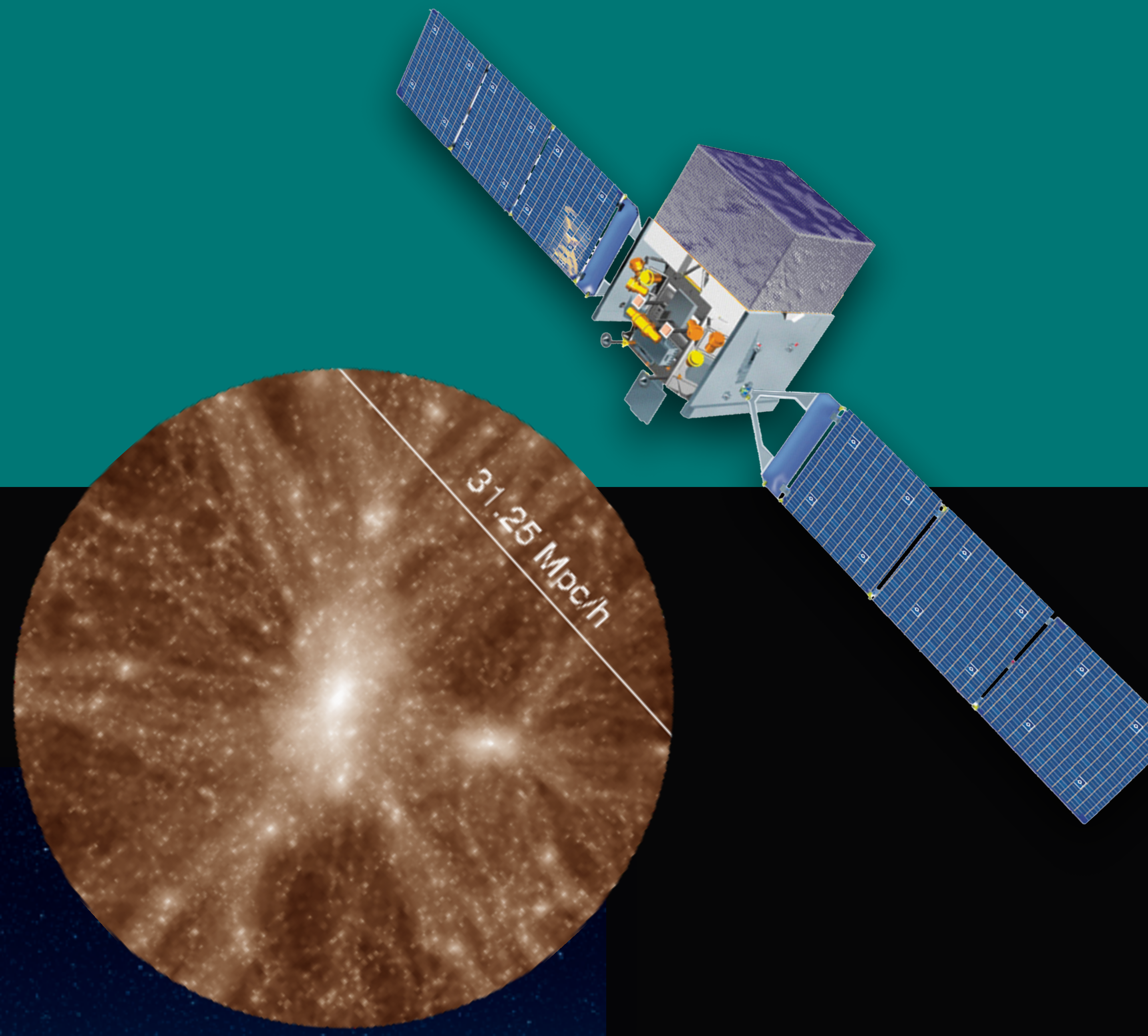
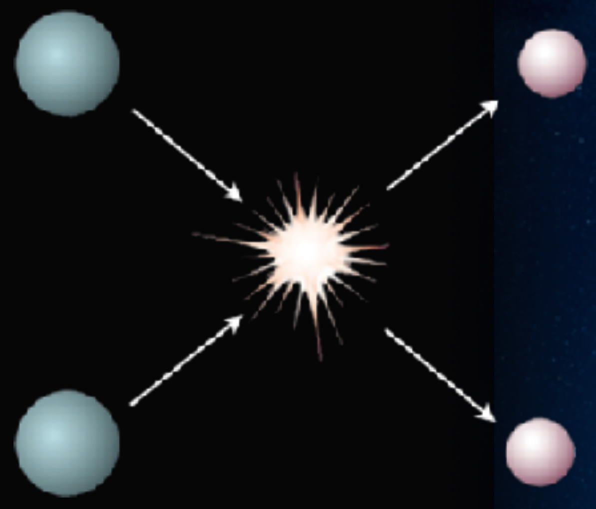
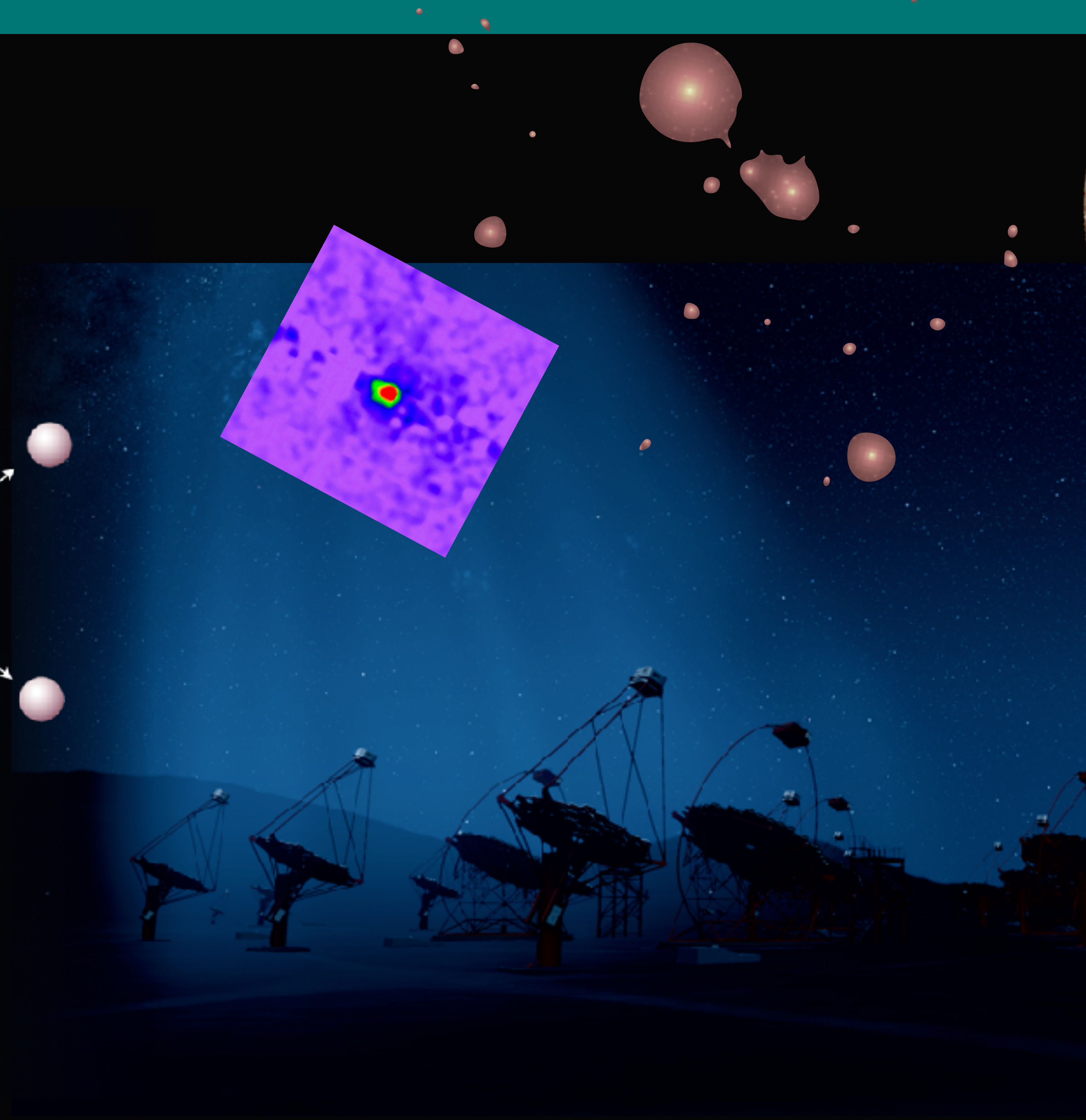
Indirect searches for Dark Matter in the high-energy sky

Moritz Hütten (MPP)

Munich Dark Matter Meeting
March 24, 2021







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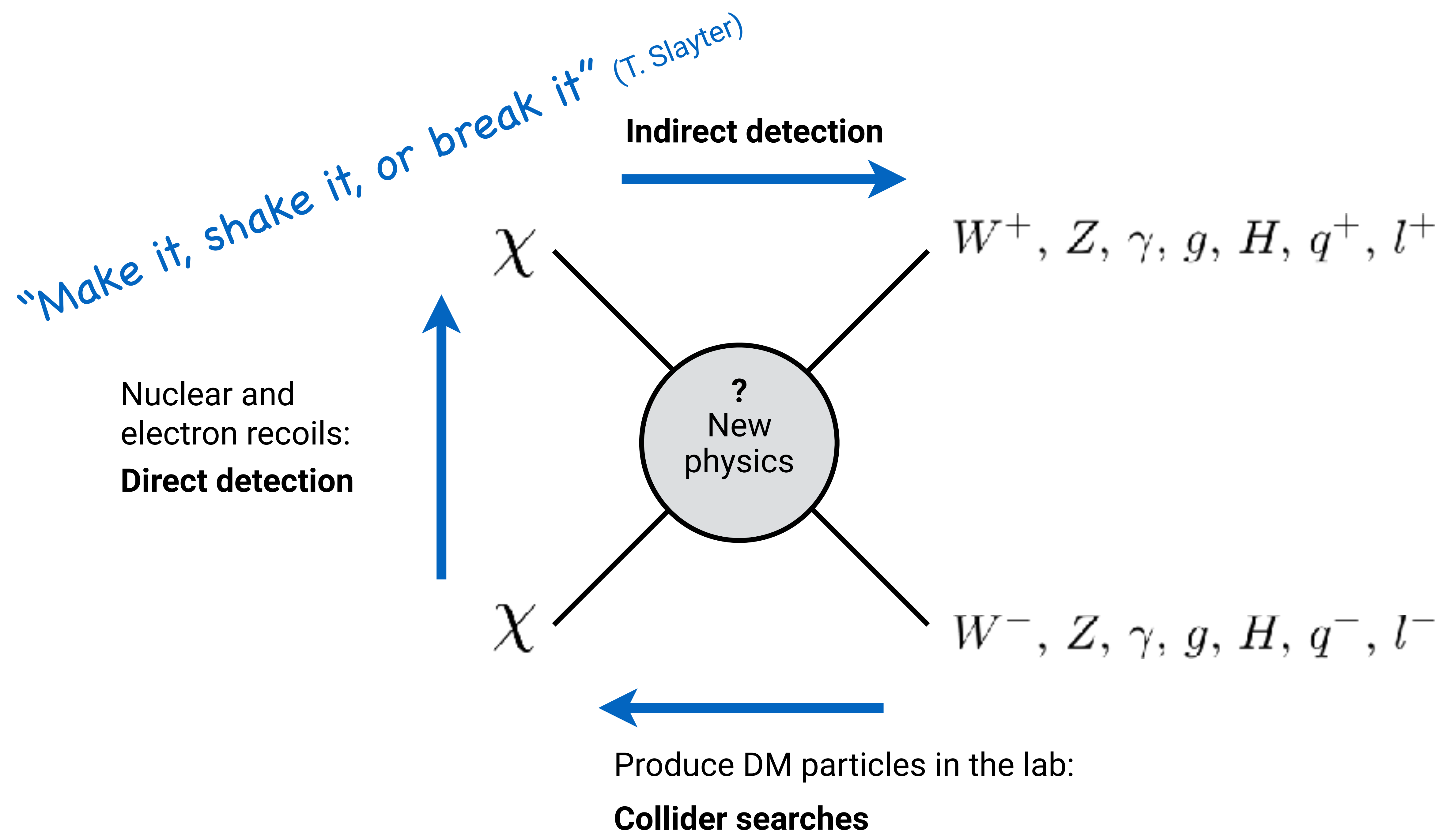
Indirect dark matter searches: A definition

After Slayter (2017), Gaskins (2016), Conrad et al. (2015), …

At least for WIMP Dark Matter:

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

} Quite "direct" probe of particle DM = gravitational DM



"Search for Standard Model particles

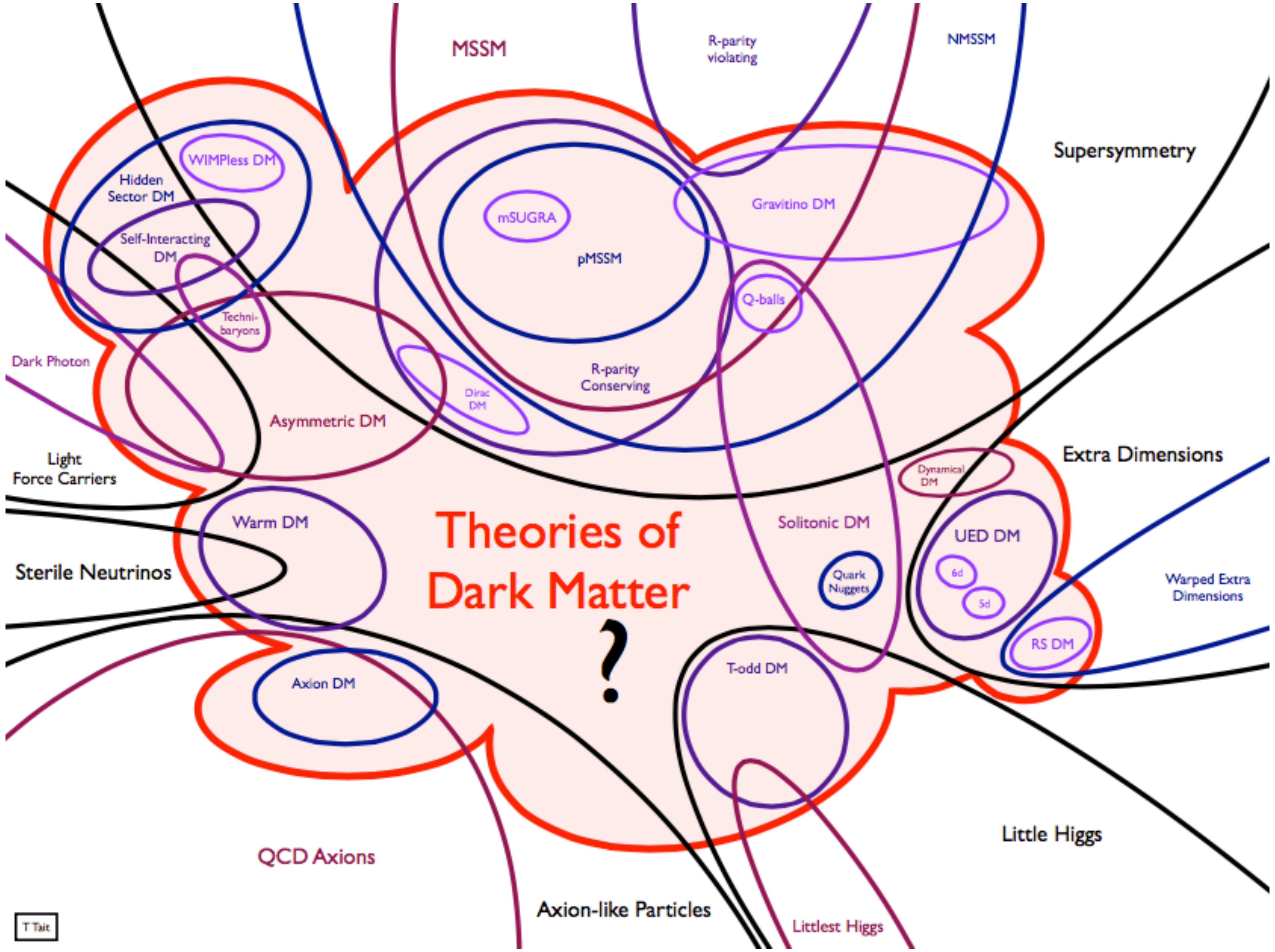
after self-annihilation, decay, or any other (exotic) process

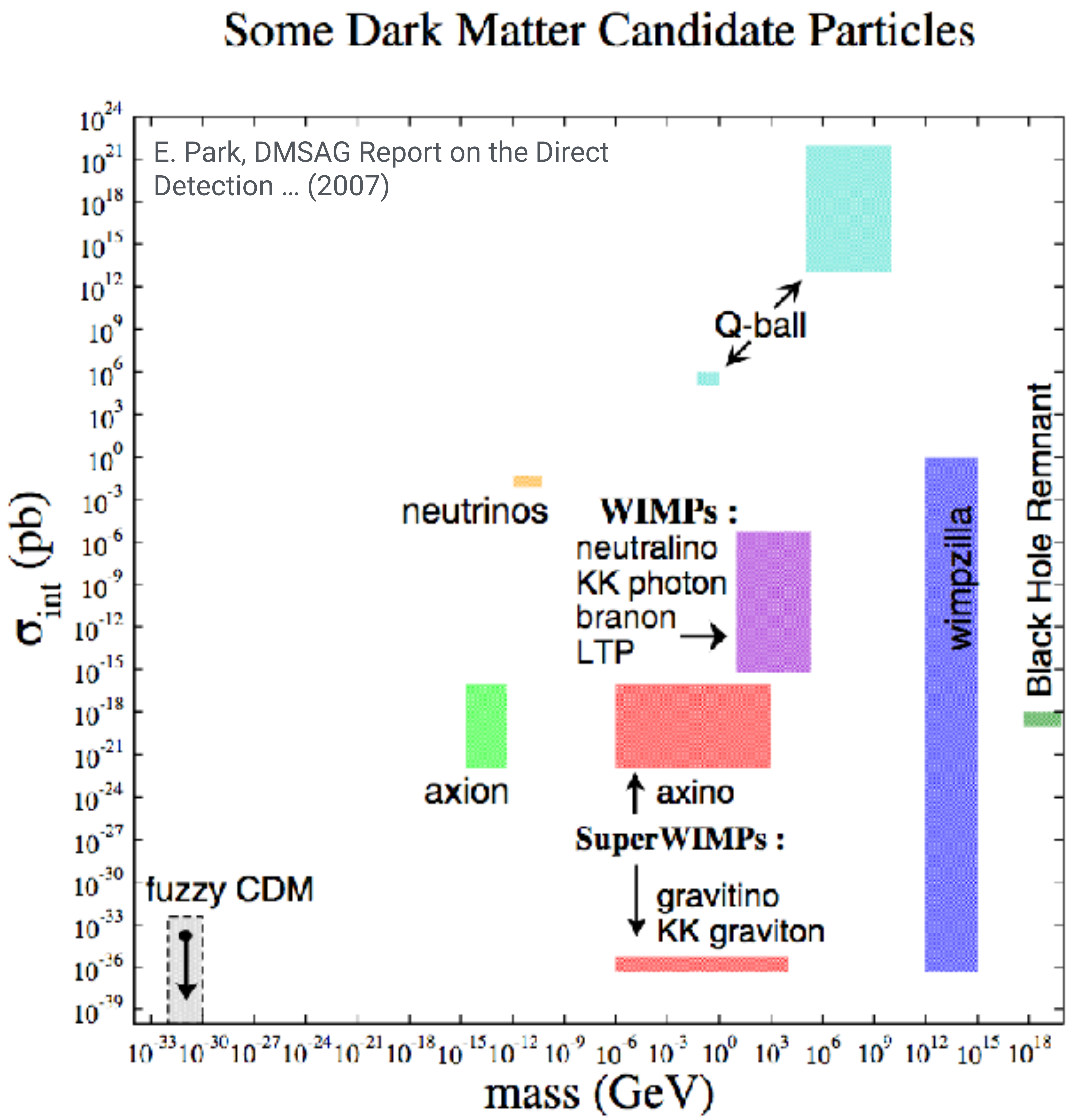
of naturally present dark matter

outside the Earth"

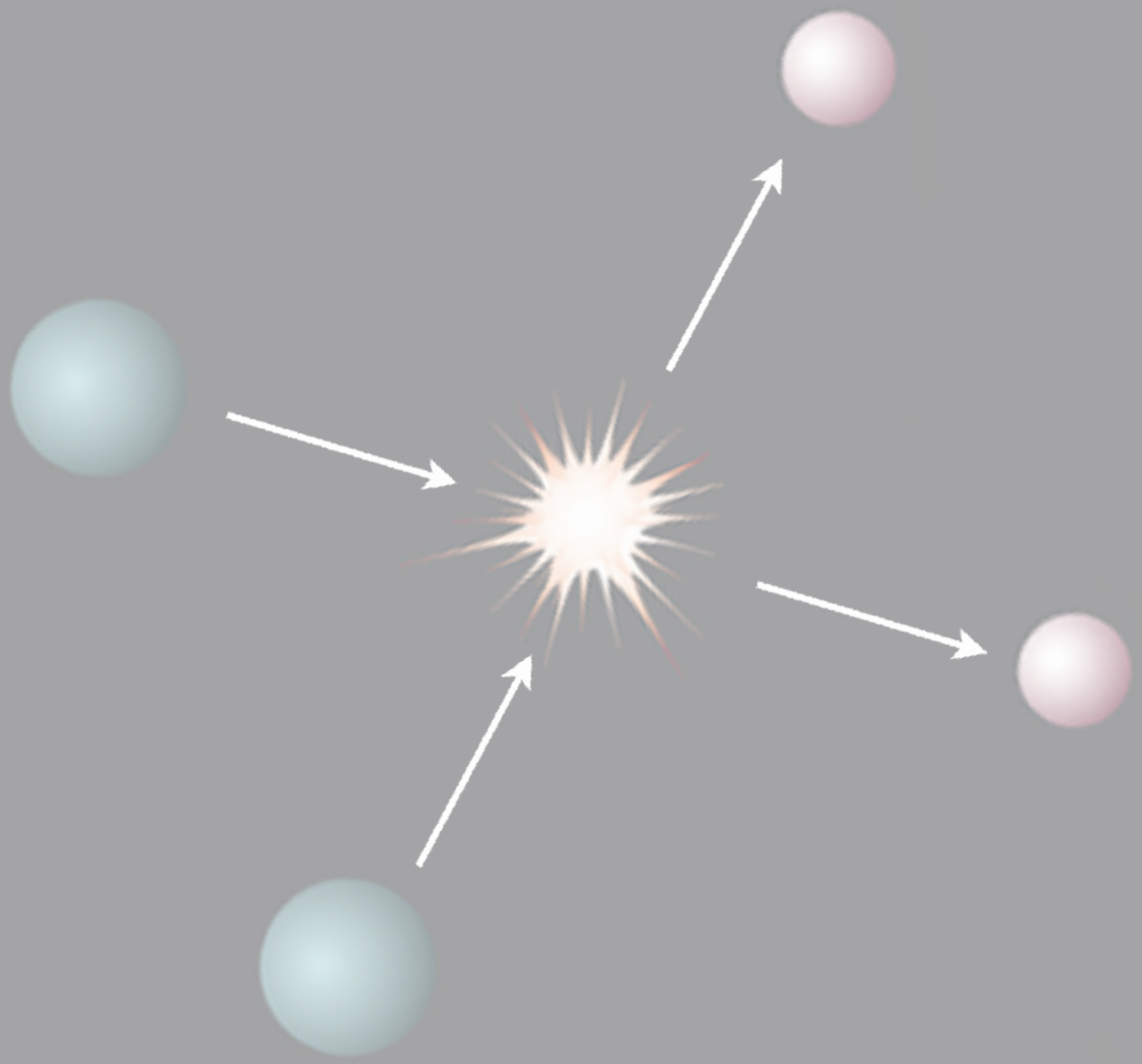
The DM theory jungle

- Indirect searches: not only WIMP annihilation



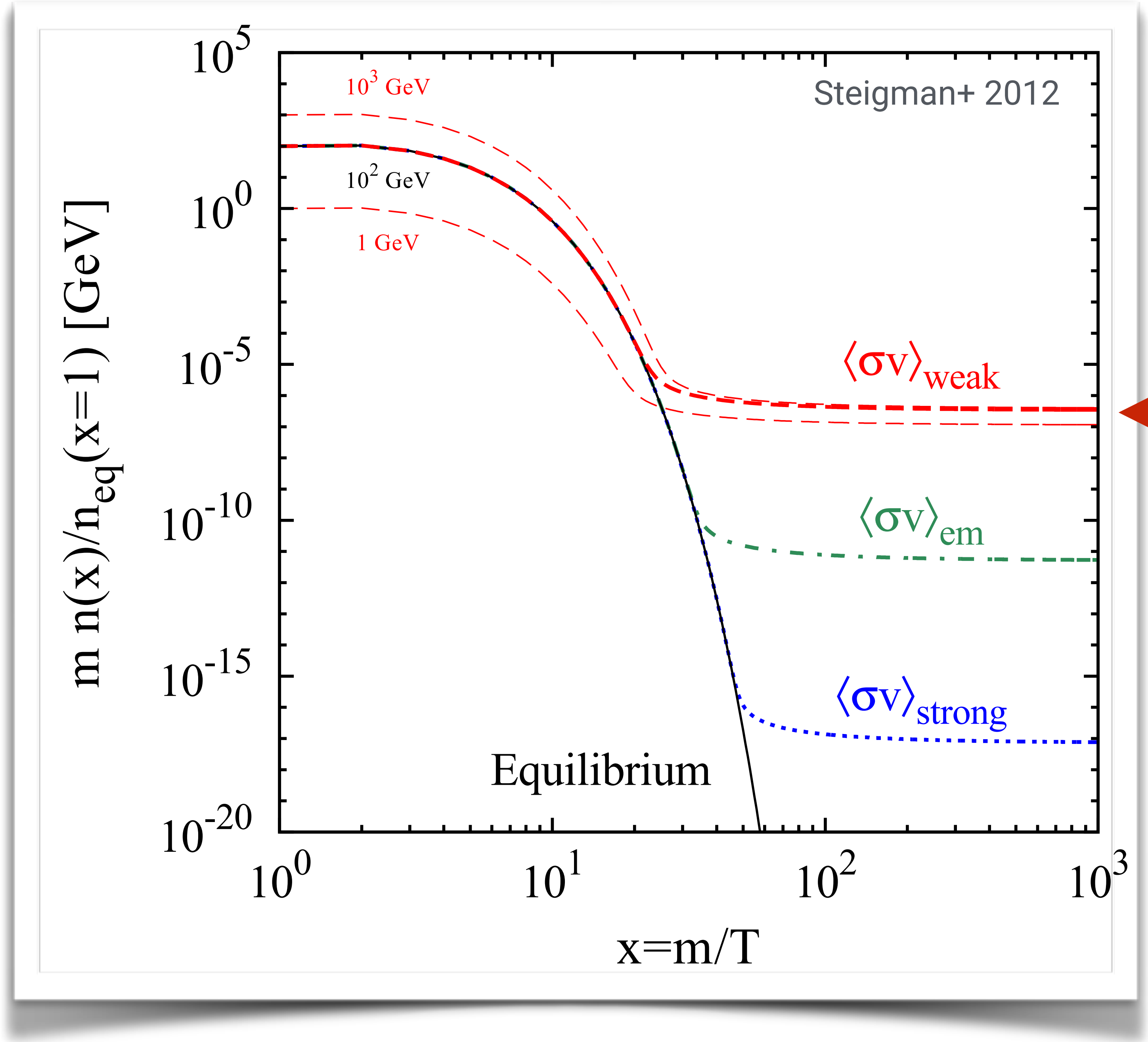


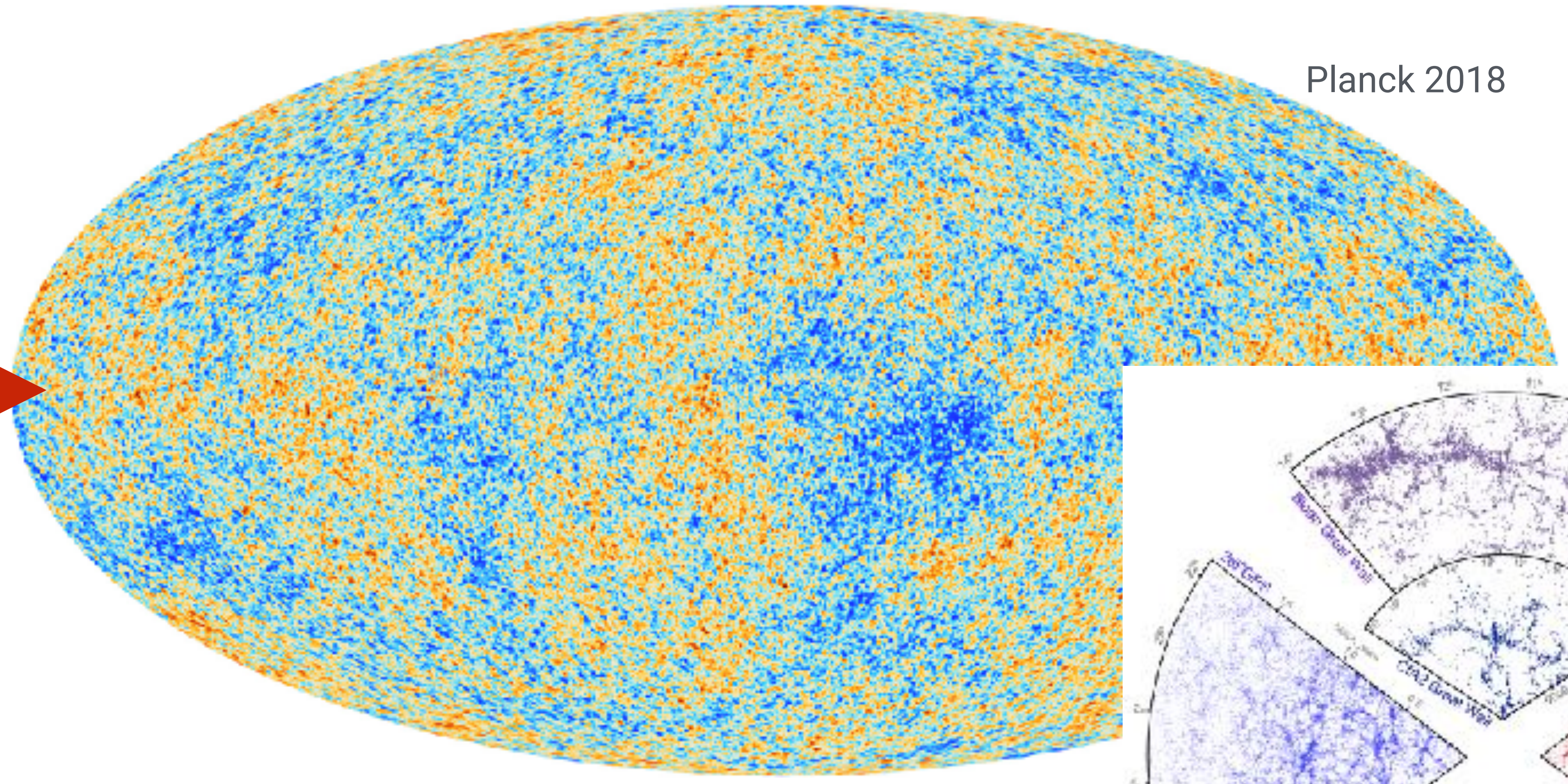
Weakly Interacting Massive Particle (WIMP) searches

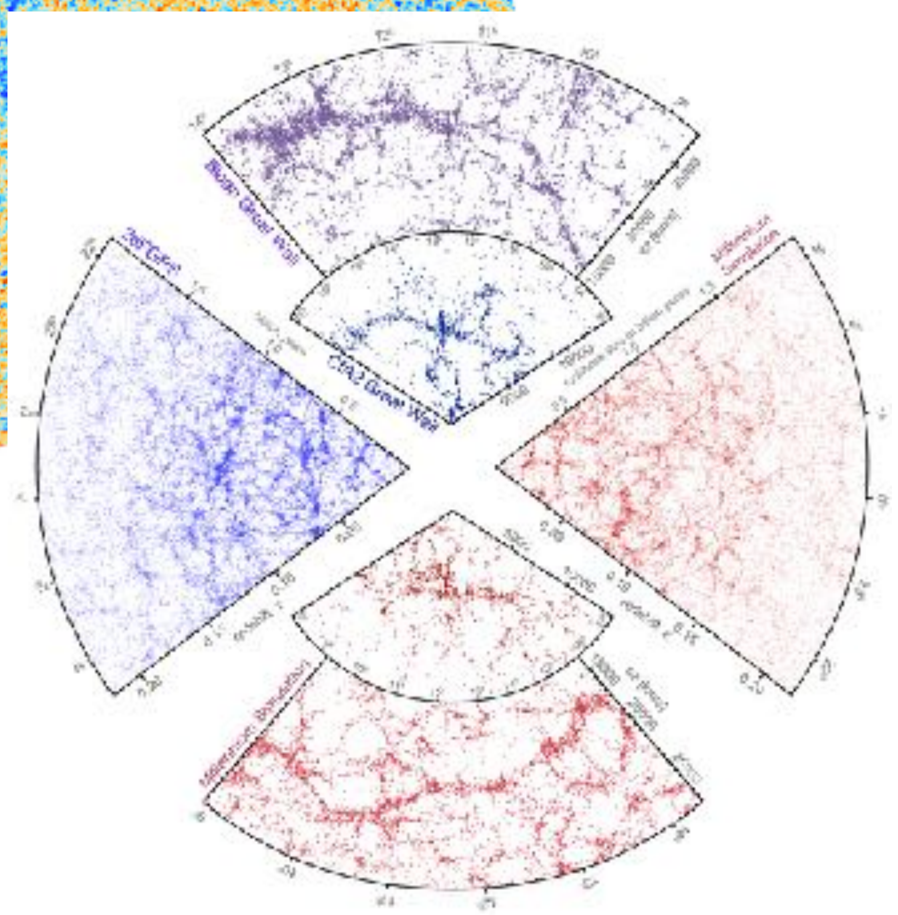


Reminder: Appeal of the WIMP paradigm

- **WIMP miracle:**





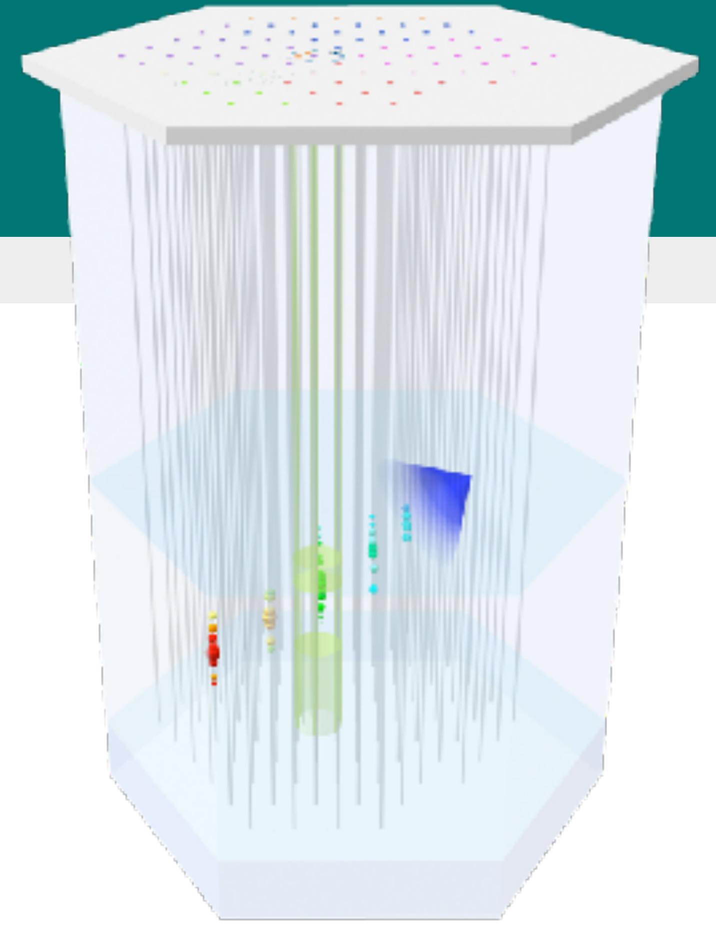


Millennium ΛCDM simulation vs. 2dFGRS survey

$$\rho_\chi h^2 \simeq 0.12\rho_{crit} \left(\frac{80}{g^*}\right)^{1/2} \left(\frac{m_\chi}{25\,T_F}\right) \left(\frac{2.2\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle}\right)$$

Non-relativistic $>$ GeV particle with weak-scale cross section gives relic abundance well matching observed cosmic DM density and can explain today's large scale structure

How many relic interactions do we expect?



