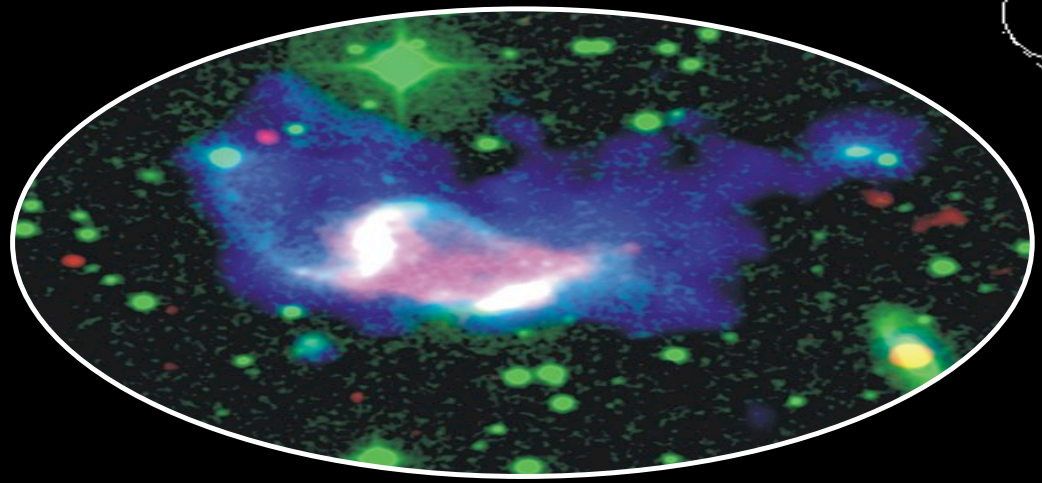
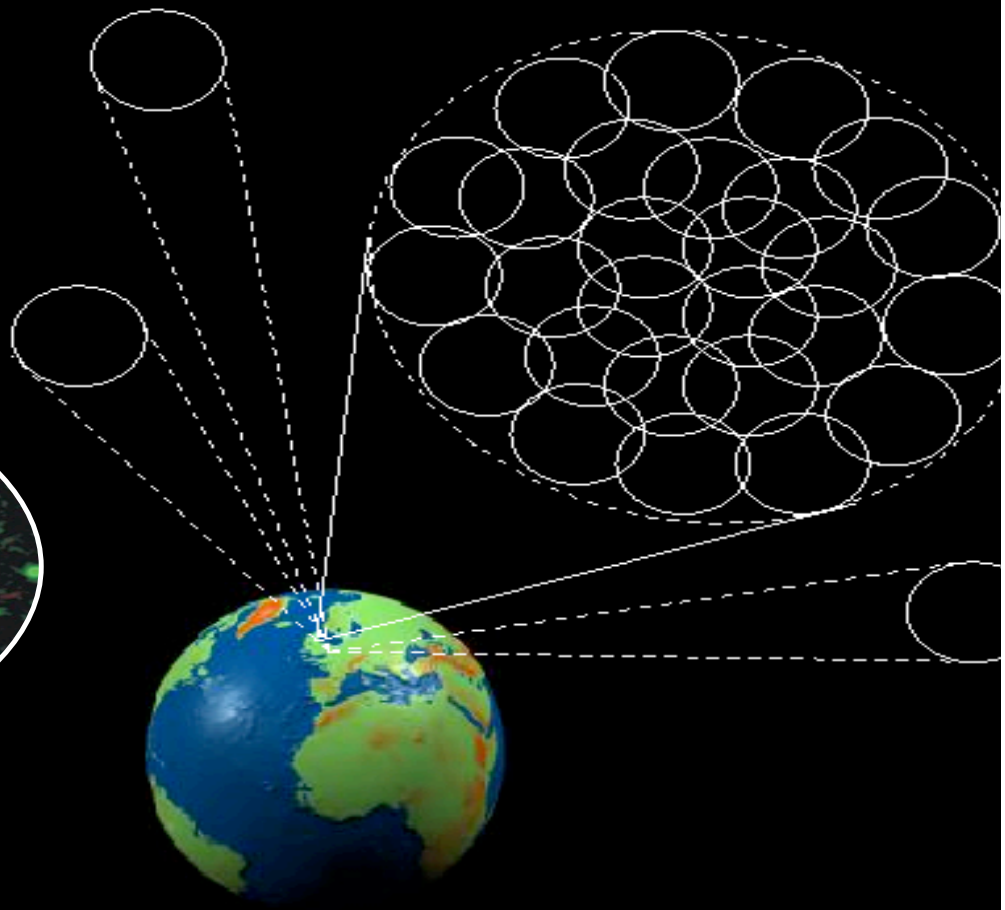
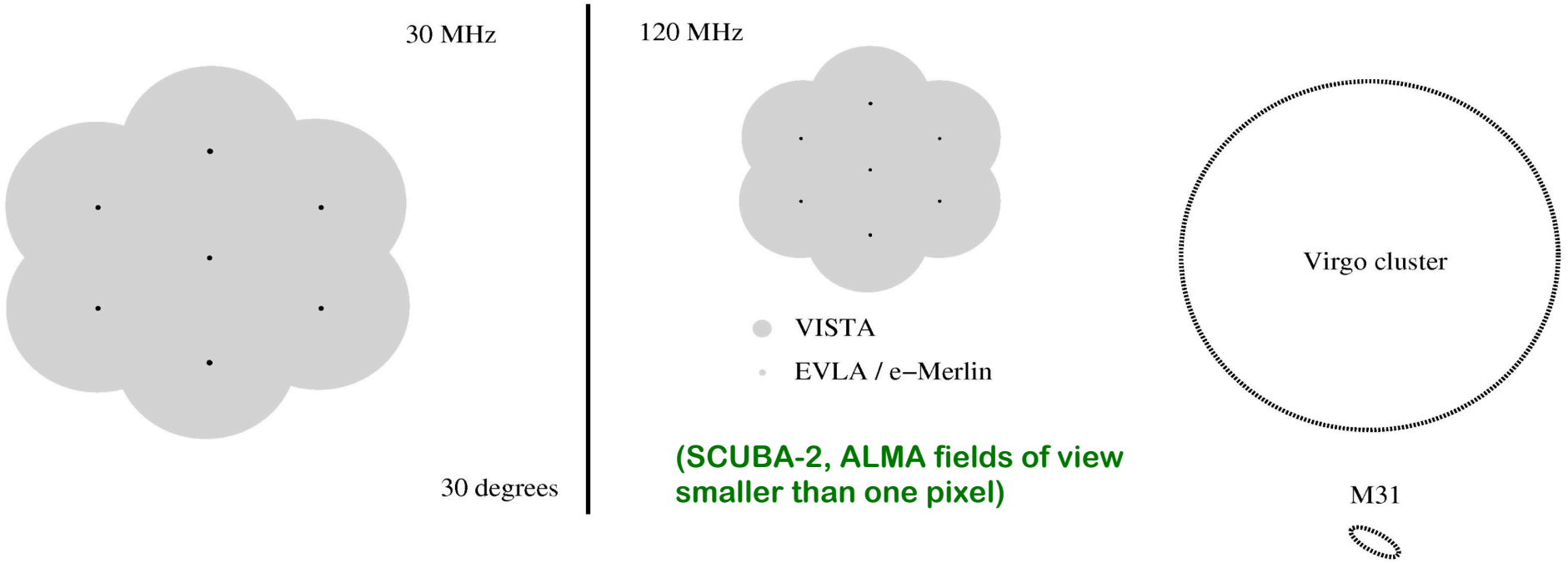
Radio Transients With LOFAR





Rob Fender, Ben Stappers and Ralph Wijers on behalf of the Transients Key Science Project

LOFAR: survey machine and transient monitor

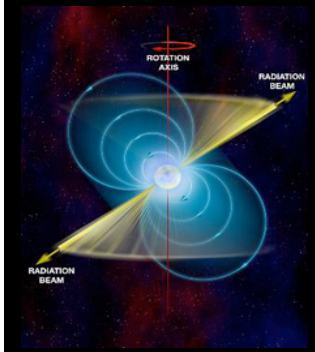


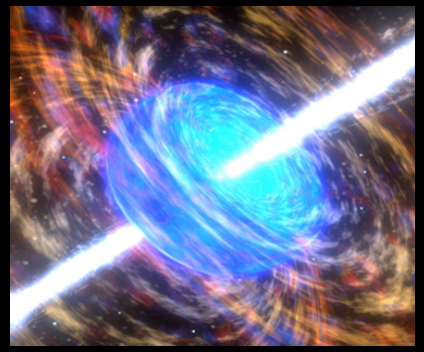
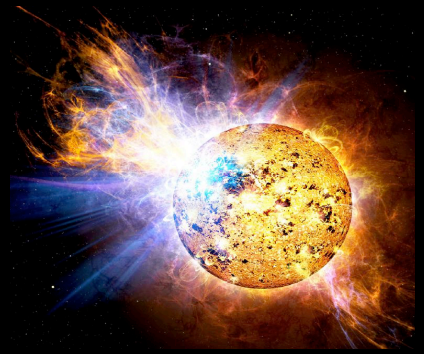
Large collecting area **x** ***vast field of view*** **x** ***multiple beams*** **= unprecedented survey speed (<u>while maintaining arcsec resolution</u>)**

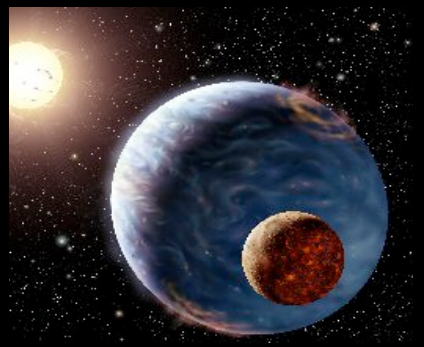
→ Very deep and wide surveys / all-sky monitoring for transients

Transient Radio Sky

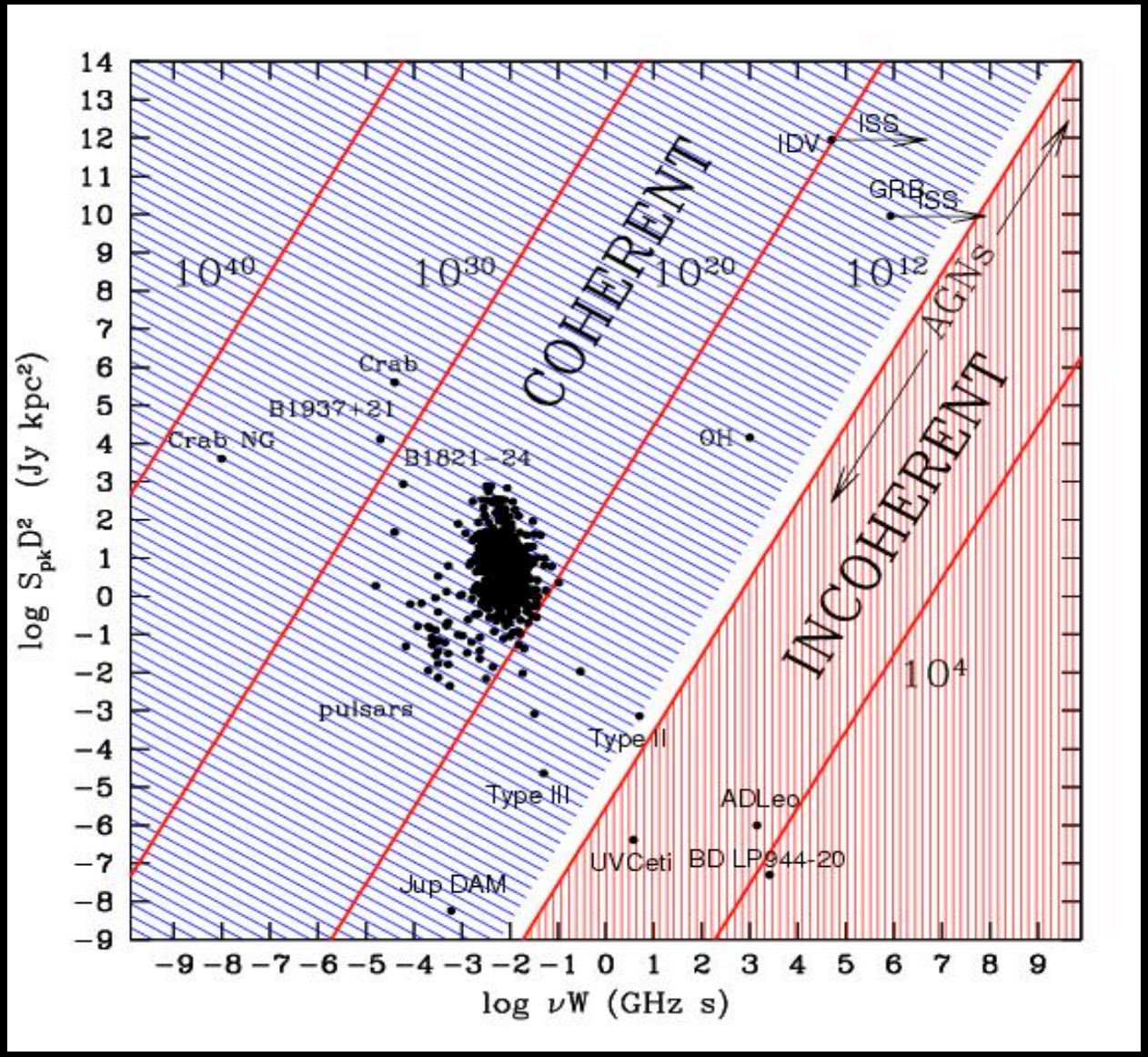
- Compact objects; explosive/dynamic events.
- Timescales of ns to years.
- Known sources:
  pulsars (also magnetars), gamma-ray bursts,
  flare stars, supernovae, planets.
- Likely unknown source classes as well.





