VERITAS Dark Matter search in dwarf Spheroidal galaxies

An extended analysis

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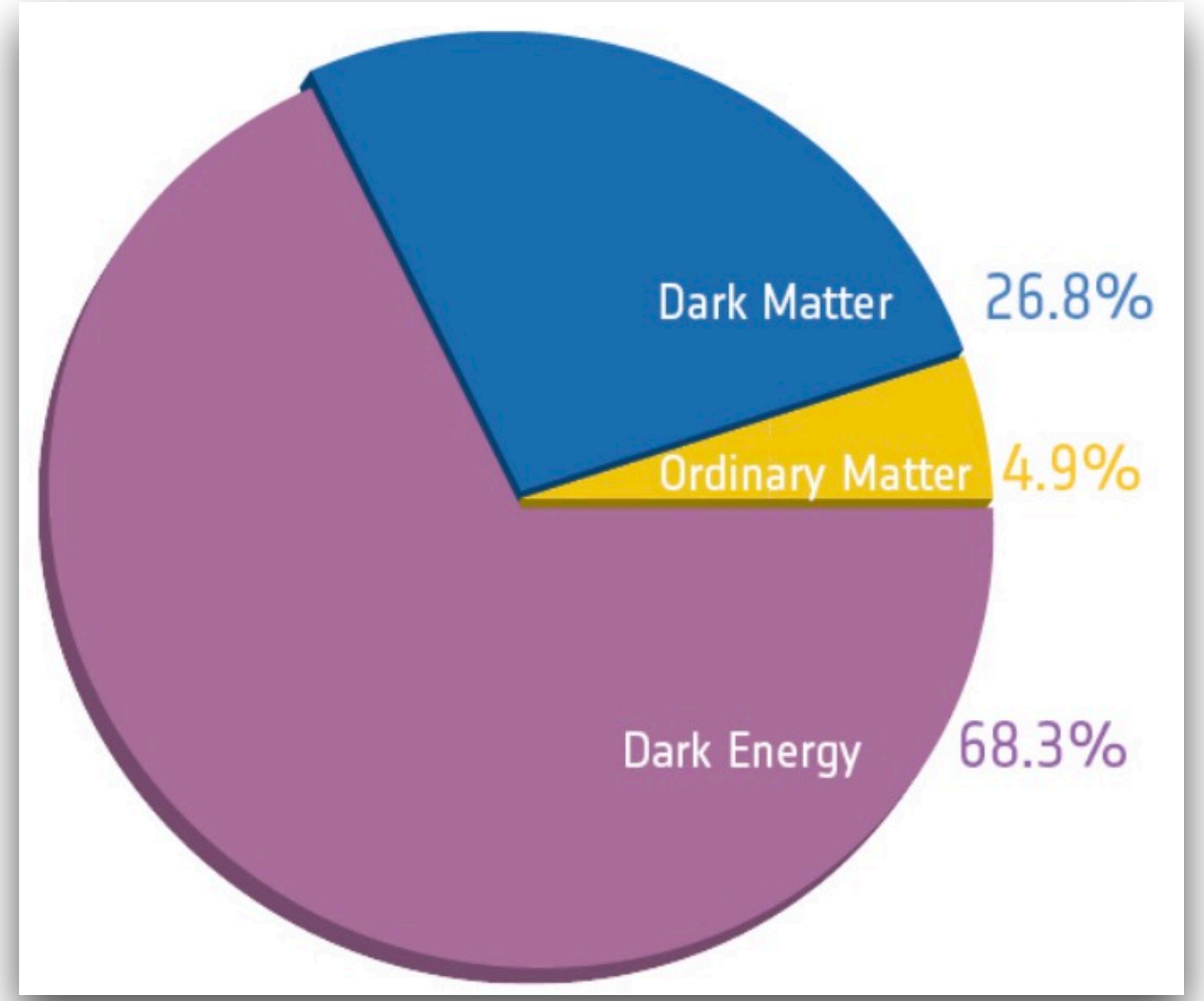
Universität Potsdam

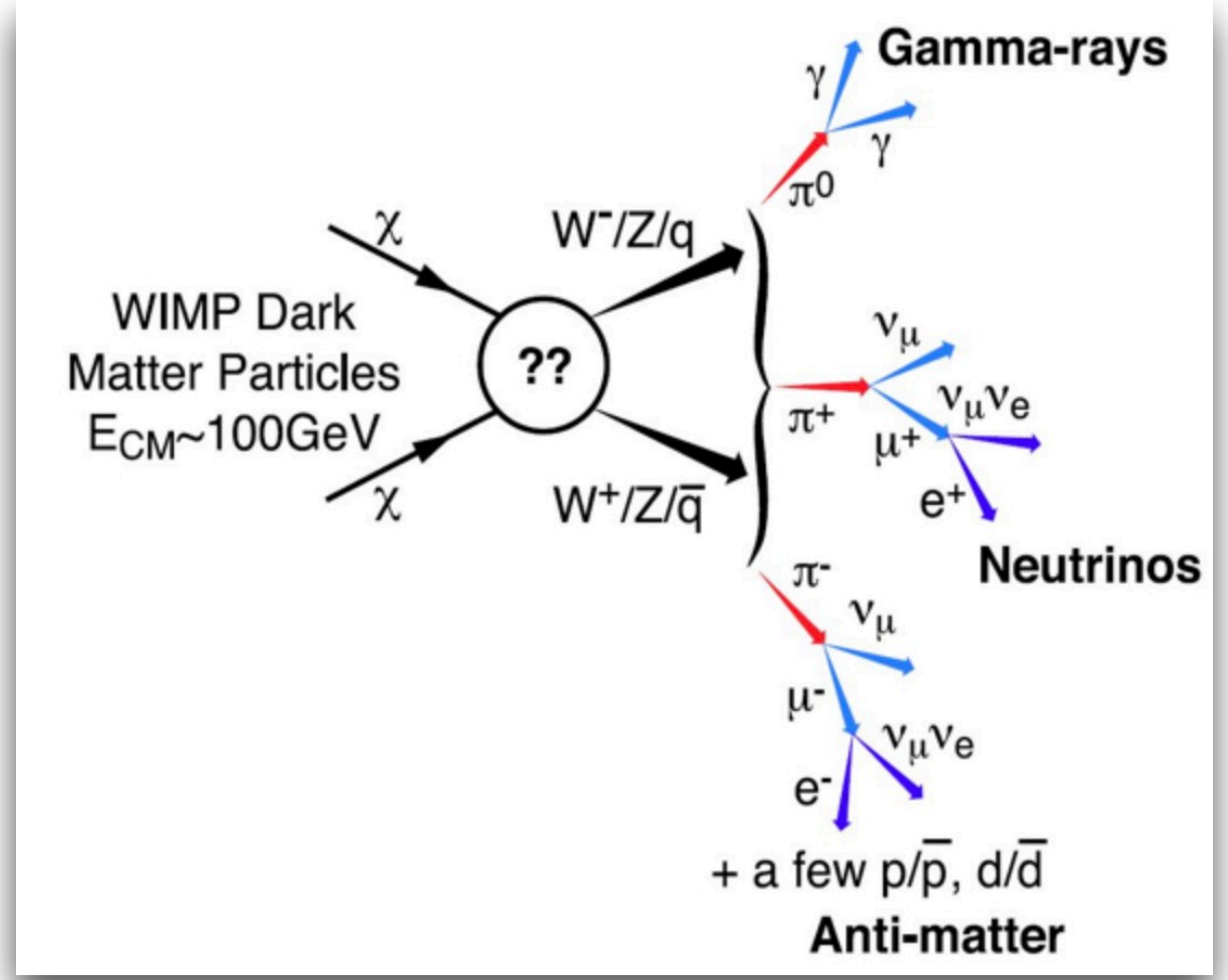
DESY.

