Astroparticle Physics with H.E.S.S. – past and future

Emmanuel Moulin for the H.E.S.S. Collaboration

H.E.S.S.

7th Roma International Conference on AstroParticle Physics

RICAP 18

INFN Istituto Nazionale di Fisica Nucleare

Università degli Studi di Roma Tor Vergata

Sapienza Università di Roma

Roma Tre Università degli Studi Dipartimento di Fisica

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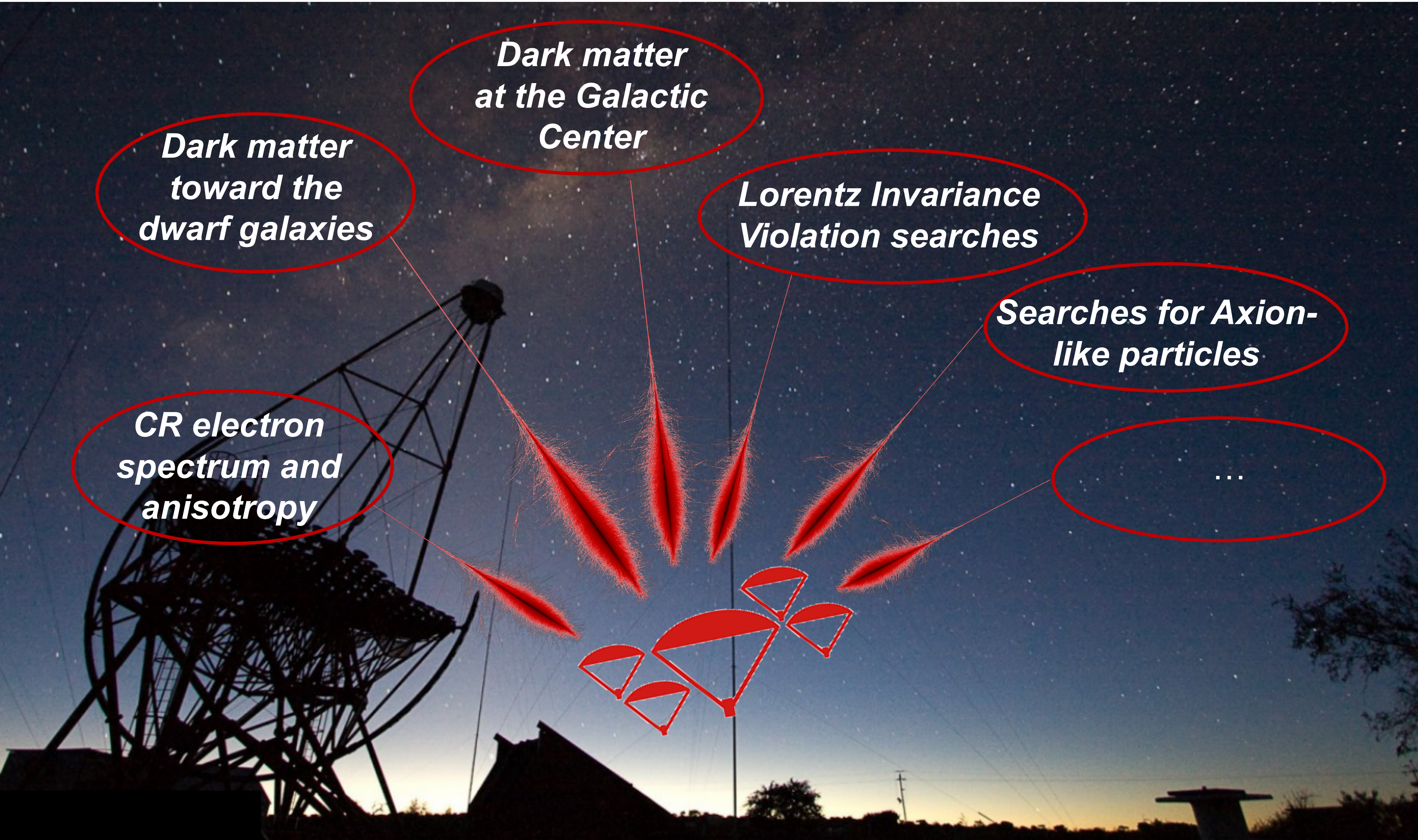
Astroparticle Physics with H.E.S.S.



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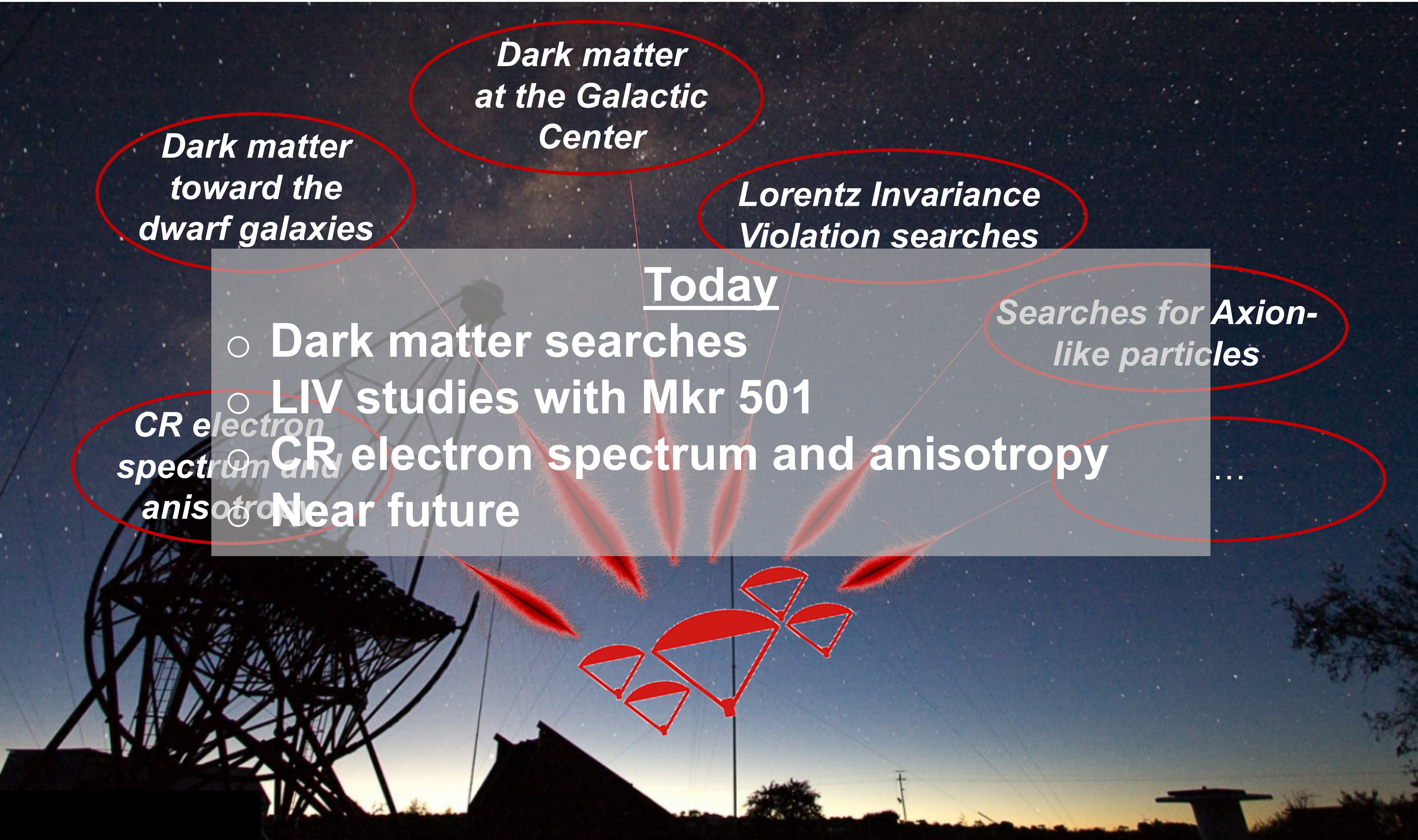

Today

- Dark matter searches
- LIV studies with Mkr 501
- CR electron spectrum and anisotropy
- Near future

Dark matter search with VHE gamma rays

$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{DM}^2}\frac{dN_\gamma}{dE_\gamma}}\times\underbrace{\int_{\Delta\Omega}d\Omega\int_{l.o.s}\rho^2(r[s])ds}$$

Particle physics:

- Cross sections
- Differential photon yield
- DM particle mass

Astrophysics: J-factor

→ DM distribution in the target

Large uncertainties (baryon feedback, tidal stripping, clustering, …)

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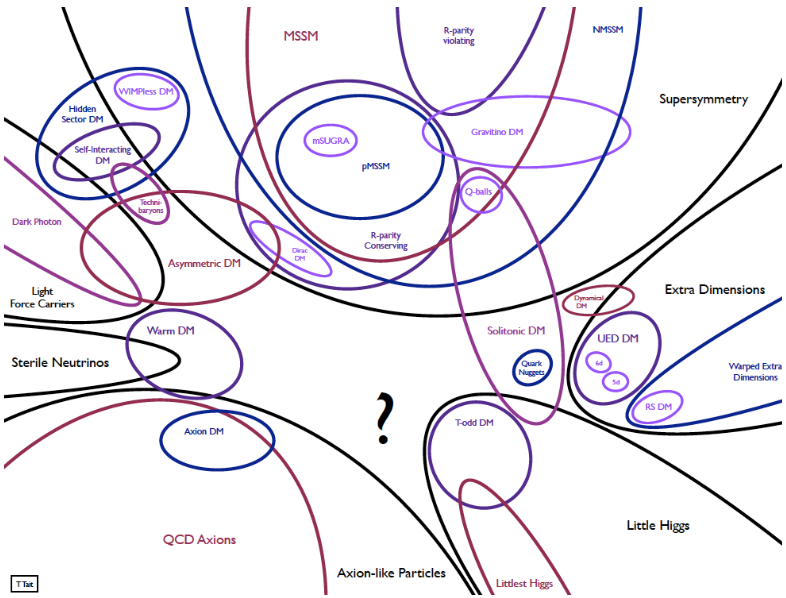

No lack of options…

Particle physics:

- Cross sections
- Differential photon yield
- DM particle mass

No target dependence but huge uncertainties on the particle Physics model

Astrophysics: J-factor

→ DM distribution in the target

Large uncertainties (baryon feedback, tidal stripping, clustering, …)

Hunting for the largest J-factors

Dark matter search with VHE gamma rays

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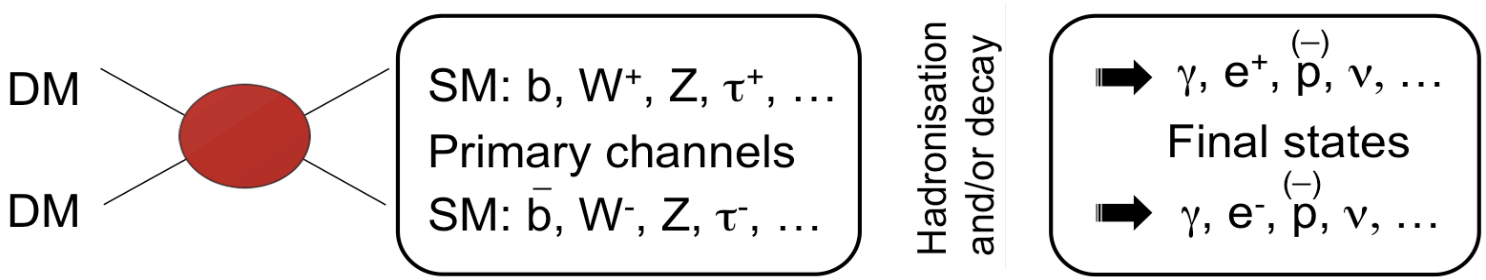
- **Weakly Interacting Massive Particles (WIMPs)**
  - The weak interaction mass scale and ordinary gauge couplings give right relic DM density without fine-tuning.

$$\Omega_{\mathrm{DM}} h^2 = \frac{3 \times 10^{-27}\ \mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle} \quad \langle\sigma v\rangle_{\mathrm{W}} \sim \frac{\alpha^2}{m_{\mathrm{WIMP}}^2} \sim 3 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$$

  - Mass scale GeV-TeV, makes them Cold Dark Matter
  - **Provides benchmark for indirect detection**: thermally-produced WIMPs

DM spectral and spatial signatures in VHE gamma rays



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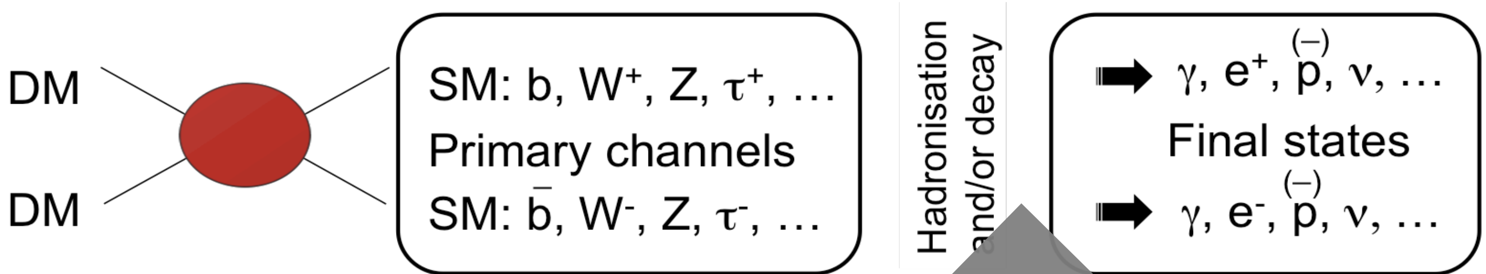