- **Relic annihilation @ Earth:**

A few kg of DM inside Earth volume

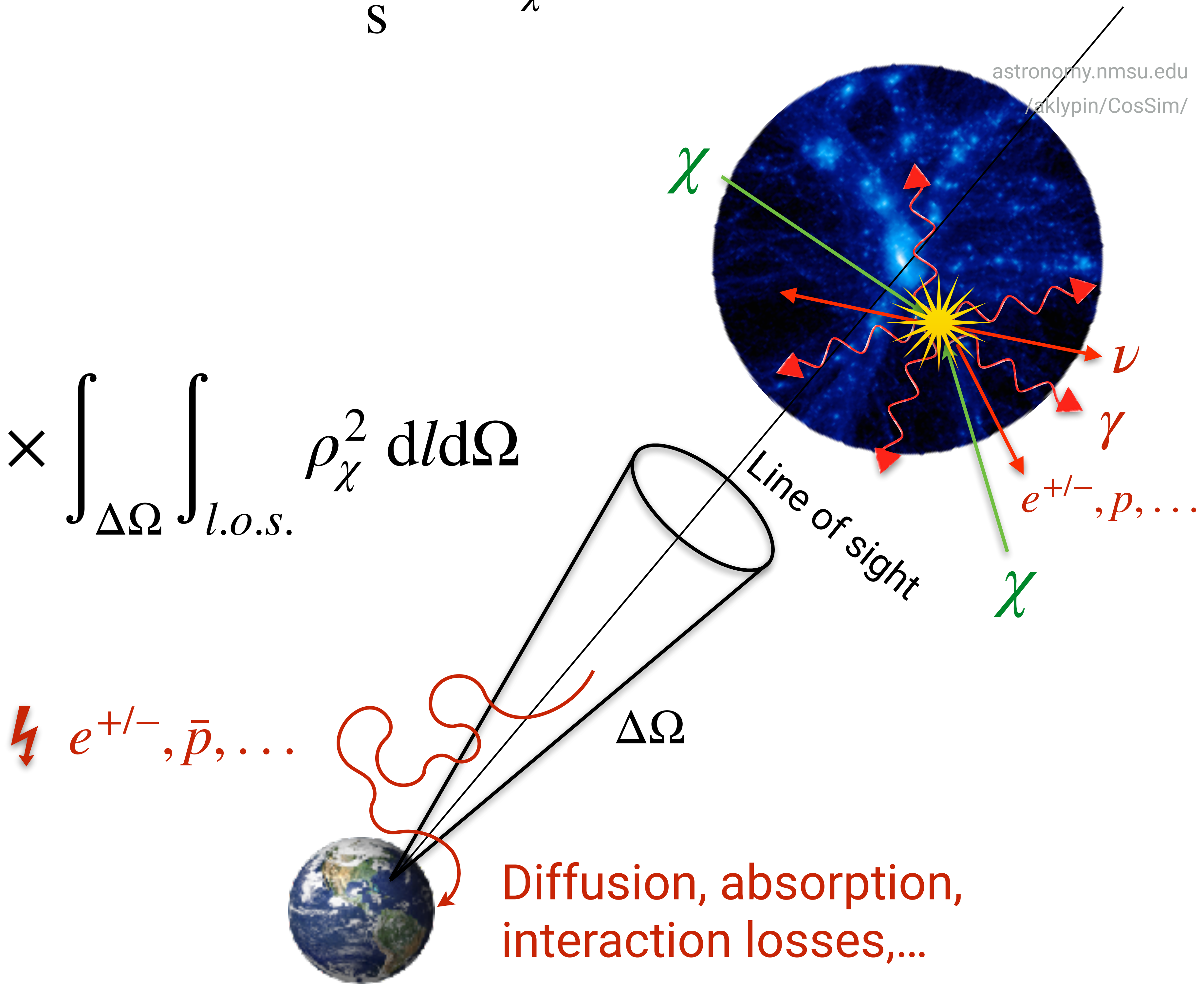
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}V} = \frac{\rho_\chi^2}{\delta\, m_\chi^2}\langle\sigma v\rangle \quad \text{with} \quad \delta = \begin{cases} 4, \chi \neq \bar{\chi} & \text{Dirac DM} \\ 2, \chi = \bar{\chi} & \text{Majorana DM} \end{cases}$$

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

- **Relic annihilation in space:**

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

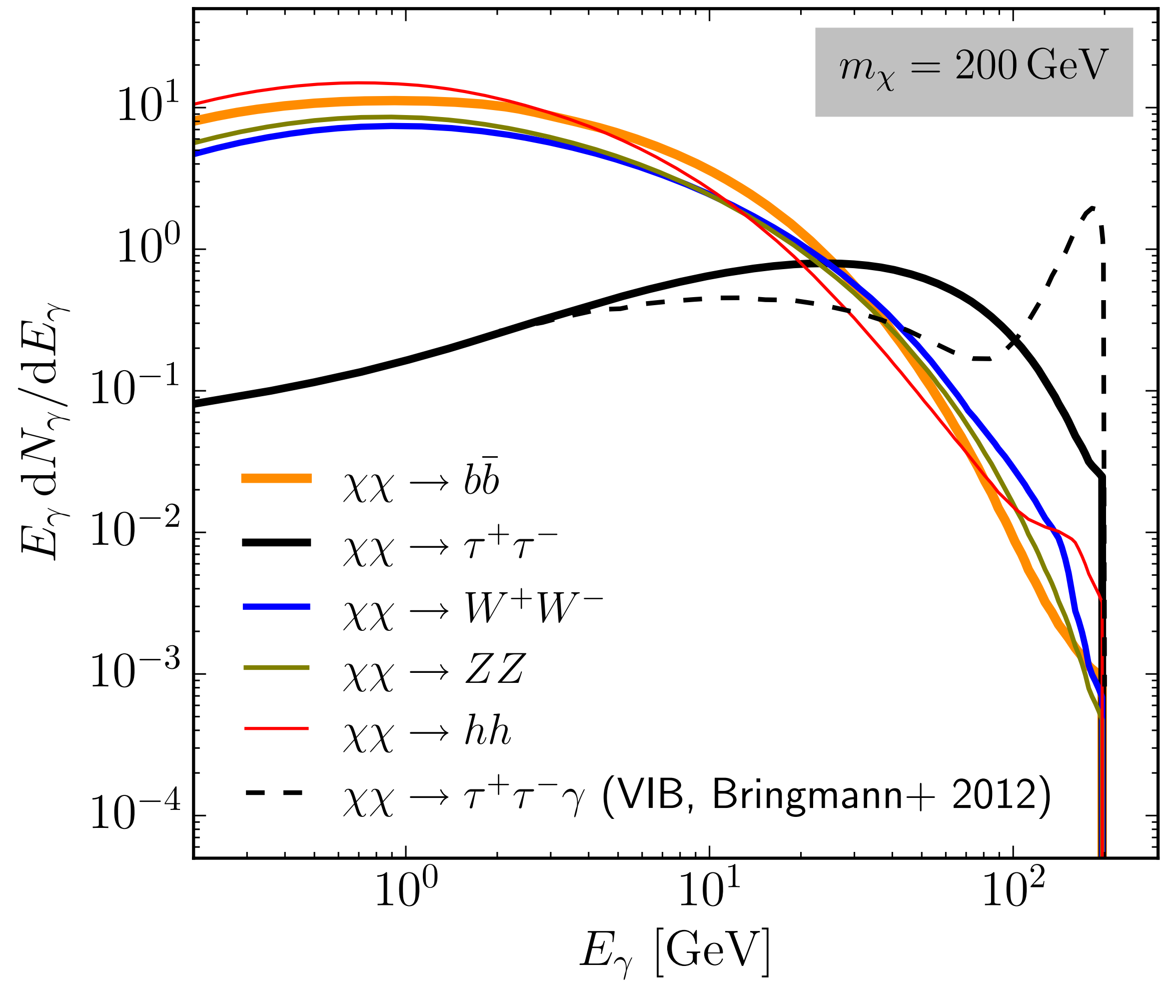
Detectable fluxes!



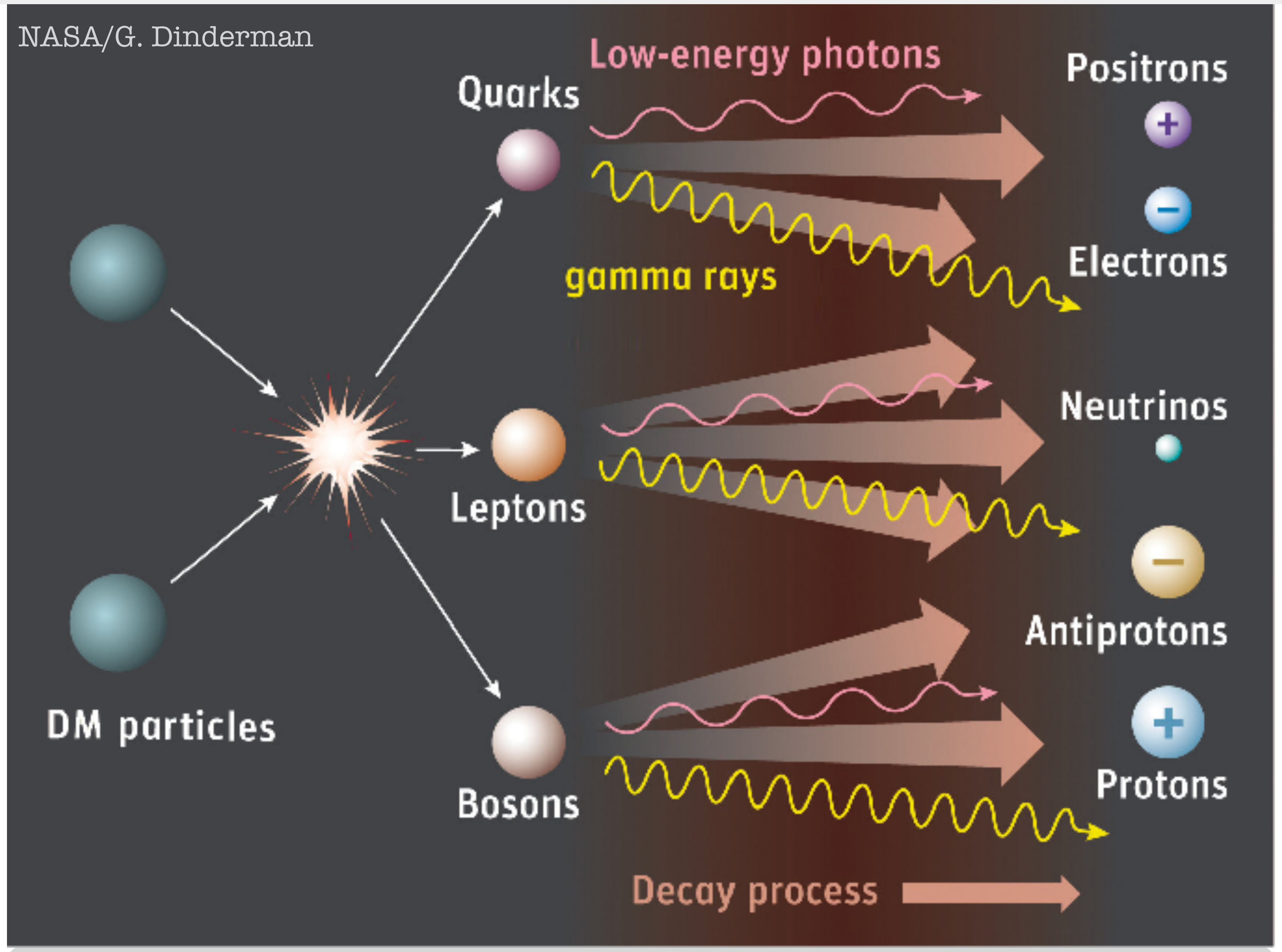
Indirect detection ingredients: Spectra

- **Secondary spectra ("particle physics term")**

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



Once first SM product/particle fixed, final state particle spectra at source robustly computed (Pythia, DarkSusy, micrOMEGAs,…)



Role of thumb:

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

High energy astronomy

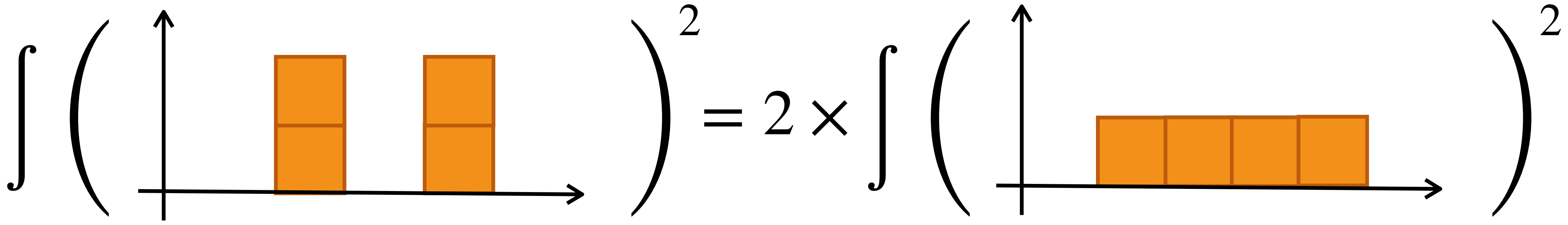
Caveat: Interaction of final state products with astrophysical environments (magnetic and radiation fields): Synchrotron, inverse Compton emission, …

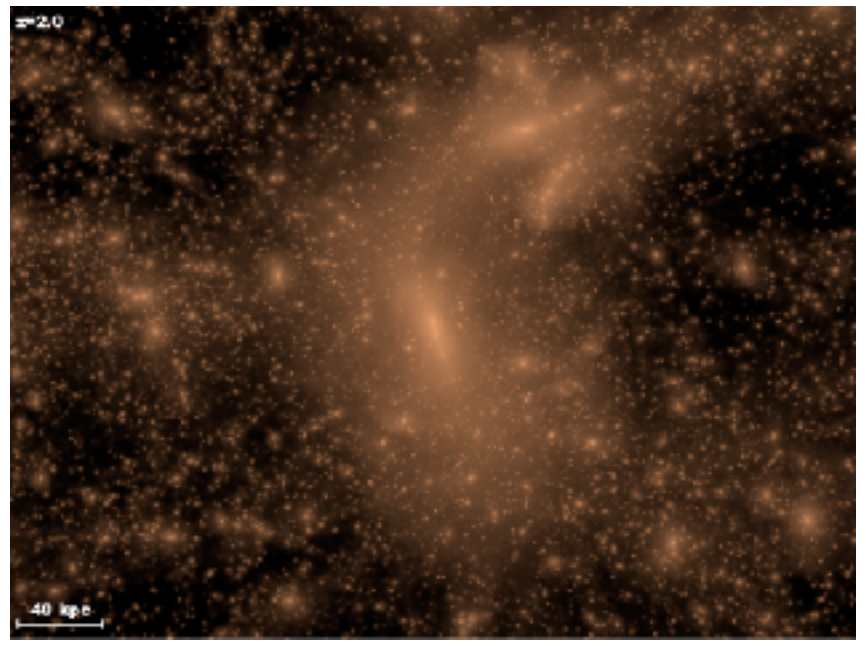
Indirect detection ingredients: Densities

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

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

- **Annihilation boost: boon and bane of indirect detection:**

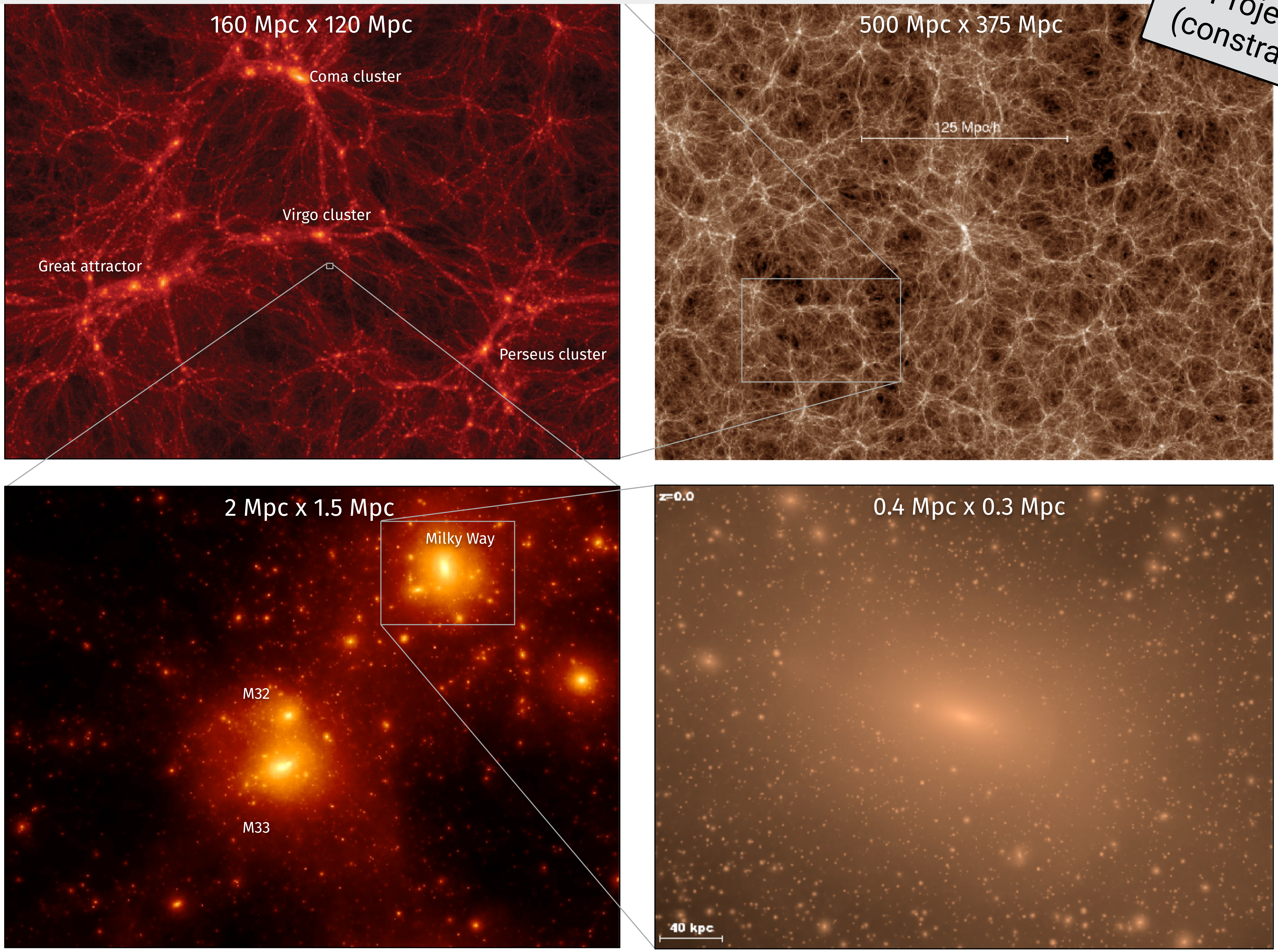




Need…

1. Close and/or massive DM budget
2. High density ("concentrated")
3. no astrophysical back-/foregrounds

Where to search? Dark matter structures at all scales



Projected DM density (constrained) simulations

Springel et al. (2005), Millenium simulations

S. Gottlöber et. al. (2010), CLUE simulations

Diemand, Kuhlen, Madau (2006), Via Lactea simulations

color code: brighter = denser

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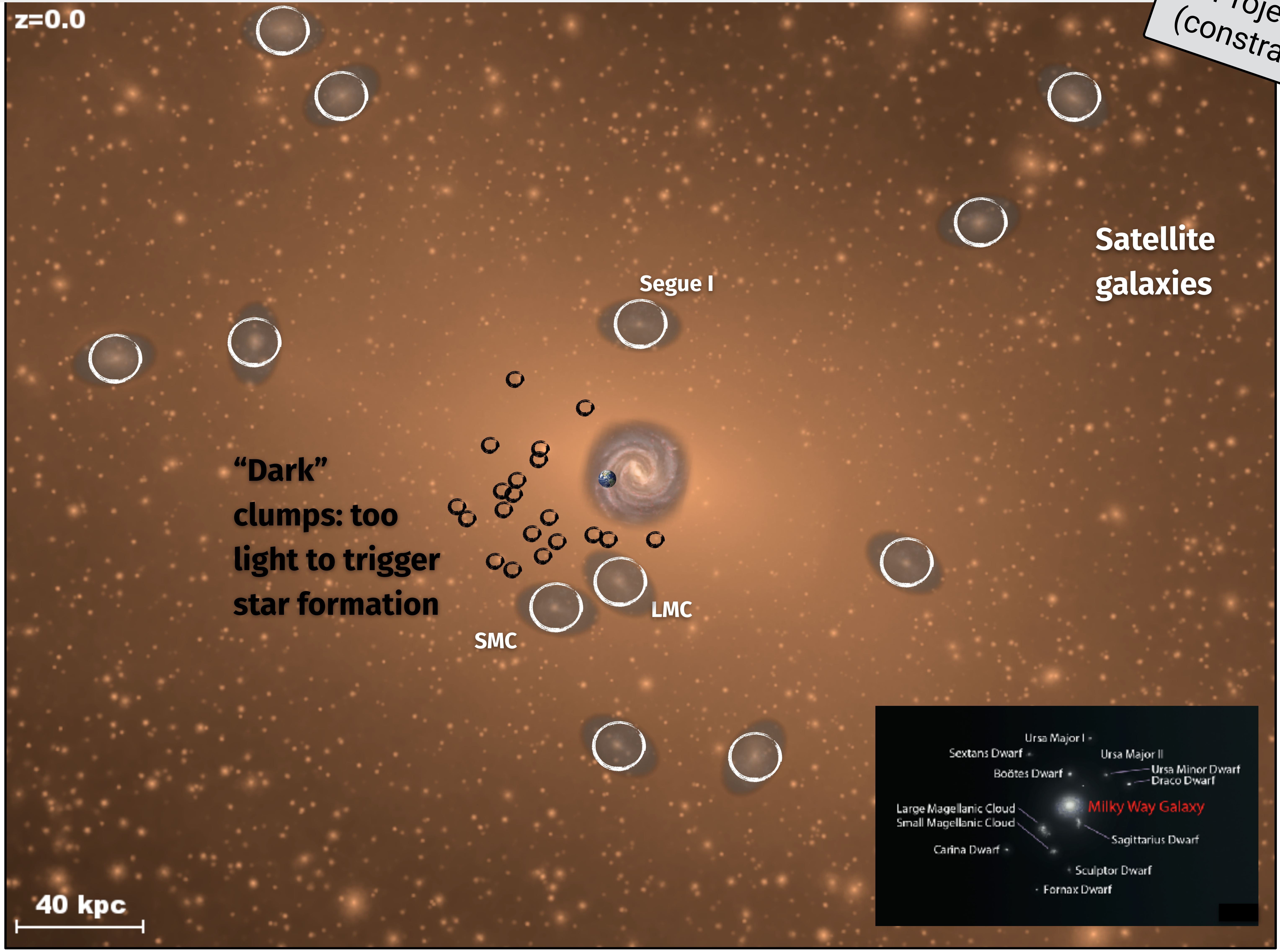
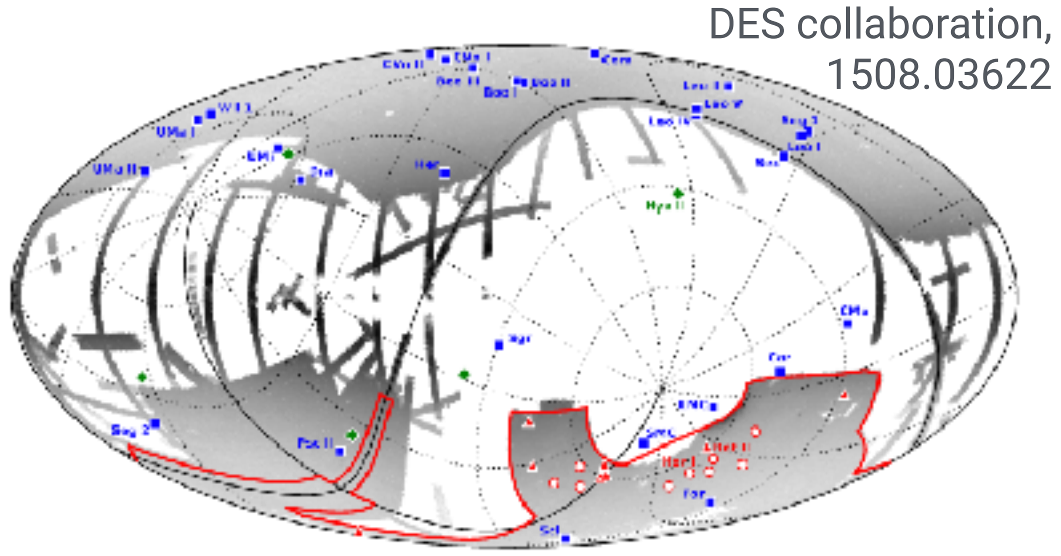
Where to search? Dark matter structures at all scales

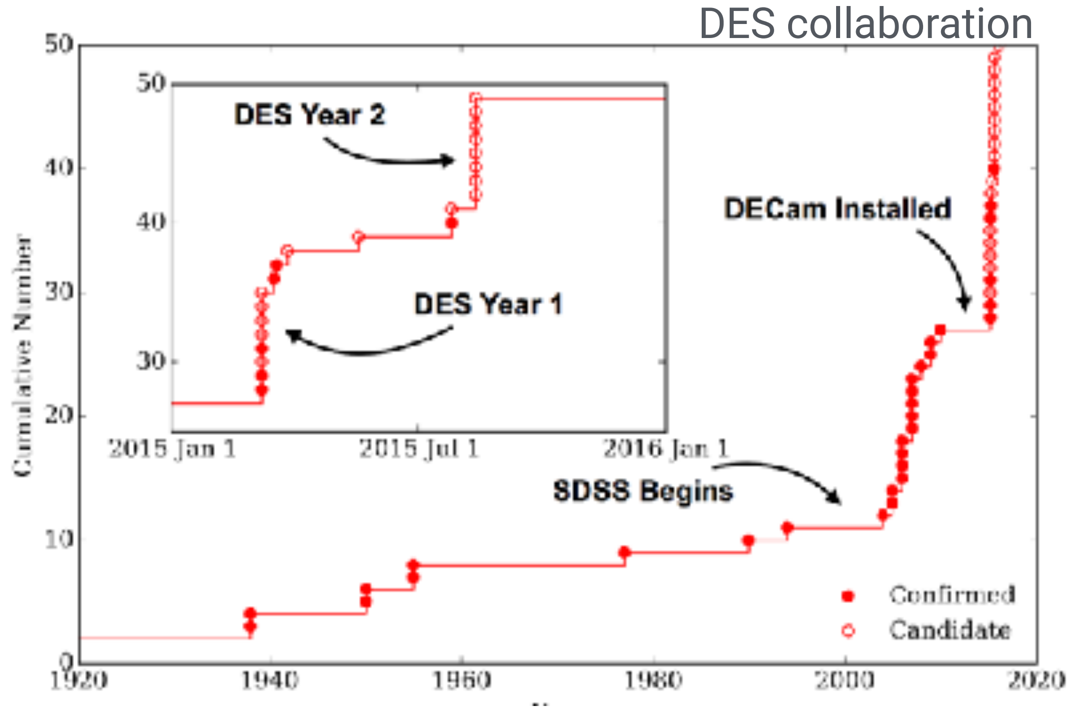
Projected DM density (constrained) simulations



DES collaboration, 1508.03622



DES collaboration



Springel et al. (2005), Millenium simulations

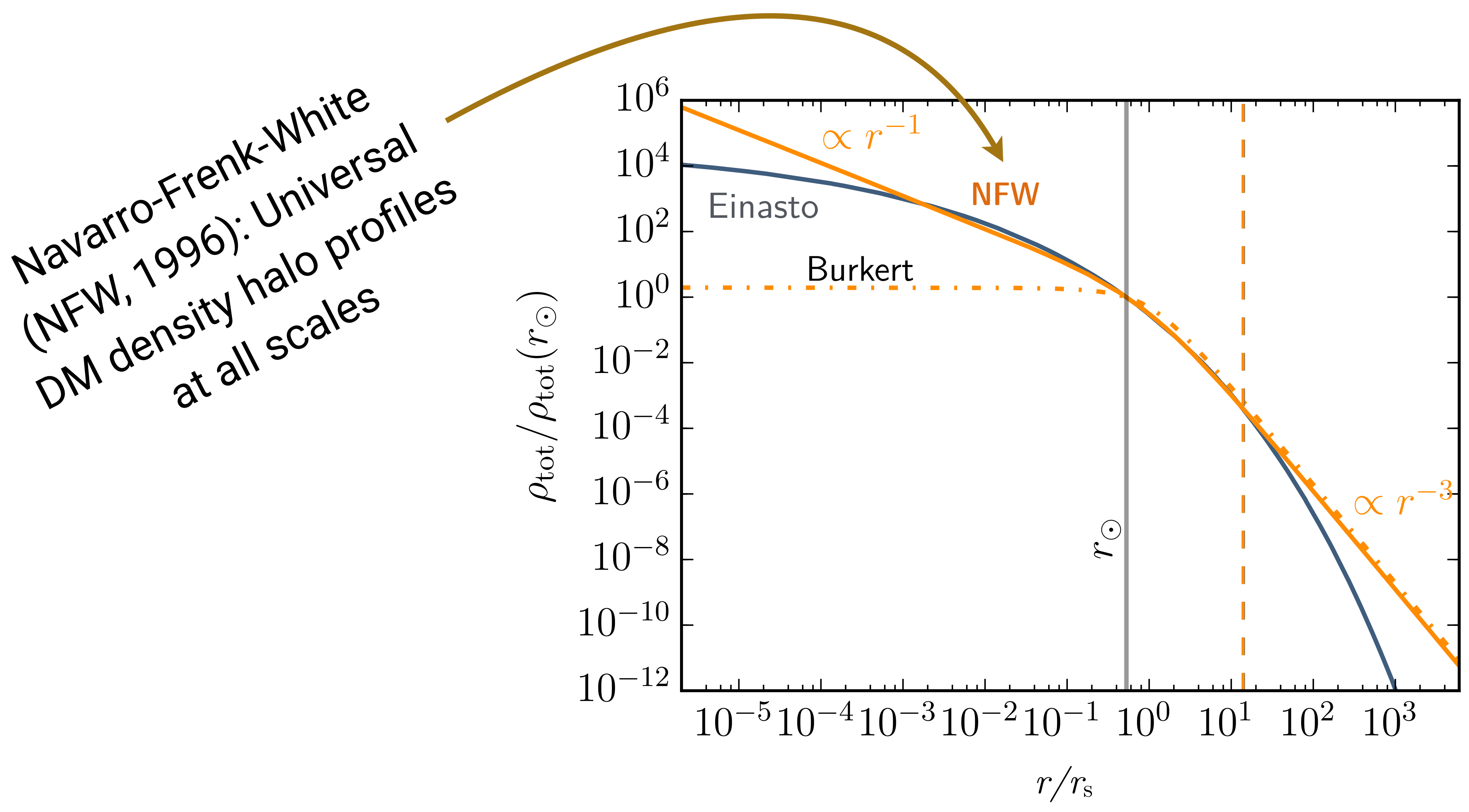
S. Gottlöber et. al. (2010), CLUE simulations

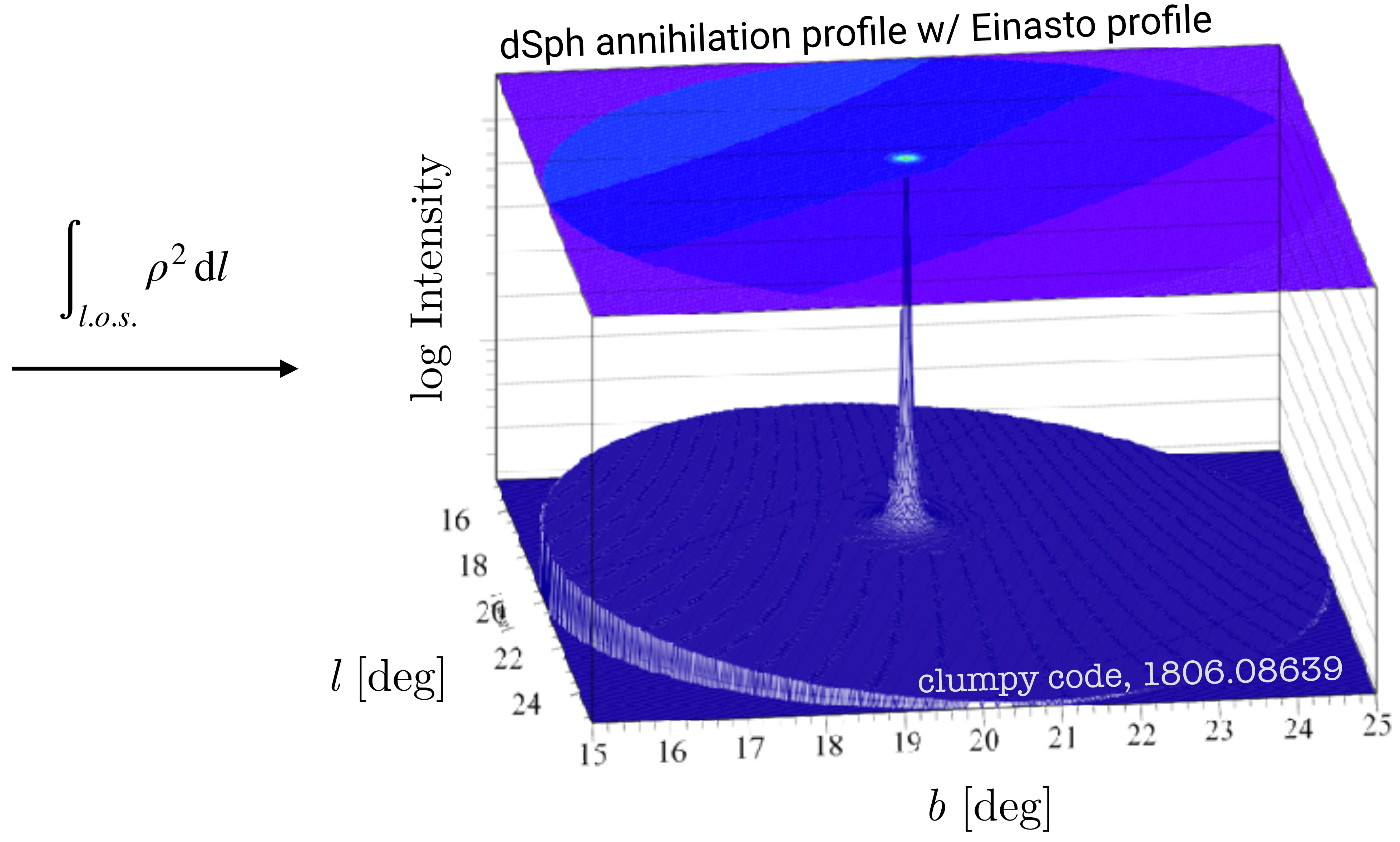
Diemand, Kuhlen, Madau (2006), Via Lactea simulations

color code: brighter = denser

Indirect detection ingredients: Densities (II)

- Annihilation boost also boosts uncertainty:





Innermost $0.1°$ Galactic DM halo signal ***NFW or Einasto*** vs. ***Burkert*** profile:

annihilation ($\int_{l.o.s.} \rho^2 \, dl$) : Factor **2000**

Decay ($\int_{l.o.s.} \rho \, dl$) : Factor **10**

J-factor main uncertainty in indirect DM searches

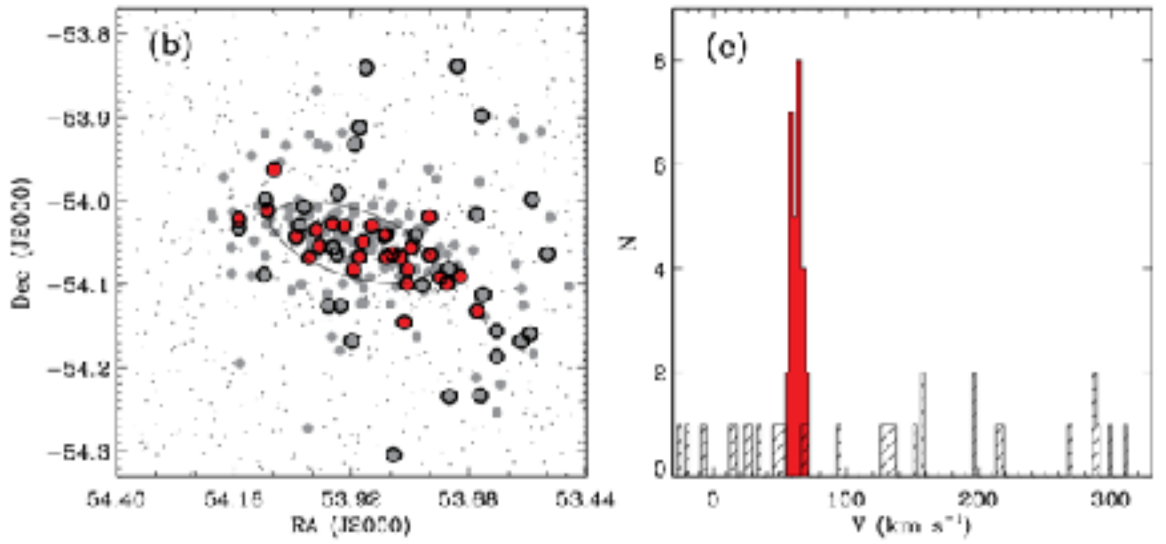
DM density profiles: empirical knowledge

- **Dwarf spheroidal galaxies**

  Solve spherical Jeans equation $\frac{1}{\nu}\frac{\mathrm{d}\left(\nu\bar{v}_r^2\right)}{\mathrm{d}r} + \frac{2\,\beta_{\mathrm{ani}}\,\bar{v}_r^2}{r} = -\frac{G\,M(r)}{r^2}$

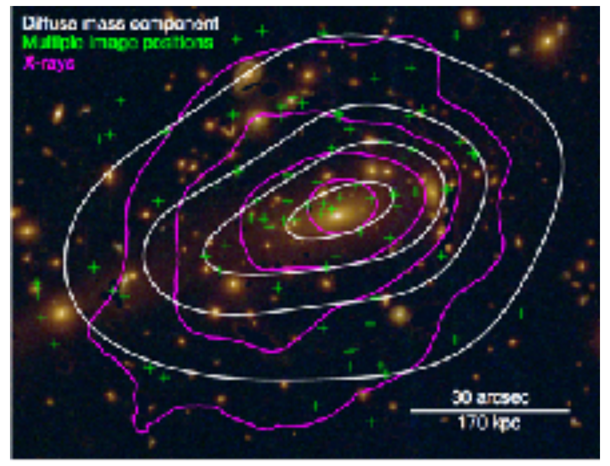
  3D light profile ν + spectroscopic velocity dispersion $\bar{v}^2$ to best-fit DM density profile

Review of 1805.05883



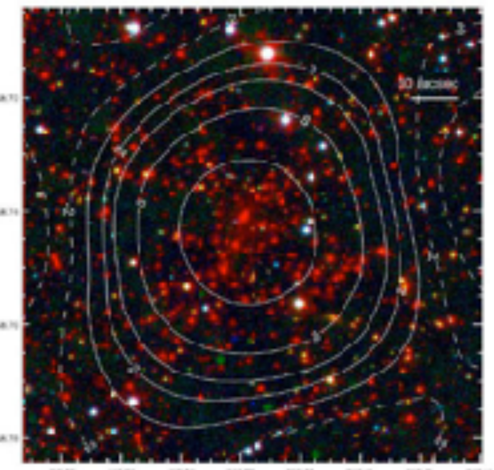
- **Galaxy clusters**

1707.00690



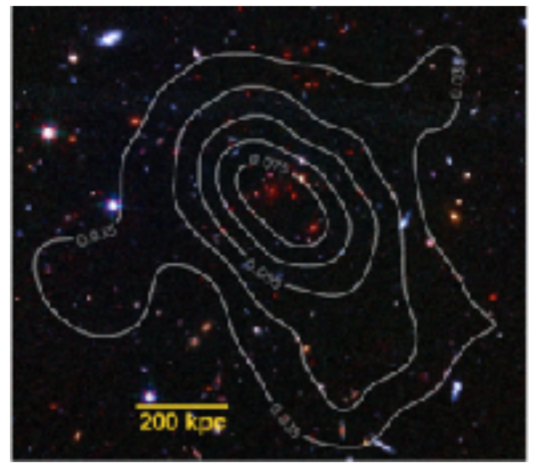
Strong lensing + X-ray

1101.1286



SZ + X-ray

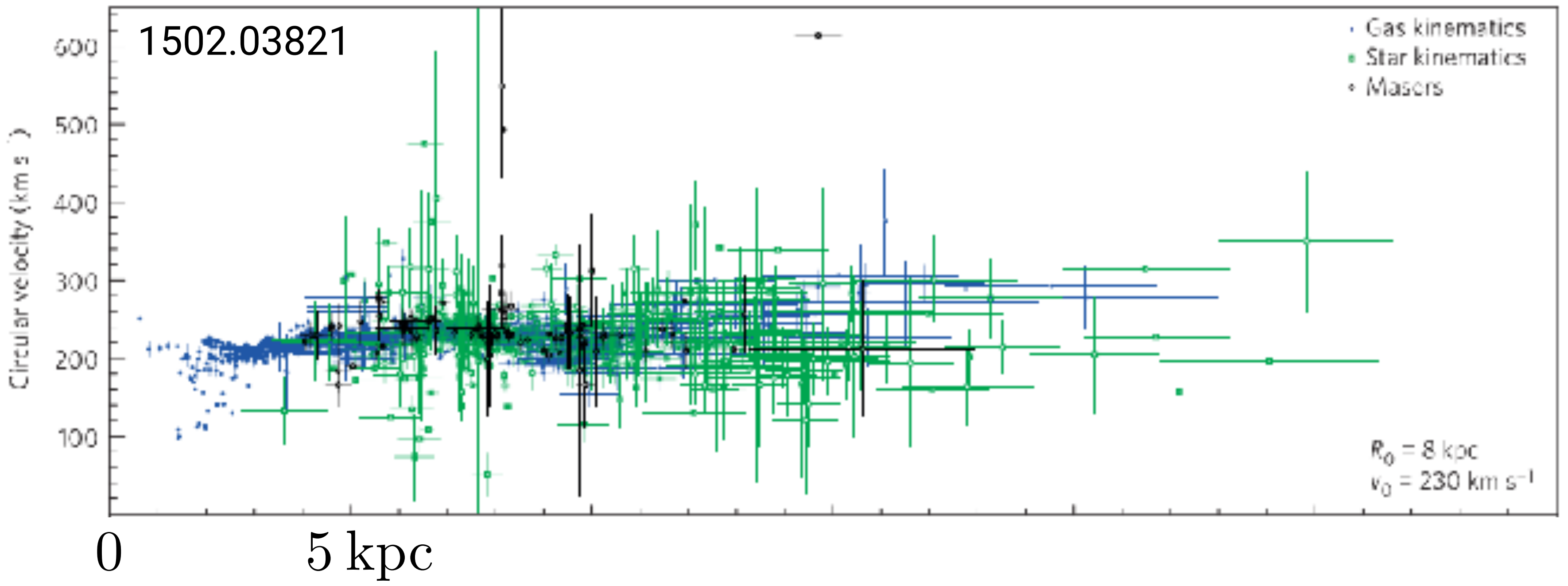
1601.07967



Weak lensing

- **Milky Way:**

  Rotation curves, but poorly constrained in inner Galactic halo: 1611.09861, 1901.02460, 1901.02463