Searching for Dark Matter with gamma-rays

In a nutshell

- Dark Matter ~ 27% total Universe mass
- DM properties: neutral, stable on cosmological scale, gravitationally interacting
- WIMPs: non-SM candidate for Cold Dark Matter in mass range 100 GeV-1 TeV
- Formed ~ 200 s after Big Bang in thermal plasma
- "WIMP miracle": weak interactions DM particle → relic density ~ observed abundance
- Annihilate (or decay) into SM particles leading to production of VHE γ-rays
- Indirect DM detection: searching for DM SM products via ground- (or space-) based experiments
- γ-rays propagate unperturbed, pointing directly to source (no $\vec{B}$ deflection)

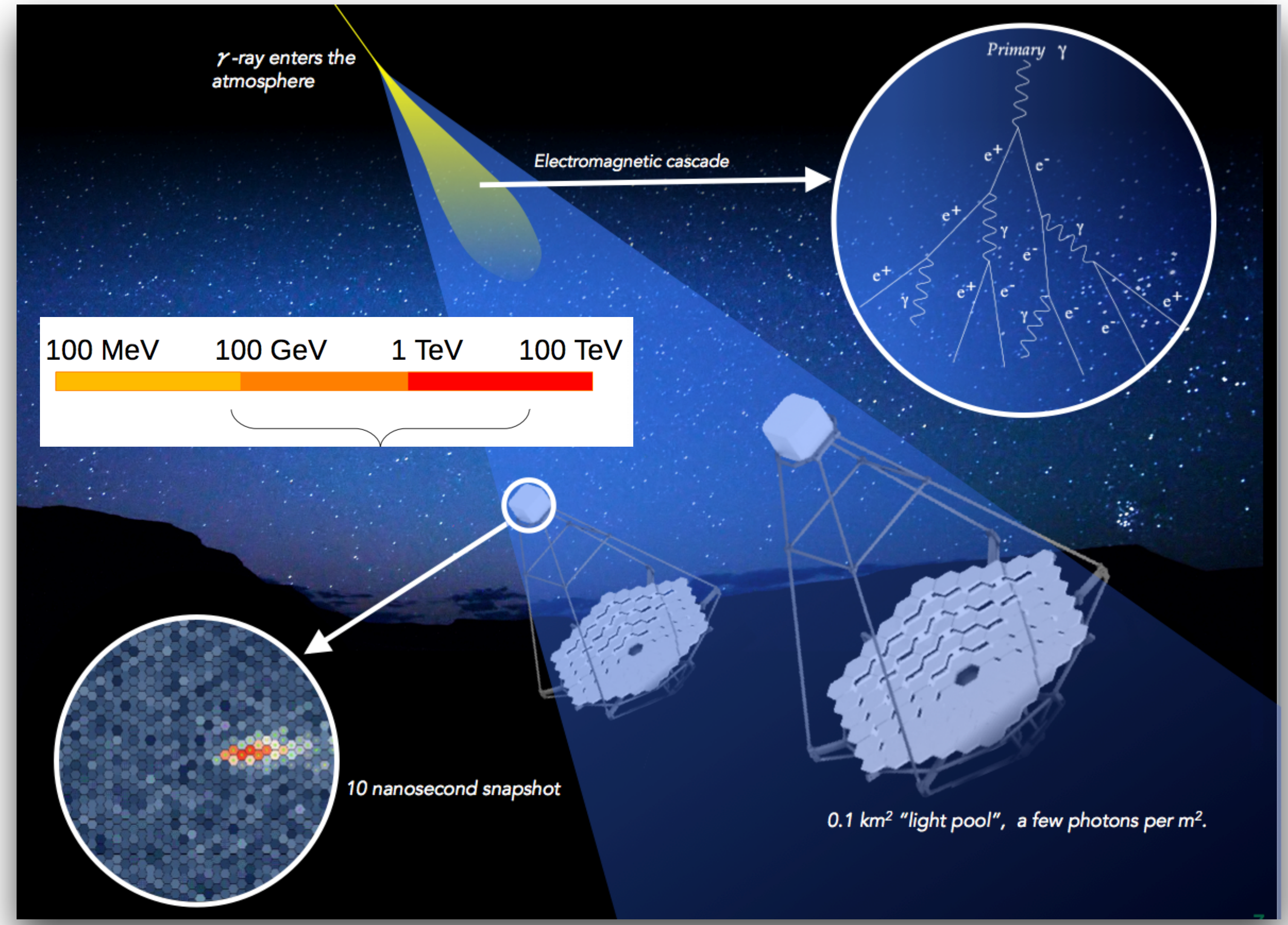




G. Bertone, D. Hooper and J. Silk, Phys.Rept, 2004

VERITAS

An Imaging Atmospheric Cherenkov Telescope

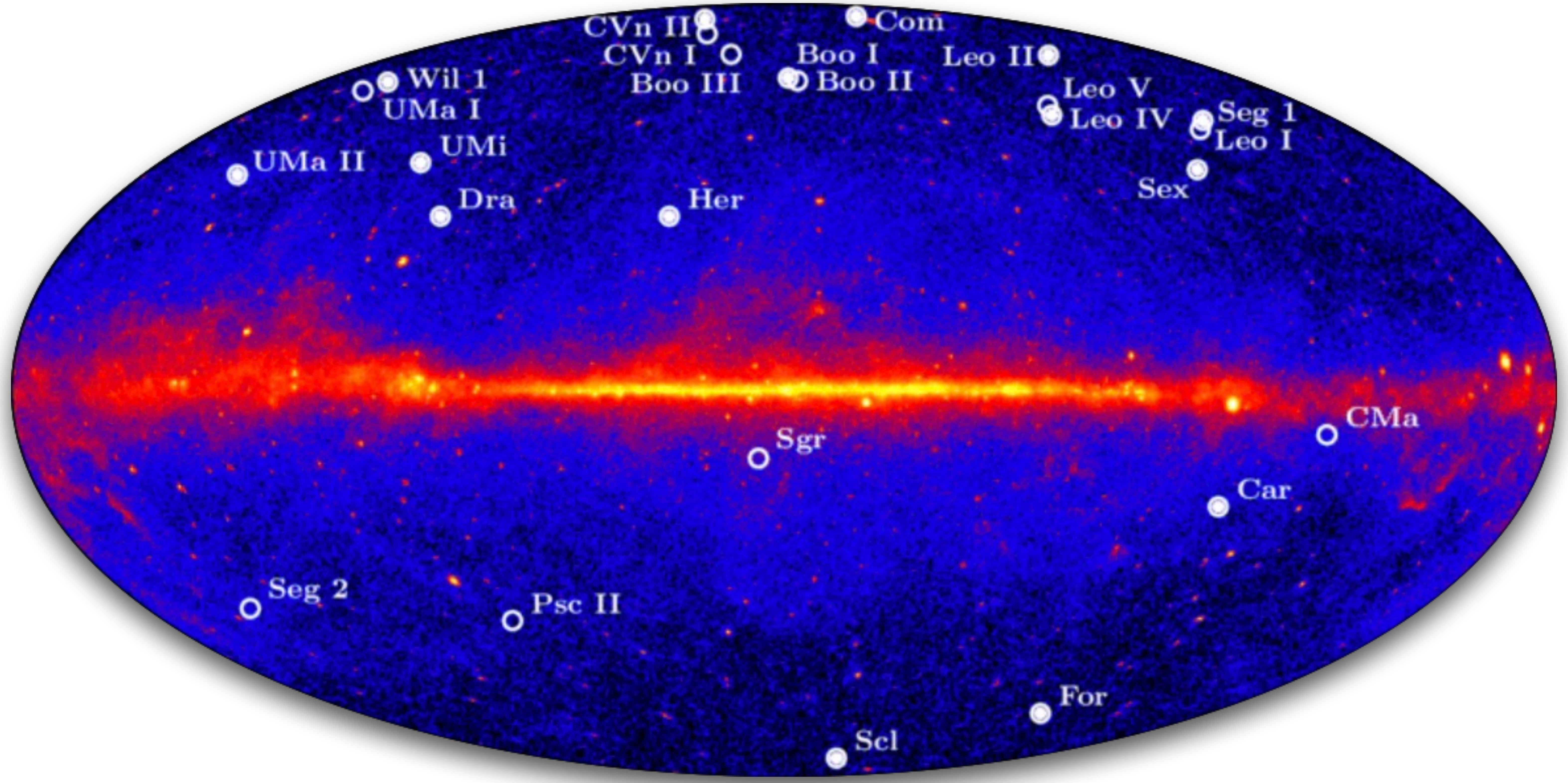


- Located at the F. L. Whipple Observatory in Southern Arizona, USA
- Four 12-meter telescopes spaced ~ 100 meters apart
- Detects γ-rays in energy range of 100 GeV - 30 TeV
- Energy resolution of 15 - 25%
- Angular resolution < 0.1° at 1 TeV
- Detects source ~1% flux of the Crab Nebula in 25 hrs of observation

Park, in Proceedings of the 34th International Cosmic Ray Conference (ICRC 2015)

Dwarf Spheroidal Galaxies

Why to look for DM towards dSphs?



