Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
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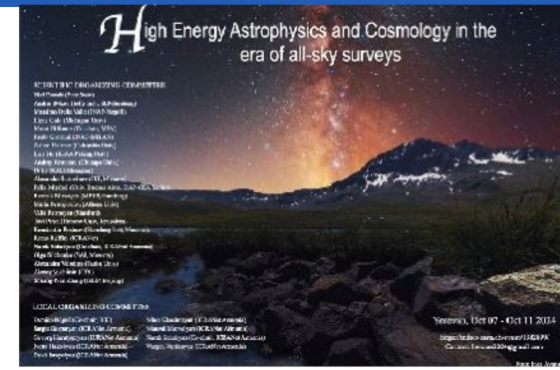
INAF ISTITUTO NAZIONALE DI ASTROFISICA



8 October 2024

Multi-wavelength surveys in the Cherenkov Telescope Array Era

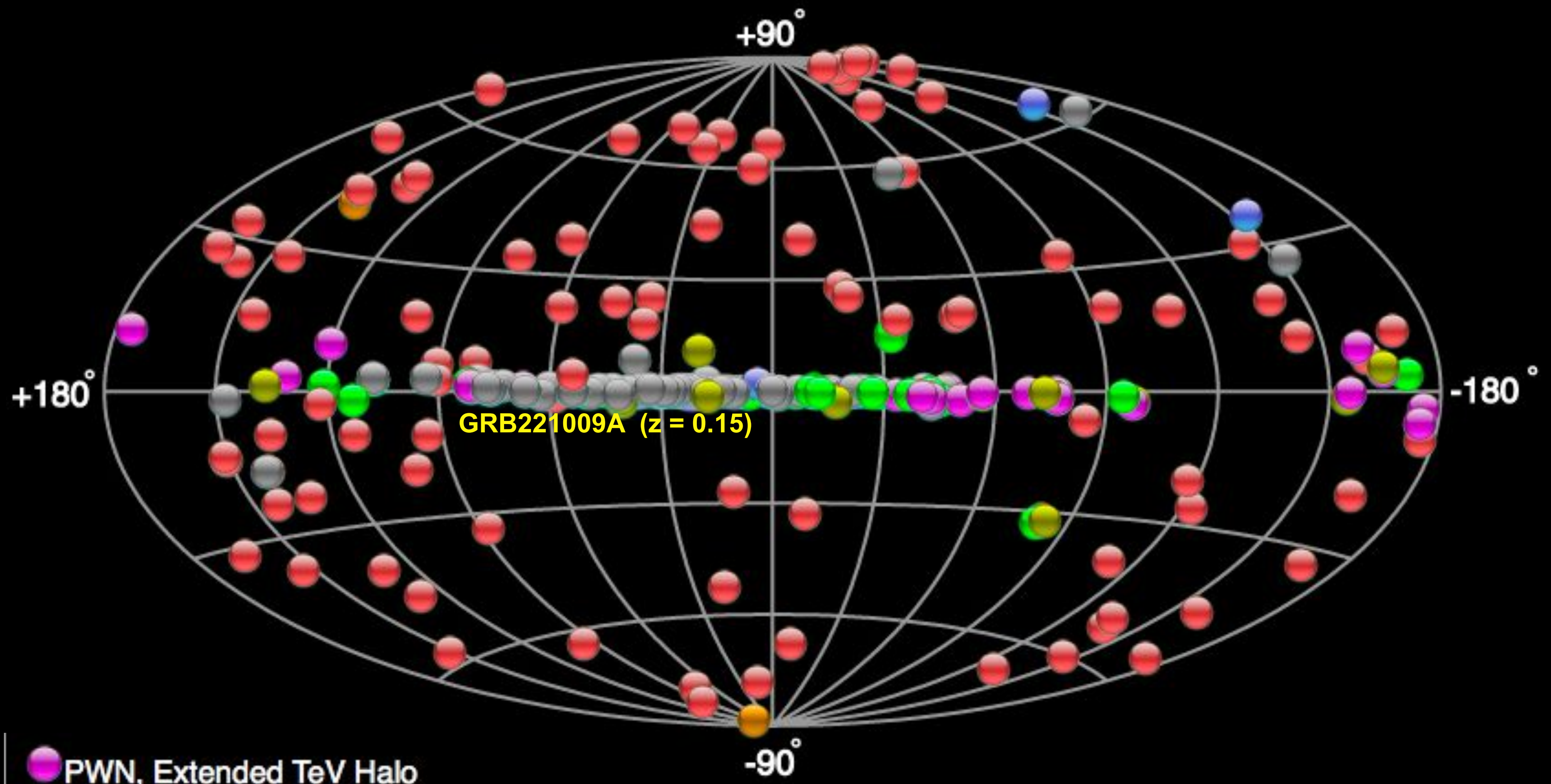
Elena Pian
INAF-OAS, Bologna

Progetto PNRR CTA+
Proposta IR0000012
CUP: C53C22000430006

Missione 4 Istruzione e Ricerca
Componente 2 Dalla ricerca all'impresa
Linea di investimento 3.1

TeV Sky interactive map

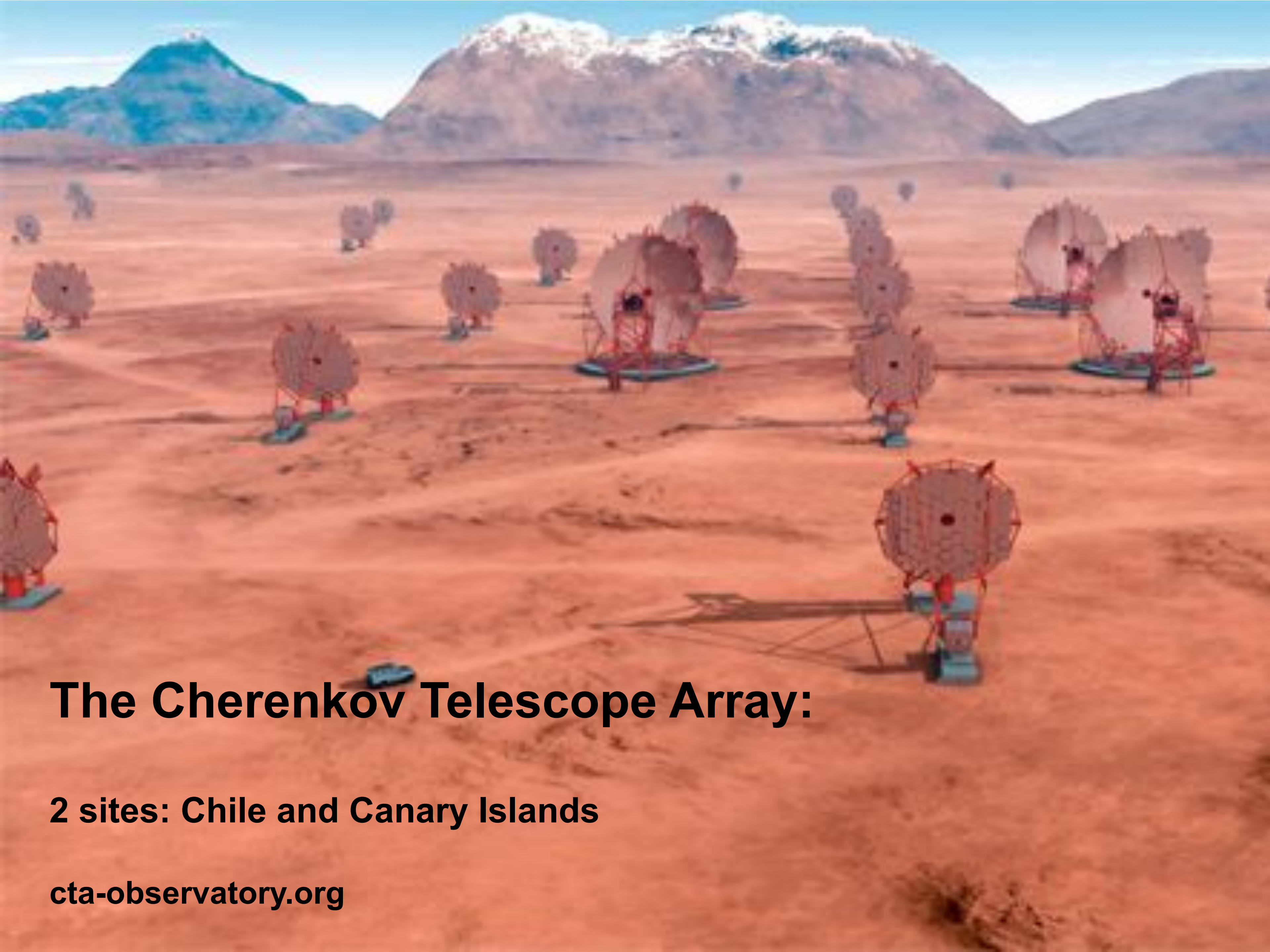
http://tevcat.uchicago.edu



PWN, Extended TeV Halo
Starburst (M82, NGC253)
HBL, IBL, GRB, FSRQ, LBL, AGN (unknown type), FRI, Blazar
Globular Cluster, Star Forming Region, Massive Star Cluster, BIN, uQuasar, Cat. Var., BL Lac (class unclear), WR

~300 sources
(~40% unidentified)

Shell, SNR/Molec. Cloud, Composite SNR, Superbubble
DARK, UNID, Other
XRB, Gamma BIN, Binary, PSR
SNe, TDE, FRB, dark matter decays…

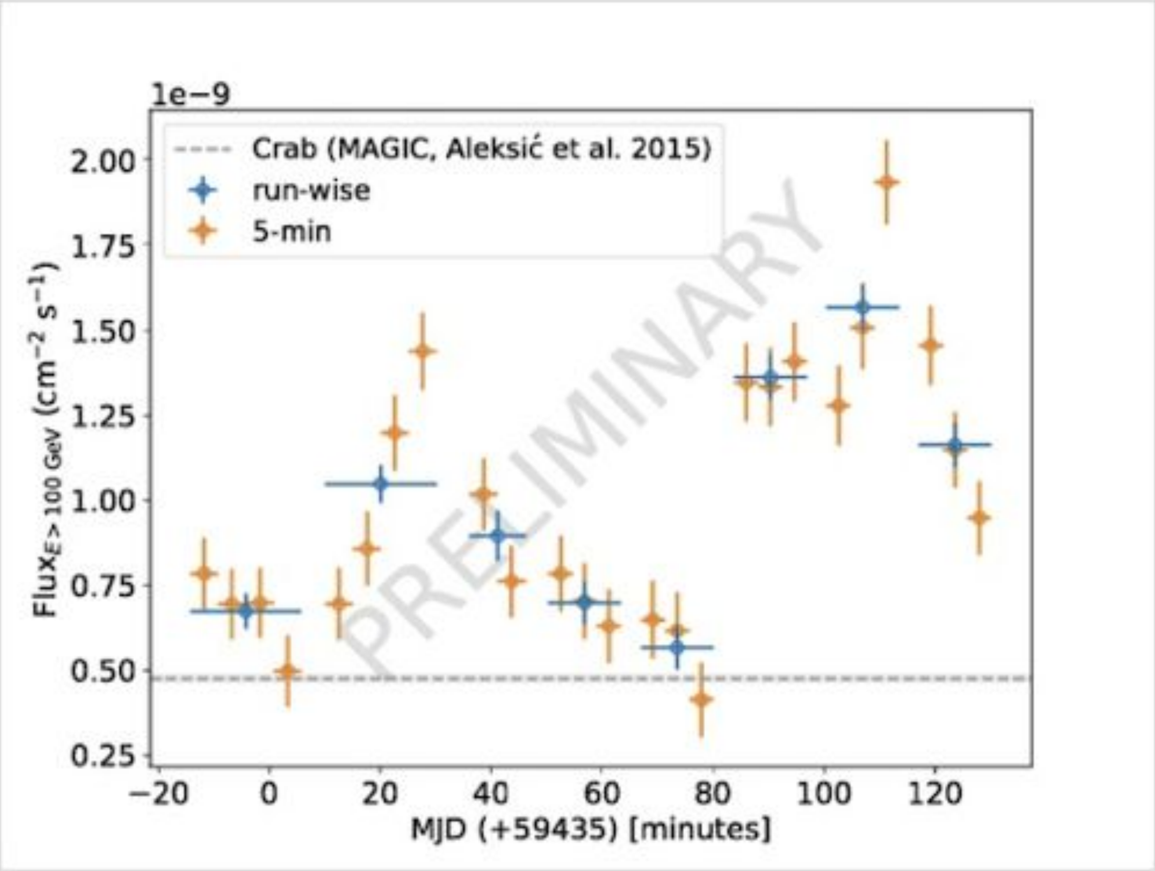


The Cherenkov Telescope Array:

2 sites: Chile and Canary Islands

cta-observatory.org

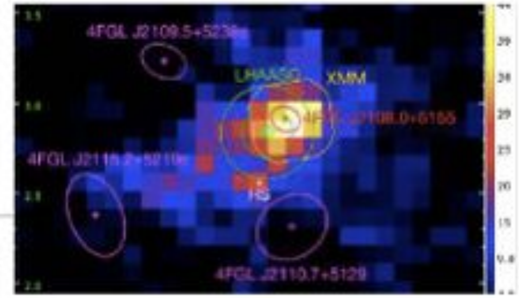
CTA LST-1 observation of BL Lac (z = 0.069) on Aug 9, 2021



