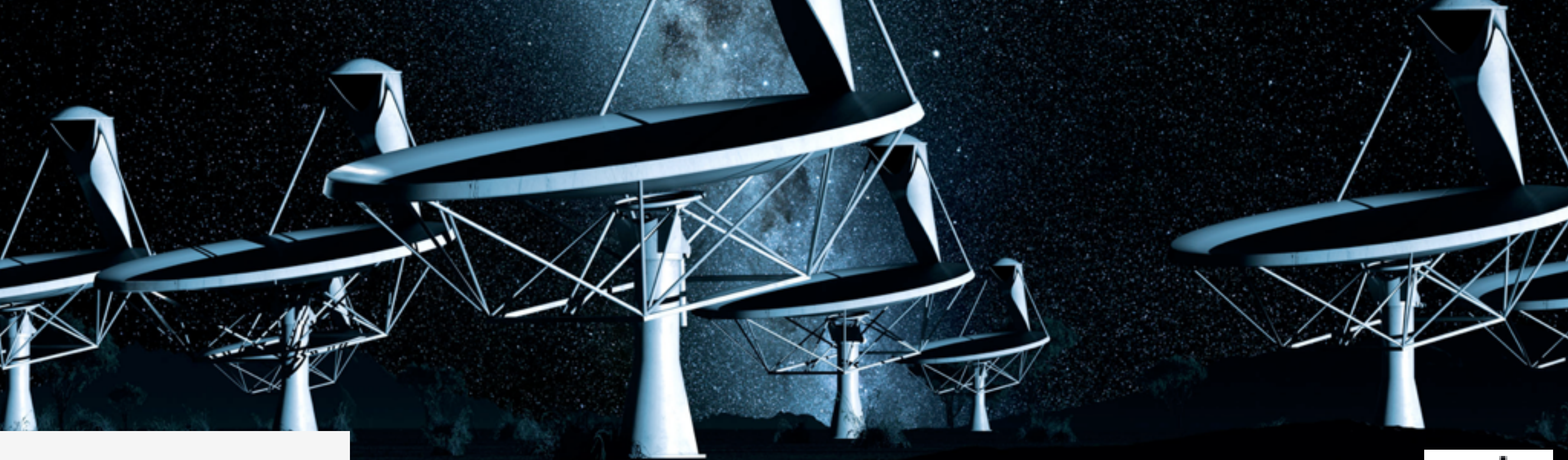
A coming revolution in radioastronomy: Towards the SKA



Stéphane Corbel

Univ. Paris Diderot & CEA/IRFU/SAp & IUF

Outline

- **Radioastronomy**: beginning of an already successful story
- The **SKA** telescope
- **Sciences** with the SKA
- The current generation of radio telescopes and the coming SKA **pathfinders**
- SKA in **France**

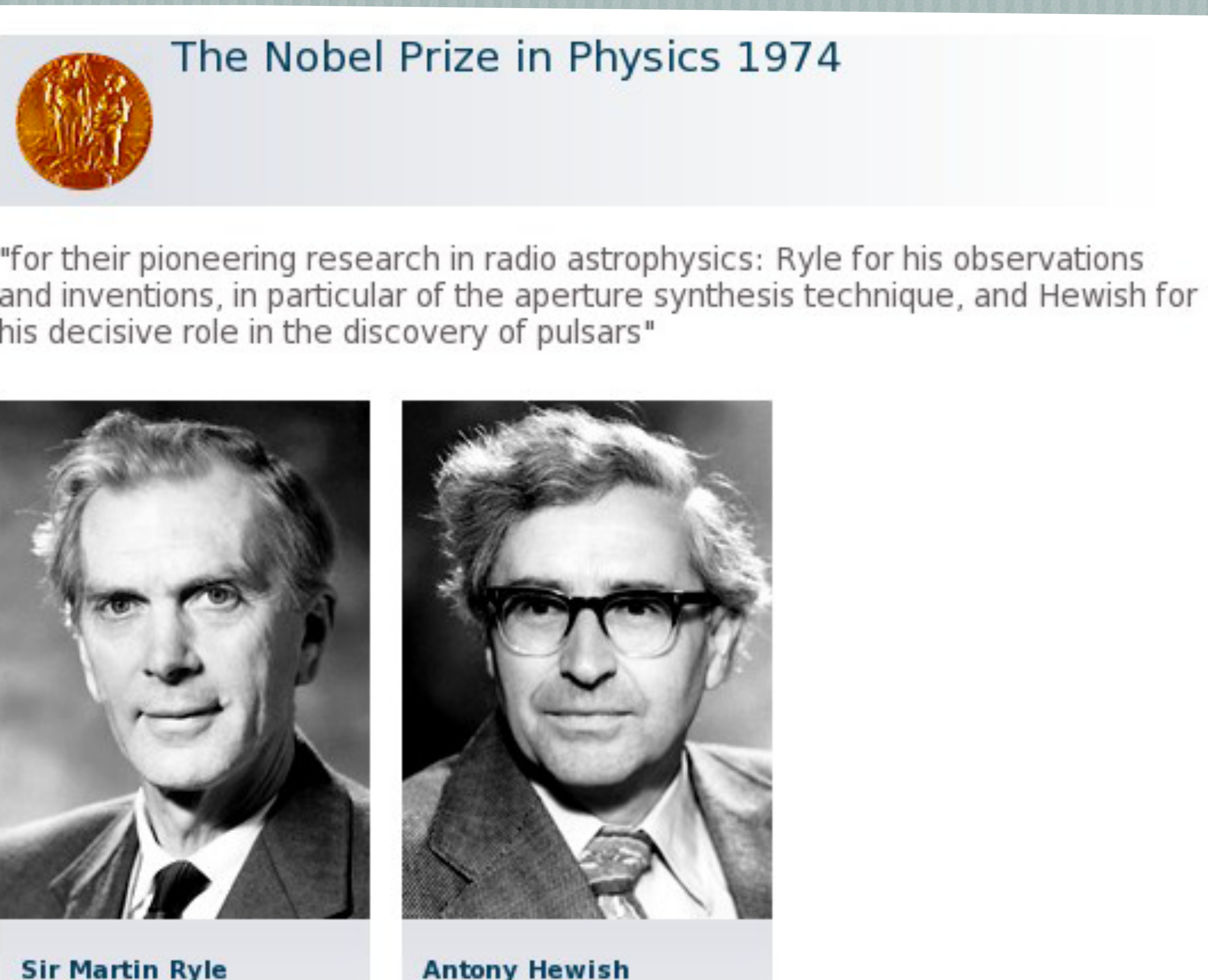
Searching for the unknown

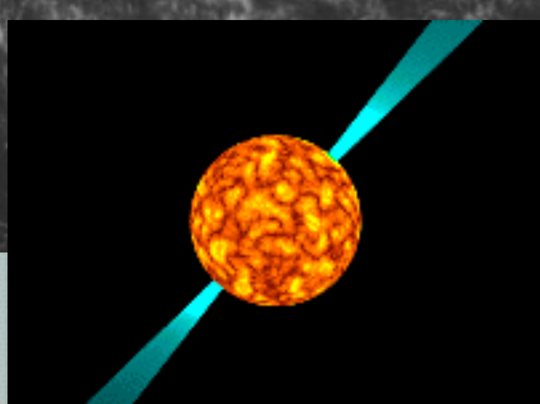
Pushing the knowledge frontier much beyond our current limits will likely results in **unexpected discoveries**

New parameter space: sensitivity, spectral resolution, polarisation, time domain, multi-beaming, ...