Transient Radio Sky

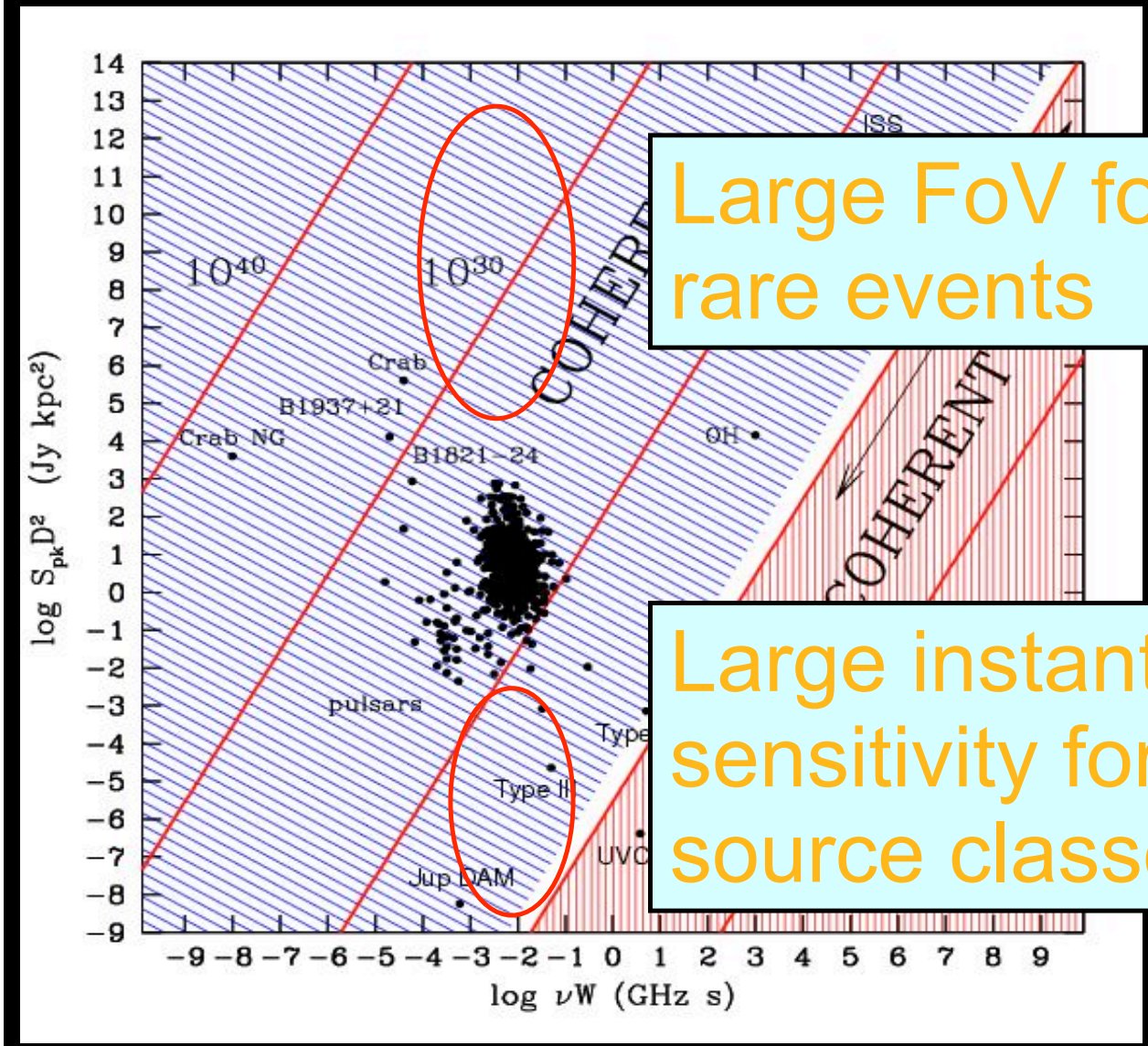


$(W\nu)^2 \propto SD^2/T$

Large portions of phase space empty and unexplored!

(Cordes et al. 2004)

Parameter Space Coverage

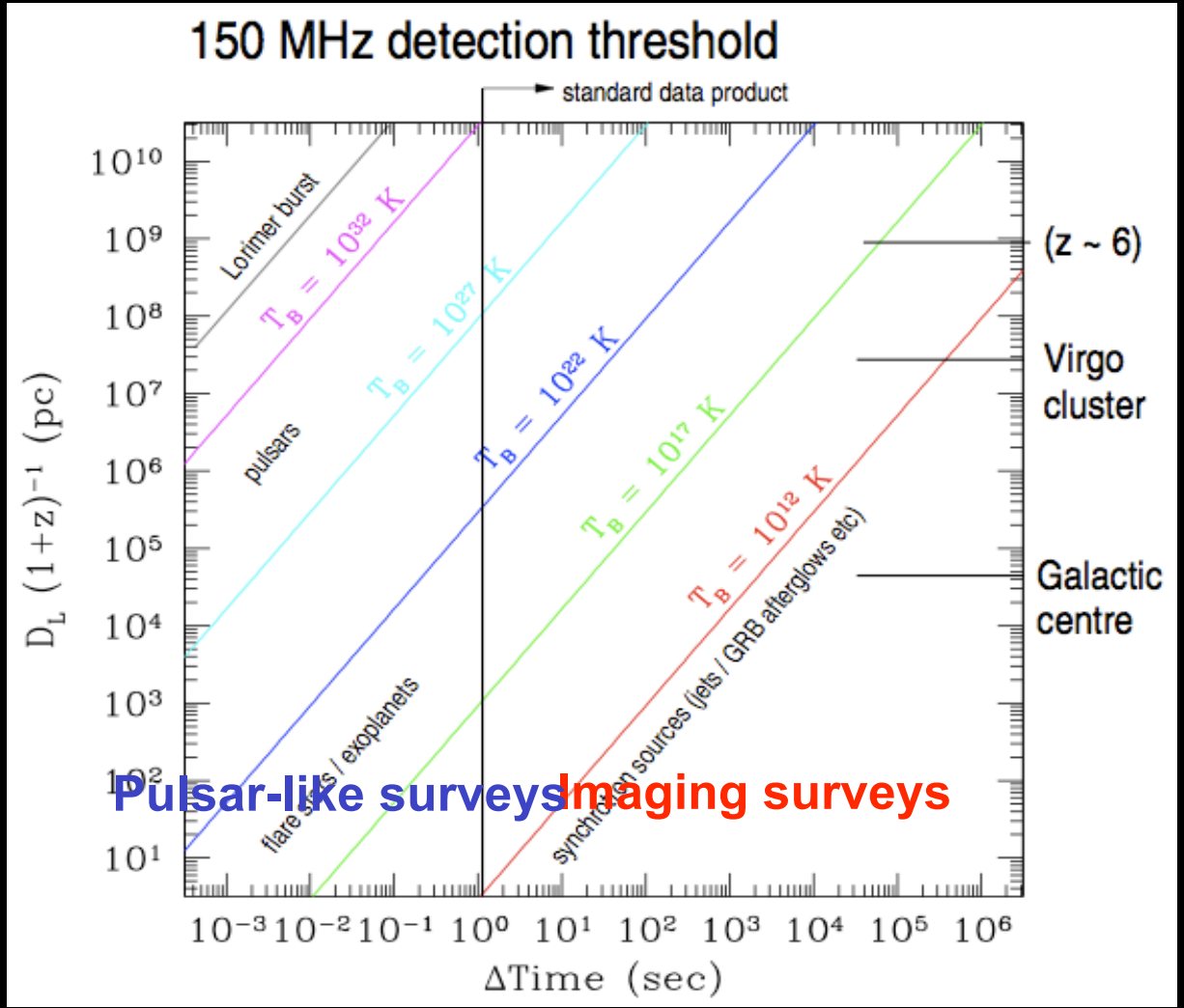


Large FoV for rare events

Large instantaneous sensitivity for weak source classes

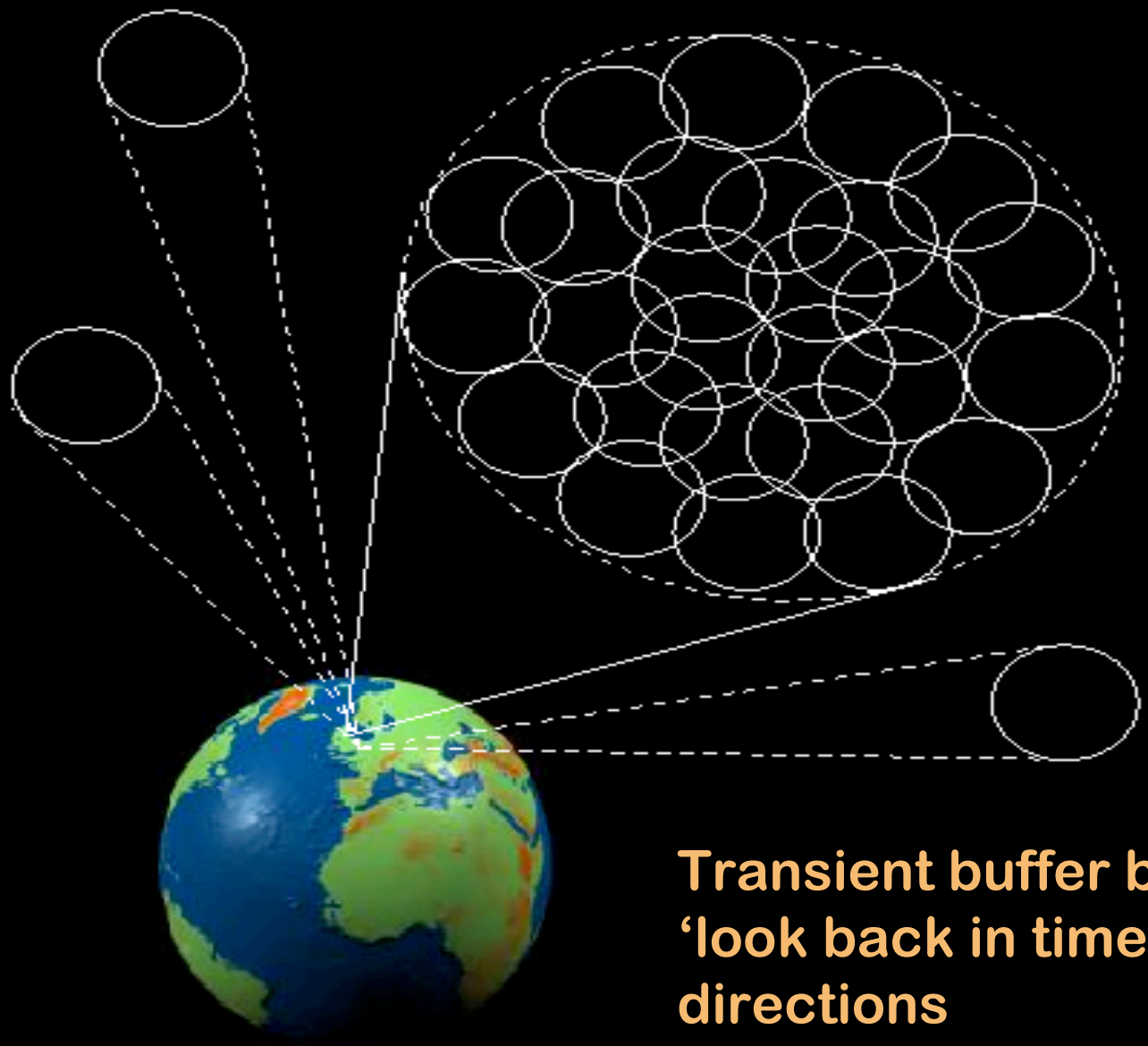
“Fast” Radio Transients

- Timescales of ns - seconds.
- Internal source variability and singular bursts.
- Probed only by non-imaging (timeseries) techniques.
- Propagation effects in ISM (e.g. scattering and dispersion) *very* important.
- RFI contamination.



