Future Astroparticle Infrastructures

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Université de Genève

Disclaimer: I will focus on ground-based RI
Many links provided clicking on pictures

EPS
EUROPEAN PHYSICAL SOCIETY
HEP2021
VIRTUAL EDITION

29/7/2021

Summary

- General aspects on APP RI and relation to astronomy and particle physics, ESFRI Roadmap, common challenges (organisational and technical)
- The horizon of Multi-Messenger RI: gamma-rays, gravitational waves (GWs), neutrinos, charged cosmic rays and science challenges

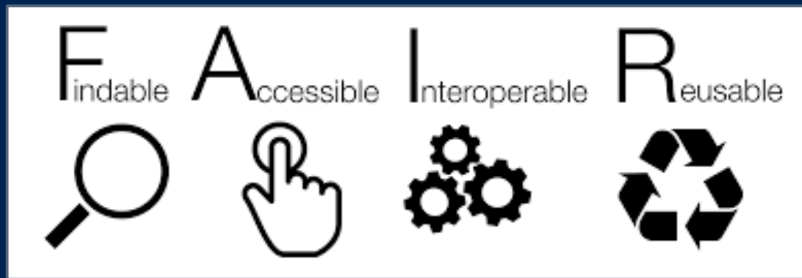
What are Research Infrastructures (RI)?

'Research infrastructures' mean facilities, resources and services that are used by the research communities to **conduct research** and **foster innovation** in their fields. Where relevant, they may be used beyond research, for example for education or public services. They include **major scientific equipment** or **sets of instruments**; **knowledge-based resources** such as collections, archives or scientific data; e-infrastructures such as data and computing systems and communication networks; and any other infrastructure of a unique nature essential to achieving excellence in research and innovation. Such infrastructures may be 'single-sited', 'virtual' or ‘distributed’;

EC Parliament Regulations

RI are key investments in research in all areas as they meet both the demand of the scientific community for state-of-the-art resources for supporting excellent science, and the demand of knowledge transfer for innovation at **social** and **economic** level.
The RIs are often generators of large volumes of FAIR **data** which need technical and policy solutions to curate, document, preserve and make available these data (perhaps through the EOSC in a future) upon request by other scientists or developers .
ESFRI 2018 Roadmap

Understand the right balance between FAIR and its cost…

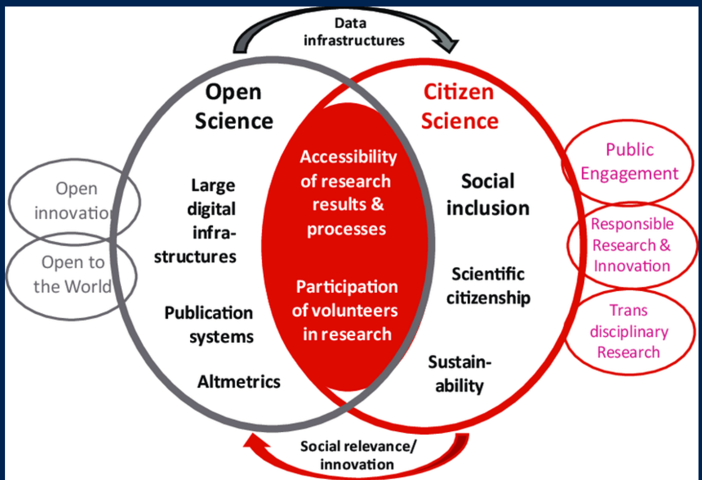


The **global** challenge of RI

- Implement policies and actions to :
  - **Value people**: invest on training, career development, implement policies on diversity
  - **Engage in a change of paradigma** where RI offer a service to the broad community
    - Open Science requires data/simulation/tools, remote computing, cross-field, innovation & technology, knowledge transfer, engaging activities in city science.
    - The response of the EC is the EOSC action towards Open Science with FAIR data.

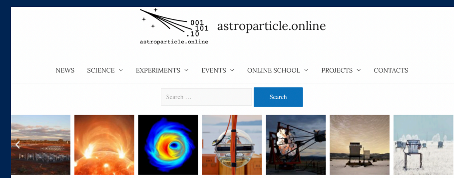
EUROPEAN CLOUD INITIATIVE
UNLOCKING THE POWER OF BIG DATA FOR OPEN SCIENCE

REINFORCE
REsearch INfrastructures FOR Citizens in Europe

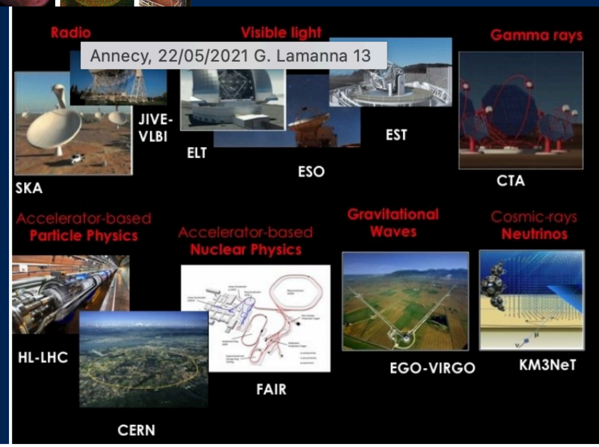


Source: Vohland and Göbel

Examples of projects involving APP:



- ESCAPE joins 7 ESFRI projects & landmarks: CTAO, ELT, EST, FAIR, HL-LHC, KM3NeT, SKAO with the vision to integrate distributed RI into a single virtual facility through the Virtual Observatoy



APP RI in ESFRI Roadmap

ESFRI LANDMARKS

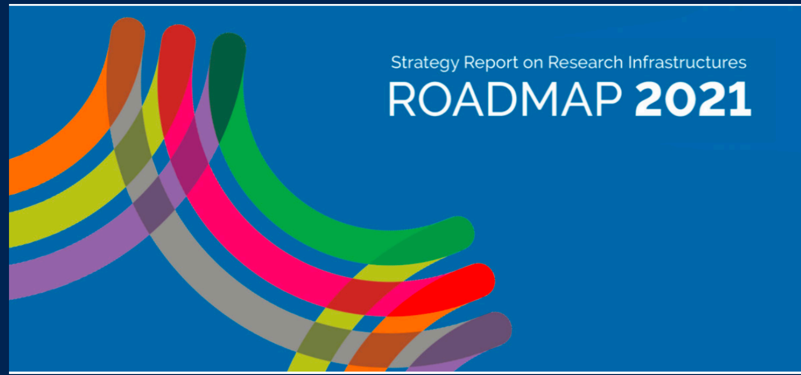
NAME	FULL NAME	TYPE	LEGAL STATUS (Y)	ROADMAP ENTRY (Y)	OPERATION START (Y)	CAPITAL VALUE (M€)	OPERATION COSTS (M€/Y)
CTA	Cherenkov Telescope Array	single-sited	gGmbH, 2014	2008	2024*	400	20
ELI	Extreme Light Infrastructure	distributed	AISBL, 2013	2006	2018	850	80
ELT	Extremely Large Telescope	single-sited	ESO#	2006	2024*	1.120	45
EMFL	European Magnetic Field Laboratory	distributed	AISBL, 2015	2008	2014	170	20
ESRF EBS	European Synchrotron Radiation Facility Extremely Brilliant Source	single-sited	ESRF#	2016	2023*	128	82
European Spallation Source ERIC	European Spallation Source	single-sited	ERIC, 2015	2006	2025*	1.843	140
European XFEL	European X-Ray Free-Electron Laser Facility	single-sited	European XFEL#	2006	2017	1.490	118
FAIR	Facility for Antiproton and Ion Research	single-sited	GmbH, 2010	2006	2025*	NA	234
HL-LHC	High-Luminosity Large Hadron Collider	single-sited	CERN#	2016	2026*	1.408	136
ILL	Institut Max von Laue-Paul Langevin	single-sited	ILL#	2006	2020*	188	97
SKA	Square Kilometre Array	single-sited		2006	2027*	1.000	77
SPIRAL2	Système de Production d'Ions Radioactifs en Ligne de 2e génération	single-sited	GANIL	2006	2019*	281	6

ESFRI PROJECTS

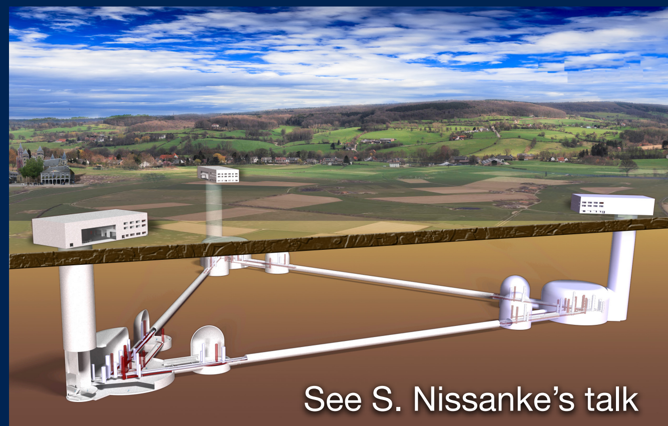
PHYSICAL SCIENCES & ENGINEERING

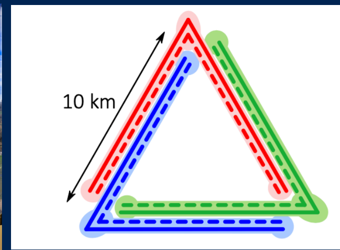
NAME	FULL NAME	TYPE	LEGAL STATUS (Y)	ROADMAP ENTRY (Y)	OPERATION START (Y)	CONSTRUCTION COSTS (M€)	OPERATION COSTS (M€/Y)
EST	European Solar Telescope	single-sited		2016	2029*	200	12
KM3NeT 2.0	KM3 Neutrino Telescope 2.0	distributed		2016	2020*	151	3

Landmarks = RIs now established as major elements of competitiveness of the European Research Area, needing continuous support for successful completion, operation and upgrade.
ESFRI Projects = project of scientific excellence and maturity included in the Roadmap in order to underline their strategic importance for the European RI system and support their timely implementation.



30.06.2021: 11 new RI in ESFRI 2021 Roadmap, including ET!
ET Preparation & Construction : 2018-2035. Cost: 1.9 billion€
Site selection: 2024-2025
ET Operation : 2036-2080; Annual operation cost: 37M€





Two nested interferometers with 10 km arms

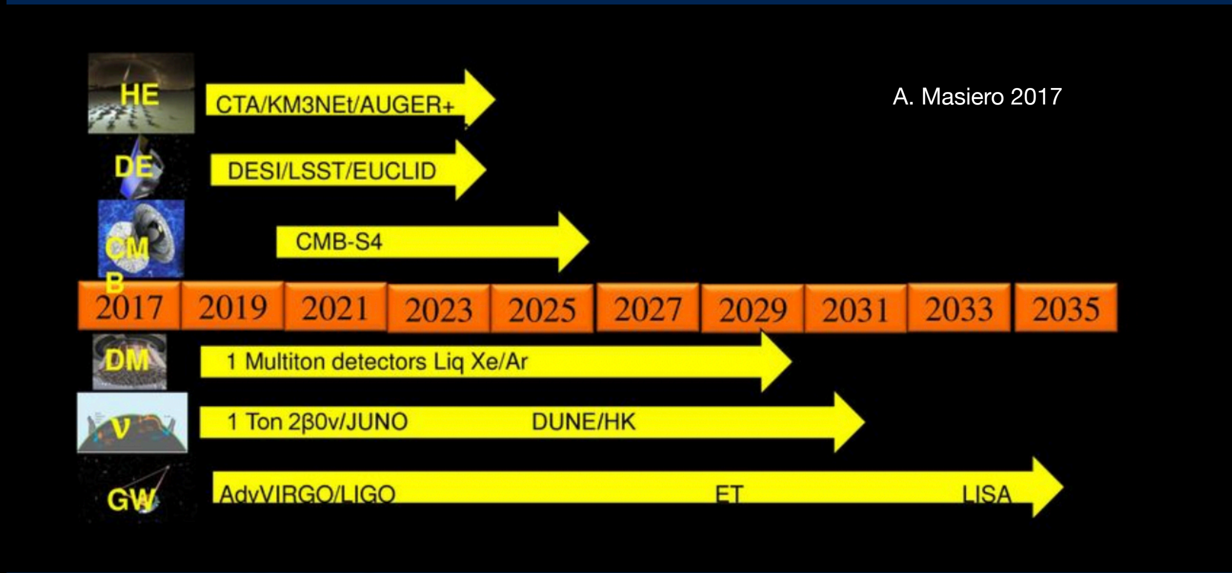
Astroparticle Physics European Consortium Science Challenges and Roadmapping

Magnificent 7

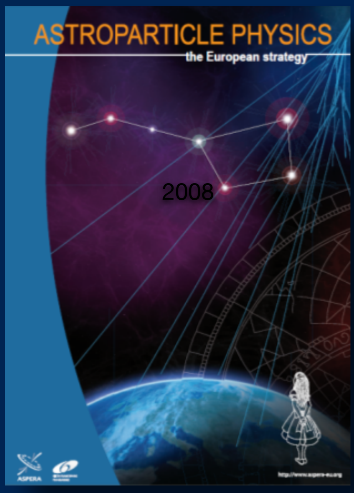
1. *HE gammas*
2. *HE neutrinos*
3. *HE cosmic rays*
4. *Gravitational waves*
5. *Dark matter*
6. *ν-mass*
7. *ν-mixing & p-decay*

   CMB

   Dark Energy



From ASPERA to last APPEC Roadmap plans are consistent …but evolution from concept to implementation takes time…



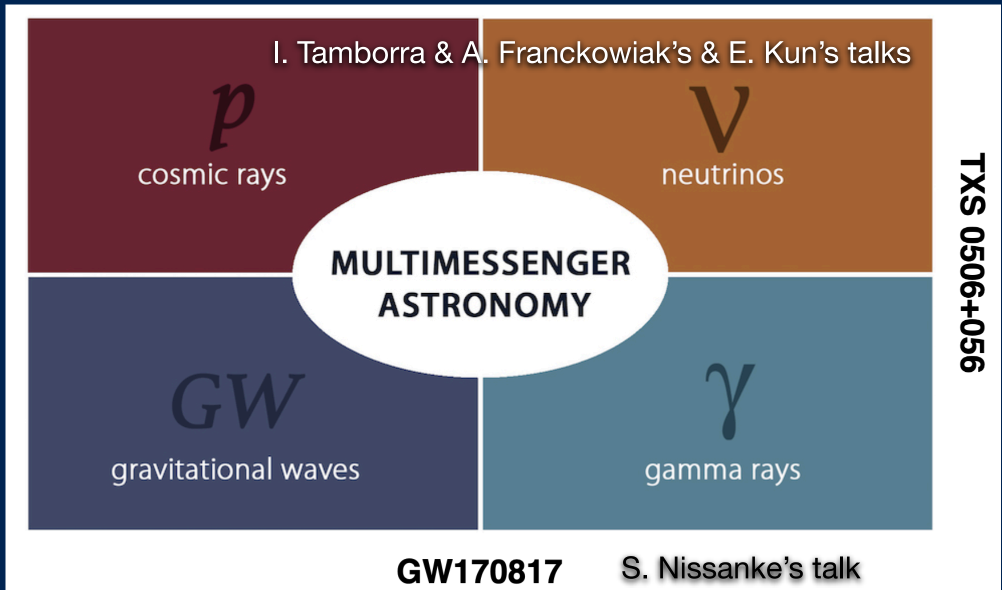
APPEC 2017-2026 Resource aware Roadmap : 21 detailed recommendations. An implementation process for DM and $0\nu\beta\beta$ is taking place.

