Synergies with radio and the Square Kilometre Array Observatory

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Hands on the Extreme Universe with high energy gamma rays, Sesto, 21/7/2022

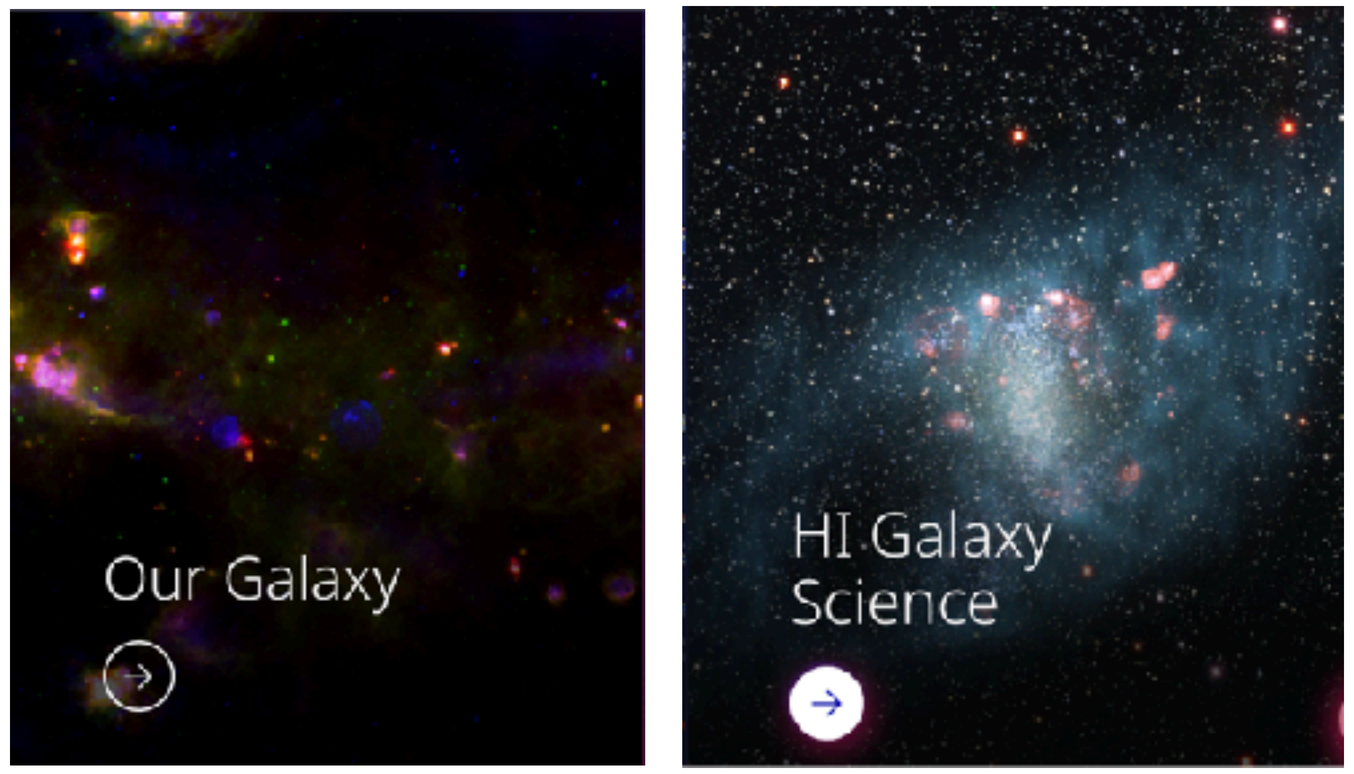
2 Synergies

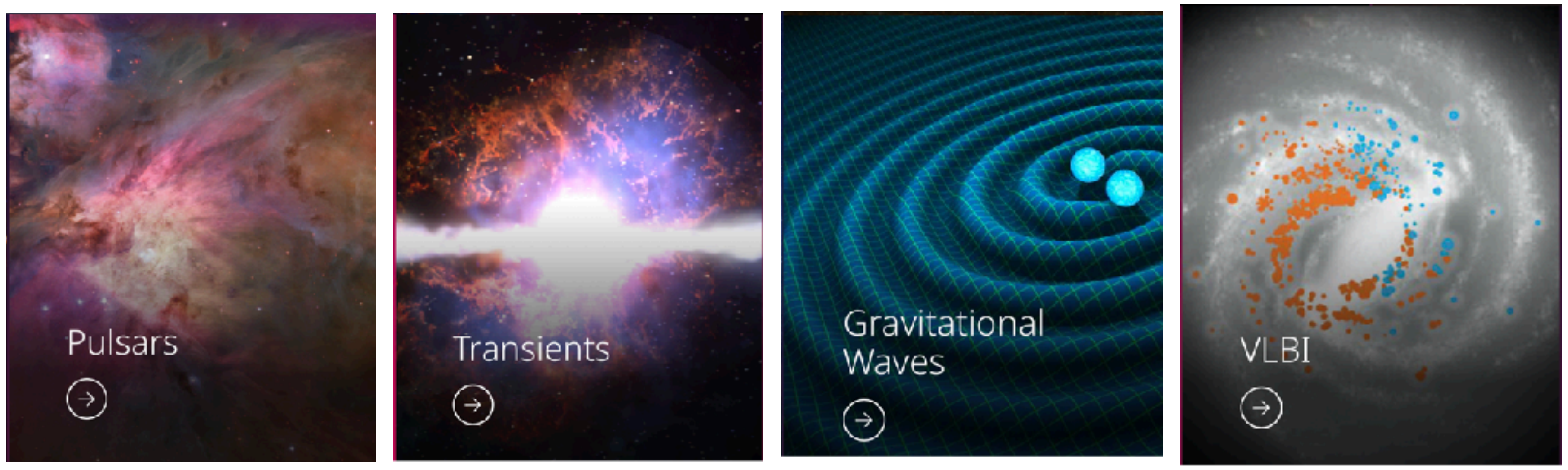
CTA will have important synergies with many of the new generation of astronomical and astroparticle observatories. As the flagship VHE gamma-ray observatory for the coming decades, CTA plays a similar role in the VHE waveband as the SKA in radio, ALMA at millimetre, or E-ELT/TMT/GMT in the optical wavebands, providing excellent sensitivity and resolution compared to prior facilities. At the same time, the scientific output of CTA will be enhanced by the additional capabilities provided by these instruments (and vice-versa). Multi-wavelength (MWL) and multi-messenger (MM) studies using CTA provide added value to the science cases in two main ways:

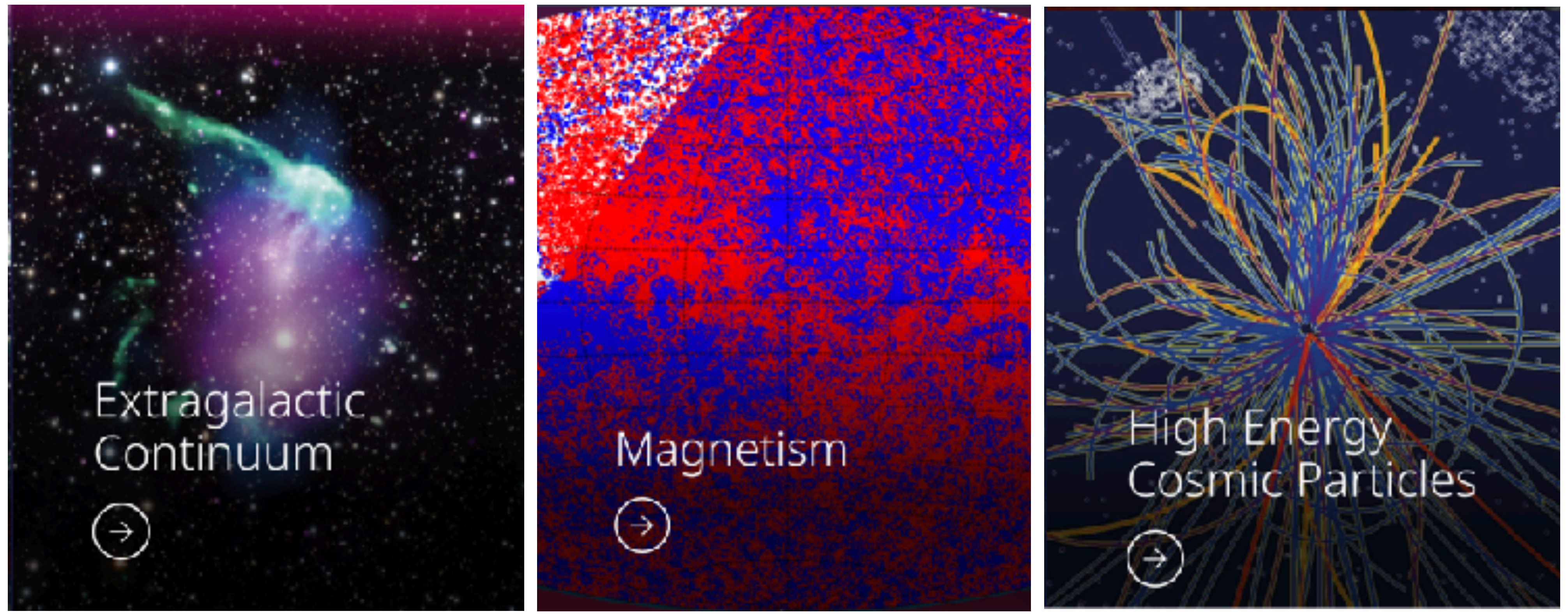
- Non-thermal emission
  - origin of cosmic rays and extreme conditions
  - time-variable emission: simultaneous observations
- Source properties
  - nature of gamma-ray sources (object class, environmental conditions)

Science with the CTAO

- Chapters (KSP) explicitly mentioning the SKA:
  - #7: Large Magellanic Cloud survey
  - #9: Transients
  - #11: Star Forming Systems
  - #12: Active Galactic Nuclei
  - #13: Clusters of Galaxies
- Radio observations cited throughout