(Fender et al. 2008)

The LOFAR Radio Sky Monitor

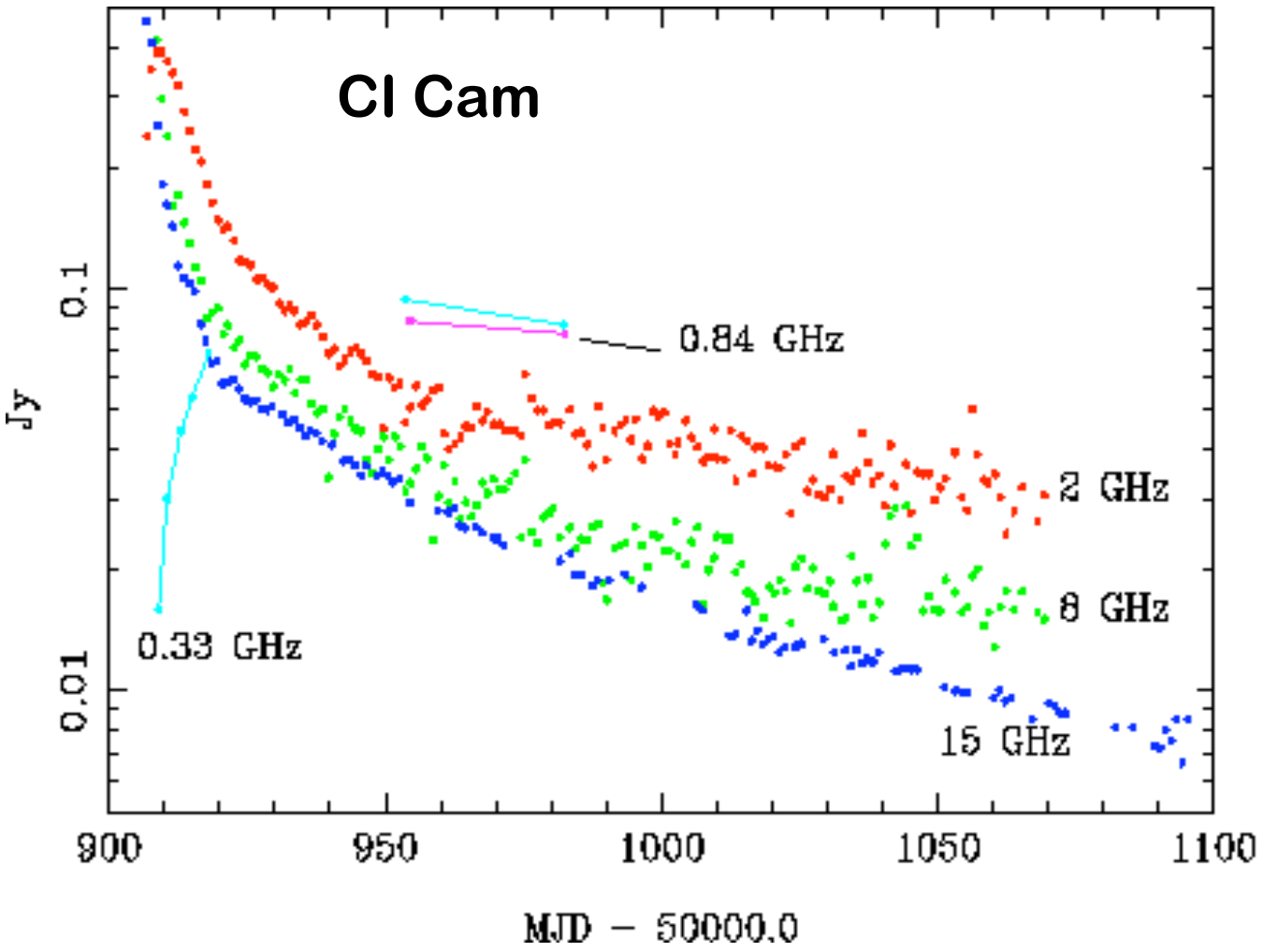


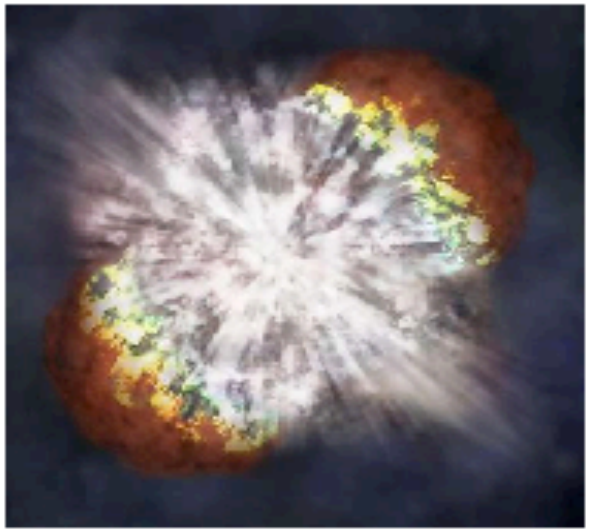
We will monitor entire visible sky ~daily to mJy level at 50/150 MHz

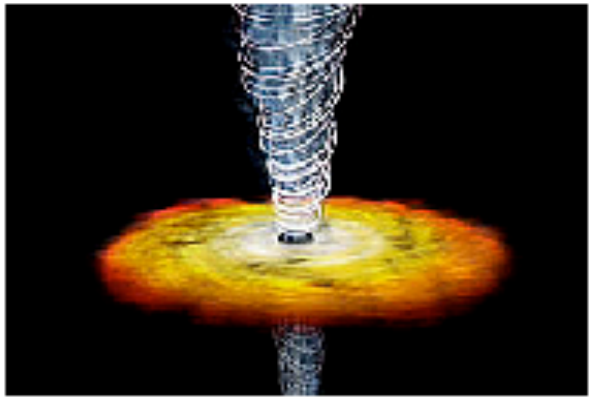
Localisation of transient sources to arcsec or better

Instant reporting of events

Transient buffer boards allow us to ‘look back in time in other directions





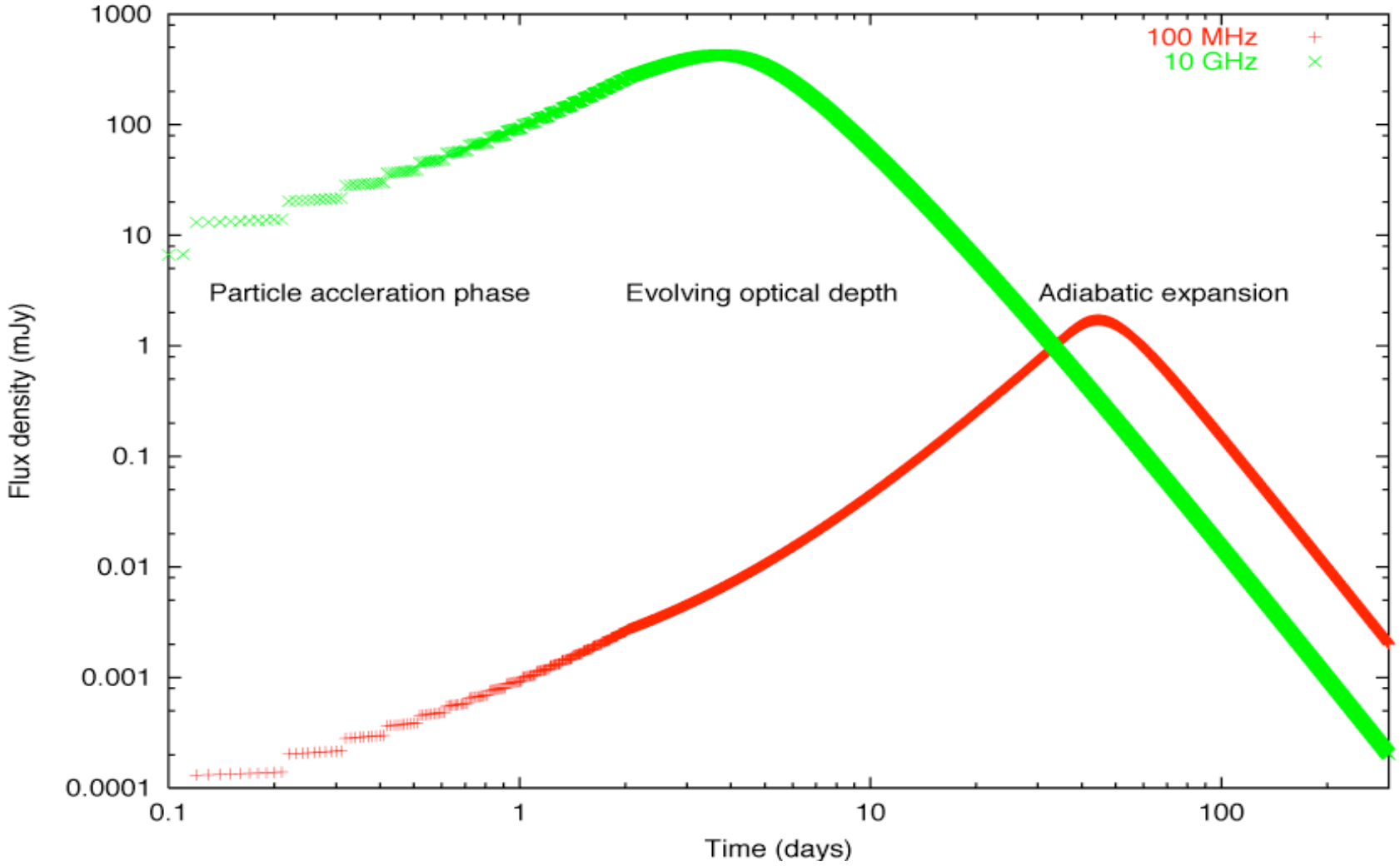


Explosive particle acceleration in GRB afterglows, microquasar jets, supernovae → long-lived low-frequency synchrotron emission

→Time-resolved census of particle acceleration in our galaxy

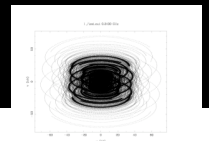
→ BUT low frequencies not optimum for early warning

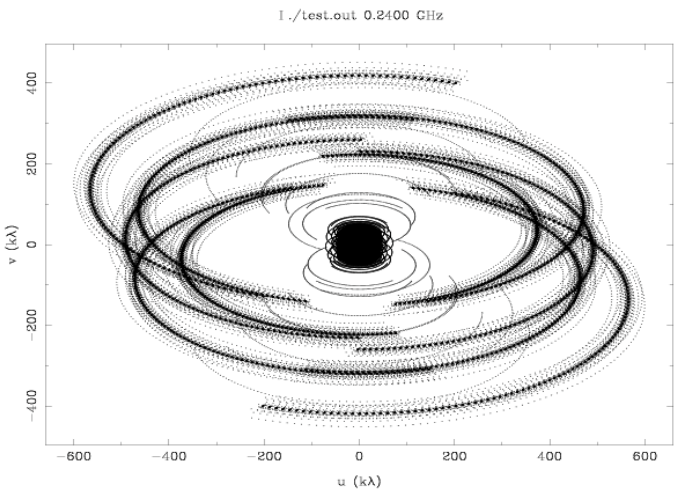
Simulated 'van der Laan' single expanding blob