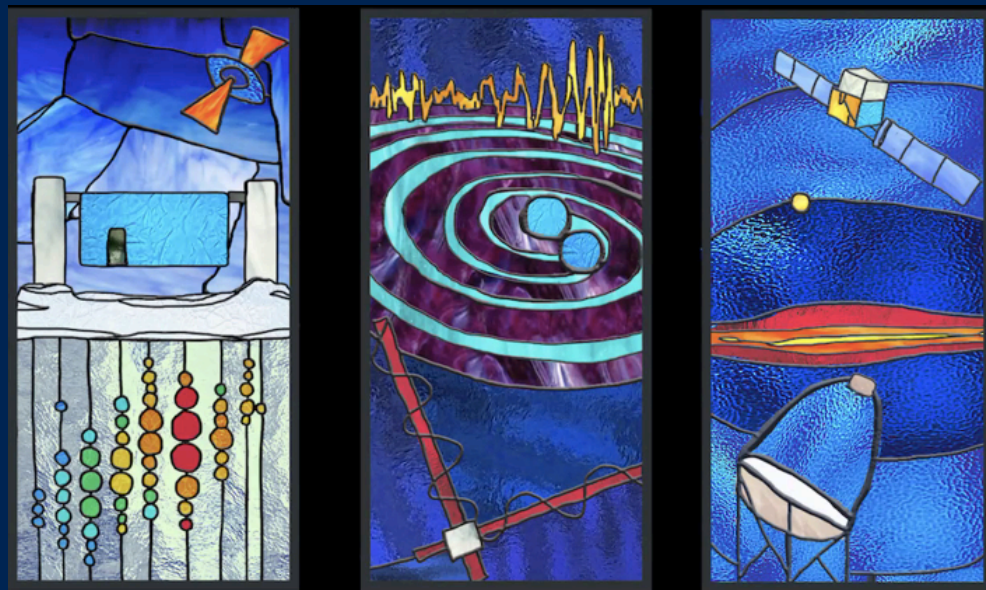
3G for GW is ET in Europe.

Challenges of RI in APP

- Lack of International Coordination: a Board of Directors table where agreed policies are translated into governance adapted to the needs of large RI:
  - APP International Forum (APIF) of the Organisation for Economic Co-operation and Development (OECD) **Global science Forum**. “APIF brings together officials and representatives of funding agencies of countries that make significant investments in astroparticle physics research. It is a venue for **information exchange, analysis, and coordination, with special emphasis on strengthening international cooperation**, especially for large programmes and infrastructures.”
  - A IUPAP WG10 (APPIC) from community side exists but not active. A renewed IUPAP neutrino panel was recently formed.
- Lack of well defined governance framework of large established legal entities (CERN, ESO, ESA for space,..)
  - Pathfinder solutions are now becoming available which require executive offices , STAC, Council, a defined relation with the Collaboration organisation:
    - EC ERIC solution challenges non-EC countries (CTAO, ESS,..);
    - Intergovernmental organisations (eg pathfinder SKAO, ET?)
  - APPEC is setting up a governance WG.
- RI require long-term commitments and comparable budget for operation than for full exploitation. Ensuring **sustainability** is a long-standing issue.

A new paradigma in Multi-Messenger Astrophysics



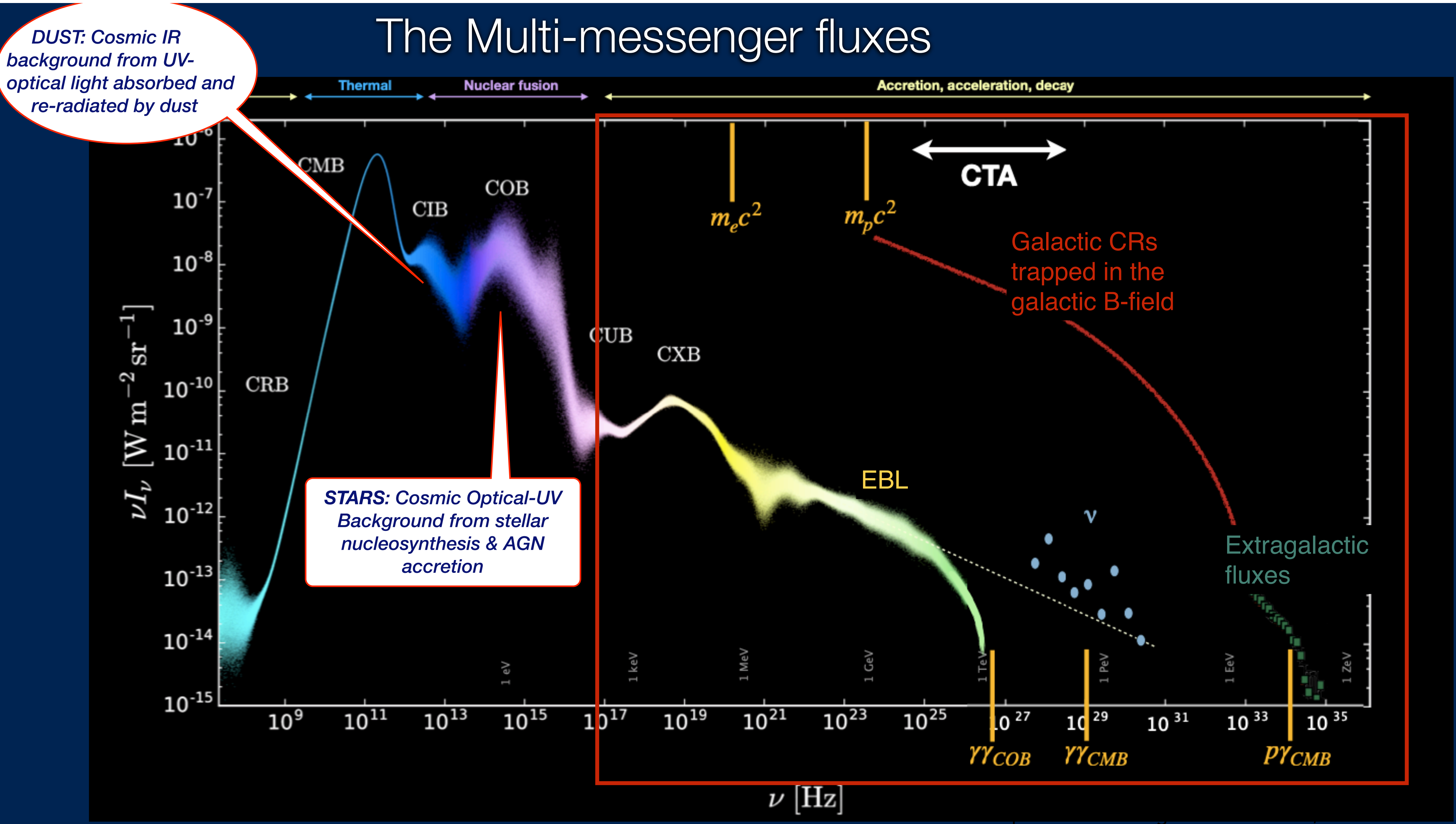


Since APPEC 2011 Roadmap, a **new revolution** in astroparticle physics started after the discovery of a diffuse flux of $\gtrsim 50$ TeV neutrinos by IceCube, the electromagnetic counterparts of GW170817 and an IceCube neutrino alert of most probable energy of 290 TeV from the region including TXS 0506+056, then found in a high state by Fermi-LAT and other IACT arrays. Acknowledged also by EPSSU and ASTRONET community consultation for its roadmap.

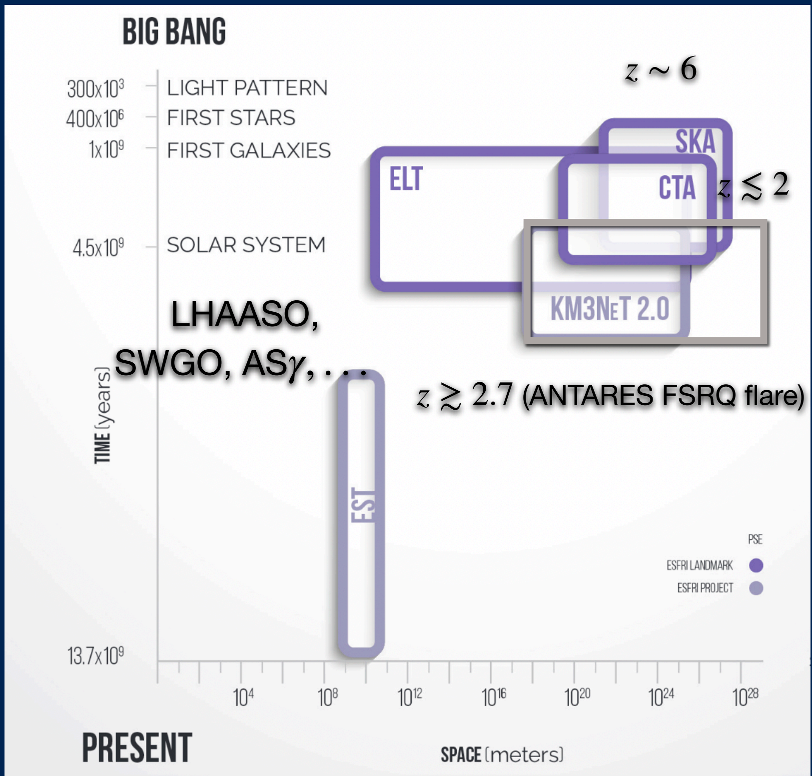
B. Astroparticle physics, coordinated by APPEC in Europe, also addresses questions about the fundamental physics of particles and their interactions. The ground-breaking discovery of gravitational waves has occurred since the last Strategy update, and this has contributed to burgeoning multi-messenger observations of the universe. ***Synergies between particle and astroparticle physics should be strengthened through scientific exchanges and technological cooperation in areas of common interest and mutual benefit.***

ASTRONET
www.astronet-eu.org
eas

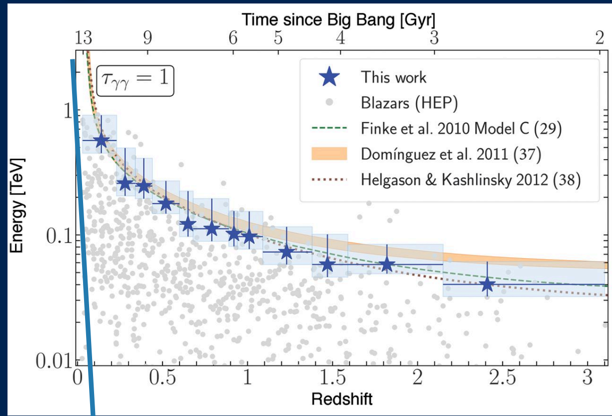
The Multi-messenger fluxes



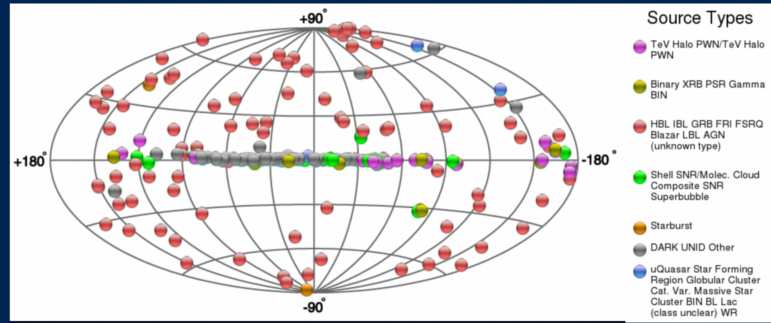
The horizon of messengers

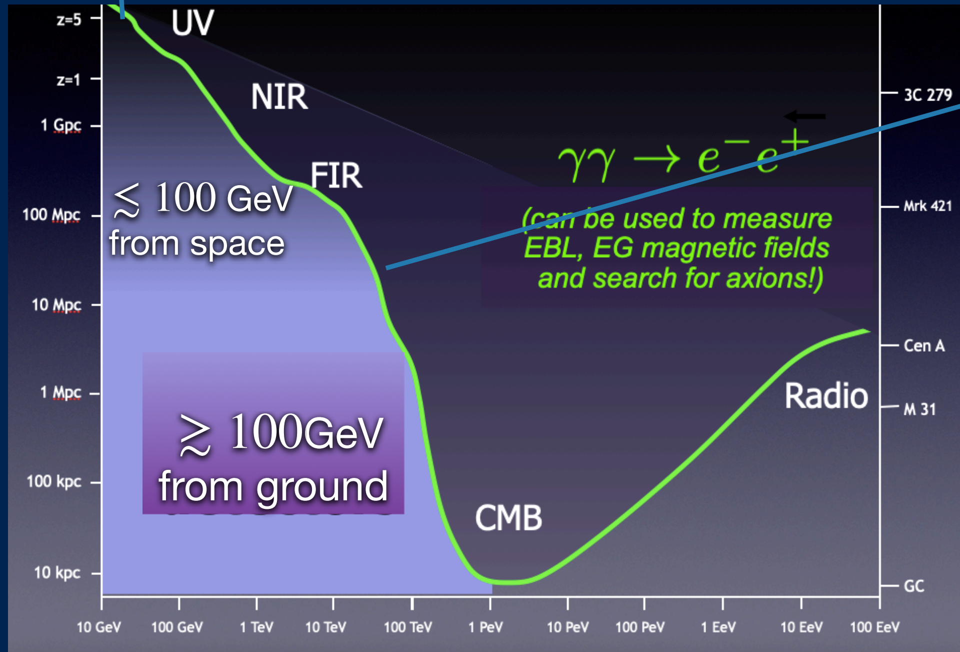


From ESFRI Roadmap 2018



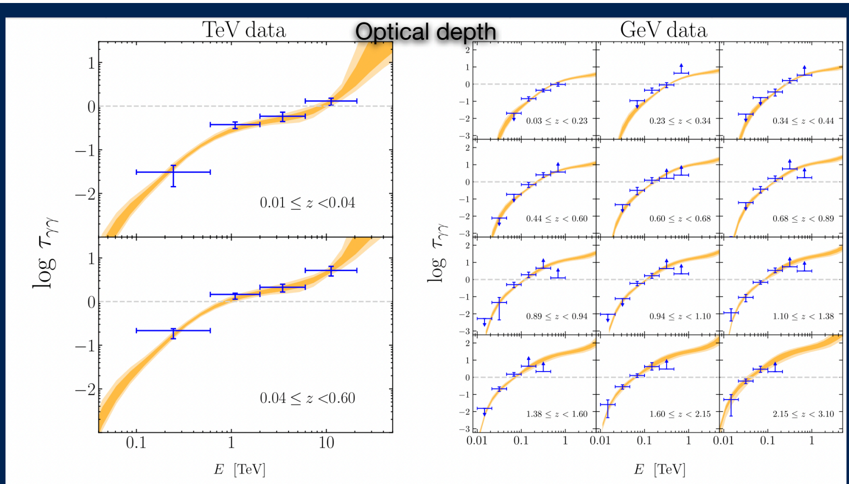
Currently 243 sources in tevcat.uchicago.edu from TeV detectors





