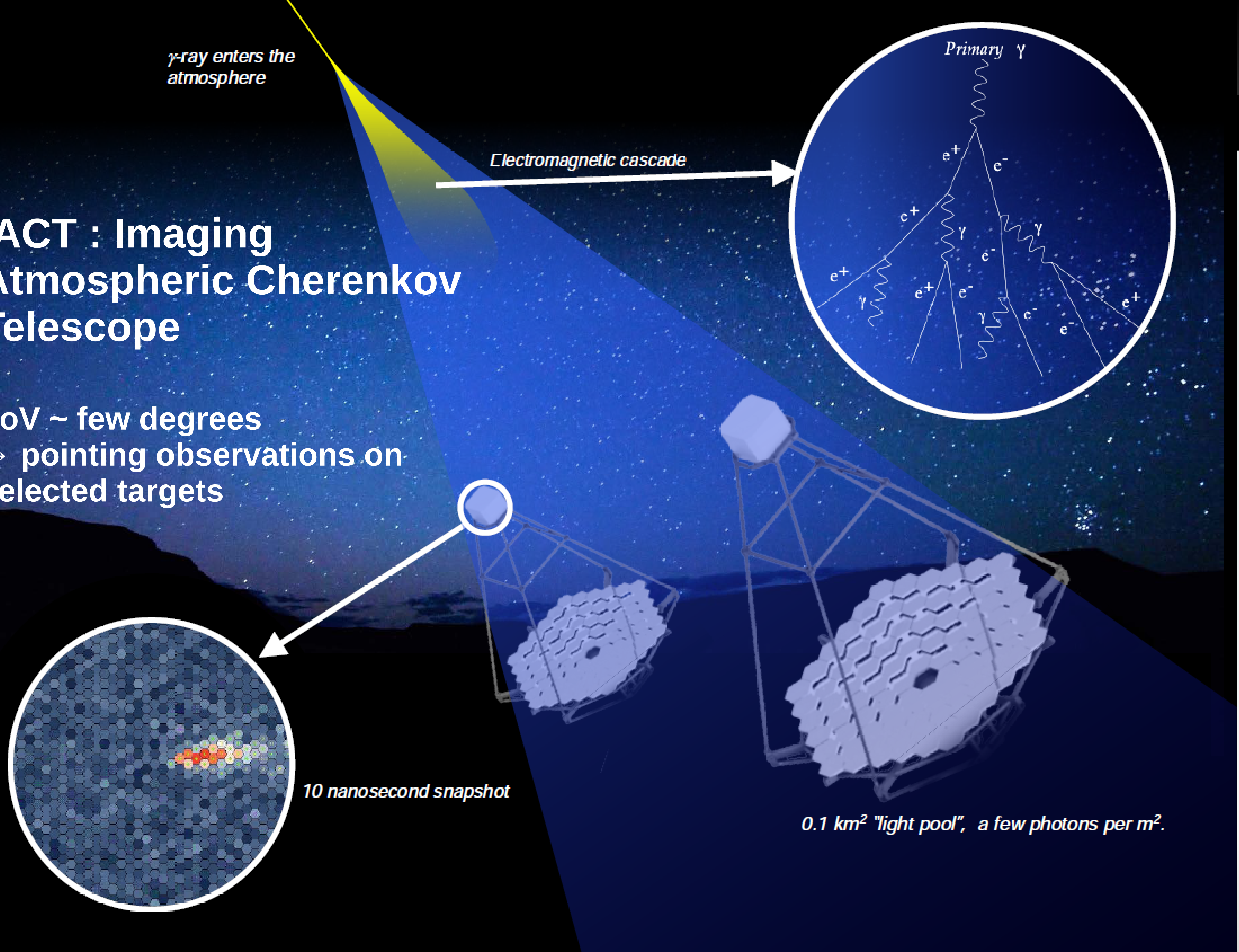
Indirect TeV searches for Dark Matter with Cherenkov telescopes

Christian Farnier
Oskar Klein Centre – Stockholm University
Linnœus University

Gamma Rays & Dark Matter
Obergurgl, Austria
December 2015, 7-11

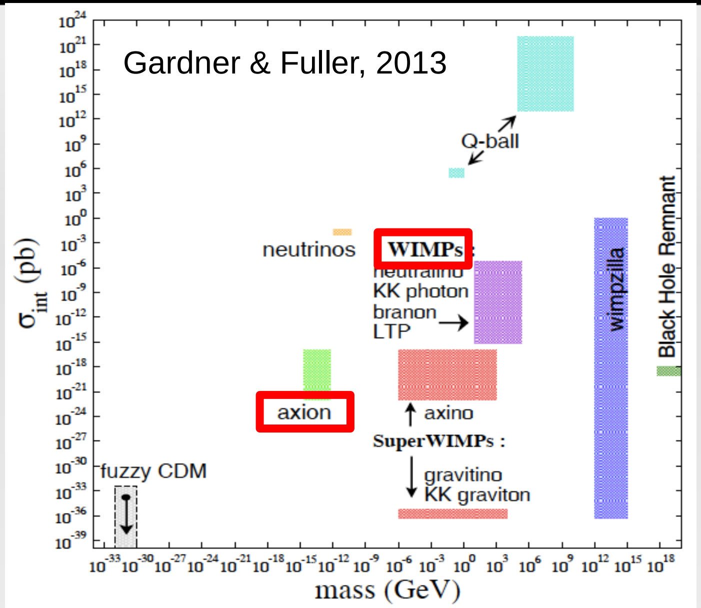
IACT : Imaging Atmospheric Cherenkov Telescope

FoV ~ few degrees
→ pointing observations on selected targets

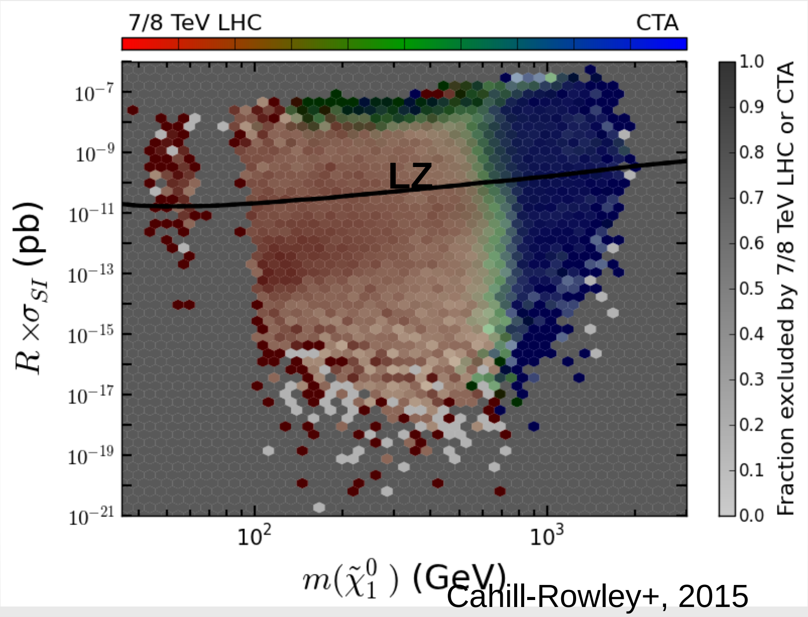


What is Dark Matter?

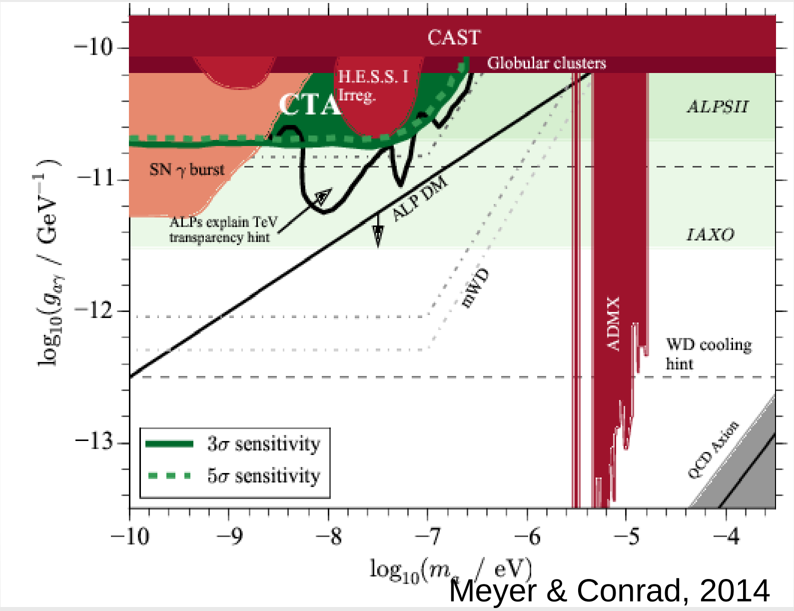
- We don't know... (...yet)
- We have a huge parameter space of potential candidates
- Cherenkov telescopes can explore parts that are out of reach of other experiments



Gardner & Fuller, 2013



Cahill-Rowley+, 2015



Meyer & Conrad, 2014

Hand picked selection of WIMP searches

γ-ray flux from WIMP annihilations

$$\Phi^{\gamma}_{WIMP}(E,\Psi) = J(\Psi) \times \Phi^{PP}(E)$$

$$J_{ann}(\Psi) = \int_{los} dl(\Psi)\rho^2(l)$$

$$\Phi^{PP}_{ann}(E) = \frac{1}{2}\frac{\langle \sigma v \rangle}{m^2_{DM}} \sum_f B_f \frac{dN^{\gamma}_f}{dE}$$

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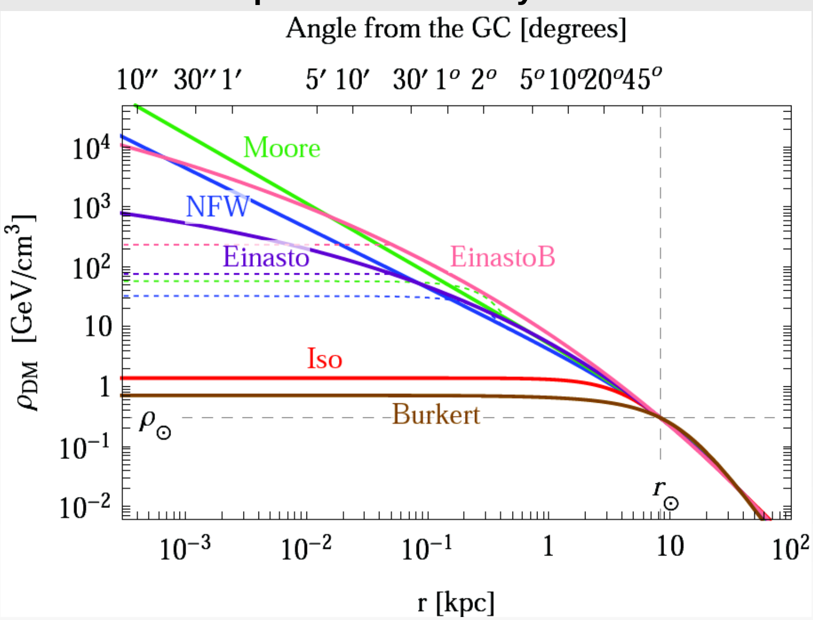
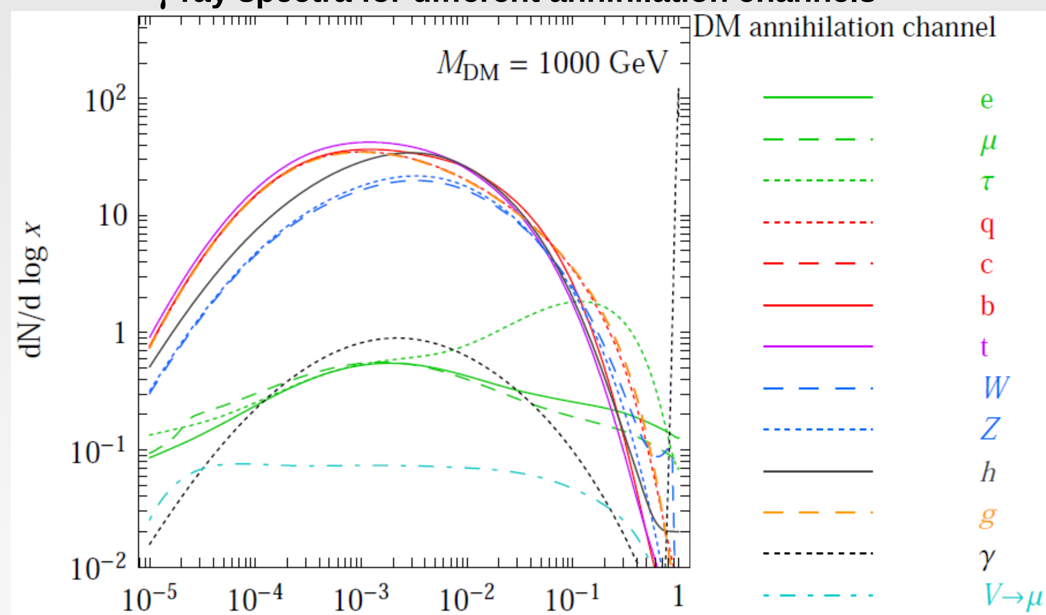
Examples of GC density models



