# The multi-wavelength and multi-messenger context I


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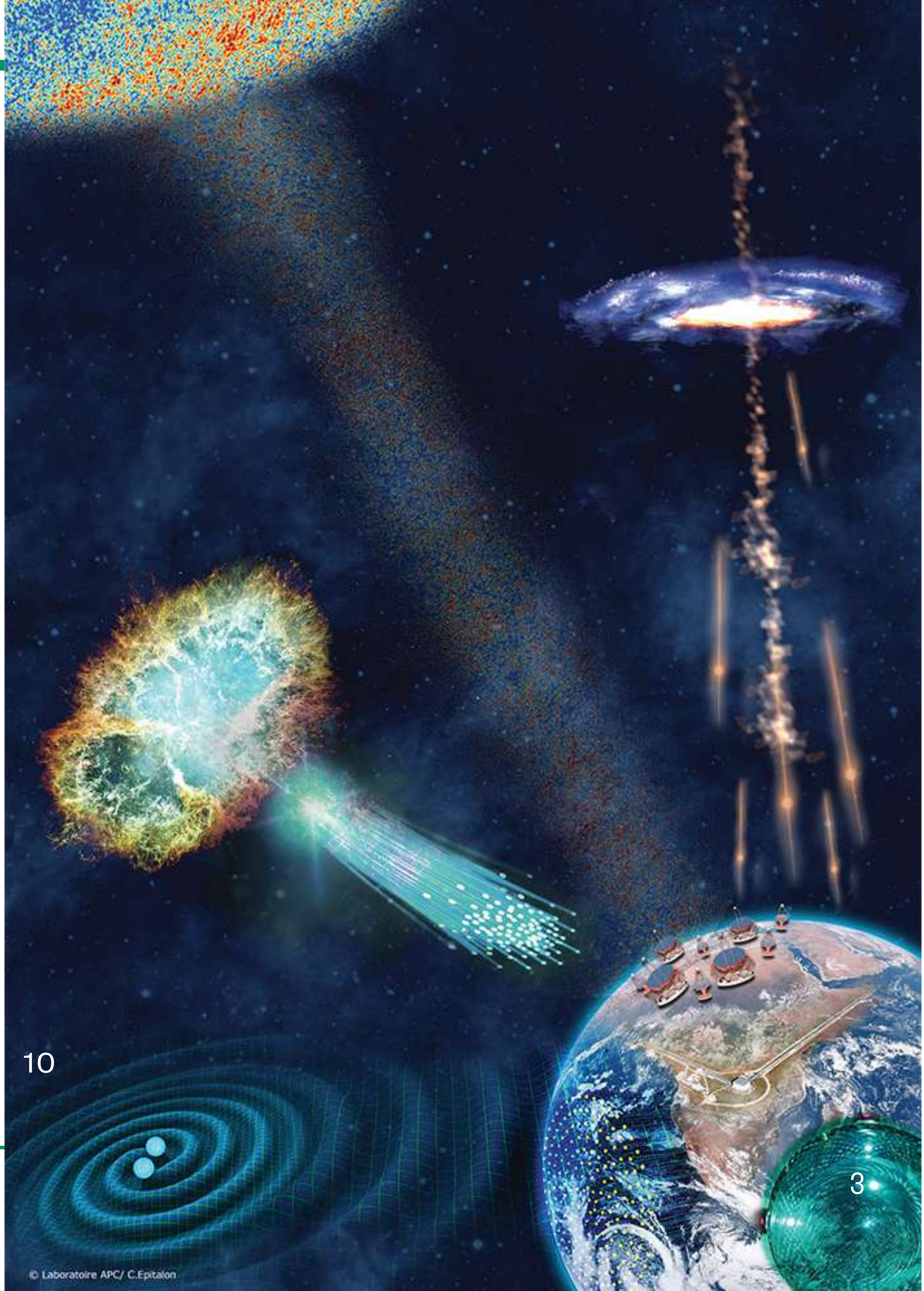
Brazilian Center for Physics Research (CBPF)


**ICTP-SAIFR Advanced School 2023**

- Posing the problem
- Setting up the stage
- CTA as a player in the MWL-MM scene
- CTA MWL-MM Coordination activities
- The CTA MWL Synergies

# Posing the Problem



# Perspective of Cosmic-ray Physics

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**1912 – V Hess descobre radiação cósmica** ★

**1912 – Wilson inventa a câmara de núvens (primeira ferramenta para se observar a radiação)** ★

Discoveries in the laboratory (radiation)

Discoveries with cosmic-rays

Discoveries in accelerators

★ Revolutions in experimentation

1919 – Ernest Rutherford descobre o próton;

1932 – James Chadwick descobre o neutron;

1932 – Carl Anderson descobre o positron;

**1933 – Pierre Auger detecta chuveiros atmosféricos** ★

1936 – Carl D. Anderson descobre o lepton muon ao estudar a radiação cósmica;

1936 – Pierre Auger identifica chuveiros atmosféricos formados por um único raio-cósmico energéticos (E até **$10^{15}$ eV**)

1947 – George Rochester e Clifford Butler descobrem o kaon, a primeira partícula estranha;

1947 – Cecil Powell, César Lattes e Giuseppe Occhialini descobrem o lepton pion;

★ **1948** - Lattes and Gardner identify the artificial production of mesons in the first cyclotron, at Berkeley.

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1955 – Owen Chamberlain descobre o antiproton;

1956 – Clyde Cowan e Frederick Reines descobrem o neutrino (do elétron);

1962 – Leon M. Lederman, Melvin Schwartz e Jack Steinberger descobrem o neutrino do muon;

1974 – Burton Richter e Samuel Ting descobrem a partícula J/ψ composta de quarks charm;

1977 – Partícula Upsilon descoberta no Fermilab, demonstra a existência do quark bottom;

1977 – Martin Lewis Perl é levado à descobre o lepton tau após uma séria de experimentos;

1979 – O Gluon é observado diretamente em eventos tri-jet no DESY;

1983 – Carlo Rubbia e Simon van der Meer descobrem os bosons W e Z;

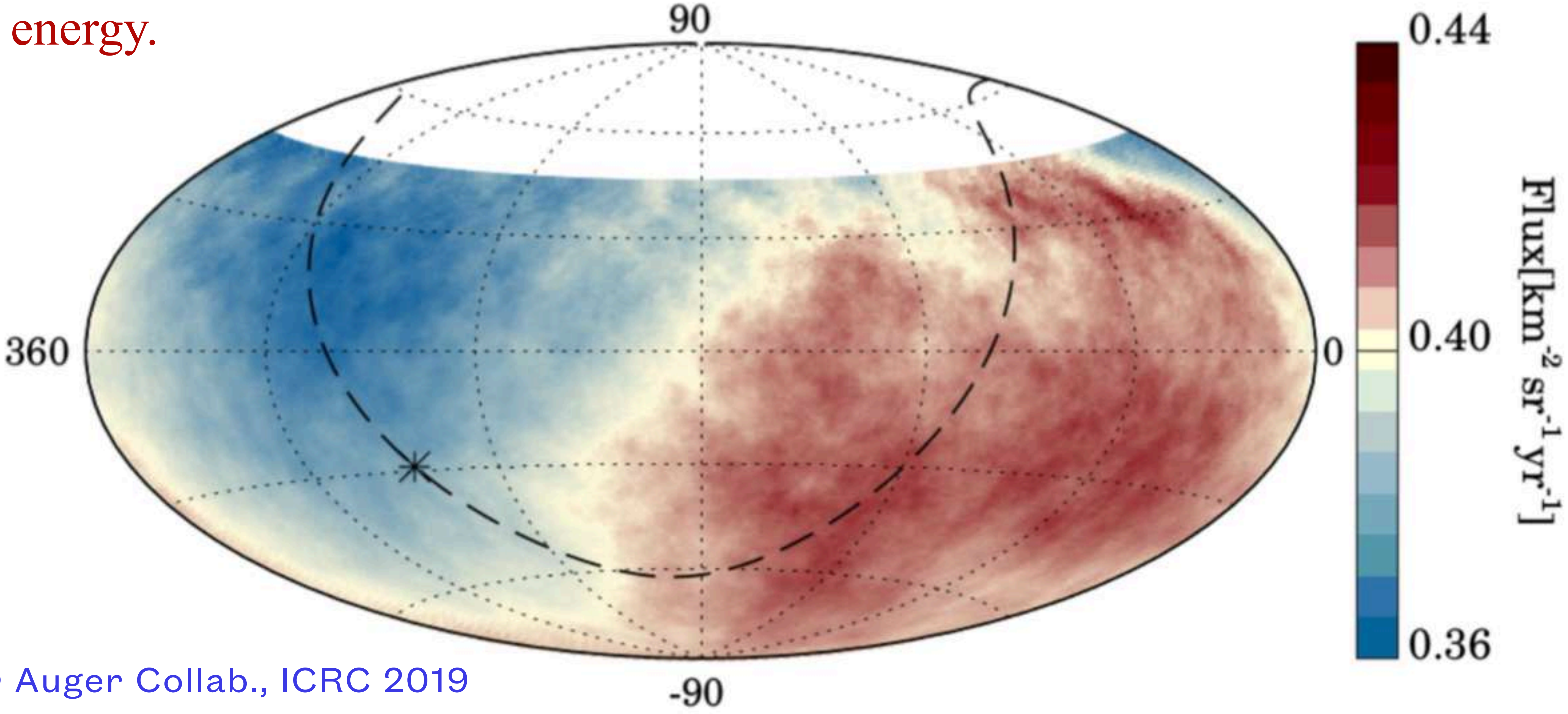
1995 – Quark top é descoberto no Fermilab;

2000 – Estudos do neutrino do tau no Fermilab

2012 – Higgs boson descoberto no CERN - Large Hadron Collider (LHC).

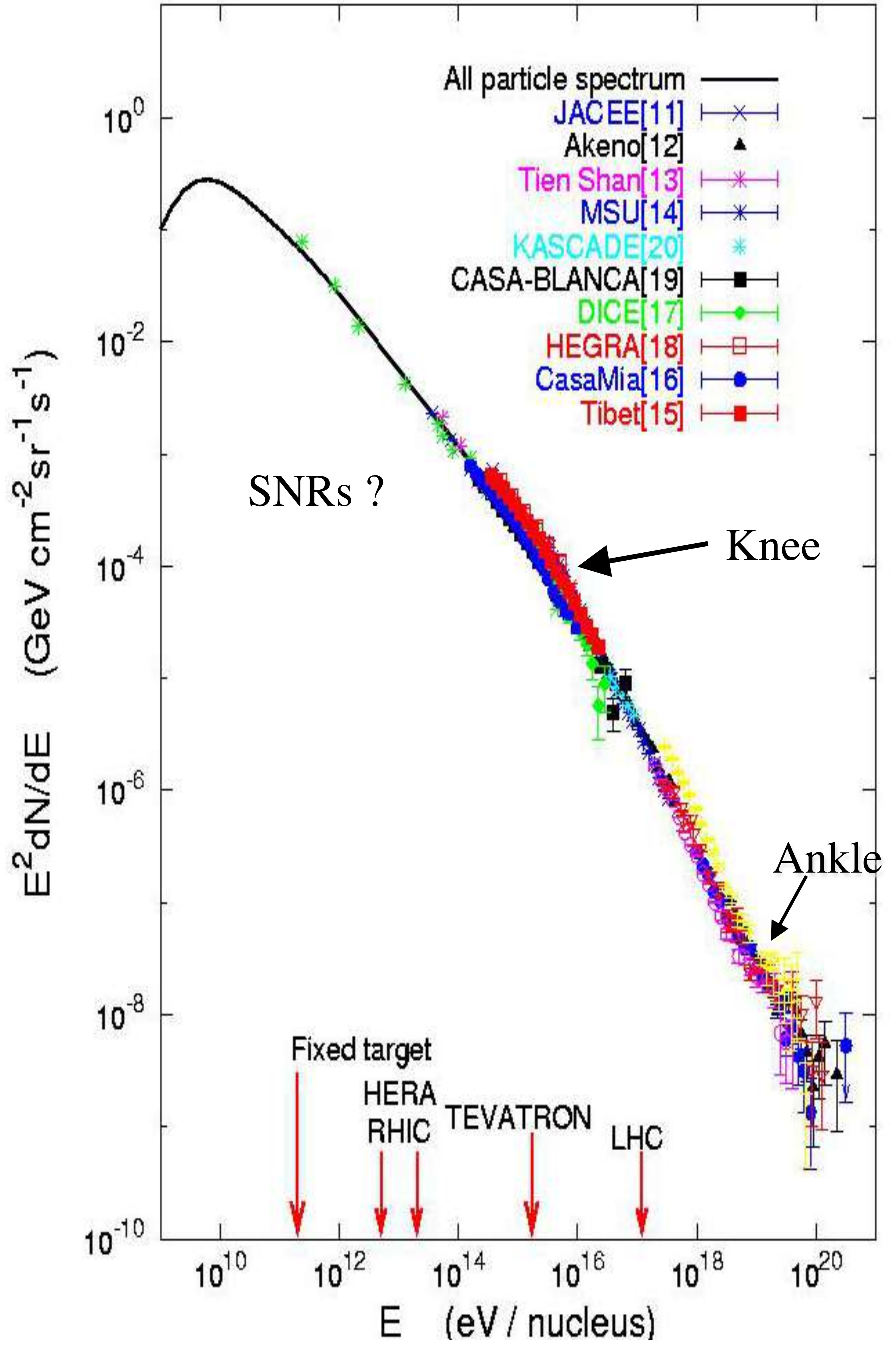
# The fundamental question: Origin of Cosmic Rays

Dipole above EeV, with amplitude growing with energy.




© Auger Collab., ICRC 2019

*Exposure >92000 km²sr yr for events with ϑ<80⁰*



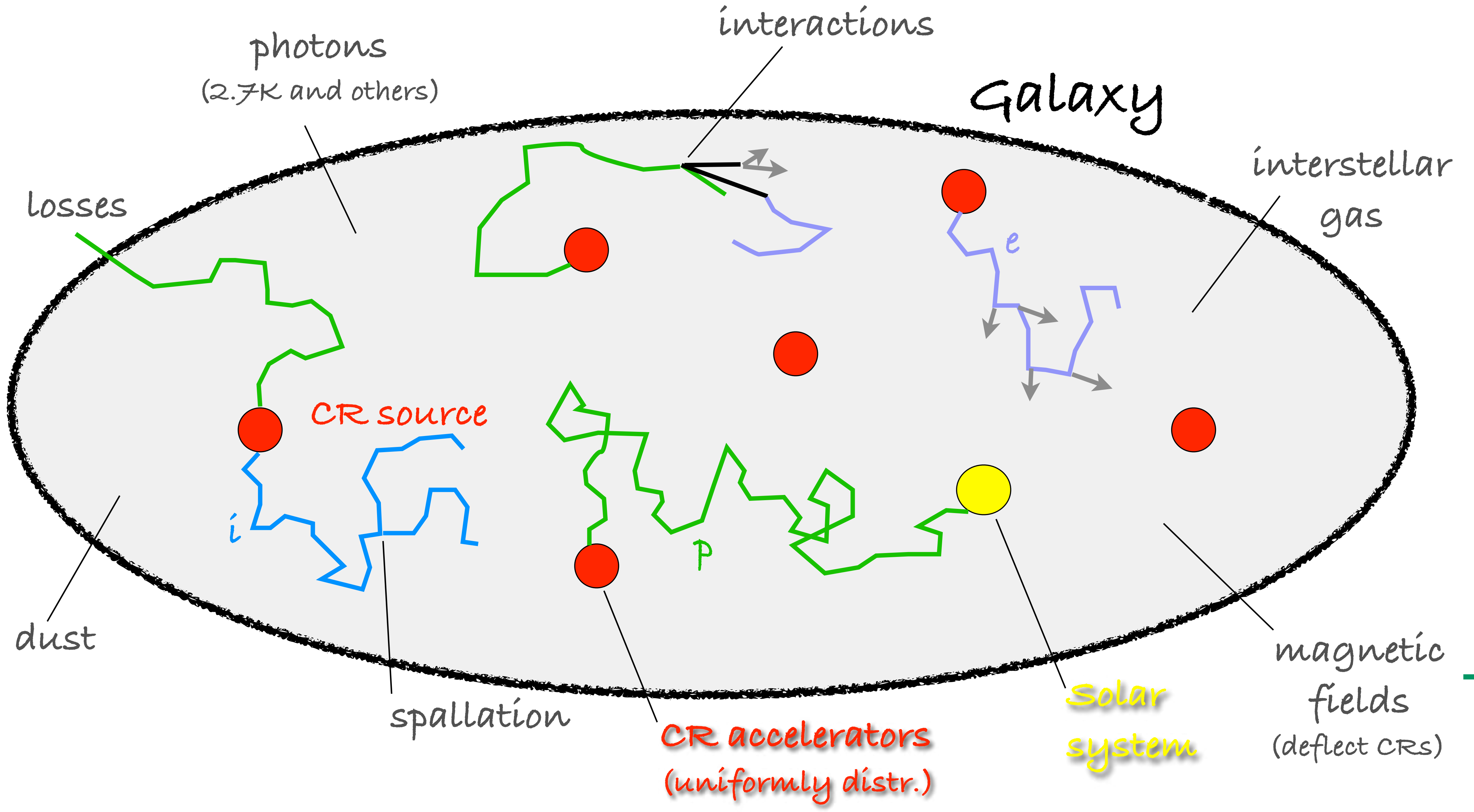

T. Gaisser

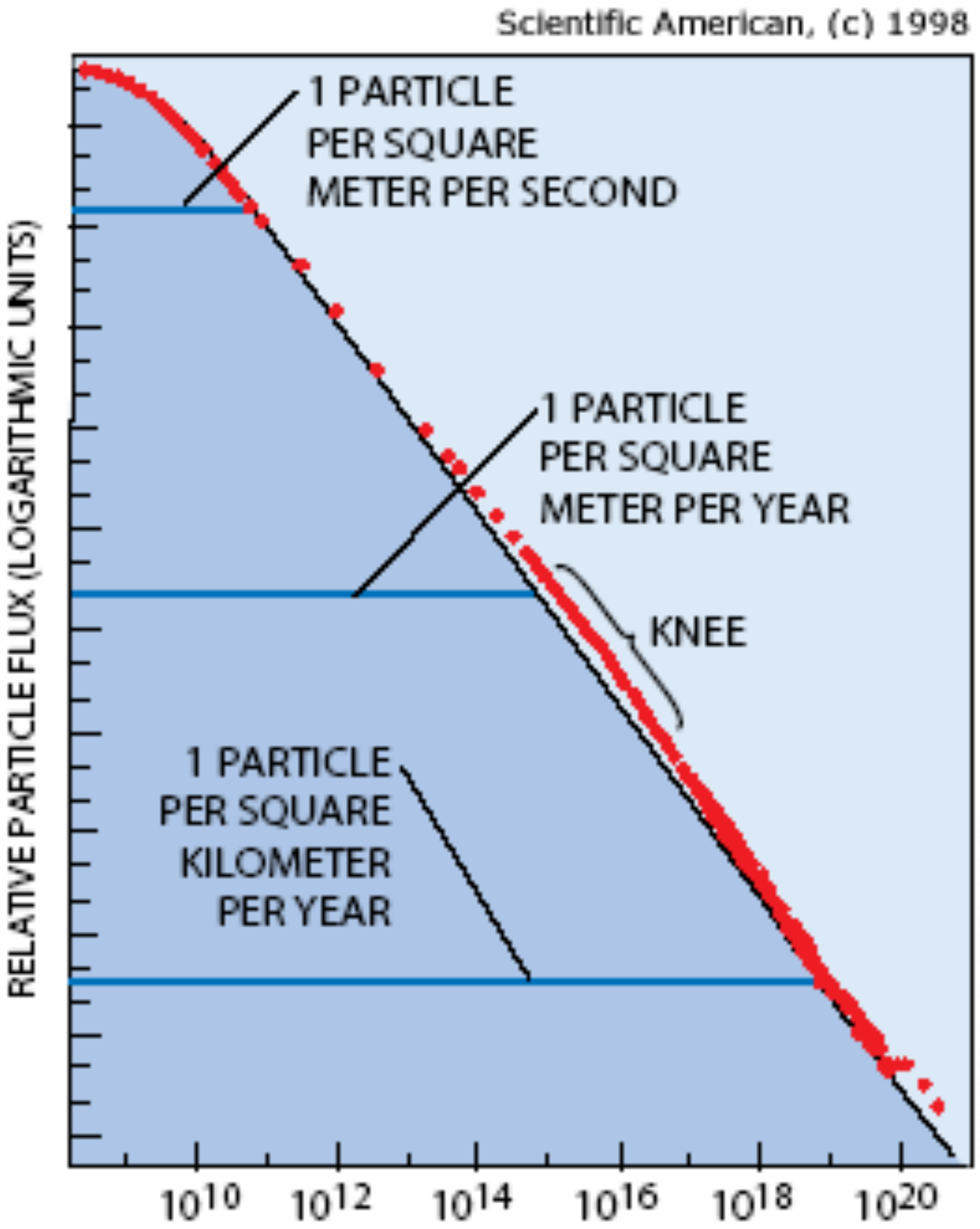
# The fundamental question: Origin of Cosmic Rays

The Astrophysical relevance importance of cosmic-rays:

$E_{CR} \sim E_{*} \sim E_{CMB} \sim E_{mag} \sim E_{k,gas} \sim 1\ eV/cm^3$

$\Sigma_{total} \sim 10^{49}$ J na Galáxia



# The fundamental question: Origin of Cosmic Rays

Galactic Cosmic Rays - before the knee (+ between knee and ankle)

<u>energy density:</u> ~ 1 eV/cm$^3$ (~ CMB, gas, B, etc.)

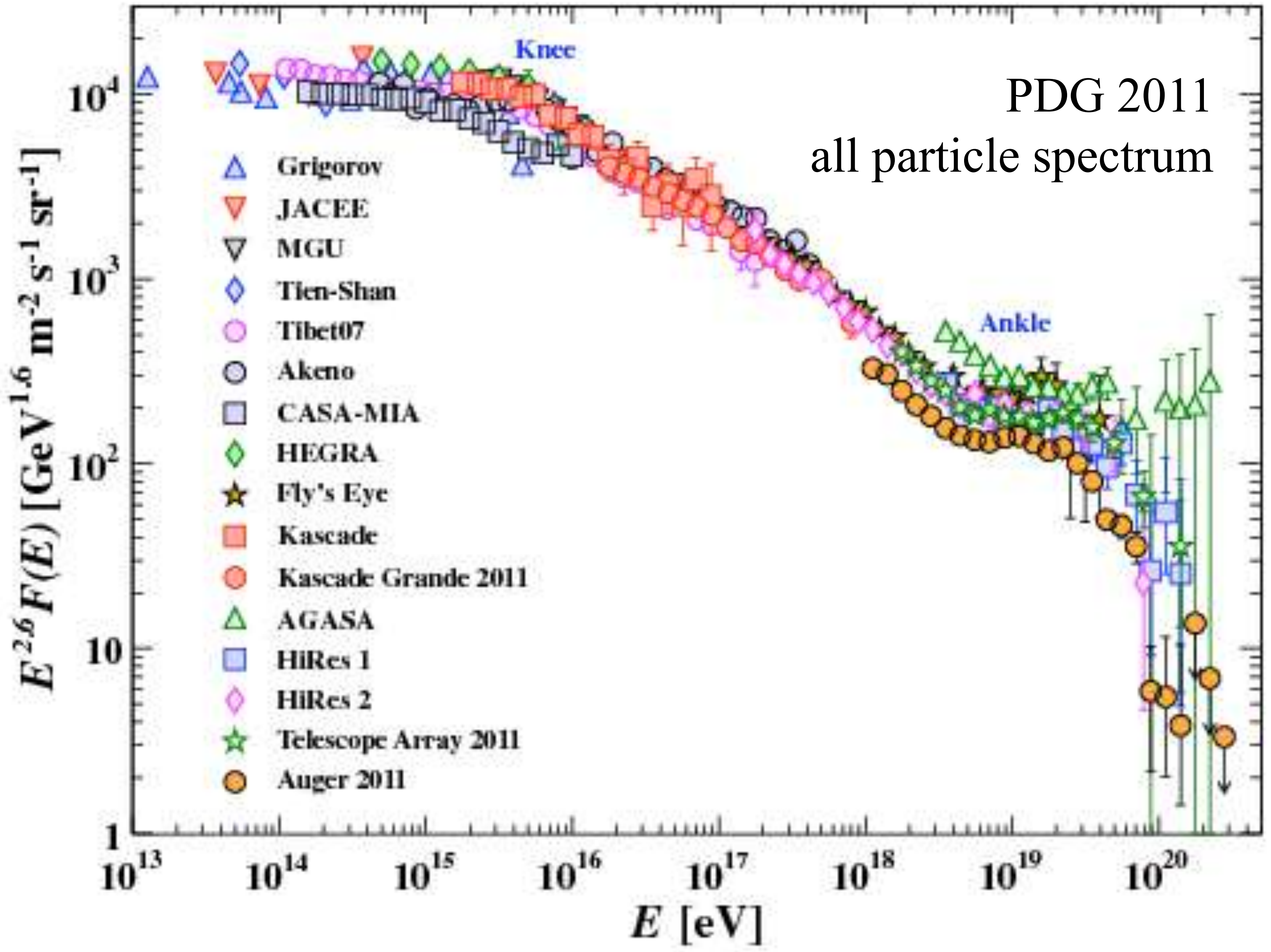
<u>age:</u> ~ $10^7$ yrs,

<u>production rate:</u> (0.3-1) x $10^{41}$ erg/s, source

<u>spectrum:</u> hard, Q(E) ~ $E^{-2.1}$ x $E^{-0.6}$ ~ $E^{-2.7}$

Sources? Strong shocks with enhanced magnetic fields (SNRs)

Stellar winds, such as in cluster and OB associations, galactic center, etc.



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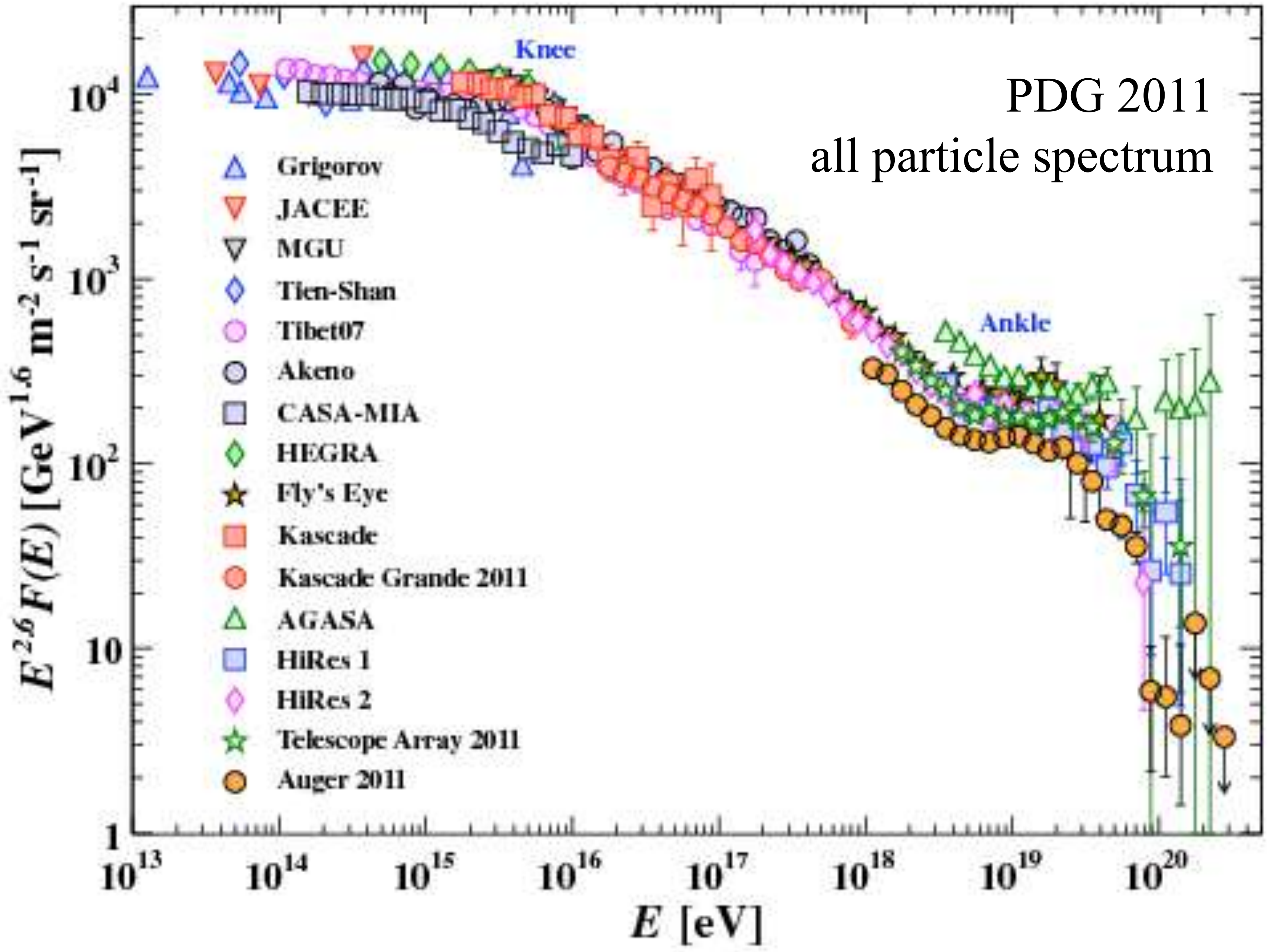


Energy density of cosmic-rays: $\varrho \approx 1$ eV / cm$^3$ (~ CMB, IGMF, Kgas, …)
"Lifetime" of cosmic rays: $t \approx 6 \times 10^6$ years
Galaxy Volume: $V \approx \pi r^2 d \approx 4.2 \times 10^{66}$ cm$^3$

$$dE/dt = \varrho V / t \approx 4 \times 10^{33} \text{ J/s}$$

Rate of Supernovae: $f \approx 1 / 30$ years
Kinect energy of ejections: $E \approx 10^{44}$ J
Cosmic-ray fraction: $\varepsilon \approx 10$ %

$$dE/dt = f \varepsilon E \approx 10^{34} \text{ J/s}$$

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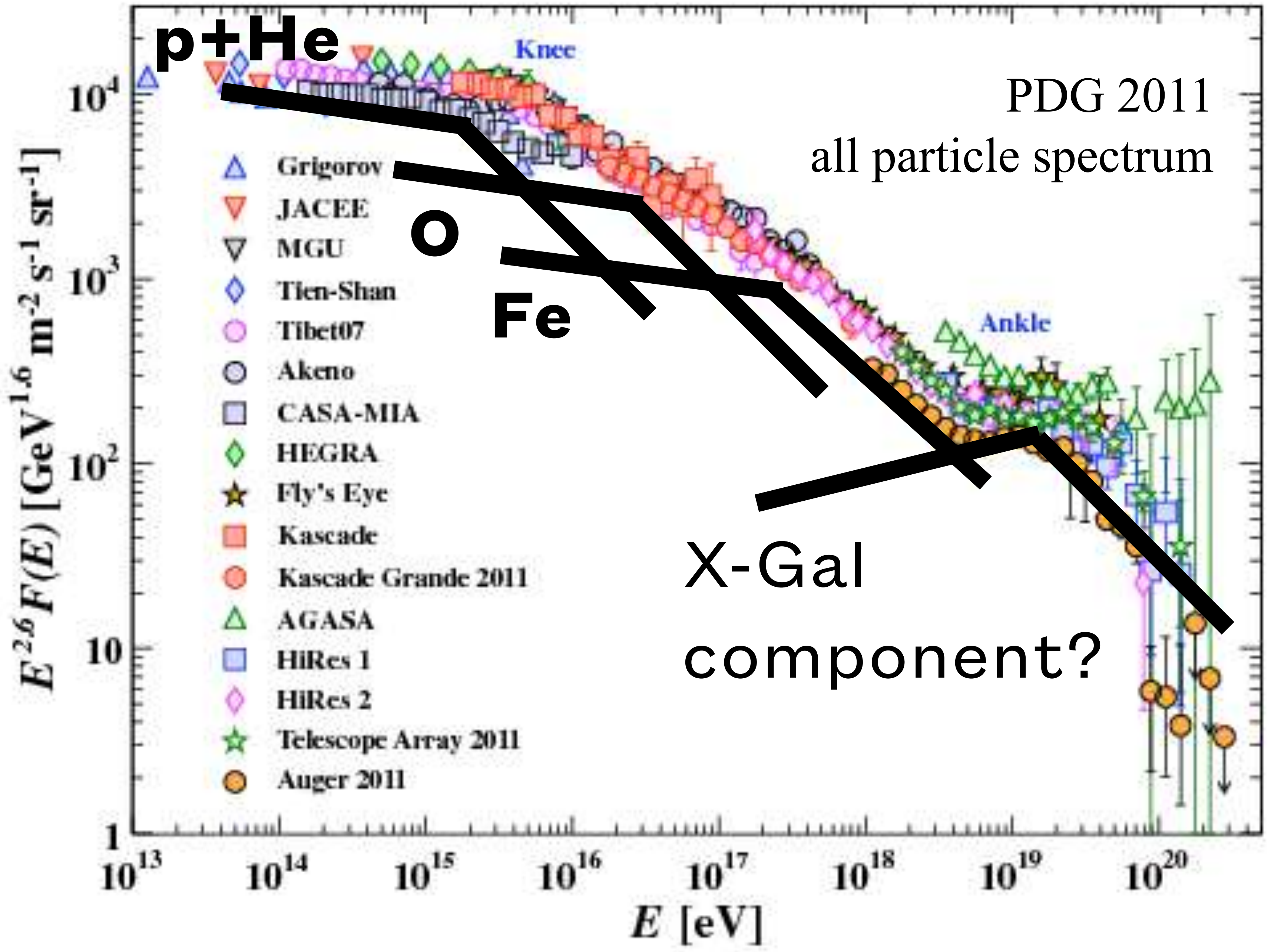
Sources? SNRs, under strong shocks with enhanced magnetic fields.
But also, stellar winds, in cluster and OB associations, galactic center, etc.




