LOFAR

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with inputs from
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OUTLINE

- The International LOFAR Telescope: **the ILT** and associated science.
- **LOFAR** in France and and its coming extension **NenuFAR**
- Perspectives and technical developments in France
- Conclusions

THE INTERNATIONAL LOFAR TELESCOPE

Onsala

Europe-wide radio interferometry array @ 10-270 MHz
Resolution: 2 arcmin - 0.3 arcsec

2010-2012: Commissioning phase
Dec. 2012: Cycle 0 observing cycle
Sep. 2013: Correlator upgrade
Dec. 2013: Start Cycle 1 cycle
Mars. 2014: Cycle 2 call for prop. ,
May 2014: Start Cycle 2 cycle

Chilbolton

Potsdam

Poland funded

- 44 operational stations completed
- 36 NL stations, 8 international stations
- 4 new stations funded in:
Germany (1), Poland (3),
- Proposed stations: Ireland (1),
Italy (1), Finland (1) , NL (2+)

Jülich

Effelsberg

Tautenburg

Nançay

Unterweilenbach

LOFAR SCIENCE DRIVERS

- **Key Science Projects**
  - Epoch of Reionization
  - **Transients and Pulsars: PNHE**
  - High Energy Cosmic Rays: PNHE and see talks on CODALEMA and AERA
  - **Surveys and the Distant Universe: PNHE**
  - Cosmic Magnetism: PNHE
  - Solar Physics and Space Weather: PNHE
- Large fraction of time to Key Science Projects, 10-20% open skies. KSPs have reserved access time in exchange for contributing software, expertise, commissioning, etc.
- KSP membership not limited to member states, expertise-based. Still open to contributions

MULTI-FREQUENCY SNAPSHOT SKY SURVEY = MSSS

Project Leader: George Heald

MSSS-LBA

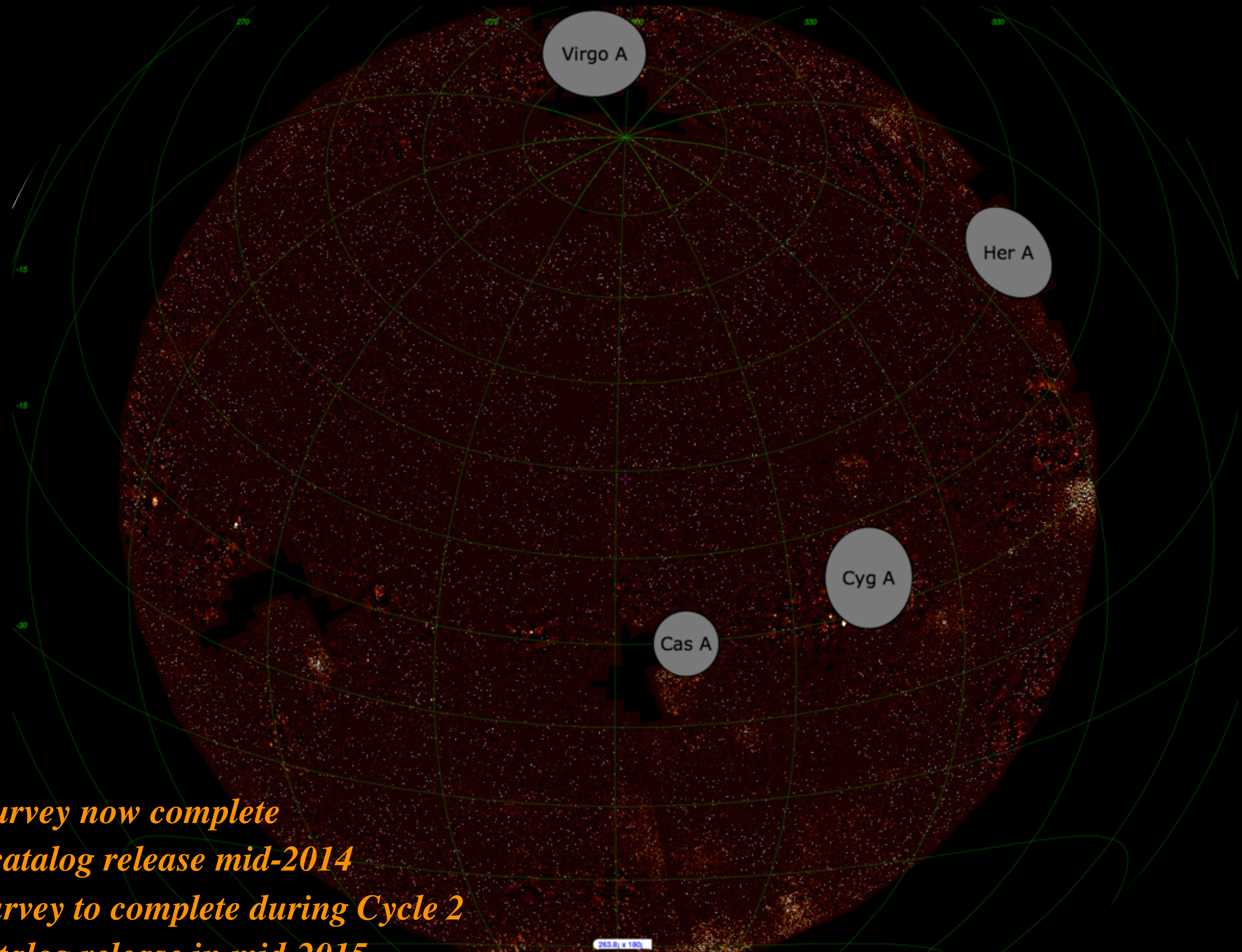
Frequency: 30-75 MHz (8 x 2 MHz bands)
Resolution: ≤100 arcsec
Sensitivity: ≤15 mJy/beam
Area: 20,000 square degrees
Number of Fields: 660

MSSS-HBA

Frequency: 115-180 MHz (8 x 2 MHz bands)
Resolution: ≤120 arcsec
Sensitivity: ≤5 mJy/beam
Area: 20,000 square degrees
Number of Fields: 3616