D.R.
Department of

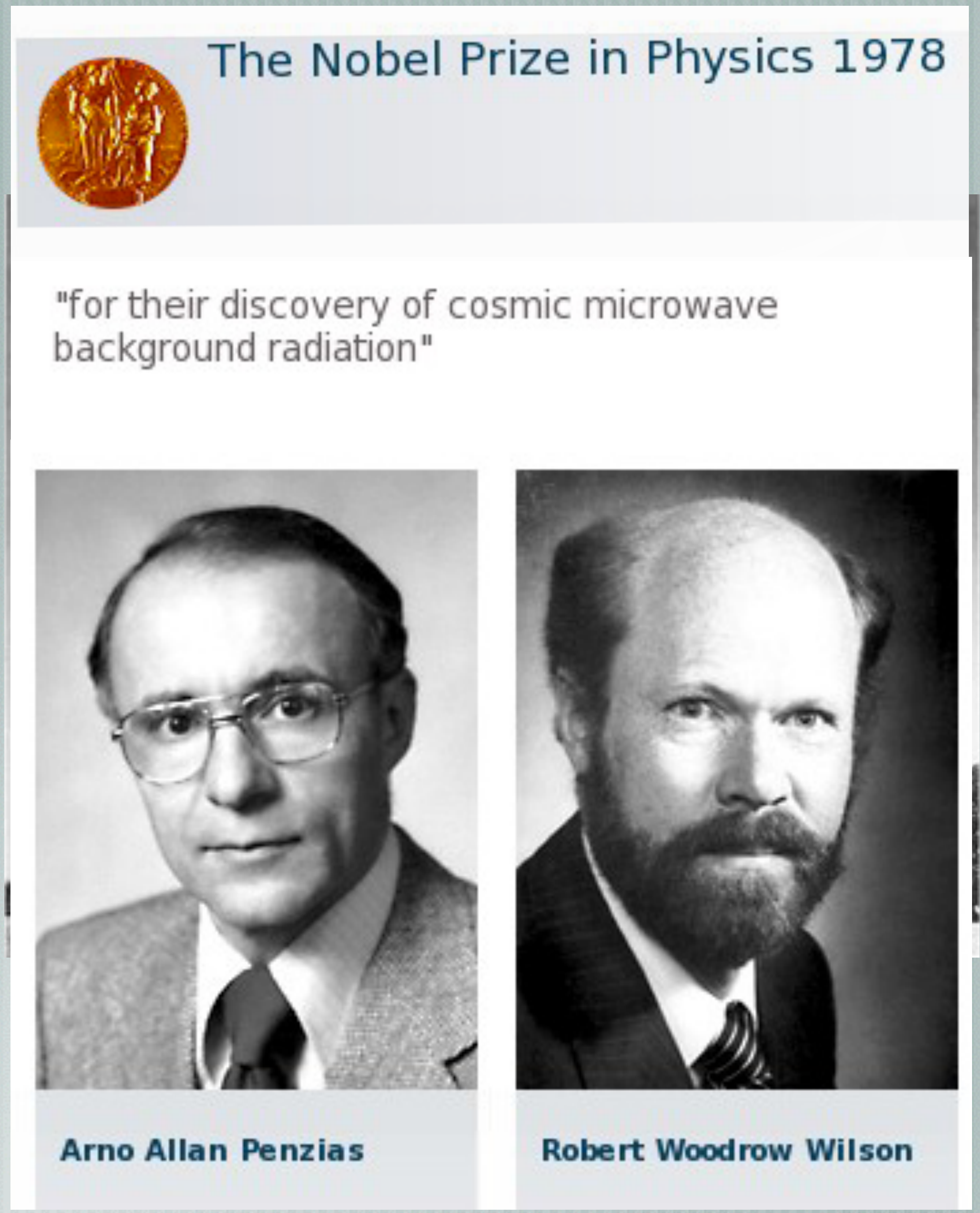
...e know,
...n **knowns**.
There are k...
That is to say
We k...
...**own unknowns**,
...we don't know
We don't know.

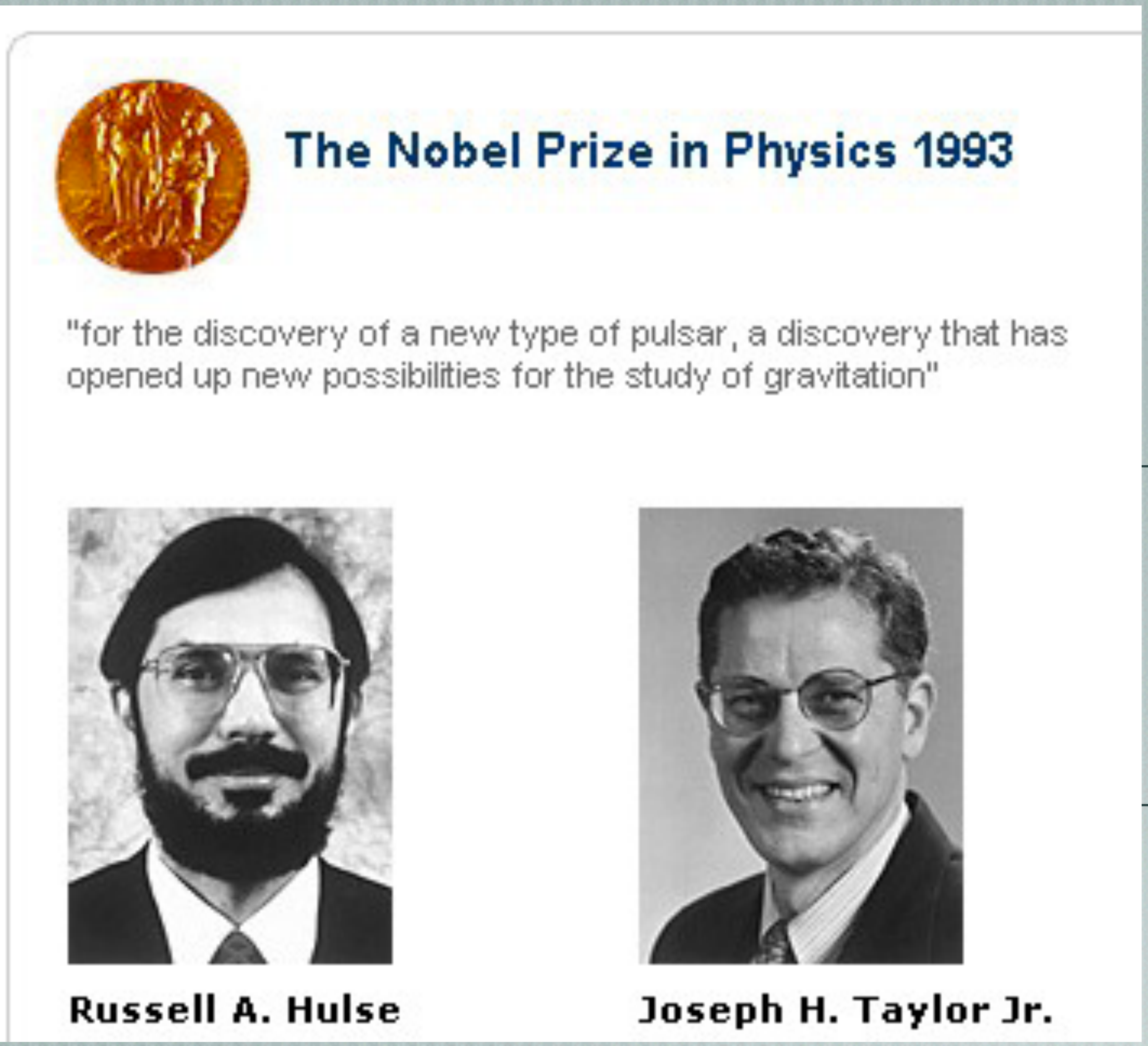




- The Mullard (Cambridge) telescope was built to measure interplanetary scintillation (for quasars)
- It lead to the discovery of **pulsars** by J.Bell
- but the 1974 Nobel prize to Hewish (pulsar) and Ryle (aperture synthesis)