Extragalactic Cosmic Rays - certainly above the ankle

Origin? At $10^{18\text{-}19}$ eV, t ~ $R^2/D$, propagation time from multi-Mpc can exceed Hubble time (~ $10^{10}$ yr).
At $10^{20}$ eV, horizon ~100 Mpc due to interactions with the 2.7 K CMB ("GZK cutoff")

:: **"Local fog"** - extragalactic (but also Galactic) cosmic-rays (arXiv: 1003.0082v1)

# The fundamental question: Origin of Cosmic Rays

Galactic Cosmic Rays - before the knee (+ between knee and ankle)

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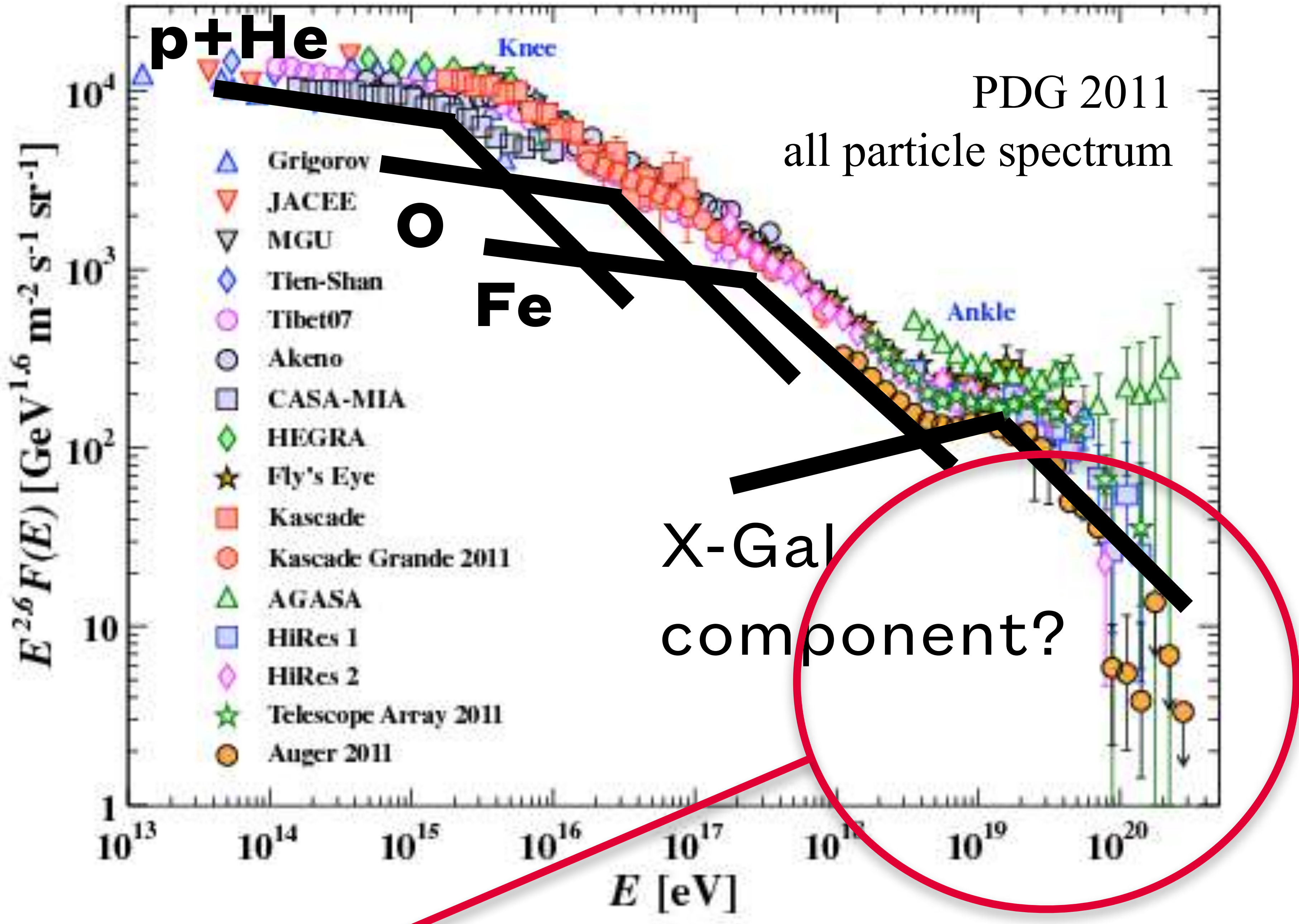



## Interaction with CMB

Above E ~ 6x$10^{19}$ eV protons rapidly lose energy by photo-pions production at an energy loos rate of circa ~15% per interaction (very efficient!)

Interaction length 5-10 Mpc

Universe is opaque E > 5x$10^{19}$ eV.

The spectrum suffers a cutoff (cosmic-ray absorption from distante sources, > 100 Mpc)

$$p + \gamma_{CMB} \rightarrow n + \pi^+$$
$$p + \pi^0$$

$\Delta^+$ production

$\{\gamma$ from $\pi^0$, $\nu$ from $\pi^+\}$

# Potential sites for ZeV CRs

**Hillas Plot:** ”B - L relation" based on the most trivial confinement condition for acceleration $L > R_L$

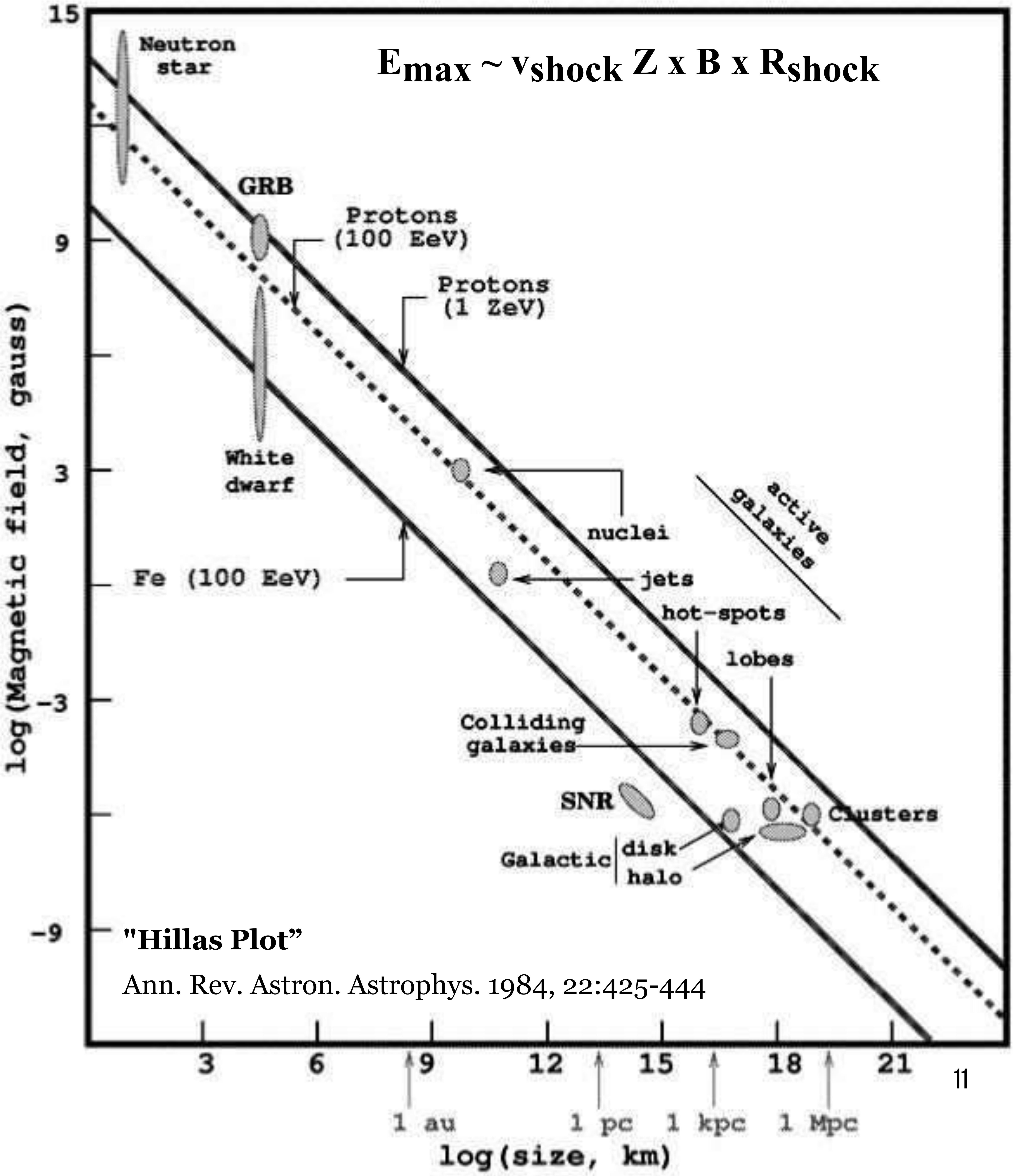
$$B_{\mu G} L_{Mpc} > 2 E_{21} / Z\beta$$

and shows that viable options for acceleration are quite limited ($t_{conf} > t_{acc}$) :

- $t_{conf} \sim L^2/D \sim L^2/cR_L \sim L^2B/E$
- $t_{acc} \sim \eta \beta^2 R_L/c \sim E/eBc.$

  **=> $L > \eta (1/2) R_L$ ($\eta \sim 1$, extreme)**

- absence of radiation losses, important in compact objects




"Hillas Plot”
Ann. Rev. Astron. Astrophys. 1984, 22:425-444

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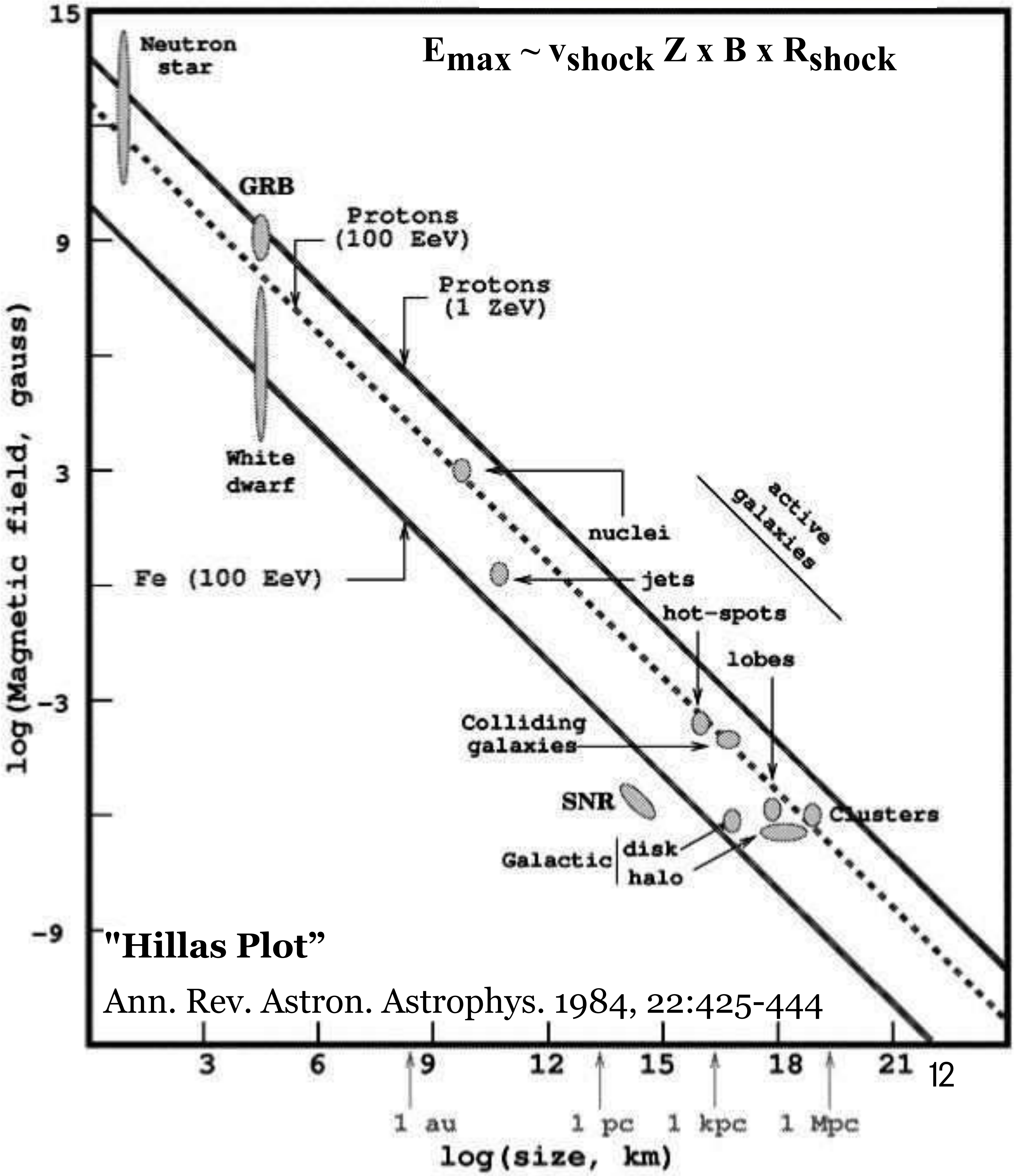
### Potential Sources?

- extreme compact objects (but, radiation losses?),
- inner jets of AGN (fbut, ast variability?),
- extended structures in AGNs, galaxy clusters (but, Bethe-Heitler?)
- M87 and Cen A best "local" candidates.



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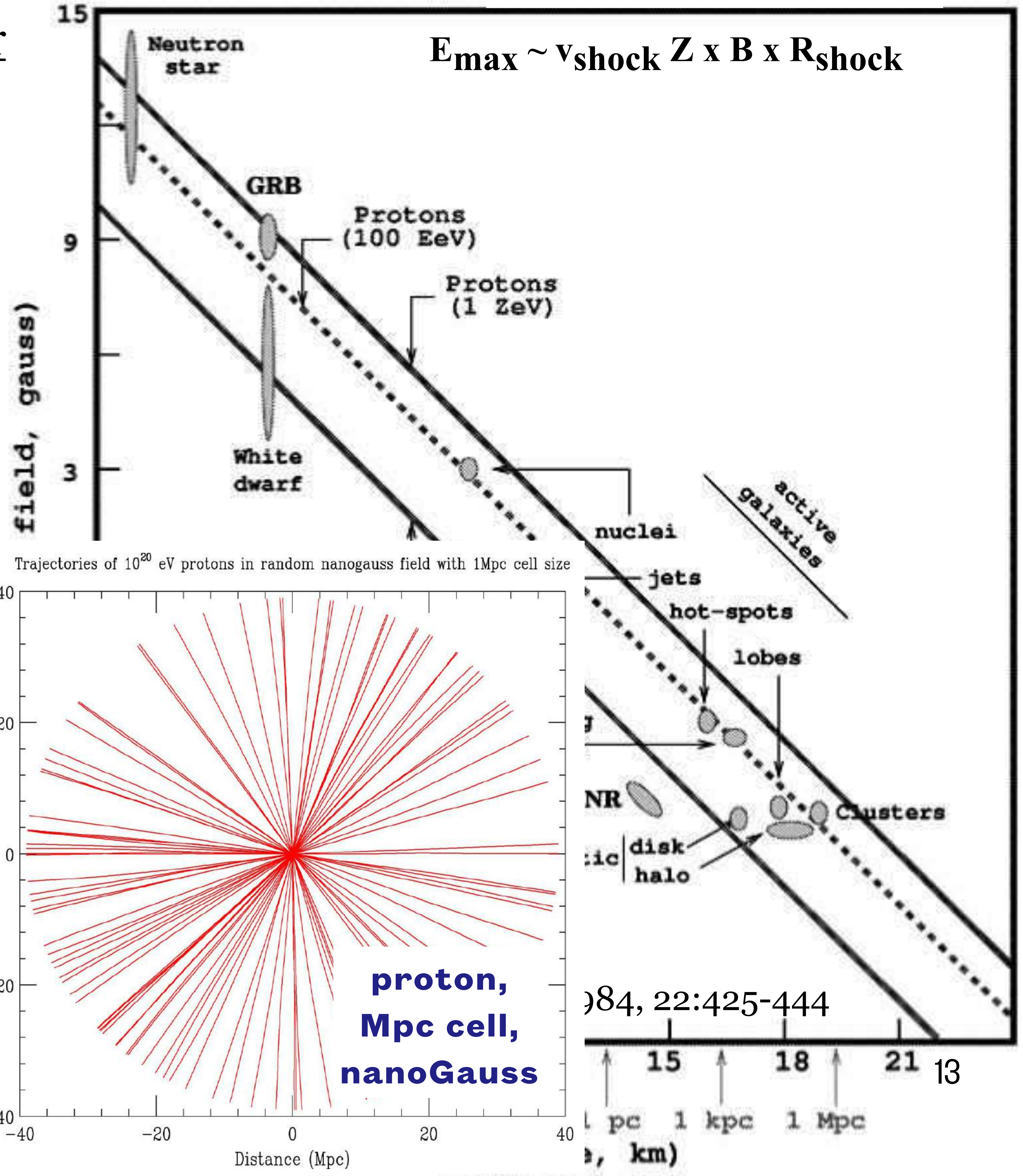
- absence of radiation losses, important in compact objects

**In principle,** proton astronomy would be possible above $10^{20}$ eV in the presence of very low intergalactic magnetic fields < $10^{-9}$ G, for nearby sources (< 100 Mpc) : $\phi \sim 1^o$-$2^o$



# Cosmic ray astrophysics?

The probe of the astrophysical origins of cosmic rays depends on proper astronomical messengers, i.e. **stable and neutral**

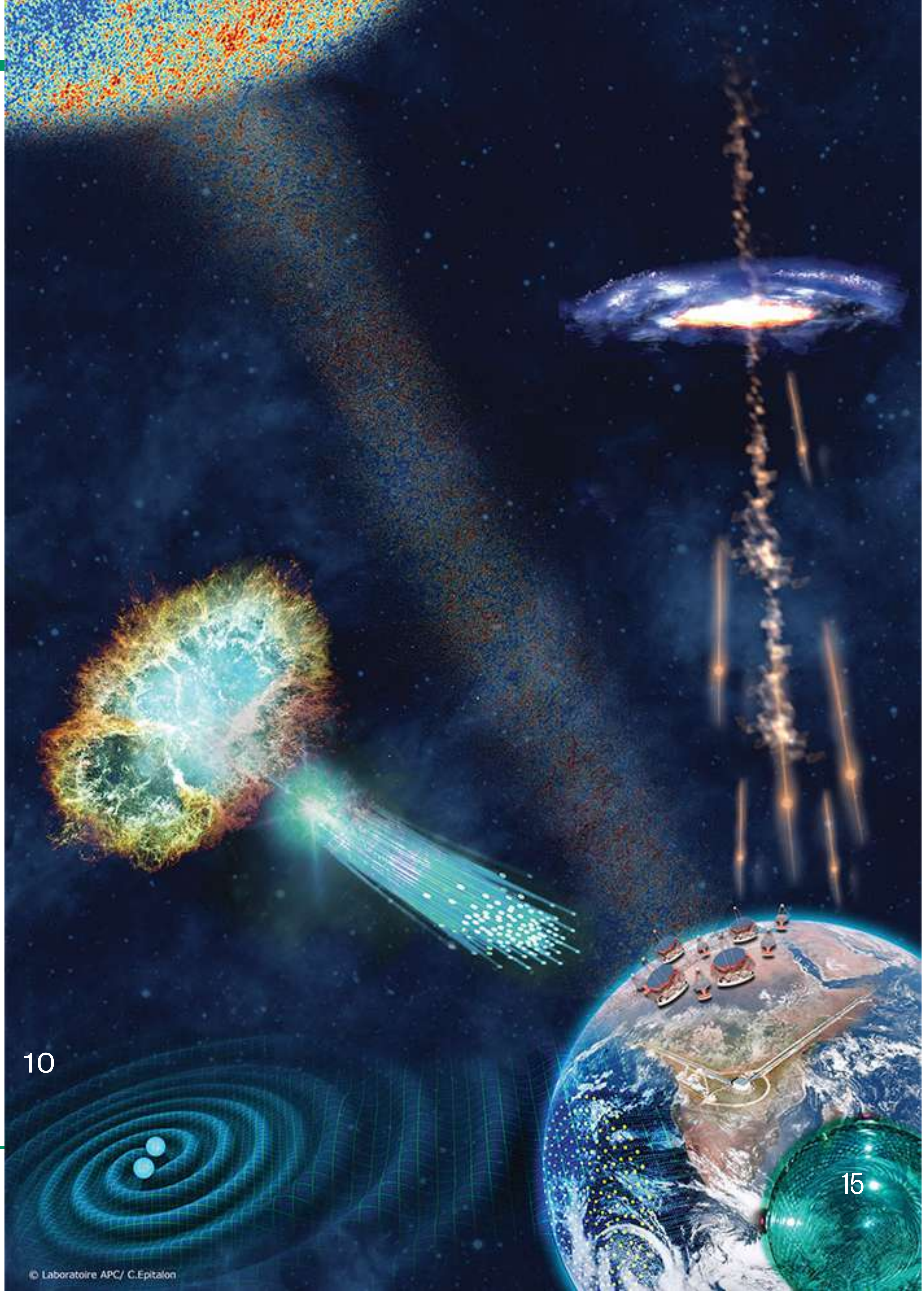
… among which gamma-rays are unique carriers of information about non thermal phenomena, both on Galactic and extragalactic sources.

- effectively produced in both leptonic and hadronic interactions ("ubiquitous" but "dubious")
- effectively detected over a very large energy range from MeV to PeV, from space and from the ground.
- but also, effectively interact with matter, radiation and magnetic fields (beware of some distortion)

**VHE gamma-ray astronomy** has gone through a revolution over the past couple of decades, and now with CTA and LHAASO is about to enter a new era: it has shown that the universe is full of extreme TeV accelerators, and the first PeVatrons have recently been unveiled.

**Neutrinos** also satisfy the stability-neutrality conditions and unequivocal signature of hadronic processes, but are extremely hard to detect (+ "hidden accelerators")

# Setting up the Stage



# 1st July, 1989

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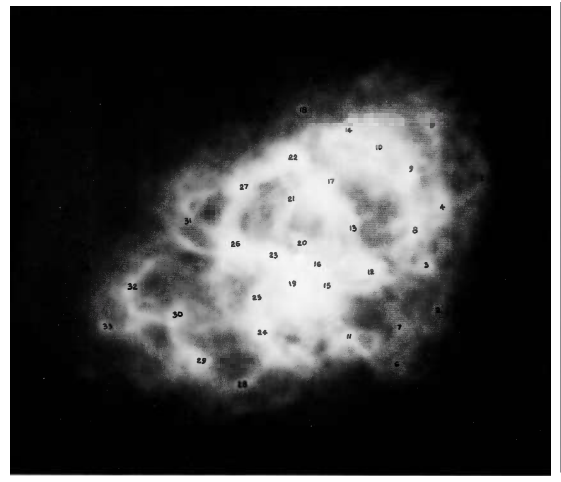
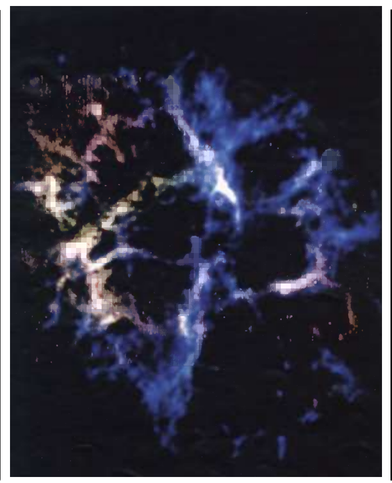
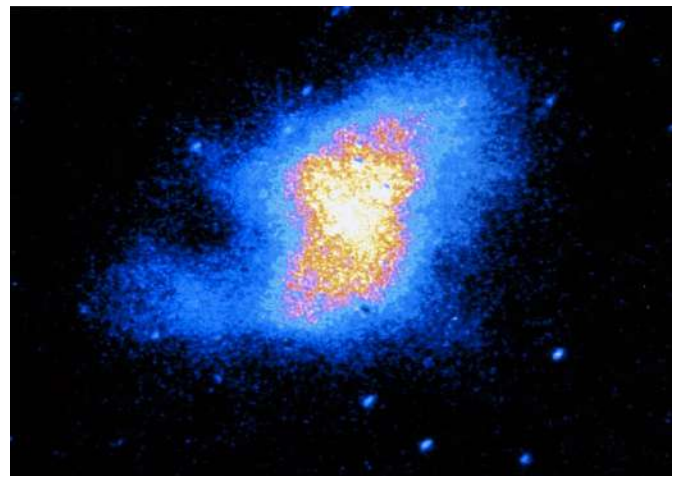


MHz Radio
Velusamy+ 1992

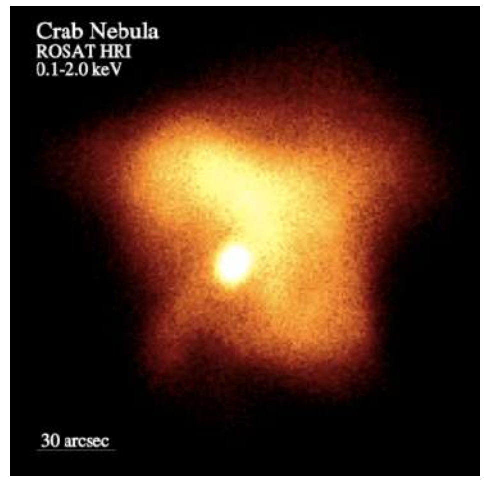


Infra-red
Hester+ 1990

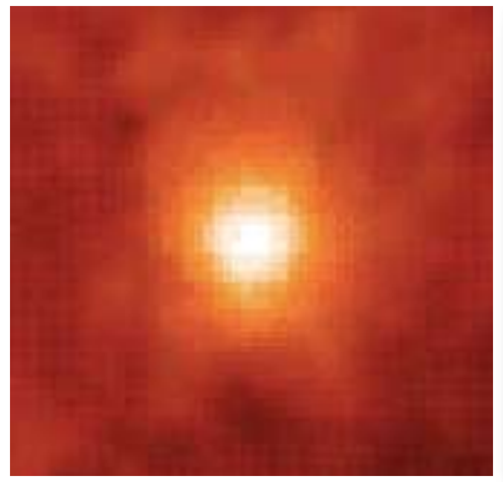
Optical image
Fesen+, 1990



Far-UV image
ASTRO-1, 1990

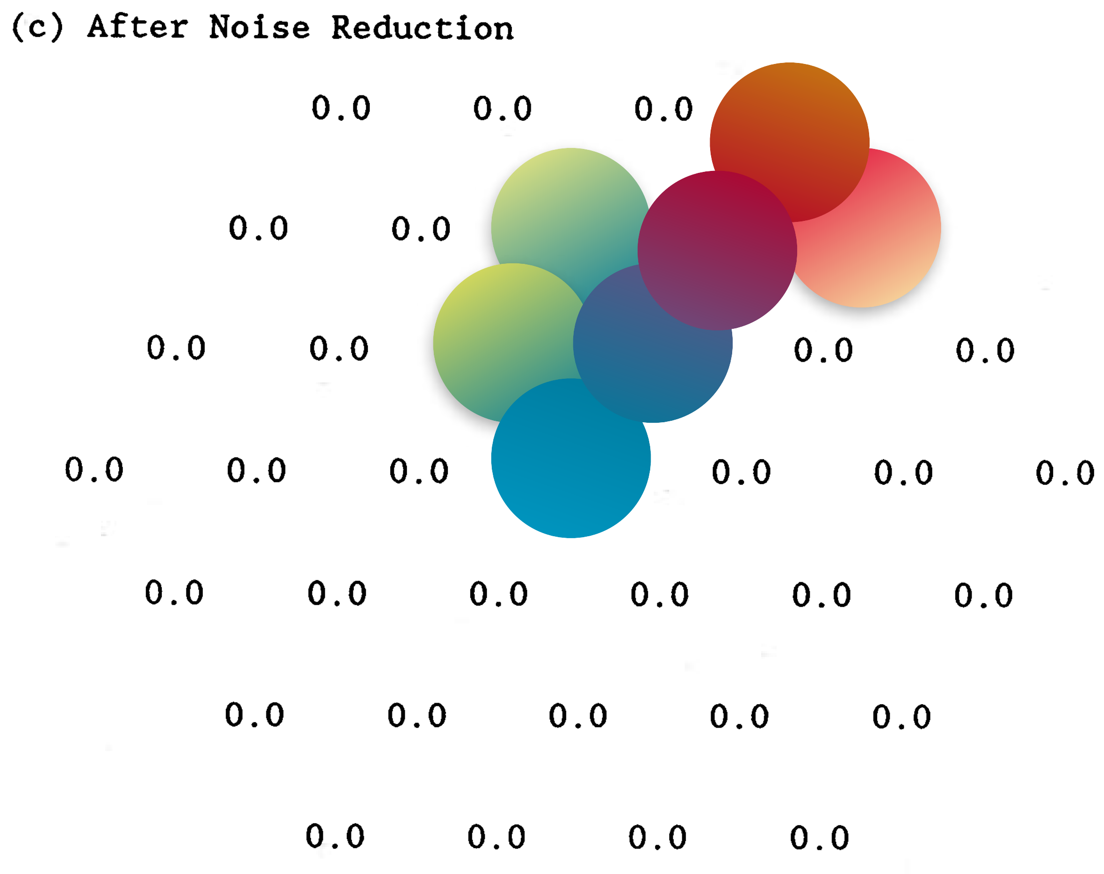



X-ray image
ROSAT, 1991



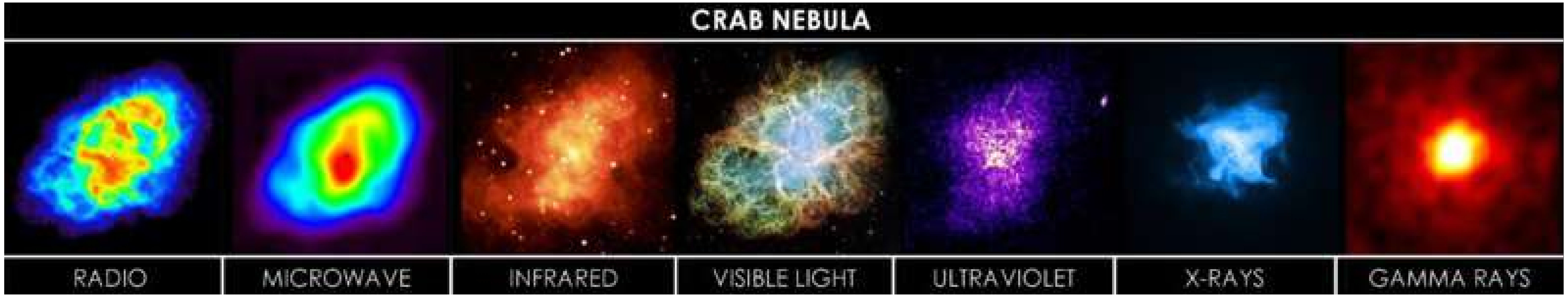
Gamma-rays
EGRET, 1992

- Following the gamma-hadron discrimination by Hillas (1985), the Whipple team detected the first VHE gamma-ray signal from the Crab Nebula (Weeks et al. 1989)
  - 10 m reflector, 37-pixel camera, 19 channels
  - Threshold 0.7 TeV, 9 σ detection, 80 hours integration



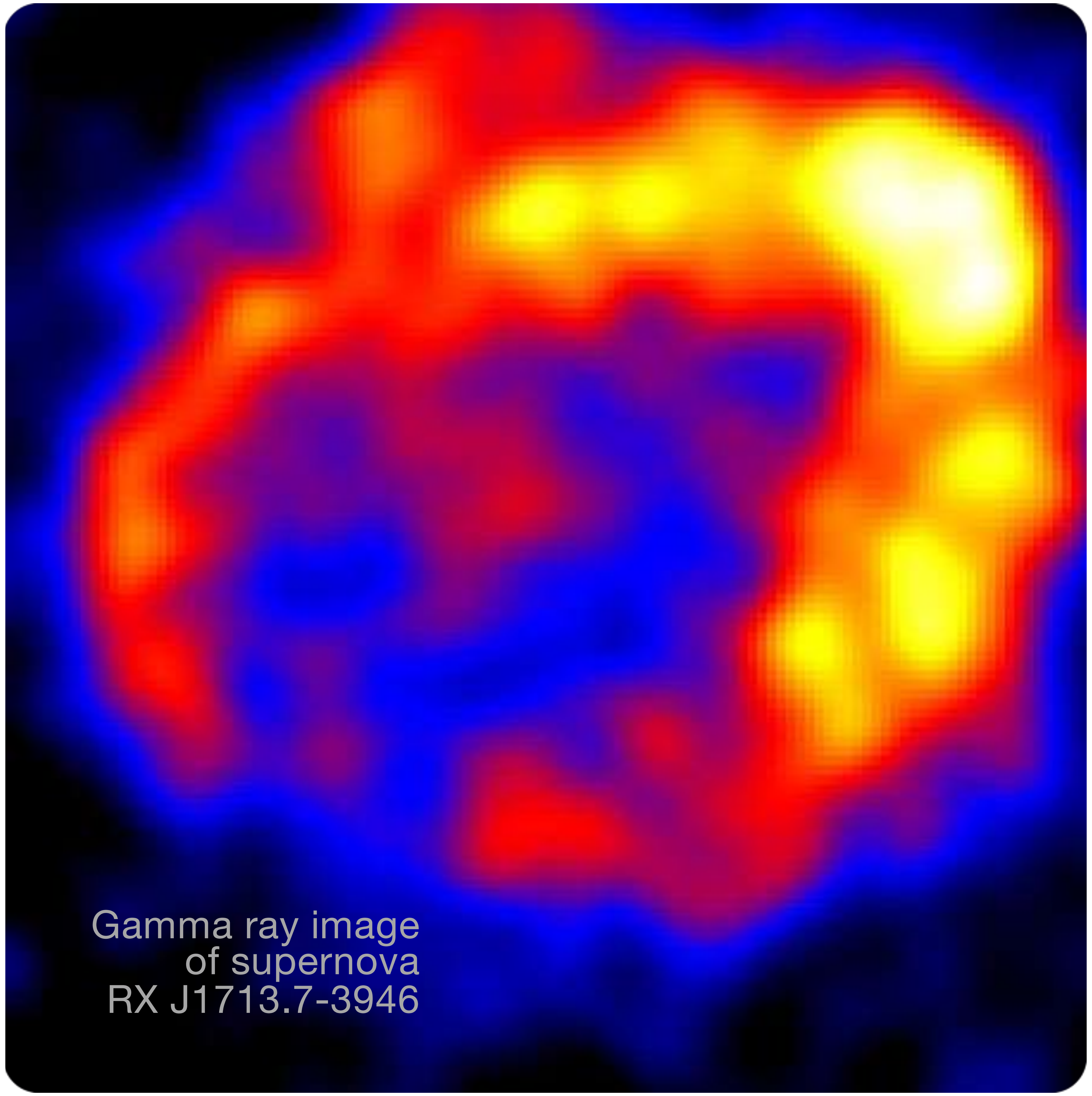

Typical whipple 37-pixel VHE gamma-ray Cherenkov signal from the Crab Nebula, 1989

# A brief CV of the Crab at VHEs




- Since then, we have learned much an been much surprised by the Crab
- Source extension at VHEs finally measured by H.E.S.S. (2019) to be 52.2'' +/- 2.9''(stat) +/- 6.6''(sys), with an energy dependent morphology that ties the origin of energetic electrons to the center of the nebula;
- Spectrum was shown to extend up to 100 TeV (HAWC 2019, MAGIC, 2019) following a log-parabola profile;
- Recent claims by Tibet (2019) of photons up to 300 TeV establish the source as a powerful PeV $e^-$ accelerator working near theoretical efficiency (Khangulyan et al. 2019);
- MAGIC detection of pulsed emission above 25 GeV and up to 1.5 TeV, favouring outer-gap models and an origin of the gamma-rays from curvature radiation.