DM-dominated objects

High mass-to-light ratios

Nearby systems

25-250 kpc

Clean γ-ray environment

No known γ-ray sources, high Galactic latitudes

DM distribution in dSphs

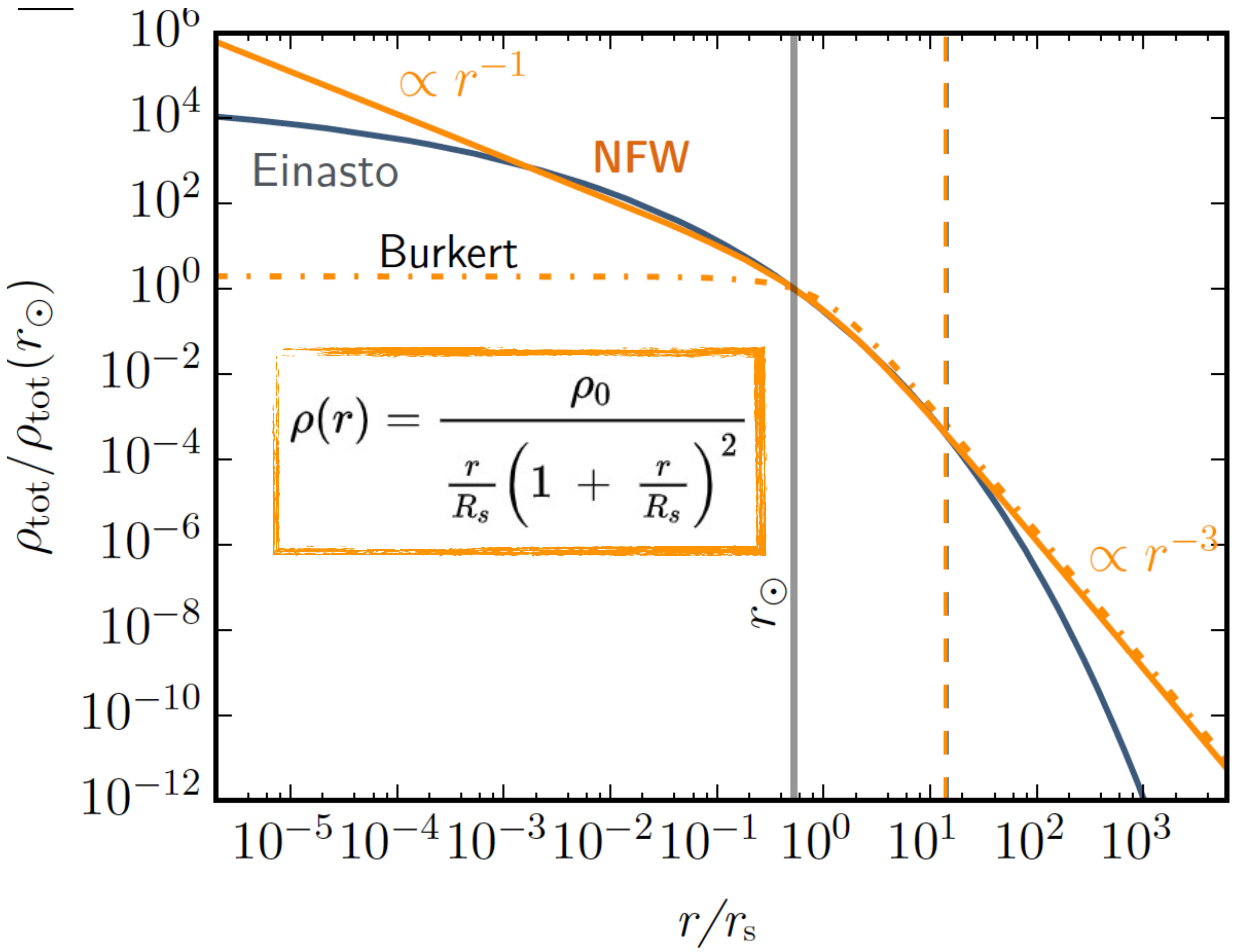
What if we consider dSphs as extended sources?

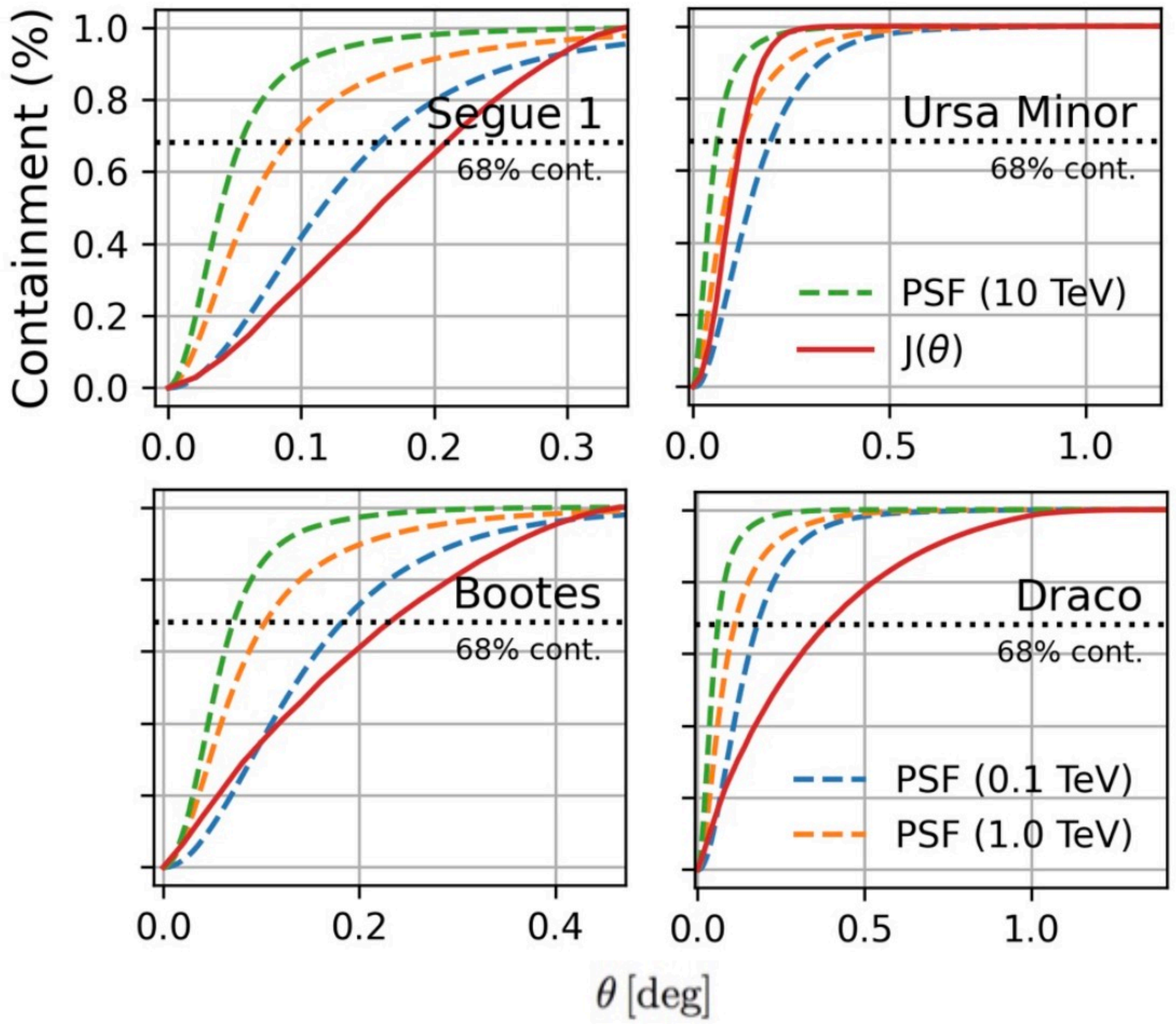
γ-ray flux from DM annihilation

$$\phi_s(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\Phi_{\rm PP}} \cdot \underbrace{\int_{\Delta\Omega}\left\{\int_{\rm l.o.s.}\rho^2(\boldsymbol{r}){\rm d}l\right\}{\rm d}\Omega'}_{\text{J-factor}}$$

