The multi-wavelength and multi-messenger context I

Ulisses Barres de Almeida

Brazilian Center for Physics Research (CBPF)
• Posing the problem
• Setting up the stage
• CTA as a player in the MWL-MM scene
• CTA MWL-MM Coordination activities
• The CTA MWL Synergies
Posing the Problem
Perspective of Cosmic-ray Physics

1912 – V Hess descobre radiação cósmica
1912 – Wilson inventa a câmara de núvens (primeira ferramenta para se observar a radiação)

1919 – Ernest Rutherford descobre o próton;
1932 – James Chadwick descobre o neutron;
1932 – Carl Anderson descobre o positron;
1933 – Pierre Auger detecta chuveiros atmosféricos
1936 – Carl D. Anderson descobre o lepton muon ao estudar a radiação cósmica;
1936 – Pierre Auger identifica chuveiros atmosféricos formados por um único raio-cósmico energéticos (E até $10^{15}$ eV)

1947 – George Rochester e Clifford Butler descobrem o kaon, a primeira partícula estranha;
1947 – Cecil Powell, César Lattes e Giuseppe Occhialini descobrem o lepton pion;
1955 – Owen Chamberlain descobre o antiproton;
1956 – Clyde Cowan e Frederick Reines descobrem o neutrino (do elétron);
1962 – Leon M. Lederman, Melvin Schwartz e Jack Steinberger descobrem o neutrino do muon;
1974 – Burton Richter e Samuel Ting descobrem a partícula $J/\psi$ composta de quarks charm;
1977 – Partícula Upsilon descoberta no Fermilab, demonstra a existência do quark bottom;
1979 – O Gluon é observado diretamente em eventos tri-jet no DESY;
1983 – Carlo Rubbia e Simon van der Meer descobrem os bosons W e Z;
1995 – Quark top é descoberto no Fermilab;
2000 – Estudos do neutrino do tau no Fermilab
2012 – Higgs boson descoberto no CERN - Large Hadron Collider (LHC).

Discoveries in the laboratory (radiation)
Discoveries with cosmic-rays
Discoveries in accelerators
Revolutions in experimentation

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

Discoveries in the laboratory (radiation)
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The fundamental question: Origin of Cosmic Rays

Dipole above EeV, with amplitude growing with energy.
The fundamental question:
Origin of Cosmic Rays

The Astrophysical relevance importance of cosmic-rays:

\[ E_{CR} \sim E^* \sim E_{CMB} \sim E_{\text{mag}} \sim E_{k,\text{gas}} \sim 1 \text{ eV/cm}^3 \]

\[ \Sigma_{\text{total}} \sim 10^{49} \text{ J na Galáxia} \]
The fundamental question: Origin of Cosmic Rays

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

- **energy density:** ~ 1 eV/cm³ (~ CMB, gas, B, etc.)
- **age:** ~ 10^7 yrs,
- **production rate:** (0.3-1) x 10^{41} erg/s, source
- **spectrum:** hard, Q(E) ~ E^{-2.1} x E^{-0.6} ~ E^{-2.7}

**Sources?** Strong shocks with enhanced magnetic fields (SNRs)
Stellar winds, such as in cluster and OB associations, galactic center, etc.
The fundamental question: Origin of Cosmic Rays

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

energy density: $\rho \approx 1 \text{ eV/cm}^3$ ($\sim$ CMB, gas, B, etc.)
age: $\sim 10^7$ yrs,
production rate: $(0.3-1) \times 10^{41}$ erg/s, source
spectrum: hard, $Q(E) \sim E^{-2.1} \times E^{-0.6} \sim E^{-2.7}$

Sources? Strong shocks with enhanced magnetic fields (SNRs)
Stellar winds, such as in cluster and OB associations, galactic center, etc.

