

Dark matter searches with ground based Cherenkov gamma-ray telescopes

Javier Rico



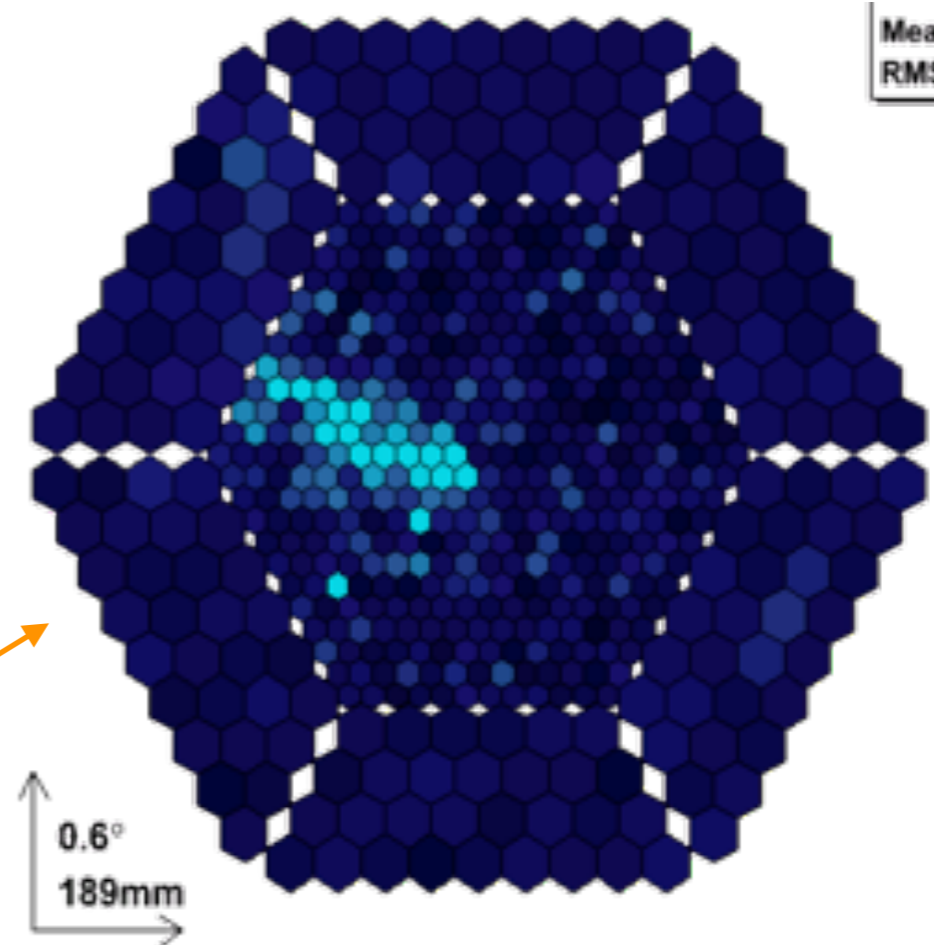
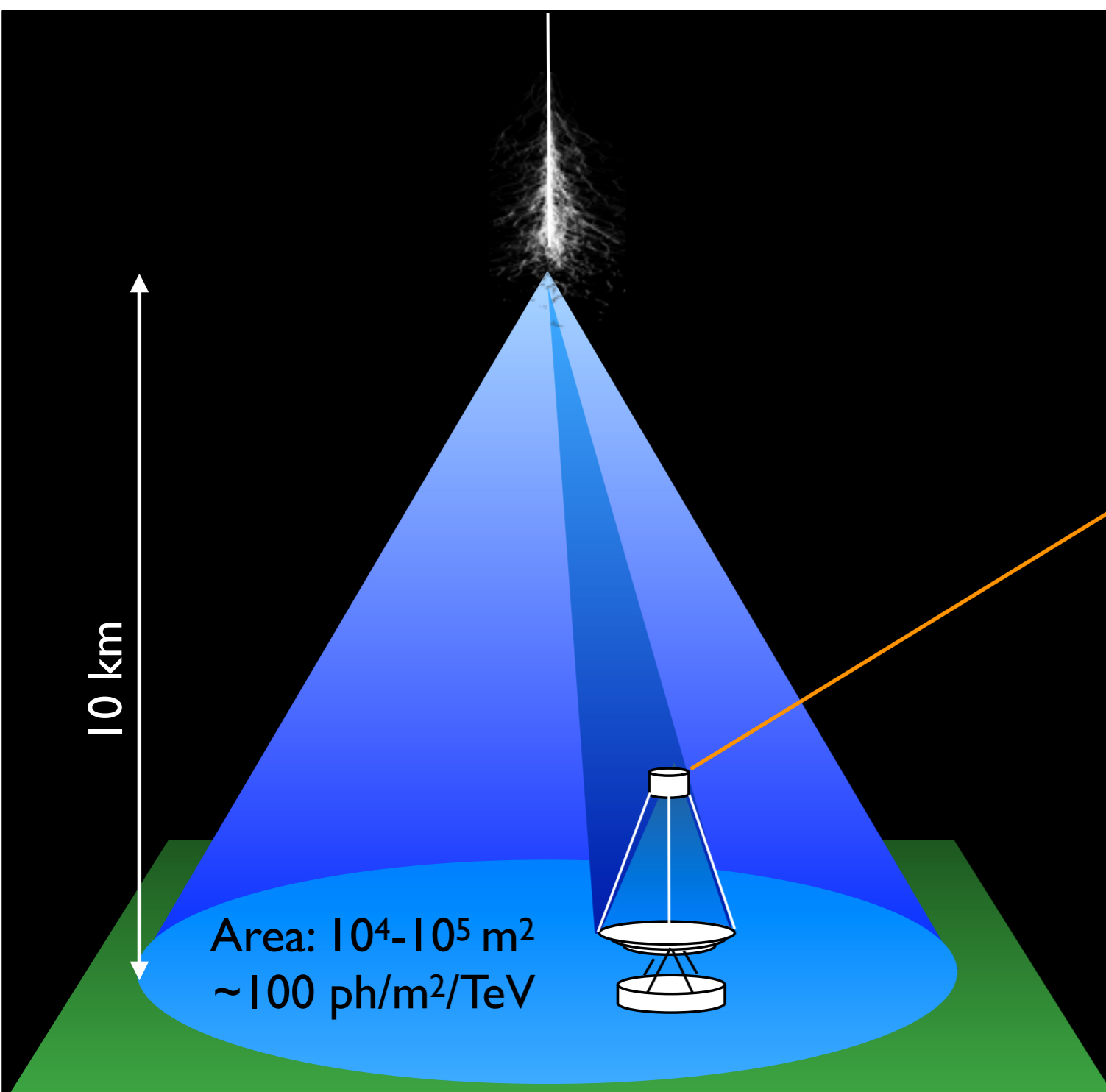


Program

- ★ Imaging Cherenkov Technique
- ★ Indirect DM searches with Cherenkov telescopes
- ★ Current results with MAGIC, HESS and VERITAS
- ★ Future prospects with the Cherenkov Telescope Array (CTA)
- ★ Conclusions

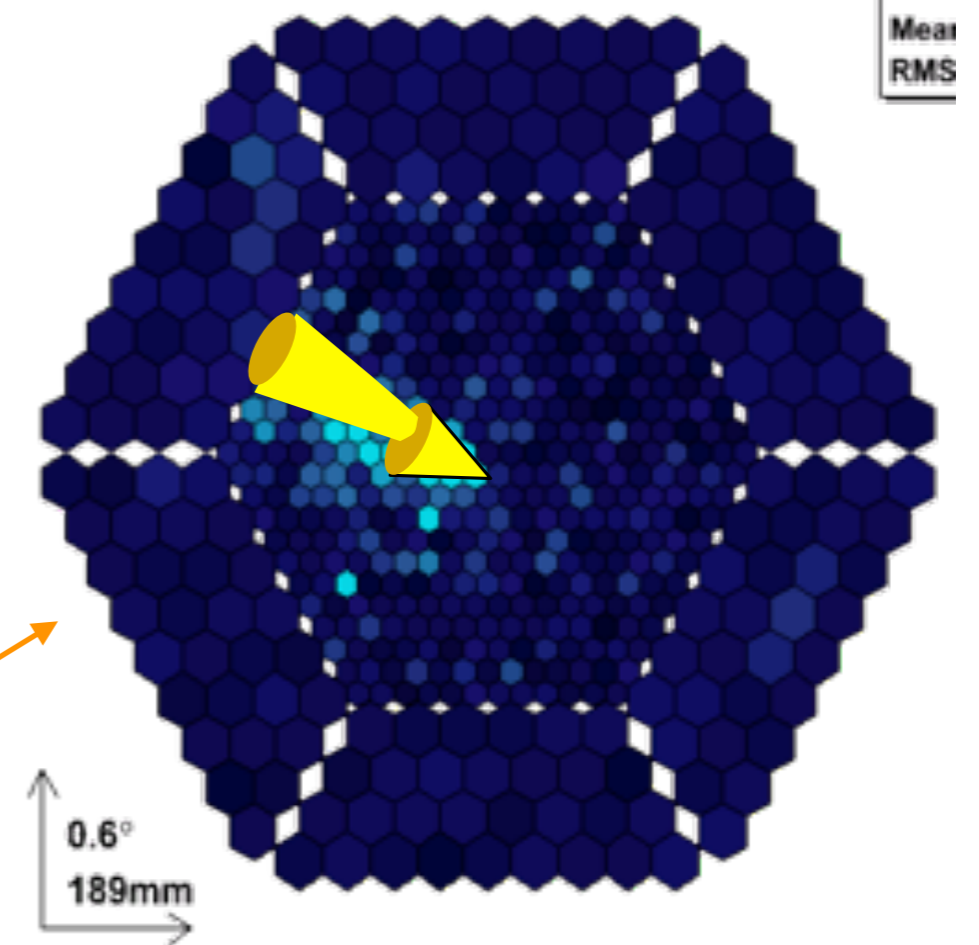
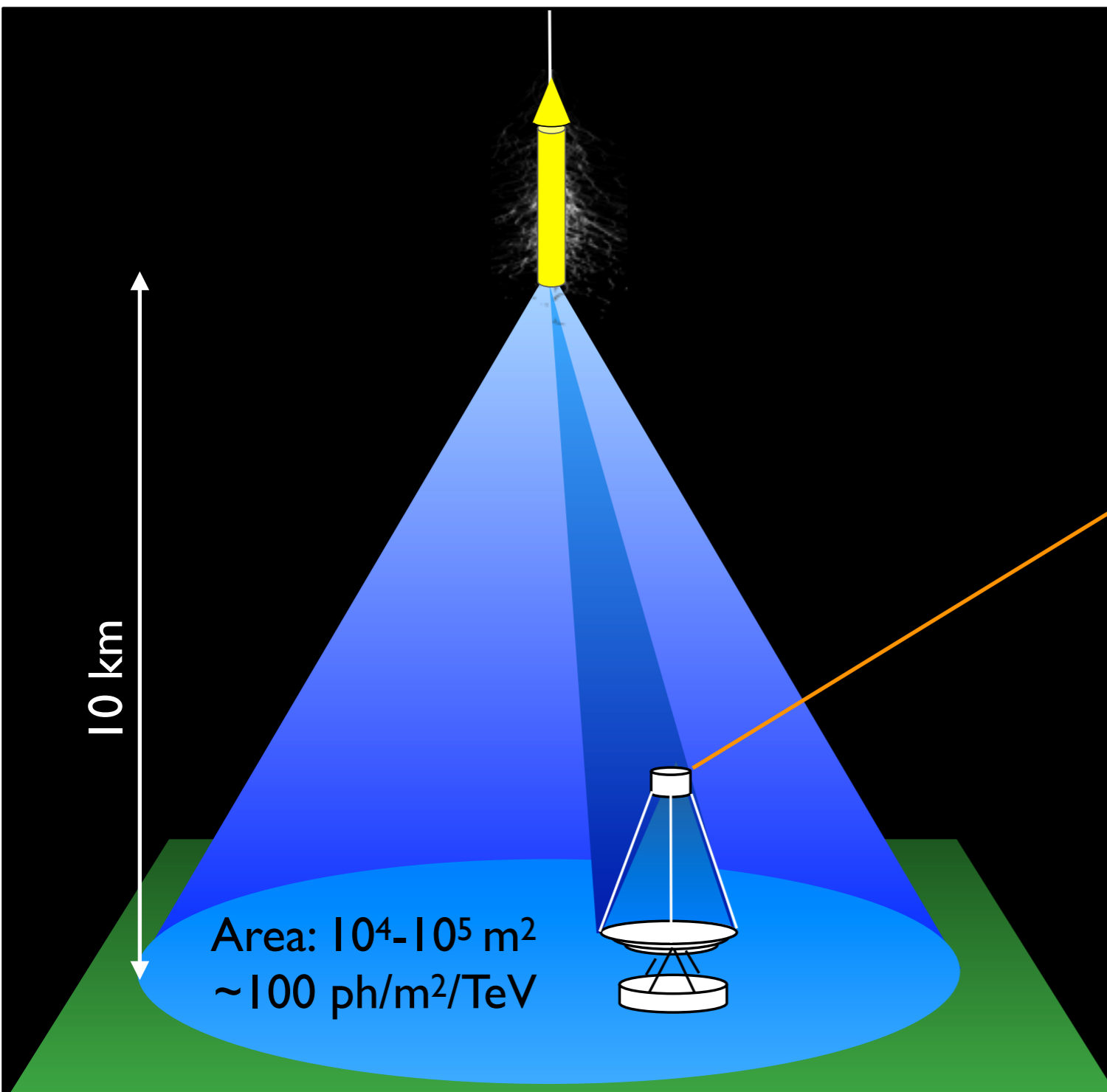
Imaging Cherenkov Technique

