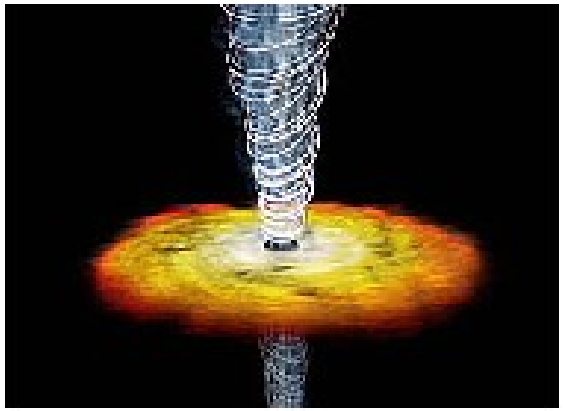


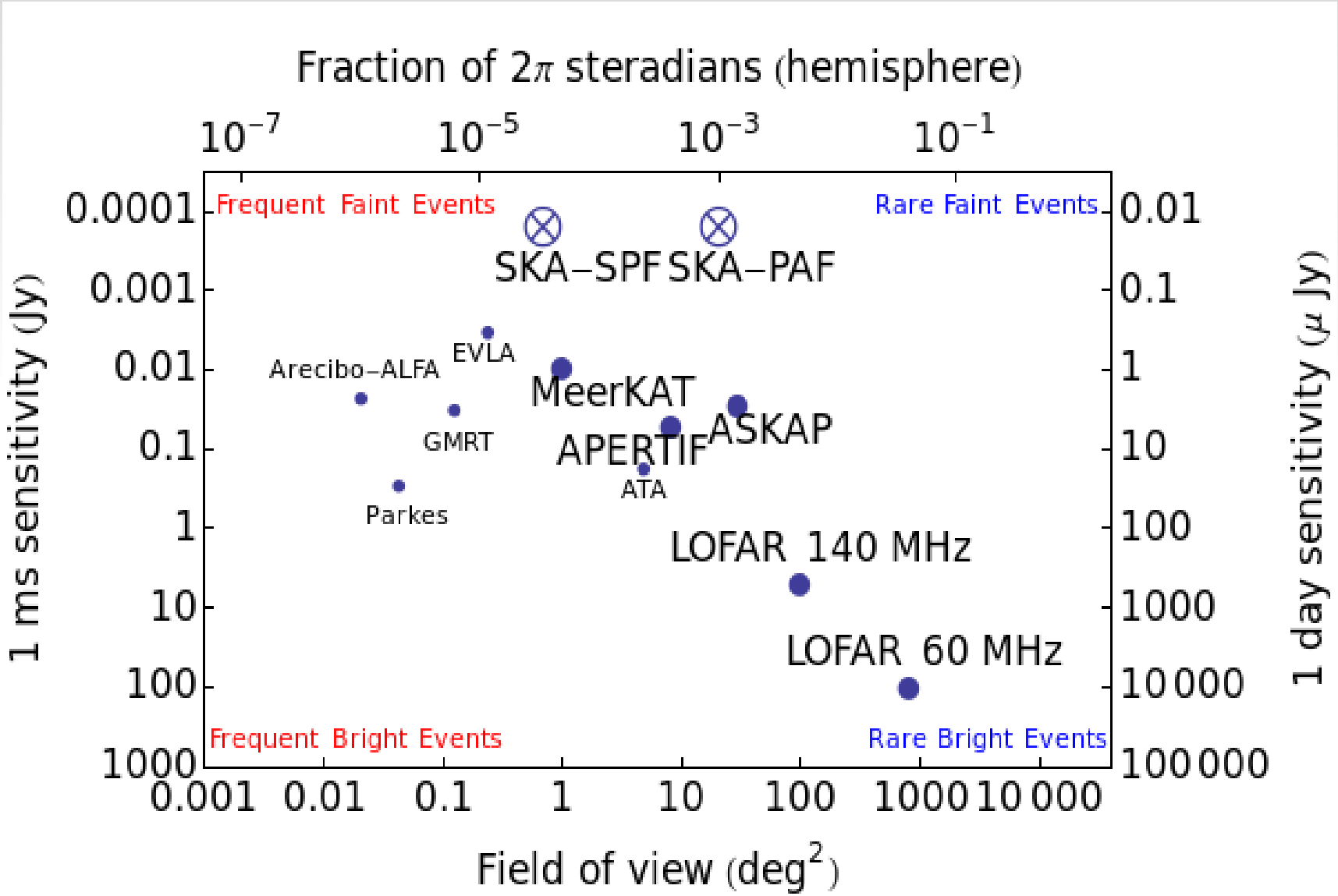
The LOFAR Transients Key Science Project

Rob Fender
(University of Southampton)
Ben Stappers
(University of Manchester)
Ralph Wijers
(University of Amsterdam)

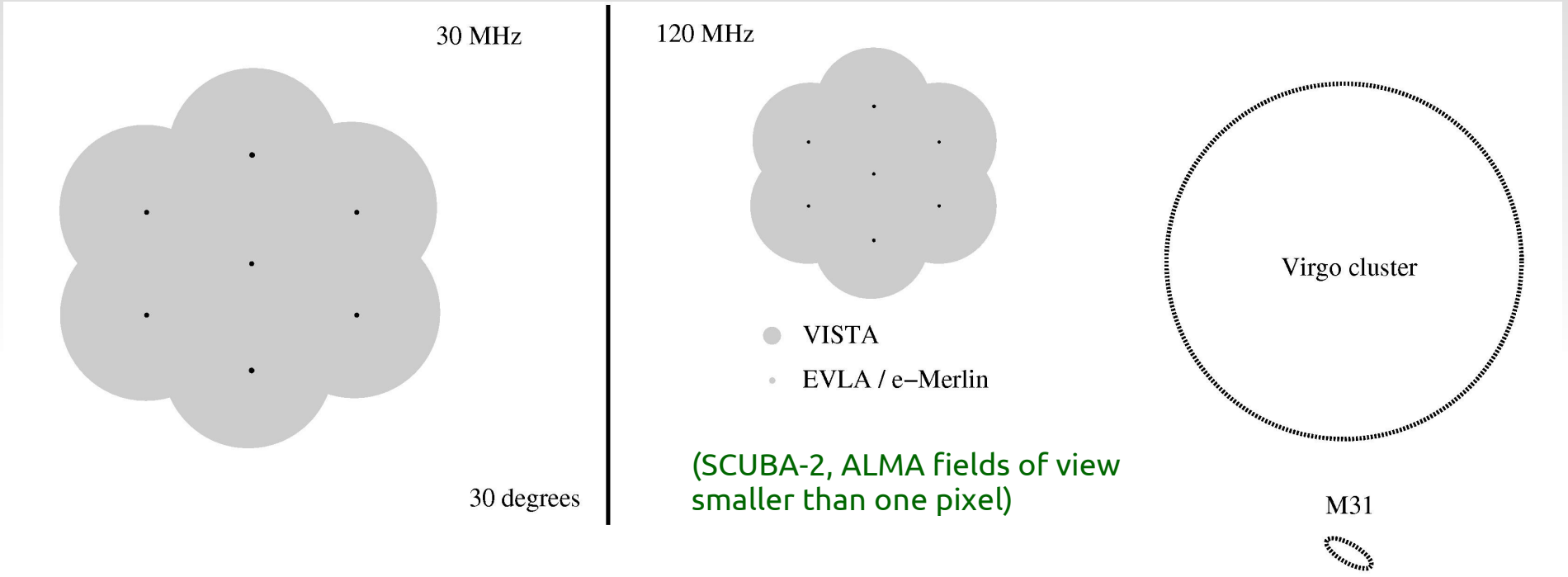
+ about 50 other people

Next-gen radio astronomy: good for transients:

(i) sensitivity, (ii) field(s) of view (iii) software telescopes –
rapid response, 'lookback', simultaneous imaging and μs time series



