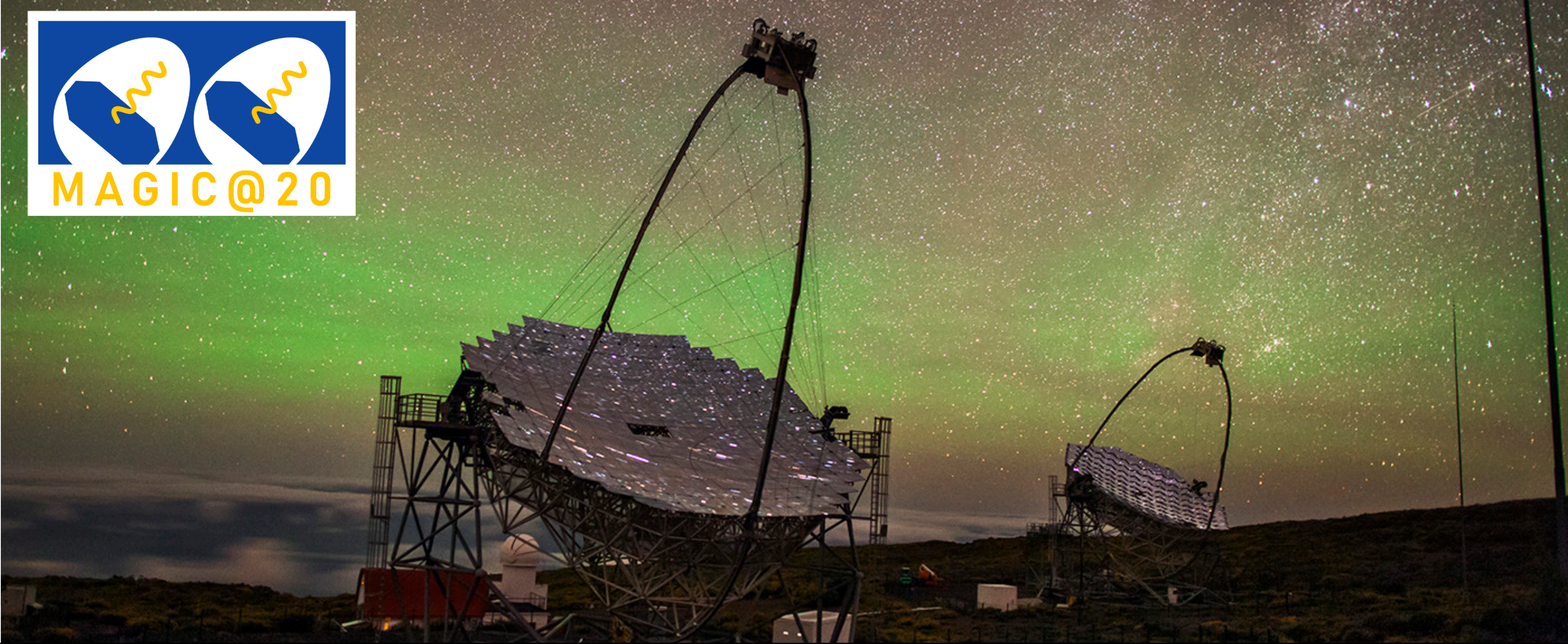


Intensity interferometry with MAGIC and LST

Juan Cortina (CIEMAT + IAC)

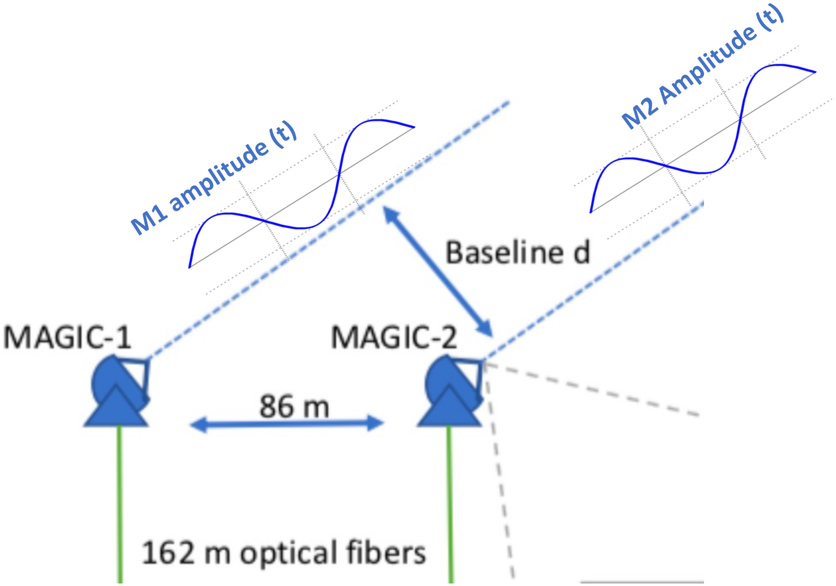
MAGIC 20th anniversary symposium, La Palma, October 2023

Outlook

- Interferometry: phase vs intensity.
- Intensity Interferometry with MAGIC.
- Extension to CTA/LSTs.
- Science with the interferometer.

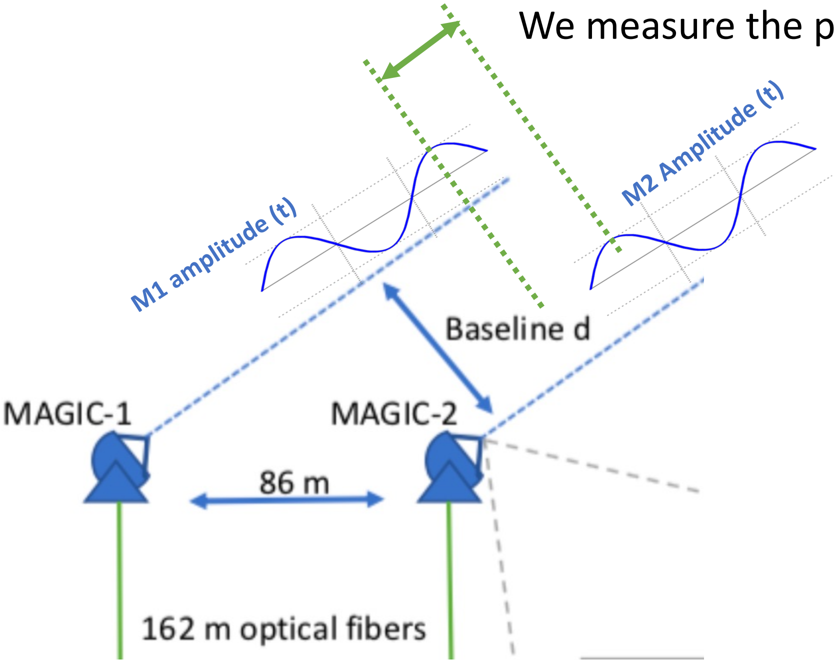
Interferometry: phase vs intensity

Phase interferometry

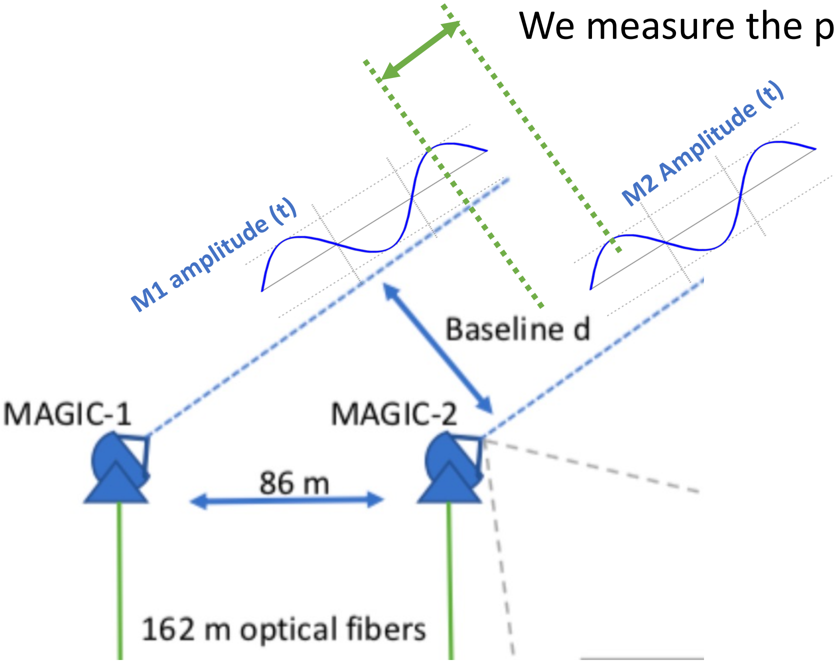


Phase interferometry

We measure the phase difference at different telescopes



Phase interferometry

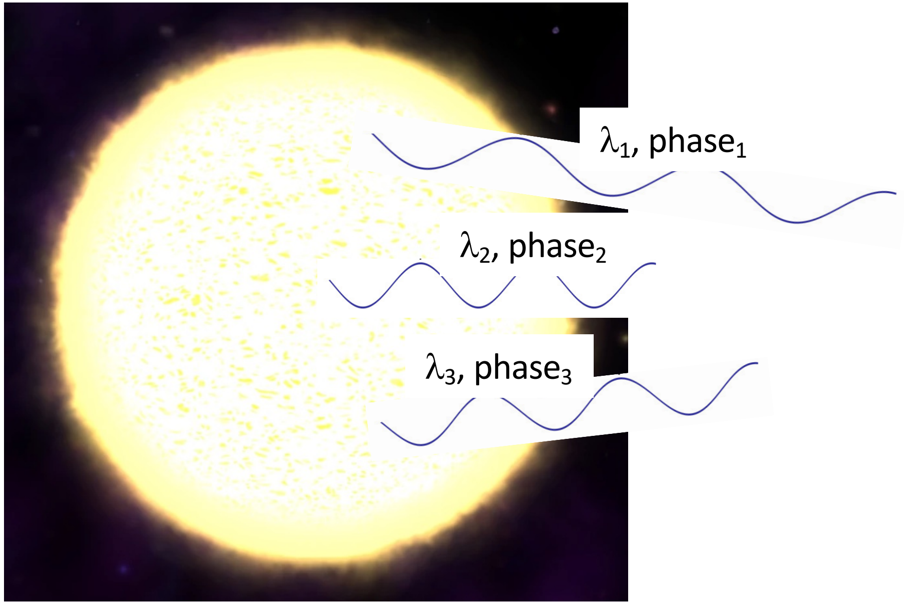


We measure the phase difference at different telescopes

This allows to infer:
- Angular distances between astronomical objects
- Angular size of objects

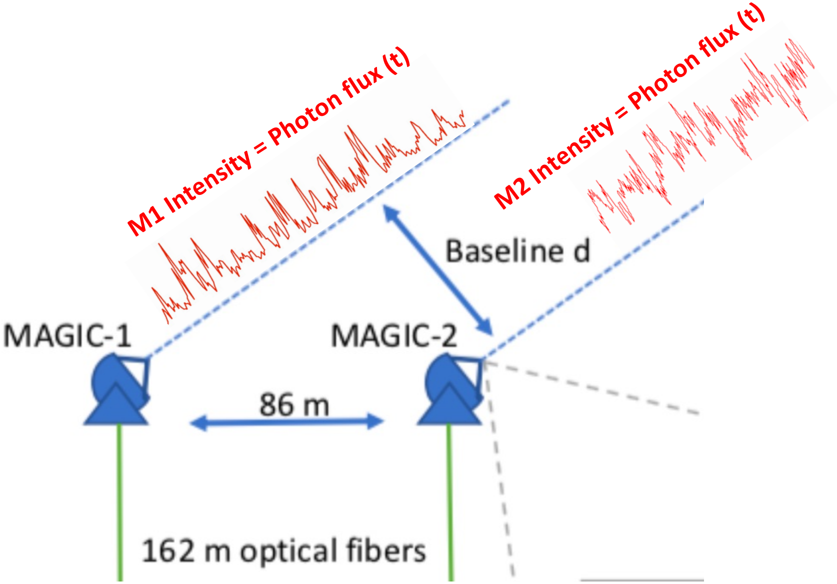
Intensity time modulation

Hanbury-Brown & Twiss 1950s



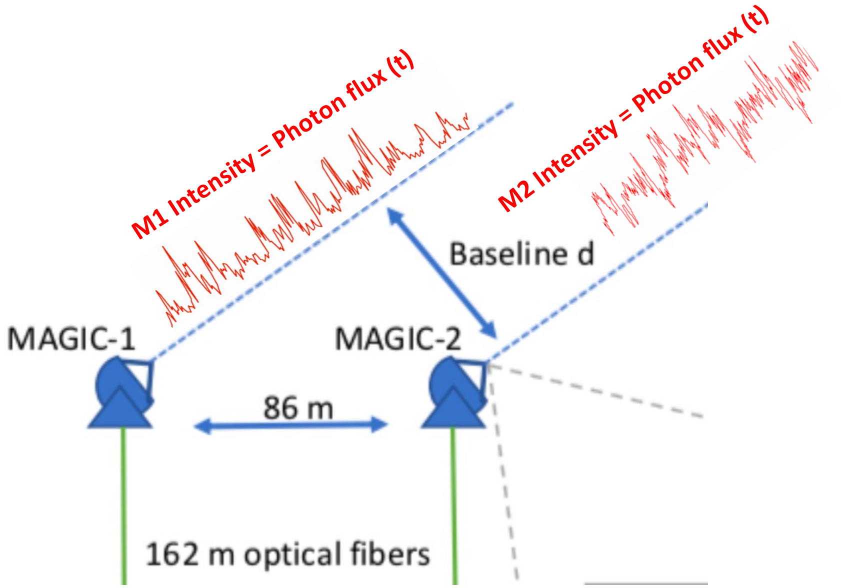
Star photons come from random points of stellar surface , i.e. random angles, different phases and wavelengths.

Intensity interferometry



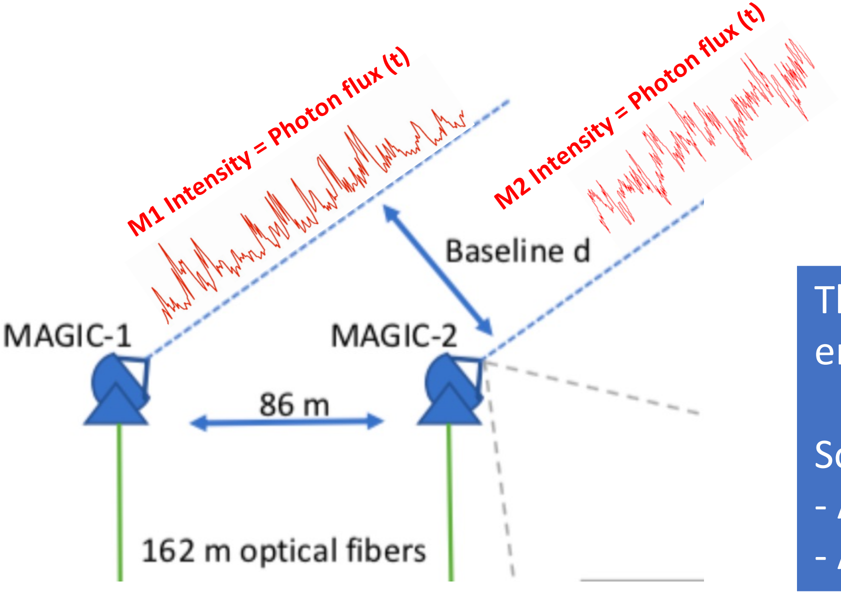
Intensity interferometry

We measure the time correlation of intensity at different telescopes



Intensity interferometry

We measure the time correlation of intensity at different telescopes

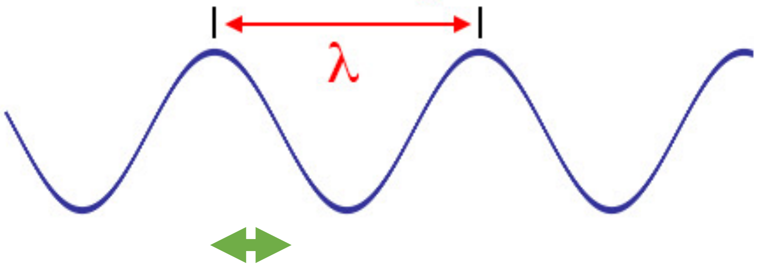


This correlation also depends on light distribution of emitter.

So we can also infer:
- Angular distances between astronomical objects
- Angular size of objects

Challenges of phase interferometry

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

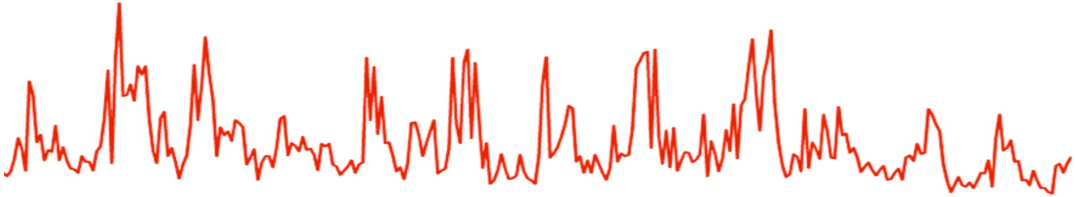


precision in optical path <∼**50 nm**

- Can’t be digitized.
- One must bring light from two telescopes into one place to produce the interference pattern.
- Optical path between telescopes and in the atmosphere must be stabilized to this precision!

… overcome with intensity interferometry

Intensity time modulation:
Time scale >∼ 10^{-11} s (10 ps)
independent of λ!