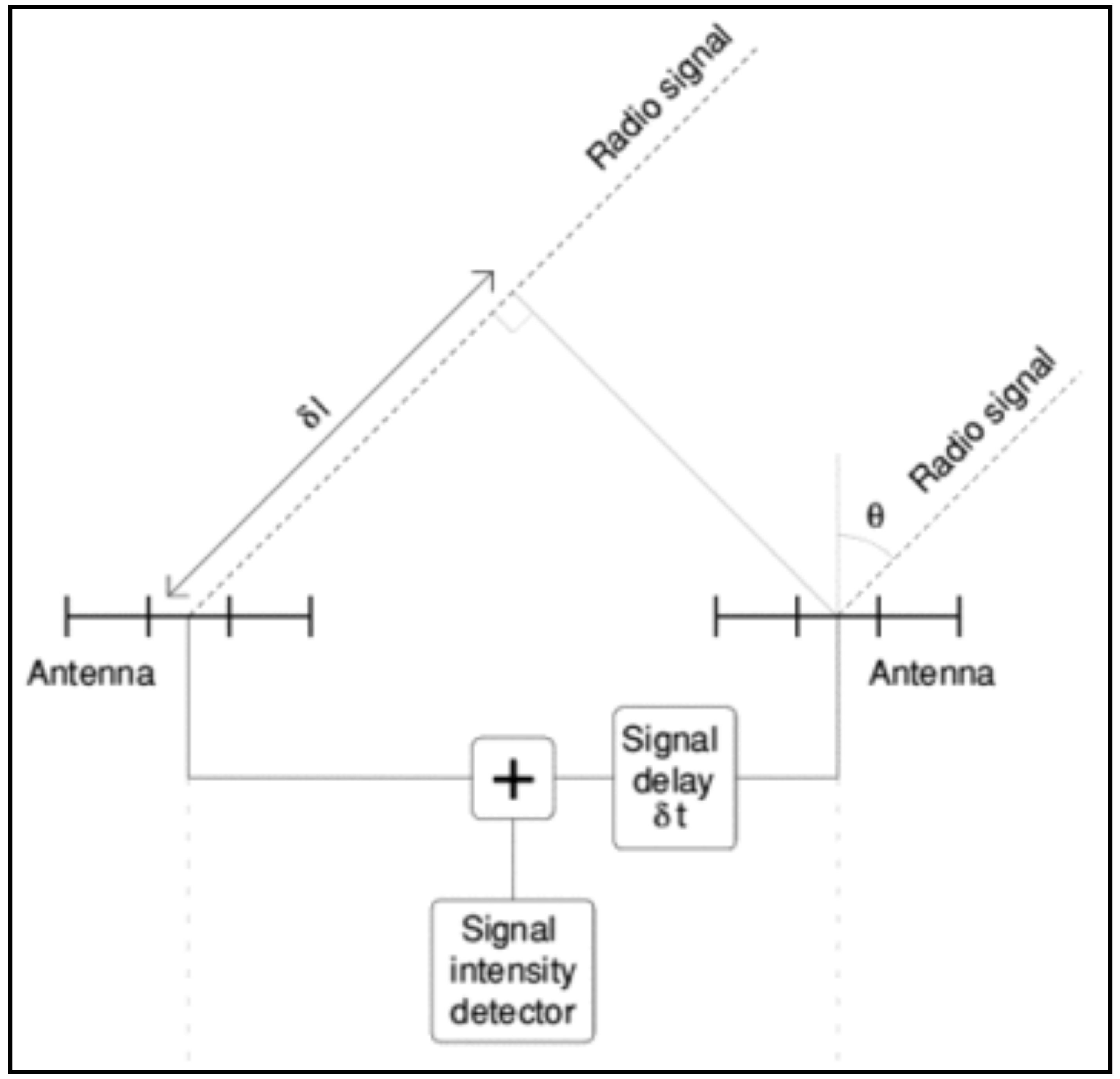
(some) SKAO science working/focus groups

Radio astronomy in a nutshell

- Wavelength range ~10-10^{-3} m; frequency range ~0.01-100 GHz
- Emission processes: thermal, spectral lines, non-thermal (synchrotron)
- Astrophysical sources: radio galaxies, quasars/blazars, supernovae, binaries, novae, pulsars, FRBs, GRB afterglows

Radio *arrays*

- For single dish, angular resolution $\theta \sim \lambda/d$ is limited by λ (~arcmin even with d=100m)
- Interferometry can synthesise a much larger aperture, where $\theta \sim \lambda/B$, with B=separation between interferometer elements
- adding more telescopes (realising $N(N-1)/2$ pairs) and exploiting Earth rotation, rich spatial information can be reconstructed (also helping sensitivity)



- VLBI (*Very Long Baseline Interferometry*) reaches up to B~10000km (and longer with satellites!), and $\theta < 1$ mas

Current arrays and SKA precursors

Connected arrays

LOFAR (LOw Frequency ARray)

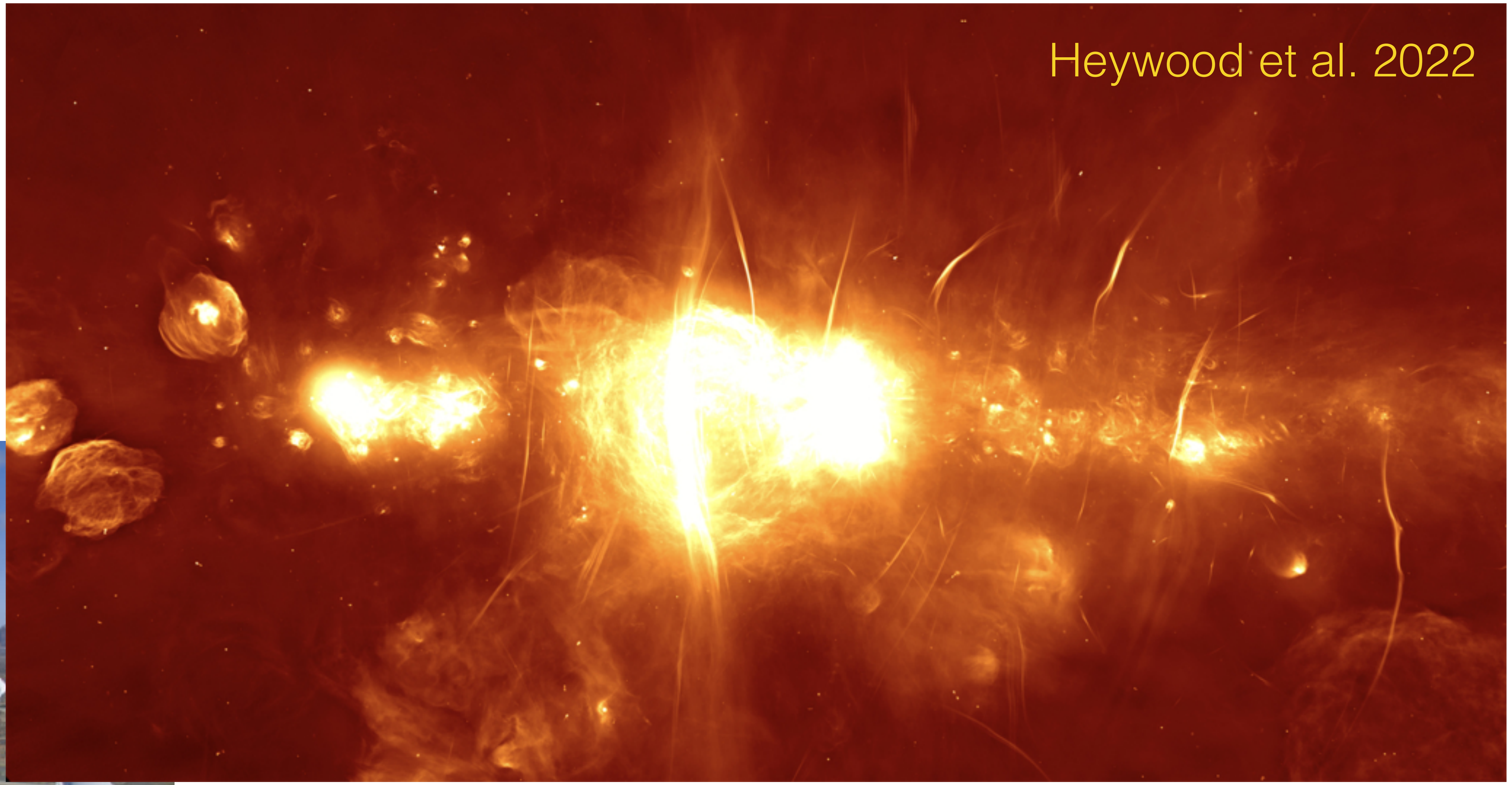
VLA (Very Large Array)

ALMA (Atacama Large Millimeter Array)

	LOFAR	VLA	ALMA
Location	The Netherlands	USA (New Mexico)	Chile (Atacama)
Start of operation	2012	1979 (major upgrade in 2011)	2011
Frequency range	10-240 MHz	70 MHz - 50 GHz	30-1000 GHz
Angular resolution	arcsec to degrees	up to 0.1 arcsec	up to 0.01 arcsec

MeerKAT

- 64x16m dishes, 1-1.75 GHz
- 4km radius
- pulsars, HI, transients, large scale structures, and more…



- First light image in 2016
- Now open for regular proposals
- Will become part of SKA1-MID

Very Long Baseline Interferometers

- EVN: the European VLBI Network, a SKA pathfinder
  - a VLBI consortium of independently built and operated radio telescopes in Europe, extending to Asia, Africa, America
  - Includes some of the largest apertures in the world (Effelsberg, Lovell, Sardinia, Tianma); yet only ~0.03 km^{-2}
  - Development to transmit data with fast optical fibre links and correlating in real time
- VLBA: Very Long Baseline Array
  - 10 stations across the US, continuous operation 24/7
- Other arrays: LBA (Australia), EAVN (East Asia), EHT (Event Horizon Telescope, mm)

SKA Observatory

8 member countries, 8 observers, and 8 African partner countries for future expansion.

Collaboration with major facilities/observatories, including CTAO

member countries

observers

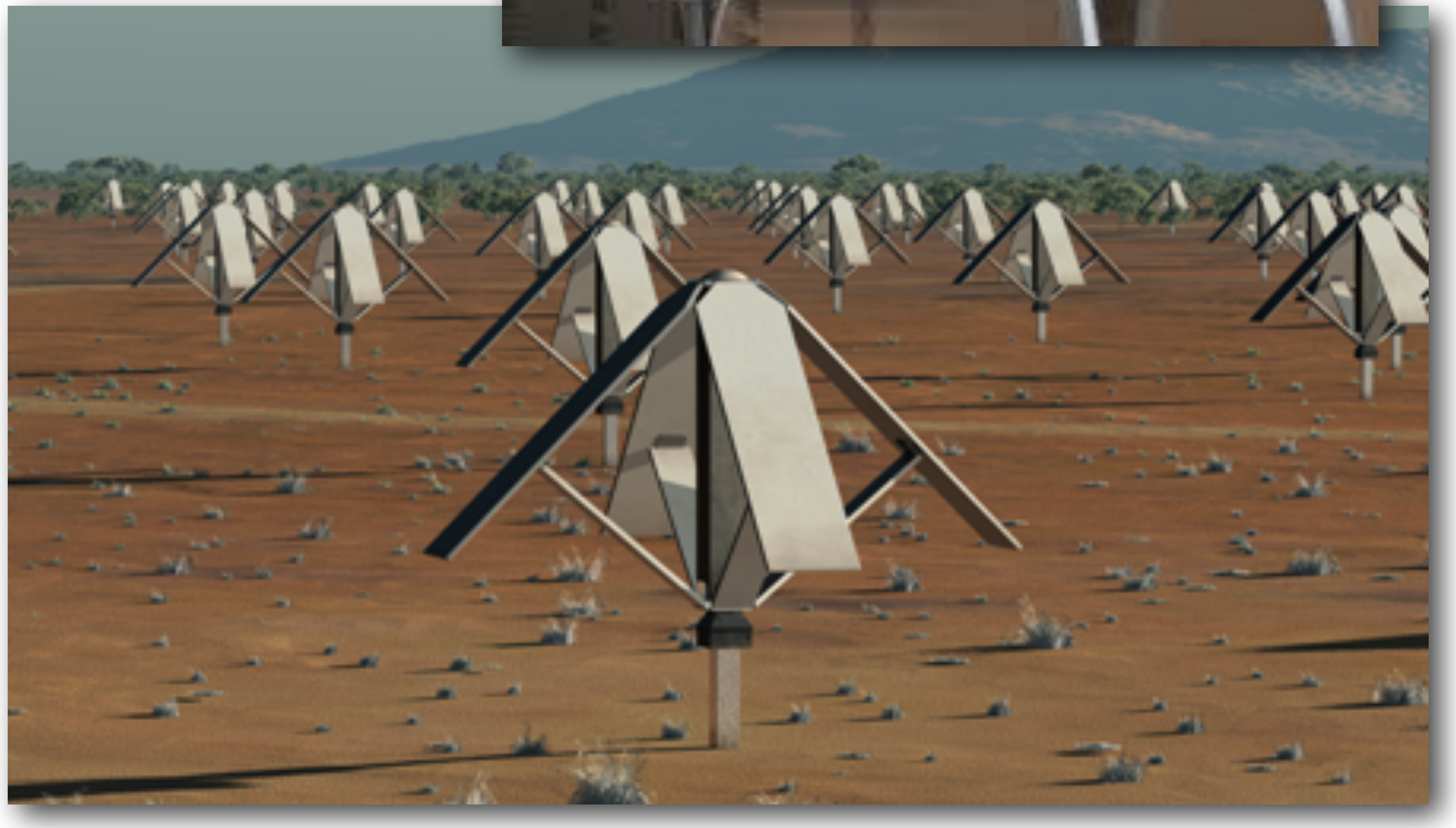
from https://www.skao.int/ (new website!)

