Astroparticle physics - New messengers of the Universe

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European biased perspective

A Decade of Discoveries in High Energy Physics

Brussels, March 9th 2023

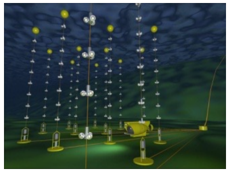
Outline

Motivations for a Multi-messenger approach

Success of multi-wavelength

Onset of Astroparticle Physics

Key scientific questions



Historical aspects

Detection principles

Achievements

Future challenges

Cosmic-rays

VHE gamma-rays

Neutrinos

Gravitational waves

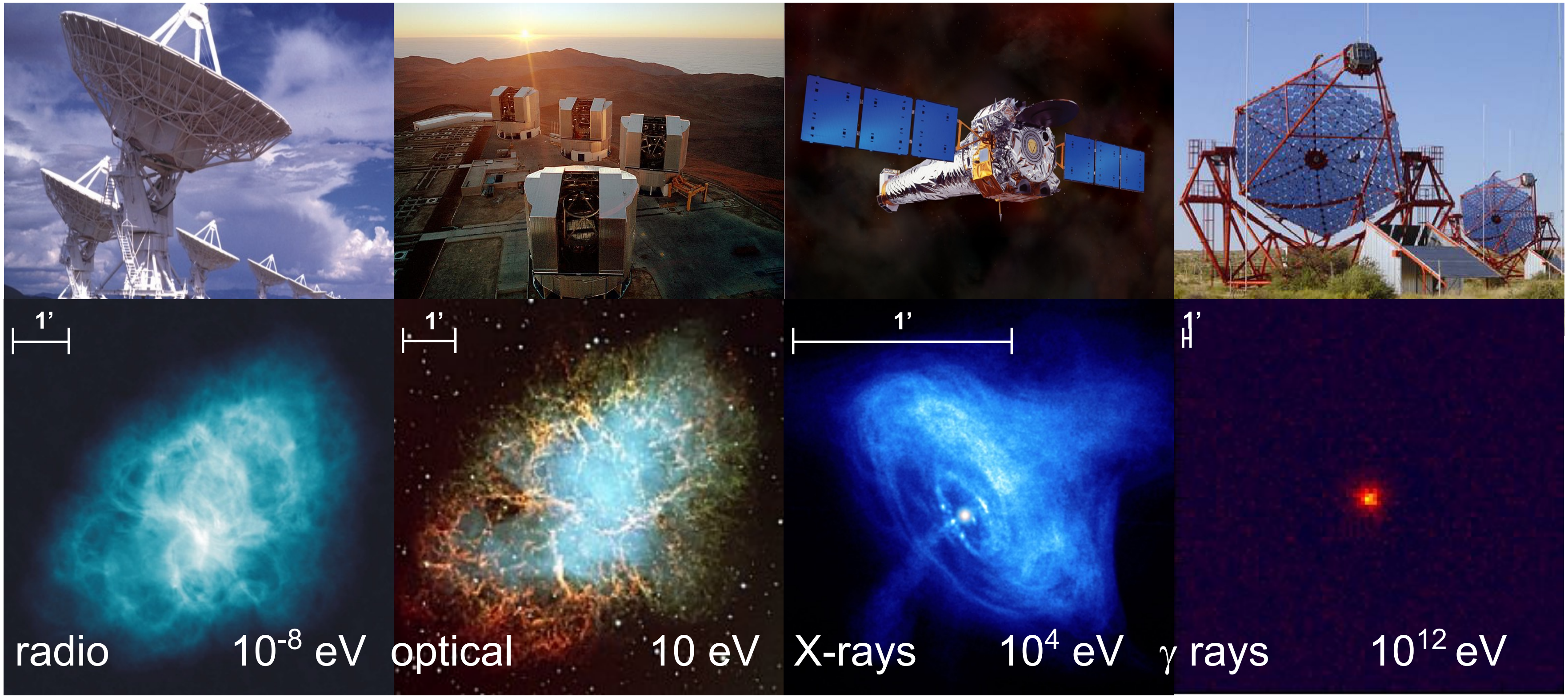
→ Livia Conti

Concluding remark

Multi-wavelength Astronomy

The Crab Nebula

(first source seen in the TeV gamma domain)



Thermal emission, dusts, molecular clouds, non-thermal processes…

Multiwavelength studies enable to get a more complete modelling of the source

Why several messengers ?

What is Astroparticle Physics?

Astroparticle physics, also called **particle astrophysics**, is a branch of particle physics that studies elementary particles of astronomical origin and their relation to astrophysics and cosmology. It is a relatively new field of research emerging at the intersection of particle physics, astronomy, astrophysics, detector physics, relativity, solid state physics, and cosmology. Partly motivated by the discovery of neutrino oscillation, the field has undergone rapid development, both theoretically and experimentally, since the early 2000s.[1]

1) Associate physics at different scales to explain the phenomena

- E.g. Nuclear Physics and Gravity to understand the equilibrium of the stars

2) Use multi-messenger probes adapted to the corresponding space-time scales and study cosmological events in different times and depths of interaction

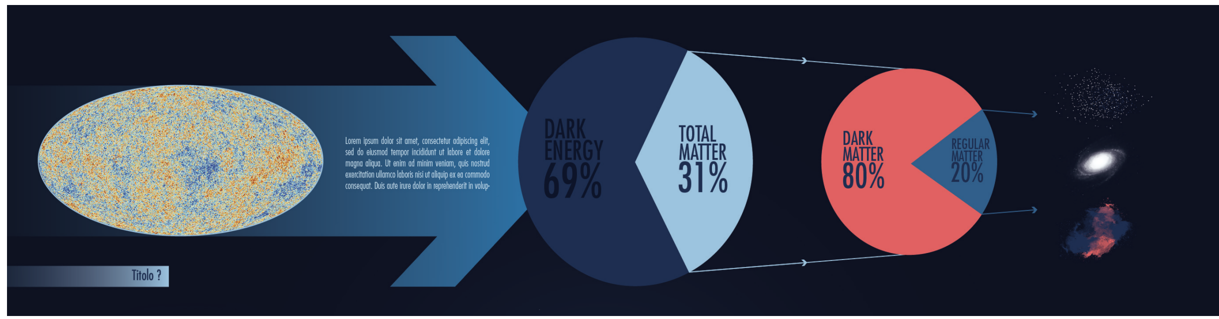
- Neutrinos and Gravitational waves to probe “deep and early processes” vs electromagnetic interactions coming at later stages
- Establish a global, low latency network to share fast enough the incoming signals

3) Discover new physics by comparing multi-messenger representations /cartographies of the Universe

- E.g. how different can be an ”early” vs a “late” cartography of the Universe (Hubble values tension) or black hole populations vs this of “living” stars

Key questions

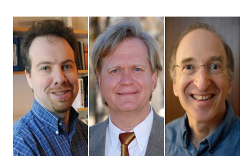
- The Primordial Universe
  - Inflation

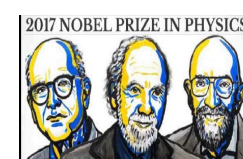


- The Dark Universe
  - Dark energy
  - Dark matter
  - Matter/antimatter

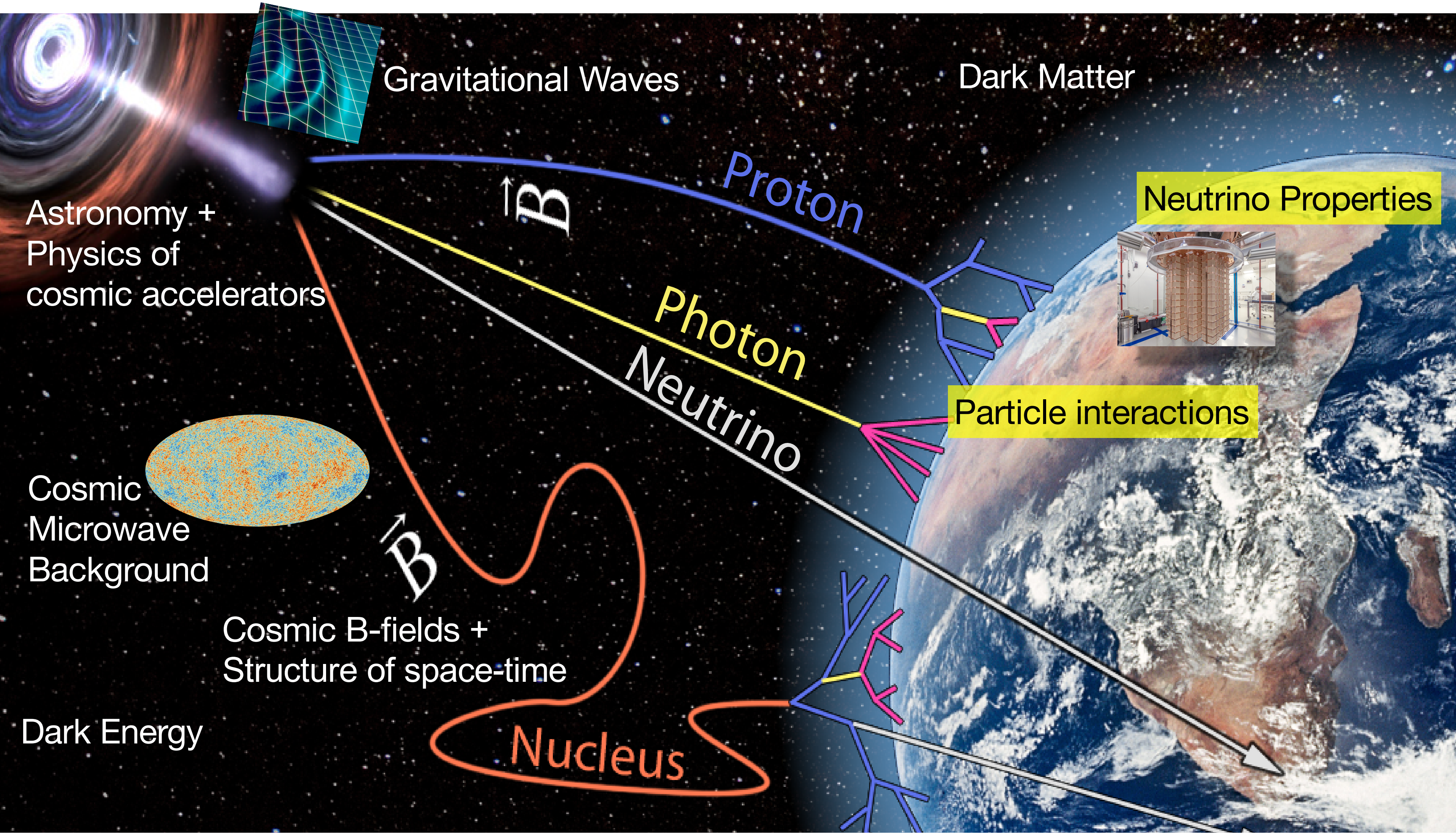
- The Violent Universe
  - Nature of black holes, neutron stars and white dwarfs
  - Formation and evolution of galaxies
  - Violent phenomena
  - Physics of dense matter and strong EM fields

A Nobel Prize field !