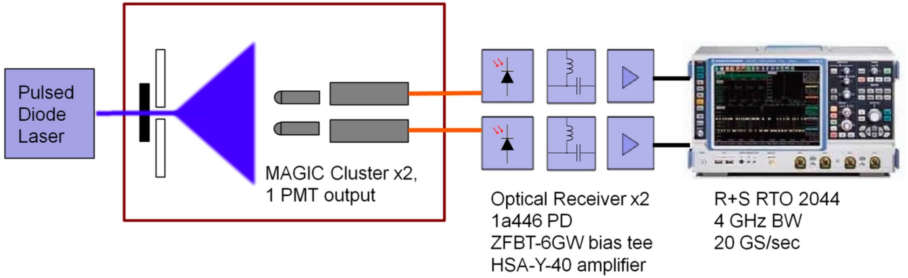


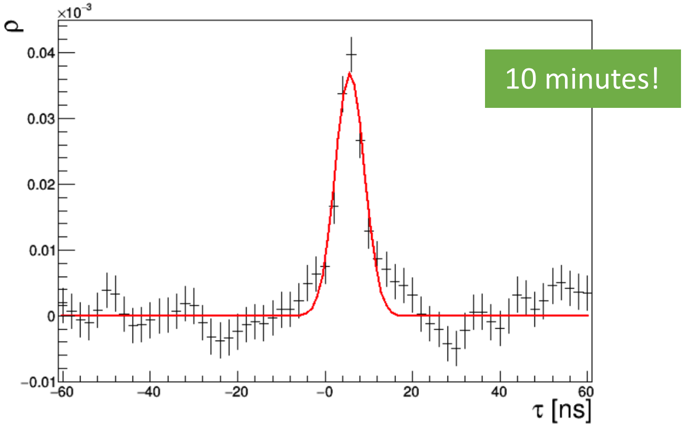
- Right now with MAGIC we work at the 1 ns scale.
- Atmosphere is negligible down to ∼30 ps.
- **We can digitize at each telescope**!
- <u>Go to blue or even UV.</u>
- <u>Reach km scales.</u>

Intensity interferometry with MAGIC

Cherenkov telescopes

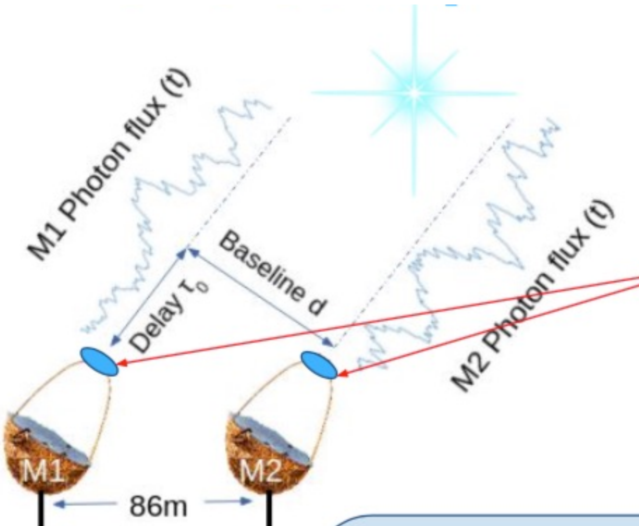
- Easy to use IACTs for **intensity interferometry:** they come in arrays and have large mirrors and fast time response.
- VERITAS made the first measurements (*Nat. Astr. 4 (2020) 1164*).
- With MAGIC we started in 2019 (*MNRAS 491 (2020) 1540–1547*).

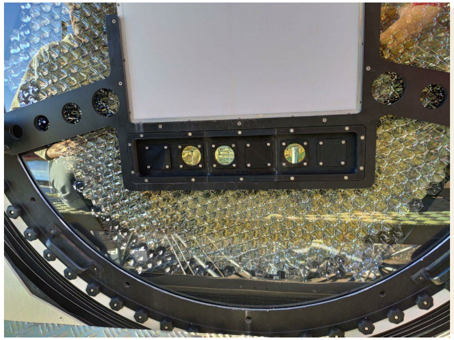




10 minutes!

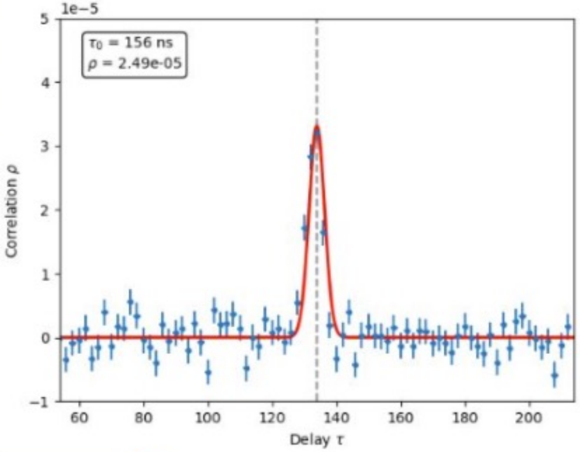
MAGIC interferometry setup

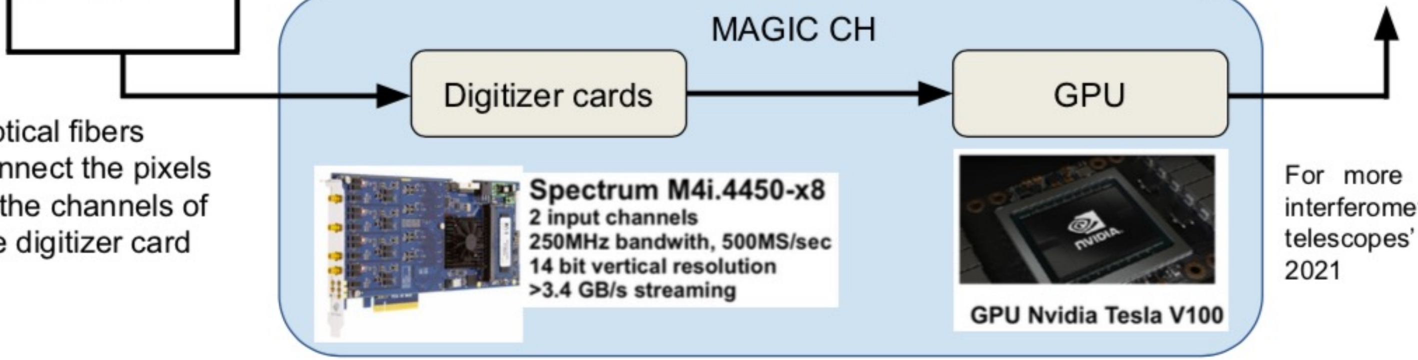




Optical filters in front of certain pixels

Correlation calculated in real time!





MAGIC CH

Digitizer cards

GPU

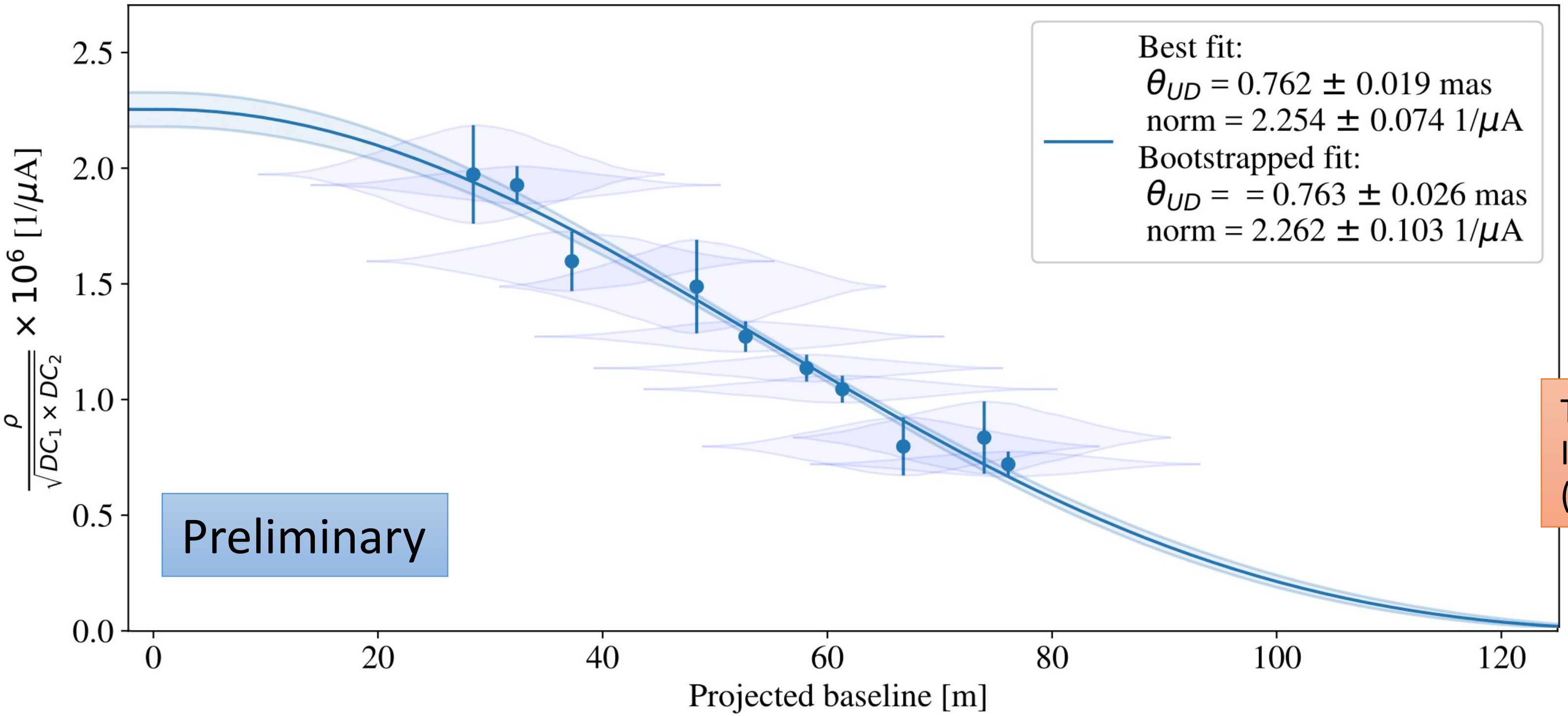
Spectrum M4i.4450-x8
2 input channels
250MHz bandwith, 500MS/sec
14 bit vertical resolution
>3.4 GB/s streaming

GPU Nvidia Tesla V100

Optical fibers connect the pixels to the channels of the digitizer card

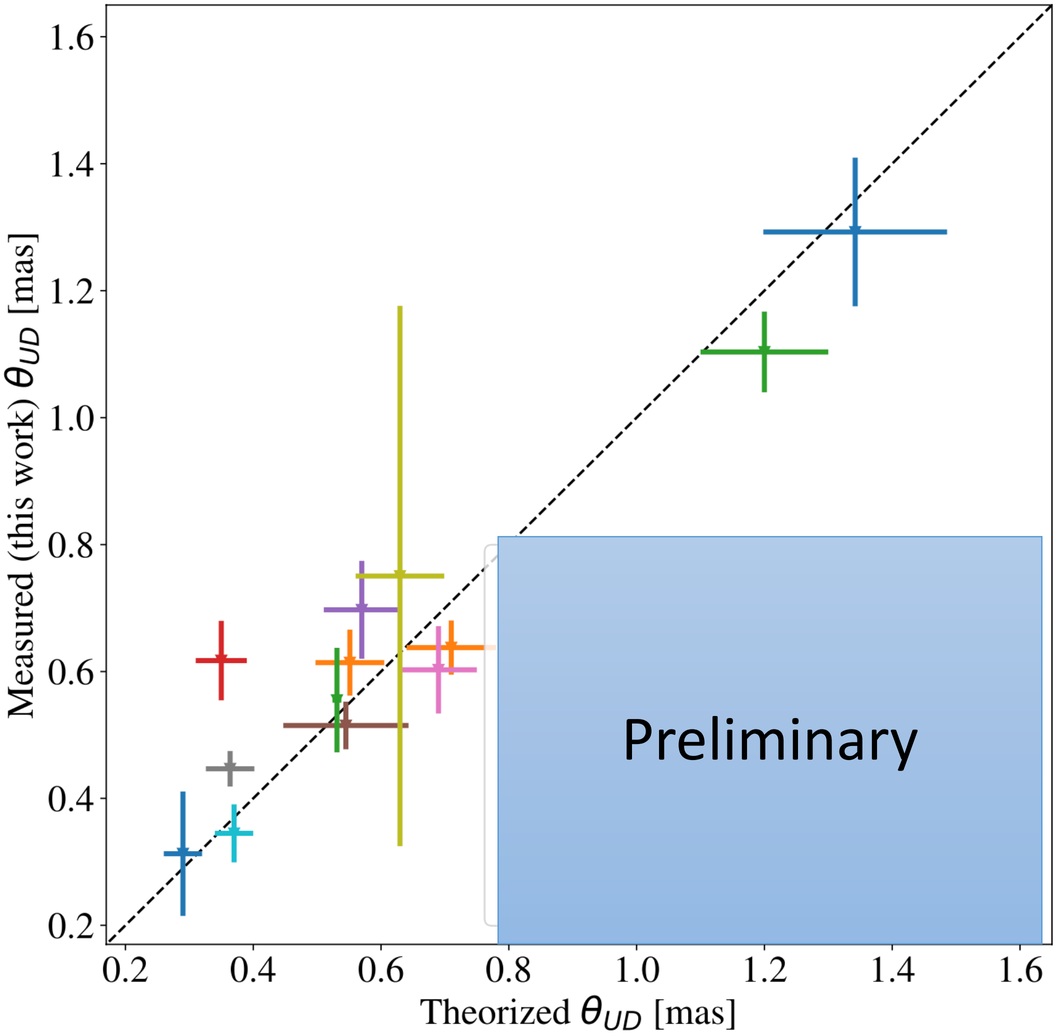
For more info. see 'Intensity interferometry with the MAGIC telescopes' proceeding at ICRC 2021

First results with full instrument (2022)



T. Hassan
I. Jiménez
(CIEMAT)

New star diameter measurements



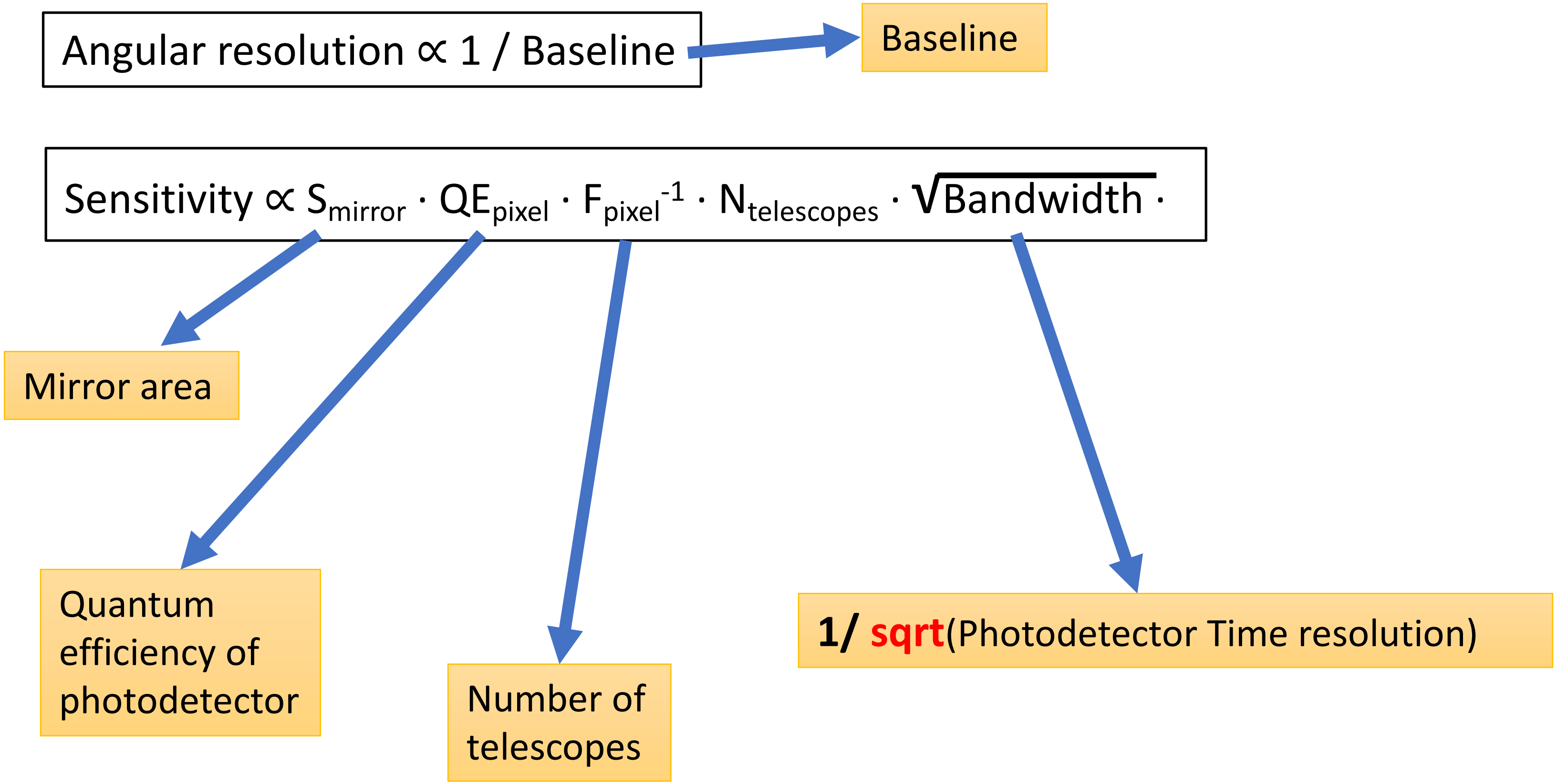
Draft almost ready!

MAGIC: performance summary

The significance of our detections is consistent with expectations based on our hardware parameters and consistent with the publication in 2019 with a totally different setup.

- Sensitivity 10x better than Narrabri: **magnitude limit = 5^m**
- Our baseline is <86 m so **our angular resolution is ~500 μas**.

What’s limiting us?