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

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

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

$$dE/dt = f \varepsilon \ E \approx 10^{34} \text{ J/s}$$
The fundamental question: Origin of Cosmic Rays

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

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

Extragalactic Cosmic Rays - certainly above the ankle

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

:: "Local fog" - extragalactic (but also Galactic) cosmic-rays (arXiv: 1003.0082v1)
The fundamental question: Origin of Cosmic Rays

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

energy density: \( \sim 1 \, \text{eV/cm}^3 \) (\( \sim \) CMB, gas, B, etc.)
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production rate: \((0.3-1) \times 10^{41} \, \text{erg/s, source} \)
spectrum: hard, \( Q(E) \sim E^{-2.1} \times E^{-0.6} \sim E^{-2.7} \)

Interaction with CMB

Above \( E \sim 6 \times 10^{19} \, \text{eV} \) protons rapidly lose energy by photo-pions production at an energy loss rate of circa \( \sim 15\% \) per interaction (very efficient!)

Interaction length 5-10 Mpc

Universe is opaque \( E > 5 \times 10^{19} \, \text{eV} \).
The spectrum suffers a cutoff (cosmic-ray absorption from distant sources, > 100 Mpc)
Potential sites for ZeV CRs

Hillas Plot: "B - L relation" based on the most trivial confinement condition for acceleration \( L > R_L \)

\[
B_{\mu G} L_{\text{Mpc}} > 2 E_{21}/Z\beta
\]

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

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

\( \Rightarrow L > \eta (1/2) R_L (\eta \sim 1, \text{extreme}) \)

- absence of radiation losses, important in compact objects

Potential sites for the ZeV CRs

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

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$=>$ $L > \eta (1/2) R_L (\eta \sim 1, \text{extreme})$

- absence of radiation losses, important in compact objects

Potential Sources?

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

Hillas Plot: "B - L relation" based on the most trivial confinement condition for acceleration \( L > R_L \)

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- absence of radiation losses, important in compact objects

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

The probe of the astrophysical origins of cosmic rays depends on proper astronomical messengers, i.e. stable and neutral … among which gamma-rays are unique carriers of information about non thermal phenomena, both on Galactic and extragalactic sources.

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

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

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

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Setting up the Stage
1st July, 1989

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

Since then, we have learned much an been much surprised by the Crab

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

Cherenkov Astronomy has reached the status of "real astronomy"

- good-resolution skymaps, ~ 5'
- 200+ sources detected
- spectra from c. 30 GeV to 30 TeV
- times resolved light curves down to minute timescales
Today, gamma-ray astronomy counts over 250 sources thanks to the Imaging Atmospheric Cherenkov Technique, working between 0.1 and 100 TeV

- 1989: Whipple first detection of a TeV gamma-ray source
- 1990s 2nd Generation: HEGRA, CAT - recognized as the most advanced field of astroparticle physics, but still few (c. 10) sources
- 2000s 3rd Generation: HESS, MAGIC, VERITAS - revolution and rise of a new astronomical discipline (hundreds of sources)
- 2010 CTA: Start of CTA planning, the worldwide gamma-ray observatory
Principais resultados da Astronomia Gama

- **HESS**, High energy particle acceleration in the shell of a supernova remnant, *Nature* 432, 75-77 *(2004)*
- **HESS**, Discovery of very high energy gamma rays associated with an X-ray binary, *Science* 309 746-749 *(2005)*
- **HESS**, Fast variability of Tera-Electron Volt gamma-rays from the radio galaxy M87, *Science* 314, 1424 - 1427 *(2006)*
- **HESS**, Discovery of very-high-energy gamma-rays from the Galactic Centre ridge, *Nature* 439, 695-698 *(2006)*
- **HESS**, H.E.S.S. observations of the Galactic Center region and their possible dark matter interpretation, *PRL* 97 221102 *(2006)*
- **MAGIC**, Variable very-high-energy gamma-ray emission from the microquasar LS I+ 61 303, *Science* 312 ,1771–1773 *(2008)*
- **HESS**, The energy spectrum of cosmic-ray electrons at TeV energies, *PRL* 101, 261104 *(2008)*
- **HESS**, Limits on an energy dependence of the speed of light from a flare of the active galaxy PKS 2155-304, *PRL* 101, 170402 *(2008)*
- **VERITAS**, M87 - Gamma-rays from the edge of a supermassive black hole, *Science* 325, 444, *(2009)*
- **HESS**, Search for a Dark Matter annihilation signal from the Galactic Center halo with H.E.S.S. *PRL* 106, 161301 *(2011)*
Principais resultados da Astronomia Gama