LOFAR – the biggest field of view of them all



(SCUBA-2, ALMA fields of view smaller than one pixel)

Large collecting area **x** *vast field of view* **x** *multiple beams*
= unprecedented survey speed (while maintaining arcsec resolution)

Very deep and wide surveys / all-sky monitoring for transients

LOFAR Key Science Projects (KSPs)

- Surveys (Leiden)
- EoR (Groningen)
- Transients (Amsterdam/Southampton/Manchester)
- Cosmic Rays (Nijmegen)
- Solar (Potsdam)
- Magnetism (Bonn)

The first four are the 'original KSPs'

Transients should get 5–15% of LOFAR time in first five years, plus 100% commensal searches

Two flavours of transients

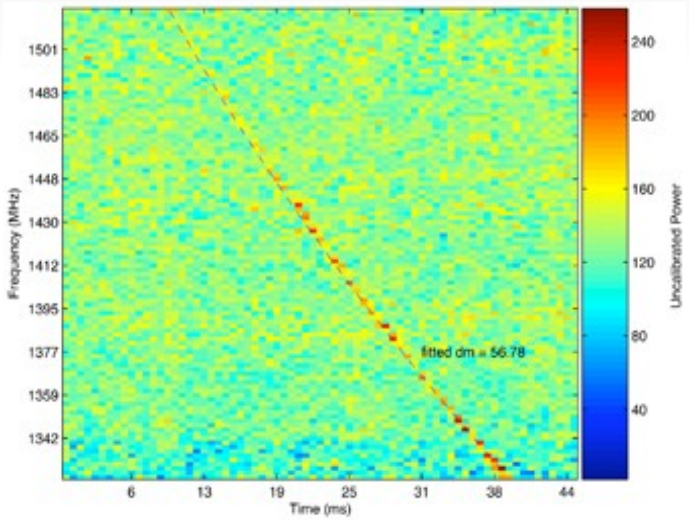
Incoherent synchrotron emission

Relatively slow variability
Brightness temperature limited
Associated with all explosive events

Early branch in classification pipelines

Coherent emission

Relatively fast variability
High brightness temperature
Often highly polarised

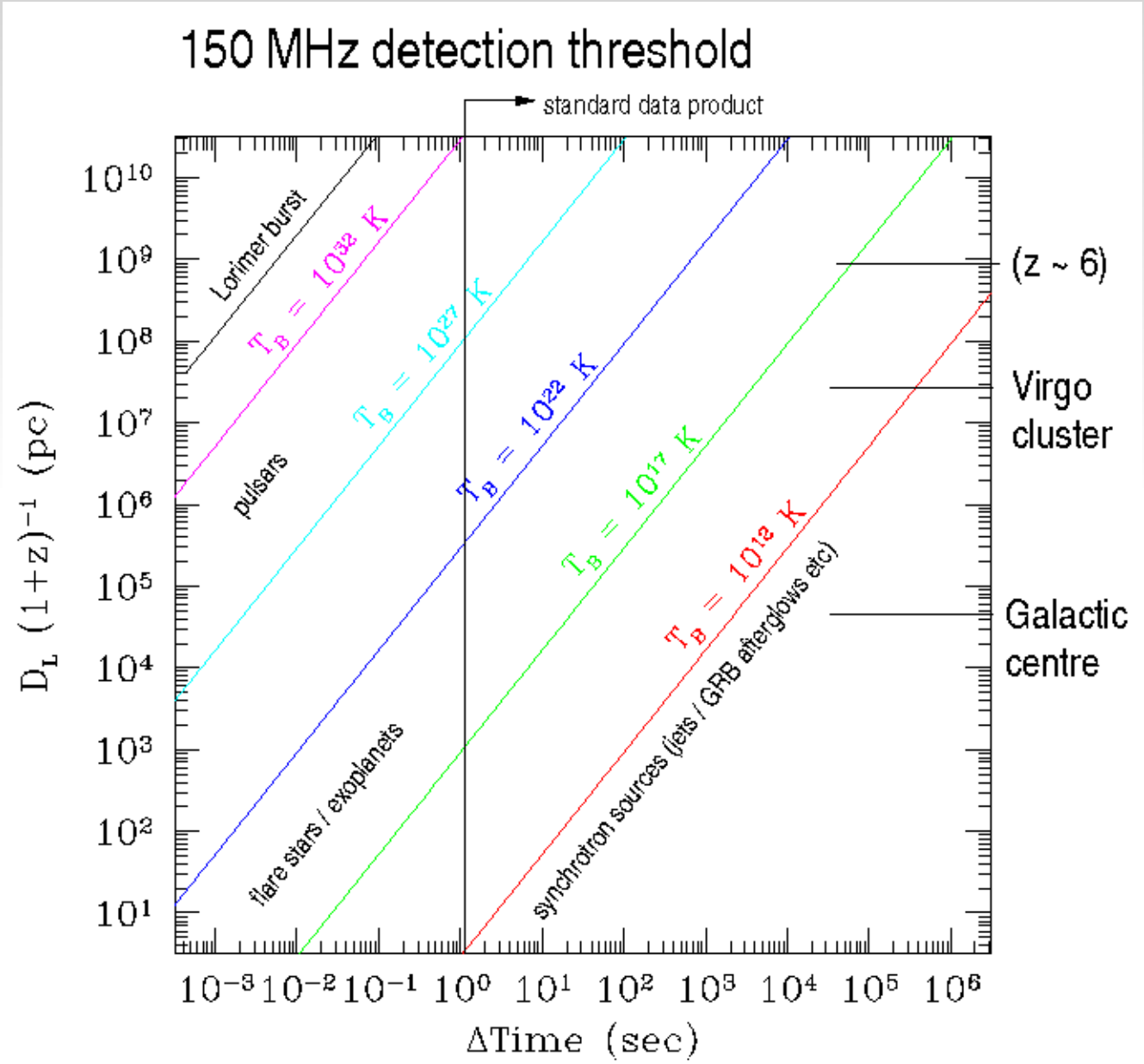


Find these (mostly) in images (~ThunderKAT)

Find these (mostly) in time series (~TRAPUM)

Transient parameter space (LOFAR example)

COHERENT



SYNCHROTRON

Synchrotron emission
(GHz → EVLA, eMerlin, ATA, APERTIF, MeerKAT, ASKAP)

All cases of explosive injection of energy into the ambient medium result in particle acceleration and/or an amplification of the local magnetic field → synchrotron emission.