Particle physics factor — Astrophysics factor

Kinematic observations





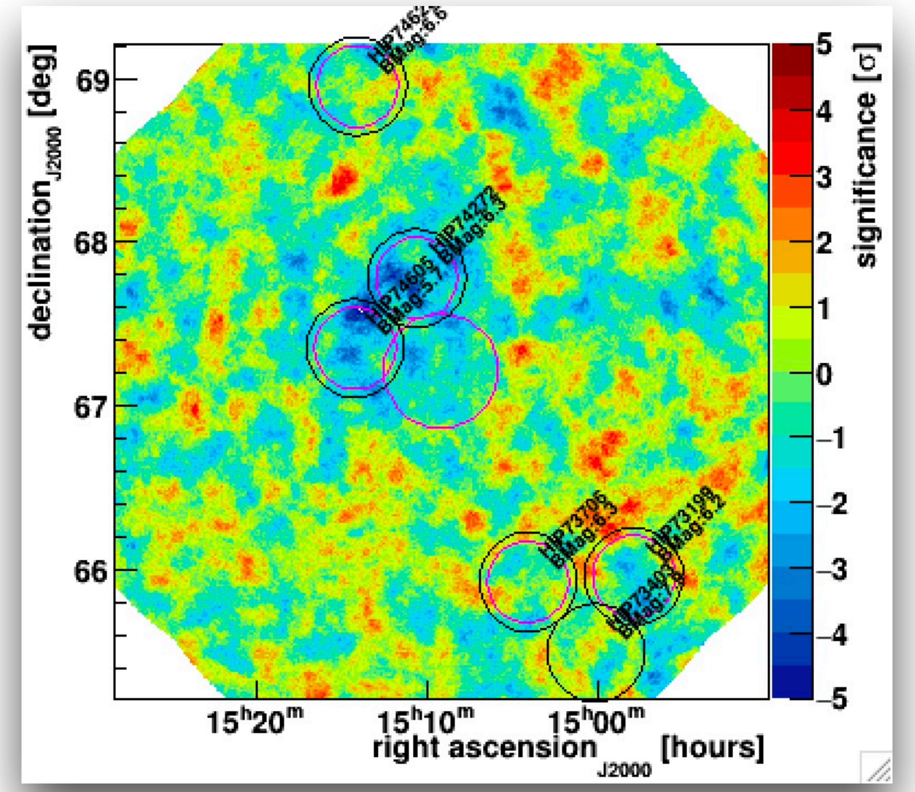
IACTs PSF (68% containment fraction) < 0.1° at 1 TeV

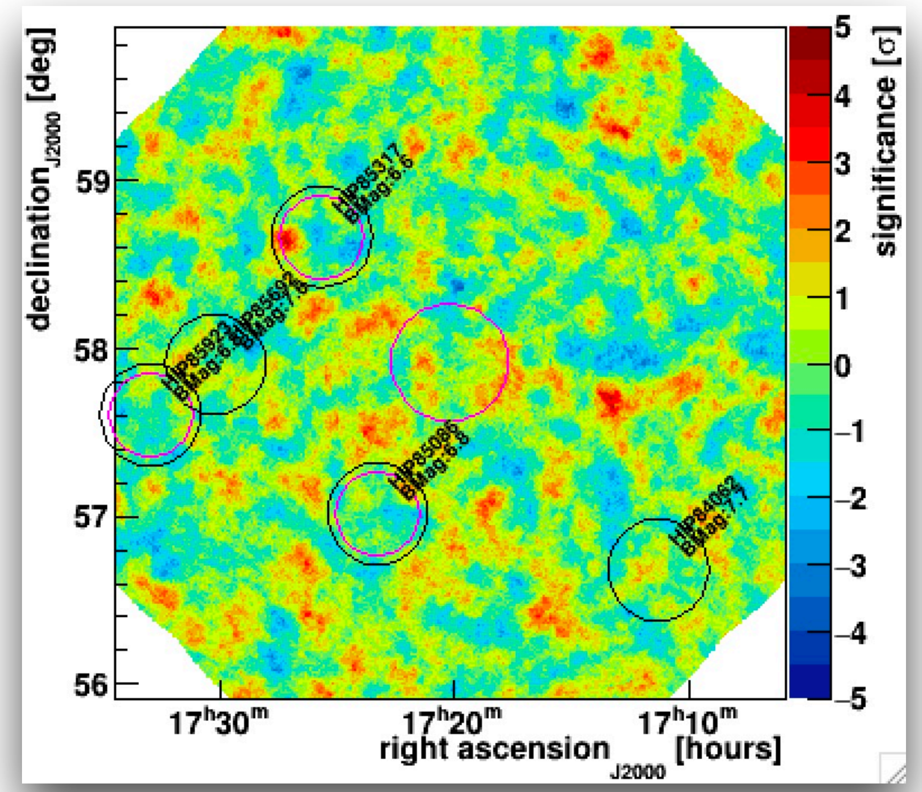
Dwarfs predicted to be extended sources for IACTs

