Cherenkov Telescopes: the highest photon energies, the highest angular resolution

JUAN CORTINA (CIEMAT, MADRID)

SEMINAR @ DPNC, UNIVERSITÉ DE GENÈVE

MAY 3RD 2023

GOBIERNO DE ESPAÑA
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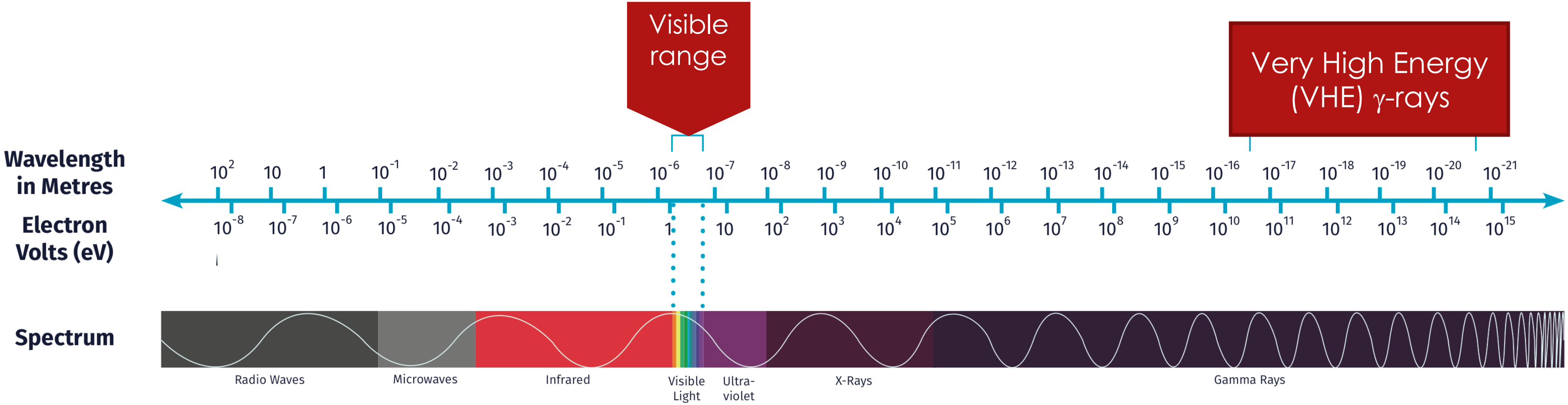
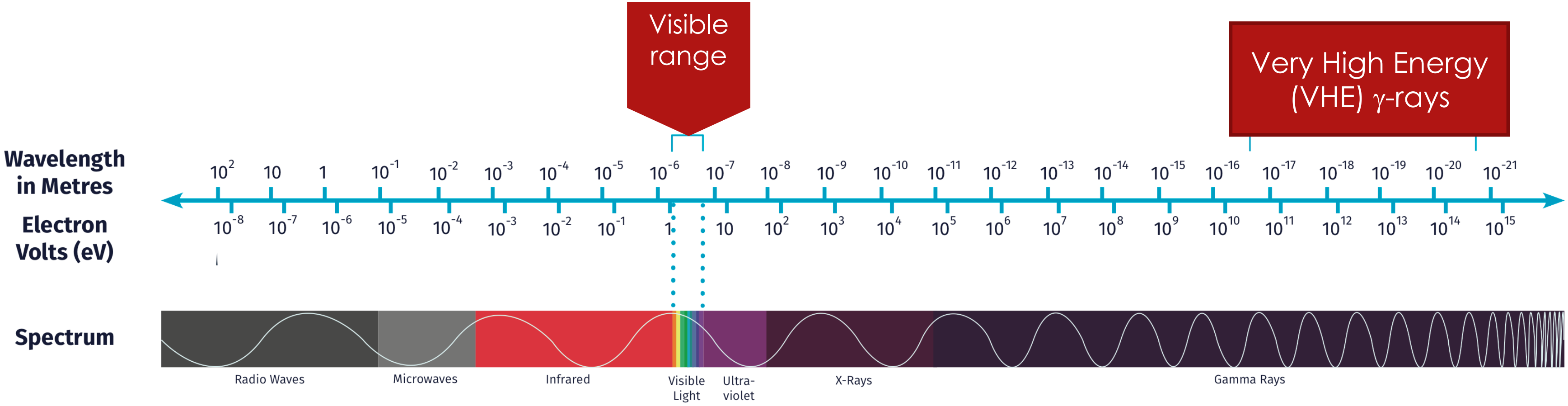
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Electromagnetic spectrum

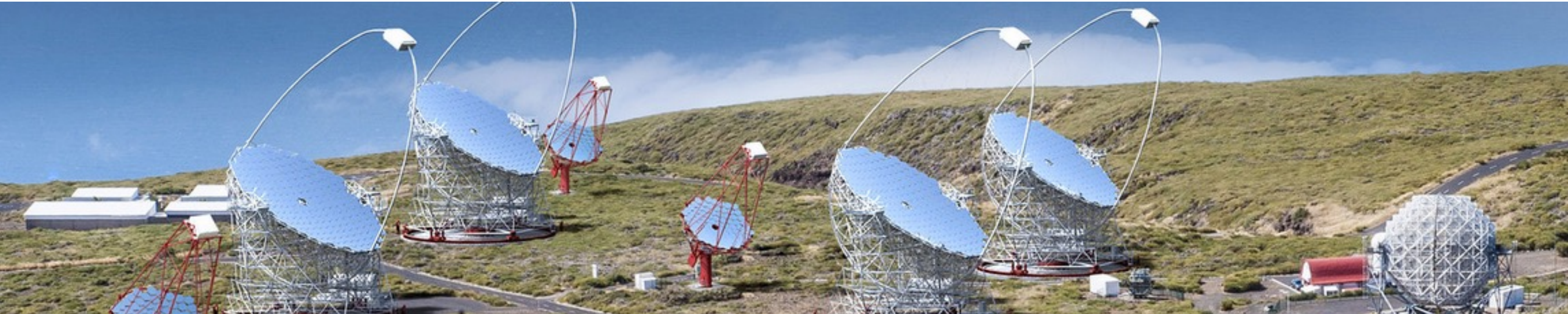


Credit: CTAO

Electromagnetic spectrum



Credit: CTAO



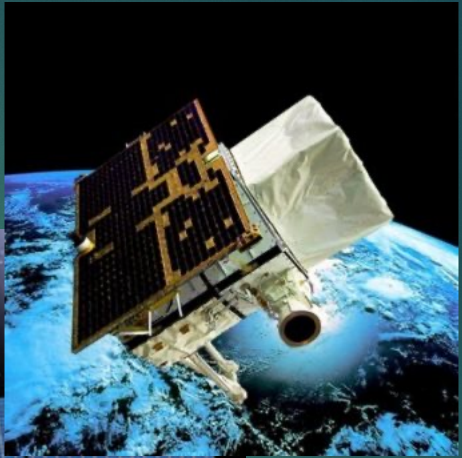
Outlook

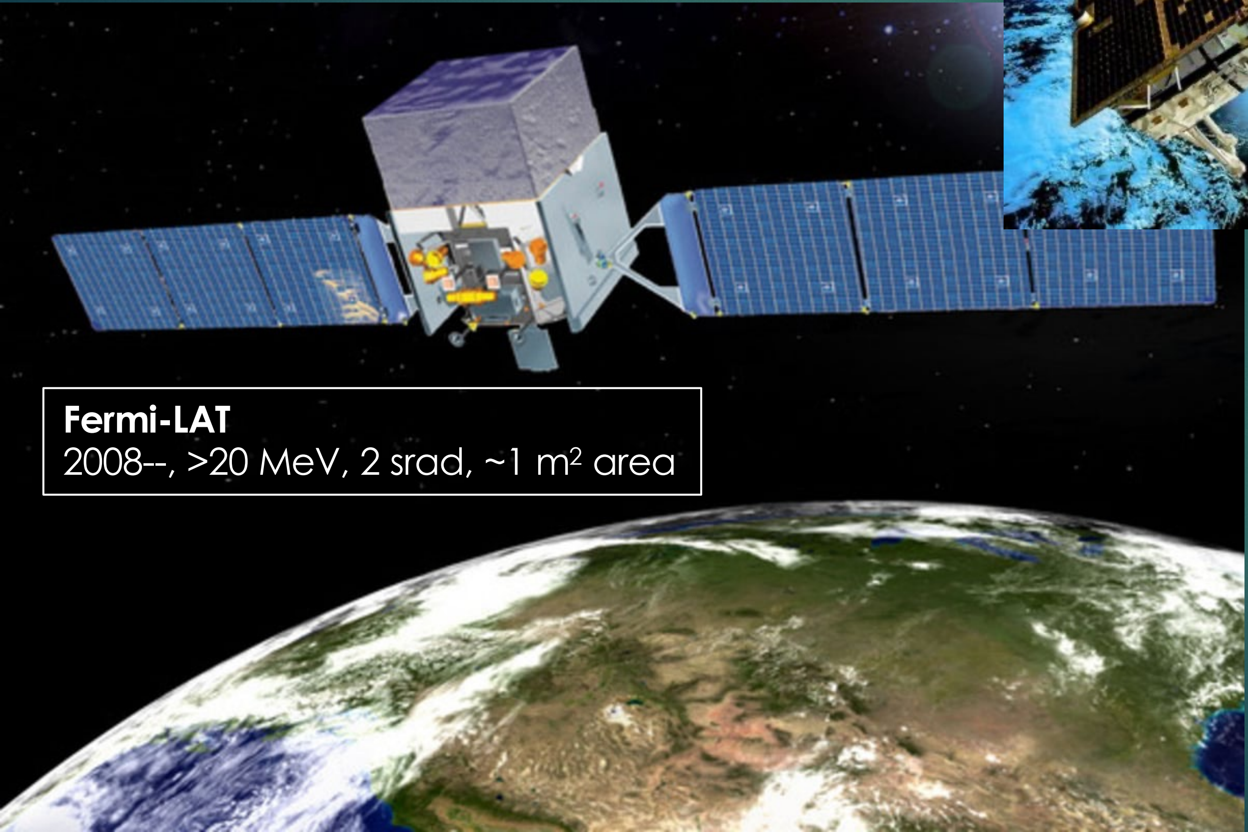
- The highest energies:
  - VHE γ-ray detection principle
  - Science with MAGIC and CTA
  - CTA: construction status
- The highest angular resolution:
  - Intensity interferometry in the visible range
  - Science with the sharpest eyes

VHE γ-ray detection principle

From space

Agile
2007--, >30 MeV, 3 srad, ~0.5 m^2 area

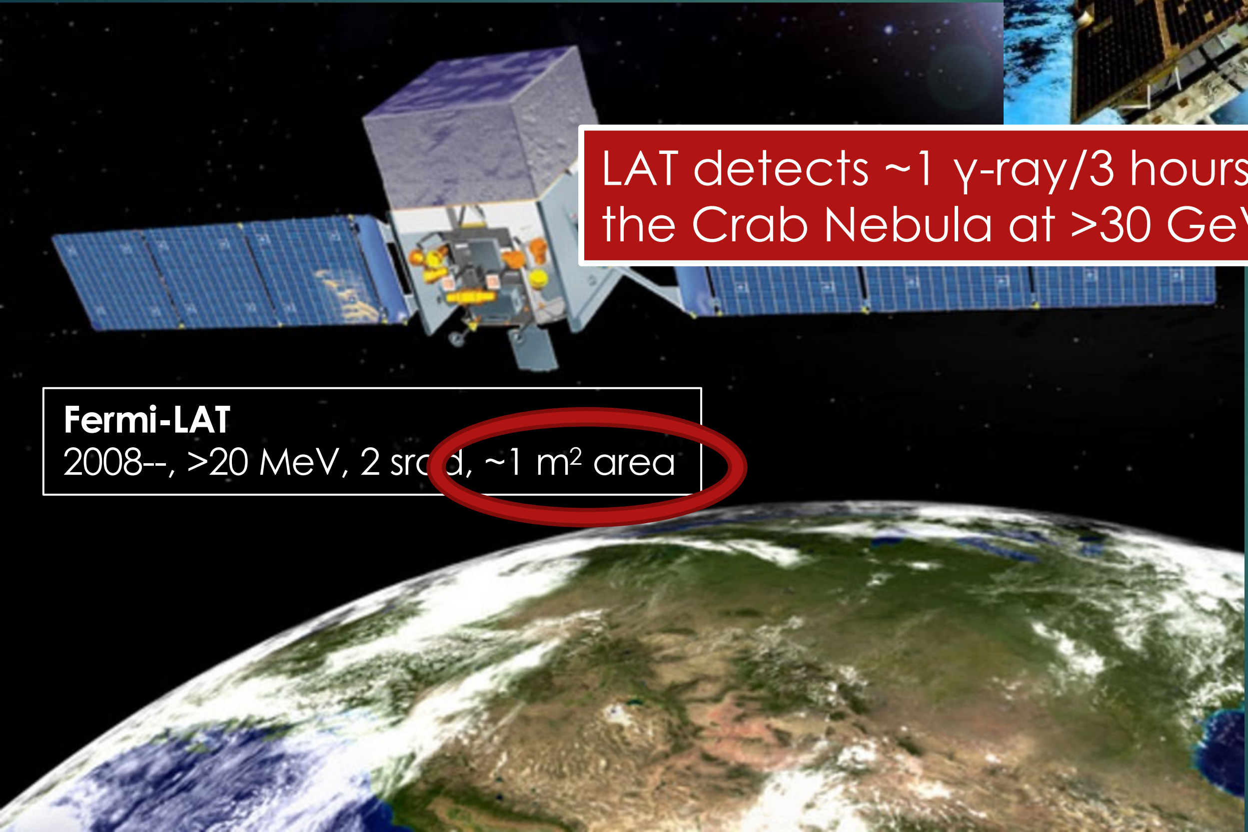




Fermi-LAT
2008--, >20 MeV, 2 srad, ~1 m^2 area

From space

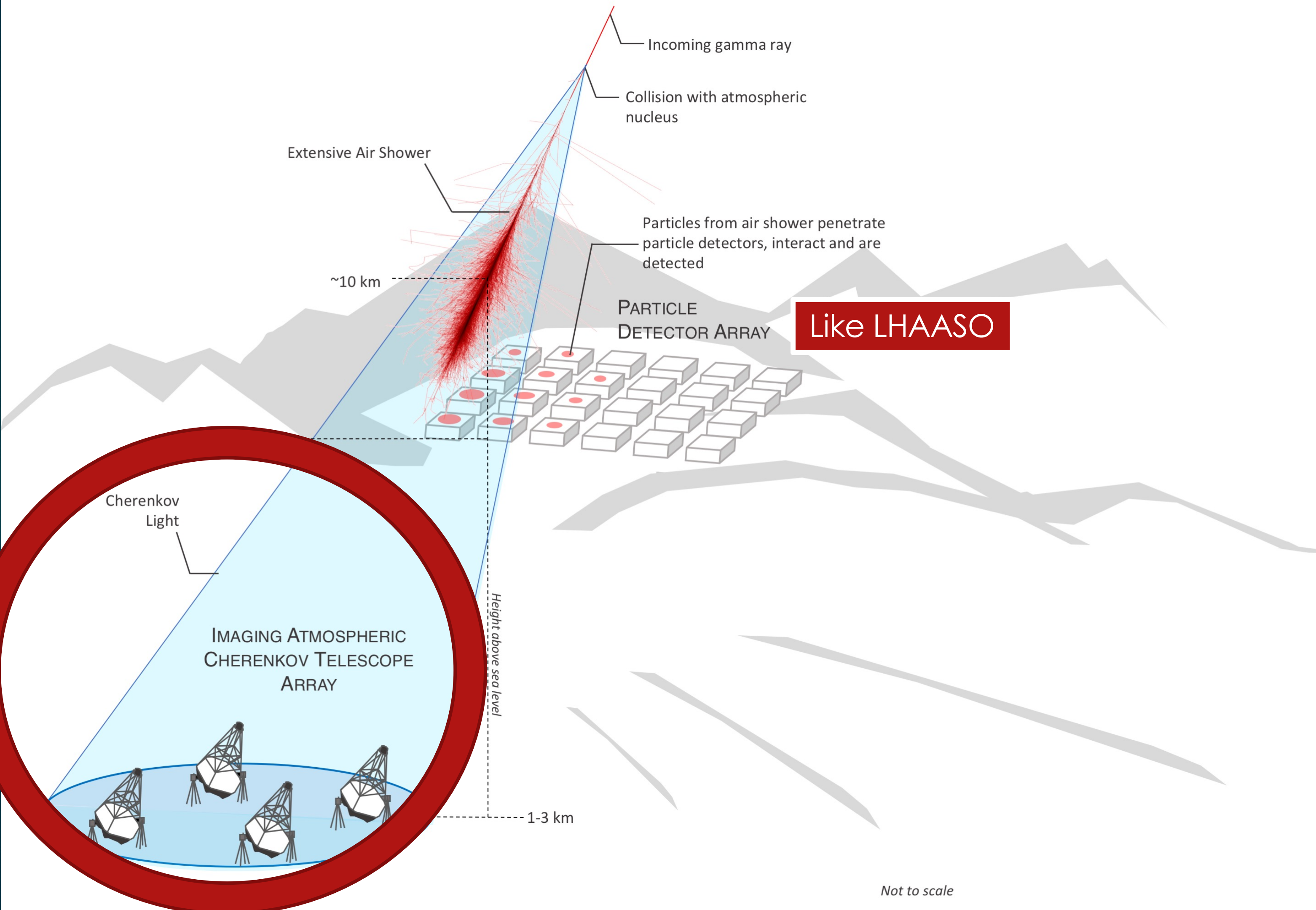
Agile
2007--, >30 MeV, 3 srad, ~0.5 m^2 area



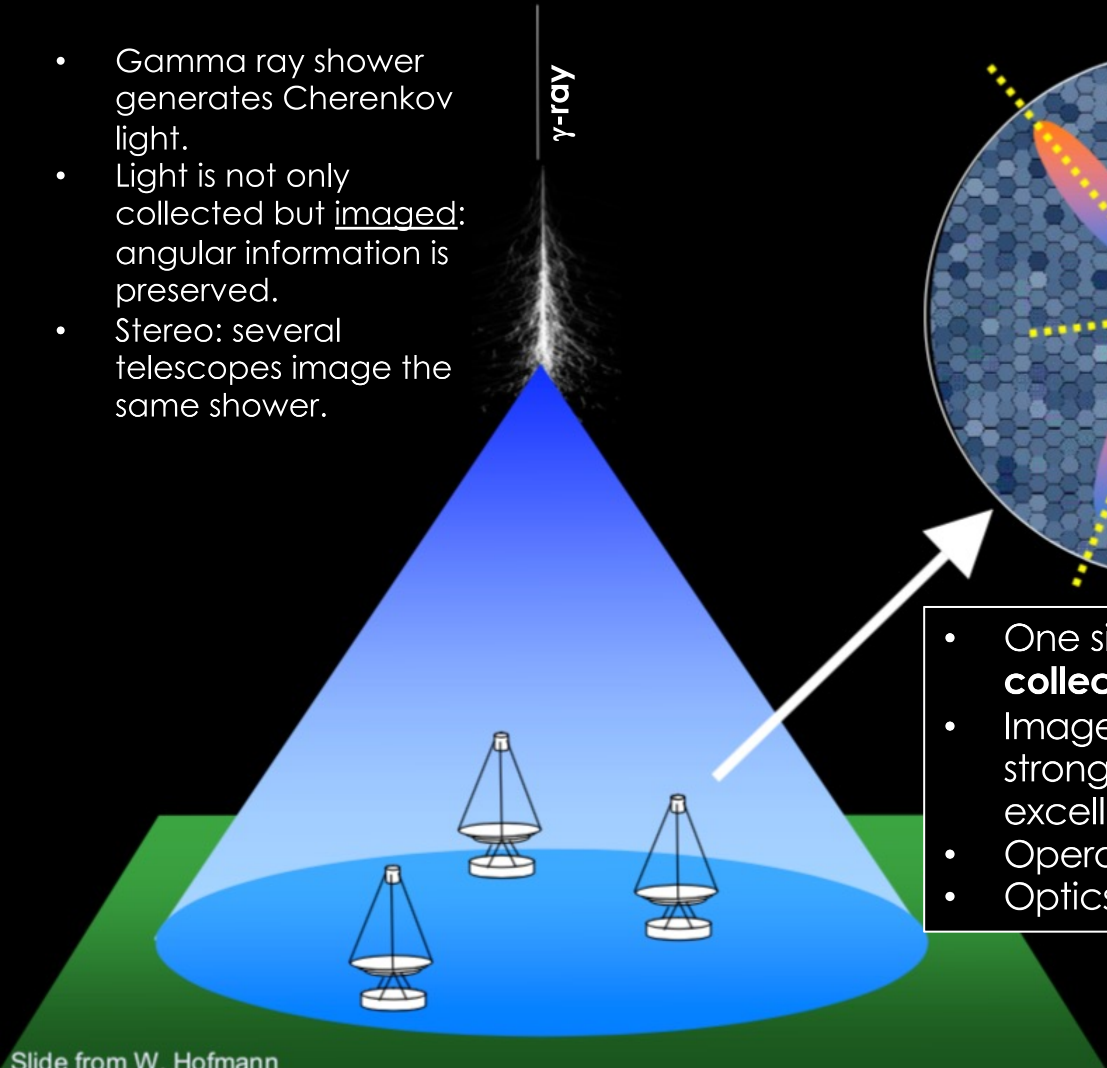
LAT detects ~1 γ-ray/3 hours from the Crab Nebula at >30 GeV

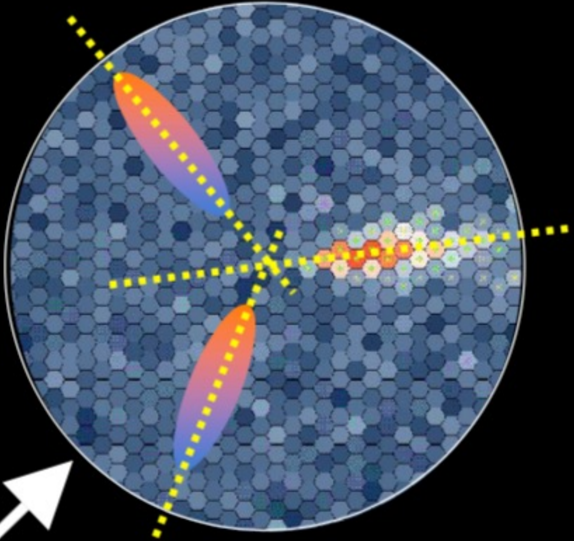
Fermi-LAT
2008--, >20 MeV, 2 srad, ~1 m^2 area

Cherenkov light imaging

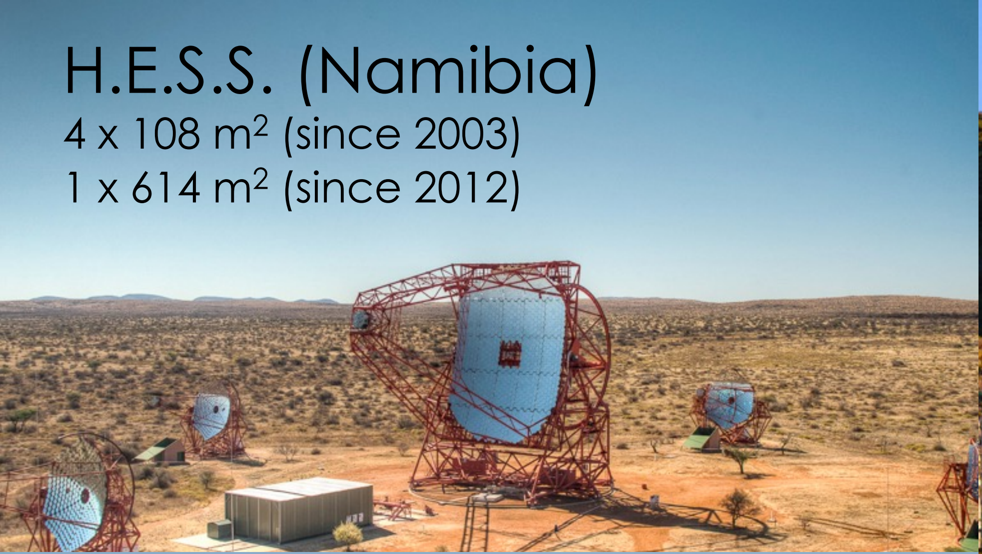


- Gamma ray shower generates Cherenkov light.
- Light is not only collected but imaged: angular information is preserved.
- Stereo: several telescopes image the same shower.