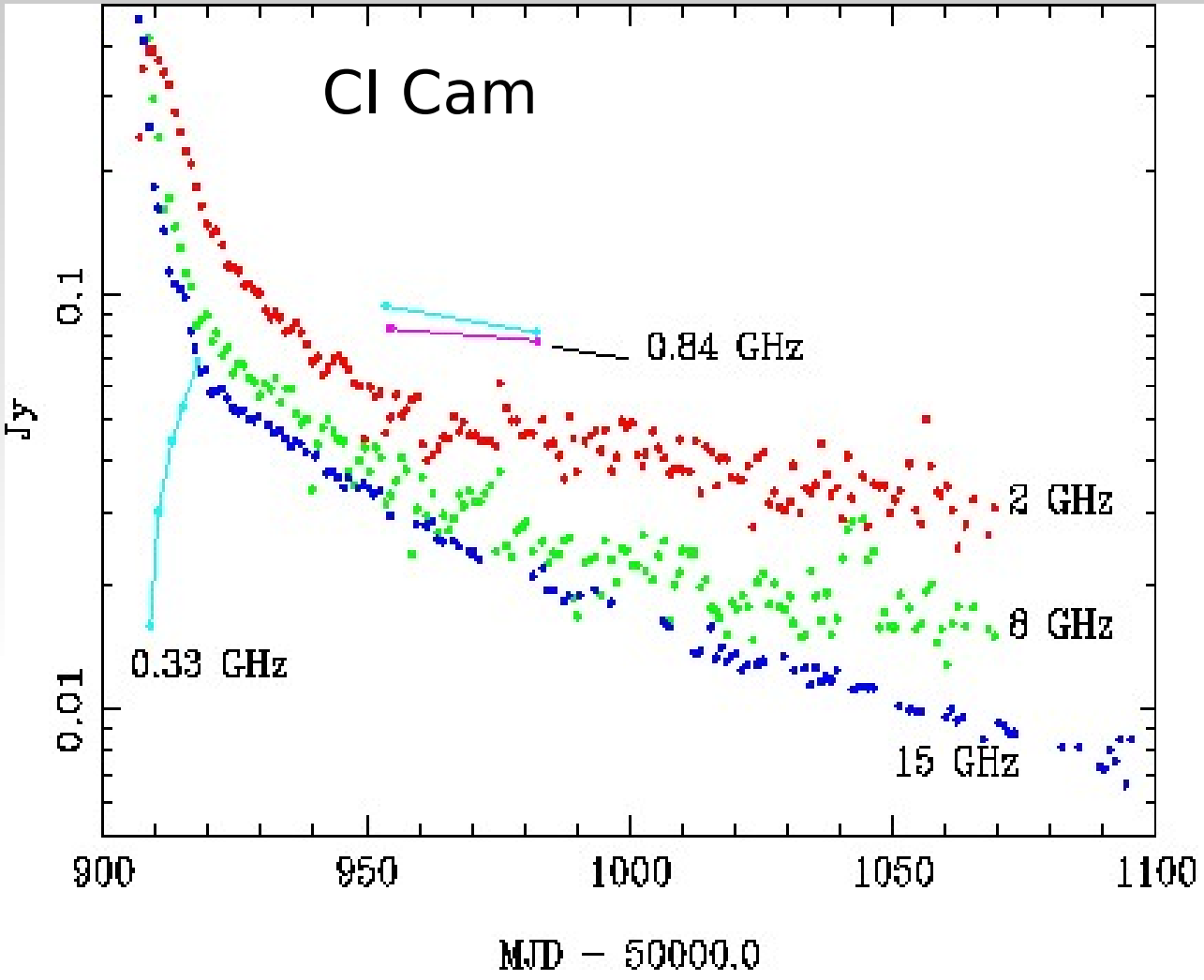
Examples of these include

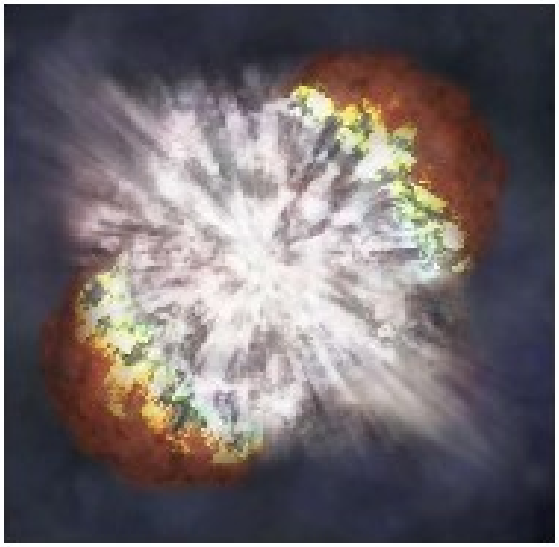
(i) Relativistic jets from X-ray binaries ('microquasars') / AGN

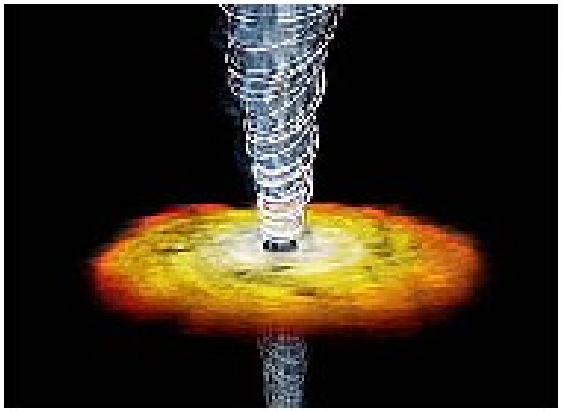
(ii) Supernovae and GRB afterglows

(iii) Giant outbursts from magnetars

Well established multiwavelength communities for such objects – usually associated X-ray and optical activity. However, limited to $B_T \leq 10^{12}$ K and can be self-absorbed at low freq.





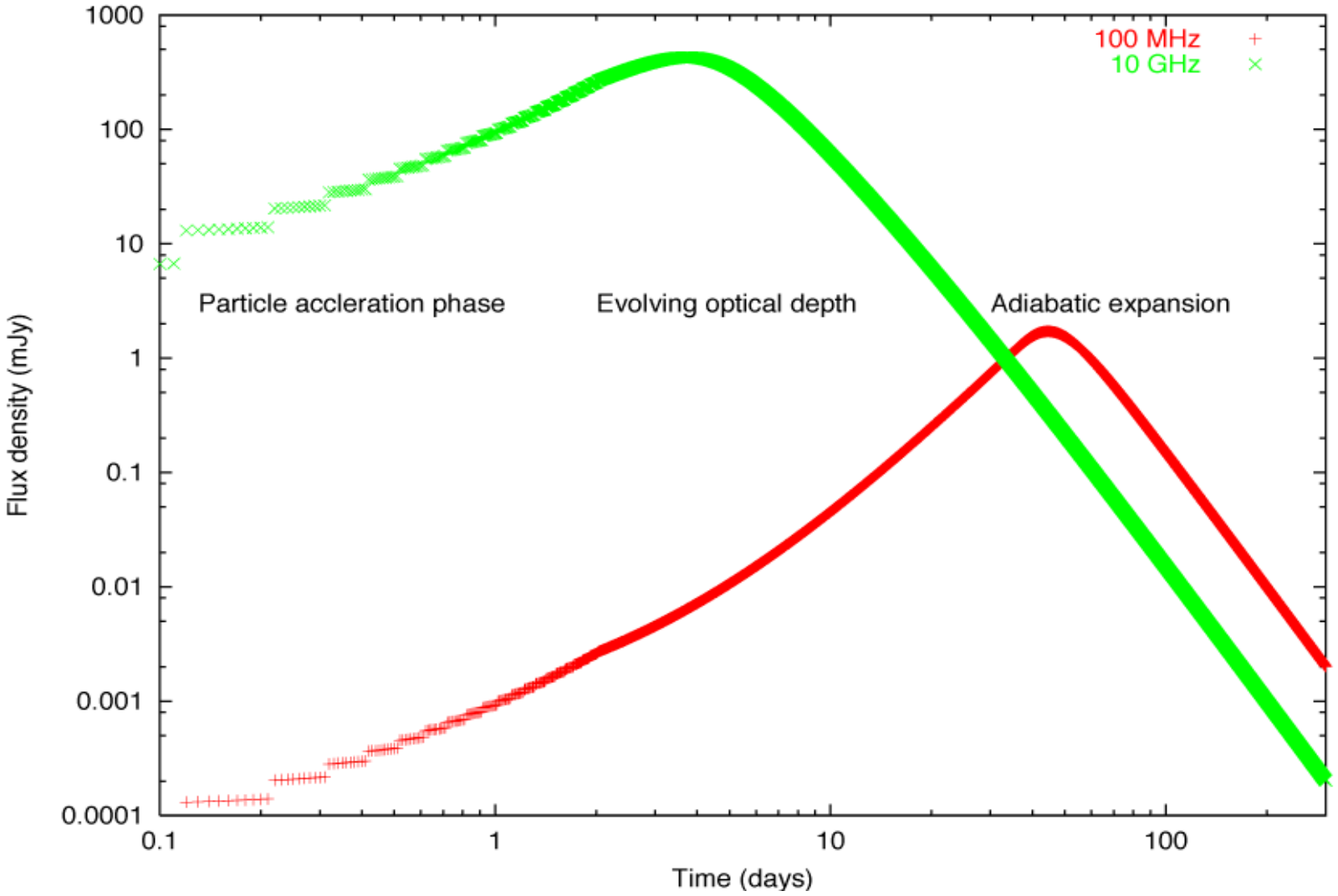


Explosive particle acceleration in GRB afterglows, microquasar jets, supernovae → long-lived low-frequency synchrotron emission