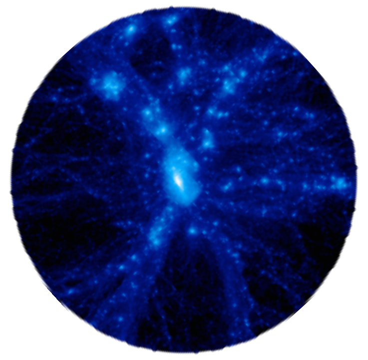


“Cusp-versus-core” problem:
N-body simulations predict cuspier profiles than suggested by observation (Moore ’94, 1108.2404, 1703.08410)

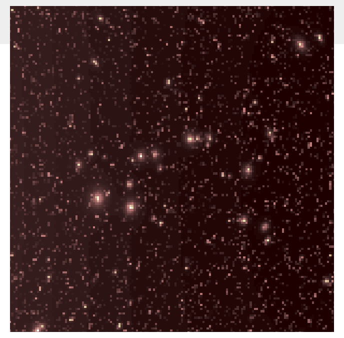
Possible solutions: (Self-)scattering DM (1404.7012, 1508.03339), observation bias (1707.06303), **baryonic feedback** (1404.3674, 1505.00825, 1611.09922, 2004.10817, 2007.13780,…)

Where to look? Dark matter sky at Earth

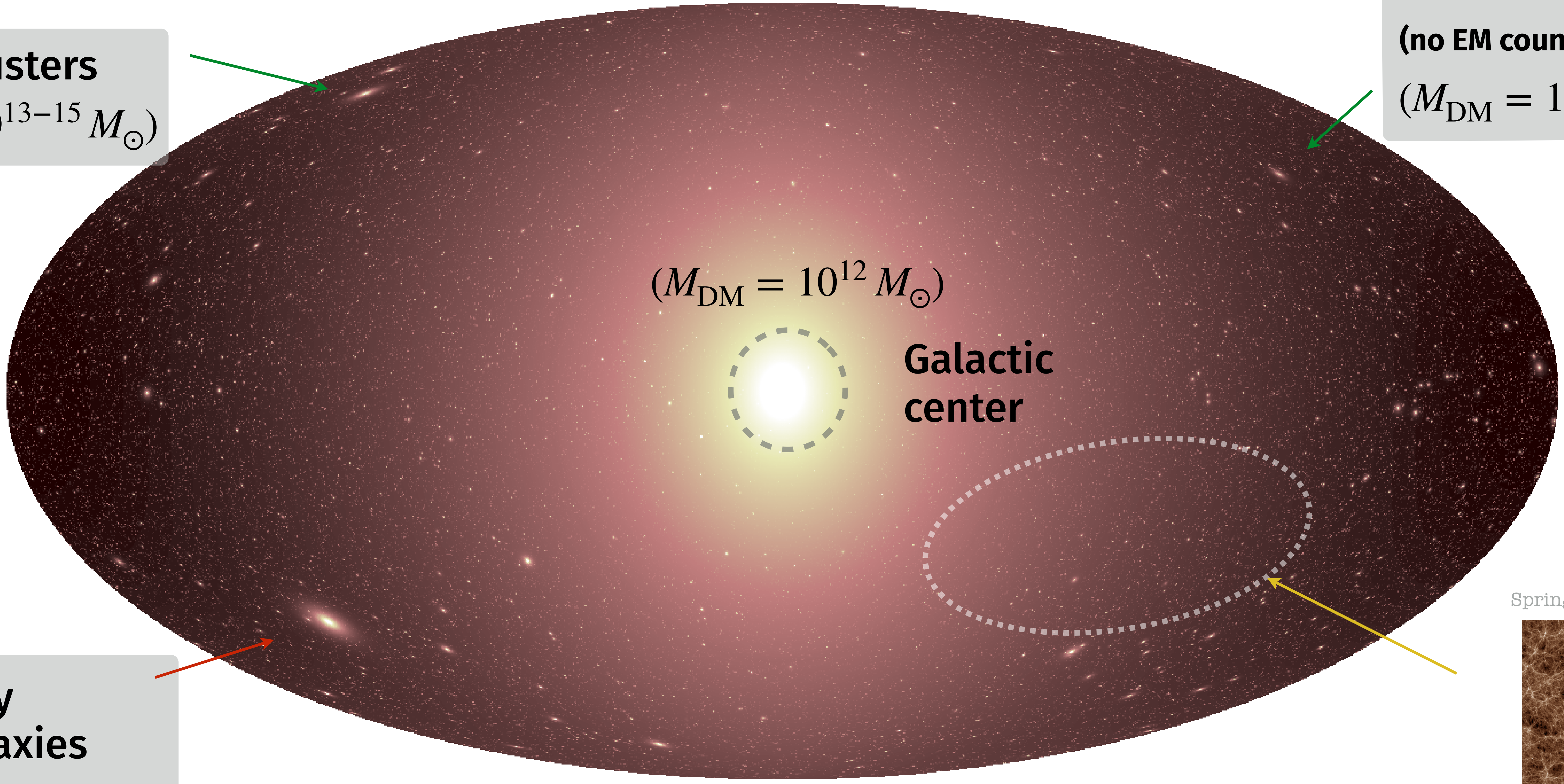
astronomy.nmsu.edu/
aklypin/CosSim/



Galaxy clusters
$(M_{\rm DM} = 10^{13-15}\, M_\odot)$



Dark clumps
(no EM counterpart)
$(M_{\rm DM} = 10^{6-8}\, M_\odot)$

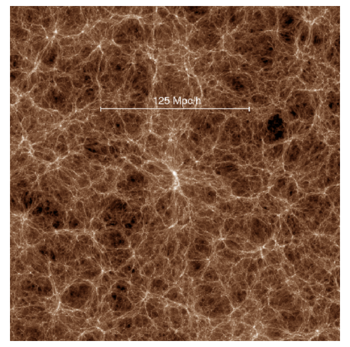


log (γ-ray intensity from DM annihilation), Galactic coordinates
synthetic map calculated with CLUMPY (MH et al., 1806.08639)

Fornax dSph

Milky Way dSph galaxies
$(M_{\rm DM} = 10^{8-10}\, M_\odot)$

Springel et al. (2005)



Gal. + extragal. diffuse
$(M_{\rm DM} = \text{obs. Universe})$

Target example: Perseus cluster

without substructure
random triaxiality

Target example: Perseus cluster

Target example: Perseus cluster

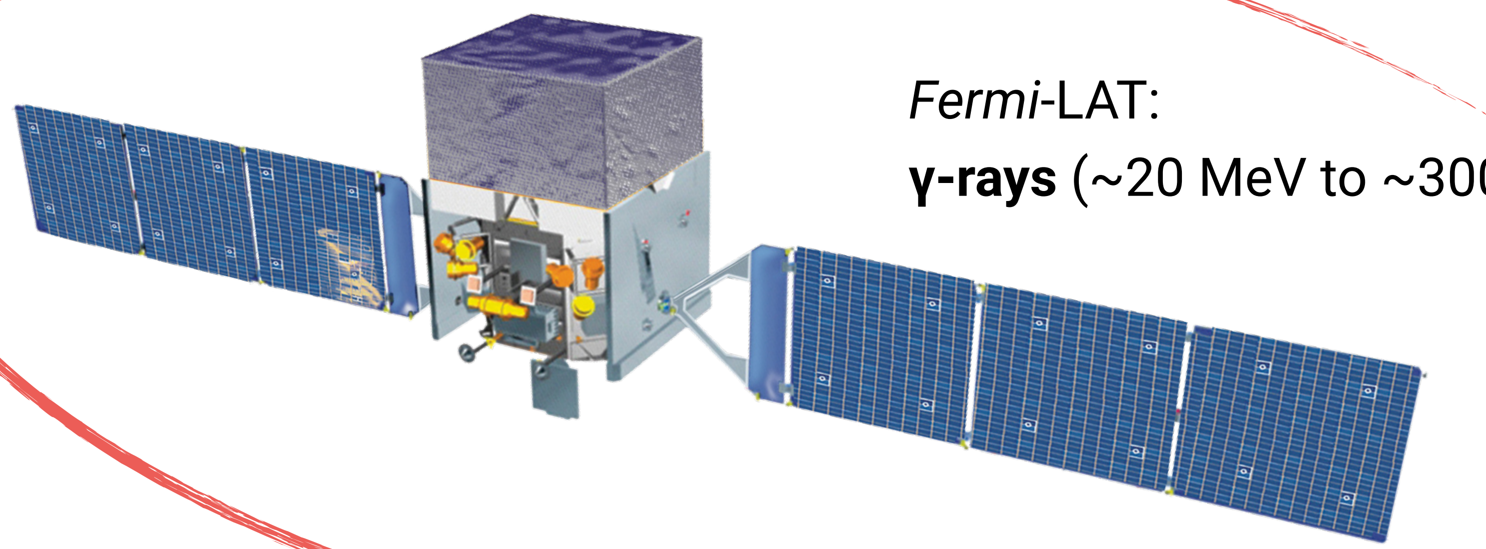
γ-ray telescope resolution

with substructure
random triaxiality

Target example: Perseus cluster

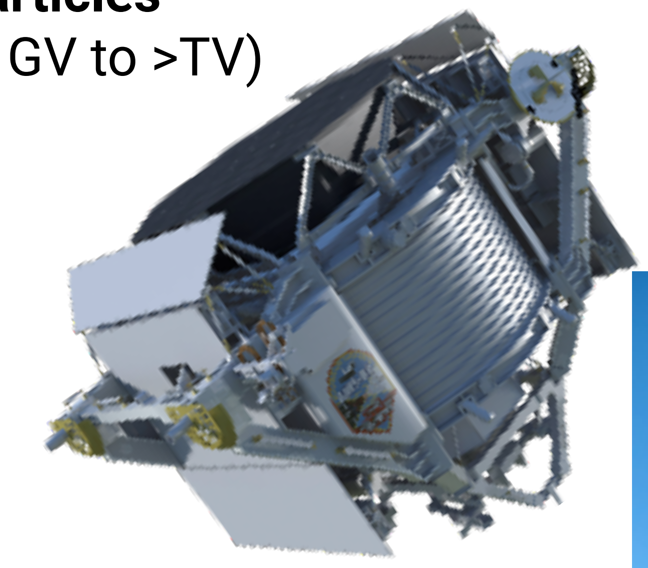
Indirect detection instruments

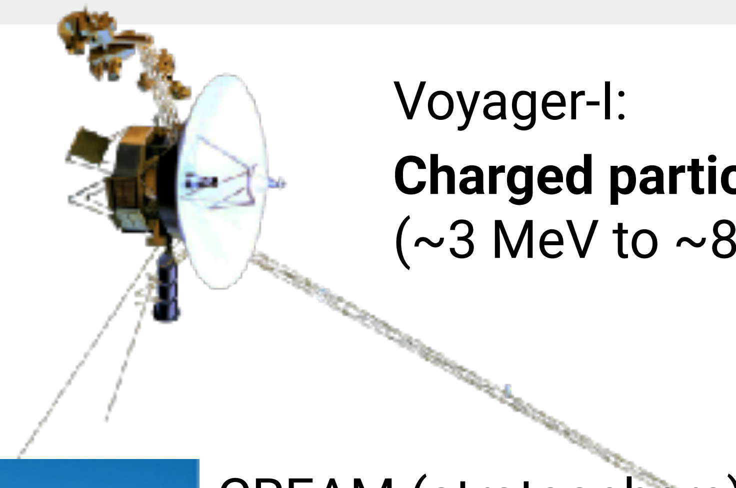
- Detect particles from space:



Fermi-LAT:
γ-rays (~20 MeV to ~300 GeV)

AMS-02:
Charged particles
(rigidity ~2 GV to >TV)



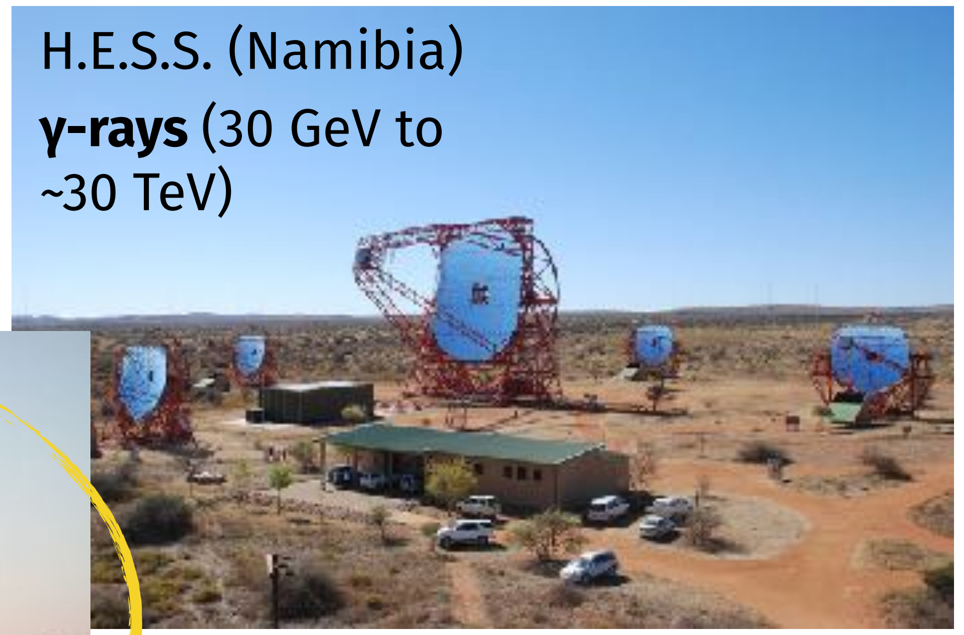


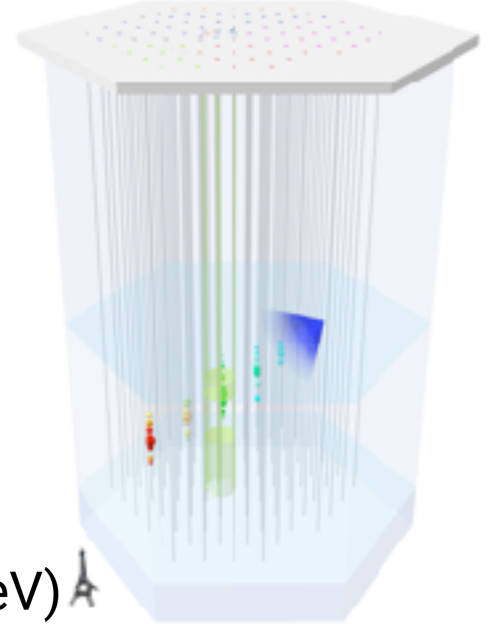
Voyager-I:
Charged particles.
(~3 MeV to ~80 MeV)

CREAM (stratosphere)
Charged particles
(TeV to PeV)

VERITAS (USA)
γ-rays (85 GeV to ~30 TeV)

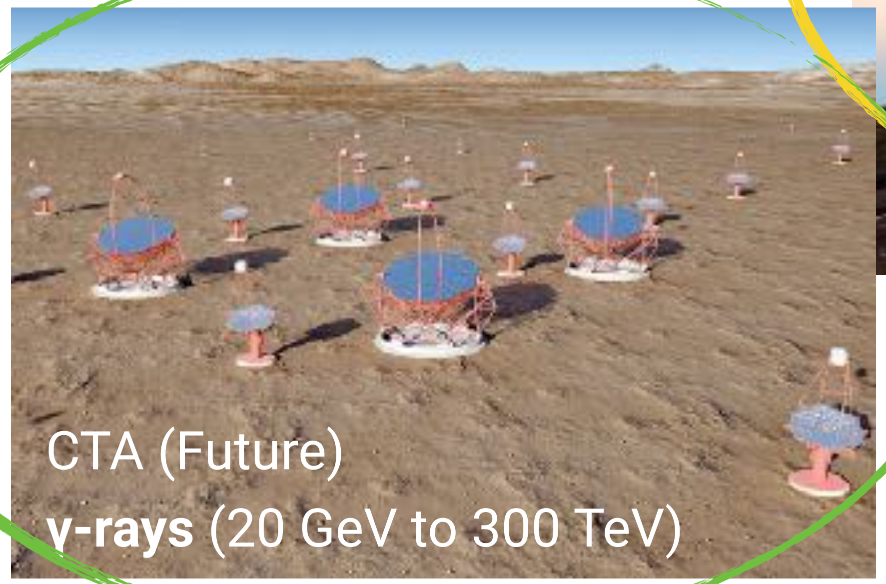
H.E.S.S. (Namibia)
γ-rays (30 GeV to ~30 TeV)





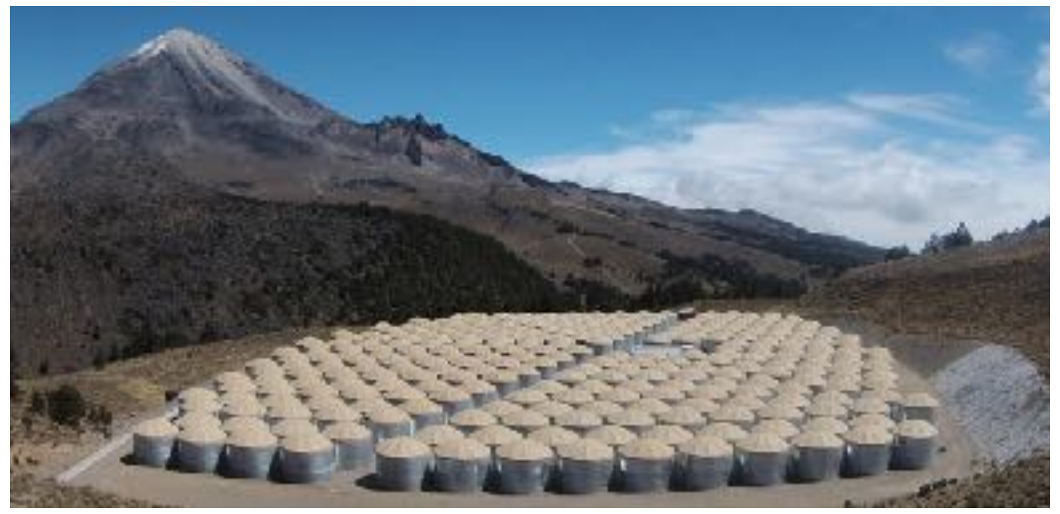
IceCube (South Pole)
Neutrinos (~100 GeV to >PeV)

MAGIC (Spain)
γ-rays (50 GeV to ~50 TeV)



CTA (Future)
γ-rays (20 GeV to 300 TeV)

HAWC (Mexico)
γ-rays (~ 3TeV to >100 TeV)



Antares (Mediterranean Sea)
Neutrinos (~10 GeV to PeV)

The *Fermi* satellite

- Designed & operated by NASA
- Launched 2008, still operational
- 4300 kg, 530 km a.s.l. orbit
- Carries

  Gamma-ray burst monitor (GBM): 8keV - 40 MeV

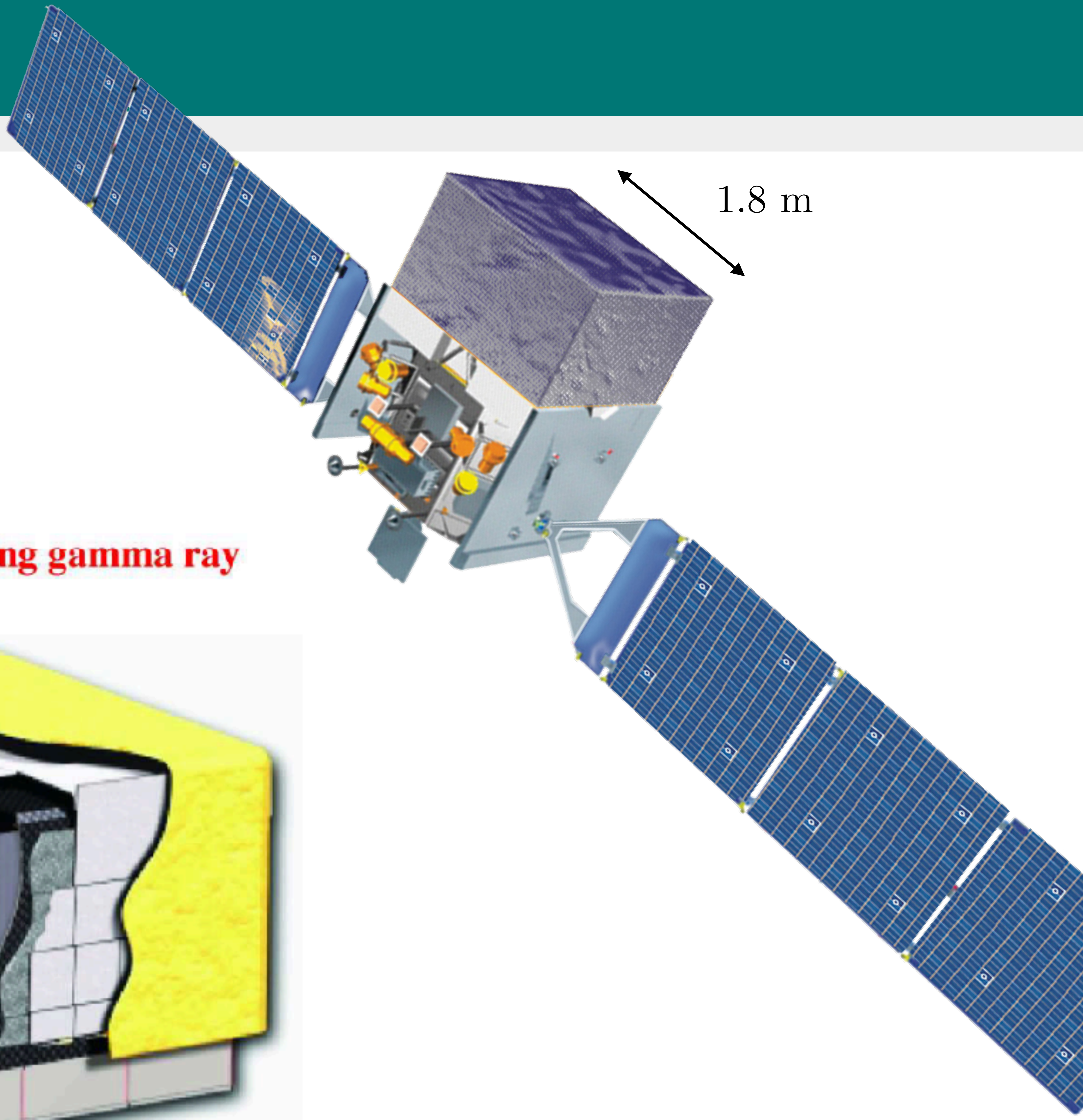
  Large Area Telescope (LAT):
  20 MeV - 300 GeV

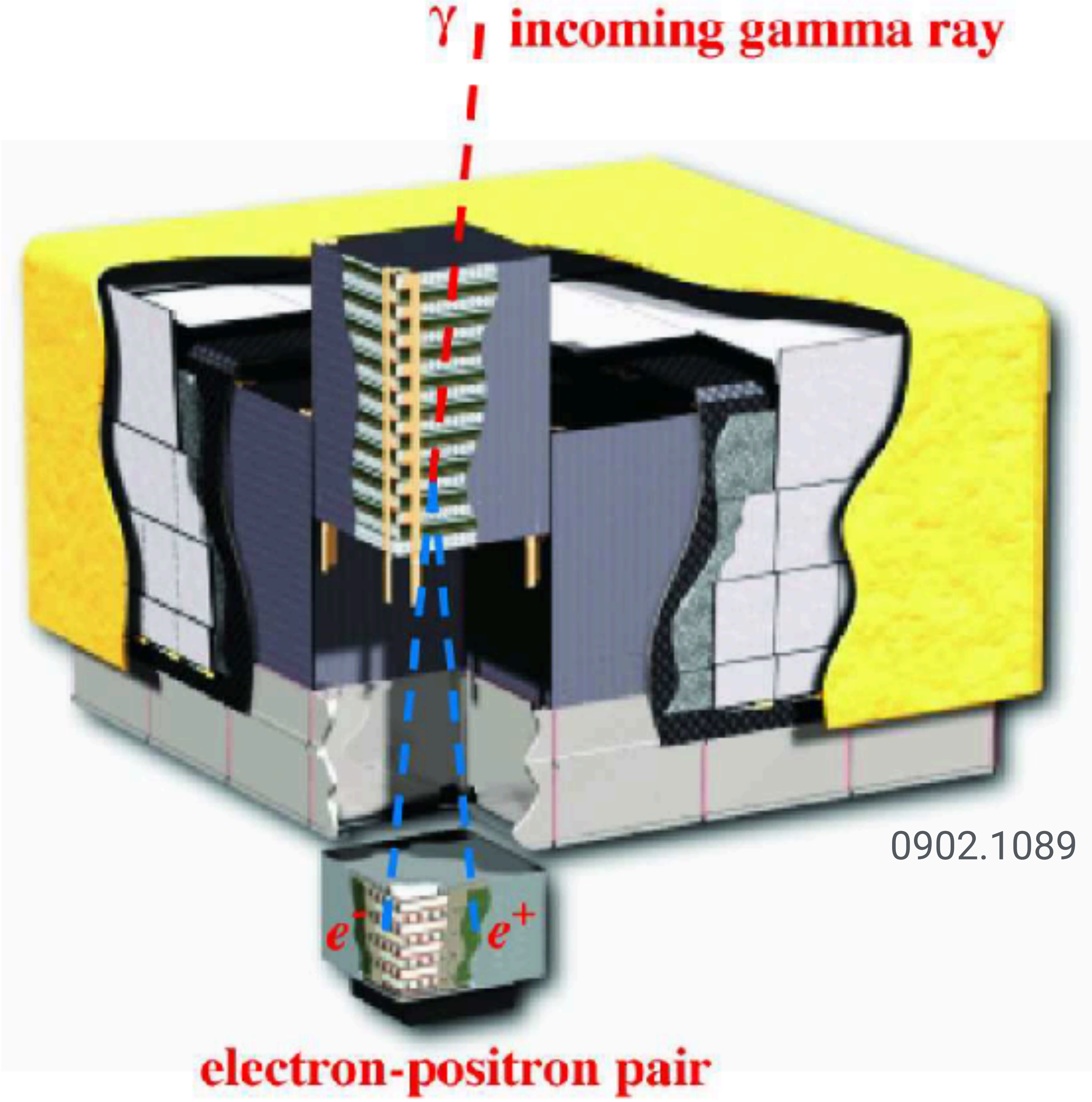
- LAT has...

  FOV: 2.4 sr

  Energy resolution: 5% - 25%

  Angular resolution: $0.1°$ - $10°$





The MAGIC telescopes

System of two Major Atmospheric Gamma-ray Imaging Cherenkov telescopes

In operation for 18 years (12 years in stereo)

Picture credit: L. Heckmann

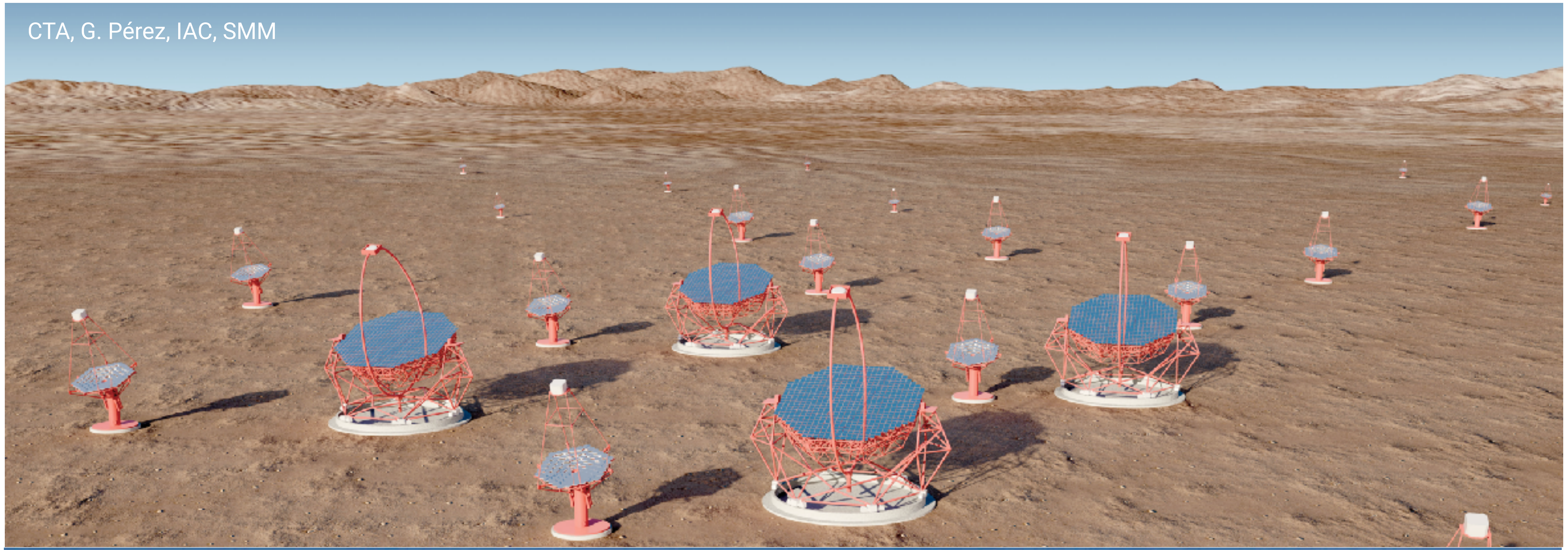
The MAGIC telescopes

Picture credit: L. Heckmann

The MAGIC telescopes

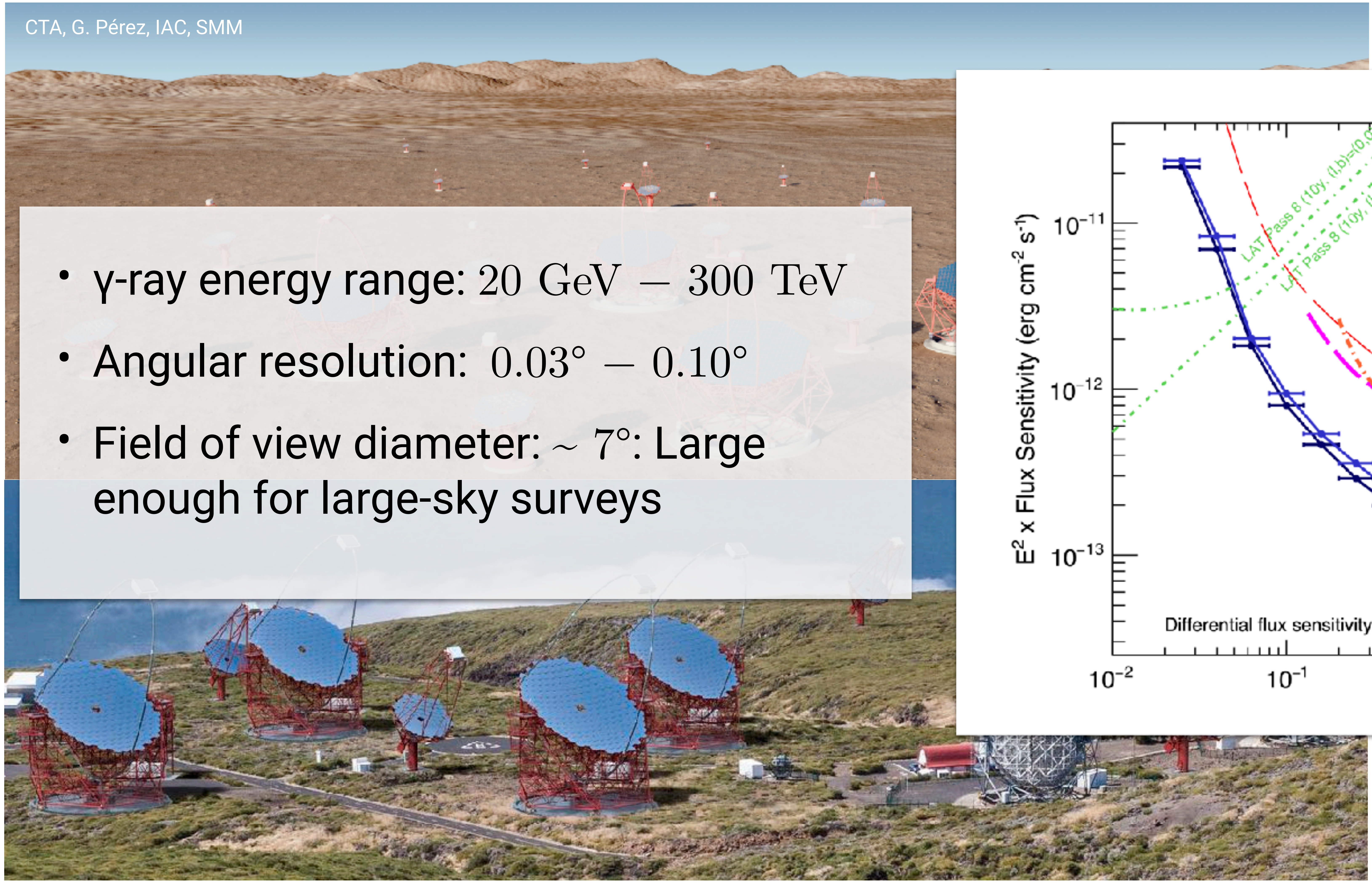
- **Mirror diameter:** $17\,\mathrm{m}$
- **Camera field of view:** $3.5°$
- **Energy range:** $50\,\mathrm{GeV} - 50\,\mathrm{TeV}$
- **Energy resolution:** $15\% - 20\%$
- **Angular resolution:** $0.05° - 0.10°$

The Cherenkov Telescope Array



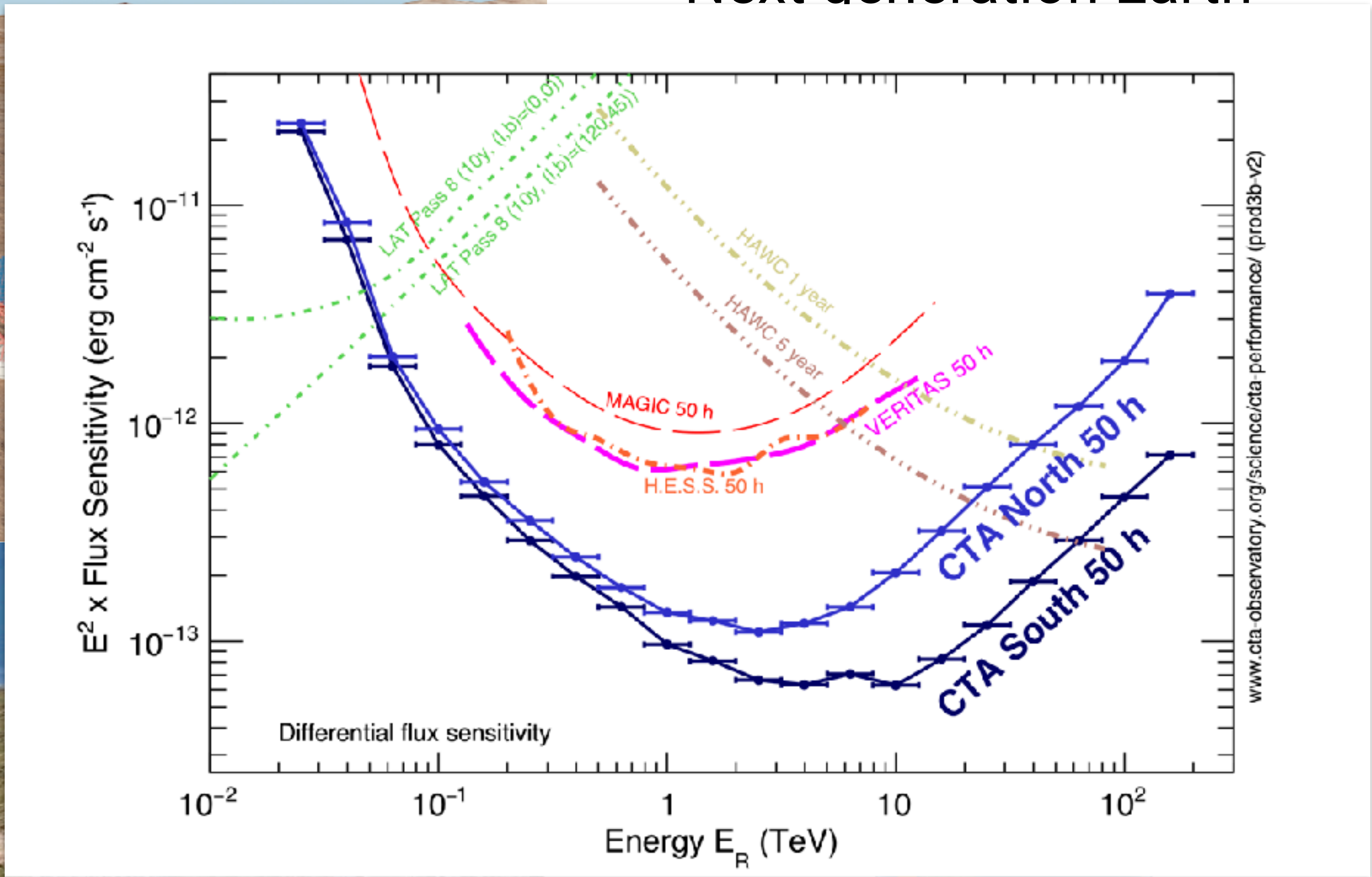
- Next generation Earth-bound γ-ray telescope
- Two arrays of Cherenkov telescopes in Chile / La Palma

The Cherenkov Telescope Array

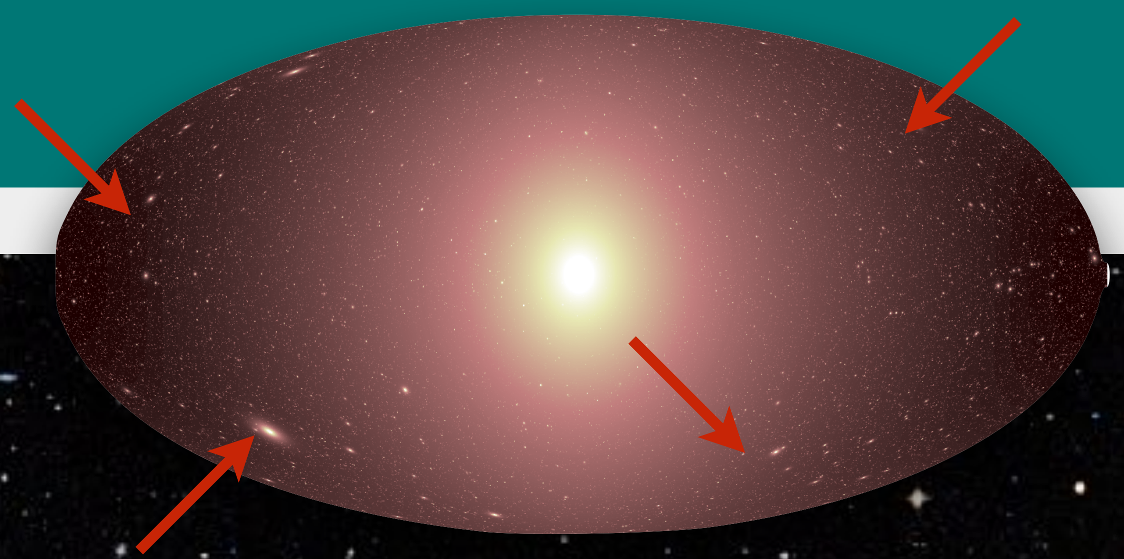


- γ-ray energy range: $20\ \mathrm{GeV} - 300\ \mathrm{TeV}$
- Angular resolution: $0.03° - 0.10°$
- Field of view diameter: $\sim 7°$: Large enough for large-sky surveys

