







Instrumentation et observations de transitoires

julien.girard [at] cea.fr

UnivEarthS O





à l'ère de SKA

Julien Girard

AIM/IRFU/CEA Paris Saclay Université Paris Diderot

Plan

I. SKA et ses précurseurs

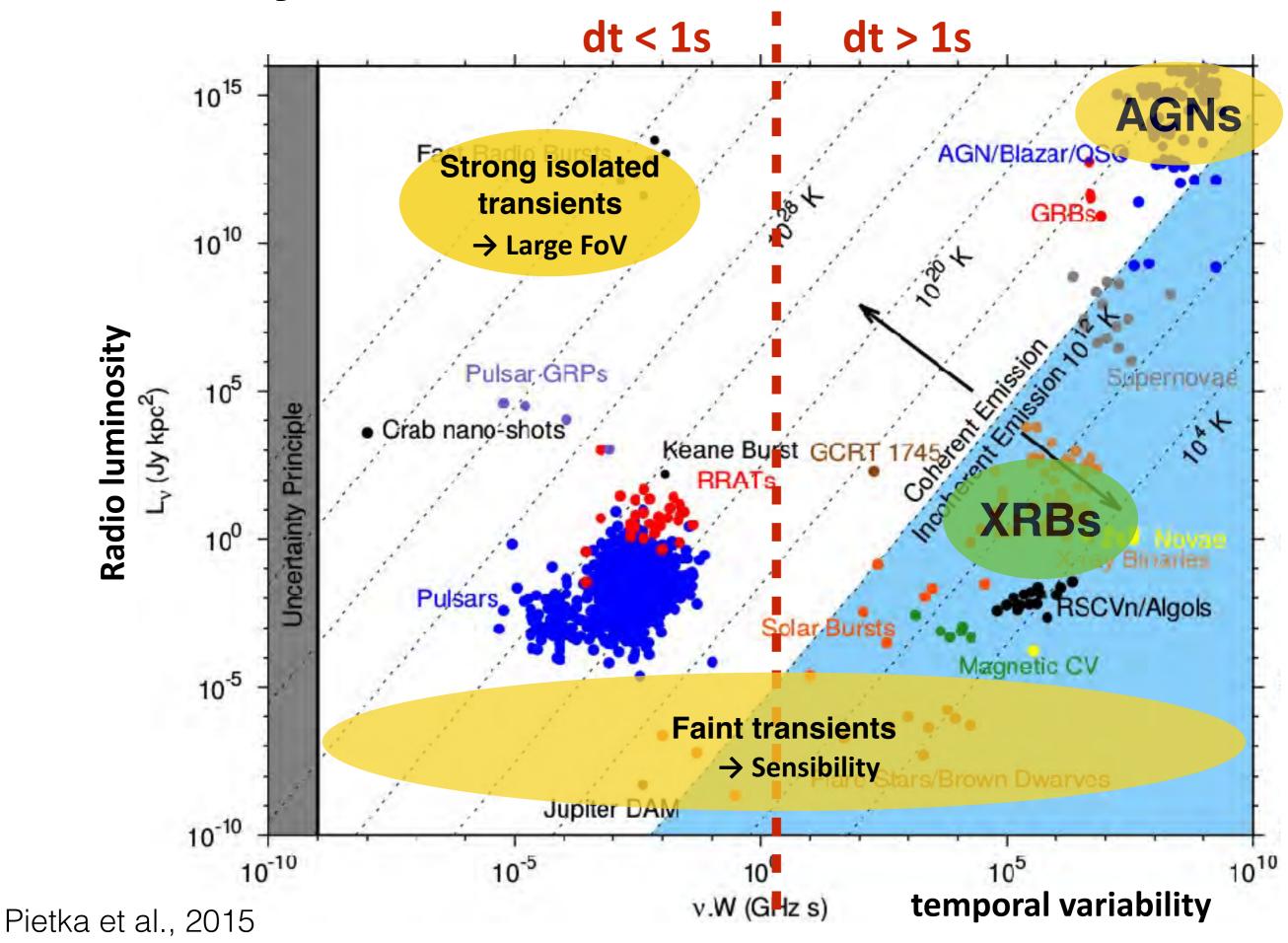
LOFAR, MeerKAT, NenuFAR

II. Les programmes d'observation radio

MeerKAT ThunderKAT

TRAPUM / MeerTRAP

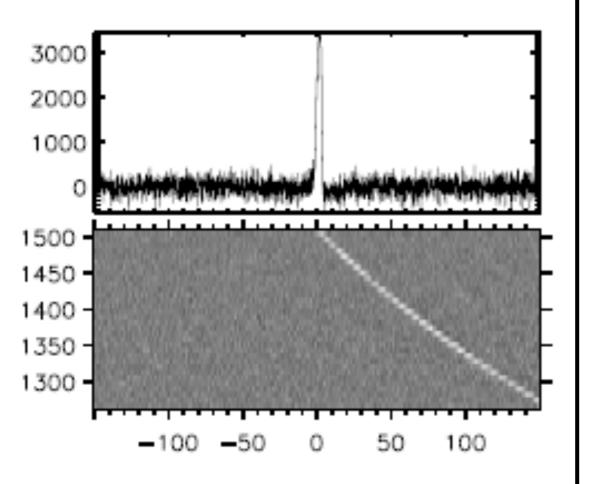
Universality of transients in radio



Universality of transients in radio



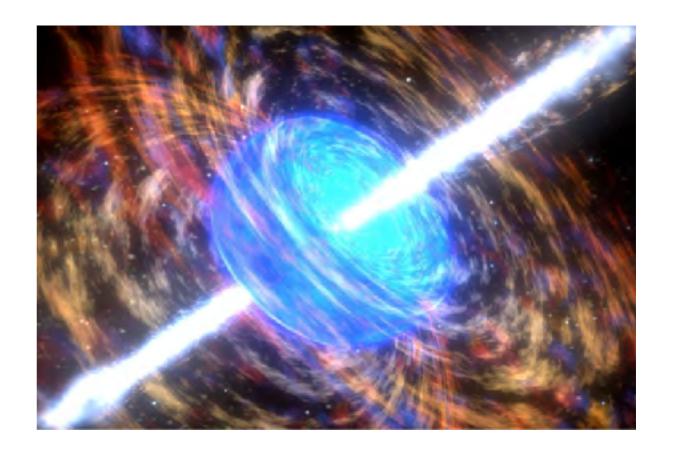
• Fast transient sources



Time series

• Slow transient sources

Variability timescale

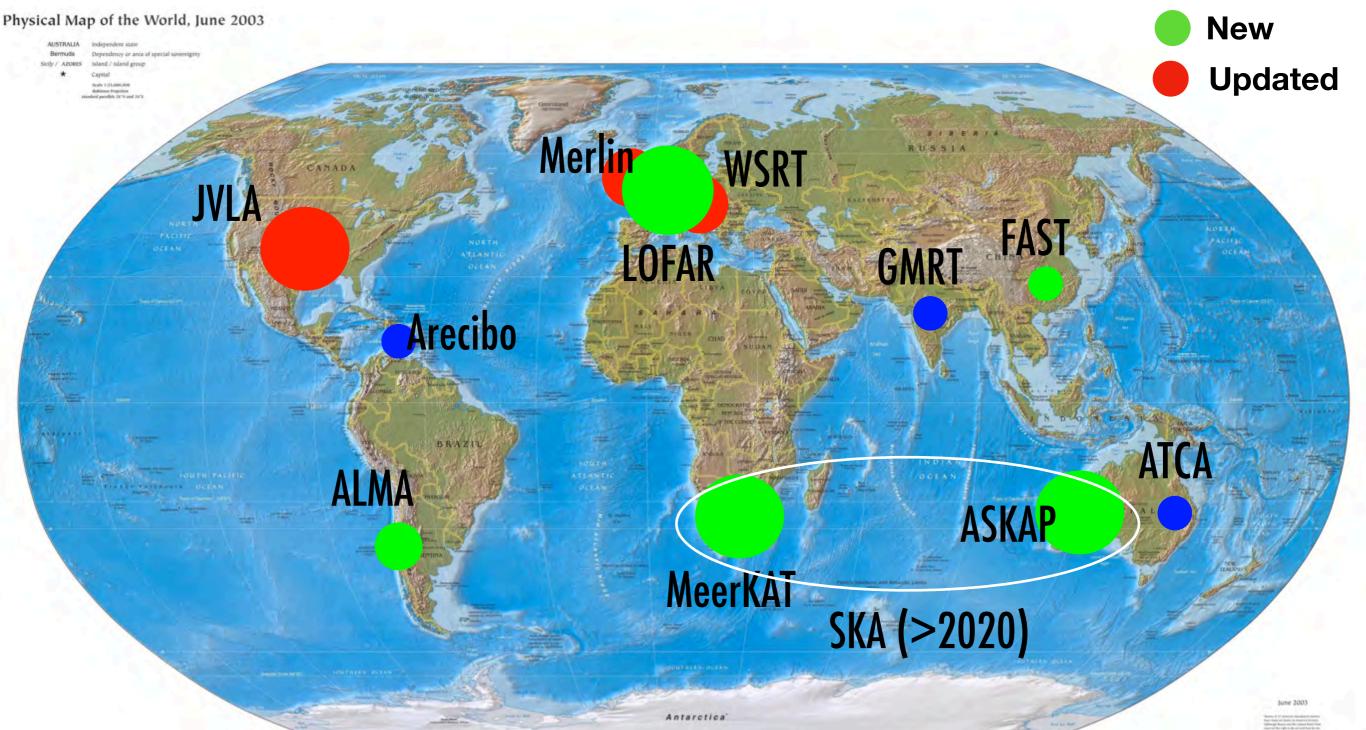


Imaging

New golden age for (ground-based) radioastronomy

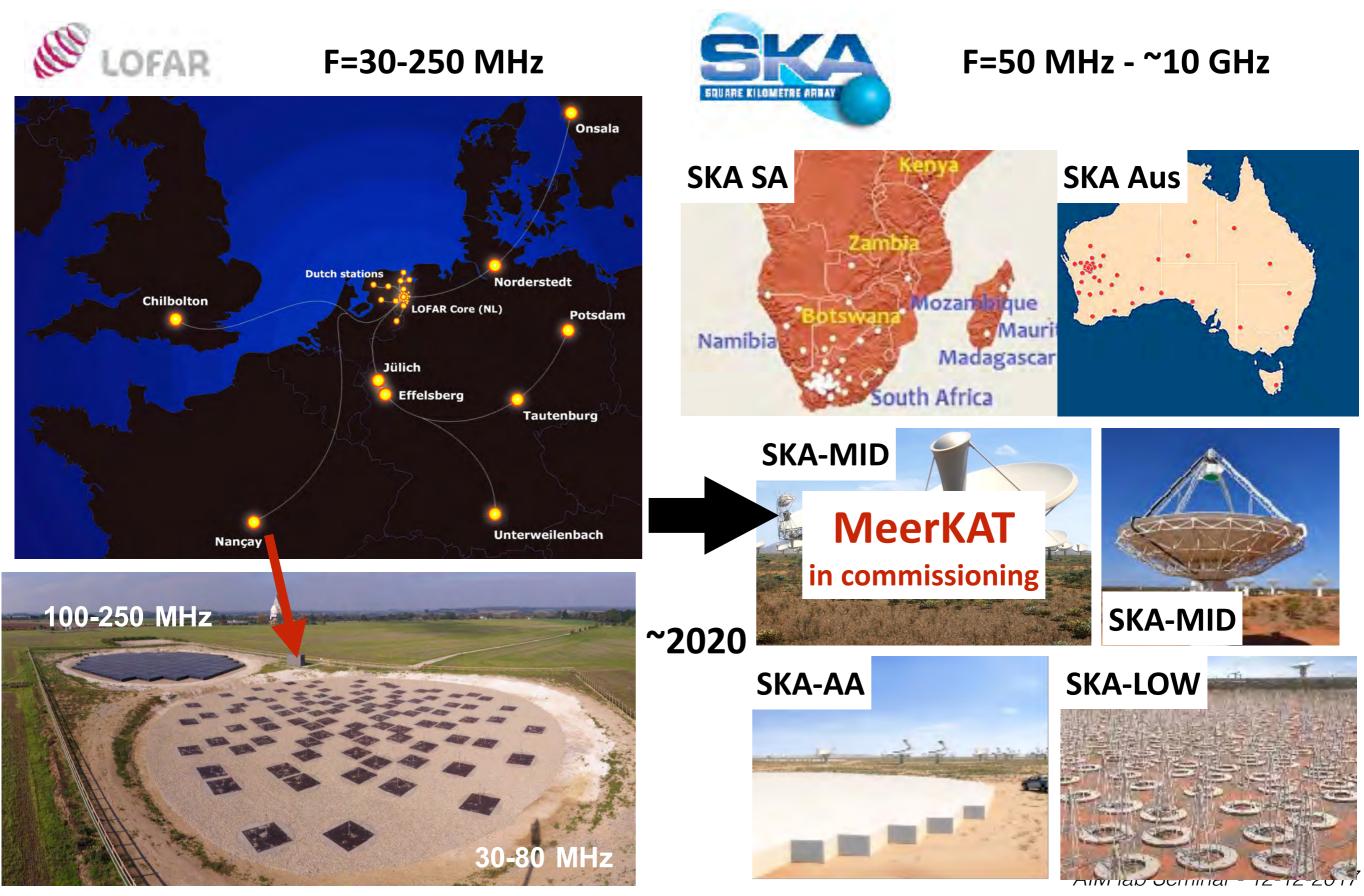
Sensitive instruments (~ μJy)

- $1 \text{ Jy} = 10^{-26} \text{ W.m}^{-2}.\text{Hz}^{-1}$
- High temporal (~1s), spectral (< kHz), angular (1") resolutions
- Almost continuous coverage (in lon, lat, frequency, fields)

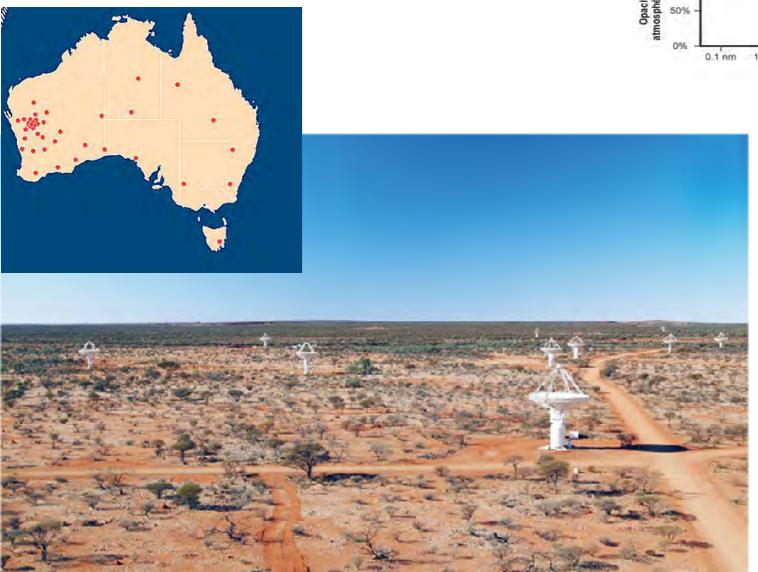


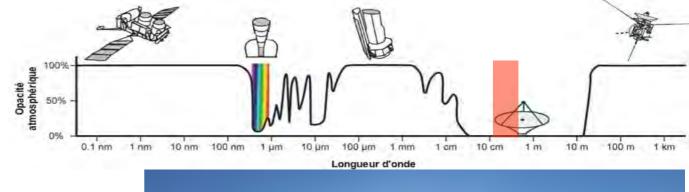
New golden age for (ground-based) radioastronomy

Interferometers: VLA, ATCA, WSRT, ...



SKA Precursors: ASKAP







Location: Australia

Max Baseline: 6 km

Frequency coverage: 0.7-1.8 GHz

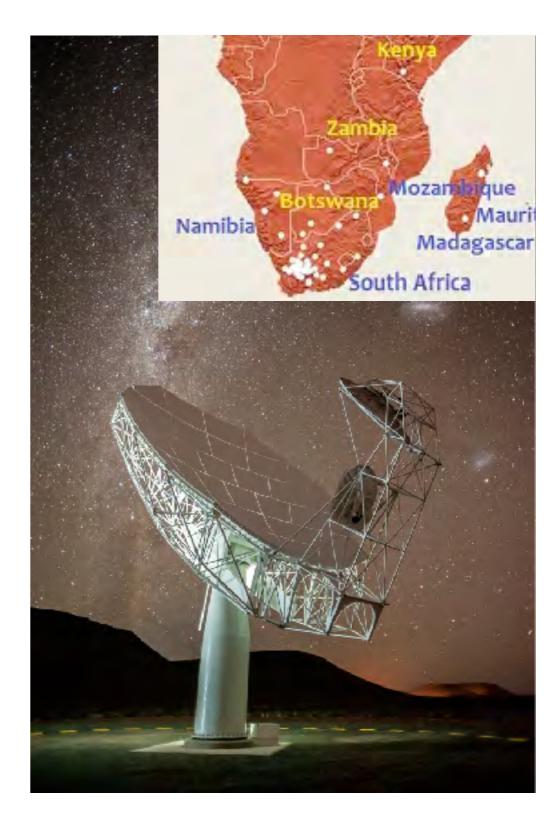
36 antennas (12 m) with PAF (30 deg² FOV)

