Search for Dark Matter with Imaging Atmospheric Cherenkov Telescopes and the Cherenkov Telescope Array

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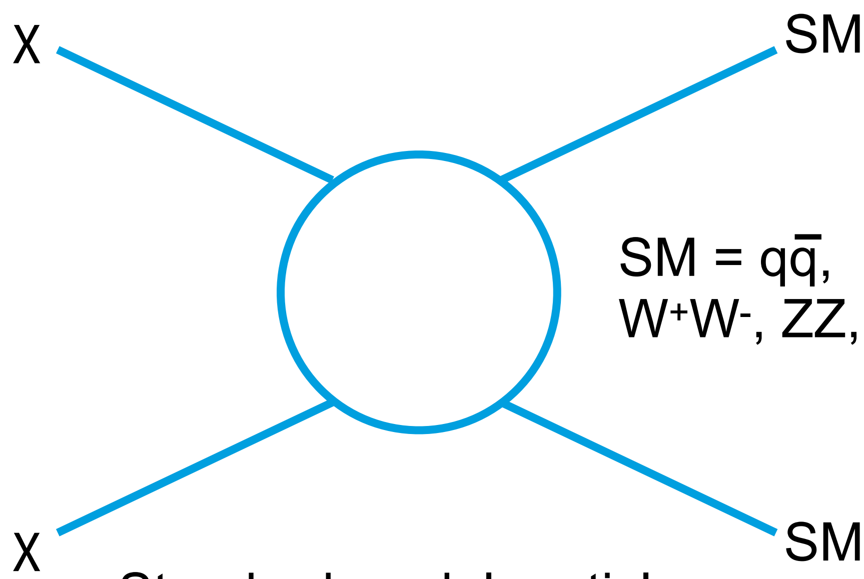
UCLA Dark Matter 2023
2023.03.29

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Indirect Searches for Dark Matter



SM = $q\bar{q}$,
W^+W^-, ZZ, l^+l^-,…

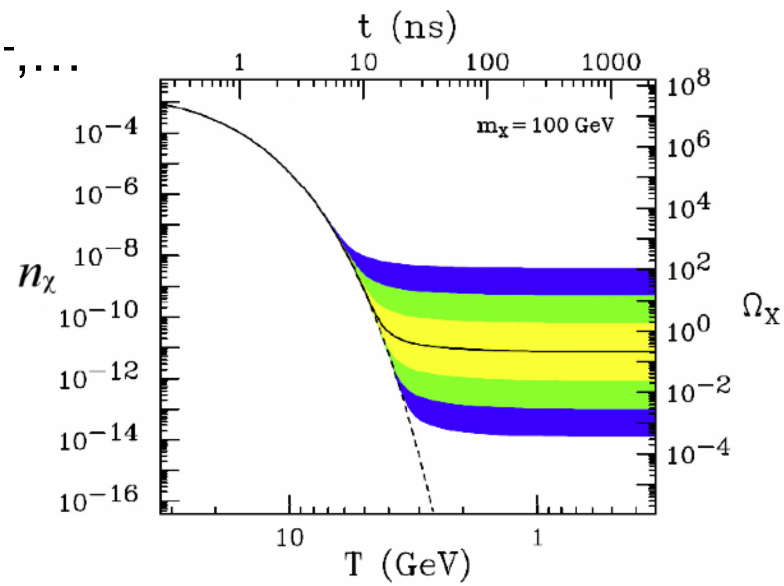
Standard model particles hadronize, decay, radiate

↓

Gamma rays, neutrinos, p^+/p^-, e^+/e^-

Appealing to consider **GeV-TeV mass, weakly-interacting** particle

Feng 2010 arXiv:1003.0904



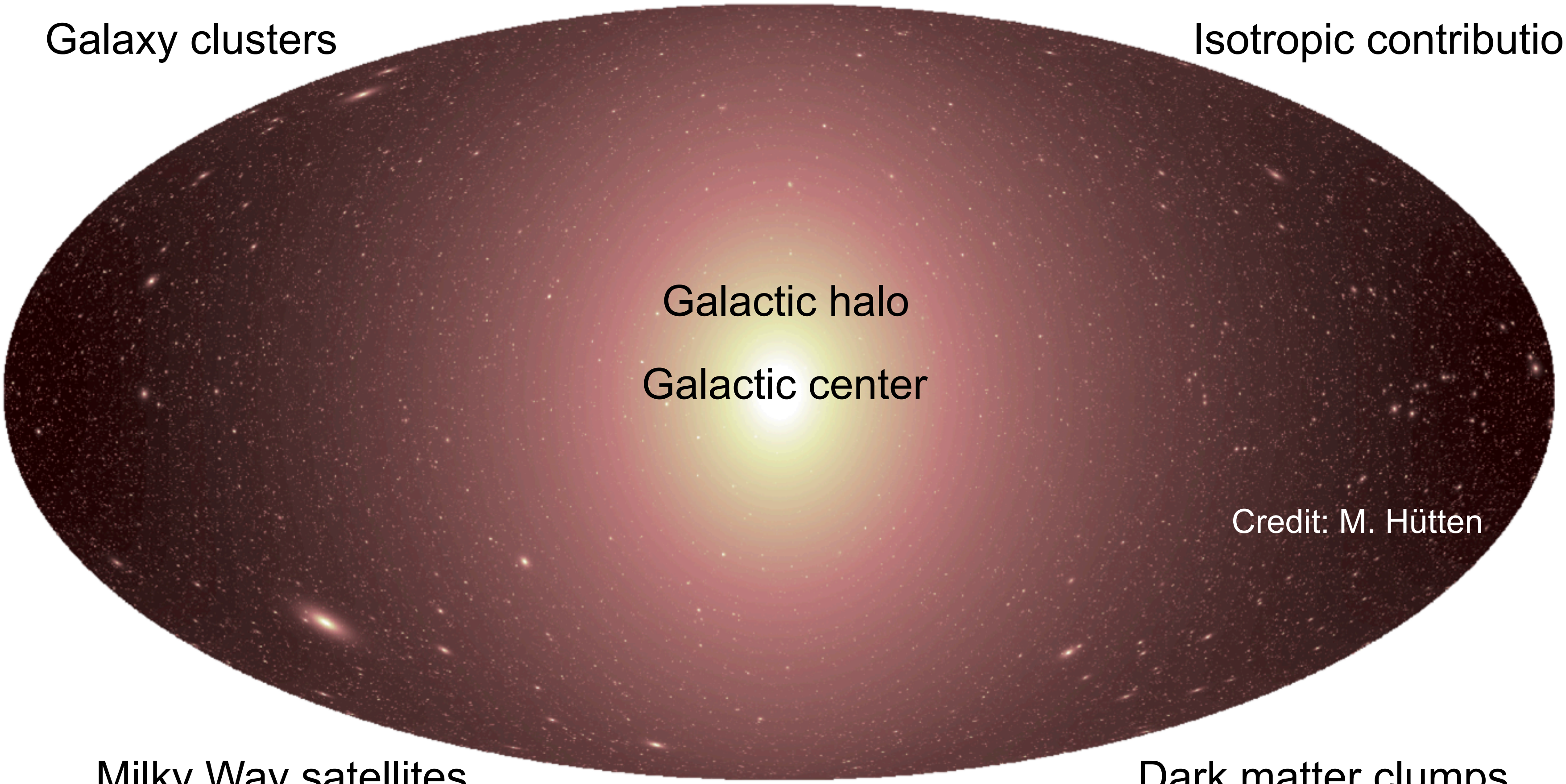
"WIMP Miracle"

$\langle\sigma v\rangle \sim 3\times10^{-26}\ \mathrm{cm^3 s^{-1}}$

Astrophysical signal from **annihilation** or **decay** to standard model particles

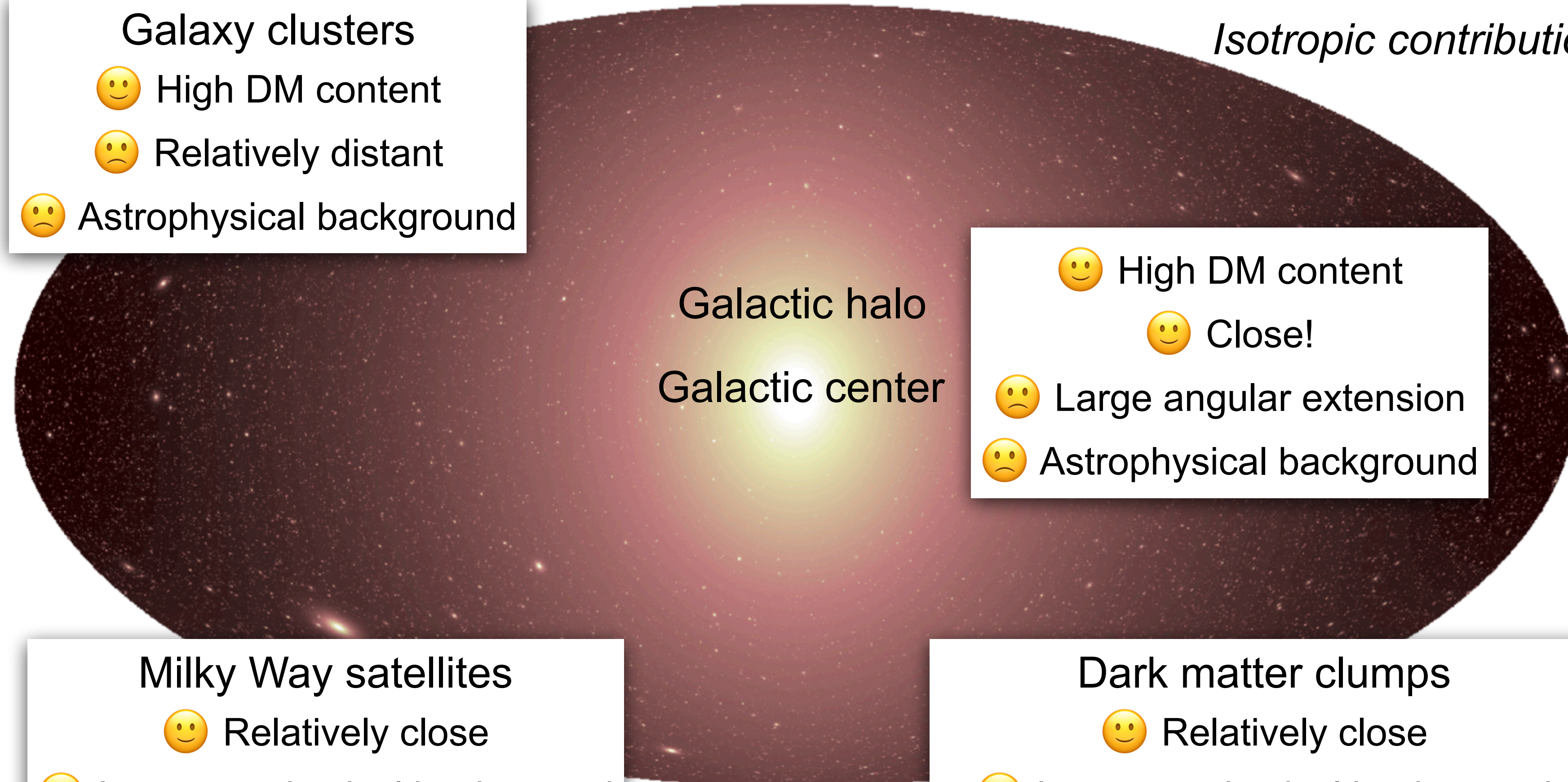
Focus on final-state **gamma rays**

Targets: Milky Way and Beyond



Balance between **signal strength** & astrophysical **backgrounds**
Litmus test: consistent signal from multiple targets

Targets: Advantages and Disadvantages



Galaxy clusters
- 🙂 High DM content
- 🙁 Relatively distant
- 🙁 Astrophysical background

Galactic halo / Galactic center
- 🙂 High DM content
- 🙂 Close!
- 🙁 Large angular extension
- 🙁 Astrophysical background

Milky Way satellites
- 🙂 Relatively close
- 🙂 Low astrophysical background
- 🙂 Modest angular extension
- 🙁 Modestly high DM content

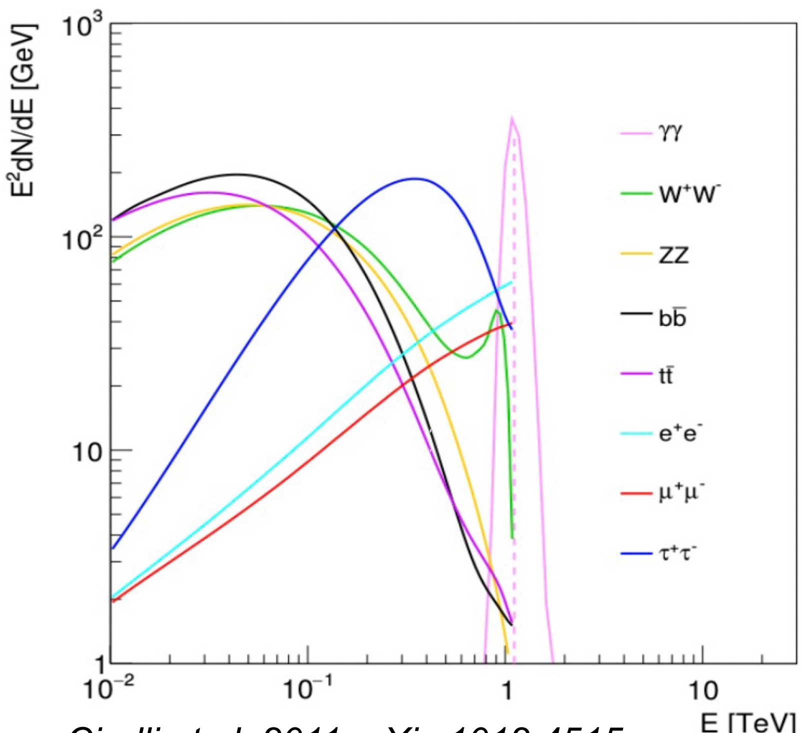
Dark matter clumps
- 🙂 Relatively close
- 🙂 Low astrophysical background
- 🙂 Modest angular extension
- 🙁 Very modest/uncertain DM content