- One single telescope is sensitive to a large γ-ray **collection area** >100,000 m^2.
- Image of the whole shower, not only the tail: strong γ/h discrimination and **high sensitivity**, excellent **angular and spectral resolutions**.
- Operates only on dark nights: **duty cycle** <15%
- Optics limits **FOV**: $\lesssim$50 arcdeg^2 (~10^{-3} of the sky)


H.E.S.S. (Namibia)
4 x 108 m² (since 2003)
1 x 614 m² (since 2012)


MAGIC (La Palma)
2 x 236 m² (since 2003 / 2009)


VERITAS (Arizona)
4 x 110 m² (since 2007)

News from the VHE γ-ray frontier

Multimessenger astronomy: neutrino / γ-ray sources

1. IceCube, Science, **342** (2013) 1242856 : **Evidence for high-energy extraterrestrial neutrinos,**

Multimessenger astronomy: neutrino / γ-ray sources

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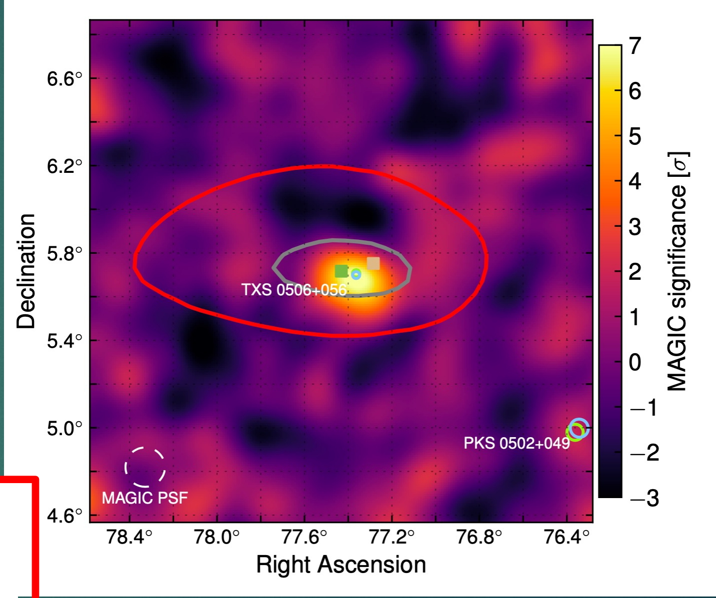
2. IceCube, Fermi-LAT, MAGIC, HESS and HAWC coll., Science 361 (2018) 1378 : **an AGN emits simultaneously in neutrino and γ-rays**



First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; ***Razmik Mirzoyan for the MAGIC Collaboration***
*on **4 Oct 2017; 17:17 UT***

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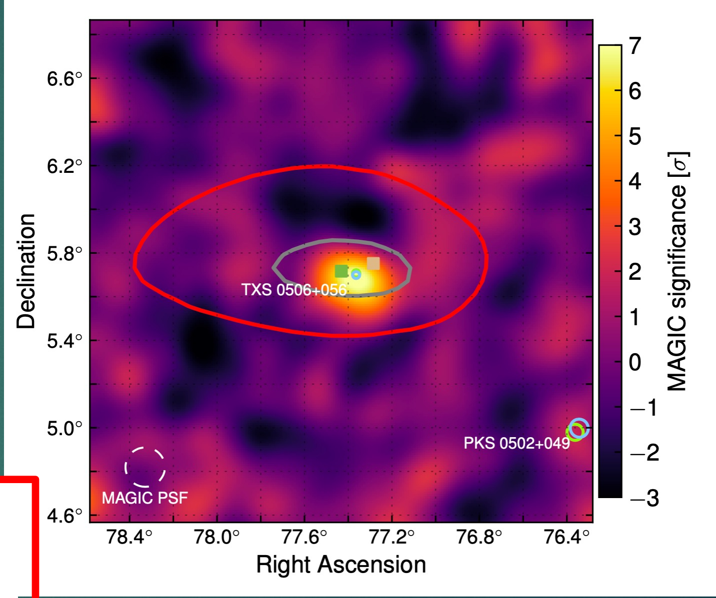
2. IceCube, Fermi-LAT, MAGIC, HESS and HAWC coll., Science 361 (2018) 1378 : **an AGN emits simultaneously in neutrino and γ-rays**
3. IceCube, Science 378 (2022) 538 : **Evidence for neutrino emission from the nearby active galaxy NGC 1068,**... And IceCube warns that 3 more AGNs are significant



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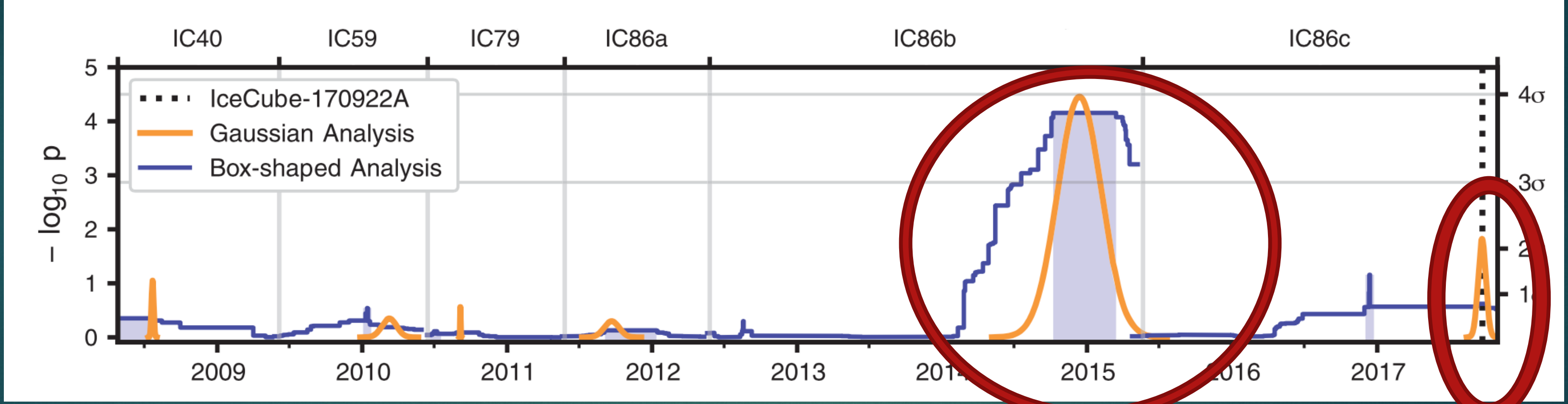
Multimessenger astronomy: neutrino / γ-ray sources

4. IceCube: Science 361 (2018) 147: **neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube+MAGIC event**



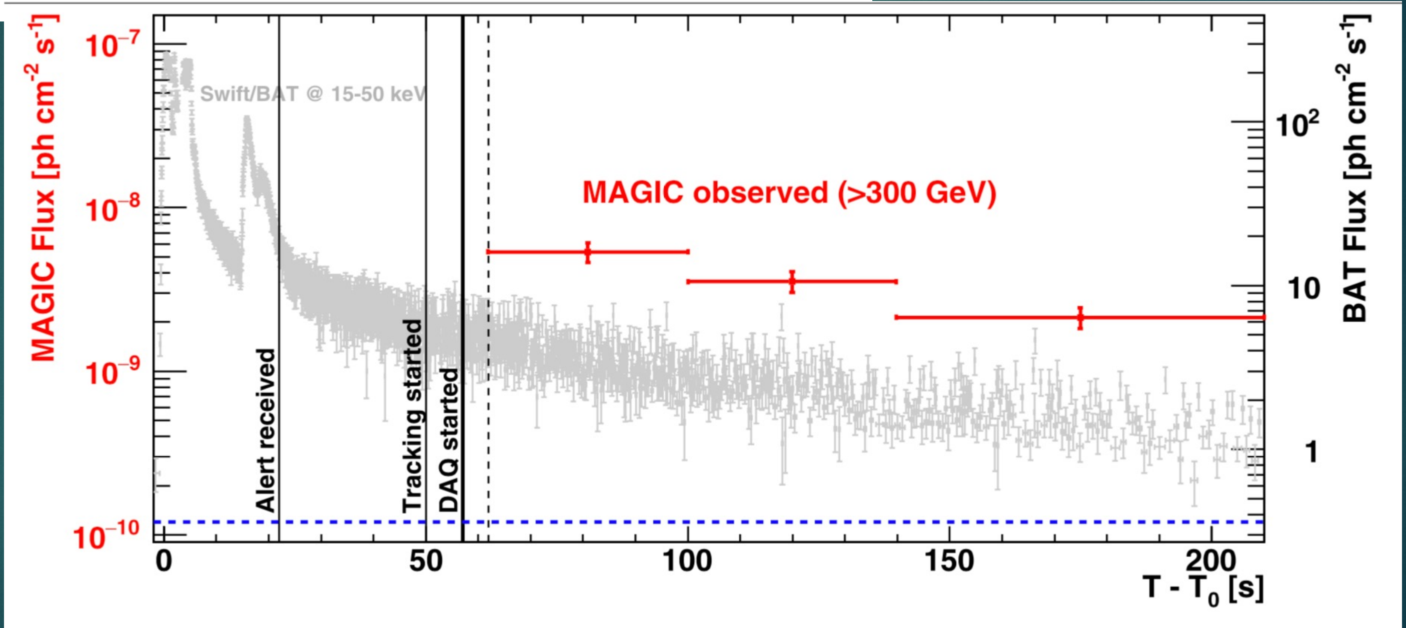
Much larger flare around 2015
No γ-ray active state in Fermi-LAT!
"Dark accelerator"?

MAGIC flare

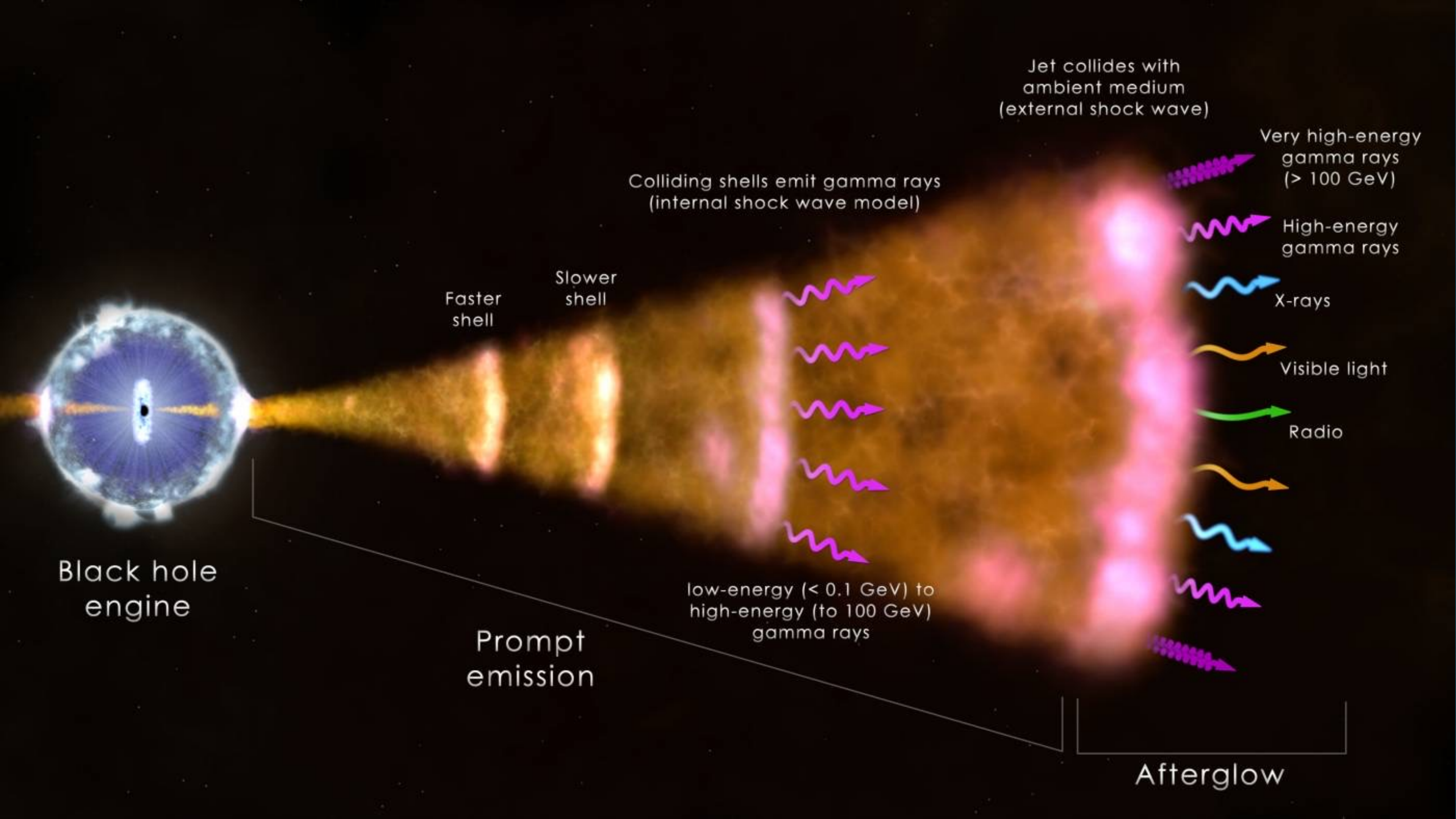
First **Gamma Ray Burst** at VHE

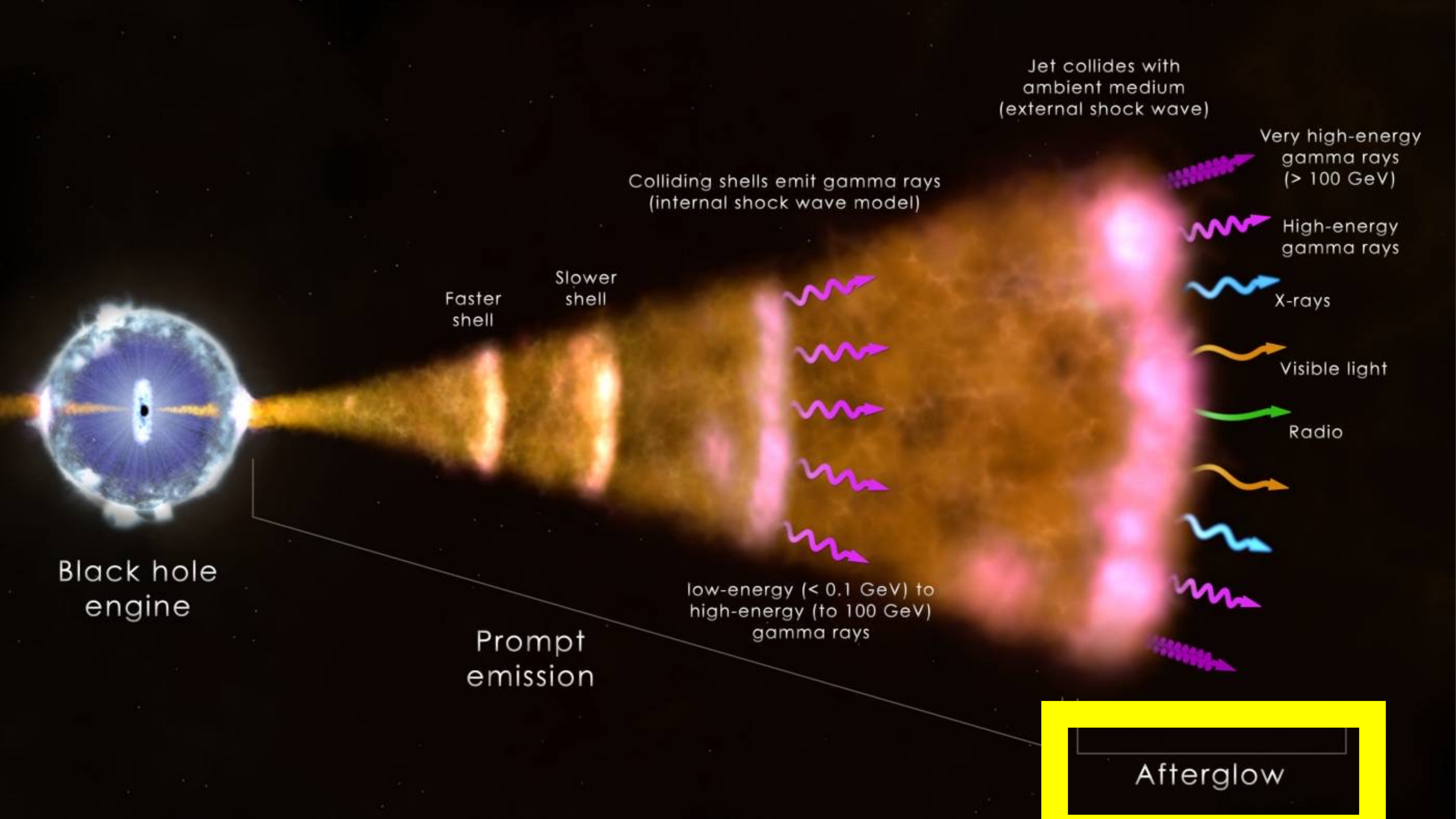
Article

Teraelectronvolt emission from the γ-ray burst GRB 190114C



MAGIC, Nature 2019, https://doi.org/10.1038/s41586-019-1750-x


Jet collides with ambient medium (external shock wave)
Very high-energy gamma rays (> 100 GeV)
Colliding shells emit gamma rays (internal shock wave model)
High-energy gamma rays
Slower shell
Faster shell
X-rays
Visible light
Radio
Black hole engine
low-energy (< 0.1 GeV) to high-energy (to 100 GeV) gamma rays
Prompt emission
Afterglow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Prompt
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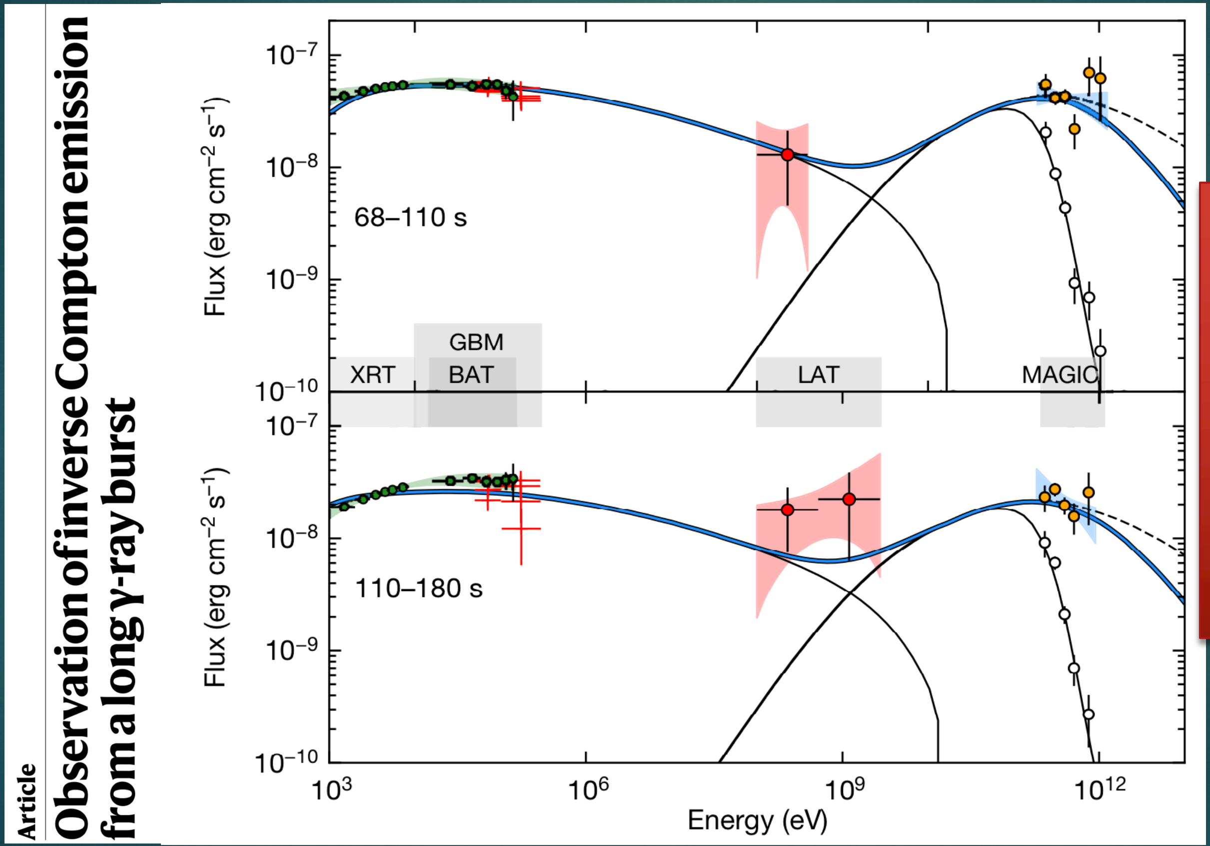
First GRB: emission mechanism

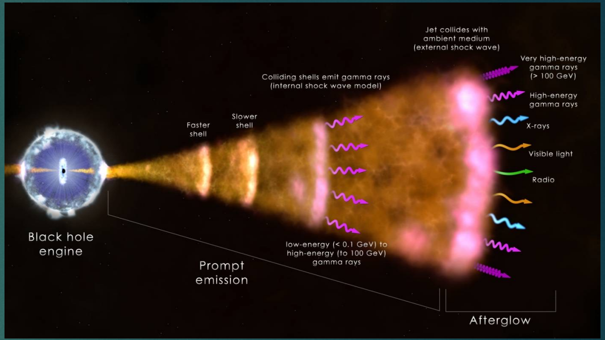
MAGIC, Nature 2019,
https://doi.org/10.1038/s41586-019-1754-6



- New component: Inverse Compton of jet photons with jet electrons, i.e. Self-Synchroton Compton
- Similar amount of energy radiated in synchroton and VHE!
- Nothing special with this GRB

GRB: common VHE sources!!