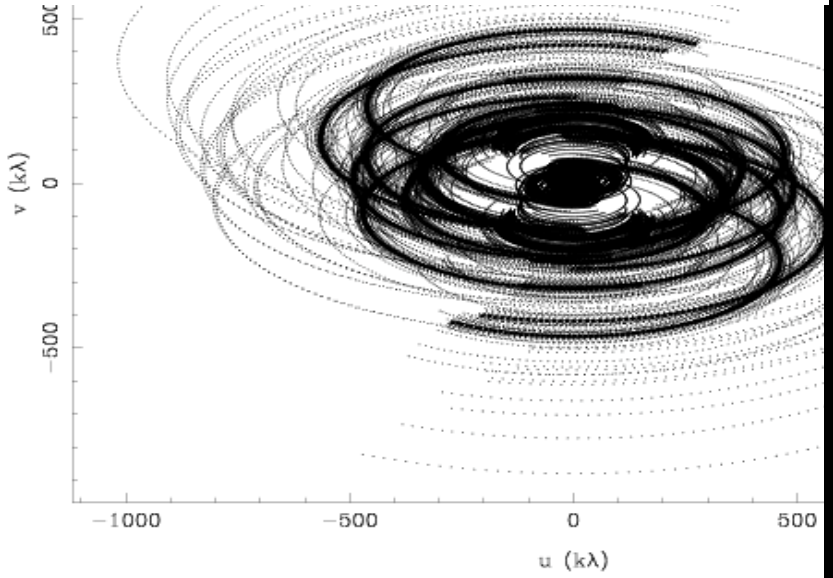


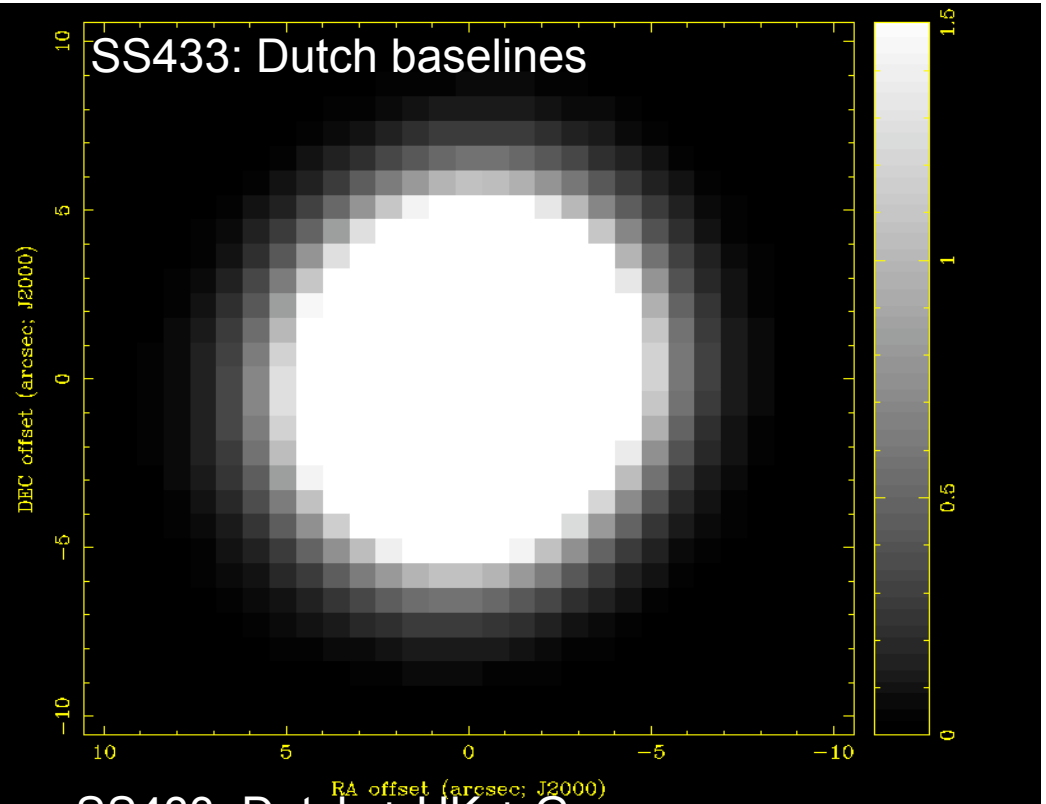
Delays may be **years** for the most luminous events (e.g. GRB afterglows)
See Alexander van der Horst's talk from yesterday.

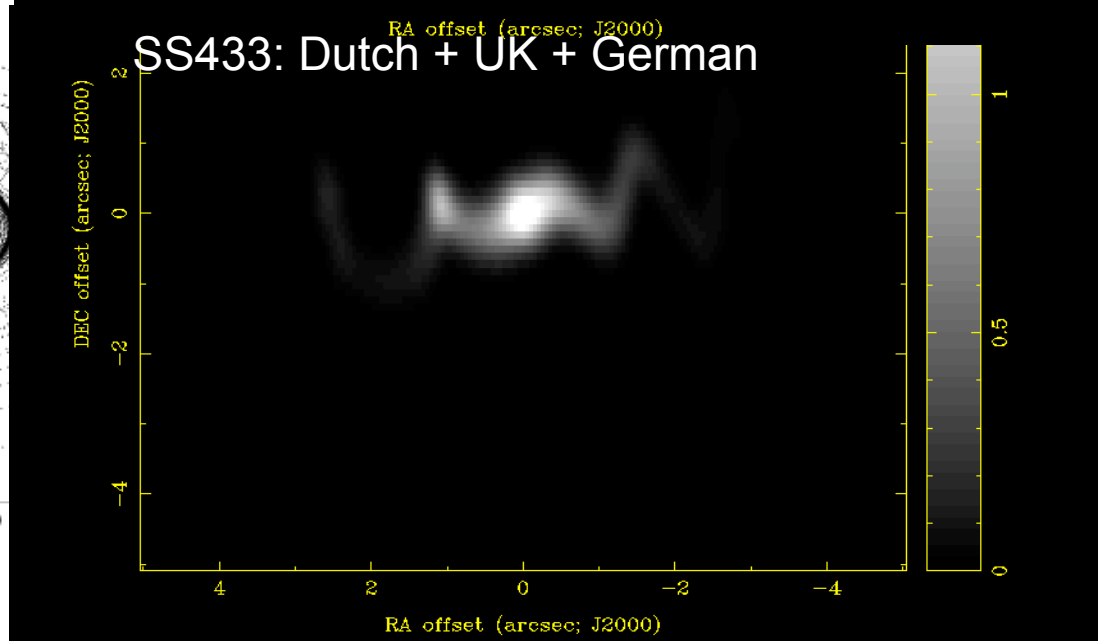
‘E-LOFAR’



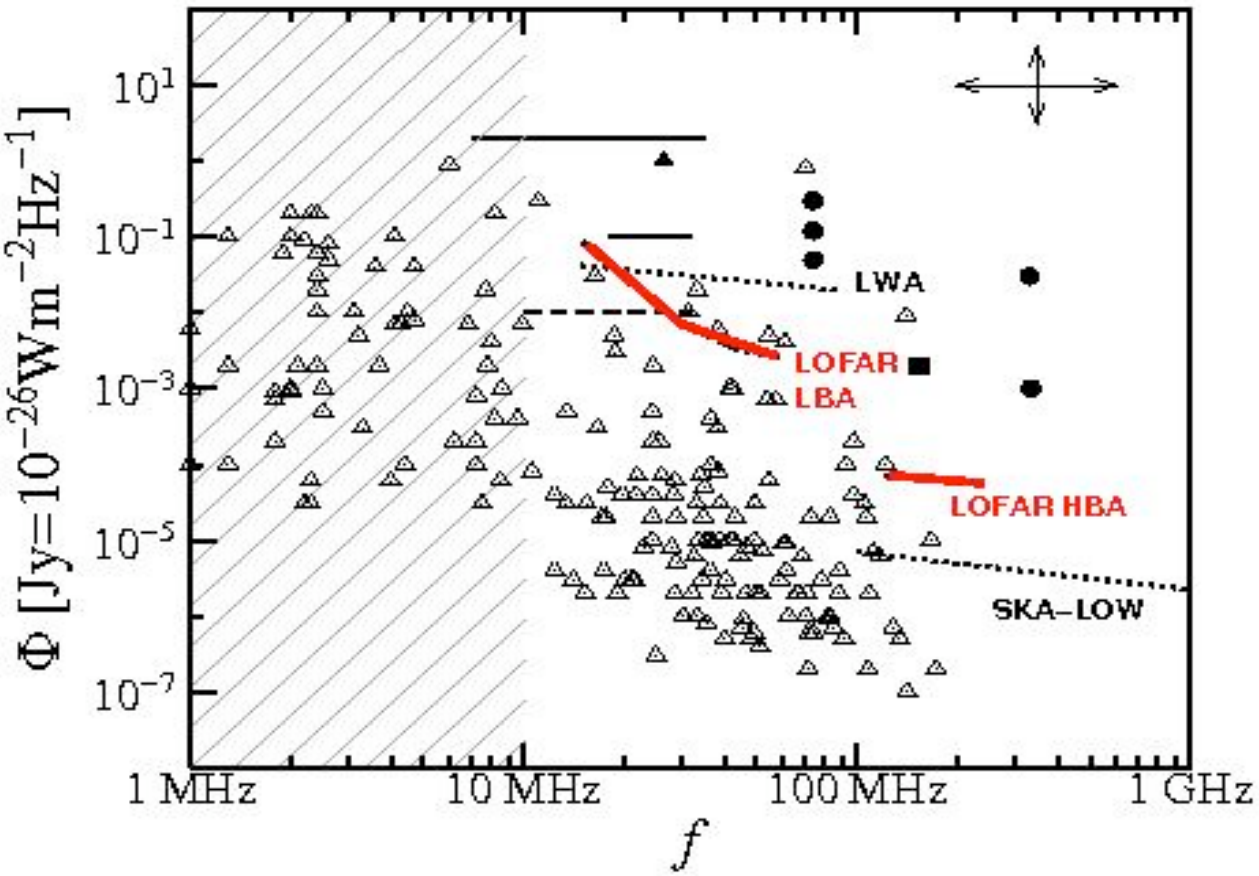

./test.out 0.2400 GHz
v (kλ)
u (kλ)


v (kλ)
u (kλ)


SS433: Dutch baselines
DEC offset (arcsec; J2000)
RA offset (arcsec; J2000)


SS433: Dutch + UK + German
DEC offset (arcsec; J2000)
RA offset (arcsec; J2000)

Extrasolar planets



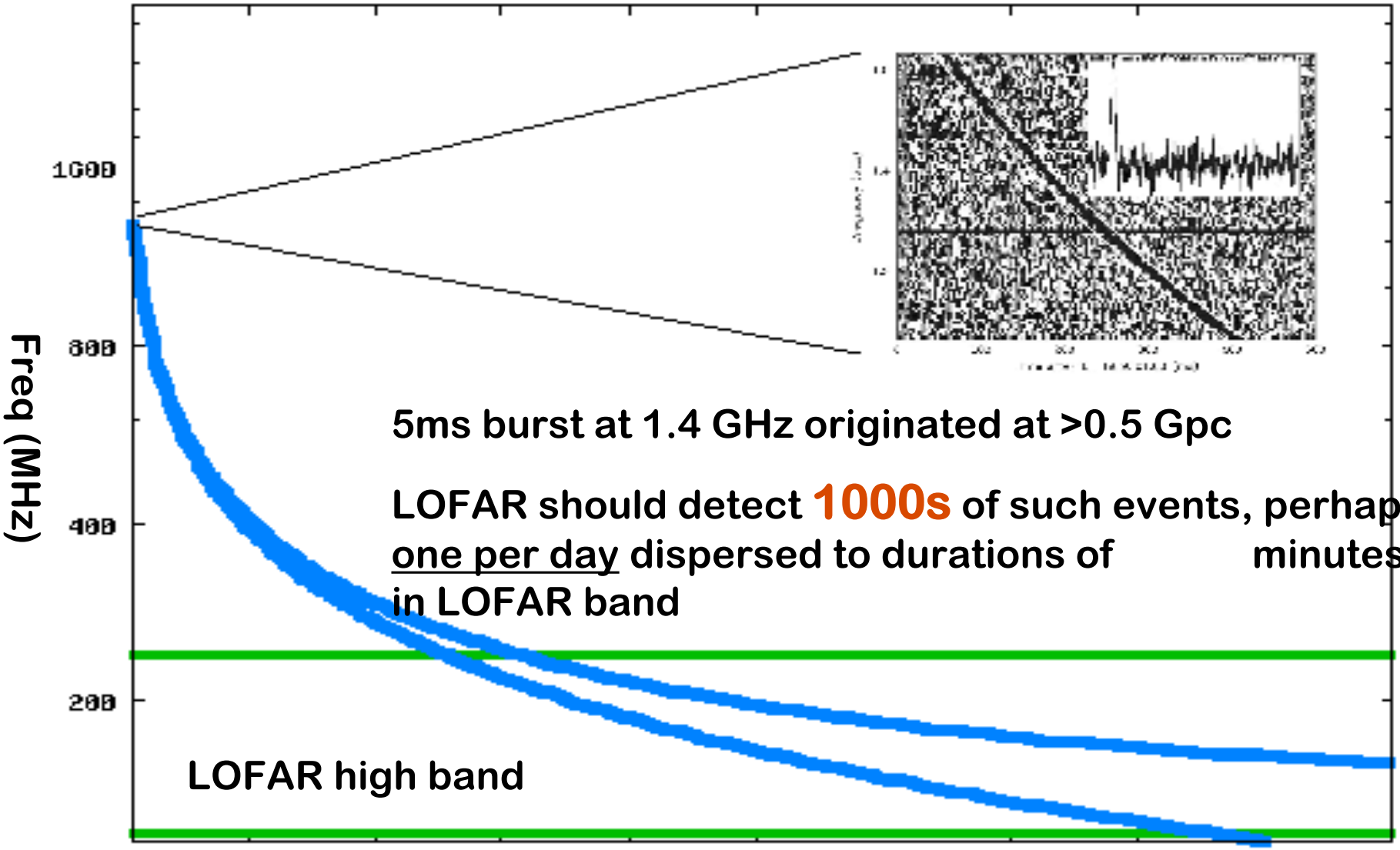
Scaling Jupiter's emission for 'Hot Jupiters' experiencing much stronger stellar winds, we could discover radio bursts to distances of 10s of pc