- Next generation Earth-



WIMP searches in dwarf spheroidal galaxies (dSphG)



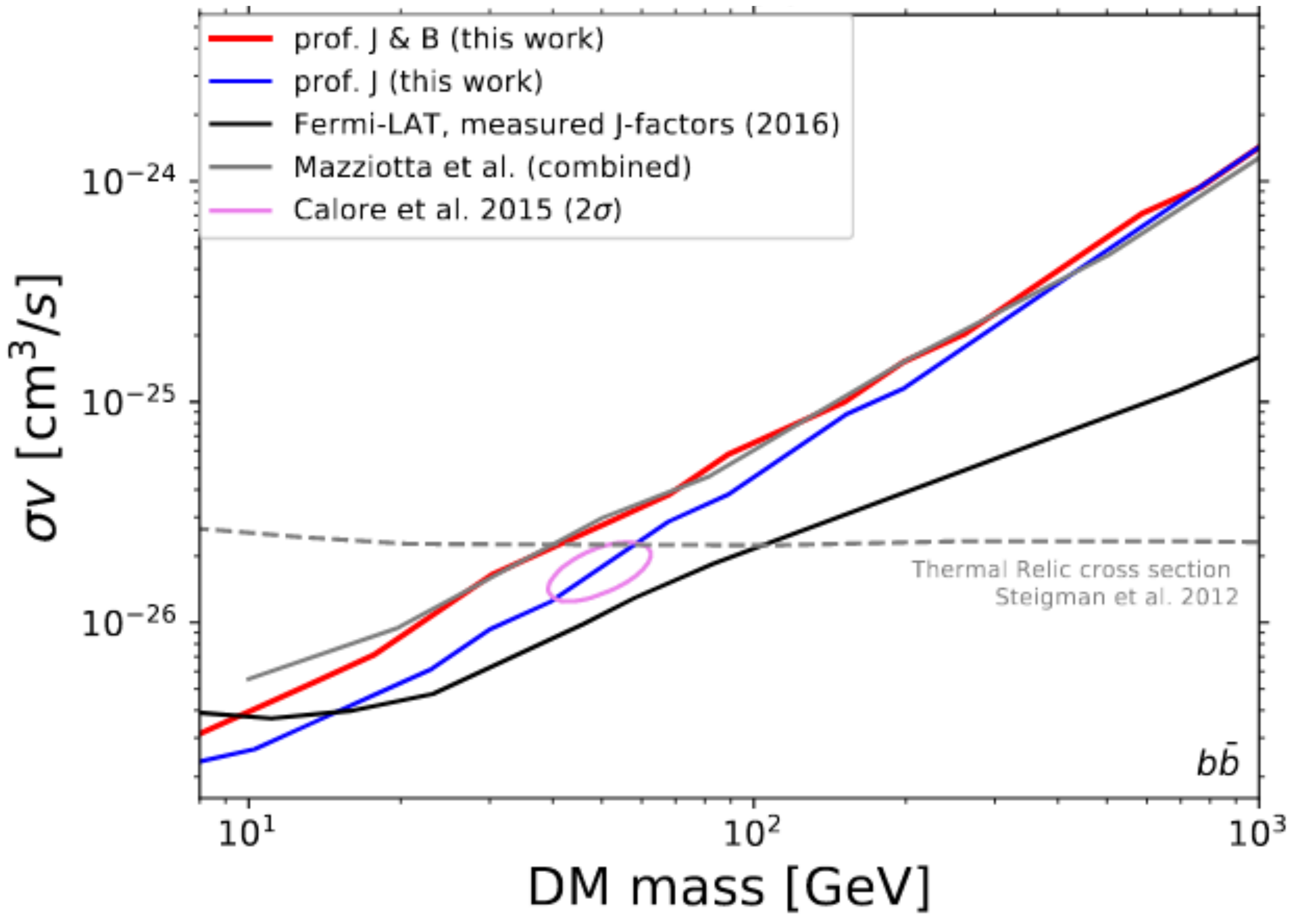
+	-
no astrophysical background: clean targets	lower fluxes than from GC region
Relatively robust *J*-factor constraints	Systematic *J*-factor uncertainties in ultrafaint dSphG (stellar interlopers + bias)

Picture credit: ESO/DSS2

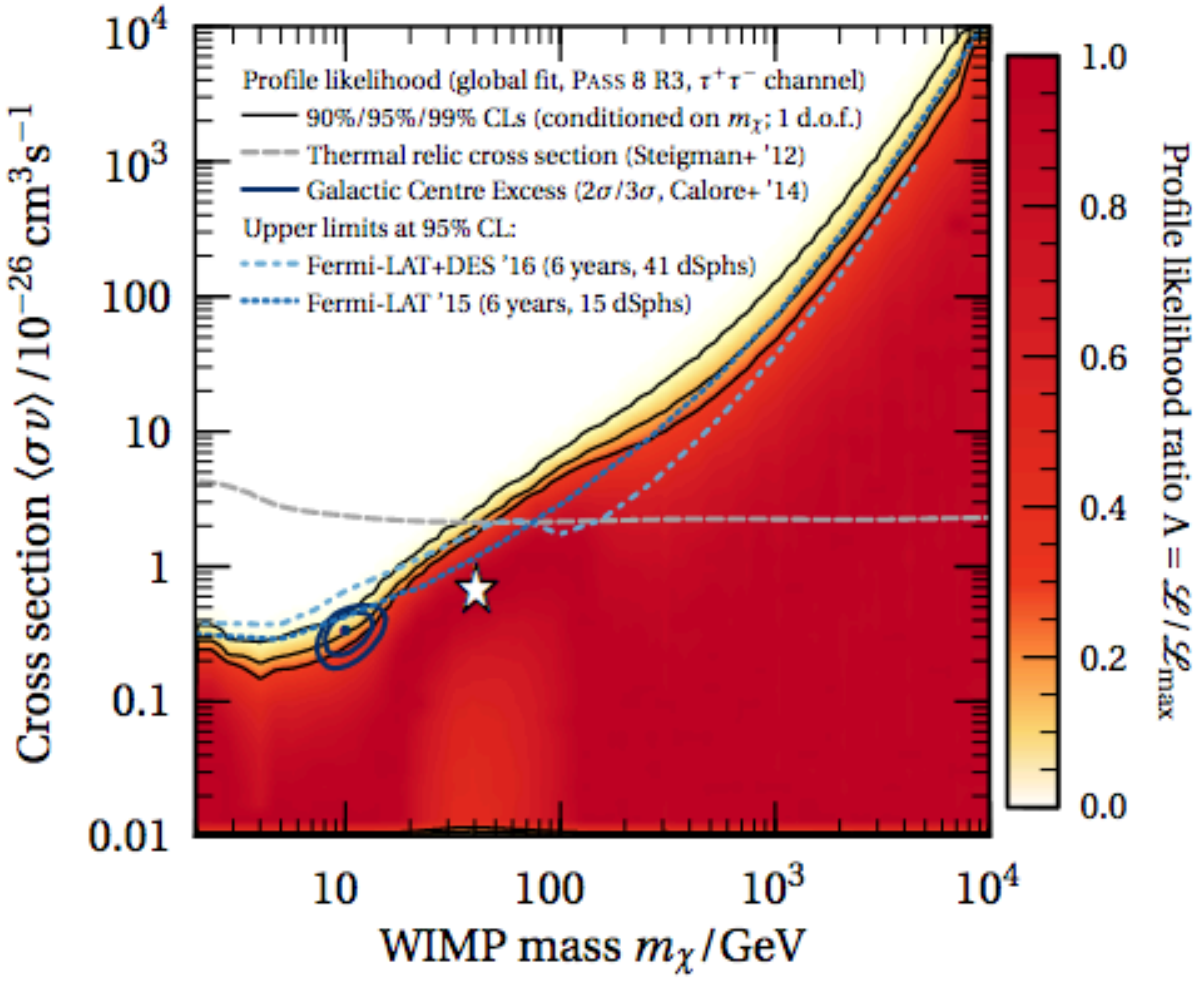
dSph Galaxies: Limits by *Fermi*-LAT

- No excess seen in combined analysis of γ-ray data from known dSph positions

Calore et al., 1803.05508, 25 dSph, 7 years



Hoof et al., 1812.06986, 27 dSph, 11 years

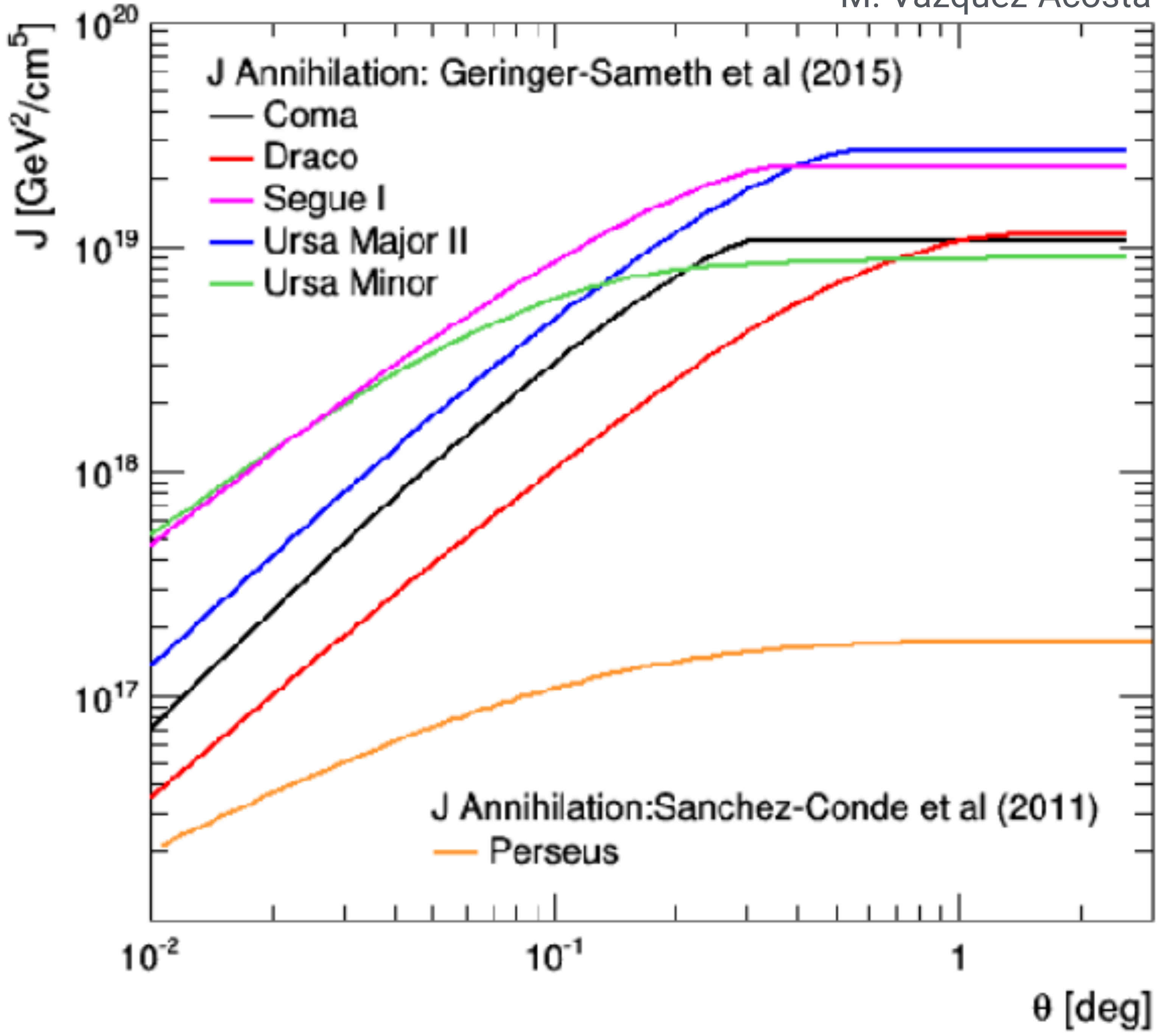


- Similar results in 1611.03184, 1704.03910, 2101.11027, …

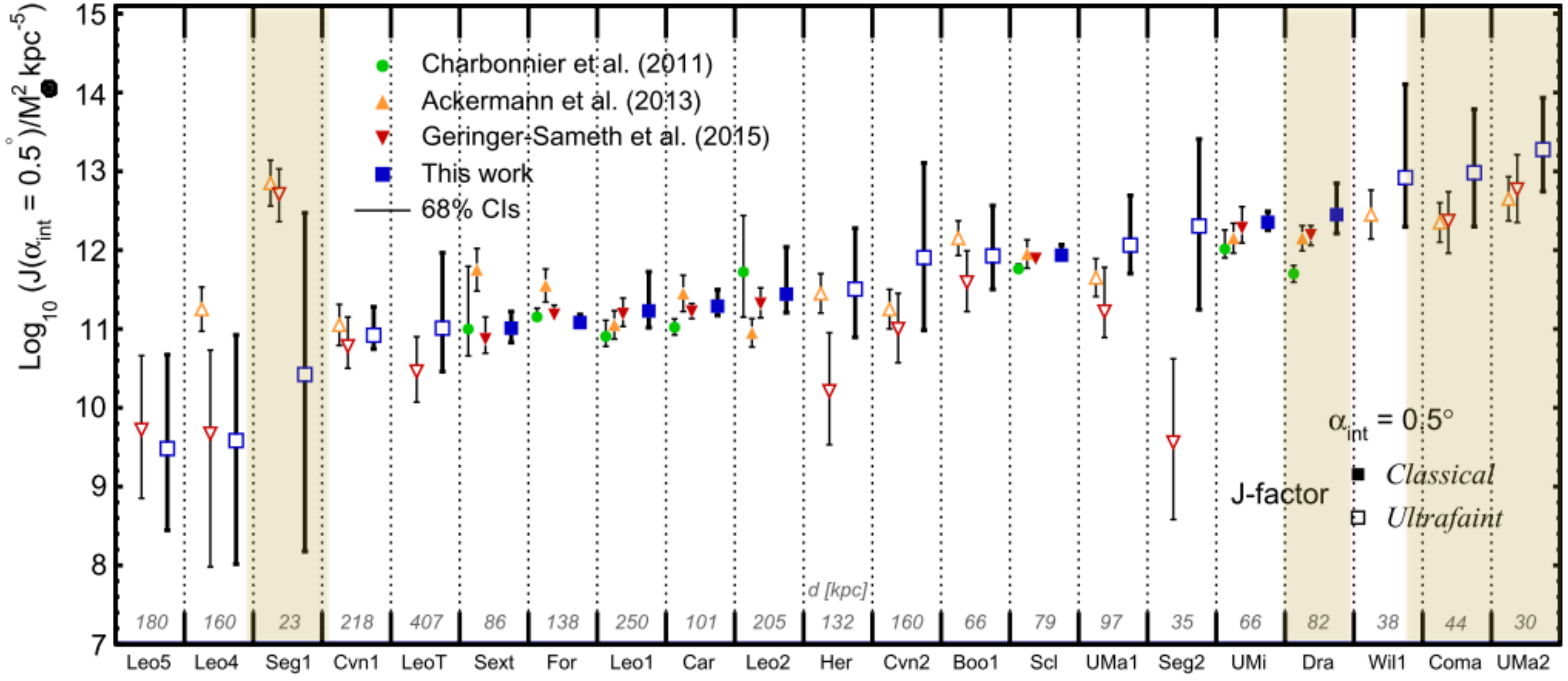
dSph Galaxies: Limits by MAGIC

- **MAGIC does pointed observations: Choose the best target(s)**

M. Vazquez-Acosta



Bonnivard et al., 1504.02048

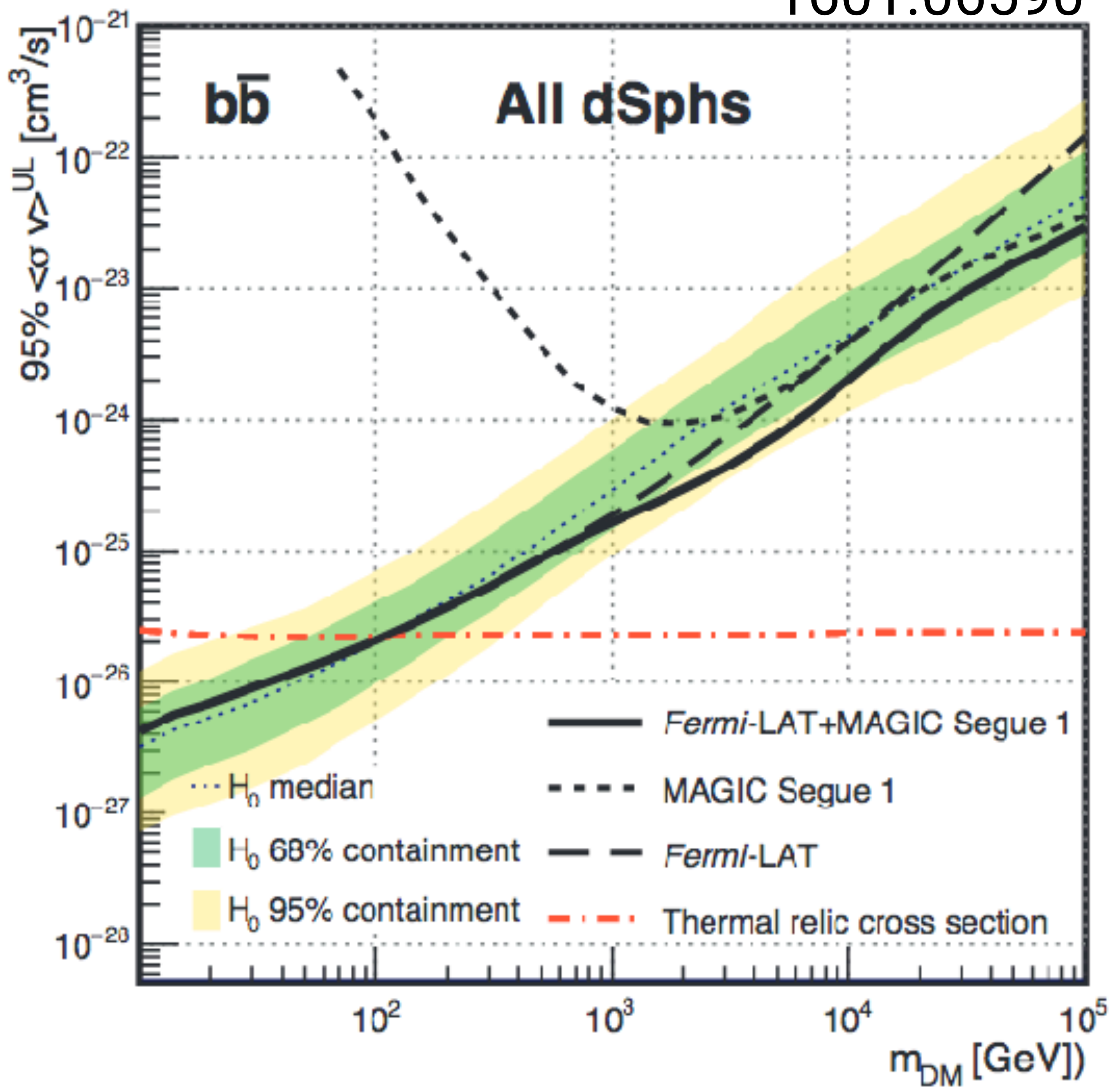


Due to J-factor uncertainties, diversify targets to increase chance of discovery and to obtain more robust limits

dSph Galaxies: MAGIC single results & combined with *Fermi*-LAT

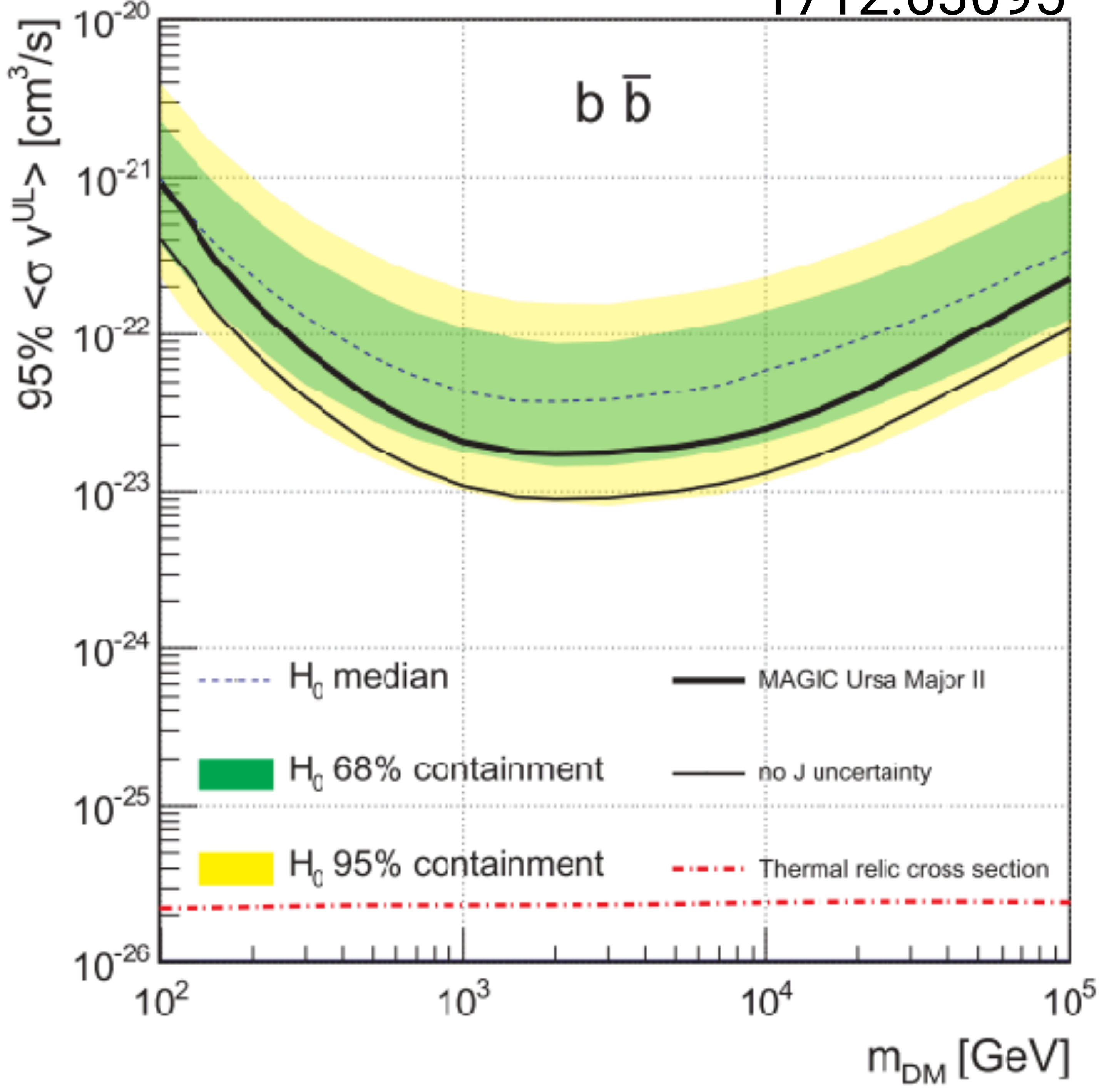
- **No signal seen in Segue I or Ursa Major II:**

1601.06590



Segue I, 158h MAGIC +
Fermi 6 years 15 dwarfs combined

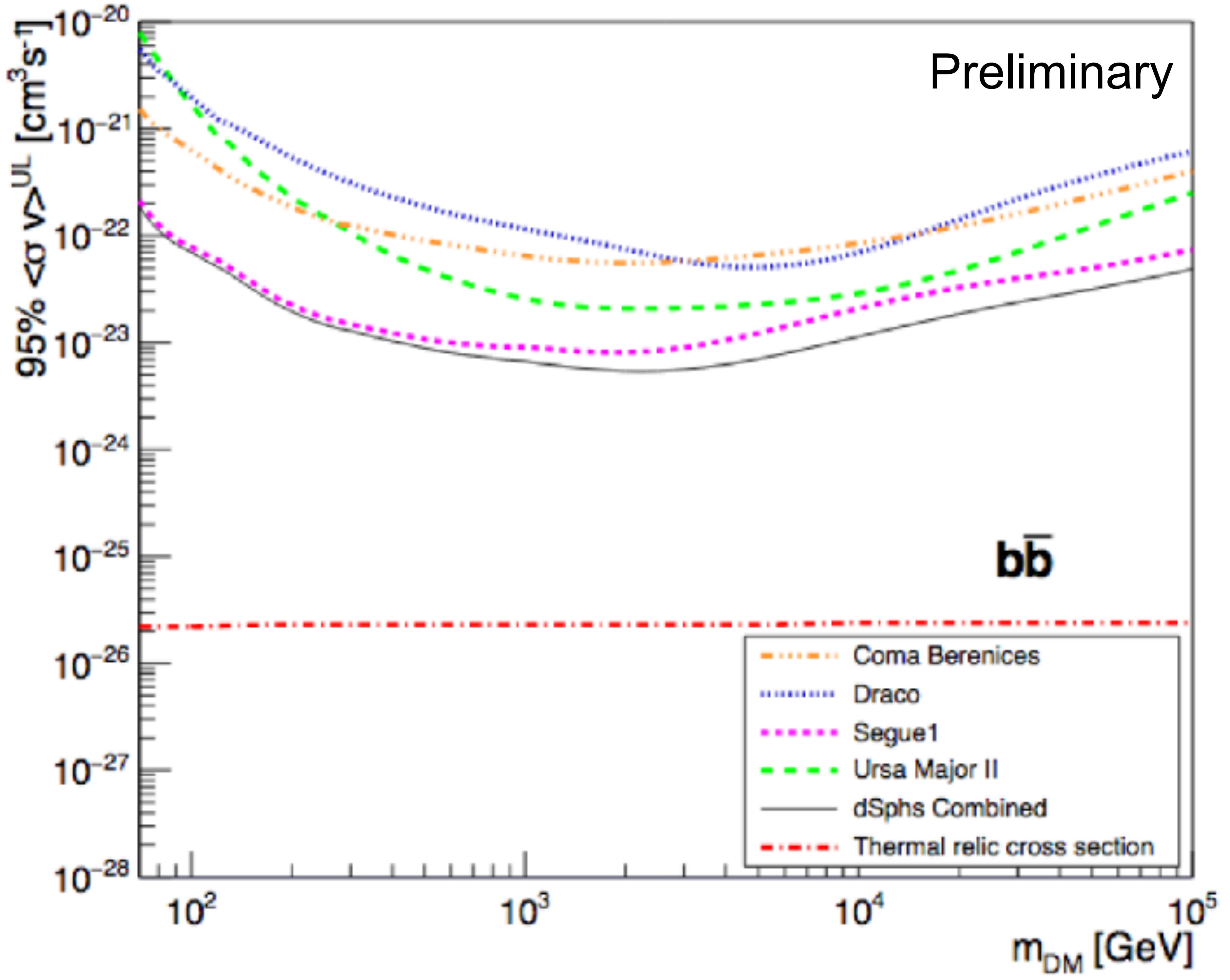
1712.03095



Ursa Major II, 95h MAGIC

dSph Galaxies: Combined limits by MAGIC

- No signal neither in Draco, Coma, Tri II, nor after combination:



Target	Obs. time	*J*-factor log[GeV²cm⁻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: 355h

Tri II	62h	19.35±0.37

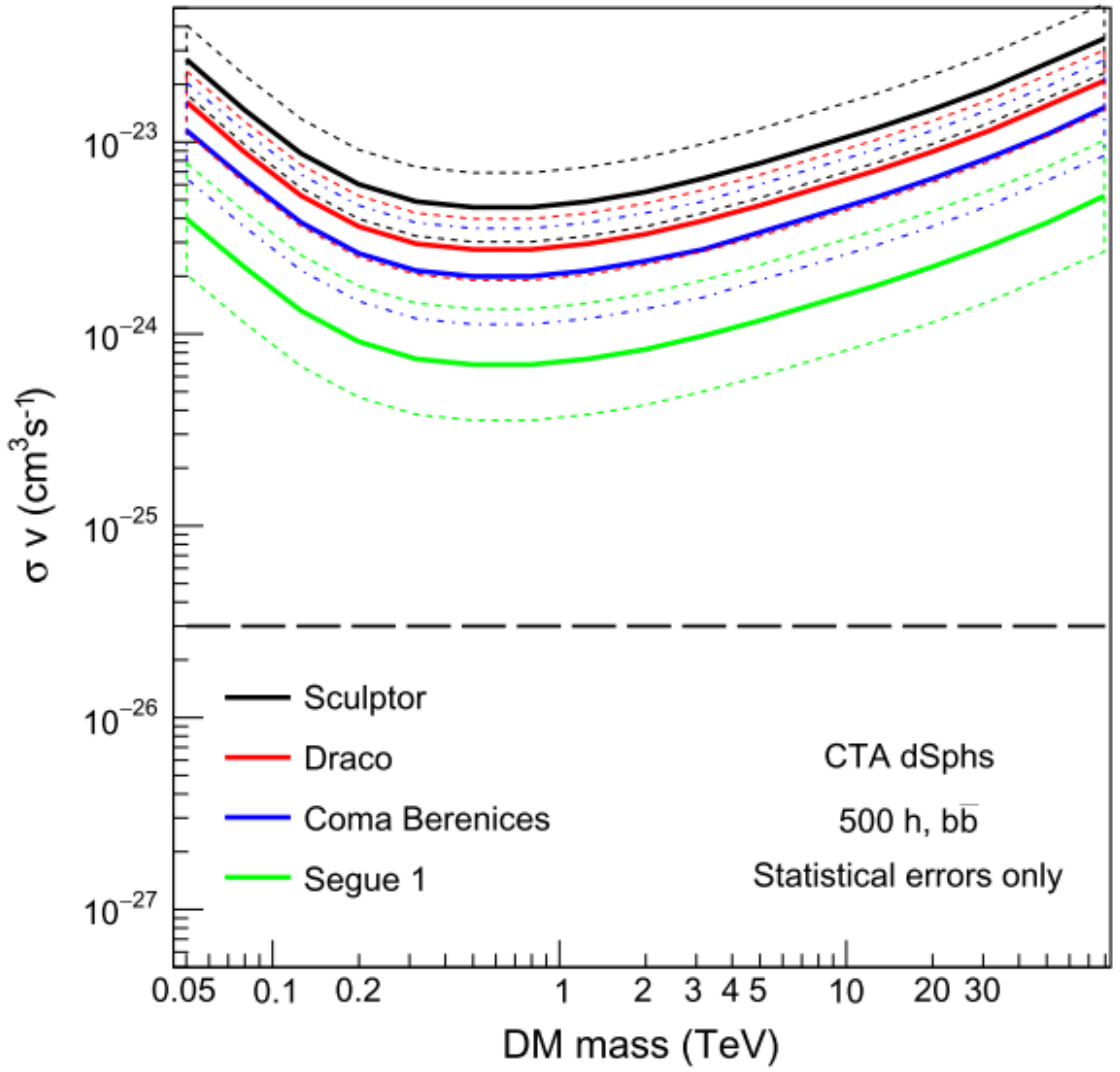
Separately: Acciari et. al., 2020.100529

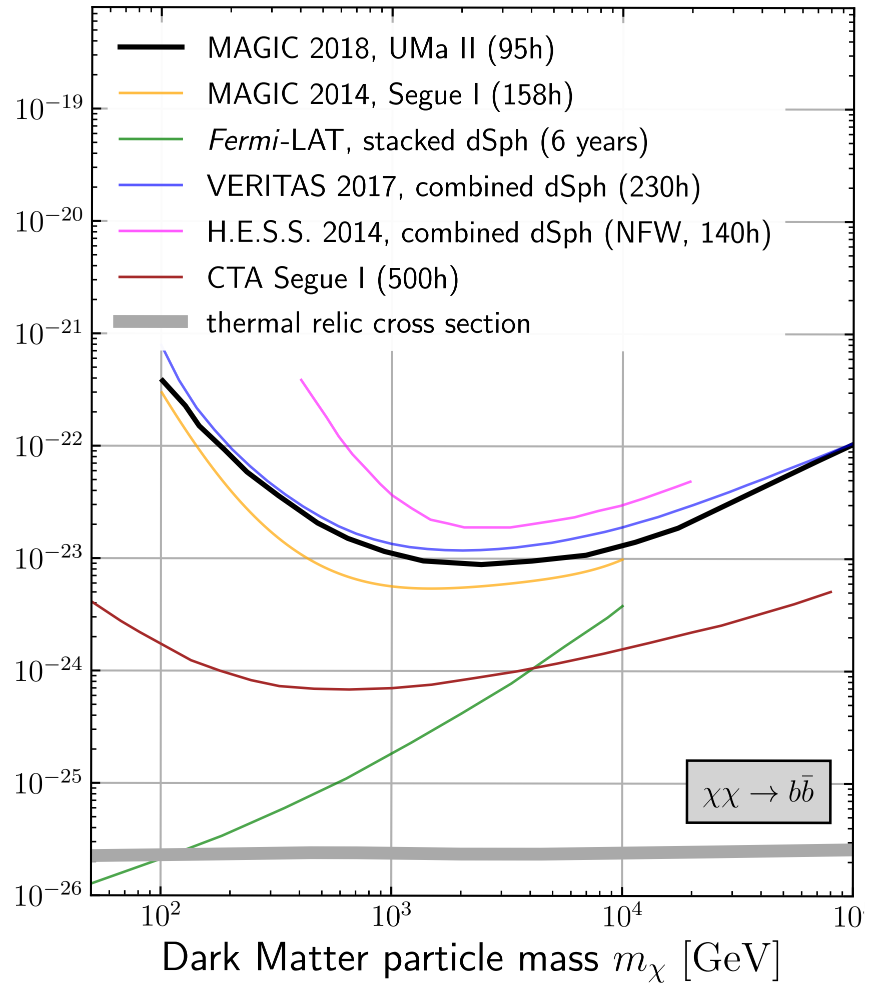
- Combination with Fermi-LAT multi-dwarfs + other Cherenkov telescopes + HAWC also ongoing

dSph Galaxies: What to reach with CTA

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

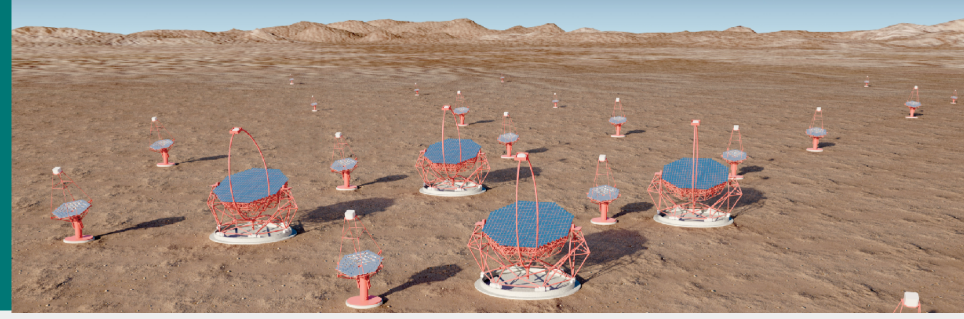
1709.07997





- Dedicated & updated study in preparation

dSph Galaxies: What to reach with CTA



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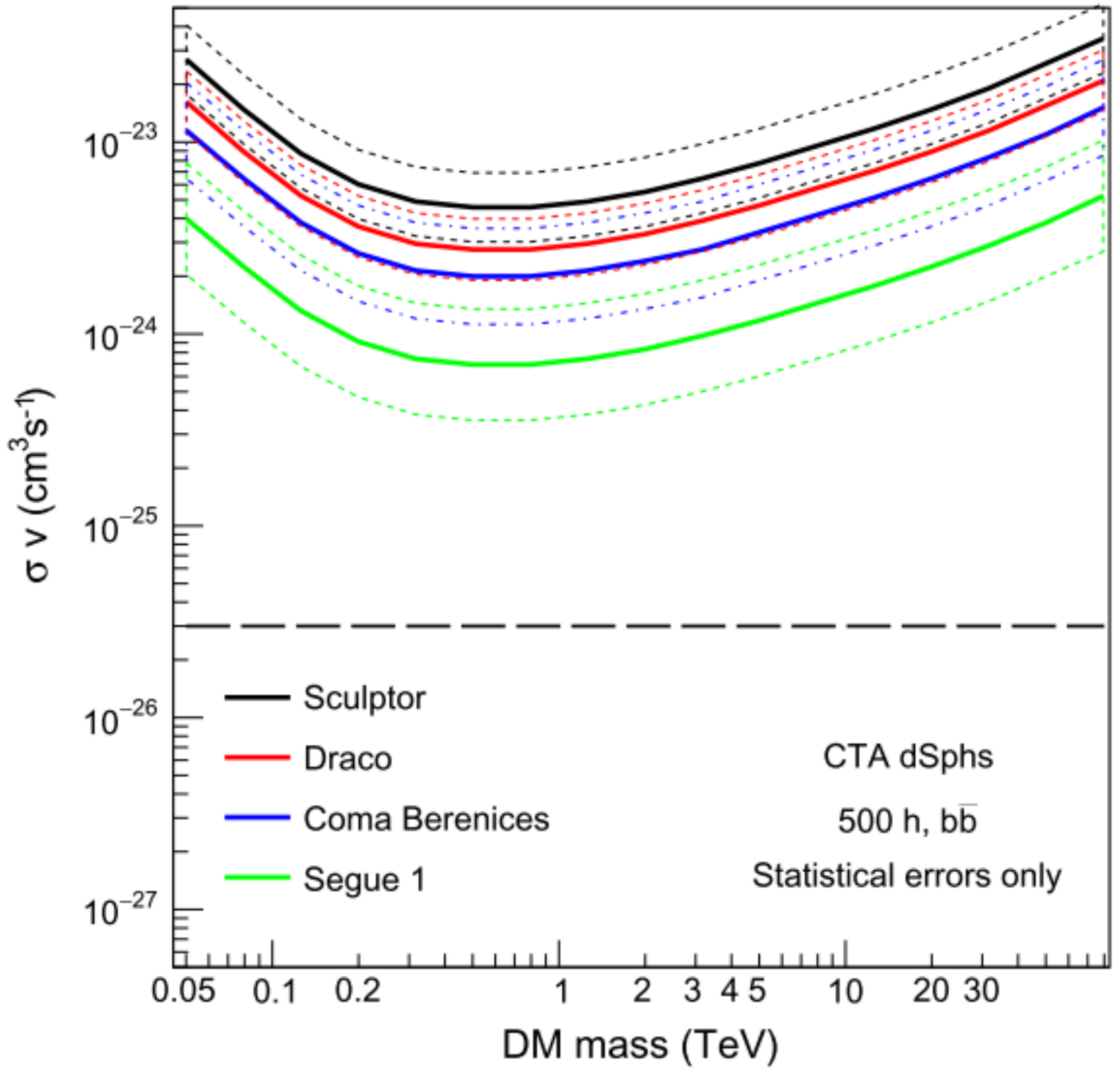
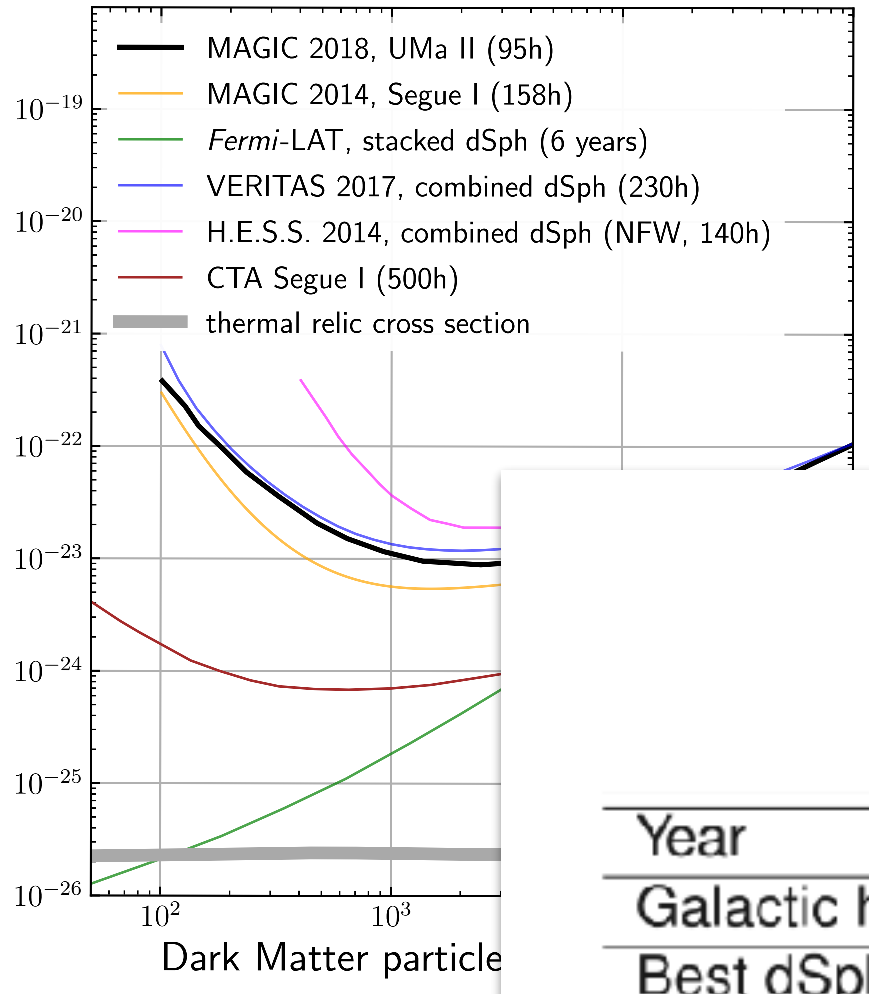
1709.07997