- No discovery for 15 years and then 4 GRBs in a row!
  - GRB 190114C, z~0.4245 (MAGIC)
  - GRB 180720B, z~0.654 (H.E.S.S.)
  - GRB 190829A, z~0.08 (H.E.S.S.)
  - GRB 201216C, Z~1.1 (MAGIC)
- Are we stupid or what?
  - We were just pessimistic: we were focusing too much on the prompt emission, we didn’t believe the afterglow was so bright so we didn’t observe long enough.
- Our next targets:
  - Larger statistics!
  - Detection of prompt emission.
  - Detection of short GRB - **together with a GW event!?**



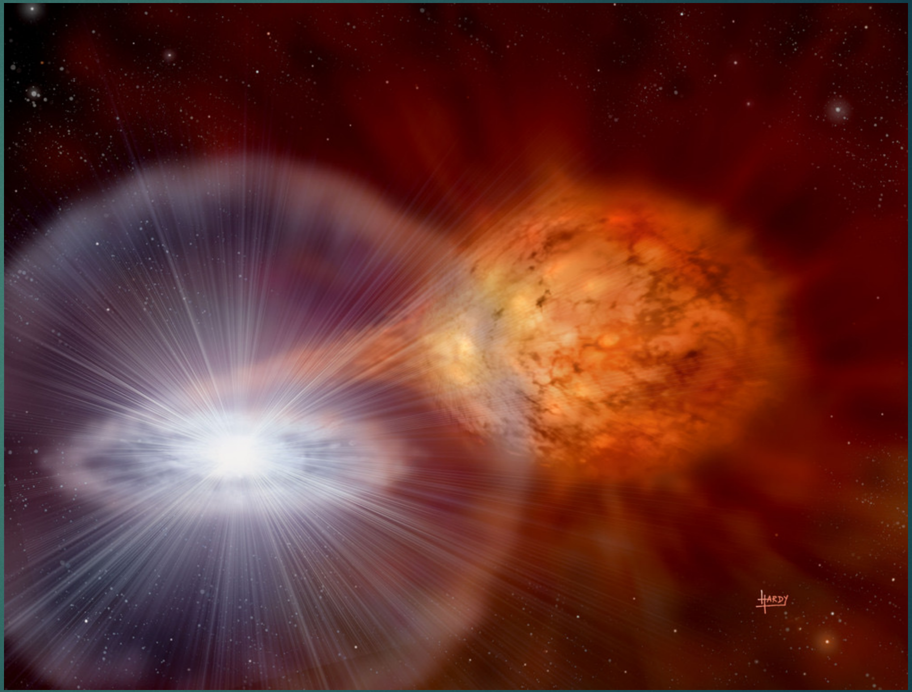
GRB 221009A: γ-rays above 10 TeV!

- GRB 221009A:
  - Brightest GRB in X-rays
  - LAT detection up to 99 GeV (highest GRB photon energy ever detected by LAT)
  - $z=0.15$ $E_{iso} = 2\times10^{54}$ erg
- LHAASO detection!
  - Up to ~18 TeV.
  - >100 σ significance.
  - Thousands of γ-rays: prompt emission probably detected
- Unfortunately Full Moon, so we couldn't observe with IACTs.
- Multi TeV energies!

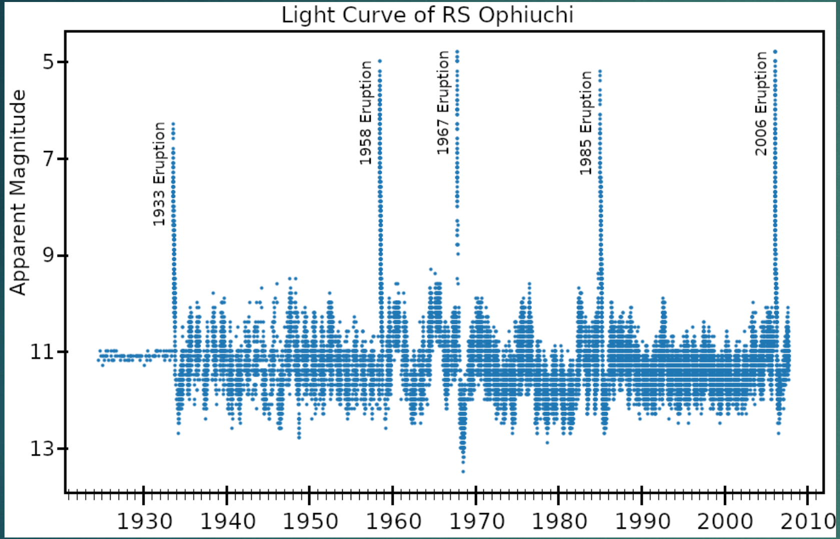
```
TITLE:   GCN CIRCULAR
NUMBER:  32677
SUBJECT: LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18 TeV
DATE:    22/10/11 09:21:54 GMT
FROM:    Judith Racusin at GSFC  <judith.racusin@nasa.gov>

Yong Huang, Shicong Hu, Songzhan Chen, Min Zha, Cheng Liu, Zhiguo Yao and
Zhen Cao report on behalf of the LHAASO experiment

We report the observation of GRB 221009A, which was detected by Swift (Kennea
et al. GCN #32635), Fermi-GBM (Veres et al. GCN #32636, Lesage et al. GCN #32642),
Fermi-LAT (Bissaldi et al. GCN #32637), IPN (Svinkin et al. GCN #32641) and so on.

GRB 221009A is detected by LHAASO-WCDA at energy above 500 GeV, centered at
RA = 288.3, Dec = 19.7 within 2000 seconds after T0, with the significance above
100 s.d., and is observed as well by LHAASO-KM2A with the significance about 10 s.d.,
where the energy of the highest photon reaches 18 TeV.

This represents the first detection of photons above 10 TeV from GRBs.
```

Newest type of VHE emitter: **novas**

- Binaries, where a white dwarf accretes from a companion.
- Novae: large optical outbursts (6-9 mag) when matter accreted into WD atmosphere suffers thermonuclear explosion.
- Several novas had been detected by Fermi-LAT (<10 GeV), none at VHE.
- LAT: shock luminosities needed to produce the γ-rays can be comparable to the bolometric output. Relevant spectral component!



Recurrent nova RS Oph

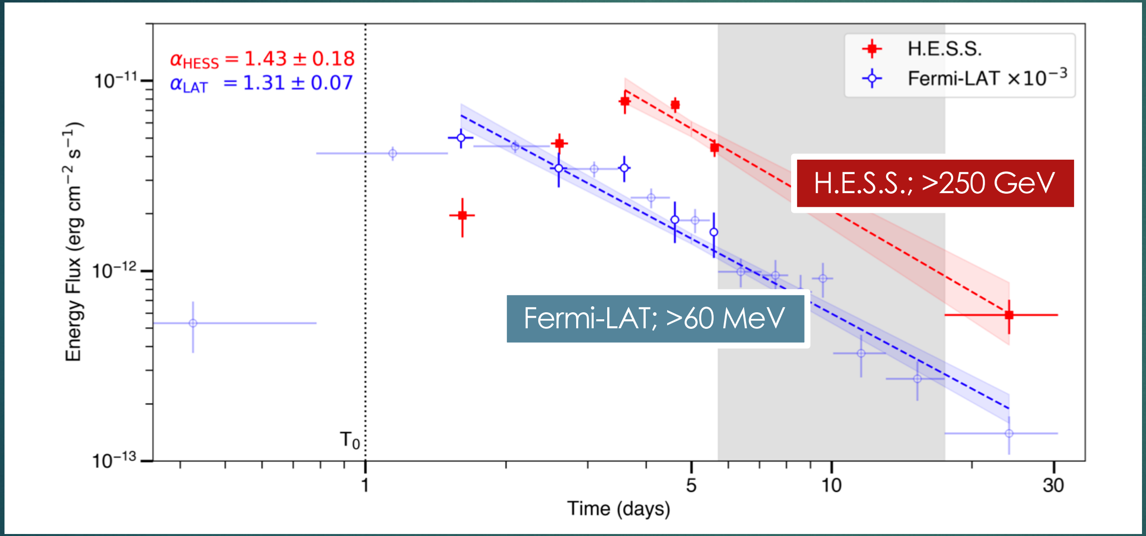


- Symbiotic nova = red giant + white dwarf.
- Dense red giant wind. Plenty of target matter for shock accelerated particles.
- Recurrent: eruptions in average every 14.7 years.

RS Oph eruption in August 2021

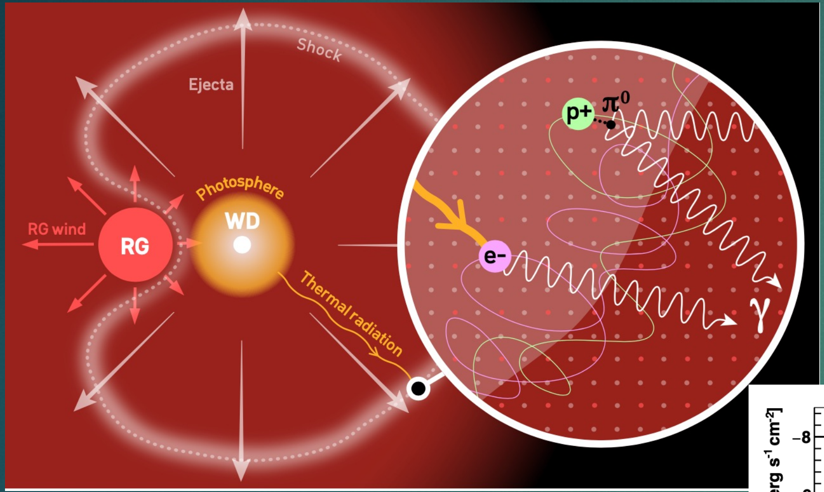
Eruption reported in optical (500x) and Fermi-LAT.

Quick follow-up, clear detection by H.E.S.S. and MAGIC, Atel by H.E.S.S



H.E.S.S. coll, Science, 376-6588 (2022) 77

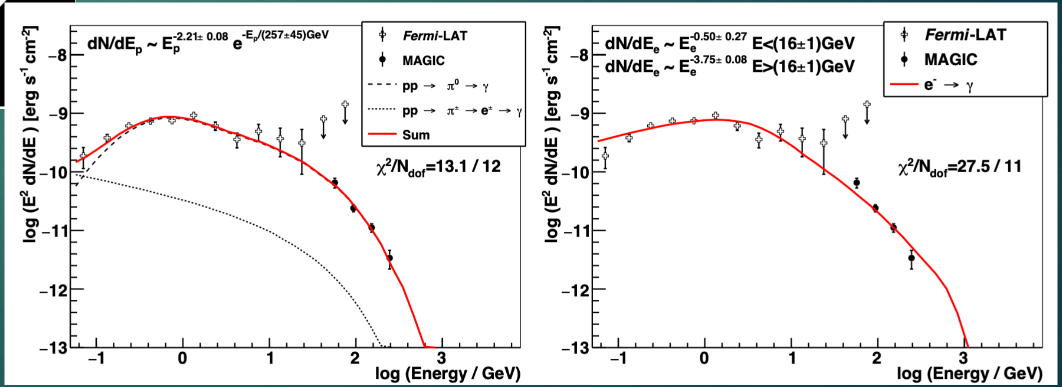
RS Oph: hadronic or leptonic?



MAGIC coll., Nat. Astr. 6 (2022) 689

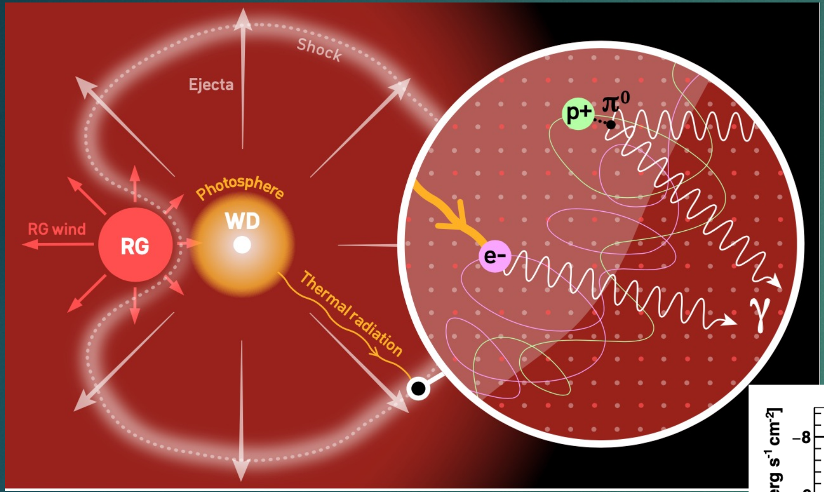
protonic

leptonic



Much worse fit to leptonic model: too high γ-ray production at low energy, unable to reproduce spectral breaks.

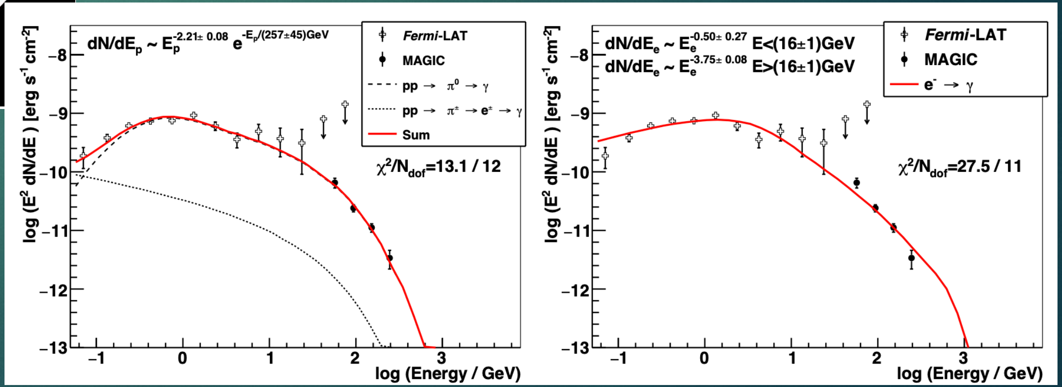
RS Oph: hadronic!



MAGIC coll., Nat. Astr. 6 (2022) 689

Remember that a nova is a "micro-supernova": here we are testing the limits of hadronic acceleration in shocks

protonic **leptonic**



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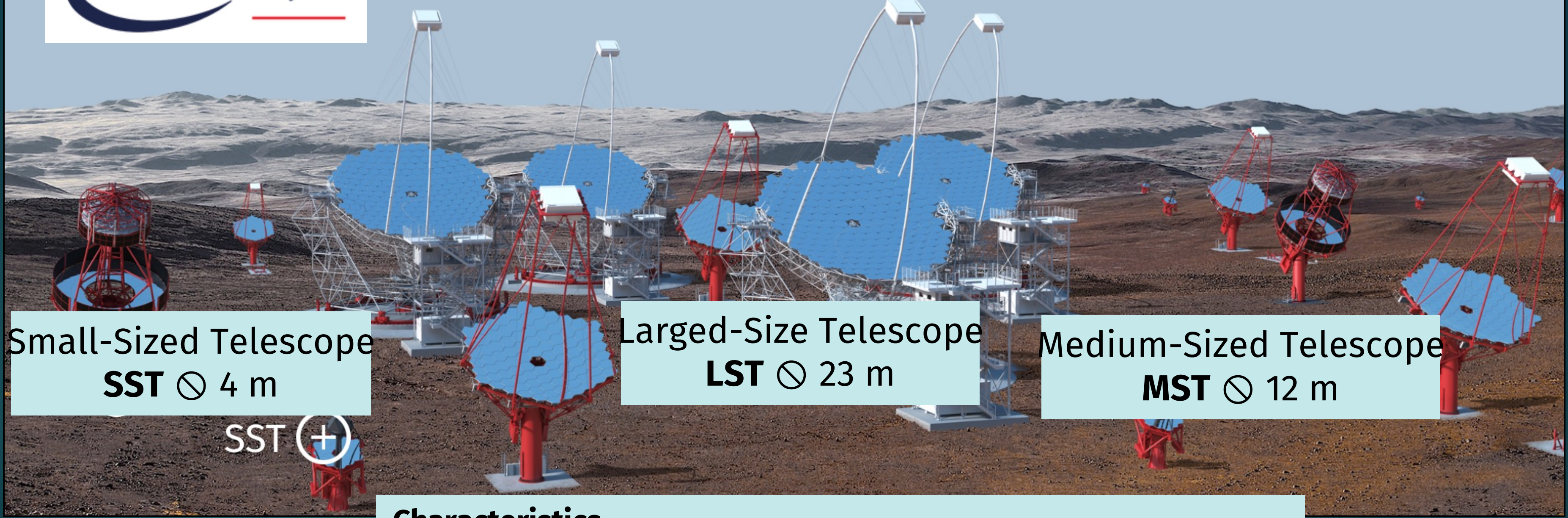
4 x 108 m^2 (since 2003)
1 x 614 m^2 (since 2012)
MAGIC
a Palma)
2 x
2003 / 2009)
THIS IS NOT ENOUGH

Cherenkov Telescope Array

cherenkov telescope array

How does it work?



