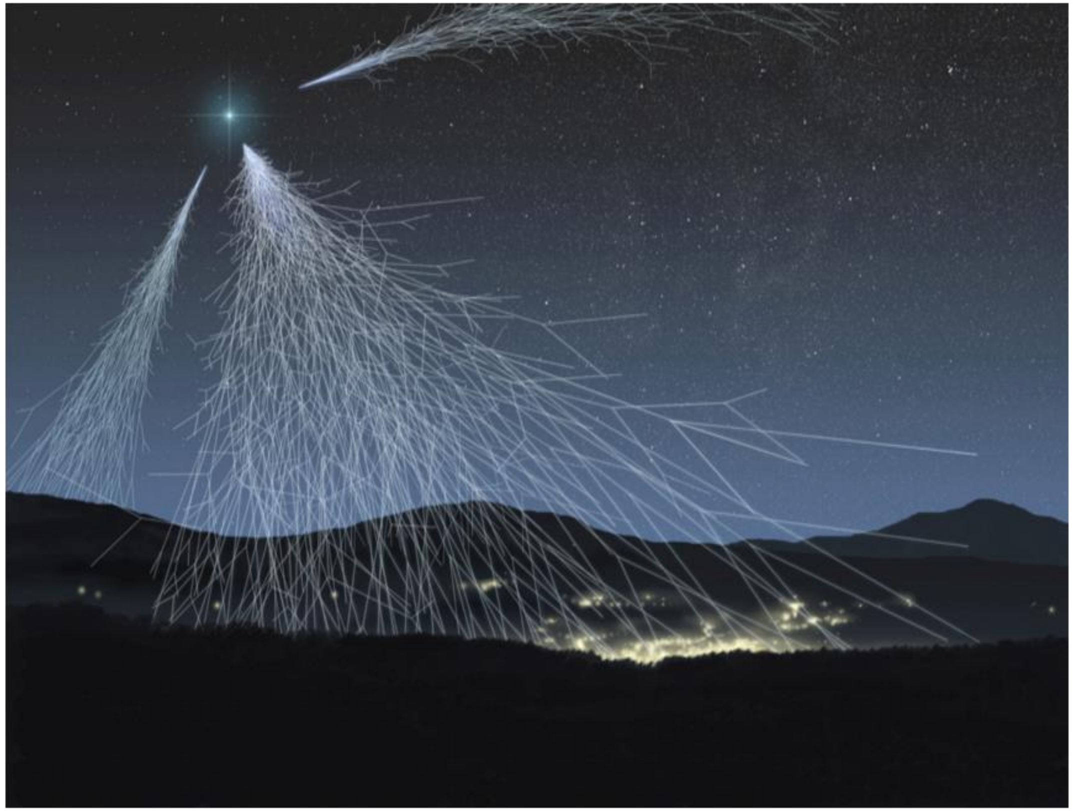
INFN’s 70 year – Tor Vergata – Frascati - Villa Mondragone

– 11th May 2022 –

New frontiers in space exploration

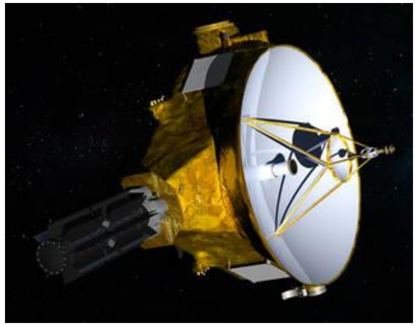
Étienne Parizot
(APC, Université de Paris)



Google search on “new frontiers in space exploration”

1. "New frontiers" program: of NASA

Explore by actually going there!



New horizons
(Pluto, Kuiper’s belt…)

Juno
(Jupiter)

OSIRIS-REx
(Asteroid Bennu)

DRAGON-fly
(Saturn’s moon Titan)

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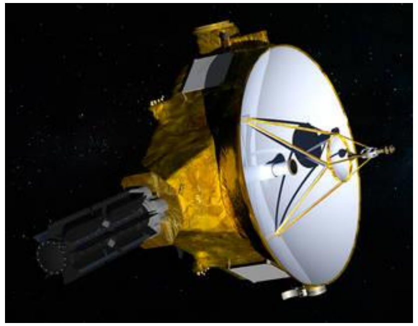


New horizons (Pluto, Kuiper’s belt…)

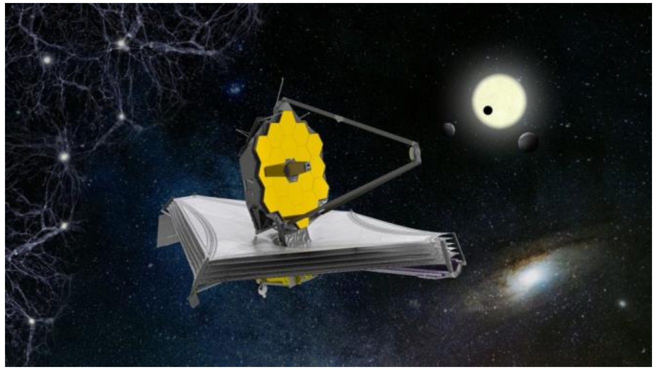
Juno (Jupiter)

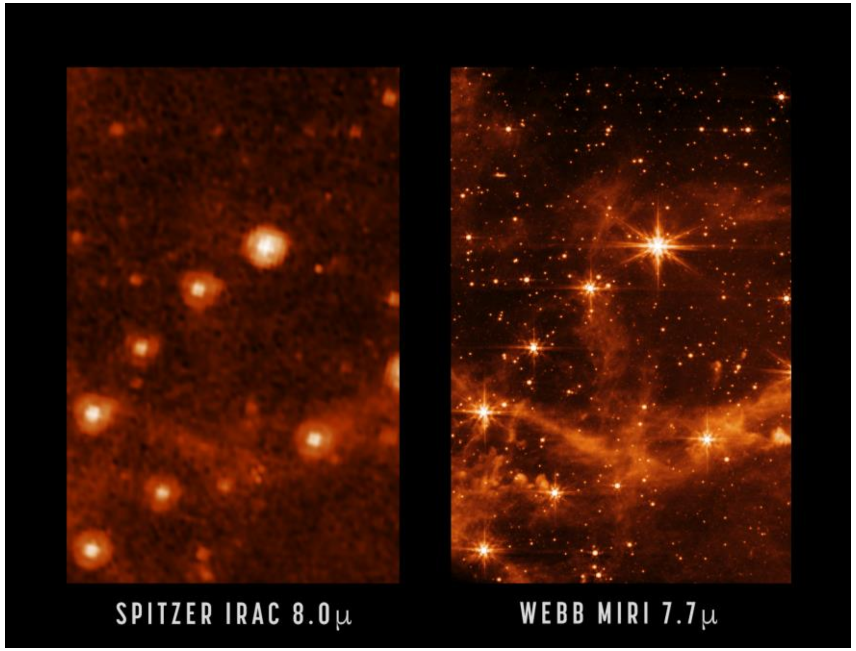
OSIRIS-REx (Asteroid Bennu)

DRAGON-fly (Saturn’s moon Titan)

2. JWST (James Webb space telescope):

Explore from where you are!



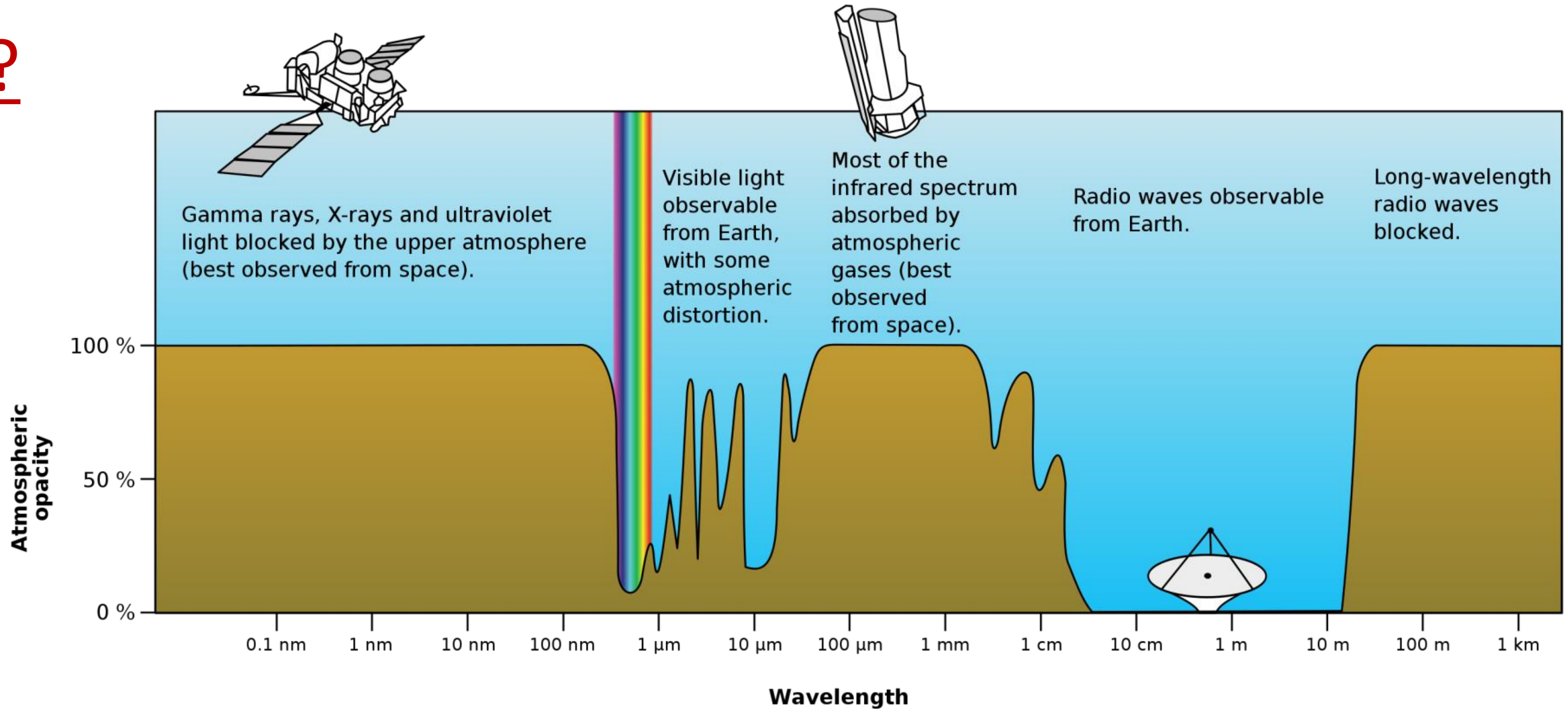


May 9th, 2022
Large Magellanic Cloud

Why go to space?

★ Because we must:

multi-wavelength astronomy!



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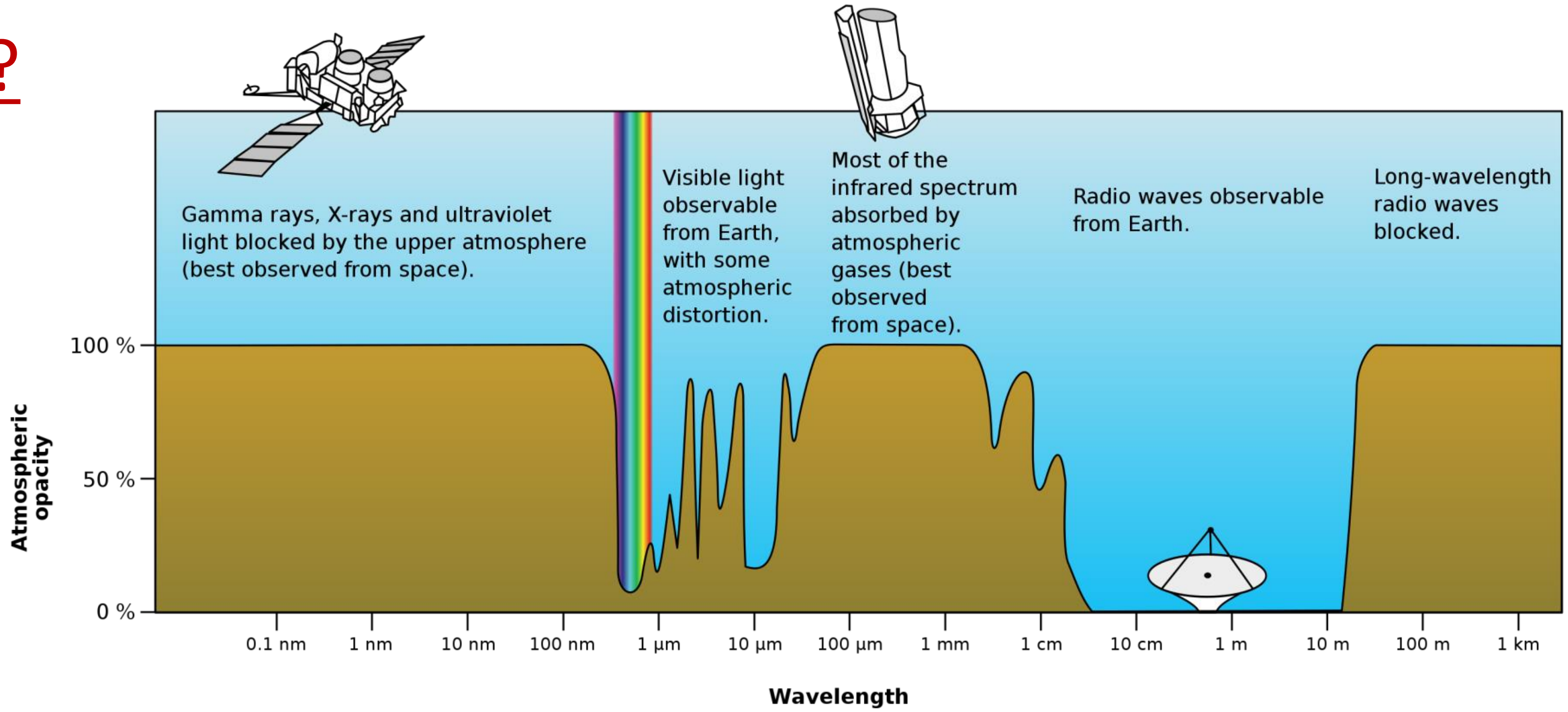


★ Basic rule: “Don’t go to space if you don’t have to!”

