

# Constraining the Dark Matter annihilation cross section with a combined analysis of dwarf spheroidal galaxy observations from *Fermi*-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS

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Grupo de Altas Energías - UCM

# Motivation

- ▶ Perform multi-instrument and multi-target analysis (global Dark Matter searches) to obtain the most sensitive and robust results yet
- ▶ Produce legacy results of DM searches in dwarf galaxies with current generation of gamma-ray telescopes

# Dark Matter evidence

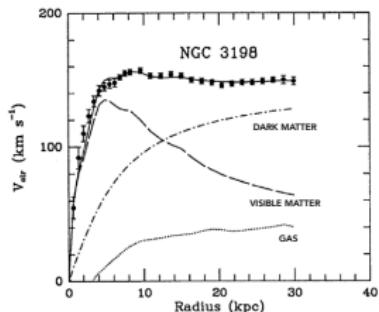
## Dynamics of galaxies and gal. clusters

In 1933, Zwicky found a deficit of ~90% in mass in Coma cluster.

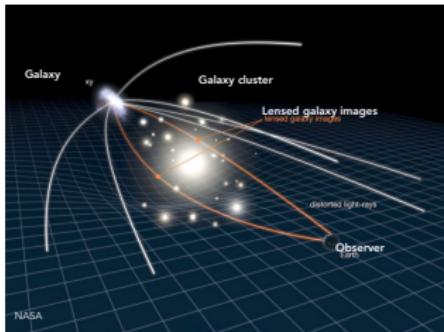
If Newtonian dynamics apply:

Inner system: Outer system:

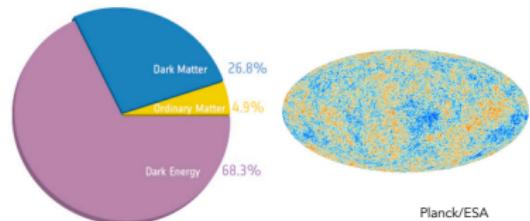
$$M(r) \propto r^3 \Rightarrow v \propto r \quad M(r) \approx \text{const} \Rightarrow v \propto \frac{1}{r}$$



## Gravitational lensing



## Standard Cosmological Model



# Dark Matter targets

Expected gamma-ray flux produced by DM annihilation:

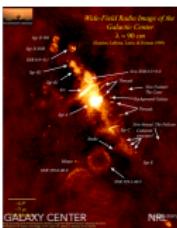
$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \underbrace{\mathcal{J}(\Delta\Omega)}_{\text{Astrophysics}} \cdot \underbrace{\frac{1}{4\pi} \frac{\langle \sigma_{ann} v \rangle}{2m_\chi^2} \sum_i \text{BR}_i \frac{dN_\gamma^i}{dE_\gamma}}_{\text{Particle physics}}$$

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

Key concepts:  $\rho$ , distance, background

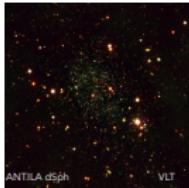
## Galactic Center & Halo

- High flux
- Background issues (source confusion)