Imaging Cherenkov Technique



- ★ Image intensity → Energy of primary
- ★ Image orientation → Direction of primary
- ★ Image shape → Kind of primary

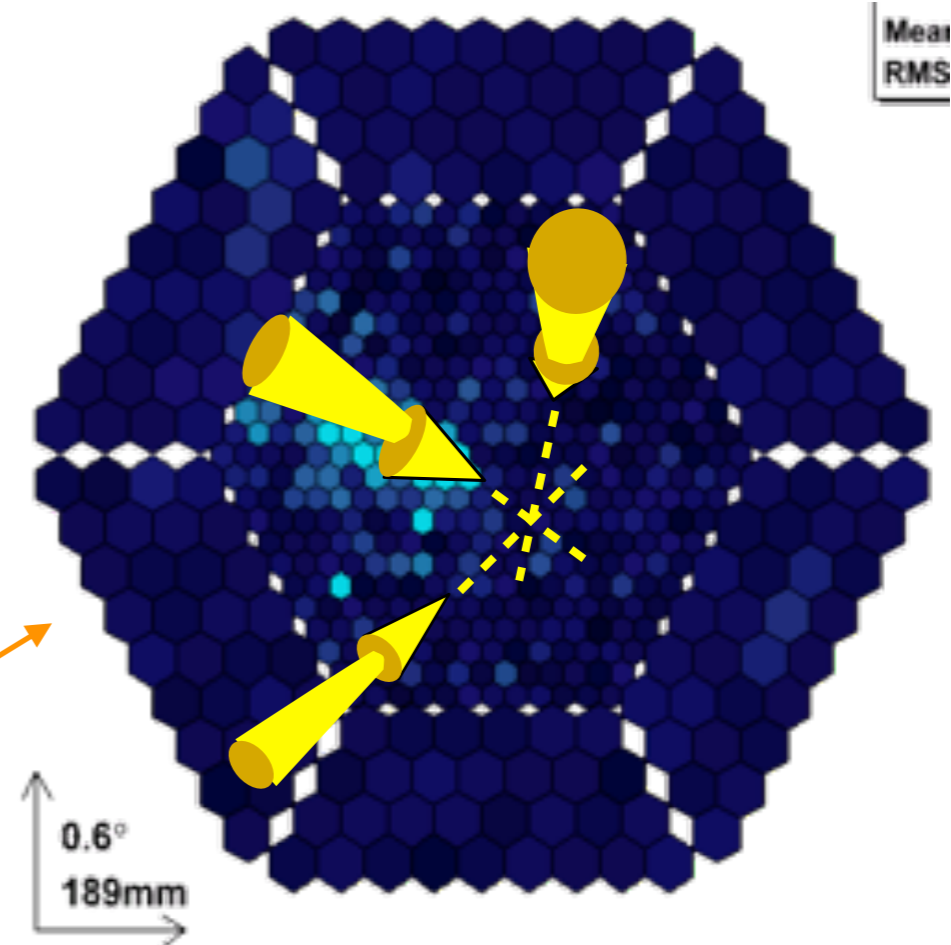
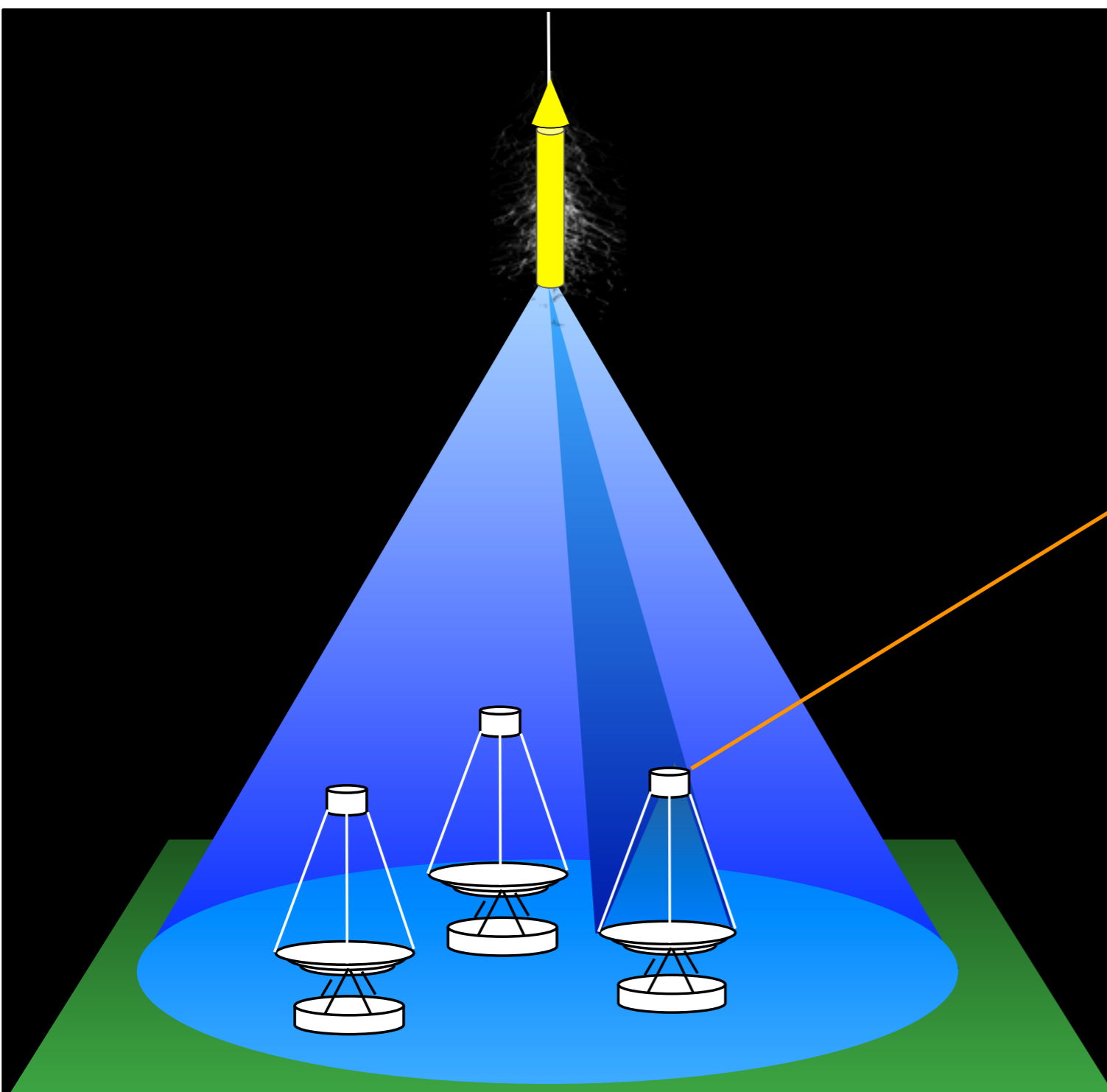
Imaging Cherenkov Technique



- ★ Image intensity → Energy of primary
- ★ Image orientation → Direction of primary
- ★ Image shape → Kind of primary



Stereoscopy



- ★ Better determine
 - ♦ Energy
 - ♦ Arrival direction
 - ♦ Particle Id

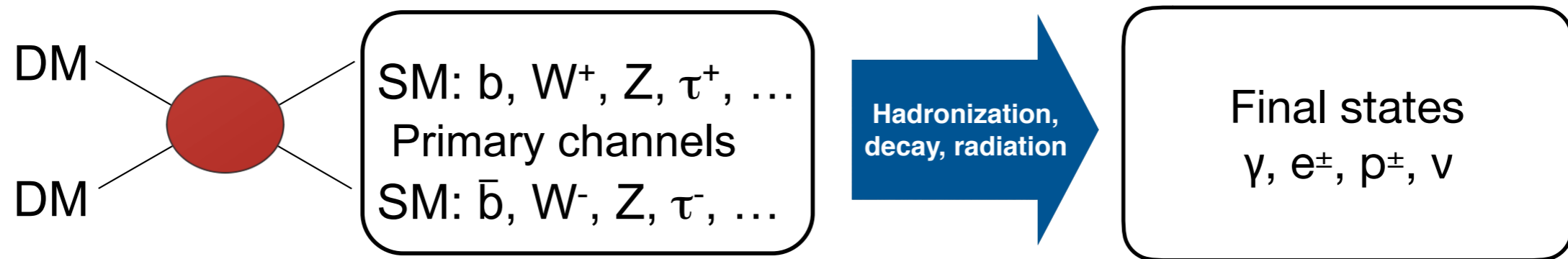
Current Cherenkov telescopes

- ★ **Gamma-ray flux** drops exponentially with energy
 → for $E > 100$ GeV large collection areas needed
 → Cherenkov telescopes
- ★ **Intense CR background**
 → Imaging technique
- ★ **Energy range** ~ 100 GeV - ~ 100 TeV
- ★ **Energy resolution** 10-15%
- ★ **Angular resolution** $\sim 0.1^\circ$ at 1 TeV
- ★ **Field of view** $3-5^\circ$
- ★ **Pointed observations**, systematic scans of limited regions
- ★ **Several telescopes** for better performance



Indirect DM searches with Cherenkov telescopes

Indirect dark matter searches

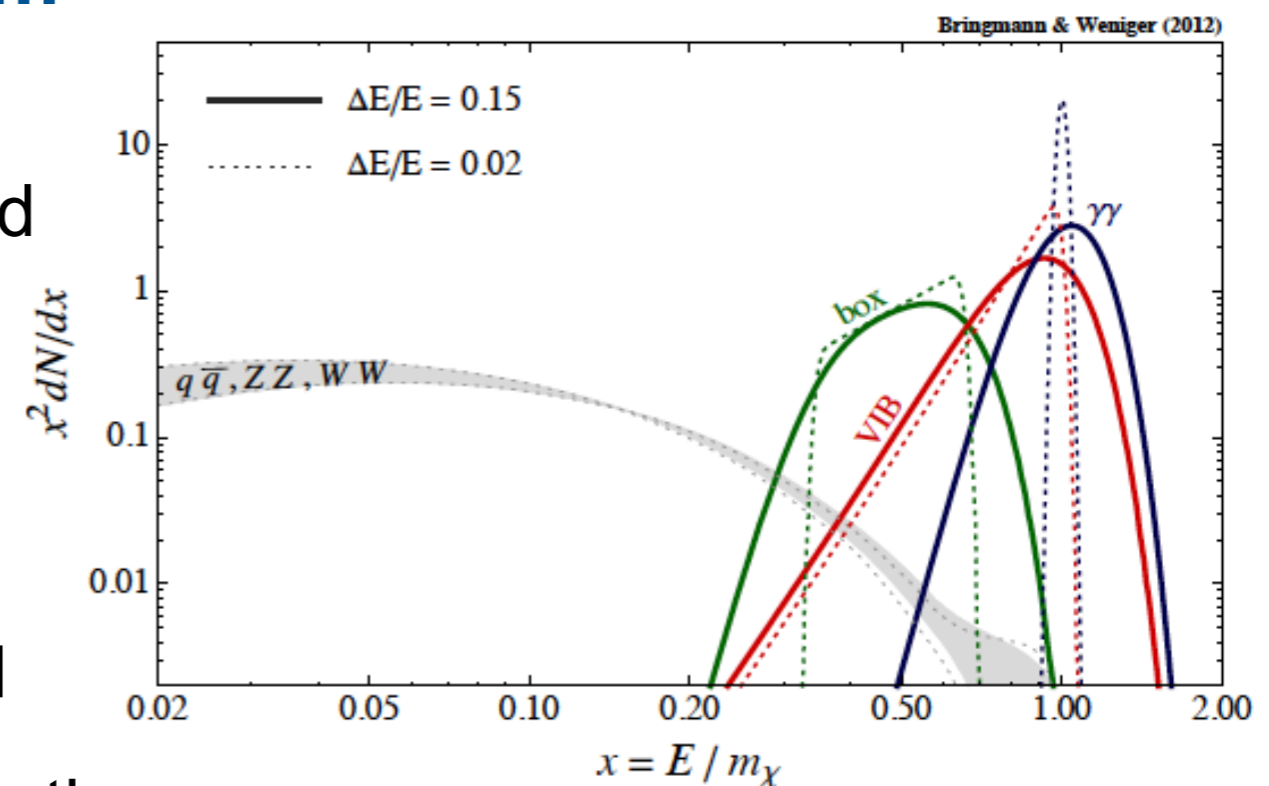


★ Gamma-rays do not suffer from propagation effects:

- ◆ Can determine DM abundance and distribution in the Universe

★ Can present characteristic spectral features:

- ◆ Good separation from background
- ◆ Can measure basic physical properties: mass, cross-section / lifetime

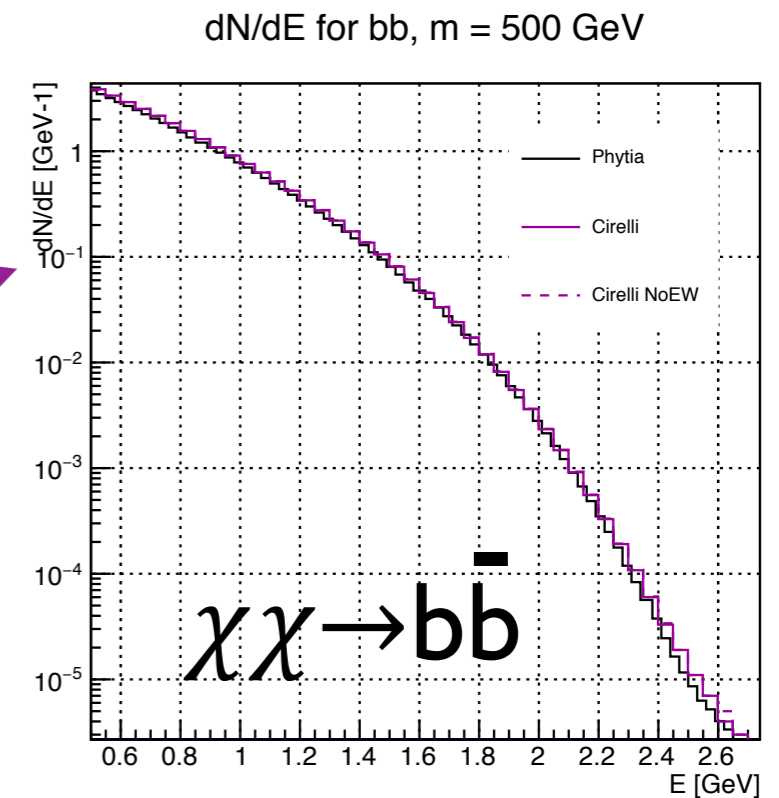


Gamma-ray fluxes

- ★ Expected **differential gamma-ray flux**:

$$\frac{d\Phi}{dE}(\Delta\Omega) = \frac{1}{4\pi} \frac{\langle\sigma v\rangle J(\Delta\Omega)}{2m_{\text{DM}}^2} \frac{dN}{dE}$$

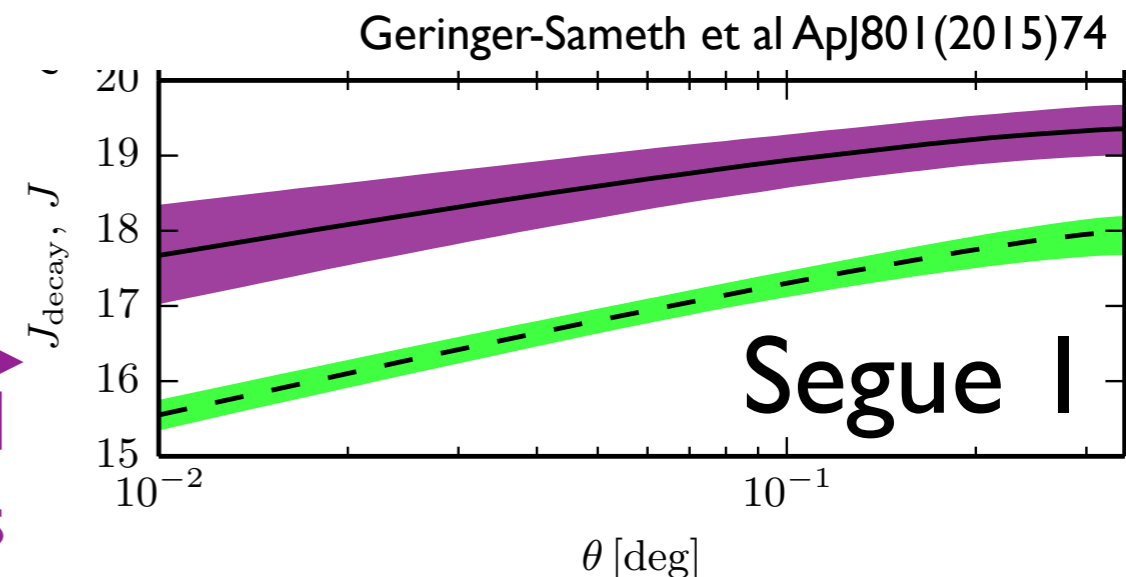
Pythia



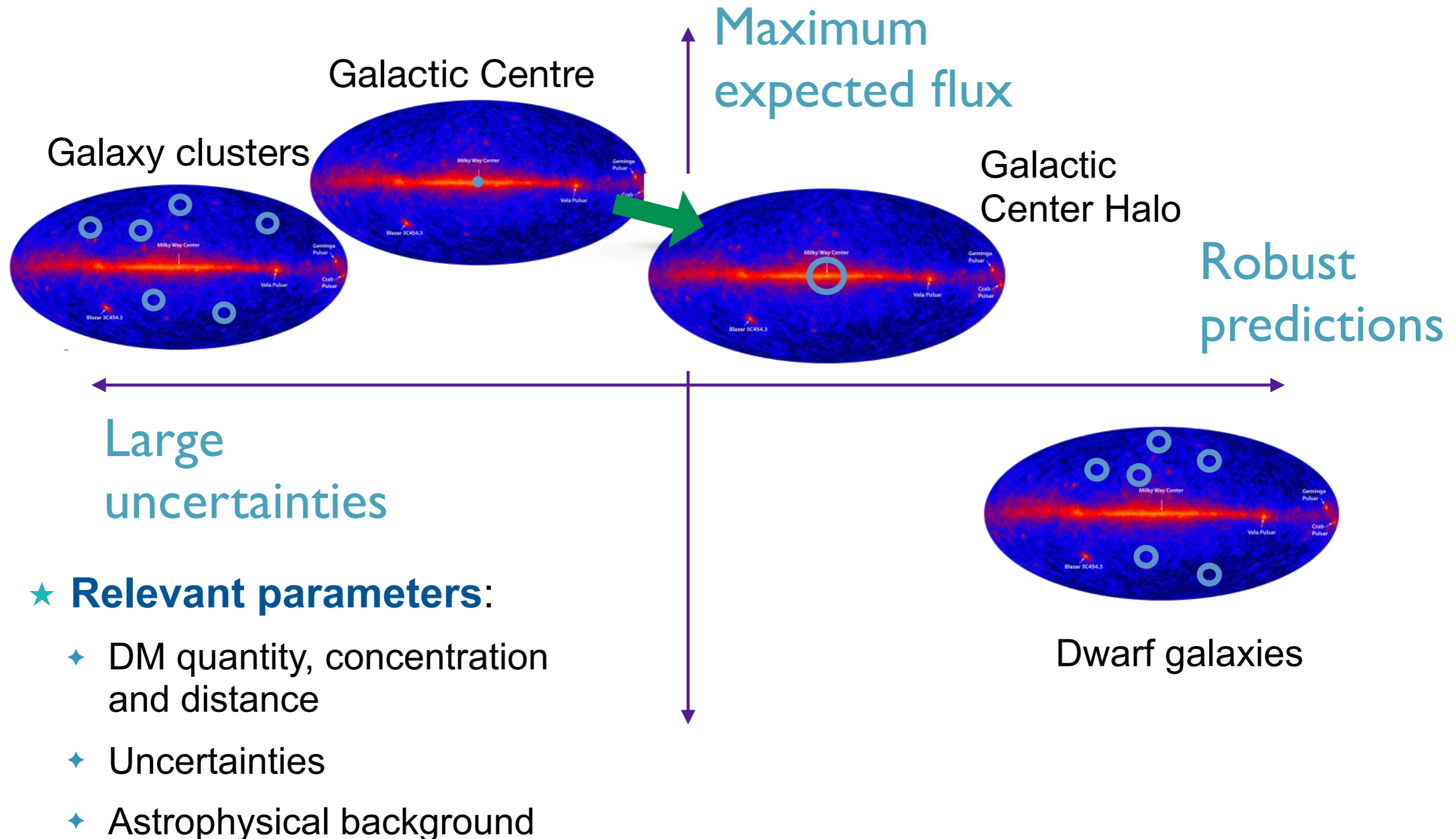
- ★ The **astrophysical** or **J-factor** depends on the DM distribution:

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{\text{l.o.s.}} dl \rho^2(l, \Omega)$$

Fit to stellar surface density and velocity dispersion profiles



Targets for DM searches



Current results with HESS, MAGIC, and VERITAS



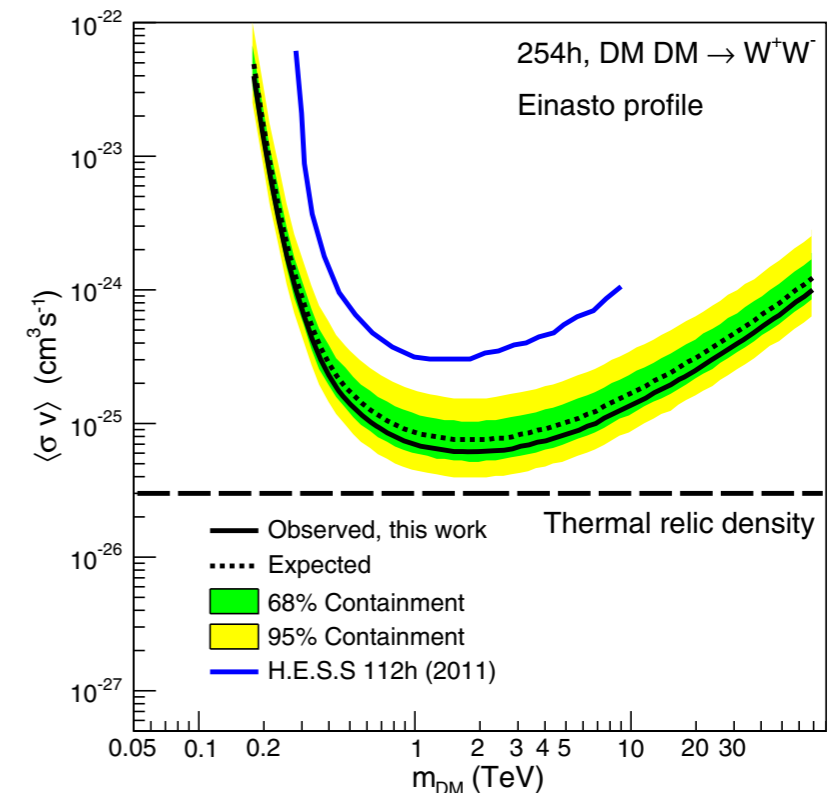
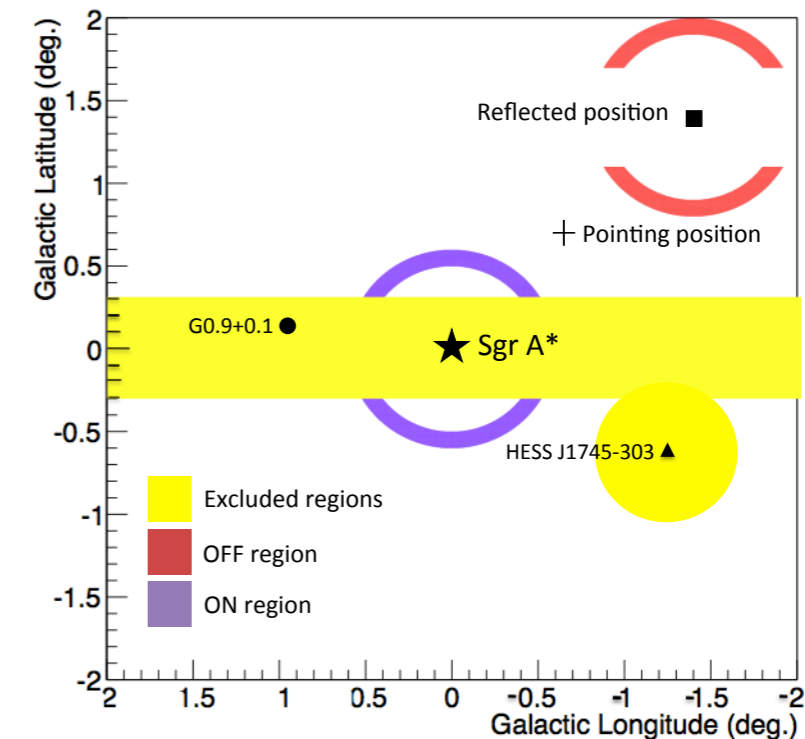
Observed targets