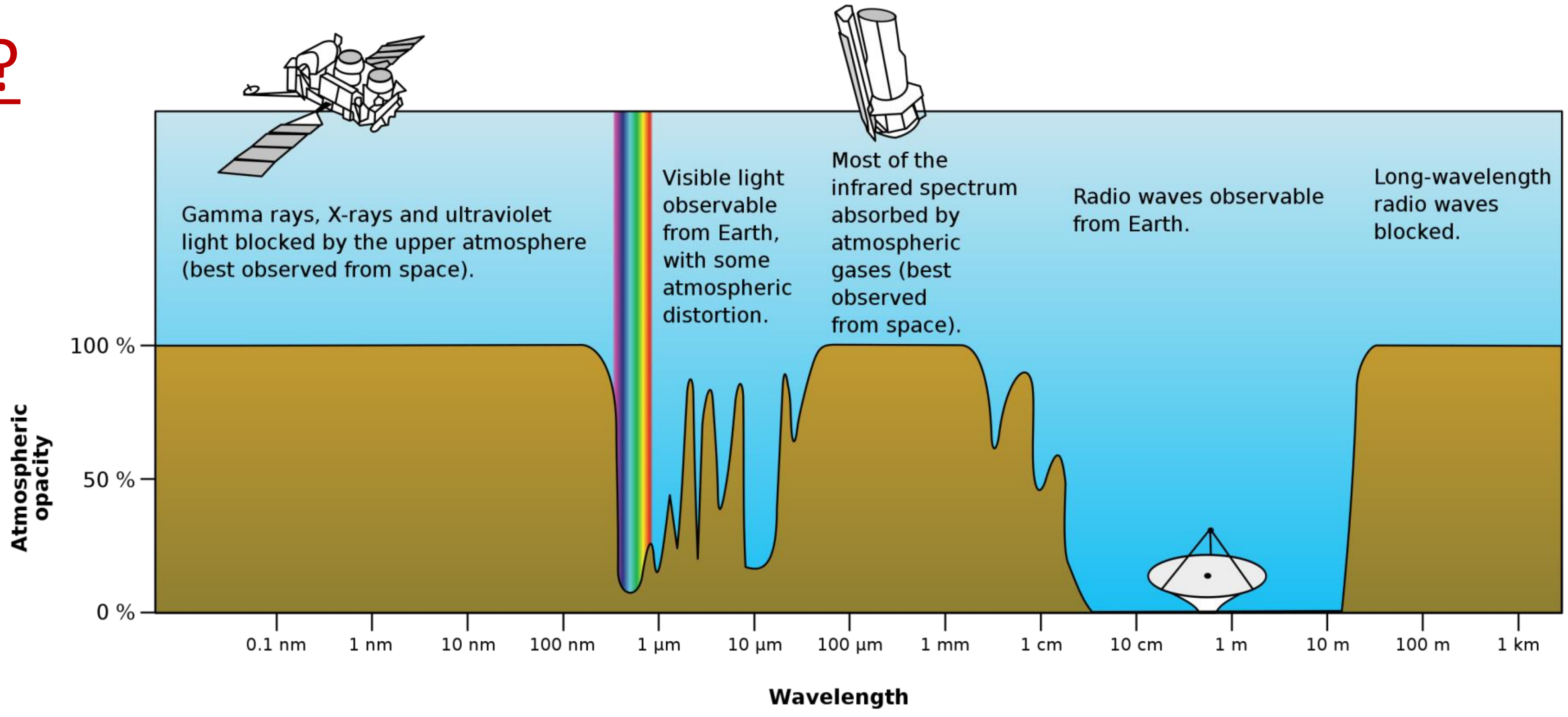
- many technological challenges

  materials, radiation hardness, mass, power, remote operation, data flux, no repairing, no upgrade… (+ cost!)

Why go to space?

★ Because we must:

multi-wavelength astronomy!



★ Basic rule: “Don’t go to space if you don’t have to!”

- many technological challenges

materials, radiation hardness, mass, power, remote operation, data flux, no repairing, no upgrade… (+ cost!)

★ Rule #2: “Do go to space if you can!”

- immense scientific reward
- huge technological return + expertise

(>> cost!)

New frontiers in space exploration:

★ New frontiers are… old frontiers!

how to make sense of the information we can collect about the physical world and universe

very little information faint, and often confuse…

(frontiers are always between the obvious and the mysterious)

★ …but with new messengers!

Today's challenge: opening the multi-messenger era!

✧ NB: astrophysics is NOT an *experimental* science, but an *observational* science ➡ collect data!!!

✧ but we cannot prepare our own set up, change the conditions, parameters, etc.

✧ observations of classes of objects with similar behavior or aspects, with different parameters or environmental conditions

+ "numerical experiments": simulations of processes with chosen ingredients
→ trying to fit (reproduce) observations + identify new observables

Light and beyond

- Light: THE cosmic messenger

  - Until recently, everything we knew about the universe comes from the observation of light from the cosmos!

    \+ the knowledge of the laws of Physics!

    (which also comes, partly, from the observation of the cosmos!)

  - Masses, distances, temperatures, magnetic fields, chemical compositions, energy densities, mechanical power, nuclear reactions, ages, velocities, gravitational fields… everything!

- Important notion: astrophysical sources!

  - relatively well-defined, localized “objects”, which can be isolated from the “environment” or background
  - observed through their emissions at various wavelengths → spectrum made of continuum + lines
  - sources contrast with the so-called “diffuse emission” (NB: this may depend on the instrument resolution!)

- New cosmic messengers:
  - Cosmic-rays
  - Neutrinos
  - Gravitational waves

Progress and revolutions

☆ –10 000 to ~0 A.D. :	"binary" position astronomy
☆ ~0 – 1609 A.D.:	positions and magnitudes
☆ 17th–18th centuries:	enhanced astronomy (telescopes)
☆ 19th century:	Spectroscopy revolution
☆ 20th century:	Multi-wavelength revolution
☆ 21st century:	Multi-messenger revolution

High-energy astrophysics and astroparticles

- The development of spectroscopy and spectro-imagery has brought powerful tools to ***understand*** astrophysical sources

- The development of "non visible astronomy" led to the discovery of new types of sources

  ↘ (radio waves, IR, UV, X-rays, gamma-rays…)

- Not just stars out there!

  Necessity to understand the new sources → model them, identify the emission processes, describe their structure and dynamics, etc.

  Non thermal astronomy and astrophysics!

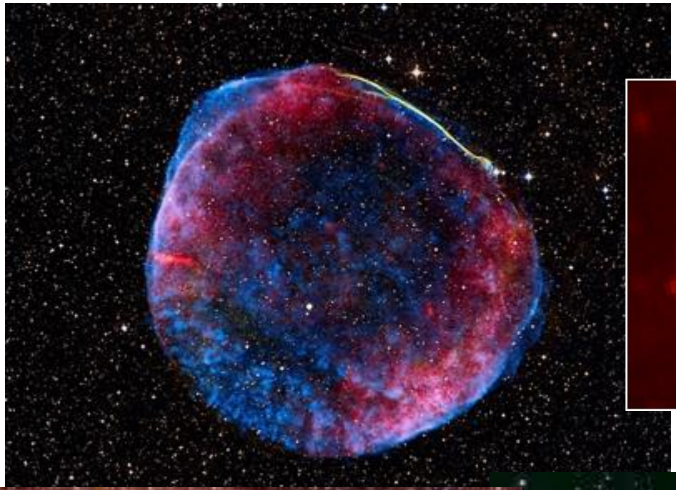
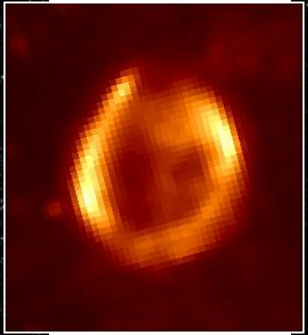
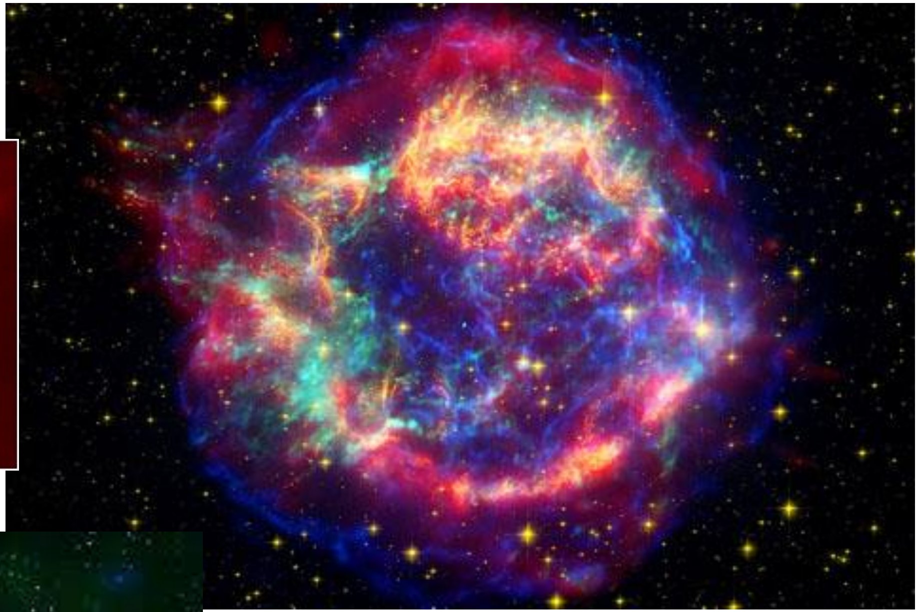
- Not just matter!
  - anti-matter?
  - dark matter?
  - dark energy?

  Fundamental physics to be discovered and/or explored!

  Multi-messenger astronomy is the tool.
  Fundamental physics and the understanding the universe are the goal!