SKA design

- 2 phases
  - SKA1: construction 2021-2026
  - SKA2: detailed design in late 2020's
- SKA1: dual site, dual scope (frequency & design)
  - **SKA1-low: Australia, dipoles, <0.3 GHz**
  - **SKA1-mid: South Africa, dishes, >0.3 GHz**

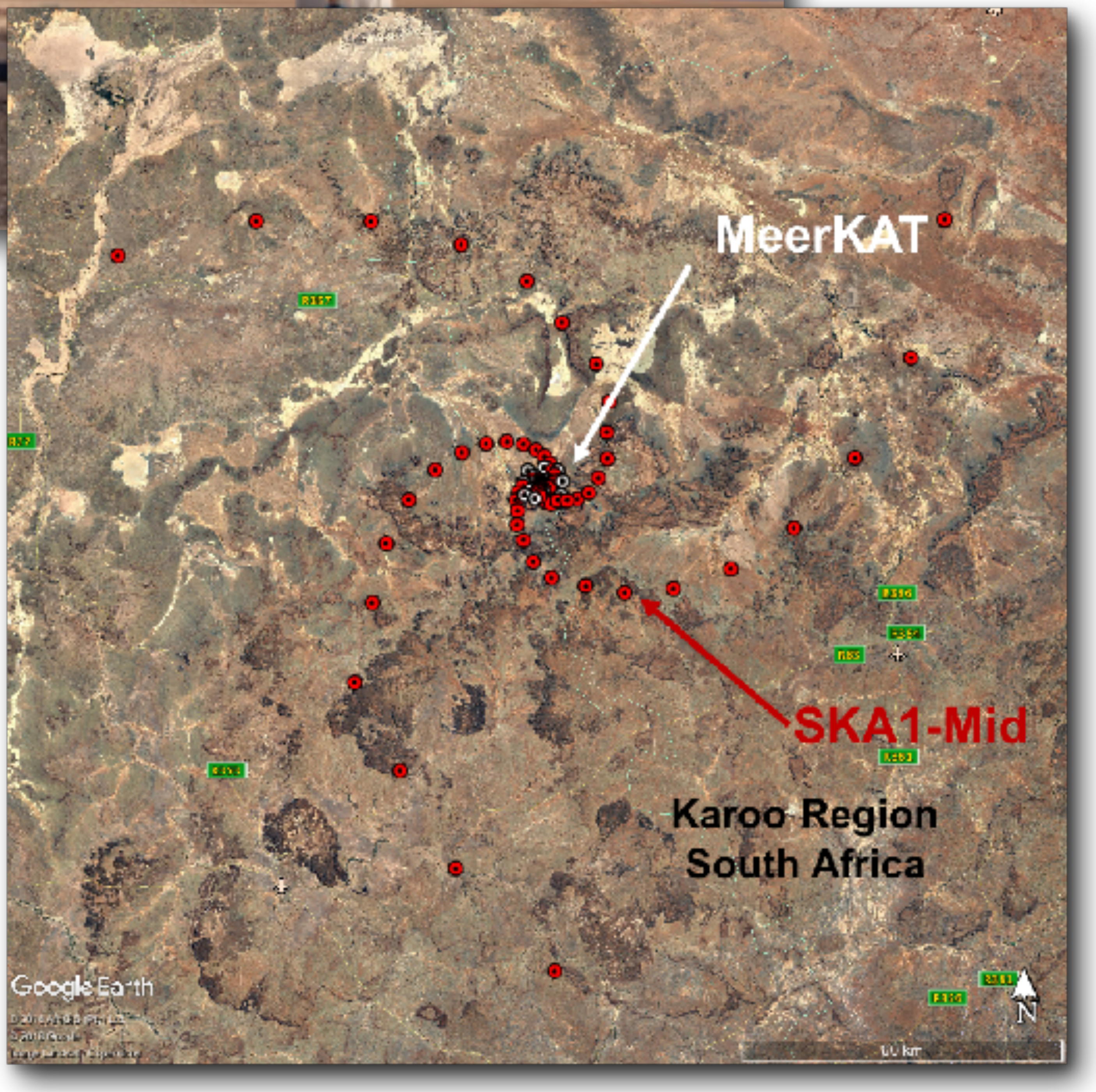
SKA1-low

- Location: Australia
- Main driver: **highly redshifted 21 cm HI line** from the Epoch of Reionisation and earlier
    - pulsars, magnetised plasma, extrasolar planets
- **131,072 dipoles**, grouped in stations
- **50-350 MHz**
- 50% of the stations within ~1 km radius core
- remaining distributed up to 70 km maximum baseline
- 20 deg^2 field of view



SKA1-mid

- Location: South Africa
- Drivers: **pulsars**, nearby to mid-z **HI line**, high sensitivity **continuum** sources
- **133x15m** SKA dishes and **64x13.5m** MeerKAT dishes
- **0.35-1.76 GHz & 4.5-15.3 GHz**; ready for additional receivers
- ~150 km maximum baseline <u>and</u> VLBI capable



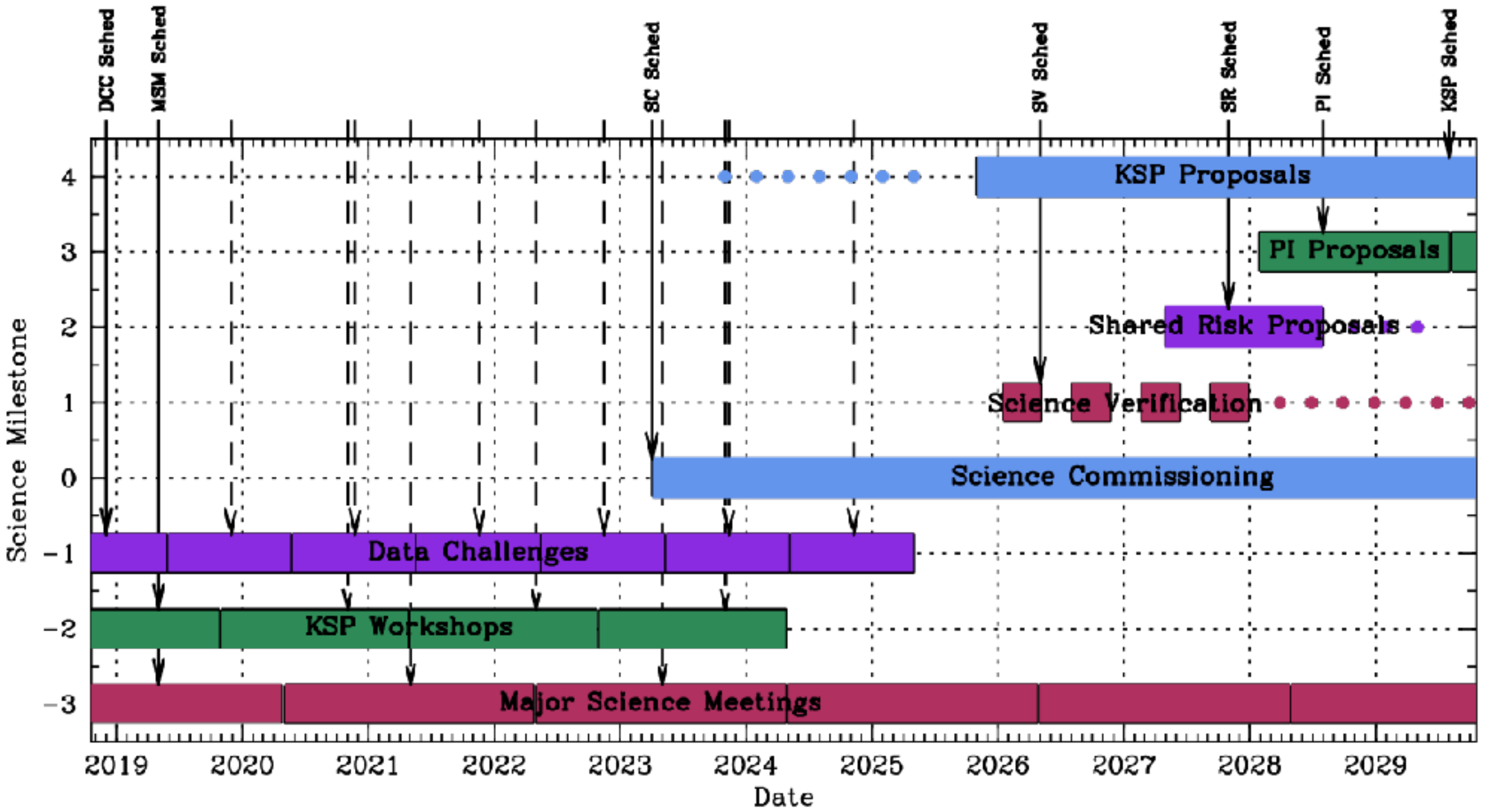
SKA2 - early view

- 4-10 x SKA1 sensitivity in the frequency range of 50–350 MHz
- 10 x SKA1 sensitivity in the frequency range of 350 MHz–24 GHz (including deployment of all five frequency bands)
- 50% of the “natural” sensitivity of the facility over a wide range of beam size
- 20 x SKA1 Field-of-View in the frequency range of 350 MHz–1.5 GHz
- 20 x SKA1 maximum angular resolution in the frequency range of 50 MHz–24 GHz

Array Assembly Key Information

Name	Low Stations	Date for Low	Mid Dishes (SKA+MeerKAT)	Date for Mid
AA1	18	C0+35	8+0	C0+34
AA2	64	C0+47	64+0	C0+44
AA3	256	C0+58	120+8	C0+58
AA4	512	C0+70	133+64	C0+67

