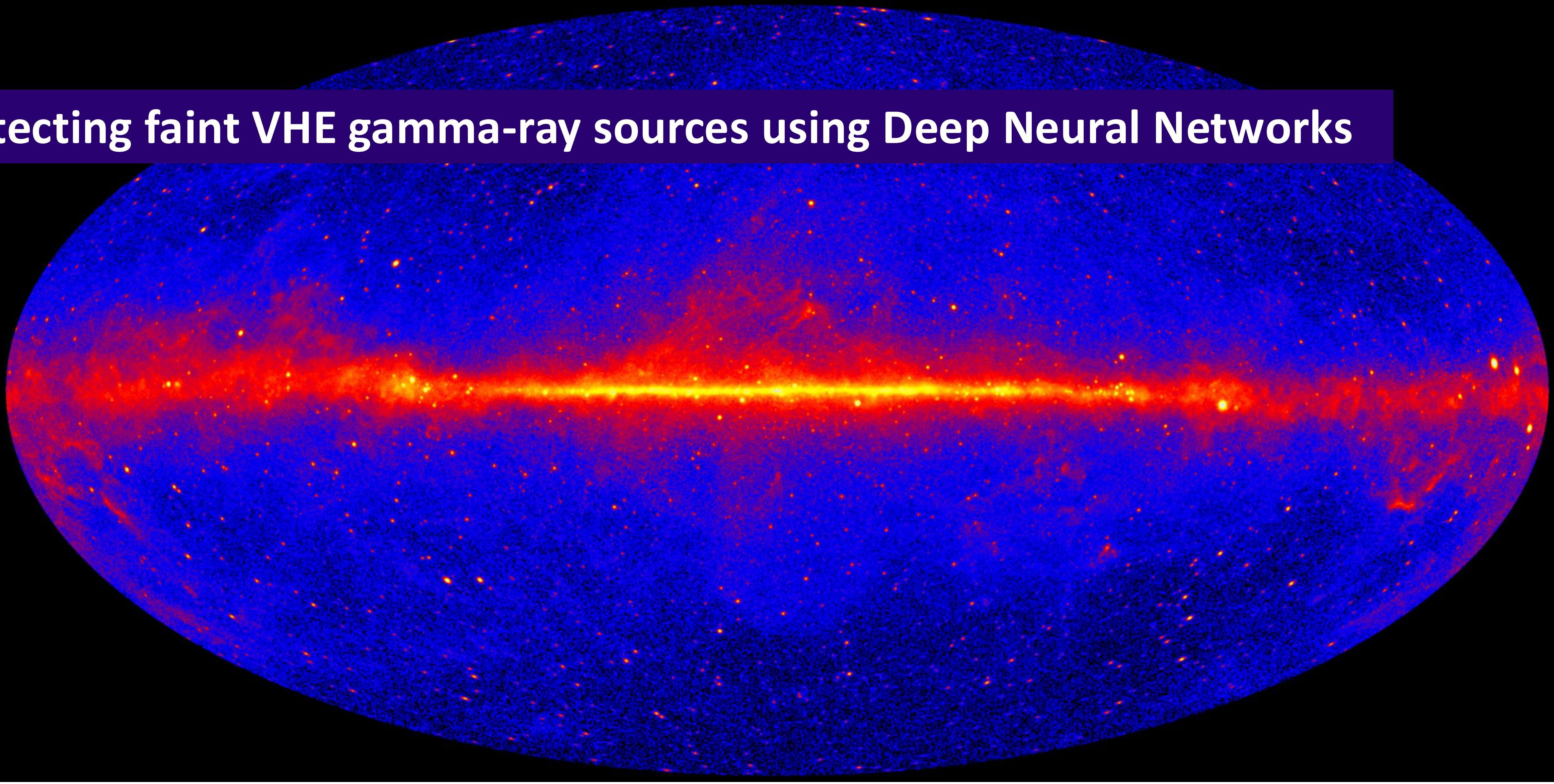
Detecting faint VHE gamma-ray sources using Deep Neural Networks



SMASH
machine learning for science and humanities postdoctoral program

Co-funded by the European Union

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UNIVERZA V NOVI GORICI SCIENTIA 1995 VINCES

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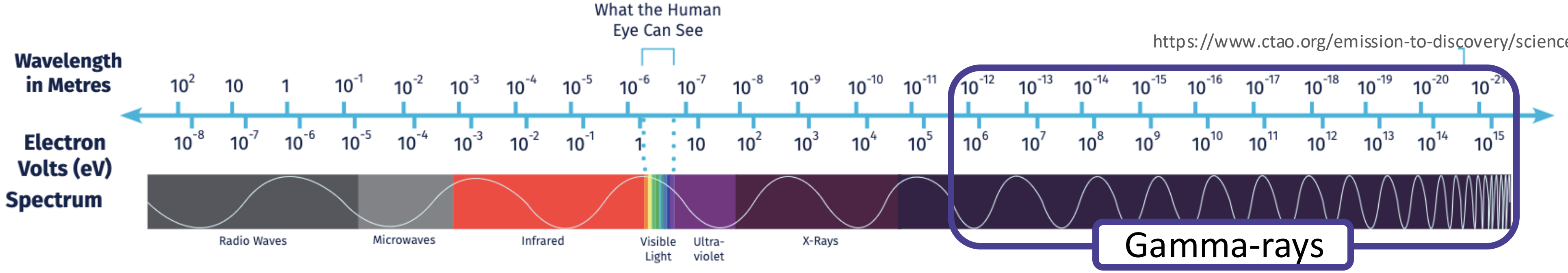
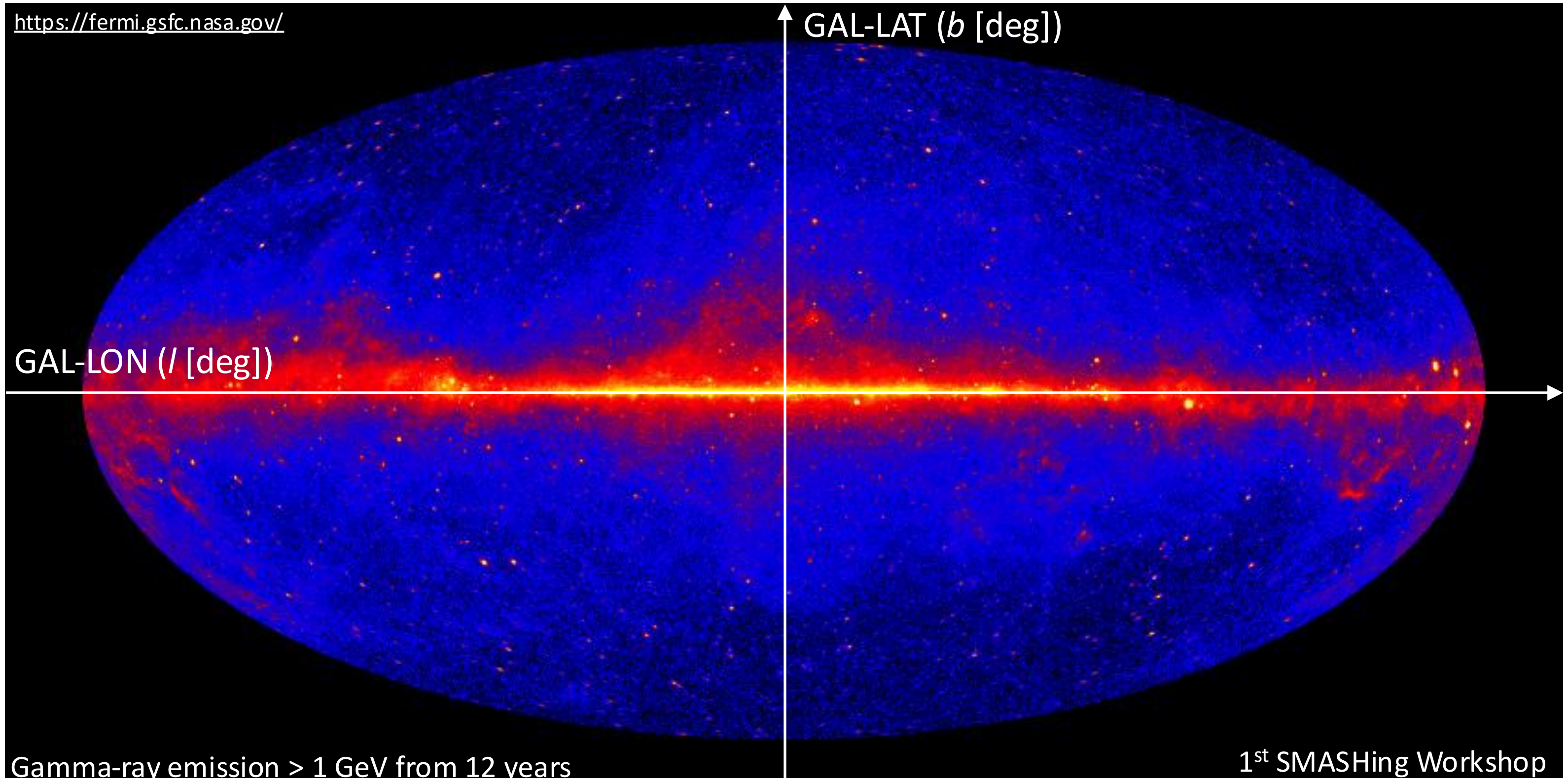
1st SMASHING WORKSHOP machine learning for science and humanities OCTOBER 7th – 11th 2024 LANTHIERI MANSION VIPAVA

10/10/2024

THE GAMMA-RAY SKY



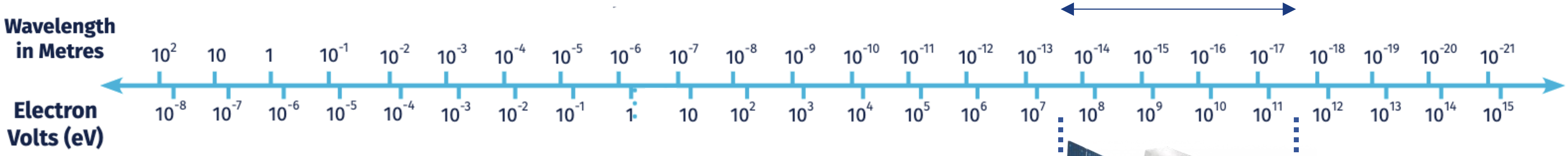
Gamma-rays are electromagnetic radiation > 100 keV



- Gamma-rays travel in straight lines, allowing to determine their origin
- Originated from non-thermal processes due to extremely violent phenomena
- Gamma-ray sources:
  - Galactic
  - Extragalactic
  - Exotic (?)

THE GAMMA-RAY SKY: BACKGROUNDS

- Different techniques for gamma-ray detection, wide energy range



Space-born telescope: Fermi Large Area Telescope (LAT)

- Instrument is based on:

Tracker (e$^-$e$^+$ tracks from the gamma-ray) → Direction (position)

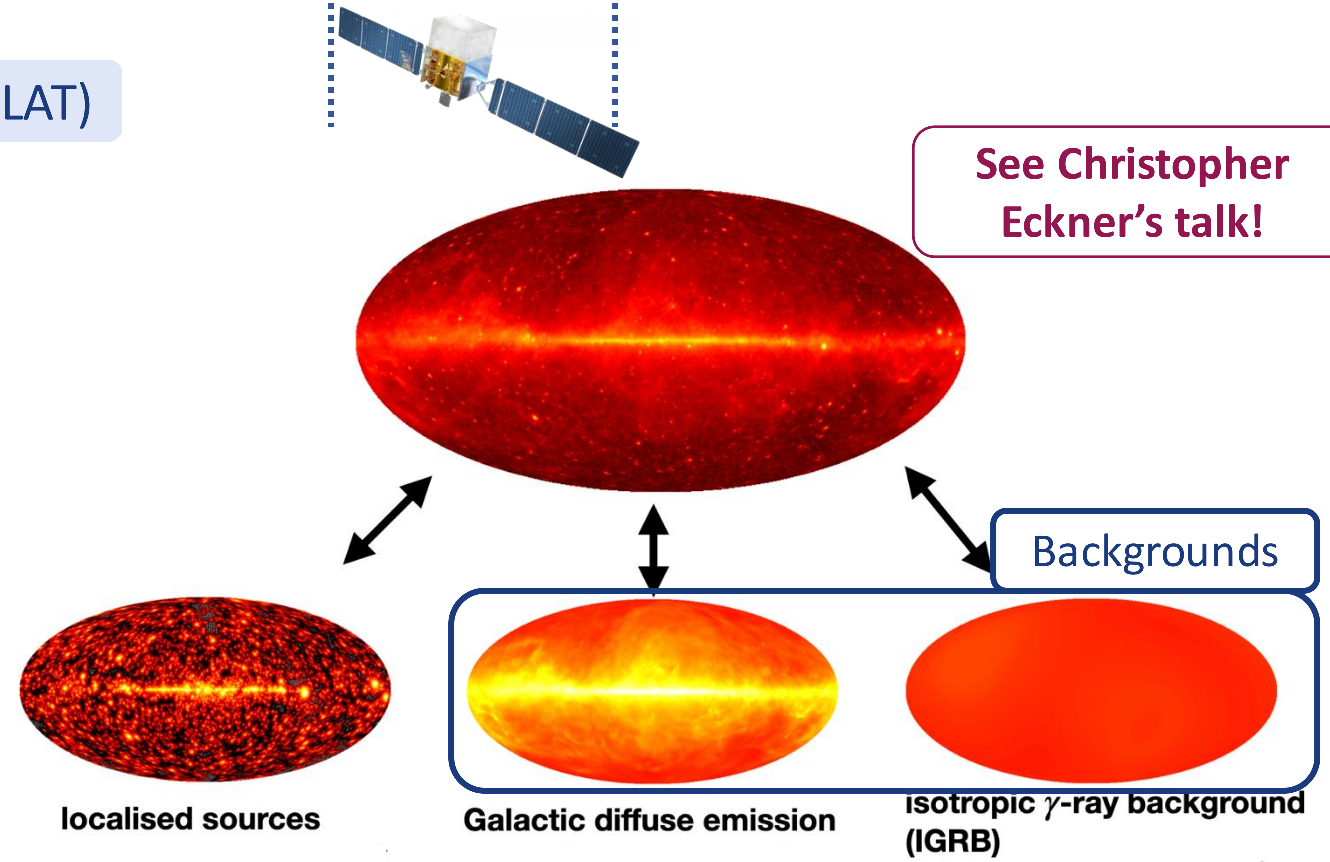
\+

Calorimeter → Energy

\+

Anti-coincidence detector → Background rejection

See Christopher Eckner's talk!



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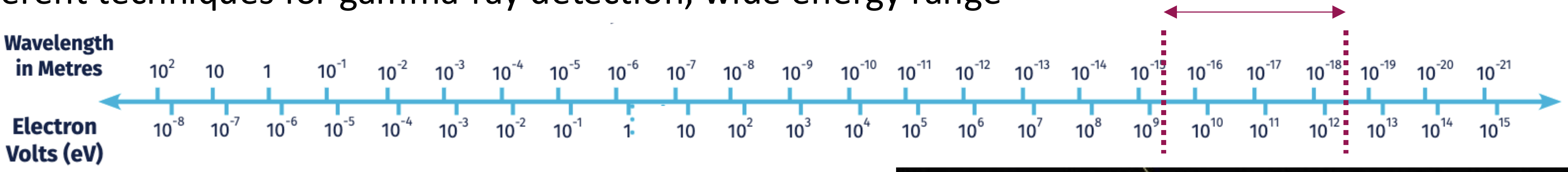
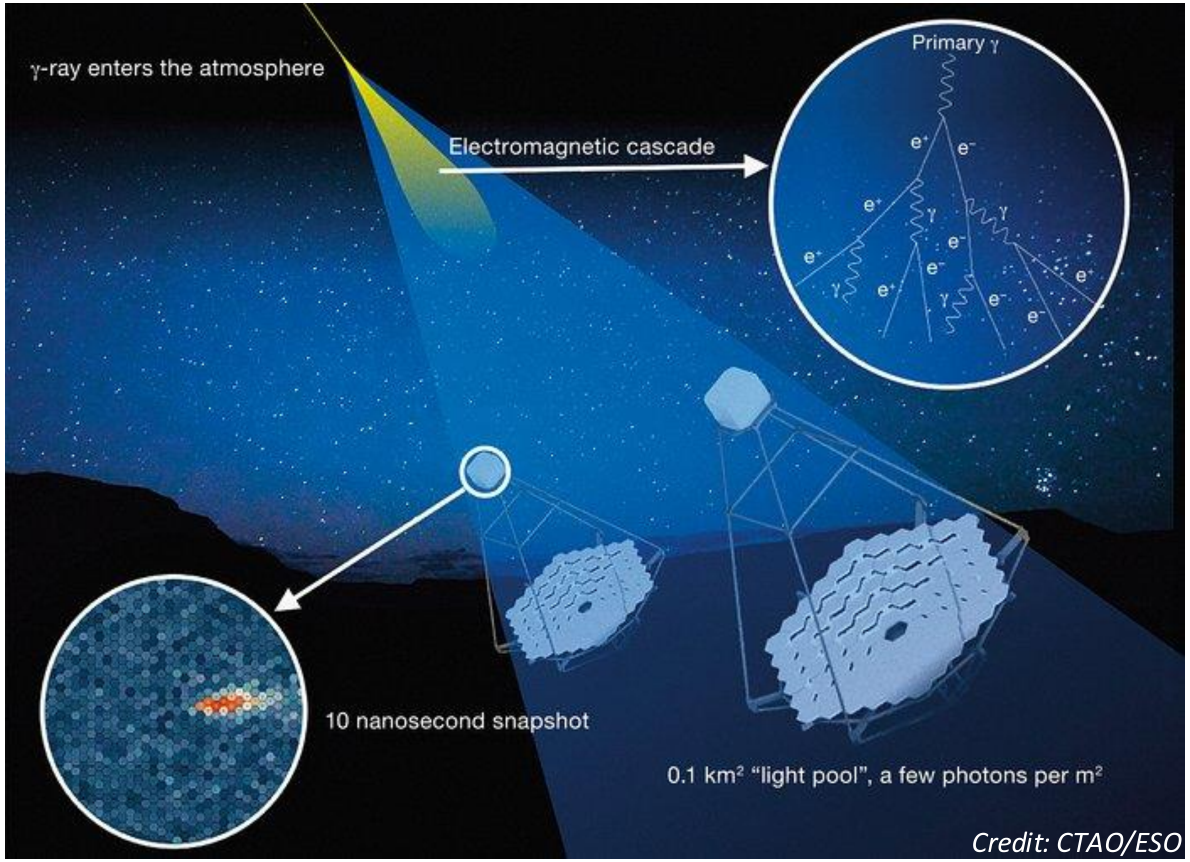


Imaging Air Cherenkov Telescopes (IACTs)

- Ground-based telescopes
- Detect secondary products from the interaction between the gamma-ray and the atmosphere
- Protons also produce air showers: up to 10^4 larger than rate of gamma-rays