γ-ray spectra for different annihilation channels



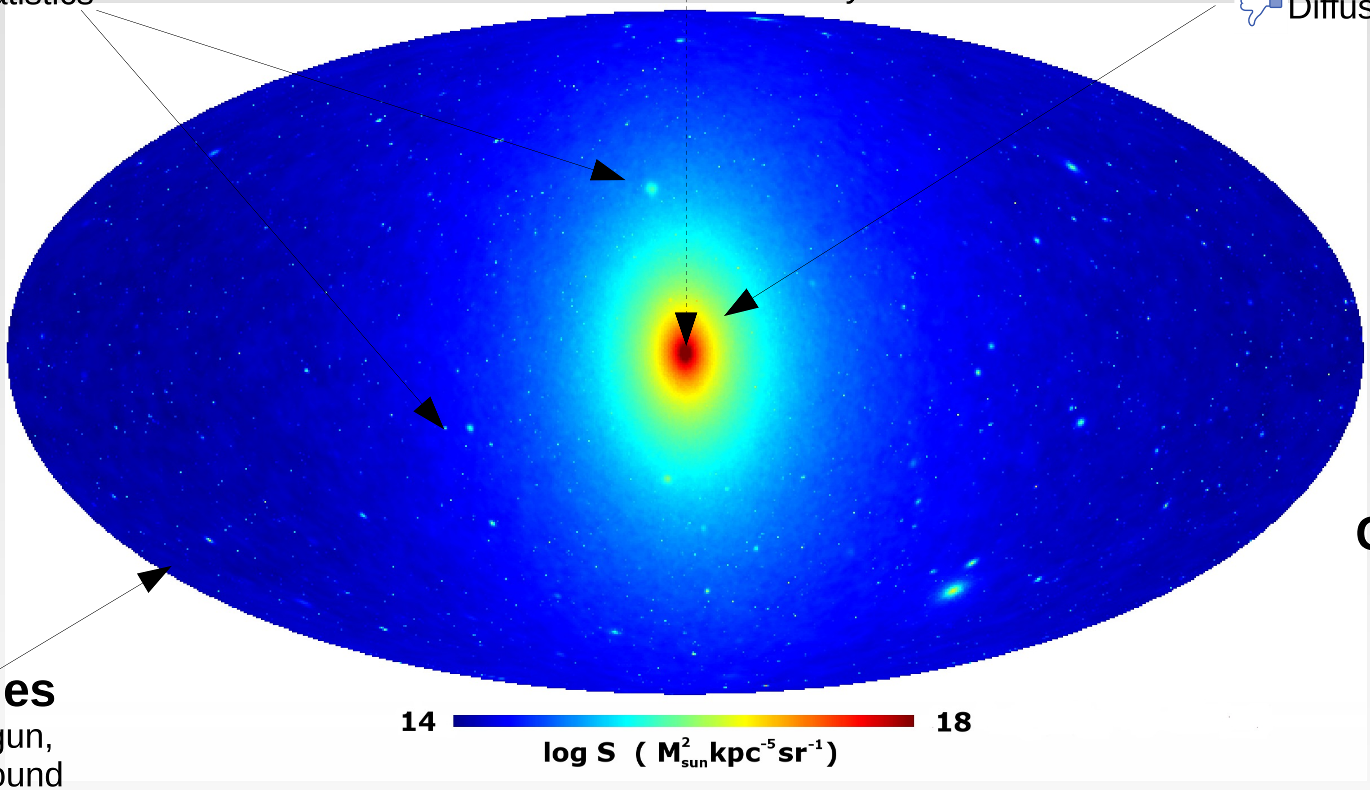
Cirelli+, 2012

Targets for WIMP searches

Dwarf galaxies
- 👍 Low background, small uncertainties
- 👎 Low statistics

Galactic centre
- 👍 Large statistic
- 👎 Source confusion, DM density uncertainties

Galactic halo
- 👍 Large statistic
- 👎 Diffuse emission



Galaxy clusters
- 👍 Largest DM reservoir (decay)
- 👎 Low statistics, astrophysical bkg

Spectral lines
- 👍 Smoking gun, no background
- 👎 Low statistics

Extragalactic
- 👍 Large statistics
- 👎 Astrophysical bkg

Targets for WIMP searches & background

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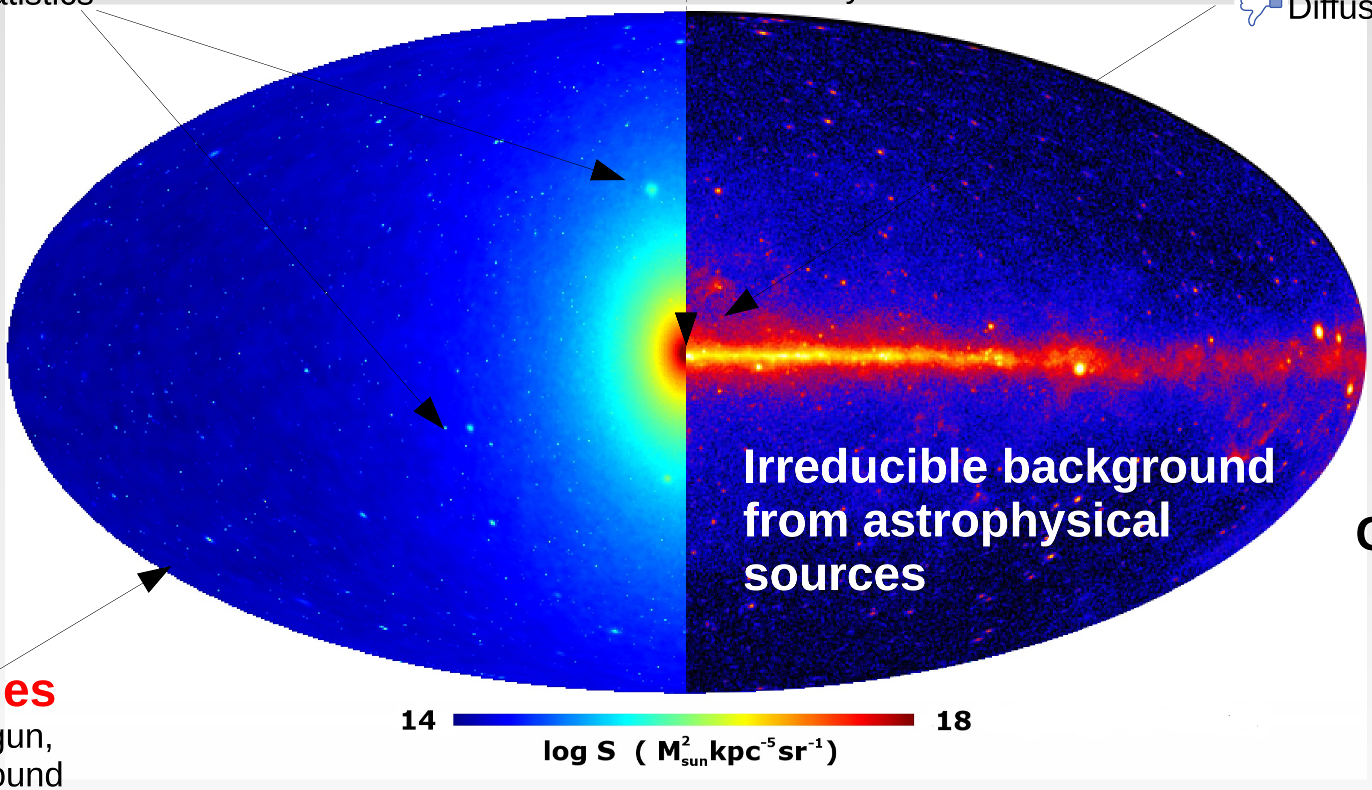

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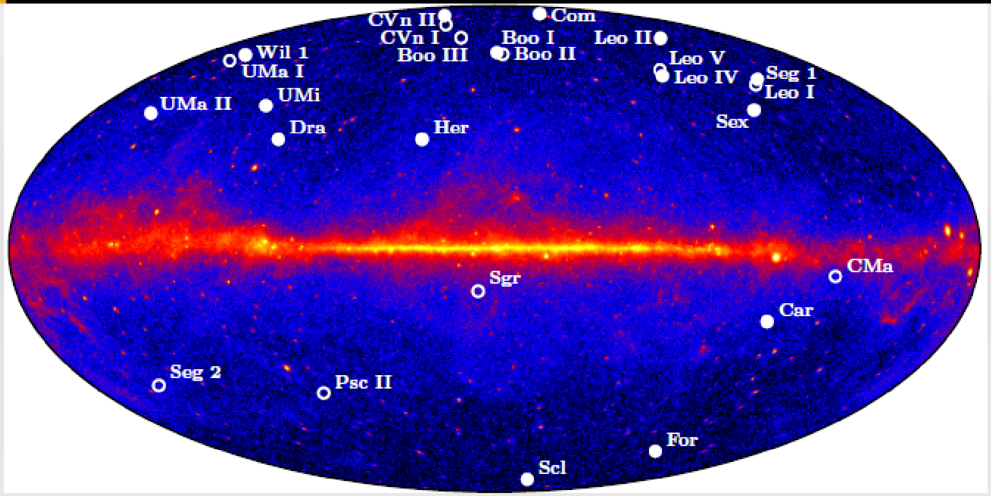
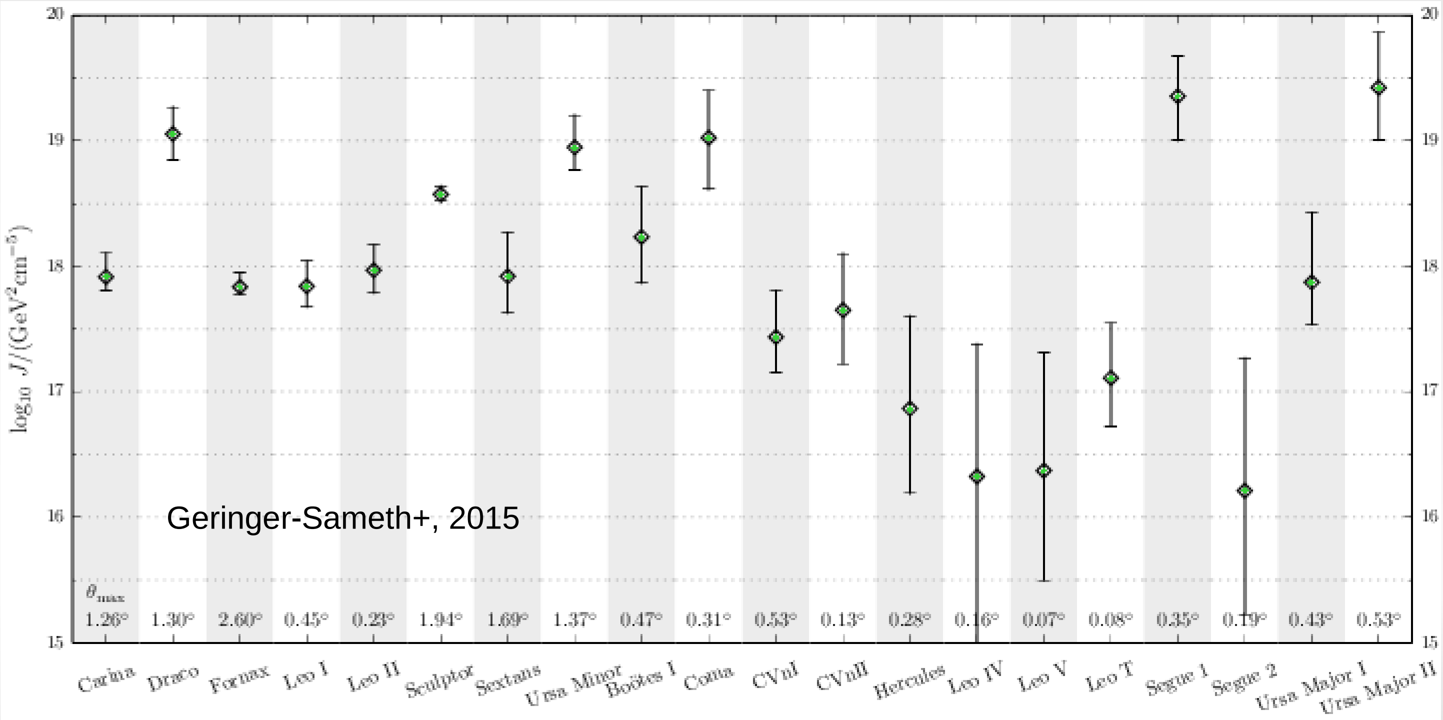
Dwarf spheroidal galaxies