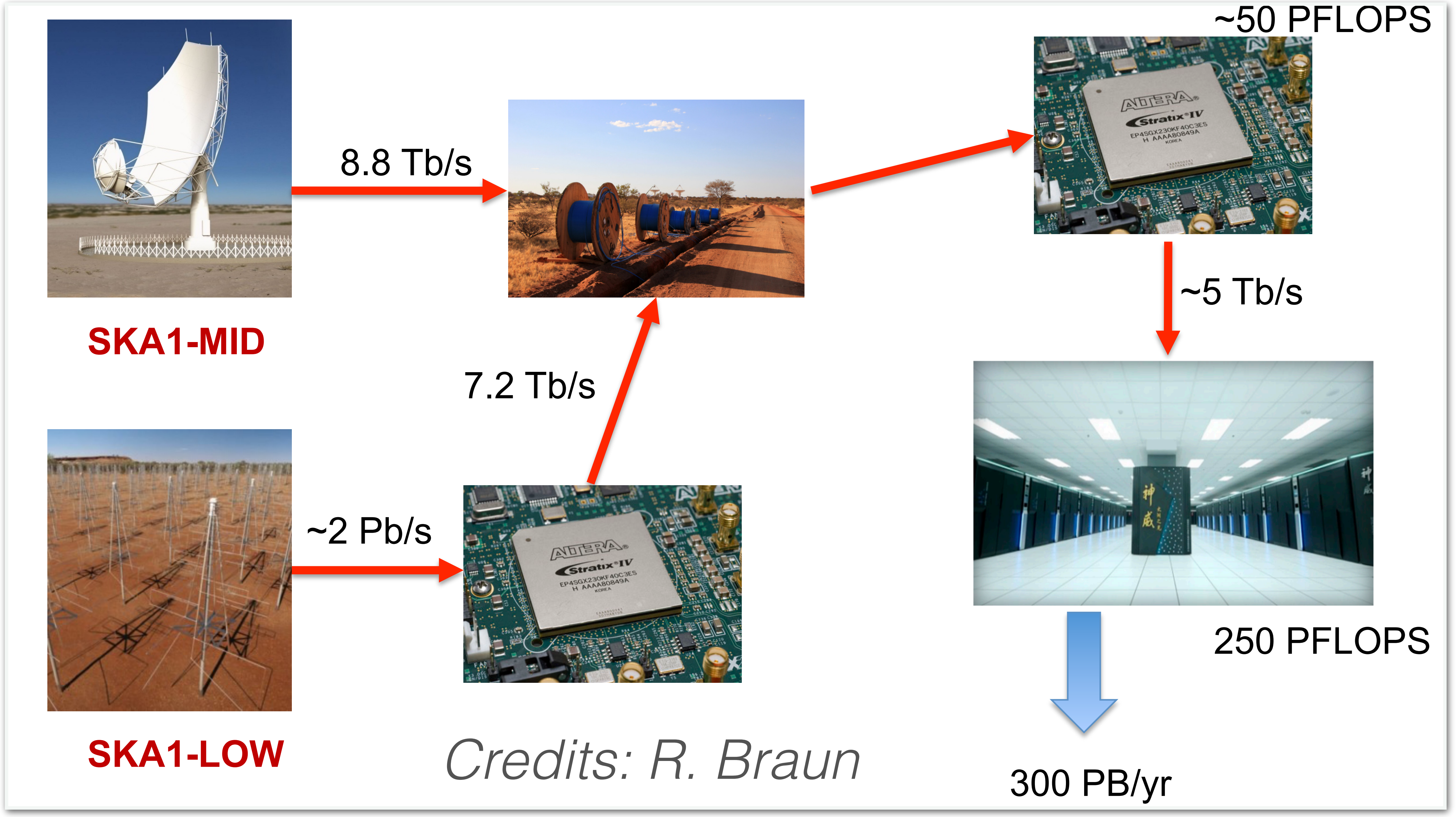
C0="construction start"=1 July 2021



- Key Science Projects (KSP): over many cycles, process starting early and completion about 24 months after AA4
- PI Science: 12 months after AA4
- "Shared risk" PI Science: 3 months after AA4
- Science Verification (SV): 9 months after AA2, with "Call for suggestions"

SKAO-CTAO similarities

- International projects involving large teams of scientists and engineers
- Order of magnitude improvement with respect to existing instrumentation
- Big (huge!) computational challenges: data rates, analysis, storage
- Dual site projects



SKAO-CTAO differences

- SKA sites are both in the southern hemisphere (ngVLA, LOFAR, VLBI will play important roles in the northern hemisphere) & SKA sites have completely different designs from each other
- Traditional (~century) radio astronomy features: high duty cycle, great sensitivity, many sources, spectral lines, wide field of view and large survey speed
- For many classes, CTA will allow study of individual cases at extreme energies, SKA will perform population studies: complementary approach and plenty of room for synergy

A rich radio Universe

- More mature technology (around for a century, and useful for telecommunication)
- Lower energy photons
- Various types of radio emission:
  - thermal (free-free)
  - non-thermal (synchrotron: relativistic particles in magnetic fields)
  - coherent emission (eg pulsars)
  - spectral lines (redshifted)

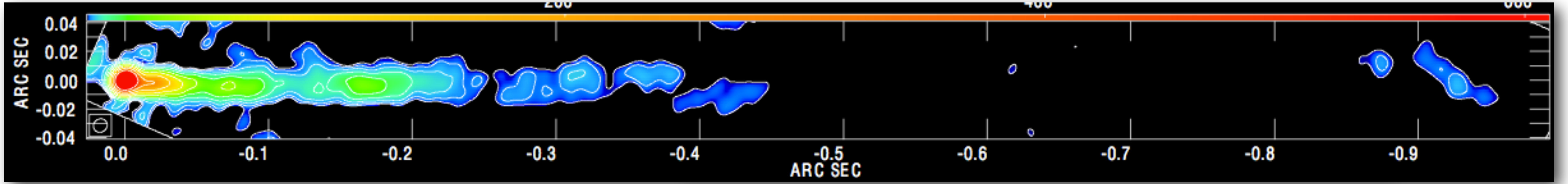
CTA-SKA synergies

- Main areas of synergy with CTA:
  - cosmic rays - eg in supernova remnants
  - astroparticle physics - neutrinos from blazars, dark matter from gamma rays, dark energy and cosmology from matter dipole etc.
  - star formation history - continuum emission in radio and EBL absorption in VHE gamma rays
  - particle acceleration, primarily in blazars but also other extragalactic and galactic jets (GRBs, radio galaxies, binaries, etc.), galaxy clusters, etc.

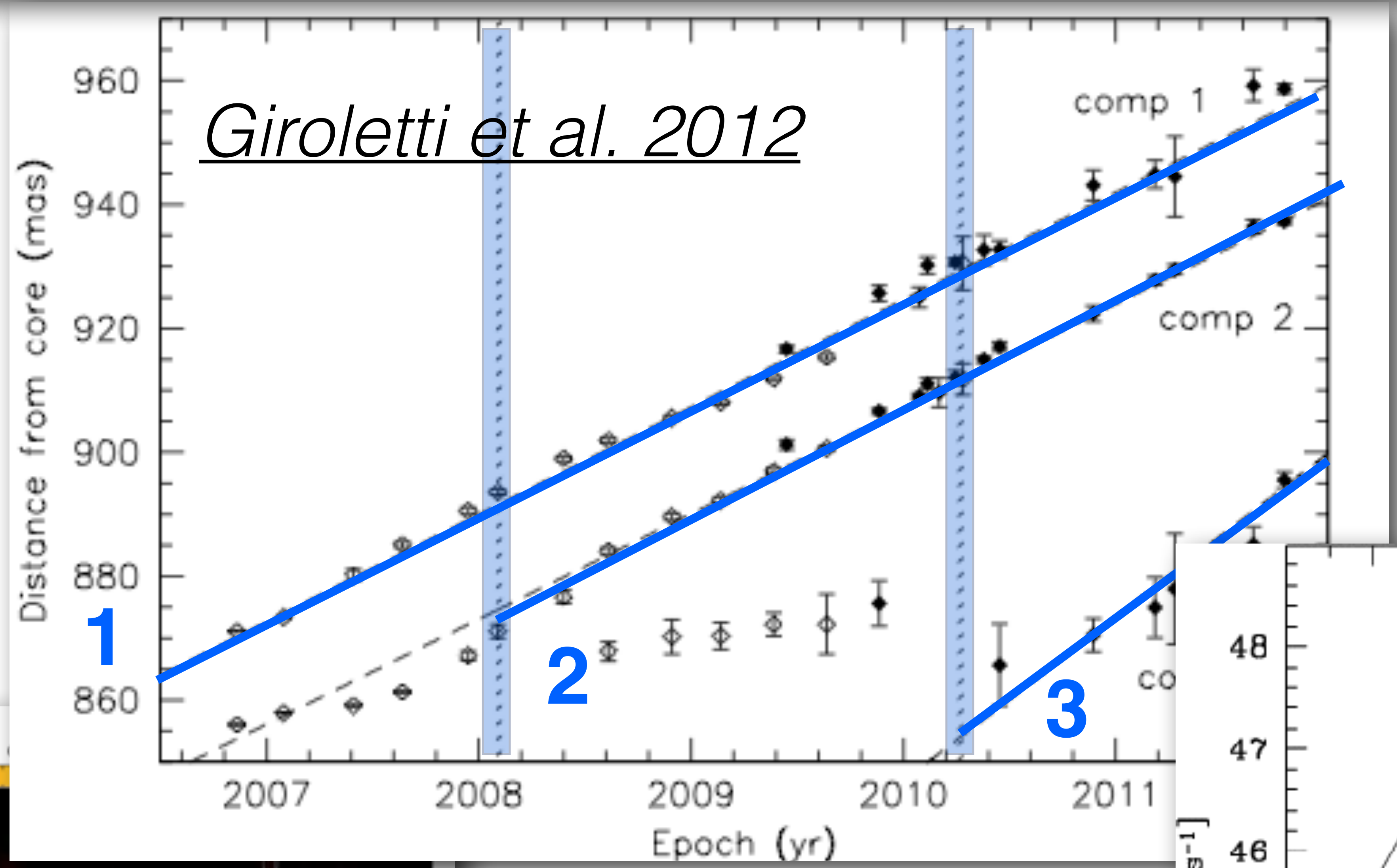
Synergies with SKAO as a stand-alone observatory