Predicted Gamma-ray Signal

"Particle physics term"

$$\frac{\mathrm{d}^2\Phi\left(\langle\sigma v\rangle, J\right)}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1}{4\pi}\boxed{\frac{\langle\sigma v\rangle}{2M_\chi^2}\sum_f \mathrm{BR}_f \frac{\mathrm{d}N_f}{\mathrm{d}E}}\int_{\mathrm{l.o.s.}} \rho_{\mathrm{DM}}^2(r(s,\theta))\,ds$$

M_χ = 1 TeV



Cirelli et al. 2011 arXiv:1012.4515

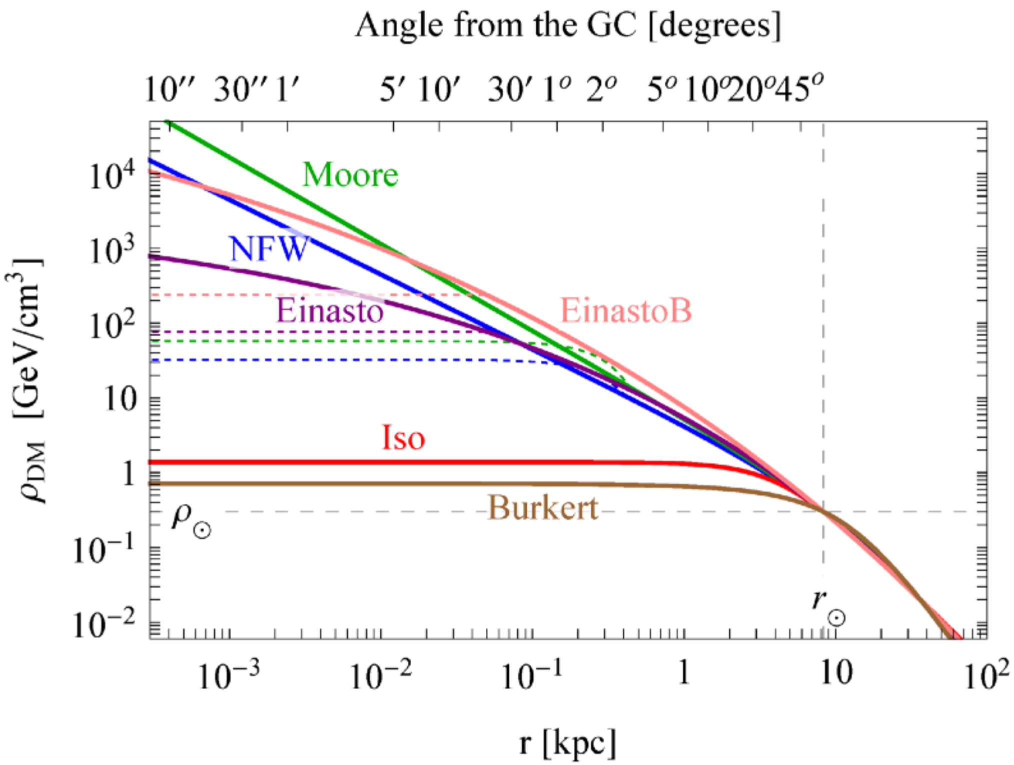
- Assuming branching ratio of 1 to a given final state
- Spectral shape is a key input!
  - Continuum emission from χχ → quark pairs, lepton pairs, W^+W^-, ZZ
    - Cut-off at M_χ (assuming annihilation)
  - "Line" emission from χχ → γX, X = h, Z, γ

Predicted Gamma-ray Signal

"Astrophysics term"

$$\frac{d^2\Phi\left(\langle\sigma v\rangle, J\right)}{dE\,d\Omega} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2M_\chi^2}\sum_f \mathrm{BR}_f \frac{dN_f}{dE}\int_{\mathrm{l.o.s.}} \rho^2_{\mathrm{DM}}(r(s,\theta))\, ds$$

J-factor

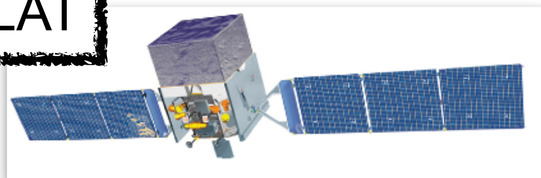


Cirelli et al. 2011 arXiv:1012.4515

- J-factor depends on
  - Dark matter distribution in target
  - Distance to target
  - Instrument response (point spread function)
- Significant source of uncertainty in extracted limits on ⟨σv⟩

Detecting Gamma Rays

Fermi-LAT



- Energy range: 20 MeV to 1 TeV
- Large duty-cycle
- Full-sky coverage

- Imaging Atmospheric Cherenkov Telescopes (IACTs)
  - E ~100 GeV to > 30 TeV
  - Precise energy & angular reconstruction
  - High sensitivity
  - Limited duty-cycle/FOV

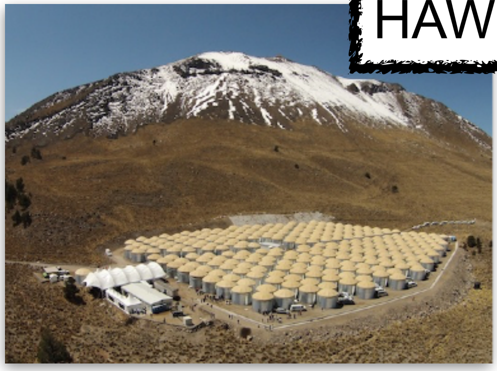
MAGIC

VERITAS

H.E.S.S.

- Water Cherenkov Technique
  - E ~1 - 100 TeV
  - Large duty-cycle
  - Large field of view

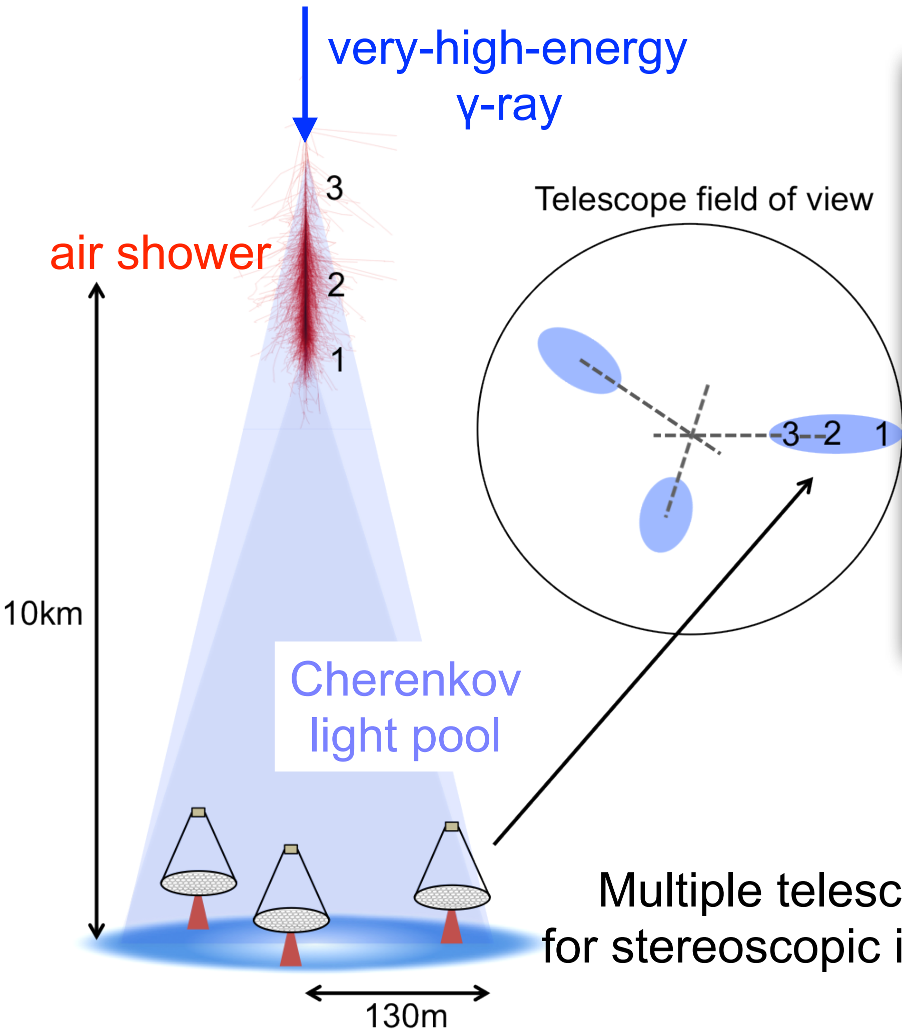
HAWC



- Multiple detection methods
  - E ~ < 1 TeV - 1 PeV
  - Large duty-cycle
  - Large field of view

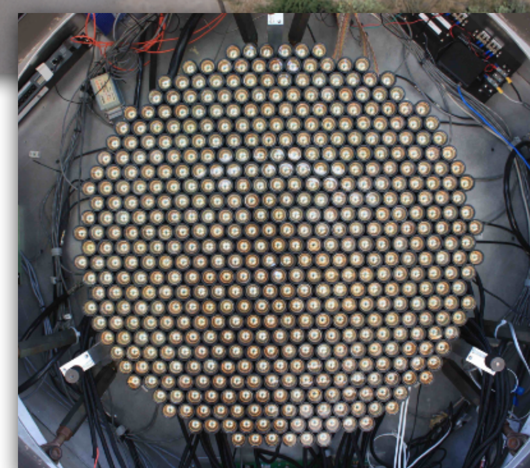
LHAASO

Imaging Atmospheric Cherenkov Technique



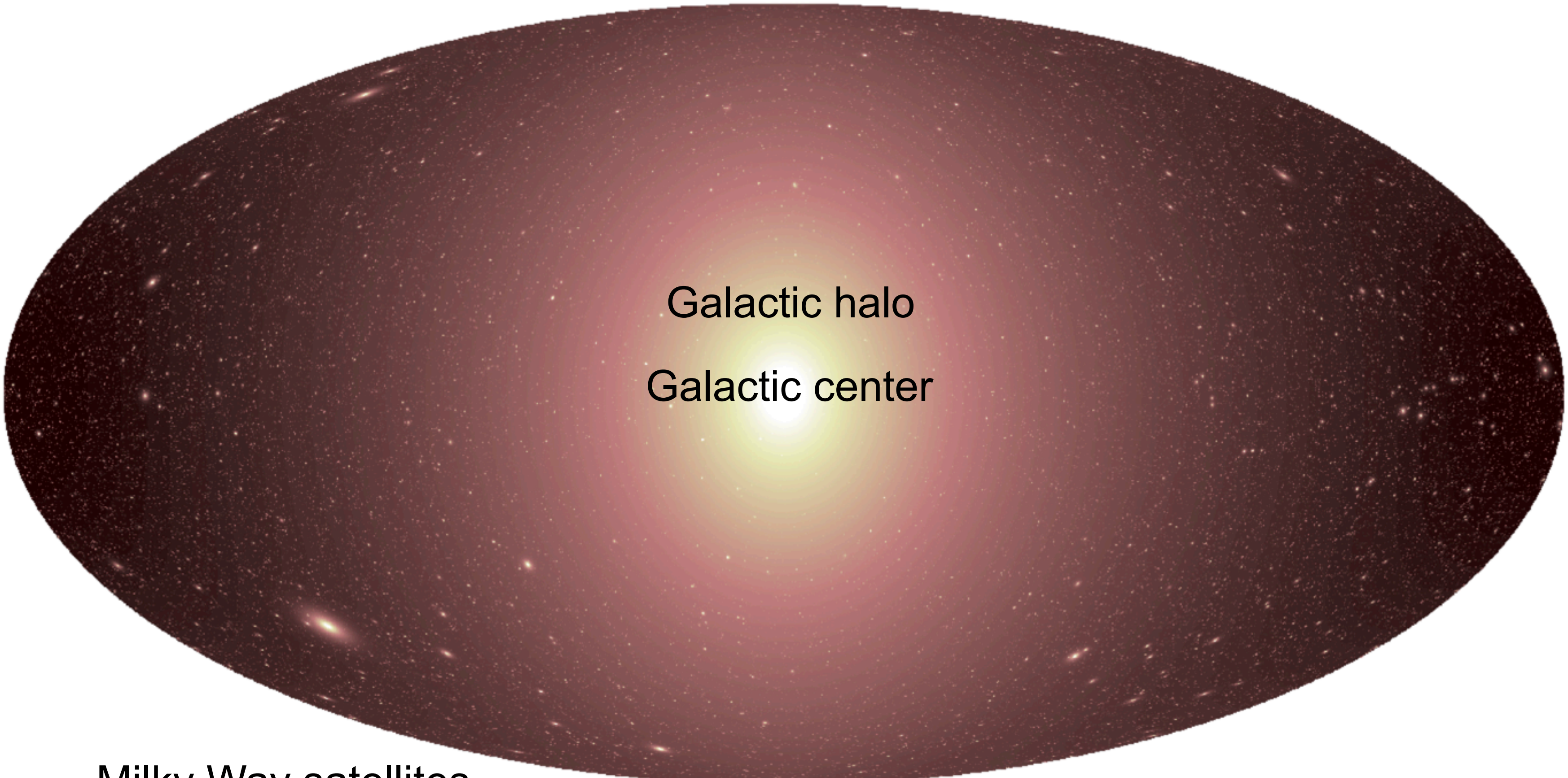
Multiple telescopes
for stereoscopic imaging

Credit: J. Holder



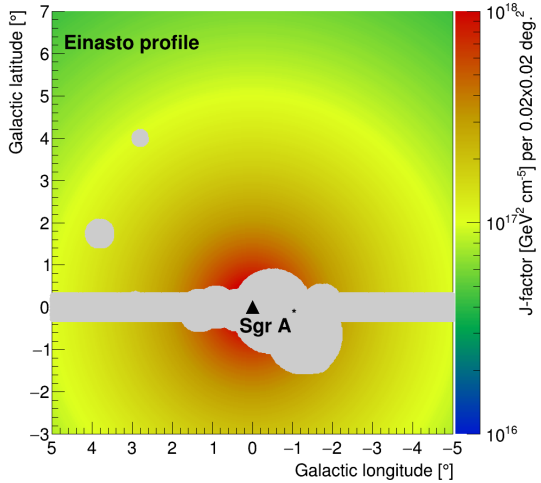
Photomultiplier tube cameras
for faint & fast signal