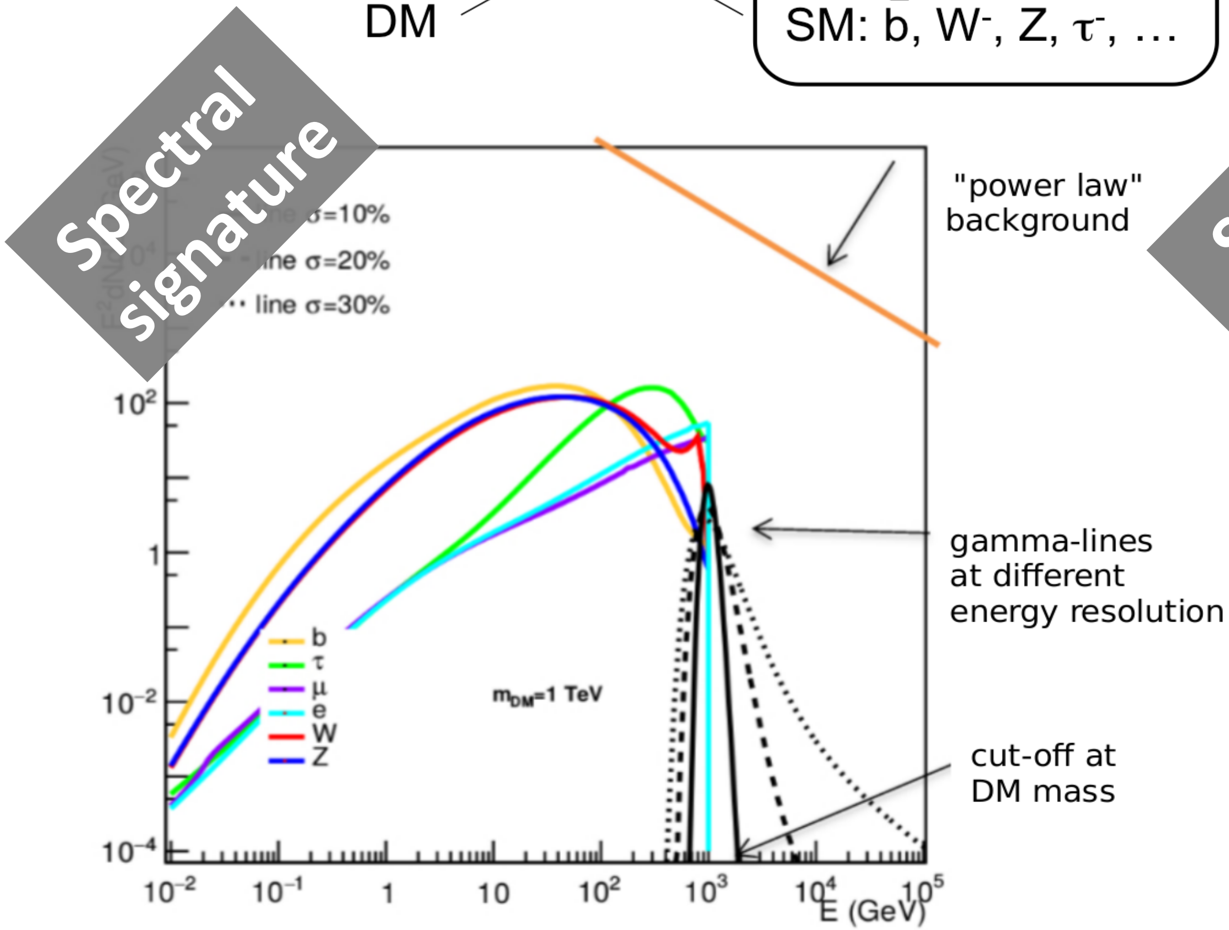

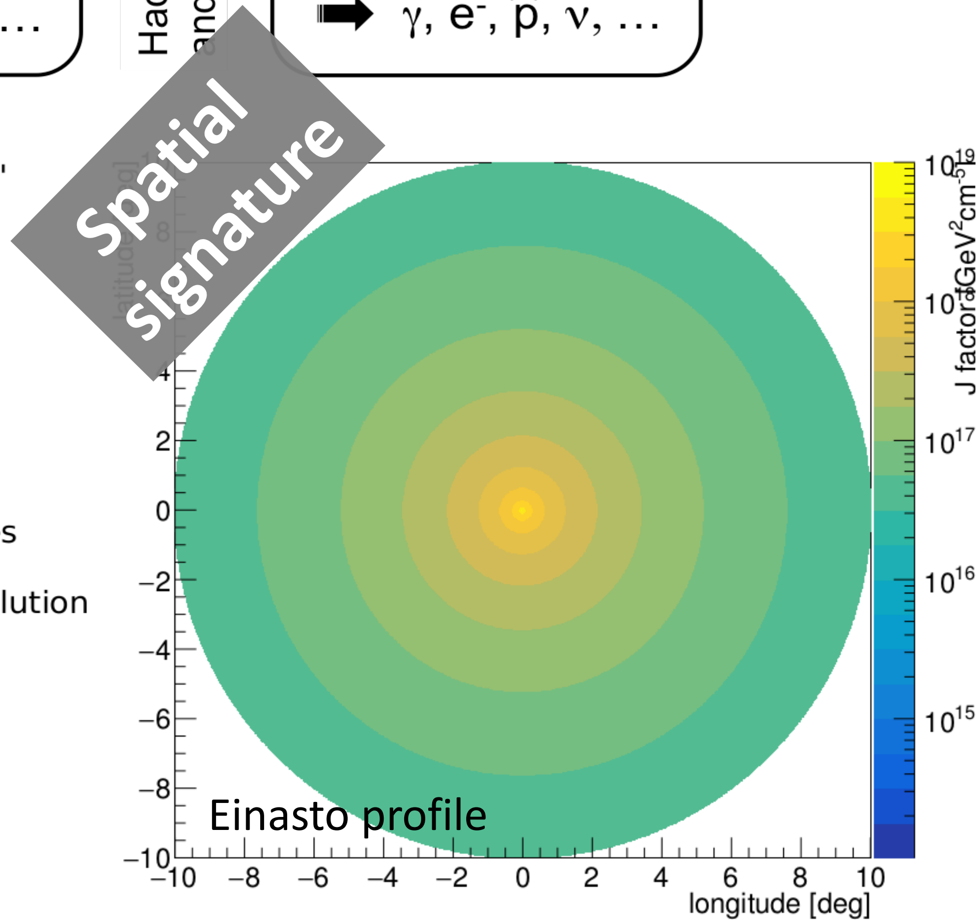

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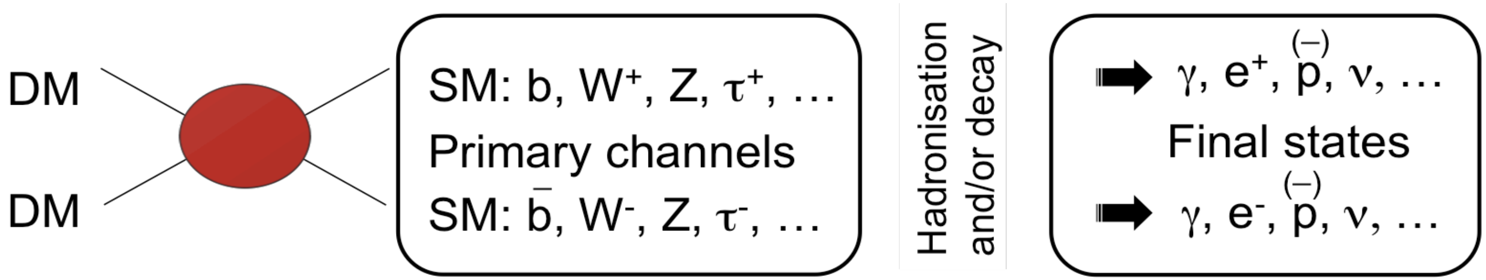
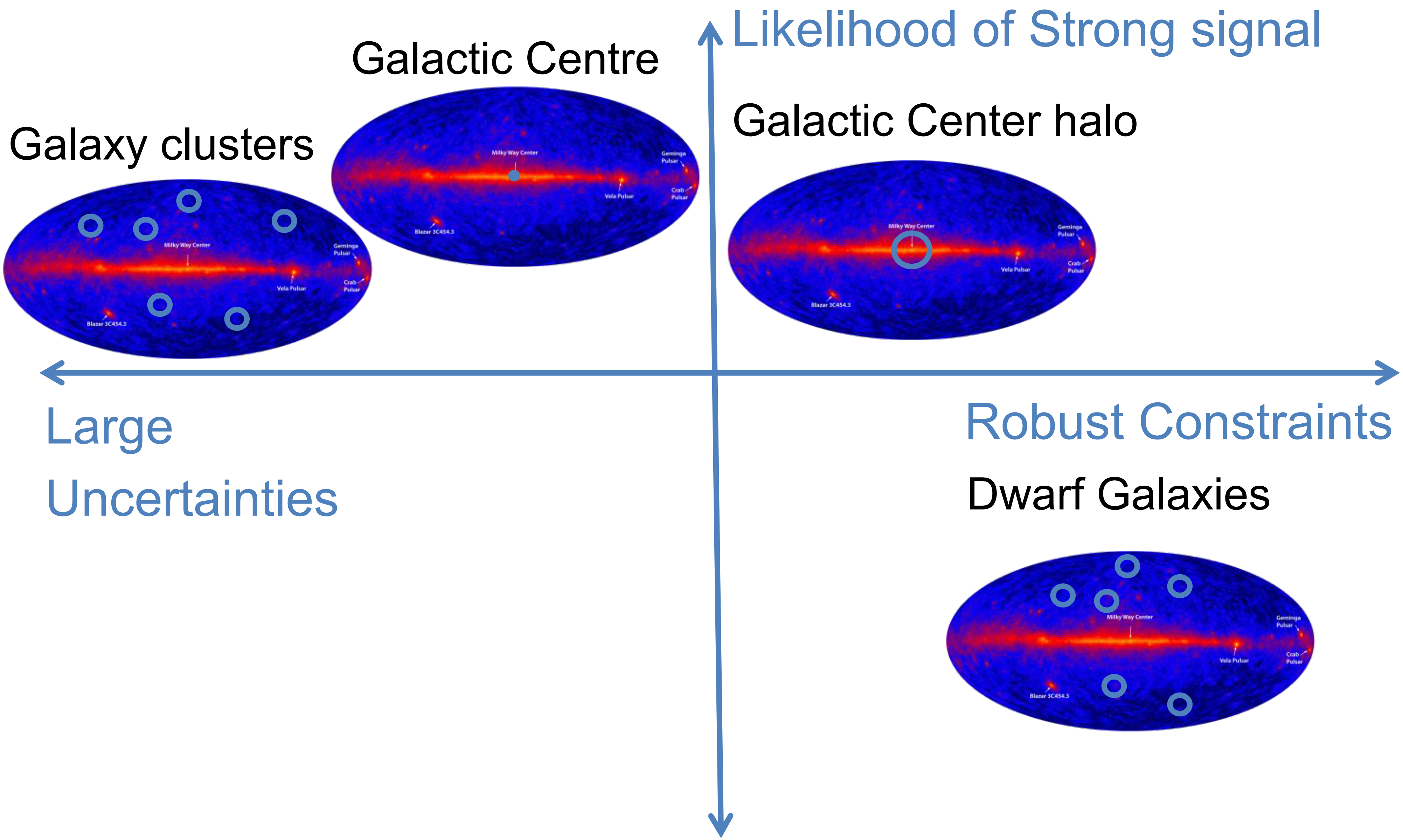


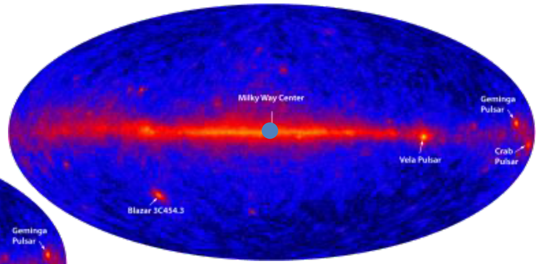
- VHE (E> 100 GeV) gamma rays do not suffer from propagation effects at Galactic scale : they point back to the source
  – Can reveal the abundance and distribution of DM
- Characteristic spectral features may be present in the spectrum at these energies
  – Good discrimination from background
- **Identification of DM is possible**
  – the gamma-ray distribution in the sky can tell us the DM density distribution
  – the gamma-ray spectrum can tells us the reaction process and DM mass

Targets and challenges



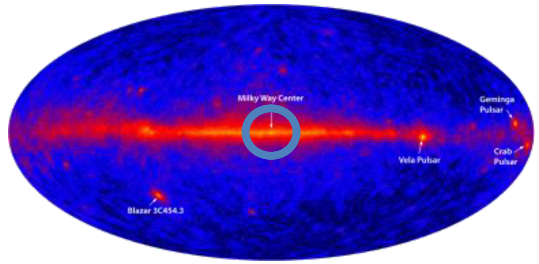
Targets and challenges

Galactic Centre

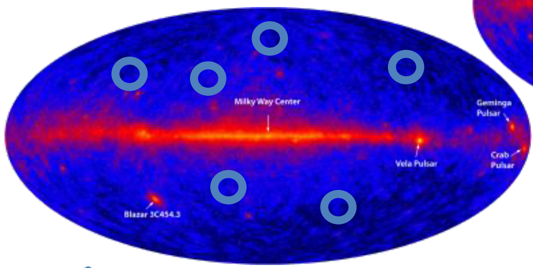


Likelihood of Strong signal

Galactic Center halo



Galaxy clusters

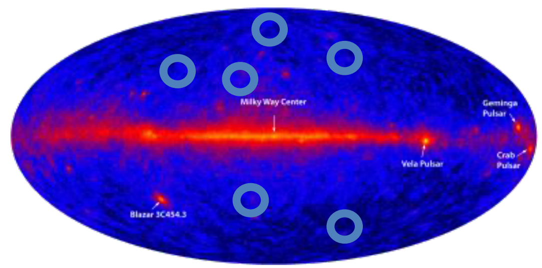


Large

Uncertainties

Robust Constraints

Dwarf Galaxies



Maximize the quantity of DM signal (close distance and large DM density) wrt background (astrophysical sources)

H.E.S.S.