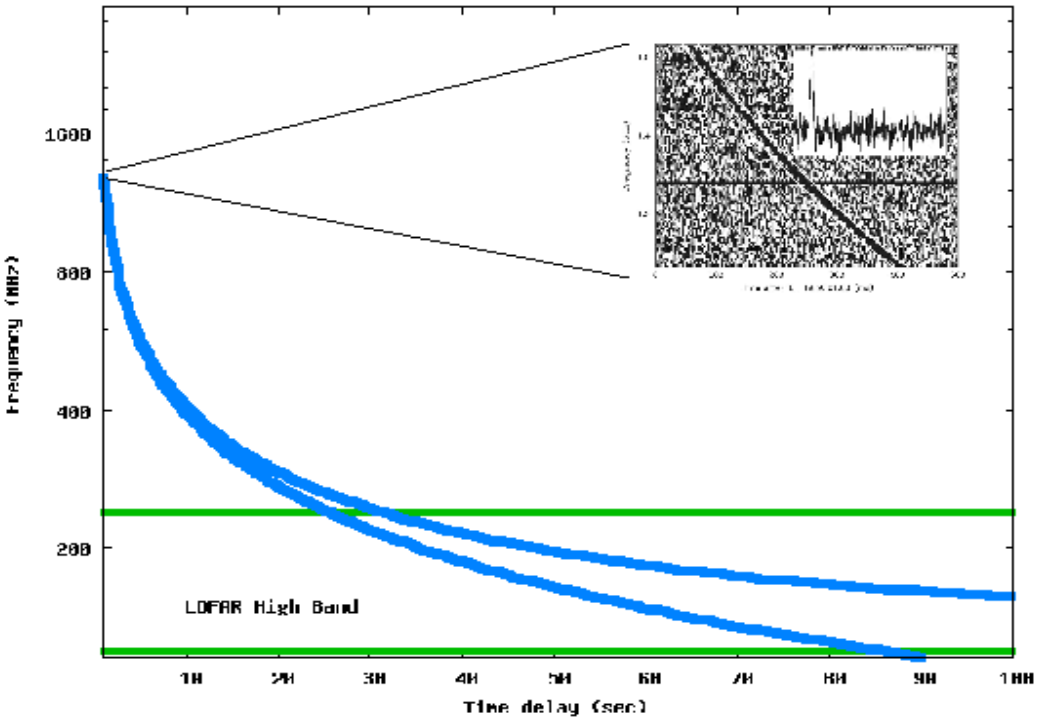
→Inclination independent method for finding planets

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

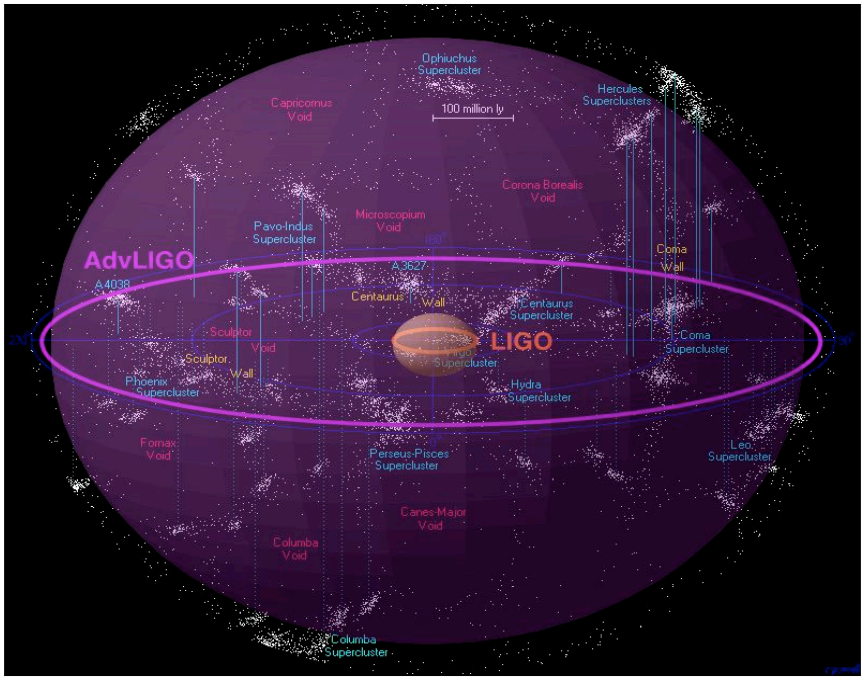
Note that the lowest frequencies are required

Extragalactic radio bursts





The bursts will 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



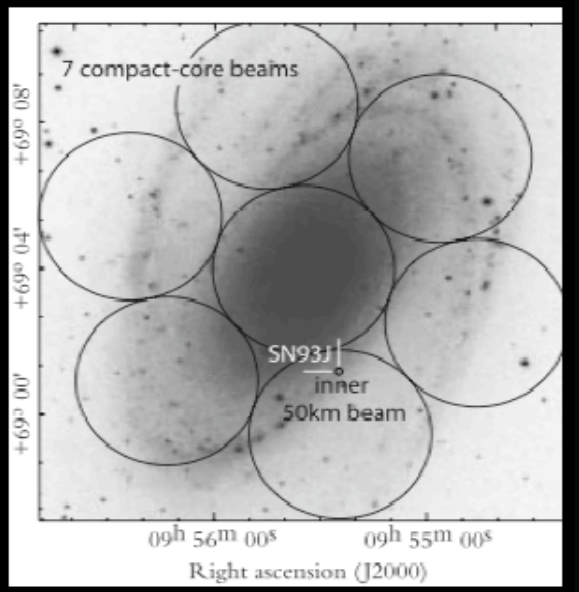
If these burst are associated with 'LIGO events' – such as a NS-NS merger – LOFAR may provide the first electromagnetic localisation of a gravitational wave event

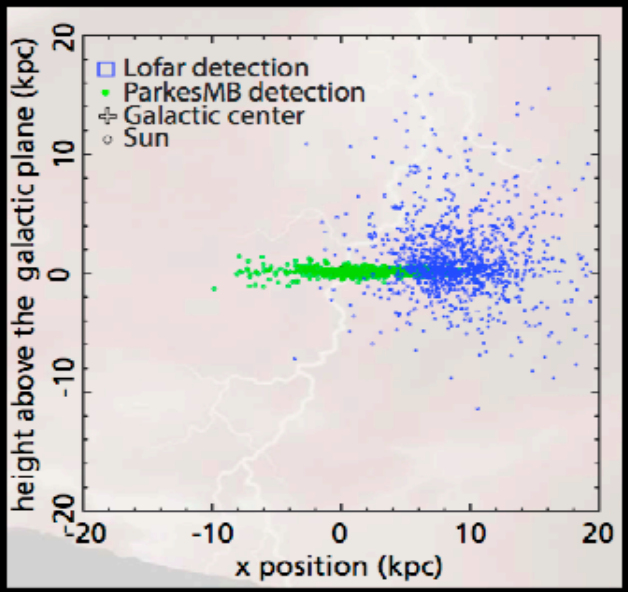
Combining LIGO and LOFAR measurements will provide two completely independent measurements of distance on cosmological scales, test theories of gravity etc.

All Northern Sky Survey will find more than 1000 pulsars, 50% more than currently known.

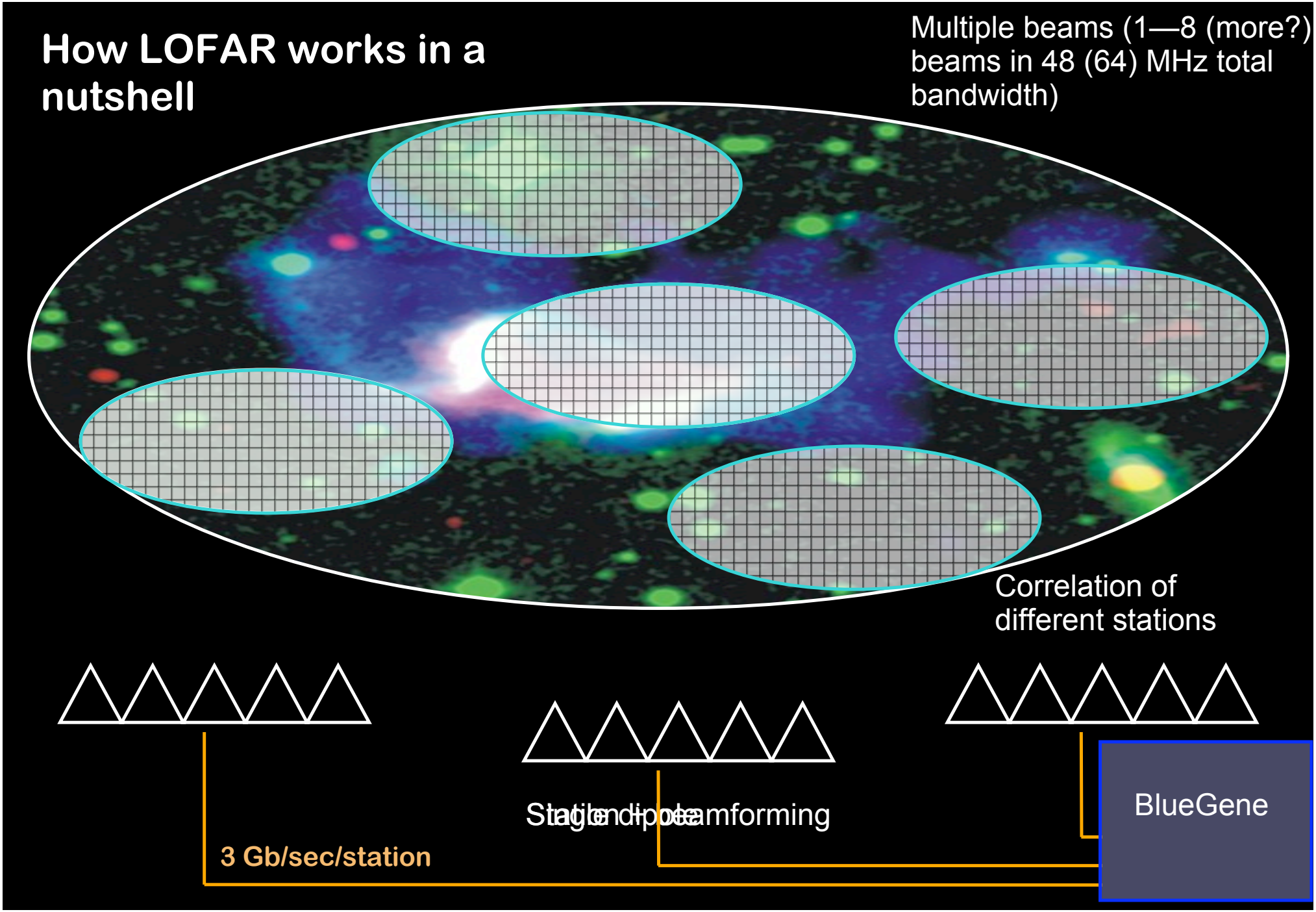
Will be so sensitive it will find entire local population allowing studies of luminosity function in detail.

So many new pulsars exotic objects like pulsar-pulsar and pulsar-BH binaries possible
Sufficiently sensitive to find pulsars in external galaxies for the first time.





How LOFAR works in a nutshell



LOFAR Transients science working groups

JETS (Sera Markoff)
Accreting binaries, YSOs, rapid AGN variability

synchrotron

PULSARS (Ben Stappers)
Pulsar / friends of pulsars survey / monitoring

FLARE STARS (Rachel Osten)
Active stars, brown dwarfs

coherent

PLANETS (Philippe Zarka)
Solar system and extrasolar planetary radio bursts

SERENDIPITY & TRANSIENT DETECTION (Michael Wise)
Source classes and source detection

ANOTHER NEW TOOL: The transient buffer

what was going on over there 20 seconds ago ?

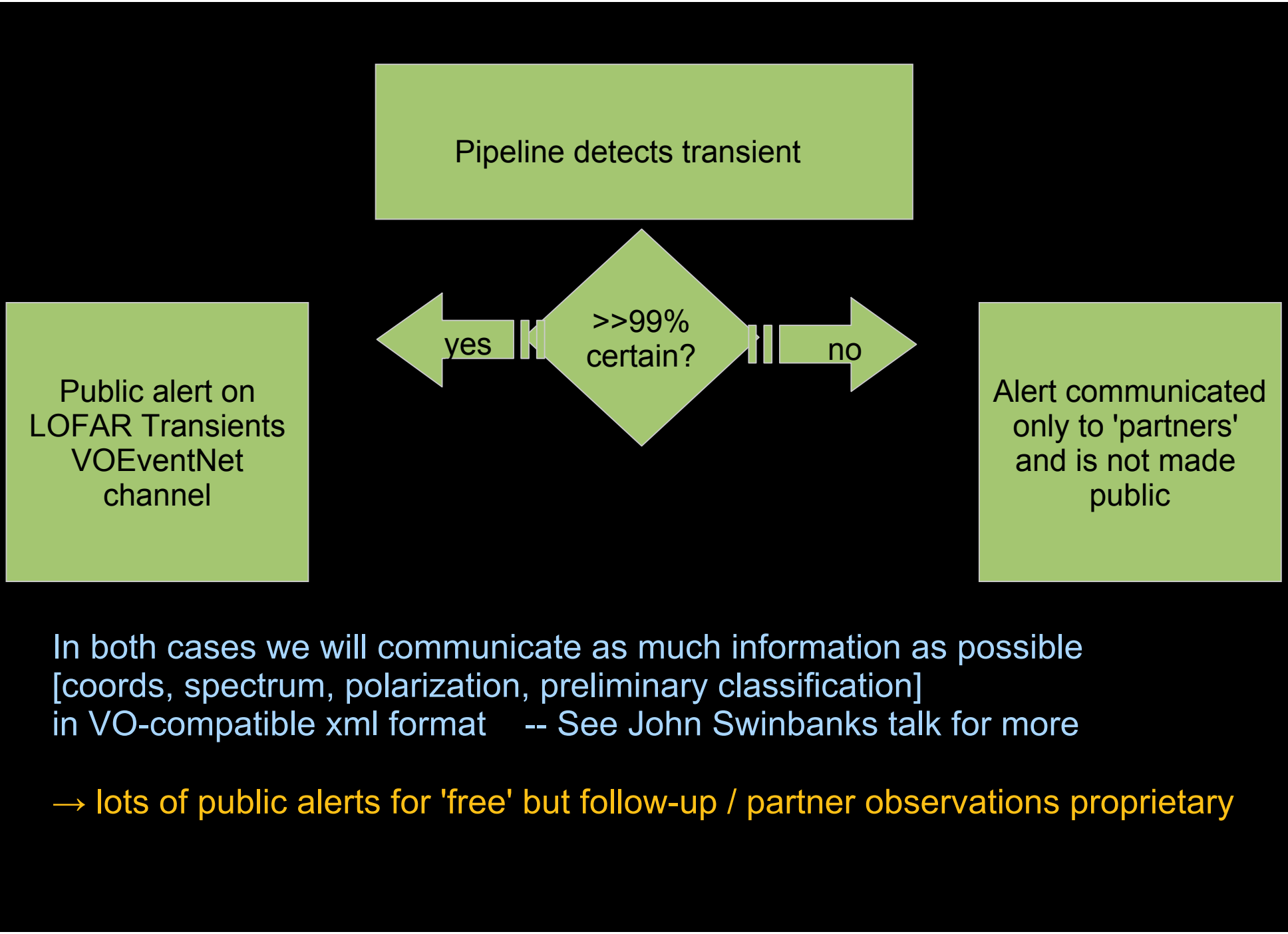
Record all raw data in RAM buffers (per 8 antennae).

