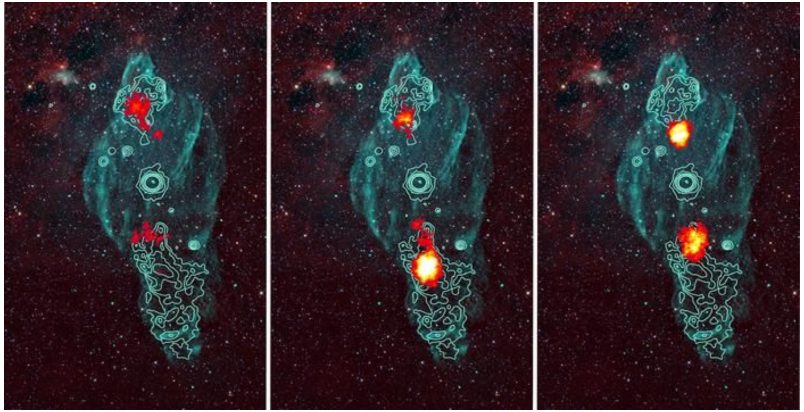
GAMMA-RAY ASTRONOMY HIGHLIGHTS



LI - International Meeting on Fundamental Physics
Benasque, 12/09/2024
Cosimo Nigro, IFAE

Outline of the talk

> **Part 1, technique:**

> 1.1. Detection principles and instruments of gamma-ray astronomy;
> 1.2. Hardware technical advancements - gamma-ray instruments in the 2020s;
> 1.3. Software technical advancements - standardisation of data and analysis tools.

> **Part 2, science:**

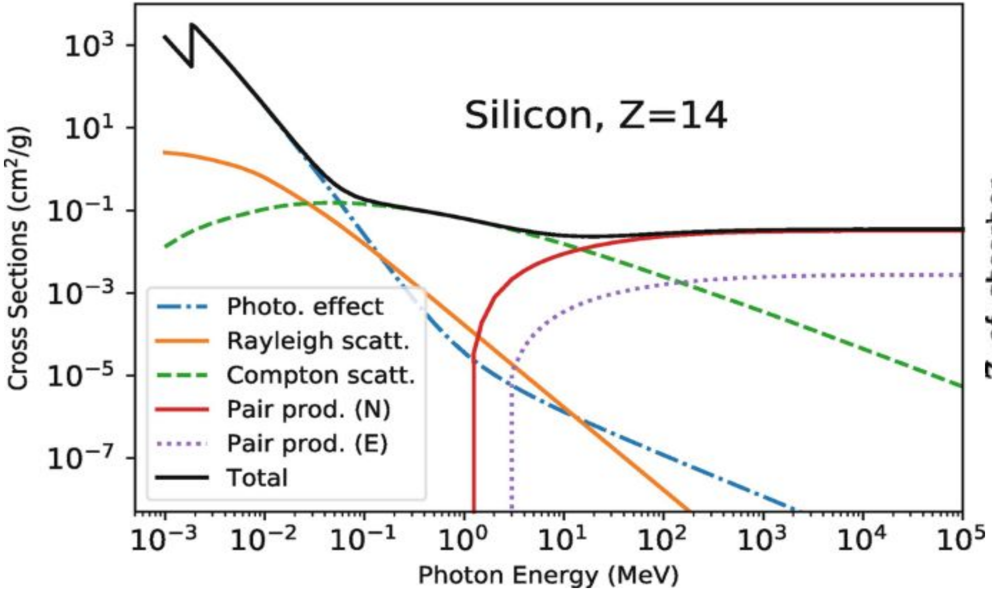
> 2.1. Gamma-ray emission mechanisms in astrophysical sources (connection to Cosmic Rays);
> 2.2. Recent results in gamma-ray astronomy;

> **Prospects and Conclusion.**

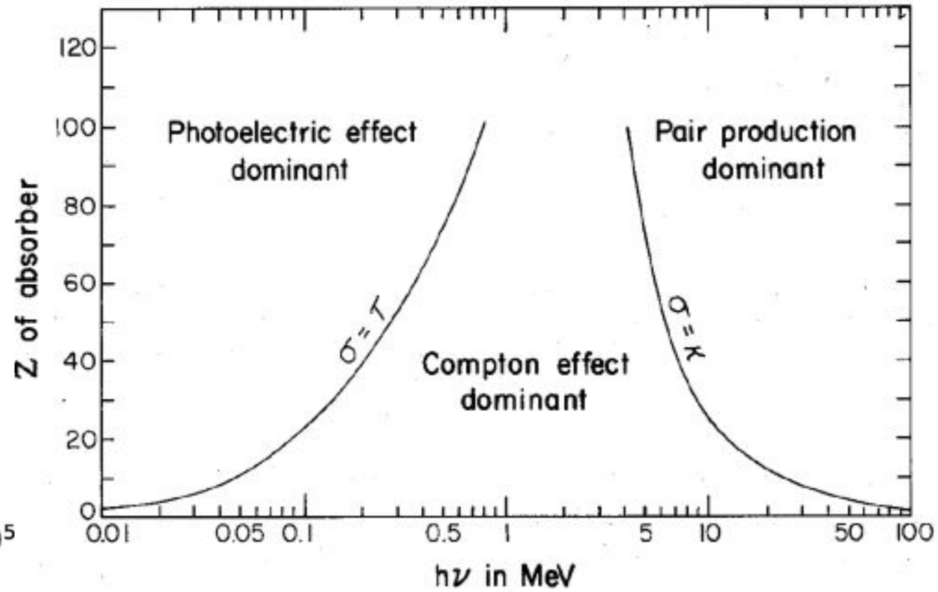
PART I: TECHNIQUE

1.1. Detection principles and instruments of gamma-ray astronomy

Detection principles



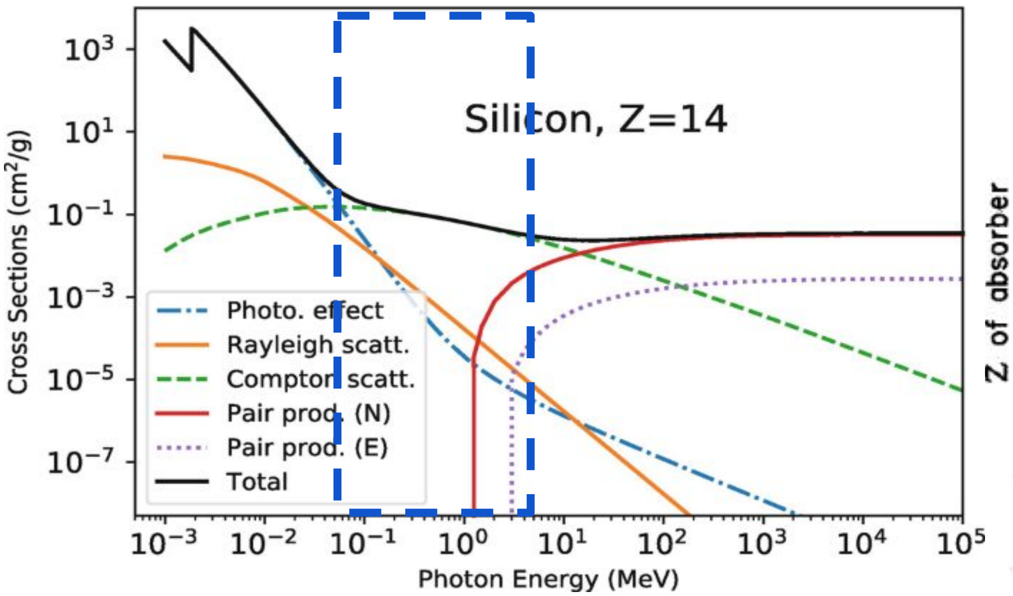
Credit: Caputo et al. (2022)



Credit: Kierans et al. (2022)

> Division based on detection principle:

Detection principles



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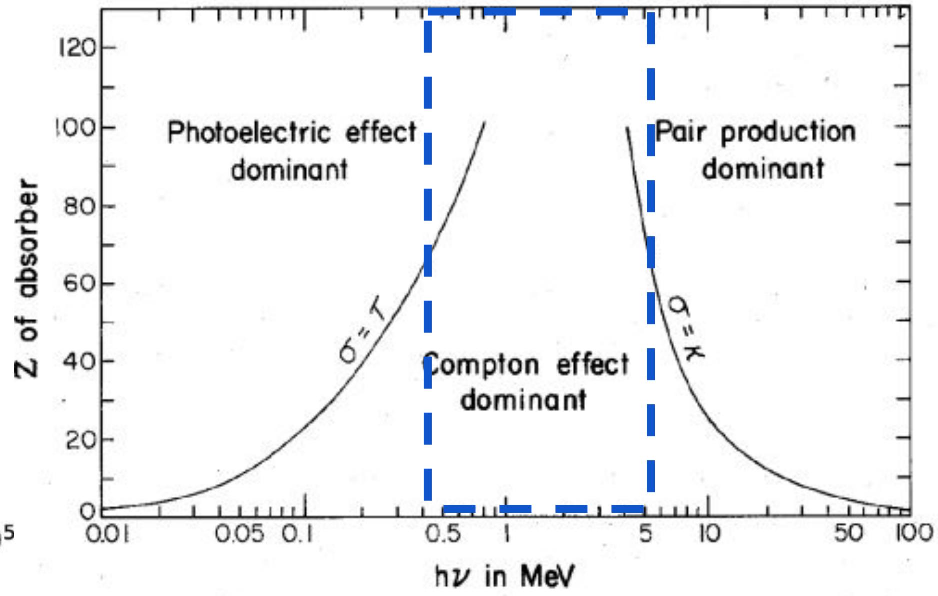
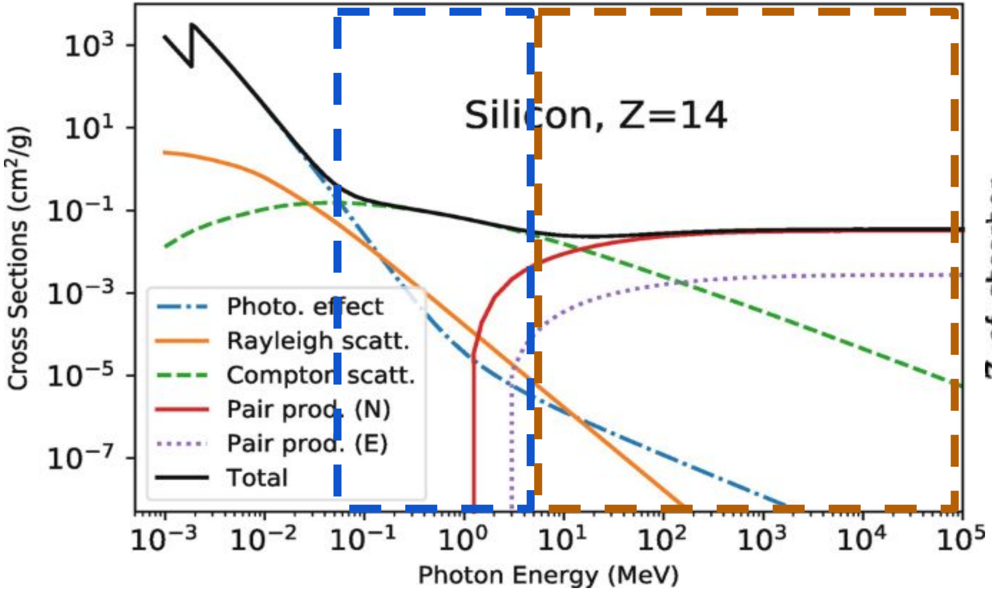


Credit: Kierans et al. (2022)

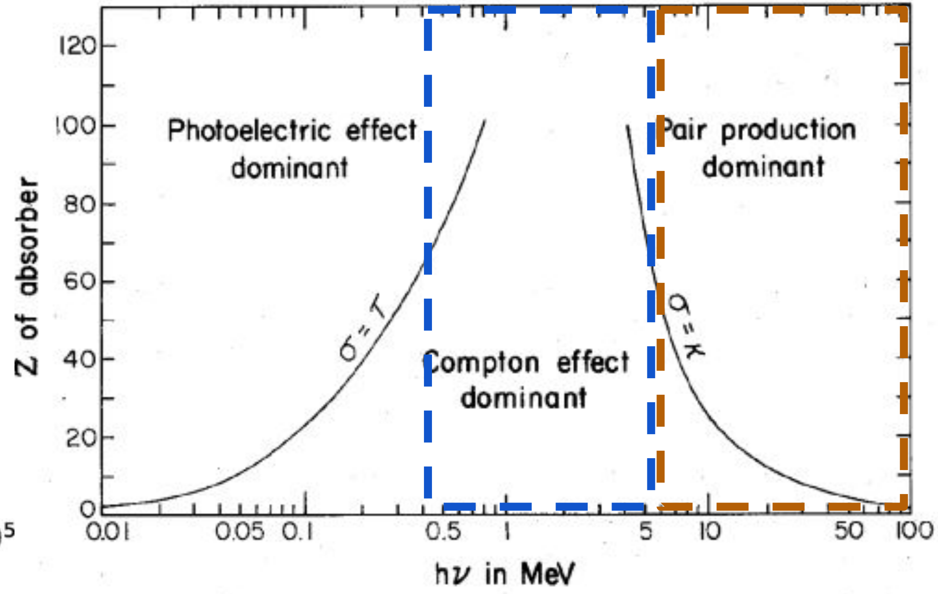
> Division based on detection principle:

- **Compton gamma-ray astronomy**;

Detection principles



Credit: [Caputo et al. (2022)]

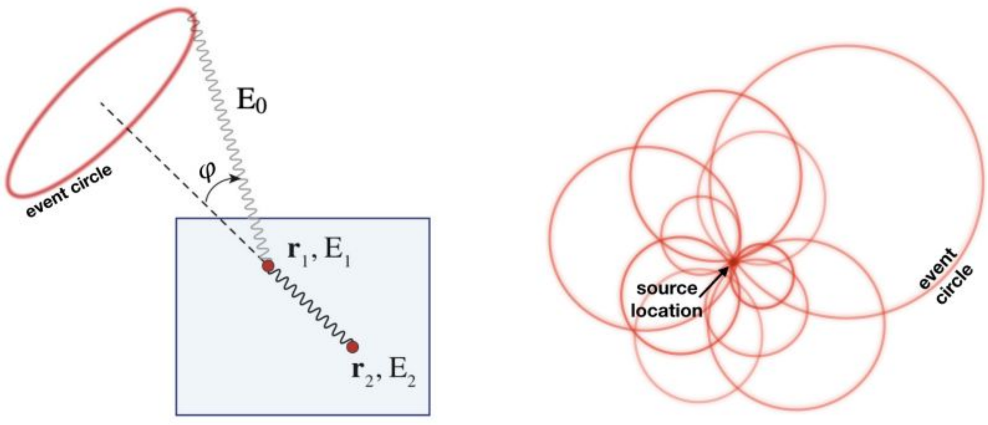


Credit: [Kierans et al. (2022)]

> Division based on detection principle:

- **Compton gamma-ray astronomy**;
- **Pair-production gamma-ray astronomy**.

Compton Gamma-ray telescopes

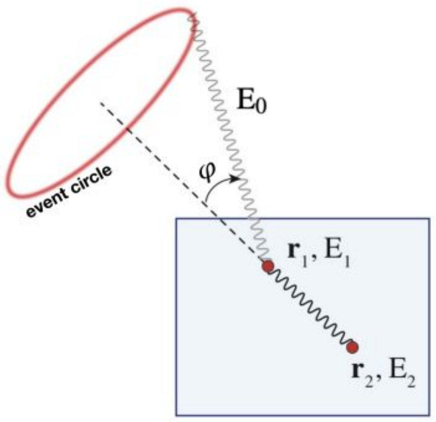


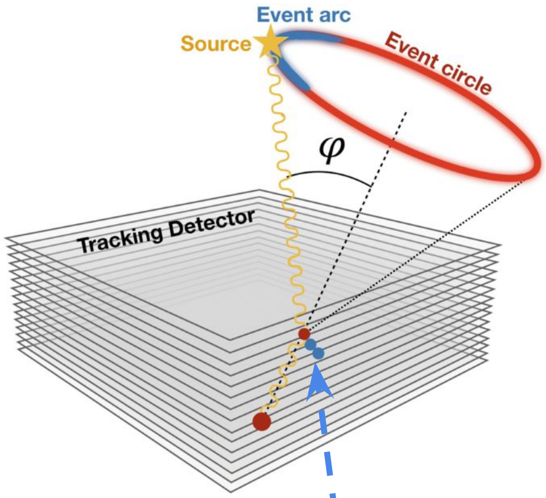
Credit: Caputo et al. (2022)

> **Compton gamma-ray telescope**:

- measure scattered electron (E_1) and absorb the photon (E_2);
- ambiguity on φ resolved w/ multiple photons from source;

Compton Gamma-ray telescopes





Credit: [Caputo et al. (2022)]

> **Compton gamma-ray telescope**:

- measure scattered electron (E_1) and absorb the photon (E_2);
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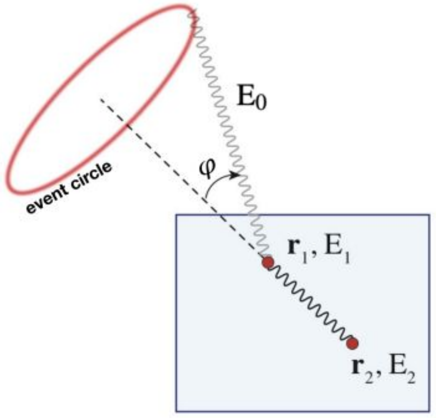
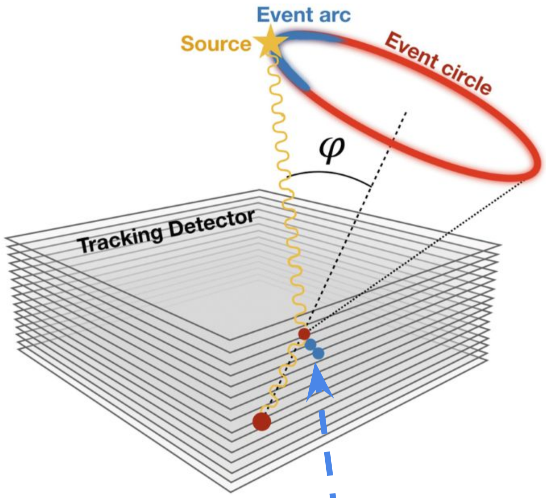
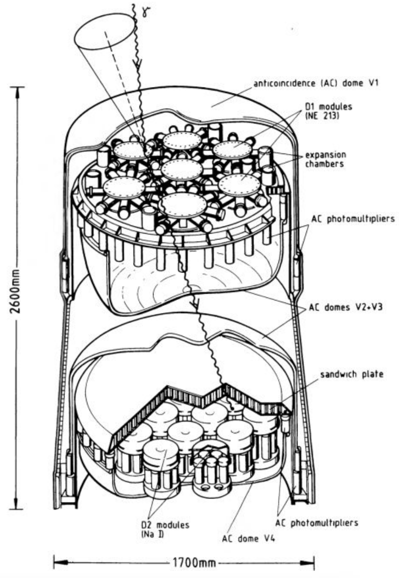
- uncertainty can be reduced tracking the **recoiling electron**.

Compton Gamma-ray telescopes





Credit: [Caputo et al. (2022)]

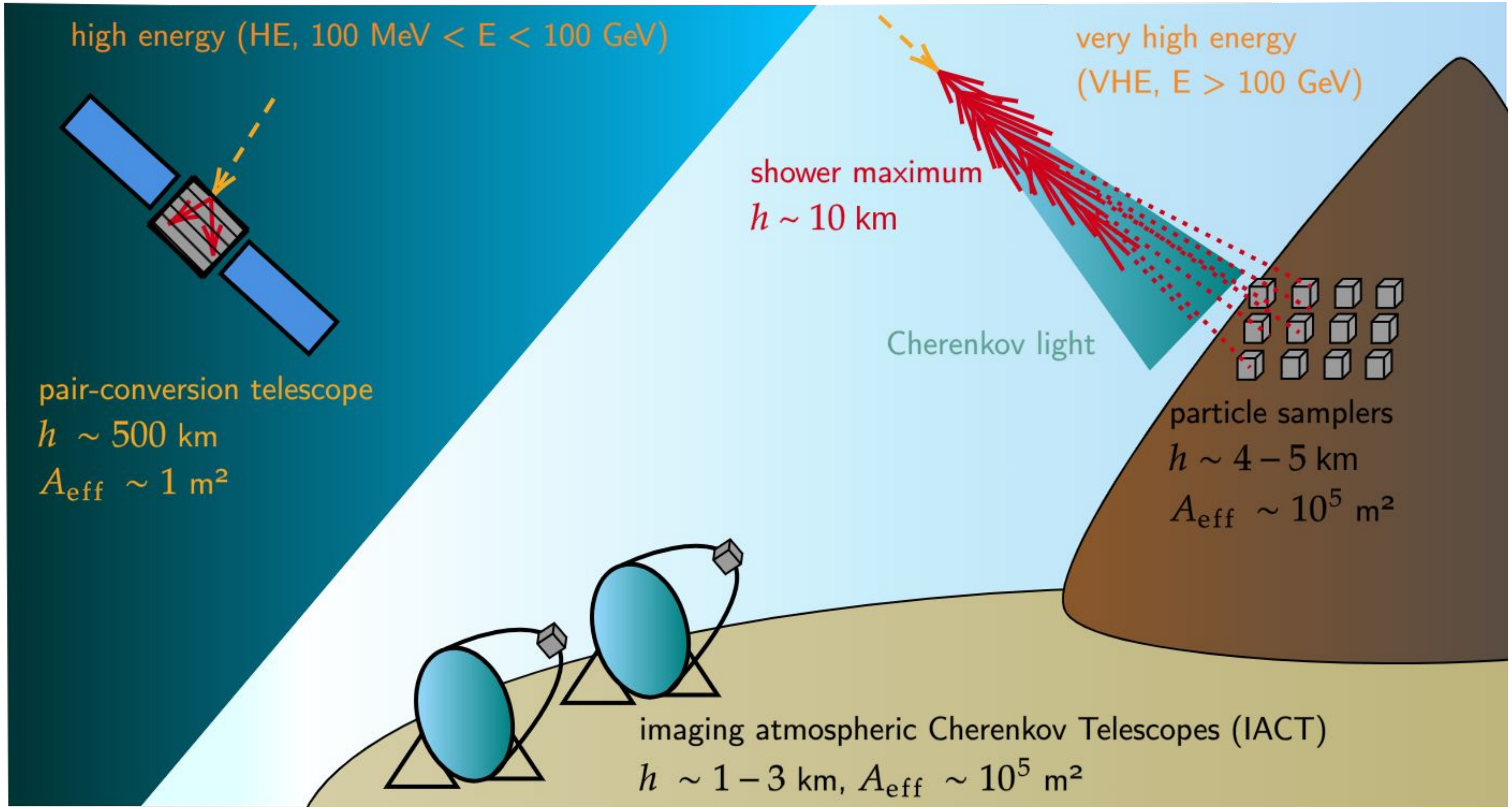


[COMPTEL (1990s)]

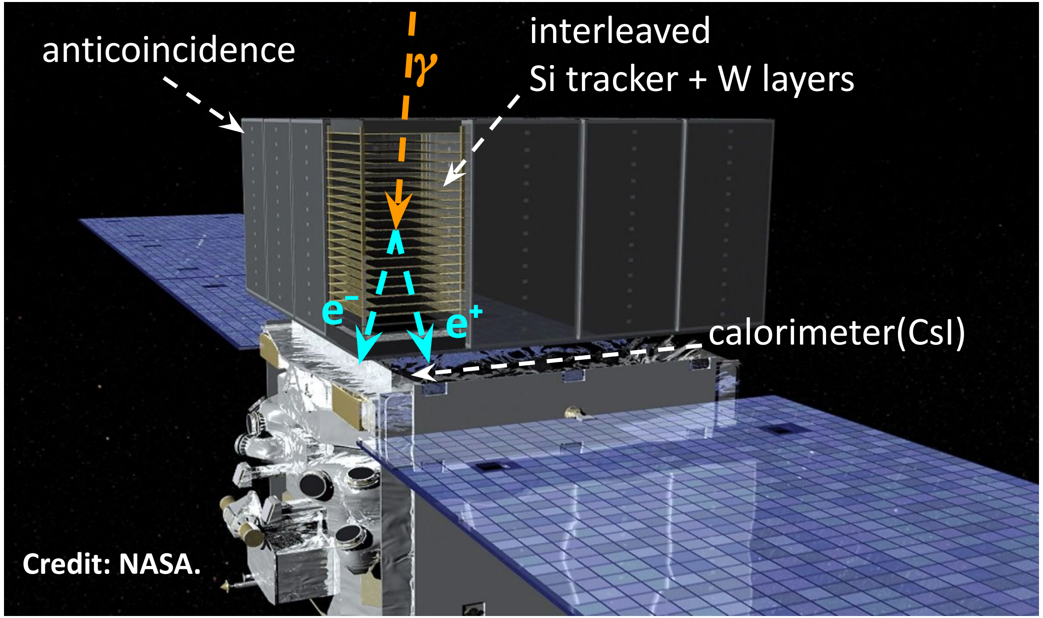
> **Compton gamma-ray telescope:**
- measure scattered electron (E_1) and absorb the photon (E_2);
- ambiguity on φ resolved w/ multiple photons from source;
- uncertainty can be reduced tracking the **recoiling electron**.

> **(balloon- or) satellite-borne:**
- atmosphere opaque MeV photons;
- A_{eff} ~ 10-100 cm²;
- survey instruments.

Pair-production Gamma-ray astronomy



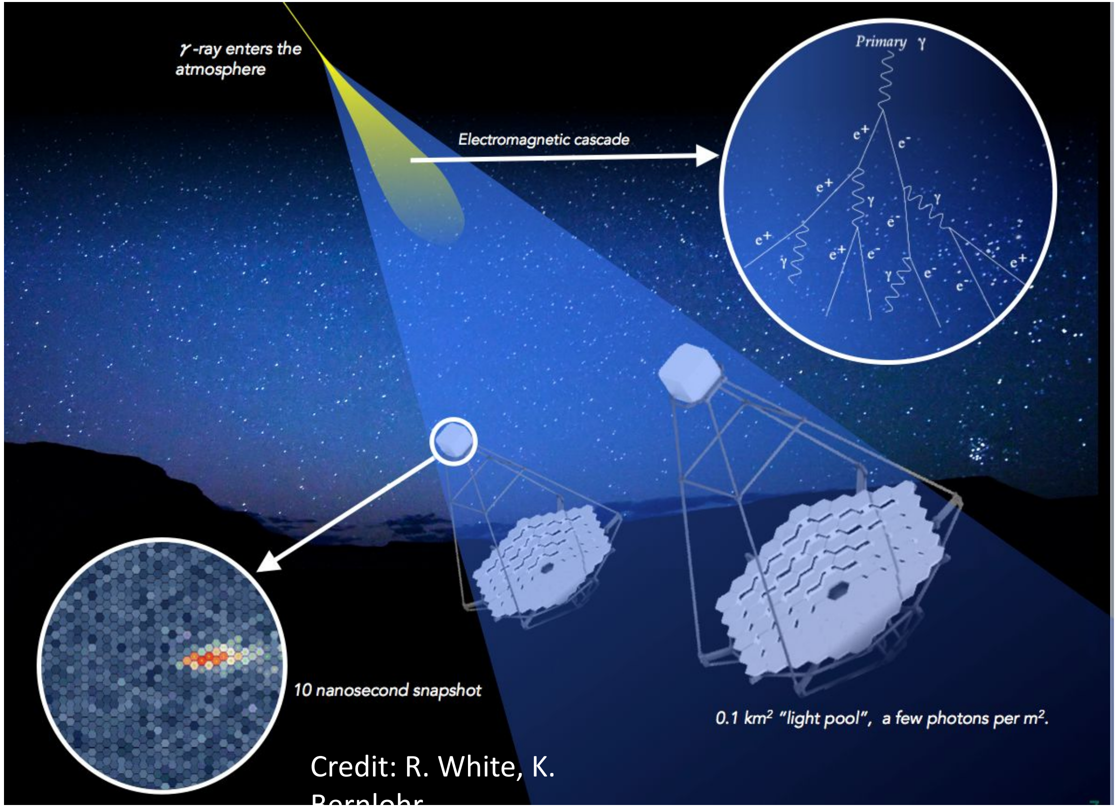
HE: Pair-conversion telescopes



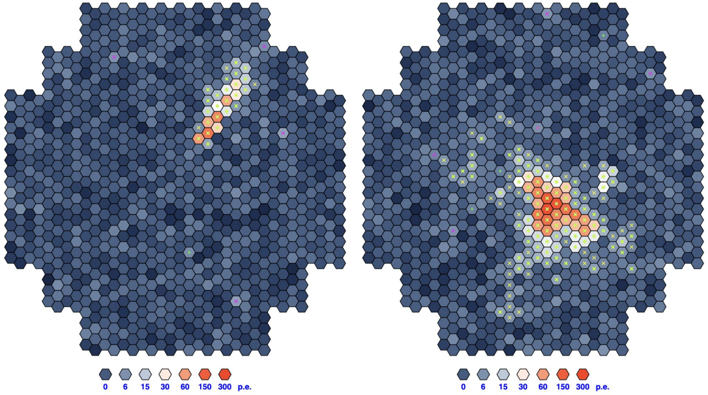
> **Performance**:

- on orbit, **F.o.V.** ~2 sr (whole sky covered every ~2 hr);
- effective area ~m²;
- angular resolution [0.2, 3]°, energy resolution ~10%;
- duty cycle 100%.

