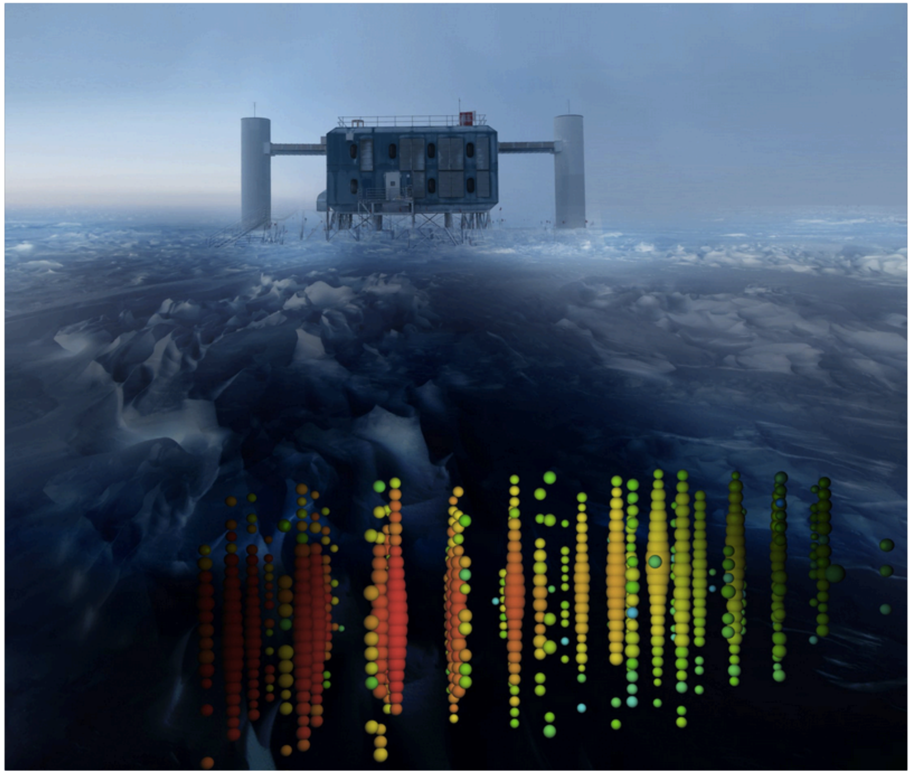


MASTER YOUR PHYSICS CONFERENCE

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UNIVERSITÉ DE GENÈVE

GAMMA-RAY ASTROPHYSICS

IN A MULTI-MESSENGER CONTEXT

16 June 2021

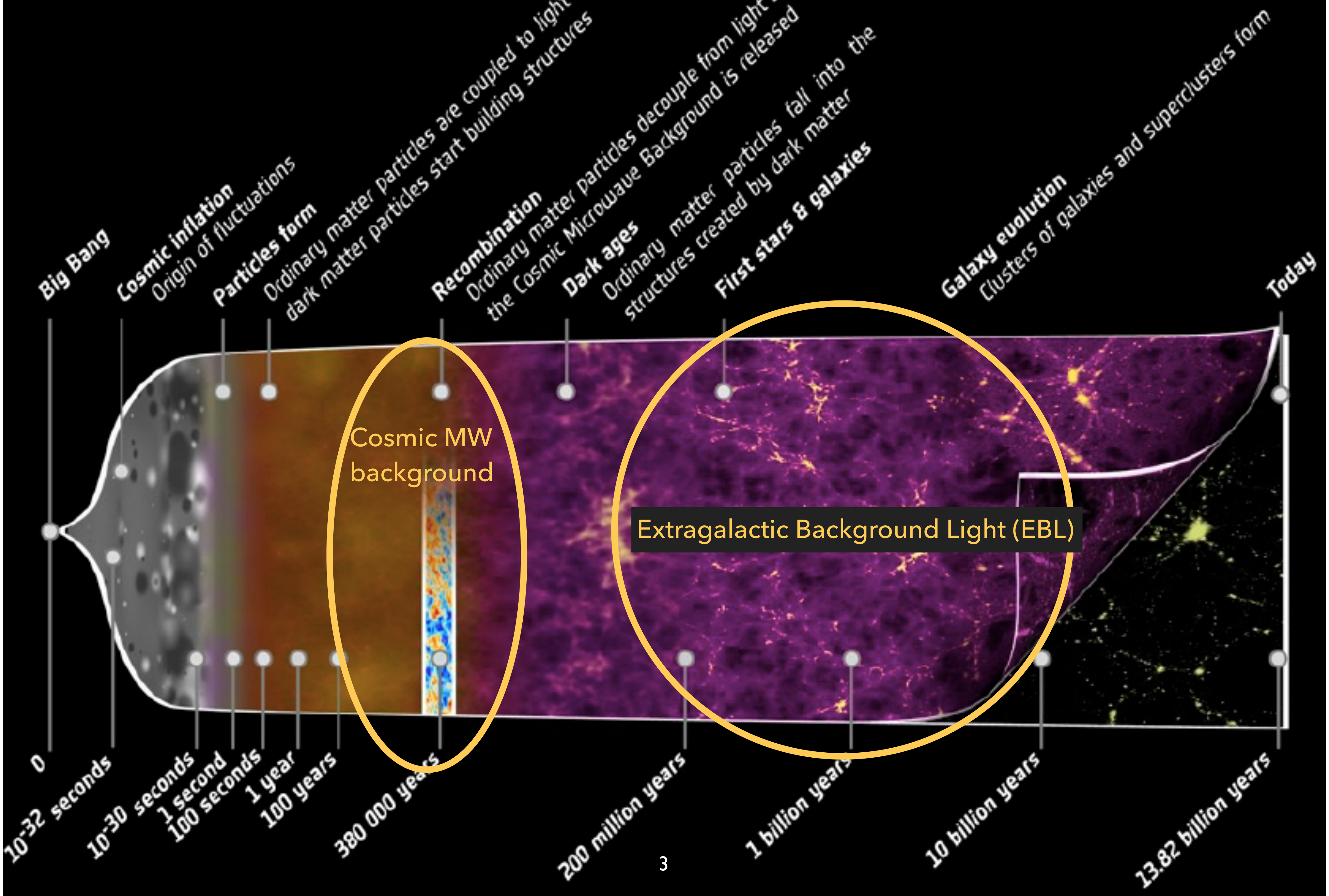
WHY THE SKY IS DARK?

Olber's paradox (XIX century): In a static, infinite Universe every line of sight should eventually intercept the surface of a star, so the sky should be as bright as a stellar surface.

Solution:

- finite speed of light : we can see only galaxies where light has had the time to reach us;
- Finite age of universe in the Big Bang cosmology;
- Expansion of the universe: stars only radiate for finite time, limiting the energy density of the background light)

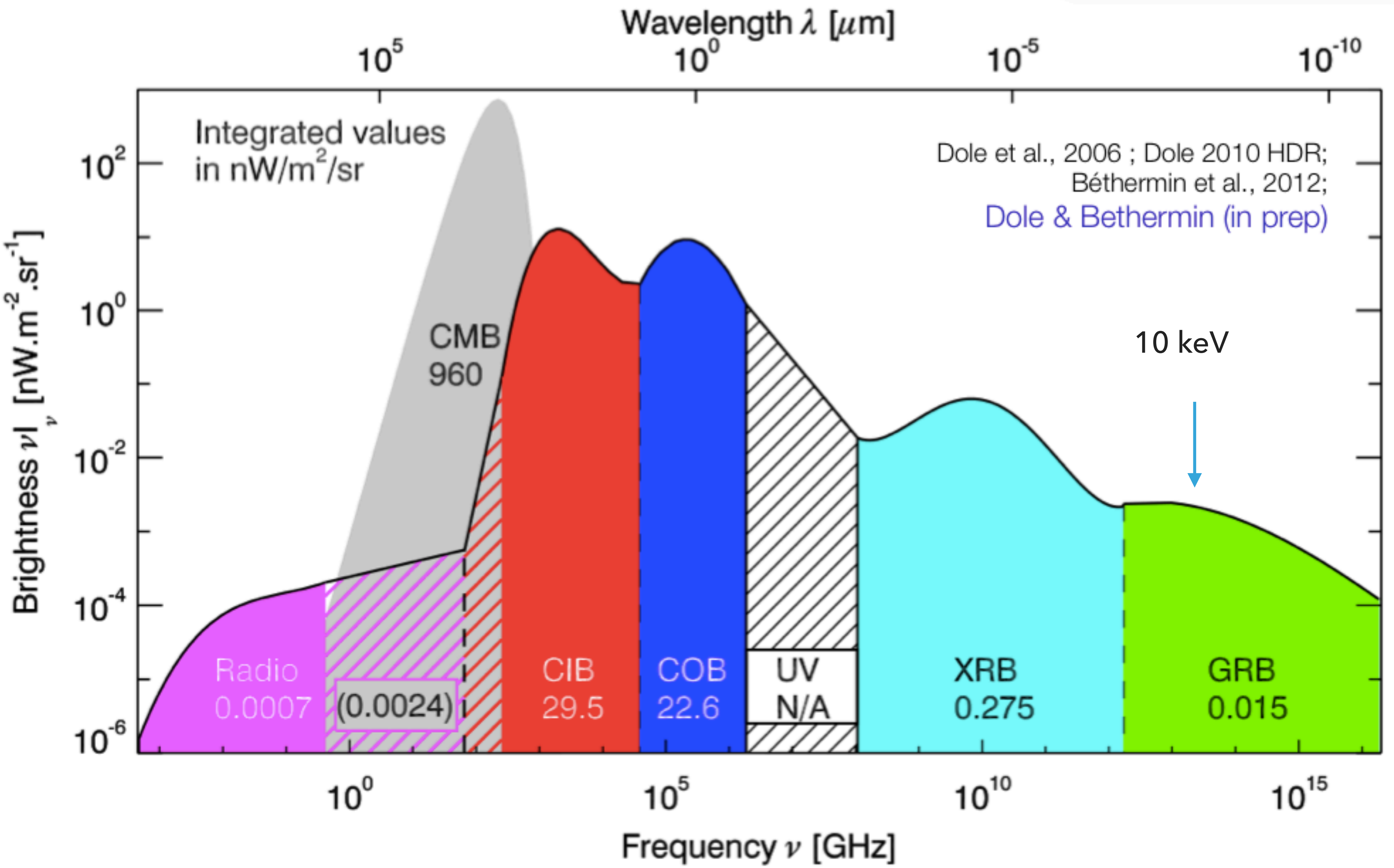
The expanding universe



THE SKY IS PERVADED OF RADIATION!

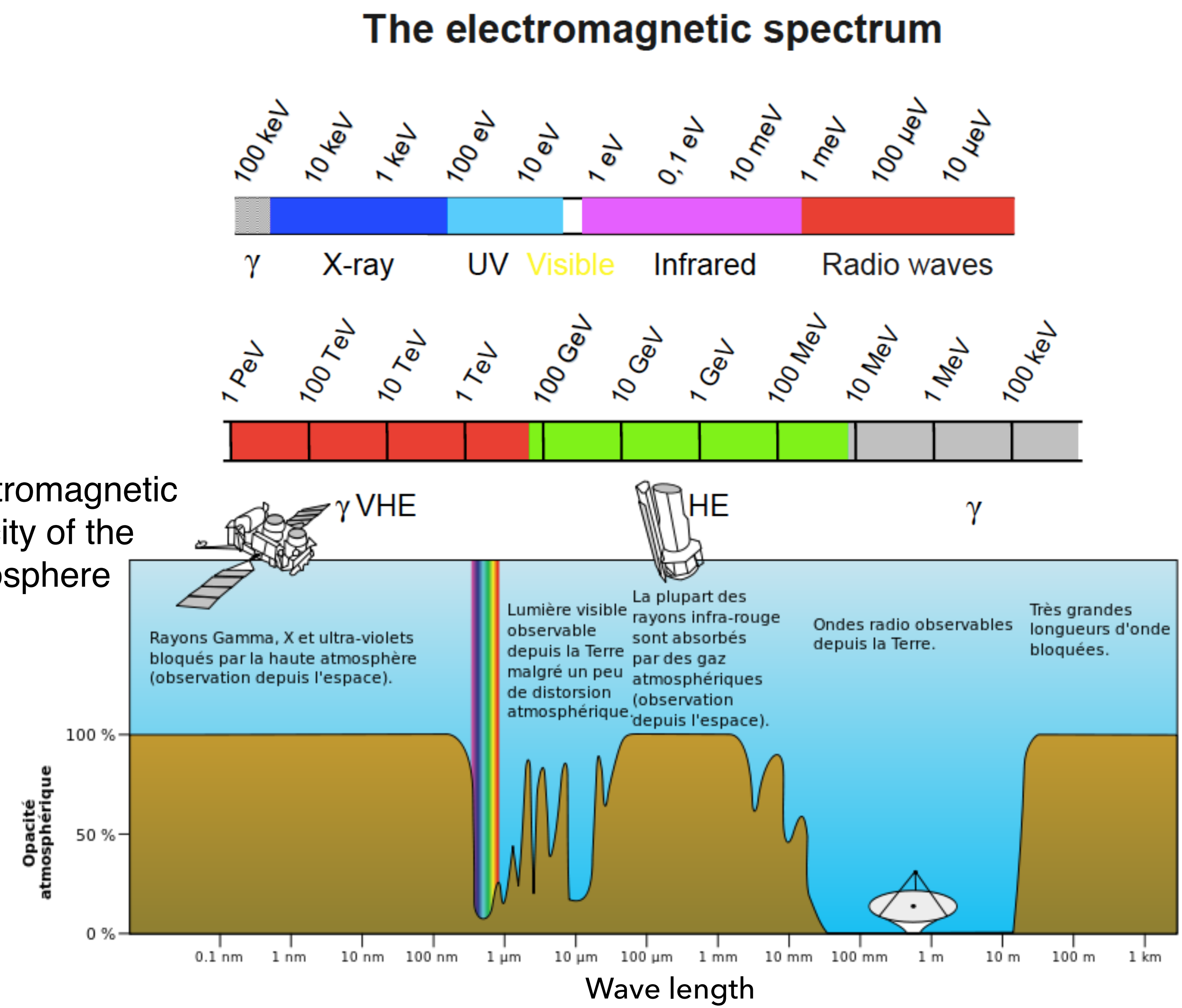
The CMB is a picture of the Universe 380'000 yr after the Big Bang

The Extragalactic Background Light (EBL) encodes the output of galaxy formation evolution

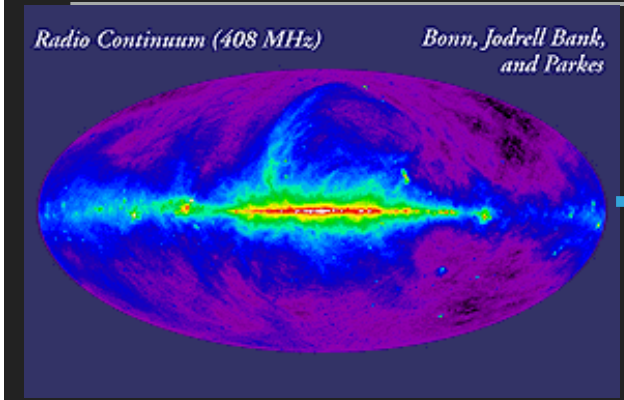


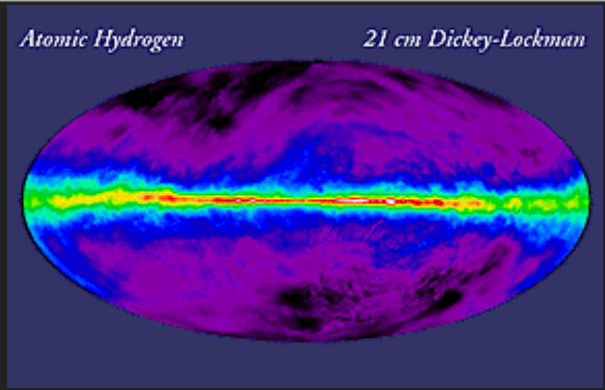
MULTI-WALENGTH ASTRONOMICAL OBSERVATIONS

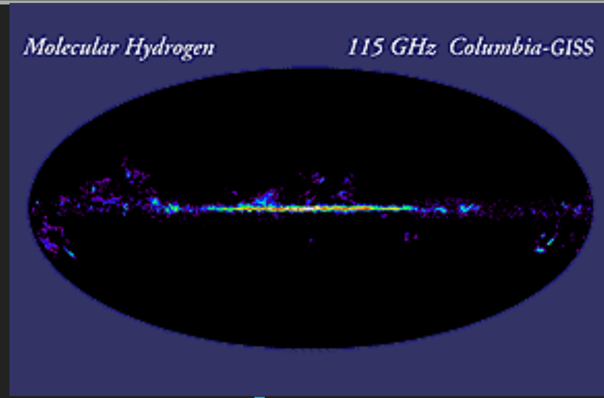
Electromagnetic opacity of the atmosphere



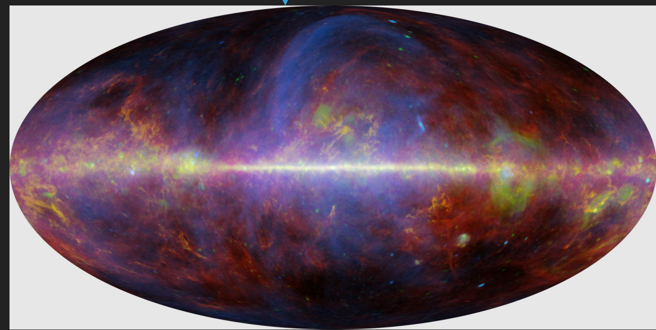
THE MULTI-WALENGTH SKY

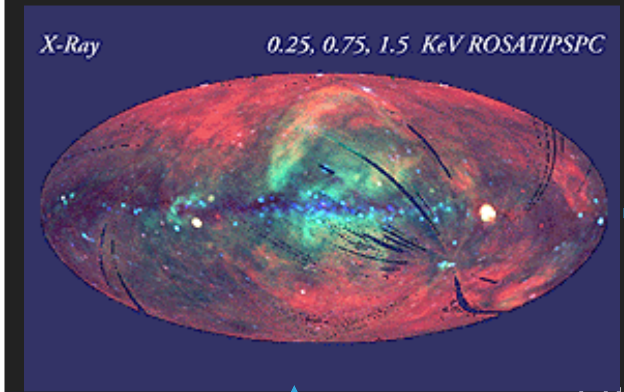


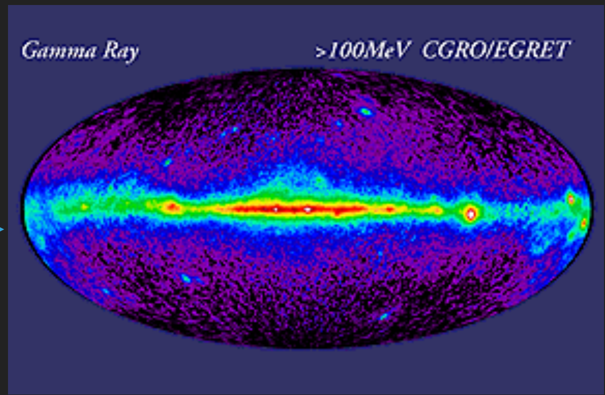




Planck 10-0.3 mm

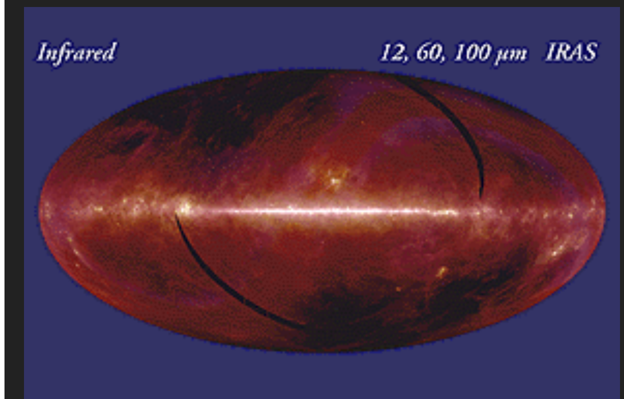


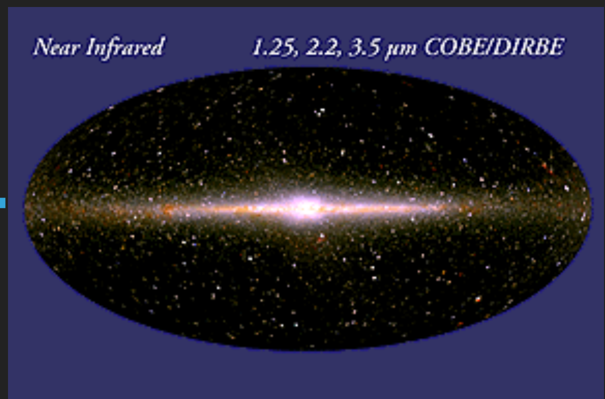




https://mwmw.gsfc.nasa.gov/mmw_allsky.html

http://www.chromoscope.net





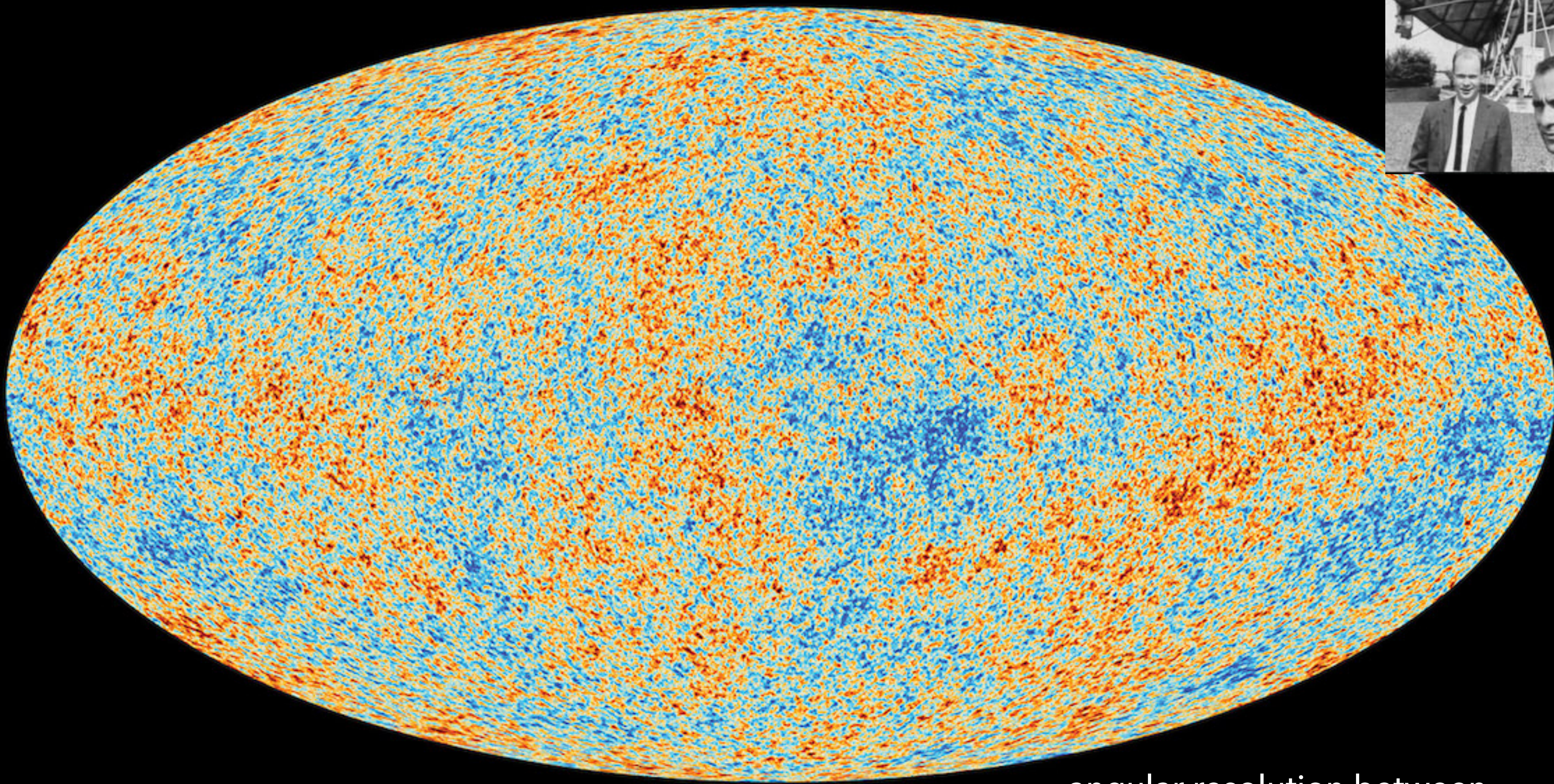
COSMIC MICROWAVE RADIATION

Penzias&Wilson, 1965

esa

→ THE COSMIC MICROWAVE BACKGROUND

Planck Legacy Release 2018



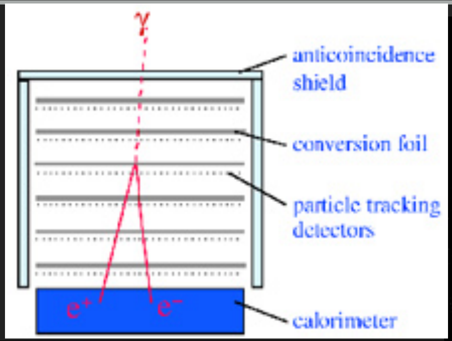
Blackbody spectre with T = 2.7 °K

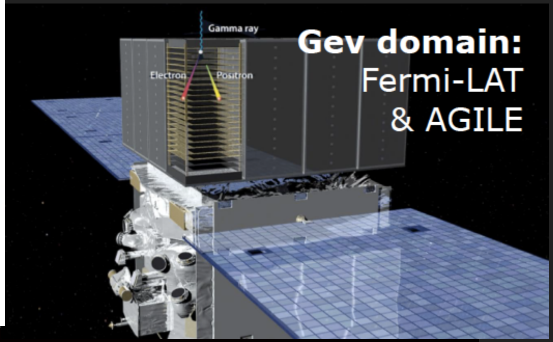
angular resolution between 0.5°-0.08° => $\Delta T/T \sim 2 \times 10^{-6}$