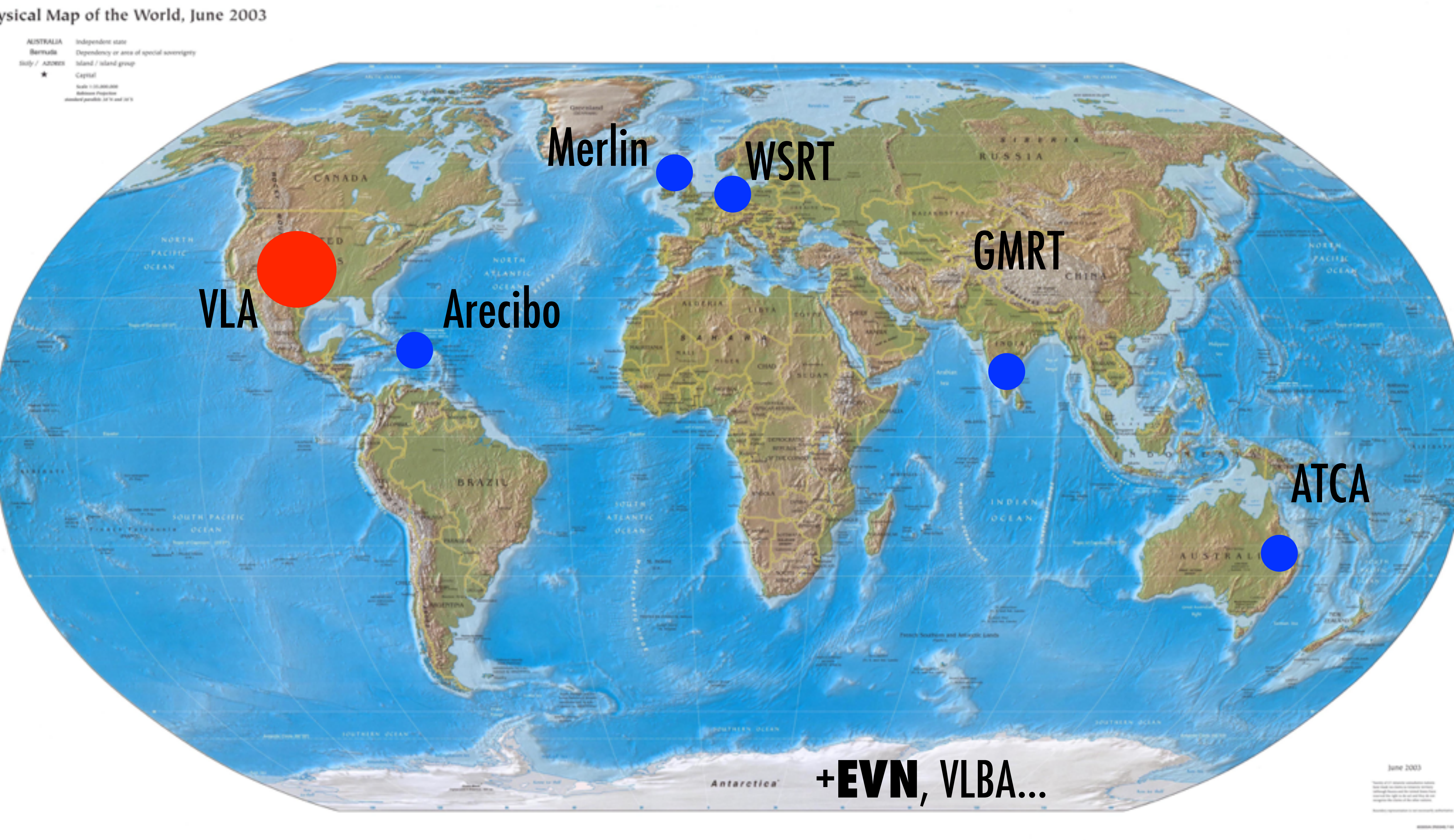
- An antenna communication satellite refurbished to measure radio emission from the Galaxy
- An additional isotropic noise
- leading to the discovery of the **cosmic microwave background**
- and a Nobel Prize in 1978



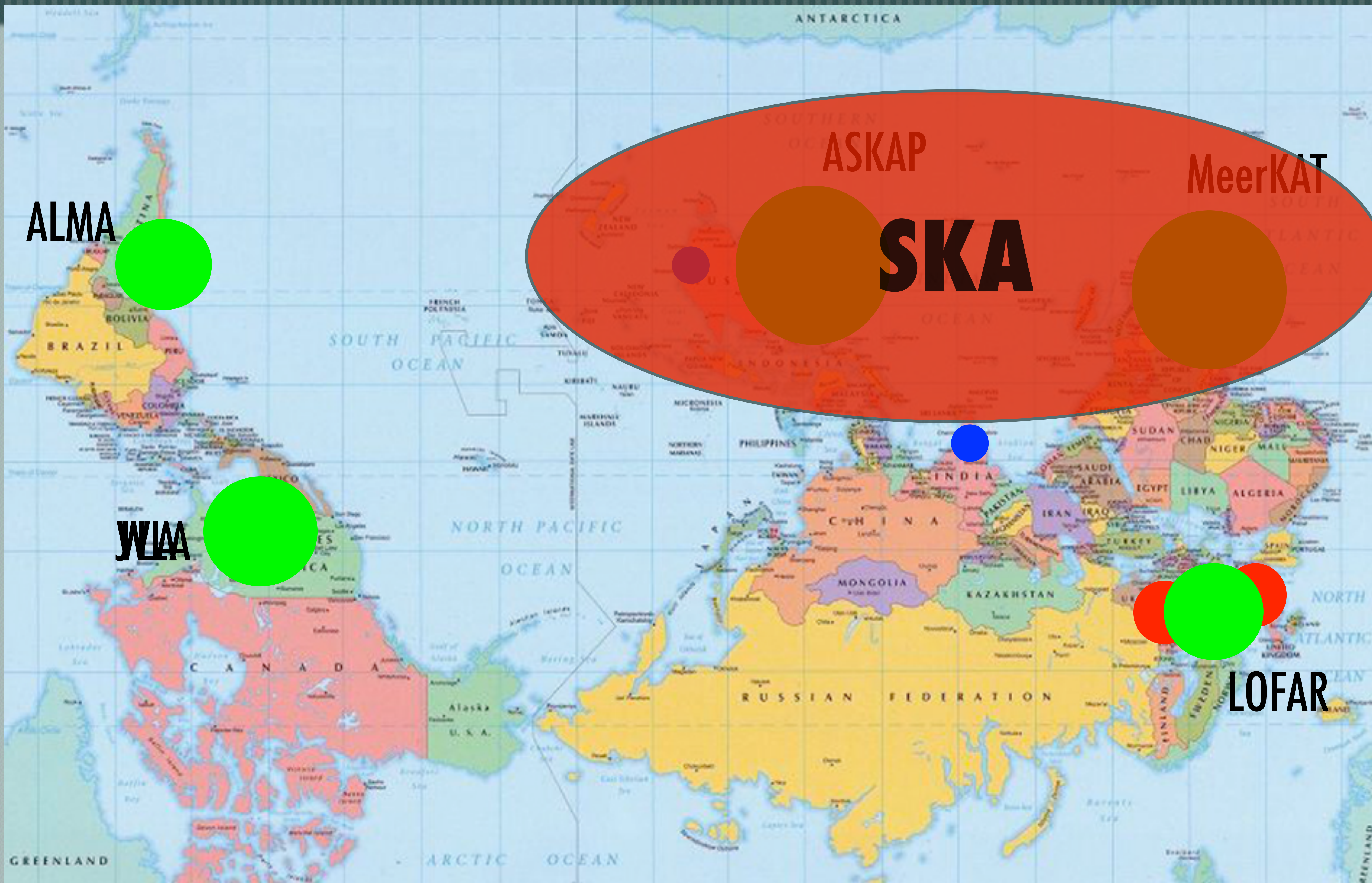


- Arecibo telescope (305m): plasma properties in the ionosphere
- It lead to the first discovery of an exoplanet in 1991 (not 1995 !)
- and the indirect detection of **gravitational wave** radiation
- and again a Nobel !