Multi-Messenger Astroparticle Physics



A very large Scientific Scope

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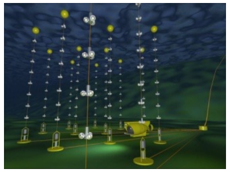

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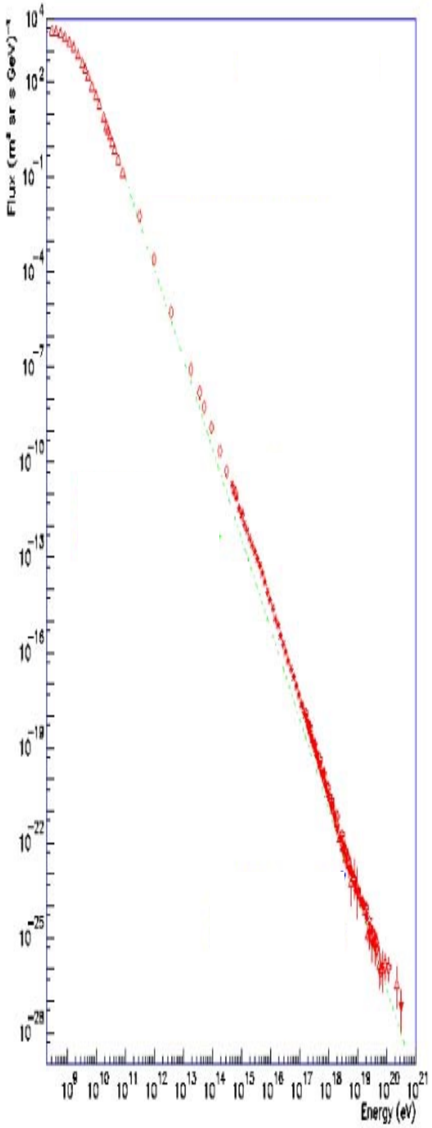
Cosmic rays, challenging since 1900

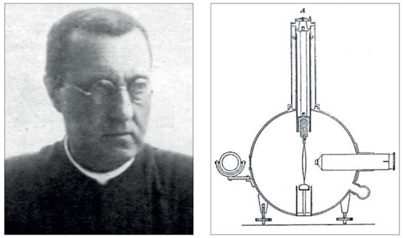
> 12 orders of magnitude!



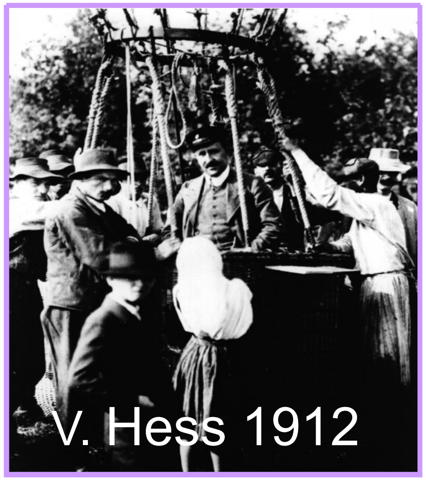
4 per cm^2 per second

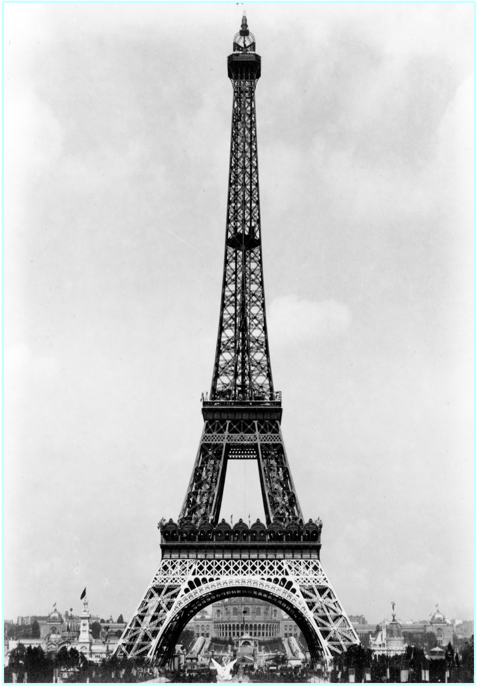
32 orders of magnitude ($/m^2/sr/GeV$)

1 per m^2 per billion years



T. Wulf (1909)





1932 Positron

1936 Muon

1947 Pions : π^0, π^+, π^-

1949 Kaons (K)

1949 Lambda (Λ)

1952 Cascade (Ξ)

1953 Sigma (Σ)

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> 12 orders of magnitude!

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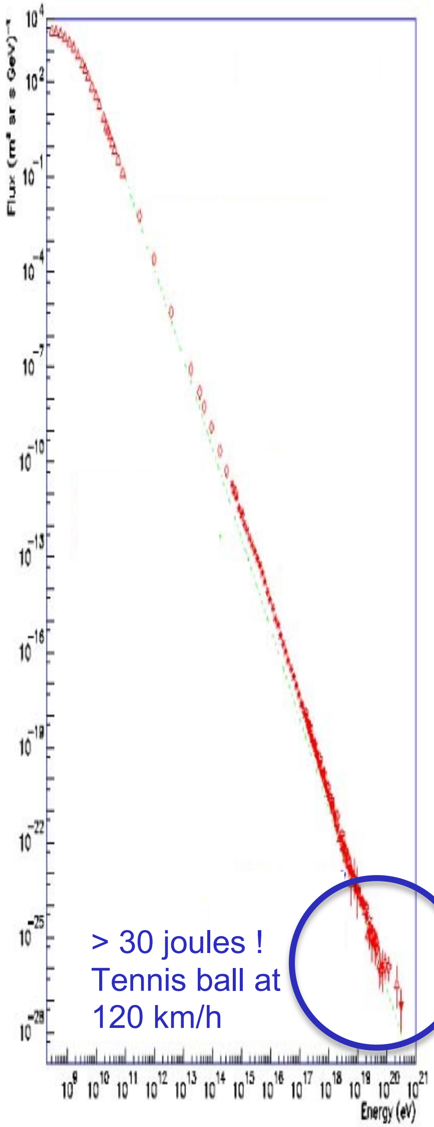


32 orders of magnitude ($/m^2/sr/GeV$)

1 per m^2 per billion years

- ✧ Major role in Galactic ecosystem !
  - ✧ Energy density ~ star light, thermal, B field
  - ✧ Regulate the equilibrium between the different phases of the interstellar medium
  - ✧ Control ionisation, heating
  - ✧ Regulate star formation
  - ✧ Produce Li, Be and B!
- ✧ Major unknowns
  - ✧ Sources are unknown (Galactic and Extragal.)
  - ✧ Acceleration processes are uncertain
- ✧ 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

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

Indirect detection

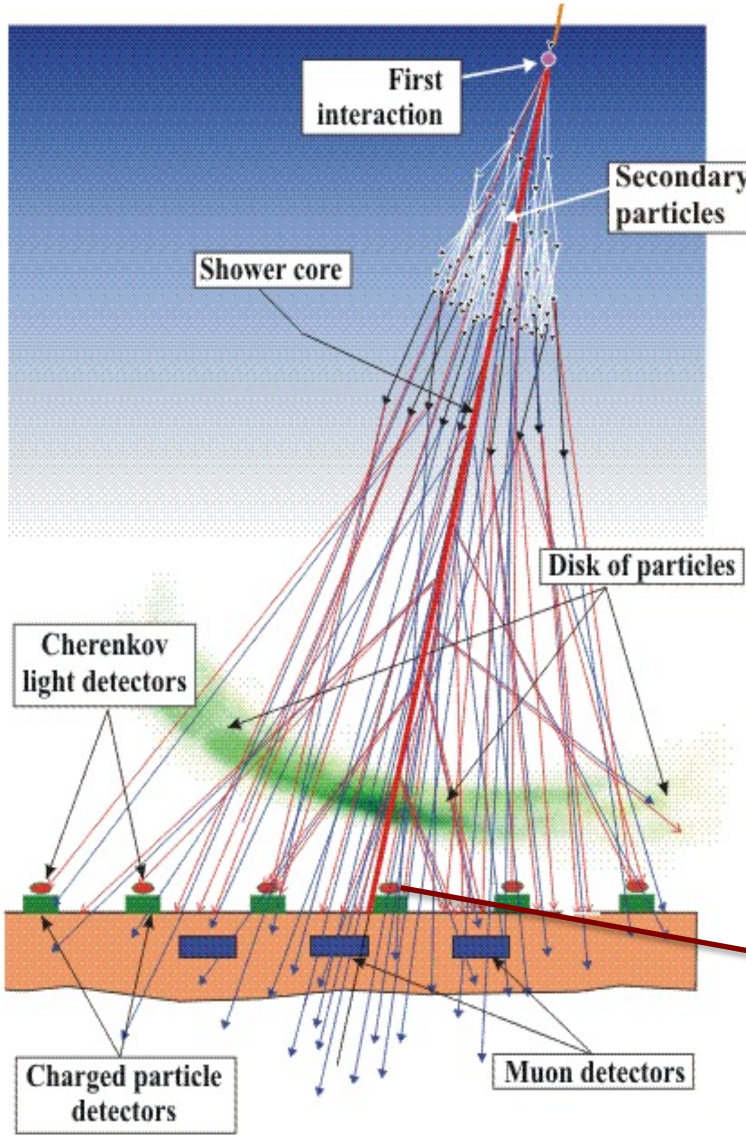
The atmosphere is the primary cosmic ray detector!

Detection of the shower particles

(sampling of the "shower front")

Volcano Ranch (1959–1963)

February, 22nd 1962: 10^{20} eV !

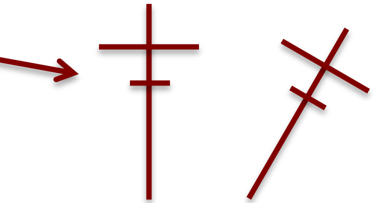


Detection of the induced effect of shower particles

(fluorescence light)

Fly's Eye (1981–1995)

October, 15th 1993: 3 10^{20} eV !



+ radio signal !

Current generation ground detectors

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

700 km^2 (Utah, USA)

- The Pierre Auger Observatory

3000 km^2 (Argentina)

- 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)
- Warm spots at intermediate angular scales at the highest energies
- Shower physics: "muon excess" (indirect)
- Declination-dependent energy spectrum (4.3 σ)

However, no clear progress regarding sources and acceleration mechanisms

What next ?

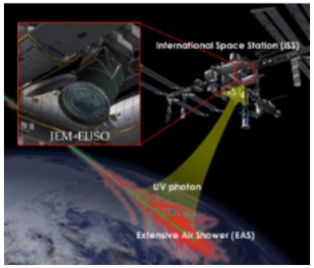
- Larger statistics, full sky coverage
- Complementarity between low energies (10^{18}–10^{19} eV) and high energies (10^{20} eV)
- Complementarity between ground-based (precision) et space-based (statistics) instruments
- New techniques (radio)

→ energy spectrum, composition, anisotropy over a large energy range

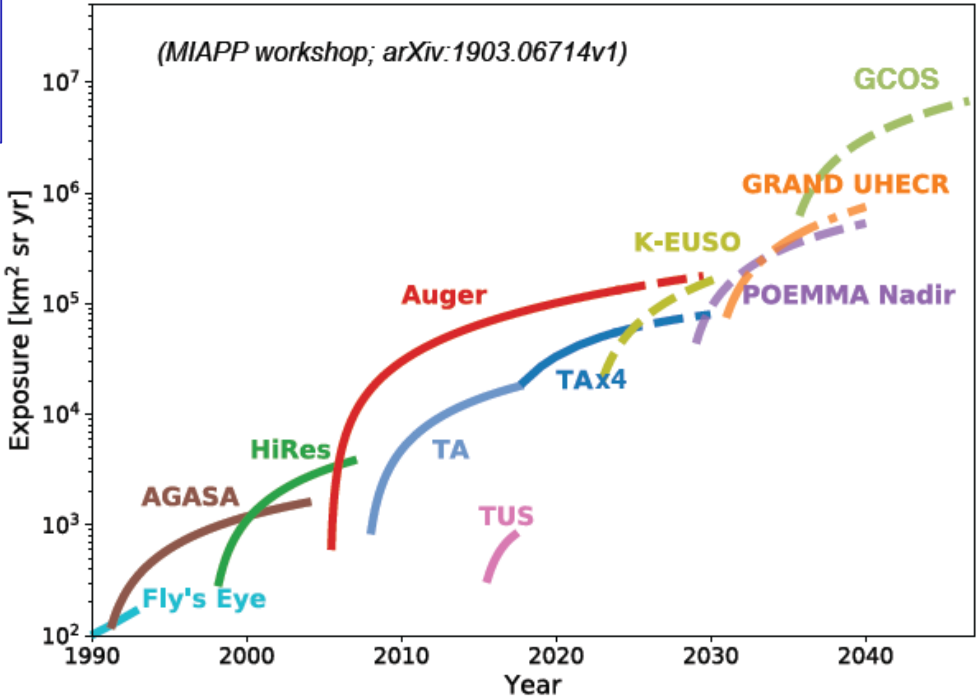
- Auger Upgrade to AugerPrime
  - completion in 2023, operation time >2030
- Preparation and R&D e.g. GRAND, GCOS

Towards UHECR and high-energy neutrino detection from space

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



Prototype on ISS (mini-EUSO)



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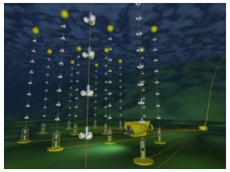

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High-Energy Gamma Rays (MeV-TeV)

The last spectral domain in photonic astrophysics

- Covers large energy range with different observatories
- Satellites (Fermi, AMEGO (launch 2029), ASTROGAM)
- Imaging Air Cherenkov Telescopes (H.E.S.S., Veritas, MAGIC)
- Ground-based arrays (GRAPES, TAIGA, HAWC, LHAASO, SWGO)
- Main future project within APPEC: CTA (ESFRI)

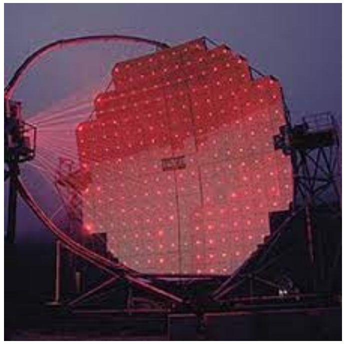
FERMI

Veritas

LHAASO

HAWC

MAGIC



H.E.S.S.