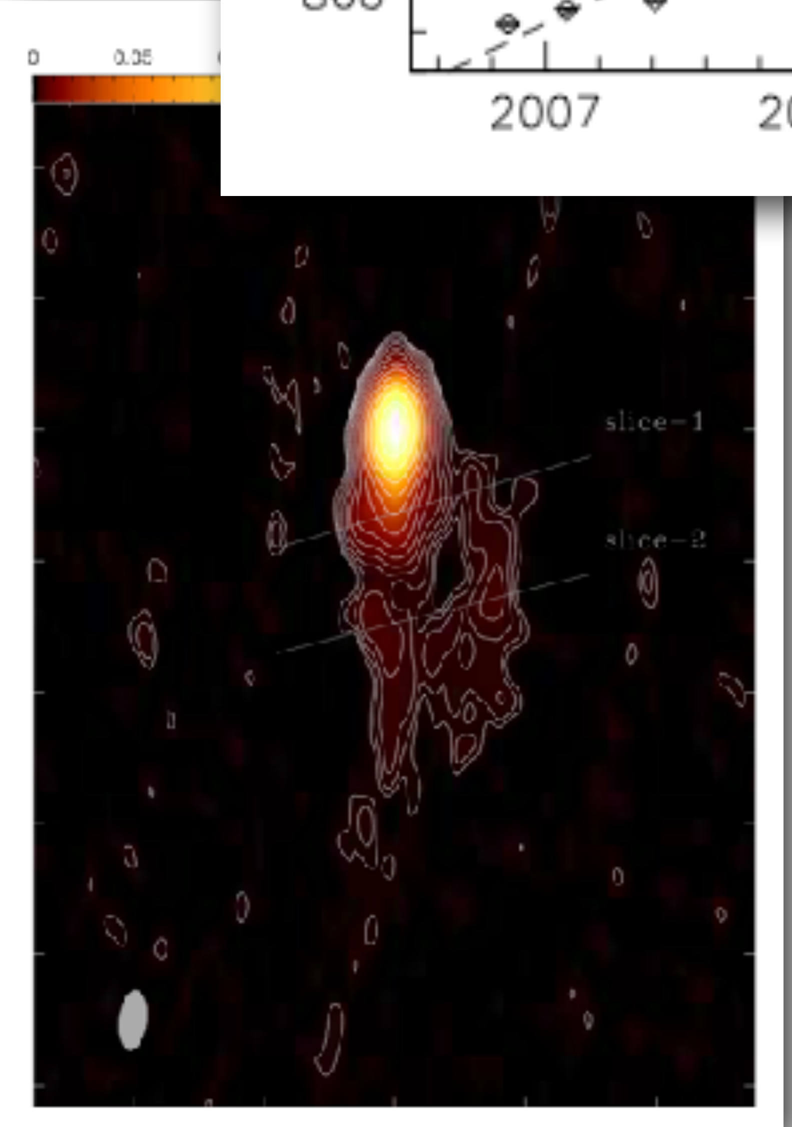
- analysis of the dust and synchrotron polarized emission from the LMC
- map the three-dimensional neutral gas distribution of our Galaxy with unmatched spatial and velocity resolution and will cover the Galactic stellar clusters and star-forming regions discussed in the Star-forming system CTA KSP
- determine magnetic fields in clusters and narrow-down parameter space for emission mechanism and dark matter content
- discover (e.g. FRB) and follow-up (e.g. GRB afterglows, TDEs) transients

High angular resolution synergies - AGNs

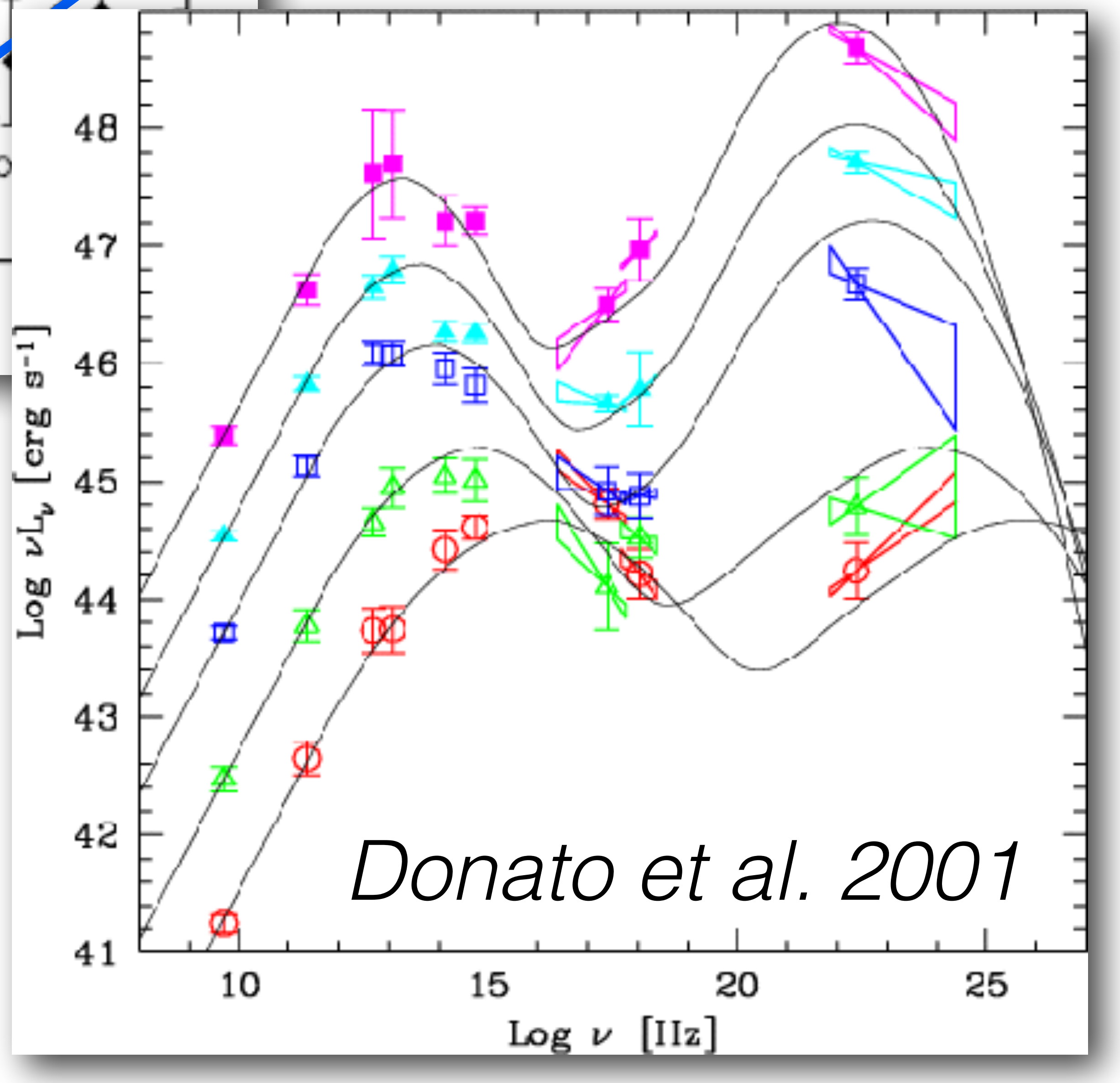


- Radio galaxies (M87 location of gamma-ray emission)
- Blazars, especially extreme/hard (faint in radio)
- Polarization, core-shift magnetic fields independent of SED
  - Neutrino connection





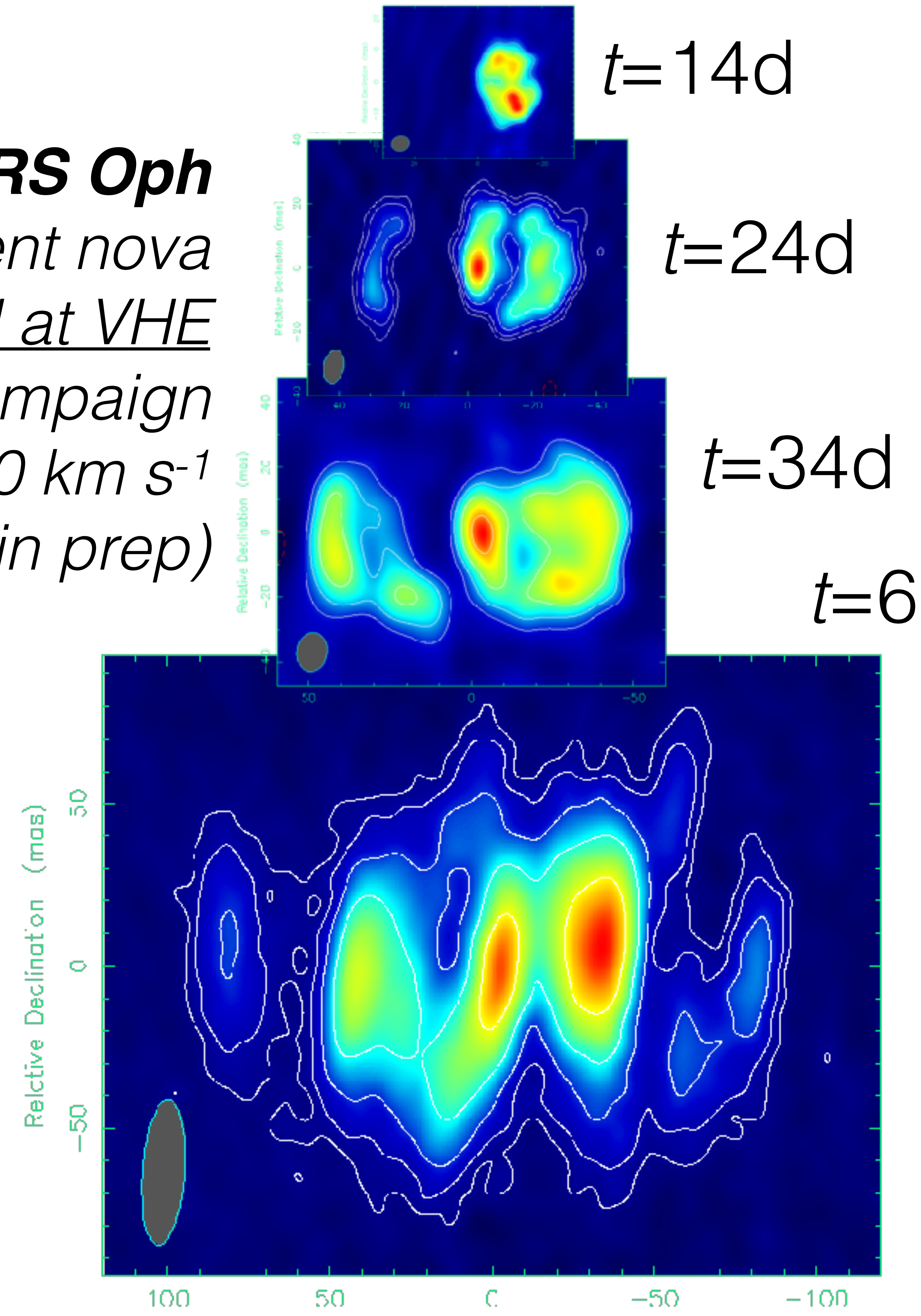
TXS 0506+056
Ros et al. 2020
Li et al. 2021
Nanci et al. 2022