- Nearby (~100 kpc) Milky-Way satellites
- DM dominated (M/L ~ 10 – 1000)
- Low background
- Stellar velocities → estimate of DM density (and uncertainties can be propagated to constraints)



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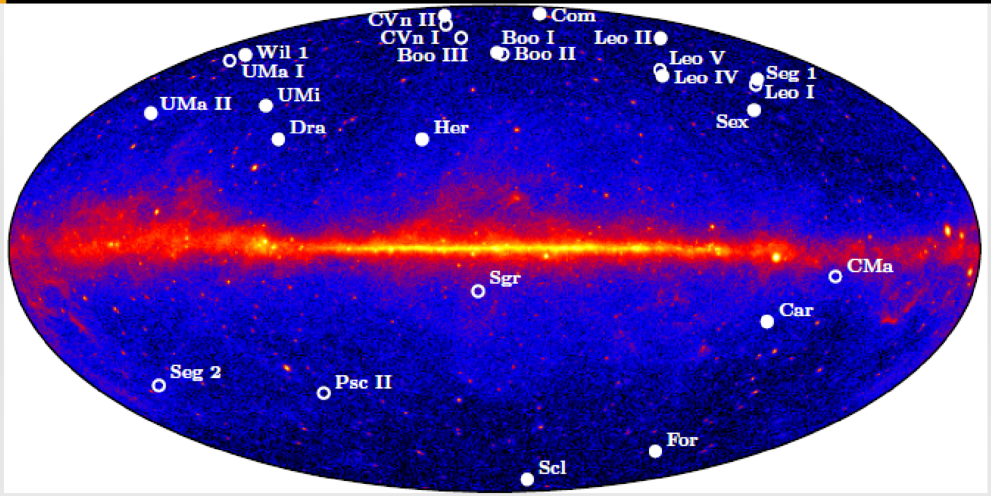

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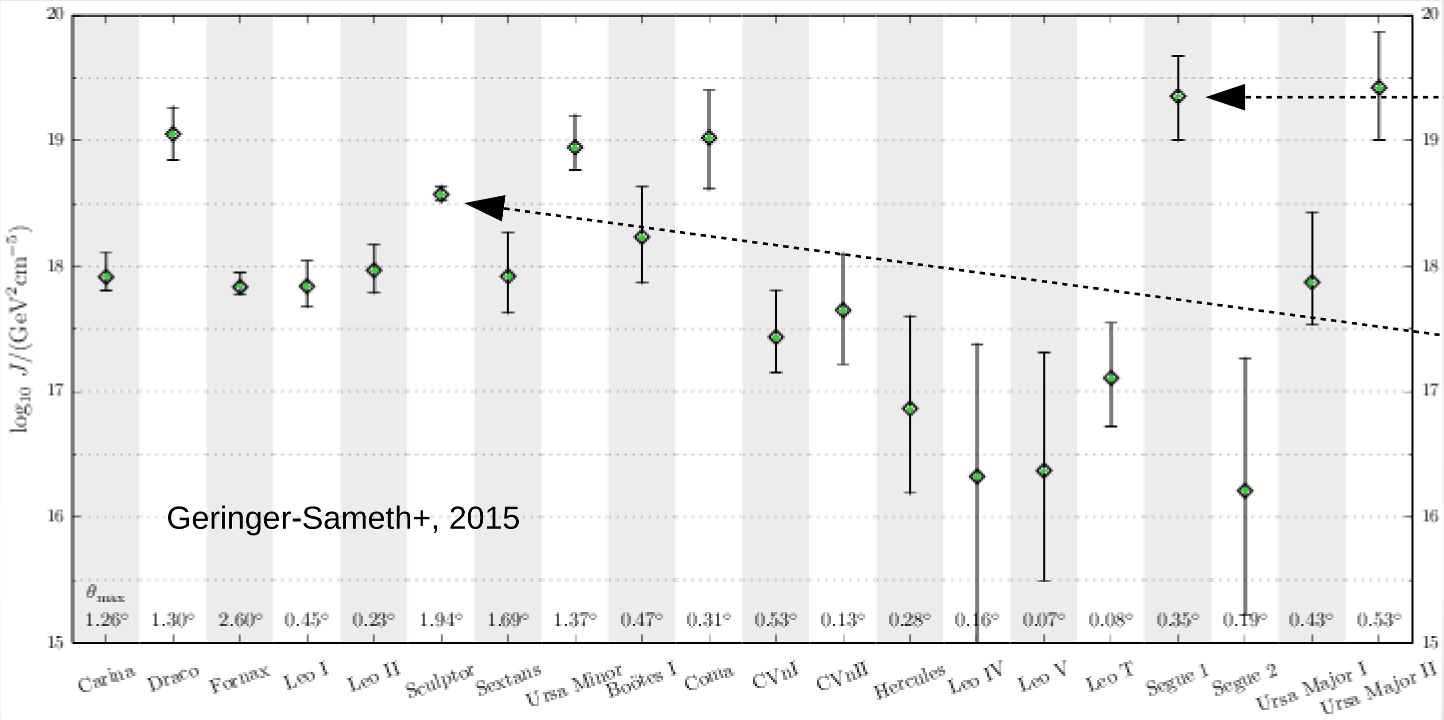
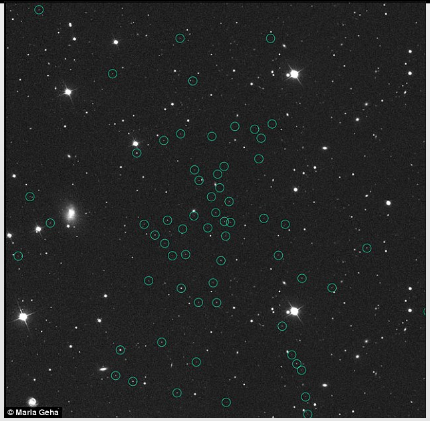
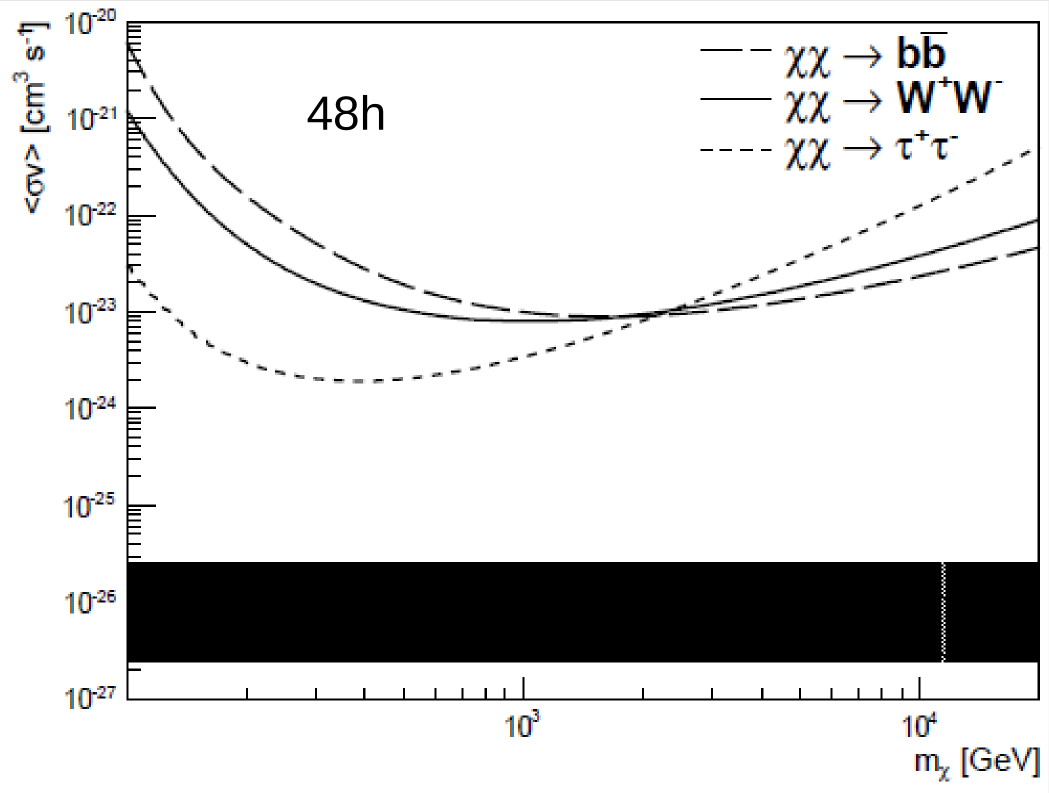


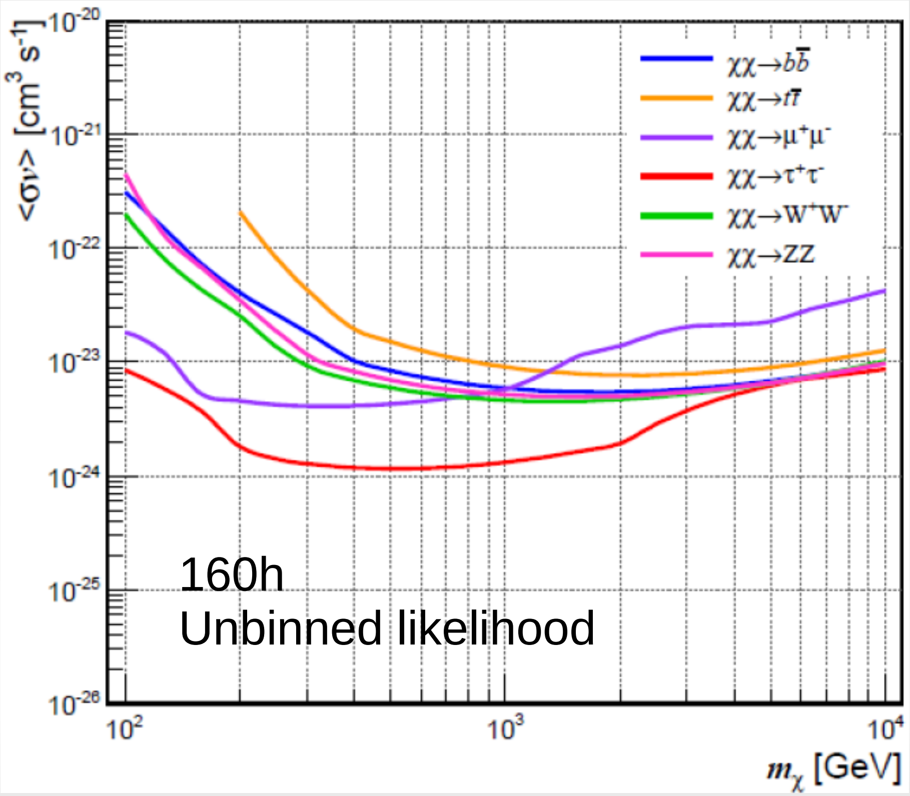
Segue 1 by VERITAS & MAGIC

- Ultra-faint dSph discovered in SDSS data
- Most promising dSph for DM discovery visible from nothern experiments
- Observed by VERITAS (48h) & MAGIC (160h)