Credit: ESA/Planck Collaboration

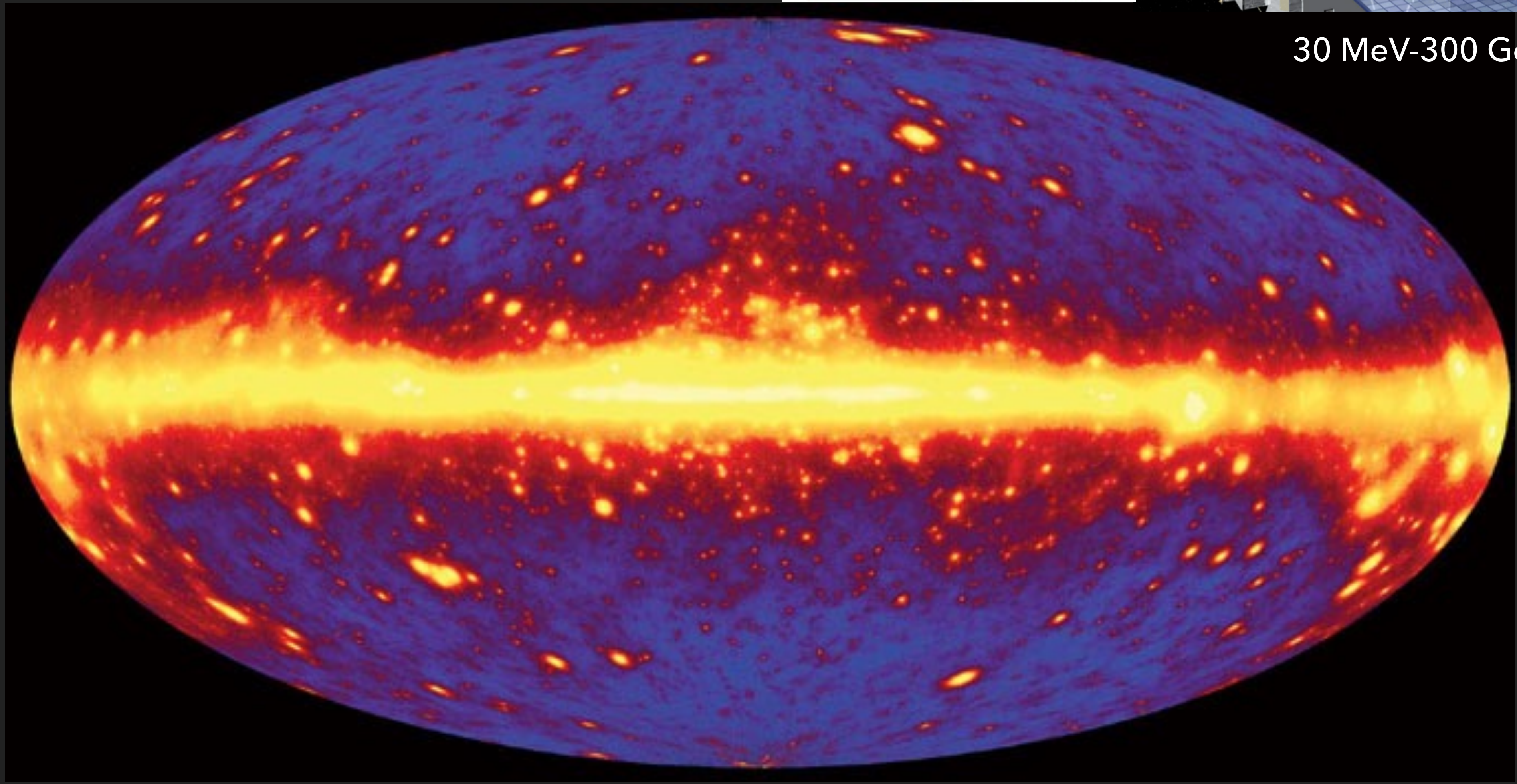
www.esa.int

THE ACCELERATORS SKY IN THE TEV SEEN BY FERMI-LAT





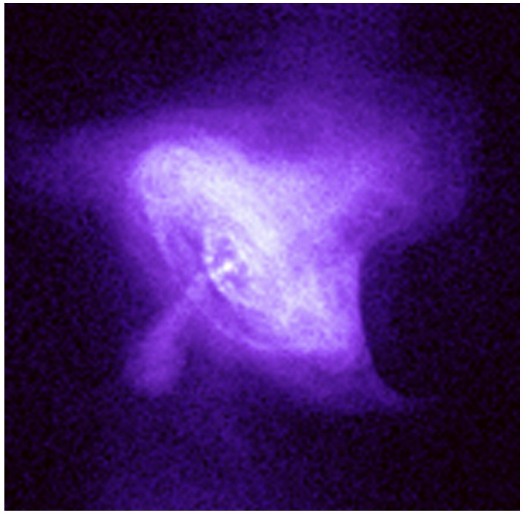
30 MeV-300 GeV



http://www.nasa.gov/mission_pages/GLAST/news/gammaray_best.html

THE MULTI-WALENGTH OBSERVATIONS: THE CRAB NEBULA

Hystorical Supernova remnant observed in the year 1054 by Chinese Astronomers

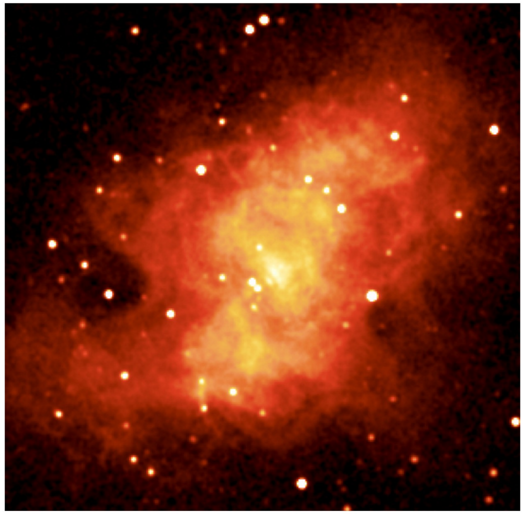


X-ray

~ 10^4 eV

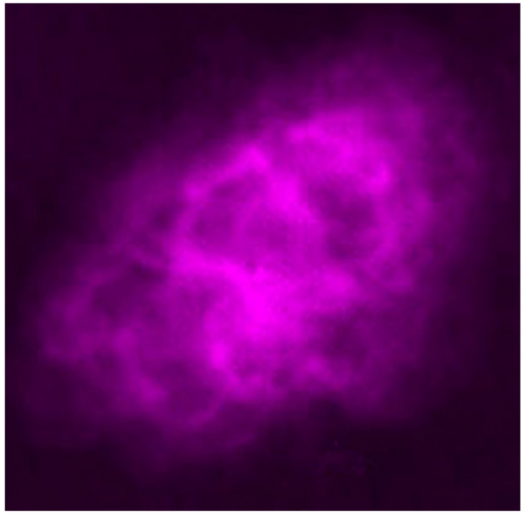
Optical

~ few eV



Infrared

~ 1 eV

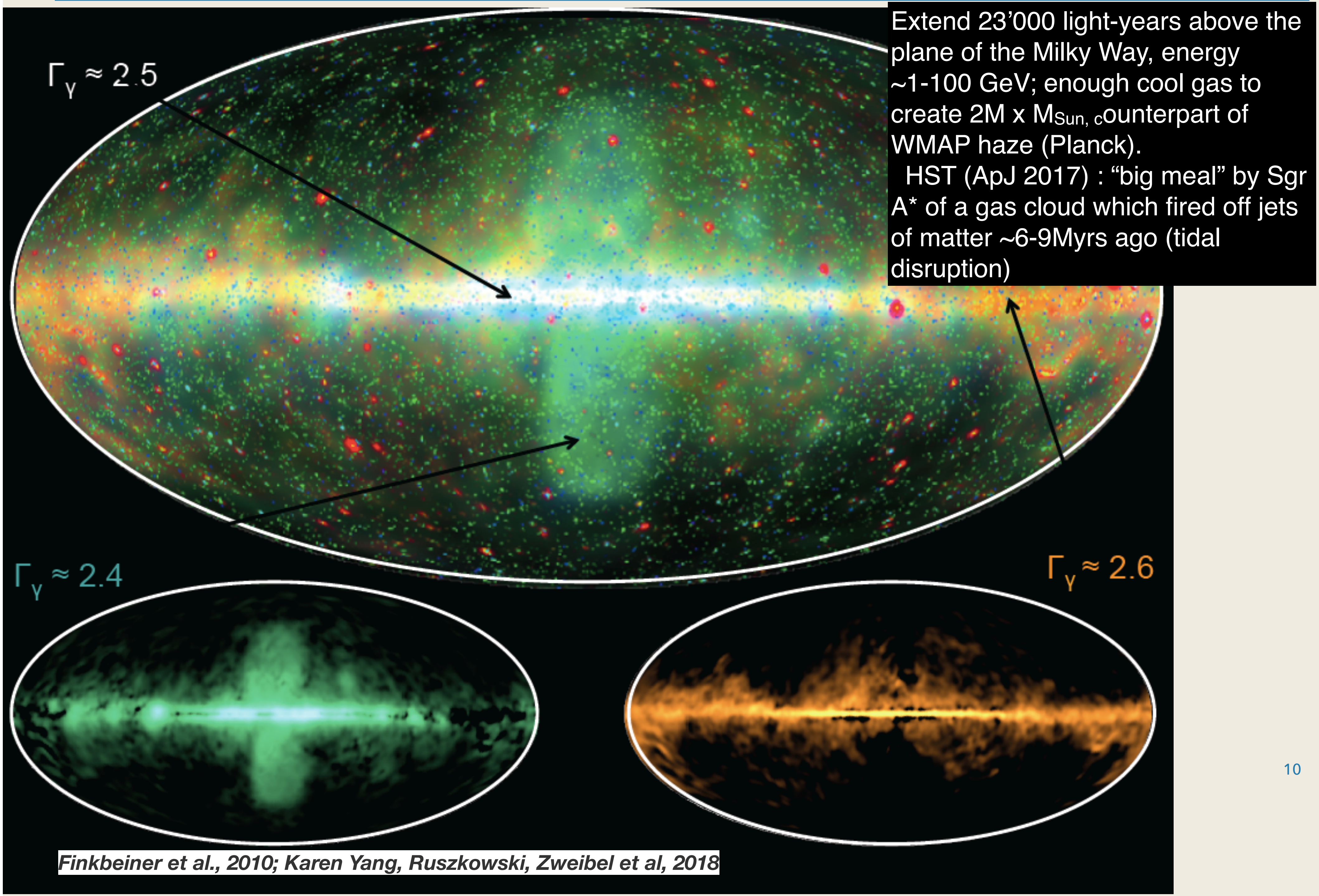


Radio

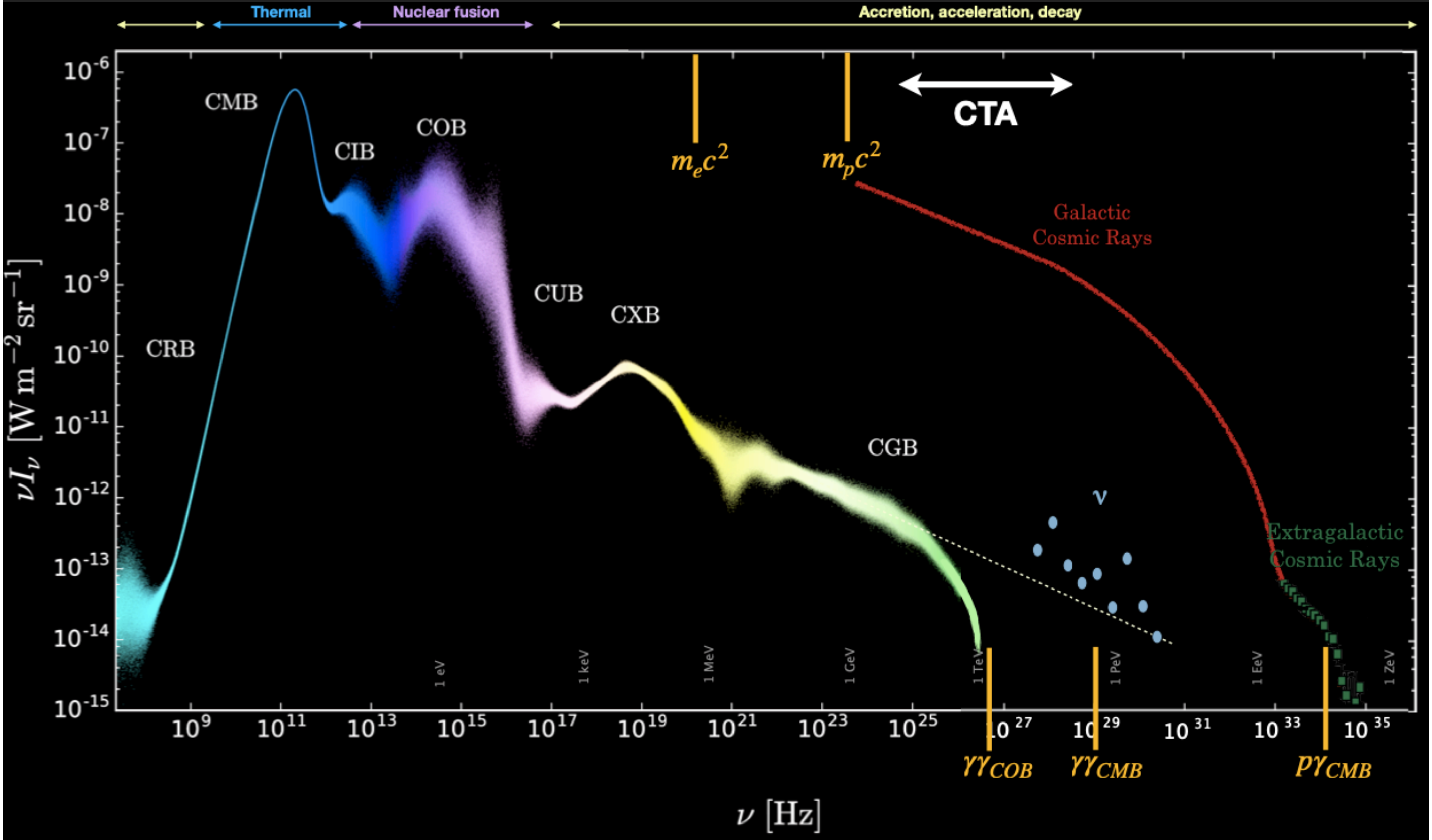
~ 10^{-4} eV

Credit: NASA/CXC/SAO (X-ray), Paul Scowen and Jeff Hester (Arizona State University) and the Mt. Palomar Observatories (optical), 2MASS/UMass/IPAC- Caltech/NASA/NSF (infrared), and NRAO/AUI/NSF (radio)

Opening windows to the unexpected...

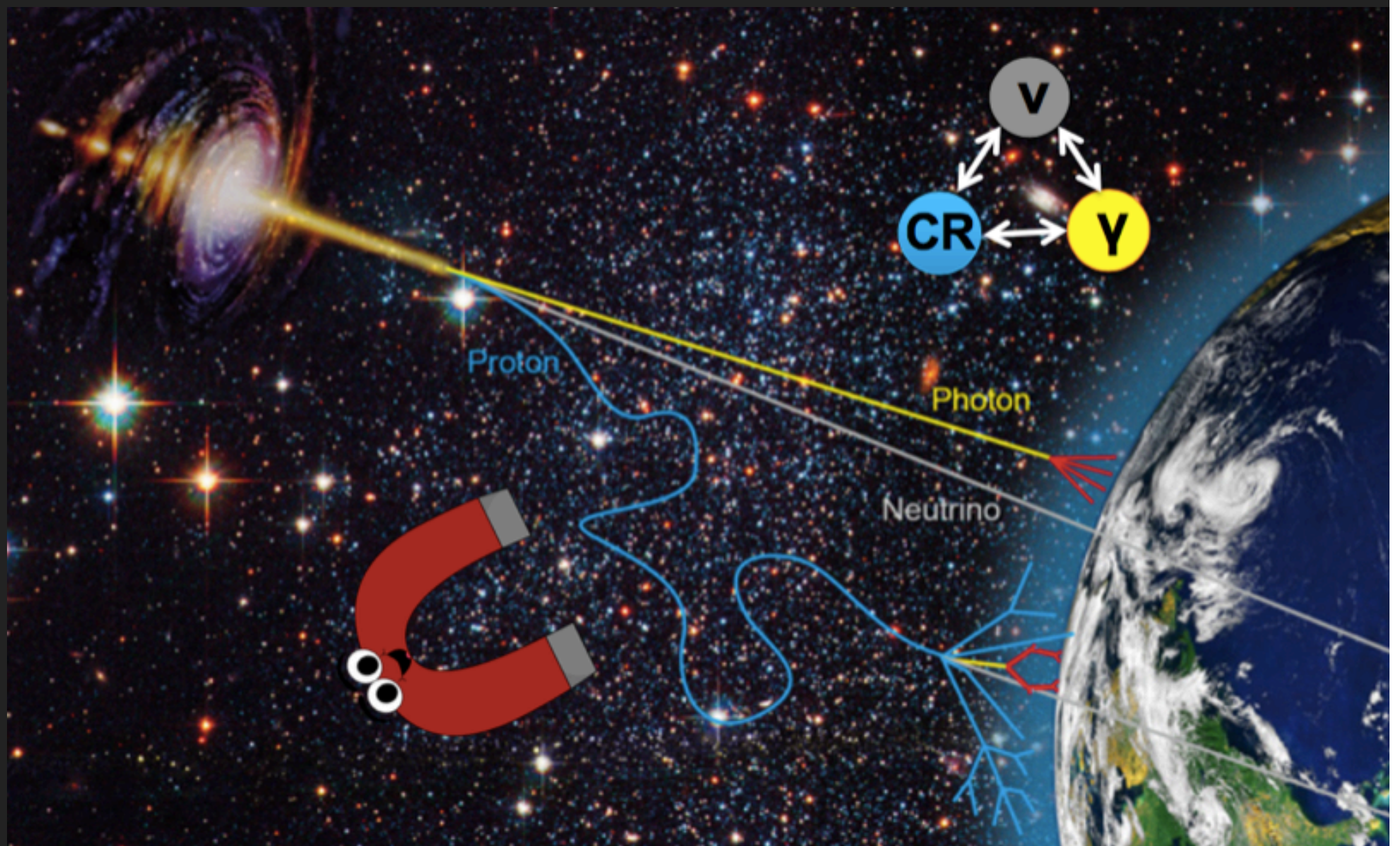


...AND OF PARTICLES!



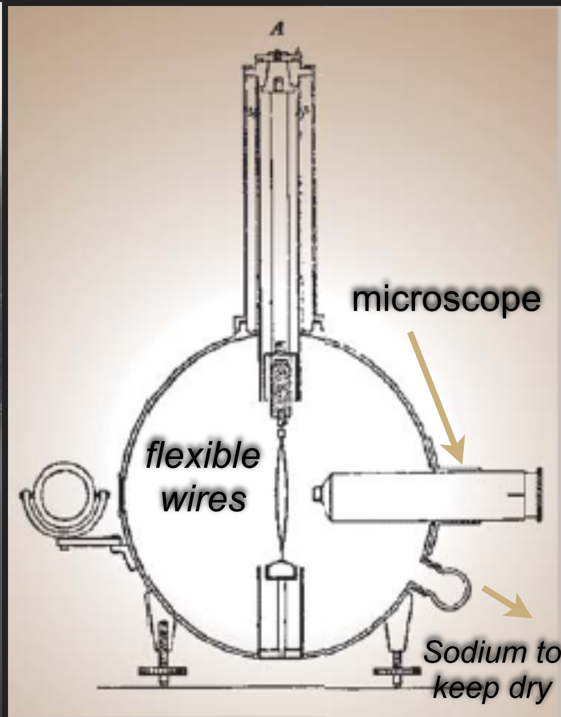
CONTENTS OF TWO LECTURES

- What are cosmic rays and why we study them?
- The new astronomy: multi-messenger high energy astrophysics
- Gamma-Ray and neutrino high-energy telescopes



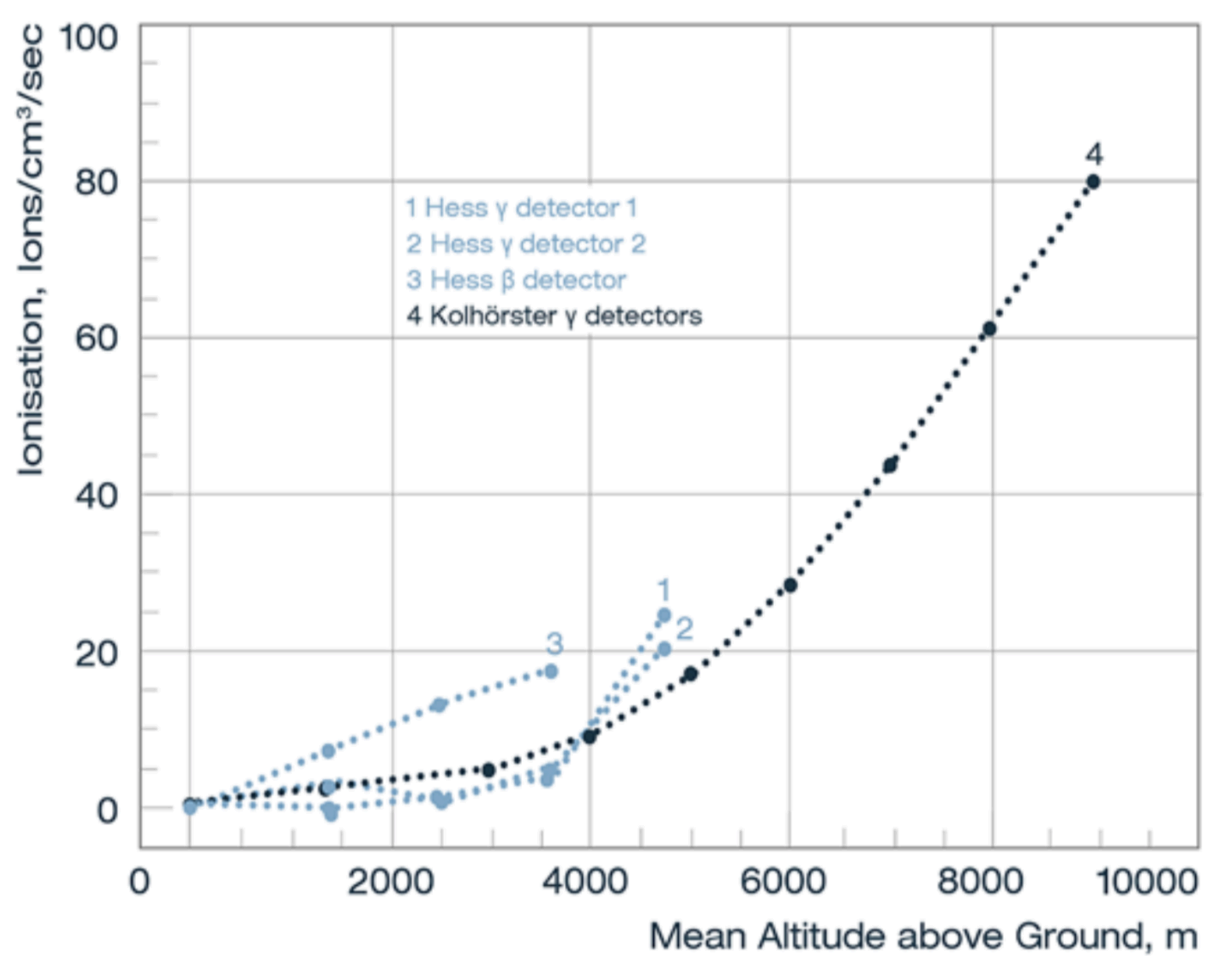
COSMIC RAY HISTORY

- < 1909: 3 hypothesis for observed discharge of electroscope: Wilson had visionary idea on extraterrestrial radiation (e.g. Sun), radiation from radioactive elements in the Earth crust or atmosphere.
- 1910 Wulf: inclusive measurements from Eiffel Tower.
- A. Gockel (Swiss, 1909-1911): with a Wolf-type electroscope on 3 balloon flights discovers that the radiation discharging the electroscopes not from ground but increases with altitude. Wrong interpretation: gamma-rays from radioactive sources in the atmosphere
- V.F. Hess (1912, Nobel prize with Anderson in 1936) reaches 5000 m of altitude and interprets results as due to a ionising radiation that increases with altitude.



COSMIC RAY HISTORICAL HINTS

- Kolhörster took more data between 1911-1914 up to 9 km improving Hess results
- Millikan studied the penetration properties in water and atmosphere and called the radiation ‘cosmic rays’ (1928)

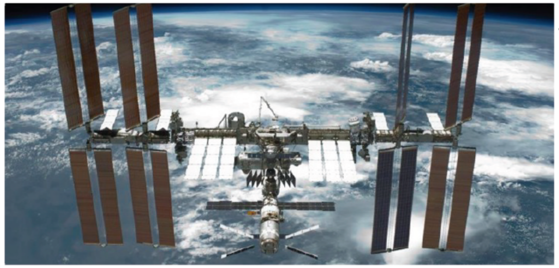


Nature (suppl) 121, 19, (1928)
Lecture at Leeds University

These facts, combined with the further observation made both before and at this time, that within the limits of our observational error the rays came in equally from all directions of the sky, and supplemented finally by the facts that the observed absorption coefficient and total cosmic ray ionisation at the altitude of Muir Lake predict satisfactorily the results obtained in the 15·5 km. balloon flight, *all this constitutes pretty unambiguous evidence that the high altitude rays do not originate in our atmosphere, very certainly not in the lower nine-tenths of it, and justifies the designation ‘cosmic rays,’* the most descriptive and the most appropriate name yet suggested for that portion of the penetrating rays which come in from above. We shall discuss just how unambiguous the evidence is at this moment after having presented our new results.

These represent two groups of experiments, one carried out in Boliviá in the High Andes at altitudes up to 15,400 ft. (4620 m.) in the fall of 1926, and the other in Arrowhead Lake and Gem Lake, California, in the summer of 1927.

COSMIC RAY MEASUREMENTS



AMS on space station

Direct detection balloon-borne or satellite experiments generally use **energy per nucleon** on x-axis, the natural variable for studying propagation of nuclei because energy per nucleon is conserved in spallation processes .

ANITA at South Pole

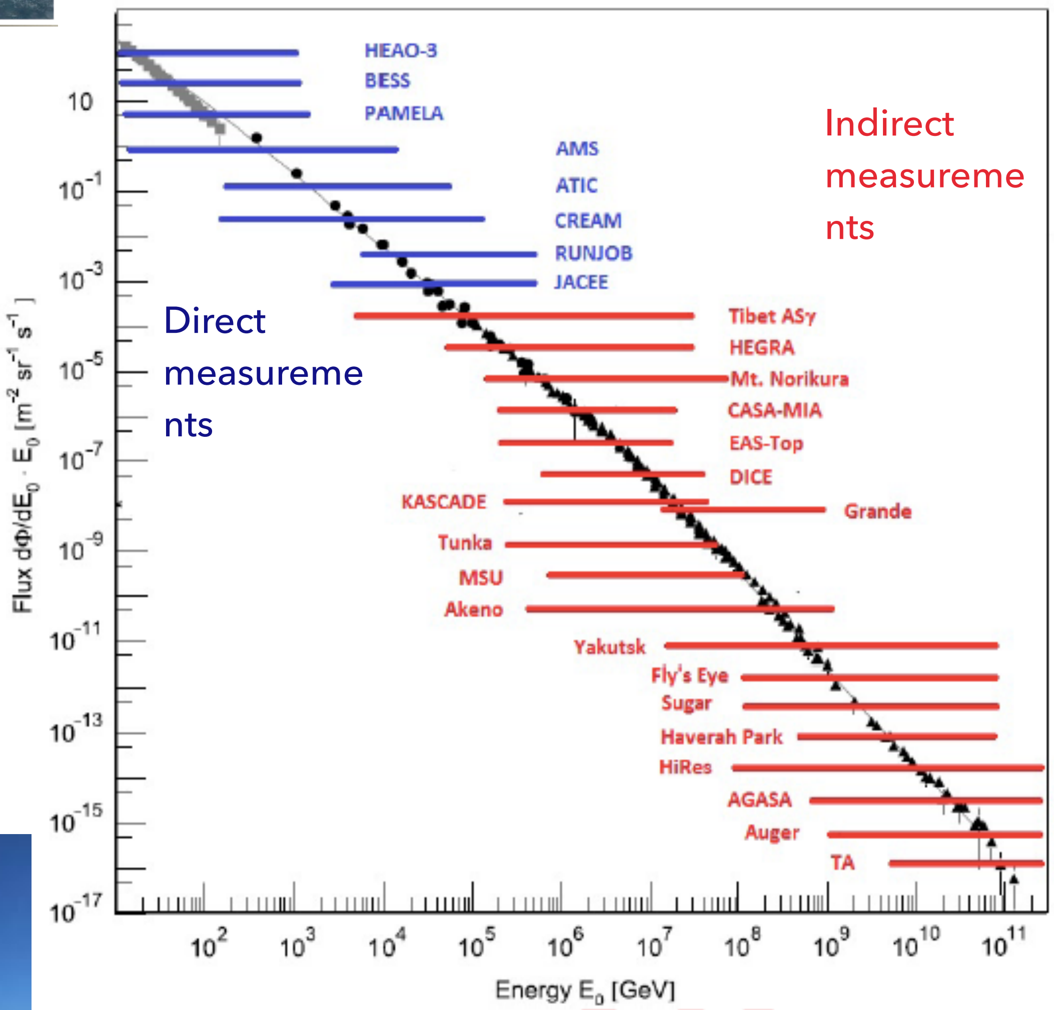


Figure from M. Spurio's book, Particles & Astrophysics

Pierre Auger in the Argentinian Pampa

Indirect measurements: Since air shower measurements are calorimetric in nature, the natural energy variable to use is **total energy per nucleus.**

IceTop at South Pole

THE COSMIC RAY ALL-PARTICLE SPECTRUM

Particles per unit of surface, unit of time, unit of solid angle, unit of energy $[m^2\ s\ sr\ GeV]^{-1}$.
The spectrum spans 12 orders of magnitude in energy and 24 in intensity. Below the knee:

$$\frac{dN}{dE} = 1.8 \times 10^4 (E/1GeV)^{-2.7} \frac{\text{nucleons}}{\text{m}^2\,\text{sr}\,\text{s}\,\text{GeV}}$$

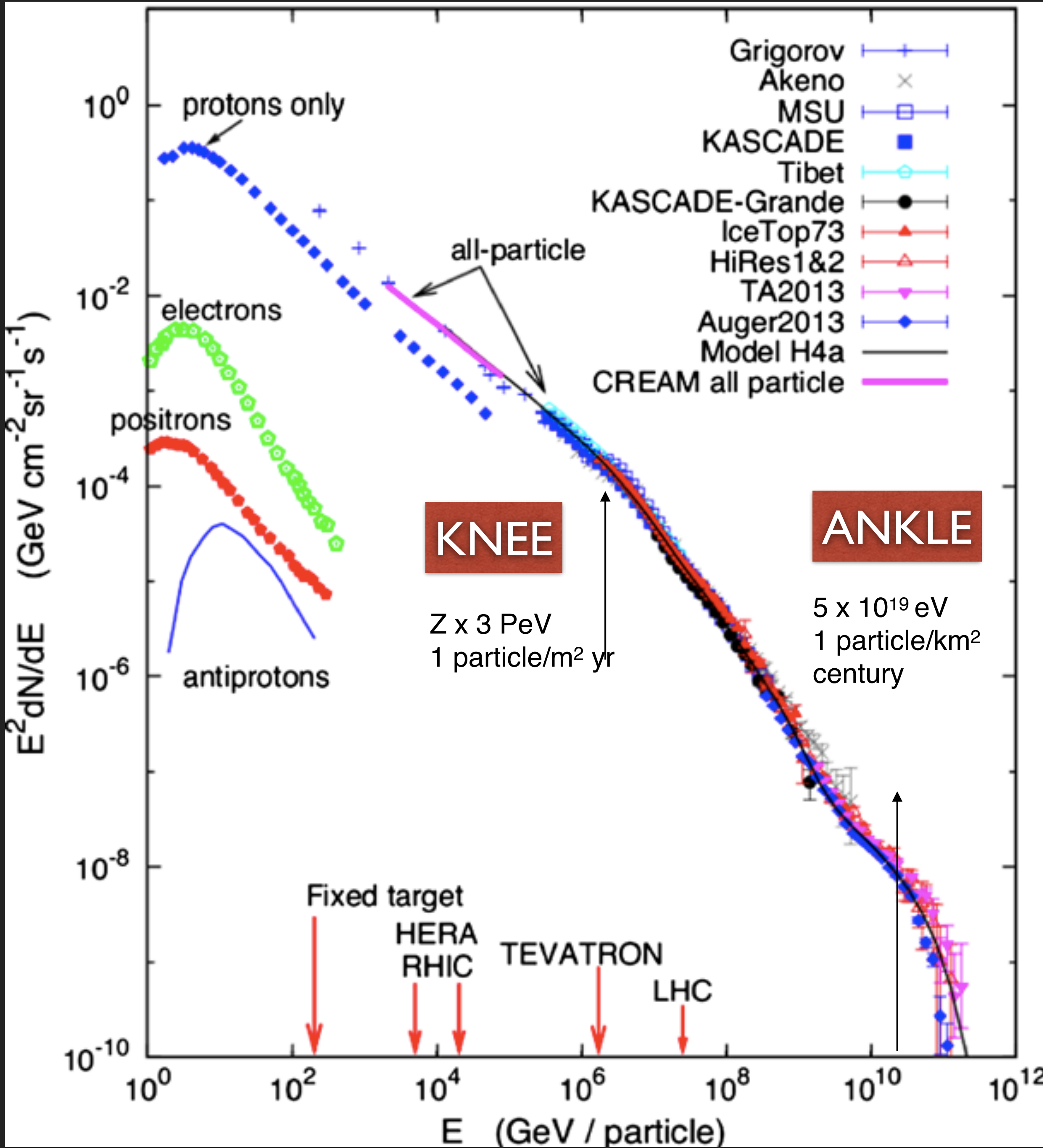
$E_{knee} \sim Z \times 3$ PeV

$E_{ankle} \sim 5 \times 10^{19}$ eV

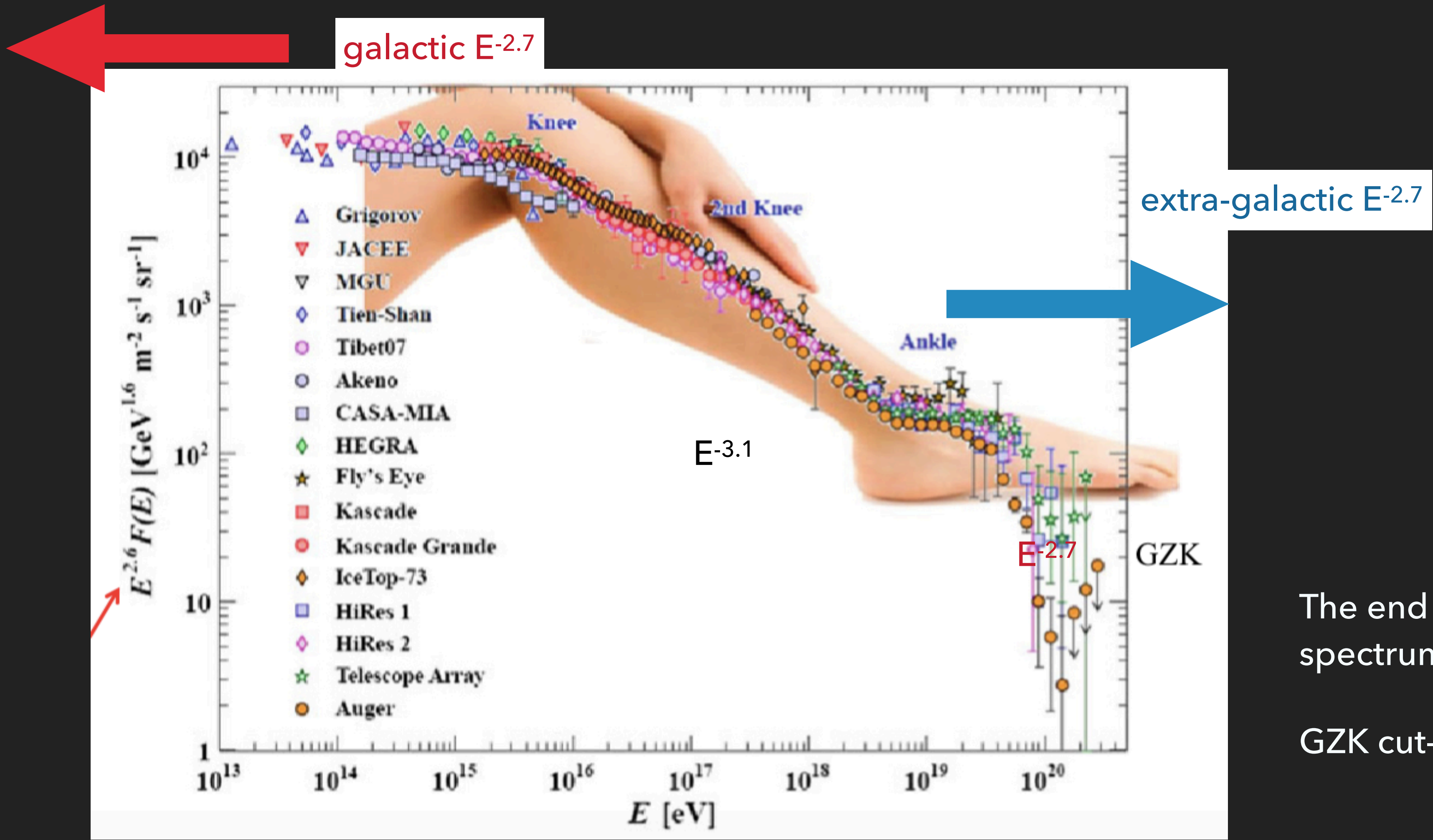
Notice: $$\log\left[\frac{dN}{dE}\right] = log[A] - \alpha \cdot log[E]$$