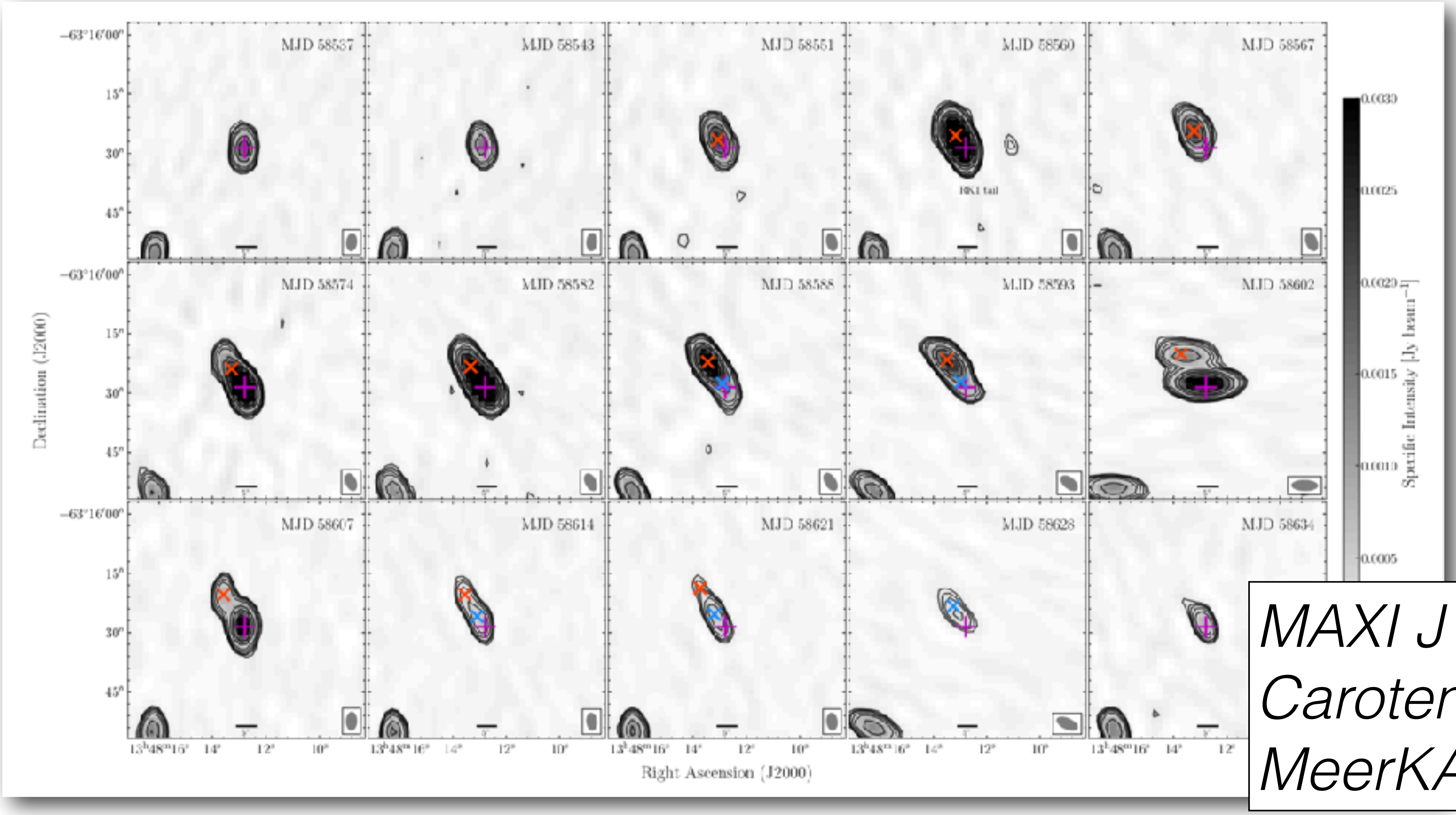


High angular resolution synergies - binaries

- microquasars
- novae
- (both also as connected interferometer)

RS Oph
2021 Aug 8th recurrent nova
first nova detected at VHE
EVN+e-MERLIN campaign
v~4000 km s^{-1}
(Giroletti et al. in prep)

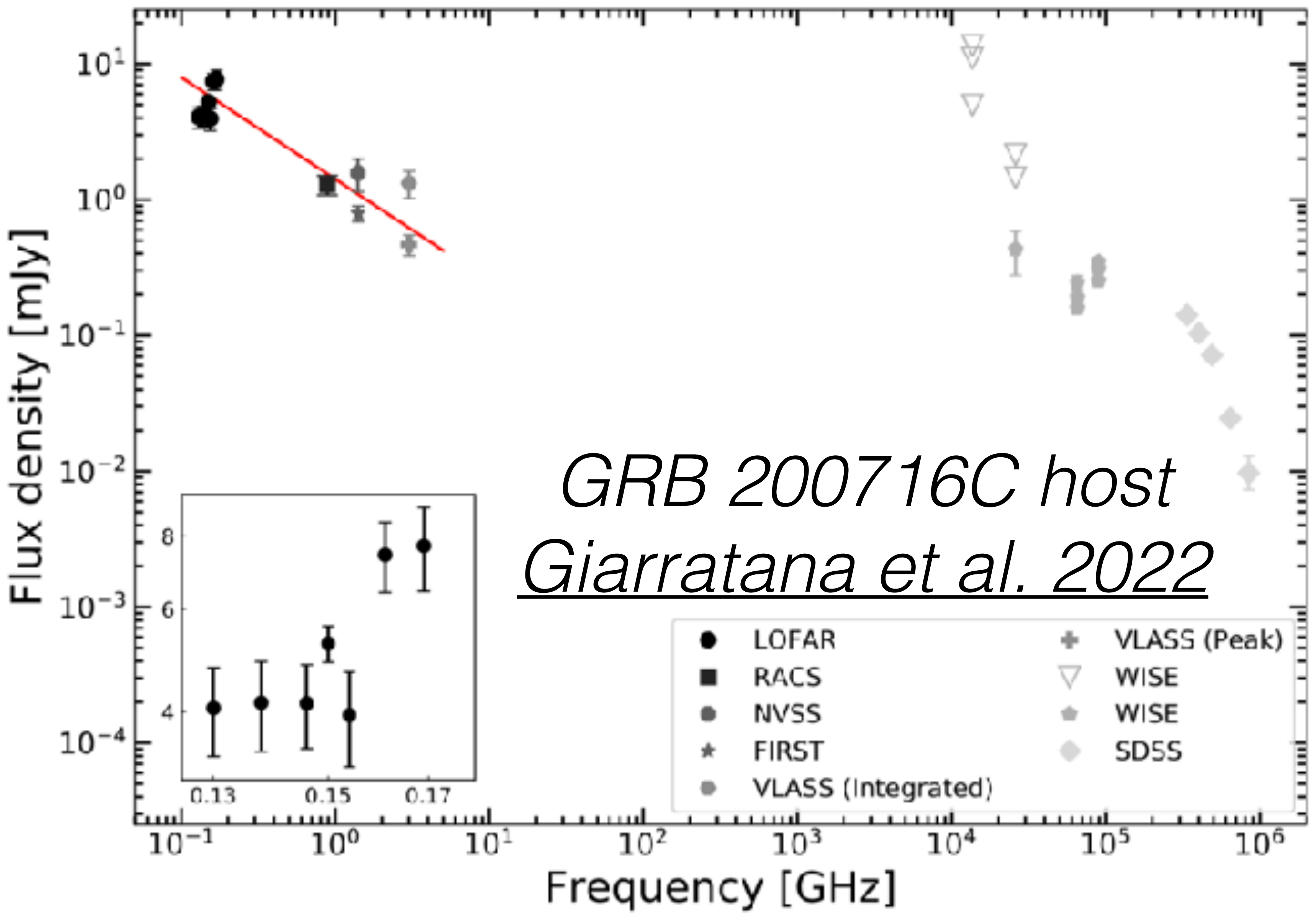




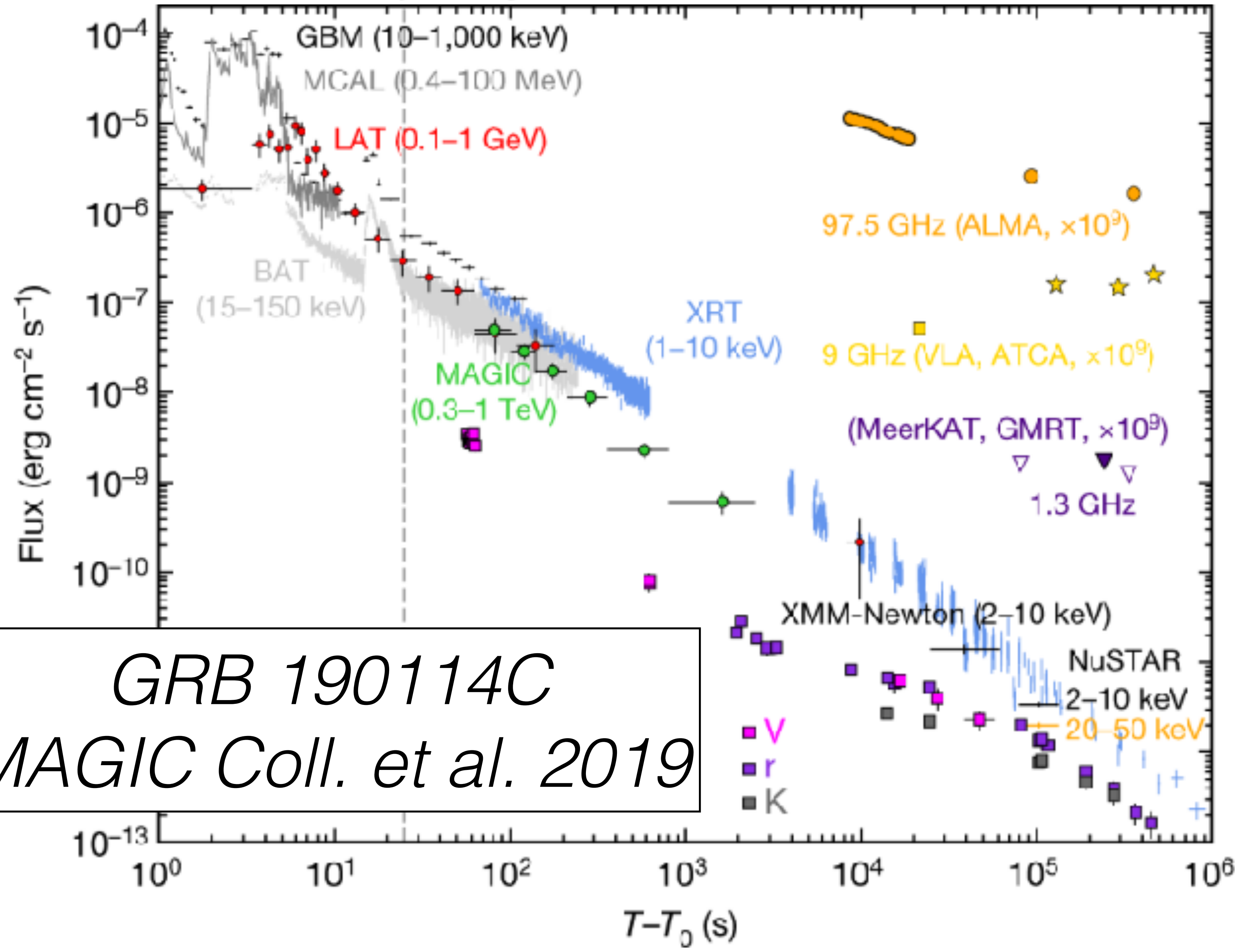
MAXI J1348–630
Carotenuto et al. 2021
MeerKAT monitoring

High angular resolution synergies - GRBs

- connected interferometer for light curves; orphan afterglow searches; characterisation of hosts & progenitors
- GRBs: SKA1 can detect and monitor the light curve and spectra of many afterglows
- detailed understanding of any CTA detected GRB (just a handful so far!)
- population study, including off-axis afterglows



