cherenkov telescope array

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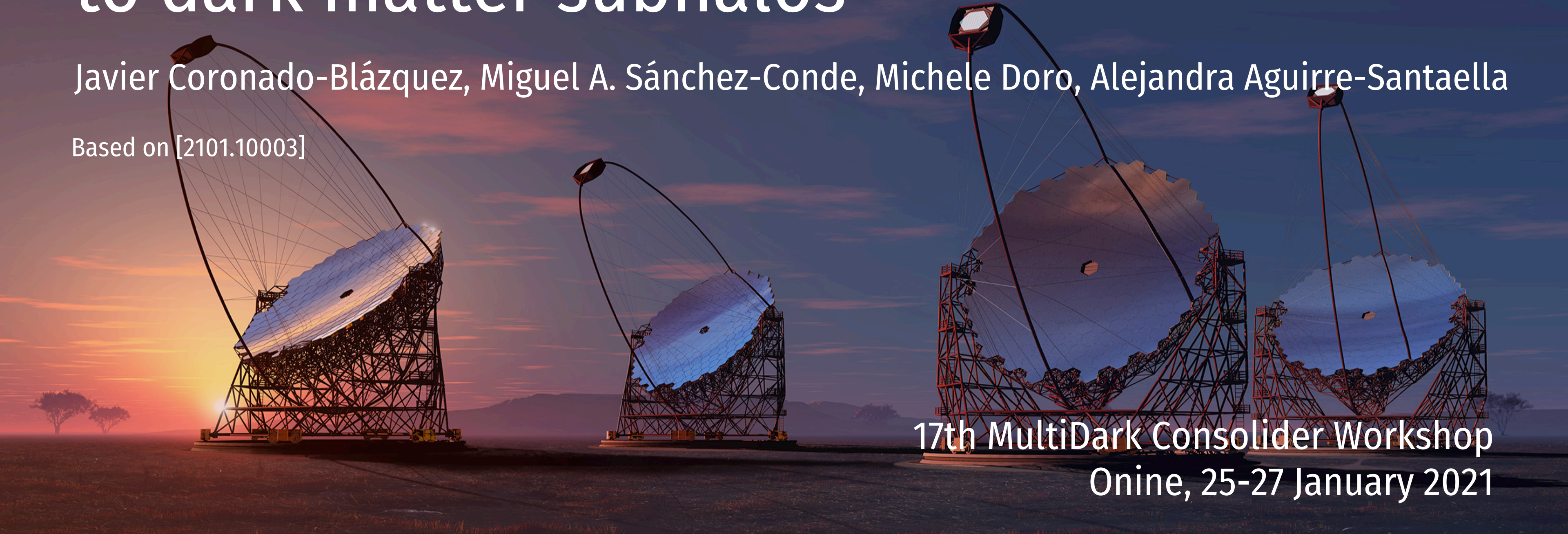
Sensitivity of the Cherenkov Telescope Array to dark matter subhalos

Javier Coronado-Blázquez, Miguel A. Sánchez-Conde, Michele Doro, Alejandra Aguirre-Santaella

Based on [2101.10003]



17th MultiDark Consolider Workshop
Onine, 25-27 January 2021

cta cherenkov telescope array

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ctools cherenkov telescope array

Sensitivity of the Cherenkov Telescope Array to dark subhalos

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Abstract

In this work, we study the potential of the Cherenkov Telescope Array (CTA) for the detection of Galactic dark matter (DM) subhalos. We focus on low-mass subhalos that do not host any baryonic content and therefore lack any multiwavelength counterpart. If the DM is made of weakly interacting massive particles (WIMPs), these dark subhalos may thus appear in the gamma-ray sky as unidentified sources. A detailed characterization of the instrumental response of CTA to dark subhalos is performed, for which we use the *ctools* analysis software and simulate CTA observations under different array configurations and pointing strategies, such as the scheduled extragalactic survey. This, together with information on the subhalo population as inferred from N-body cosmological simulations, allows us to predict the CTA detectability of dark subhalos, i.e., the expected number of subhalos in each of the considered observational scenarios. In the absence of detection, for each observation strategy we set competitive limits to the annihilation cross section as a function of the DM particle mass, that are at the level of $\langle\sigma v\rangle \sim 4\times10^{-24}$ (7×10^{-25}) cm^{3}s^{-1} for the $b\bar{b}$ $(\tau^+\tau^-)$ annihilation channel in the best case scenario. Interestingly, we find the latter to be reached with no dedicated observations, as we obtain the best limits by just accumulating exposure time from all scheduled CTA programs and pointings over the first 10 years of operation. This way CTA will offer the most constraining limits from subhalo searches in the intermediate range between $\sim 1-3$ TeV, complementing previous results with *Fermi*-LAT and HAWC at lower and higher energies, respectively.

Keywords: Dark matter, Gamma rays, Cosmology

Why DM subhalos?

ΛCDM cosmological model predicts a bottom-up structure formation model → halo substructure

DM Halo

DM subhalo

DM sub-subhalo

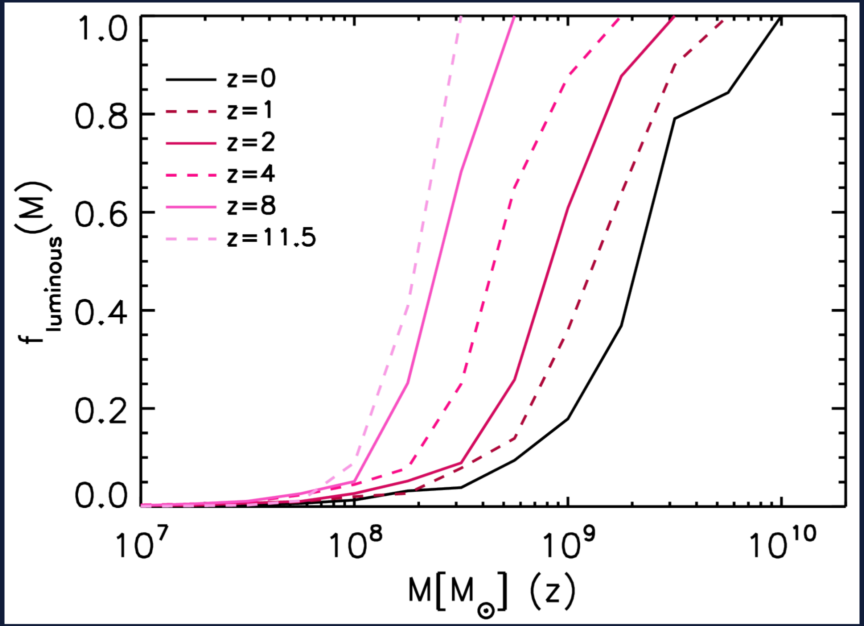
DM sub-sub-subhalo

DM sub-sub-sub-subhalo

DM sub-sub-sub-sub-subhalo

Why DM subhalos?