# Status of ground-based gamma-ray astronomy



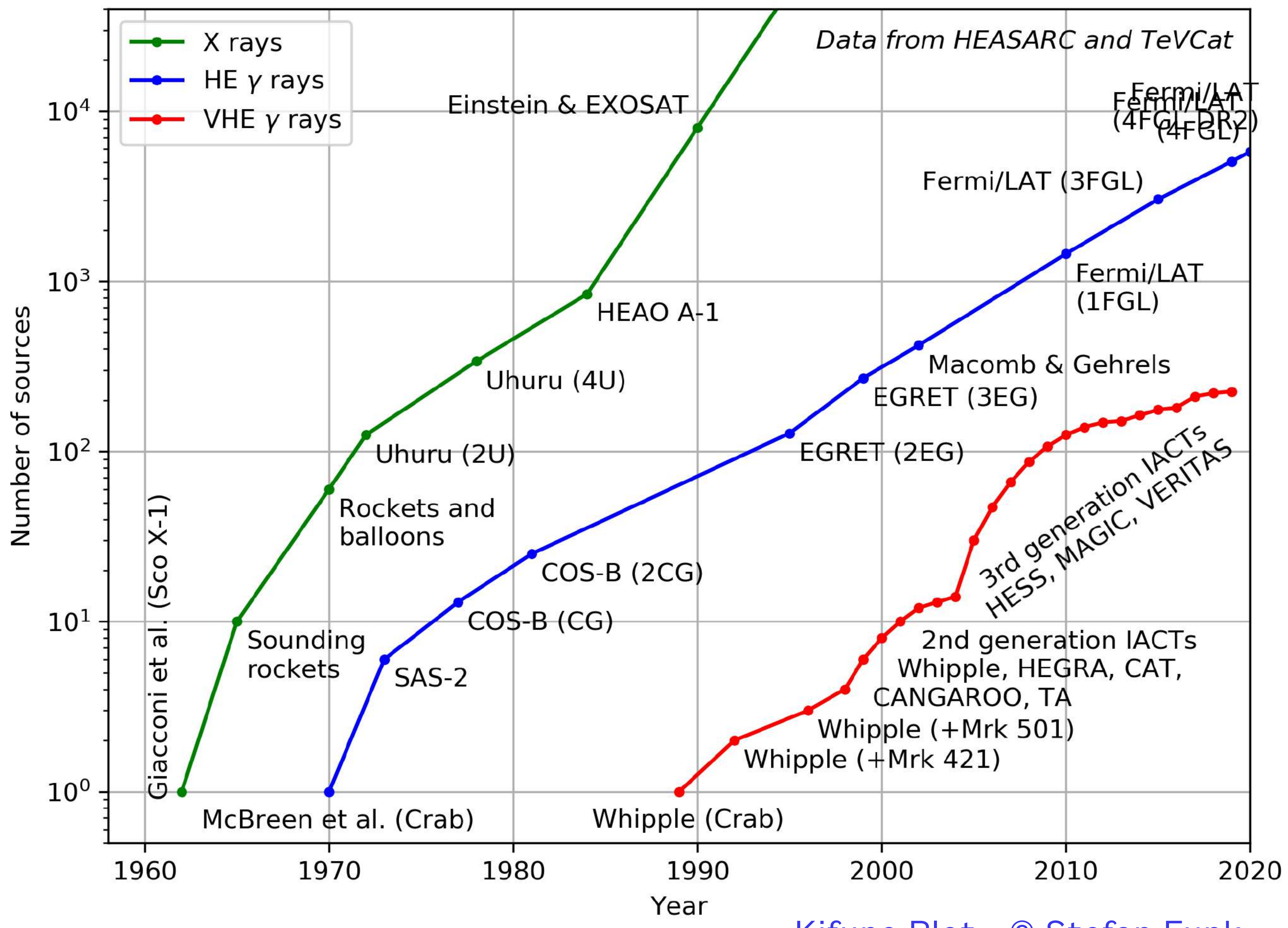

**Cherenkov Astronomy has reached the status of "real astronomy"**

- good-resolution skymaps, ~ 5'
- 200+ sources detected
- spectra from c. 30 GeV to 30 TeV
- times resolved light curves down to minute timescales

# VHE-UHE Gamma-ray Astronomy (ground-based)

Today, gamma-ray astronomy counts over 250 sources thanks to the Imaging Atmophseric Cherenkov Technique, working between 0.1 and 100 TeV

- 1989 : Whipple first detection of a TeV gamma-ray source
- 1990s 2ª Generation : HEGRA, CAT - recognized as the most advanced field of astroparticle physics, but still few (c. 10) sources
- 2000s 3ª Generation : HESS, MAGIC, VERITAS - revolution and rise of a new astronomical discipline (hundreds of sources)
- 2010 CTA : Start of CTA planning, the worldwide gamma-ray observatory
- 2020 LHAASO and SWGO : Rise of UHE / PeV Gamma-ray Astronomy.




Kifune Plot - © Stefan Funk

# Principais resultados da Astronomia Gama

- HESS, High energy particle acceleration in the shell of a supernova remnant, Nature 432, 75-77 **(2004)**
- HESS, A new population of very high energy gamma-ray sources in the Milky Way, Science 307 1938-1942 **(2005)**
- HESS, Discovery of very high energy gamma rays associated with an X-ray binary, Science 309 746-749 **(2005)**
- HESS, Fast variability of Tera-Electron Volt gamma-rays from the radio galaxy M87, Science 314, 1424 - 1427 **(2006)**
- HESS, Discovery of very-high-energy gamma-rays from the Galactic Centre ridge, Nature 439, 695-698 **(2006)**
- HESS, A low level of extragalactic background light as revealed by gamma-rays from blazars, Nature 440,1018-1021 **(2006)**
- HESS, H.E.S.S. observations of the Galactic Center region and their possible dark matter interpretation, PRL 97 221102 **(2006)**
- MAGIC, Variable very-high-energy gamma-ray emission from the microquasar LS I+ 61 303, Science 312 ,1771–1773 **(2006)**
- HESS, The energy spectrum of cosmic-ray electrons at TeV energies, PRL 101, 261104 **(2008)**
- HESS, Limits on an energy dependence of the speed of light from a flare of the active galaxy PKS 2155-304, PRL 101, 170402 **(2008)**
- MAGIC, Very-High-Energy gamma rays from a Distant Quasar: How Transparent Is the Universe?, Science 320 1752- **(2008)**
- MAGIC, Observation of Pulsed gamma-Rays Above 25 GeV from the Crab Pulsar with MAGIC, Science, 322, 1221- **(2008)**
- HESS, Detection of Gamma Rays from a Starburst Galaxy, Science 326, 1080-1082 **(2009)**
- MAGIC, Radio Imaging of the Very-High-Energy gamma-Ray Emission Region in the Central Engine of a Radio Galaxy, Science, **325,** 444- **(2009)**
- VERITAS, M82 - TeV gamma-ray emission from a new class of source: starburst galaxies, Nature, volume 472, 770-772, **(2009)**
- VERITAS, M87 - Gamma-rays from the edge of a supermassive black hole, Science 325, 444, **(2009)**
- HESS**,** Search for a Dark Matter annihilation signal from the Galactic Center halo with H.E.S.S. PRL 106, 161301 **(2011)**
- VERITAS, Detection of Pulsed Gamma Rays Above 100 GeV from the Crab Pulsar, Science 334: 69, (**2011)**

# Principais resultados da Astronomia Gama

- MAGIC, Black hole lightning due to particle acceleration at subhorizon scales, Science, 346,1080 **(2014)**
- HESS, The exceptionally powerful TeV gamma-ray emitters in the Large Magellanic Cloud, Science 347, 406-412 **(2015)**
- HESS, Search for dark matter annihilations towards the inner Galactic halo from 10 years of observations with H.E.S.S., PRL 117, 111301 **(2016)**
- HESS, Acceleration of petaelectronvolt protons in the Galactic Centre, Nature 531, 476 **(2016)**
- HAWC, Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth, Science 6365, 911-914 **(2017)**
- HAWC, Very high energy particle acceleration powered by the jets of the microquasar SS 433, Nature 562 82-85 **(2018)**
- HESS, Search for gamma-ray line signals from dark matter in the inner Galactic halo from ten years of observations, PRL 120, 201101 **(2018)**
- MAGIC, Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A, Science, 361 eaat1378 **(2018)**
- HESS, A very-high-energy component deep in the gamma-ray burst afterglow, Nature 575 464 **(2019)**
- HESS, Resolving the Crab pulsar wind nebula at teraelectronvolt energies, Nature Astron. 476 **(2019)**
- MAGIC, Observation of inverse Compton emission from a long γ-ray burst, Nature, 575, 459-463 **(2019)**
- MAGIC, Teraelectronvolt emission from the γ-ray burst GRB 190114C, Nature, 575, 455-458 **(2019)**
- TIBET**,** First detection of photons with energy beyond 100 TeV from an astrophysical source, PRL, **123,** 051101 (6 pp.) **(2019)**
- VERITAS, Direct measurement of stellar angular diameters by the VERITAS Cherenkov Telescope, Nature Astron. 3: 511 **(2019)**
- HESS, Resolving acceleration to very high energies along the jet of Centaurus A, Nature 82, 356–359 **(2020)**
- MAGIC, Bounds on Lorentz invariance violation from MAGIC observation of GRB 190114C, PRL 125 021301 **(2020)**
- VERITAS, Demonstration of stellar intensity interferometry with the four VERITAS telescopes, Nature Astron. **(2020)**
- HAWC, Hawc observations of the acceleration of very-high-energy cosmic rays in the cygnus cocoon, Nature Astron. **(2021)**
- HESS, Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow, Science Vol. 372, pp. 1081-1085 **(2021)**
- LHAASO, Extended Very-High-Energy Gamma-Ray Emission Surrounding PSR J0622 + 3749 Observed by LHAASO-KM2A, PRL 126, 241103 **(2021)**
- LHAASO, PeV gamma-ray emission from The Crab Nebular, Science, 08 Jul (**2021)**
- LHAASO, Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources, Nature, volume 594, pages 33–36 **(2021)**

# Astroparticle Physics : MM scenario

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sub-mm IR-UV X-rays **Gamma-rays** →

**meV … eV … keV … MeV …** GeV … TeV … PeV … EeV … ZeV

**Realm of Astroparticle Physics**

**Astronomy with photons**

**Charged cosmic-ray physics: p, e-, He, Fe, …**

**Neutrino signals**

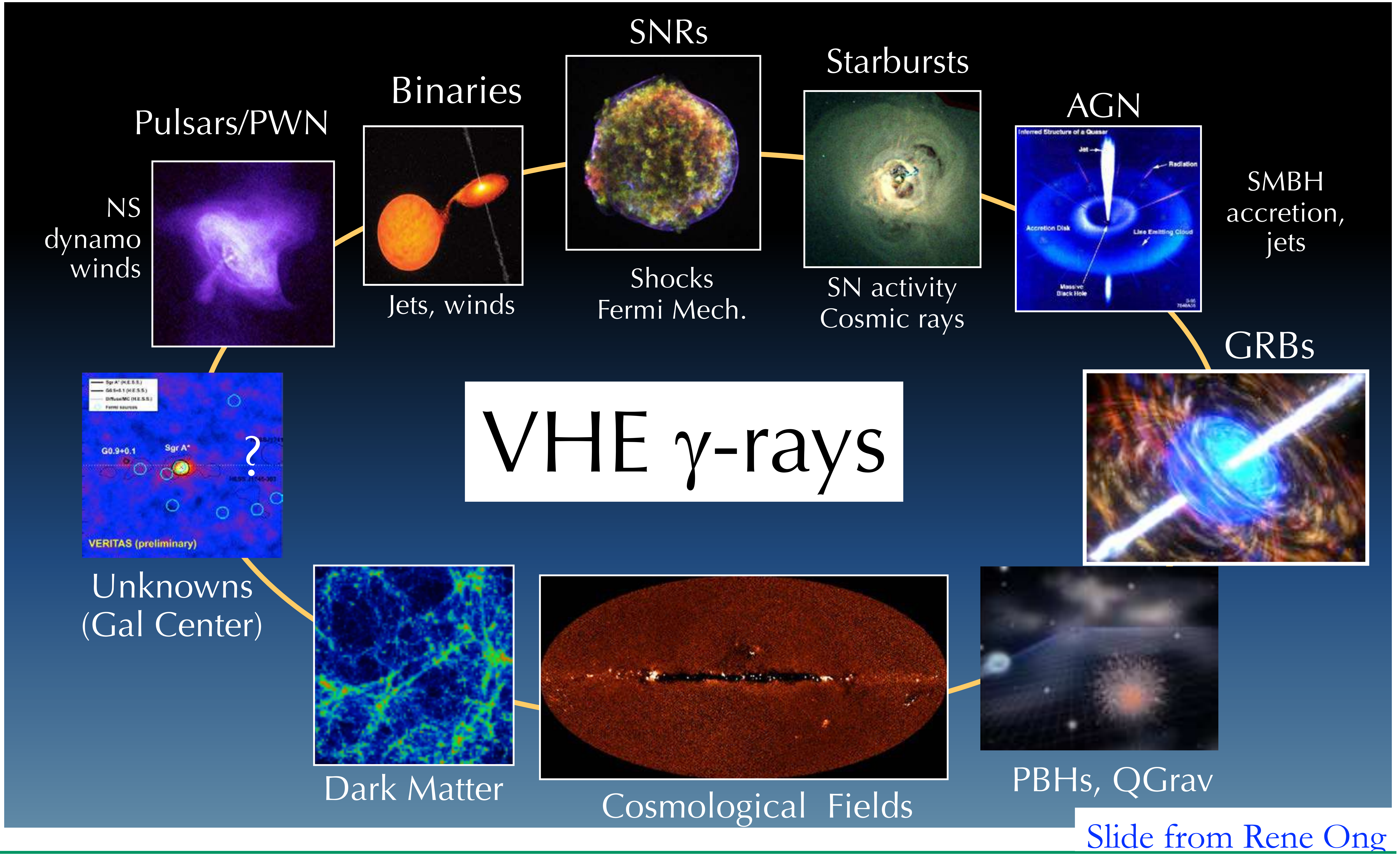
**All messengers are interconnected and relate back to the same sources: multi-messenger astrophysics**



**GRAVITATIONAL WAVES? PROBES OF COMPACT SOURCES**

## Non-thermal Astrophysics

## Astro-particle Physics



# Connecting the puzzle

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**All messengers are connected and relate back to the same sources: logic behind the multi-messenger astrophysics**

$p^+$, He, Fe,....

Interactions with matter and photon-fields → $\pi^{+/-}$ → $\mu^{+/-}$ $\nu_\mu$

$\pi^0$ → $\gamma\gamma$

$\mu^{+/-}$ → $e^{+/-}$ $\nu_e$ $\nu_\mu$

$p^+$,$e^-$ → MWL

**Only charged particle are accelerated in EM fields**

**Synchrotron in B-fields, inverse-Compton… $p^+$, inefficient**

**Intense radiative losses => hadronic hard X-rays or soft-gamma signature**

**Easy detection**

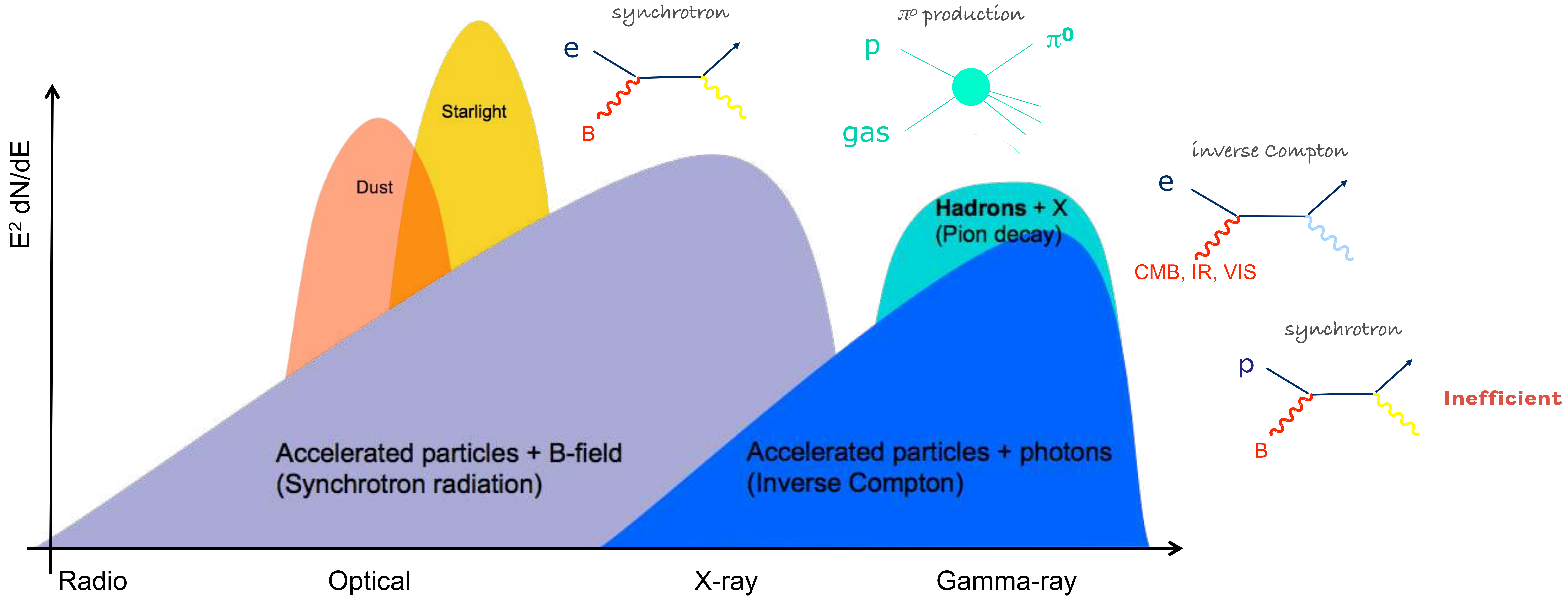
**Difficult detection**

MM Astronomy : Directionality information preserved, but strong backgrounds.

**Gamma-rays are the cornerstone of multi-messenger astrophysics**

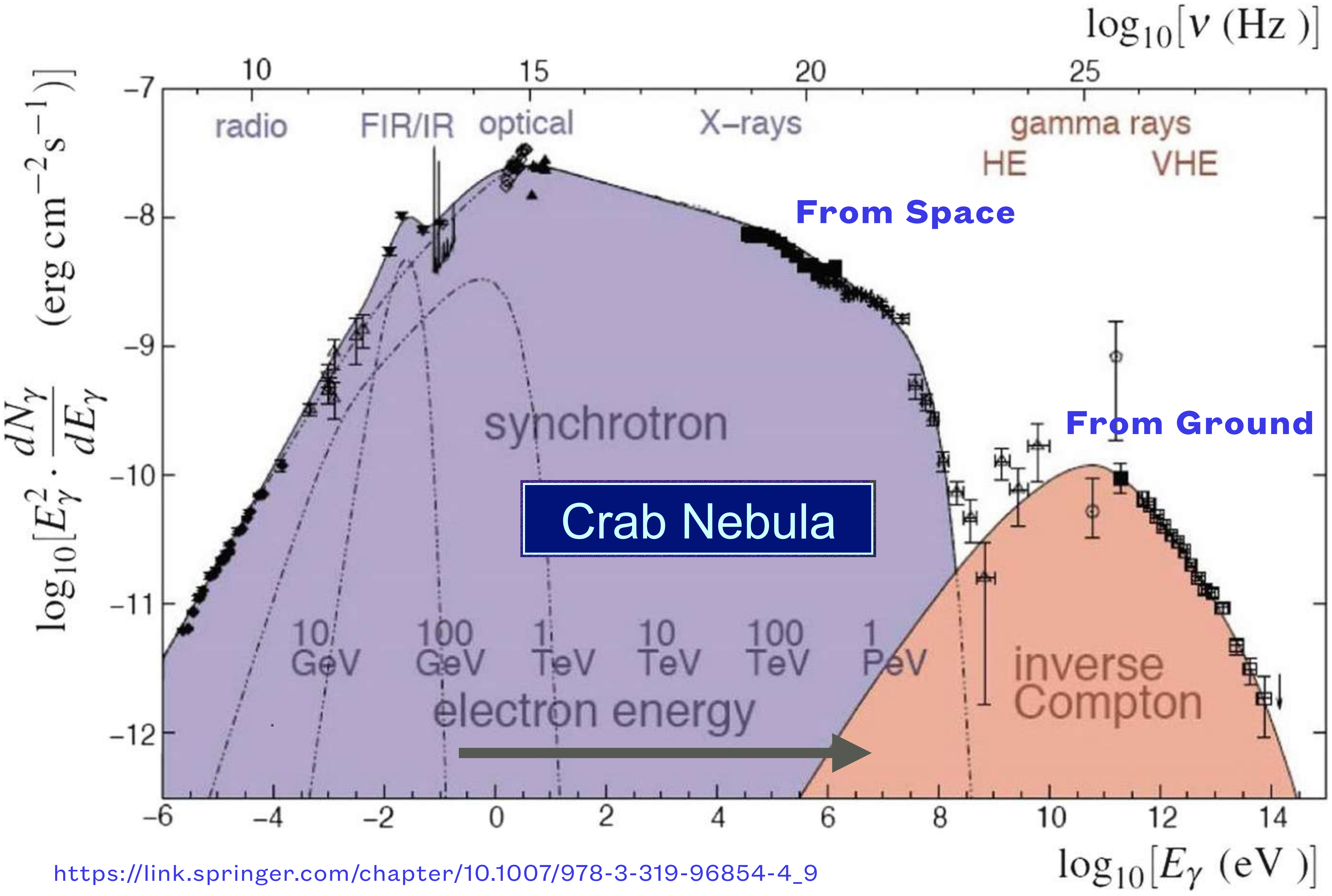
© adapted from a slide by Johannes Knapp

# Anatomy of a relativistic astrophysical source




© plot by Christian Stegmann, DESY, MG XIV Meeting 2015 (modified)

# Electron PeVatrons and hadronic X-rays?




https://link.springer.com/chapter/10.1007/978-3-319-96854-4_9

The synchrotron spectrum of sources like the Crab Nebula point towards **multi-100 TeV electron populations**.

MeV Sy emission could be the result from primary accelerated, or secondary multi-100 TeV electrons produced from proton interactions => hadronic marker at hard X-rays (also ambiguous and model dependent)

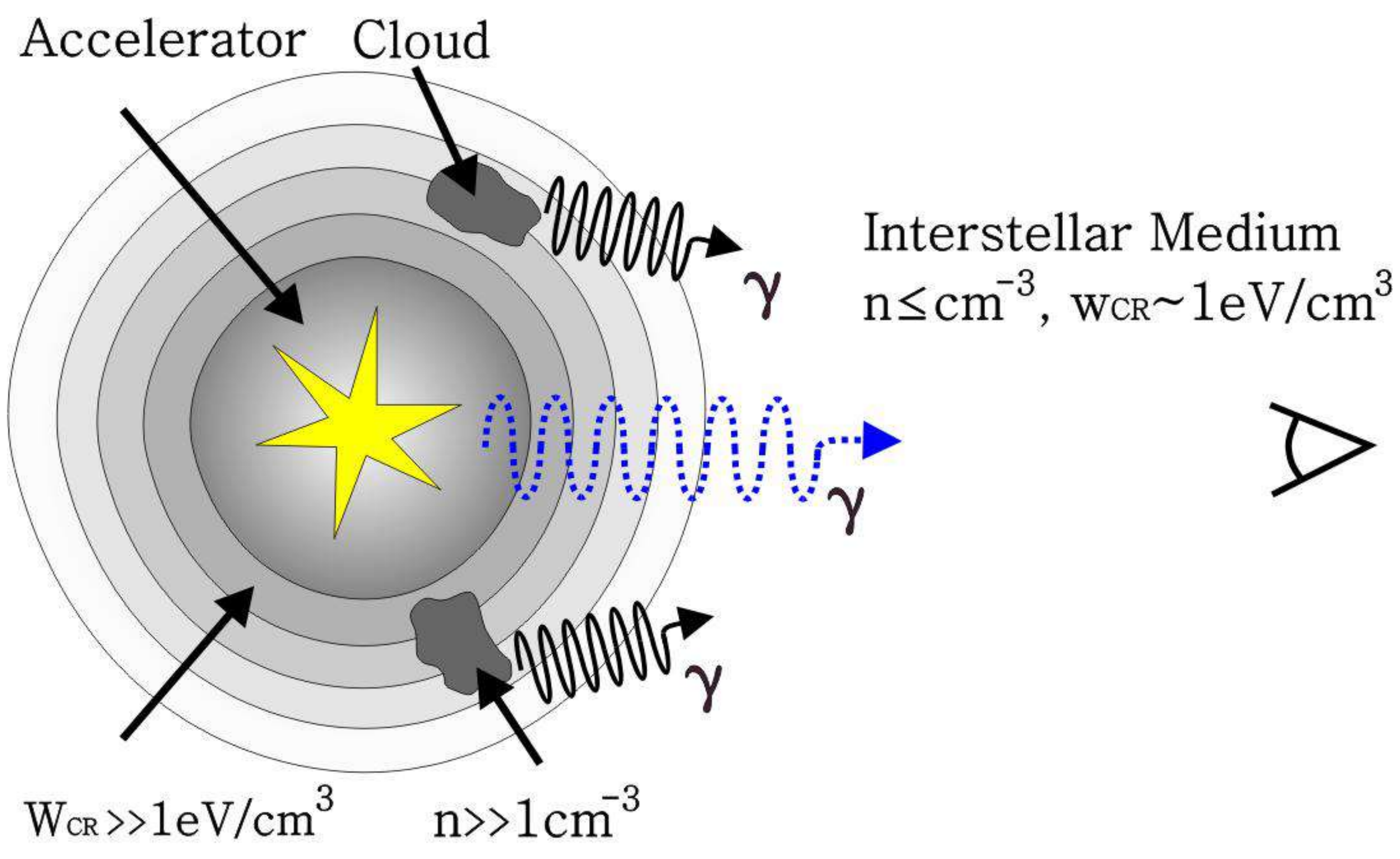
(1) pp(γ) => π, K, Λ; (2) π, K, Λ => γ, ν, e, μ (3) e B => X-rays

(1) pγ=> e+e-; (2) eB => X-rays

# Gamma-ray signals : source + target

The presence of a powerful accelerator is not sufficient for the production of gamma-rays from charge particle populations; a dense target is also necessary.

The gamma-rays track, therefore the target, and not necessarily the sources of particle acceleration.

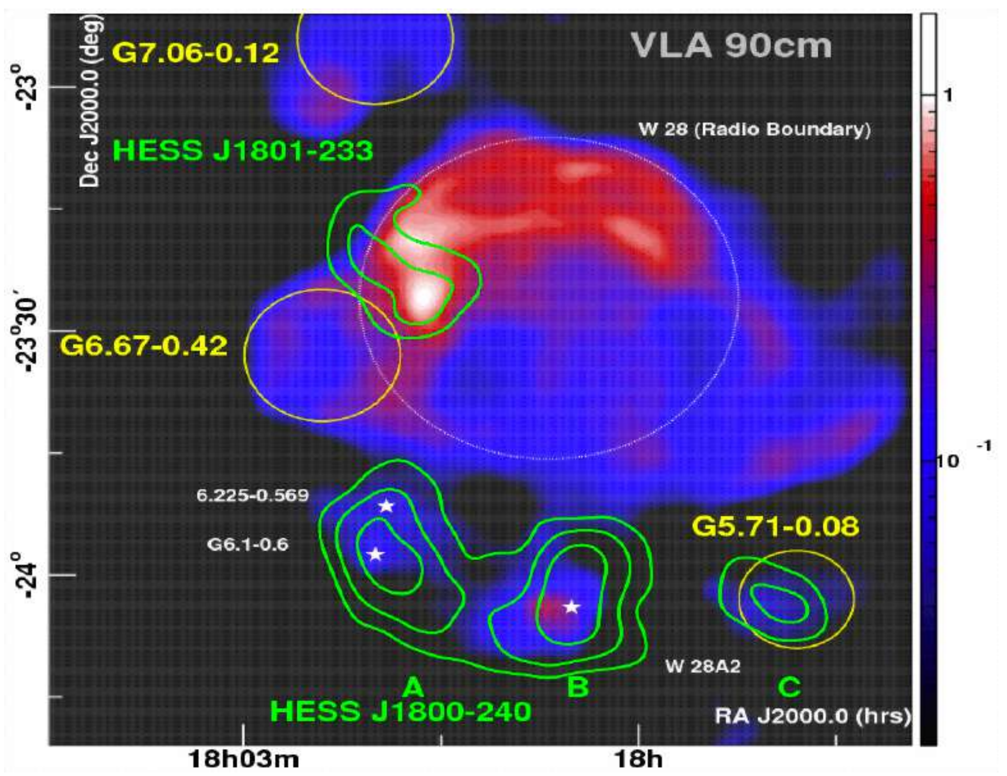


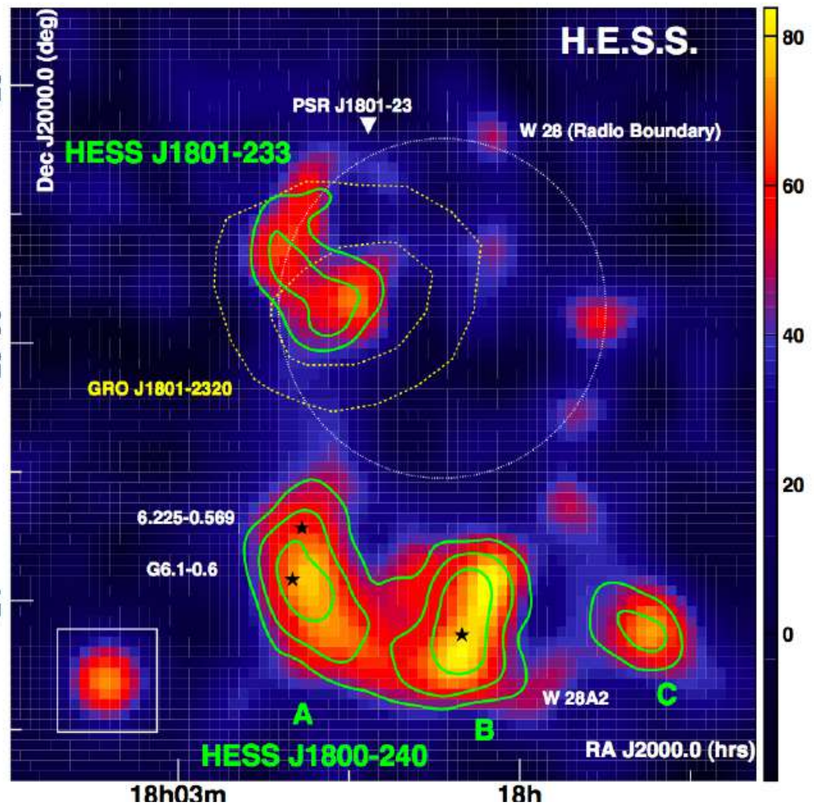

Targets - matéria, radiation, magnetic fields

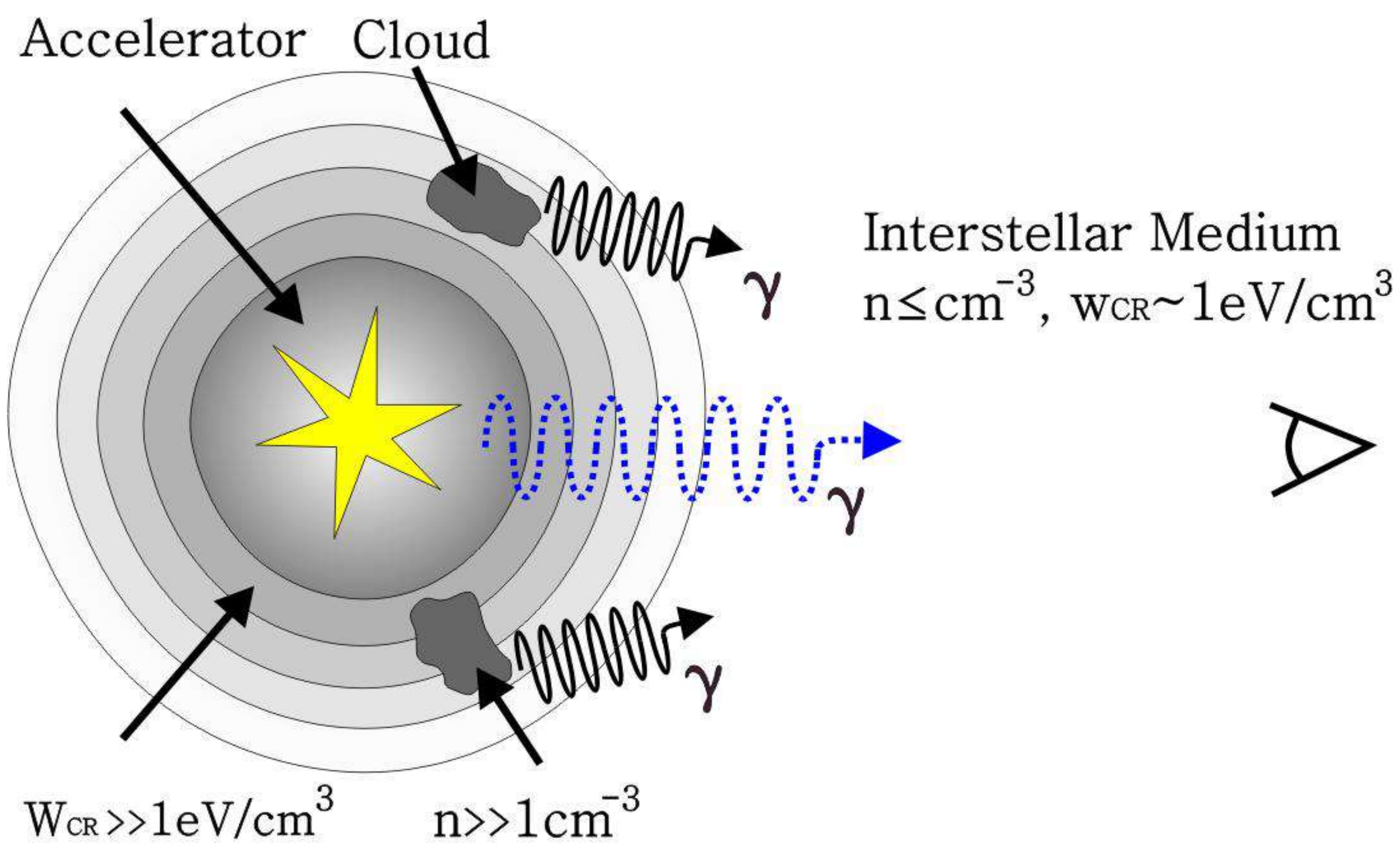
# Example:

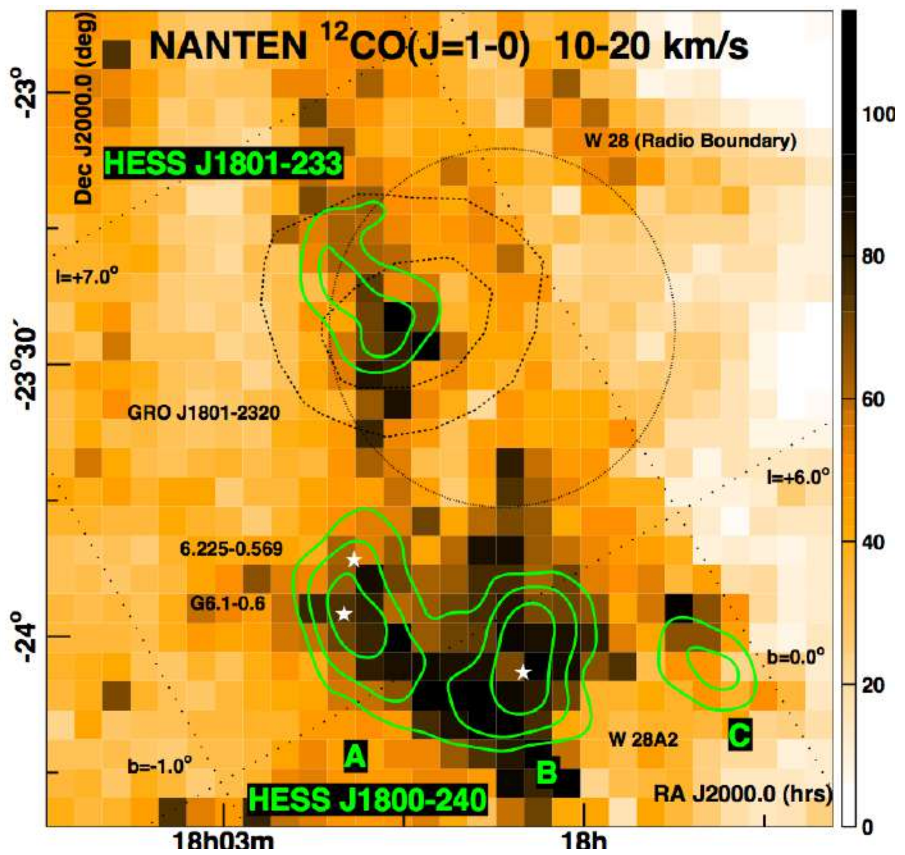
Gamma-ray source around W28

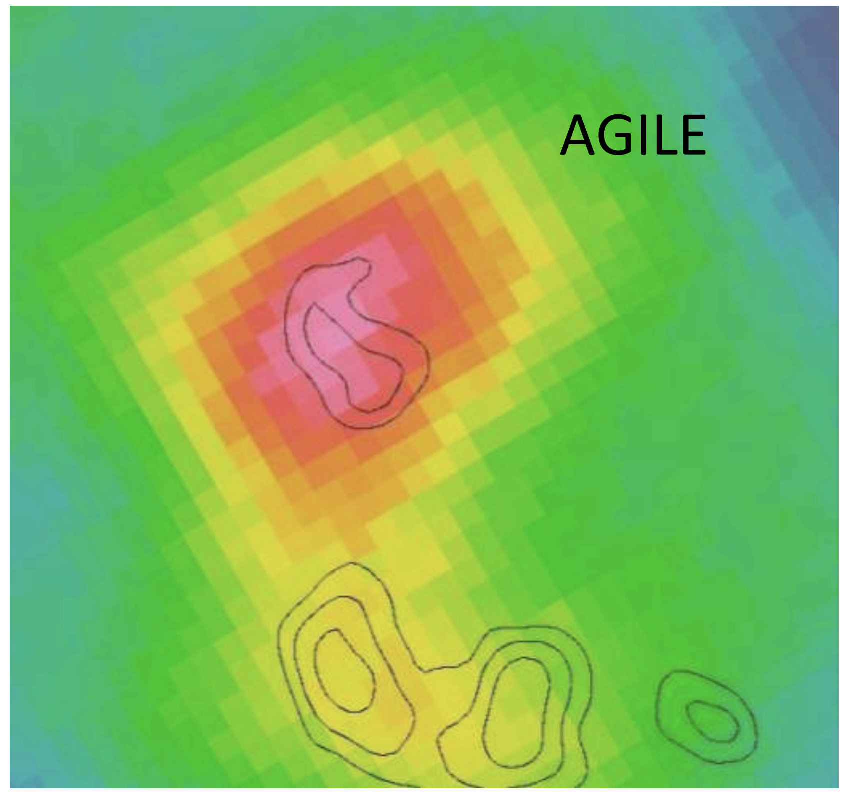
Cosmic-rays from an old SNR interacting with matter from a surrounding molecular cloud?




Targets - matéria, radiation, magnetic fields

# CTA SYNERGIES WITH MWL INSTRUMENTS



# CTA SYNERGIES WITH MWL INSTRUMENTS

© slide by Werner Hofmann, modified


- Non-thermal emission in radio
- High-resolution VLBI to image emission zones
- Mapping of the diffuse gas (CR targets) to complement CTA view of diffuse emission around accelerators

- Detection of fast-variability signals from compact sources
- Optical polarimetry to isolate non-thermal component in mixed emission scenarios

- X-ray study of shock regions, accretion, high-speed outflows, which connect back to particle acceleration
  - Soft gamma-ray telescopes for detection of high-energy transients

MWL

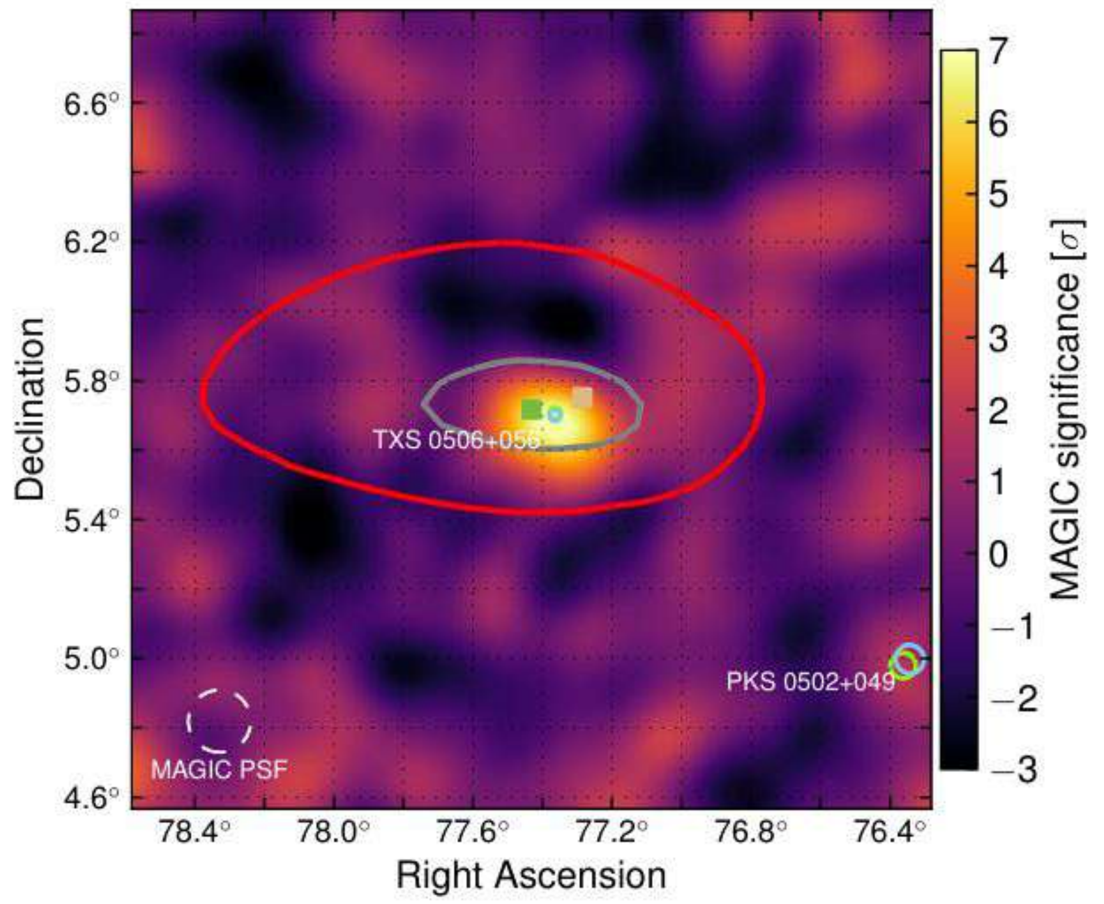
# Multi-messenger Phenomenology

## Multi-messenger Astrophysics has emerged in the past decade, with gamma-ray astronomy at its very center.

- **Attempt at a neutrino / VHE connection for TXS 0506+056**

  IceCube / Fermi-LAT / MAGIC

  2018 - Science 361, 6398



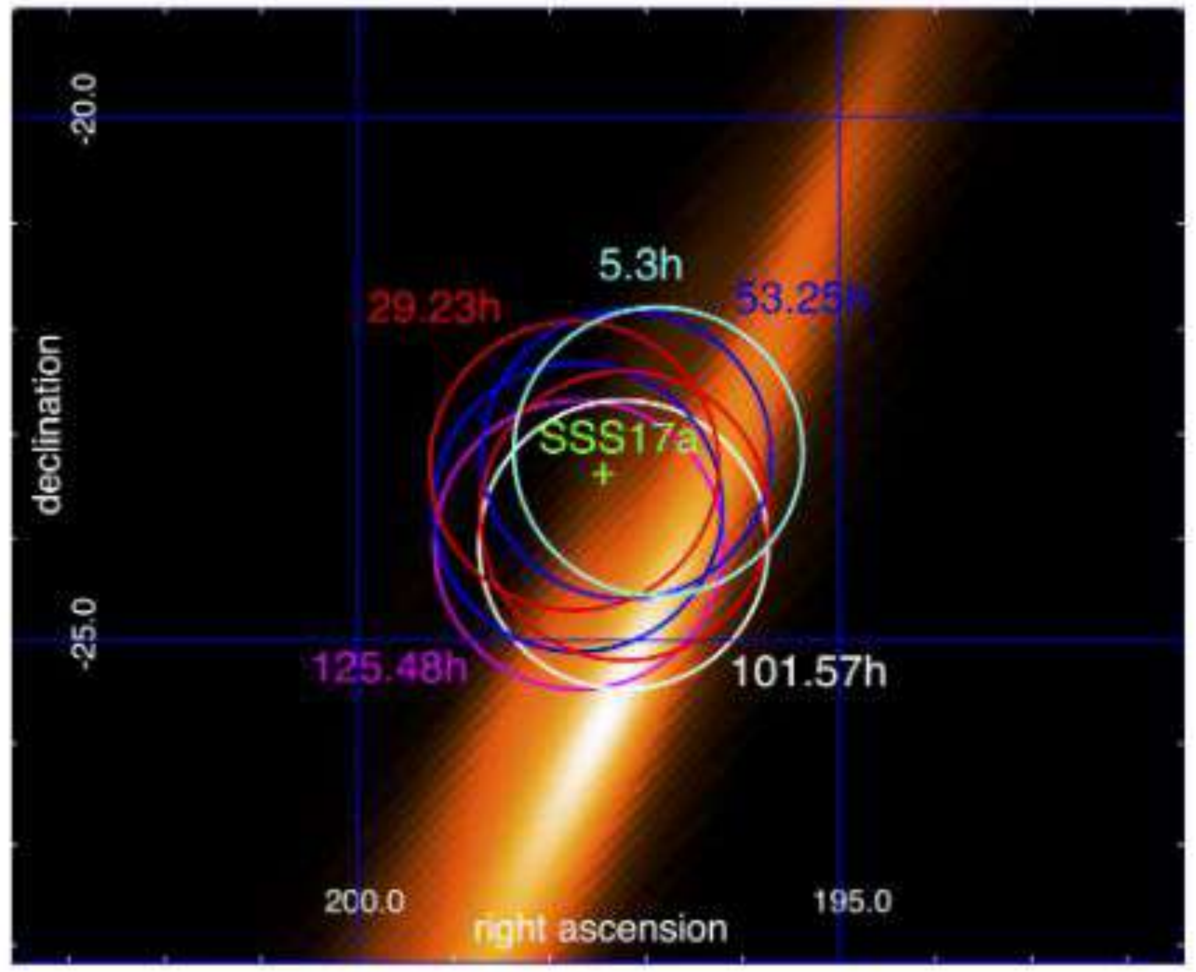

- **TeV Observations of event GW 170817**

  Upper-limits from HESS.

  2017 - ApJL 850, L22

  Upper-limits from Fermi-LAT.

  2018 - ApJ 861, 85



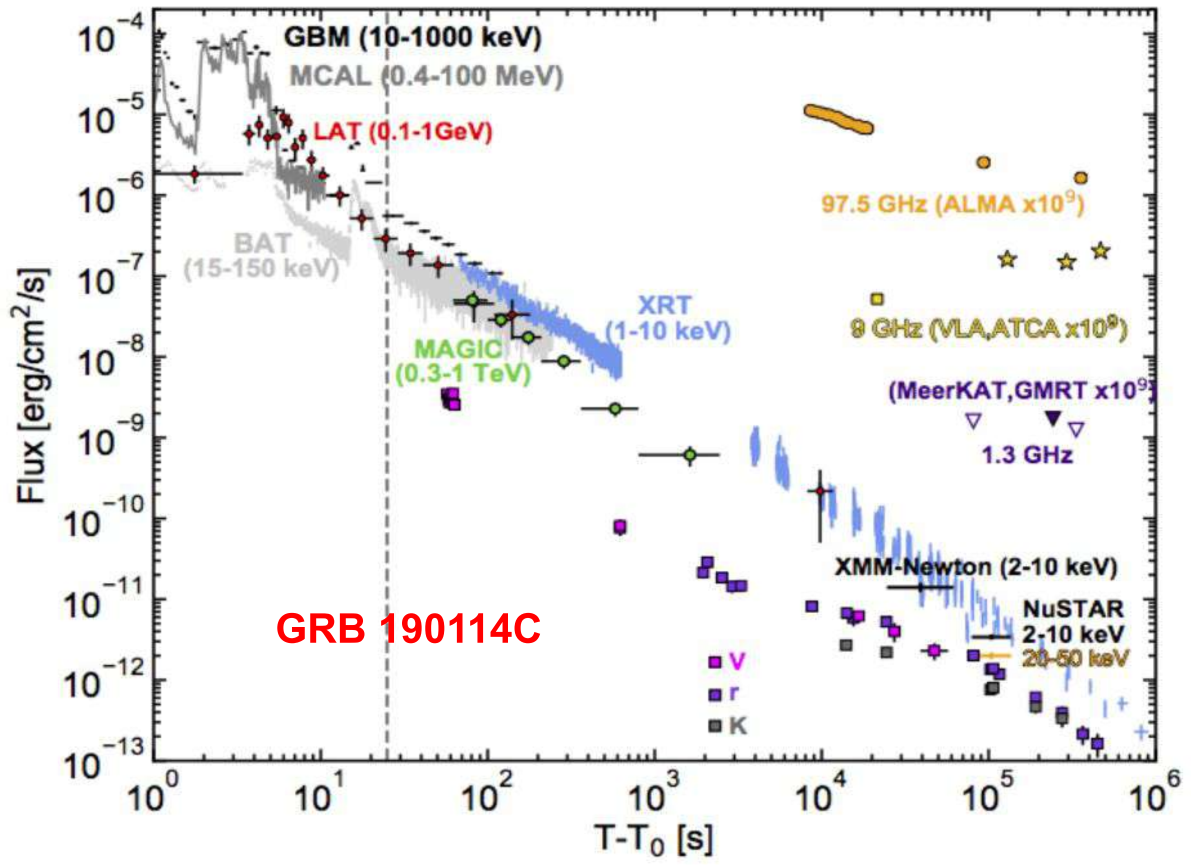

- **GRB detection at VHE: a breakthrough and a gateway to probing GW events at TeV energies**

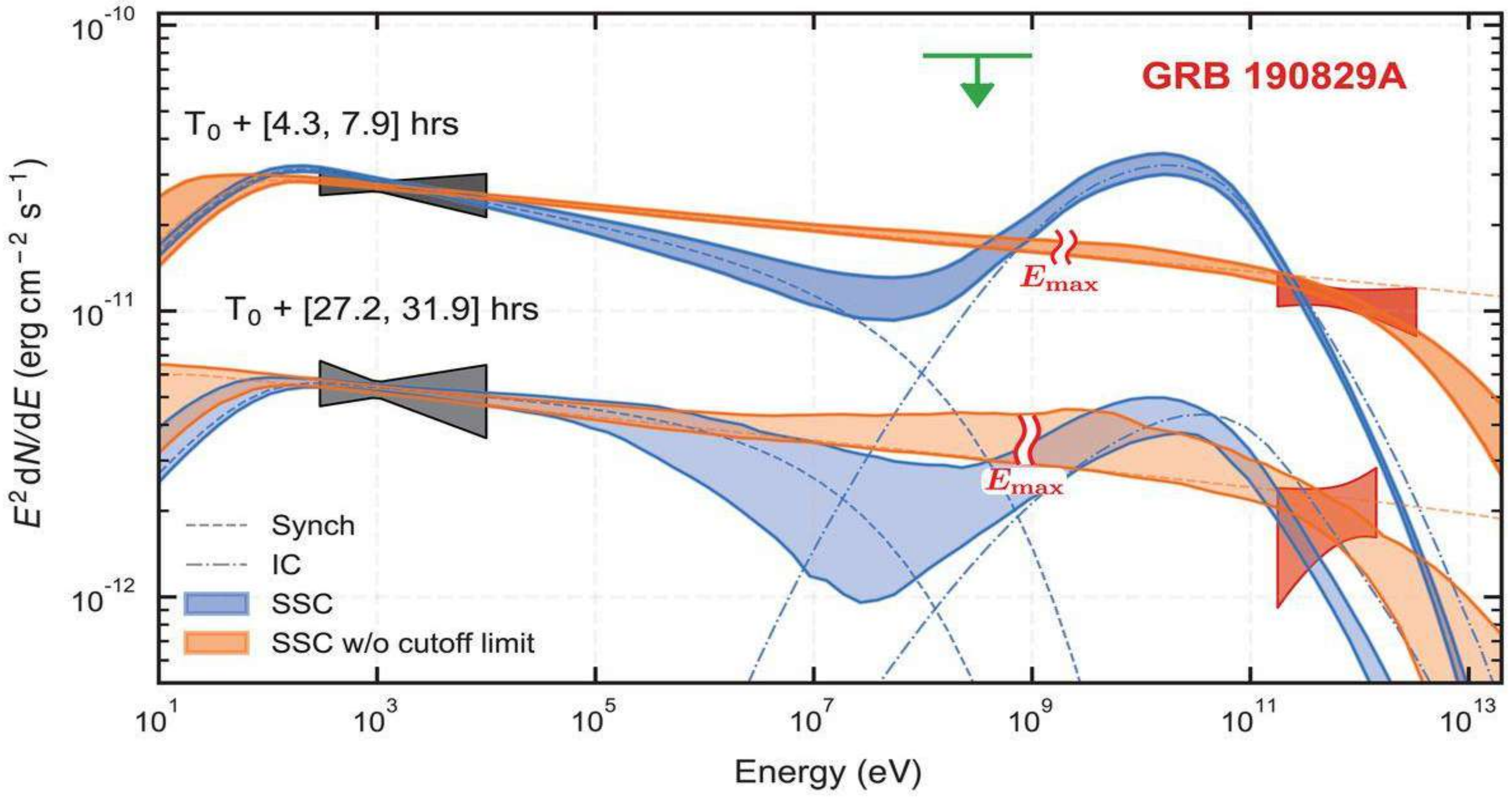
  GRB 190114C / MAGIC

  early afterglow detection (< 100s)

  GRB 190829A / HESS

  late afterglow detection (> ks)



# Multi-messenger Phenomenology

CBPF Centro Brasileiro de Pesquisas Físicas
UNIDADE DE PESQUISA DO MCTI

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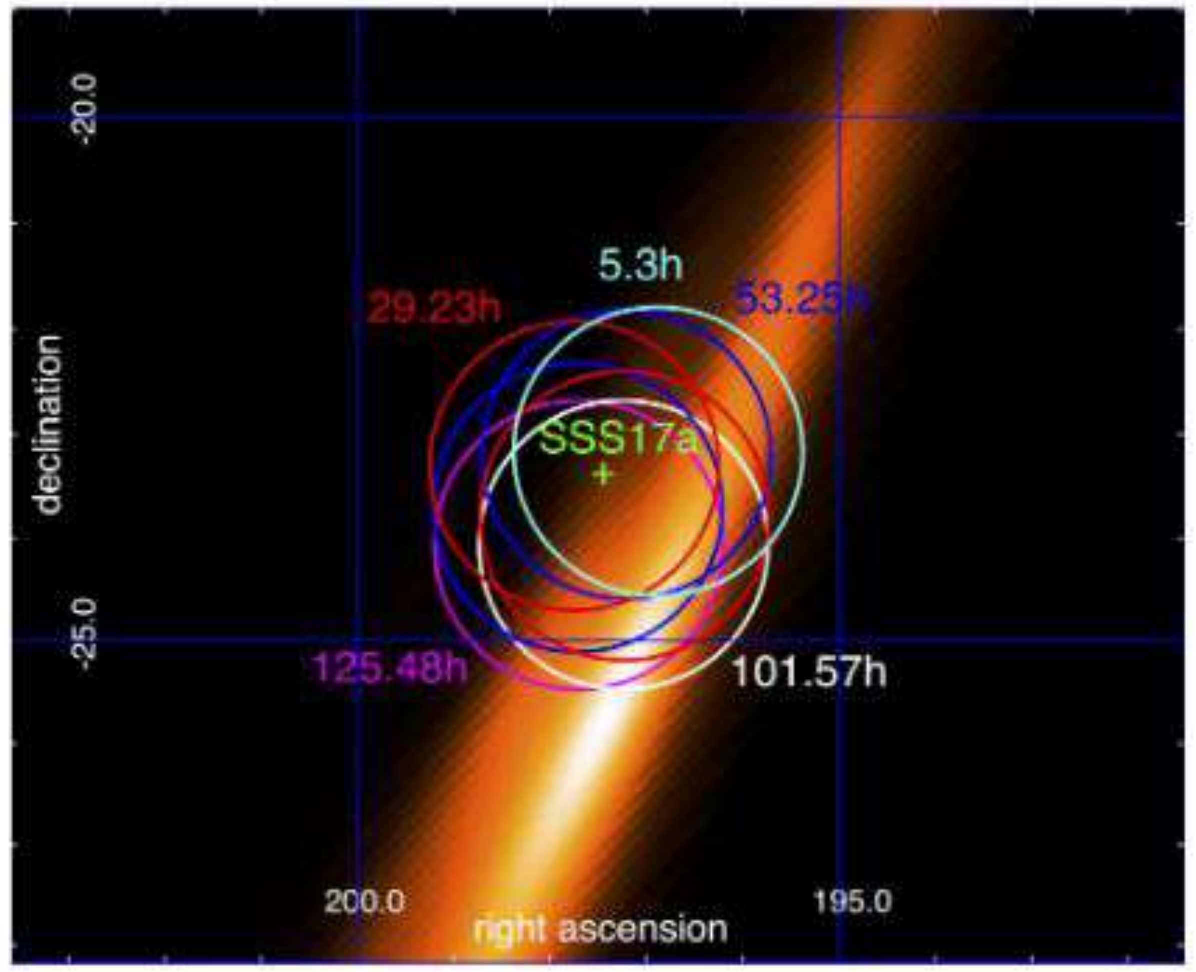


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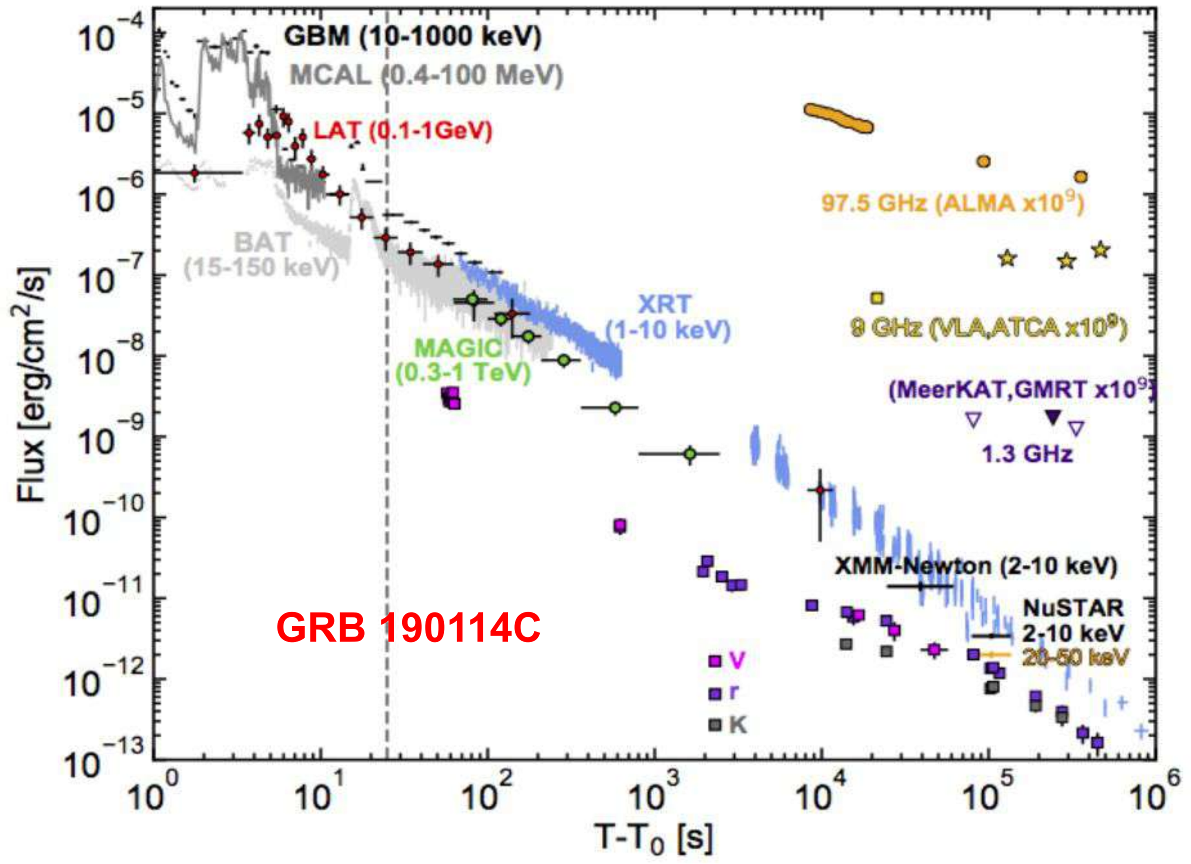
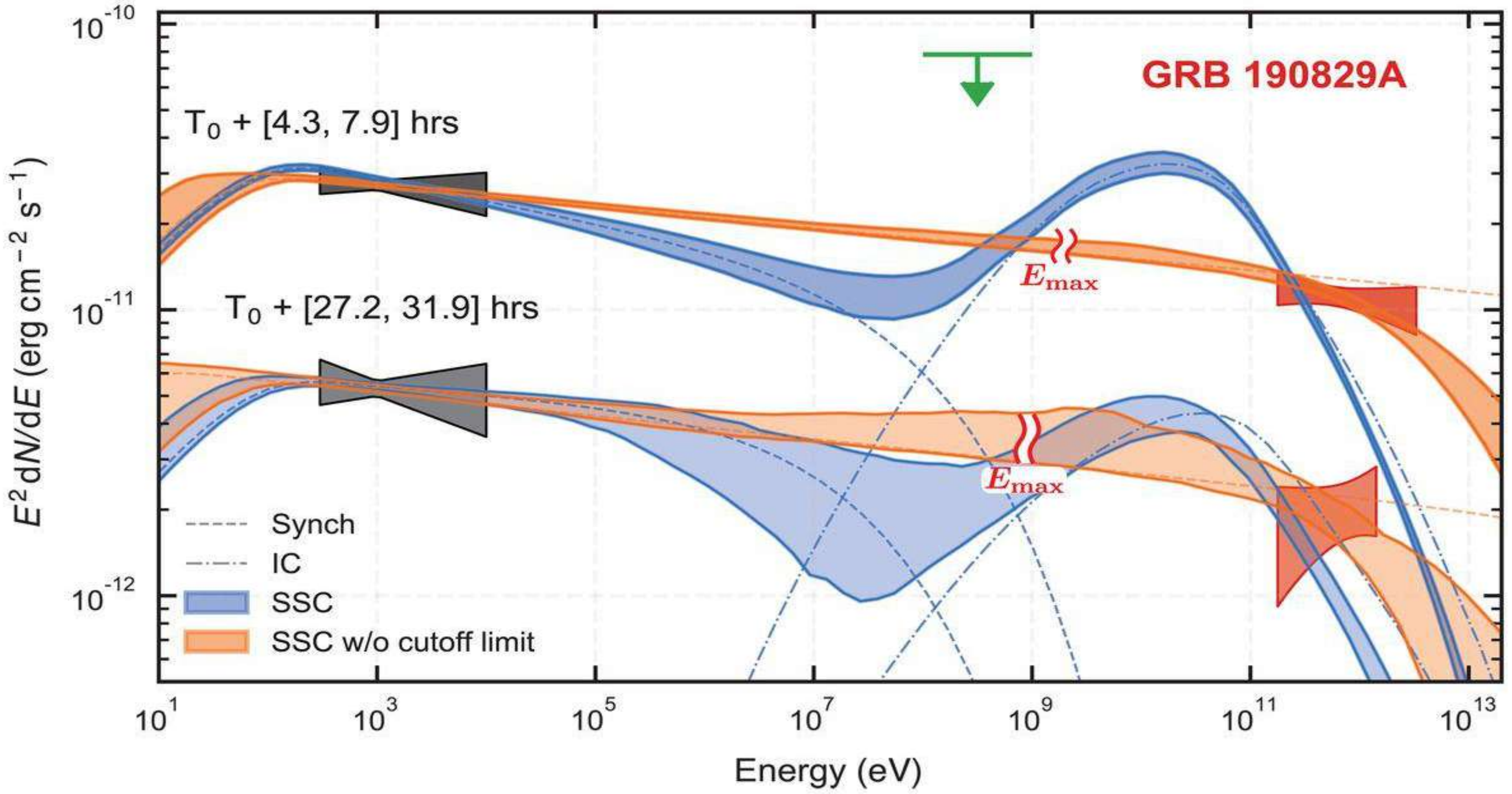
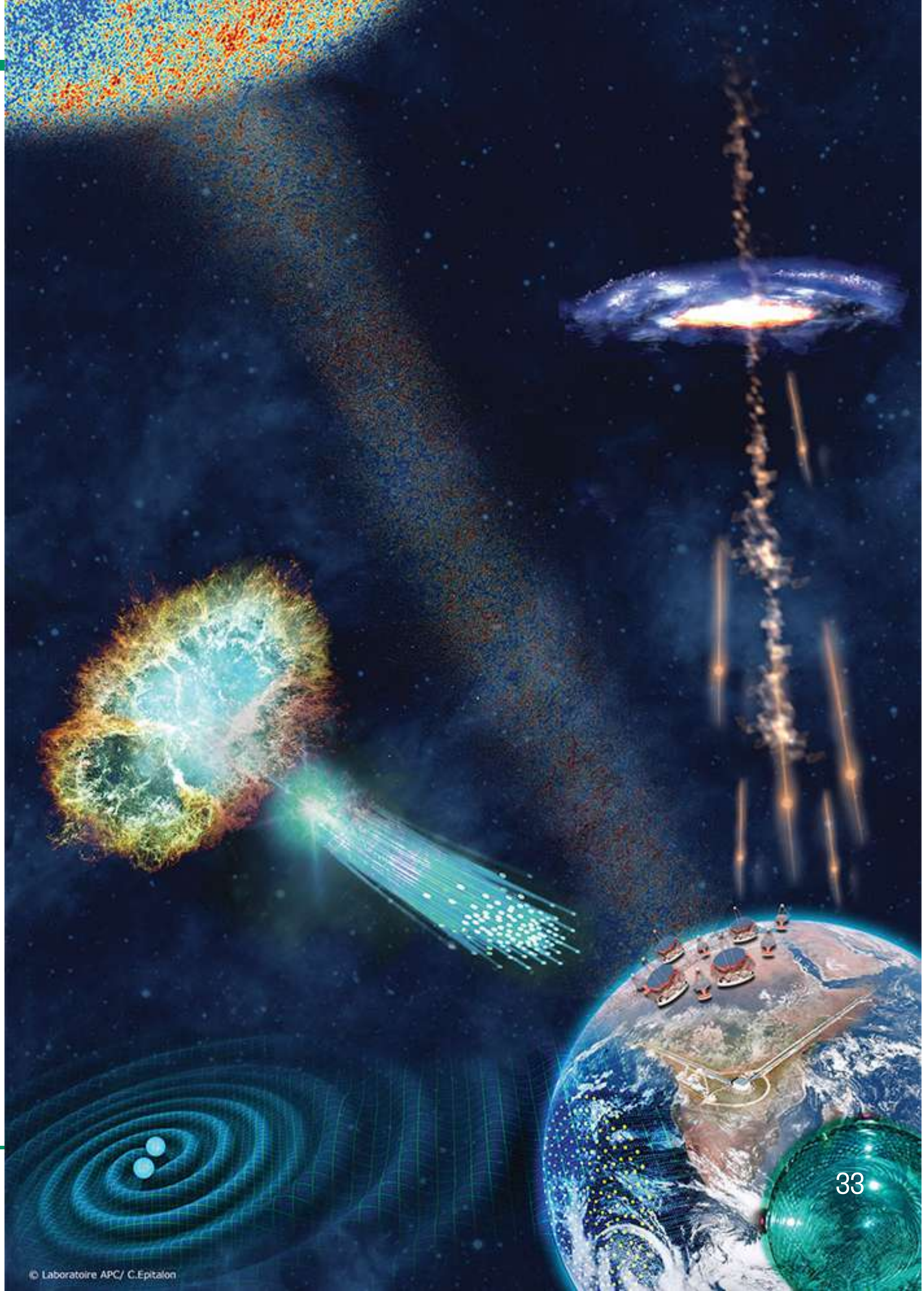