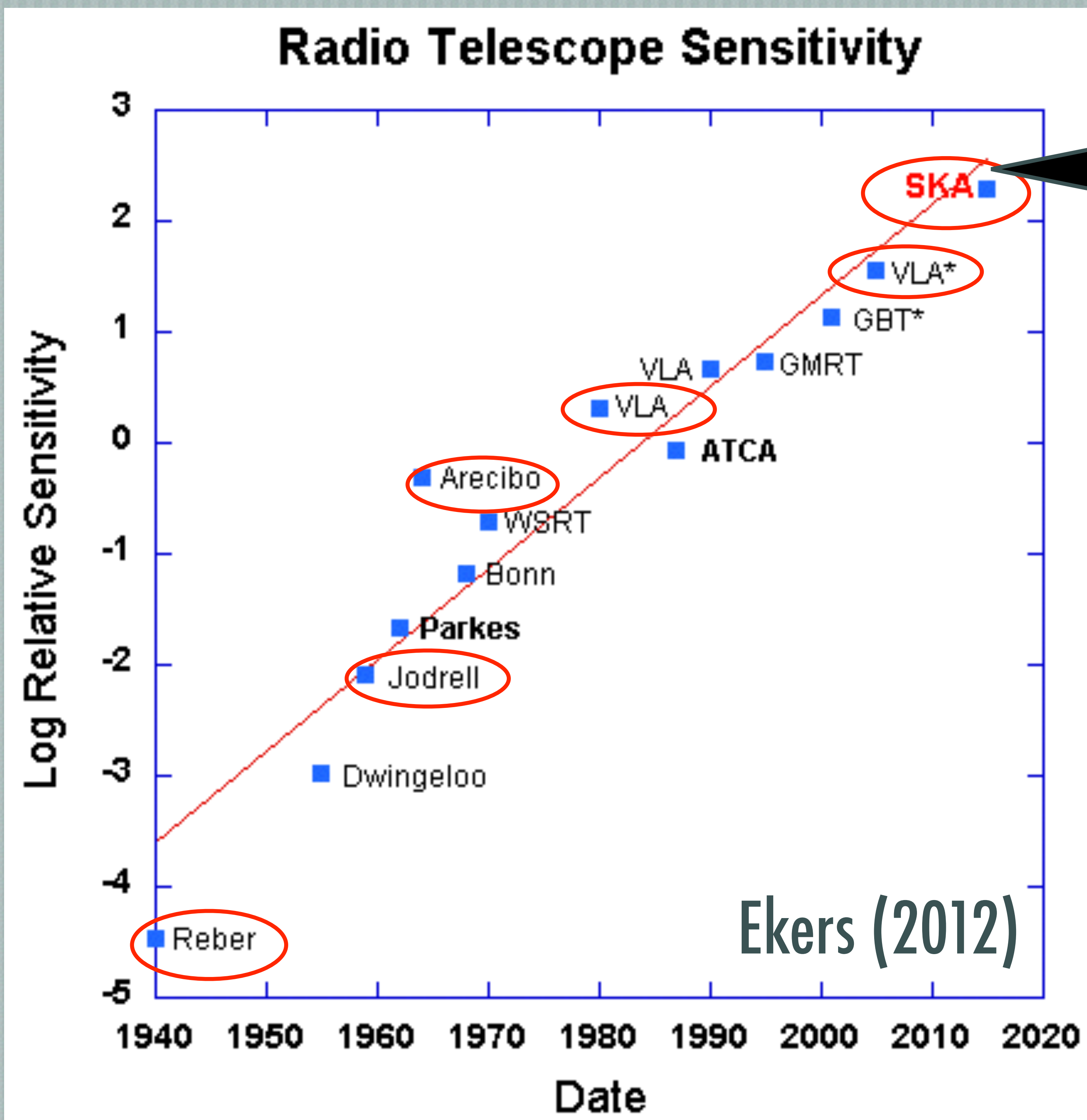
Radio astronomy in the 2000s



In a few years: radio goes south !!



Radio telescope sensitivity



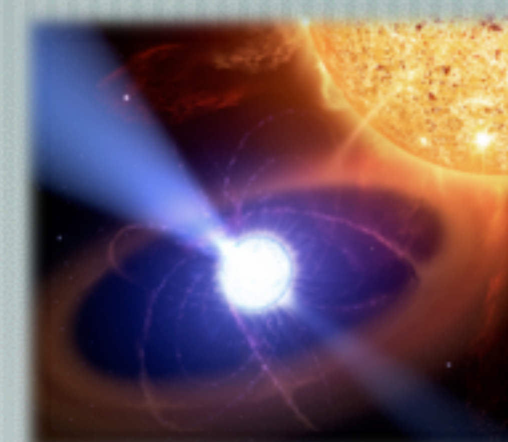
Ekers (2012)

A radar on a planet 50 l.y away

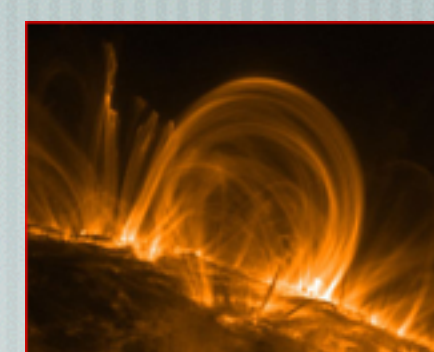
The SKA telescope

SKA Key Science Projects

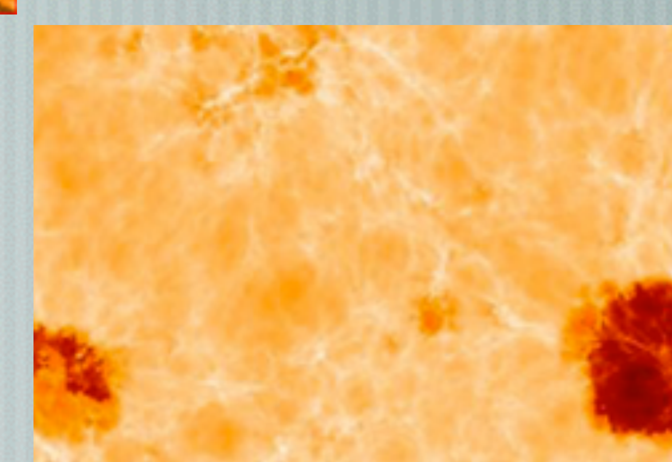
- **Hydrogen survey – dark energy**
- **Pulsar survey – strong field tests of gravity**
- Cosmic magnetism – origin of B fields