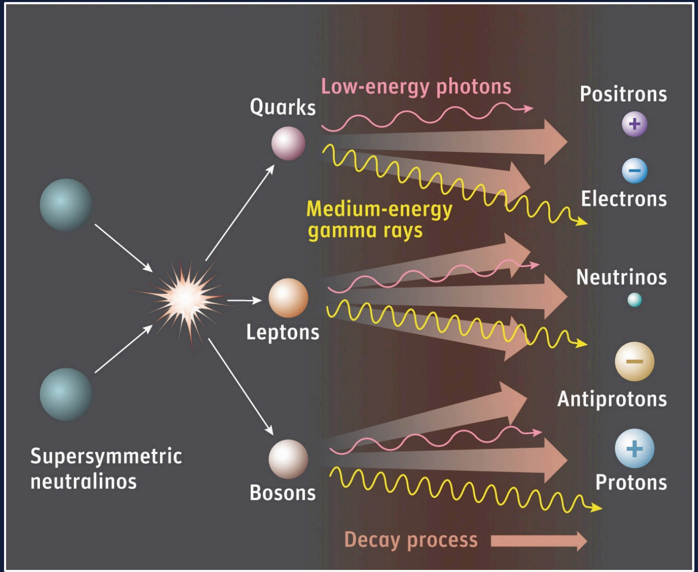
Fraction of subhalos hosting a galaxy



Sawala+14 [1406.6362]

Subhalos with masses below $\sim 10^8 M_\odot$ do not retain gas (baryons) → no emission

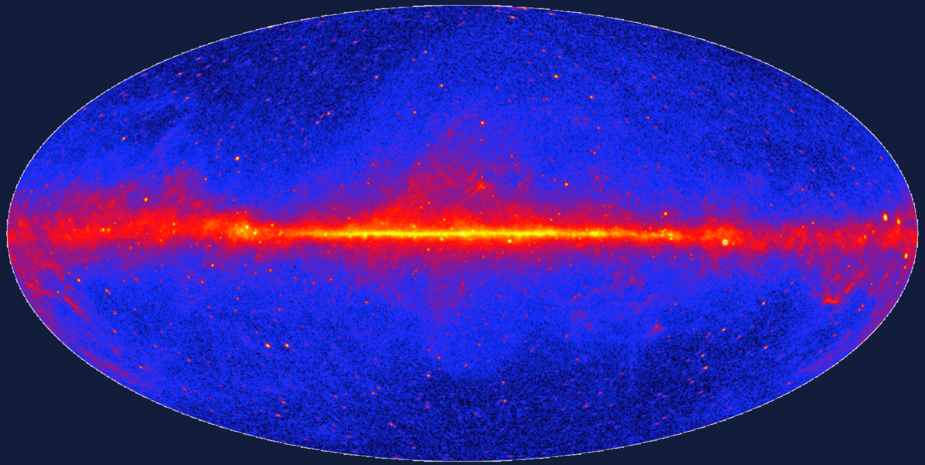
Why DM subhalos?



But if they annihilate (WIMP model)

→ DM-induced gamma-ray emission

Why DM subhalos?

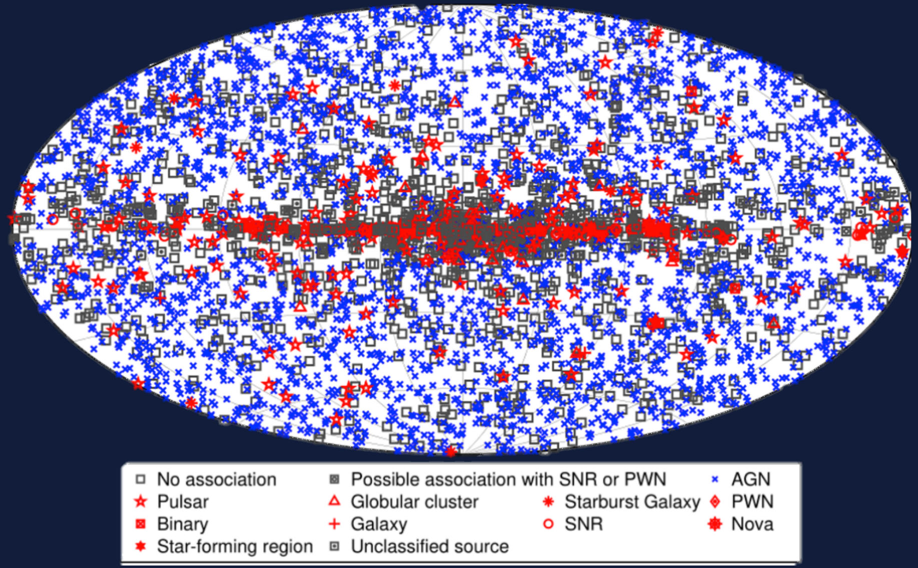


Fermi-LAT 8 year skymap

With CTA we will have gamma-ray source catalogs

In LAT and IACTs, ~1/3 of the sources are unidentified (unIDs) → maybe some of them are DM subhalos!

Why DM subhalos?



With CTA we will have gamma-ray source catalogs

In LAT and IACTs, ~1/3 of the sources are unidentified (unIDs) → maybe some of them are DM subhalos!

Why DM subhalos?

DM subhalos

- Zero astrophysical background
- Very compact and near objects
- Many below $10^8 M_\odot$ (non-visible objects)
- Lack of a priori knowledge about position
- Confusion with astrophysical sources
- Statistical knowledge on their structural properties (may differ from the actual one for individual objects)

dSphs

- Uncertain background
- Less compact and farther objects
- Few $>10^8 M_\odot$ (visible) observed targets
- Well-known position
- Plenty of observations with other instruments
- Relatively good determination of their J-factors
- Stacking (a priori) possible

Subhalos among unIDs are a complementary and independent method

Methodology

Based on comparison between N-body simulations and gamma-ray data - JCB+19 (1906.11896)

$$F(E > E_{th}) = \frac{1}{8\pi\, m_\chi^2} \langle \sigma v \rangle \cdot J_{factor} \cdot N_\gamma(E > E_{th})$$

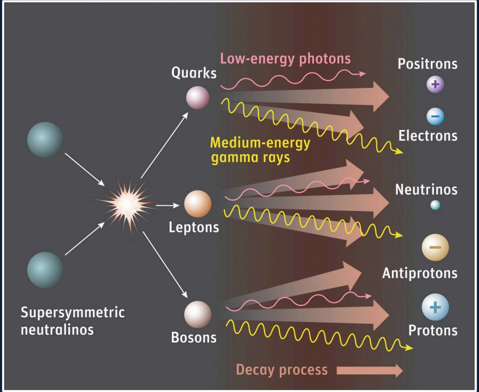
$$J_{factor} = \int_{\Delta\Omega} d\Omega \int_{l.o.s} \rho_{DM}^2[r(\lambda)]d\lambda$$

$$N_\gamma = \int_{E_{th}}^{E} \left(\frac{dN}{dE}\right) dE$$

We can achieve constraints by comparing the number of observed unIDs to the subhalos predicted by simulations, i.e., if we see some subhalos, these will be the brightest

Methodology

Based on comparison between N-body simulations and gamma-ray data - JCB+19 (1906.11896)



$$F(E > E_{th}) = \frac{1}{8\pi\, m_\chi^2} \langle \sigma v \rangle \cdot J_{factor} \cdot N_\gamma(E > E_{th})$$

$$\langle \sigma v \rangle \propto \frac{m_\chi^2 \cdot F_{min}}{N_\gamma \cdot J_{factor}}$$

Instrument

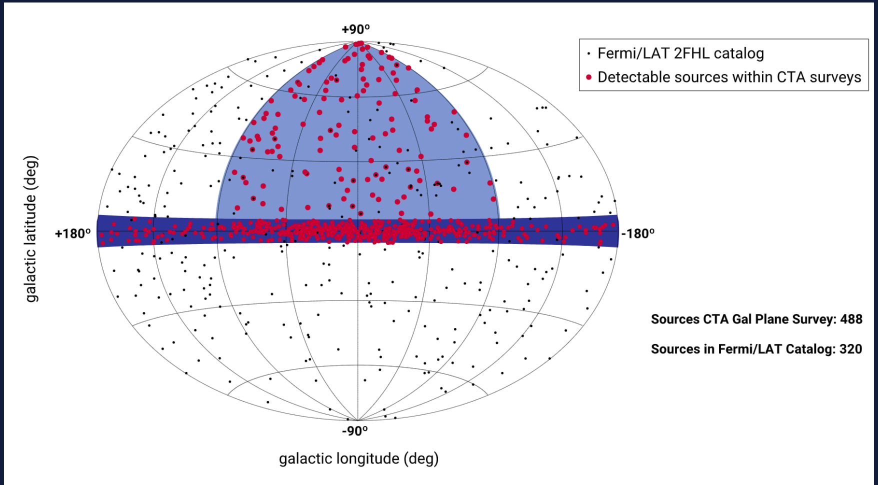
N-body Simulations

Theory

The critical point is F_{min} a.k.a. the CTA sensitivity to subhalos, i.e., the minimum flux required to be detected by CTA at 5σ

Sensitivity to DM spectrum

- One of the obvious choices for unID DM searches is the Key Science Project (KSP) of the Extragalactic (EGAL) CTA Survey, which will observe ~25% of the sky in 3 years



CTA Consortium 2017 (1709.07997)

- It is expected to reach a nominal sensitivity of ~6 mCrab, but this is for a Crab-like spectrum (power law), while DM has a complex and highly curved spectrum, which changes with the WIMP mass and the annihilation channel.