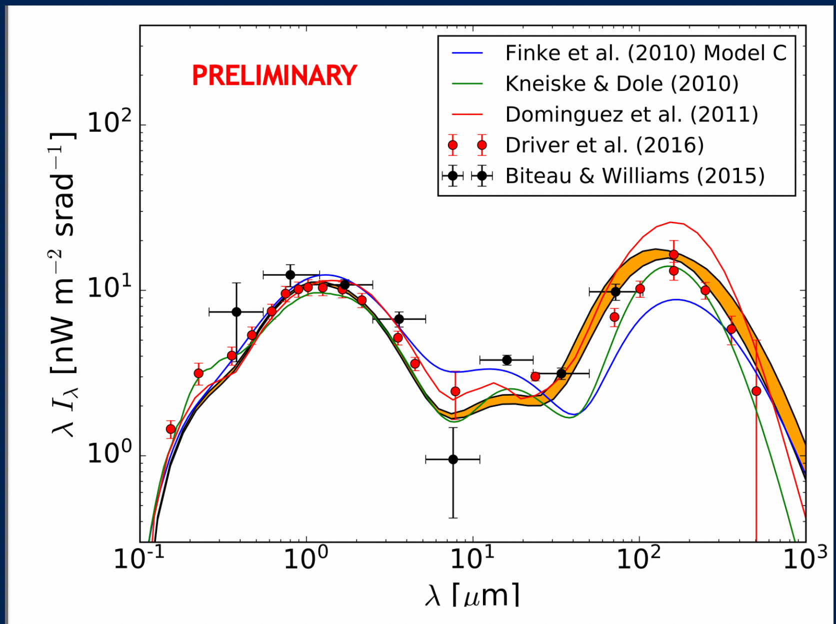
Gamma-ray horizon

Tuning the EBL model: future perspective



Desai et al. (2019) 106 VHE spectra, 38 blazars
IACTs

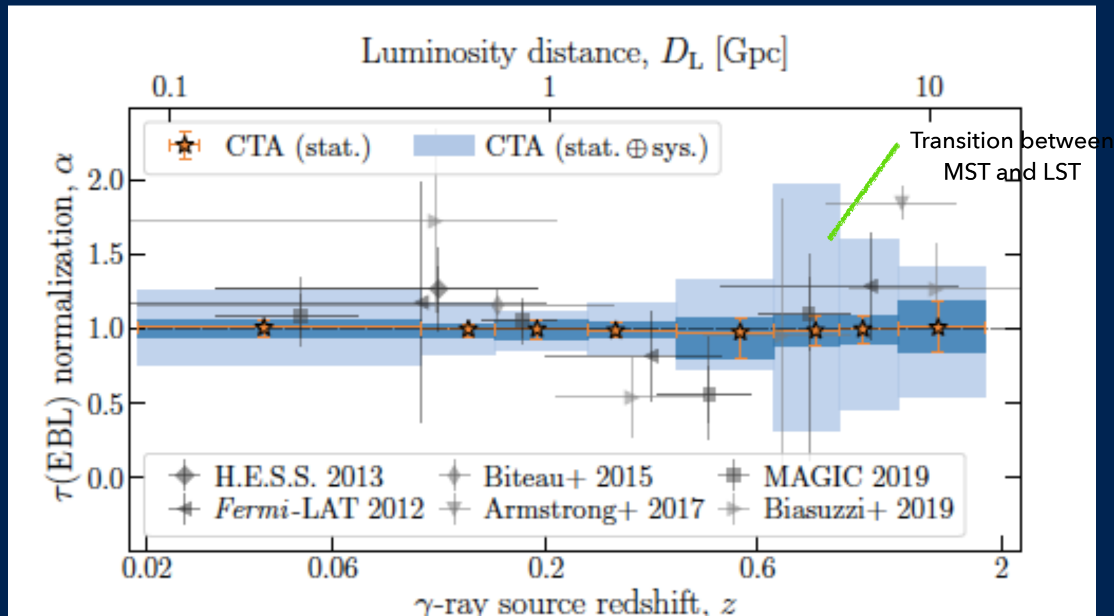
Abdollahi et al. (2018) 739 blazars
Fermi LAT



(see J. Finke 2021)

830 hours of CTA observations

H. Abdalla et al, CTA Consortium arXiv:2010.01349



The deviation of the EBL parameter : deviation from α= 1 quantifies the departure from the model, namely $\tau(E, z, \pi_{EPL}) = \alpha \times \tau(E, z)$ where π_{EBL} are the the EBL density parameters.

MAGIC arXiv:1904.00134
VERITAS arXiv:1910.00451
H.E.S.S. arXiv:1707.0609

Novel strategies for the Hubble constant

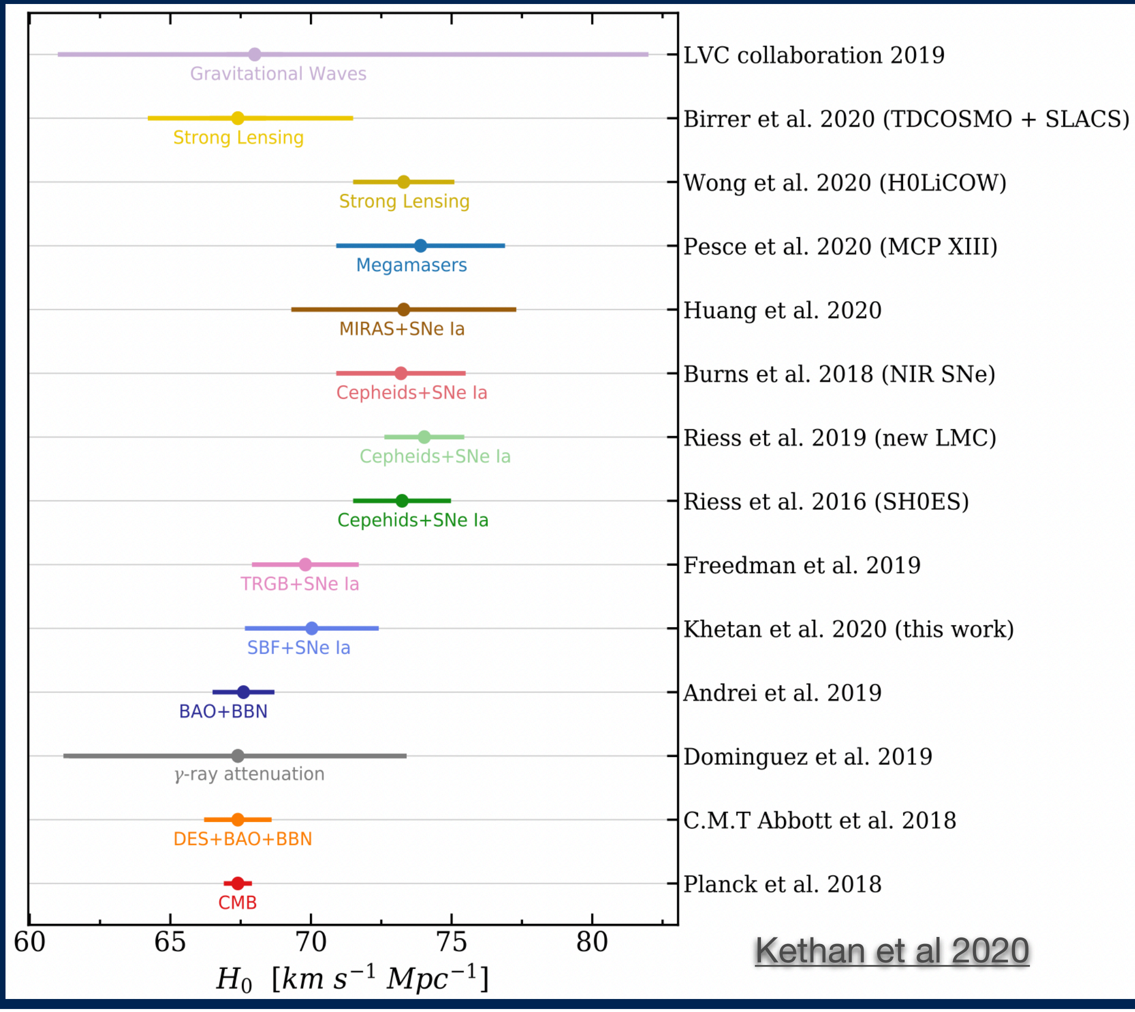
The amount of γ-ray attenuation along the line of sight depends on the expansion rate and stellar luminosity density (EBL models still affected by uncertainties).If Ω_m is not fixed, the most likely values from the γ- rays are $H_0 = 67.4^{+6.0}_{-6.2}$ kms/s/Mpc (9% error), $\Omega_m = 0.14\pm^{+0.06}_{0.07}$ (50% error).

2G: at small z: $H_0 D_L = cz$

NS-NS merger GW170817

$H_0 = 70^{+12}_{-8}$ km/s/Mpc

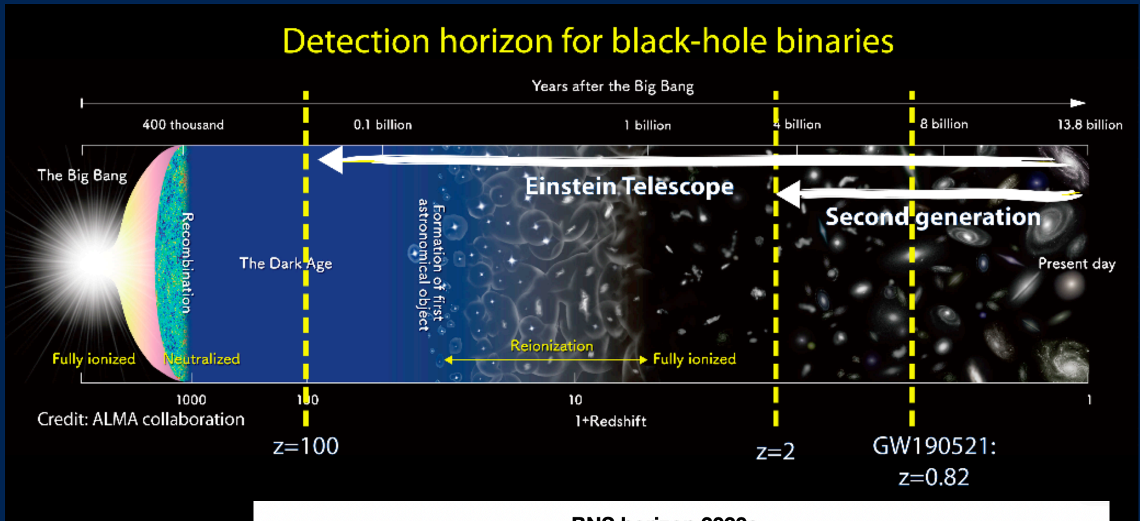
(Abbott et al.,Nature 2017) thanks to independent electromagnetic measurement of $z \sim 0.01$



Kethan et al 2020

How far can GW detectors hear?

Gravitational provide an absolute measurement of the distance of the merger (standard sirens)



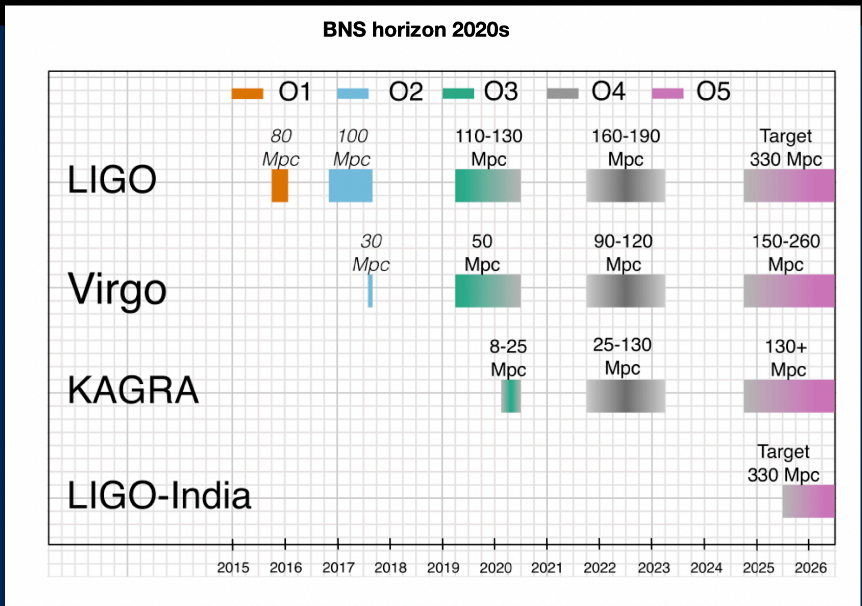
3G horizon: for moderate z

D_L depends also from $\Omega_m = \dfrac{\rho_m(t_0)}{\rho_0}$ and ρ_{DE}.