VHE: Imaging Atmospheric Cherenkov Telescopes (IACT)

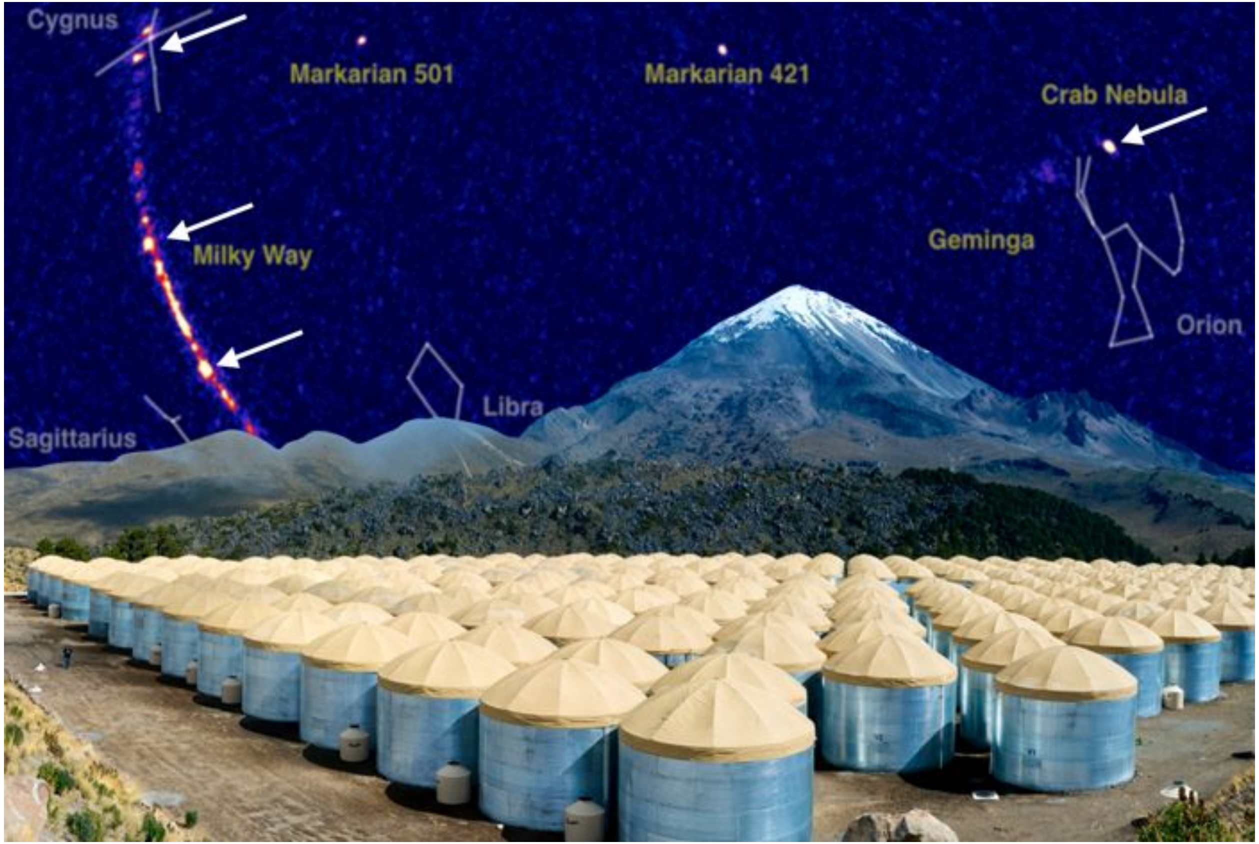


> **Performance**:
- ground-based, pointing;
- **F.o.V.** (a few^o)^2;
- angular resolution [0.04, 1]^o;
- energy resolution ~15%;
- effective area ~10^5 m^2;
- duty cycle 10-15%;
- gamma / hadron discrimination through image topology.



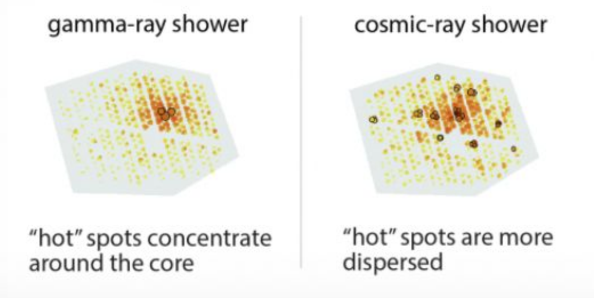
1.0 TeV gamma shower   2.6 TeV proton shower

VHE (UHE): Particle Samplers

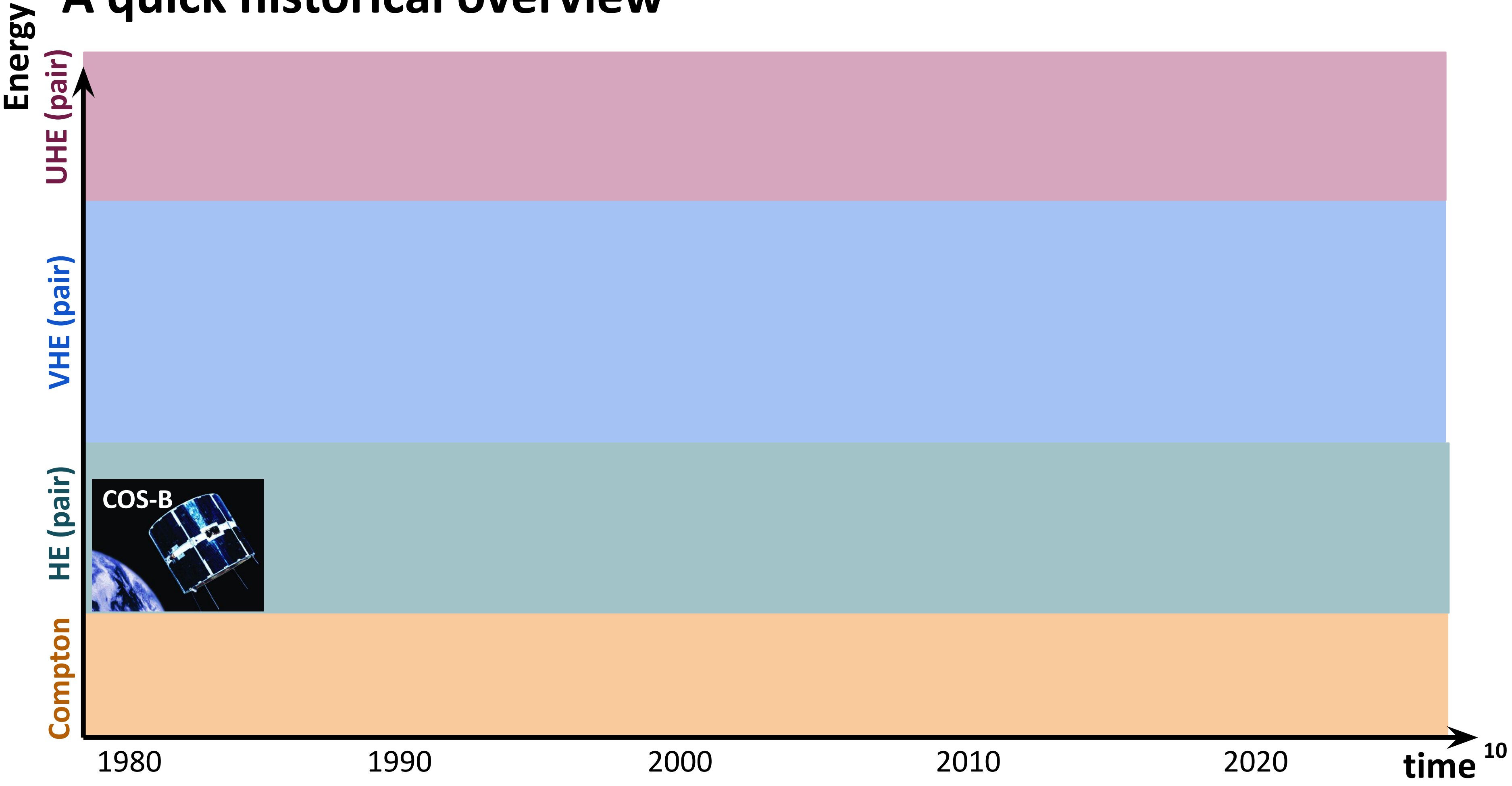


Credit: J. Goodman.

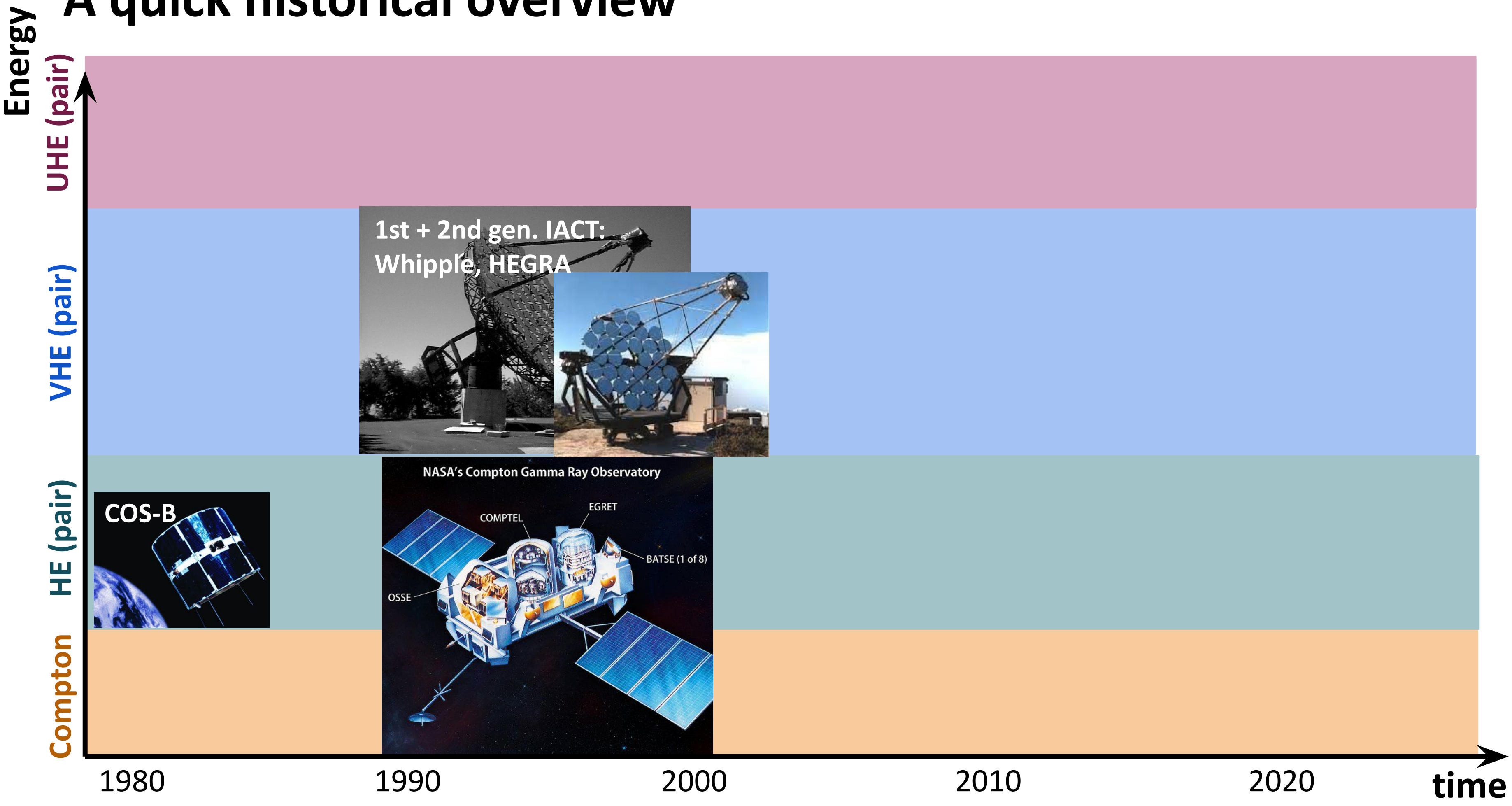
> **Performance**:
- ground-based;
- **F.o.V.** ~2 sr;
- angular resolution [0.1, 1]^{o};
- energy resolution ~30%;
- effective area ~10^5 m^2;
- duty cycle 100%;
- can explore the **ultra-high-energy regime (UHE, E > 100 TeV)**;
- gamma / hadron separation through events topology.



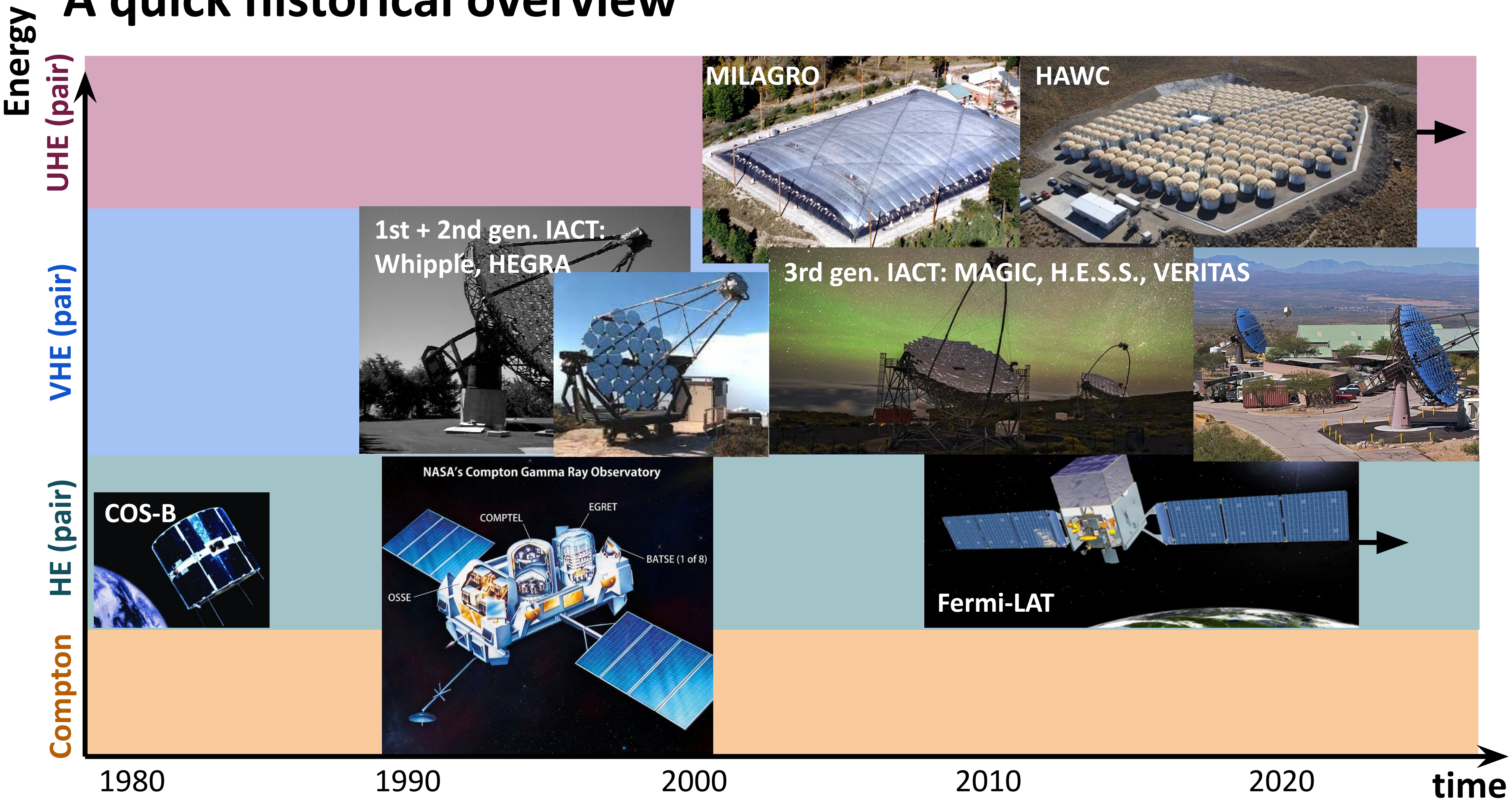
A quick historical overview



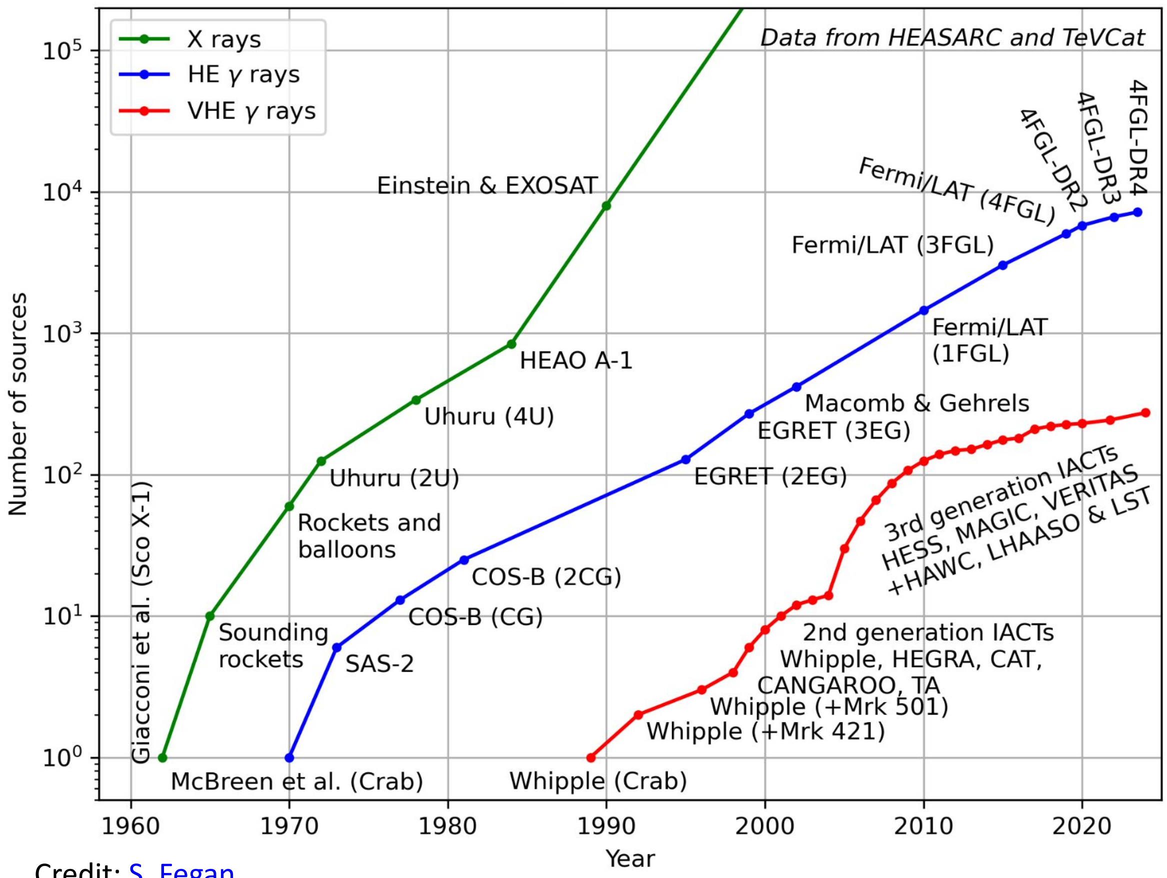
A quick historical overview



A quick historical overview



A quick historical overview



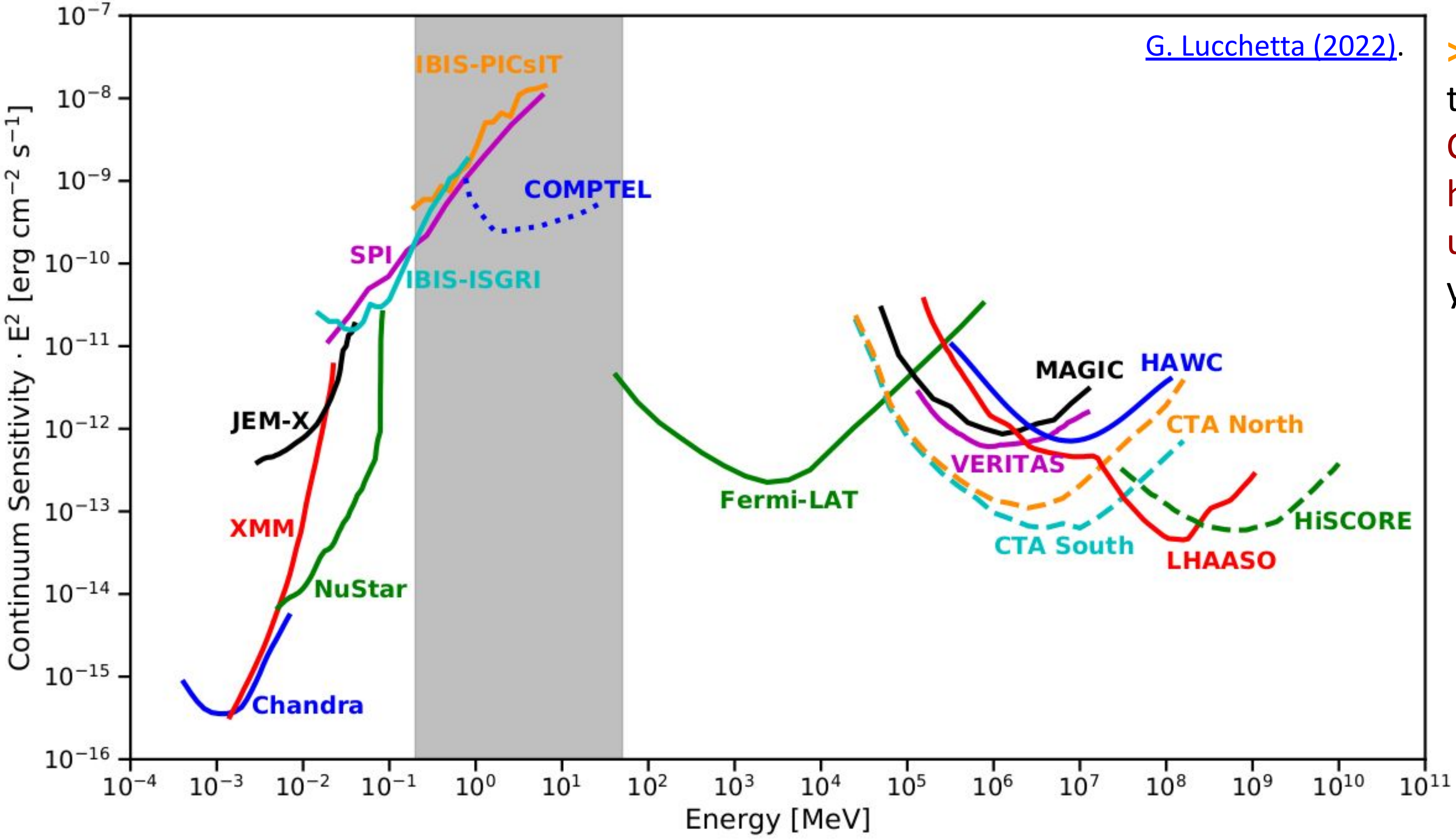
Credit: S. Fegan.

> Fermi-LAT order of magnitude jump in number of detected sources;

> VHE instruments with 100s of sources detected, discovery curve flattening for this generation (will we make an order-of-magnitude jump with the next generation?).

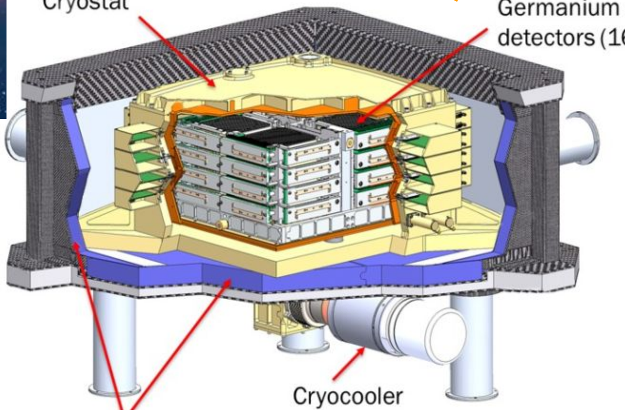
1.2. Hardware technical advancements - gamma-ray instruments in the 2020s

The MeV gap



> After COMPTEL on the CGRO, the Compton / MeV regime has remained unexamined for 25 years.

Compton telescopes: COSI

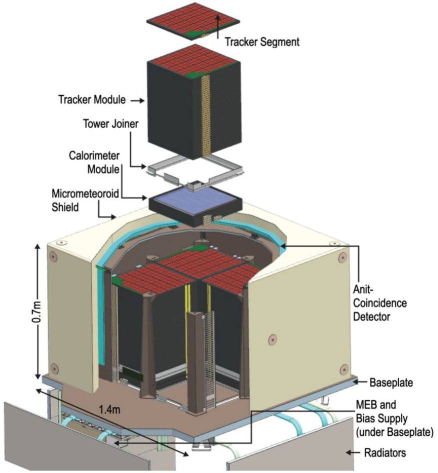


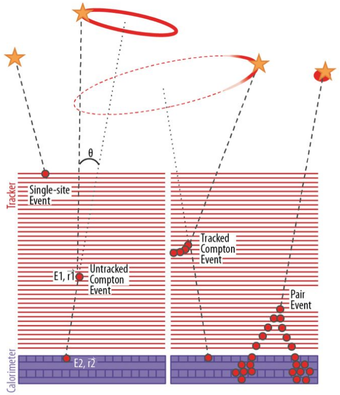
Tomsick (2023)

> **Co**mpton **S**pectrometer and **I**mager **(COSI):**
- **selected by NASA** as small explorer, launch: 2027;
- 4 balloon campaigns completed;
- pure Compton detector: Ge strips + BGO anticoincidence;
- F.o.V. 25% of the sky;
- energy range: [0.2, 5] MeV;
- energy resolution: 0.2%;
- angular resolution: a few deg (large scale structures).

> **objectives**:
- line measurements;
- **polarisation**;
- multi-messenger studies.

Pair-conversion telescopes: AMEGO-X, HERD

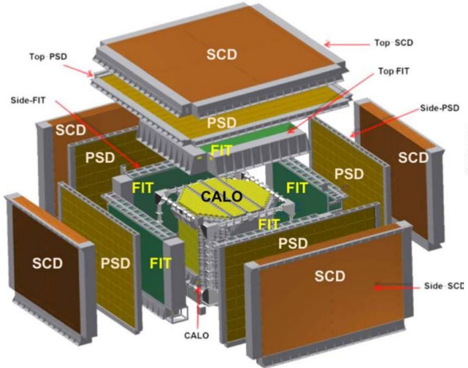




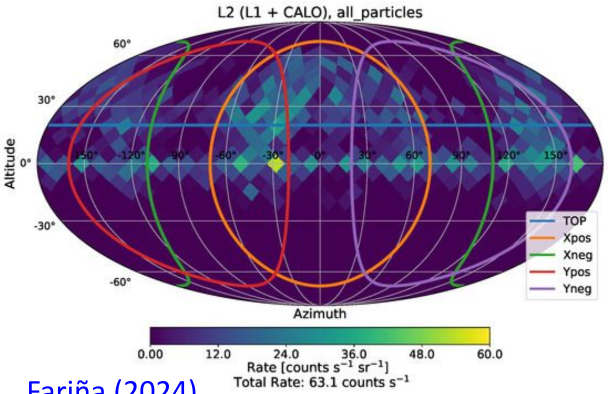
Caputo (2022)

> **A**ll-sky **M**edium **E**nergy **G**amma-ray **O**bservatory e**X**plorer (**AMEGO-X**) [proposed as NASA medium explorer]:

- hybrid Compton + pair telescope;
- Si tracker + calorimeter;
- energy range: 100 keV - 1 GeV;
  [down to 25 KeV with photabs. but no imaging];
- energy resolution ~10%, angular resolution ~1°;
- effective area ~m², F.o.V. ~2sr.



Credit: HERD Collab.



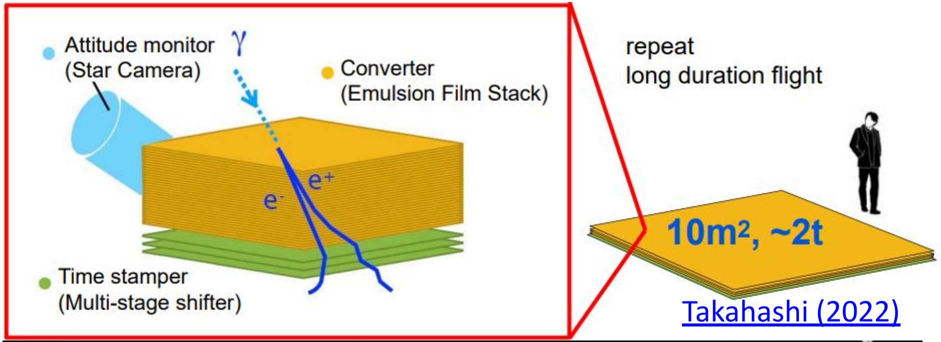
Fariña (2024)

> **H**igh-**E**nergy **C**osmic **R**adiation **D**etector Facility (**HERD**):

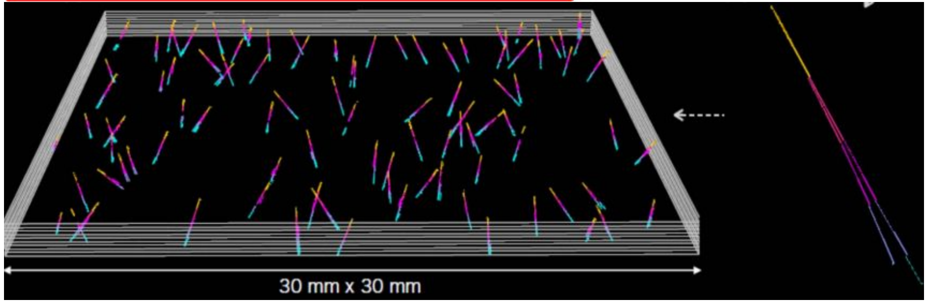
- to be installed on China's SS by 2027;
- CR + gamma detector;
- central 3D CALO + 3 layers of detectors;
- almost 4π F.o.V. (5 instrumented faces);
- energy range: [0.01, 100] GeV;
- angular resolution ~1°.

Other Compton / Pair-conversion telescopes: GRAINE, GECCO

Gamma-**R**ay **A**stro-**I**mager with **N**uclear **E**mulsion (**GRAINE**)

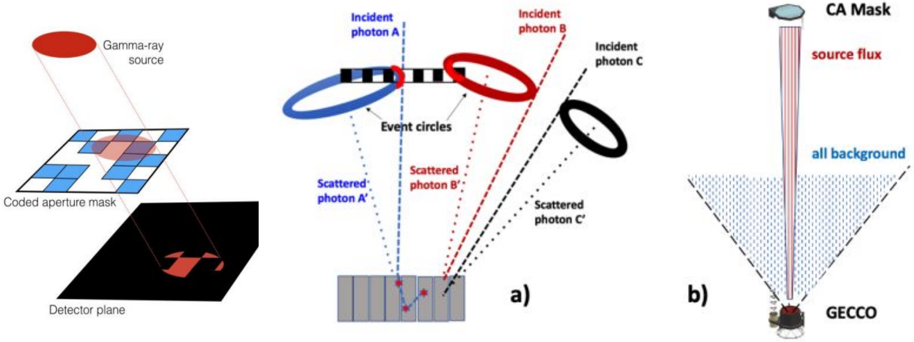


Takahashi (2022)



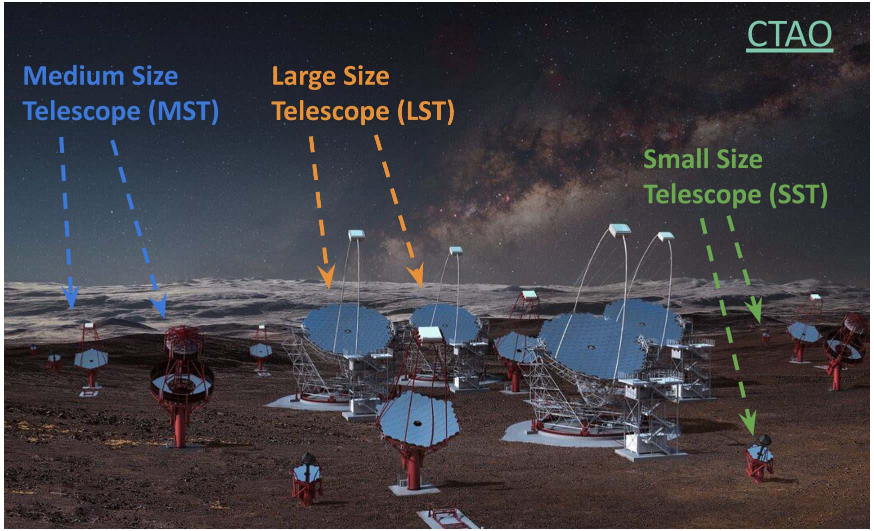
- balloon-borne nuclear emulsion stack;
- track accuracy ~50 nm @ 0.1 deg angular resolution;
- polarisation in GeV!
- effective area a few m²;
- 4 successful flights: detection of Galactic Centre, Vela.