Imaging Atmospheric Cherenkov Telescopes

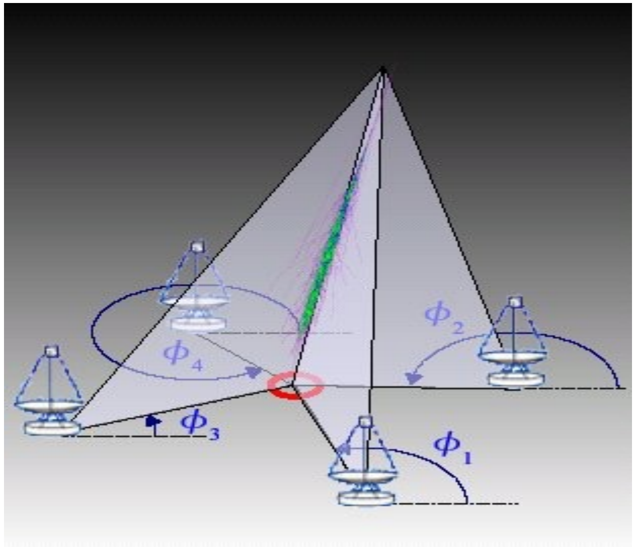
- Cherenkov light is emitted on a very narrow cone (θ < 1°) illuminating an area of about 300 m diameter at 1800 m a.s.l. on the ground.

- A telescope located within the light pool detects the shower if it collects enough Cherenkov photons → effective detection area ~ 10^5 m^2

- With an array of several telescopes, the shower can be reconstructed in 3D (stereoscopy)

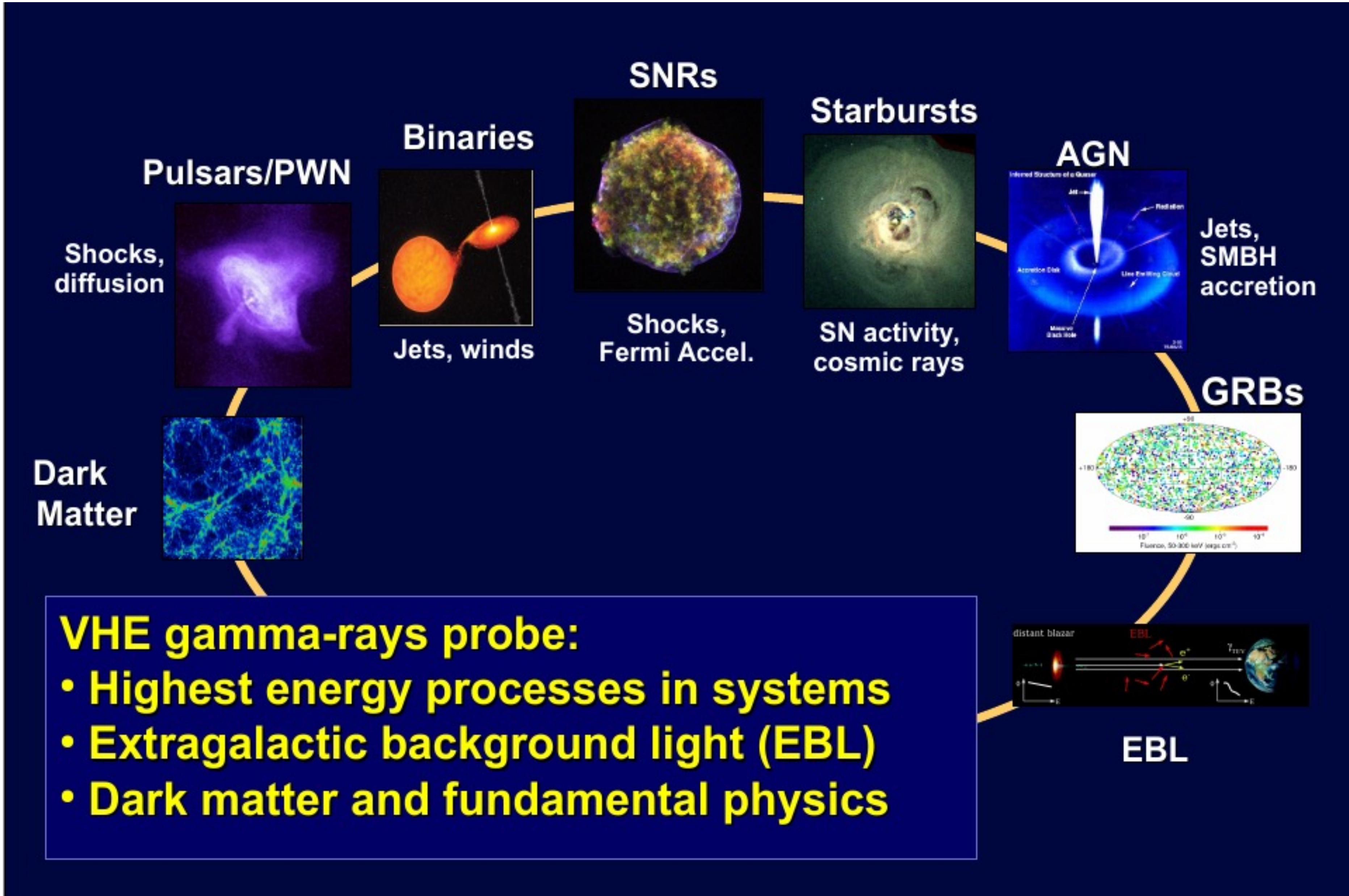
  → total number of photons (energy estimator)

  → better angular resolution

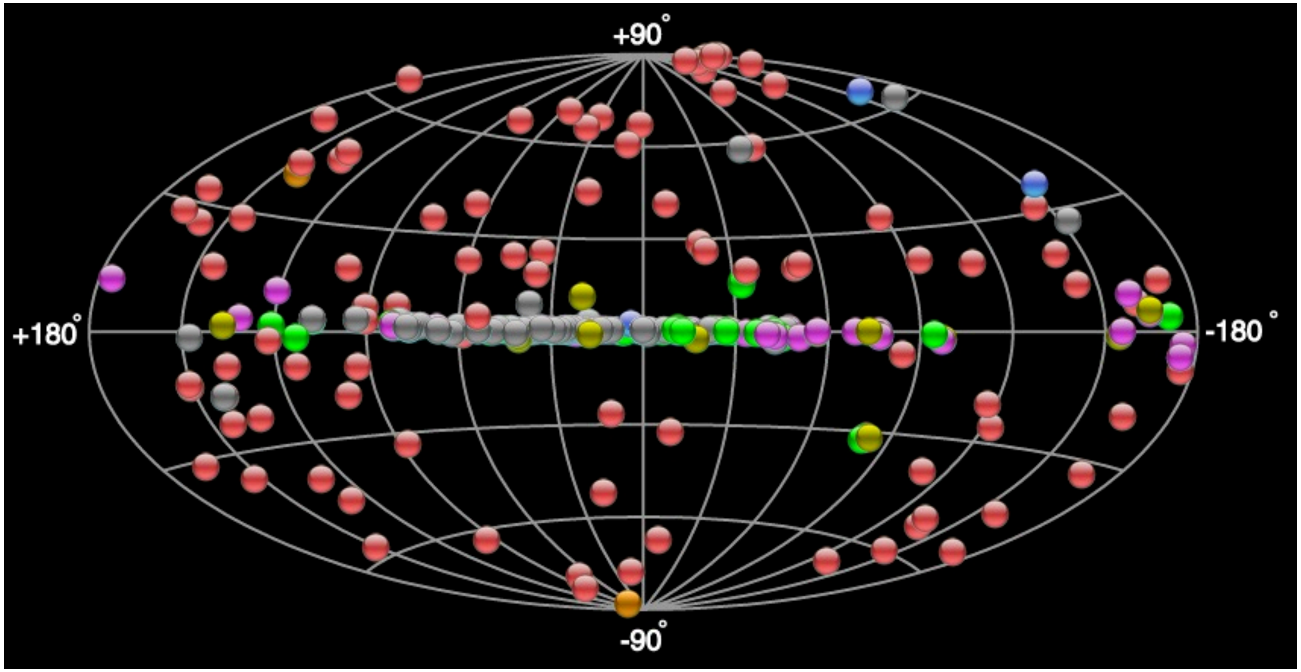


Mor than 30 years ago, the Crab nebula was the first γ-ray source firmly detected (9σ) at very high energies by The Whipple Observatory

Astronomy with IACTs

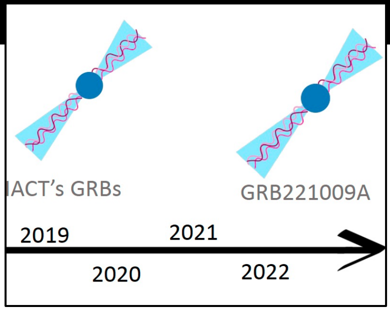


The VHE gamma sky



Source Types

- PWN TeV Halo PWN/TeV Halo TeV Halo Candidate
- XRB Nova Gamma BIN Binary PSR
- HBL IBL GRB FSRQ LBL AGN (unknown type) FRI Blazar
- Shell Giant Molecular Cloud SNR/Molec. Cloud Composite SNR Superbubble SNR
- Starburst
- DARK UNID Other
- Star Forming Region Globular Cluster Massive Star Cluster BIN uQuasar Cat. Var. BL Lac (class unclear) WR



Black Holes, Jets, and the History of Star-Formation

How do black holes make jets and accelerate particles?
Spectrum and redshift distribution of extragal. background light ?