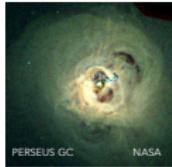
## Dwarf Galaxies

- Large M/L
- Less background
- Low flux



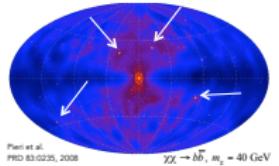
## Galaxy Clusters

- Huge DM content
- Large distance
- High background

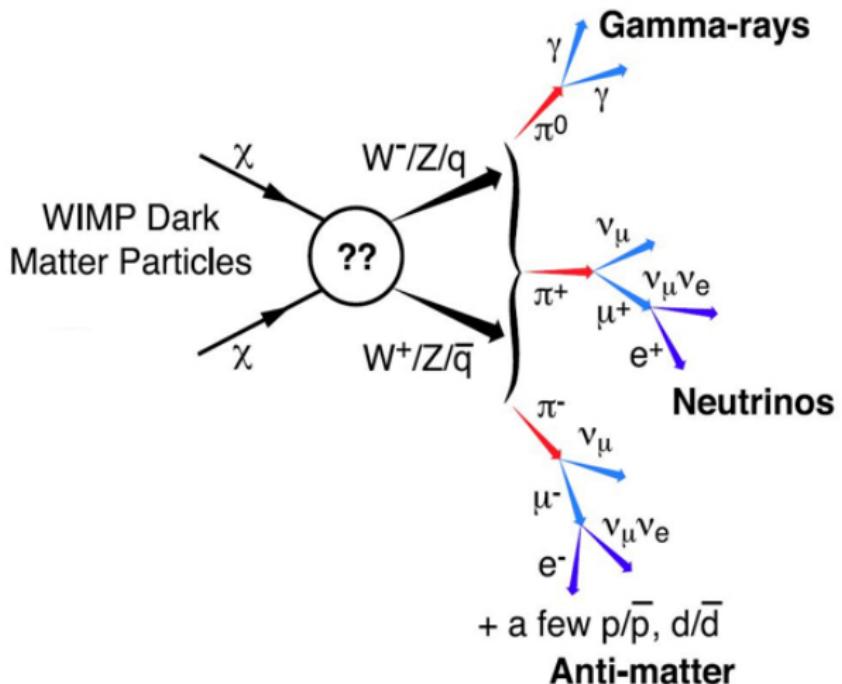


## Unassociated HE Sources:

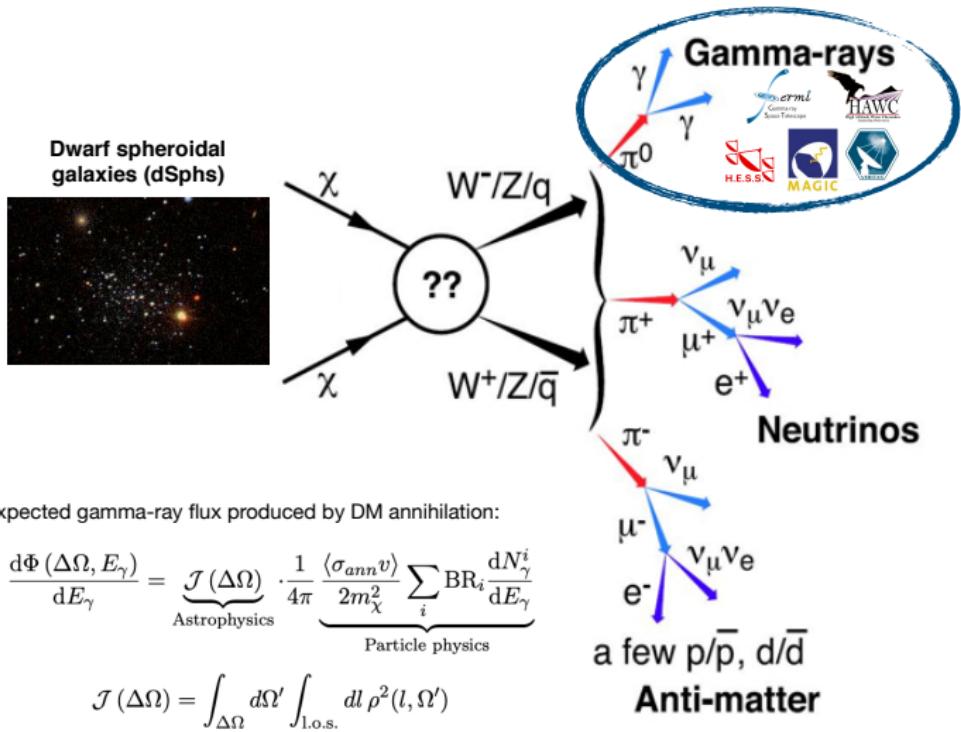
- DM Subhalos?



