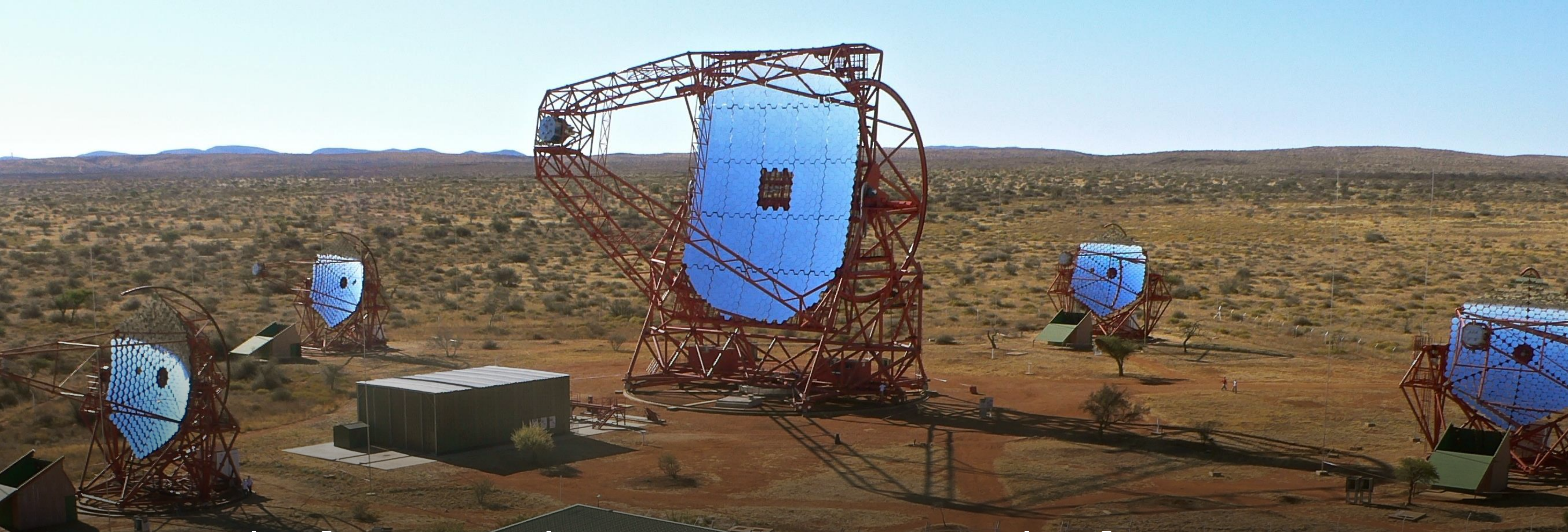


Search for Dark Matter signals from Unidentified *Fermi*-LAT Objects

Alessandro Montanari on behalf of the H.E.S.S. collaboration

July 6th, 2021 – IRN@ZOOM

Arxiv: arXiv:2106.00551

OUTLINE

- ✓ Indirect Dark Matter search
- ✓ Unidentified Fermi Objects (UFOs) as DM candidates subhalos
- ✓ *Fermi*-LAT and H.E.S.S. data analysis
- ✓ Spectral Energy Distribution and DM emission models
- ✓ Constraints from H.E.S.S. observations
- ✓ Prediction for N-body simulations on subhalo J-factors
- ✓ Conclusions → UFOs, very unlikely DM subhalos

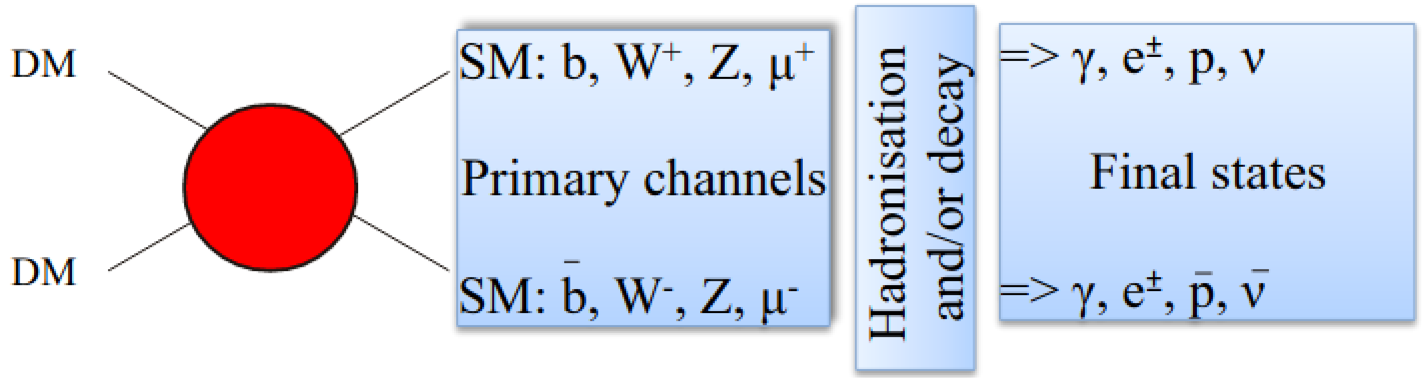
Indirect Dark Matter search

- Growing astrophysical and cosmological evidence about the existence of Dark Matter (DM);

- WIMPs → one of the most compelling DM particle candidates;
  - WIMPs created thermally in the Early Universe:

  → Annihilation cross section expected for thermal WIMPs ($<\sigma v>_{th}=3x10^{-26}\ cm^{3}\ s^{-1}$);

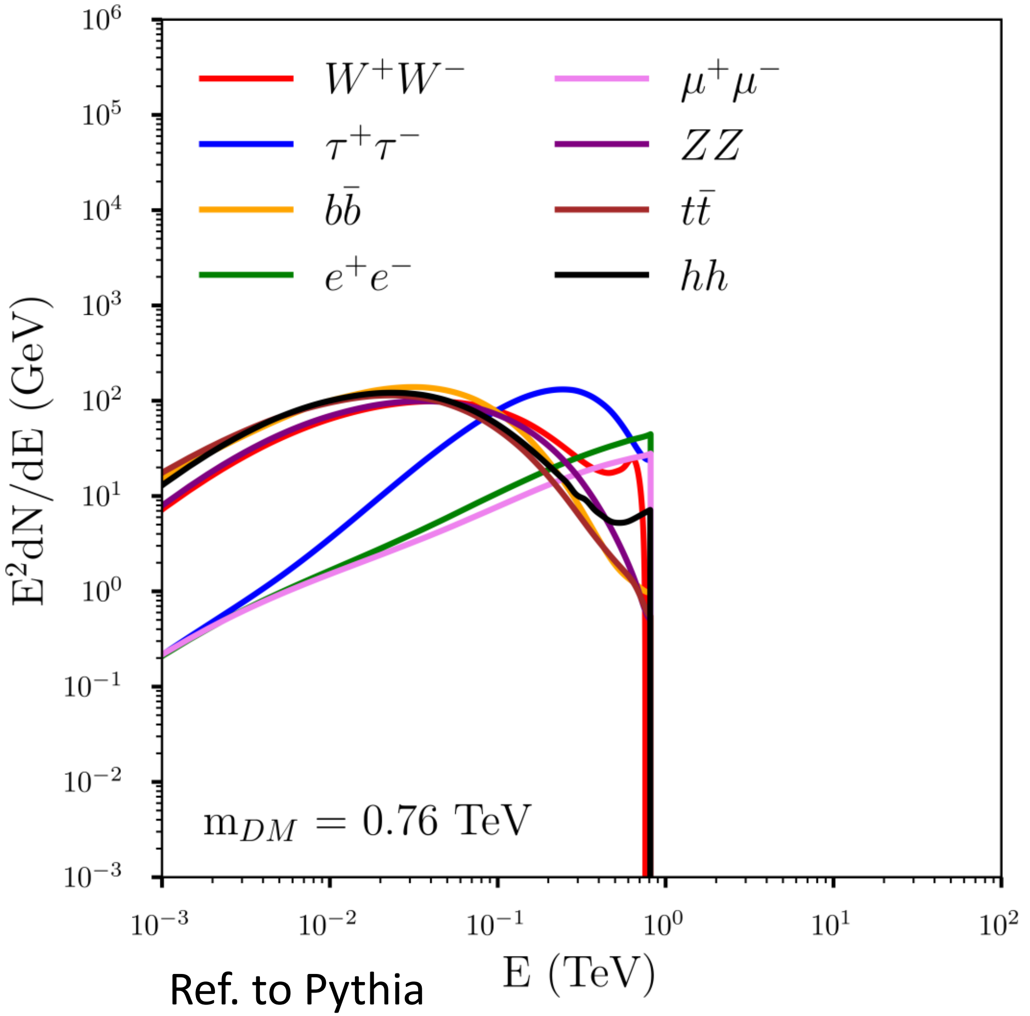
- WIMPs can self-annihilate and produce gamma rays in the final states eventually detectable by satellite (*Fermi*-LAT) and ground-based experiments (H.E.S.S., MAGIC, VERITAS).



Indirect Dark Matter search with gamma rays

- WIMPs can self-annihilate and produce gamma-rays eventually detectable by H.E.S.S;
- Assuming annihilation process almost at rest:
  - A smoking-gun signature for DM is a very distinct energy cut-off, close to the DM particle mass;
- Gamma-ray flux expected from DM annihilations:

$$\frac{d\phi_\gamma}{dE}(E_\gamma, \Delta\Omega) = \frac{\langle\sigma v\rangle J(\Delta\Omega)}{8\pi m_{DM}^2} \sum_f Br_f \frac{dN_f}{dE_\gamma}$$