# The CTA Context



# Gamma-ray ground-based facilities

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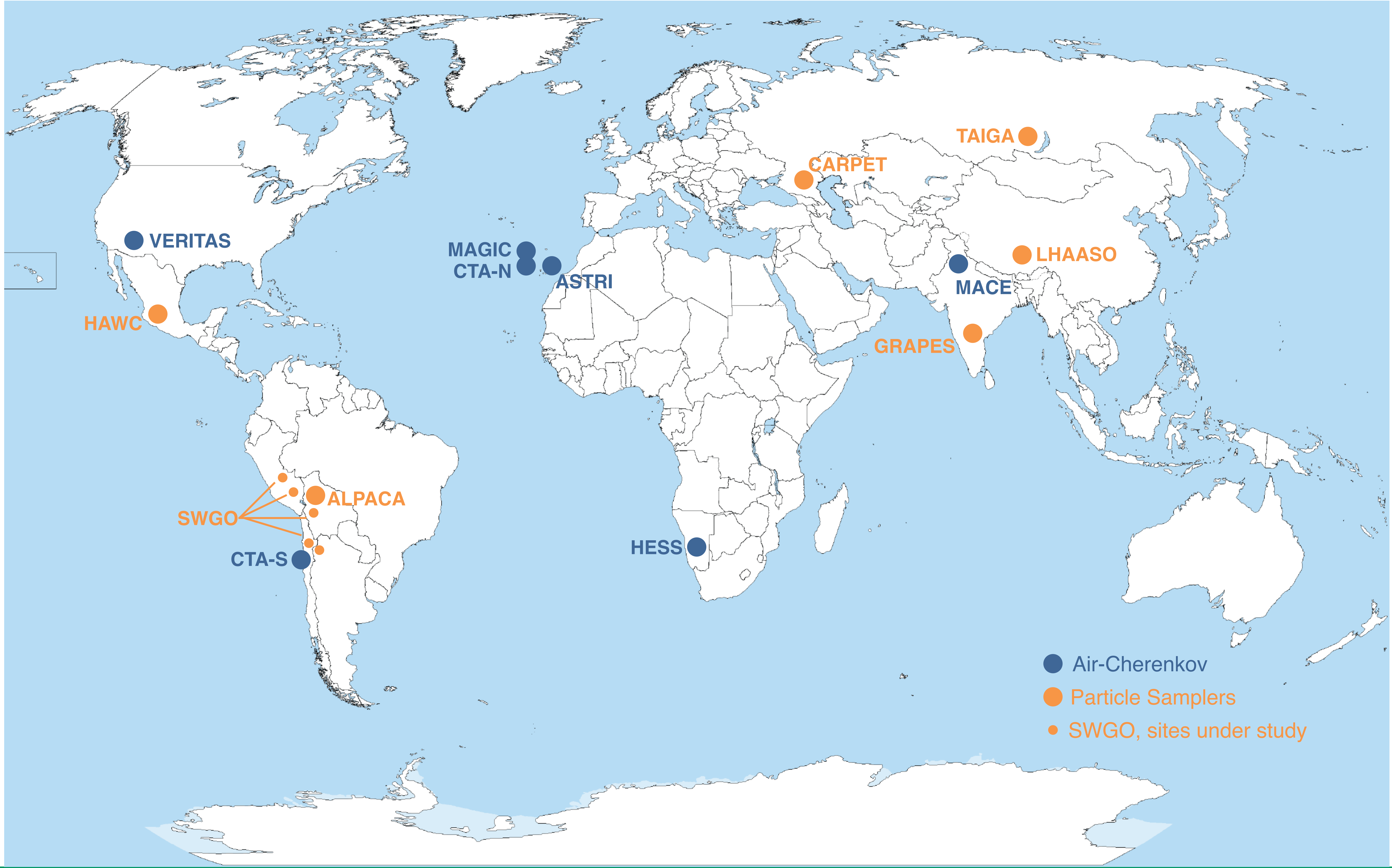



**IACTS -** ASTRI and MACE = extended longitude coverage capabilities, with low-E threshold and deep source observations towards high energies

**Particle arrays -** LHAASO & SWGO = unprecedented all-sky coverage at VHE-UHE for alert and monitoring, as well as all-sky surveys.

Thanks to Werner Hofmann

# WHAT DRIVES HIGH IMPACT SCIENCE?

Number of H.E.S.S Nature & Science papers

Year →

| 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | | | 2 | | | | | | 1 | 1 | | 1 | 2 | 1 | 1 |

CT1 operat

**New instrument**

28 m telescope CT5 added

CT1-4 camera upgrade

CT5 camera upgrade

**MWL/MM:**

- Multimessenger observations of a flaring blazar coincident with high-energy neutrino
- A very-high-energy component deep in the gamma-ray burst afterglow
- Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow

**Deep observations:**

- The exceptionally powerful TeV gamma-ray emitters in the Large Magellanic Cloud
- Acceleration of petaelectronvolt protons in the Galactic Centre

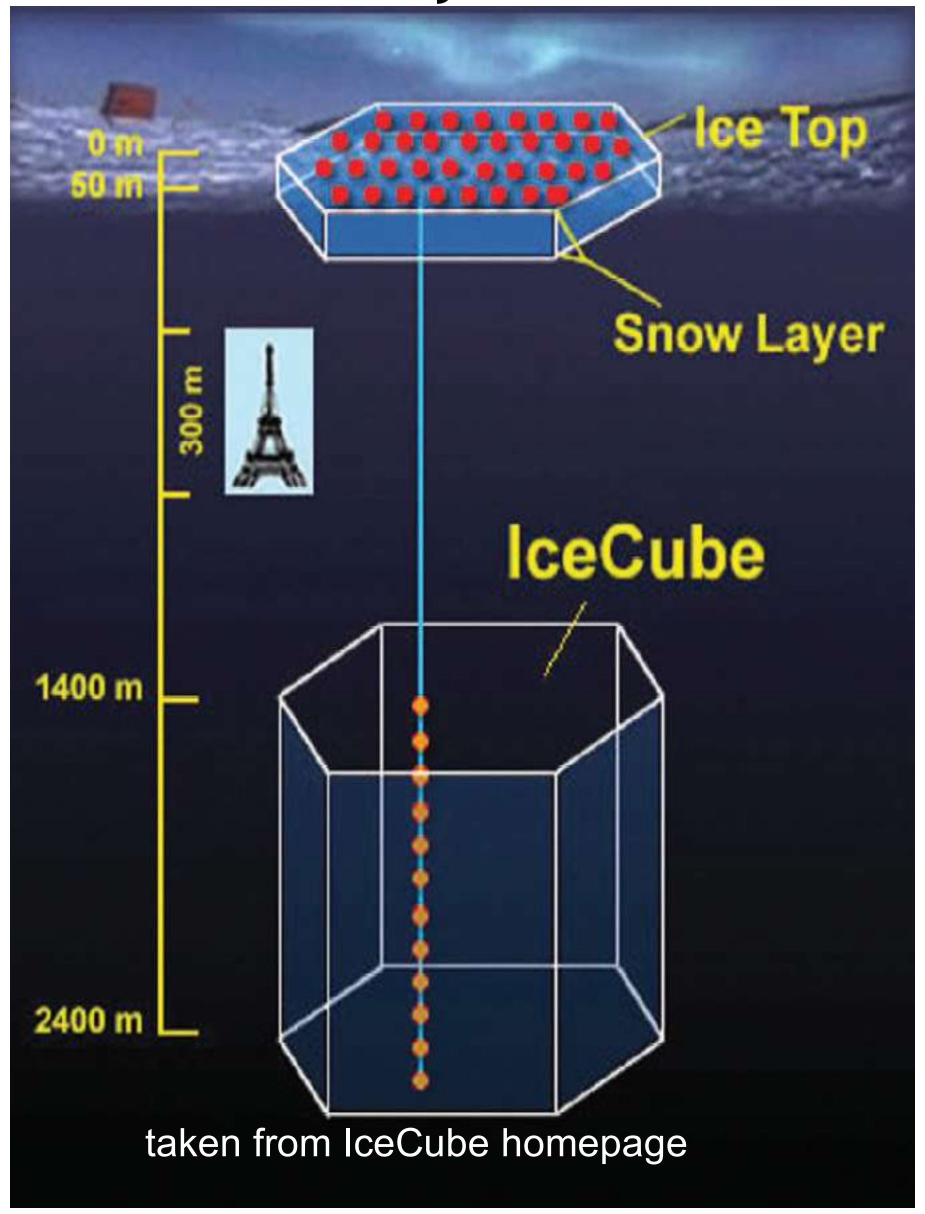
**New analysis techniques**

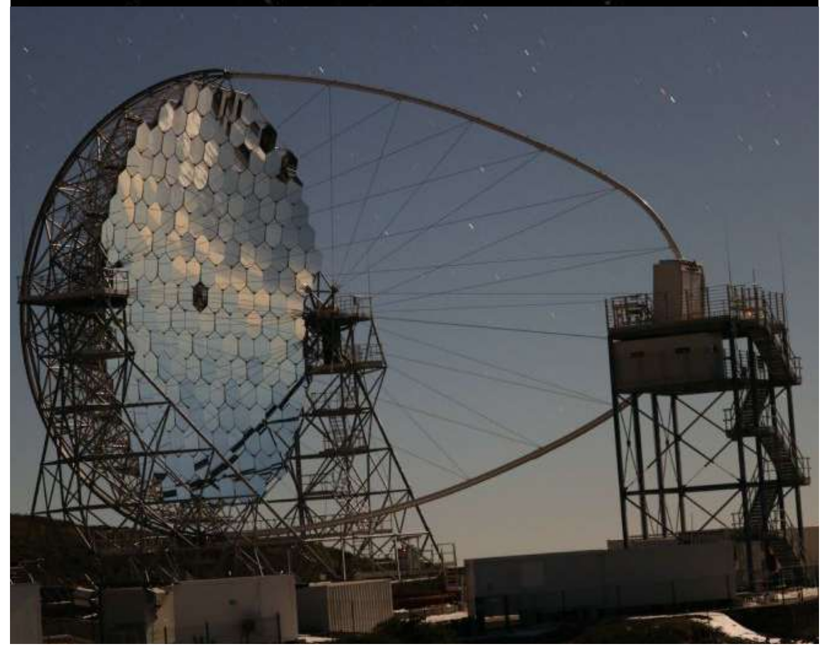
- Resolving the Crab pulsar wind nebula at teraelectronvolt energies
- Resolving acceleration to very high energies along the jet of Centaurus A

# CTA as a player in the MWL+MM arena

## Neutrinos

IceCube, KM3Net



## Gamma-rays

Fermi, LHAASO, IACT…

## Cosmic rays

AMS-02, Auger,…

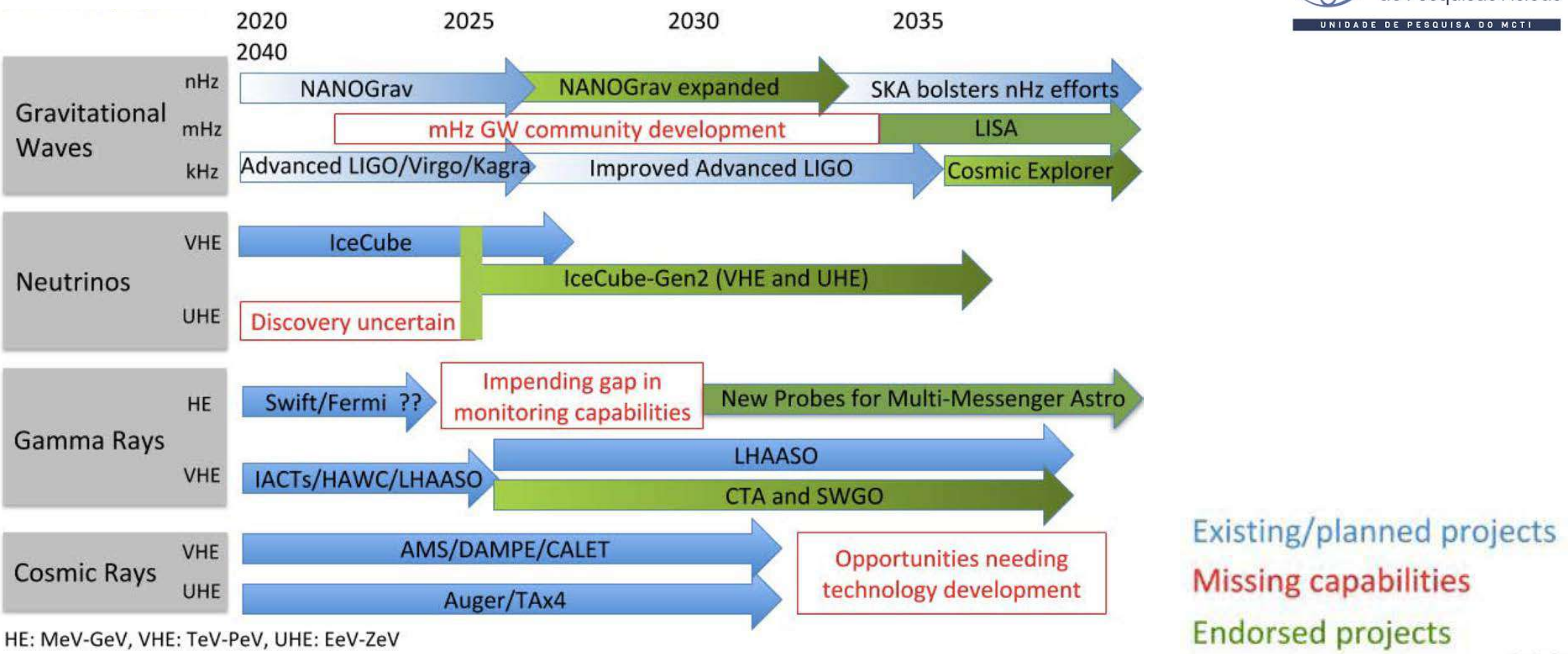
## MWL Facilities


## Gravitational Waves

LIGO, VIRGO, KAGRA

(Reshmi Mukherjee)

# MM Perspective from Astro 2020



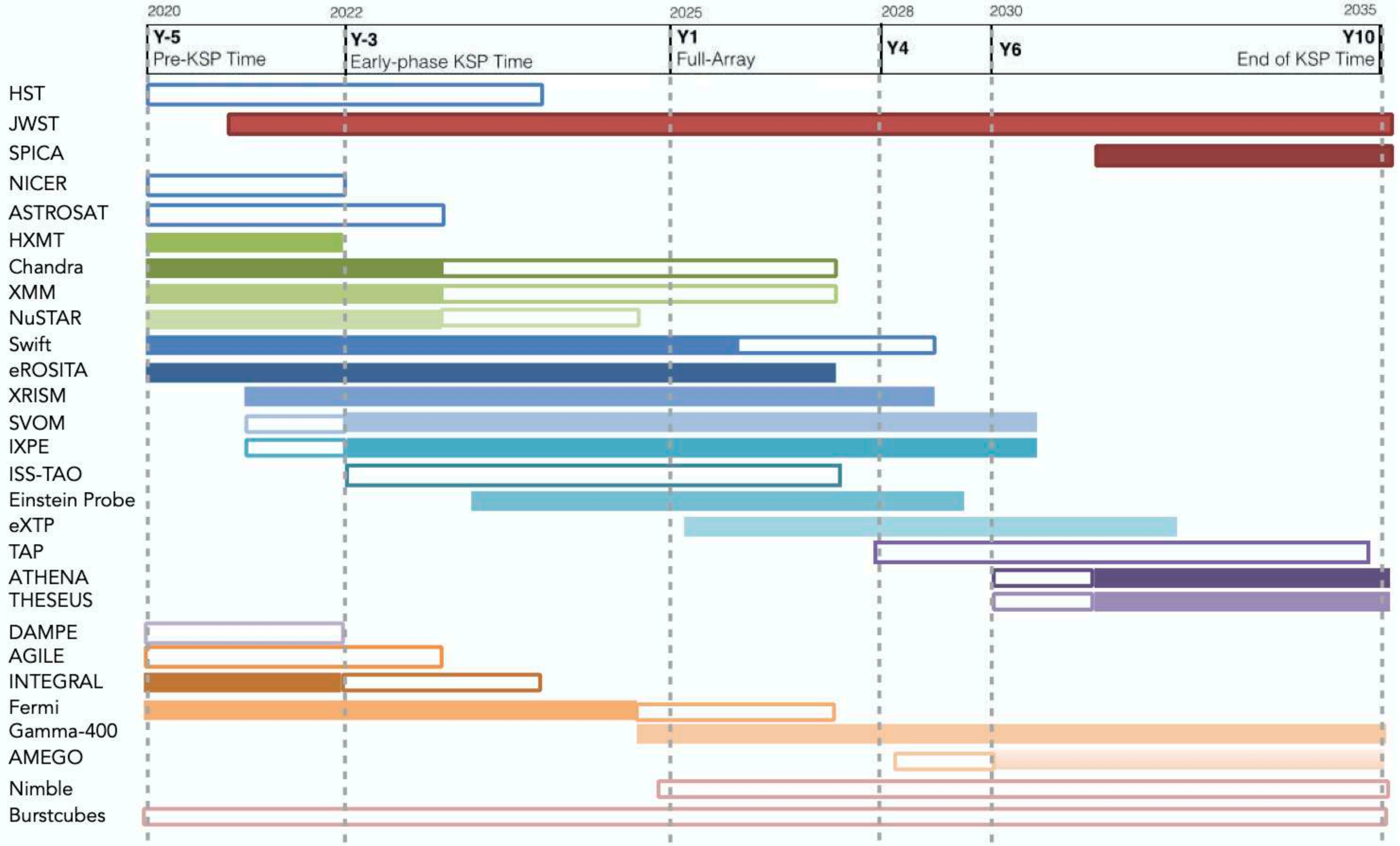
# CTA as a player in the MWL+MM arena

**CTA will be the largest <u>(open)</u> observatory in the VHE range (20 GeV - 300 TeV), with two sites in both hemispheres for full sky access**


- most sensitive in the range below < 10s TeV
- unique short timescale sensitivity (> $10^3$ x Fermi-LAT) < 300 GeV
- unique angular resolution < 0.01° in entire energy range
- largest FoV in a pointing instrument (~ 8°), ideal for surveys
- rapid response of LSTs (< 30 s)

A powerful and large precision instrument in the TeV range

**Operations expected to start in 2027 : contemporaneous to a new generation of MWL and MM instruments**



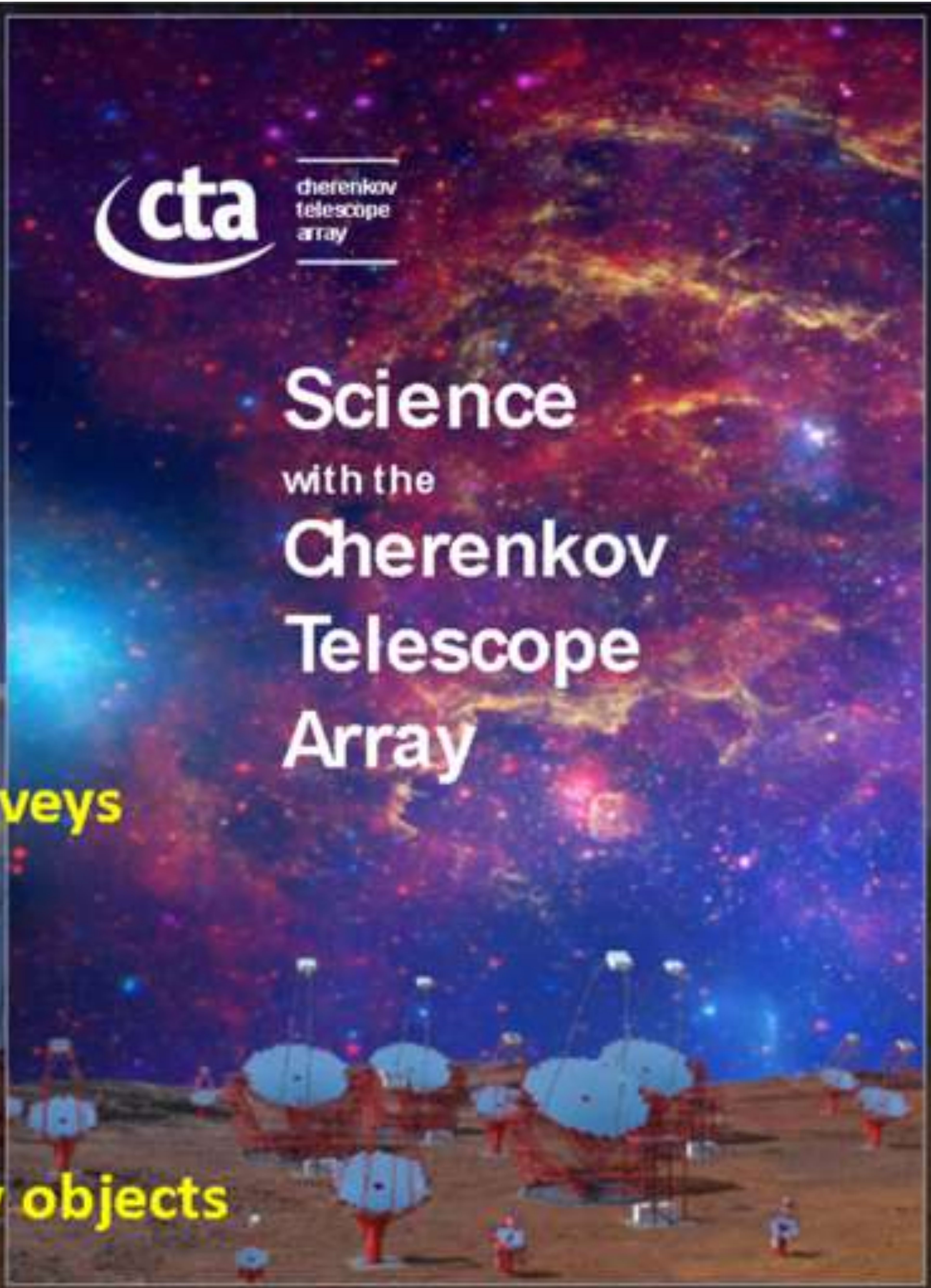
# KEY SCIENCE PROJECTS

provide legacy data sets and data products

1. Dark Matter Programme
2. Galactic Centre
3. Galactic Plane Survey
4. Large Magellanic Cloud Survey
5. Extragalactic Survey
6. Transients
7. Cosmic-ray PeVatrons
8. Star-forming Systems
9. Active Galactic Nuclei
10. Cluster of Galaxies
11. Beyond Gamma Rays

Surveys

Key objects



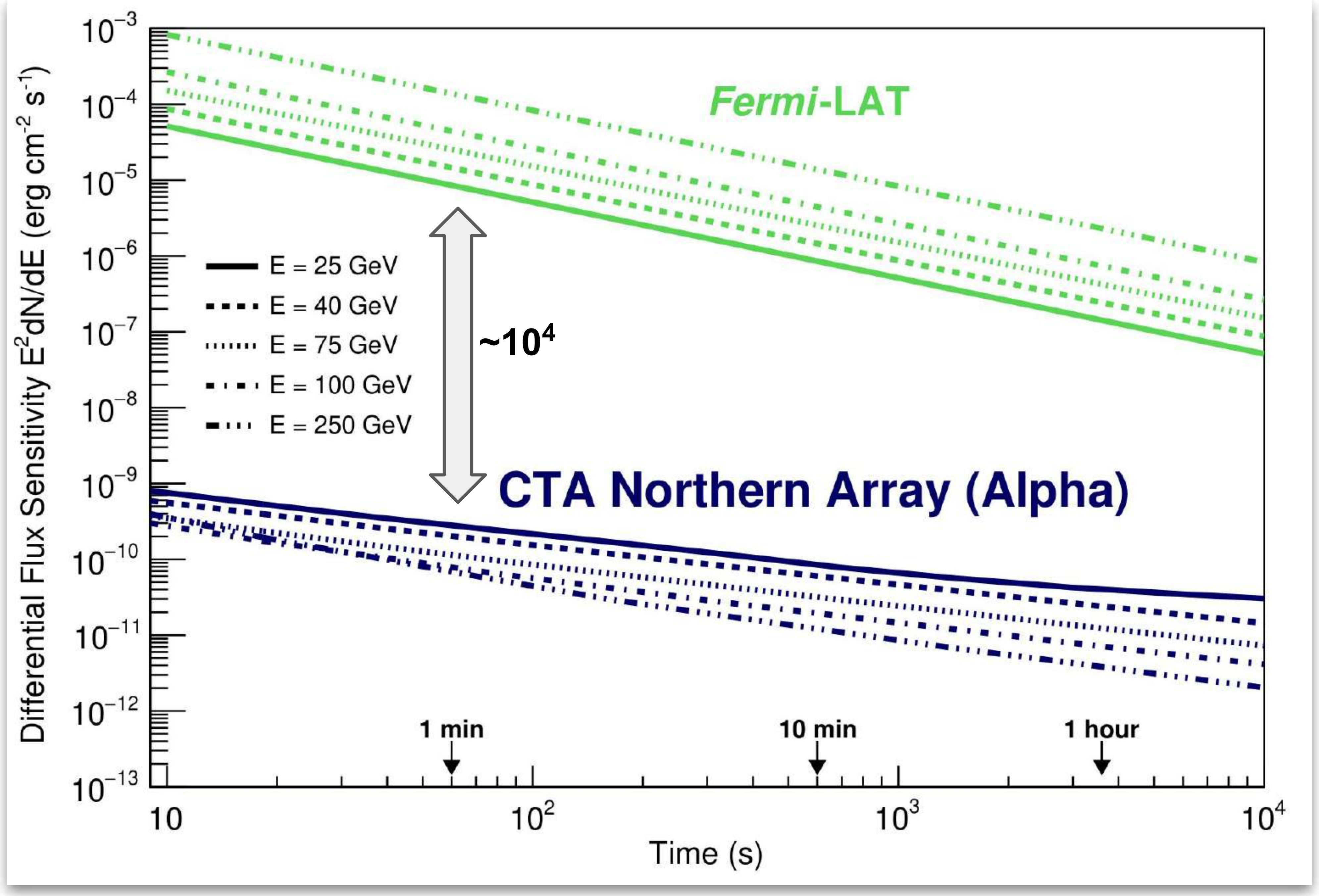

www.worldscientific.com/worldscibooks/10.1142/10986

Thanks to Franz Longo

# CTA Transient and MM Programme

**CTA will have a strong transient and multi-messenger programme, following its unique short-timescale sensitivity in the multi-GeV range, ~$10^4$x superior to Fermi-LAT for timescales up to several ks.**

- **Gamma-ray bursts (GRBs)**, external alerts from monitoring facilities. Simulations of a realistic GRB populations estimate CTA detection prospects to few GRBs per year.
- **Galactic transients**, serendipitous detection of a wide range of galactic transients expected from CTA regular Galactic Plane Survey monitoring: flares from pulsar wind nebulae (PWN), X-ray binaries, novae, microquasars, magnetars, etc.
- **High-energy neutrino transients**, CTA strategy is to follow-up (golden) neutrino to maximize the chance of detecting a VHE counterpart.
- **GW transients**, follow-up by CTA can play a unique role to ID counterparts thanks to large FoV and divergent pointing strategy.
- **Core-collapse Supernovae**, investigation of CTA prospects in detecting a wide range of different types of CCSNe and their different signature in the VHE regime.




https://www.cta-observatory.org

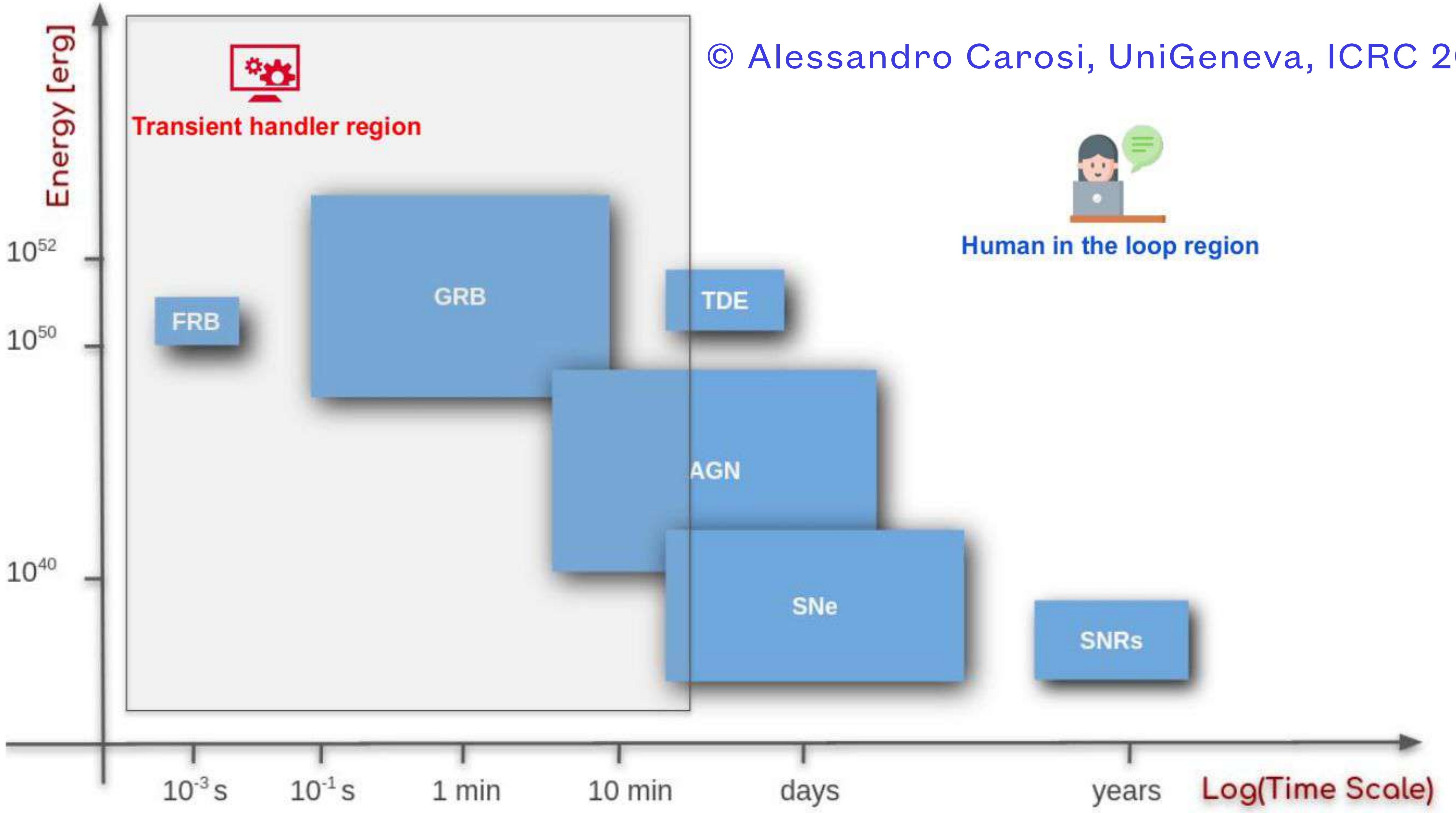
# CTA Transient and MM Programme

**Multi-messenger research will require large cooperation between CTA and other facilities, operating at all bands of the EM and at different 'messengers'.**

<u>Key elements being</u>

- Ability to receive alerts from many different sources, which will be implemented in CTA via a dedicated '*<u>transient handler</u>*'

- Ability to deliver <u>alerts in near real-time</u> to the external astrophysical community for follow-up by other instruments