Target	Year	Time	Experiment	Target	Year	Time	Experiment
Globular Clusters				Galaxy Clusters			
M15	2002	0.2	Whipple	Abell 2029	2003–2004	6	Whipple
	2006–2007	15.2	H.E.S.S.	Perseus	2004–2005	13.5	Whipple
M33	2002–2004	7.9	Whipple		2008	24.4	MAGIC
M32	2004	6.9	Whipple	Fornax	2005	14.5	H.E.S.S.
NGC 6388	2008–2009	27.2	H.E.S.S.	Coma	2008	18.6	VERITAS
Dwarf Satellite Galaxies				The Milky Way central region			
Draco	2003	7.4	Whipple	MW Center	2004	48.7	H.E.S.S.
	2007	7.8	MAGIC	MW Center Halo	2004–2008	112	H.E.S.S.
	2007	18.4	VERITAS				
Ursa Minor	2003	7.9	Whipple	Other searches			
	2007	18.9	VERITAS	IMBH	2004–2007	400	H.E.S.S.
Sagittarius	2006	11	H.E.S.S.		2006–2007	25	MAGIC
Canis Major	2006	9.6	H.E.S.S.	Lines	2004–2008	112	H.E.S.S.
Willman 1	2007–2008	13.7	VERITAS		2010–2013	158	MAGIC
	2008	15.5	MAGIC	UFOs	–	–	MAGIC
Sculptor	2008	11.8	H.E.S.S.		–	–	VERITAS
Carina	2008–2009	14.8	H.E.S.S.	All-electron	2004–2007	239	H.E.S.S.
Segue 1	2008–2009	29.4	MAGIC		2009–2010	14	MAGIC
	2010–2011	48	VERITAS	Moon-shadow	–	–	MAGIC
	2010–2013	158	MAGIC				
Boötes	2009	14.3	VERITAS				

Doro, NIM A742 (2014) 99

- ★ About 10% dedication in terms of observation time
- ★ I try to summarise the most relevant/recent results

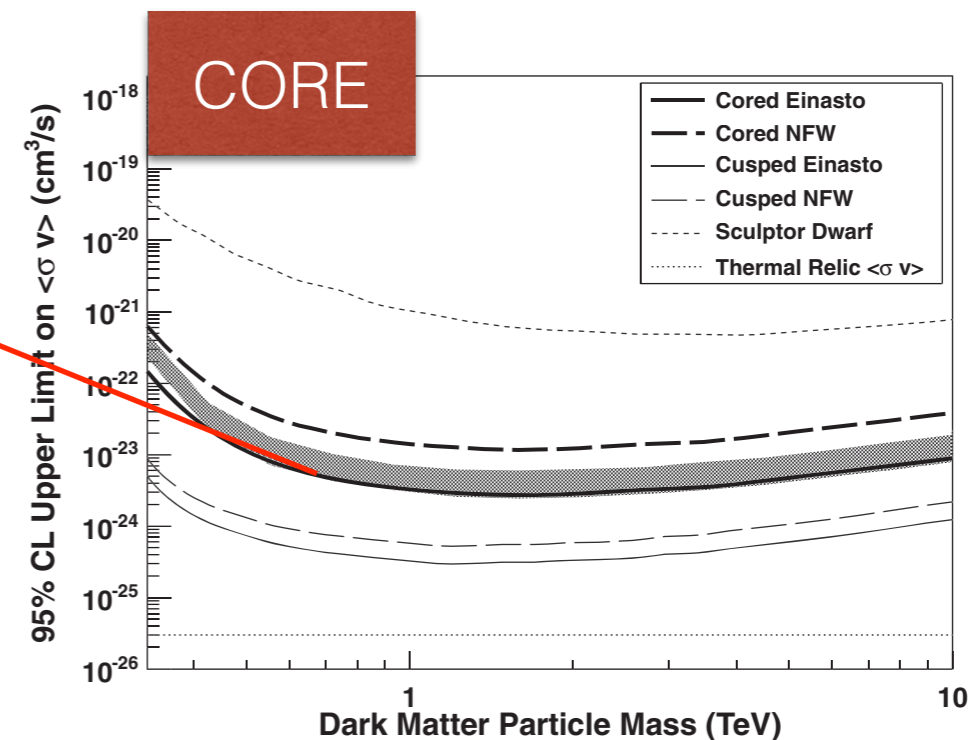
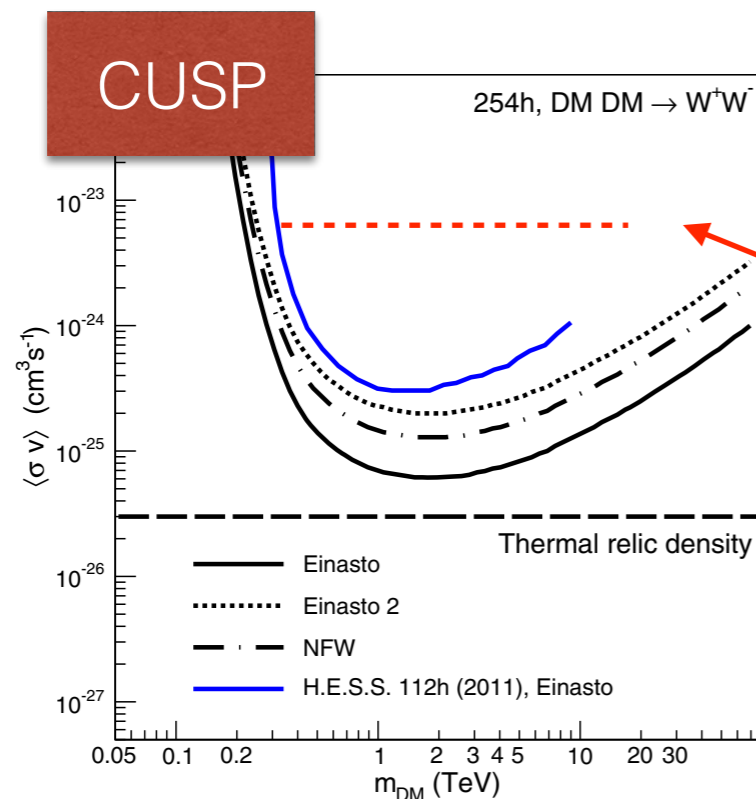
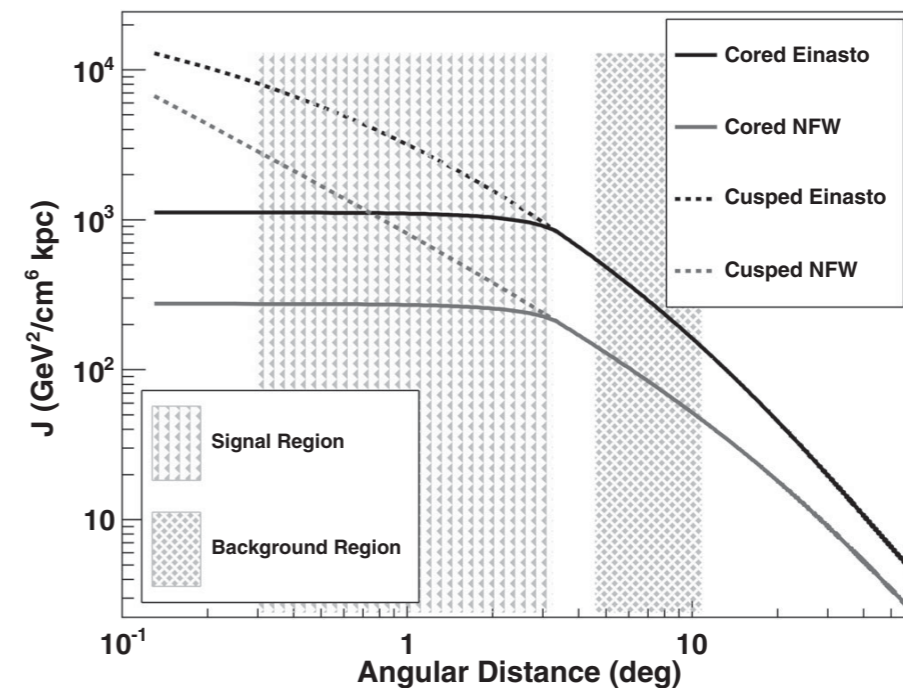
- ★ **Highest J-factor from Earth** ($\sim 10^{21} \text{ GeV}^2 \text{ cm}^{-5}$)
→ obvious target
- ★ **Observed by HESS** for 10 years (2004-2014), 254 hours
- ★ **Crowded central part and Galactic plane** excluded due to intense astrophysical background
- ★ **2D** (Energy+radial distance) **maximum likelihood analysis**
- ★ **Improved analysis + deeper observations**
→ 4-5 times better sensitivity
- ★ **No signal detected**
→ upper limits to $\langle \sigma v \rangle \sim 10^{-25} \text{ cm}^3 \text{ s}^{-1}$ for $\chi\chi \rightarrow W^+W^-$



Abdallah et al. PRL 117(2016)111301

Drawbacks of GC analysis

- ★ Sensitive to the **choice of DM density profile**
- ★ For very deep observations, both **statistical and systematic uncertainties on background estimation** become important (more complex analysis needed)



Abramowski et al. PRL 114(2015)081301



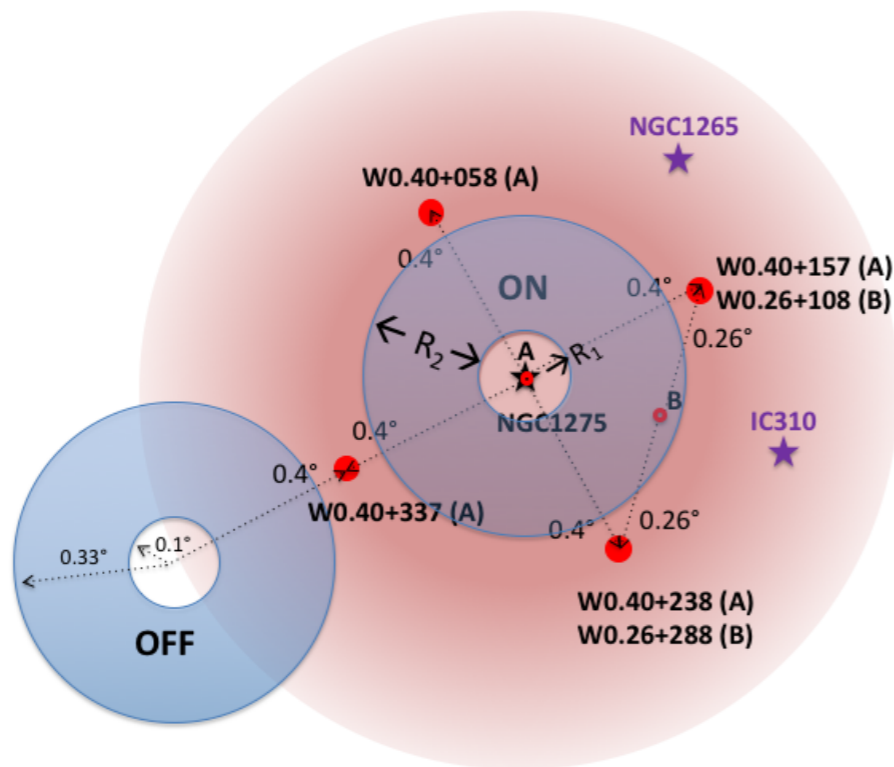
Galaxy clusters

- ★ **Largest structures** in the Universe:
 - ✦ Mass: 10^{14} - $10^{15} M_{\odot}$
 - ✦ Size: few Mpc
- ★ DM makes **~80% of their mass**
- ★ **Contain substructure**
 - boost to DM annihilation signal (by factors 10-100)
 - big uncertainties due to extrapolation from simulations
- ★ **DM decay signal intensity**
 - depends only on total mass (huge) and therefore can set strong and robust limits from galaxy clusters
- ★ **Extended sources** for IACTs
 - more difficult analysis