Irreducible CR background inherent to each IACTs



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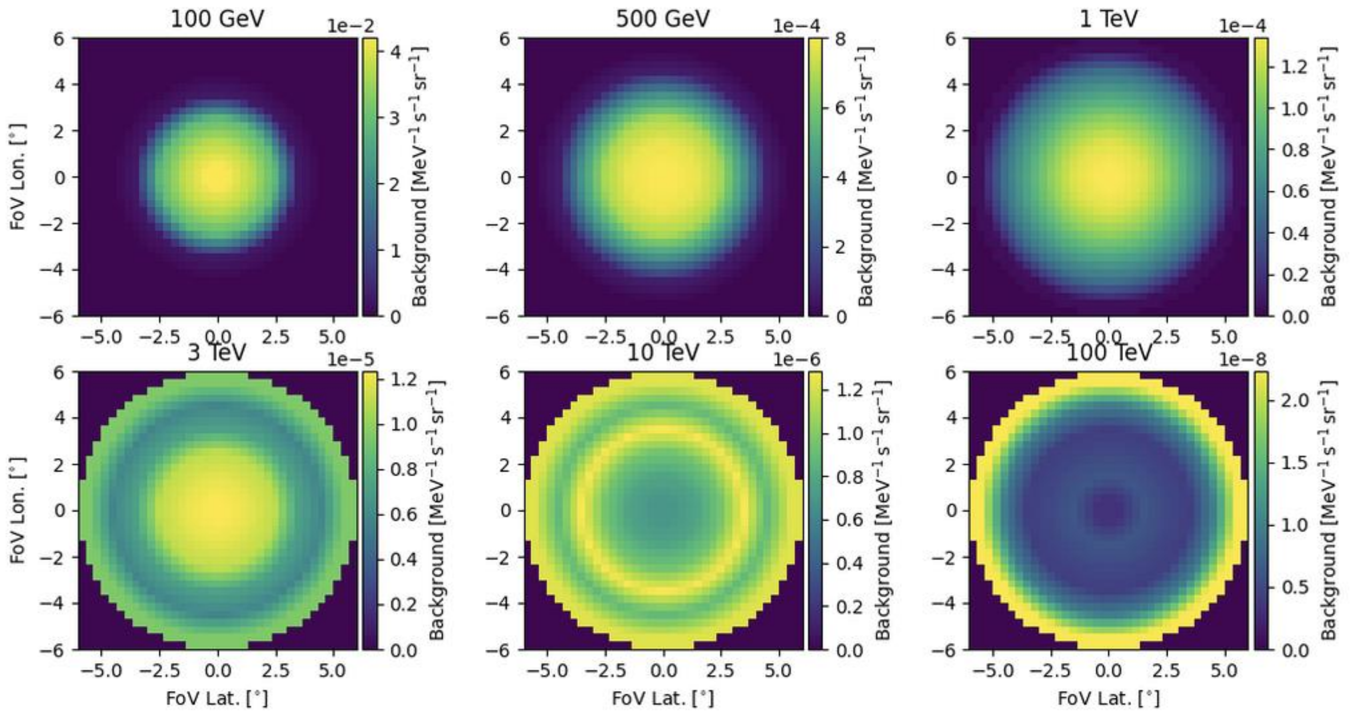
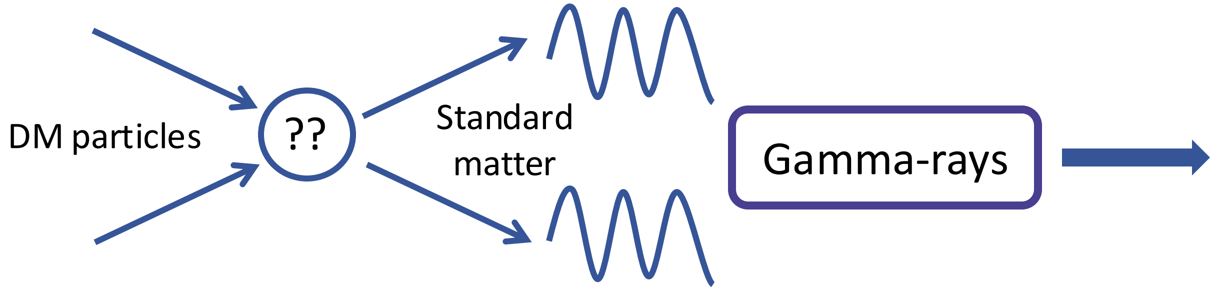


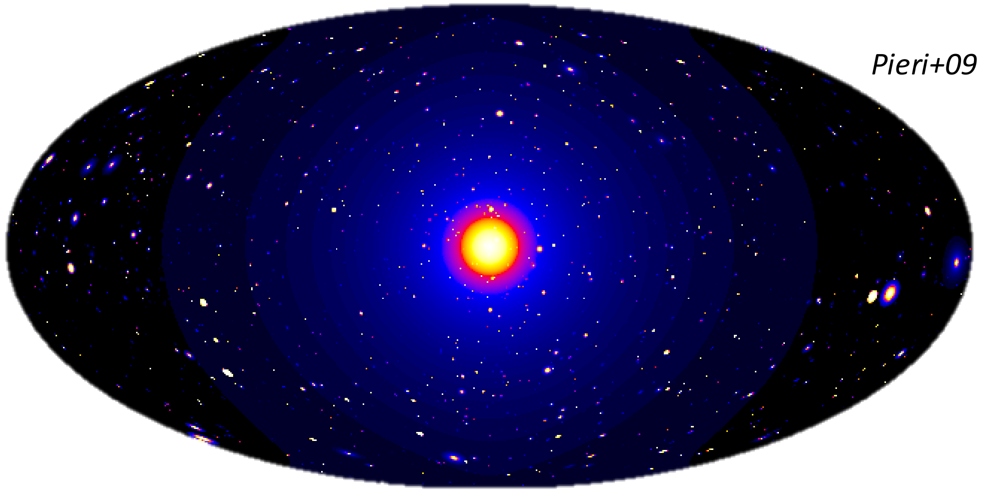
https://docs.gammapy.org/1.2/tutorials/data/cta.html

THE GAMMA-RAY SKY: FAINT SOURCES

- These backgrounds hinder the detection of faint gamma-ray sources
- Faint sources enclose a lot of new physics information:

Dark Matter (DM)

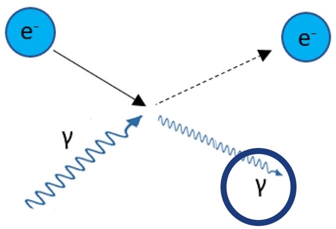




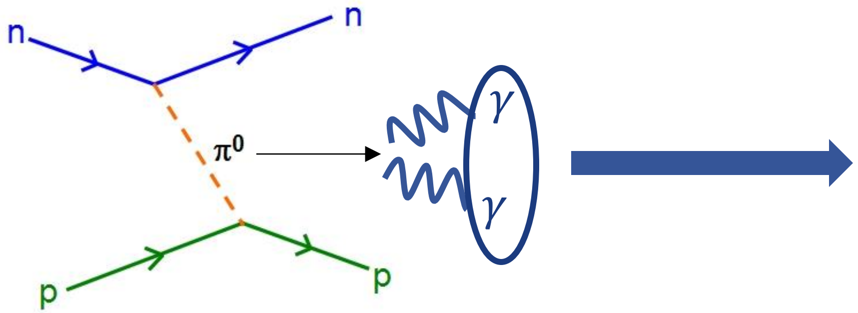
Pieri+09

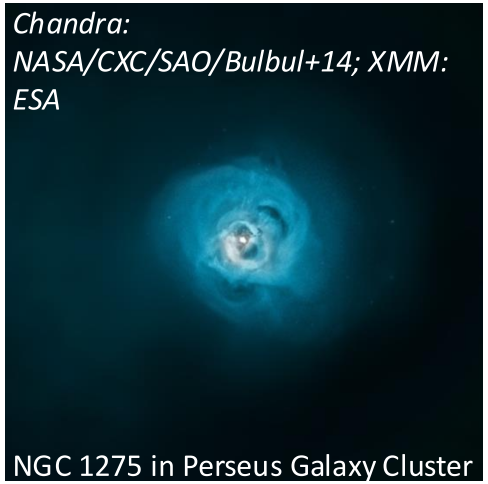
Cosmic ray (CR) production & populations

- Particles in the vicinity of violent phenomena are accelerated:



Inverse Compton (IC)





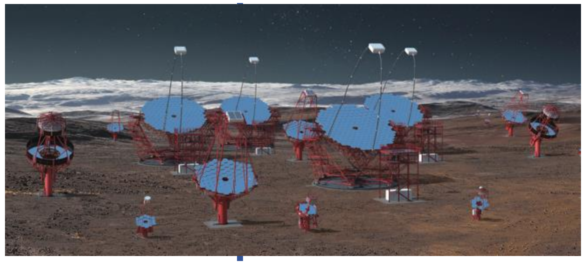
Galaxy clusters:
- DM dominated
- CR poulations

ML TO DETECT FAINT GAMMA-RAY SOURCES

Long-term problem for robustly detect faint sources (lower the detection threshold)

1. Use Machine Learning (ML) techniques to improve the efficiency of the analysis and fully exploit the data

2. Use the most complete and state-of-the-art datasets →



Cherenkov Telescope Array Observatory (CTAO)

Fermi-LAT

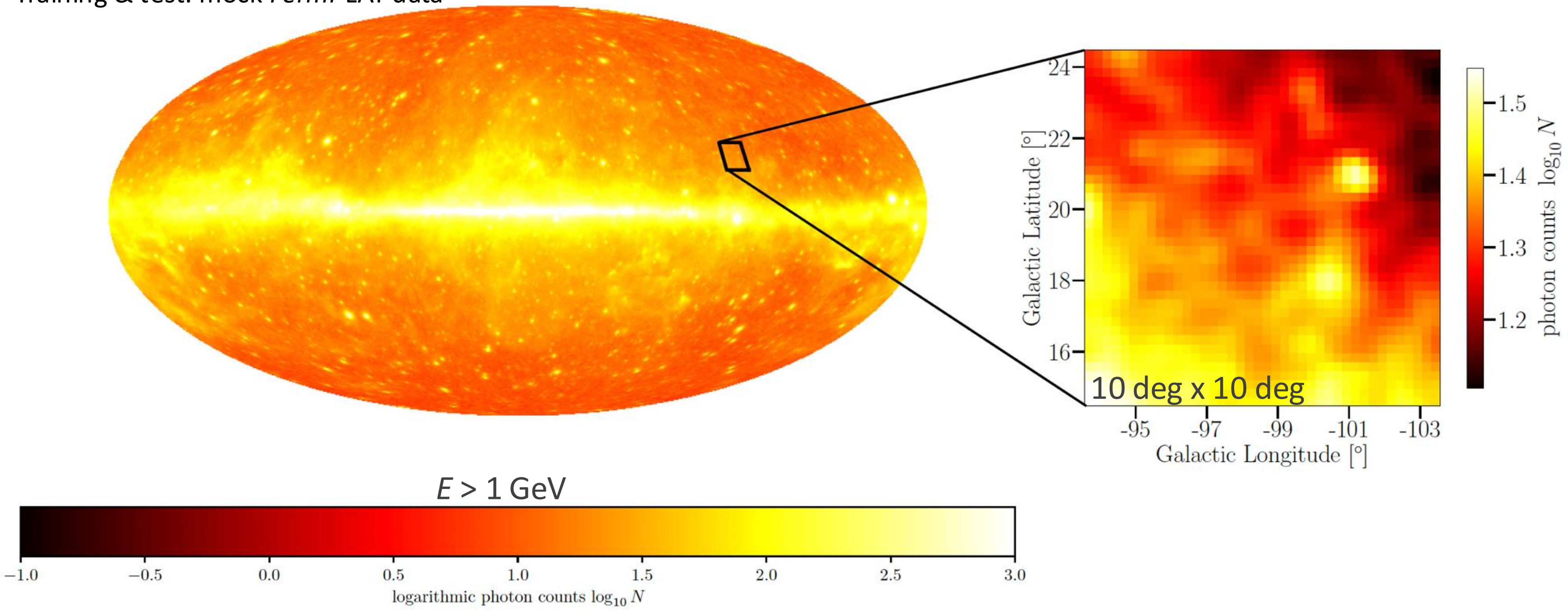
ML TO DETECT FAINT GAMMA-RAY SOURCES

- Standard gamma-ray analysis:

Models for the signal + **background** + Likelihood fitting → ! Lack of knowledge of backgrounds can introduce strong biases

AutoSourceID (ASID) *[Panes+21]*
https://www.nikhef.nl/%7EEscaron/autosourceid/

Training & test: mock *Fermi*-LAT data



- CNN pipeline based on U-Net algorithms
- Goal: **detect** and classify **point-like** sources

1. Detection: U-NET + clustering algorithm (*k-means*, Centroid-NET)
2. Classification: deep NN to classify different sources (from energy features)

ML TO DETECT FAINT GAMMA-RAY SOURCES

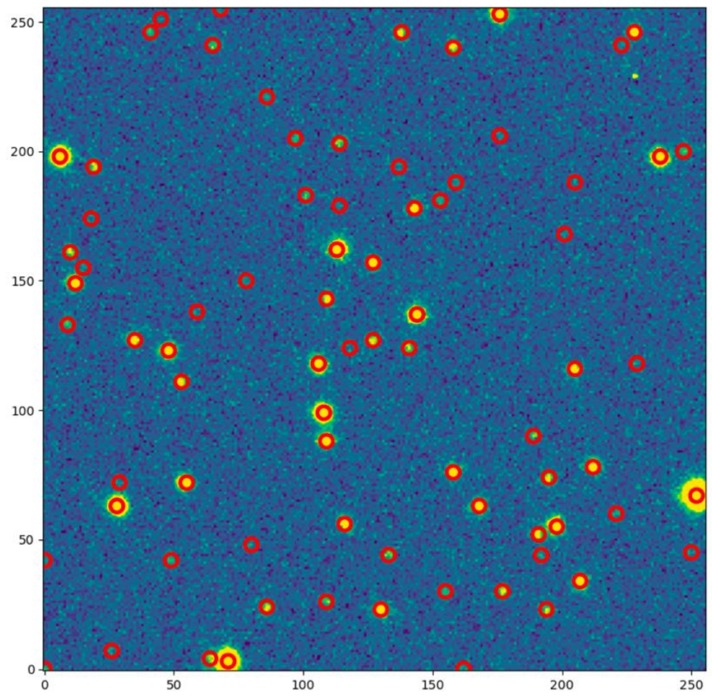
Localization

AutoSourceID-Light (ASID-L) *[Stoppa+22]*

https://github.com/FiorenSt/AutoSourceID-Light

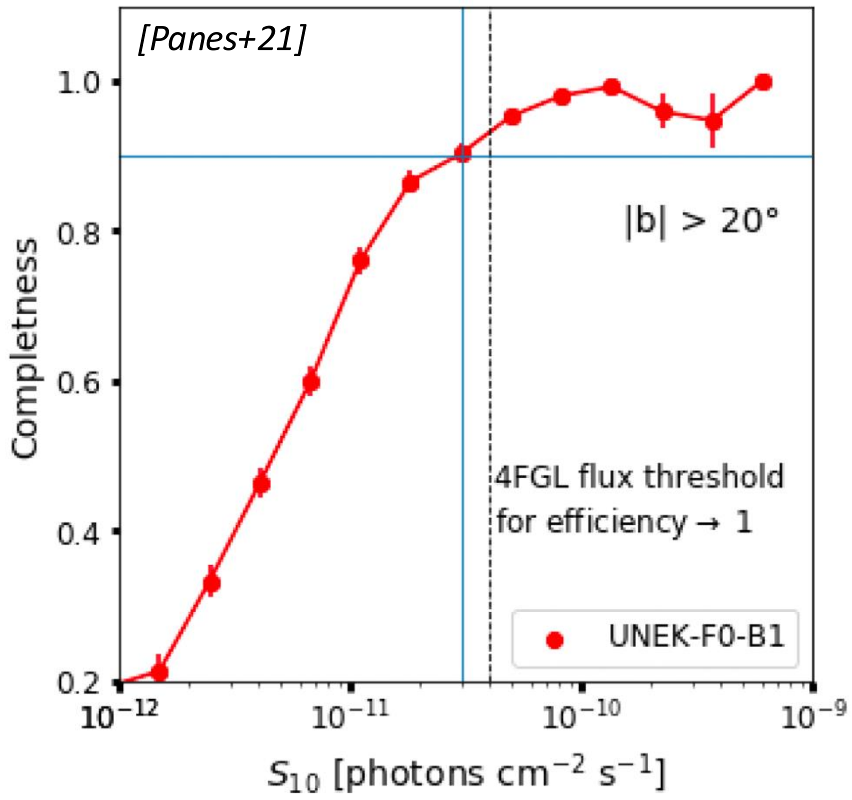
ASID enhanced with a Laplacian of Gaussian filter applied to optical data

$$\mathrm{LoG}(x,y;\sigma^2) = -\frac{1}{\pi\sigma^4}\left[1-\frac{x^2+y^2}{2\sigma^2}\right]e^{-\frac{x^2+y^2}{2\sigma^2}}$$



Detection (flux)

$$\text{Completeness} = \frac{\text{True positives}}{\text{True positive} + \text{False negatives}}$$



ML TO DETECT FAINT GAMMA-RAY SOURCES

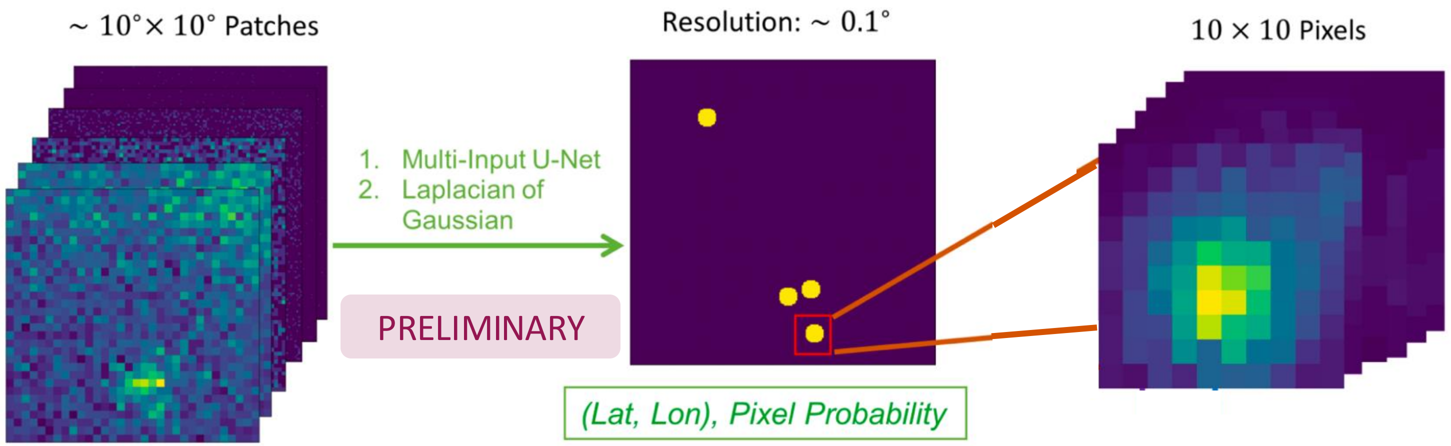
AutoSourceID (ASID) *[Panes+21]*

https://www.nikhef.nl/%7EEscaron/autosourceid/

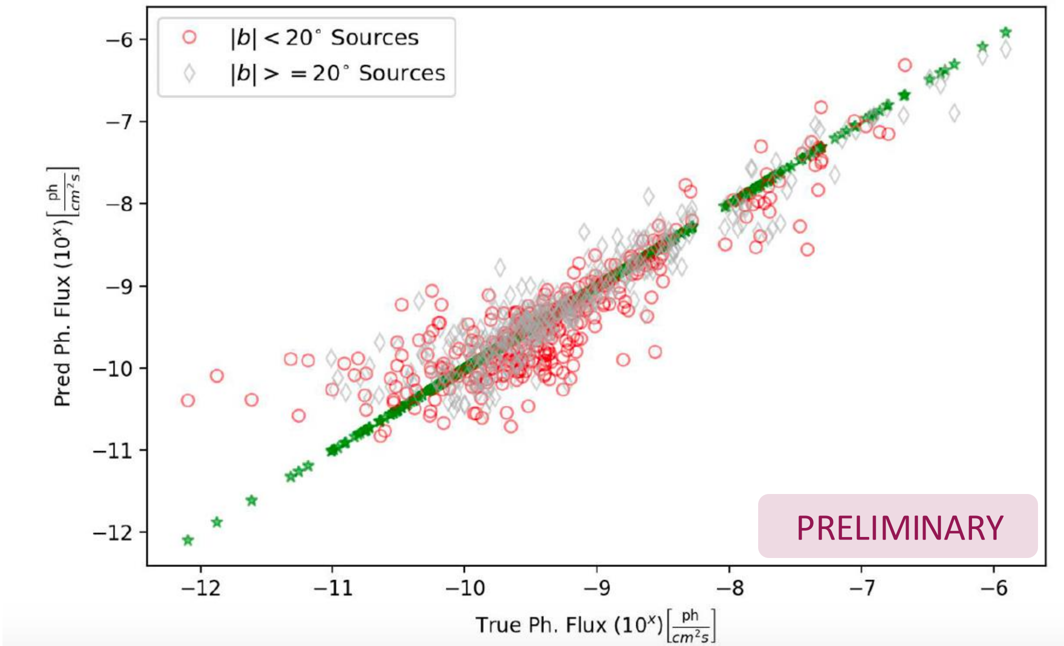
Current ASID work in progress!