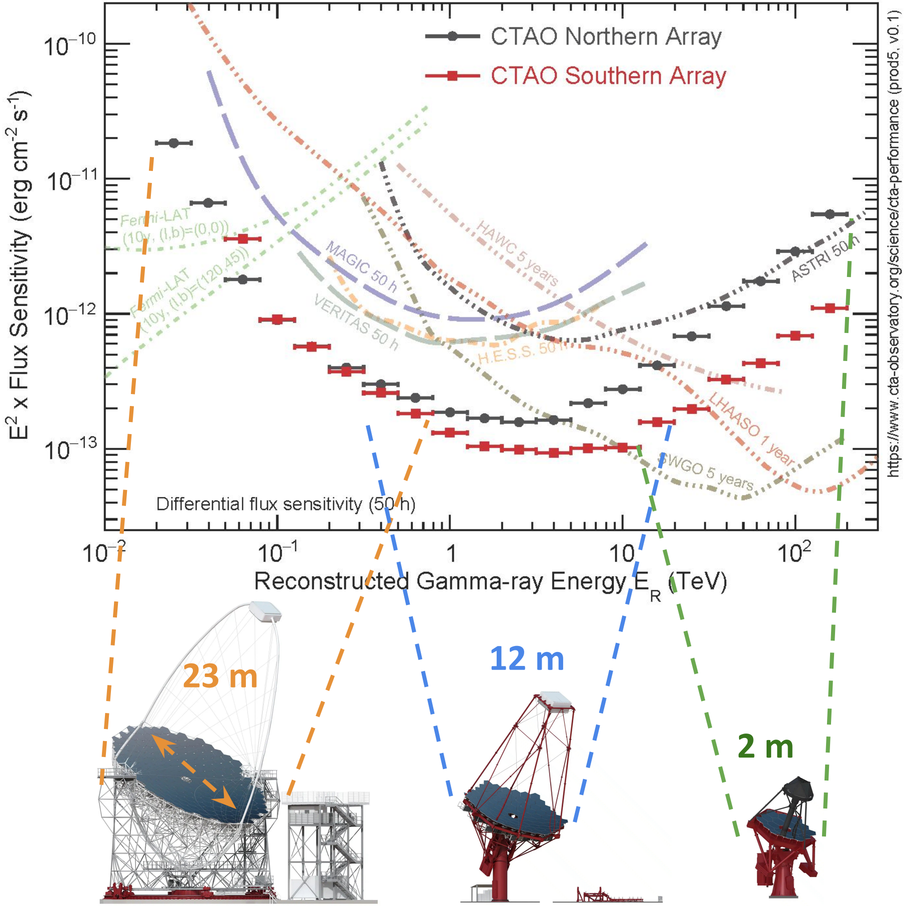
Galactic **E**xplorer with a **C**oded Aperture Mask **Co**mpton Telescope (**GECCO**)



- energy Range: 50 keV to 10 MeV;
- **coded aperture mask** for high angular resolution;
- **Si + CZT detectors** for improved energy resolution and detection efficiency.

IACTs: The Cherenkov Telescope Array Observatory (CTAO)





> Two sites (La Palma, Chile) for full sky coverage:
- 13 telescopes North (extragalactic science),
- 51 telescopes South (galactic science);

> energy range [20 GeV, 300 TeV];

> F.o.V. 5^o;

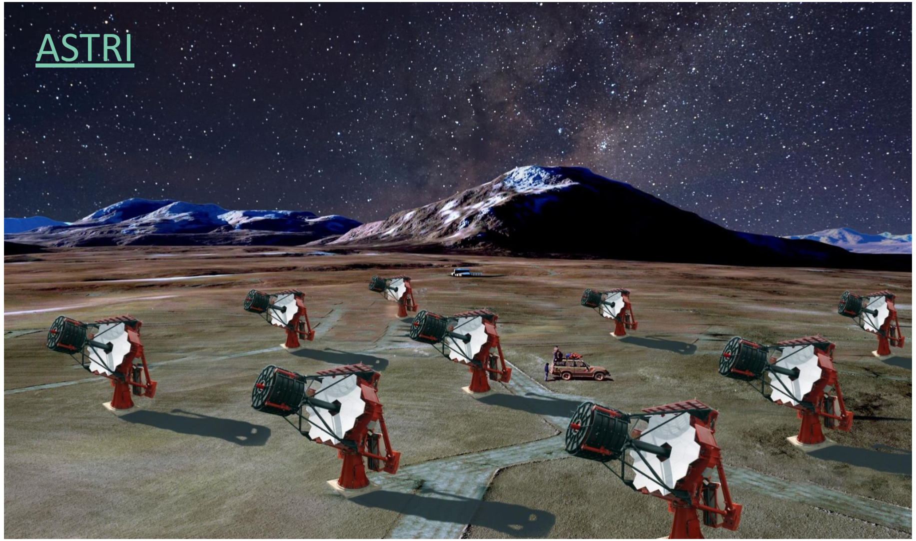
> performance improved by a factor ten over current generation of IACT.

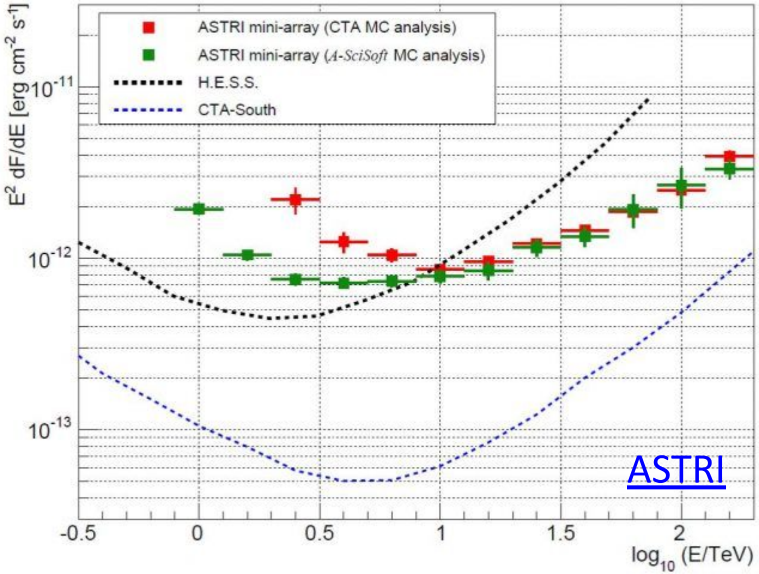
IACTs: The Cherenkov Telescope Array Observatory (CTAO)

> LSTs in the Northern site already in construction;
- LST-1 completing its commissioning phase, already performing science;
- LST-4 assembled;
- LST-2 and SLT-3 in construction (rail);

> Early LST-1 science: Galactic Centre, PeVatrons, active galaxies.

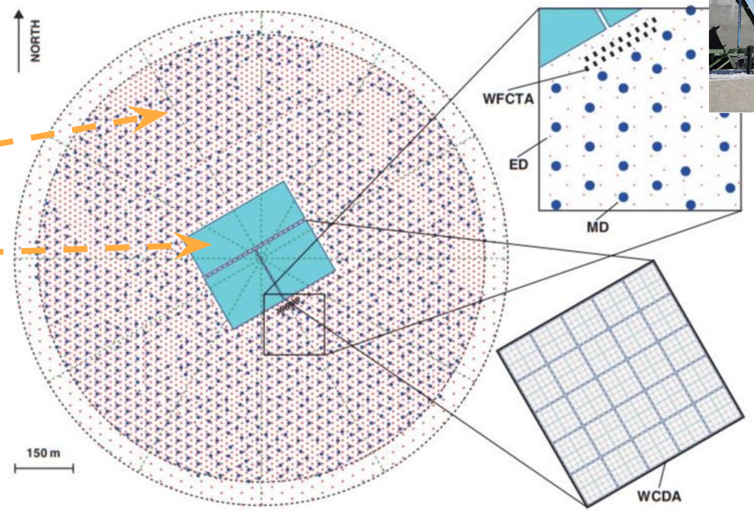
IACTs: ASTRI mini-array





- Mini-Array of nine small-sized (4-m diameter) and large field of view (~10°) IACTs;
- to be built at the Observatorio del Teide (Tenerife) [complementing CTAO-N at the highest energies];
- energy range 1-100 TeV;
- one prototype in Serra La Nave (Etna).

Particle Samplers: LHAASO

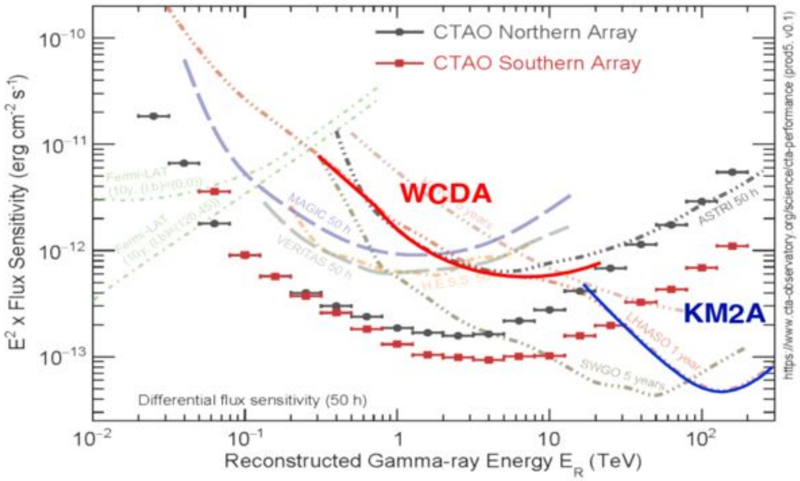


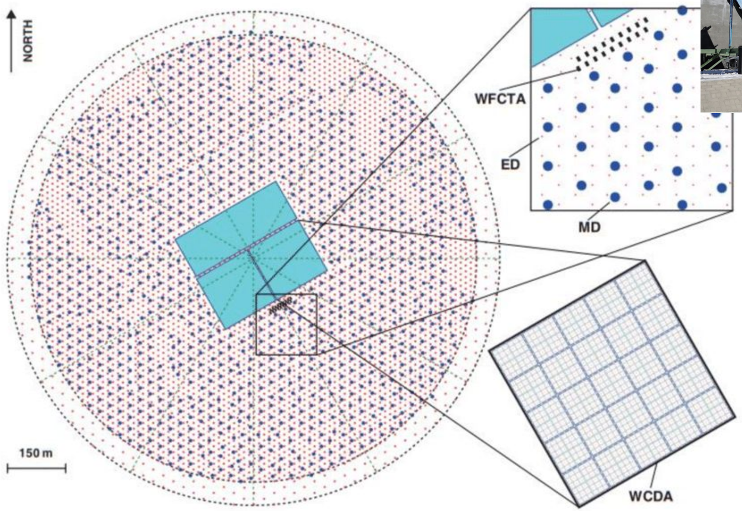
> **L**arge **H**igh-**A**ltitude **A**ir **S**hower **O**bservatory, in Daocheng, Sichuan Province, China (h ~ 4410 m):
- Water Cherenkov Detector Array (WCDA), 3 ponds / tanks instrumented with array of PMTs,
- array of particle detector (KM2A), 1.3 km^2, ED (scintillators for $e^{\pm}$), MD (water bags for $\mu^{\pm}$),
- Wide Field-of-view air Cherenkov/fluorescence Telescope Array (WFCTA) [not used for gamma science].

> instantaneous F.o.V. 1/7 of the northern sky, scanned every 24 h;

> energy range: sub-TeV to beyond 1 PeV;

Particle Samplers: LHAASO





> Large **H**igh-**A**ltitude **A**ir **S**hower **O**bservatory, in Daocheng, Sichuan Province, China (h ~ 4410 m):
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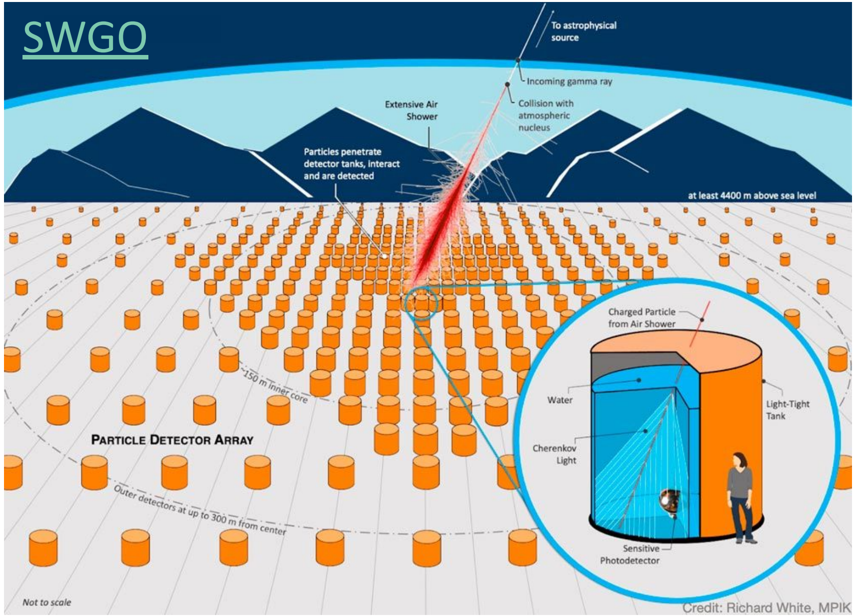
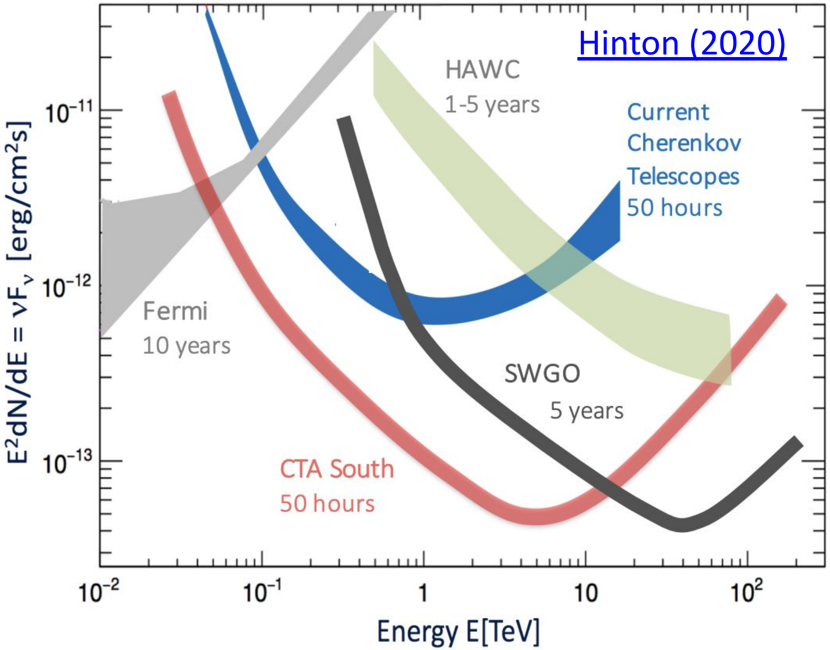
> instantaneous F.o.V. 1/7 of the northern sky, scanned every 24 h;

> energy range: sub-TeV to beyond 1 PeV;

> complementary to CTAO and **more sensitive above 100 TeV** (PeVatrons!).

Particle Samplers: SWGO

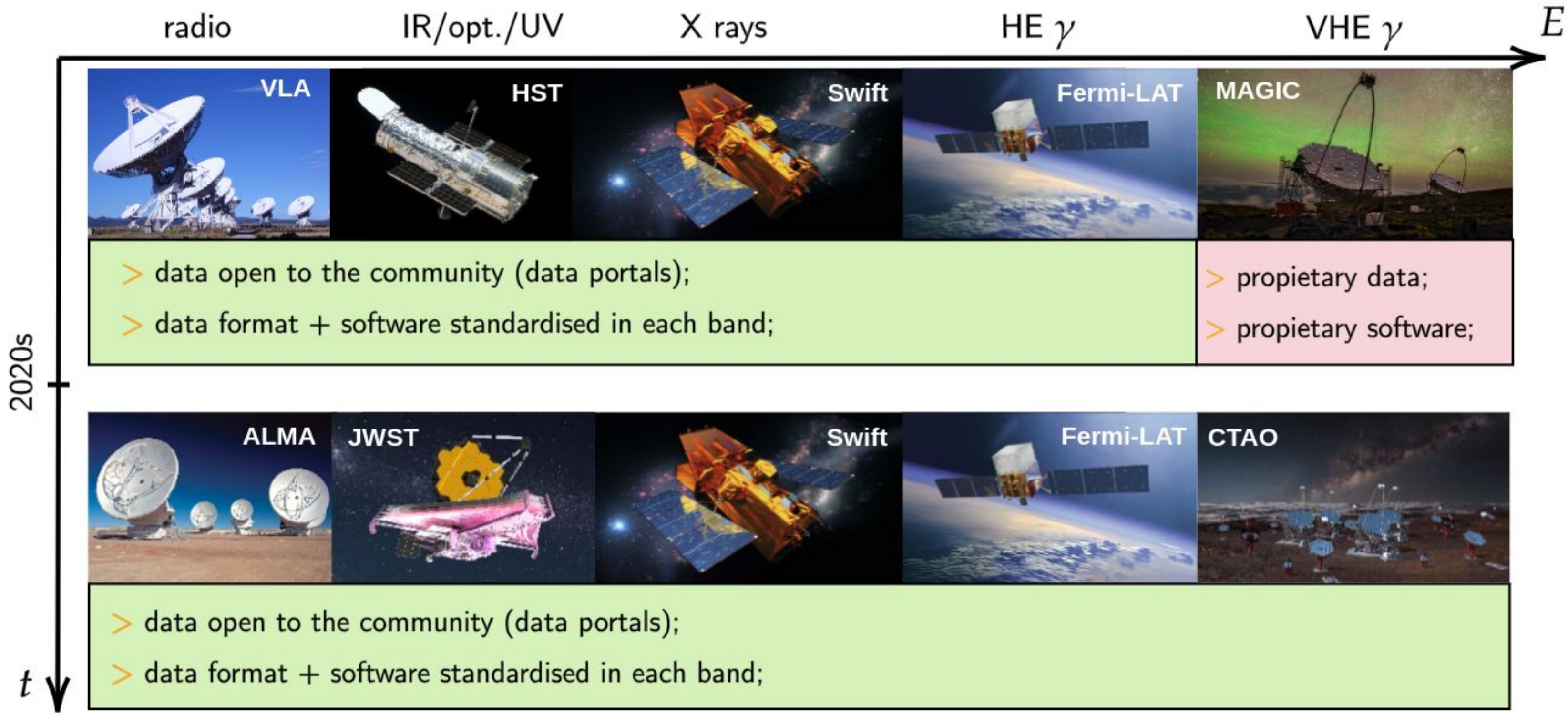




- > **S**outhern **W**ide-field **G**amma-ray **O**bservatory, proposed for Atacama, Chile, h ~ 4770 m;
- > array of water tanks (high fill-factor in the core and a low density outer array);
- > steradian field of view;
- > energy range: 100s of GeV up to the PeV scale;
- > less sensitive than LHAASO, but complementary sky coverage (Southern hemisphere) + synergy with CTAO-S.

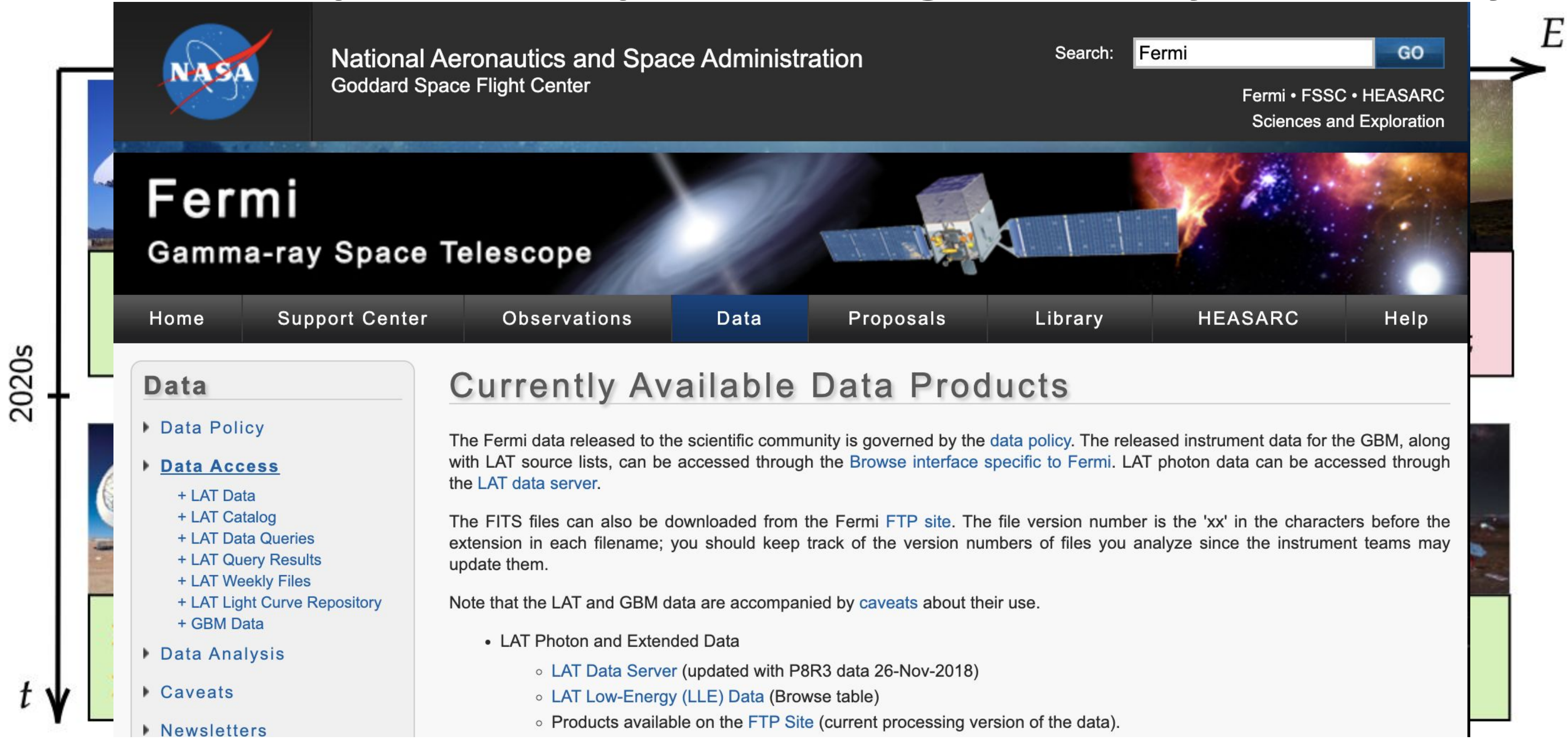
1.3. Software technical advancements - standardisation of data and analysis tools

Towards an open and reproducible gamma-ray astronomy



> current VHE instruments: operation as experiments (proprietary data + software);
> future VHE instruments: operation as observatory (open time + data + software);
> **necessity** of standardised data and software for the community.

Towards an open and reproducible gamma-ray astronomy



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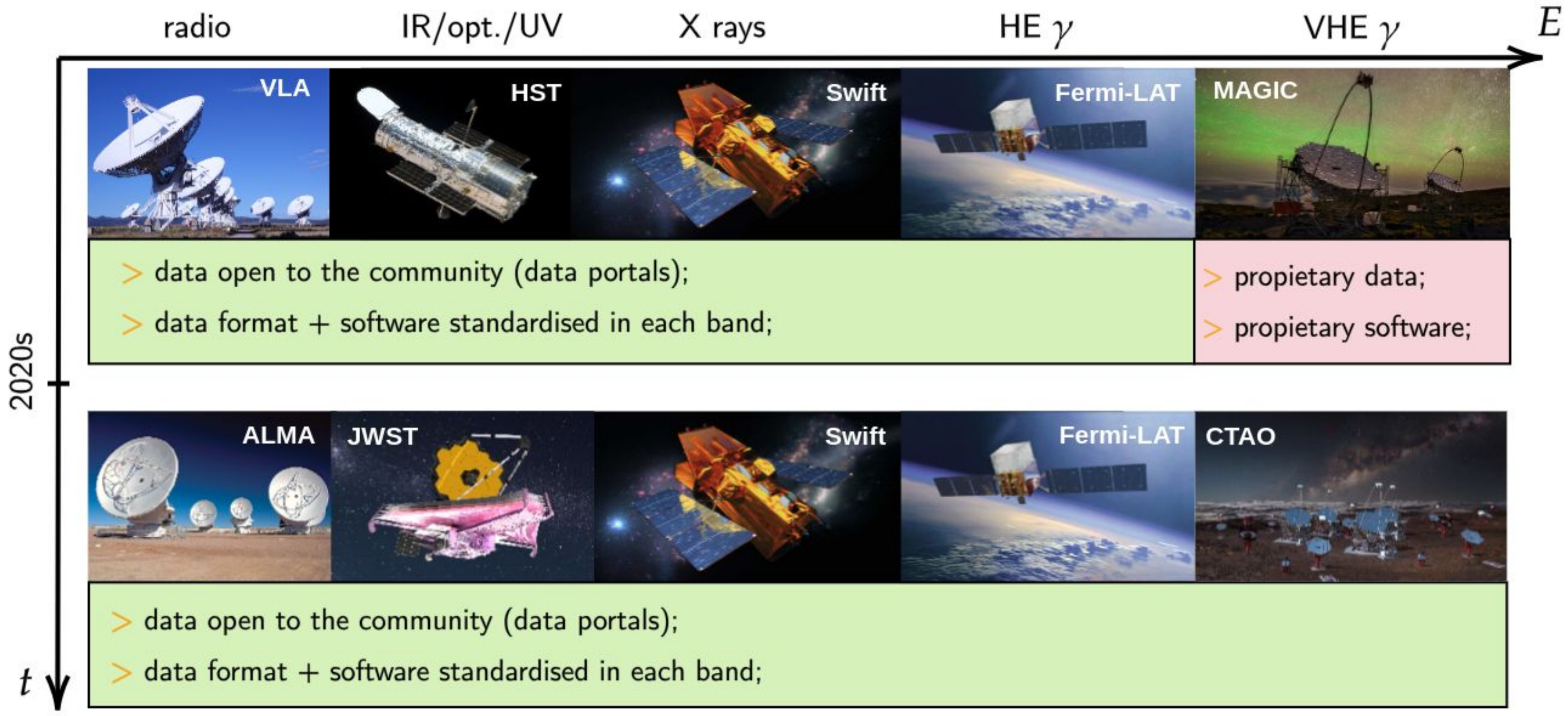
Towards an open and reproducible gamma-ray astronomy



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> future VHE instruments: operation as observatory (open time + data + software);
> **necessity** of standardised data and software for the community.

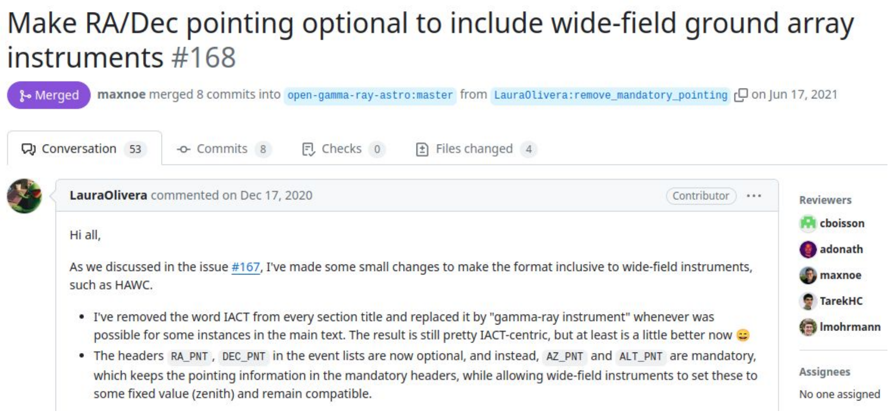
GADF: towards standardised gamma-ray astronomical data

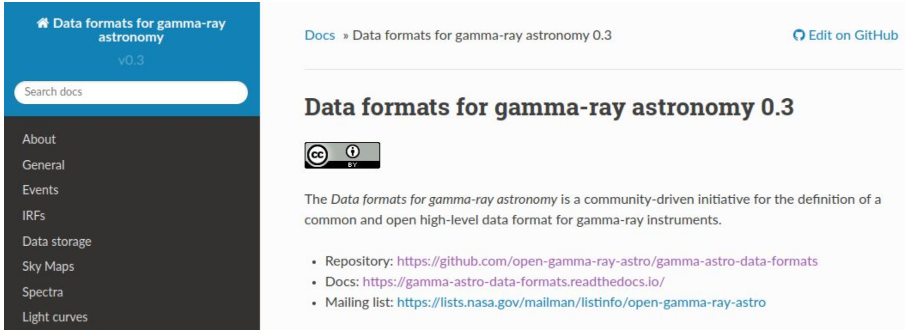
> 2015-2016: several software-independent implementations of VHE (IACT) high-level data to prototype the CTA data format and to exploit open-source science tools developed for CTA;

> efforts channelled in the *Data Formats for Gamma-ray Astronomy* (GADF) initiative;

> documentation hosted on GitHub with specifications for high-level gamma-ray astronomical data;

> **community-driven standards**, discussed via GitHub workflow (issues, PR);





VODF: towards standardised gamma-ray astronomical data

> 2015-2016: several software-independent implementations of VHE (IACT) high-level data to prototype the CTA data format and to exploit open-source science tools developed for CTA;

> efforts channelled in the *Data Formats for Gamma-ray Astronomy (GADF) initiative*;

> documentation hosted on GitHub with specifications for high-level gamma-ray astronomical data;

> **community-driven standards**, discussed via GitHub workflow (issues, PR);

> a formal Coordination Committee established to ensure the development and usage of the data format.