Searches for Dark Matter Annihilation



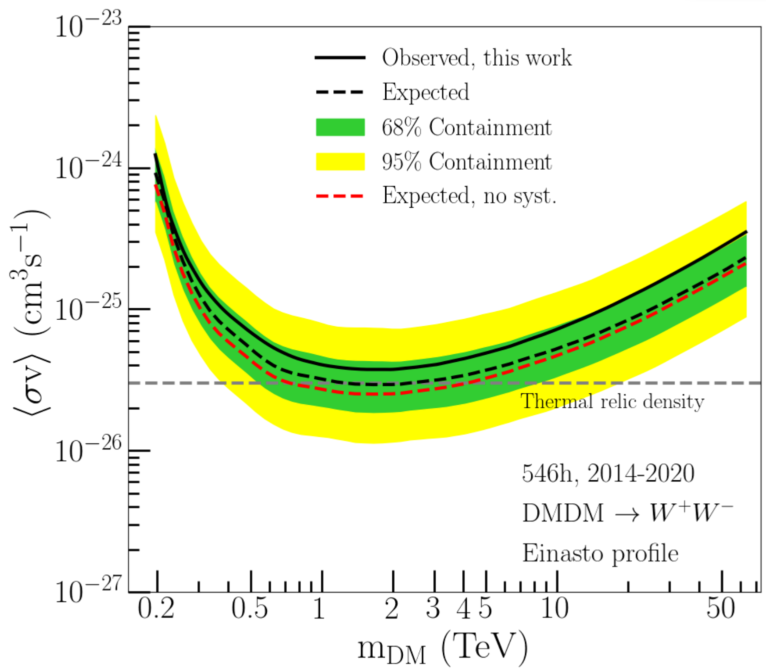
Milky Way satellites

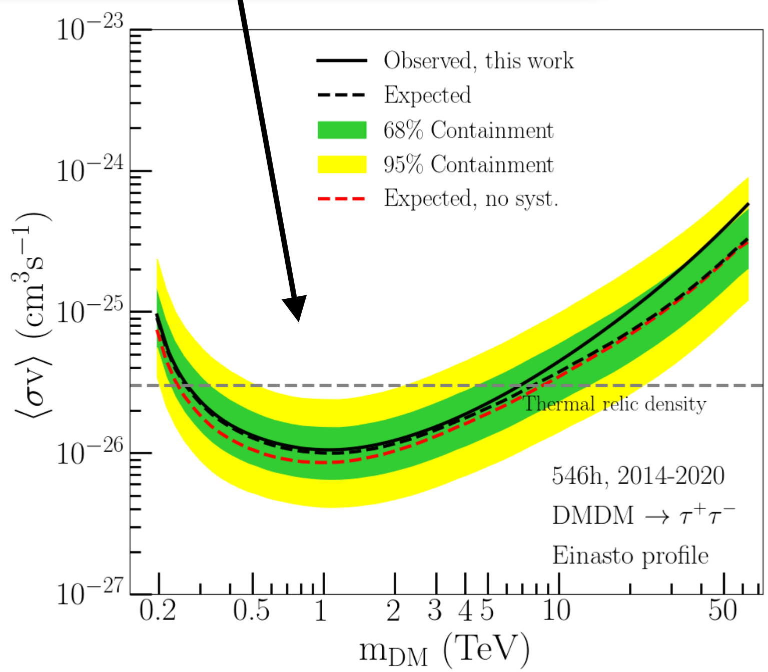
Annihilation in the Galactic Center: Continuum Emission



- H.E.S.S. location → good visibility for Galactic Center
- Deep survey observations of inner region of Galactic halo (546 hours, 5 telescopes)
- Exclude Galactic plane and known gamma-ray emitters

Probe below thermal relic density for annihilation to $\tau^+\tau^-$





H.E.S.S. collaboration 2022 arXiv:2207.10471

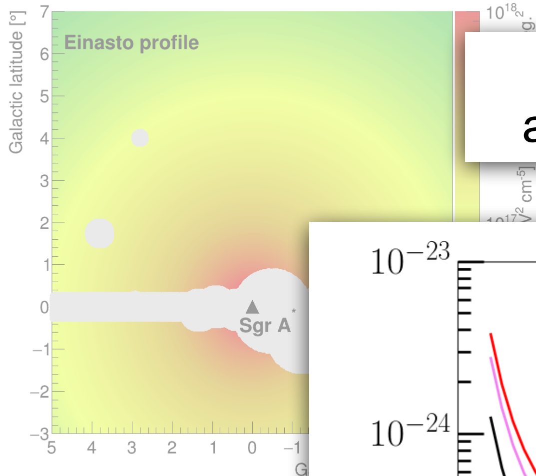
Annihilation in the Galactic Center: Continuum Emission

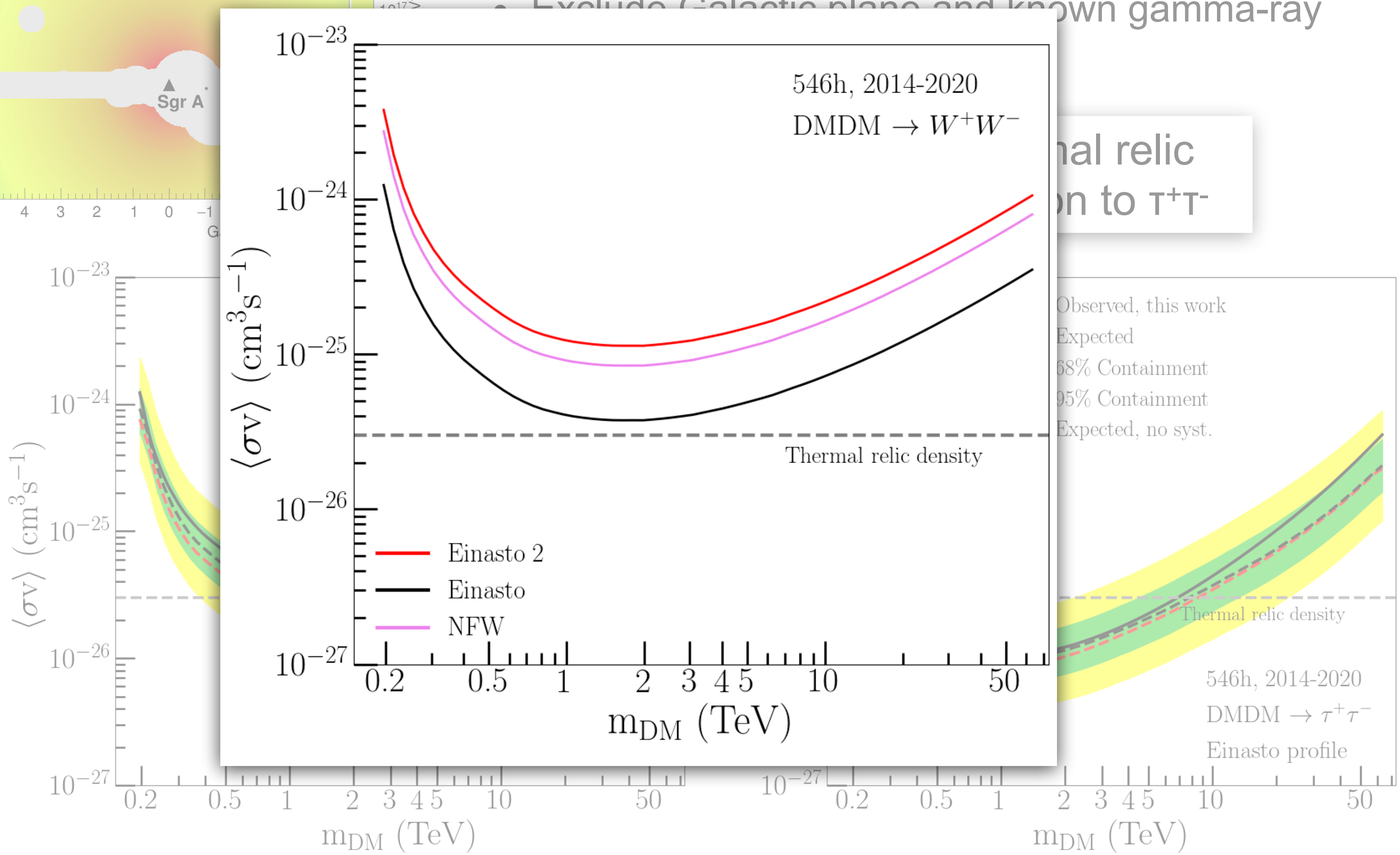
Strong dependence on assumed dark matter profile

isibility for Galactic Center
f inner region of Galactic
halo (546 hours)

- Exclude Galactic plane and known gamma-ray

nal relic
on to $\tau^+\tau^-$



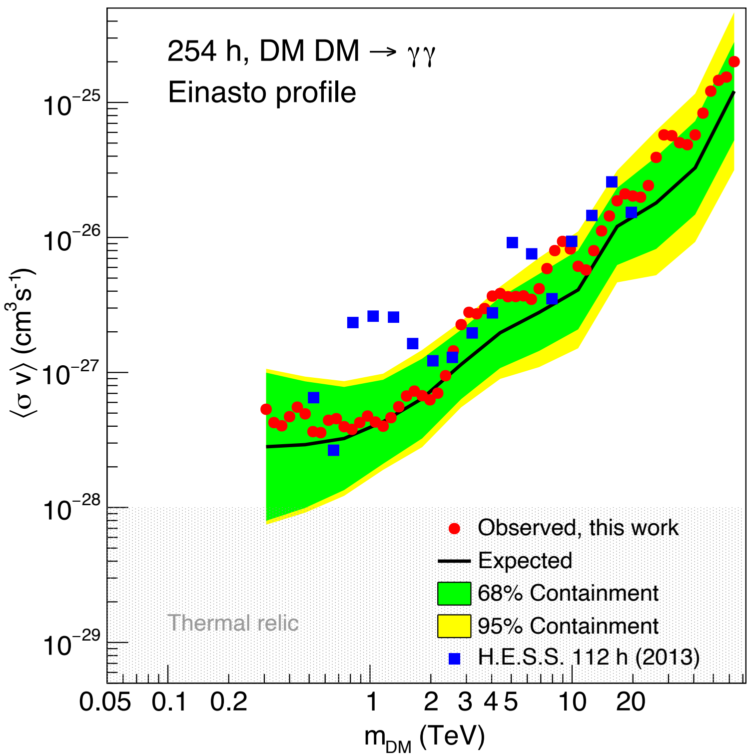


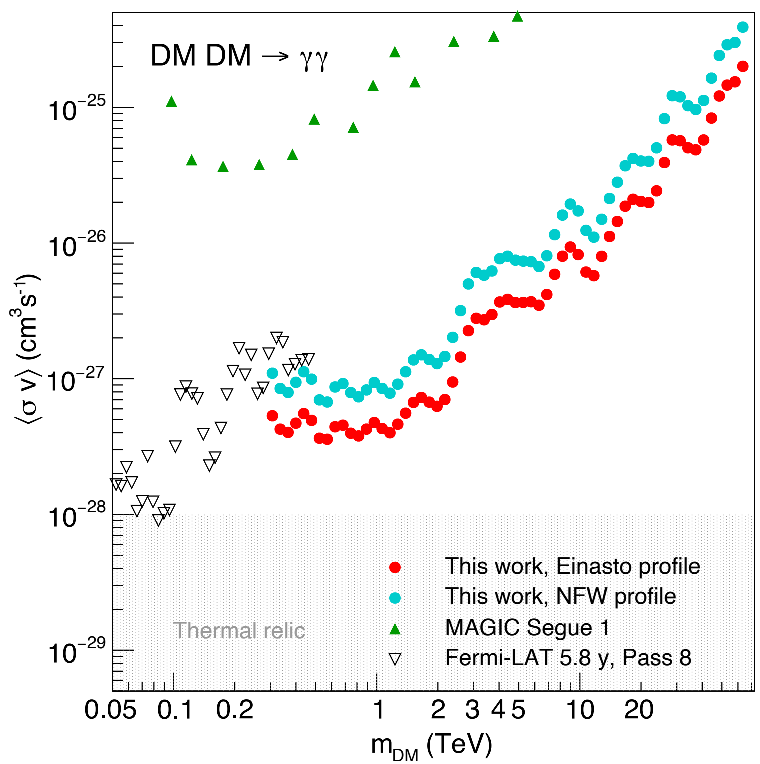
H.E.S.S. collaboration 2022 arXiv:2207.10471

Annihilation in the Galactic Center: Line Emission

- H.E.S.S. location → good visibility for Galactic Center
- Earlier survey observations of inner region of Galactic halo (254 hours, 4 telescopes)
- Gaussian “line” at $E_\gamma = M_\chi$ with width set by H.E.S.S. energy resolution @ E_γ

Approaching thermal relic cross section (note loop suppression)