GRB 200716C host
Giarratana et al. 2022

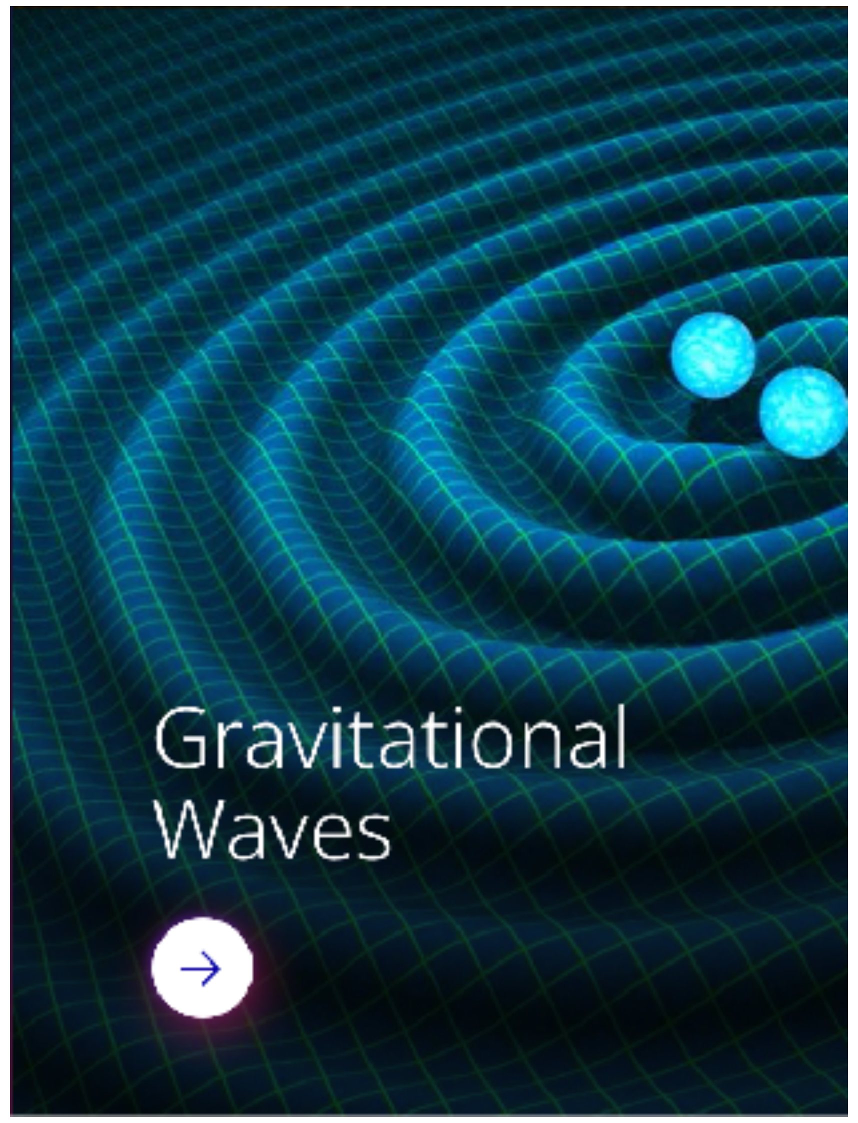


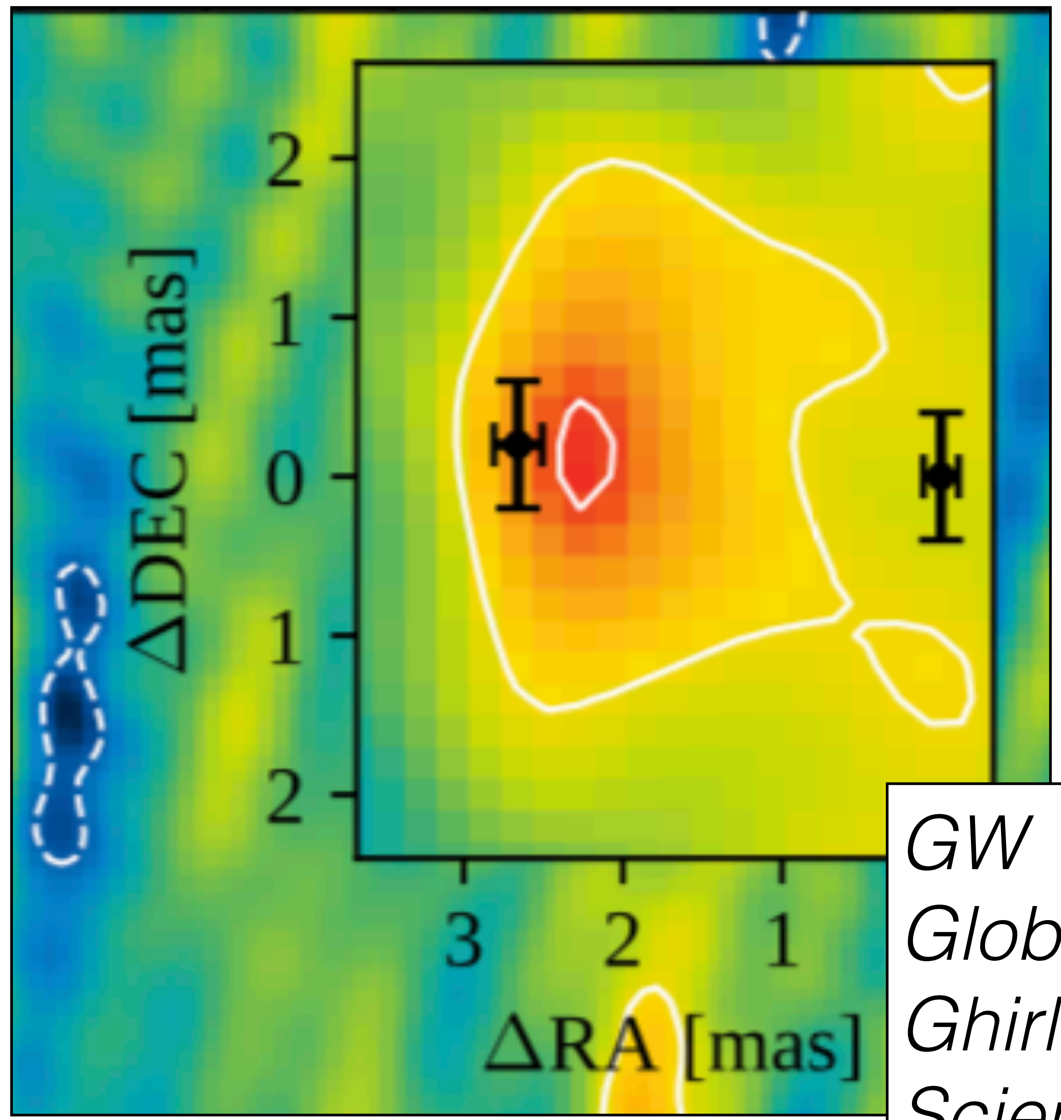
GRB 190114C
MAGIC Coll. et al. 2019

High angular resolution synergies - GWs, FRBs

- Gravitational waves
  - Stellar and SMBH progenitors
  - Connection to search for high-freq (10-1000 Hz) GW progenitor systems
  - Directly detect low-freq (~nHz) GW through pulsar timing

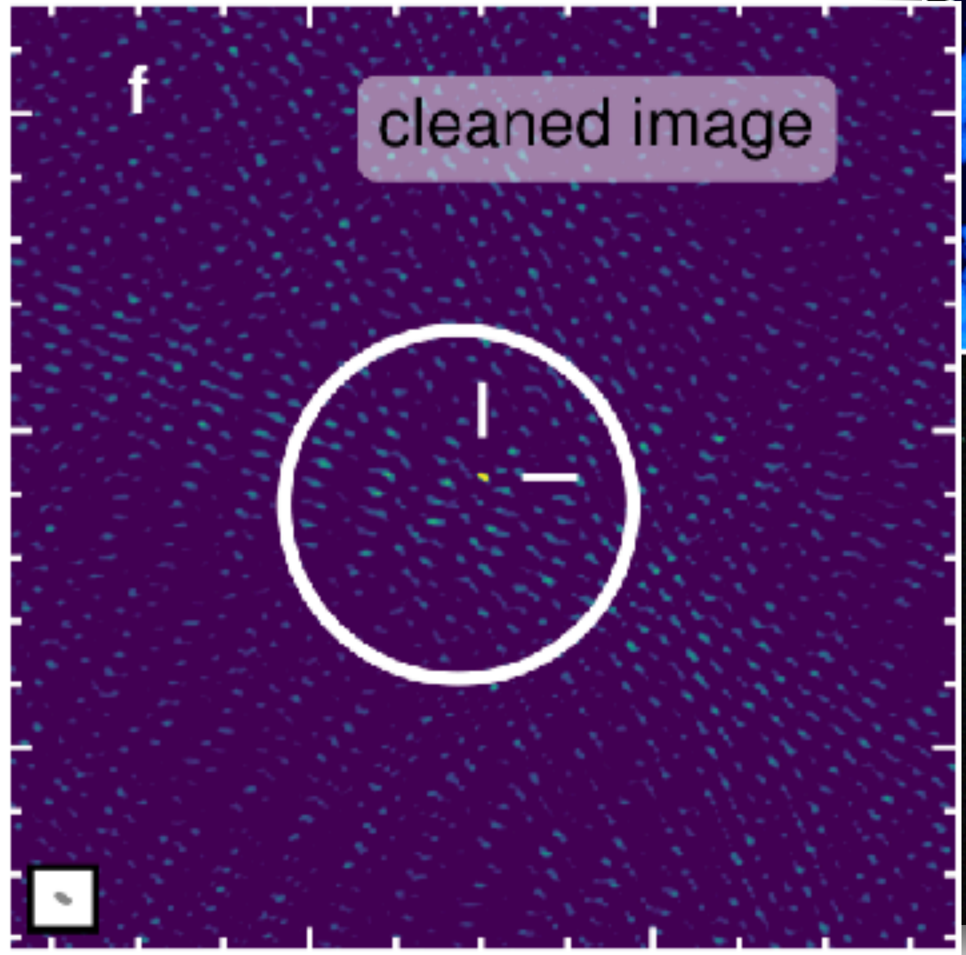
- Fast Radio Bursts
  - one or more populations? (repeaters vs non-rep.)
  - localisation/progenitros
  - probes of plasma density
  - need MWL detection!!!