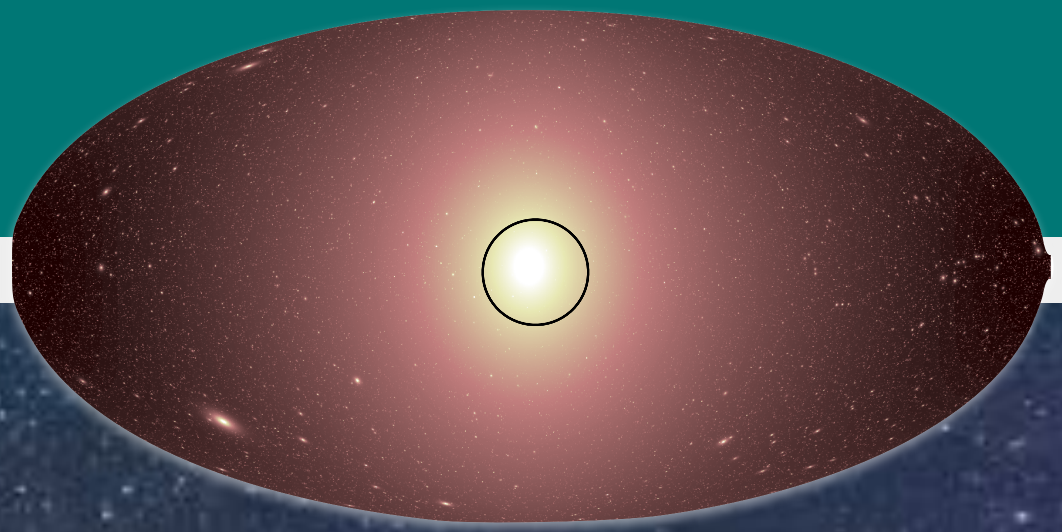
Use dSph observations to confirm DM origin of a signal detected at Galactic Center:

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 σv										
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 σv										
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)

- Dedicated & updated study in preparation

WIMP searches at the Galactic center



The classical prime target

- Silk and Bloemen (1987), Horns (2004), astro-ph/0408192, …

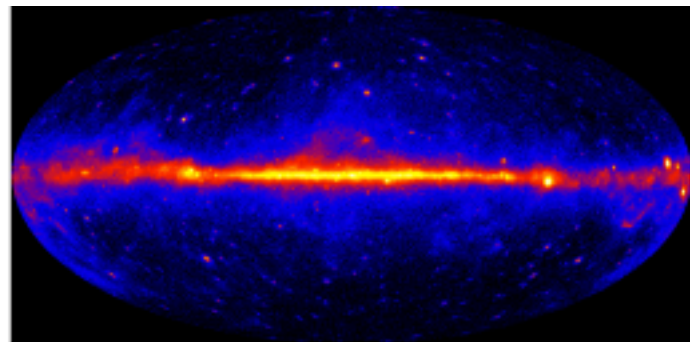
+	-
By far strongest signal for all DM models	Limits: Uncertainty on cusp/ core
No problem for DM upper limits in neutrinos	Astrophysical γ-ray backgrounds
Large solid angle with high intensity	Cosmic-ray background for Earth-bound instruments

Galactic Center rising only 32° above horizon for MAGIC

Picture credit: D. López

Fermi-LAT Galactic Center excess

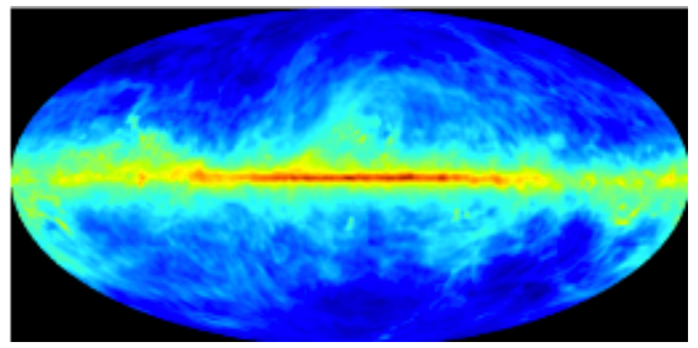
All γ-ray emission



(Illustration from M. Di Mauro)

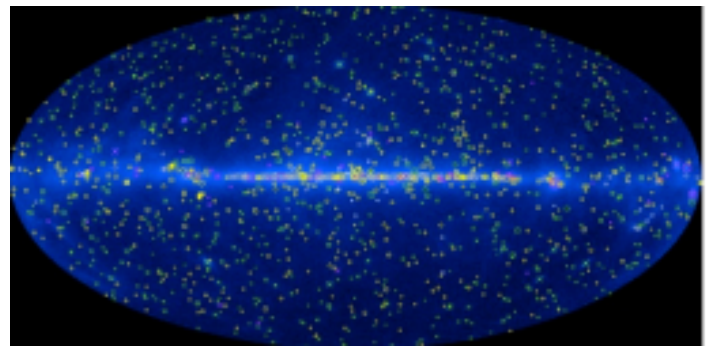
=

Interstellar emission



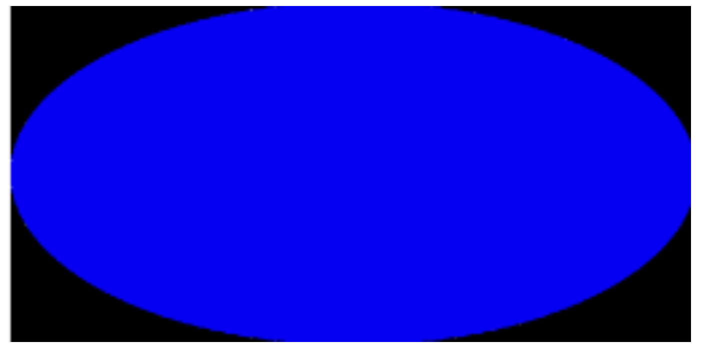
+

Point sources



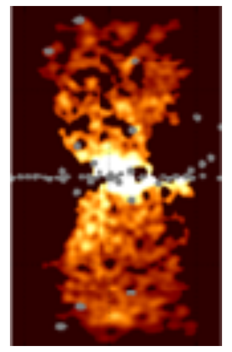
+

Diffuse



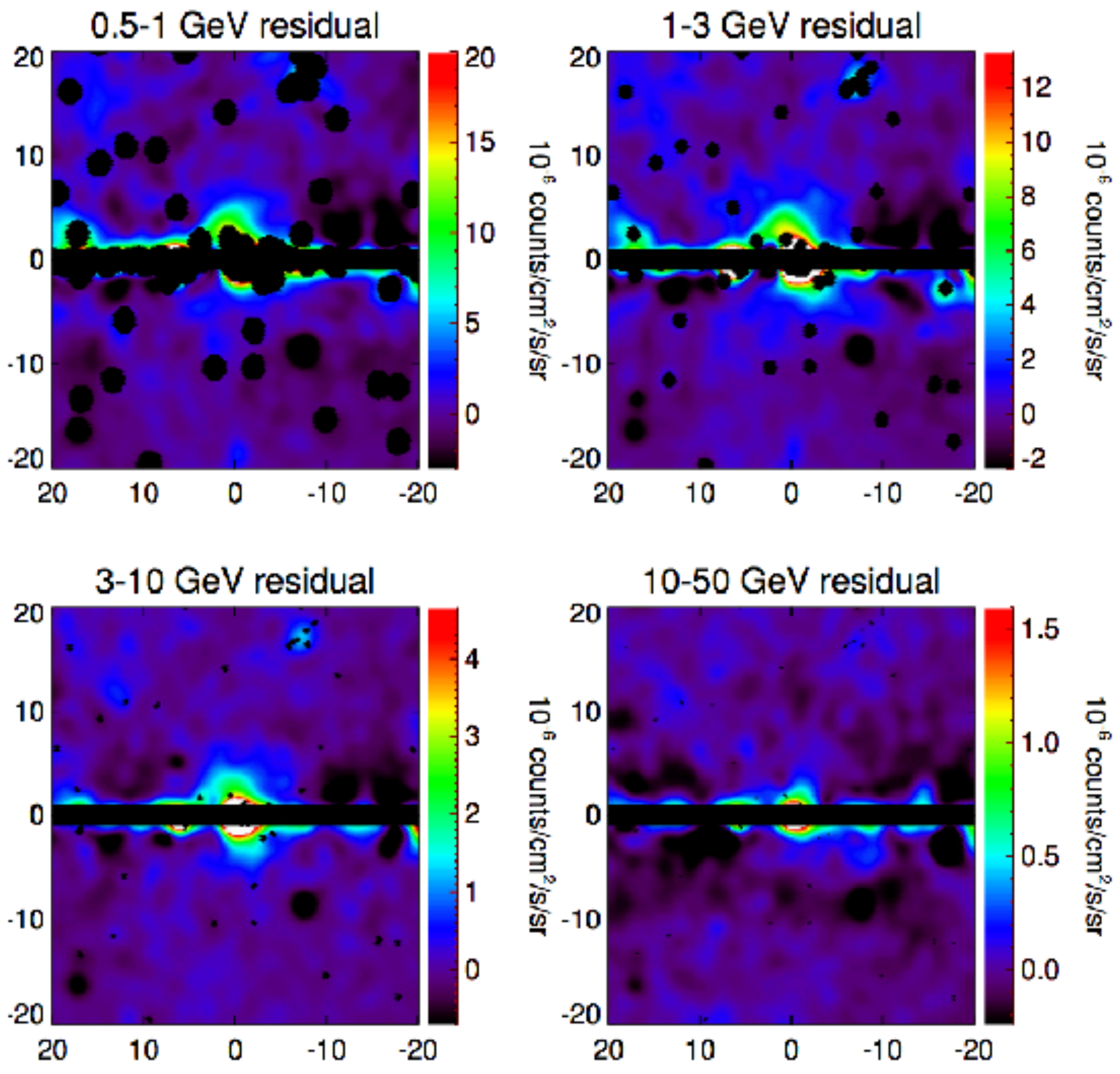
+

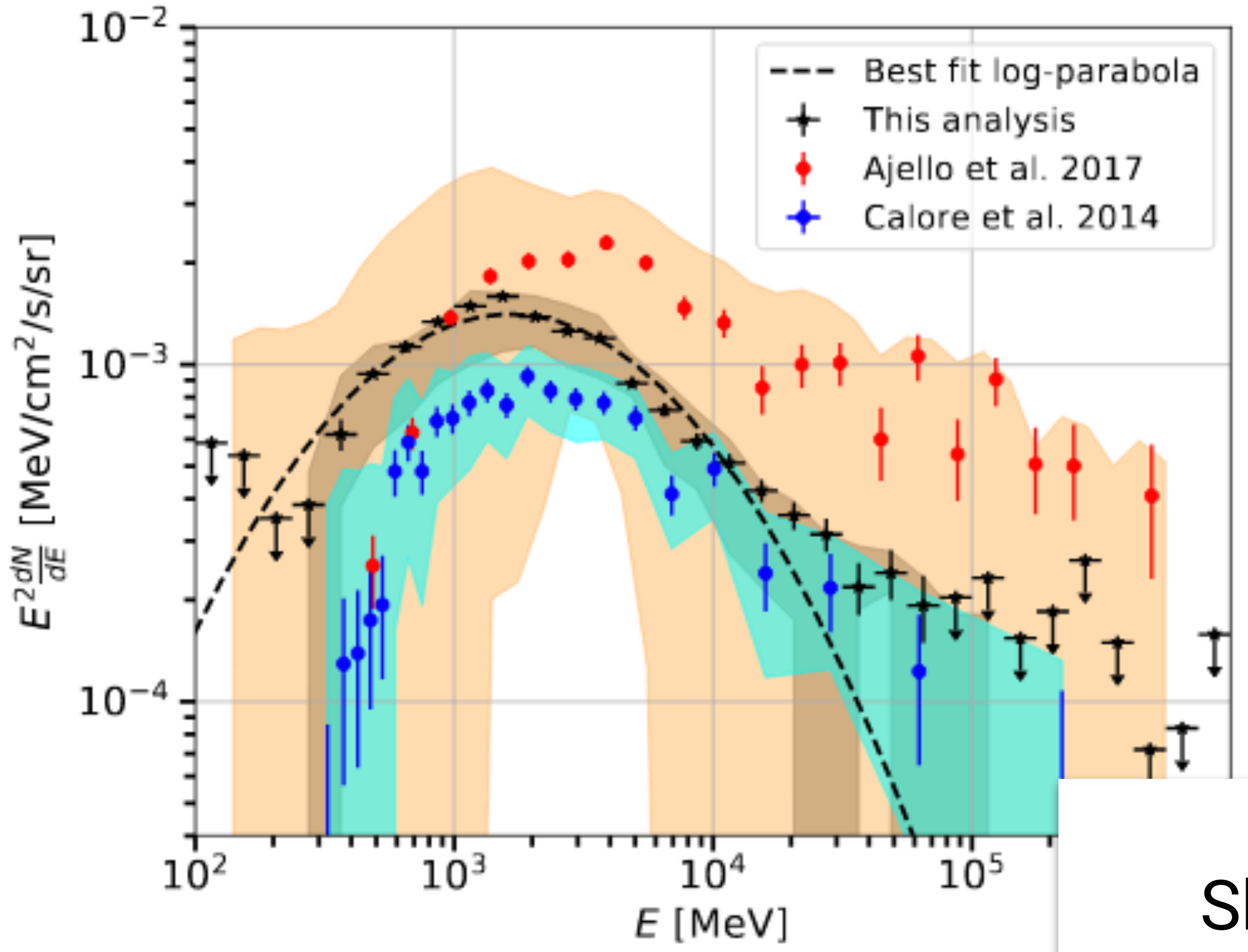
Fermi bubbles



+ X (Dark Matter, MSPs,…)

Daylan et al., 1402.6703





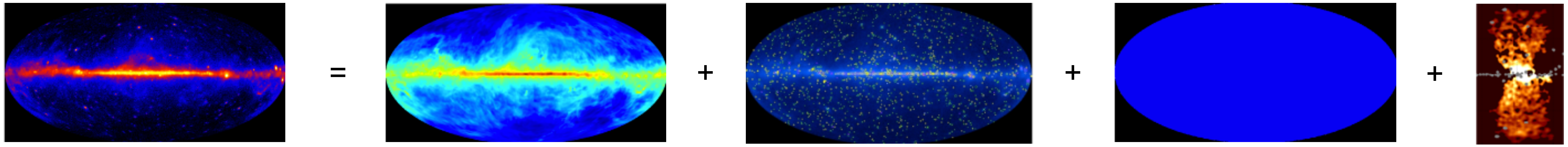
Spectrum of GC excess, Di Mauro, 2101.04694

Shed light on excess with CTA, Macias et al., 2102.05648

- It is considered real
- Milli-second pulsar population in Galactic bulge? (1506.05104, 1711.04778, 1901.03822, 2003.10416,…)
- Recent doubts on pulsar origin: 1904.08430, 1908.10874

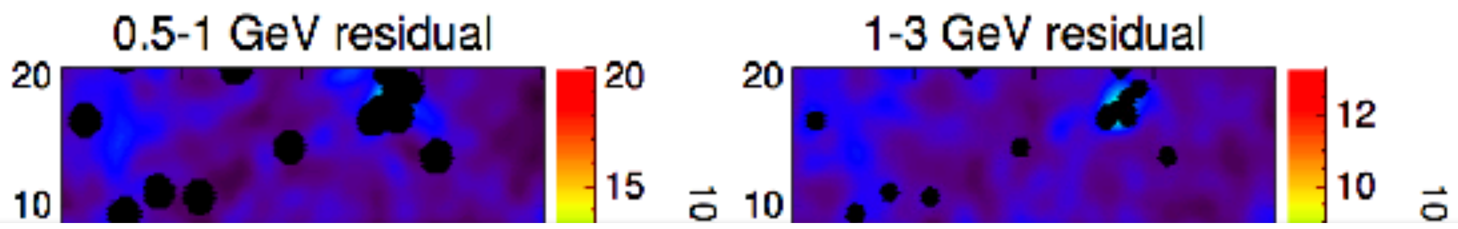
Fermi-LAT Galactic Center excess

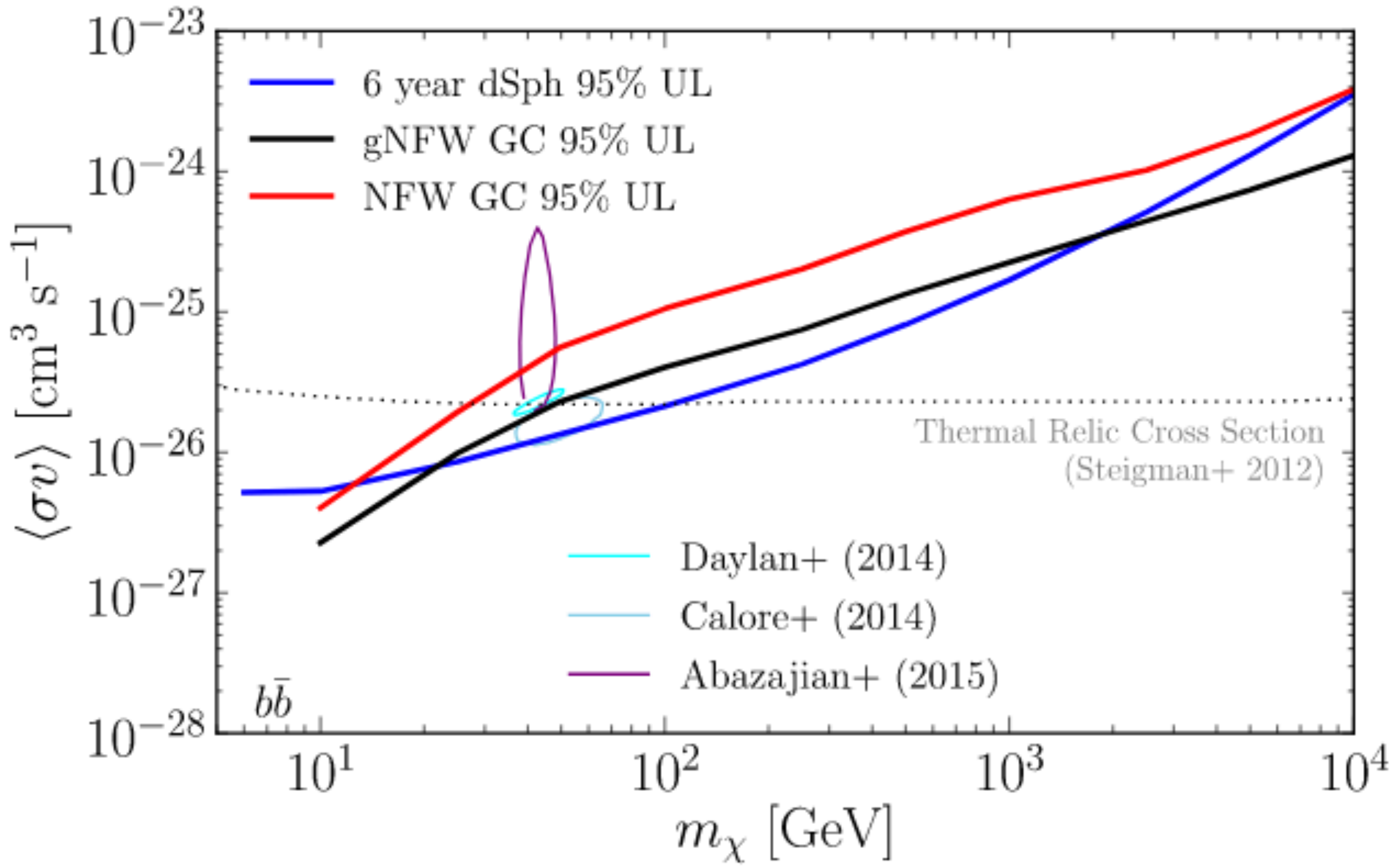
All γ-ray emission = Interstellar emission + Point sources + Diffuse + Fermi bubbles + X (Dark Matter, MSPs,…)



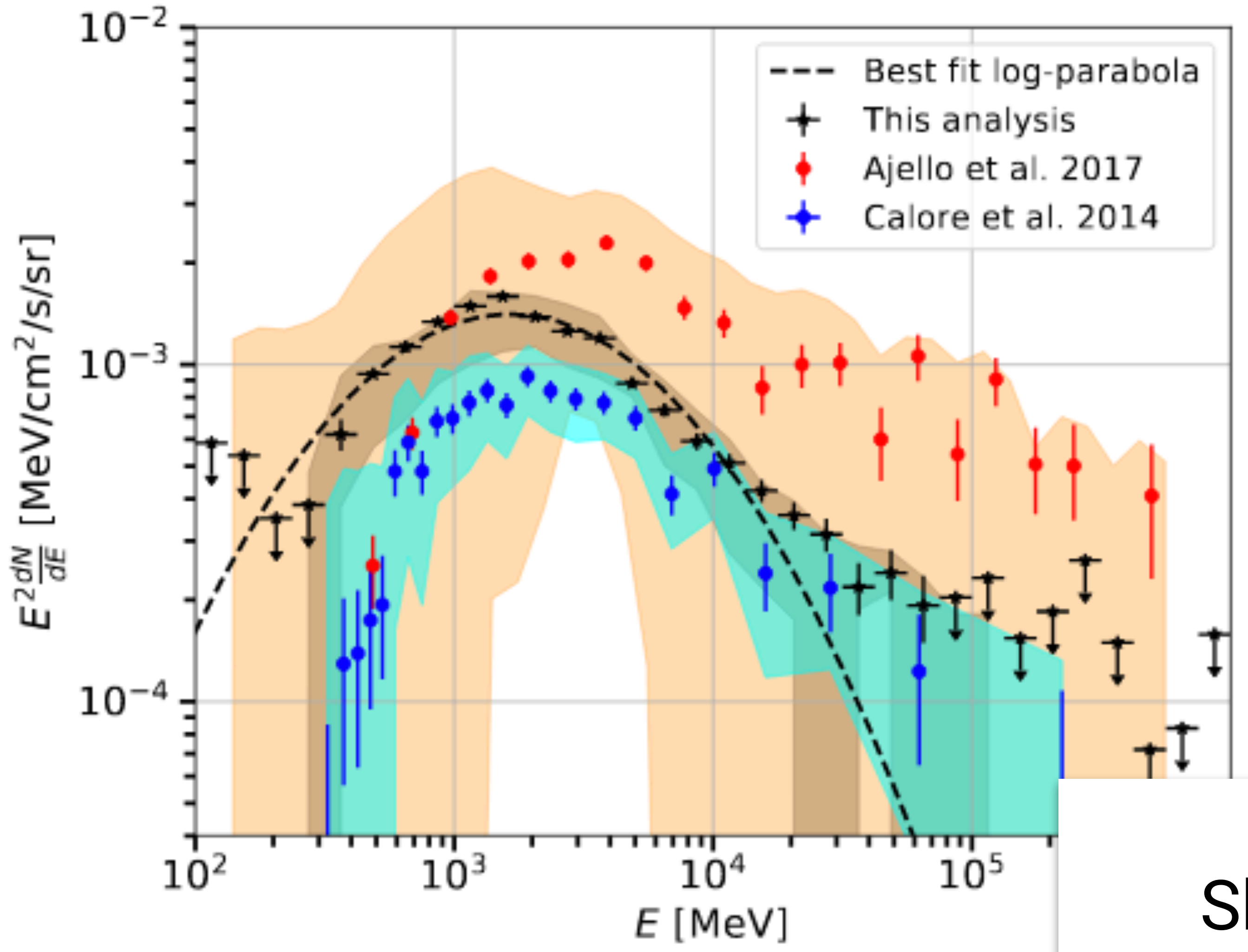
(Illustration from M. Di Mauro)

Daylan et al., 1402.6703





Fermi-LAT, 1704.03910



Spectrum of GC excess, Di Mauro, 2101.04694

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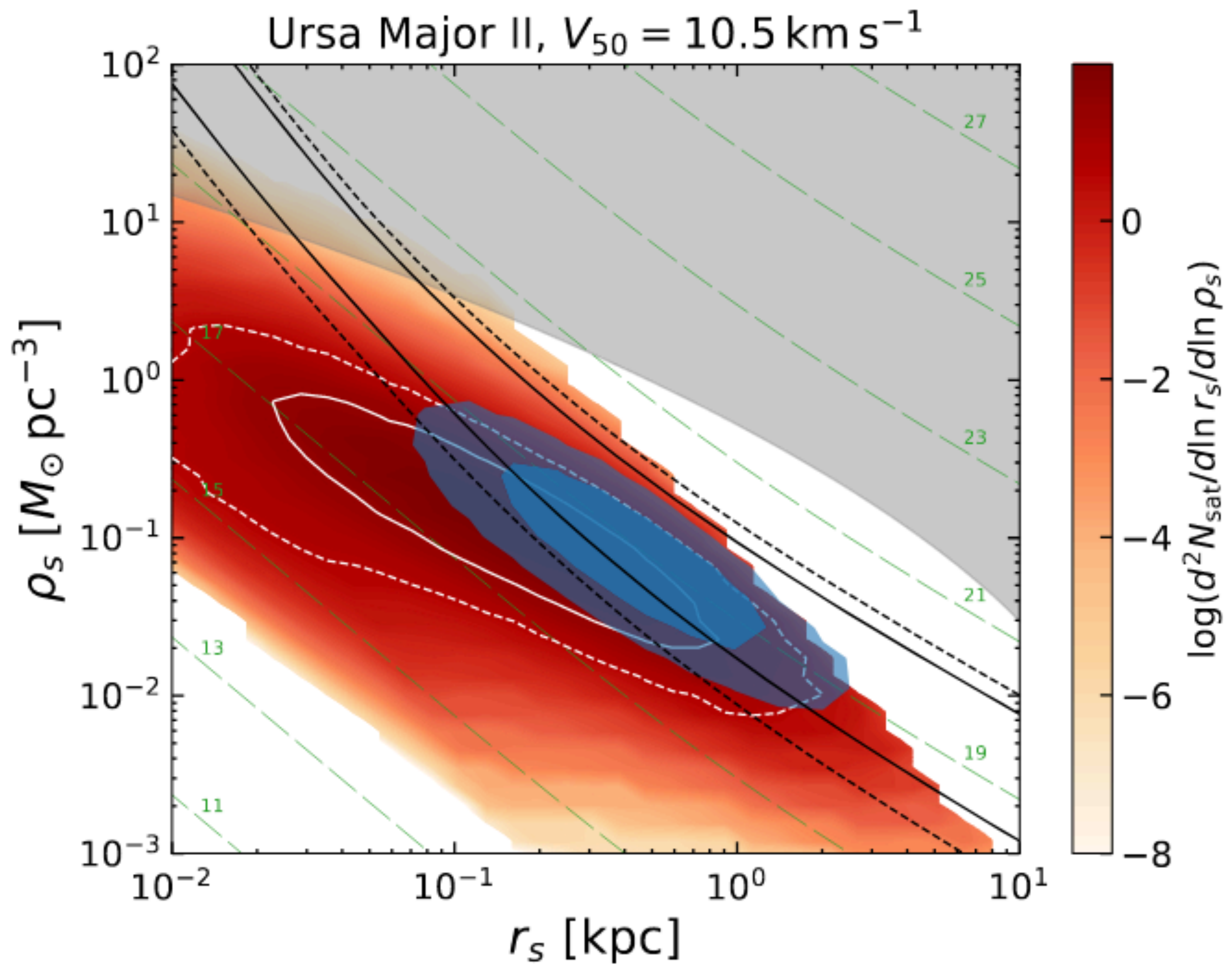
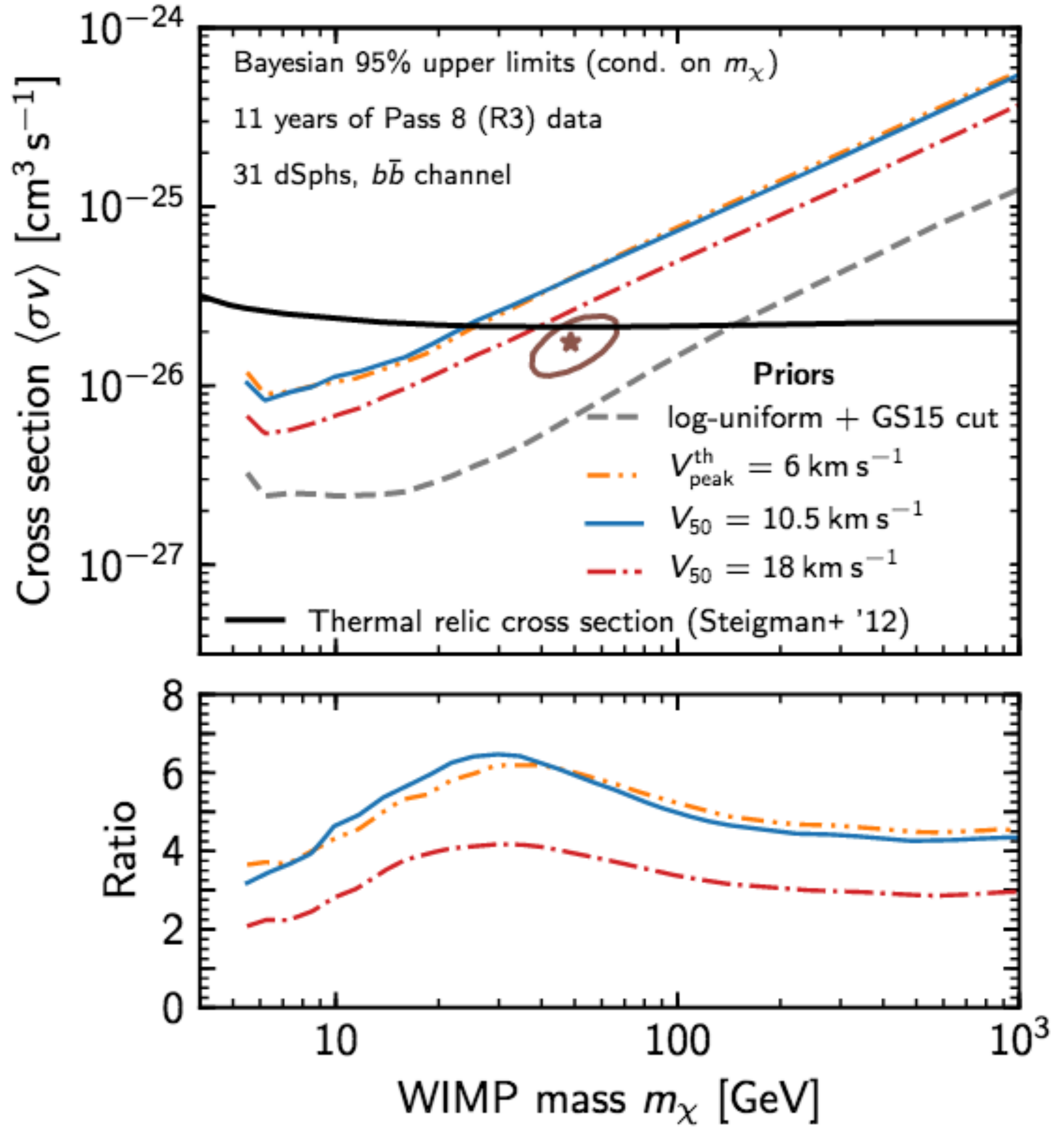
- Recent doubts on pulsar origin: 1904.08430, 1908.10874

Lower expectations for the ultra-faint dSphs?