Goals: Obtain broadband sky model, test LOFAR operations

MULTIFREQUENCY SNAPSHOT SKY SURVEY



HBA Survey now complete

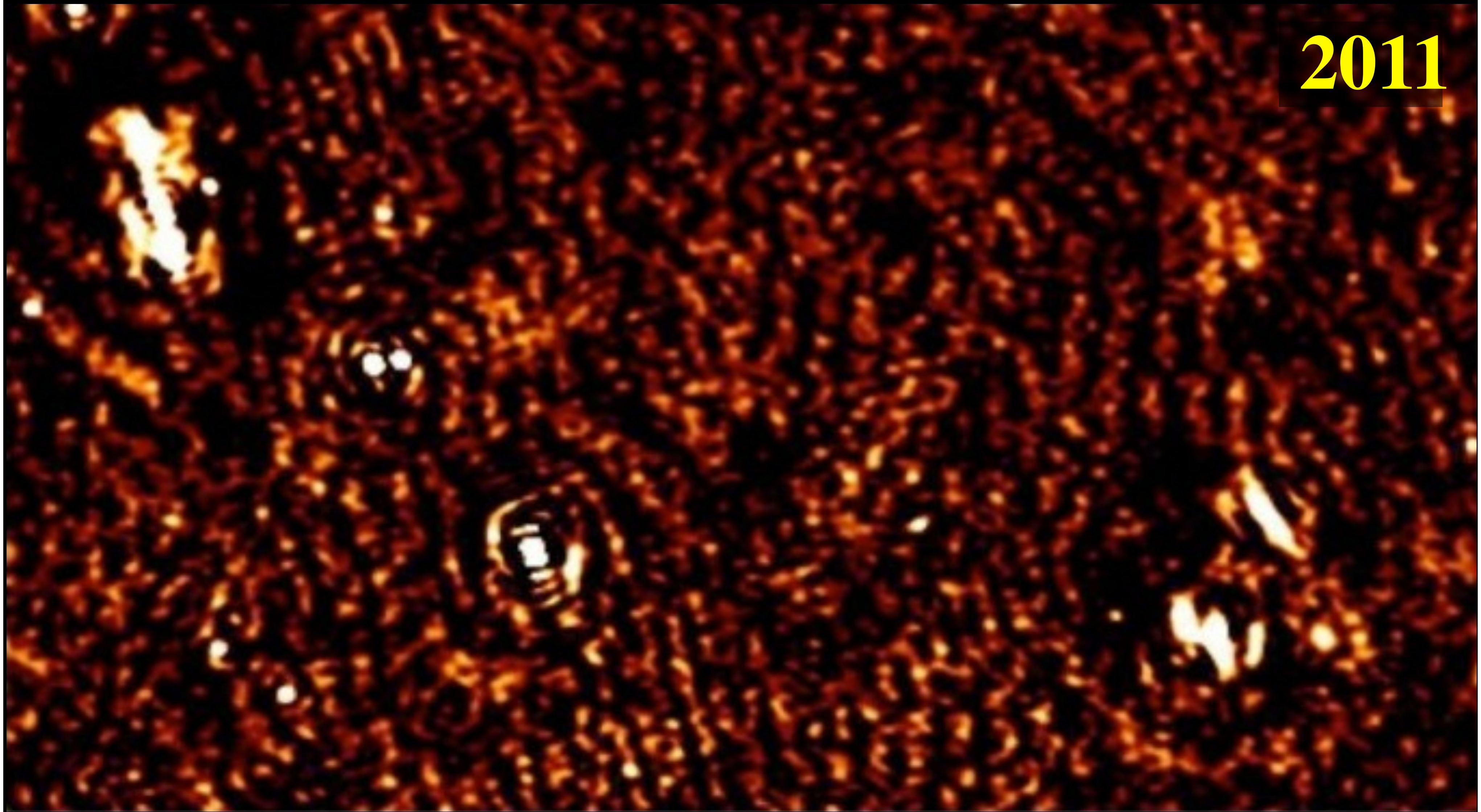
Initial catalog release mid-2014

LBA Survey to complete during Cycle 2

LBA catalog release in mid-2015

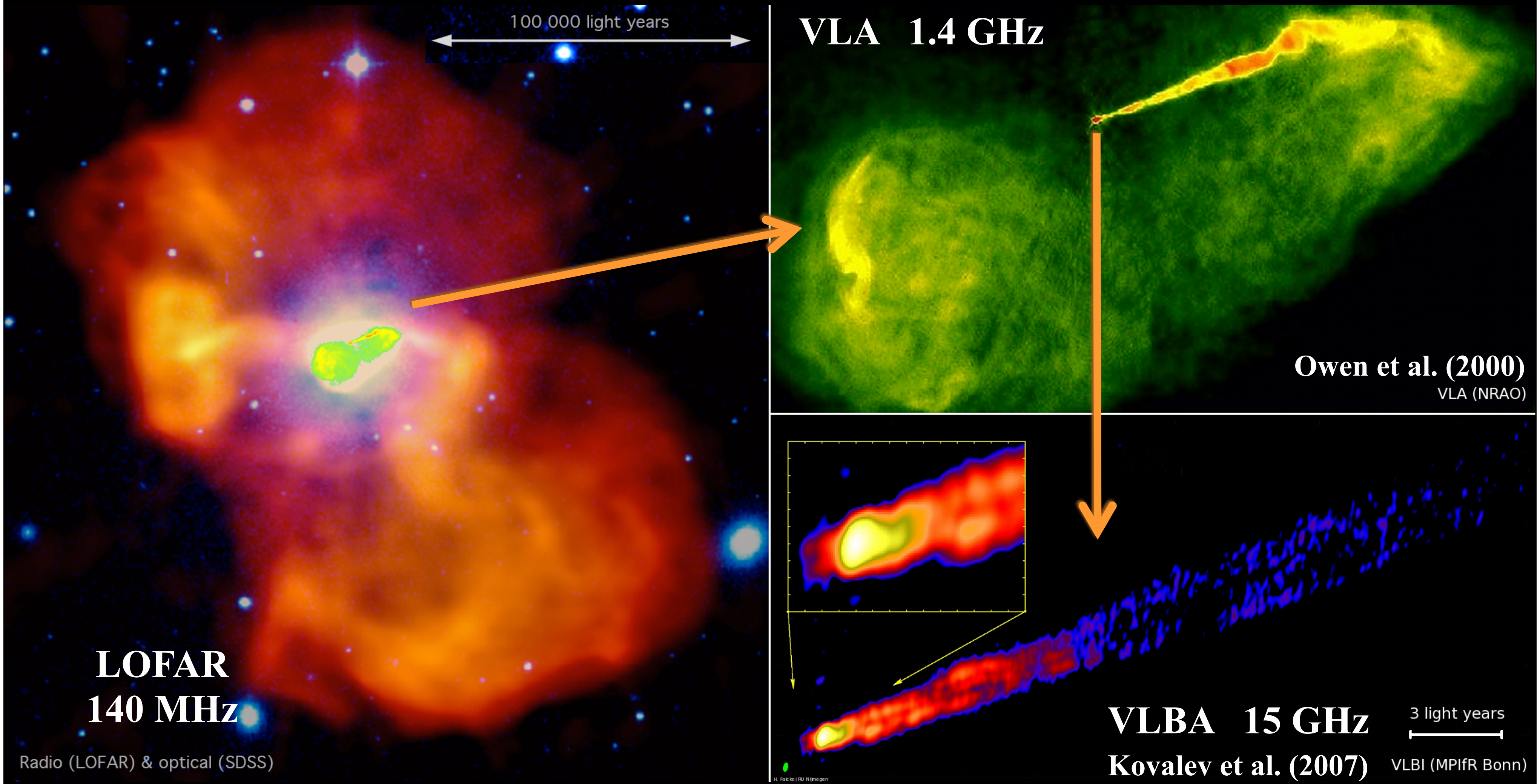
MSSS HBA Mosaic

NCP field ≈ 180 μJy / beam *(image courtesy S. Yatawatta)*



NCP field ≈ 30 μJy / beam *(image courtesy S. Yatawatta)*

M87 at Low Frequencies



de Gasperin et al. (2012)