VERITAS, 2012



MAGIC,, 2014

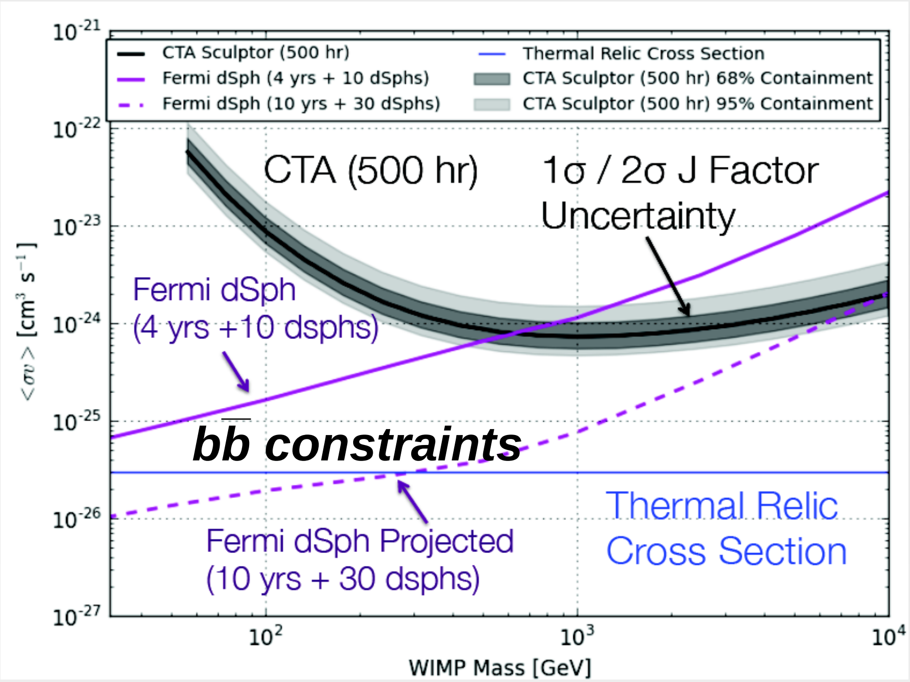
CTA view of dSph

Limits for Sculptor with 500h of obs.
Most constrained J → very robust

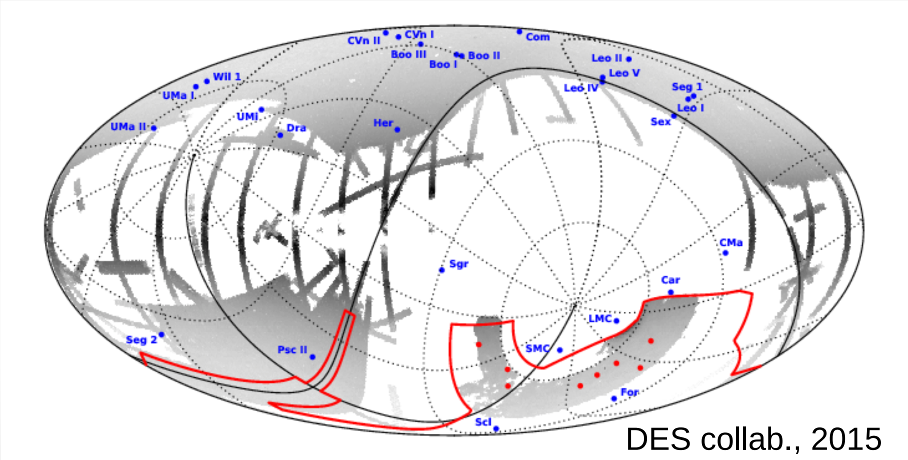
Larger Aeff → better sensitivity
Approching the natural scale, but not quite there yet

Exploration of WIMP parameter space requires better candidates
→ ongoing surveys: new Milky-Way satellites

- DES: 17
- PanSTARRS: 5



Wood, UCLA 2014



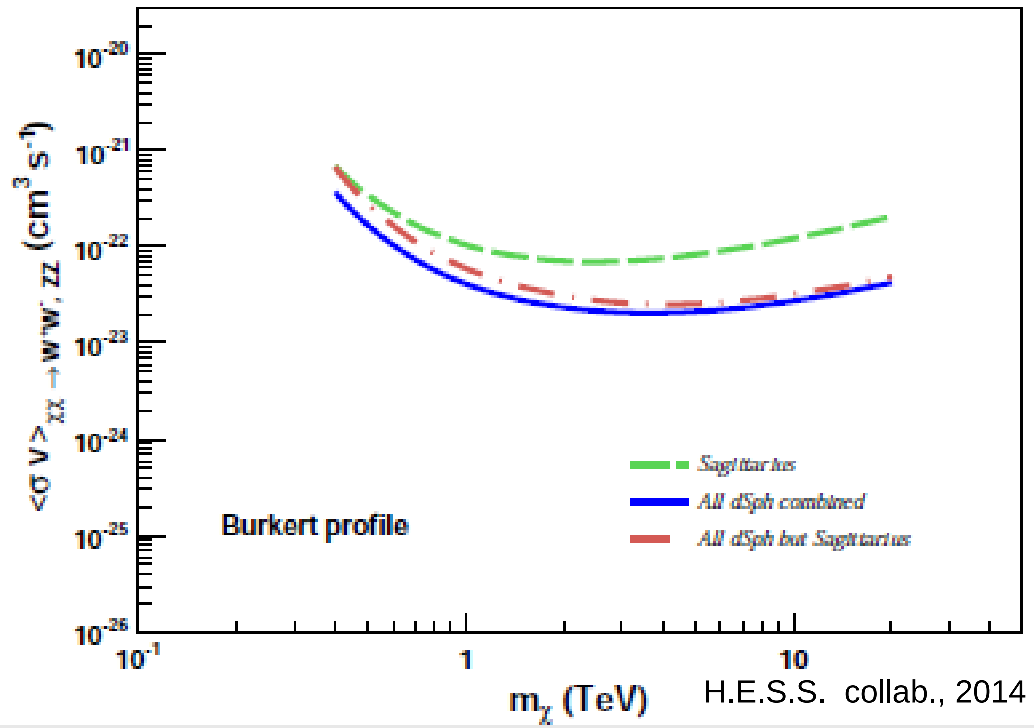
DES collab., 2015

Combined dSphs analysis

- 5 dSphs observed during the phase 1 of H.E.S.S.
  140h (including 90h for Sgr dSph)
- First IACT combined analysis, including propagation of J-factors uncertainties within the UL calculation
  → more robust constraints
- Final limits are improved by the combination of different data sets

$$\lambda(\langle\sigma_{\mathrm{ann}}v\rangle) = \frac{\mathcal{L}(\langle\sigma_{\mathrm{ann}}v\rangle, \hat{\hat{J}}_i, \hat{\hat{b}}_i)}{\mathcal{L}(\widehat{\langle\sigma_{\mathrm{ann}}v\rangle}, \hat{J}_i, \hat{b}_i)}$$

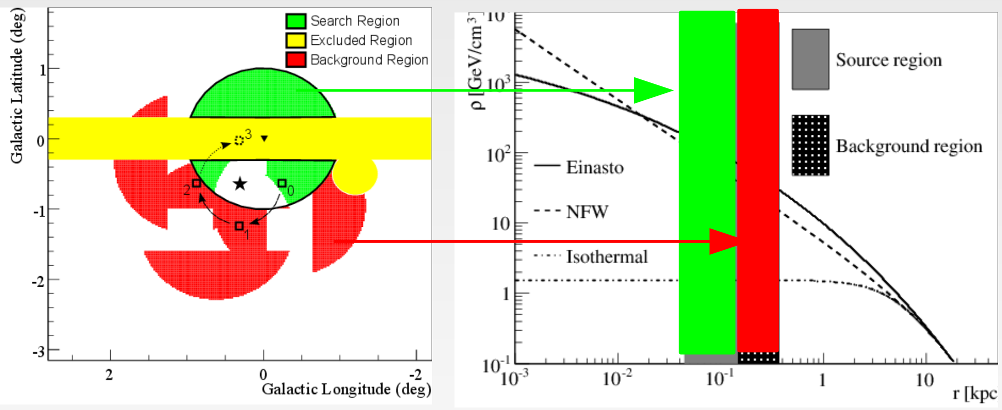
dSph	$\log_{10}\left(\frac{J}{\mathrm{GeV^2 cm^{-5}}}\right)$ NFW	Burkert
Sagittarius	19.1 ± 0.5	18.5 ± 0.5
Coma Berenices	18.8 ± 0.4	19.1 ± 0.2
Fornax	18.1 ± 0.3	18.4 ± 0.3
Carina	18.0 ± 0.4	18.4 ± 0.2
Sculptor	18.5 ± 0.3	18.8 ± 0.2

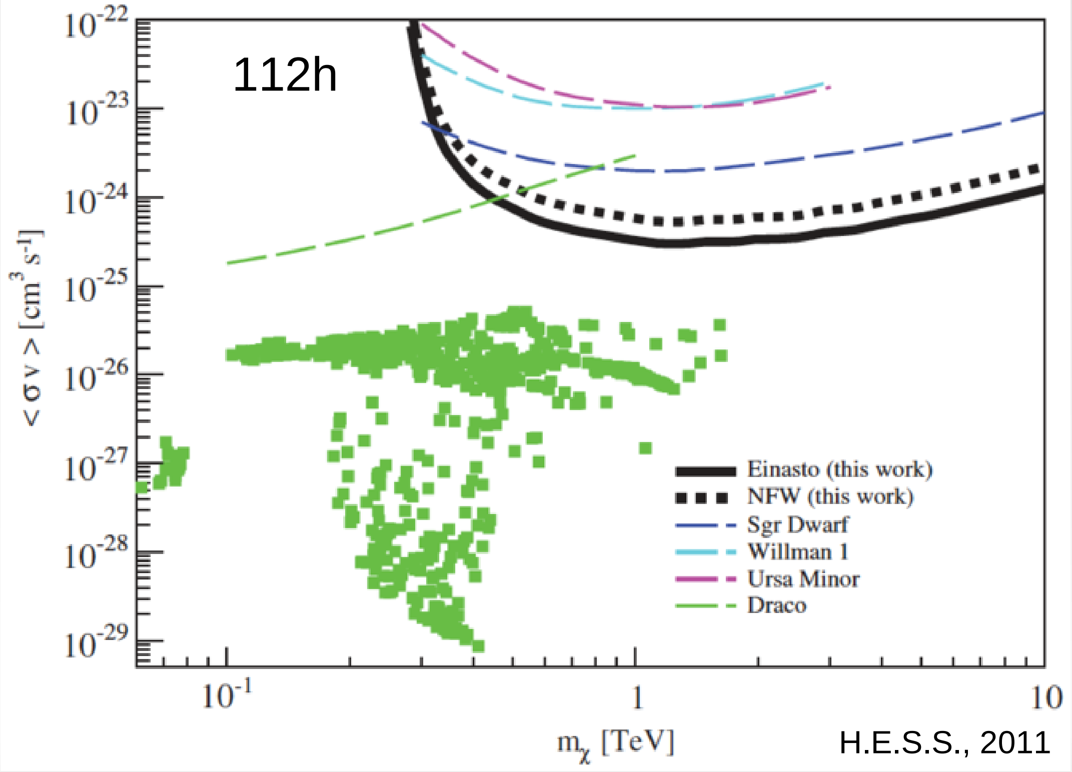


H.E.S.S. collab., 2014

Galactic halo

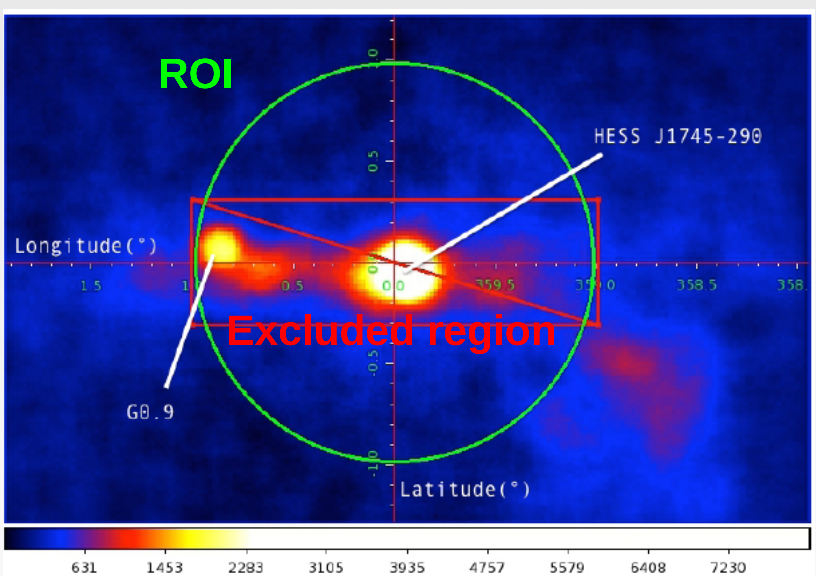
- Close-by and strong signal expected
- Reduced uncertainties on DM density and better control of background wrt GC itself
- Assuming a cusp DM density profile → much better constraints wrt dSphs