Source	Telescope	Year	T [h]	$J_{\text{ann}} [\text{GeV}^2/\text{cm}^5]$
Fornax	HESS	2005	15	10^{18}
Coma	VERITAS	2008	19	10^{18}
Perseus	MAGIC	2008	24	10^{17}
				$J_{\text{dec}} [\text{GeV}/\text{cm}^2]$
Perseus	MAGIC	2009-2017	200	10^{19}

Limits on decay lifetime from Perseus

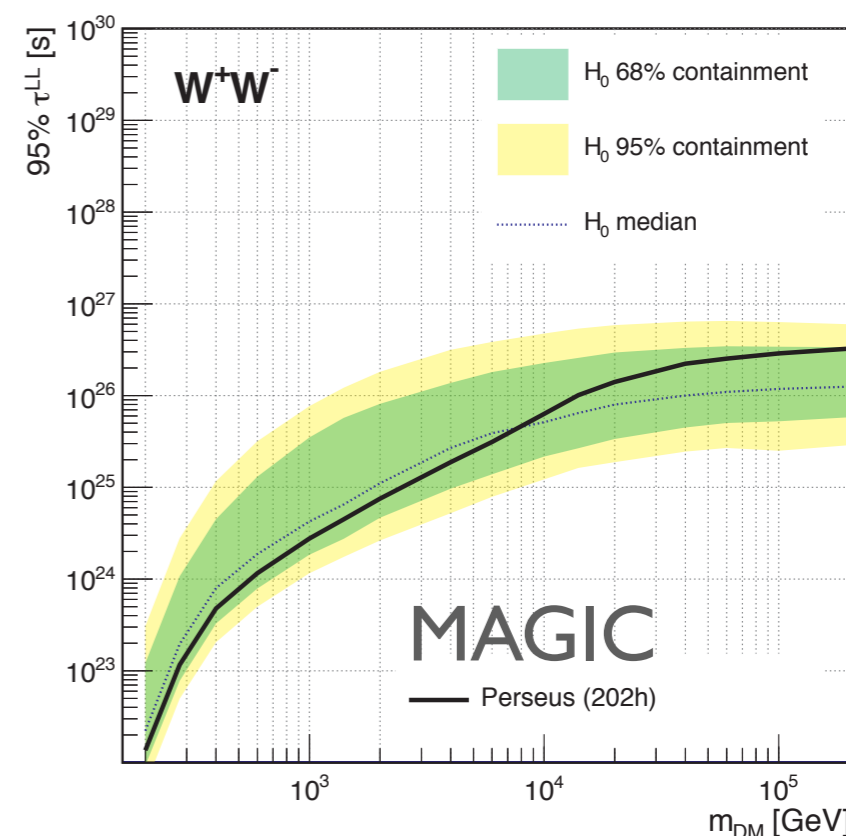


$$\begin{aligned} \mathcal{L}(1/\tau_{\text{DM}}; \nu | \mathcal{D}) &= \prod_{i=1}^{N_{\text{samples}}} \mathcal{K}(\kappa_i | \kappa_{\text{obs},i}, \sigma_{\kappa,i}) \\ &\times \prod_{j=1}^{N_{\text{bins}}} \left[\frac{(g_{ij}(\tau_{\text{DM}}) + b_{ij} + f_{ij})^{N_{\text{ON},ij}}}{N_{\text{ON},ij}!} e^{-(g_{ij}(\tau_{\text{DM}}) + b_{ij} + f_{ij})} \right. \\ &\times \left. \frac{(\kappa_i b_{ij} + g_{ij}^{\text{OFF}}(\tau_{\text{DM}}))^{N_{\text{OFF},ij}}}{N_{\text{OFF},ij}!} e^{-(\kappa_i b_{ij} + g_{ij}^{\text{OFF}}(\tau_{\text{DM}}))} \right], \end{aligned}$$

★ Complex analysis:

- ★ Very deep MAGIC observations (200 h), demanding:
 - ✦ merge data taken under very different conditions
 - ✦ consider systematic uncertainties on background
- ★ Gamma-ray source (NGC1275) coinciding with center of DM halo
- ★ Signal “contamination” of background

★ **DM lifetime** $> 10^{25}$ (10^{26}) s for 1 (10) TeV WIMPS

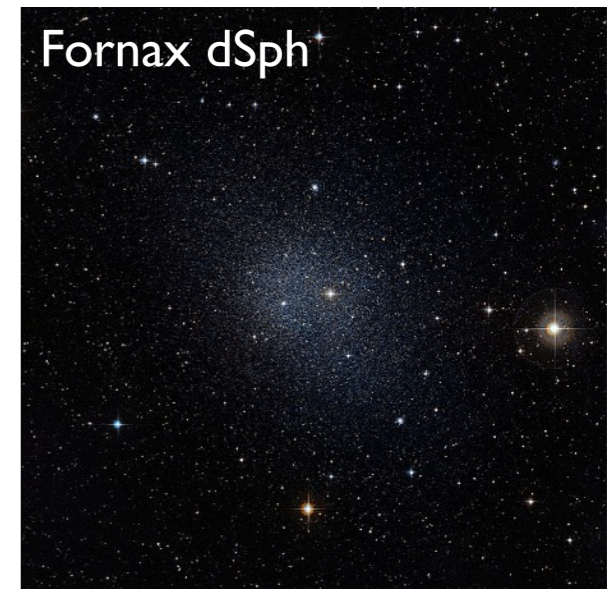


Acciari et al. PDU submitted



Dwarf satellite galaxies

- ★ **Dark matter clumps** in the Galaxy with stellar activity
- ★ **O(30) known so far:**
 - ◆ 8 classical
 - ◆ ~12 ultra-faint discovered by SDSS
 - ◆ ++ by DES, Pan-STARRs...
- ★ **DM distribution** fitted to reproduce observed stellar kinematics
 - Up to O(1000) M/L ratios
- ★ **Most robust astrophysical probe into nature of dark matter**

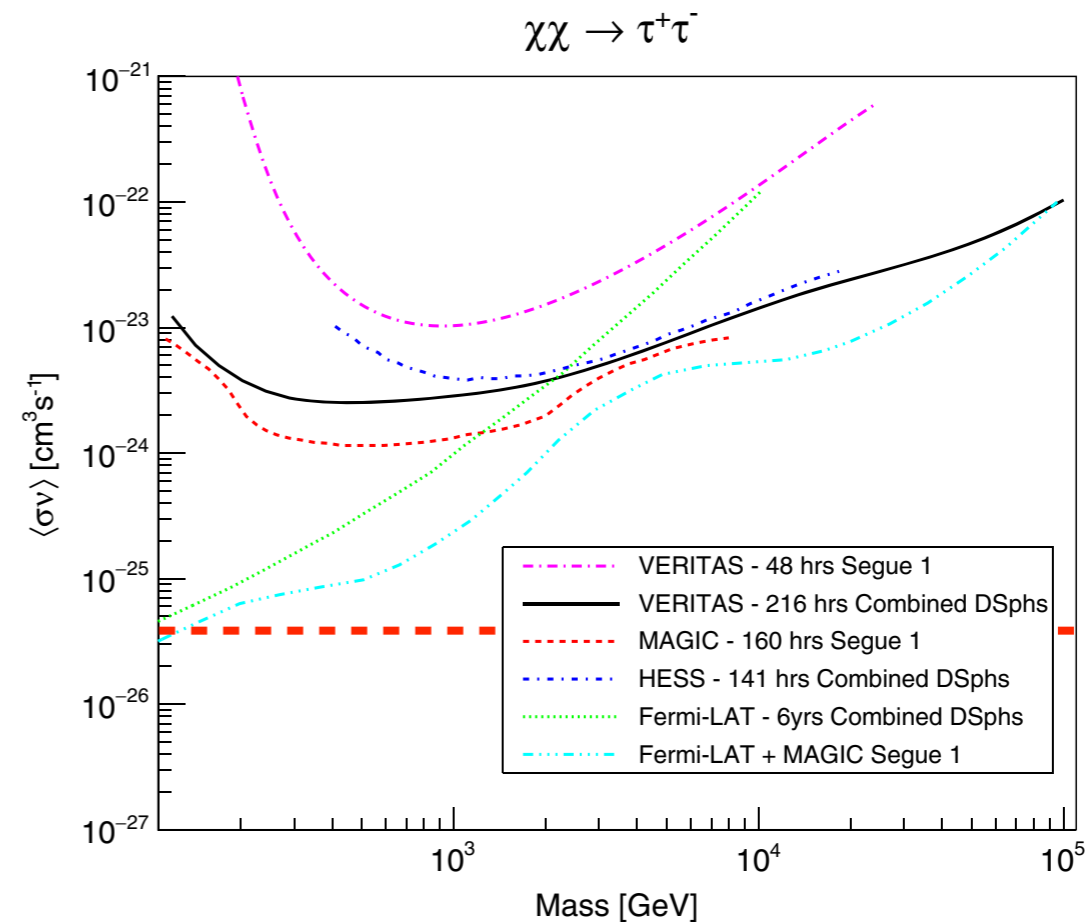
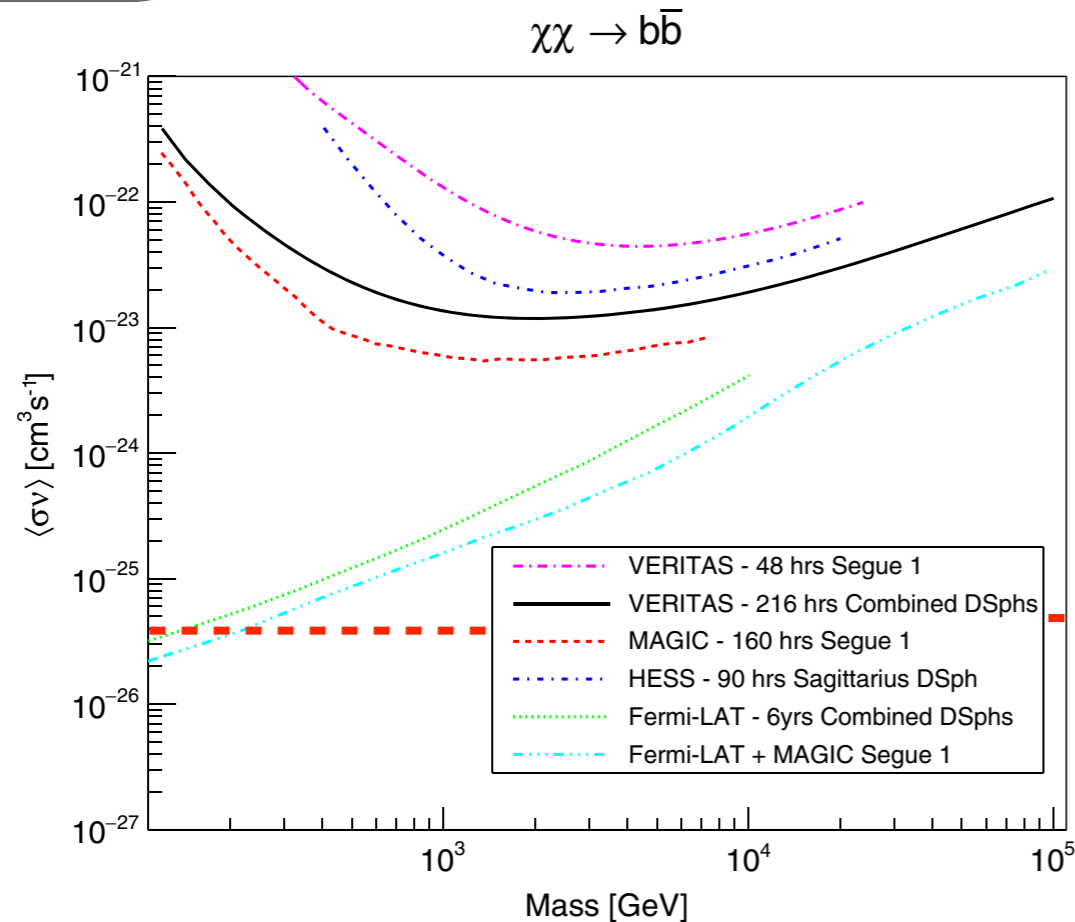


