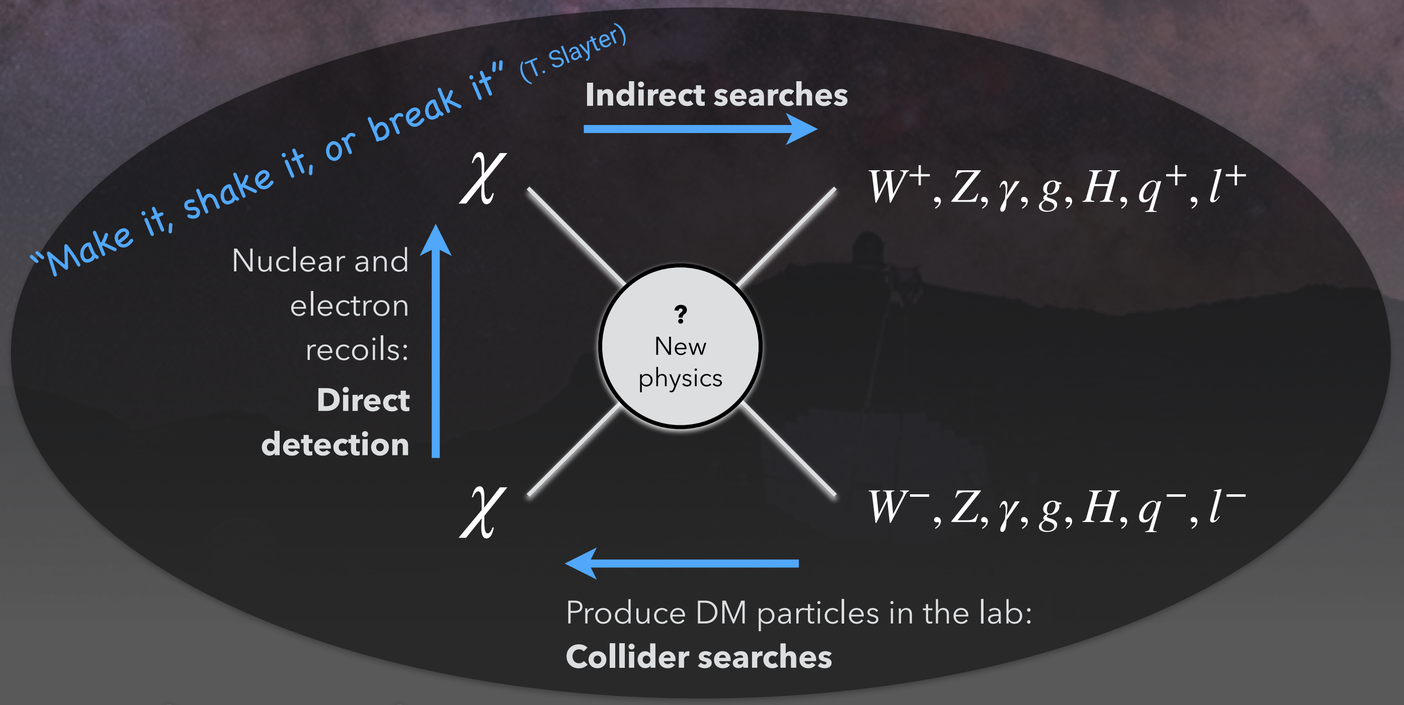
Indirect Dark Matter searches: Experiments, status, and future plans

Moritz Hütten

Physics in LHC and Beyond

Matsue, May 12, 2022

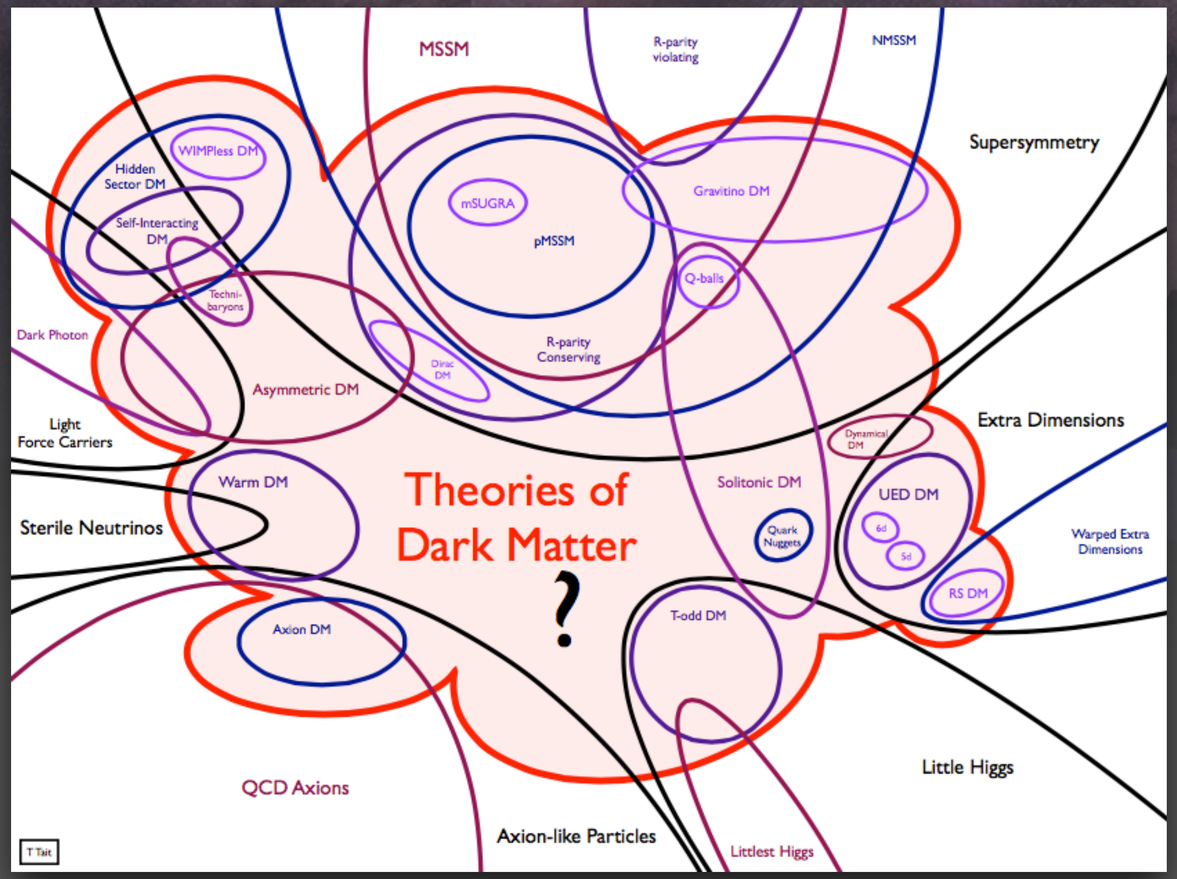
Appeal of **indirect** dark matter searches

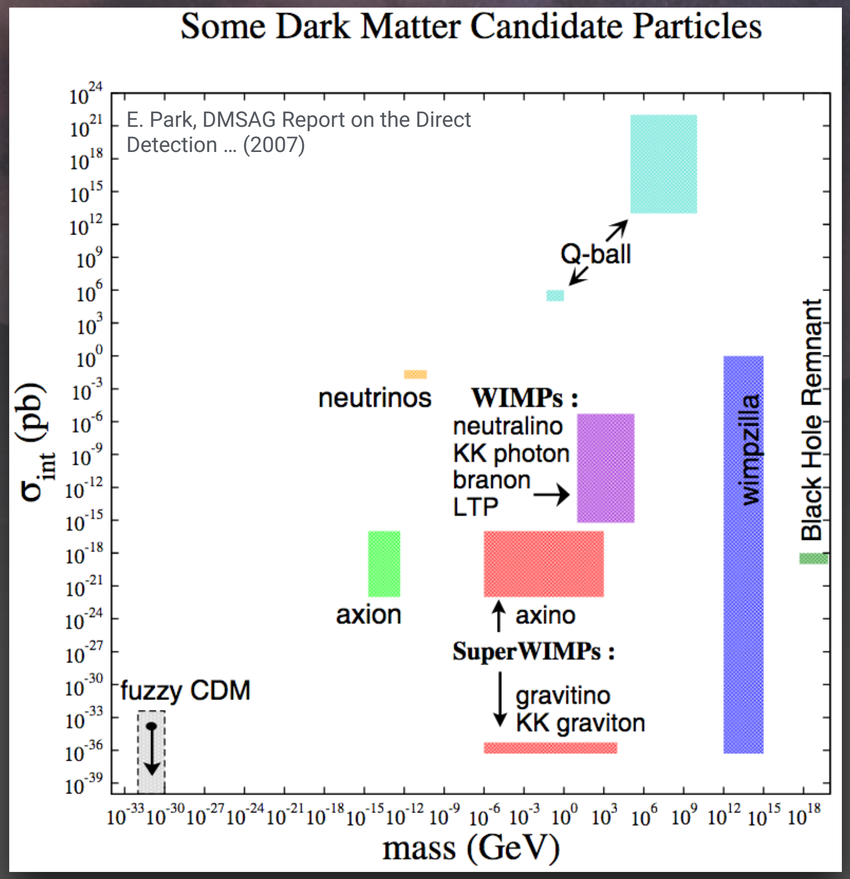


Indirect WIMP searches probe:

- **same mass budgets** providing DM gravitational evidence
- **same interaction** (annihilation) causing DM relic abundance

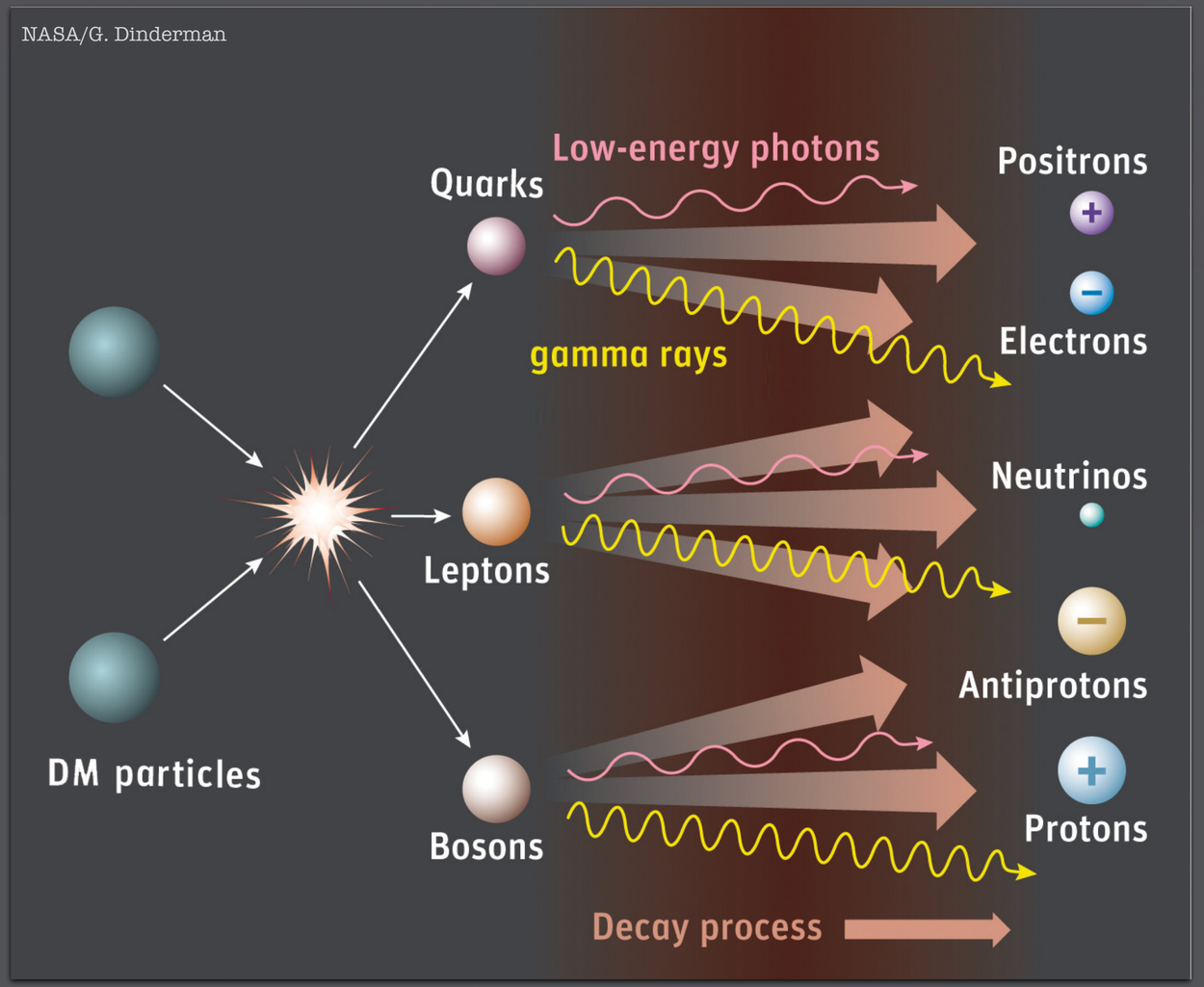
The DM theory jungle



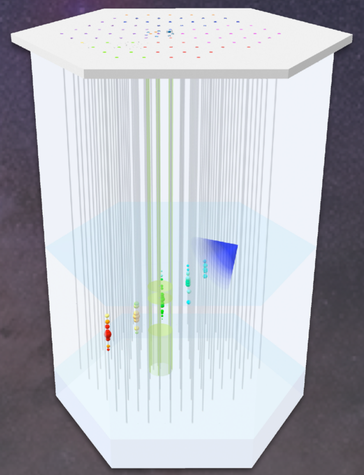


Indirect searches: not only WIMP annihilation (but today focus on WIMPs)

Searches for WIMP annihilations (or decays)



How many relic interactions do we expect?



Relic annihilation @ Earth (in a detector):

A few kg of DM inside Earth volume

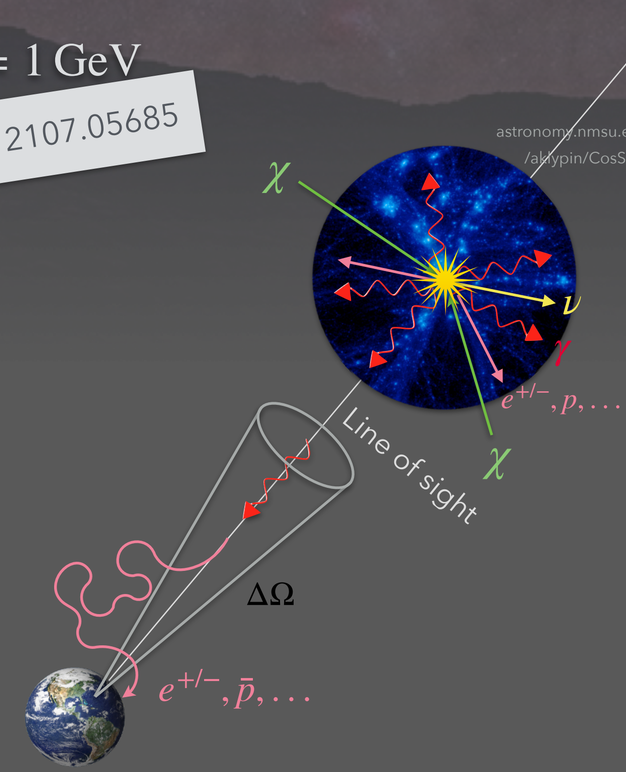
$$\frac{\mathrm{d}\Gamma}{\mathrm{d}V} = \frac{\rho_\chi^2}{\delta\, m_\chi^2}\langle\sigma v\rangle \quad \text{with} \quad \delta = \begin{cases} 4, \chi \neq \bar{\chi} & \text{Dirac DM} \\ 2, \chi = \bar{\chi} & \text{Majorana DM} \end{cases}$$

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

However see 2107.05685

Relic annihilation in space:

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



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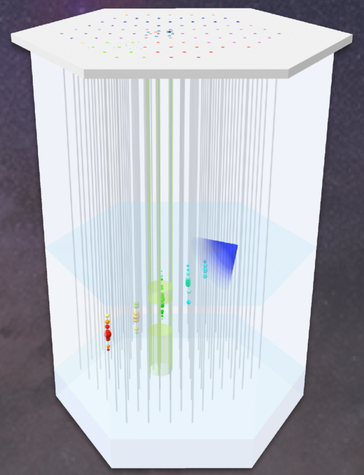

Relic annihilation @ Earth (in a detector):

A few kg of DM inside Earth volume

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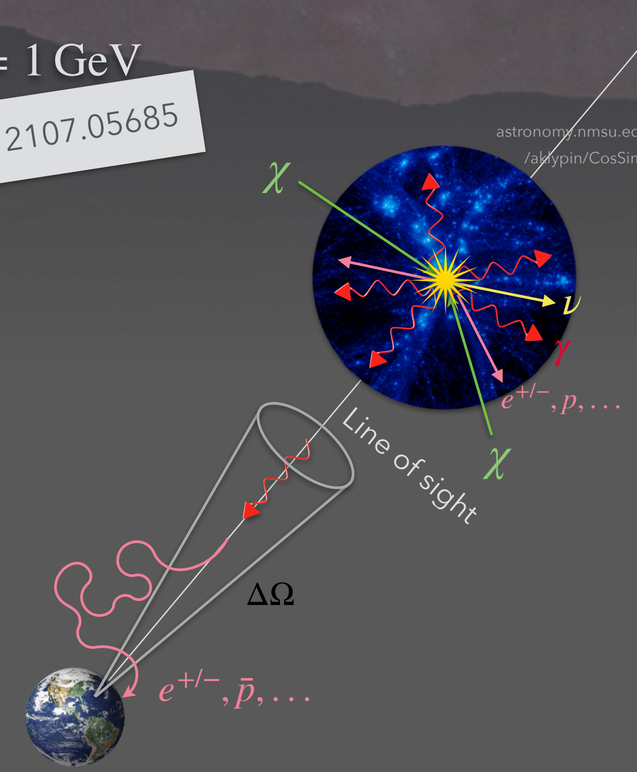
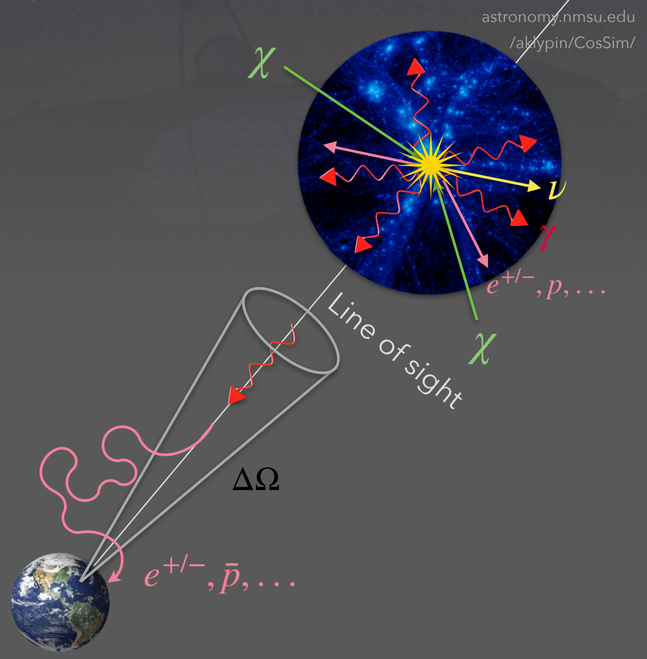


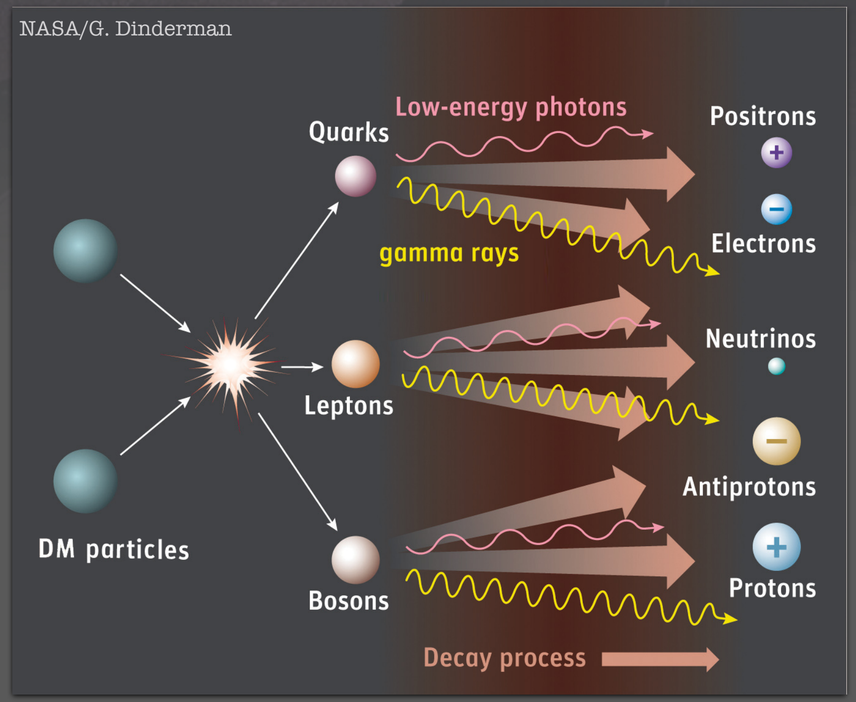
Detectable fluxes!