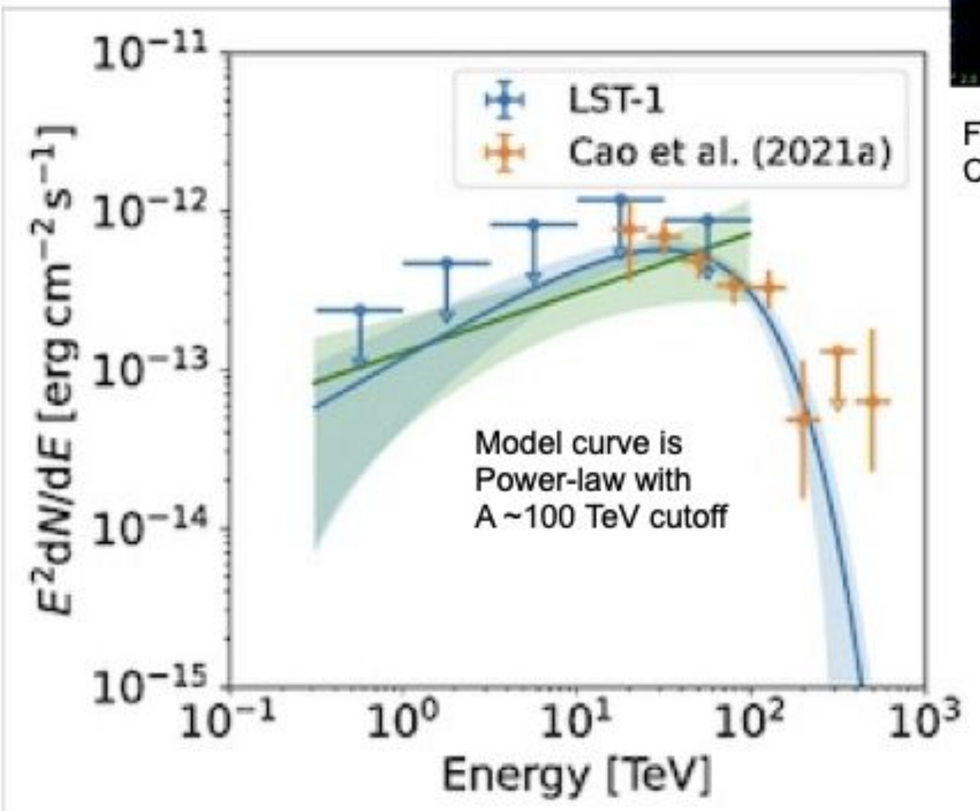
Intra-night light curve (>100 GeV) observed by the LST-1 on Aug 9. Blue and orange points correspond to run-wise and 5-min duration. The error bars on the flux level show statistical uncertainties. The gray line shows the integral flux of the Crab Nebula obtained by the MAGIC~\citep{magic_crab} as a reference.

Nozaki et al., CTA-LST Project Collaboration 2023

CTA LST-1 observation of Pevatron candidate LHAASO J2108+5157



Fermi/LAT image (>2 GeV).
Contours are at 95% confidence.



3.7 sigma
Excess at >3 TeV

Abe et al., CTA-LST Collaboration 2023

PNRR CTA+ Program:

2 LSTs at CTAO South

5 SSTs at CTAO North

R&D new detectors for Cherenkov telescopes or complementary (e.g. SWGO); water Cherenkov technique; muon tomography…

Training & education of young scientists

4 optical/NIR/radio facilities in support of CTA

Program office: E. Pian
G. Castignani, INAF, OAS Bologna
E. Cappellaro, INAF, OA Padova

CTA Suite of telescopes

CTAO
CTAPlus

	North	South
LST (23m)	4	**2**
MST (12m)	9	14
SST (4m)	**5**	37

Optical/NIR/Radio follow-up

Implementation of 4 innovative ground-based radio-to-optical observational facilities of unique importance for CTA science.

Three of these are oriented to the observation of TeV sources:

- **VST Polarimeter (1 deg^2) to be mounted on INAF VST (PI: P.Schipani)**
- **e-SiFAP – optical/NIR photopolarimeter for TNG (PI: F.Ambrosino)**
- **RadioFast VLBI (PI: M.Giroletti)**

One - to be prototyped on the ASTRI MiniArray - represents an optimal secondary use of the SSTs:

- **Stellar Intensity Interferometer, (PI: L.Zampieri)**

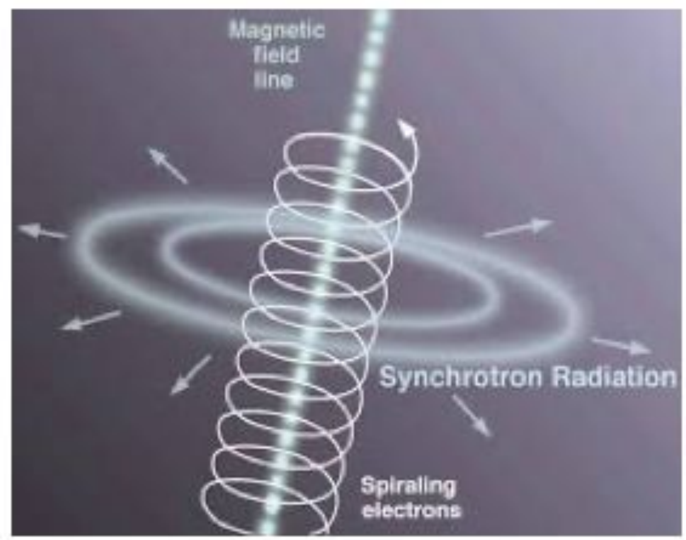
MOTIVATION FOR MULTIWAVELENGTH POLARIMETRY

Many astrophysical sources show polarization, which carries info on their geometry and physical processes:

Preferential geometric directions (e.g. symmetry axis)

Scattered radiation

Magnetic fields (from nano-Gauss In IGM, to 1-100 Gauss in AGN and GRB, to e15 Gauss in magnetars)

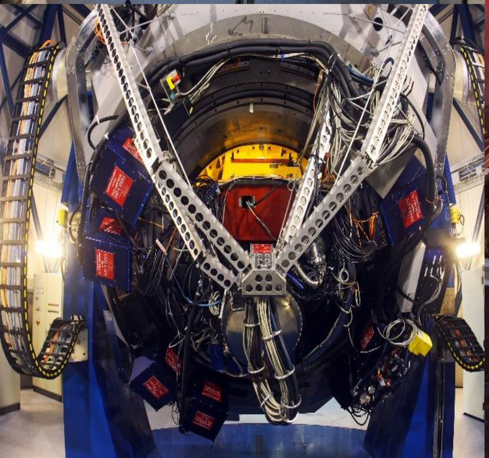


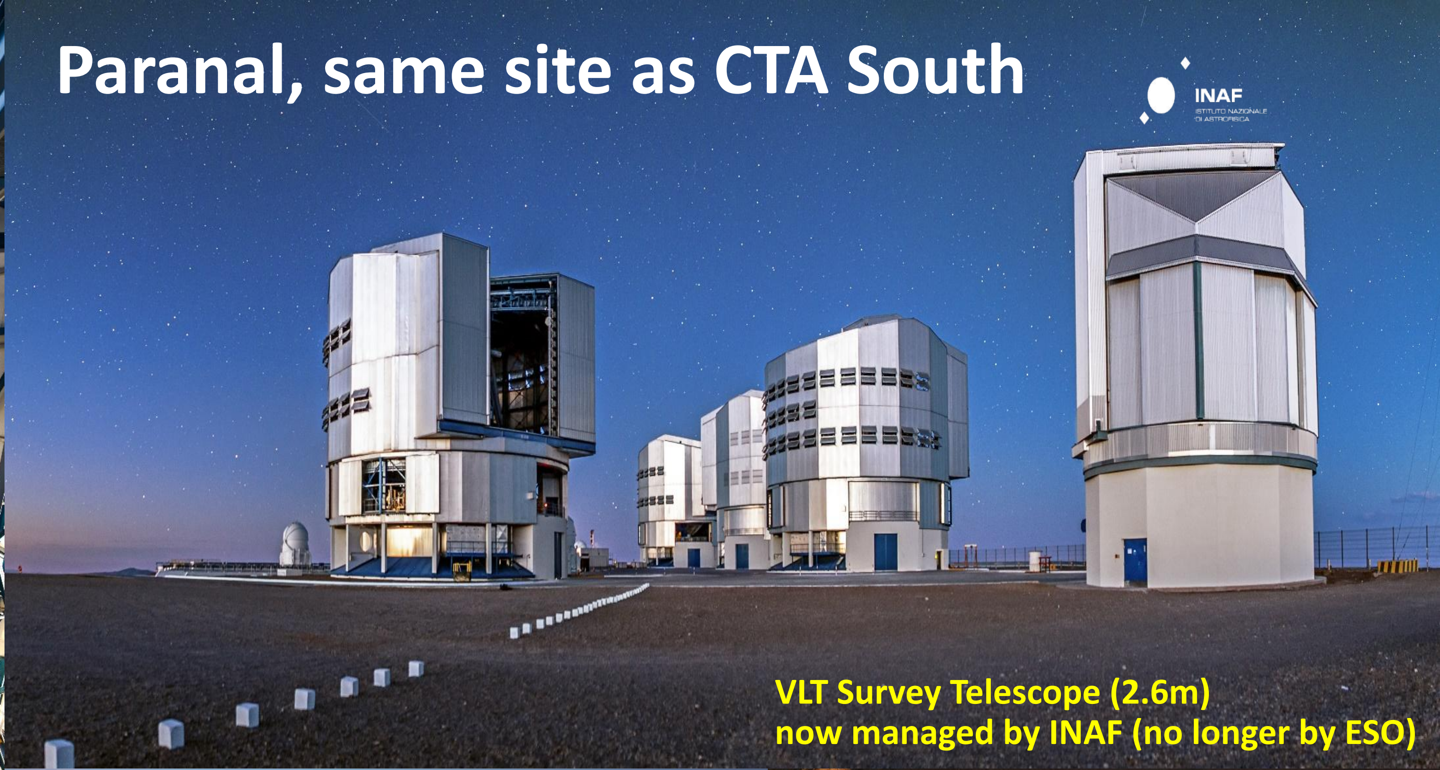
VSTPol: large field-of-view polarimetric camera for surveys

Pietro Schipani
INAF, OA Naples

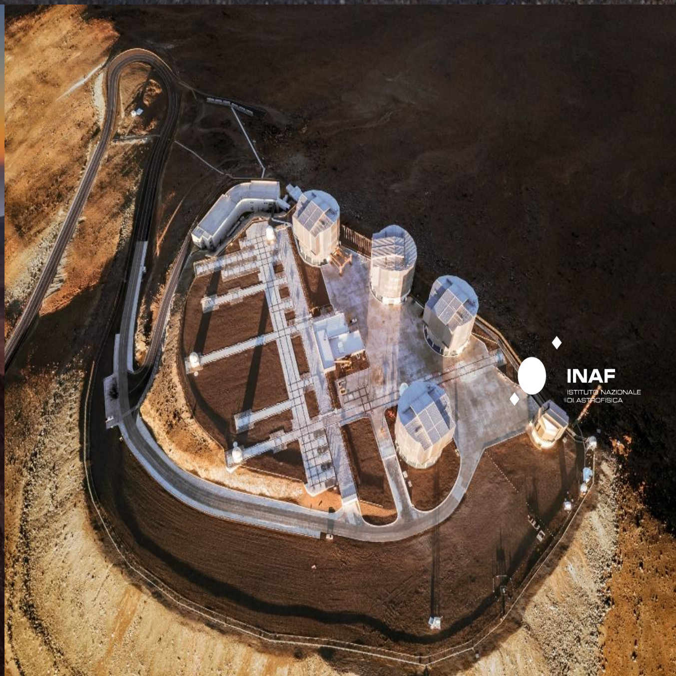
Stefano Covino
INAF, OA Brera

Paranal, same site as CTA South





VLT Survey Telescope (2.6m)
now managed by INAF (no longer by ESO)



VSTPol is a rotating polaroid filter in the optical path

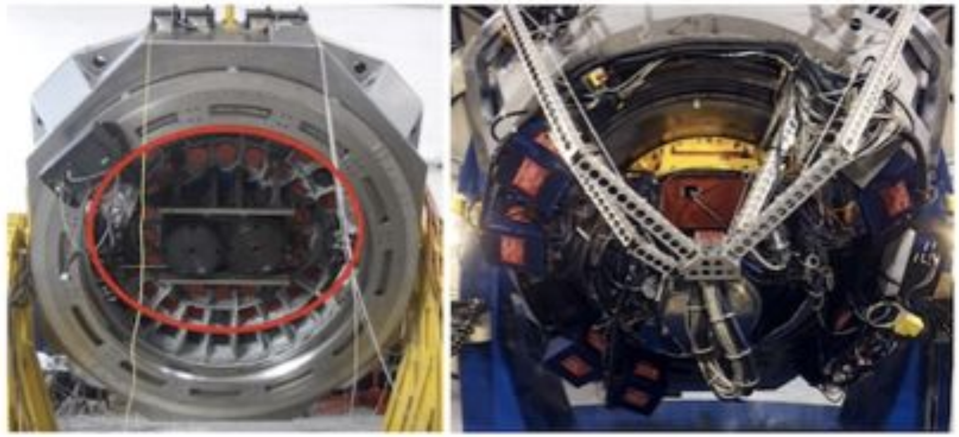


Figure 2. Left: inner view of the VST telescope after removal of OmegaCAM instrument and telescope probe. Right: external view of the telescope in the same position with OmegaCAM installed.