Since the spectrum is steep, we multiply by E^β:

$$\log\left[E^\beta \frac{dN}{dE}\right] = log[A] - (\alpha - \beta) \cdot log[E]$$



THE SPECTRAL FEATURES: THE KNEE AND THE ANKLE

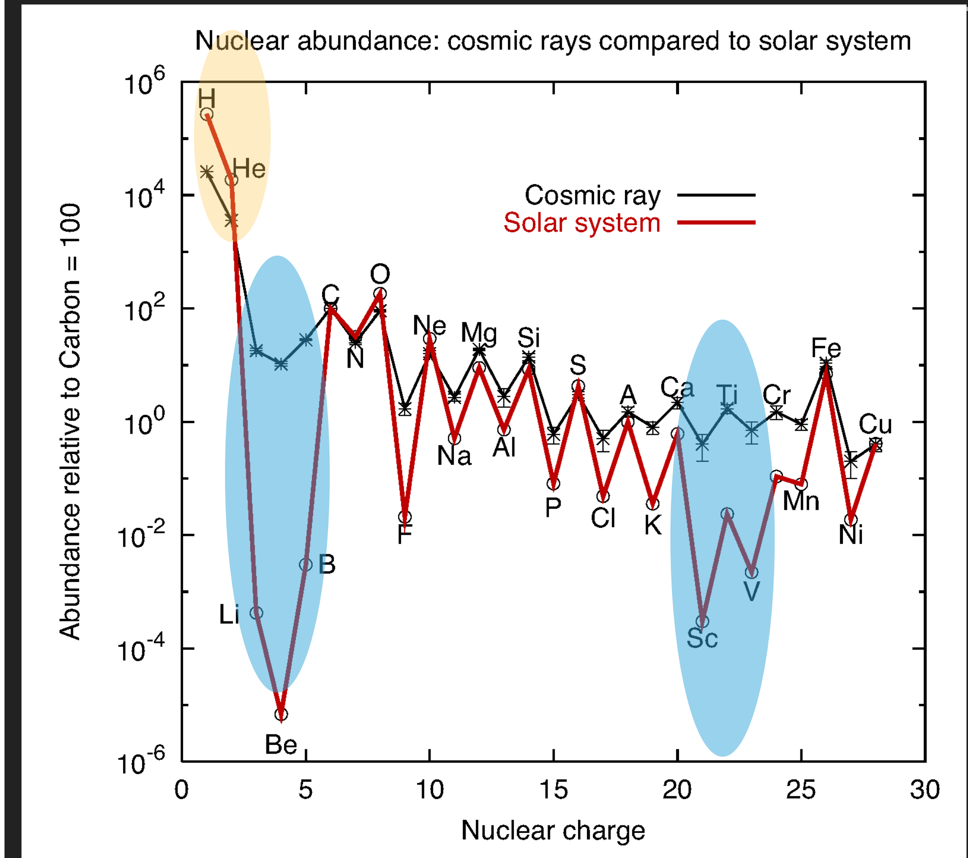


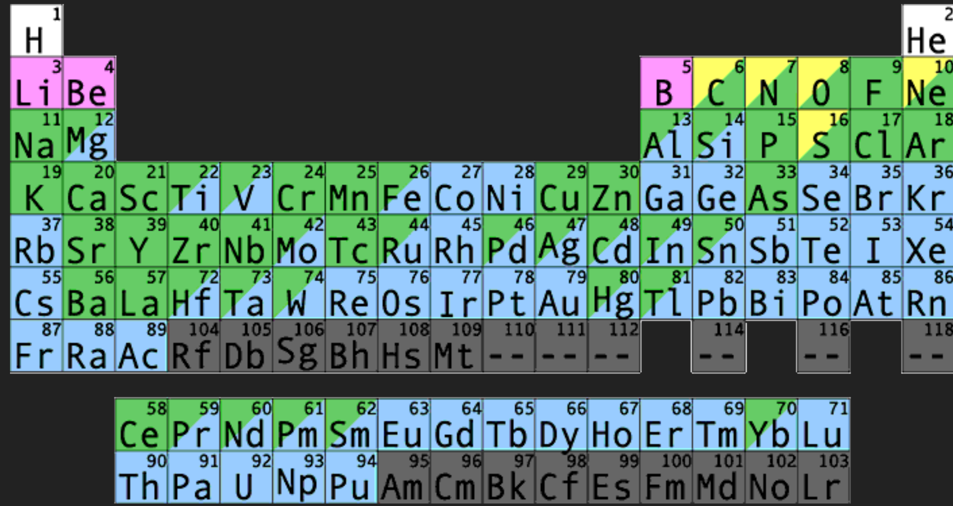
The end of the spectrum:

GZK cut-ff

- The changes of slope are connected to changes of sources and/or propagation features

COSMIC RAY COMPOSITION BELOW THE KNEE





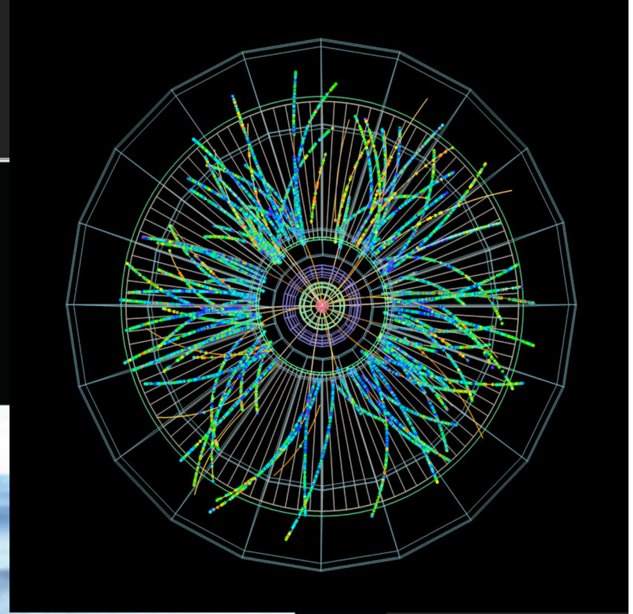
White - Big Bang
Pink - Cosmic Rays
Yellow - Small Stars
Green - Large Stars
Blue - Supernovae

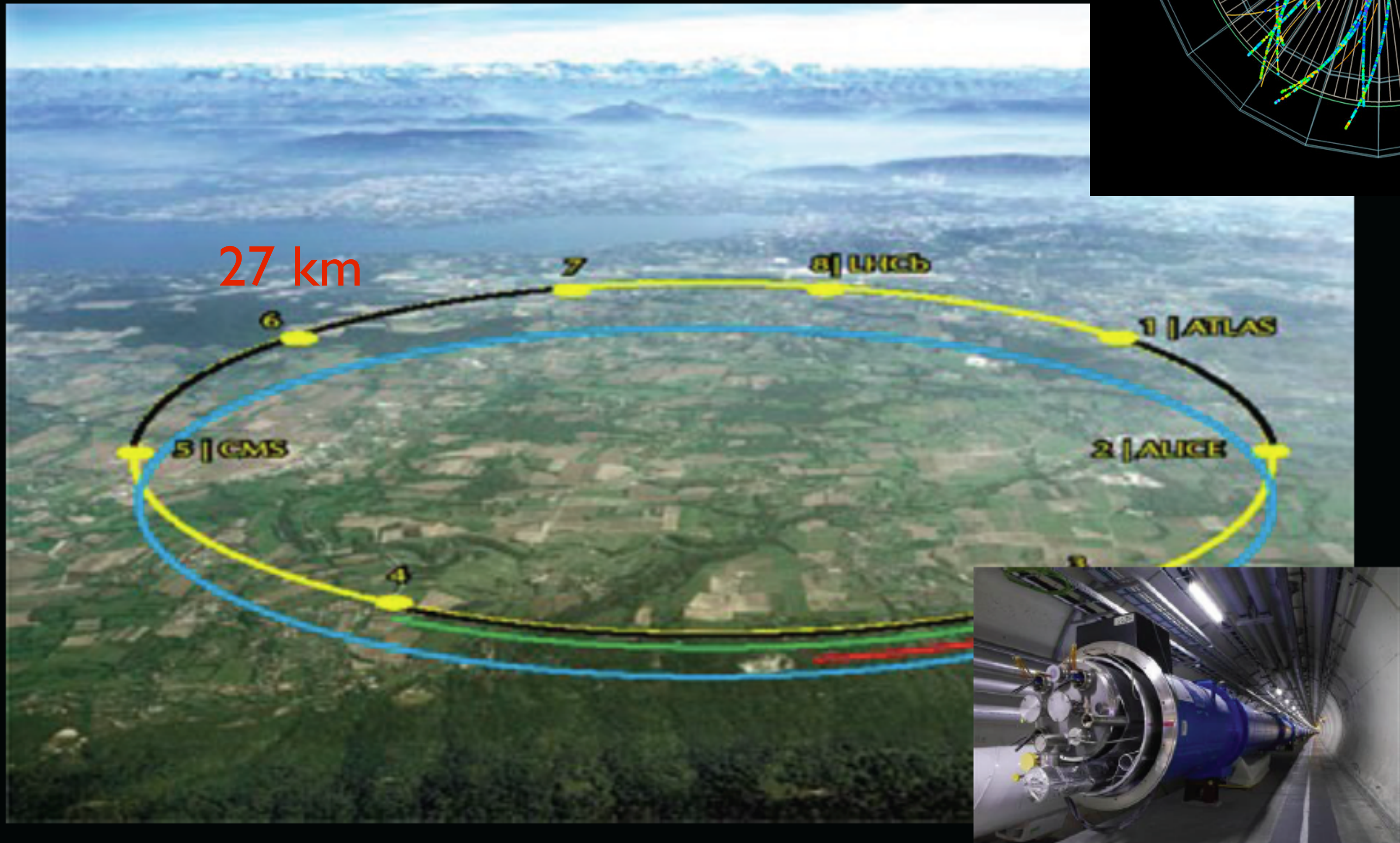
- All stable elements of the periodic table are found in galactic CRs
- The CRs composition is similar to the elements in the Sun indicating that they have stellar origin
- H, He directly accelerated in stars. Li, Be, B are secondary nuclei produced in the spallation of heavier elements (C and O). Also Mn, V, and Sc come from the fragmentation of Fe.
- The zig-zag is due to the fact that nuclei with odd Z and/or A have weaker bounds and are less frequent products of thermonuclear reactions

ACCELERATORS

Large Hadron Collider:

$E_{max} = c \cdot e \cdot B \cdot R = 7 \times 10^{12}$ eV

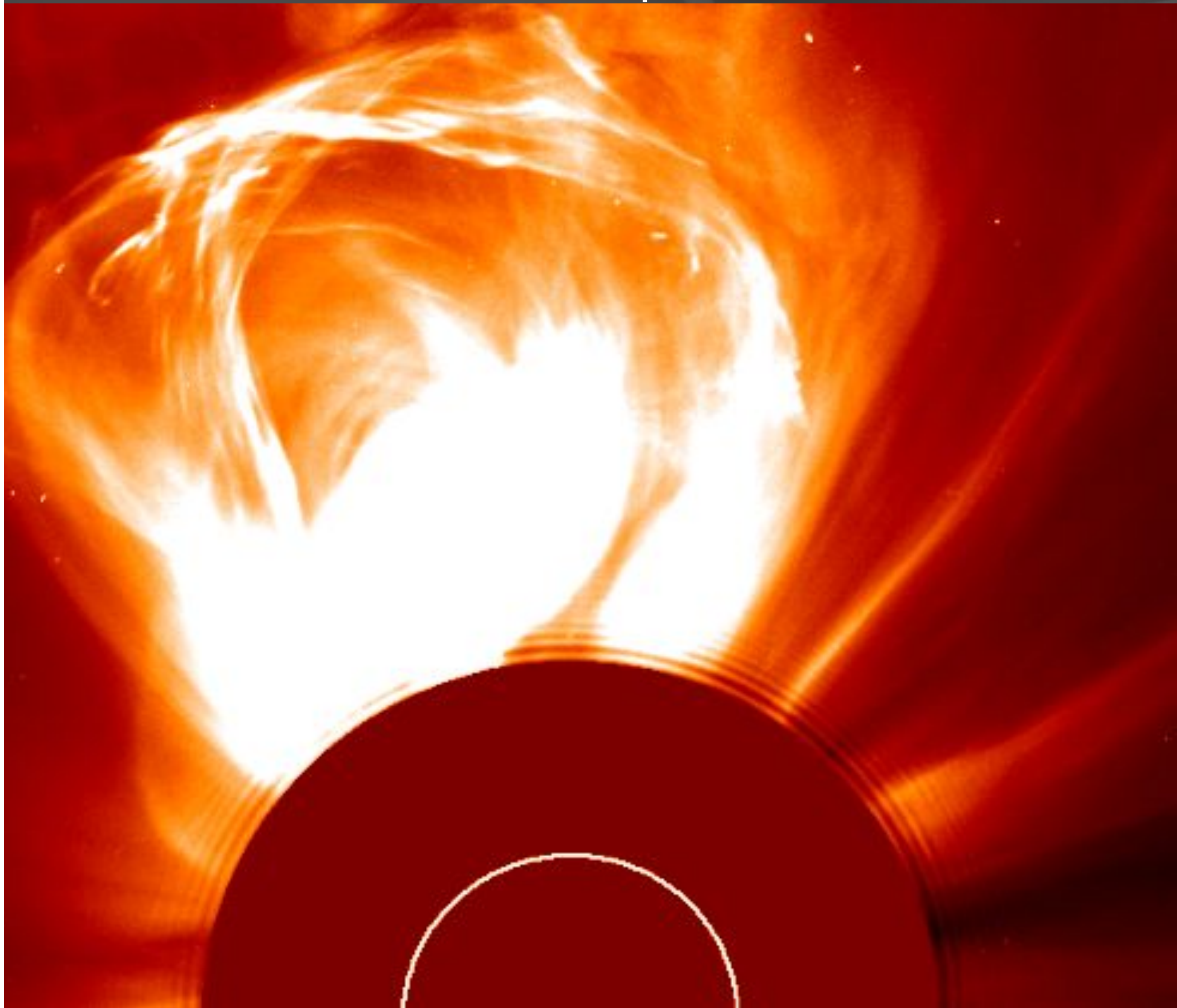


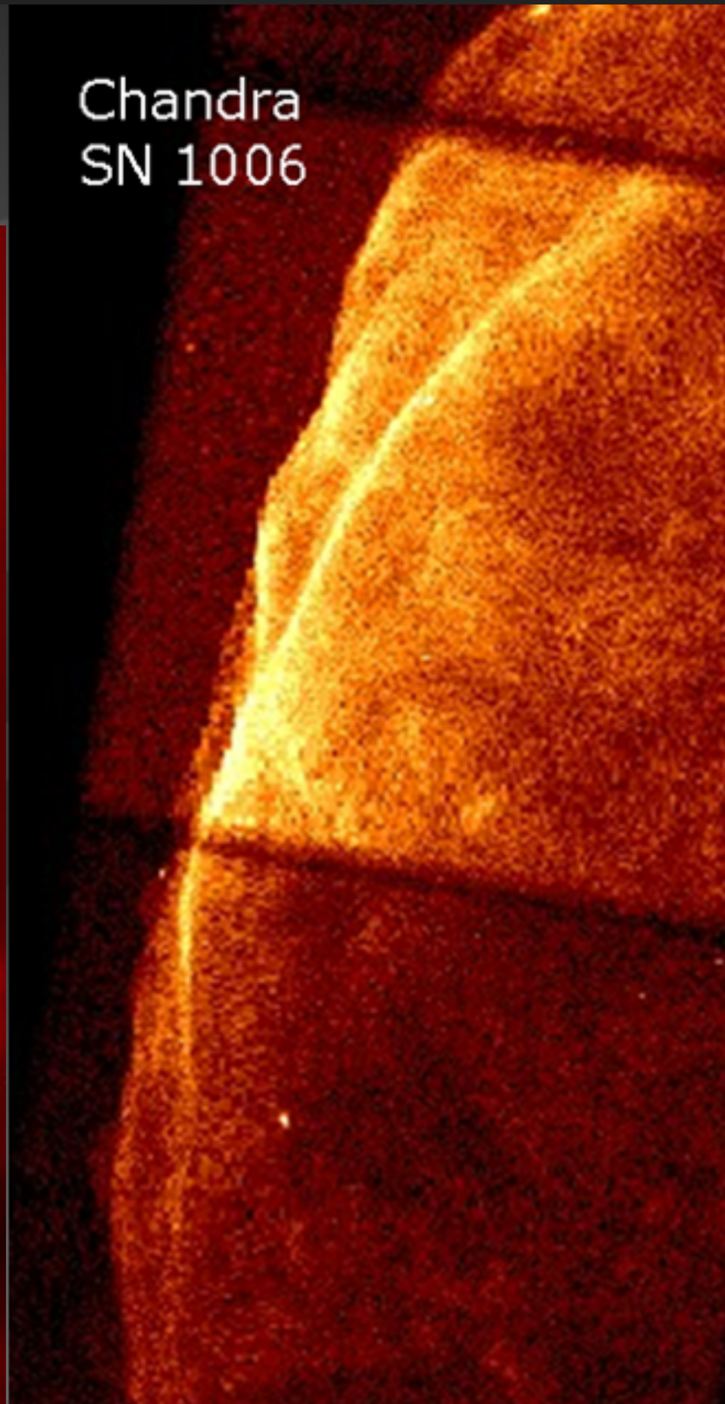


9593 superconducting magnets at -271.3 °C accelerate protons to collide in 4 points instrumented to analyse matter and its constituents in which it decomposes at these extreme conditions similar to 3×10^{-15} seconds after the Big Bang (~15 TeV correspond to abt. 10^{17} Kelvin)

THE NON-THERMAL ACCELERATORS

coronal mass
ejection→
10 GeV protons

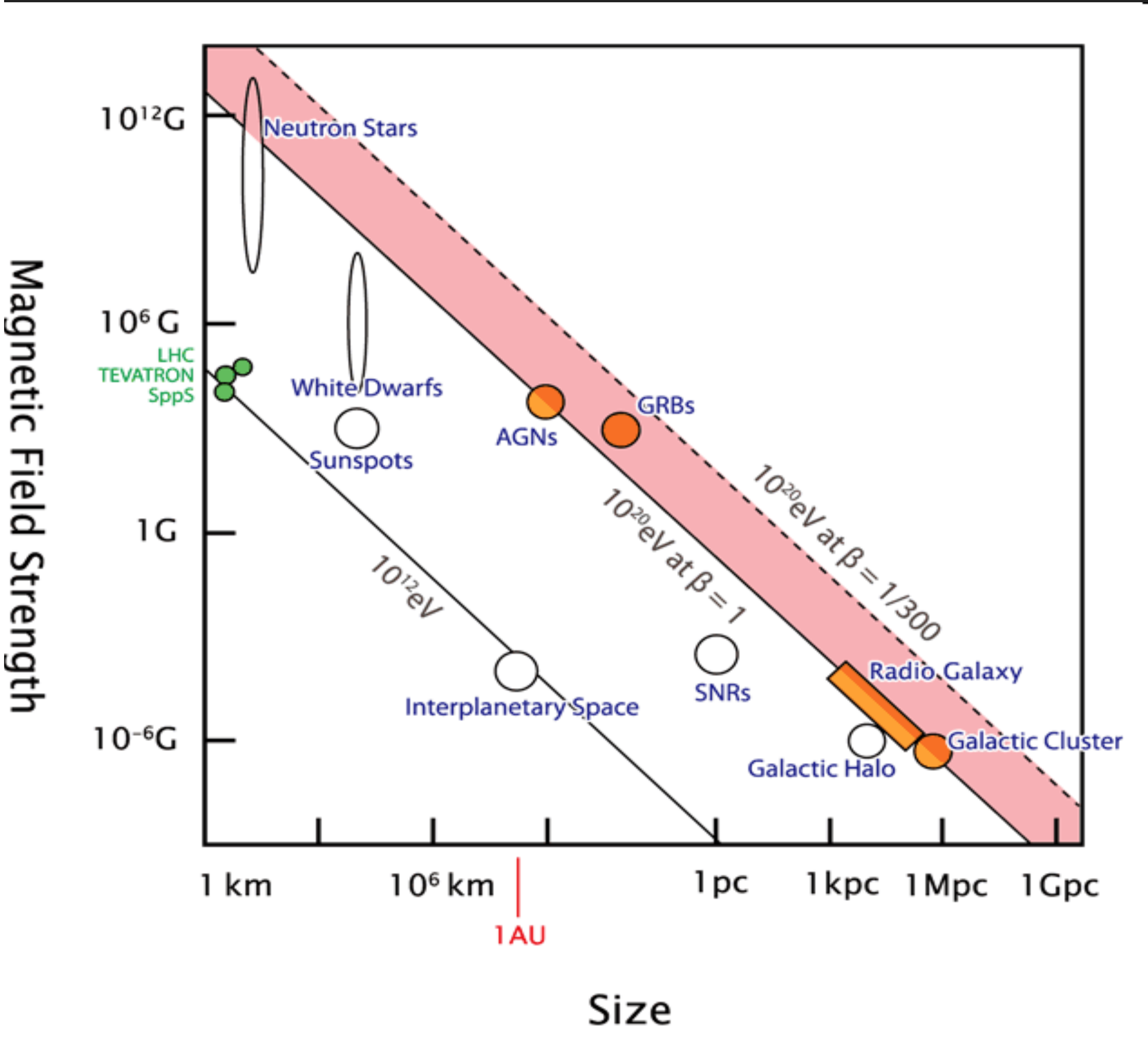




COSMIC ACCELERATORS

An LHC with the radius of the Mercury orbit could accelerate protons to 10^{20} eV = 10^{7} x LHC!

MESSENGER ACCELERATION: THE HILLAS' PLOT



Lorentz force

$$F_L = qvB = m\frac{v^2}{R}$$

Imposing that the Larmour is equal to the accelerating region

$R = R_{acc}$

We find the maximum energy at which the charged relativistic particle with q = Ze can be accelerated

$$E_{\rm max} \simeq Z\left(\frac{B}{\mu\rm G}\right)\left(\frac{R_{\rm source}}{\rm kpc}\right) \times 10^9\ \rm GeV$$

For jets with Lorentz factor Γ, E_{max} ≅ Γ ZBR (maximum energy depends on cosmic ray charge Z!!)

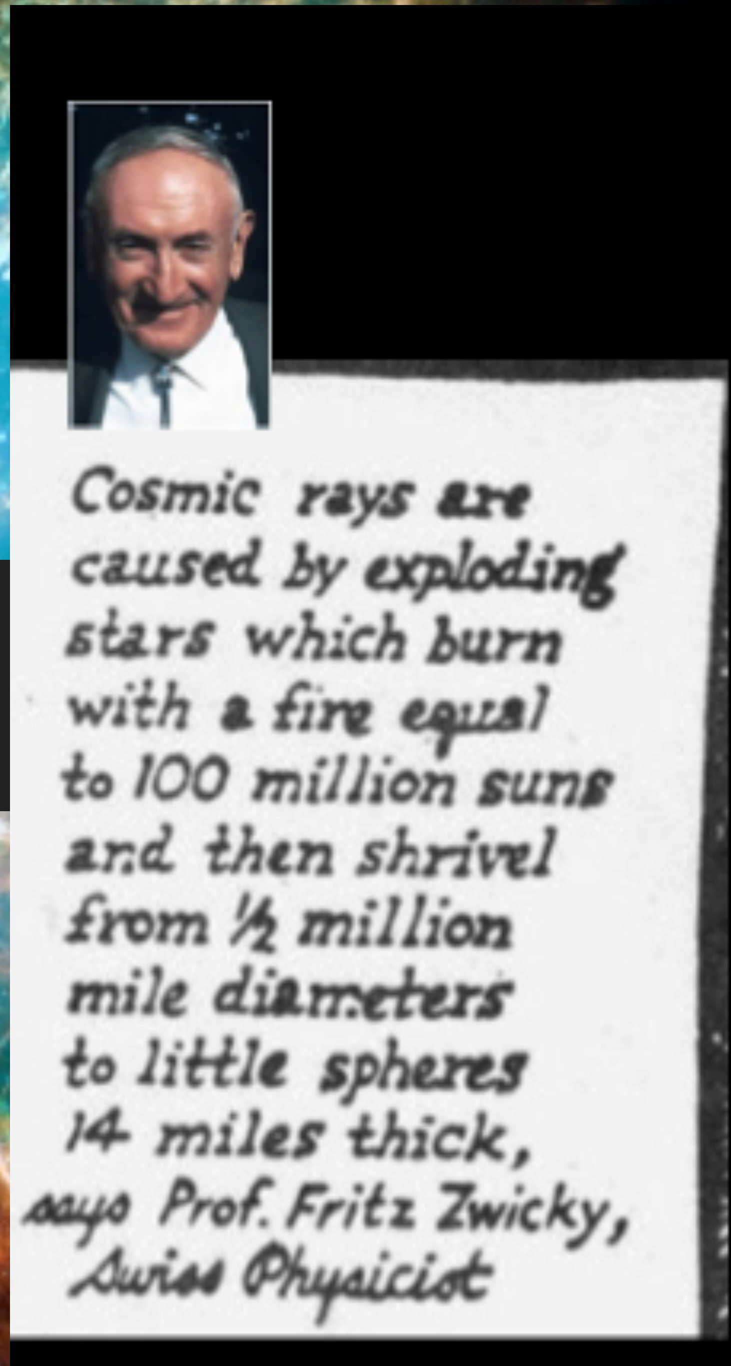
WHICH ARE THE COSMIC RAY SOURCES? POSSIBLE CANDIDATES

In a SN gravitational energy released is transformed into acceleration of particles → E^{-2} spectrum

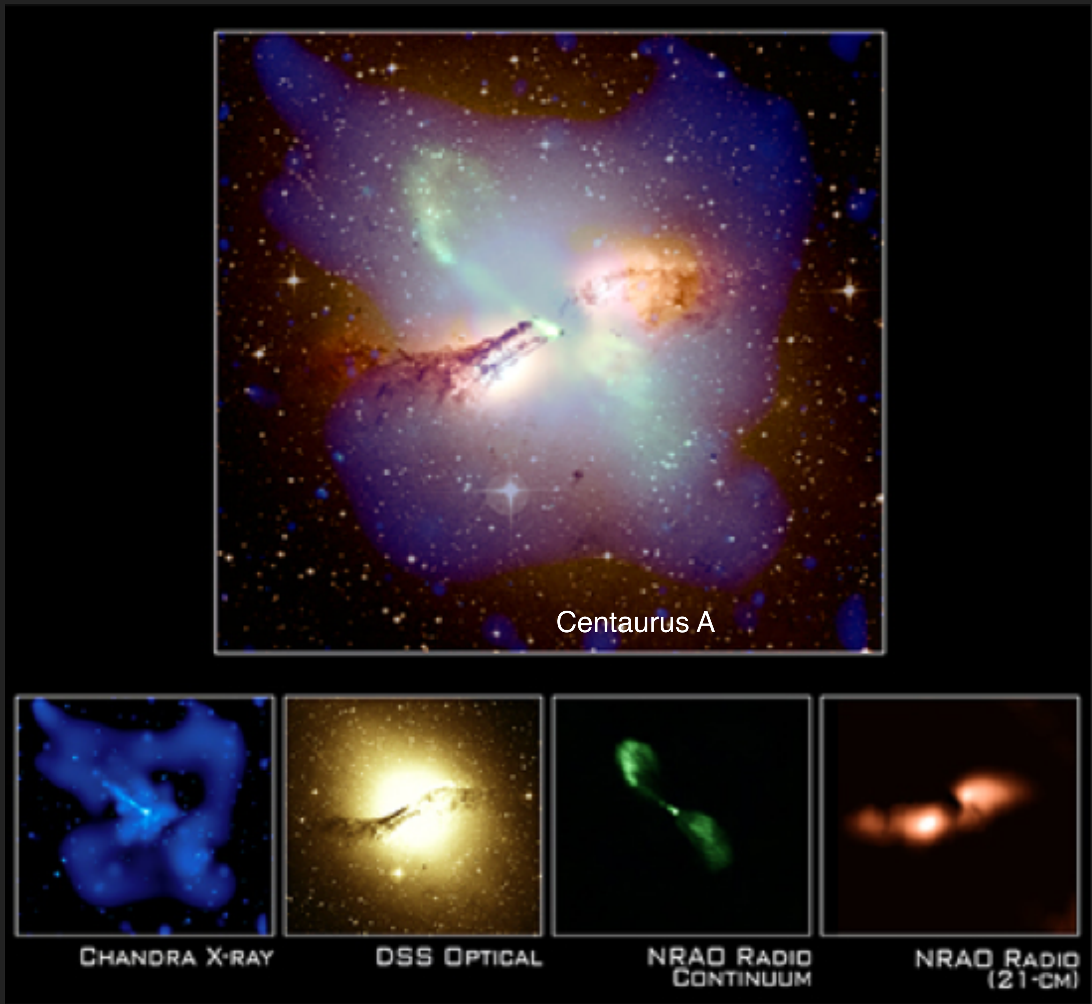
For an isotropic source the emitted energy density is connected to energy flux:

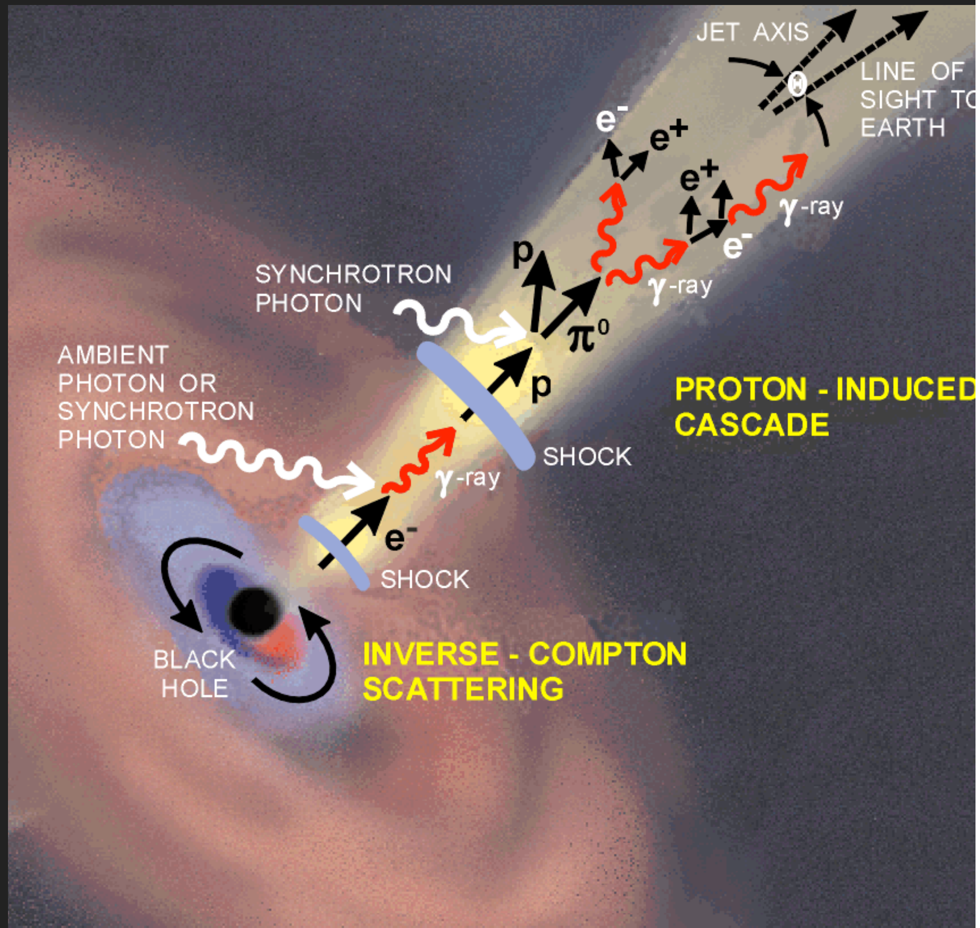
$$\rho_E = 4\pi \int_{1\,\mathrm{GeV}}^{1\,\mathrm{PeV}} \frac{E}{\beta c} \frac{dN}{dE} dE \sim 1 \frac{eV}{cm^2} \sim \frac{B^2}{8\pi}$$

If 10% of the energy of the ejecta of all SNR in the Galaxy goes into acceleration of CRs the spectrum to the knee is explained.