Targets and challenges

Likelihood of Strong signal

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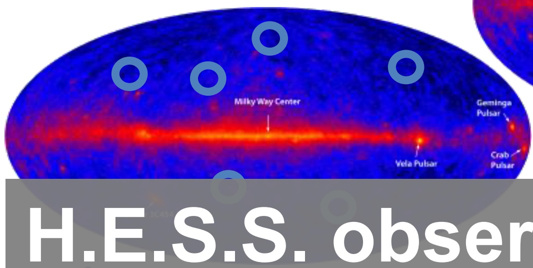

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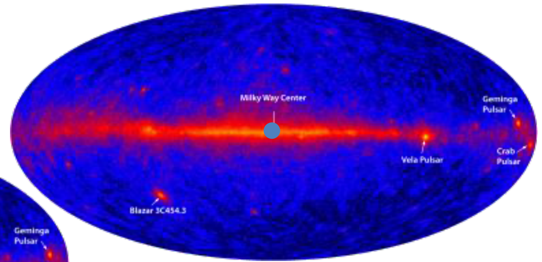

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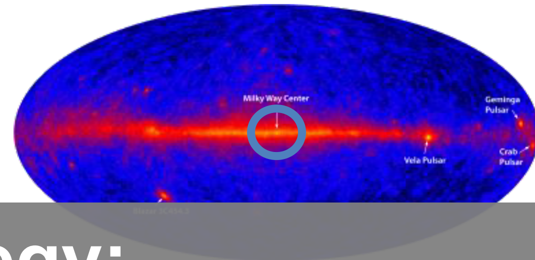
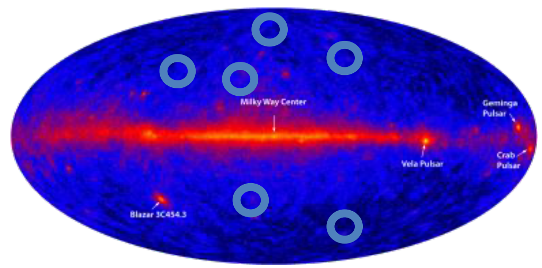


H.E.S.S. observational strategy:

- Deep observations of the **Galactic Center region**
- Observations of the **most promising dwarf galaxies**

Large Uncertainties

Robust Constraints Dwarf Galaxies



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Observations of the GC with H.E.S.S. I

- H.E.S.S. is in an ideal location to observe the Galactic Center region
- GC is a very crowded region in VHE: HESS J1745-290 coincident with Sgr A*, TeV diffuse emission, SNR HESS J1745-303, PWN G09+01, …

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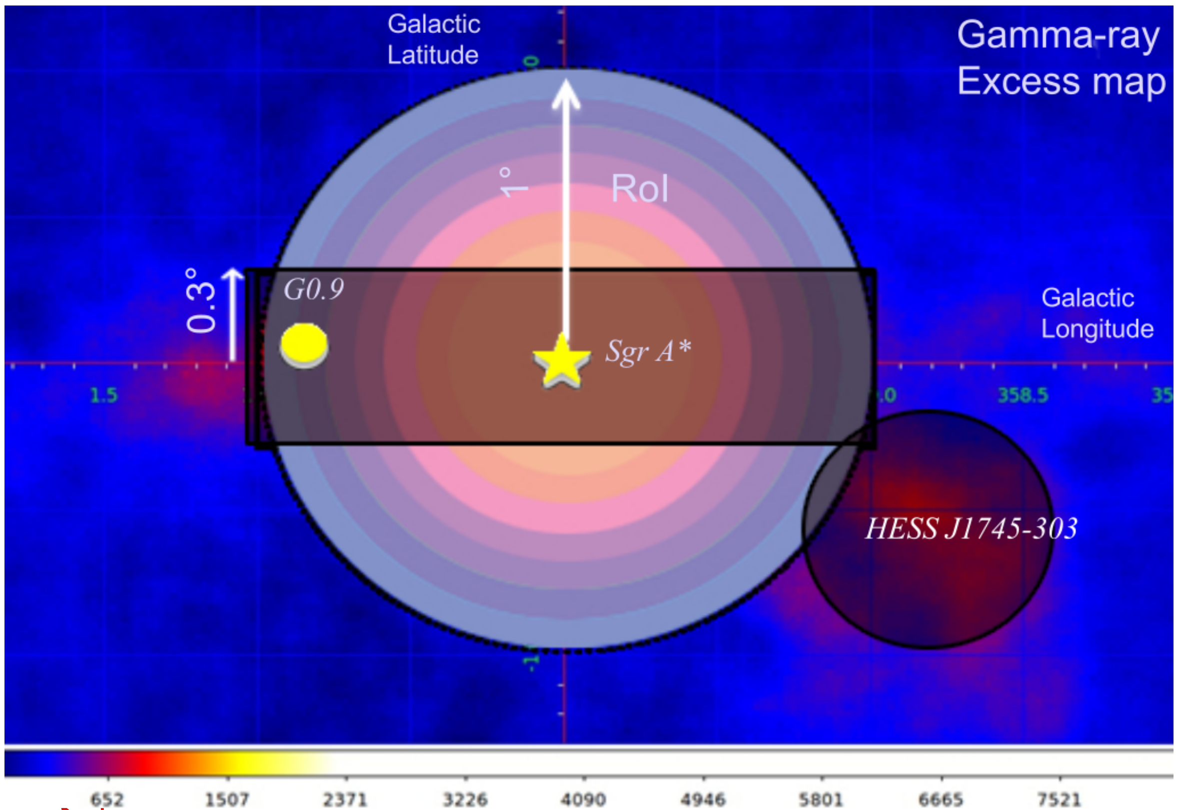

254 live hours of observations with H.E.S.S. I (2004-2014)

- **Region of interest:** circle of 1° radius around GC, split in 7 sub-regions (RoI) of with 0.1°
- **Exclusion masks on regions with standard astrophysical sources**

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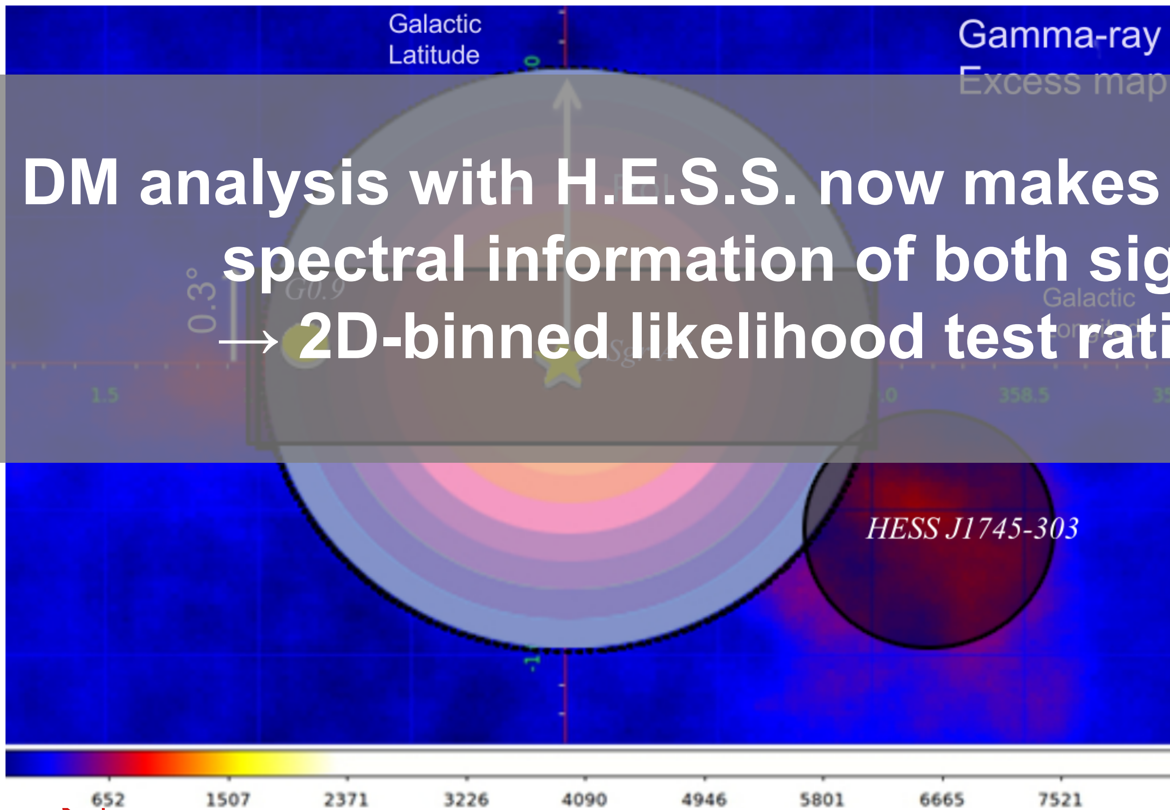

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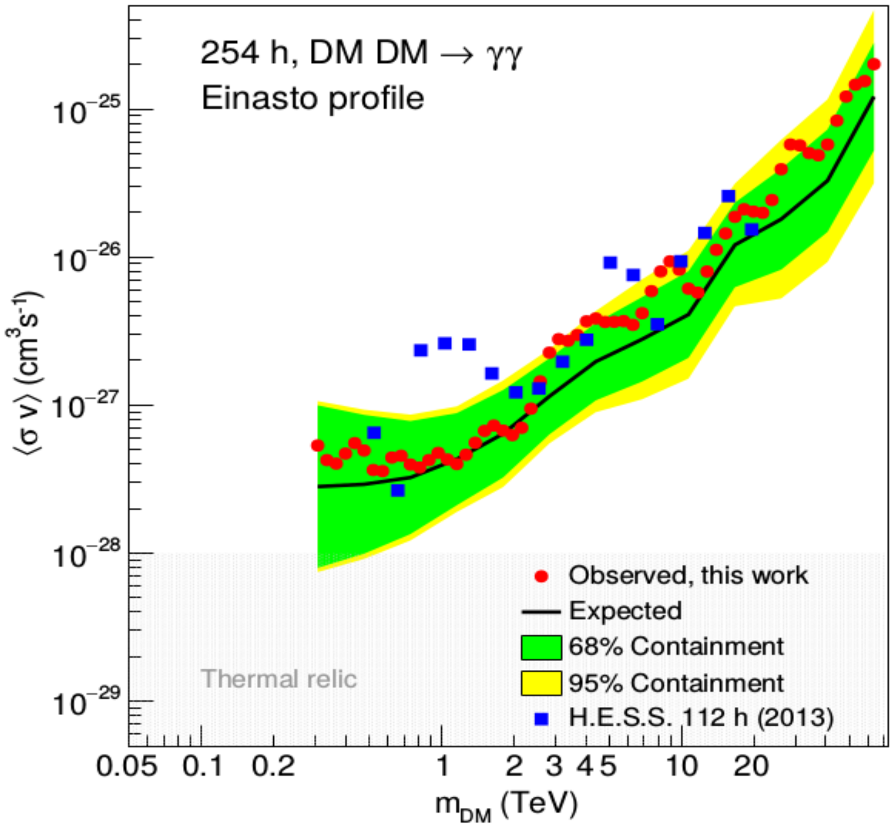
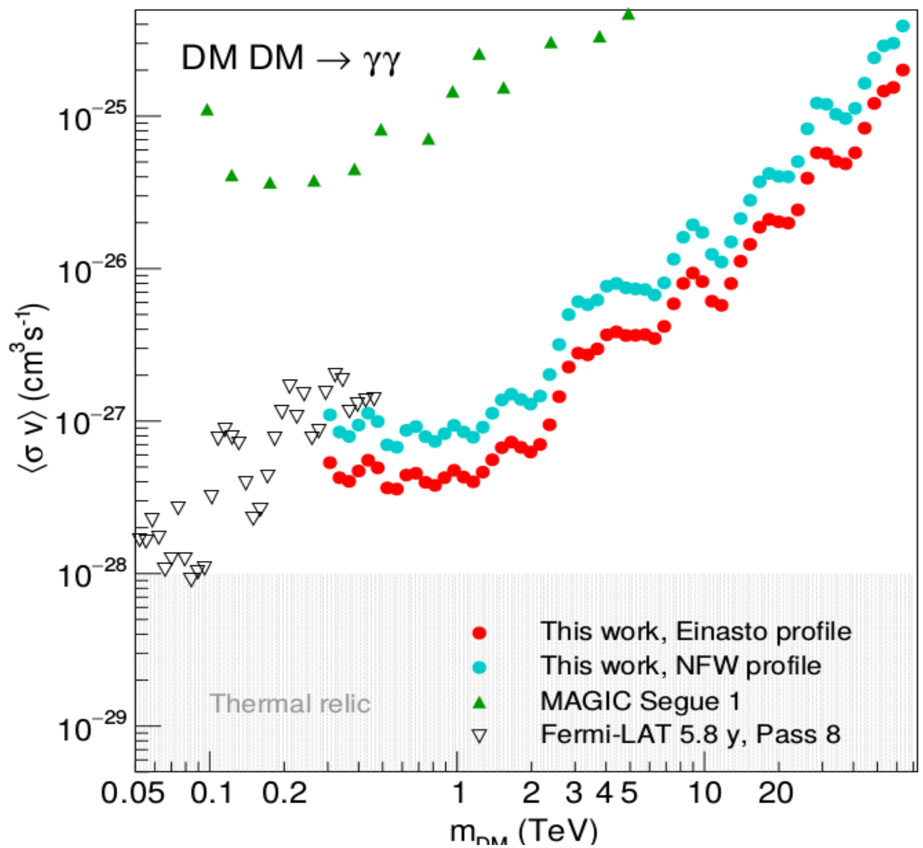
DM analysis with H.E.S.S. now makes use of both the spatial and spectral information of both signal and background
→ 2D-binned likelihood test ratio statistic technique

DM line search at the GC with H.E.S.S. I





Phys. Rev. Lett. 120, 201101 (2018)

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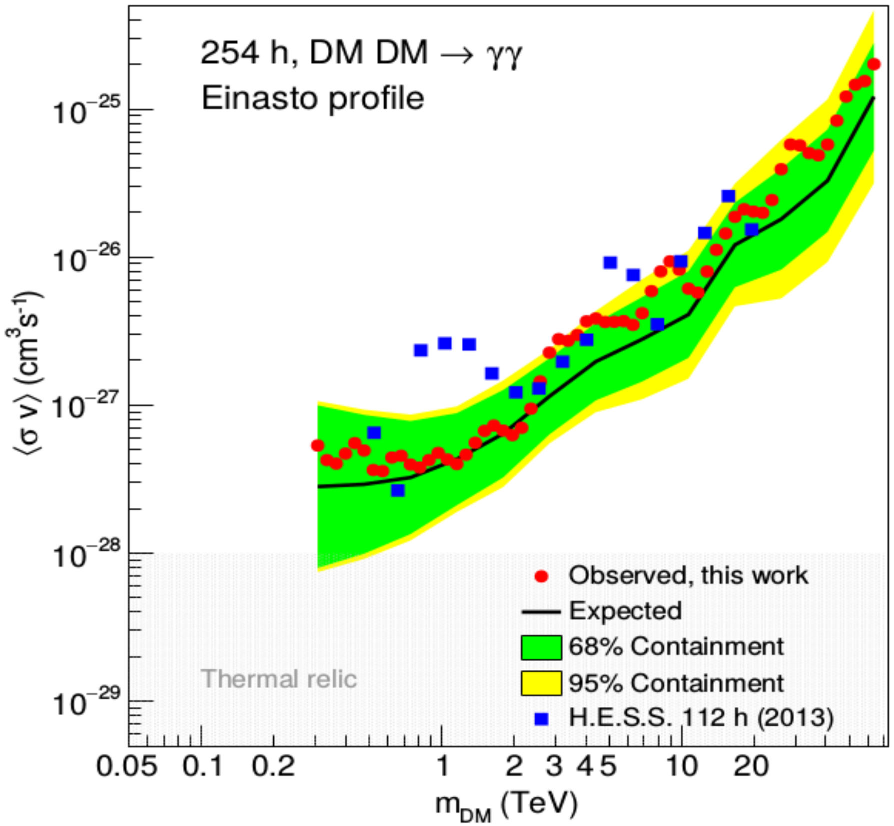