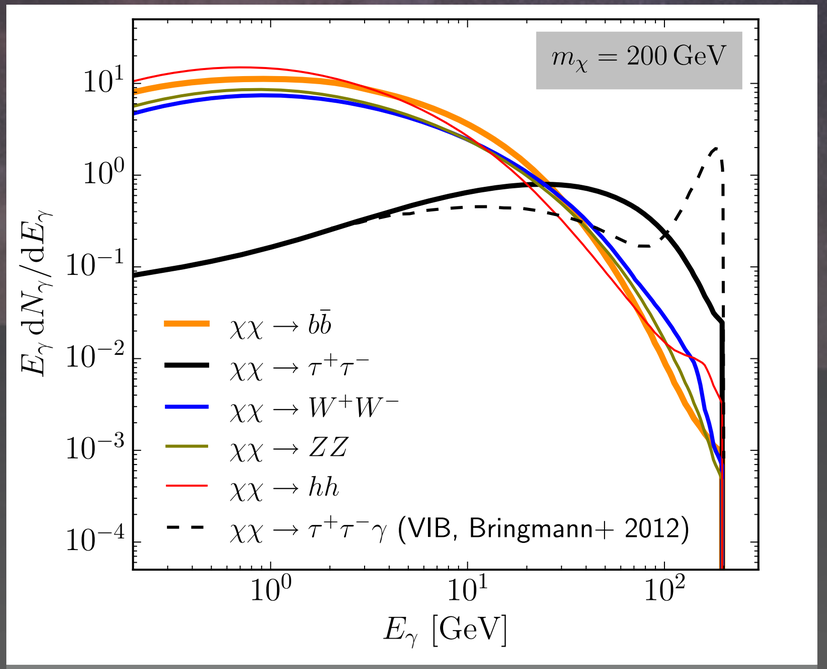
Indirect searches for WIMP Dark Matter annihilation

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

1. Secondary spectra ("particle physics term")







Role of thumb:

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

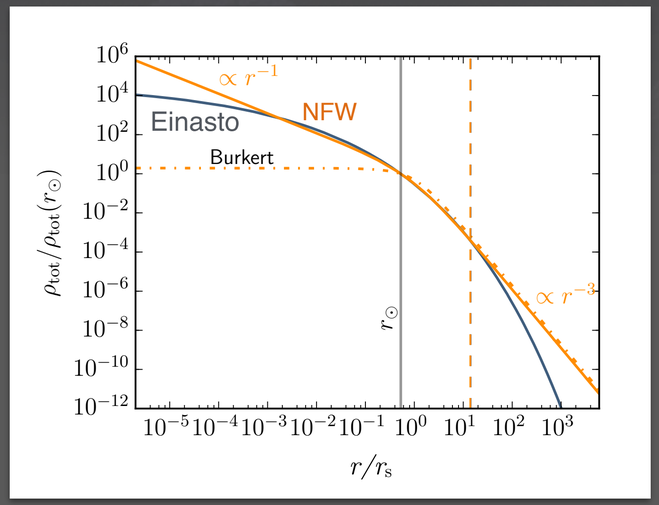
High energy astronomy

Indirect detection ingredients: Dark Matter densities

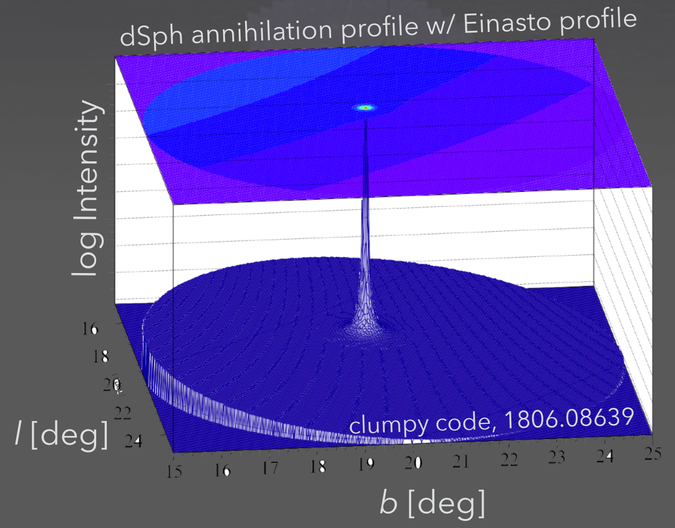
2. *J*-factor ("astrophysical term")

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

Annihilation boost: Increased signal, but also increased uncertainty:



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

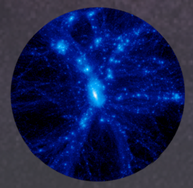


Need:

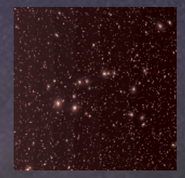
1. Close and/or massive DM budget
2. High density ("concentrated")
3. no astrophysical back-/ foregrounds

Where to look? Dark matter sky at Earth

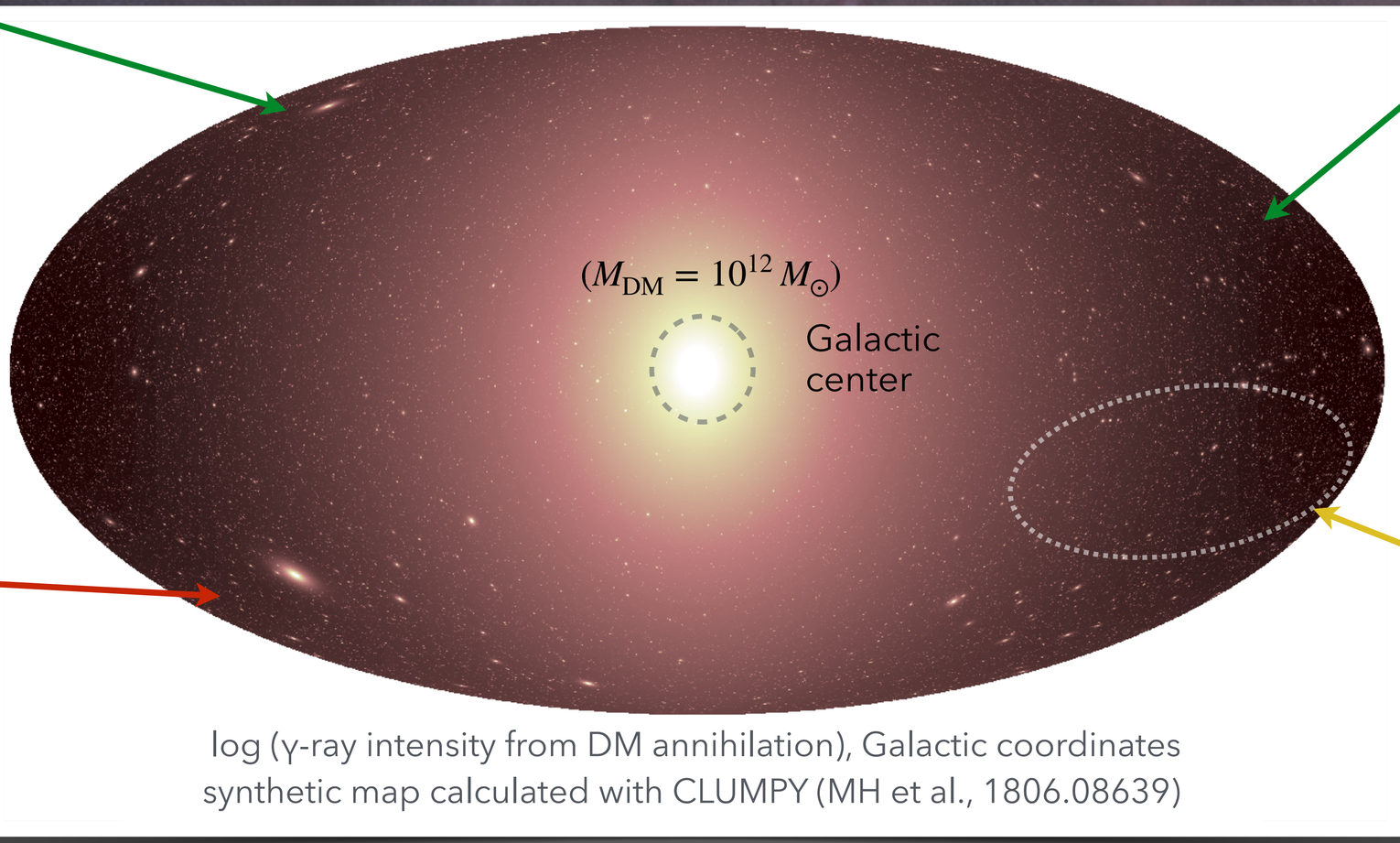
astronomy.nmsu.edu/aklypin/CosSim/



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



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

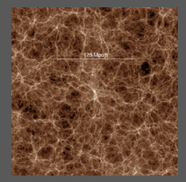


log (γ-ray intensity from DM annihilation), Galactic coordinates
synthetic map calculated with CLUMPY (MH et al., 1806.08639)

Fornax dSph

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

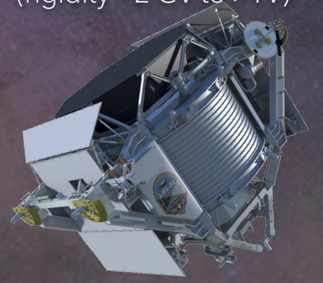
Springel et al. (2005)



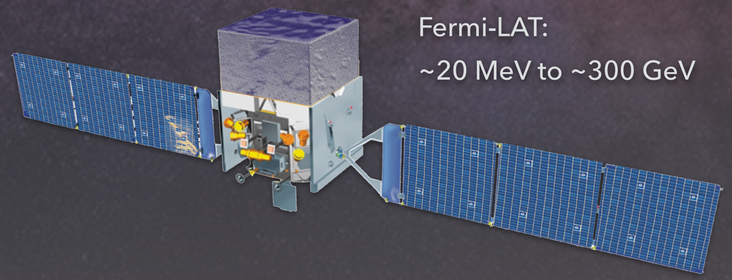
Gal. + extragal. diffuse
$(M_{\rm DM} =$ obs. Universe$)$

Indirect detection instruments

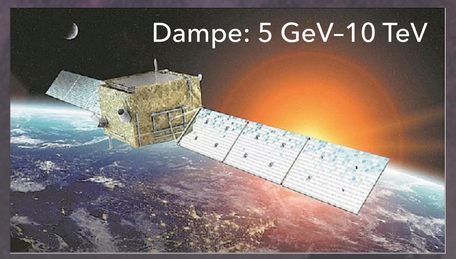
AMS-02:
Charged particles
(rigidity ~2 GV to >TV)

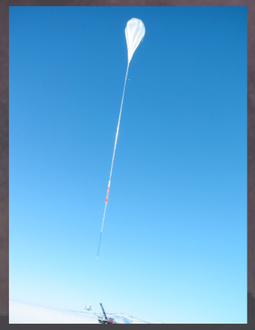


Energy



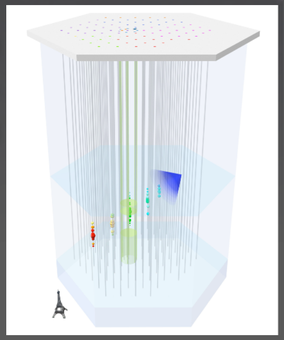
Fermi-LAT:
~20 MeV to ~300 GeV

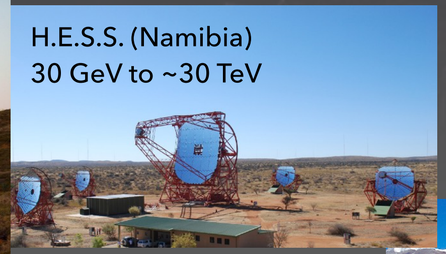


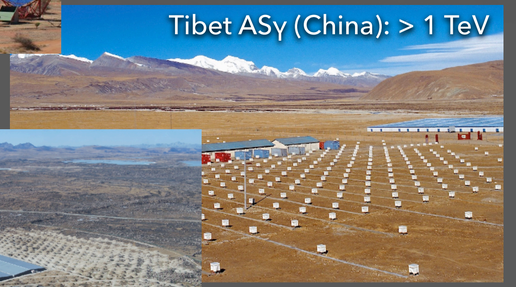


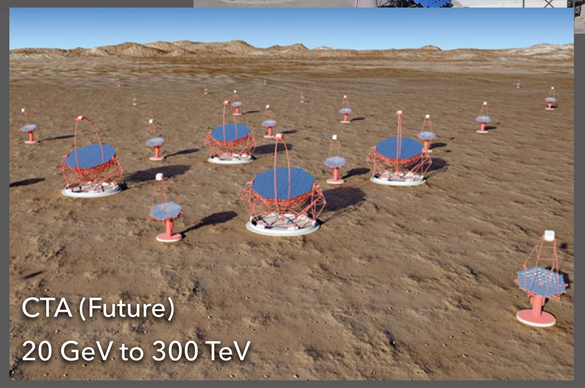
CREAM (stratosphere)
Charged particles
(TeV to PeV)

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



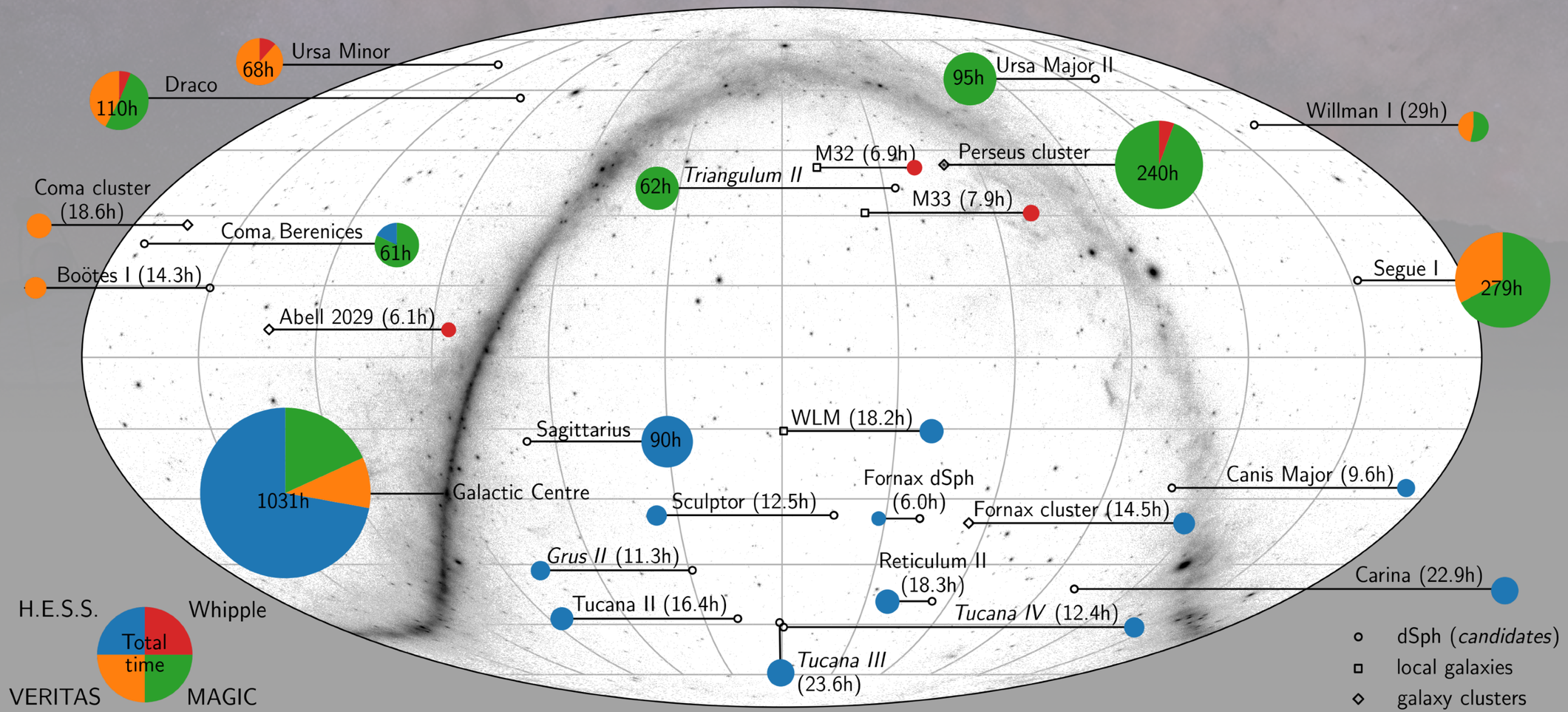






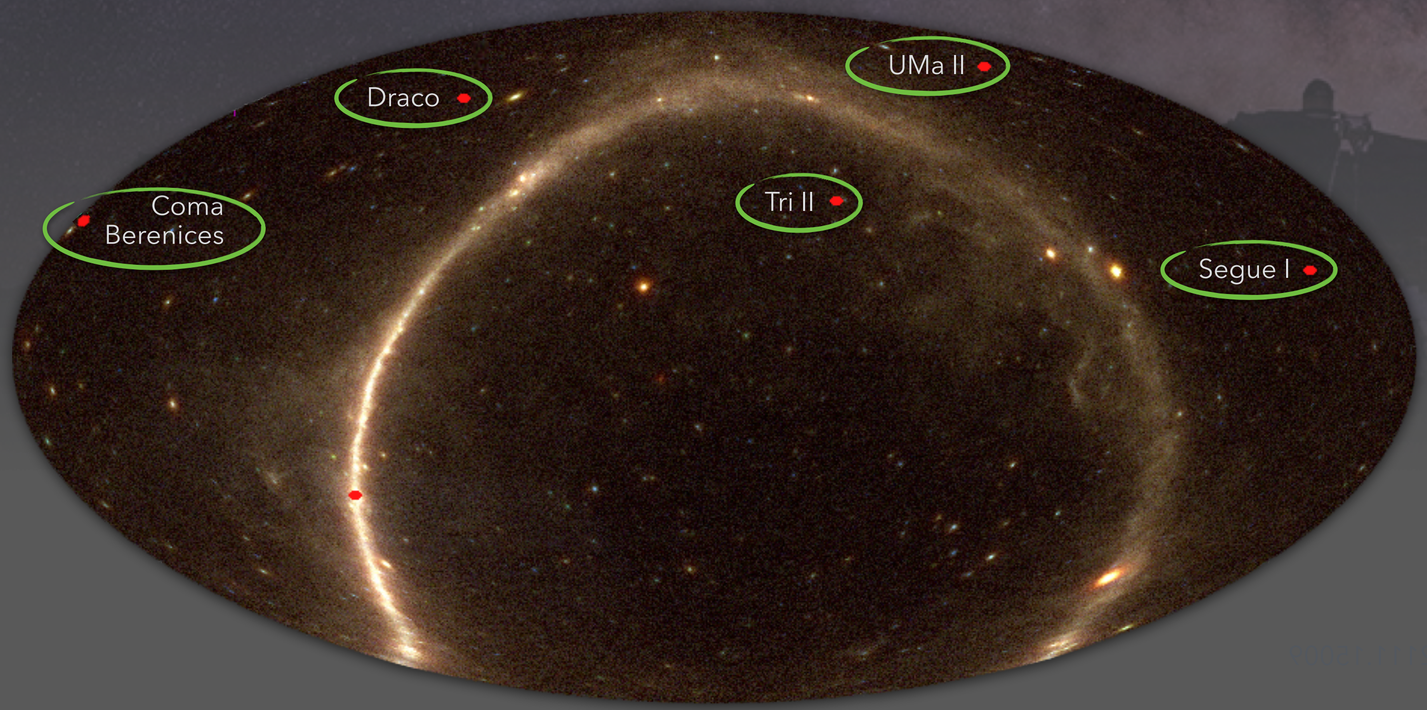
WIMP searches with Imaging Air Cherenkov Telescopes

So far no detection after 20+ years: (M. Doro, M. Sánchez-Conde, MH, 2111.01198)



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

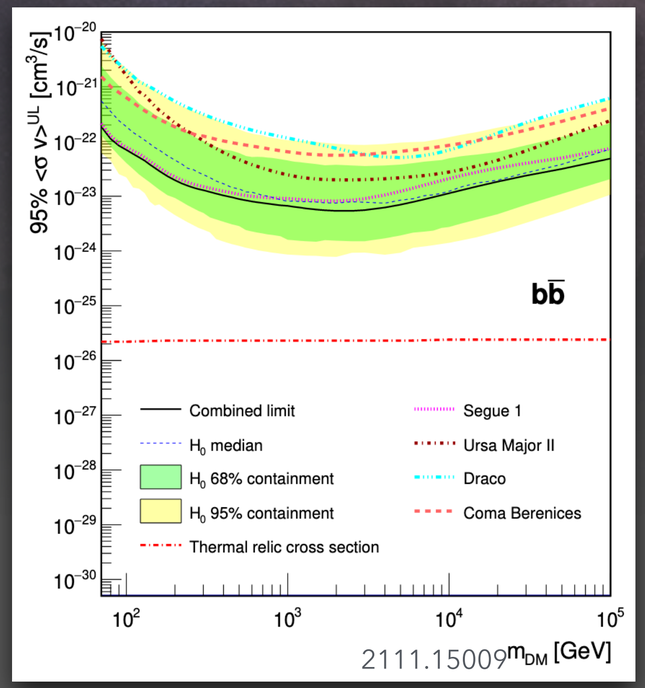
Total observation time: 354h

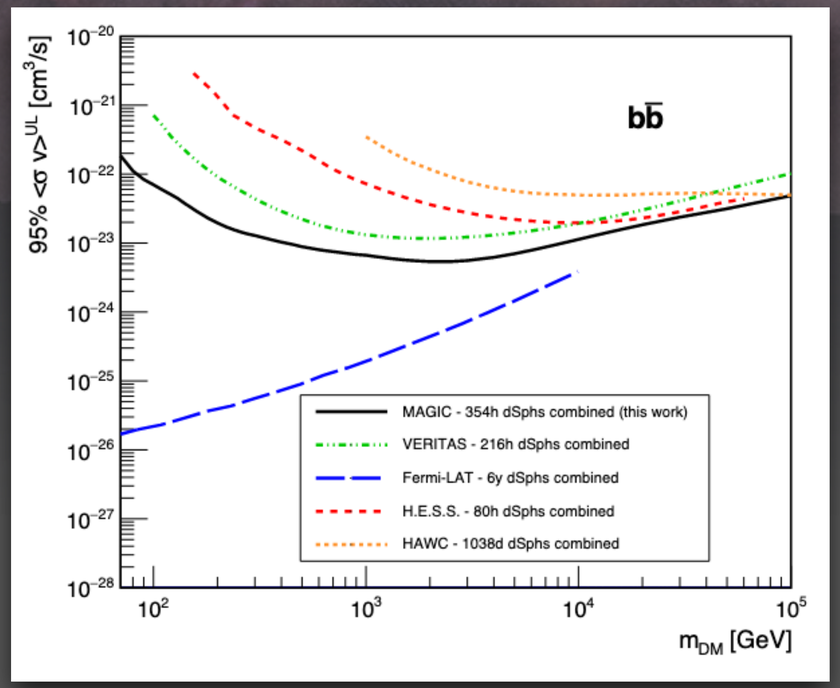
Tri II	62h	19.35±0.37

Separately: Acciari et. al., 2020.100529

dSph Galaxies: Combined limits by MAGIC

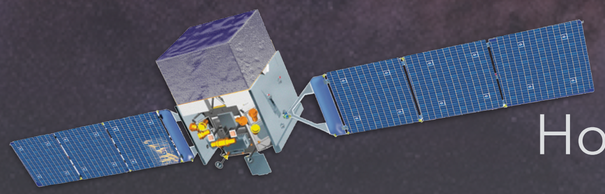
No signal neither in Segue 1, UMa II, Draco, Coma, Tri II, nor after combination:



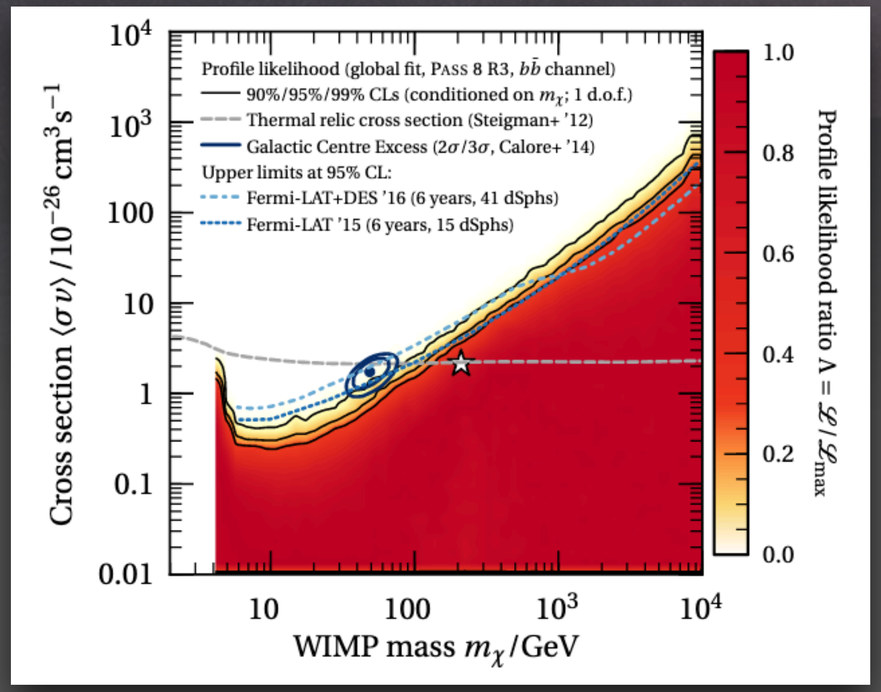


PDU 35, 100912 (2022), arXiv:2111.15009

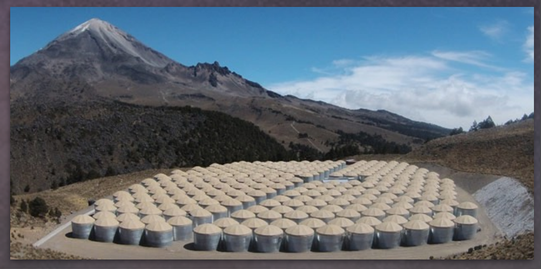
Combined dSph Galaxies: Limits by *Fermi*-LAT and HAWC

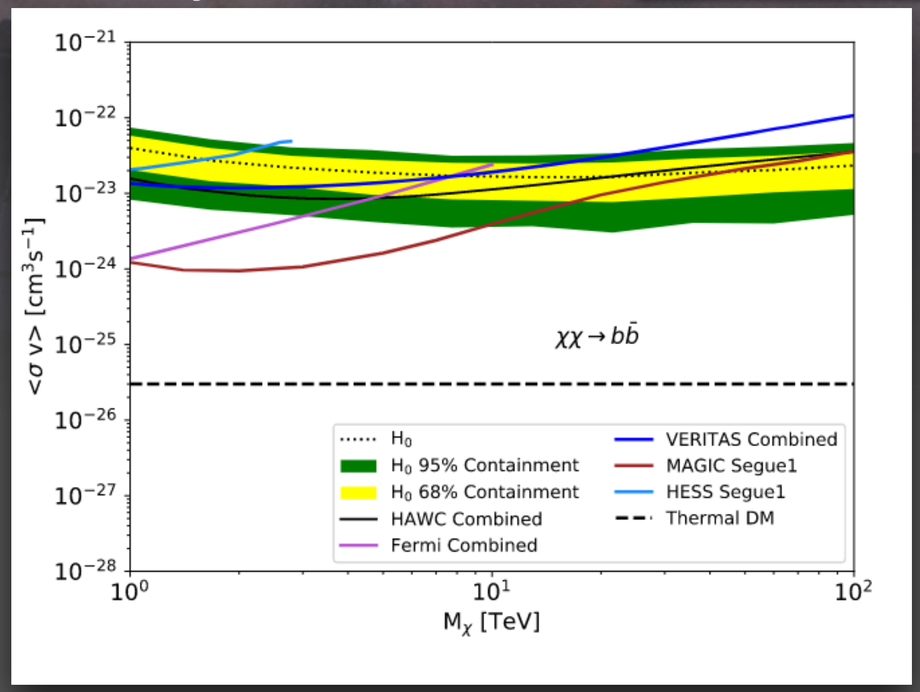


Hoof et al., 1812.06986,
27 dSph, 11 years



HAWC coll.,
1706.01277, 15 dSphs,
507 days





Similar results in 1611.03184, 1704.03910, 2101.11027, …

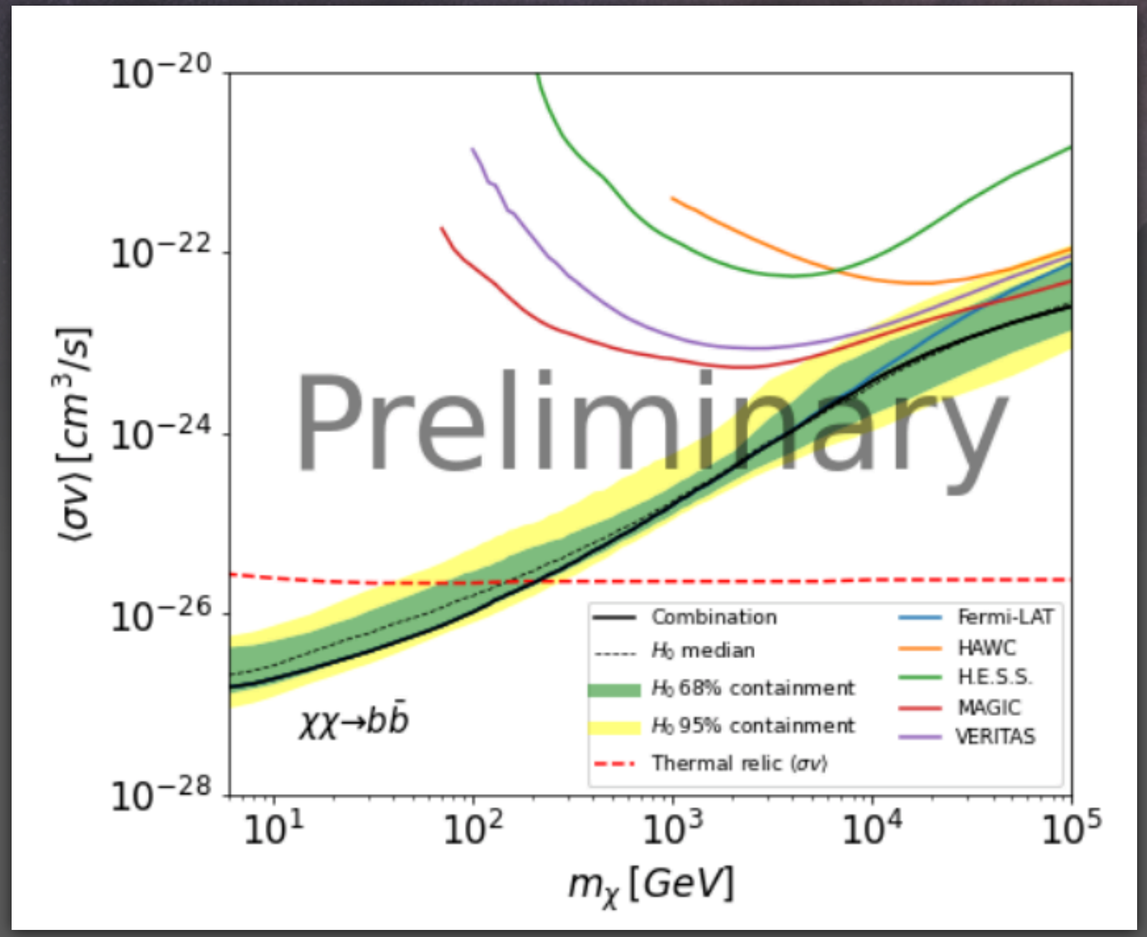
dSph Galaxies: Combined limits by all instruments

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	$18.95^{+0.26}_{-0.18}$

ICRC 2021, 2108.13646

- 500+ h of IACT data on 9 dSphs
- 10 yrs *Fermi*-LAT exposure on 20 dSphs
- 1038 days HAWC exposure on 12 dSphs

dSph Galaxies: Combined limits by all instruments



ICRC 2021, 2108.13646

- 500+ h of IACT data on 9 dSphs
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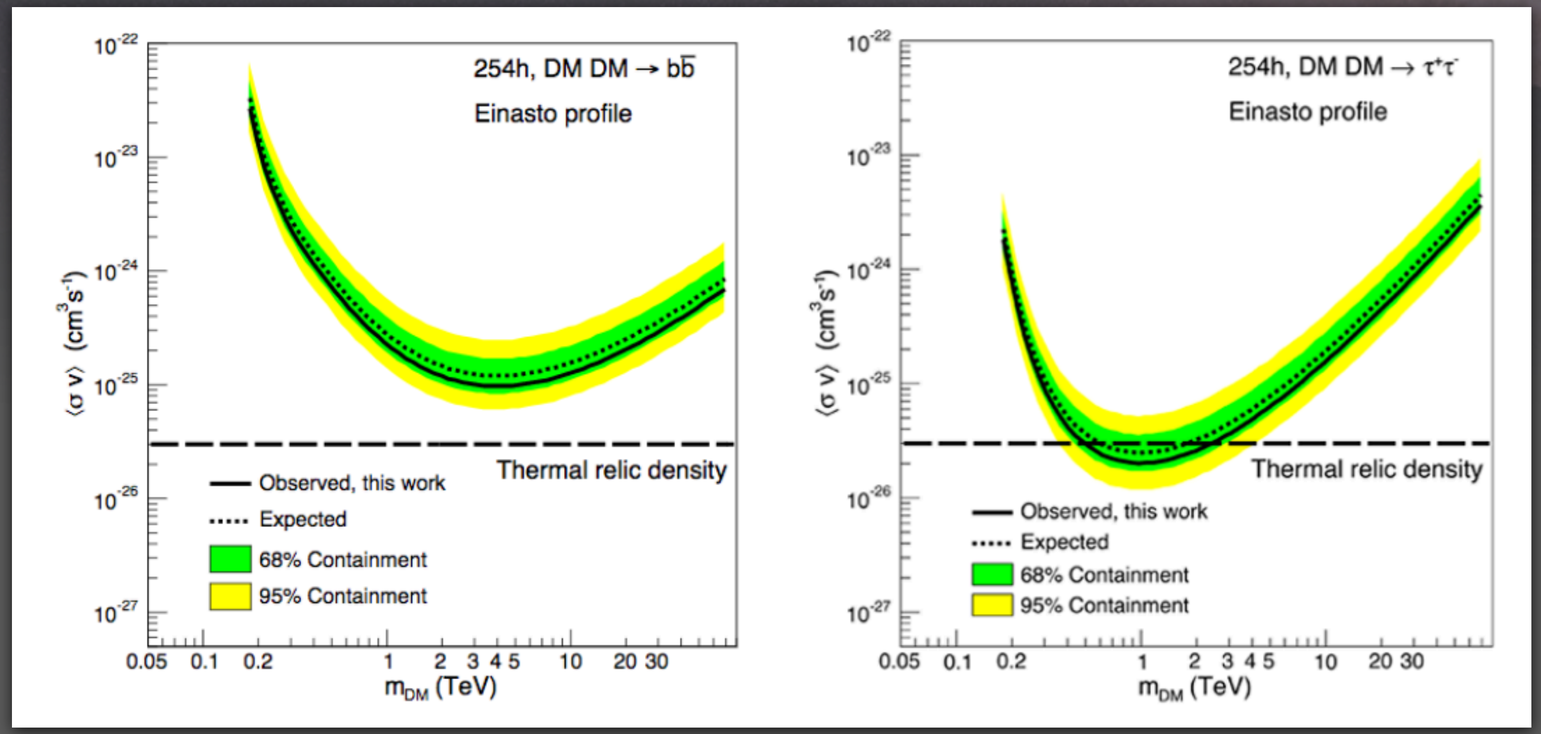
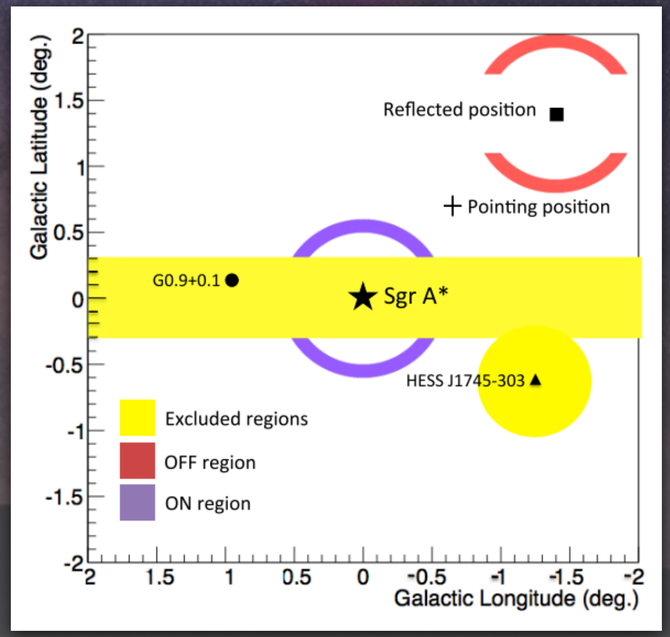
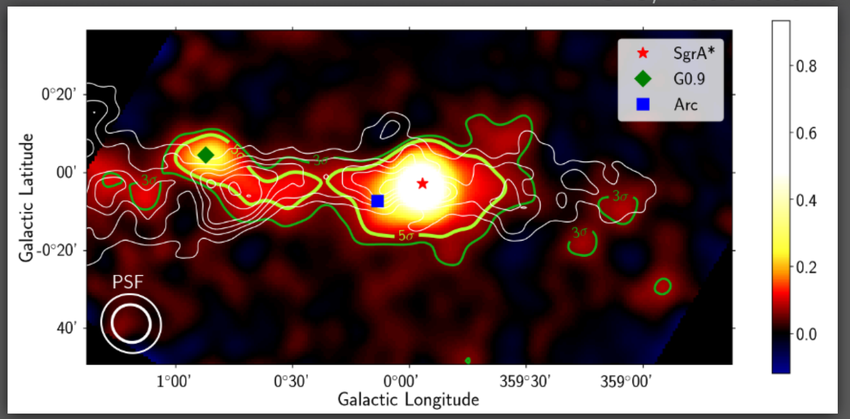
Galactic center: Limits by H.E.S.S.

H.E.S.S. coll., 1607.08142, 254h



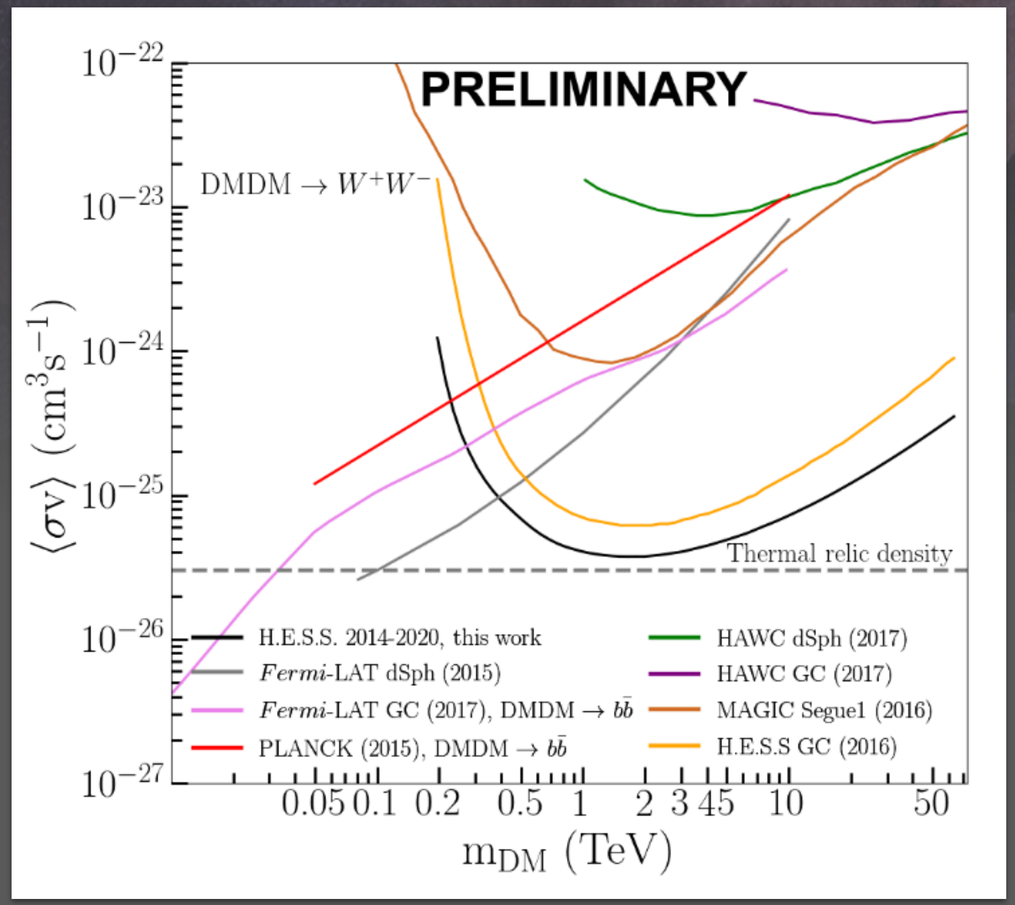


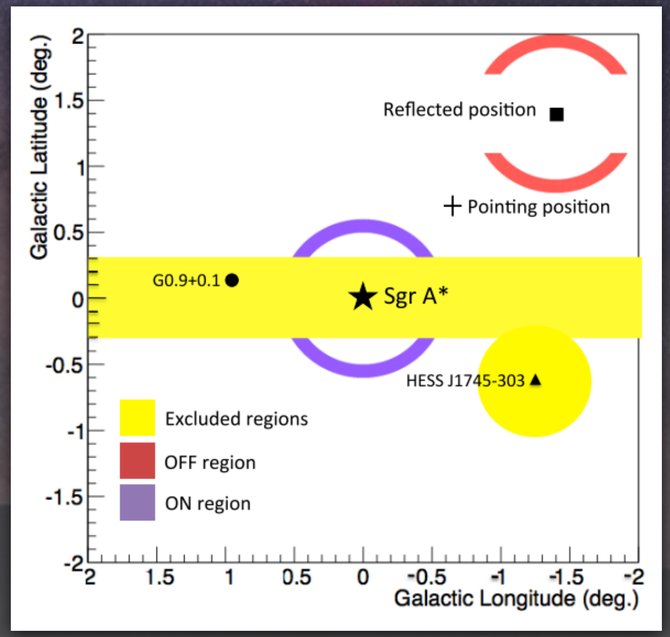
MAGIC, 2006.00623



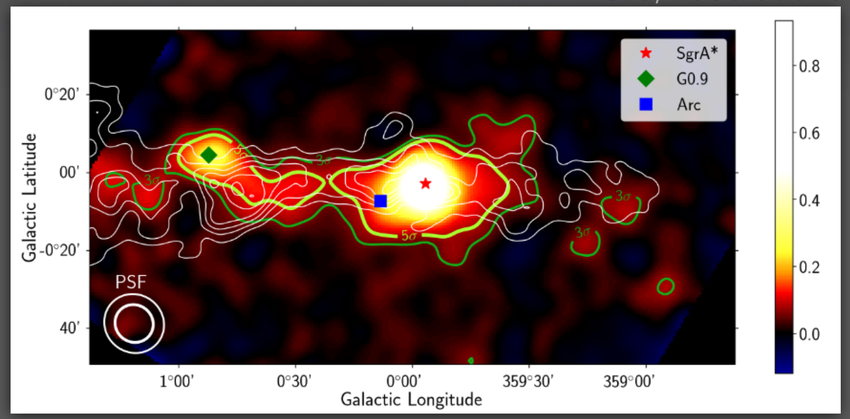
Galactic center: Limits by H.E.S.S.