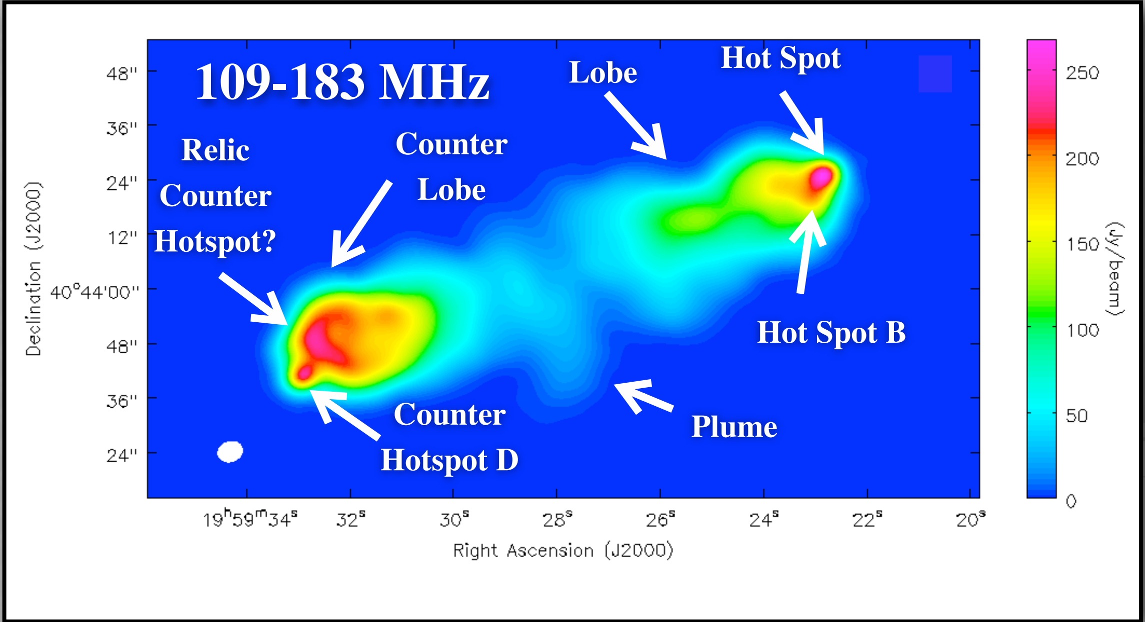
Need extra pressure in the bubbles (protons, non-equip.) …

Cygnus A in the Low-Frequency Radio

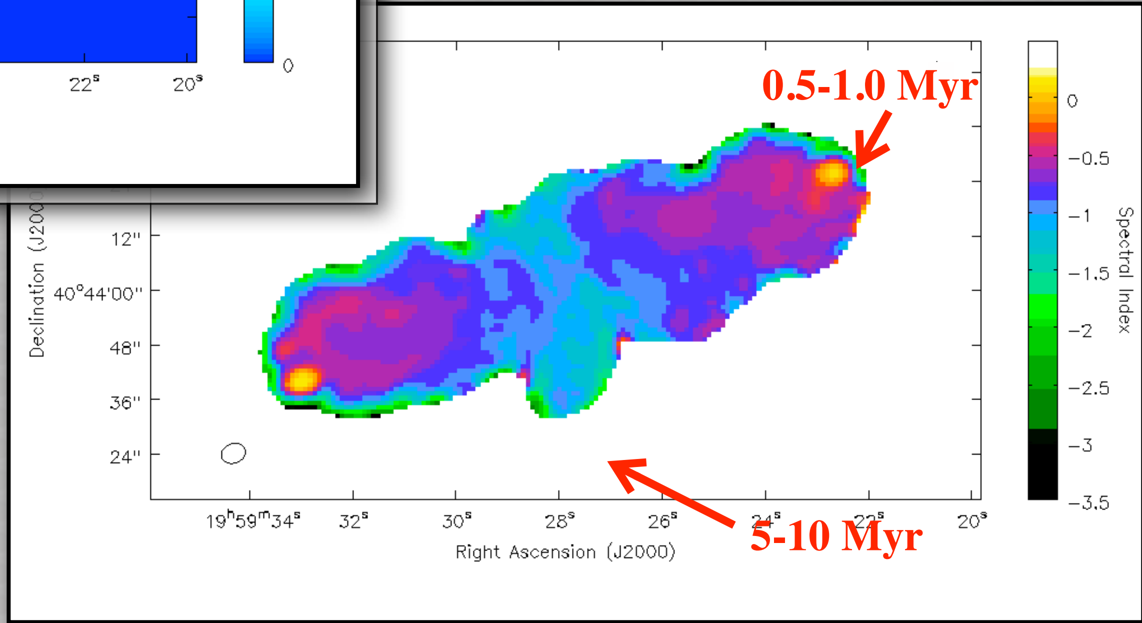
Spectral aging analysis consistent with higher frequency (Carilli et al. 1991)

No evidence for extended diffuse emission beyond shock (yet!)

No diffusion of plasma to large radii



Spectral index map



McKean et al. (2014)