- Cradle of Life



- Cosmic dawn. Reionization



- Exploration of the Unknown

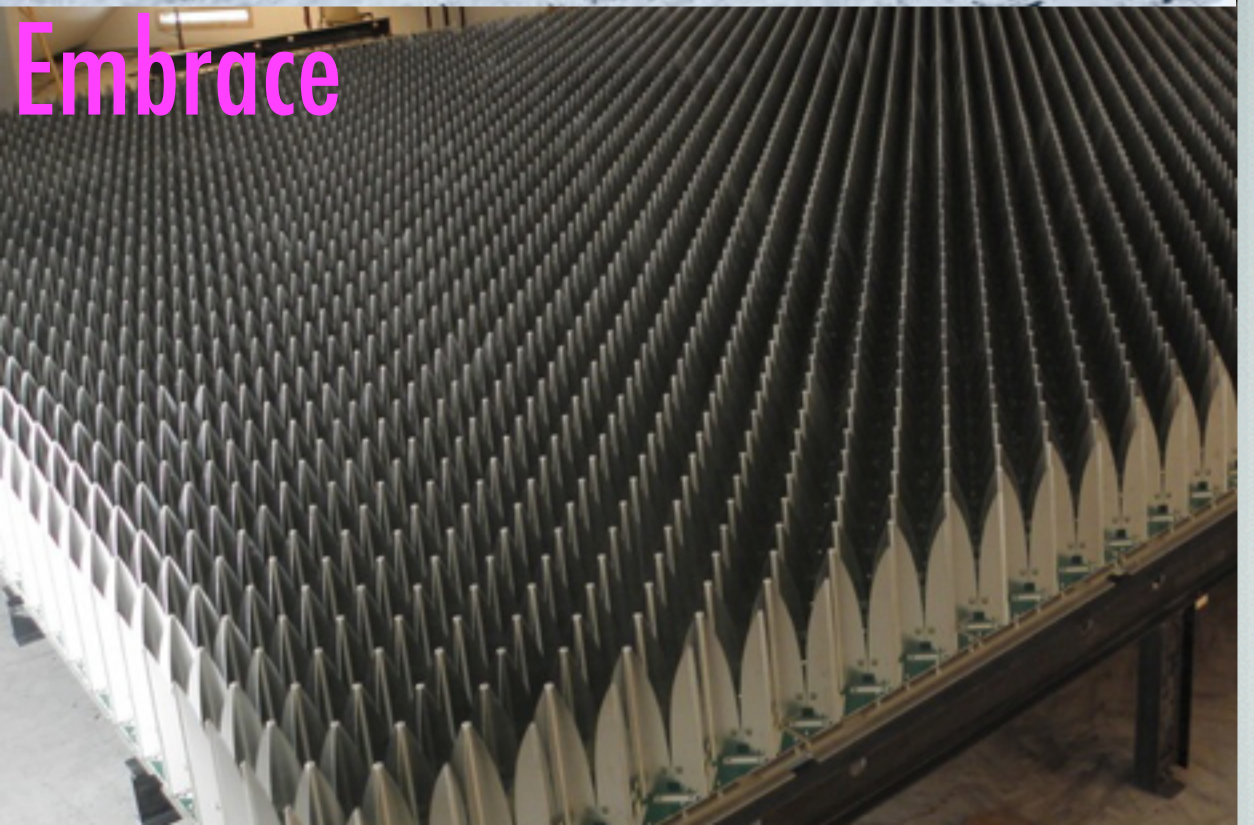
SKA: basic parameters

- A collecting area of 1 km^2. Increased in sensitivity x 50
- Frequencies: 70 MHz – 10 GHz (SKA1) ➟ 25 GHz (SKA2) λ: 4 m to 1 cm
- Field of View: from 200 deg^2 at 70 MHz to few deg^2 at 1.4 GHz (21 cm).
- Large FOV + Independent beams ➟ increased survey speed (10^4 to 10^6 faster than today)
- Angular resolution better than 0.01 arcsec. Stations up to 200 km, with possibly 3 extended arms up several 1000 km
- Multiple precursors/pathfinders are now being built around the world (see more later)

SKA Timelines

- The project can be traced back to the early 90s. Born global.
- 2011: SKA legal entity + project office in Manchester - Jodrell Bank (UK)
- 2012: Site : South Africa + Australia/New Zealand. 3 telescopes 1 Observat.

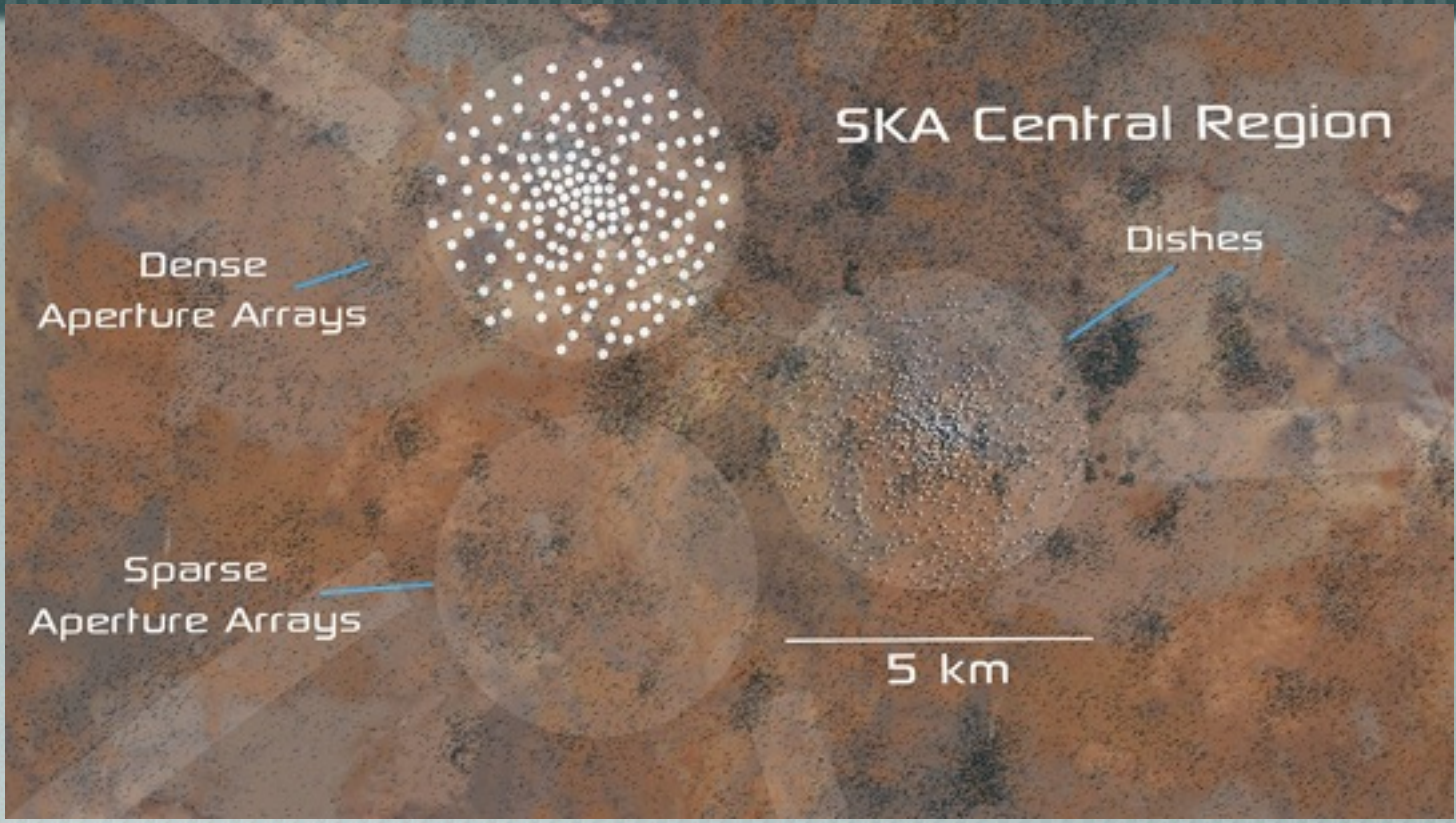
Sparse/Dense Aperture Array



- $\lambda > 20$ cm. Survey speed requires antenna with large instantaneous FOV (only possib. with ap. array)
- Set of small antennas : small collecting area but very large FOV.
  - If used as phased array ➡ aperture array (electronic beam-forming)
  - $d <$ or $> \lambda/2$ (dense/sparse)

The SKA telescope

Dense aperture array



Sparse aperture array

1 station =
a set of AAs

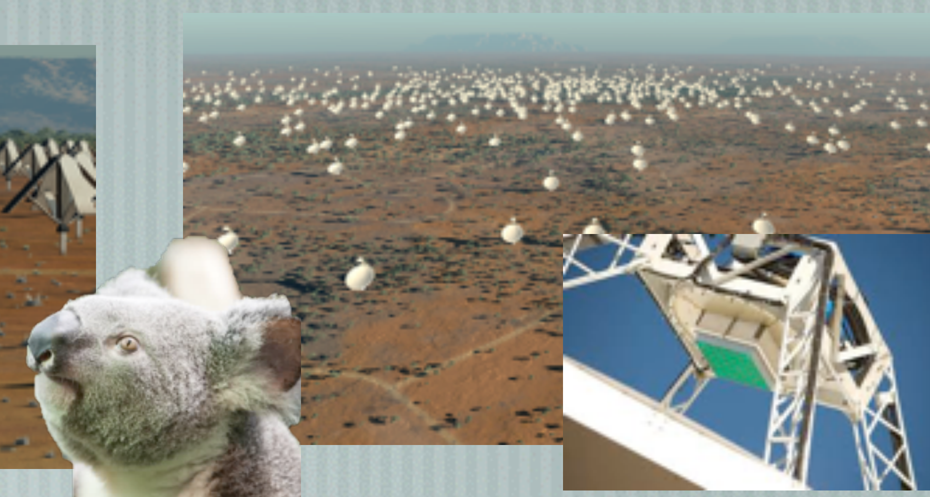
Dishes

Phase 1 Dual Site

SKA1 implementation will use existing (or currently being built) infrastructure at both sites