Sensitivity to DM spectrum

To properly compute F_{min} for DM we need to take into account:

- DM spectrum, for every mass and annihilation channel
- Source coordinates
- CTA instrumental response functions (IRFs)
- Pointing strategy
- Array configuration

This can be performed with *ctools*, a CTA data analysis software package

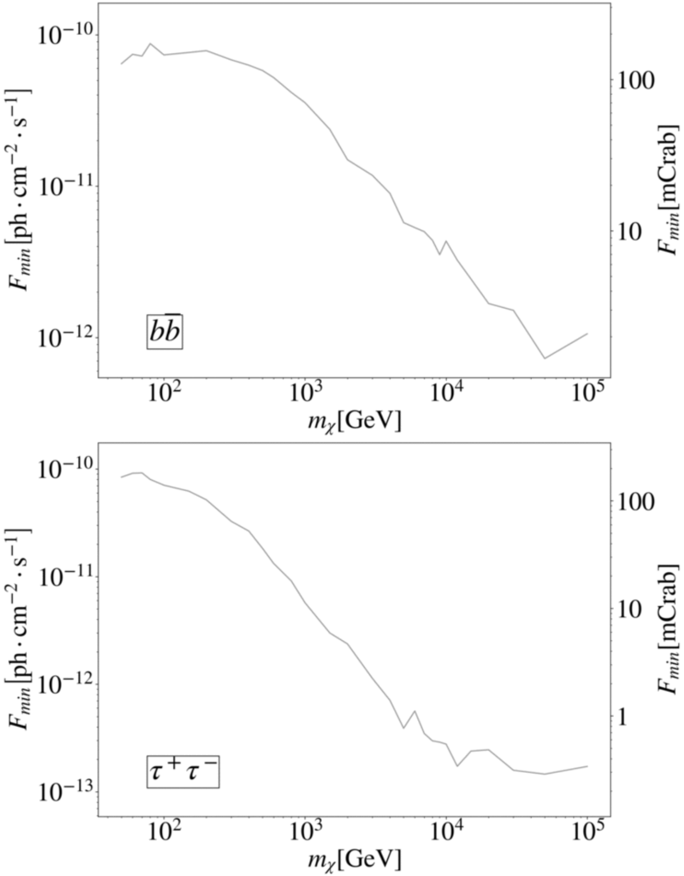
Sensitivity to DM spectrum

- We perform 100 simulations of a subhalo for $b\bar{b}$ and $\tau^+\tau^-$ annihilation channels, changing the random seed in event generator, and using the latest IRFs for CTA-North

- The integration time is set to 3h, as reported in the "Science with CTA" paper (1709.07997) for the EGAL survey

- We compute the source detection significance with *ctlike*, and repeat the simulation changing the normalization (flux) until we reach 5σ. The flux value at that point is F_{min}

- These simulations can be extrapolated for larger exposure times; instead of 100 computationally-expensive new simulations, we check for a handful the scaling, which is $\sqrt{t}$ to a very good approximation



JCB+21 [2101.10003]

Sensitivity to DM spectrum

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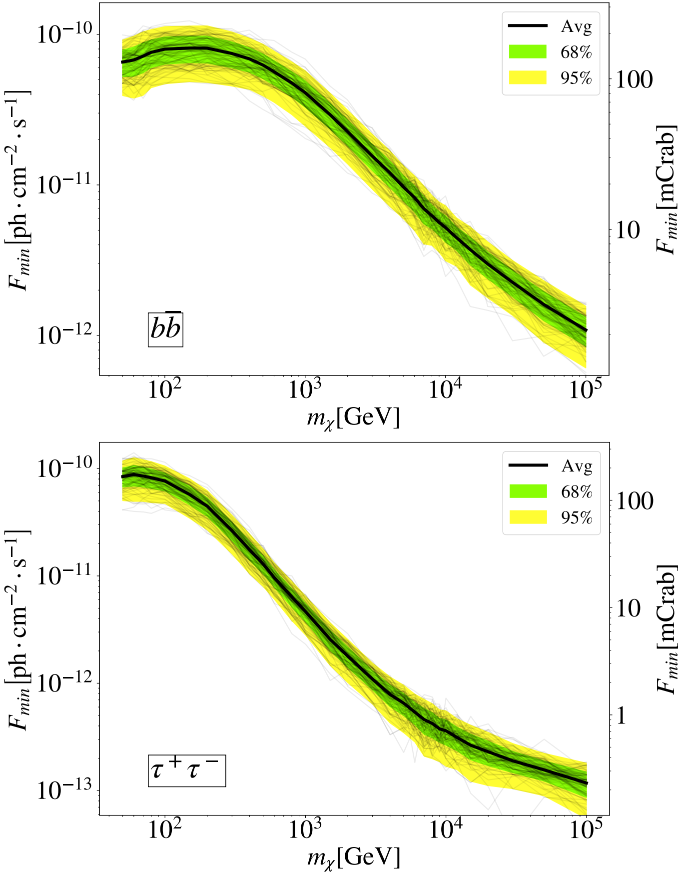
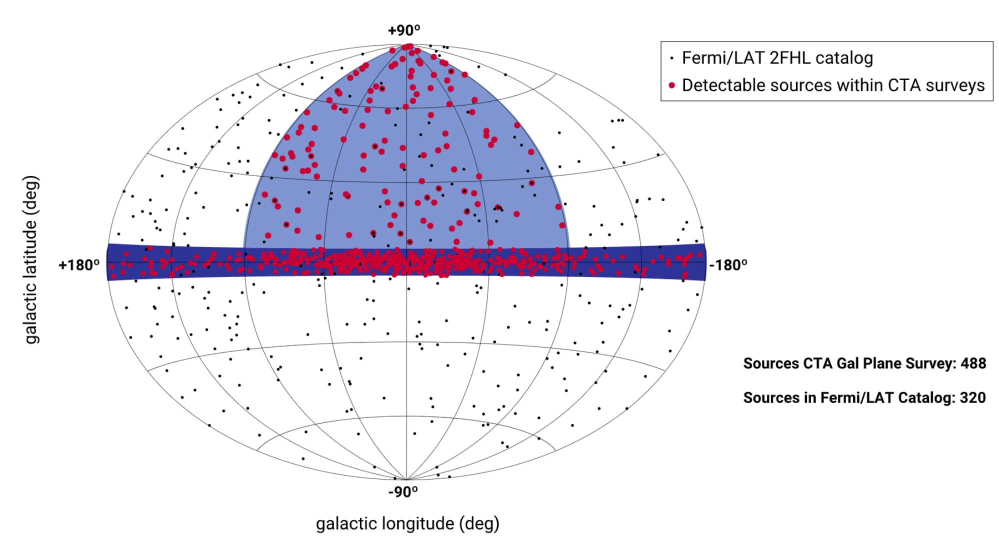


JCB+21 [2101.10003]

Pointing strategies

The EGAL survey is the obvious choice, but there are at least two more strategies



CTA Consortium 2017 (1709.07997)

Pointing strategies

EGAL survey (*EGAL*)

CTA KSP, 25% of the sky, 3h per pointing

Pros: large area, uniform exposure

Cons: only 3h of exposure

Overall exposure (*EXPO*)

Serendipitous discovery in the FoV of any CTA pointing

Pros: larger area, larger exposures

Cons: difficult to estimate time+area, off-axis sensitivity

Deep field (*DEEP*)

Dedicated observation in clean e.g. 8x8° field, e.g. ~100h

Pros: extreme sensitivity, serendipitous discoveries

Cons: very small area, not a KSP

Pointing strategies

Overall exposure (*EXPO*)

Serendipitous discovery in the FoV of any CTA pointing

Pros: larger area, larger exposures

Cons: difficult to estimate time+area, off-axis sensitivity

Best strategy

Pointing strategies

How to estimate the sky fraction that will be observed by CTA in 10 years?

