LOFAR

An all sky transient instrument

Ben Stappers (co-PI transients KSP)

JBCA

University of Manchester

Not your usual radio telescope.

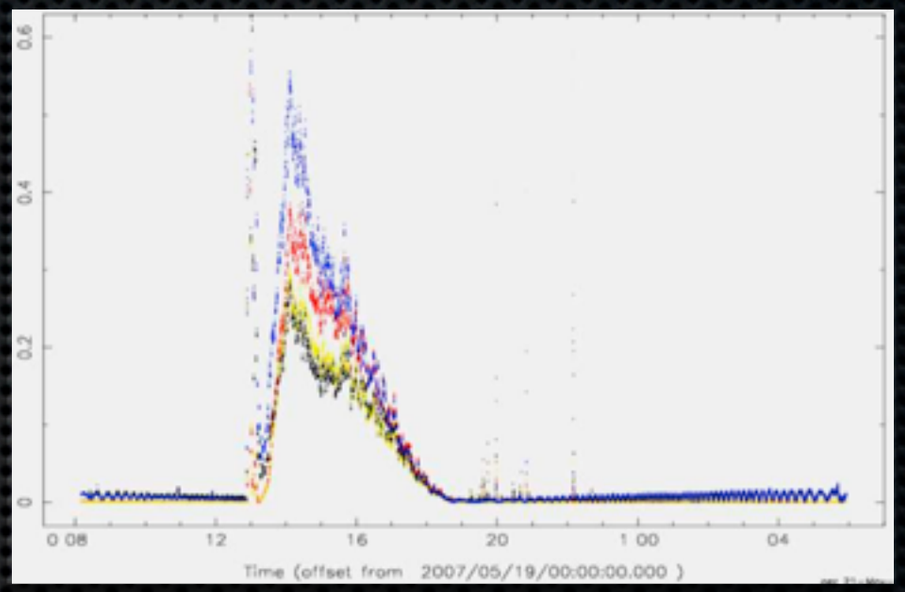
Lovell

WSRT

LOFAR: LOw Frequency ARray

- Distributed in NL & EU
- 30 - 240 MHz
- LBA & HBA
- > 30000 dipoles
- 36Core/18NL/>10EU
- 2.5km/100km/1000km

Basic Facts

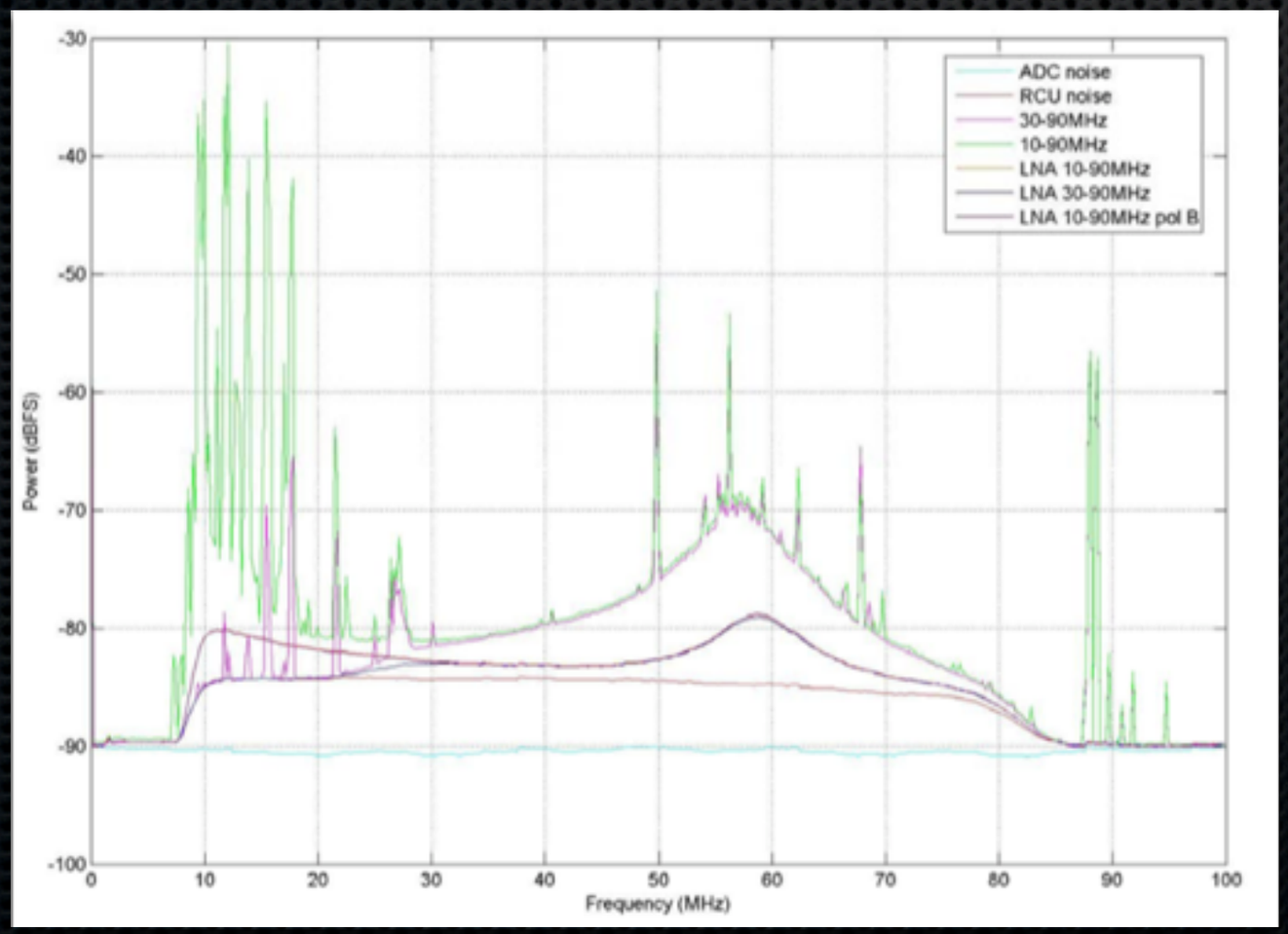


1 GJy solar burst: Importance of 12 bits

System Characteristic	Options	Values	Comments
Frequency Range	Low Band Antenna	10-80 MHz	
		30-80 MHz	With digital filter
	High Band Antenna	110-190 MHz	200 MHz sampling (2nd Nyquist zone)
		170-230 MHz	160 MHz sampling (3rd Nyquist zone)
		210-250 MHz	200 MHz sampling (3rd Nyquist zone)
Number of Polarizations		2	
Bandwidth	Default	32 MHz	
	Maximum	48 MHz	
Number of Simultaneous Beams	Minimum	8	
	Maximum	20	Limited by LCU performance
Sample bit depth		12	
Sample Rate	Mode 1	160 MHz	
	Mode 2	200 MHz	
Beamformer Spectral Resolution	Mode 1	156 kHz	
	Mode 2	195 kHz	
Channel Width	Mode 1	610 Hz	
(raw correlator resolution)	Mode 2	763 Hz	
Baseline length	Superterp	320 m	
	NL Core	2 km	
	Full NL	100 km	
	Full array	1000 km	

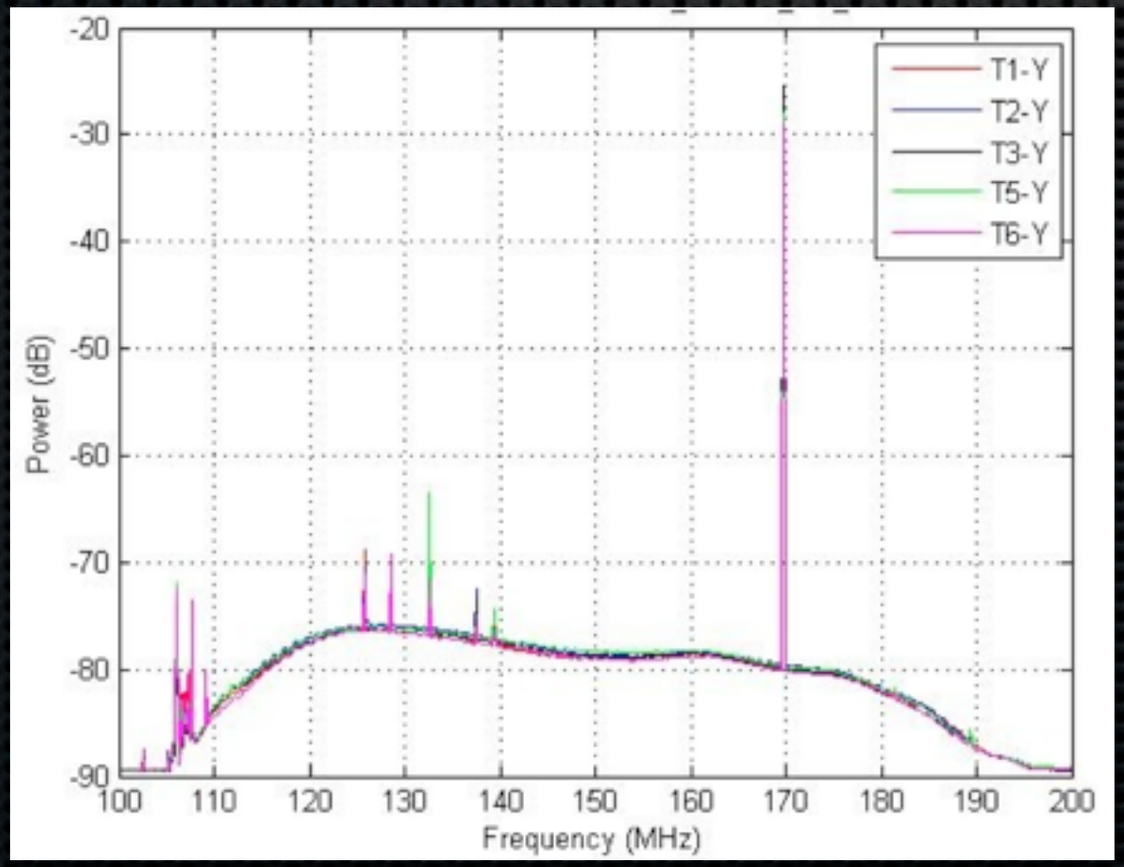
Low Band Antenna

- 48/96 per station
- (10)30-80 MHz
- Simple Dipole
- Electronics in top
- Full Stokes