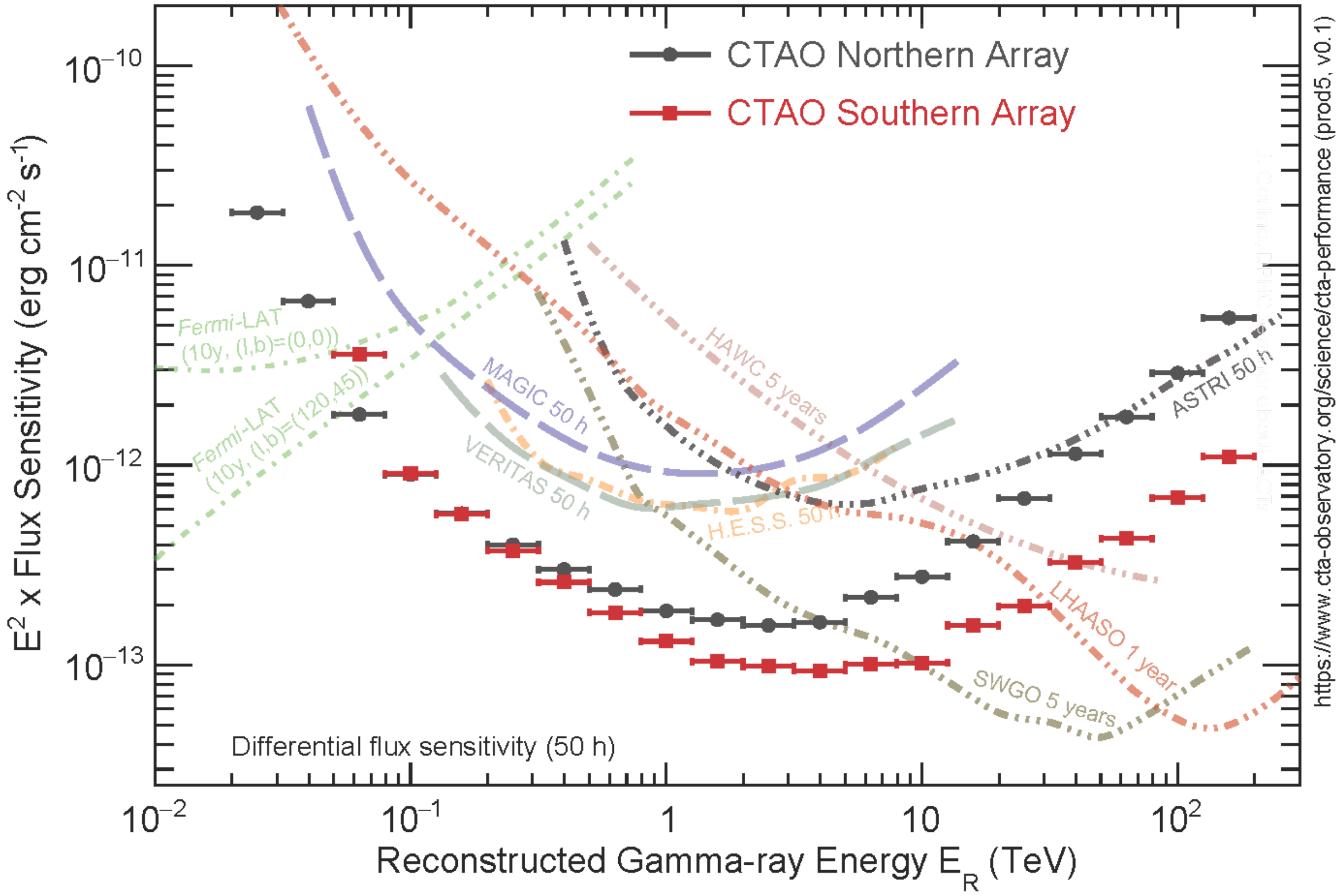
Small-Sized Telescope
SST ⌀ 4 m

Larged-Size Telescope
LST ⌀ 23 m

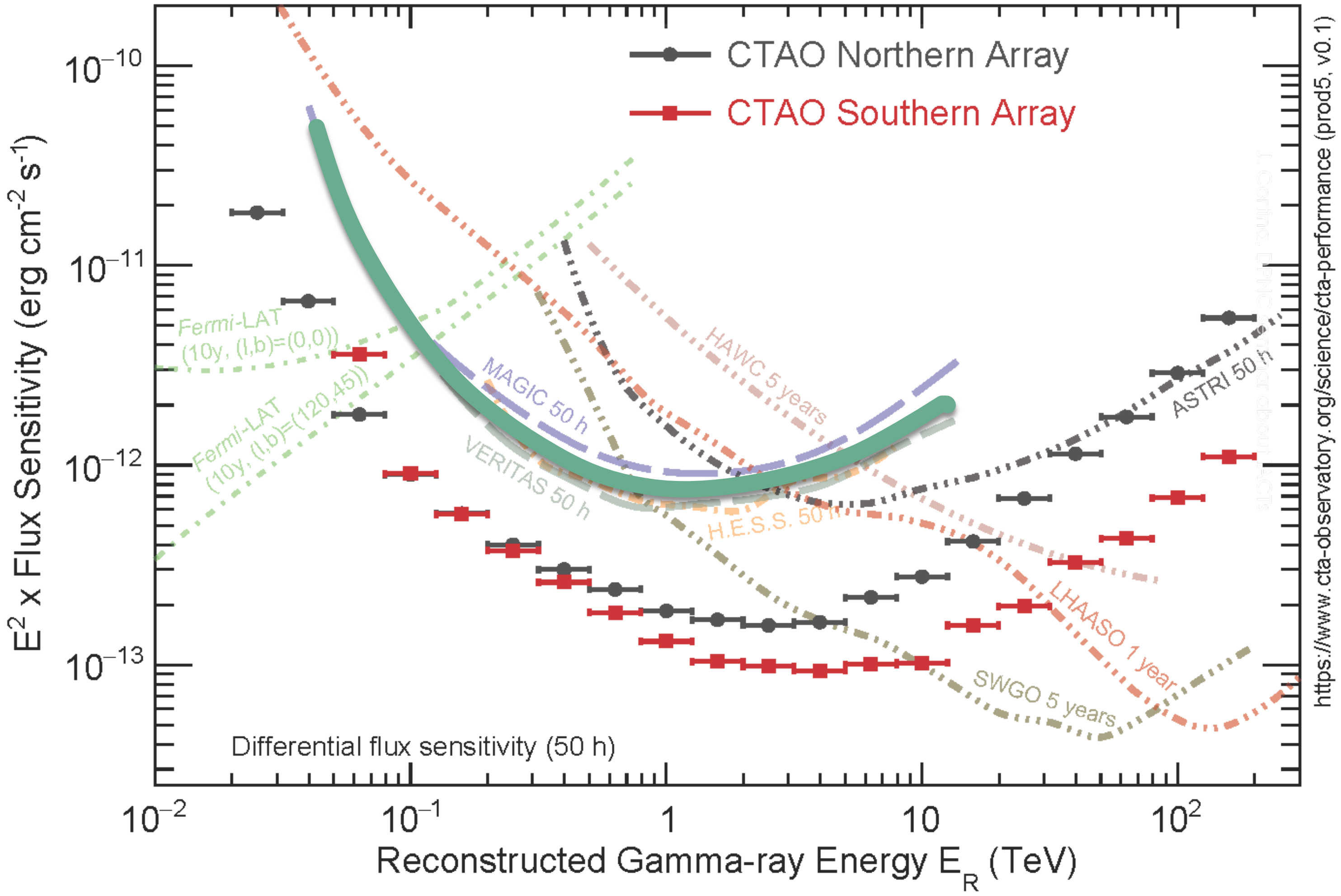
Medium-Sized Telescope
MST ⌀ 12 m

Characteristics
2 sites (north & south) → full sky coverage
3 telescope size classes → wider energy range
Tens of telescopes → Larger area i.e. higher sensitivity

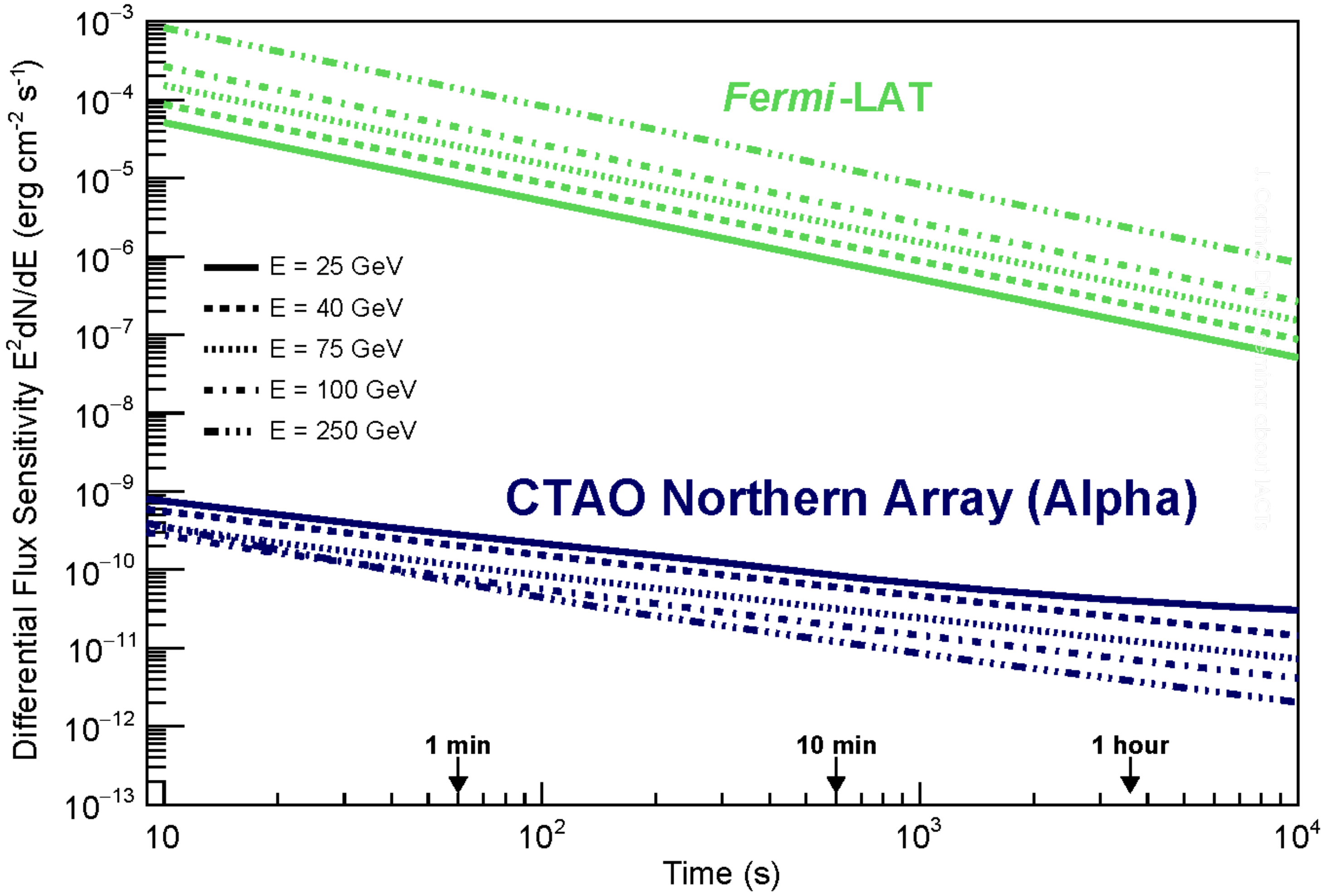
Sensitivity

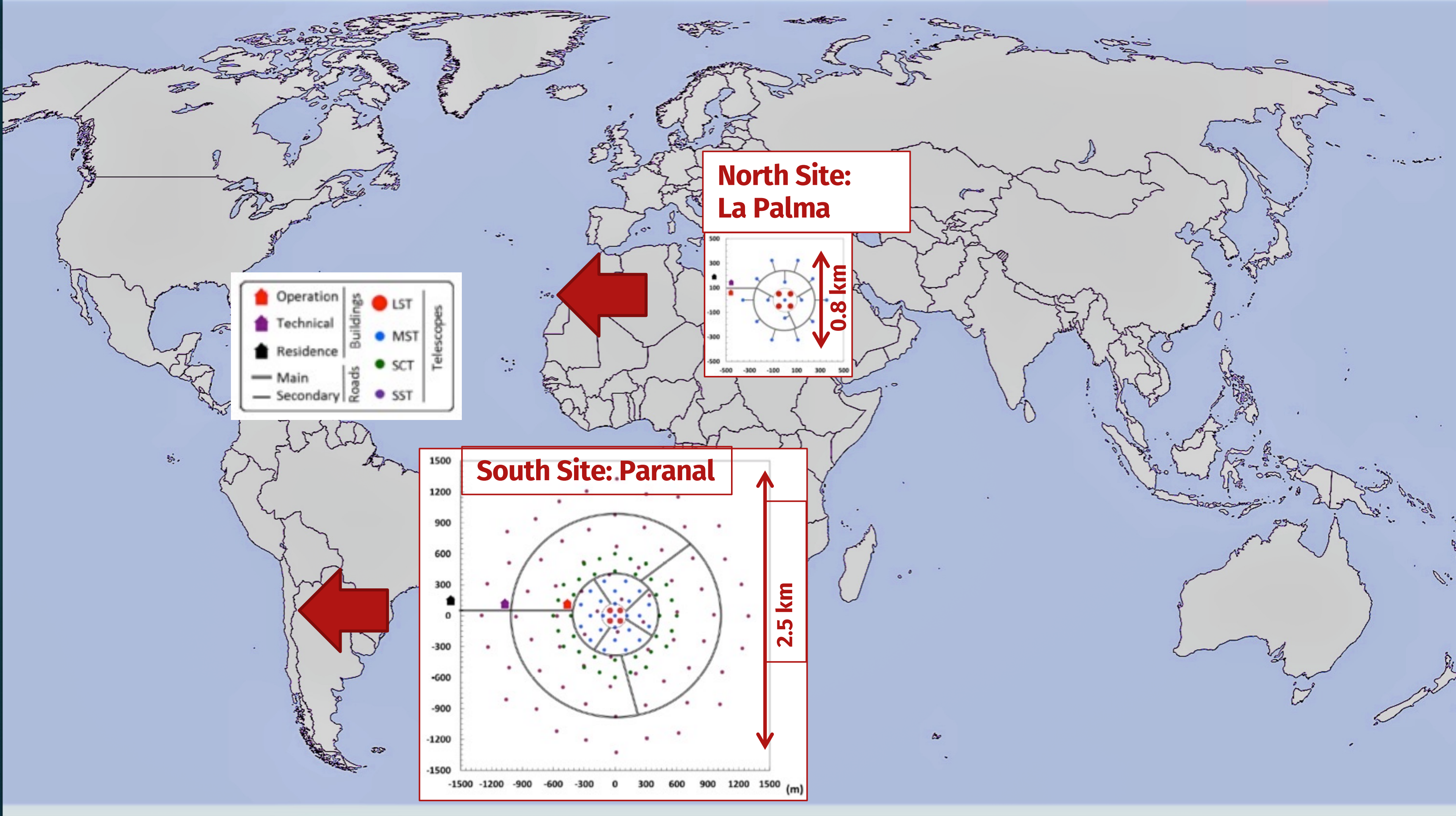


Sensitivity



Short term sensitivity




North Site:
La Palma
0.8 km
South Site: Paranal
2.5 km
Operation
Technical
Residence
Buildings
Main
Secondary
Roads
LST
MST
SCT
SST
Telescopes
(m)

CTAO: general status

- Country representatives of Germany, Italy, Spain, France, Japan, Poland, Switzerland (observer), etc agreed last year to finance the "**alpha configuration**"

Telescope Design	Northern Site	Southern Site
Large-Sized Telescope	4	+2
Medium-Sized Telescope	9	14
Small-Sized Telescope		37
Total	**13**	**51**

- New organization "CTAO ERIC" to be established in September.
- Then the two arrays should be built after ~5 years.

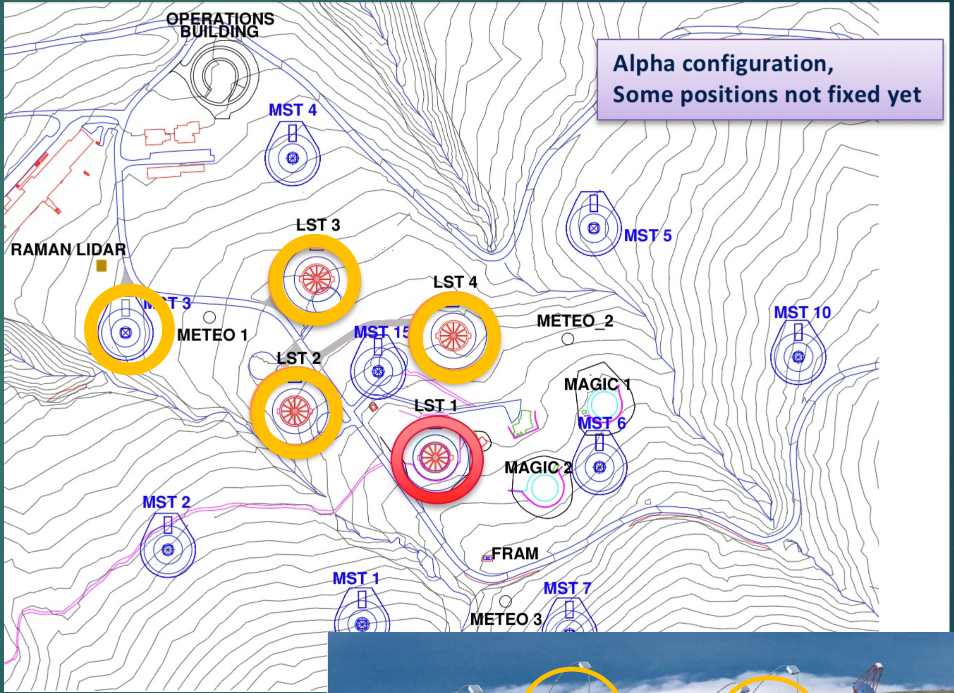
CTA: advanced construction

CTAO-North

Roque de los Muchachos, La Palma, Spain

α-configuration:

- LST1, a fully functional prototype, is already built.
- 3 remaining LSTs and 1 MST to be installed until 2025
- 8 remaining MSTs shortly afterwards.



J. Cortina, DPNC seminar about IACTs

First CTA telescope on site: LST-1, installed on 2018

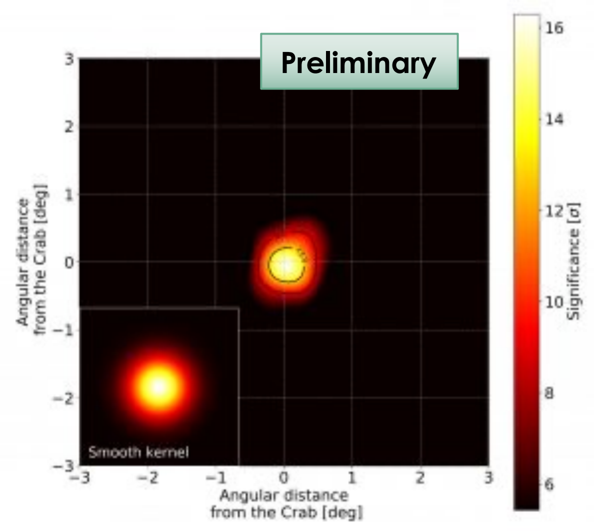
J. Cortina, DPNC seminar about IACTs

LSTs:
The largest telescopes, the lowest energies

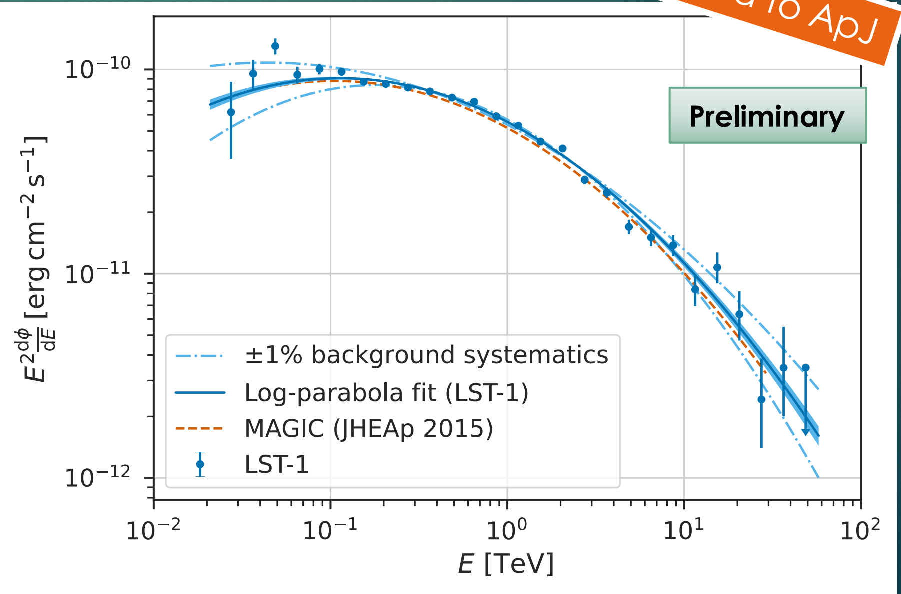
- 23m diameter mirror
- Targeting an energy threshold <u>~20 GeV.</u> Stereo at the lowest energies ever observed from the ground.
- Good overlap with satellites but with <u>collection areas >10^4 times larger</u>
- Able to reposition to any place in the sky within 20 seconds: GRBs.

LST1: taking data, Crab Nebula

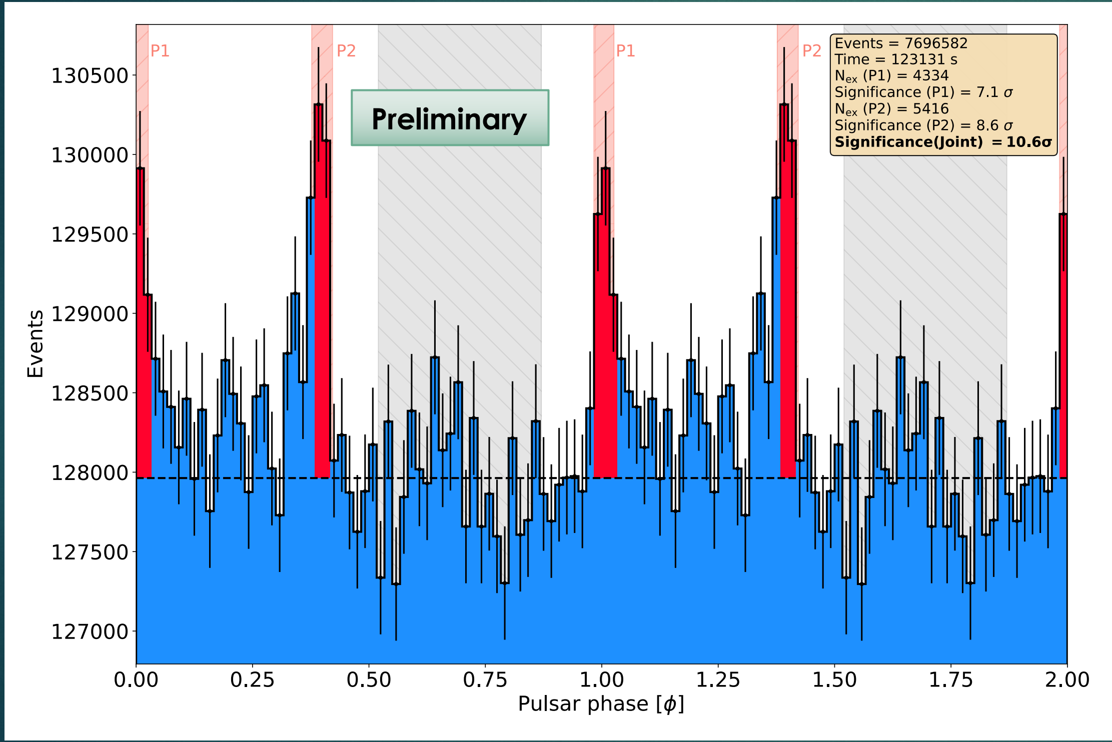
- Detection achieved "off-the-shelf": energy threshold ∼50 GeV.
- Consistent with MAGIC and Fermi-LAT.
- Lowest data point at 25 GeV!