Angular resolution $\propto 1 / \text{Baseline}$

Baseline

$$\text{Sensitivity} \propto S_{\text{mirror}} \cdot QE_{\text{pixel}} \cdot F_{\text{pixel}}^{-1} \cdot N_{\text{telescopes}} \cdot \sqrt{\text{Bandwidth}} \cdot$$

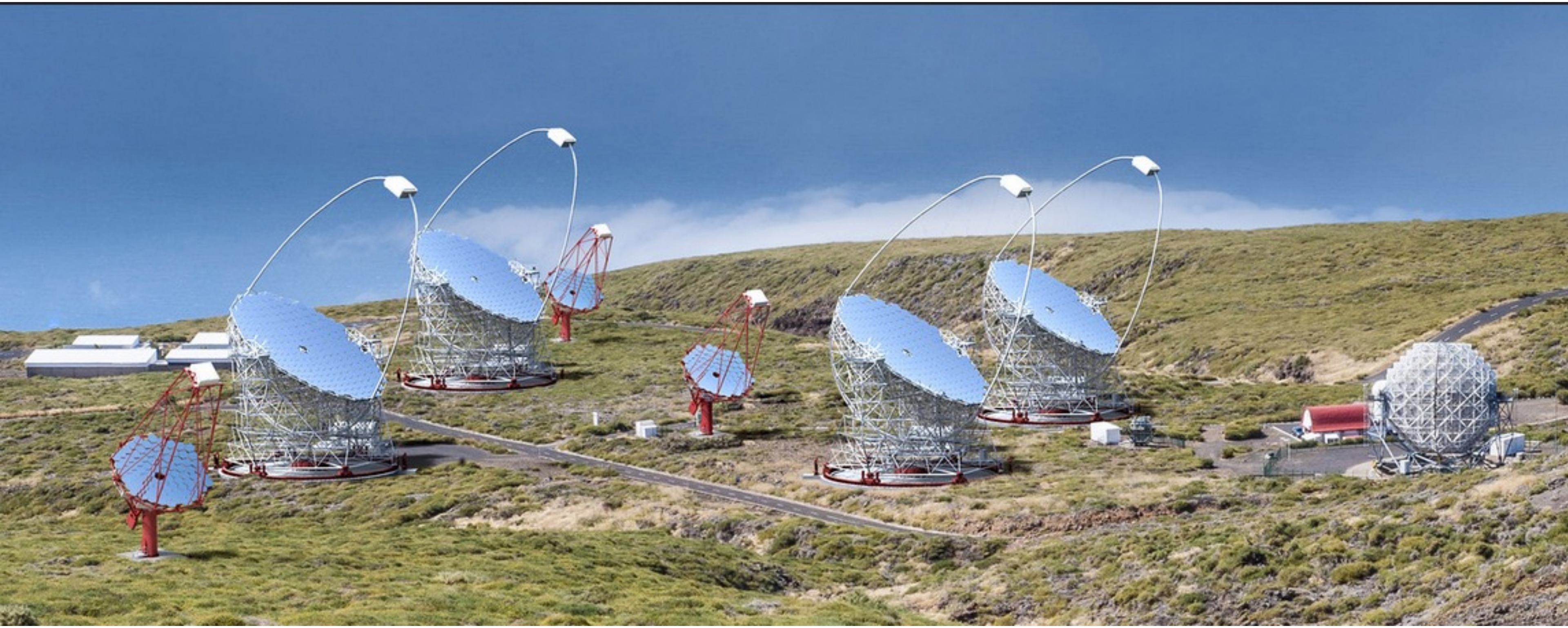
Mirror area

Quantum efficiency of photodetector

Number of telescopes

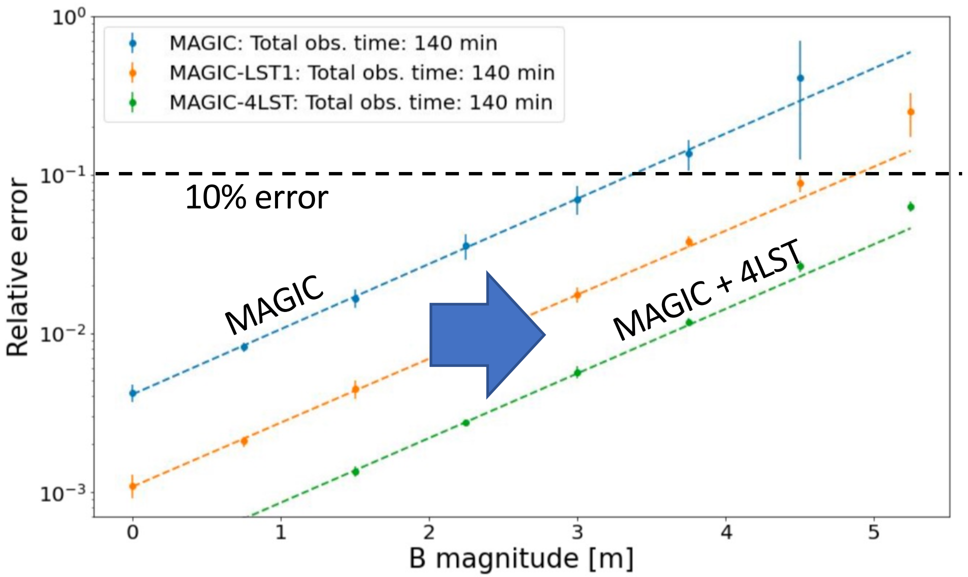
1/ sqrt(Photodetector Time resolution)

More telescopes, longer baselines: MAGIC > CTA



CTA LSTs: Impact on sensitivity

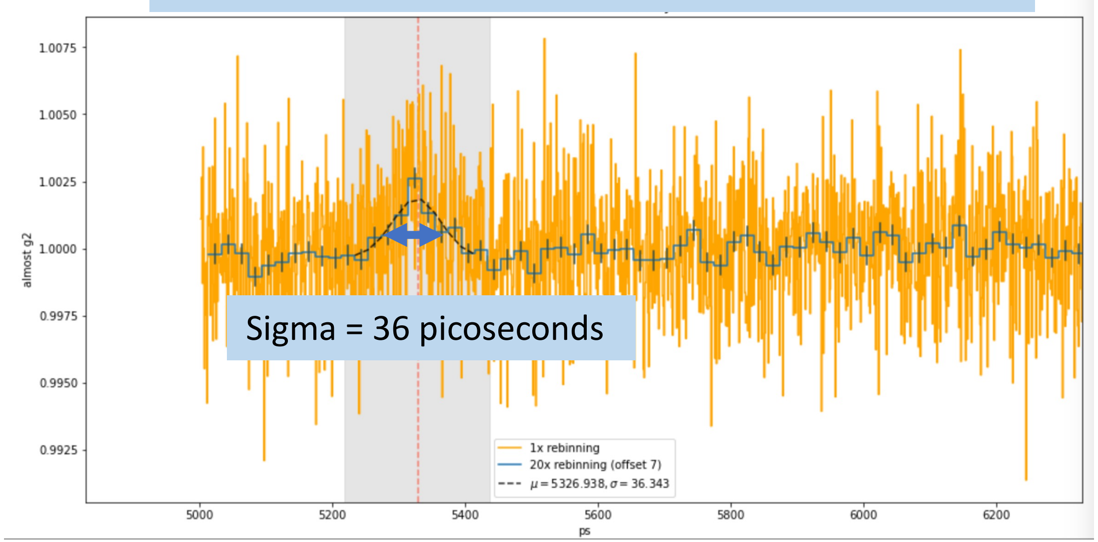
Simulation by Tarek Hassan (proc. SPIE 2022)



- We expect to increase sensitivity by a factor 10.
- <u>Reach 6m</u> (for 10% error in diameter in <u>2 hours</u>)
- Granted an ERC starting grant to Tarek Hassan (CIEMAT) to design and test interferometer for MAGIC+LSTs.

Faster photodetectors

- Current PMTs are limited to time resolutions ∼1 ns.
- Faster photodetectors **(<100 ps**) with photosensitive areas compatible with IACTs (1 cm scale): **SiPM** and **HPDs**.
- Sensitivity of MAGIC + LSTs <u>may improve by a factor 4</u>



Lab measurement of HBT effect using SPADs (U. Geneva)

Sigma = 36 picoseconds

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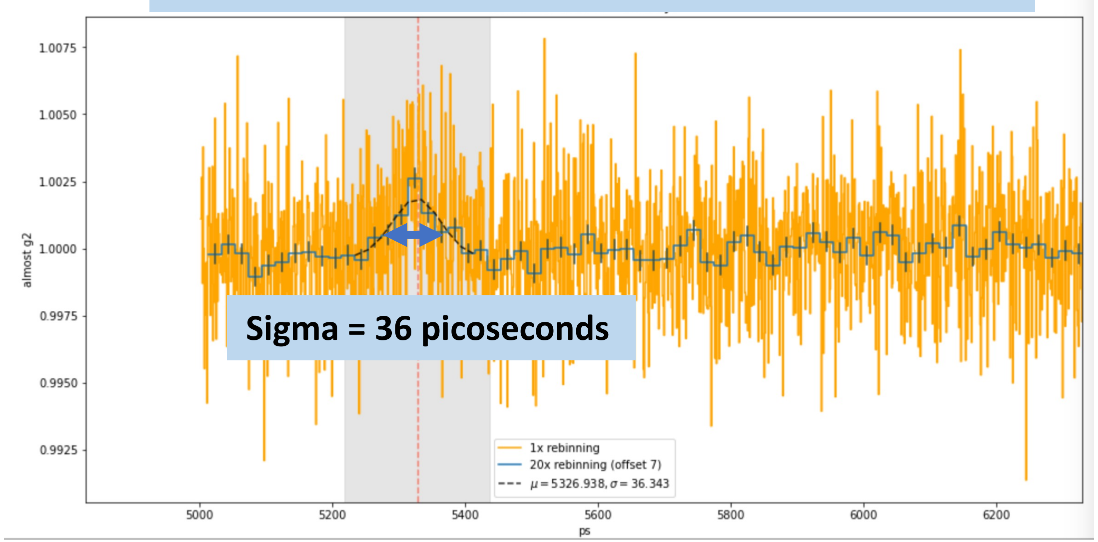
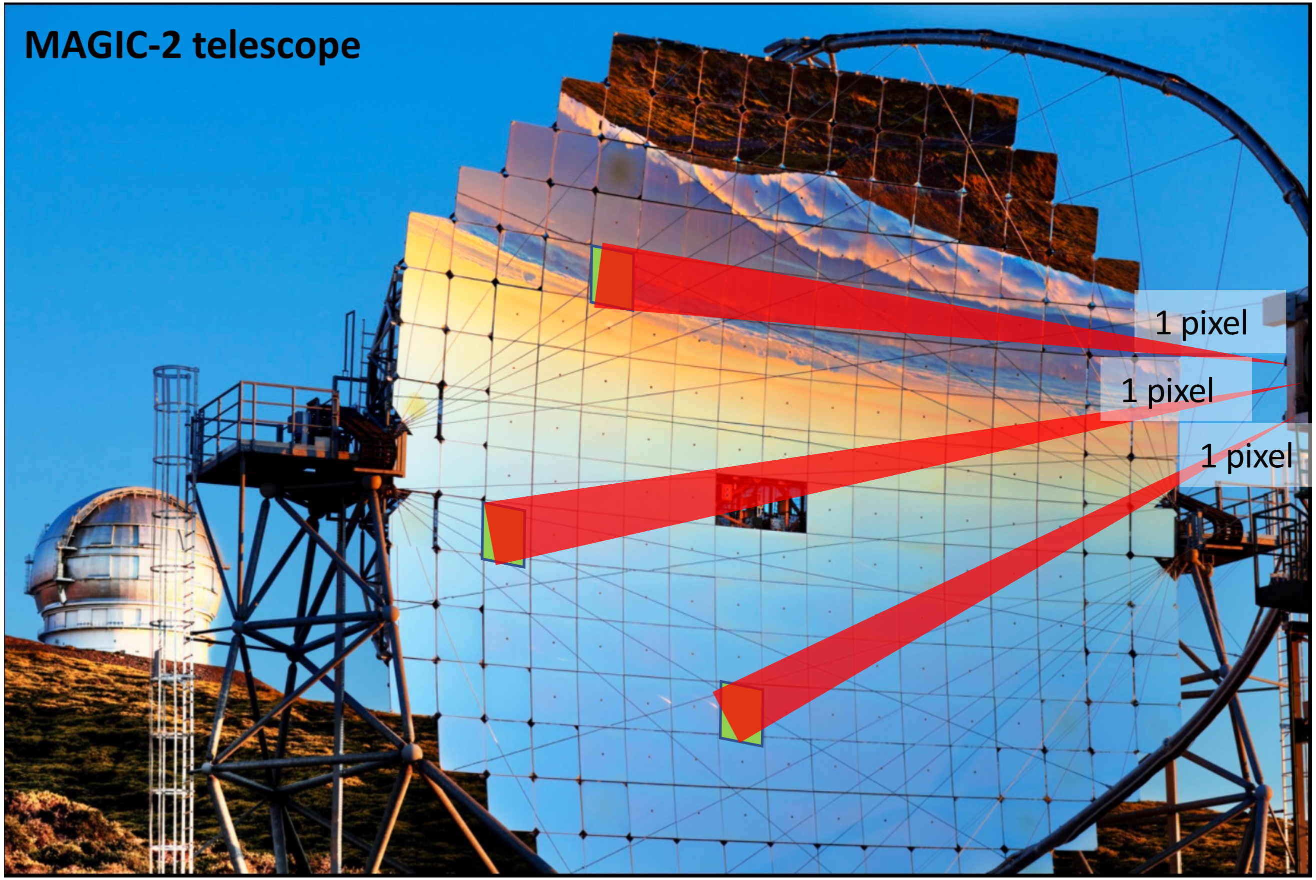


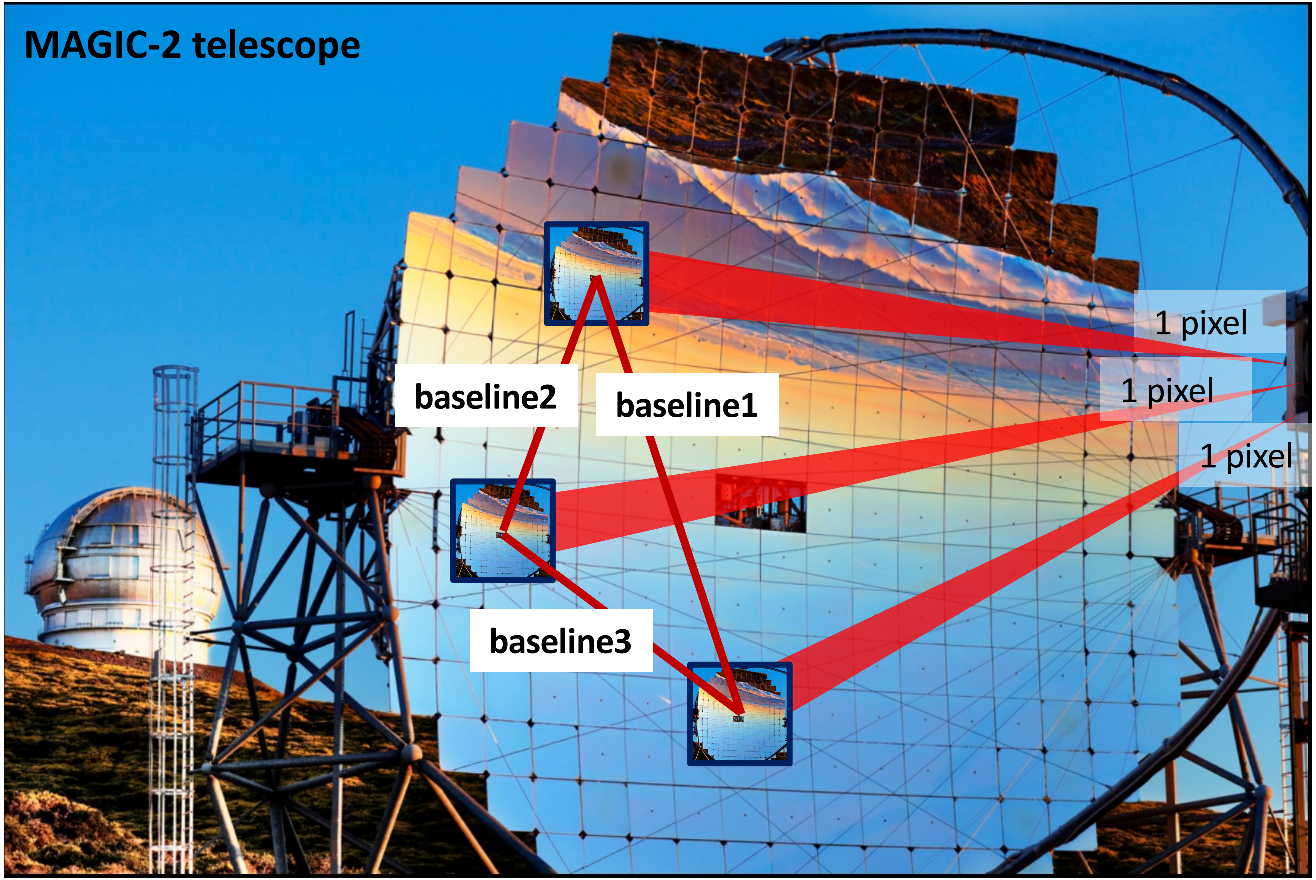
Sigma = 36 picoseconds

Limit magnitude of $B=7.5^{m}$ in 2 hours

Complement with shorter baselines



Complement with shorter baselines



- **I3T concept** (Gori et al, *MNRAS*, 505-2 (2021) 2328)
- Shorter baselines: 0-17m in MAGIC
- <u>Angular scales: 3 – 50 mas</u>.