SKA1-MID (incl. MeerKAT)

SKA1-LOW



SKA1-Survey (incl. ASKAP)

	Description	Location
Dish array	SKA1-MID: 254 x 15 m + SPFs	South Africa
Low freq. aperture	SKA1-LOW: 50 AA stat. = 250 000 elts	Australia/New Zealand
Survey instrument	SKA1-SUR: 96 x 15m + PAFs	Australia/New Zealand

Phase 2 Dual Site

SKA2-MID_Dish

SKA2-MID_AA

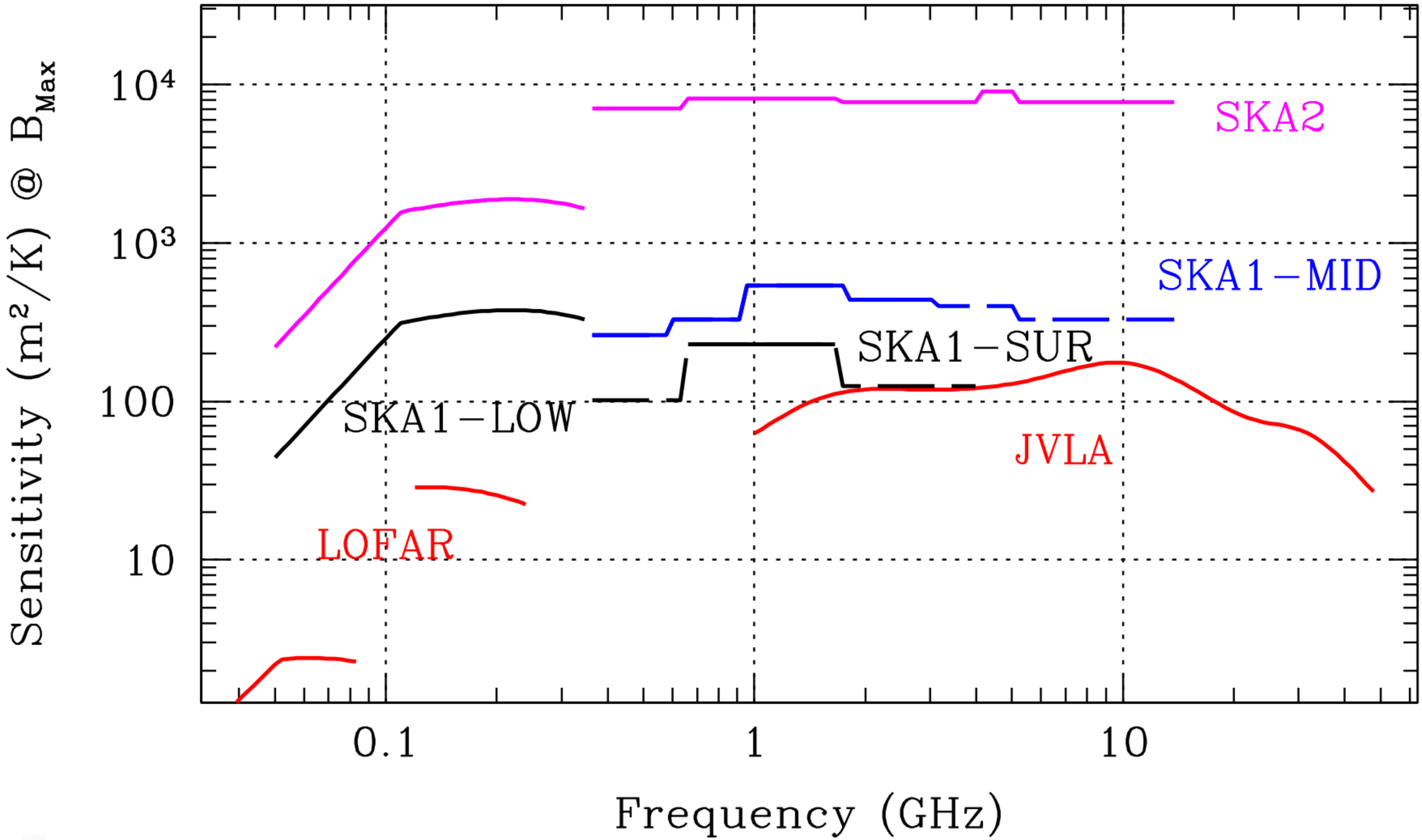
SKA2-LOW

	Description	Location
Low freq. aperture array	SKA2-LOW: 250 AA stations	Australia/New Zealand
Mid freq. dish array	SKA2-MID_Dish: 2500 x 15m	South Africa
Mid freq. aperture array	SKA2-MID_AA: 250 x 15m	South Africa

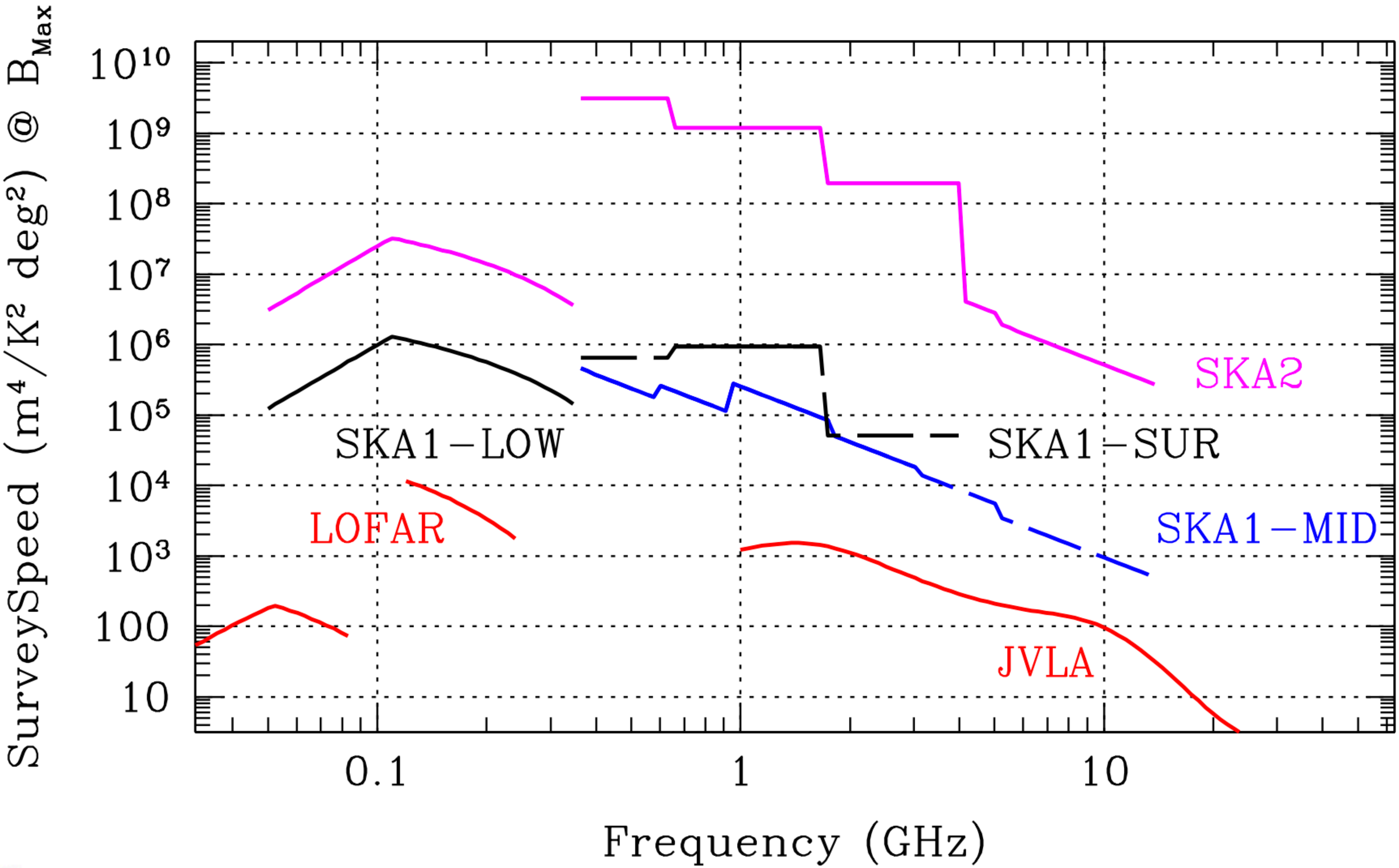
- Extra cost for two sites not an issue. All the SKA1 and SKA2 component have their own independent cores where most of the antennas are located. **Power is the dominant cost.**

- Duplication only become apparent on the longer baselines (Minor issue).