Submitted to ApJ



LST1: Crab PULSAR

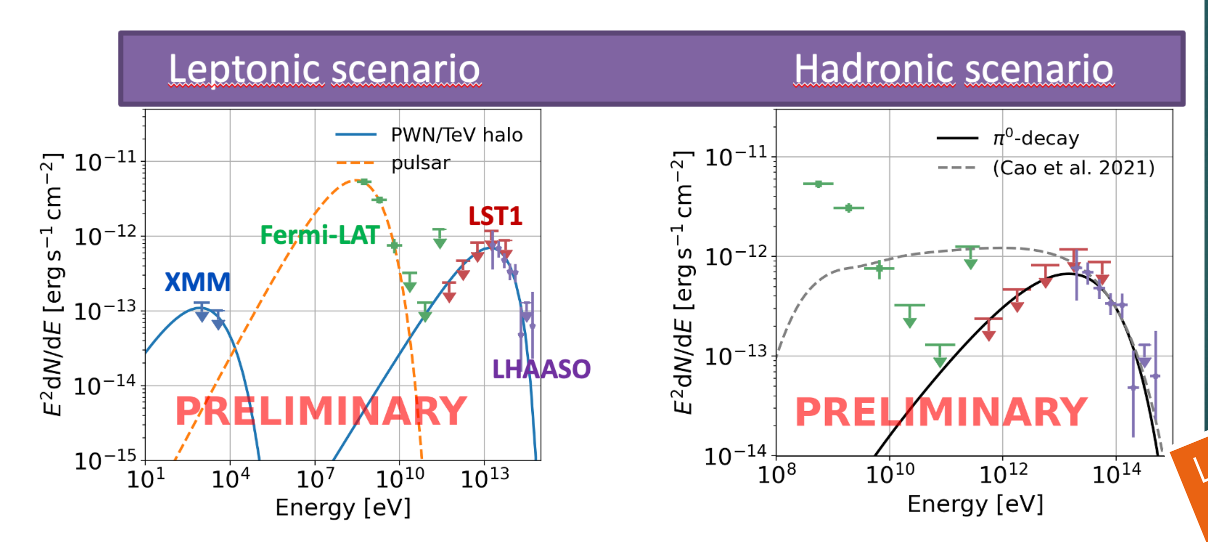


- Only 4 pulsars are detected at VHE. First detection by MAGIC took years. With LST1 the detection of Crab pulsar has been achieved during telescope commissioning.
- Preliminary ratio of P1 and P2 points to an energy threshold ~50 GeV.

Submitted to ApJ

LST1, 1st paper: LHAASO J2108+5157

- Cao et al. 2021: candidate "PeVatron", reported to be point-like. No X-ray or VHE counterpart, maybe LAT counterpart.
- LST1: no detection but useful upper limits - point to leptonic emission.

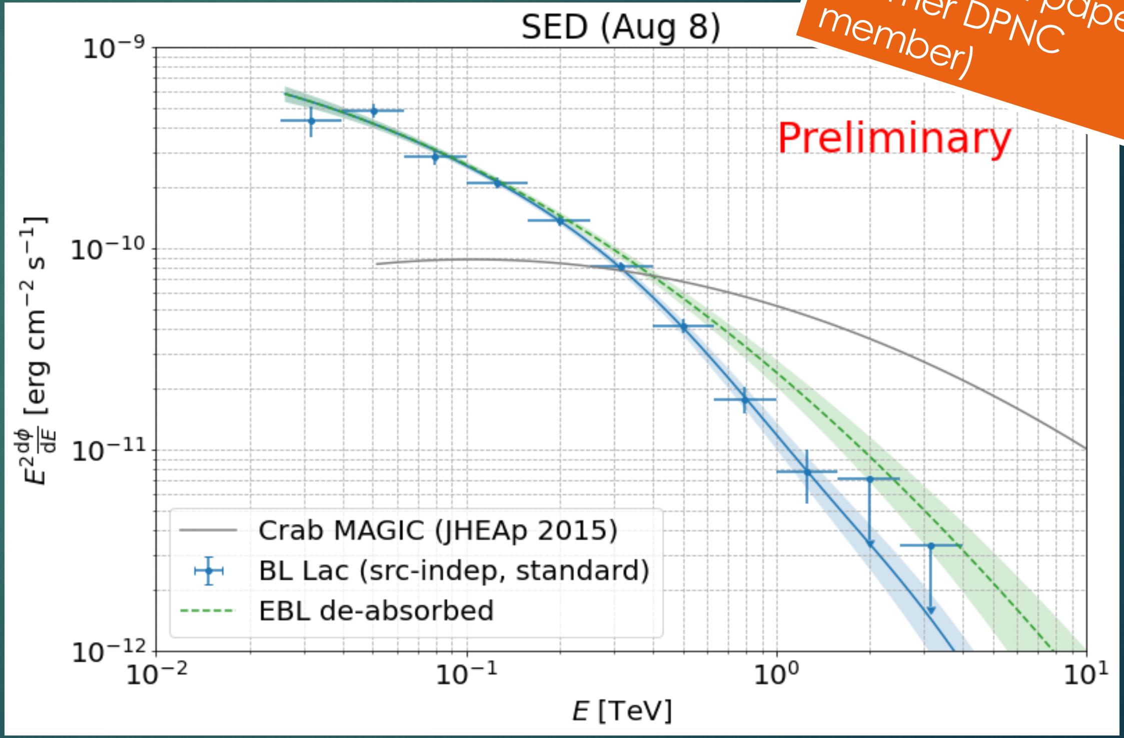


Led by obs Geneva, accepted in A&A, March 2023

LST1: BL Lac flare 2021

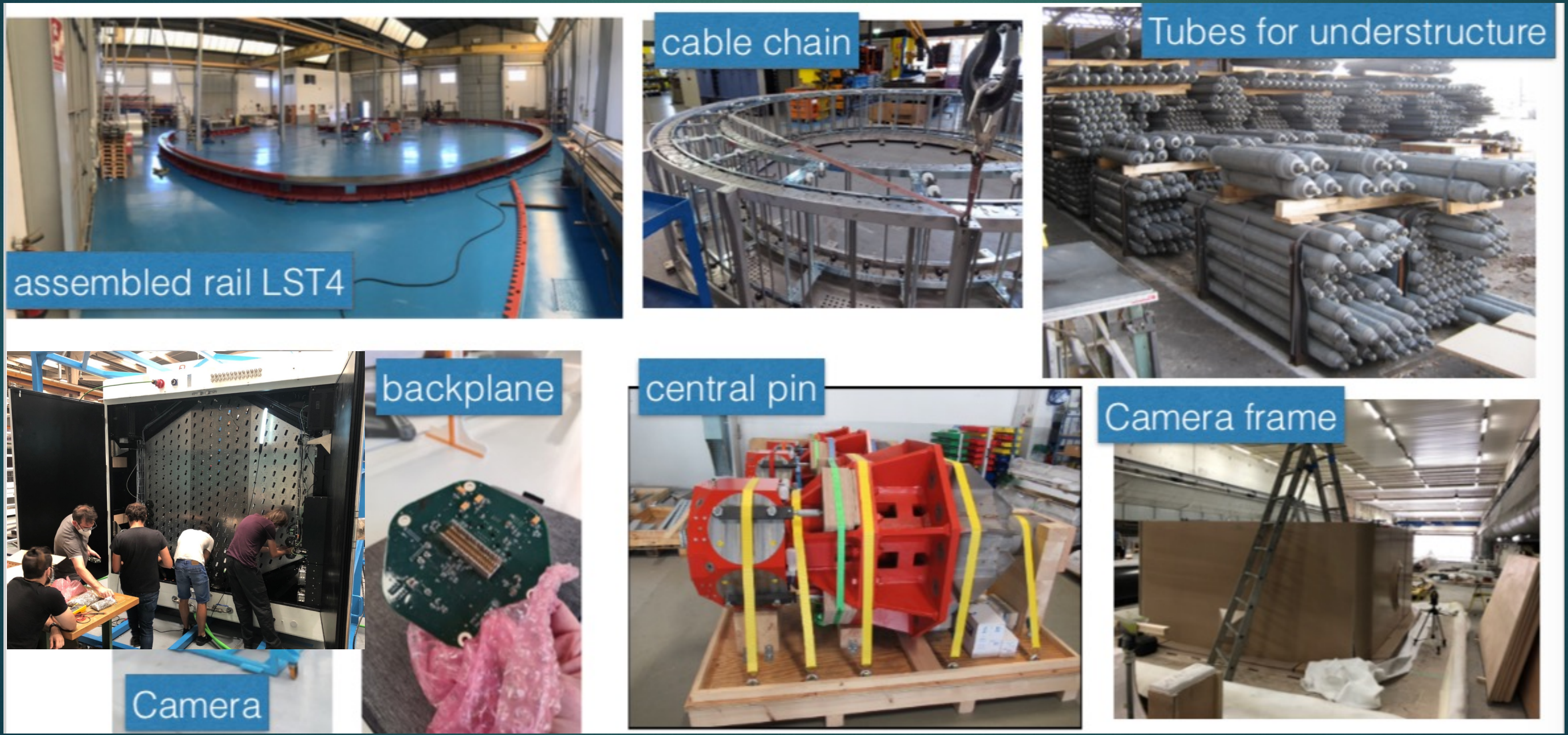
Working on paper (former DPNC member)

- First astronomical alert issued by a CTA telescope.
- August 8th 2021: High state >1 crab for E<300 GeV.
- Soft spectrum allows to extract spectral point at 30 GeV in <2 hour observation.



CTAO-north: completing 4 LST

Next three LSTs: hardware production almost done

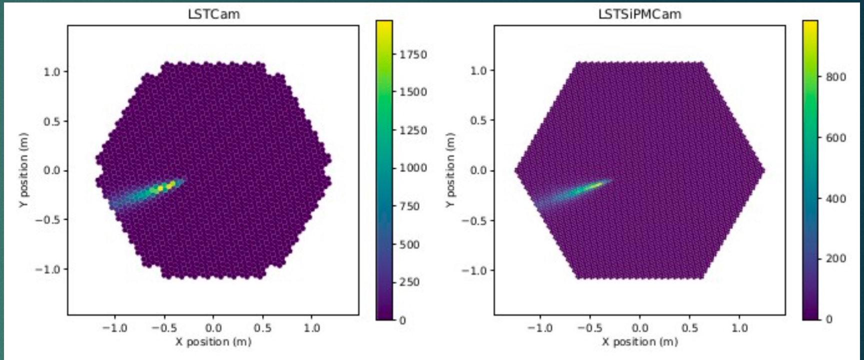


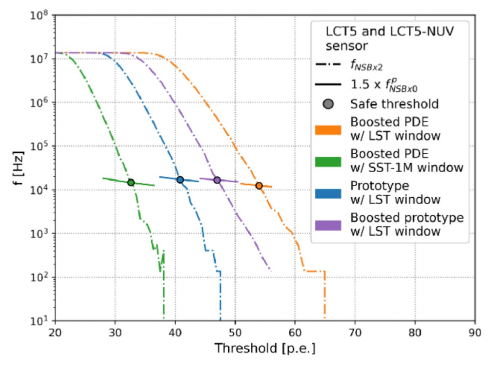
Next three LSTs: civil works ongoing

Installation to finish in 2025

LST: advanced camera

- Moving from PMT to SiPM + finer spatial sampling + more efficient trigger may allow to reduce threshold with the same mirror.
- We are already working on an upgrade for the current cameras.
- Effort led by DPNC. Recently joined by many groups in Spain.
- Completing design: trigger scheme, readout.

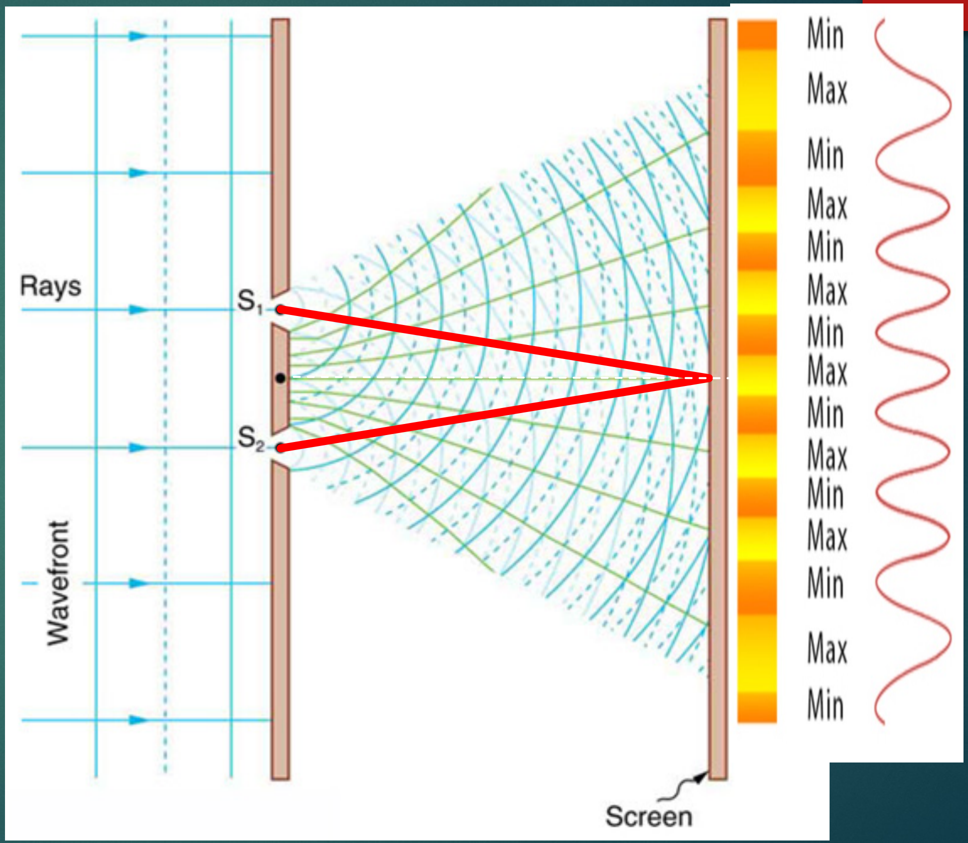




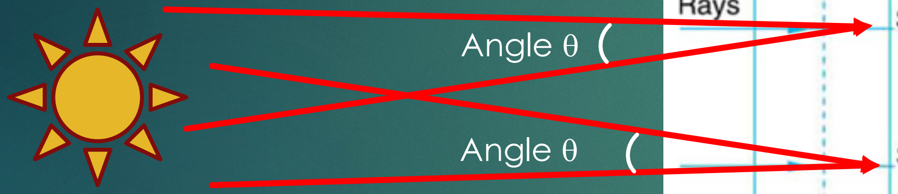
Intermission

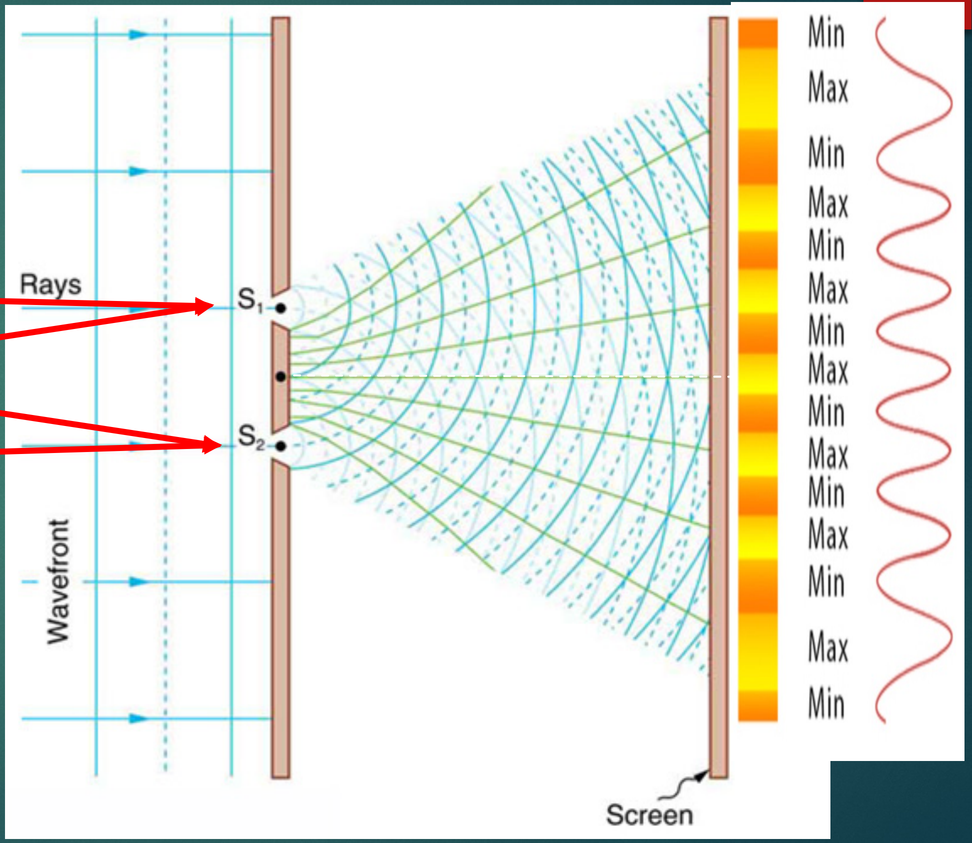
The highest angular resolutions

Young's double slit experiment



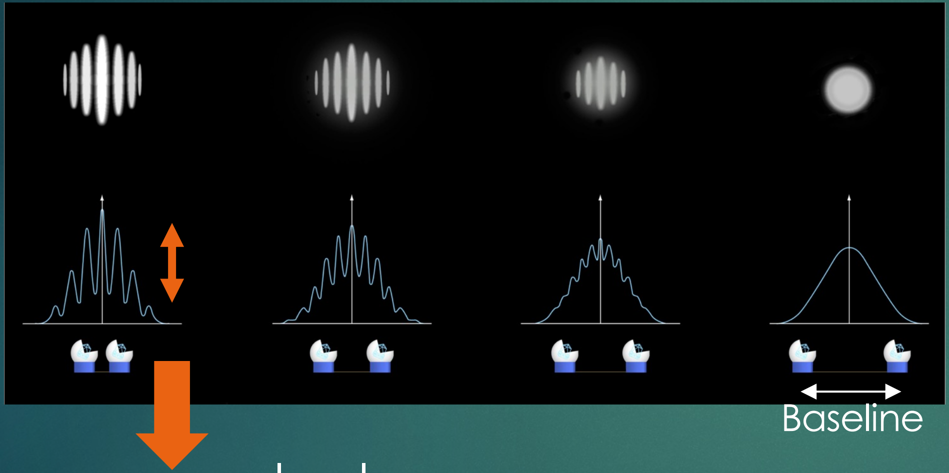
Real stars





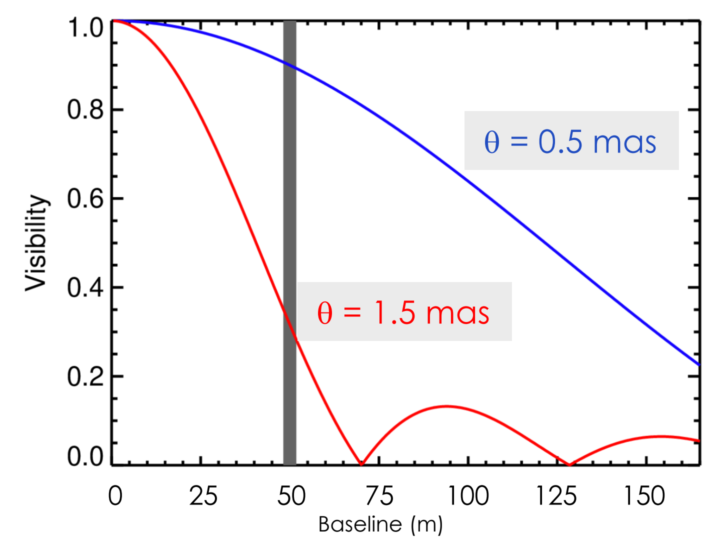
- Real stars are not at infinity so they are not a point source. Light arrives with an angular distribution.
- And in fact we are interested to measure that distribution!

How does coherence evolve with baseline? Amplitude interferometry

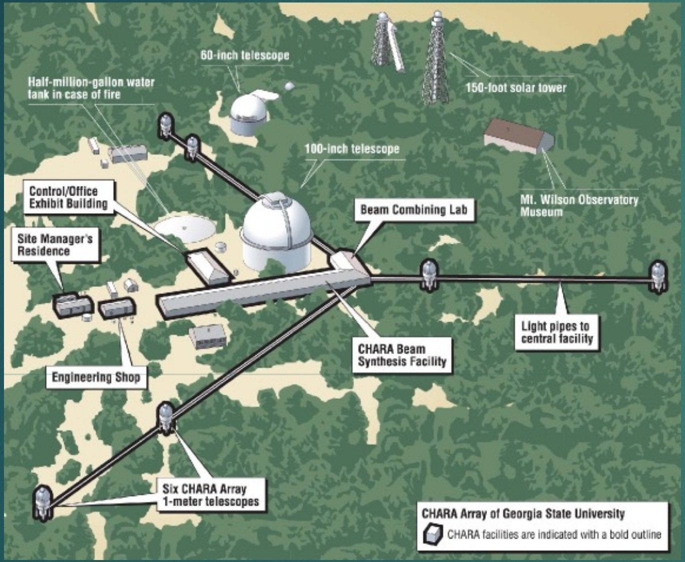


$$\text{Visibility} = \frac{I_{max}-I_{min}}{I_{max}+I_{min}}$$

λ = 400 nm
Visibility for stars of 0.5 and 1.5 mas diameter



Optical amplitude interferometry: state of the art



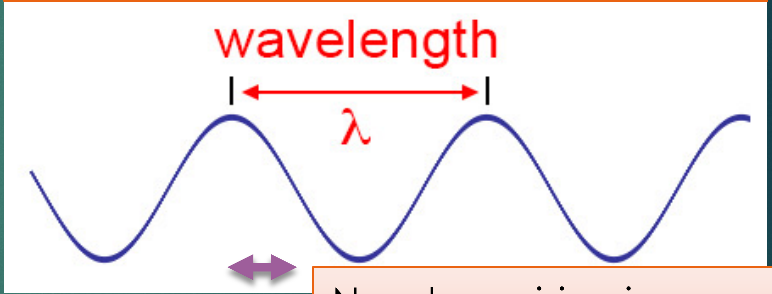
CHARA in California: 6x 1 m telescopes, connected to correlator. Baseline <331 m. 200 μas resolution in visible (V,R) for $V<10^m$.