SKA Precursors: MeerKAT

100% always beautiful and 10 mm 100 mm 1 μm 100 μm 1 mm 1 cm 10 cm 1 m 10 m 100 m 1 km Longueur d'onde



- Location: South Africa
- 64 antennas (13.5 m) over an 8-km baseline.
 All installed.
- Frequency coverage: 0.5-10 GHz
- FOV: 1.69 deg² @ 1 GHz
- Fully deployed in March 2018 (32 in march 2017)



MeerKAT

Dishes 64 (13.5m offset Gregorians).

Sensitivity $> 320 \text{ m}^2/\text{K}$

Frequencies (GHz) 0.6-1.0, 0.9-1.7, 1.6-3.2

Bandwidth 300, 750,1600 MHz

Incoherent FoV (1250 MHz) ~1.27 sq. degs.

Coherent FoV (1250 MHz) ~0.1 sq. degs. (assuming 400 beams)

AR-1: 16 receptor array

First light: 30 June 2016 -- achieved

L-band receivers only

ROACH-2 correlator/beamformer (CBF)

AR 2: 32 receptor array

32 single-polarisation inputs (ROACH-2 CBF): 31 March 2017

32 dual-polarisation inputs (SKARAB CBF): late 2017

AR 3: 64 receptor array Available by 31 March 2018 Additional CBF functionality 64 dual-polarisation stations

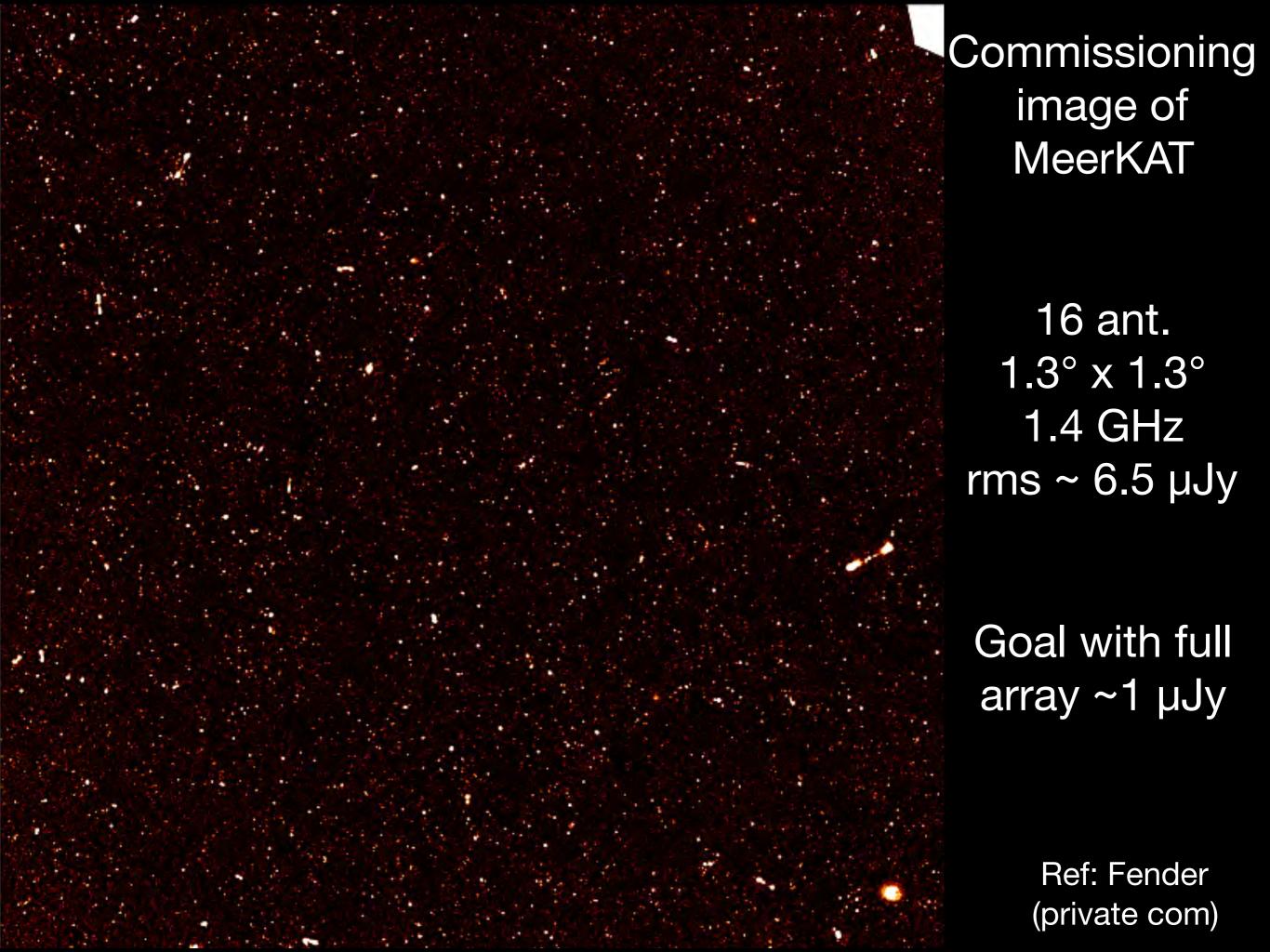
ÅR 4,5,6 --- further functionality like Fly's Eye modes.



() () () () () ()

View showing 10% of the full MeerKAT First Light radio image. More than 200 astronomical radio sources (white dots) are visible in this image, where prior to MeerKAT only five were known (indicated by violet circles). This image spans about the area of the Earth's moon.