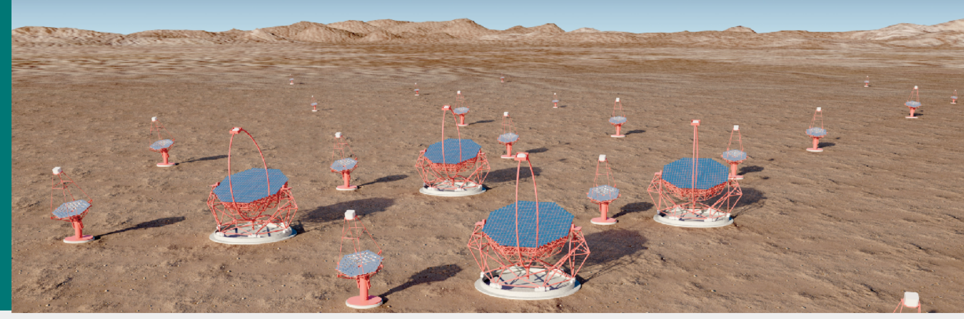
- **More informative priors from N-body simulations weaken ultrafaint dSphs' *J*-factors by factor ~5**

Ando et al, 2002.11956

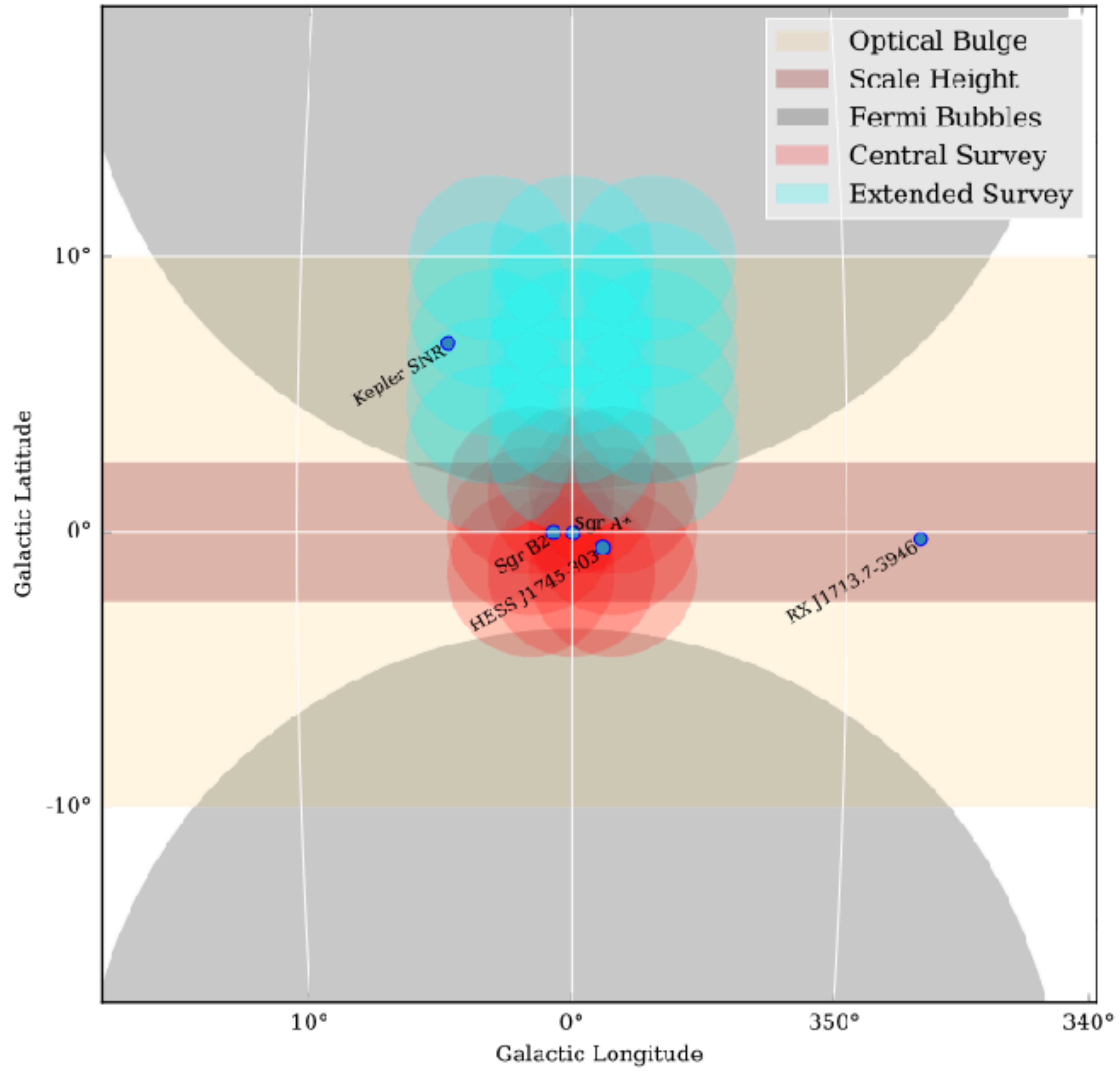




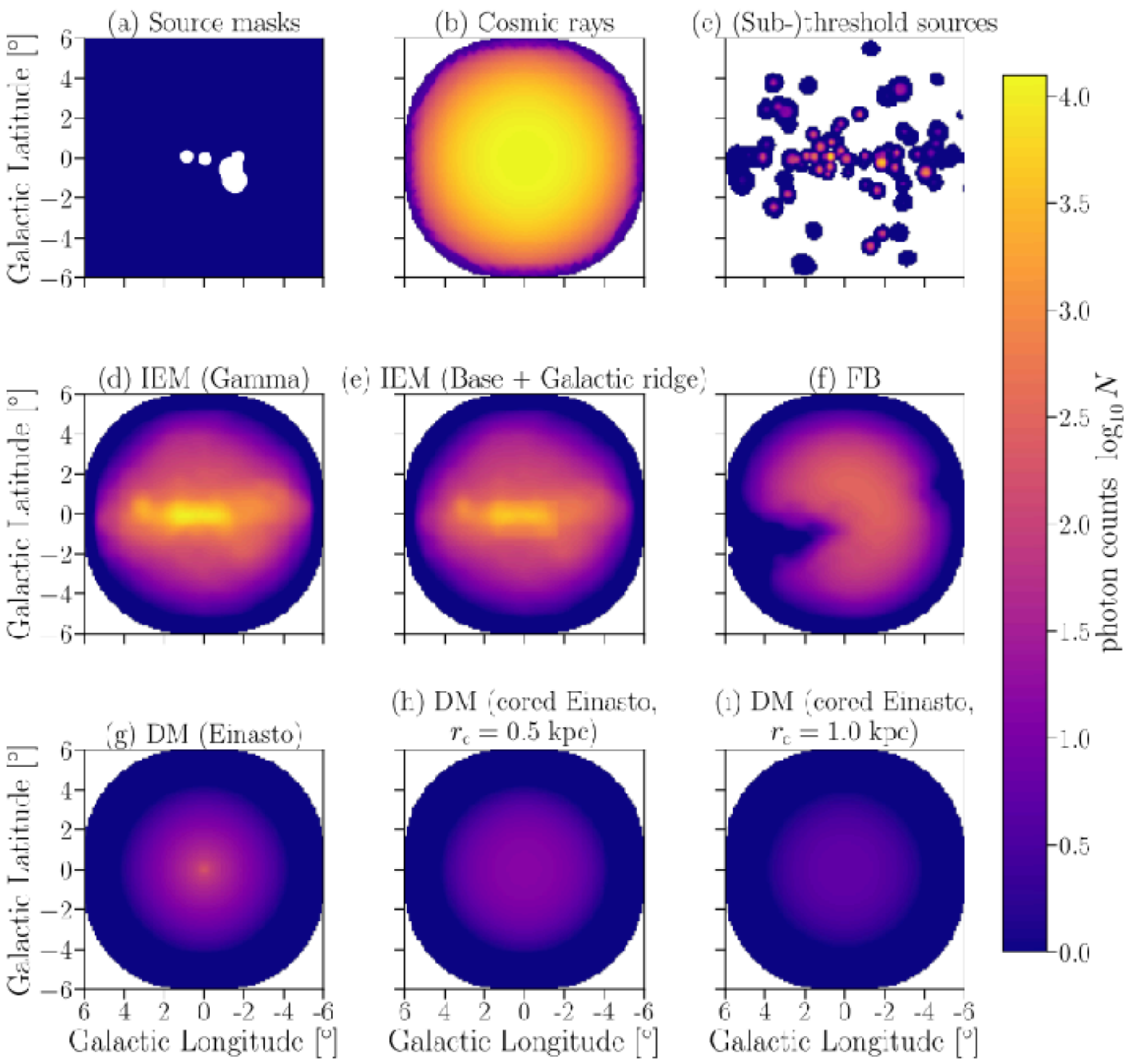
Galactic center: Sensitivity with CTA



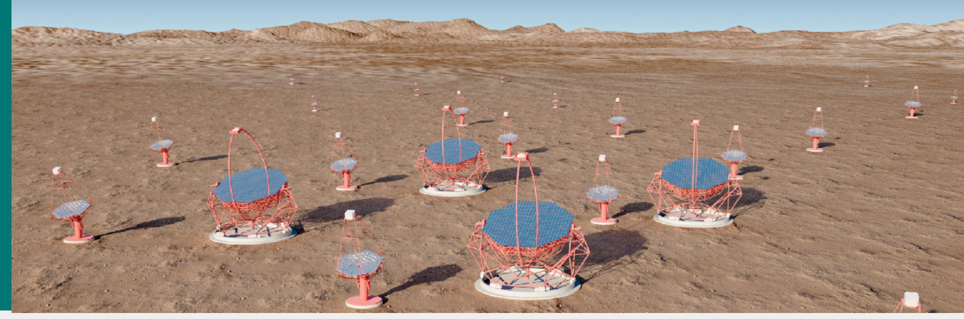
- Galactic Center survey: Key Science project with CTA: 525h + 300h in 1st decade
- Prime Dark Matter target with CTA



CTA, 1709.07997



CTA, 2007.16129



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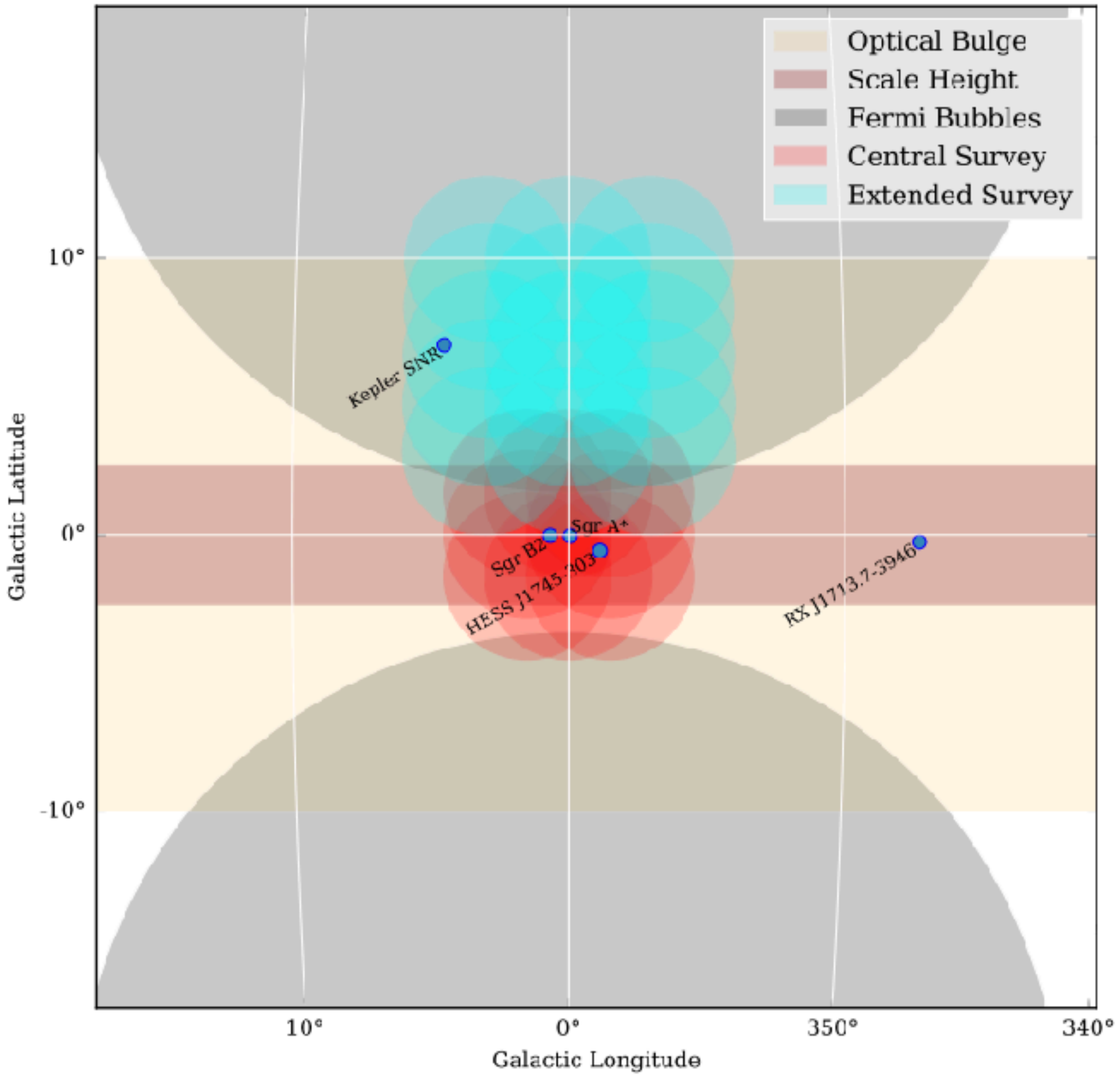
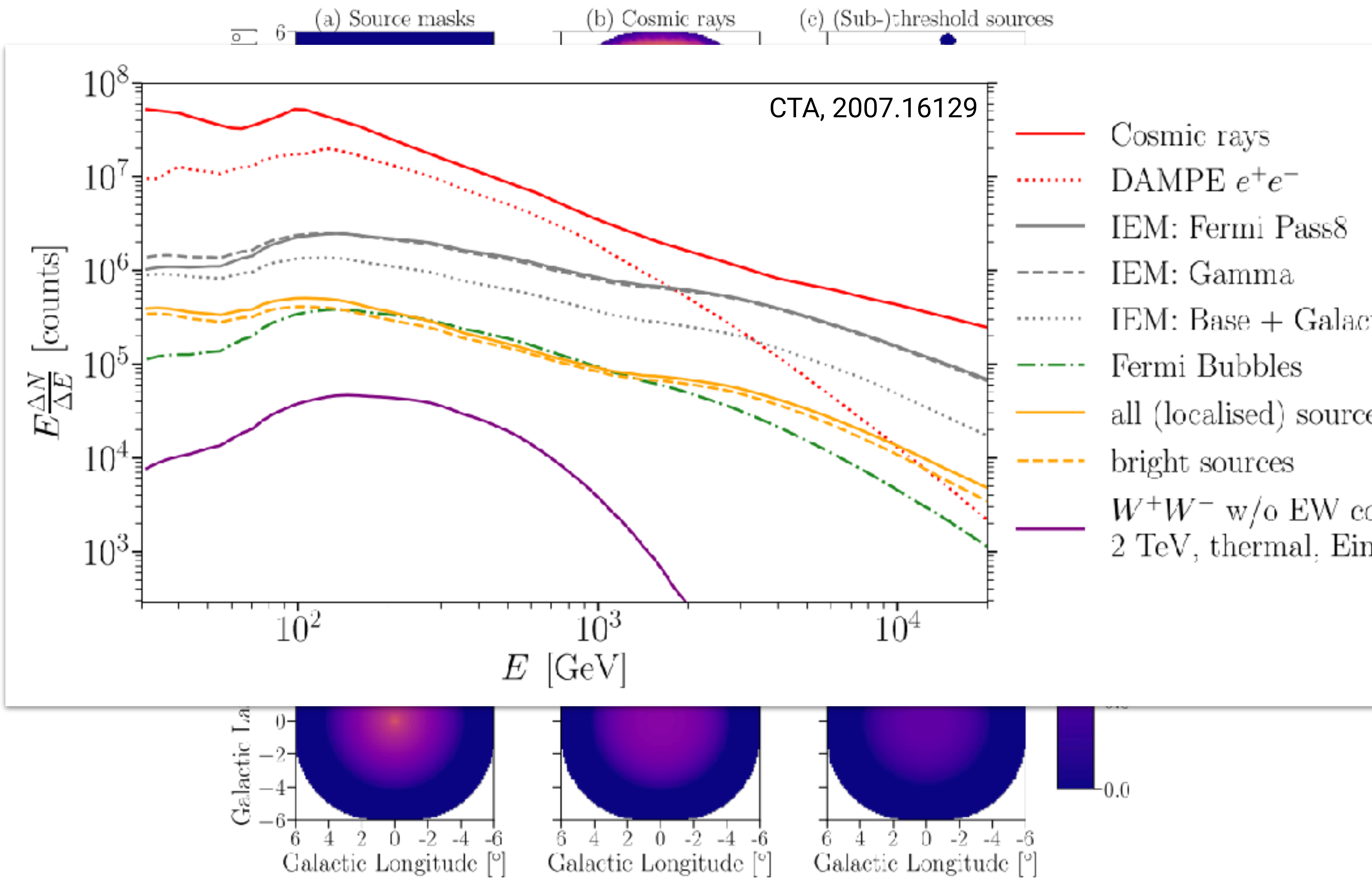
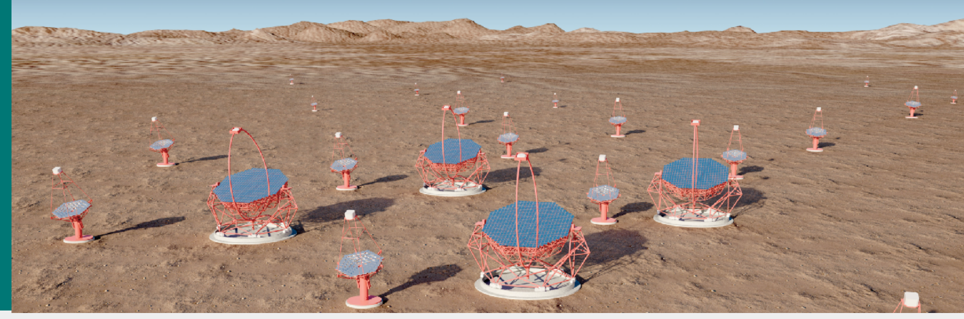


CTA, 1709.07997



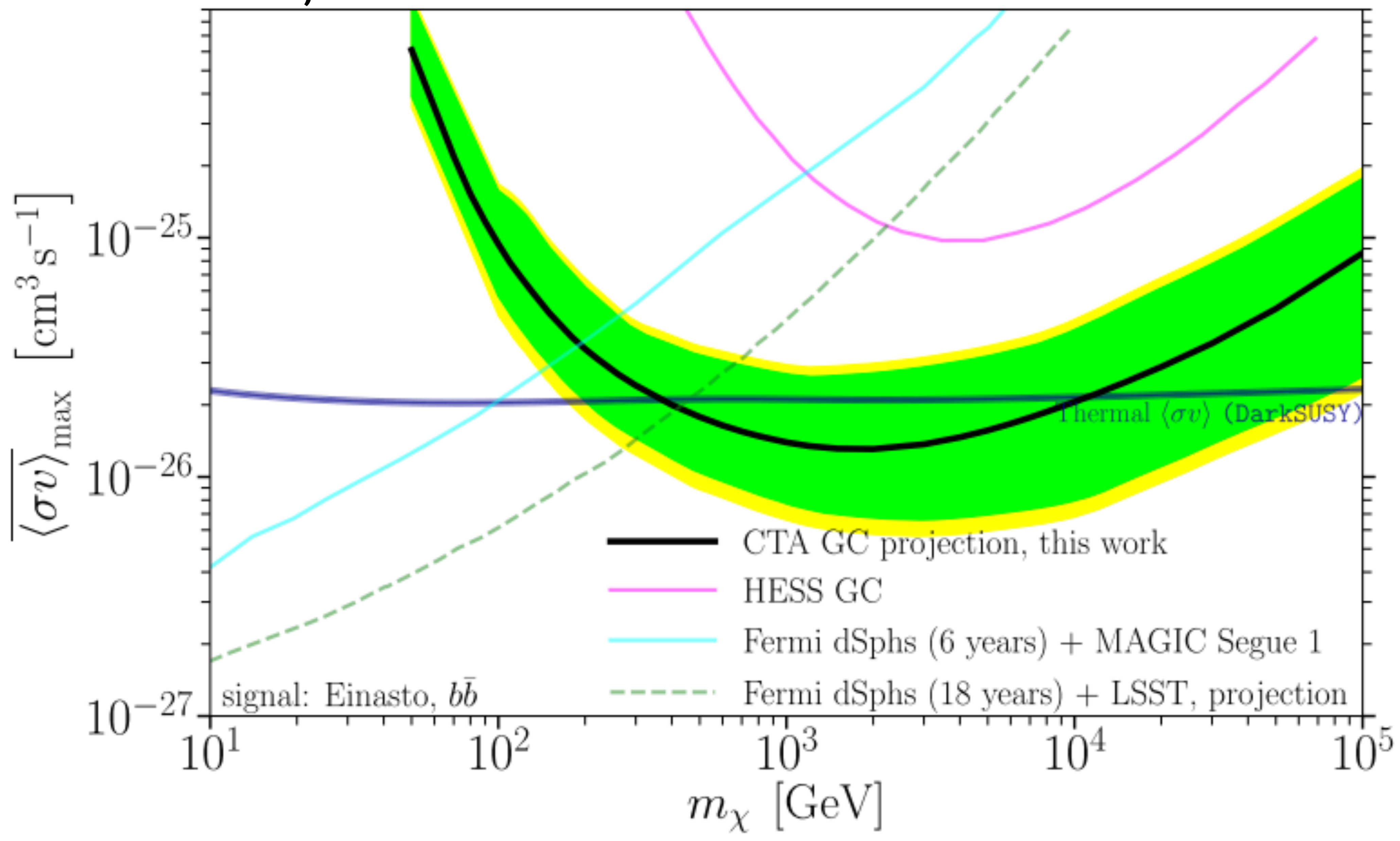
CTA, 2007.16129

CTA sensitivity to DM signal from Galactic Center

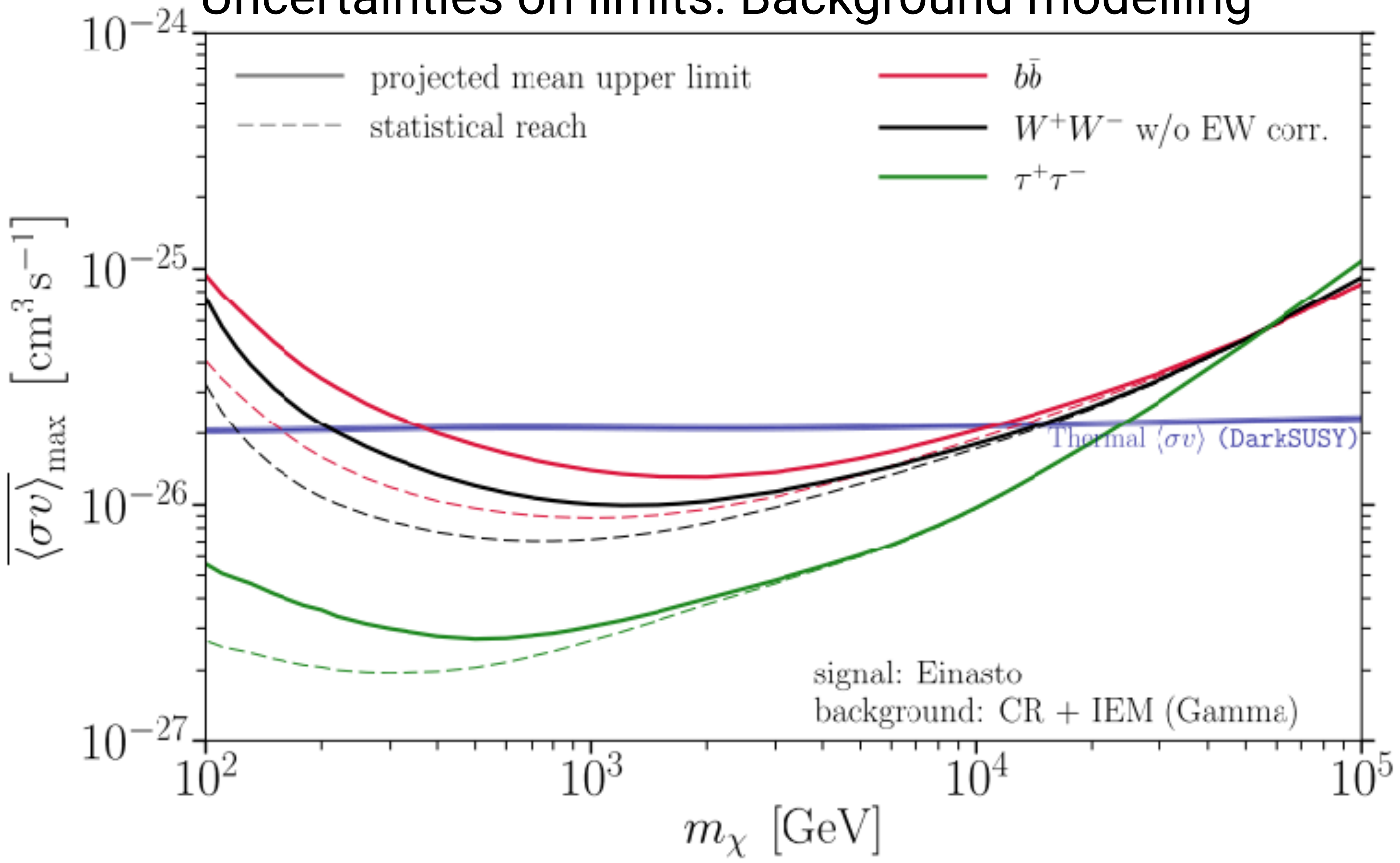


- Galactic center observations with CTA can probe the thermal relic cross section of 500 GeV - 10 TeV WIMPs

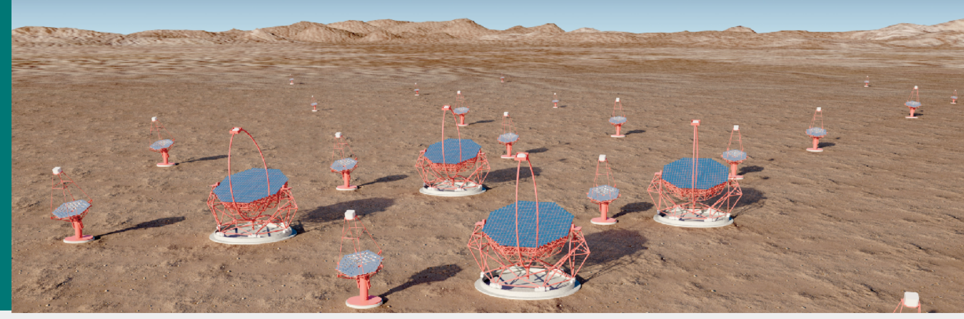
CTA, 2007.16129



Uncertainties on limits: Background modelling

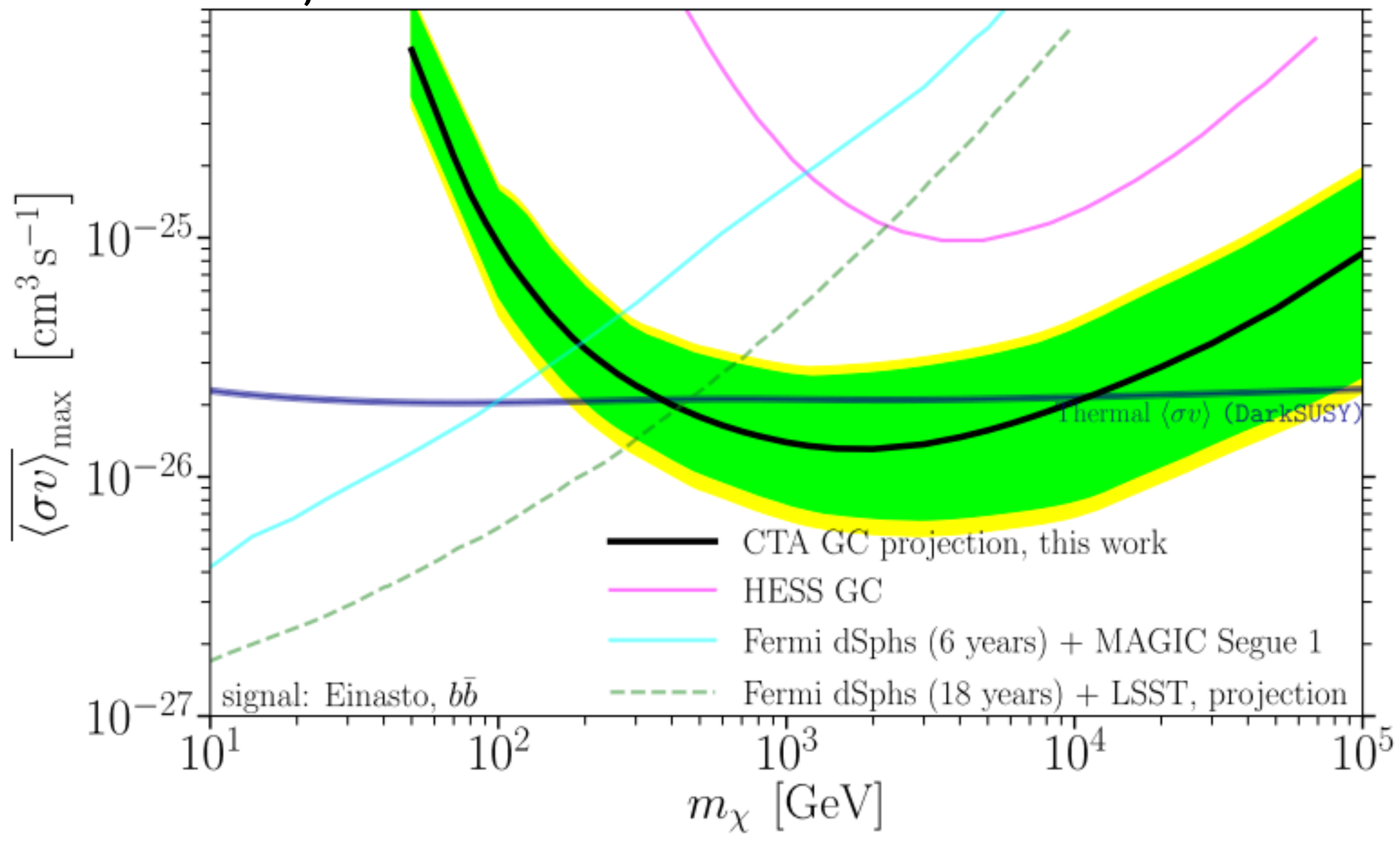


CTA sensitivity to DM signal from Galactic Center

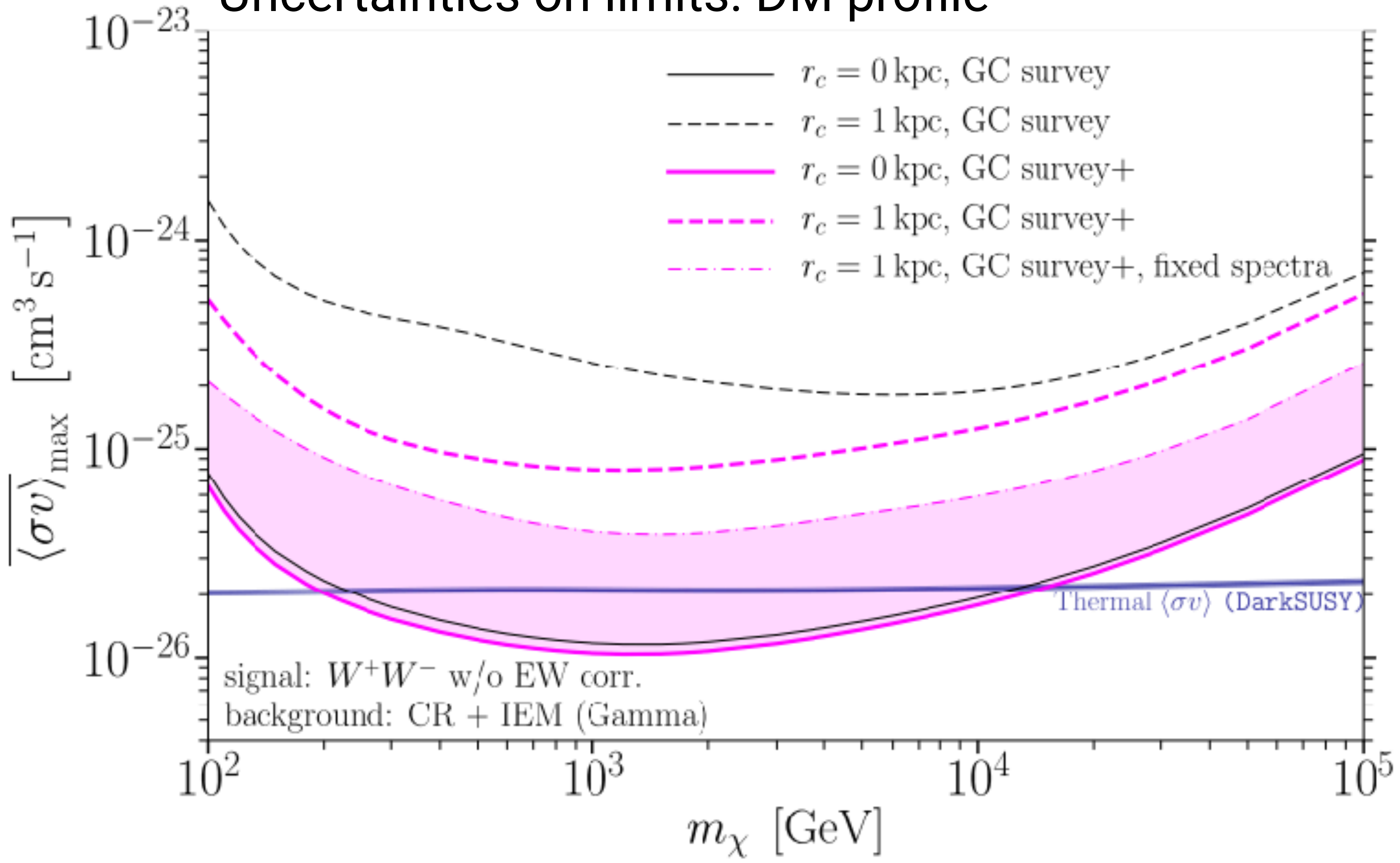


- **Galactic center observations with CTA can probe the thermal relic cross section of 500 GeV - 10 TeV WIMPs**

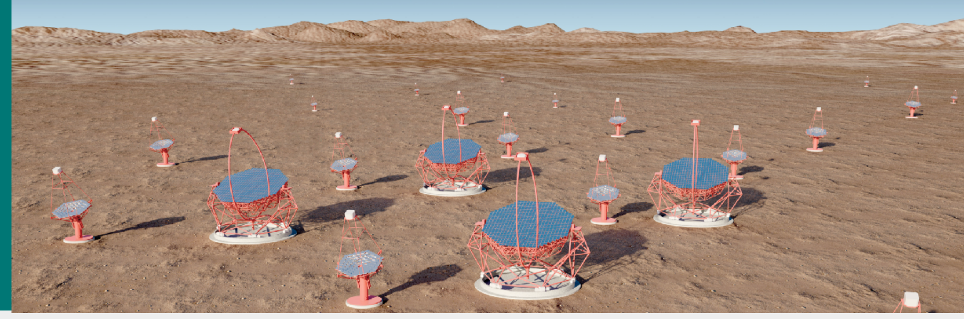
CTA, 2007.16129



Uncertainties on limits: DM profile

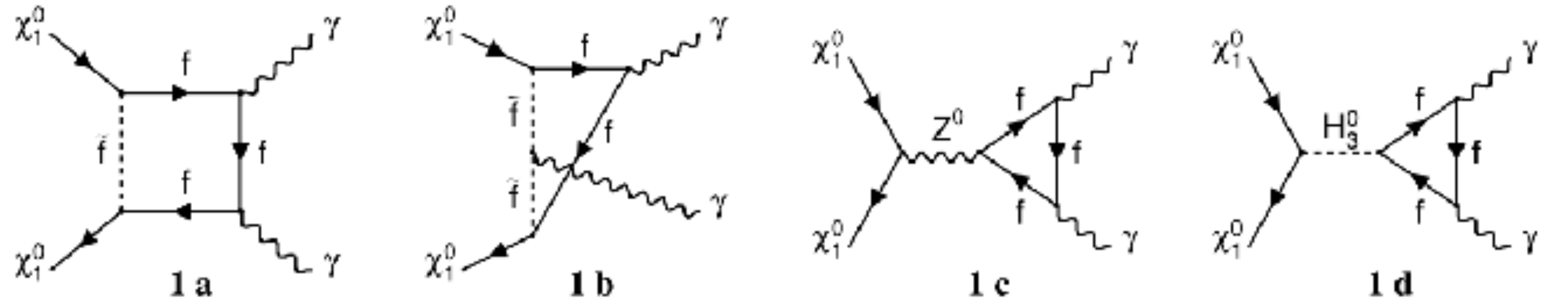


Search for line-like signals at the Galactic Center



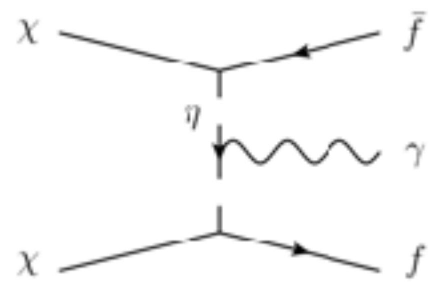
- Sign for new physics, less susceptible to spectrally smooth backgrounds

Annihilation into two γ's loop suppressed:



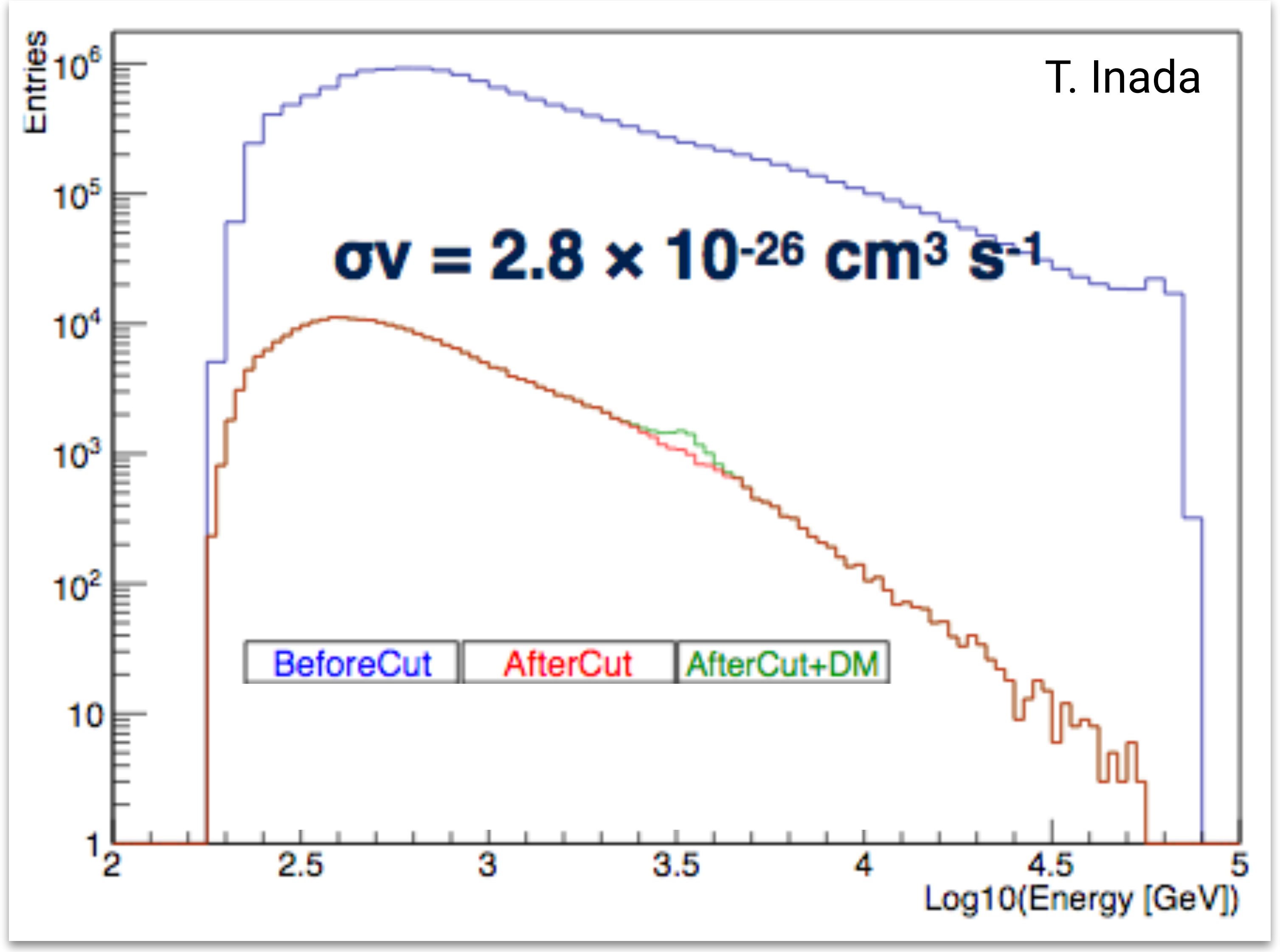
hep-ph/9706232

3-body annihil./VIB:

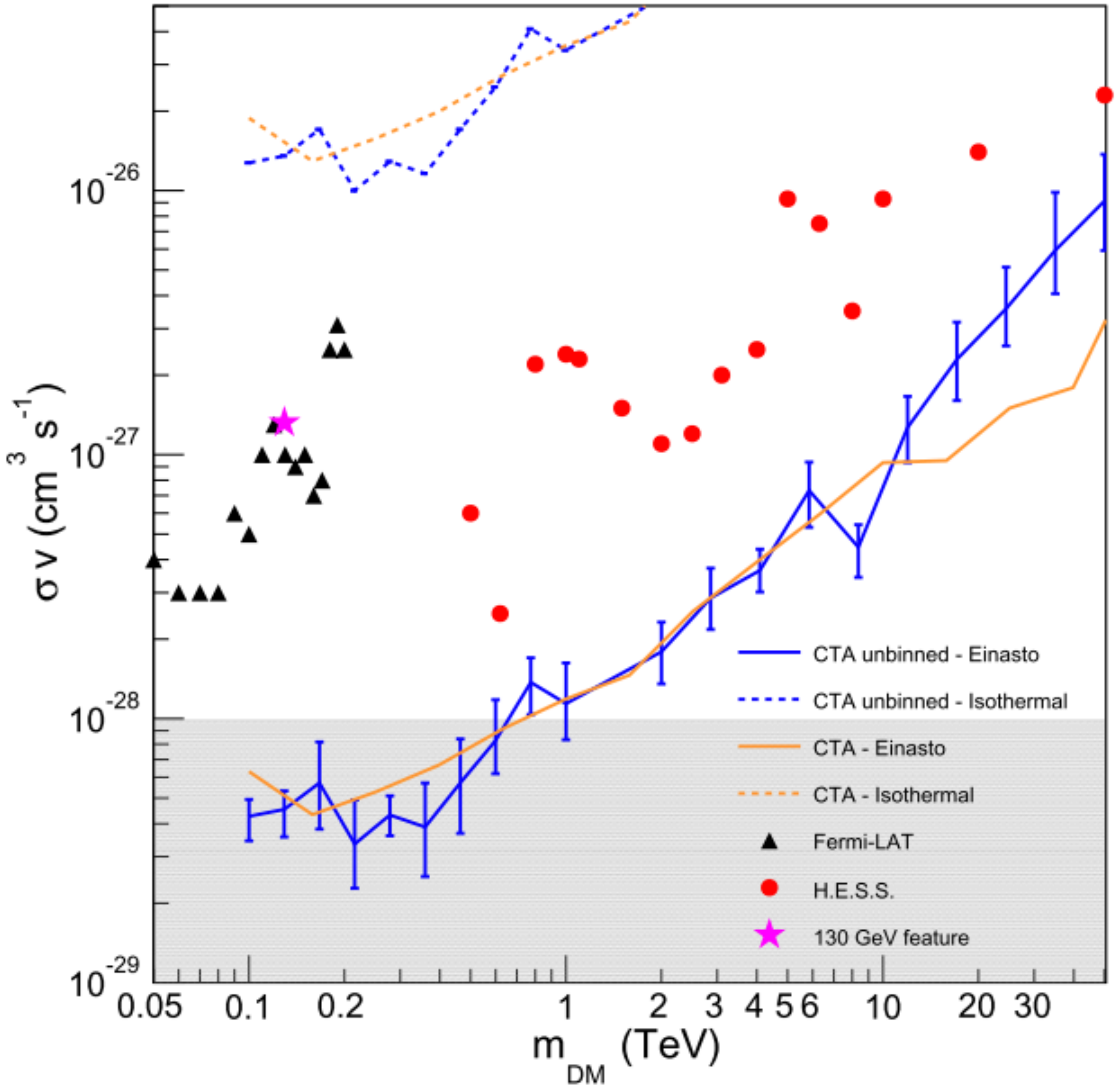


1203.1312

- MAGIC result to be published soon
- Refined CTA analysis ongoing

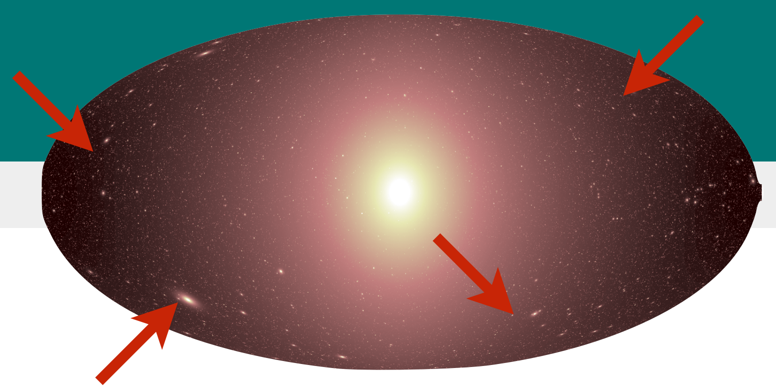


CTA, 1709.07997



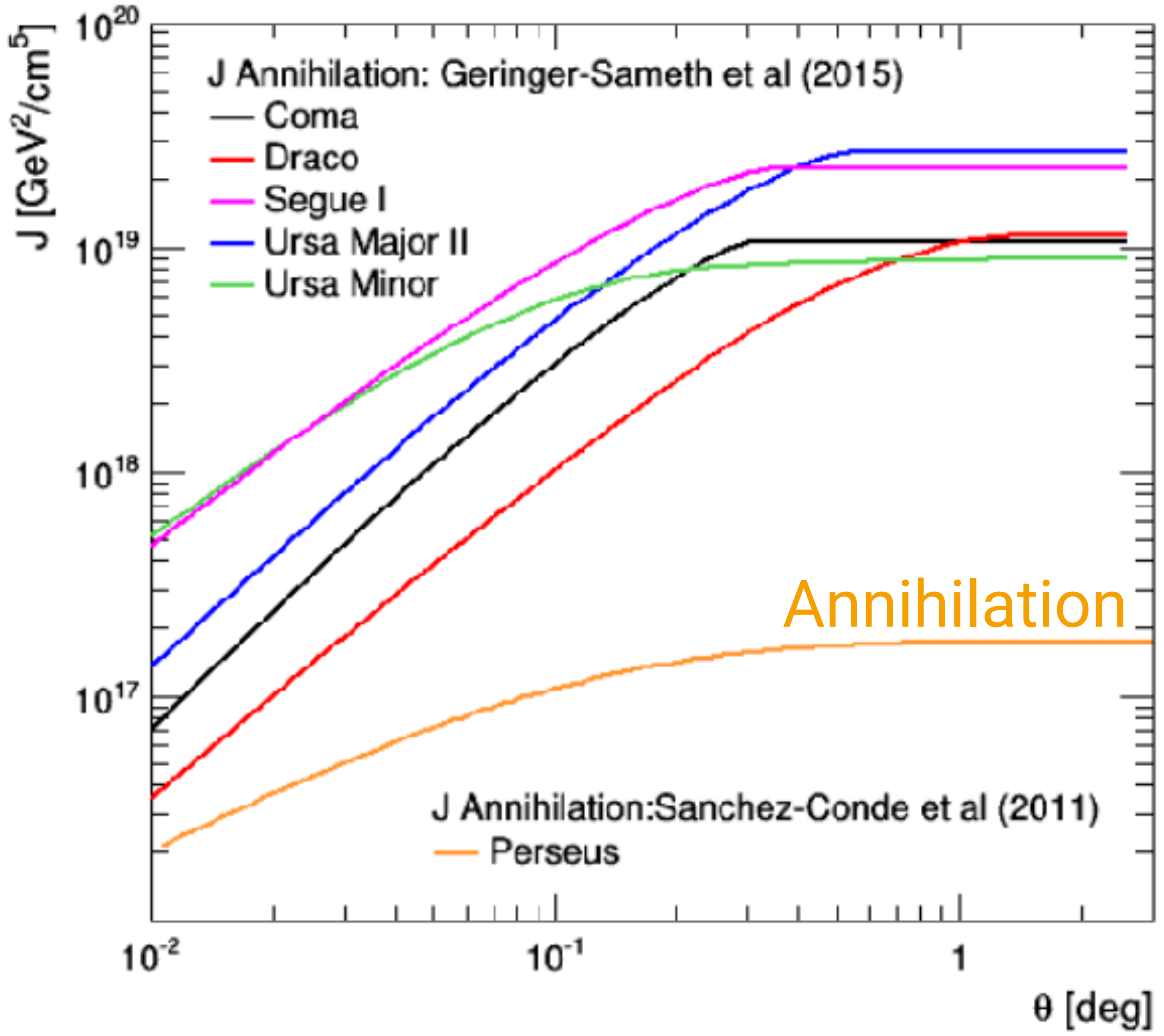
MAX-PLANCK-INSTITUT FÜR PHYSIK

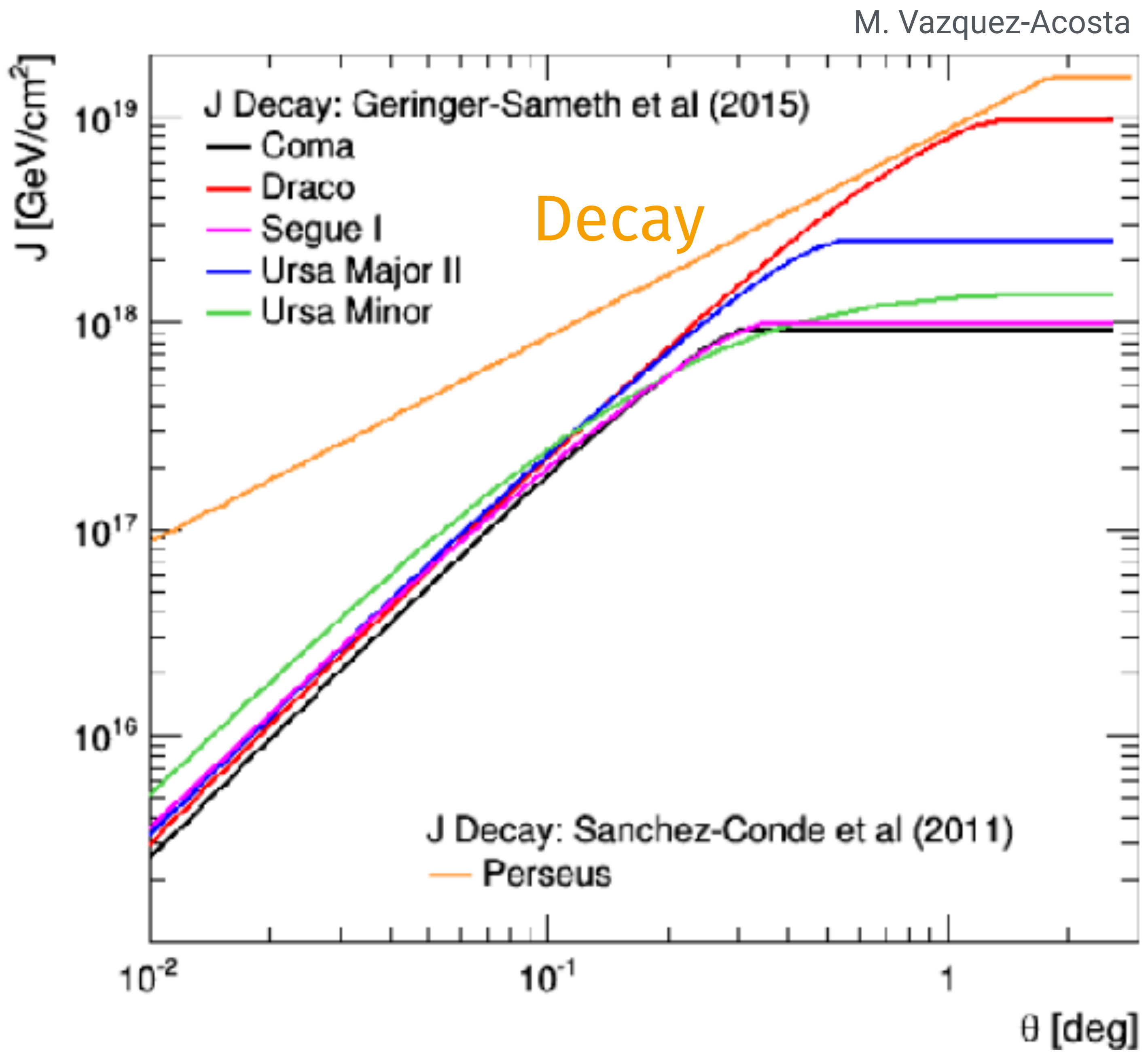
Dark Matter decay searches in Galaxy clusters



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

Good for constraining DM particle **lifetime**, ALP conversion in magnetic fields

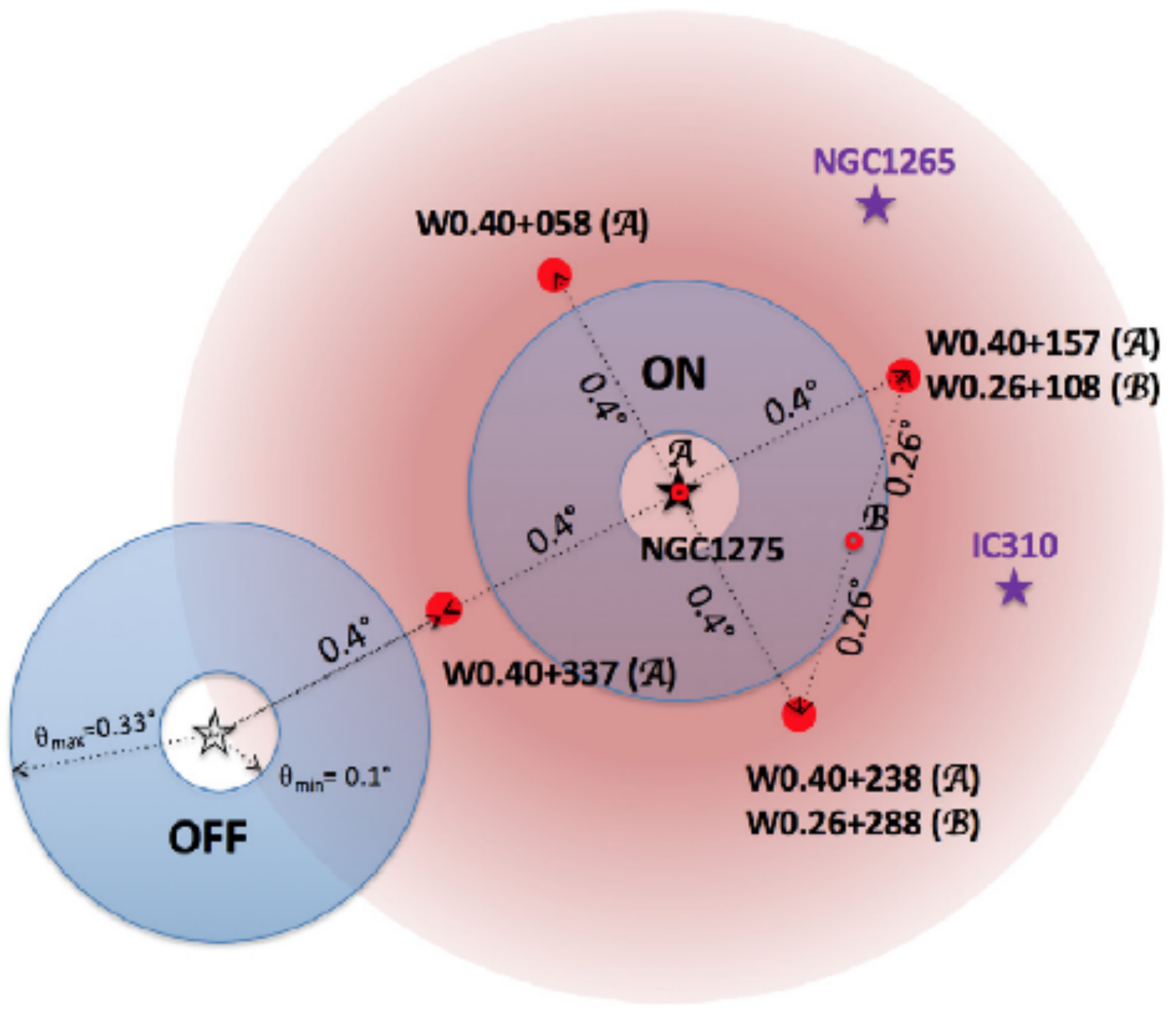


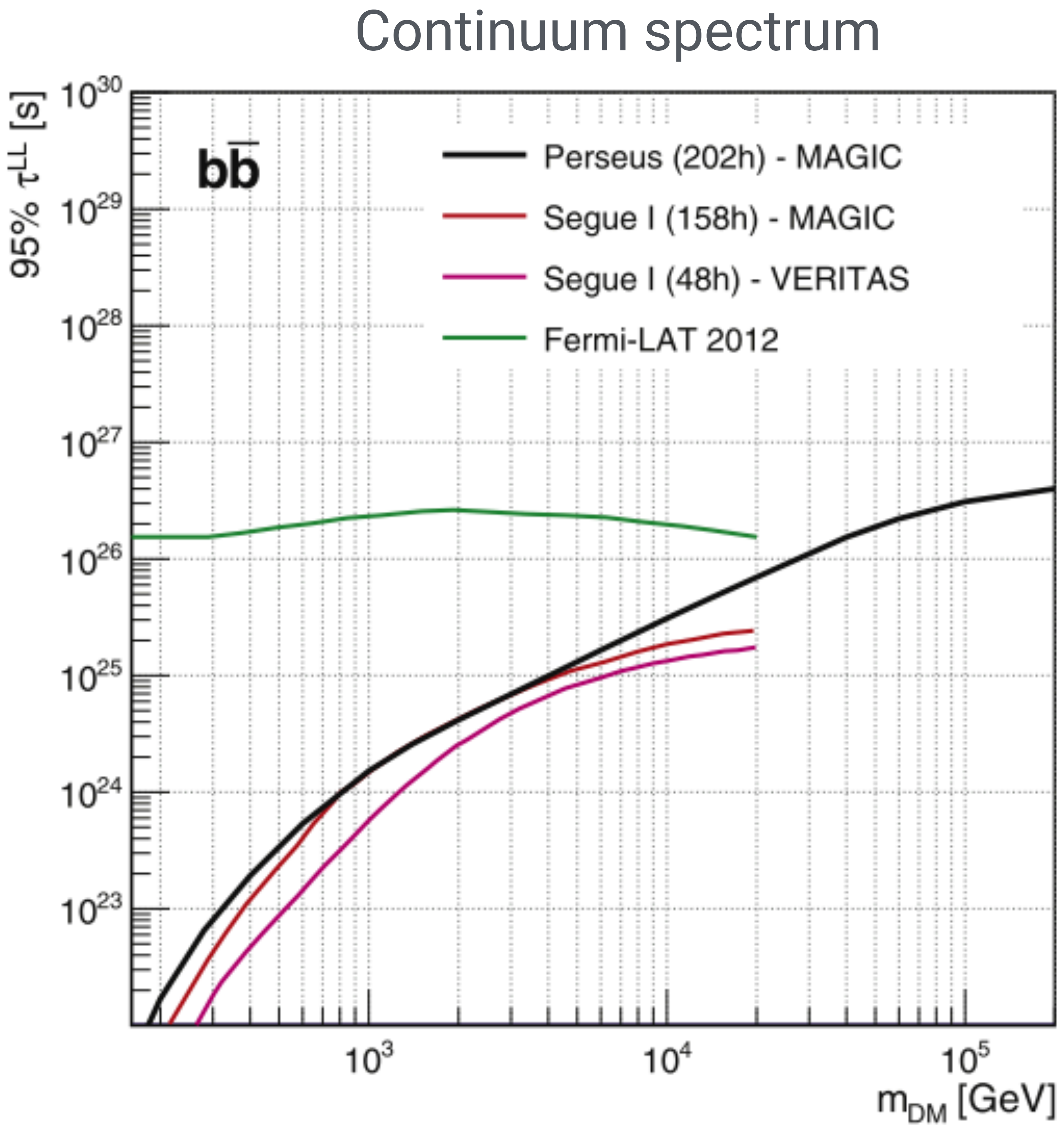


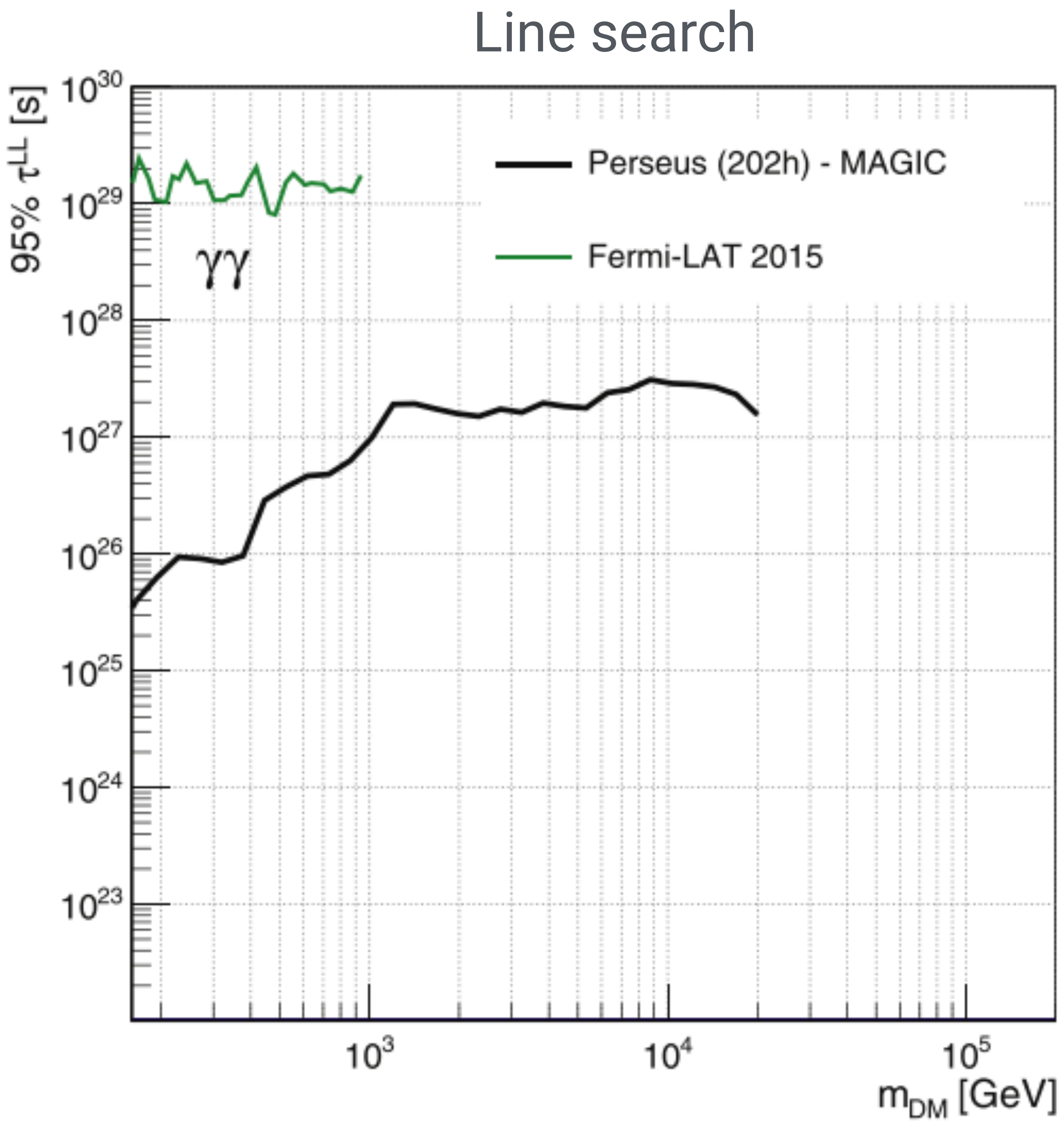
$$\frac{d\Phi^{\text{dec.}}}{dE_\gamma} = \frac{1}{4\pi}\,\frac{1}{\tau_{\rm DM}\, m_\chi} \times \frac{dN_\gamma}{dE_\gamma} \times \int_{\Delta\Omega}\int_{l.o.s.} \rho_{\rm DM}\, dl\, d\Omega$$

MAGIC Dark Matter decay search in the Perseus cluster

MAGIC, 1806.11063





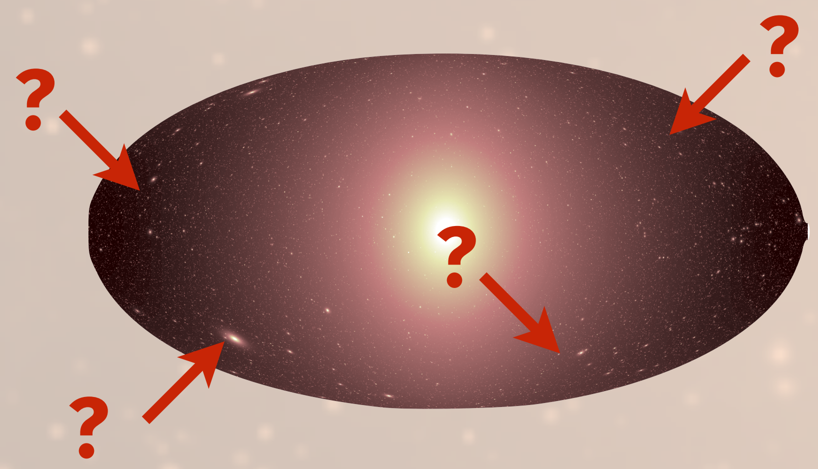


- Optimal ON-region to set DM decay limits — yet only ~8% of the total *J*-factor
- *J*-factor largest uncertainty - proportional to cluster mass uncertainty

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

WIMP annihilation in Dark Galactic Subhalos

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

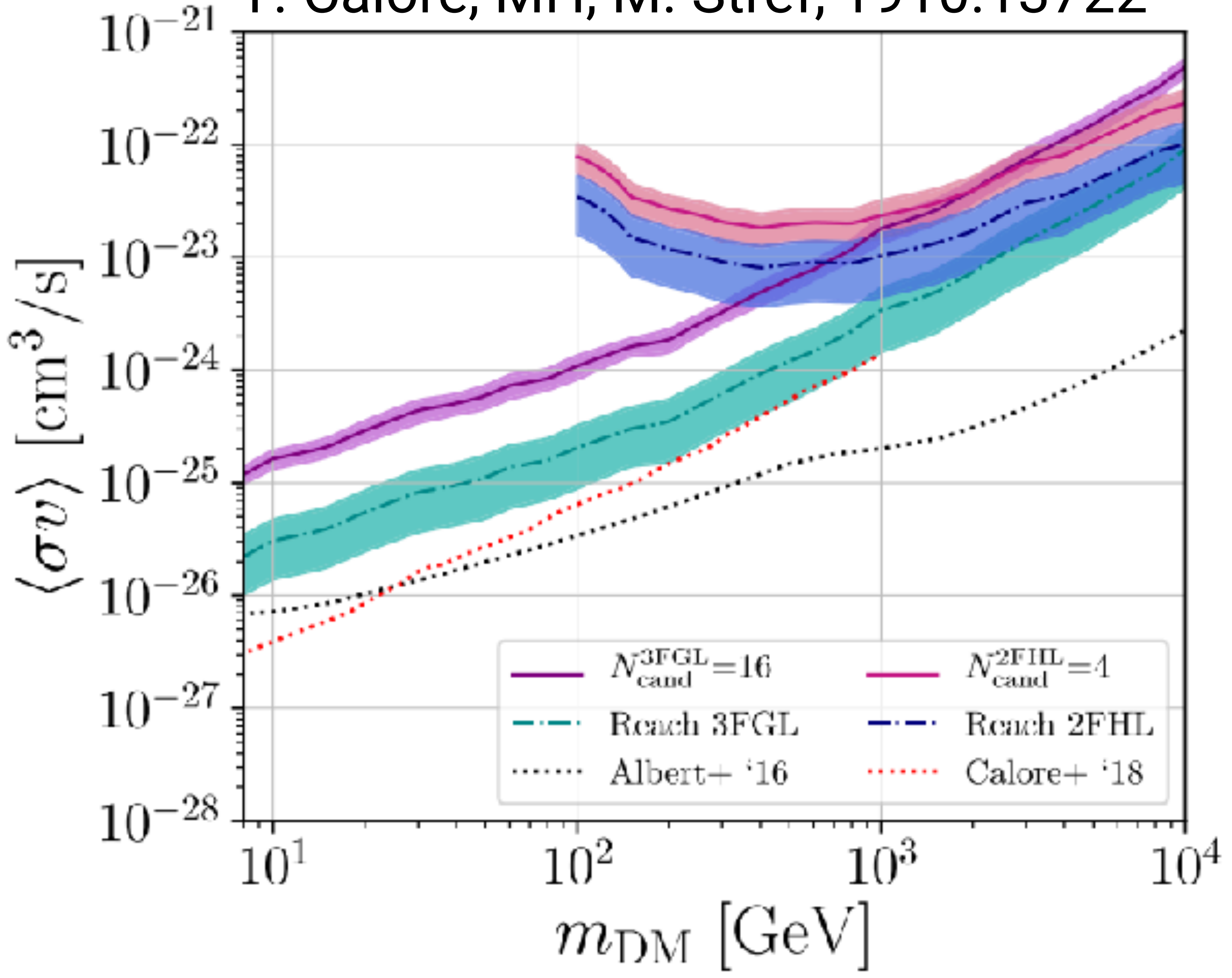


Good for serendipitous discovery

Dark Galactic Subhalos

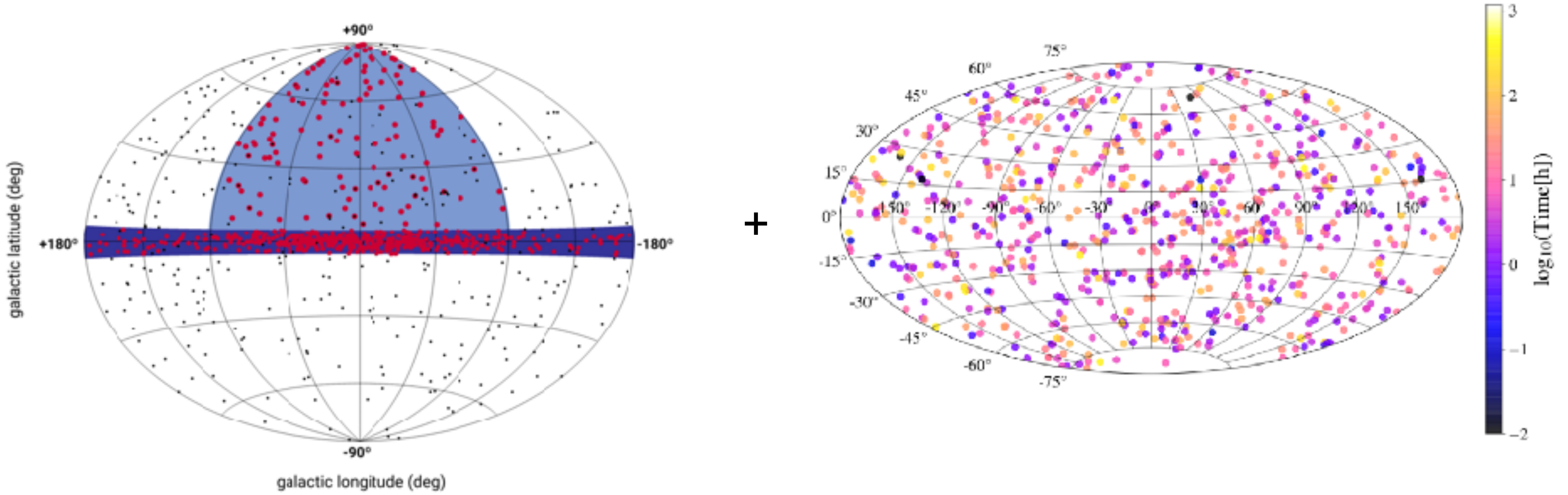
- **Limits from unidentified objects in Fermi-LAT catalogs:**

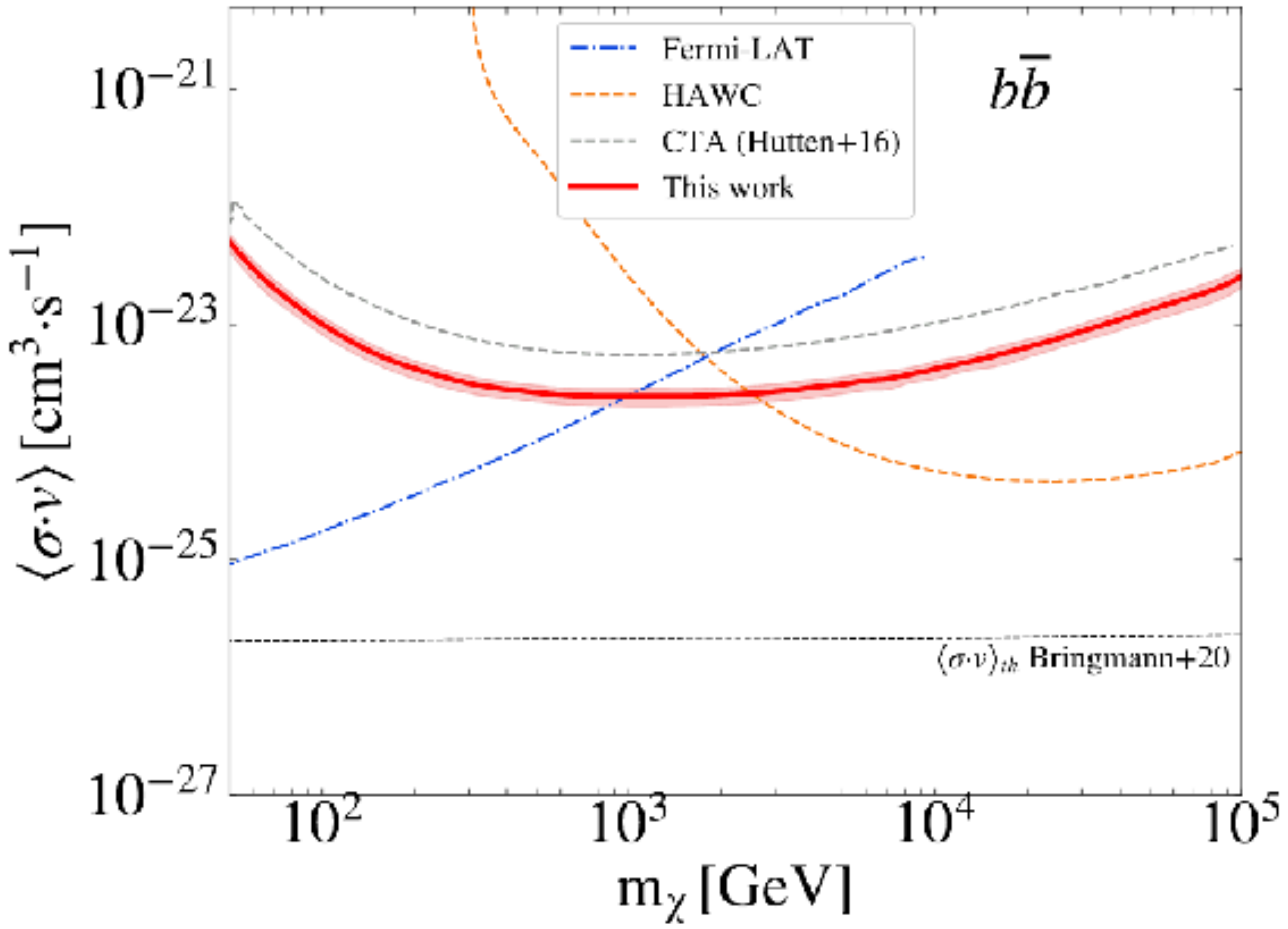
F. Calore, MH, M. Stref, 1910.13722



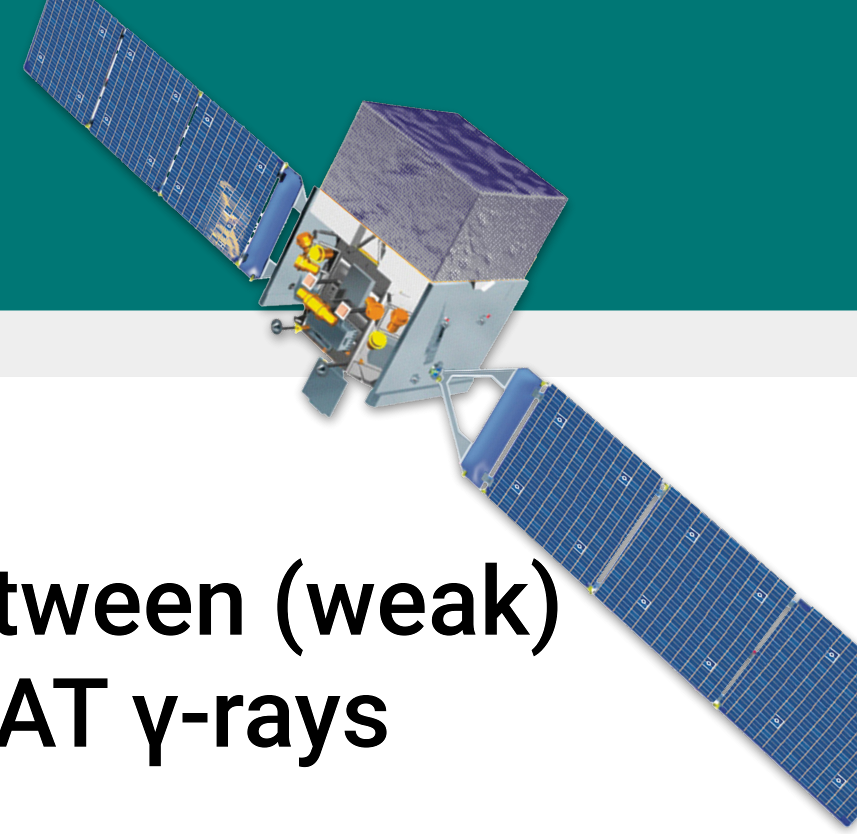
- **Chance detection sensitivity for CTA:**

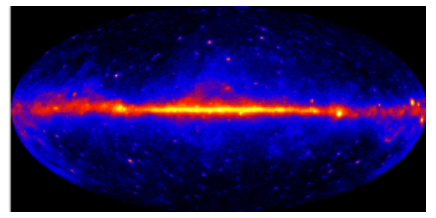
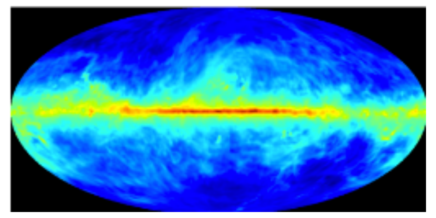
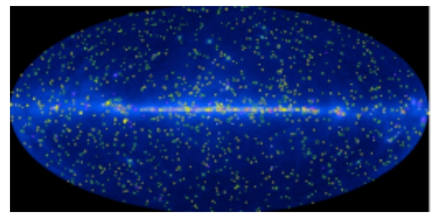
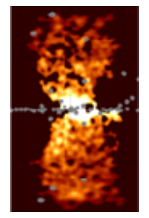
Coronado-Blázquez et al., 2101.10003



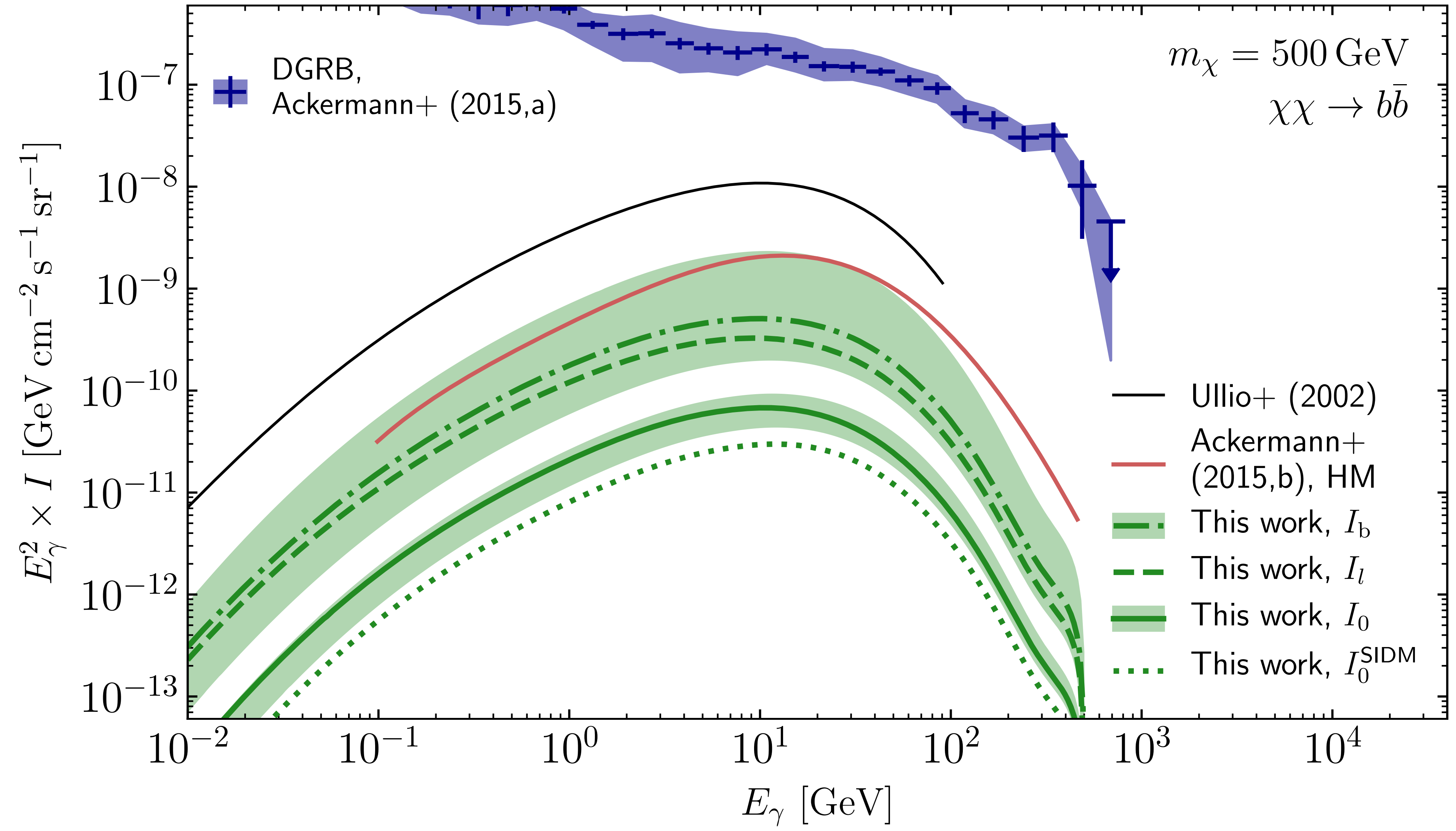


WIMP annihilation in diffuse γ-ray background



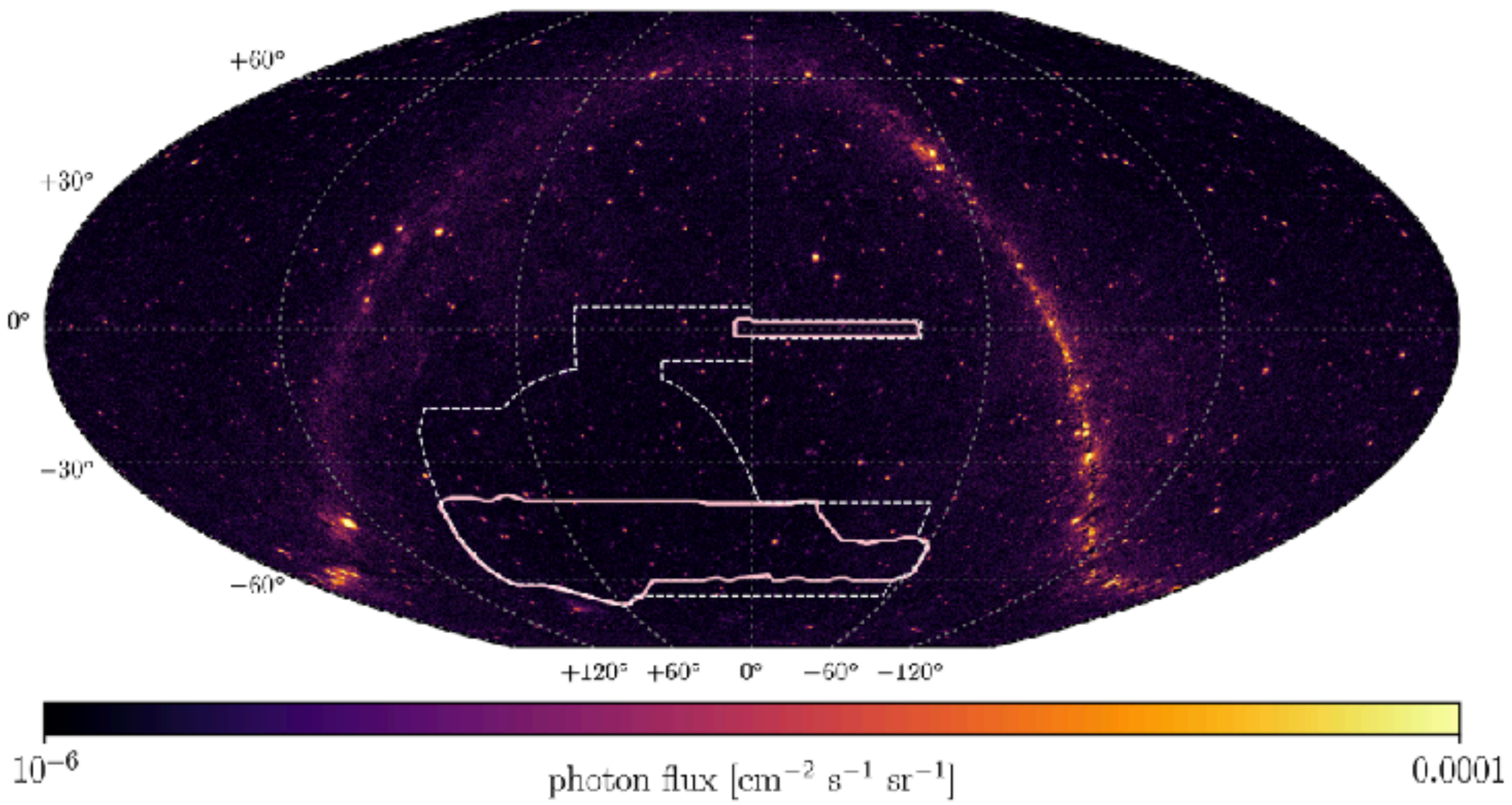
Diffuse =  -  -  - 

MH et al. 1711.08323



- **Detection of Cross-Correlation between (weak) Gravitational Lensing and *Fermi*-LAT γ-rays**

Ammazzalorso et al, 1907.13484



Clear detection, but unresolved blazars most likely origin

Complementary analysis techniques:

1-point PDF 1506.05118, 1711.03111
Angular power spectrum 1301.5901, 1608.07289, MH et al. 1806.01839
Large-scale structure correlation 1212.5018, 1411.4651, 1503.05922, 1506.01030,...