H.E.S.S. coll. preliminary, 2108.10302, 546h



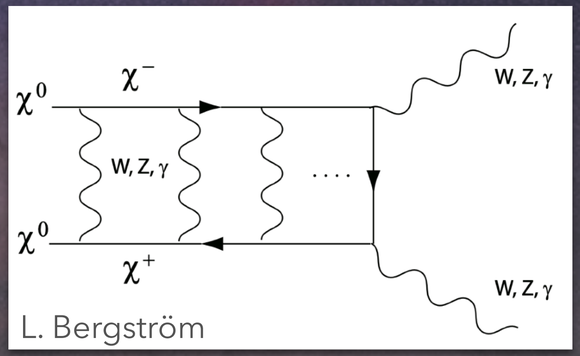


MAGIC, 2006.00623

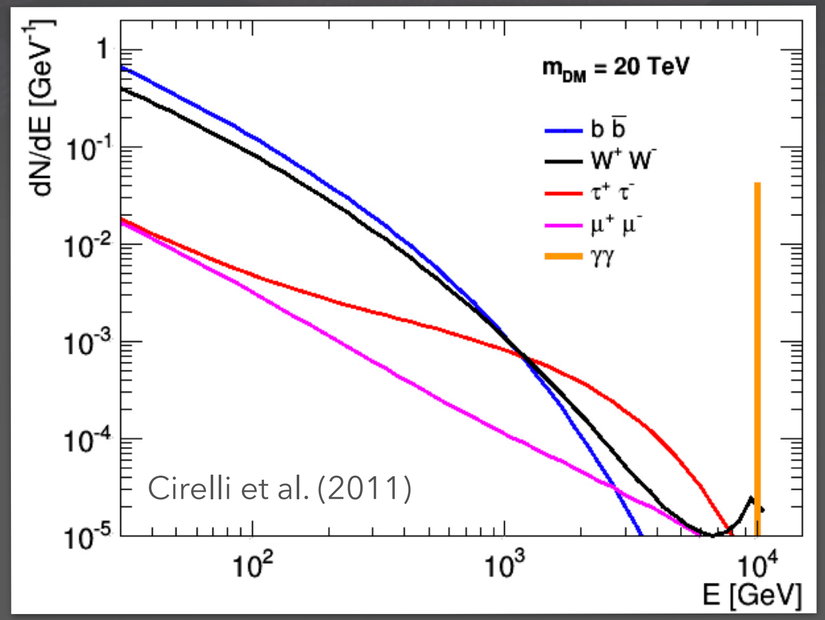


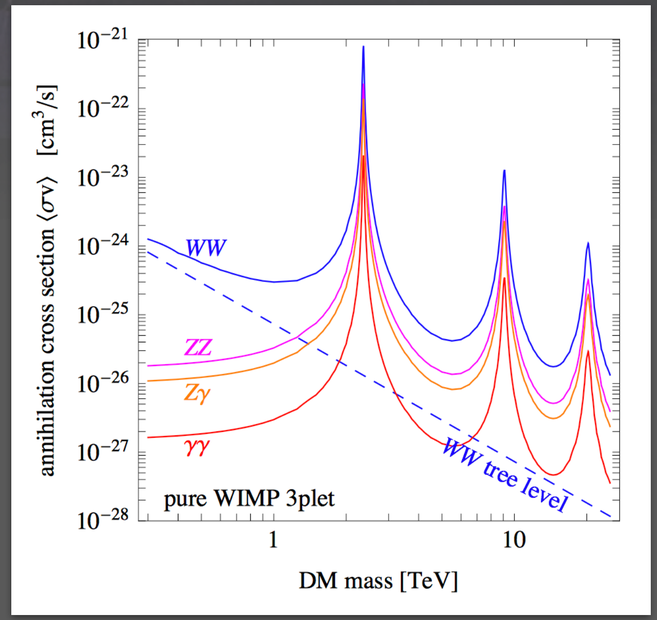
Search for DM line emission

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



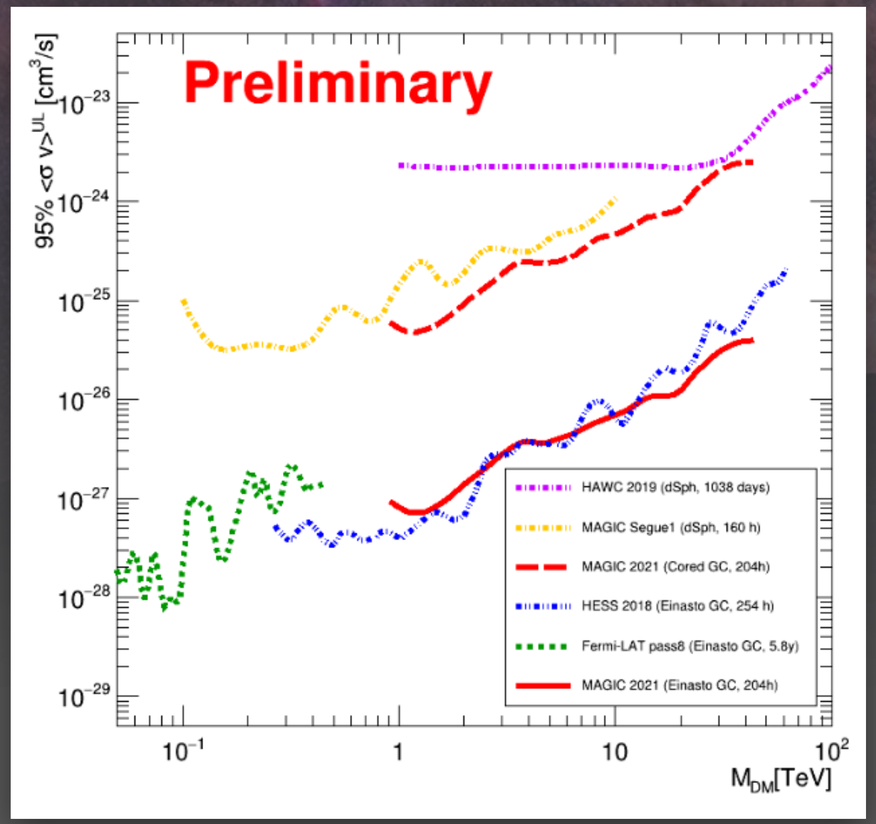
- Sharp peak at DM mass
- $\chi\chi \to \gamma\gamma$ channel loop-suppressed by α^2 (Some TeV DM models expected with Sommerfeld enhanced σv)
- Line-like features also by three-body annihilations (virtual internal bremsstrahlung)





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

Galactic Center line search: Results

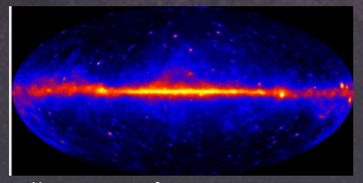


ICRC 2021,
https://pos.sissa.it/395/520/

- No significant line-like excess found in 204h of observation
- Set upper limits at 95% C.L. on 15 masses between 912 GeV - 43 TeV

Fermi-LAT Galactic Center excess

All γ-ray emission



(Illustration from M. Di Mauro)

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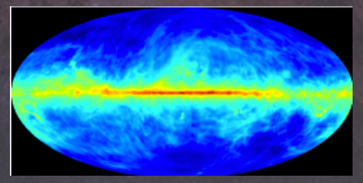
Interstellar emission



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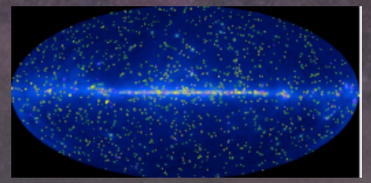
Point sources



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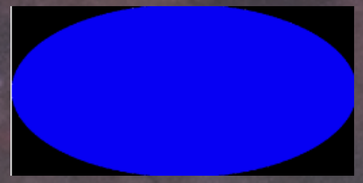
Diffuse



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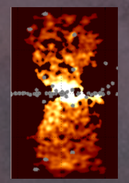
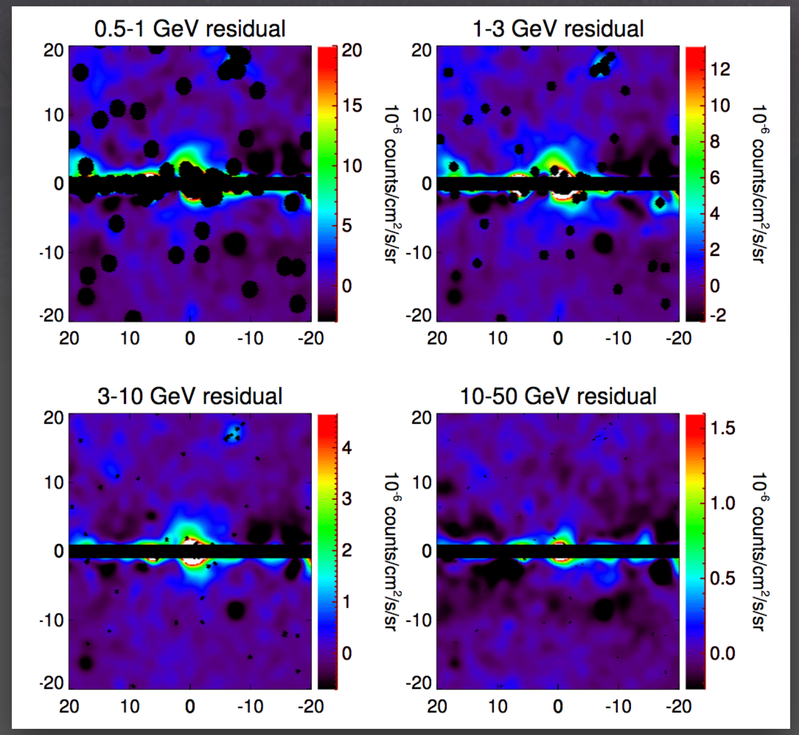
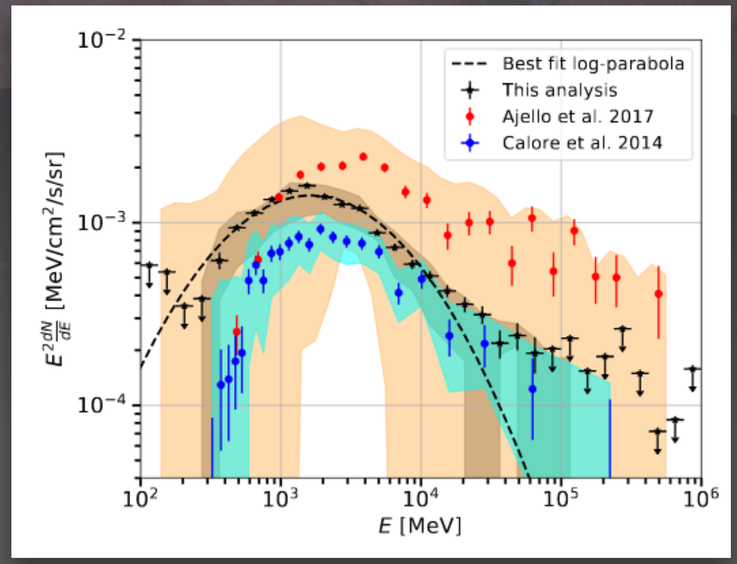
Fermi bubbles



+ X (Dark Matter, MSPs,…)

Daylan et al., 1402.6703





Spectrum of GC excess, Di Mauro, 2101.04694

- It is considered real
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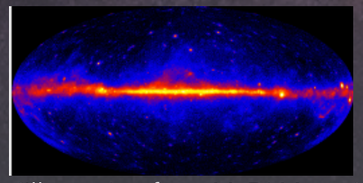
Fermi-LAT Galactic Center excess

All γ-ray emission



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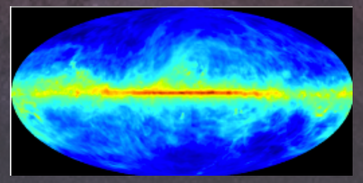
=

Interstellar emission



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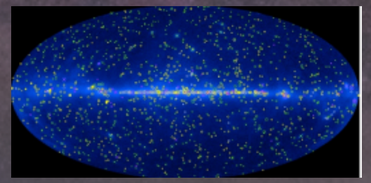
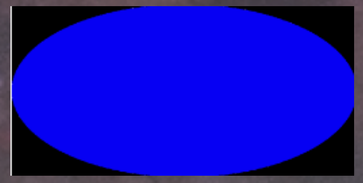
Point sources



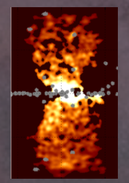
+

Diffuse



+

Fermi bubbles



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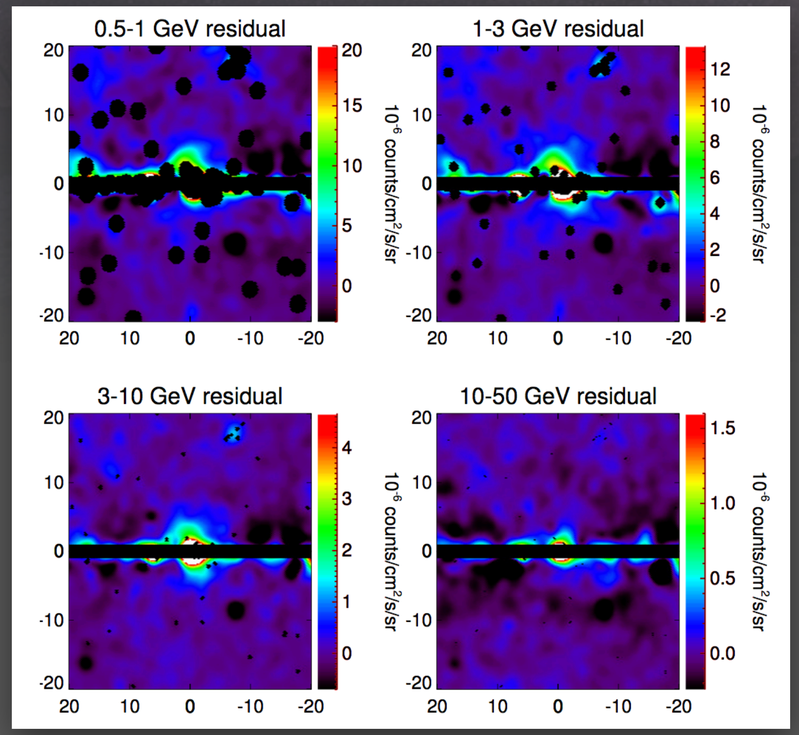

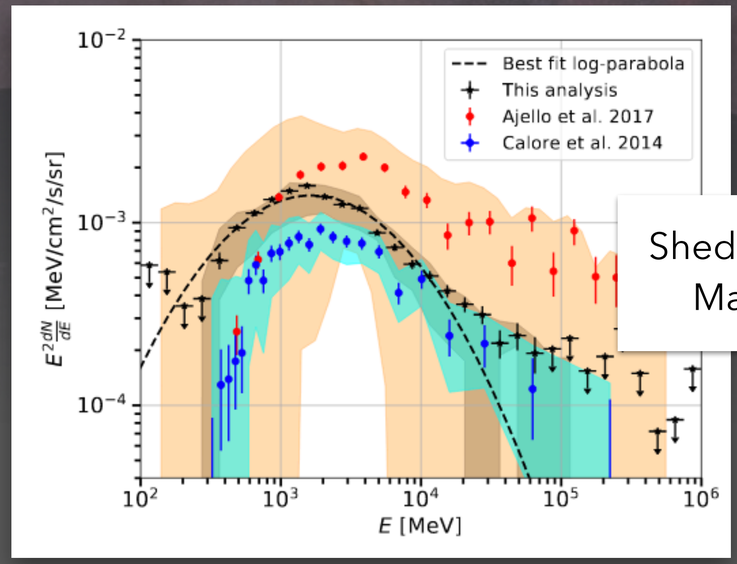

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Shed light on excess with CTA, Macias et al., 2102.05648

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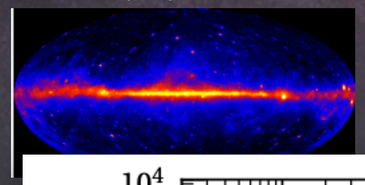
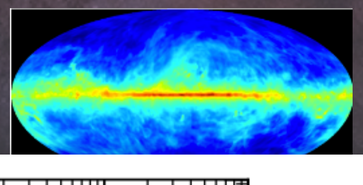
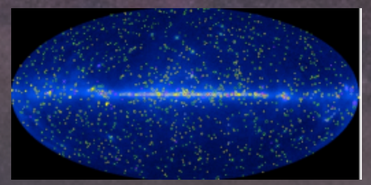
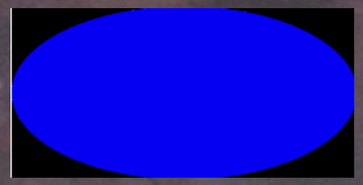
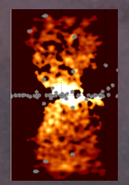
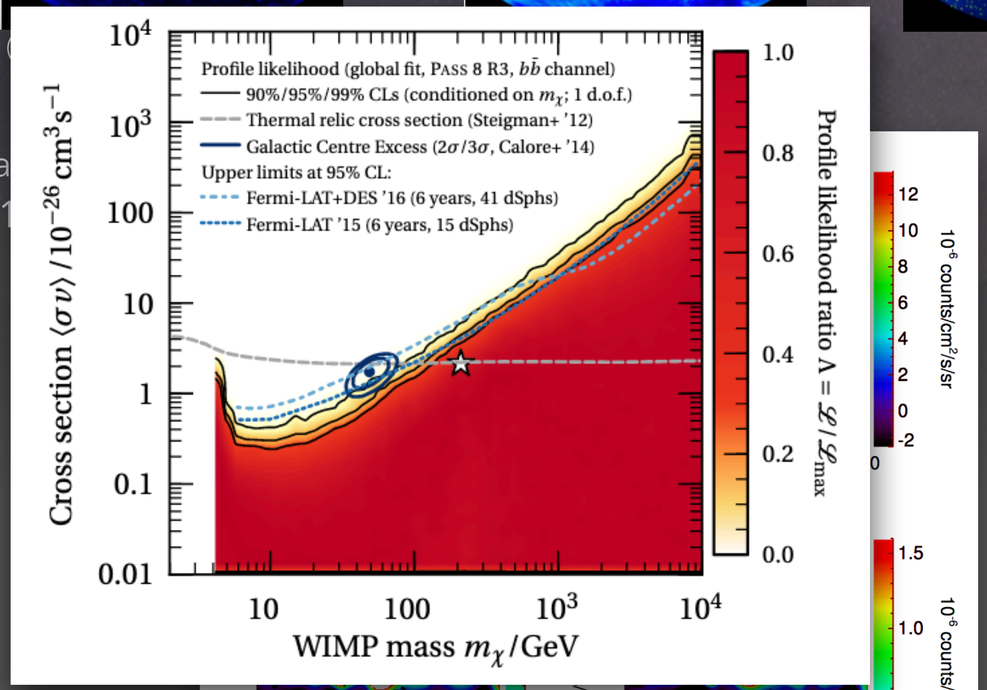
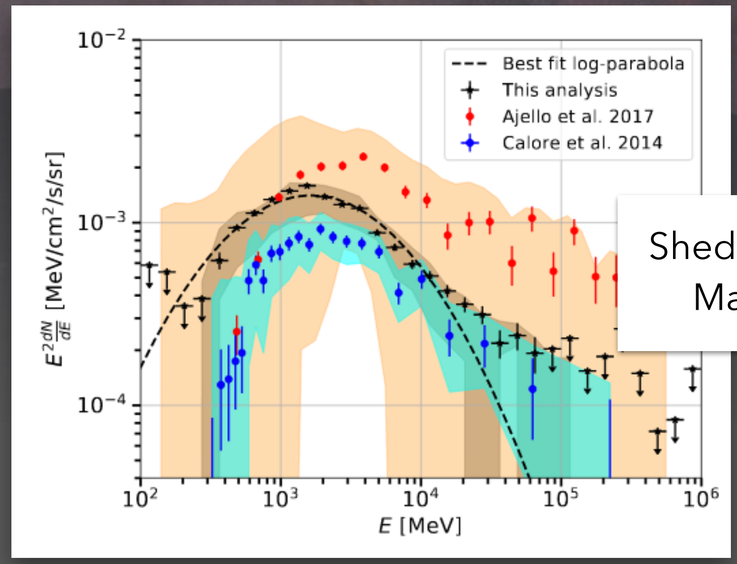
Fermi-LAT Galactic Center excess

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





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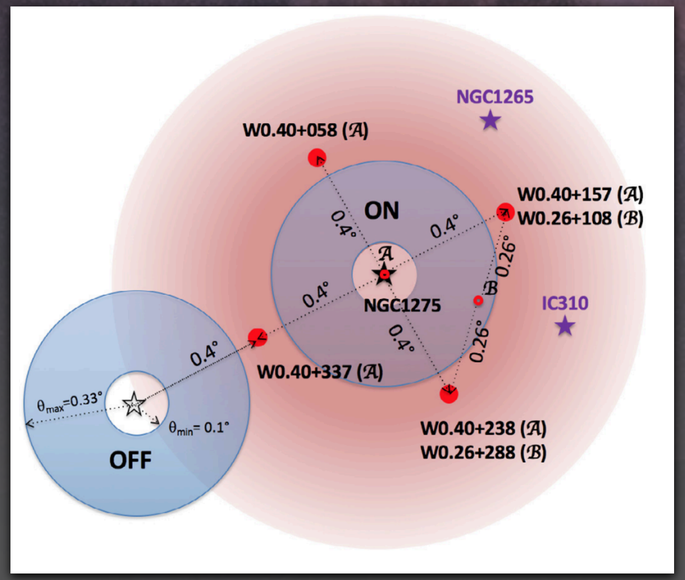
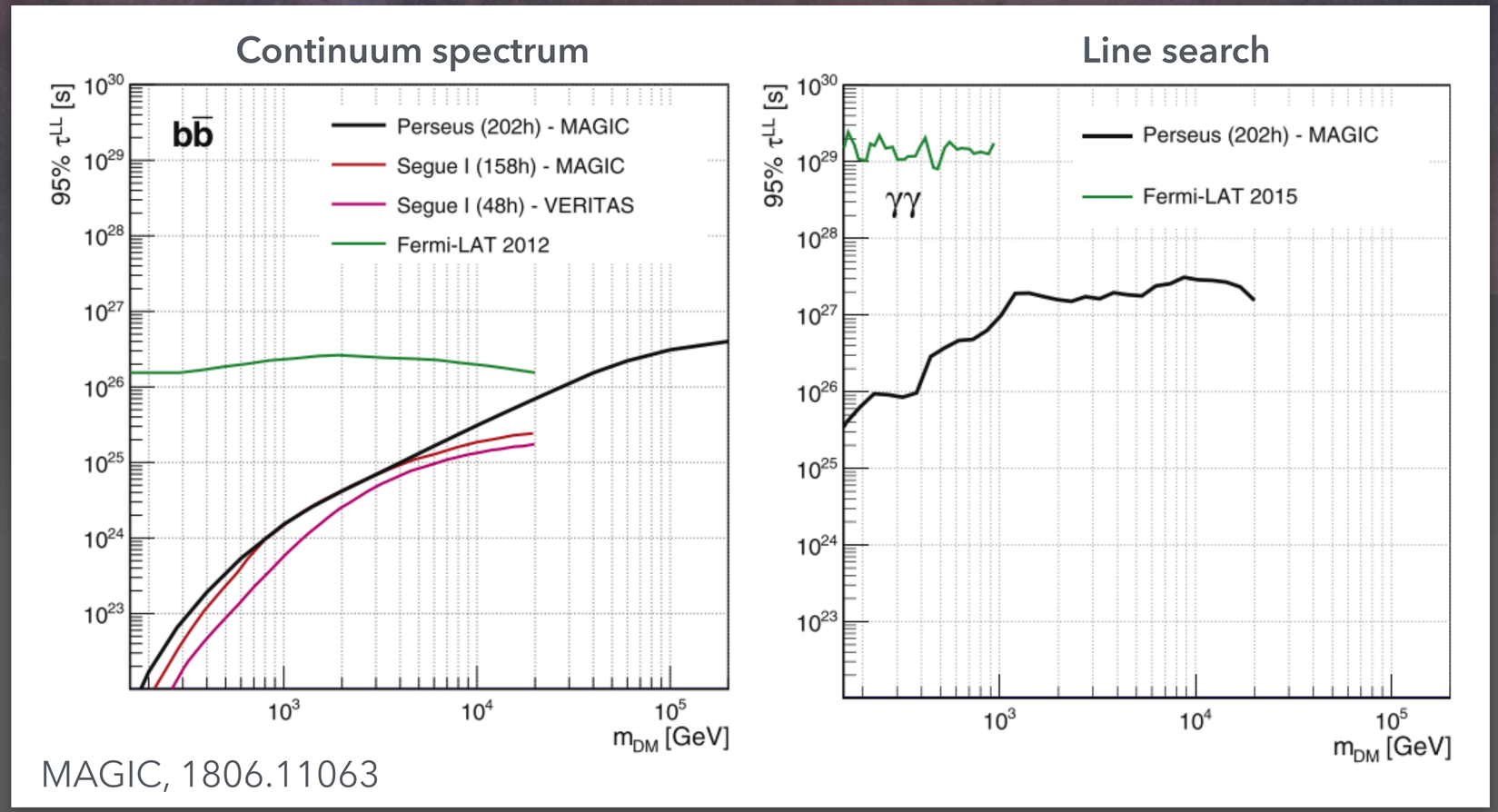
MAGIC Dark Matter *decay* search in the Perseus cluster