Slide: Ben Stappers



MeerKAT & MeerLICHT

Effort joint NL/SA/UK

Radio - Optical synergy

Early science: 2018 (June+)

Science operations: 2018/9 – 2022/3



1.65 x 1.65 degrees, 0.57" pixel size, ugriz(q), 60s = 21 mag

MeerKAT & MeerLICHT

MeerLICHT observation of NGC 4993 on 25/8/17 (8 days after GW event) (Kerry Paterson)

Performances

30 deg² in 12 minutes to a depth 40 times fainter than the peak brightness of GW170817

Size of the full Moon for comparison of scales

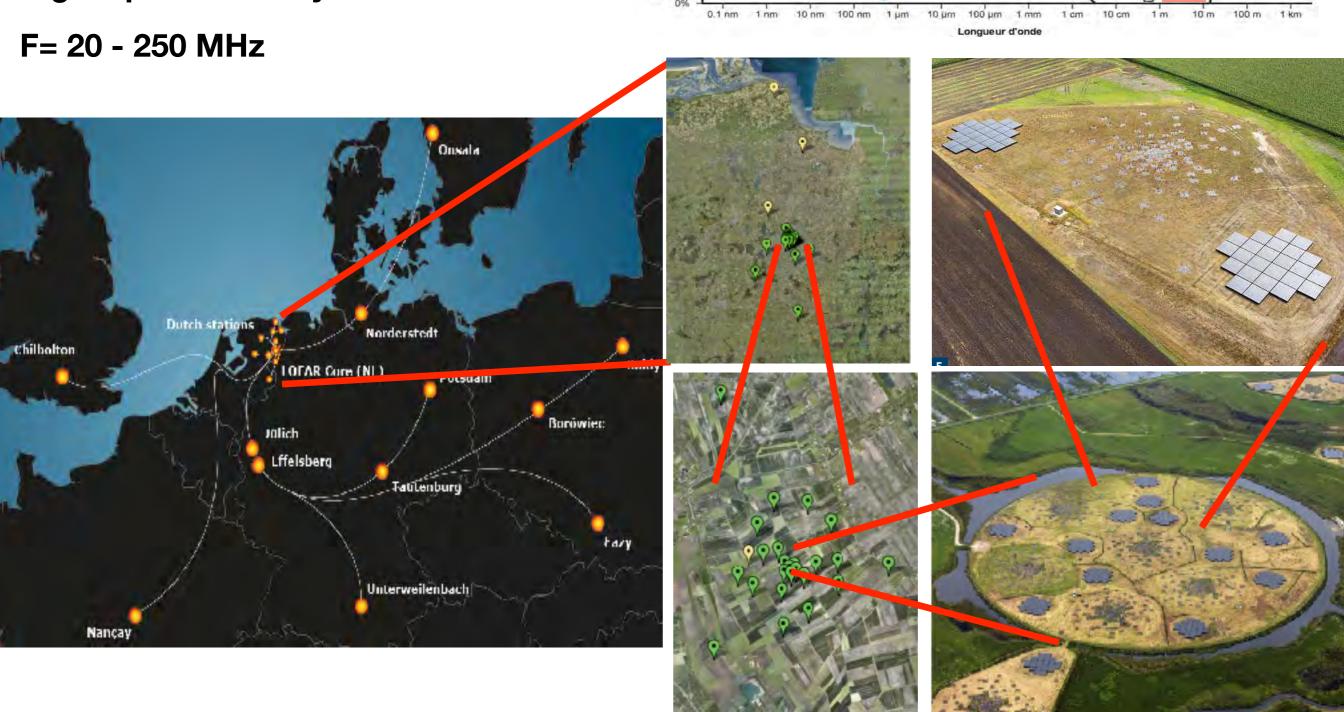


Slide: P. Woudt

1.65 degrees at 0.57 arcsec/pixel

SKA Precursors: LOFAR

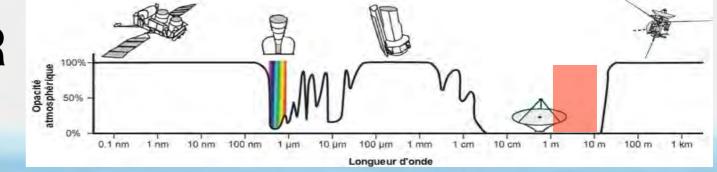
Digital phased-array interferometer

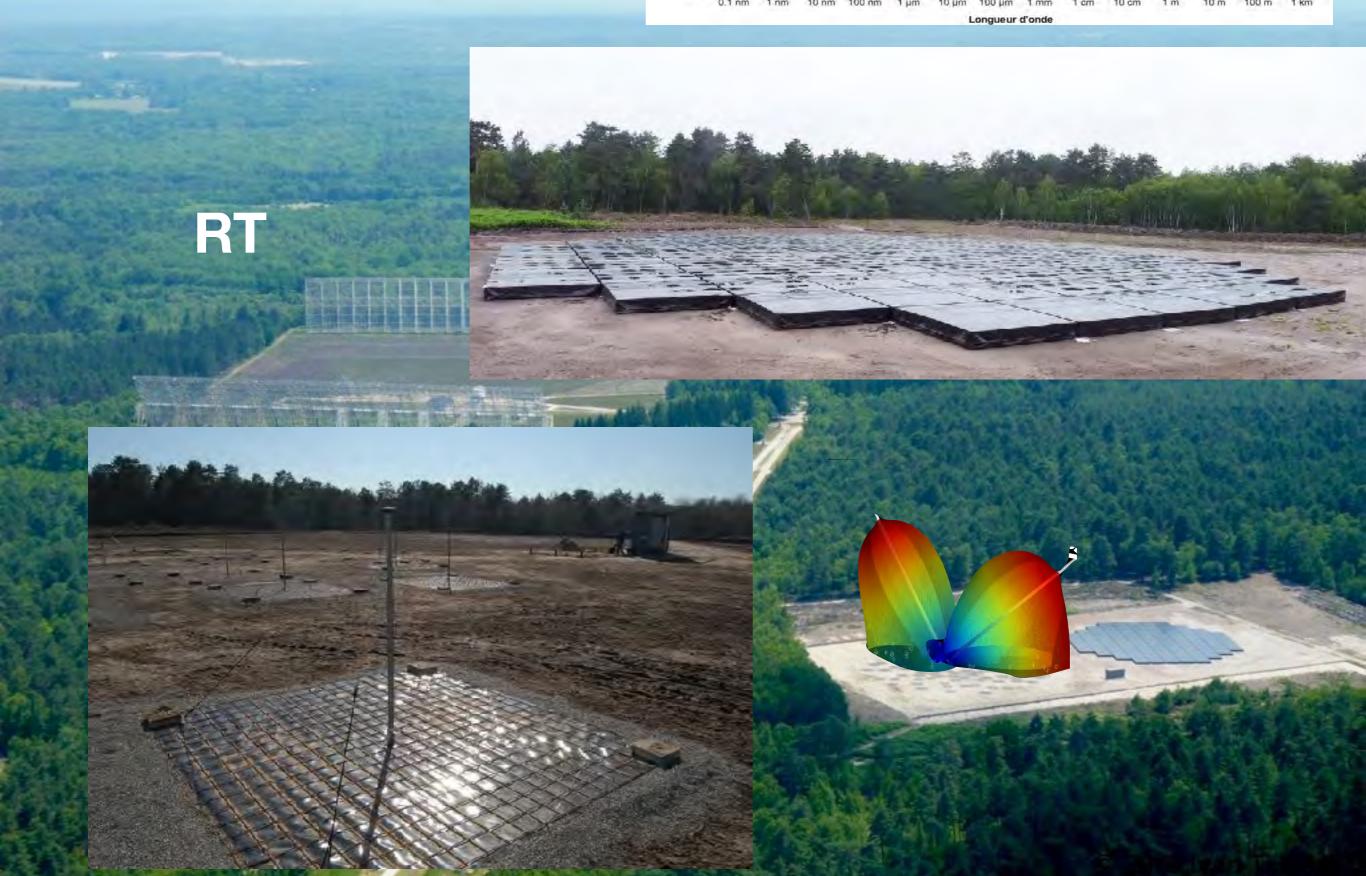


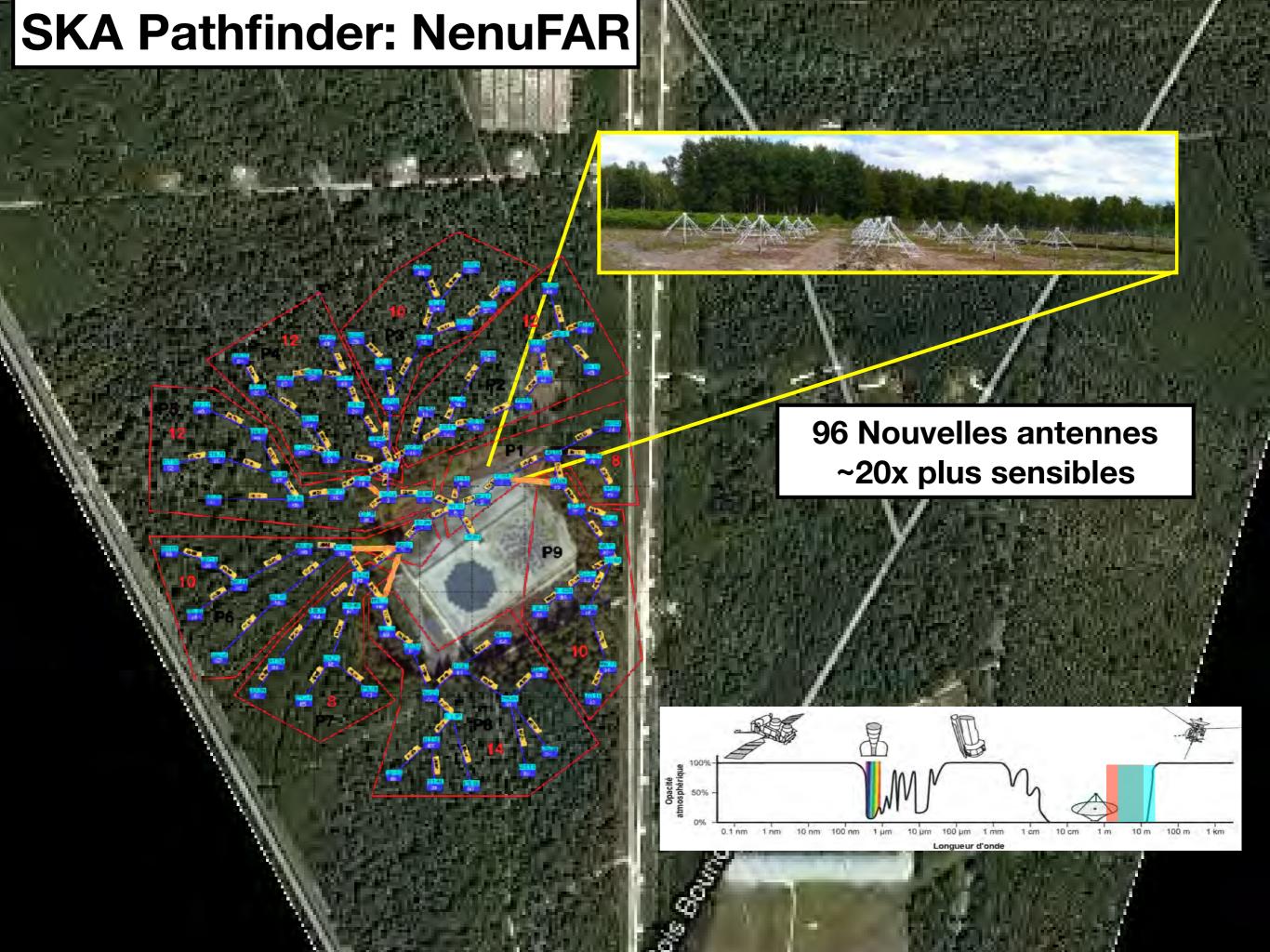
LOFAR Superterp

- 1824 antennas / NL tiles + 1248 International
- (Polarimetric) imaging, Beamforming, waveforms