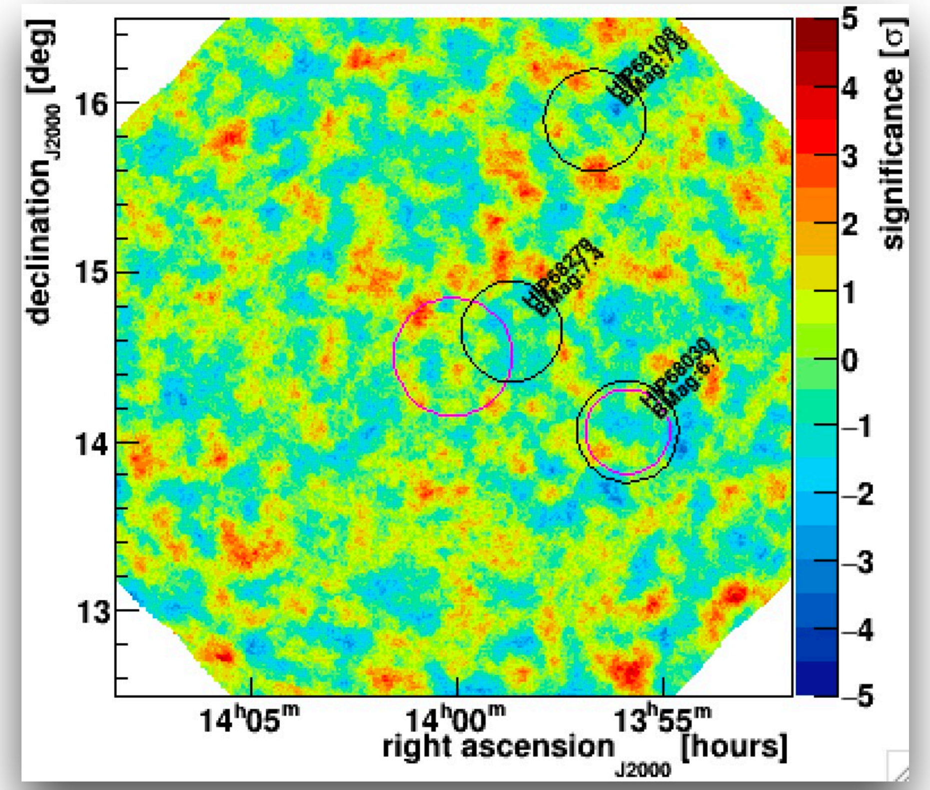
Data analysis and observations

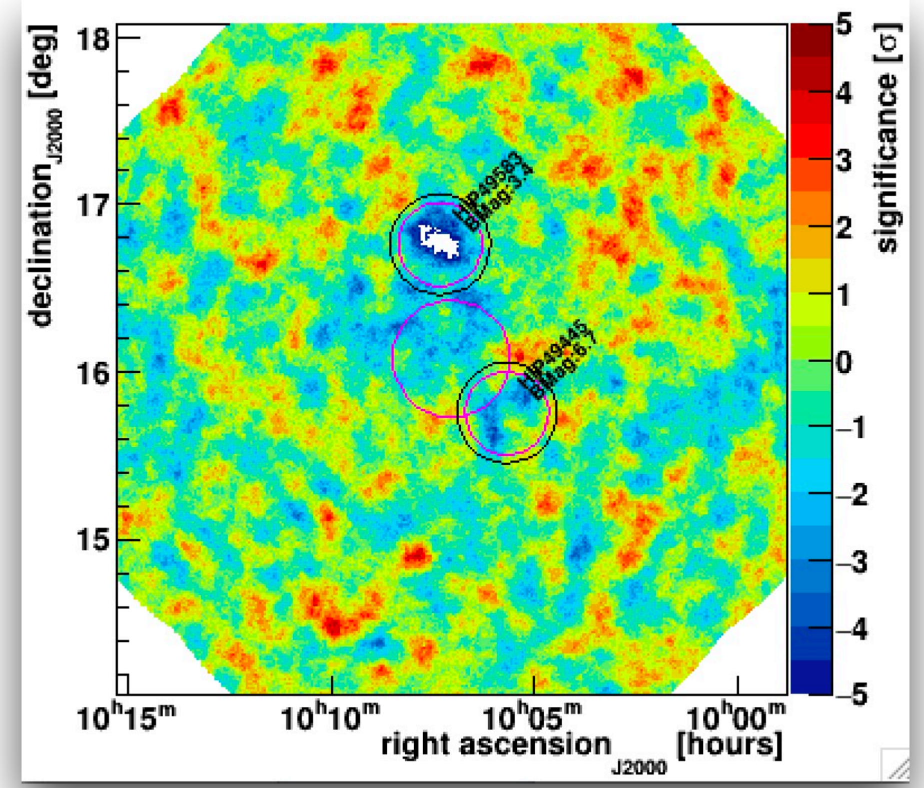
VERITAS reconstruction analysis of dSphs data

- Four dSphs analysed: Bootes, Draco, Segue1 and Ursa Minor
- Data from 2007-2013 (published data: https://arxiv.org/pdf/1703.04937.pdf)
- Total observation time of 475.65 hrs
- Point-source analysis (θ^2 cut = $0.008\ deg^2$)
- Gamma-hadron selection based on Boosted Decision Trees
- Selection optimized to reach lowest analysis energy threshold







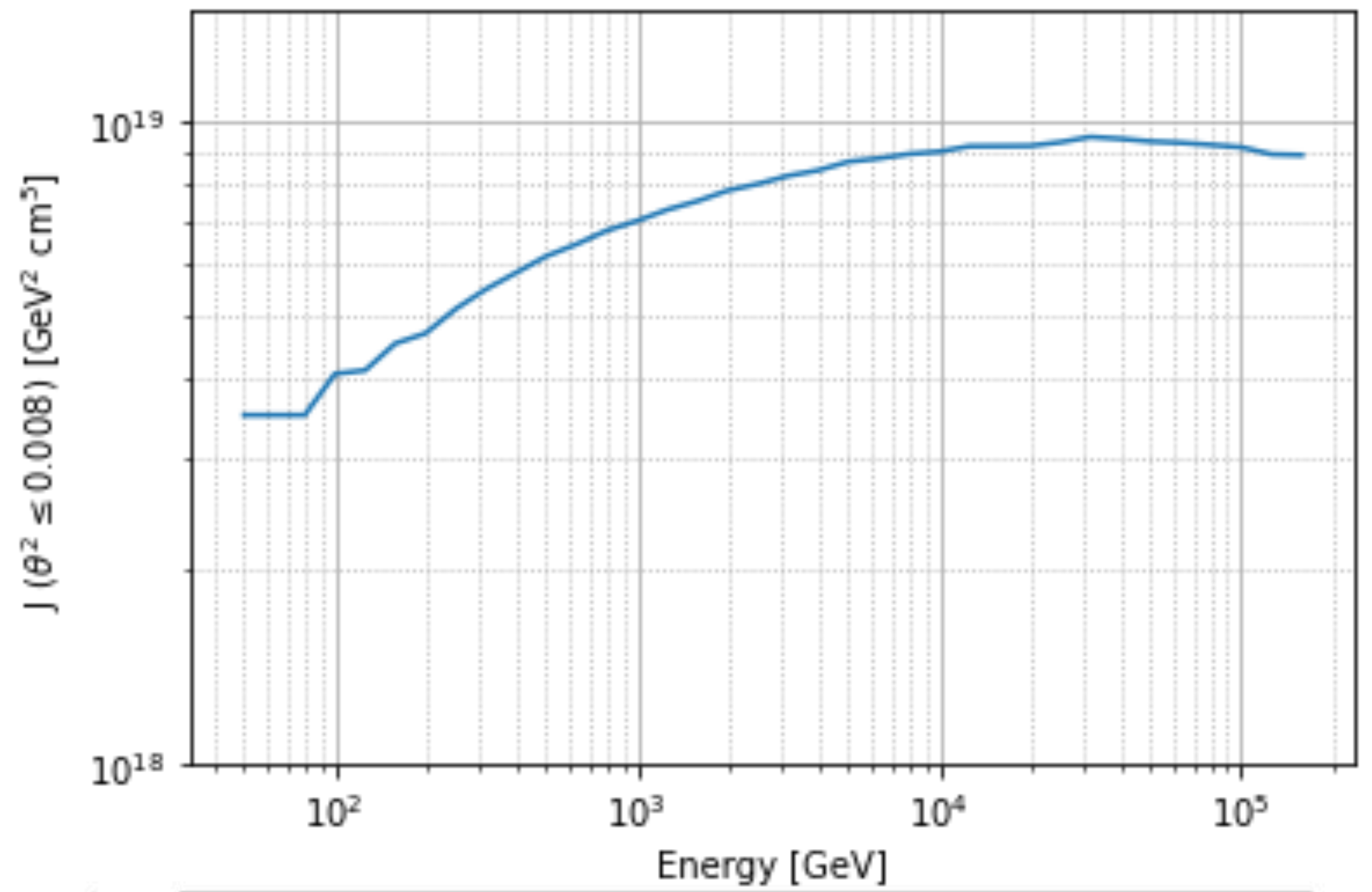


Source	Distance [kpc]	r_{max} [pc]	θ_{max} [deg]	$\log_{10} J(\theta_{max})$ $\log_{10}[\mathrm{GeV^2 cm^{-5}}]$	Obs.Time [min]	N_{on} [counts]	N_{off} [counts]	σ
Boötes I	66 ± 2	544^{+252}_{-135}	0.47	$18.24^{+0.40}_{-0.37}$	950	398	2351	0.3
Draco	76 ± 6	1866^{+715}_{-317}	1.30	$19.05^{+0.22}_{-0.21}$	6813	1326	8119	−0.7
Segue I	23 ± 2	139^{+56}_{-28}	0.35	$19.36^{+0.32}_{-0.35}$	11042	3227	19947	−1.5
Ursa Minor	73 ± 3	1580^{+626}_{-312}	1.37	$18.95^{+0.26}_{-0.18}$	9724	1328	8204	−1.5

Maximum likelihood estimation (MLE)

Conventional method: 1D analysis

Likelihood function only-energy dependent → Comparing measured and expected spectral distributions