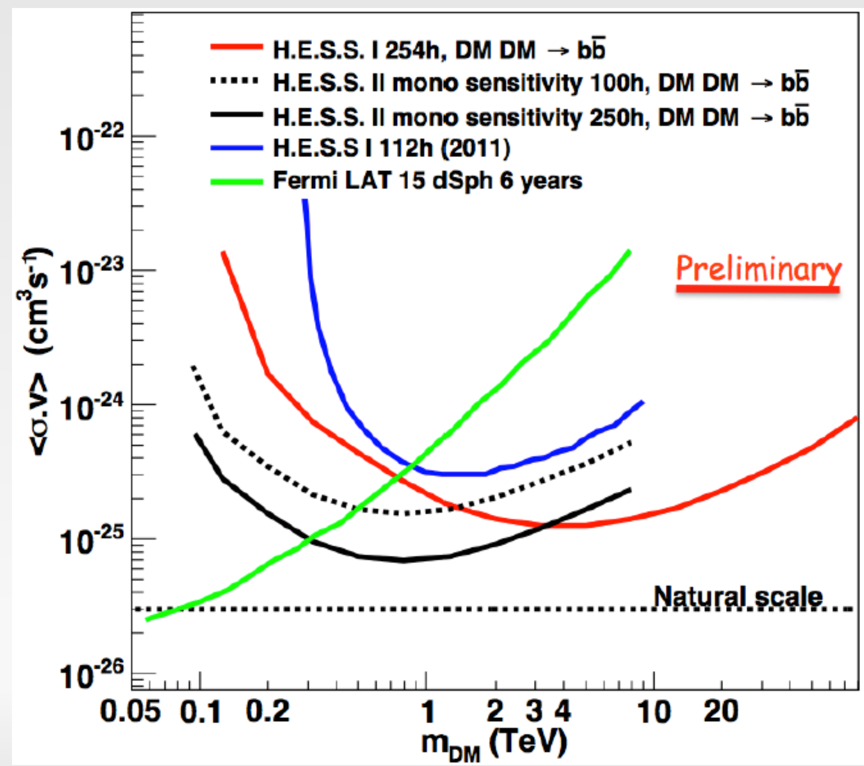




Galactic halo: new results

- Additional data: now up to 254h of obervations performed with H.E.S.S. 1
- New likelihood analysis including both spectral and spatial information
  ROI splitted in 7 annuli from 0.3 to 1º
- H.E.S.S. phase II: lower energy threshold → complementary to Fermi-LAT & H.E.S.S. 1

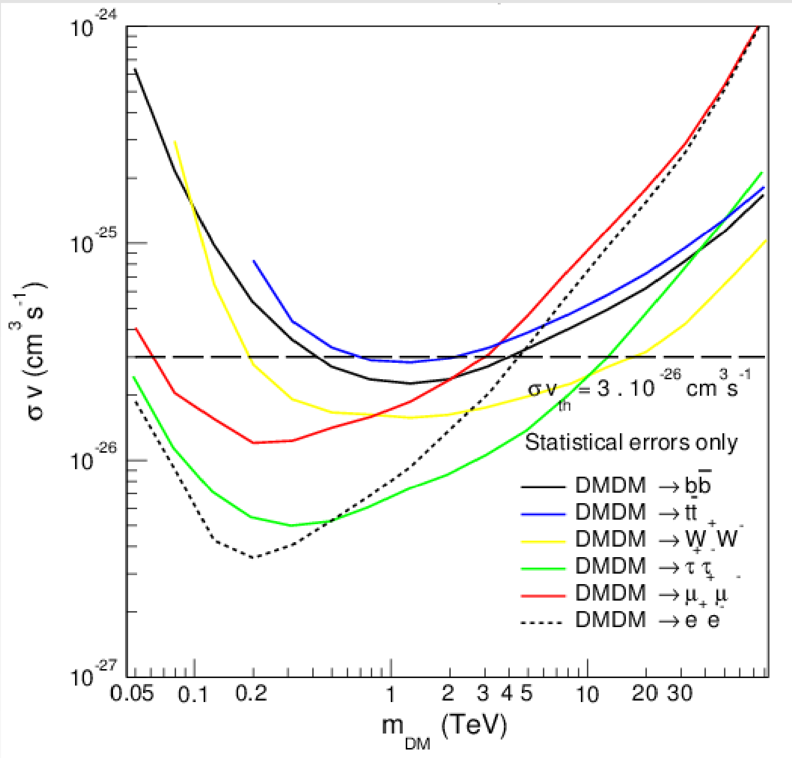


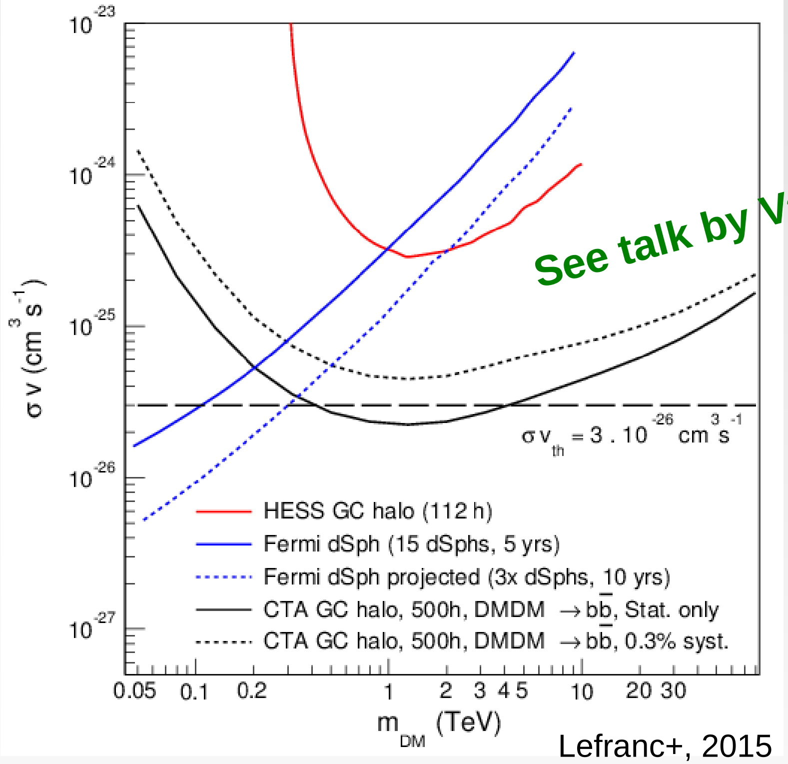


H.E.S.S., ICRC 2015

Galactic centre halo with CTA

- 2D-likelihood analysis with ROI splitted in 5 annuli up to 5º (CTA will have a much larger FoV)
- Assumptions: Einasto DM density profile & 500h of observations





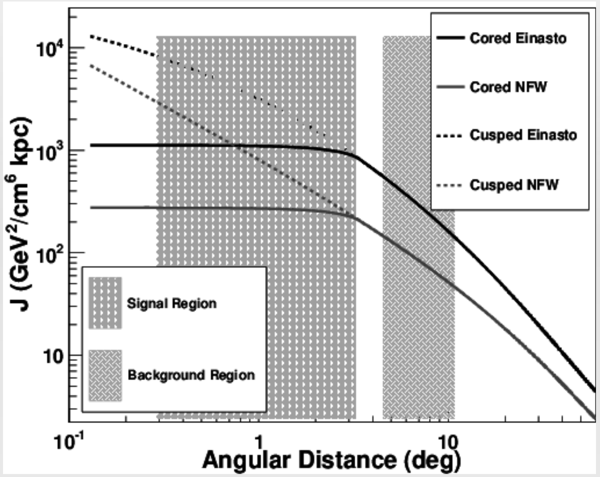
Lefranc+, 2015

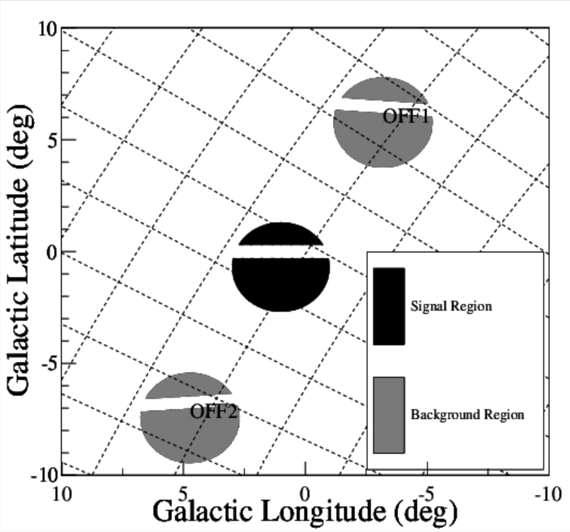
See talk by Valentin

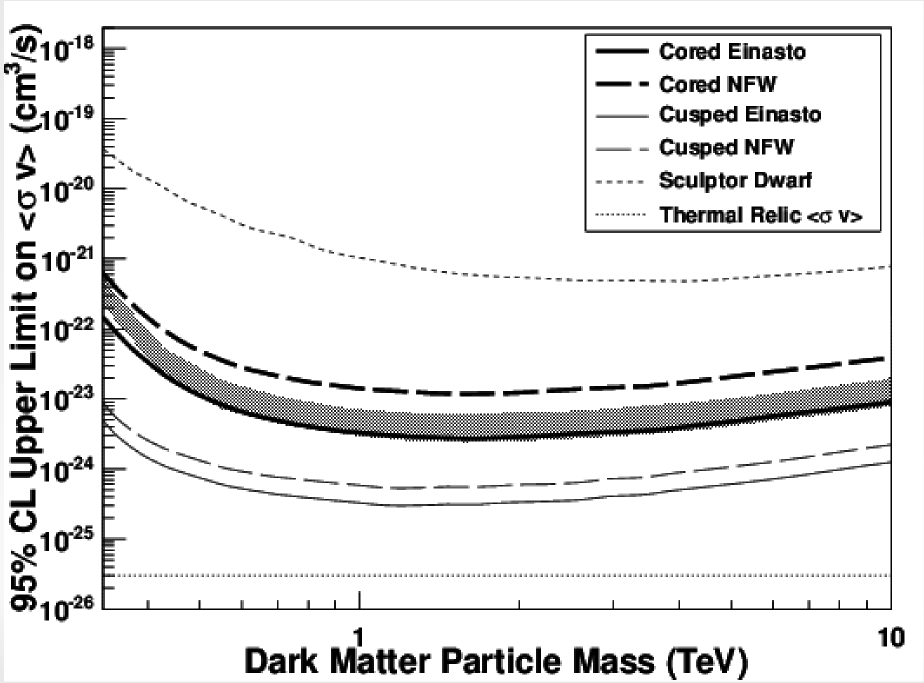
CTA will be the key player for WIMP searches > few 100th GeV
Control of systematic uncertainties mandatory to reach natural scale

Searching for a cored DM profile at the GC

- GC DM density profile not known → cored profiles have been suggested (ex: Kuhlen+, 2013)
- IACT FoV ≅ few º
  → new observation scheme to probe cored DM profiles: OFF1 → ON → OFF2 observations
- Proof of concept: small data set (9h of ON/OFF) leads to promising results