SKA Precursors: LOFAR

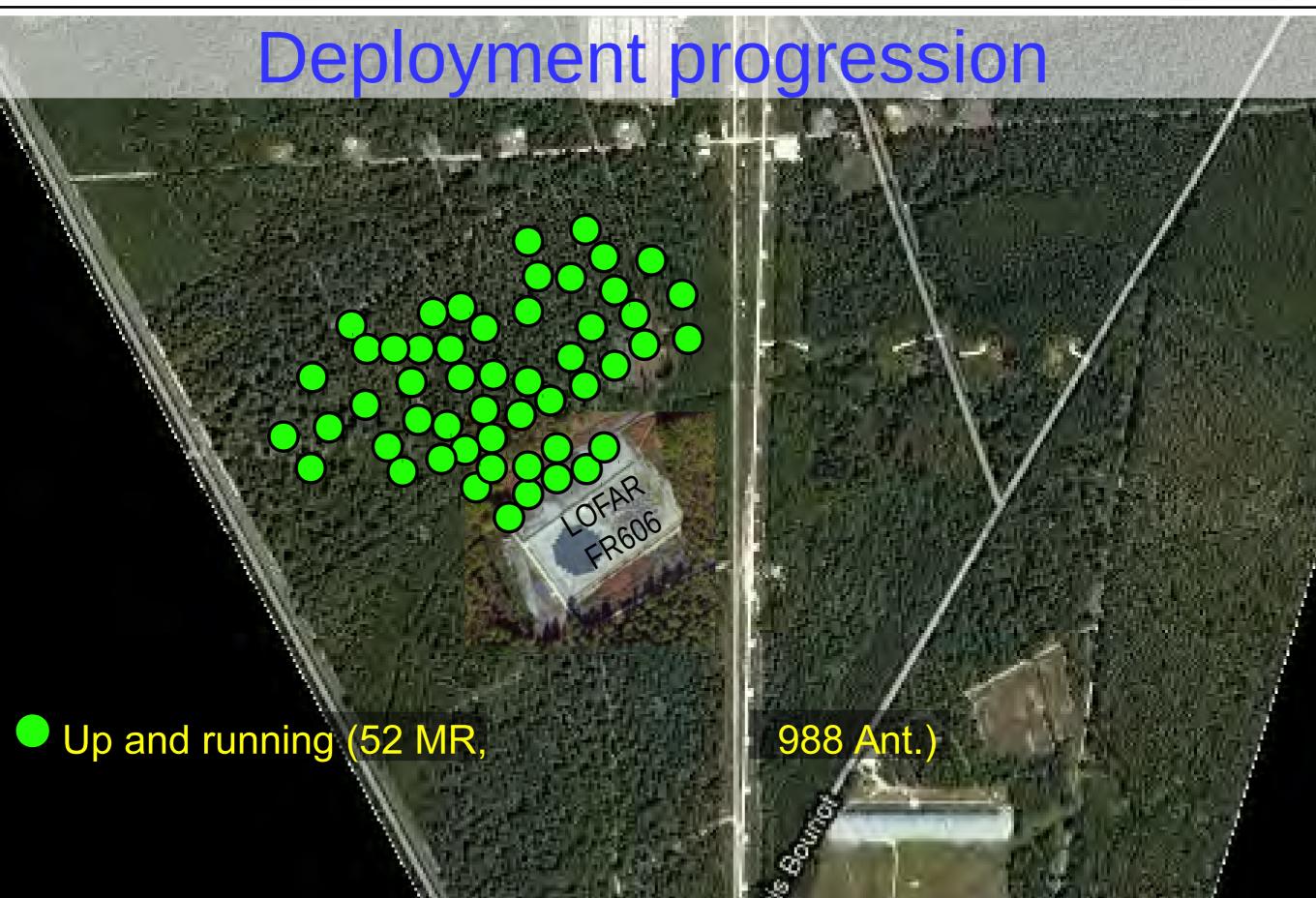






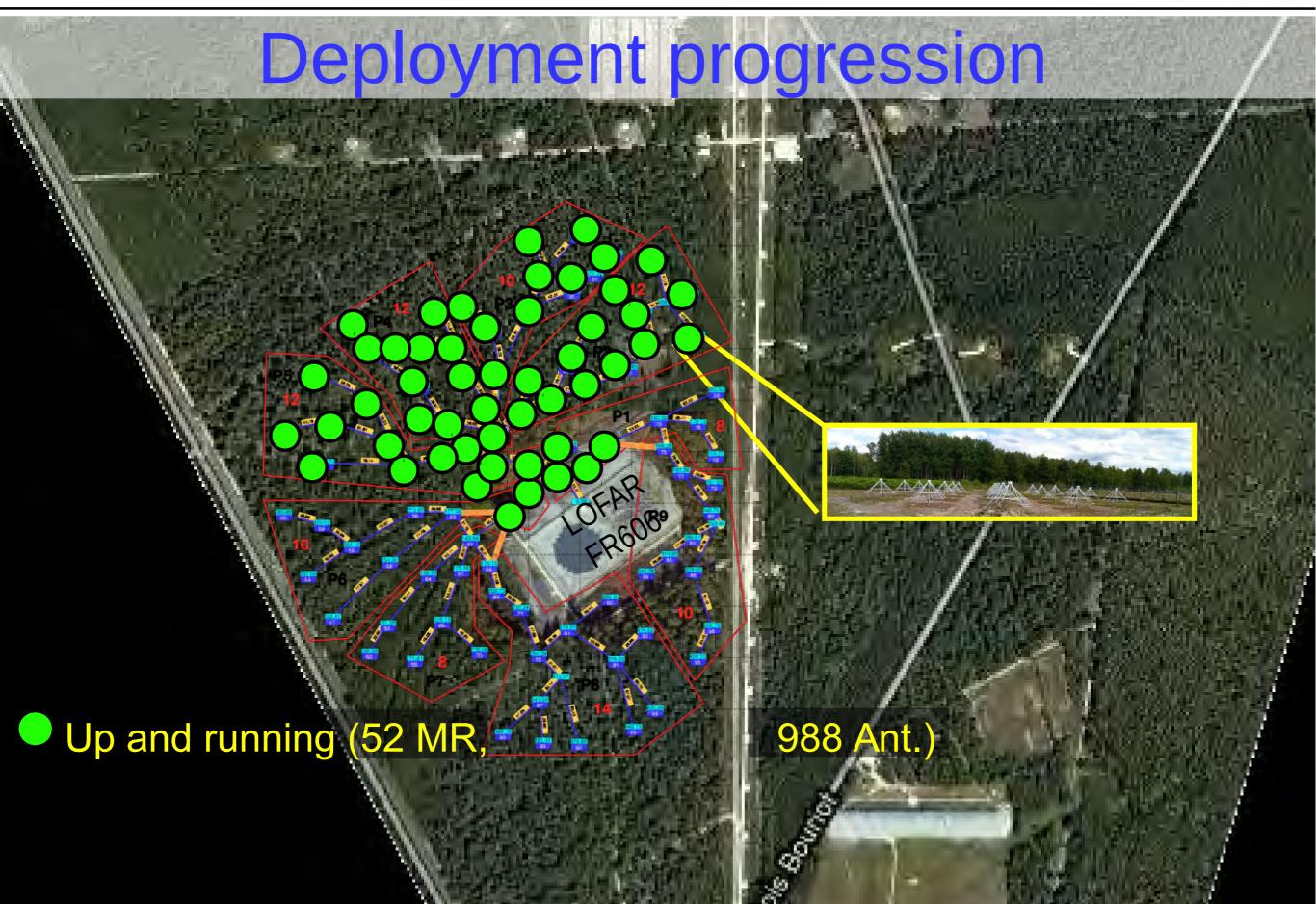






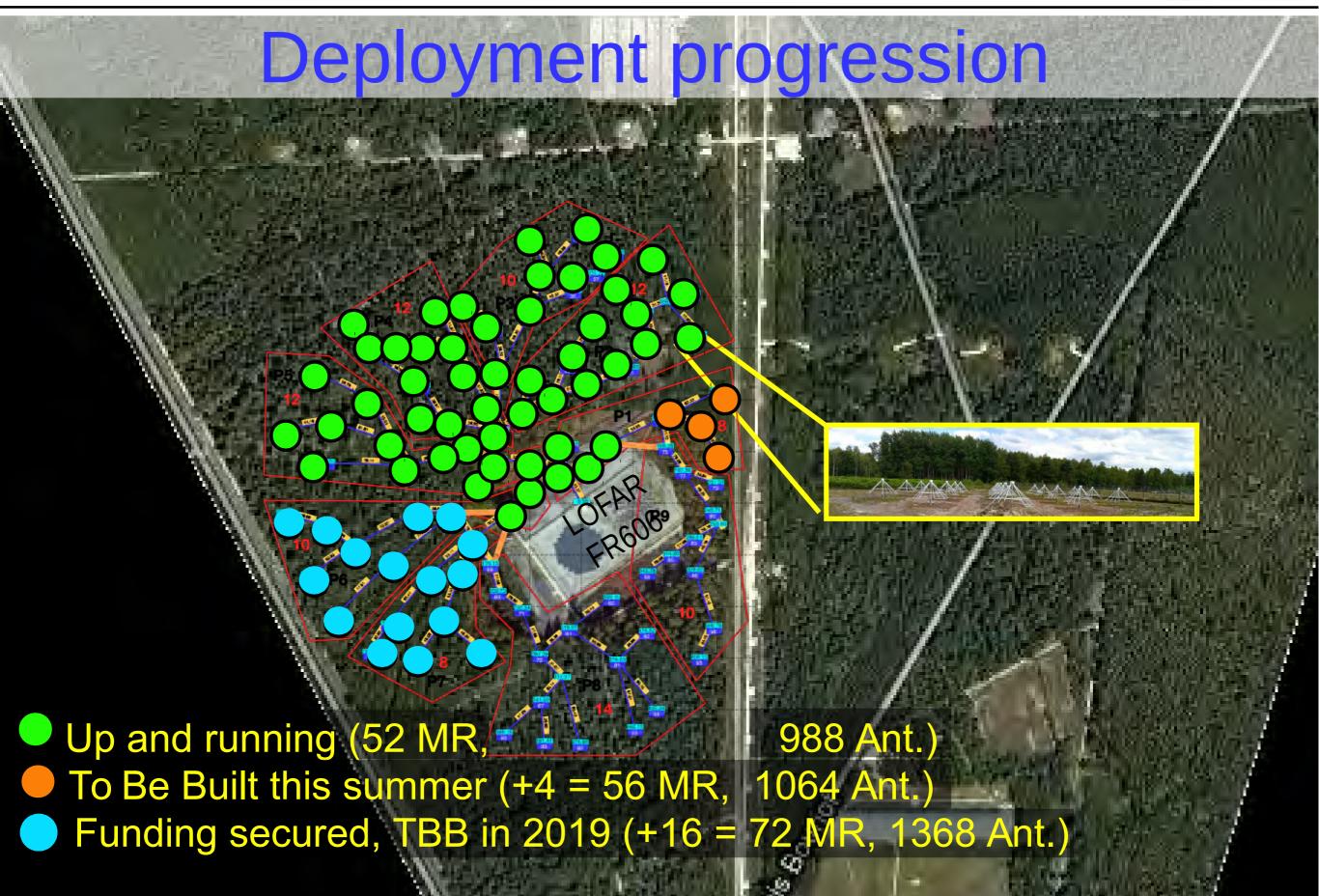








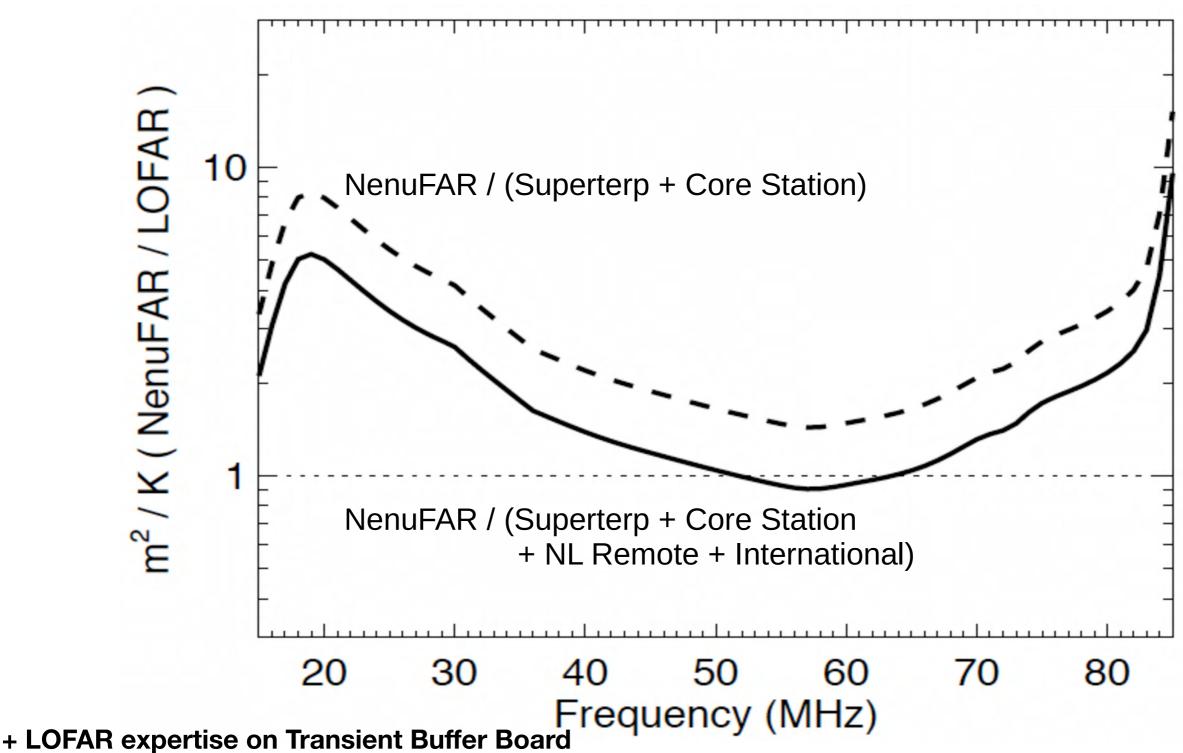








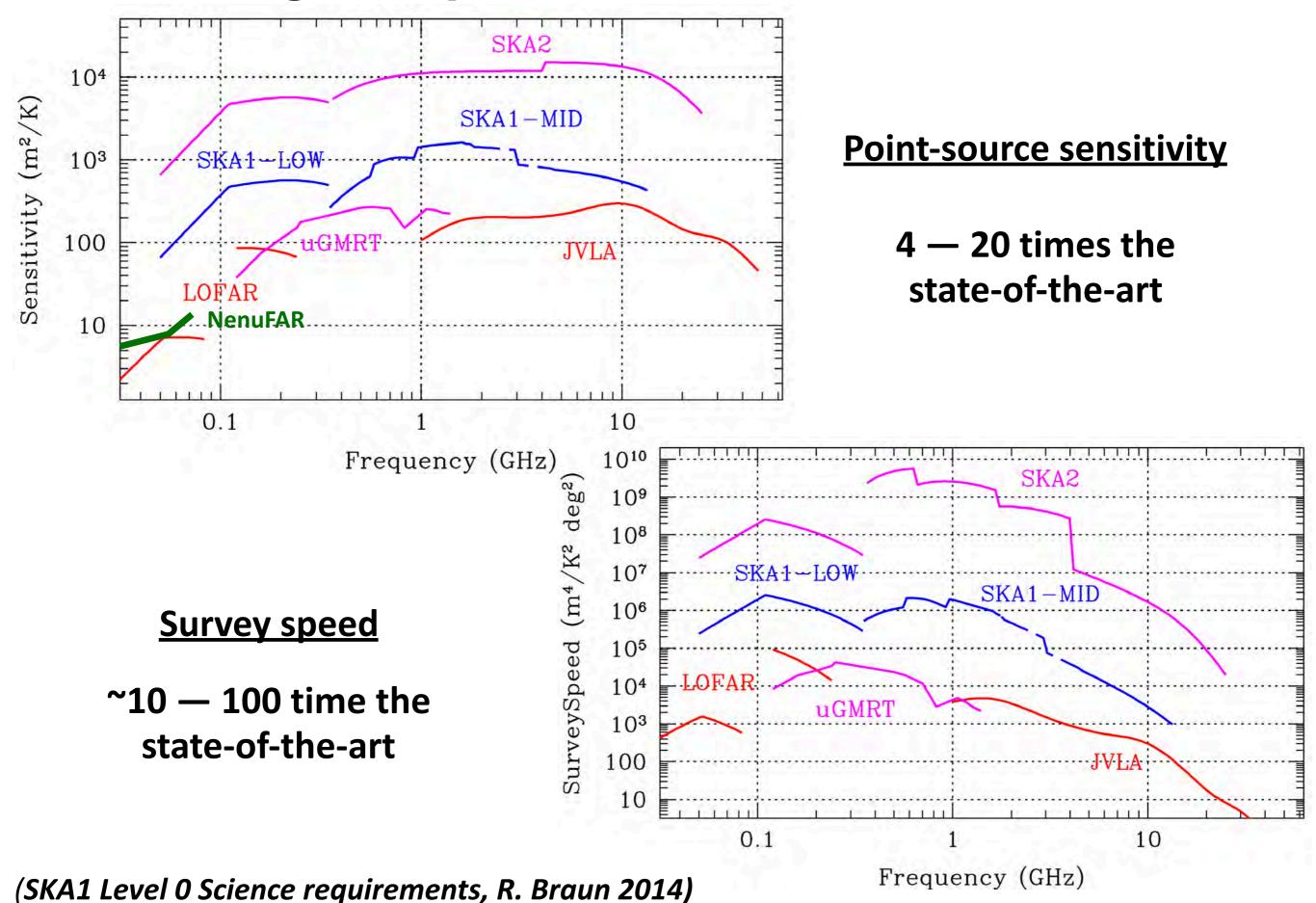
Extrapolated sensitivity based on current observations



+ VO-Paris Expertise for VOEvent implementation

Slide: NenuFAR coll. 69

SKA-1 Targeted performances



SKA1 LOW - the SKA's low-frequency instrument

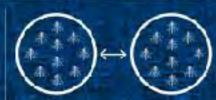
The Square Klometre Array [SKA] will be the world's largest radio telescope, revolutionising our understanding of the Universe. The SKA will be built in two phases - SKA1 and SKA2-starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - SKA1 MID and SKA1 LDW - observing the Universe at different inequancies.



WWW/V/V/V Frequency renge. 50 MHz ... 350 MHz

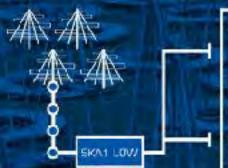


Total collecting area:



between stations

65km



Total raw data output:

157 terabytes per second

4.9 zettabytes



Enough to fill up 35,000 DVDs

every second

5x gooal internet traffic in 2015



Compared to LOFAR Netherlands the current pest similar instrument in the world



resolution

sensitive

P Square Klometre Array D waska palassope of to be The Square Knometre Array

the survey



SKA1 MID - the SKA's mid-frequency instrument

The Equare Kilometre Array (SKA) will be the world's largest radio telescope, revolutionising. our uncerstanding of the Universe. The SKA will be built in two phases - SKA1 and SKA2 - starting in 2016, with SKA1 representing a fraction of the full SKA SKA1 will include two instruments. SKA1 MD and SKA1 LOW lobberlying the Universe at different frequencies.



WWWVVVVV

Frequency range 350 MHz to 14 GHz



200 dishes

SKA telescope

credits:

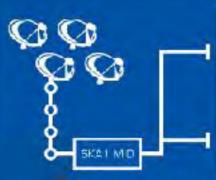
Total collecting area 33,000m²





Maximum distance between dishes

150km



Intel naw data cutput:

2 terabytes per second

62 exabytes per year



Enough lo lill

0,000