VODF — Context | Data Model | Data Format | Tools | Contributing | Contact

VODF
very-high-energy open data format

The *Very-high-energy Open Data Format*, VODF, is an open data model and format for Very-High-Energy (VHE) gamma-ray and neutrino astronomy. Its goal is to provide a standard set of file formats and standards for data starting at the reconstructed *event* level as well as higher-level products such as N-dimensional binned data cubes (including sky images, light curves, and spectra) and source catalogues. With these standards, common science tools can be used to analyze data from multiple high-energy instruments. VODF aims to follow as much as possible the IVOA standards.

Note

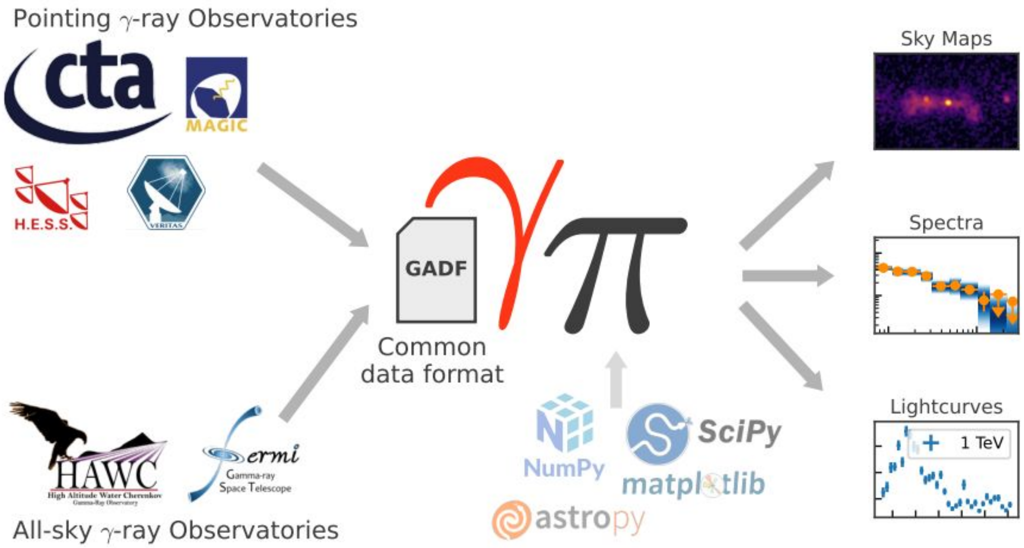
This web site is still under construction

The VODF Working group

The VODF working group contains members from the following astronomical telescopes and observatories:

- **ASTRI** - Astronomia a Specchi a Technologica Replicante Italiana, (IACT telescope)
- **CTAO** - Cherenkov Telescope Array Observatory (IACT observatory)
- **FACT** - First APD Cherenkov Telescope (IACT telescope)
- **Fermi-LAT** - Large Area Telescope on the Fermi Space Telescope (High-energy Space Observatory)
- **HAWC** - High-Energy Water Cherenkov telescope (WCT)
- **H.E.S.S.** - High Energy Stereoscopic System (IACT Array)
- **IceCube** - Neutrino Observatory

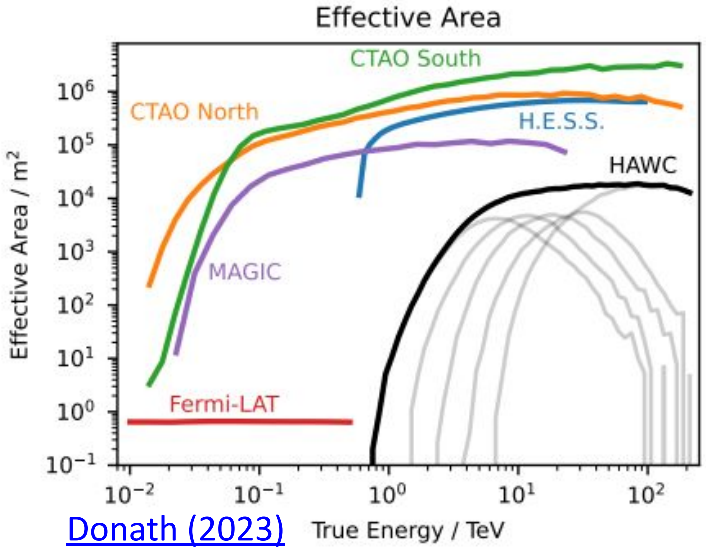
Gammapy: A Python Package for Gamma-ray Astronomy



> Open-source python package for high-level gamma-ray data analysis;

> affiliated with [*astropy*];

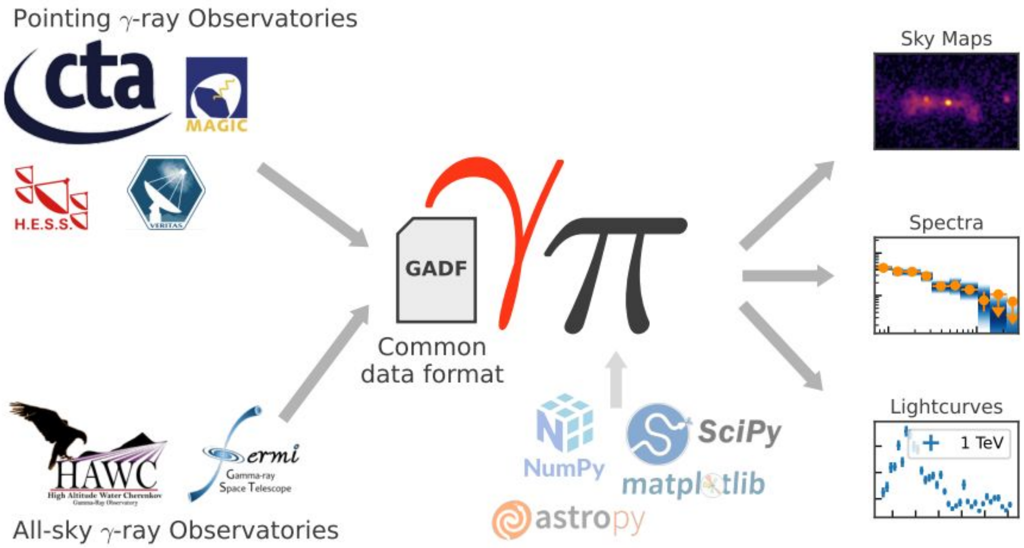
> community of 500 users, 100 contributors.



Donath (2023)

> **technical specs**:
- starts from standardised high-level data and produces scientific results
- implements GADF specs → supports data from different instruments (*Fermi*-LAT, IACTs, HAWC);
- **adopted by CTAO as its analysis tool**;

Gammapy: A Python Package for Gamma-ray Astronomy



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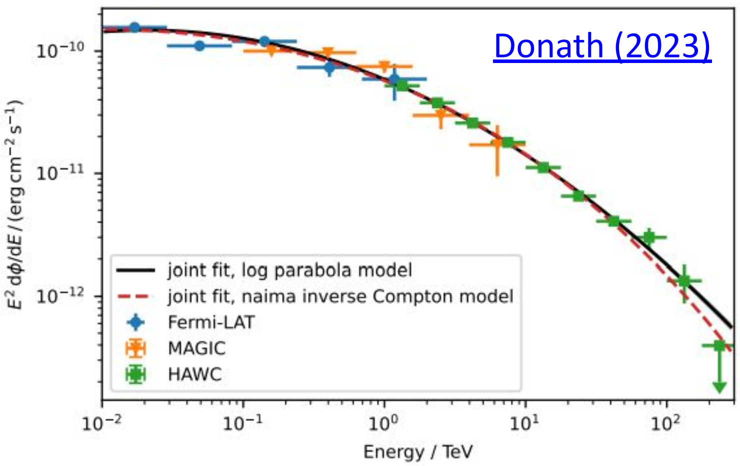
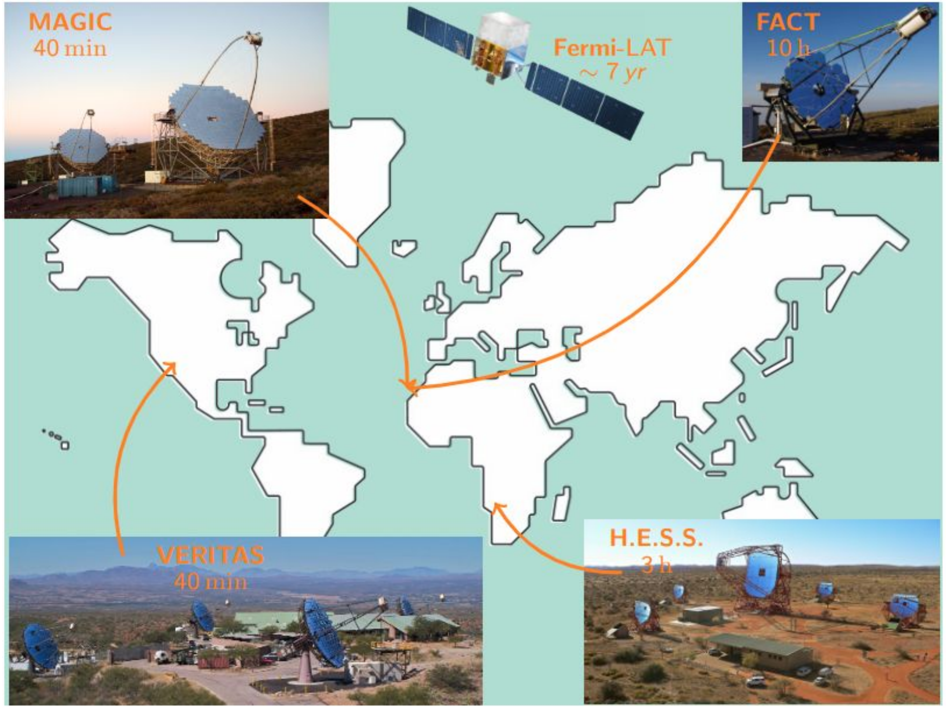
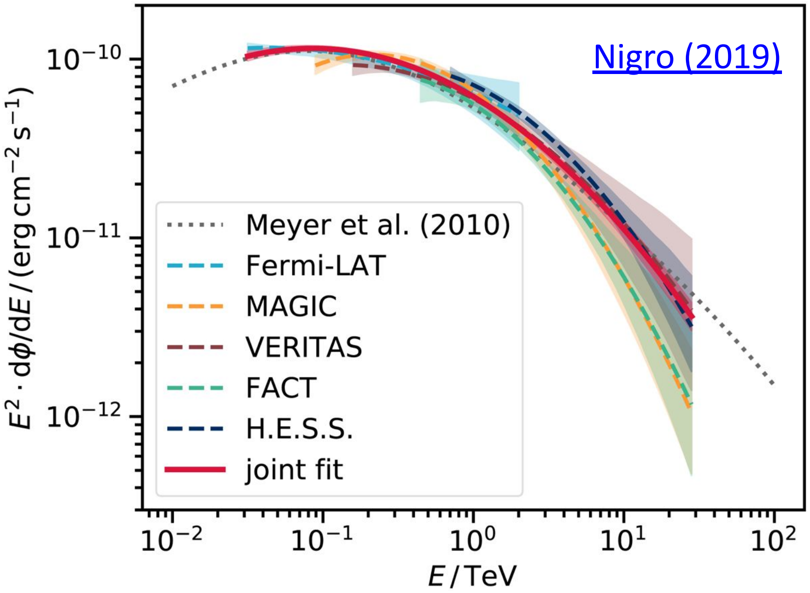


> **technical specs**:

- starts from standardised high-level data and produces scientific results
- implements GADF specs → supports data from different instruments (*Fermi*-LAT, IACTs, HAWC);
- **adopted by CTAO as its analysis tool**;
- allows for data combination within the same pipeline!

The Joint Crab Project: First Demonstration of Standardisation

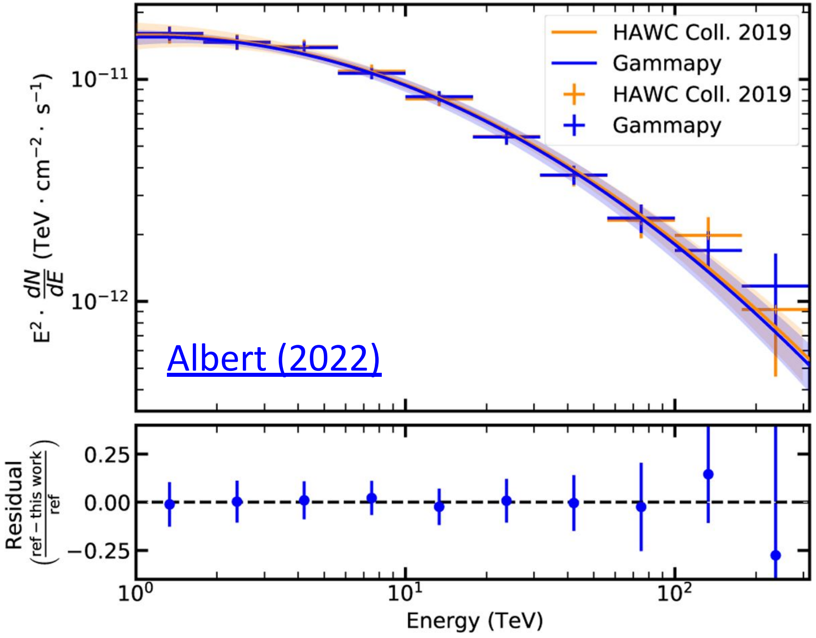


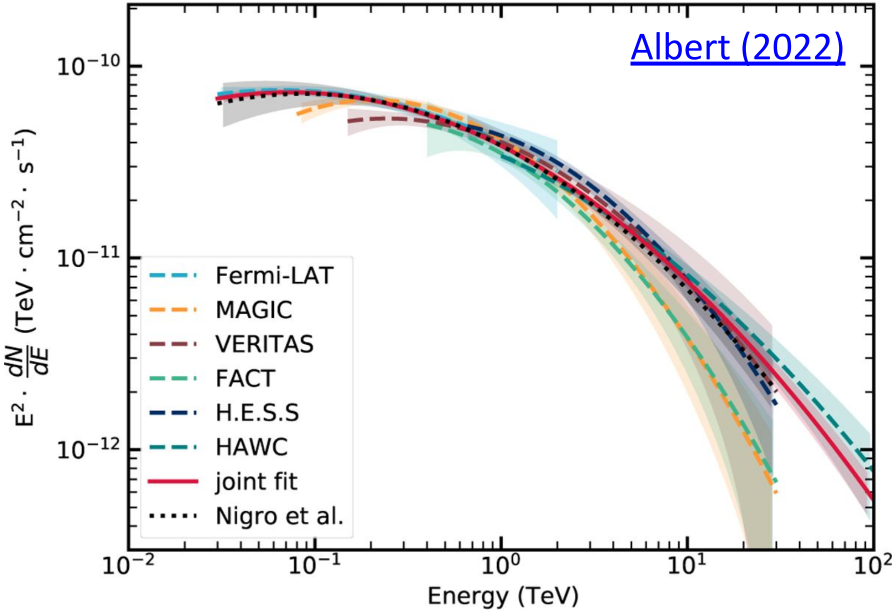


1st combined measurement of the gamma-ray spectrum of the Crab Nebula.

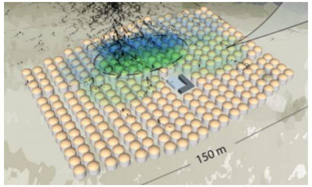
> Demonstrate, **once the effort of data-standardisation is taken, the ease and power of combined analyses**;
> small data sets from *Fermi*-LAT and all the then-operating IACTs (Crab Nebula observations) produced in the GADF and analysed with Gammapy;
> project reproducible down to the computational environment github, Zenodo, Docker container.

HAWC standardised gamma-ray data





> GADF specifications (independent of the detection technique) applied to particle samplers, HAWC data;
> analysed with Gammapy and validated against HAWC official analysis tool;
> **demonstrated the reproducibility of the joint-crab project**
(combined spectral measurement extended to 5 orders of magnitude in energy);
> **first public release of HAWC data**!



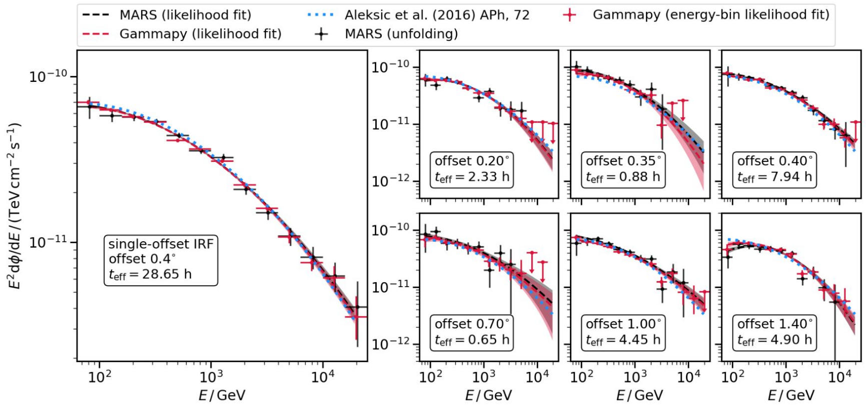
The MAGIC Data Legacy

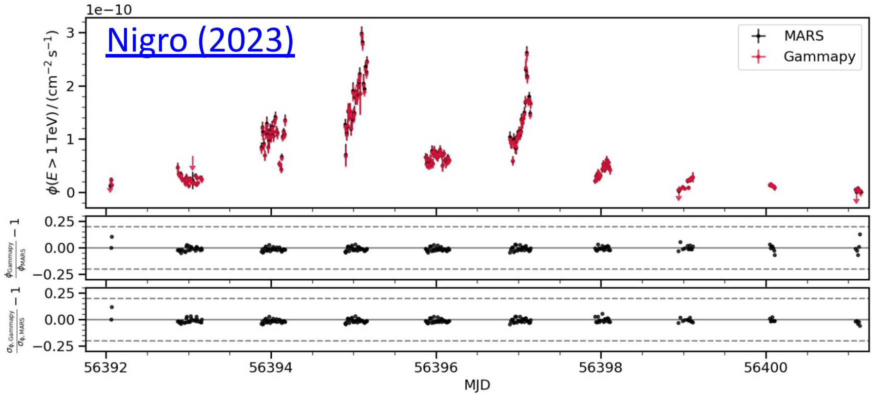
> **MAGIC Collaboration** working towards the systematic conversion of their data to the GADF format;

> ~160 h of observations converted to GADF and validated (Gammapy vs MAGIC proprietary software);

> **Data Legacy**: release all the MAGIC stereoscopic data after the end of its scientific operations;

> **First public release of MAGIC data**.





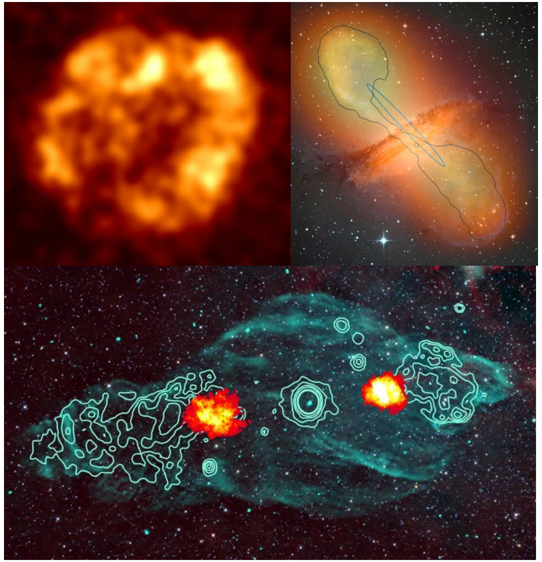
source	period	obs. time	science case
Crab Nebula	2011-2012	42 h	bright steady source
Crab Nebula (moon)	2018-2019	20 h	bright steady source
Mrk421	Apr. 2014	42 h	bright variable source
M15	2015-2016	57 h	dim source

PART II: SCIENCE

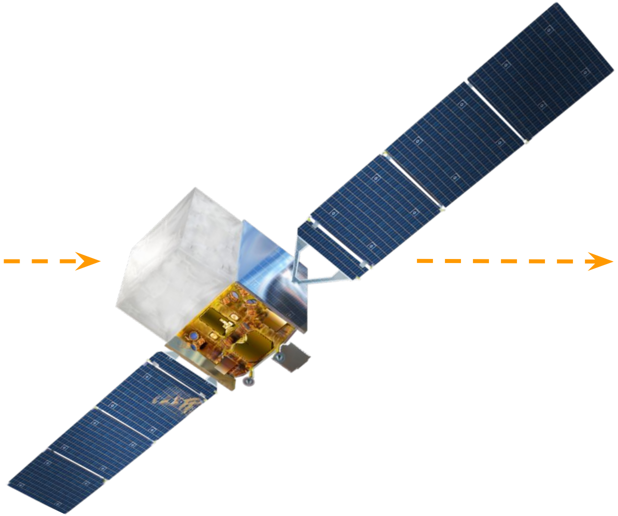
2.1. Gamma-ray emission mechanisms in astrophysical sources (the Cosmic-Ray connection)

What can we infer from the high-energy universe?

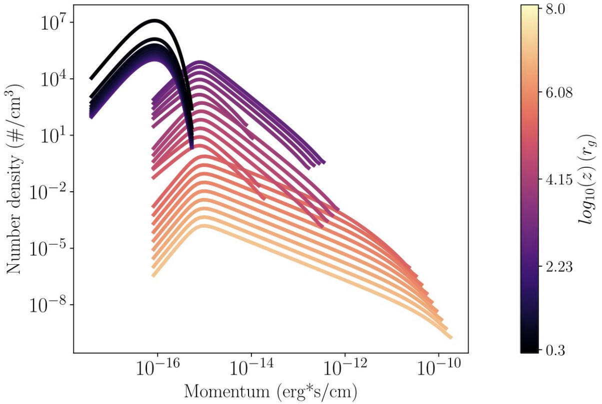
energetic and inaccessible phenomenon



observer



inference & interpretation



Lucchini (2022)

> **high-energy non-thermal emission from astrophysical plasma**

> high-energy telescopes

> **gamma-ray emission as manifestation of particle acceleration**

> Small scale: infer the radiation processes and the population of accelerated particles responsible;

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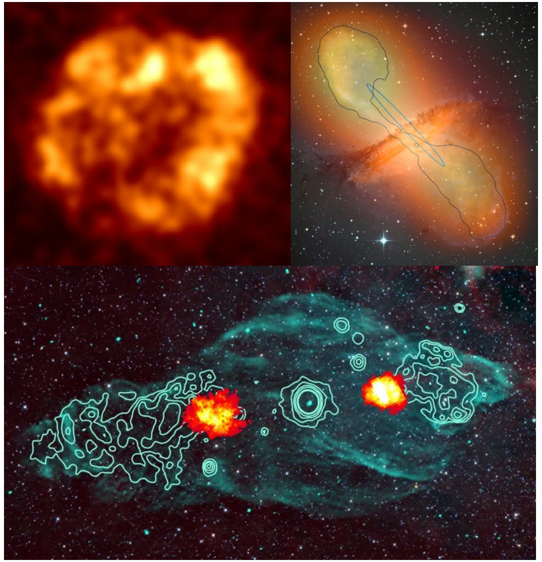

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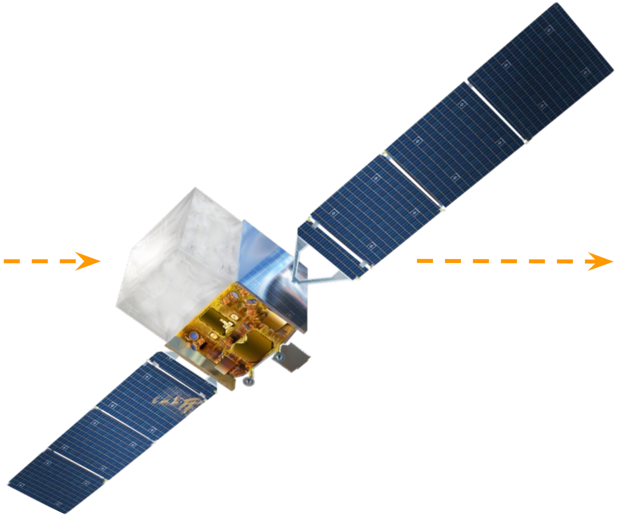

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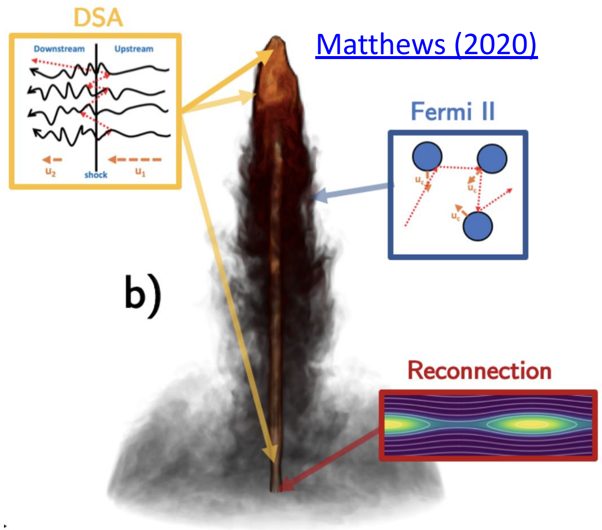
inference & interpretation

Matthews (2020)

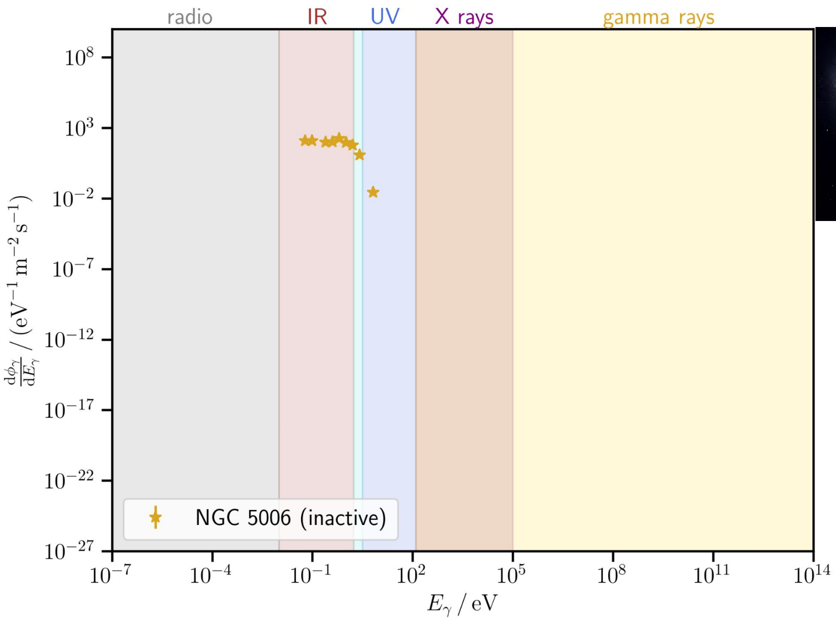


> gamma-ray emission as manifestation of particle acceleration

> Small scale: infer the radiation processes and the population of accelerated particles responsible;

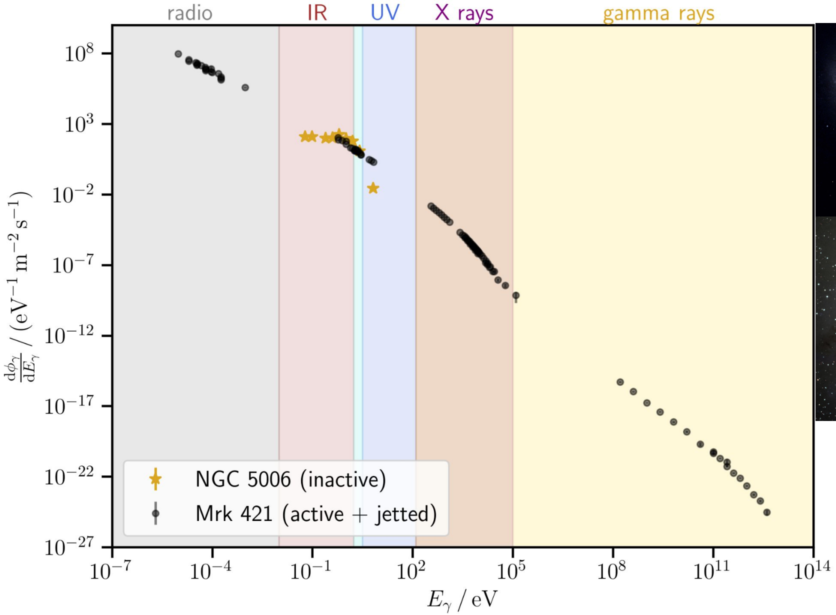
> large scale: study the acceleration mechanisms and eventually the structure of the forge.

The non-thermal universe



> **Thermal radiation**: thermodynamic equilibrium, Black Body spectrum dependent on the temperature;

The non-thermal universe



> **Thermal radiation**: thermodynamic equilibrium, Black Body spectrum dependent on the temperature;

> **Non-thermal radiation:** no equilibrium, power-law spectrum over several orders of magnitude in energy;

- any physical power law spanning tens of orders of magnitude in flux and energy?