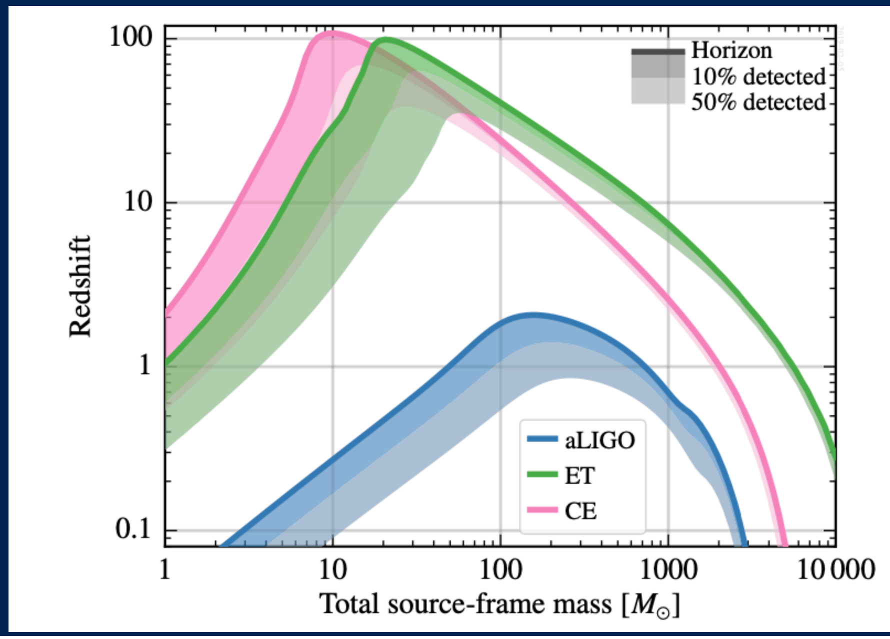
The degeneracy of the inclination angle of the plane of the system will be removed measuring the 2 polarizations (Einstein Telescope)

Hall & Evans 2019

2G horizon:

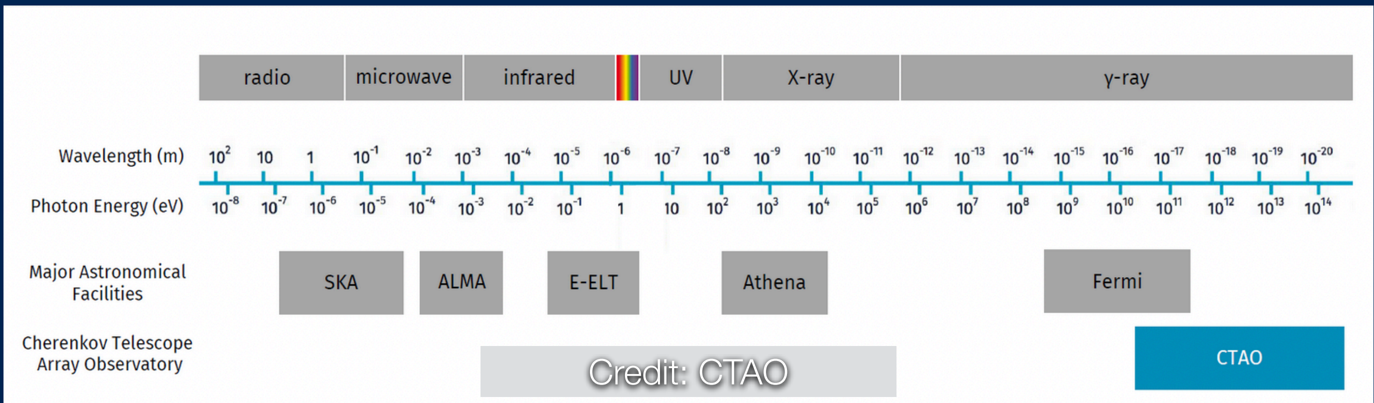


Abbott et al. 2020 LRR



Gamma-ray science cases

- ***Understanding of the origin of the cosmic rays*** in a multi-messenger context ;
- ***Probing extreme environments,*** such as neutron stars and pulsar wind nebulae, black holes and gamma-ray bursts, the physics of the jets and how particles are accelerated by them;
- ***The Galactic plane Survey*** (*deep survey to 2 mCU, faster by ~100 than current generation)*;
- ***Exploring frontiers in physics***, such as the nature of Dark Matter in the Galactic Centre, axions and their interplay with magnetic fields and photons, the extragalactic background light and how it informs on galaxy formation, and quantum gravity effects in photon propagation.



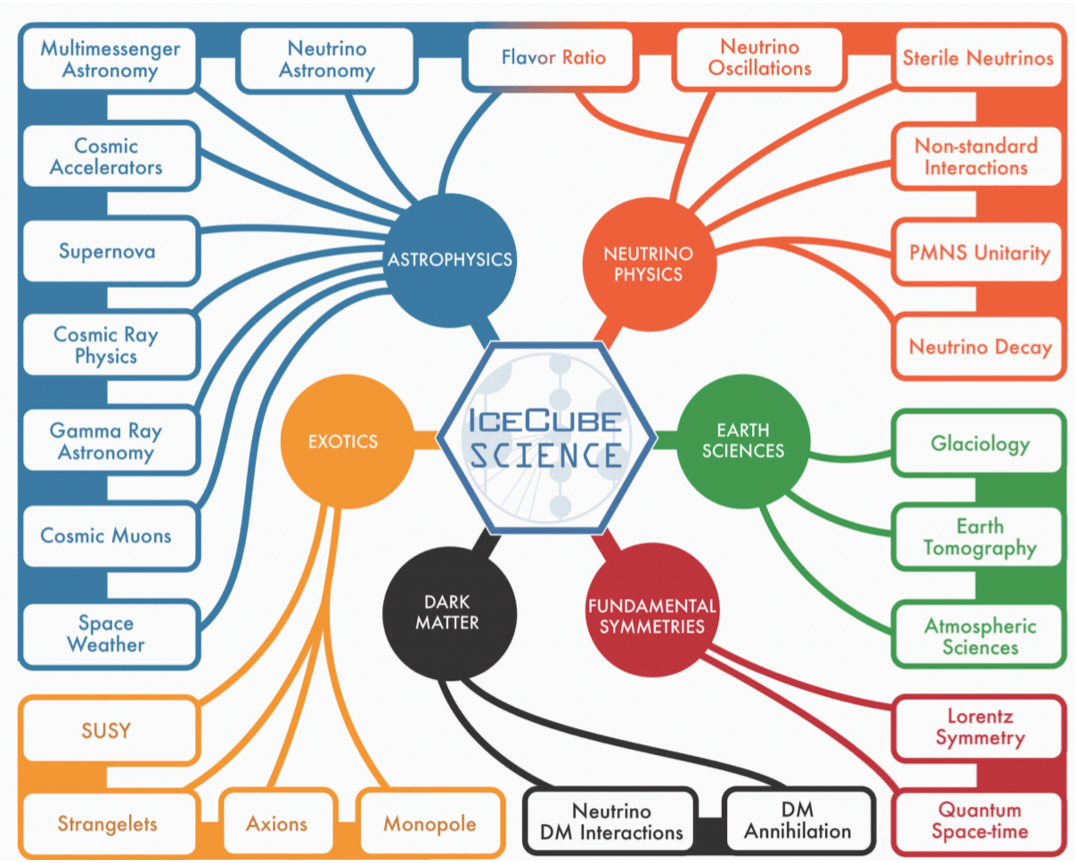
Comparison of CTAO's Energy Range to other Instruments

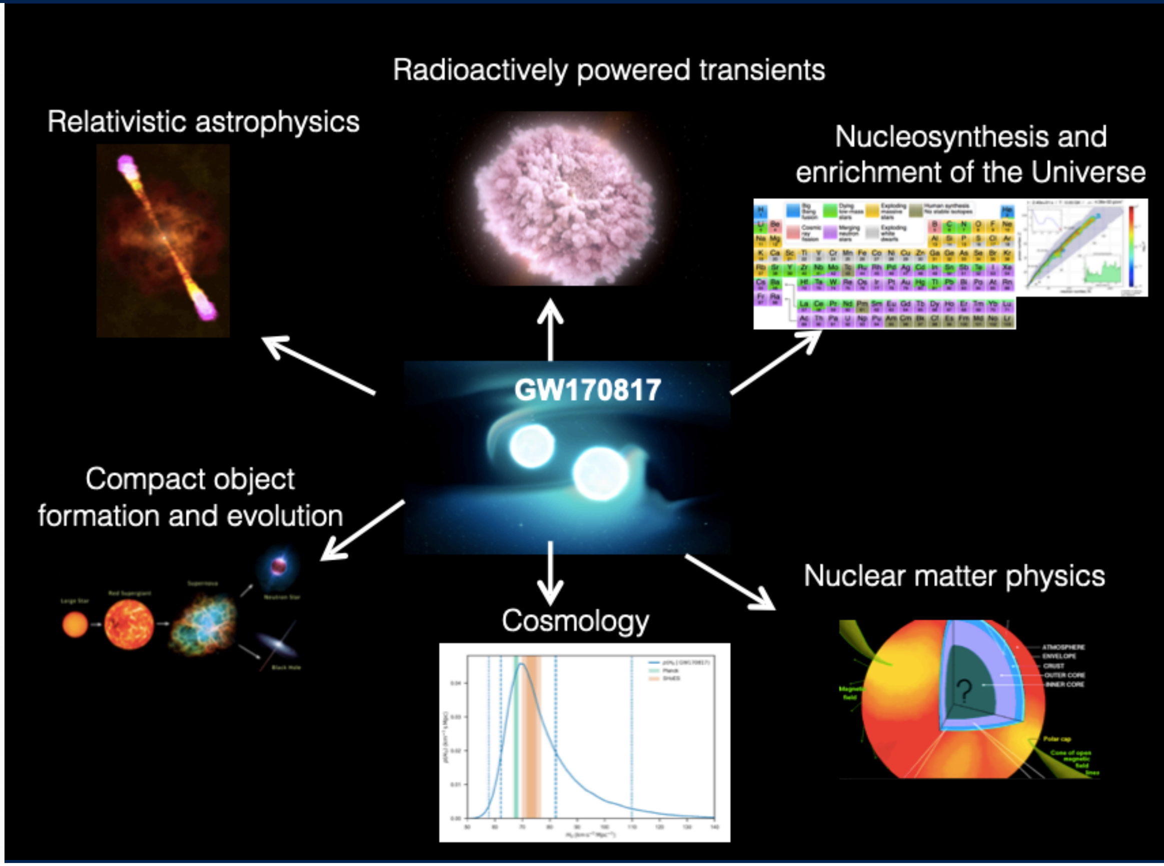
The science case of the unstoppable messengers:

See S. Nissanke's talk

IceCube-Gen2/KM3NeT

GW170817 Science LIGO / VIRGO,





Technical Global Challenges

IACTs

Interferometers

EAS-hybrid

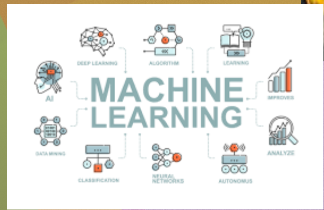
Accelerators

Neutrino Telescopes

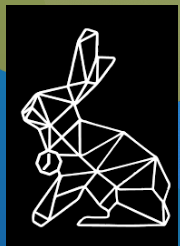
Active noise mitigation

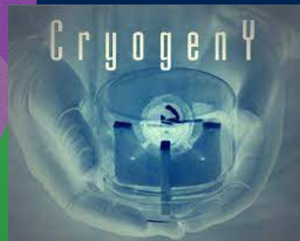
Optics, mirrors, coating

AI & Software



Fast synchronisation
Power distribution





Vacuum and cryogenics in large volumes

Remote site monitoring and Access

Integrated electronics, ASICS, FPGA

Superconducting magnets

Technical challenges : photosensors

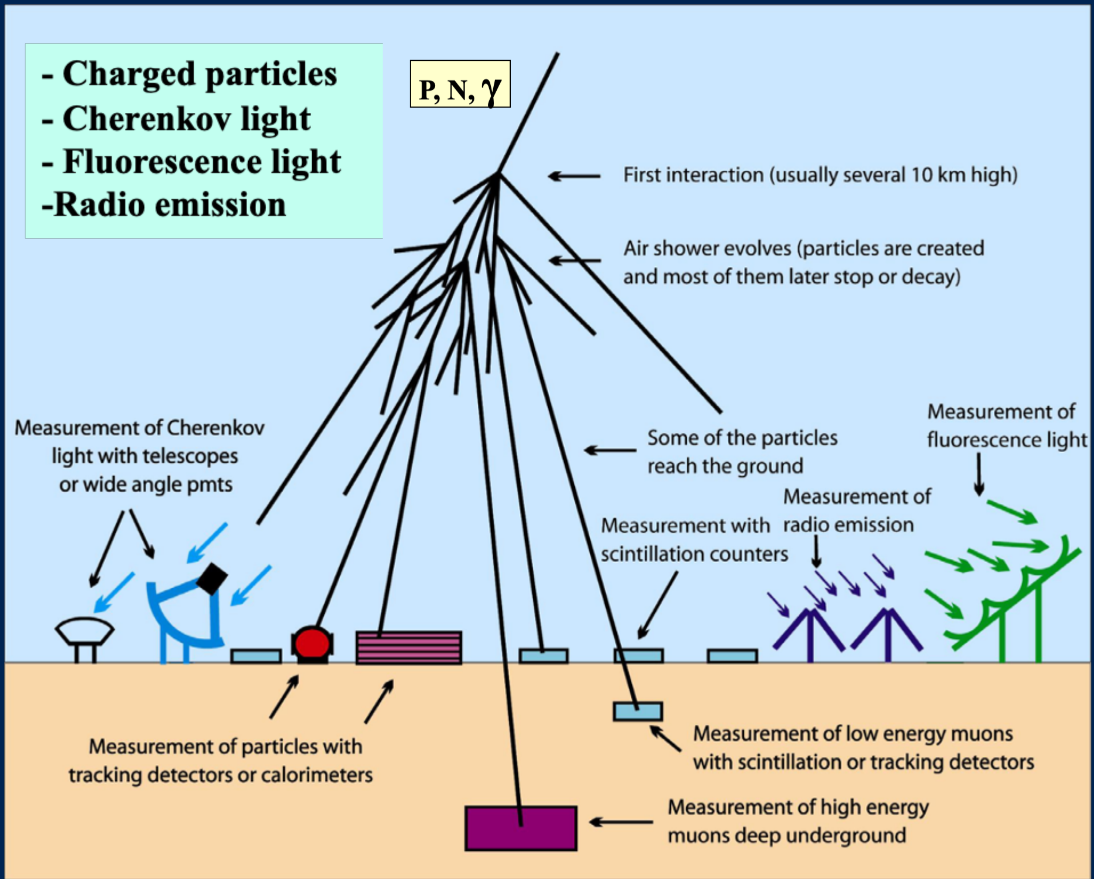
Radiation hard materials

See talks:
A. Freise

APPEC Technical Fora

Detector R&D Roadmap 2021
Ongoing

Existing technologies in Astroparticle:



Recent updates at ICRC 2021 https://icrc2021.desy.de

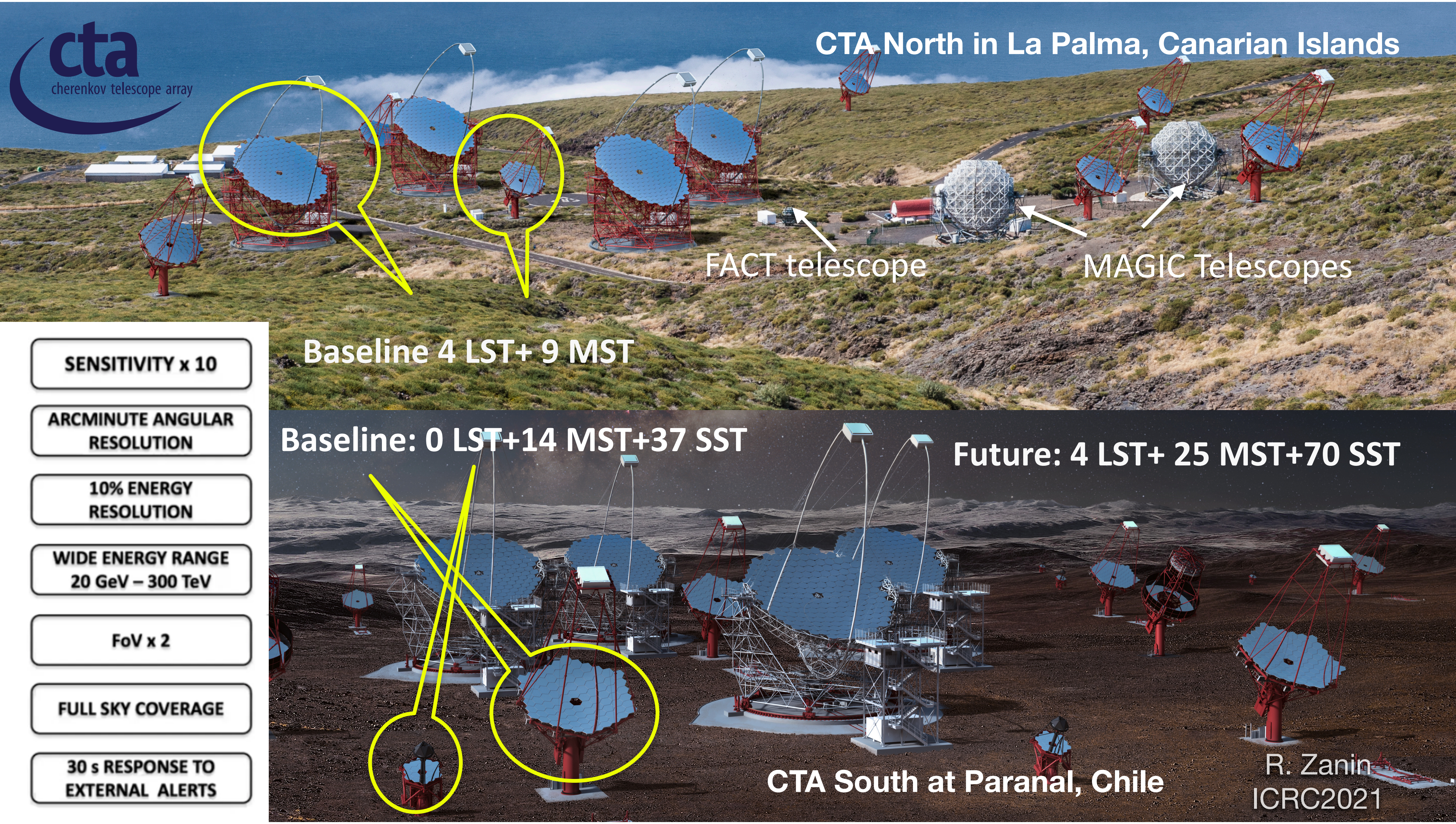
Imaging Air Cherenkov Telescopes (IACTs)

- atmosphere is calorimeter
- Sets of mirrors focus Cherenkov light pool into a fast camera in the focal plane
- Angular resolution has achieved 5'
- ~10% duty cycle due to Moon and weather
- decreasing efficiency by ~ 2% due to mirror deterioration

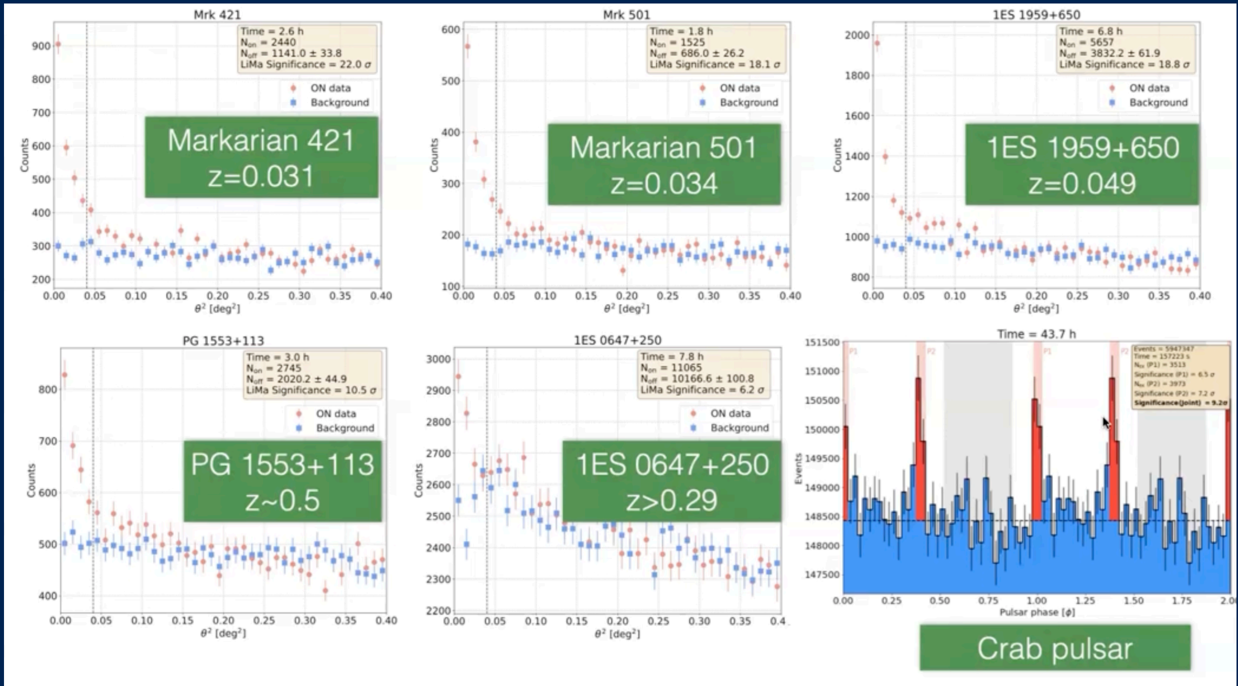
EAS and timing wide-FoV arrays : $\gtrsim$1 TeV

- collect Cherenkov radiation produced by charged particles in water tanks or ponds with photosensors which require water purification and recycling (HAWC, LHAASO, P. Auger,…)
- Often combined with EAS arrays of scintillation counters with muon trackers
- > 90% duty cycle and large FoV

The Cherenkov Telescope Array Observatory (CTAO) ~330 M€ with Alpha configuration = 64 IACTs
Large High Altitude Air Shower Observatory (LHAASO) ~150 M€
SWGO (Southern Wide Field $\gamma-$ray observatory) ~50M€

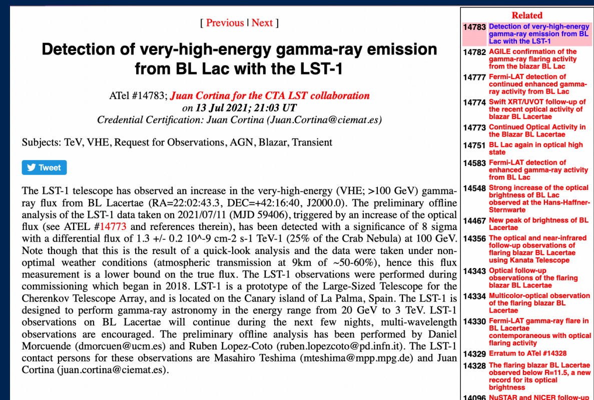

cta
cherenkov telescope array
CTA North in La Palma, Canarian Islands
FACT telescope
MAGIC Telescopes
Baseline 4 LST+ 9 MST
SENSITIVITY x 10
ARCMINUTE ANGULAR RESOLUTION
10% ENERGY RESOLUTION
WIDE ENERGY RANGE 20 GeV – 300 TeV
FoV x 2
FULL SKY COVERAGE
30 s RESPONSE TO EXTERNAL ALERTS
Baseline: 0 LST+14 MST+37 SST
Future: 4 LST+ 25 MST+70 SST
CTA South at Paranal, Chile
R. Zanin
ICRC2021

First telescope of CTAO: LST-1 in commissioning phase



D. Mazin, ICRC2021

First GCN circular on 13 July 2021



[Previous | Next]

Detection of very-high-energy gamma-ray emission from BL Lac with the LST-1

ATel #14783; *Juan Cortina for the CTA LST collaboration*
on 13 Jul 2021; 21:03 UT
Credential Certification: Juan Cortina (Juan.Cortina@ciemat.es)

Subjects: TeV, VHE, Request for Observations, AGN, Blazar, Transient

Tweet

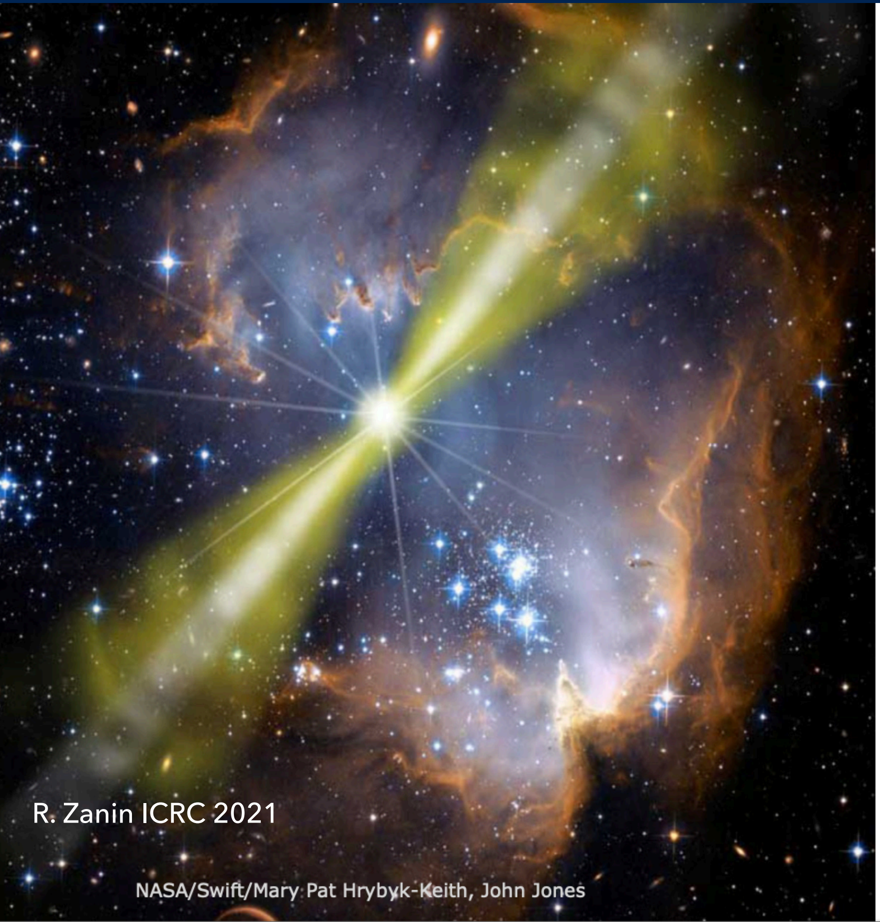
The LST-1 telescope has observed an increase in the very-high-energy (VHE; >100 GeV) gamma-ray flux from BL Lacertae (RA=22:02:43.3, DEC=+42:16:40, J2000.0). The preliminary offline analysis of the LST-1 data taken on 2021/07/11 (MJD 59406), triggered by an increase of the optical flux (see ATEL #14773 and references therein), has been detected with a significance of 8 sigma with a differential flux of 1.3 +/- 0.2 10^-9 cm-2 s-1 TeV-1 (25% of the Crab Nebula) at 100 GeV. Note though that this is the result of a quick-look analysis and the data were taken under non-optimal weather conditions (atmospheric transmission at 9km of ~50-60%), hence this flux measurement is a lower bound on the true flux. The LST-1 observations were performed during commissioning which began in 2018. LST-1 is a prototype of the Large-Sized Telescope for the Cherenkov Telescope Array, and is located on the Canary island of La Palma, Spain. The LST-1 is designed to perform gamma-ray astronomy in the energy range from 20 GeV to 3 TeV. LST-1 observations on BL Lacertae will continue during the next few nights, multi-wavelength observations are encouraged. The preliminary offline analysis has been performed by Daniel Morcuende (dmorcuen@ucm.es) and Ruben Lopez-Coto (ruben.lopezcoto@pd.infn.it). The LST-1 contact persons for these observations are Masahiro Teshima (mteshima@mpp.mpg.de) and Juan Cortina (juan.cortina@ciemat.es).

Related

14783	Detection of very-high-energy gamma-ray emission from BL Lac with the LST-1
14782	AGILE confirmation of the gamma-ray flaring activity from the blazar BL Lac
14777	Fermi-LAT detection of continued enhanced gamma-ray activity from BL Lac
14774	Swift XRT/UVOT follow-up of the recent optical activity of blazar BL Lacertae
14773	Continued Optical Activity in the Blazar BL Lacertae
14751	BL Lac again in optical high state
14583	Fermi-LAT detection of enhanced gamma-ray activity from BL Lac
14548	Strong increase of the optical brightness of BL Lac observed at the Hans-Haffner-Sternwarte
14467	New peak of brightness of BL Lacertae
14356	The optical and near-infrared follow-up observations of flaring blazar BL Lacertae using Kanata Telescope
14343	Optical follow-up observations of the flaring blazar BL Lacertae
14334	Multicolor-optical observation of the flaring blazar BL Lacertae
14330	Fermi-LAT gamma-ray flare in BL Lacertae contemporaneous with optical flaring activity
14329	Erratum to ATel #14328
14328	The flaring blazar BL Lacertae observed below R=11.5, a new record for its optical brightness
14096	NuSTAR and NICER follow-up

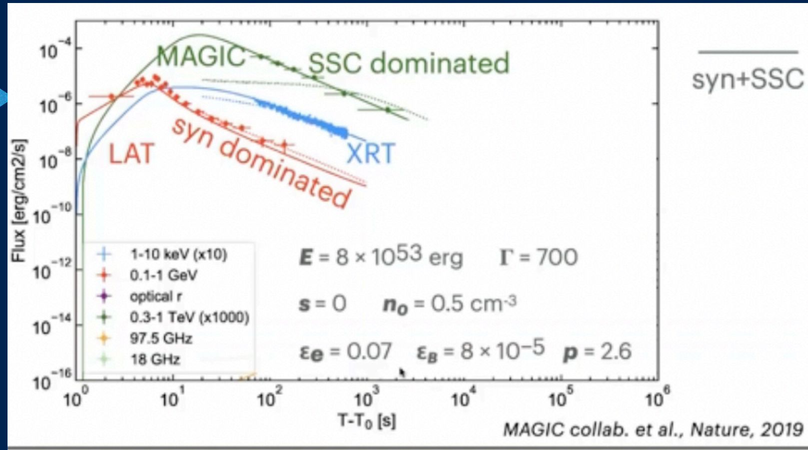
The transient domain: TeV Gamma-ray bursts

Another component in afterglow phase: Synchrotron self Compton?