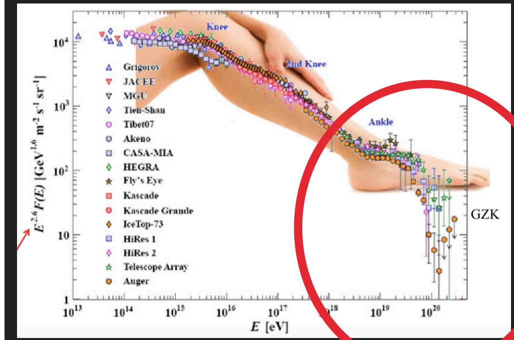


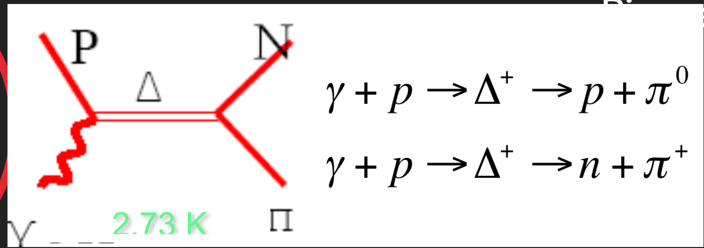
EXTRAGALACTIC ACCELERATORS





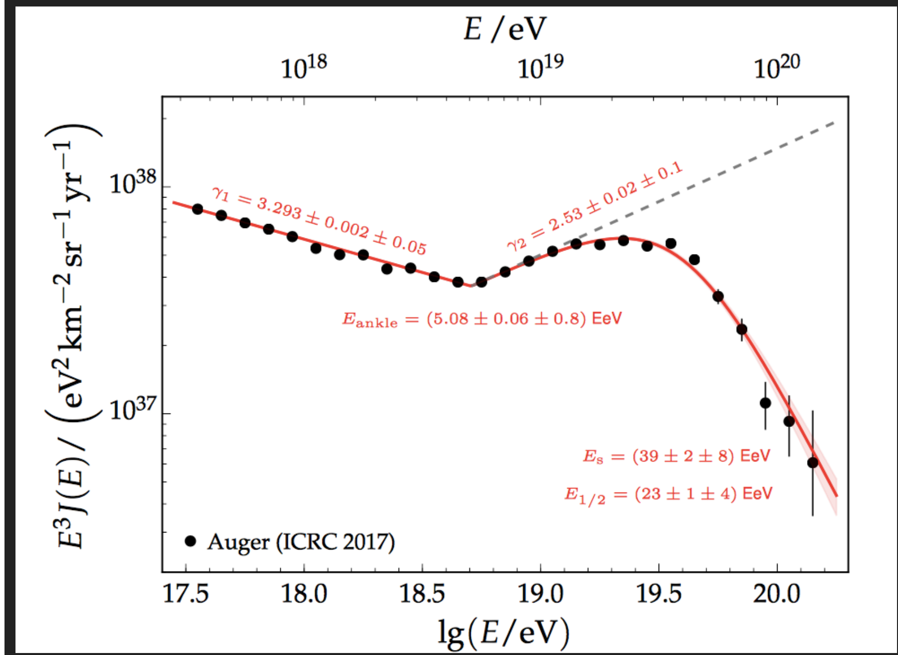
THE ANKLE AND THE UHECR

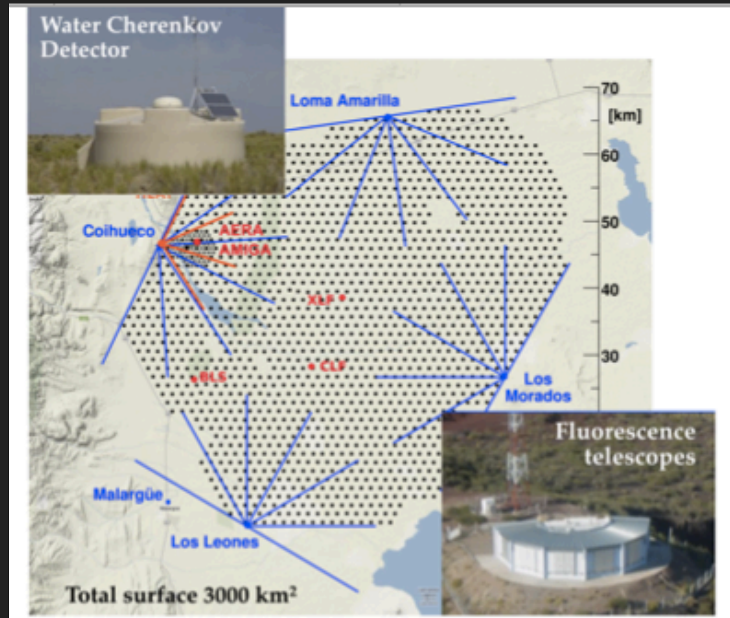


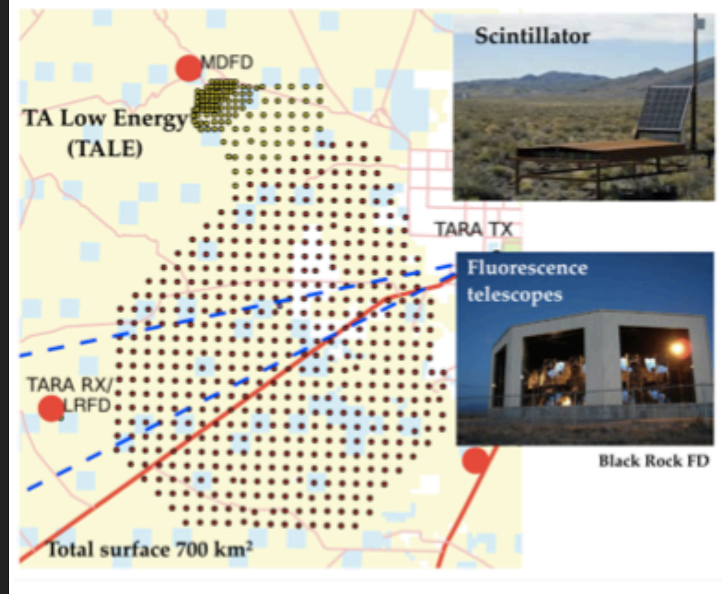


Shower sampling and fluorescence techniques in Pierre Auger (3000 km2!) and Telescope Array

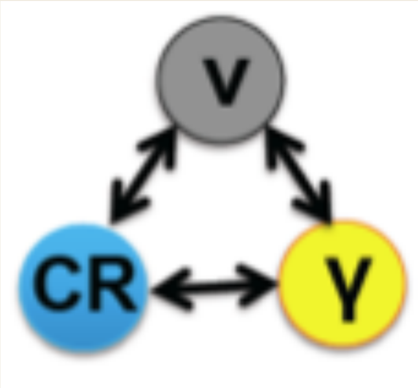
The end of the spectrum of CRs could be due to GZK cutoff and/or effect of sources exhausting their energy. The GZK cut-off is due to proton interactions. The threshold for production of delta resonance is around 5 x 10^{19} eV.

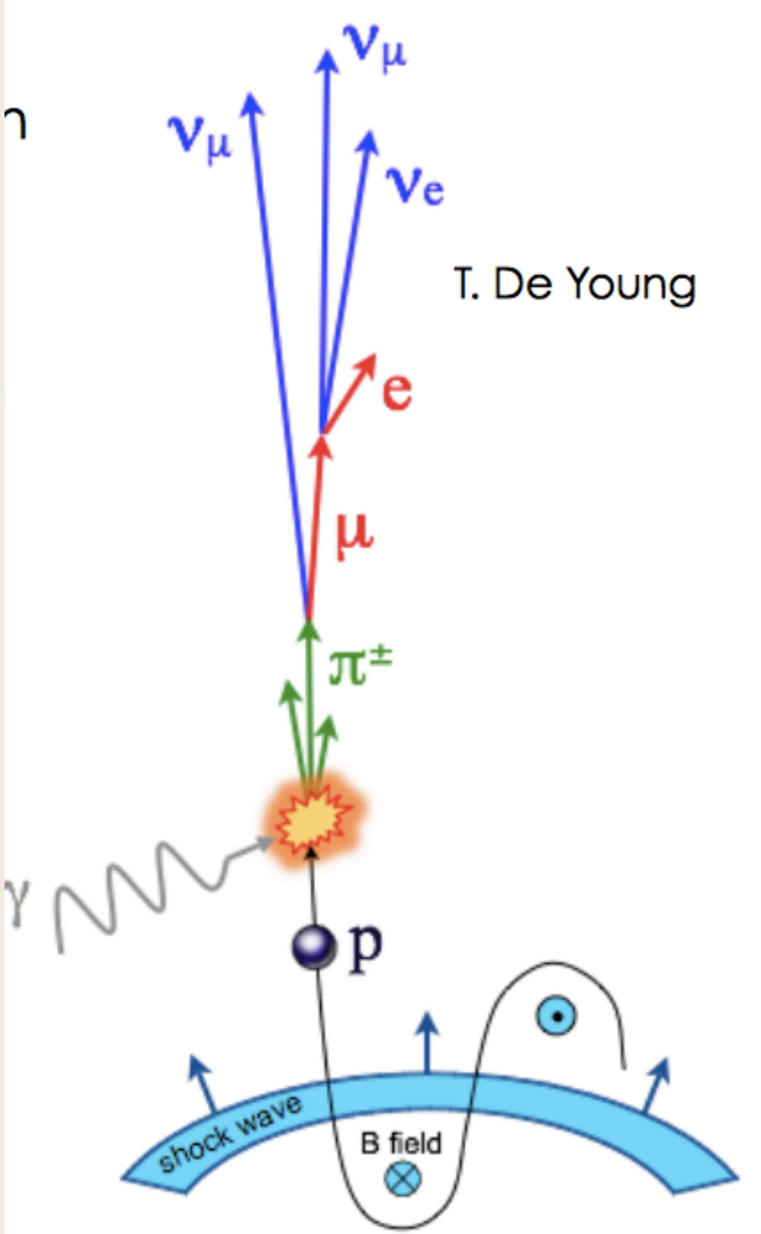






The generic model of a cosmic ray accelerator

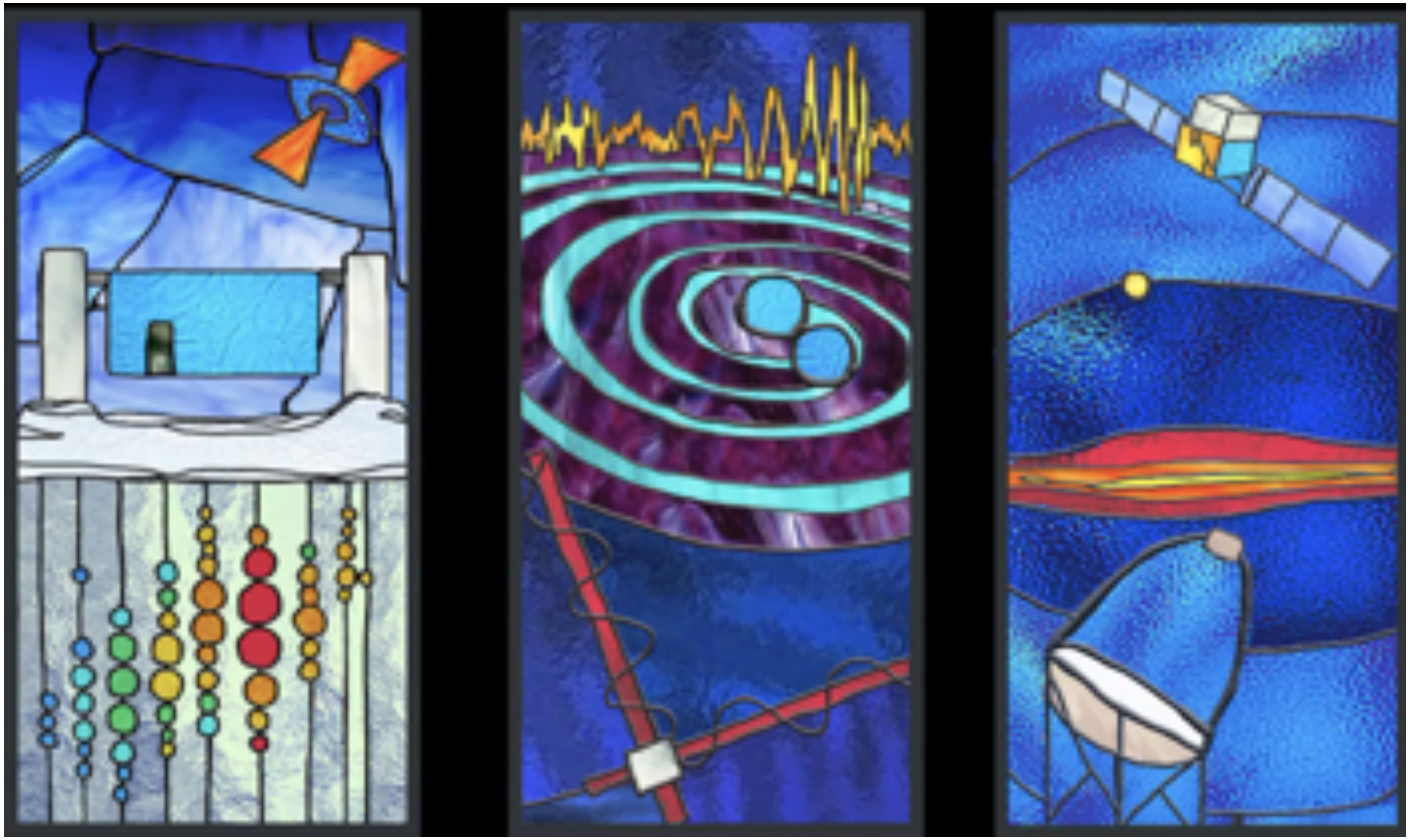




Multi-messengers

Astroparticle Physics
Nowadays

Neutrino GW Gamma-ray Astrophysics



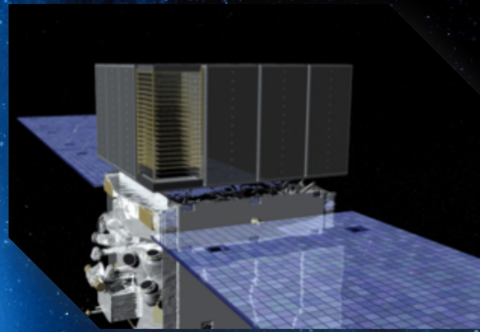
Gamma-ray detection

From ground

Imaging Air Cherenkov Telescopes (IACT)

- atmosphere is calorimeter
- Sets of mirrors focus Cherenkov pool light into fast camera in focus
- ~10% duty cycle due to Moon and weather and exposed mirrors
- decreasing efficiency by order of 2% due to mirror deterioration

Space-based : 0.1 - 100 GeV Large FoV and duty cycle



EAS: $\gtrsim$1 TeV

- collect Cherenkov radiation produced by charged particles in water tanks or ponds equipped with photosensors

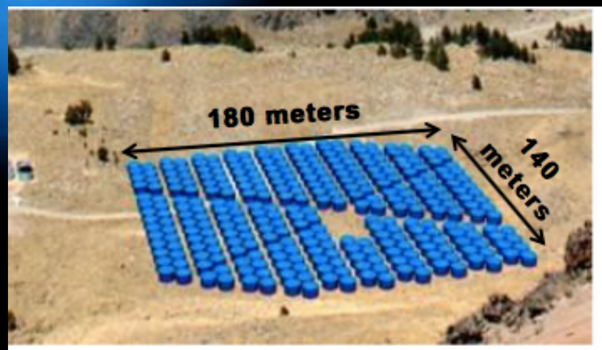
> 90% duty cycle and large FoV

Needs water purification and recycling (HAWC, LHAASO)

Future Southern Widefield Gamma-ray Observatory (SWGO)

Quantity	*Fermi*	IACTs	EAS
Energy range	20 MeV – 200 GeV	100 GeV – 50 TeV	400 GeV – 100 TeV
Energy res.	5–10 %	15–20 %	∼ 50 %
Duty cycle	80 %	15 %	> 90 %
FoV	$4\pi/5$	5 deg × 5 deg	$4\pi/6$
PSF (deg)	0.1	0.07	0.5
Sensitivity	1 % Crab (1 GeV)	1 % Crab (0.5 TeV)	0.5 Crab (5 TeV)

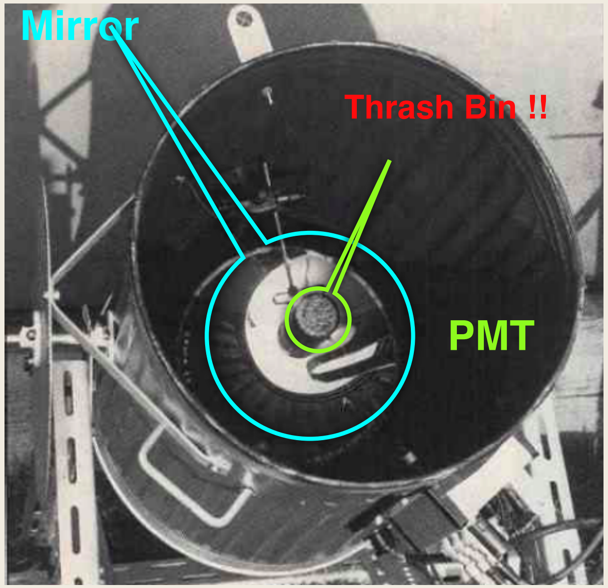
Table from De Angelis, Mallamaci, arXiv:0805.05642

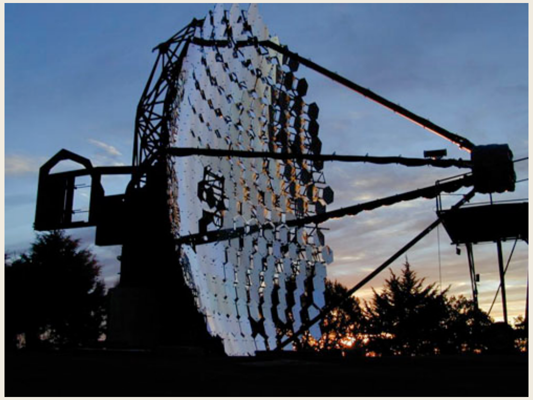


Imaging Air Cherenkov Telescopes

C. Galbreith & J. Jelley, when visiting the Harwell Air Shower Array in UK in 1952, used a a 5 cm PMT mounted on the focal plane of a 25 cm parabolic mirror in a garbage can. They observed oscilloscope triggers from light pulses that exceeded the average night-sky background every 2 min. In 1953, from the polarisation and spectral distribution, they confirmed P. Backett's assertion that Cherenkov light is produced by charged CRs in the atmosphere on top of the night sky background.

In 1959 G. Cocconi proposed to measure TeV gamma-rays using air shower detectors.



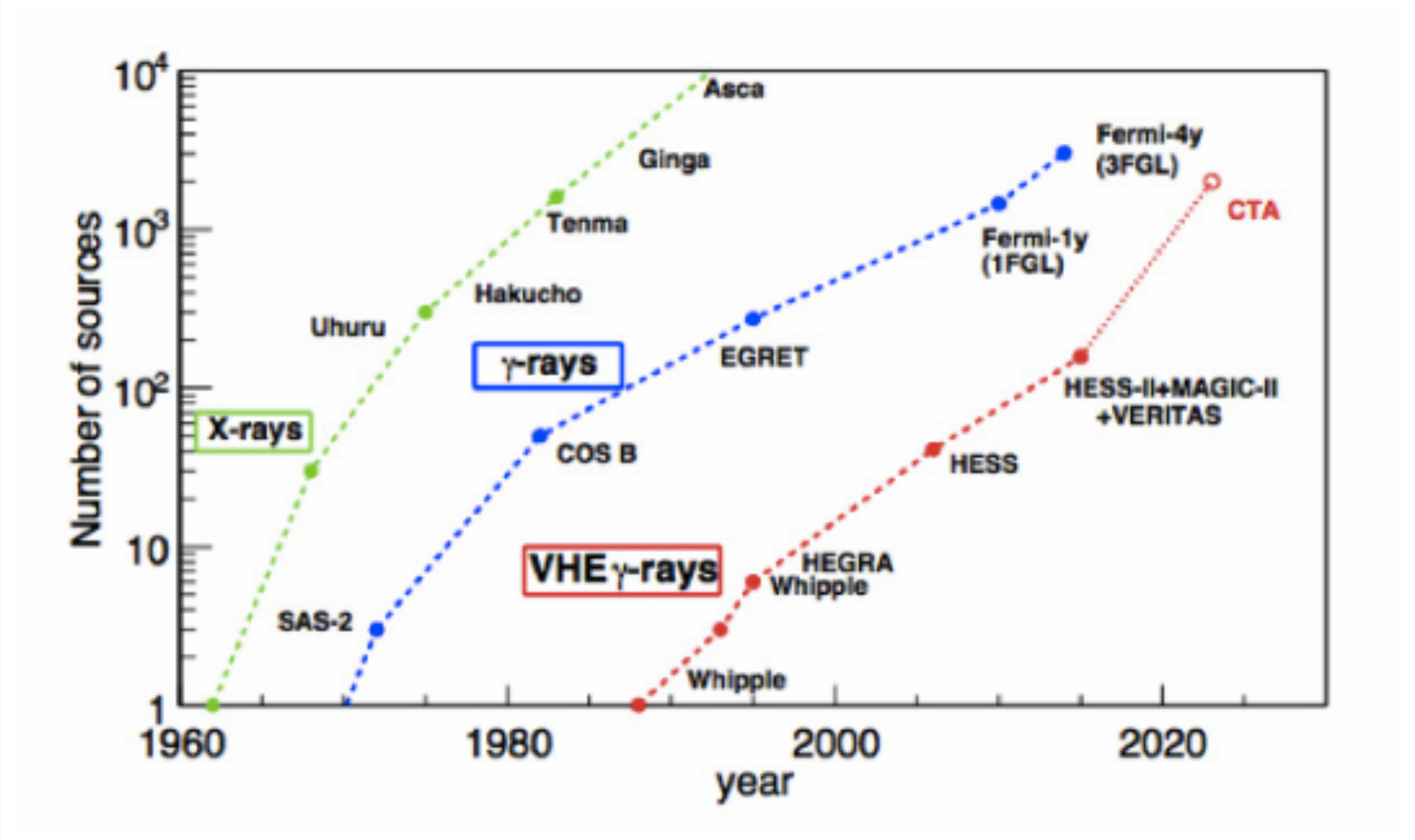


Trevor Weekes (1940-2014)
Whipple: first image of the Crab Nebula in 1989, the most studied TeV source

Eckart Lorenz (1938-2014)
HEGRA+AIROBICC, MAGIC arrays

High-energy sources in the years

https://github.com/sfegan/kifune-plot



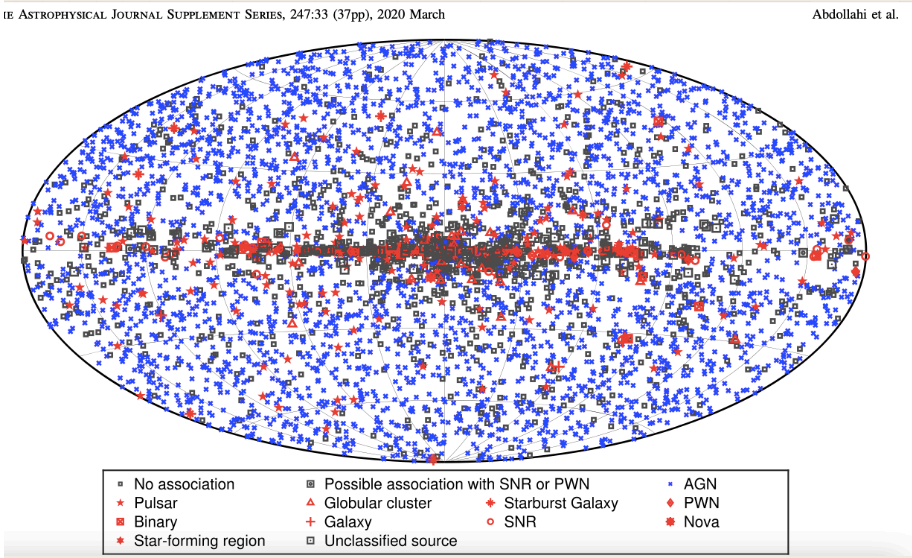
Gamma-ray sources from space: 10 GeV-100GeV

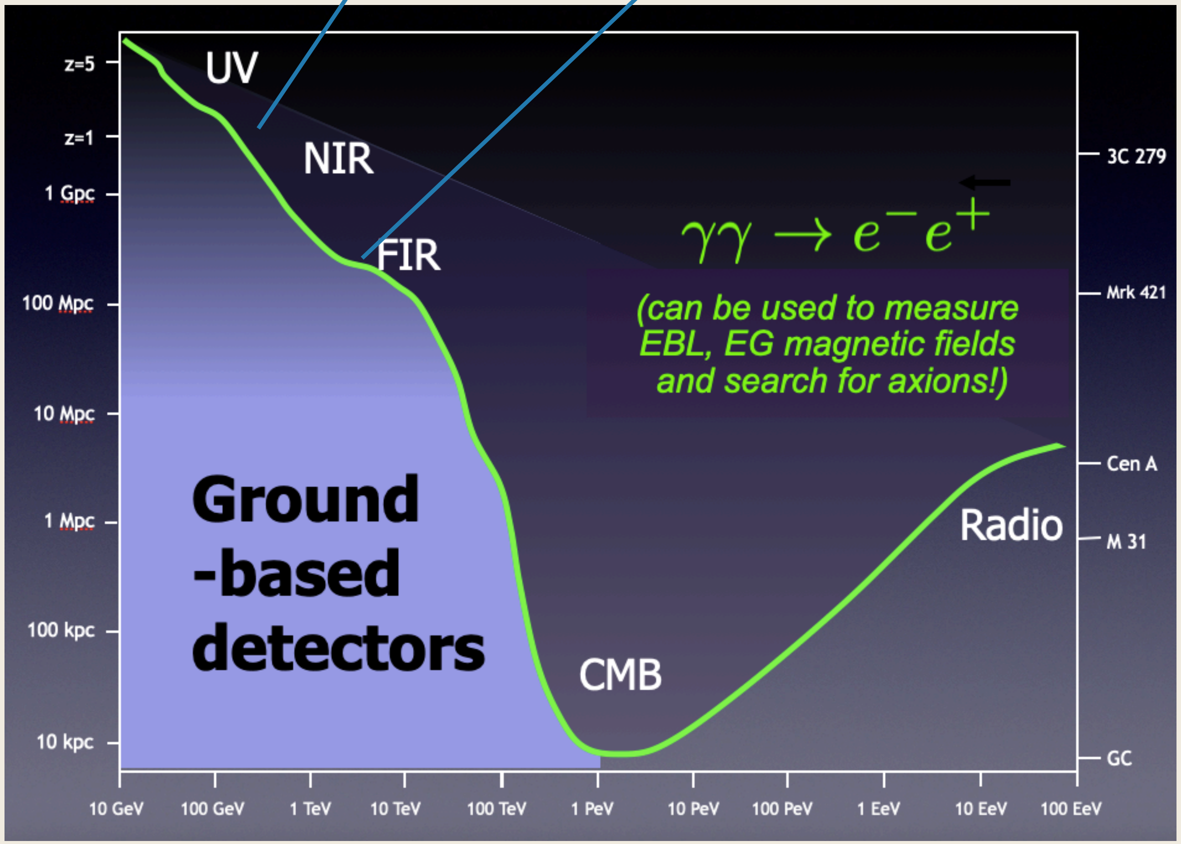
Fermi 8 yr catalogue (4FGL) 50 MeV - 300 GeV 5064 sources, 62% blazars, 1.5% 2.7% SNR & PWN, 4.7% Pulsars

Space-based experiments accesses redshift Z < 2.5

Ground based detectors accesses redshift Z < 1.5.

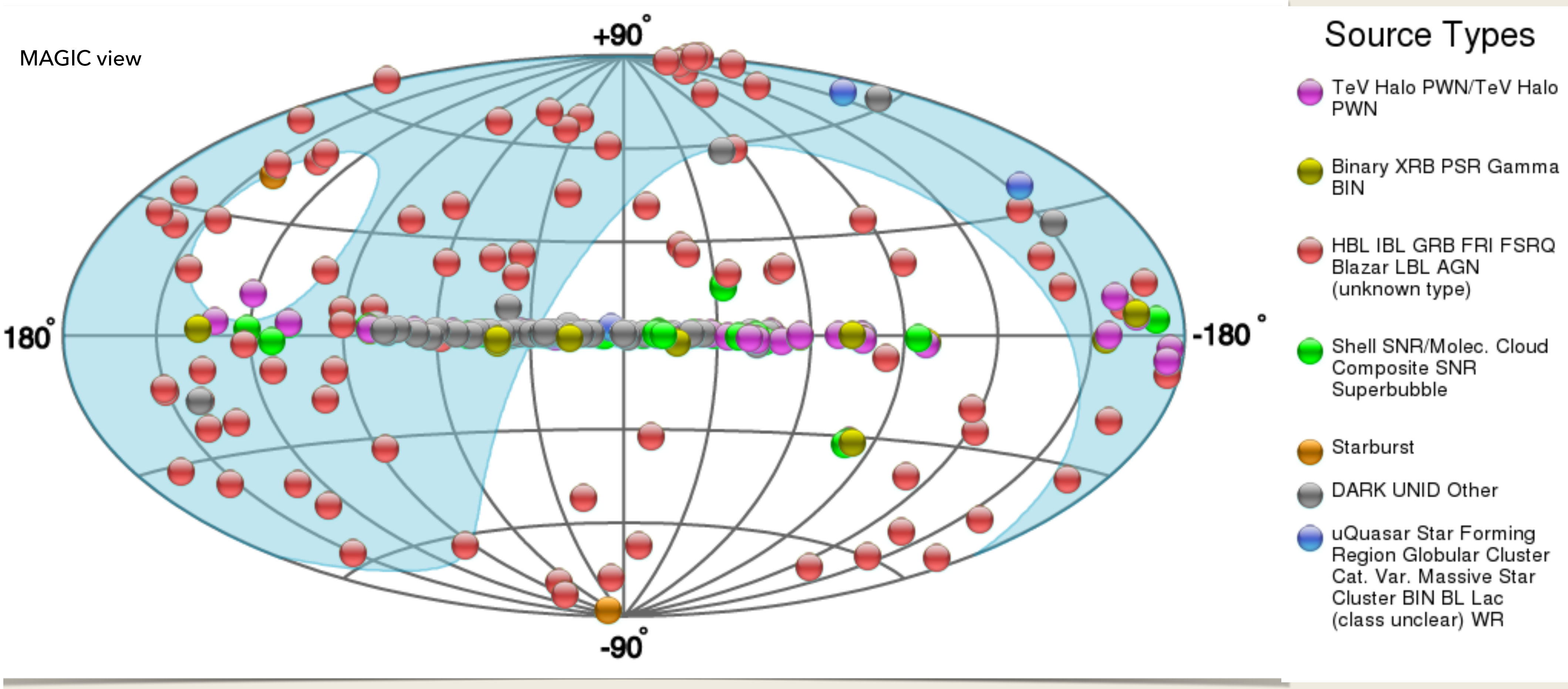
At PeV energy only the Galactic plane is visible!