→Time-resolved census of particle acceleration in our galaxy

→ **BUT** low frequencies not optimum for early warning

Simulated 'van der Laan' single expanding blob



Delays may be **years** for the most luminous events (e.g. GRB afterglows)

Coherent emission
(MHz facilities – LOFAR, MWA, LWA, phase I SKA-low)

Resulting from the coherent movement and emission of radiation by electrons

Examples of these include

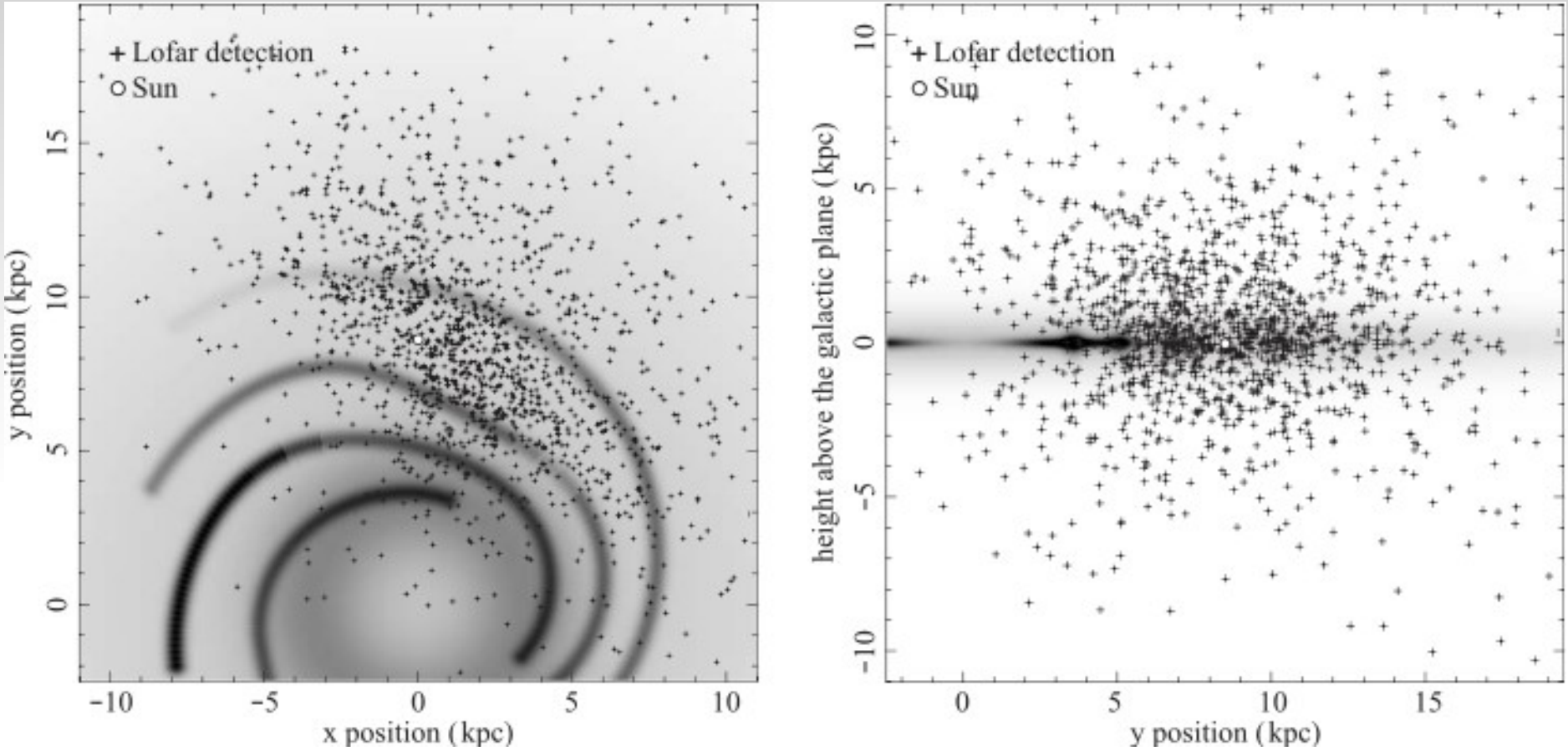
(i) Pulsars and other neutron star phenomena

(ii) Flare stars / Planets / cyclotron masers

(iii) Who knows ?

These can have extremely high brightness temperatures and usually rise steeply at low frequencies → very exciting area for exploration with LOFAR

Pulsars

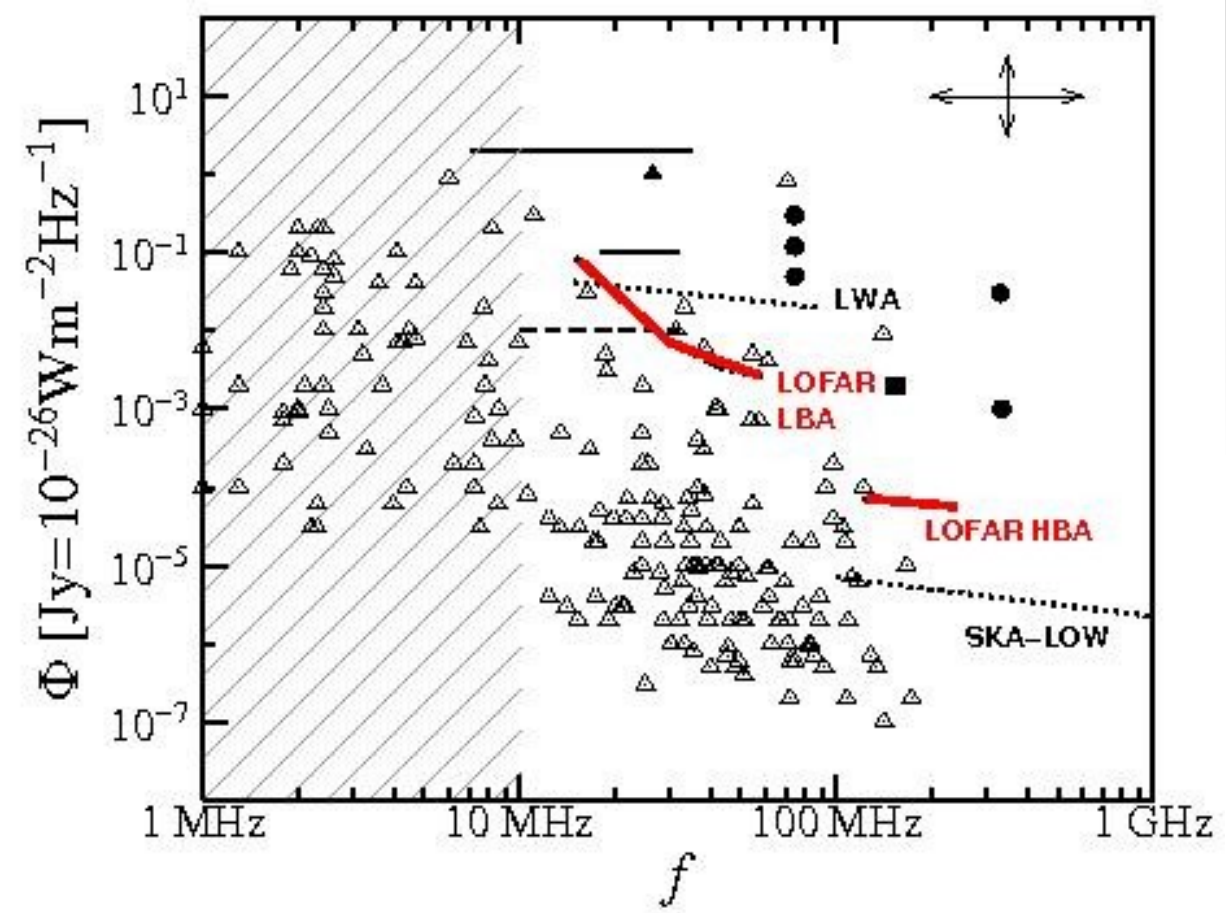


Pathfinder survey of pulsars in the northern skies

→Northern sources for the pulsar timing array (→ gravitational waves)