Cosmic Rays

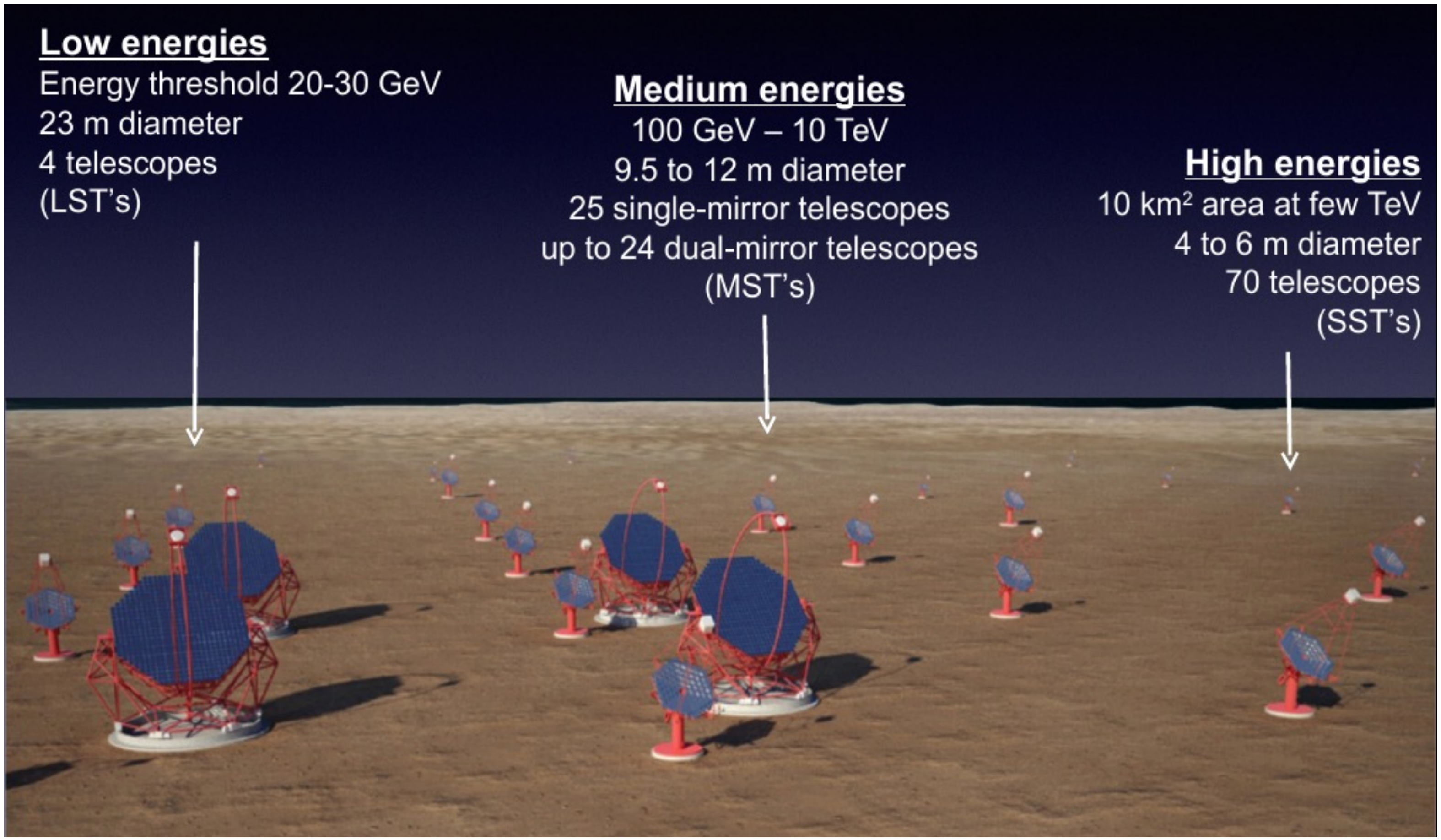
How and where are particles accelerated ?
What is the connection between star formation and cosmic rays ?

Dark Matter and Lorentz Invariance

What is the nature of Dark Matter ? How is it distributed ?
Is the speed of light a constant for high energy photons ?

Next: Cherenkov Telescope Array

- ESFRI Project
- Open, proposal-driven observatory
- 3 telescope types: LST, MST, SST
- 2 sites: La Palma + Chile
- Governance: ERIC (established 2022)
- 31 countries, >200 institutes, ~1400 scientists
- Construction next 3-5 years
- 10 x more sensitive than precursors



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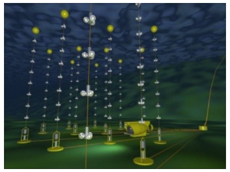

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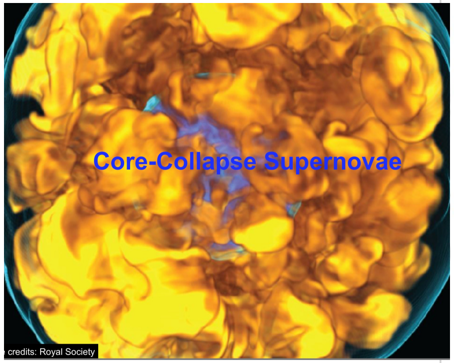
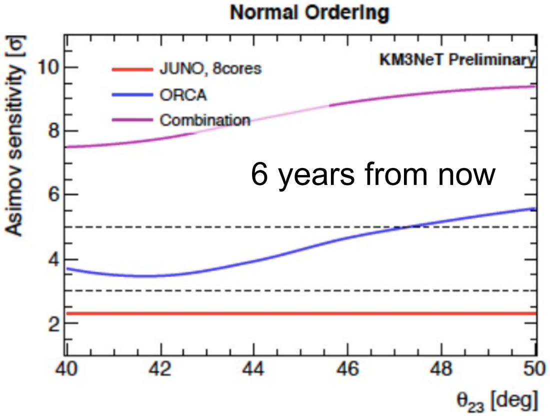
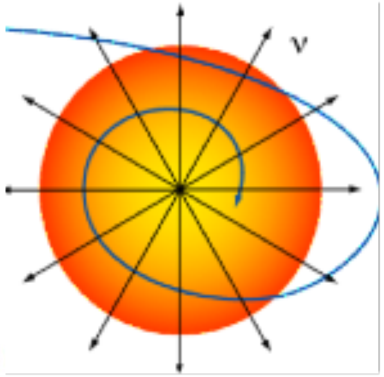
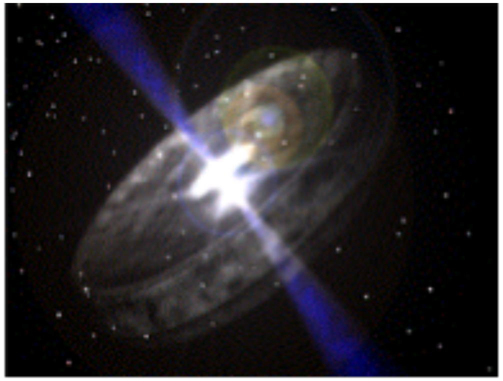
Neutrino Telescopes

The Science scope









MeV Energy
No reco. in HE NT

CCSNe

Full Galactic coverage
All mass progenitors
Triangulations

Low Energy
GeV < E < 50 GeV

Oscillation

PMNS Unitarity KM3NeT & IC
Neutrino Mass Ordering
with KM3NeT (ORCA ≥3σ 3yrs)

Medium Energy
10GeV < E < 1 TeV

Dark Matter

Not covered
here

High Energy
E > 1 TeV

HE Astrophysics

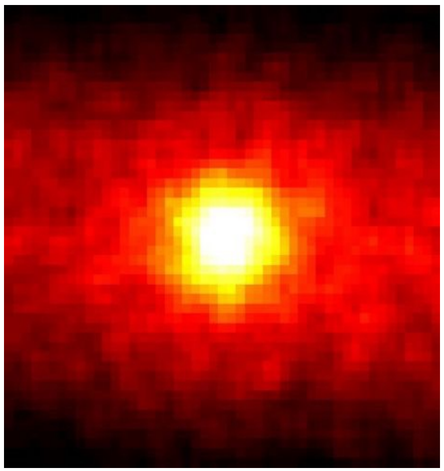
Focus of this talk

+ Exotics (Monopoles, Nuclearites, etc.)

+ Environnemental Sciences

First extraterrestrial neutrinos – Multi-messengers

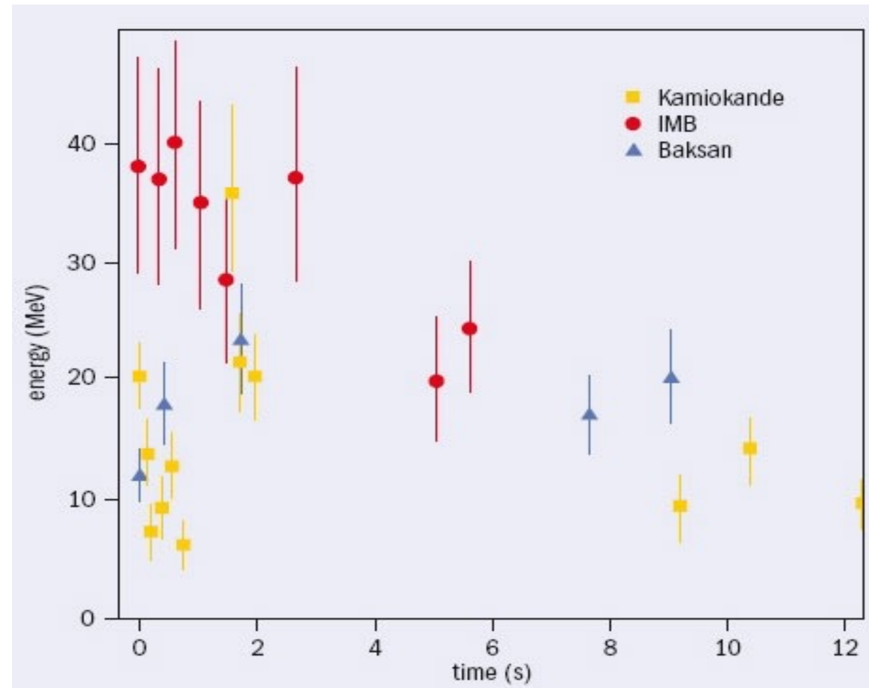
- ❖ 1960's: SUN seen by Homestake
- ❖ 1988 : Kamiokande



→ Confirmation of deficit of ν_e already observed in radiochemical experiments

Neutrino Oscillate

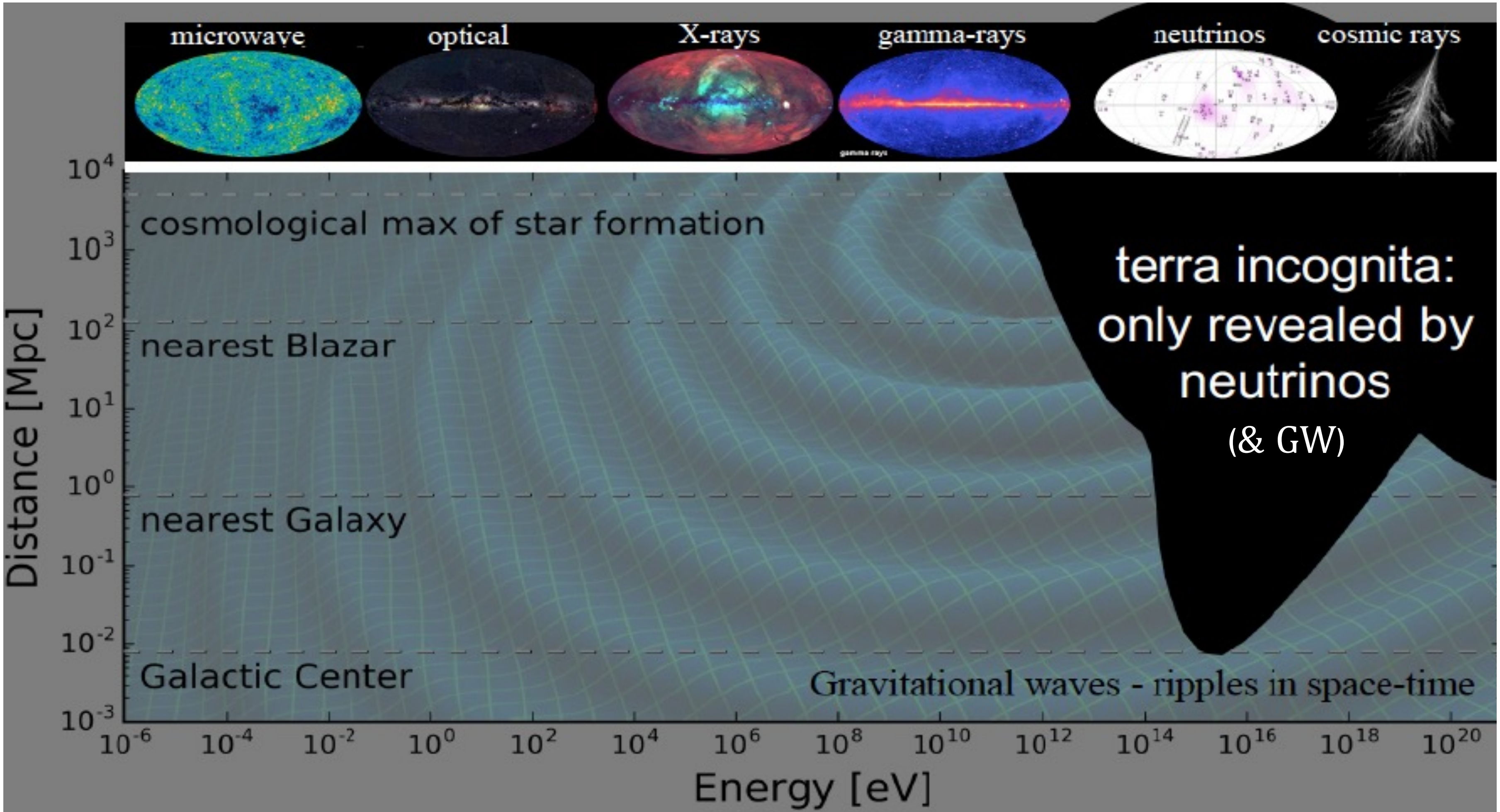
- ❖ 1987: Observation of a neutrino burst from the supernova SN1987A in the Large Magellanic Cloud