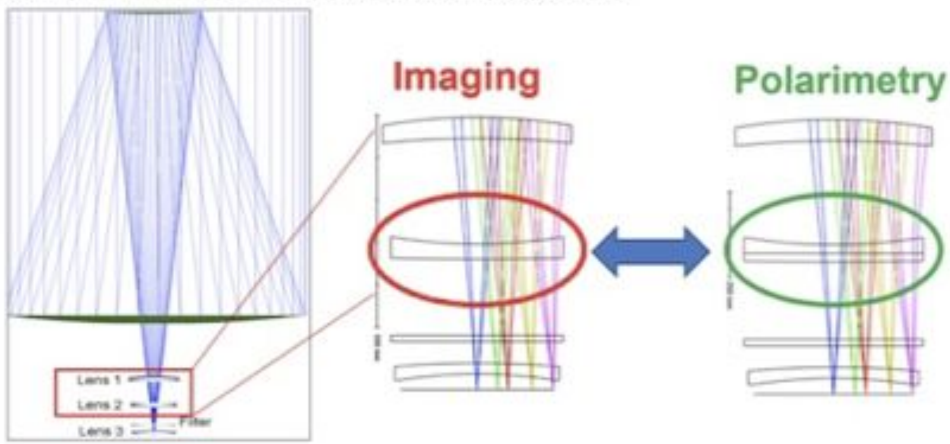


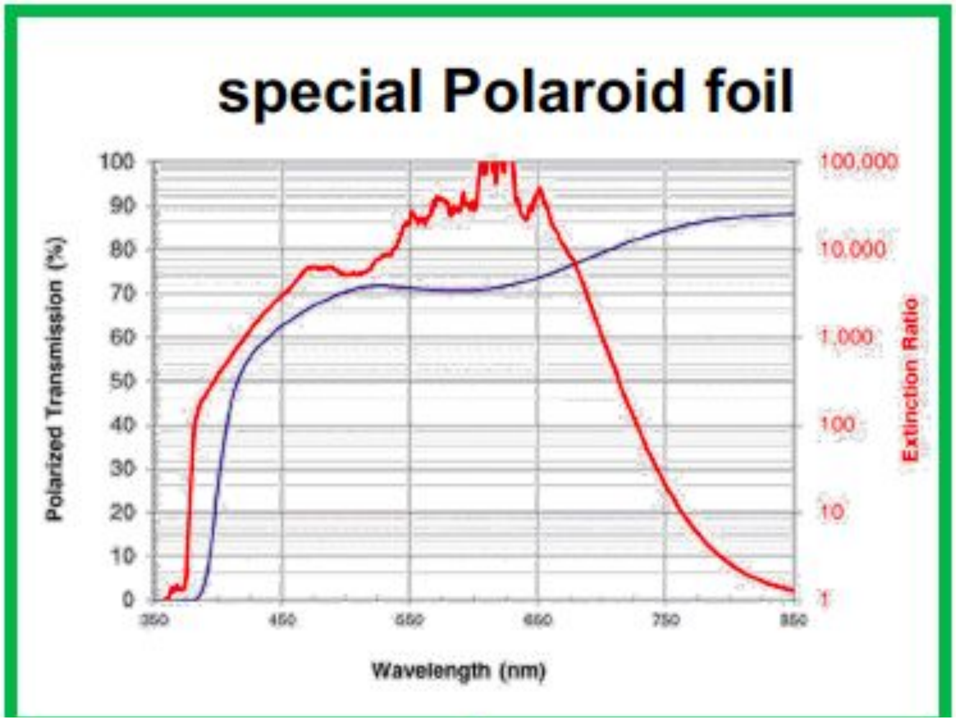
Figure 3. Left: optical configuration of the telescope, the red rectangle includes the two lenses belonging to the field corrector, which are installed in the old optomechanical device. Center: the unchanged future configuration in imaging mode, where the red oval includes the existing lens which will be made exchangeable. Right: the future configuration in polarimetric mode, where the green oval includes a sandwich of two half-lenses with a polaroid filter in the middle.

Schipani et al. 2024, SPIE

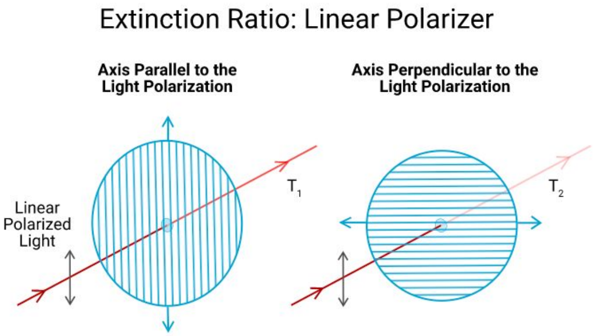
Optical/polarimetric support for CTA

	CTA OST requirements	*VSTpol estimated performance*
Limiting magnitude (photometry)	~ 20	~ 22.9 – 24.8 for ugri
Limiting magnitude (polarimetry)	~ 17 *	~ 20
Polarimetric sensitivity and accuracy	0.5 – 1%	36 min at V~16 for 0.16% sensitivity
Field of view	5' x 5'	1^o x 1^o
Cadence	Intra-night	Possible, depends on time allocation
Repointing speed	Better than 2'	(30+(separation in deg)/1.5) seconds

Rapid Response Mode: start observation 6 to 8 min after trigger



Extinction ratio

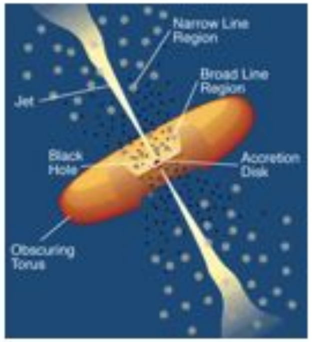


* Markoff et al. (2018)
Critical Assessment of Optical Support Needs for CTA Science and Consensus Proposal

Ann. Rev. Astron. Astrophys. 1980. 8: 321–61

OPTICAL AND INFRARED POLARIZATION OF ACTIVE EXTRAGALACTIC OBJECTS

×2169



J. R. P. Angel and H. S. Stockman
Steward Observatory, University of Arizona,
Tucson, Arizona 85721

Strong polarization is a defining property of blazars

I *Introduction*

In bringing together the material for this review our attention was drawn repeatedly to the remarkably similar characteristics of virtually all strongly polarized extragalactic objects, which are found as the nuclei of giant elliptical galaxies or as quasi-stellar sources. These are violent variability, a compact, flat-spectrum radio source, and a very smooth continuum extending at least to 10 μ. These properties are common to the polarized sources in BL Lac objects over a wide range of luminosity and to some QSOs and radio galaxies. In view of the similarities, which suggest a common process of energy release close to the central core of these objects, we will treat them all as a single group. In a memorable banquet speech at the Pittsburgh meeting on BL Lac objects (the only words spoken not faithfully reported in the proceedings) Ed Spiegel suggested the name "blazar" for this class of object. A combination of BL Lac object and quasar, with a strong feeling of the characteristic violent optical flaring, blazar seems an excellent name, one which we will adopt throughout the review.

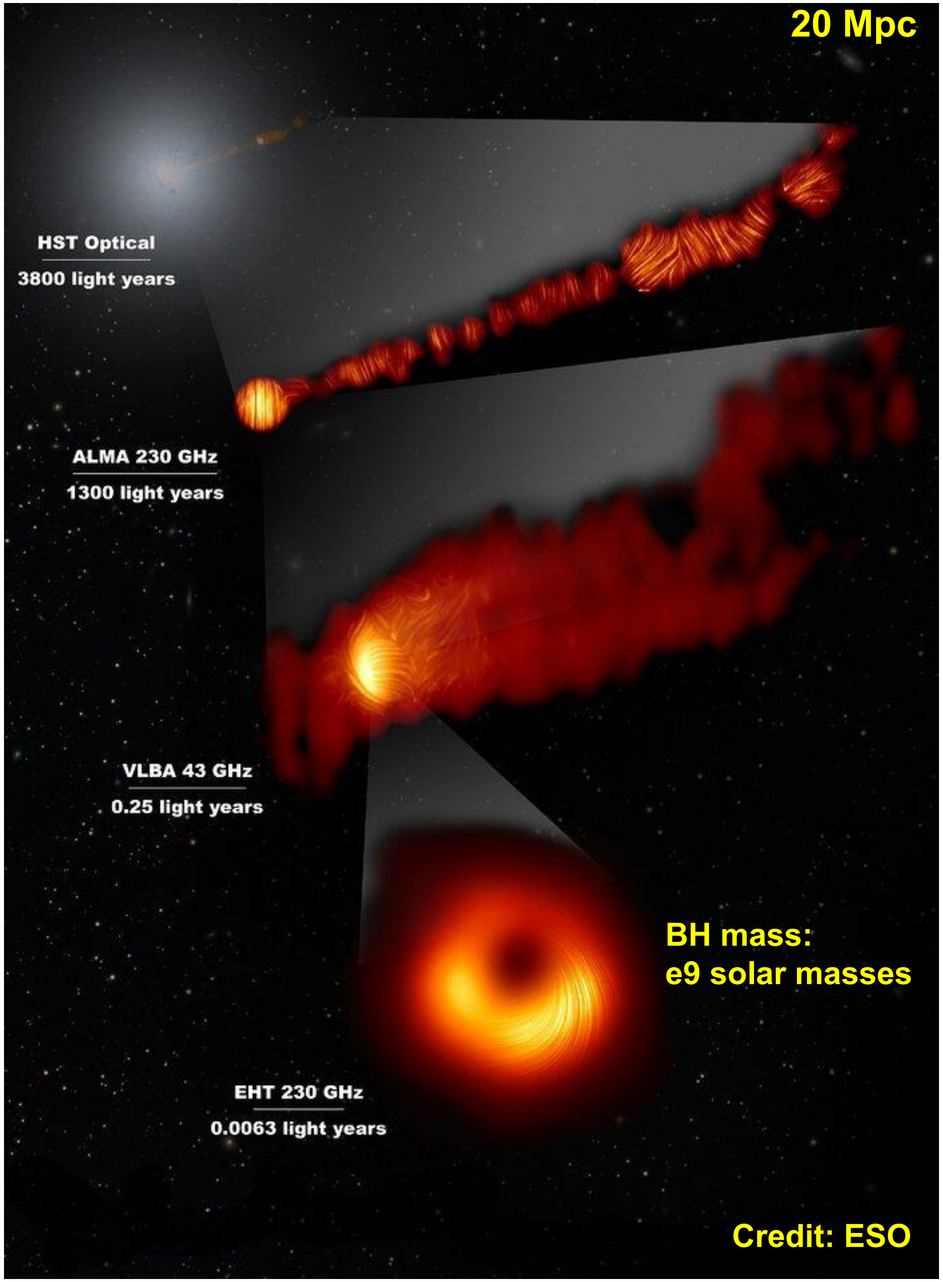
P_lin <~ 30-40%

The jet of M87 in polarized light

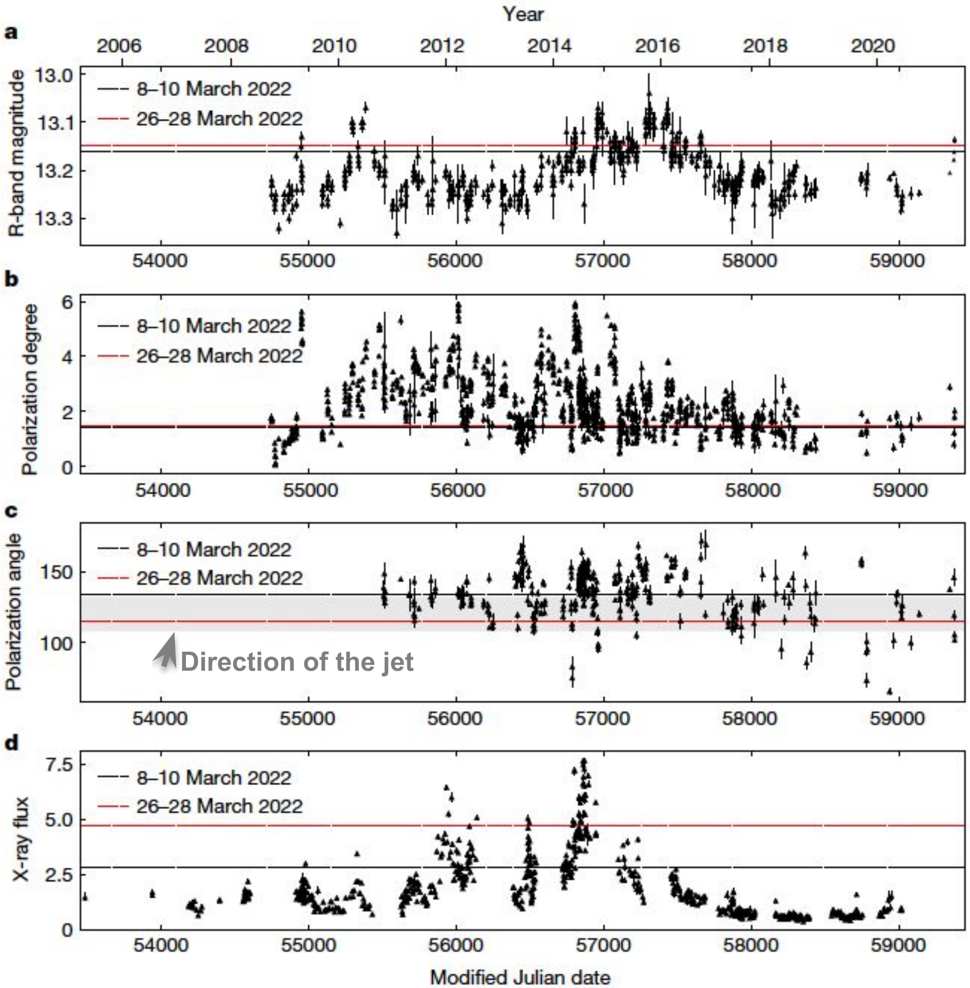
Time-variable millimetric linear polarization with a maximum of ~15%