Also constrain pulsar | RRAT branching / BH + NS binary / probe ISM

Extrasolar planets



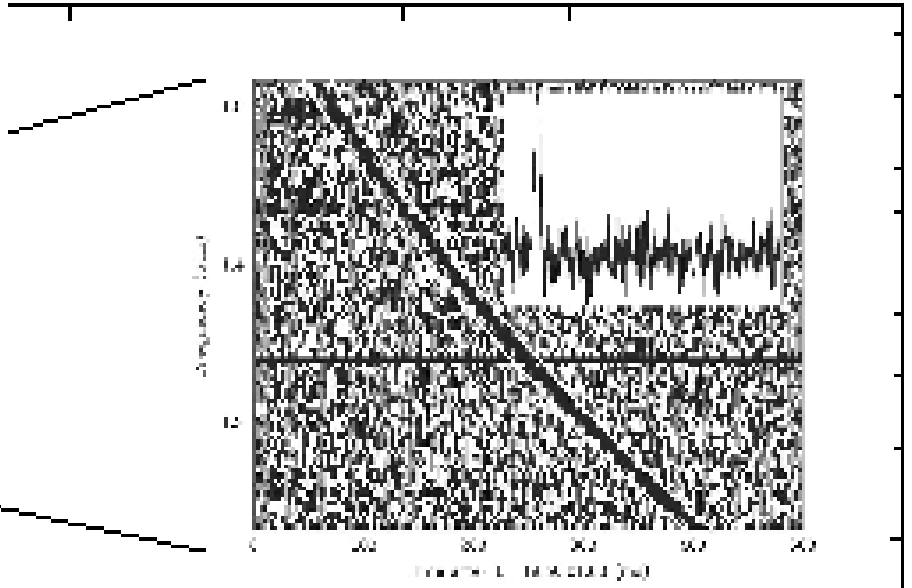
Scaling Jupiter's emission for 'Hot Jupiters' experiencing much stronger stellar winds, we could discover radio bursts to distances of 10s of pc

→Inclination independent method for finding planets

→Provide <u>physical information</u>: rotation rate / magnetic field strength unavailable by any other means

Note that the lowest frequencies are required

Extragalactic radio bursts



Freq (MHz)

600

400

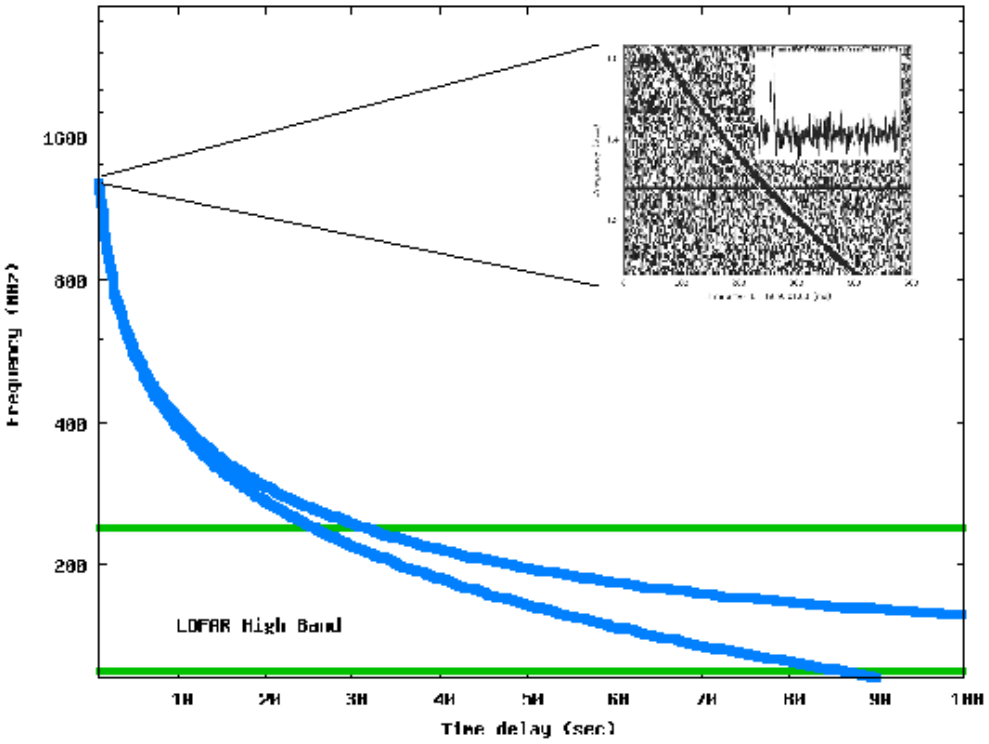
200

5ms burst at 1.4 GHz originated at >0.5 Gpc

LOFAR should detect **1000s** of such events, perhaps <u>one per day</u> dispersed to durations of minutes in LOFAR band

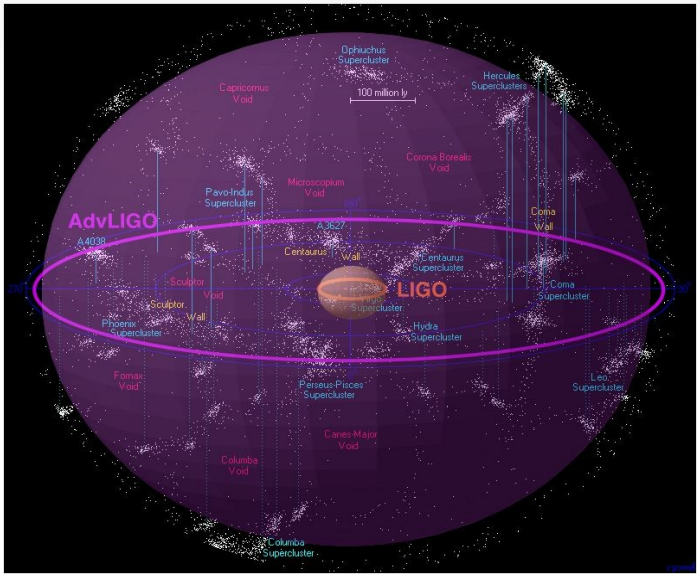
LOFAR high band

10 30 Time delay (sec) 90



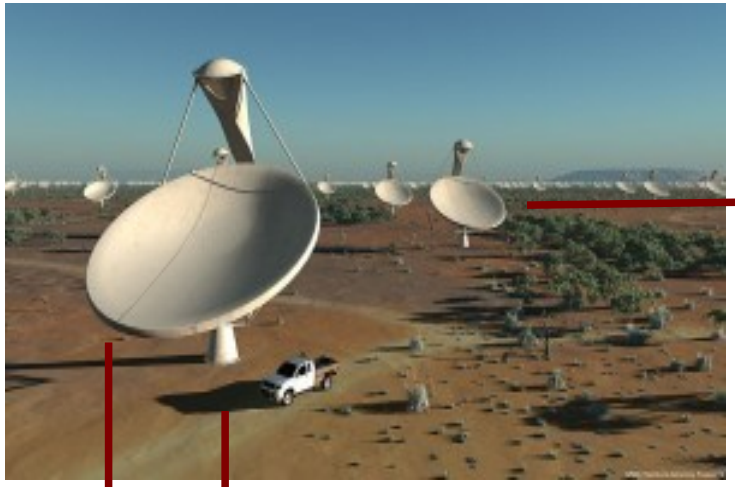
Such bursts would allow us to probe the physics of the IGM/ICM all the way back to EoR ▪we can measure dispersion measure and (maybe) rotation measure to probe the electron and magnetic field content / turbulence

If these burst are associated with ‘LIGO events’ – such as a NS-NS merger – LOFAR may provide the first electromagnetic localisation of a gravitational wave event



Combining LIGO and LOFAR measurements will provide two completely independent measurements of distance on cosmological scales, test theories of gravity etc.