24 neutrinos detected in ~10 seconds about 3 hours before the electromagnetic emission

Typical energy ~10 MeV

Neutrinos as cosmic messengers



From F. Halzen

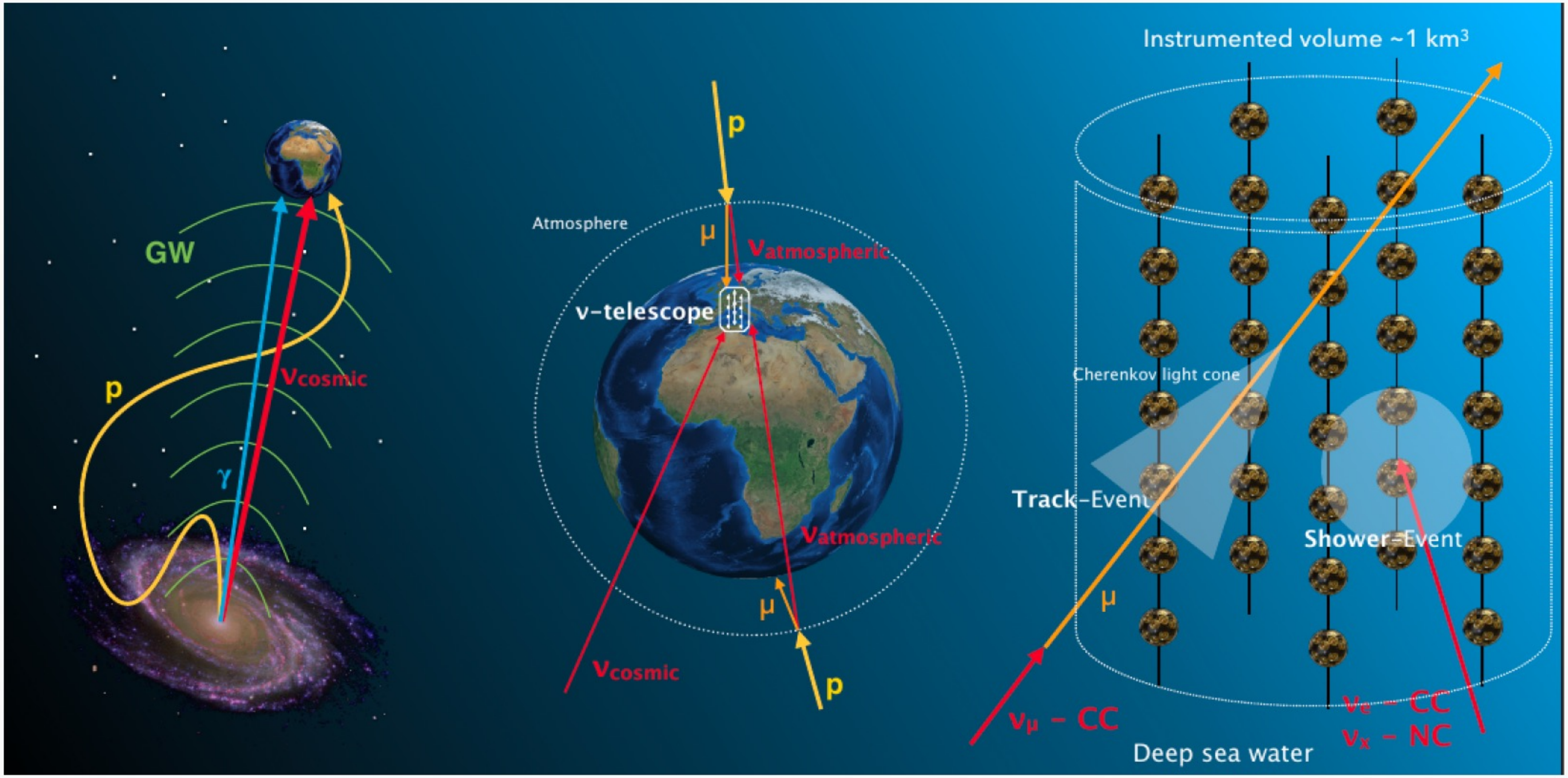
Neutrinos

✓Transient sources ✓Core of astrophysical bodies

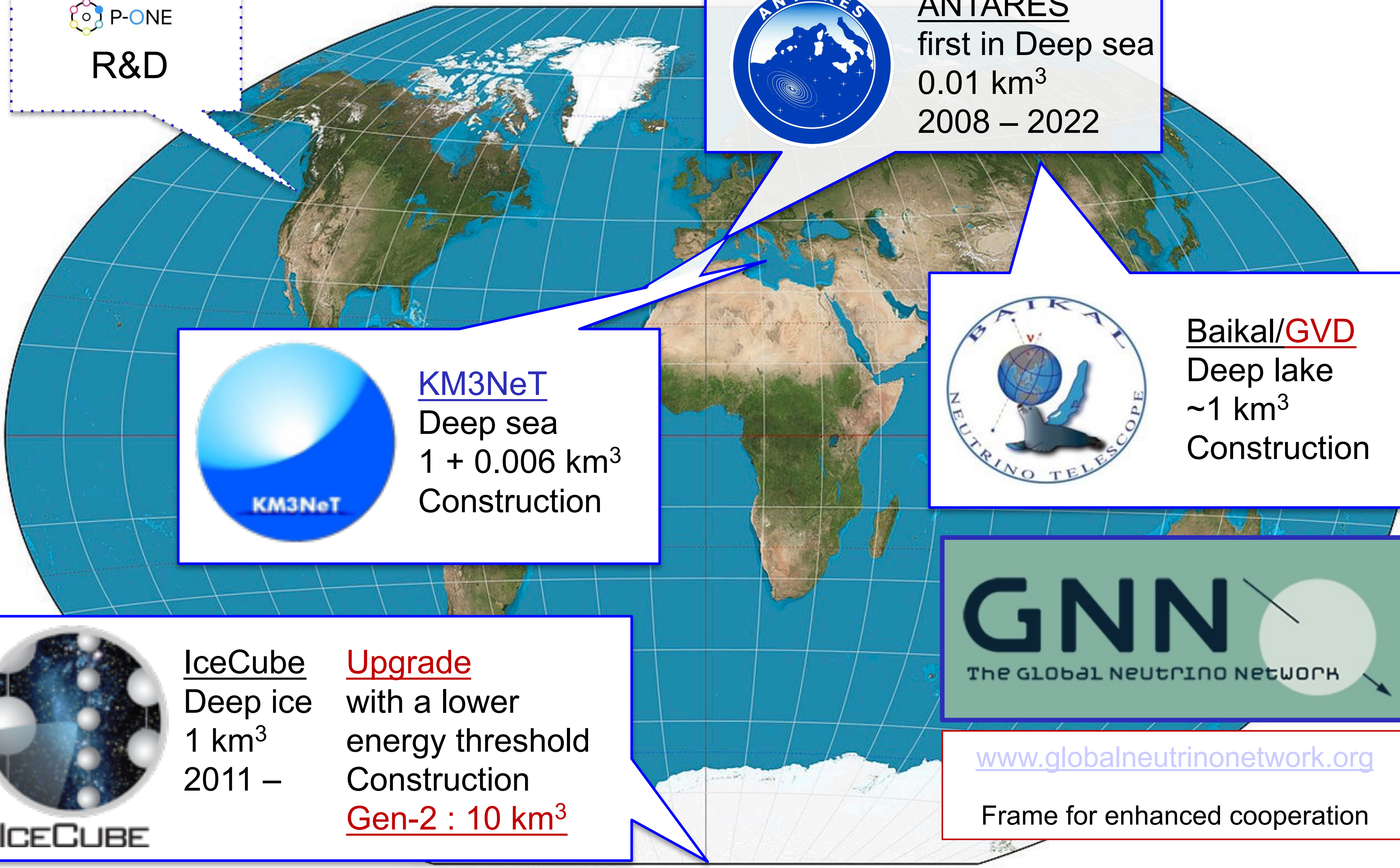
✓ Point source ✓Cosmological distance

⇒ Signature of hadronic acceleration

Detection principles



The neutrino telescope world map



P-ONE
R&D

ANTARES
first in Deep sea
0.01 km^3
2008 – 2022

KM3NeT
Deep sea
1 + 0.006 km^3
Construction

Baikal/GVD
Deep lake
~1 km^3
Construction

IceCube
Deep ice
1 km^3
2011 –

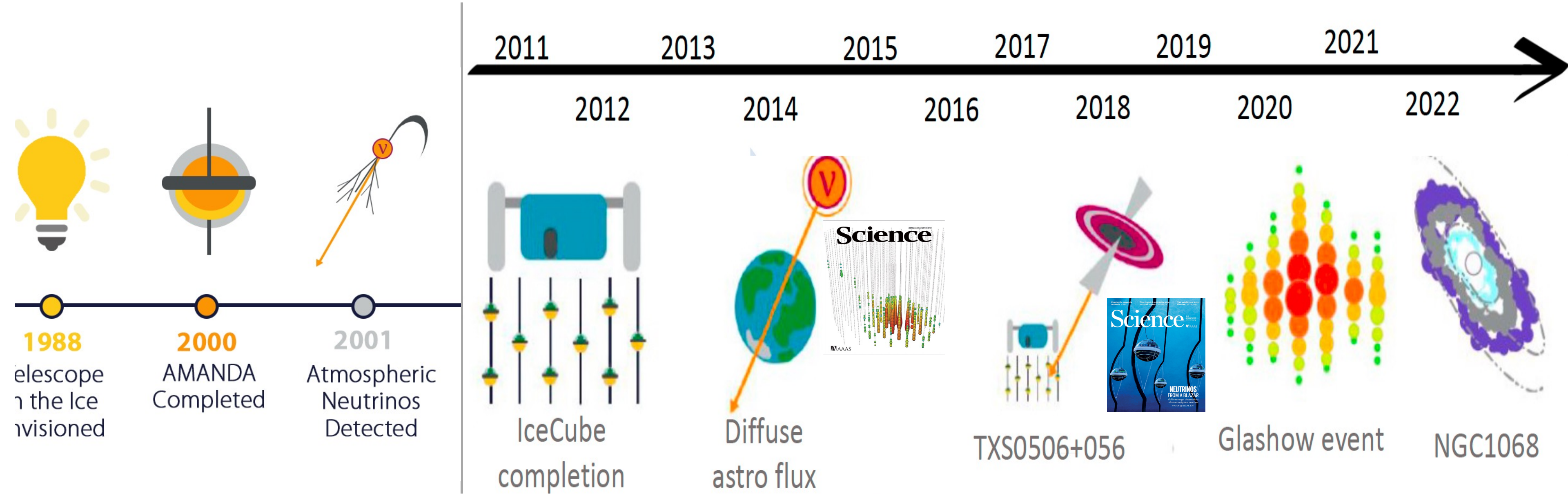
Upgrade
with a lower
energy threshold
Construction
Gen-2 : 10 km^3