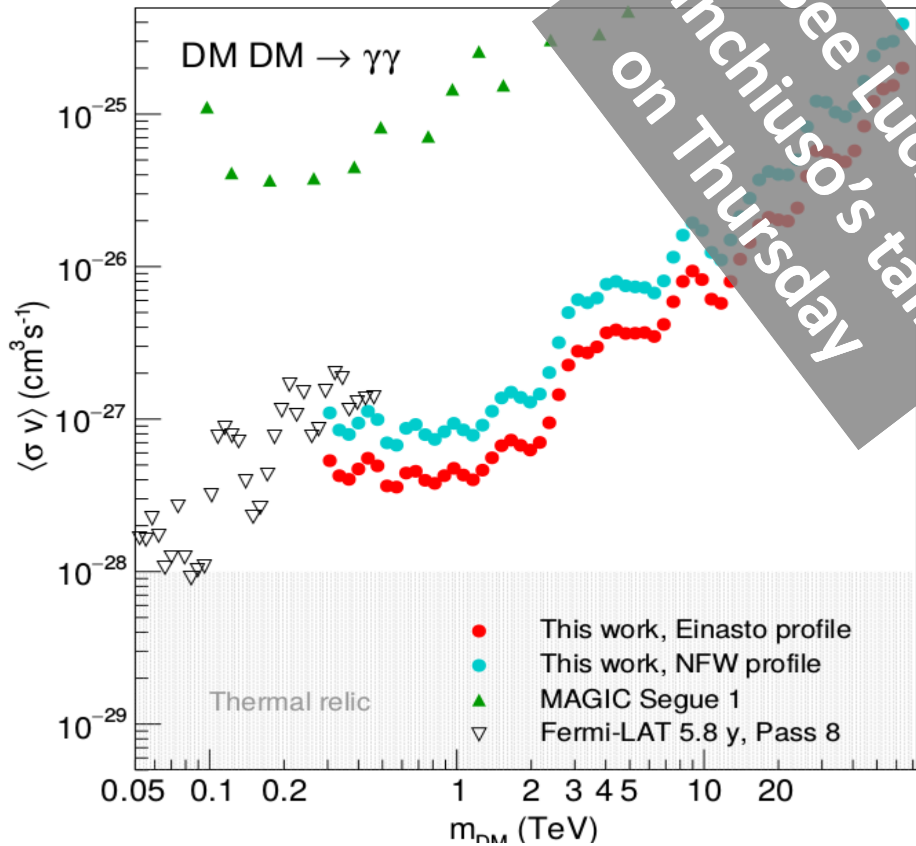

See Lucia Rinchiuso's talk on Thursday

Phys. Rev. Lett. 120, 201101 (2018)

- ***Caveat: for kpc-sized core profiles, limits weaken by two orders of magnitude***

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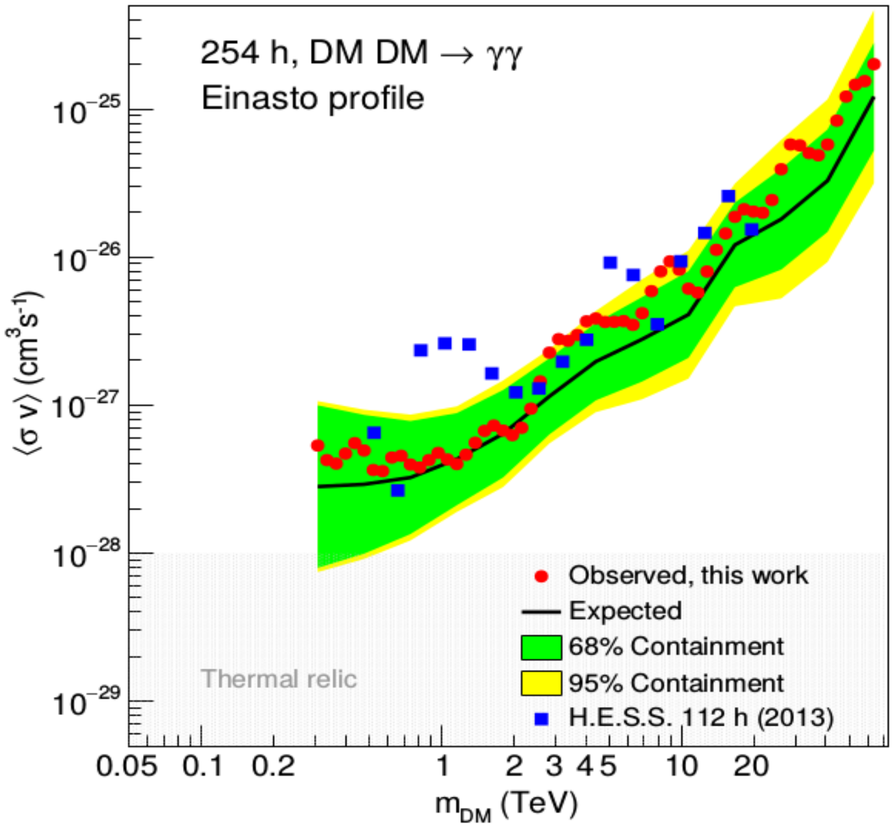

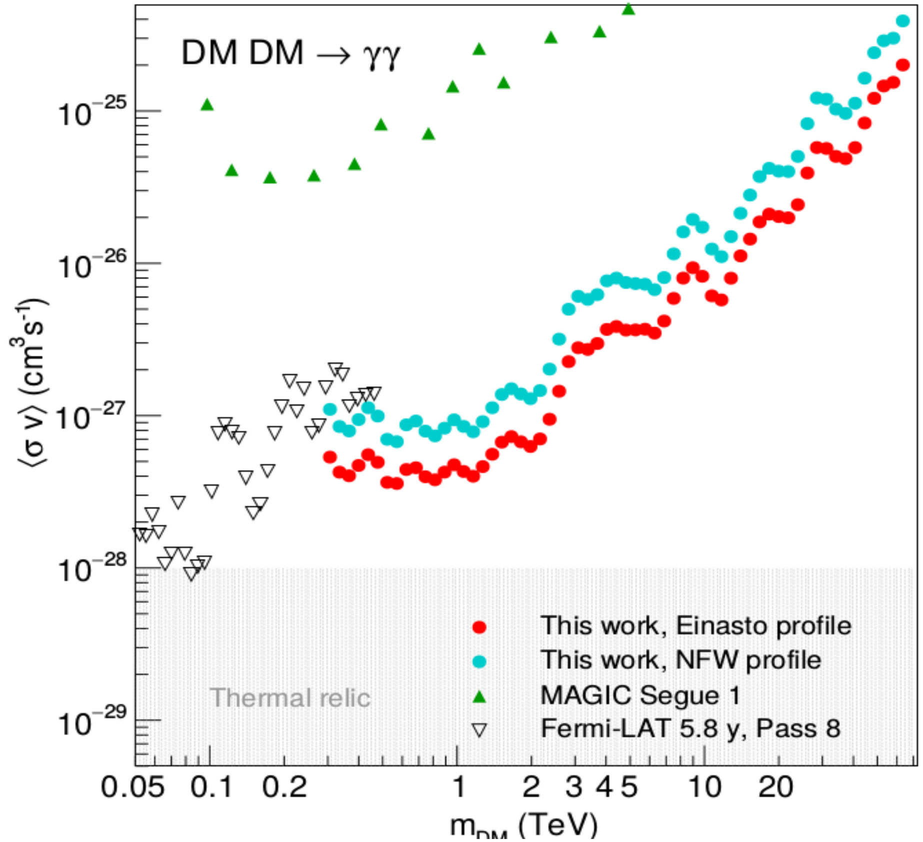

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- ***Fermi and H.E.S.S. provides strong limits in the mass range from few GeV up to several ten TeV***
- ***The GC region is the only DM target for which IACT sensitivity can probe the natural annihilation cross-section expected in WIMP models***

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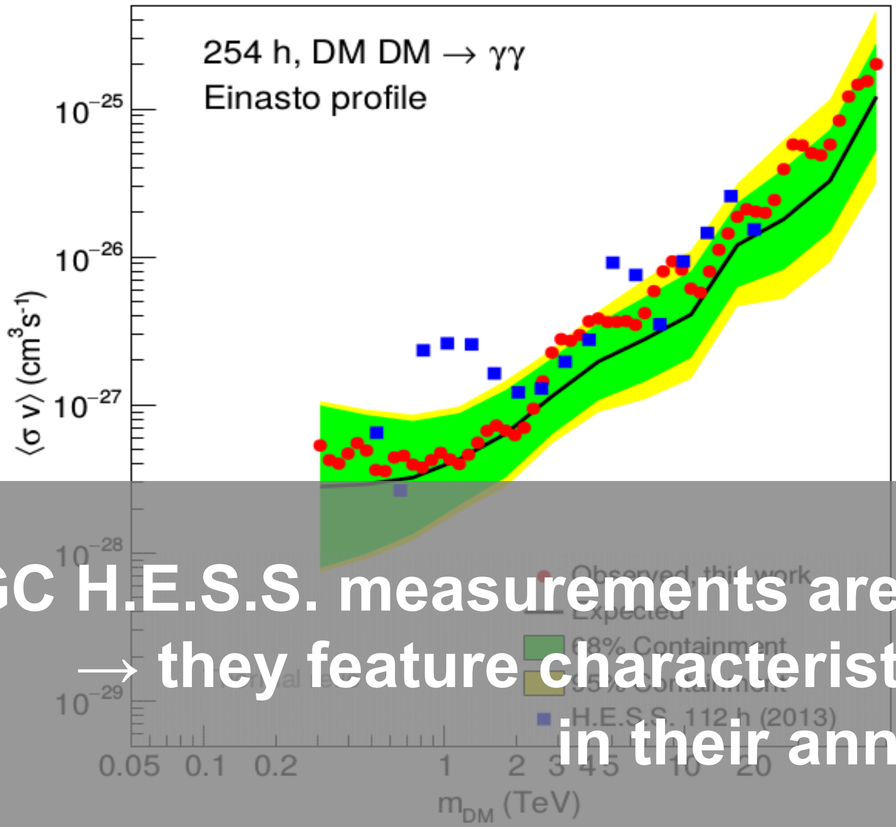

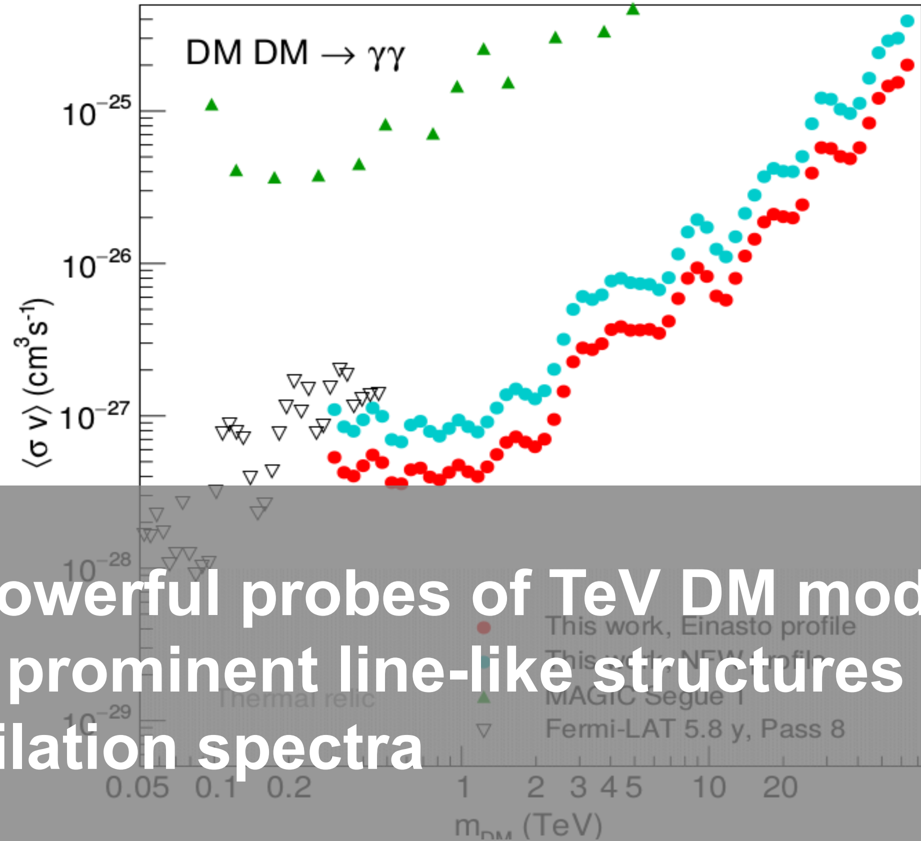

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GC H.E.S.S. measurements are powerful probes of TeV DM models → they feature characteristic prominent line-like structures in their annihilation spectra