- **GRB 190114C** *(MAGIC Coll., Nature, 2020)*
  - long GRB
  - z = 0.42
  - for 40' after T0 +60 s
  - 0.2 -1 TeV
  - 50σ
- **GRB 180720B** *(H.E.S.S. Coll., Nature, 2020)*
  - long GRB
  - z = 0.65
  - after T_0 + 10h
  - < 440 GeV hrs 5σ
- **GRB 190829A** *(H.E.S.S. Coll., Science)*
  - long GRB
  - z = 0.078
  - for 3 nights after T_0 + 4,3h
  - 0.18-3.3 TeV
- **GRB 160821B** *(MAGIC Coll. ApjL 2021)*
  - short GRB
  - z =0.162
  - 3σ @ E>500 GeV
  - for 4h after T_0+24s
  - → Kilonova?
- **GRB 201015A** *(PoS ID 305, Y.Suda)*
  - long GRB
  - z=0.42
  - for 3,4 h after T_0+40s
  - 3.5σ above 50 GeV
- **GRB 201216C** *(PoS ID 395, S.Fukami)*
  - long GRB
  - $\boxed{z=1.1}$
  - for 20' after T_0+56s
  - 6σ E<100 GeV
  - 5σ

6



MAGIC collab. et al., Nature, 2019

Networks of fast alerts become more and more demanding (GCN-TAN, AMON, SNEWS),… as well as classifiers (use Machine learning !)
Efficient computing facilities that address carbon footprint (see ASTRONET discussions)

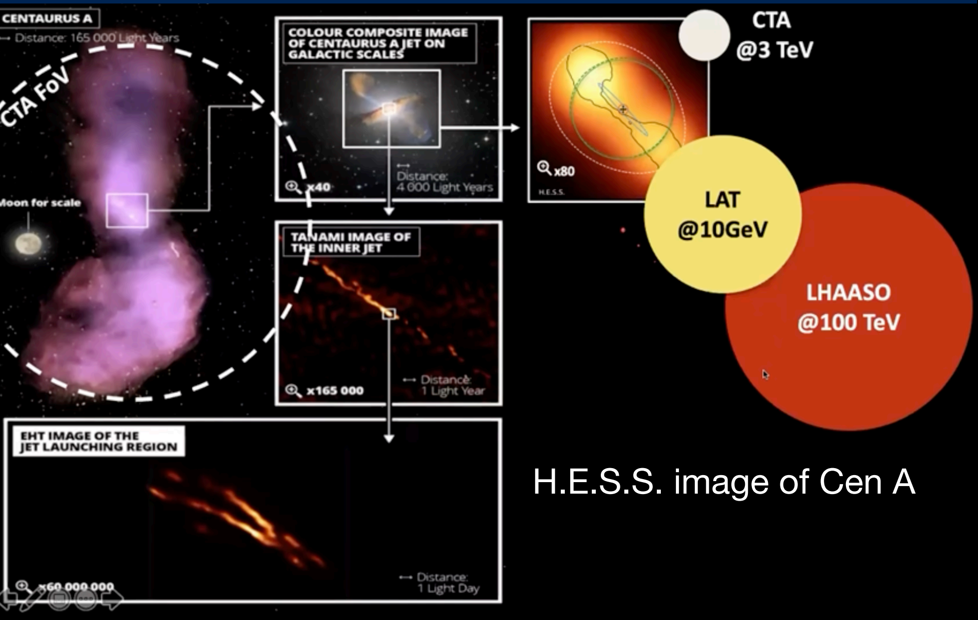
Until 2019, no detection claimed. Then 4 GRBs detected > 5σ up to z = 1.1 and 3TeV from ground by MAGIC and H.E.S.S. and 2 hints, one of a short GRBs indicating promising joint programs with GWs.
Beautiful Artist's movie from DESY: https://www.youtube.com/watch?v=oHEpiv33fZQ

See Berti's Talk

Extended sources

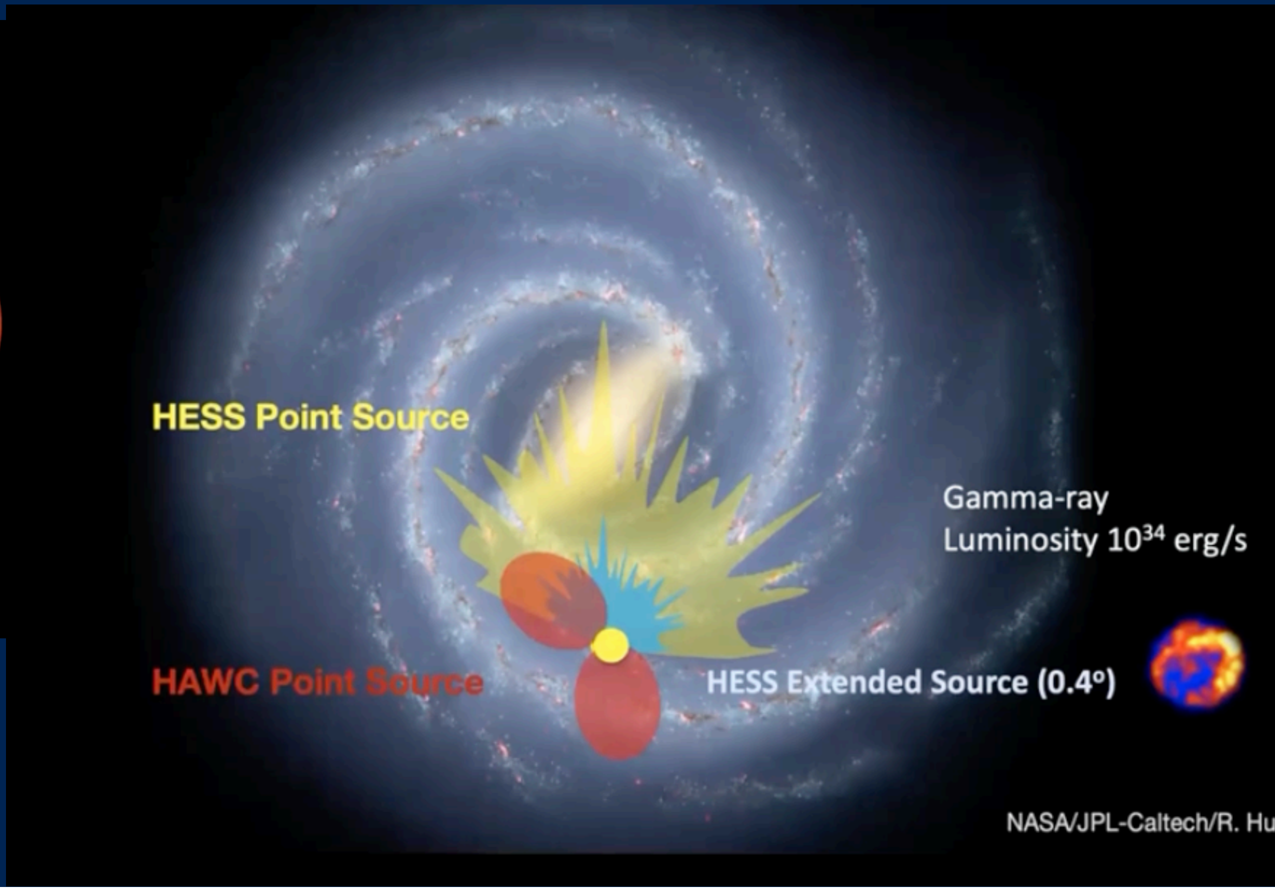
HESS sensitivity decreases with extension of sources (here 0.4°)

HAWC detected extended emission from Gaming Pulsar of 2°

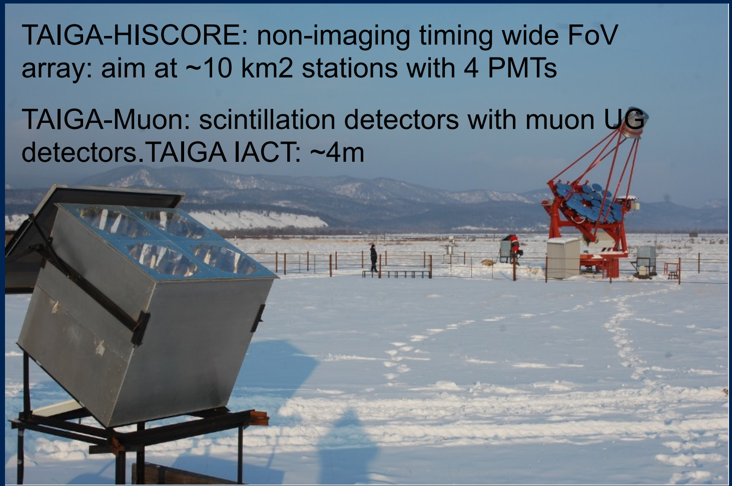


H.E.S.S. image of Cen A

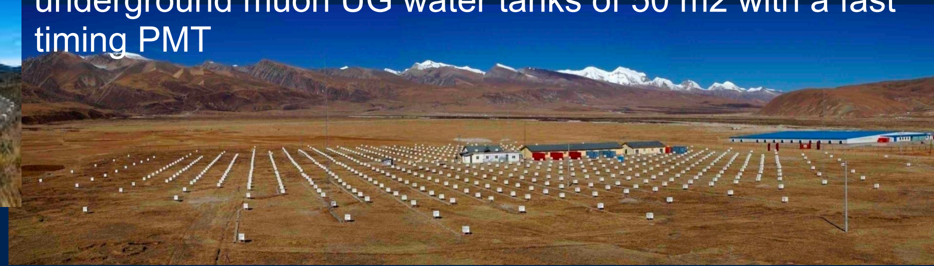
R. Zanin ICRC 2021



Non imaging wide-FoV arrays



ASγ at 4300 mil ~65’700 m2 of 597 x 0.5 + ~3400 m2 underground muon UG water tanks of 50 m2 with a fast timing PMT



Which PeVatrons explain the knee in the Galactic Cosmic Ray spectrum?

Diffuse emission from the galaxy: is there a hardening towards the GC?

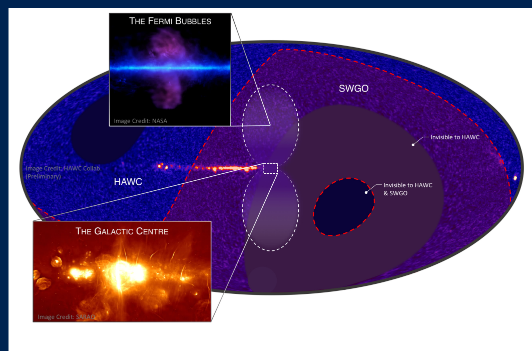
Breaking down the degeneracy between diffuse galactic photons from GCR interactions in the ISM (dominant > 100 TeV)/ IC from electrons or $p, He + \gamma \rightarrow \gamma + \ldots$ / DM / resolved sources, diffuse extra-galactic background

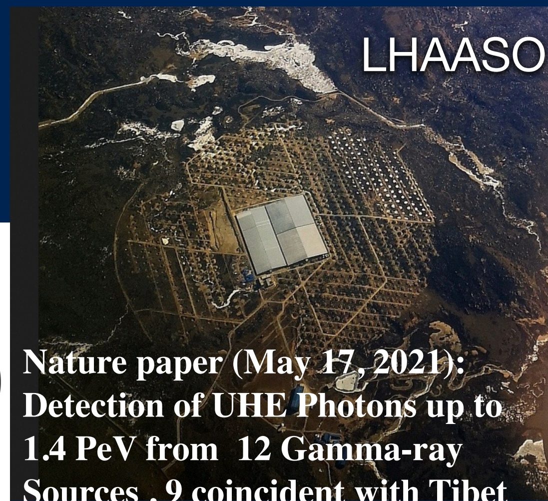
Pulsar halos, SNR+molecular clouds

Fermi bubbles and Galactic Centre for a array (SWGO)

Transients

ALPACA in construction: $83'000 \mathrm{m}^2 \mathrm{EAS} + 5'400$ underground muon stations at 4.7 km altitude Bolivia

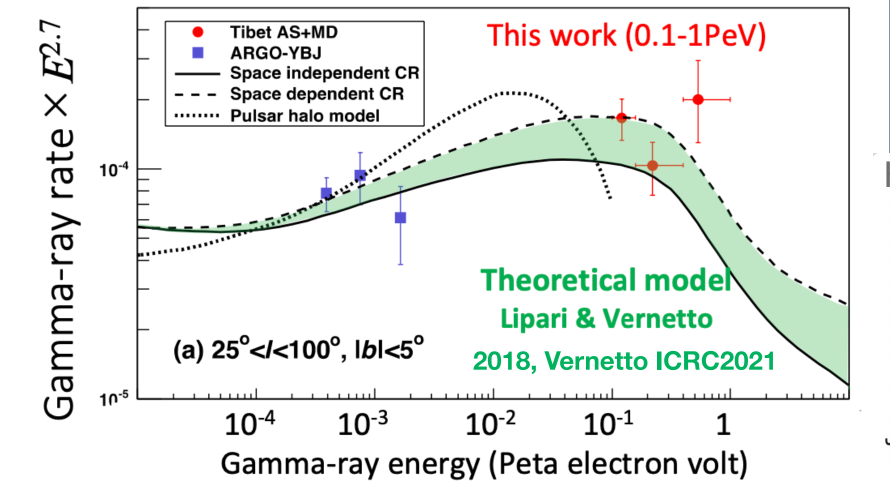


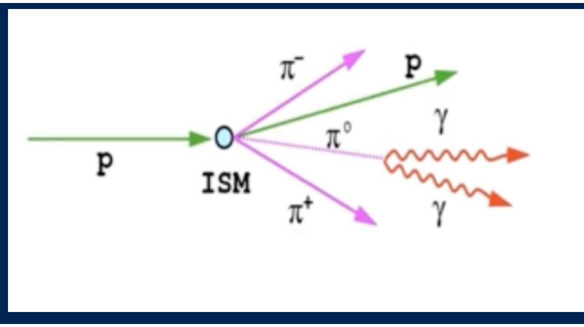


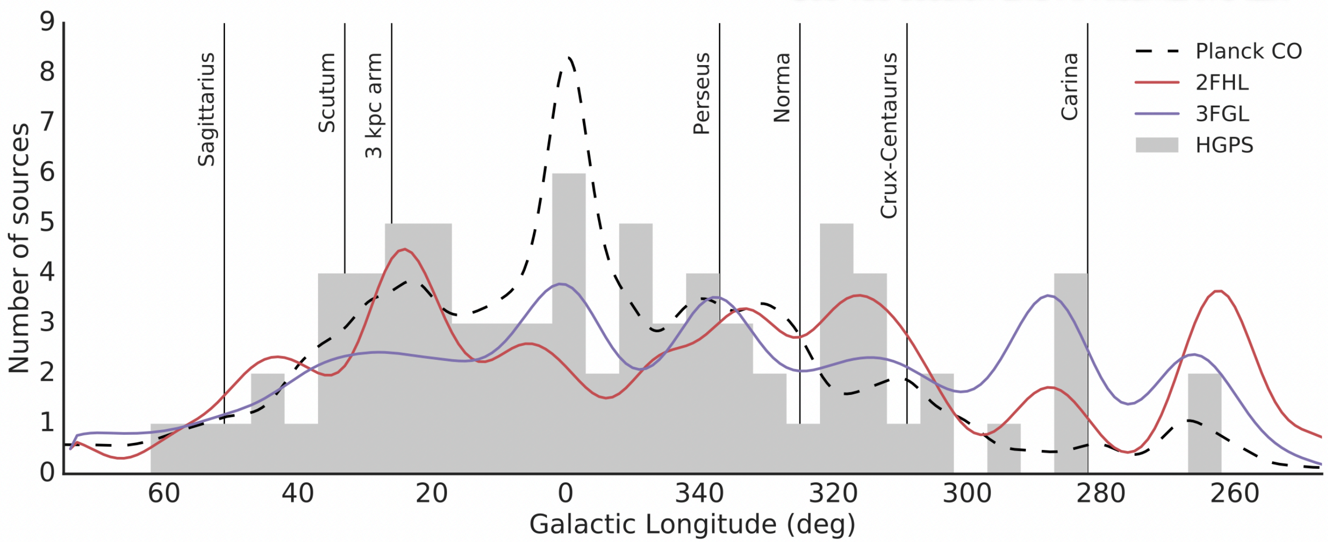
Nature paper (May 17, 2021): Detection of UHE Photons up to 1.4 PeV from 12 Gamma-ray Sources , 9 coincident with Tibet Asγ (ICRC2021)