GNN
The Global Neutrino Network

www.globalneutrinonetwork.org

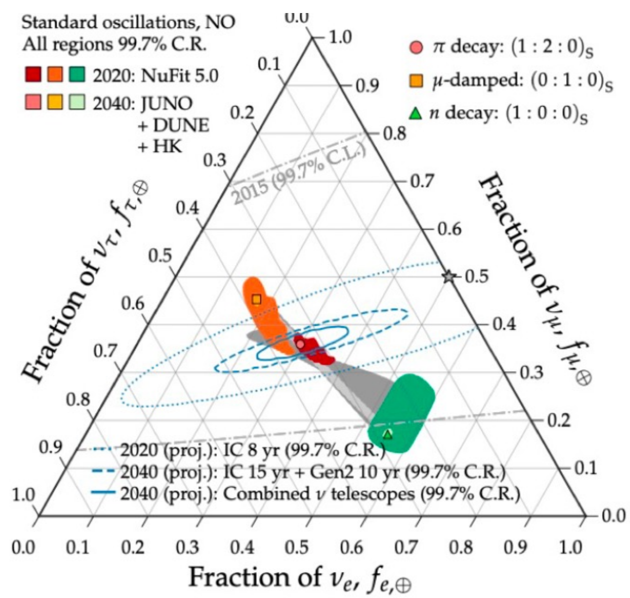
Frame for enhanced cooperation

IceCube opened the field with km-scale detector



Next Challenge
flavour physics
→ Source scenarios
→ New physics

Needs statistics
& more detectors
→IC-Gen2

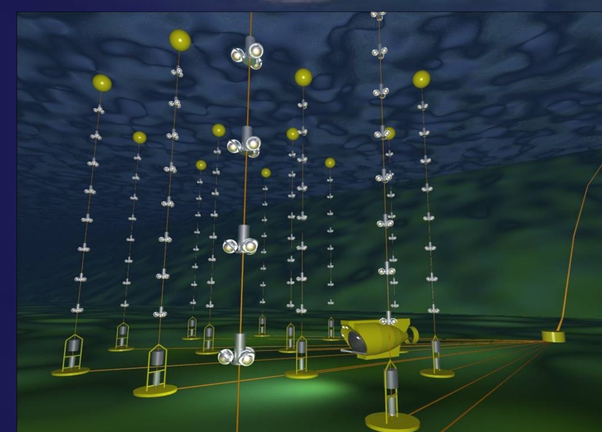


Developments in the Mediterranean Sea

ANTARES – the first undersea neutrino telescope

A multi disciplinary observatory with > 15 years of data

- **Competitive physics results & intriguing hints**
- **Constraints on neutrinos as seen by IceCube.**
- **Extensive multi-messenger program.**
- **Joint studies with several partners.**
- **About 100 papers published & 100 PhD students**
- **QUITE AN ADVENTURE ! But only the beginning …**



Site ANTARES
42 50'N, 6 10'E

Developments in the Mediterranean Sea

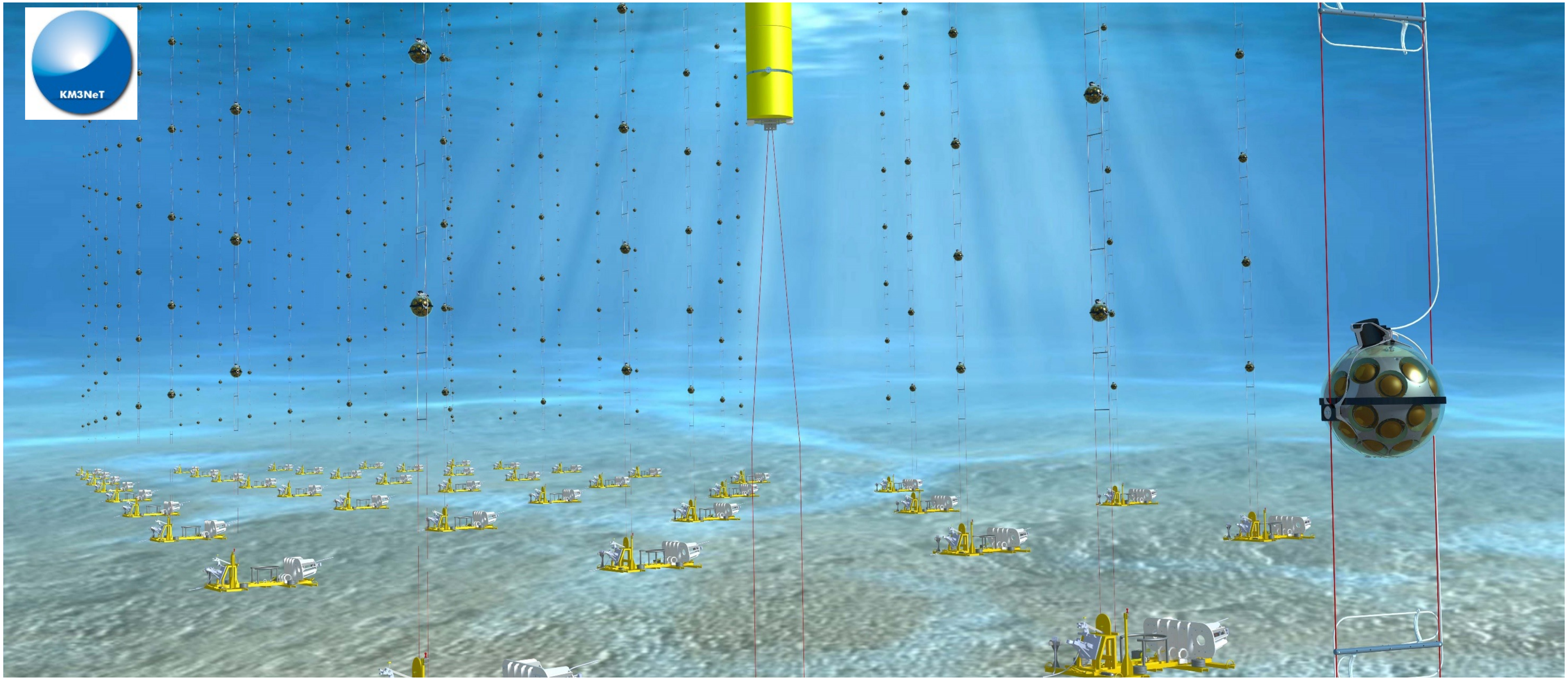
Next is KM3NeT - ESFRI project

- ARCA (high-energy neutrino astronomy, Italian site)
- Installation started, completed 2026

→ Discovery and subsequent observation of neutrino sources

- ORCA (low-energy neutrino physics, French site)
- Installation started, completion 2025

→ Determination of mass ordering of neutrinos



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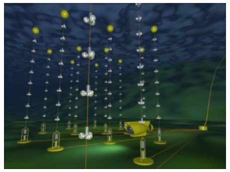

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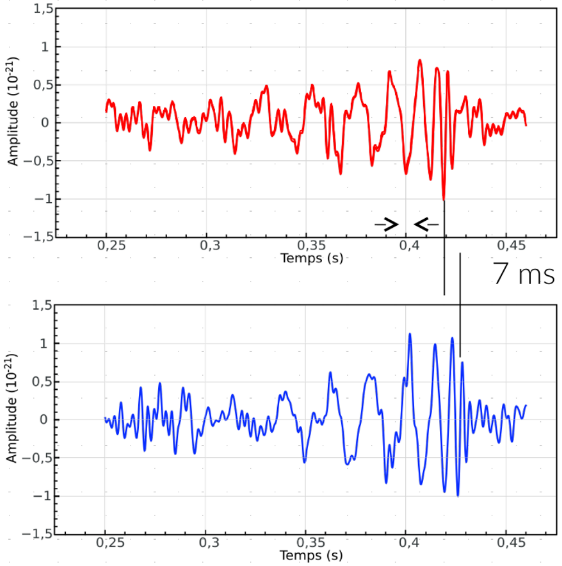
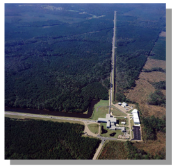
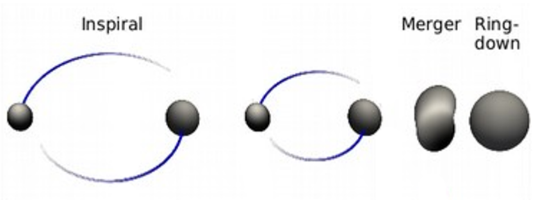
First Detections