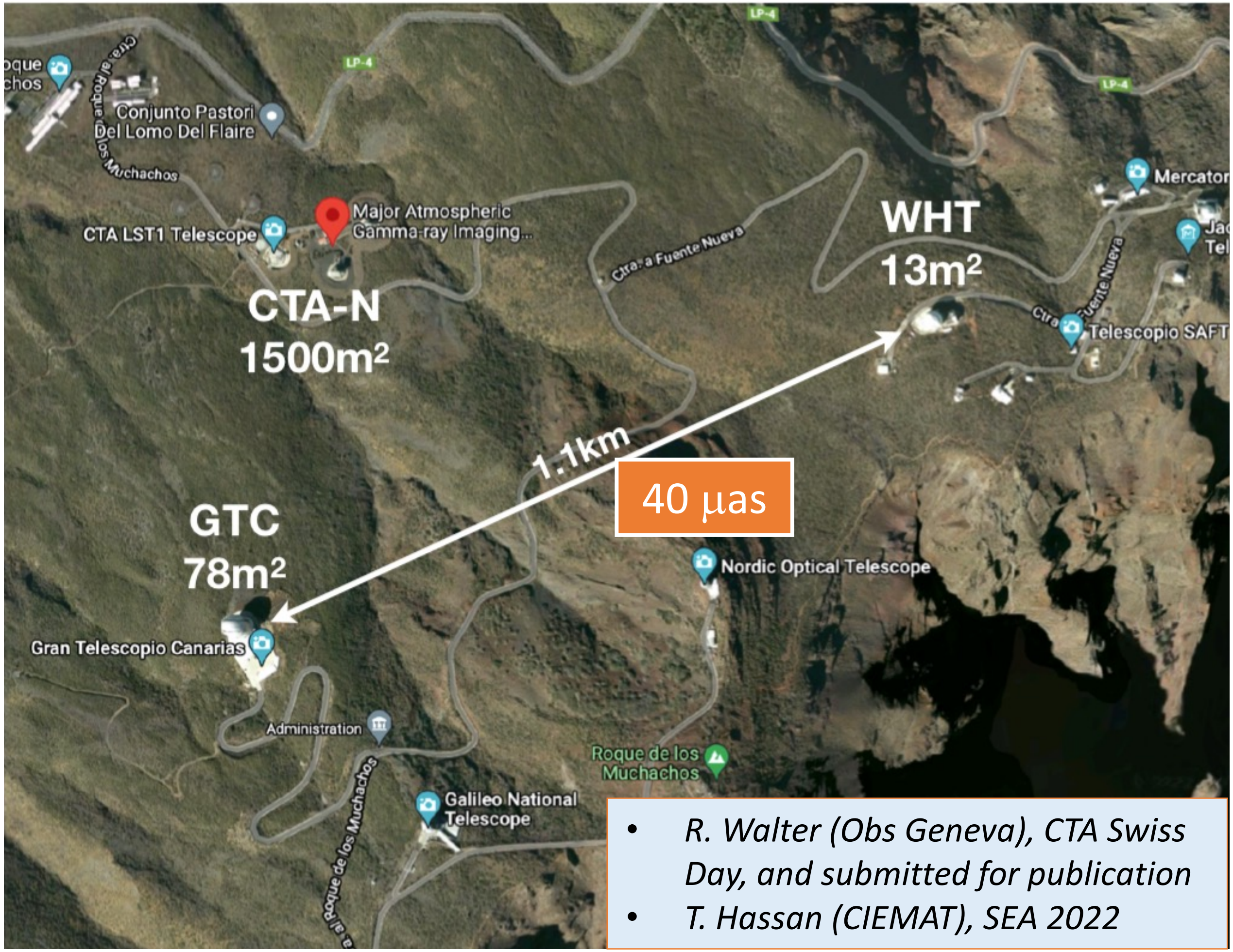
And longer baselines?

Other large diameter telescopes are available or coming online

At ORM:

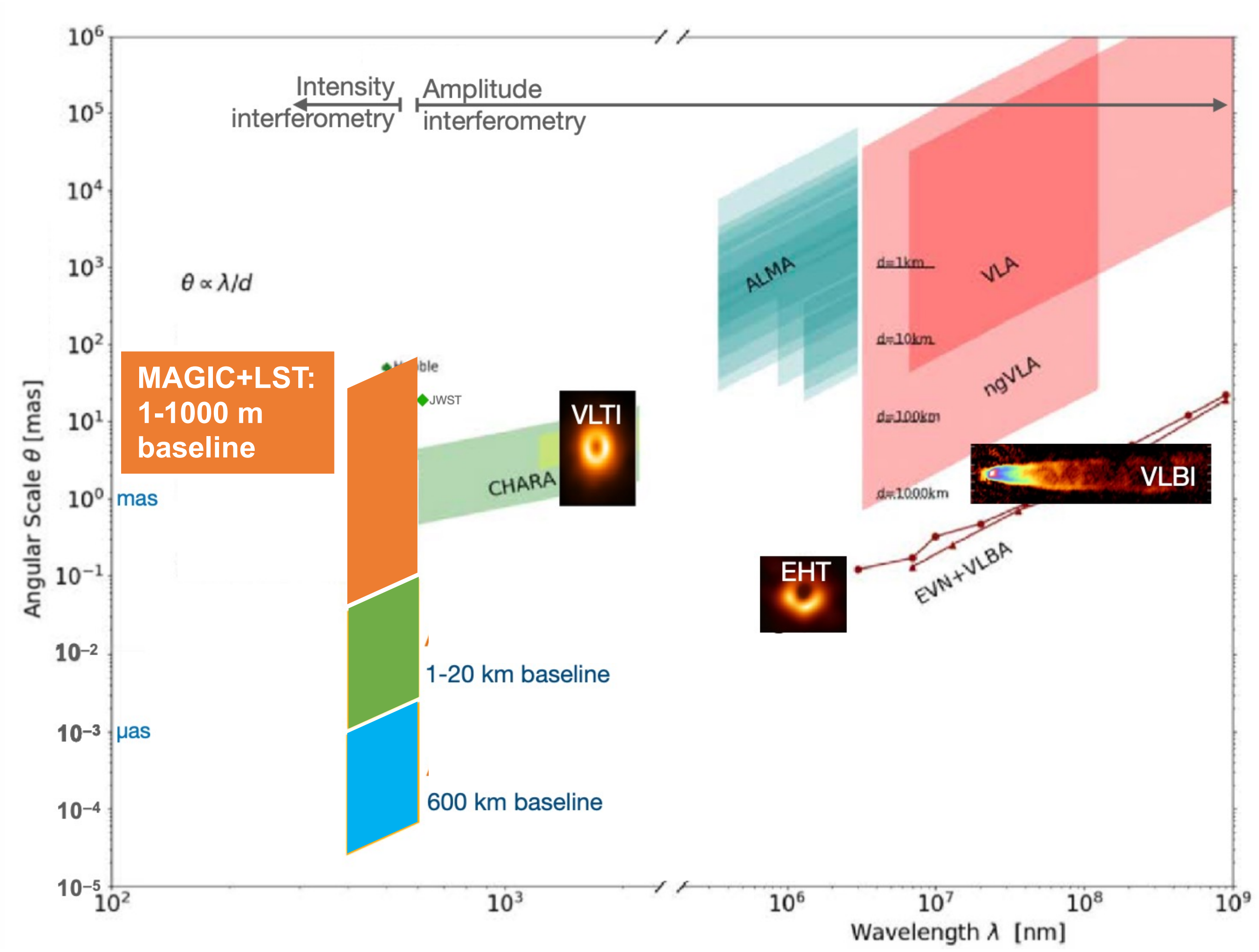
- **CTA MSTs (12 m)**
- **GTC (10 m)**
- **WHT (4.2 m)**
- **TNG (3.6 m)…**

(QUASAR project)



- *R. Walter (Obs Geneva), CTA Swiss Day, and submitted for publication*
- *T. Hassan (CIEMAT), SEA 2022*

Covering many angular scales

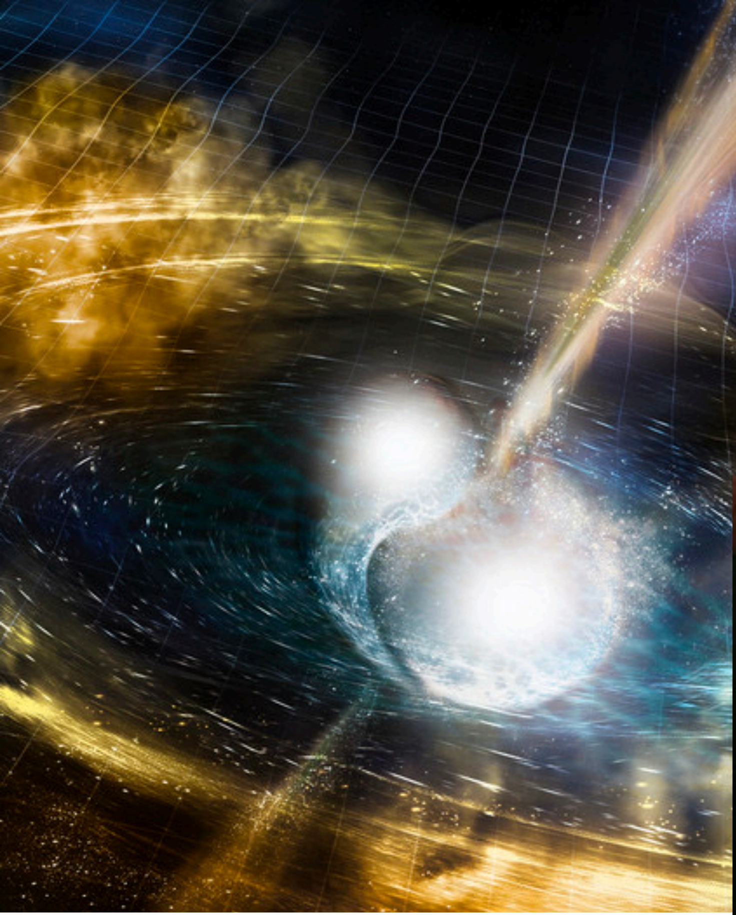


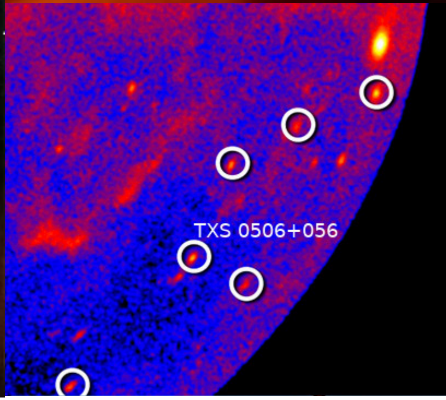
MAGIC+LST: 1-1000 m baseline

1-20 km baseline

600 km baseline

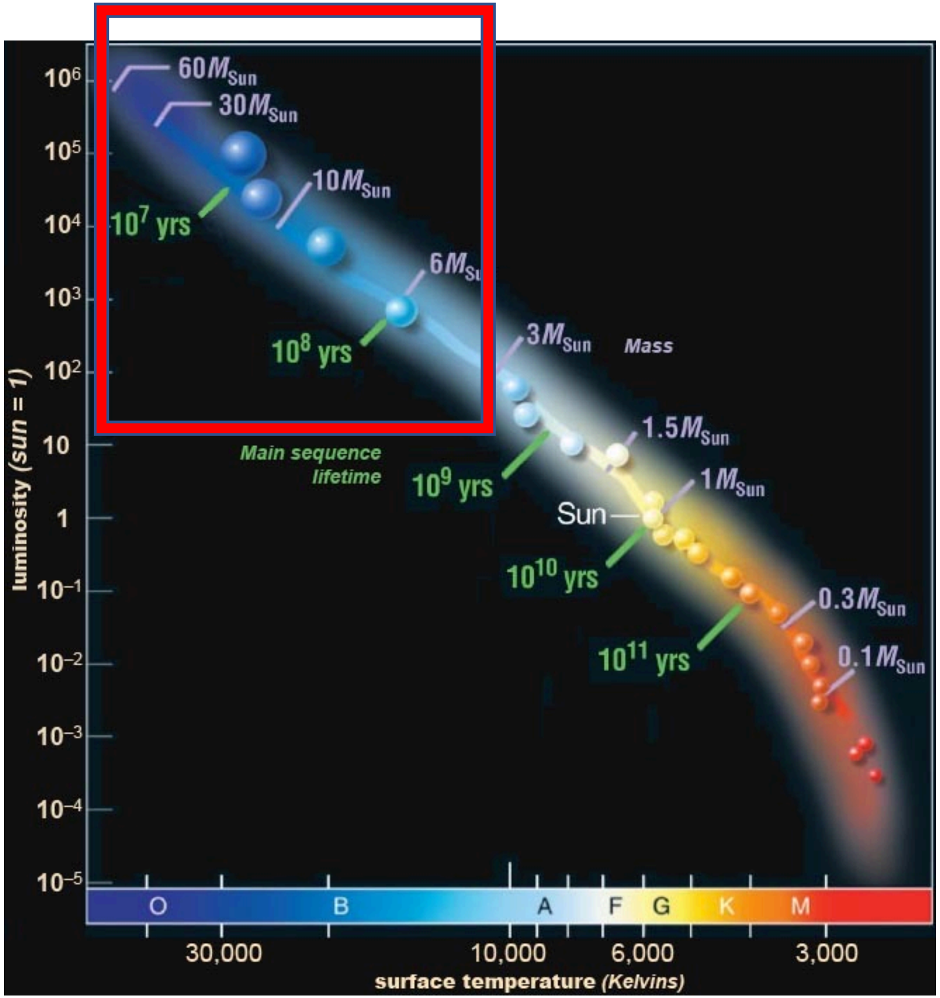
Original plot by M. Daniel, R. Walter





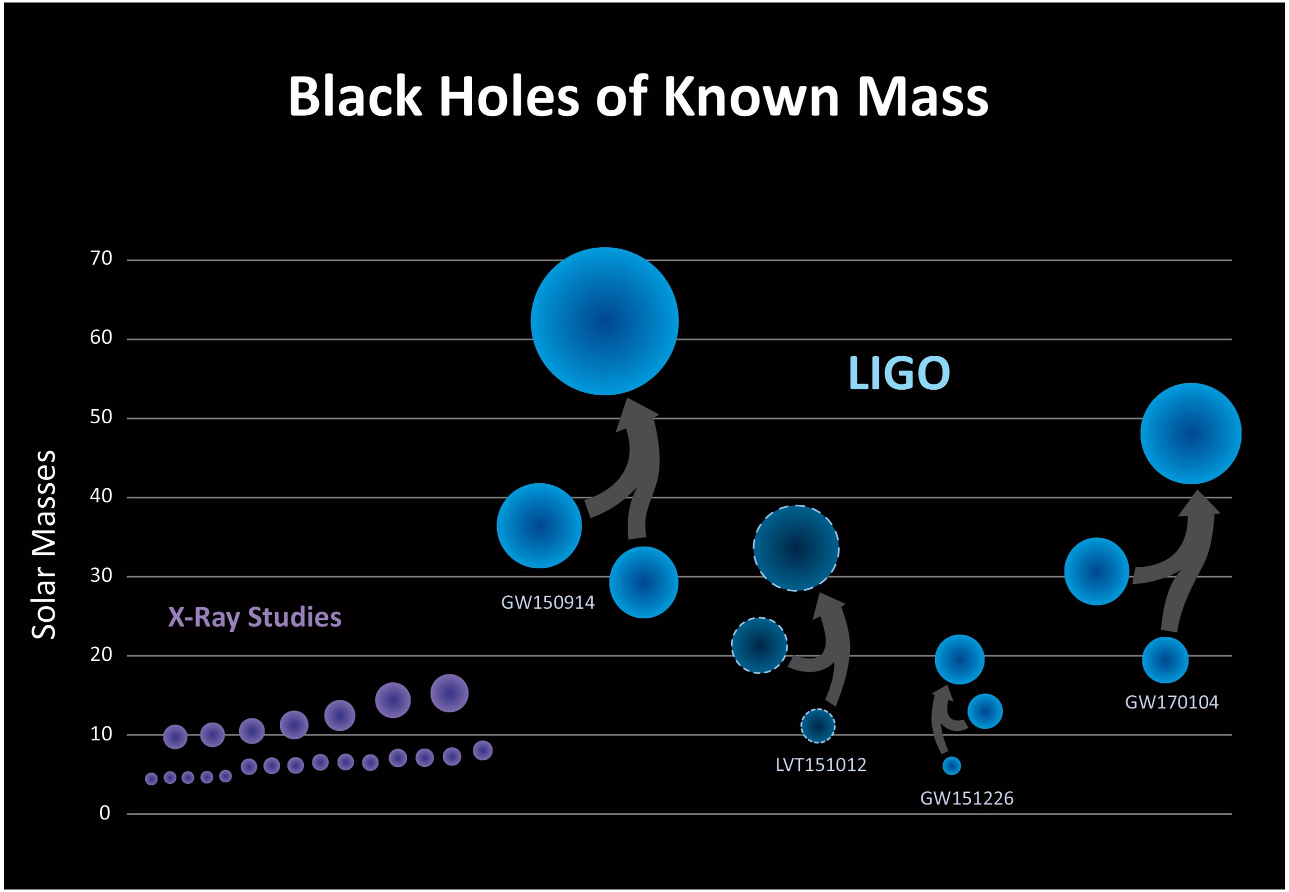
Science

Massive stars



Winds and black hole mass

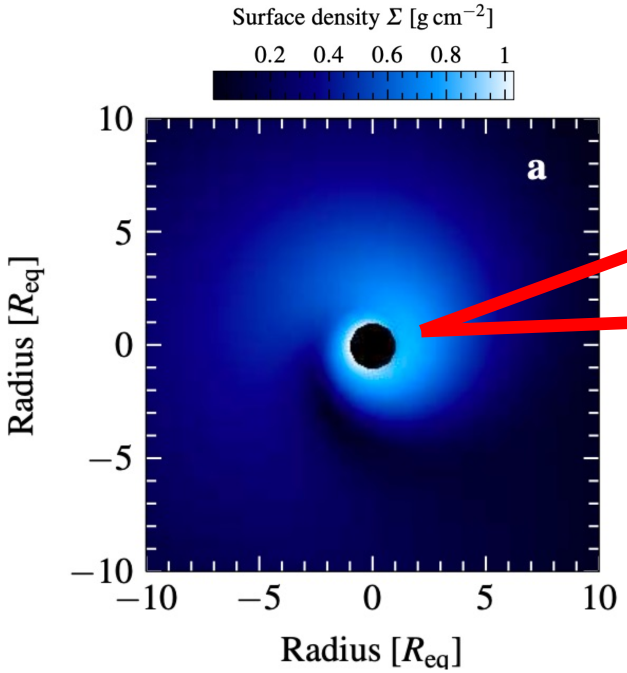
- LIGO's big surprise: <u>why so many Black Hole pairs with tens of $M_\odot$</u>.
- The fact: very difficult to predict the BH mass!
- **Strong effects of metallicity, <u>wind mass loss</u> or binarity.**



Be stars or WR stars

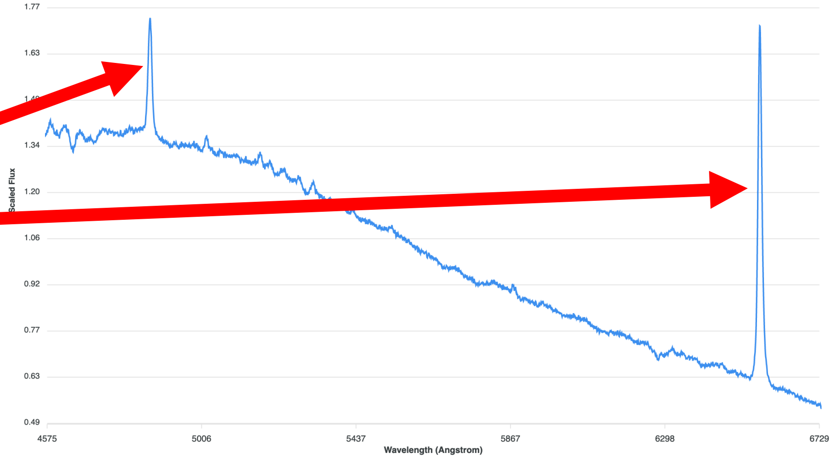
- Stars with a slow outflow (“decretion disk”).
- Strong emission in Hα and Hβ emission lines.