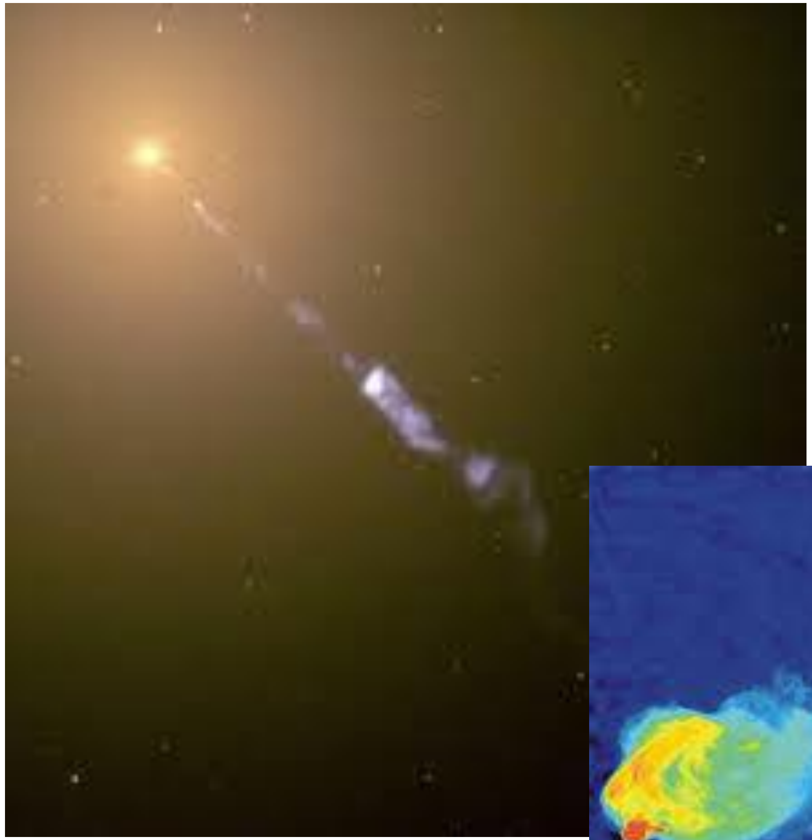
High-Energy astrophysics sources

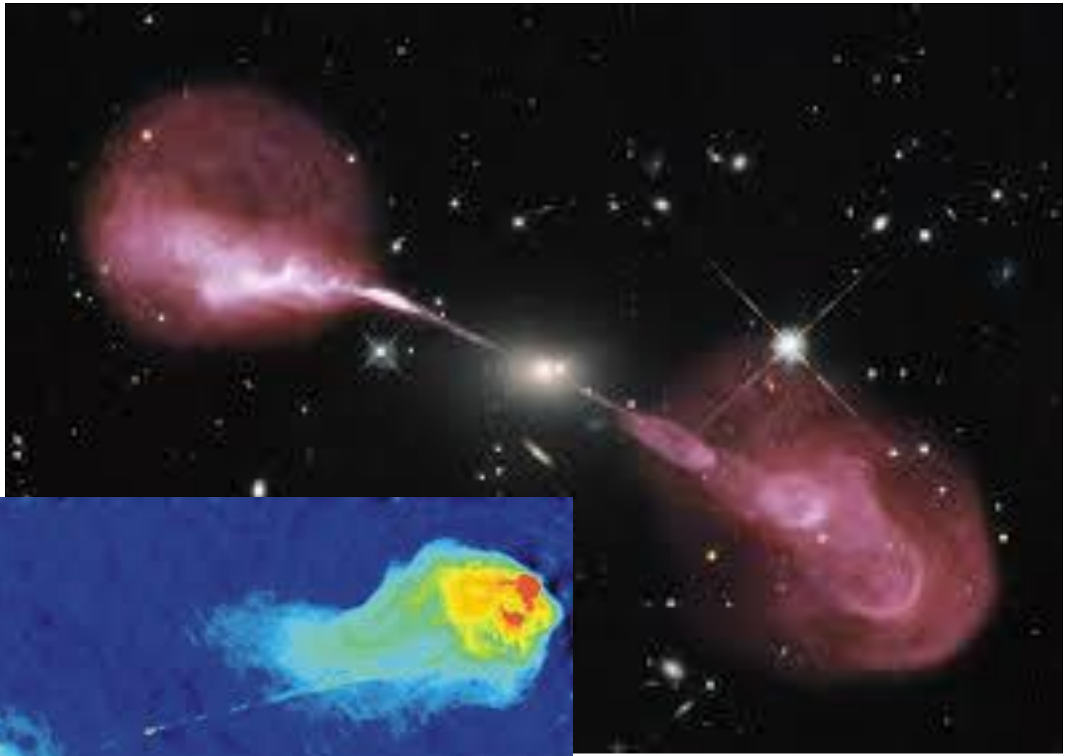
- Supernova remnants

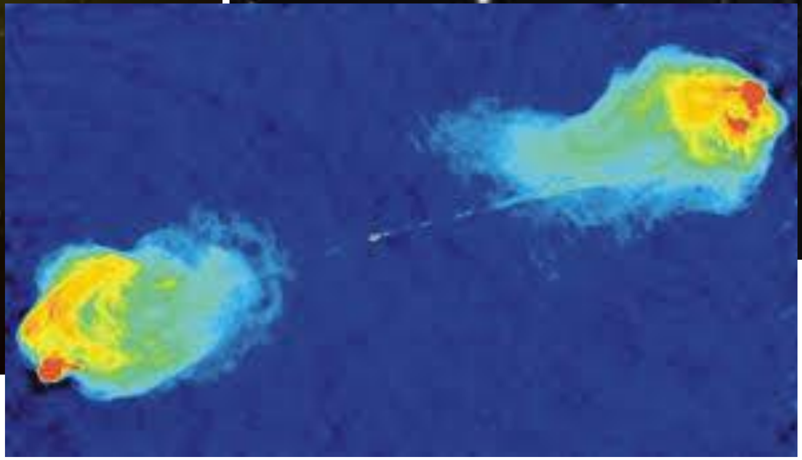





High-Energy astrophysics sources

- ✧ Active Galactic Nuclei (AGNs)

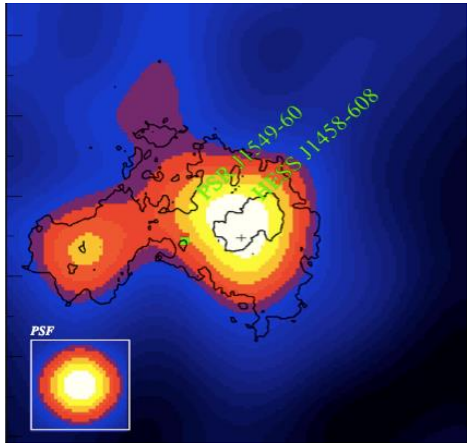






- ✧ Pulsars

- ✧ Pulsar wind nebulæ



- ✧ Micro-quasars
- ✧ Magnetars
- ✧ X-ray binaries

- ✧ Gamma-ray bursts
- ✧ Hot spots

- ✧ Superbubbles
- ✧ Relativistic jets

<u>Indeed: not just stars out there!</u>

Non thermal sources!

- Common feature to all high-energy astrophysical sources: non-thermal emission!

  - Non-thermal radiation spectrum

    => produced by a population of energetic particles which are not thermalized => out-of-equilibrium

  - Non-thermal particles

    Energetic particles accelerated *in situ* by some dynamical process, through some electromagnetic mechanism

    - NB: energetic particles are ubiquitous in the universe

      => the modeling of high-energy astrophysics sources always involves the description of energetic particle acceleration

  - Non-thermal processes

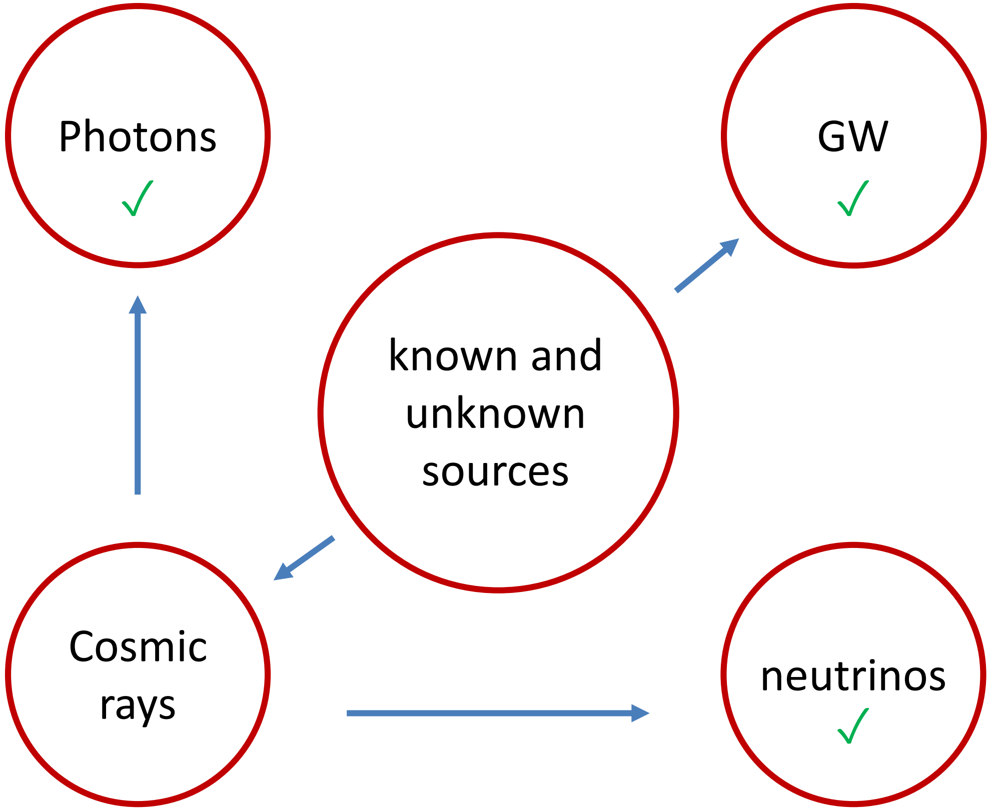
    Synchrotron, Bremsstrahlung, Inverse Compton, nuclear de-excitation, fluorescence, π^0 decay, X-ray lines, etc.

- Energetic particles are one step closer to the actual physical processes than the light we observe!

- Energetic particles also reach us from some sources! => cosmic messenger!

Multi-messenger era

- Multi-messenger strategy: 4 inseparable pillars
- Focus of important international efforts



What is at stake?

★ Explore the Physics of the extreme: Physics in extreme environment: mass and/or energy density, extreme EM and/or gravitational fields (EM et grav.), extreme spatial and temporal scales + multi-scale, unexplore energy domain, quantum space-time, etc.

★ Understand the Physics of the sources: High-energy astrophysics: energetic content and processes in the universe

Multi-messenger => complementary observables and new contraints

★ Understand particle acceleration: At the origin of all non thermal radiation observed (multi-λ)

★ Probe the univers: (new messengers)

Use UHECRs to probe magnetic fields

Use HE neutrinos to reach beyond γ and CR horizons

Use both to constrain the cosmological evolution of sources…

★ Discover the origin of cosmic rays: Still no real progress on the bottom-up origin of UHECRs…

(And of GCRs !)

Multi-messenger era

★ Multi-messenger strategy: 4 inseparable pillars

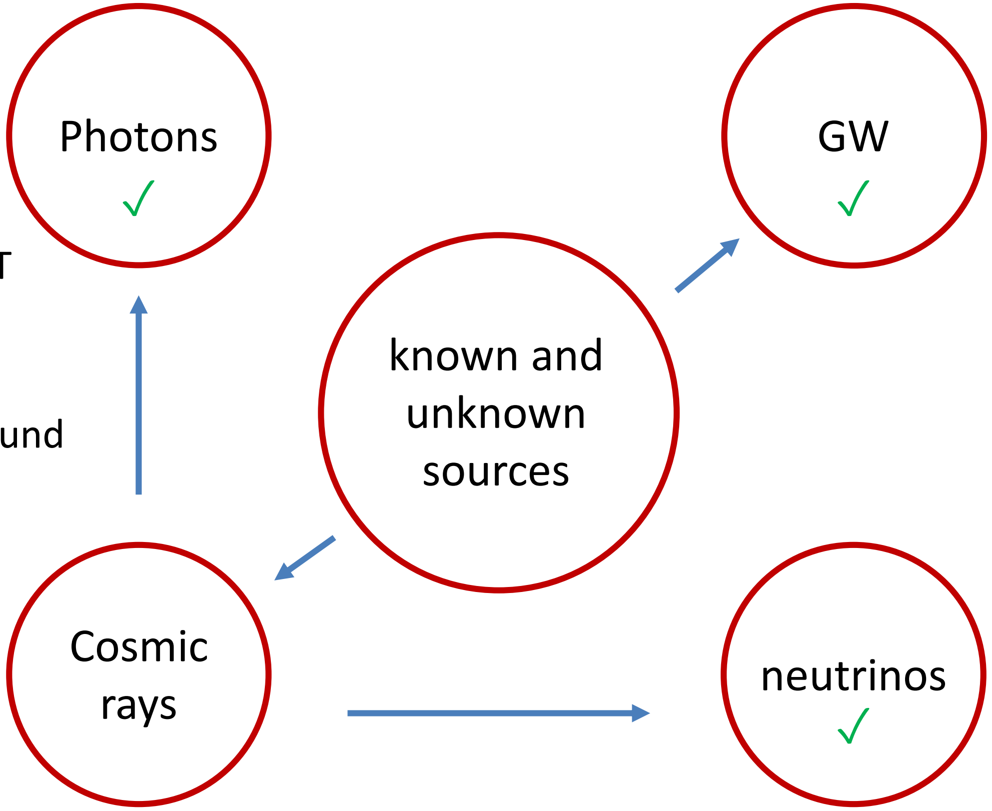
★ Focus of important international efforts

radio: from the ground

X-rays: Chandra, XMM-Newton
=> Athena/X-IFU, Hitomi-XRISM

gamma-rays: CGRO, INTEGRAL, Fermi-LAT
=> Gamma-400 (~20MeV to few TeV, with improved angular resolution)

gamma-rays from showers: from the ground



VIRGO-LIGO: from the ground

eLISA: MAJOR mission!

