The Galactic Center
seen at very high energies

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13th Rencontres du Vietnam
Exploring the Dark Universe 2017
Why VHE gamma rays?

- Effectively produced through electromagnetic and hadronic interaction at the sources or in their vicinity
  - inverse Compton of electrons/positrons off ambient photons
  - inelastic collisions of protons/nuclei with gas
  - dark matter annihilation
- Effectively photon-by-photon detected by ground-based instruments with > $10^5$ m$^2$ effective detection area

... but effectively interact with matter, radiation and B-field
  → information could arrive with some distortion
Why VHE gamma rays?

- Effectively *produced* through electromagnetic and hadronic interaction at the sources or in their vicinity
- Effectively *detected* by ground-based instruments
- … but effectively interact with matter, radiation and B-field: information could arrive with some distortion

→ provide unambiguous proof of particle acceleration beyond TeV energies
→ provide mapping of acceleration/propagation/creation sites
→ provide direct tracer of relativistic proton populations
**Gamma-rays from $pp$ interaction**

CRs deflected by magnetic fields

Molecular gas clouds illuminated by cosmic rays → Gamma-rays and gas are spatially correlated

\[ p + p_{ISM} \rightarrow \pi + \chi \]

\[ \pi^0 \rightarrow \gamma + \gamma \]

\[ \pi^\pm \rightarrow \mu^\pm + \nu \]

Graph showing the energy distribution of gamma-rays and neutrinos.
\( \gamma \)-rays penetrating in the atmosphere

Electromagnetic cascade

Cherenkov light

Light flash \(~10 \text{ ns}\)

Light pool \(~100 \text{ m radius on ground, Few photons per m}^2\)
\( \gamma \text{-rays penetrating in the atmosphere} \)

Electromagnetic cascade

Current IACTs:
- 2 - 5 telescopes
- 500-2000 pixel cameras
- 3.5 - 5.0° field of view
- \( \sim 0.1 \)° angular resolution
- \( \sim 10\% \) energy resolution
- flux sensitivity (50 h) \(< 1\% \) Crab
- \( \sim 30 \text{ GeV} < E < \sim 50 \text{ TeV} \)

Light flash \( \sim 10 \text{ ns} \)

Light pool \( \sim 100 \text{ m radius on ground}, \) Few photons per \( m^2 \)
γ-rays penetrating in the atmosphere

Electromagnetic cascade

Light flash ~10 ns

Light pool ~ 100 m radius on ground, Few photons per m²

γ-rays penetrating in the atmosphere

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Crab ~30 GeV < E < ~50 TeV
Ground-based Cherenkov Telescopes

MAGIC
Canari Island, Spain

VERITAS
Arizona, USA

HAWC
Mexico

CTA North
Canari Island, Spain

H.E.S.S.
Namibia

CTA South
ESO, Chili

Tibet AS
ARGO
China

> Telescope locations in both hemispheres is crucial
Sky coverage

Northern instruments

Southern instruments

Galactic Center
HAWC’s view of the TeV sky

The H.E.S.S. Galactic plane survey

- Almost 2700 hours of pointed observations taken on the galactic plane by H.E.S.S.
- Coverage to at least 10% Crab Flux
- Much better in most places

> First systematic catalog of Galactic TeV sources with $E > 200$ GeV: 78 sources detected

Emmanuel Moulin, EDU 2017, 13th Rencontres du Vietnam
The Galactic Center region

- Extremely complex and energetic region at all wavelengths
- Due to the location of H.E.S.S., it is an excellent target for observations
- VHE emission first discovered in 2004
- Diffuse emission
- Target for dark matter search

(c) F. Acero & H. Gast
The Galactic Centre region

- 90cm radio map
  - multiple SNRs (e.g. G 0.9, G 1.9,...)
  - multiple PWNe (e.g. Mouse)
  - Central Radio lobes (central ±1°) and arc features

- Central Molecular Zone (CMZ):
  - giant molecular clouds: ~10% of all the gas of the Galaxy
The GC region seen in 2004 by Whipple

- 26 hours
- Single telescope observations
The GC region seen by H.E.S.S. in 2005

Two bright pointlike sources
- HESS J1745-290: still unidentified
- G 0.9+01: SNR/PWN association

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Angular resolution

Strongly energy-dependent
- H.E.S.S. ~5' @ 1 TeV
- CTA: ~3' @ 1 TeV
- shower fluctuations: ultimate limit ~20'' @ 1 TeV

Source identification is limited from VHE angular resolution
VHE morphology of the ridge emission

Substraction of the two pointlikes sources: look for fainter emissions...