Ref. to Pythia

Indirect Dark Matter search with gamma rays

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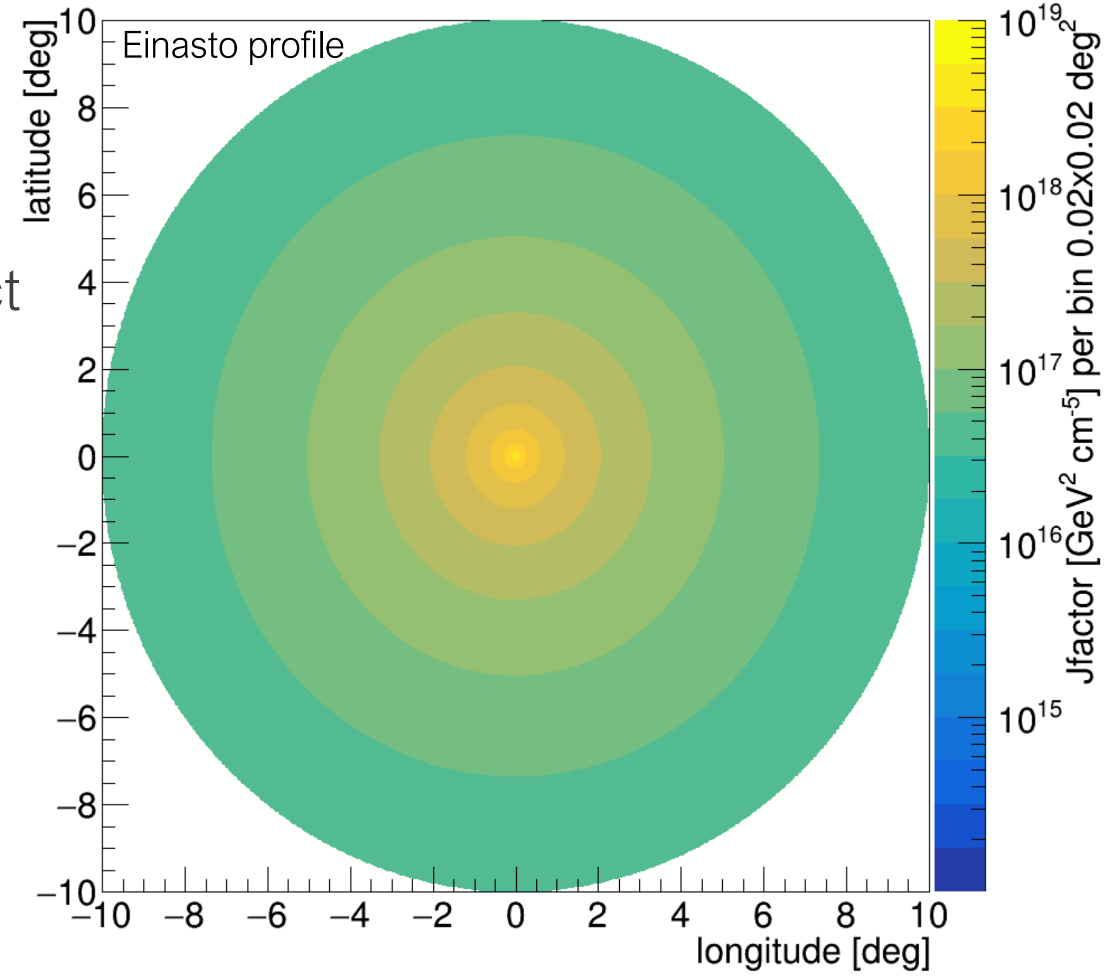
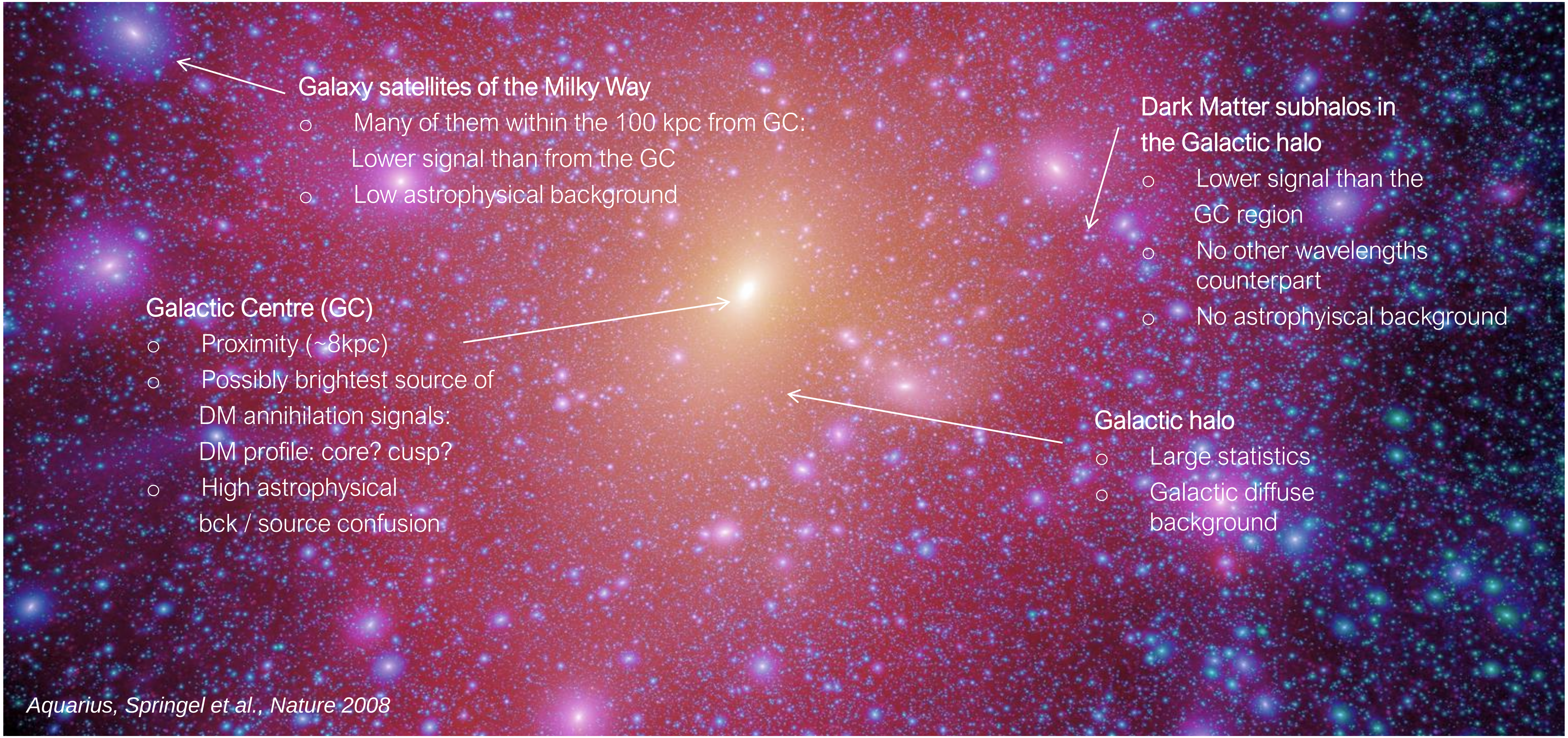
- Astrophysical term $J(\Delta\Omega) = \int \rho^2\,(r(s,\theta))\,ds\,d\Omega$:
  - Model needed for the density profile;
  - Dependence on dark matter halo modeling.



Dark Matter targets in gamma rays



Galaxy satellites of the Milky Way

- Many of them within the 100 kpc from GC: Lower signal than from the GC
- Low astrophysical background

Dark Matter subhalos in the Galactic halo

- Lower signal than the GC region
- No other wavelengths counterpart
- No astrophyiscal background

Galactic Centre (GC)

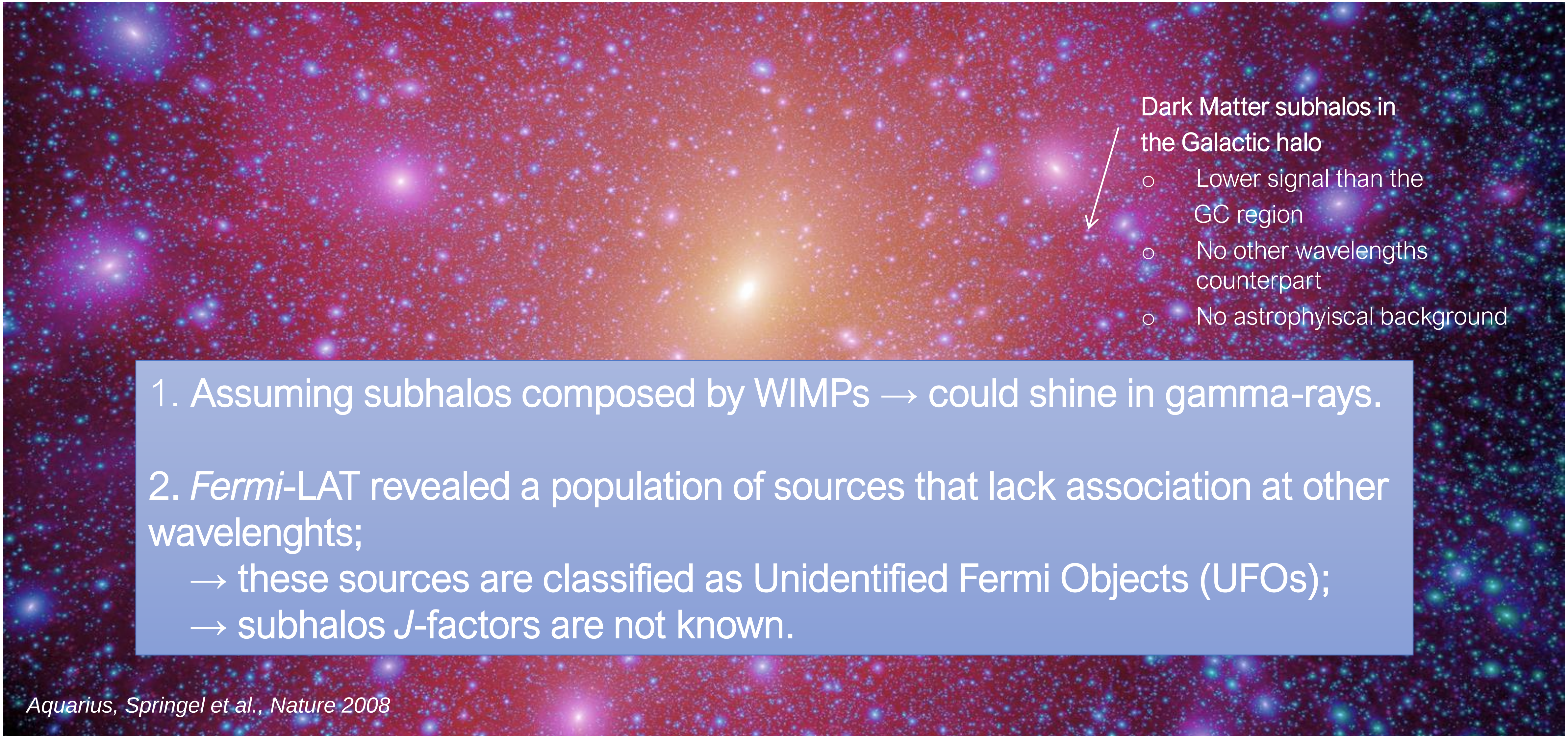
- Proximity (~8kpc)
- Possibly brightest source of DM annihilation signals: DM profile: core? cusp?
- High astrophysical bck / source confusion

Galactic halo

- Large statistics
- Galactic diffuse background

Aquarius, Springel et al., Nature 2008

Dark Matter targets in gamma rays



Dark Matter subhalos in the Galactic halo

- Lower signal than the GC region
- No other wavelengths counterpart
- No astrophyiscal background

1. Assuming subhalos composed by WIMPs → could shine in gamma-rays.

2. *Fermi*-LAT revealed a population of sources that lack association at other wavelenghts;
   → these sources are classified as Unidentified Fermi Objects (UFOs);
   → subhalos *J*-factors are not known.