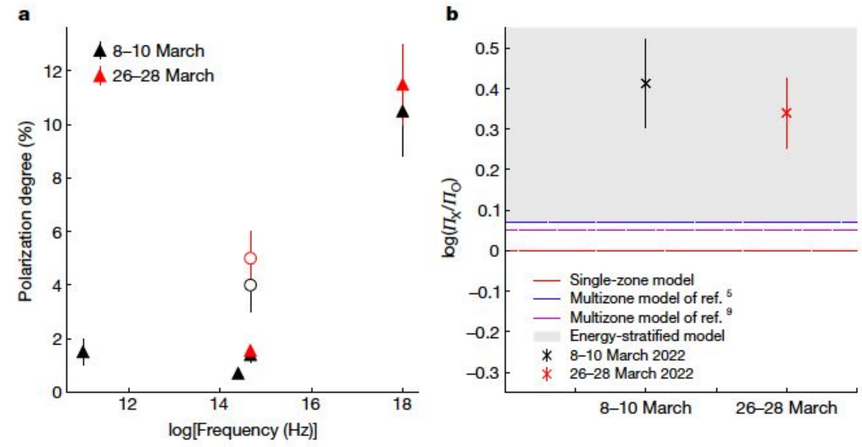
GRMHD simulations return magnetic fields of 1-30 Gauss and an accretion rate of (3-20)e-4 solar masses per year

EHT Collaboration 2021
Goddi et al. 2021



Markarian 501 (z = 0.034): multi-wavelength polarization

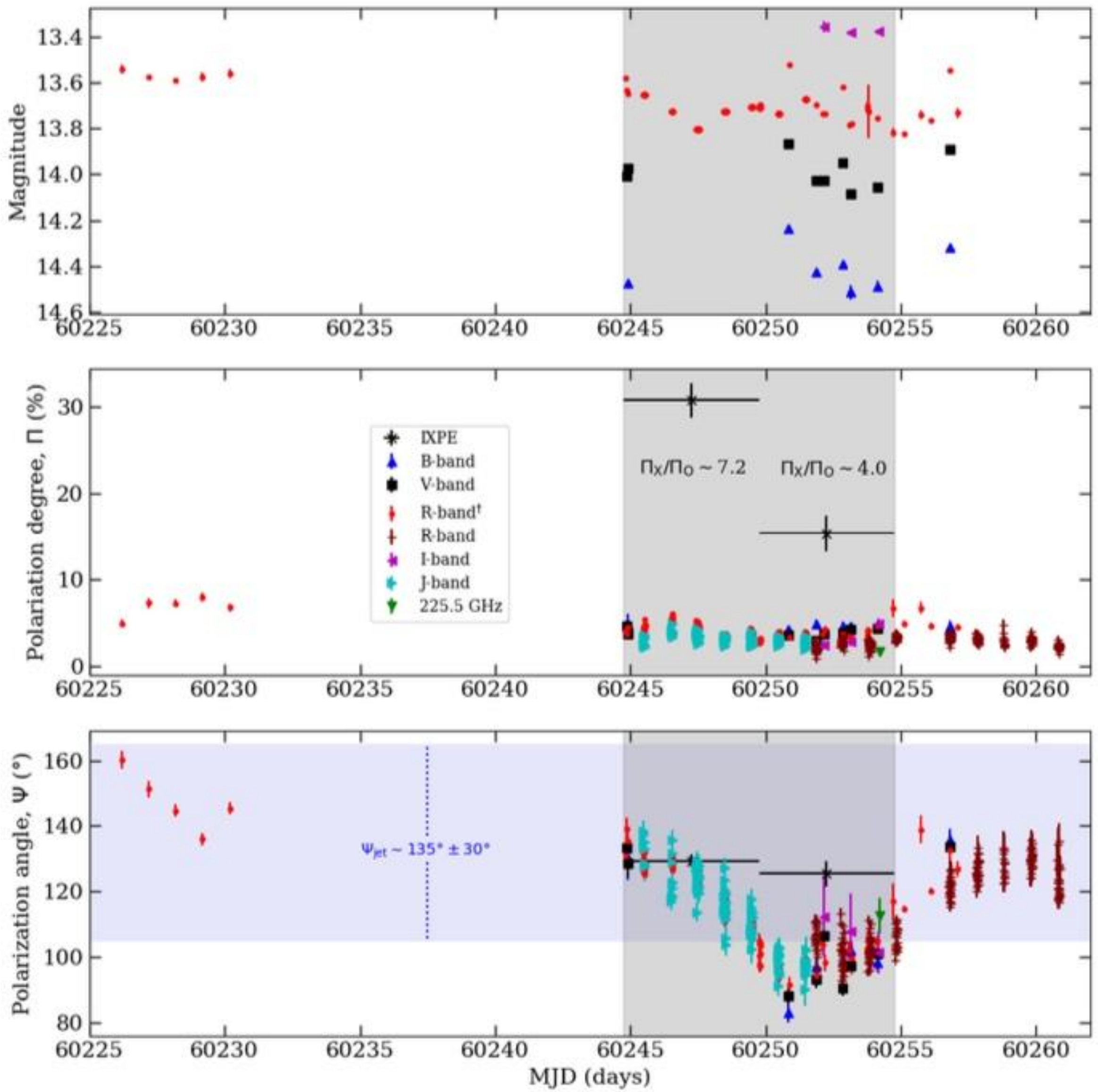


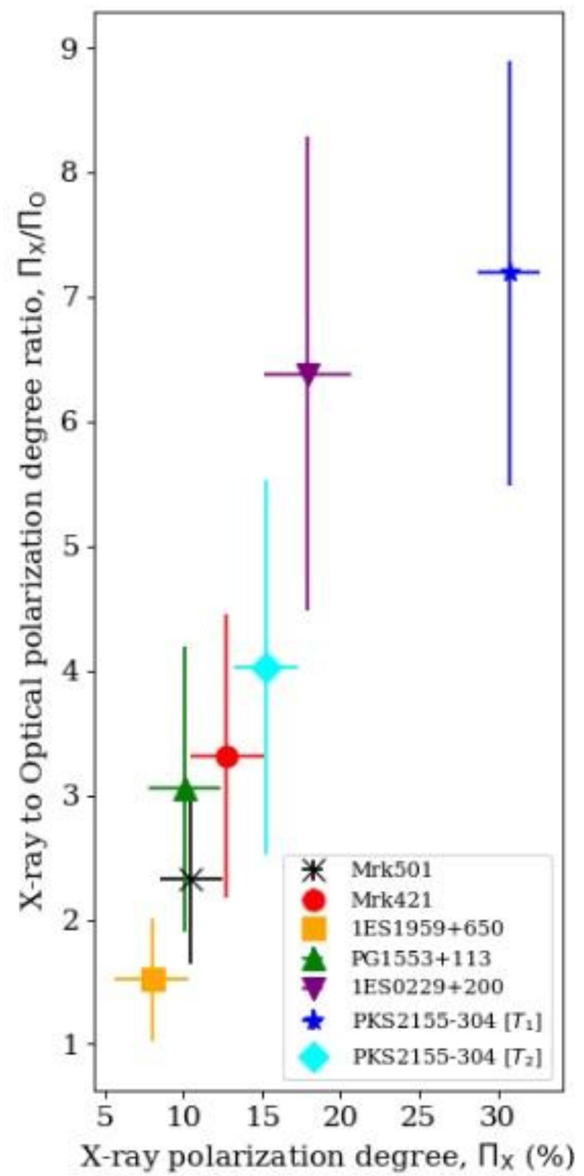


Polarization increases towards higher frequencies and does not vary between the 2 IXPE epochs; polarization angle is aligned with jet direction → shock-accelerated, energy-stratified electron population model

Liodakis et al. 2022

IXPE observations of the blazar PKS2155-304 (z = 0.1)



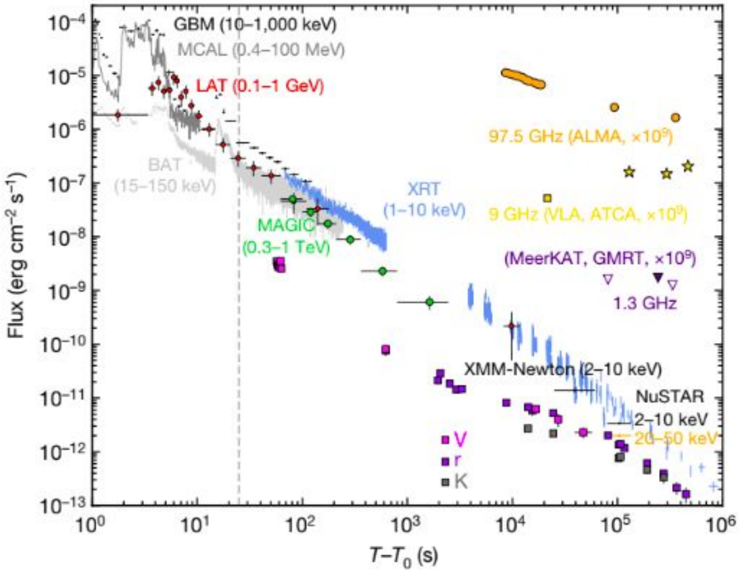


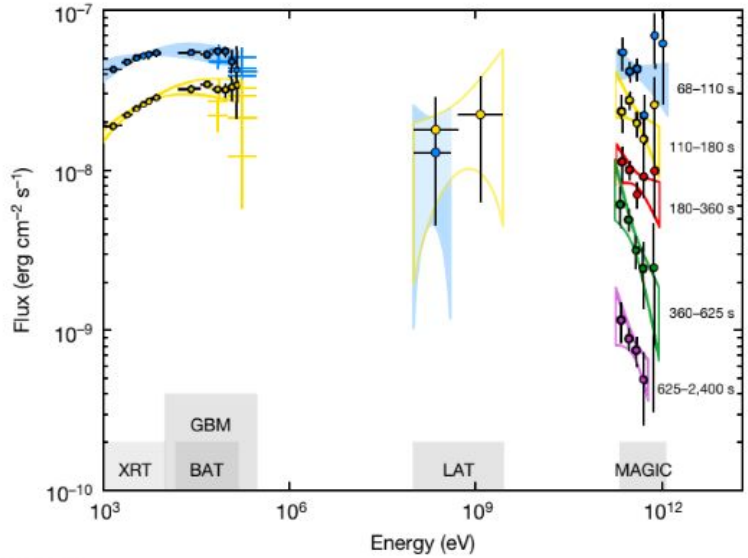
2023 Oct 27 - Nov 7

Kouch et al. 2024

Optical polarization of the early counterpart of GRB190114C (z = 0.42)