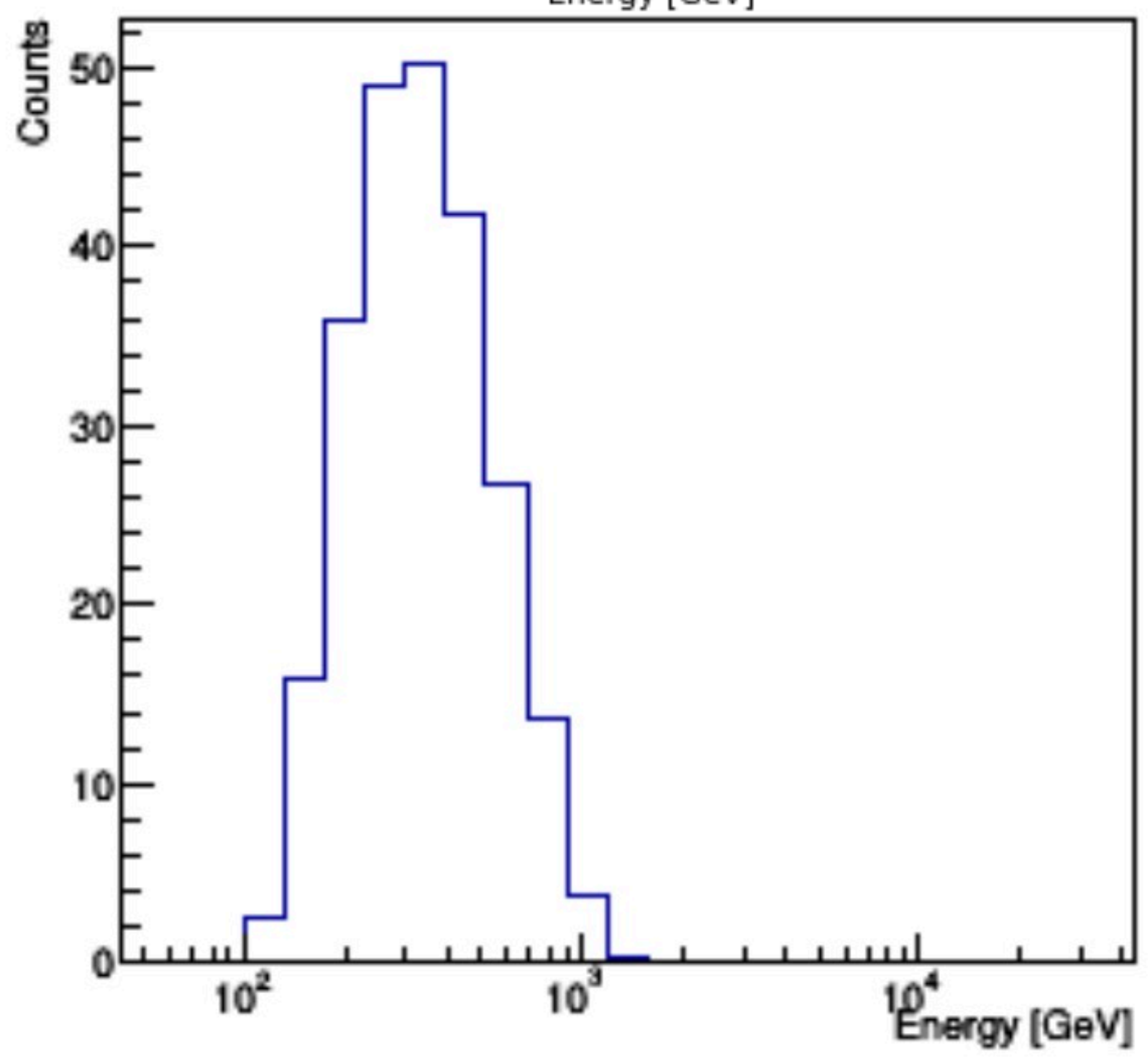
$$L = \frac{(g+\alpha b)^{N_{on}} e^{-(g+\alpha b)}}{N_{on}!} \frac{b^{N_{off}} e^{-b}}{N_{off}!} \prod_{i=1}^{N_{on}} P_{on}(E_i | M, \langle \sigma_v \rangle) \prod_{j=1}^{N_{off}} P_{off}(E_j)$$

Ahnen et al., 2016

N_{on} (N_{off}) observed counts in ON (OFF) region, α background normalisations factor,
$P_{on(off),i}$ the likelihood of i-th event in the ON (OFF) region,
g the total expected number of DM counts,
b the expected background

$$g = \frac{\langle \sigma v \rangle T_{obs}}{8\pi M^2} \int_E \int_{E'} \frac{dN}{dE'} J(E') A(E') D(E|E') dE dE'.$$

→



$\sigma \nu$ the annihilation cross-section, M DM mass, T_{obs} total exposure time, A the effective area,
D the energy dispersionmatrix, dN/dE the DM spectrum (from Cirelli et al 2014),
J(E') the J factor (from Geringer Sameth 2015)

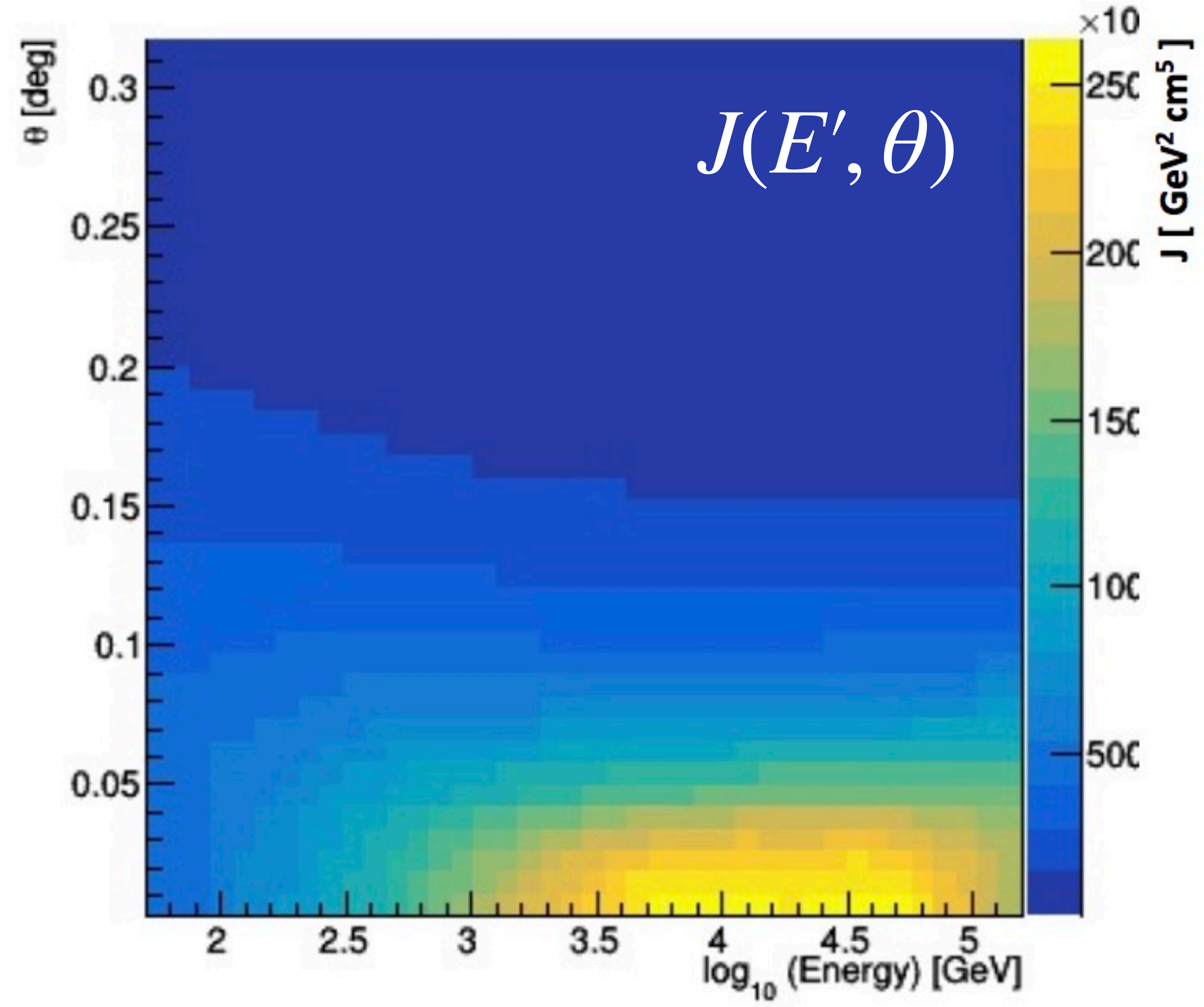
Maximum likelihood estimation (MLE)

New method: 2D analysis

Likelihood function including dSph angular extension as well → Comparing measured and expected spatial AND spectral distributions