Aquarius, Springel et al., Nature 2008

Dark Matter candidate subhalos

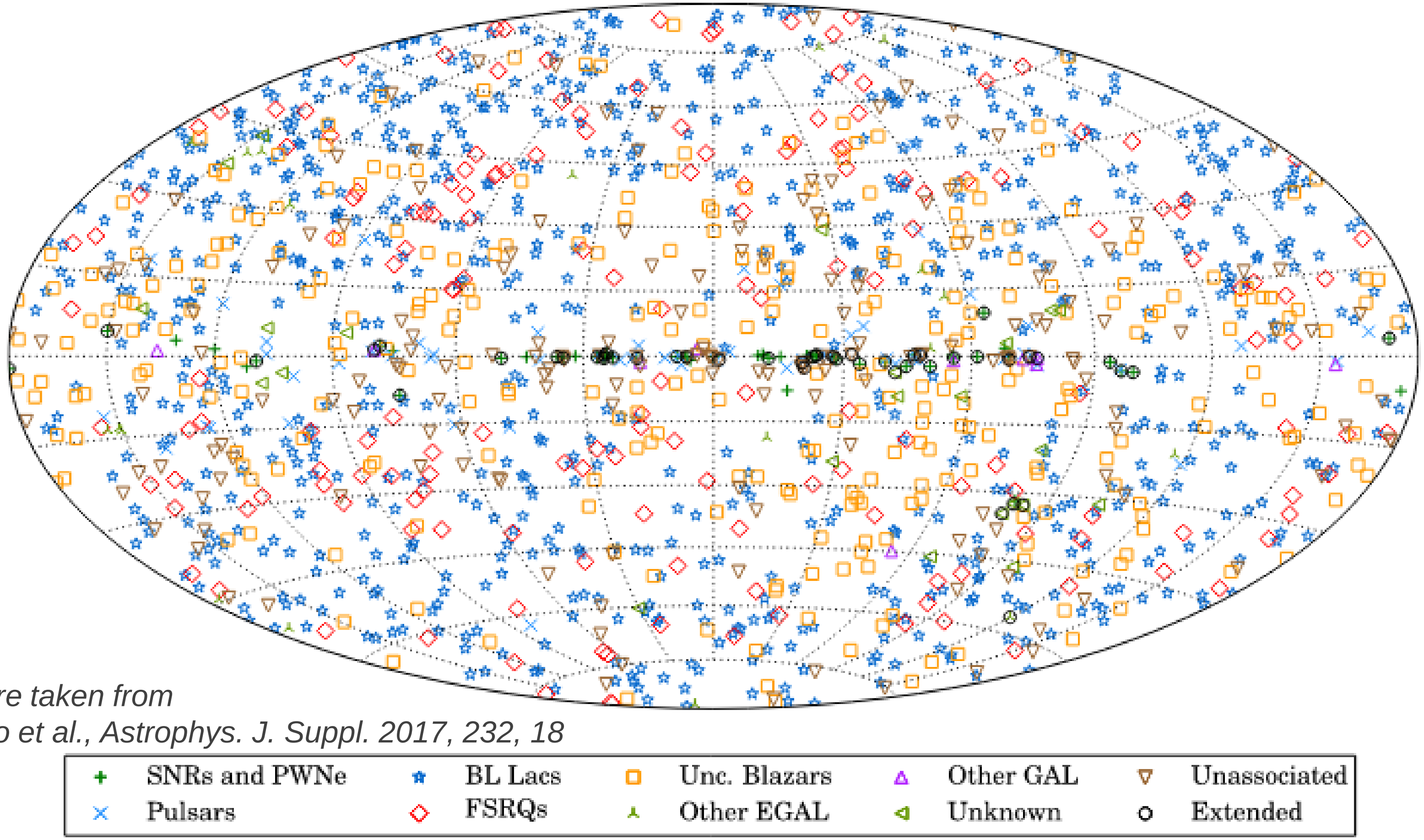


Figure taken from
Ajello et al., Astrophys. J. Suppl. 2017, 232, 18

→ these sources are classified as Unidentified Fermi Objects (UFOs);

Selection through the Third catalog of Hard *Fermi*-LAT sources (3FHL) to obtain the most promising UFOs for the H.E.S.S. observations.

Dark Matter candidate subhalos

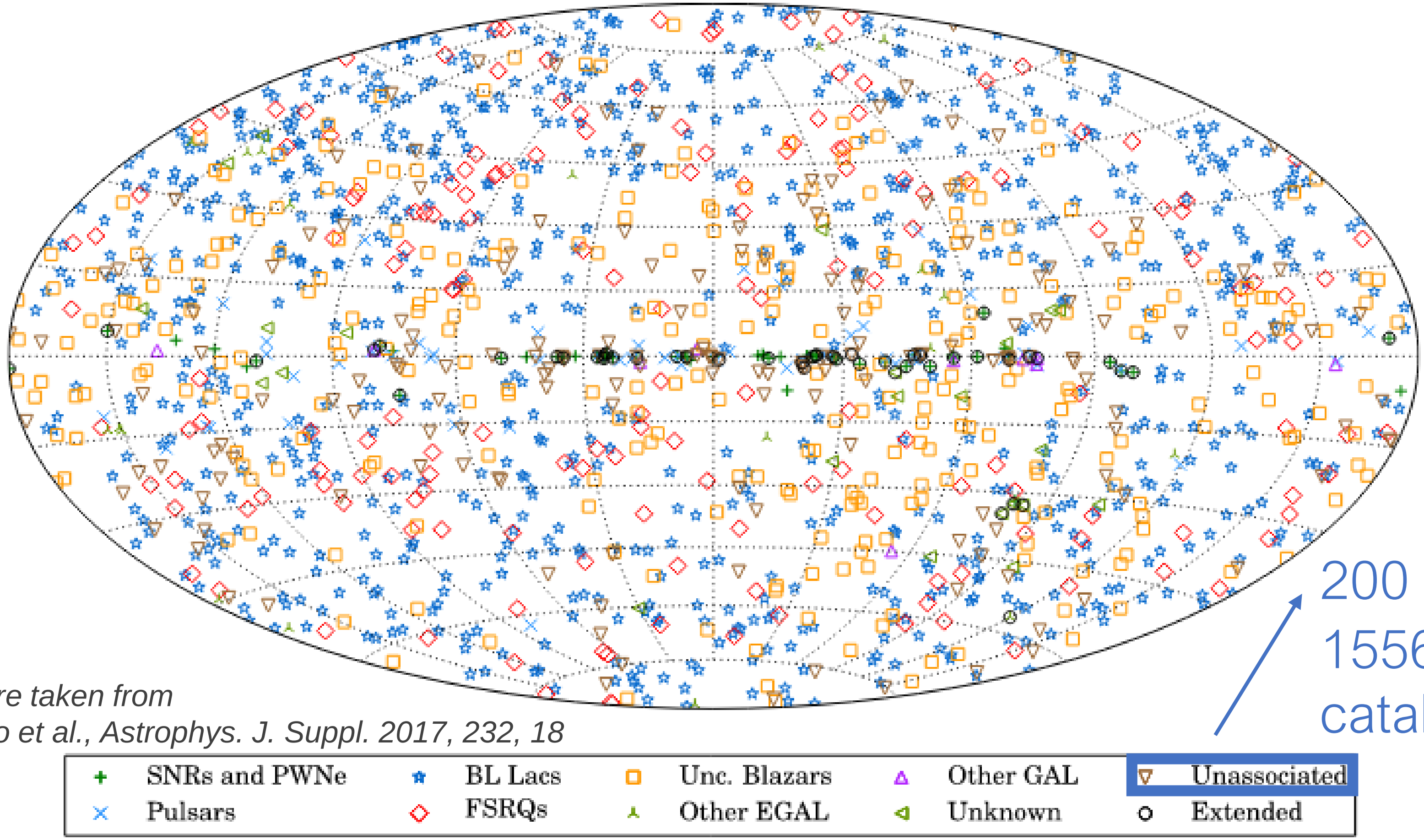


Figure taken from
Ajello et al., Astrophys. J. Suppl. 2017, 232, 18

200 unassociated over 1556 sources in the catalog;

→ these sources are classified as Unidentified Fermi Objects (UFOs);

Selection through the Third catalog of Hard *Fermi*-LAT sources (3FHL) to obtain the most promising UFOs for the H.E.S.S. observations.

UFOs selection for H.E.S.S. observations

- Selection through the Third catalog of Hard *Fermi*-LAT sources (3FHL*) to obtain the most promising candidates for the H.E.S.S. observations:
  - No association w/ other astrophysical sources;
  - Sufficiently far from the Galactic Plane;
  - No flux variability over time;
  - Maximum zenith angle for the H.E.S.S. observations;
  - Hard power law spectral index ($\Gamma<2$);
  - No conventional astrophysical counterpart in other wavelenghts (radio, optical, X);

** Ref. Ajello et al. Astrophys. J. Suppl. 2017, 232, 18*

UFOs selection for H.E.S.S. observations

- Selection through the Third catalog of Hard *Fermi*-LAT sources (3FHL*) to obtain the most promising candidates for the H.E.S.S. observations:
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  - No flux variability over time;
  - Maximum zenith angle for the H.E.S.S. observations;
  - Hard power law spectral index (Γ<2);
  - No conventional astrophysical counterpart in other wavelenghts (radio, optical, X);

→ 6 selected,
4 observed by H.E.S.S.

Criteria	Numbers of sources
Without association	178
Far enough from the Galactic plane, cut in Galactic latitude of $\|b\| > 5°$	126
Non-variable, cut in variability index (No. of Bayesian blocks in var. analysis) equal to 1	125
Maximum zenith angle at H.E.S.S. site of 45°	83
Follow a simple power law with significance for curvature $< 3\sigma$	83
Hard spectrum, cut in spectral index below 2	18
No MWL counterparts	6

** Ref. Ajello et al. Astrophys. J. Suppl. 2017, 232, 18*

UFOs selection for H.E.S.S. observations

- Selection through the Third catalog of Hard *Fermi*-LAT sources (3FHL*) to obtain the most promising candidates for the H.E.S.S. observations:
  - No association w/ other astrophysical sources;
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  - Maximum zenith angle for the H.E.S.S. observations;
  - Hard power law spectral index ($\Gamma<2$);
  - No conventional astrophysical counterpart in other wavelenghts (radio, optical, X);

→ these sources are classified as Unidentified Fermi Objects (UFOs);
→ H.E.S.S. observations performed in 2018.

Name	RA [degrees]	Dec. [degrees]	TS for $E \geq 10$ GeV	Position uncertainty [arcmin]	Pivot energy [GeV]	Spectral energy distribution at pivot energy [10^{-13} TeV cm^{-2}s^{-1}]	Power-law index	$\Delta\chi^2$	E_{cut} [GeV]
3FHL J0929.2-4110	142.3345	-41.1833	36	2.4	0.39	0.12 ± 0.01	1.37 ± 0.07	0.15	> 33
3FHL J1915.2-1323†	288.8182	-13.3916	23	3.0	62.8	2.1 ± 0.9	1.5 ± 0.4	0.05	> 35
3FHL J2030.2-5037	307.5901	-50.6344	40	2.6	6.3	1.9 ± 0.3	1.85 ± 0.1	0.40	> 67
3FHL J2104.5+2117[a,b]	316.1226	21.2831	58	2.2	1.56	5.3 ± 0.5	2.22 ± 0.06	0.02	> 85

[a] The spectral index in the 3FHL catalogue is 1.8 (Ajello et al. 2017).
[b] 3FHL J2104.5.2117 was recently associated in the 4FGL catalogue (Abdollahi et al. 2020) with an AGN with a probability of 0.4.

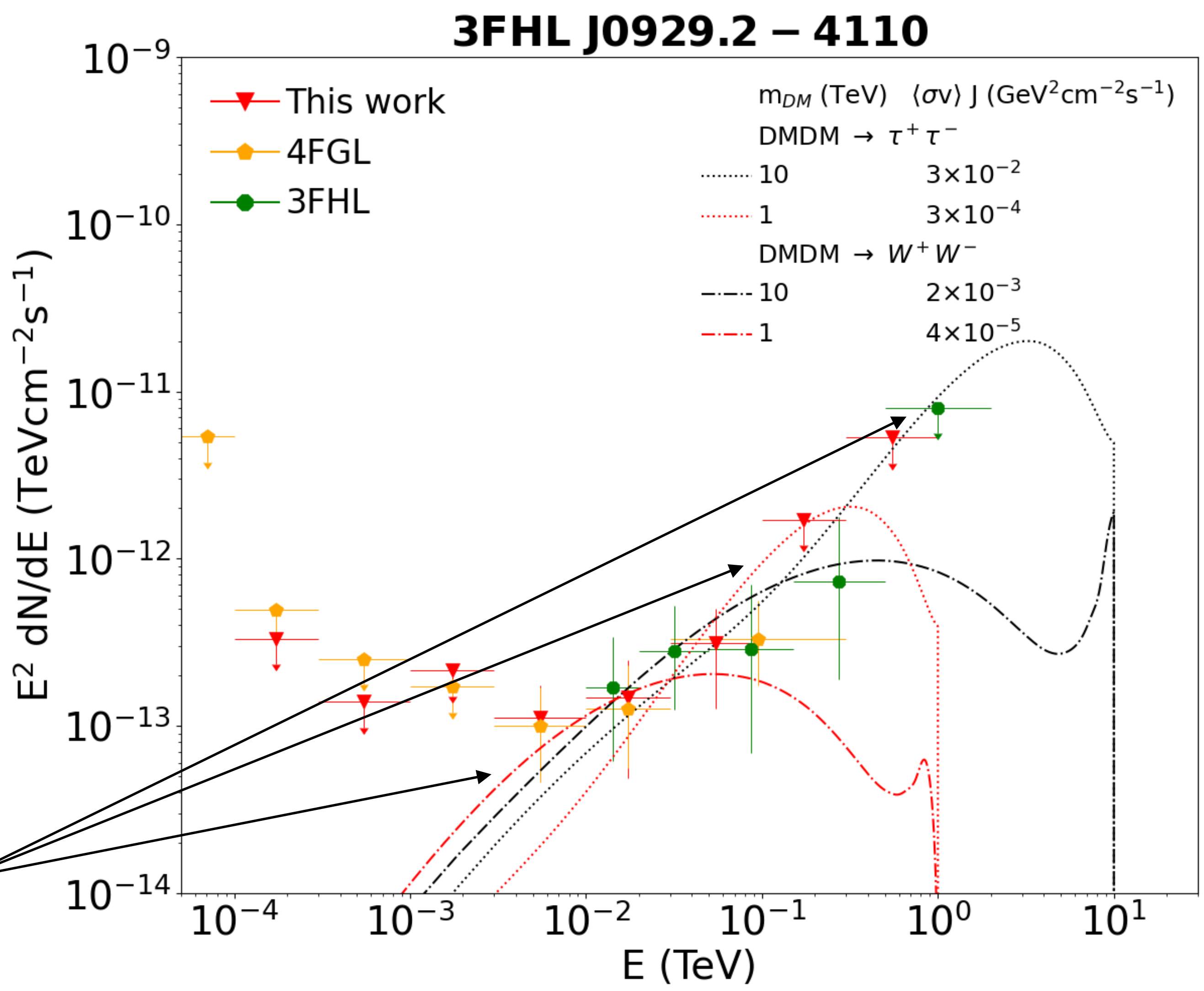
** Ref. Ajello et al. Astrophys. J. Suppl. 2017, 232, 18*