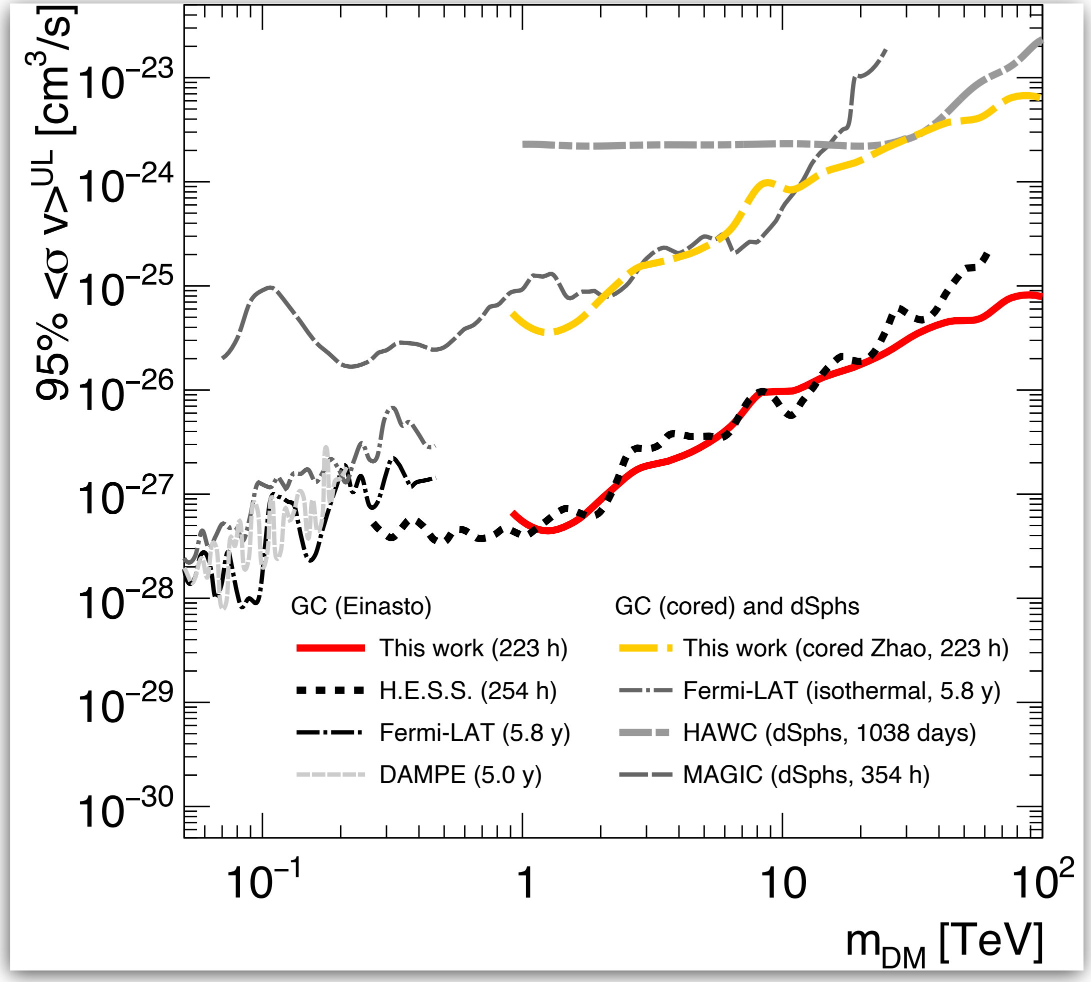




H.E.S.S. collaboration 2018 arXiv:1805.05741

Annihilation in the Galactic Center: Line Emission

Similar limits from MAGIC with 223 hours of observation



MAGIC collaboration 2022 arXiv:2212.10527

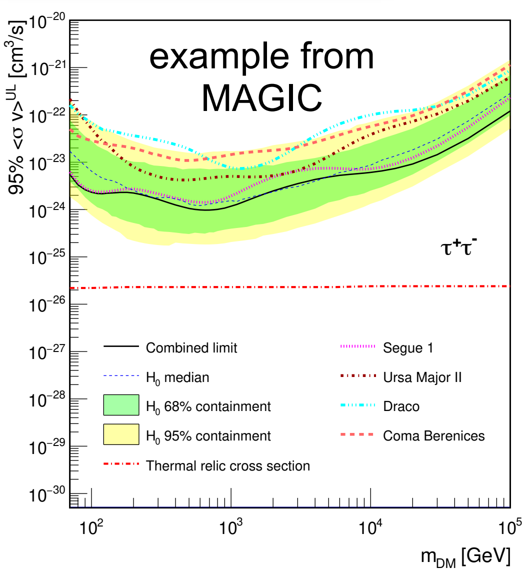
Annihilation in Dwarf Spheroidal Galaxies

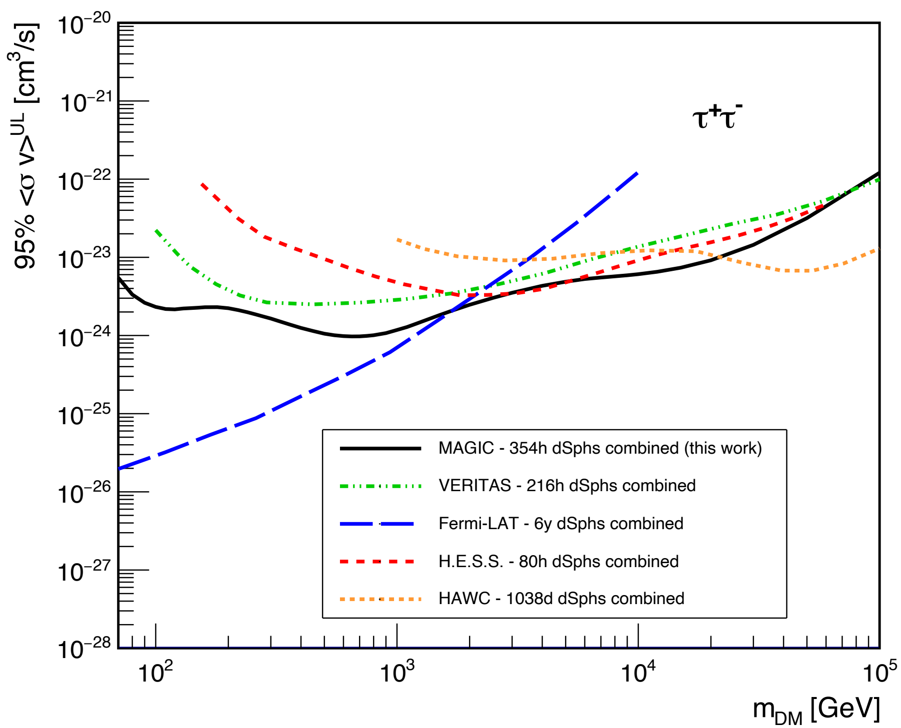
H.E.S.S.	Live time (hours)
Reticulum II	18.3
Tucana II	16.4
Tucana III	23.6
Tucana IV	12.4
Grus II	11.3

MAGIC	Exposure (hours)
Coma Berenices	49.5
Draco	52.1
Ursa Major II	94.8
Segue 1	157.9

VERITAS	Exposure (hours)
Segue 1	92.0
Draco	49.8
Ursa Minor	60.4
Boötes 1	14.0
Willman 1*	13.6

New targets from Dark Energy Survey





H.E.S.S. collaboration 2020 arXiv:2008.00688

MAGIC collaboration 2022 arXiv:2111.15009

VERITAS collaboration 2017 arXiv:1703.04937

Annihilation in Dwarf Spheroidal Galaxies

H.E.S.S.	Exposure (hours)
Reticulum II	18.3
[illegible]	[illegible]
Grus II	11.3

MAGIC	Exposure (hours)
Coma Berenices	49.5
Draco	[illegible]
Ursa Major II	[illegible]
Segue 1	[illegible]

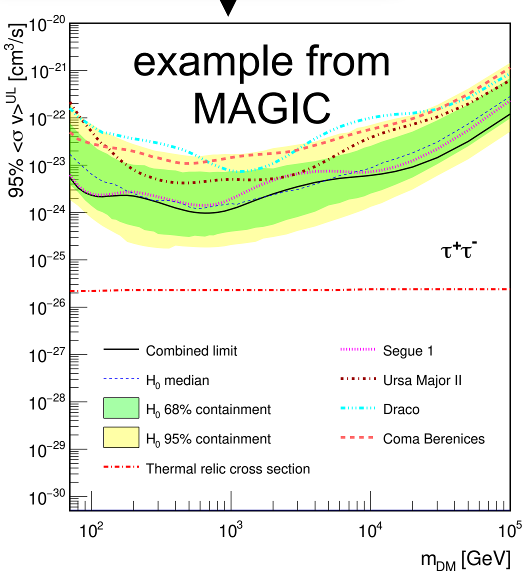
VERITAS	Exposure (hours)
Segue 1	92.0
[illegible]	[illegible]
Willman 1*	13.6

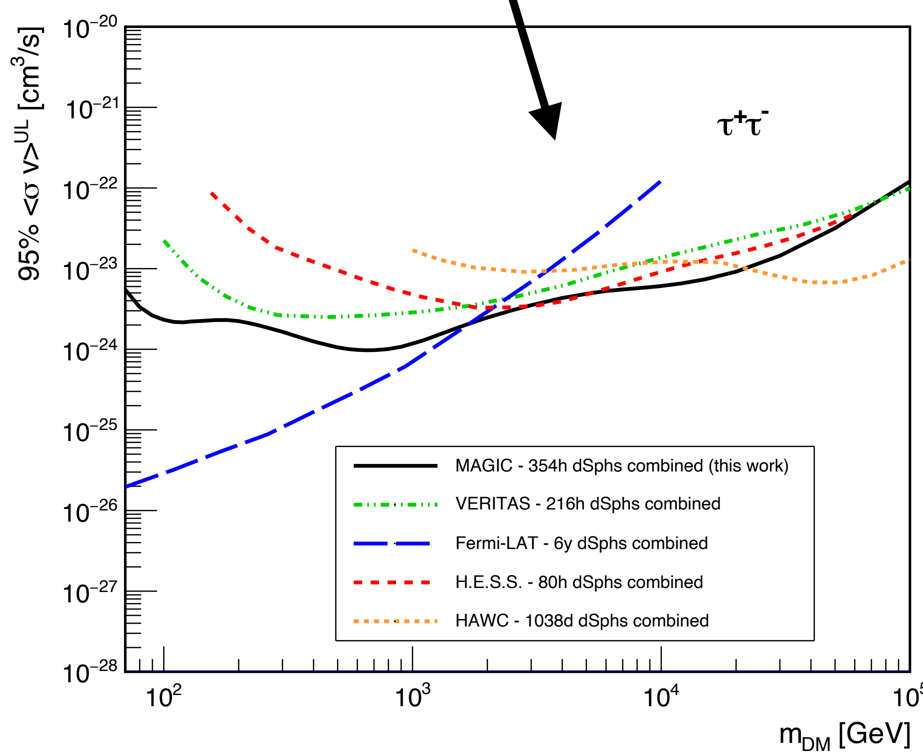
Still ~2 orders of magnitude from the thermal relic cross section

IACT limits are most sensitive available between ~1 TeV & ~10 TeV

New targets from Dark Energy Survey

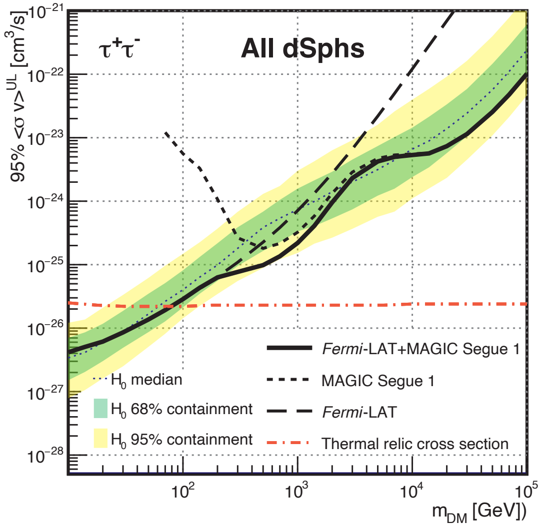
example from MAGIC

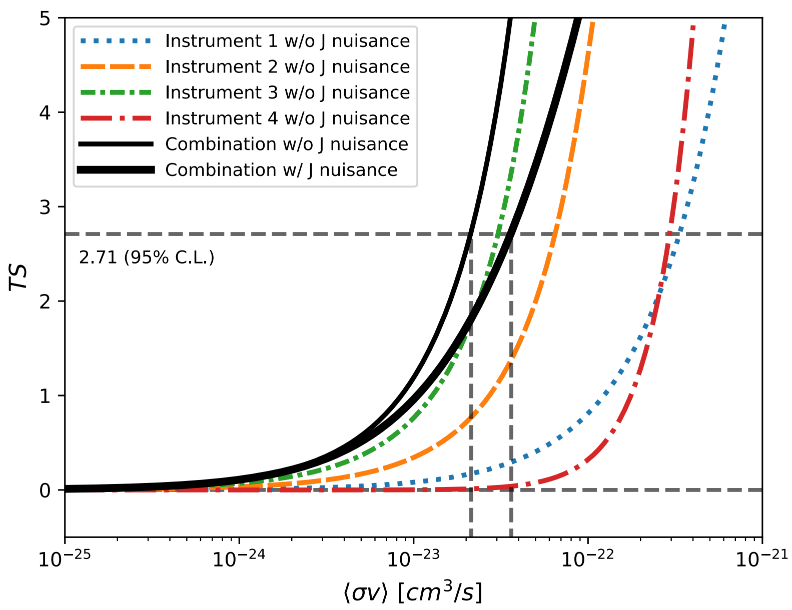




Joint Dark Matter Limits from Gamma Rays

- Combine gamma-ray results
  - Improve statistical power
  - Present consistent picture
- Groundwork: MAGIC + Fermi-LAT combined likelihood analysis (*arXiv:1601.06590*)
- Combine Fermi-LAT, H.E.S.S., MAGIC, VERITAS, HAWC datasets





- Each instrument performs likelihood analysis with internal software
- Common statistical format
  - Share high-level data
- Common expected signal inputs
  - Expected photon spectrum from Cirelli et al. 2011 *(arXiv:1012.4515)*
  - Identical J-factors

Joint Gamma-ray Limits: Observation Summary

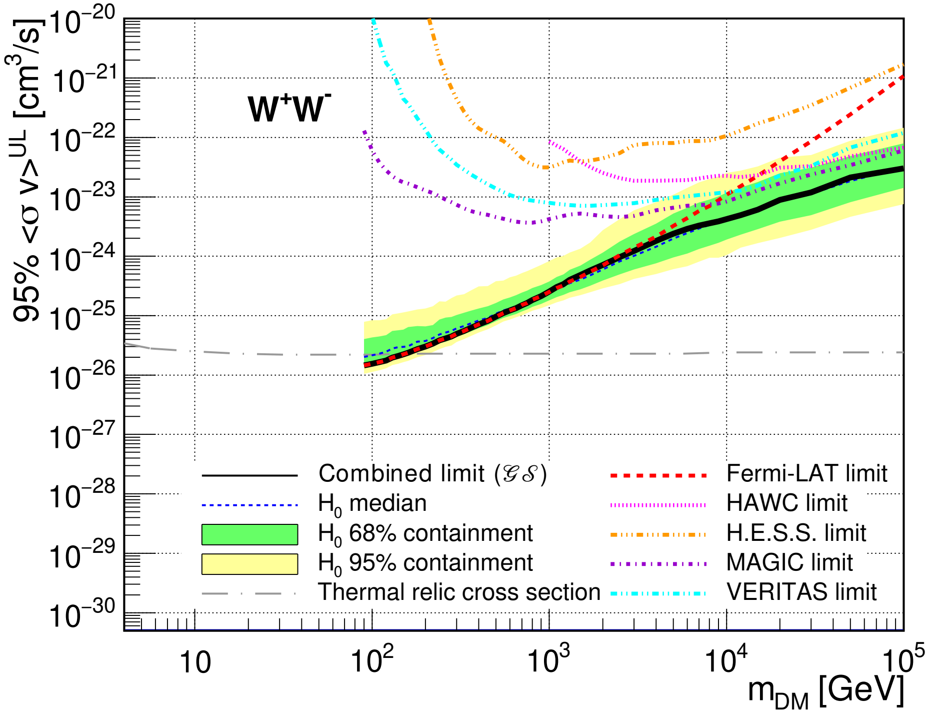
Dwarf Spheroidal Galaxy	IACT	IACT Exposure (hours)	HAWC
Böotes I	VERITAS	14.0	✓
Canes Venatici I			✓
Canes Venatici II			✓
Carina	H.E.S.S.	23.7	
Coma Berenices	H.E.S.S., MAGIC	11.4, 49.5	✓
Draco	MAGIC, VERITAS	52.1, 49.8	✓
Fornax	H.E.S.S.	6.8	
Hercules			✓
Leo I			✓
Leo II			✓
Leo IV			✓
Leo V			
Leo T			
Sculptor	H.E.S.S.	11.8	
Segue 1	MAGIC, VERITAS	158.0, 92.0	✓
Segue 2			
Sextans			✓
Ursa Major I			✓
Ursa Major II	MAGIC	94.8	✓
Ursa Minor	VERITAS	60.4	