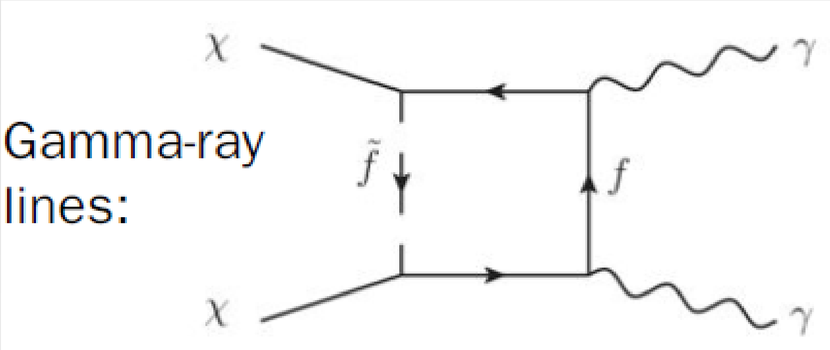


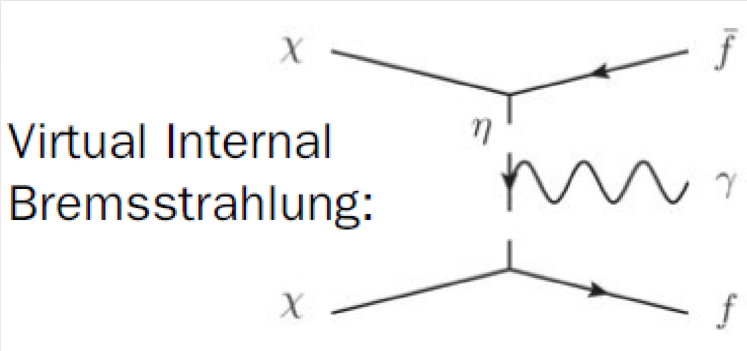


H.E.S.S., 2015

Line-like signal from WIMP annihilations

- **Smoking gun** of WIMPs since no other astrophysical sources are foreseen to mimic such signal





- Line arising from $\chi\chi \rightarrow \gamma X$ [X = γ,Z,H]

$$E_\gamma = m_\chi \left(1 - \frac{m_X^2}{4 m_\chi^2}\right)$$

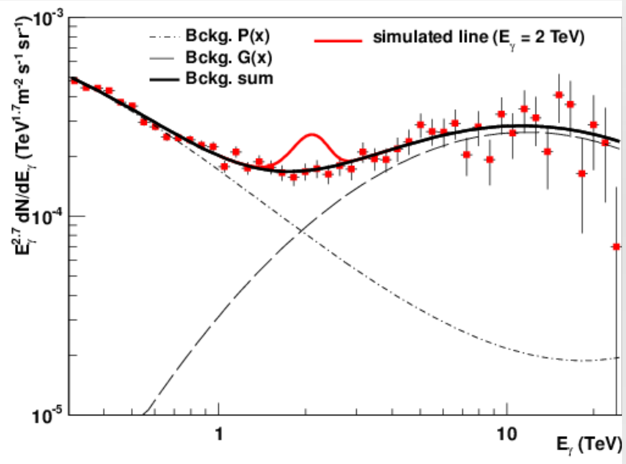
- Internal Bremsstrahlung
  - Final state radiation
  - Virtual IB

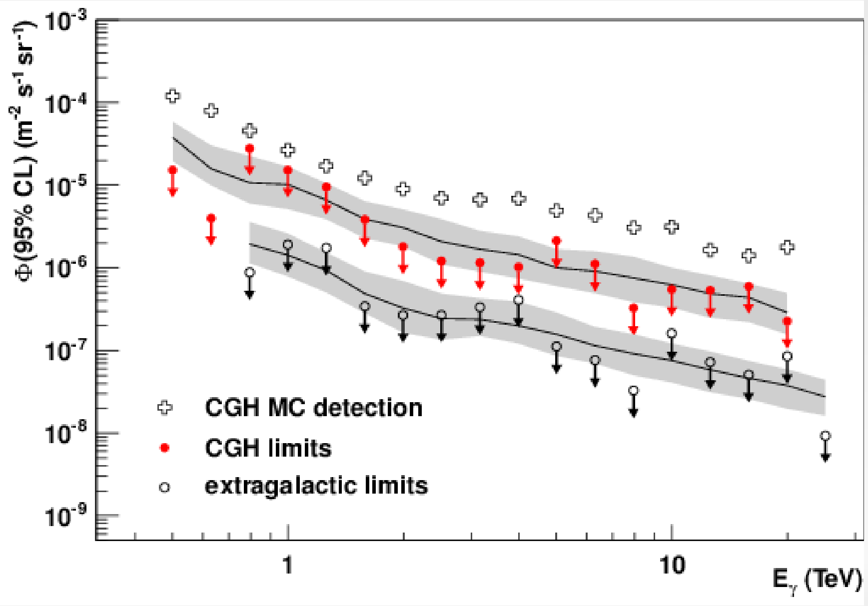
  is (very) model dependant
  → broader feature

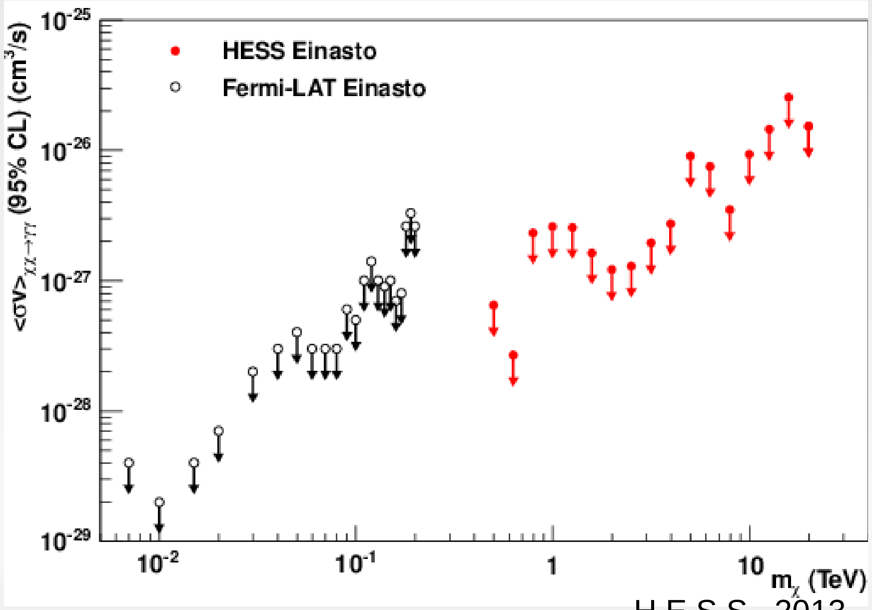
- Search for a bump/sharp excess over the distribution of background events
  → easier to disentangle from background spectra wrt continuum searches

DM line searches with H.E.S.S.

- γ-like events spectrum extracted from GC halo (and extragalactic fields) (H.E.S.S. 2011)
- Search for sharp line-like feature on top
- First IACT line search – complement Fermi limits at lower energies



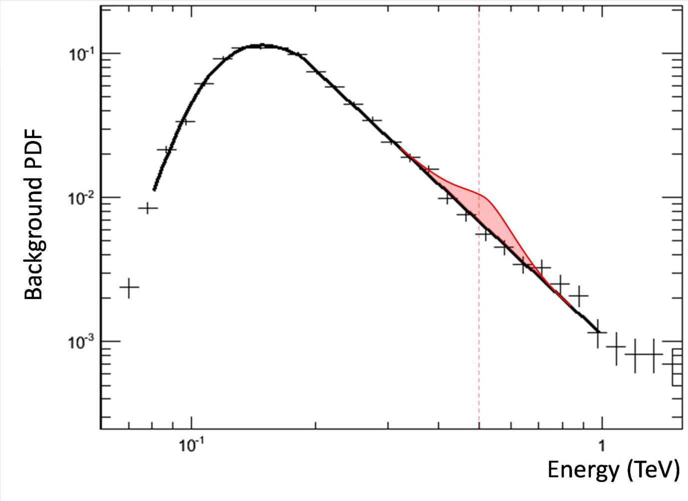


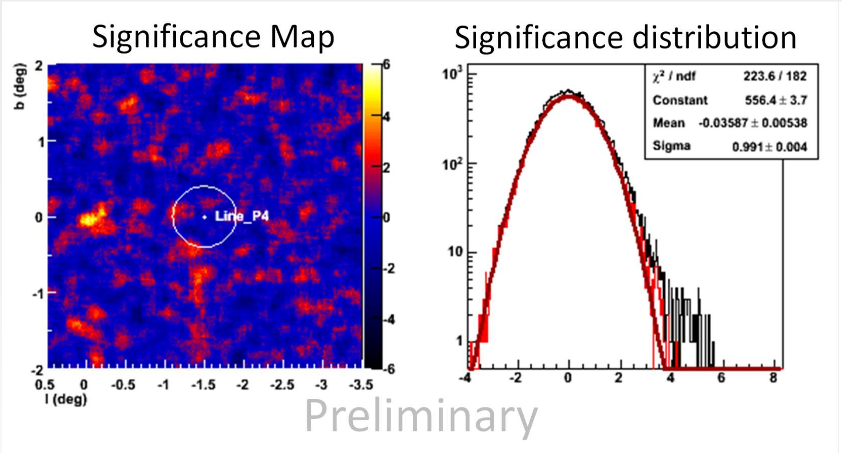


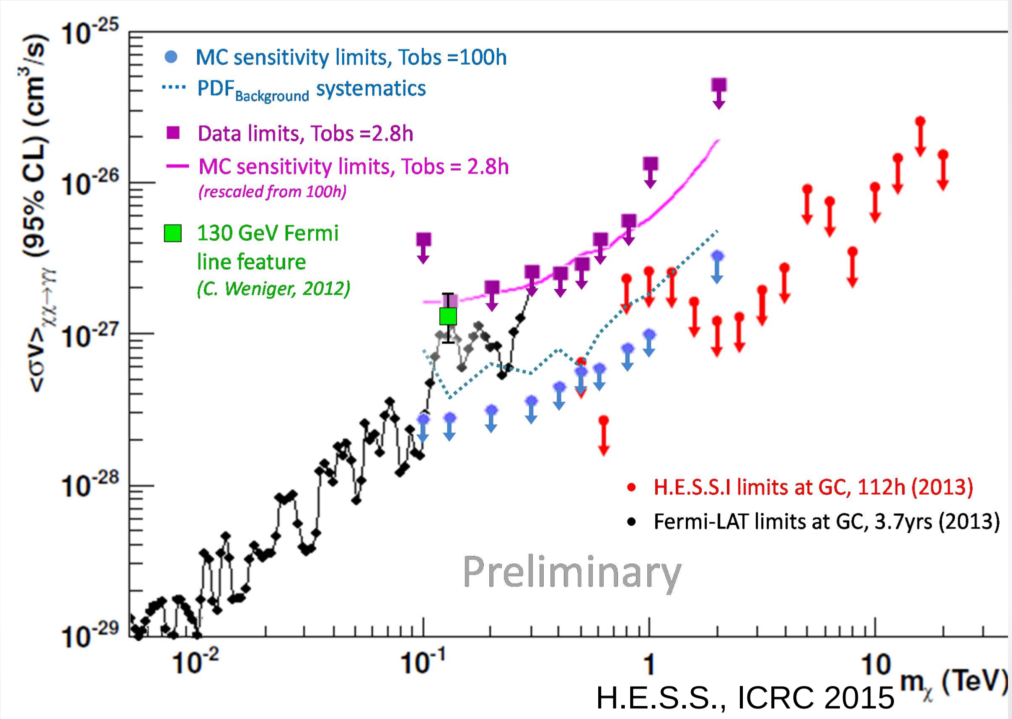
H.E.S.S., 2013

DM line searches with H.E.S.S. 2

- Lower energy threshold thanks to much larger collection area
- Unbinned likelihood: PDF_{OFF} from control regions, PDF_{ON} from MC
- 2.8h data analysing the previously reported 130 GeV monochromatic excess at (l,b)=(-1.5,0)