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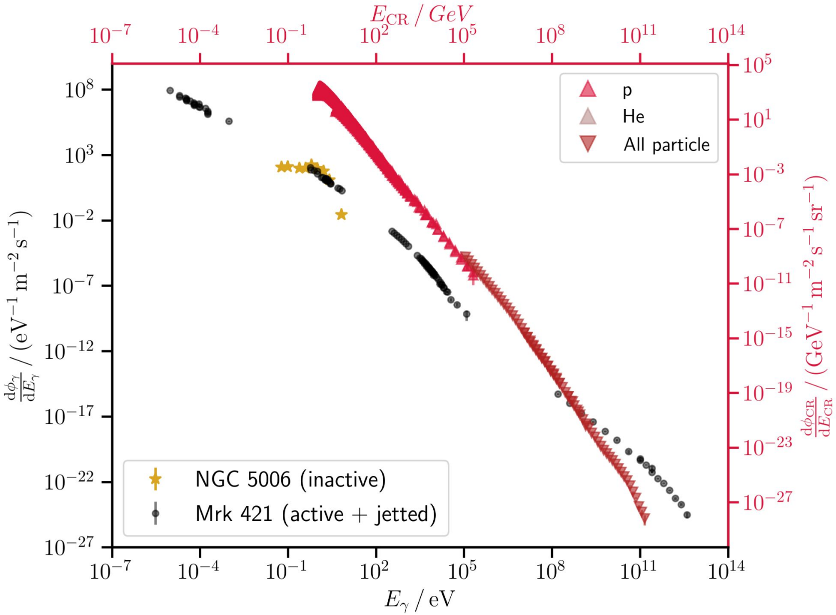

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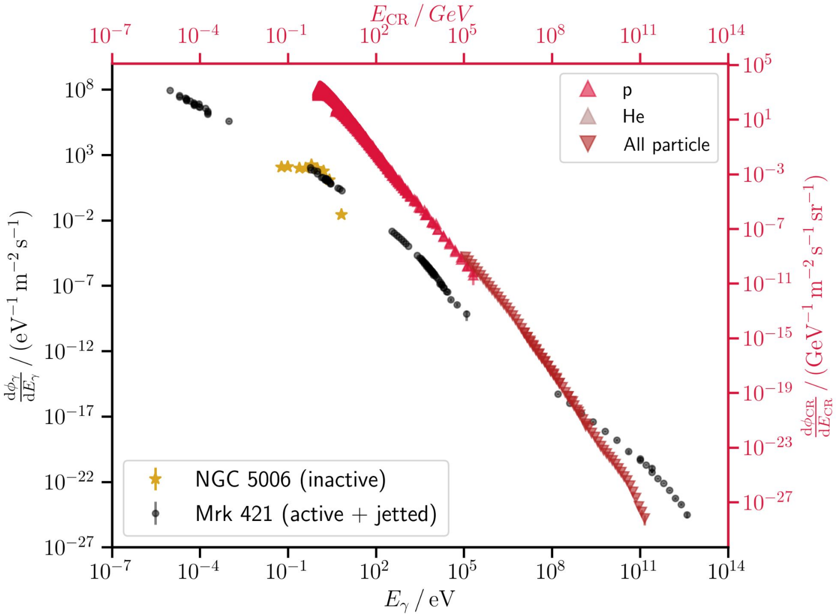
- any physical power law spanning tens of orders of magnitude in flux and energy? **COSMIC RAYS!**
- **power-law of photons $d\phi/dE \sim E^{-\Gamma}$ ⟺ radiation of power-law of relativistic particles $N(\gamma) \sim \gamma^{-p}$**;

The non-thermal universe



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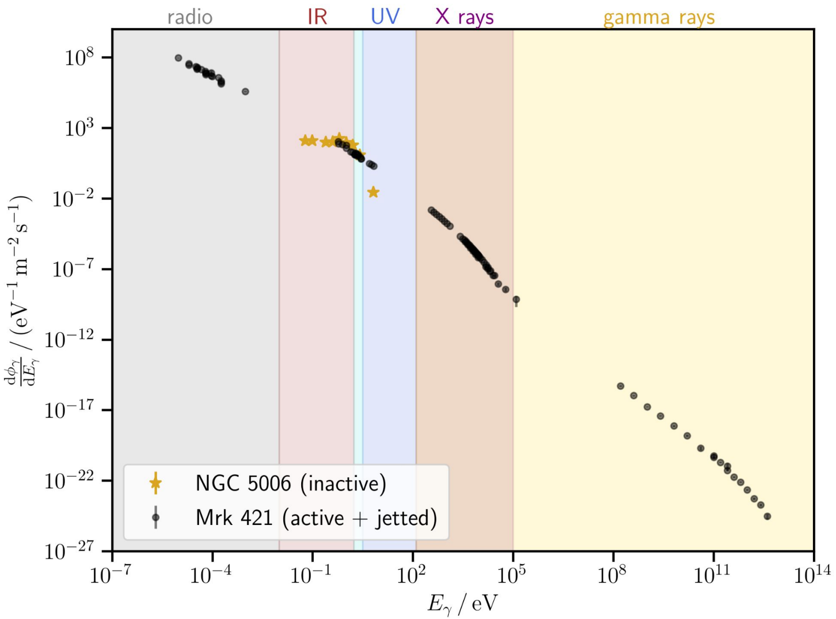
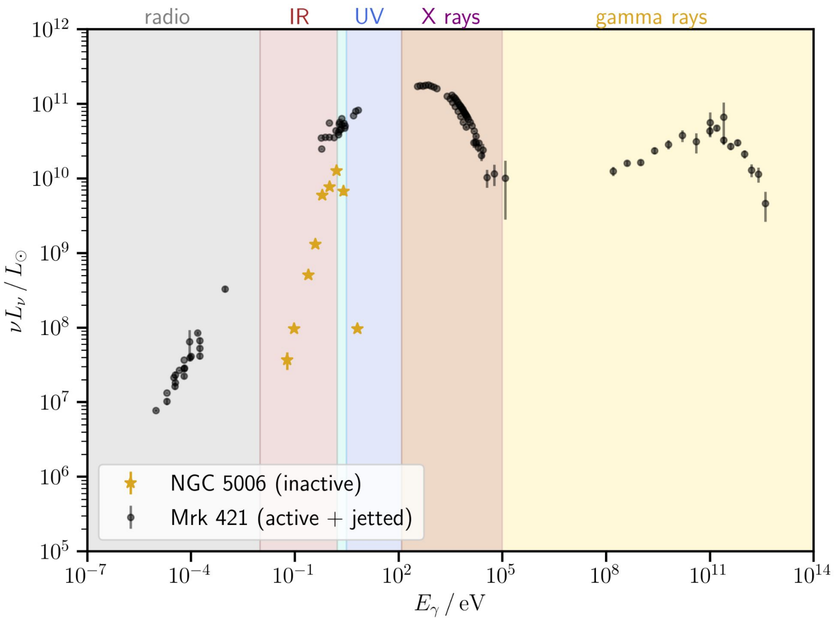
- **power-law of photons $d\phi/dE \sim E^{-\Gamma}$ ⇔ radiation of power-law of relativistic particles $N(\gamma) \sim \gamma^{-p}$**;
- astrophysical forges show us their work of acceleration **directly (CR)** or **indirectly (gamma)**;
- use non-thermal emission to infer the acceleration mechanisms.

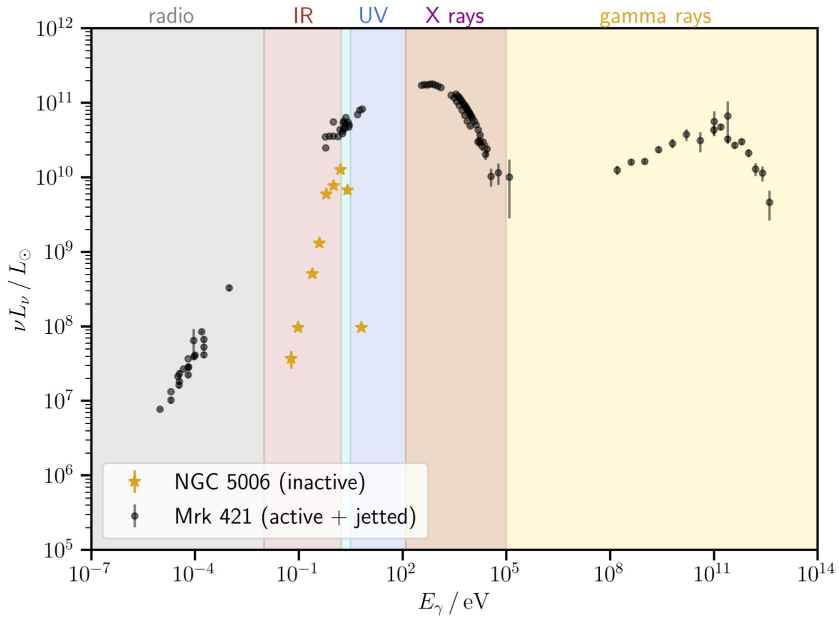
The non-thermal universe



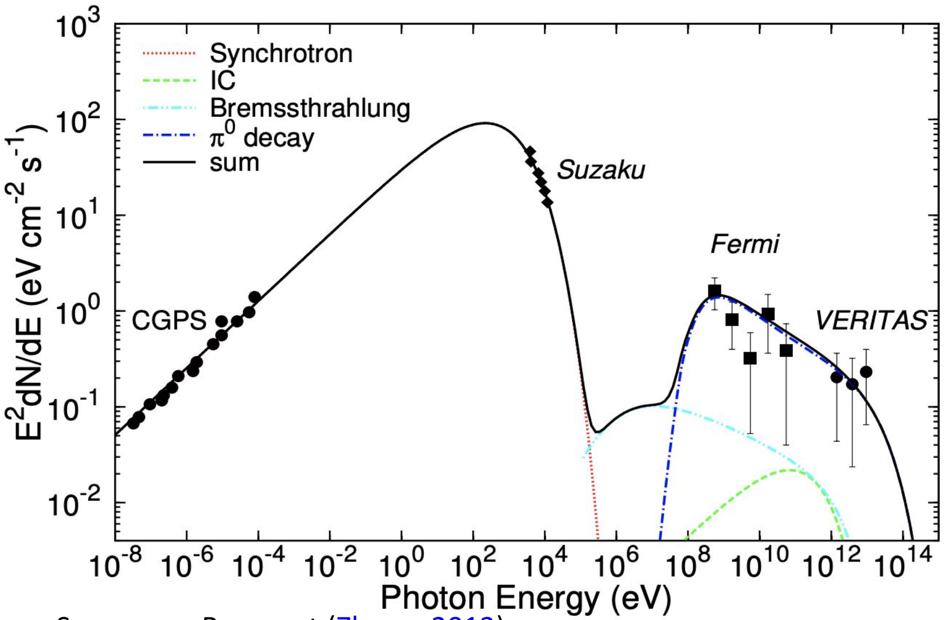


> **Differential flux** → **Spectral Energy Distribution:** power emitted across the electromagnetic spectrum;
> **astrophysical accelerators (forges) release roughly half of their EM energy in gamma-rays!**

The non-thermal universe



A galaxy with relativistic jets of plasma;



Supernova Remnant ([Zhang, 2013](#))

> Differential flux → Spectral Energy Distribution: power emitted across the electromagnetic spectrum;

> astrophysical accelerators (forges) release roughly half of their EM energy in gamma-rays!

> double-humped EM emission characteristic of all high-energy sources.

Gamma-ray Emission Processes

line

> **Nuclear / line processes**
- line emission: $A^* \rightarrow A + \gamma$;
- annihilation: $e^+ + e^- \rightarrow 2\gamma$ (511 keV line);

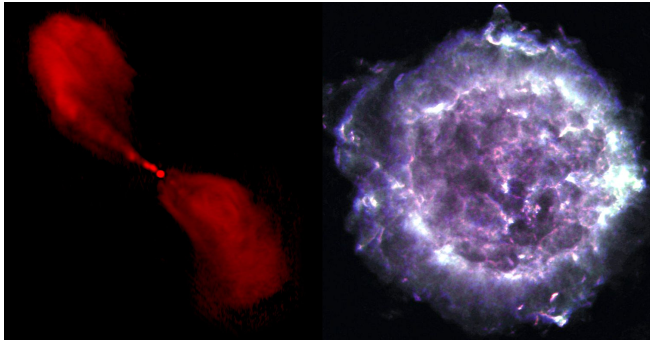
Non-thermal radiative processes, not directly associated with plasma dynamics.

continuum

> **E.M. processes**
- interactions with matter:
  - Bremsstrahlung: $e^\pm + N\ (e^\pm) \rightarrow e^\pm + N\ (e^\pm) + \gamma$;
- interactions with radiation and magnetic fields:
  - synchrotron radiation: $e^\pm\ (p) + B \rightarrow \gamma$;
  - inverse Compton $e^\pm + \gamma \rightarrow e^\pm + \gamma'$;
  - pair production $\gamma + \gamma \rightarrow e^+ + e^-$ (not radiative).

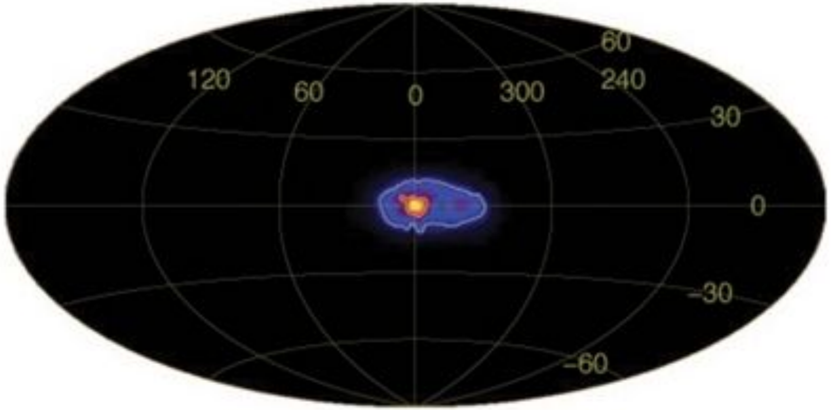
> **strong interactions**
- interactions with matter:
  - $p + p \rightarrow \pi^0 \rightarrow 2\gamma$;
- interactions with radiation fields:
  - $p + \gamma \rightarrow p + \pi^0 \rightarrow 2\gamma$
    $n + \pi^+ \rightarrow \ldots \rightarrow \nu$!

Non-thermal radiative processes "tracing" particle acceleration and plasma dynamics.

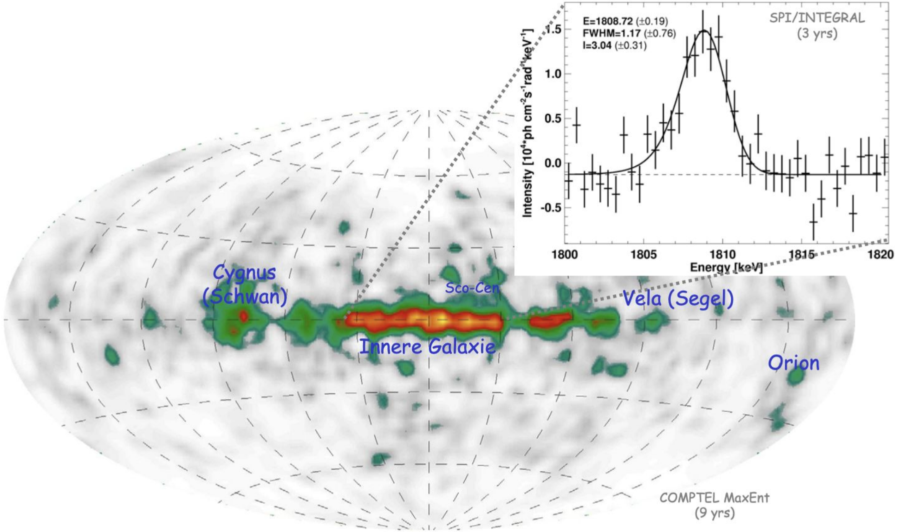


Astrophysical plasma seen through its synchrotron radiation (NASA/ESA).

Gamma-ray Line Emission



511 keV map of the Galaxy (INTEGRAL).



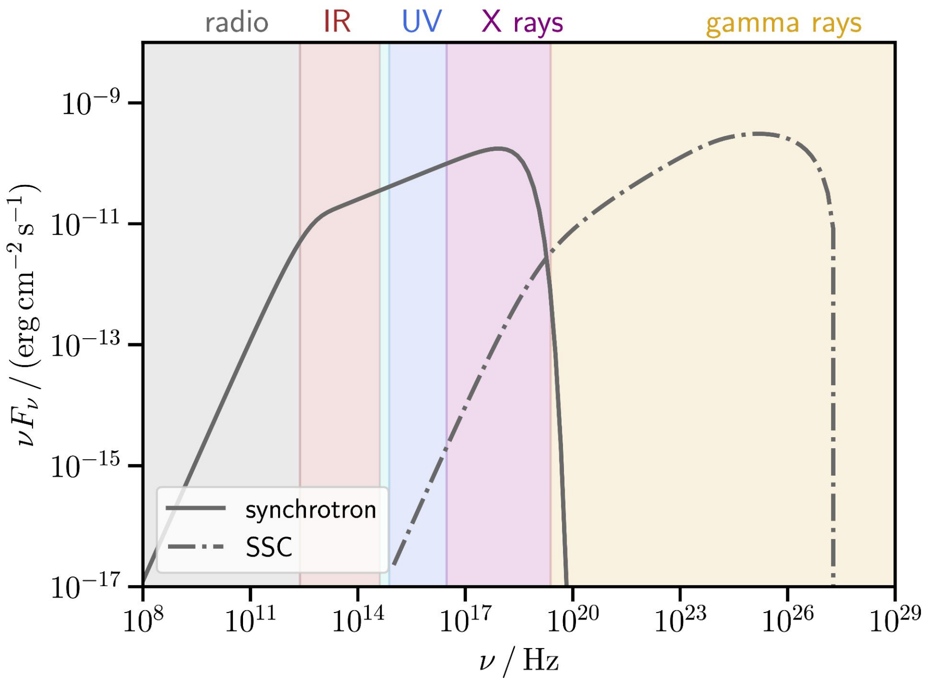
^{26}Al map of the Galaxy, COMPTEL + INTEGRAL, (Diehl, 2017).

> <u>511 keV positron-annihilation</u>. Origin: decay of isotopes, pair production near pulsars or BHs, CR interactions (p+p $\longrightarrow \pi^{+}$ + …), DM annihilation, …?

> <u>unstable radioactive isotopes</u> (^{26}Al, ^{44}Ti, ^{56}Ni, …). Origin: nuclear reactions within stars, exploding stars or stellar surface regions;

> positron annihilation and ^{26}Al line emission is **diffuse** ($\text{rate}_{\text{emission}} \gg \text{rate}_{\text{fading}}$), ^{26}Al can trace star formation and SNR explosion rate (estimate ~ 10^{-2} yr).

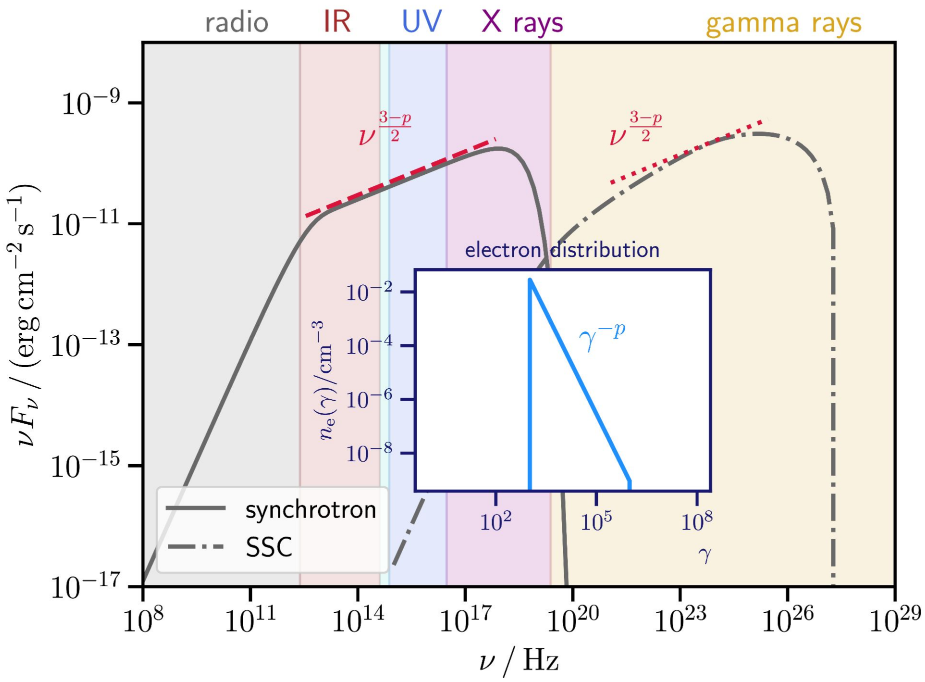
Gamma-ray Continuous Emission: EM processes



> Radiation of $e^{\pm}$ (synchrotron, inverse Compton, Bremsstrahlung) classical electrodynamics;

> one particle distribution modelling radio-to-gamma emission (both low- and high-energy bumps with different processes);

Gamma-ray Continuous Emission: EM processes



> Radiation of $e^{\pm}$ (synchrotron, inverse Compton, Bremsstrahlung) classical electrodynamics;

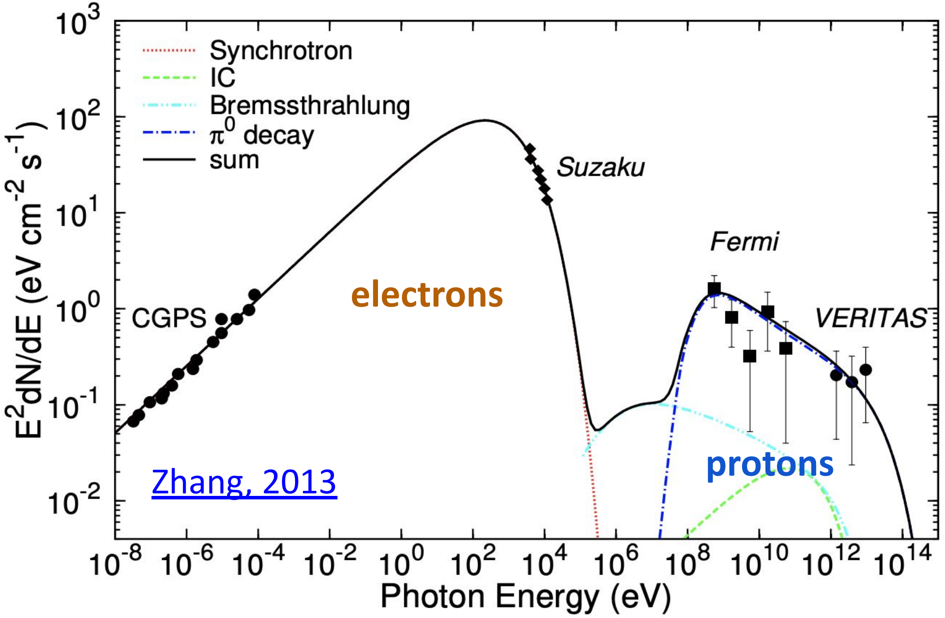
> one particle distribution modelling radio-to-gamma emission (both low- and high-energy bumps with different processes);

> we can always relate the measured photon index with the index of the particle energy distribution;

> $e^{\pm}$ do not reach us as CRs (especially for EGAL sources), lose all their energy in a few pc;

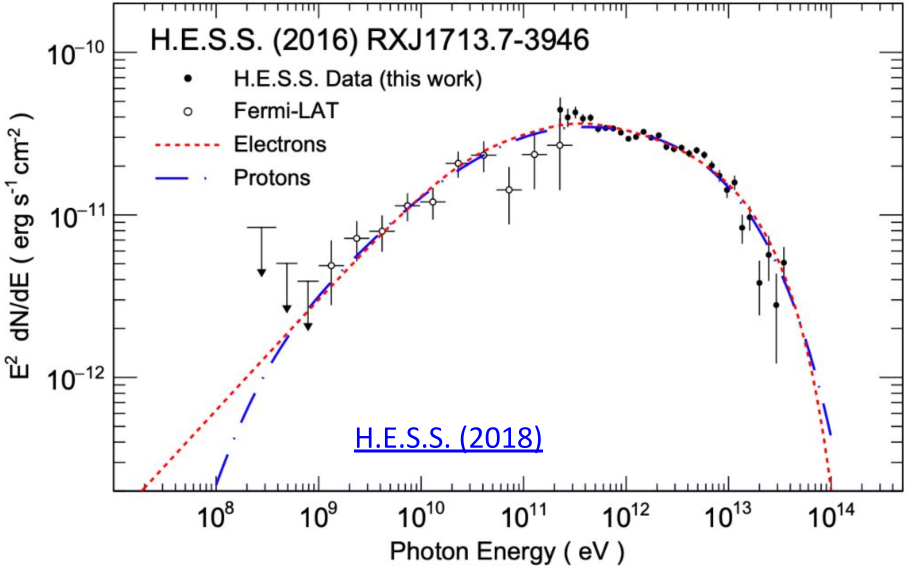
> **“cold” protons** still present in the bulk of the plasma, but not ultra-relativistic.

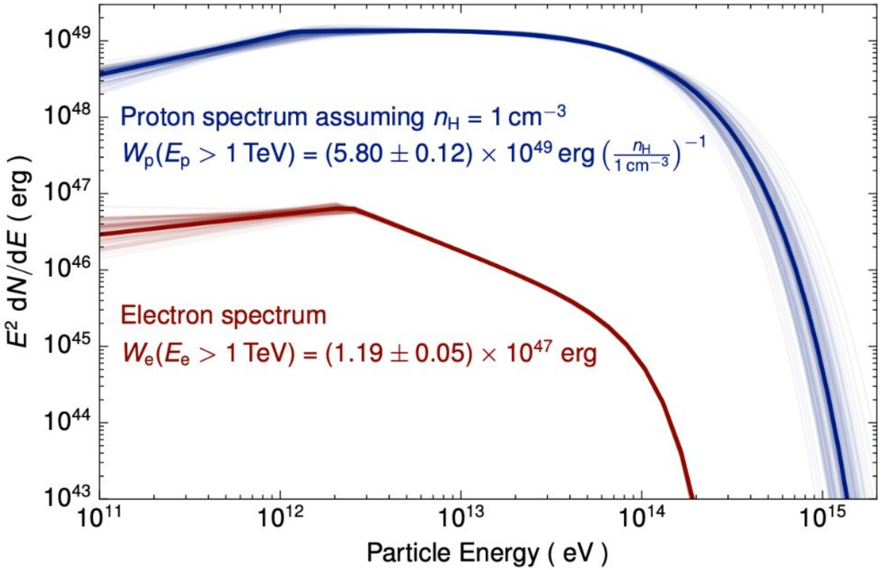
Gamma-ray Continuous Emission: hadronic processes (pp)



> For sources dense in surrounding matter (galactic sources e.g. SNR): p + p $\longrightarrow \pi^0 \longrightarrow 2\gamma$;
> can directly relate the radiating particle distribution (**ultra-relativistic p**) with the **CR**!
> need another ultra-relativistic particle population to explain the non-thermal radio-to-X emission;

Gamma-ray Continuous Emission: hadronic processes (pp)





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> can directly relate the radiating particle distribution (**ultra-relativistic p**) with the **CR**!

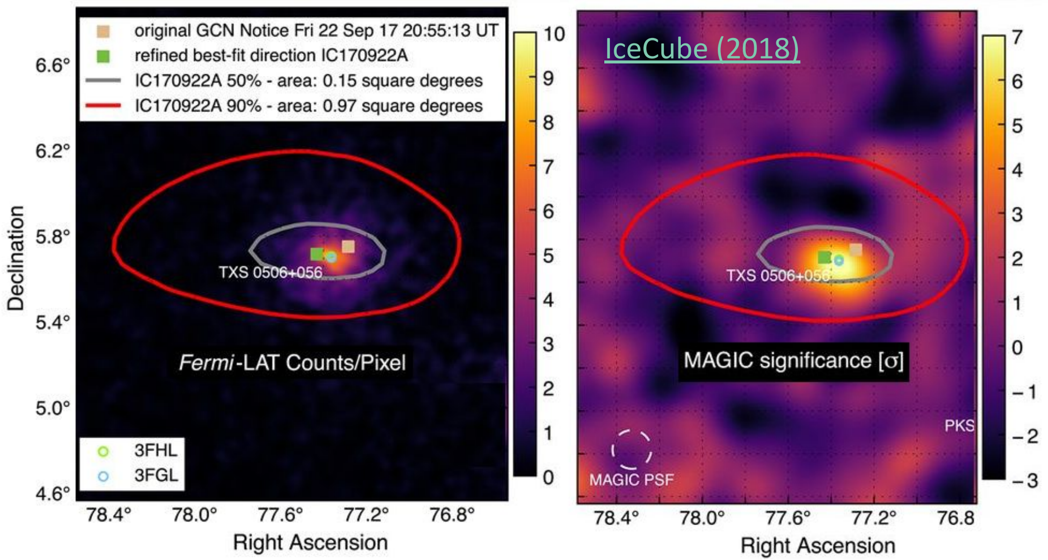
> need another ultra-relativistic particle population to explain the non-thermal radio-to-X emission;

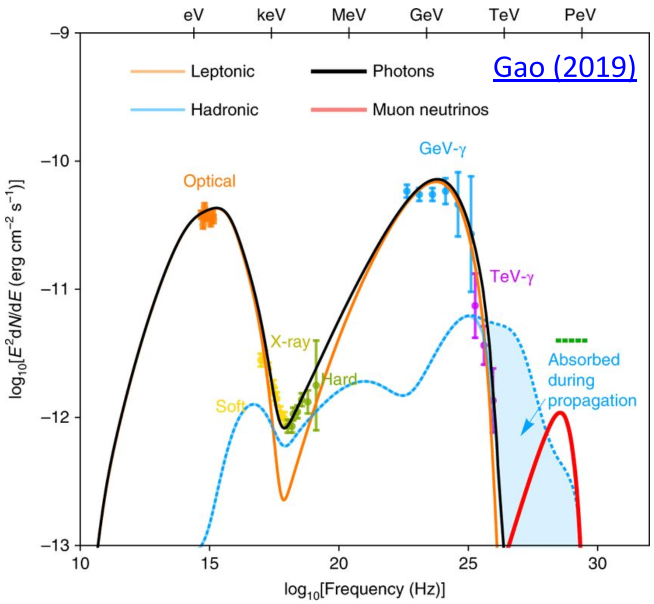
> for π^0 decay: $\mathbf{E_\gamma^{max} \approx 0.1\ E_p^{max}}$:

- if we observe gamma-ray emission up to 100 TeV, **we have found a PeVatron**;

> leptonic / hadronic dilemma: $e^\pm$ Bremsstrahlung can fit gamma spectra well as the π^0 bump.