# Dark Matter self-annihilation



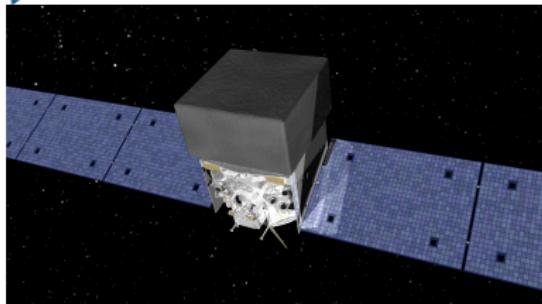
# This project



# Instruments



Fermi - Large Area Telescope



- Energy range: 20 MeV - 1 TeV
- Large FoV (20-60 deg)
- ~85% duty cycle
- Full sky coverage every two orbits (~3h)
- Collection area:  $\sim 1\text{m}^2$



High Altitude Water Cherenkov gamma-ray Observatory



- Energy range: 300 GeV - 100 TeV
- Covers 2/3 sky in 24h
- Large FoV (15% sky)
- ~90% duty cycle
- 300 4.5m x 7.3m tanks (4 PMTs)
- Collection area:  $\sim 12.000\text{m}^2$

# Instruments



Namibia

- 4+1 telescope array
- Reflectors: 4 x 13 m Ø, 1 x 28 m Ø
- Cameras: 4 x 960 PMT, 5° FoV, 1 x 2048 PMT, 3.2° FoV
- Energy threshold: 100 GeV
- ~10-20% duty cycle
- Collection area: ~ $5 \times 10^5 \text{m}^2$



La Palma Island (Spain)

- Two telescope array
- Reflectors: 2 x 17 m Ø
- Cameras: 1039 PMT, 3.5° FoV
- Energy threshold: 50 GeV
- ~10-20% duty cycle
- Collection area: ~ $5 \times 10^5 \text{m}^2$



Tucson (USA)

- Four telescope array
- Reflectors: 4 x 12 m Ø
- Cameras: 499 PMT, 3.5° FoV
- Energy threshold: 100 GeV
- ~10-20% duty cycle
- Collection area: ~ $5 \times 10^5 \text{m}^2$

# Observations of dwarf spheroidal galaxies

Source name	Instruments
Boötes I	VERITAS (14h), HAWC, <i>Fermi-LAT</i>
Canes Venatici I	HAWC, <i>Fermi-LAT</i>
Canes Venatici II	<i>Fermi-LAT</i>
Carina	H.E.S.S. (23h), <i>Fermi-LAT</i>
Coma Berenices	H.E.S.S. (11h), MAGIC (49h), HAWC, <i>Fermi-LAT</i>
Draco	MAGIC (52h), VERITAS (50h), HAWC, <i>Fermi-LAT</i>
Fornax	H.E.S.S. (6h), <i>Fermi-LAT</i>
Hercules	HAWC, <i>Fermi-LAT</i>
Leo I	HAWC, <i>Fermi-LAT</i>
Leo II	HAWC, <i>Fermi-LAT</i>
Leo IV	HAWC, <i>Fermi-LAT</i>
Leo T	<i>Fermi-LAT</i>
Leo V	<i>Fermi-LAT</i>
Sculptor	H.E.S.S. (12h), <i>Fermi-LAT</i>
Segue I	MAGIC (158h), VERITAS (92h), HAWC, <i>Fermi-LAT</i>
Segue II	<i>Fermi-LAT</i>
Sextans	HAWC, <i>Fermi-LAT</i>
Ursa Major I	HAWC, <i>Fermi-LAT</i>
Ursa Major II	MAGIC (95h), HAWC, <i>Fermi-LAT</i>
Ursa Minor	VERITAS (60h), <i>Fermi-LAT</i>