Fermi-LAT data analysis

- *Fermi*-LAT differential flux points and upper limits:
  - This work;
  - 4FGL observations;
  - 3FHL observations.

- *Fermi*-LAT data analysis → determining the DM-model independent spectra of UFO sources;
- Fitting a spatial and spectral model of the sky region around the source of interest to the data;
- All parameters, except normalization, fixed to *Fermi*-LAT catalogue values.

→ DM-induced emission models are viable according to *Fermi*-LAT measurements;



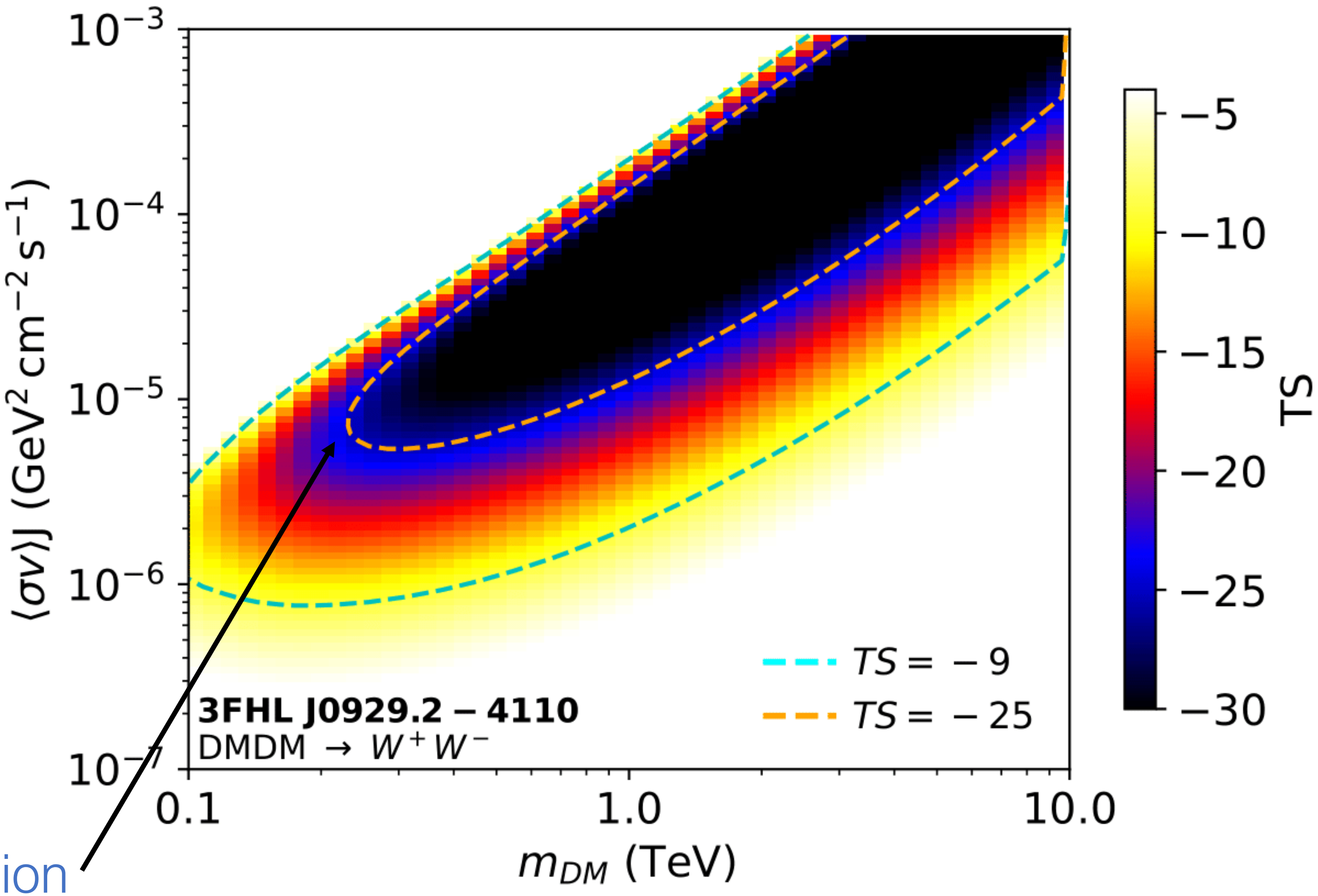
DM-induced models for UFO emissions

- Testing the DM induced emission model on *Fermi*-LAT UFO 3FHL J0929.2-4110 dataset

- Change of test statistics:

  $TS = -2\,log(L/L_0)$:
  - L_0 model: null hypothesis
  - L model: DM hypothesis described by (m_{DM}, $\langle\sigma v\rangle\,J$)

  Cyan contour: TS≃-9 → 3σ
  Orange contour: TS≃-25 → 5σ detection



Spectral Energy Distribution

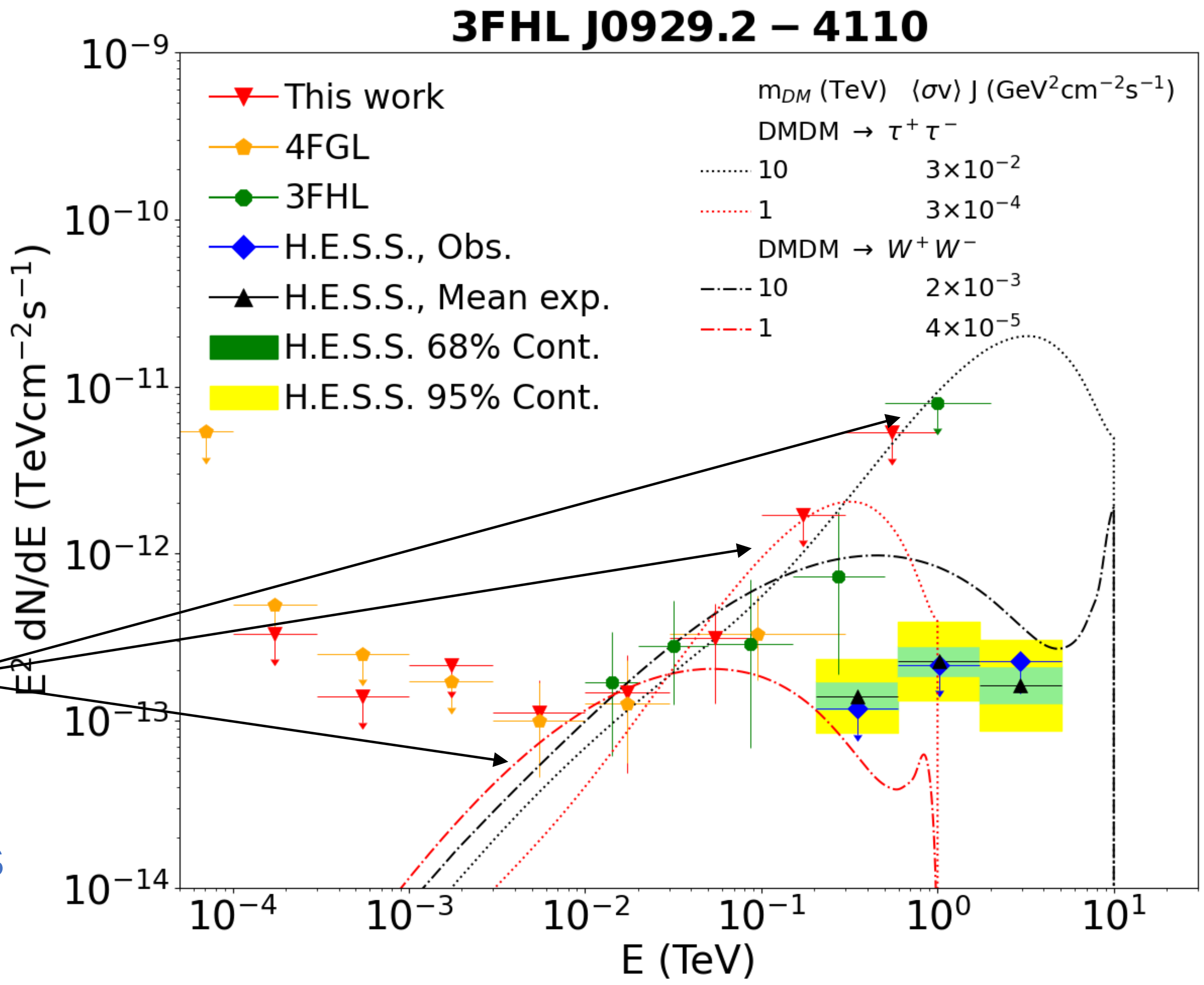
- *Fermi*-LAT differential flux points and upper limits.

- No significant excess any of the H.E.S.S. datasets → differential flux upper limits

  - Observed;
  - Mean Expected from 100 Poisson realizations;
  - 68% Containment, 95% Containment.

- DM-induced emission models are viable according to *Fermi*-LAT measurements;

→ **H.E.S.S. upper limits can constrain** some viable DM-induced emission models that explain *Fermi*-LAT detection.