Possibility to reform images *in almost any direction on the sky* up to *n* seconds in the past, where

$$n = 1 / \ (\text{bandwidth} / 100\ \text{MHz})$$

-- at a sampling rate of up to 200 Msamples/s (Nyquist)
This mode may be used in response to both 'internal' or – with more difficulty - 'external' triggers.

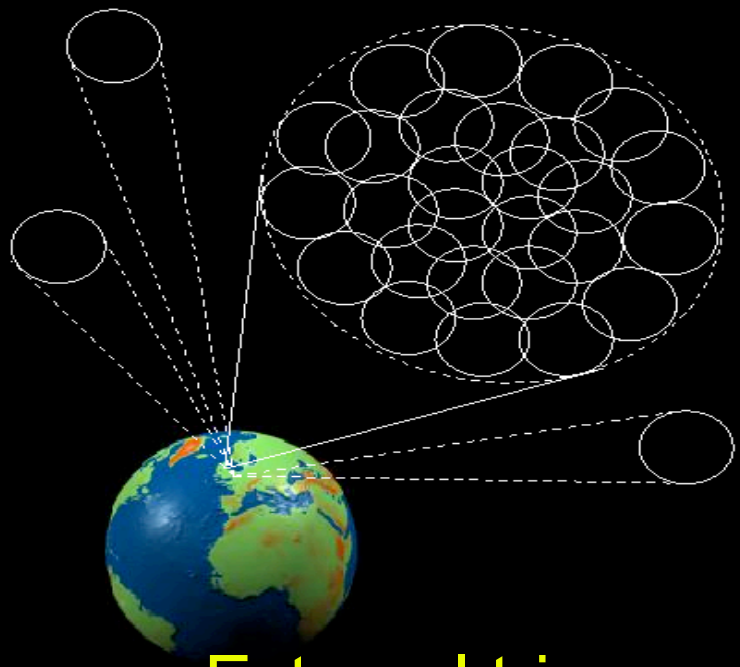
This will be a tool employed to search for very rapid events: (i.e. 'coherent' events)



In both cases we will communicate as much information as possible
[coords, spectrum, polarization, preliminary classification]
in VO-compatible xml format -- See John Swinbanks talk for more

→ lots of public alerts for 'free' but follow-up / partner observations proprietary

RSM data
→ Transients pipeline
→ Transient detected
[localised to ~arcmin /
alert via *VOEventNet*
or 'sub prime' channel]



External trigger
(e.g. MAGIC, MAXI..)

Full array override
→ radio spectrum /
arcsec localization

Links to other KSPs

Surveys
Very clear potential overlap – we can use their data and vice versa

Solar
High time-resolution modes for coherent sources very similar to those required for solar flare monitoring

Cosmic rays
Use of the transient buffers

Magnetism
Polarisation a key diagnostic for transient classification

Commissioning observations from the Transients KSP in 2009/10

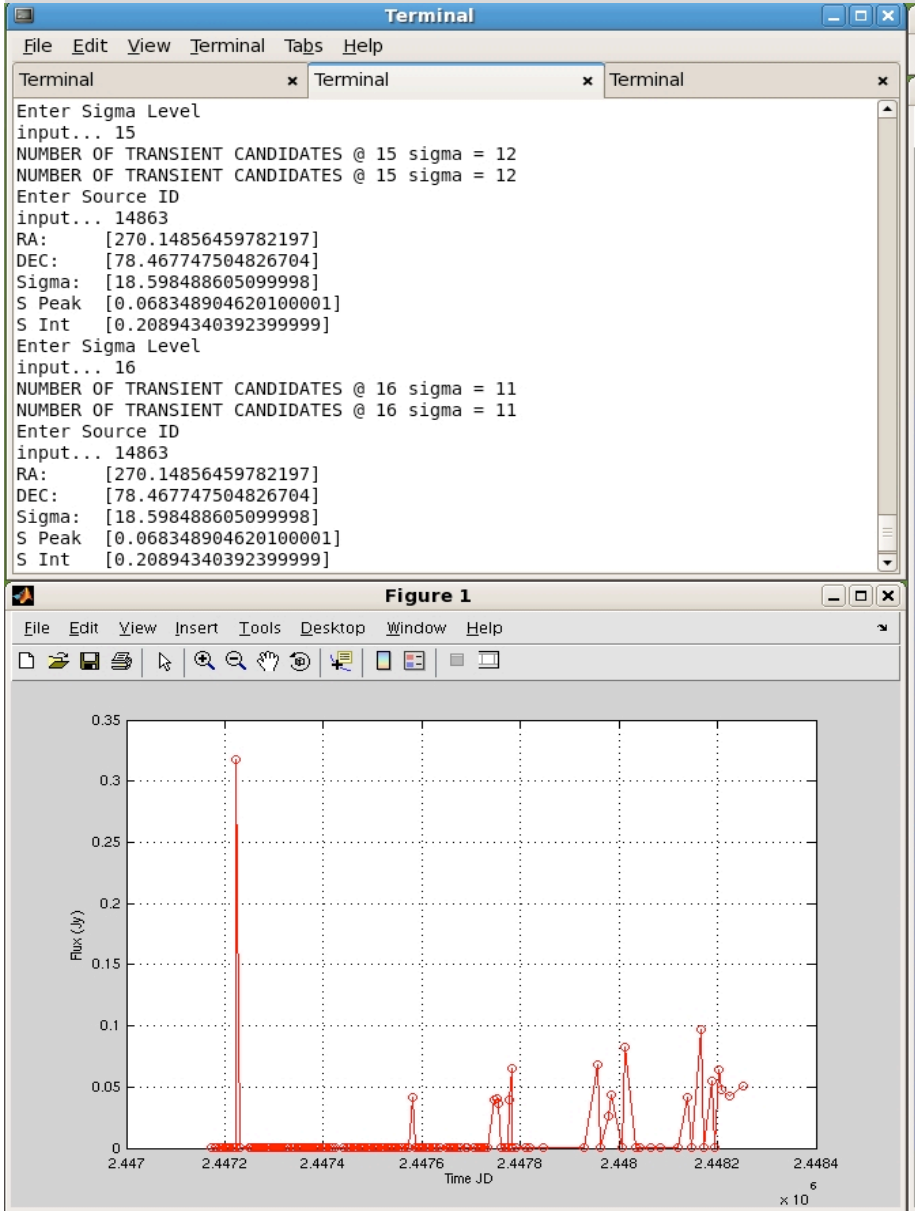
- LOFAR Transients Pipeline

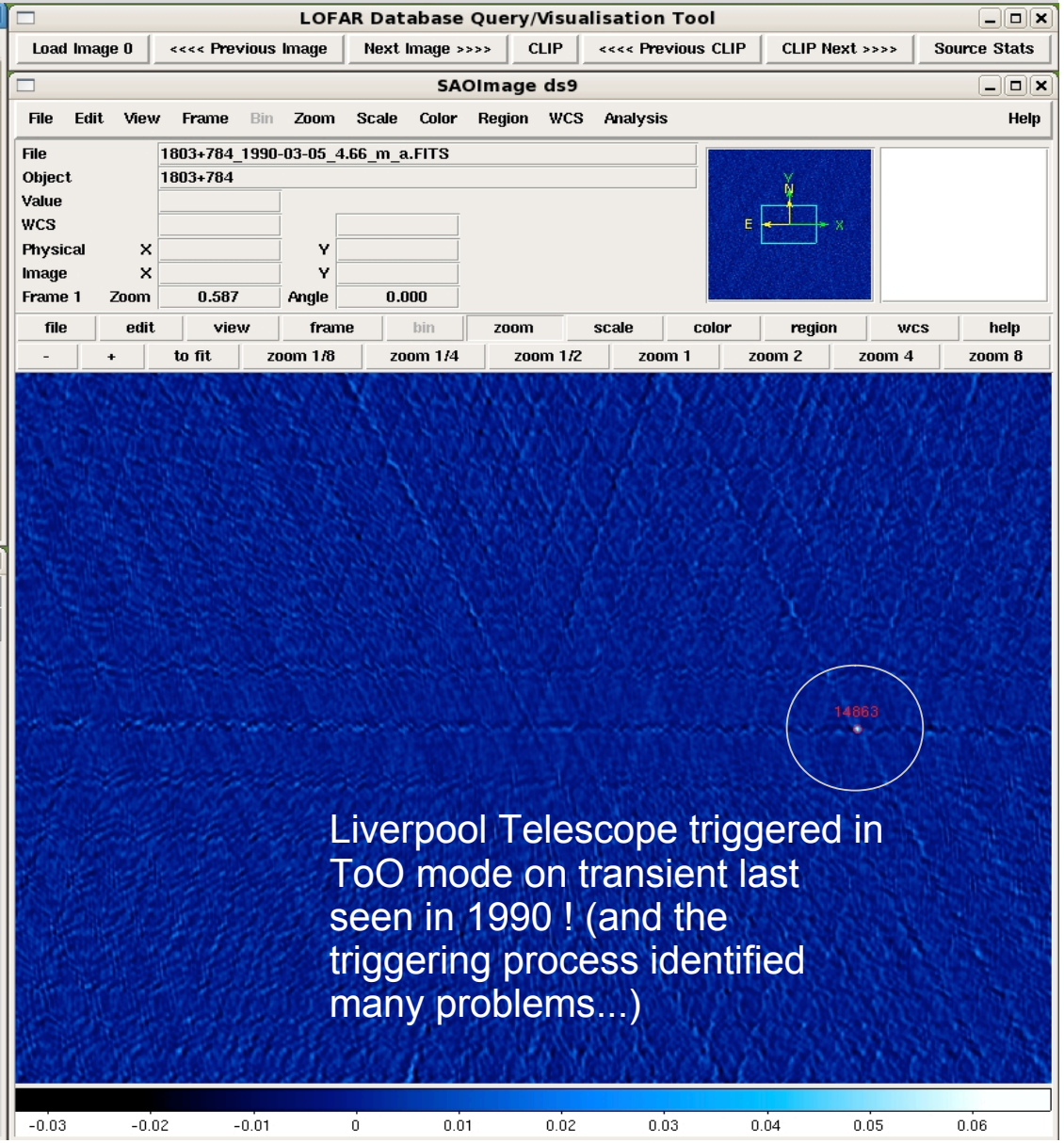
Inspect all data for significantly variable objects. Compile light curves, apply preliminary classification / if above some threshold trigger additional observations (many software tests to be performed e.g. blind tests on fake events)