LOFAR HBA

6 hr / 109 - 183 MHz / 28 MHz

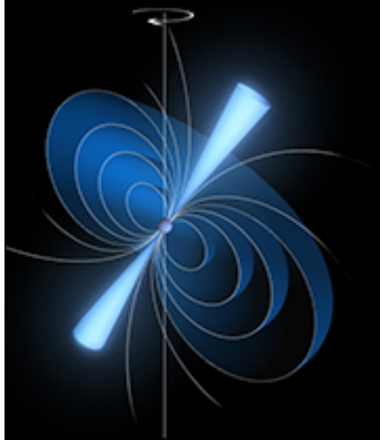
σ ~ 43 mJy / DR ~ 5000

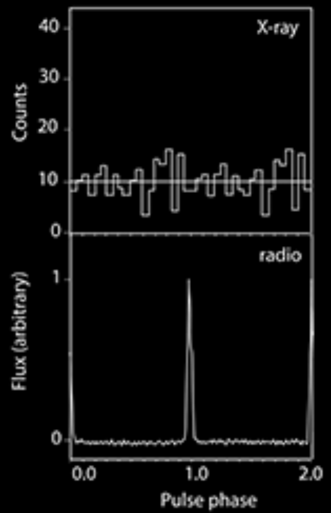
NL baselines only

3.8 x 2.7 arcsec beam

JOINT X-RAY AND RADIO PULSAR MONITORING

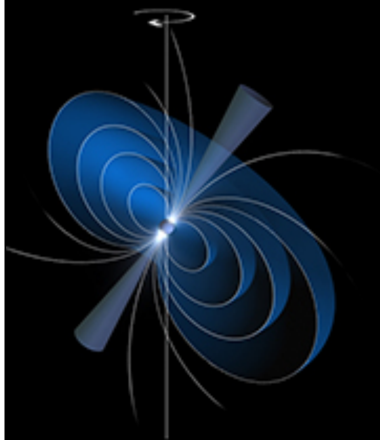
PSR B1931+24

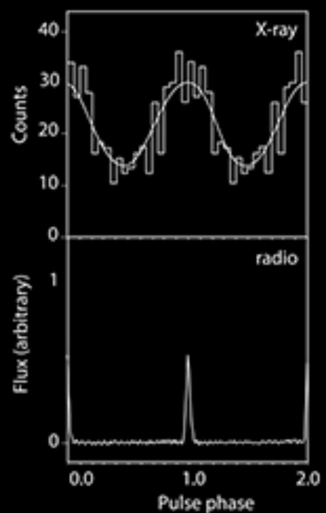




X-ray dim

Radio bright



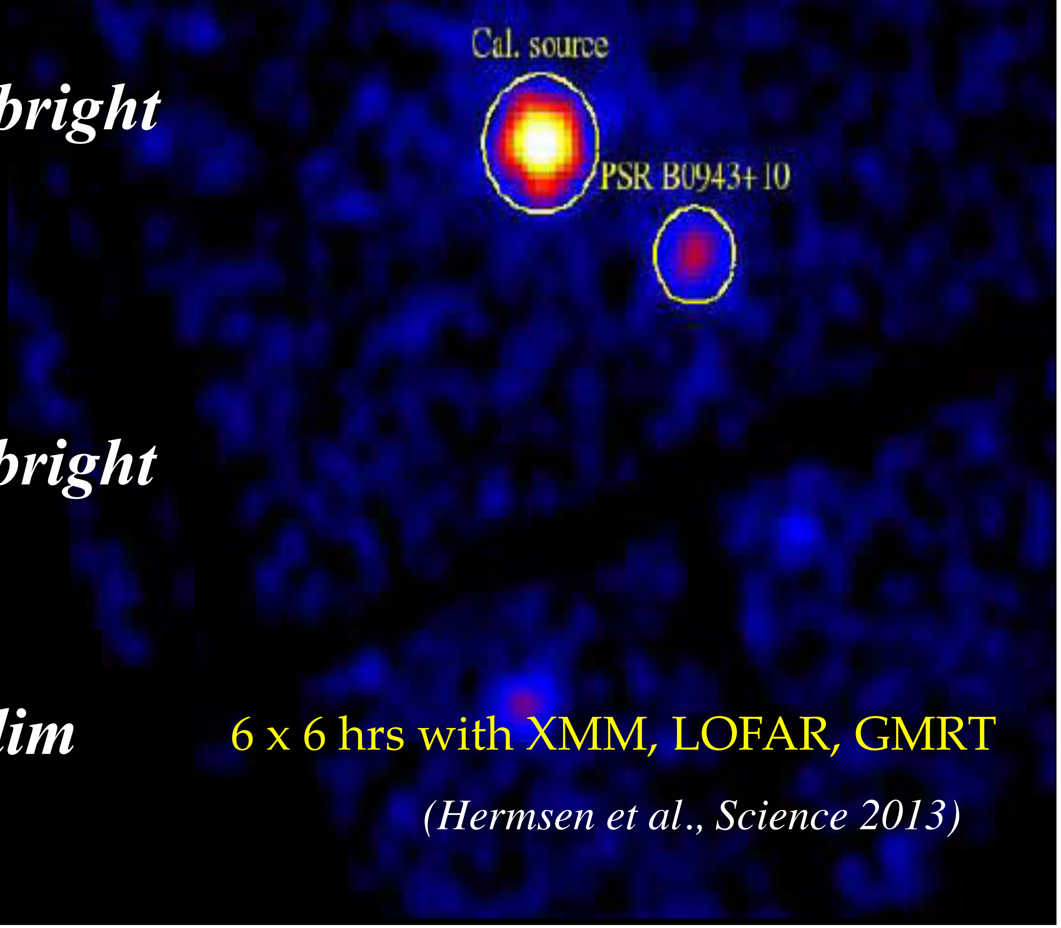


X-ray bright

Radio dim