Flux prediction

Real *Fermi*-LAT data



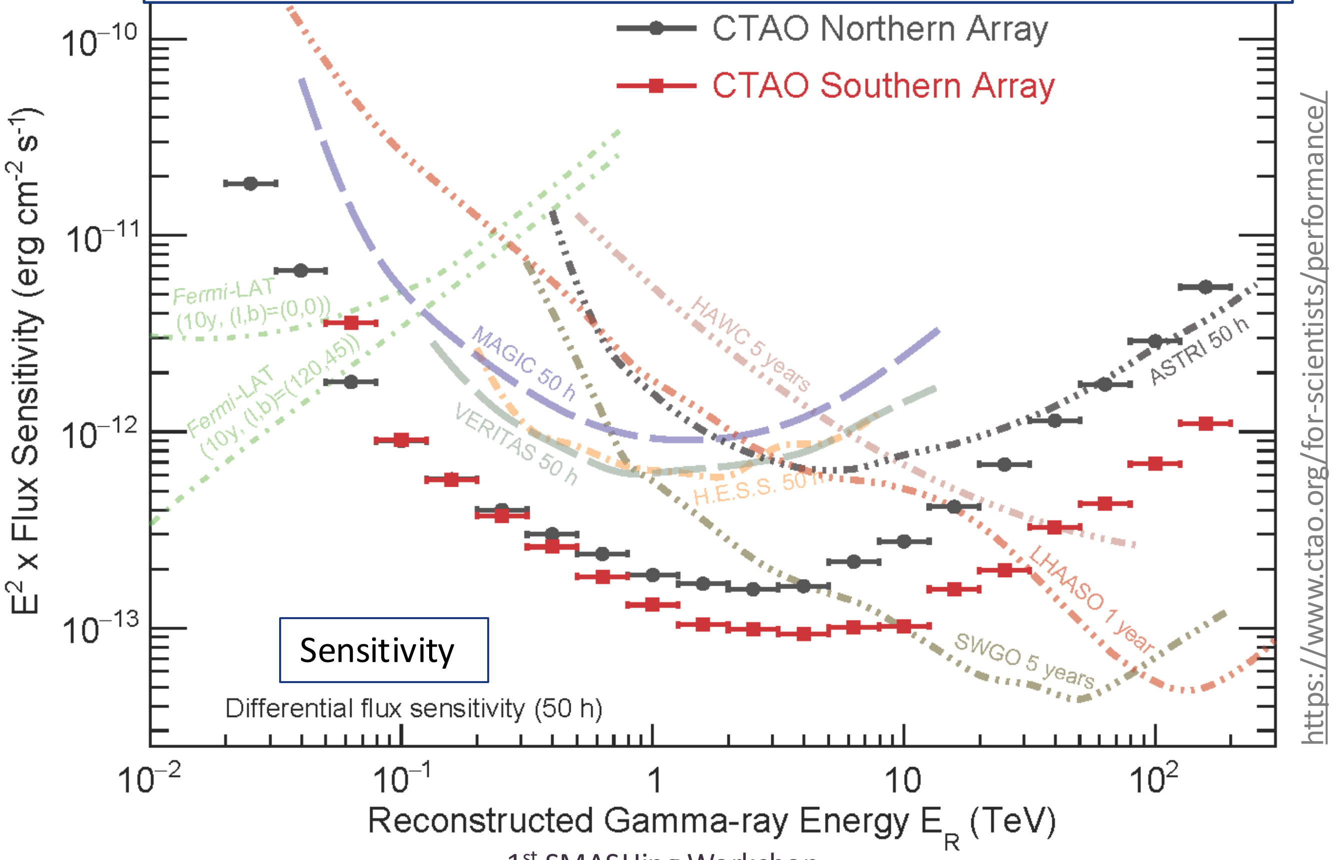
Courtesy of S. *Bhattacharyya*



ML TO DETECT FAINT GAMMA-RAY SOURCES: CTAO

- Future of IACTs for very-high energy gamma-ray astronomy
- 2 arrays: Northern Array (La Palma, Spain) and Southern Array (Paranal, Chile)
- First telescope already in operations!

Preliminary Performance Capabilities of the Alpha Configuration



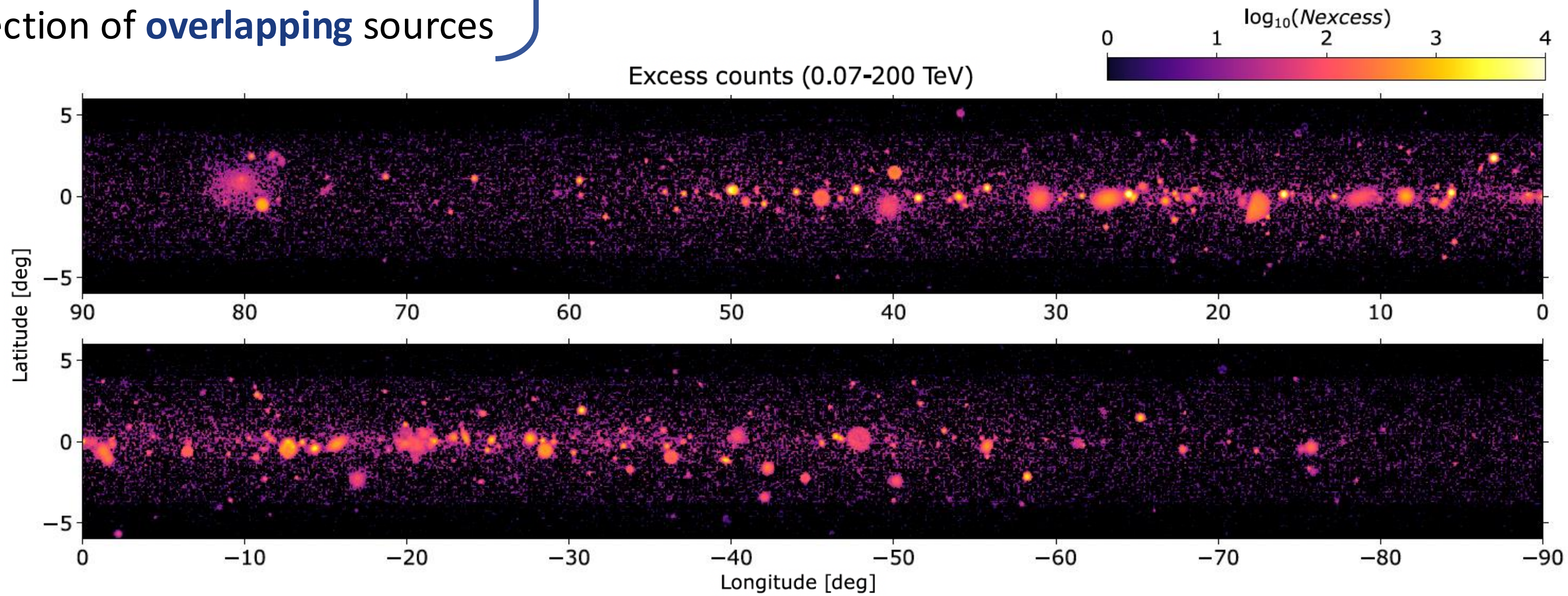
ML TO DETECT FAINT GAMMA-RAY SOURCES: CTAO

- Use `ASID` + `ASID-L` to aid in the detection of faint gamma-ray sources in CTAO data

How?

- Extend the reach of `ASID` to:
  - Simulated (but realistic) **CTAO** data
  - Detection of **extended** sources
  - Detection of **overlapping** sources

The galactic plane is the perfect environment for test!

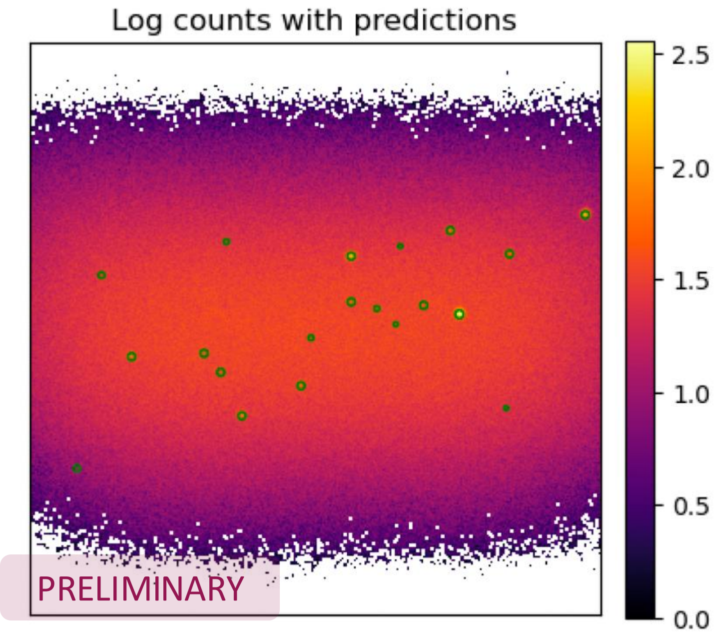


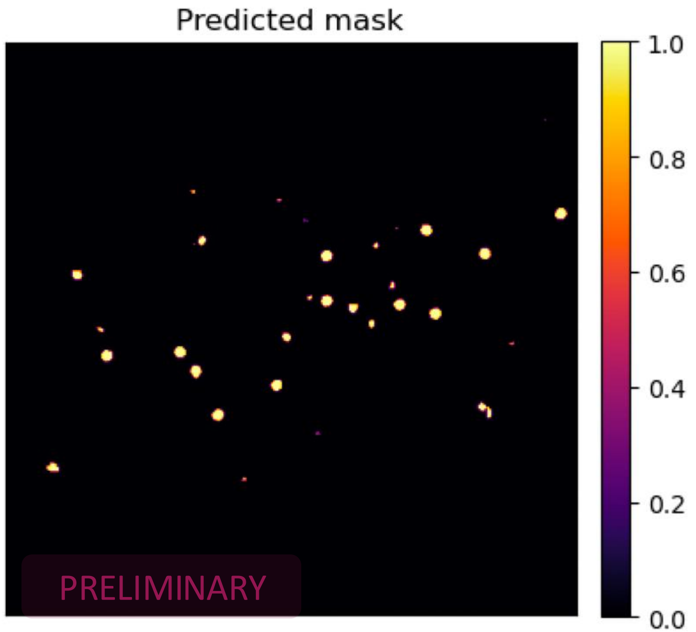
[CTAO Cons. 23]

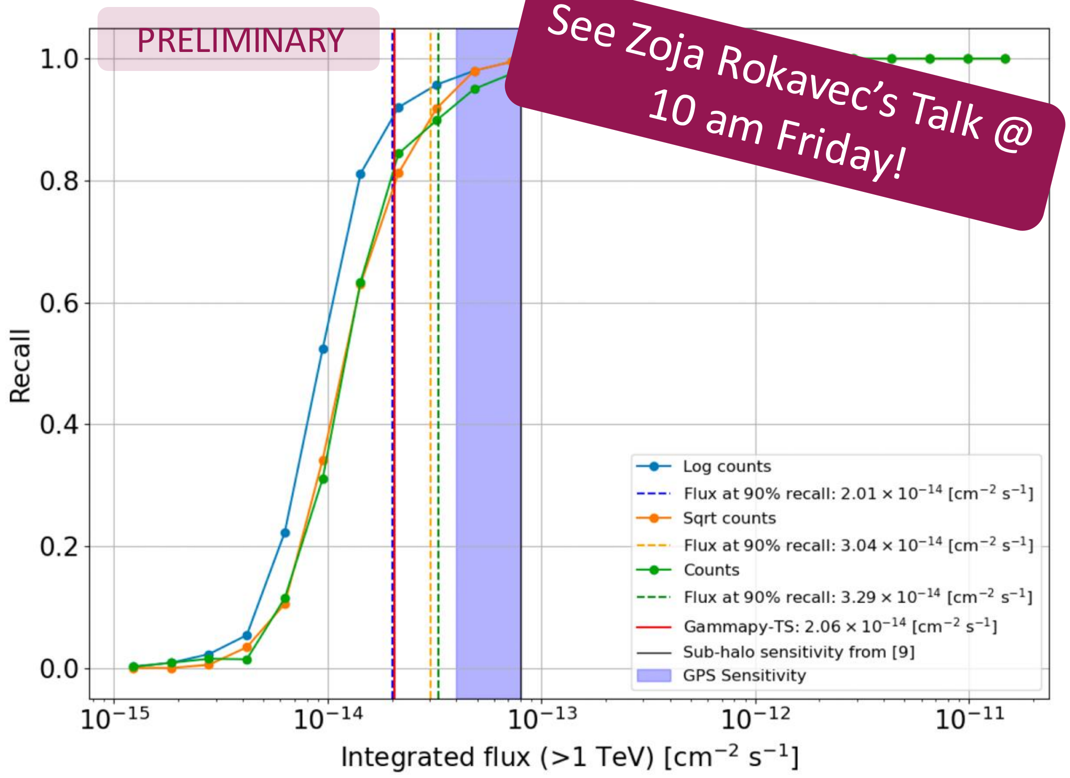
ML TO DETECT FAINT GAMMA-RAY SOURCES: CTAO

- Start testing `ASID` with:
  - Simulated **CTAO** data
  - Point-like sources

→ Toy model for the galactic plane sources







See Zoja Rokavec's Talk @ 10 am Friday!

SUMMARY AND FUTURE WORK

- CTAO will improve sensitivity of current IACTs ~O(1), boosting the chances for discovery of faint and still undetected sources

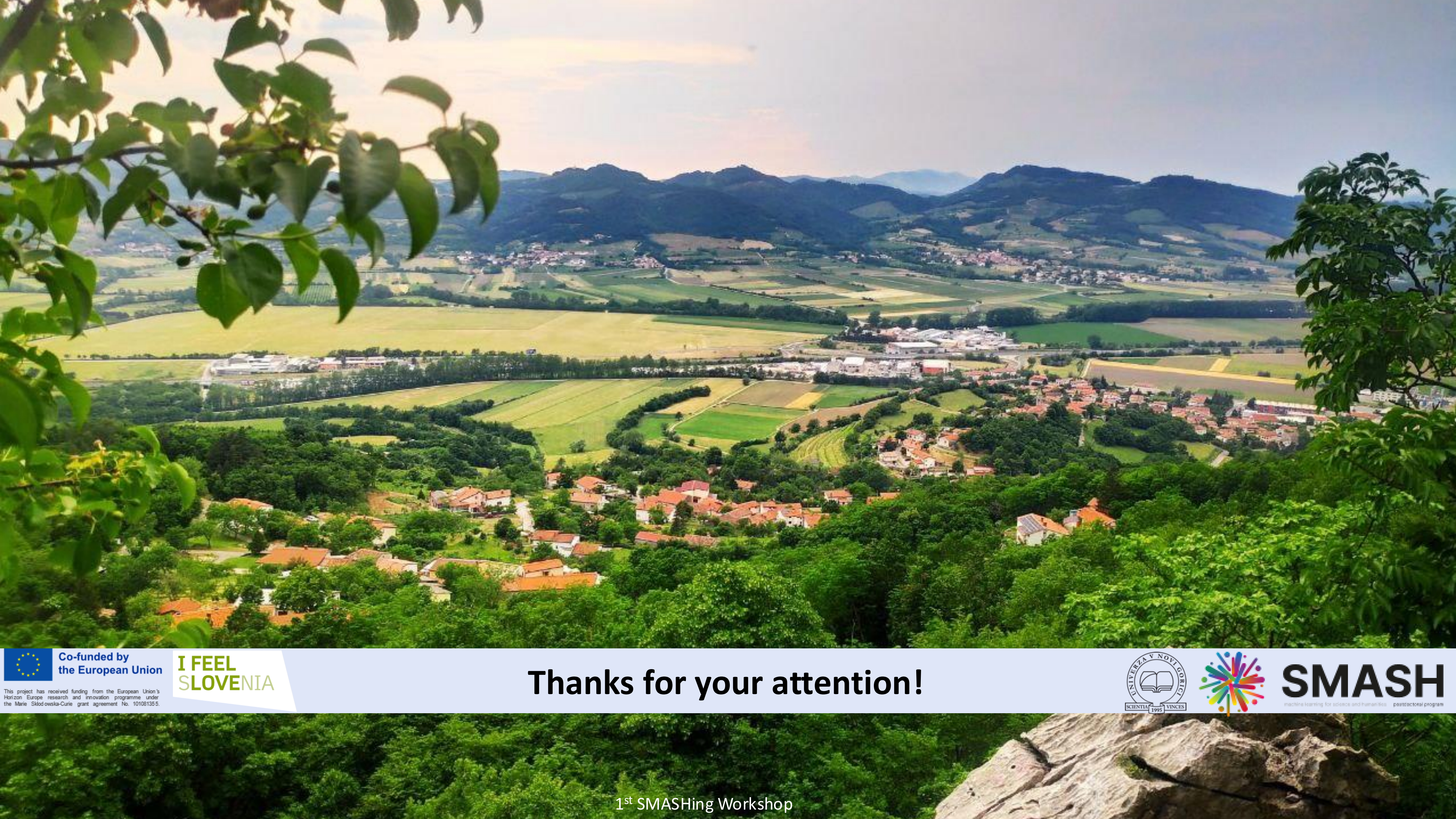
- Faint sources hold plenty of interesting physics, from unveiling the fundamental nature of DM to a better understanding of CR acceleration and production mechanism

- Gamma-ray data has to deal with irreducible backgrounds: GDE & IGRB (*Fermi*-LAT) and atmospheric CR BKG (IACTs), obstructing the analysis

- ML (specifically U-NET architecture like `ASID`) has show its potential to detect point-like sources in (simplified) gamma-ray data, obtaining comparable results as the standard likelihood analyses

- Next step ⟶ CTAO simulation of the galactic plane

    - Adapt `ASID` to simplified CTAO data ⟶ **See results at Zoja Rokavec's talk!**
    - Explore the potential of the LoG filter to detect extended sources and characterize extensions in realistic CTAO simulations (overlapping sources)
    - Test other possibilities to detect source extension (open discussion!)



Co-funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 101081355.

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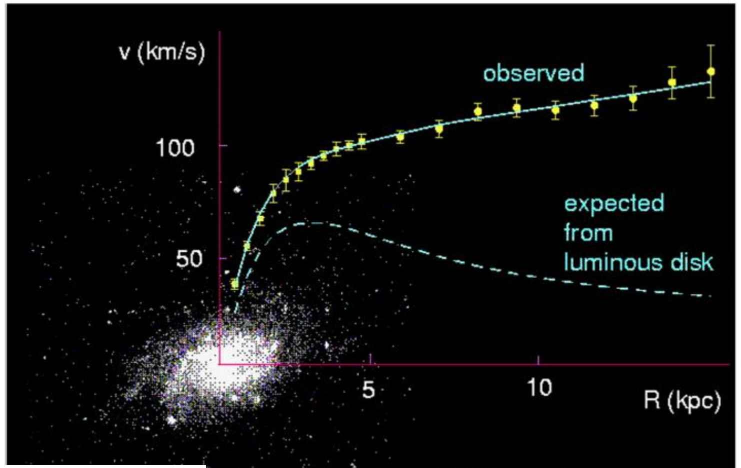
Thanks for your attention!