Model of Be star with decretion disk

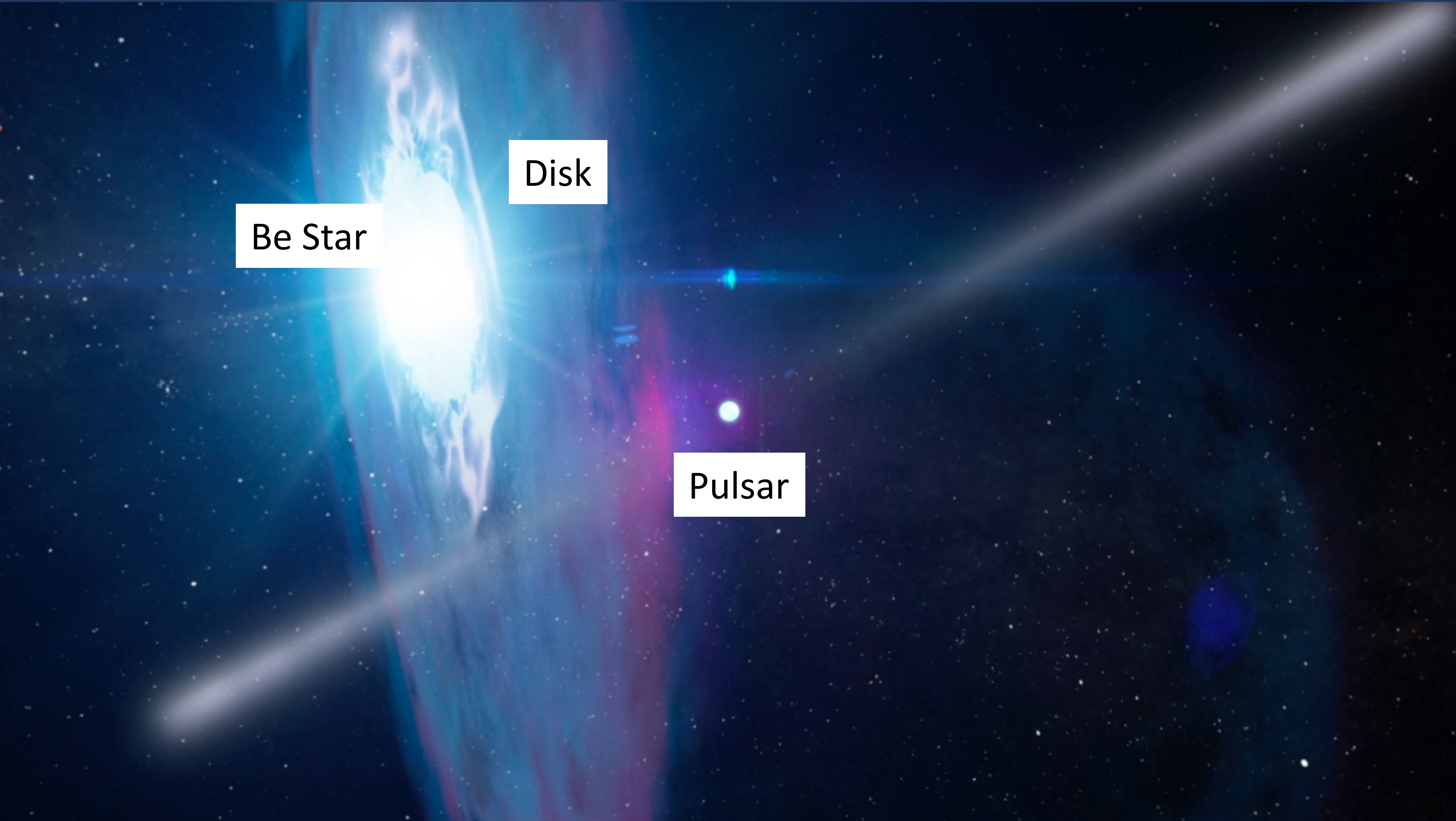


Rivinius et al, arXiv:1310.3962

Spectrum of Be star γ Cas



Be stars and pulsar = VHE γ-rays



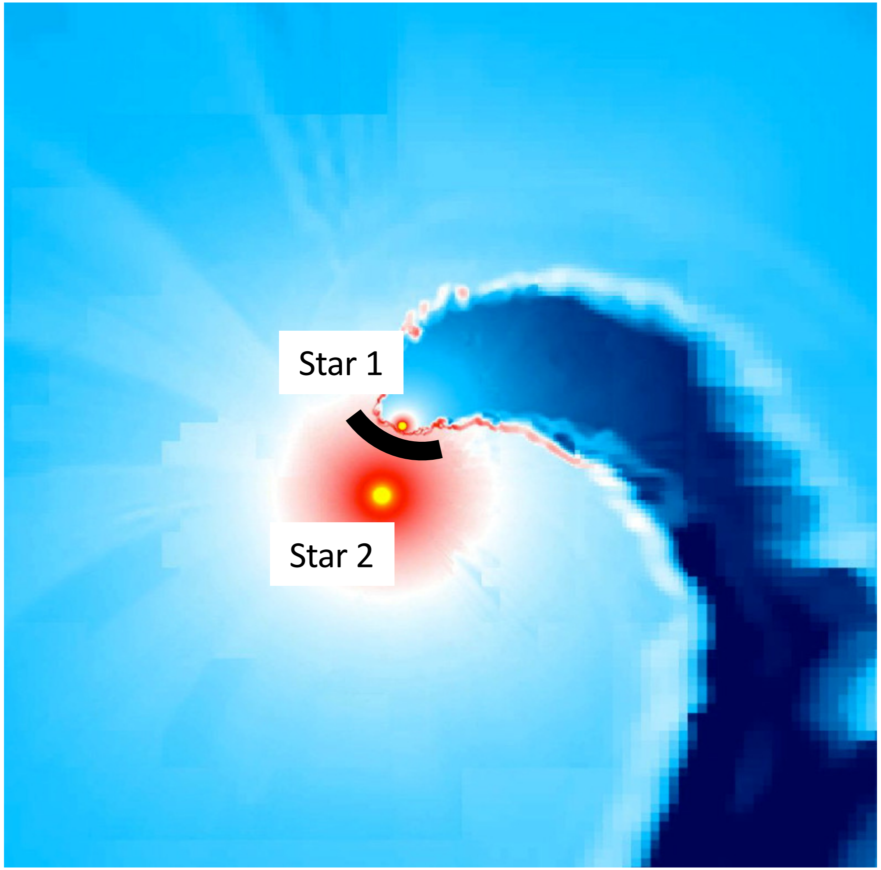
γ-ray binaries: observability

	HE	VHE	Class	Components	P_{orbit}	Companion Rmag	Companion Hα mag
PSR B1259-63	yes	yes	PSR binary	Oe + NS	~3.4 yrs	10.03	
LS I +61 303	yes	yes	**PSR binary**	B0 Ve + NS	26.5 d	10.19	
HESS J0632+057	**yes**	yes	?	B0 pe + ?	**317.3 d**	9.5	7.8
PSR J2032+4127	**~yes**	**yes**	**PSR binary**	**B0 Ve + PSR**	**~50 yrs**	11.2	
HESS J1832-093	**yes**	**yes**	**?**	**B8V - B1.5V + ?**	**86.3 d**	J=15	
LS 5039	yes	yes	**PSR binary (?)**	ON6.5V + **PSR?**	3.9 d	11.04	
1FGL J1018.6–5856	yes	yes	?	O6V + ?	16.5 d		
LMC P3	yes	yes	?	O5III + ?	10.3 d		
4FGL J1405.1-6119	**yes**	no	**?**	**O6.5 III + ?**	**13.7 d**	H=14	

MAGIC+LST with HPDs

Pol Bordas, Gamma2022, Barcelona

Colliding wind binaries



Cyg OB 9, simulation of bow shock.

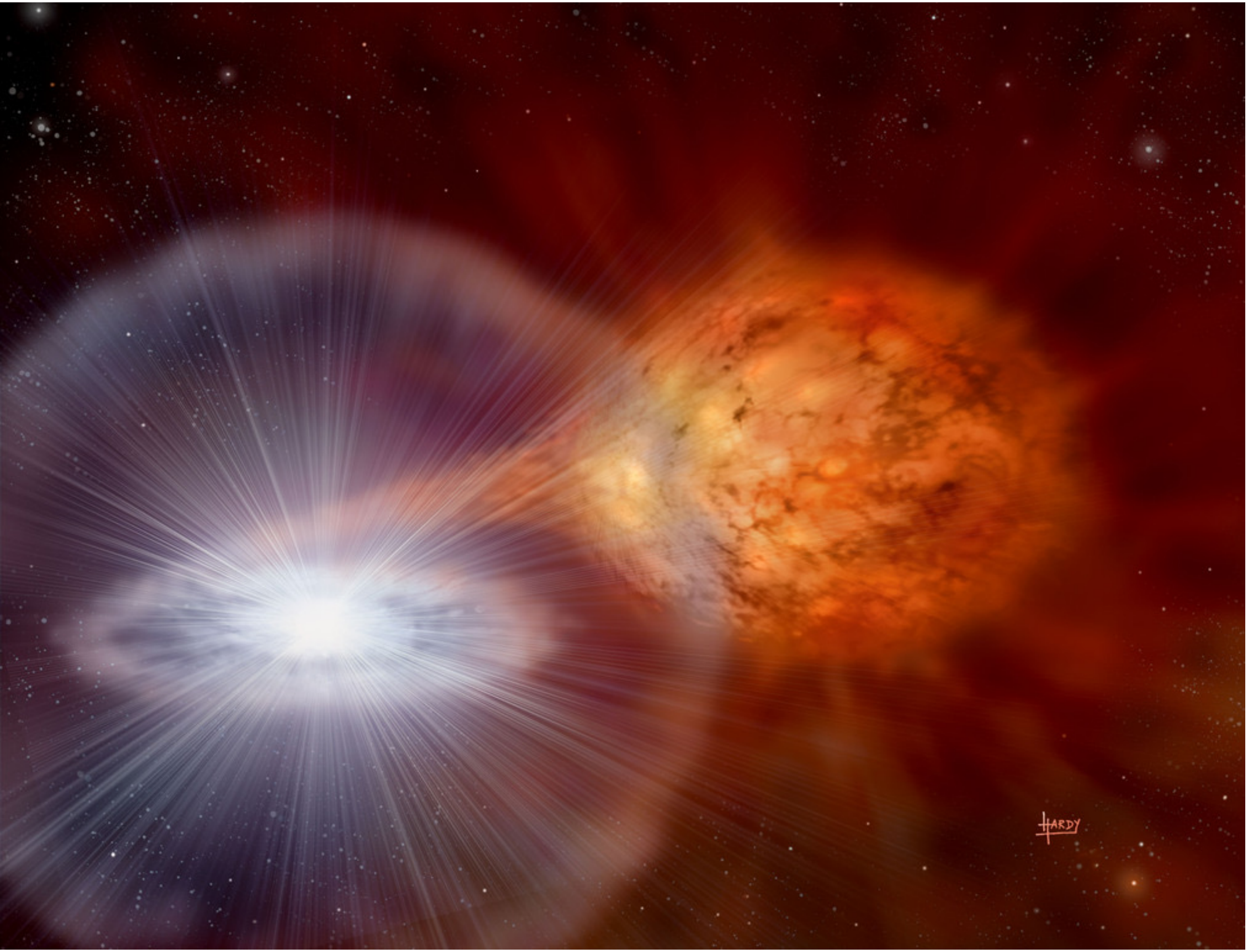
Credit: Australian National Univ./E. R. Parkin and Univ. of Liege/E. Gosset

HE and VHE γ-ray sources:

- **Eta Car**
- **γ^2 Velorum**

Both very bright in visible.

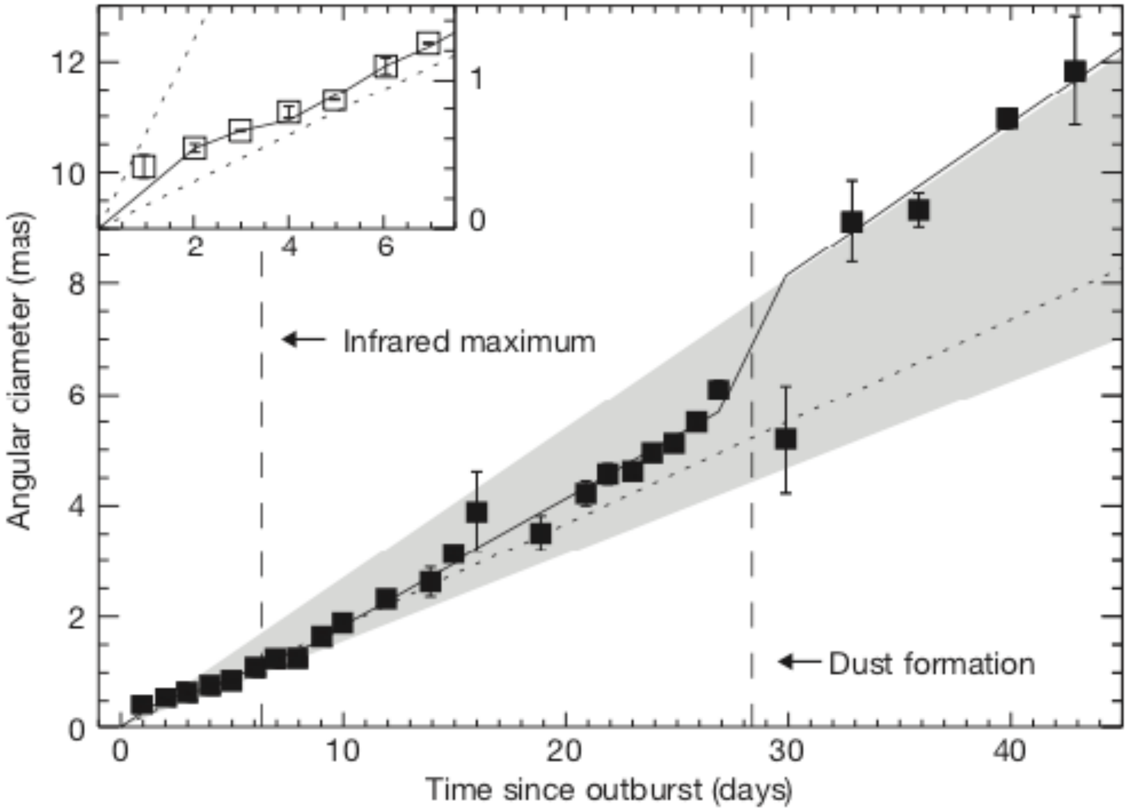
Newest type of VHE source: **novas**



Recurrent nova RS Oph detected at VHE:

- H.E.S.S., Science, 376-6588 (2022) 77
- MAGIC, Nat. Astr. 6 (2022) 689

Novas: speed of expanding shell

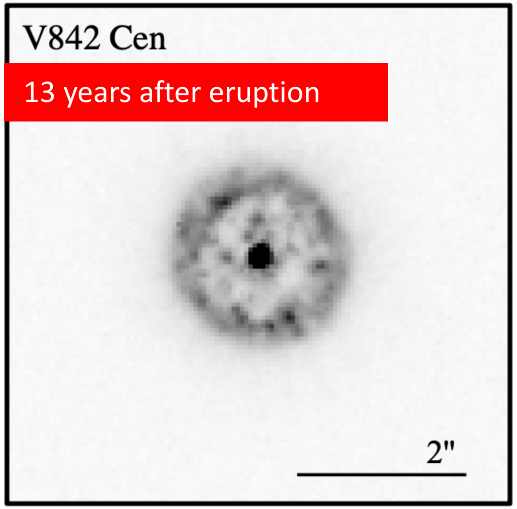


Expansion speed: 0.14 mas/day
Distance: 4.5 ± 0.6 kpc
Peak at V=4.3^m

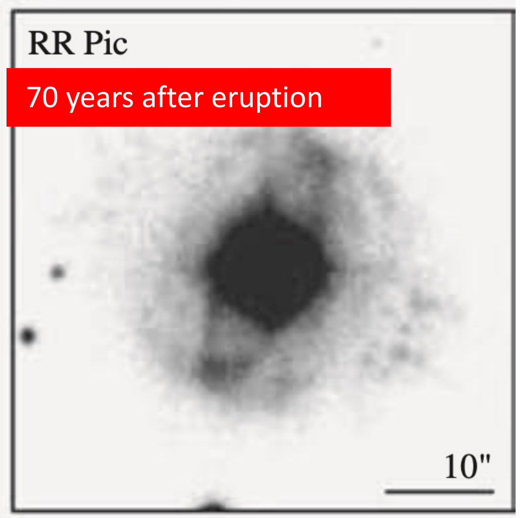
The expanding fireball of Nova Delphini 2013
G. H. Schaefer,
T. ten Brummelaar…
P. S. Muirhead
Nature ***515****, 234–236 (2014)*