The ThunderKAT spigot (~1 yr away?)



Correlator

spigot

CPU cluster running standard imaging pipeline

User

Data rate for full f.o.v. and full b/w ~700 Mb/sec

ThunderKAT system

Imaging (cluster)

Source finding

Analysis

Report if interesting

≤1 sec cycles

Collaborators / outside world (via e.g. *VOEventNet*)
Rate estimate ≥ 1 day^{-1}

LOFAR 1 sec real-time imaging (~1 yr away?)

Correlator

spigot

CPU cluster running standard imaging pipeline

User

LOFAR Transients pipeline
(see J Swinbank talk this p.m.)
'piggybacking' mode

Imaging (cluster)

Source finding

Analysis

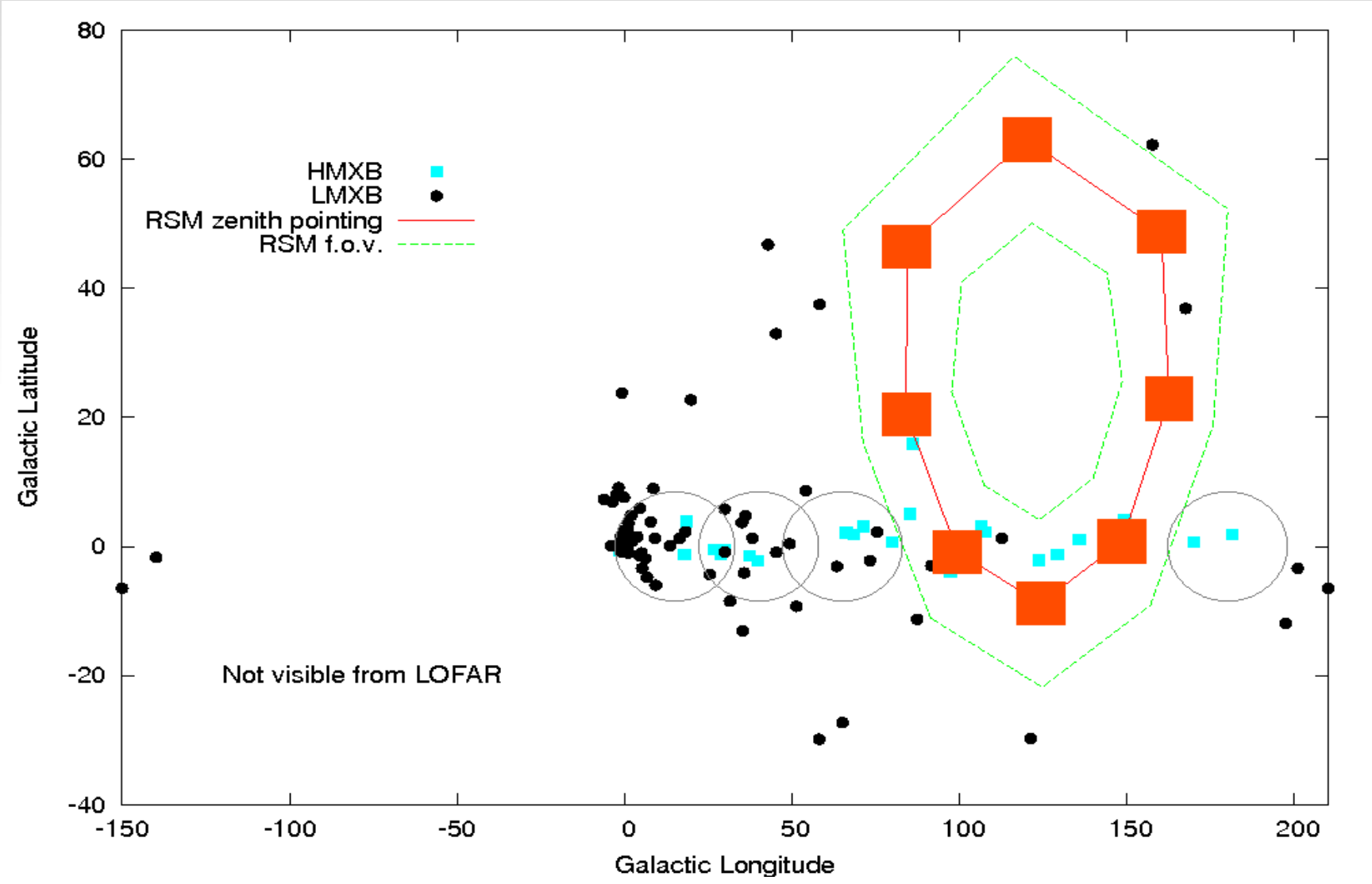
Report if interesting

≤1 sec cycles

Collaborators / outside world
(via e.g. *VOEventNet*)
Self-triggered ToOs
Rate estimate ≥ 1 day^{-1}

Monitoring modes: the Radio Sky Monitor:

e.g. joint zenith- and galactic plane-monitoring programs



Special LOFAR Transients capabilities

- Simultaneous imaging and high time res modes

There is 'spare' capacity on the BlueGene CEP to allow both 'standard' imaging and 'pulsar' modes → all observations can be searched commensally for both image-plane and time-series transients

- Transient buffer boards

RAM chips at the station level can be frozen to record raw data for (few seconds)/(fraction of total b/w). For LBAs this means potential imaging 'back in time' in any part of the accessible hemisphere. Used by both Transients and Cosmic Rays KSPs.

Transients KSP Organisation

Fender,
Stappers,
Wijers

All-KSP face to face:
Southampton (Dec 10)
Amsterdam (Jun 11)
France (Dec 11) + + . . .

Jason Hessels

Jochen Eisloeffel

JETS
Markoff,
Miller-Jones

PULSARS / H/W
Stappers

COUNCIL
(telecons)

MULTI-MESSENGER
Jonker,
Wijnands

PLANETS
Zarka

DISCOVERY
Wise,
Swinbank

FLARE STARS
Osten

FRATs
James

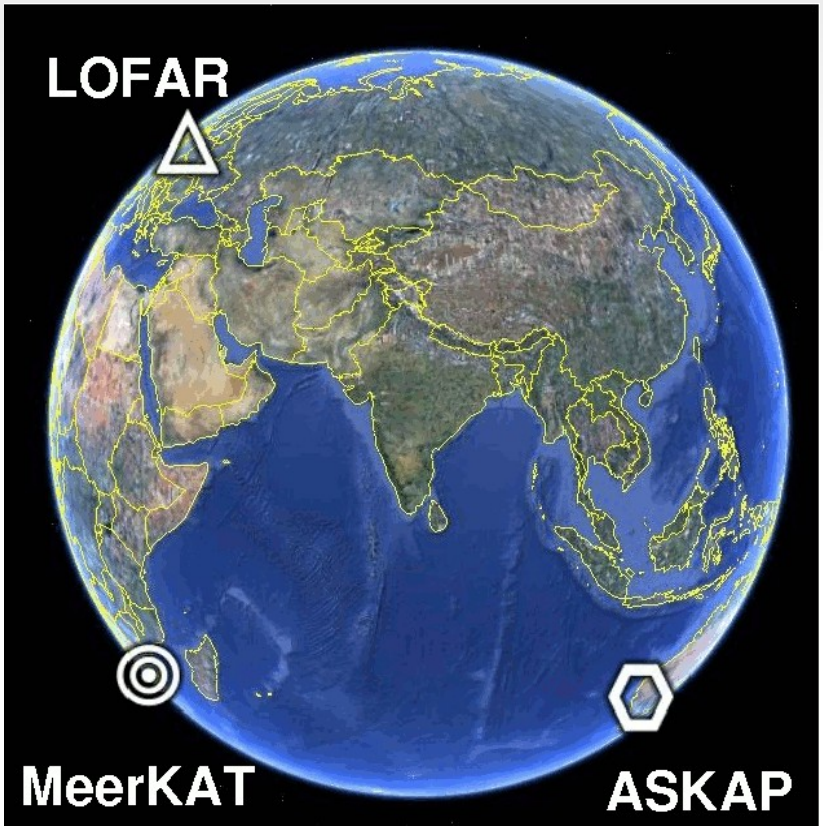
LOFAR and ThunderKAT

Should be a strong collaboration. Can share experience, algorithms, software... even follow-up programs.