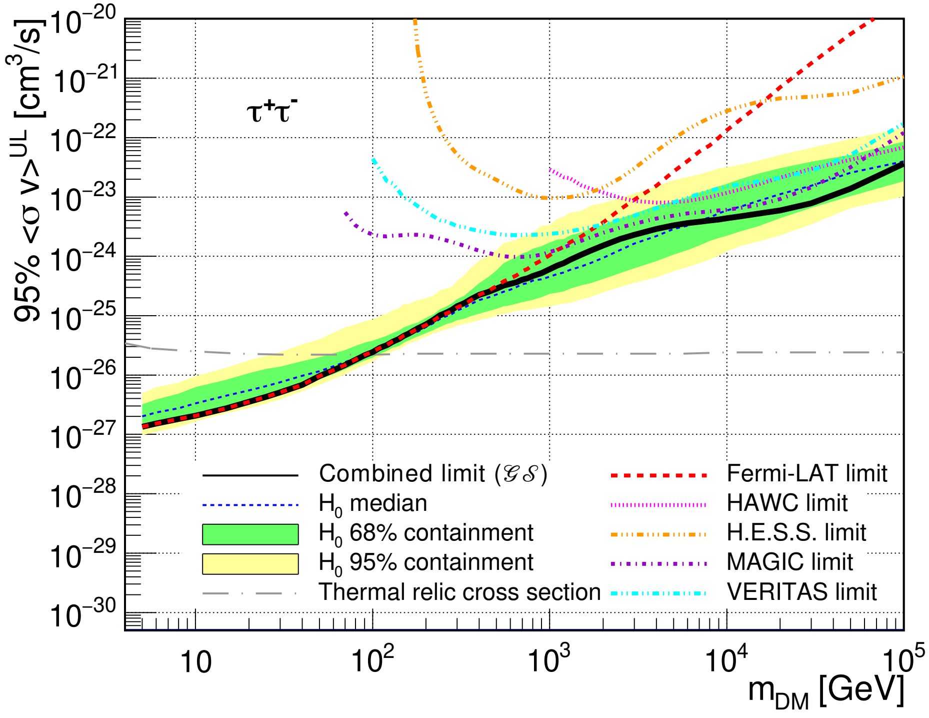
Fermi-LAT exposure on all objects

- 20 dwarf spheroidal galaxies observed, including classical and ultrafaint objects
- ~625 hours IACT, 10 years Fermi-LAT, ~1000 days HAWC observations

Joint Gamma-ray Limits: Results

No signal observed; extract 95% confidence level limits on dark matter annihilation cross section

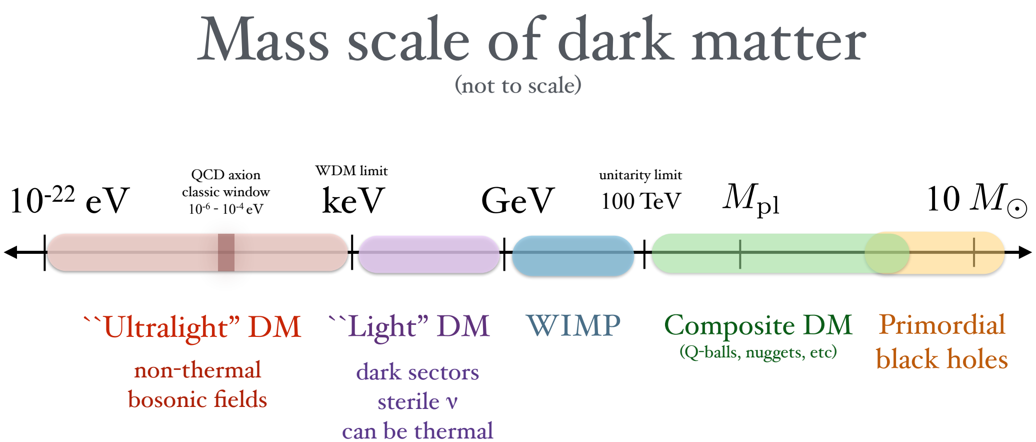




Factor 2-3 improvement in limits

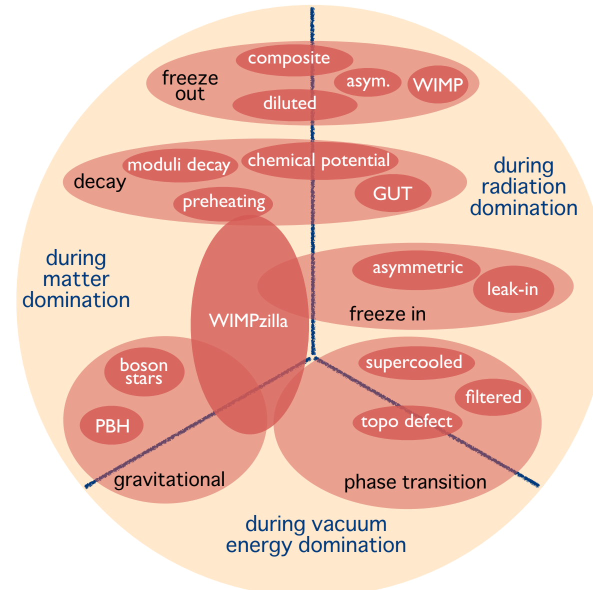
Consistency between observed and expected limits

Beyond WIMPs: Ultra-heavy Dark Matter



Lin 2019 arXiv:1904.07915

production of ultra-heavy dark matter



Carney et al. 2022 arXiv:2203.06508

- Searches with IACTs motivated by TeV-scale weakly interacting massive particles (M_χ ~ 0.1 - 1 TeV)
  - More phase space to explore
    - Current & future instruments detect gamma rays that access > 100 TeV dark matter annihilation

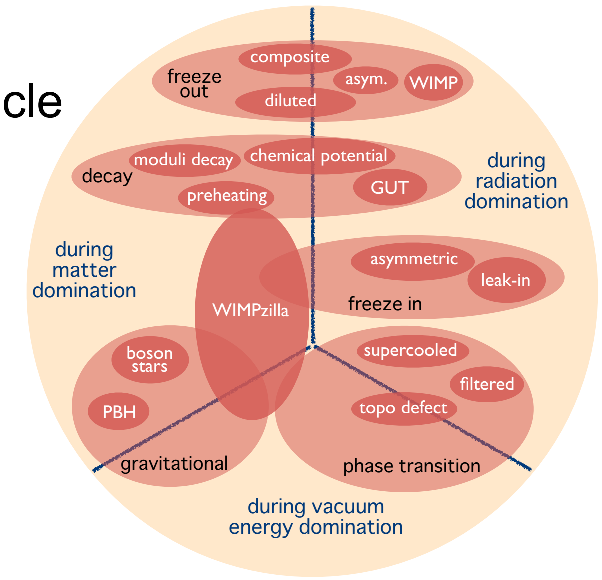
Unitarity Bound and Ultra-heavy Dark Matter

Simple thermal-relic scenario with point-like DM particle
→ heavy DM (>~100-200 TeV) overproduced

$$\langle \sigma v \rangle_{max} \propto \frac{1}{M_\chi^2} \quad \text{(unitarity limit)}$$

and $$\Omega_\chi \propto \frac{1}{\langle \sigma v \rangle} \quad \text{(thermal relic)}$$

production of ultra-heavy dark matter



Carney et al. 2022 arXiv:2203.06508

- Unitarity bound can be evaded with various extensions
  - Dark sector: *Berlin et al. 2016 (arXiv:1602.08490)*,…
  - Composite DM (with/without geometrical cross section): *Baldes et al. 2022 (arXiv:2110.13926)*, *Harigaya et al. 2019 (arXiv:1606.00159), Contino et al. 2019 (arXiv:1811.06975)*,…
  - Capture to bound states: *Geller et al. 2018 (arXiv:1802.07720)*,…

From TeV Gamma Rays to PeV Dark matter

Study sensitivity to UHDM annihilation for three instruments

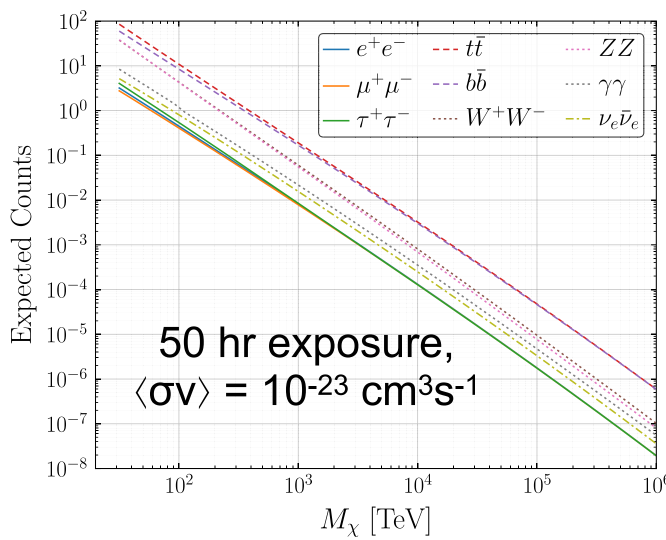
Tak et al. 2022
arXiv:2208.11740

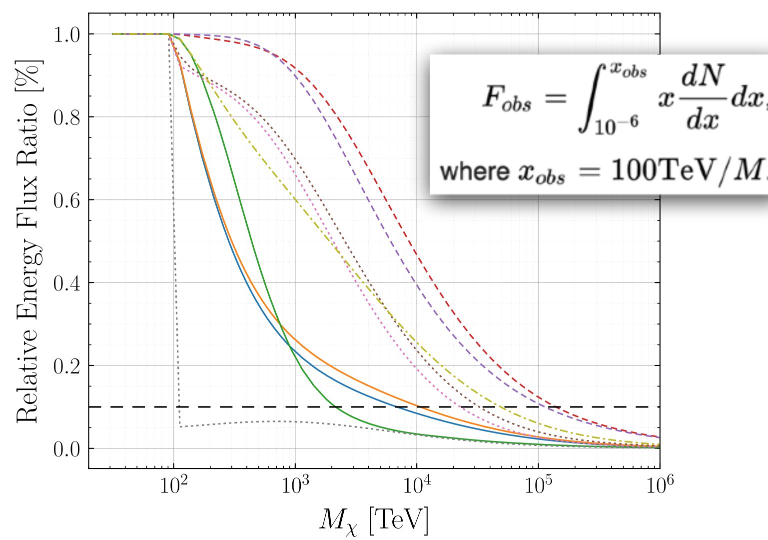
VERITAS-like instrument

HAWC-like instrument

Cherenkov Telescope Array

- All instruments considered detect gamma rays up to ~100 TeV
  - Corresponds to a much heavier initial dark matter particle





>10% flux deposited in <100 TeV gamma rays for DM particles up to PeV masses

From TeV Gamma Rays to PeV Dark matter

Tak et al. 2022
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Study sensitivity to UHDM annihilation for three instruments

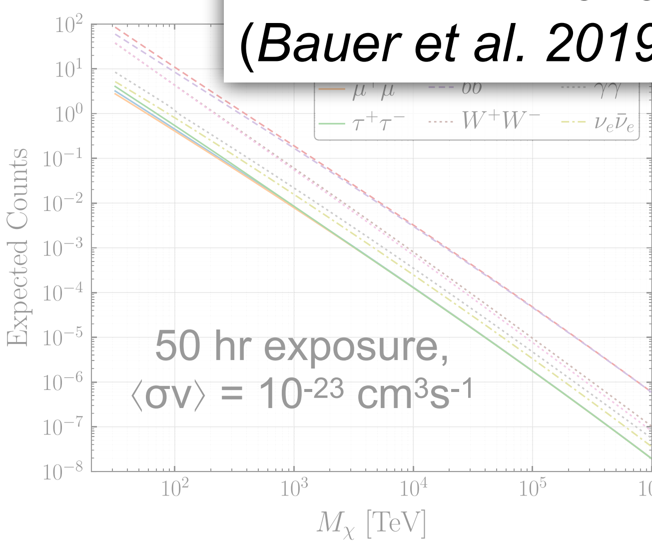
VERITAS-like instrument

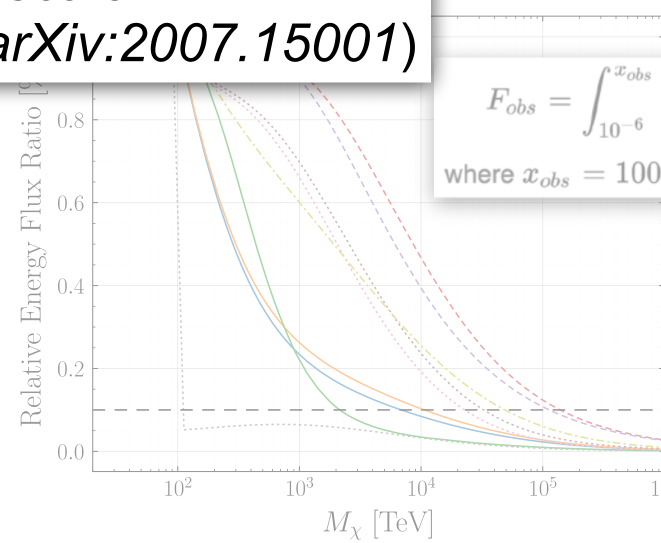
HAWC-like instrument

Cherenkov Telescope Array

- All instruments c … TeV
  - Correspond … icle

Enabled by new calculation of gamma-ray spectrum for DM annihilation with DM masses to Planck scale
(*Bauer et al. 2019 arXiv:2007.15001*)