High Band Antenna

- 48/96 per station
- Tile of 4X4 dipoles
- 1.25m/25m^2
- 110-240 MHz
- Analog beamformer
- Full Stokes



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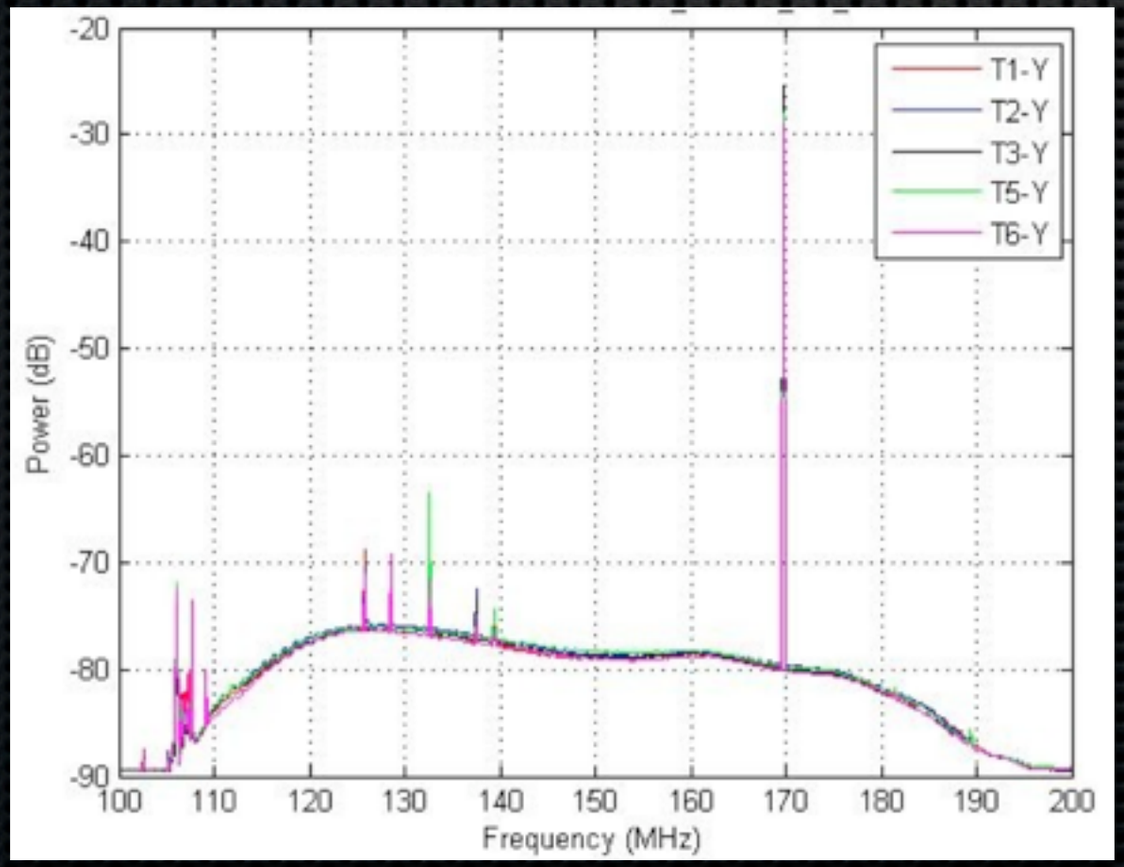
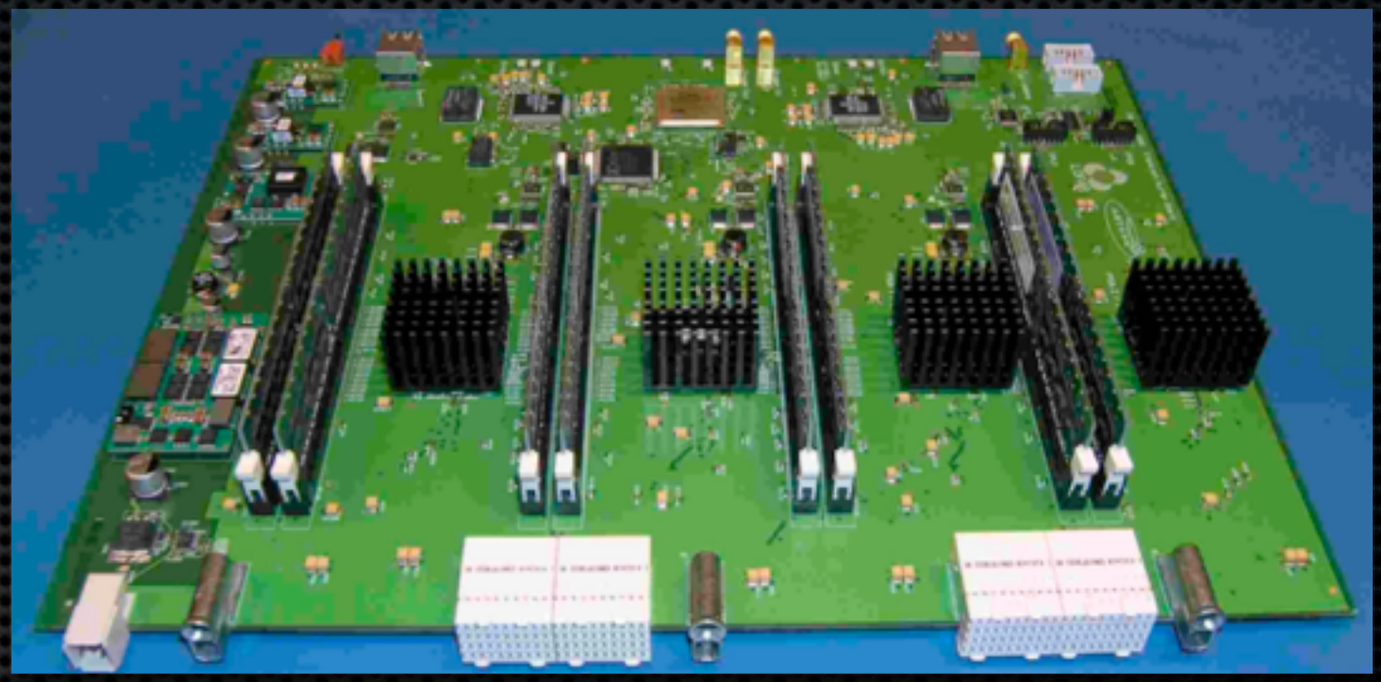
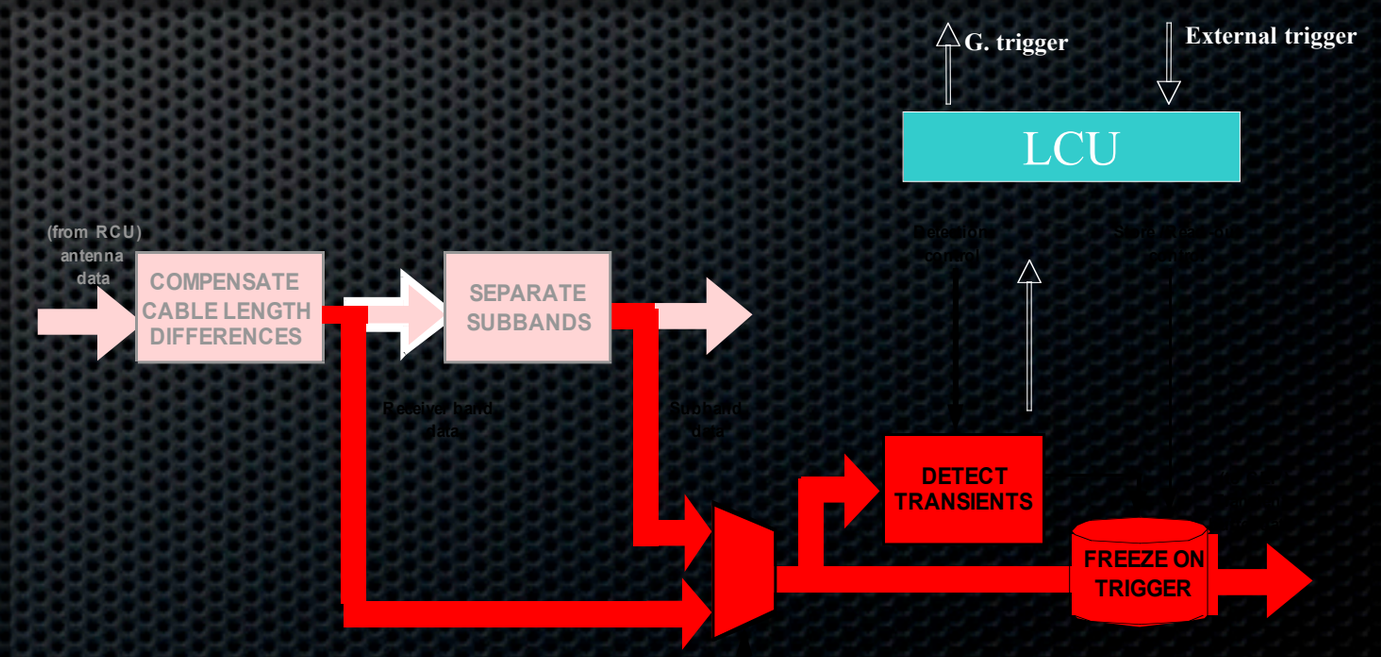