XMM EPIC 1-2 keV

Simultaneous monitoring of transitions between bright and quiet states

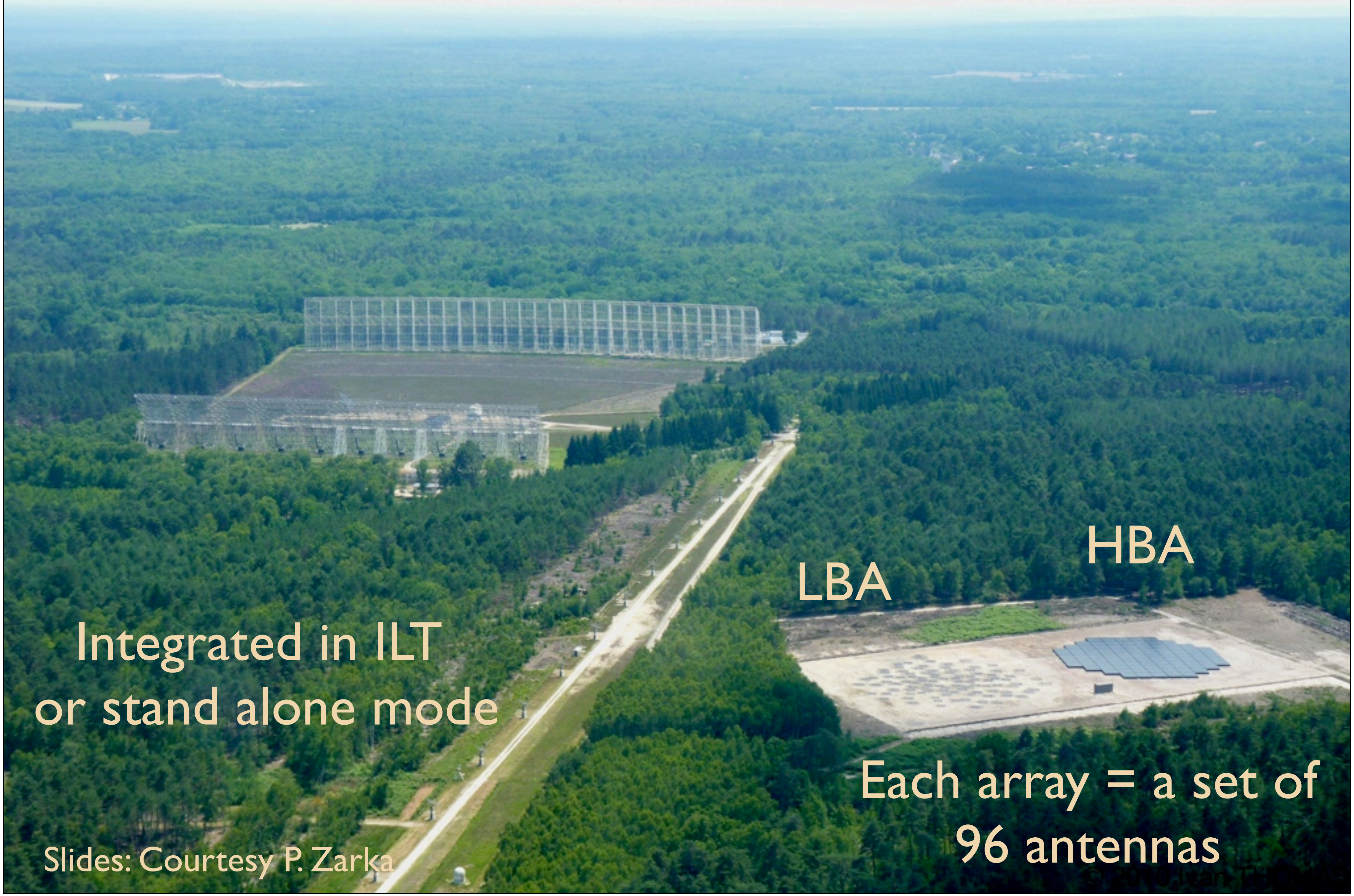


6 x 6 hrs with XMM, LOFAR, GMRT

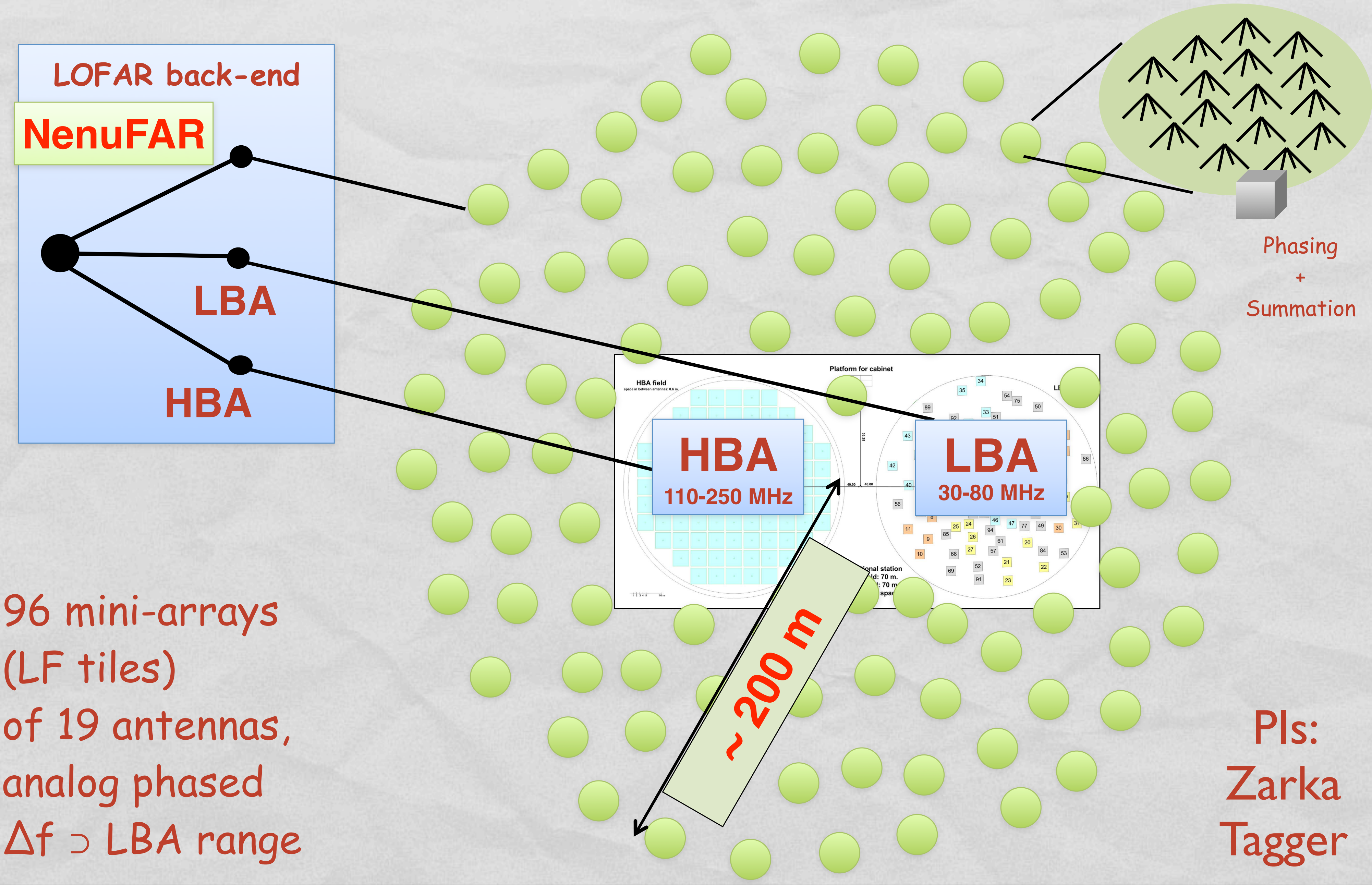
(Hermsen et al., Science 2013)

LOFAR IN FRANCE AND ORIGINAL FRENCH CONTRIBUTIONS

A LOFAR STATION IN NANÇAY



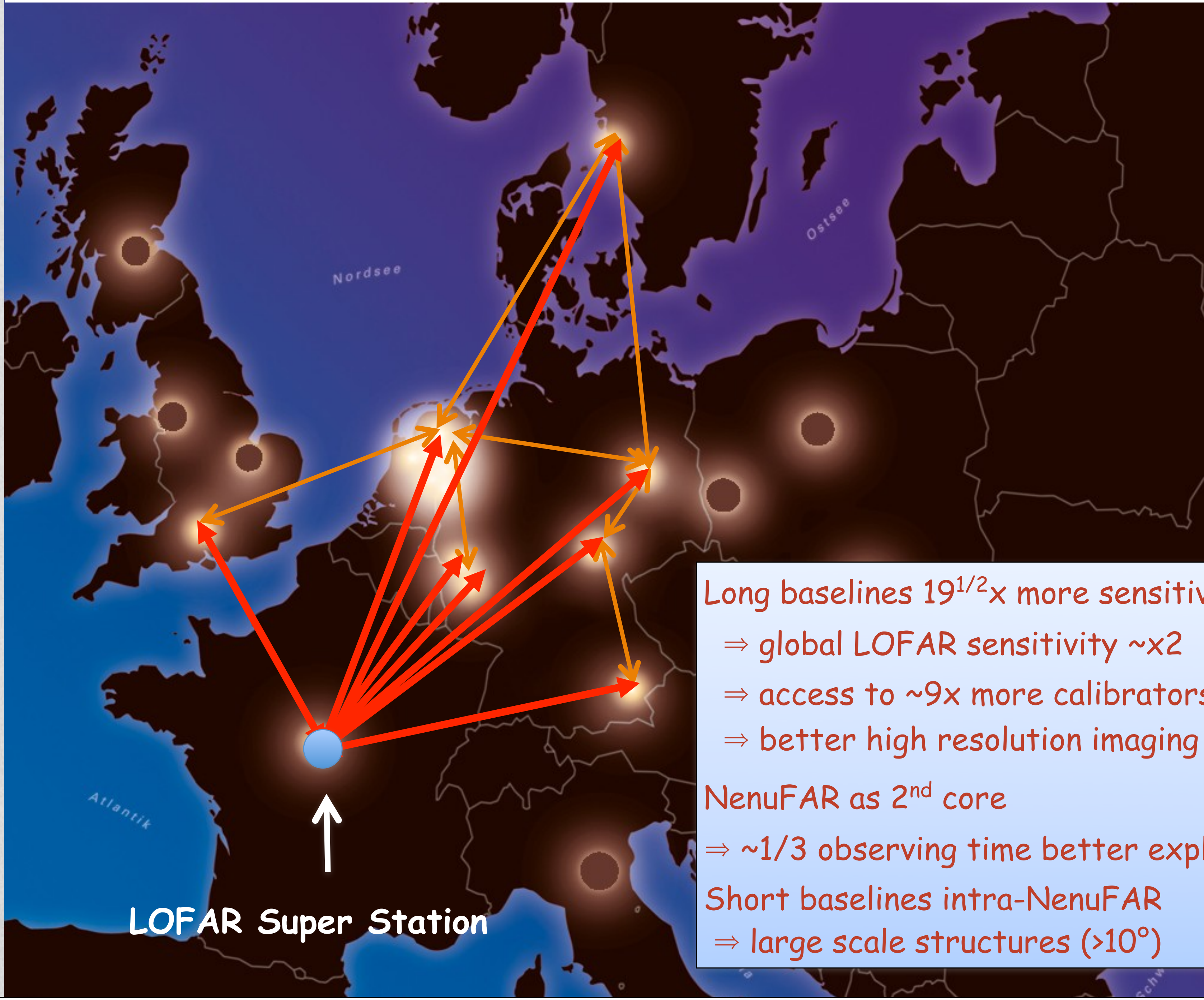
The NenuFAR concept : giant local phased array + interferometer