SMASH machine learning for science and humanities postdoctoral program

BACK-UP MATERIAL

DARK MATTER EVIDENCE

Galactic scales

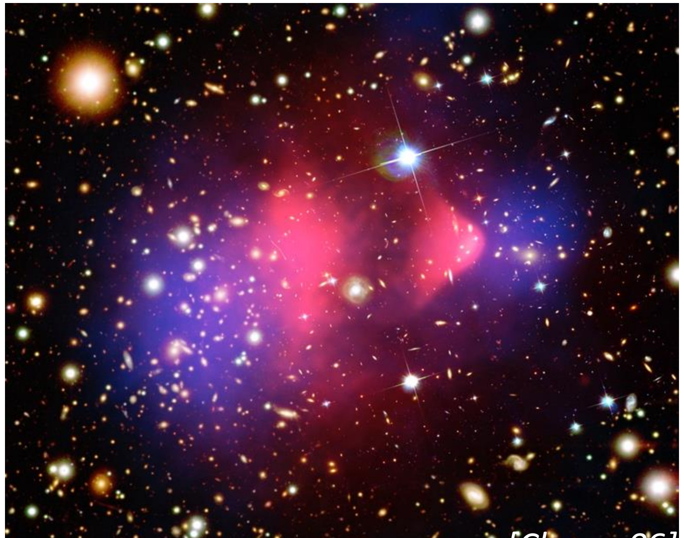


$$v = \sqrt{\frac{GM(r)}{r}}$$

[Bergstrom 00]

- Rotational curves
- Velocity dispersion

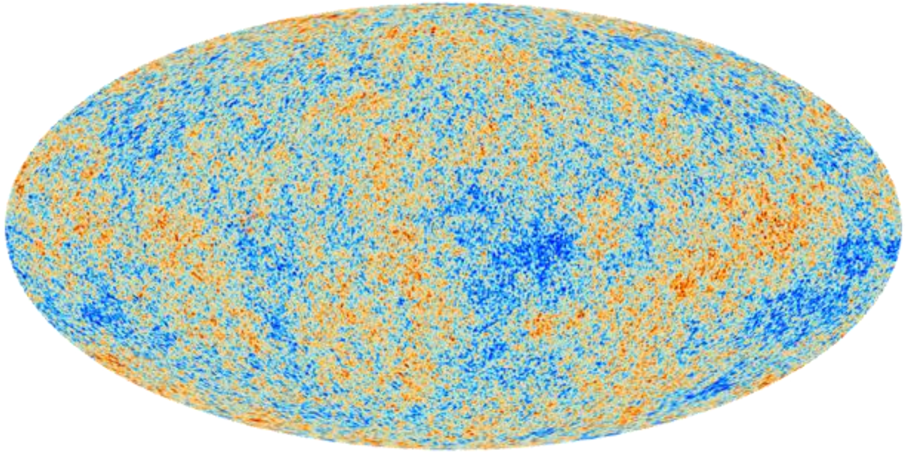
Galaxy cluster scales



[Clowe+06]

- Peculiar velocity flows
- Mass tracers (X-rays, Sunyaev–Zeldovich, strong&weak lensing)
- Dynamical systems

Cosmological scales

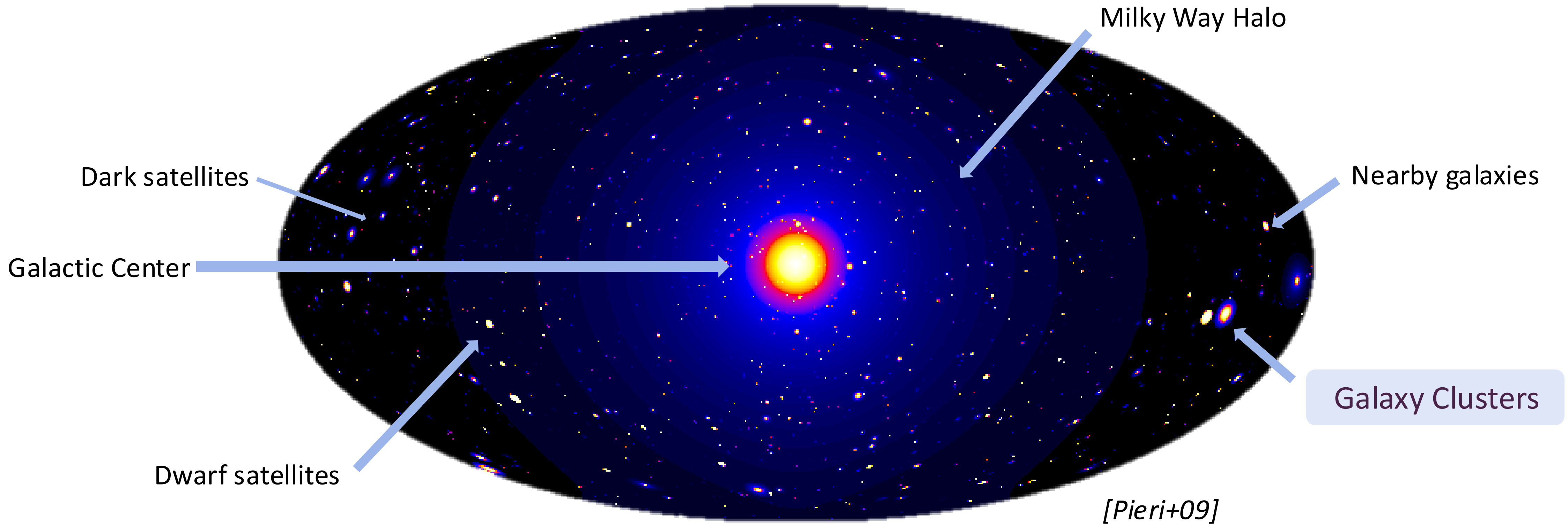


[Planck Website]

- Cosmic Microwave Background (CMB) anisotropies
- Large Scale Structure (LSS)

UNVEILING THE NATURE OF DARK MATTER THROUGH GAMMA-RAYS

- There is a large variety of objects that are heavily dominated by DM
  - High DM density
  - Massive nearby objects
  - Low astrophysical background



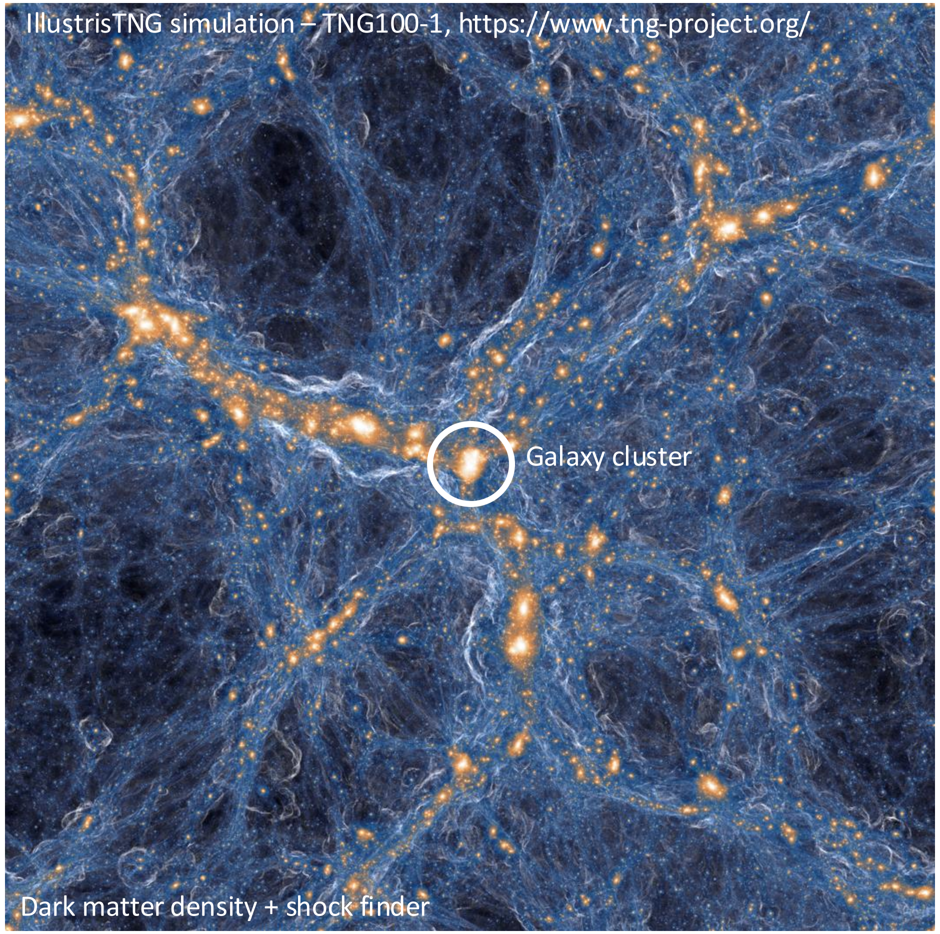
[Pieri+09]

GAMMA-RAYS FROM GALAXY CLUSTERS

- Largest gravitationally bound structures formed by gravitational collapse
- Masses of order ~10^{14}-10^{15} $M_\odot$
- Components:
  - Standard Matter →
    - Galaxies (3% - 5%)
    - Intra Cluster Medium (15% - 17%) (ICM)
  - **Dark Matter (~80%)**
- Several in closeby Universe
- Even supposedly stable objects, a lot of activity (magnetic fields, turbulence motions…)

These processes act as acceleration mechanisms for the ICM producing cosmic rays (CRs)

- $\mathrm{CR_e} + \mathrm{Mag.fields} \rightarrow \gamma_{\mathrm{X-rays,radio}}$
- $\mathrm{CR_p} + \mathrm{ICM} \rightarrow \pi^0 \rightarrow \gamma\gamma$



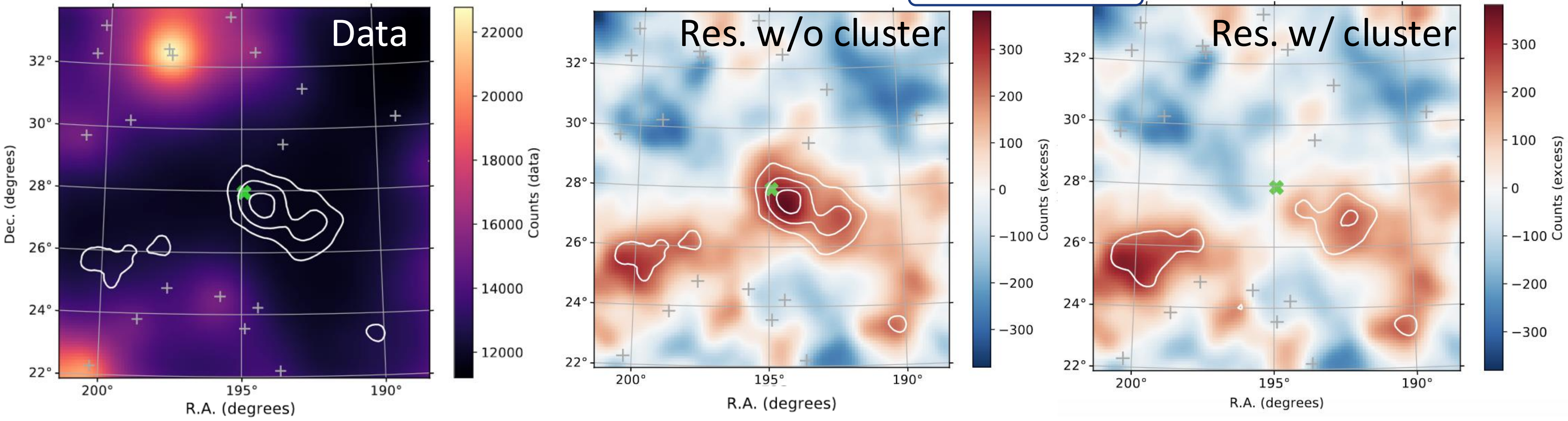
GAMMA-RAYS FROM GALAXY CLUSTERS

- Galaxy clusters should shine brightly in the gamma-ray sky
- This search has been going on for over two decades (either from DM or/and CRs), but signal has remained elusive

Reimer+03
Aharonian+08 [HESS Collab.]
Ackermann+10 [Fermi-LAT Collab.]
Aleksic+10 [MAGIC Collab.]
Dugger+10
Colafrancesco+10
Han+12 – Various clusters, **hint**
Ando & Nagai 12
Huang+12
Aleksic+12 [MAGIC Collab.]
Arlen+12 [VERITAS Collab.]
Nezri+12
Abramowski+12 [HESS Collab.]
Cirelli+12
Hektor+12 – Various clusters, **3.6σ**
Huber+13
Prokhorov & Churazov 14 – Various clusters, **4-5σ**
Ackermann+14 [Fermi-LAT Collab.] – Various clusters, **2.4σ**
Griffin+14
Zandanel & Ando 14
Ackermann+15 [Fermi-LAT Collab.] – Virgo cluster, **hint**
Ahnen+16 [MAGIC Collab.]
Ackermann+16 [Fermi-LAT Collab.] – Coma cluster, **hint**
Xi+18 – Coma cluster, **hint**
Aleksic+18 [MAGIC Collab.]
Lisanti+18
Colavizenzo+19 – Various clusters, **3.5-3.8σ**
Tan & Colavicenzo 19
Adam+21 – Coma cluster, **4.9-5.8σ**
Thorpe-Morgan+21
***di Mauro, JPR + 23 – Various clusters,* 2.5-3.0σ**

[Adam+21] – *Fermi*-LAT data of the Coma cluster

Hints of signal

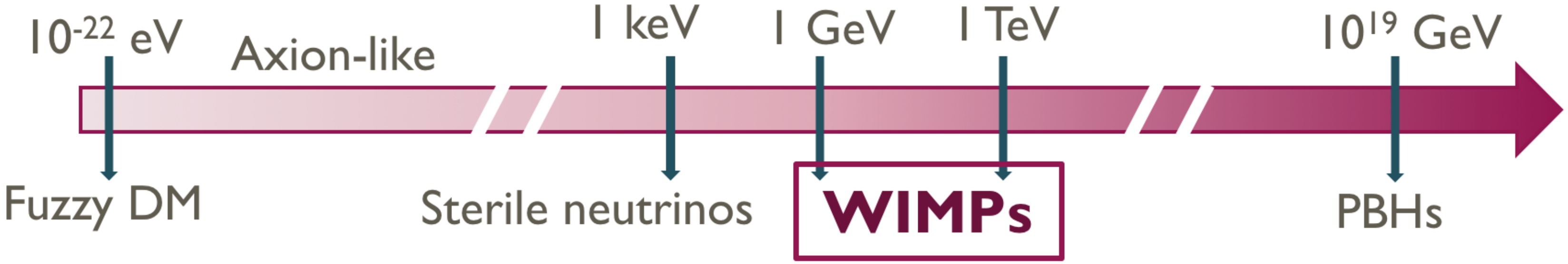


Galaxy clusters are amongst the most promising examples for detection of faint gamma-ray sources

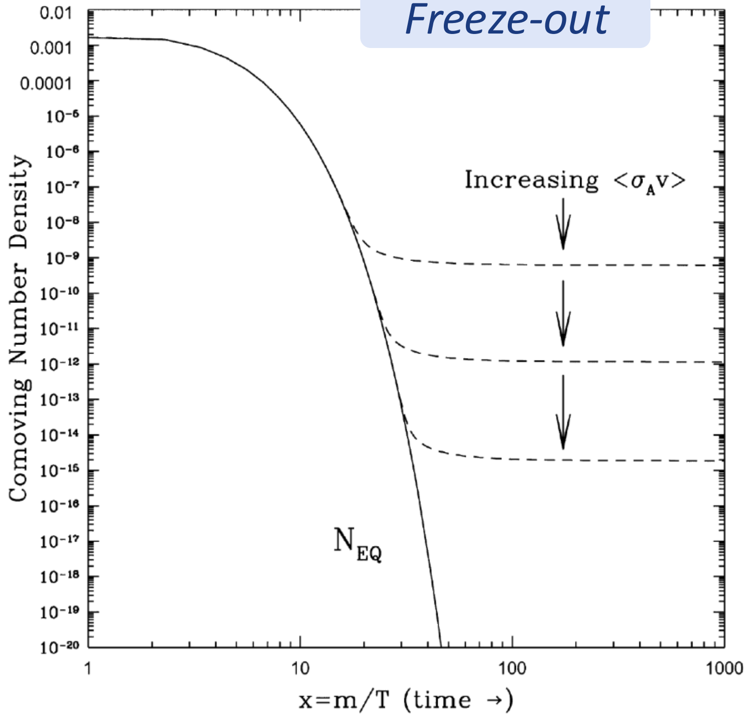
DM CANDIDATES: WIMPS

- Different DM candidates:
  - Non-baryonic
  - Electrically neutral
  - Non-relativistic & colissionless
  - Long-lived

Weakly Interacting Massive Particles



Freeze-out



- Only interact via weak nuclear force with SM
- Produced as a thermal relic

WIMP miracle

$$\Omega_\chi h^2 = \frac{10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{< \sigma v >}$$

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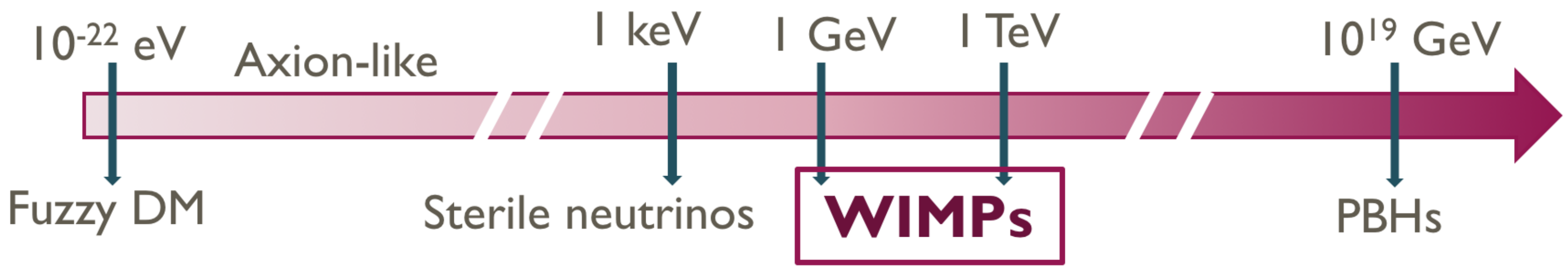
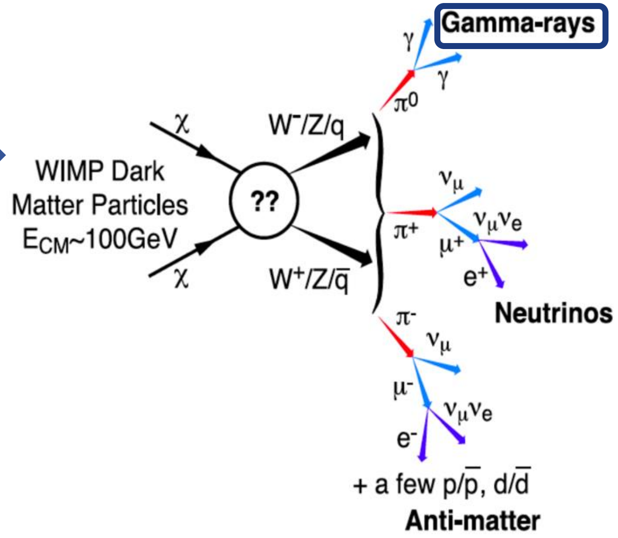
Weakly Interacting Massive Particles