Transient Buffer Boards

- 96 Gbytes/station
- Excellent for transients and essential for CRs
- Allows look back time
- 1.3 s at 100 MHz BW
- 10's s of PPF data
- Transported and correlated "offline"
- About to be expanded





Central Processing

- BG/P
- > 300 Gbits/s input (>70 stations at about 3 Gbits/s)
- International capacity > 40 Gbits/s link AMS - GN
- > 50 Gbits/s output
- Multiple TeraFlop “offline” cluster
- Initially 1.5 PetaBytes storage, which will grow

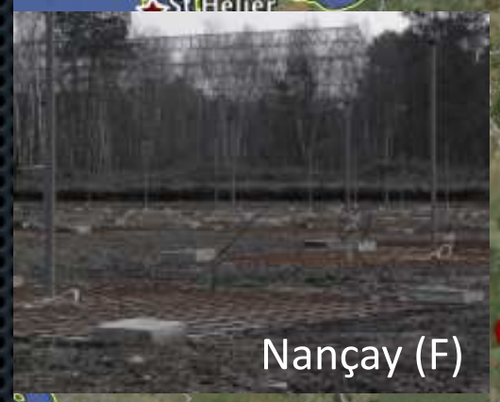
49	The Earth Simulator Center Japan	Earth-Simulator / 2002 NEC	5120	35.86	40.96	
50	ERDC MSRC United States	Sapphire - Cray XT3, 2.6 GHz dual Core / 2006 Cray Inc.	8192	35.20	42.60	
51	ASTRON/University Groningen Netherlands	Blue Gene/P Solution / 2008 IBM	12288	35.12	41.78	94.50
52	RZG/Max-Planck-Gesellschaft MPI/IPP Germany	Genius - Blue Gene/P Solution / 2008 IBM	12288	35.12	41.78	94.50
53	Turboinstitute Slovenia	BladeCenter HS21 Cluster, Xeon QC HT 3 GHz, Infiniband / 2008 IBM	4096	35.08	49.15	191.08

LOFAR Status (NL)

- Construction of stations started March 2009
- Network + Phase 1 Central Processing Completed
- On-line CEP based on 3 IBM BlueGene/P racks
- 33 stations completed in 2009 and 2010
- Phase 2 CEP complete by mid 2011
- 7 stations went in 2011

First LOFAR Station - CS 302 – early May 2009

The view from bing!



Onsala
(Malmö)
Malmö
Sylt
Amrum
Spiekeroog
Juist
Douglas
Dublin
United Kingdom
Amsterdam
Netherlands
Potsdam
London
Chilbolton
Jülich
Brussel
Belgium
Germany
Tautenburg
Effelsberg
(Prague)
St Peter Port
St Helier
Luxembourg
Paris
Garching bei Mü
Nançay
Vaduz
Bern
Switzerland
9 Google
nsnavi.com, Ltd
Tele Atlas
pa Technologies
1 m

LOFAR Stations Across Europe

Stations perhaps coming in Hamburg/Poland / Latvia and beyond...

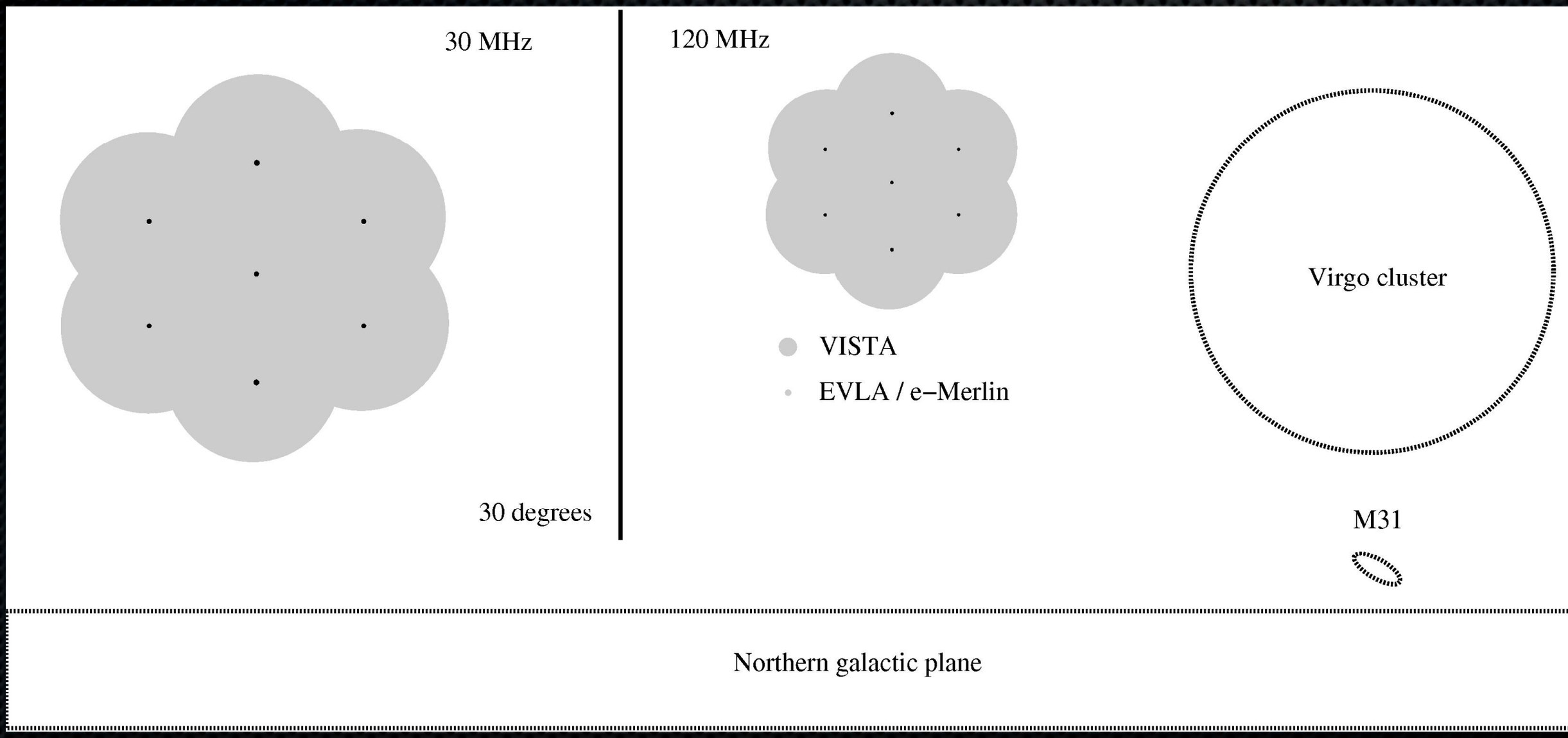
LOFAR Beams

element beam station beam tied-array beam

Mode	Sensitivity (Norm.)	FoV (sq. deg.)	Resolution (deg)	Data Rate (TB/hr)	FoM (Norm.)
High-Band Antennas (HBAs)					
Single HBA “ear”	1.0 / 0.4	18.4 / 147	4.8	0.23	1.0 / 1.3
Single Core Station	2.0 / 0.8	2.5 / 20.0	0.5	0.23	5.2 / 6.8
Single Rem. Station	2.0 / 0.8	10.3 / 82.4	3.6	0.23	/ 3.0 / 3.8
Single Intl. Station	4.0 / 1.6	7.5 / 60.3	2.6	0.23	12.0 / 15.5
Fly’s Eye	1.0 / 0.4	883 / 7066	4.8	11.0	48.0 / 61.4
Dutch Inc. Sum	15.4 / 5.4	10.3 / 82.4	3.6	0.23	177 / 230
Intl. Inc. Sum	11.3 / 4.0	7.5 / 60.3	2.6	0.23	96 / 125
Coherent Superterp	12.0 / 4.2	110 / 880	0.3	23	13800 / 17900
Coherent Sum Core	84.0 / 29.7	16.1 / 129	0.04	23	741000 / 963000
Low-Band Antennas (LBAs)					
Single Core Station Outer	1.0 / 0.4	16.5 / 132	4.6	0.23	1.0 / 1.3
Single Core Station Inner	< 1.0 / < 0.4	105 / 840	11.6	0.23	< 1.0 / < 1.3
Single Rem. Station	1.0 / 0.4	16.5 / 132	4.6	0.23	1.0 / 1.3
Single Intl. Station	2.0 / 0.8	16.5 / 132	4.6	0.23	1.0 / 1.3
Fly’s Eye	6.5 / 2.3	693 / 5544	4.6	9.7	1775 / 2308
Dutch Inc. Sum	6.5 / 2.3	16.5 / 132	4.6	0.23	42.3 / 55.0
Intl. Inc. Sum	5.7 / 2.0	16.5 / 132	4.6	0.23	32.5 / 41.6
Coherent Superterp	6.0 / 2.1	450 / 3560	1.2	23	3764 / 4818
Coherent Sum Core	42.0 / 14.9	66.8 / 534	0.2	23	164255 / 210246