• MAGIC, Black hole lightning due to particle acceleration at subhorizon scales, Science, 346,1080 (2014)
• HESS, Search for dark matter annihilations towards the inner Galactic halo from 10 years of observations with H.E.S.S., PRL 117, 111301 (2016)
• HESS, Acceleration of petaelectronvolt protons in the Galactic Centre, Nature 531, 476 (2016)
• HAWC, Extended gamma-ray sources around pulsars constrain the origin of the positron flux at Earth, Science 6365, 911-914 (2017)
• HAWC, Very high energy particle acceleration powered by the jets of the microquasar SS 433, Nature 562 82-85 (2018)
• MAGIC, Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A, Science, 361 eaat1378 (2018)
• HESS, A very-high-energy component deep in the gamma-ray burst afterglow, Nature 575 464 (2019)
• HESS, Resolving the Crab pulsar wind nebula at teraelectronvolt energies, Nature Astron. 476 (2019)
• MAGIC, Observation of inverse Compton emission from a long γ-ray burst, Nature, 575, 459-463 (2019)
• TIBET, First detection of photons with energy beyond 100 TeV from an astrophysical source, PRL, 123, 051101 (6 pp.) (2019)
• VERITAS, Direct measurement of stellar angular diameters by the VERITAS Cherenkov Telescope, Nature Astron. 3: 511 (2019)
• HESS, Resolving acceleration to very high energies along the jet of Centaurus A, Nature 82, 356–359 (2020)
• MAGIC, Bounds on Lorentz invariance violation from MAGIC observation of GRB 190114C, PRL 125 021301 (2020)
• VERITAS, Demonstration of stellar intensity interferometry with the four VERITAS telescopes, Nature Astron. (2020)
• HAWC, Hawc observations of the acceleration of very-high-energy cosmic rays in the cygnus cocoon, Nature Astron. (2021)
• LHAASO, PeV gamma-ray emission from The Crab Nebular, Science, 08 Jul (2021)
Astroparticle Physics: MM scenario

Astronomy with photons

Charged cosmic-ray physics: p, e-, He, Fe, ...

Neutrino signals

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

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Non-thermal Astrophysics

Astro-particle Physics

SNRs
Dark Matter
Pulsars/PWN
Gravitational Waves

Binaries
Shocks
Fermi Mechanism

Starbursts
SN activity
Cosmic rays

AGN
SMBH accretion, jets

GRBs

VHE $\gamma$-rays

Unknollns
(Gal Center)

Dark Matter

Cosmological Fields

PBHs, QGrav

Slide from Rene Ong
Connecting the puzzle

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

- \( p^+, \text{He}, \text{Fe}, \ldots \)
- \( p^+, e^- \)

Only charged particles are accelerated in EM fields.

- Interactions with matter and photon-fields
- Synchrotron in B-fields, inverse-Compton...
- \( p^+, \text{inefficient} \)

\( \pi^+/- \rightarrow \pi^0 \rightarrow \mu^+/- \nu_\mu \)

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

\( \gamma \gamma \)

- Easy detection
- MM Astronomy: Directionality information preserved, but strong backgrounds.