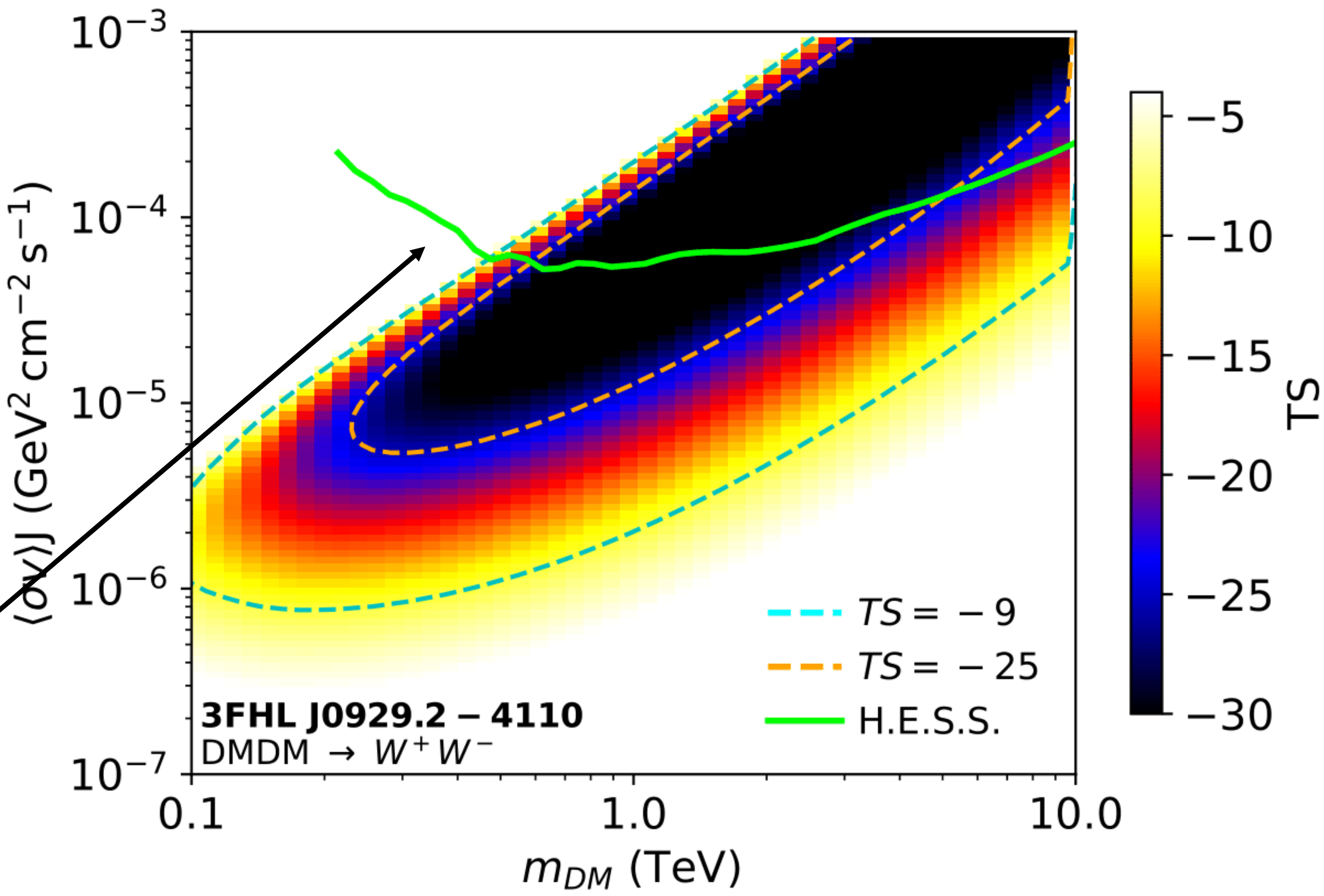
DM-induced models for UFO emissions

- Testing the DM induced emission model on *Fermi*-LAT UFO 3FHL J0929.2-4110 dataset

- Definition of a Likelihood function and the Test Statistic *(LLRTS)*
  - $LLRTS\ (1\ \mathrm{d.o.f.}) = 2.71$ for the 95% C.L. UL

Ref. Cowan, G., Cranmer, K., Gross, E. *et al.*, *Eur. Phys. J. C* **71**, 1554 (2011).

- **95% C.L.** H.E.S.S. upper limits on $\langle \sigma v \rangle$ x J

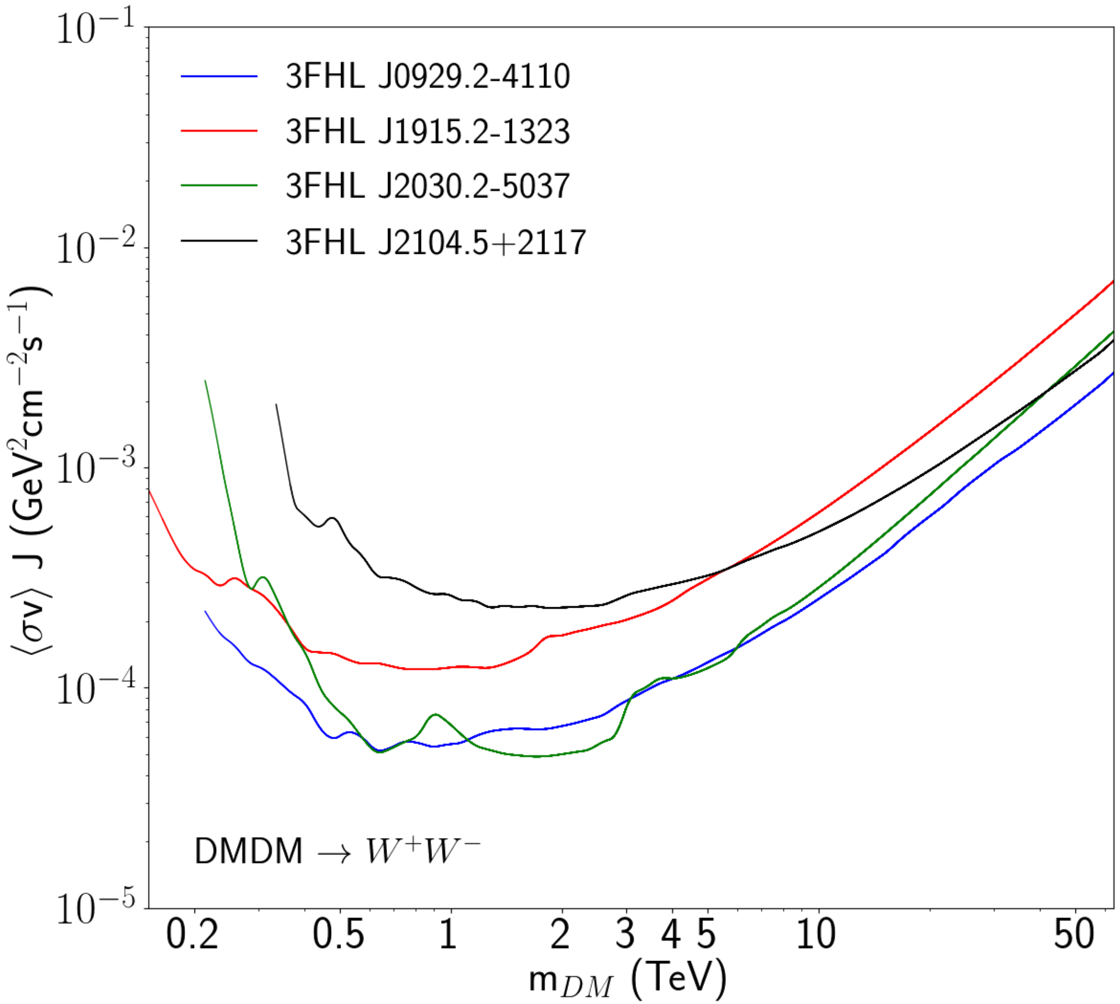


DM-induced models for UFO emissions

- Definition of a Likelihood function and the Test Statistic *(LLRTS)*
  - $LLRTS\ (1\ \mathrm{d.o.f.}) = 2.71$ for the 95% C.L. UL

Ref. Cowan, G., Cranmer, K., Gross, E. *et al.*, *Eur. Phys. J. C* **71**, 1554 (2011).

- No significant excess in any of the the four H.E.S.S. datasets
  → 95% C.L. U.L. on $\langle\sigma v\rangle$ x J for the four UFOs sources

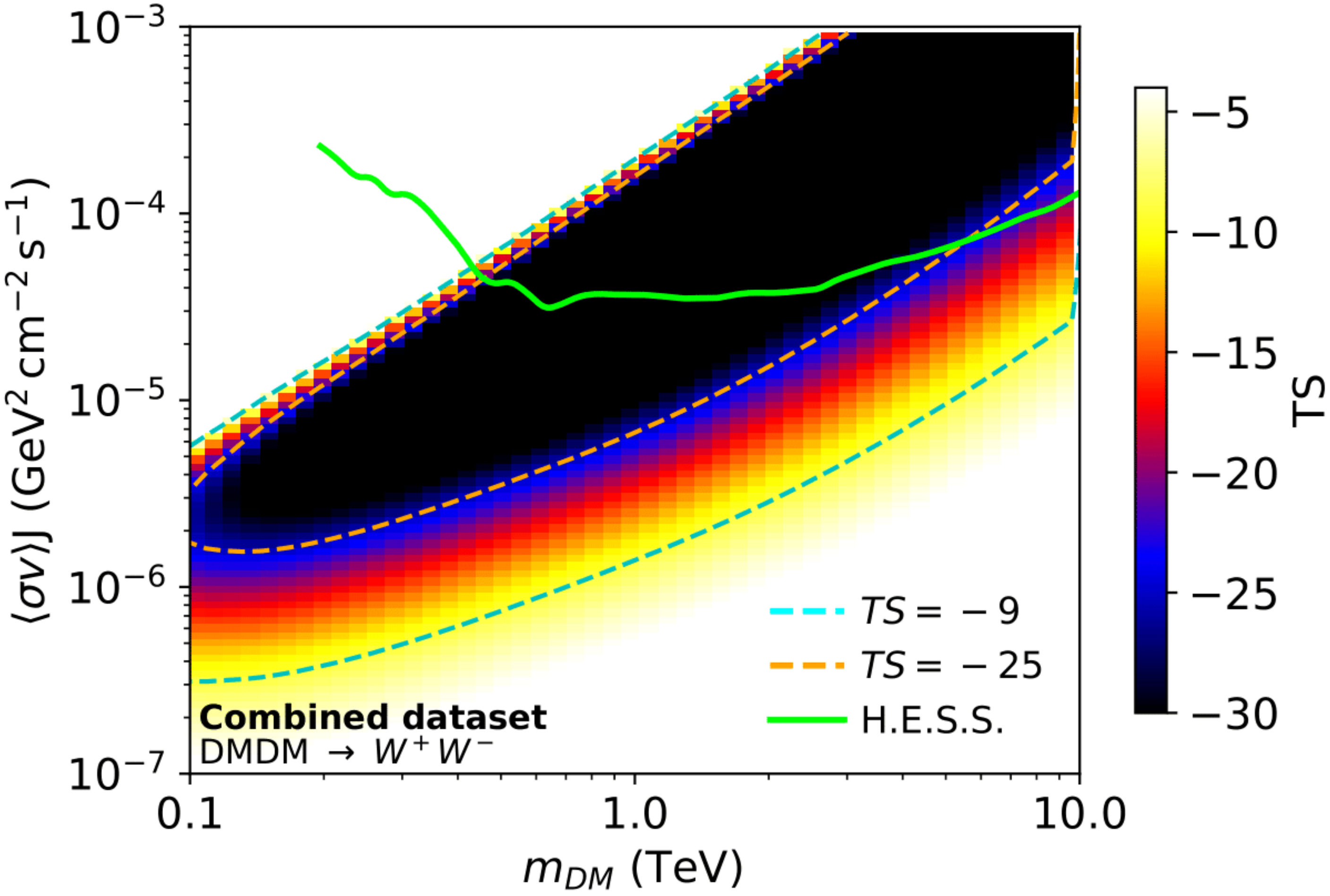


95% CL $\langle\sigma v\rangle$ x J stacked U.L.

- Stacking at the likelihood level:
  - no significant overall excess;
  - average J-factor.

→ 95% C.L. stacked U.L. on $\langle\sigma v\rangle$ x J
  - Improvement of about 10% at 1TeV;
  - 3FHL J2104.5+2117 excluded from the stacking (possible association with an AGN);

→ $\langle\sigma v\rangle$ x J values vs m_{DM} explaining stacked *Fermi*-LAT dataset given stacked H.E.S.S. ULs.