Gamma-ray Continuous Emission: hadronic processes (pγ)





> For sources dense in surrounding photon fields (active galaxies): $p + \gamma \longrightarrow p + \pi^0$ $(n + \pi^+) \longrightarrow \ldots \longrightarrow \boldsymbol{\nu}$!;

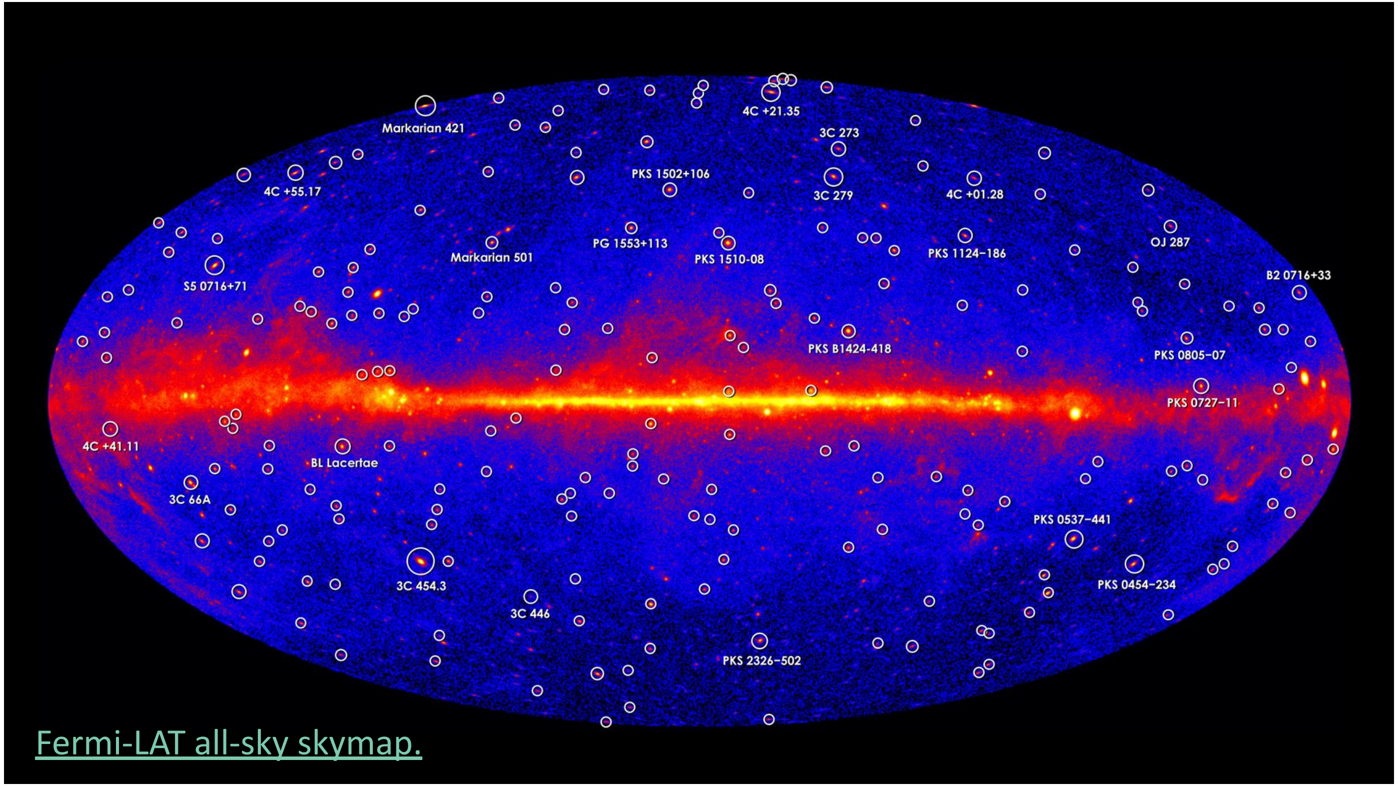
> can directly relate the radiating particle distribution (**ultra-relativistic p**) with the **CR**!

> can predict **high-energy neutrino cosmic fluxes** (multi-messenger astronomy);

> Sep. 2017: coincidence astrophysical neutrino with gamma-ray flare of active galaxy TXS 0506+056;

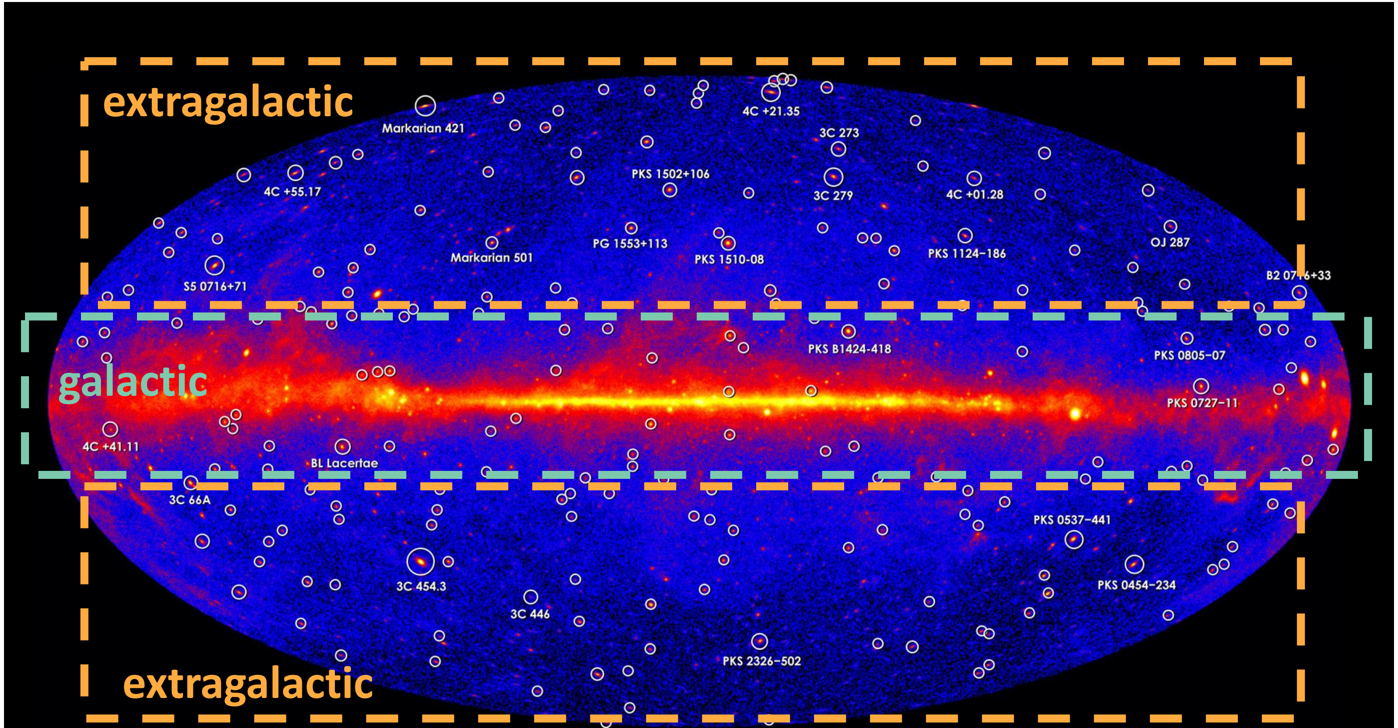
> consensus: if present, hadronic emission is sub-dominant.

Astrophysical gamma-ray sources



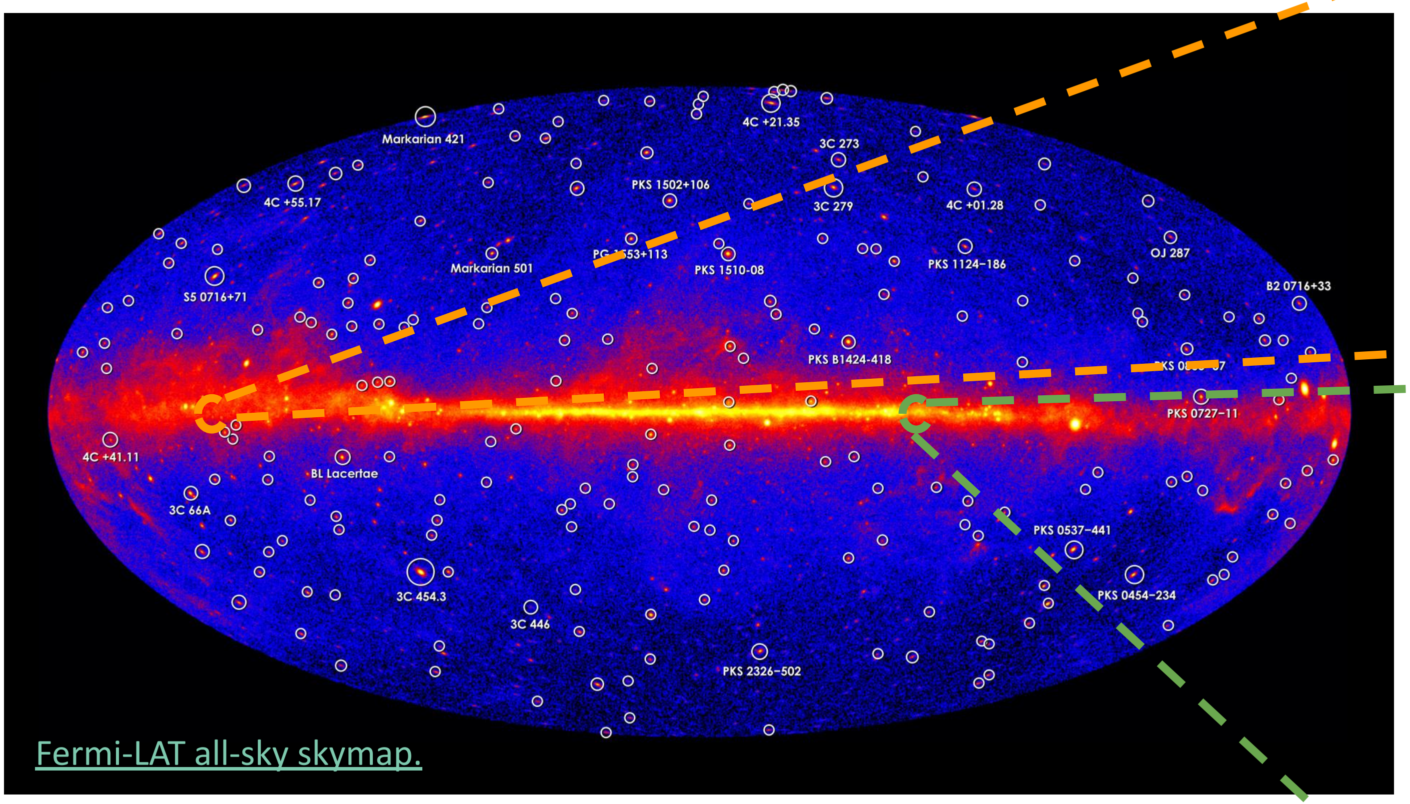
Fermi-LAT all-sky skymap.

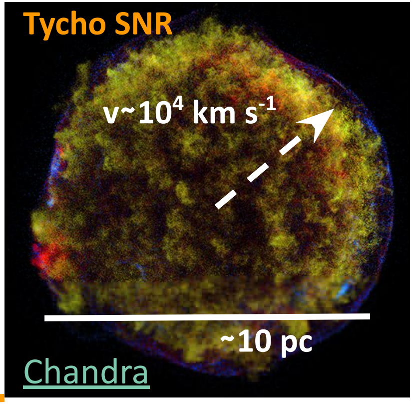
Astrophysical gamma-ray sources

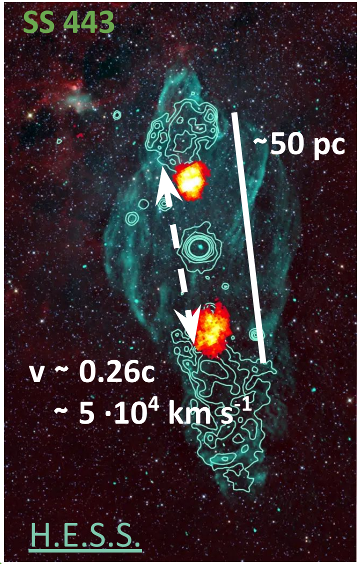


[Fermi-LAT all-sky skymap.]

Galactic gamma-ray sources



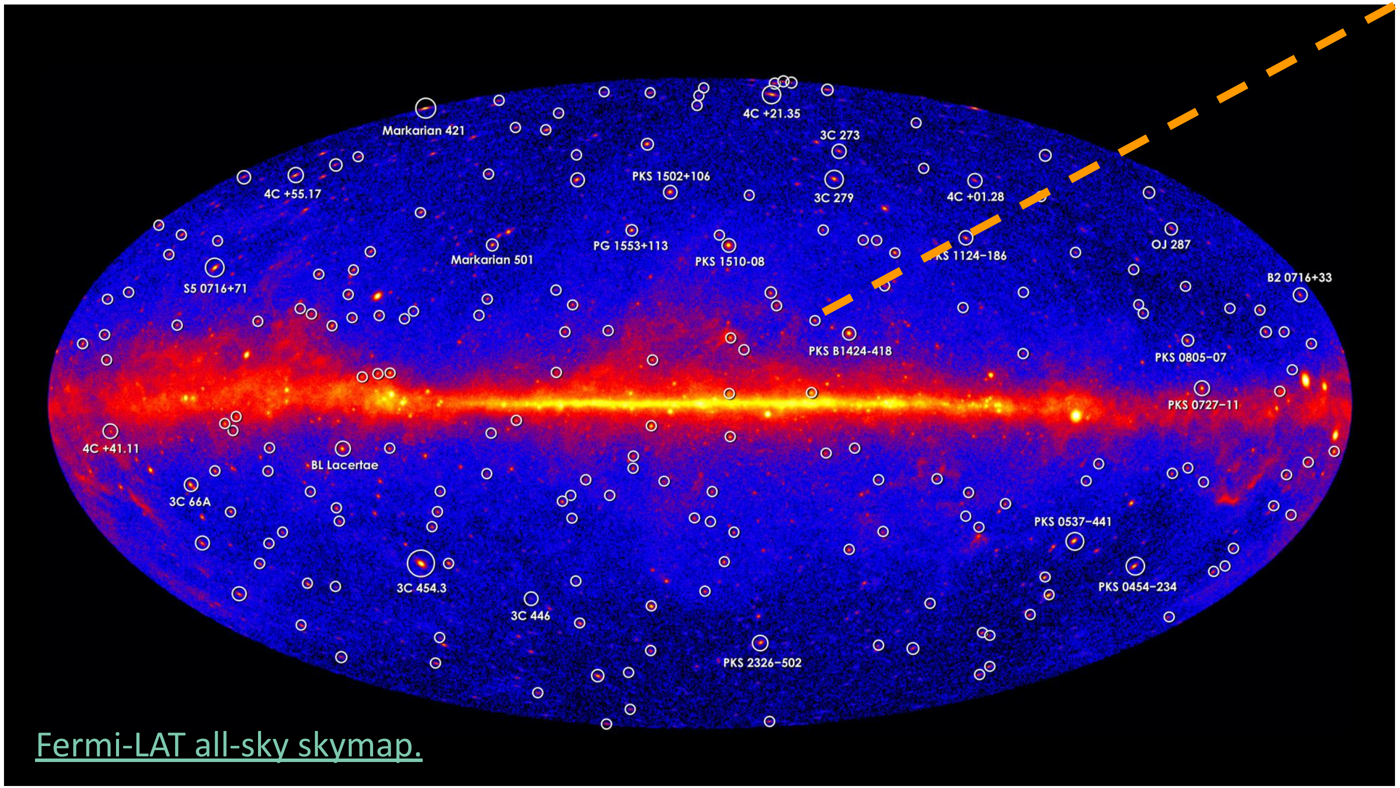




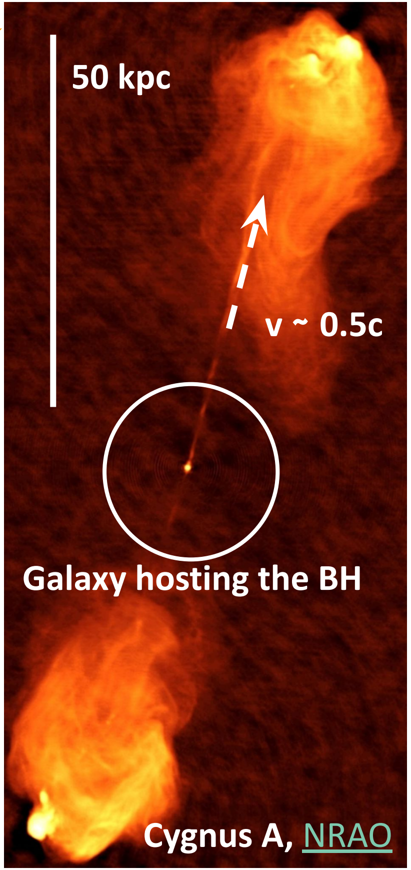
> **Galactic sources** [general - not absolute - characterisation]:

- non- or mildly relativistic plasma outflows;
- interaction of $e^{\pm}$ and p with their surrounding material (bremms, pp).

Extragalactic gamma-ray sources



Fermi-LAT all-sky skymap.

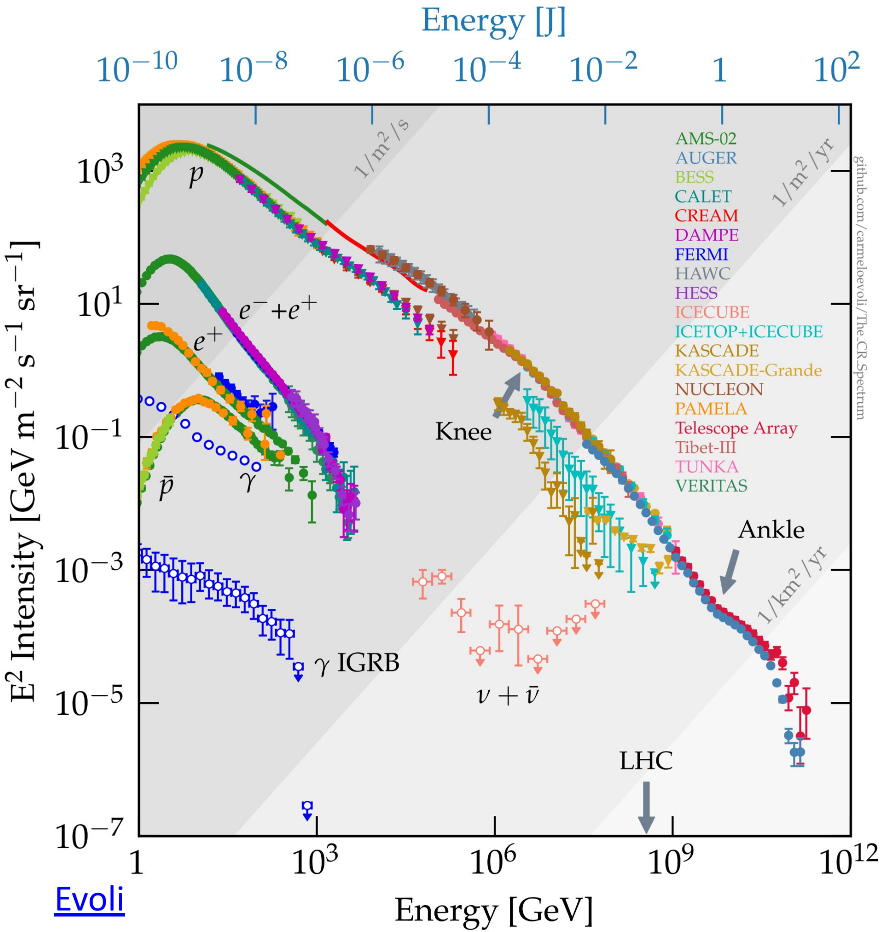


Cygnus A, NRAO

> **Extragalactic sources** [general - not absolute - characterisation]:

- highly relativistic and collimated plasma outflows (Doppler-boosted emission);
- interaction of $e^{\pm}$ and p with surrounding photon fields (inverse Compton, pγ).

The quest for cosmic accelerators

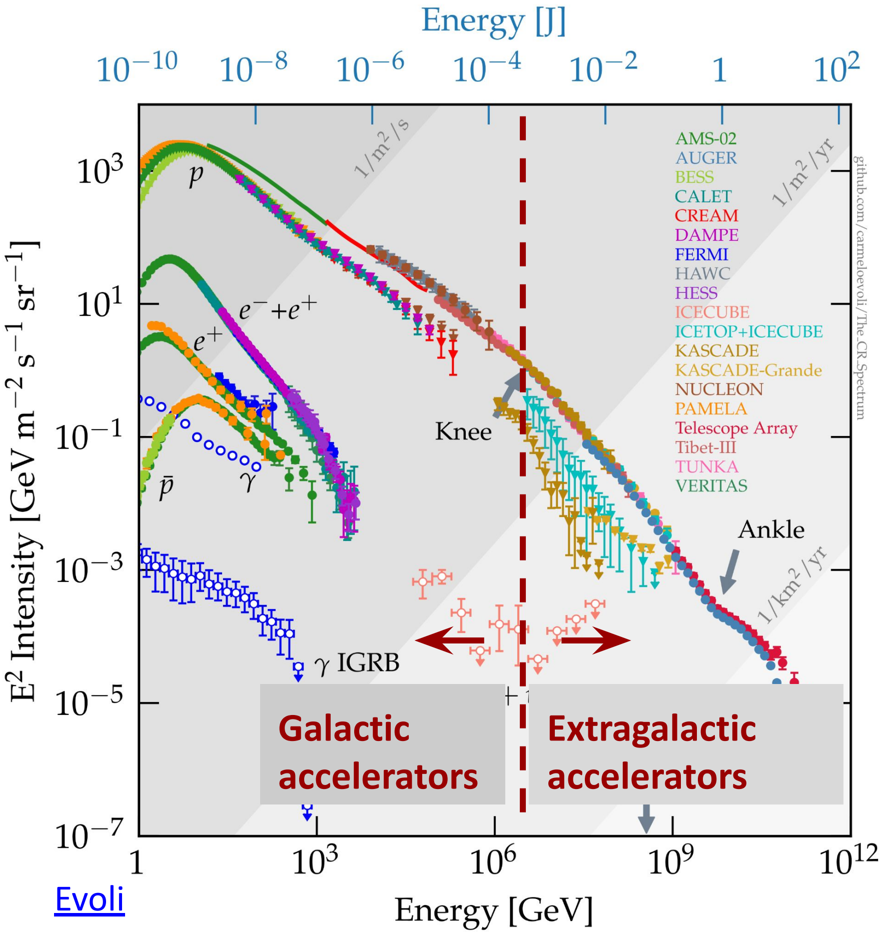


Evoli

> The CR spectrum is not a simple straight power-law;

> different spectral indexes correspond to different components ⟺ **different accelerators;**

The quest for cosmic accelerators



Evoli

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> different spectral indexes correspond to different components ⟺ **different accelerators;**

> Criterio de Hillas: $E_{\max} = Z \, \frac{U}{c} \left(\frac{B}{\mu\mathrm{G}}\right) \left(\frac{R}{\mathrm{kpc}}\right)$ EeV

acelerador	U/c	$B/\mu\mathrm{G}$	R/kpc	$E_{\max}$
shock supernova	0.01	4	$4 \cdot 10^{-3}$	100 TeV (~ knee)
shock AGN jet	0.5	10^{6}	10^{-5}	5 EeV (> ankle)

> the two different classes of gamma-ray emitters also correspond to different classes of cosmic ray accelerators.

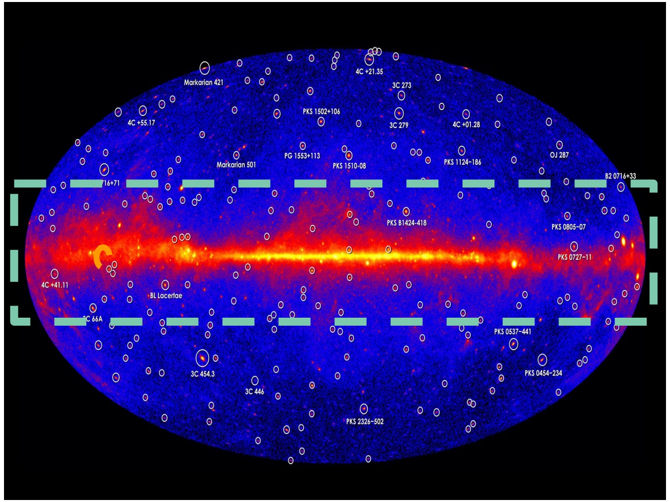
PART II: SCIENCE

2.2. Recent results in gamma-ray astronomy

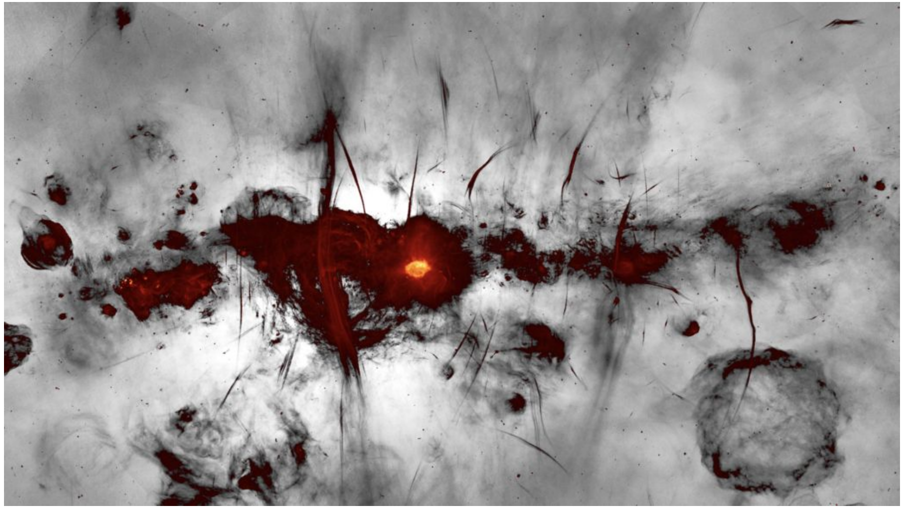
PART II: SCIENCE

2.2. Recent results in gamma-ray astronomy

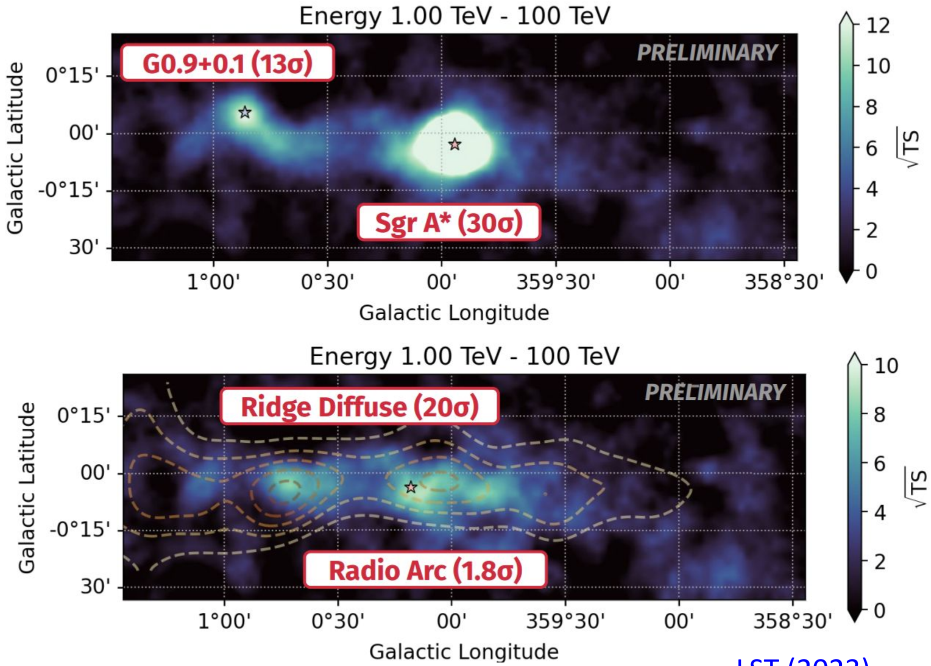
2.2.1 Galactic Science



The galactic centre (GC)



GC mosaic, MeerKAT (Heywood, SARAO).

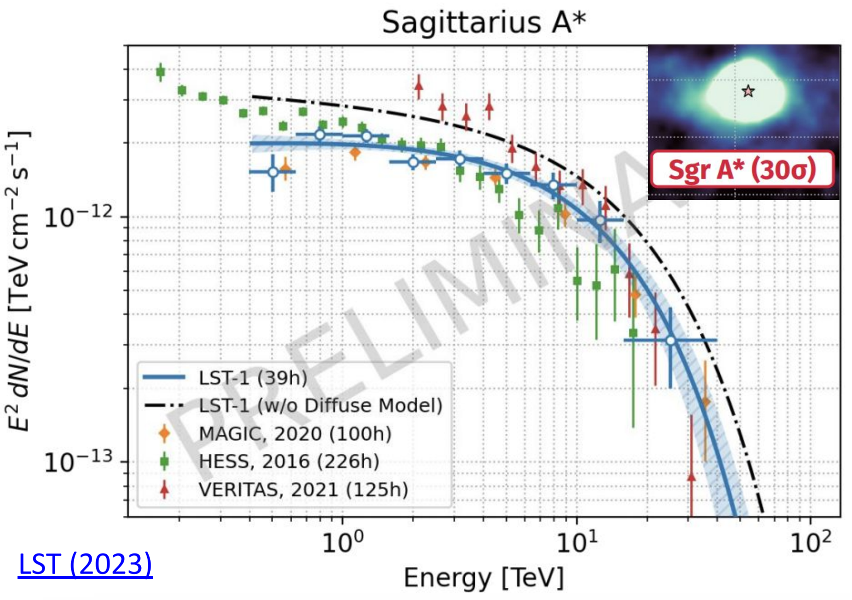


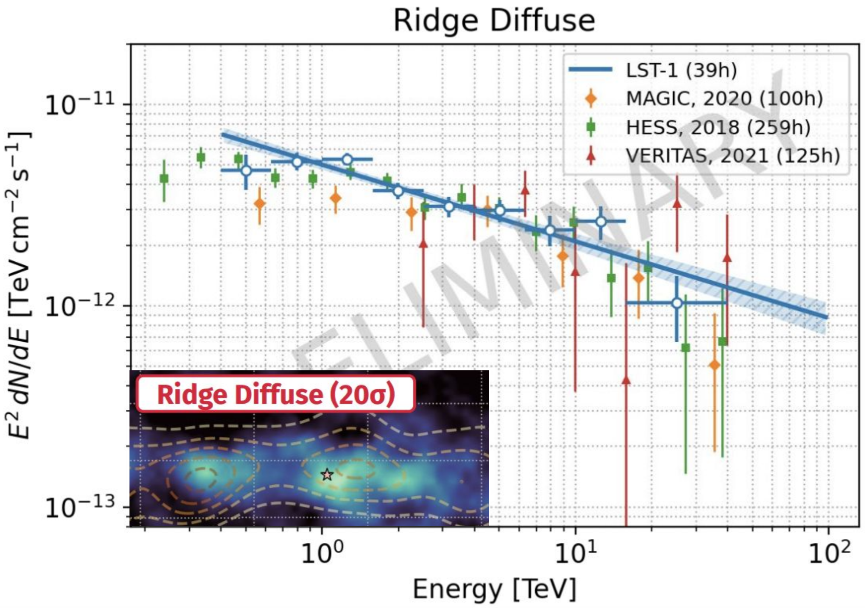
LST (2023)

> **GC area** of <u>paramount interest</u>:

- already surveyed by several VHE instruments, latest: 40h observation by CTAO's LST;
- TeV point-source 13" from **Sgr A*** (dynamical centre of our galaxy, $M_{BH} \sim 4 \cdot 10^6\ M_\odot$);
- diffuse gamma emission "below" two point sources: **ridge**;

The galactic centre (GC)

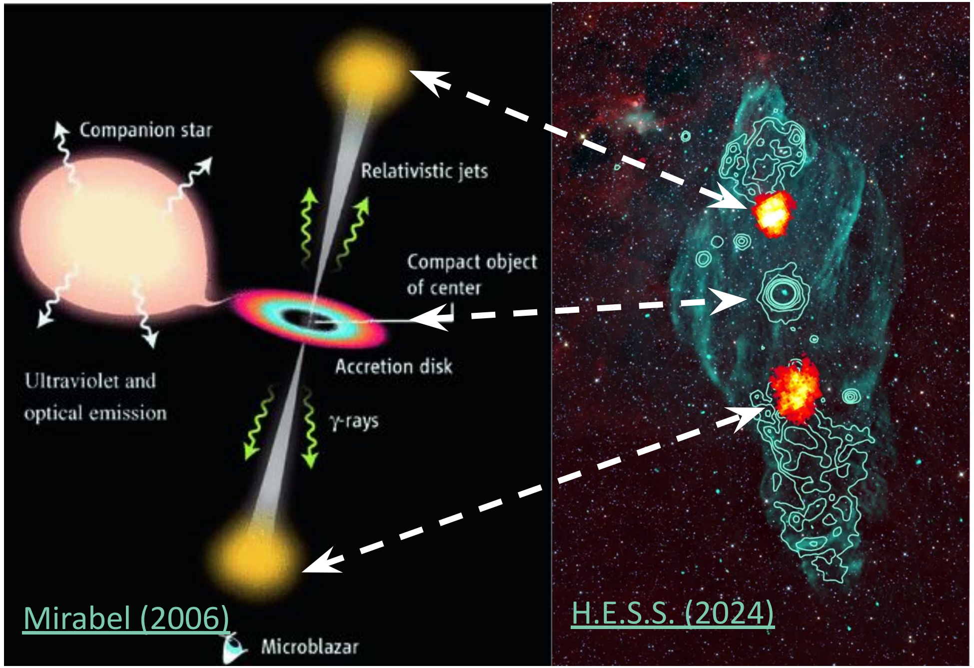




LST (2023)

> **GC area** of paramount interest:
- already surveyed by several VHE instruments, latest: 40h observation by CTAO's LST;
- TeV point-source 13" from **Sgr A*** (dynamical centre of our galaxy, $M_{BH} \sim 4 \cdot 10^6\ M_\odot$;
- diffuse gamma emission "below" two point sources: **ridge**;
- Sgr A* emission mechanism? (BH, interactions of CR w/ cluster of young stars);
- ridge emission: no cutoff or breaks up to 30 TeV! ⇒ acceleration of PeV cosmic rays?