average laptops with content every day

Compared to the JVLA, the current best similar instrument in the world:



4х

5x more sensitive

60x the survey



SKA-1 & Radio transients

Distribution des alertes

SKA1-SCI-20: « All components of SKA1 shall enable a capability **for searching of data streams** (imaging and/or beam-formed) for astrophysical transients and be able to report unambiguous detections with a latency of less than 100 seconds. »

Réponses aux alertes

SKA1-SCI-21: « All components of **SKA1** will be able to respond to alerts, which may be human- or robotically-generated, on a timescale of 1-20 seconds. SKA1-Mid and SKA1-Survey will begin slewing on this timescale; SKA1-Low will begin beam-forming in the new direction on this timescale. »



Large Survey Projects

A call for MeerKAT observing proposals by SKA South Africa in 2009 resulted in 10 Large Survey Projects (LSPs, defined to require more than 1000 hours of telescope time over 5 years) being approved in 2010. In 2016, with MeerKAT in an advanced state of construction (and substantially different from the telescope planned in 2009), and with the natural evolution in some of the key questions in astrophysics that MeerKAT LSPs seek to address, SKA South Africa requested revised project plans from eight LSPs:

- LADUMA: Looking at the Distant Universe with the MeerKAT Array
- MALS: The MeerKAT Absorption Line Survey
- MeerKAT Fornax Survey
- . MeerTime: The MeerKAT Key Science Project on Pulsar Timing
- MHONGOOSE: MeerKAT HI Observations of Nearby Galactic Objects: Observing Southern Emitters
- MIGHTEE: The MeerKAT International GHz Tuned Extragalactic Exploration Survey
- ThunderKAT: The Hunt for Dynamic and Explosive Radio Transients with MeerKAT
- TRAPUM: Transients and Pulsars with MeerKAT

Dedicated to transients

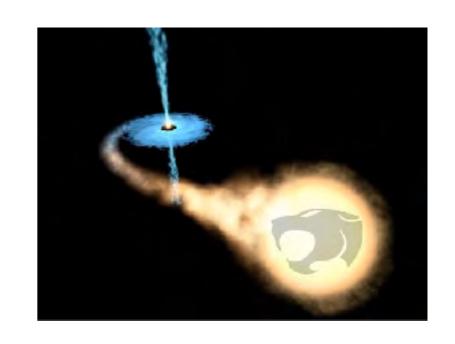
commensal

The two remaining LSPs (MESMER and MeerGAL) were not required to submit revised plans since they primarily require X-band receivers, which are not currently planned.