© Alessandro Carosi, UniGeneva, ICRC 2021

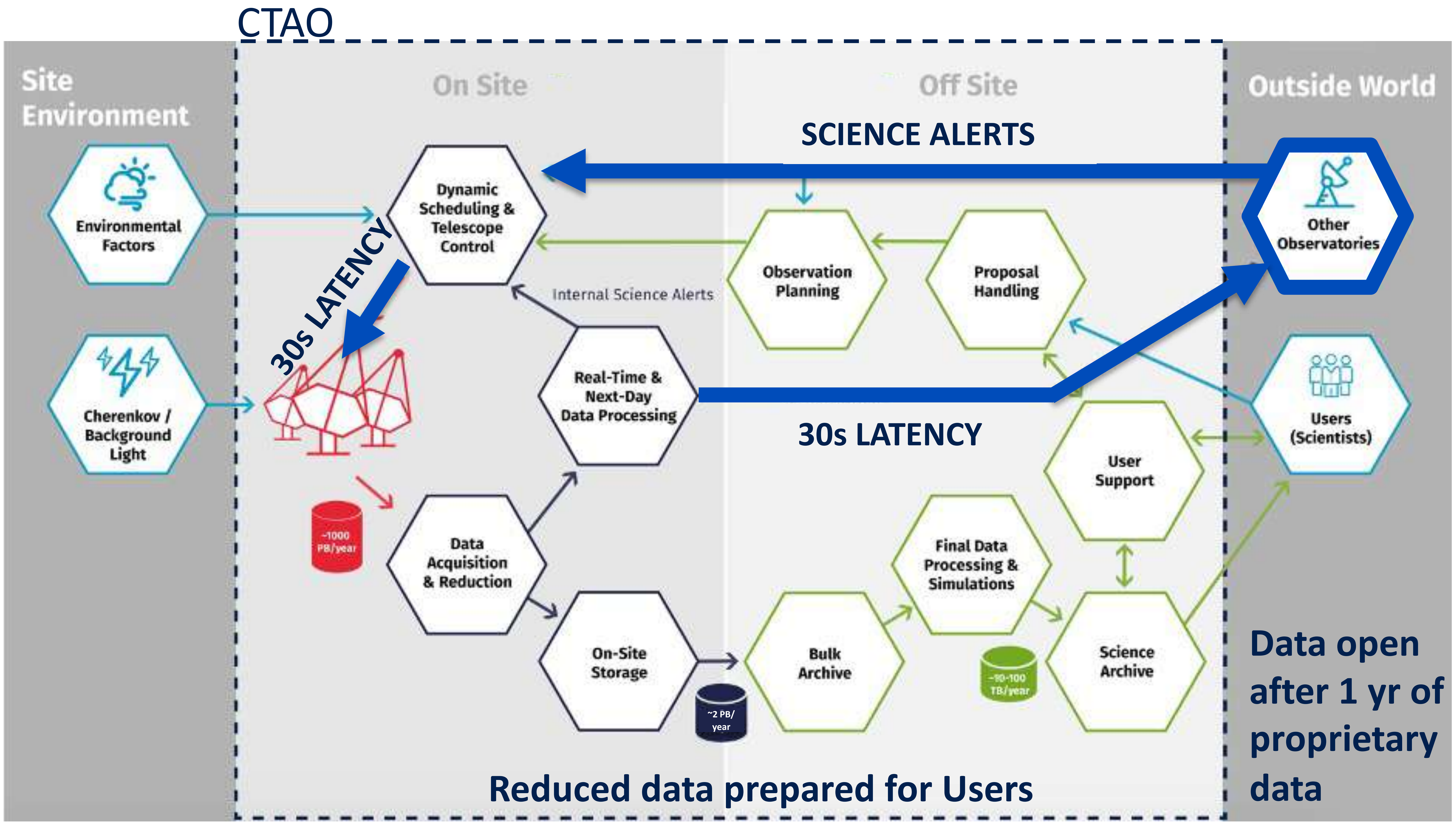
**PROTOCOLS FOR EXTERNAL COMMUNICATIONS HANDLING**

**ALERT FILTERING AND OBSERVABILITY ASSESSMENT**

**RECEIVING AND HANDLING OF ALERTS**

**INTERNAL COMMUNICATIONS HANDLING FOR SCHEDULING**

# CTA : alert and follow-up system




**Online analysis -** On time scales from 10s to 30 min

**Efficient science alert generation -** Alerts will be generated with a latency of 30s

**Fast follow-up and short term detections -** CTA will quickly follow-up on external triggers (within 30s of alert received)

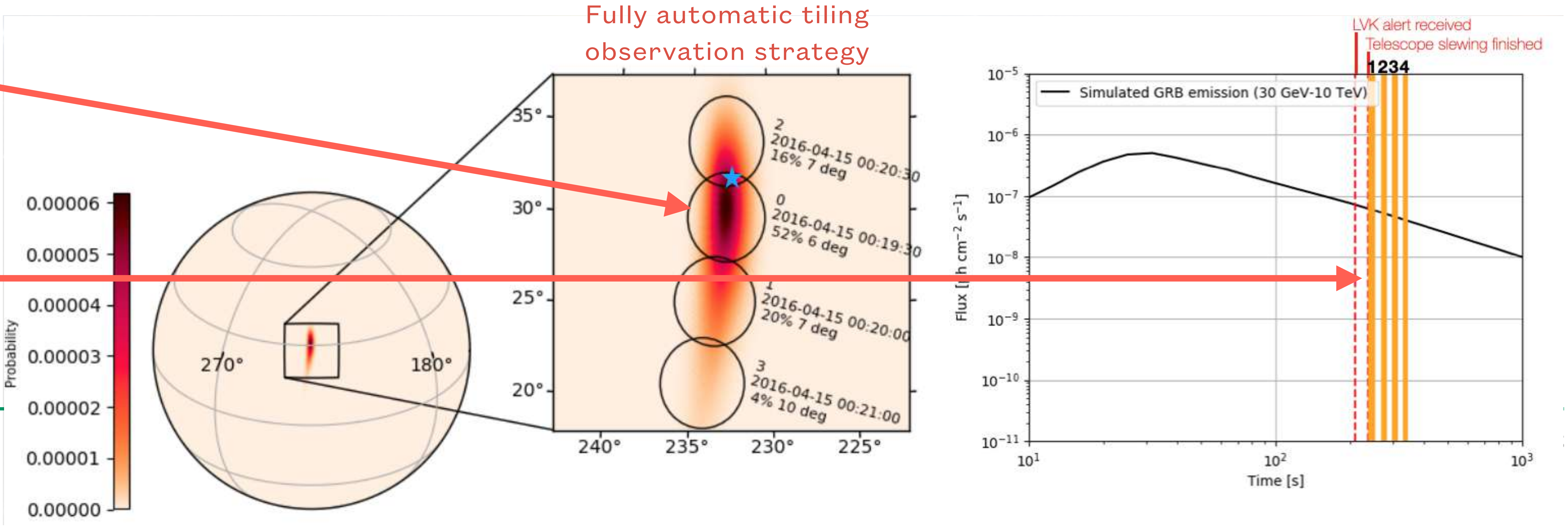
**DETAILED OPERATIONS REQUIREMENTS UNDER DEVELOPMENT**

# CTA follow-up observation strategy

- **CTAO will perform regular (1-3x per week) follow-up observations of GW-GRB and (golden) ν alerts**
- **The observational strategy** is a key element for the success of the programme
  - Optimal pointing pattern to cover the largest total alert uncertainty region (10-1000 deg$^2$) *(Patricelli+2018, Bartos+2019)*
  - Optimal pointing cadence: exposure time tailored to achieve 5σ detection
  - Site coordination to prioritize best observational conditions (sky brightness and quality, zenith angle) and to guarantee lowest energy threshold
  - Divergent array pointing mode to increase the FoV

I. Start with highest probability position, favoring lowest Z

II. Optimise exposure time based on source model



# CTA follow-up observation planning

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**CTAO is conducting different studies for the planning and optimization of its follow-up programme, based on tailor-made population studies**

- GRB population study : POSyTIVE *(Ghirlanda+2019)*
- Neutrino source population : FIRESONG *(Tung+2021)*
- Neutron Star-Neutron Star mergers : GWCOSMoS *(Patricelli+2018)*

**simulation of source population** based on open-source theoretical codes

**estimation of gamma-ray emission** based on phenomenological assumptions

**optimization of the CTAO observation strategy**

**simulation of CTA response**

**Estimation of the CTA detection rate**

**ctools and gammapy pipelines**

© Roberta Zanin, CTAO, ICRC 2021 (adapted)

# The neutrino event IC 170922A

CBPF Centro Brasileiro de Pesquisas Físicas
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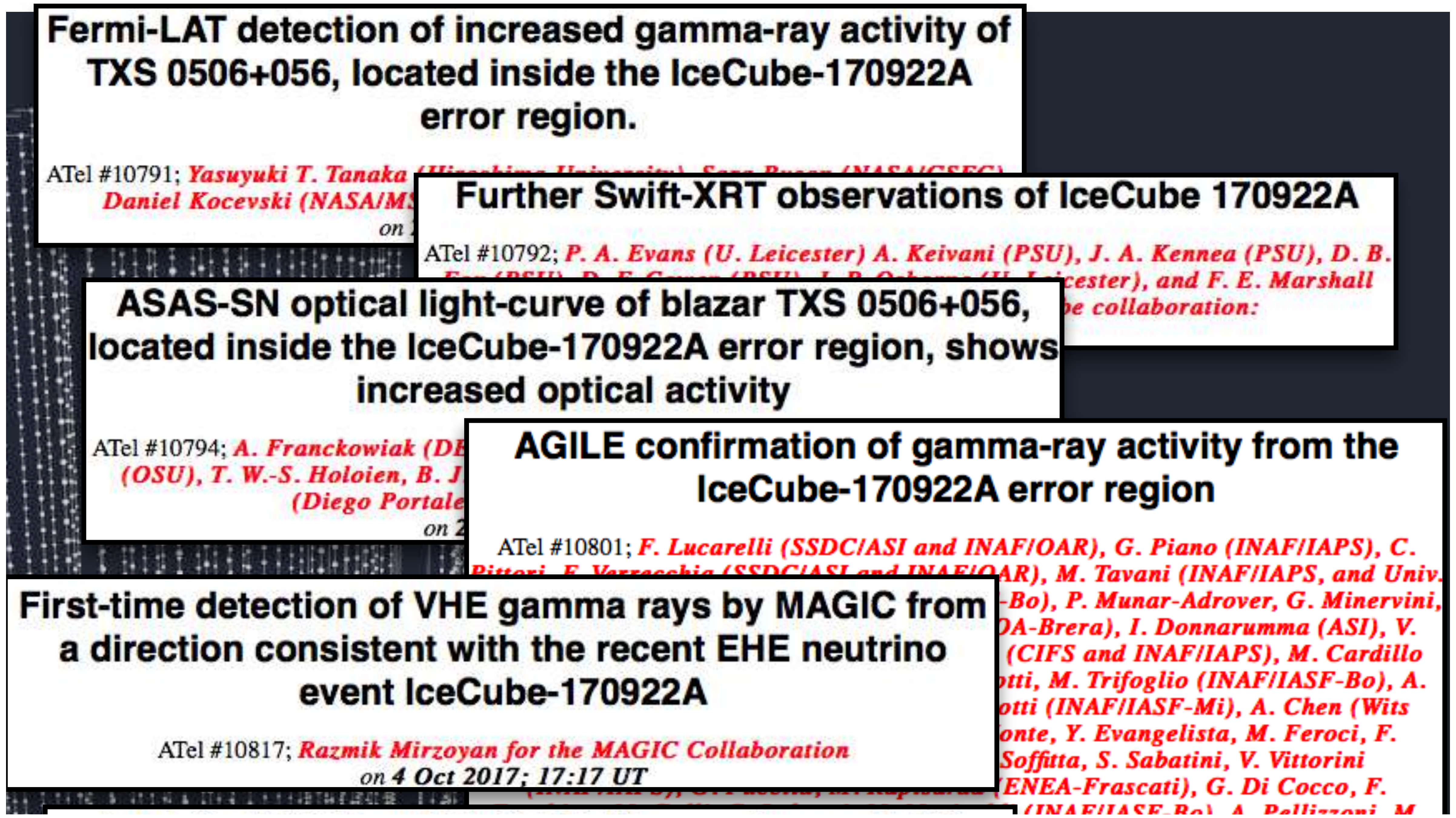

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka* ... *Daniel Kocevski (NASA/MS*...

Further Swift-XRT observations of IceCube 170922A

ATel #10792; *P. A. Evans (U. Leicester) A. Keivani (PSU), J. A. Kennea (PSU), D. B.* ... *cester), and F. E. Marshall* ... *be collaboration:*

ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity

ATel #10794; *A. Franckowiak (DE*... *(OSU), T. W.-S. Holoien, B. J*... *(Diego Portale*...

AGILE confirmation of gamma-ray activity from the IceCube-170922A error region

ATel #10801; *F. Lucarelli (SSDC/ASI and INAF/OAR), G. Piano (INAF/IAPS), C. Pittori, F. Verrecchia (SSDC/ASI and INAF/OAR), M. Tavani (INAF/IAPS, and Univ.* ... *-Bo), P. Munar-Adrover, G. Minervini,* ... *DA-Brera), I. Donnarumma (ASI), V.* ... *(CIFS and INAF/IAPS), M. Cardillo* ... *otti, M. Trifoglio (INAF/IASF-Bo), A.* ... *otti (INAF/IASF-Mi), A. Chen (Wits* ... *onte, Y. Evangelista, M. Feroci, F.* ... *Soffitta, S. Sabatini, V. Vittorini* ... *ENEA-Frascati), G. Di Cocco, F.*

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
*on 4 Oct 2017; 17:17 UT*

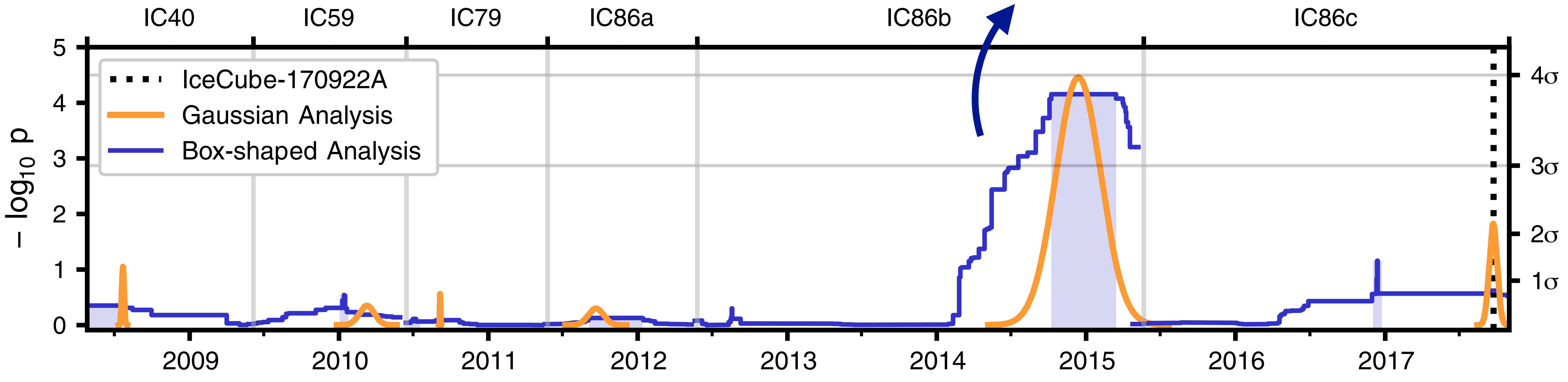
**Up to now, only "serious" evidence of a blazar counterpart comes from spatial-temporal "clusters" from the direction of TXS 0506+056, but…**

**IC 170922A : High-energy, through-going track**

**TXS 0506+056 : An extreme blazar**

Coincidence at the 3.5 sigma level

T. Kintscher




**Science 361 (2018) no.6398, 147-151**

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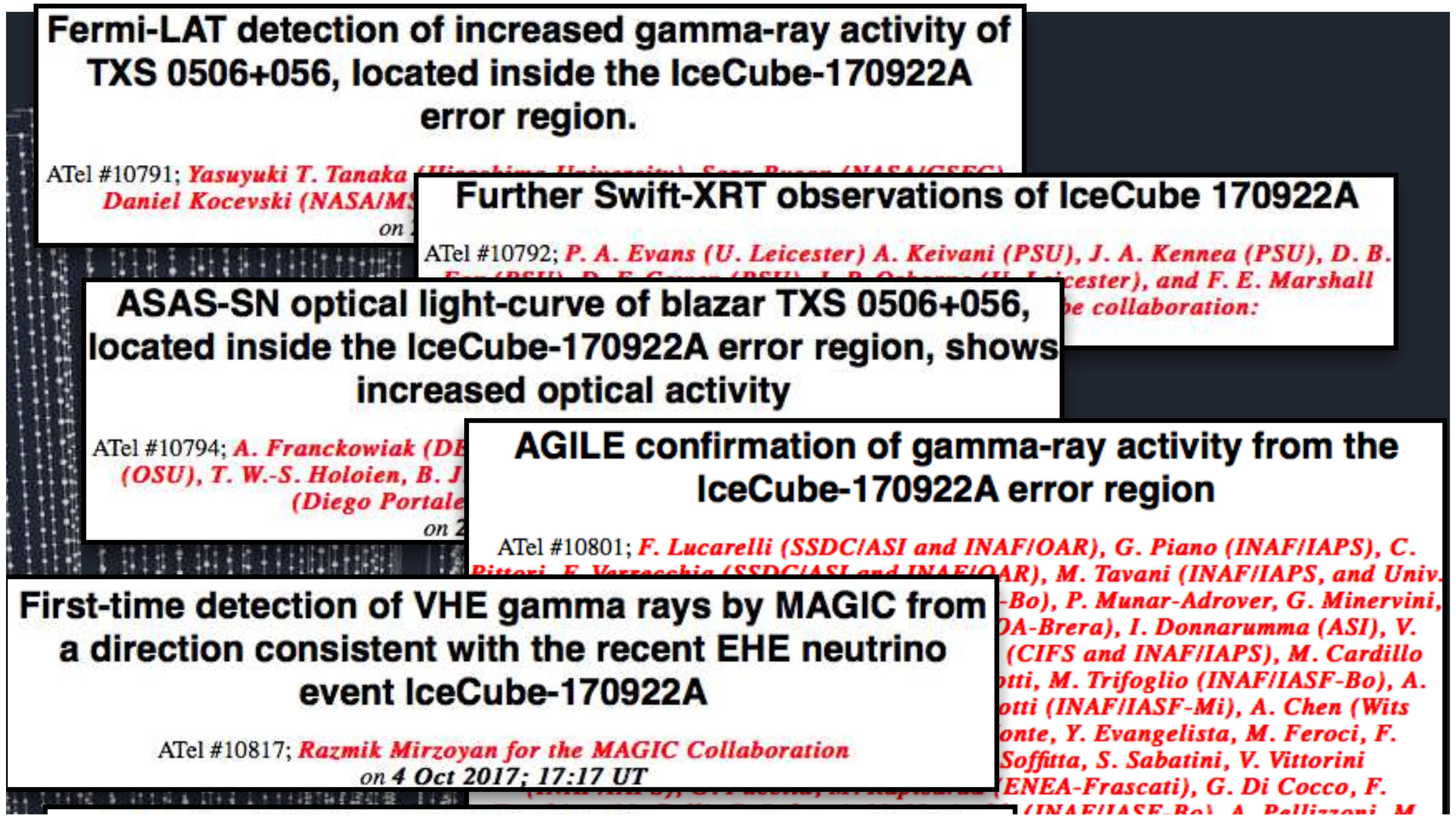
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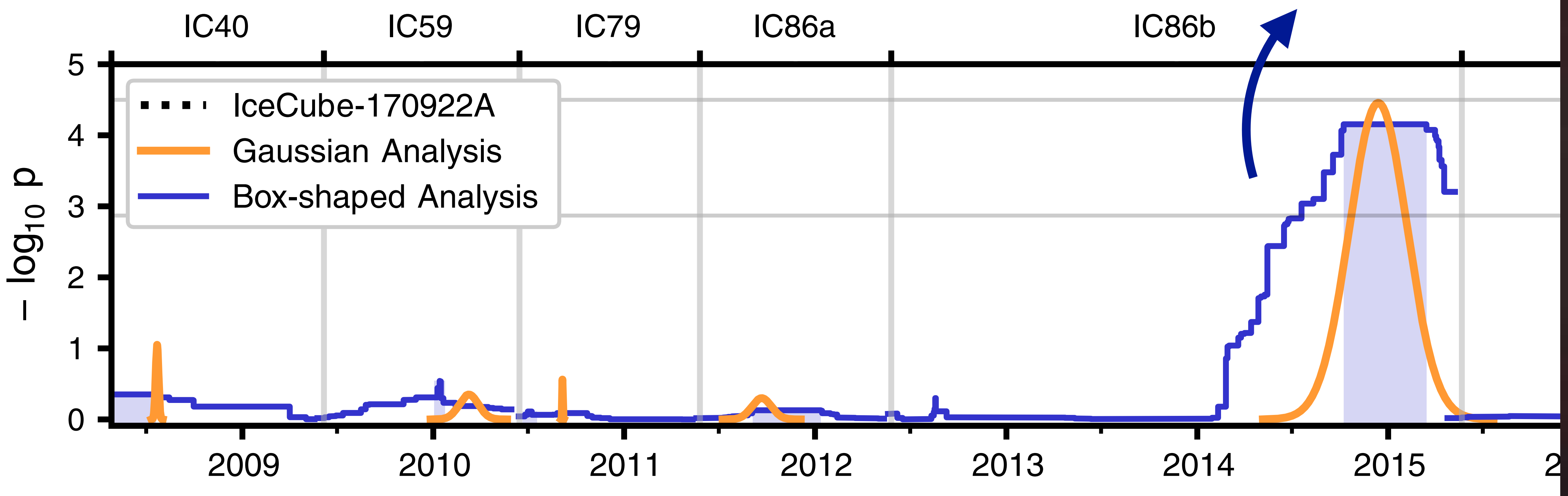
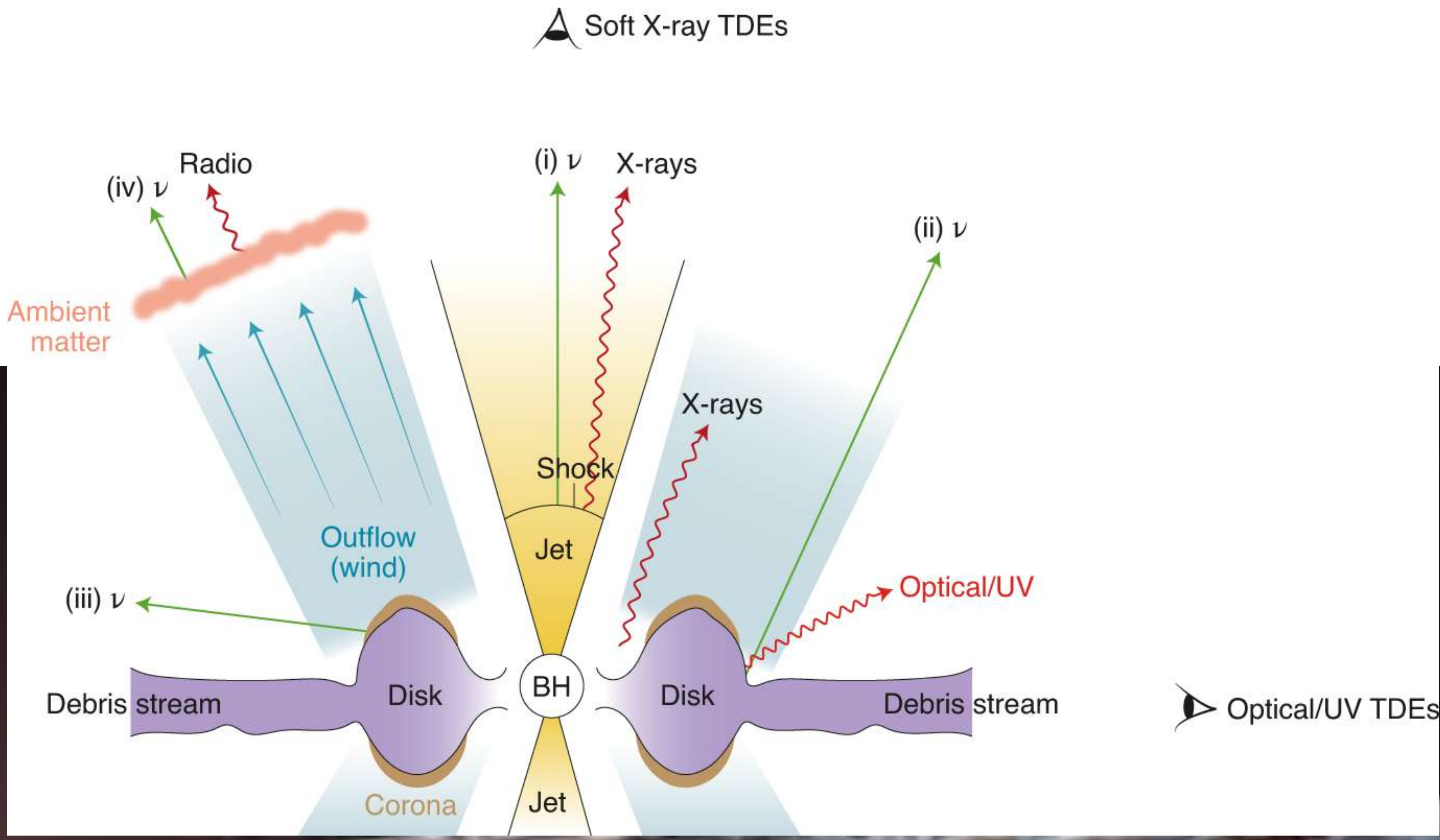



Science 361 (2018) n

**Up to now, only "serious" evidence of a blazar counterpart comes from spatial-temporal "clusters" from the direction of TXS 0506+056, but...**

**Tidal disruption event coincident with IceCube neutrino**




R. Stein et al., Nature Astron. 5, 510 (2021)

# The neutrino event IC 170922A

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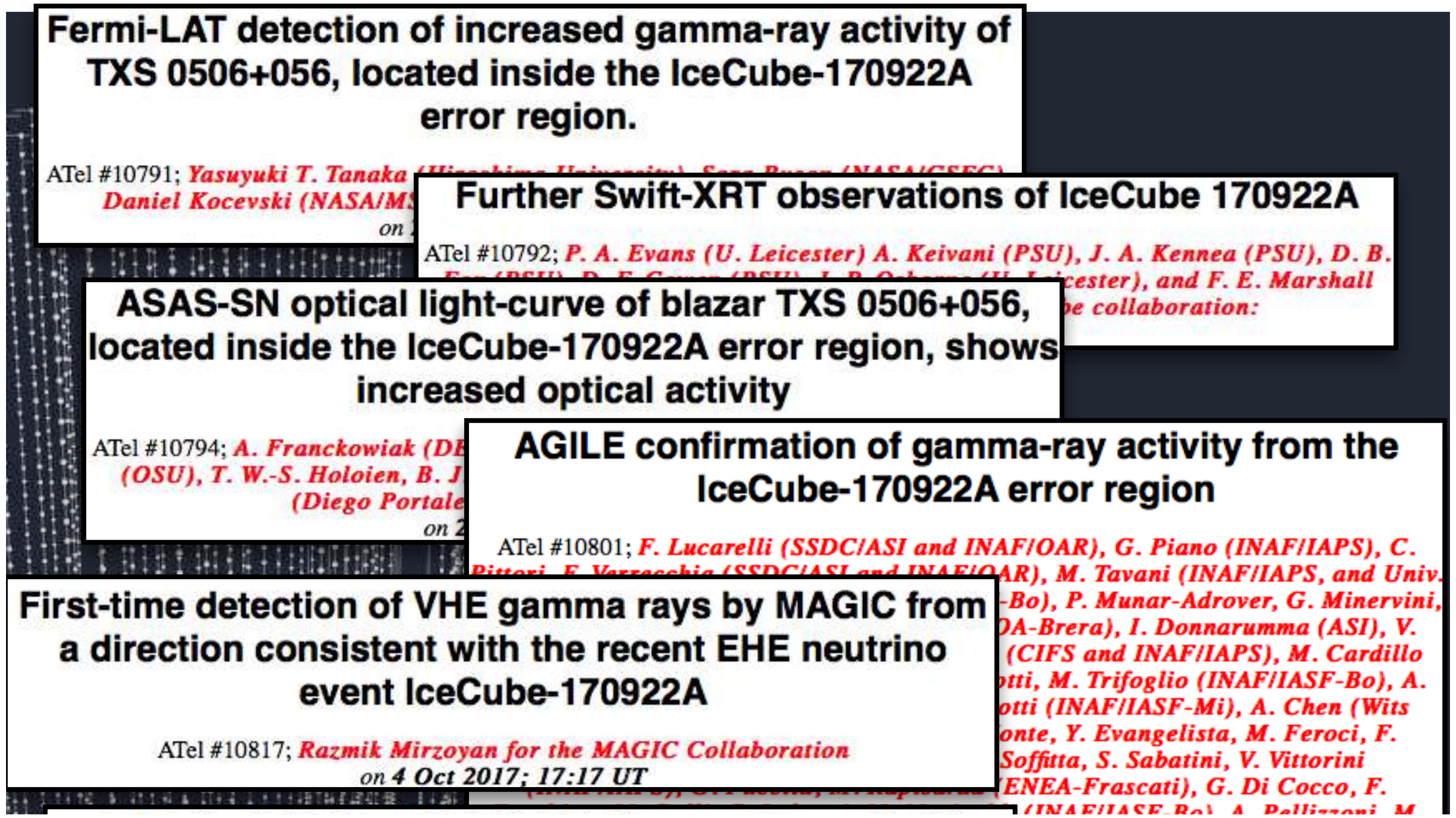
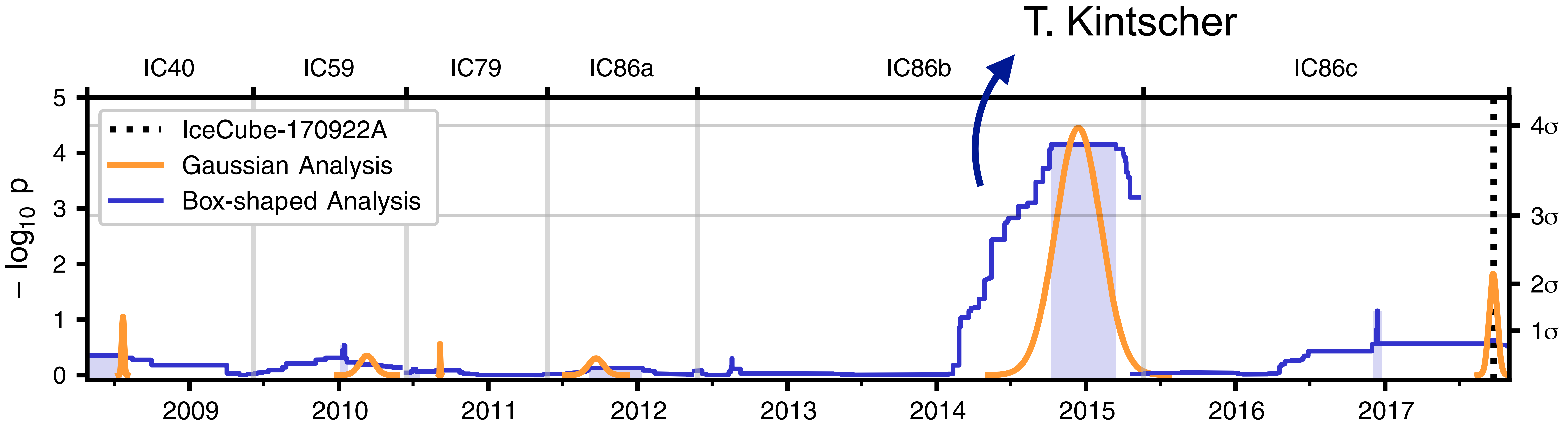



Up to now, only "serious" evidence of a blazar counterpart comes from spatial-temporal "clusters" from the direction of TXS 0506+056, but...

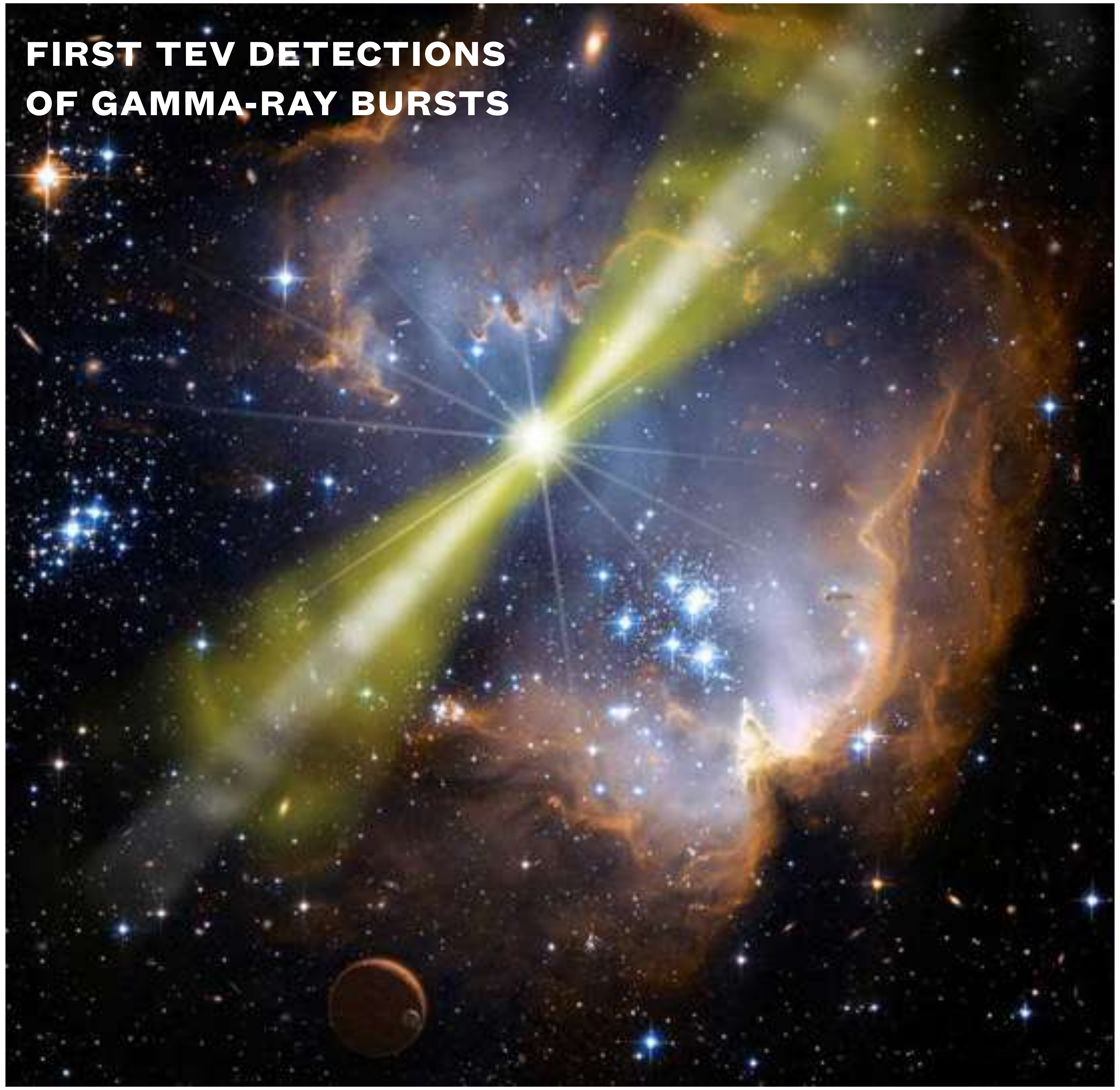
- THE ANSWER IS ON PUBLIC ALERT STREAMS (ACTIVE SINCE 2016)
- SHORT TIME DELAYS (~ MIN) FROM TRIGGER TO PUBLIC ALERT
- A LARGE NETWORK FOR FOLLOW-UP OF NEUTRINOS WITH HIGH SIGNAL PROBABILITY (GOLDEN) :

GAMMA-RAY SATELLITES AND GROUND-BASED, X-RAY SATELLITES, OPTICAL TRANSIENT FACTORIES.