Gamma-rays are the cornerstone of multi-messenger astrophysics

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Anatomy of a relativistic astrophysical source

- **Gamma ray production**
  - Protons
  - Pion decay: \( \pi^0 \rightarrow \gamma \gamma \)
  - Electrons: Inverse Compton Scattering: \( e^\pm \gamma \rightarrow e^\pm \gamma \)

**Energy flux/Decade**

- Accelerated particles + B-field (Synchrotron radiation)
- Accelerated particles + photons (Inverse Compton)
- Hadrons + X (Pion decay)
- CMB, IR, VIS
- Synchrotron
- Inverse Compton

© plot by Christian Stegmann, DESY, MG XIV Meeting 2015 (modified)
Electron PeVatrons and hadronic X-rays?

The synchrotron spectrum of sources like the Crab Nebula point towards multi-100 TeV electron populations. MeV Sy emission could be the result from primary accelerated, or secondary multi-100 TeV electrons produced from proton interactions => hadronic marker at hard X-rays (also ambiguous and model dependent)

(1) $pp(\gamma) \Rightarrow \pi, K, \Lambda$; (2) $\pi, K, \Lambda \Rightarrow \gamma, \nu, e, \mu$

(3) $eB \Rightarrow X$-rays

(1) $p\gamma \Rightarrow e^+e^-; (2) eB \Rightarrow X$-rays
Gamma-ray signals: source + target

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

The gamma-rays track, therefore the target, and not necessarily the sources of particle acceleration.
Gamma-ray source around W28

Cosmic-rays from an old SNR interacting with matter from a surrounding molecular cloud?
CTA SYNERGIES WITH MWL INSTRUMENTS

Target selection & ToOs

Object characterization

Wide-band / MM SED

SKA

ALMA

Athena, eROSITA

LIGO, VIRGO, KAGRA, ET

ELT, LSST, ...

Fermi

IceCube KM3NeT
CTA SYNERGIES WITH MWL INSTRUMENTS

© slide by Werner Hofmann, modified

- Non-thermal emission in radio
- High-resolution VLBI to image emission zones
- Mapping of the diffuse gas (CR targets) to complement CTA view of diffuse emission around accelerators
- Detection of fast-variability signals from compact sources
- Optical polarimetry to isolate non-thermal component in mixed emission scenarios
- X-ray study of shock regions, accretion, high-speed outflows, which connect back to particle acceleration
- Soft gamma-ray telescopes for detection of high-energy transients

MWL
Multi-messenger Phenomenology

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

- Attempt at a neutrino / VHE connection for TXS 0506+056
  IceCube / Fermi-LAT / MAGIC
  2018 - Science 361, 6398

- TeV Observations of event GW 170817
  Upper-limits from HESS.
  2017 - ApJL 850, L22
  Upper-limits from Fermi-LAT.

- GRB detection at VHE: a breakthrough and a gateway to probing GW events at TeV energies
  GRB 190114C / MAGIC early afterglow detection (< 100s)
  GRB 190829A / HESS late afterglow detection (> ks)
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  early afterglow detection (< 100s)
  GRB 190829A / HESS
  late afterglow detection (> ks)
The CTA Context
Gamma-ray ground-based facilities

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

**Particle arrays** - LHAASO & SWGO = unprecedented all-sky coverage at VHE-UHE for alert and monitoring, as well as all-sky surveys.
### WHAT DRIVES HIGH IMPACT SCIENCE?

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

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- **New instrument**
- **28 m telescope CT5 added**
- **CT1-4 camera upgrade**
- **CT5 camera upgrade**

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

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

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

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Thanks to Werner Hofmann
CTA as a player in the MWL+MM arena

**Neutrinos**
IceCube, KM3Net

**Gamma-rays**
Fermi, LHAASO, IACT...

**Gravitational Waves**
LIGO, VIRGO, KAGRA

**Cosmic rays**
AMS-02, Auger,...

**MWL Facilities**
Alma, Athena, E-Rosita, SKA, LSST, Livingston, Hanford
MM Perspective from Astro 2020

Gravitational Waves
- nHz: NANOGrav, NANOGrav expanded, SKA bolsters nHz efforts
- mHz: mHz GW community development
- kHz: Advanced LIGO/Virgo/Kagra, Improved Advanced LIGO, Cosmic Explorer