Deepest published observations by IACTs

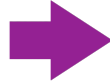
Source	Telescope	Year	T [h]	J [GeV ² /cm ⁵]
Sagittarius	HESS	2006-2012	90	2.2×10 ¹⁸
Sculptor	HESS	2008-2009	12	2.3×10 ¹⁸
Carina	HESS	2008-2009	23	7.2×10 ¹⁷
Coma Berenics	HESS	2010-2013	11	3.3×10 ¹⁹
Draco	VERITAS	2007-2013	50	2.0×10 ¹⁸
Ursa Minor	VERITAS	2007-2013	60	7.9×10 ¹⁸
Segue 1	VERITAS	2010-2013	92	1.1×10 ¹⁹
Segue 1	MAGIC	2010-2013	160	1.1×10 ¹⁹
Ursa Major II	MAGIC	2014-2016	100	2.6×10 ¹⁹

...

Limits from dSph



Archambault et al. PRD95(2017)082001

- ★ **Most constraining limits** for leptonic (hadronic) channels and masses above 1 (10) TeV
 - ★ **Comparison between results sometimes difficult** due to different assumptions/conventions used during analysis
 - ★ **Sensitivity improves** when considering all observations
- 
Combined analysis!

Combination of results: MAGIC+Fermi-LAT

- ★ **Joint-likelihood** depending on one free parameter (proportional to gamma-ray intensity), one term per target:

$$\mathcal{L}(\langle\sigma v\rangle; \nu | \mathcal{D}) = \prod_{i=1}^{N_{\text{target}}} \mathcal{L}_i(\langle\sigma v\rangle; J_i, \mu_i | \mathcal{D}_i) \cdot \mathcal{J}(J_i | J_{\text{obs},i}, \sigma_i)$$

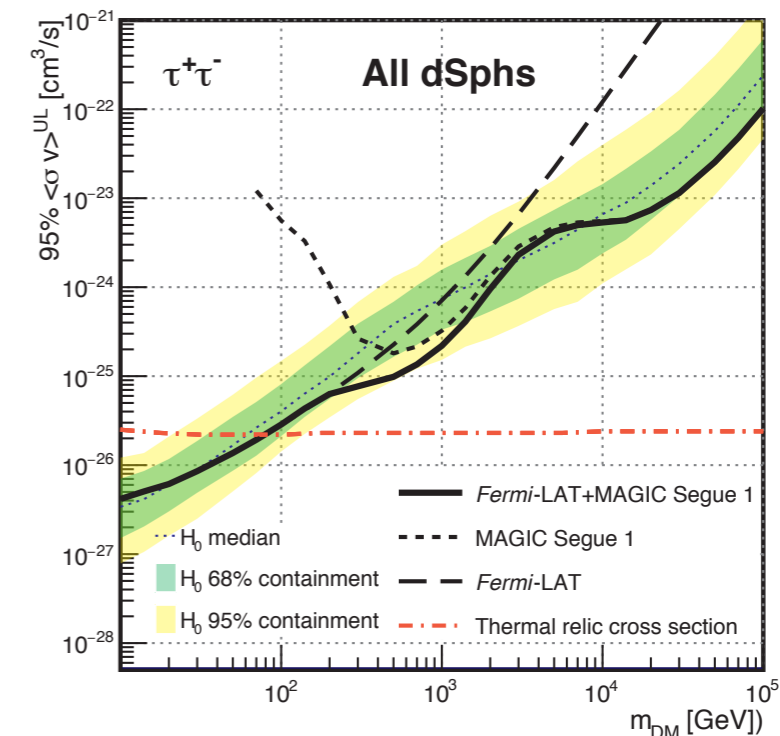
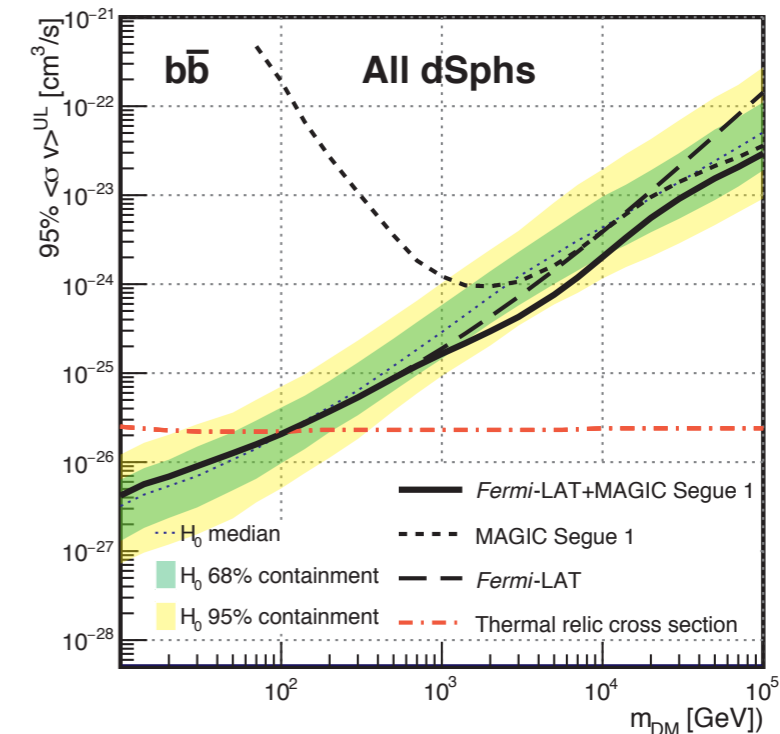
- ★ Can include **target-wise uncertainties on J-factor**

$$\mathcal{J}(J | J_{\text{obs}}, \sigma) = \frac{1}{\ln(10) J_{\text{obs}} \sqrt{2\pi} \sigma} \times e^{-\left(\log_{10}(J) - \log_{10}(J_{\text{obs}})\right)^2 / 2\sigma^2}$$

- ★ For each target, **one term per instrument** having observed it:

$$\mathcal{L}_i(\langle\sigma v\rangle; J_i, \mu_i | \mathcal{D}_i) = \prod_{j=1}^{N_{\text{instrument}}} \mathcal{L}_{ij}(\langle\sigma v\rangle; J_i, \mu_{ij} | \mathcal{D}_{ij})$$

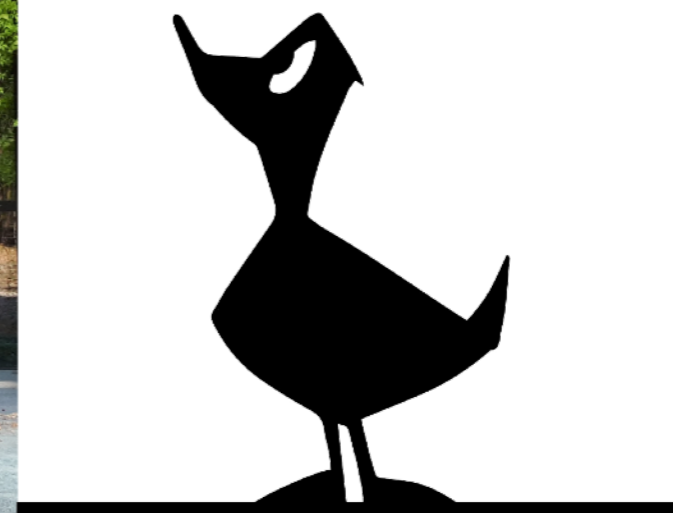
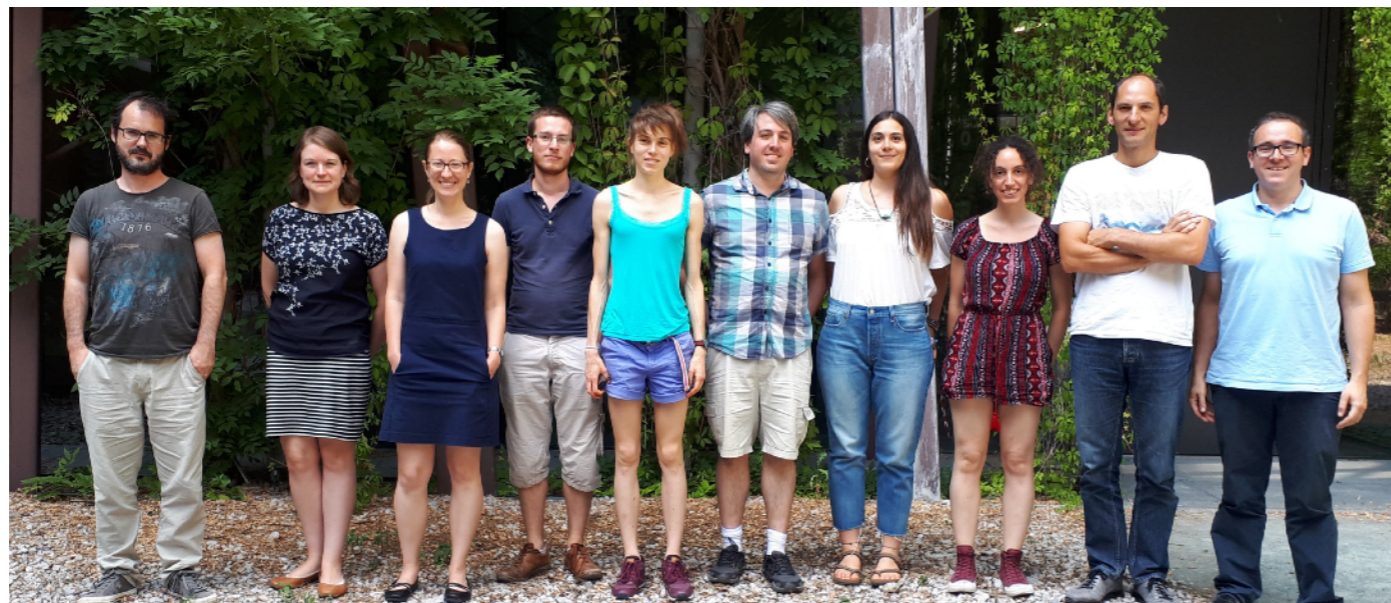
- ★ **Combined analysis** can be done by just sharing likelihood values vs free parameter



Ahnen et al. JCAP1602(2016)039

The future: combining all IACTs

★ The Glory Duck Group:



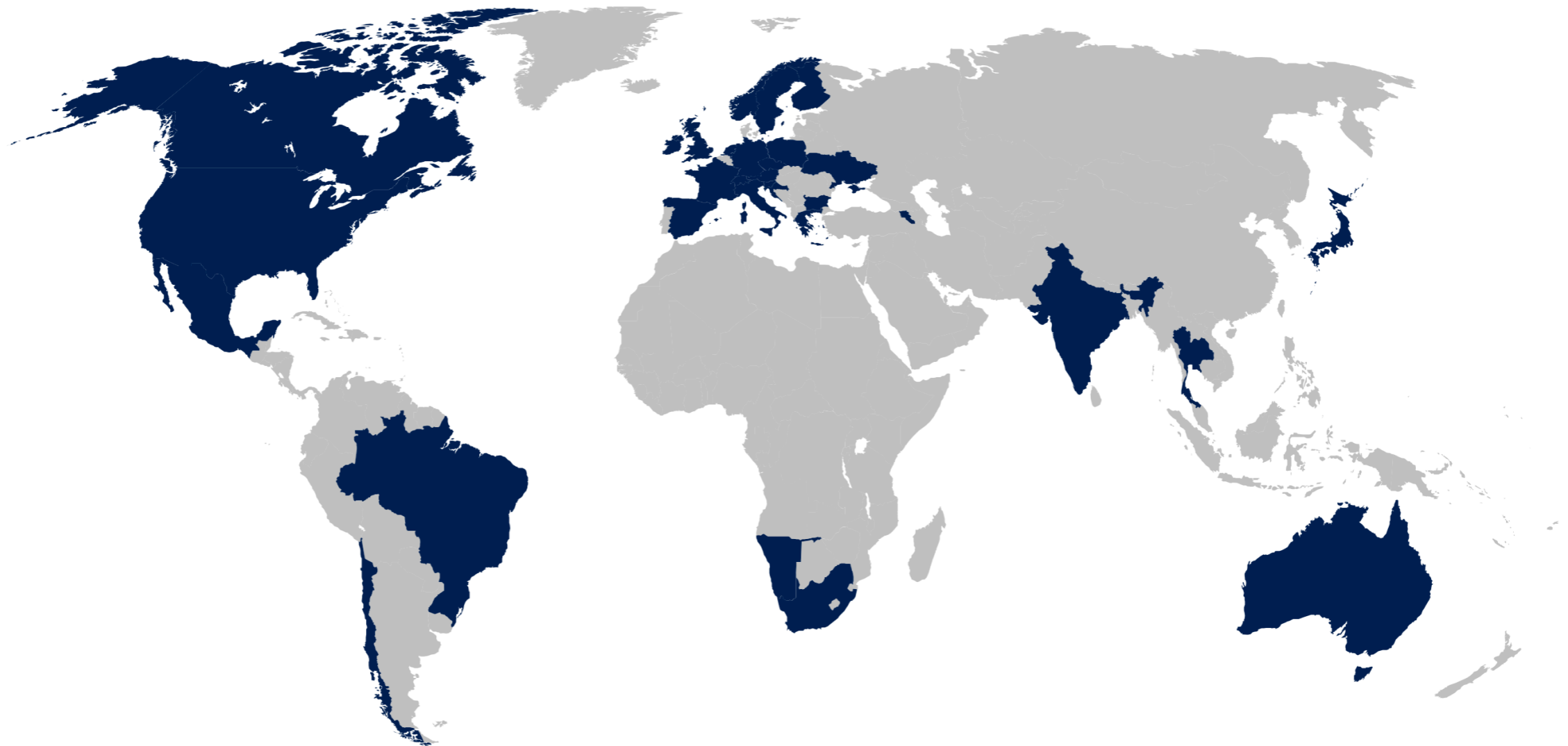
- ★ Aim: **Produce a global DM result** combining all dSph observations by HESS, MAGIC and VERITAS
Also exploring including Fermi-LAT and HAWC
- ★ **First meeting in Berlin** past June, many decisions taken: working group, targets, analysis, inputs (spectra, J-factors), treatment of systematic uncertainties (J-factor, background estimation), sharable likelihood table formats, publication policies... (some TBC by governing boards of the participating collaborations)
- ★ **Stay tuned:** Estimated time of completion: ~1 year

Future prospects with CTA



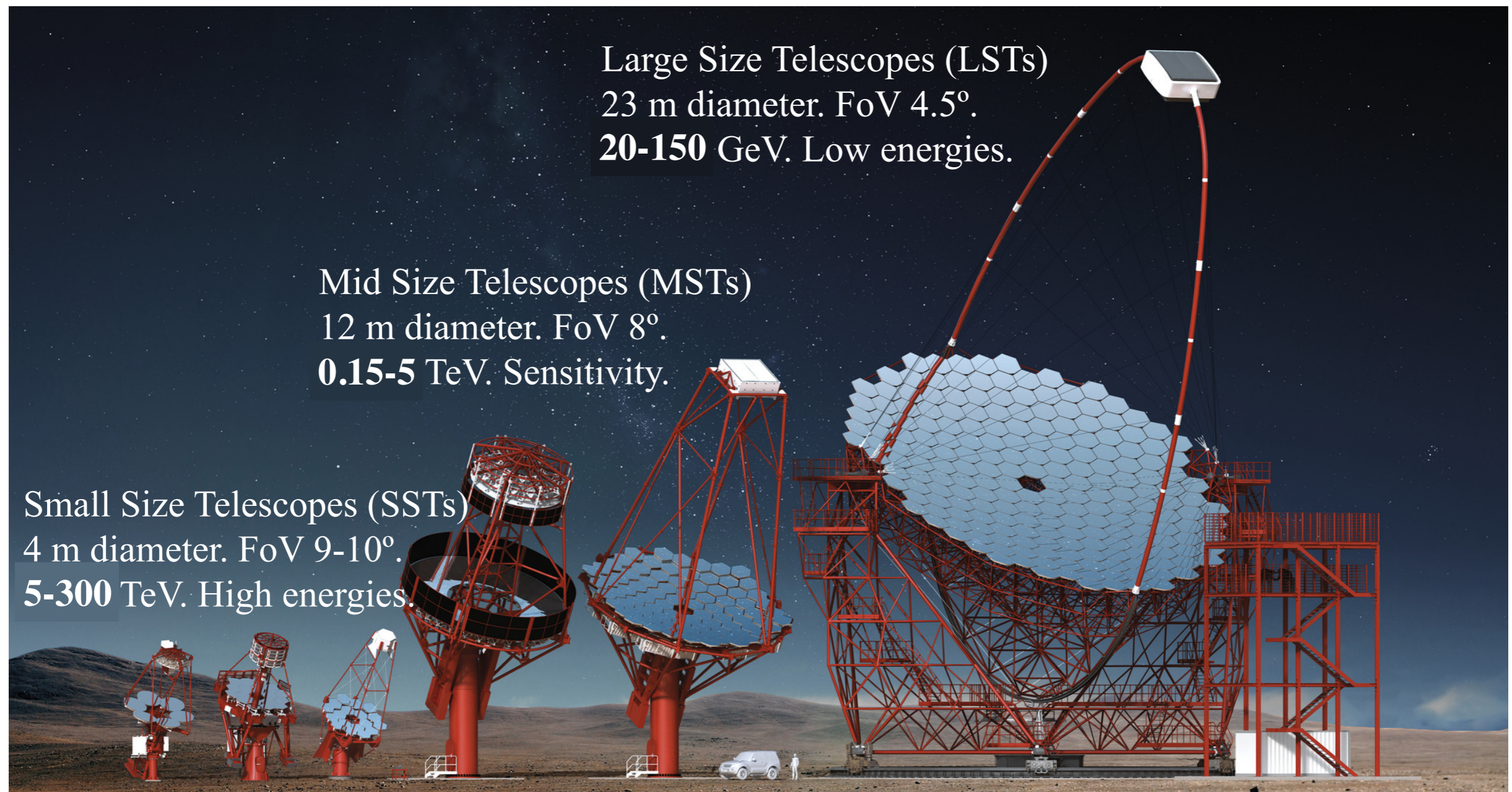
CTA: a World Wide effort

CTA science goals and design is being developed by the **CTA Consortium**:
> **1.400 scientists and engineers** from about **200 institutes in 31 countries**.
<http://www.cta-observatory.org/>



CTA: three telescope sizes

Different telescope **sizes** for different **energy ranges**.
Slightly different technologies.





CTA: Full-sky coverage

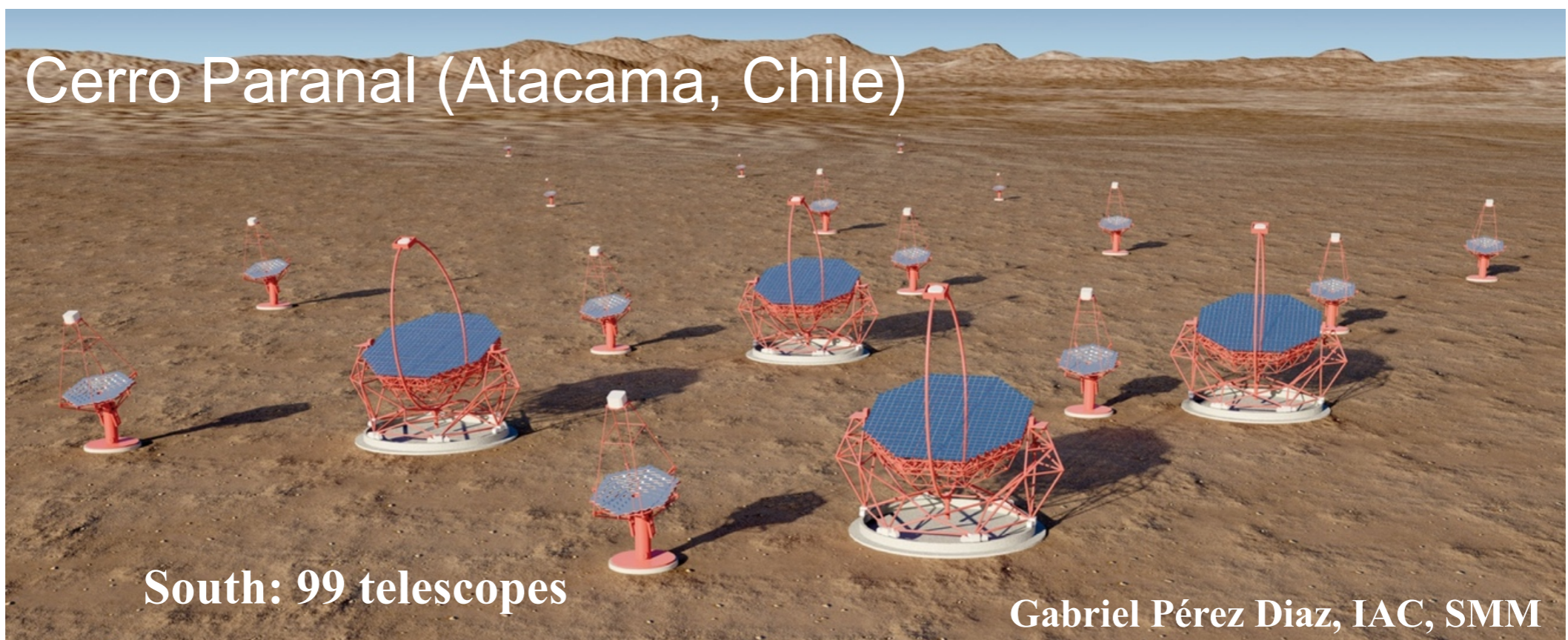
Palma (Canary Islands, Spain)



North: 19 telescopes

Gabriel Pérez Diaz, IAC, SMM

Cerro Paranal (Atacama, Chile)



South: 99 telescopes

Gabriel Pérez Diaz, IAC, SMM



CTA: under construction!