Axion-like Dark Matter

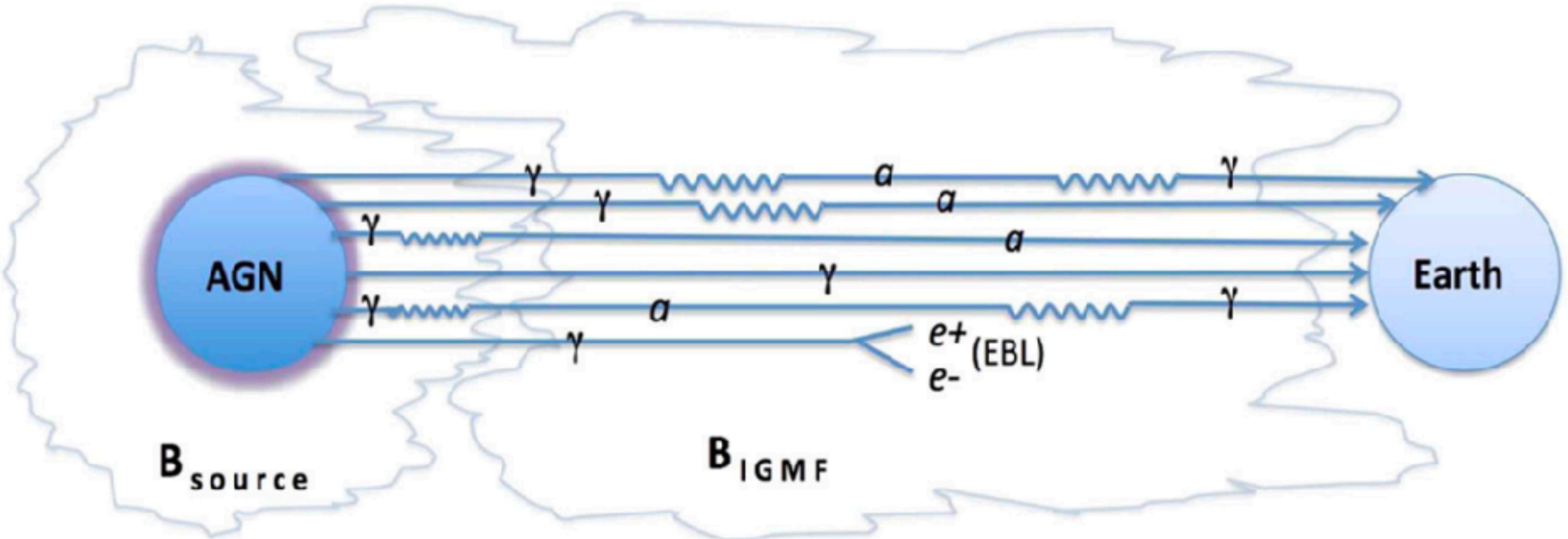
Picture credit: SLAC/Chris Smith

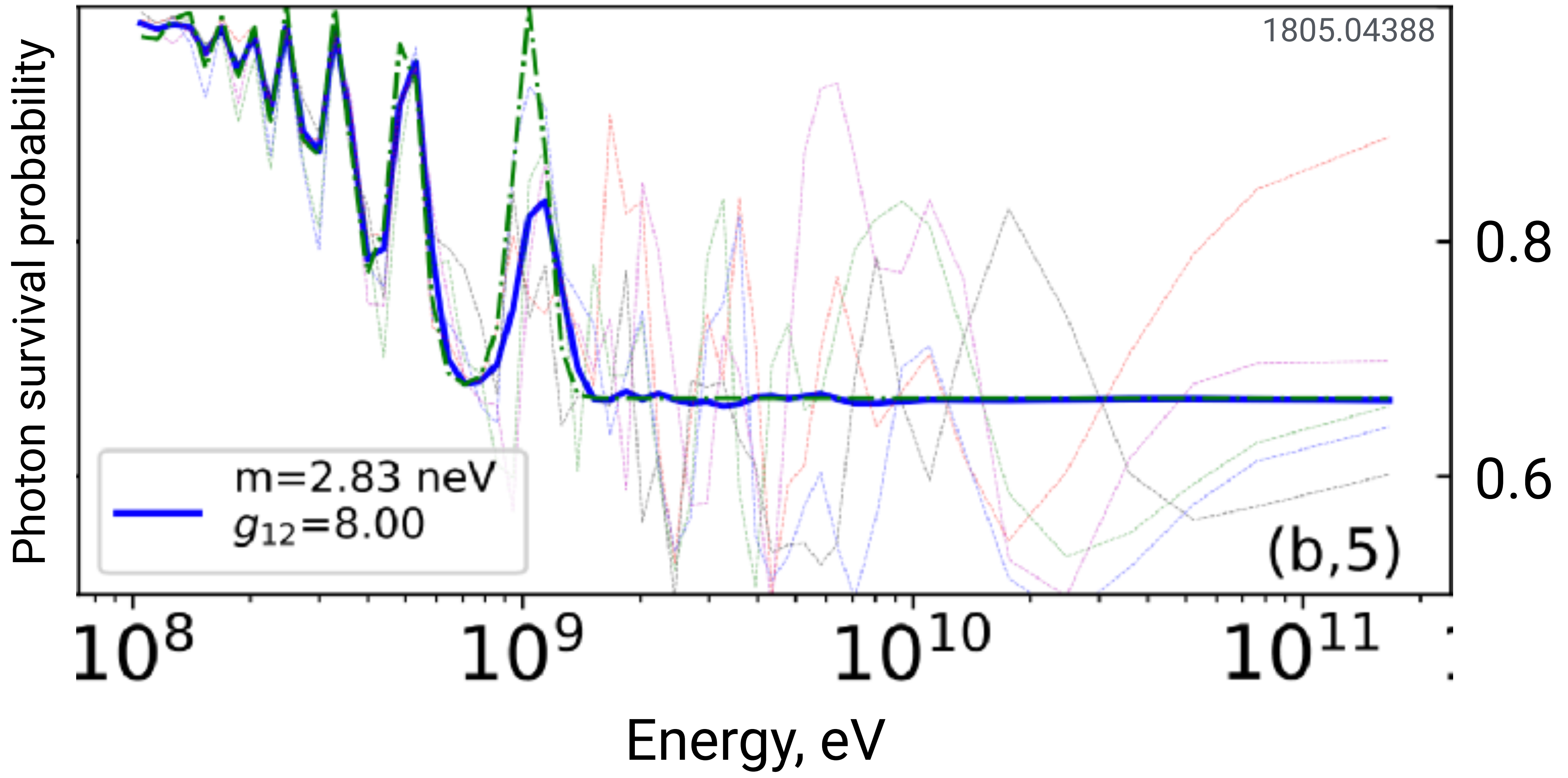
Astrophysical signatures from Axion-like particles (ALPs)

- **Conversion/oscillation in the presence of magnetic fields**

$$\mathscr{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E} \cdot \mathbf{B}\, a$$

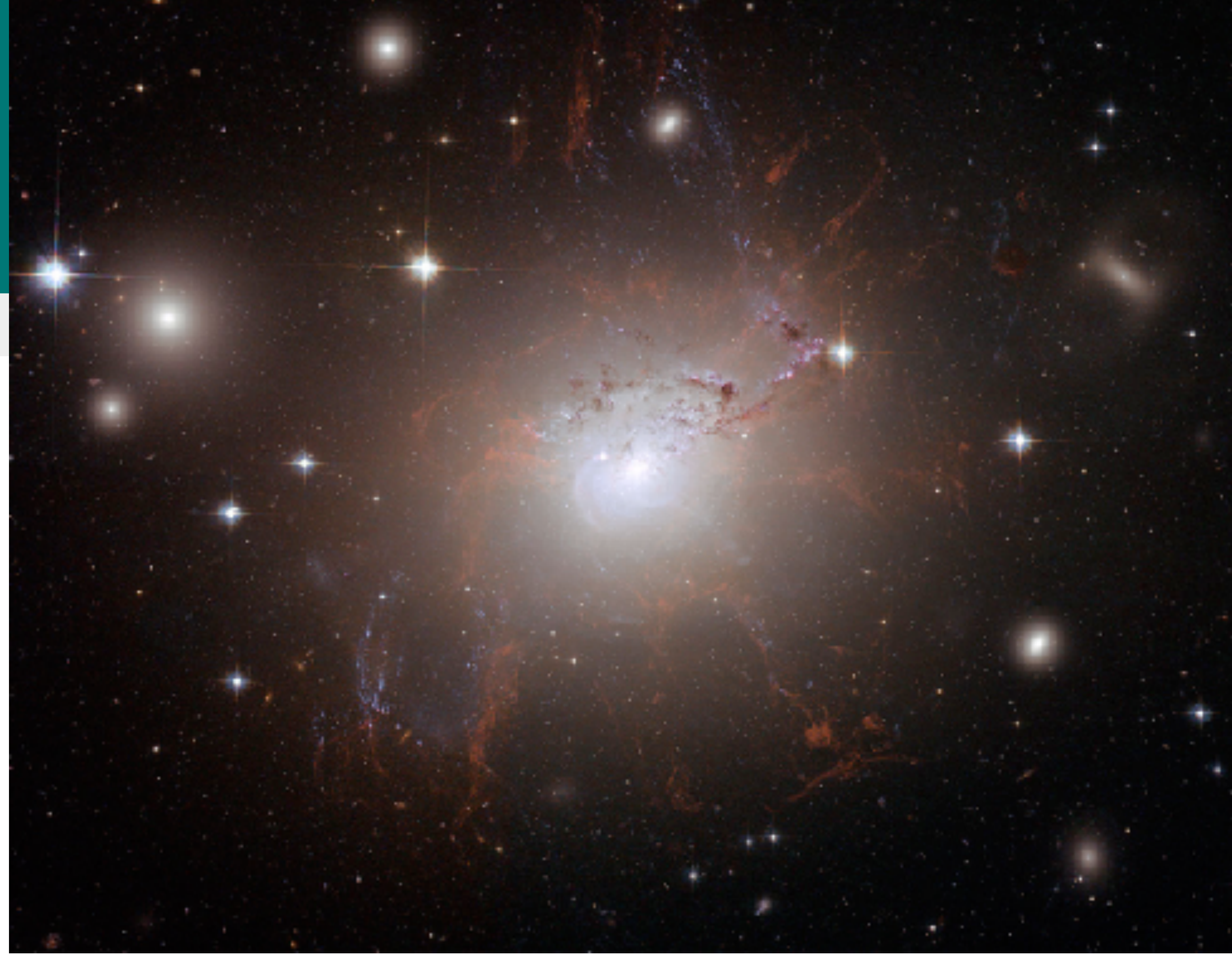
M. Sánchez-Conde, D. Paneque et al., 0905.3270



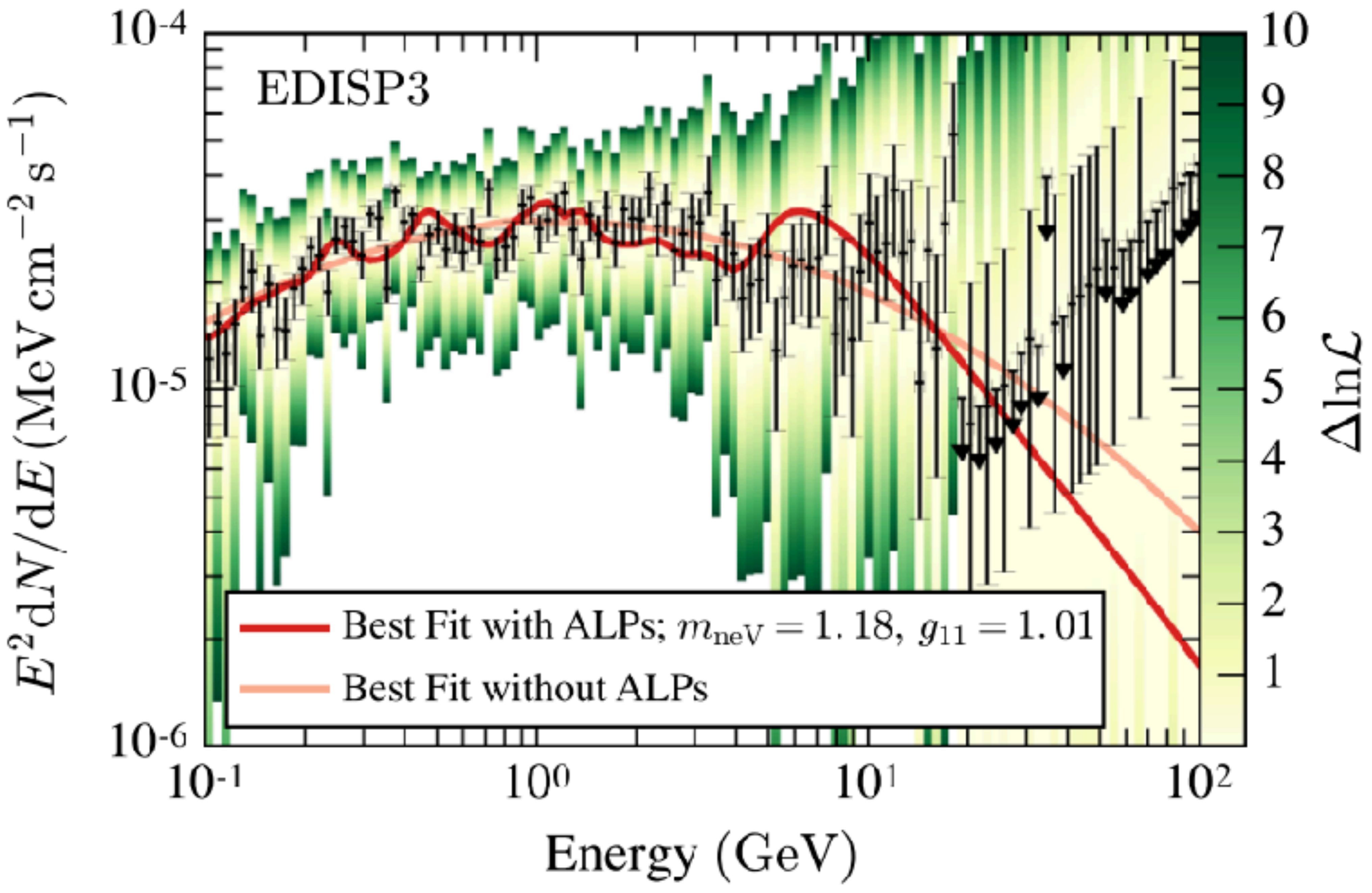


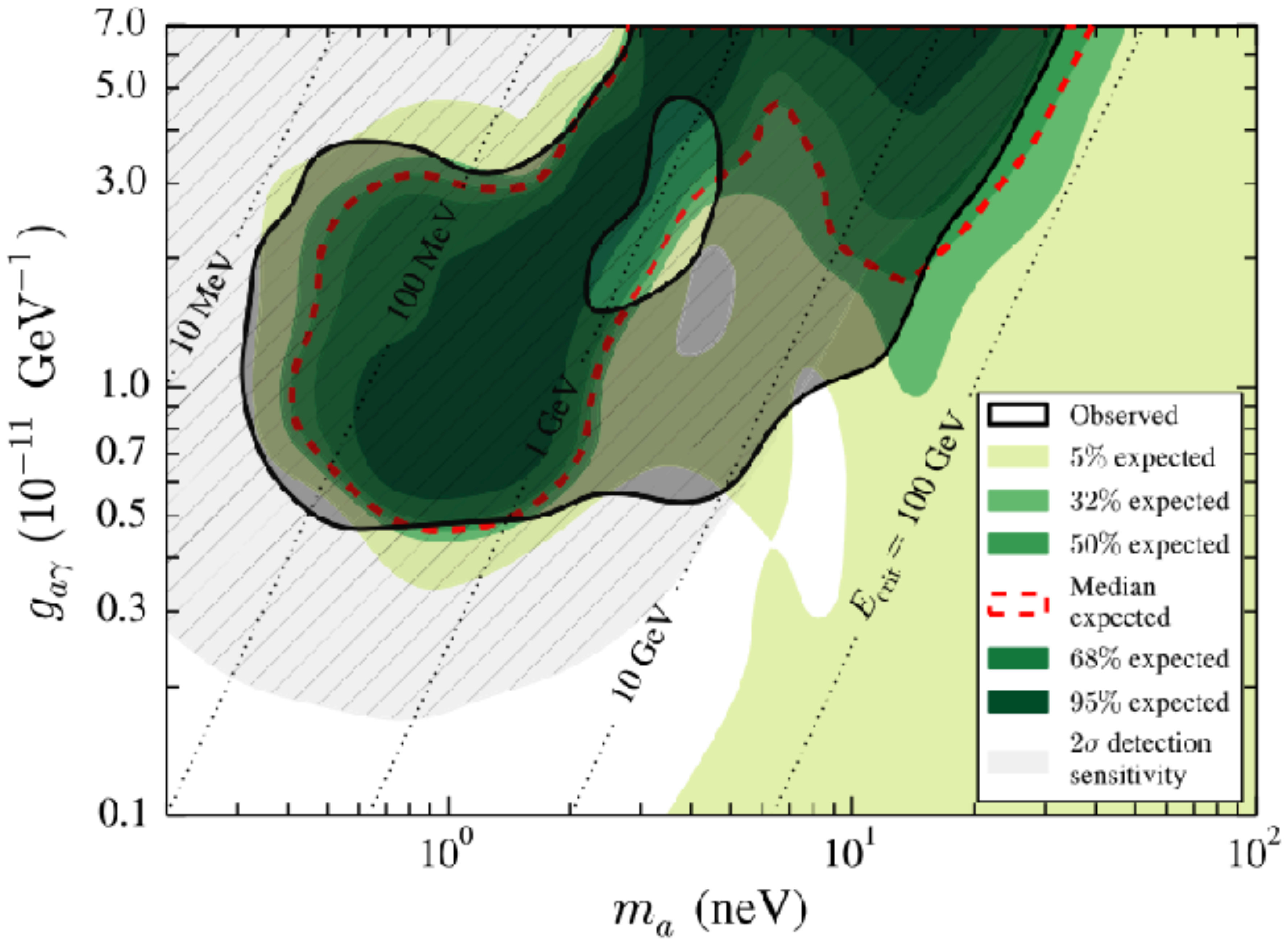
- **ALPs: a dark matter candidate** (Preskill et al., 1983; Abbott and Sikivie, 1983; Arias et al., 2012, 1201.5902): $g_{a\gamma} < \frac{10^{-12}}{\mathrm{GeV}} \sqrt{\frac{m_a}{\mathrm{neV}}}$

ALP searches towards NGC 1275 with *Fermi*-LAT

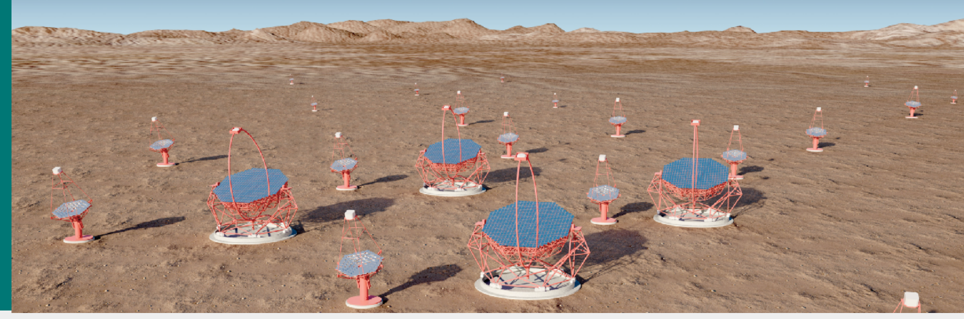


- NGC 1275: An excellent γ-ray beam for ALP searches
- Seen both by *Fermi*-LAT and MAGIC
- *Fermi*-LAT, 1603.06978:



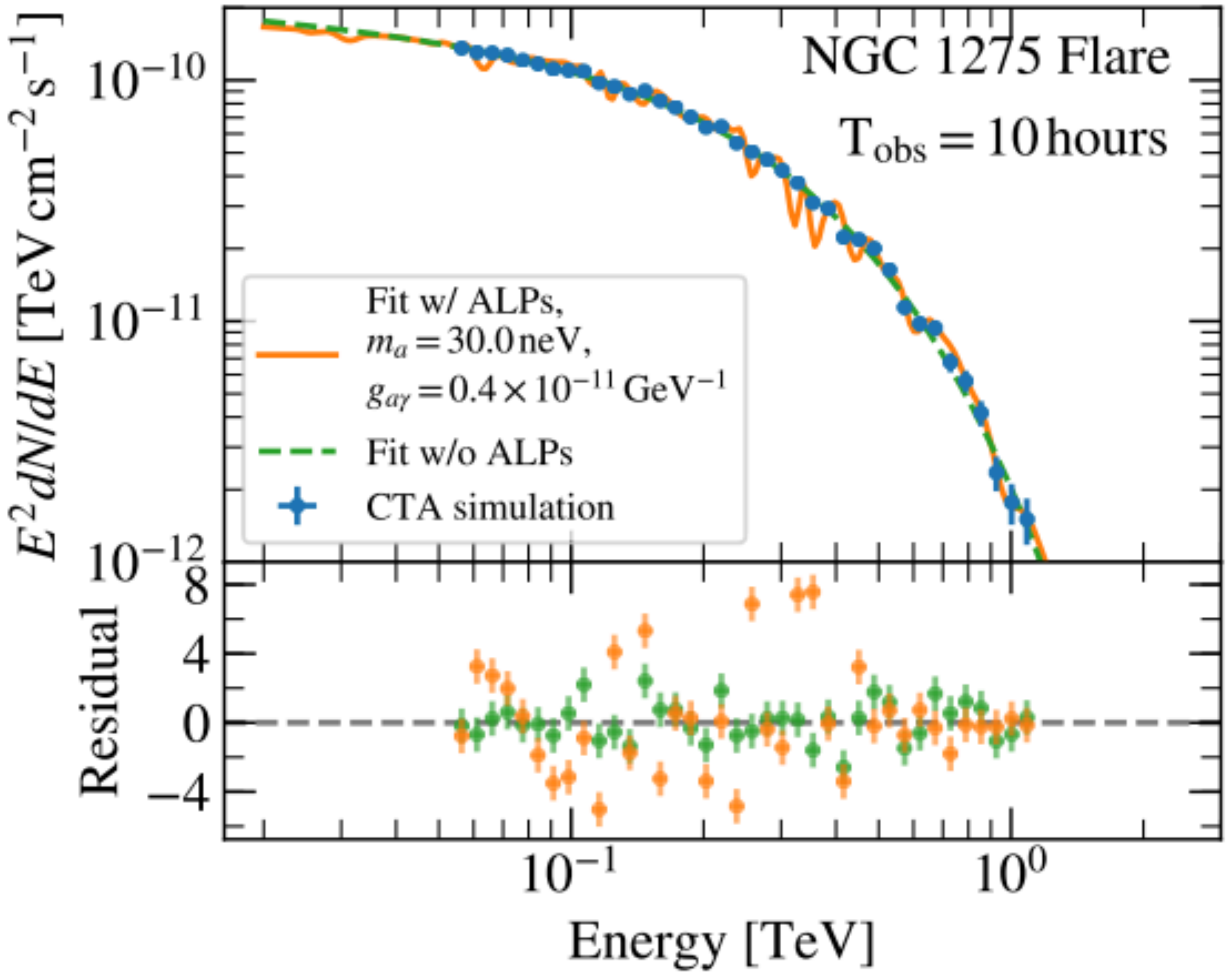


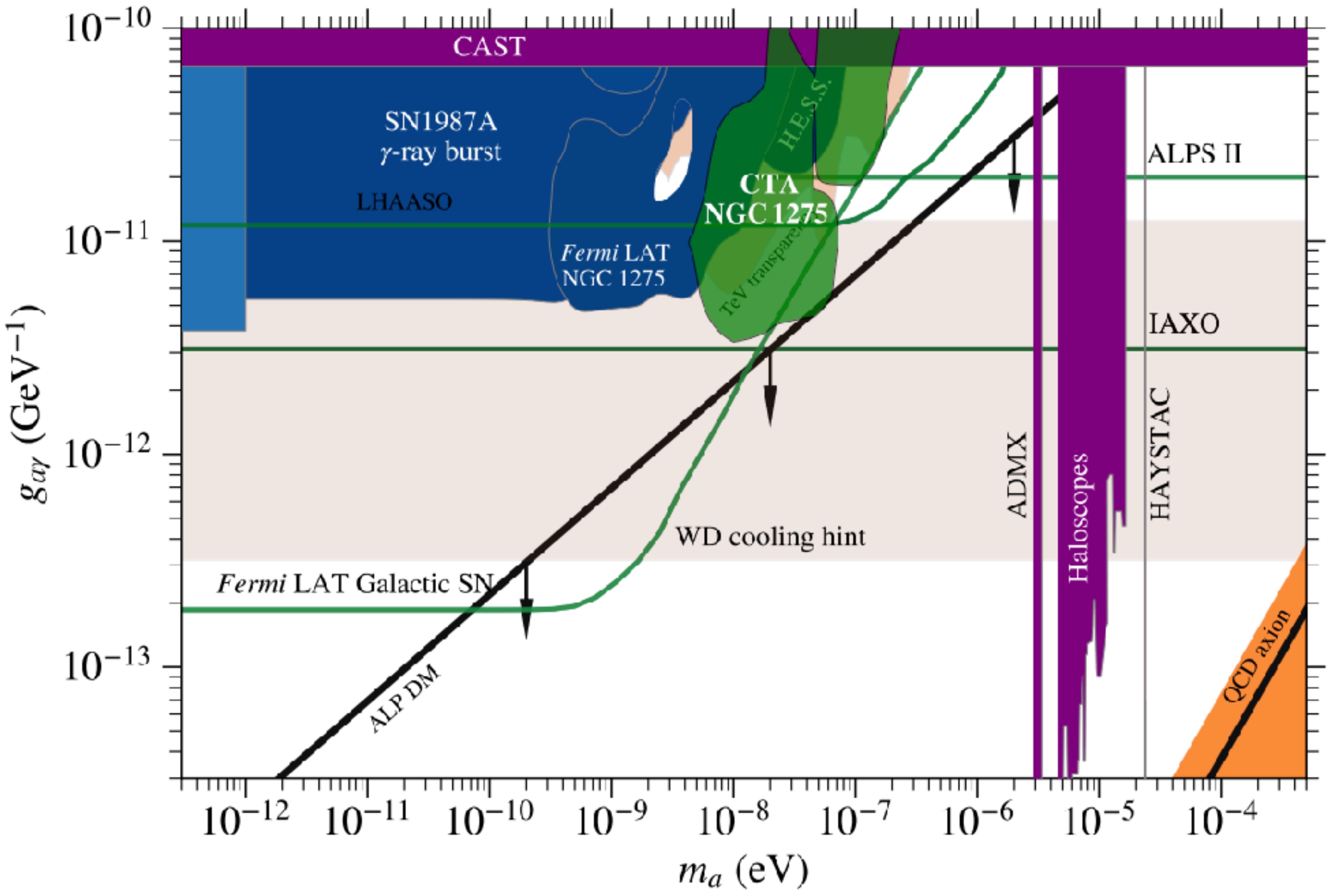
ALP searches towards NGC 1275 with CTA



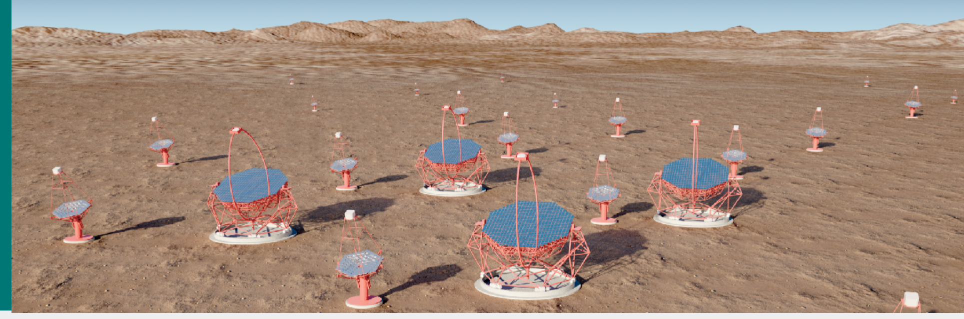
- Assume $300\,\mathrm{h}$ observations, among them $10\,\mathrm{h}$ in flaring state
- Sensitivity driven by flaring state

CTA, 2010.01349





ALP searches towards NGC 1275 with CTA



CTA, 2010.01349

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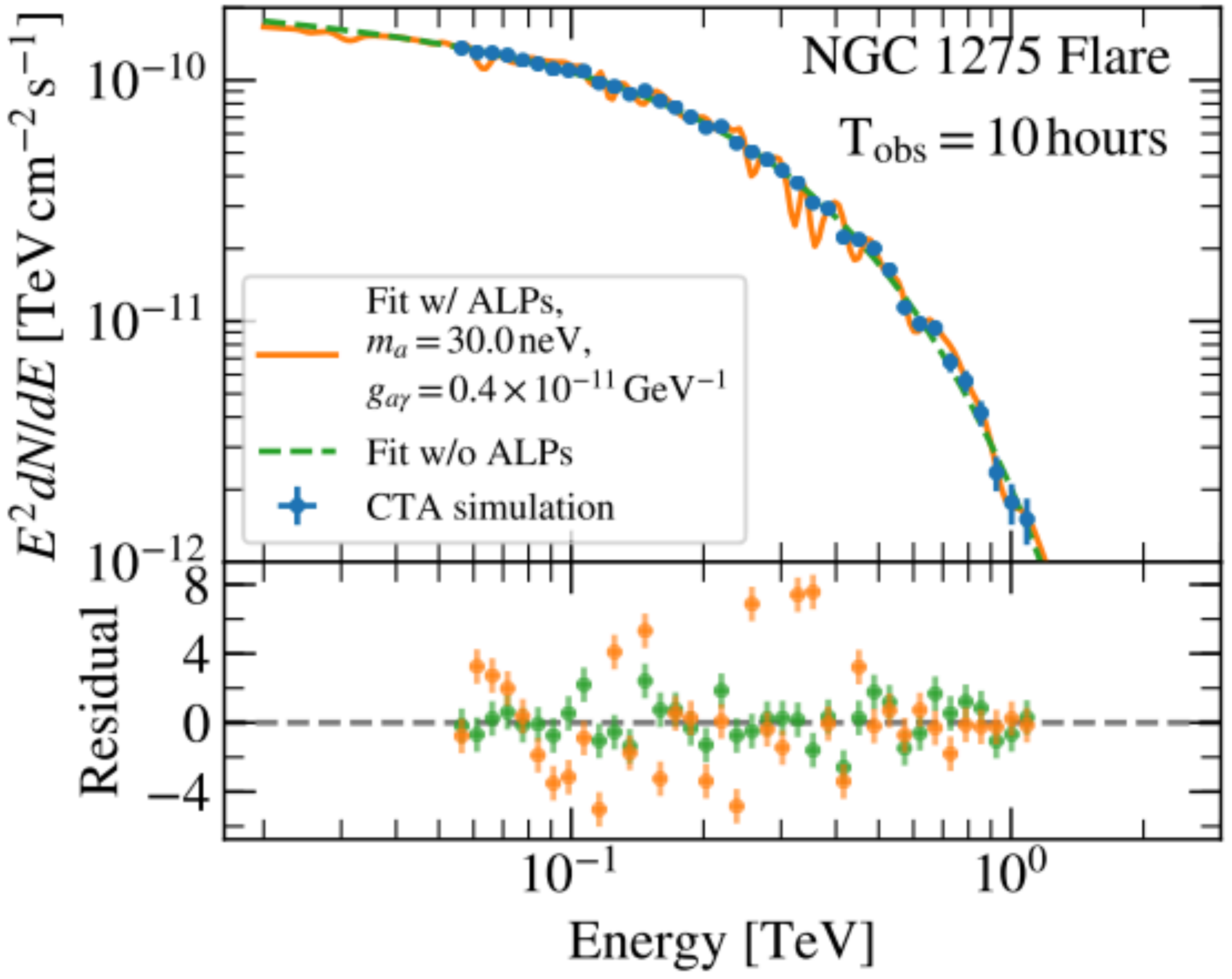

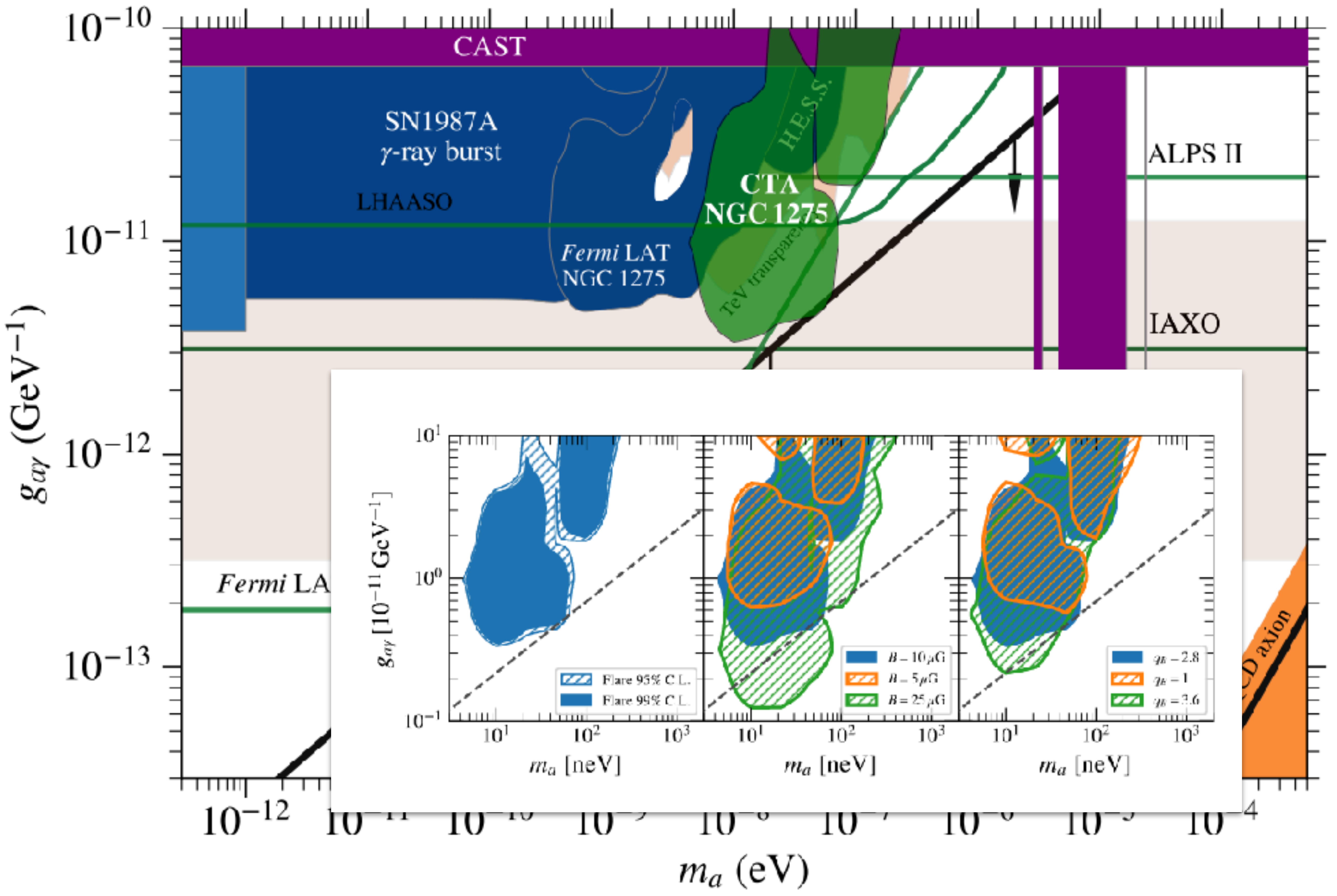

Conclusions

Let's continue to "turn every stone"

- No unambiguous indirect DM detection so far.
- Already tight limits for WIMP DM, but
  - Large *J*-factor uncertainties
  - Limits only valid for s-wave annihilation. For p-wave, virtually no relic annihilation = no limits
  - DM could have been produced differently in early Universe: No need for WIMP miracle
- Seek for detection:
  - Just starting to probe thermal relic cross sections for TeV DM with CTA
  - Exotic spectral features able to boost signal (resonances, enhanced lines,…)
- Astrophysical gamma-ray observations can also probe ALP DM