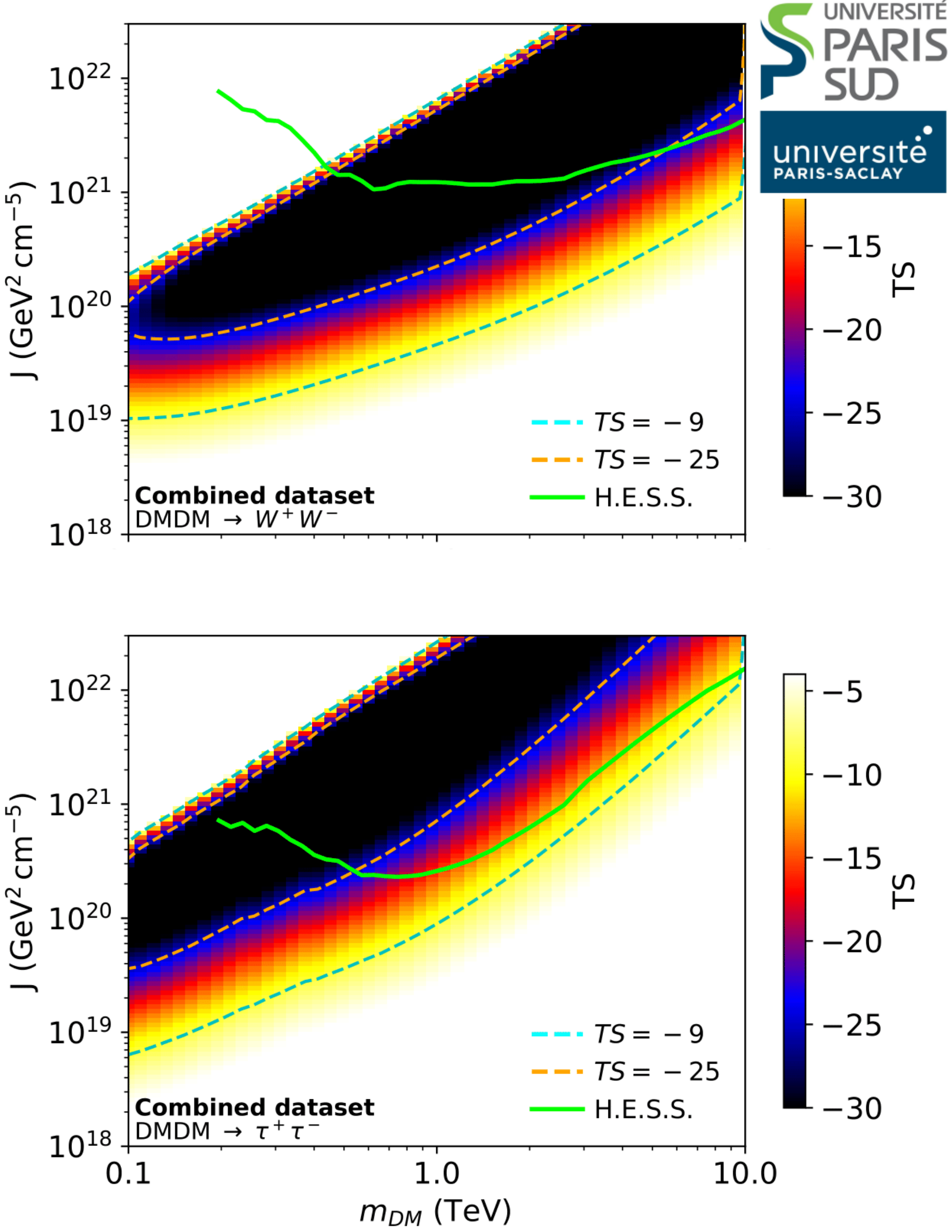
Constraints on J- factor values

- **Stacking** at the likelihood level:
  - no significant overall excess;
  - average J-factor.

- Assume **thermally-produced WIMPs:** $\langle \sigma v \rangle = 3x10^{-26}\ \mathrm{cm}^3/s$
  → **95% C.L. stacked U.L.** on the J-factor.

→ **We derive J-factor vs m_{DM} allowed (5σ) given stacked H.E.S.S. ULs.**

- Different annihilation channels produce different spectral shape:
  → some annihilation channels more constraining than others.

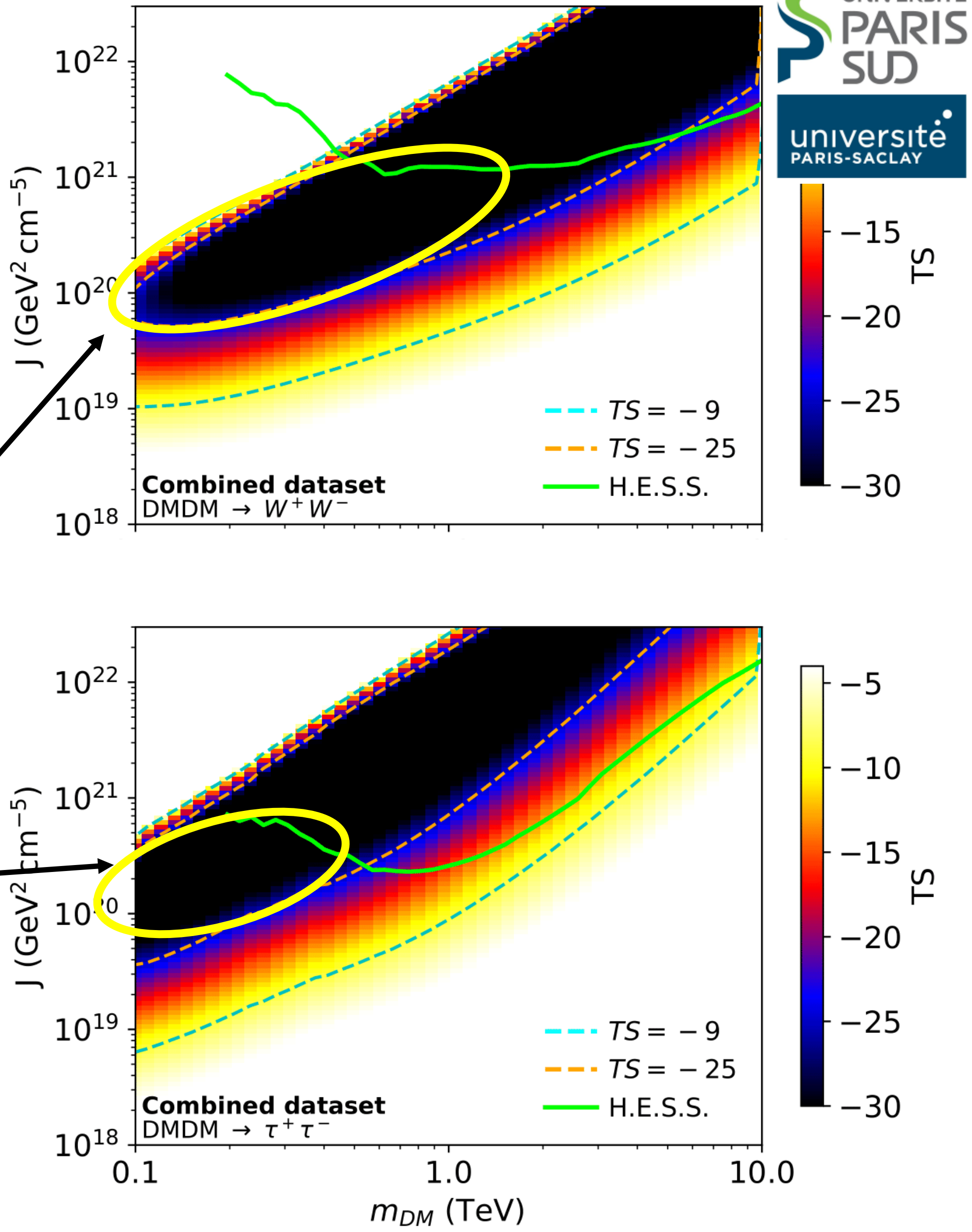


Constraints on J- factor values

- **Stacking** at the likelihood level:
  - no significant overall excess;
  - average J-factor.

- Assume **thermally-produced WIMPs:** $\langle\sigma v\rangle = 3\text{x}10^{-26}\ \mathrm{cm}^3/\mathrm{s}$
  → **95% C.L. stacked U.L.** on $\langle\sigma v\rangle$

→ We derive J-factor vs m_{DM} allowed (5σ) given stacked H.E.S.S. ULs
→ $J \in$ [few 10^{20}, 10^{21}]$\mathrm{GeV}^2\mathrm{cm}^{-5}$



J-factors predictions from cosmological simulations…

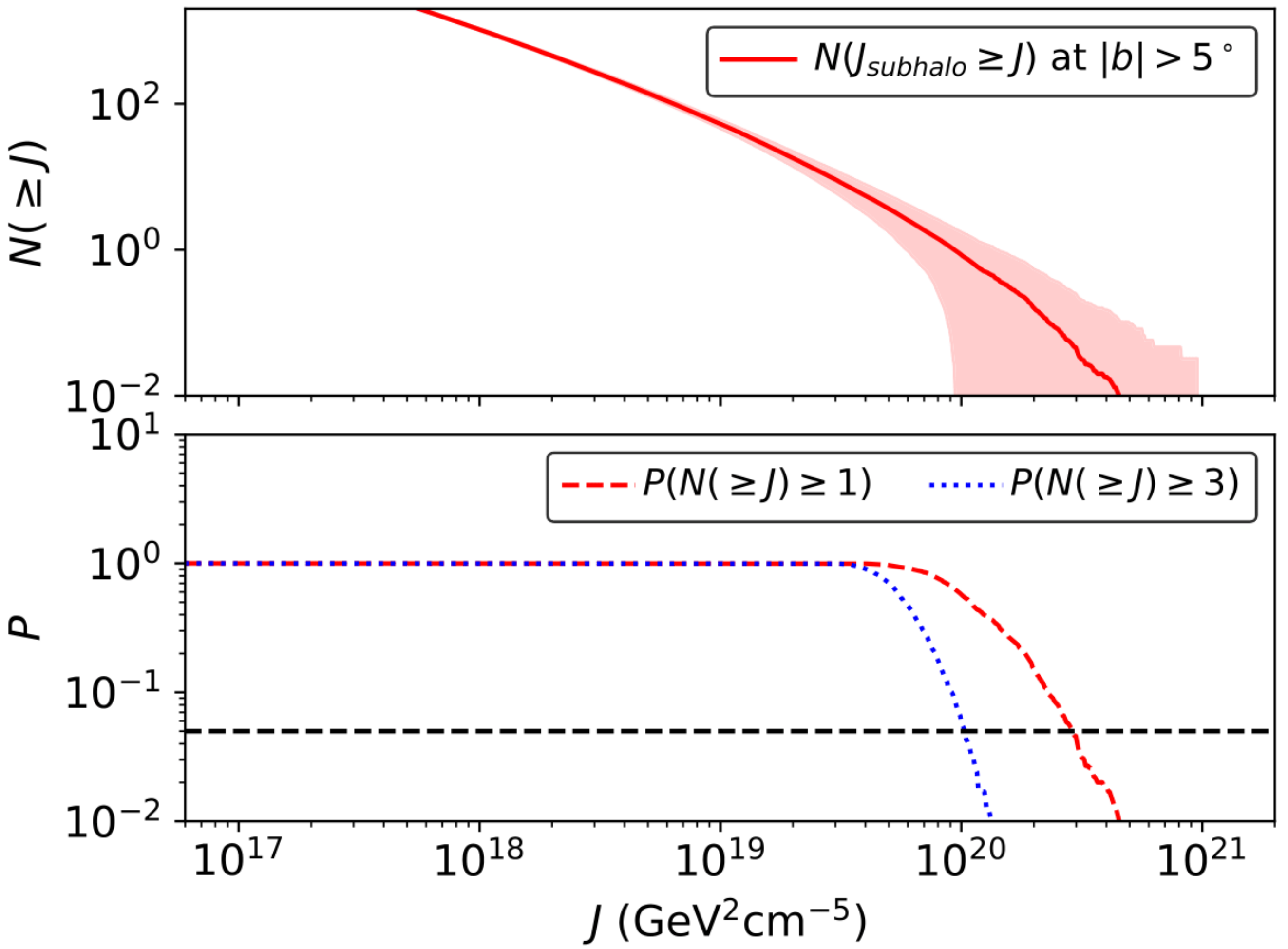
Cumulative J-factor distribution and number of halos

In a more model-dependent way, we can use cosmological simulations….