THUNDERKAT

(PI: FENDER/WOUDT)





Systematic observation
3h / day
Sensitivity
3 µJy / day

A MeerKAT Large Survey Project for synchrotron radio transients

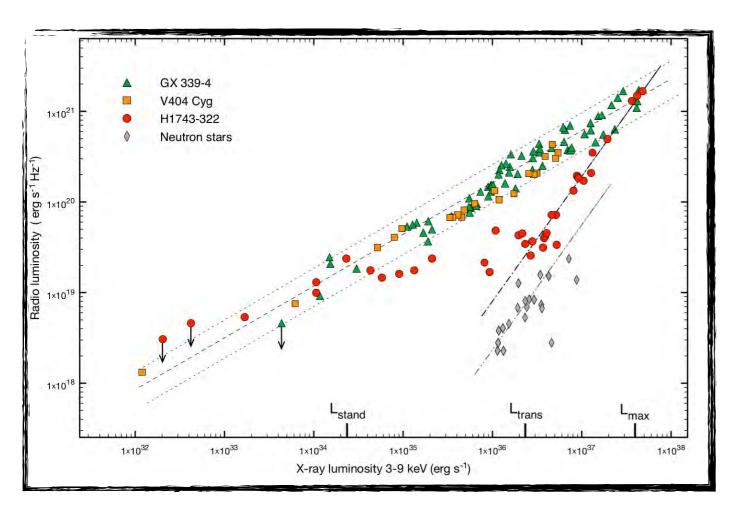
- Survey and monitor populations of Galactic and extragalactic synchrotron radio transients
- Commensal observations + pointed observations (~2000 h) typically for follow-up + simultaneous optical observations with MeerLicht.
- Large international collaboration (56 co-ls from 9 countries)



ThunderKAT [targeted] - observing modes

Relativistic Accretion

Black holes and neutron stars in X-ray binaries



Targets:

- 1) 1000 observations over 5 years of selected XRBs in outburst, quasi-simultaneous with X-ray
- 2) deep observations for selected **faint** targets
- 3) newly discovered systems

Characteristics:

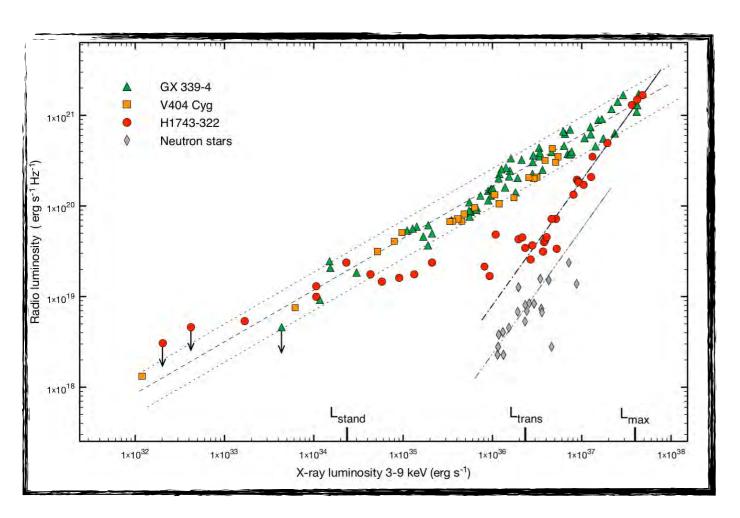
- 1) Regular monitoring (2x30 min/week) for bright targets
- 2) Scheduled deep observations (30 min/week) for faint targets



ThunderKAT [targeted] - observing modes

Relativistic Accretion

- Black holes and neutron stars in X-ray binaries



Observing mode:

- 1) sub-array for monitoring
- 2) full array for deep observations
- 3) **ToO** for newly found systems before insertion in monitoring program

Data processing:

IDIA [standard], partners

Inter-University Institute for Data Intensive Astronomy

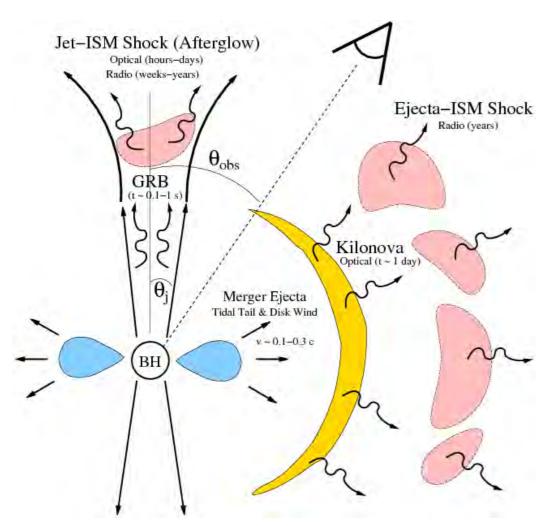




ThunderKAT [targeted] - observing modes

Cosmic Explosions

Gamma-ray bursts; Type Ia supernovae



What is the Most Promising Electromagnetic Counterpart of a Neutron Star Binary Merger? Metzger, B.D. et al. Astrophys.J. 746 (2012) 48

Targets:

BNS mergers, nearby supernovae

Characteristics:

faint (few - few tens of microJy)

Observing mode:

- triggered by external alerts
- adequate coverage of outburst
- (< 24 hr trigger time, 10 hr/GRB in < 72hr
- + later time coverage)

Data processing:

IDIA [standard], partners

Patrick Woudt (University of Cape Town) - on behalf of the ThunderKAT team



ThunderKAT [targeted] - components

White Dwarf Accretion [250 hr]

- Disk instability outbursts (disk/jet coupling in CVs), outflows from thermonuclear eruptions on white dwarfs

Relativistic Accretion [500 hr / 200 hr]

Black holes and neutron stars in X-ray binaries,
 Tidal Disruption Events, Ultra luminous X-ray sources

approved rejected not reviewed/deferred

Cosmic Explosions [<= 530 hr]

- Gamma-ray bursts; Core-collapse supernovae; Type la supernovae

Fast and Coherent Transients [200 hr]

Fast radio bursts (fast imaging)

Gravitational Wave Sources [<= 400 hr]

- Gravitational wave events and electro-magnetic counterparts





ThunderKAT [targeted] - data readiness

White Dwarf Accretion

VLA: good sample of northern CVs at ~ few microJy RMS.

Groups: UCT, Radboud (NL), Northwestern (Chicago), Curtin (Aus)

Relativistic Accretion

MeerKAT-16 (AR 1.5): Circinus X-1, GX 339-4 (recent)

Groups: Oxford, CEA, Curtin (Aus), ESA (Madrid) + ZA collaborations/students

Cosmic Explosions

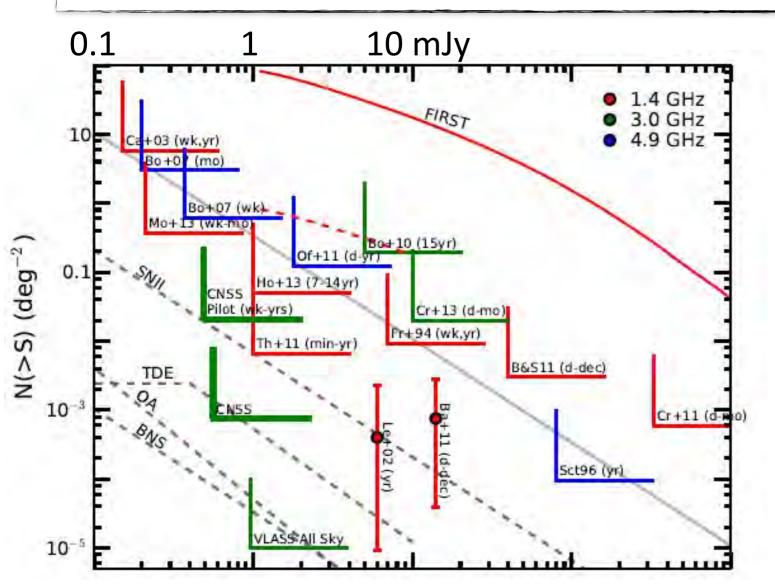
MeerKAT-16 (AR 1.5): GW170817 (multiple epochs)

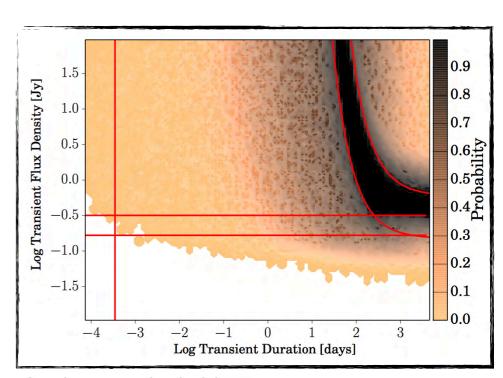
Groups: Oxford, Radboud (NL), GWU (USA), IAA (Spain), + ZA collaborations



ThunderKAT [commensal]

Model expected detections based on crude level 0 observing schedule - Dario Carbone





Carbone et al. 2017, MNRAS 465, 4106





ThunderKAT [commensal] - data readiness

ThunderKAT Real-Time Transients

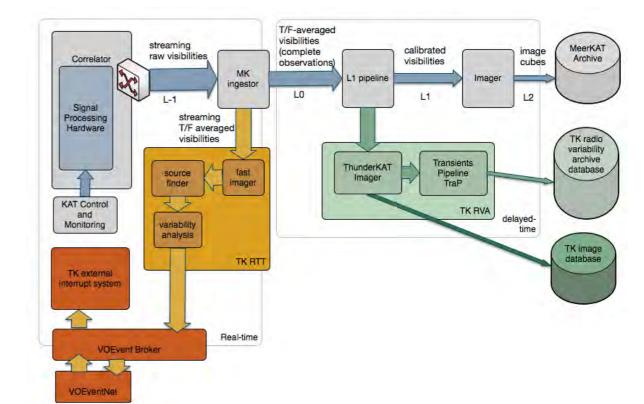
- Pipeline developed by Richard Armstrong
- To be implemented in Karoo > June 2018
- 2 sec, 16 sec, 2 min, 16 min, 2 hours
- To be tested with GX 339-4 data

ThunderKAT Radio Variability Archive

- Standard data products (time/freq. av.)
- Optimised for speed (not dynamic range)
- New ThunderKAT PDF (CEA) with experience in commensal transient searches