- 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

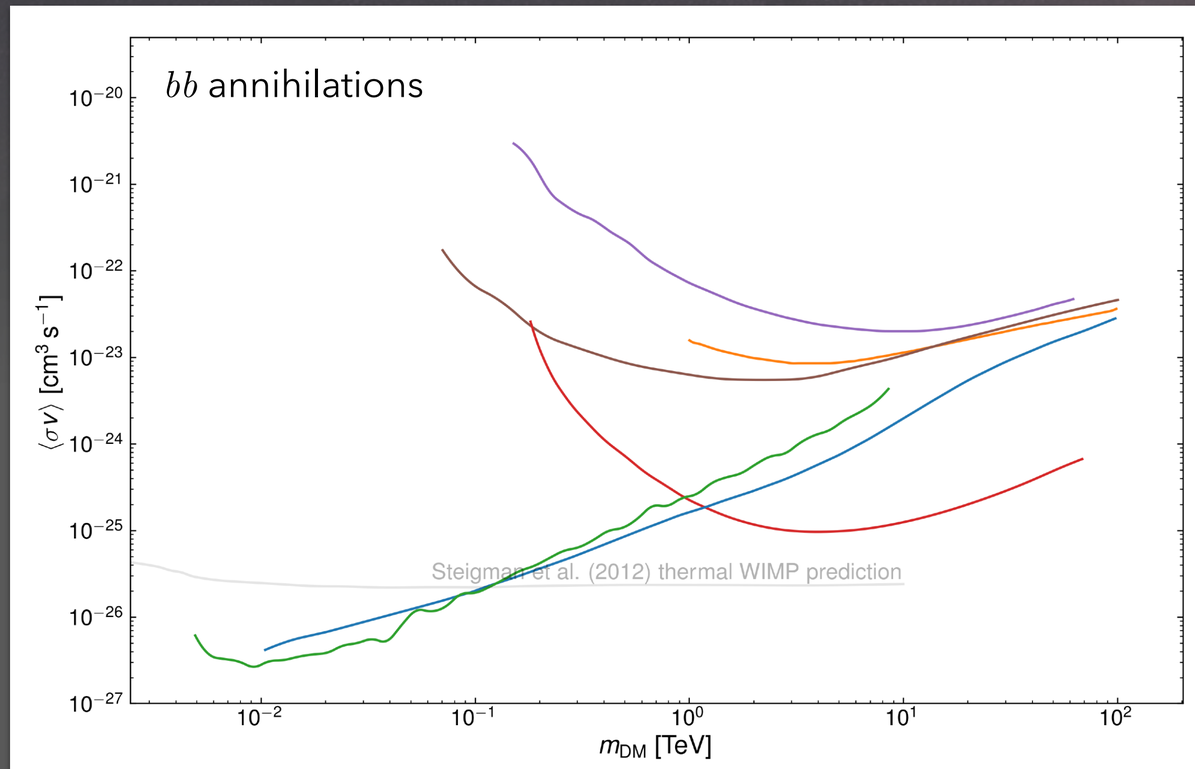


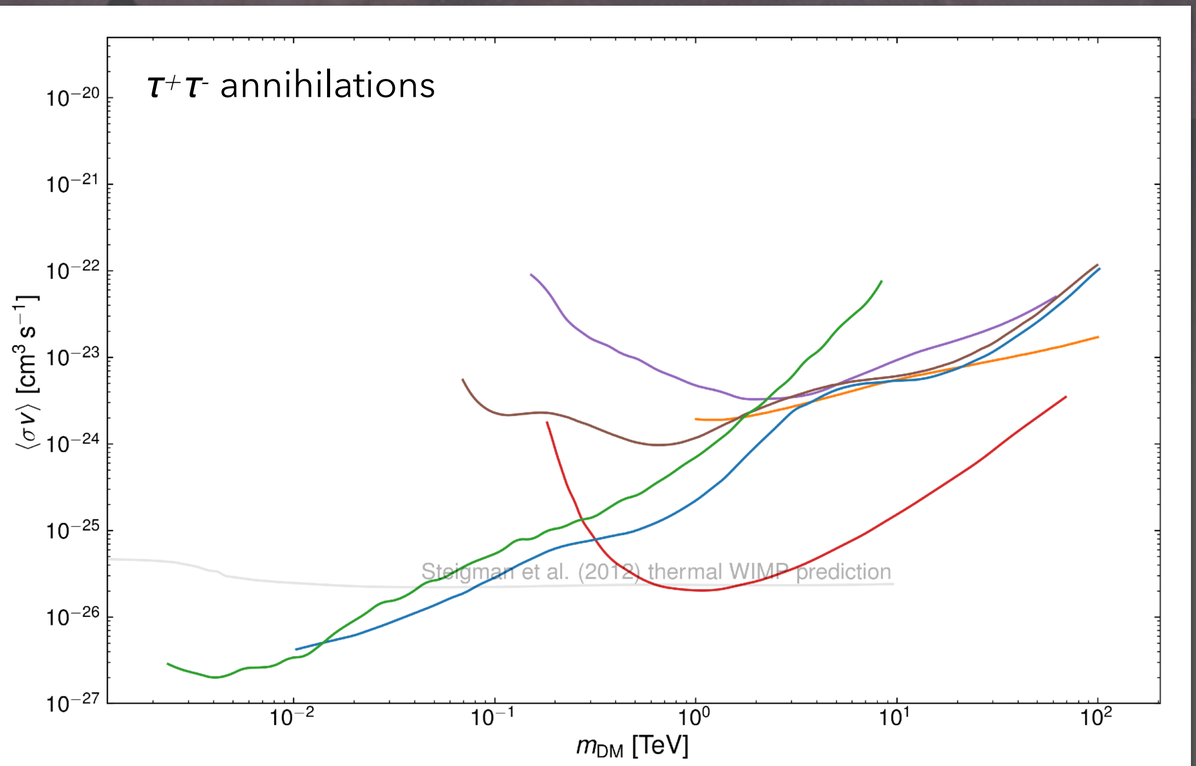
MAGIC, 1806.11063

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

Summary: current limits from gamma-ray observations

H.E.S.S. (2020): Combined dSphs (5), $b\bar{b}$
HAWC (2018): Combined dSphs (15), $b\bar{b}$
MAGIC (2022): Combined dSphs (4), $b\bar{b}$
H.E.S.S. (2016): MW Inner Halo, $b\bar{b}$
MAGIC/FERMI-LAT (2016): Combined dSphs (15), $b\bar{b}$
FERMI-LAT (2020): Combined dSphs (27), $b\bar{b}$

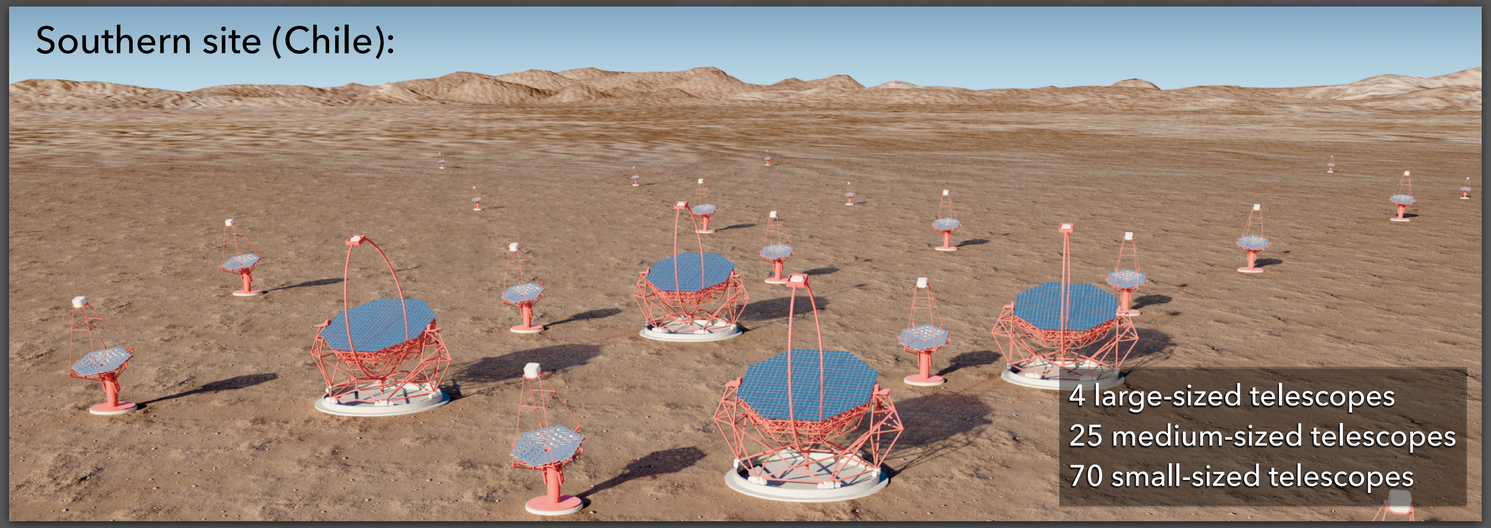




Future: The Cherenkov Telescope Array

Northern site (La Palma):

Southern site (Chile):



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

Future: The Cherenkov Telescope Array

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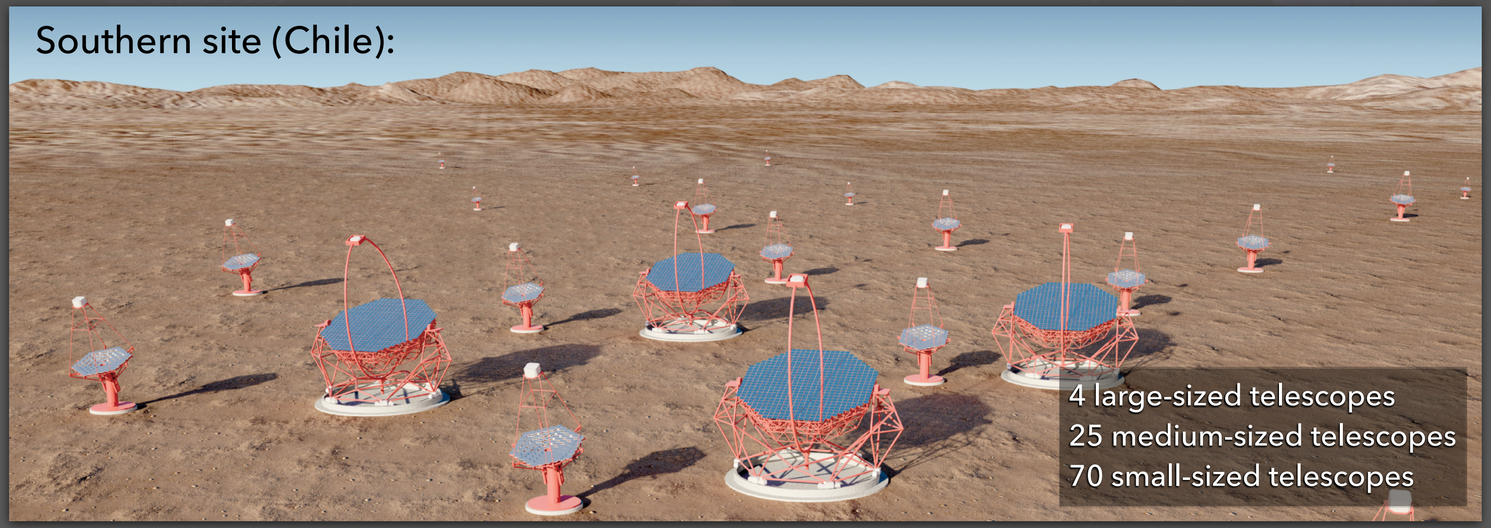

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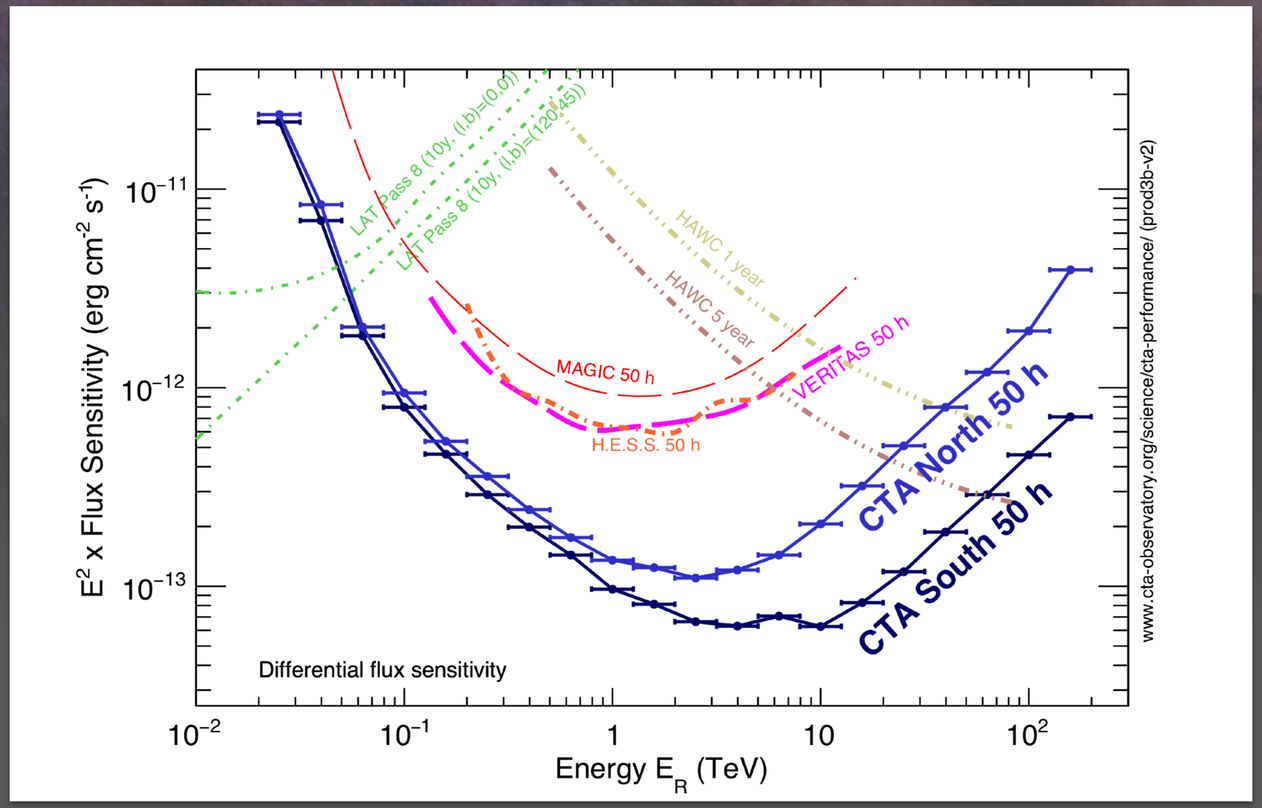
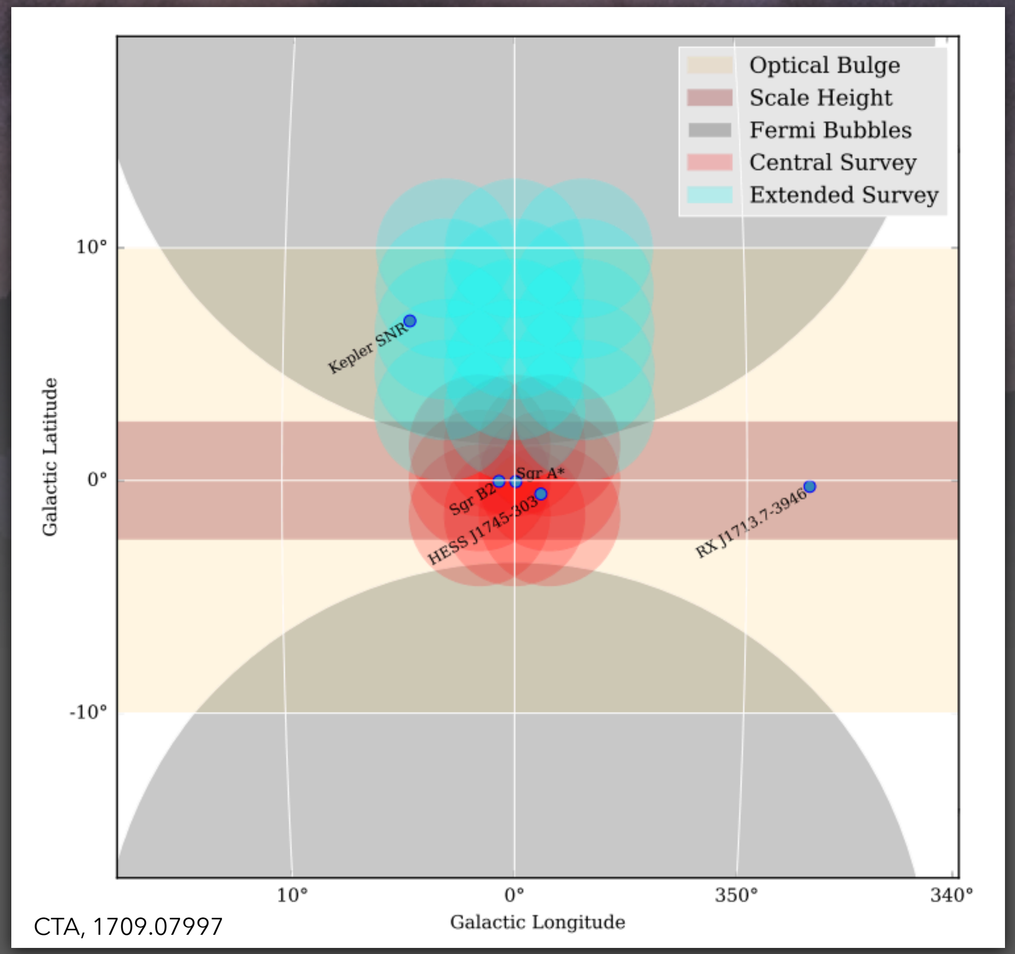
CTA: Sensitivity



γ-ray energy range: 20 GeV – 300 TeV

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

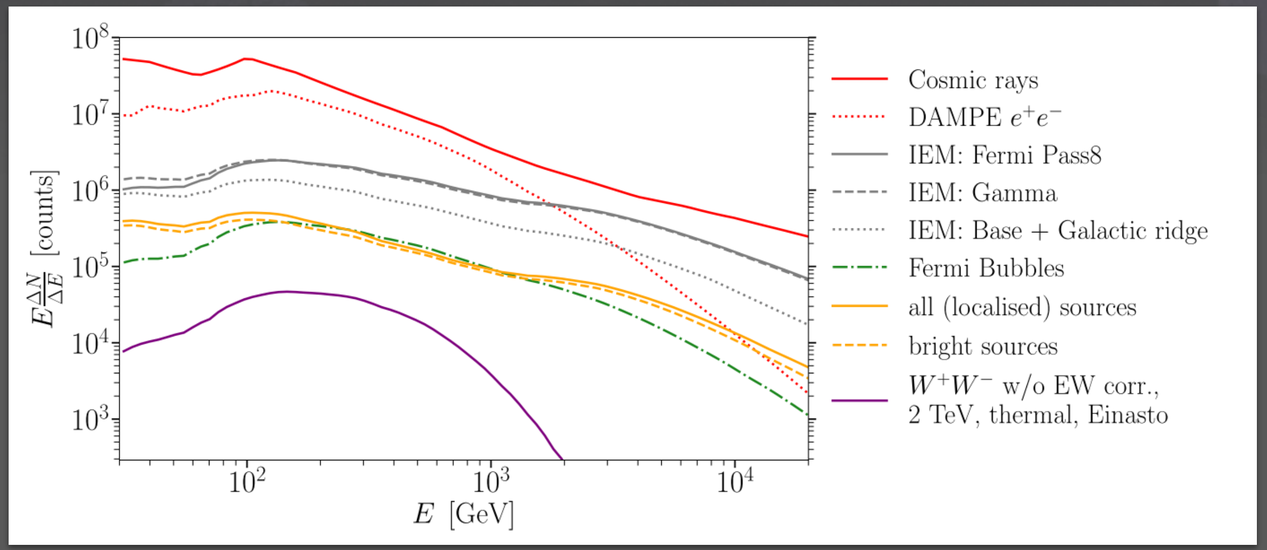
Detailed sensitivity study published (2007.16129)

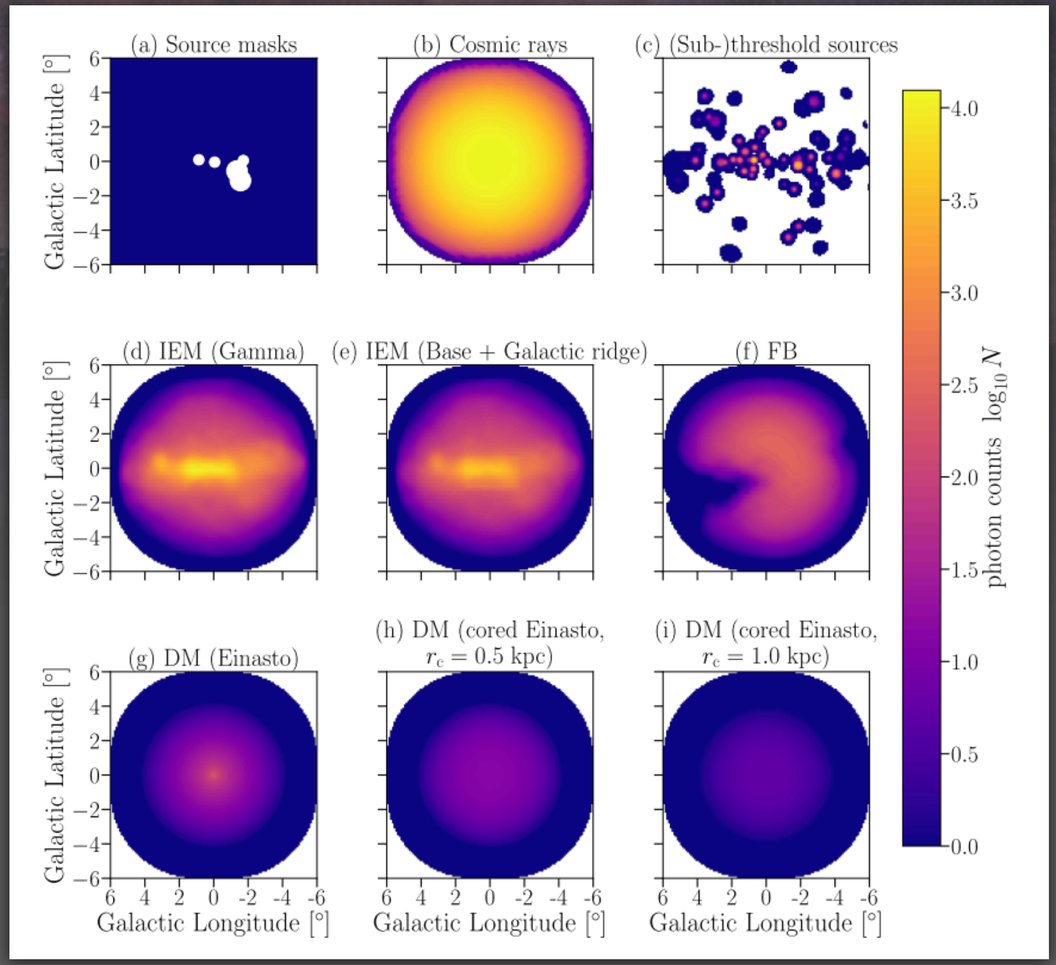
Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