Novas: anisotropy of expanding shell

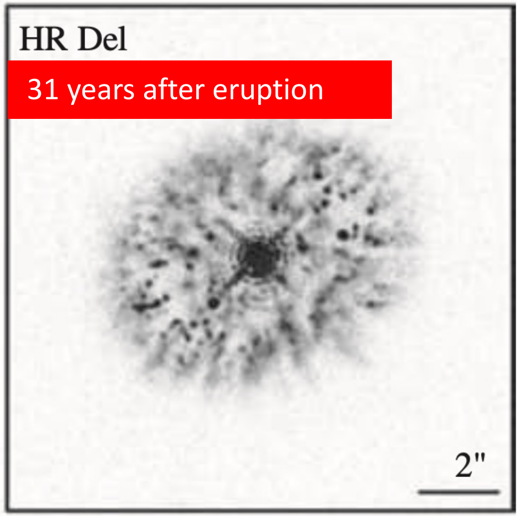
Nova remnant images in visible range **years** after nova explosion



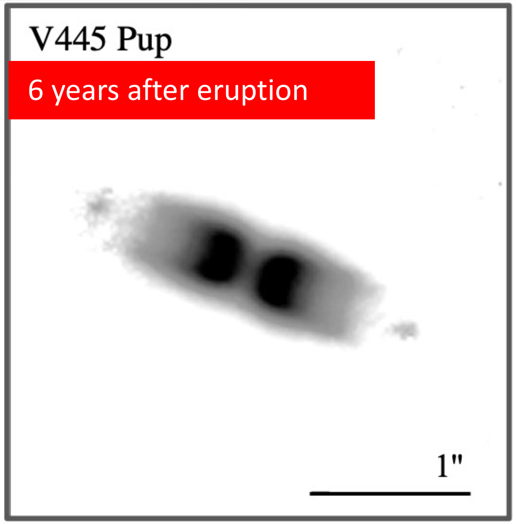
13 years after eruption



70 years after eruption



31 years after eruption

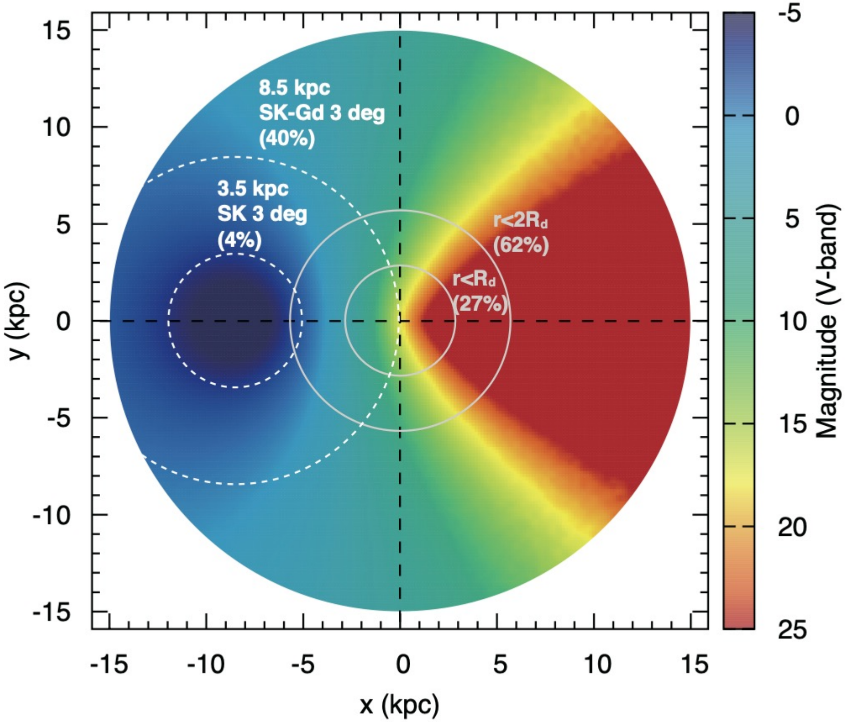


6 years after eruption

Chomiuk et al., arXiv:2011.08751

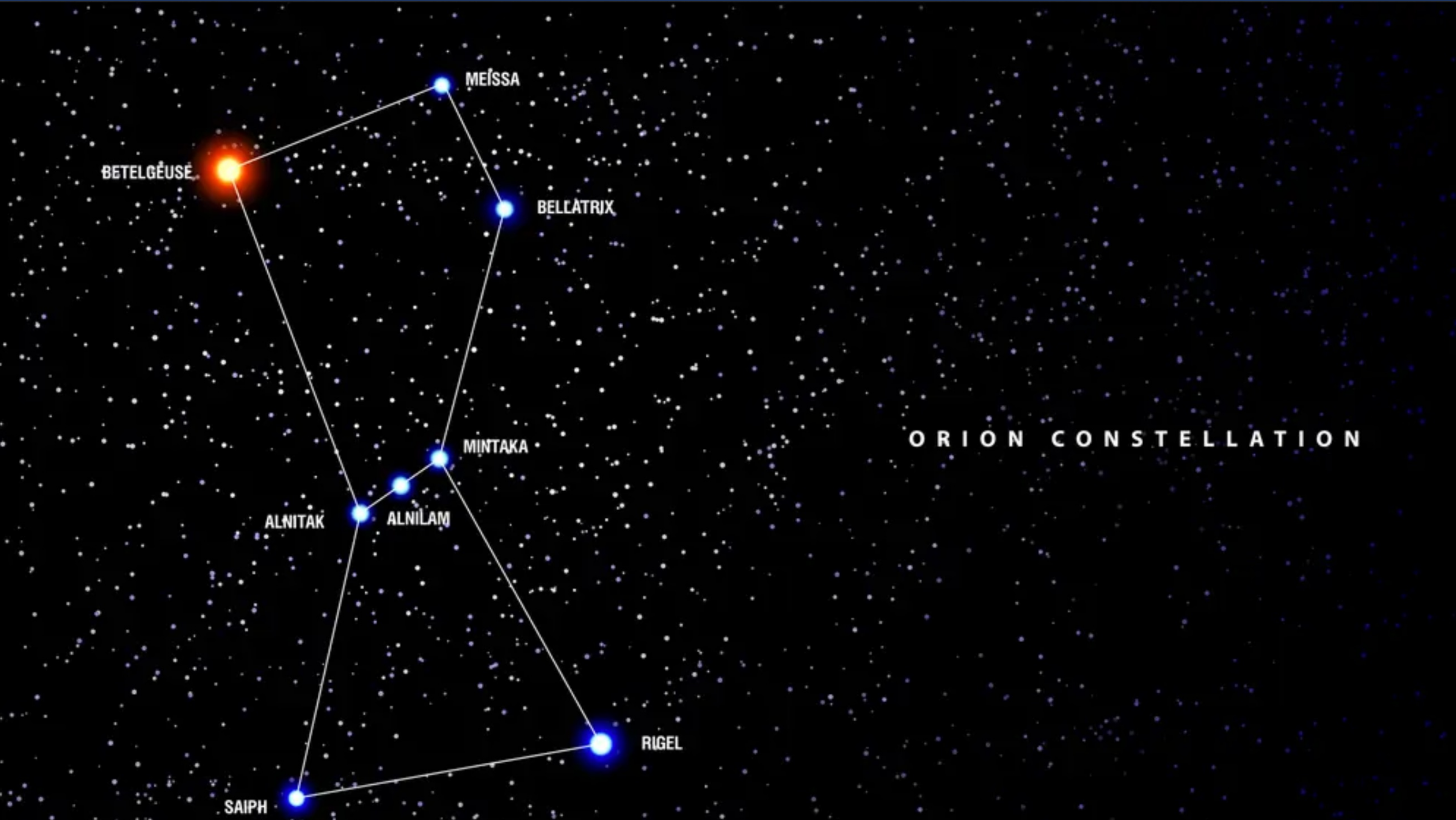
Supernovae: observability

Ko Nakamura et al., MNRAS, 461, 3296 (2016)



- V<5^{m}, observable with current MAGIC in 50h: roughly 35% of galactic SNe.
- 5<V<8m, observable with ORM array (50-500 uas) and MAGIC-Butterfly (5-50 mas): fraction increases to 50%.
- Same as with novas: study expansion speed and asymmetry.

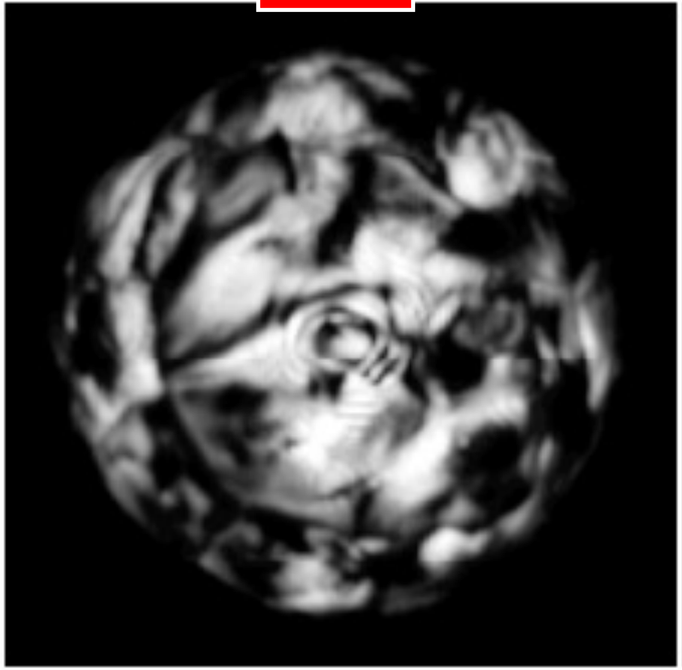
Betelgeuse


MEISSA
BETELGEUSE
BELLATRIX
ORION CONSTELLATION
MINTAKA
ALNITAK
ALNILAM
RIGEL
SAIPH

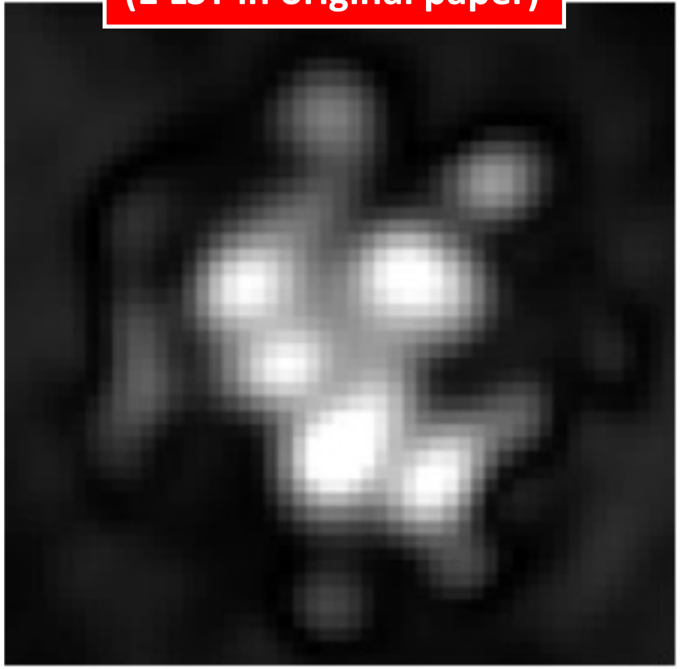
Imaging Betelgeuse

Gori et al, *MNRAS*, 505-2 (2021) 2328

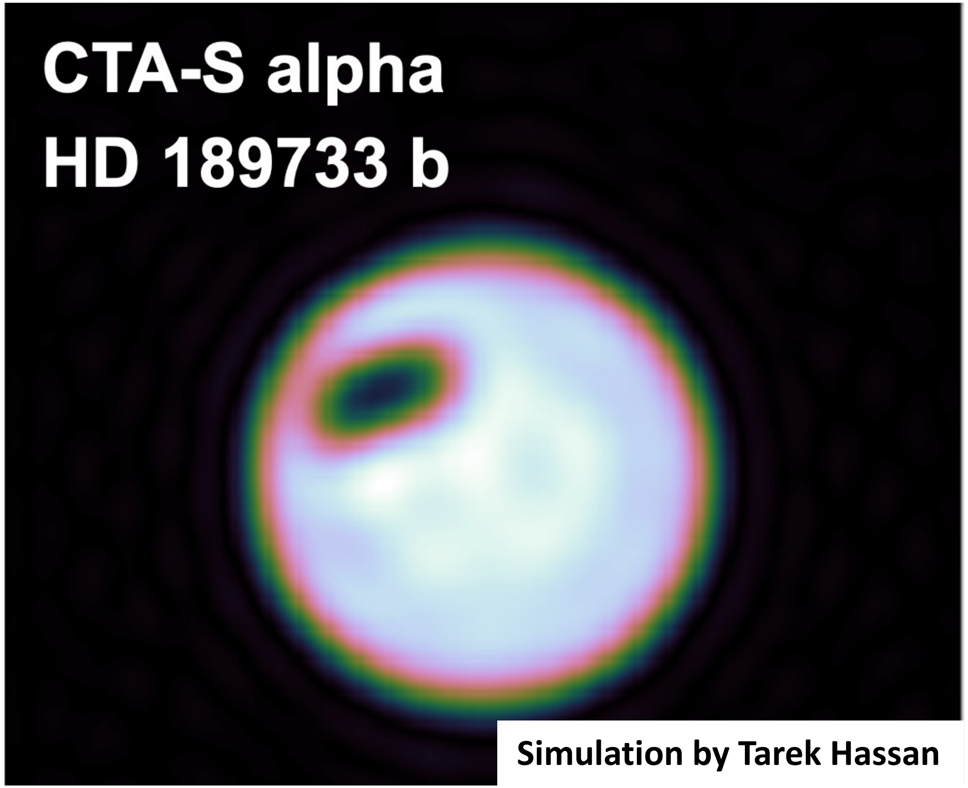
Model



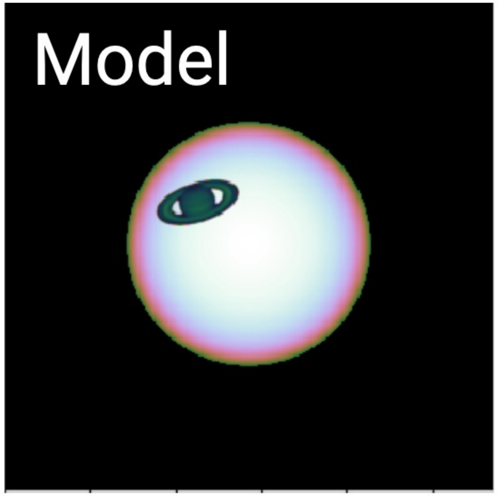
MAGIC, 10 hours
(1 LST in original paper)



Shadow of exoplanets



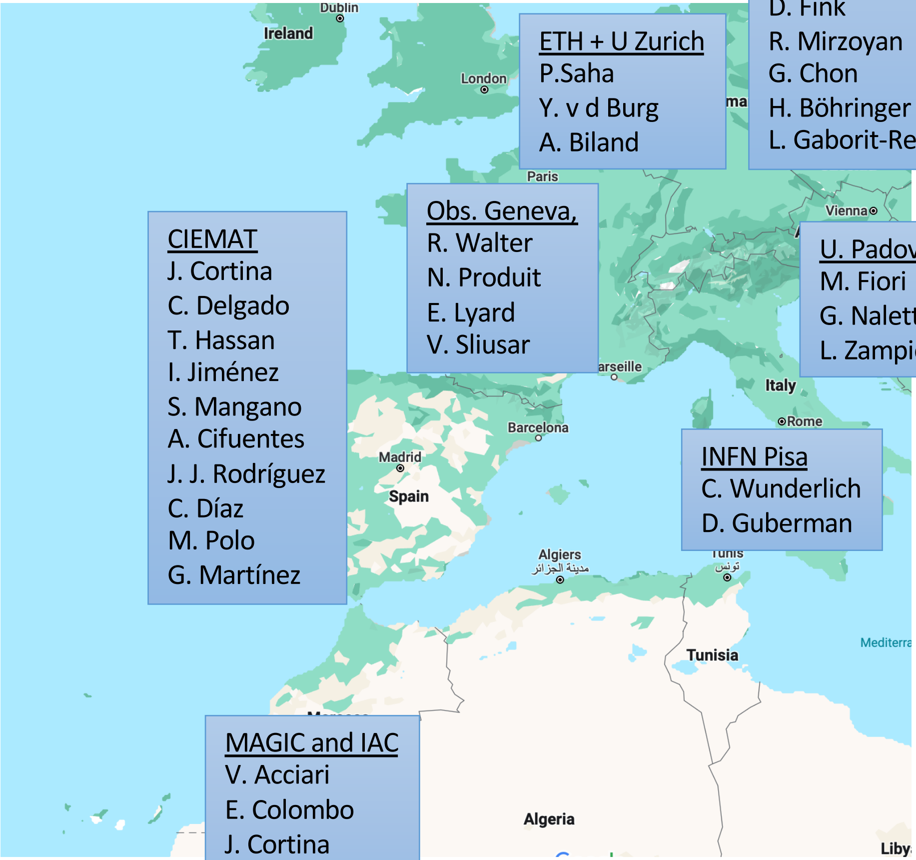
Simulation by Tarek Hassan



Or a combination of MAGIC, LSTs and GTC at Roque?

Conclusions

- Intensity interferometry optimal for short wavelengths and long baselines.
- IACTs are already using this technique to study bright stellar objects in the 0.5 – 1.5 mas angular scale.
- Adding the four LSTs: ~200 μas and 6^{m}.
- Faster photodetectors: go to weaker objects (~8^{m}).
- With MSTs and optical telescopes at ORM: higher angular resolutions ~50 μas.
- Strong impact on stellar astrophysics and Multimessenger: improve our understanding of BH progenitors, VHE γ-ray emitters based on stellar winds, novas or supernovas.



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V. Acciari
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F. Barnes

Thank you for your attention!