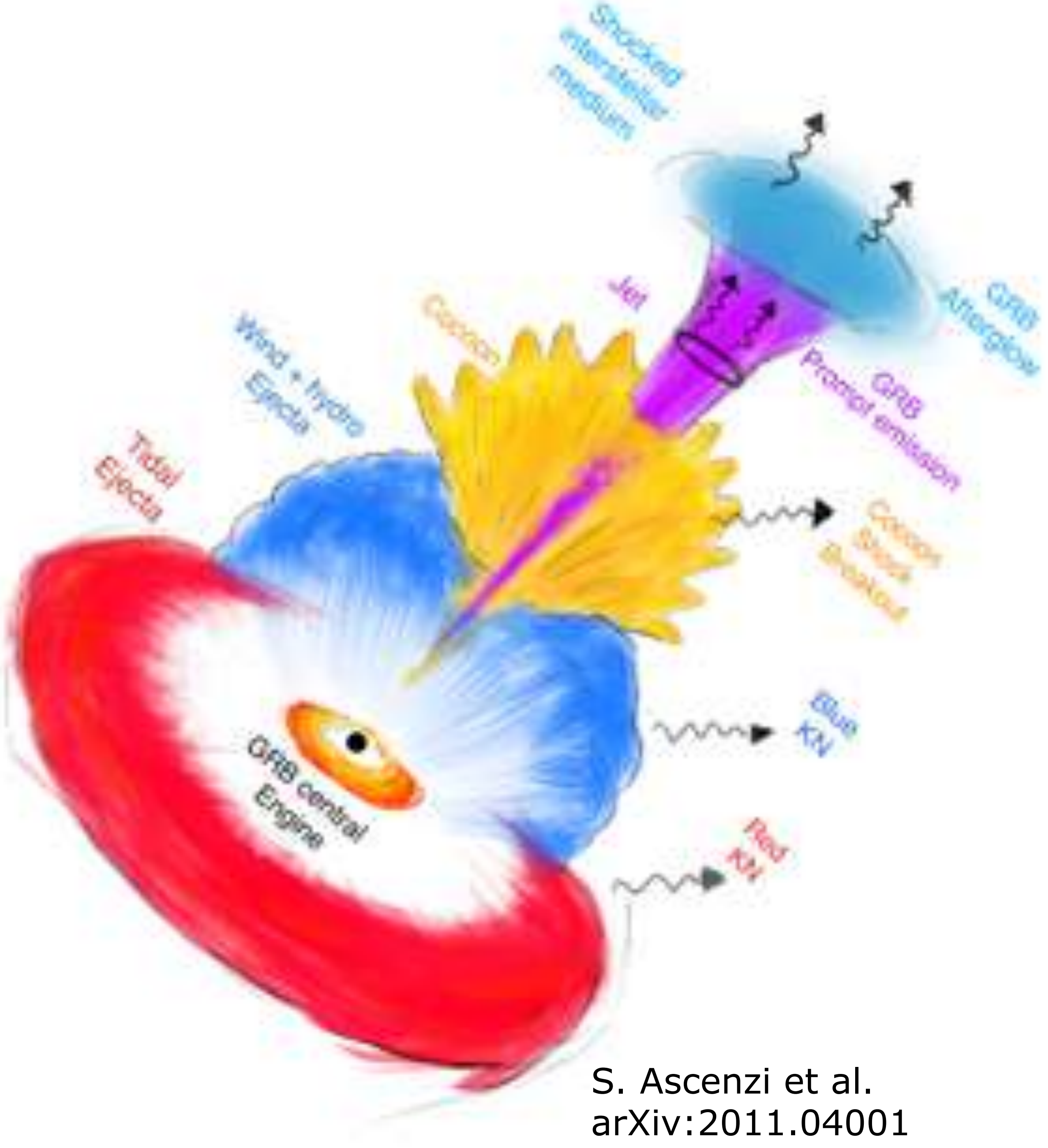

Science 361 (2018) no.6398, 147-151

# The steep path towards GW-VHE connection




**After two decades of attempts, first long GRBs were detected at VHE (early and late afterglow emission).**

**The next step lies in the detection of short GRBs and perhaps (maybe with EAS arrays), the prompt emission!**




S. Ascenzi et al. arXiv:2011.04001

- **GRB 190114C** *(MAGIC Coll., Nature, 2020)*
  - long GRB at z = 0.42
  - early detection at T0 + 60s (2 ks),
  - E = [0.2, 1] TeV
- **GRB 180720B** *(H.E.S.S. Coll., Nature, 2020)*
  - long GRB at z = 0.65
  - late detection after $T_0$ + 10h
- **GRB 190829A** *(H.E.S.S. Coll., Science, 2020)*
  - long GRB at z = 0.078 (very close!)
  - for 3 nights, after $T_0$ + 4h
  - E = [0.2, 3.3] TeV
- **GRB 160821B** *(MAGIC Coll. ApJL, 2021)*
  - **short GRB** at z = 0.162
  - data taking starting at $T_0$ + 24s, for 4h
  - 3σ hint, E > 500 GeV
- **GRB 201015A** *(ICRC 2021, PoS ID 305, Y.Suda)*
  - long GRB at z = 0.42
  - early detection at $T_0$ + 40s
  - 3σ hint, E > 500 GeV
- **GRB 201216C** *(ICRC 2021, PoS ID 395, S.Fukami)*
  - long GRB at z = 1.1
  - early detection after $T_0$ + 56s
  - E < 100 GeV

# GW source localization

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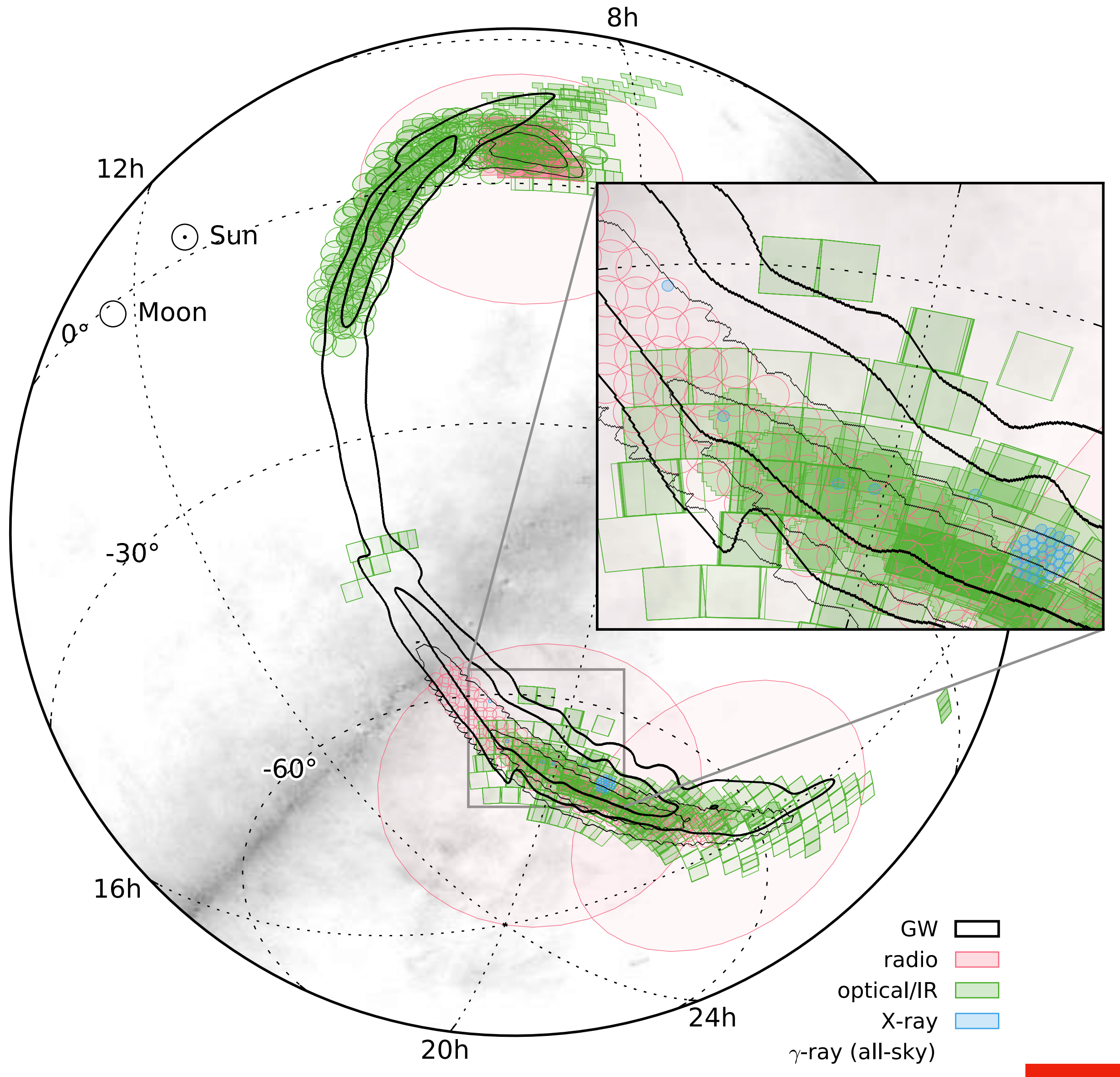
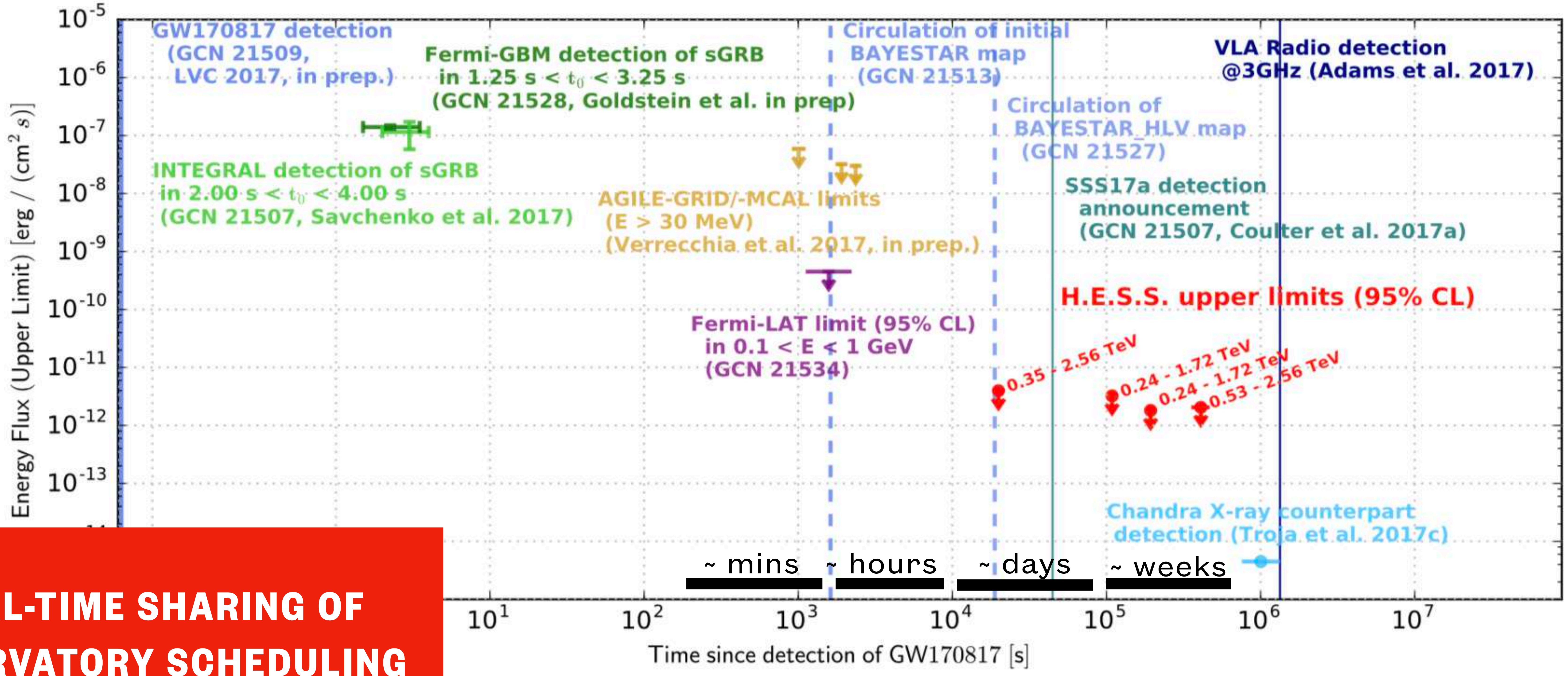
**Arrival direction** of GW is estimated from time delays (and amplitude modulation) of the signal.

Triangulation with VIRGO has allowed for a better sky localisation (down to ~ few $deg^2$)
Challenge for EM counterpart ID : time vs. space localisation



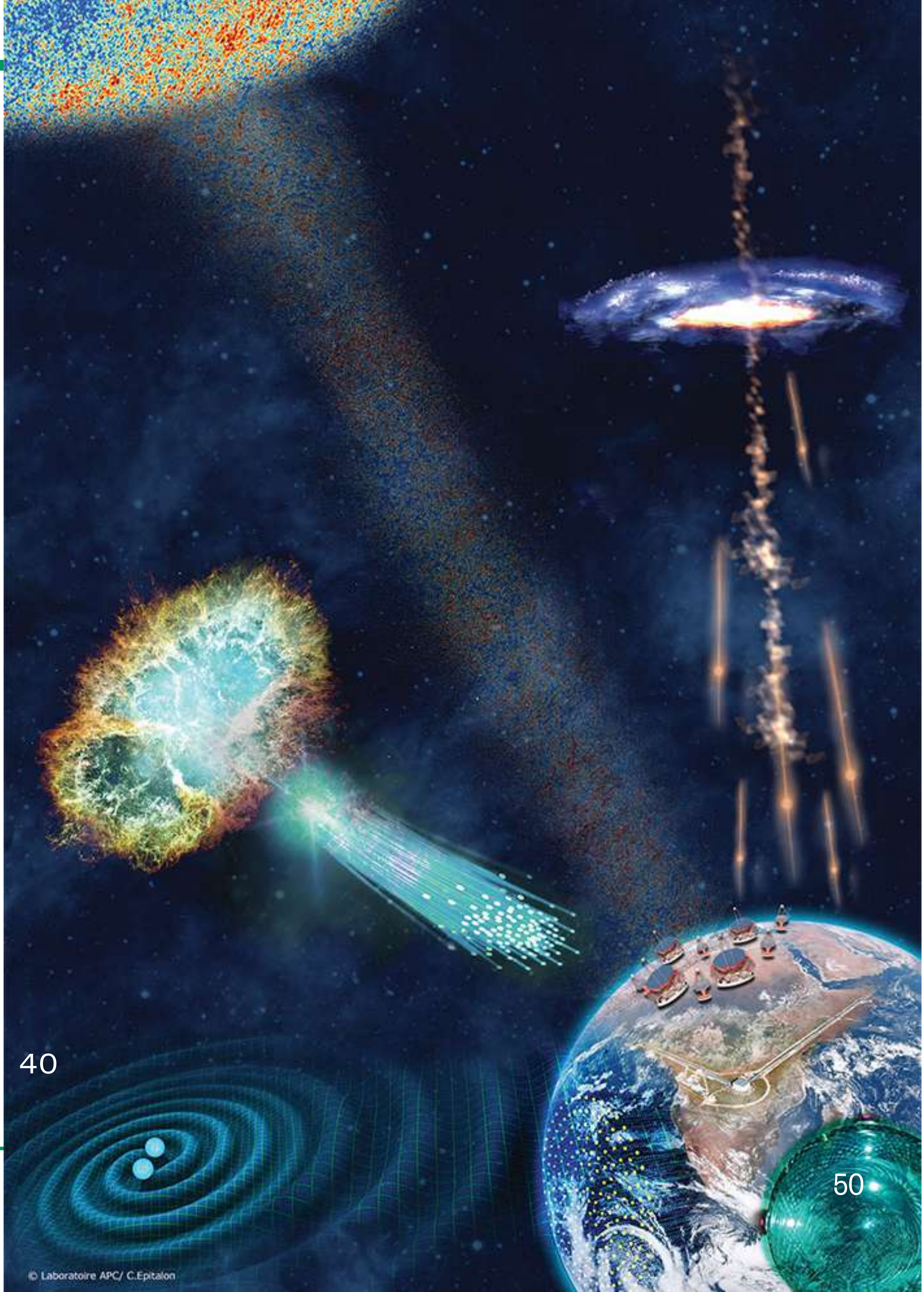




**Tilling by EM observatories :** coordinated scheduling and follow-up of observations.

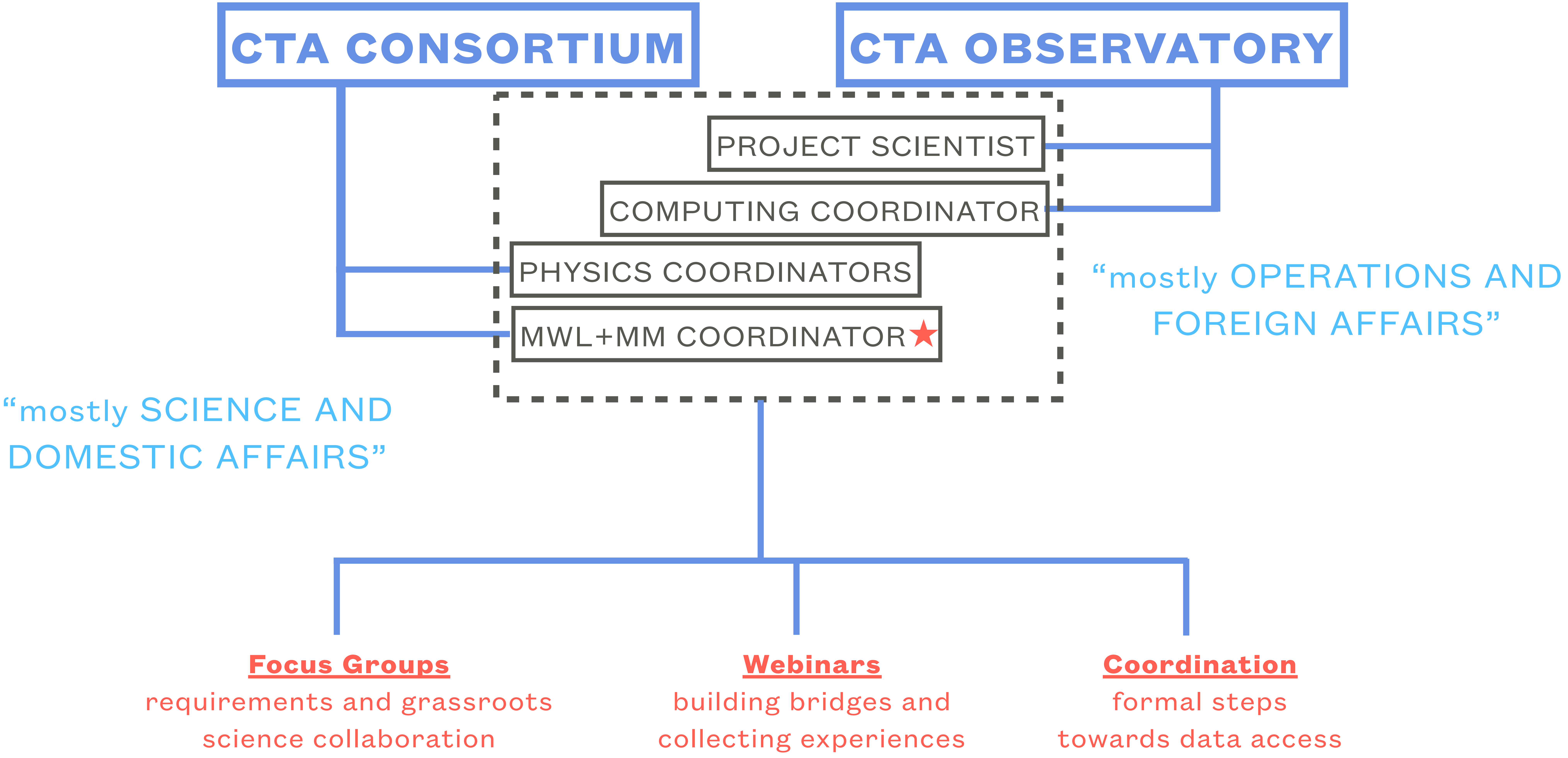
**REAL-TIME SHARING OF OBSERVATORY SCHEDULING**

# CTA Coordination Activities

ULISSES BARRES DE ALMEIDA - MARCH 2023 - ICTP-SAIFR CTA SCHOOL



# CTA MWL & MM Coordination Structure



# CTA MWL & MM Coordination Task Force

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The achievement of the **CTA core Science Goals** depends on a wealth of MWL and MM data (often involving intense coordination between facilities), and the purpose of the MWL&MM Coordination Task Force is to identify, plan and secure those.

| Band or Messenger | Astrophysical Probes | Galactic Plane Survey | LMC & SFRs | CRs & Diffuse Emission | Galactic Transients | Starburst & Galaxy Clusters | GRBs | AGNs | Radio Galaxies | Redshifts | GWs & Neutrinos |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Radio | Particle and magnetic-field density probe. Transients. Pulsar timing. | 🟢 | 🟢 | 🟢 | 🟢 | 🟢 | 🟠 | 🟠 | | | 🔴 |
| (Sub)Millimetre | Interstellar gas mapping. Matter ionisation levels. High-res interferometry. | 🟢 | 🟢 | | 🟢 | 🟢 | 🔴 | 🟠 | 🟢 | | |
| IR/Optical | Thermal emission. Variable non-thermal emission. Polarisation. | 🟢 | 🟢 | | 🟠 | 🔴 | 🟠 | 🟢 | 🟢 | 🟢 | 🔴 |
| Transient Factories | Wide-field monitoring & transients detection. Multi-messenger follow-ups. | | | | 🟠 | | 🟢 | 🟠 | | | 🟠 |
| X-rays | Accretion and outflows. Particle acceleration. Plasma properties. | 🟢 | 🟠 | 🟠 | 🟢 | 🟠 | 🟢 | 🟢 | 🟢 | | 🟠 |
| MeV-GeV Gamma-rays | High-energy transients. Pion-decay signature. Inverse-Compton process | 🟢 | 🟠 | | 🟢 | 🟠 | 🟢 | 🟢 | 🟢 | | 🟢 |
| Other VHE | Particle detectors for 100% duty cycle monitoring of TeV sky. | 🟢 | 🟠 | | 🟢 | 🟠 | 🟠 | 🟢 | | | 🟢 |
| Neutrinos | Probe of cosmic-ray acceleration sites. Probe of PeV energy processes. | 🔴 | 🔴 | 🟠 | | 🔴 | 🟠 | 🟠 | | | 🟢 |
| Gravitational Waves | Mergers of compact objects (Neutron Stars). Gamma-ray Bursts. | | | | | | 🟠 | | | | 🟢 |

🟢 Essential
🟠 Important
🔴 Useful

**Spatial Coordination for Surveys**

**Extension of Spectral Coverage**

**Catalogue cross-matching for resolving counterparts and source ID**

**Temporal coordination for variable sources**

**Alerts for Transient Phenomena**

# CTA MWL & MM Coordination Task Force

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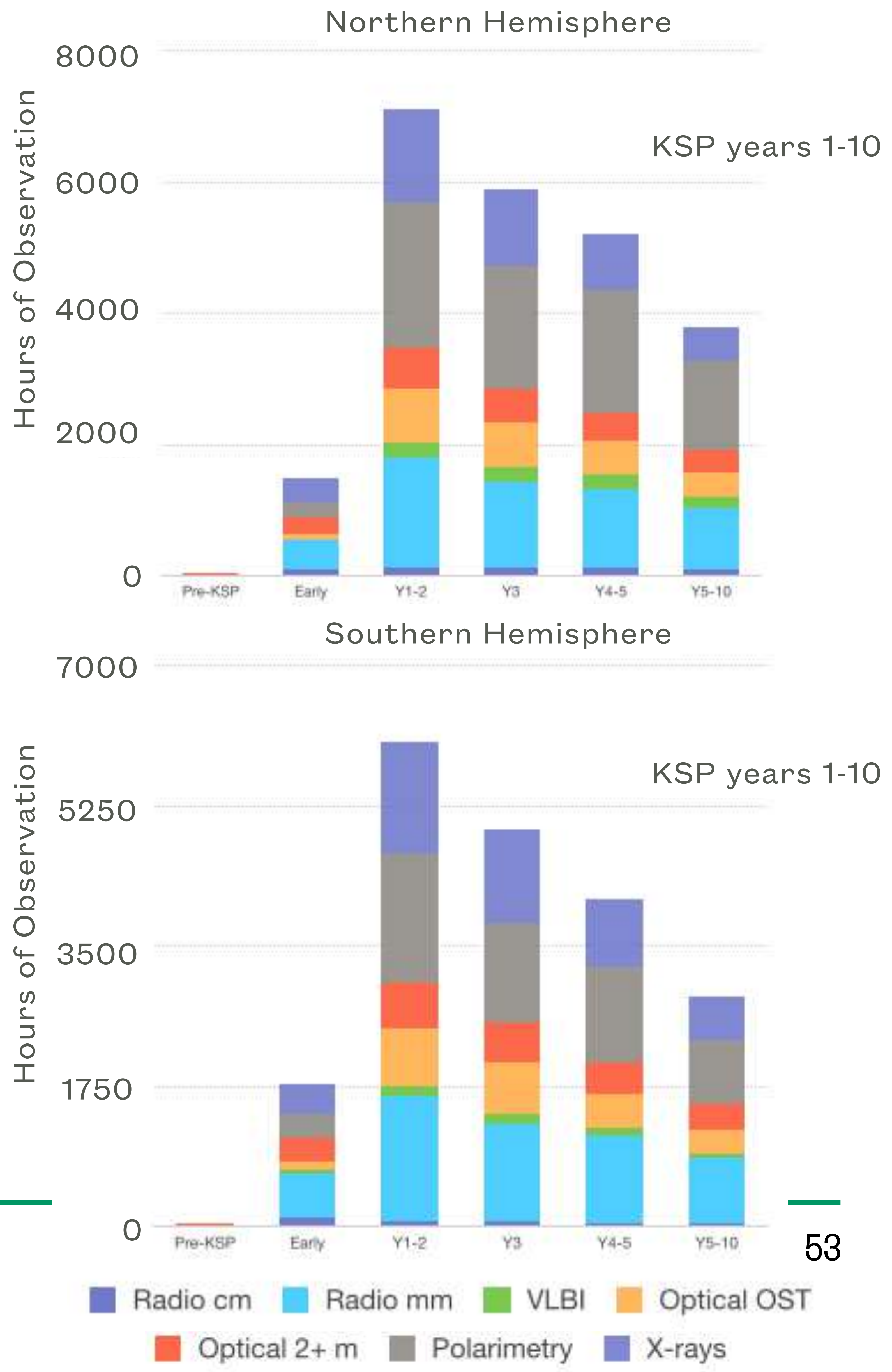
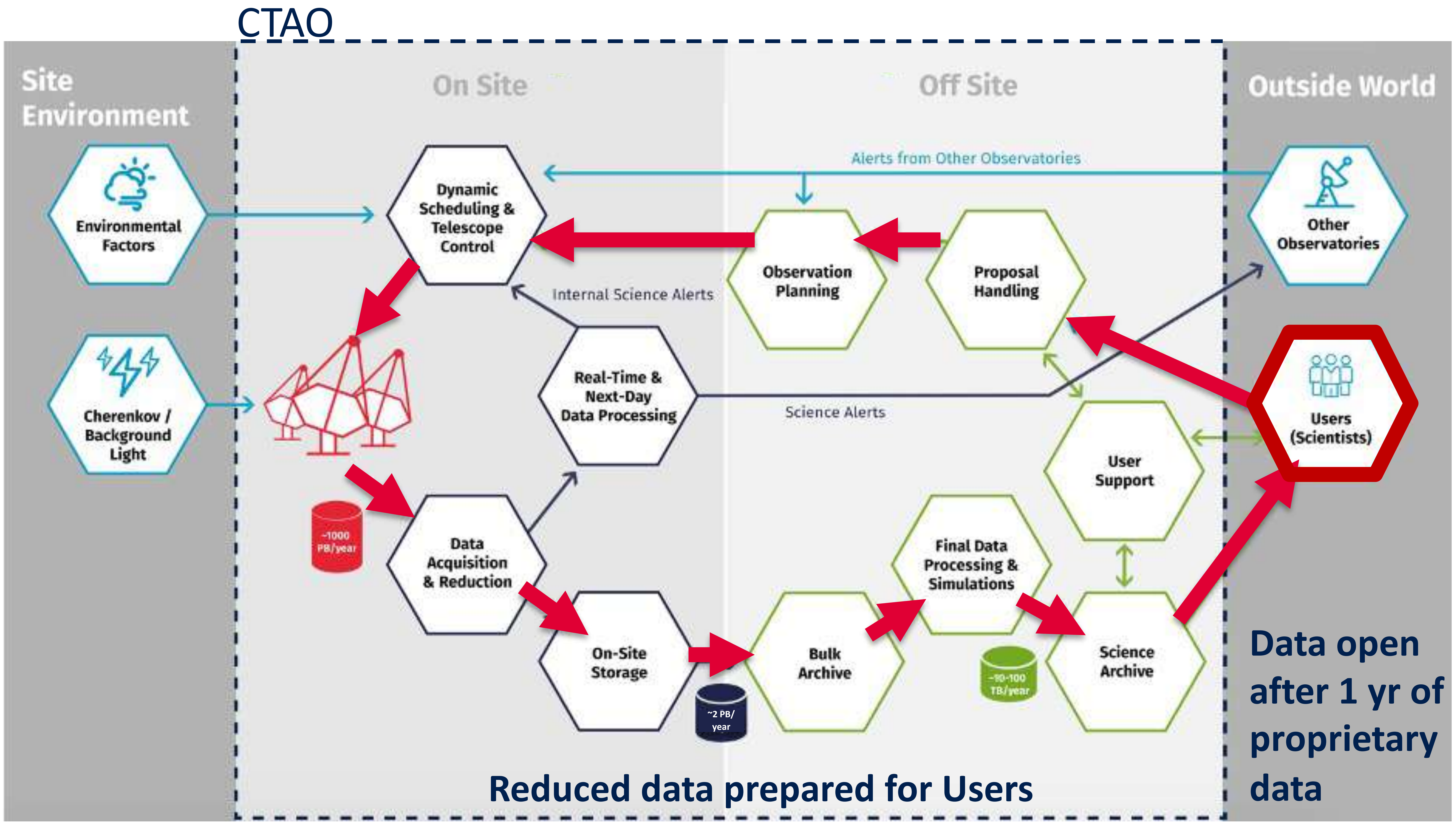
|---|---|---|---|---|---|---|---|---|---|---|---|
| Radio | Particle and magnetic-field density probe. Transients. Pulsar timing. | green | green | green | green | green | orange | orange | | | red |
| (Sub)Millimetre | Interstellar gas mapping. Matter ionisation levels. High-res interferometry. | green | green | | green | green | red | orange | green | | |
| IR/Optical | Thermal emission. Variable non-thermal emission. Polarisation. | green | green | | orange | red | orange | green | green | green | red |
| Transient Factories | Wide-field monitoring & transients detection. Multi-messenger follow-ups. | | | | orange | | green | orange | | | orange |
| X-rays | Accretion and outflows. Particle acceleration. Plasma properties. | green | orange | orange | green | orange | green | green | green | | orange |
| MeV-GeV Gamma-rays | High-energy transients. Pion-decay signature. Inverse-Compton process | green | orange | | green | orange | green | green | green | | green |
| Other VHE | Particle detectors for 100% duty cycle monitoring of TeV sky. | green | orange | | green | orange | orange | green | | | green |
| Neutrinos | Probe of cosmic-ray acceleration sites. Probe of PeV energy processes. | red | red | orange | | red | orange | orange | | | green |
| Gravitational Waves | Mergers of compact objects (Neutron Stars). Gamma-ray Bursts. | | | | | | orange | | | | green |



# CTA : an open observatory




**Open Observatory -** Allows external teams to propose observational programs to CTA, adding flexibility and multiplying its science potential

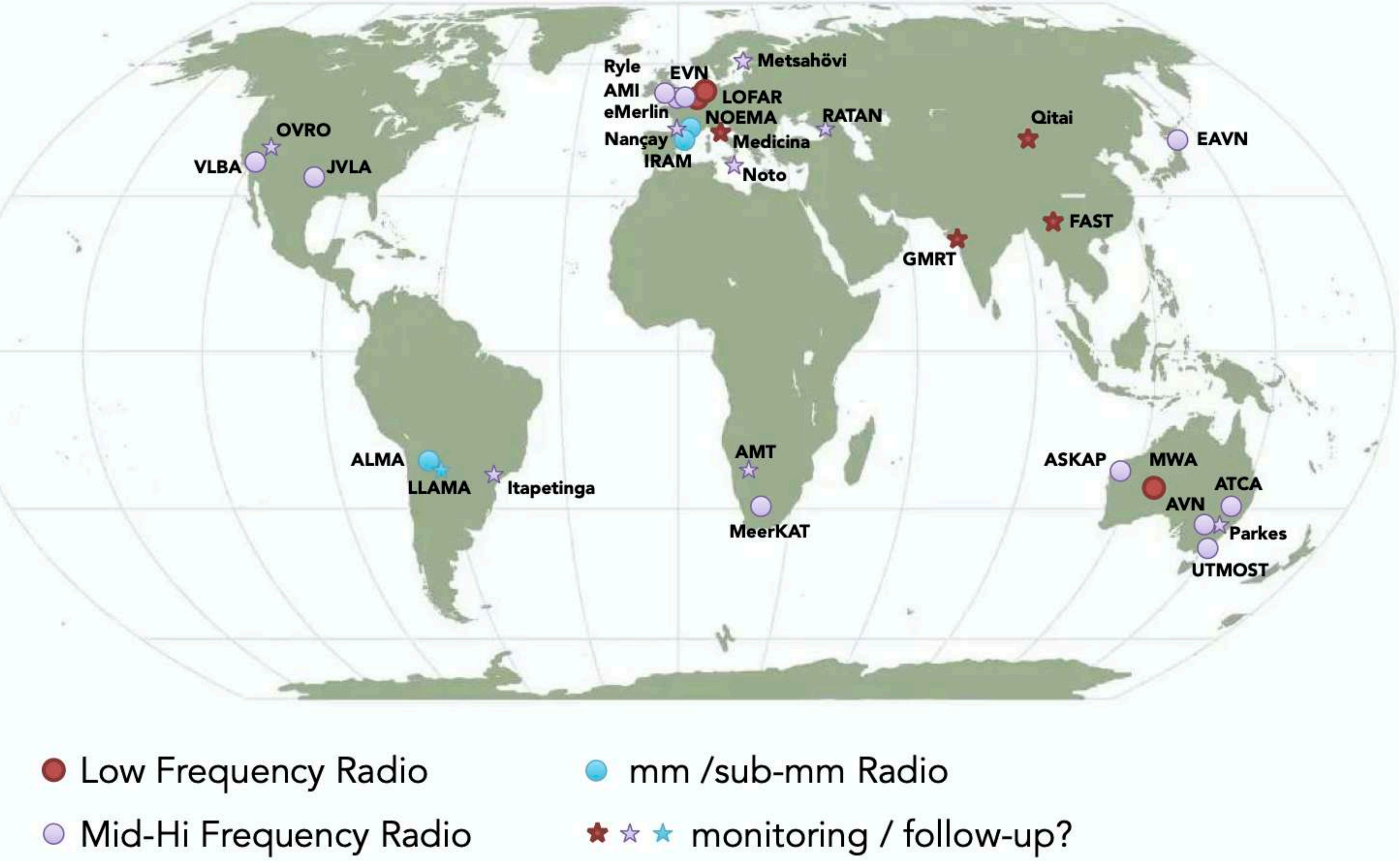
**Open Data -** A fundamental ingredient for MM science, not only from the point of view of alerts, but data archives which are necessary for pursuing MWL & multi-messenger science programme.