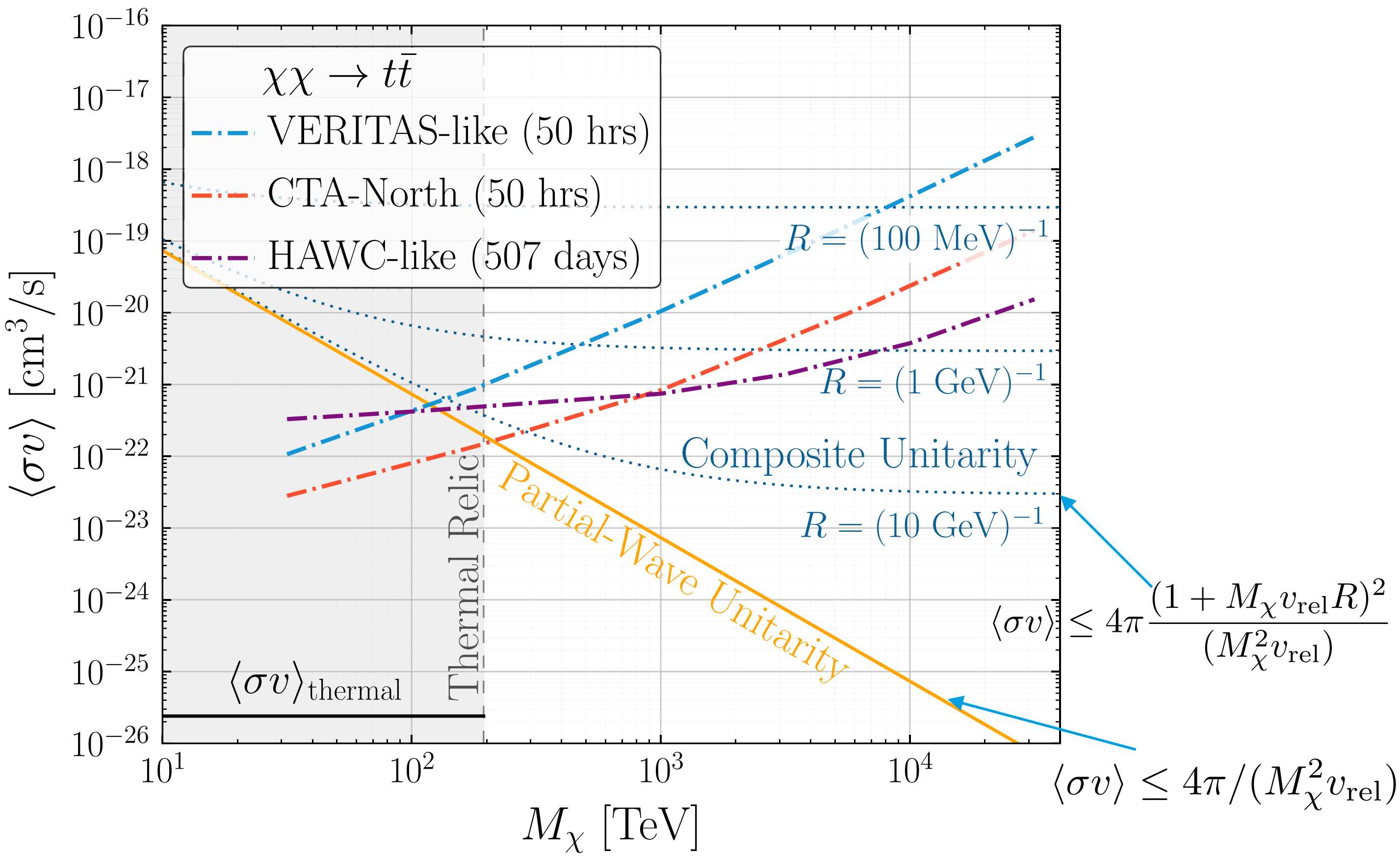


$$F_{obs} = \int_{10^{-6}}^{x_{obs}} x \frac{dN}{dx} dx,$$

where $x_{obs} = 100\text{TeV}/M$.

>10% flux deposited in <100 TeV gamma rays for DM particles up to PeV masses

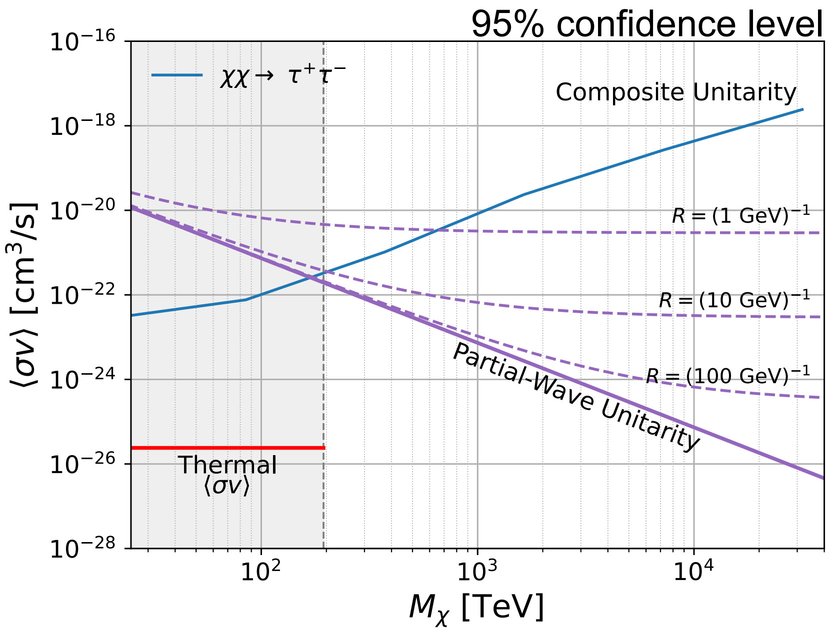
Expected Limits in Theoretical Context

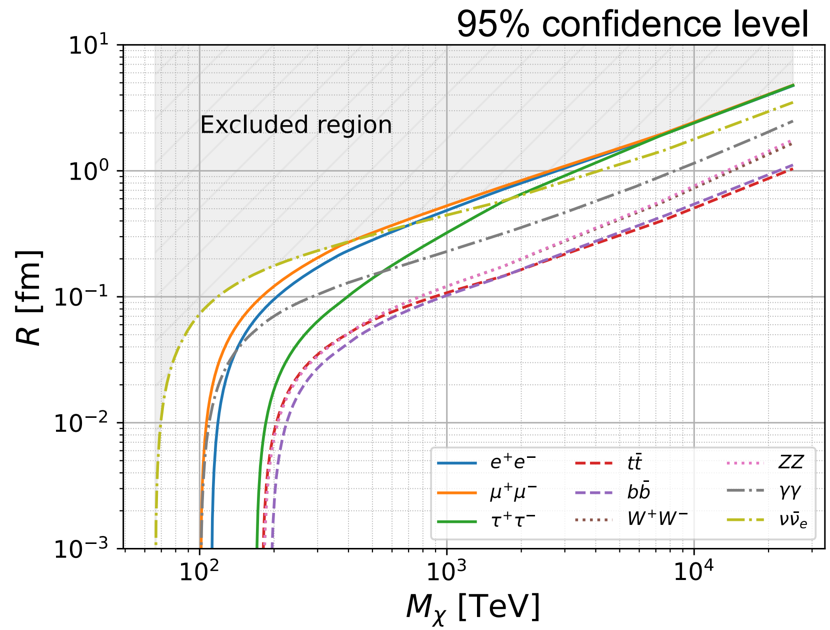


- Expected limits (95% confidence level) on annihilation cross section based on (shallow) observations of Segue 1
- Constrain benchmark scenario set by partial-wave unitarity below 100 TeV
- Constrain benchmark scenarios set by composite unitarity for particle radius > (100 MeV)$^{-1}$

~~Expected~~ Observed UHDM Limits from VERITAS

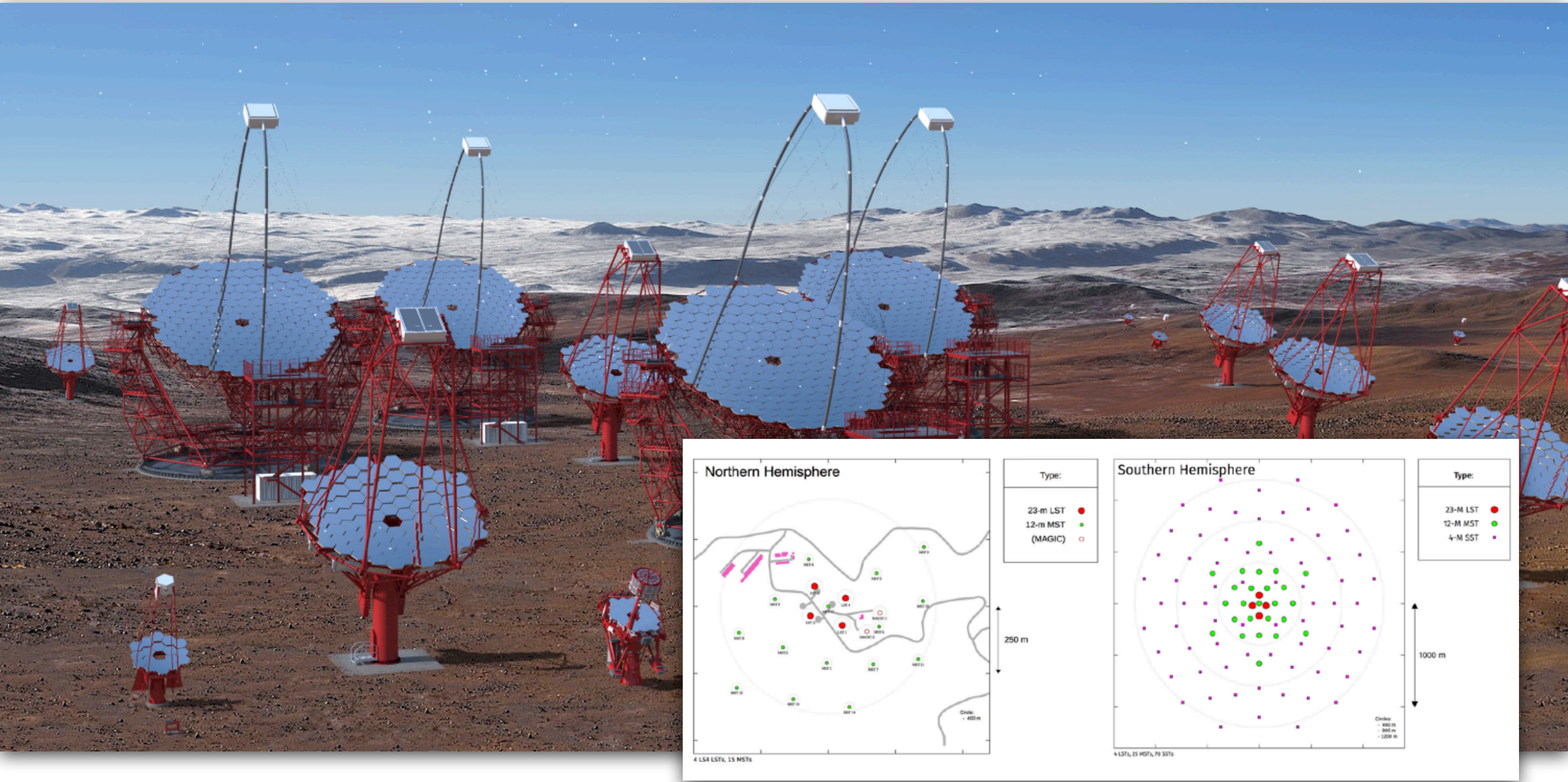
VERITAS collaboration 2023
arXiv:2302.08784





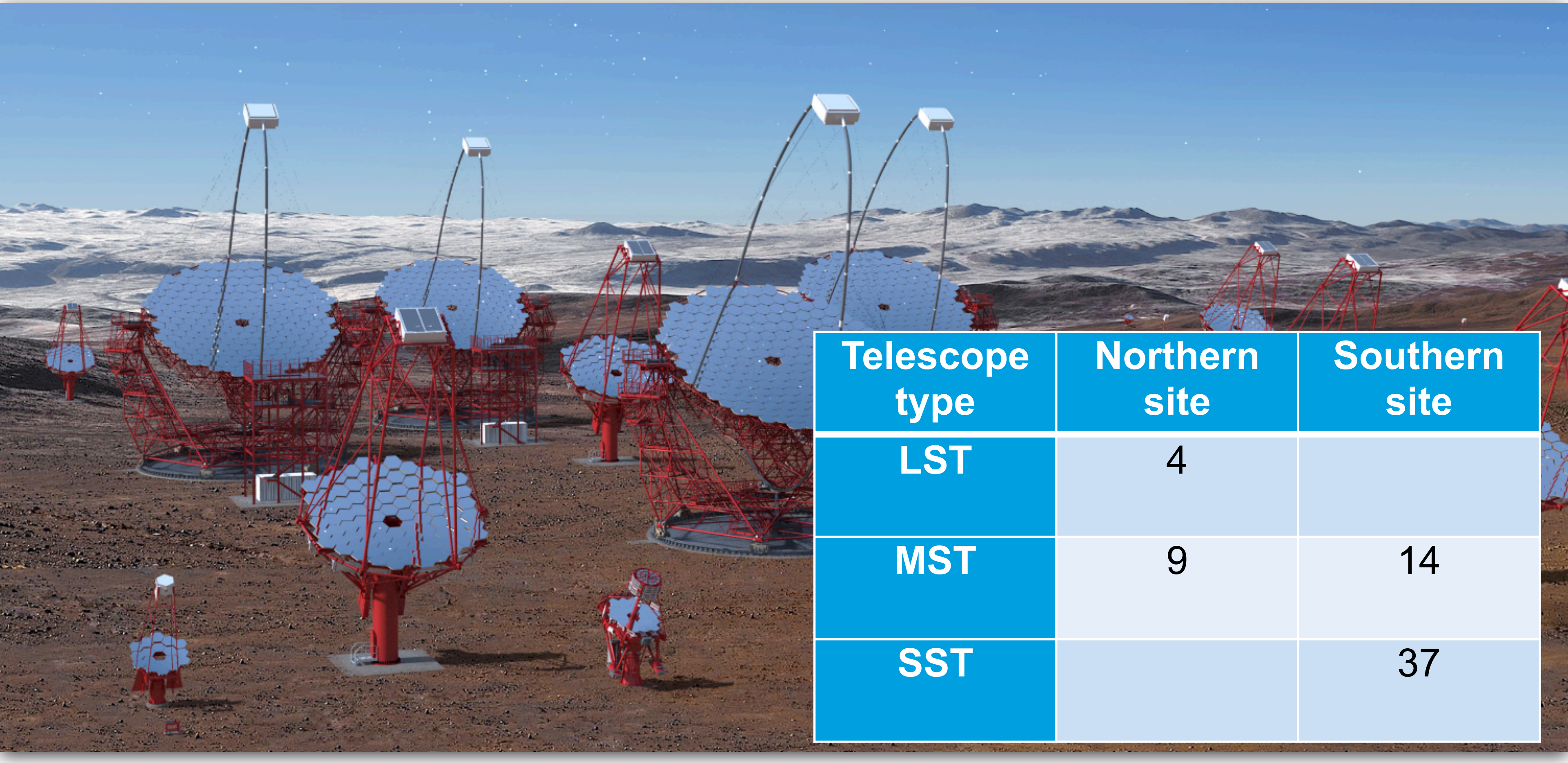
- Repurpose published VERITAS dwarf spheroidal observations for UHDM search
- Constraining limits <200 TeV for benchmark scenario considering partial-wave unitarity bound
- Set limits on radius of a composite particle with a geometric cross section