96 mini-arrays
(LF tiles)
of 19 antennas,
analog phased
Δf ⊃ LBA range

PIs:
Zarka
Tagger

What NenuFAR will bring ?



Long baselines $19^{1/2}$x more sensitive

⇒ global LOFAR sensitivity ~x2

⇒ access to ~9x more calibrators

⇒ better high resolution imaging

NenuFAR as 2nd core

⇒ ~1/3 observing time better exploited

Short baselines intra-NenuFAR

⇒ large scale structures (>10°)

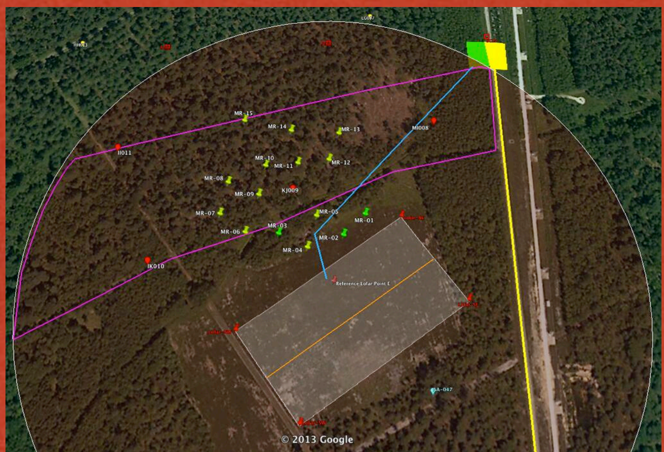
TECHNICAL CHARACTERISTICS OF NENUFAR

- Giant phased array LOFAR-compatible
- 1824 antennas : 96 mini-arrays of 19 antennas each
- Diameter ~400 m. Collective area ~ 62 000 m2 @ 30 MHz ($\propto\lambda^2$)
- Frequency range = 10-85 MHz (λ=3.5-30m). **SKA-Low pathfinder**
- Broad FoV (8°-60°), pointing -23° → +90°
- Angular Resolution ~ 1° (Standalone) - 0.1 " (LSS)
- Time Resolutions <<1 msec × 1 kHz (TBD), Full polarization (4 Stokes)
- Sensitivity <10 mJy (10^{-28} $Wm^{-2}Hz^{-1}$) [+confusion]
- **Privileged access for french community, incl. PNHE**

NENUFAR STATUS

http://nenufar.obs-nancay.fr/

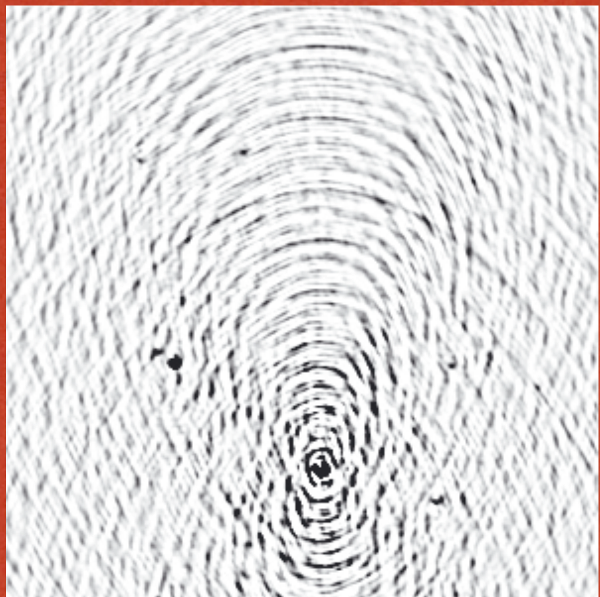
- Construction cost : ~4.5 M€. Low operation cost
- ≥1 M€ secured in 2013 ; 0.5 - 1 M€ expected in 2014 ...
- Phase 1 (NenuFAR-1) received green light from OP/OSUC/UO (15/11/2013) → construction or ≥15 mini-arrays started, operational in ~ 1 year



Name	Antennas	Eff. area	Freq. range	Ang. Res.	N beams	Polar.
NDA	144 circ. dipoles	2400 m² (*)	10-100 MHz	7.5° (*)	1 beam	4 Stokes
UTR-2	2040 dipoles	143000 m²	8-32 MHz	0.5°	5 beams	1 lin. polar.
VLA	27 dish.× 25 m	~2000 m²	73-74.5 MHz	0.5'	1 beam	4 Stokes
LWA (LWA1)	256 X dipoles	~8000 m² (*)	10-88 MHz	6° (*)	4 beams ×20 MHz	4 Stokes
OLWA	256 X dipoles (→2000)	~8000 m² (*) (→ 65000 m²)	10(28)-88 MHz	≤5° (*) (→ ≤1°)	Full-sky imaging	4 Stokes
NenuFAR-1	285 X dipoles	~9000 m² (*)	10-85 MHz	5° (*)	2 beams	4 Stokes
AARTFAAC-LBA	288 X dipoles	~8000 m² (*)	30-80 MHz	2° (*)	All-Sky	4 Stokes
LOFAR-LBA	2688 X dipoles	72000 m² (*)	30-80 MHz	2" (*)	8+beams ×4 MHz	4 Stokes
NenuFAR standalone	*1824 X dipoles*	*62000 m² (*)*	*15-80 MHz*	*1.5° (*)*	*4 beams ×65 MHz*	*4 Stokes*
NenuFAR +LOFAR-LBA	*4512 X dipoles*	*134000 m² (*)*	*30-80 MHz*	*2" (*)*	*8+beams ×4 MHz*	*4 Stokes*
SKA	>3000 dishes +Apert. Array	~10^6 m²	0.05 - >10 GHz	<0.1"	many (?) beams	4 Stokes