**LEARN THE LESSONS FROM FERMI:**

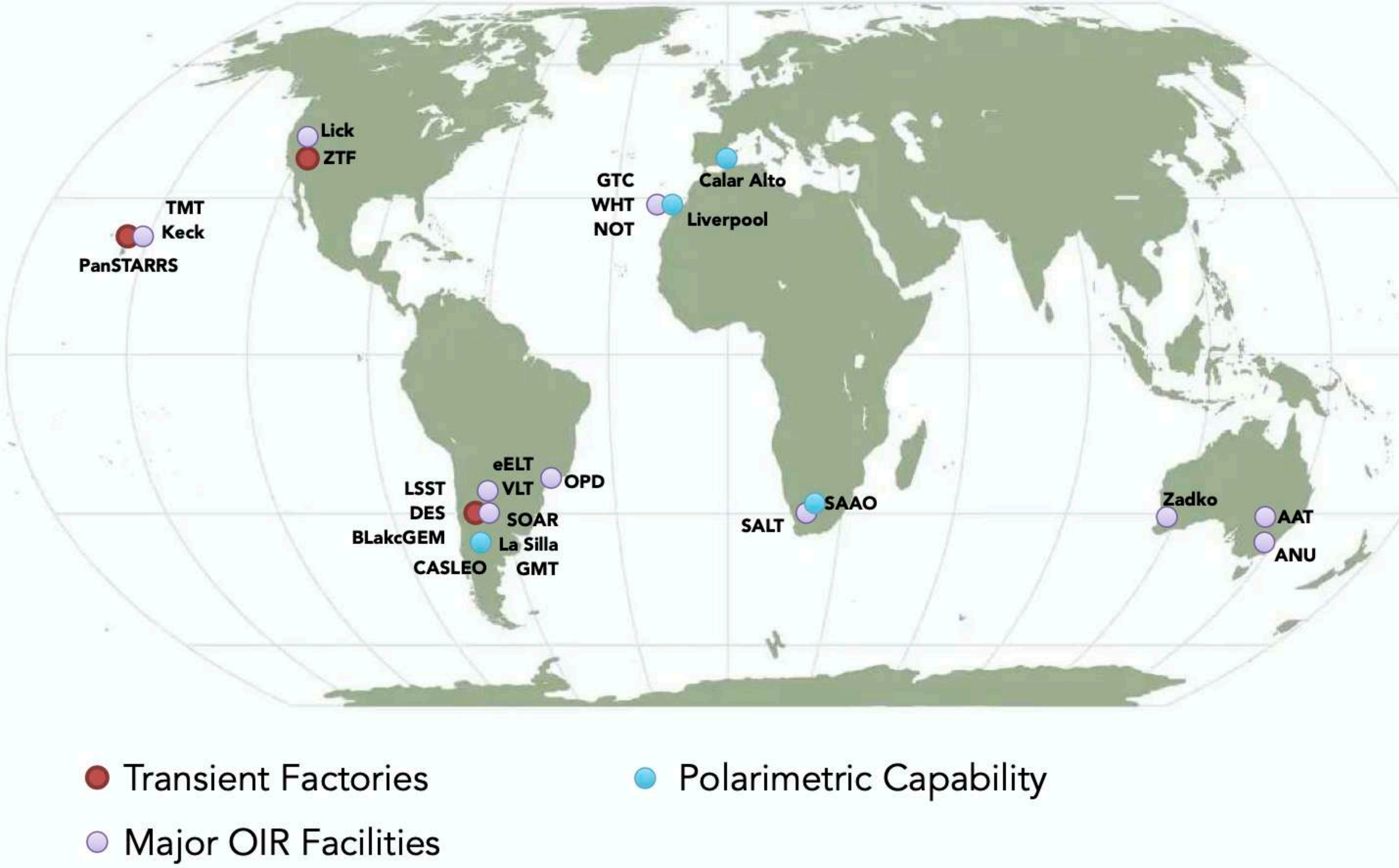
- **FAST SHARING OF KEY DATA PRODUCTS**
- **BUILD UP EARLY YOUR NETWORK OF FRIENDS**

# An ecosystem of ground-based facilities

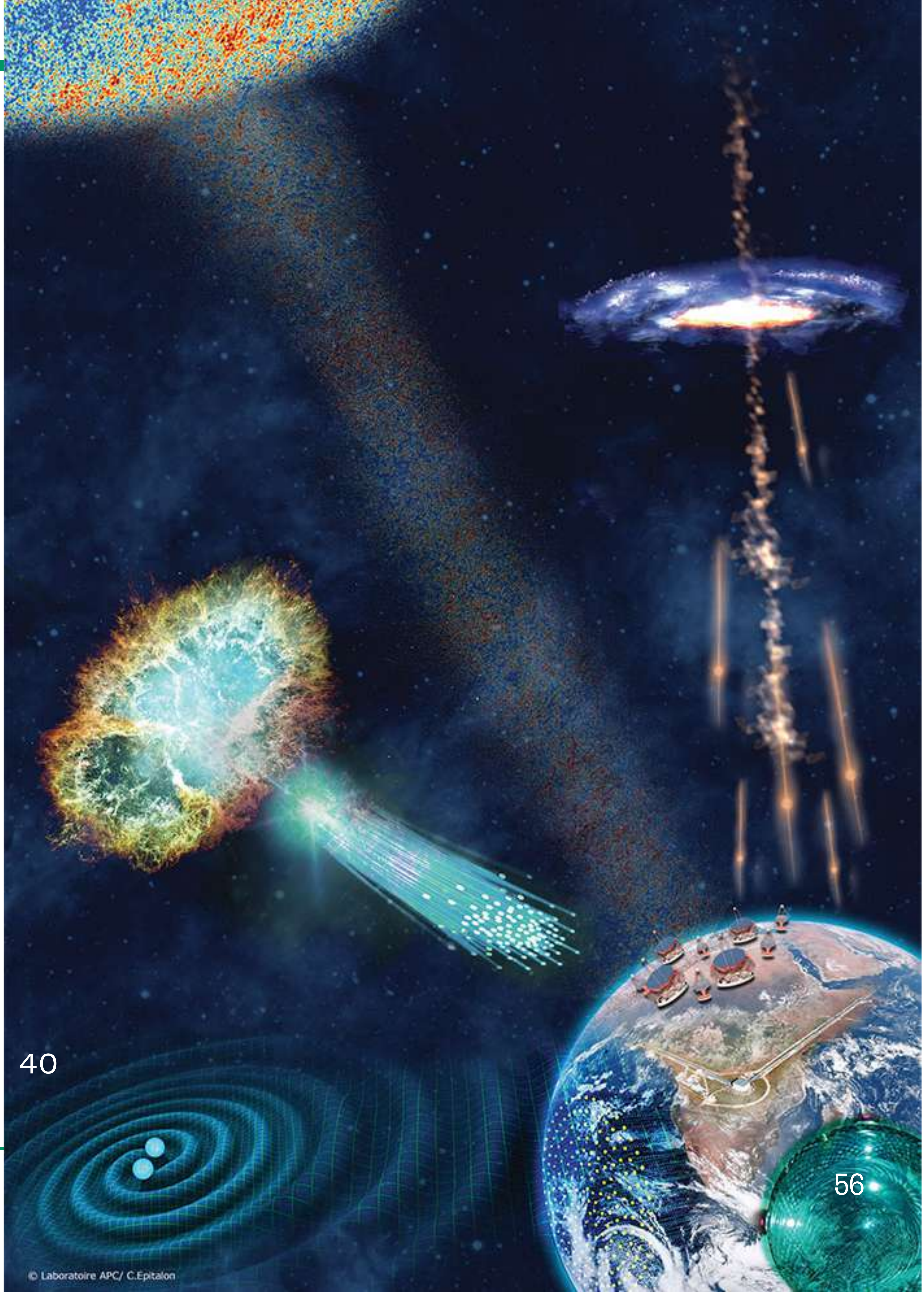
**Radio Facilities Map**




**Optical Facilities Map**



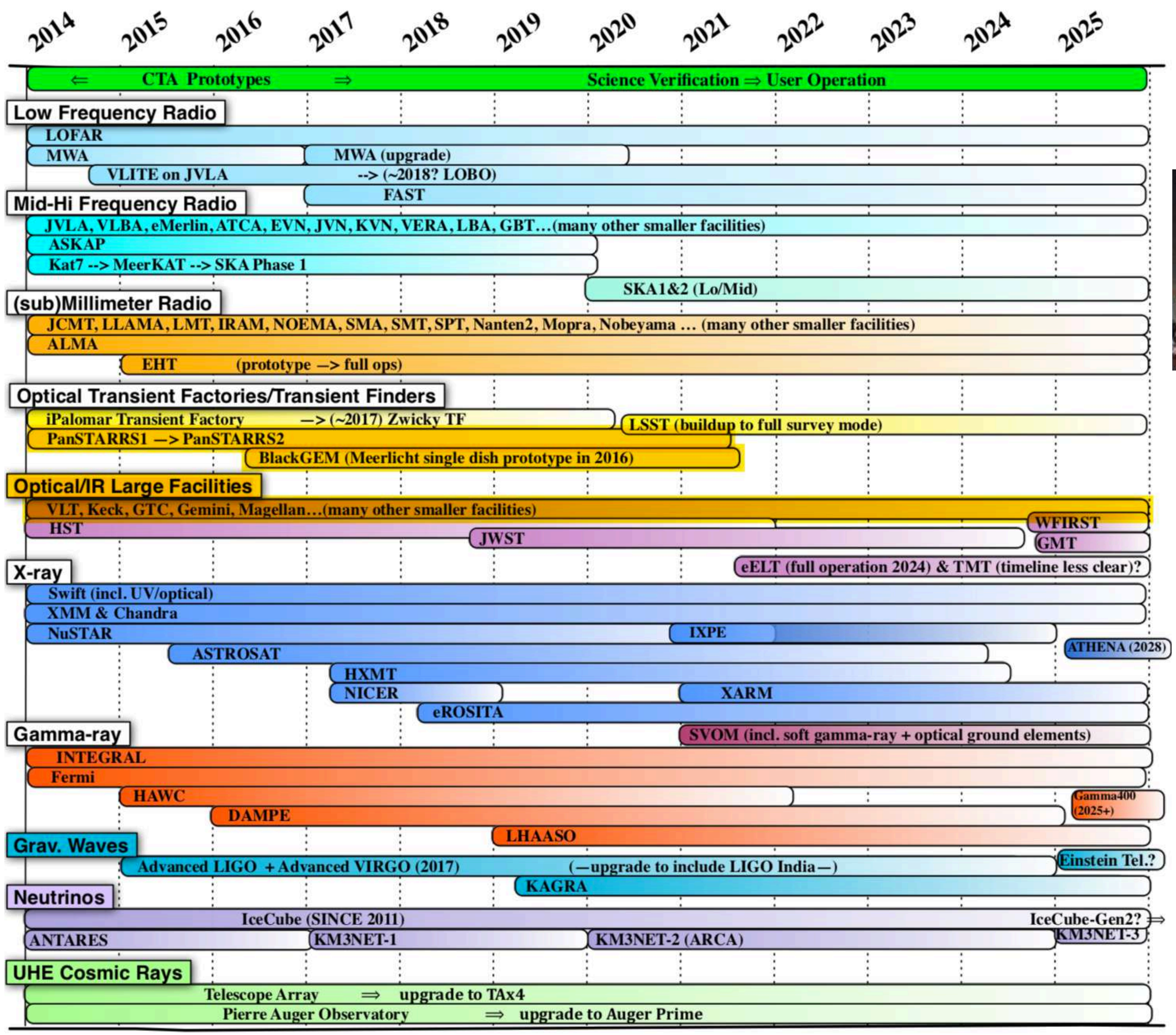
# The CTA MWL Synergies



# CTA Key Science Project Synergies


Sketch by R. Ong

# CTA Synergies with MWL instruments



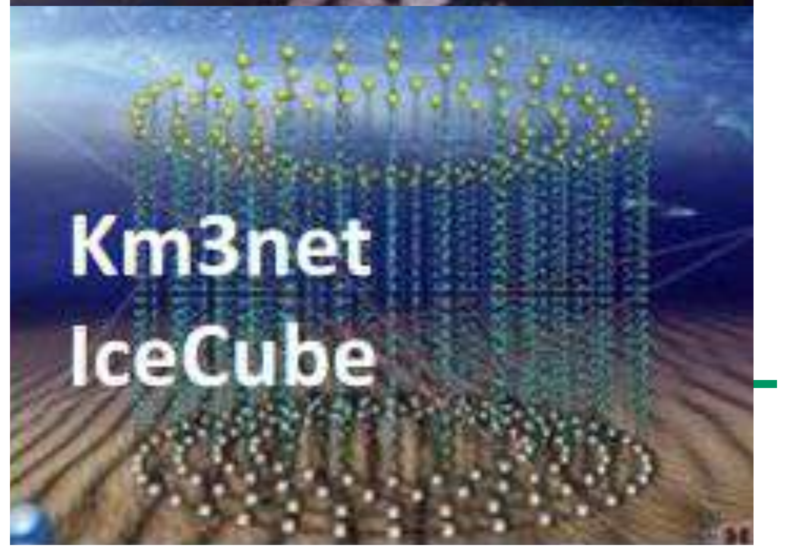


- Non-thermal emission in radio
- High-resolution VLBI to image emission zones


- Mapping of the diffuse gas (CR targets) to complement CTA view of diffuse emission around accelerators


- Detection of fast-variability signals from compact sources
  - Optical polarimetry to isolate non-thermal component in mixed emission scenarios


- X-ray study of shock regions, accretion, high-speed outflows, which connect back to particle acceleration



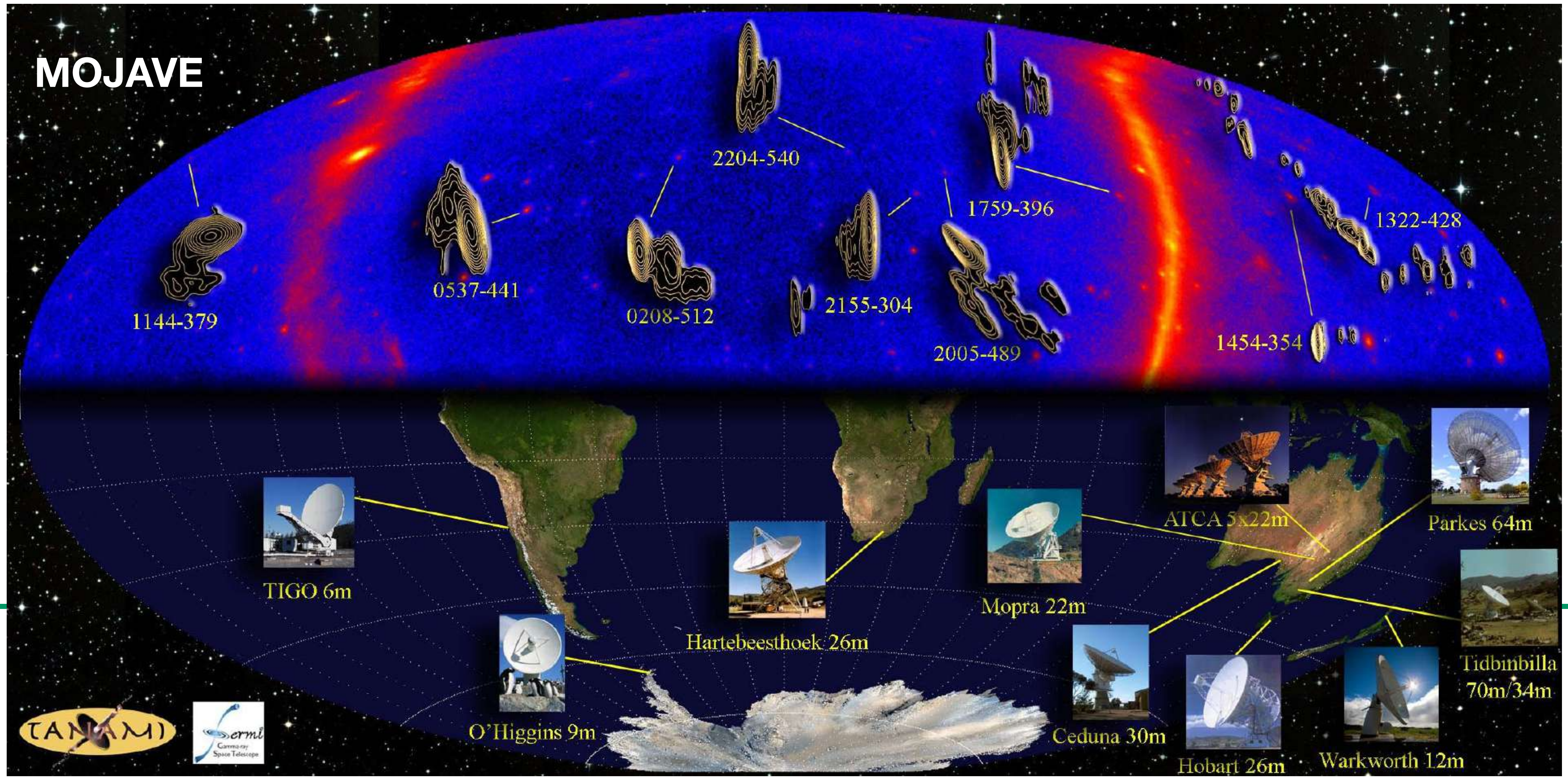

- Soft gamma-ray telescopes for detection of high-energy transients

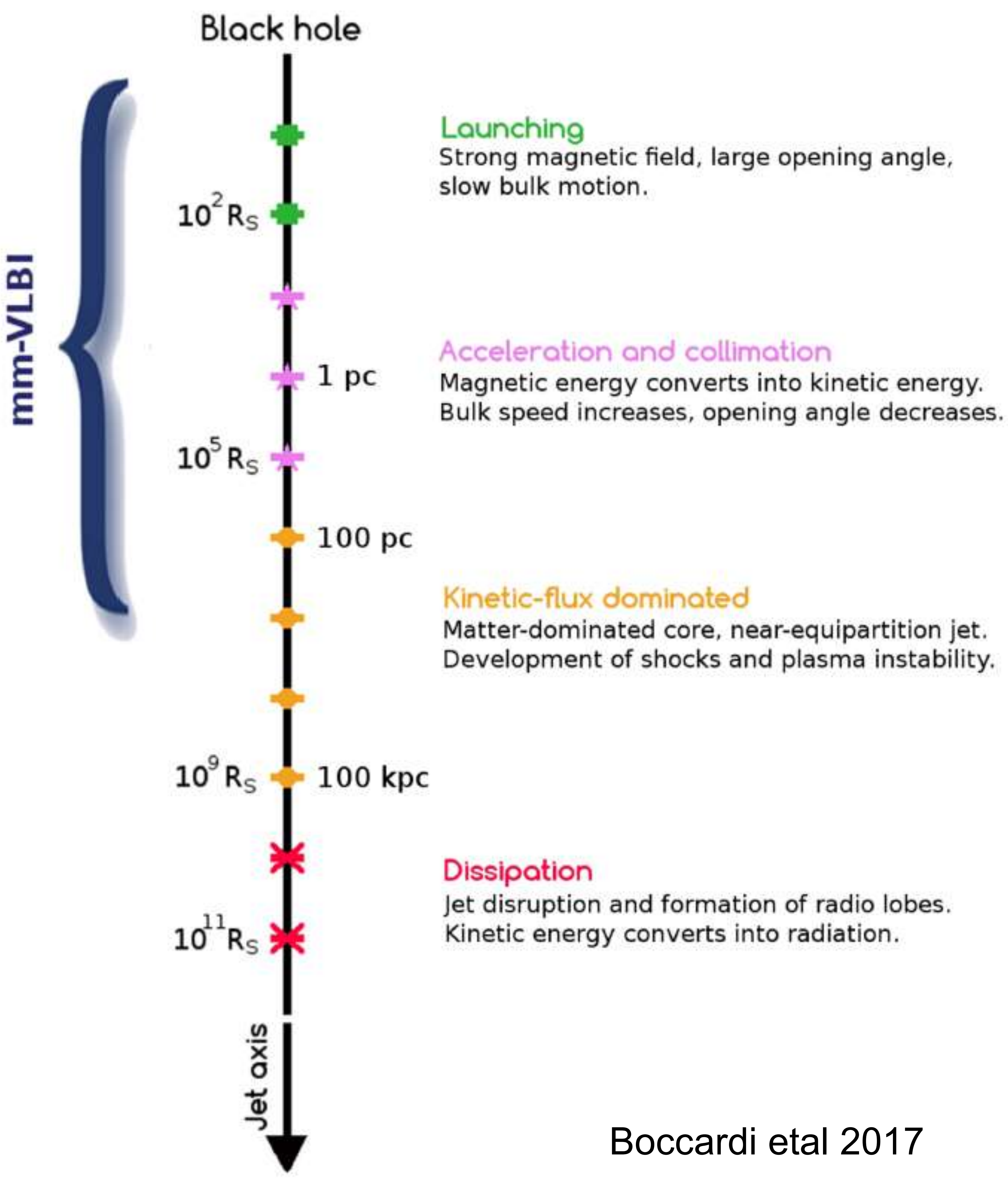
# CTA Synergies with VLBI

Radio and Gamma-rays are two **windows into the non-thermal universe.**

**Radio VLBI :** provides a deep and unique look into the innermost regions of relativistic jets and outflows, and allows to gather direct information on magnetic field structure and shock propagation.

**VHE Observations :** provide direct probes of particle acceleration, seed photons for IC scattering, hadronic processes as well as the EBL.




Boccardi etal 2017

# CTA Synergies with VLBI

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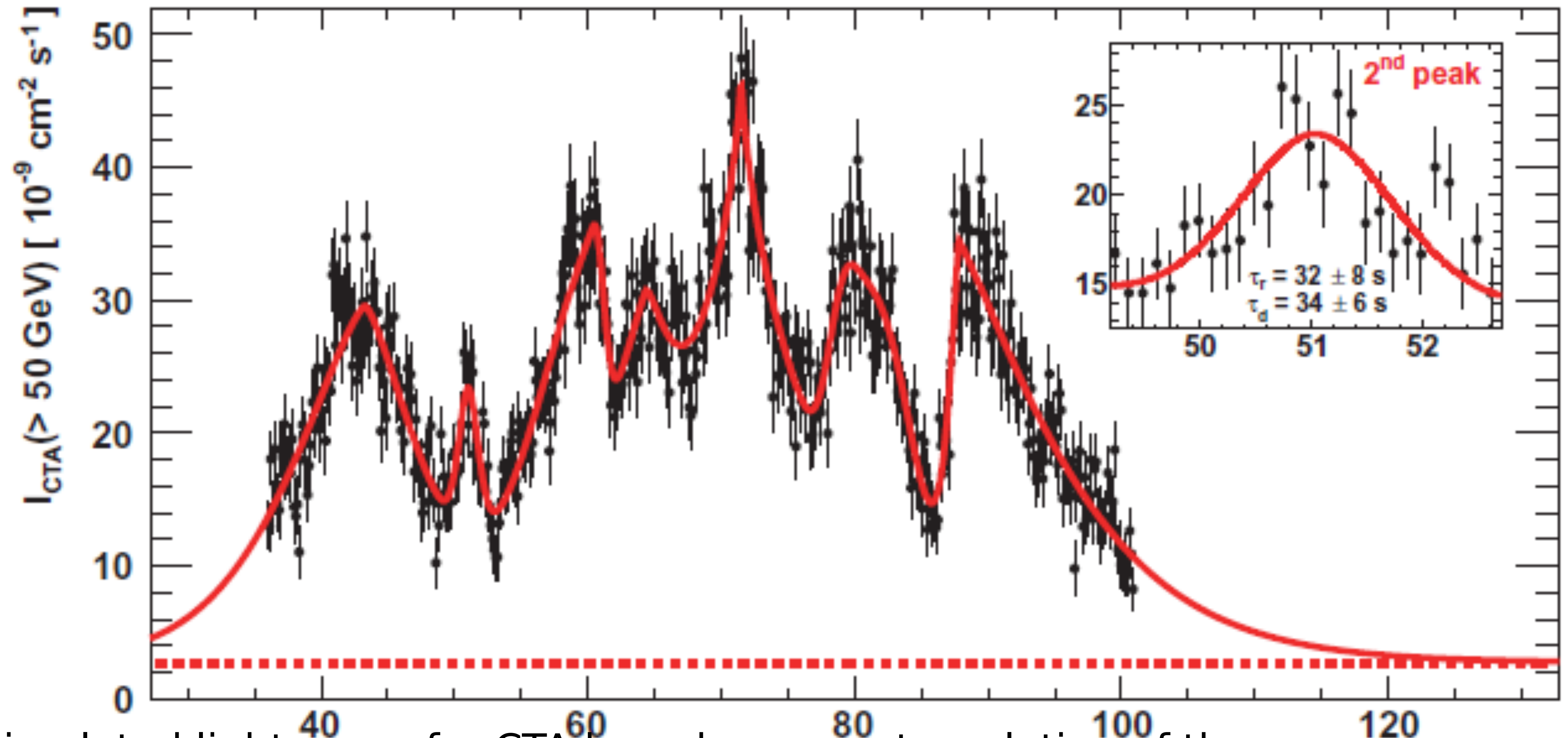
## Some Synergies within the **CTA Science Programme**

**Joint long-term monitoring:** use joint, long-term observations in VLBI and gamma-rays to locate the high-energy emitting regions in AGN (unresolved in VHE).

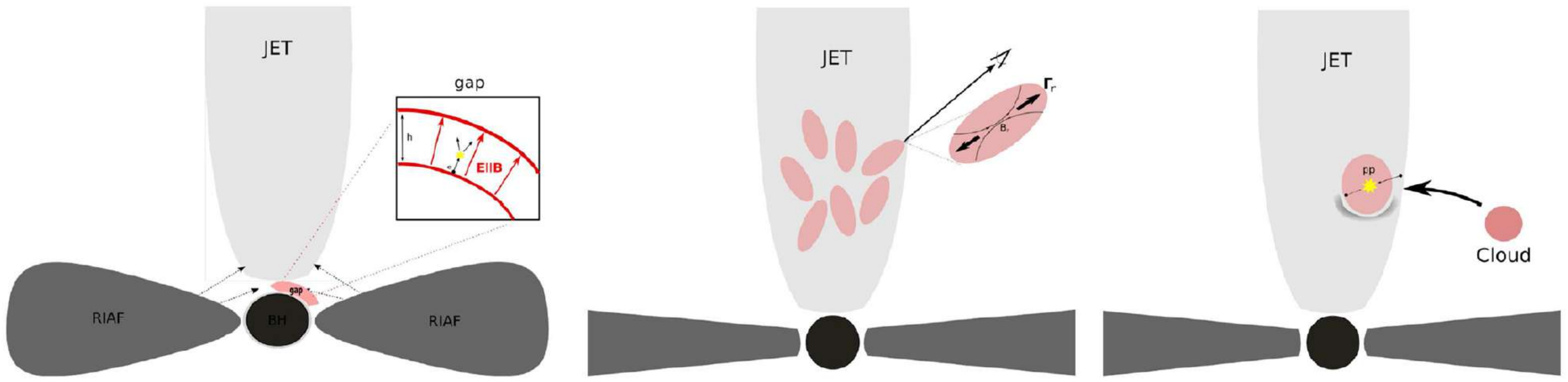
**Detailed spectra of emitting regions:** combine resolved VLBI spectral data and gamma-ray spectra to provide a deeper look into the gamma-ray emitting process in AGN.




Simulated light curve for CTA based on an extrapolation of the spectrum of the 2006 flare from PKS 2155-304

**Variability seen in γ-rays implies a variety of possible models for the (compact) origin of HE radiation which need high-resolution radio-imaging to probe.**

F. Rieger 2019



# CTA Synergies with SKA

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SKA will be the principal radio-telescope of the coming decades, and will have great impact in transients science:

**Transients localization :** SKA can provide precise (arc second or less) localization of transients and proper motions characterization for the study of TDEs, FRBs, GRBs, neutrinos…)

**High-resolution view of the Galactic Center :** fundamental for resolving sources and identify acceleration mechanisms associated to TeV emission and the GC PeVatron.

**Resolving emission regions in AGN jets :** SKA will expand the number of sources for which resolved jets will be accessible, expanding the possibilities for joint investigations with CTA.

**Study of AGN jets along cosmic time :** SKA will expand the horizon for AGN jet studies, seeing radio-loud AGN up to z ~ 8, providing a view at AGN and IGM evolution.

# CTA Synergies with X-rays

**ATHENA** will be a major X-ray Mission (planned, 2028) with wide-field / high-spectral and imaging capability at ~ keV energies.

**Cluster of Galaxies:** CTA hopes to finally detected TeV emission from Galaxy Clusters, associated to their non-thermal emission component, with enormous synergy potential to joint studies with ATHENA, such as in cluster energetics and AGN feedback in the intra-cluster medium.

**THESEUS** will serve as a future GRB trigger provider to the world

**Gamma-ray burst science:** As Swift has demonstrated, there is great potential for synergies in GRB science between THESEUS and CTA, in the provision and follow-up of triggers — critically important here is also the future availability of a GeV gamma-ray mission (such as Fermi-LAT today) to help select most promising follow-ups for CTA.

# Thank you for the attention!

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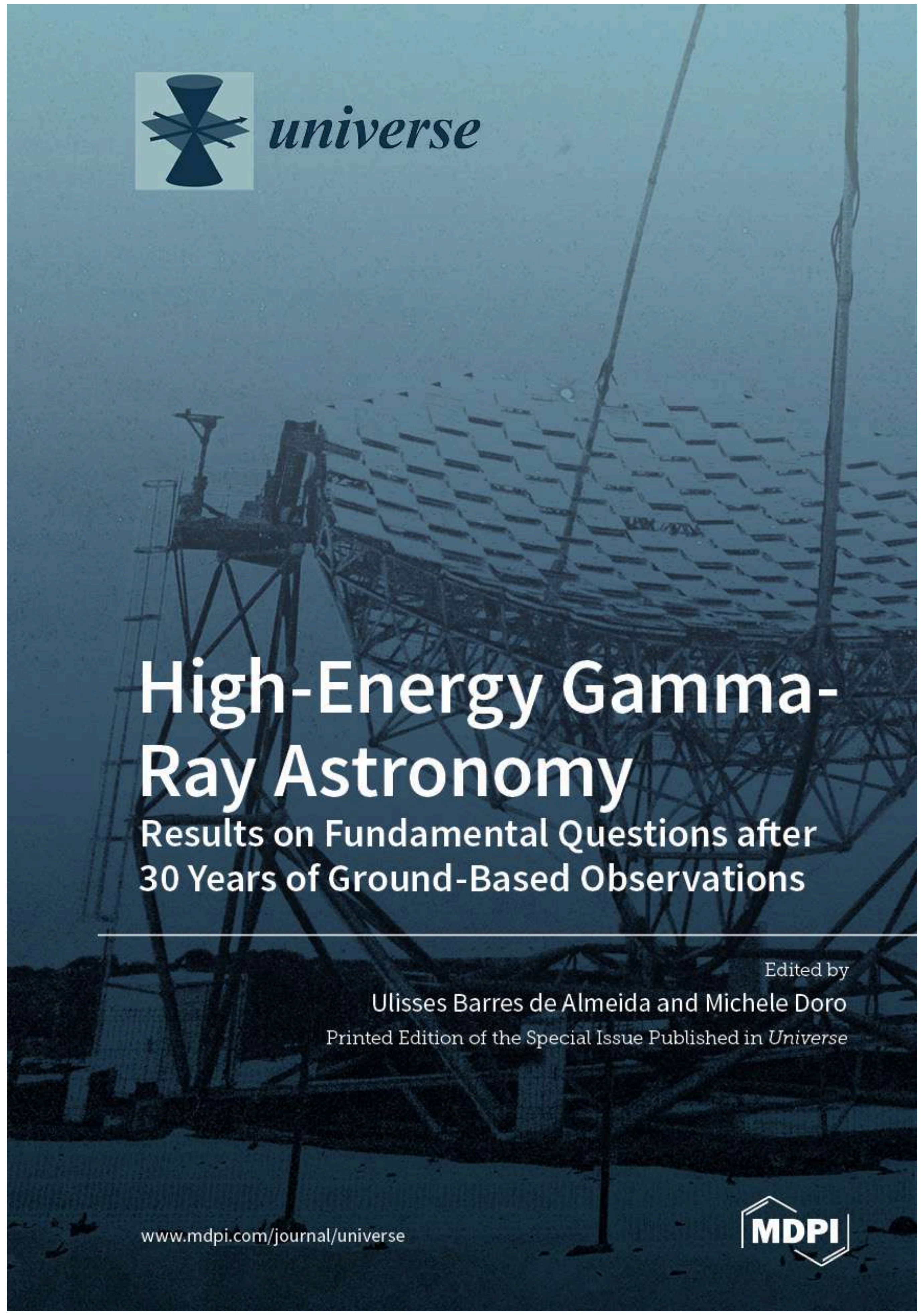


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