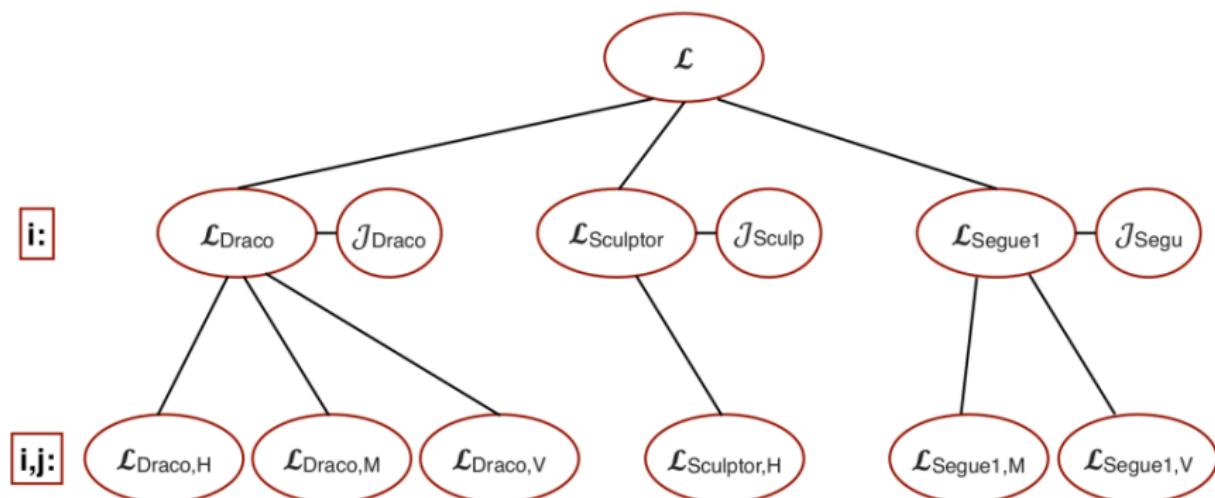
# Observations of dwarf spheroidal galaxies

- ▶ *Fermi*-LAT includes ten years of Pass 8 data from April 8th, 2008 to March 3rd, 2018
- ▶ HAWC provides data corresponding to 1038 days of livetime starting on November 26th, 2014.
- ▶ The total amount of accumulated observation hours from IACTs for this project is 624 hours (H.E.S.S. 54 h; MAGIC 354 h; VERITAS 216 h).

# Combining likelihoods

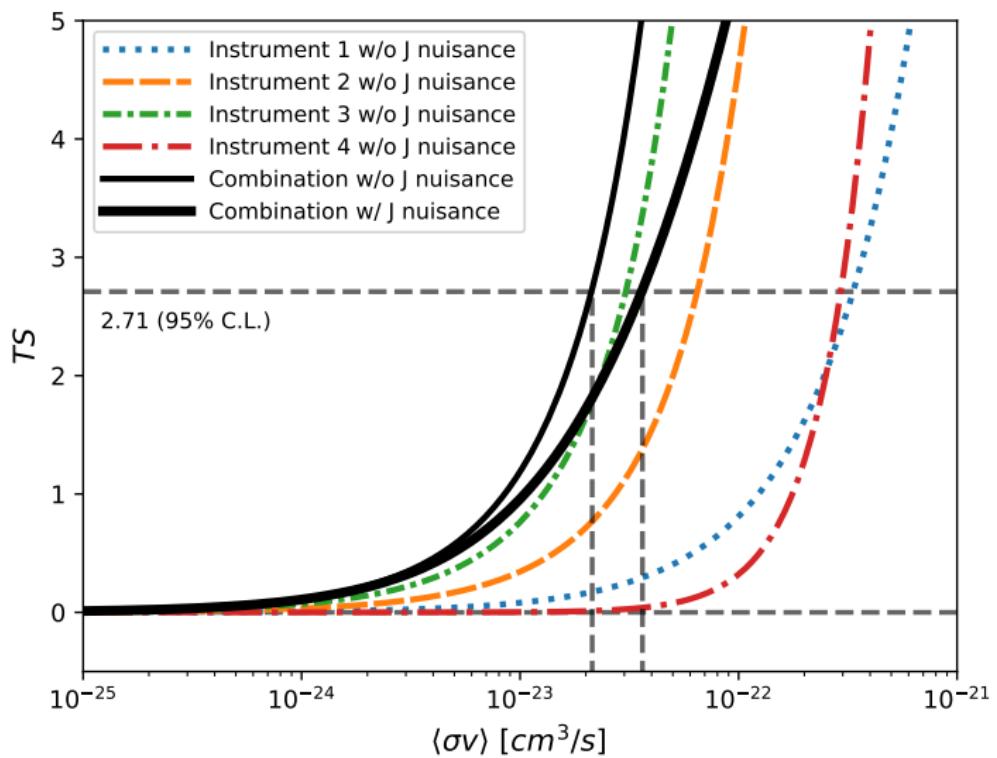
Likelihood formula:

$$\mathcal{L}(\langle\sigma v\rangle; \nu | \mathcal{D}_{\text{dSphs}}) = \prod_{l=1}^{N_{\text{dSphs}}} \mathcal{L}_{\text{dSph},l}(\langle\sigma v\rangle; J_l, \nu_l | \mathcal{D}_{l,\text{measured}}) \times \mathcal{J}_l(J_l | J_{l,\text{obs}}, \sigma_{\log J_l})$$



J. Rico

# Combining likelihoods

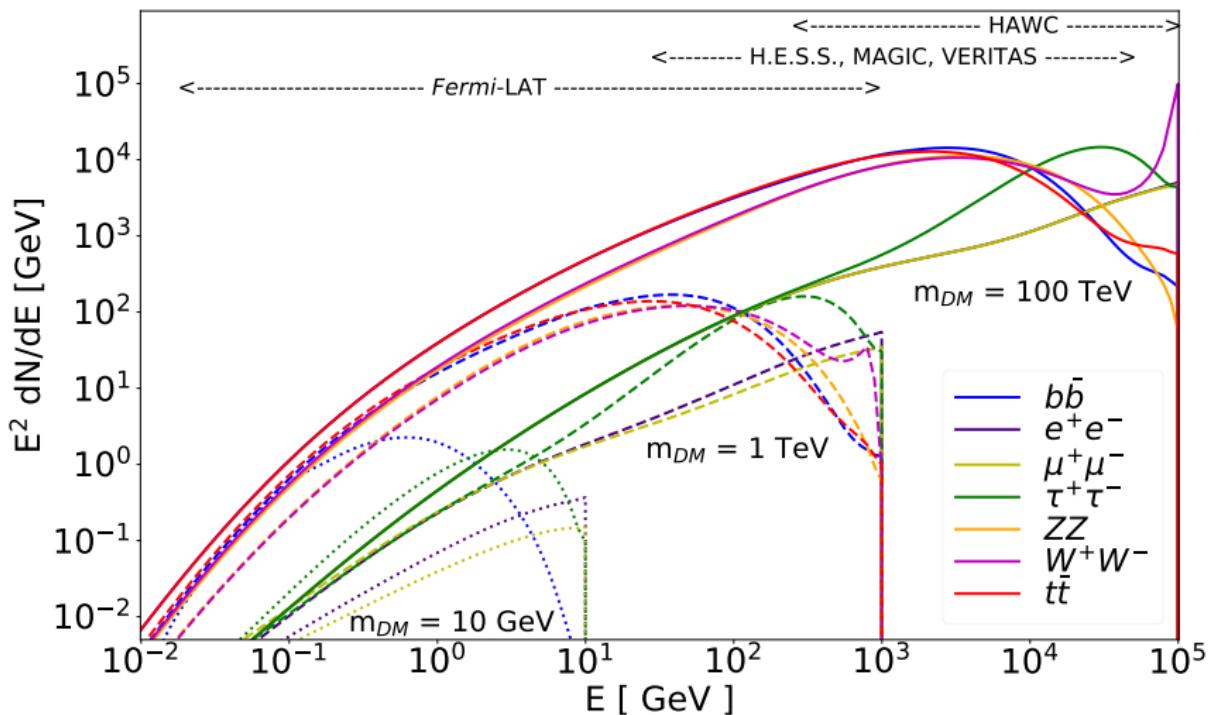


# Our combination recipe

We are using as many common ingredients as possible:

- ▶ Two sets of J-Factors and their statistical uncertainties are taken from A. Geringer-Sameth et al., *Astrophys.J.* 801, no.2, 74, 2015 and V. Bonnivard et al., *Mon. Not. Roy. Astron. Soc.*, 453, no.1, 849, 2015
- ▶ DM spectra and DM mass spacing are taken from M. Cirelli et al, *JCAP* 1103:051, 2011
- ▶ Analysis technique:
  - ▶ Binned likelihood
  - ▶ Extension of the dwarf if relevant
  - ▶ Use  $\langle \sigma v \rangle > 0$  prescription
  - ▶ J-factor as nuisance parameter