Binaries: the microquasar SS 443



> **Binary system**: two stars gravitationally bound to each other:

- microquasar, NS or BH + companion massive star;
- SS433 detected at VHE by H.E.S.S.;

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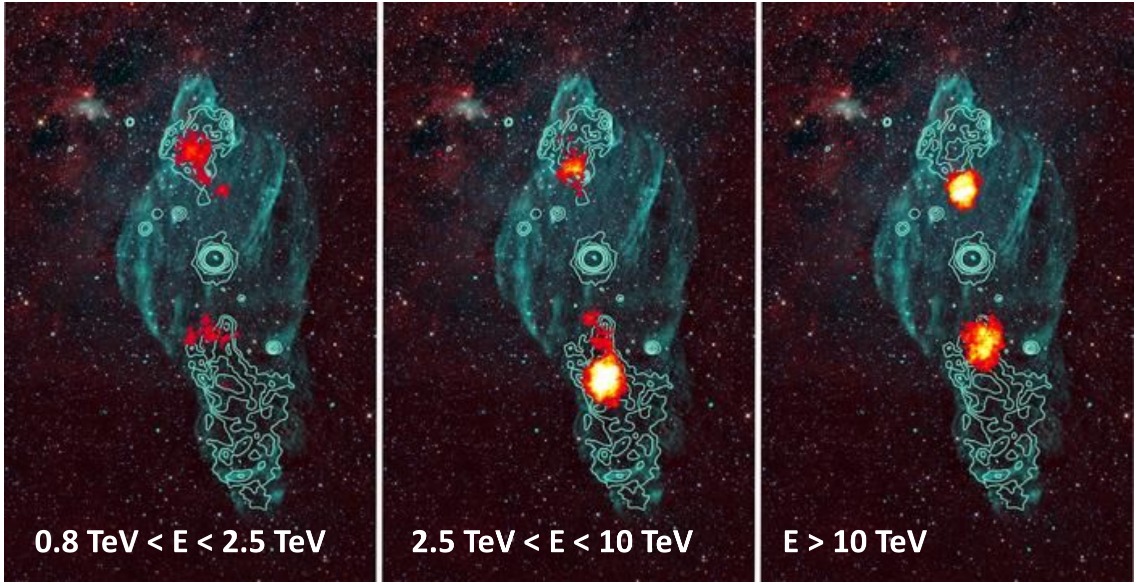
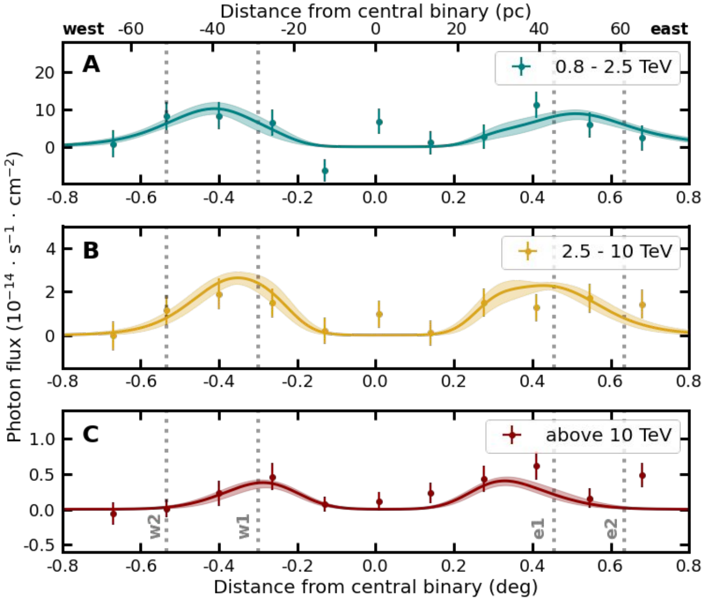


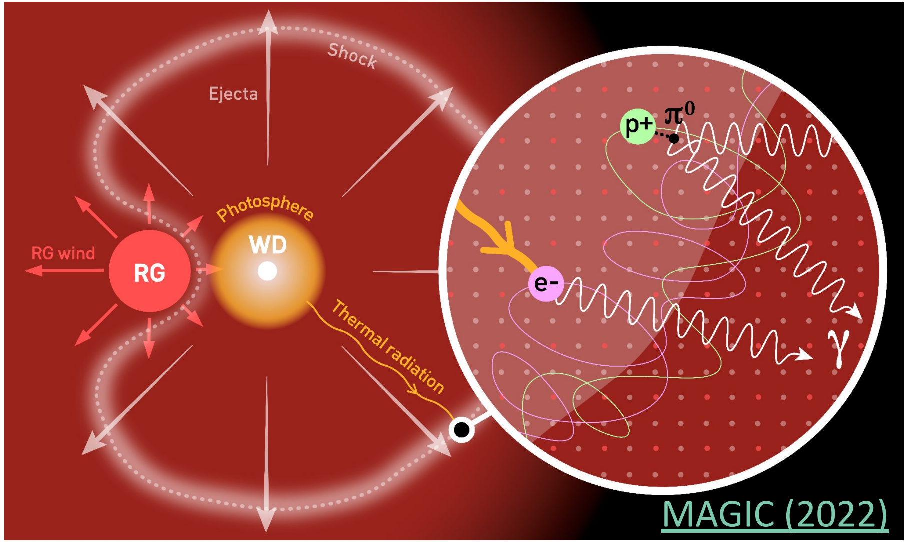


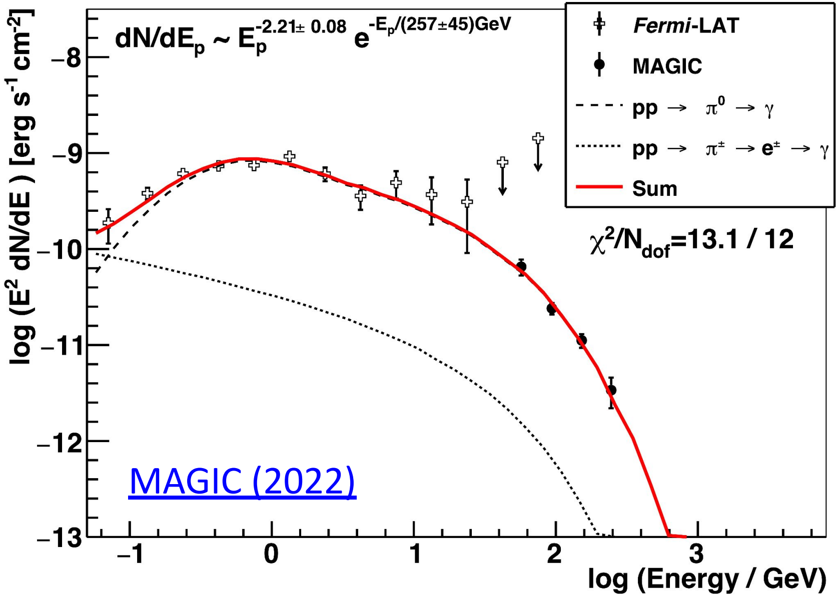
NRAO/AUI/NSF, WISE, ROSAT, H.E.S.S.

H.E.S.S. (2024)

> **Binary system**: two stars gravitationally bound to each other:
- microquasar, NS or BH + companion massive star;
- SS433 detected at VHE by H.E.S.S.;
- **energy-dependent morphology, first-ever observed in the gamma emission of an astrophysical jet**;
- simple model of electrons transported in the jet and radiating via inverse Compton.

Novae in VHE gamma rays





> Cataclysmic binary star systems (recurrent Novae):

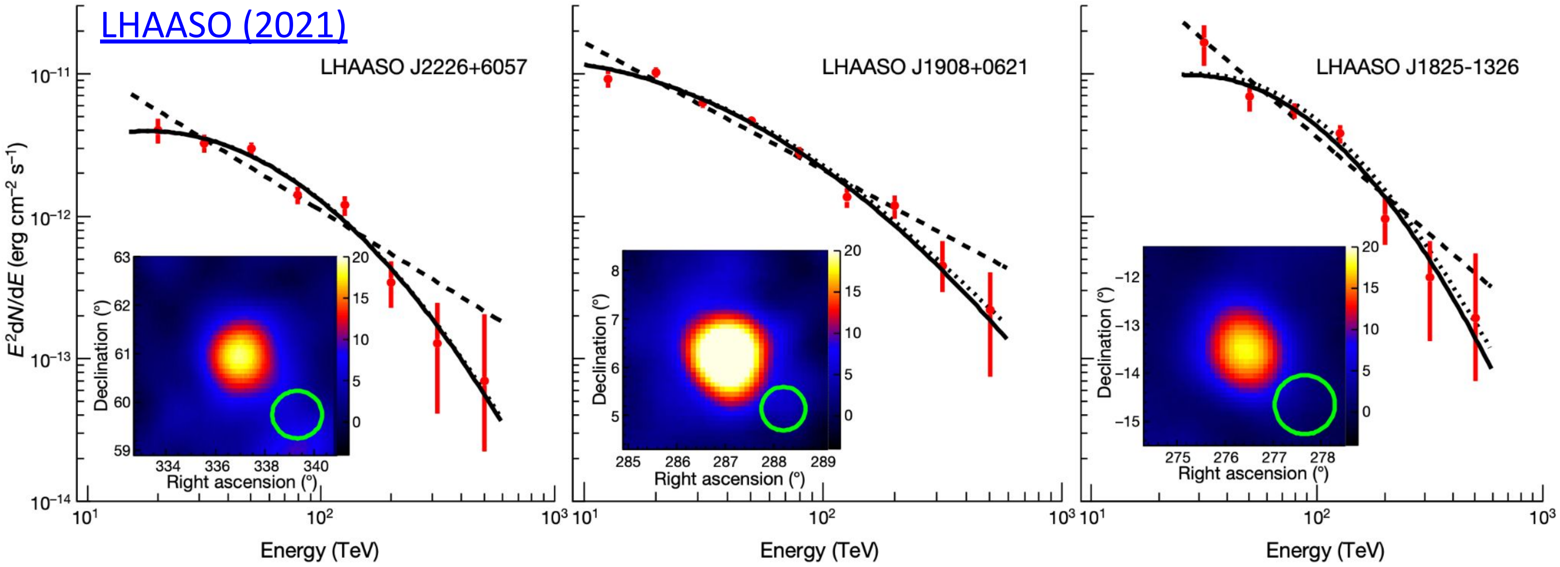
- matter accreted on a white dwarf (WD) by a companion red giant (RG);
- accumulation of H in a layer causes a thermonuclear explosion on the surface of the WD,
- brightening to $10^5\ L_\odot$ and triggering ejection of the accumulated material.

> First detection at VHE by H.E.S.S. and MAGIC of the Nova RS Oph;

> modelling: protons accelerated to hundreds of GeV in the nova shock;

> **not a significant contributor to the galactic CR power**: $5 \cdot 10^{43}$ erg $\times$ 50 year^{-1} $\approx$ 1% P_{CR}.

LHAASO detects emission from galactic sources > 100 TeV!



> In less than a year, incomplete configuration, **LHAASO detected 12 GAL sources above 100 TeV**:

- did we finally find the PeVatrons?
- some known VHE emitters, many unidentified;
- many sources spatially correlated with leptonic accelerators (PWNe);

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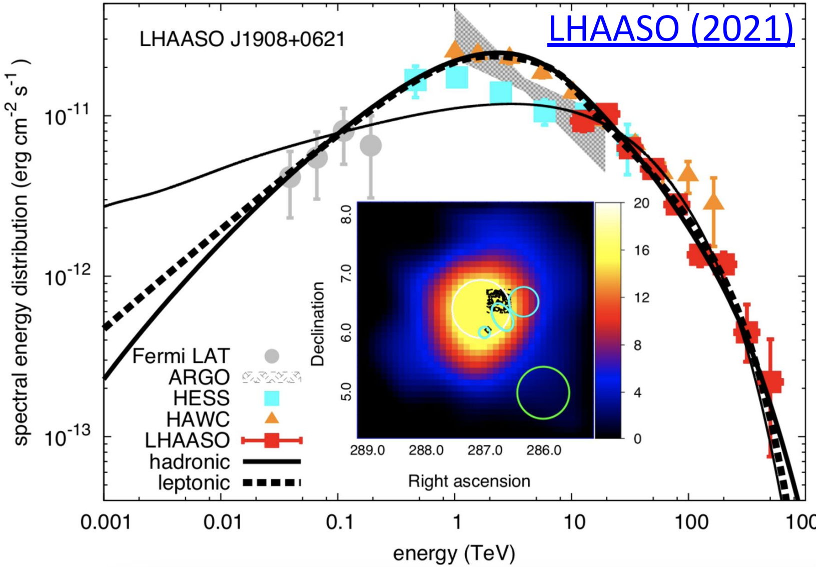

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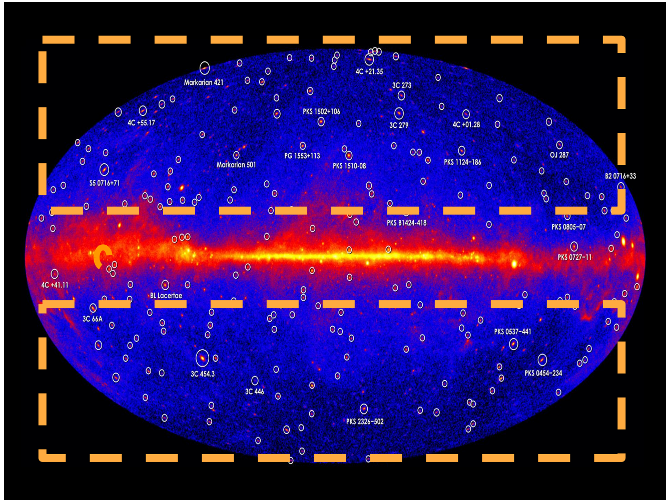
- did we finally find the PeVatrons?
- some known VHE emitters, many unidentified;
- many sources spatially correlated with leptonic accelerators (PWNe);
- leptonic / hadronic dilemma for many sources!

> First LHAASO catalogue: 43 galactic sources detected by LHAASO at E > 100 TeV.

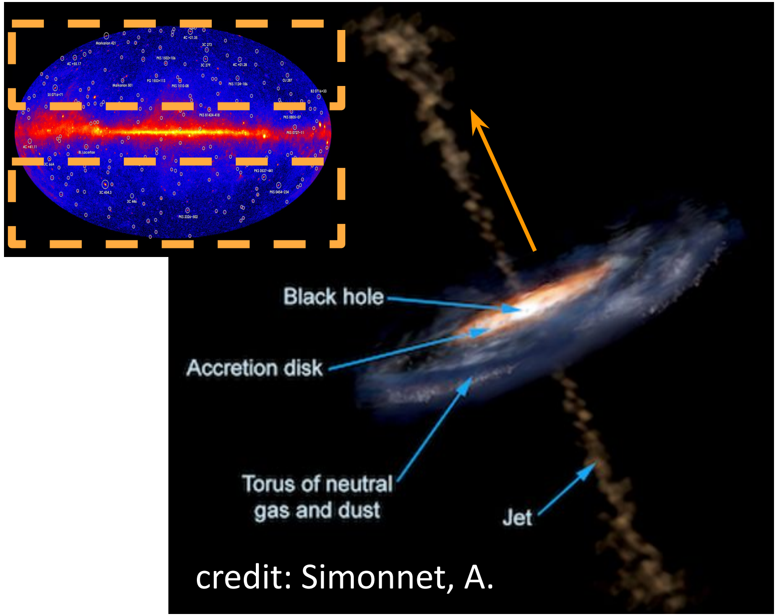
PART II: SCIENCE

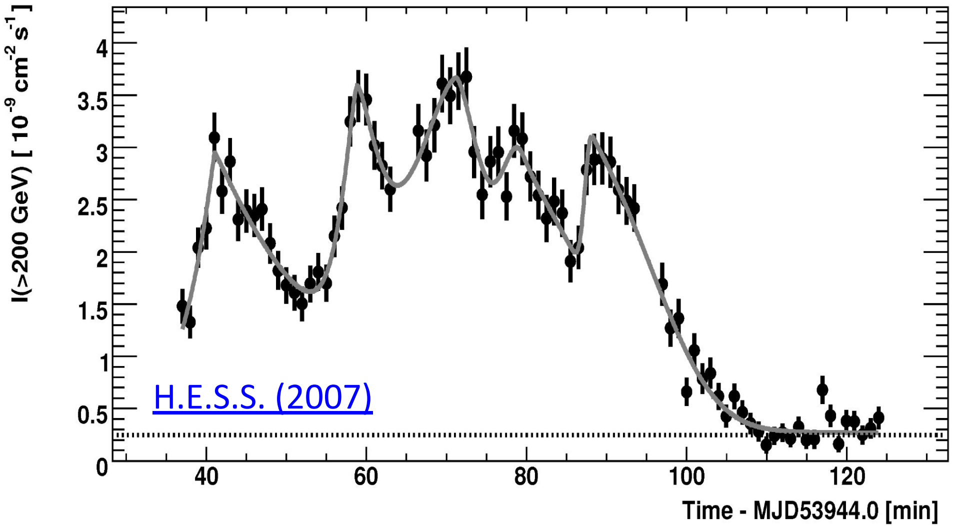
2.2. Recent results in gamma-ray astronomy

2.2.1 Extragalactic Science



Active galaxies: understanding the structure of the jet





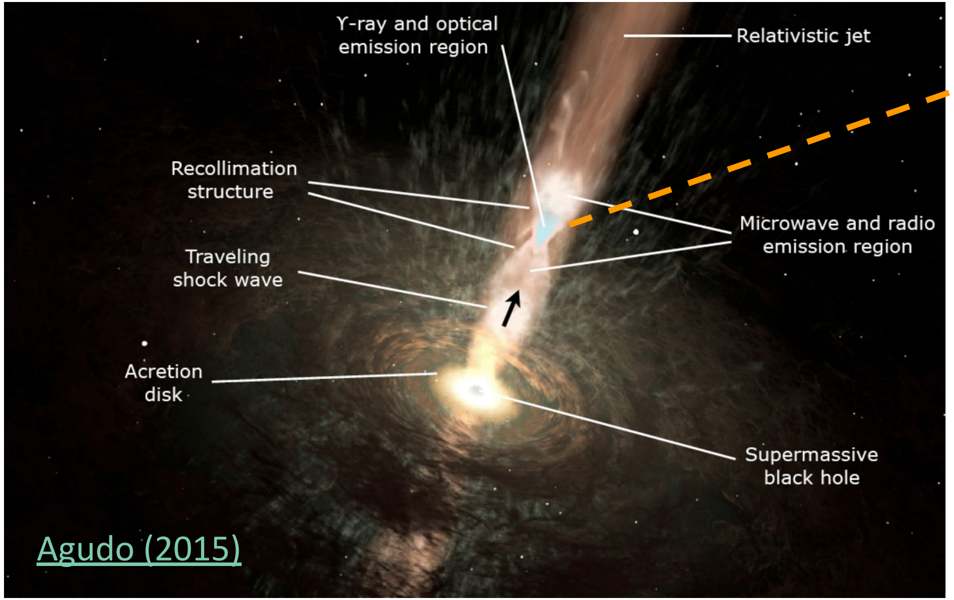
> Active galaxies with jets dominate the gamma-ray sky:
  - 1856/5064 sources detected at HE, 90 / 308 sources detected at VHE;

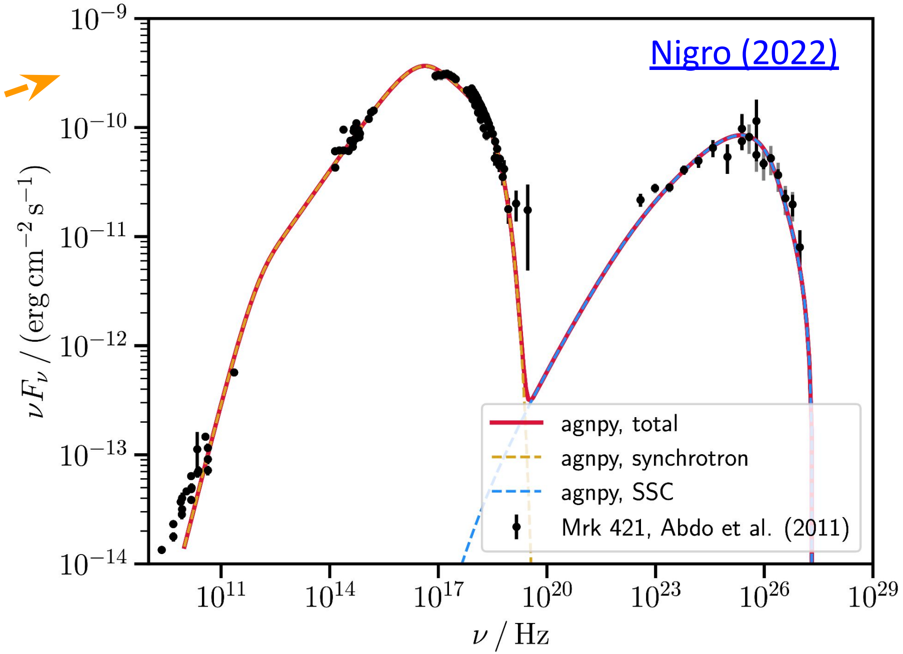
> most powerful persistent forges in the Universe (L $\gtrsim 10^{45}$ erg s^{-1});

> bulk of the jet moving at relativistic speed ⇒ Doppler boost of their emission;

> very fast variability in gamma rays, $t_{var} \gtrsim 10$ min ⇒ $R_{\rm em} \sim c\delta_{\rm D} t_{\rm var}/(1+z) \underset{\delta_{\rm D}=10,\, z=0.1}{\sim} 10^{-4}\,{\rm pc} \ll d_{\rm jet}$

Active galaxies: understanding the structure of the jet





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> leptonic radiation from a spherical emission / acceleration region.

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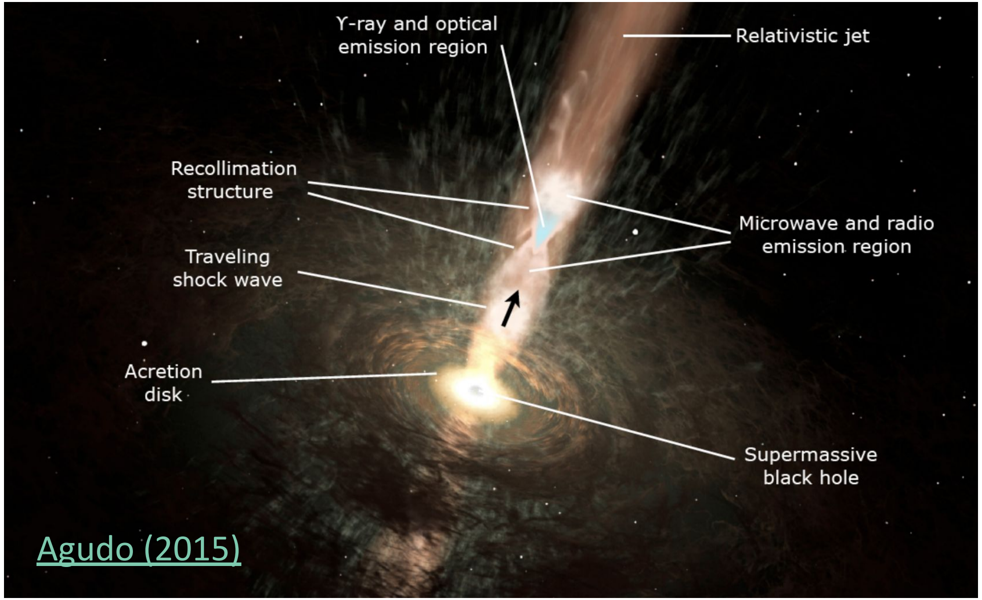

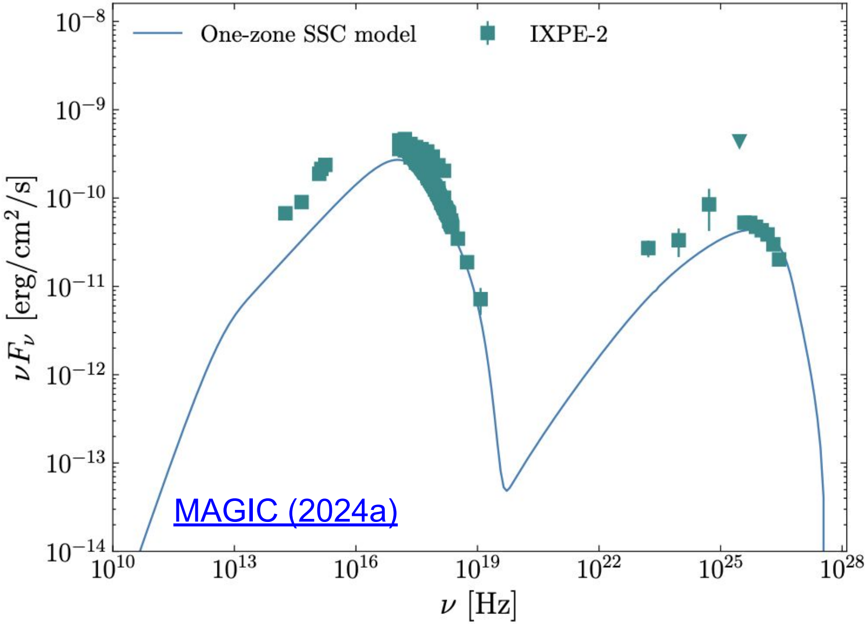

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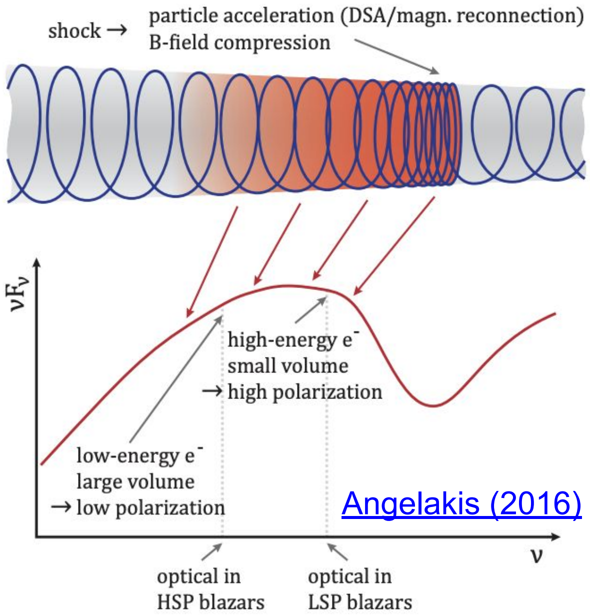
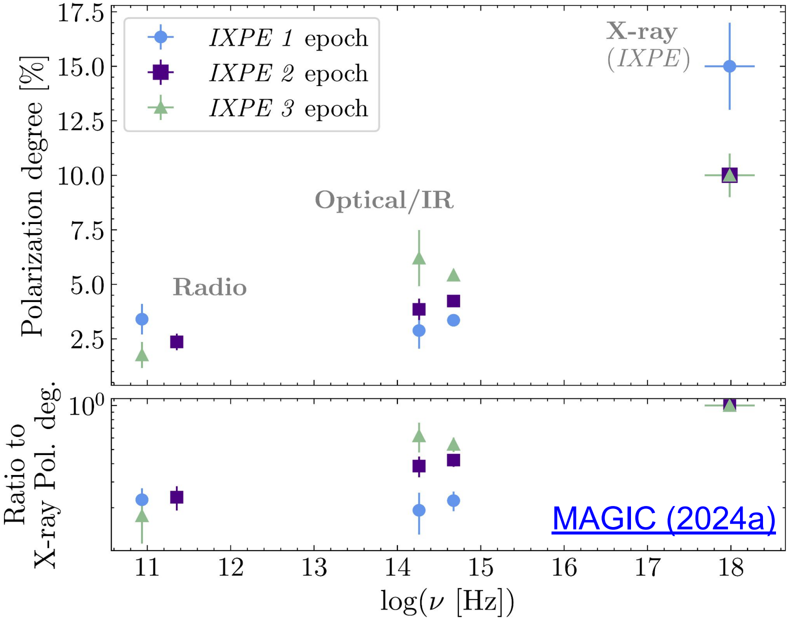
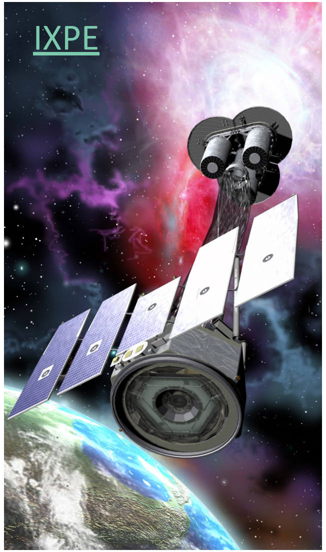
MWL Polarisation measurements and the jet structure