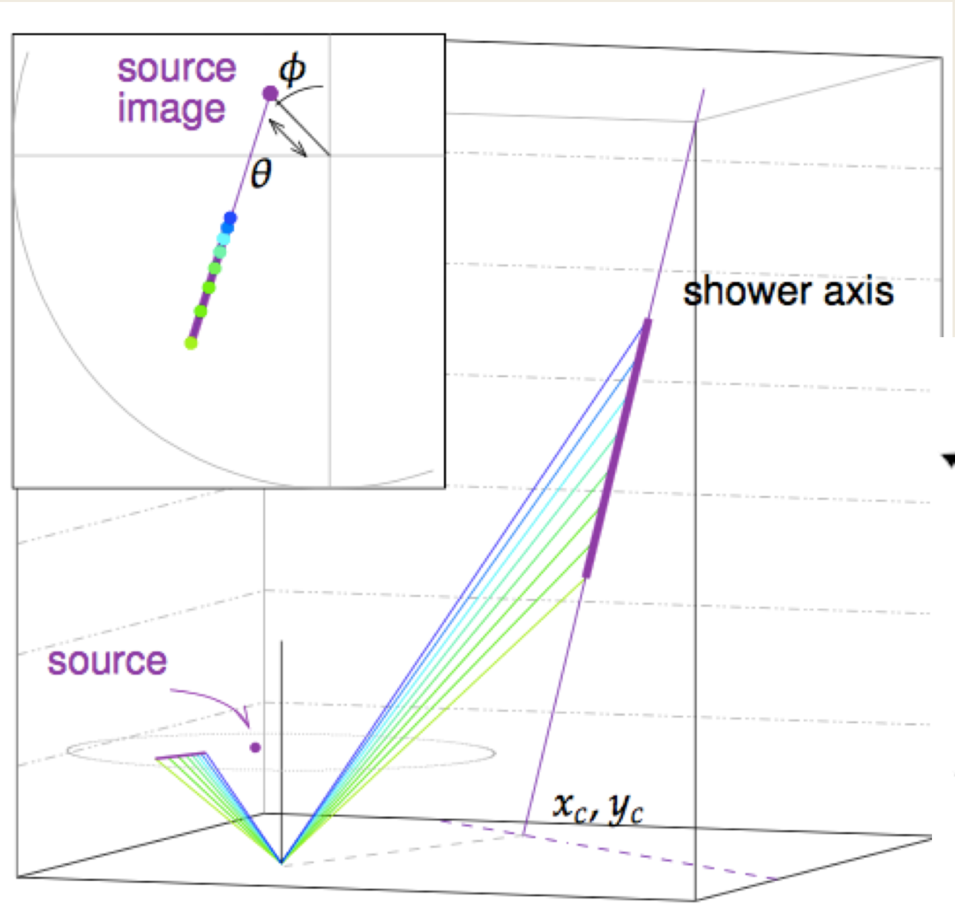
Gamma-ray sources from ground

Z < 1.5



Currently 232 sources in

Imaging Cherenkov technology



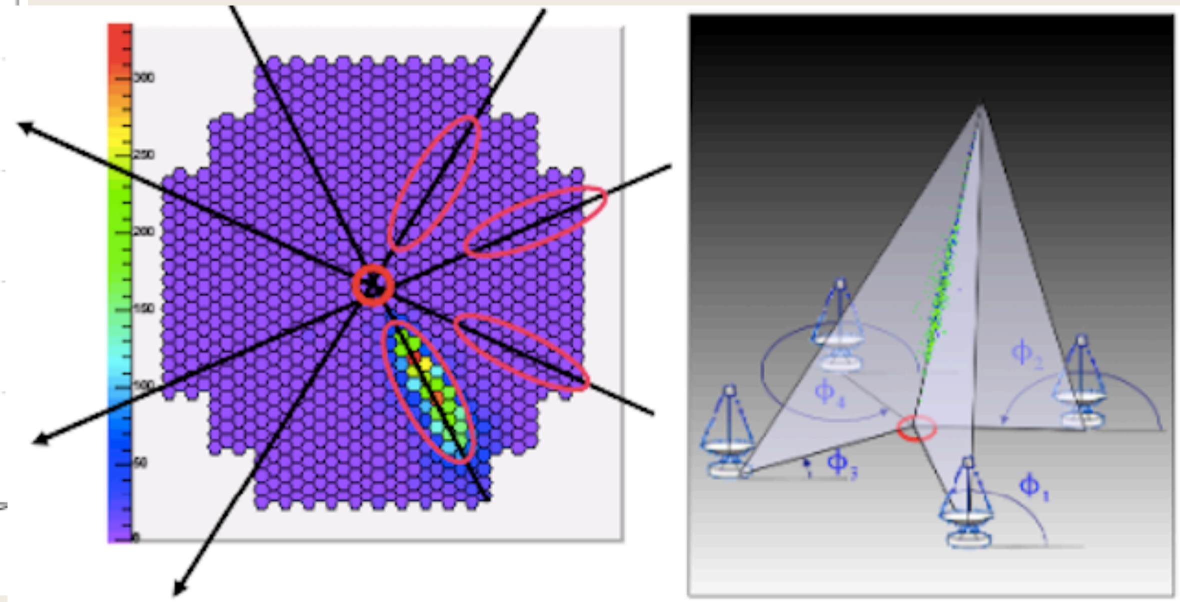
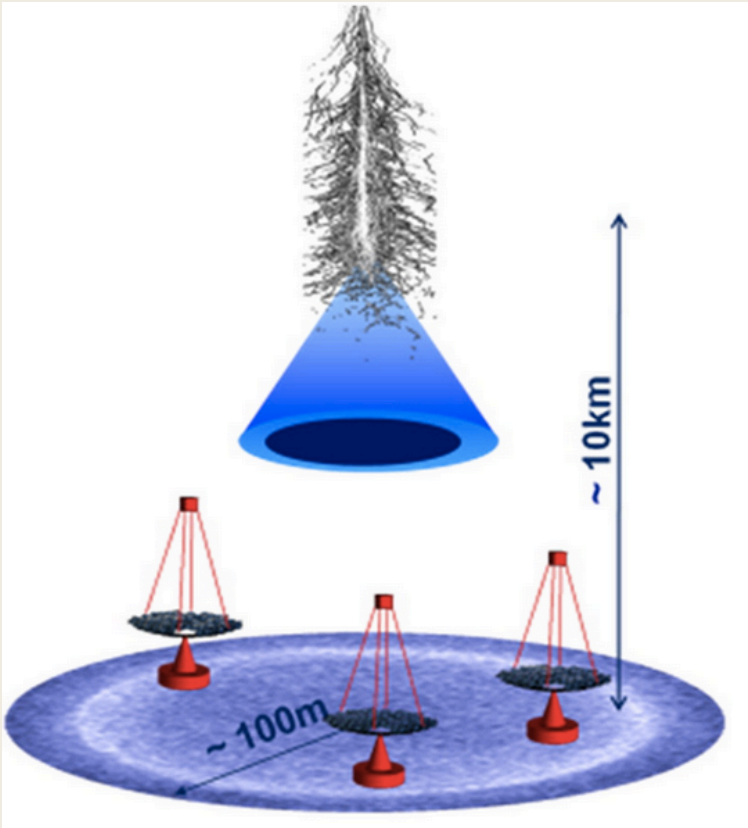
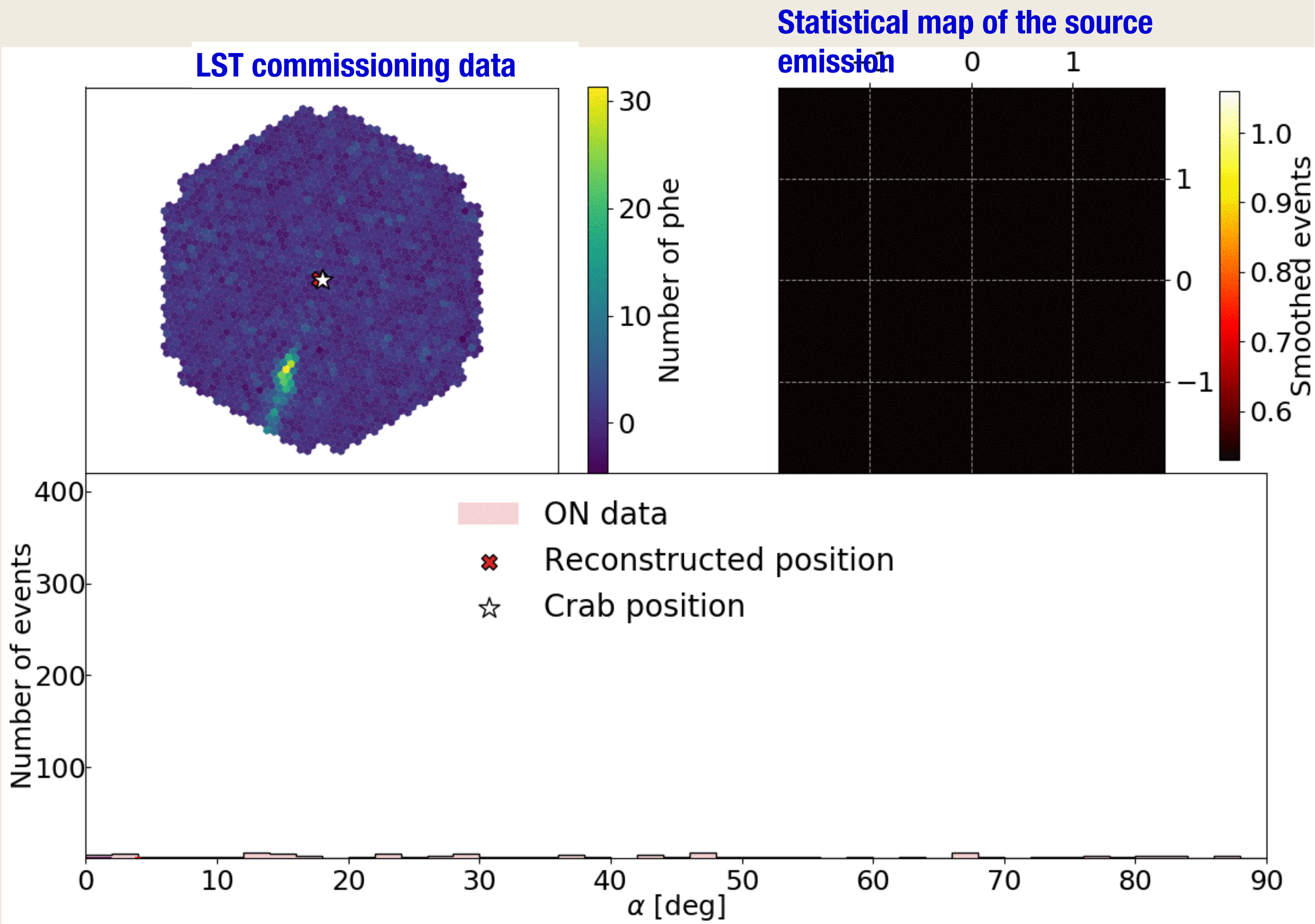


Image from events

γ



Light pool

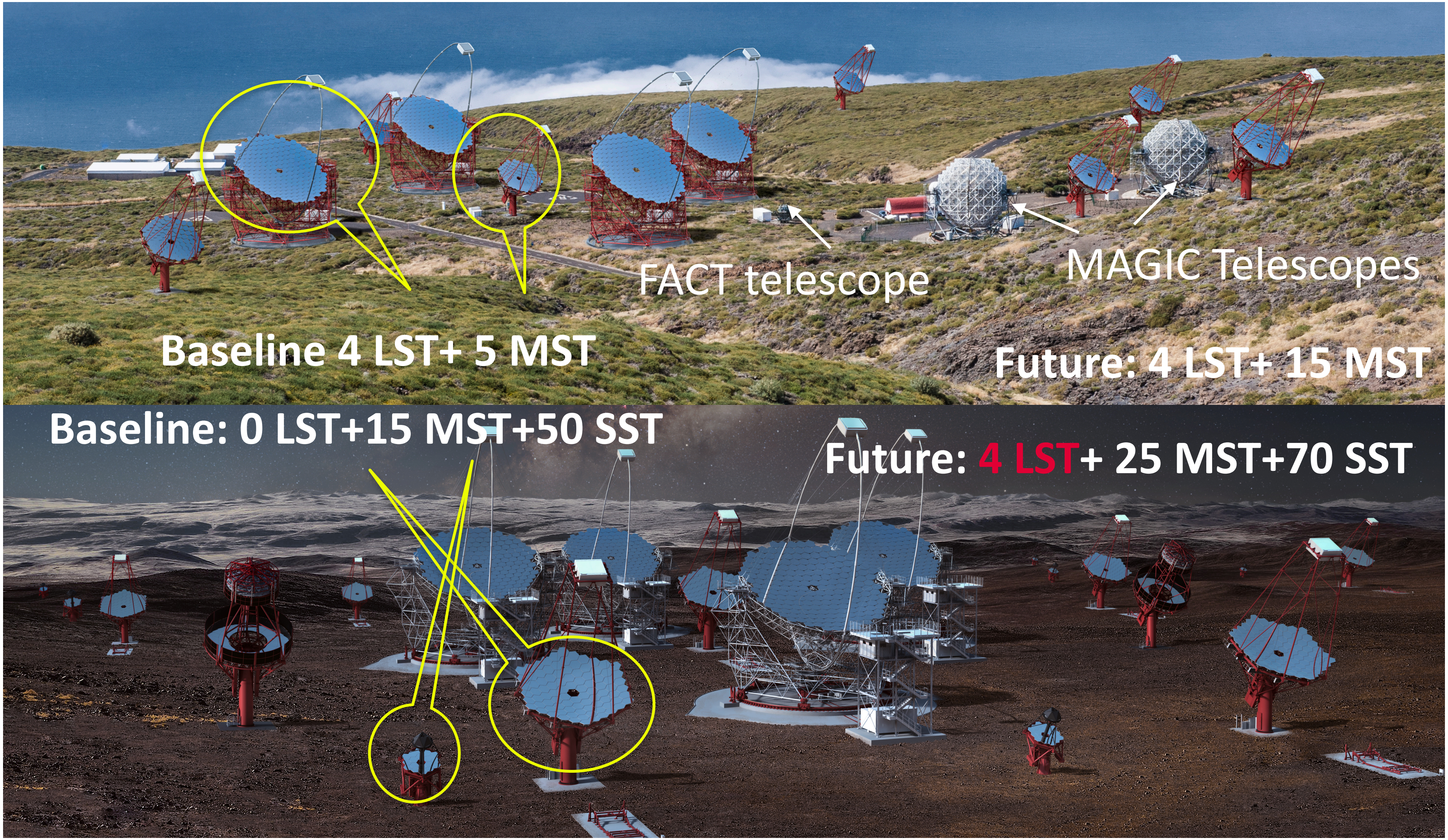


When the measurement is stereoscopic the background is largely reduced and the source is observed in a S/N regime not $S/\sqrt{N}$

and $E_{th} \propto 1/A_{mirror}$ rather than $E_{th} \propto 1/\sqrt{A_{mirror}}$

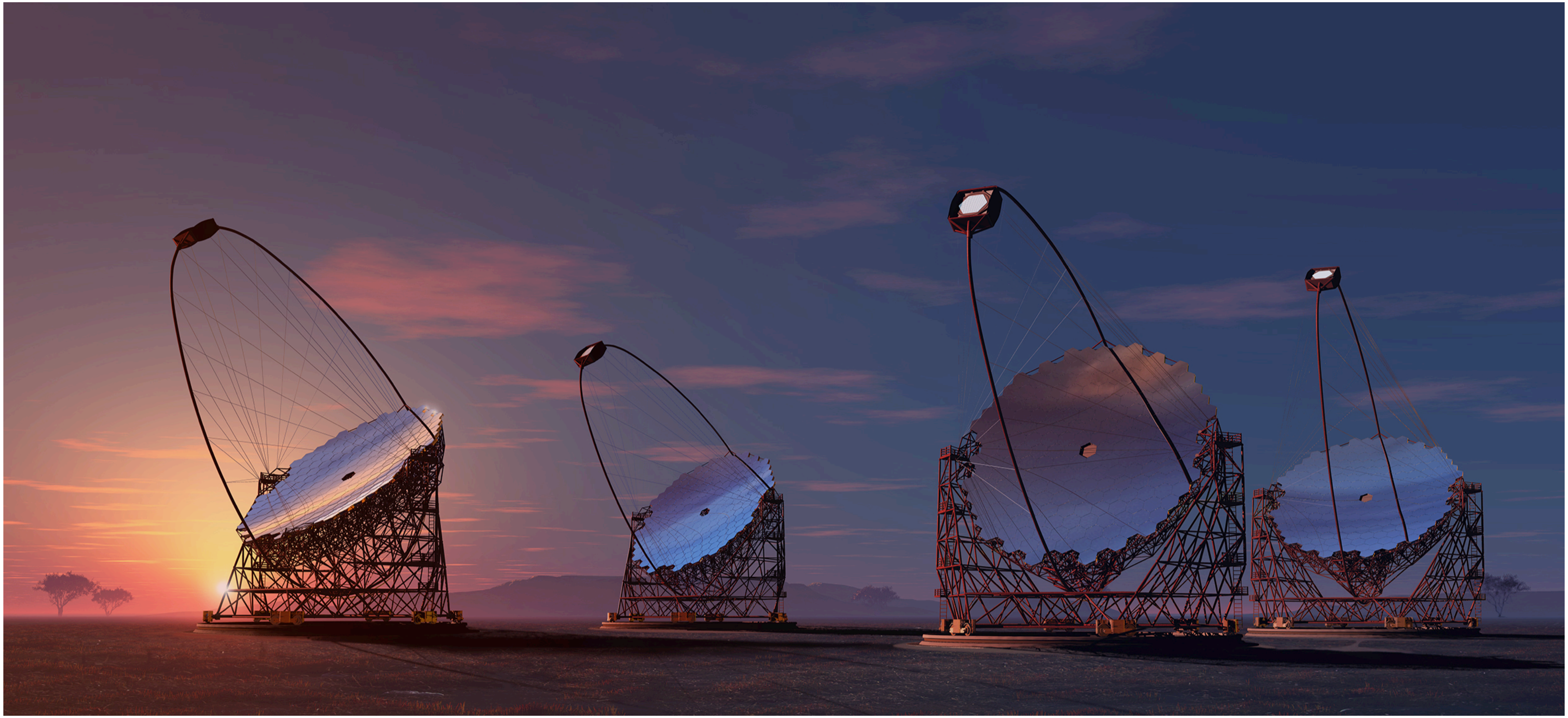
https://www.cta-observatory.org/lst1-detects-first-gamma-ray-signal/

CTA North in La Palma, Canarian Islands

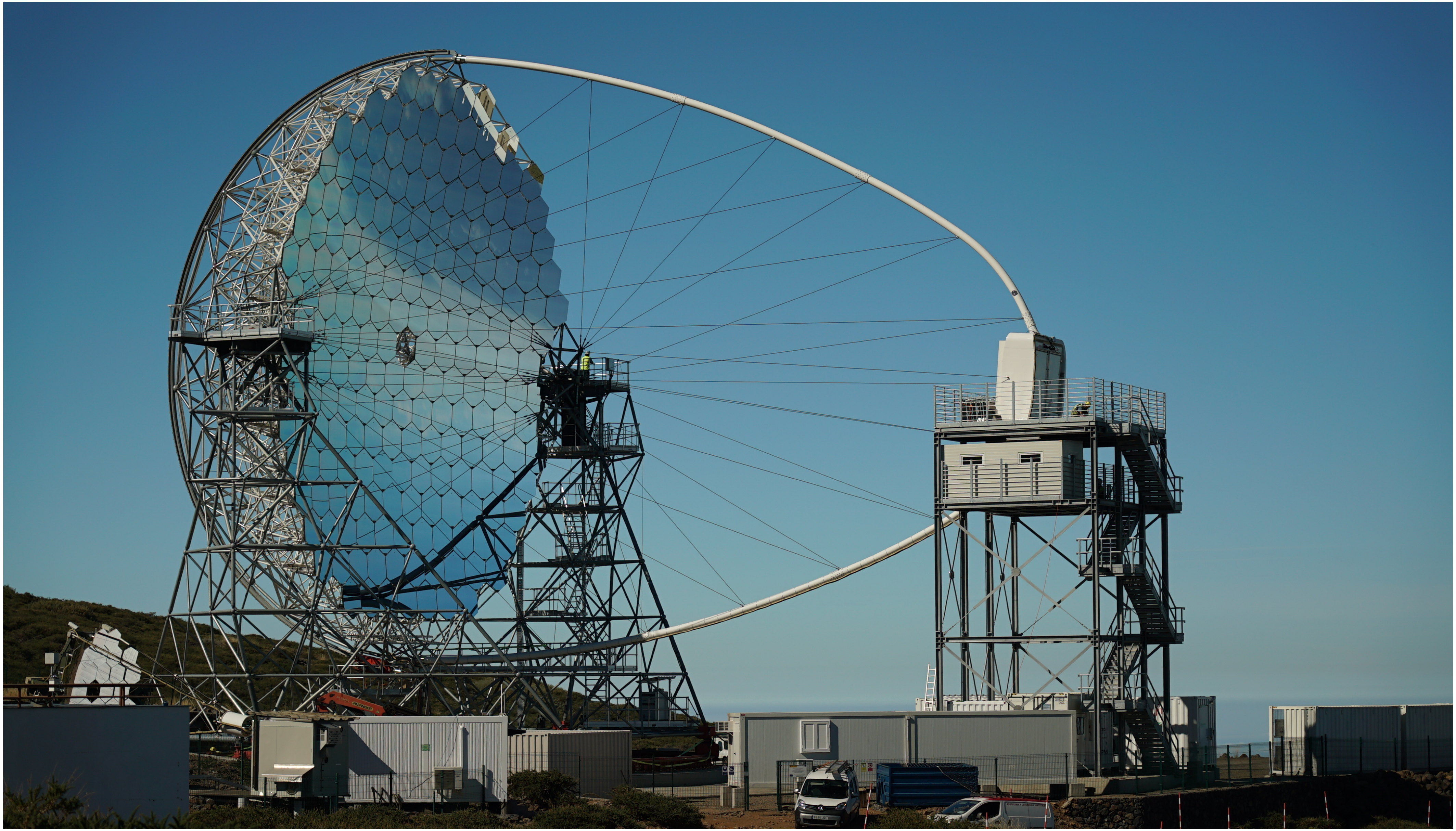


CTA South at Paranal, Chile

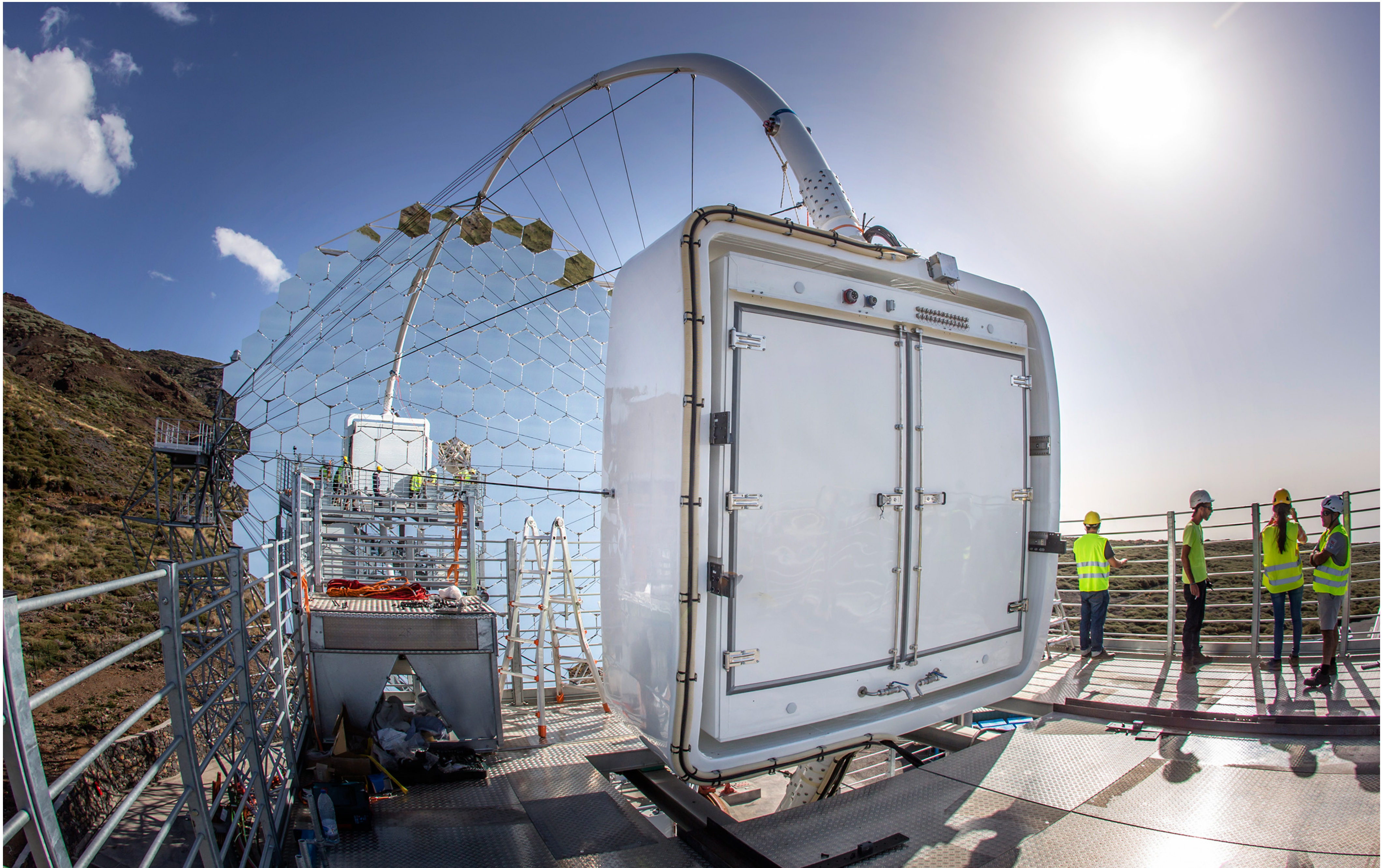
The Northern array of CTAO



The LST-1

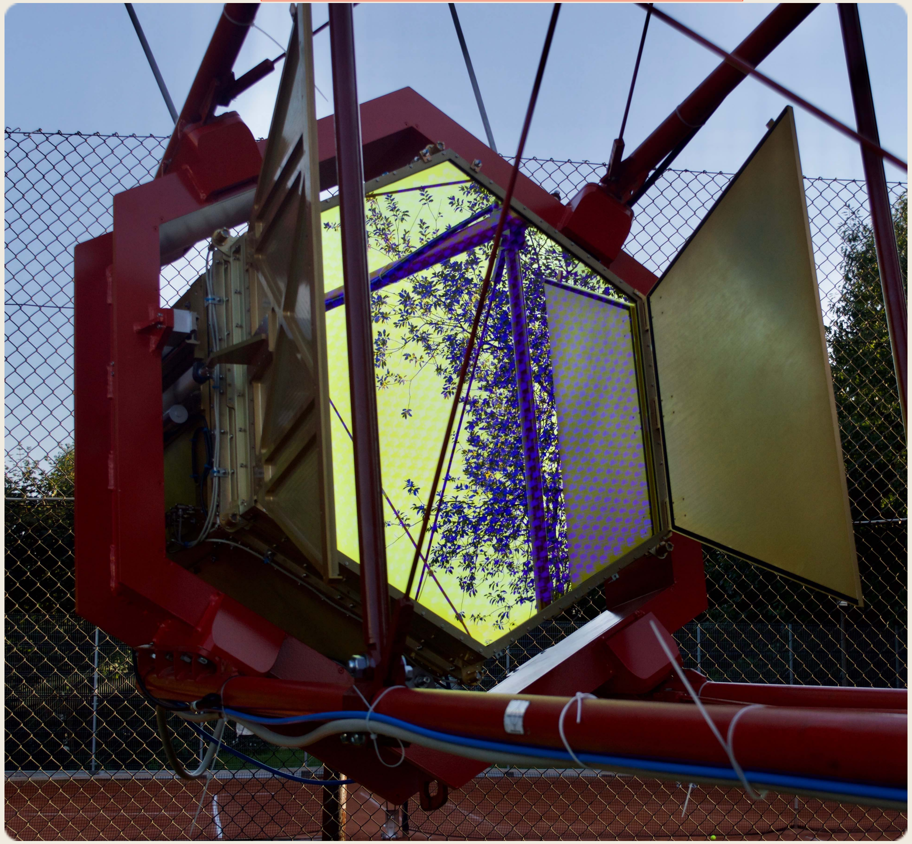


Its camera



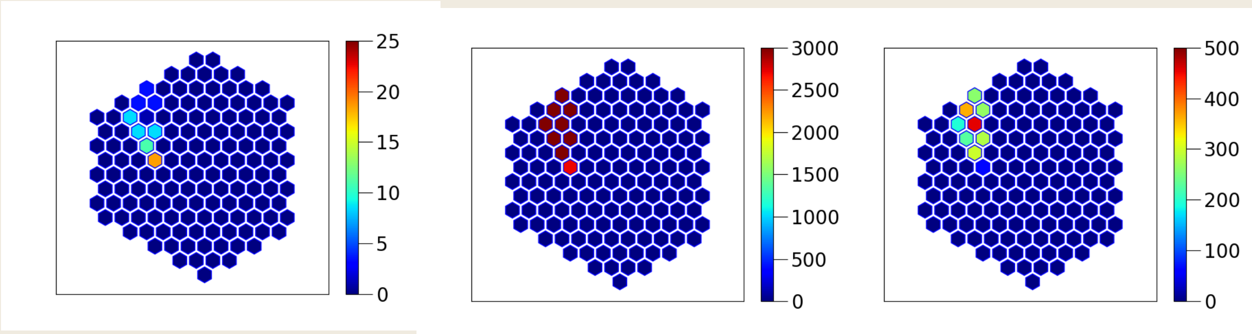
The SST-1M

- √ ***Dish = 4 m***
- √ ***FoV = 9°***
- √ ***f/D = 1.4***

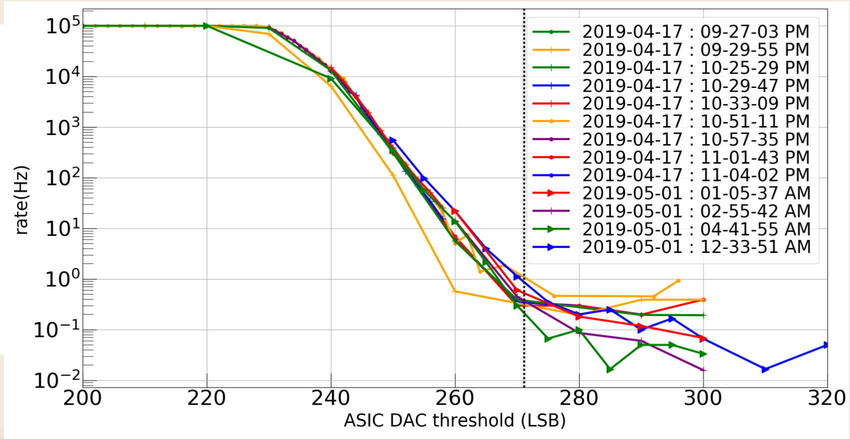


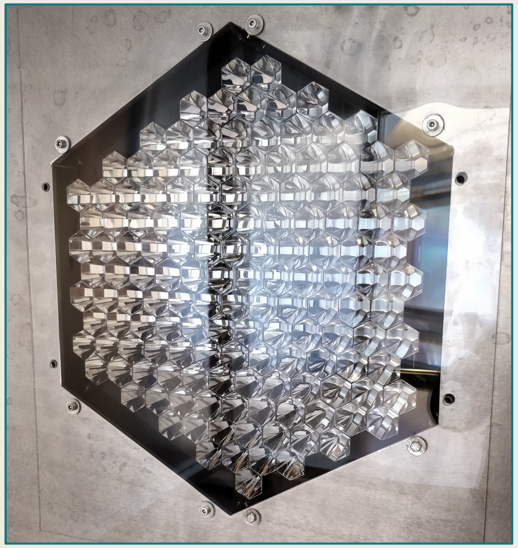
Pixel size = 4· min(σ_x, σ_y) = 0.24°
Camera size (D_c) = 88 cm
Pixel size (linear) = 2.32 cm
n_p = 1296 pixels