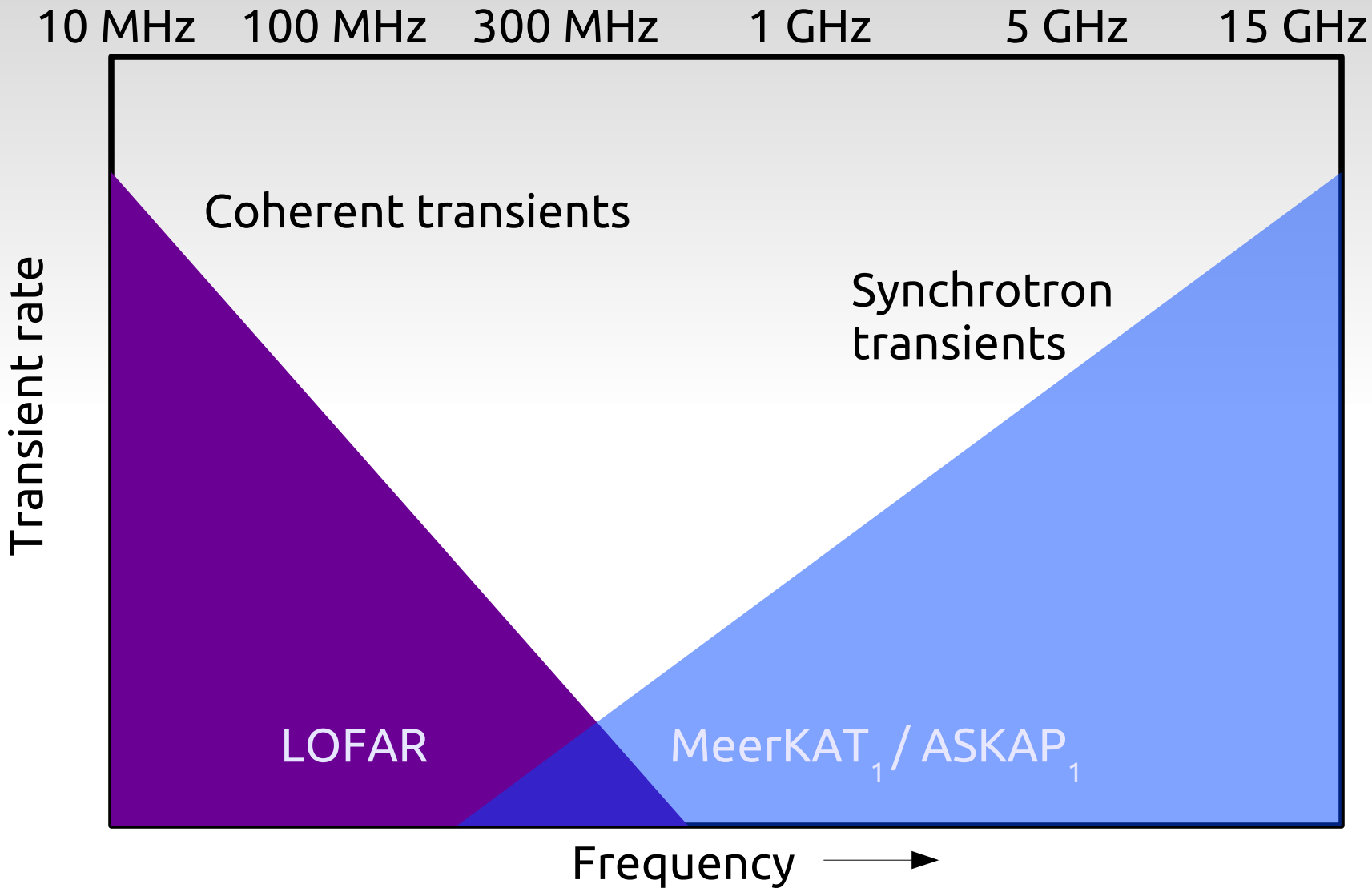
Can imagine a global transients 'system' in which LOFAR, MeerKAT and ASKAP work together

Total combined rate of transients 10 – 1000 day^{-1}

Both (all?) projects need to implement their (spigots/transient pipelines) on a timescale of ~1 yr



Comparison of low- and high-freq transient populations is very interesting. Use LOFAR/MWA compared to ASKAP/MeerKAT



Speculation: is L-band close to a local min in total transient rate ?

We are taking data and doing transient / variable science (finally!)

- Pulsars
- 0329+54 zenith field (see talk by Martin Bell)
- SS 433 (see talk by Jess Broderick)
- Cygnus X-1
- Cygnus X-3
- (flaring) Crab
- We will also look at e.g. Virgo and other extragalactic fields for transients

Summary

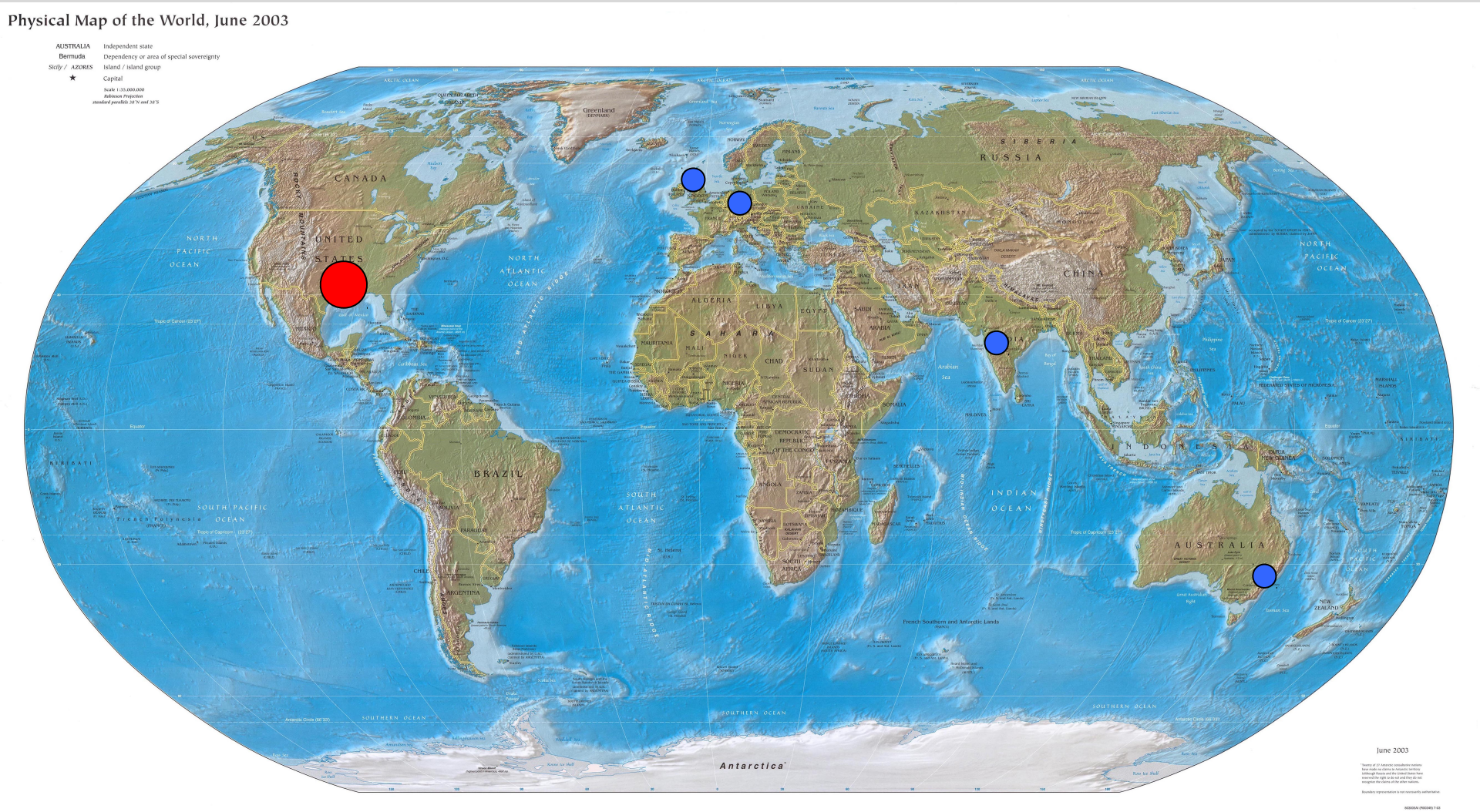
Radio Astronomy is undergoing a massive expansion.