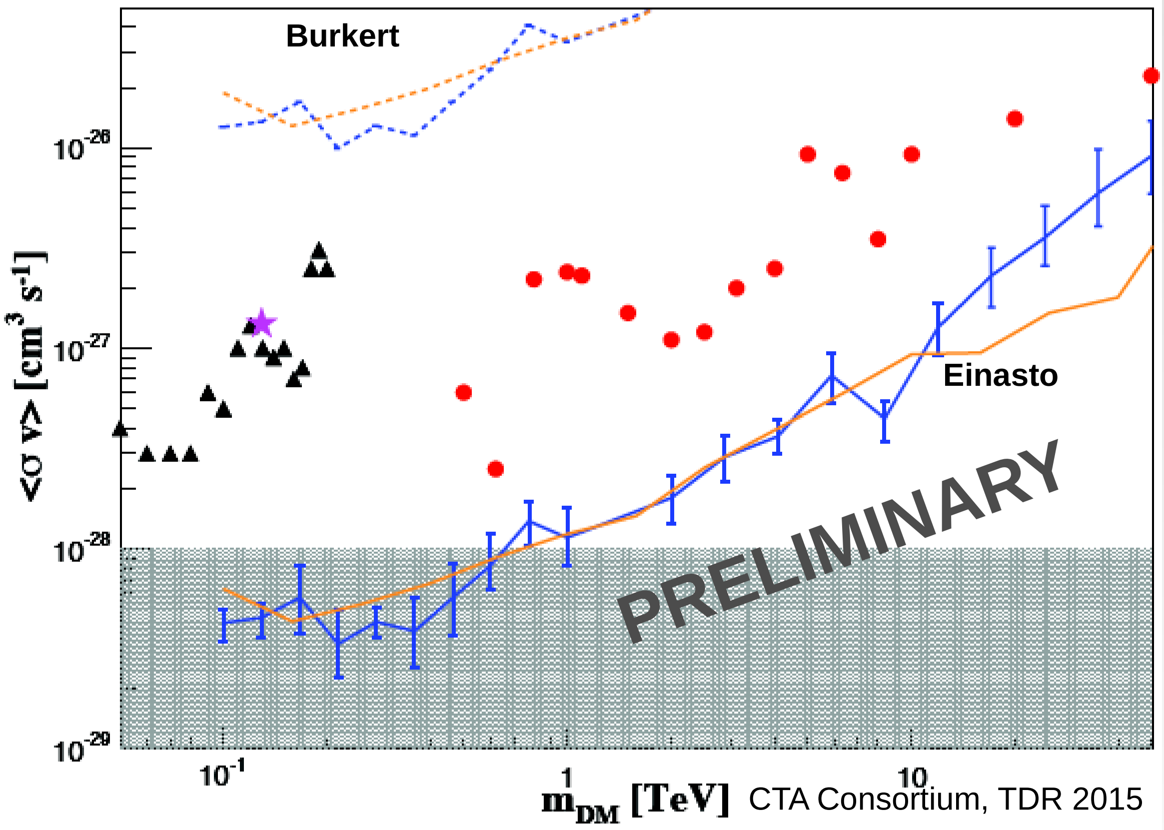




CTA expectations

Analysis: energy dependant unbinned likelihood with sliding energy window

500h observations focusing on the 1º central region



CTA Consortium, TDR 2015

CTA γγ line searches will start to probe SUSY parameter space

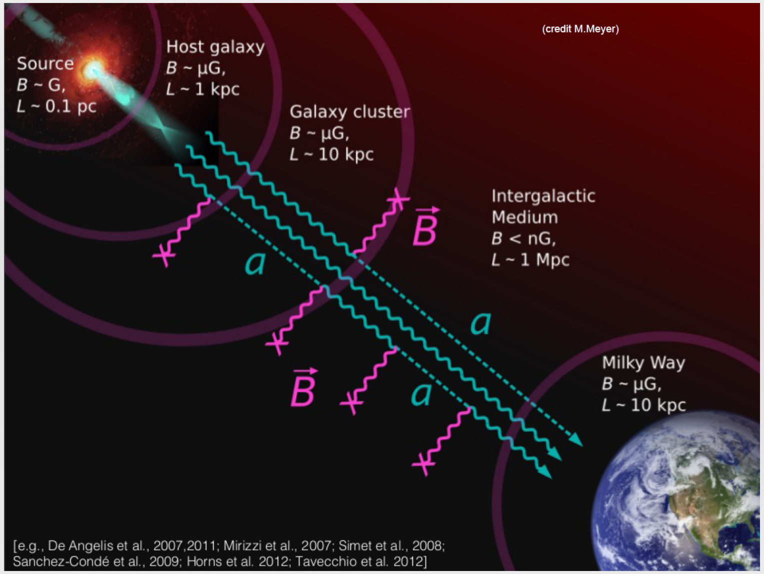
Selection of axion-like particle searches

Looking for axion-like particles (ALPs)

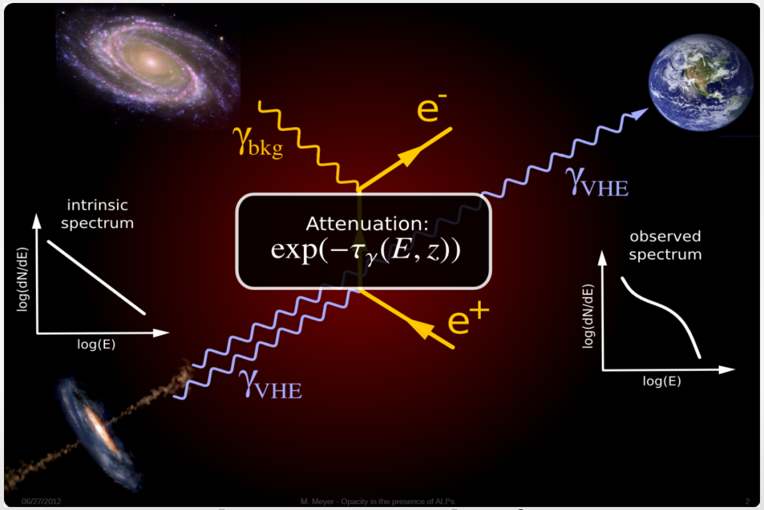
- ALP similar to axions but mass m_a and coupling $g_{\gamma a}$ unrelated

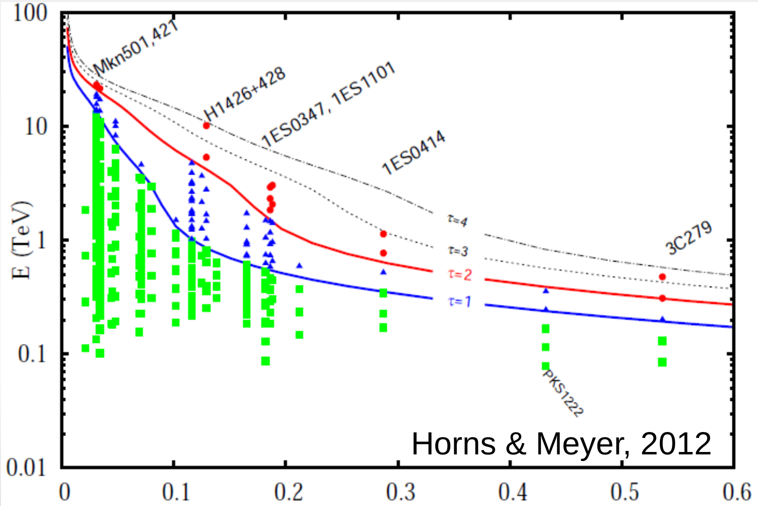
$$L_{a\gamma} = \frac{-1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma} \boldsymbol{E}.\boldsymbol{B}\, a$$

- γ/ALP conversion in presence of B-field
  ⇒ modification of opacity



Hints of Universe transparency from observations of AGNs located at large optical depth

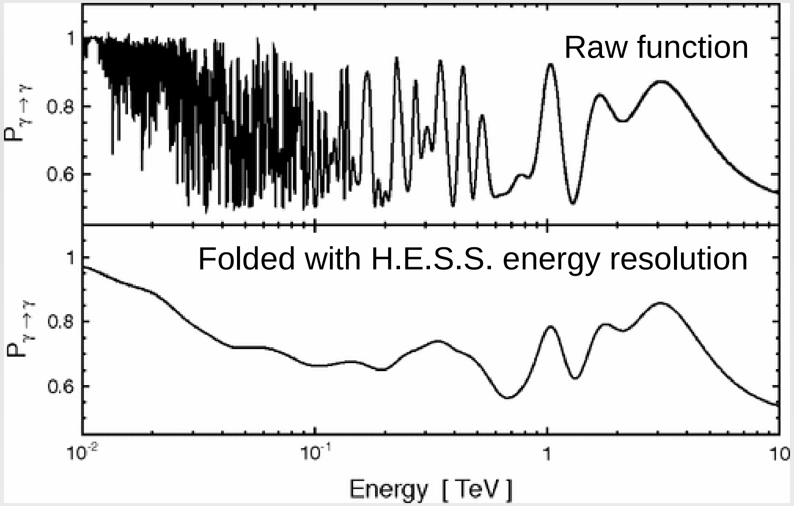


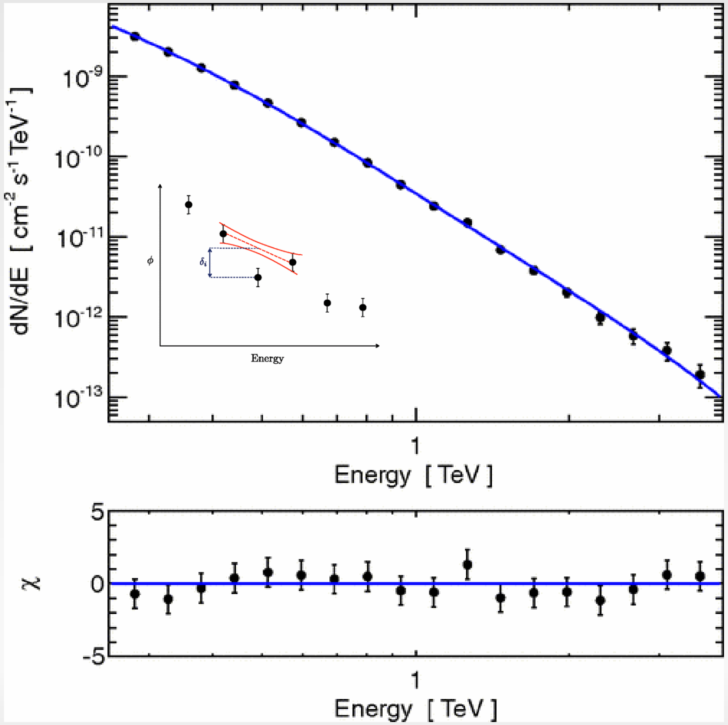


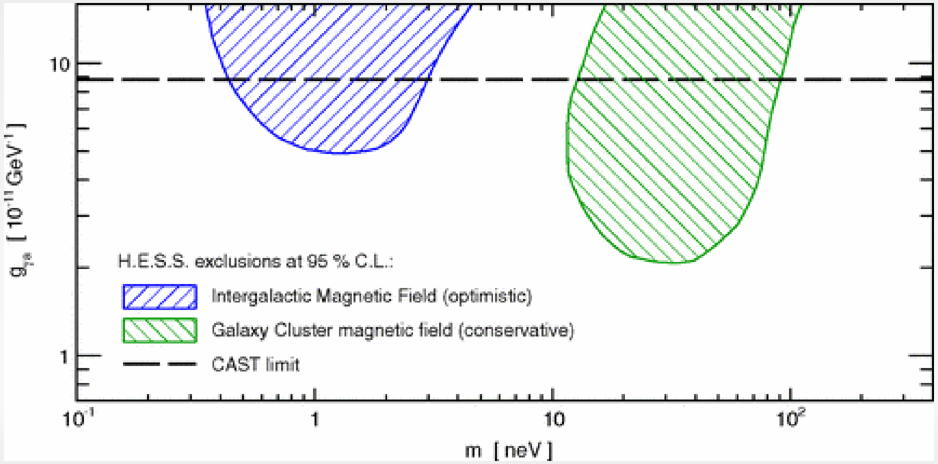
Search for spectral irregularities with H.E.S.S.