The mini-telescope

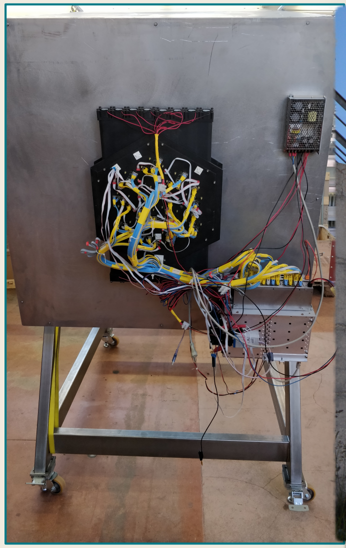


Arrival time [ns] ADC counts HG ADC counts LG

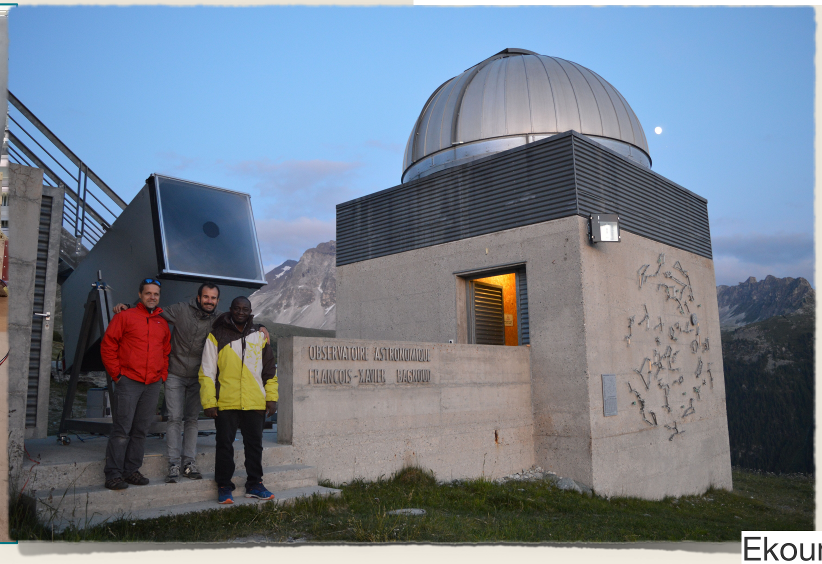




144 pixels camera



Readout system based on CITIROC custom adapted version



Telescope structure

- Observation campaign @ OFXB in Saint Luc (Valais, Switzerland)
- Trigger rate scan to determine acquisition threshold

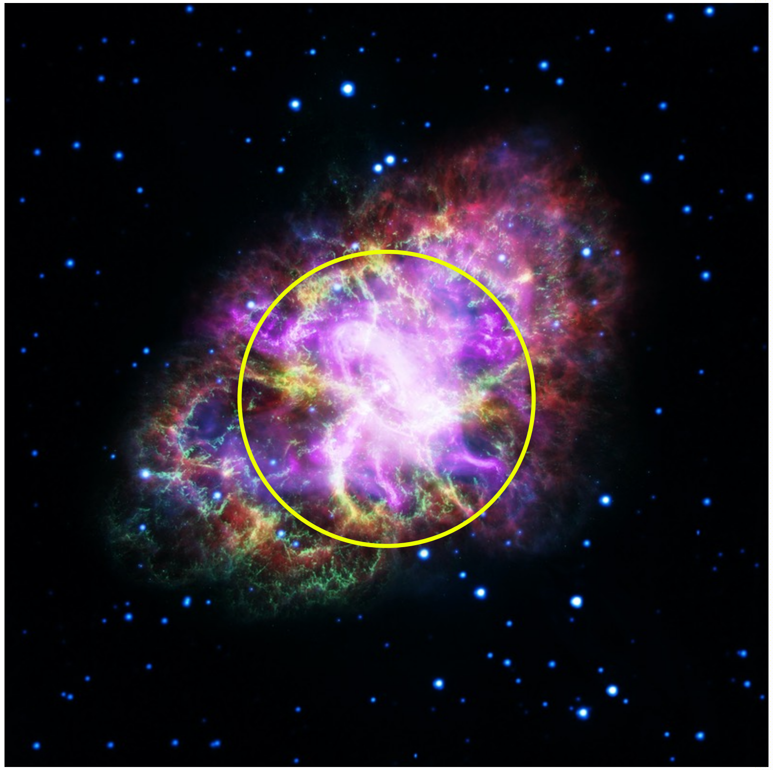
Ekoume et al, *JINST* 15 (2020) 04, P04004
e-Print: 1912.05894 [astro-ph.IM]

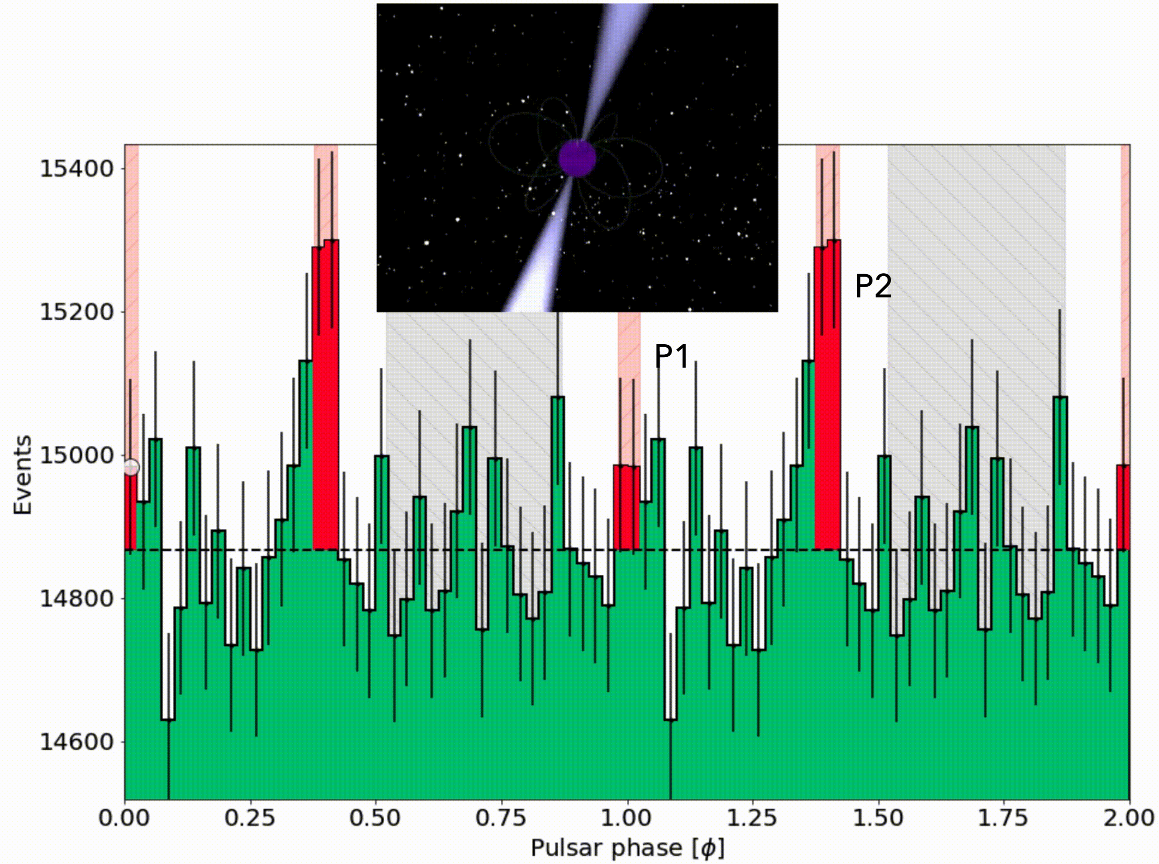
Gamma-astronomy `themes’

https://arxiv.org/abs/1709.07997

- ***Understanding of the origin of the cosmic rays*** in a multi-messenger context
- ***Probing extreme environments,*** such as neutron stars, black holes and gamma-ray bursts, the physics of the jets and how particles are accelerated by them;
- ***The Galactic plane Survey*** (*deep survey 2faster by ~100 than current generation)*;
- ***Exploring frontiers in physics***, such as the nature of Dark Matter in the Galactic Centre

Commissioning LST-1



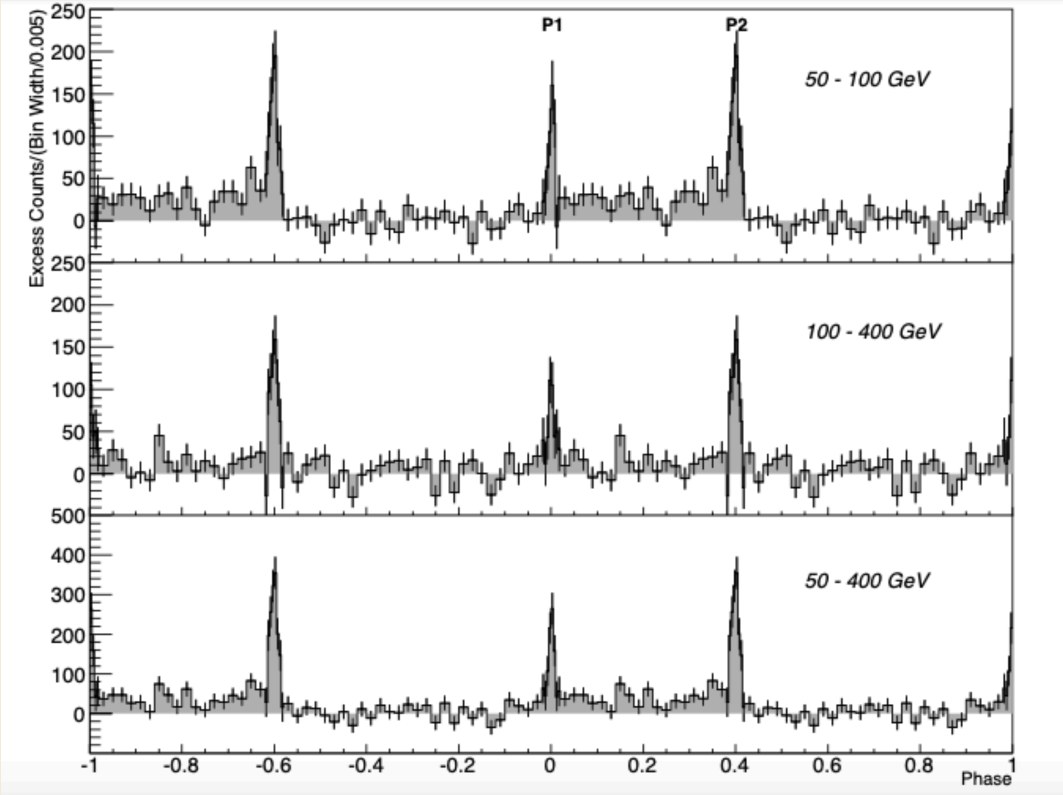


The neutron star pulsations at the centre of the Crab Nebula. P2/P1 >1 indicates a large threshold

https://www.cta-observatory.org/lst1-detects-vhe-emission-from-crab-pulsar/

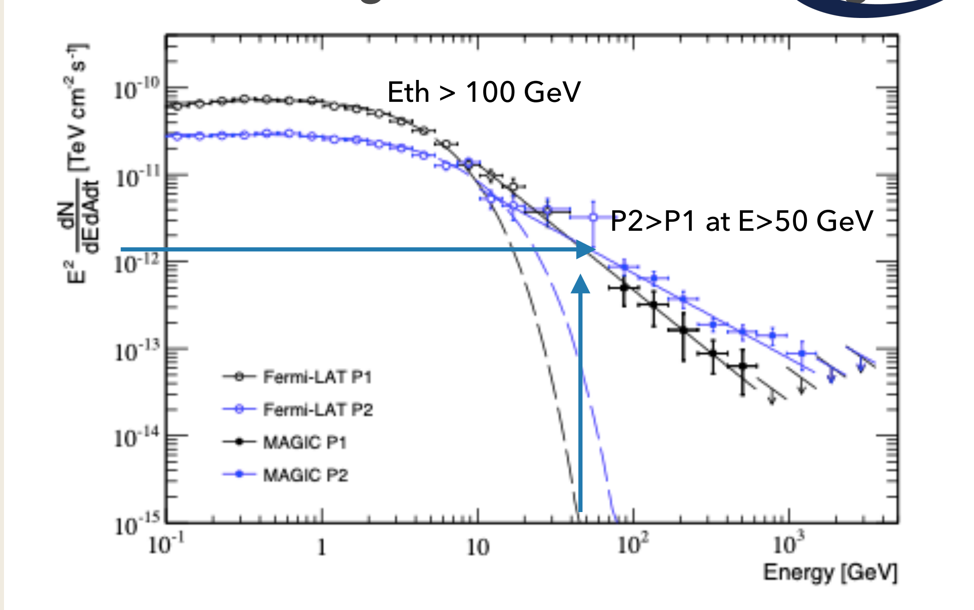
he `standard candle' of gamma-ray astronomy

MAGIC data

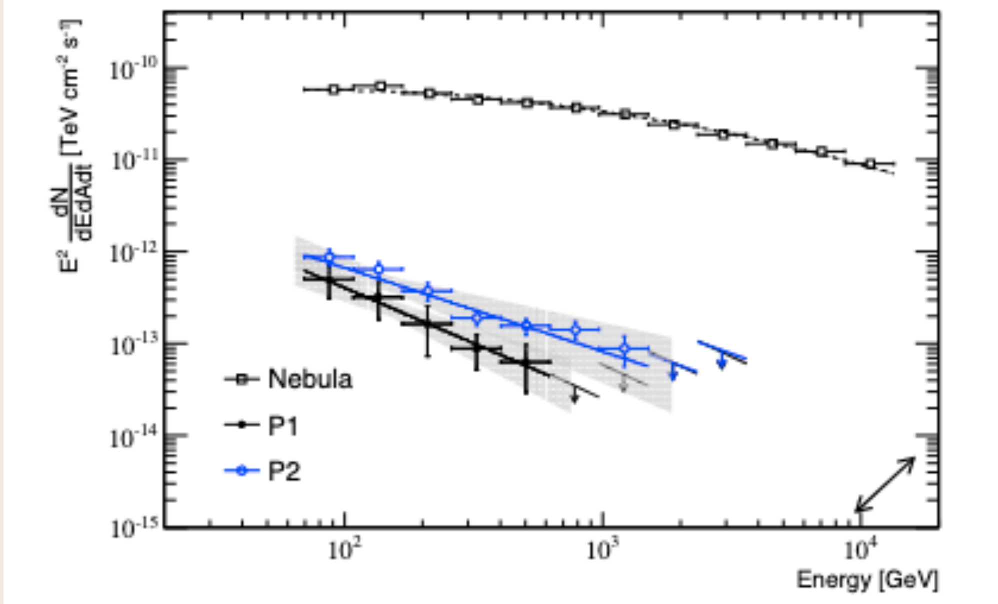


Saito et al for the MAGIC Collaboration, arXiv:1502.02757

320 hours

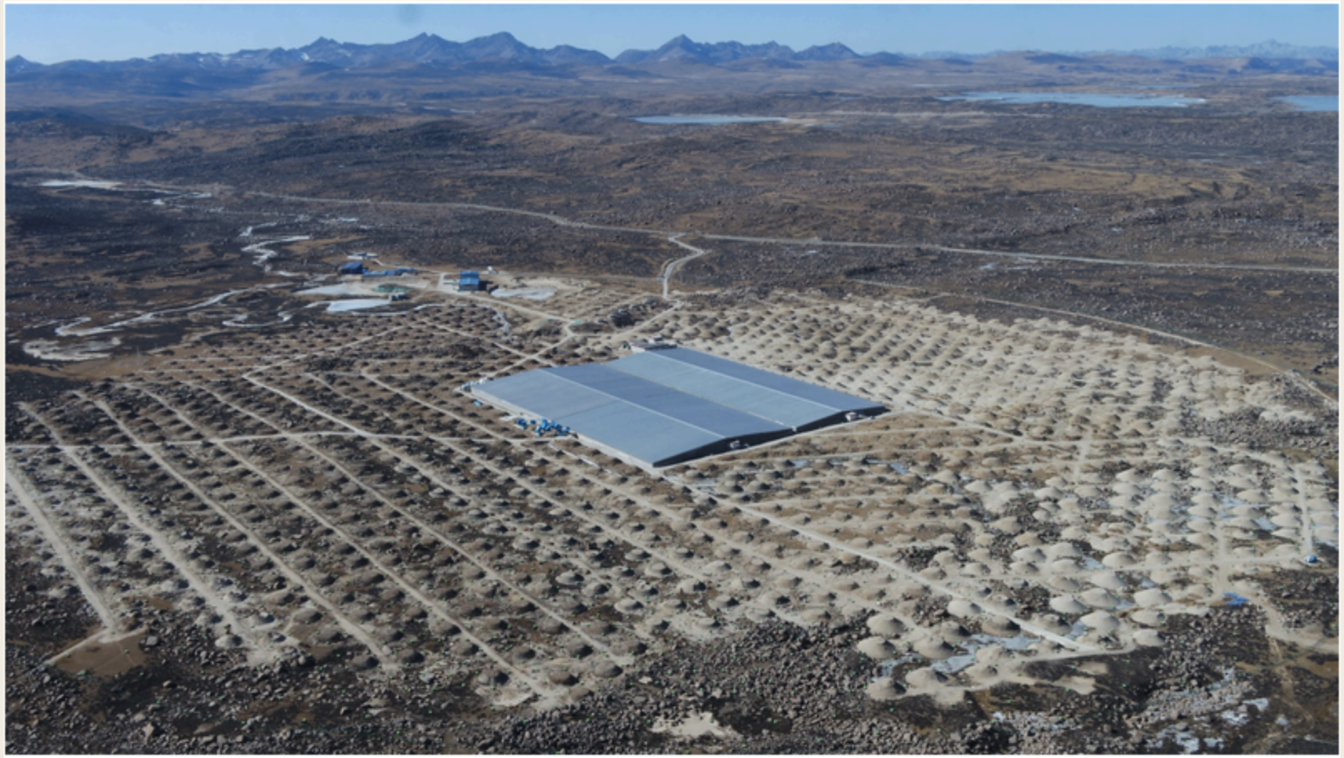


Pulsed emission up to 1.5 TeV!



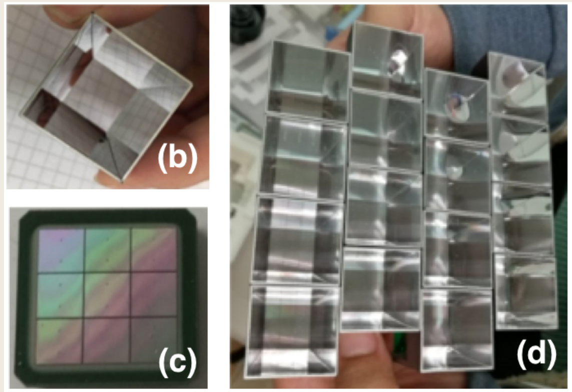
LHAASO: Large High Altitude Air Shower Observatory

WFCTA



Aerial photograph of LHAASO (Image by IHEP)

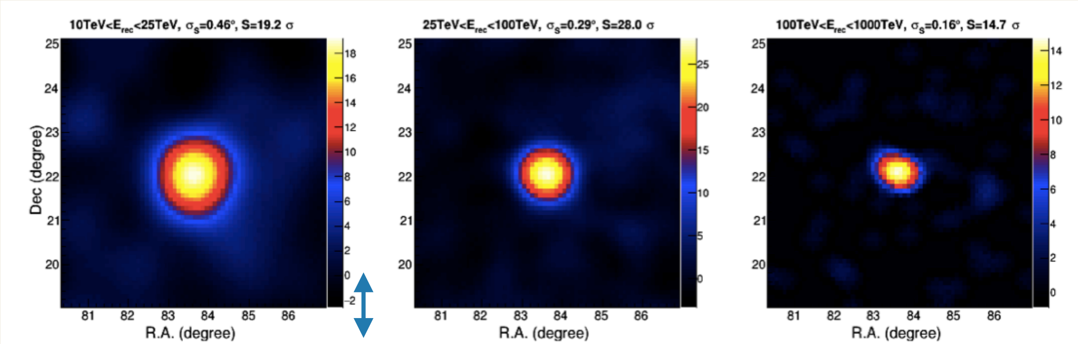
Lightguides produced in Switzerland



80’000 m^2 water pools
WCDA,
~200 GeV-20 TeV and
~9mCU @ few TeV

KM2A with EM & muon detectors
> 10 TeV

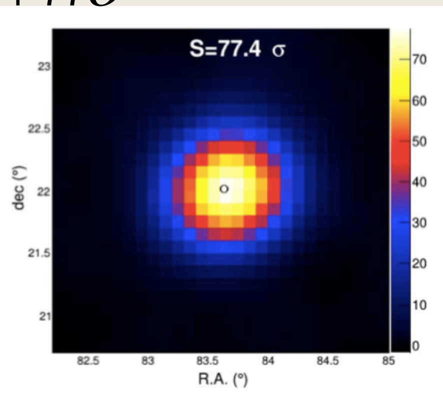
UHE astronomy : Crab Nebula with LHAASO



Crab Nebula a clear PeVatron with secondary gammas > 100 TeV; also seen by HAWC and Tibet ASγ with no cut -off above 400 TeV indicating that primary electrons can reach above 0.1 PeV.

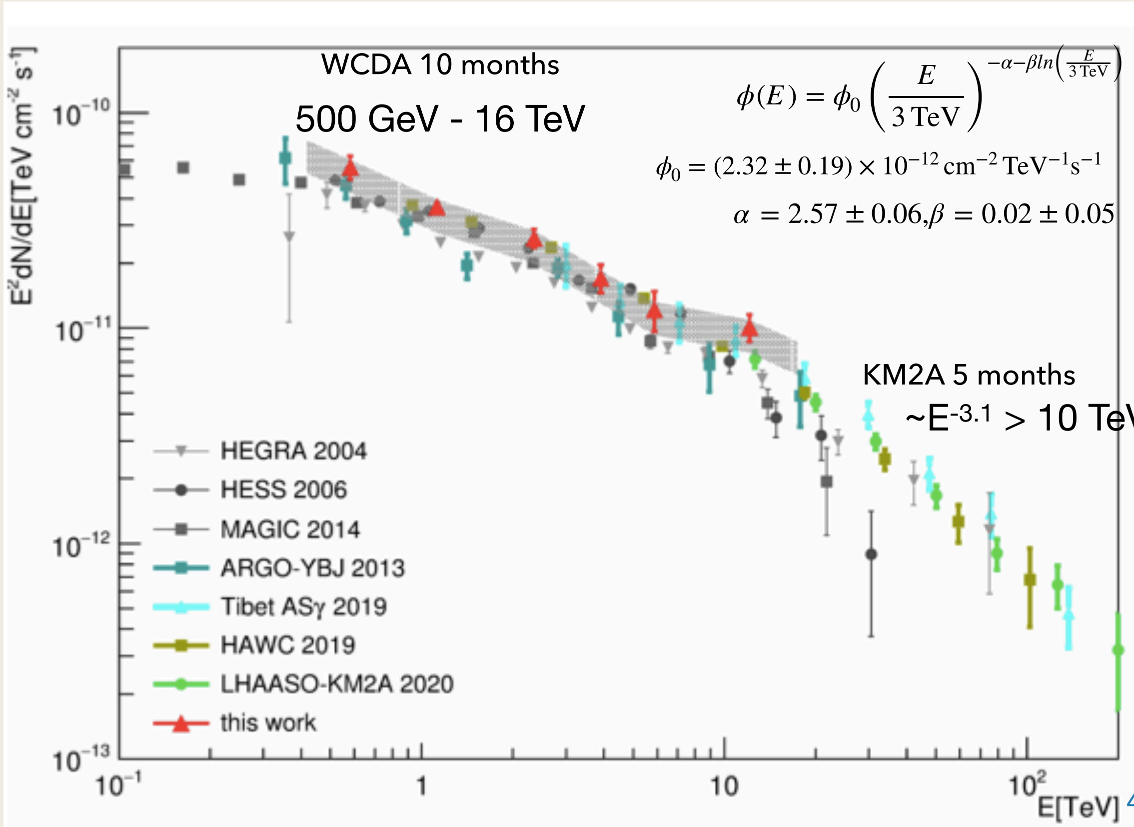
Crab Nebula image from the KM2A of LHAASO

WCDA: 0.45°(<0.2°) @ 1 TeV (>6 TeV) with the pointing accuracy < 0.05°. Significance in image 4-77σ



1° range

, WFCDA



PeVatron candidates (> 100 TeV)

12 young massive star clusters and supernova remnants, PWN, 1 yet unidentified. E_{max} = 1.42 PeV for LHAASO J2032+4102 Cygnus cocoon!!)

source name	R.A. (°)	dec (°)	Significance (σ) above 100 TeV	E_{Max} (PeV)	Flux (± error) (CU) at 100 TeV
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ±0.11	1.00(0.14)
LHAASO J1825-1326	276.45	-13.45	16.4	0.42 ±0.16	3.57(0.52)
LHAASO J1839-0545	279.95	-5.75	7.7	0.21 ±0.05	0.70(0.18)
LHAASO J1843-0338	280.75	-3.65	8.5	$0.26^{+0.16}_{-0.10}$	0.73(0.17)
LHAASO J1849-0003	282.35	-0.05	10.4	0.35 ±0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ±0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71^{+0.16}_{-0.07}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ±0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ±0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ±0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ±0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ±0.19	1.05(0.16)

Crab Nebula 0.30°

MGRO 1908+06 0.58°

Cygnus OB2 TeV J2032+41

Image credit: Chandra, Hubble, Spitzer, NASA

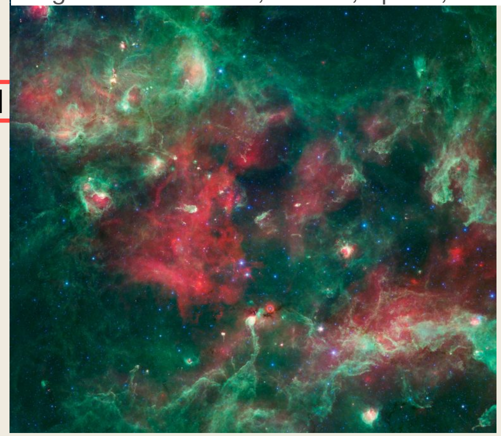
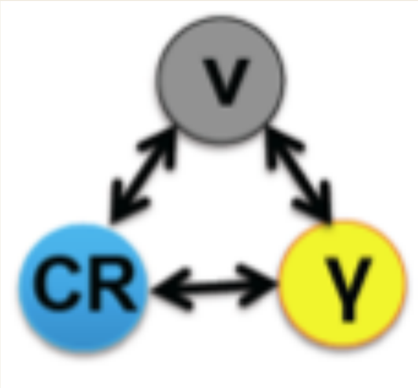


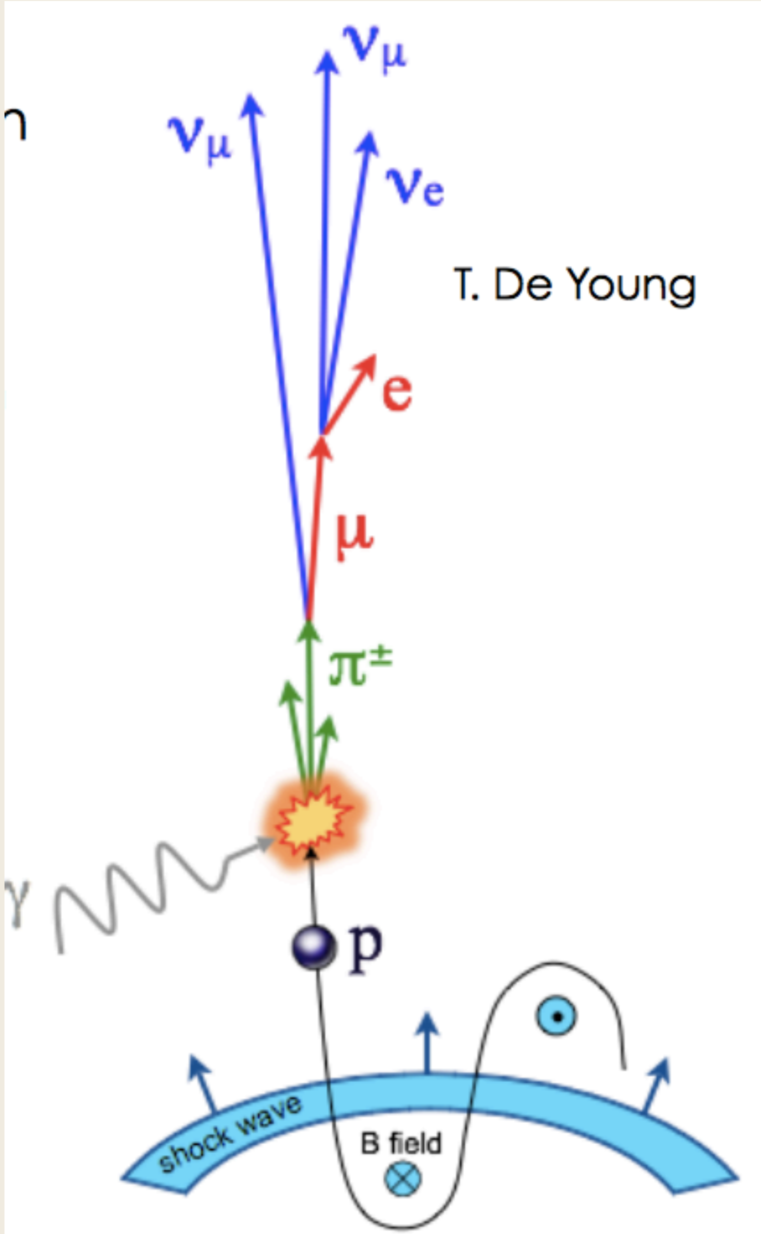
Image credit: NASA/JPL-Caltech/Harvard-Smith

`…photons exceeding 1 PeV from it, can be treated as evidence of the operation of massive stars as hadronic PeVatrons. The leptonic (IC) origin of radiation can be excluded because of the lack of brightening of the gamma-ray image towards Cygnus OB2. A decisive test for the acceleration of protons, presumably via collisions of the stellar winds, and continuous injection into the circumstellar medium over million-year timescales, would be the derivation of hard injection spectra and radial dependence of the density of UHE protons'

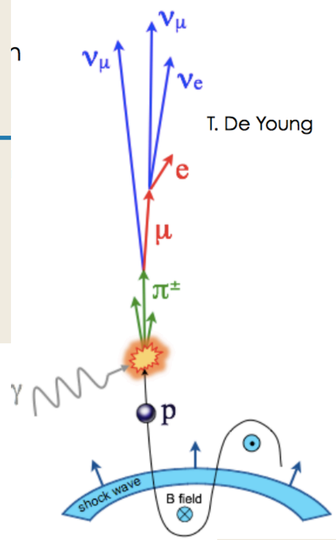
Nature paper (press release on May 17): Detection of Ultra-high Energy Photons up to 1.4 PeV from 12 Gamma-ray Sources