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

The CTA consortium

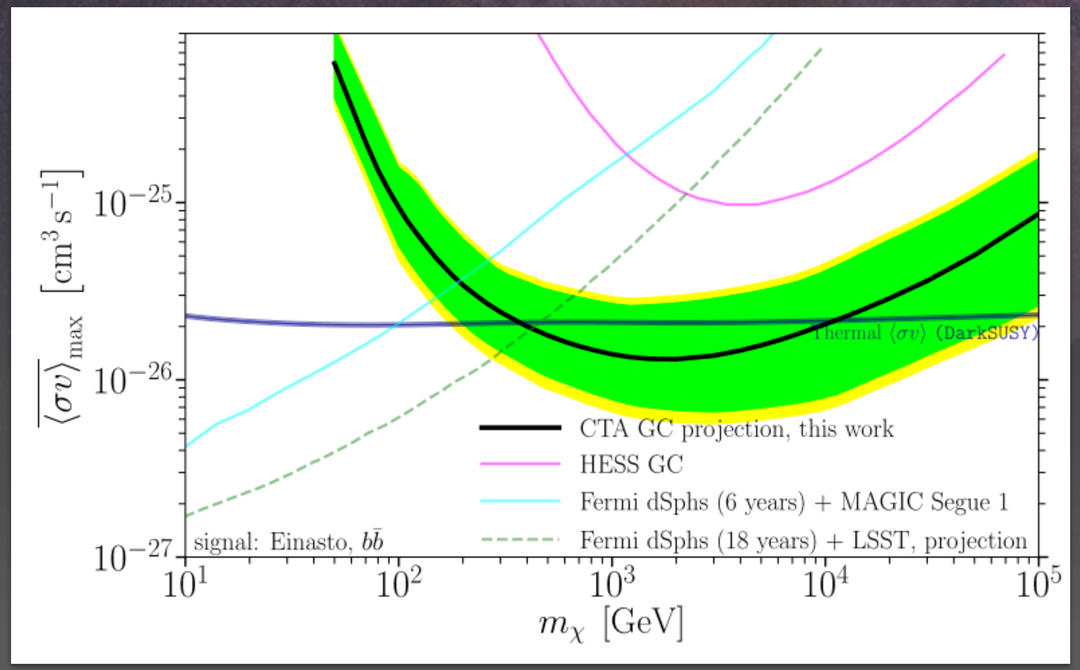
E-mail: torsten.bringmann@fys.uio.no, christopher.eckner@ung.si, Anastasia.Sokolenko@oeaw.ac.at, yanglli5@mail.sysu.edu.cn, gabrijela.zaharijas@ung.si





CTA: Sensitivity to DM signal from Galactic Center

CTA, 2007.16129



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

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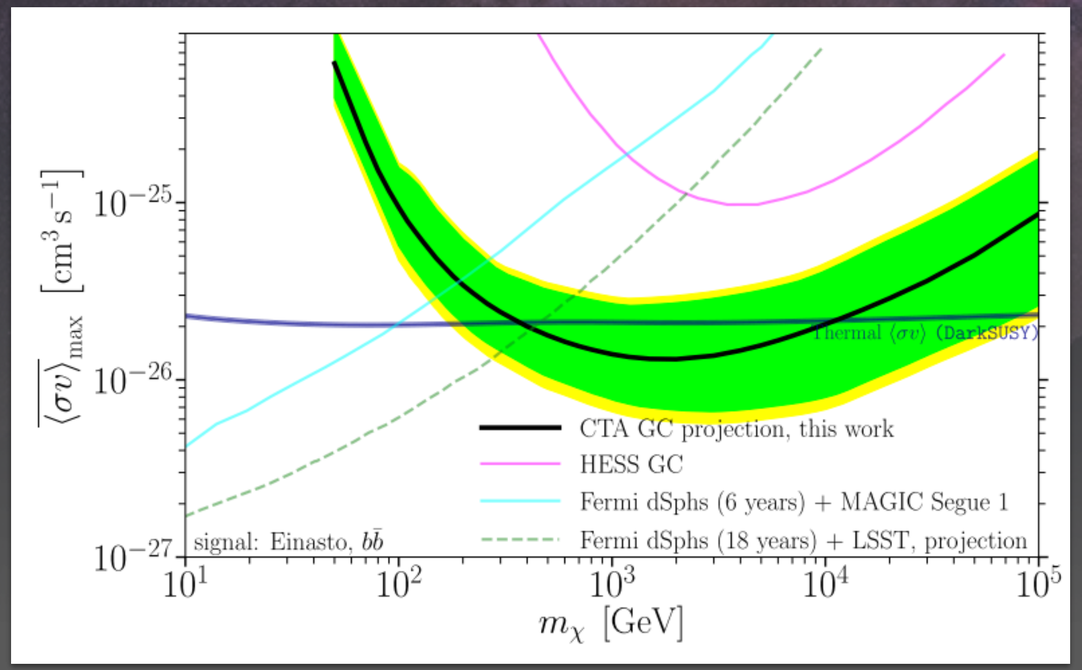
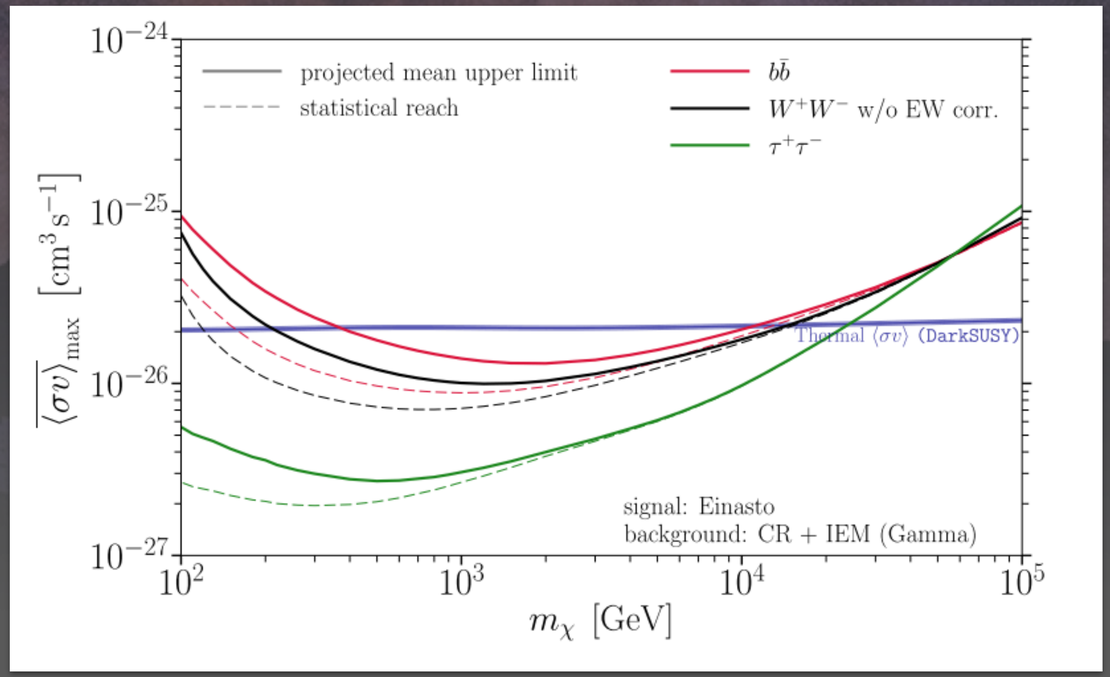


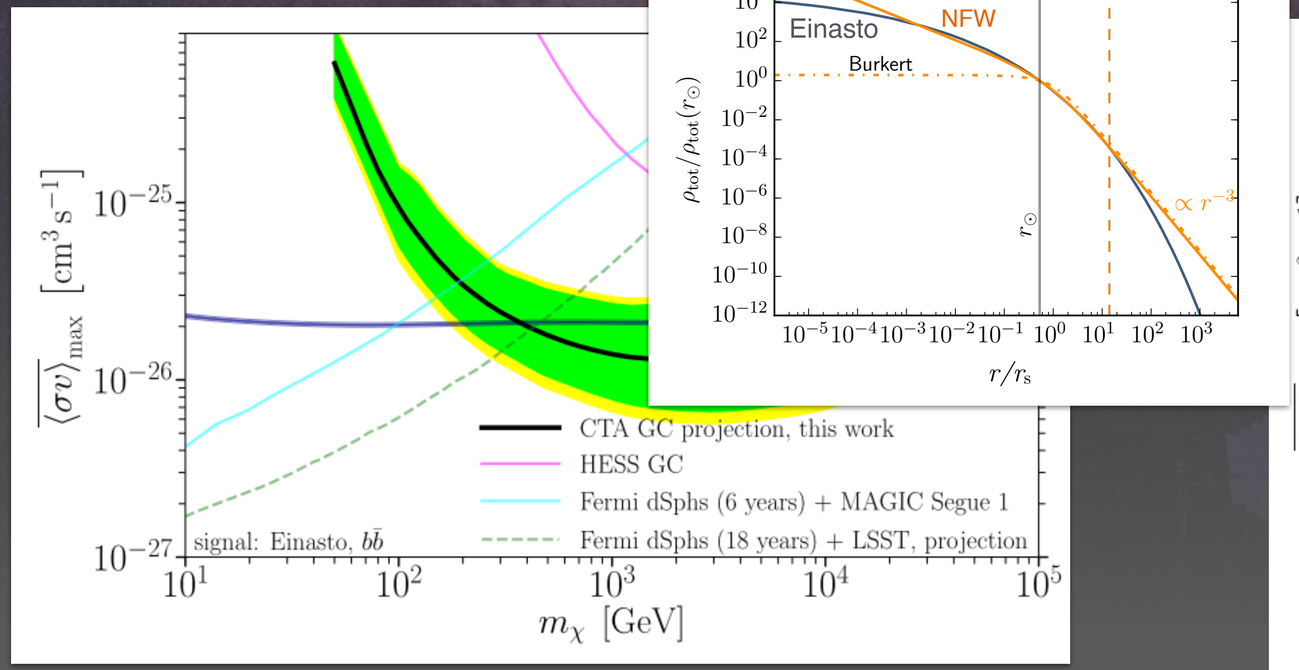


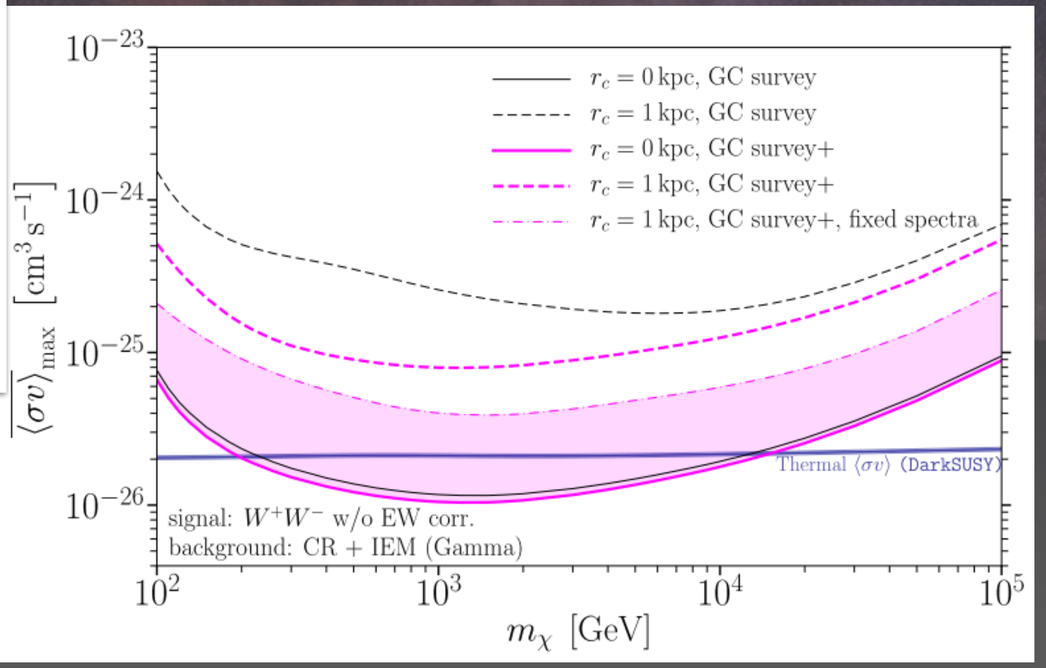
Uncertainties on limits: Background modelling

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

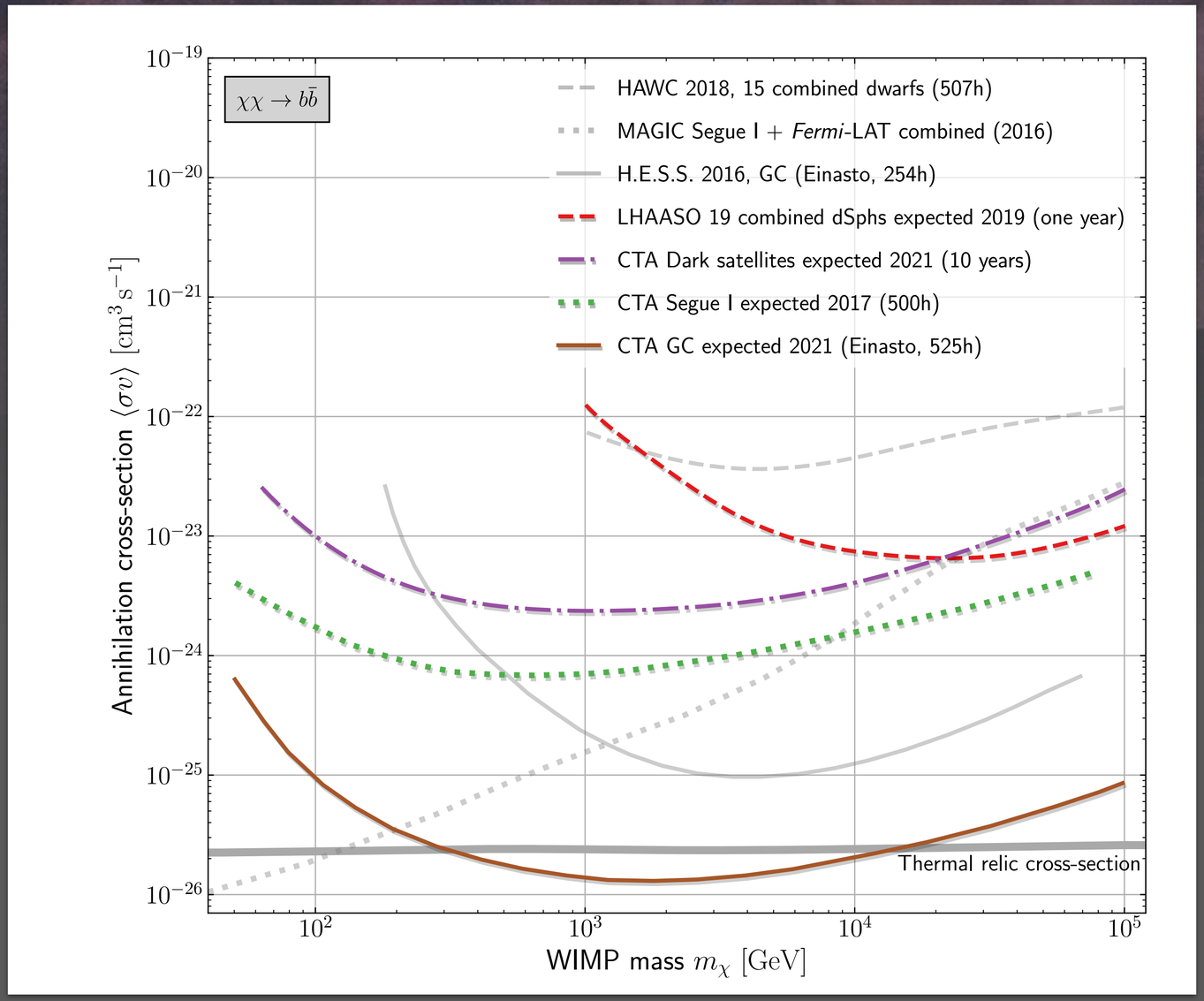




Uncertainties on limits: DM profile

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

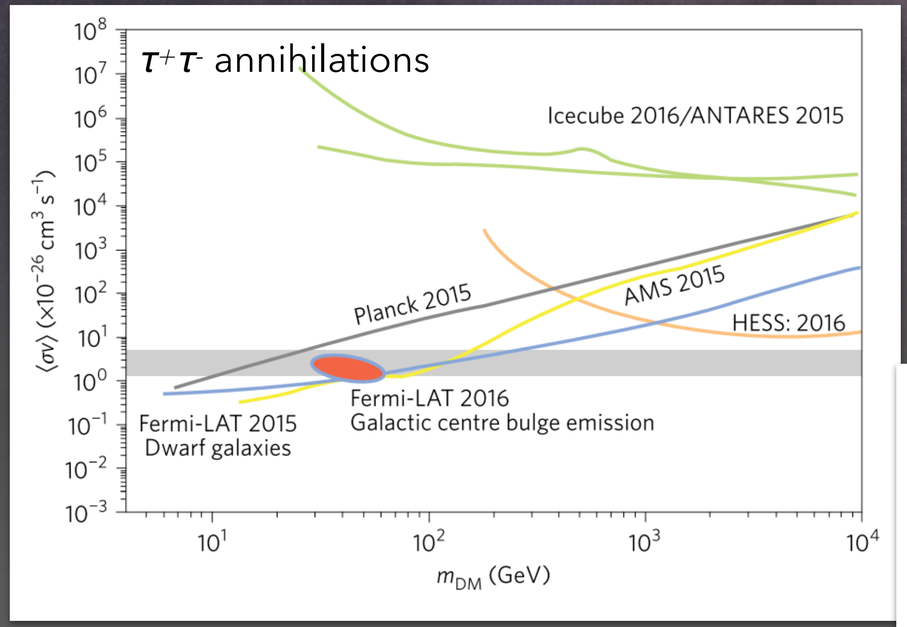
Outlook of gamma-ray observations



Doro, Sánchez-Conde, MH, 2111.01198

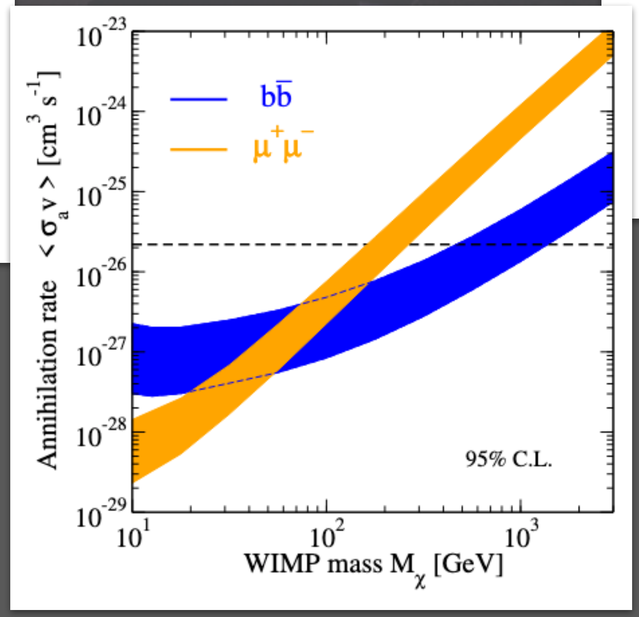
Charged particles, radio and neutrinos

1705.11165



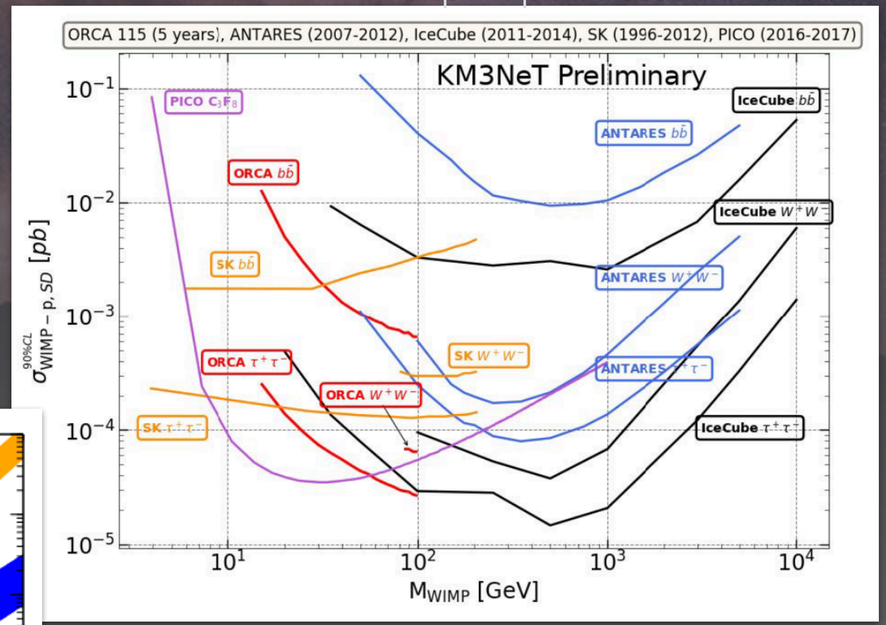
Neutrinos: Galactic Center
AMS: Antiprotons
Planck: CMB