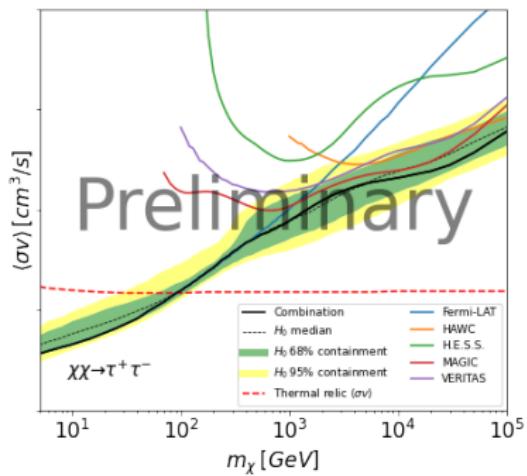
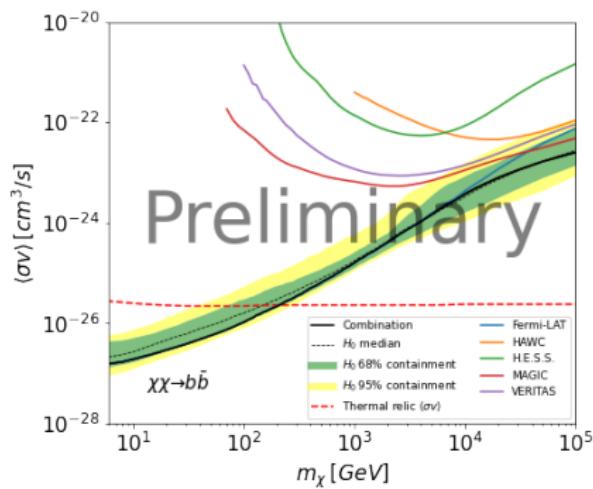
# Differential photon yield per DM annihilation



- ▶ gLike is a code framework for the numerical maximization of joint likelihood functions.
- ▶ gLike can estimate the Dark Matter annihilation cross-section combining observations of Dark Matter targets by different ground-based gamma-ray telescopes, satellite gamma-ray detectors, neutrino telescopes, ...
- ▶ We implemented the LikelihoodCombiner for an independent cross-check
- ▶ Open source on GitHub: <https://github.com/javierrico/gLike> & [https://github.com/TjarkMiener/likelihood\\_combiner](https://github.com/TjarkMiener/likelihood_combiner)

# Results

- We are showing representative two annihilation channels:  $b\bar{b}$  (hadronic) and  $\tau^+\tau^-$  (leptonic) DM annihilation.



## Summary & outlook

- ▶ In this **multi-instrument** analysis, we have used observations of 20 dSphs, carried out with *Fermi*-LAT, H.E.S.S., MAGIC, VERITAS, and HAWC to perform a **collective search** for DM annihilation signals.
- ▶ Our combined analysis improves the sensitivity over previously published results from each of the considered individual detectors, producing the **most stringent limits** to DM annihilation towards dSphs.
- ▶ This **analysis framework** could be **extended** in the future to include **next generation gamma-ray detectors** like CTA, LHAASO and/or SWGO and **neutrino observatories**, i.e. KM3NeT and IceCube.
- ▶ Please see also my poster: *Exotic dark matter searches in dwarf spheroidal galaxies with the MAGIC telescopes: From secluded and branon DM to probing DM annihilation into neutrinos*

¡Gracias por su atención!



## Acknowledgments

- ▶ TM acknowledge financial support from  
PID2019-104114RB-C32 and the former *Spanish Ministry of Economy, Industry, and Competitiveness / European Regional Development Fund* grant FPA2015-73913-JIN.