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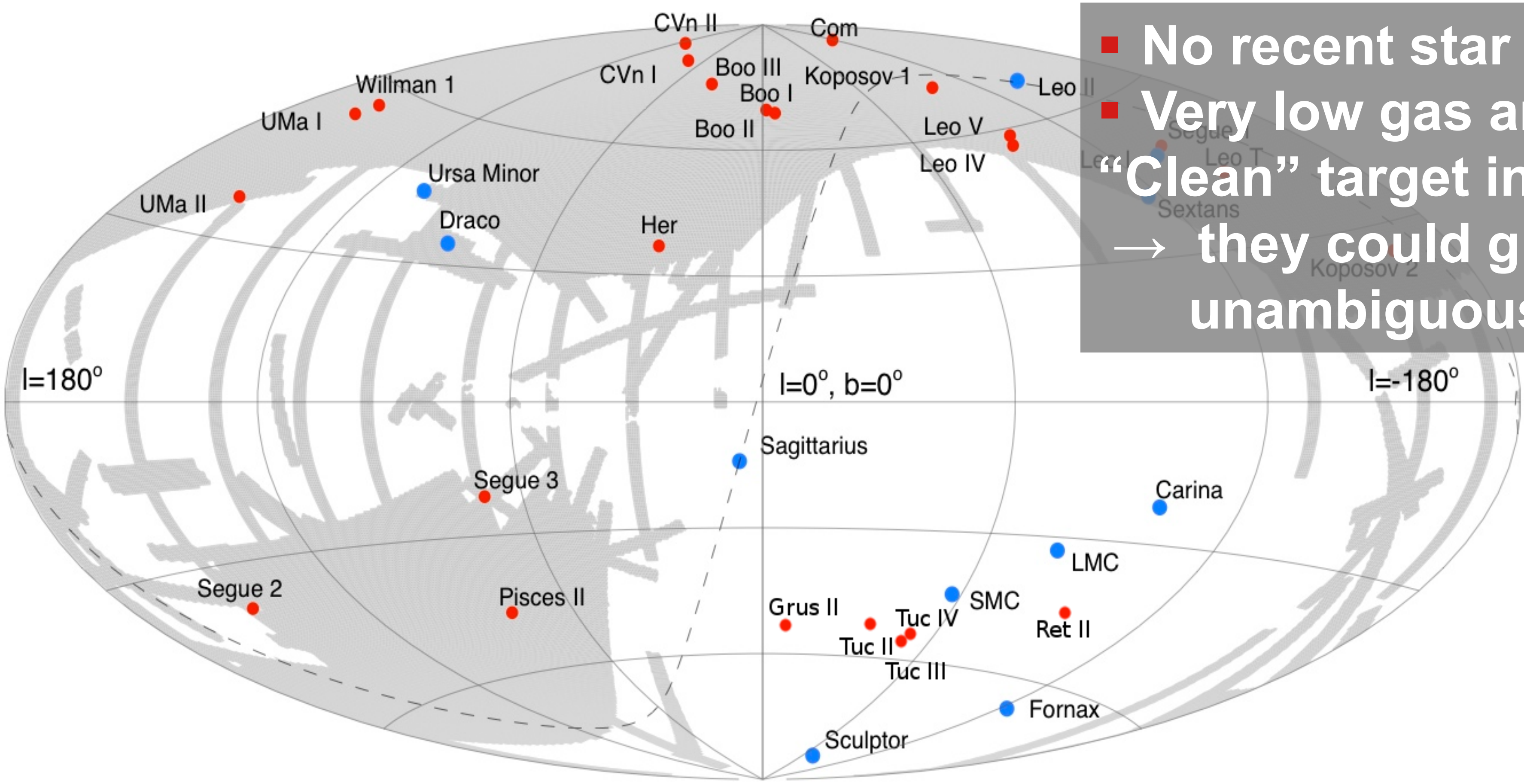
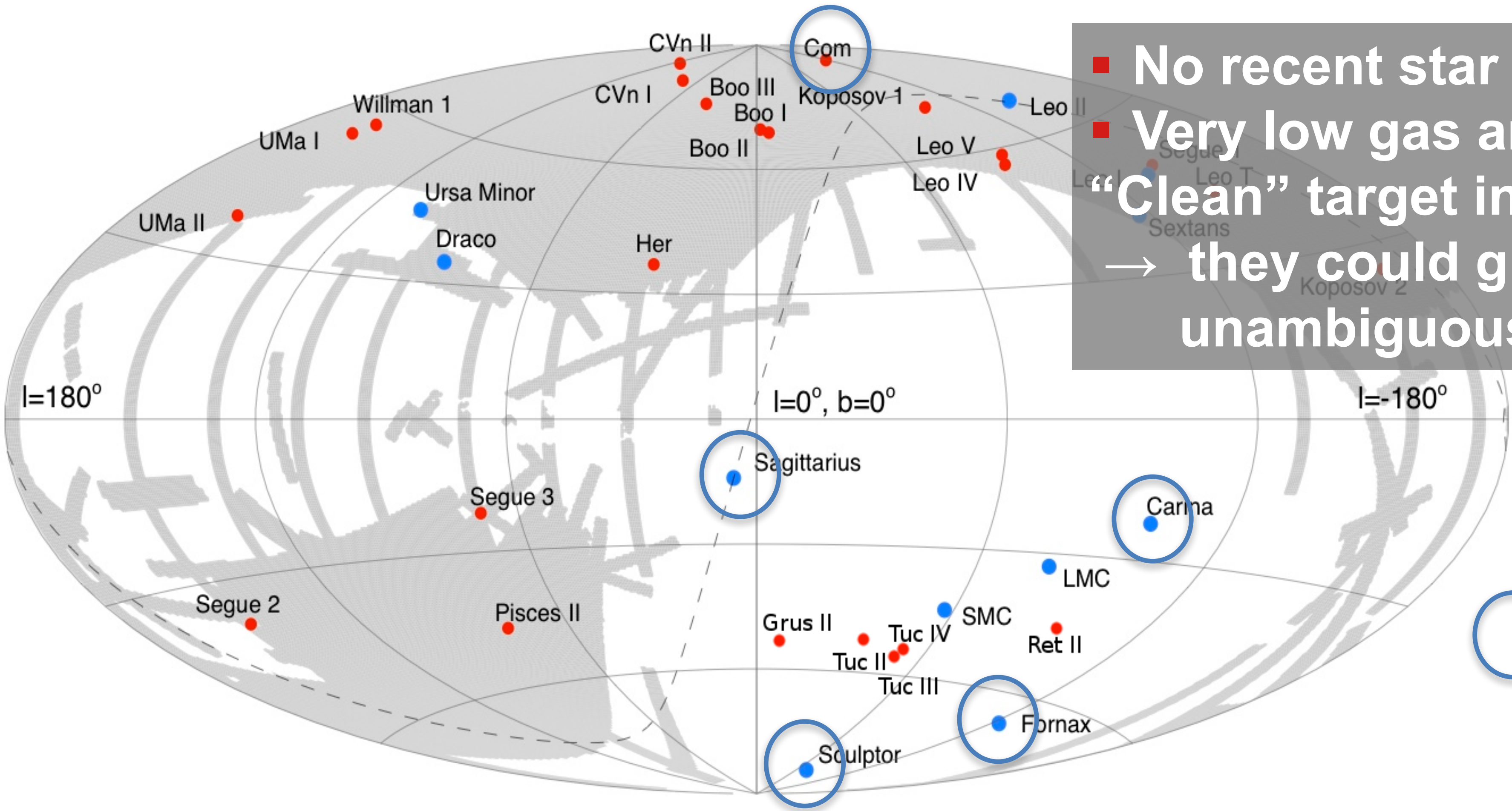
Nearby dwarf galaxy satellites



- No recent star formation
- Very low gas amount

"Clean" target in VHE γ-rays
→ they could give unambiguous detection

Dwarf galaxy observations with H.E.S.S.



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- Long-term observation program towards nearby dSph
- Dataset on LMC and SMC

H.E.S.S.

Dwarf galaxy observations with H.E.S.S.

CEA - Saclay

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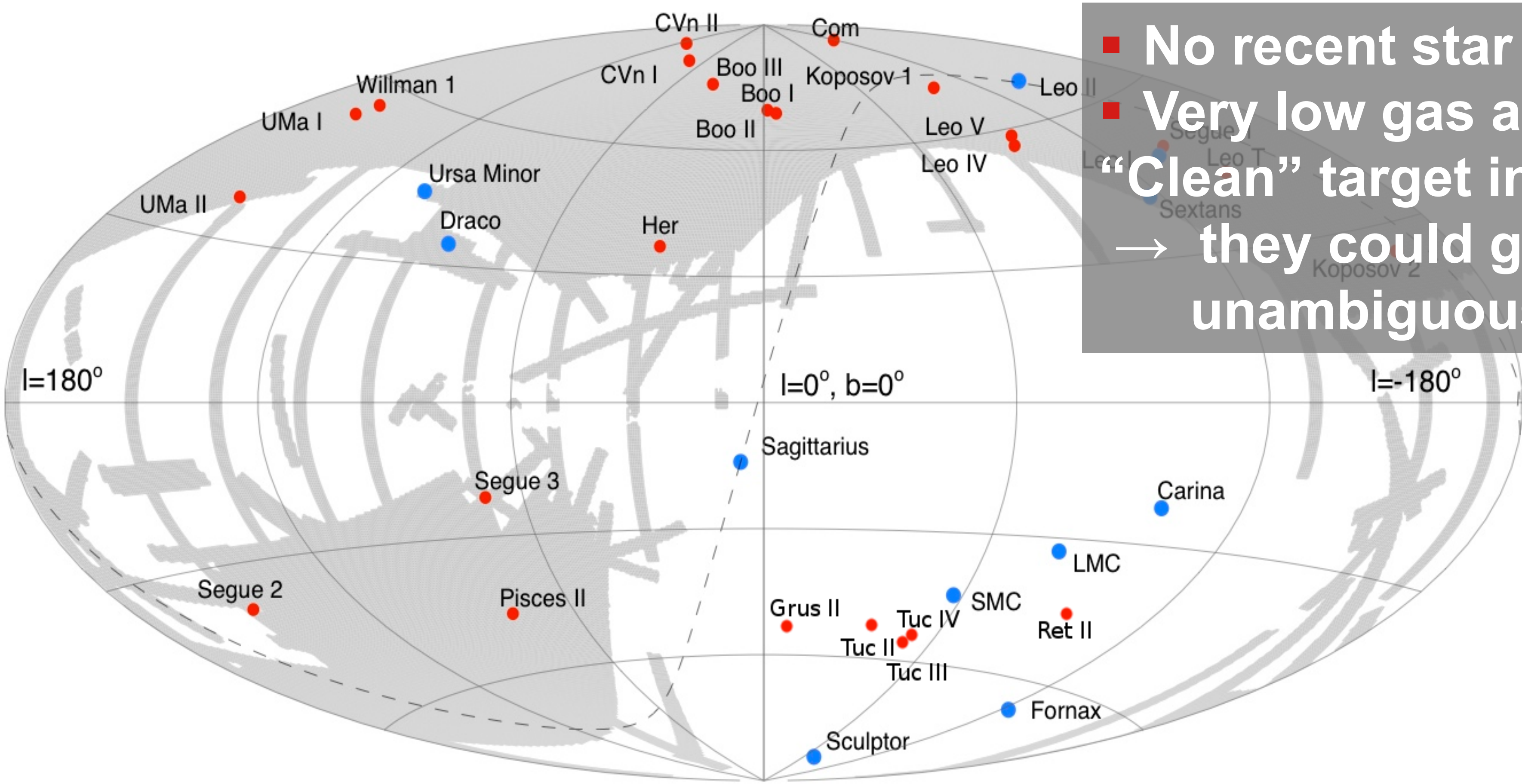

- Long-term observation program towards nearby dSph
- Datasets on LMC and SMC
- New DES (candidate) dSphs observed

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Searches towards dSph in TeV DM models

- Combined limit using 5 dSph datasets at the level of $5 \times 10^{-25}\,cm^3 s^{-1}$ for monoenergetic DM line from 1 TeV WIMP mass
- Tests of specific models: pure WIMP 3plet and 5plet
  → full γ-ray spectrum including WW, ZZ, γγ, Zγ contributions

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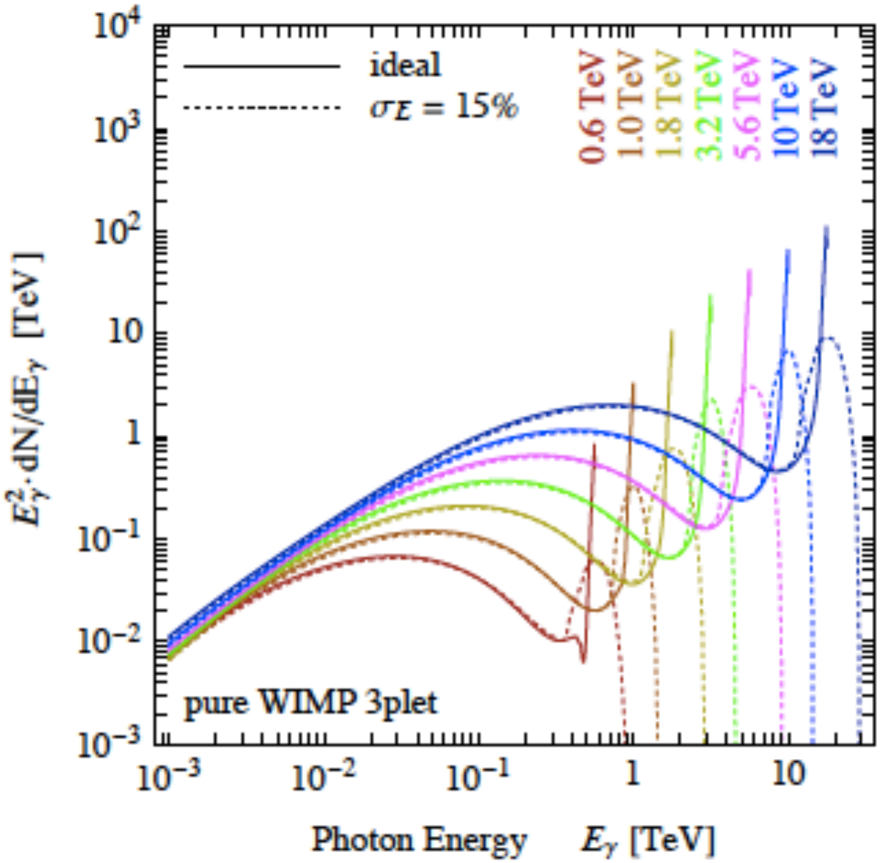

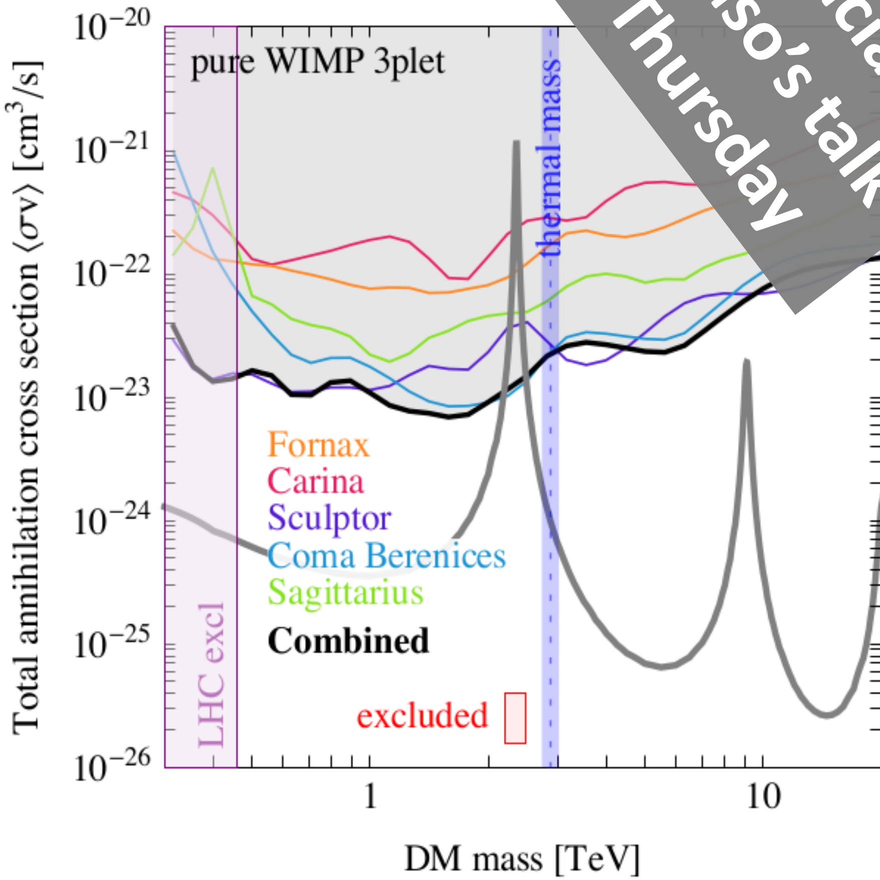

Submitted to JCAP (2018)

Combining all IACT dSph observations

Aim: Produce a global DM result combining all dSph observations by HESS, MAGIC and VERITAS

- Also exploring including Fermi-LAT and HAWC

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GLORY DUCK

- First meeting in Berlin last July, 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

Search for Lorentz Invariance Violation

- Lorentz invariance might be broken at energies close to the Planck scale $E_{Planck} \simeq 1.22 \times 10^{28}$ eV
  - Effective parametrization of LIV with modified dispersion relation for photons

$$E^2 \sim p^2 c^2 \left[1 \pm \left(\frac{E}{E_{QG}}\right)^n\right]$$

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VERY SMALL EFFECT, BUT IT CUMULATES ON LARGE DISTANCES

- **Main observables in VHE gamma rays:**
  - energy-dependent time delay in the arrival time of gamma rays traveling over astrophysical distance
    Amelino-Camelia et al. 1998 ; Ellis & Mavromatos 2013
  - deviations in the spectrum for LIV-modified pair production process w.r.t standard EBL absorption
    Stecker & Glashow 2001 ; Jacob & Piran 2008