ICE-Cube, KM3NET: from the ground

ANITA: radio

JEM-EUSO, POEMMA: Cherenkov!

direct: PAMELA, AMS-02

indirect : ground and space: JEM-EUSO, MINI-EUSO, Balloons

Cosmic Rays

Seven Wonders of the Ancient World

Seven Wonders of the Physical Universe

?	?	?	?	?	?	?

Cosmic rays!

Their energy spectrum is unmatched
in the entire physical universe!

Cosmic Rays

Seven Wonders of the Ancient World

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Their energy spectrum is unmatched
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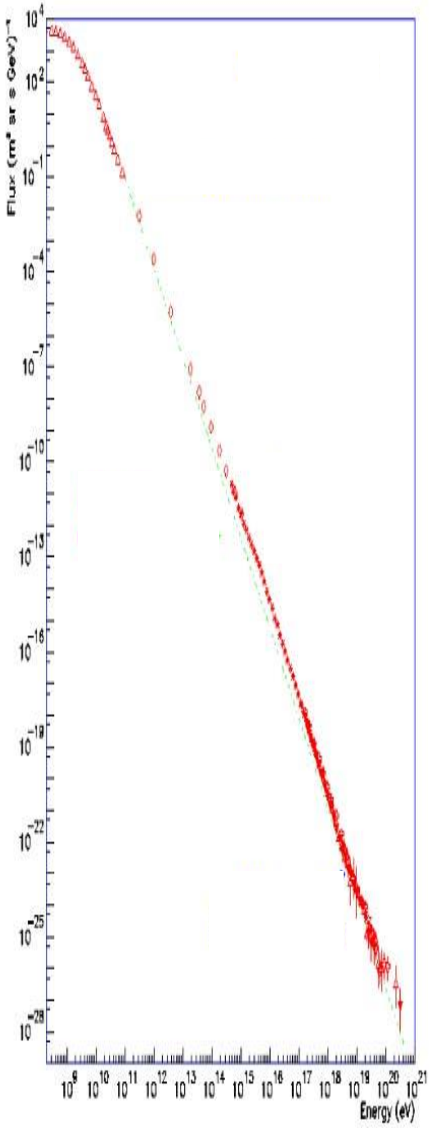
Cosmic rays' remarkable energy spectrum

> 12 orders of magnitude!



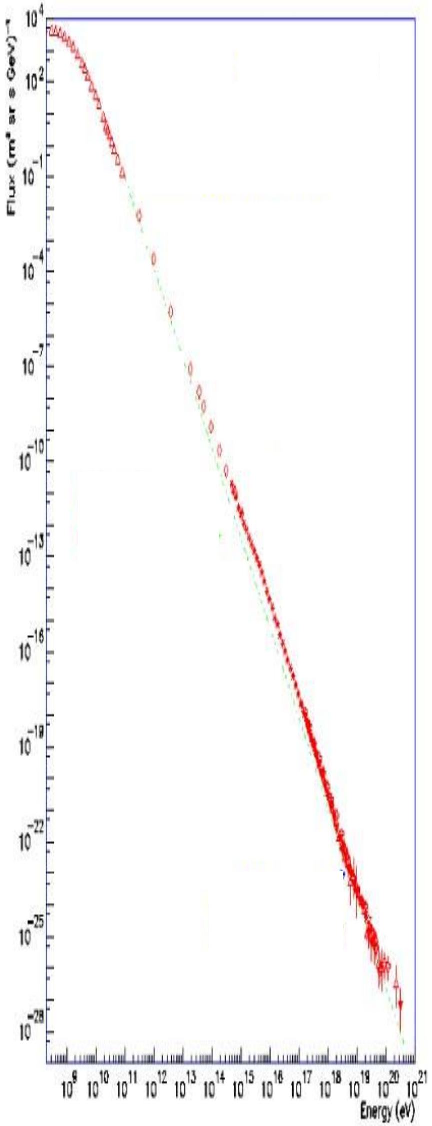
4 per cm^2 per second

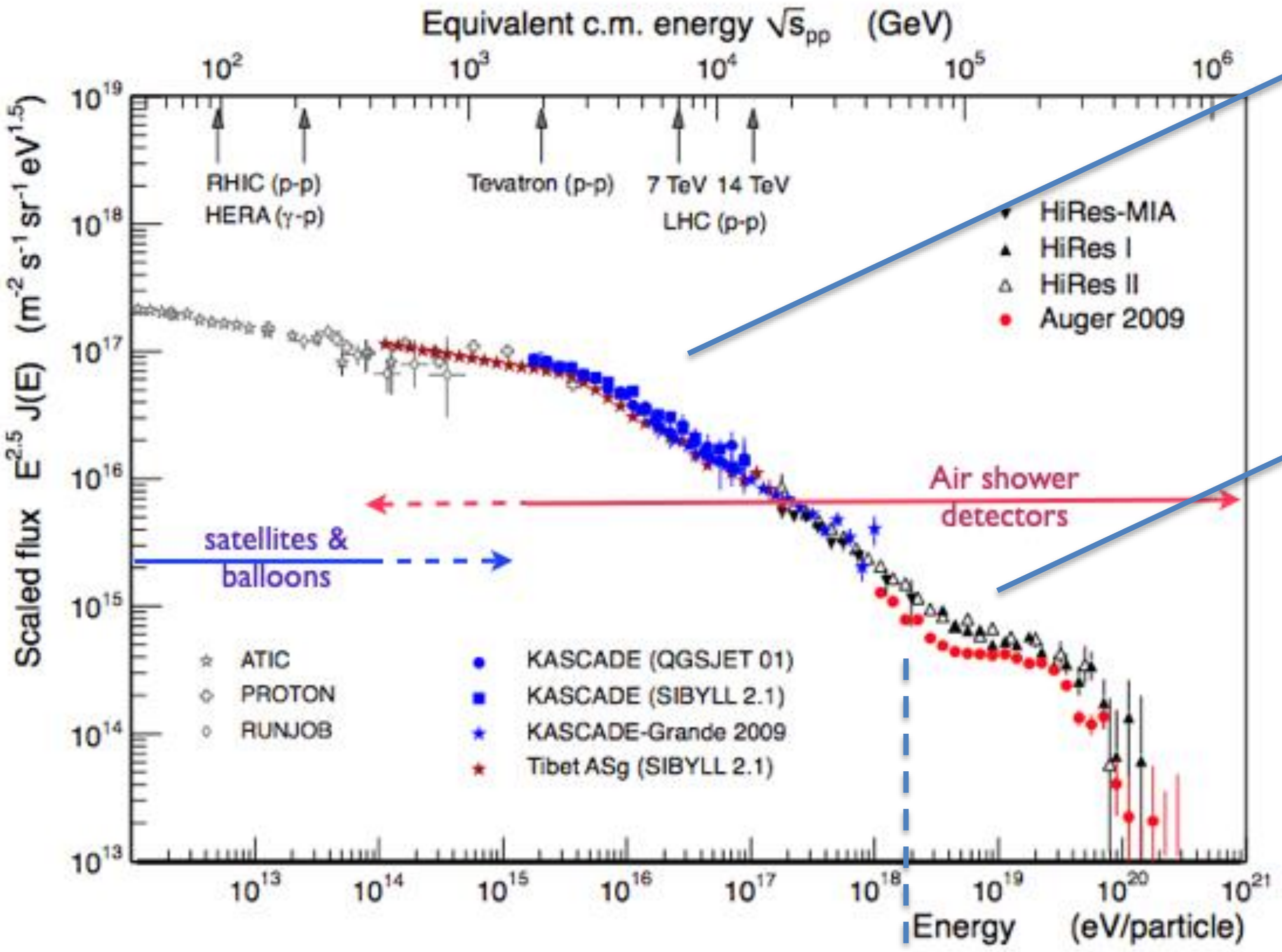
32 orders of magnitude ($/m^2/sr/GeV$)

1 per m^2 per billion years

- Major phenomenon!
  - Universal
  - Out of equilibrium!!!
- Major role in Galactic ecology!
  - Energy density ~ star light, thermal, B field
  - Regulate the equilibrium between the different phases of the interstellar medium
  - Control ionisation, heating
  - Regulate star formation
  - Control astrochemistry
  - Generate turbulent magnetic field
  - Produce Li, Be and B!
- Multi-messenger strategy + cosmogenic backgrounds!
- Major unknown!
  - Sources are unknown (Galactic and Extragal.)
  - Acceleration processes are uncertain

Cosmic Rays are so important that our current state of ignorance is truly exciting!





so-called "knee"

so-called "ankle"

Undoubtedly Galactic

G/EG transition

(almost

Undoubtedly Extragalactic

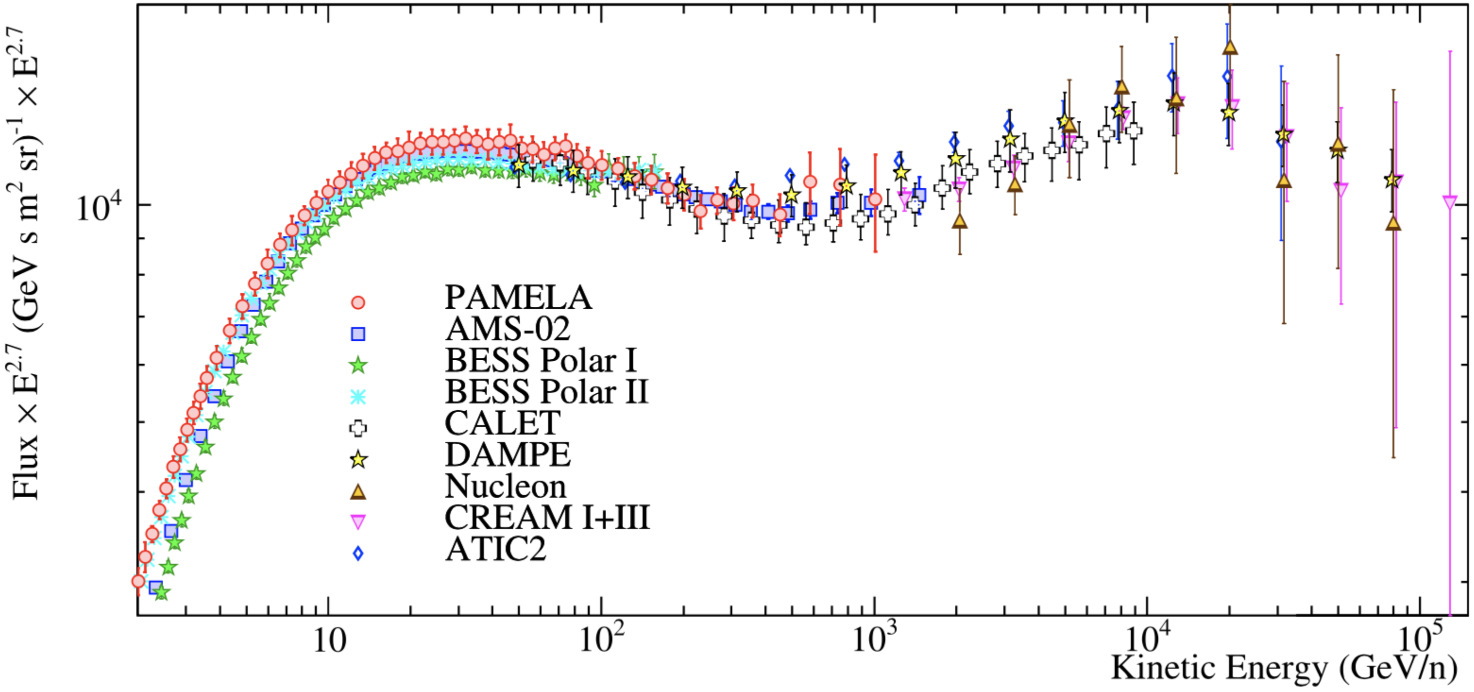
Very interesting phenomenology!

=> crucially depending on composition analyses

=> constraining both Galactic and extragalactic cosmic rays!

Low-energy cosmic-rays

- PAMELA major results!