- 1000 realizations of the DM subhalo population in a MW-like galaxy assuming a NFW profile for the Galactic halo;

- Upper panel: cumulative J-factor distribution N(≥J);

→ Cumulative J-factor distribution: number of subhalos with *J*-factor exceeding a given value.



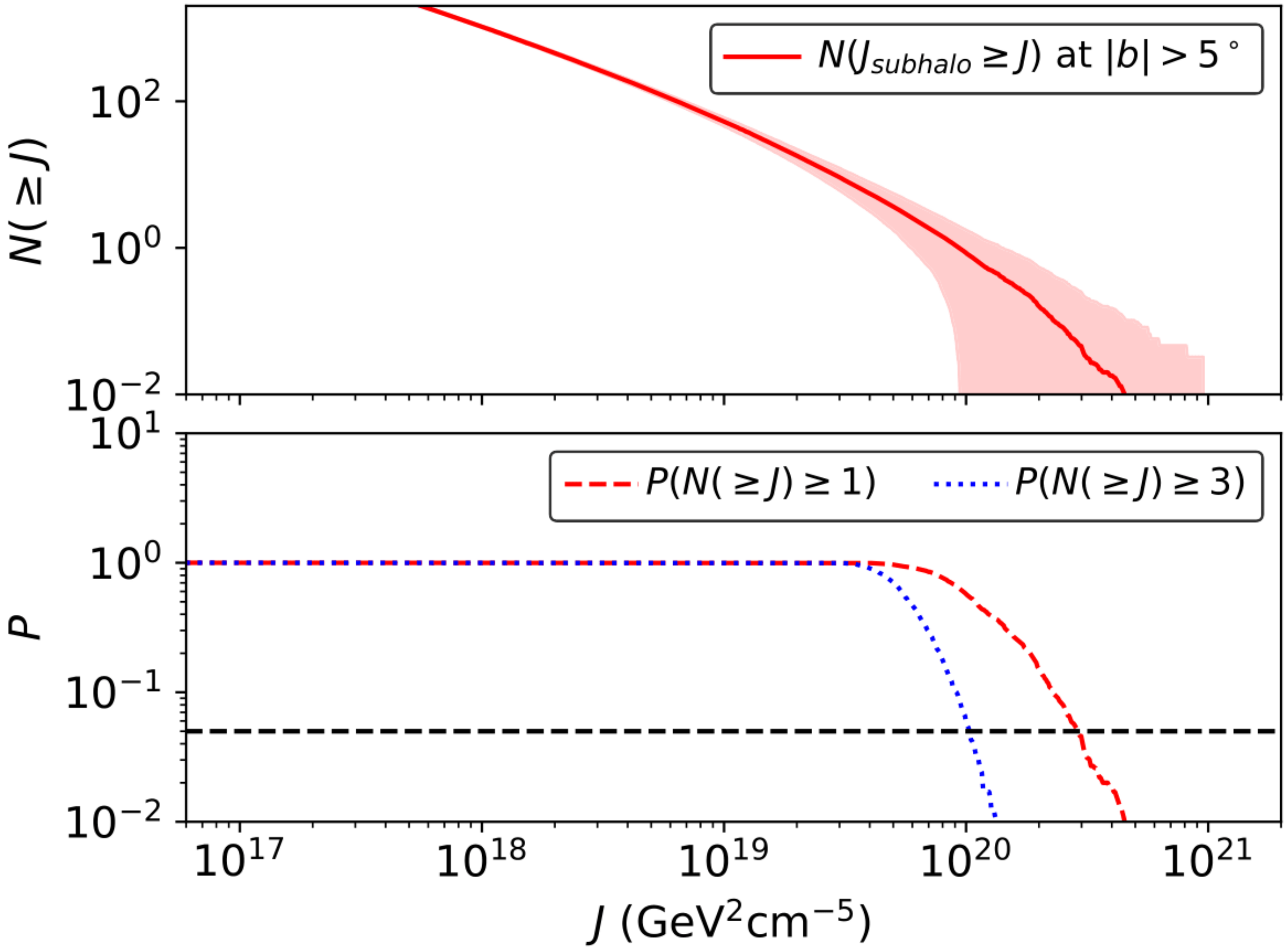
Cumulative J-factor distribution and number of halos

- Lower panel: probabilities to find at least one or three subhalos with J-factor exceeding a given value;

At 95% C.L. :

- $\exists\ N_{halo} \geq 1$ with $J_{halo} < 3\text{x}10^{20}\text{GeV}^2\text{cm}^{-5}$
- $\exists\ N_{halo} \geq 3$ with $J_{halo} < 1\text{x}10^{20}\text{GeV}^2\text{cm}^{-5}$

→ probability to have at least three subhalos with a J-factor of $\geq 3\text{x}10^{20}$ GeV^{2}cm^{-5} is only about 5%.



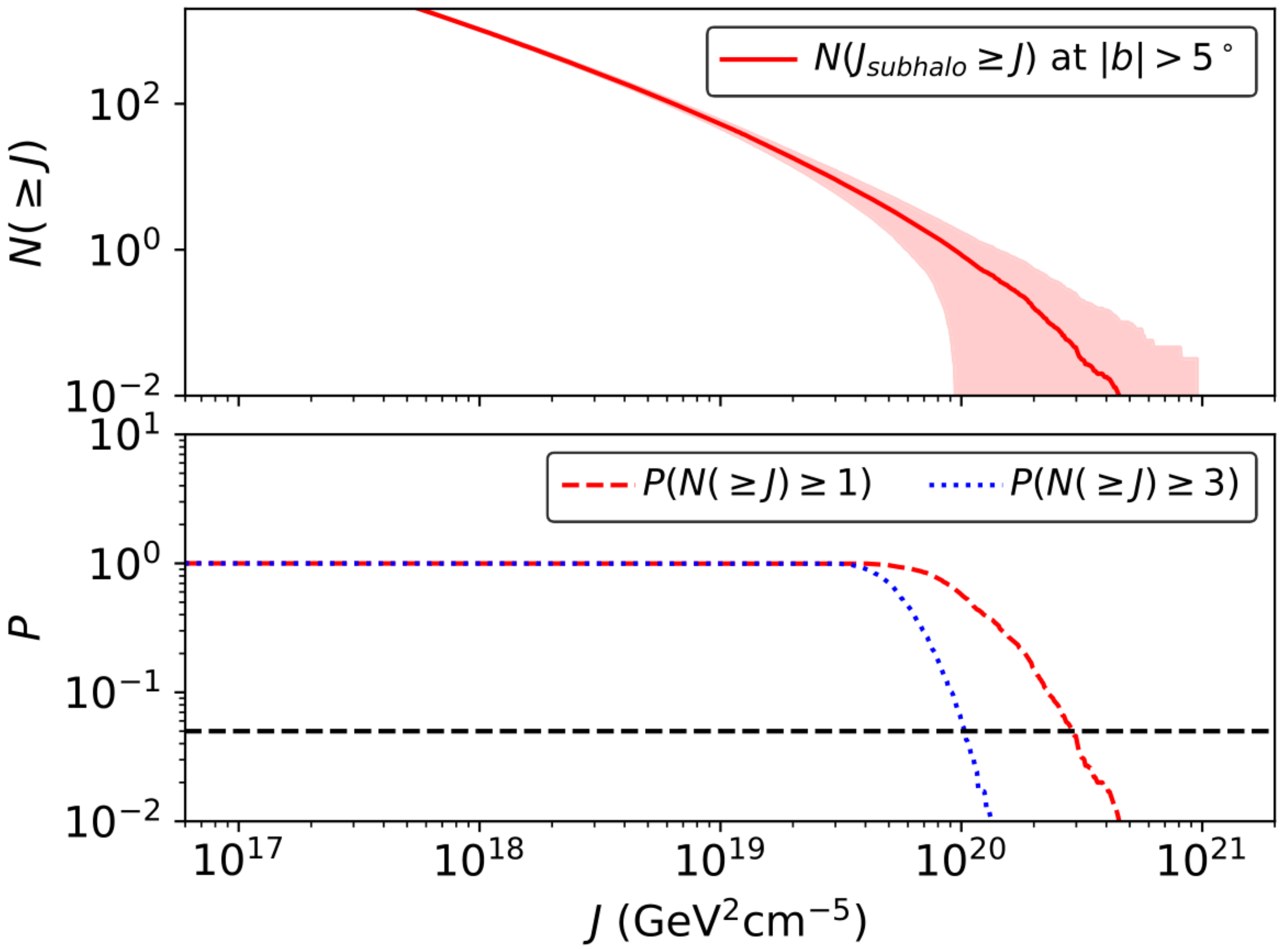
Cumulative J-factor distribution and number of halos

At 95% C.L. :

- $\exists\, N_{halo} \geq 1$ with $J_{halo} < 3\text{x}10^{20}\,\text{GeV}^2\text{cm}^{-5}$
- $\exists\, N_{halo} \geq 3$ with $J_{halo} < 1\text{x}10^{20}\,\text{GeV}^2\text{cm}^{-5}$

→ probability to have at least three subhalos with a J-factor of ≥ $3\text{x}10^{20}$ $\text{GeV}^2\text{cm}^{-5}$ is only about 5%.

- *Caveat:* uncertainties on the highest predicted J-factor values
  - Baryon feedback → the highest J-factor values even more unlikely;
  - Highest subhalo J-factors are usually subject to a large statistical variance;



Refs. Hütten et al., Galaxies, 2019b, 7, 60
Stref and Lavalle, Phys. Rev. D., 2017
Despali and Vegetti, MNRAS, 2017

Conclusions

- UFOs dataset and stacked dataset;
  → $\langle \boldsymbol{\sigma v} \rangle$ $\boldsymbol{x}$ $\boldsymbol{J}$ **values that explain DM-induced emission models for the UFOs.**

- $\langle \sigma v \rangle_{th} = 3\text{x}10^{-26}\ \text{cm}^3/\text{s}$;
  → $\boldsymbol{J}\boldsymbol{\epsilon}$[few $\mathbf{10^{20}}$, $\mathbf{10^{21}}$]$\mathbf{GeV^2 cm^{-5}}$ allowed by Fermi-LAT fit and H.E.S.S. U.L..

- Cumulative J-factor distribution:
  → **probability ≃ 5% to have at least three subhalos with a J-factor ≥ $3\text{x}10^{20}$ GeV^2cm^{-5};**
  - large systematic uncertainties on the prediction fot the highest J-factor values

→ **UFO emissions in terms of annihilations of DM particles is excluded down to masses of few hundreds of GeV at a high C.L..**

→ **H.E.S.S. model-independent constraints relevant and robust ones for interpretation of the UFOs as Galactic subhalos of annihilating DM.**

✓ Ref. Abdalla, H. et al. *Search for dark matter annihilation signals from unidentified Fermi-LAT objects with H.E.S.S.*, [H.E.S.S. collaboration], arXiv:2106.00551.

Appendix slides

H.E.S.S. analysis

- For each UFO, *WobbleMultipleOFF* H.E.S.S. measurement;
- Std pointlike RoI: 0.12°- radius disk;
- Std excluded region around RoI: disk of 0.25° radius.