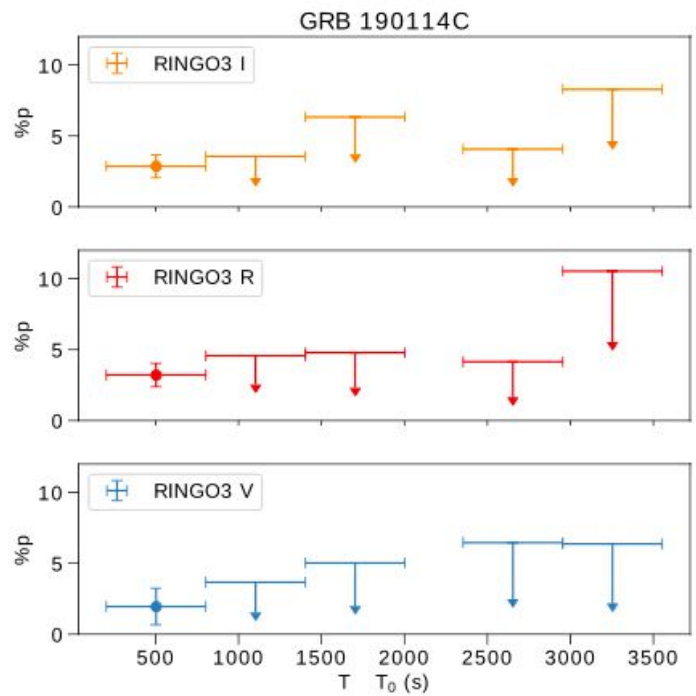
MAGIC Collaboration 2019



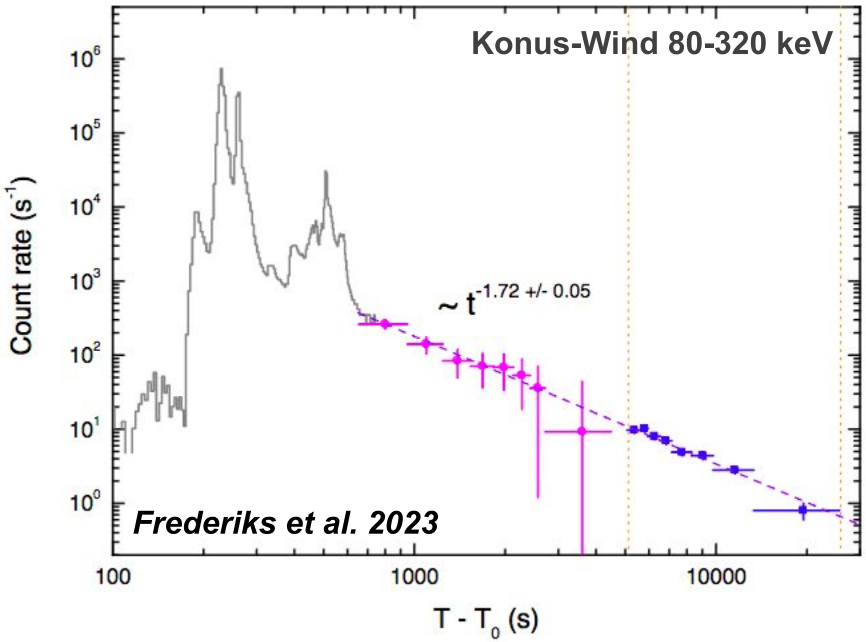


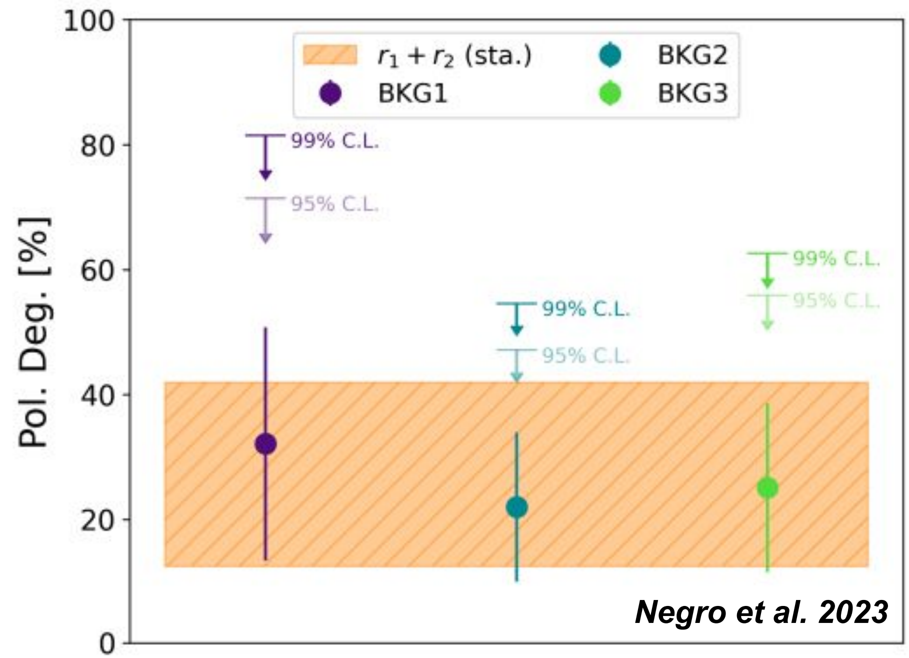
Liverpool Telescope + RINGO3 polarimeter

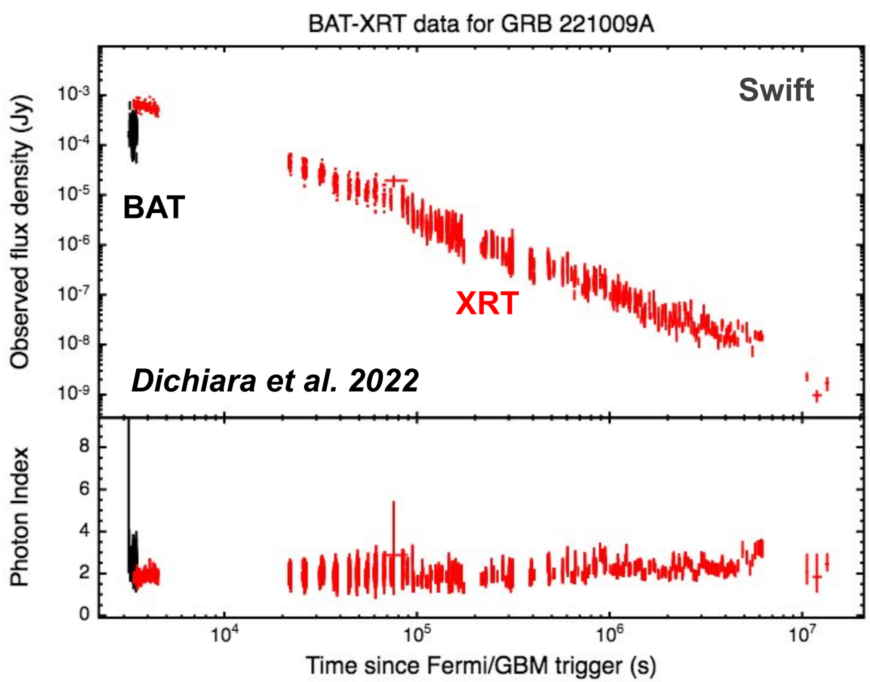
Shrestha et al. 2022

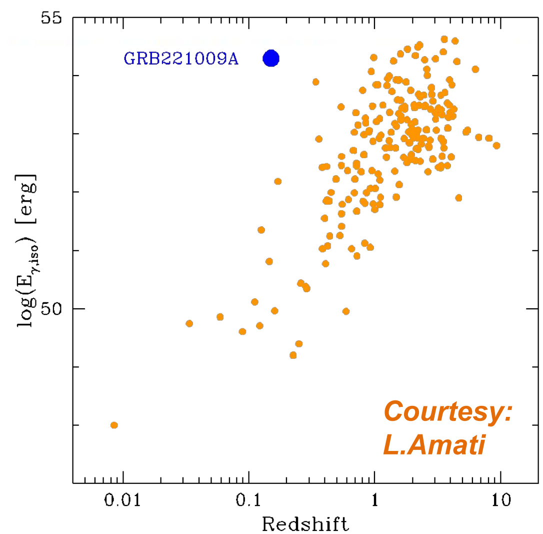


GRB221009A (z = 0.15): upper limits on X-ray polarization





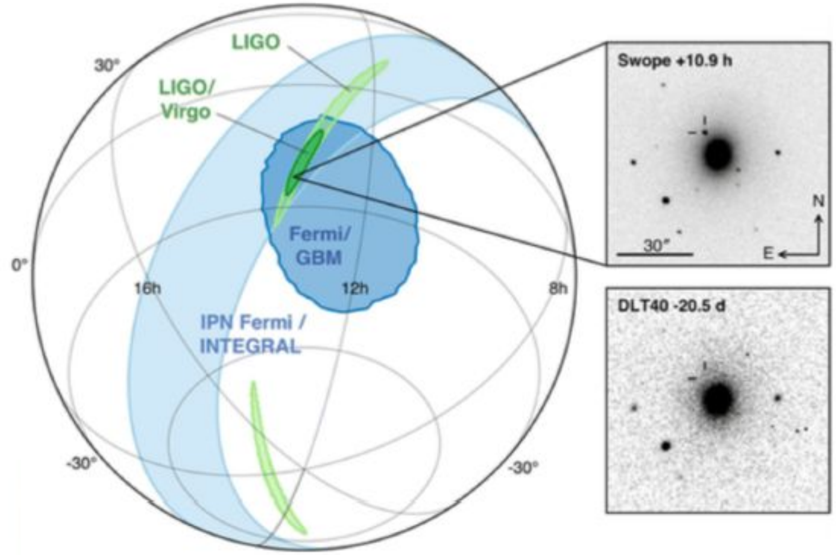


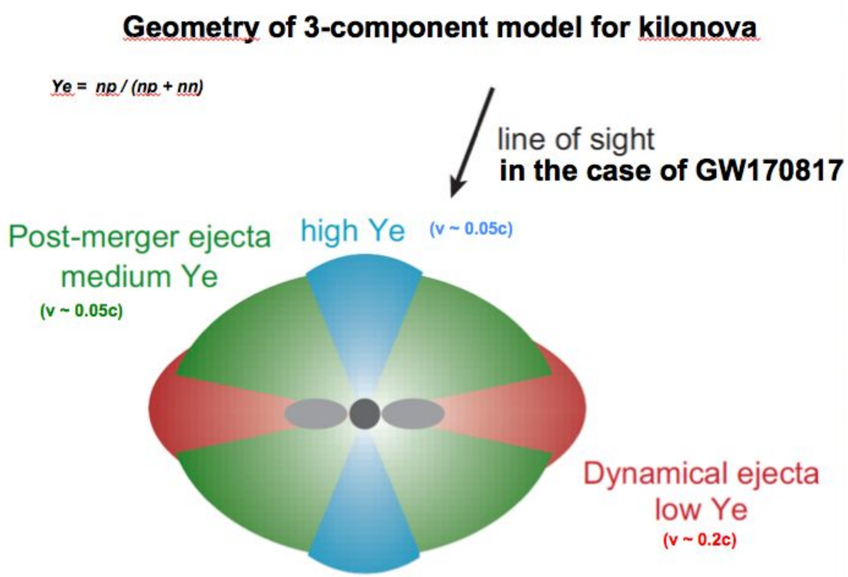


Isotropic gamma-ray energy of GRB221009A Compared with Other GRBs

GW electromagnetic counterparts

- GW localizations for good S/N events will be even better than 10°
- Early-time (hr) kilonova polarisation is a powerful and unique diagnostics.
- Only a large FoV polarimeter could make these observations feasible.

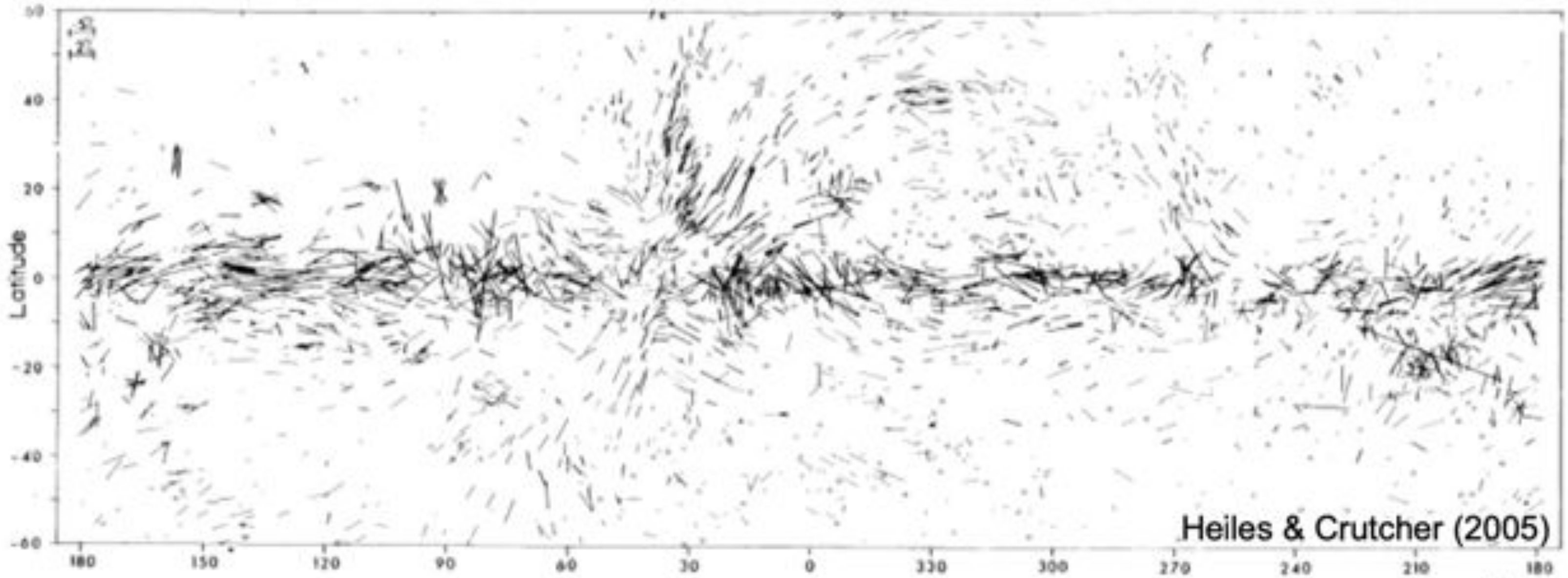




Kilonova AT2017gfo: Upper limit on linear polarization ~0.5% (Covino et al. 2017)