The generic model of a cosmic ray accelerator

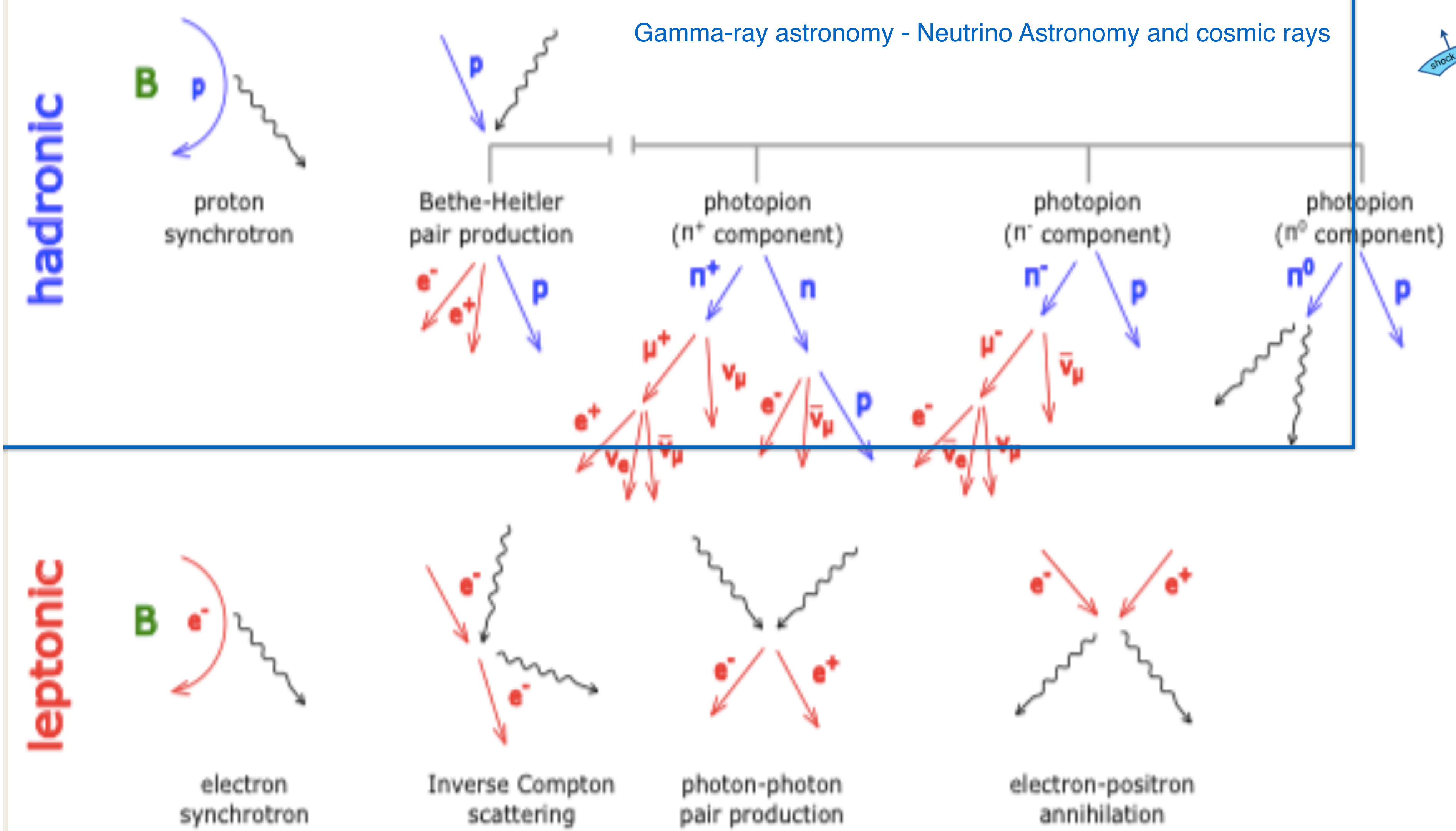




Reactions in matter accelerators



Gamma-ray astronomy - Neutrino Astronomy and cosmic rays



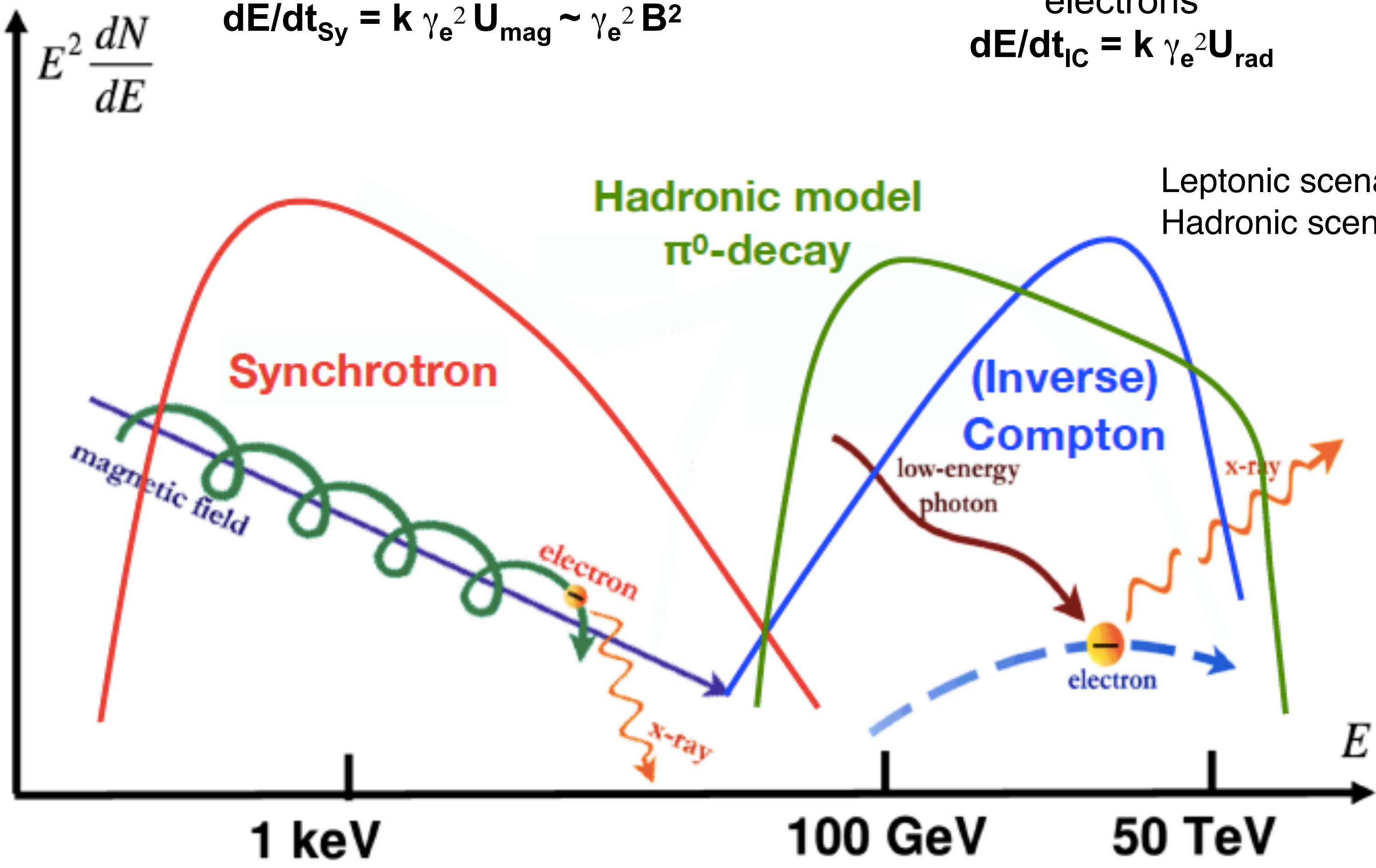
HADRONIC SIGNATURES IN SPECTRAL EMISSION DISTRIBUTION

energy flux $E^2\, d/dE \sim \nu F(\nu)$

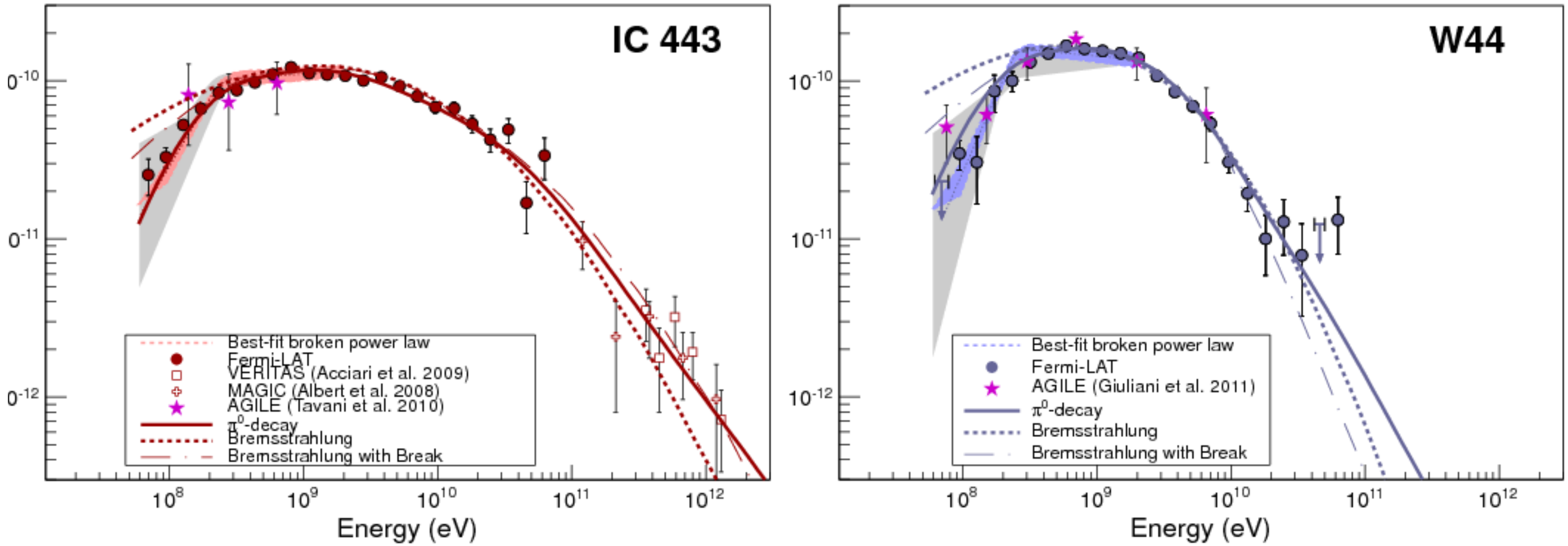
synchrotron radiation from electrons
$\mathbf{dE/dt_{Sy} = k\, \gamma_e^2\, U_{mag} \sim \gamma_e^2\, B^2}$

Inv. Compton scattering by the same electrons
$\mathbf{dE/dt_{IC} = k\, \gamma_e^2 U_{rad}}$

Leptonic scenario: red and blue
Hadronic scenario: pion decay



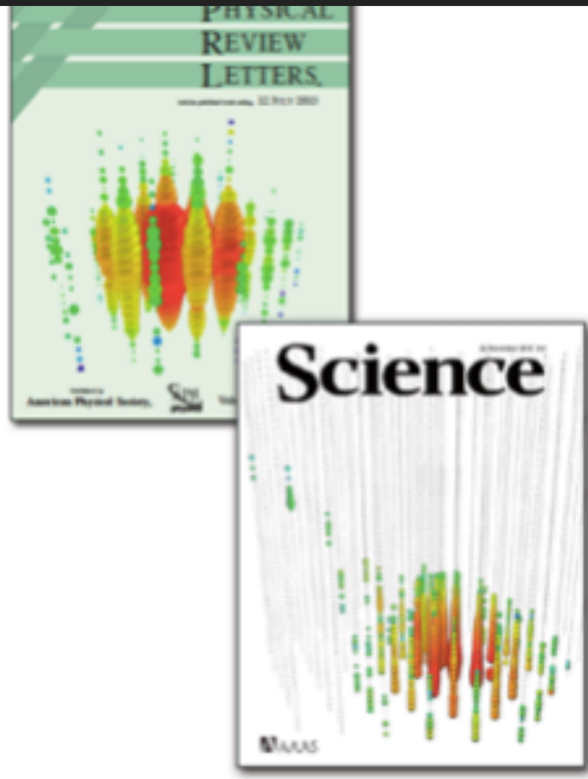
HADRONIC SUPERNOVAE

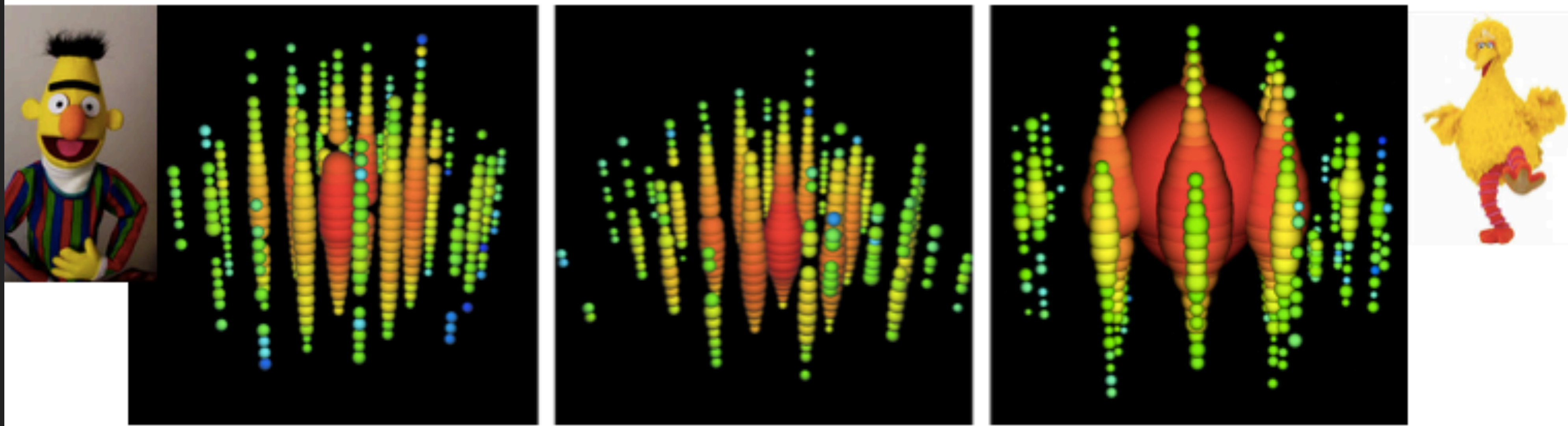


Fermi, Science 2013

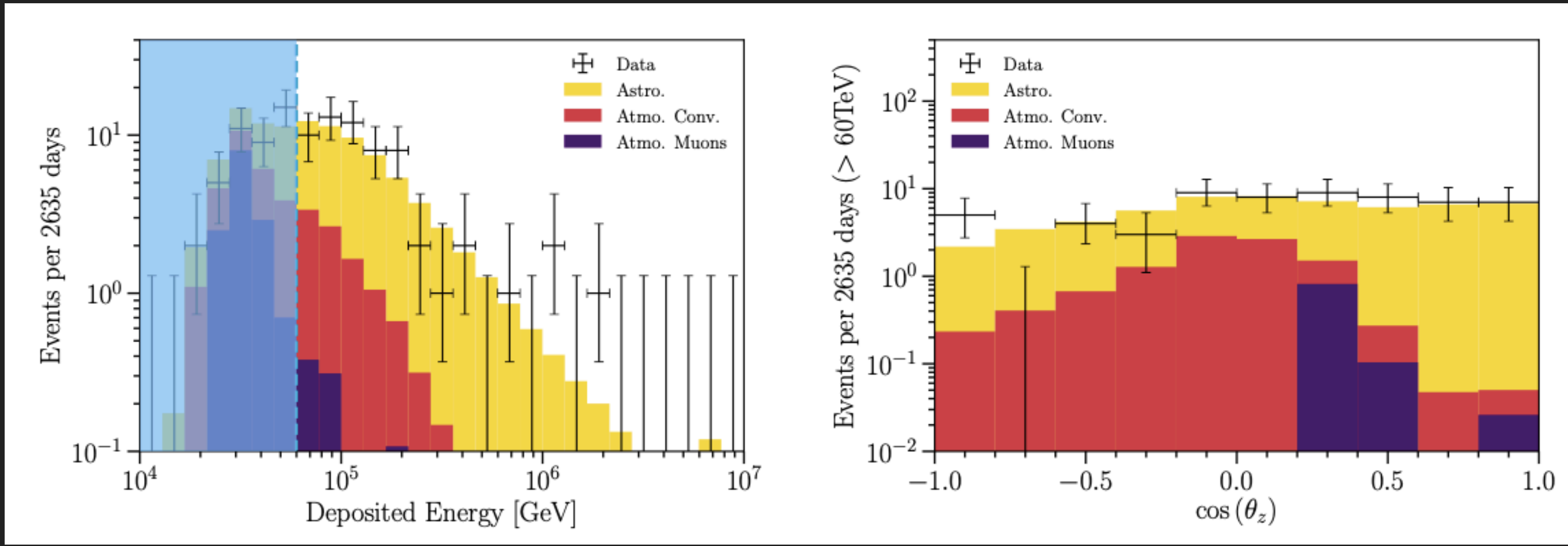
THE DISCOVERY OF COSMIC NEUTRINOS

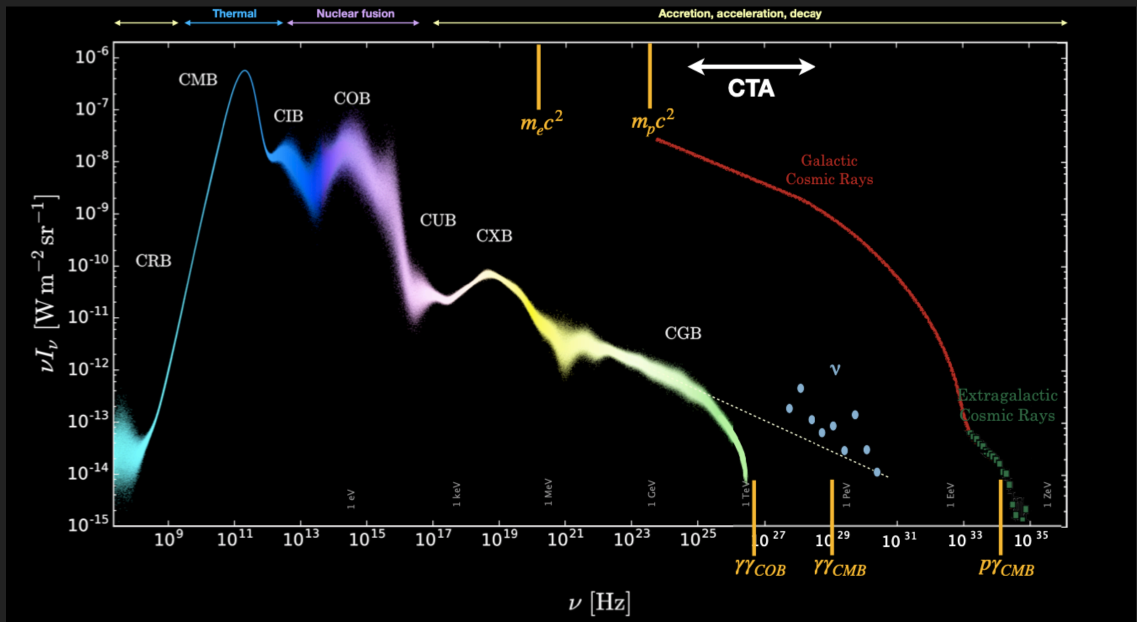
Nov. 2013. Currently, more than 8 yrs are available and a negligible probability that these high energy neutrinos are originating in the atmosphere.





A DIFFUSE FLUX



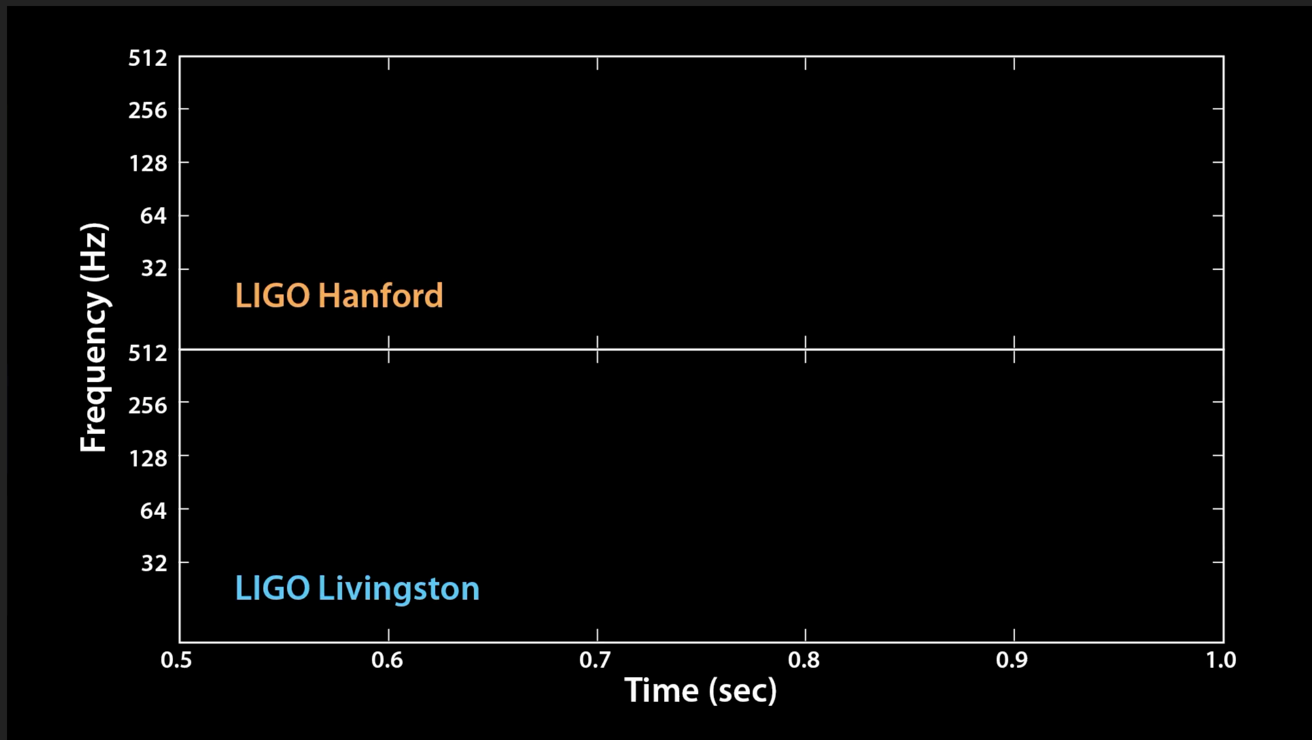


Category	$E < 60$ TeV	$E > 60$ TeV	Total
Total Events	42	60	102
Up	19	21	40
Down	23	39	62
Cascade	30	41	71
Track	10	17	27
Double Cascade	2	2	4

FIRST SIGNAL IN GRAVITATIONAL WAVES

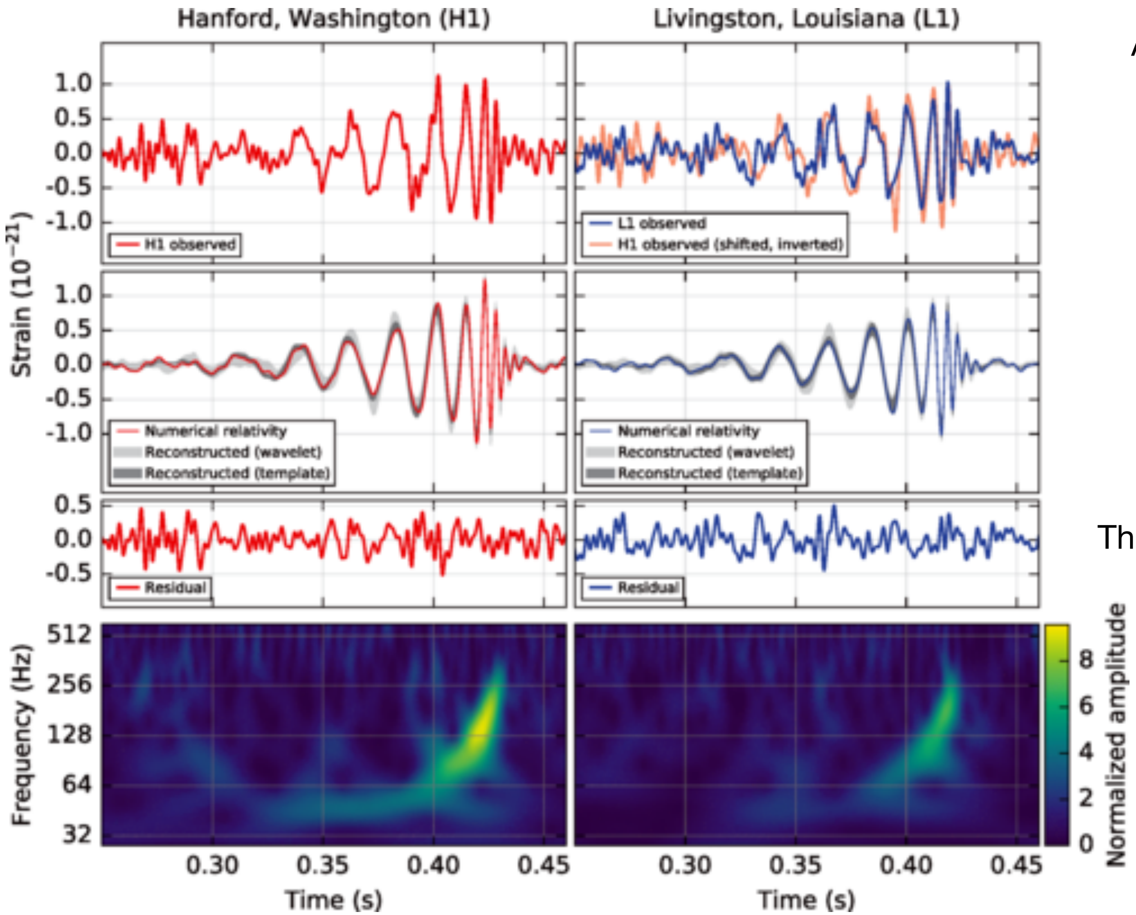
On Sep. 2015 the LIGO interferometers transmitted the `chirp' of coalescent BHs with 36 and 29 solar masses. This sound traversed the Earth. The waves are perturbations of gravitational field produced by a cataclysmic astrophysical event and are an important confirmation of the Einstein Theory of gravitation.

The frequency of GWs is a sound.



The first event of BH-BH merger: raw data!

GW arrived first at L1 and then after 6.9–0.4+0.5 ms at H1



Fit to simple formulas bring a lot of information!

At first order, the rate of change of the frequency is

$$\frac{df}{dt} = \frac{96\pi^{8/3}(G\mathcal{M})^{\frac{5}{3}} f^{\frac{11}{3}}}{5\,c^5},$$

And the chirp mass

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}.$$

The polarization of the waves provides the angle of emission
And the distance is a multiple of the laser wavelength

Templates are calculated from General Relativity for NS-NS / BH-BH mergers and matched to data (matched template technique)

A direct detection which requires only a pass band filter in 35–350 Hz!

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102

PARAMETERS

Abbott et al., PRL, 116, 061102 (2016)

Primary black hole mass	$36^{+5}_{-4}\,M_\odot$
Secondary black hole mass	$29^{+4}_{-4}\,M_\odot$
Final black hole mass	$62^{+4}_{-4}\,M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$

TOTAL ENERGY RADIATED IN GW: $3.0^{+0.5}_{-0.5} M_\odot c^2$

PEAK GW LUMINOSITY: $3.6^{+0.5}_{-0.4} \times 10^{56}$ erg/s

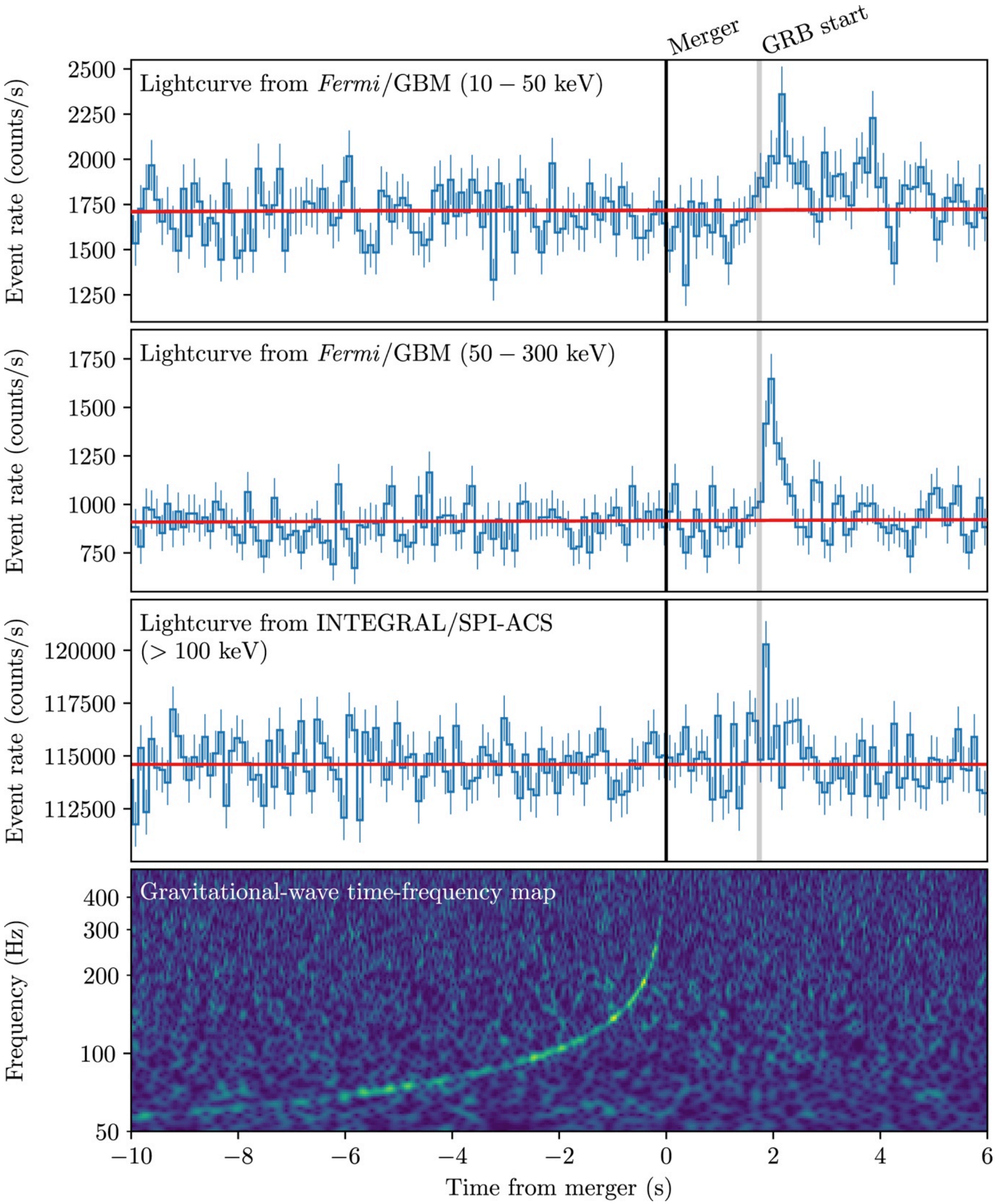
The most luminous event ever observed

First observation of the largest known stellar mass BH (>25 $M_\odot$)

First observation of a binary black hole (BBH) system and BBH merger

First binary neutron star merger

Aug 17th 2017 at 12:41 UTC Advanced LIGO-Virgo detected a binary neutron star inspiral



Resulting mass 90cl

$$2.73 < M_{\rm Total} < 3.29\ M_\odot$$

Two mass interval

$$0.86 < m_i < 2.26\ M_\odot$$

Luminosity distance

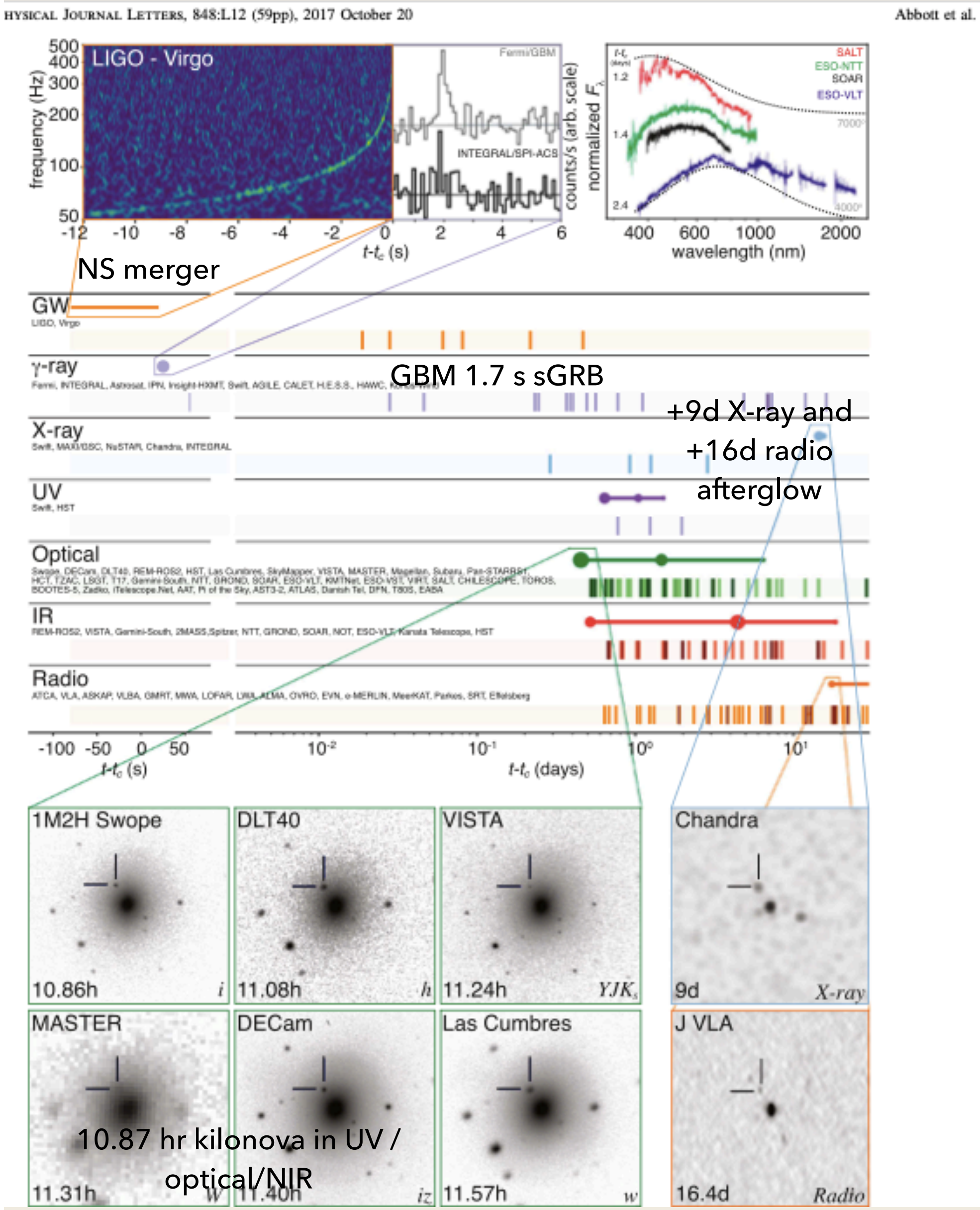
$$D_L = 40^{+8}_{-14}\ \mathrm{Mpc}$$

A GRB event, 1.7 sec after…

First direct evidence that BNS mergers are progenitors of short GRB
Optical counterpart in host galaxy NGC4993
Optical/infrared/UV counterpart detected
First identification of a kilonova

Abbott et al., PRL., 119, 161101 (2017) Abbott et al., ApJL., 848:L13 (2017)

The multi-messenger event!