GRAVITY in VLT, Chile: 6x 8 m telescopes, connected to correlator. Baseline <130 m. 2 mas resolution in IR for $K<17^m$, 50 μas astrometry

Amplitude interferometry: longer baselines?

- The wave oscillates too fast: it can't be digitized and stored to disk (like they do in radio). One must bring bring light from two telescopes to one place to produce the interference pattern.
- Optical path between telescopes and optical path in the atmosphere must be stable to better than 1 wavelength.

Visible light:
Period $\sim 10^{-15}$ s = 1 femtosecond
λ = 400-700 **nm**



Need precision in optical path ~ **100 nm**

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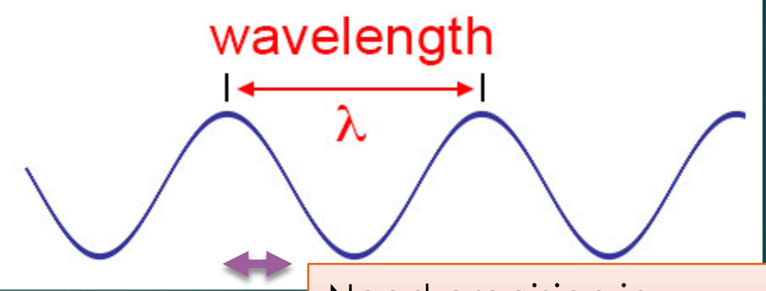
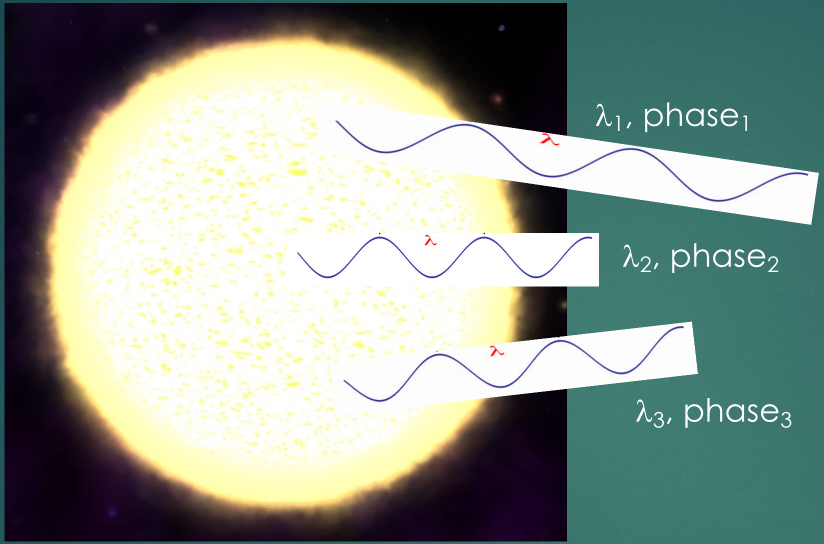


Need precision in optical path $\sim$ **100 nm**

This type of interferometry is currently limited to:
1. Baseline of hundreds of meters, i.e. angular resolutions around 100 μas.
2. Long visible wavelengths (red) and infrared.

Intensity time modulation

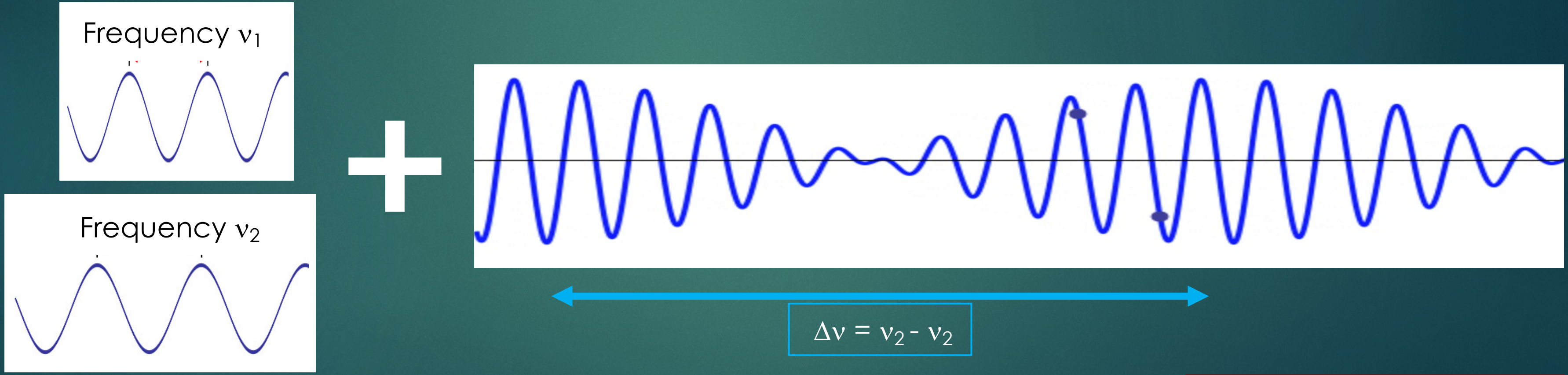
Hanbury-Brown
&
Twiss
1950s



Star photons come from random points at the star surface
i.e. random angles, different phases and wavelengths.

"Beats"

- Consider for instance two waves of frequencies ν_1 and ν_2
- Amplitude of sum has characteristic frequency $\Delta\nu = \nu_1 - \nu_2 < \nu_1$, <u>smaller</u> than original frequencies!

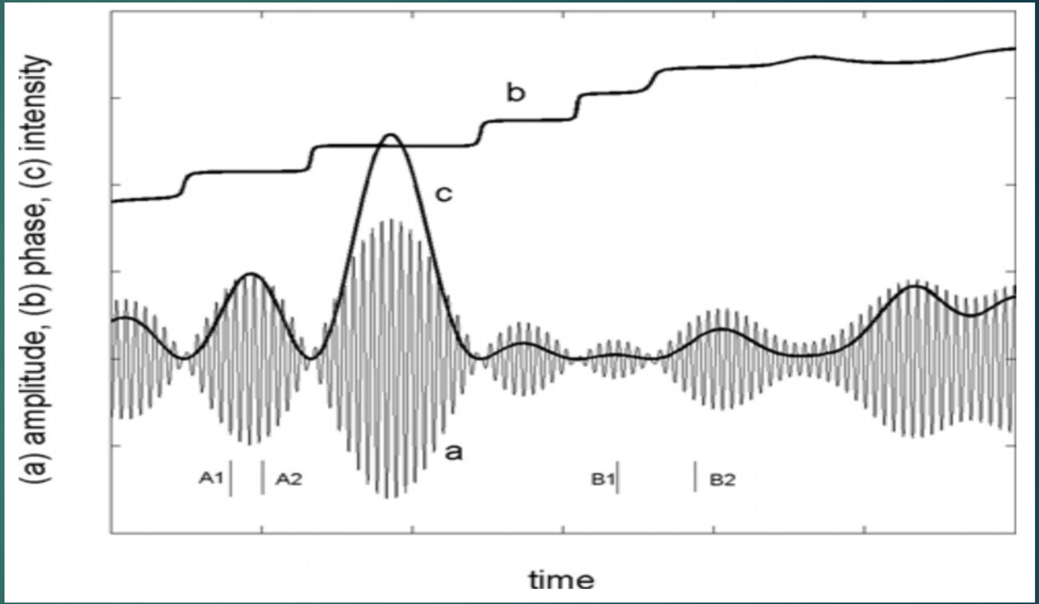


These are called "beats" in music

Intensity time modulation

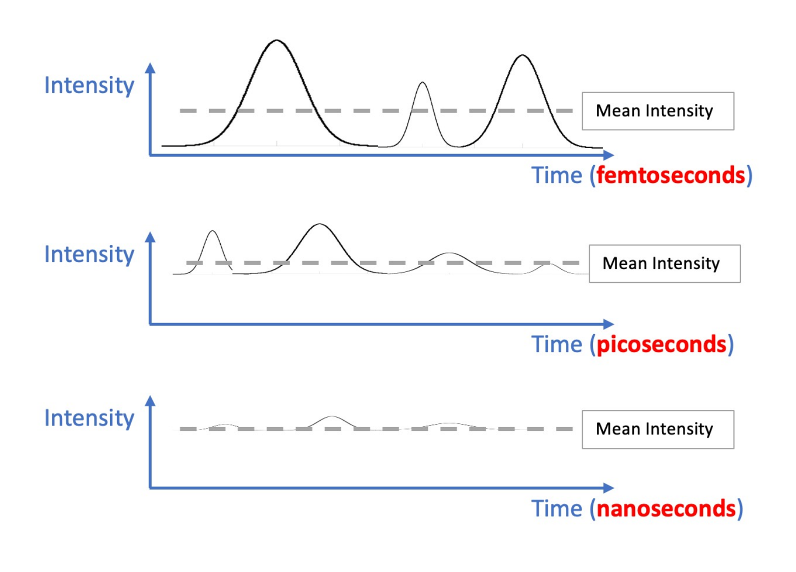
Now consider e.g.:

- Many sinusoidal components
- unit amplitude
- Randomly chosen frequencies within a band $\nu_0 \pm 0.05 \cdot \nu_0$



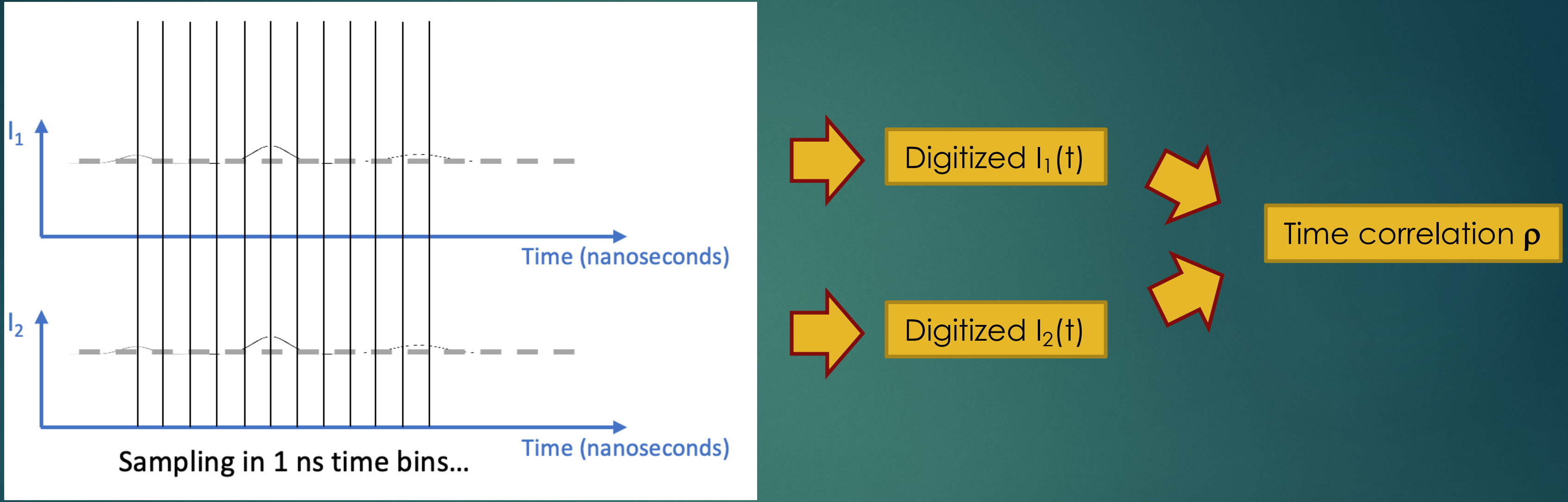
- One can see many different time scales: from $1/\nu_0$ to the longest for the two components that happen to be closest in frequency, $1 / (\nu_i - \nu_j)$
- For a continuum in $\nu_0 \pm \Delta\nu_0$ there is always some degree of modulation for **any** time scale

Changing time resolution



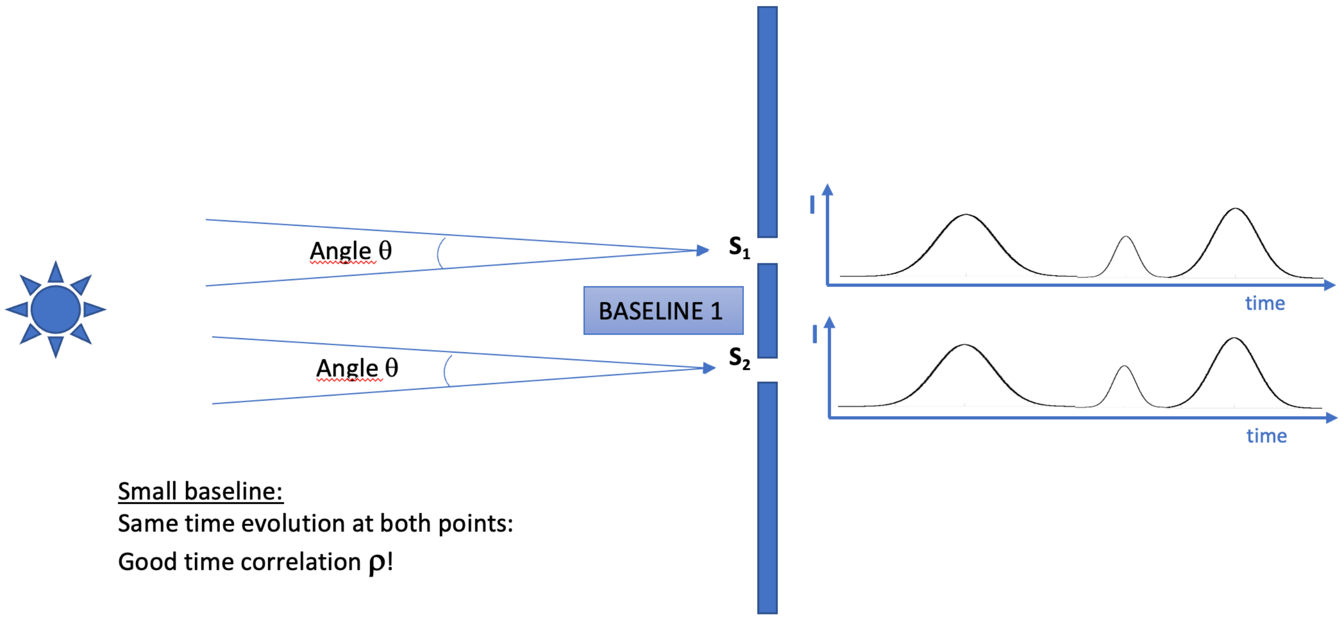
- Relative amplitude gets smaller and smaller with time scale, i.e. harder to detect
- But there is always some modulation! At any scale!

Conclusion 1: We can digitize the signal



Allows to increase baseline indefinitely: **100 m, 1 km, 10 km….**
And correspondingly angular resolution!

How does time modulation evolve with baseline?



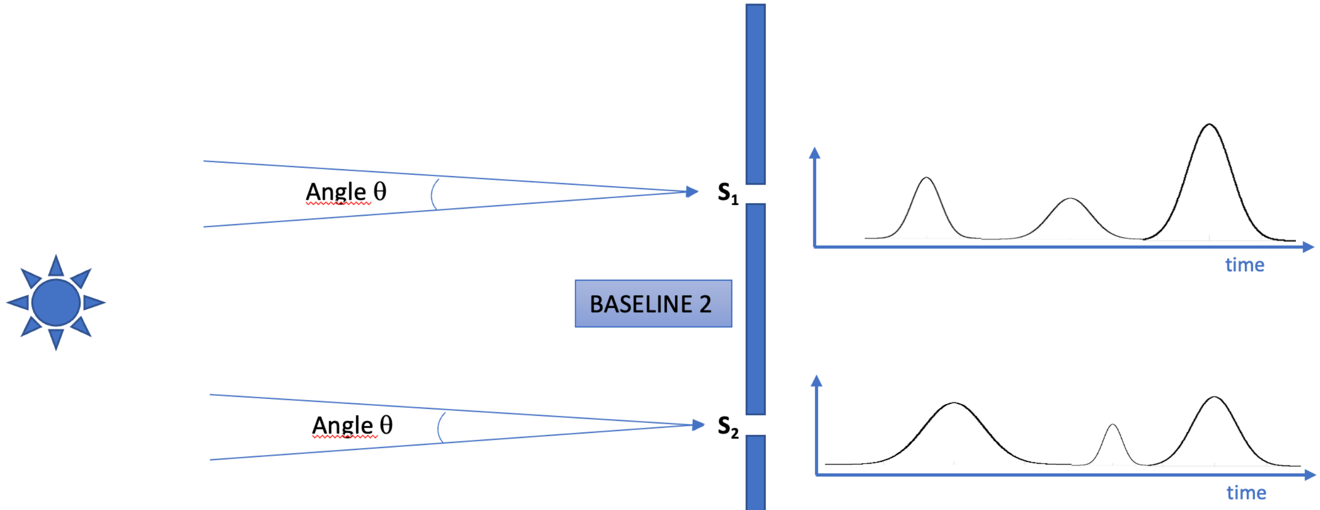
<u>Small baseline:</u>

Same time evolution at both points:

Good time correlation ρ!

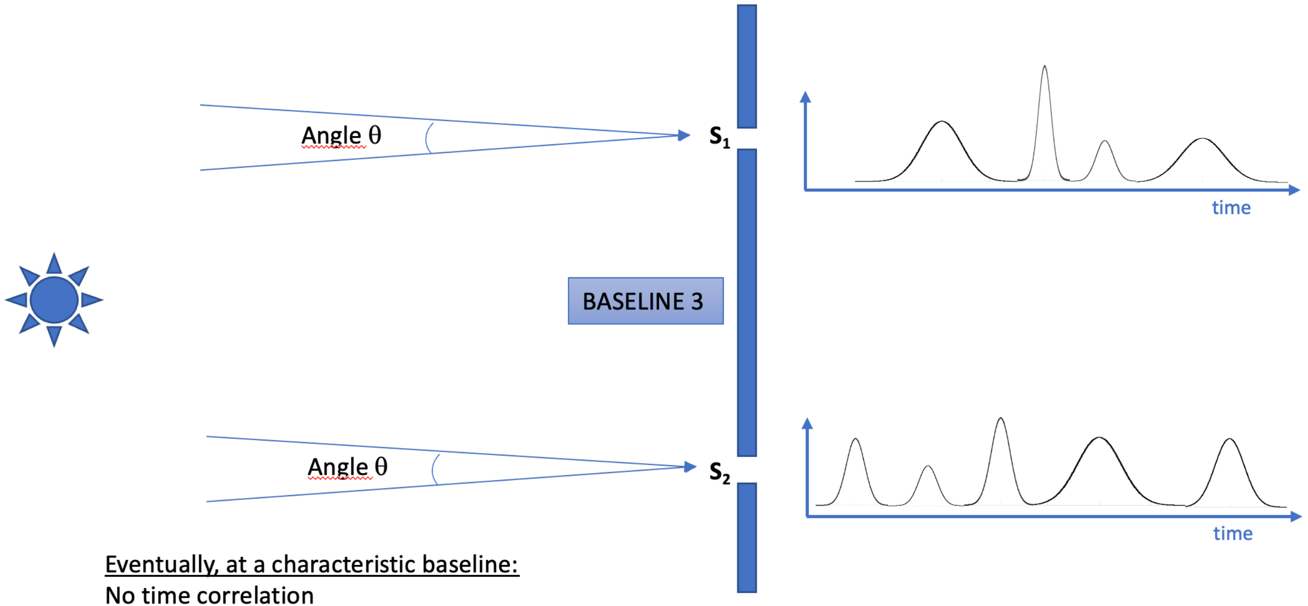
J. Cortina, DPNC seminar about IACTs

How does time modulation evolve with baseline?



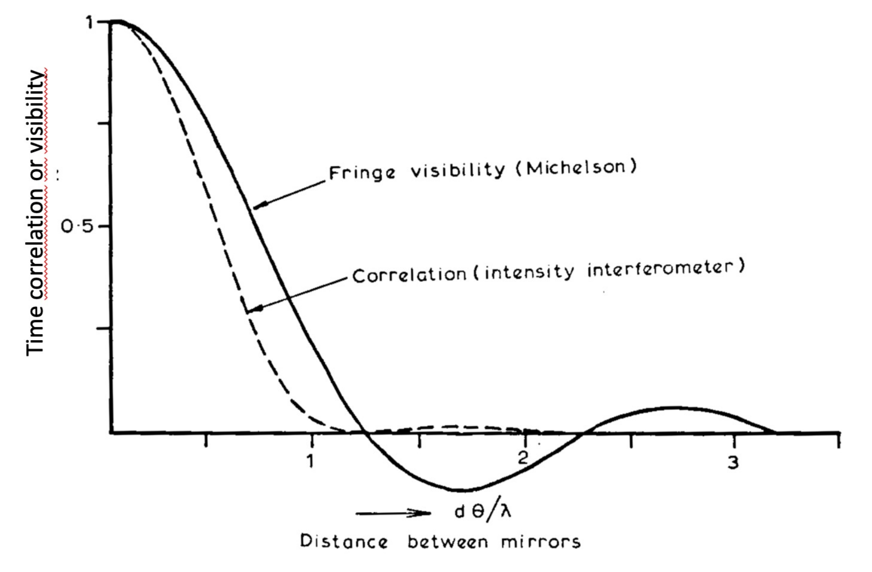
As baseline increases:
Time pattern starts to change…
Time correlation degrades

How does time modulation evolve with baseline?