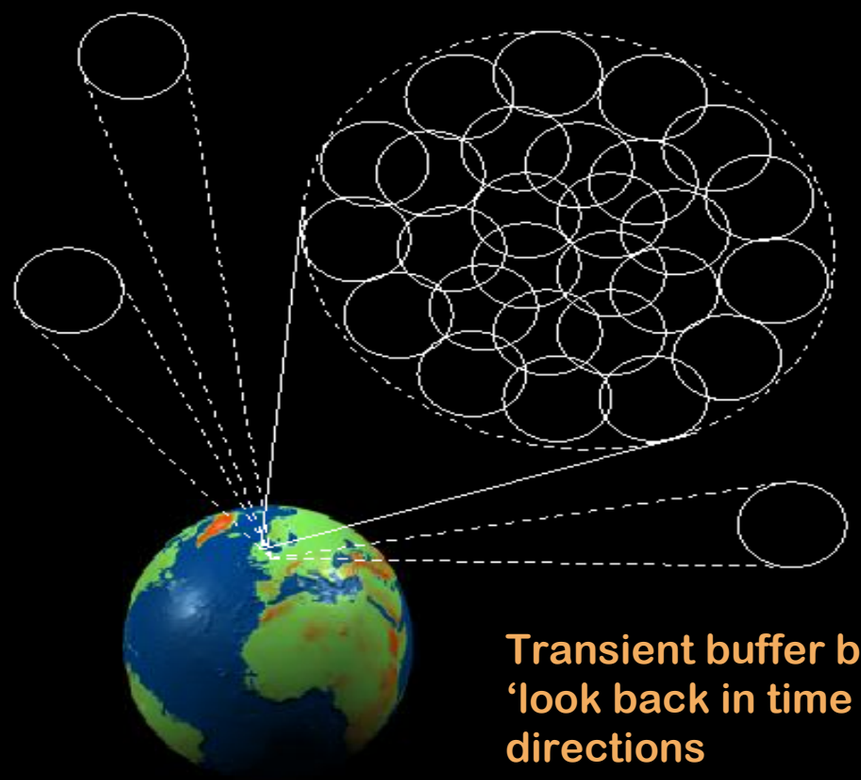
Including international stations gets you to 1” or below

A superlative survey instrument



Large collecting area X wide FoV X multiple beams
= unprecedented survey speed.
very deep and wide surveys/ all sky monitoring

Transients



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

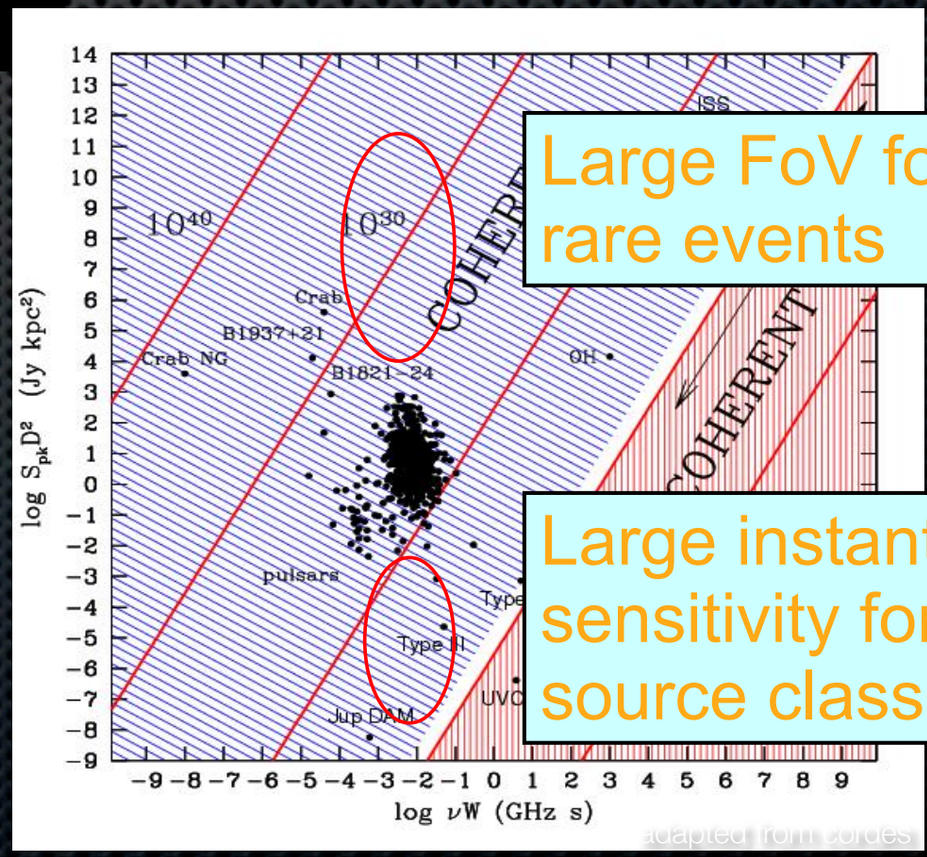
Localisation of transient sources to arcsec or better

Instant reporting of events

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

- XRBs, AGN, GRBs
- Pulsars
- Flare Stars
- Planets
- SETI
- GW sources
- Unknown!