- Only interact via weak nuclear force with SM
- Produced as a thermal relic

- The search for the WIMP
  - **Annihilation/Decay** → **Indirect detection**
  - Collision → Direct detection
  - Production → Colliders detection



This γ-ray emission allows to perform Indirect DM Searches with current telescopes

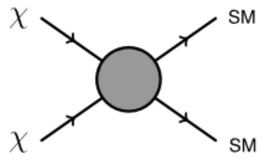
INDIRECT GAMMA-RAY WIMP DM SEARCHES

- DM-induced gamma-ray flux from an astrophysical object

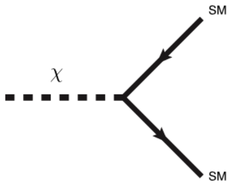
$$\frac{d\Phi_{DM}}{dE}(E, l.o.s, \Delta\Omega, z) = \frac{d\phi}{dE}(E, z) \times \text{Astrophysical factor}$$

Particle Physics Model

Annihilation

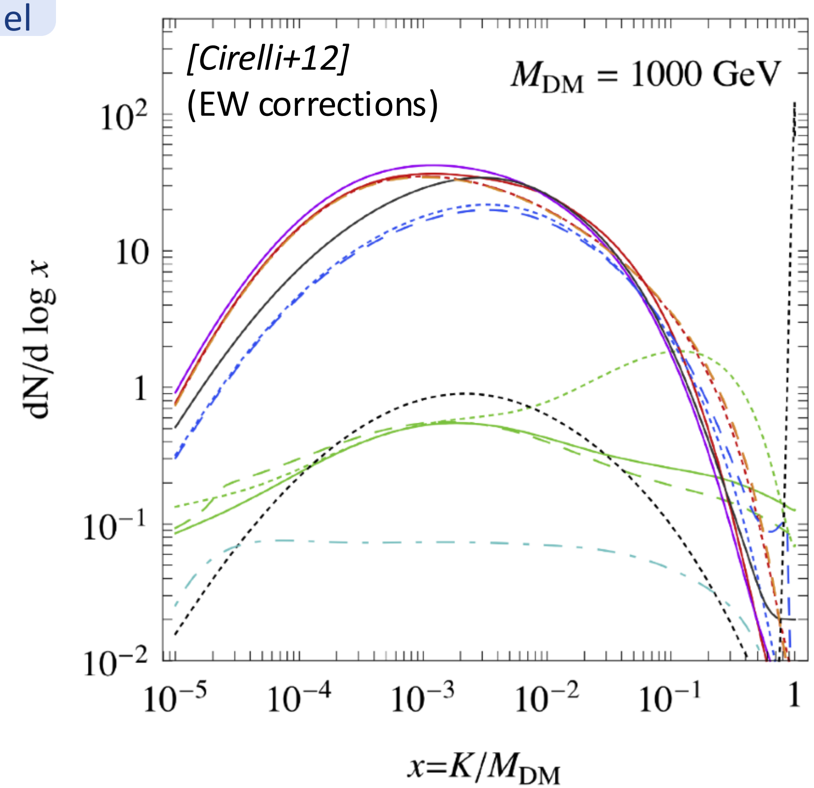


$$\frac{d\phi}{dE}(E, z) = \frac{<\sigma v>}{8\pi m_{DM}^2}\frac{dN}{dE}$$



$$\frac{d\phi}{dE}(E, z) = \frac{1}{4\pi m_{DM}\tau_{DM}}\frac{dN}{dE}$$

Decay

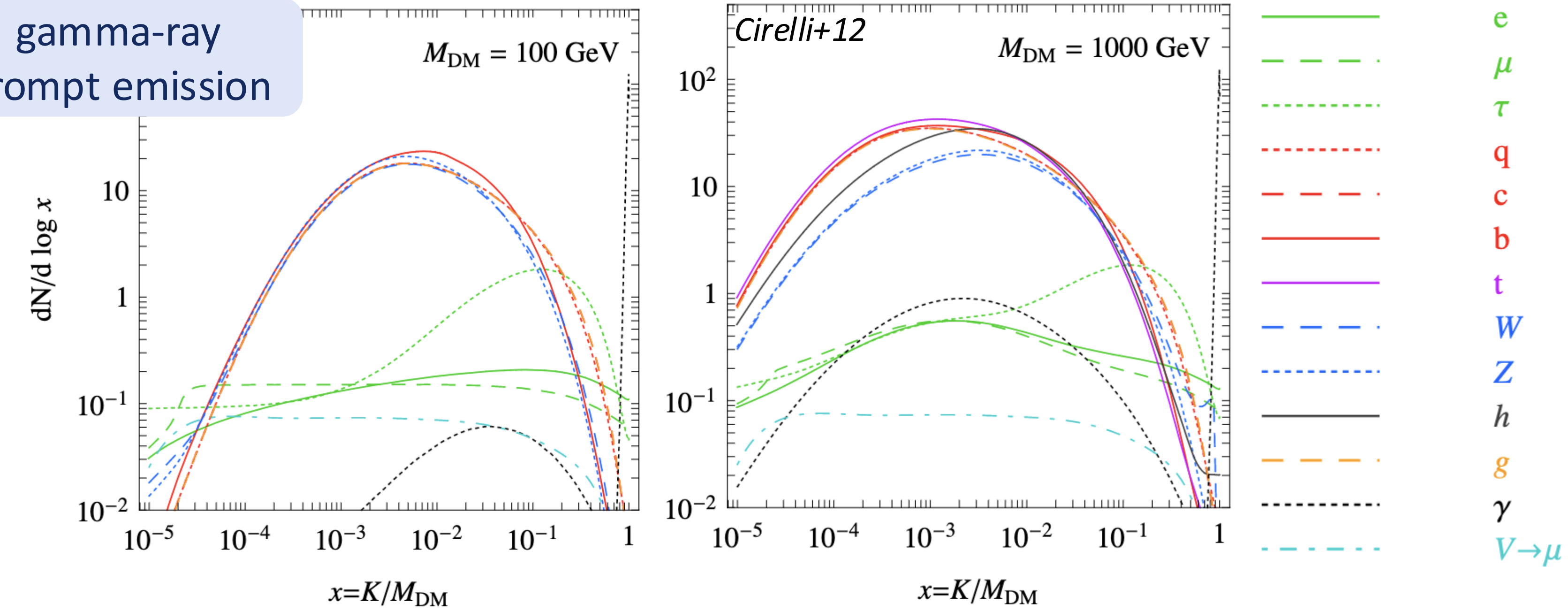


- DM mass
- Interaction channel

INDIRECT GAMMA-RAY WIMP DM SEARCHES

- DM production at source: *Cirelli+12* (EW corrections)
  - includes electroweak radiation effects, specially important for the flux of γ and $e^{\pm}$ for energies around m_{DM}
  - s-wave non-relativistic DM-DM annihilation/decay
  - annihilation/decay into primary channel + photon radiation of quarks and leptons, as well as photon branching into quark or lepton pairs
  - gamma-ray fluxes only include prompt emission and not the secondary radiation (e.g. Inverse Compton)

gamma-ray prompt emission



INDIRECT GAMMA-RAY WIMP DM SEARCHES

- DM-induced gamma-ray flux from an astrophysical object

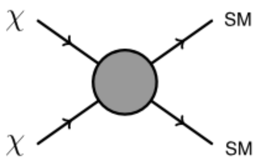
[Cirelli+12]
(EW corrections)

$$\frac{d\Phi_{DM}}{dE}(E, l.o.s, \Delta\Omega, z) = \frac{d\phi}{dE}(E, z) \times \text{Astrophysical factor}$$

Particle Physics Model

Quantifies the significance of the signal

Annihilation



$$J(l.o.s, \Delta\Omega, z) = \int_{\Delta\Omega} \int_{l.o.s} \rho_{DM}^2(r) dr$$

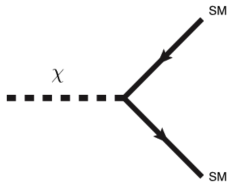
DM density profile

$$D(l.o.s, \Delta\Omega, z) = \int_{\Delta\Omega} \int_{l.o.s} \rho_{DM}(r) dr$$

$$\rightarrow J \propto \frac{M_{200} c_{200}^3}{D_{\mathrm{Earth}}^2}$$

$$\rightarrow D \propto \frac{M_{200}}{D_{\mathrm{Earth}}^2}$$

Decay



MAIN UNCERTAINTY OF DM DENSITY PROFILES

- To model the DM density profile in the objects, we split the contributions:

$$\langle\rho_{\rm tot}\rangle(r) = \rho_{\rm sm}(r) + \langle\rho_{\rm subs}\rangle(r)$$

$\langle\rho_{\rm subs}\rangle(r)$ → Subhalo population (if any)

$\rho_{\rm sm}(r)$ → **Main halo**

- Cuspy-like, from N-body simulations

$$\rho_{\rm NFW}(r) = \frac{\rho_0}{\left(\frac{r}{r_{\rm s}}\right)\left(1+\frac{r}{r_{\rm s}}\right)^2}$$

$$\rho_{\rm Ein}(r) = \rho_{\rm s}\exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_{\rm s}}\right)^{\alpha}-1\right]\right)$$

- Cored-like, phenomenologically motivated

$$\rho_{\rm Bur}(r) = \frac{\rho_c\, r_c^3}{(r+r_c)\,(r^2+r_c^2)}$$

- Fit the profiles either:
  - Rotational curves (spiral galaxies, dwarf irregular galaxies)
  - Velocity dispersion measurements (dSphs)
  - Normalize to the measured mass (galaxy clusters) → $M_\Delta = \int_0^{R_\Delta} \rho(r) r^2 dr d\Omega$

DM MODELLING: SUBSTRUCTURE

- Galaxy clusters are the most massive objects today, large amount of substructure expected
- Inclusion through $\rho_{\rm DM}$ using state-of-the-art subhalo models

$$\langle\rho_{\rm tot}\rangle(r) = \rho_{\rm sm}(r) + \langle\rho_{\rm subs}\rangle(r)$$

$$\frac{d^3N}{dV dM dc} = N_{\rm tot} \frac{d\mathcal{P}_V}{dV}(r) \cdot \frac{d\mathcal{P}_M}{dM}(M) \cdot \frac{d\mathcal{P}_c}{dc}(M, c)$$

DM subhalo profile: NFW

$$\rho(r) = \frac{\rho_0}{(\frac{r}{r_s})[1+\frac{r}{r_s}]^2}$$

Subhalo Radial Distribution (SRD)

$$\rho_{\rm sub}^{VLII}(R) = \frac{\rho_{\rm tot}^{VLII}(R)\,(R/R_a)}{\left(1+\frac{R}{R_a}\right)}$$

Via Lactea - II

Anti-biased relation

[Diemand+08]

Subhalo Mass Function (SHMF)

$$dN/dm = A/M(m/M)^{-\alpha}$$

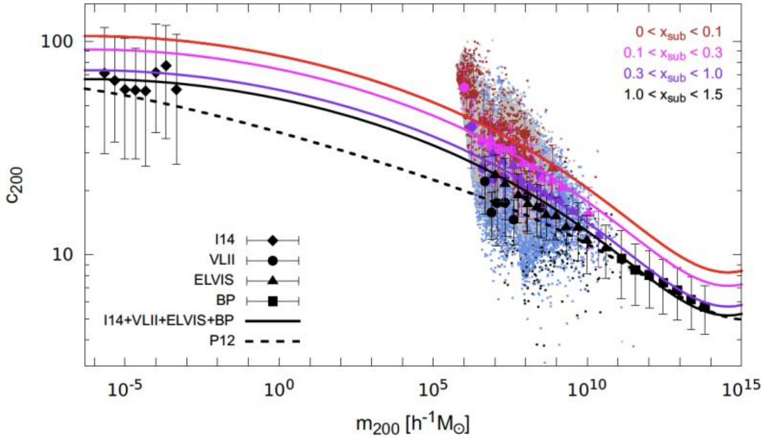
α = 1.9

[Springel+08]

α = 2.0

[Diemand+08]

Subhalo Concentration-Mass relation (c_{200}-M_{200})



Dependence on the subhalo position

$$c_{200}(m_{200}, x_{\rm sub})$$

$$x_{\rm sub} \equiv R_{\rm sub}/R_\Delta$$

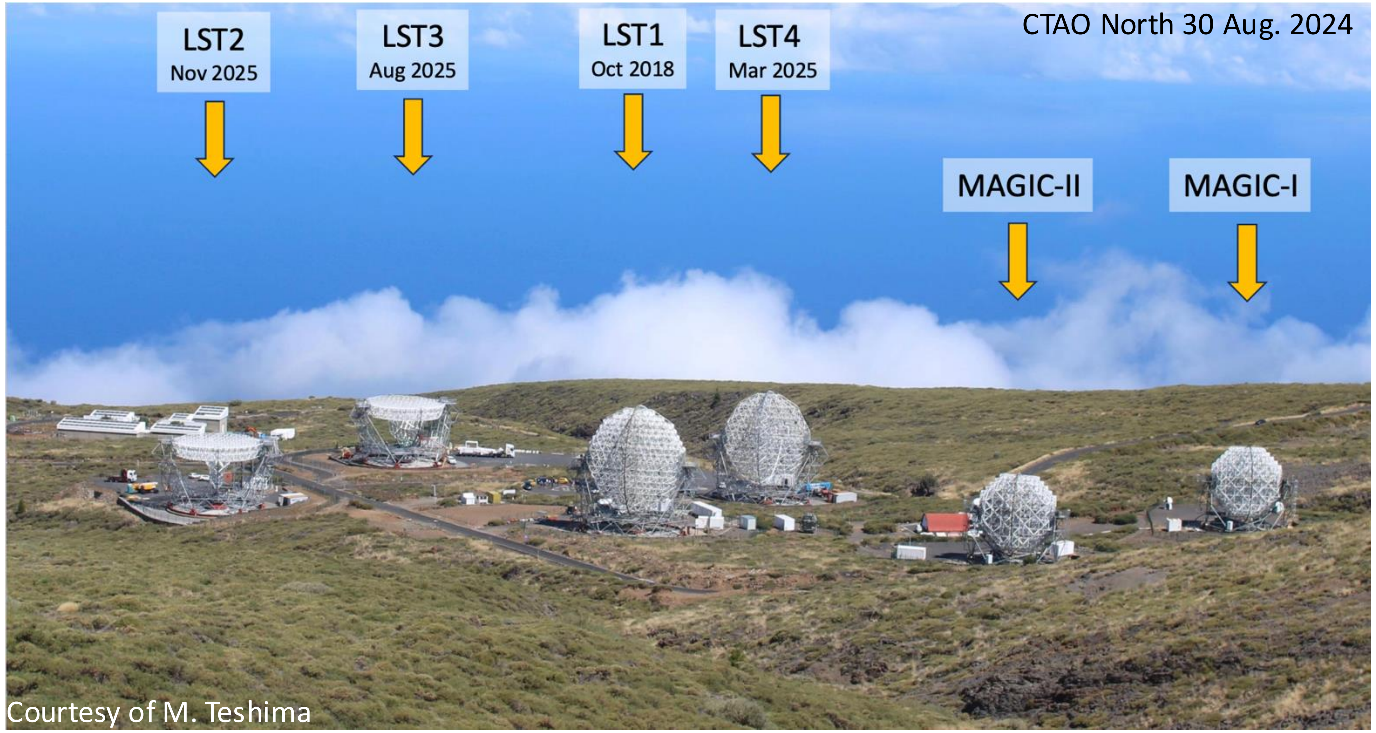
[Moliné+17]

ML TO DETECT FAINT GAMMA-RAY SOURCES: CTAO

- Future of Imaging Atmospheric Cherenkov Telescopes for VHE gamma-ray astronomy
- 2 arrays: Northern Array (La Palma, Spain) and Southern Array (Paranal, Chile)
- First LST already in operations!

CTAO

https://www.cta-observatory.org/

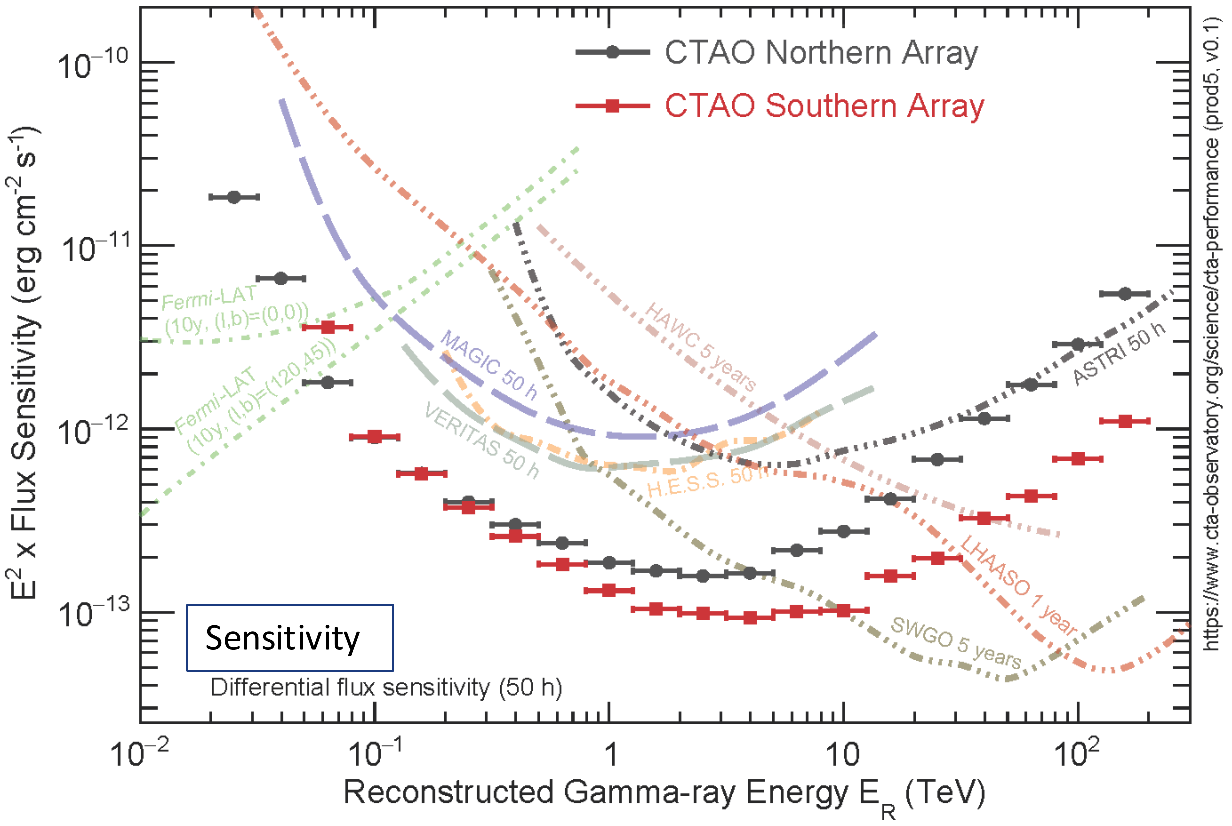


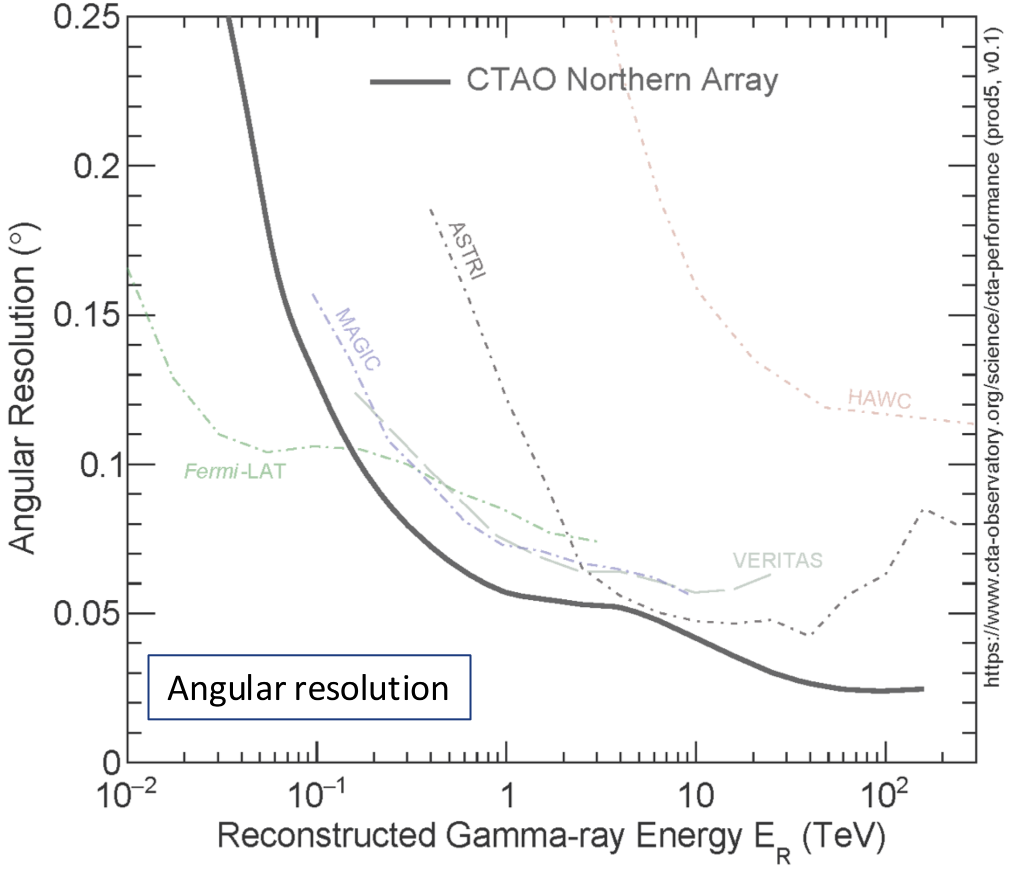
SST	MST	LST	Energy range
5 - 300 TeV	150 GeV - 5 TeV	20 - 150 GeV	20 GeV - 300 TeV
$D_{\emptyset}$ = 4.3m	$D_{\emptyset}$ = 11.5m	$D_{\emptyset}$ = 23m	