Pointing strategies

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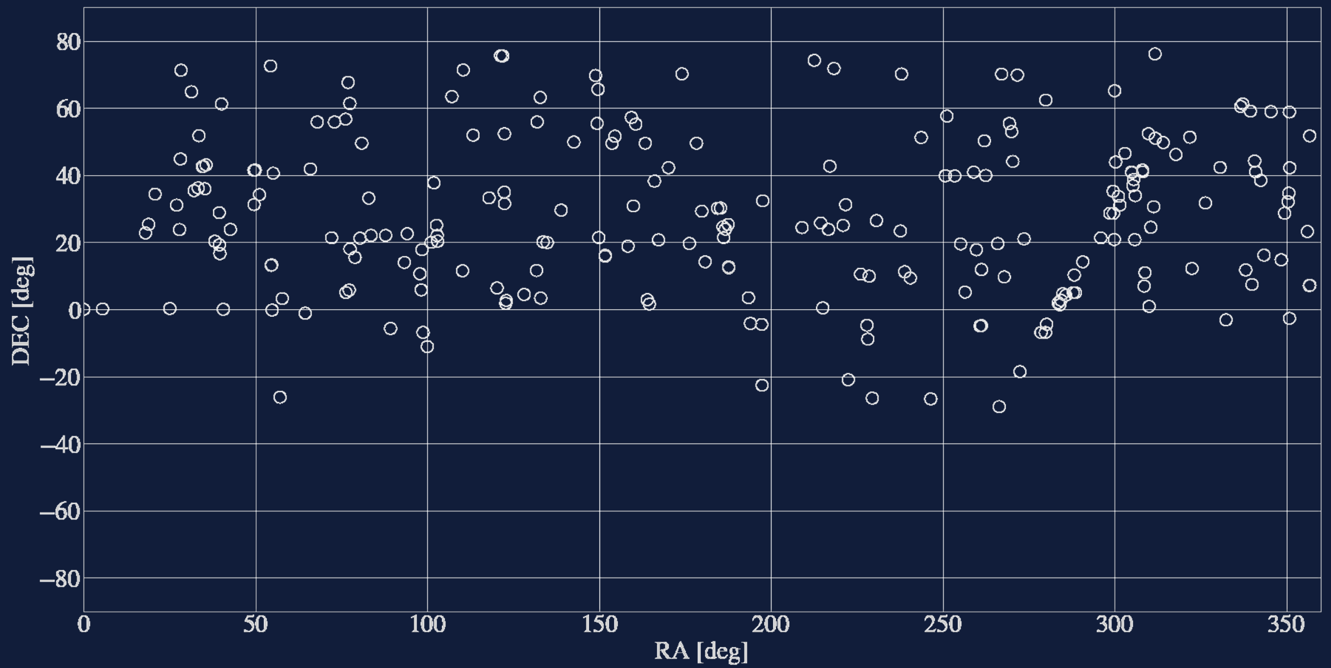
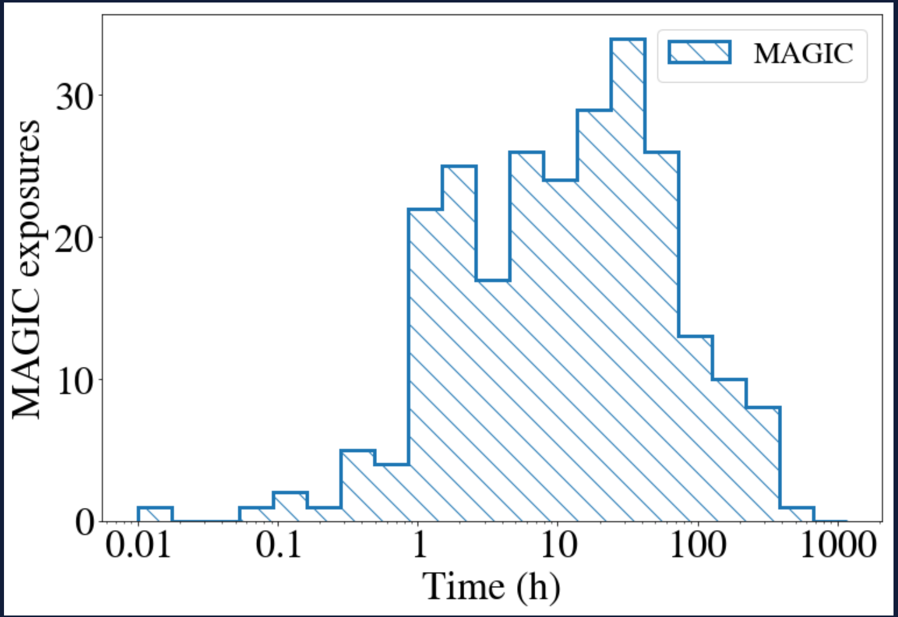
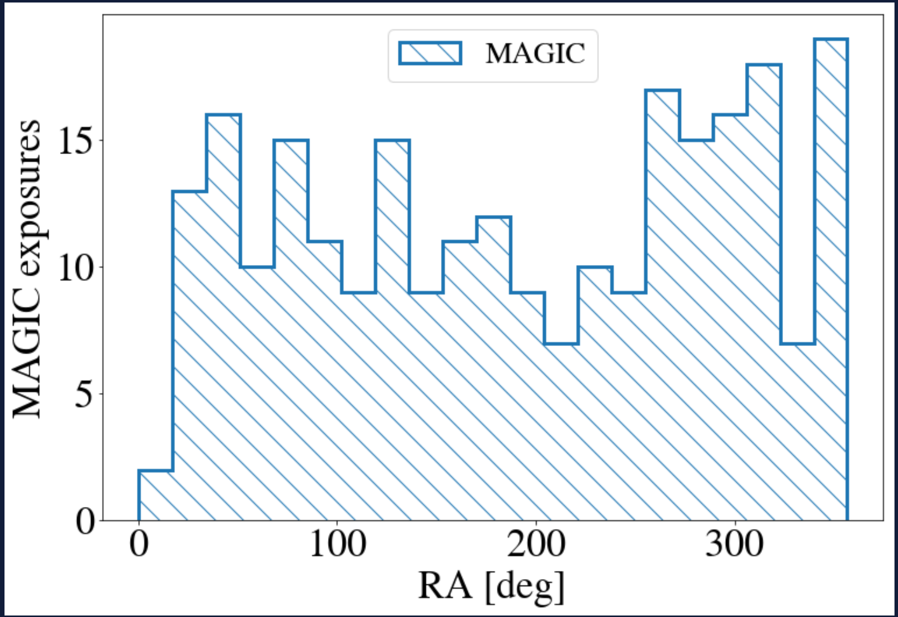


1. Take the currently in operation MAGIC Cherenkov telescopes pointings in 6.5 years (2012-2019)

Pointing strategies

How to estimate the sky fraction that will be observed by CTA in 10 years?