All Sky Monitor



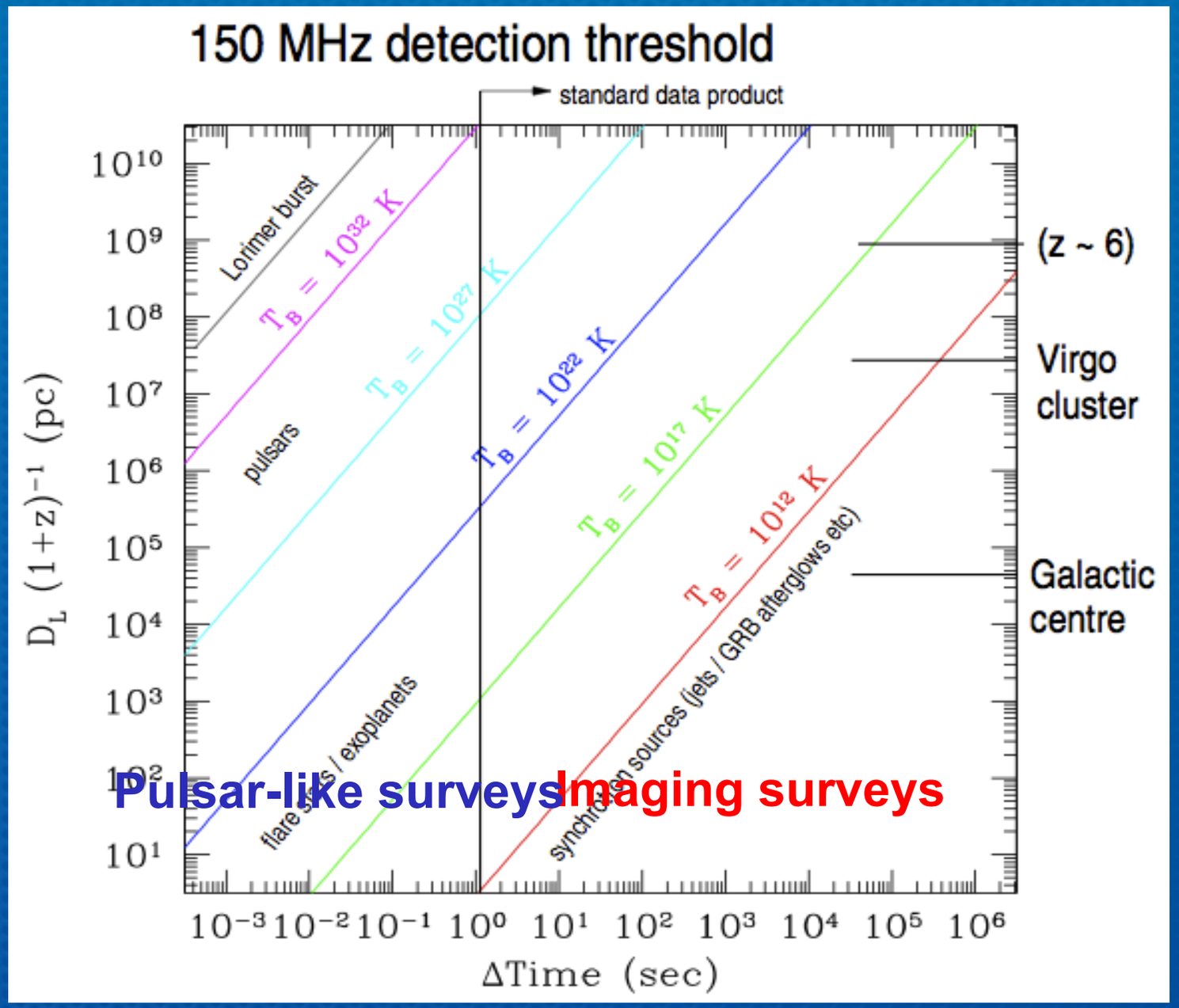
Large FoV for rare events

Large instantaneous sensitivity for weak source classes

adapted from Cordes

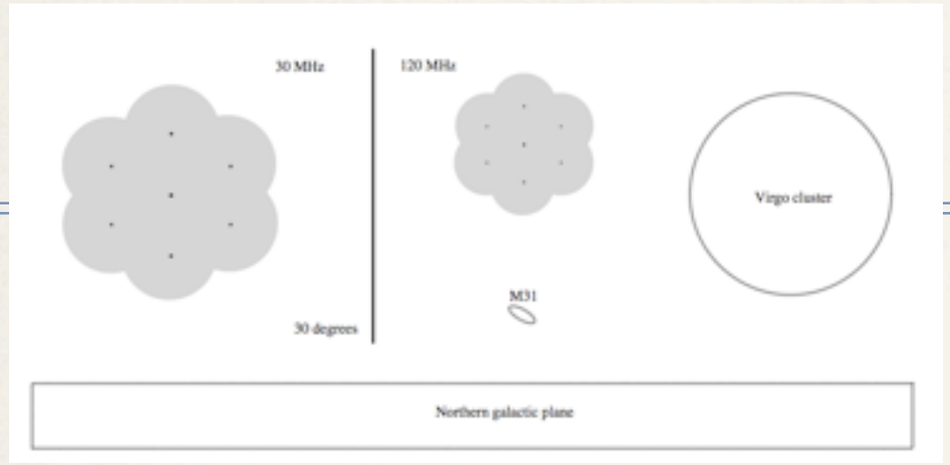
“Fast” Radio Transients

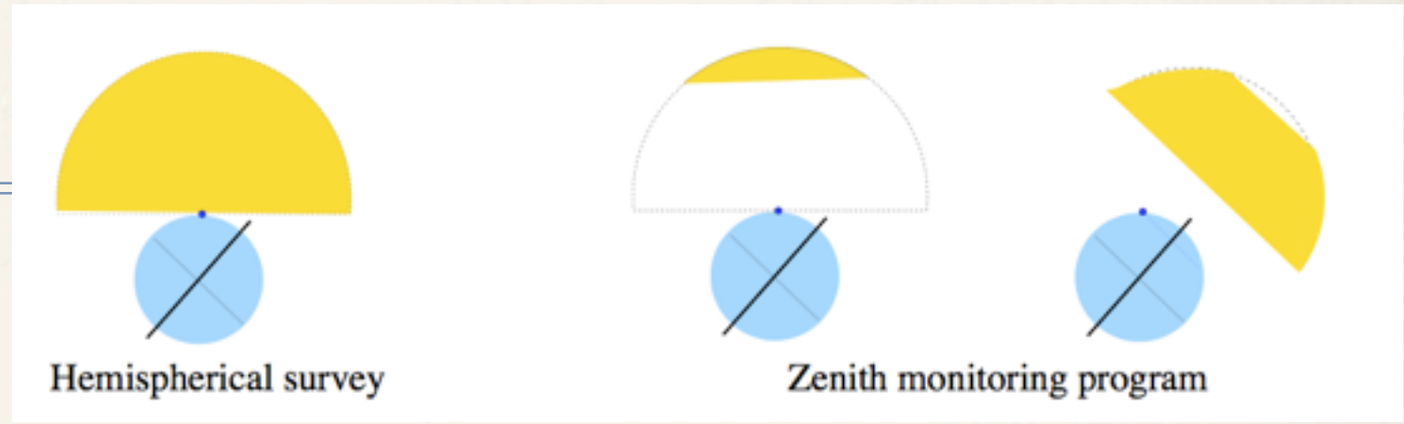
- Timescales of ns - seconds.
- Internal source variability and singular bursts.
- Probed only by non-imaging (timeseries) techniques.
- Propagation effects in ISM (e.g. scattering and dispersion) *very* important.
- RFI contamination.



(Fender et al. 2008)