Sensitivity comparison



Survey speed comparison



SKA

SQUARE KILOMETRE ARRAY

www.skatelescope.org

The Square Kilometre Array

The SKA organisation

France ???

Science with the SKA

SKA Key Science Projects

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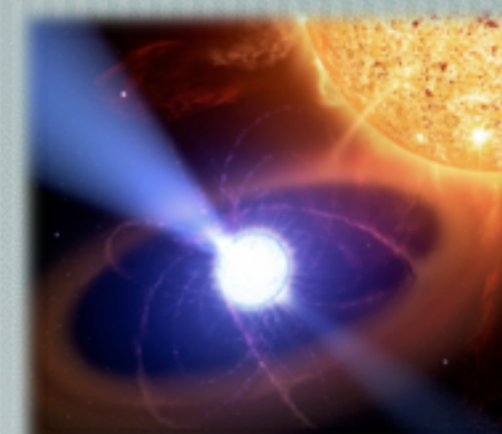
- **Pulsar survey – strong field tests of gravity**
- Cosmic magnetism – origin of B fields



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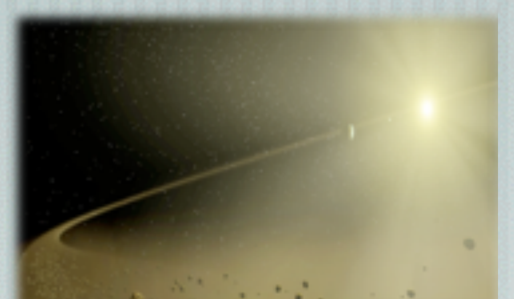

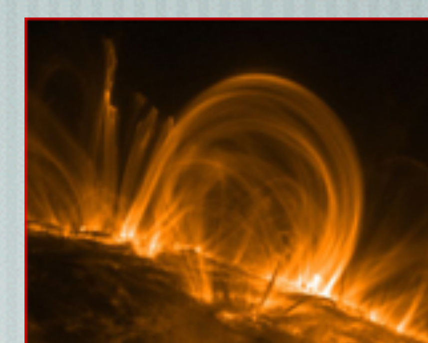

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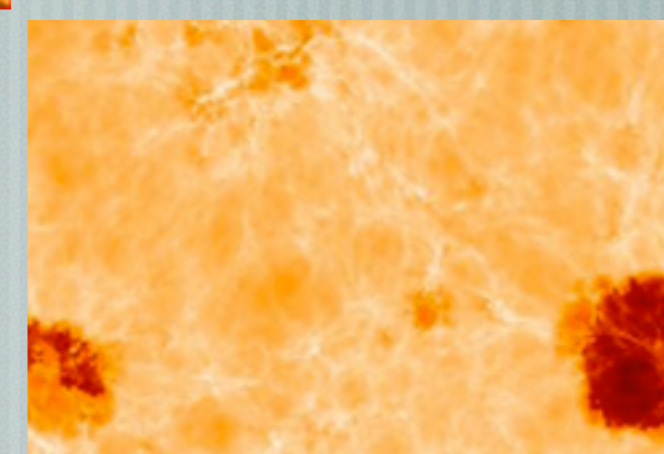
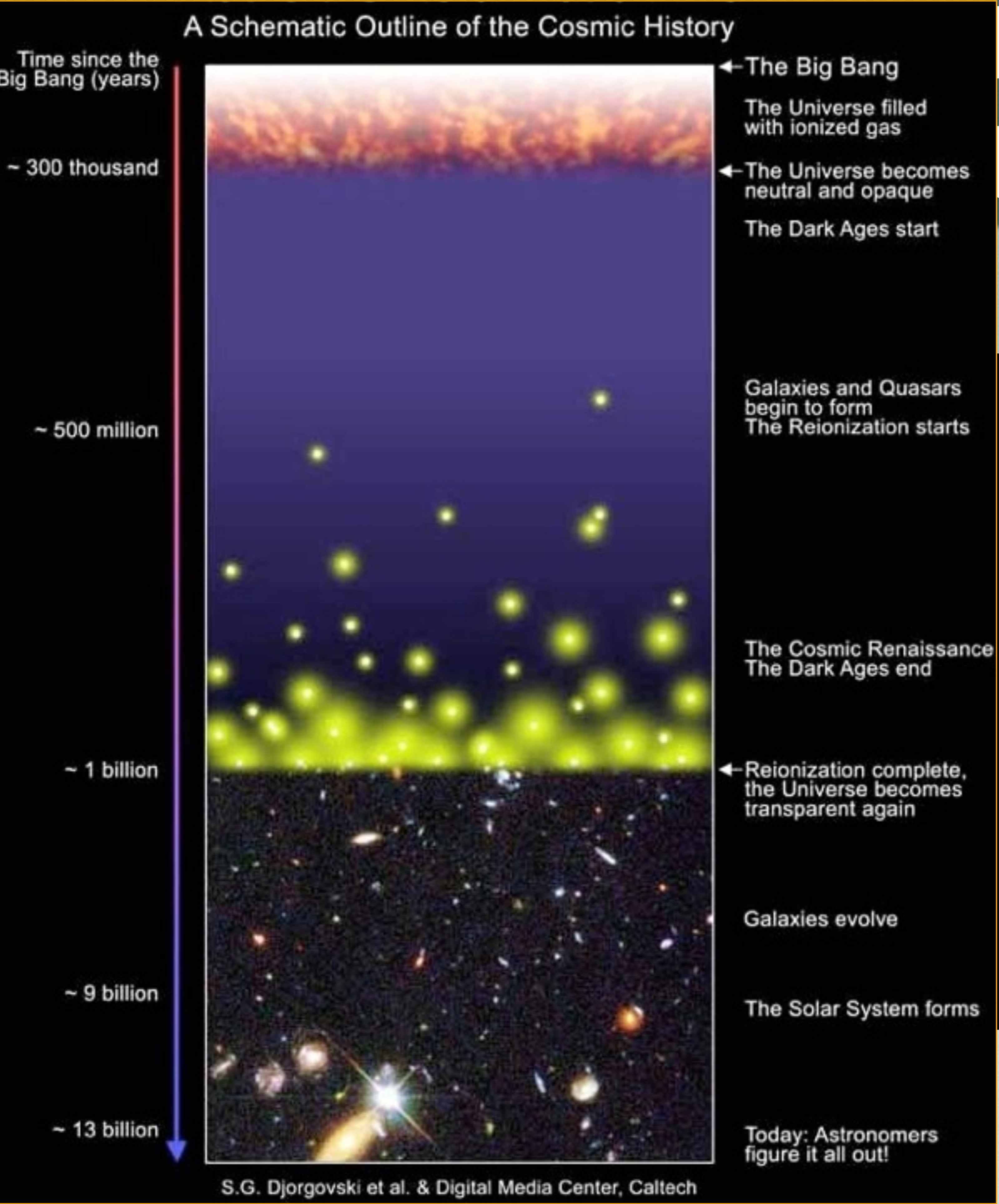


- Exploration of the Unknown

How to get precise information ?

- The most recent updates on the SKA scientific case:
  - https://indico.skatelescope.org/conferenceCFA.py?confId=270
- or type : Advancing astrophysics with the SKA (conference in Italy, June 2014)
- Presentations online + the new SKA book to come.