Prospectives: Cherenkov Telescope Array



- **Two arrays** for observations of northern and southern sky (La Palma & Paranal)
- **Three telescope sizes** for broad energy coverage
  - LSTs (23 m diameter dish), MSTs (12 m), SSTs (4 m)

Cherenkov Telescope Array: Alpha Array

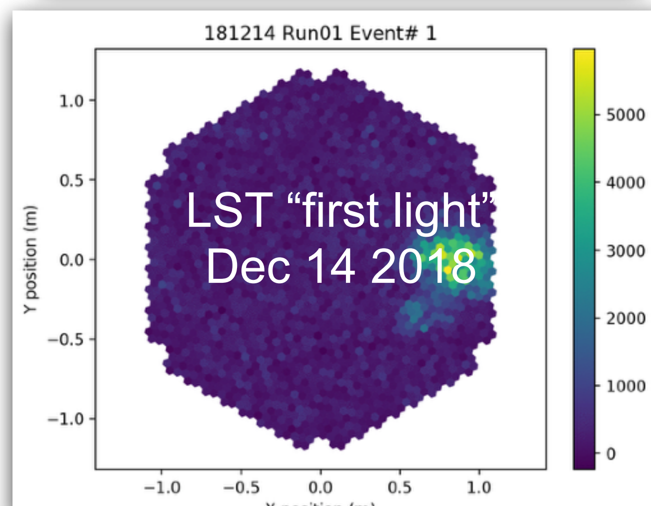


Telescope type	Northern site	Southern site
LST	4	
MST	9	14
SST		37

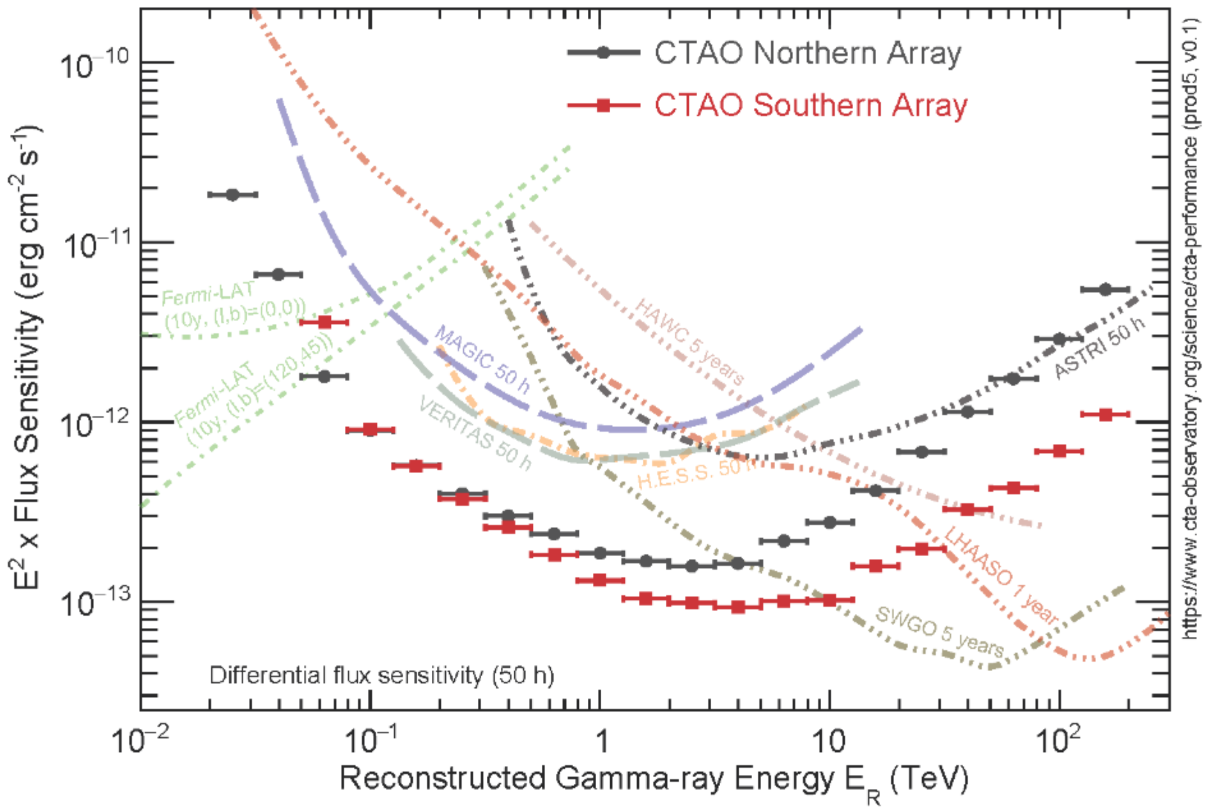
- **Two arrays** for observations of northern and southern sky (La Palma & Paranal)
- **Three telescope sizes** for broad energy coverage
  - LSTs (23 m diameter dish), MSTs (12 m), SSTs (4 m)

Prototyping & Construction

- Prototypes well-advanced for all telescope types
- First LST finishing commissioning, further LSTs in production
- MST/SST production and start of further construction upcoming



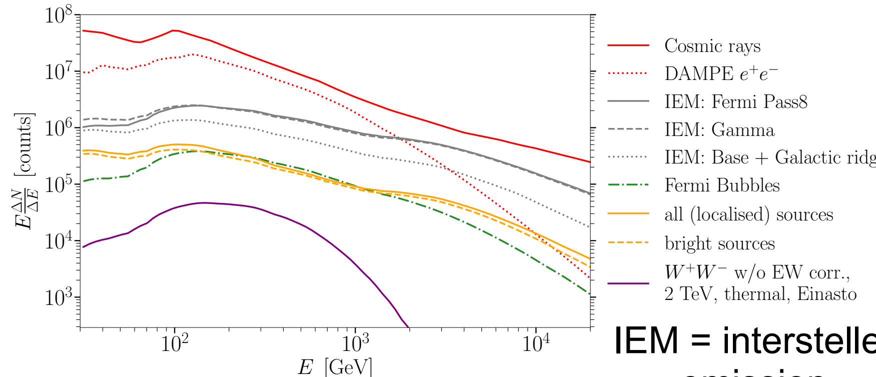
CTA Flux Sensitivity



- Factor of 5-20 improvement in sensitivity
- Factor of ~5 improvement angular & energy resolution
- Better performance for all dark matter targets: Galactic Center, dwarf spheroidal galaxies, galaxy clusters, dark matter subhalos…

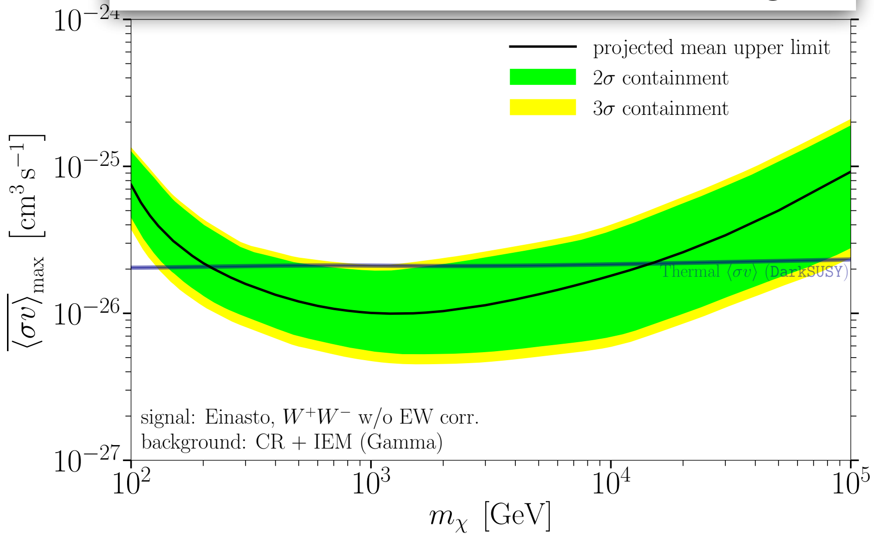
Dark Matter in the Galactic Center with CTA

- Galactic Center survey: 525 hours
- Extended survey: 300 hours
- Background templates derived mainly from Fermi-LAT & H.E.S.S. measurements

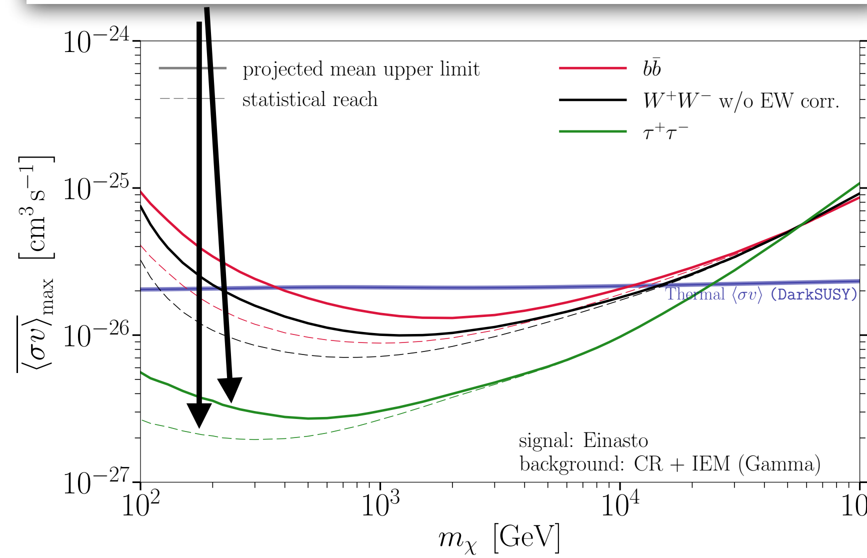


IEM = intersteller emission

Probe below thermal relic cross section for a broad mass range



Note impact of systematic uncertainties

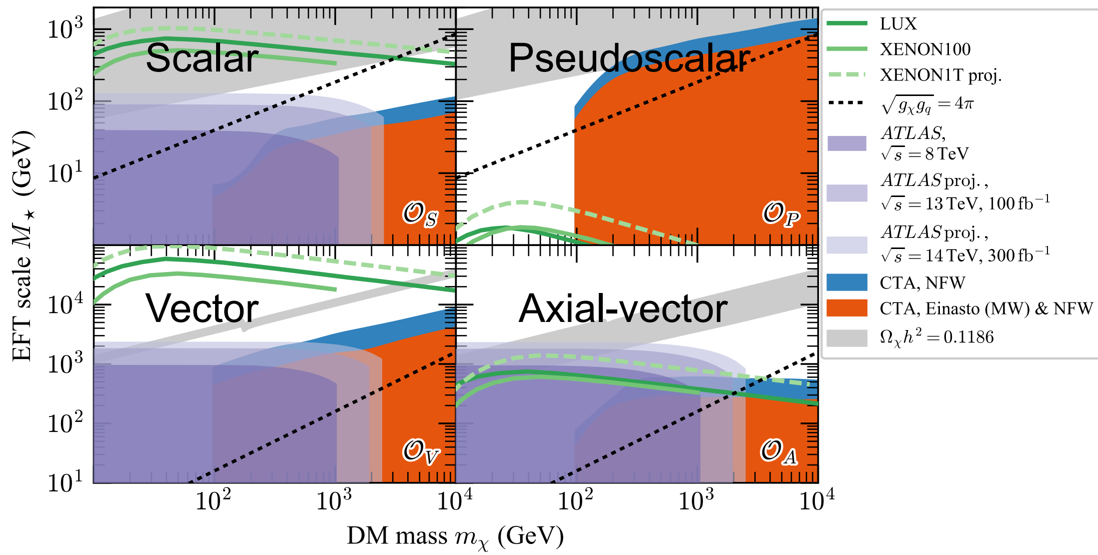


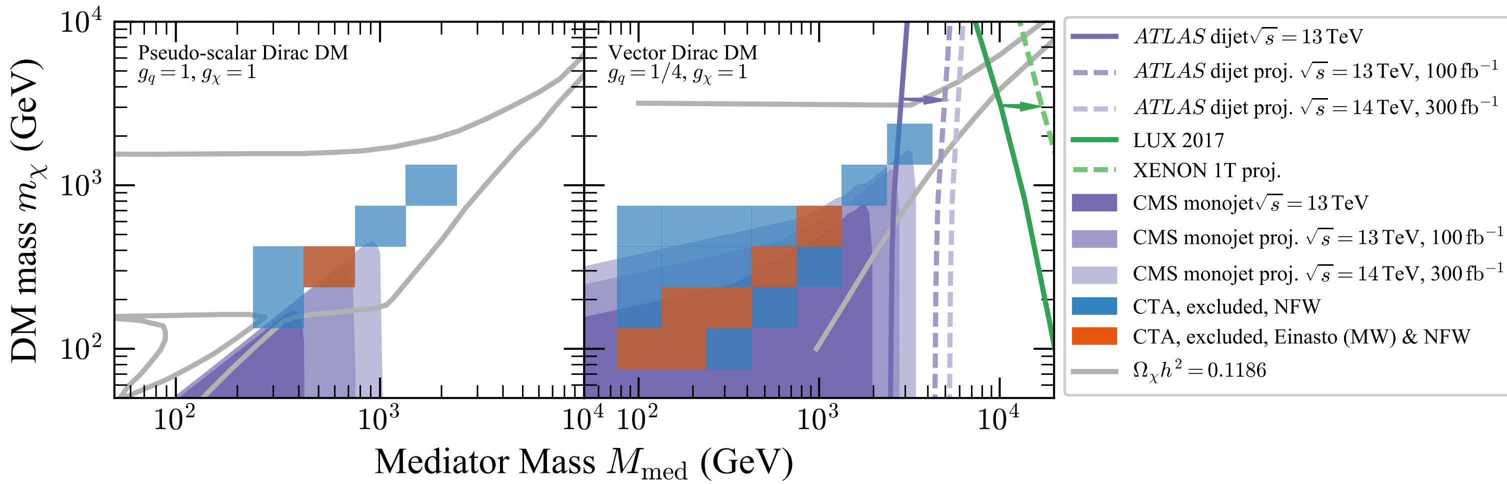
* Cored DM profile decreases sensitivity by factor of a few