New facilities have huge fields of view, extremely rapid response and revolutionary software developments – multiple fields, lookback etc. Perfect for transients.

LOFAR has the largest field of view and is going to be the broadest survey of the *coherent* radio transient sky until at least SKA_1. We will operate *Radio Sky Monitor* acting as a transients alert mechanism for the worldwide community.

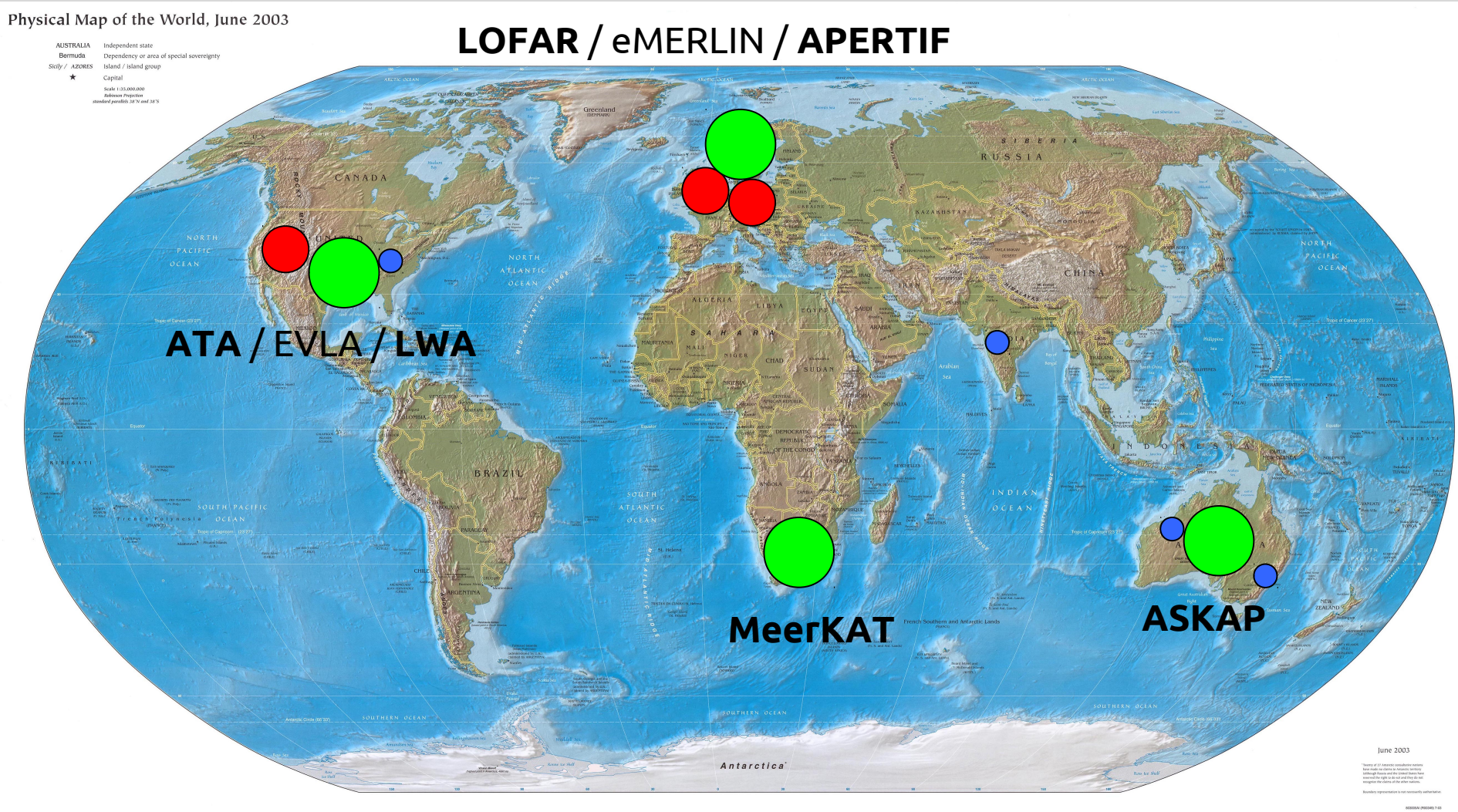
We are in 'partnership' with ThunderKAT and willing to share experience, expertise, code etc.

A new 'golden age' for radio astronomy



Major facilities as of 2009

The next five years...



Discussion: coordination between surveys

- 'Top three' radio transient surveys: LOFAR TKSP / MeerKAT (ThunderKAT / TRAPUM) / ASKAP (VAST / CRAFT)

Opportunities for shared experience / algorithms / software

Also, opportunities for coordinated programs e.g.

- Simultaneous LOFAR+optical+MeerKAT observations of ~equatorial fields (e.g. SS 433, GRS 1915+105..)
- ~Continuous coverage of interesting / outbursting sources

Should we sign MoU ?

Discussion: coordination between surveys

- Multimessenger surveys

e.g. Opt/IR transient surveys (Catalina, PTF, SkyMapper, etc)

X-ray ASM / survey programs (e.g. MAXI, AstroSat ASM, eRosita all-sky survey)

Cerenkov telescopes (MAGIC, HESS, → CTA)

Gravitational wave interferometers (Adv. LIGO)

KAT-7 science:

Please think of / suggest targets before

'ThunderKAT-7' talk on Thursday a.m.

Goals of the radio transients programs

(i) study all transient and variable radio sources

(ii) search the sky for new transients and variables

(iii) rapidly alert the worldwide astronomical community

How do we do this ? By developing

(a) strategies for regular monitoring of known variables in parallel with regular sweeps of large fractions of the sky

(b) (lots of) software for **automated** analysis, recognition, classification and alerts. Targeted and commensal obs.

(c) a broad international multi-messenger collaboration for parallel / follow-up studies of the most extreme phenomena

Is there any evidence that much remains to be discovered in the variable radio sky ? Yes !

Hyman et al. (2005, 2009) : unidentified, sometimes repeating, radio transients towards the galactic centre at 330 MHz

Lorimer et al. (2006) : a radio burst of possible extragalactic origin

McLaughlin et al. (2006) : coherent bursts from RRATs – 'intermittent pulsars'

Bower et al. (2007) : weak (mJy) unidentified transients in VLA test field

Hallinan et al. (2007) : periodic coherent pulses from an ultracool dwarf

Kida et al. (2008) : several unidentified >1 Jy transients at 1.4 GHz

Rubio-Herrera (in prep) discovers giant pulses from local group galaxies

Plus many new optical transients being discovered (e.g. PTF)