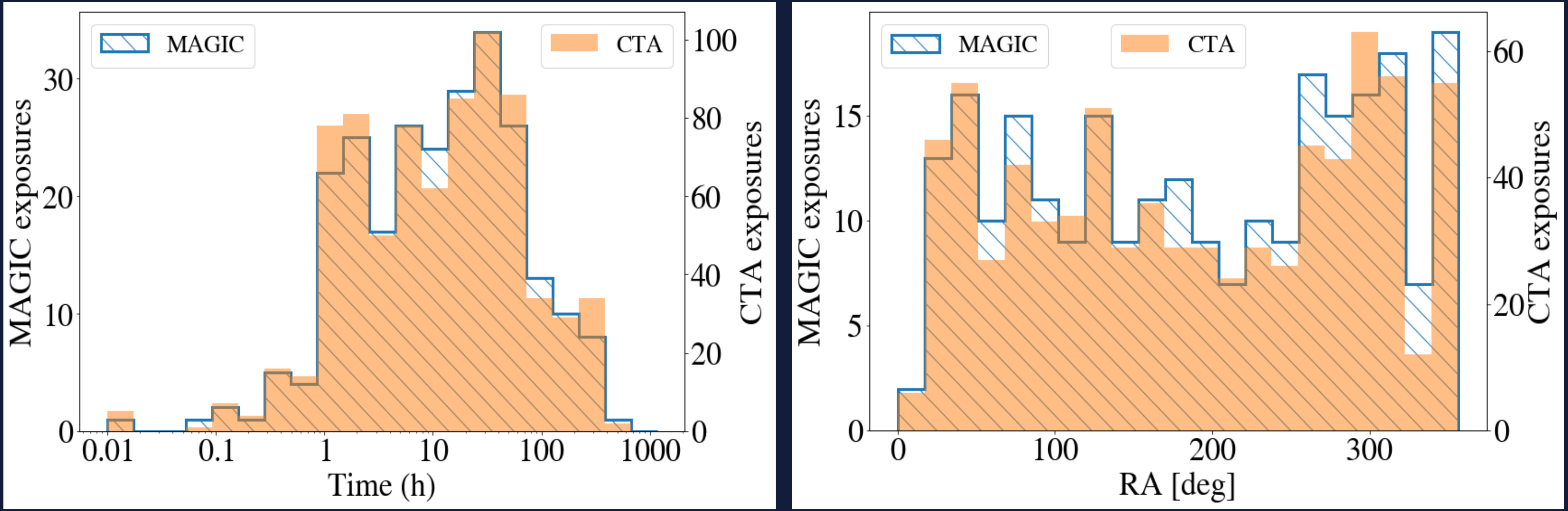




2. Characterize their distribution in exposure time, RA and DEC

Pointing strategies

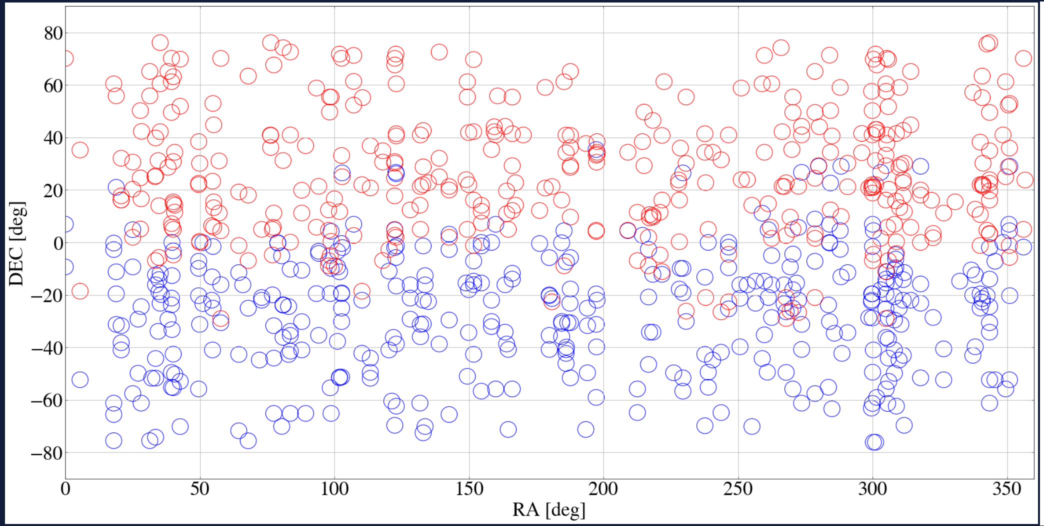
How to estimate the sky fraction that will be observed by CTA in 10 years?

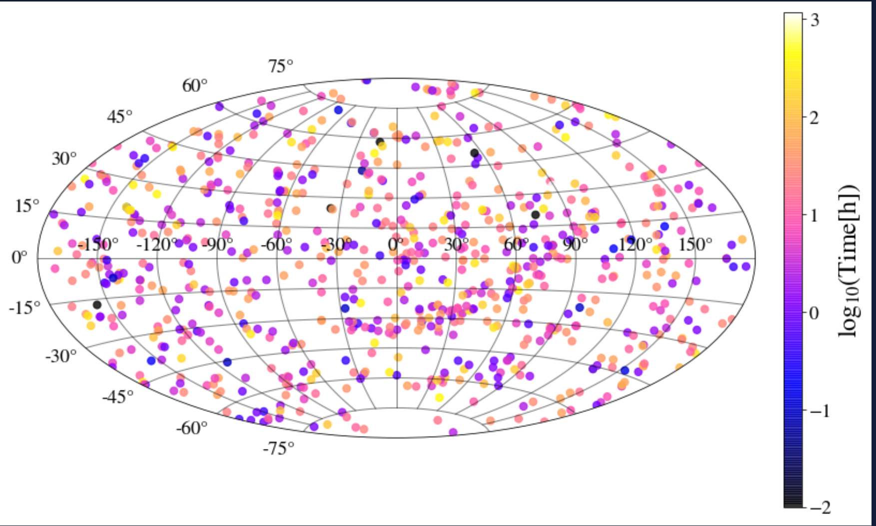


3. Generate random pointings following the MAGIC distributions

Pointing strategies

How to estimate the sky fraction that will be observed by CTA in 10 years?





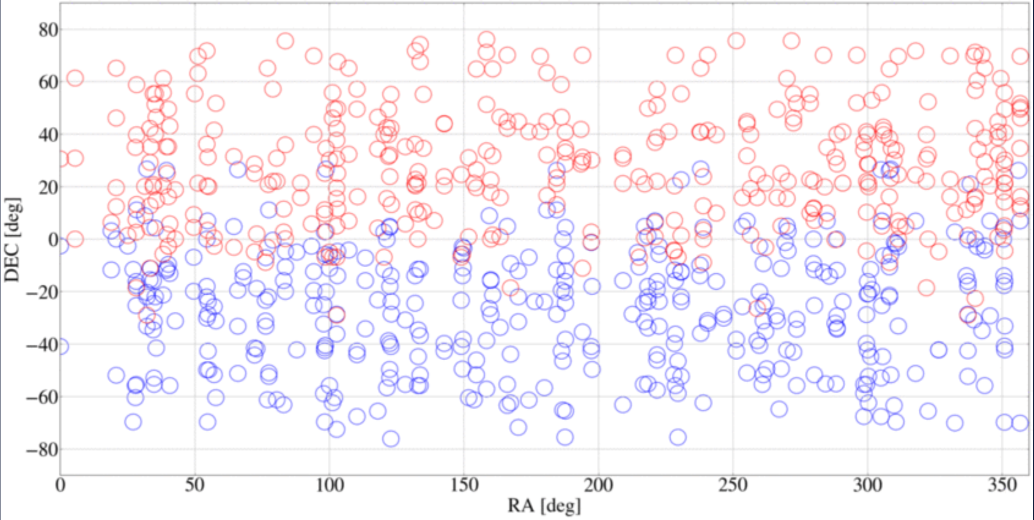
Red – North Array

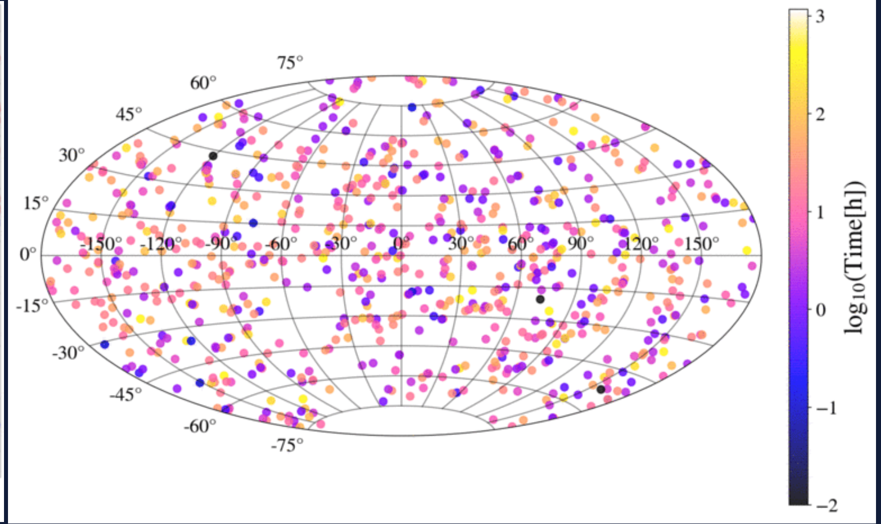
Blue – South Array

4. Check results for 10 yr and two arrays, mirroring DEC in half of the pointings

Pointing strategies

How to estimate the sky fraction that will be observed by CTA in 10 years?