SOME ORIGINAL CONTRIBUTIONS FROM THE FRENCH COMMUNITY

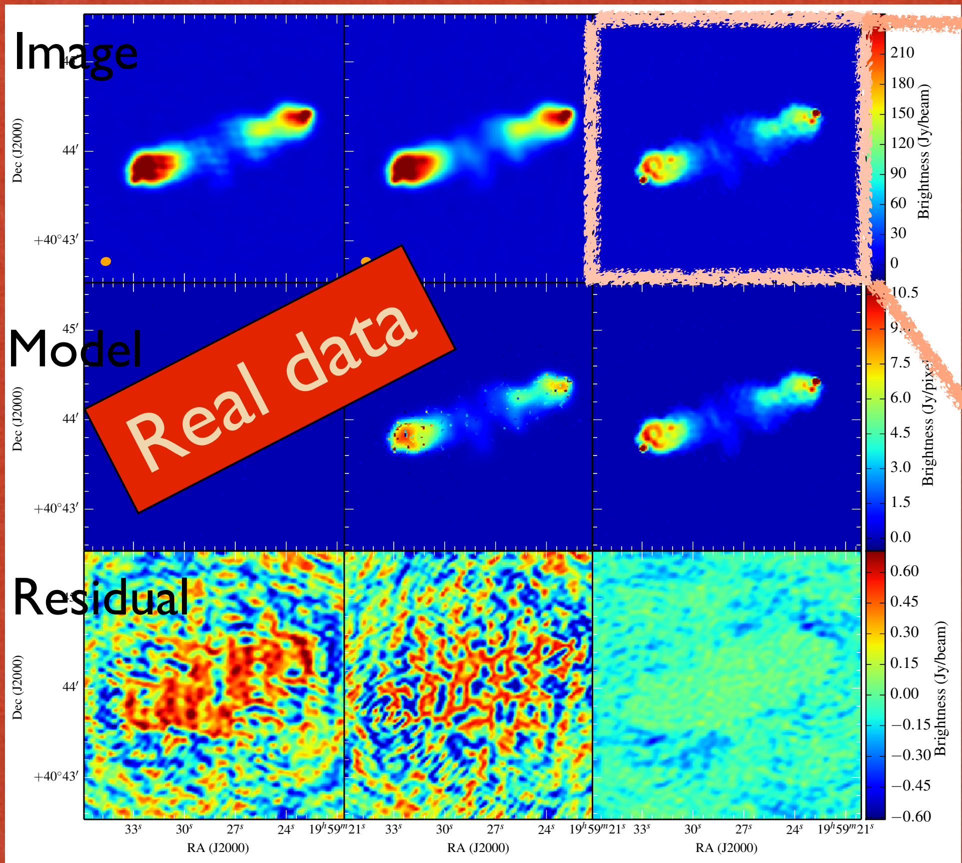
- A full radio imager taking into account direction dependent effects (Tasse et al. 2013) : *awimager*



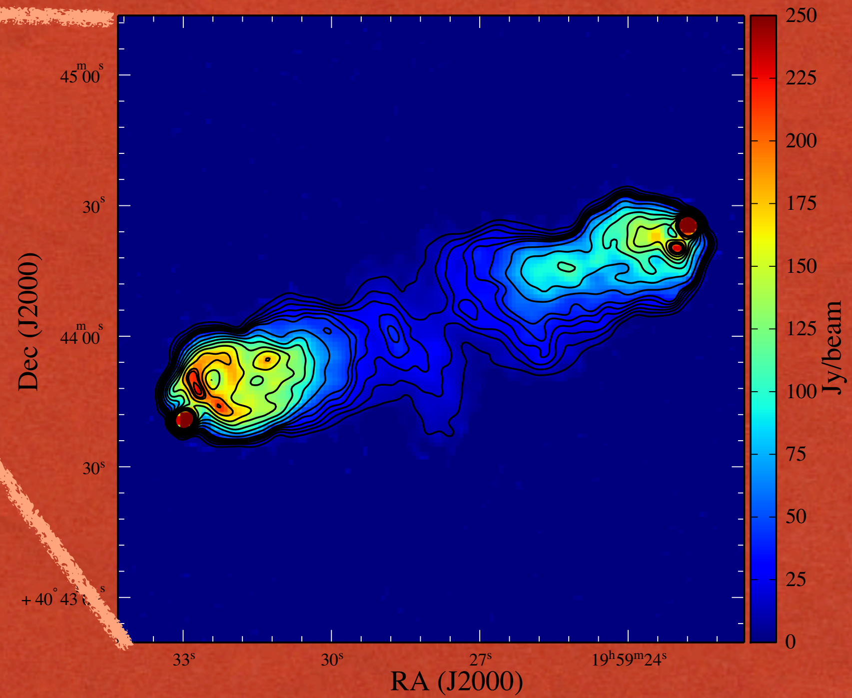
w term

w term + array + element beam

IMPLEMENTING COMPRESSING SENSING IN RADIOASTRONOMY



Clean MS Clean CS



Real LOFAR data of Cyg A (with VLA contours at higher freq=LOFAR x3)

Garsden, Girard et al. submitted

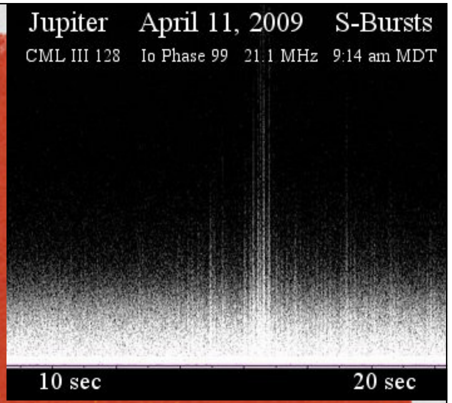
UnivEarthS
LabEx

TIME DOMAIN ASTRONOMY

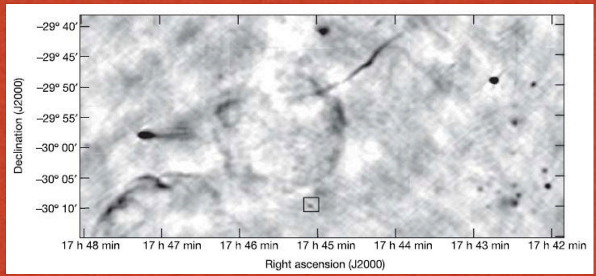
THE TRANSIENTS RADIO SKY

- A glimpse of physics in extreme environments.
- Time domain astronomy: a huge discovery potential, recognized in all recent prospective reports. Testing relativity. Cosmic lighthouses for probing the IGM.
- Example of unexpected transients: Discovery of pulsar by J. Bell (Nobel for Hewish), SN1a, GRB, ...
- Even now, new types of transients are still discovered: TDEs and FRBs
- A huge variety of transients on very different timescales: X-ray binaries, pulsars, black holes at cosmological distance, atmospheric γ-ray flashes, exoplanets, EM signature of GW, the unknown, …