Back up

# IACT technique

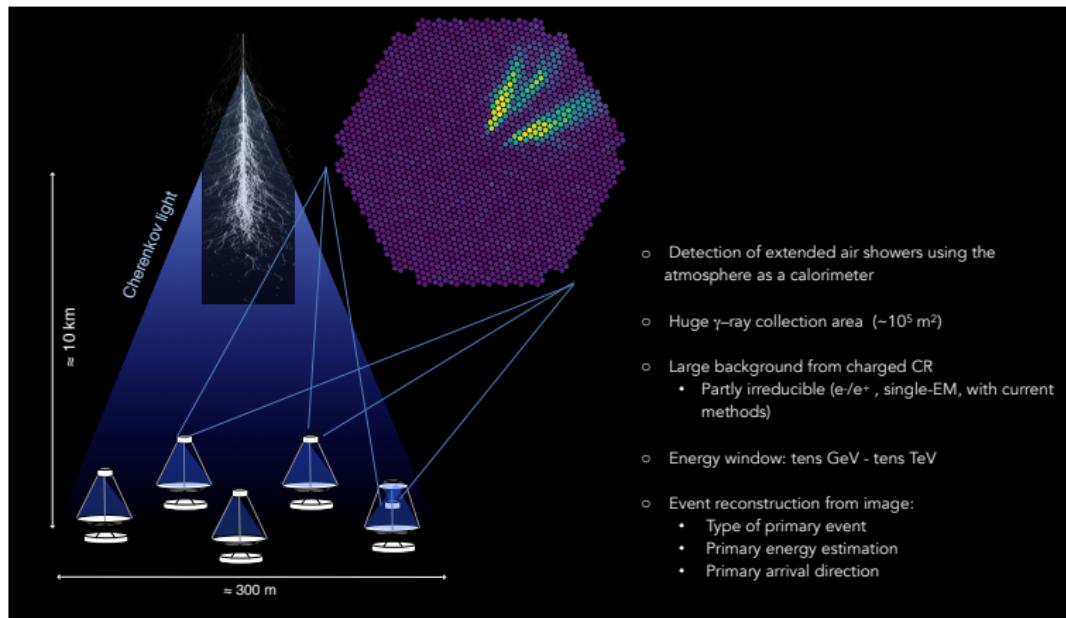


Figure: Imaging atmospheric Cherenkov telescope technique. [D. Nieto]

# IACT technique

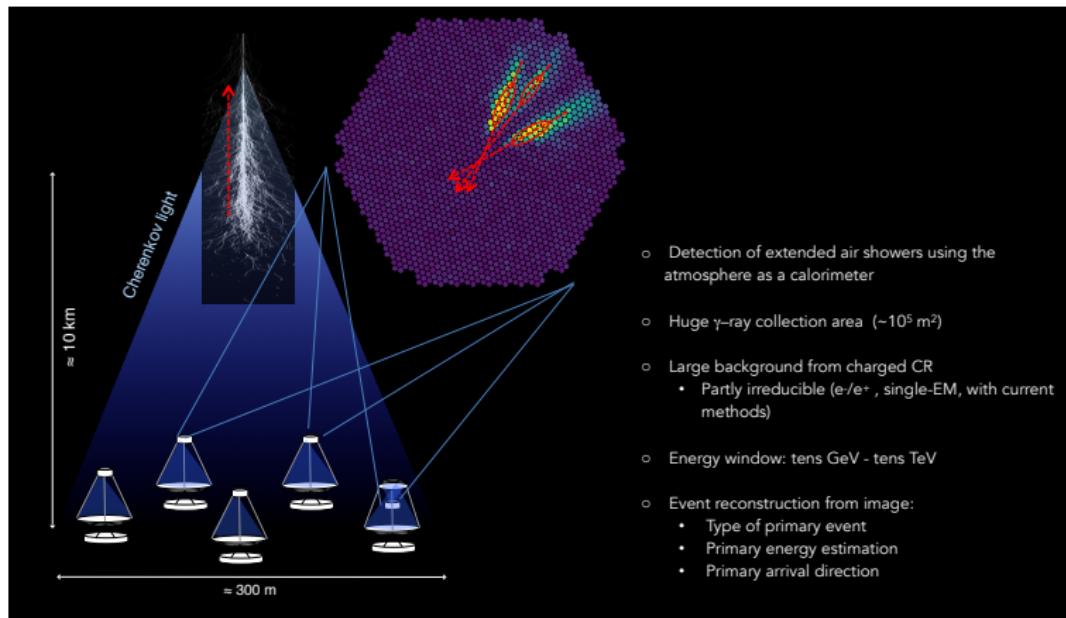


Figure: Imaging atmospheric Cherenkov telescope technique. [D. Nieto]