- γ/ALP conversion in B-field can induce spectral irregularities in distant gamma-ray source
- Spectral fluctuations quantified using a sliding window on triplet of energy bins (robust to wide energy ranges effects such as EBL absorption)

Survival probability for γ rays mixing with ALP within a galaxy cluster B-field







H.E.S.S., 2013

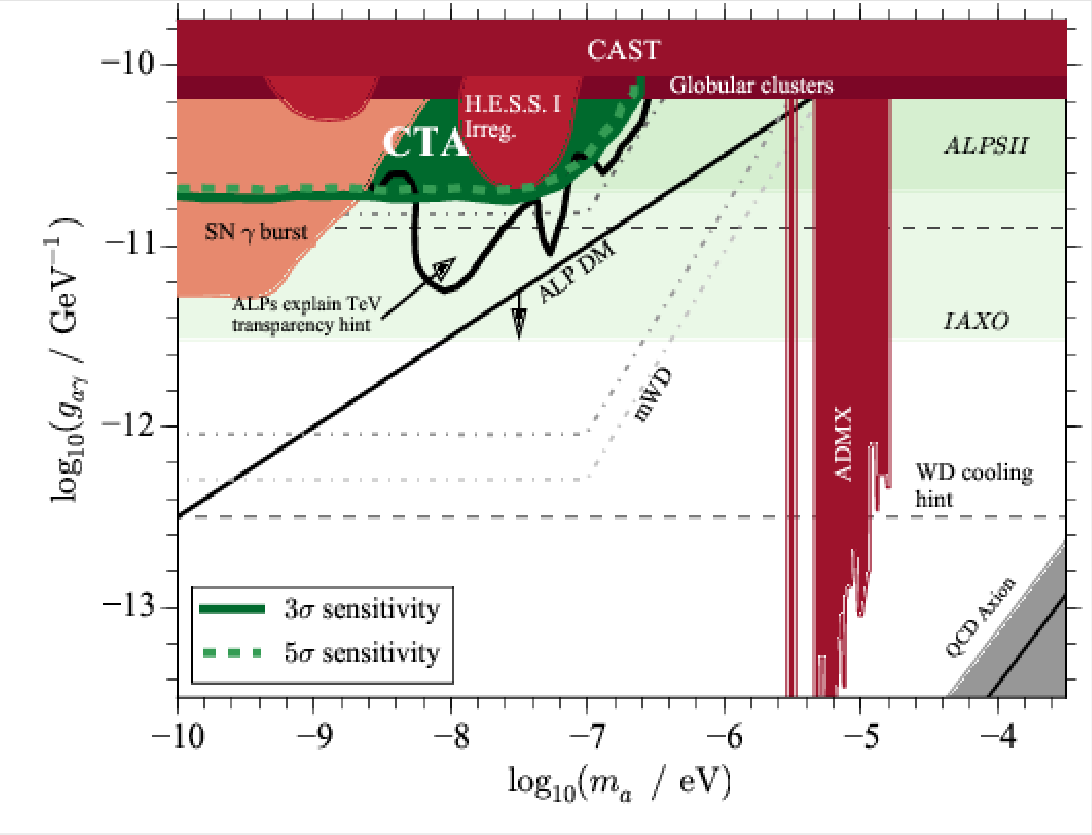
ALP with CTA: High opacity regime test

Likelihood profile (w/ and wo/ALP) study based on energy bins located in optically thick regime (τ>2)

(Meyer, Montanino & Conrad, 2014)

$$\mathcal{L}(\mu, \mathrm{b}; \alpha | N_{\mathrm{ON}}, N_{\mathrm{OFF}}) = \prod_{\substack{i \\ \tau(E_i, z) > 2}}^{n} f(N_{i,\mathrm{ON}} | \mu_i + b_i) f(N_{i,\mathrm{OFF}} | b_i / \alpha).$$

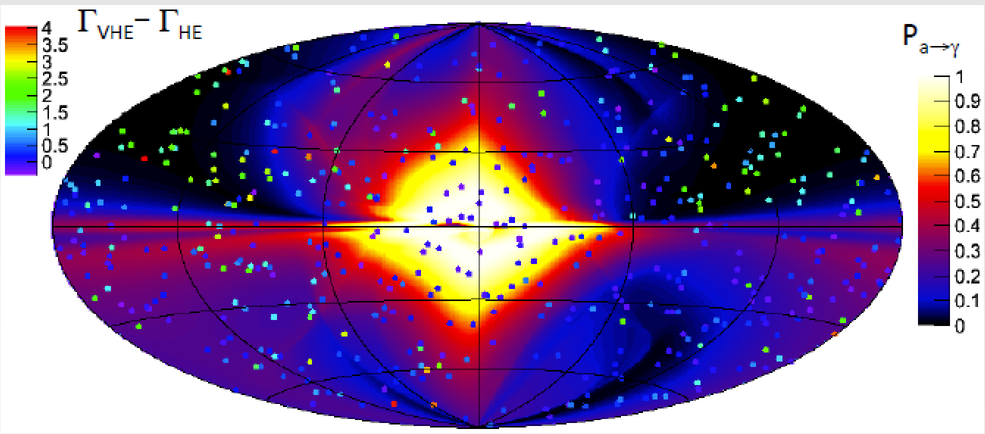
$$\lambda(\tilde{\mu}; \alpha | N_{\mathrm{ON}}, N_{\mathrm{OFF}}) = \frac{\mathcal{L}(\tilde{\mu}, \widehat{\widehat{\mathrm{b}}}(\tilde{\mu}); \alpha | N_{\mathrm{ON}}, N_{\mathrm{OFF}})}{\mathcal{L}(\widehat{\mu}, \widehat{\mathrm{b}}; \alpha | N_{\mathrm{ON}}, N_{\mathrm{OFF}})}$$

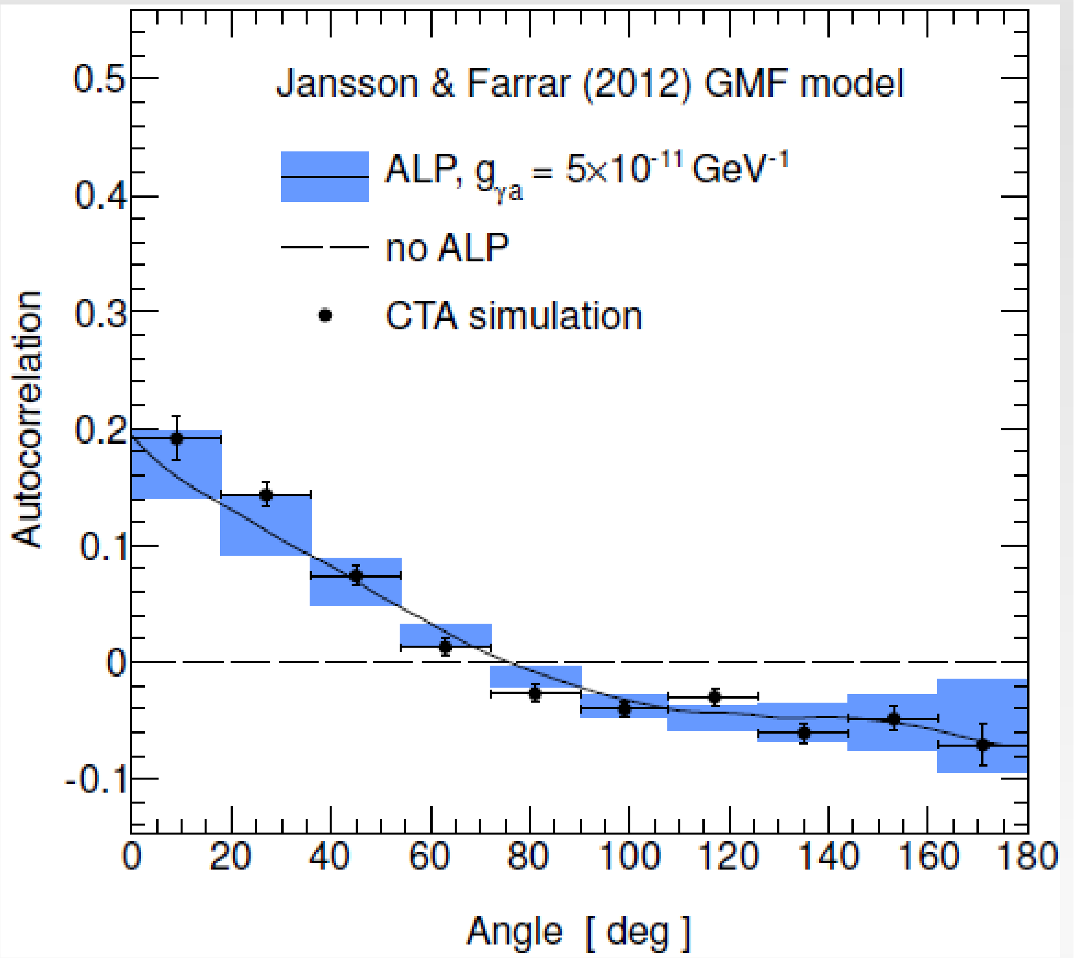


Meyer & Conrad, 2014

ALP with CTA: Anisotropy test

Hypothesis: transparency of the universe due to ALPs ⇒ expected correlation between location of AGNs and spectral variations due to galactic B-field





Wouters & Brun, 2014

Requirements for detectability:

- large statistics (1000 sources)
- good spectral measurements
- actual knowledge of the redshift of the sources

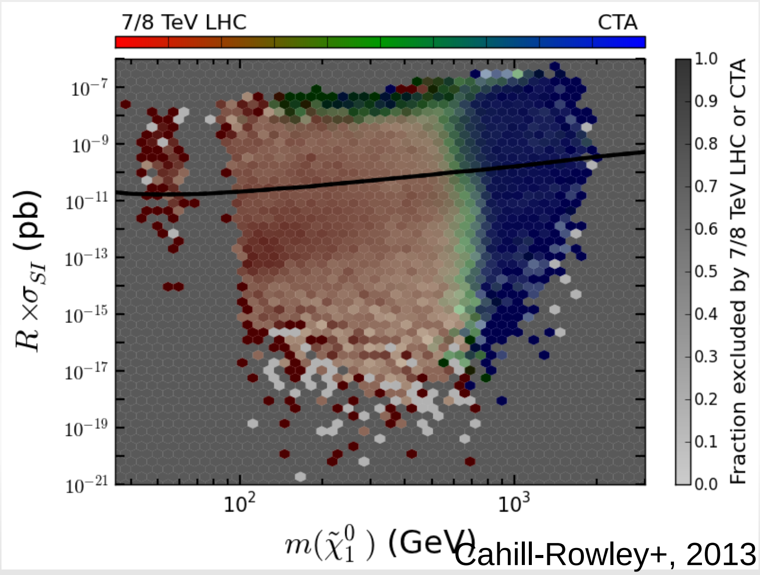
Conclusions

Cherenkov telescopes offer a **complementary approach** to look for the nature of dark matter

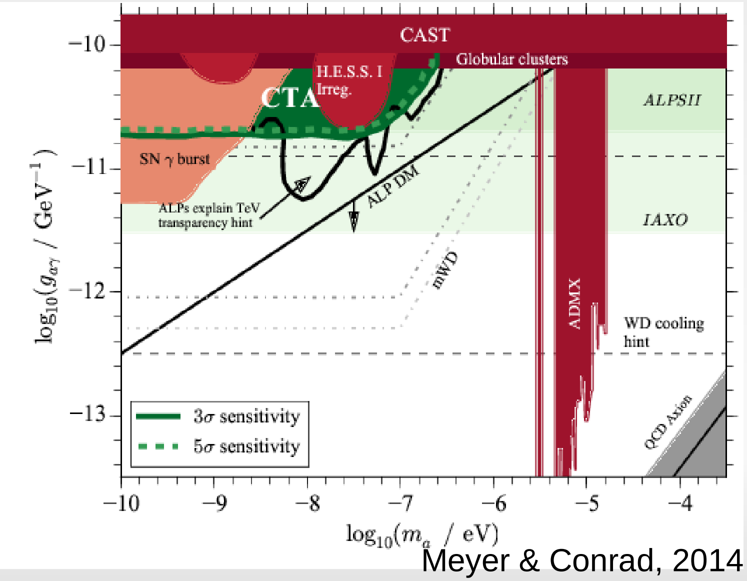
They have **unique capabilities to access large WIMPs** and potentially measure its mass

They can **probe the hint of apparent transparency of the Universe** and test the presence of ALPs

The next generation instrument, CTA will be an observatory and first data are expected by 2020



Cahill-Rowley+, 2013



Meyer & Conrad, 2014

Thank you for your attention!