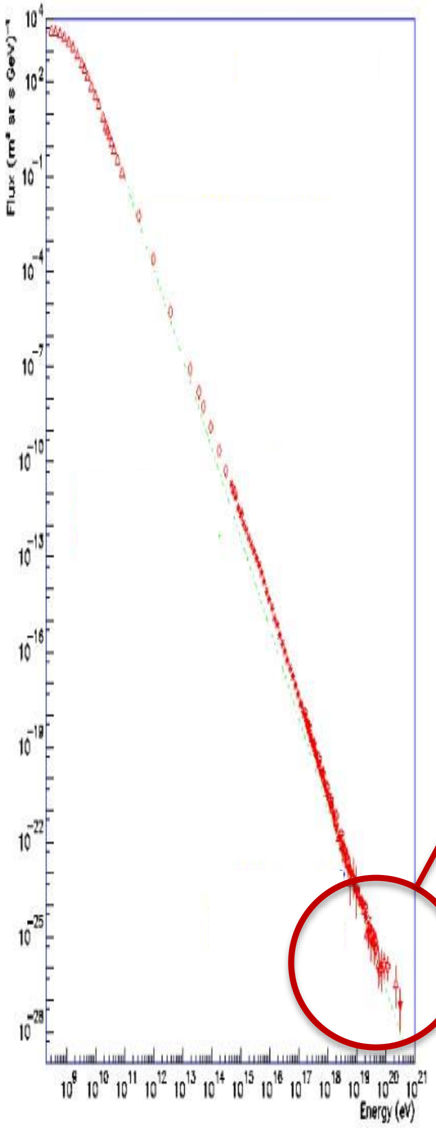
=> renewal and crucial boost for GCR theoretical studies

- AMS unprecedented precision measurements!

- Memory from ICRC 2013 (Rio de Janeiro)

Ultra-high-energy cosmic rays

> 12 orders of magnitude!



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32 orders of magnitude ($/m^2/sr/GeV$)

1 per m^2 per billion years

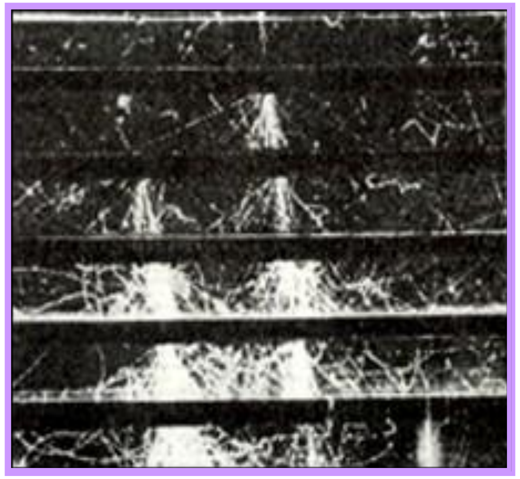
- **Macroscopic energies!**
  - > 30 joules !
  - tennis ball at 120 km/h
- **1 particle per m^2 per billion years!**
  - Very serious observational challenge
  - Huge detectors needed
- **How does Nature proceed?** to produce them
  - What, where and how?
- **How does Nature behave?** at such energies
  - Lorentz factors beyond all tests of Relativity
  - Cross section beyond LHC reach

$\Rightarrow$ What fundamental can we learn?

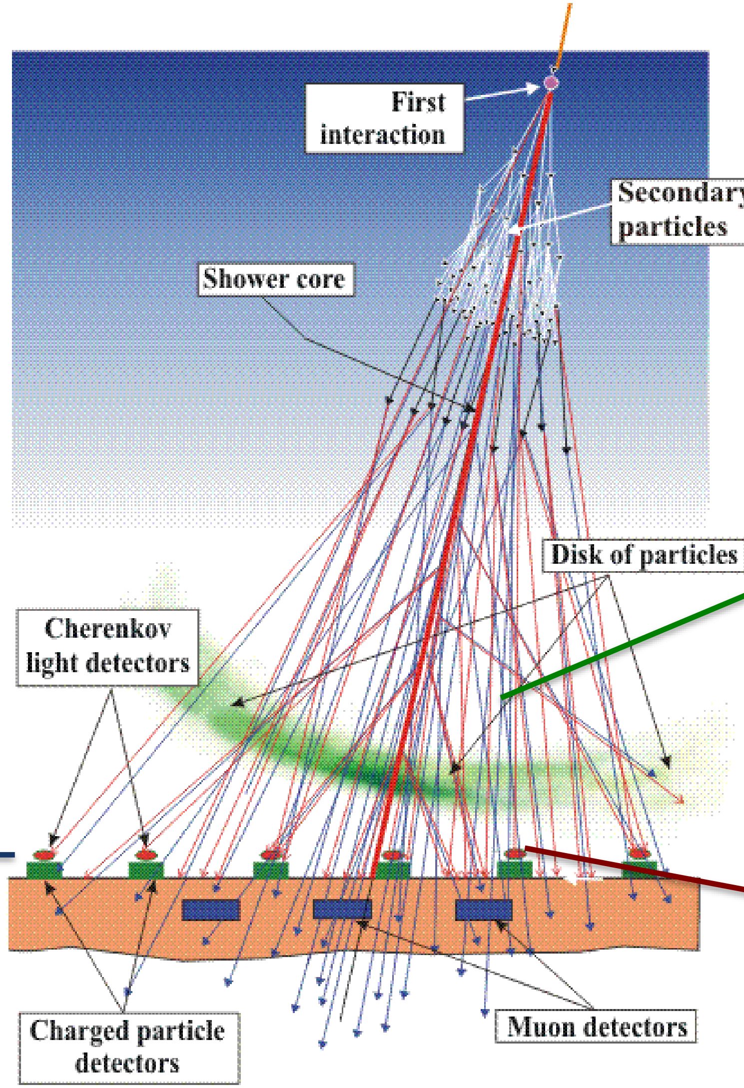
New messengers $\rightarrow$ new messages!

Indirect and “doubly indirect” detection

The atmosphere is the primary cosmic ray detector!



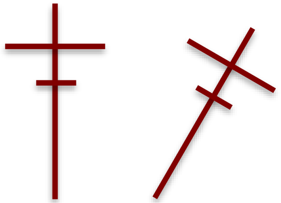
Particle shower theory (1933–1937)



Detection of the induced effect of shower particles!

+ fluorescence light!

Detection of the shower particles
(sampling of the “shower front”)



+ radio signal

New generation, mature detectors

- Hi-Res (1993–1997–2006–2010)
- The Telescope array

  700 km^2 (Utah, USA)

  Building > 2003
  First light: 2008

- The Pierre Auger Observatory

  3000 km^2 (Argentina)

  Building: 2000–2008
  First light: 2004

UHECR: state of the art

– Regarding astrophysics => we do not know what the sources are!

– Regarding Physics: => we do not know what the acceleration mechanisms are!

=> we do not fully understand the physics of the showers!

– Regarding observations:

=> Important progress have accomplished with the current generation of observatories

NB: current data provide explanation for their shortfall!

=> Now, a new generation is needed:

- larger statistics
- full sky coverage
- complementarity between low energies (10^{18}–10^{19} eV) and high energies (10^{20} eV)
- complementarity between ground-based (precision) et space-based (statistics) instruments

Encouraging results

NB: GZK effect = interaction of the UHECRs with the ambient photons!

Auger: 3000 km^2

GZK-like attenuation: established!

Composition getting heavier above a few EeV

Departure from isotropy (first order: dipole) at ”low" energies (≥8 EeV, 6%, 6σ)

Correlation with matter (but not discriminating) at intermediate energies (> 3 σ)
(and "anisotropic fraction" ~10%)

Warm spot at intermediate angular scales at the highest energies
(between 2.3 and 3.9 σ)

Shower physics: "muon excess" (indirect)

Telescope Array:
700 km^2 –>2800 km^2

GZK-like attenuation: established!

Warm spot at intermediate angular scales at the highest energies (3.4 σ)

Declination-dependent energy spectrum (4.3 σ)

However, no clear progress regarding sources and acceleration mechanisms
+ partially confused observationnal situation…

Energy spectrum

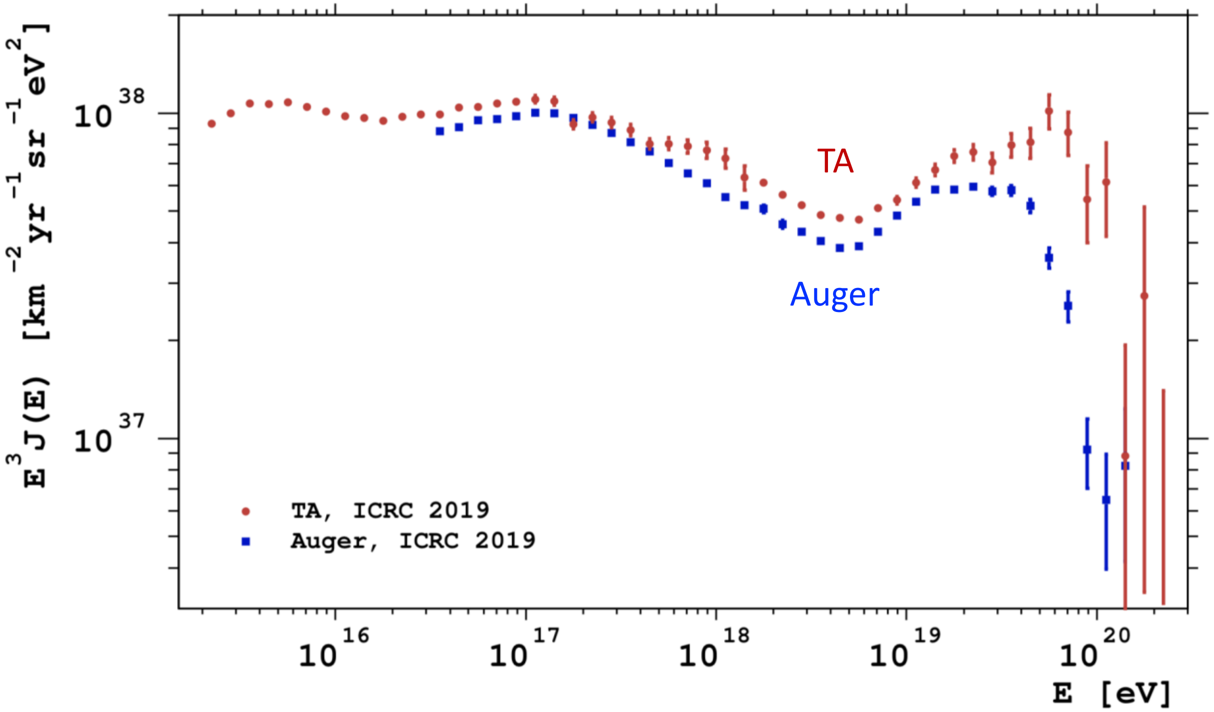
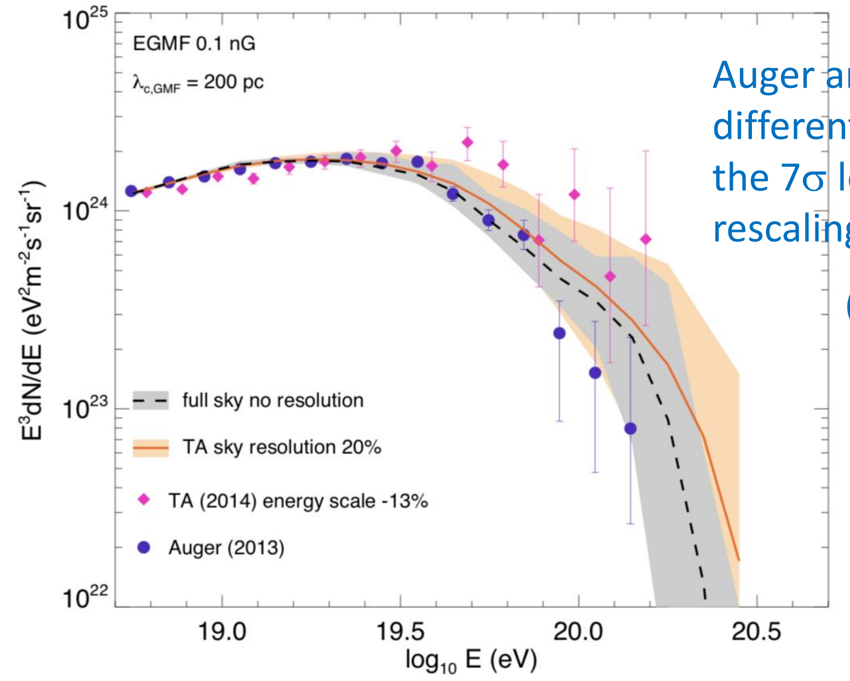


Figure 1: ICRC 2019 energy spectra of the Pierre Auger Observatory and the Telescope Array scaled by E^3. In each experiment, data of different detection techniques are combined to obtain the spectrum over a wide energy range.