LIV search with Mrk 501 – temporal study

- Energy-dependent time lag:

$$\tau_n \equiv \frac{\Delta t_n}{E_h^n - E_l^n} \simeq s_{\pm} \frac{n+1}{2 H_0} \frac{1}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} dz'$$

Energy lever arm

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Source distance parameter

LIV search with Mrk 501 – temporal study

- Energy-dependent time lag for two photons emitted at the same time:

$$\tau_n \equiv \frac{\Delta t_n}{E_h^n - E_l^n} \simeq s_{\pm} \frac{n+1}{2H_0} \frac{1}{E_{QG}^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}} dz'$$

Prerequisite for sources :

- Distant
- Variable or transient
- Energetic

→

Flaring blazars are promising target to look for LIV signatures:

- Bright flares detected at very high energies
- Short-time flux variability (down to minute timescale)
- Good statistics with IACTs

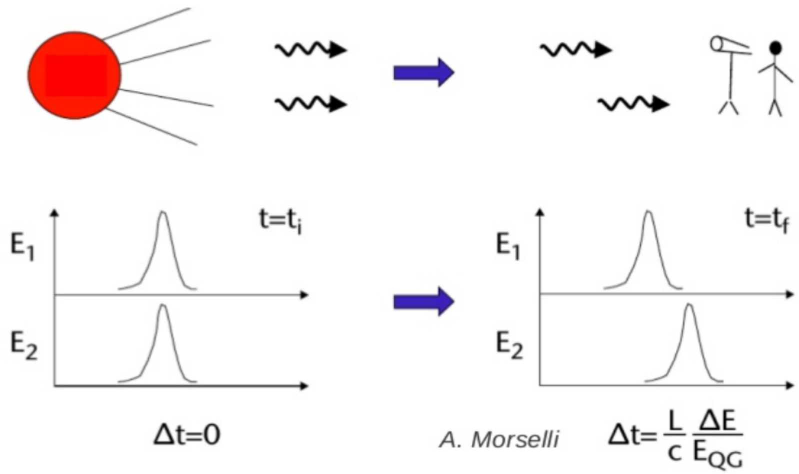
Caveat:

- Flares happen randomly
- Hints of intrinsic temporal effects
- Details of emission mechanisms poorly understood

LIV search with Mrk 501 – temporal study

- Energy-dependent time lag:

$$\tau_n = \frac{\Delta t_n}{\Delta E^n} = \pm \frac{n+1}{2} \frac{1}{E_{QG}} \int_0^z \frac{(1+z')^n}{H(z')} dz'$$



- **Target : Markarian 501**, blazar at a redshift z=0.034
  - flare detected in 2014 up to 20 TeV energies
    - evidence for multi-TeV flux variations on timescales of minutes
    - no significant time lag in two energy bins

      → used to constraint E_{QG}

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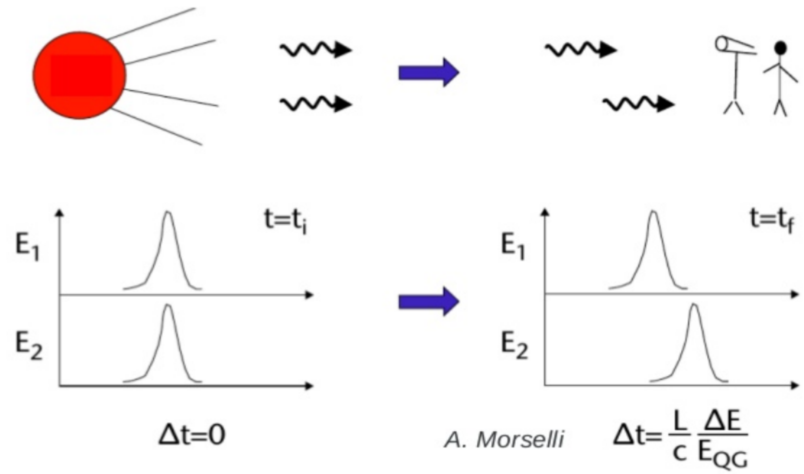

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95% C.L. lower limits

E_{QG} (GeV)	Linear case (n=1)	Quadratic case (n=2)
Subluminal	3.6×10^{17}	8.5×10^{10}
Superluminal	2.6×10^{17}	7.3×10^{10}

- **Improvement due to the high energy sample**
  → good prospects for the future studies
- **One of the best limit with a blazar**

LIV search with Mrk 501 – spectral study

- The observed VHE spectrum of a blazar at redshift z_s
  - Intrinsic spectrum
  - EBL attenuation effect

$$\Phi_{\rm obs}(E_\gamma) = \Phi_{\rm int}(E_\gamma) \times e^{-\tau(E_\gamma, z_s)}$$

- Optical depth of gamma- rays from pair production on EBL

$$\tau(E_\gamma, z_s) = \int_0^{z_s} dz \frac{dl}{dz} \int_{\epsilon_{thr}}^{\infty} d\epsilon \frac{dn_{\rm EBL}}{d\epsilon}(\epsilon, z) \int_0^2 d\mu \frac{\mu}{2} \sigma_{\gamma\gamma}(s)$$

Threshold photon energy for pair production

Pair production cross section

LIV search with Mrk 501 – spectral study

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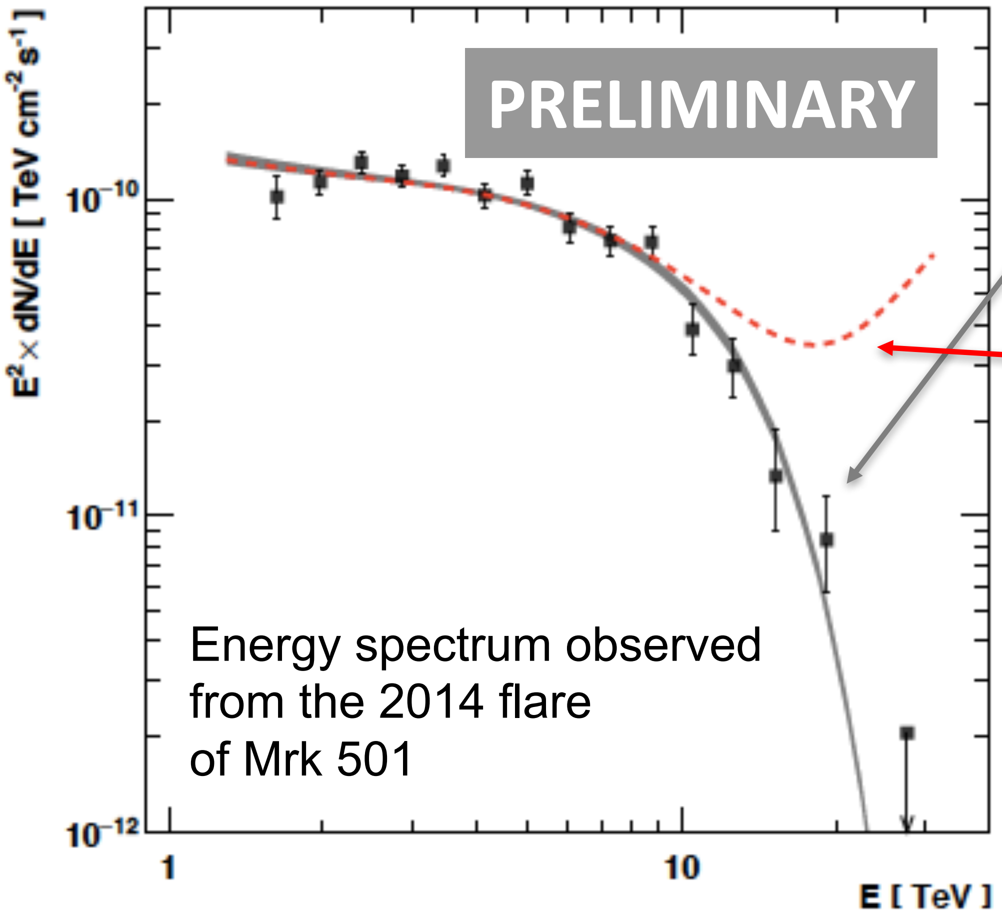
Threshold photon energy for pair production

Pair production cross section

- The perturbation from LIV in the dispersion relation propagates into the EBL optical depth :
  - the center-of-mass energy squared s, and
  - the threshold energy for pair production are modfiied with an extra term

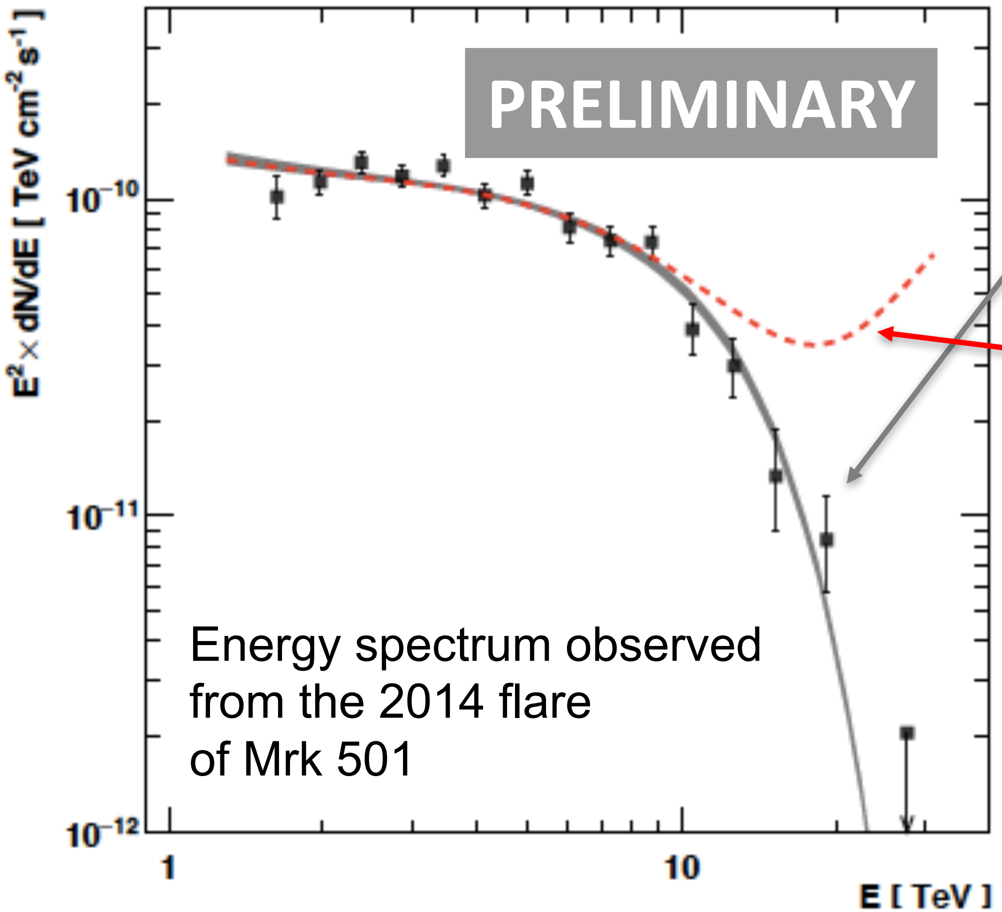
Tavecchio & Bonnoli 2016

LIV search with Mrk 501 – spectral study



- Best-fit EBL-attenuated power law
- Expected spectrum for the same intrinsic shape considering subluminal LIV with $E_{QG,n=1} = E_{Planck}$

LIV search with Mrk 501 – spectral study



<u>Caveat:</u> Excess of transparency of the Universe to rays could also be caused by the conversion of photons to axion-like particles in magnetic filelds

- Best-fit EBL-attenuated power law
  EBL SED of Franceschini et al. (2008)
- Expected spectrum for the same intrinsic shape considering subluminal LIV with $E_{QG,n=1} = E_{Planck}$
- No significant deviations with respect to standard EBL attenuation at energies above 10 TeV
  → put constraints on E_{QG}

H.E.S.S.

CEA - Saclay

LIV search with Mrk 501 – spectral study

- Optical depth of gamma- rays from pair production on EBL

$$\tau(E_\gamma, z_s) = \int_0^{z_s} dz \frac{dl}{dz} \int_{\epsilon_{thr}}^{\infty} d\epsilon \frac{dn_{\text{EBL}}}{d\epsilon}(\epsilon, z) \int_0^2 d\mu \frac{\mu}{2} \, \sigma_{\gamma\gamma}(s)$$

95% C.L. lower limits

E_{QG} (GeV)	Linear case (n=1)	Quadratic case (n=2)
Subluminal	2.6×10^{19}	7.8×10^{11}

In the linear case, E_{Pl} is excluded at the 5.8σ level

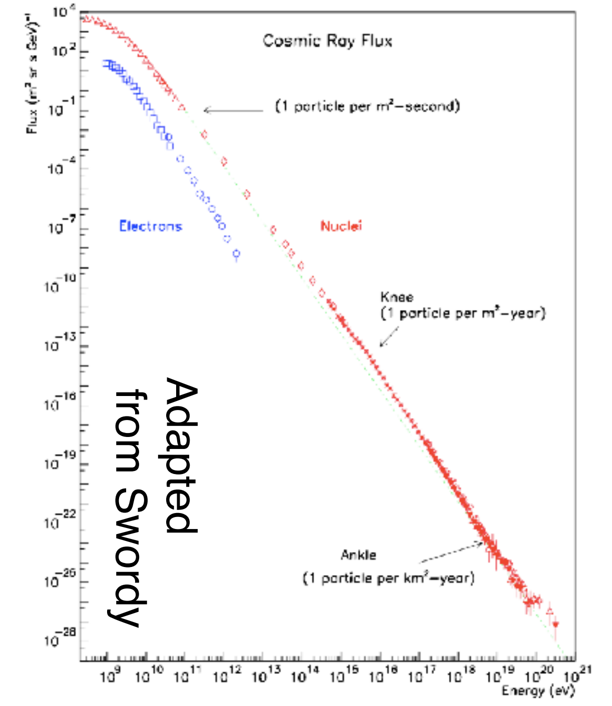
- These Planck-scale limits on linear LIV are competitive with the best limits obtained considering time delays with GRBs

- Best existing limit on quadratic LIV perturbations to the dispersion relation of photons.