IDIA support

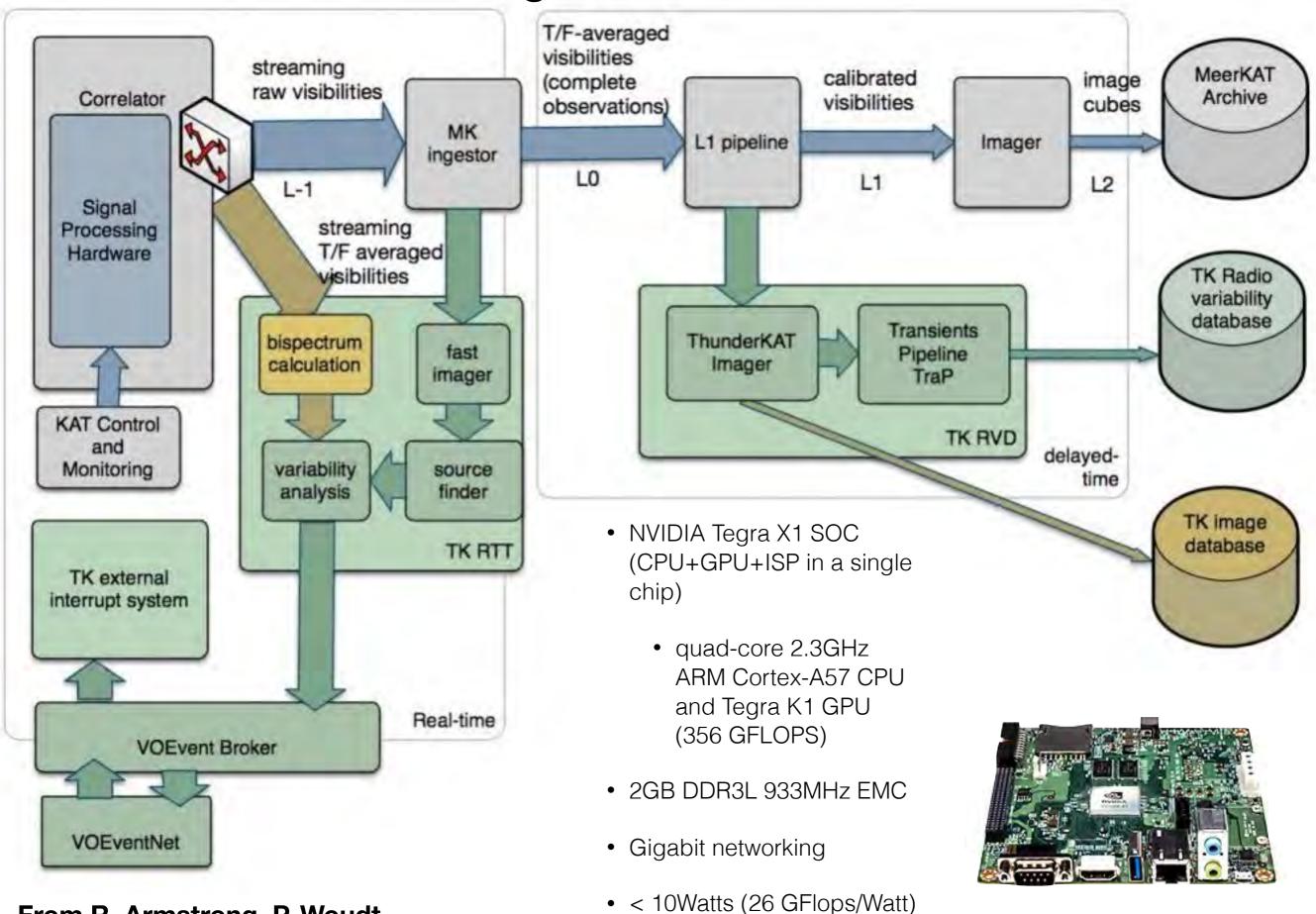
- New ThunderKAT PDF to work on commensal TK/ML integration
- MSc/PhD student to work on classification algorithms
- New SARChI chair (to start in January 2018)



Slide: P. Woudt



MeerKAT Real-time Imager



From R. Armstrong, P. Woudt



ThunderKAT

Real-time transients (IPUSE = TK-RTT)

- Deployed in the Karoo (IPUSE) date TBD: June 2018?
- Search on five different time scales: 2 sec, 16 sec, 2 min, 16 min, 2 hours
- Database of transients to IDIA (transferred daily)
- Reporting of newly found transients via **VOEvents**

Radio variability database (TK-RVD)

- Deployed at IDIA: latency of getting data to IDIA?
- Variable sky probed at five time scales: 8 sec, 1 min, 8 min, 1 hour, 8 hours
- Optimised for **speed**, not for high dynamic range
- Optical / Radio transient and variability data base (machine learning)

Targeted observations

- High dynamic range imaging, faint sources
- Use of **sub-array** for efficient monitoring (1000 obs) of **bright** sources



ThunderKAT, GW and France

- ThunderKAT: GW follow-up originally included and accepted in 2010 AO as legacy project.
- People involved in France: S. Corbel (AIM), F. Daigne (IAP), S. Vergani (GEPI), M. Coriat (IRAP), J. Girard (AIM).
- Policy of ThunderKAT: all transients would be public!

SKA Precursors: ASKAP

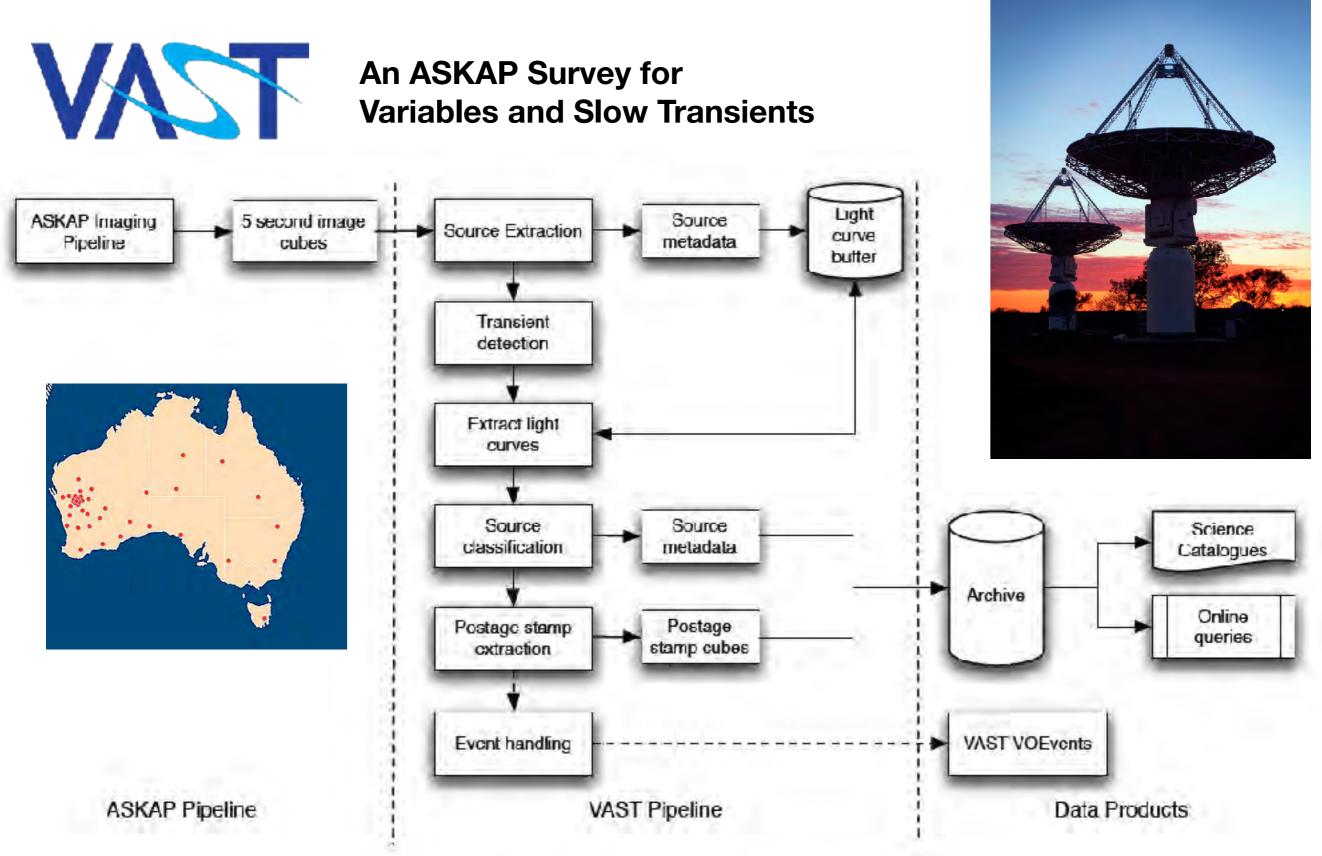


Figure 5: The VAST transient detection pipeline.

cf. VAST Memo 5 (2012)

MeerTRAP (T < 1s)

Goal #1 The bursting sky

Detect (extra)galactic short duration radio bursts

Association with events like GRB, GW.

Accurate localization of Fast Radio Bursts (origin, cosmologic probes, etc.)

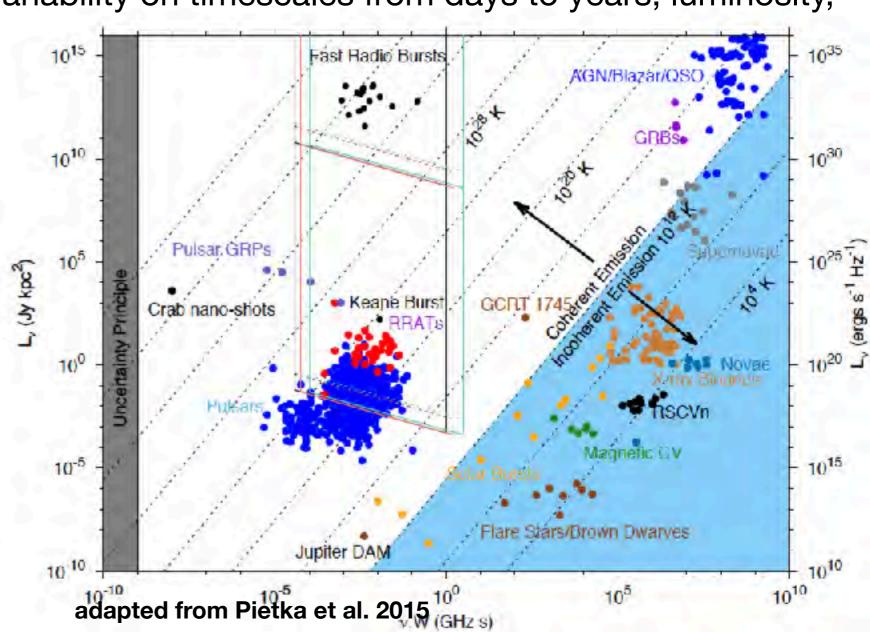
Goal #2 The periodic sky

Discover radio pulsars with variability on timescales from days to years, luminosity,

spectral index, etc.