- Diffuse emission spatially correlated with the distribution of molecular gas of the Central Molecular Zone (CMZ)
  → hadronic origin of the emission

The GC region seen in 2016

- Regular observations of the GC region have now been made with the H.E.S.S. array for over 10 years: >220 hours of observation available
- New data analysis techniques have greatly improved the angular resolution and sensitivity
  → Excellent dataset for the study of CR acceleration in this region
  → Take a closer look at the morphology of diffuse emission
  → We can also extend to analysis further into the high energy (statistics limited) regime
Breakdown GC ridge emission into components

New source
HESS J1746-285

- Good spatial coincidence with PWN G0.13-0.11 seen in X rays
- The ‘arc source’ seen in IR/radio

H.E.S.S. Coll. arXiv:1706.04535
Breakdown GC ridge emission into components

New source
HESS J1746-285
The GC seen by VERITAS in 2016

- High energy threshold from large zenith angle observations
- Morphology of the ridge seen by H.E.S.S. generally confirmed
- Evidence for emission from Sgr B2
- New source VER J1746-289
The central source HESS J1745-290

- strong emission: >10% of Crab flux (>1 TeV)
- point like source
- constant flux: ~1 gamma/min

- Significant deviation from a pure power law
- No time variability so far from tens of minutes to daily time scales
- Can be well described by a power law with an exponential cut off at 10 TeV
The central source HESS J1745-290

Counterparts:
(i) a CR source accelerating high energy protons in the vicinity of Sgr A* which produces VHE gamma rays interaction in the ISM
(ii) a pulsar wind nebula G359.95 0.04
(iii) a spike of annihilating DM particles

Exponential power law
\[
dN/dE = \Phi_0 E^{-\Gamma_0} \cdot \exp(-E/E_{cut})
\]
- \(\Phi_0 = (2.55 \pm 0.04_{\text{stat}} \pm 0.37_{\text{syst}}) \times 10^{-12} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1},\)
- \(\Gamma_0 = 2.14 \pm 0.02_{\text{stat}} \pm 0.10_{\text{syst}}\)
- \(E_{cut} = (10.7 \pm 2.0_{\text{stat}} \pm 2.1_{\text{syst}}) \text{ TeV}\)
Origin of HESS J1745-290?

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VERITAS and H.E.S.S. results agree very well
How to go further with VHE gamma-rays:
→ Spectral shape in the energy cut-off region

> A template gamma-ray spectrum for the proton-induced emission is a power law with an exponential energy cutoff

> The DM-induced spectrum template can be interpreted by a power law with superexponential energy cutoff

- Data can be well described by both EPL and a SEPL spectral templates

- Present statistics is not sufficient to significantly discriminate among the two templates
HESS J1745-290: prospects with CTA

- about 1-order-of-magnitude increase in sensitivity in the TeV regime
- a factor of 2 to 3 improvement in angular resolution compared to current instruments: 0.03°(68%) above 1 TeV
- energy resolution from about 20% at 100 GeV to better than 5% at 10 TeV
  → Generating mock spectral CTA data from EPL and a SEPL spectral templates

**CTA should be able to reliably distinguish SEPL from EPL models in about 20 hours of observation time**
10-year GC observations with H.E.S.S.

Complex and structured emissions
Gas clouds illuminated by cosmic-ray source(s)

Dark matter halo emission?
Launch of Fermi bubbles?