<u>Eventually, at a characteristic baseline:</u>
No time correlation

Conclusion 2: same angular resolution

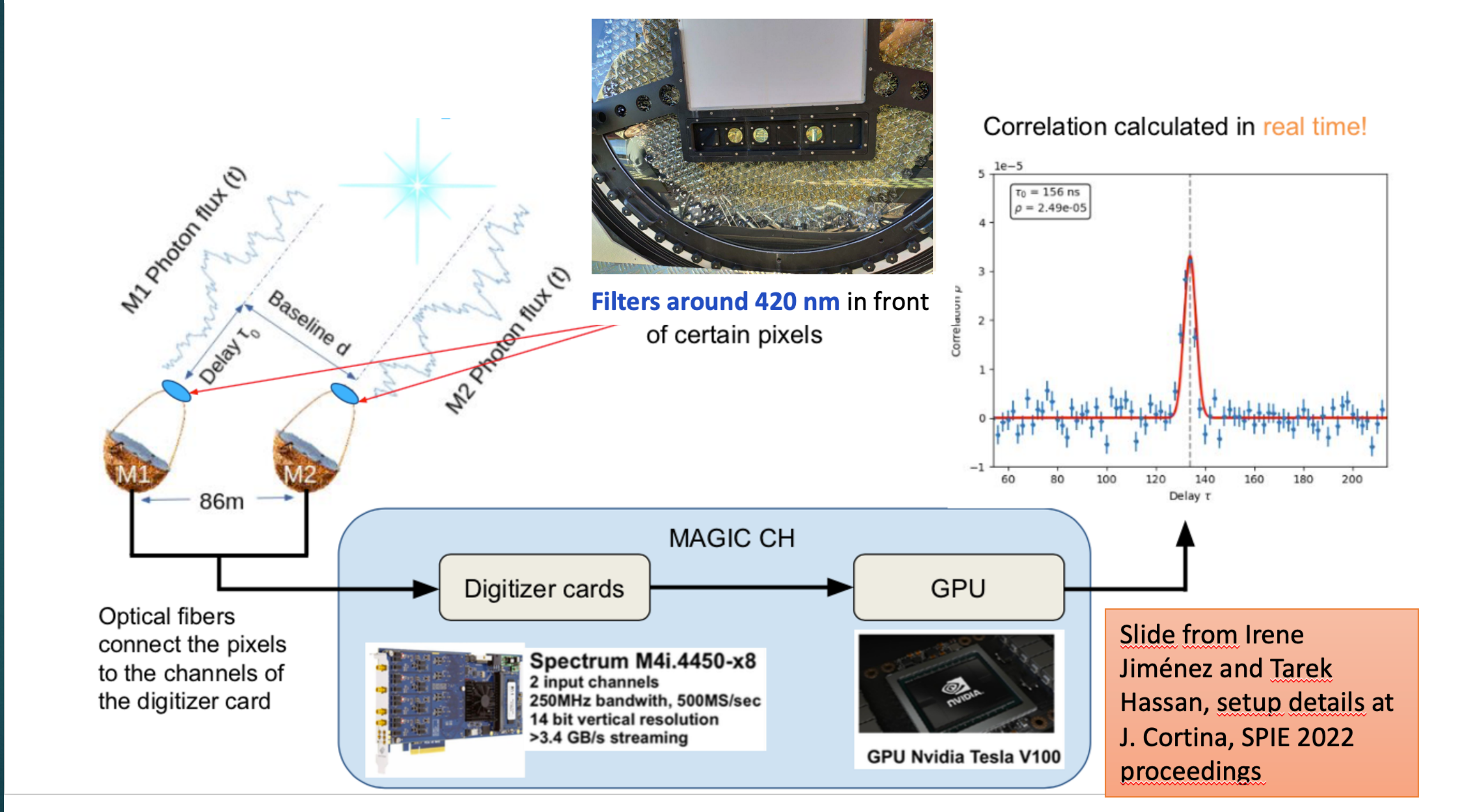


- The time correlation ρ depends on the baseline with V^2, instead of V for amplitude interferometer.
- But the characteristic distance is the same!

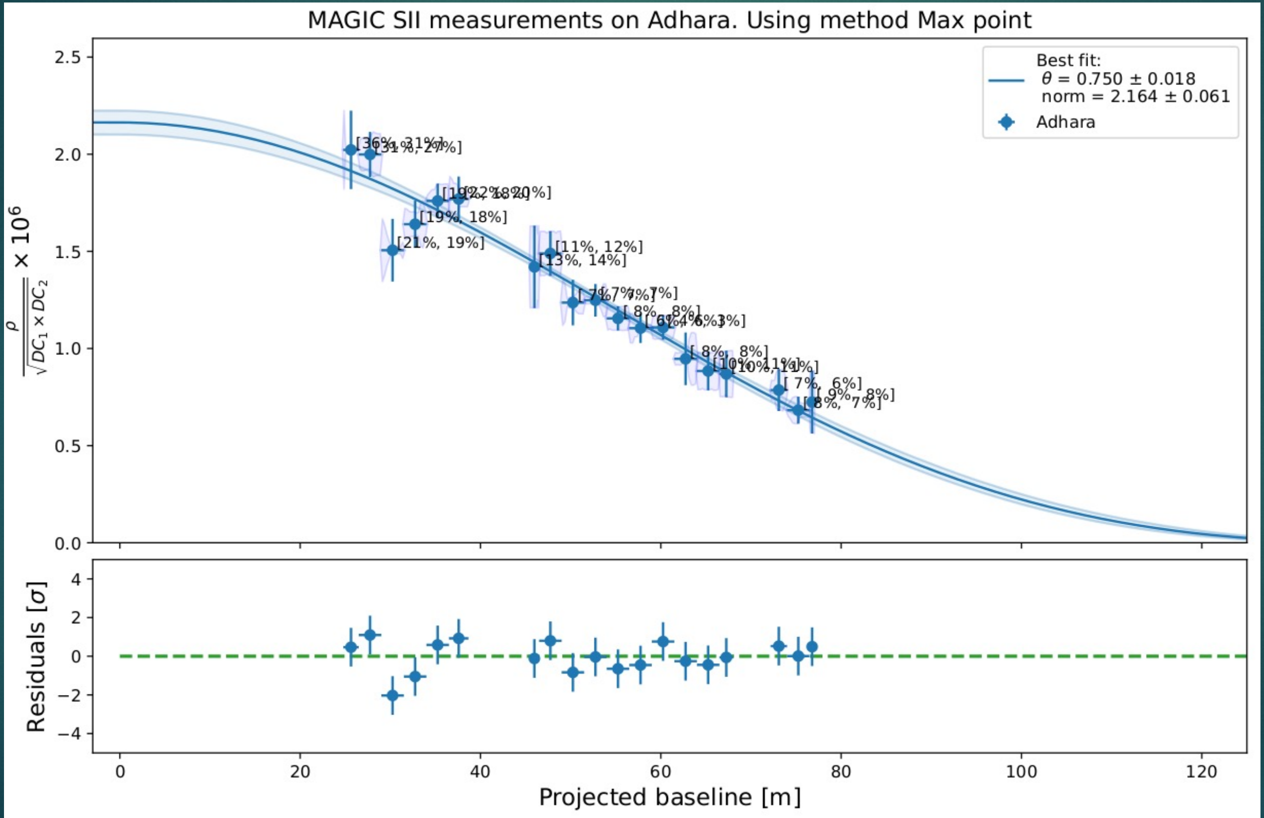
Cherenkov telescopes

- The requirements of Cherenkov telescopes are remarkably similar to those of intensity interferometry. It’s straightforward to use them for **intensity interferometry.**
- E.g. MAGIC features:
  - Two large mirrors (17 m diameter).
  - Mirror parabolic shape: time response <1 ns.
  - Sensitivity to near UV and visible wavelengths.
  - Photodetectors (PMTs) with fast time response (2.5 ns FWHM) and good single photoelectron response.
  - Fast electronics all the way to the readout (we can sample up to < 2GSps).
- The CTA telescopes have similar requirements.

MAGIC interferometry setup

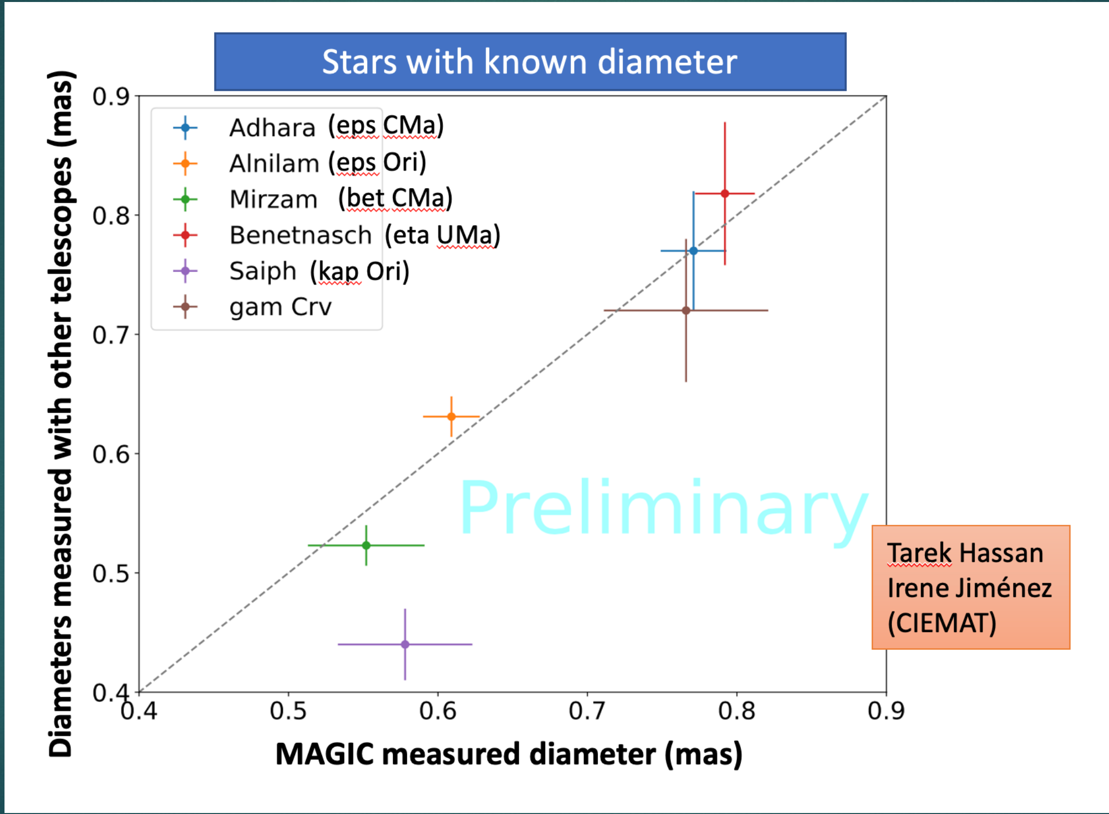


First results (2022)



Tarek Hassan
Irene Jiménez
(CIEMAT)

First results with full instrument (2022)



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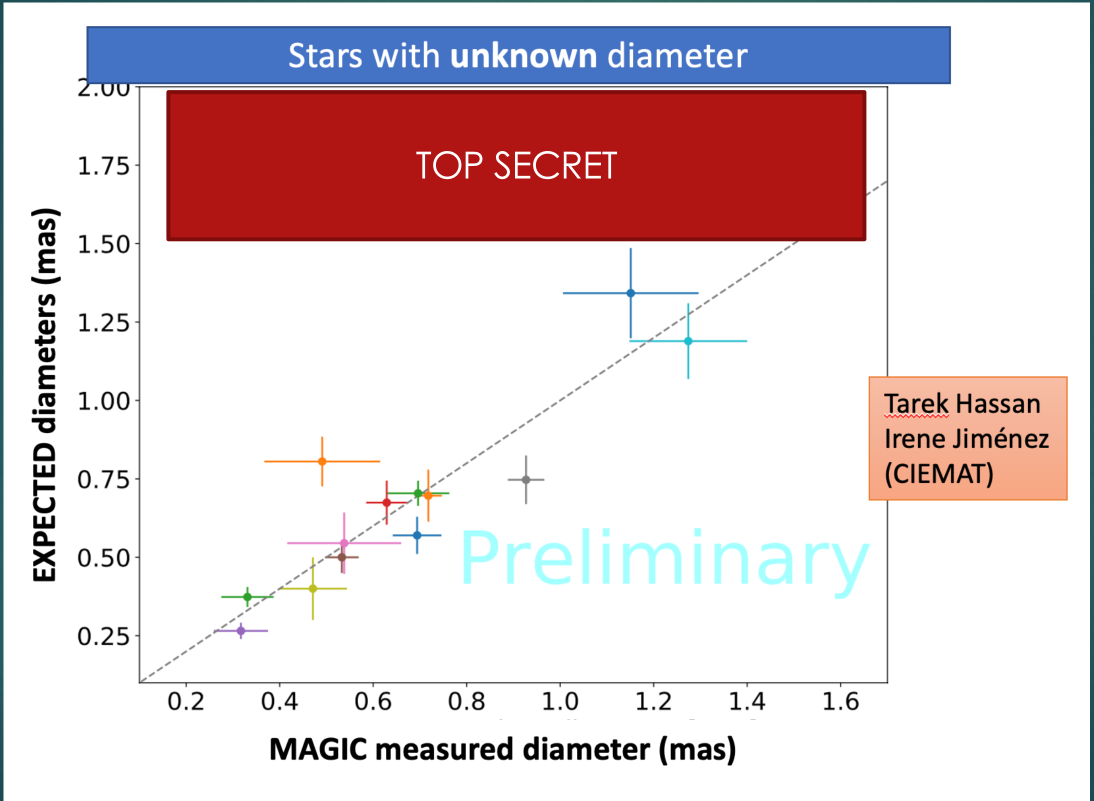
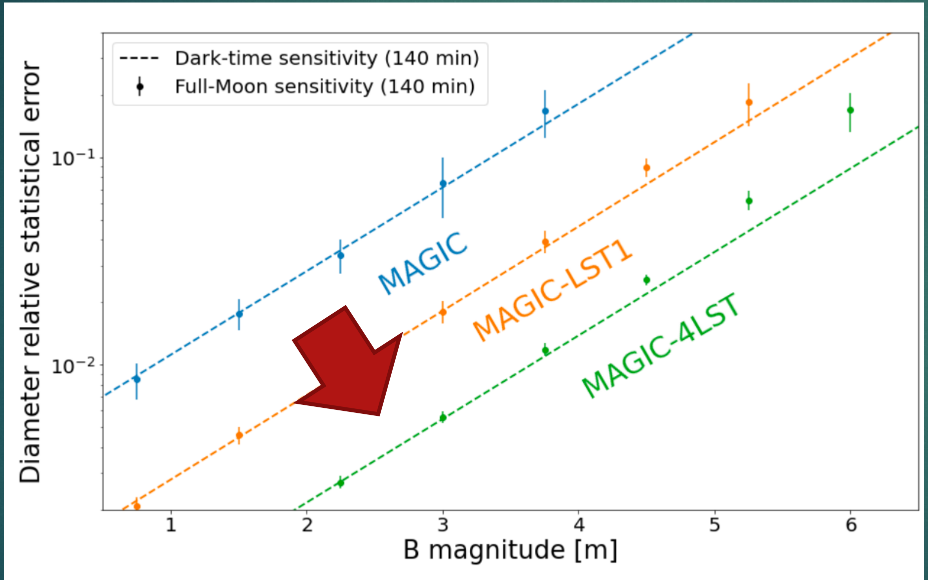


LST-north: Impact on sensitivity

- MAGIC's concept can be extended to the four LSTs in CTA-North.
- This is the purpose of Tarek Hassan's ERC starting grant at CIEMAT.



From MAGIC to 4 LSTs we expect to increase sensitivity by a factor 10, i.e. reach B~6.2^{m} (2 hour obs, 10% error in diameter)

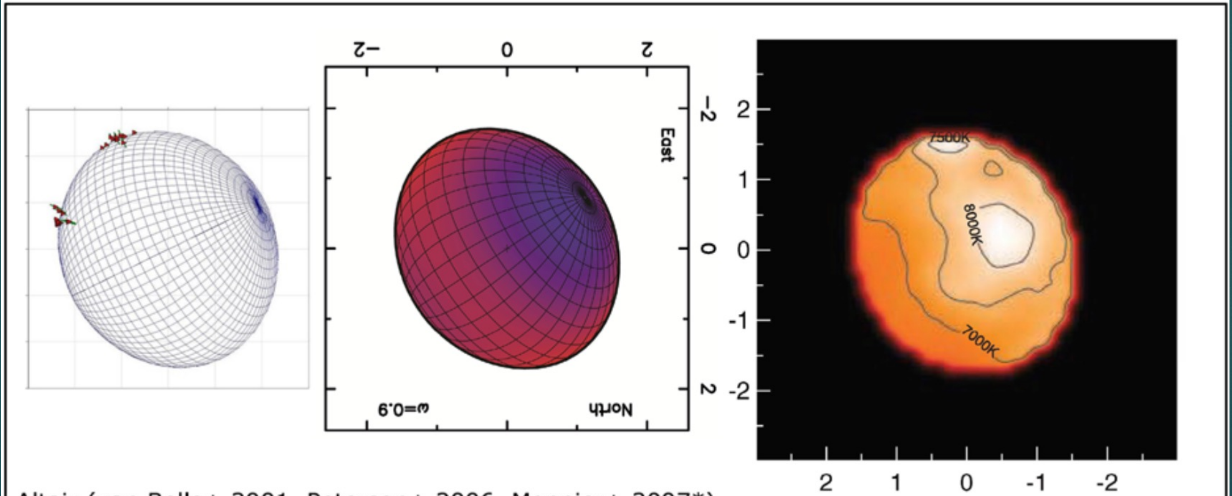
Science using intensity interferometry

1. Diameter of massive stars

- Contrary to amplitude interferometers, we are sensitive to short wavelengths, so we are especially good in the study of **massive stars** (O & B spectral types)
- … where models actually have troubles.
- You should care about massive stars: they are the precursors of core-collapse supernovae and black holes.

2. Shape of stars

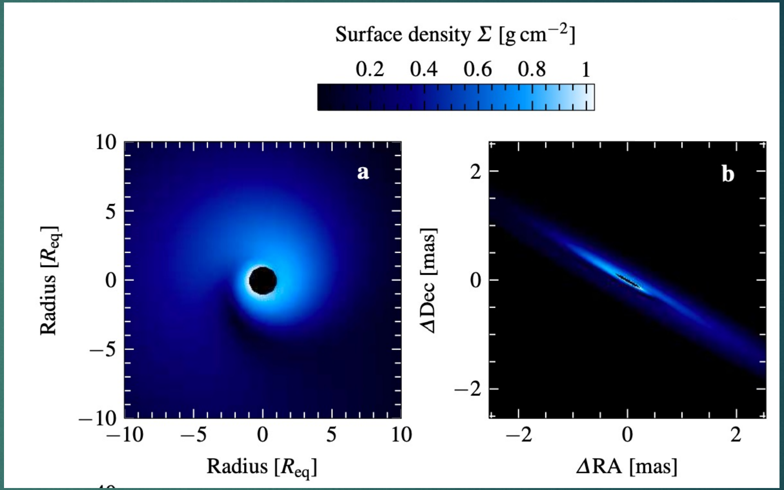
- Some stars rotate so fast that they deform. Measurements are scarce.
- Impact on stellar models, abundance of stars, wind geometry, irradiance geometry, exoplanet characterization…



Altair (van Belle+ 2001, Peterson+ 2006, Monnier+ 2007*)

3. Stellar outflows, winds

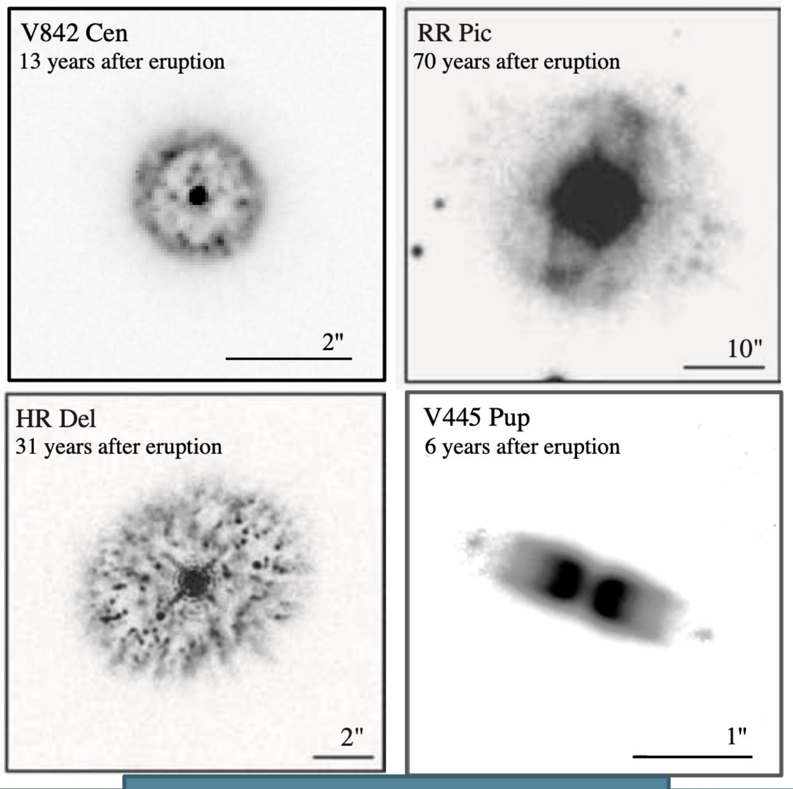
- Massive stars lose a significant fraction of their mass through winds.
- The mass of the future black hole depends on how much mass is shed through the wind.
- This is a key parameters to understand the black hole mass distribution: remember LIGO+Virgo’s surprisingly massive black holes?



Rivinius et al, arXiv:1310.3962

4. Novas

Chomiuk et al., arXiv:2011.08751

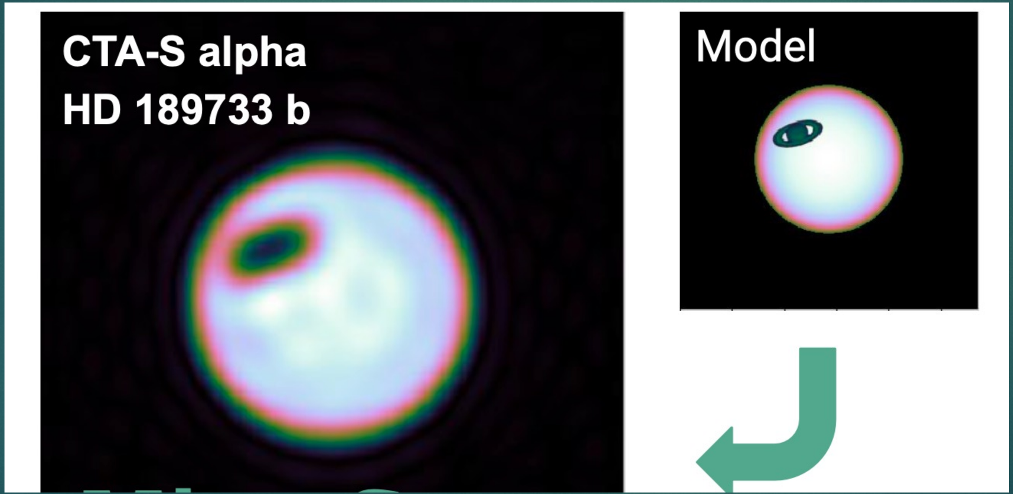


Nova images in visible range

- We can measure directly the <u>expansion speed</u> of the nova ejecta.
- And we know that these ejecta are often <u>asymmetric</u> -> so far never done for the first days of the explosion.