UFO	Live Time (h)	Mean zenith angle (°)	N_{ON}	N_{OFF}	α	S[σ]
3FHL J0929.2-4110	27.4	29.0	424	5884	13.9	0.1
3FHL J1915.2-1323	3.6	19.1	87	1181	13.9	0.2
3FHL J2030.2-5037	9.8	31.3	160	2192	13.9	0.1
3FHL J2104.5+2117	6.8	46.7	73	853	13.9	1.1

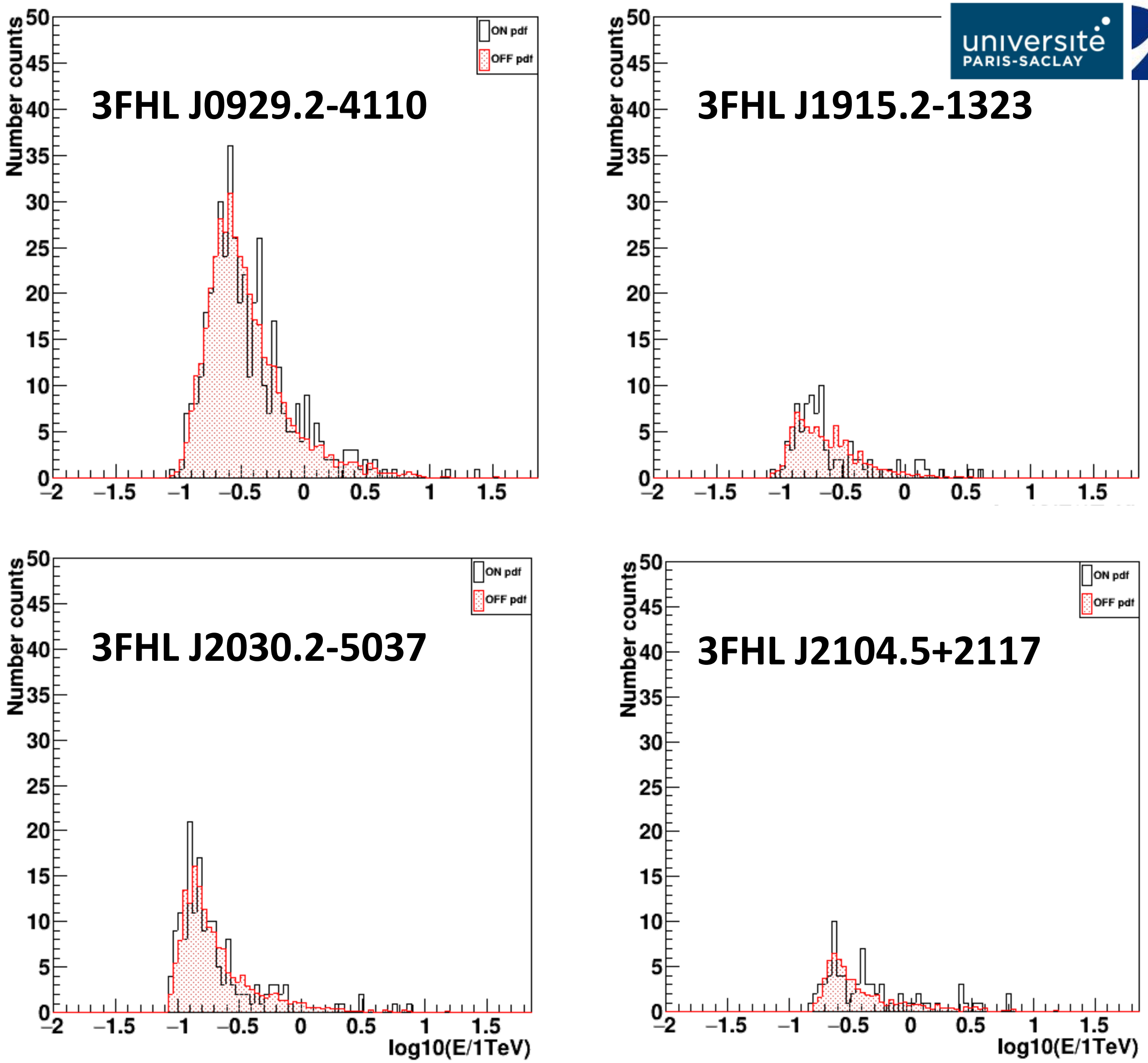
H.E.S.S. analysis

- ON/OFF energy count distribution

- *WobbleMultipleOFF* measurement;
- RoI: 0.12°- radius disk;
- excluded region around the RoI: disk of 0.25° radius.

- No significant excess found between ON and normalized OFF distributions;

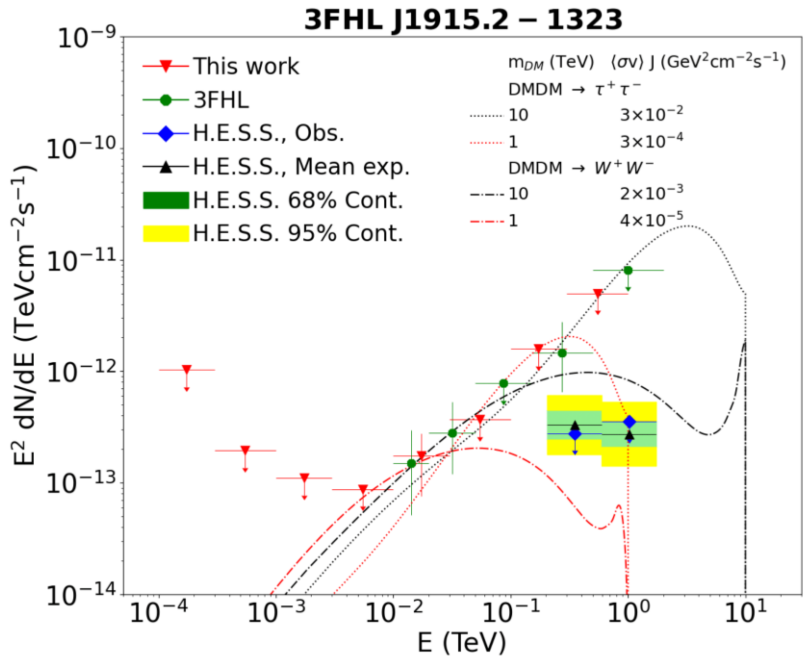
→ 95% C.L. U.L. derivation.

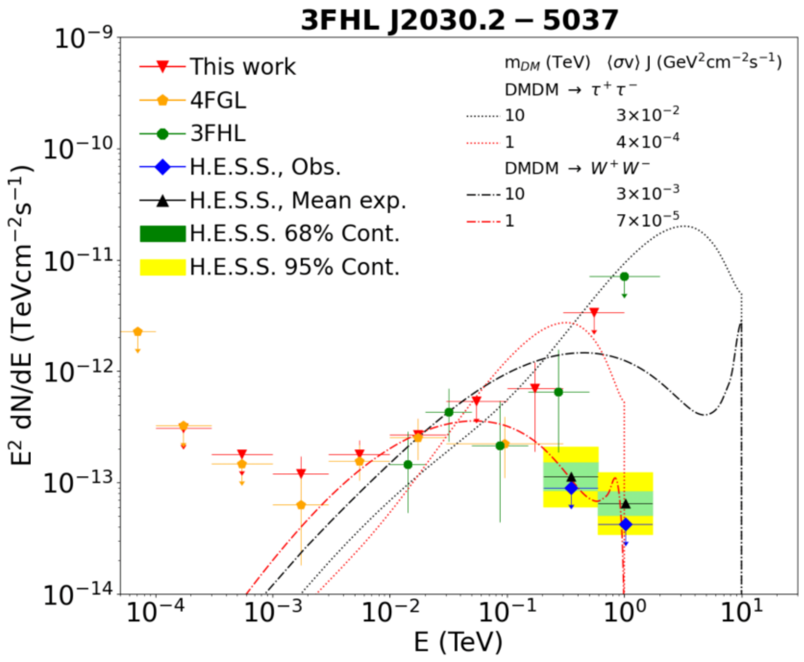


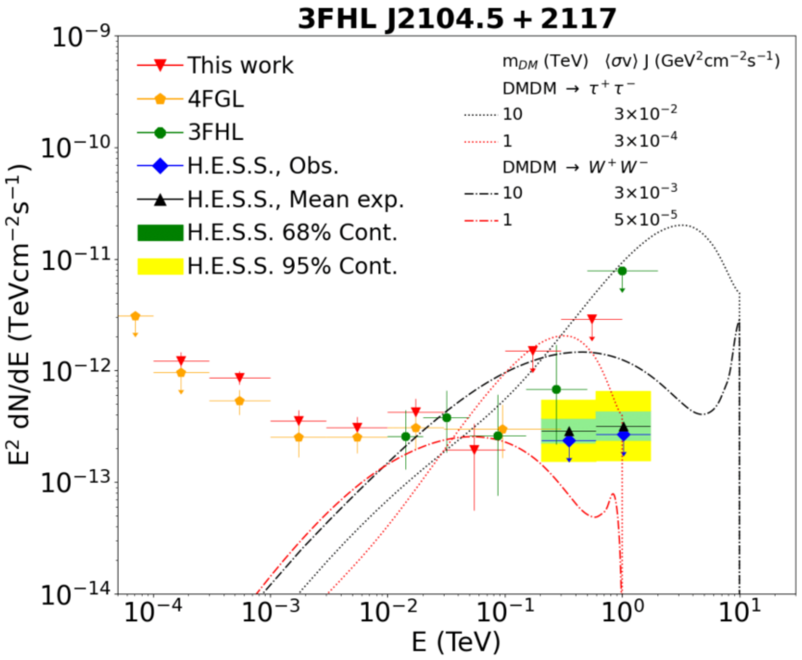
Spectral Energy Distribution for the other UFOs

- *Fermi*-LAT differential flux point
  1σ statistical error bars
- *Fermi*-LAT differential flux upper limits
  95% C.L. upper limits

H.E.S.S. differential flux upper limits:
- Observed
- Mean Expected
- 68% Containment, 95% Containment







Likelihood analysis method and test statistics definition

- No significant excess in any UFO:
  - 95% C.L UL on the free parameter $\langle \sigma v \rangle$ x J

- Likelihood definition :
  - $L(\mu, \beta, \alpha | N_{ON}, N_{OFF}) = \prod_k \frac{(\mu+\beta)^{N_{ON}}}{N_{ON}!} \exp -(\mu + \beta) \frac{(\mu\prime+\alpha\beta)^{N_{OFF}}}{N_{OFF}!} \exp -(\mu' + \alpha\beta)$
    - 1D binned Poisson likelihood functions to exploit
      - energy bins inside the RoI (k index)
      - stacking of the UFOs datasets
    - OFF regions from the *WobbleMultipleOFF*: different α values

- LLRTS definition :
  - $LLRTS = -2 \ln(L(\mu, \bar{\bar{\beta}}, \alpha | N_{ON}, N_{OFF}) / L(\bar{\mu}, \bar{\beta}, \alpha | N_{ON}, N_{OFF}))$
    - $LLRTS$ (1 d. o. f.) = 2.71 for the 95% C.L. UL

    see Cowan, G., Cranmer, K., Gross, E. *et al.*, *Eur. Phys. J. C* **71**, 1554 (2011).

DM-induced models for UFO emissions

- Definition of a Likelihood function and the Test Statistic *(LLRTS)*

•Likelihood $L(\mu, \beta, \alpha | N_{ON}, N_{OFF}) =$

$$\prod_k \frac{(\mu+\beta)^{N_{ON}}}{N_{ON}!} e^{-(\mu+\beta)} \frac{(\mu\prime+\alpha\beta)^{N_{OFF}}}{N_{OFF}!} e^{-(\mu\prime+\alpha\beta)}$$

- $LLRTS = -2\ \ln(L(\mu, \bar{\bar{\beta}}, \alpha | N_{ON}, N_{OFF}) / L(\bar{\mu}, \bar{\beta}, \alpha | N_{ON}, N_{OFF}))$
  - $LLRTS\ (1\ \mathrm{d.o.f.}) = 2.71$ for the 95% C.L. UL

Ref. Cowan, G., Cranmer, K., Gross, E. *et al., Eur. Phys. J. C* **71**, 1554 (2011).

- No significant excess in the H.E.S.S. dataset
  → 95% C.L. U.L. on $\langle \sigma v \rangle$ x J for the four UFOs sources