- Largest H.E.S.S. dataset from a regular monitoring over 10 years
  - More than 1000 hours of observations: ~150000 gamma
- Most detailed map in VHE astronomy
  - Location in the Southern hemisphere is crucial
  - High-accuracy spectral and spatial measurements
Diffuse emission and CR transport

Diffuse emission correlated with molecular cloud distribution

→ the ratio of the TeV flux to the gas density provides the CR density

HESS collaboration, Nature 531, 476 (2016)
Diffuse emission: CR distribution

Diffuse emission correlated with molecular cloud distribution

→ the ratio of the TeV flux to the gas density provides the CR density

- Gamma-ray luminosity measurement in several regions
- Use of cloud mass measurements gas density from CS (CO, HCN)

CR energy density proportional to $L_\gamma / M$

$$w_{CR}(\geq 10E_\gamma) = \frac{W_p(\geq 10E_\gamma)}{V} \sim 1.8 \times 10^{-2} \left( \frac{L_\gamma(\geq E_\gamma)}{10^{34} \text{erg/s}} \right) \left( \frac{M}{10^6 M_\odot} \right)^{-1} \text{eV/cm}^3$$

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Measurement of CR density in the inner 200 pc of the Milky Way
→ Localization of the accelerator in the central 10 parsecs
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CR density radial distributions:
- Homogeneous/constant: impulsive injection of CRs and diffusive propagation
- $1/r^2$: wind-driven or ballistic propagation
- $1/r$: continuous injection and diffusive propagation

Central accelerator located within 10 pc and injecting CRs continuously over more than 1000 years
Diffuse emission: CR injection spectrum

Diffuse emission correlated with molecular cloud distribution
→ the ratio of the TeV flux to the gas density provides the CR density

Gamma-ray spectrum measured up to 50 TeV
→ power law with index 2.3 with no energy cut-off

→ Parent proton spectrum should extend at least to PeV energies
Diffuse emission: CR injection spectrum

Spectrum diffuse emission extracted from large ring around Sgr A*:

- Spectrum of diffuse emission: power-law with index 2.3 extending up to 50 TeV without energy cut-off

HESS collaboration, Nature 531, 476 (2016)
Diffuse emission: CR injection spectrum

Spectrum diffuse emission extracted from large ring around Sgr A*

- Spectrum of diffuse emission: power-law with index 2.3 extending up to 50 TeV without energy cut-off

→ Parent proton injection spectrum should extend to PeV energies
- quasi-continuous injection lasting over $> 10^3$ years
- total CR power injected at the GC $\sim 10^{38}$ erg/s

*First robust detection of a cosmic PeVatron*

[HESS collaboration, Nature 531, 476 (2016)]
Cosmic PeVatron counterpart: SMBH Sgr A*

- Given the location (<10 pc), accelerated energies (PeV), continuous (kyrs) injection power of the accelerator → SMBH Sgr A* is a viable counterpart
- A significant fraction of accretion in Sgr A* is released through acceleration of high-energy particles
- Sgr A* may have been more active in the past:
  if injection power \( \geq 10^{39} \) erg/s, GC PeVatron can explain the fluxes of Galactic CRs above 100 TeV to a few PeV (region of the “knee”)

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A privileged region for DM search

- The inner region of the Milky Way halo harbors a large amount of dark matter
- Given its proximity, it is one of the most promising targets to look for DM

- … GC region is a crowded environment at VHE: pointlike sources (PWN, SNR, Unidentified sources) and diffuse emission(s)
A privileged region for DM search

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- 10-year observations with H.E.S.S. 1 toward the GC
- Gamma-ray statistics: 254 h compared to 112 h as used in 2011/2013 analyses
DM search in the GC: regions of interest

- The inner region of the Milky Way halo harbors a large amount of dark matter (DM).
- Given its proximity, it is one of the most promising targets to look for DM.
- 10-year observations with H.E.S.S. 1 provides a valuable dataset for that.

- Excluded region $\pm 0.3^\circ$: dominated by astrophysical sources and diffuse emission.
- Does not require standard astrophysical emission modelling in the region of interest.
- Whole region of Interest: $1^\circ$ in radius
  $\rightarrow$ divided in 7 sub-regions of $0.1^\circ$: spatial binning.
DM distribution in the GC region

We assume cusped DM density profiles, e.g. the Einasto, NFW, …

$$\rho_{Ein1}(r) = \rho_s \exp \left[ \frac{-2}{\alpha} \left( \frac{r}{r_s} \right)^\alpha - 1 \right]$$

parametrized with
$$\alpha = 0.17$$
$$r_s = 21 \text{ kpc}$$
$$\rho_s = 0.07 \text{ GeV cm}^{-3}$$

as used in HESS GC 2011, 2013 papers
DM distribution in the GC region

We assume **cusped** DM density profiles, e.g. the Einasto, NFW, ...