Potentially

- Incoherent mode:200 new FRB within 5 years
- Coherent mode:
 100s of faint FRB with subarcsec localization
- 100s of new pulsars

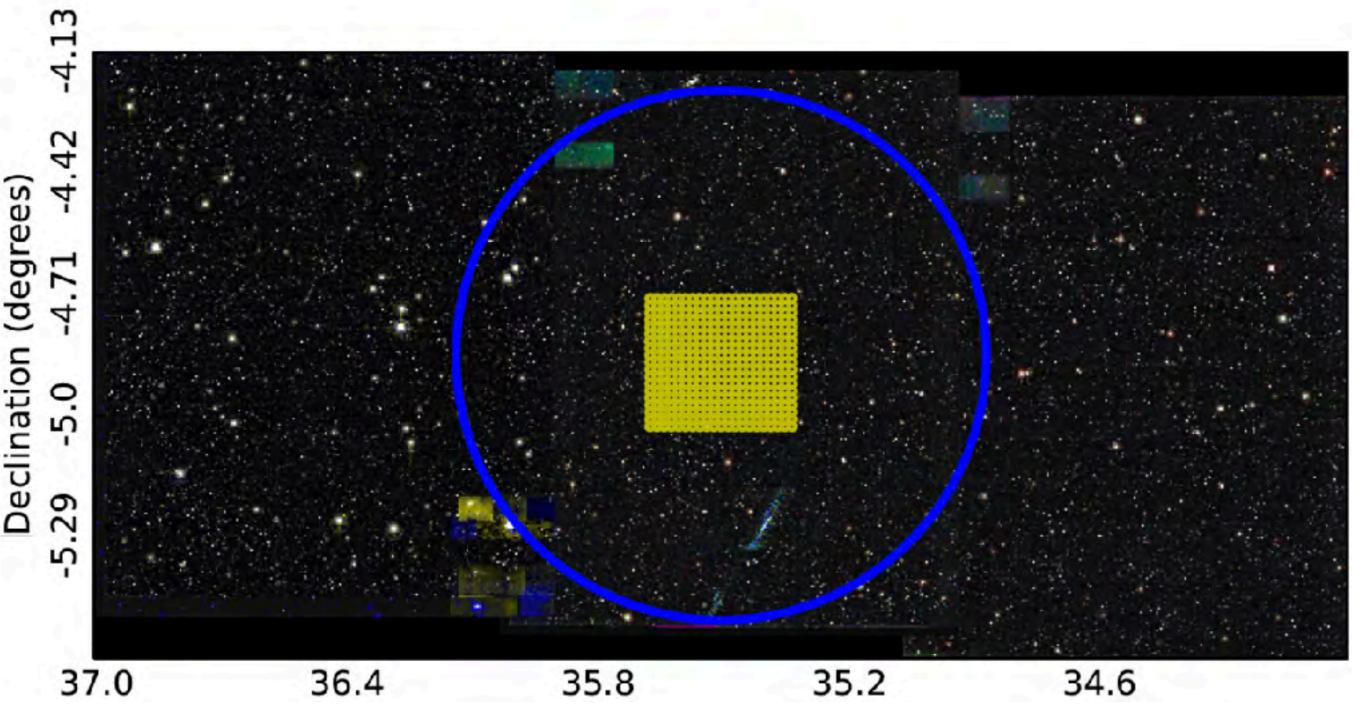


erc

MeerTRAP MeerLICHT Buffer = 30 sec**Positions** correlator transient imager buffers Transient Triggers Optical Detections Ethernet switch MeerKAT real-time heamformer fast transient External triggers pulsar detector Pulsars & Transients **GPU** Data **Archive Incoherent mode** or coherent mode Time after UT 19.50.01.00 (ms)

 $DM > 3000 \text{ pc.cm}^{-3} (z>2)$

MeerTRAP



A 4.5 square degree part of the XMMLSS field that will be observed by MeerKAT Large Survey (MIGHTEE)

- incoherent mode beam (blue)
- 400 coherent mode beams (yellow)

Dectection and distribution of events

Transient Discovery TraP

Swinbank et al. 2015

Already used for LOFAR, ALARRM, JVLA-CHILES VERDES

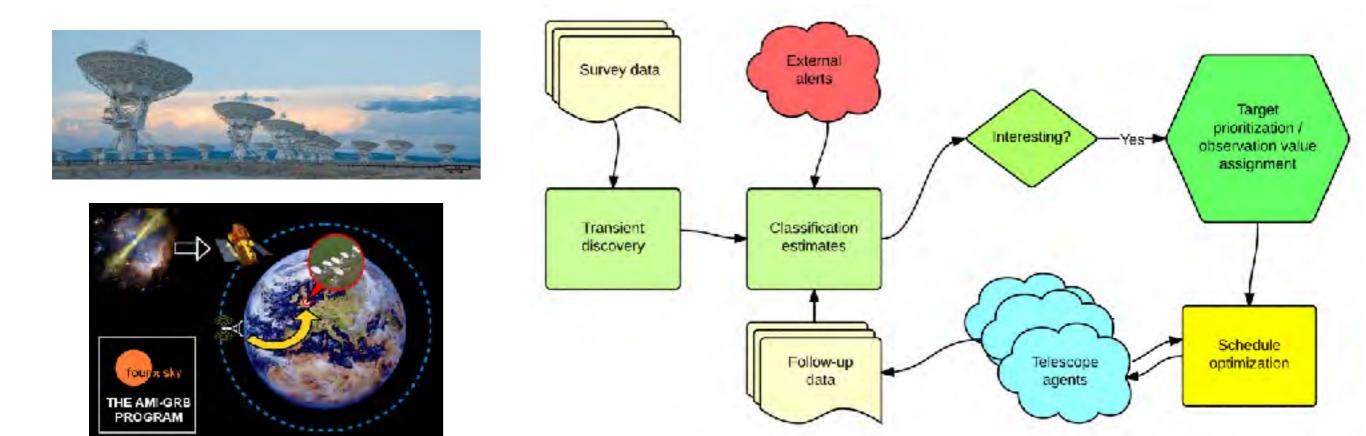


Alerts distribution and processing

VOEvent with **Comet** Swinbank 2014 4πsky VOEvent Broker

Automated data reduction

Classification and smart follow-up schedule



Figures from 4PI Sky website http://4pisky.org/

Extra references

Leon Houben

See presentations in Aspen 2017

A VOEvent standard for FRBs

Emily Petroff

http://aspen17.phys.wvu.edu/Houben.pdf

BlackGem & MeerLICHT (GW)

http://www.ing.iac.es/astronomy/science/Steven_Bloemen_ING_2018.pdf

http://aspen17.phys.wvu.edu/Stappers.pdf TRAPUM & MeerKAT www.trapum.org

https://4pisky.org/ 4pisky

Comet http://comet.transientskp.org/en/stable/

http://wiki.ivoa.net/twiki/bin/view/IVOA/IvoaVOEvent **IVOA-VOEvent**

SKA1 Level 0 Reqs

https://www.skatelescope.org/wp-content/uploads/2014/03/SKA-TEL_SCI-SKO-SRQ-001-1_Level_0_Requirements-1.pdf

VAST Online & Offline transient classification http://www.physics.usyd.edu.au/sifa/vast/ http://www.physics.usyd.edu.au/sifa/vast/uploads/Main/vast_memo5.pdf

LOFAR Transient pipeline https://arxiv.org/abs/1503.01526

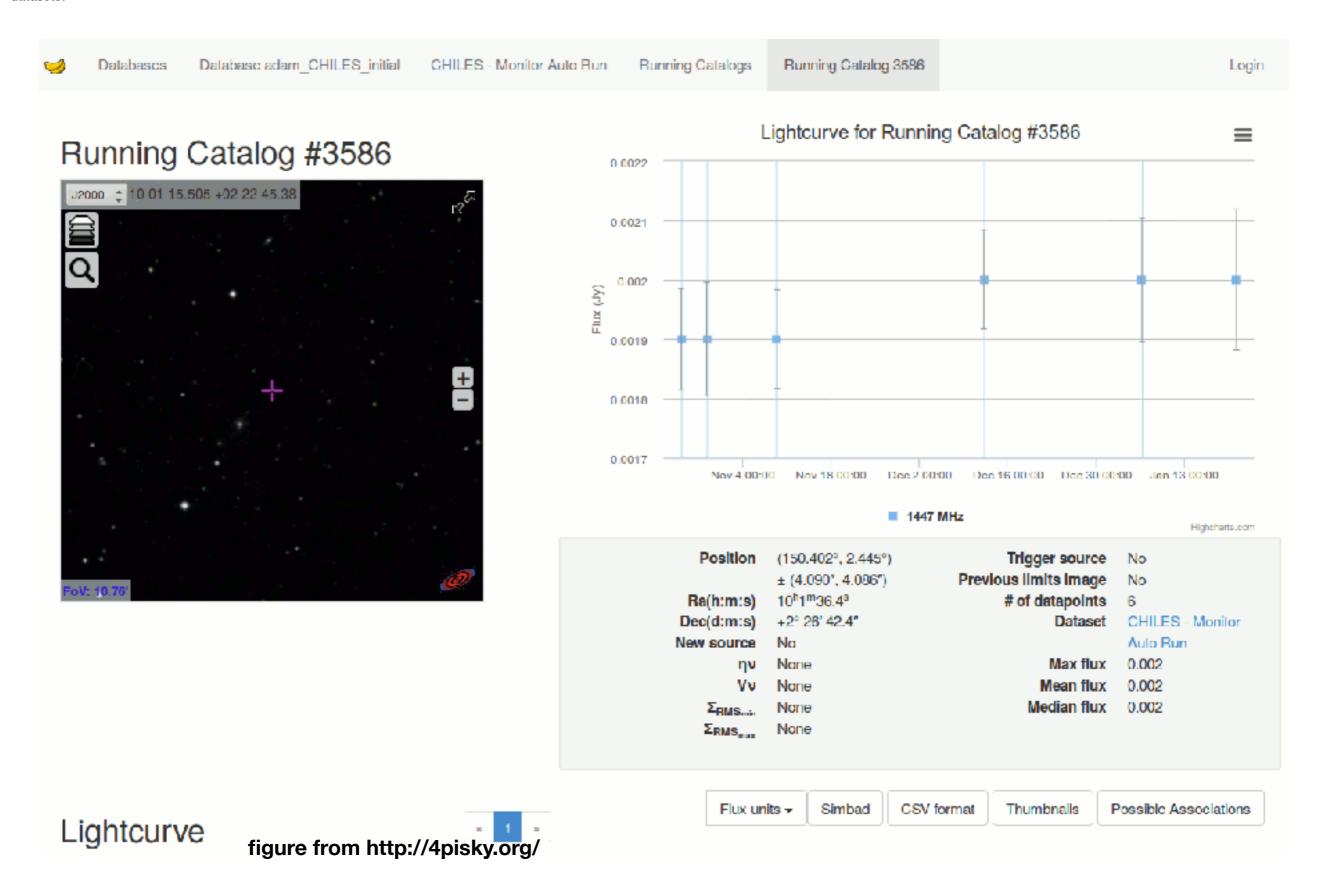
https://github.com/transientskp/tkp

Highlight from the SKA conference in GOA

https://www.skatelescope.org/news/highlights-from-the-ska-science-conference-in-goa/

All presentations, figures and references belongs to their respective authors.

The TraP has already been put to good use on data from the LOFAR RSM, ALARRM, and JVLA-CHILES surveys (see our <u>projects page</u>). Hopefully this open release will allow profitable use with many more datasets.



CHILES Transients

CHILES = COSMOS HI Large Extragalactic Survey

VERDES = Variable & Explosive Radio Dynamic Evolution Survey

Transient Search of the COSMOS HI Large Extragalactic Survey

The COSMOS HI Large Extragalactic Survey (CHILES) is a project using the JVLA, centred on the COSMOS field, to produce the first HI deep field covering a redshift range from z=0 to z=0.45. The project offers deep, multi-epoch observations and 4 Pi Sky will be involved in searching these data for transient events with the TraP software. The COSMOS field is also widely covered by other wavelengths (for example the Pan-STARRS project) and 4 Pi Sky will also observe the field concurrently in the optical waveband using the Liverpool Telescope. Please refer to Fernandez et al. (2013) for more information on CHILES

In a three-hour-long observing epoch, we will reach a rms sensitivity of 10 microJy/beam. In the co-add of all 1000 hours of CHILES data, our continuum rms sensitivity will be 500 nanoJy/beam.

While the field of view of CHILES VERDES is relatively small (~30' in diameter), its many epochs and truly incomparable depth probe a whole new region of radio transient parameter space.

CHILES VERDES is a deep survey for transient and variable objects in the radio sky. We piggy-back off 1000 hours of <u>VLA</u> observations on the <u>CHILES HI Deep Field</u> to "deep drill" at 1--2 GHz in the <u>COSMOS</u> field, searching for explosions, collisions, and disruptions.