Cosmic-ray electron+positron spectrum

- Only small fraction of Cosmic Rays are electrons:
→ Very low fluxes at TeV energies

- Energy loss by inverse Compton scattering and synchrotron radiation
  - Propagation of TeV e-/e+ limited to ~1 kpc
  - TeV e± must have been injected not much longer than ~10^5 yr ago

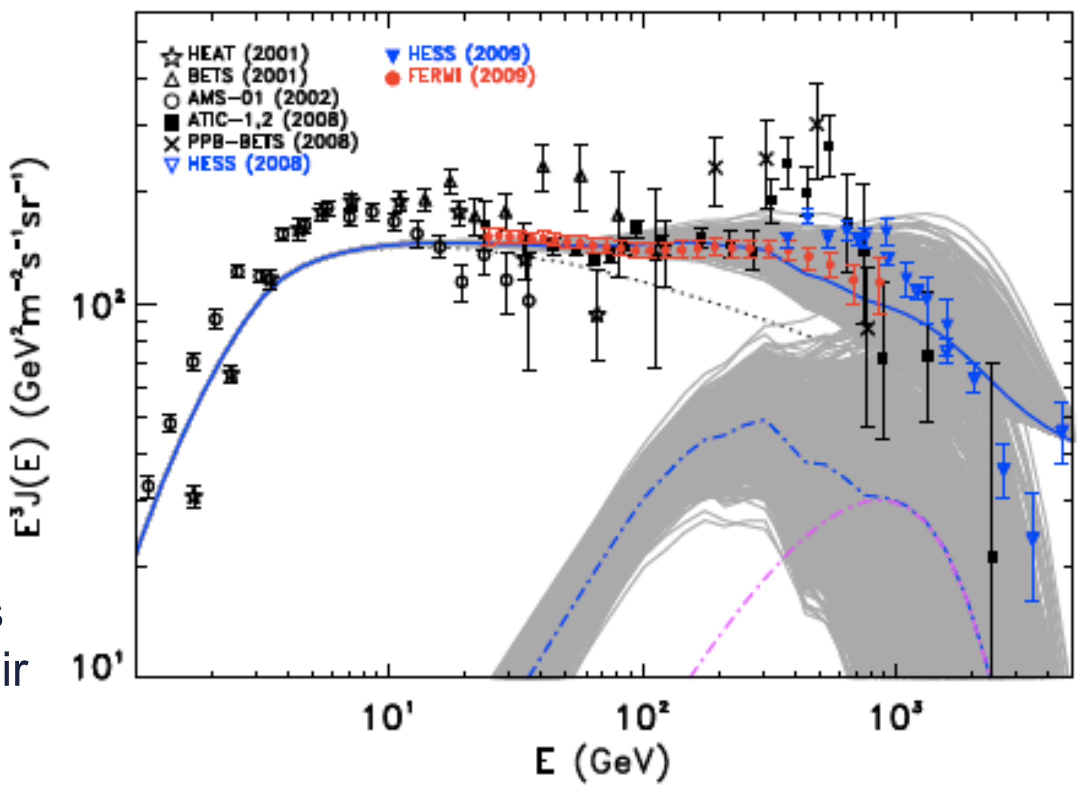


Cosmic-ray electron+positron spectrum

- Energy loss by inverse Compton scattering and synchrotron radiation
  - Propagation of TeV electrons/positrons limited to ~1 kpc
  - TeV e± must have been injected not much longer than ~10^5 yr ago

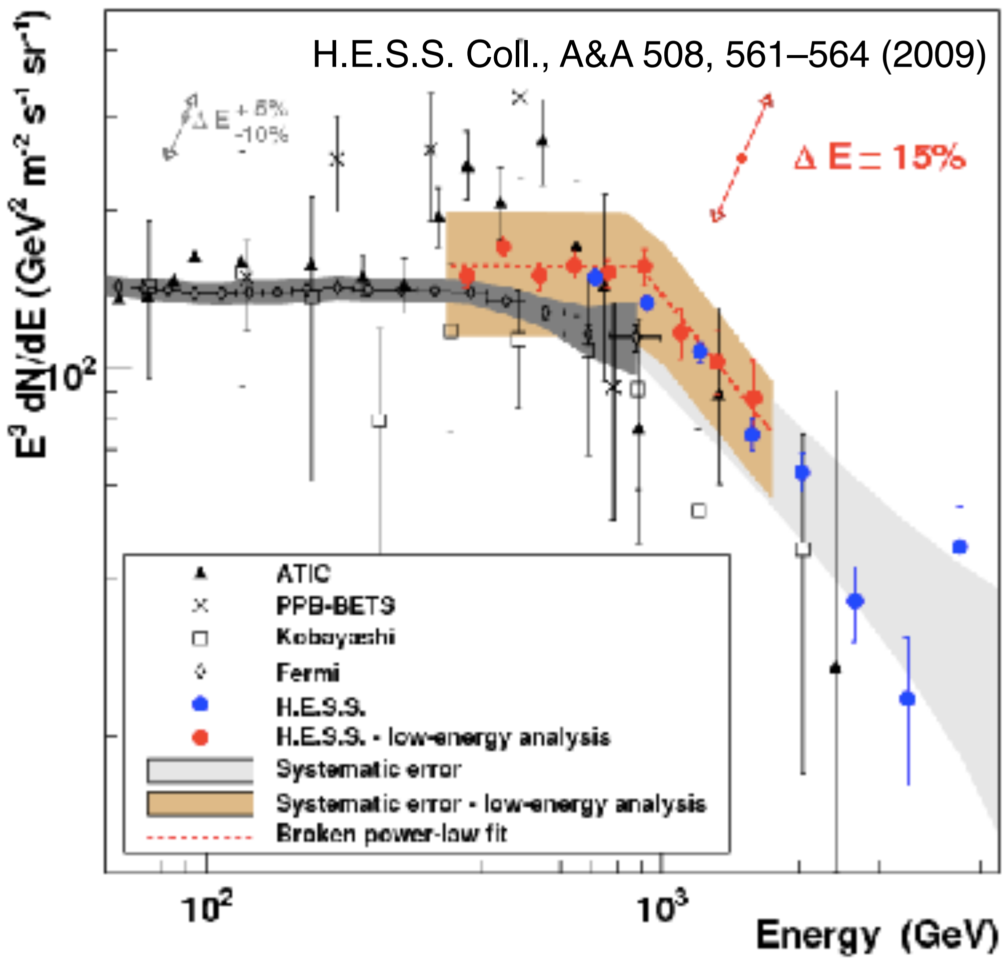
- Only limited number of nearby accelerators can contribute to the overall spectrum, e.g. Vela, Monogem

- Shape of the spectrum very sensitive to both propagation characteristics and source properties:
  - distribution and number of sources in our Galactic neighbourhood, their individual properties



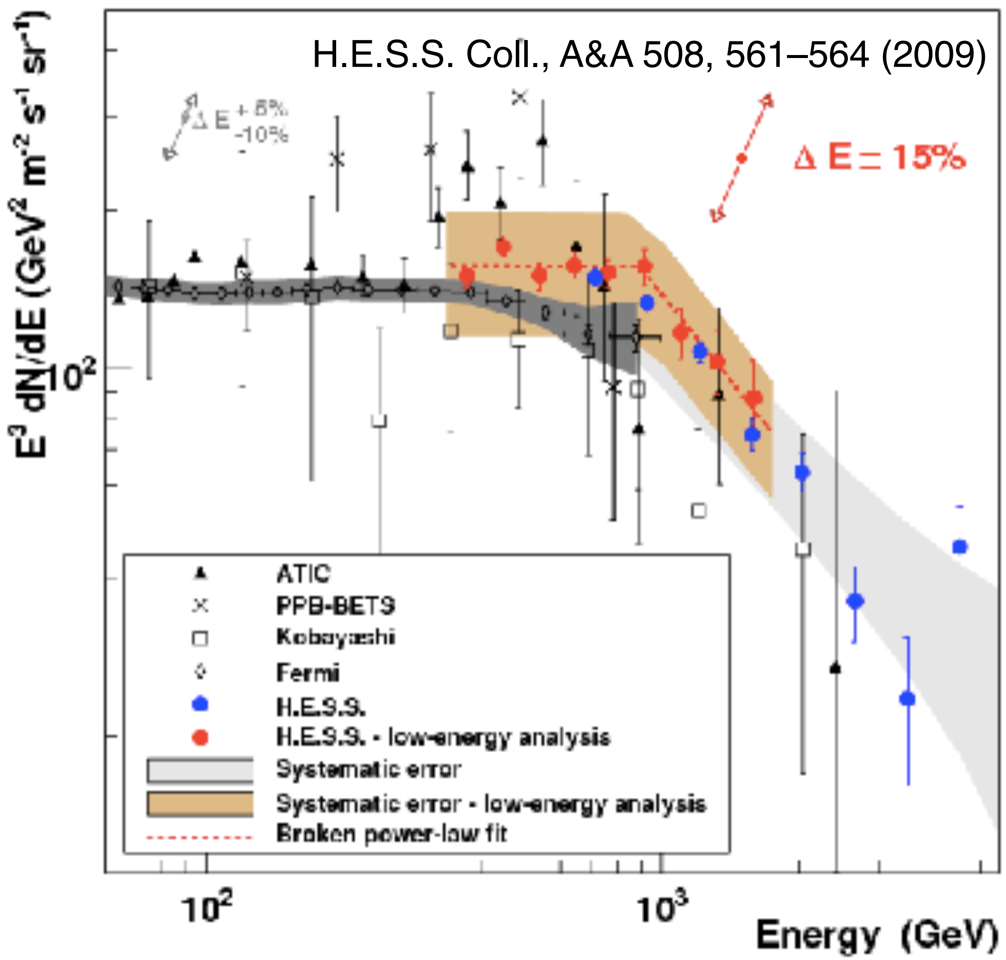
Grasso et al., Astropart. Phys. 32, 2 (2009)

The H.E.S.S. CR electron spectrum



- Discovery of break at 1 TeV
- Measurement dominated by systematic uncertainties due to hadronic interaction model and atmospheric uncertainties

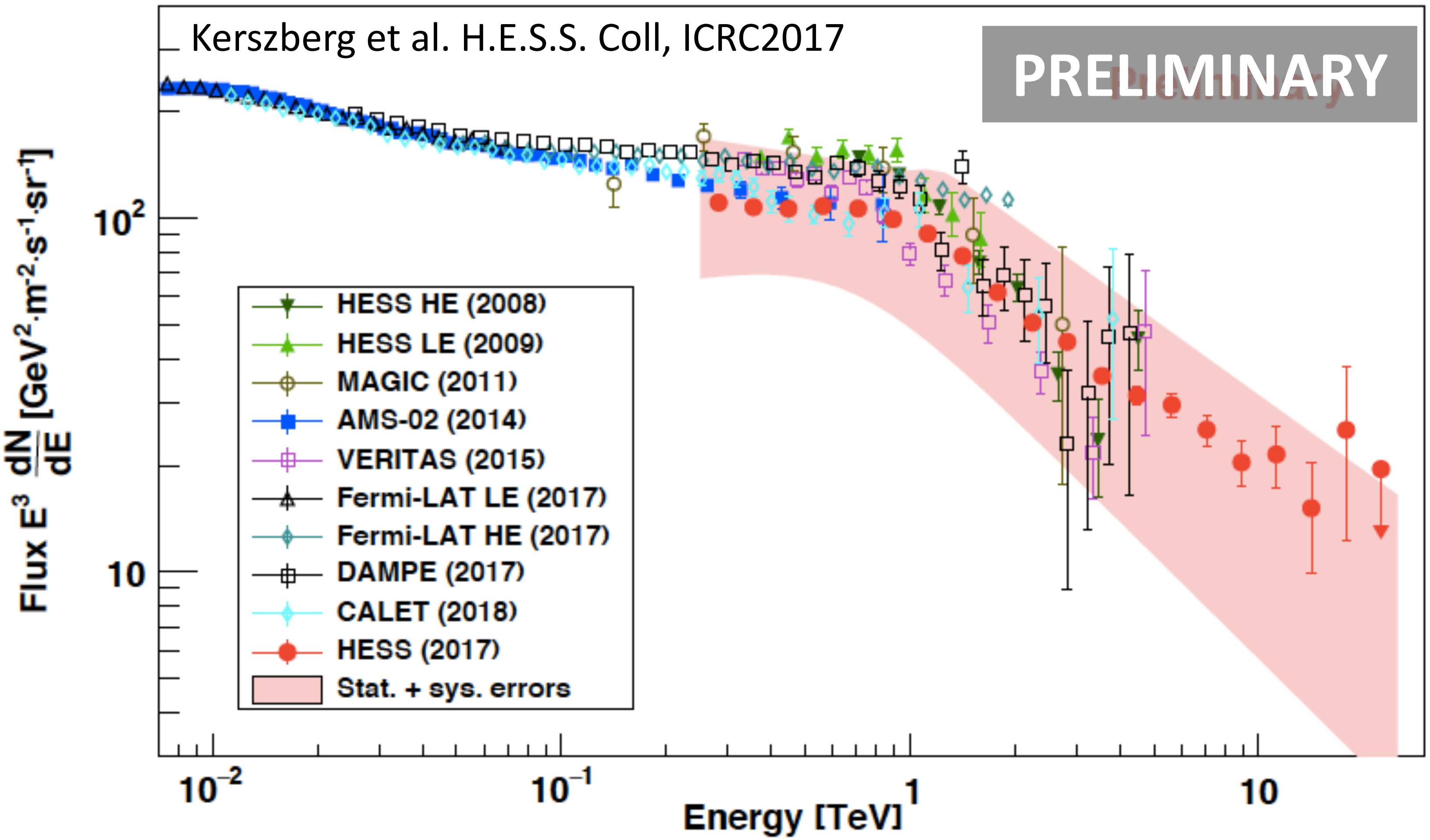
The H.E.S.S. CR electron spectrum



- Discovery of break at 1 TeV
- Measurement dominated by systematic uncertainties due to hadronic interaction model and atmospheric uncertainties

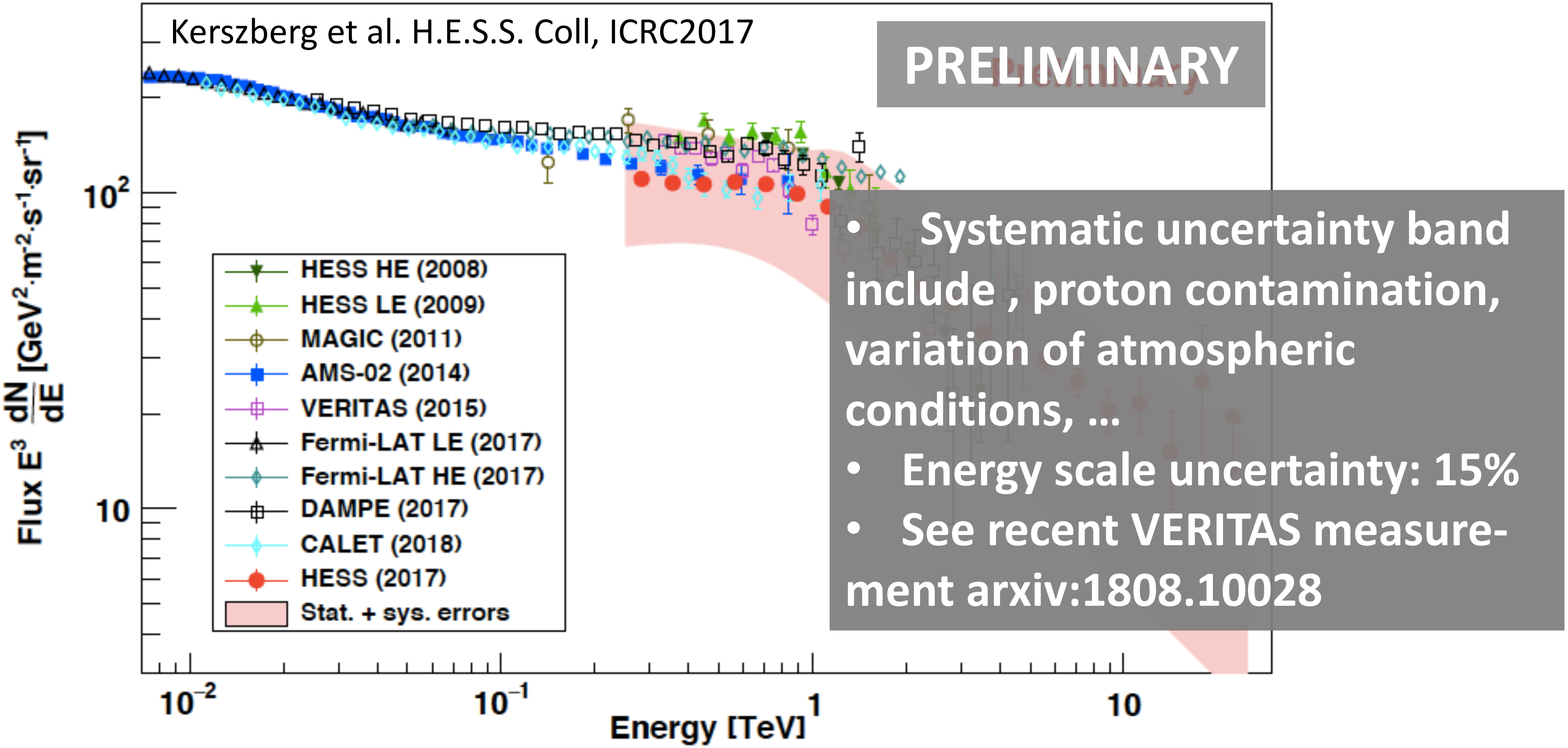
- Between 2008 and 2018: increased data set - 239 h → 1186 hours
- Improvements in the analysis methods yielding a higher hadron rejection
- Discrimination based on goodness of fit
  → standard H.E.S.S. analysis