FoV & Observing Modes



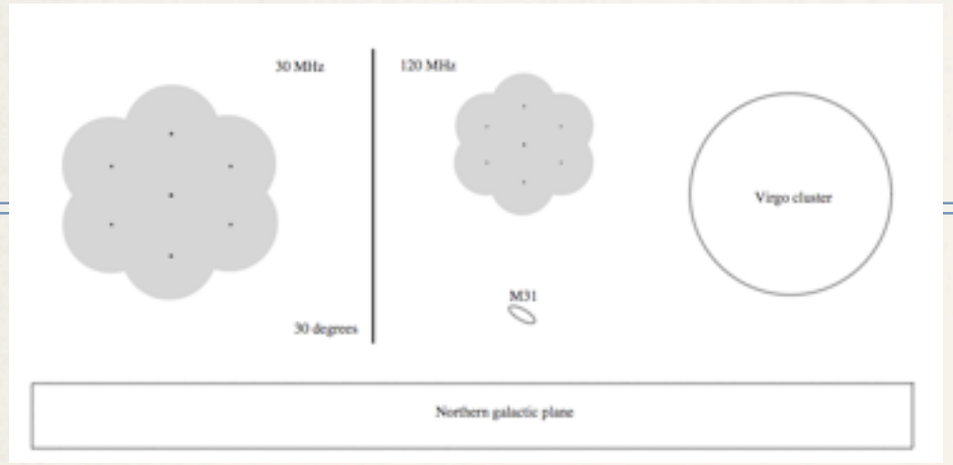


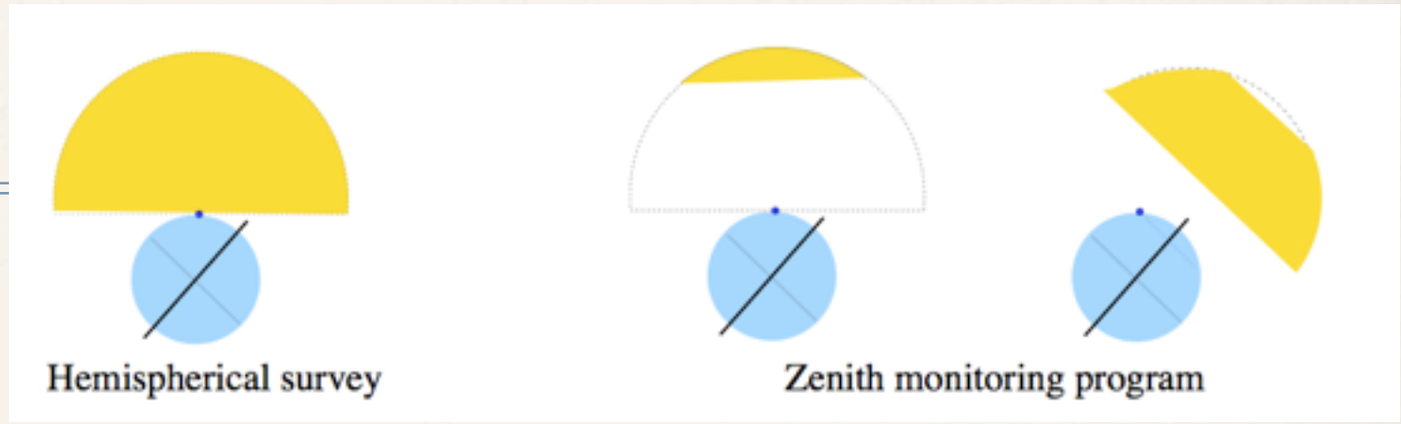
Dedicated observing and commensurate

Commissioning

3C 295

FoV & Observing Modes



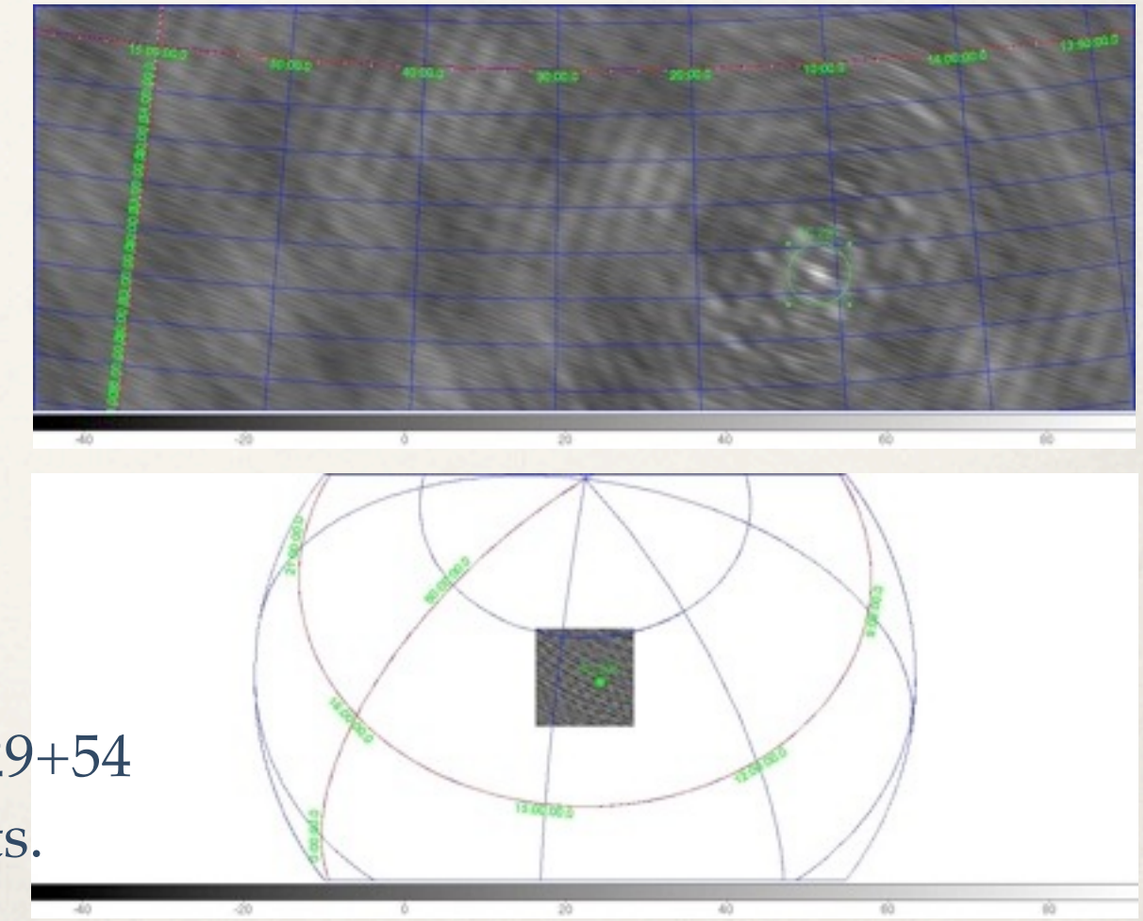


Dedicated observing and commensurate

- First zenith monitoring couple months ago
- Observed for 24 hours to get a full scan
- One field has bright source 3C295 in it
- Single sub band at about 150 MHz
- 25 degrees FoV in single pointing

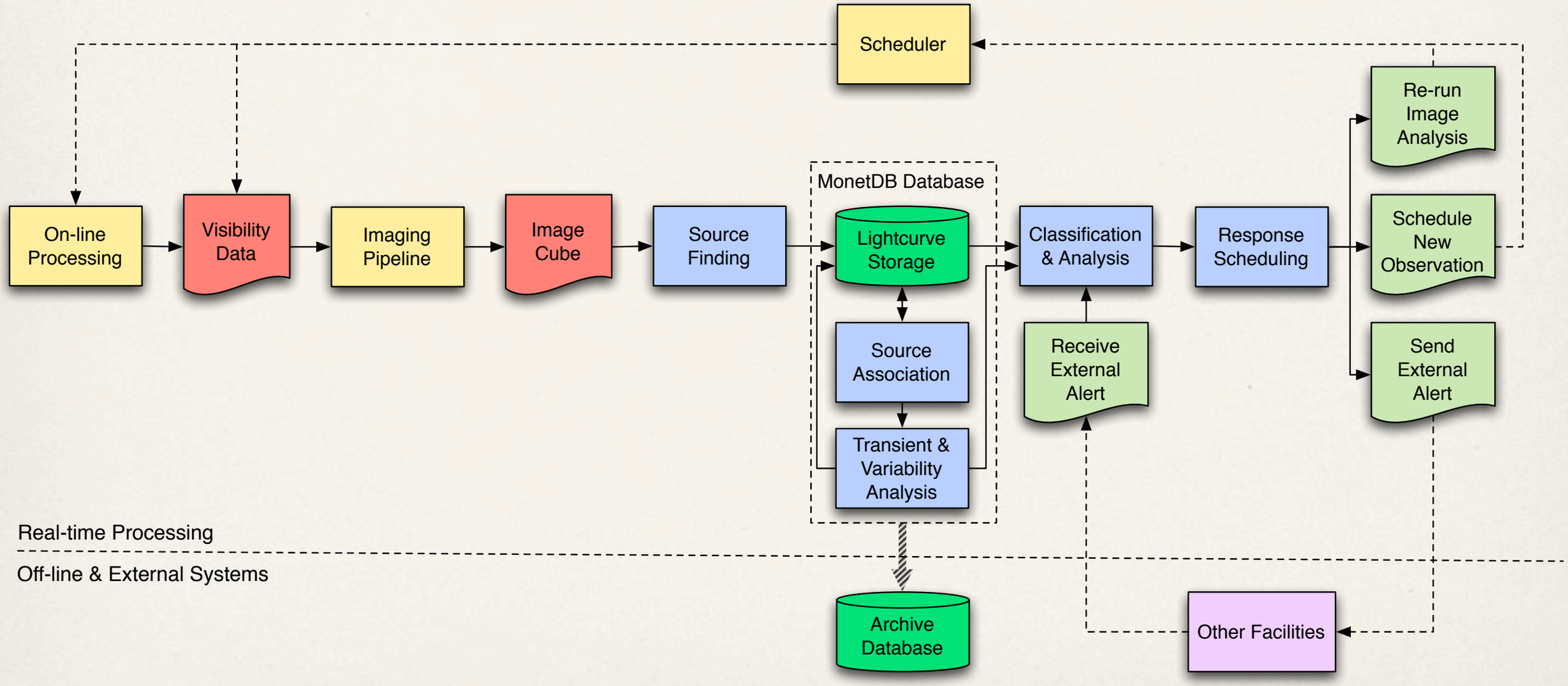
Commissioning

- Follow up LIGO events
- Multiple (~10) observations of field of PSR B0329+54
- Observations of recent SS433 and Crab outbursts.



3C 295

Triggers: Detailed LOFAR pipeline



LOFAR/THUNDERKAT/TRAPUM

courtesy: Fender / 4pisky

LOFAR Spigot

correlator & beamformer

CPU cluster running standard imaging pipeline

User

spigot

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

≤1 sec cycles

LOFAR

Imaging (cluster)

Source finding

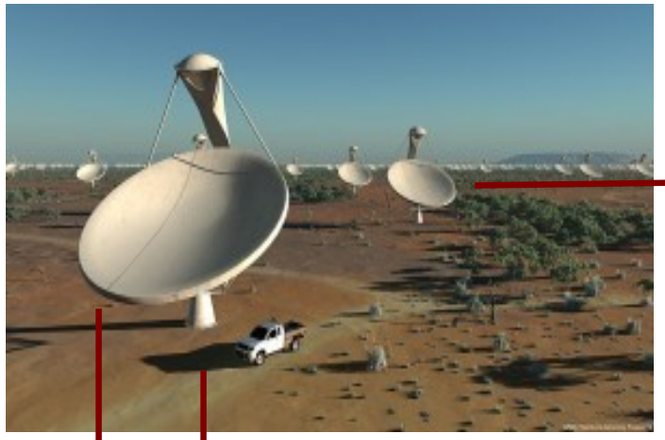
Analysis

Report if interesting

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

LOFAR/THUNDERKAT/TRAPUM

courtesy: Fender / 4pisky



The ThunderKAT spigot

correlator & beamformer

CPU cluster running standard imaging pipeline

User

spigot

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

≤1 sec cycles

ThunderKAT system

Imaging (cluster)