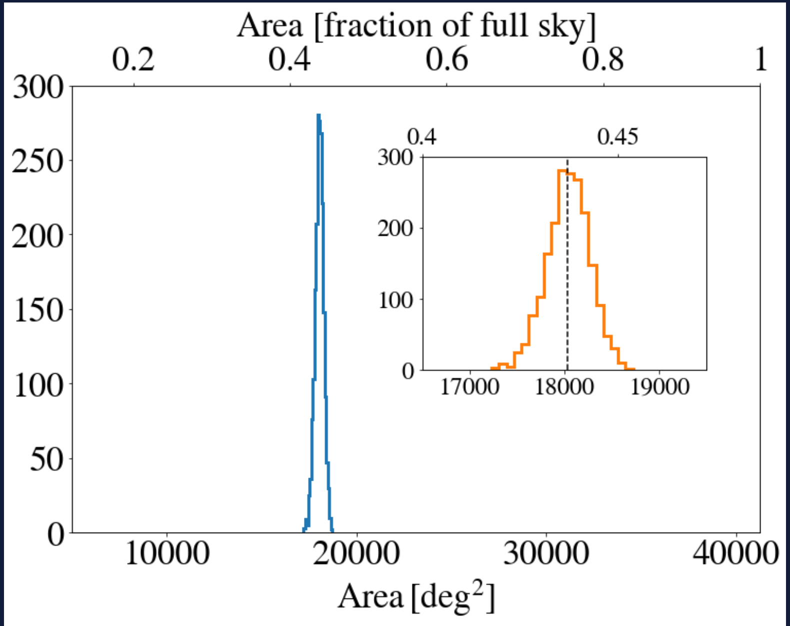
Red – North Array

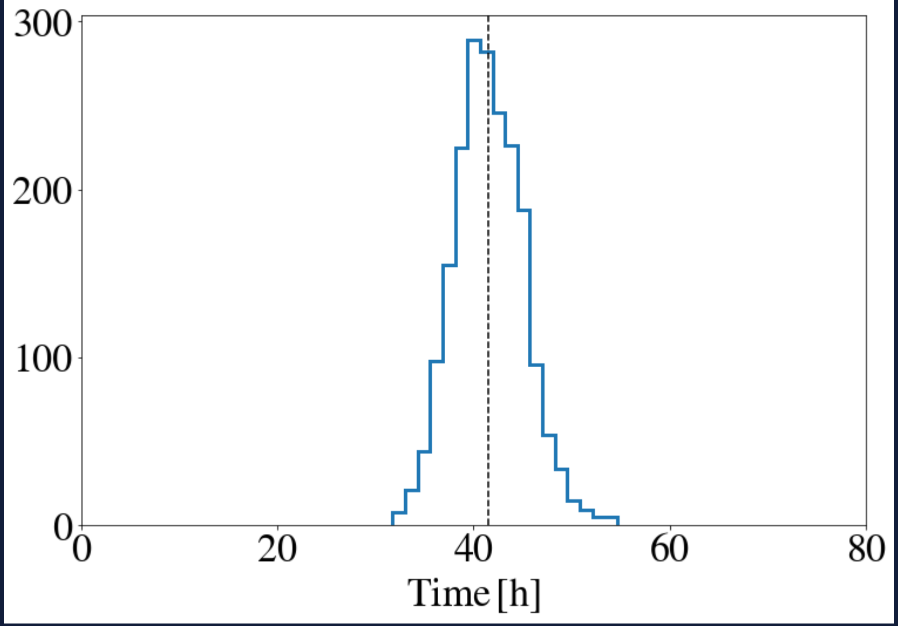
Blue – South Array

5. Repeat 2000 times to have proper statistics

Pointing strategies

How to estimate the sky fraction that will be observed by CTA in 10 years?





6. Distribution of the realizations to compute the effective average time and area

Pointing strategies

	Number of subhalos ($\geq J_{min}$)		
$\log_{10}(J_{min})$	EGAL	DEEP	EXPO
17	392 ± 18	26 ± 8	728 ± 23
~Carina → 18	115 ± 11	5.1 ± 2.5	206 ± 14
~Draco → 19	6.5 ± 2.6	0.3 ± 0.5	13 ± 4
~Sagittarius → 20	0.3 ± 0.5	0	0.5 ± 0.7

Although we expect, e.g. 13 "Dracos" in EXPO, to actually observe them we would need very large annihilation cross sections, due to the instrumental sensitivity

DM constraints

If we do not observe any DM subhalo, we can place constraints to the DM space

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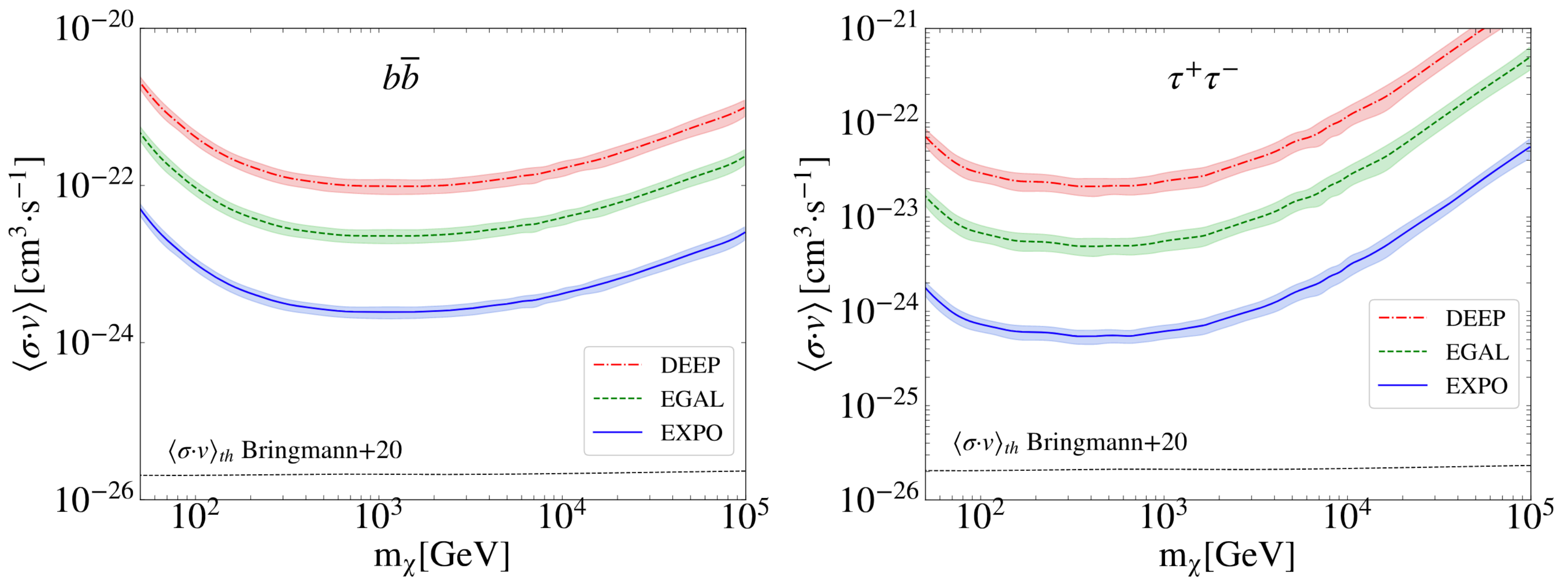