Spatial information can be used to discriminate from the isotropic residual background
Background measurement

- Significant DM gradient between ON and OFF regions

We assume **cusped DM density profiles**, e.g. the Einasto, NFW, …

**Einasto profile**

Example for one OFF region for a given pointing

- Significant DM gradient between ON and OFF regions
Background measurement

- Given the possible complex emission in the GC, optimized background measurement technique is required.

- OFF regions are chosen symmetrically to ON regions with respect to the pointing position in the same observational field of view.
  → same observational/instrumental conditions for signal and background measurement.

- Procedure is done for each observation run and each ROI.
  → same acceptance in ON and OFF region.
  → strong dark matter gradient that improves the limits.
Dark matter search in the GC

- 2D likelihood analysis with spectral and spatial information of signal and background
- Likelihood-ratio test statistics
- No significant excess if found in any of the 7 ROIs
  → Upper limits derived on the annihilation cross section

\[ TS = 2.71 \]
for a 95% CL limit
Constraints on the DM continuum signal

- 2D likelihood analysis with spectral and spatial information of signal and background
- No significant excess if found in any of the 7 ROIs
  → Upper limits derived through a likelihood ratio test statistics

For the Einasto profile, strongest limits so far in the TeV mass range:
- in the WW channel: $6 \times 10^{-26}$ cm$^3$ s$^{-1}$ at 1.5 TeV
- in the $\tau \tau$ channel: $2 \times 10^{-26}$ cm$^3$
Constraints on the DM continuum signal

For the Einasto profile, strongest limits so far in the TeV mass range:

→ in the $W^+W^-$ channel: $6 \times 10^{-26}$ cm$^3$ s$^{-1}$ at 1.5 TeV

They well complement the Fermi-LAT limits down to about 300 GeV

Full H.E.S.S.-II array observations within the inner Galaxy Survey programme with pointings up to $3^\circ$ in Galactic latitudes started in 2015

Constraints on the DM line signal

- 2D likelihood analysis with spectral and spatial information of signal and background
- No significant excess if found in any of the 7 ROIs
  → Upper limits derived through a likelihood ratio test statistics

- Improvement of a factor about 8 observed @ 1 TeV on the mean expected limits
- Improvement from the analysis: exclusion regions, 2D binned likelihood analysis approach, improved raw data analysis, higher statistics

E. Moulin et al. (H.E.S.S. Coll.), ICRC 2017
Constraints on the DM line signal (2)

- 2D likelihood analysis with spectral and spatial information of signal and background
- No significant excess if found in any of the 7 ROIs → Upper limits derived through a likelihood ratio test statistics

- Best sensitivity $2 \times 10^{-28} \text{cm}^3\text{s}^{-1}$ @1TeV
- Mass range extended down to 300 GeV and up to 70 TeV
Constraints on the DM line signal (3)

- 2D likelihood analysis with spectral and spatial information of signal and background
- No significant excess if found in any of the 7 ROIs
  → Upper limits derived through a likelihood ratio test statistics

- Best sensitivity $2 \times 10^{-28} \text{cm}^3\text{s}^{-1}$ @1 TeV
- Mass range extended down to 300 GeV and up to 70 TeV
- Fermi-LAT limits surpassed of a factor about 6 @300 GeV
Dark matter at the GC halo with CTA

- Priority target in the CTA Dark Matter programme
  - Fair balance between brightness and robustness

- CTA is a unique player for TeV dark matter with great discovery possibility
Summary and outlook

- The Galactic Centre is an interesting and very complex region in VHE gamma-rays
  - Large dataset and improved analysis from the H.E.S.S. observations over more than 10 years has allowed a deep analysis of this region
  - Spectral and spatial morphology of the diffuse emission detected suggests a continuous injection of cosmic rays from the central source
    - strongly suggests that SMBH Sgr A* is a hadronic cosmic-ray accelerator
    - first Galactic Pevatron discovered

- GC is one the most important target for dark matter detection
  - It provides the strongest dark matter constraints in the TeV dark matter mass range

- The H.E.S.S. Inner Galaxy Survey started in 2015 will allow to significantly the photon statistics in the inner 5 degrees of the GC

- The inner Galactic halo region is the priority target in the CTA KSP dark matter programme