Palma (Canary Islands, Spain)



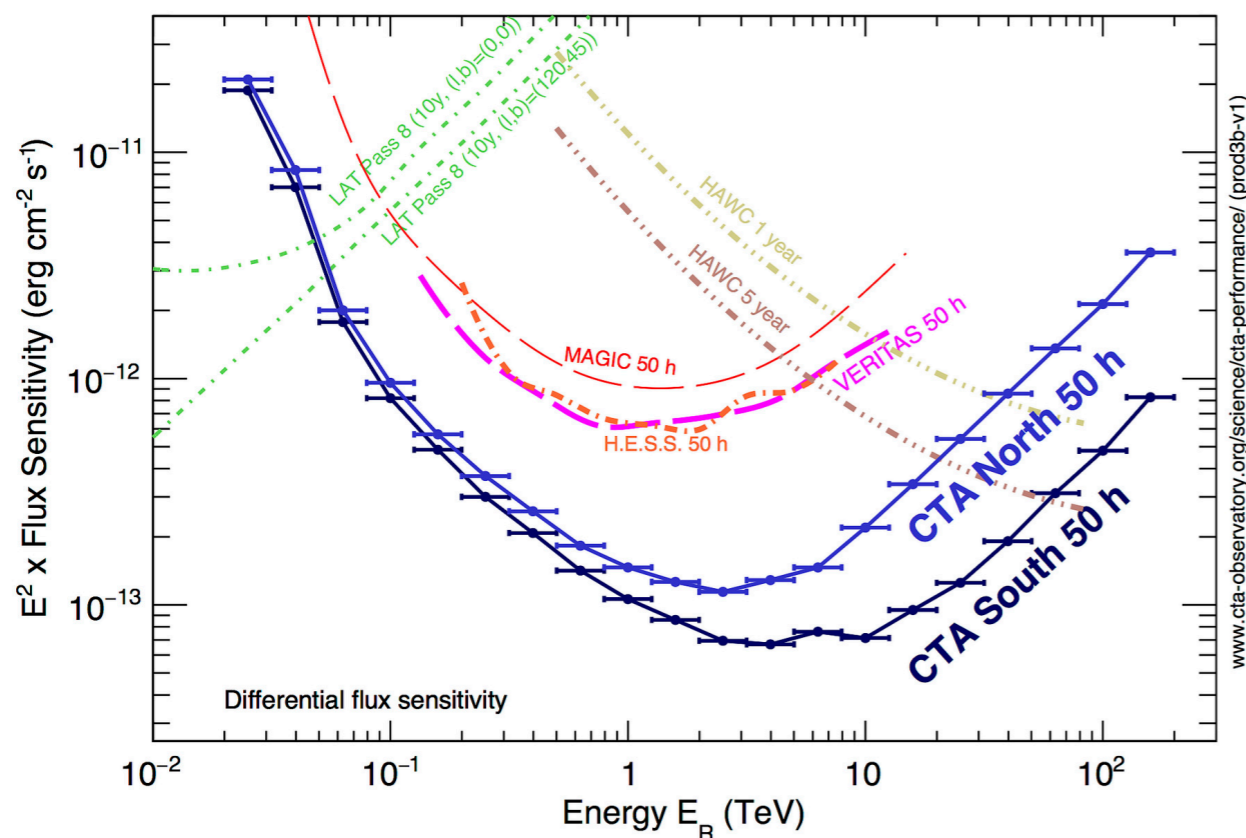
**LST prototype at ORM,
La Palma, Spain
Inauguration 2018 Oct**



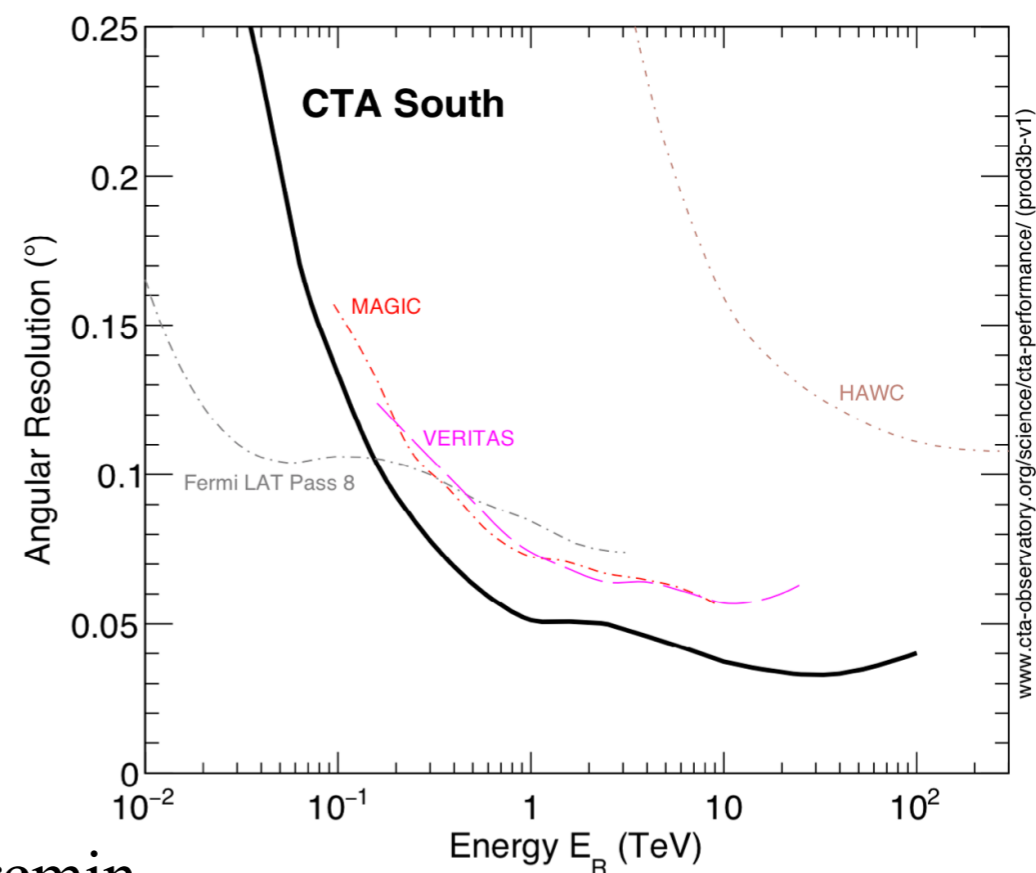


CTA performance

CTA **sensitivity**: a factor 5-20 better than current facilities (energy dependent).



Acharya et al arXiv:1809.07997



Angular resolution: down to 0.03 deg. or 2 arcmin.

Energy resolution: 5-10% above 100 GeV.



CTA DM search strategy

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							
<i>in case of detection at GC, large σv</i>										
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
<i>in case of detection at GC, small σv</i>										
Galactic halo				100 h	100 h	100 h	100 h	100 h	100 h	100 h
<i>in case of no detection at GC</i>										
<i>Best Target</i>				100 h	100 h	100 h	100 h	100 h	100 h	100 h

Acharya et al arXiv:1809.07997

★ High priority program for 10 years

★ First 3 years:

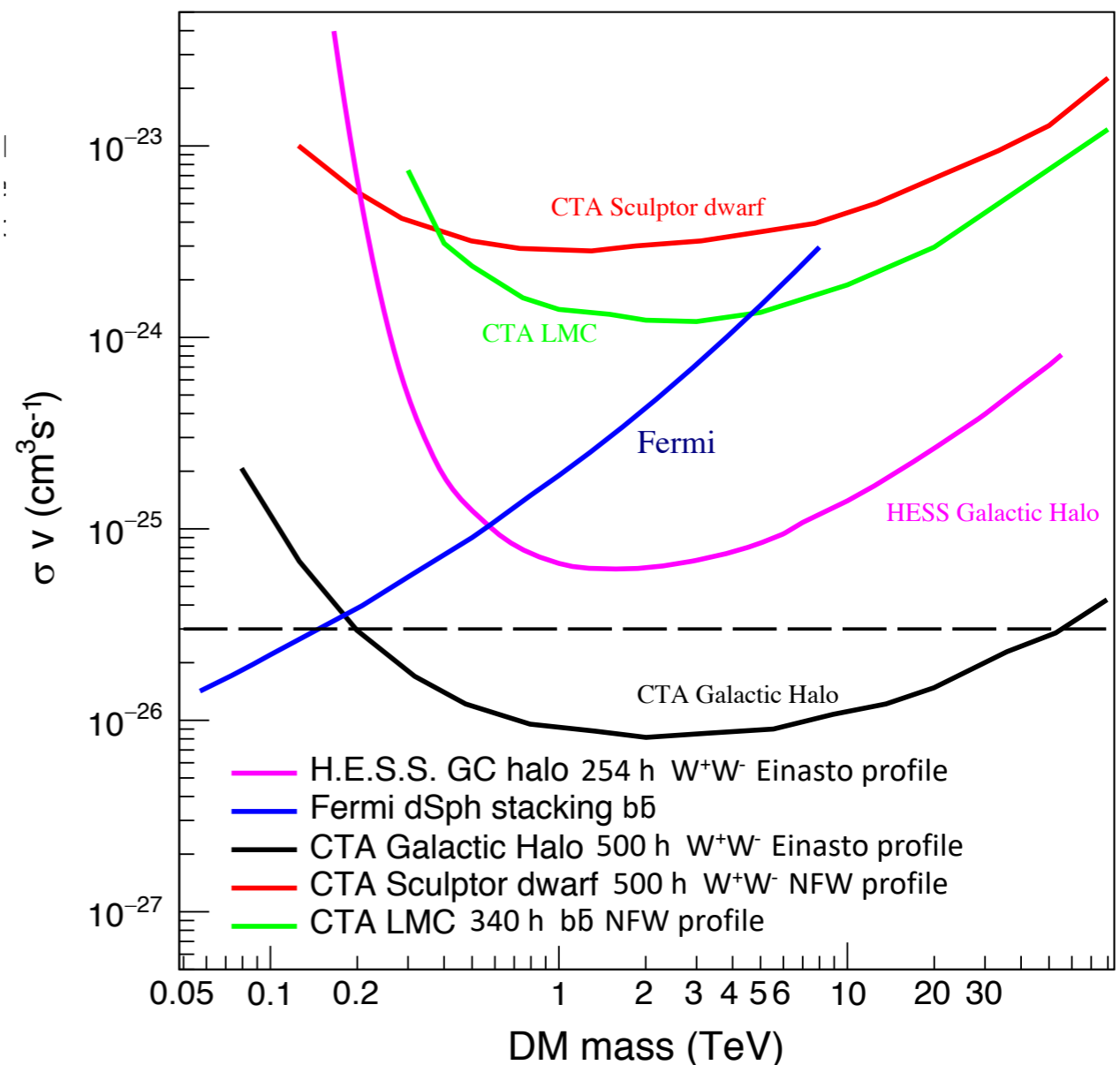
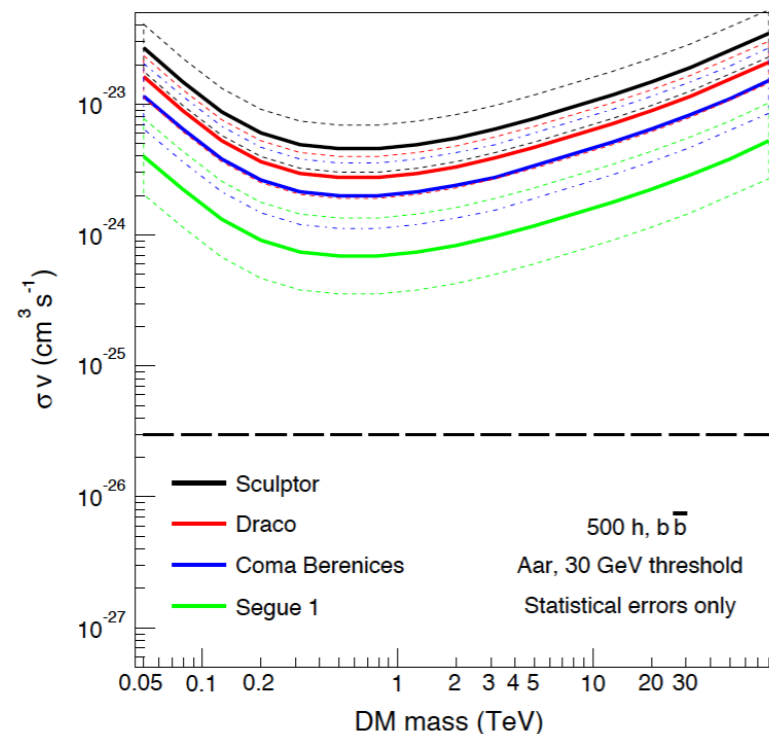
- ♦ Deep observations of the Galactic Center Halo (~500 h)
- ♦ Complemented by observations of best dSph (~300 h)

★ Follow-up observations:

- ♦ In case of detection at GC halo:
 - ❖ $\langle\sigma v\rangle$ high enough: check DM signal towards best dSph
 - ❖ otherwise deep observations of GC region
- ♦ In case of no detection:
 - ❖ focus on best target to produce most robust limits

CTA DM sensitivity

- ★ CTA will be sensitive to the **thermal relic density** for WIMP masses above $\sim 200\text{GeV}$
- ★ **Results from dwarfs** are less constraining but depend less on systematic uncertainties



Acharya et al arXiv:1809.07997



Conclusions

- ★ **Current Cherenkov telescopes HESS, MAGIC and VERITAS** have devoted significant part of their observation time to look for DM (WIMP) annihilation and decay signals from the local Universe
- ★ **Multiple targets:**
 - ✦ Galactic Center (halo) high flux but high uncertainties
 - ✦ Dwarf satellite galaxies low flux and lower uncertainties
 - ✦ Galaxy clusters good especially for decay signal
 - ✦ More: globular clusters, unidentified Fermi objects, e^+e^- spectrum,...
- ★ **No positive signal found**
 - set most constraining limits for DM mass in the TeV range
- ★ In the near future, the **CTA will explore the region below the thermal relic cross-section** for DM mass in the TeV range