2106.08025



Large Magellanic Cloud in radio

https://pos.sissa.it/358/536/



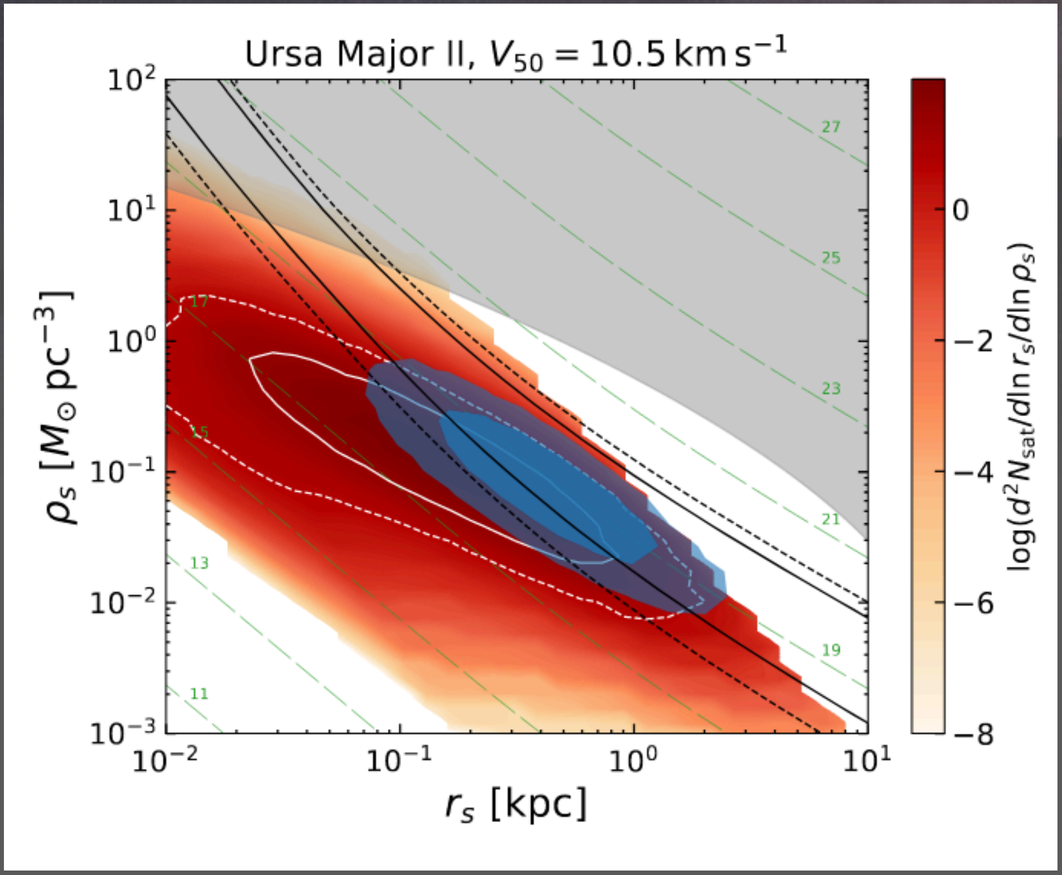
Recoil cross section from the Sun

Summary

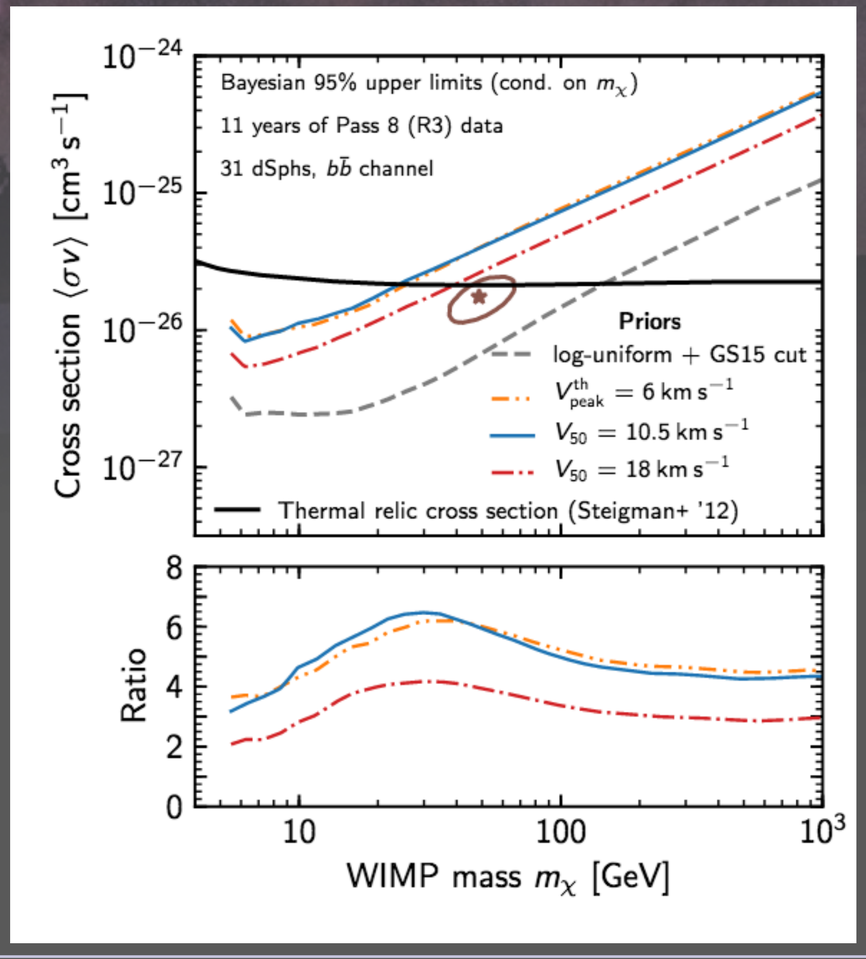
- So far, no indirect hint for Dark Matter
- Very different methods, targets, instruments, and messengers
- Allows for minimizing systematic uncertainties and cross check
- Or combine data for increasing sensitivity
- Not covered today: Search for axion-like particles and primordial black holes (→ Sunday)

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



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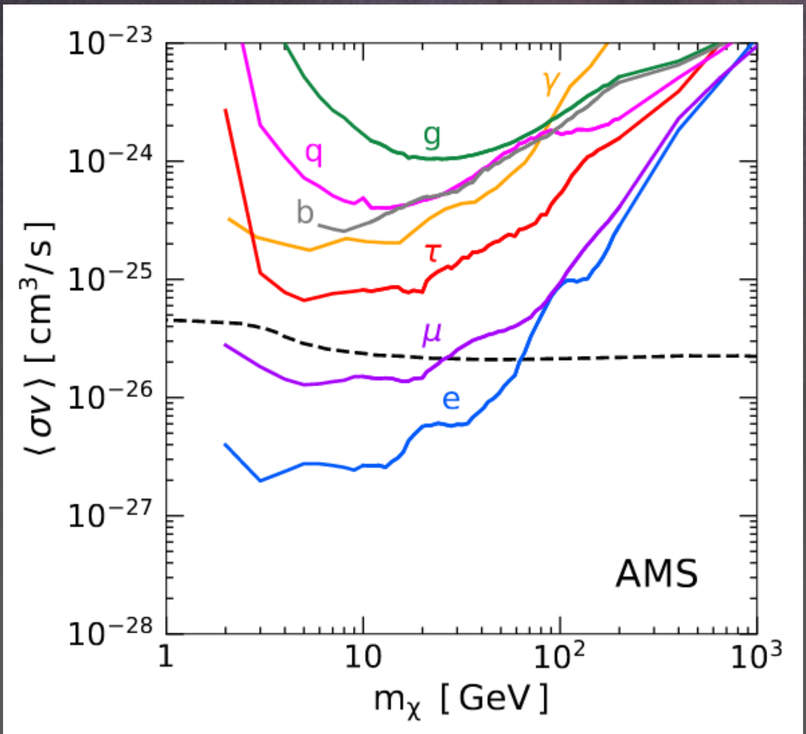
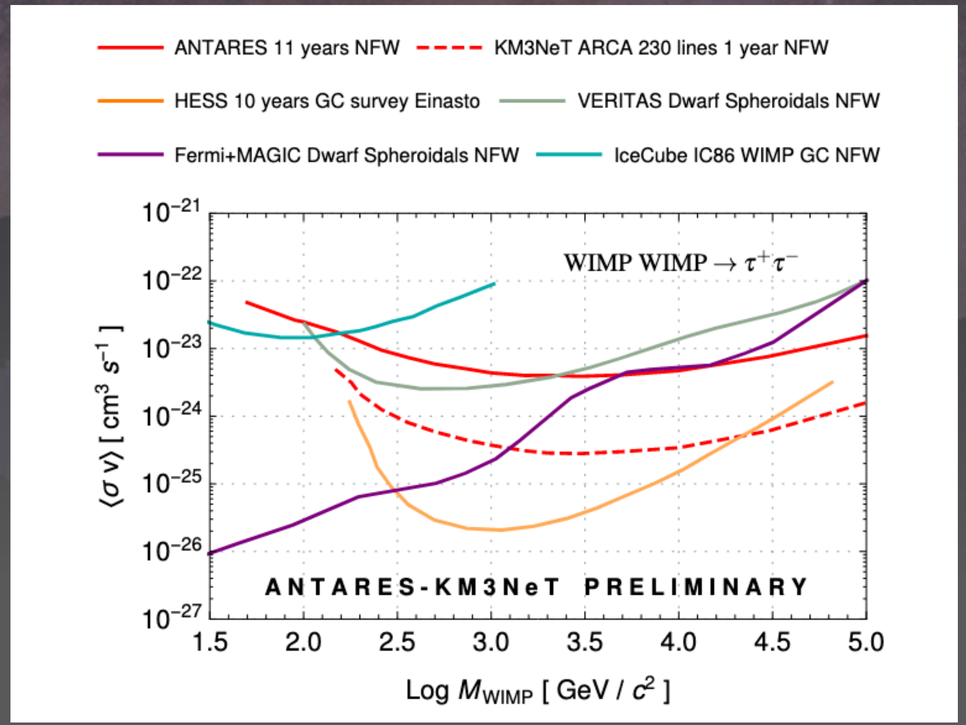


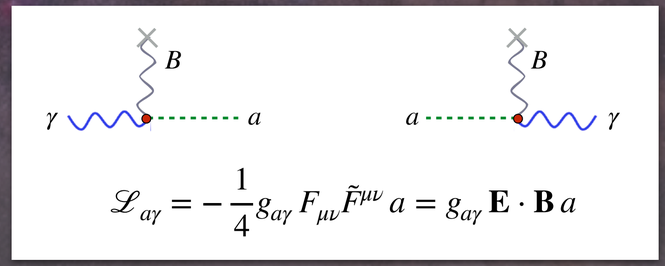
Position fraction: 1805.10305



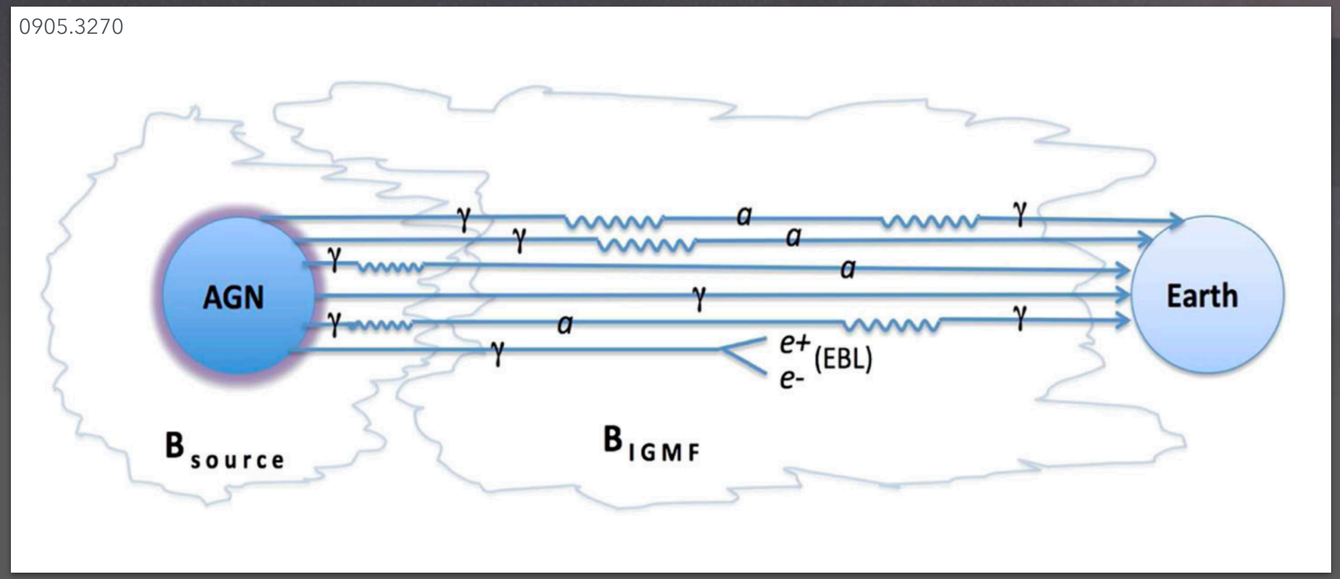
https://pos.sissa.it/358/552/

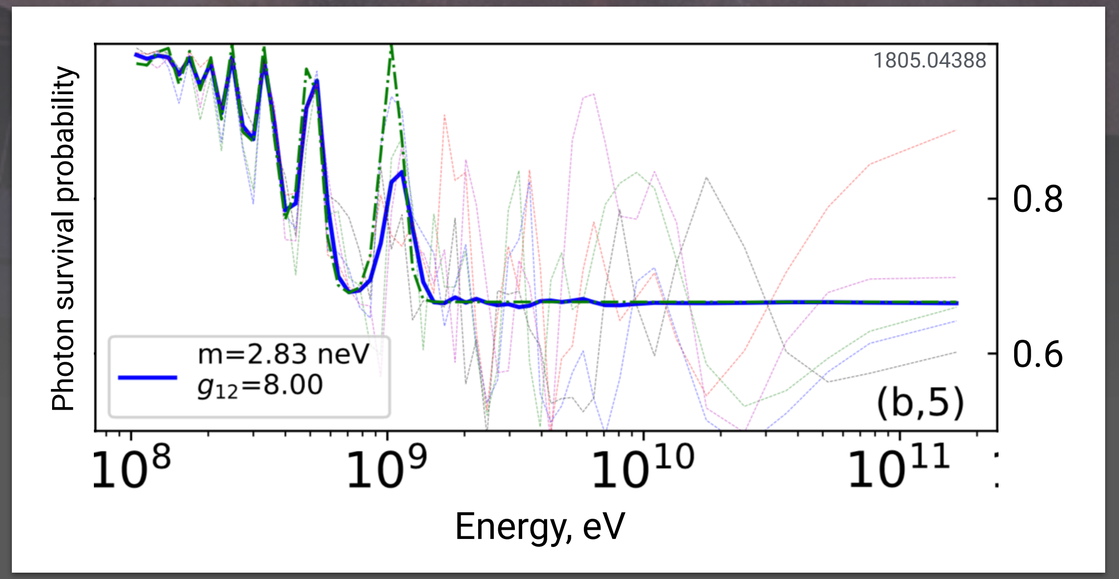
Astrophysical signatures from Axion-like particles (ALPs)

Conversion/oscillation in the presence of magnetic fields



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





ALPs: a dark matter candidate (Preskill et al., 1983; Abbott and Sikivie, 1983; Arias et al., 2012, 1201.5902):

$$g_{a\gamma} < \frac{10^{-12}}{\text{GeV}} \sqrt{\frac{m_a}{\text{neV}}}$$

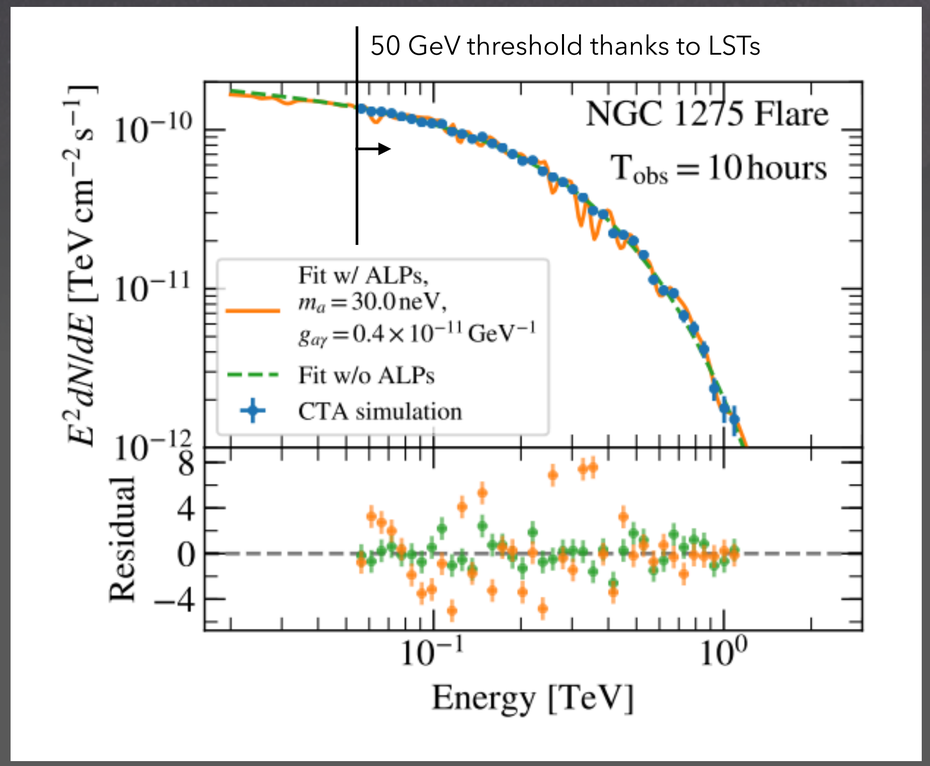
ALP searches towards NGC 1275 (Perseus) with CTA

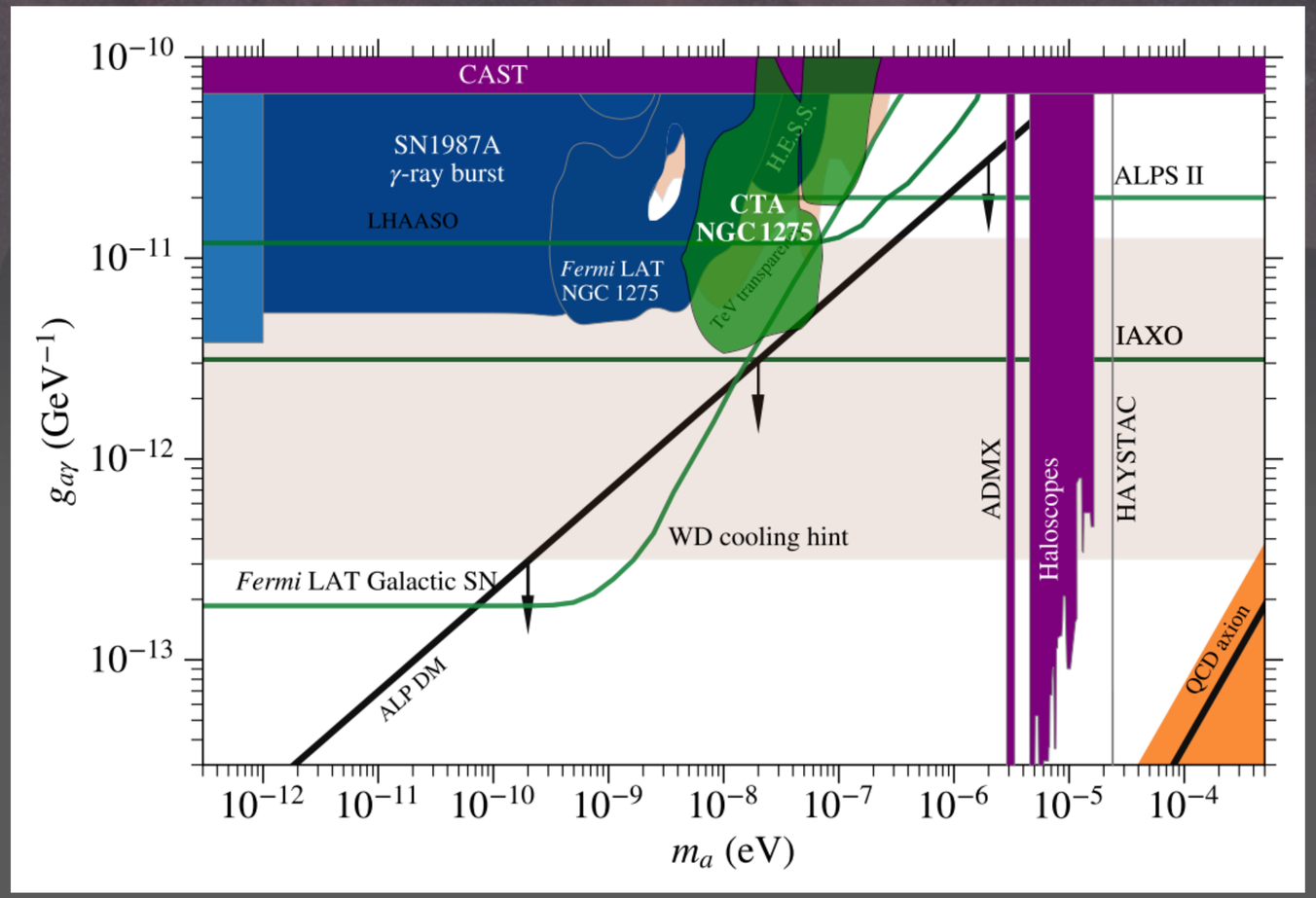
Assume $300\mathrm{h}$ observations with CTA