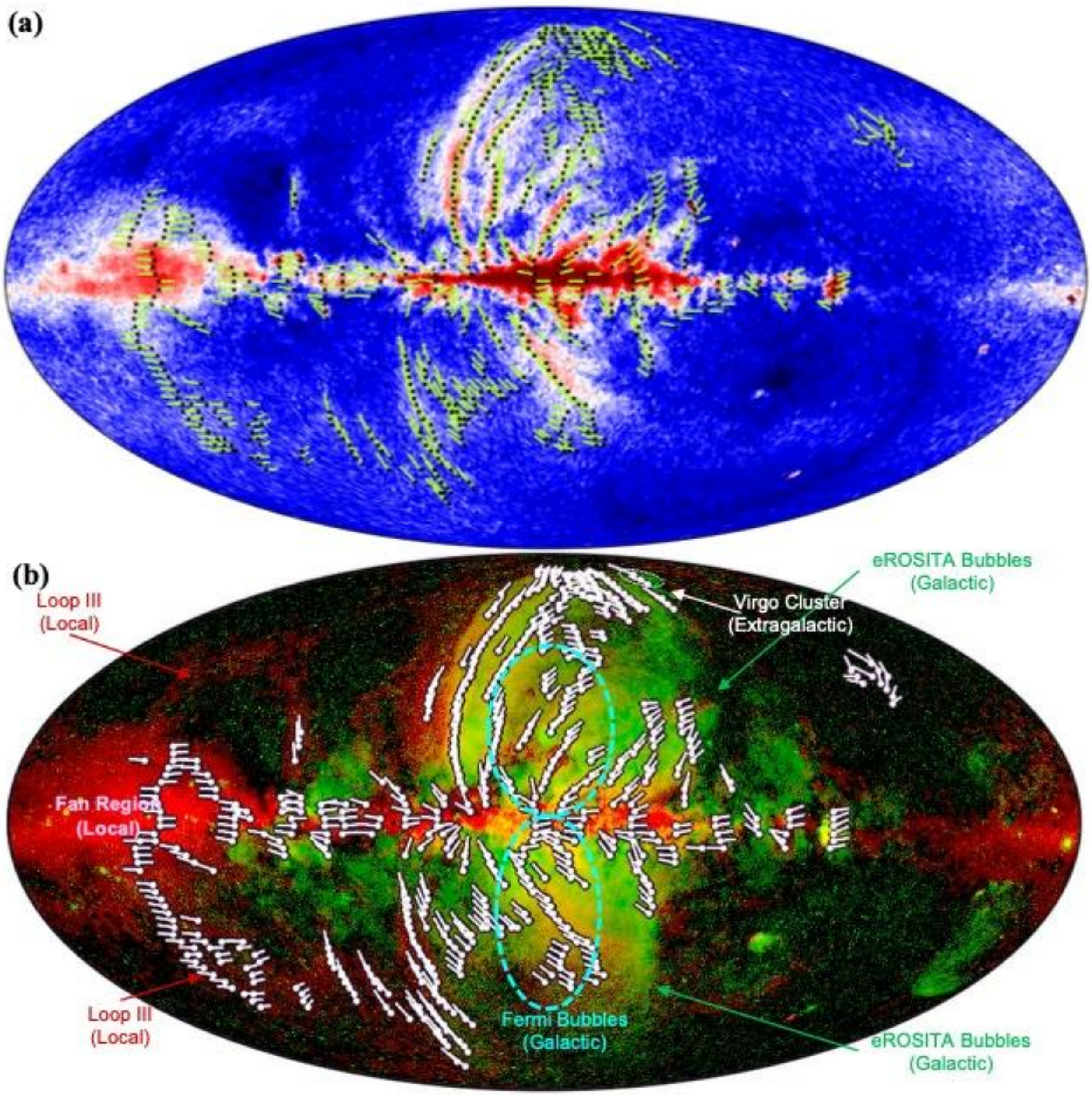
Tanaka et al. 2017; Pian et al. 2017

Optical starlight polarization: 3D galactic magnetic field



O(3,000h): correlation with accurate Gaia parallaxes: 3D mapping of the magnetic field of MW, LMC, SMC + correlation with Planck

Magnetised halo of the Milky Way

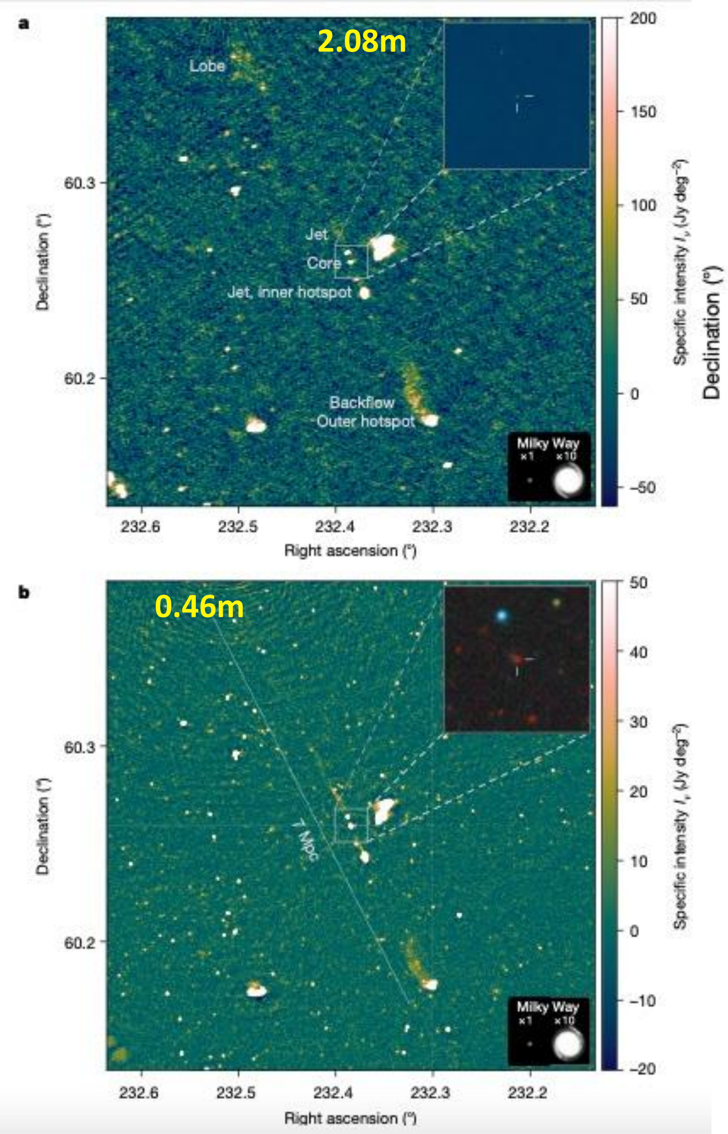


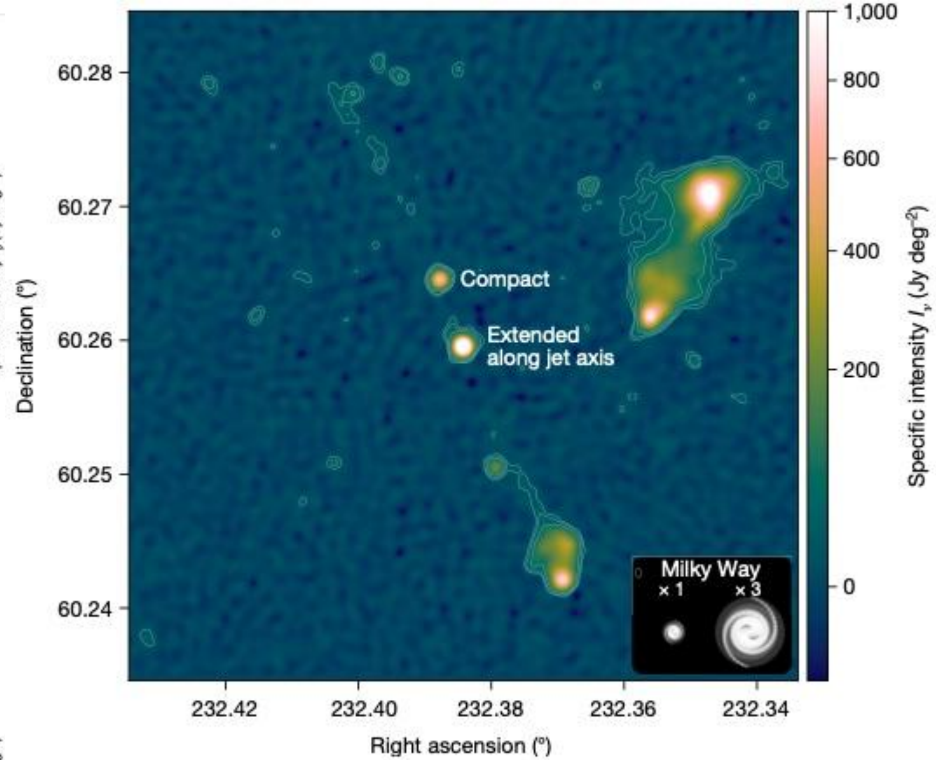
polarised emission
WMAP 22.8 GHz

radio+X-rays

Zhang et al. 2024

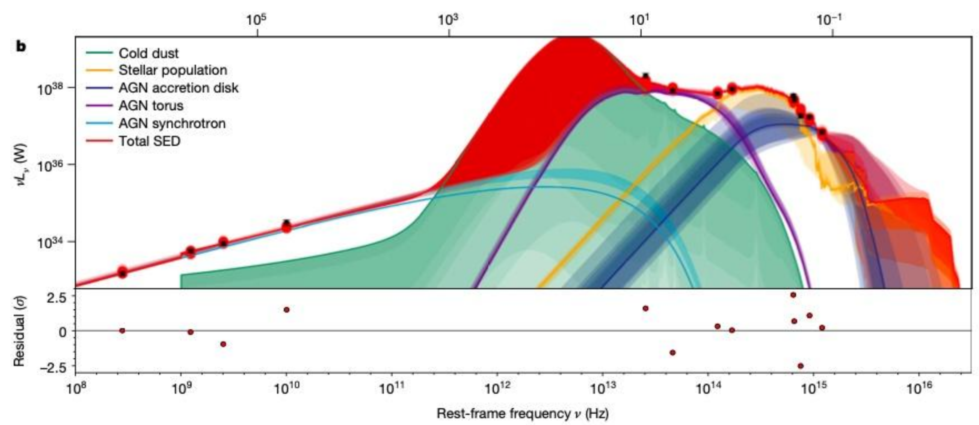
Jets on the scale of the cosmic web: Porphyrion (z = 0.896)