Diffuse gamma rays

Tibet ASγ Amenomori+., PRL 126, 141101,(2021)

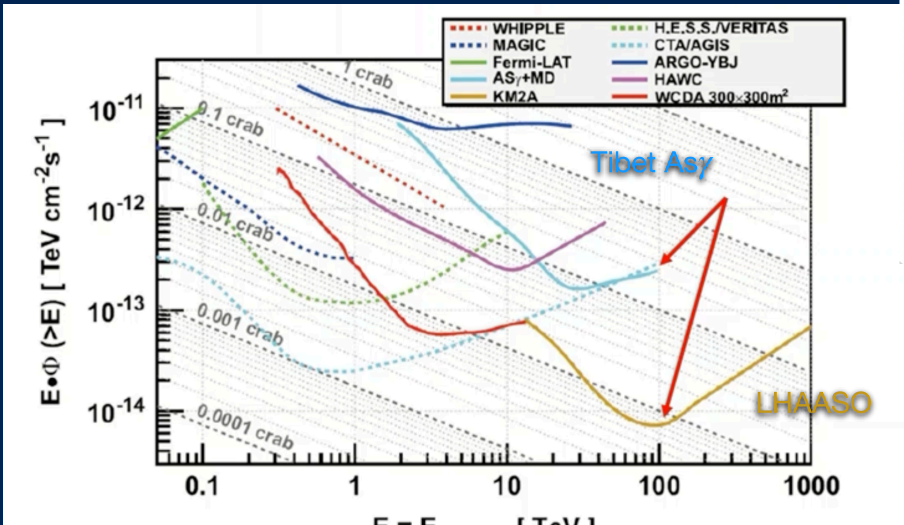






(H. E. S. S. Collaboration et al. (2018))

See Tue session and R. Kissmann's talk

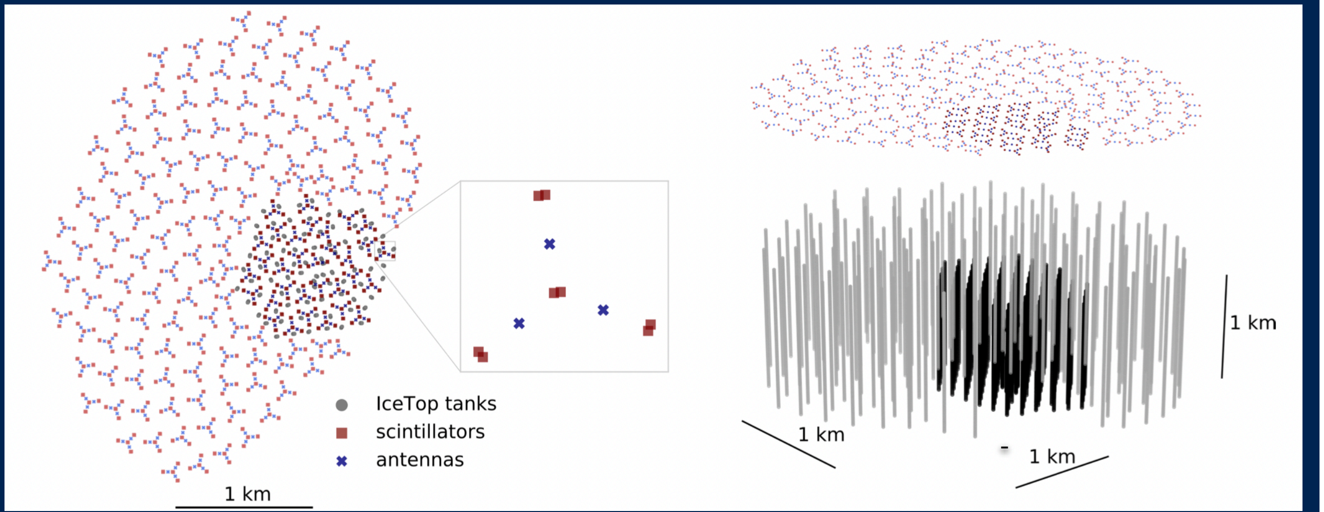


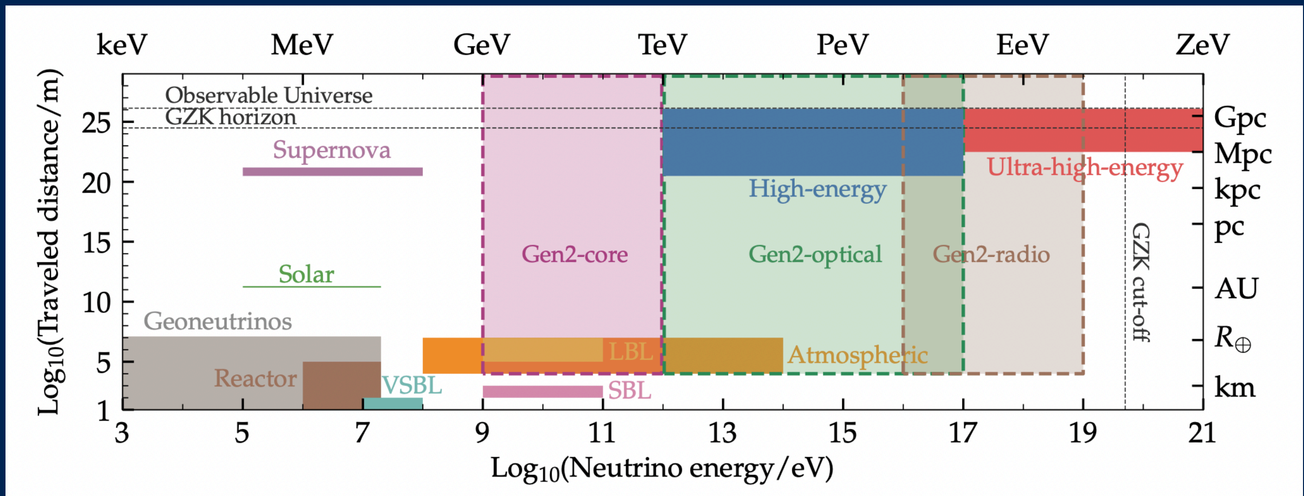
(Z. Cao, 2014)

Accelerators on the plane: PWNe, SNR, stellar clusters with massive stars and winds; decay of heavy DM? Proton cosmic ray flux uncertain by factor of 2-4. The neutrino flux from the plane seems subdominant ~10% in the diffuse IceCube flux.

Neutrino telescopes:

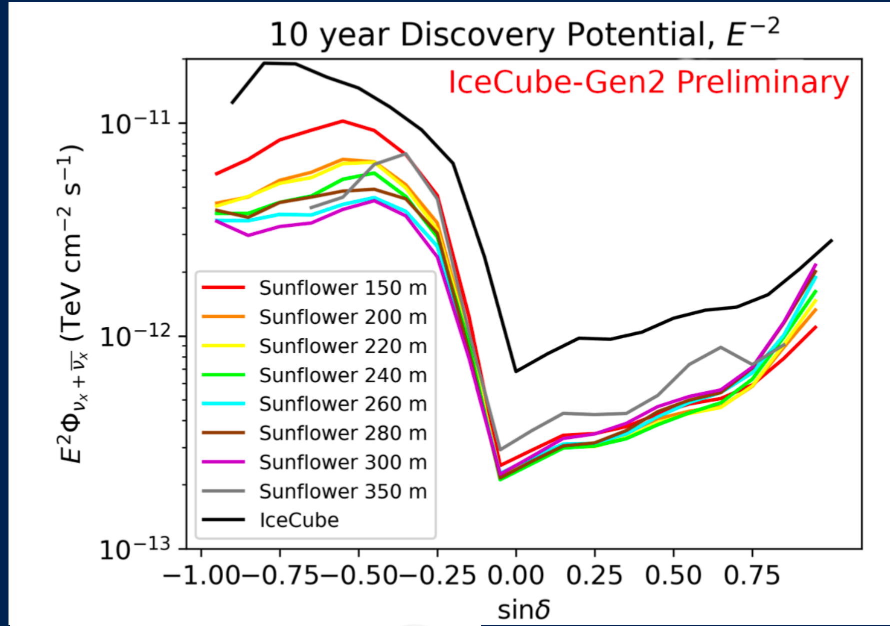
A large vetoed detector: IceCube-Gen2

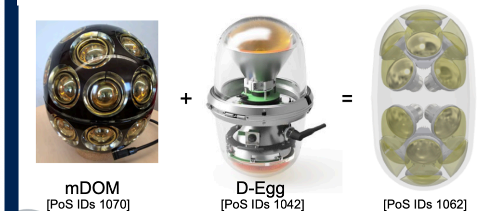




https://arxiv.org/pdf/2008.04323.pdf

Will observe fainter sources by x 5 for 250-300 m of string spacing for tracks and larger benefit for showers





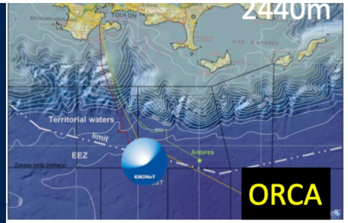
B. Clarck & A: Omeliukh ICRC2021

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031
IC Upgrade, RNO-G construction				IceCube / RNO-G Operation							
IceCube- Gen2 preparation				IceCube-Gen2 construction							

*preliminary schedule

Neutrino telescopes

Network of existing detectors: instantaneous sensitivity to horizontal tracks



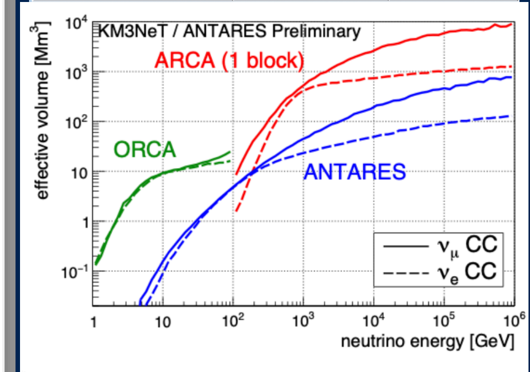
Oscillation Research with Cosmics In the Abyss

	ARCA	ORCA
Location	Italy	France
DU distance	90 m	23 m
DOM spacing	36 m	9 m
Instrumented mass	2*500 Mton	8 Mton

DU = Detector unit

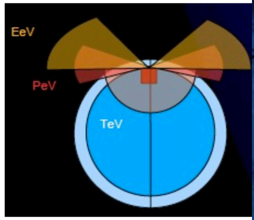
225 m-1 km size instrumented by 115 strings of 700 m / 200 m height and 18 DOMs/string

First 15 neutrinos observed



Biagi's talk

At highest energies, neutrinos don't make it through the Earth: horizontal tracks are golden channel

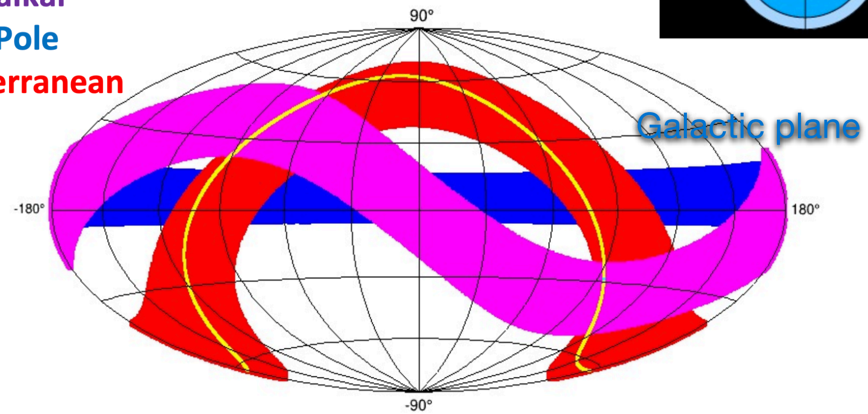


Astroparticle Research with Cosmics In the Abyss

Lake Baikal

South Pole

Mediterranean

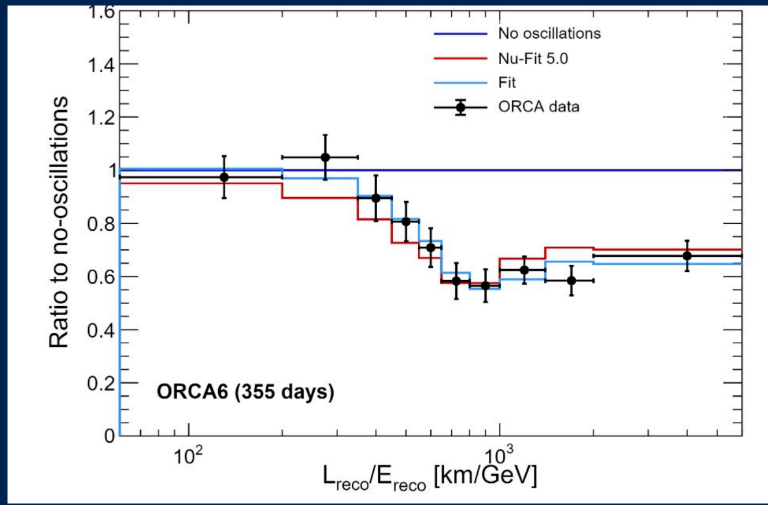


Planetary Neutrino Monitoring System (PLEnUM)): ANTARES (12 strings) in operation since 2008, KM3NeT under construction in the Mediterranean, the Gigaton Volume Detector (GVD) under construction at Lake Baikal, Russia, IceCube-Gen2 at the South Pole, and the new initiative Pacific Ocean Neutrino Explorer (P-ONE) to be installed within the Ocean Networks Canada (ONC) infrastructure in the Pacific.