Sep 14, 2015







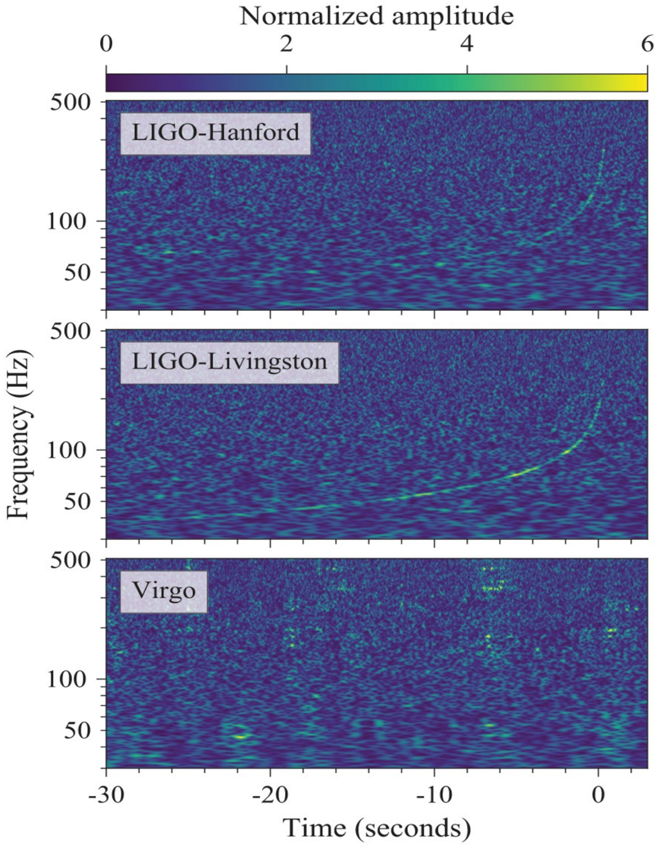
$$m_1 = 36.2^{-3.8}_{+5.2} M_\odot$$

$$m_2 = 29.1^{-4.4}_{+3.7} M_\odot$$

$$D_L = 420^{-180}_{+150}\ \mathrm{Mpc}$$

1.4 billions light-year

Aug 17, 2017



GW170817

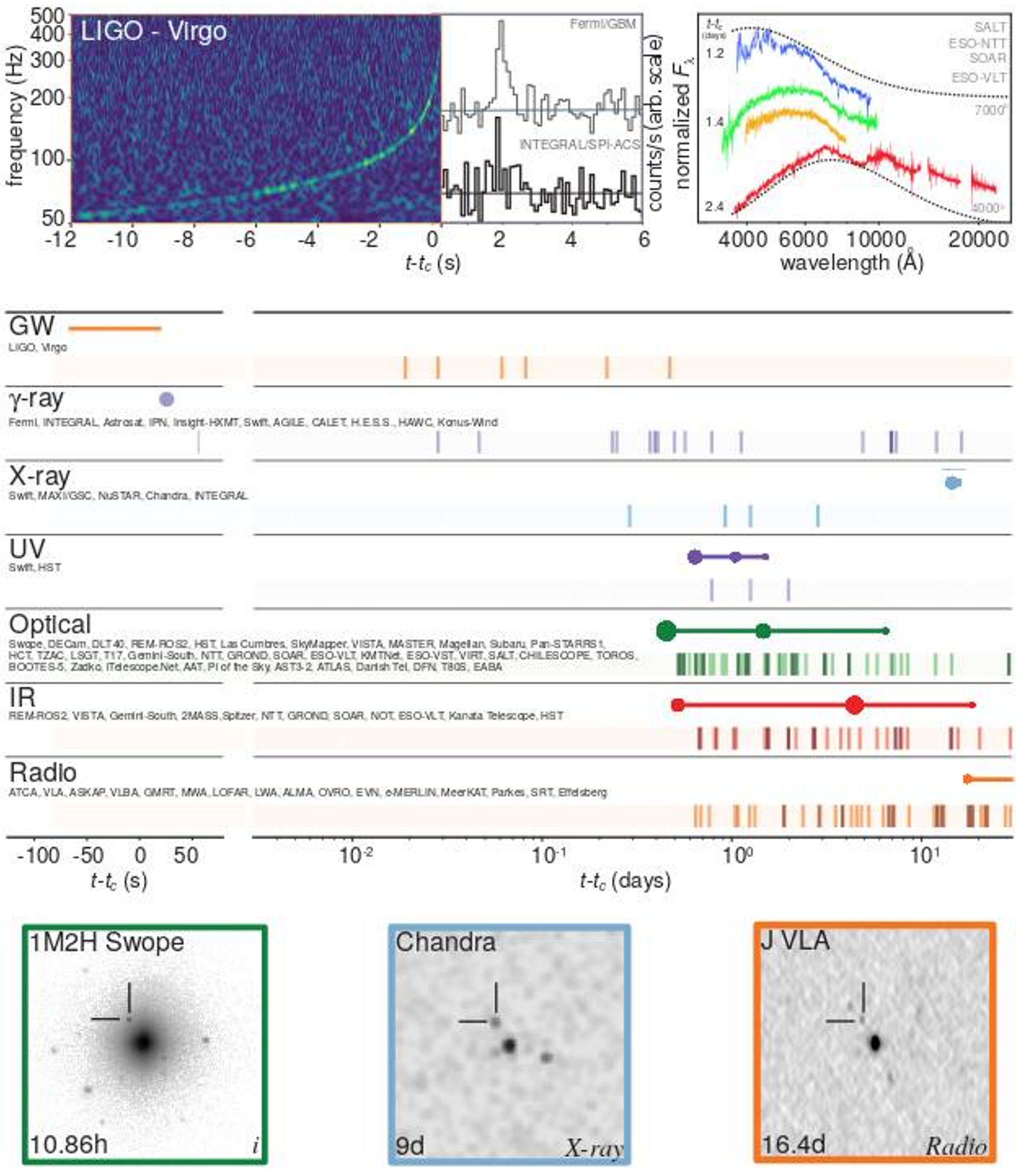
$$m_1 = 1.46^{+0.12}_{-0.10} M_\odot$$

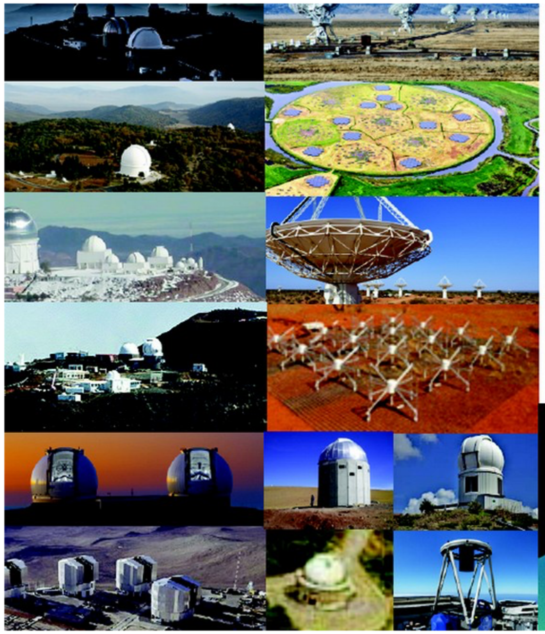
$$m_2 = 1.27^{+0.09}_{-0.09} M_\odot$$

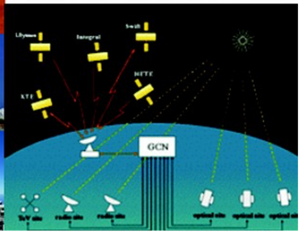
$$D_L = 40^{+7}_{-15}\ \mathrm{Mpc}$$

(130 millions light-years)

GW170817: multi-messengers !







Association with gamma-ray bursts

Jet of relativistic plasma?

$|c/c_g - 1| < 5 \times 10^{-16}$

Achievements so far

A large population of “heavy” binary black holes, so far unobserved

Raises many questions

How do they form?
In what environment?
Is their a single formation channel?

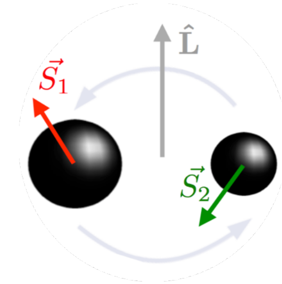
Some of the detected binaries are incompatible with the current understanding of black hole formation from massive stars

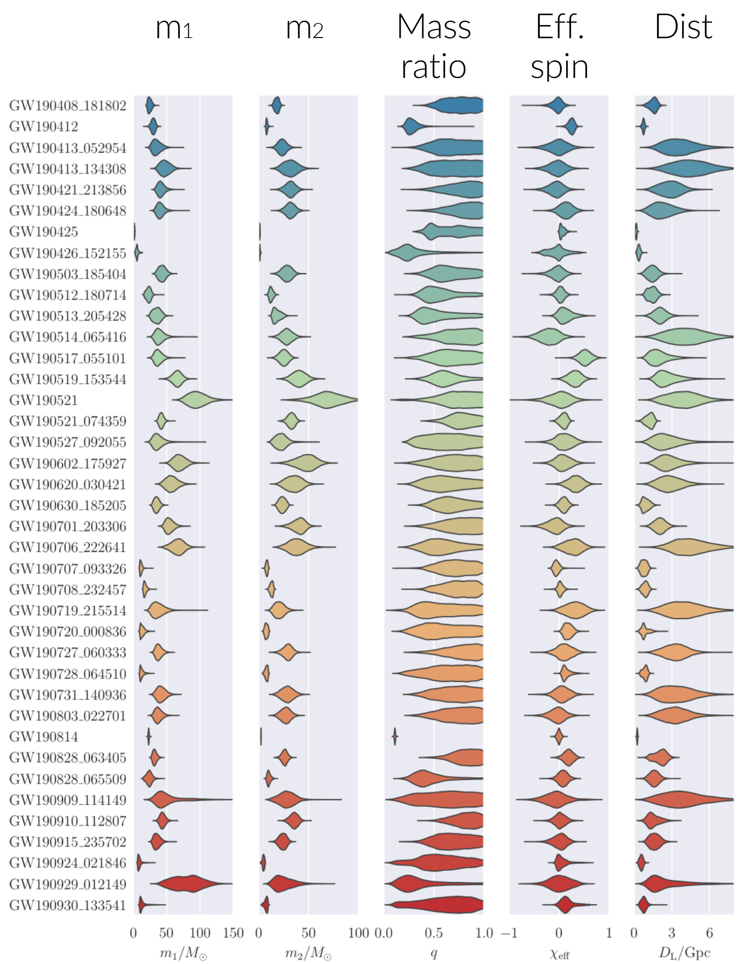
Other types of binary systems

Binary neutron stars

Possible mixed black hole and neutron star binaries

GWTC 2



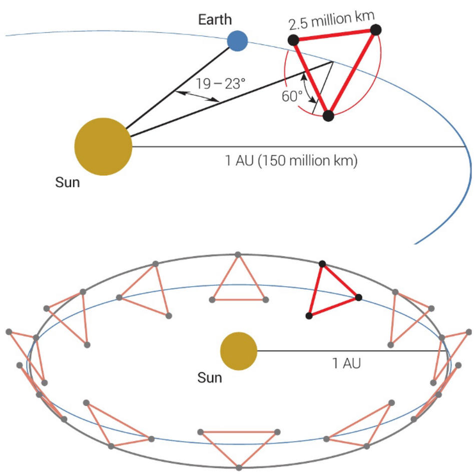


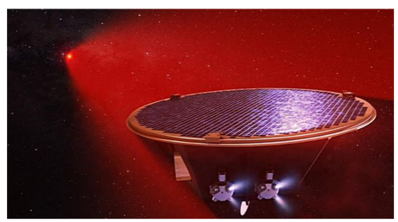
What next ? Cover frequency range

lisa

2035

Future ESA mission





Target heaviest and most diverse objects

Trace the history of black holes across all stages of galaxy evolution

Constrain deviation from the Kerr metric of General relativity.

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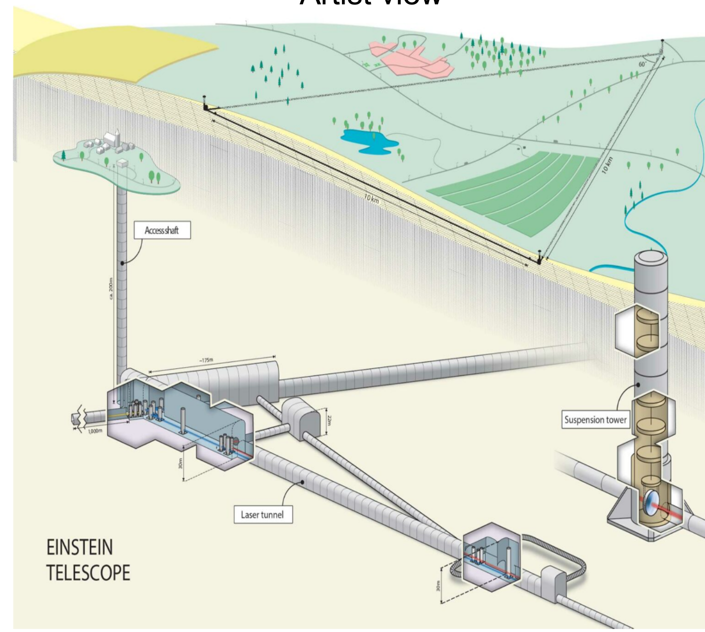
Einstein telescope Target : mid-2030

Artist view



3rd generation detectors

x 10 sensitivity improvement

Exceptional science reach

~90 % of all BBH mergers in the Universe

1 BBH every 30 sec

A Citizen Matter

Le Monde
WEEK-END

CULTURE & IDÉES
EUROPE LE SECRET MARCHANDAGE DES NORMES DIESEL
→ SUPPLÉMENT

Spécial Californie

Samedi 13 février 2016 - 72e année - N° 22108 - 4,20 € - France métropolitaine - www.lemonde.fr — Fondateur : Hubert Beuve-Méry — Directeur : Jérôme Fenoglio

Les petits calculs d'un remaniement

▸ François Hollande a choisi un remaniement tactique pour neutraliser les différentes composantes de la majorité avant 2017

▸ L'arrivée de trois ministres écologistes, dont Emmanuelle Cosse, porte un coup sévère au parti de Cécile Duflot

▸ Le retour de l'ancien premier ministre Jean-Marc Ayrault, nommé au Quai d'Orsay, tient à la volonté de rassurer la gauche du PS

▸ Le chef de l'Etat a choisi l'une de ses proches, Audrey Azoulay, pour remplacer Fleur Pellerin au ministère de la culture

▸ Plus qu'un gouvernement de combat, c'est un gouvernement de contrats qu'a choisi le président

→ LIRE PAGES 8-11 ET 14

Einstein avait raison

▸ Le physicien avait prédit l'existence des ondes gravitationnelles en 1916, la preuve directe en est aujourd'hui apportée

▸ Cette découverte majeure est à ranger parmi les plus grandes percées de la connaissance

▸ Les trous noirs existent et l'espace-temps est bien un contenant élastique susceptible d'onduler

→ LIRE PAGES 6-7

ARTHUR SASSE/AFP

Pourquoi les banques sont attaquées en Bourse

Les banques mondiales, Deutsche Bank en tête, continuent de subir les assauts du marché, faisant plonger les Bourses américaine et européennes. Les investisseurs reprochent à ces valeurs bancaires une rentabilité insuffisante et des engagements jugés hasardeux, notamment dans le secteur pétrolier. Les propos rassurants des responsables politiques de la zone euro et des dirigeants des institutions financières n'y font rien : le spectre d'un nouveau krach hante les esprits.