GW 170817 - photon connection

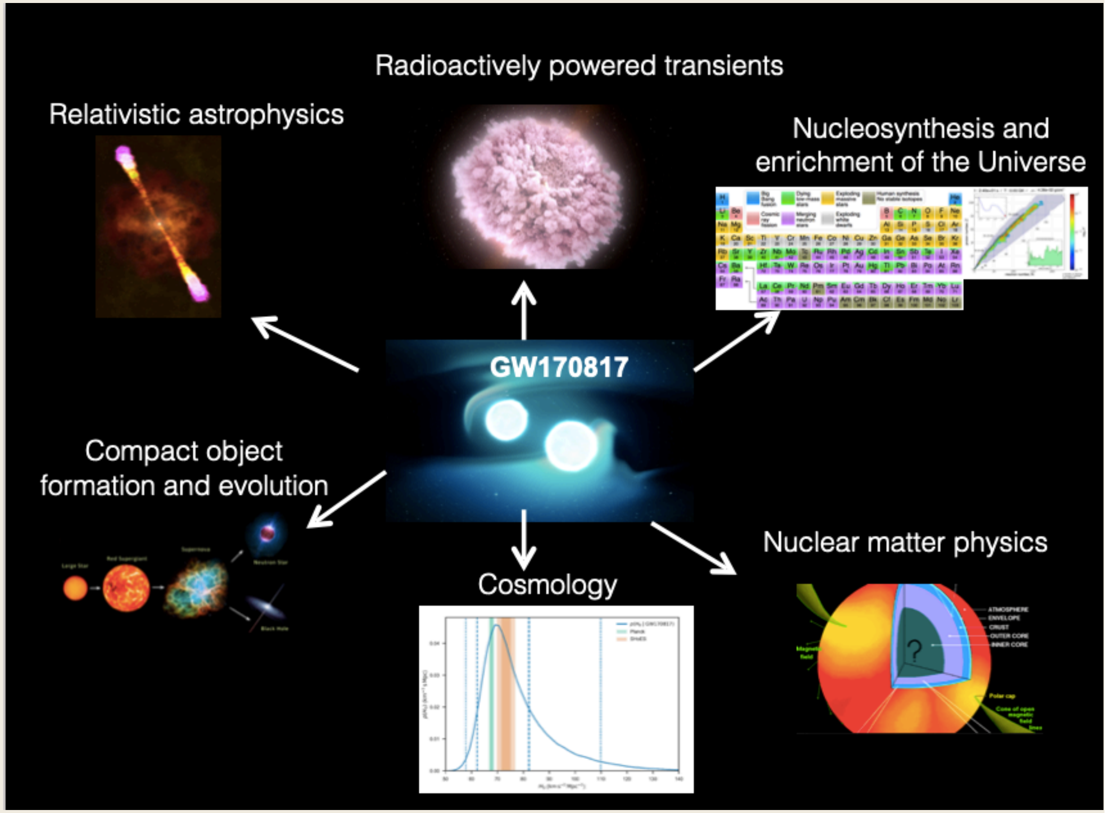
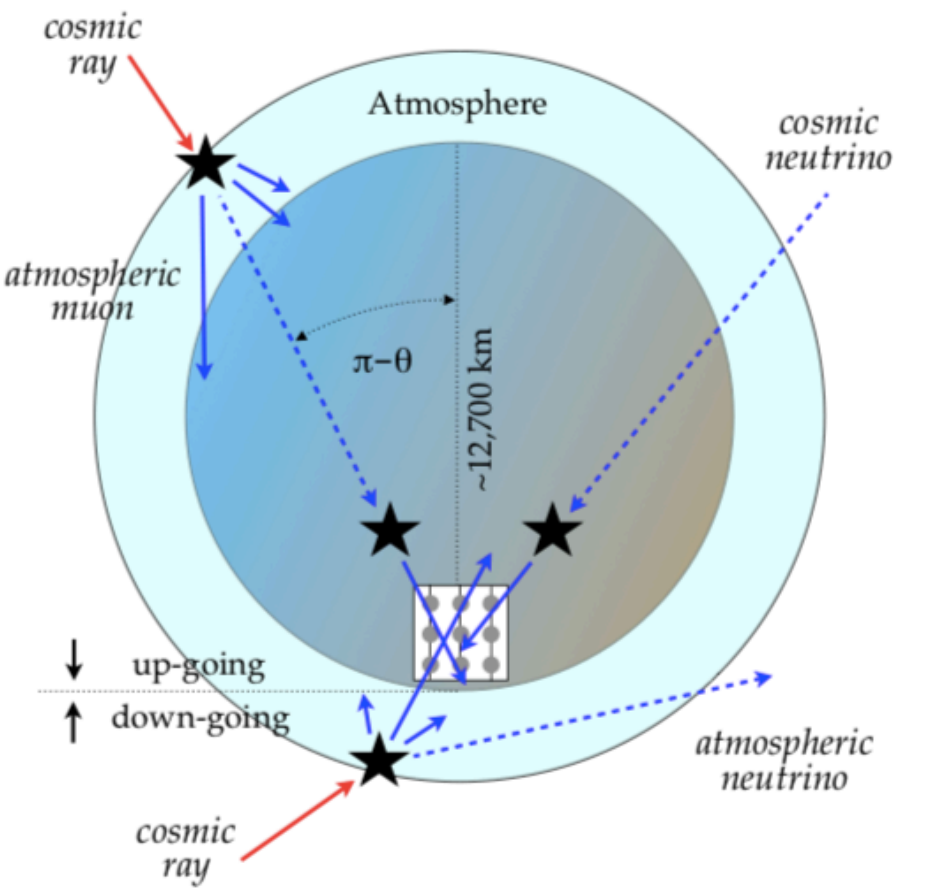


Figure from M. Branchesi's presentation at Neutrino Telescopes 2021

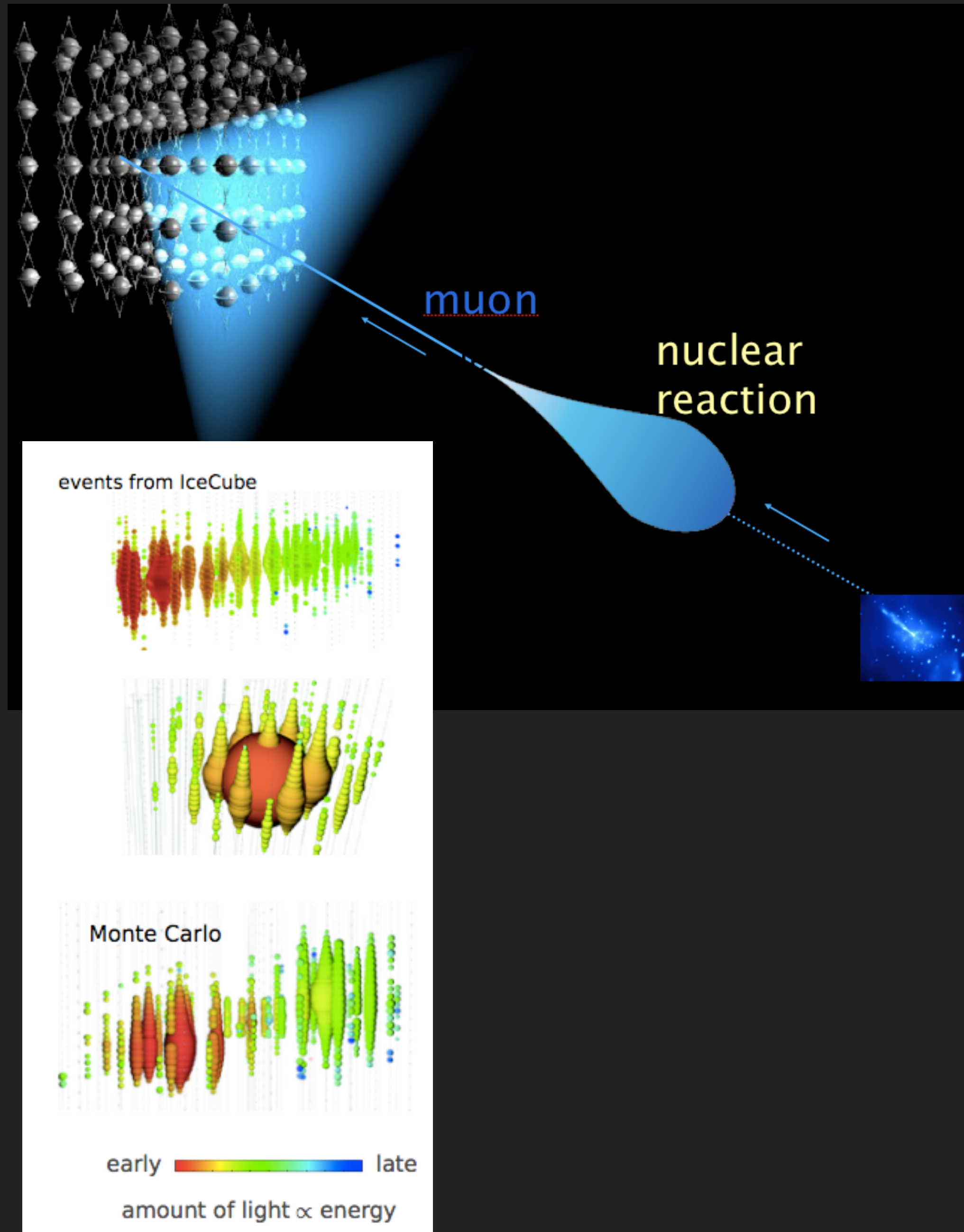
GSSI Colloquia: A. Bonanno and M.Maggiore this year

NEUTRINO TELESCOPE

Up-going Muon-Neutrino Tracks



- **10,000,000,000** atmospheric muons
- **100,000** atmospheric neutrinos
- **10** cosmic neutrinos (per year and km³)



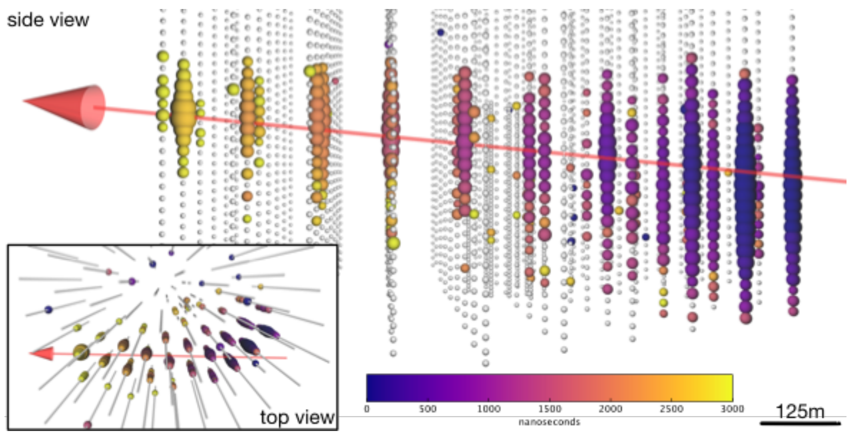
Neutrinos-gamma-rays: TXS0506+056

IceCube sent an alert including the direction of an event ~ 3 x 10^{14} eV in only 43 sec. Fermi discovered blazar a 0.06° distance from the IceCube event in a flaring state. In a follow up, MAGIC detected gamma rays of > 300 GeV energy from the source. The probability that this is not a casual coincidence is about 3.5σ.

IceCube found a second flare in 2014-15.

Science 361, 147-151 (2018) DOI:10.1126/science.aat2890
Science 361, eaat1378 (2018). DOI:10.1126/science.aat1378

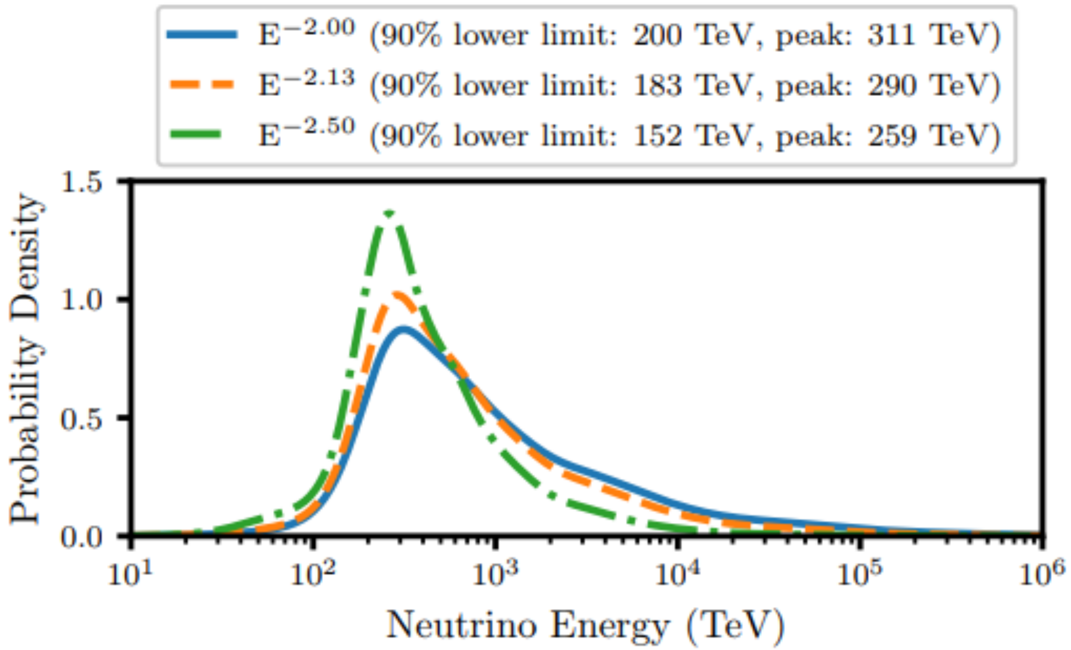
The 22/08/2017 IceCube alert event (not a neutrino, but a muon)!

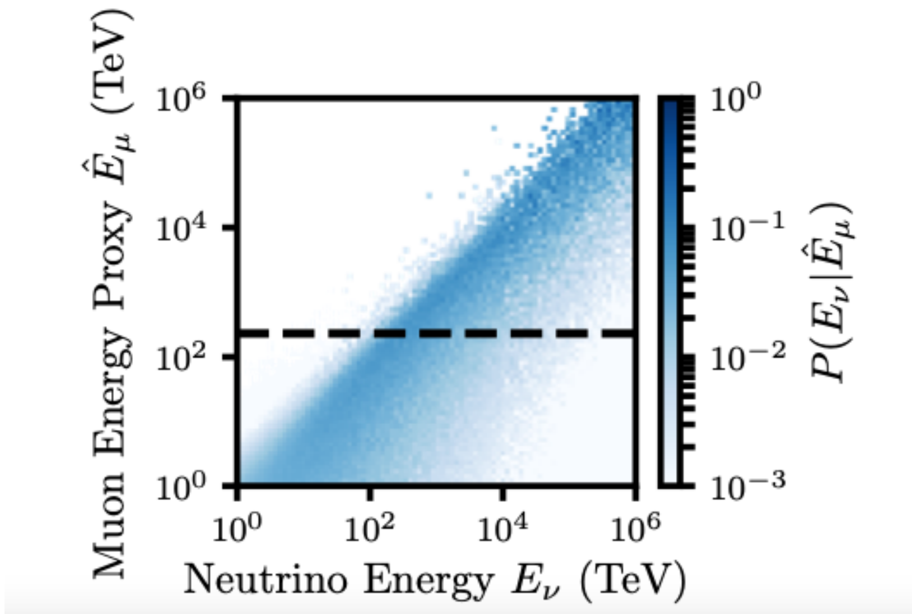


IC220817: 23.7±2.8 TeV **visible energy** in the detector from number of photoelectrons in PMTs,
15 arcmin error (50% containment), signalness 56.5%
(**GOLDEN alerts: ~10 /yr with signaless > 50%**)

Muon Energy proxy: muon energy at detector entrance: ~52 TeV = is a **lower limit to the total muon energy** since the muon **passes through the detector.**

The corresponding corresponding to a most probable neutrino energy ~290 TeV. Upper limit at 90% CL is 4.5 PeV (7.5) PeV) for a spectral index of -2.13 (-2).

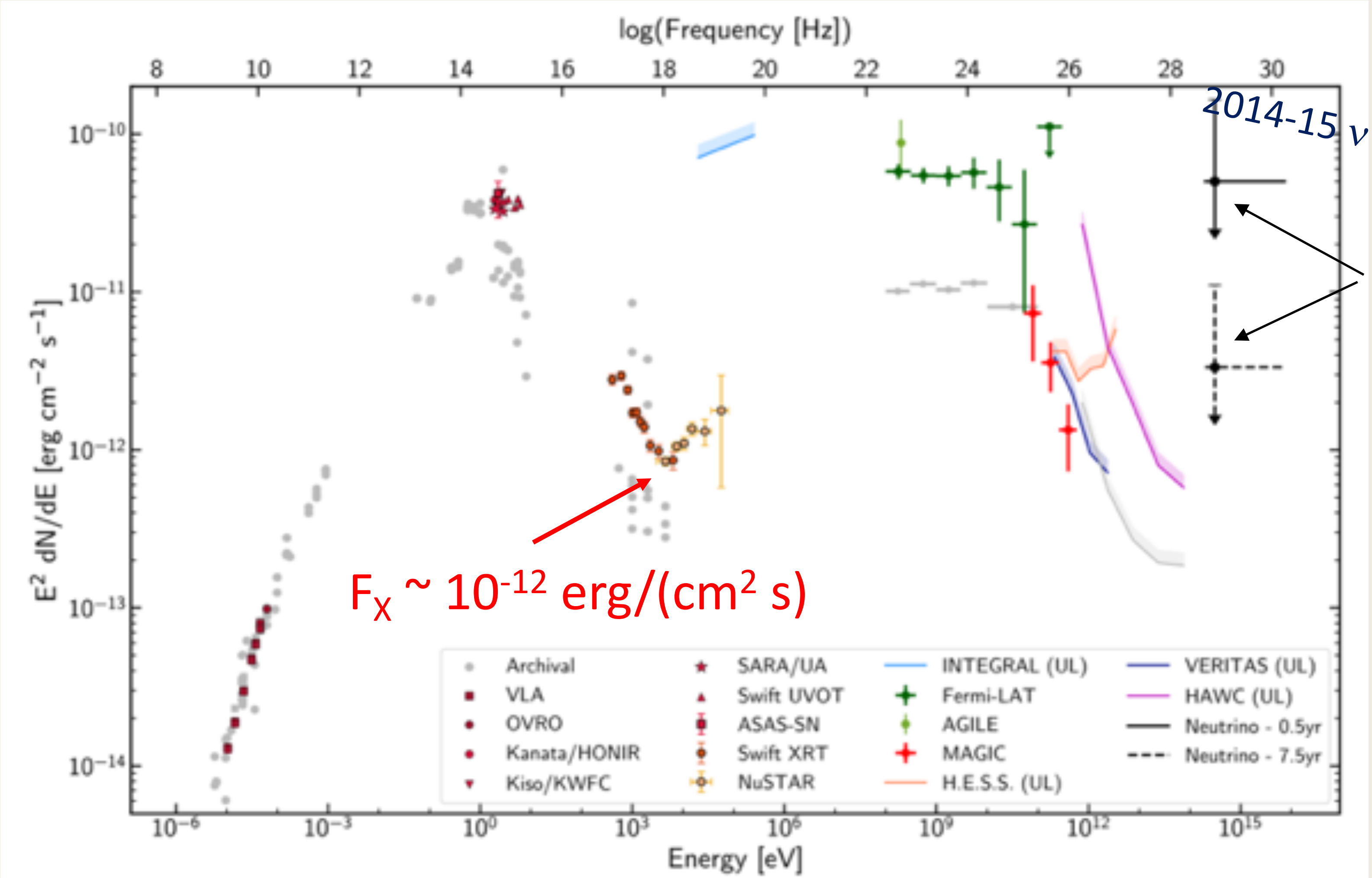


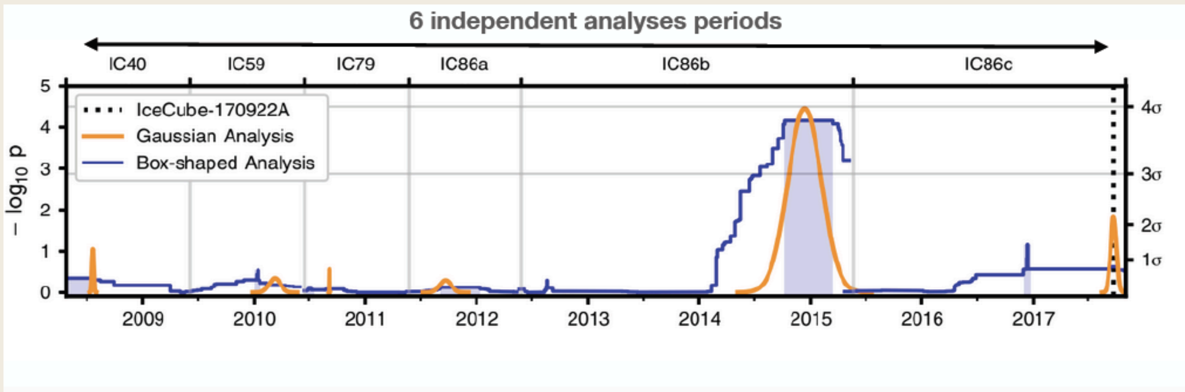


https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon

Photon - neutrino multi-messenger event

M.G. Aartsen et al. *Science 361*



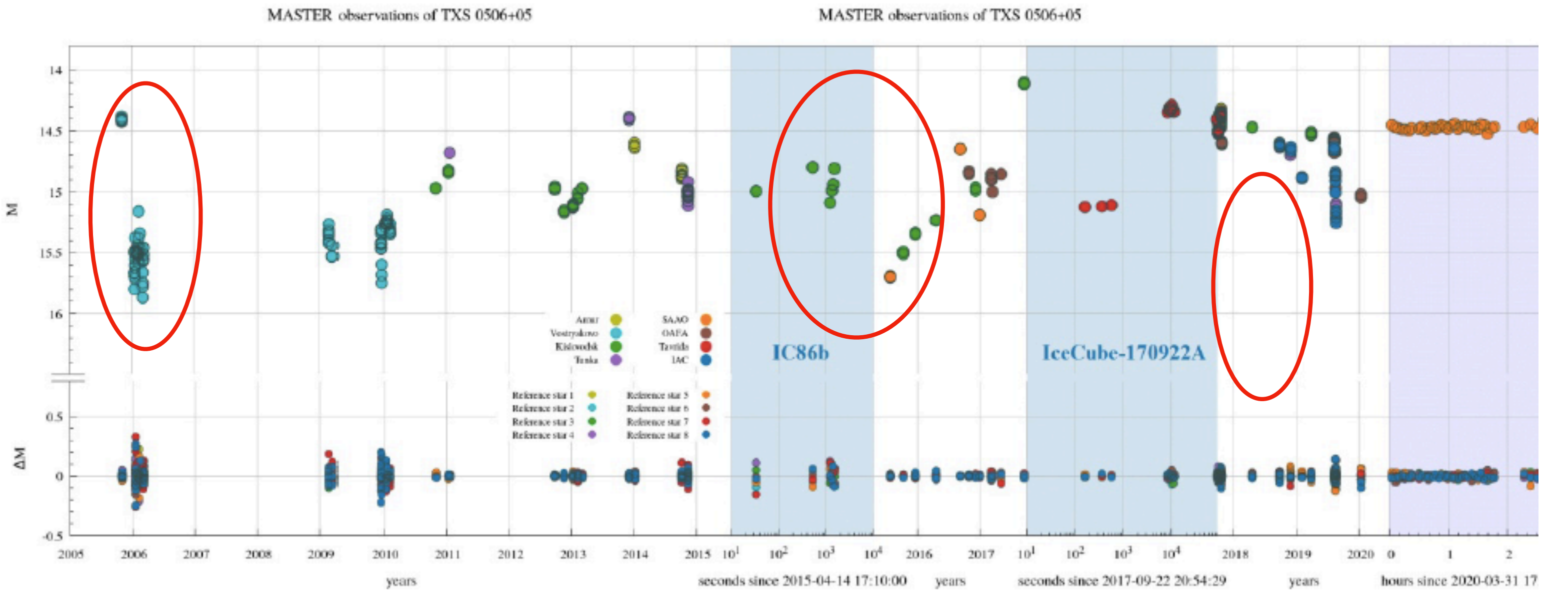


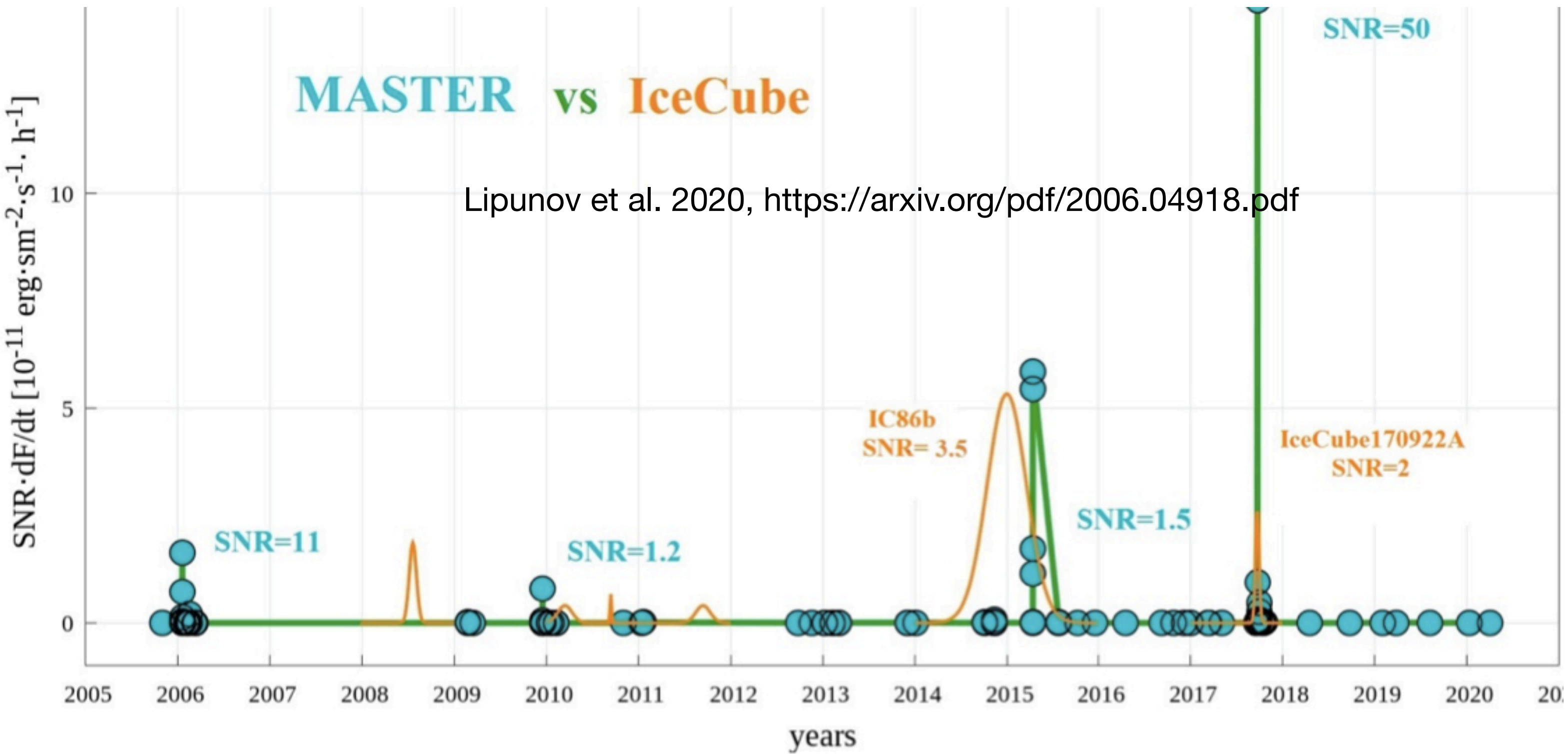
Asen Christov, PhD Thesis UNIGE

Interestingly…variability matters!

3 high variability episodes (up to hour scale) : in 2006 (IceCube had 1 string), Apr. 2015 (IceCube flare 9/2014-3/2015) and 9/2017

MASTER found the TXS 0506+056 in a quiet state 73 s after the IceCube 2017 event, but 2 hr after they observed an increase of optical flux at 50σ level (biggest variation since 2005!





Lipunov et al. 2020, https://arxiv.org/pdf/2006.04918.pdf

Le véritable voyage de découverte ne consiste pas à chercher de nouveaux paysages, mais à avoir de nouveaux yeux.

The real voyage of discovery consists not in seeking new landscapes, but in having new eyes. ***(Marcel Proust)***