CTA consortium 2021 arXiv:2007.16129

CTA Dark Matter Limits in Context

- Galactic Center survey: 100 hr
- Projected limits on
  - Effective field theory operators with Dirac fermion DM
  - Mediator mass for simplified models with Dirac fermion DM
- Compare with direct detection & collider prospects





Balázs et al. 2017 arXiv:1706.01505

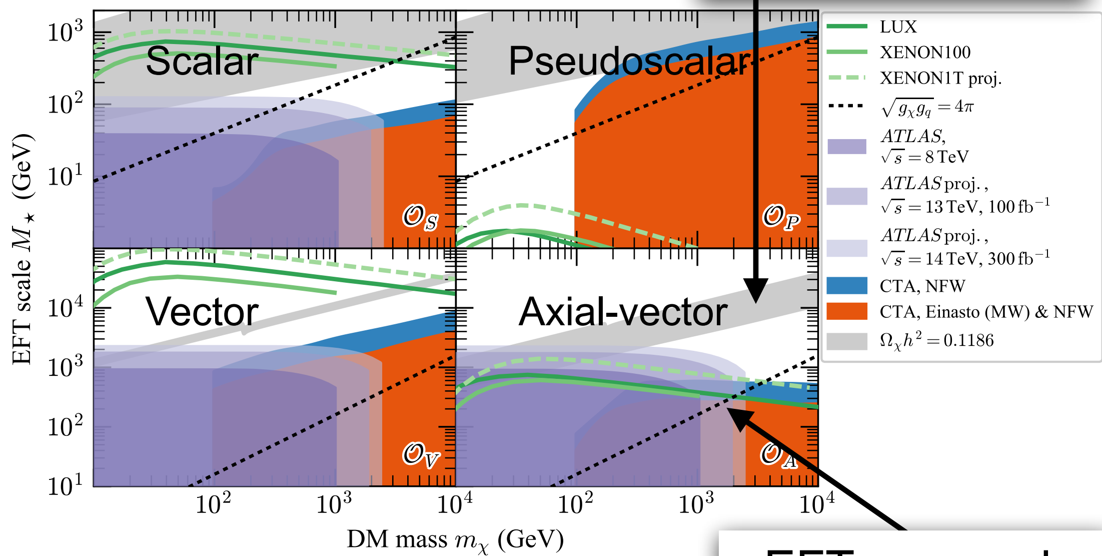
CTA Dark Matter Limits in Context

- Galactic Center survey: 100 hr

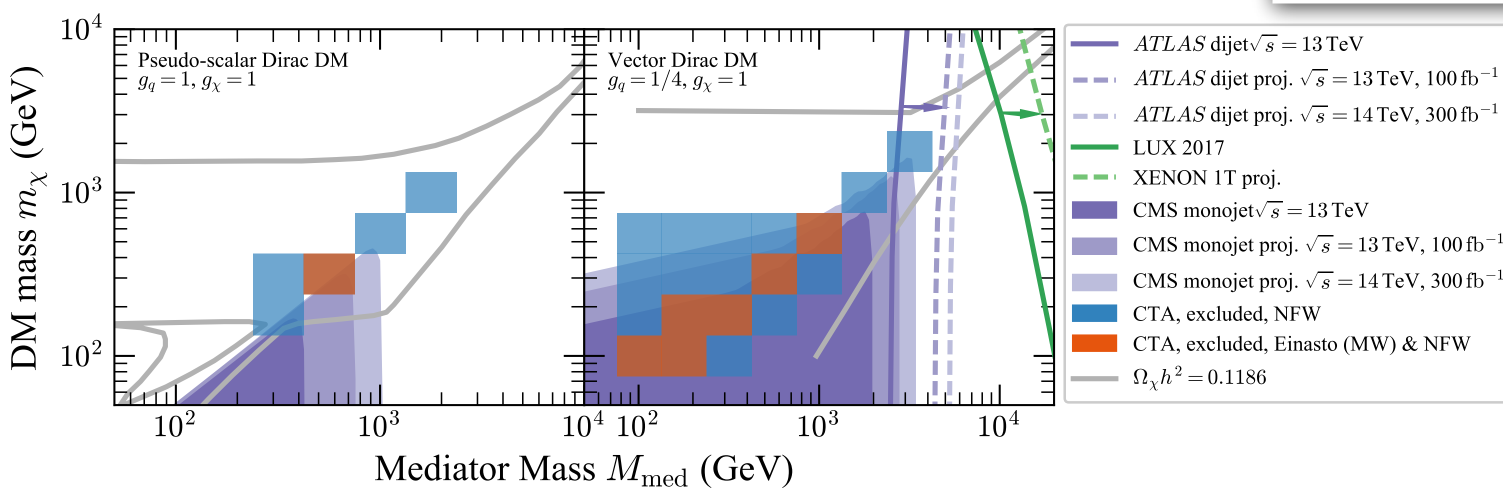
Powerful probe of pseudoscalar interaction, complementary probe of other interactions, particularly above 5 TeV

- Compare with direct detection & collider prospects

Correct DM relic abundance



EFT approach valid above line



Balázs et al. 2017 arXiv:1706.01505

z=0.0

Conclusions

- Indirect dark matter searches with imaging atmospheric Cherenkov telescopes necessary part of search strategy
  - Complement direct detection and collider searches

- Subject to substantial uncertainties (J-factor estimation, halo models)
  - Effort to quantify impact on limits

- Limits begin to probe expected cross-sections for weak-scale interaction
  - Fermi-LAT provides most sensitive limits below few hundred GeV
  - IACTs provide most sensitive limits above few hundred GeV

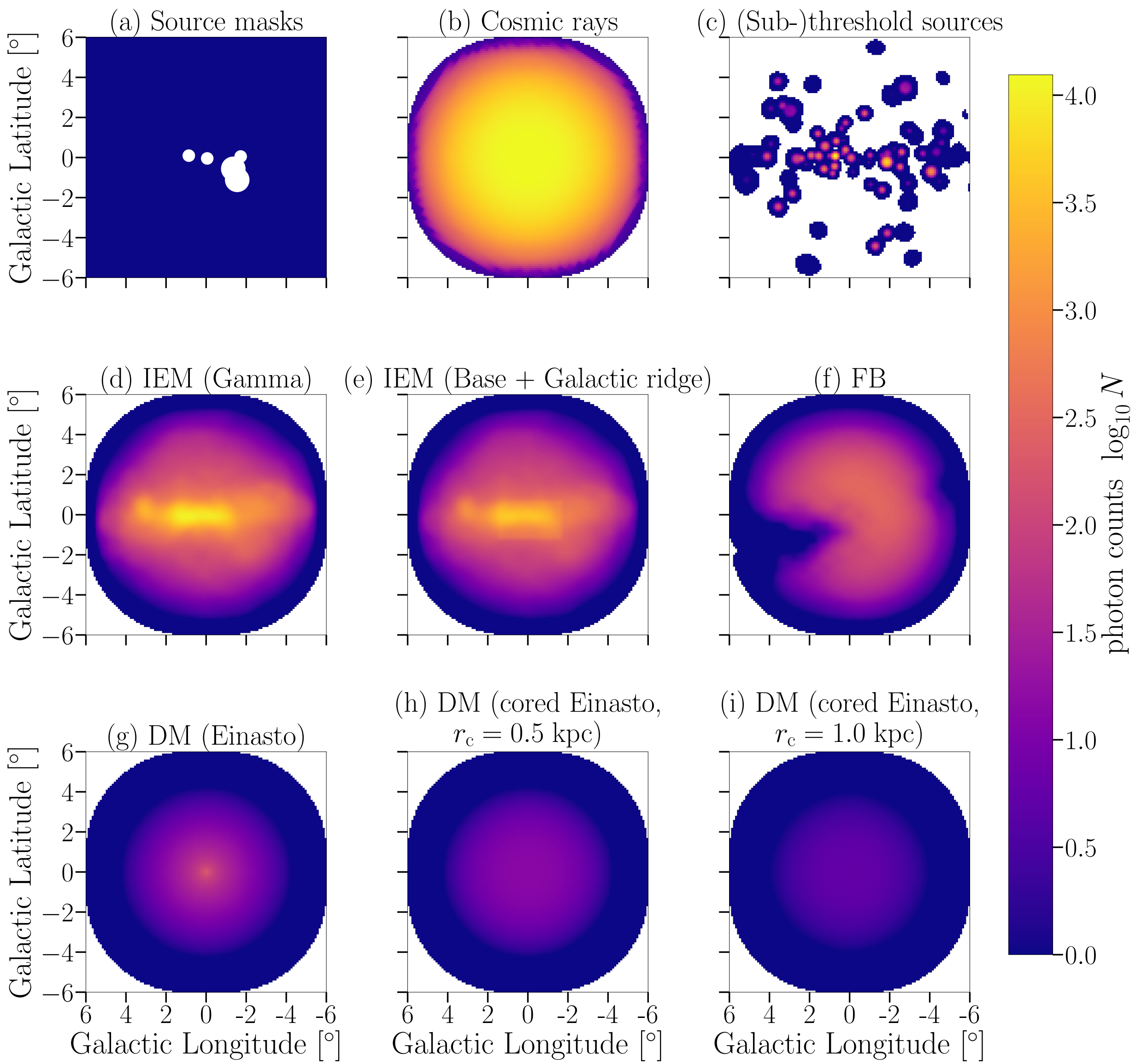
80 kpc

Backup

Dwarf Spheroidal J-factors

Name	Distance (kpc)	l, b ($^\circ$)	$\log_{10} J$ ($\mathcal{GS}$ set) $\log_{10}(\mathrm{GeV^2 cm^{-5} sr})$	$\log_{10} J$ ($\mathcal{B}$ set) $\log_{10}(\mathrm{GeV^2 cm^{-5} sr})$
Boötes I	66	358.08, 69.62	$18.24^{+0.40}_{-0.37}$	$18.85^{+1.10}_{-0.61}$
Canes Venatici I	218	74.31, 79.82	$17.44^{+0.37}_{-0.28}$	$17.63^{+0.50}_{-0.20}$
Canes Venatici II	160	113.58, 82.70	$17.65^{+0.45}_{-0.43}$	$18.67^{+1.54}_{-0.97}$
Carina	105	260.11, −22.22	$17.92^{+0.19}_{-0.11}$	$18.02^{+0.36}_{-0.15}$
Coma Berenices	44	241.89, 83.61	$19.02^{+0.37}_{-0.41}$	$20.13^{+1.56}_{-1.08}$
Draco	76	86.37, 34.72	$19.05^{+0.22}_{-0.21}$	$19.42^{+0.92}_{-0.47}$
Fornax	147	237.10, −65.65	$17.84^{+0.11}_{-0.06}$	$17.85^{+0.11}_{-0.08}$
Hercules	132	28.73, 36.87	$16.86^{+0.74}_{-0.68}$	$17.70^{+1.08}_{-0.73}$
Leo I	254	225.99, 49.11	$17.84^{+0.20}_{-0.16}$	$17.93^{+0.65}_{-0.25}$
Leo II	233	220.17, 67.23	$17.97^{+0.20}_{-0.18}$	$18.11^{+0.71}_{-0.25}$
Leo IV	154	265.44, 56.51	$16.32^{+1.06}_{-1.70}$	$16.36^{+1.44}_{-1.65}$
Leo V	178	261.86, 58.54	$16.37^{+0.94}_{-0.87}$	$16.30^{+1.33}_{-1.16}$
Leo T	417	214.85, 43.66	$17.11^{+0.44}_{-0.39}$	$17.67^{+1.01}_{-0.56}$
Sculptor	86	287.53, −83.16	$18.57^{+0.07}_{-0.05}$	$18.63^{+0.14}_{-0.08}$
Segue I	23	220.48, 50.43	$19.36^{+0.32}_{-0.35}$	$17.52^{+2.54}_{-2.65}$
Segue II	35	149.43, −38.14	$16.21^{+1.06}_{-0.98}$	$19.50^{+1.82}_{-1.48}$
Sextans	86	243.50, 42.27	$17.92^{+0.35}_{-0.29}$	$18.04^{+0.50}_{-0.28}$
Ursa Major I	97	159.43, 54.41	$17.87^{+0.56}_{-0.33}$	$18.84^{+0.97}_{-0.43}$
Ursa Major II	32	152.46, 37.44	$19.42^{+0.44}_{-0.42}$	$20.60^{+1.46}_{-0.95}$
Ursa Minor	76	104.97, 44.80	$18.95^{+0.26}_{-0.18}$	$19.08^{+0.21}_{-0.13}$

Galactic Center Components



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