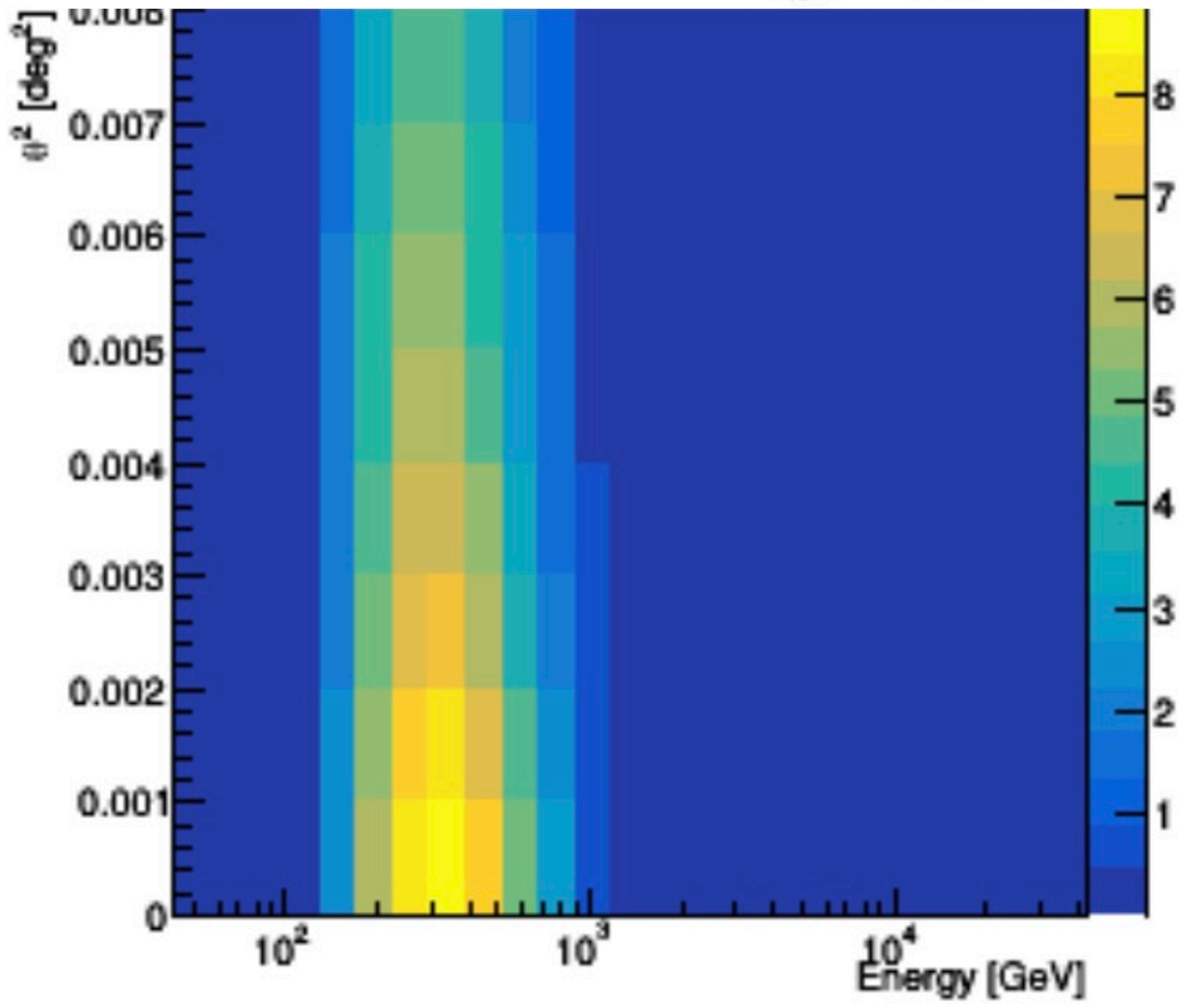
$$L = \frac{(g+\alpha b)^{N_{on}} e^{-(g+\alpha b)}}{N_{on}!} \frac{b^{N_{off}} e^{-b}}{N_{off}!} \prod_{i=1}^{N_{on}} P_{on}(E_i, \theta_i | M, \langle \sigma_v \rangle) \prod_{j=1}^{N_{off}} P_{off}(E_j, \theta_j)$$

$$\frac{d^2 g}{dE\, d\Omega} = \frac{\langle \sigma v \rangle T_{obs}}{8\pi M^2} \int_{E'} \frac{dN}{dE'} \frac{J(E', \Omega)}{d\Omega} A(E') D(E|E') dE'$$



$$g = 2\pi \int_E \int_\theta \frac{d^2 g}{dE d\Omega} sin(\theta) dE d\theta$$

→



For several DM masses we maximised the logL with 2 free parameters (b, $\sigma\nu$) and calculated TS=$-2log(L_0/L_1)$

Results

Testing sensitivity of 2D MLE vs 1D MLE analysis

NO DM signal was detected..but let’s test the effectiveness of the 2D method!

Simulation study n. 1

Test effectiveness 2D analysis in detecting possible DM signal

Simulation study n. 2

How to improve sensitivity in the 2D analysis method

Results

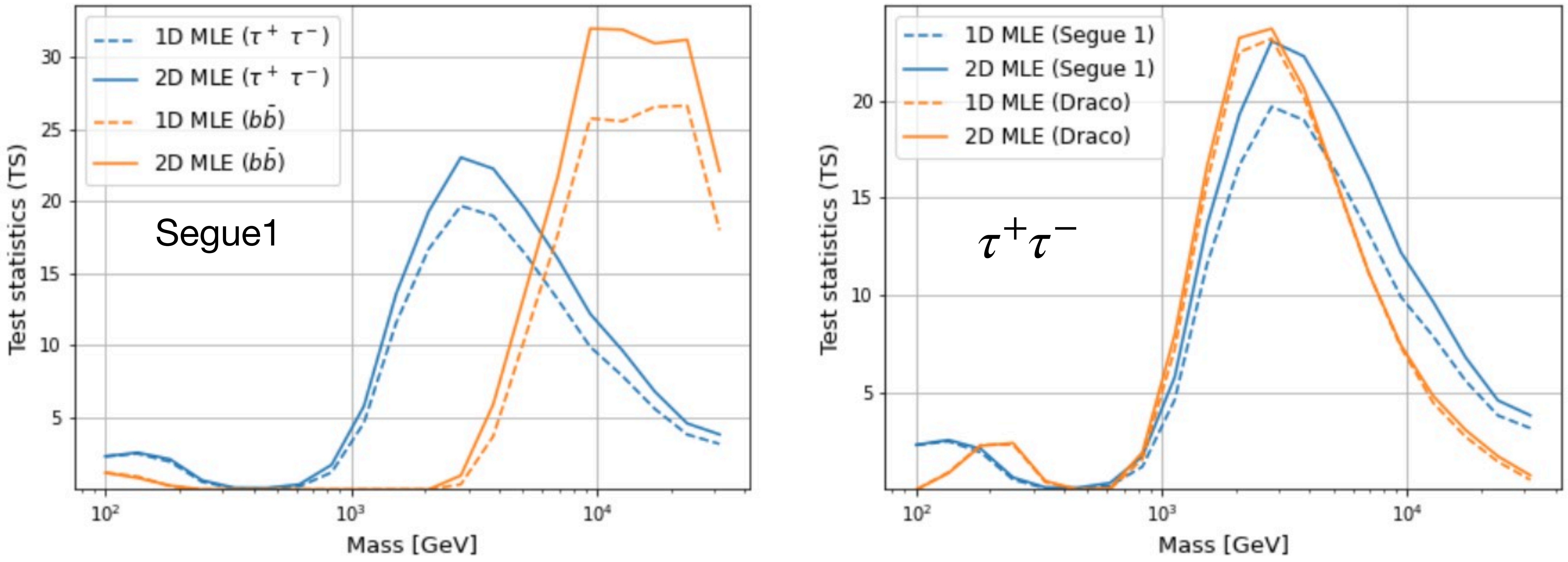
Simulation study n. 1

Assuming that:

- DM exists and its cross-section high enough to be detected*
- $D_{fake}(E,\theta) = \alpha D_{off}(E,\theta) + g(E,\theta)$

Procedure:

- N_{fake} events randomly synthesized
- Performed MLE analysis in 1D and 2D cases and calculated TS
- Repeated 1000 times and took average TS value per each mass



* **For Segue1:** $\tau^+\tau^-$: $10^{-23.8} cm^3 s^{-1}$, $b\bar{b}$: $10^{-22} cm^3 s^{-1}$, **For Draco:** $\tau^+\tau^-$: $10^{-21.6} cm^3 s^{-1}$

Including dSph angular extension could improve the sensitivity in detecting DM up to 20-30% (depending on mass/channel/dSph)