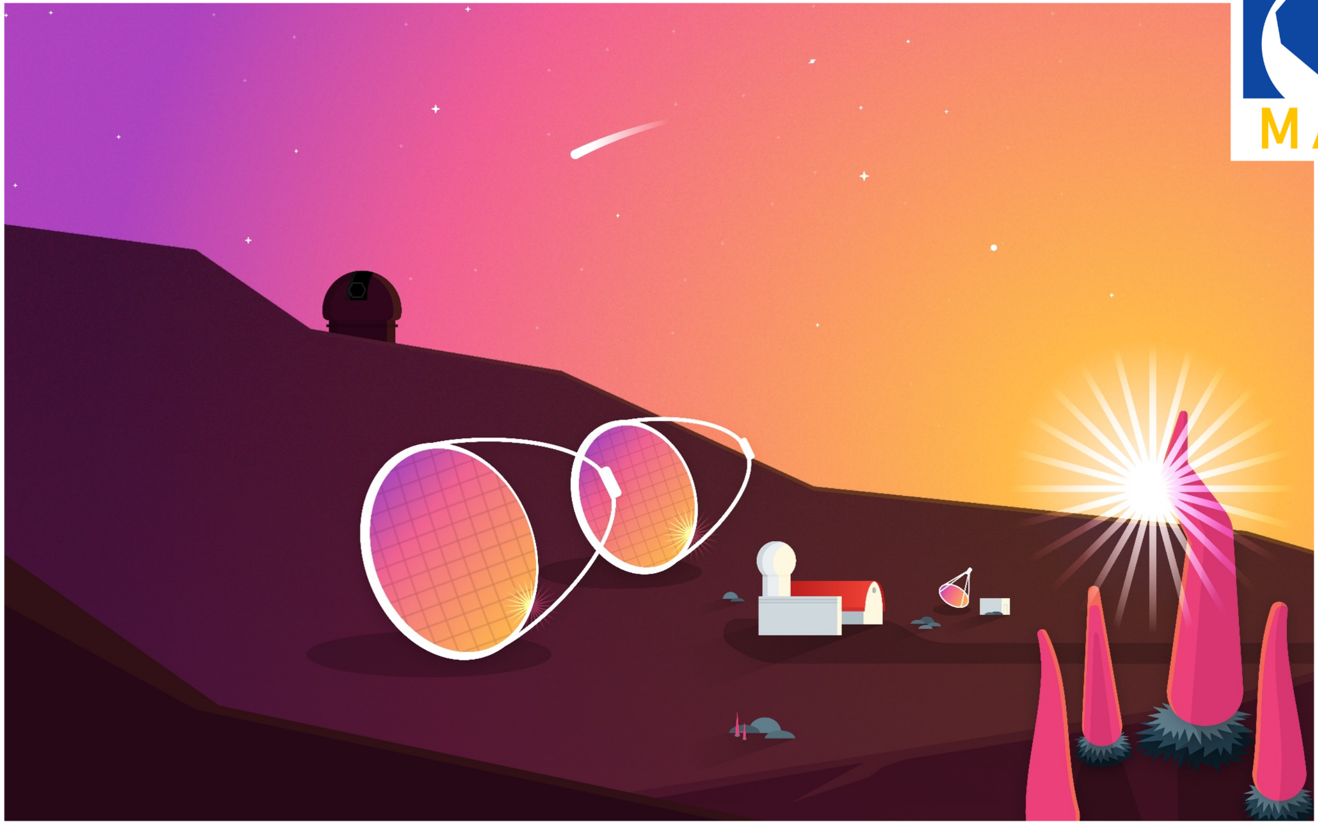
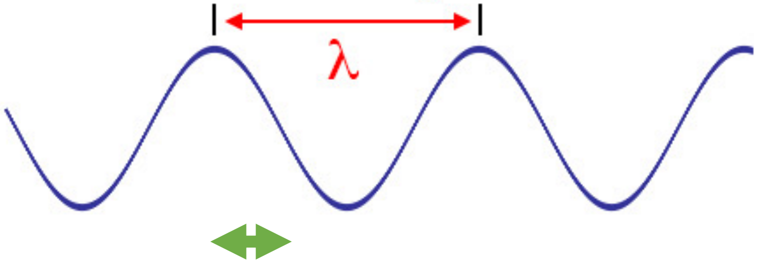


Image credit:: Jayant Abhir

Go to longer wavelengths

Martin Ryle, Nobel Prize 1974

Radio 175 MHz
Period ∼ 5.7 ns
λ = 1.7 m



precision in optical path ∼ **10 cm**

- With this precision it's much easier to bring the signal together to interfere.
- And it can be saved to tape or digitized!

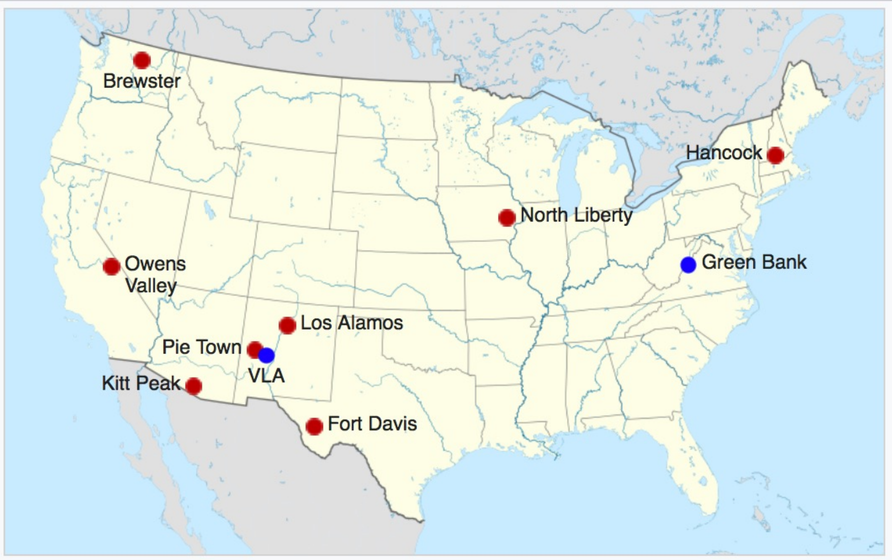
Rapid development

VLA, New Mexico, 1973.

- 50 GHz – 73 MHz
- Baseline up to 35 km
- Down to 40 mas angular resolution

VLBA, 1993

- 300 MHz – 100 GHz
- Baseline up to 8600 km
- Down to 40 mas angular resolution

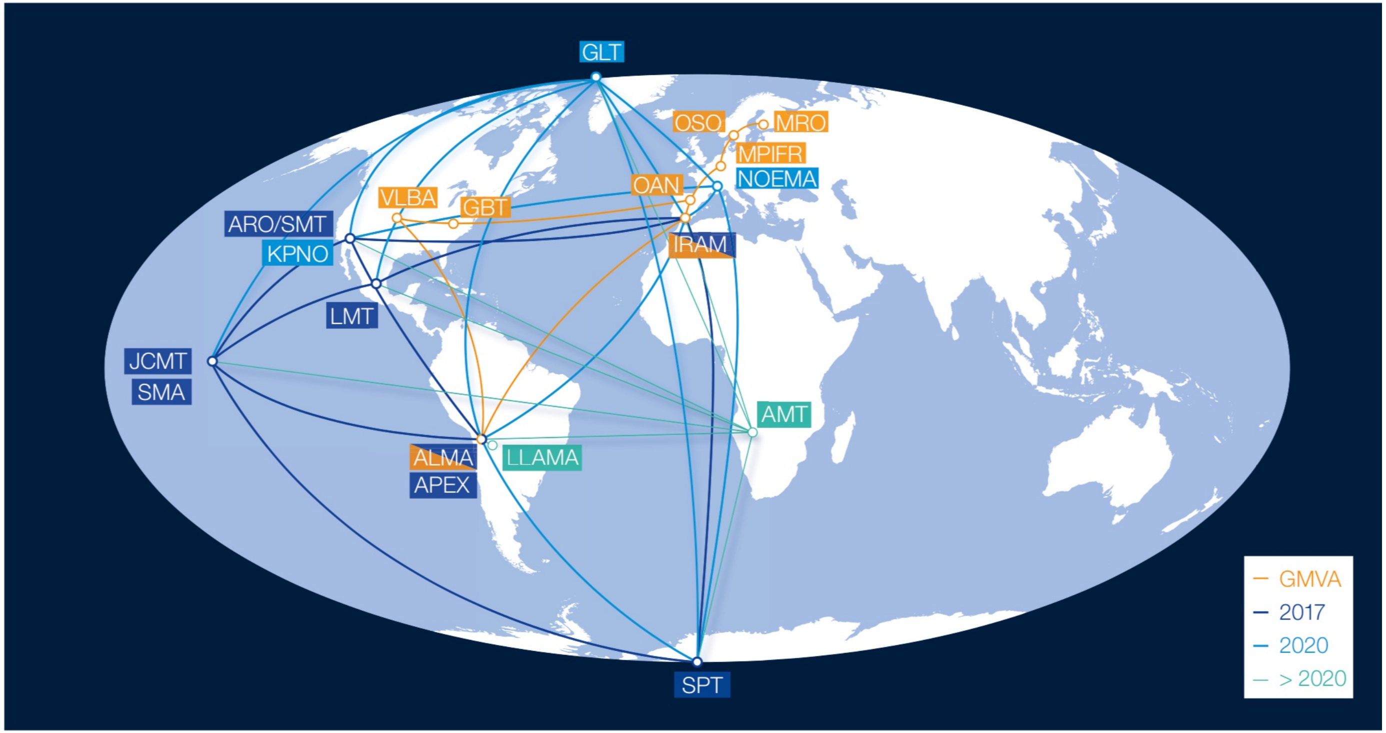


Data are stored and processed offline

Event Horizon Telescope

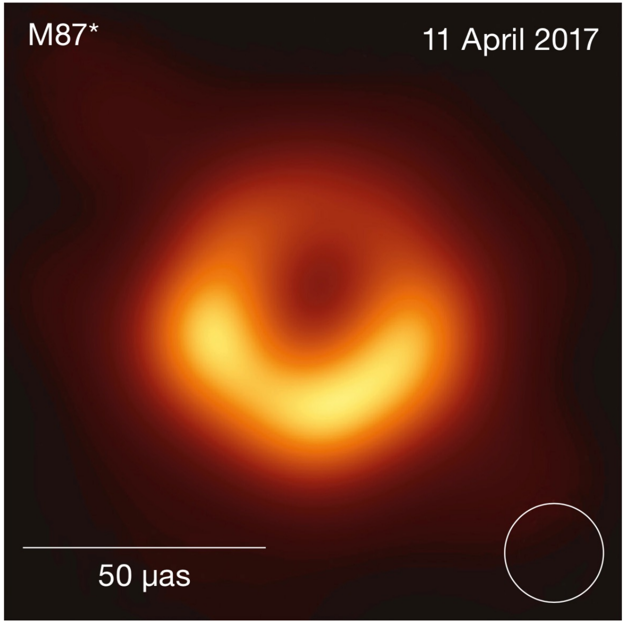
Pre-existing telescopes, made to work together

- 1.3 mm (230 GHz) - 0.65 mm (450 GHz)
- Baseline up to 20,000 km
- Down to 50 μas angular resolution



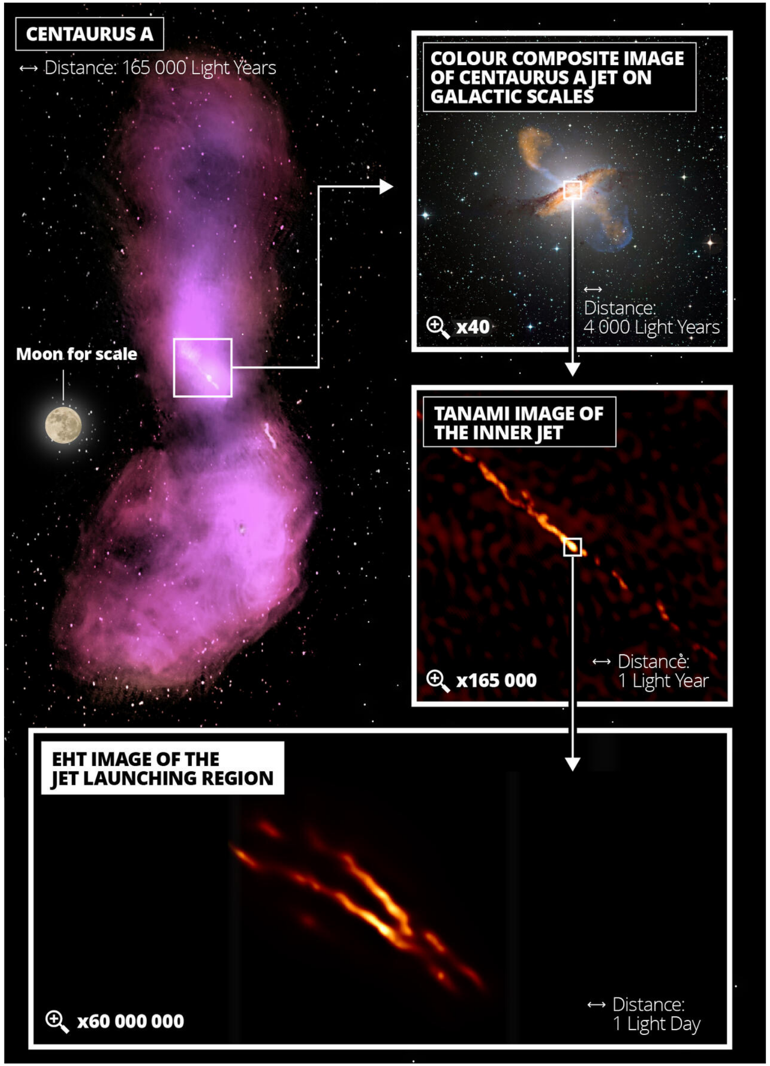
ESO/L. Benassi/O.Furtak

EHT: amazing observations



EHT Collaboration

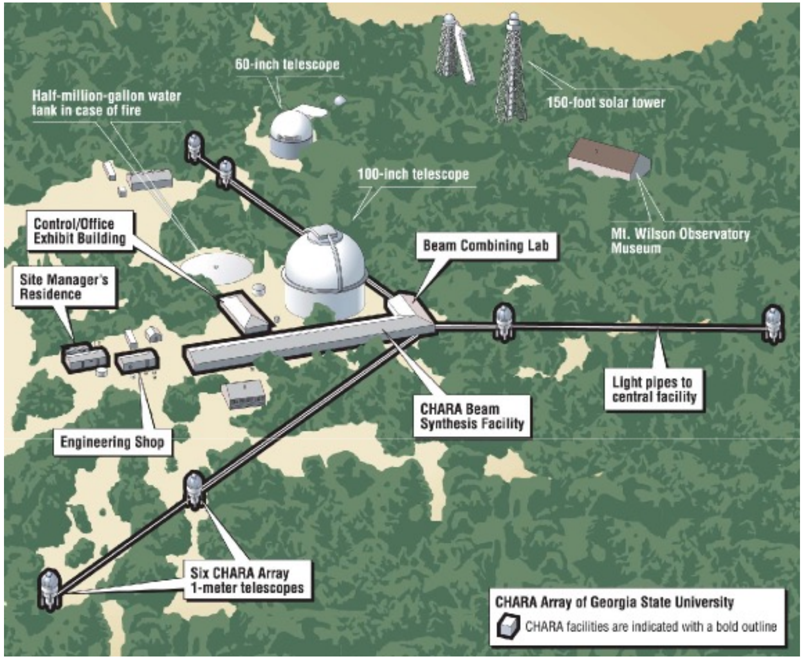
Imaging of area surrounding the supermassive black hole in M87



Imaging of innermost region of Cen A jet

Phase interferometry in VISIBLE

More accurate optics, including active optics, lasers, precision mechanics, faster electronics, more efficient photodetectors….



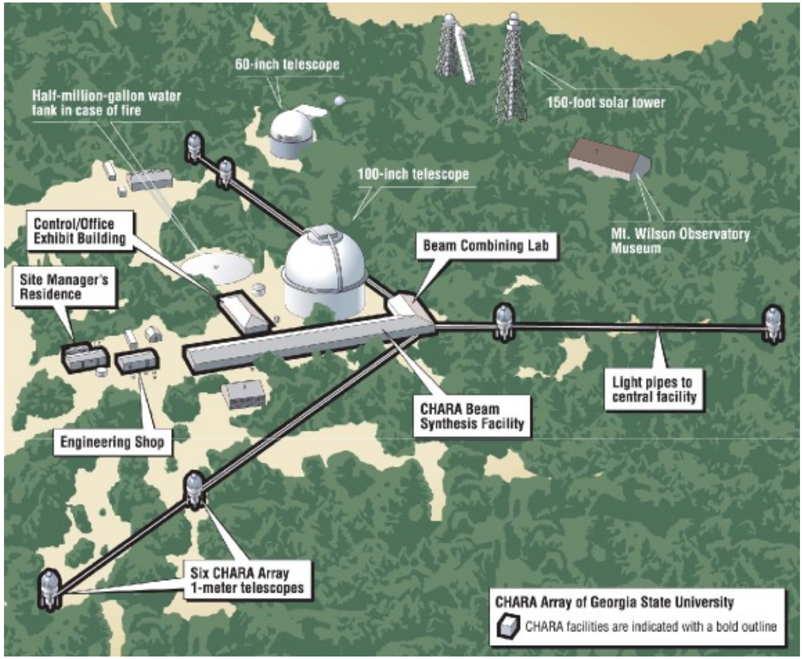
CHARA in Mt. Wilson: 6x 1 m telescopes, connected to correlator. Baseline <331 m. 200 μas resolution in visible (V,R) for $V<10^{m}$.