5. Exoplanets

- Transit observations allow to measure ratio of planet and star diameter. If we measure star diameter -> planet diameter.
- Image shadow of transiting exoplanets??



Looking into the future: longer baselines

- Intensity interferometer: no limit on telescope baseline.
- Large diameter telescopes are available or coming online: **CTA, GTC, VLT, E-ELT, GMT…**

La Palma
1.1 km -> 40 μas

But we need better sensitivity

- Higher angular resolution

  -> smaller objects

  -> larger distances

  -> **less bright objects**

- For instance:
  - Baseline 800 m means 100 x less bright
  - Baseline 8 km means 10000 x less bright

How to increase sensitivity

$$\text{Sensitivity} \propto S_{mirror} \cdot QE_{pixel} \cdot F_{pixel}^{-1} \cdot N_{telescopes} \cdot \sqrt{1/\text{Time\_Res}} \cdot \sqrt{N_{spectral\_channels}}$$

Quantum efficiency of photosensor

sqrt (1 / Time resolution)

sqrt (Num spectral channels)

We can **increase sensitivity** through several instrumental improvements:

- Higher photon efficiency: factor 1.5 possible
- Faster photodetectors: factor 1000 possible
- More spectral channels: factor 1000 possible

All in all, we may gain a factor 1500 in sensitivity, i.e. **reach ~14^m**

How to increase sensitivity

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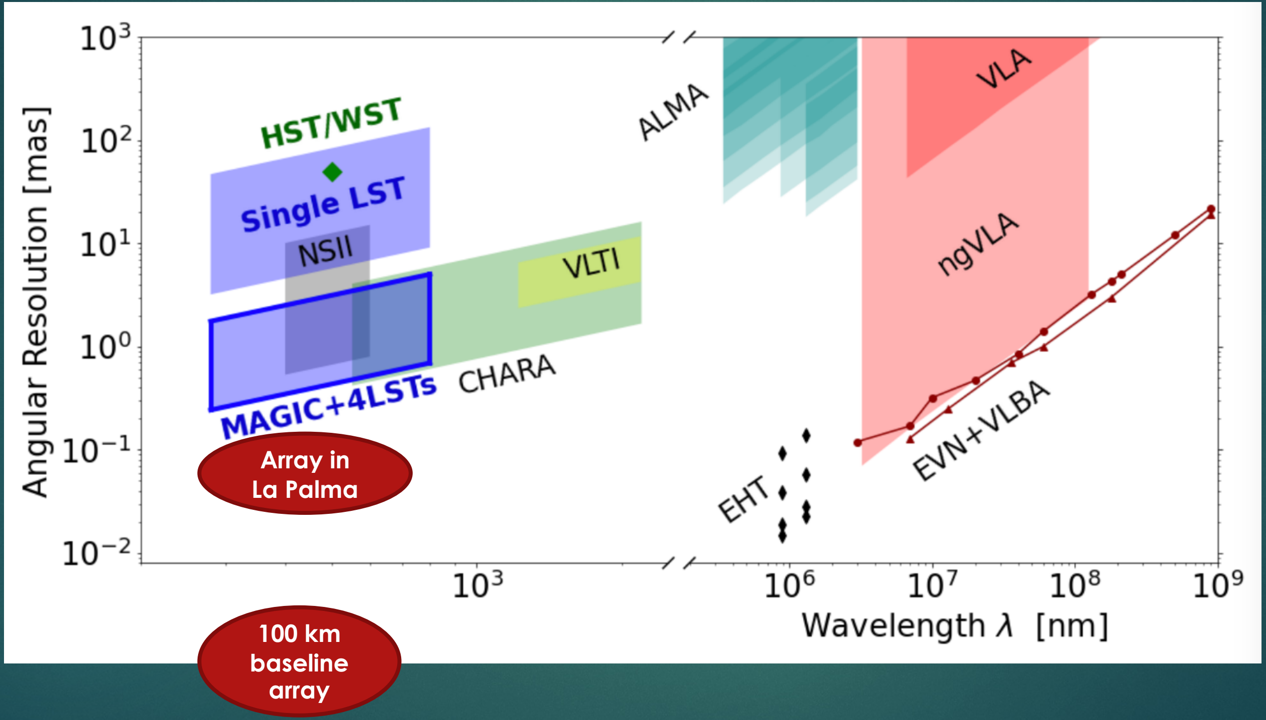
All in all, we may gain a factor 1500 in sensitiv … $\sim 14^m$

Recent SINERGIA grant awarded to R. Walter's group aims at developing such photodetectors

To **nanoarcsec** resolution



J. Cortina, DPNC seminar about IACTs

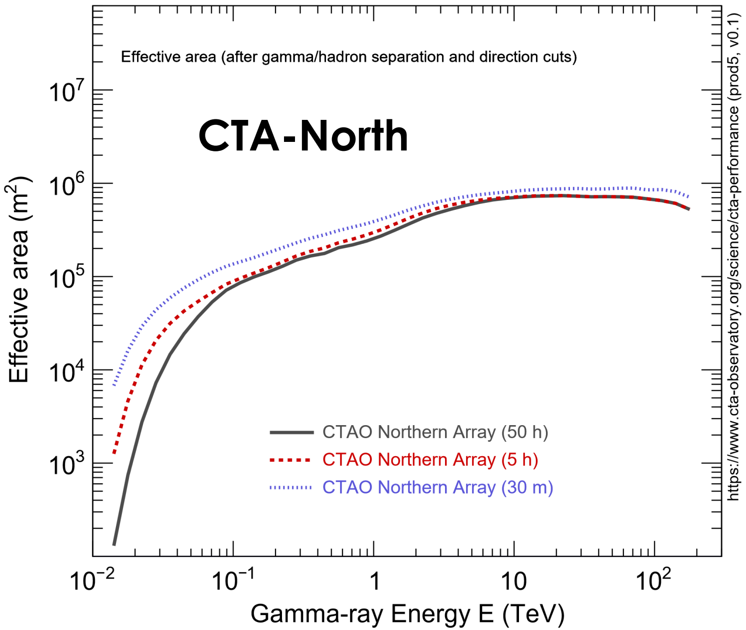
Conclusions

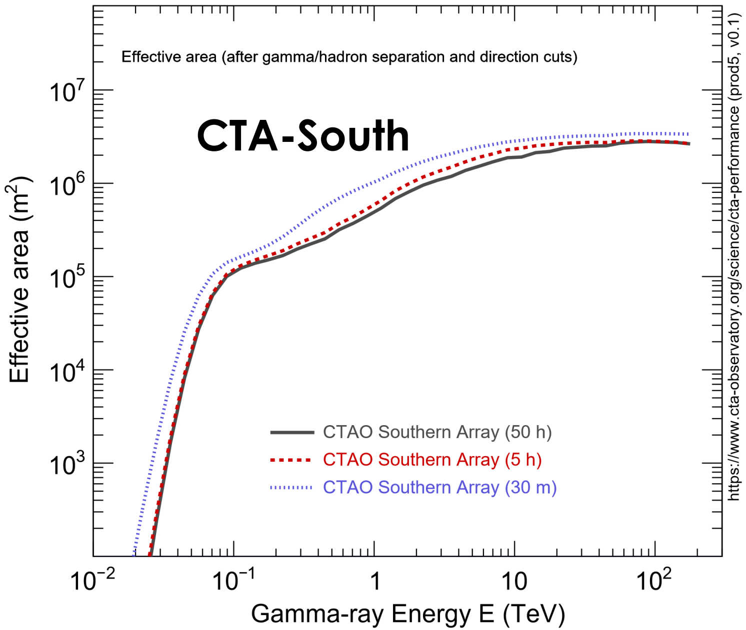
- VHE γ-ray astronomy remains a lively field:
  - Constant flow of discoveries.
  - Observationally driven.
- We urgently need a new generation of Cherenkov Telescopes: open observatory, full sky, wide energy range, **CTA**
  - CTAO ERIC under constitution, start construction in 2023.
  - Advanced construction: First LST finishing commissioning and already producing scientific papers. Next 3 LSTs expected in 2025.
- Cherenkov telescopes can be used as intensity interferometers in the visible range
  - Already implemented in MAGIC: angular resolution <1 mas
  - High impact in stellar physics, exoplanets?
  - Even higher resolution possible with more advanced photodetectors.


Thank you!

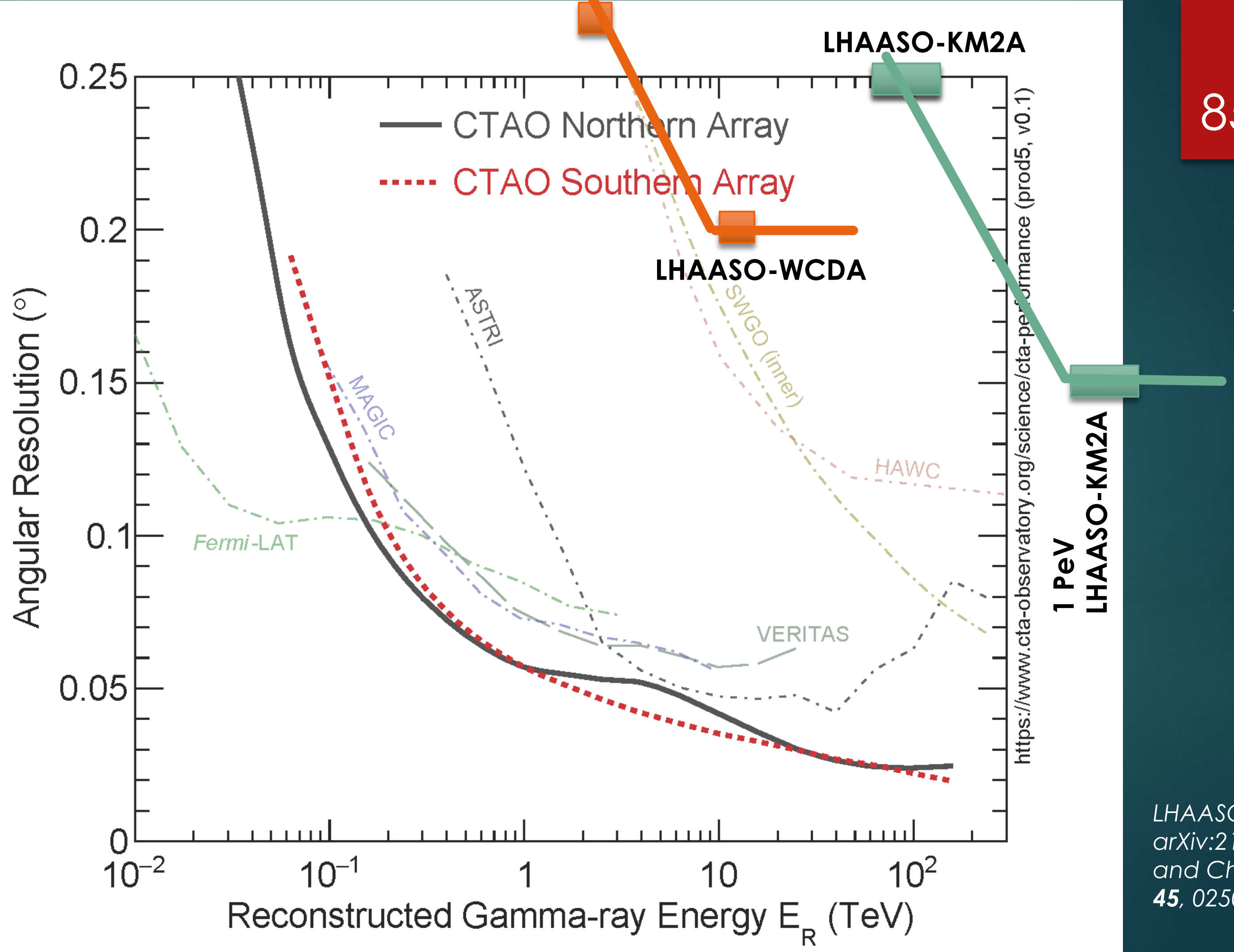
backup

Collection areas





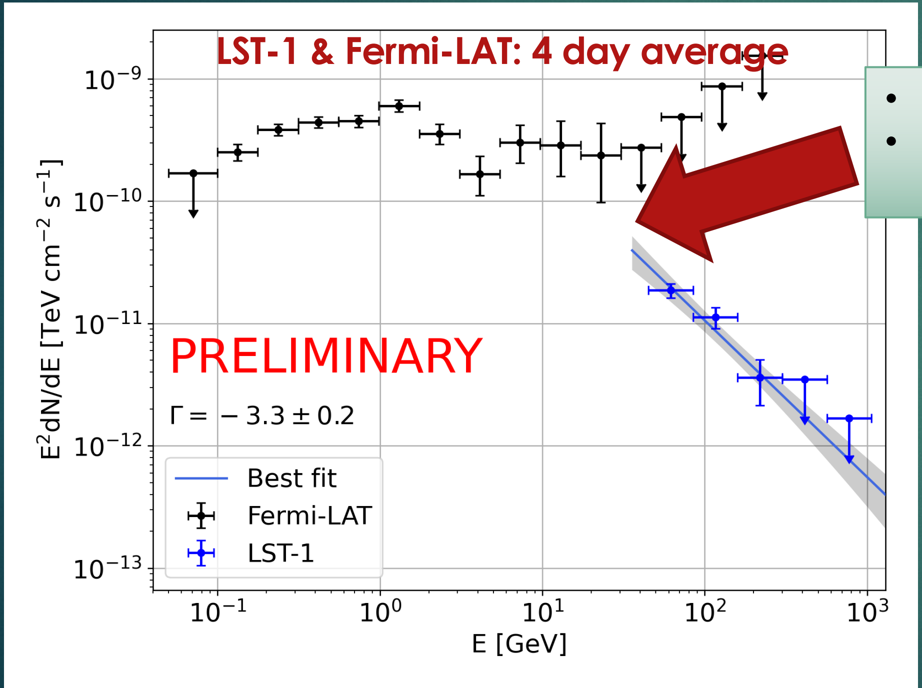
Angular resolution



J. Cortina, DPNC seminar about IACTs

*LHAASO from: arXiv:2101.03508 and Chinese Phys. C **45**, 025002 (2021)*

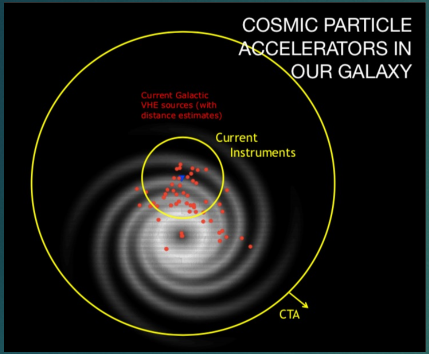
LST1: nova RS Oph

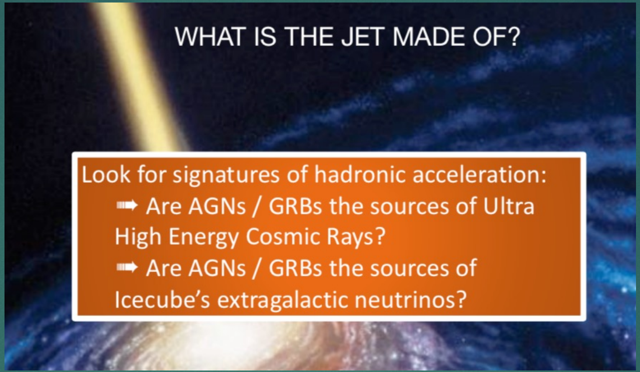


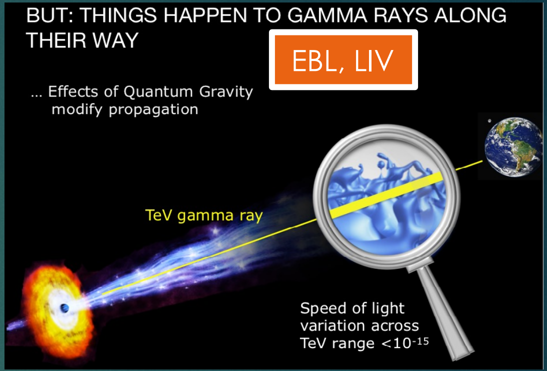
- No gap between Fermi and LST.
- Compare error bars for a few hours with LST1 and 4 days of Fermi.

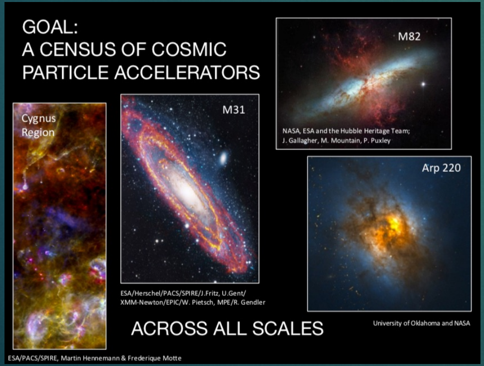
Working on paper!

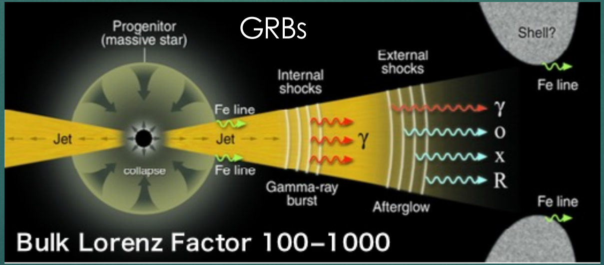
TeV+PeV Astronomy: wide science case

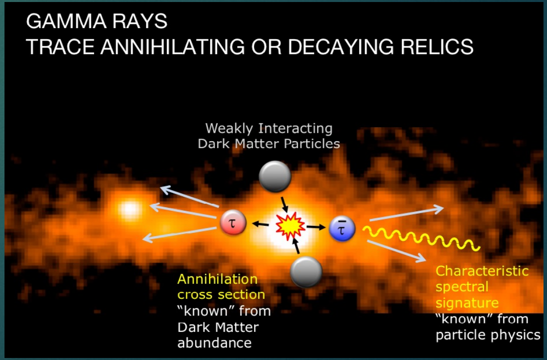












Acharya B S et al. (the CTA Consortium), Science with the Cherenkov Telescope Array, World Scientific, 2019, doi: 10.1142/10986, https://arxiv.org/abs/1709.07997

Cherenkov from showers

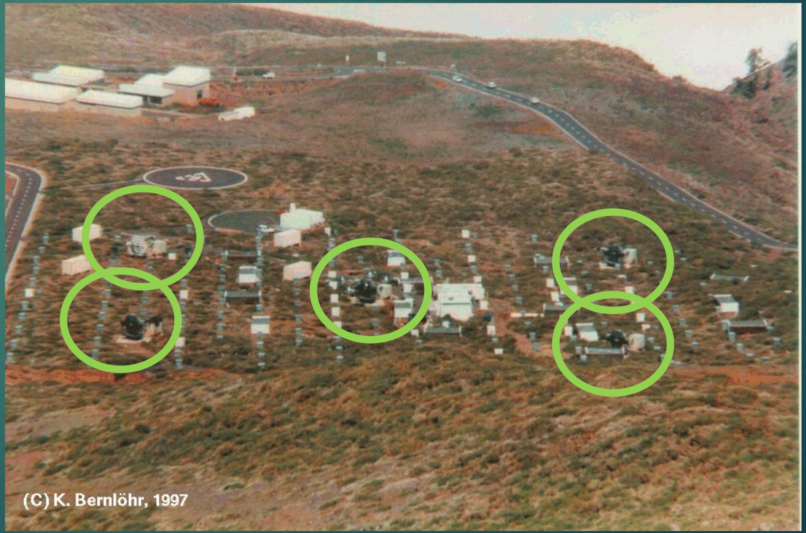
- By the end of WWII there were plenty of cheap searchlights and radar electronics around.
- Cherenkov light from showers was first detected by Galbraith and Jelley with a 2 inch photomultiplier (PMT) and a 25 cm searchlight in 1953.

Searchlights to spot airplanes during WWII in the UK

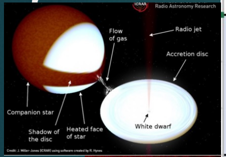
Whipple and HEGRA

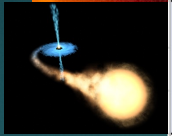
Inauguration of the Whipple IACT in 1968

- Whipple detected the first TeV gamma-ray source, the Crab Nebula in 1989 (Weekes, Hillas et al).
- HEGRA in La Palma introduced stereo in the 1990s.



Prospects (allow me a flight of





	object	M_BH (M_sun)	distance (pc)	angular size (μas)	angular size (nas)	typical magnitude
CV	RS Oph		1600	0,5	513,0	reaches 5-6m
	U Gem		93	8,8	8825,8	V=8.2 every 4 hours
	U Sco		19600	0,0	41,9	reaches 8m
AGNs	M87	5,00E+09	16000000	256,5	256500,0	reaches B~13
	Cen A	6,00E+07	4000000	12,3	12312,0	reaches B~13
	3c 273	8,86E+08	7,49E+08	1,0	970,9	reaches B=13
X-ray binaries	GRS 1915	12	2600	0,0	3,8	reaches B~10m
	Cyg X-1	21	1,90E+03	0,0	9,1	
	Cyg X-3	2	7400	0,0	0,2	

What science are we doing/planning?

Tidal deformations?

- In so-called "heartbeat stars" there's evidence for tidal deformation at certain orbital phases.
- We may be able to detect change in diameter for those specific phases.