Neutrinos
- VHE: IceCube, IceCube-Gen2 (VHE and UHE)
- UHE: Discovery uncertain

Gamma Rays
- HE: Swift/Fermi, Impending gap in monitoring capabilities, New Probes for Multi-Messenger Astro
- VHE: IACTs/HAWC/LHAASO, LHAASO, CTA and SWGO

Cosmic Rays
- VHE: AMS/DAMPE/CALET
- UHE: Auger/TAx4

HE: MeV-GeV, VHE: TeV-PeV, UHE: EeV-ZeV

Existing/planned projects
Missing capabilities
Endorsed projects
CTA as a player in the MWL+MM arena

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

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

A powerful and large precision instrument in the TeV range

Operations expected to start in 2027: contemporaneous to a new generation of MWL and MM instruments
KEY SCIENCE PROJECTS
provide legacy data sets and data products

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

Thanks to Franz Longo
CTA Transient and MM Programme

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

- **Gamma-ray bursts (GRBs)**, external alerts from monitoring facilities. Simulations of a realistic GRB populations estimate CTA detection prospects to few GRBs per year.

- **Galactic transients**, serendipitous detection of a wide range of galactic transients expected from CTA regular Galactic Plane Survey monitoring: flares from pulsar wind nebulae (PWN), X-ray binaries, novae, microquasars, magnetars, etc.

- **High-energy neutrino transients**, CTA strategy is to follow-up (golden) neutrino to maximize the chance of detecting a VHE counterpart.

- **GW transients**, follow-up by CTA can play a unique role to ID counterparts thanks to large FoV and divergent pointing strategy.

- **Core-collapse Supernovae**, investigation of CTA prospects in detecting a wide range of different types of CCSNe and their different signature in the VHE regime.

https://www.cta-observatory.org
Multi-messenger research will require large cooperation between CTA and other facilities, operating at all bands of the EM and at different ‘messengers’.

**Key elements being**

- Ability to receive alerts from many different sources, which will be implemented in CTA via a dedicated ‘transient handler’
- Ability to deliver alerts in near real-time to the external astrophysical community for follow-up by other instruments
CTA: alert and follow-up system

CTAO

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

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

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

Detailed operations requirements under development
CTA follow-up observation strategy

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

I. Start with highest probability position, favoring lowest Z

II. Optimise exposure time based on source model

Fully automatic tiling observation strategy
CTA follow-up observation planning

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

- GRB population study: POSyTIVE (Ghirlanda+2019)
- Neutrino source population: FIRESONG (Tung+2021)

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The neutrino event IC 170922A

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

IC 170922A : High-energy, through-going track
TXS 0506+056 : An extreme blazar
Coincidence at the 3.5 sigma level
The neutrino event IC 170922A

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

Tidal disruption event coincident with IceCube neutrino
The neutrino event IC 170922A

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

- THE ANSWER IS ON PUBLIC ALERT STREAMS (ACTIVE SINCE 2016)
- SHORT TIME DELAYS (~ MIN) FROM TRIGGER TO PUBLIC ALERT
- A LARGE NETWORK FOR FOLLOW-UP OF NEUTRINOS WITH HIGH SIGNAL PROBABILITY (GOLDEN):
  GAMMA-RAY SATELLITES AND GROUND-BASED, X-RAY SATELLITES, OPTICAL TRANSIENT FACTORIES.
The steep path towards GW-VHE connection

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

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

- **GRB 190114C** *(MAGIC Coll., Nature, 2020)*
  - long GRB at $z = 0.42$
  - early detection at $T_0 + 60s$ (2 ks),
  - $E = [0.2, 1] \text{ TeV}$

- **GRB 180720B** *(H.E.S.S. Coll., Nature, 2020)*
  - long GRB at $z = 0.65$
  - late detection after $T_0 + 10h$