- Piggybacking

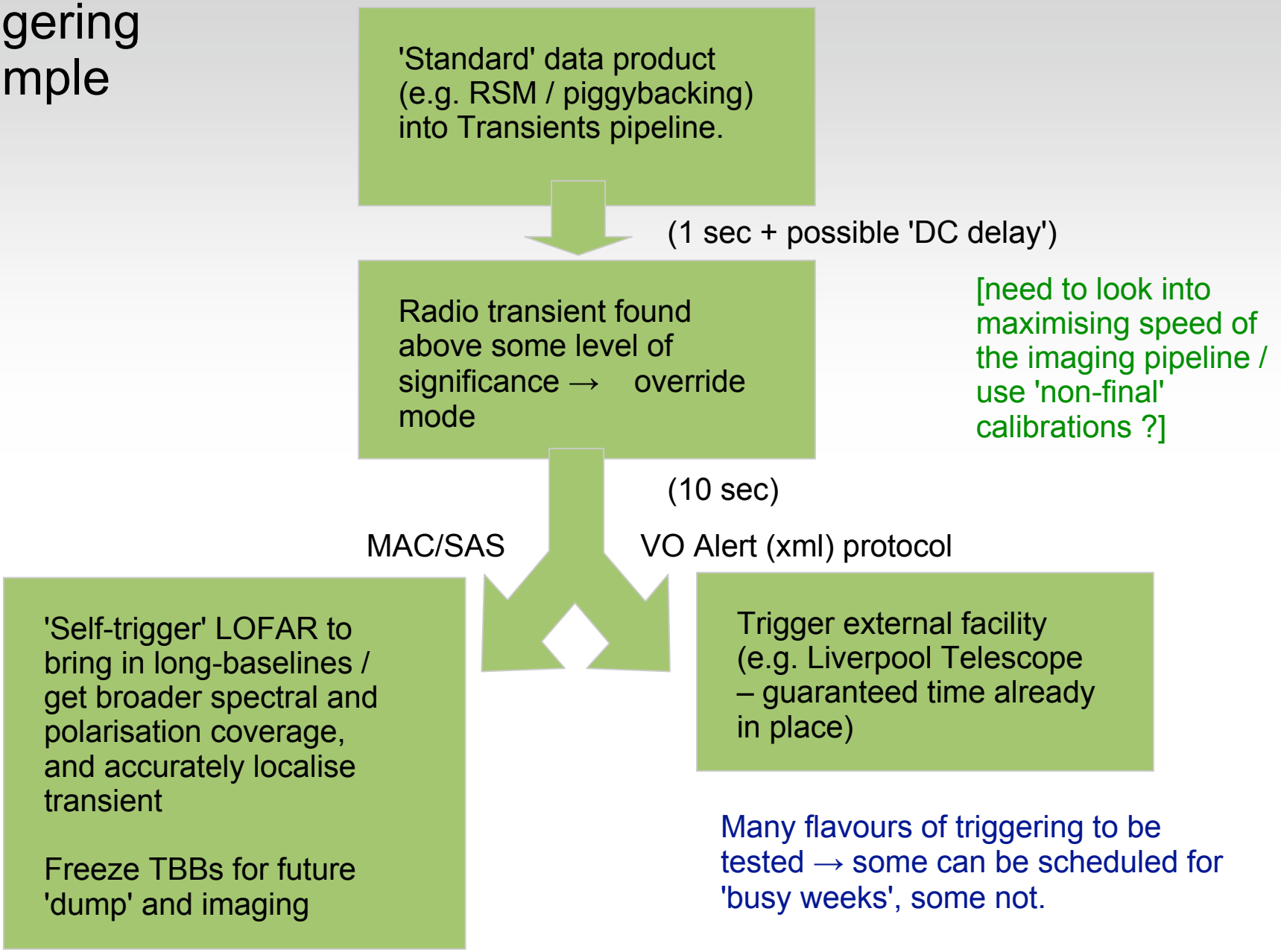
Application of the pipeline to all LOFAR data, in real time *(including MSSS)*

Discovery of radio transient in VLA archive using LOFAR Transients pipeline





Triggering Example



Collaborating facilities → 'Multi-messenger' science with LOFAR

Other radio:

WSRT / e-Merlin / e-EVN / MWA / ASKAP

Optical/infrared:

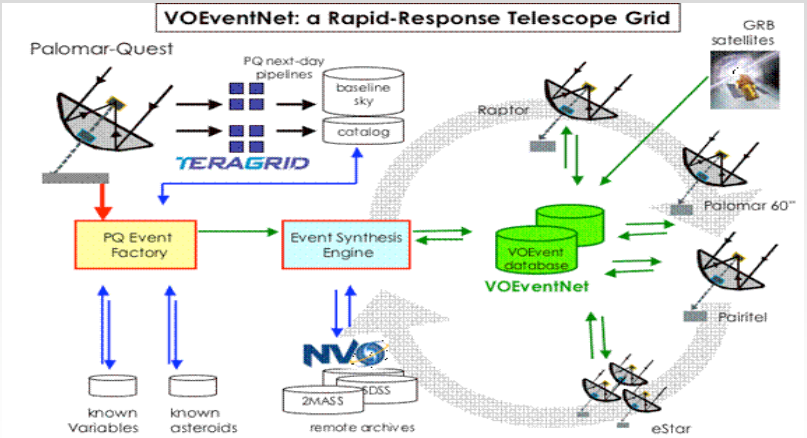
The Liverpool Telescope / PAIRITEL

X-ray / Gamma-ray:

Fermi, Swift, INTEGRAL

GW / Particle:

LIGO / VIRGO
MAGIC / VERITAS / HESS



www.voeventnet.org

Triggering modes

- Transient Buffer Boards

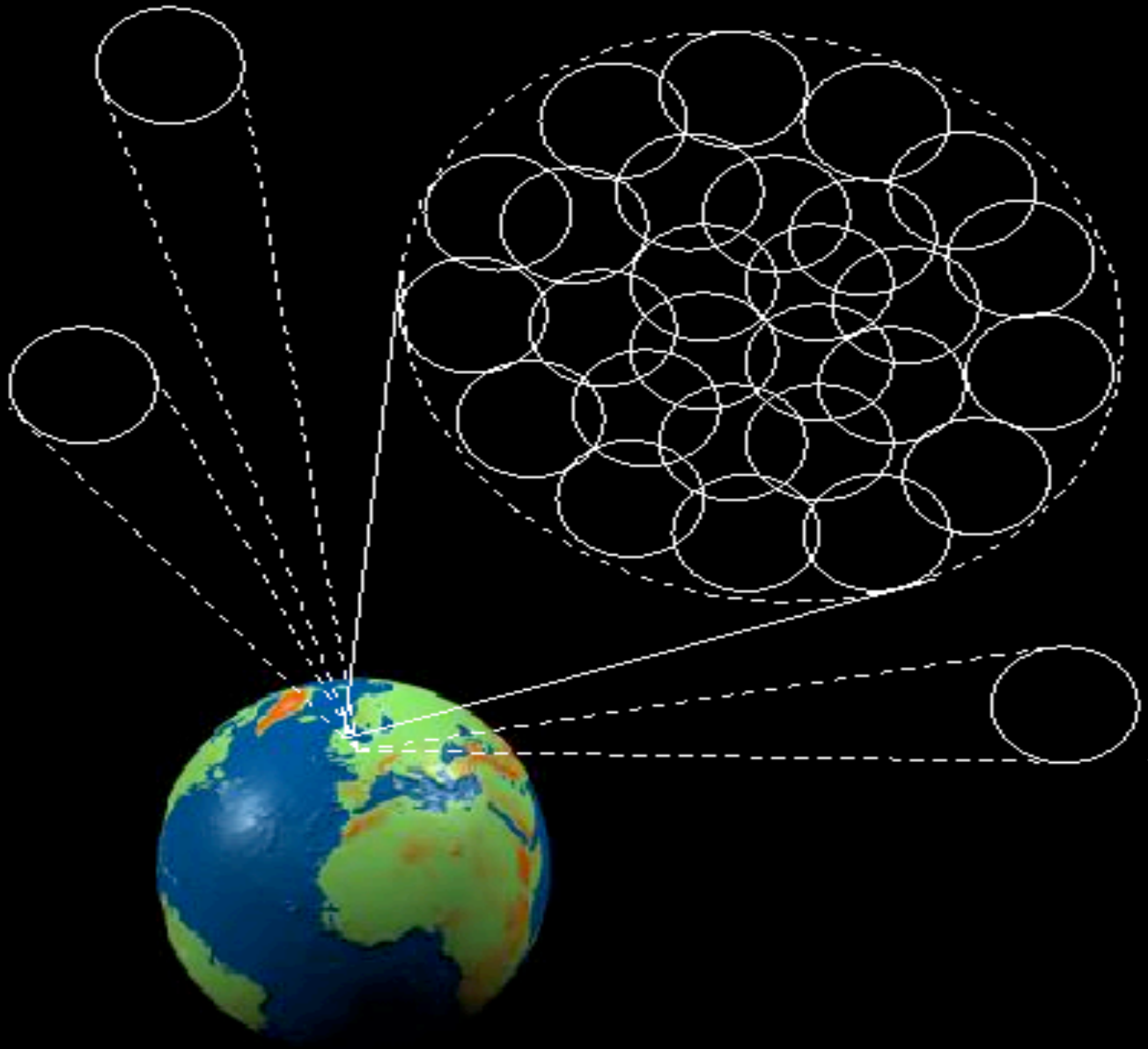
Testing freeze → playback → image modes

Testing frequency – time trade off
(and independent settings of these across a range of stations)

1-sec all-sky survey

CR ↔ Transients dual-operation of TBBs

Radio Sky Monitor modes



Test modes e.g. Repeated zenith / galactic plan pointings

Repeated observations are required to test:

- Stability of flux calibration → how many sources appear to vary / are really varying ?

- Stability of pointing

- Uniformity of tiling multiple beams etc

- Rapid sky sweeps → wide shallow monitor

Testing low-frequency (high time-resolution) imaging with Jupiter

Jupiter can be the brightest source in the sky below 40 MHz when bursting (10 MJy), and its mechanism is the key to prospects of detecting extrasolar planets

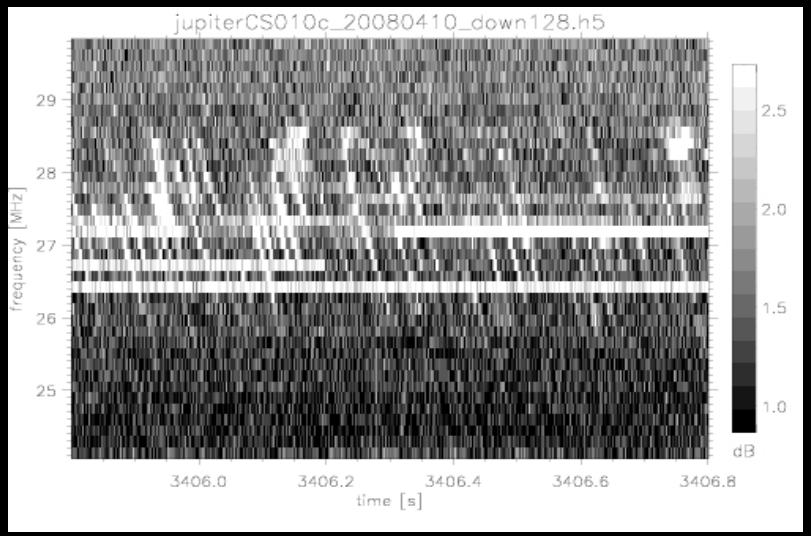
It will be a detectable point source for LOFAR as low as **10 MHz**

Emission is strongly elliptically polarized and can be tested against simultaneous observations with Nancay

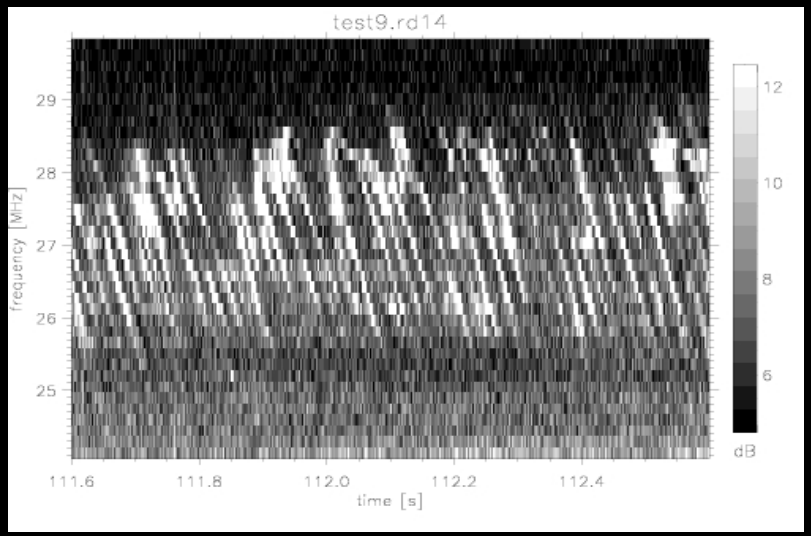
(also Saturn lightning (unpolarised) – a mere 100 Jy – in collaboration with *Cassini* team)

Simultaneous Jupiter observation 10/04/2008

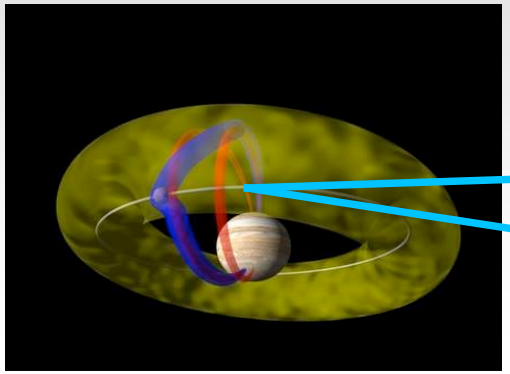
LOFAR (CS10)