LOFAR
GMRT

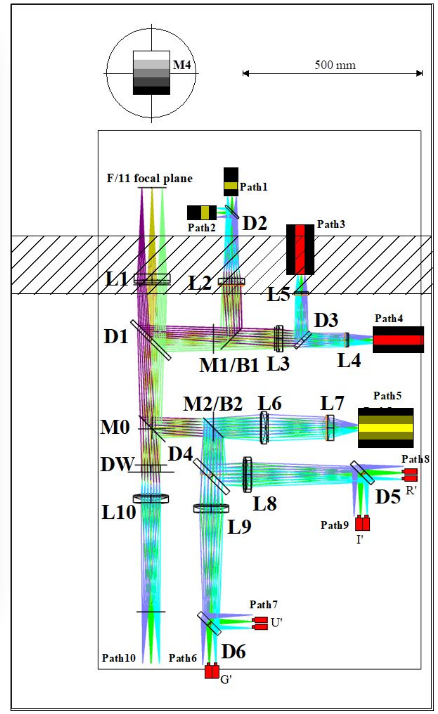
Oei et al. 2024

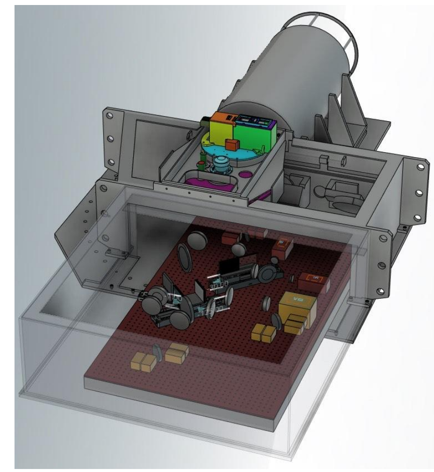


e-SiFAP: fast photopolarimetry in the optical/nIR bands

Filippo Ambrosino
INAF, OA Rome

TNG (ORM) same site as CTA North



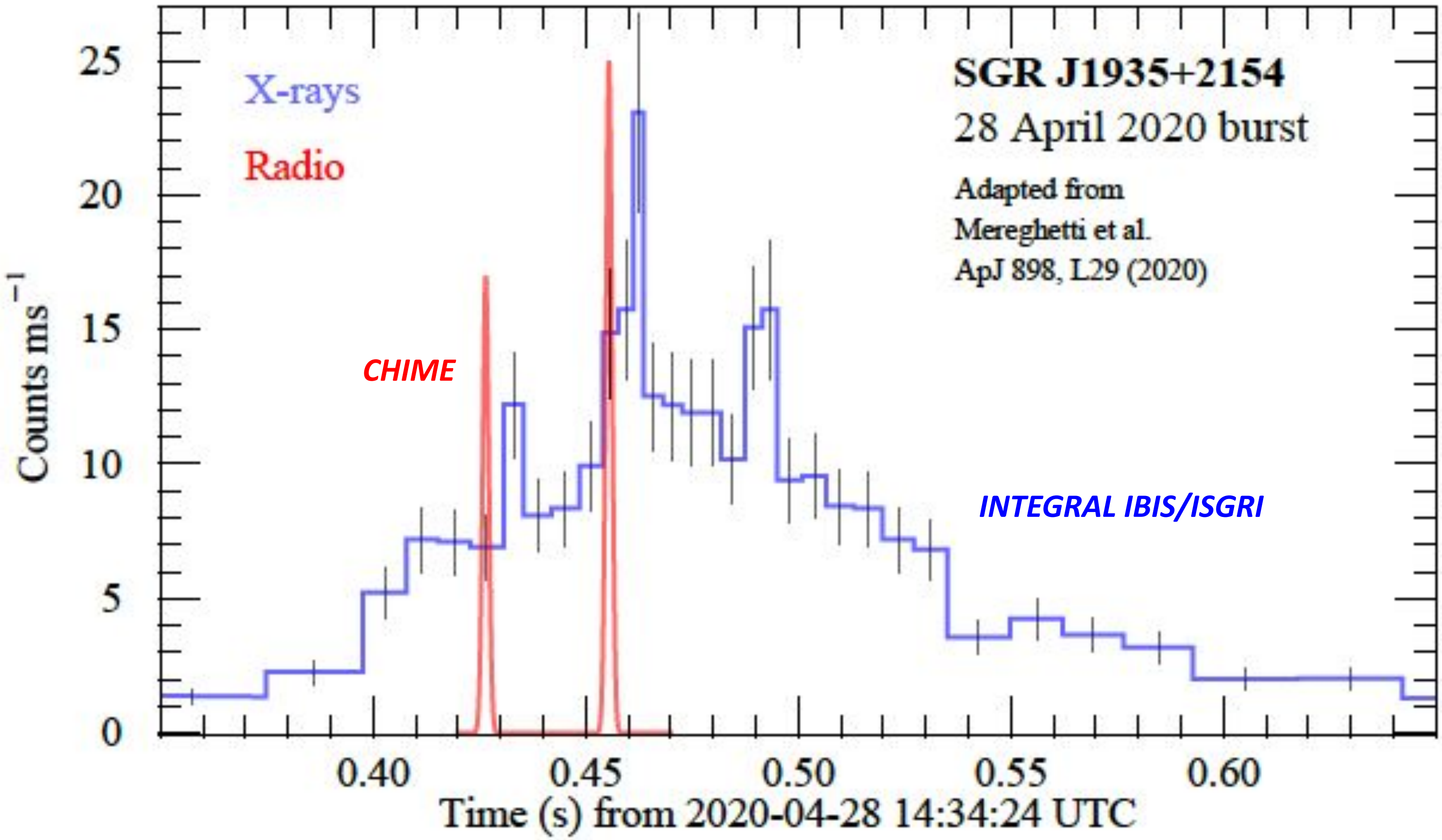


- ❑ **SiFAP2/4XP** heritage
- ❑ **Differential simultaneous** fast (< 1 μs) photometry in the optical/nIR bands
- ❑ Optical measurement of **linear polarisation**
- ❑ **Versatile** optomechanical **configuration** for TNG

⇒ Optical/NIR follow-up of CTA targets, multiwavelength campaigns on transients

e-SiFAP Science: magnetars and fast radio bursts

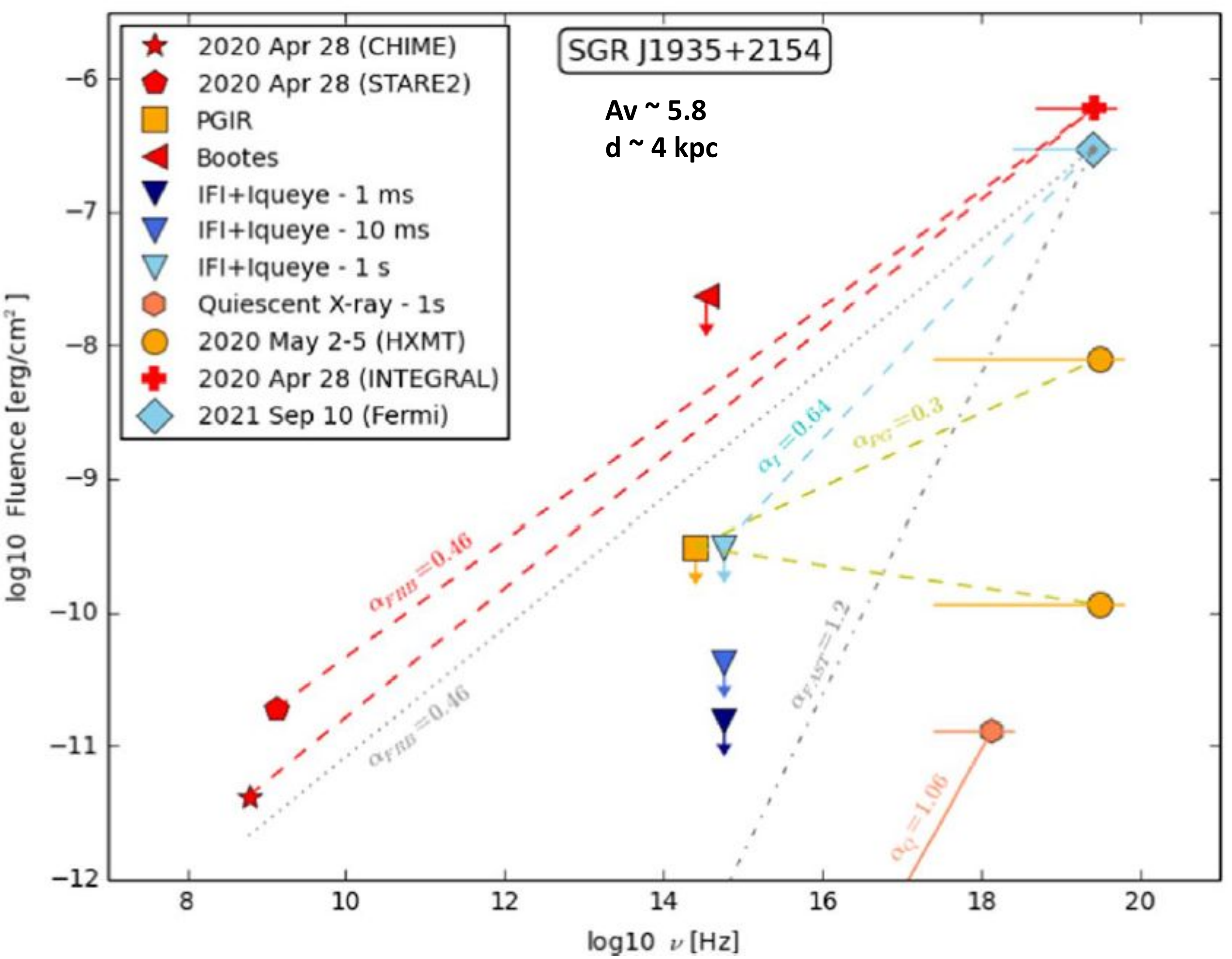
Over 1500 Fast radio bursts, millisecond flashes of GHz radiation (emitted energies of ~e40 erg), have been detected so far. They are extragalactic, but their optical/NIR counterparts are unknown. In April 2020 a Galactic FRB-analogue was detected also in hard X-rays from magnetar SGR J1935+2154

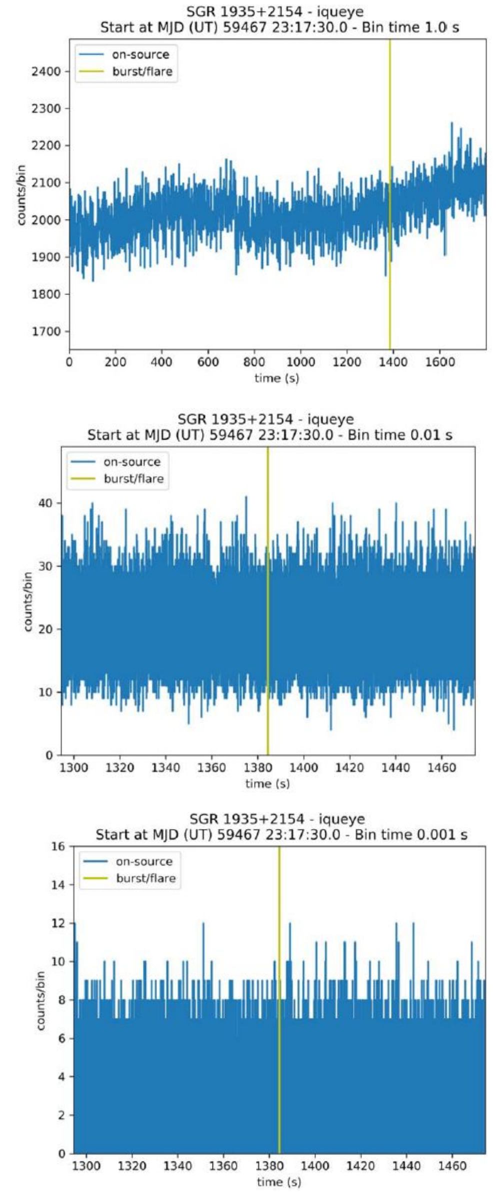


Mereghetti et al. 2020; Tavani et al. 2020; Ridnaia et al. 2020; Nicastro et al. 2021

e-SiFAP Science: magnetars and fast radio bursts

Search of variable optical counterpart of SGR J1935+2154 with 1.22 Asiago Telescope + Iqueye (time resolution down to ~1 ns) during the Fermi/GBM flare of September 2021

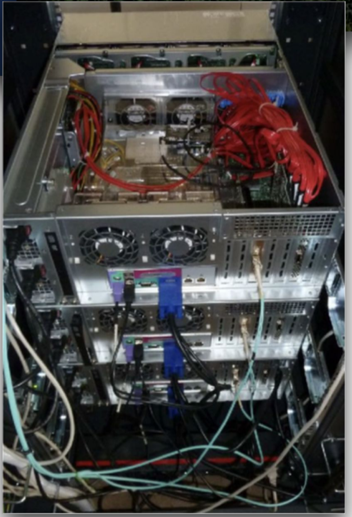




Zampieri et al. 2022

RadioFast VLBI

Marcello Giroletti
INAF, Inst. Radioastronomy

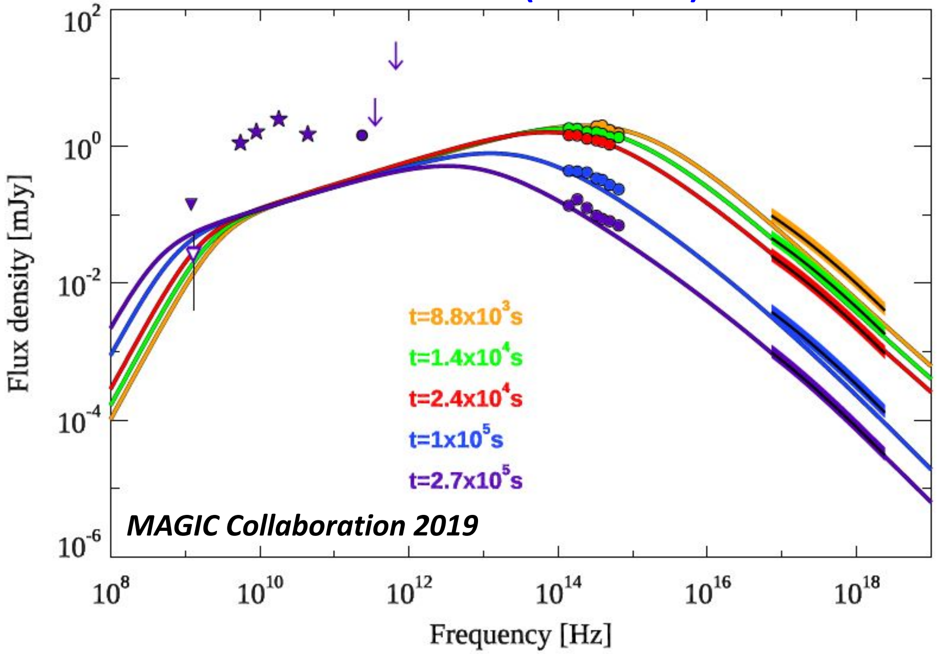


Sardinia, 64m, Medicina, 32m, Noto, 32m
Bologna, software correlator (DiFX)
Italian PNIR facility