GRAVITY in VLT, Chile: 4x 8 m telescopes, connected to correlator. Baseline <130 m. 2 mas resolution in IR for $K<17^{m}$, 50 μas astrometry

Phase interferometry in VISIBLE

More accurate optics, including active optics, las
mechanics, faster electronics, more efficient ph

RESTRICTED TO
RED/INFRARED AND
BASELINES < 1 km



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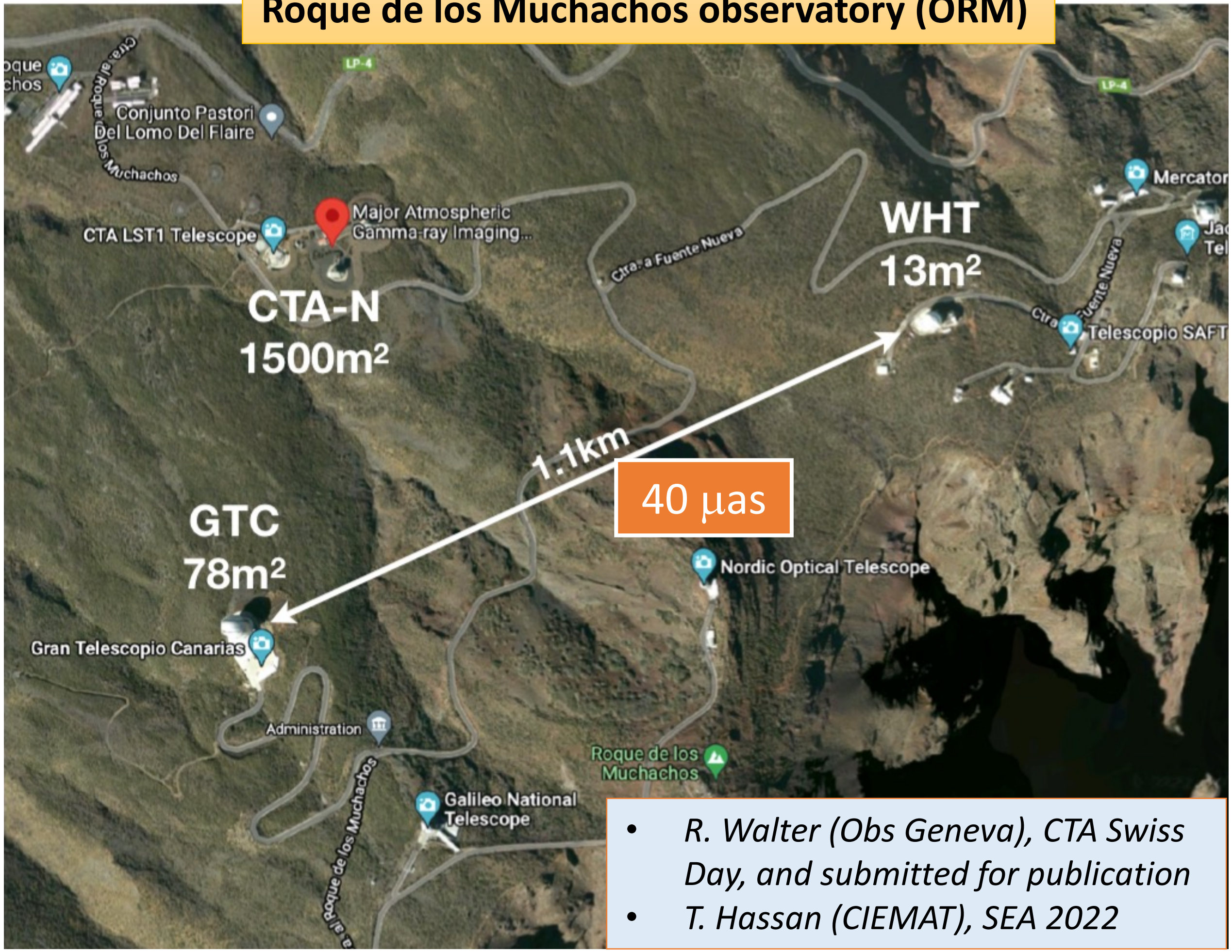
Longer baselines

Large diameter telescopes are available or coming online:

- **CTA (3 – 12 – 23 m)**
- **GTC (10 m)**
- **VLT (8 m)**
- **E-ELT (39 m)**
- **GMT (25 m)**

ORM, La Palma: we are developing instrumentation to correlate **MAGIC/LST, GTC and TNG** (QUASAR project)

Can reach limit magnitude 8^m using many spectral channels.

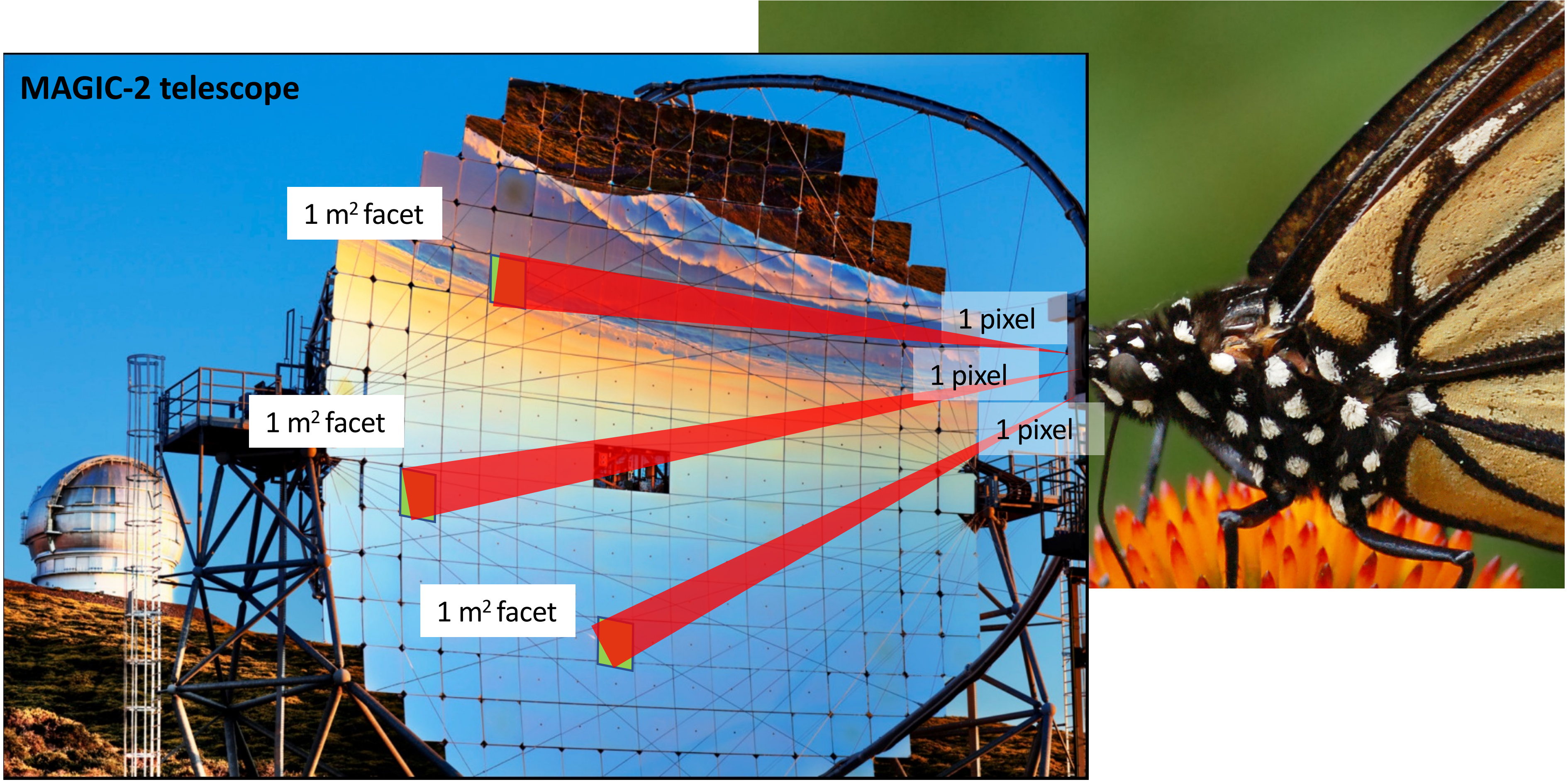


Roque de los Muchachos observatory (ORM)

40 µas

- *R. Walter (Obs Geneva), CTA Swiss Day, and submitted for publication*
- *T. Hassan (CIEMAT), SEA 2022*

MAGIC / LST Butterfly’s Eye

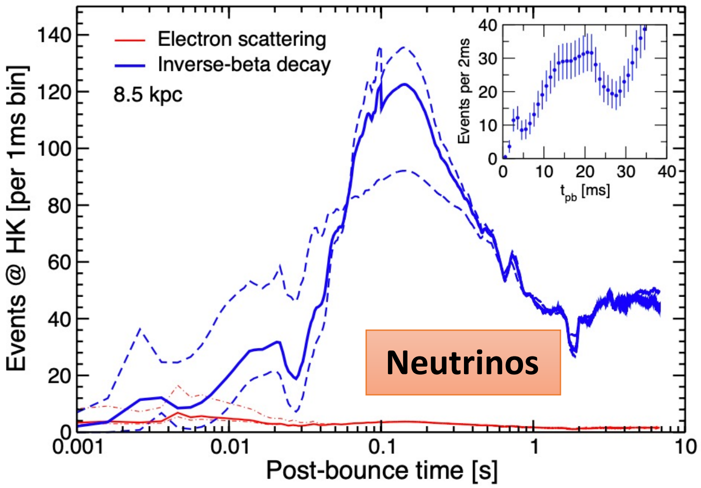


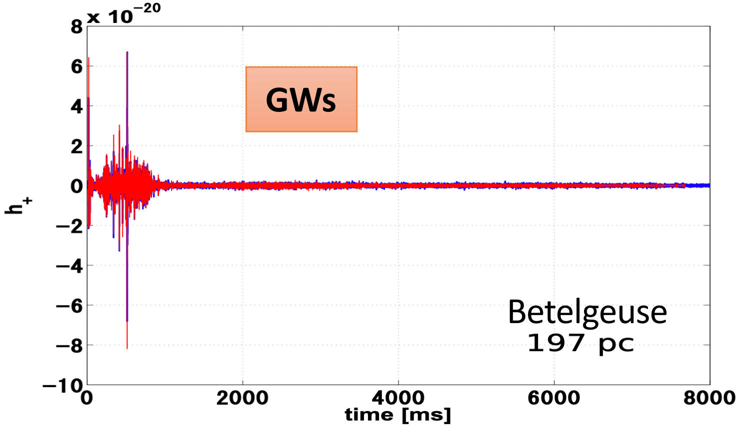
Supernovae

A galactic supernova would be the **Ultimate Multimessenger event**:

- Prompt emission of low energy (MeV) neutrinos, and gravitational waves if the explosion is (at least fractionally) asymmetric.
- Even prompt axions (M. Meyer et al., PRL 118 (2017) 011103)
- After a few days it may shine up in VHE γ-rays and HE neutrinos.
- After a few years it may enter into a phase where PeV cosmic rays are produced. Distance would allow to study to map the cosmic ray density using γ-rays.

A galactic supernova is long overdue...





Ko Nakamura et al., MNRAS, 461, 3296 (2016)

Novas: observability with interferometers

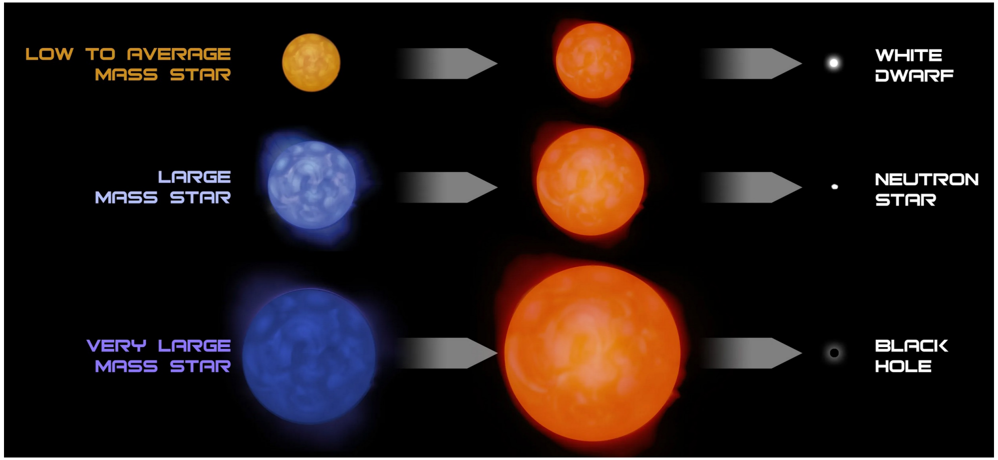
Nova typical ranges in speed and distance:

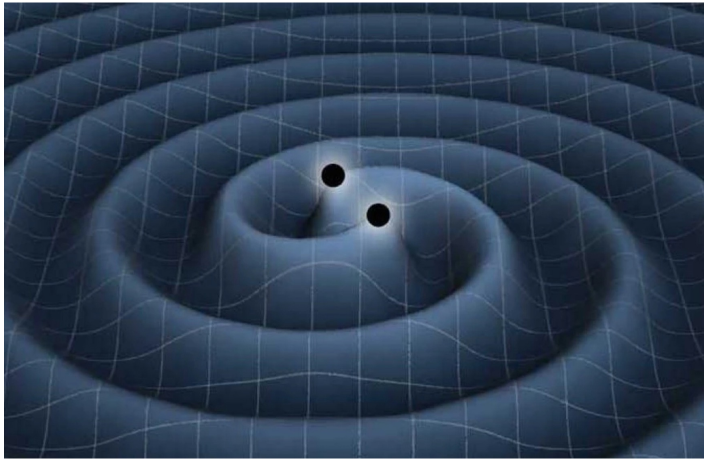
- ejecta speed: 200 – 7000 km/s
- distance: 0.5 – 5 kpc

Diameter angular expansion rate (mas/day)	**0.5 kpc**	**5 kpc**
200 km/s	0.5 mas/d	0.05 mas/d
7000 km/s	17.5 mas/d	1.75 mas/d

Massive stars <-> black hole mergers

In general, progress in our understanding of massive stars is key for gravitational wave astronomy, because massive stars are the precursors of black holes.





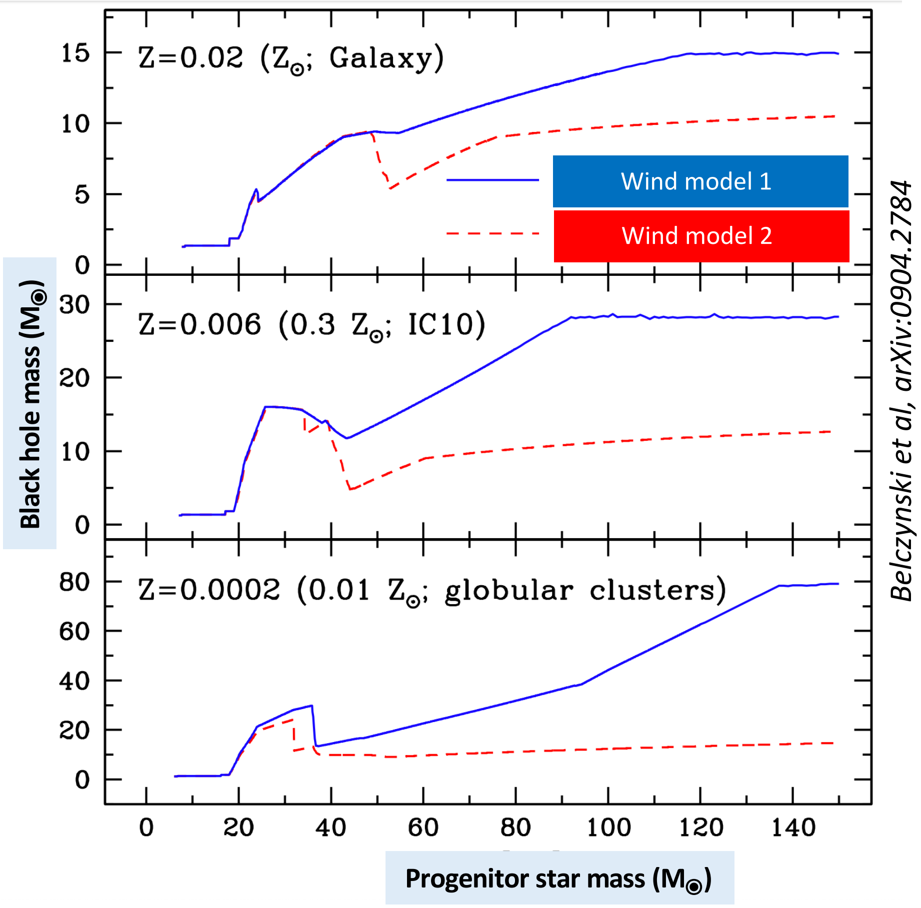
More specifically, interferometers could help in:

1. Establishing how many massive stars are binaries.

2. Studying stellar winds.

Winds and black hole mass

- When LIGO came up with the first GW events, one of the big surprises was the Black Hole mass distribution: nobody expected to see so many BH pairs with tens of M☉.
- No wonder because it's very difficult to predict the BH mass. **There are strong effects from metallicity, wind mass loss or binarity.**
- Here is e.g. the initial-remnant mass relation for single stellar evolution and two wind prescriptions.



Belczynski et al, arXiv:0904.2784

Proto-supernovas: Betelgeuse & Antares

- α Ori (Betelgeuse) or α Sco (Antares) are red supergiants and very nearby (<200 pc) supernova progenitors. A supernova may happen any time soon.
- They have a large angular extent (~50 mas).
- They are actually very dynamic: strong convection and mass ejection. The recent dimming of Betelgeuse is associated to surrounding dust recently ejected from the star.
- Understanding their pre-supernova behaviour is important.
- With interferometry:
  - We can study <u>how the star generates the circumstellar medium</u>. That medium has strong implications in VHE γ-ray and neutrino emission.
  - We can make coarse <u>images and movies of the atmosphere</u>.

Study stellar winds with interferometry

- The wind is probably inhomogeneous ("clumpy") and this inhomogeneity evolves in time
- The star produces a spectral continuum while the stellar wind produces emission lines.
- Let's observe only the **emission lines** (which in fact increases our sensitivity).

1. **Rough image** of the wind.
2. "**movies**" with time evolution.

Wolf-Rayet WR 137
T=10^5 K, 2000 km/s wind
B=8.20^m