# Example of a txt file in GloryDuck format

Mass  
J-Factor



**bb\_Segueill\_Dummy.txt**

J-Factor	100	200	500	1000	2000	5000	10000
1e-18	27905.1	176678	701816	1.06334e+06	1.08639e+06	785953	525160
9.77237e-19	27269.8	172656	685840	1.03914e+06	1.06166e+06	768062	513206
9.54993e-19	26649	168726	670229	1.01549e+06	1.03749e+06	750579	501524
9.33254e-19	26042.3	164885	654972	992370	1.01388e+06	733494	490108
9.12011e-19	25449.5	161132	640063	969781	990798	716798	478952
8.91251e-19	24870.1	157464	625494	947706	968244	700481	468049
8.70964e-19	24303.9	153880	611256	926134	946204	684536	457395
8.51138e-19	23750.7	150377	597342	905052	924666	668954	446984
8.31764e-19	23210	146954	583745	884451	903618	653727	436809
8.12831e-19	22681.6	143609	570457	864318	88049	638846	426866
7.94328e-19	22165.2	140340	557472	844614	862949	624305	417149
7.76247e-19	21660.6	137145	544782	8254.7	8.3305	610094	407654
7.58578e-19	21167.5	134023	532381	8066.6	824109	596206	398374
7.41311e-19	20685.6	130973	520263	78826	805350	582635	389306
7.24436e-19	20214.7	127991	507420	770324	787018	569372	380445
7.07946e-19	19754.4	125078	494747	752790	769104	556412	371785
6.91831e-19	19304.7	122231	4825.7	735654	751597	543746	363322
6.76083e-19	18865.2	119448	7440.5	718908	734488	531369	355052
6.60693e-19	18435.7	116729	72684	702544	717769	519274	346970
6.45654e-19	18016	114072	453130	686553	701431	507454	339072
6.30957e-19	17605.9	111475	442815	6704.4	685464	495903	331353
6.16595e-19	17205	108938	432735	6562	669861	484614	323811
6.02566e-19	16813.3	106458	422885	64228	654613	473583	316440
5.88844e-19	16430.6	104035	413259	626143	639712	62803	309237
5.75444e-19	16056.5	101666	403852	611890	625.1	452269	302198
5.62341e-19	15690.9	99352.2	394659	597962	609.1	441974	295319
5.49541e-19	15333.7	97090.6	385676	584350	5.14	431913	288597
5.37032e-19	14984.6	94880.5	376896	571049	583425	422081	282027
5.24807e-19	14643.4	92720.7	368317	5580.6	570144	412474	275608
5.12861e-19	14310	90610	3599.5	54534	557166	403085	269334
5.01187e-19	13984.2	88547.4	351.4	532934	544483	393909	263203
4.89779e-19	13665.9	86531.8	343735	520803	532089	384943	257212
4.78631e-19	13354.7	84562	335909	508948	519978	376180	251357
4.67735e-19	13050.7	82637.1	328263	497363	508141	367618	245635
4.57088e-19	12753.5	80756	320791	486041	496575	359250	240044
4.46684e-19	12463.2	78917.7	313488	474977	485271	351072	234580
4.36516e-19	12179.4	77121.2	306353	464166	474225	343081	229240
4.26586e-19	11902.1	75365.7	299379	453600	463430	335271	224022
4.16869e-19	11631.1	73650.1	292564	443275	452881	327639	218923
4.0738e-19	11366.3	71973.5	285905	433184	442573	320181	213939

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# Joint likelihood

- ▶ Combining likelihood functions for different targets:

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

- ▶ Combining likelihood functions (of a particular target) for different experiments:

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