CTAO PERFORMANCE

Preliminary Performance Capabilities of the Alpha Configuration

https://www.ctao.org/for-scientists/performance/



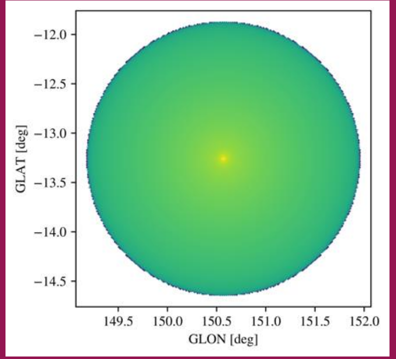


CTAO will have superb capabilities for DM γ-ray searches

CTAO DM ANALYSIS ROADMAP

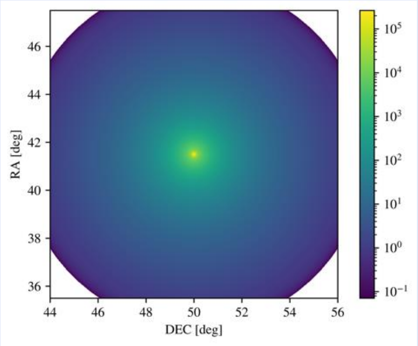
- Gamma-ray sources in a standard galaxy cluster:
  (Perseus cluster)

Total DM-induced γ-rays



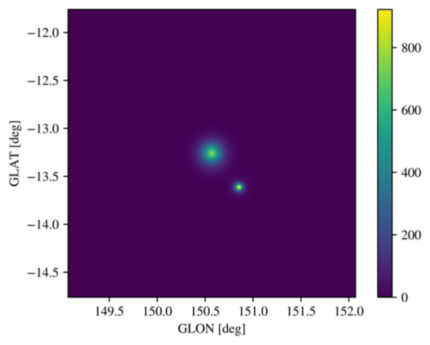
Our signal

Total CR-induced γ-rays

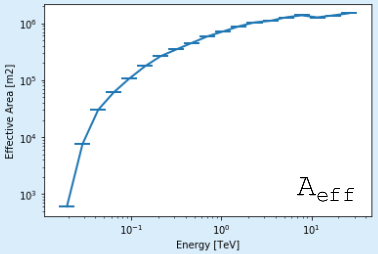


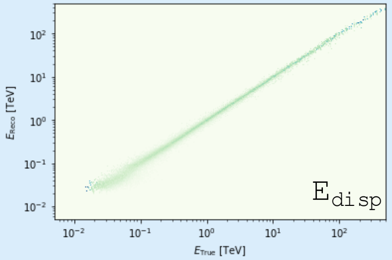
Use as BKG

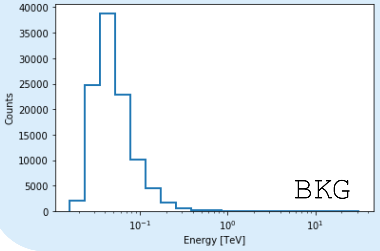
γ-rays from AGNs



Use as BKG







CTA IRFs

https://www.cta-observatory.org/science/ctao-performance/

Observation Simulation

If no signal found

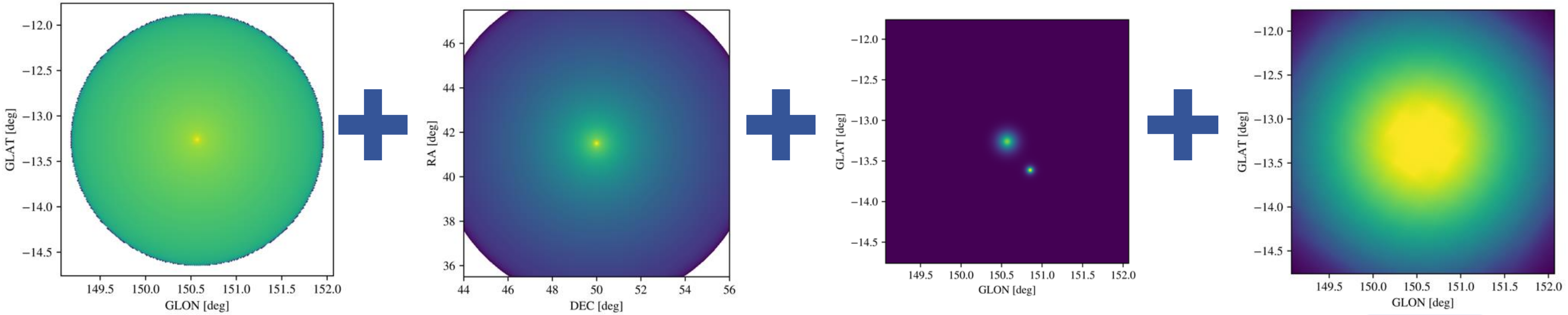
Constraints on DM models

$$\frac{d\Phi_\chi^{Ann}}{dE} = \frac{< \sigma v >}{8\pi m_\chi^2}\frac{dN}{dE} \times J$$

$$\frac{d\Phi_\chi^{Decay}}{dE} = \frac{1}{4\pi m_\chi \tau_\chi}\frac{dN}{dE} \times D$$

CTAO ANALYSIS CONFIGURATION: TEMPLATE FITTING

- Includes all expected gamma-ray sources: Target + Astrophysical Backgrounds (BKG) + BKG from Instrument Response Function (IRFs)



Target emission

BKG astrophysical emission

BKG astrophysical emission

BKG

[from IRFs]

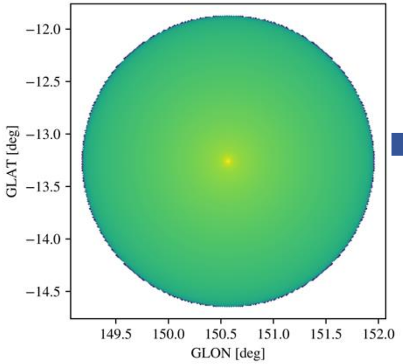
Most realistic physical scenario

- Considers the different morphologies of each emission
- Allows to check correlations between components
- Historically used in *Fermi*-LAT analysis and in a recent CTA analysis (*Acharyya+20* [*CTA Cons*.])

State-of-the-art analysis pipeline

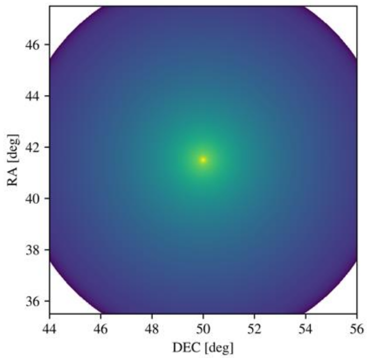
CTAO ANALYSIS CONFIGURATION: TEMPLATE FITTING

- Includes all expected gamma-ray sources: Target + Astrophysical Backgrounds (BKG) + BKG from Instrument Response Function (IRFs)



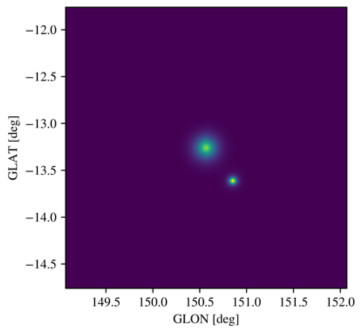
Target emission

+



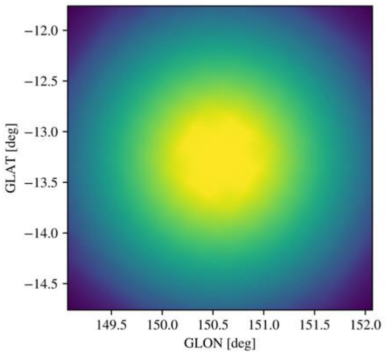
BKG astrophysical emission

+



BKG astrophysical emission

+



BKG [from IRFs]

Most realistic physical scenario

- Use likelihood ratio test to fit the models to the simulated data:

$$\ln\mathcal{L}(\vec{\theta}|D) = \sum_i \tilde{M}_i(\vec{\theta}) - d_i \ln(\tilde{M}_i(\vec{\theta}))$$

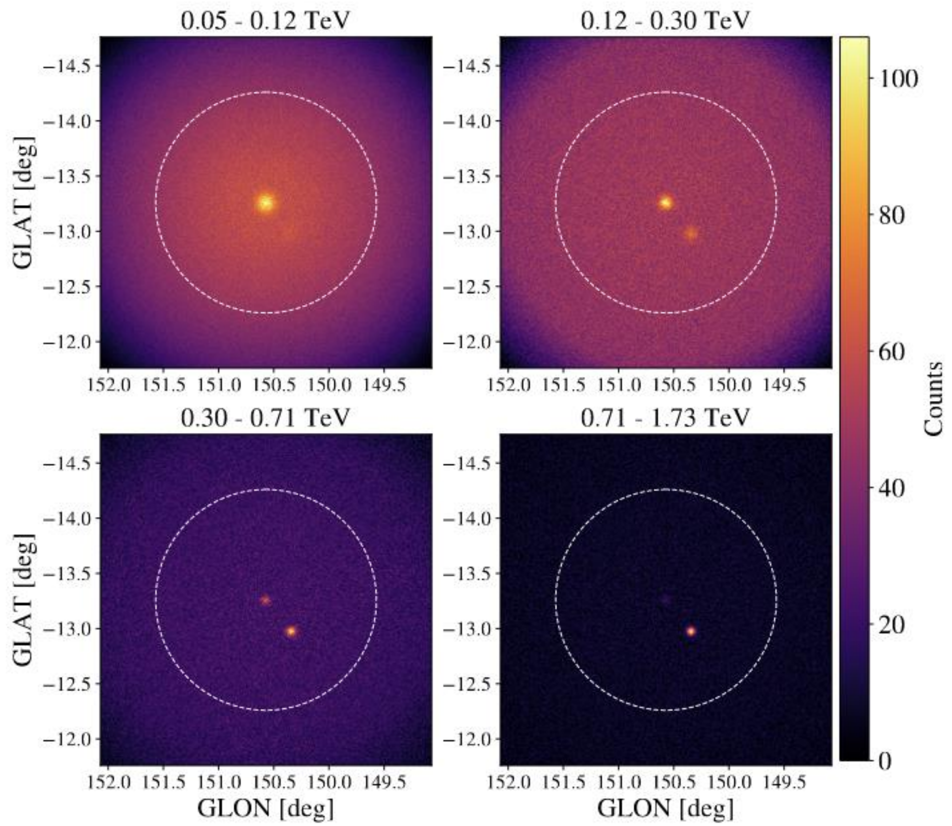
Poissonian likelihood for each parameter

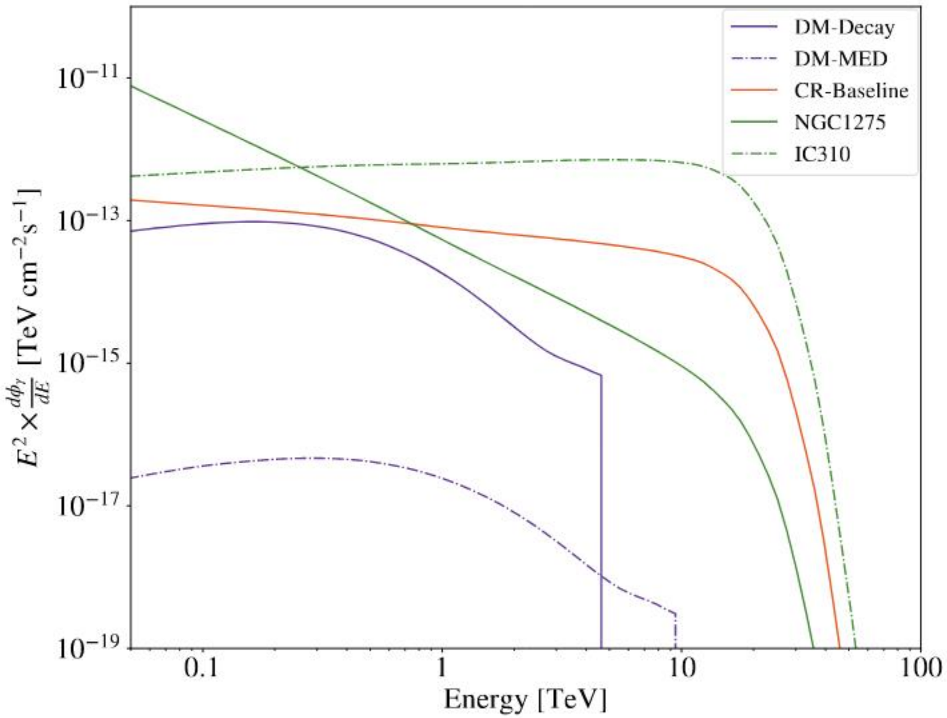
$$TS = 2\,\log\left[\frac{\mathcal{L}\left(A_\chi, \hat{\nu}\right)}{\mathcal{L}_{\text{null}}\left(A_\chi = 0, \hat{\nu}\right)}\right]$$

- $TS < 25$ → No signal

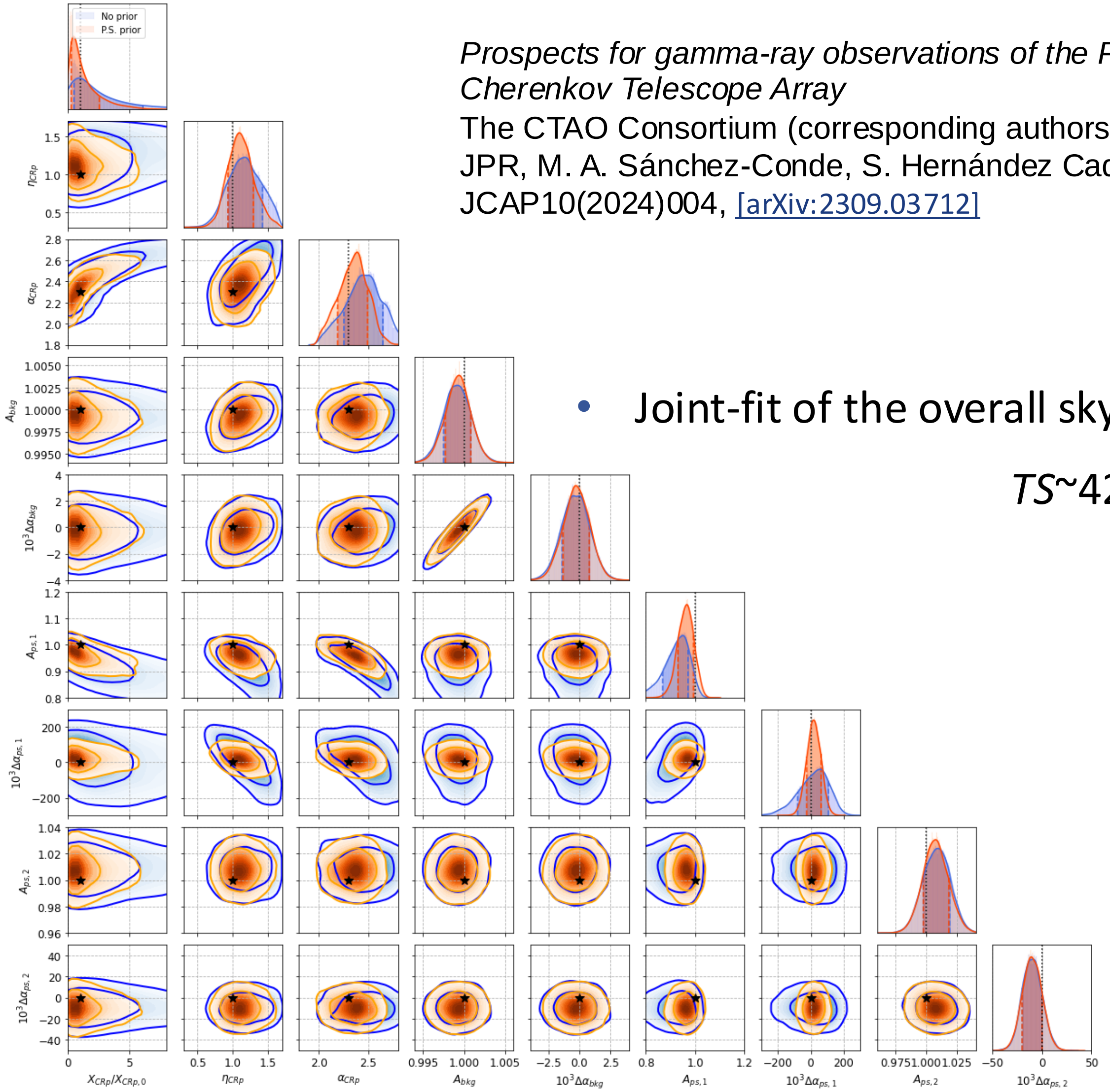
CHARACTERISTICS OF SIMULATIONS OF CLUSTER'S GAMMA-RAY EMISSION

- Input models:
  - DM Annihilation (thermal cross-section)
    DM Decay (τ_χ = 10^{27}s)
    m_χ = 10 TeV
    $b\bar{b}$
  - **+** CR baseline model
    NGC1275 & IC310
  - **+** EBL *Domínguez+11*