Nancay (NDA)



Time delay



+1.85 ms

0 ms

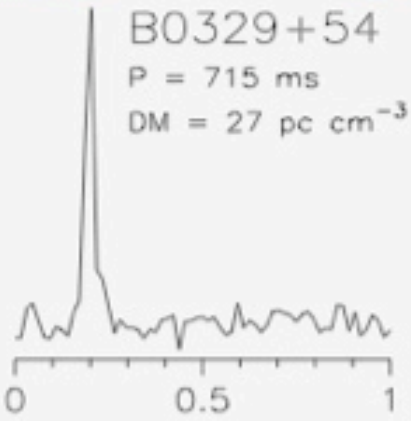
x+50 μs

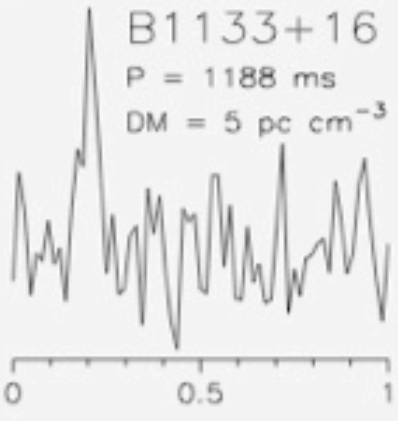
x μs

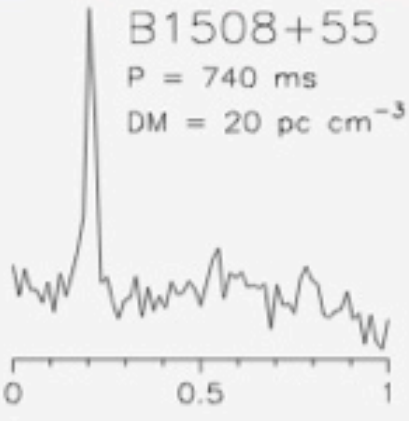
⇒ time delay could be explained slow/fast electronic -
-- now solved, FFT vs PPF

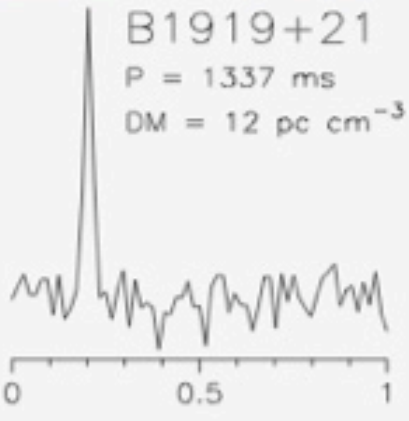
⇒ to be checked by repeating observation

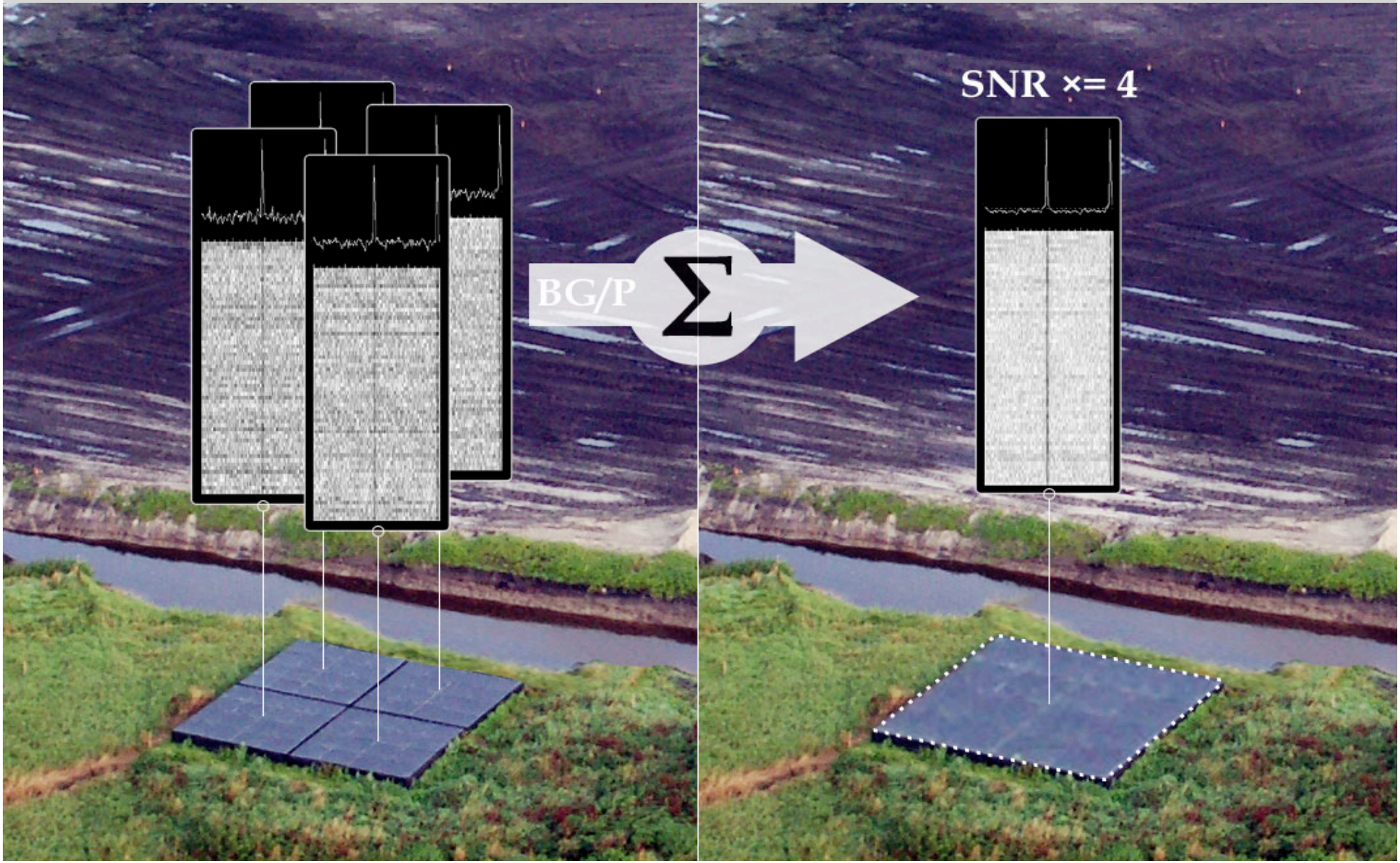
LOFAR Pulsar "Busy Week"







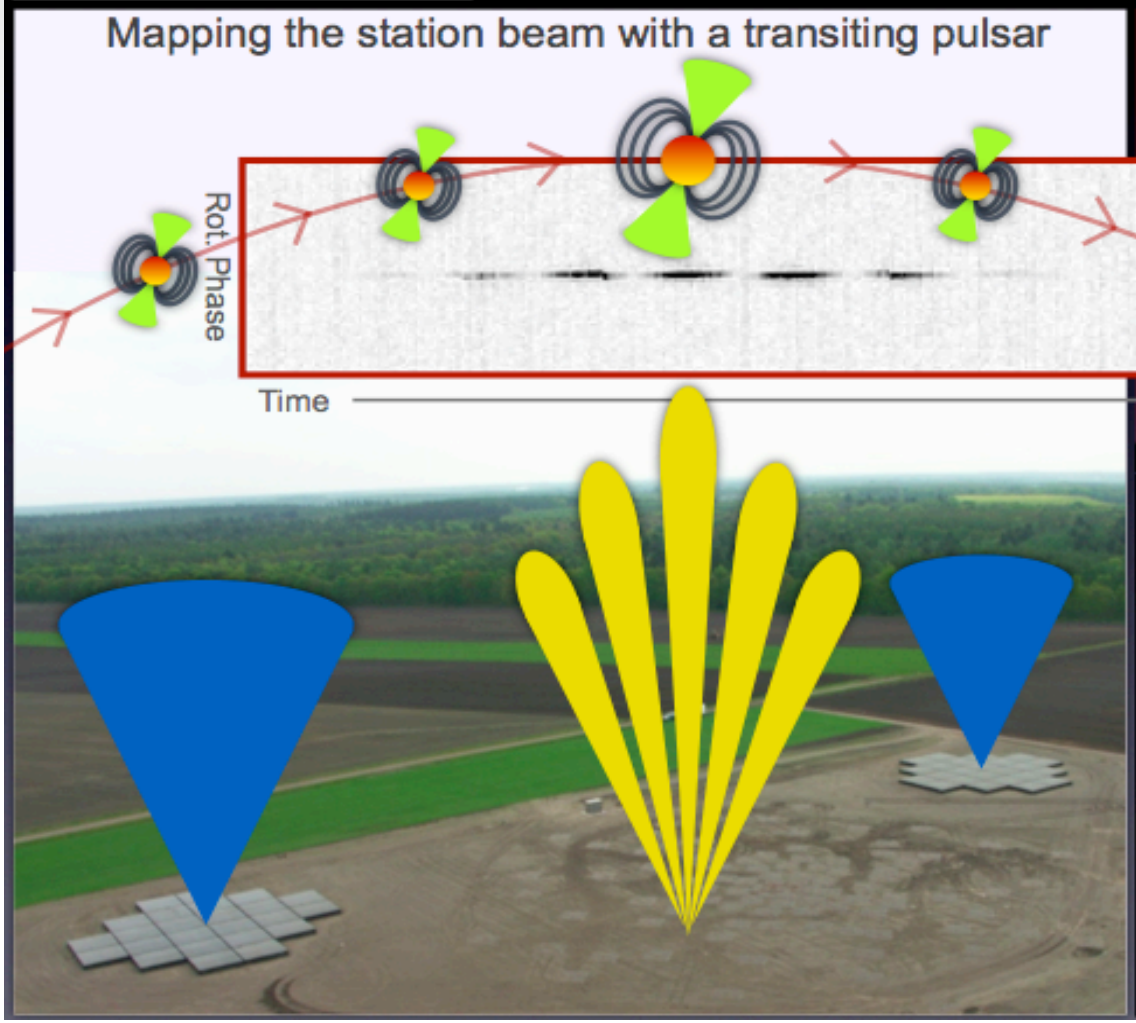


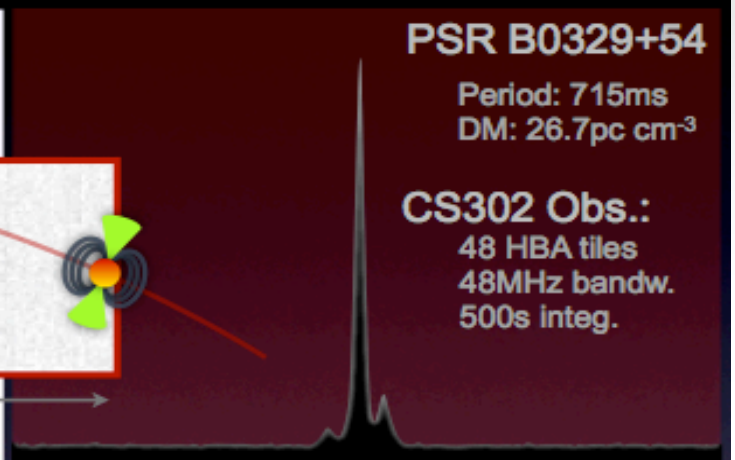

BG/P
Σ
SNR ×= 4

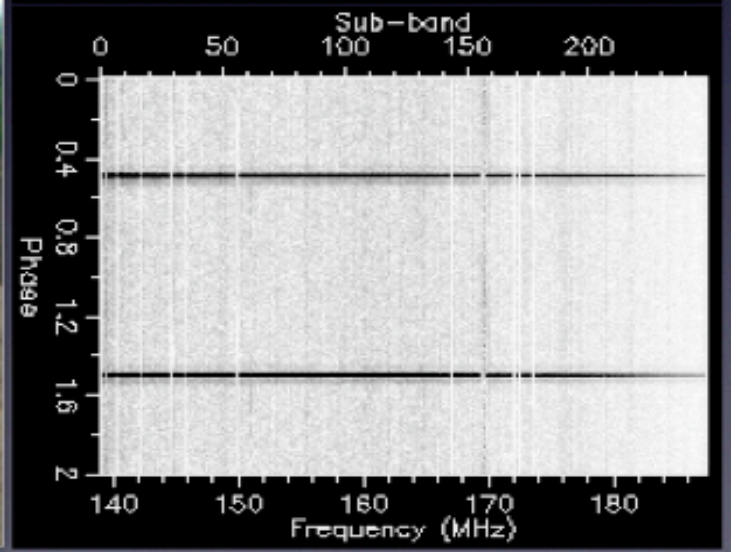
LOFAR
ASTRON

Pulsar Busy Week 3

Pulsar observations with the first full LOFAR station: CS302







Summary

LOFAR is a key wide-field instrument for the detection of transients, especially coherent events, and the low-freq component of the SKA may be very similar

We aim to tackle transient and variable sources in the LOFAR data in the most flexible and open way we can (we cannot keep all the events to ourselves!)

First observations are happening **right now**