Results

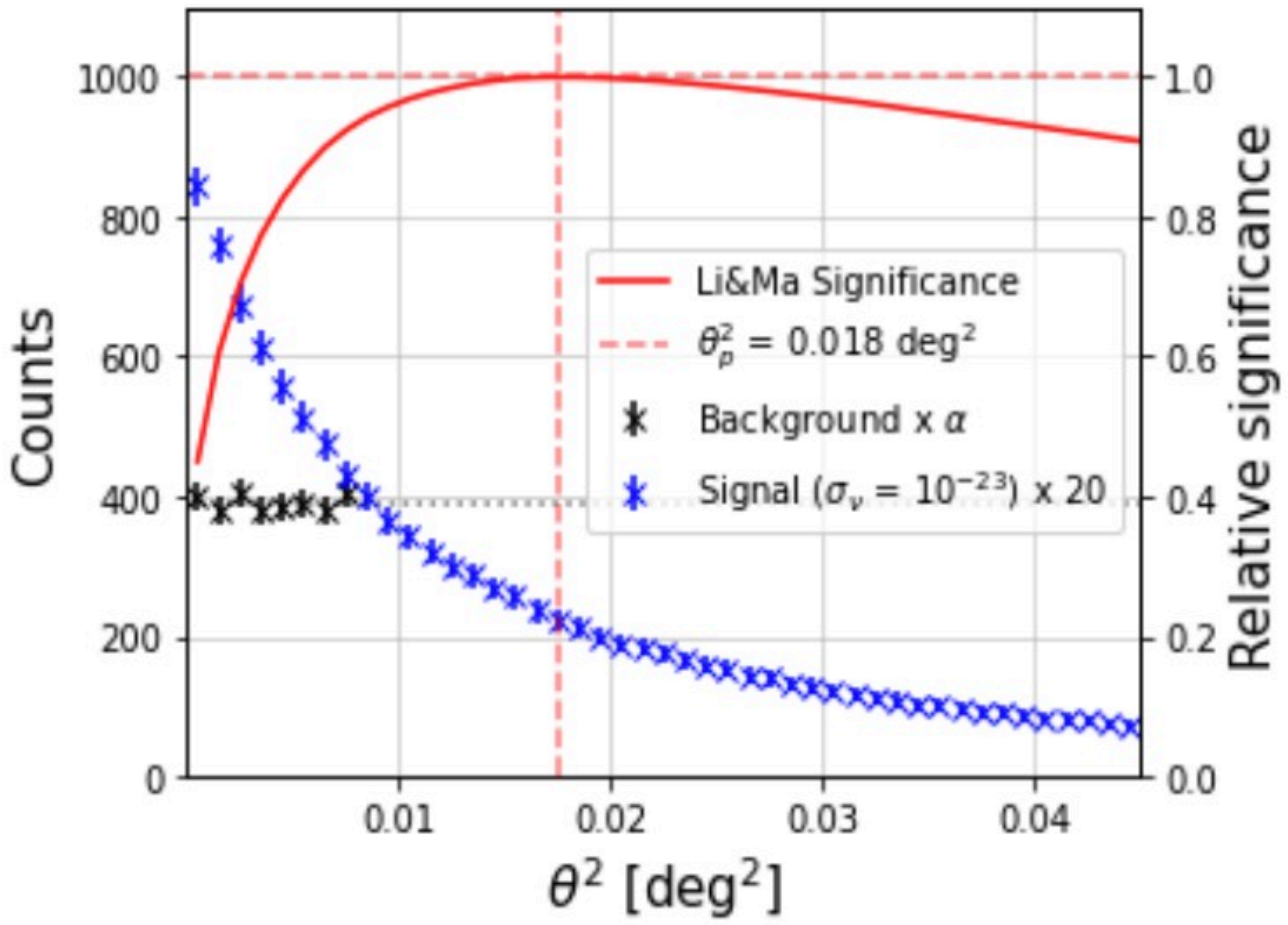
Simulation study n. 2

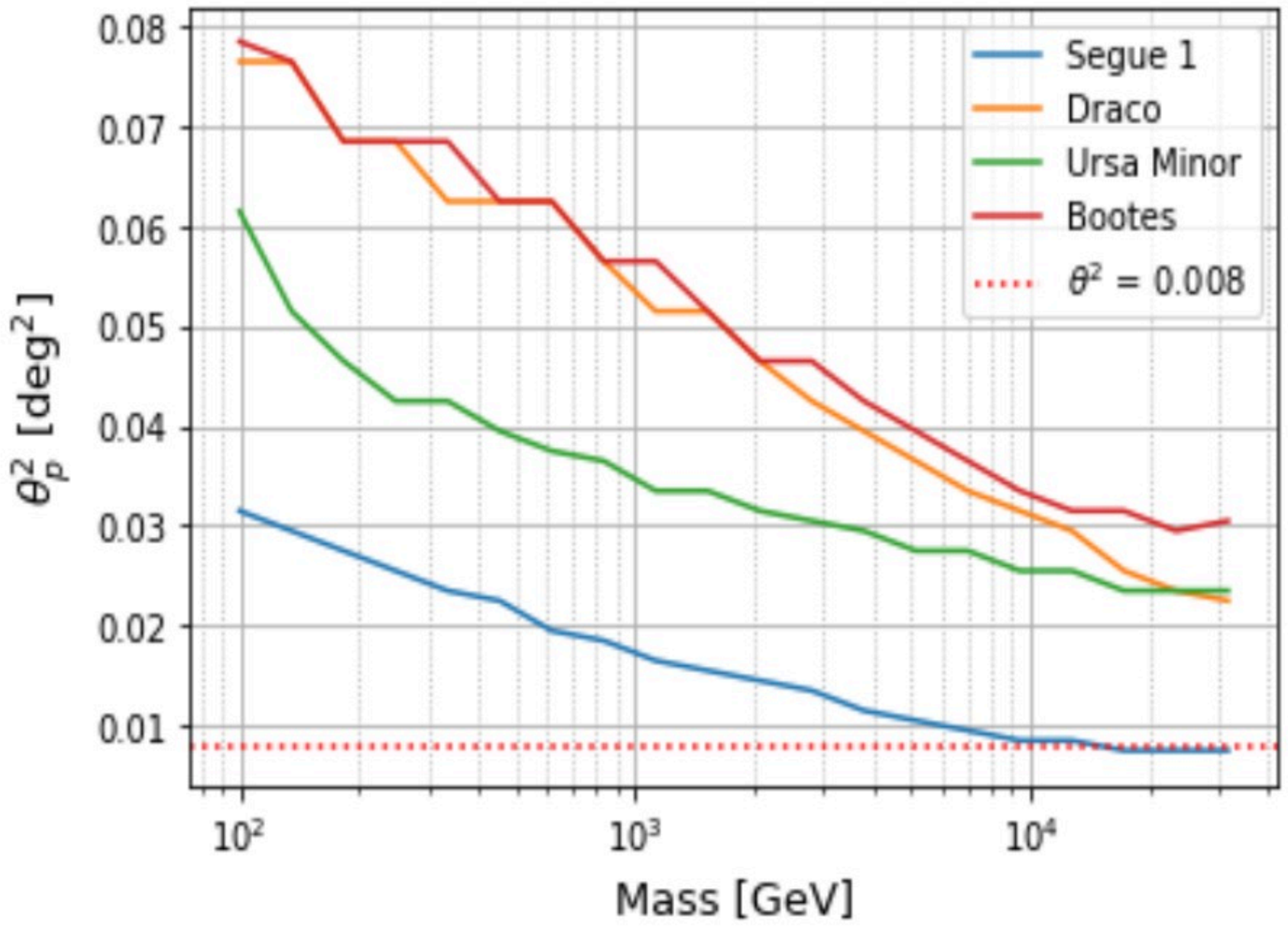
Assuming that:

- $N_{fake}(E,\theta) = \alpha N_{off}(E,\theta) + g(E,\theta)$
- N_{off} independent of θ^2 nears camera center

Procedure:

- For each mass, calculated Li&Ma significance as function of θ^2
- Found where it peaks
- Did the same for all dSphs





An extended (looser) θ^2 cut would improve the sensitivity of the 2D method

Summary and conclusions

- Analysed VERITAS data of fours dSphs from 2007-2013, for a total observation time of 475.65 hrs
- Point-source analysis optimised with θ^2 cut = $0.008\ deg^2$
- Unbinned maximum likelihood analysis including dSph angular extension (2D method)
- No DM signal detected, but we tested effectiveness of the 2D method against 1D (spectral analysis)
- 2D analysis would be more sensitive to a possible DM signal (20-30% improvement, depending on channel/dSph/mass)
- Using looser θ^2 cut will further boost sensitivity

Thanks for your attention!