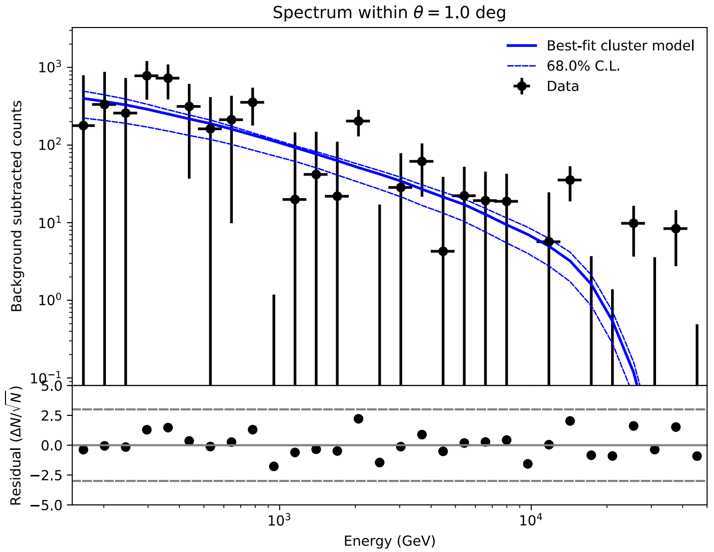
CTAO PROSPECTS: CR ANALYSIS SUMMARY

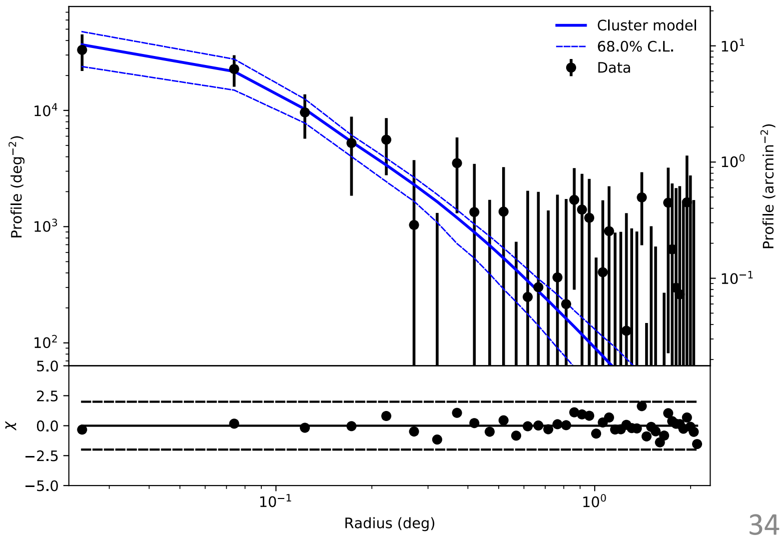


Prospects for gamma-ray observations of the Perseus galaxy cluster with the Cherenkov Telescope Array
The CTAO Consortium (corresponding authors - alphabetical: R. Adam, M. Hütten, JPR, M. A. Sánchez-Conde, S. Hernández Cadena)
JCAP10(2024)004, [arXiv:2309.03712]

- Joint-fit of the overall sky model simultaneously

TS~42





TARGET SELECTION

Constraining the dark matter contribution of gamma-rays in cluster of galaxies using Fermi-LAT data
M. di Mauro, JPR, M. A. Sánchez-Conde, N. Fornengo
Phys. Rev. D 107, 083030, [arXiv:2303.16930]

- *Fermi*-LAT does not have constraints on observation time → Sample of best clusters for DM searches
- Selection criteria:
  - Well-known M_{200} from X-rays measurements

    Masses from *Schellenberger&Reiprich17* (X-rays data from Chandra*)*

  - Local clusters

    $z < 0.1$

  - Mask of $|b| < 20$ deg to avoid galactic diffuse emission
  - Separation of at least 2 deg to account for cluster extension

HIFLUGCS catalogue (*Reiprich&Böhringer02*)

- 50 local clusters
- $f_x \geq 1.7{\cdot}10^{-11}$ erg s^{-1} cm^{-2}
- biased towards cool-cored clusters (*Käfer+19*)

\+

- Clusters used in previous searches:

  Ackermann+10 [Fermi-LAT Coll.]

  Sánchez-Conde+11

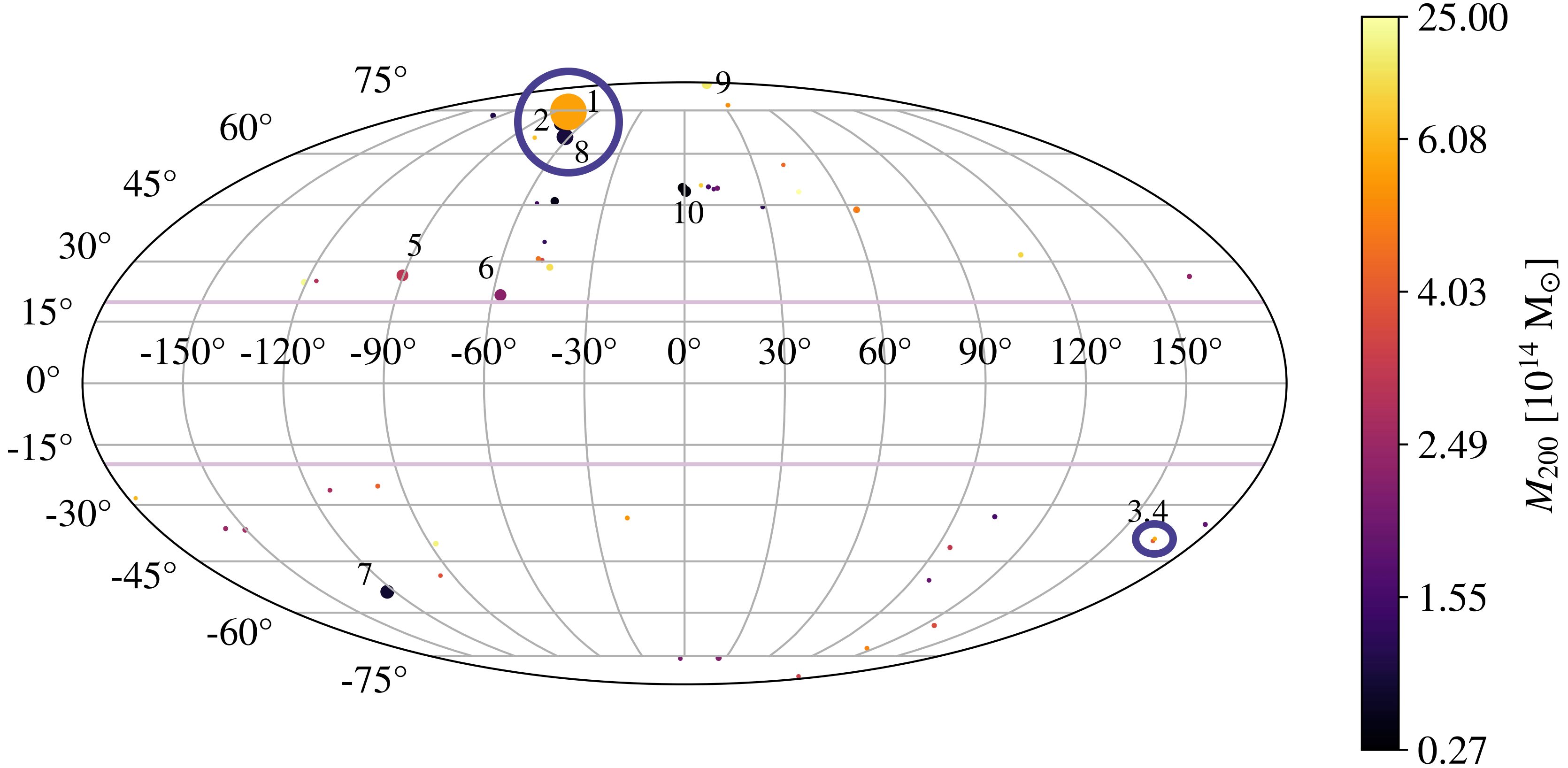
  Ackermann+14 [Fermi-LAT Coll.]

Sample of 49 local galaxy clusters

TARGET SELECTION

- Most massive and closest clusters will dominate:

1 - Virgo
2 - M49
3 - A0399
4 - A0401
5 - A1060 - Hydra
6 - A3526 - Centaurus
7 - NGC 1399 - Fornax
8 - NGC 4636
9 - A1656 - Coma
10 - NGC 5813



ASID METHODOLY FOR DETECTION OF POINT-LIKE SOURCES

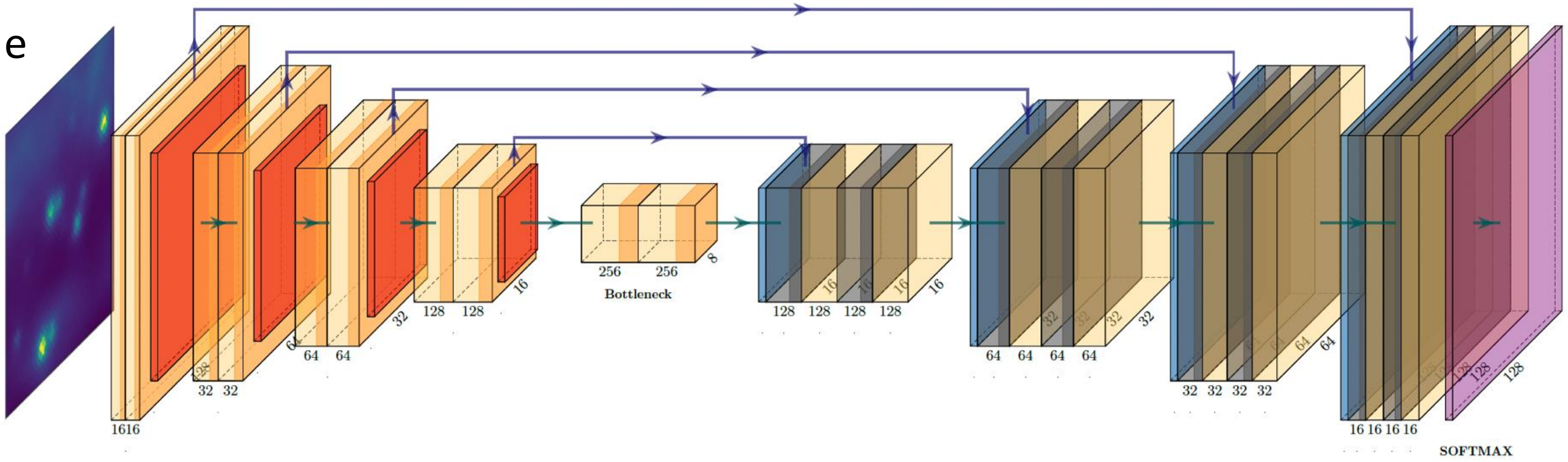
AutoSourceID (ASID) *[Panes+21]*
https://www.nikhef.nl/~scaron/autosourceid/

ML tool to directly analyse gamma-ray image datasets

U-NET scheme

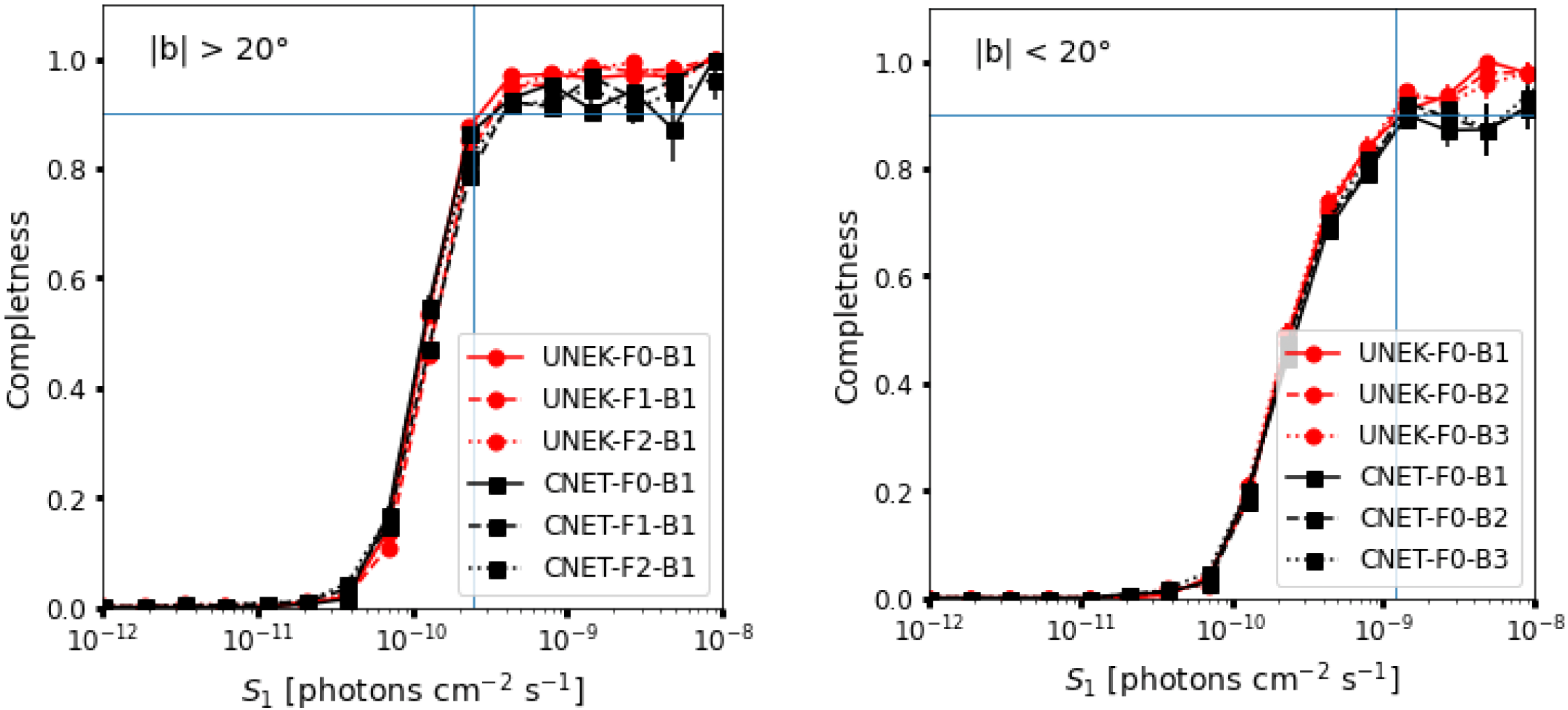
- Convolutional Neural Network (CNN) pipeline based on U-Net algorithms
- Goal: **detect** (localize) **point-like** sources

Semantic segmentation



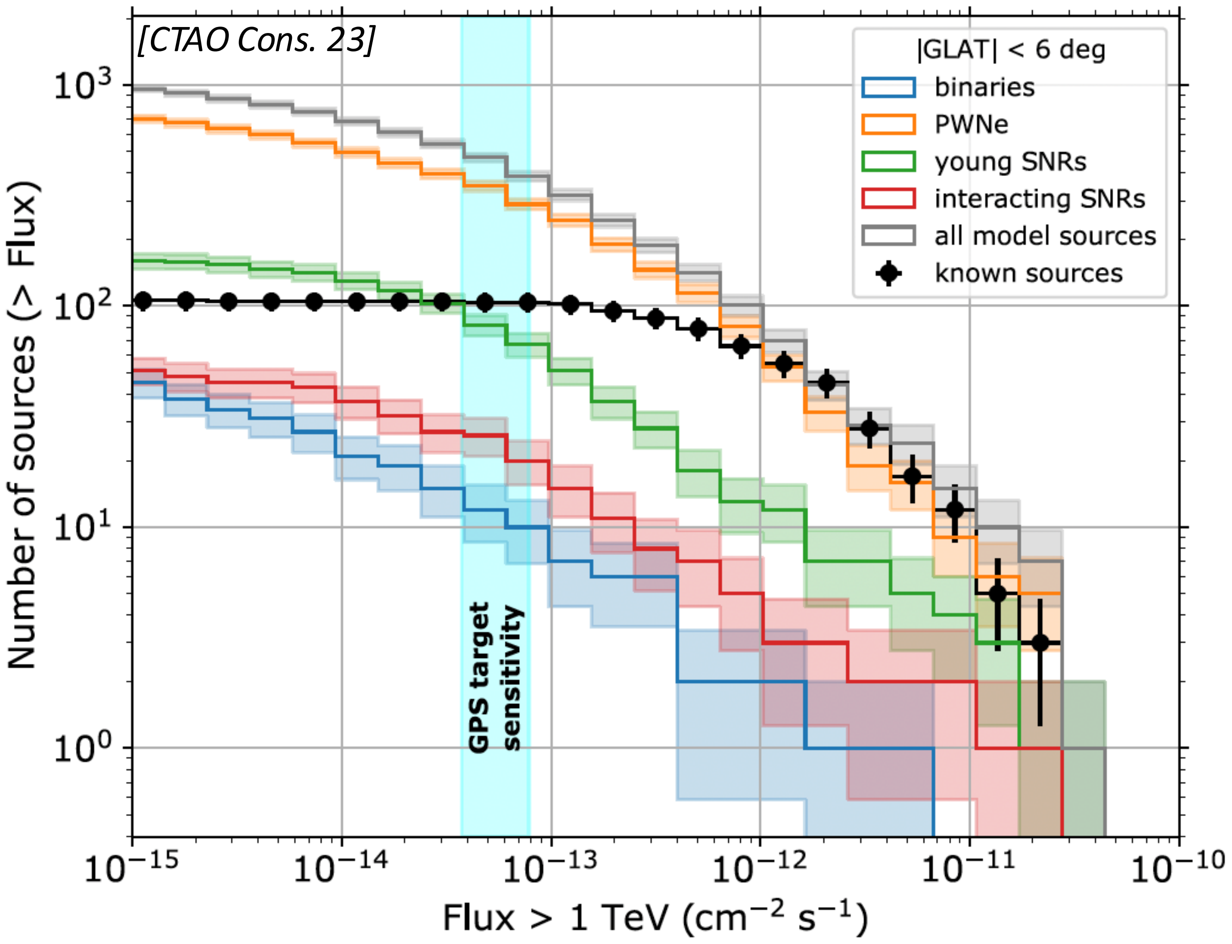
- U-Net produces segmented regions around point sources
- For each input patch there is per-pixel classification (background vs. foreground)
- Label scores: ~1 (for pixels in the region around a point source) and ~0 (otherwise)
- To translate this to positions, apply a clustering algorithm

