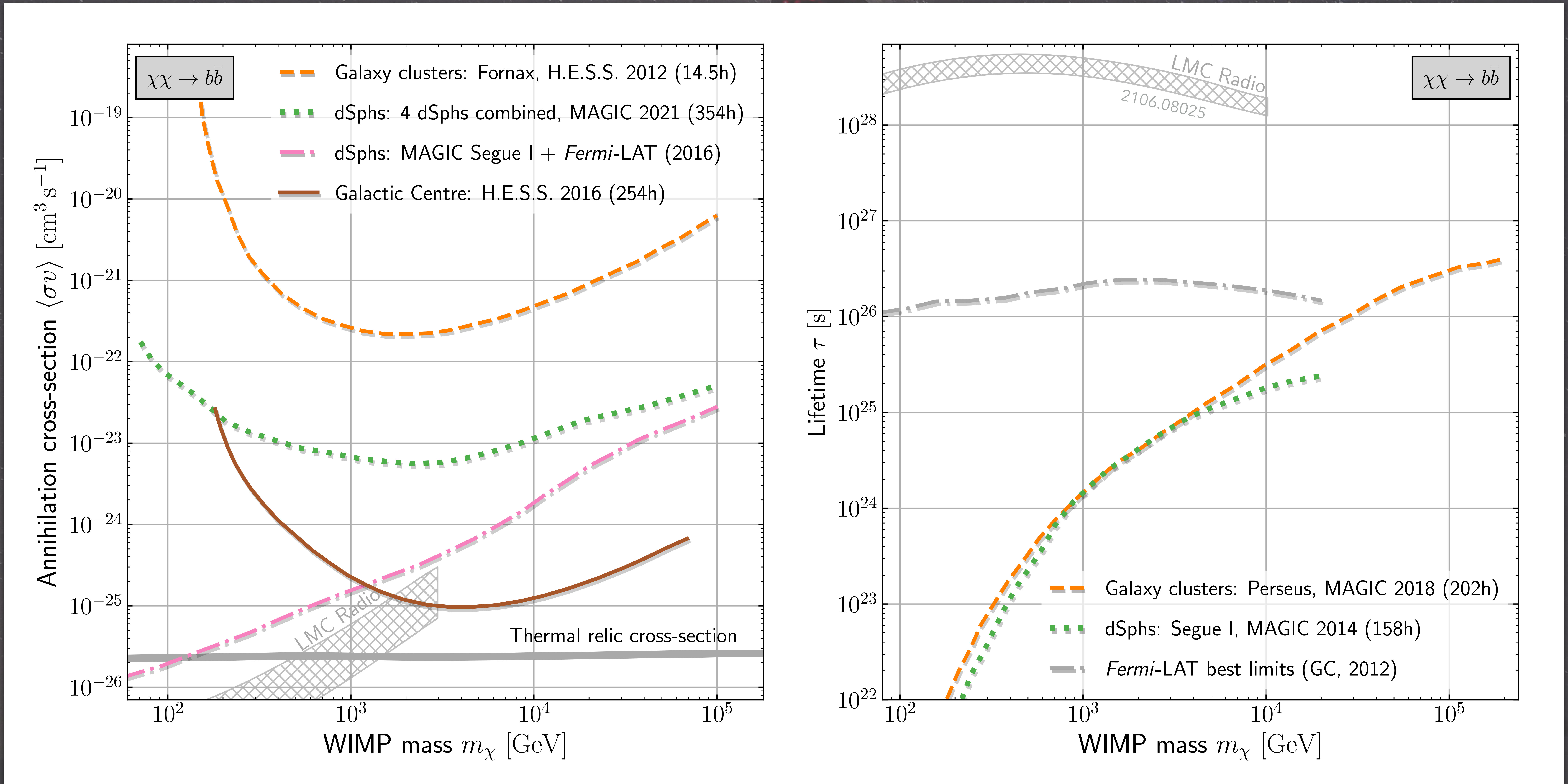


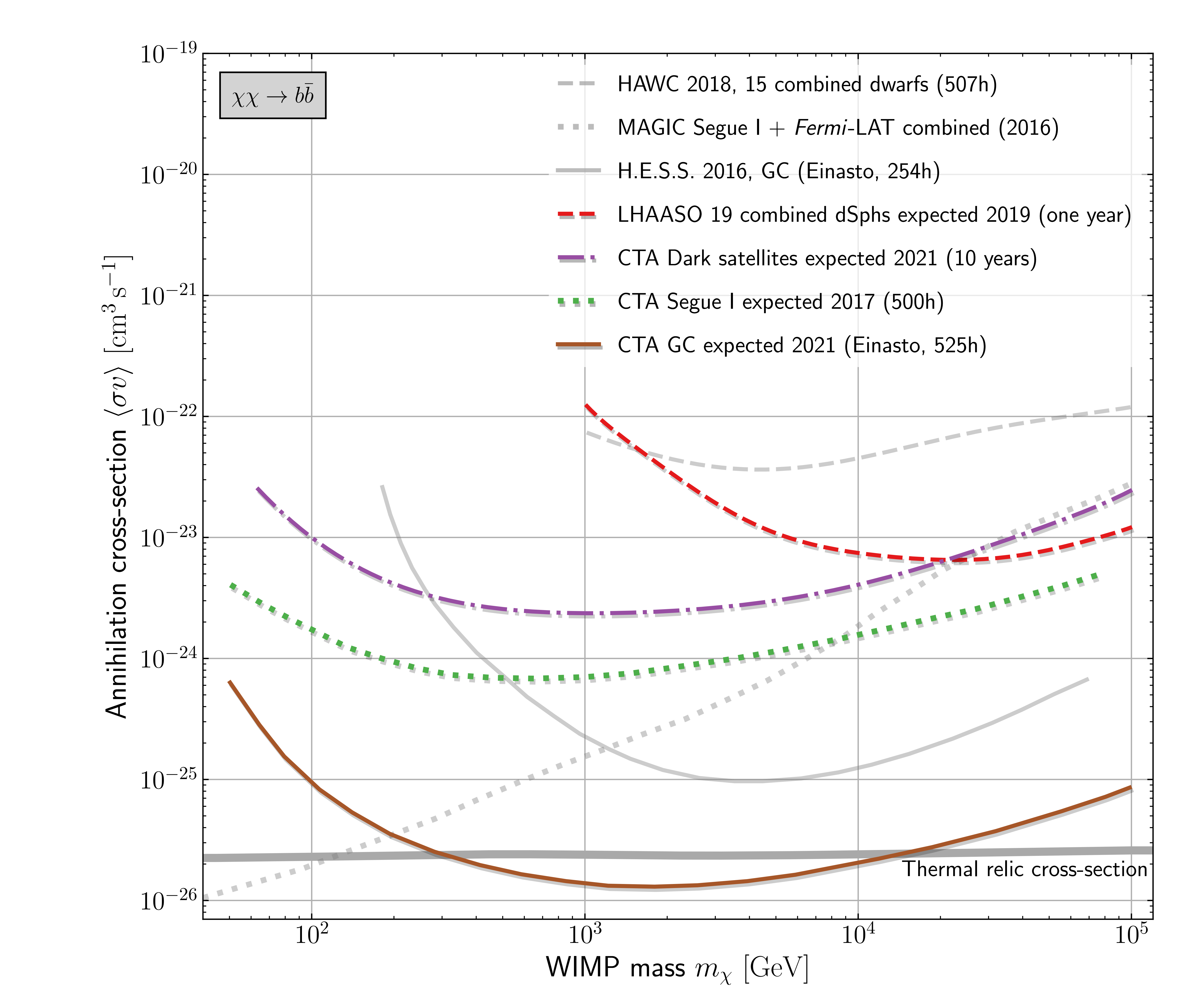




Chance detection sensitivity for CTA:
Coronado-Blázquez et al., 2101.10003

# Summary: current constraints



# Summary: Outlook



# Conclusions

- Indirect DM detection crucial to directly connect astrophysical and particle DM
- No DM detection so far with MAGIC, but competitive legacy limits
- Just starting to probe thermal relic cross sections for TeV DM with CTA
- Exotic effects may increase detection chance (resonances, enhanced lines)
- No *need* for WIMP miracle: DM could have been produced differently. Gamma-ray observations can also probe other DM candidates (next time)