Source finding

Analysis

Report if interesting

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

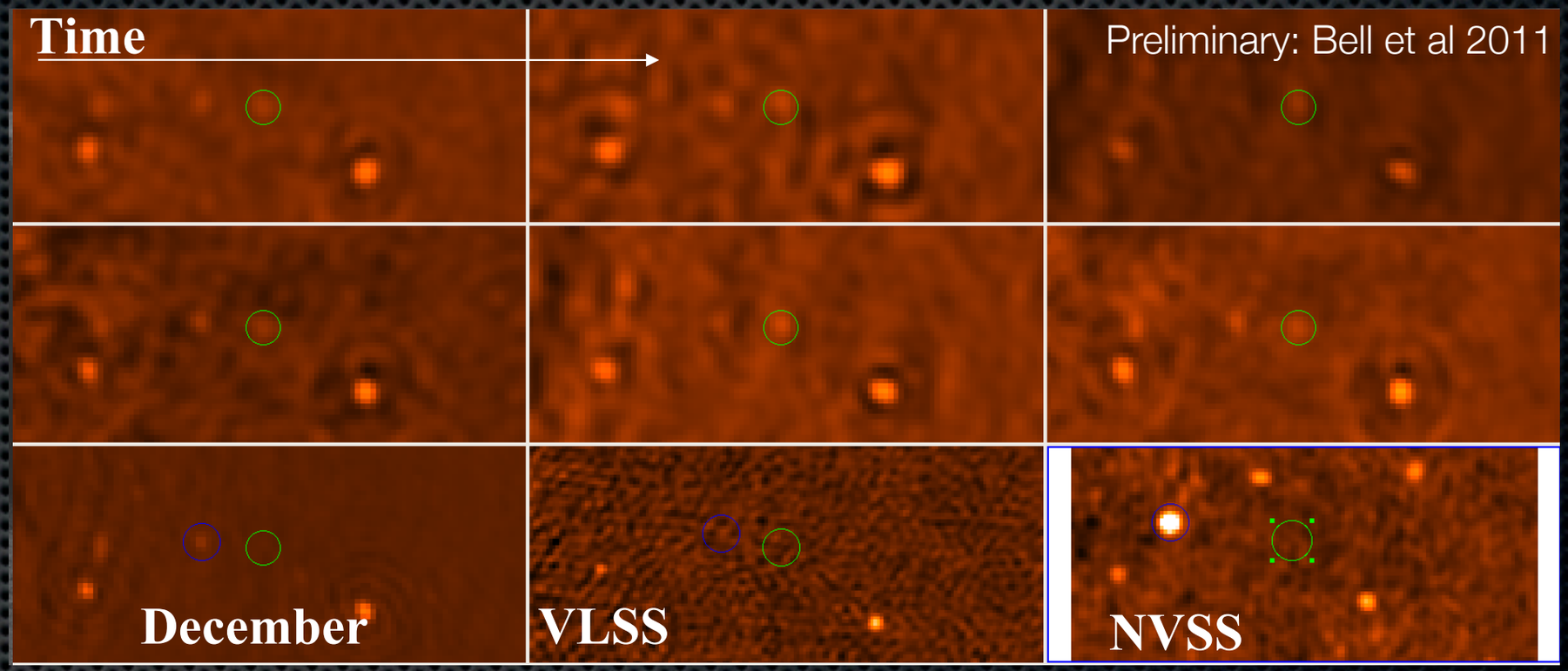
Transients Results

Field near PSR B0329+54

*12 x 12 hour observations.
*150 MHz.
*7 – 25 stations
*25 deg-2 FOV.
*Cadence ~ weekly.

pre December (typical) – 16 Channels.
* 11 core and 4 remote stations.
* Measured Noise ~ 15 mJy.
* Theoretical = 0.32 mJy.
* 46 times theoretical.

* 3rd Dec – 64 Channels.
STATION CALIBRATION
* 19 core and 6 remote stations.
* Measured Noise ~ 3.5 mJy.
* Theoretical = 0.19 mJy.
* 18 times the theoretical

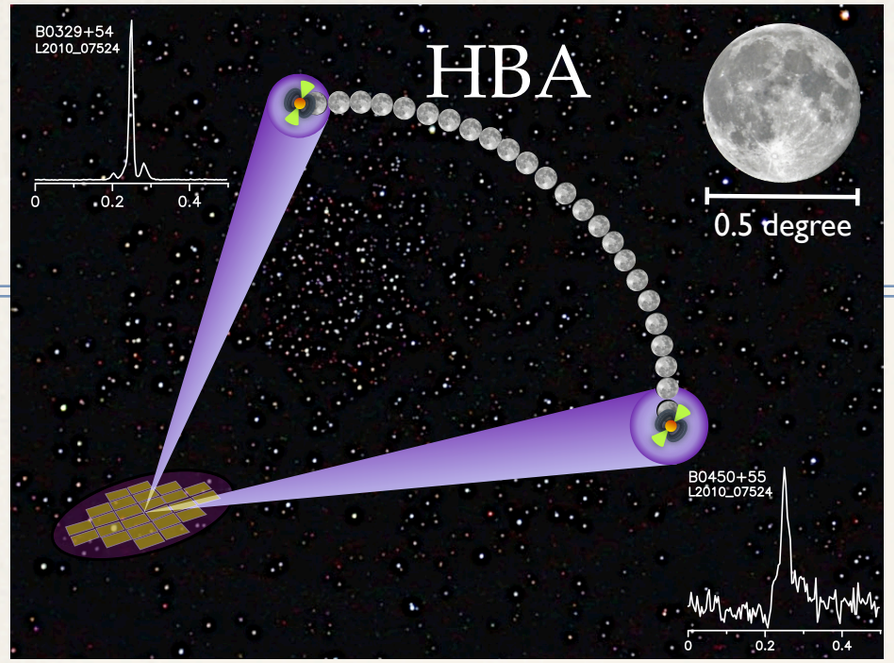


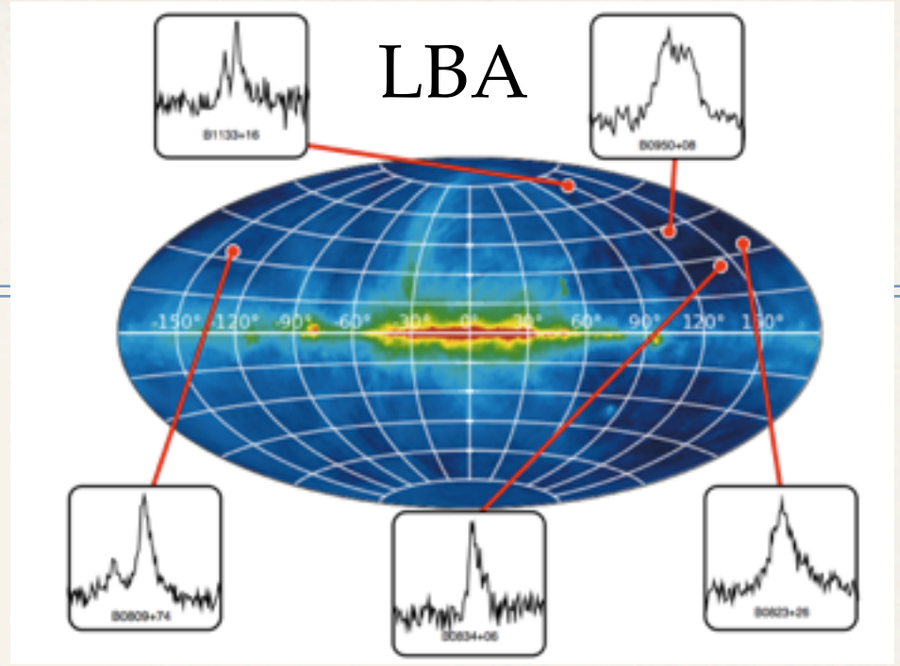
* S ~ 0.25 Jy * 20σ * No VLSS or NVSS counterpart

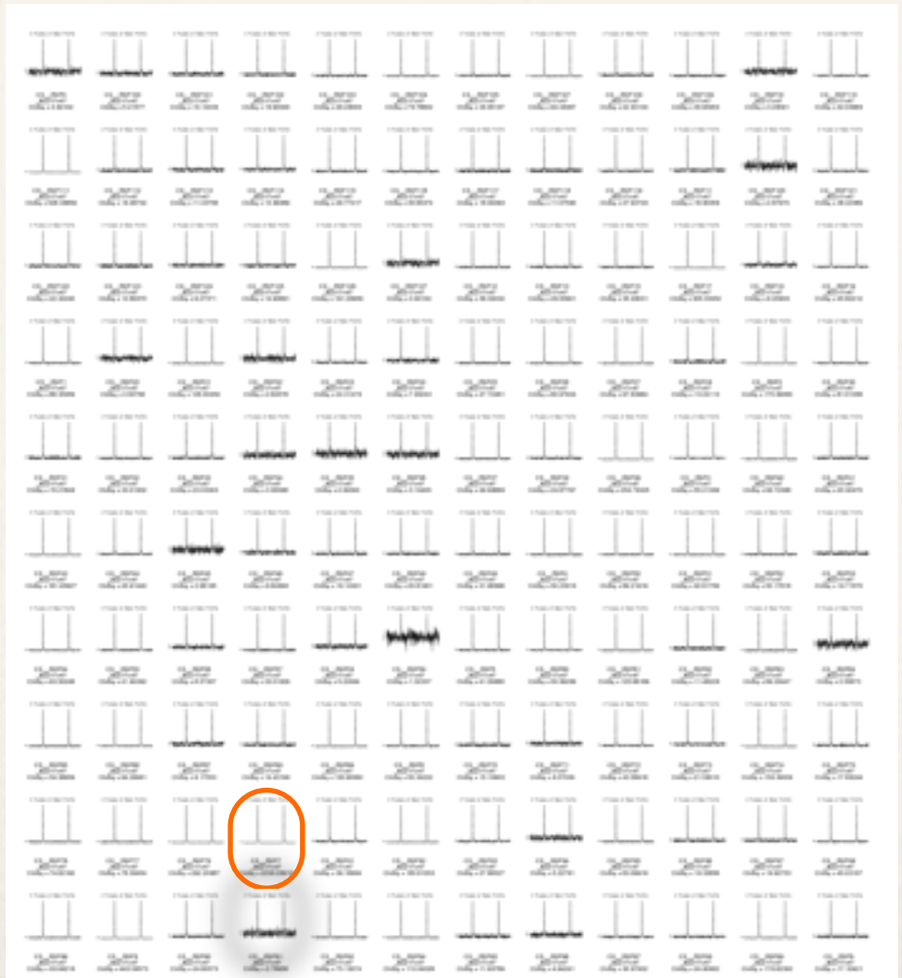
GW Trigger tests - Ed Daw

- During part of last LIGO/Virgo science run
- LOFAR triggered using VOEventNet - although human still received and planned the observations.
- Observations with duration 4-5 hours carried out within about 10 hours or so.
- Of course aiming to bring this down to minutes to seconds.
- No detections (:-)).