→ LIRE LE CAHIER ÉCO P. 4-5

ÉDITORIAL
UN AIR DE LEHMAN BROTHERS
→ LIRE PAGE 20

COMMERCE
LE GRAND BAZAR DU TRAVAIL DU DIMANCHE
→ LIRE LE CAHIER ÉCO PAGE 6

CULTURE
LE THÉÂTRE DE L'EUROPE AUX EUROPÉENS
→ LIRE PAGES 16-17

CULTURE & IDÉES
LIVRES POLITIQUES : FAUT-IL ÊTRE LU POUR ÊTRE ÉLU ?
→ LIRE LE SUPPLÉMENT

SPORT & FORME
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→ LIRE LE SUPPLÉMENT

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Plan russo-américain pour une trêve en Syrie

▸ Sergueï Lavrov et John Kerry s'accordent sur un accès humanitaire aux villes assiégées

AFP / CHRISTOF STACHE

Le secrétaire d'Etat américain, John Kerry, et le ministre des affaires étrangères russe, Sergueï Lavrov, ont présenté, vendredi 12 février, à Munich, un plan prévoyant une cessation temporaire des hostilités en Syrie et un accès humanitaire à certaines villes assiégées. Dix jours après l'offensive du régime Assad et de son allié russe contre Alep, cette trêve doit permettre la reprise *« dès que possible »* des pourparlers entre parties syriennes. L'aviation russe a conduit 510 raids et frappé près de 2 000 cibles en une semaine. Face à cet engagement intense, la « passivité » de Barack Obama est critiquée par les alliés des Etats-Unis, Turquie en tête, et par de plus en plus de voix à Washington même. ■

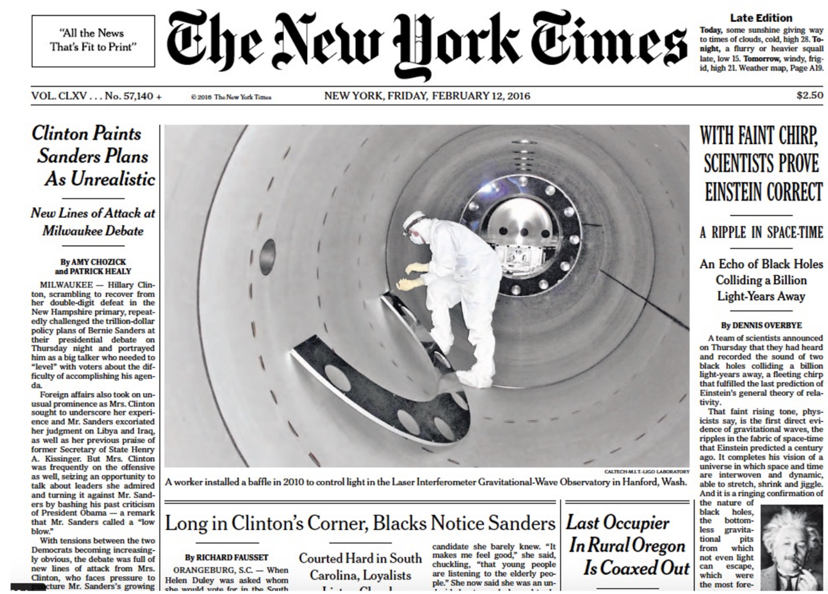
→ LIRE PAGES 2-3

MIGRANTS
L'ÉTAT VA RASER LA MOITIÉ DE LA « JUNGLE » DE CALAIS

PAR MARYLINE BAUMARD

La préfète du Pas-de-Calais va réduire de moitié la surface de la « jungle » de Calais. Fabienne Buccio devait annoncer, vendredi 12 février, qu'elle donne une semaine aux migrants qui campent dans la partie sud du bidonville pour quitter les lieux. Entre 800 et 1 000 personnes, installées sur 7 hectares dans des tentes ou des cabanes, seraient concernées. Il s'agit de la deuxième réduction du bidonville depuis le début de l'année. Une nouvelle étape avant la disparition souhaitée par l'Etat de ce lieu qui concentre, en France, les vives tensions engendrées par la crise migratoire que traverse l'Europe. Le ministère de l'intérieur souhaite, à terme, ne conserver que des hébergements structurés et contrôlés. *« Je me suis rendue sur les lieux cette semaine. J'ai constaté que, dans la partie sud du campement, deux abris sur trois n'étaient plus habités »*, explique la préfète au *Monde*.

→ LIRE LA SUITE P. 12



"All the News That's Fit to Print"

The New York Times

Late Edition
Today, some sunshine giving way to times of clouds, cold, high 28. Tonight, a flurry or heavier squall late, low 15. Tomorrow, windy, frigid, high 21. Weather map, Page A19.

VOL. CLXV . . . No. 57,140 + © 2016 The New York Times NEW YORK, FRIDAY, FEBRUARY 12, 2016 $2.50

Clinton Paints Sanders Plans As Unrealistic

New Lines of Attack at Milwaukee Debate

By AMY CHOZICK and PATRICK HEALY

MILWAUKEE — Hillary Clinton, scrambling to recover from her double-digit defeat in the New Hampshire primary, repeatedly challenged the trillion-dollar policy plans of Bernie Sanders at their presidential debate on Thursday night and portrayed him as a big talker who needed to "level" with voters about the difficulty of accomplishing his agenda.

Foreign affairs also took on unusual prominence as Mrs. Clinton sought to underscore her experience and Mr. Sanders excoriated her judgment on Libya and Iraq, as well as her previous praise of former Secretary of State Henry A. Kissinger. But Mrs. Clinton was frequently on the offensive as well, seizing an opportunity to talk about leaders she admired and turning it against Mr. Sanders by bashing his past criticism of President Obama — a remark that Mr. Sanders called a "low blow."

With tensions between the two Democrats becoming increasingly obvious, the debate was full of new lines of attack from Mrs. Clinton, who faces pressure to [...] Mr. Sanders's growing

CALTECH-M.I.T.-LIGO LABORATORY

A worker installed a baffle in 2010 to control light in the Laser Interferometer Gravitational-Wave Observatory in Hanford, Wash.

WITH FAINT CHIRP, SCIENTISTS PROVE EINSTEIN CORRECT

A RIPPLE IN SPACE-TIME

An Echo of Black Holes Colliding a Billion Light-Years Away

By DENNIS OVERBYE

A team of scientists announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prediction of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. It completes his vision of a universe in which space and time are interwoven and dynamic, able to stretch, shrink and jiggle. And it is a ringing confirmation of the nature of black holes, the bottomless gravitational pits from which not even light can escape, which were the most fore-

Long in Clinton's Corner, Blacks Notice Sanders

Courted Hard in South Carolina, Loyalists [...]

By RICHARD FAUSSET

ORANGEBURG, S.C. — When Helen Duley was asked whom she would vote for in the South [...] candidate she barely knew. "It makes me feel good," she said, chuckling, "that young people are listening to the elderly people." She now said she was an un-

Last Occupier In Rural Oregon Is Coaxed Out

Additional Challenges: citizen science

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- DEEP SEA HUNTERS
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- COSMIC MUONS IMAGES

Initiated by S. Katsanevas

Stavros Katsanevas (1953 - 2022)

Several testimonies related to his various activities including fRound table on “art & sciences”.

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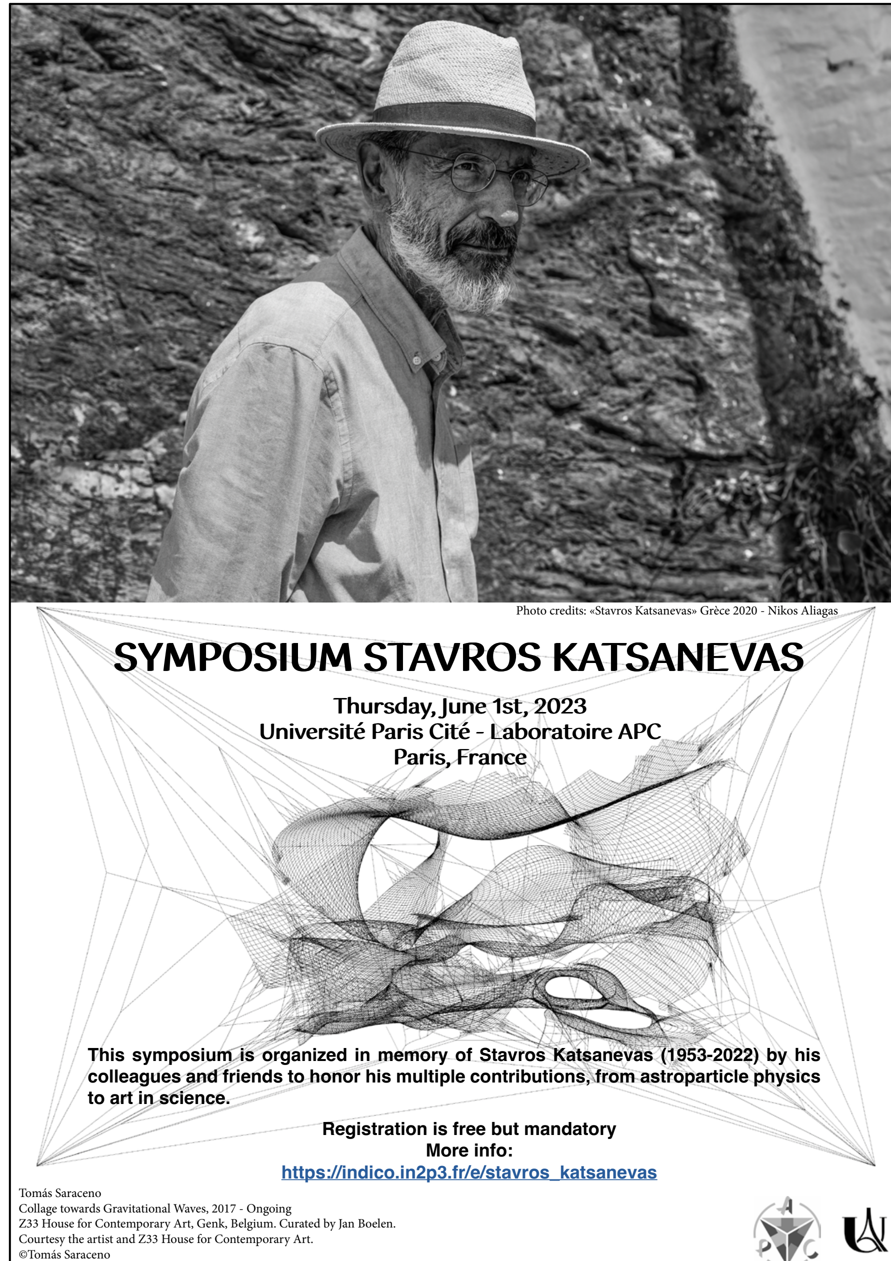
- **Astroparticle convergence in Europe** / Frank Linde - Christian Spiering
- **Early times in CERN** / Francois Richard
- **EGO - environmental aspects** / Irene Fiori - Maria Tringali
- **Onset of astroparticle in France** / Michel Spiro
- **Astrocent** / Leszek Roszkowski
- **Sonification** / Wanda Diaz Merced
- **Early career in Lyon** / Imad Laktineh
- **Muography** / Jacques Marteau
- **Gravitational wave detection on the Moon** / Philippe Lognonné
- **Geoscience and astrophysics** / Claude Jaupart
- **Creation of the DiiP** / Themis Palpanas
- **APOGEIA** / Veronique Van Elewick



Just a beginning …