ASID CONSISTENCY AGAINST GDE-BACKGROUNDS

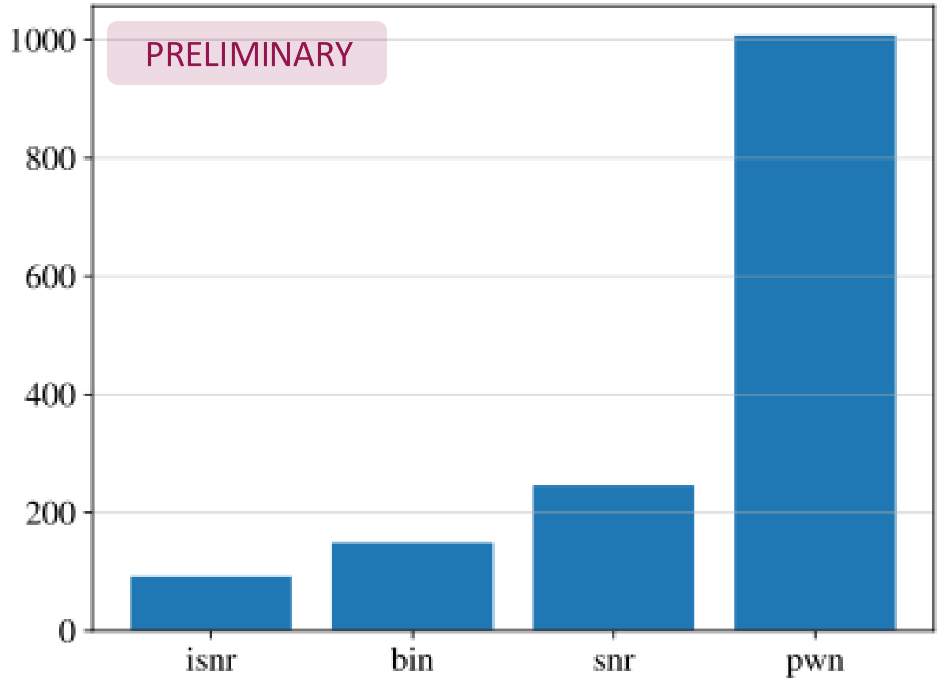


CTAO GALACTIC PLANE SIMULATION

- Original simulated population on the galactic plane



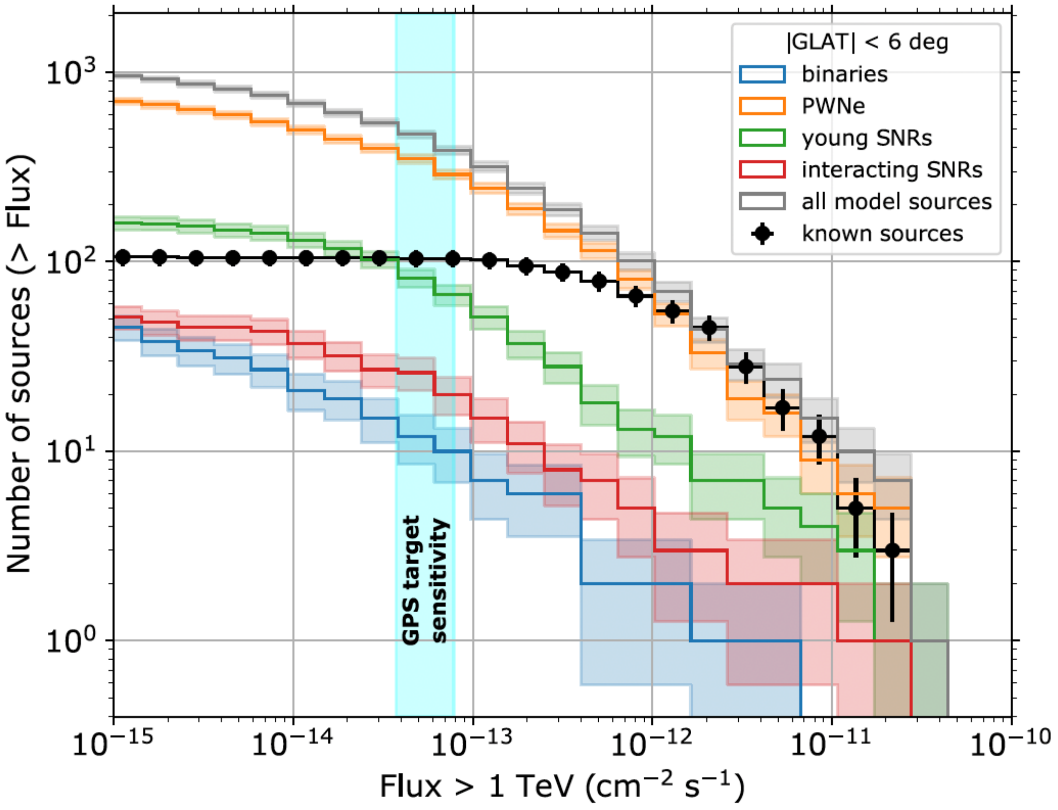
- We need several realizations (simulations) of the GP
    - Extract the physical distributions of the sample



CTAO GALACTIC PLANE SIMULATION

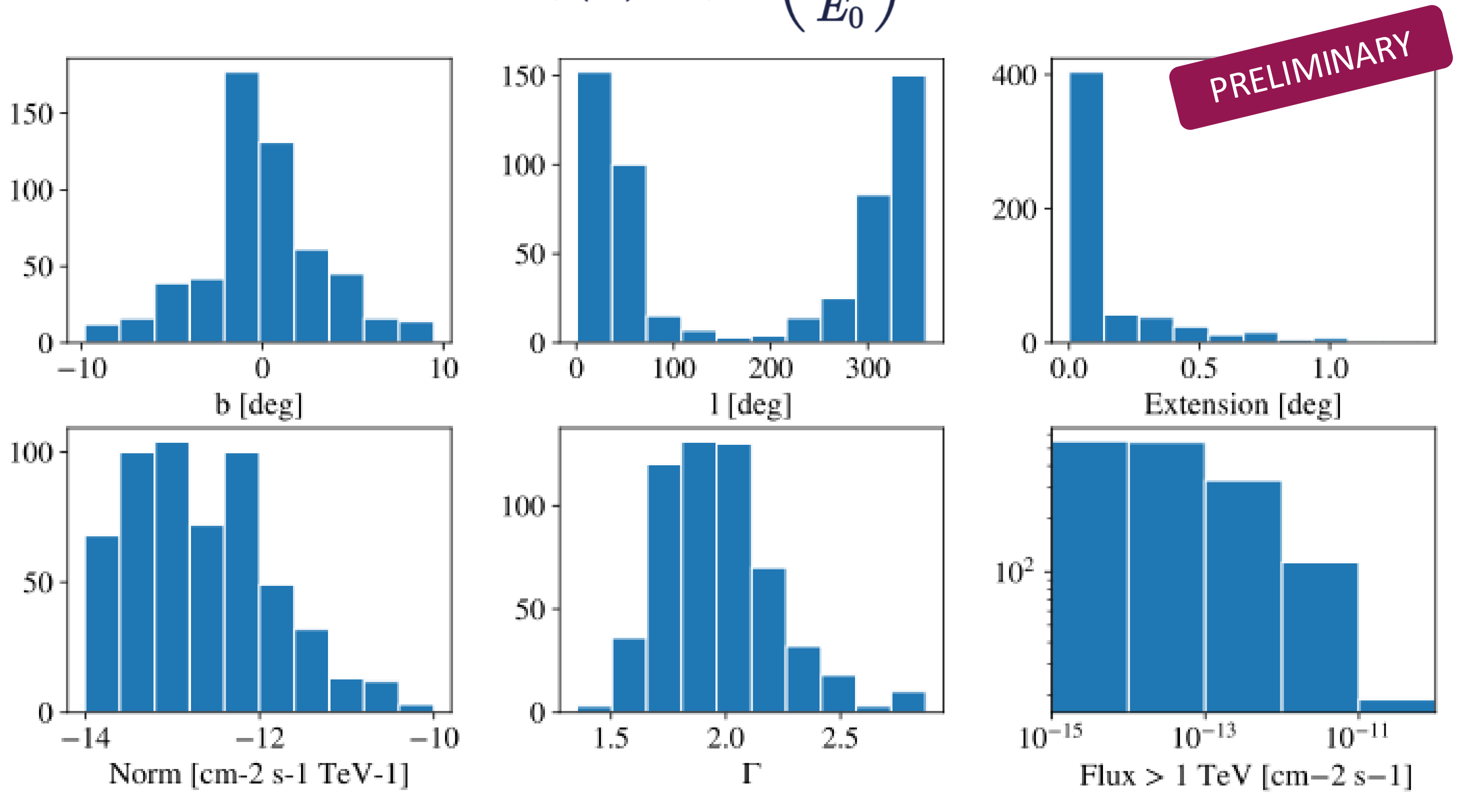
- Original simulated population on the galactic plane

[CTAO Cons. 23]



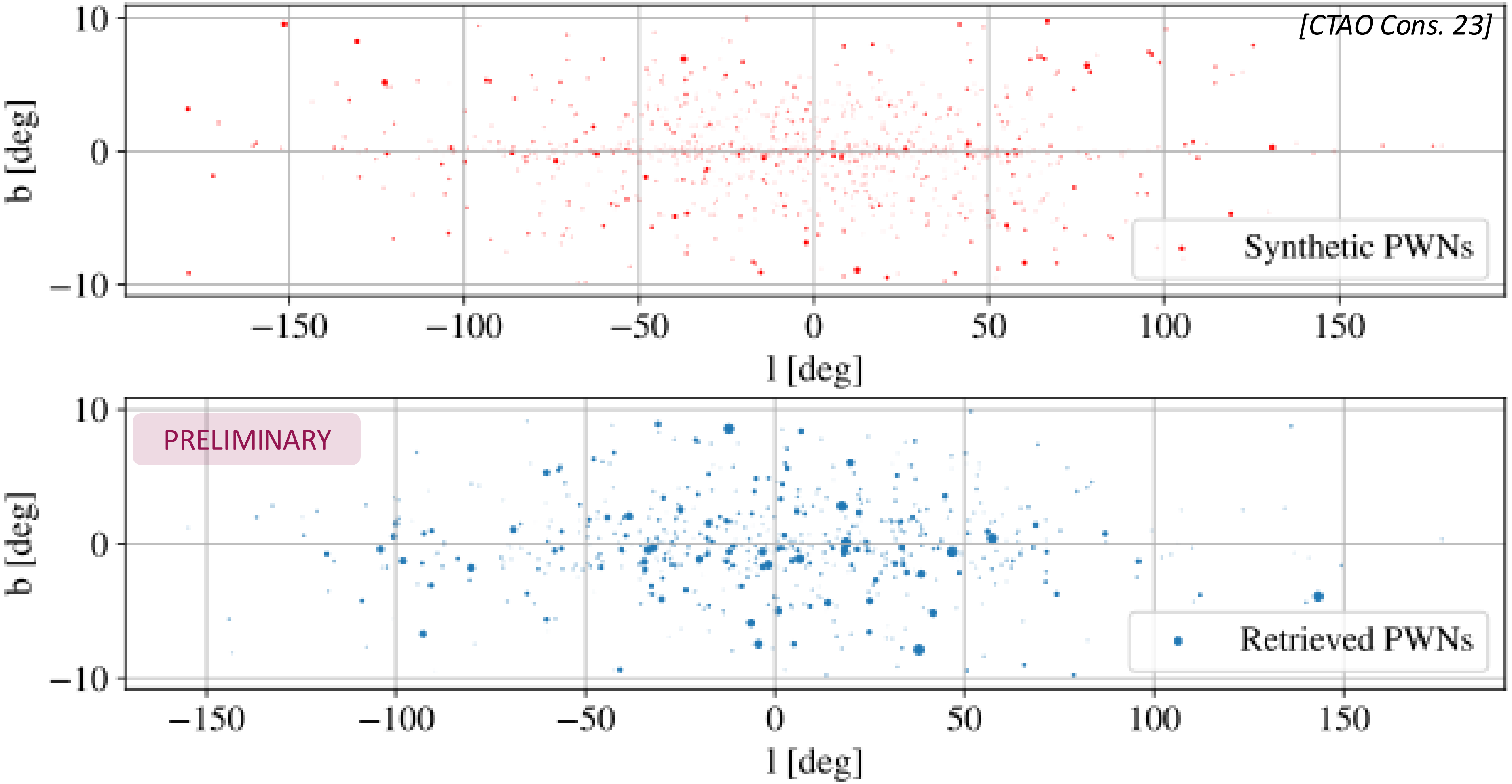
- We need several realizations (simulations) of the GP
- Extract the physical distributions of the sample

$$\phi(E) = \phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\Gamma}$$



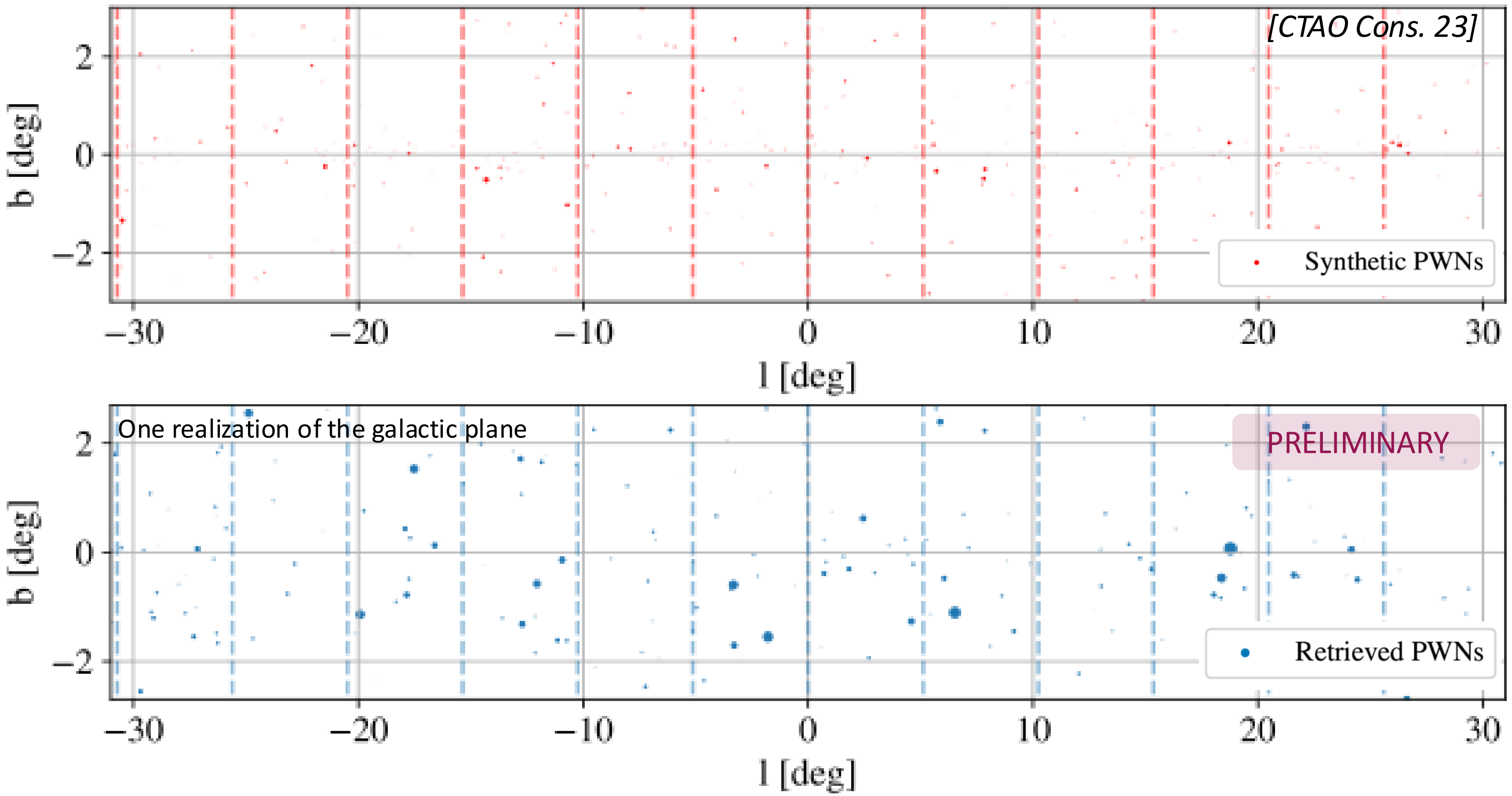
CTAO GALACTIC PLANE SIMULATION

- Comparison of original sample vs. one drawn realization from the physical distributions



CTAO GALACTIC PLANE SIMULATION

- Focus on the most crowded region
- Cover through patches: $-30 < l < 30$ deg $\quad -2.5 < b < 2.5$ deg



CTAO GALACTIC PLANE SIMULATION

- Cover the galactic plane through patches

$-30 < l < 30$ deg

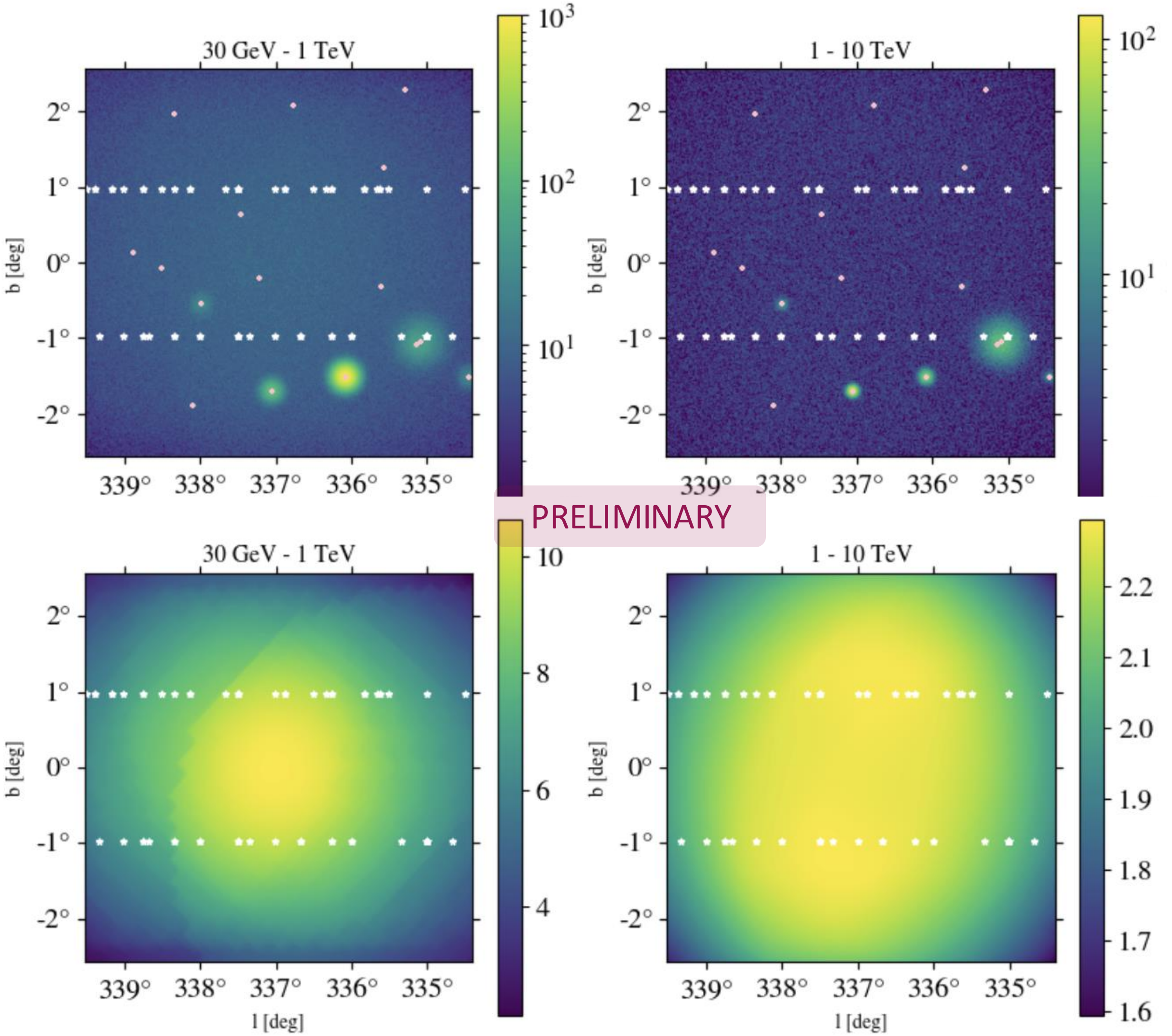
$-2.5 < b < 2.5$ deg

- 12 patches per each complete simulation of the galactic plane

$512 \text{ pix} \times 512 \text{ pix}$

$5.12 \text{ deg} \times 5.12 \text{ deg}$

- Example of one patch



Total photons

Background photons

A **Python** package for **gamma-ray** astronomy

[*Donath et al. 2023*]