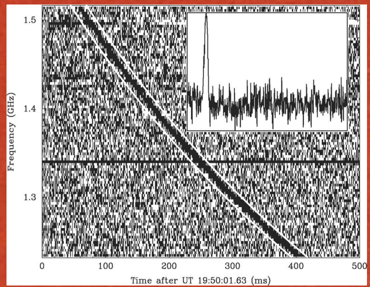
COHERENT EMISSION



- Resulting from the coherent movement and emission of radiation by electrons

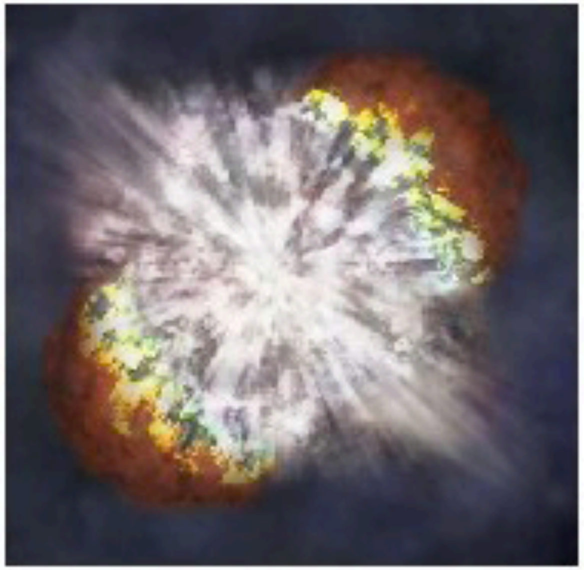


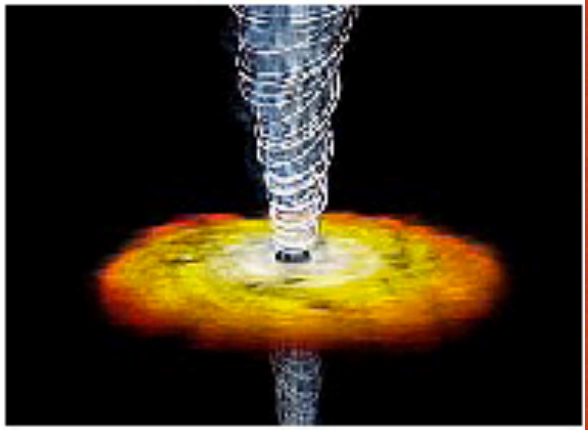
- Examples of these include:
    - Pulsars and friends (RRATs etc):



    - Flare stars / (exo)planets / cyclotron masers
    - + unknown (as originally pulsars or Lorimer burst (=FRB), ETI signal) !!
- These can have extremely high brightness temperatures and usually rise steeply at low frequencies.

INCOHERENT SYNCHROTRON EMISSION

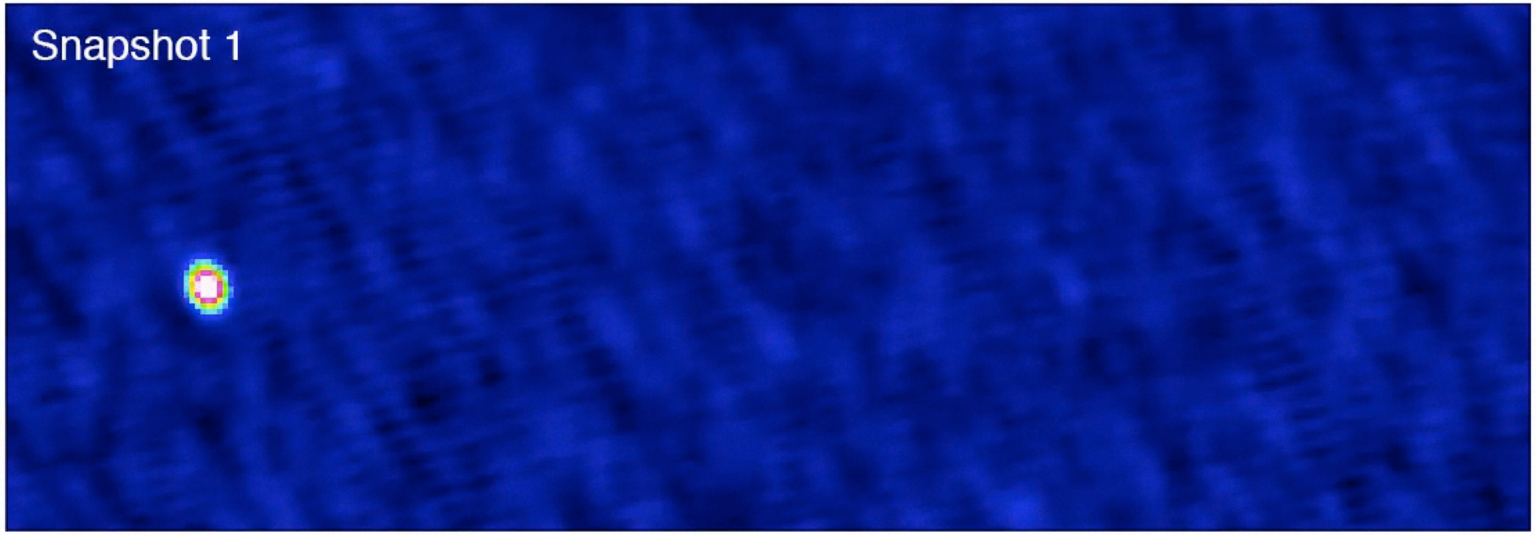




- All cases of explosive injection of energy into the ambient medium result in particle acceleration and/or an amplification of the local magnetic field → synchrotron emission.
- Examples of these include:
  - Relativistic jets from X-ray binaries (microquasars)/AGN
  - Supernovae and GRB afterglows
  - Giant outbursts from magnetars
- Well established multi-wavelength communities for such objects– usually associated X-ray and optical activity.
- Physics in strong gravitational field. Particles acceleration. Accretion-ejection coupling. Energy deposit by relativistic jets.

TRANSIENTS WITH MSSS

First MSSS(-LBA) transient candidate (Stewart et al, in prep)



- Appears in one 11-min snapshot, using 10 σ threshold of 4 Jy
- Implied rate for Δt=11min is 1/2537 transients day^{-1} deg^{-2} (~1 transient per square degree per 7 years!)

CONCLUSIONS

- The International LOFAR Telescope (ILT) is fully deployed and is working well. Regular CfP every 6 months.
- Regular scientific results coming out.
- An important French addition in construction with incremental upgrades: NenuFAR. Science case under developments. Fully open.
- PNHE emerging fields: Time Domain Astronomy. Unexpected discovery to come by observing a new parameter space !!!
- Science from -slow/fast- transients. Multi-wavelength synergies (SKA pathfinders, LSST, SVOM, SKA, ..). Topics to be explored urgently !!!