Auger and TA spectra are different above 50 EeV at the 7σ level (even after rescaling) !

(Globus et al. 2017)

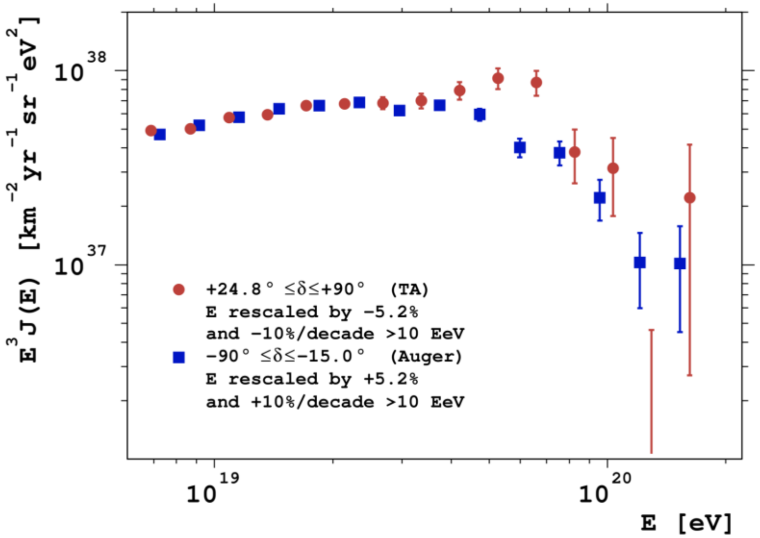
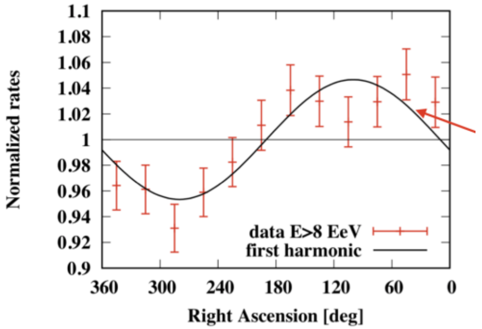


Figure 5: E^3-scaled energy spectrum in two declination ranges, namely $\delta \geq +24.8^\circ$ (red points, TA) and $\delta \leq -15.0^\circ$ (blue points, Auger). The energies are shifted to get spectra in agreement in the common declination band.

NB: EUSO => whole sky with a single instrument

Anisotropies

I – Large scale dipole: 6%, 6σ

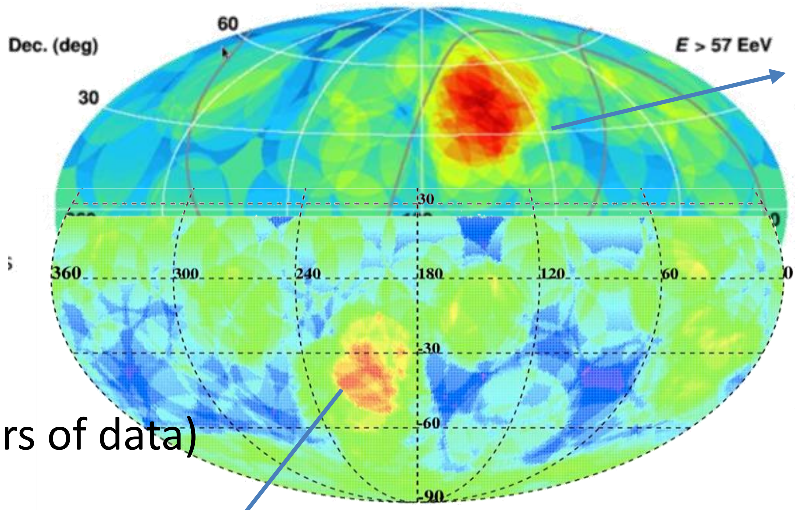


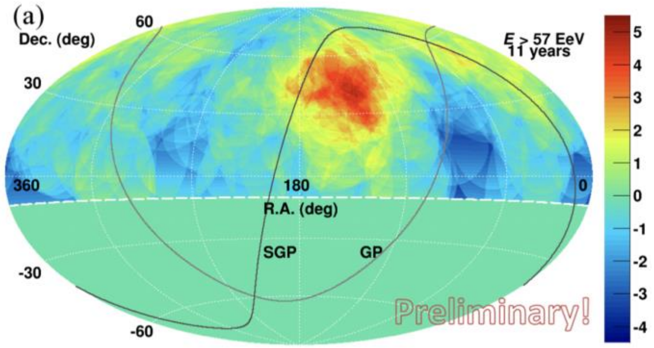
Easy to reproduce the amplitude, but not the position! (with usual GMF)

II – Correlation with local matter (~3.5 σ, not discriminative)

III – Northern and Southern "warm spot" : no overlap

smoothing: 20°–30°





TA

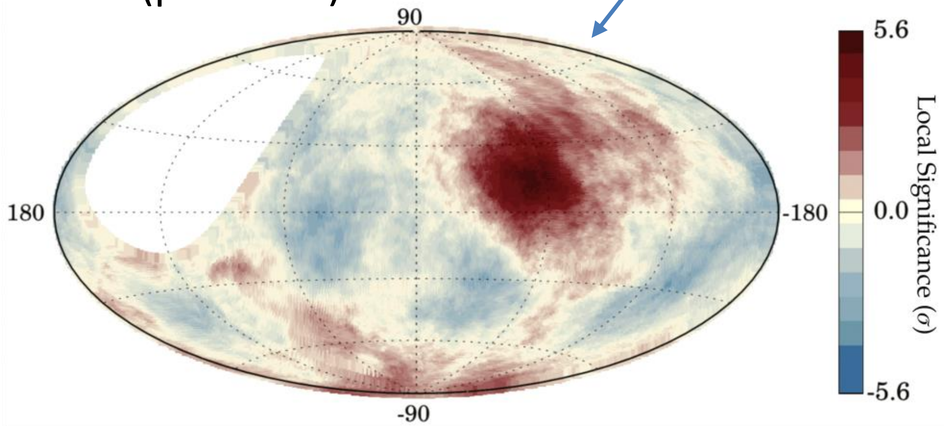
ICRC 2019 (11 years of data

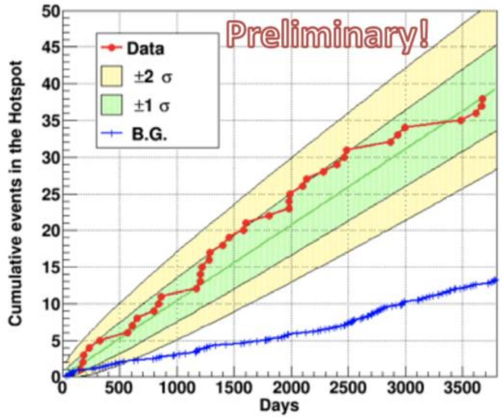
2.9 σ (post trial)

Auger

ICRC 2019 (15 years of data)

2.2 σ (post trial)





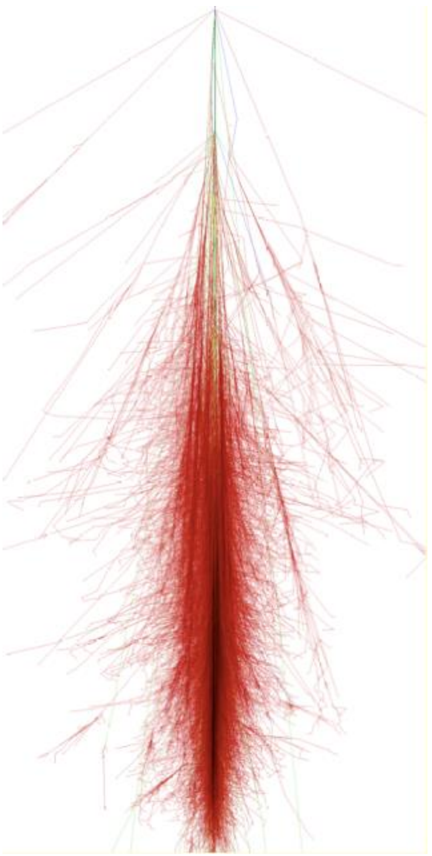
NB: inaccessible to Auger

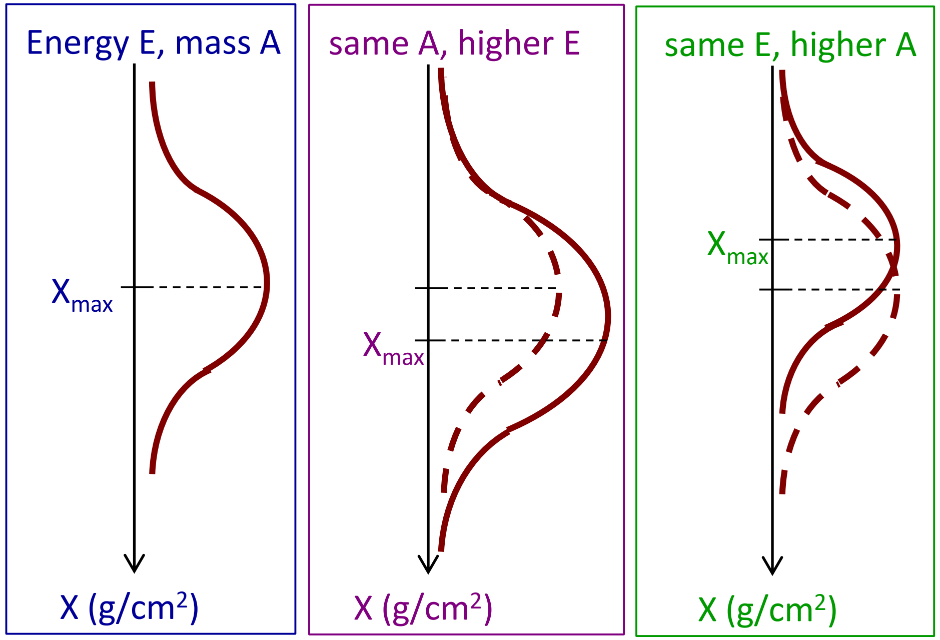
NB: EUSO => whole sky with a single instrument

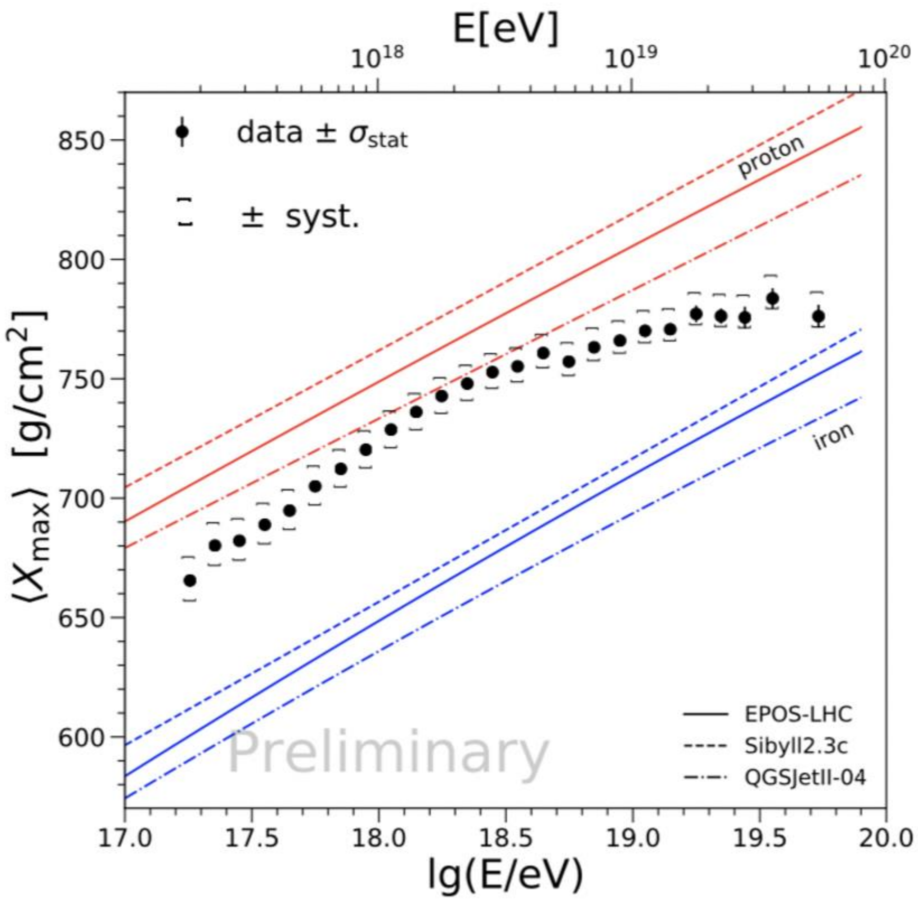
K-EUSO : acceptance multiplied by >10 in Northern hemisphere

NB: structure of the hot spot (energy vs. position)?