[Angelakis (2016)](#)



[MAGIC (2024a)](#)



> **EM emission is polarized**:

- synchrotron, up to ~70-75% in ordered **B**, much less if **B** turbulent;

> IXPE (X polarimetry) data: X rays produced in a region w/ higher polarisation ⇒ region of more ordered **B**;

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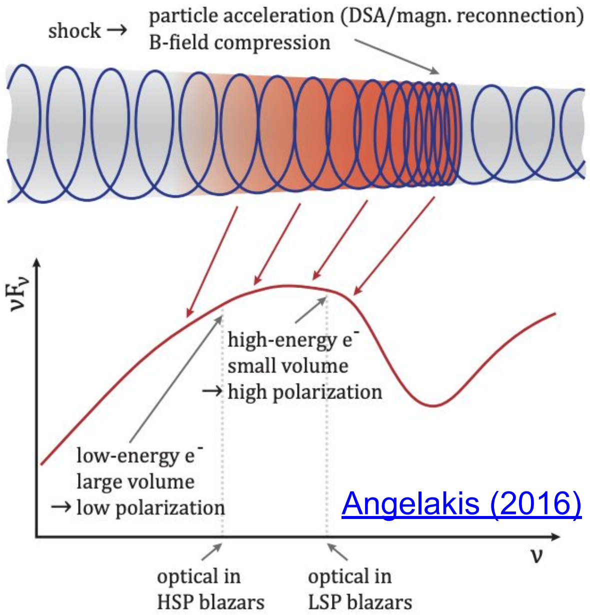
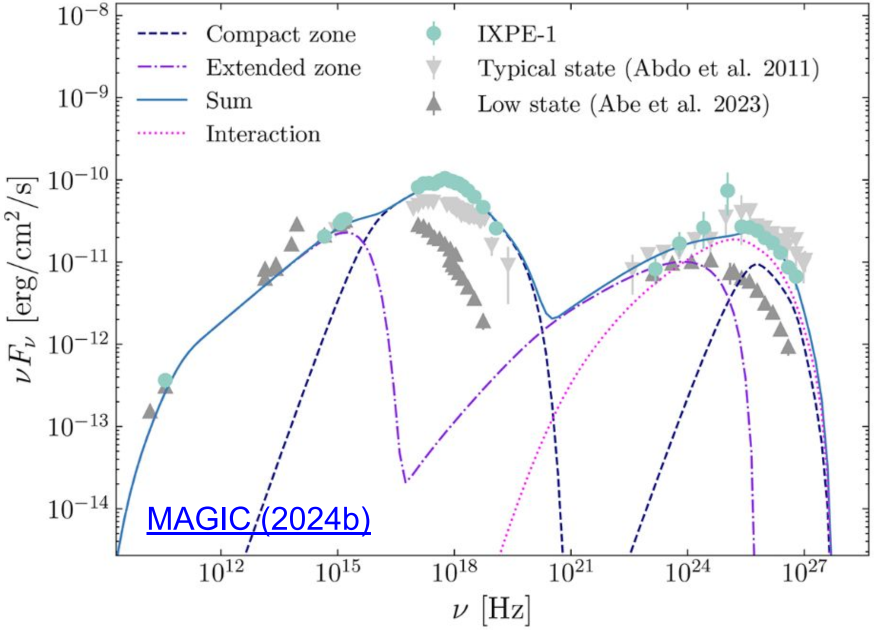


[Angelakis (2016)]



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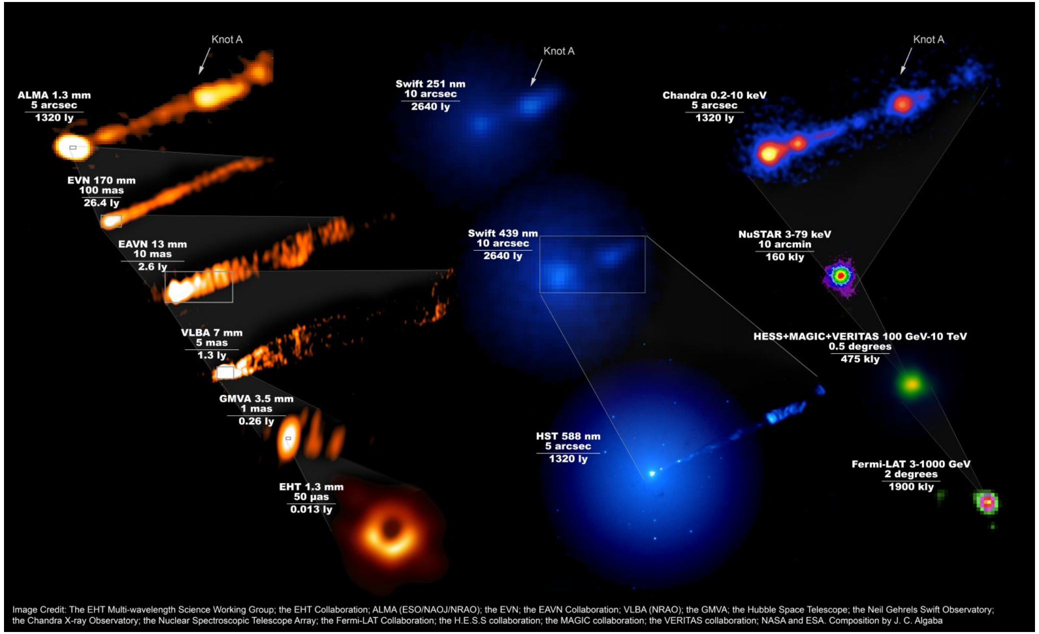
> IXPE (X polarimetry) data: X rays produced in a region w/ higher polarisation ⇒ region of more ordered **B**;

> broad-band model: necessity for model with more than a simple spherical acceleration / emission region:
- compact zone: nearby shock front, dominates X-ray and VHE gamma-ray emission;
- extended zone: larger extent downstream the shock; dominates the optical/UV emission.

Extended emission from Cen A



> Jetted AGN appear in gamma as point sources (too far);

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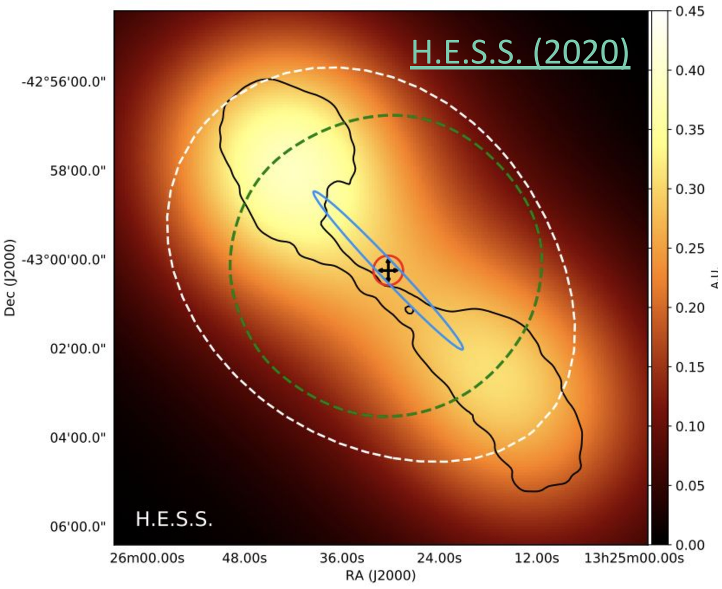
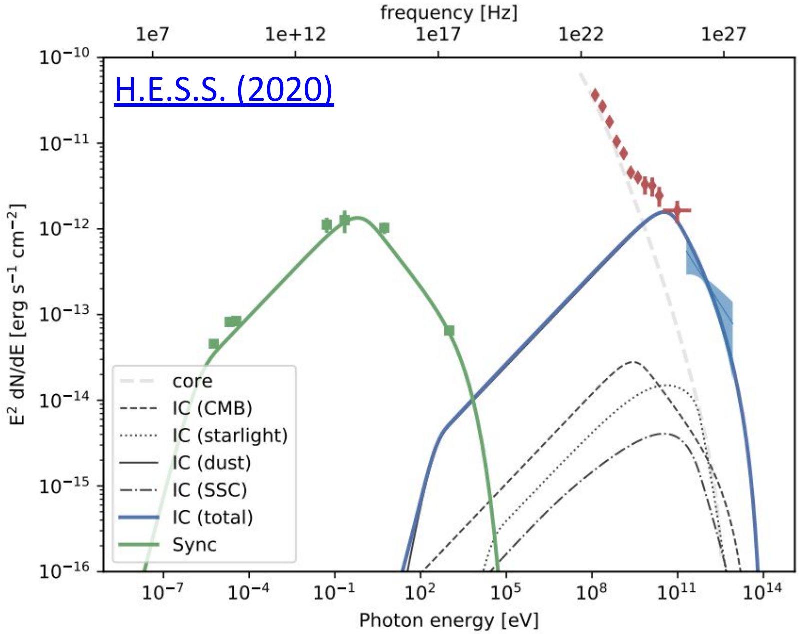




> Jetted AGN appear in gamma as point sources (too far);

> **H.E.S.S. detected the extension of a Cen A,** (one of the closest jetted AGN, closer than M87);

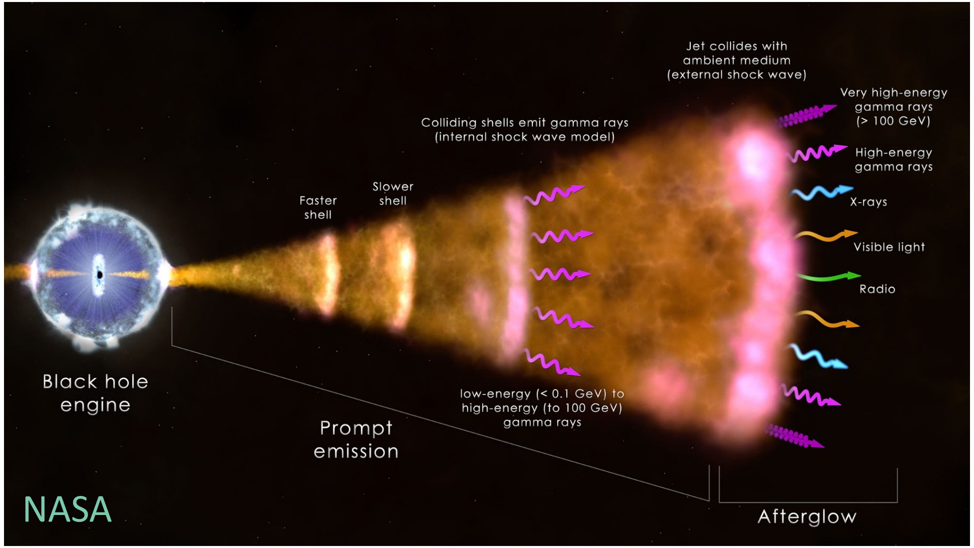
> particle acceleration not confined to the immediate vicinity of the AGN, can occur along the entire jet;

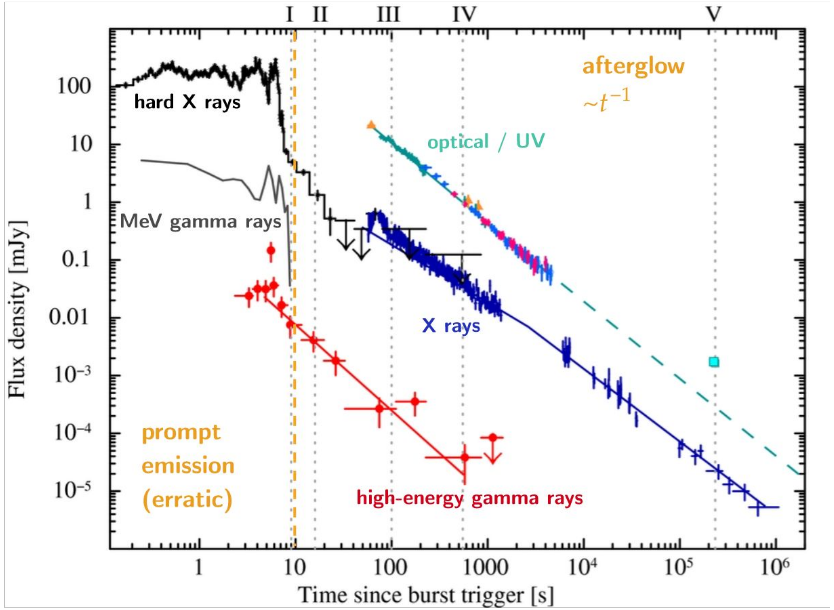
- at odds with inference from shortest variabilities (gammas from a section of the jet);

> necessity of model with more than one zone!

Extragalactic sources: VHE detection of GRB

[Ackermann (2013)]





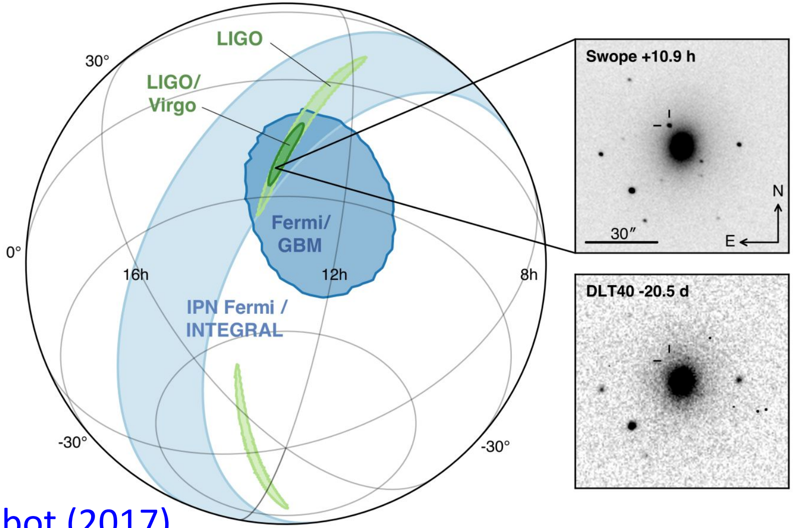
> **Brightest electromagnetic transient** ($10^{51\text{-}53}$ erg released):

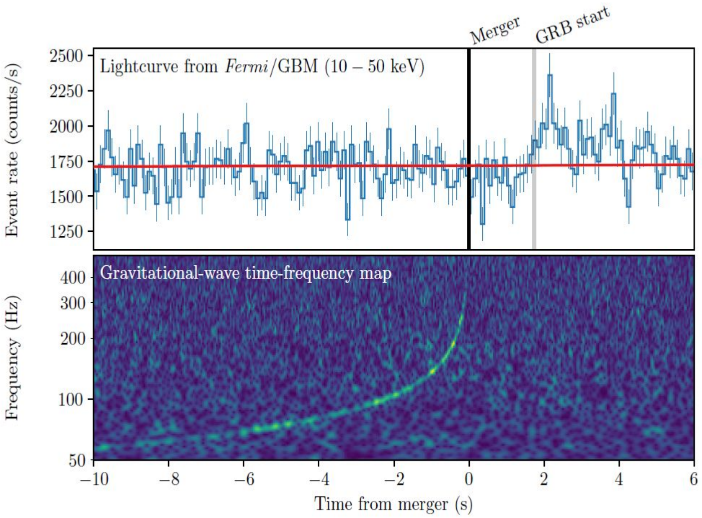
- short, T_{90} < 2 s (compact objects merger, observed in GWs),
- long, T_{90} > 2 s (massive star collapse);

> continuously detected by high-energy space-borne telescopes:

~ 90/yr in hard X rays by Swift-BAT, ~ 240/yr in MeV gamma rays by Fermi-GBM;

Extragalactic sources: VHE detection of GRB





Abbot (2017)

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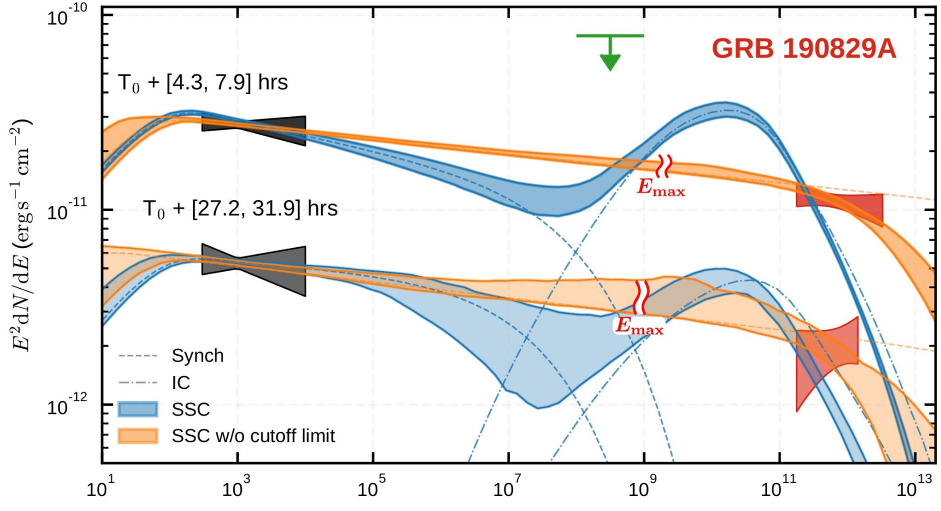
~ 90/yr in hard X rays by Swift-BAT, ~ 240/yr in MeV gamma rays by Fermi-GBM;

> **GRB170817A, first multi-messenger source**, GW (NS+NS merger) + hard X-ray prompt!

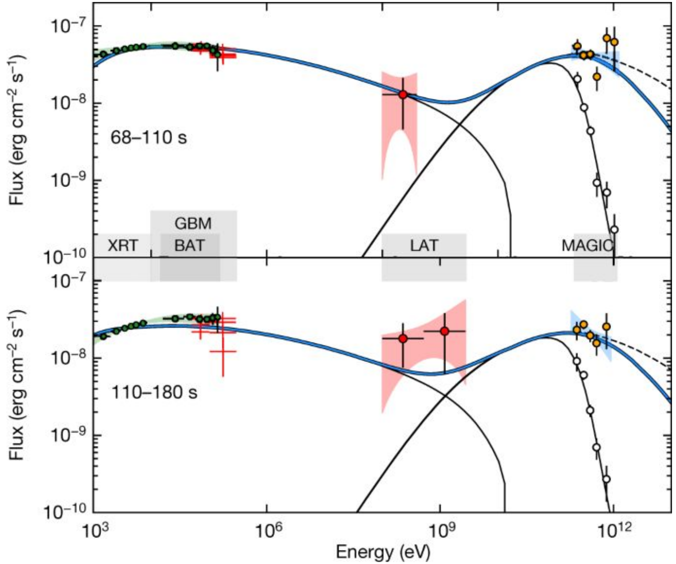
> no GRB detected in VHE gamma rays until late 2010s.

Extragalactic sources: VHE detection of GRB

MAGIC (2019)



H.E.S.S. (2019)

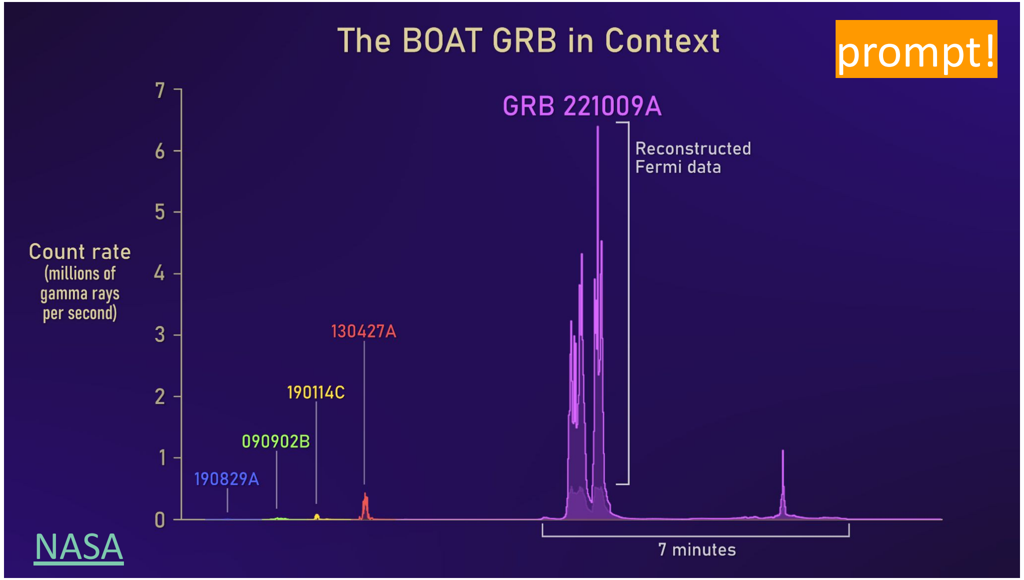


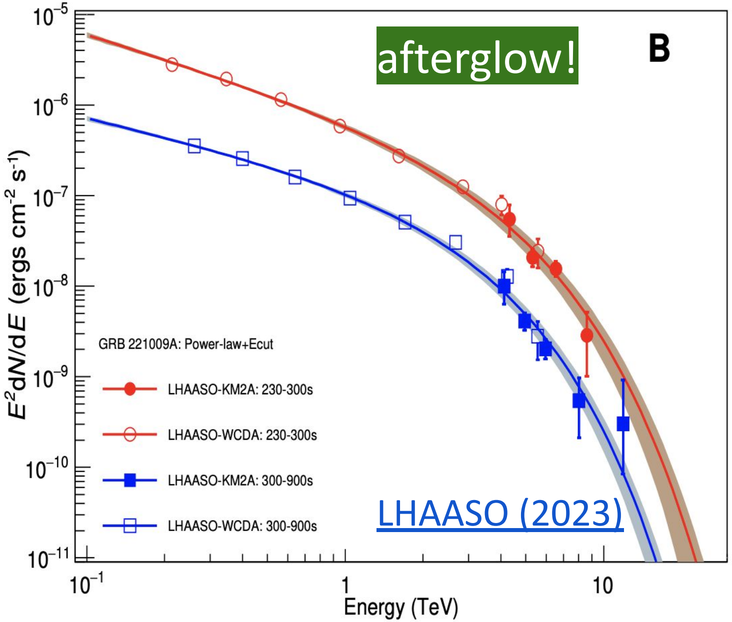
afterglows!

> 2019, *annus mirabilis* for GRBs:

- detection by H.E.S.S. and MAGIC;
- great technological success, MAGIC designed for rapid transients follow-up;
- afterglow gamma-ray emission compatible with inverse Compton (as in AGN with jets);

Extragalactic sources: VHE detection of GRB





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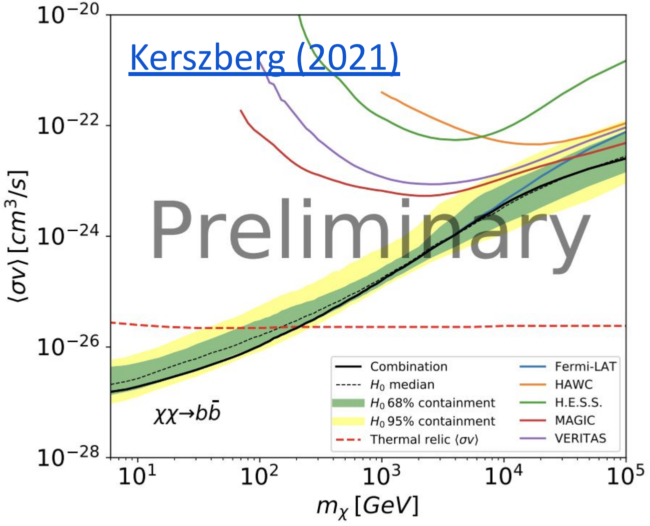
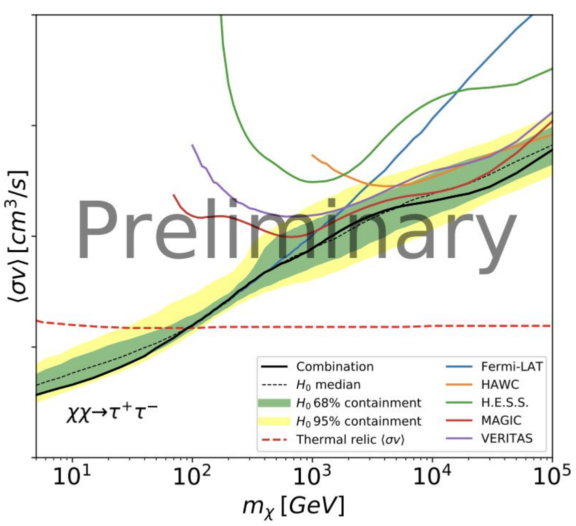
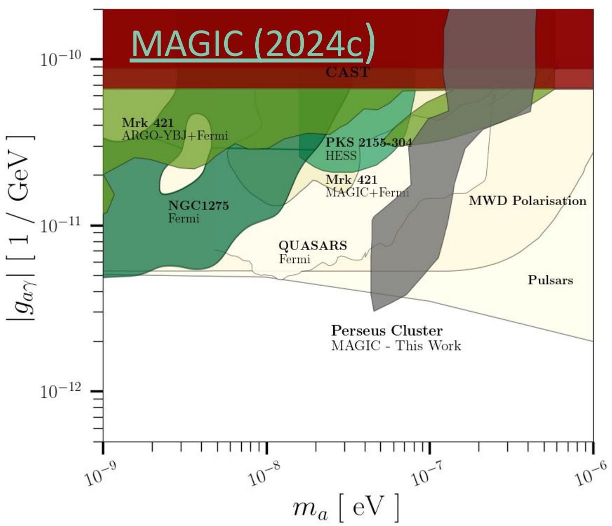
- afterglow gamma-ray emission compatible with inverse Compton (as in AGN with jets);

> 2022, *annus mirabilissimus* for GRBs:
- **GRB221009A, B**rightest **O**f **A**ll **T**imes **(BOAT), 1 in 10^5 years event**;
- detection in gamma by LHAASO (continuous monitoring + only instrument non saturable).

Fundamental physics with Gamma rays







> **An <u>incomplete list</u> of recent fundamental physics studies**:

- Combined dark matter searches in dwarf spheroidals with all gamma-ray instruments [Kerszberg, 2021];
- Constraints on axion-like particles with the Perseus Galaxy Cluster with MAGIC [MAGIC, 2024c];
- Bounds on Lorentz Invariance Violation via time of flight
  - GRB190114C [MAGIC, 2020];
  - Mrk421 2013 flare [MAGIC, 2024d].

PROSPECTS AND CONCLUSIONS

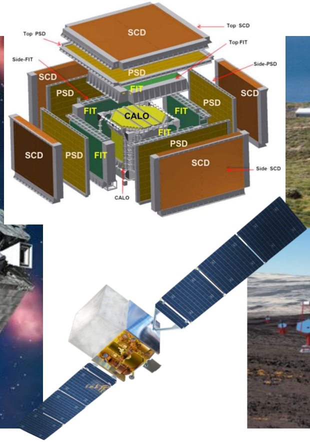
What will gamma-ray astronomy look in the 2030s?

MeV / sub-GeV

> MeV fluxes!

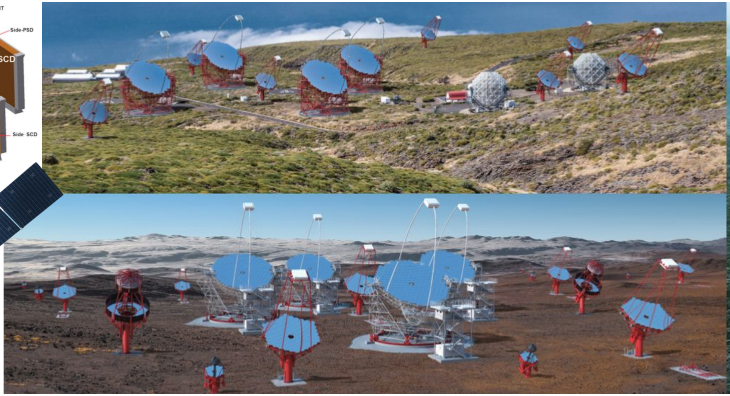
> gamma polarisation!

GeV



> ??*

sub-TeV and TeV



> resolve more sources (jets)!

> improve TeV monitoring.

hundreds of TeV

> discover more UHE sources!

> detect EGAL source > 100 TeV?

*don't know how long Fermi-LAT will operate, nor if other instruments will replicate its achievements

What will gamma-ray astronomy look in the 2030s?

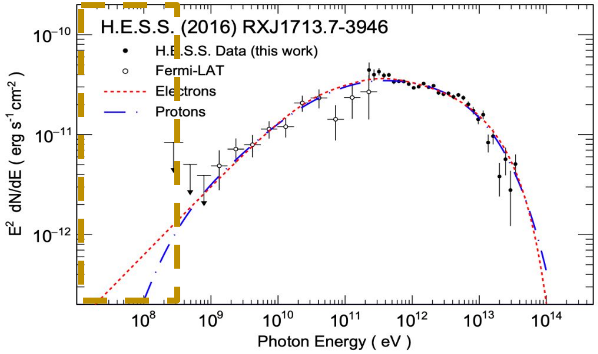
> Wealth of Archival data!

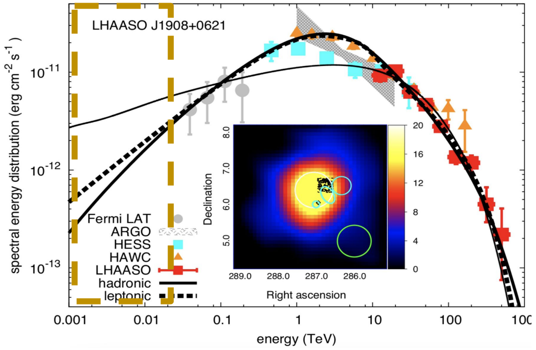
If current Collaborations continue seriously the data standardisation effort and create public data legacies the community will have 20 years of archival gamma-ray observations to analyse.

What are the most important scientific topics?

> Great excitement for the highest energies (> 100 TeV), but there is <u>so much to learn at the lowest (< GeV)</u>:

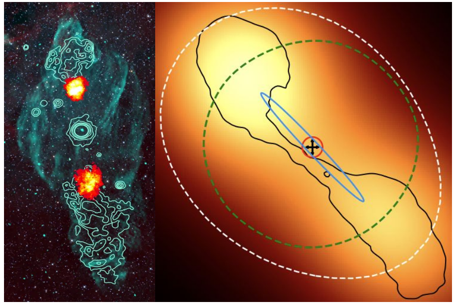
- 25 years without looking at the MeV Universe
- it's at the lowest energies that we can resolve all our leptonic / hadronic dilemmas;





> gamma imaging of relativistic plasma outflows:

- we are starting to resolve the structure of the closest jetted objects (SS 443);
- started measuring the extension of the jets in the farthest;
- infer their structure through polarisation!



> need to <u>consolidate and systematise our knowledge</u> (where do we stand with CR accelerators if most sources are leptonic?).