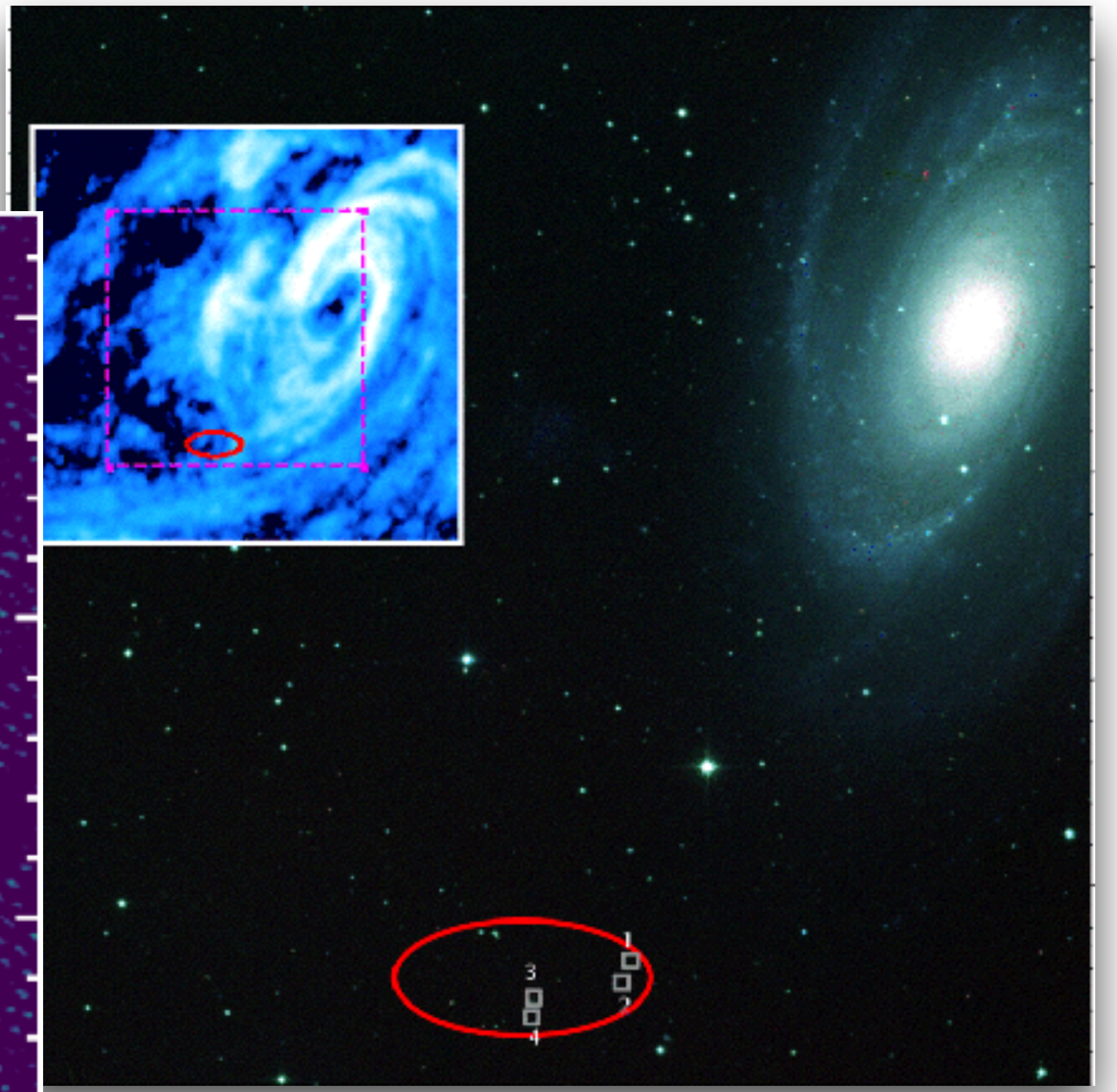




GW 170817
Global VLBI follow-up
Ghirlanda et al. 2019, Science

FRB 200120E
Kirsten et al. 2022, Nature





Take home notes

- Despite being at the opposite ends of the EM spectrum, radio and gamma rays have a deep physical connection
- SKA will be the largest radio telescope array ever constructed
- expect synergy in the field of acceleration, star formation history, astroparticle physics, transients, and unknown!

…meanwhile, let's get as much as possible from the current instruments!

- Chapter 2: Synergies:
    - By the time CTA is starting science verification, these facilities together with SKA and its prototypes will generate overwhelming numbers of triggers (e.g., thousands each of GRBs and tidal disruption events, and likely hundreds of Galactic transients per year).
- Chapter 7: Large Magellanic Cloud survey:
    - analysis of the dust and synchrotron polarized emission from the LMC … The Square Kilometer Array (SKA) and its precursors will also contribute to these science topics (page 89)
- Chapter 9: Transients
    - radio transient factories such as SKA and its pathfinders LOFAR, MeerKAT, MWA, and ASKAP [293] (see details in Chapter 2) guarantee a revolution in our physical understanding of the transient universe [260]. Besides GRBs and the Galactic transients mentioned above, thousands of sources of a very diverse nature are expected to be discovered, from nearby flaring stars with extreme non-thermal variability [294] to orphan GRB afterglows at cosmological distances [295]. Thus, following up properly selected alerts from X-ray/optical/radio transient factories with CTA will pave a new and unexplored path to study the universe in VHE gamma rays, with great promise for exciting results in widely disparate areas of astrophysics
- Chapter 11: Star Forming Systems
    - The next generation of radio surveys in HI and CO transition lines with the upgraded ATCA system and the SKA pathfinder ASKAP are underway; they will map the three- dimensional neutral gas distribution of our Galaxy with unmatched spatial and velocity resolution and will cover the Galactic stellar clusters and star-forming regions discussed in this KSP
- Chapter 12: Active Galactic Nuclei
    - these environments [ALP re-conversion sites] will be extensively studied by SKA using Faraday rotation measurements to achieve a better parametrization of the magnetic fields.
    - AGN flare programme - MWL coverage is crucial, at least for the most prominent flares, for variability studies and dynamical spectral modelling of flaring states. … The organisation of MWL campaigns should include: … flux densities and polarimetry from radio and sub-millimeter telescopes (… SKA ...)
- Chapter 13: Clusters of Galaxies:
    - The gamma-ray flux induced by secondaries from hadronic interactions must respect the measured radio synchrotron emission, as electrons are also produced from charged pion decays. Therefore, the magnetic field strength and distribution in clusters is also an important ingredient and is usually parametrised as $B = B_0 (n/n_0)^{\alpha_B}$, where n is the ICM gas density. Generally we have limited knowledge of cluster magnetic fields, apart from very detailed work on Faraday rotation measurements of the Coma cluster, which provide good estimates for the Coma magnetic field ($B_0 \approx 5$ μG, $\alpha_B \approx 0.5$). In this sense, the synergy with radio observations of clusters by the Low-Frequency Array (LOFAR) and other Square Kilometre Array (SKA) precursors will be crucial. By the same token, SKA itself is expected to shed new light on the magnetic field in clusters of galaxies and will therefore significantly narrow down the available parameter space.
    - Taking into account currently available radio data, and future data from LOFAR and SKA precursors, we will also be able to provide a complementary measure of the magnetic field strength and distribution in the cluster

Until a few decades ago, the radio band provided our main window to the non-thermal universe, via the cyclo-synchrotron emission of relativistic electrons that often dominates over thermal processes below ∼10 GHz. Synchrotron emission goes hand in hand with particle acceleration, due to the inferred presence of magnetic fields and the presence of relativistic electrons, either directly accelerated or produced as secondaries. In addition, dark matter annihilation scenarios usually lead to the production of synchrotron-emitting secondaries along with gamma-ray emission.[1]

The radio bands also have tremendous advantages for localising acceleration zones, because of the high angular resolution (e.g. down to 10's of microarcseconds with VLBI) and the ability to observe in daylight. The combination of radio measurements with those at very high energies can provide limits on the electron density independent of assumptions about magnetic field strengths and can help determine which of several competing non-thermal processes dominate at the highest energies. Radio measurements also provide important magnetic field constraints via Faraday rotation and provide the ephemerides of known pulsars, to guide the search for potential gamma-ray pulsations with CTA. The success of Fermi-LAT in this regard relied on close cooperation with radio observatories [35]. An exciting recent development in the radio domain is the discovery of Fast Radio Bursts [36, 37], with the possibility of high energy counterparts and potential synergies due to the wide field of view of CTA.

CTA science book, pp. 28-30

After decades of incremental improvements, radio astronomy has now again entered a rapid development phase. Many existing facilities have recently received major upgrades, providing much improved bandwidth and sensitivity (e.g., JVLA, e-MERLIN). At the same time windows to entirely new parts of the radio spectrum at both low and high frequencies are finally being opened. In particular, the low-frequency bands (30–80, 120–240 MHz) are now being explored using LOFAR, which can monitor 2/3 of the sky nightly in Radio Sky Monitor mode and has a Transients Key Project dedicated to the detection, triggering and cataloging of new radio transients. In China, the Five-hundred-meter Aperture Spherical radio Telescope (FAST, 70 MHz–3 GHz), the largest radio telescope ever built, had first light in 2016 and is now undergoing commissioning tests. A key new radio project is the Square Kilometre Array (SKA), whose phase 1 will come online during CTA's science verification phase, followed by a ramp up to full operation with phase 2 by about 2024. SKA will have unprecedented sensitivity and excellent angular resolution, and the use of phased-array technology allows for a very large field of view, ideal for survey studies and transient detection (see Section 2.2). The pathfinders for SKA are very powerful instruments in their own right and will be important for early multi-frequency work involving CTA. A low-frequency pathfinder (MWA; 80–300 MHz) is well into its early science phase in Australia with upgrades in progress, and new projects at somewhat higher frequencies are under development in Australia (ASKAP; 700–1800 MHz and UTMOST; 843 MHz) and South Africa (MeerKAT; eventually 3 bands between 0.6–14.5 GHz). The ThunderKAT programme for transients with 3000 hours of MeerKAT plus matching optical coverage (2017-2021) is particularly interesting for CTA. Finally, while not strictly a pathfinder for SKA, VLITE has just been commissioned with a wide bandwidth 330 MHz channel and large field of view (FoV) to conduct a new low-band survey of the sky, as well as detect new transients in real-time. VLITE is a three year pathfinder for the proposed LOBO project, a more extensive low-frequency radio monitoring project using the full JVLA. Having radio facilities in both hemispheres provides important complementarity for the two CTA sites.

CTA science book, p. 30

CTA's sensitivity to diffuse emission around accelerators makes mapping of the interstellar gas over wide areas absolutely essential to enable identification of sources in the Galactic plane and within other large-scale surveys such as that of the LMC. (Sub)- millimeter wavelengths thus complement CTA science by offering a detailed understanding of the environment into which shock waves propagate and through which accelerated particles are transported and interact. Most relevant to CTA are the facilities geared to degree-scale surveys such as Mopra (Australia), APEX and Nanten2 (Chile), and Nobeyama 45 m (Japan), whose beam sizes are well-matched to CTA's arc-minute resolution. These telescopes measure molecular gas via a variety of molecular lines that trace the matter density over a wide range of scales. Of particular interest is the missing "dark" molecular gas now attracting serious attention in the ISM community, traced by THz lines, with pathfinder telescopes in Antarctica such as HEAT (USA/Australia) paving the way for large-scale survey instruments such as the proposed DATE5 project led by China.

The recently completed Atacama Large Millimeter / sub-millimeter Array (ALMA) represents a huge leap forward for (sub)-millimeter interferometry. With sub-arcsecond resolution and the sensitivity to probe a very wide range of interstellar molecules, ALMA can carry out high fidelity probes of the density, temperature and ionisation level of material towards many CTA sources (including the LMC and nearby starburst galaxies), helping to understand the environments in which particles are accelerated and interact.

Furthermore, in recent years it has become clear that the sub-millimeter range is of particular interest for studying the particle-acceleration processes in the jets of Galactic black hole transients (microquasars), as well as in the innermost regions of nearby AGN. For the former there are many new small arrays and single dish facilities in both hemispheres available. For the latter, the upcoming Event Horizon Telescope will link ALMA and other facilities in the first global VLBI array at mm/sub-mm frequencies, offering direct imaging of the jet-launching regions of key sources such as Sgr A* and M 87. Eventually mm/sub-mm observations together with CTA can be used to directly study the relation between near event horizon physics and cosmic-ray acceleration and non-thermal processes in astrophysical jets.

At higher frequencies, the microwave all-sky survey by the Planck Satellite (decommissioned in 2013) has produced a legacy archive that can be searched for very extended microwave counterparts to CTA sources within our Galaxy, complementary information on the lobes of nearby radio galaxies and nearby clusters, and constraints on Galactic magnetic fields.

CTA science book, pp. 30-31