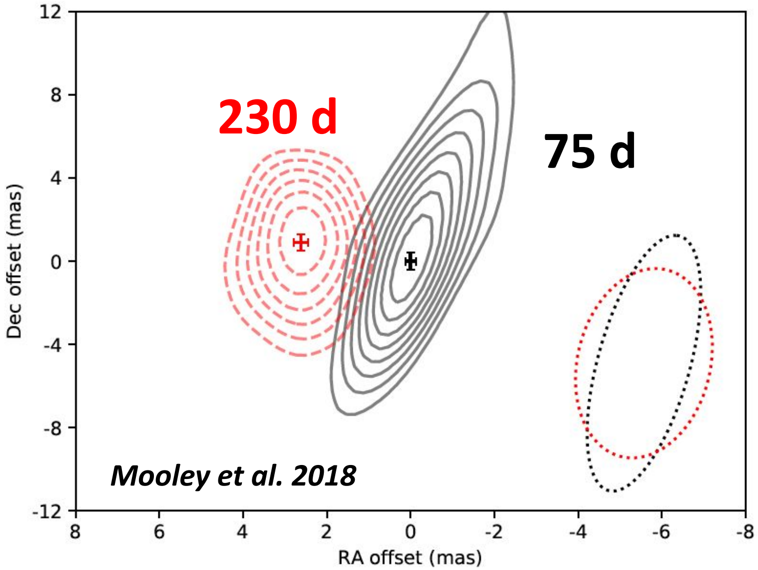
INAF collecting area: 4825 m^2
VLBA collecting area: 4909 m^2

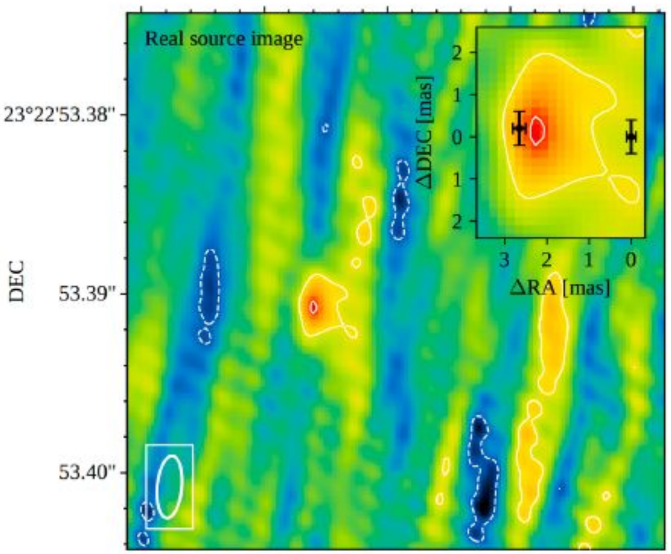
RadioFast VLBI Science

GRB190114C (z = 0.4245)



GRB170817A (40 Mpc), VLBI 4.5GHz





β_{app}~ 3-5

Angular size of source is less than 2 mas, suggesting relativistic jet rather than cocoon (opening angle ~ 3 deg, Eiso,core = 3 e52 erg, viewing angle ~15 deg, Ghirlanda et al. 2019, Science)

Stellar Intensity Interferometry

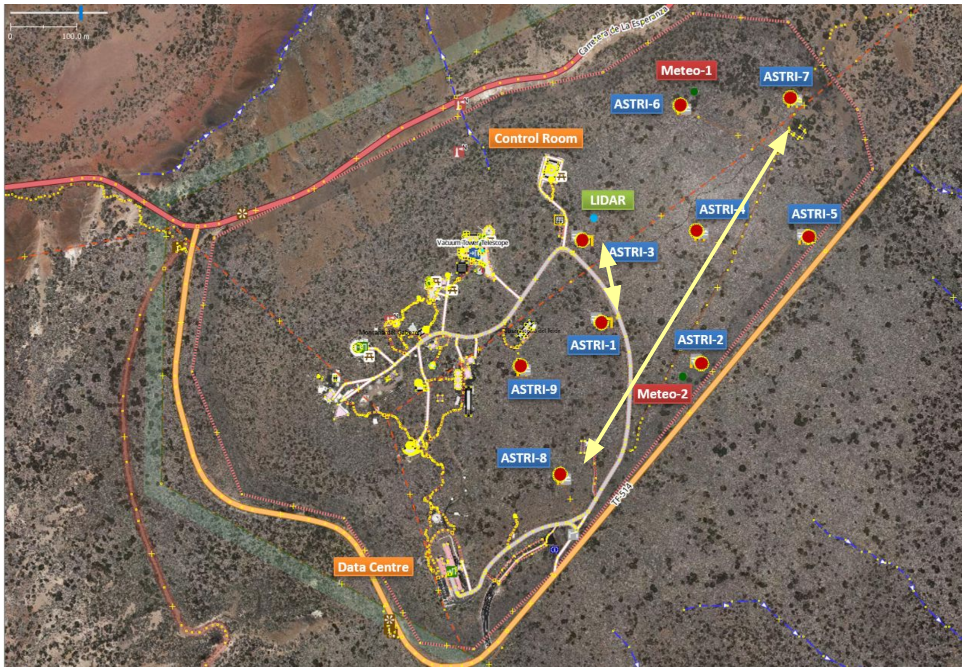
Image reconstruction is feasible from the *second-order* coherence of light, measured as the temporal correlations of arrival times between photons recorded in different telescopes (this is obviously different From classical phase interferometry).

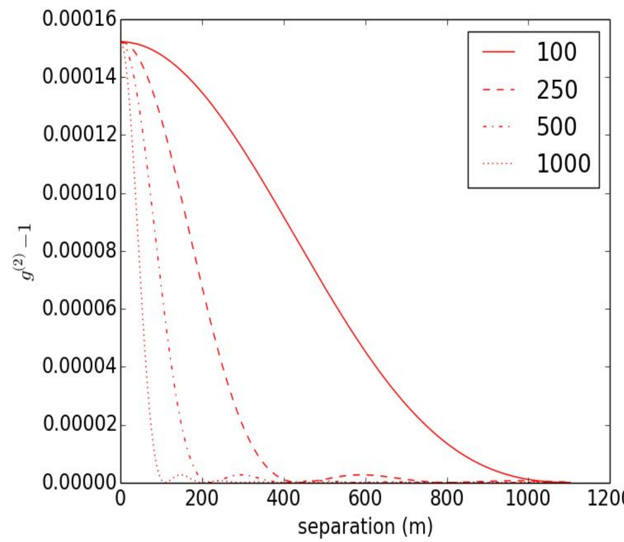
This technique connects telescopes only with electronic signals and is practically insensitive to atmospheric turbulence and to imperfections in telescope optics.

Hanbury Brown & Twiss 1956; Glauber 1963; Dravins et al. 2013; Abeysakara et al. 2020; Zampieri et al. 2022

Luca Zampieri
INAF, OA Padova

Stellar Intensity Interferometry prototyped on the ASTRI Mini-Array





Degree of coherence of a source with angular size **θ** (in μarcsec) as a function of the telescope separation **d**

The ASTRI Mini-Array (Canary Islands) provides a suitable infrastructure for prototyping SII instruments

Main goal: Achieving optical imaging with resolution of **~100 microarcseconds** using the **long multiple baselines (36)** of 9 SSTs

Stellar intensity interferometry Science

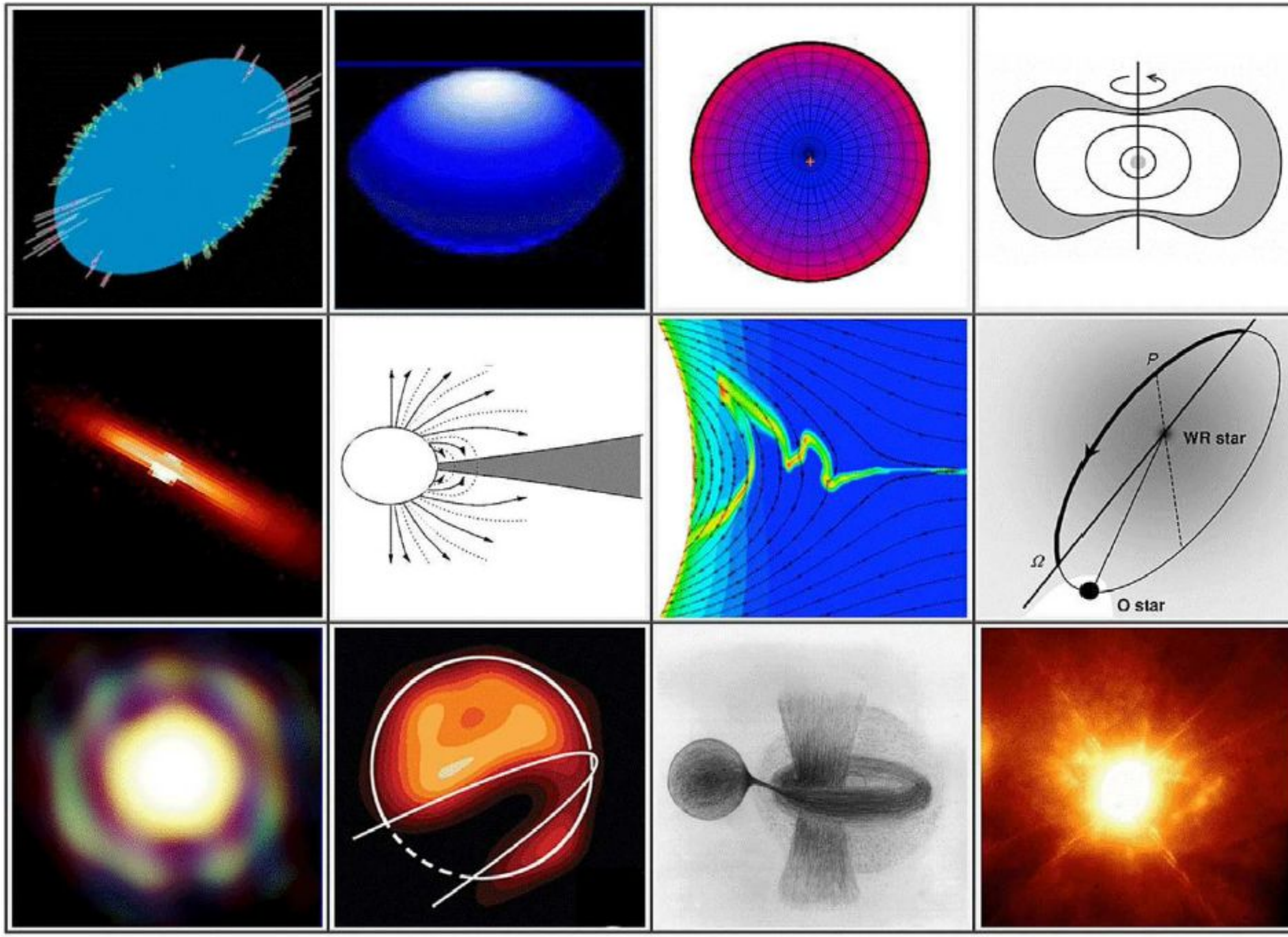


Fig. 10. Types of primary targets for kilometer-scale intensity interferometry. Top row: Stellar shapes and surfaces affected by rapid rotation – the measured shape of Achernar [20]; expected equatorial bulge and polar brightening of a very rapid rotator [113]; deduced surface brightness of the rapidly rotating star Vega, seen pole-on [95]; possible donut-shape for a rapidly and differentially rotating star [75]. Middle row: disks and winds – modeled interferometric image of the circumstellar disk of the Be-star ζ Tauri [10]; a magnetic stellar wind compresses a circumstellar disk [97]; simulation of how stronger magnetic fields distort wind outflow from hot stars [115]; the strongest stellar wind in a binary opens up cavities around the other star: the geometry around the Wolf–Rayet star γ^2 Velorum as deduced from interferometry [81]. Bottom row: stellar surroundings – interferometric image of the giant star T Leporis surrounded by its molecular shell [72]; an analogous image of the giant ϵ Aurigae, while partially obscured by a circumstellar disk [61]; artists view of the interacting β Lyrae system with a gas stream, accretion disk, jet-like structures and scattering halo [43]; an adaptive-optics, high-resolution image of the mysterious object η Carinae, the most luminous star known in the Galaxy [30].

Dravins et al. 2013

Conclusions

The 4 low-energy facilities in CTA+ cover critical and unique aspects of CTA science:

Polarization (VSTPol), expected to accompany most of non-thermal radiation from the compact sources that will be primary targets of CTA. The VST polarimeter will also guarantee a large sky area coverage. Correlated operations with IXPE, LSST, radio arrays, multi-messenger.

(ultra)-rapid optical photometry (eSiFAP), optimally suited to sample the smallest variation timescales from stellar-size compact sources, like GRBs, PSRs and the elusive FRBs

broad-band radio spectroscopy and VLBI correlation performance, intended to sample simultaneously the radio emission of a range of relativistic Galactic and extragalactic CTA targets and improve the Italian competition and performance in the VLBI network

Intensity Interferometry, aimed at developing, using a subset of the CTA experiment, a pioneering technique with critical impact on the study of stellar structure and evolution