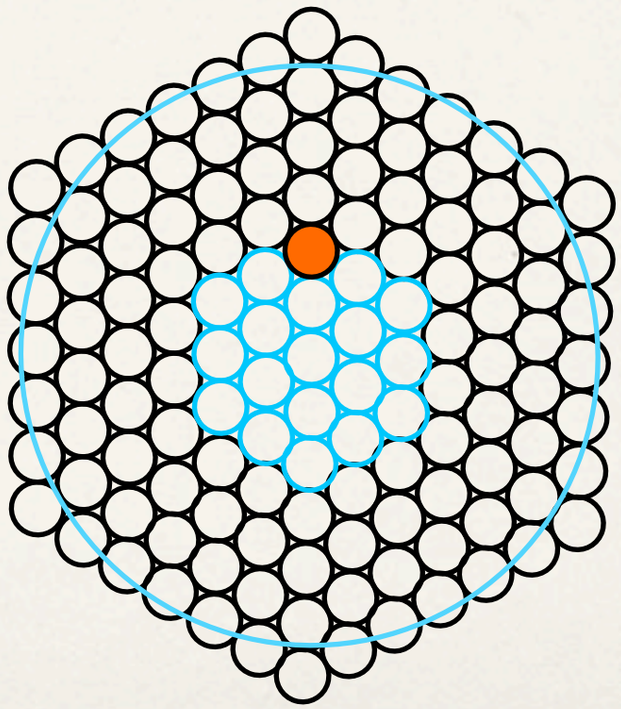
Multi-beaming







Shifted 1 deg south

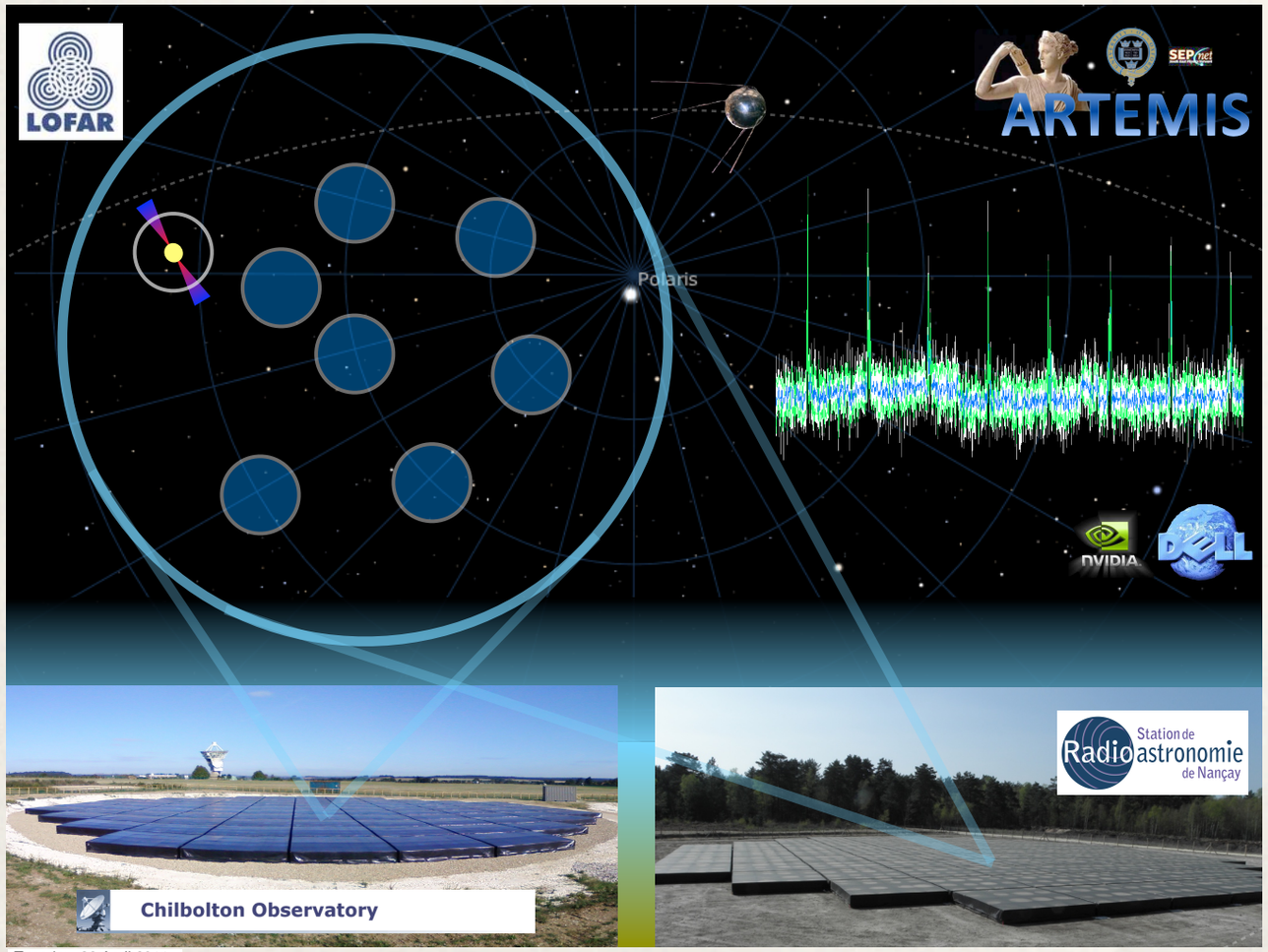


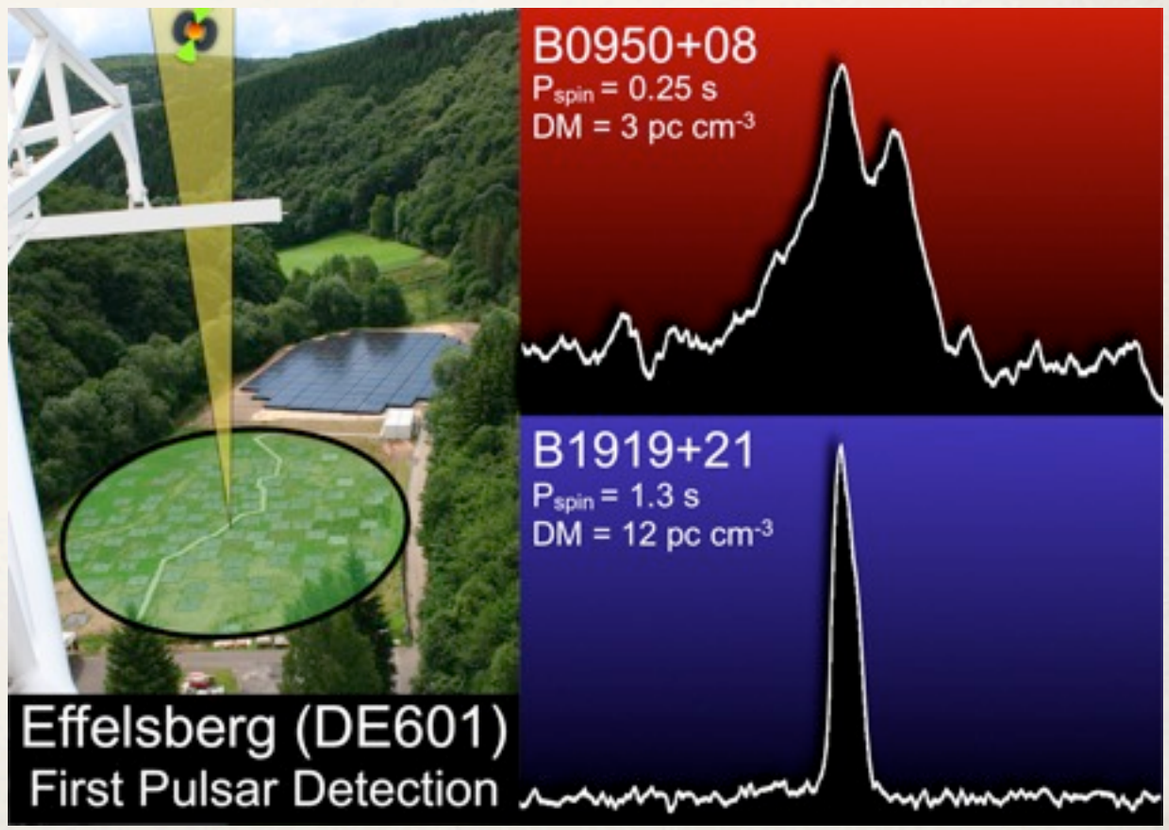
Pulsar is 10x brighter
in the correct beam

Single Station Use

Karastergiou + ARTEMIS & PWG

- Although sensitivity is 10% core it is still equivalent to 100 m dish!
- Efficient rapid surveys of entire sky (8 beams X 4.5 sq deg X 6 MHz BW!)
- Can also use multiple single stations, incoherently or fly's eye
- Useful for fast transients like RRATs, intermittent pulsars, AXPs, scintillating sources, extrem nullers, **double Pdot sources**, **new things**...
- Frequent timing observations, High Energy, GWs, Glitches, ...





LOFAR Timeline

- Official opening was in June 2010
- Currently 40 NL and 8 Eu (5DE, UK, FR, SE) stations complete
- 2 More NL stations by year end
- Another 4-5 stations to come, mainly remote.
- Commissioning is ongoing for all modes until ~ 2012
- More EU stations to be rolled out / New stations/countries joining.
- Station roll out in NL mostly complete in mid 2012
- Some of the Key Science will begin early in 2012