- **GRB 190829A** *(H.E.S.S. Coll., Science, 2020)*
  - long GRB at $z = 0.078$ (very close!)
  - for 3 nights, after $T_0 + 4h$
  - $E = [0.2, 3.3] \text{ TeV}$

  - short GRB at $z = 0.162$
  - data taking starting at $T_0 + 24s$, for 4h
  - $3\sigma$ hint, $E > 500 \text{ GeV}$

- **GRB 201015A** *(ICRC 2021, PoS ID 305, Y.Suda)*
  - long GRB at $z = 0.42$
  - early detection at $T_0 + 40s$
  - $3\sigma$ hint, $E > 500 \text{ GeV}$

- **GRB 201216C** *(ICRC 2021, PoS ID 395, S.Fukami)*
  - long GRB at $z = 1.1$
  - early detection after $T_0 + 56s$
  - $E < 100 \text{ GeV}$

FIRST TEV DETECTIONS OF GAMMA-RAY BURSTS

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

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

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

**Triangulation** with VIRGO has allowed for a better sky localisation (down to ~ few deg$^2$)

**Challenge for EM counterpart ID**: time vs. space localisation

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

---

**REAL-TIME SHARING OF OBSERVATORY SCHEDULING**
CTA Coordination Activities

ULISSES BARRES DE ALMEIDA - MARCH 2023 - ICTP-SAIFR CTA SCHOOL
CTA MWL & MM Coordination Structure

Focus Groups
requirements and grassroots science collaboration

Webinars
building bridges and collecting experiences

Coordination
formal steps towards data access

“mostly SCIENCE AND DOMESTIC AFFAIRS”

“mostly OPERATIONS AND FOREIGN AFFAIRS”

ULISSES BARRES DE ALMEIDA - MARCH 2023 - ICTP-SAIFR CTA SCHOOL
The achievement of the **CTA core Science Goals** depends on a wealth of MWL and MM data (often involving intense coordination between facilities), and the purpose of the MWL&MM Coordination Task Force is to identify, plan and secure those.

### Spatial Coordination for Surveys

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

### Extension of Spectral Coverage

- **Temporal coordination for variable sources**

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

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**Northern Hemisphere**

**Southern Hemisphere**

KSP years 1-10

Hours of Observation

- Radio cm
- Radio mm
- VLBI
- Optical OST
- Optical 2+ m
- Polarimetry
- X-rays
CTA: an open observatory

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

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

*LEARN THE LESSONS FROM FERMI:*
- FAST SHARING OF KEY DATA PRODUCTS
- BUILD UP EARLY YOUR NETWORK OF FRIENDS
An ecosystem of ground-based facilities

Radio Facilities Map

Optical Facilities Map

- Low Frequency Radio
- Mid-Hi Frequency Radio
- mm/sub-mm Radio
- monitoring / follow-up?
- Transient Factories
- Major OIR Facilities
- Polarimetric Capability
The CTA MWL
Synergies
CTA Synergies with MWL instruments

- Non-thermal emission in radio
- High-resolution VLBI to image emission zones
- Mapping of the diffuse gas (CR targets) to complement CTA view of diffuse emission around accelerators
- Detection of fast-variability signals from compact sources
- Optical polarimetry to isolate non-thermal component in mixed emission scenarios
- X-ray study of shock regions, accretion, high-speed outflows, which connect back to particle acceleration
- Soft gamma-ray telescopes for detection of high-energy transients
Radio and Gamma-rays are two windows into the non-thermal universe.

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

VHE Observations: provide direct probes of particle acceleration, seed photons for IC scattering, hadronic processes as well as the EBL.
Some Synergies within the CTA Science Programme

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

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

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

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

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

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

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

**Study of AGN jets along cosmic time**: SKA will expand the horizon for AGN jet studies, seeing radio-loud AGN up to $z \sim 8$, providing a view at AGN and IGM evolution.
ATHENA will be a major X-ray Mission (planned, 2028) with wide-field / high-spectral and imaging capability at ~ keV energies.

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

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

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

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