The new H.E.S.S. CR electron spectrum



- Broken power-law spectrum without any significant structure up to 20 TeV
  - confirmation of the energy break at around 1 TeV
- H.E.S.S. is consistent with both, AMS & CALET and Fermi & DAMPE

The new H.E.S.S. CR electron spectrum



- Broken power-law spectrum without any significant structure up to 20 TeV
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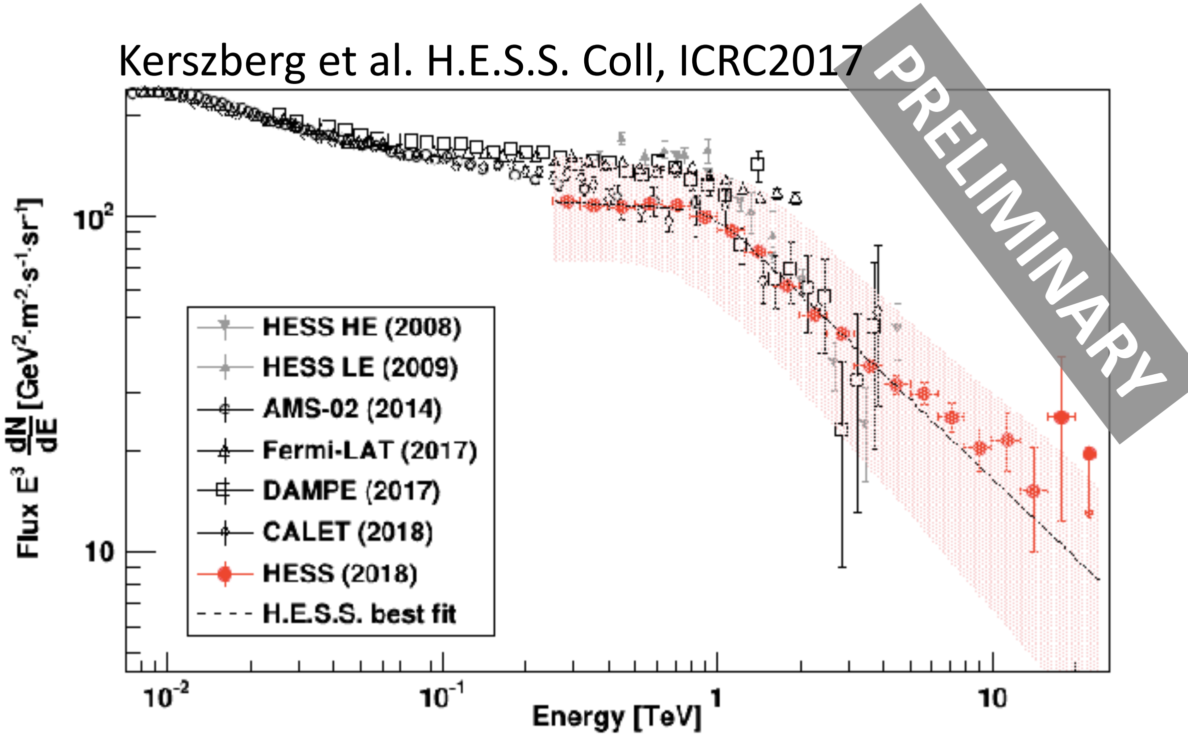
What can we learn ?

- There are no features of local accelerators in the spectrum
  - Very existence of TeV electrons points to an accelerator within ~1 kpc
  - Constraint to local source model
- No apparent features of dark matter
- Nature of the break at 1 TeV?
  - Related to the accelerator?
  - Propagation effect?

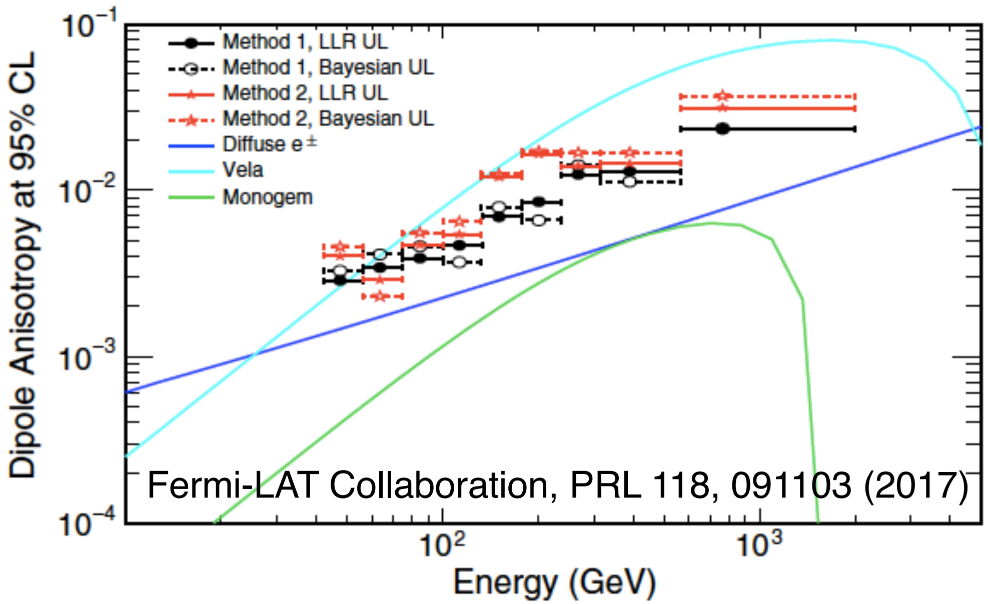
Kerszberg et al. H.E.S.S. Coll, ICRC2017



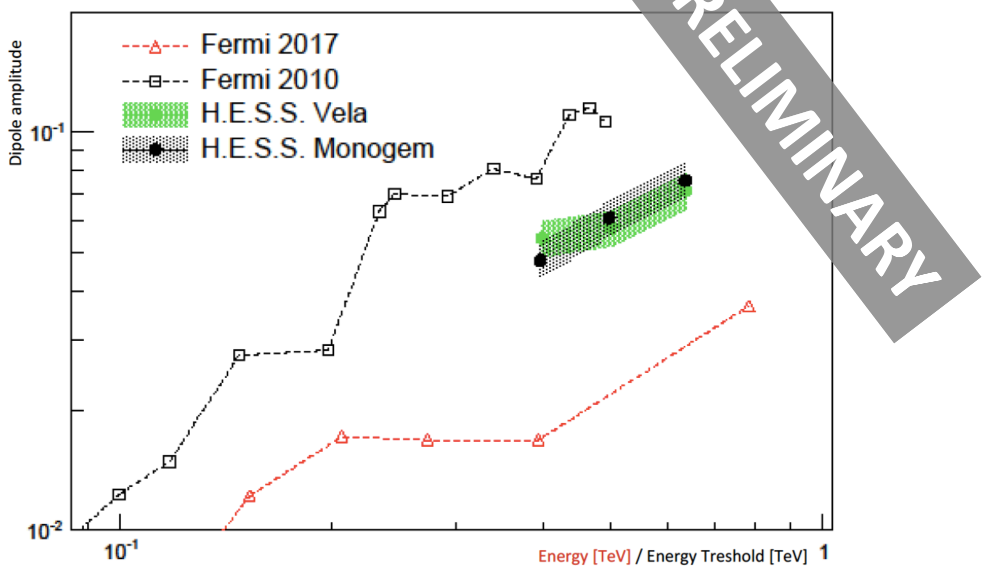
- What room is there for continuation of the spectrum?

CR electron anisotropy ?

- Expected at VHE energies due to limited number of sources, increasing with energy



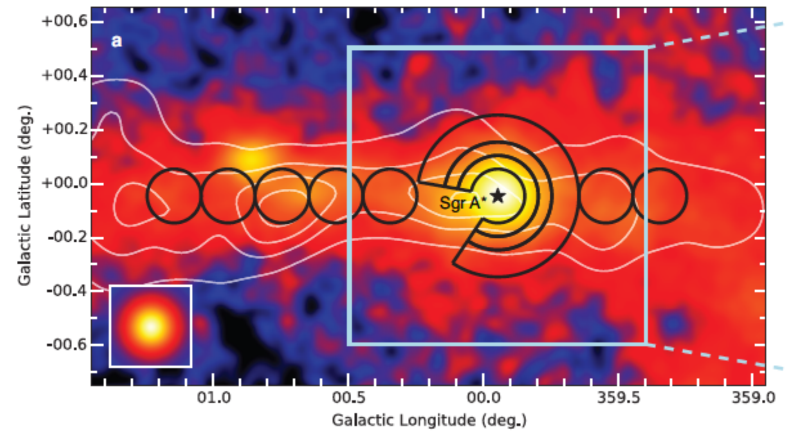
H.E.S.S. Coll. M. Kraus, et al. ICRC 2017



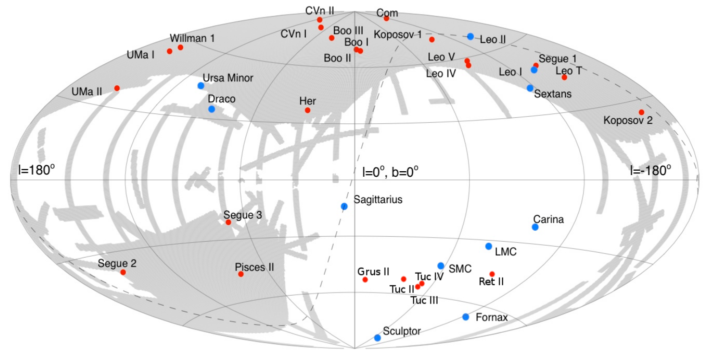
- Upper limits on dipole anisotropy by e.g. AMS (up to 100 GeV), Fermi-LAT (up to ~1 TeV)
- Challenging for ground-based instruments:
  - pointed observations/ sensitivity based on pointing pattern
  - normalisation uncertainty due to systematics

H.E.S.S. Astroparticle Physics programme

- Strategy for WIMP Dark Matter searches
  - Galactic Center
    - H.E.S.S. is pursuing an Inner Galaxy Survey (IGS) programme up to several degrees from GC



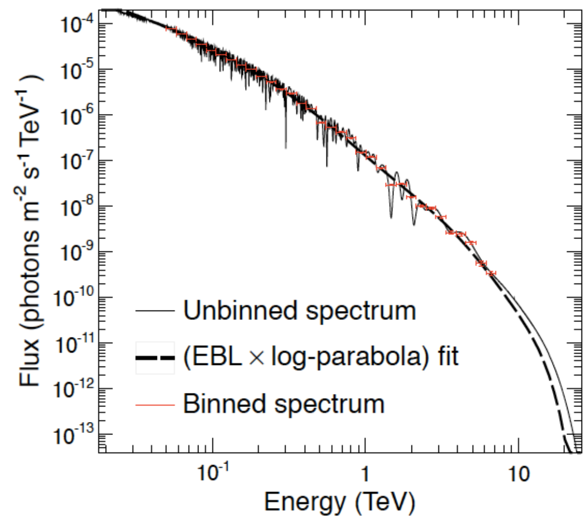
  - Dwarf galaxies
    - Combination of dSph observations by H.E.S.S., MAGIC and VERITAS
    - New (candidate) dSphs detected by DES have been observed
    - Will focus on the most promising dSphs



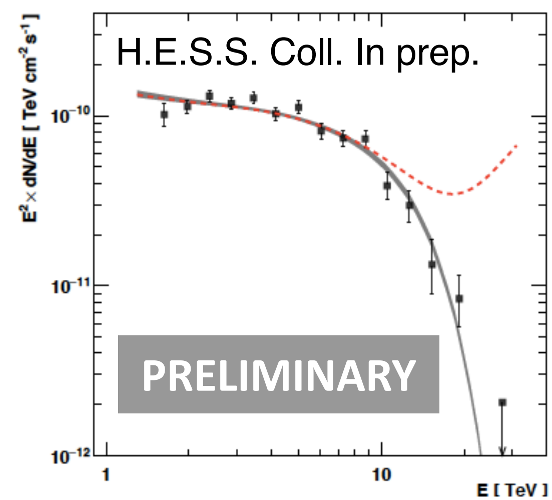
- Specific DM models with TeV spectral features can be tested

H.E.S.S. Astroparticle Physics programme

- Axion-like particle searches with AGN
  - Search for spectral irregularities
  - Bright AGNs located in galaxy clusters
    - with high meaured central magnetic field



- Tests of Lorentz Invariance
  - Bright and flaring distant sources, e.g. AGN
    - follow-up of alerts issued by other exp.
    - combination of data from H.E.S.S., MAGIC and VERITAS



- Intergalactic magnetic fields
  - Bright and Hard spectrum ($\Gamma < 2$) sources:
    - extreme HBL blazars

Summary and outlook

- H.E.S.S.-I observations of the inner GC halo put the strongest constraints for TeV dark matter
- Combination of dSph observations by H.E.S.S., MAGIC and VERITAS started
- A survey of the inner Galaxy is being carried out by H.E.S.S.
- First CR electron spectrum measured up to ~20 TeV
- Spectral studies for linear LIV searches probe the Planck scale
- The rich H.E.S.S. astroparticle physics programme will hopefully continue over the next few years till the advent of CTA