North, among them $10\mathrm{h}$ in flaring state

Sensitivity driven by flaring state

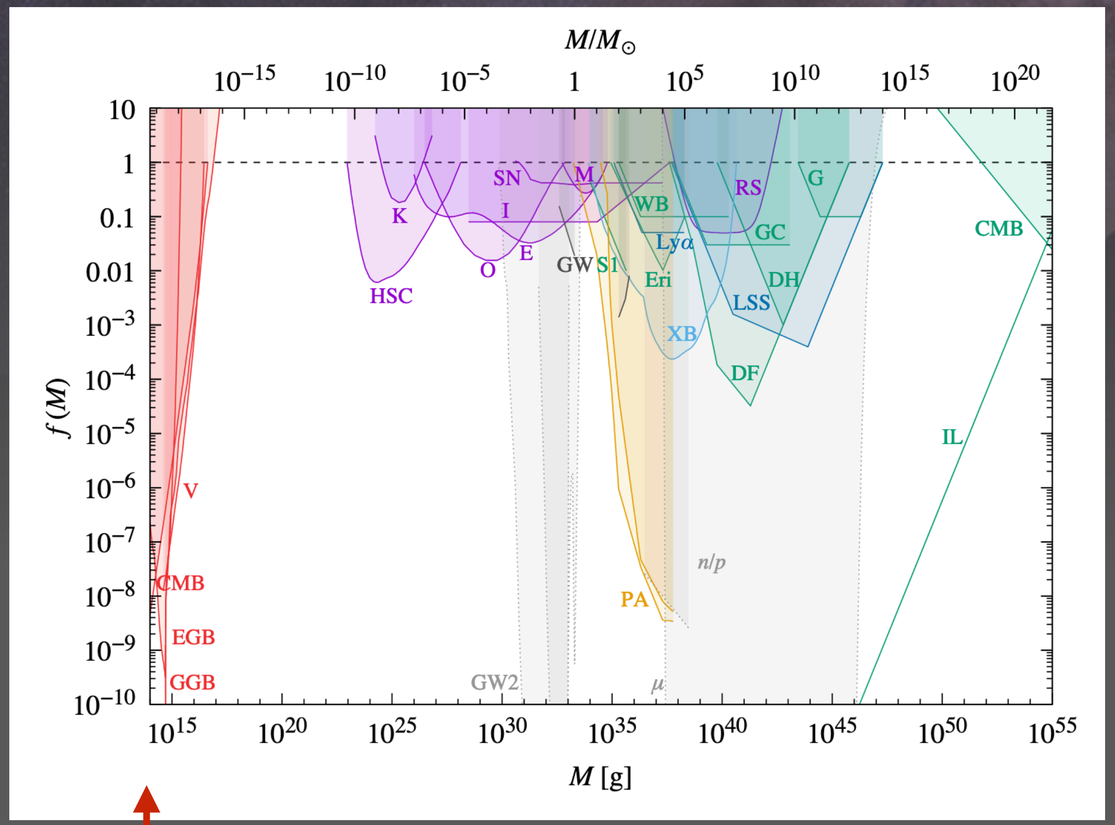
CTA, 2010.01349



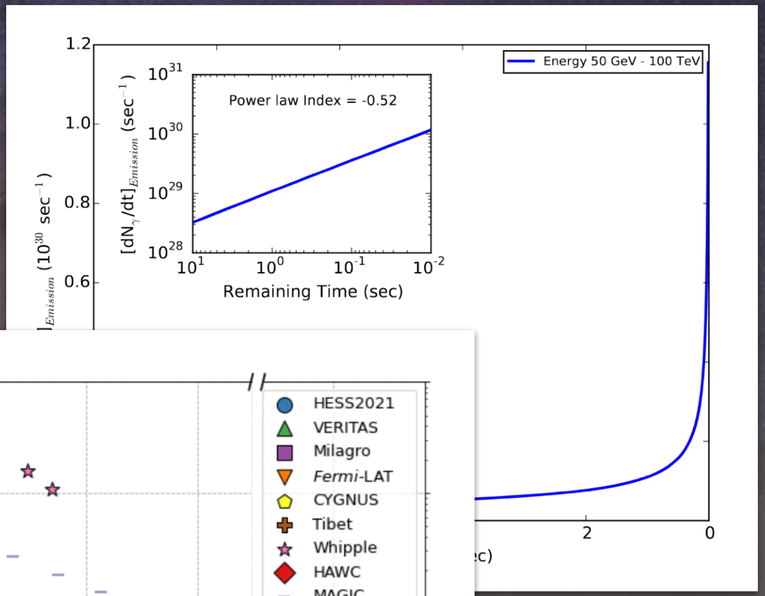


Primordial black hole evaporation

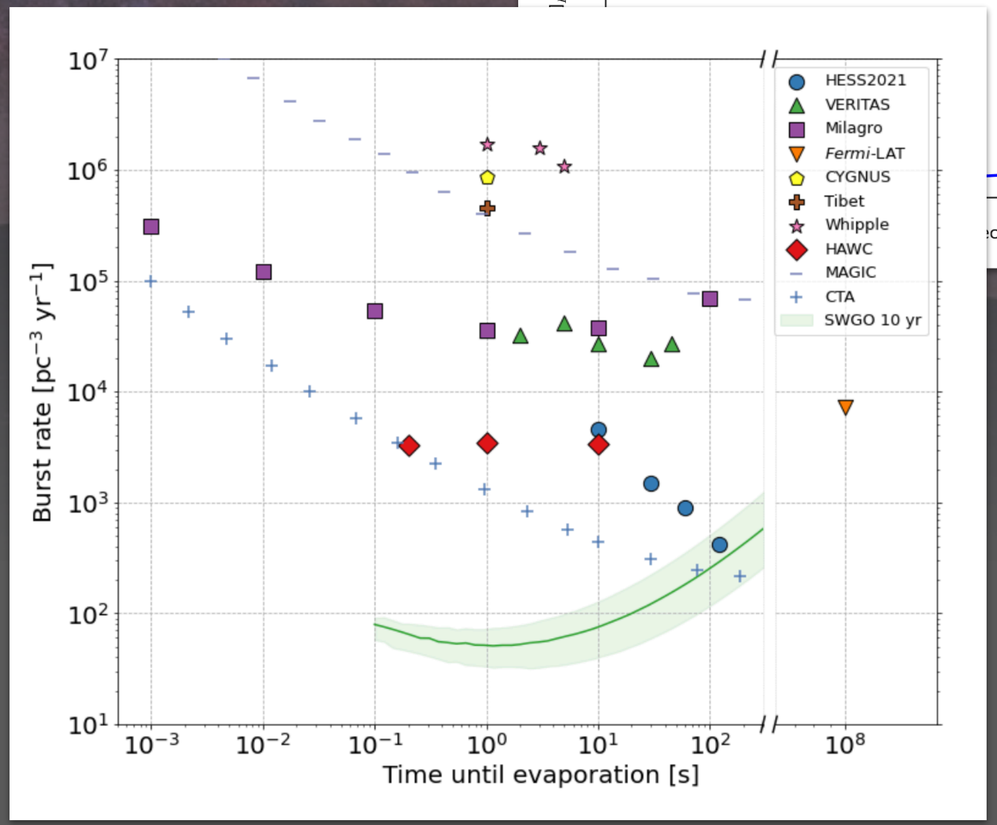
2002.12778



Evaporating now

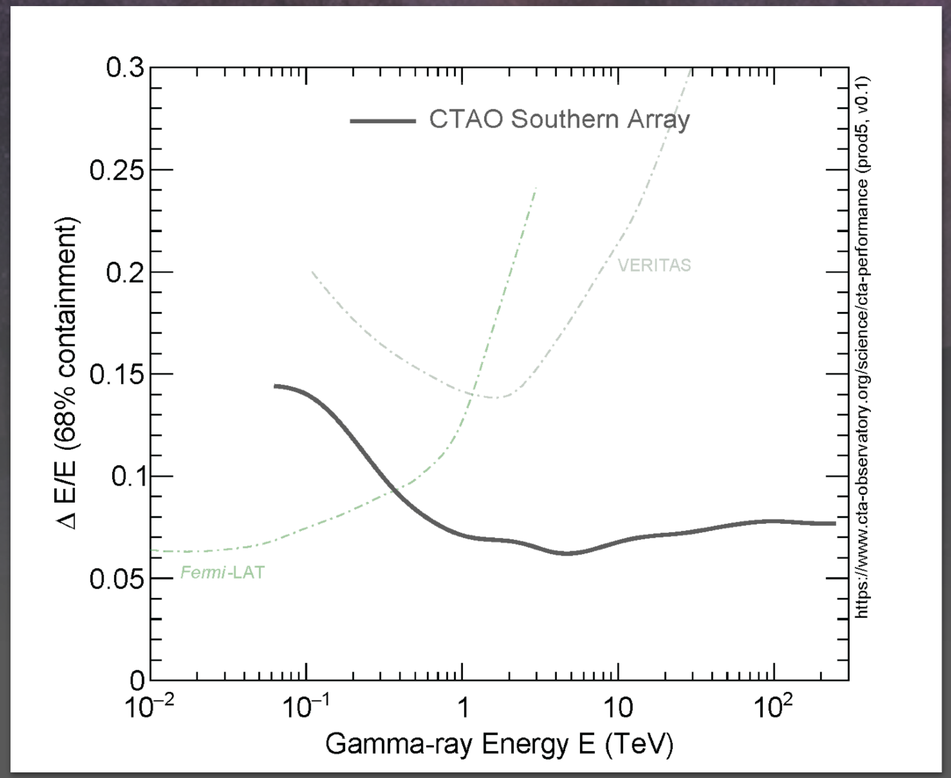


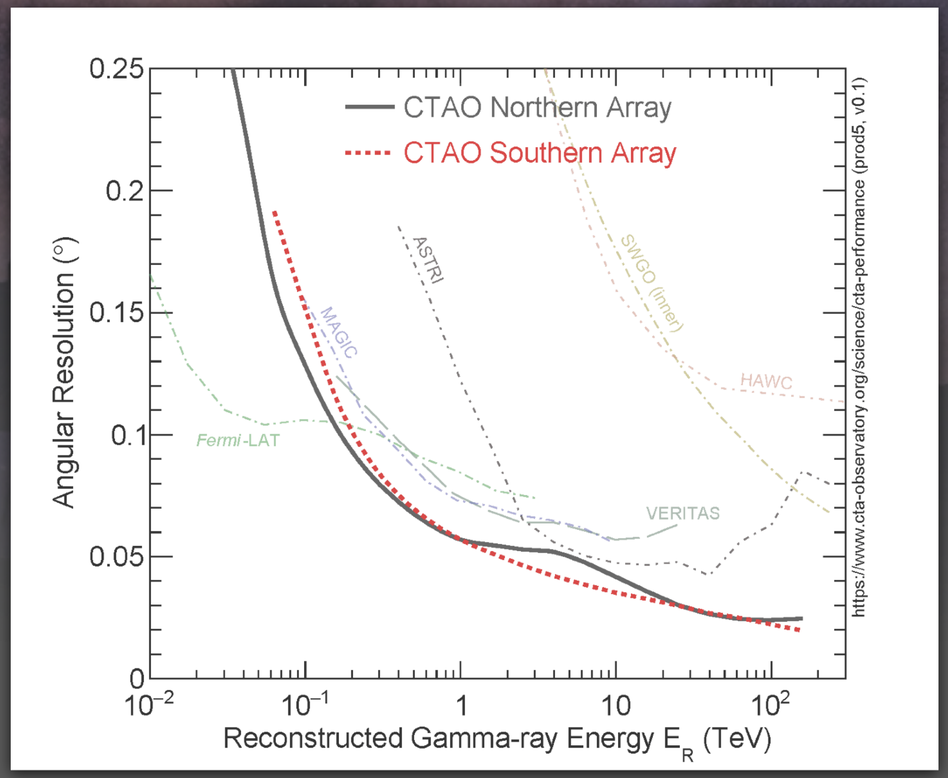
1510.04372



Doro, Sánchez-Conde, MH, 2111.01198

CTA: Angular and energy resolutions



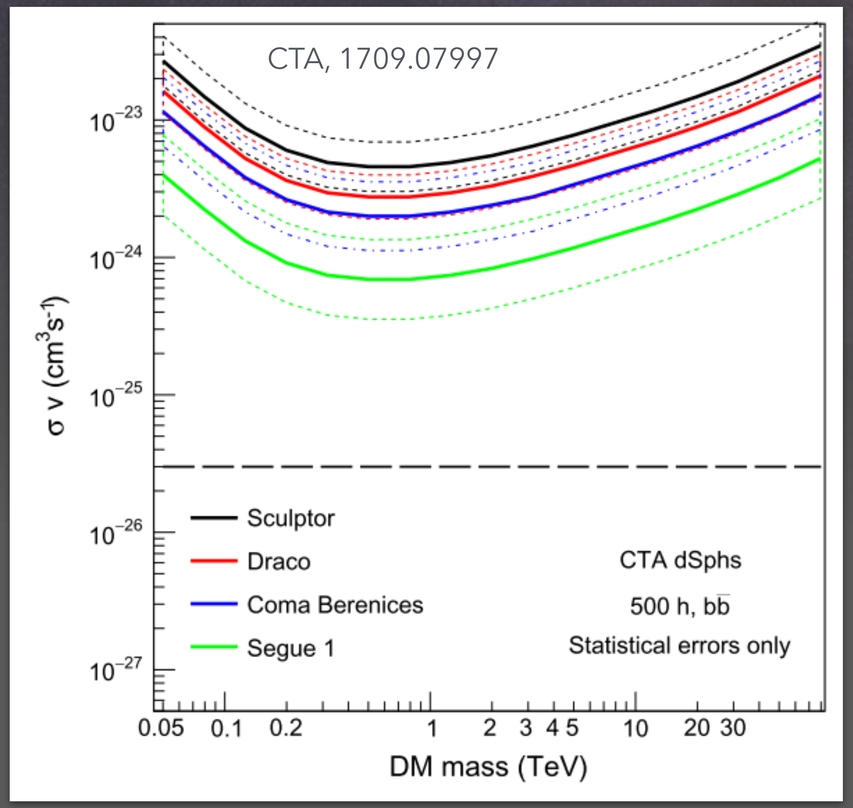


Energy resolution below 10%

Angular resolution: 0.03° – 0.10°

CTA: What to reach with dSph Galaxies

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



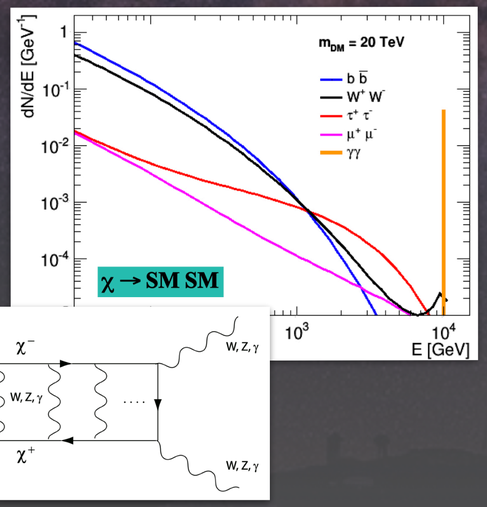
Use dSph observations to confirm DM origin of a signal detected at Galactic Center:

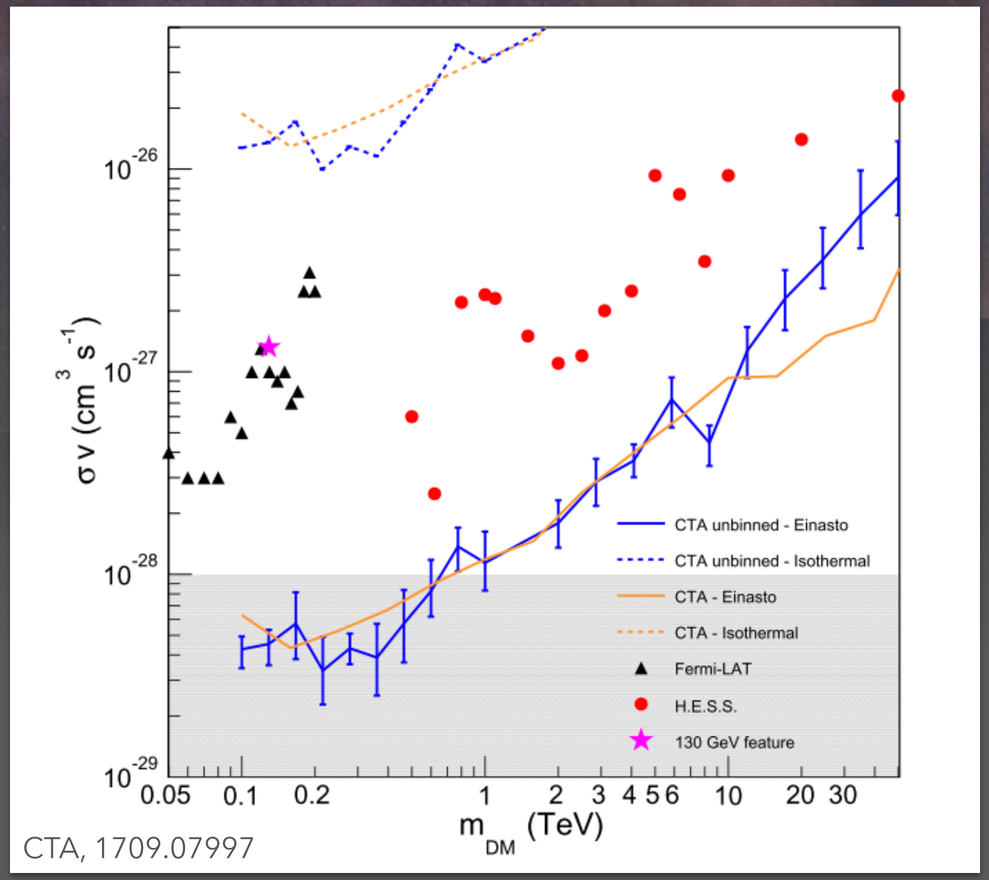
Year	1	2	3	4	5	6	7	8	9	10
Galactic halo	175 h	175 h	175 h							
Best dSph	100 h	100 h	100 h							
				in case of detection at GC, large σv						
Best dSph				150 h	150 h	150 h	150 h	150 h	150 h	150 h
Galactic halo				100 h	100 h	100 h	100 h	100 h	100 h	100 h
				in case of detection at GC, small σv						
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)

Refined analysis ongoing

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





Refined analysis ongoing (separate publication)

Imaging Air Cherenkov Telescopes (IACTs)

Picture: L. Heckmann

Imaging Air Cherenkov Telescopes (IACTs)

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

In operation for 18 years (12 years in stereo)

Picture: L. Heckmann

Imaging Air Cherenkov Telescopes (IACTs)

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

In operation for 18 years (12 years in stereo)

LST-1 (CTA)

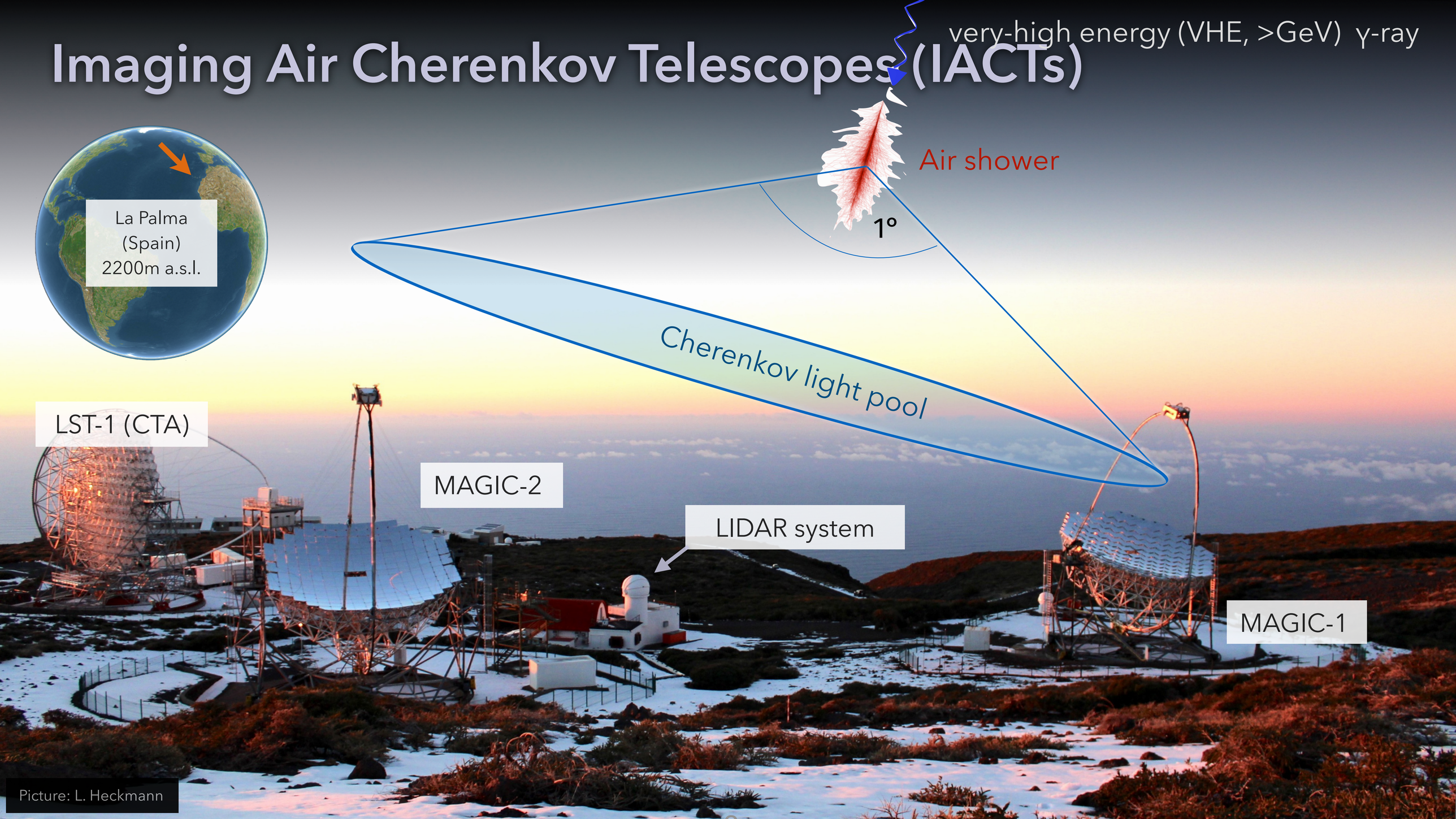
MAGIC-2

LIDAR system

MAGIC-1

Picture: L. Heckmann

Imaging Air Cherenkov Telescopes (IACTs)



Picture: L. Heckmann

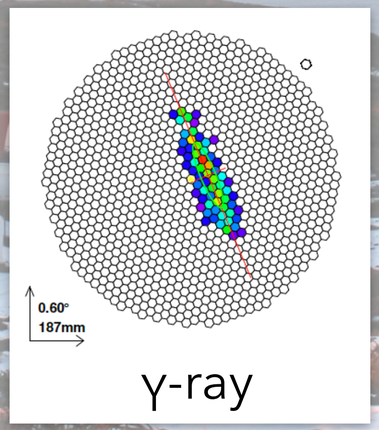
Imaging Air Cherenkov Telescopes (IACTs)

very-high energy (VHE, >GeV) γ-ray

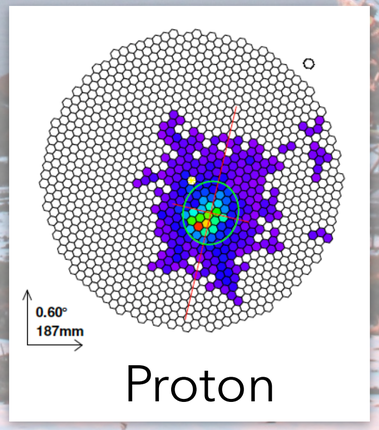
Air shower

1°

Cherenkov light pool



γ-ray



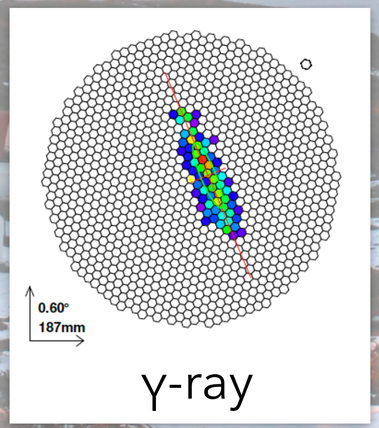
Proton

Picture: L. Heckmann

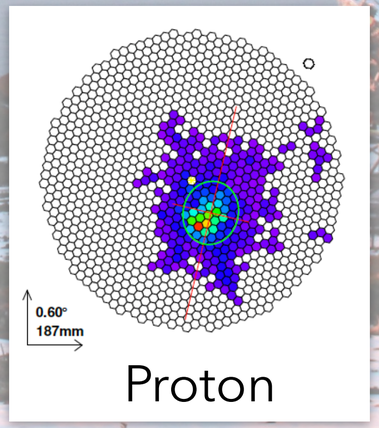
Imaging Air Cherenkov Telescopes (IACTs)

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°



γ-ray



Proton

Picture: L. Heckmann

The *Fermi* satellite

- Designed & operated by NASA
- Launched 2008, still operational
- $4300\ \mathrm{kg}$, $530\ \mathrm{km}$ a.s.l. orbit

- Carries

  Gamma-ray burst monitor (GBM):

  $8\mathrm{keV}$ - $40\ \mathrm{MeV}$

  Large Area Telescope (LAT):

  $20\ \mathrm{MeV}$ - $300\ \mathrm{GeV}$

- LAT has…

  FOV: $2.4\ \mathrm{sr}$

  Energy resolution: 5% - 25%

  Angular resolution: $0.1°$ - $10°$