GVD is currently the largest detector in the North: 0.4 km3 with 8 clusters

Completed in 2024 with 14 clusters and 4032 OMs.

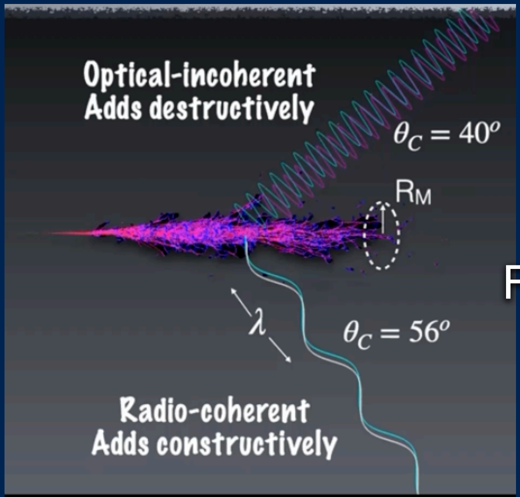
Detected first PeV event



From P. Coyle ICRC2021, L. Schumacher talk, L. Fajit's talk

Neutrino telescopes : embedded radio detectors or large volumes for skimming neutrinos

K. Hoffmann & A. Nelles ICRC2021



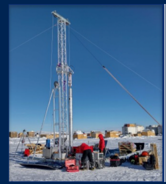
For $\lambda \sim R_M$, emission becomes coherent.

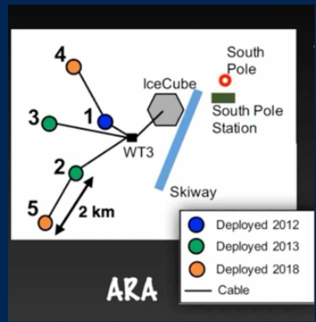
$R_M \sim 10$ cm in ice.

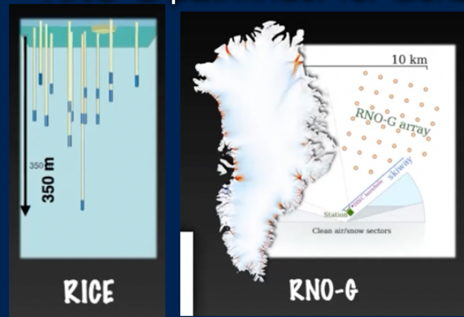
Field strength increases with shower energy.

Becomes visible for $E_{sh} > 10^{16}$ eV.

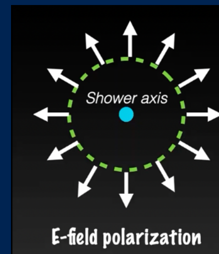
RNO-G pathfinder for Gen2-Radio



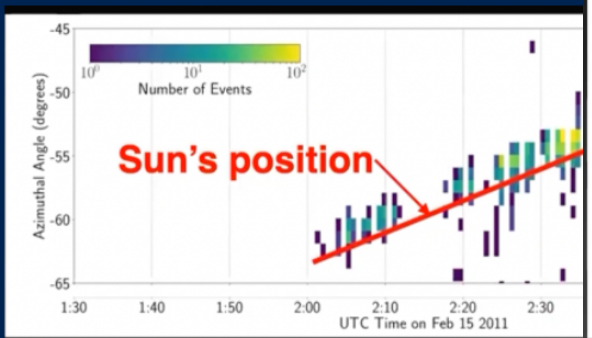


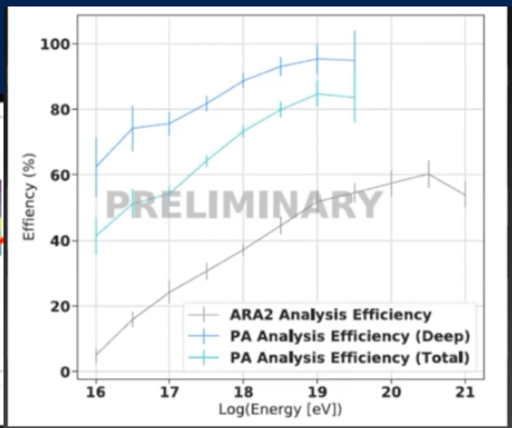


Direction determined from polarisation of the electric field perpendicular to Cherenkov cone.

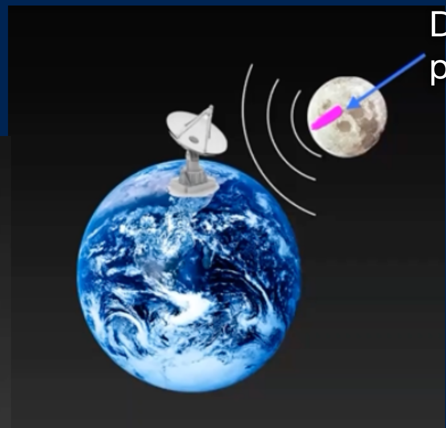


Tracking the position of the Sun during a solar flare (1807.03335)
ARA's Phase array (trigger adds waveforms assuming delays from 15 directions since S adds coherently and N not) lowers the E threshold

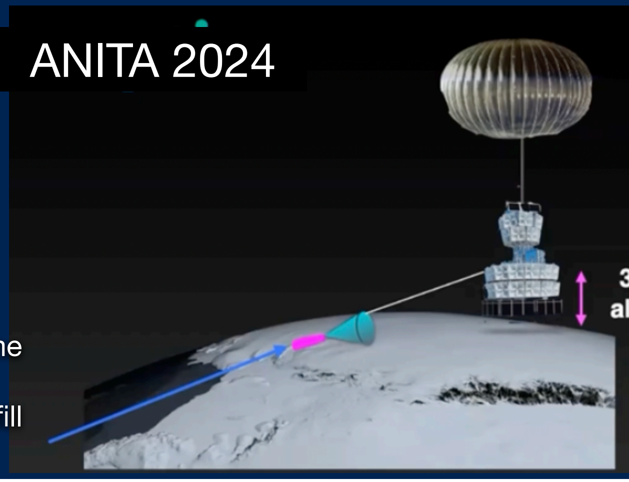




Delay between 2 antennas provides angle of plane wave



Large volume and Energy to overcome 1/R fall off with distance of signal.
Using Cherenkov can lower Eth and fill the gap between optical and radio

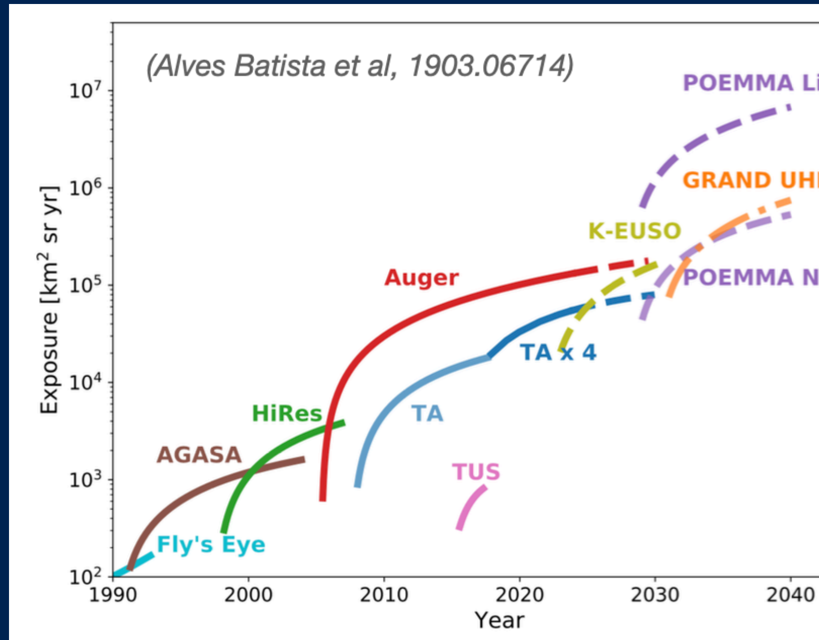


UHE and UHECRs

Radio will be playing a big role in the larger arrays for neutrinos and UHECRs.
Space projects will extend the reach as well.

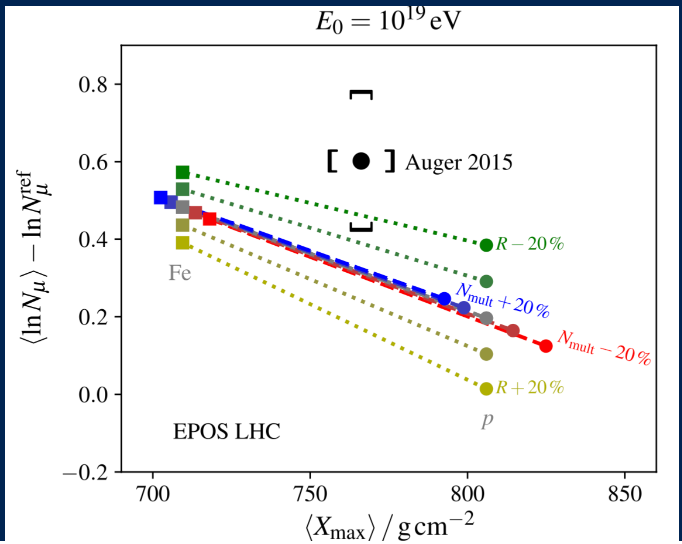
Strong-links of UHECRs hadronic interaction models with LHC experiments with forward capabilities : The muon excess observed by Auger implies that less energy in CR showers with E> 10^{18} eV goes into π^0. The possibility of reducing R comes from the ALICE discovery of enhancement of strangeness production in pp, pPb, Pb-Pb.

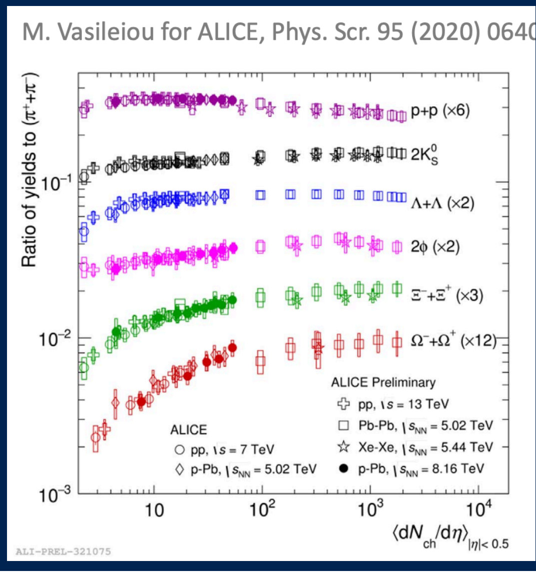
$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

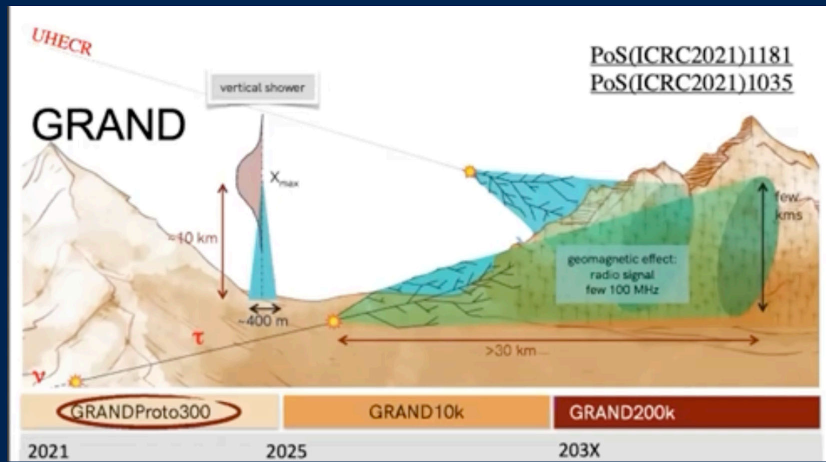


200 000 km^2 radio detector array in China

Dembinski's talk ICRC2021





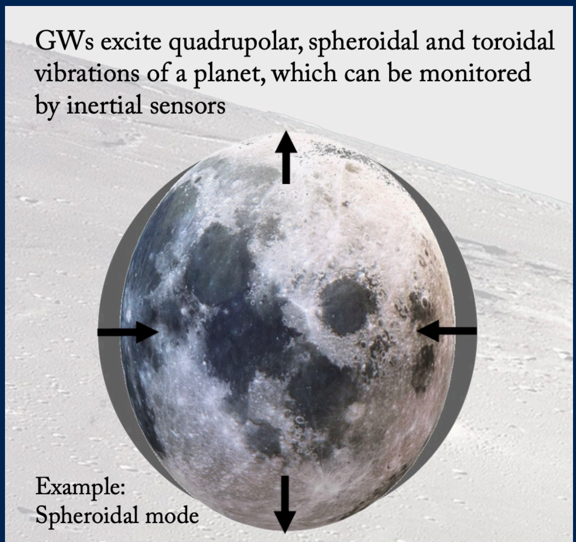


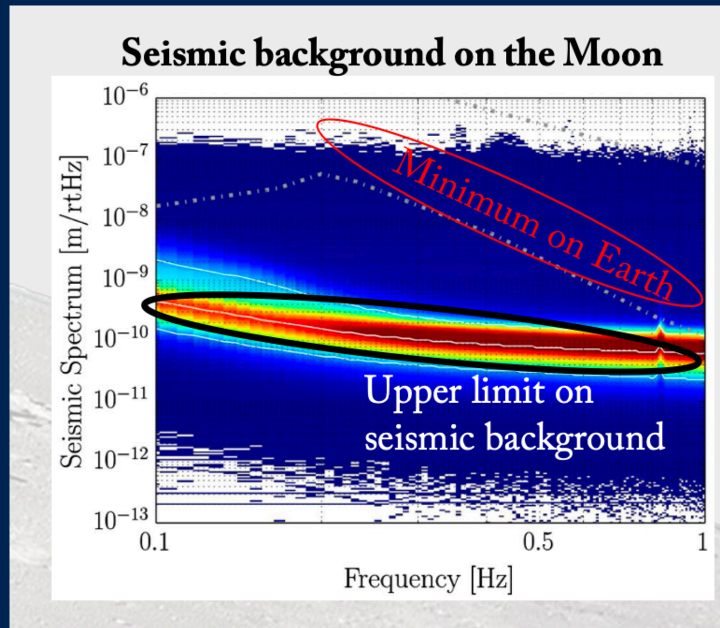
Further in the future…

Body is the moon, readout through seismometers, optical readout, magnetic levitation of a test mass

Synergy with LISA

J. Harms' talk





1 mHz-1 Hz