JCB+21 [2101.10003]

DM constraints

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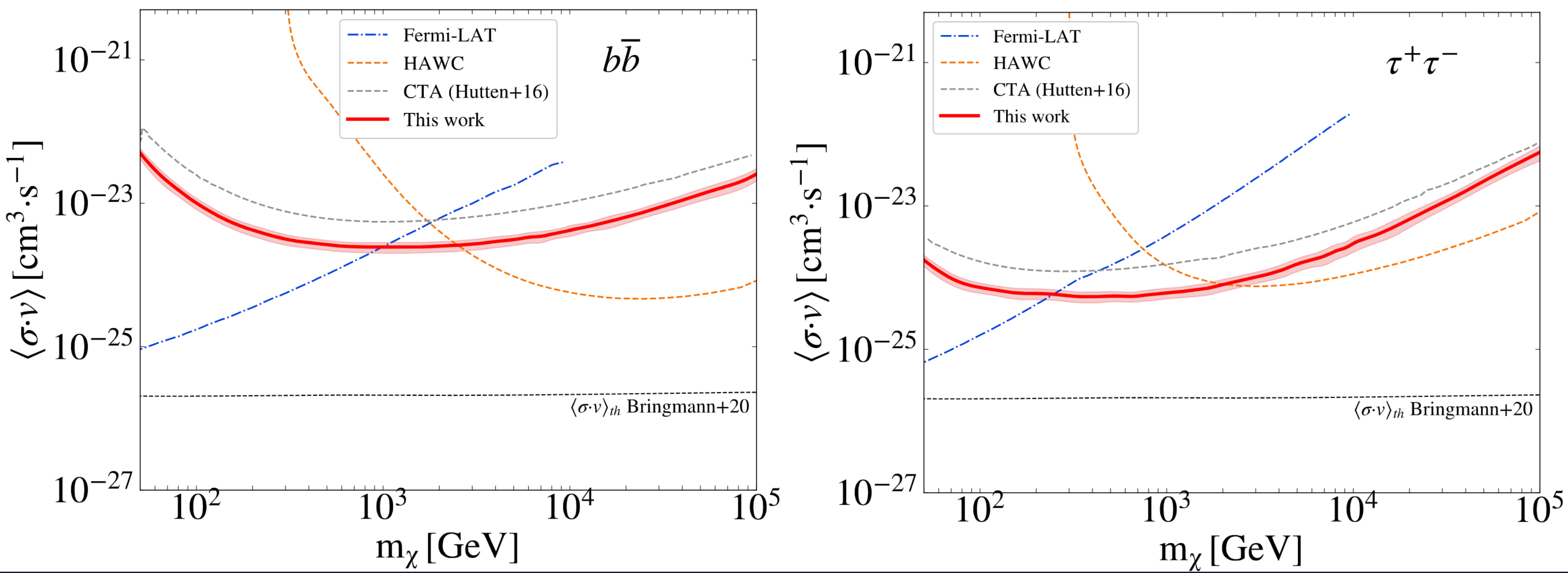


JCB+21 [2101.10003]

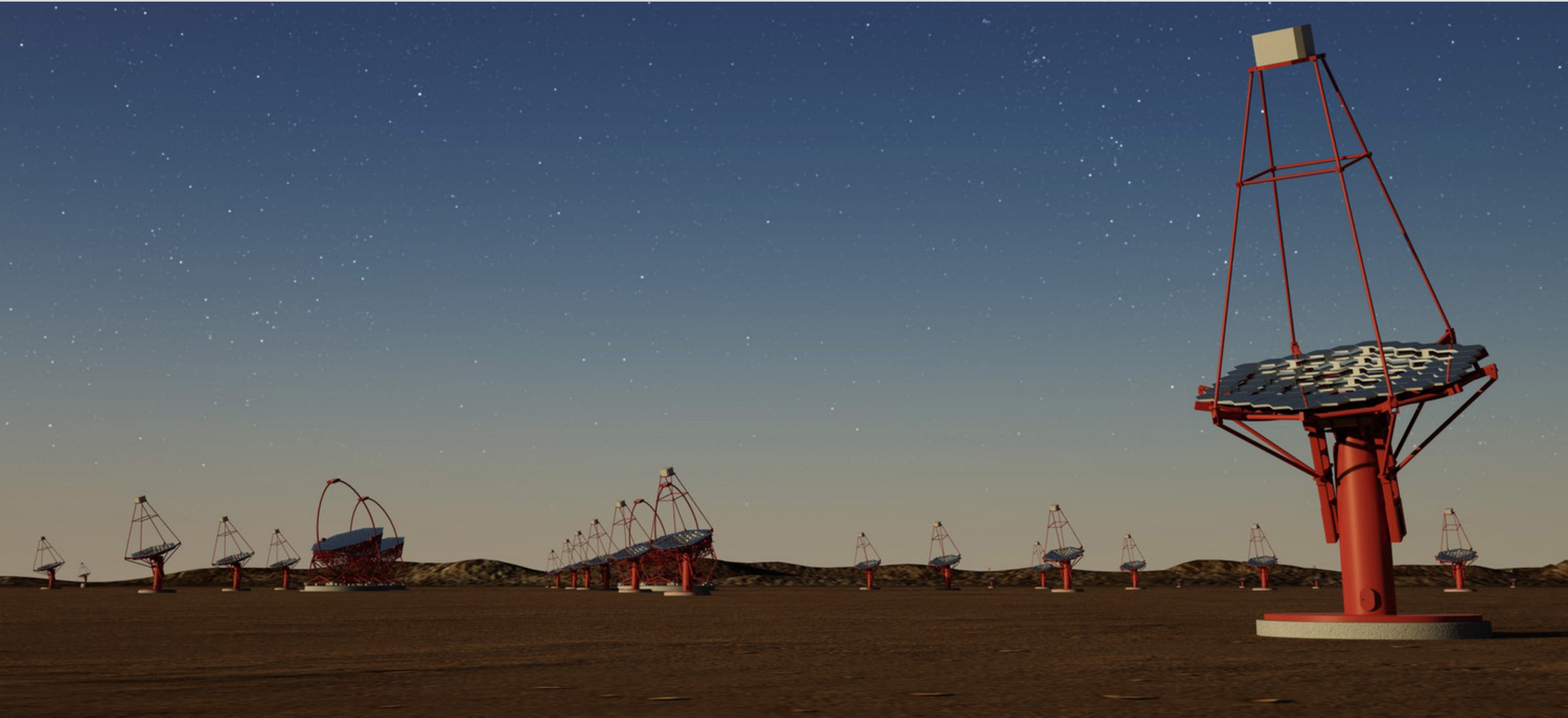
Fermi-LAT (1910.14429), HAWC (2001.02536)

Conclusions

- DM subhalos, appearing as unIDs in the gamma-ray sky, are competitive and independent targets for indirect detection
- CTA is a sensitive instrument, especially for heavy WIMP DM
- We identify three different subhalo CTA search strategies: the EGAL survey, a deep-field exposure and the overall exposure, which is the most competitive
- We can estimate CTA observations in 10 years, extrapolating actual MAGIC science operations
- The constraints we can achieve improve previous works, being complementary to other probes/instruments

Thank you very much!