Composition: a key observable!







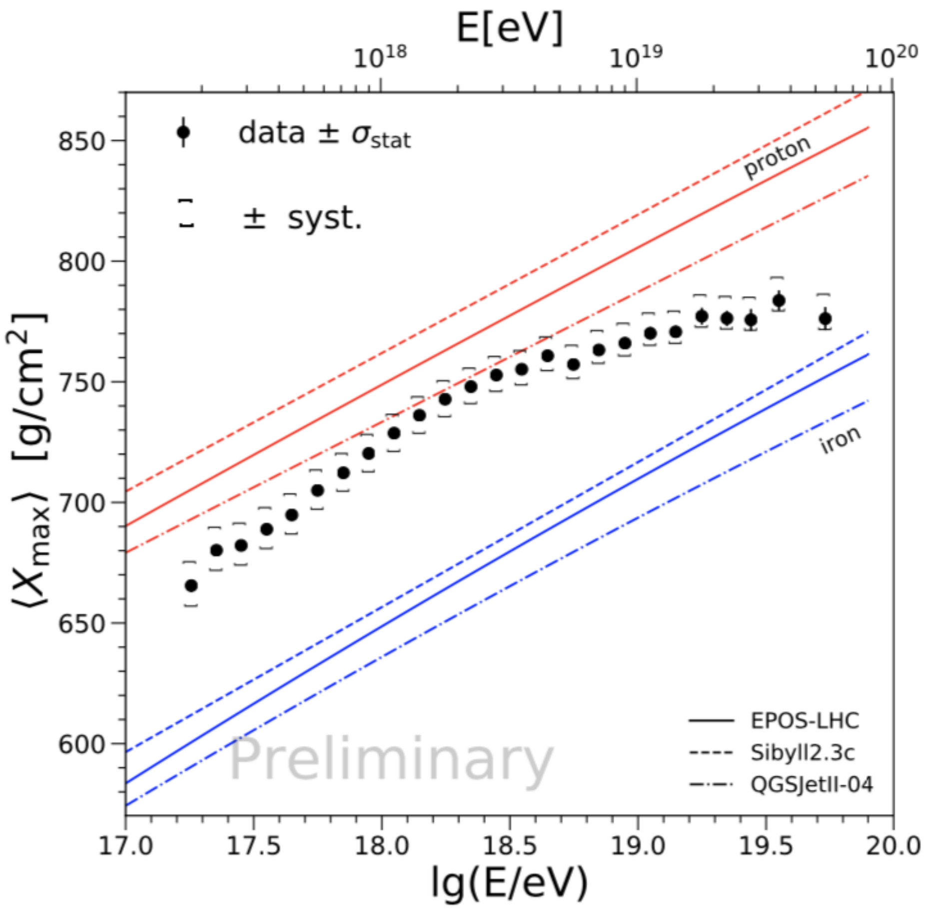
<u>NB: large shower-to-shower fluctuations</u> (from the first few generations of particles)

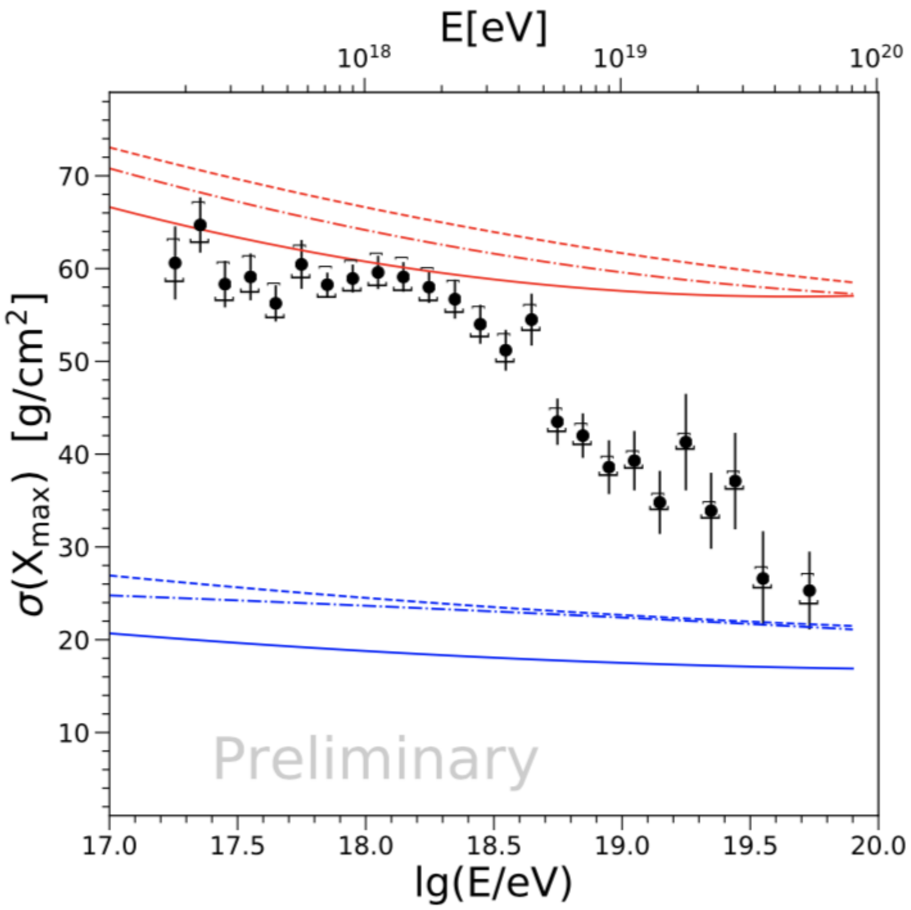
=> large overlap between p and Fe distributions!

=> but the average at a given energy can be measured with some precision

=> and the RMS can also be measured (in each energy bin)

Composition: a key result!





Relates to a physical observable, e.g. <ln(A)>, through a comparison with shower development simulations

However: simulations depend on hadronic models => uncertainty (and some generic discrepancies…)

Space-ground complementarity

- Particularly obvious case!
  - energy range
  - flux
  - performances
  - duty cycle
  - aperture
  - sky coverage
- Additional physics and science objectives from space
  - atmospheric physics
  - space weather
  - meteors
  - nuclearites
  - bioluminescence
  - etc.
- But also additional cosmic-ray physics!
  - High-altitude showers
  - composition at higher energy
  - Earth skimming (neutrinos)
  - Cherenkov detection => down to much lower energies

The JEM-EUSO Program: the space road to UHECR studies

Towards UHECR and high-energy neutrino detection from space

- Unprecedented aperture
- Only one instrument to deploy
- Full-sky coverage

Research program and instruments funded by the main space agencies and national institutions

NASA, POCKOCMOC, esa, JAXA, asi agenzia spaziale italiana, cnes CENTRE NATIONAL D'ETUDES SPATIALES ...

16 countries
300 physicist+engineers

POEMMA (2030?) NASA

K-EUSO (2025) RosCosmos (+ESA MoO?)

EUSO-SPB2 (2023) NASA

(KLYPVE) RosCosmos

Mini-EUSO (2019) RosCosmos + ASI

EUSO-SPB (2017) NASA

TUS (2016) RosCosmos

EUSO-Balloon (2014) CNES

On the ground (collaboration with Telescope Array)

EUSO-TA-2

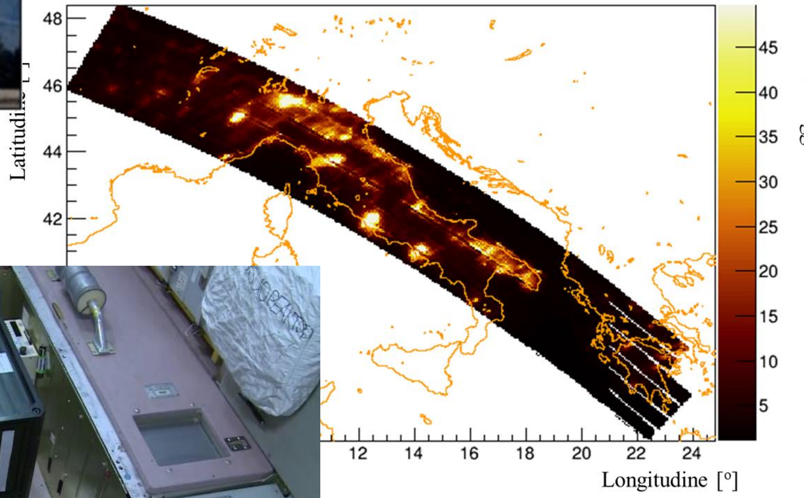
EUSO-TA-2

EUSO-TA-1

EUSO-SPB

NASA (2017)

1 PDM, 12 nights

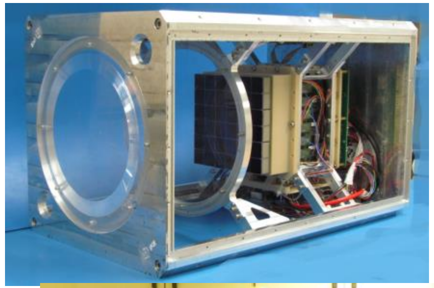


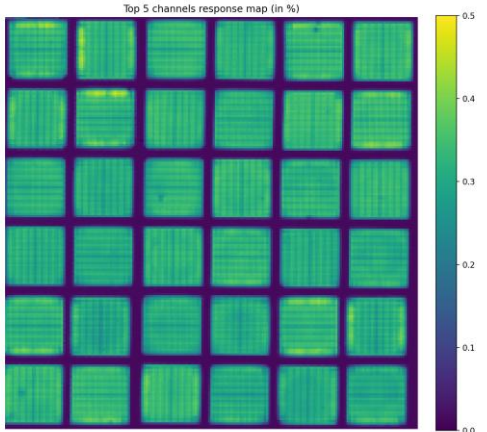
1 conteggio ≅ 10^{20} fotoni UV/ (km

Mini-EUSO

ASI + ROSCOSMOS (since 2019)

1 PDM
(~50 sessions so far)

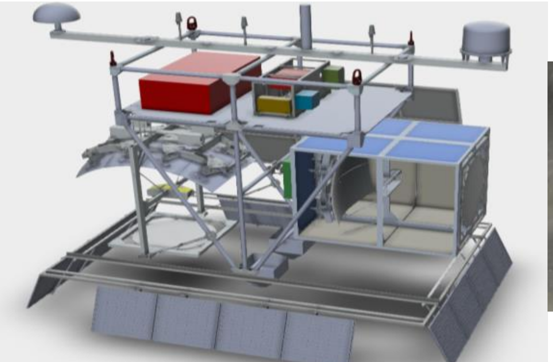


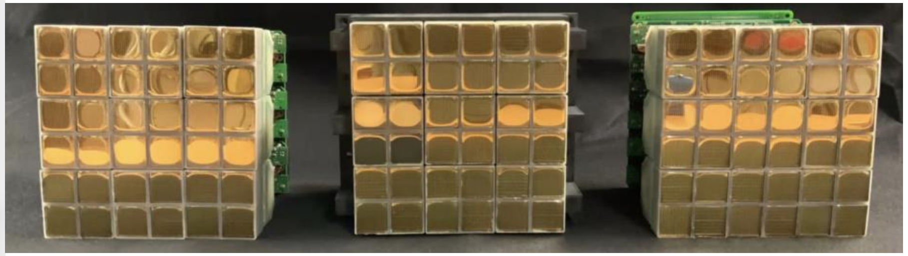


EUSO SPB2

NASA, spring 2023

3 PDM, 100 nights?





The multi-messenger era… …has already started!