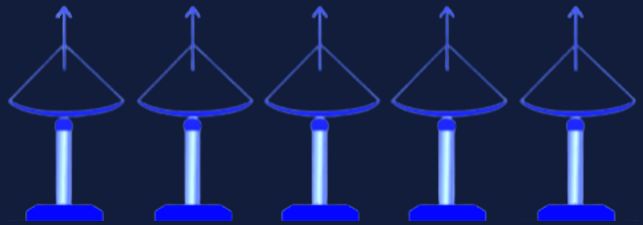
Backup



Pointing strategies

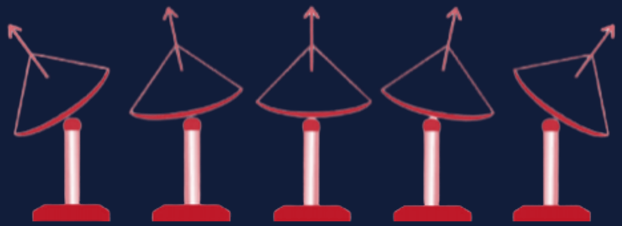
It is also interesting to ask about parallel vs. divergent pointing

Parallel pointing - default mode, all telescopes point parallely into the same direction of the sky



1501.02586

Divergent pointing - a small offset between telescopes allows larger observation areas with reduced sensitivity

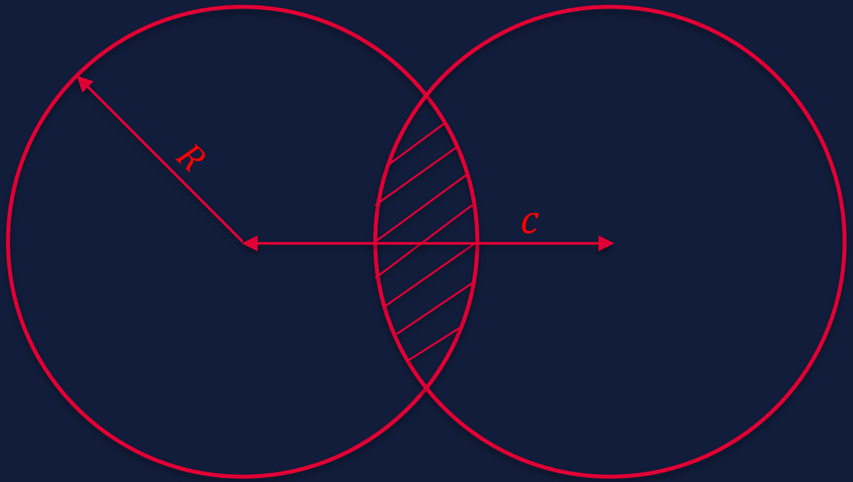


1501.02586

With the current CTA configuration, the parallel pointing is the best [1508.06197]

Pointing strategies

How to estimate the sky fraction observed by CTA in 10 years?

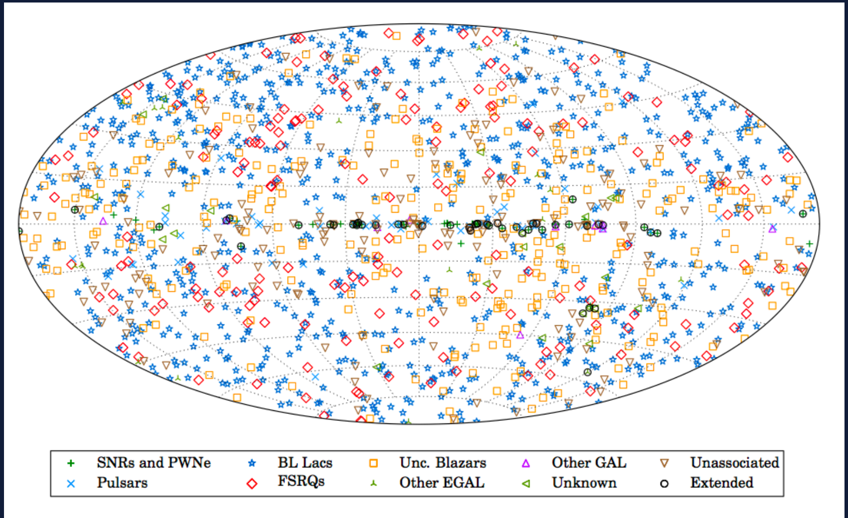


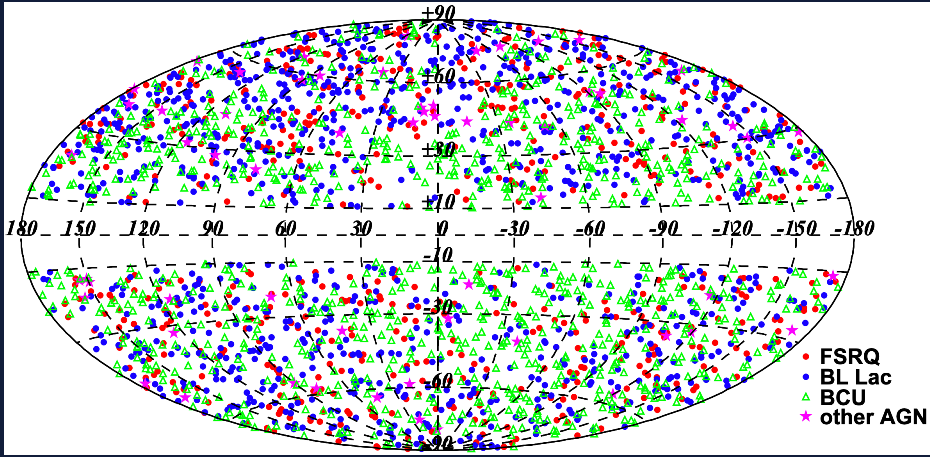
Effective Total Area = $2\pi R^2 - R^2[q - \sin(q)]$, where $q = 2 \cdot \mathrm{acos}(c/2R)$

4a. Overlaps between pointings must be taken into account to compute effective area

Pointing strategies

How to estimate the sky fraction observed by CTA in 10 years?

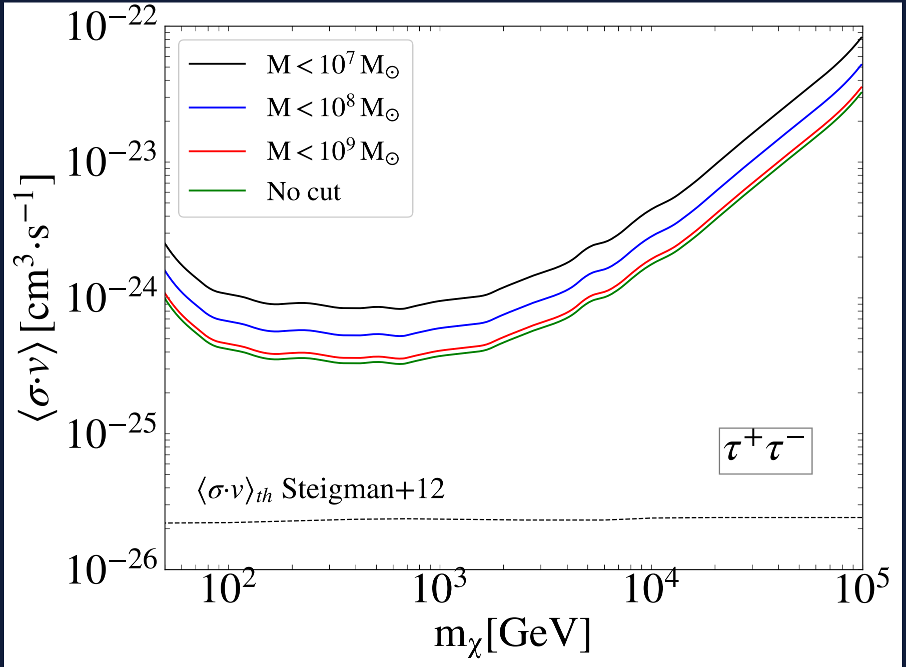




Conservative against LAT AGN catalogs (e.g. 3FHL, 4LAC)

Mass cut dependence

- We adopt as mass cut $M < 10^8 M_\odot$ to ensure we deal only with DM subhalos
- Nevertheless, this cut is uncertain
- The constraints are not very dependent - only change a factor 3 when changing the mass cut two orders of magnitude



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