★ August 17th 2017

The Astrophysical Journal Letters, 848:L12 (59pp), 2017 October 20
https://doi.org/10.3847/2041-8213/aa91c9

Multi-messenger Observations of a Binary Neutron Star Merger

Abstract

On 2017 August 17 a binary neutron star coalescence candidate (later designated GW170817) with merger time 12:41:04 UTC was observed through gravitational waves by the Advanced LIGO and Advanced Virgo detectors. The *Fermi* Gamma-ray Burst Monitor independently detected a gamma-ray burst (GRB 170817A) with a time delay of ~1.7 s with respect to the merger time. From the gravitational-wave signal, the source was initially localized to a sky region of 31 deg^2 at a luminosity distance of 40^{+8}_{-8} Mpc and with component masses consistent with neutron stars. The component masses were later measured to be in the range 0.86 to 2.26 $M_{\odot}$. An extensive observing campaign was launched across the electromagnetic spectrum leading to the discovery of a bright optical transient (SSS17a, now with the IAU identification of AT 2017gfo) in NGC 4993 (at ~40 Mpc) less than 11 hours after the merger by the One-Meter, Two Hemisphere (1M2H) team using the 1 m Swope Telescope. The optical transient was independently detected by multiple teams within an hour. Subsequent observations targeted the object and its environment. Early ultraviolet observations revealed a blue transient that faded within 48 hours. Optical and infrared observations showed a redward evolution over ~10 days. Following early non-detections, X-ray and radio emission were discovered at the transient's position ~9 and ~16 days, respectively, after the merger. Both the X-ray and radio emission likely arise from a physical process that is distinct from the one that generates the UV/optical/near-infrared emission. No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source were found in follow-up searches. These observations support the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC 4993 followed by a short gamma-ray burst (GRB 170817A) and a kilonova/macronova powered by the radioactive decay of r-process nuclei synthesized in the ejecta.

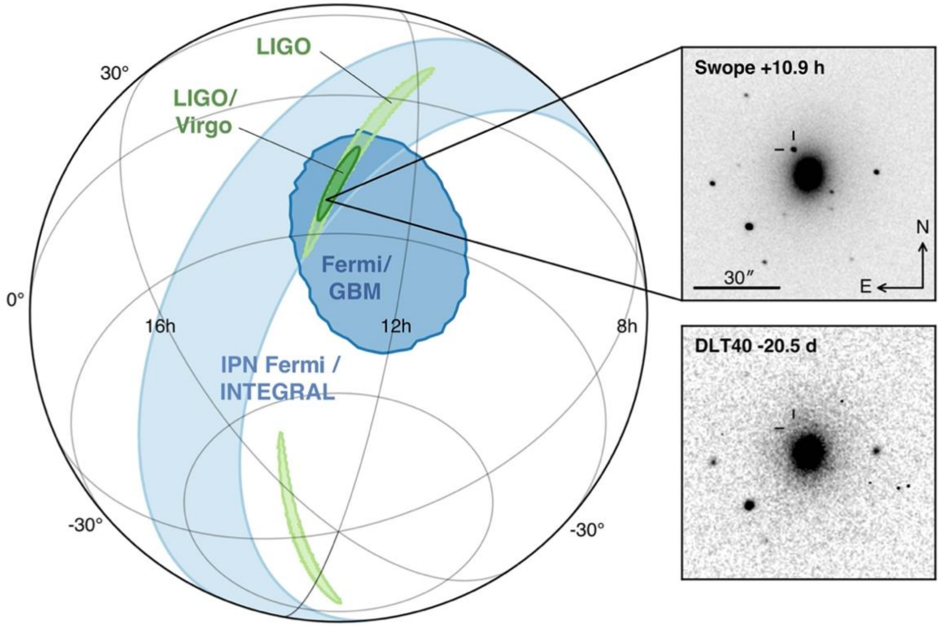
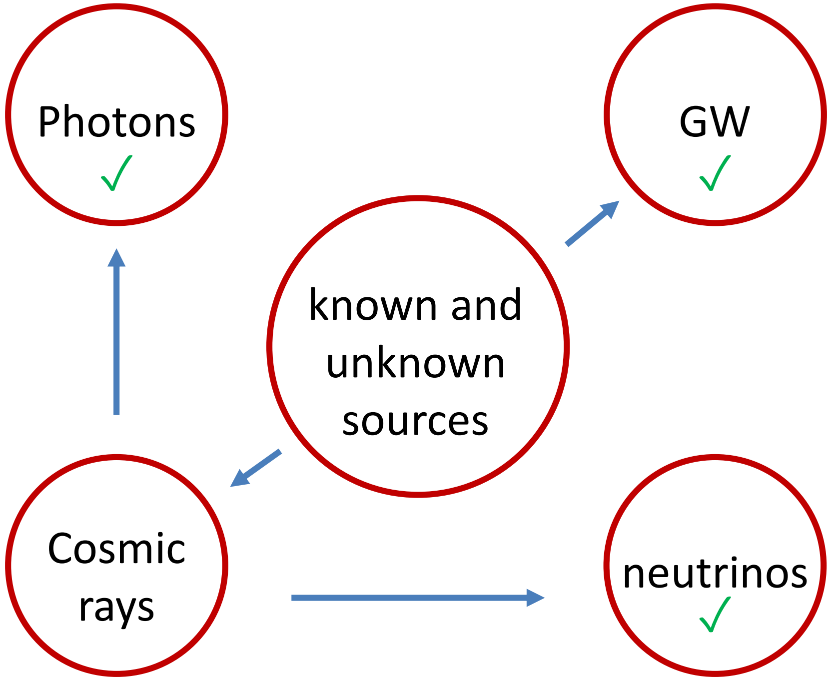


Figure 1. Localization of the gravitational-wave, gamma-ray, and optical signals. The left panel shows an orthographic projection of the 90% credible regions from LIGO (190 deg^2; light green), the initial LIGO-Virgo localization (31 deg^2; dark green), IPN triangulation from the time delay between *Fermi* and *INTEGRAL* (light blue), and *Fermi*-GBM (dark blue). The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hr after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right). The reticle marks the position of the transient in both images.

But the road will still be long

OK: keep going!

(by the way: EUCLID is great!)



- very difficult,
- but then amazingly informative

(distance, mass, energy, process, spin, GR!)

- very difficult,
- not necessarily very informative imho (at least so far)
- more to come?

Last but not least!

First discovered new messengers, last to join astronomy!

1912 < 1915 !

(But already huge contributions to astrophysics)

(And physics: birth of particle physics!!!)

Space is difficult, but very rewarding

- Fundamental physics!

  Newton: gravitation
  Romer: speed of light
  Janssen/Palmieri/Ramsay: helium
  Particle physics: from cosmic rays!
  etc.

  exotic matter?
  dark matter?
  quantum gravity?
  new cosmology?
  etc.

- New tools for astrophysics!

  e.g.: Once we understand UHECRs, they become a powerful tool

  source physics
  probes for Galactic and extragalactic magnetic fields
  multi-messenger studies

- Multi-messenger astrophysics will likely be the next revolution in the history of astrophysics.

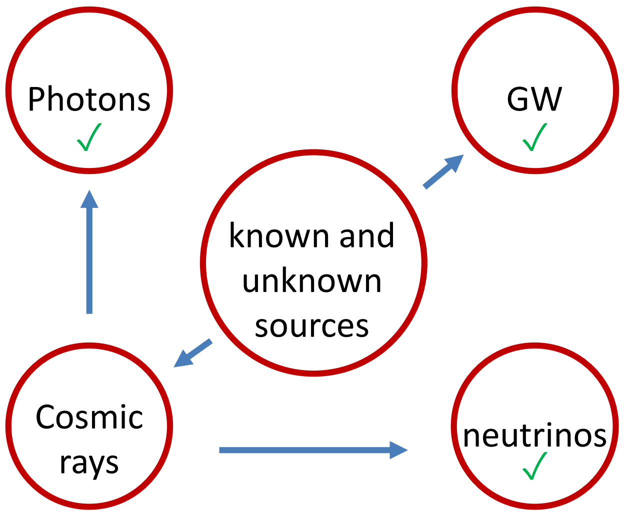
  NB: not only joint observations of sources (e.g. no time coincidence for UHECRs)
  but also full understanding of the "backgrounds"

  There is a lot of information in the backgrounds! cf. CMB!

  UHECRs => cosmogenic neutrinos and intergalactic electromagnetic cascades…

A program for the century!

☆ –10 000 to ~0 A.D. :	“binary” position astronomy
☆ ~0 – 1609 A.D.:	positions and magnitudes
☆ 17^{th}–18^{th} centuries:	enhanced astronomy (telescopes)
☆ 19^{th} century:	Spectroscopy revolution
☆ 20^{th} century:	Multi-wavelength revolution
☆ 21^{st} century:	Multi-messenger revolution



It is not easy,

Technological challenges, but also very stimulating!

By the way: a space station is great! (Resources, data storage, etc.)

A program for the century!

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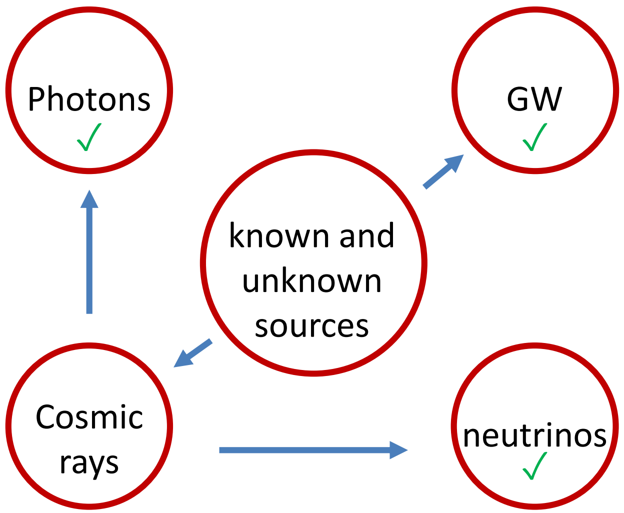

It is not easy,
it will take time,

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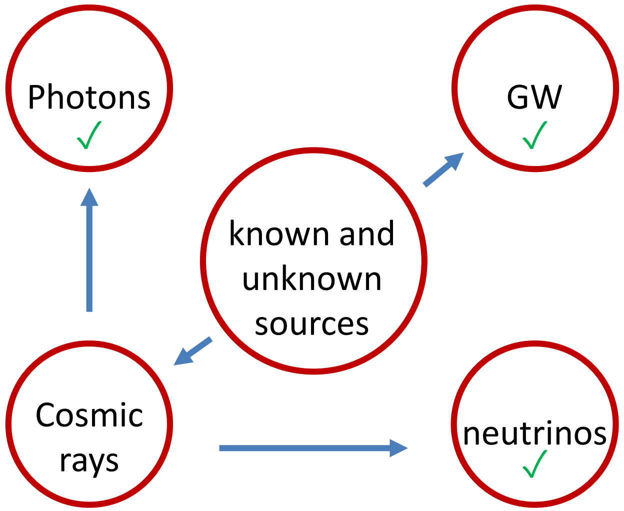

It is not easy,
it will take time,
but we have time:

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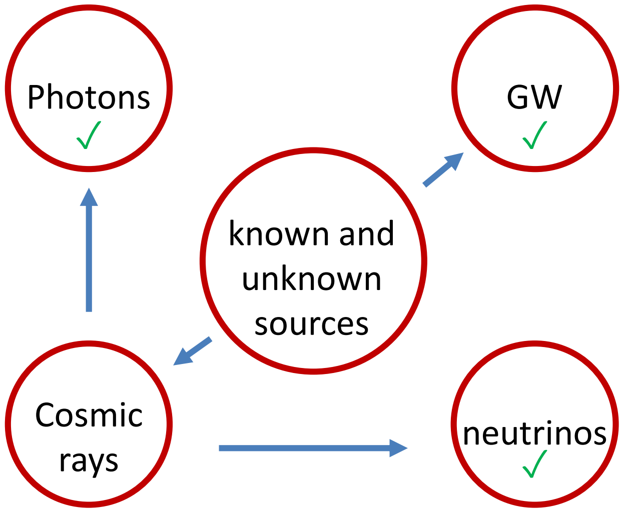

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we have one century!

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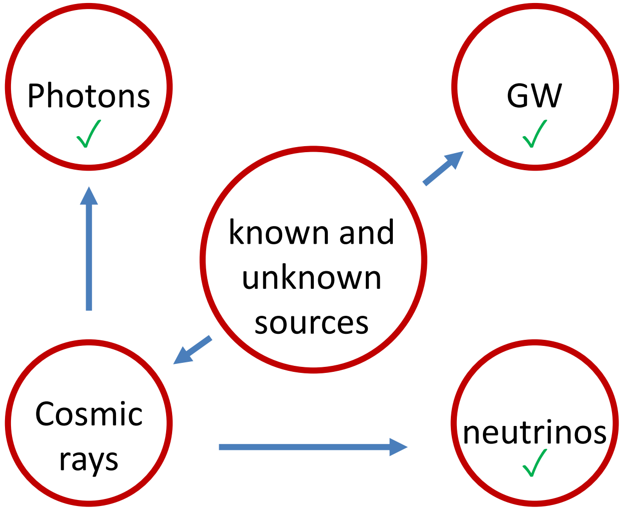

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we have one century!

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Or at least: **70 years…**

70 1951 2021 infn