Evolution of the Universe



ESO

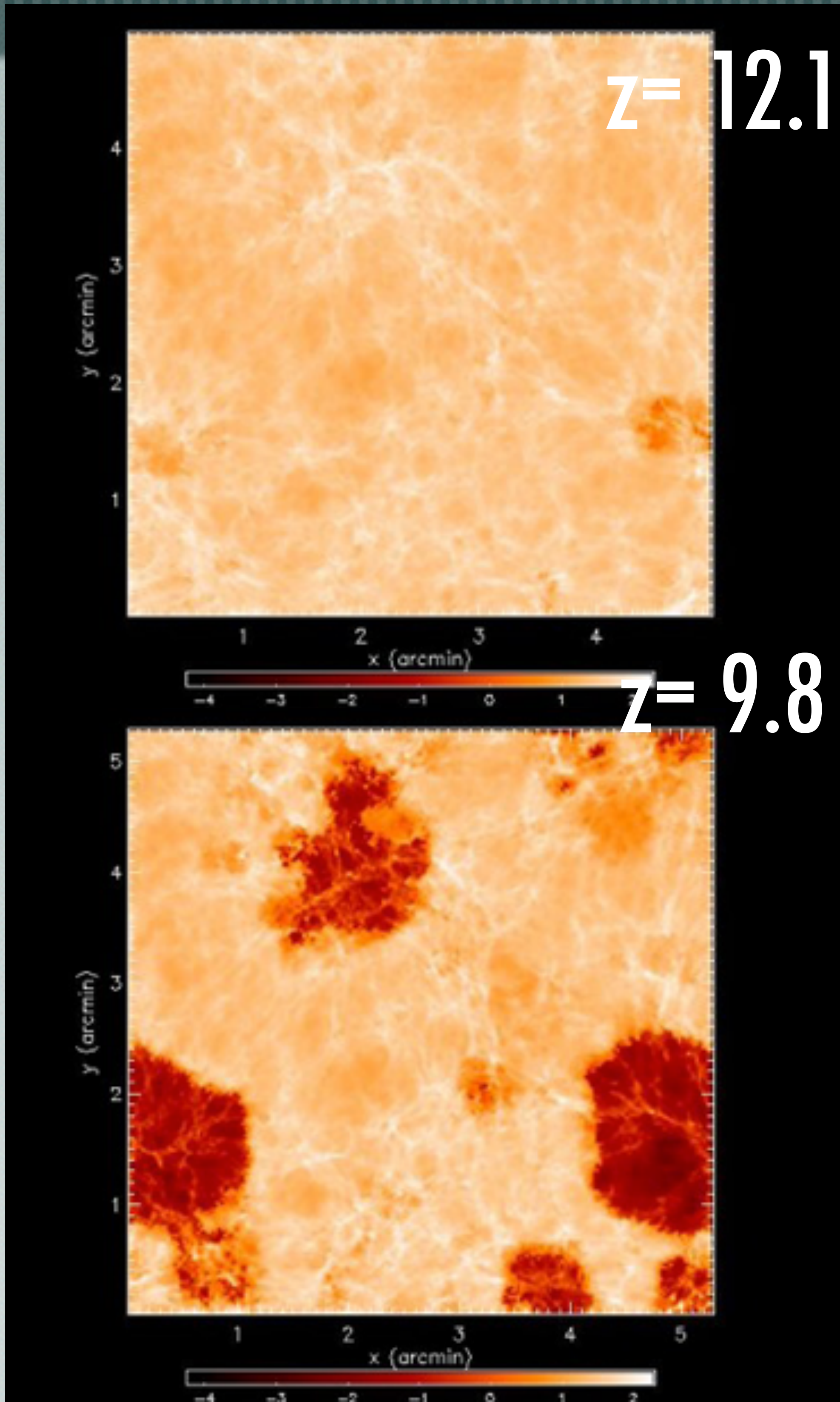
www.eso.org

Alvarez et al. 2009

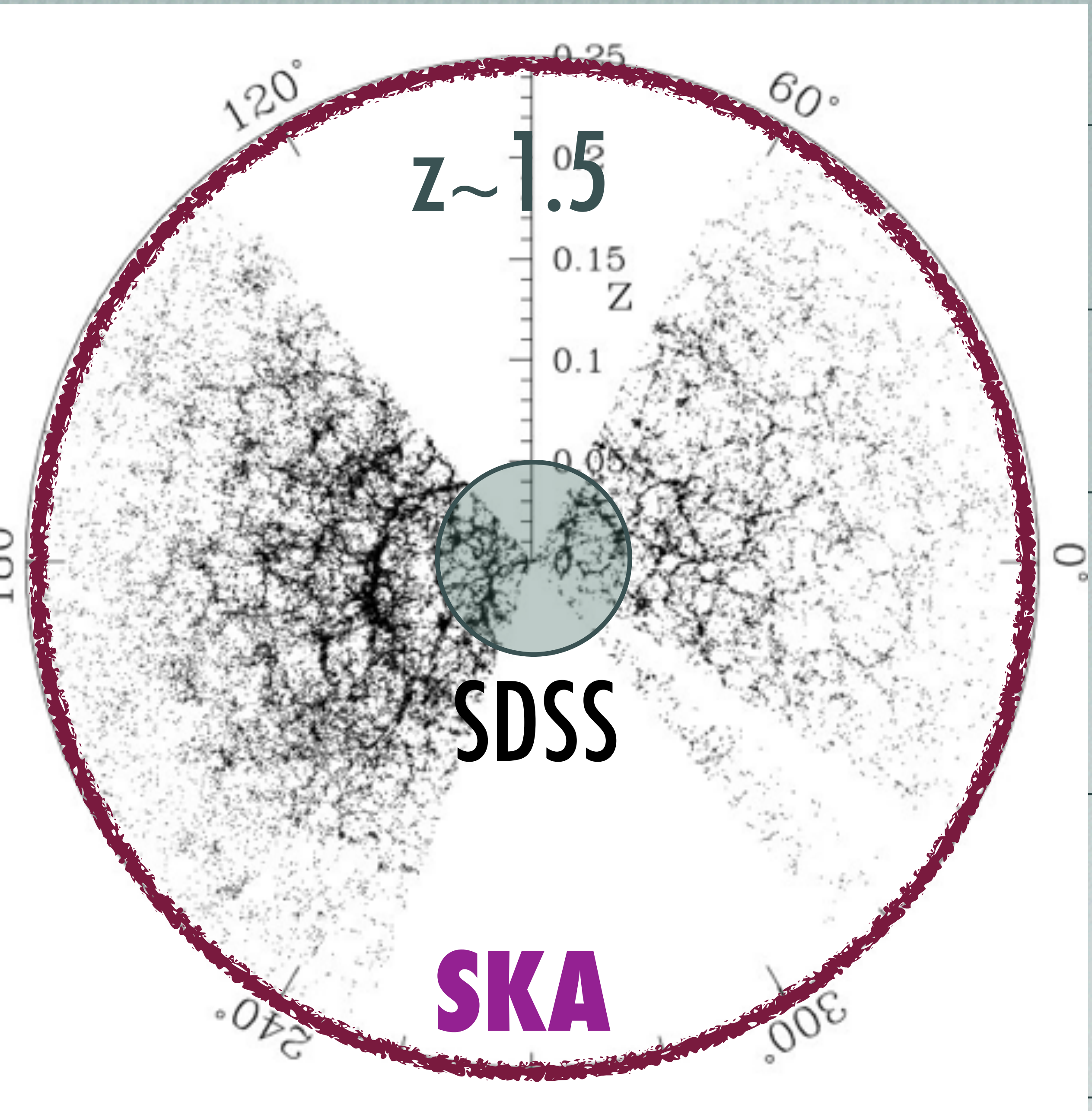
Epoch of Reionization

- Universe made rapid transition from largely neutral to largely ionised 400 Myr to 1 Gyr after the Big Bang
- Mapping and evolution of the first luminous objects
- SKA objective: Image the transition in the InterGalactic Medium in the neutral hydrogen (21-cm) spectral line

Furlanetto et al. (2003)



SKA and Dark Energy



- SDSS surveyed ~ 1 Gpc^3
- 2012: 30 000 out to z ~ 0.05
- 2020 with SKA precursors: 1 million out to z ~ 1
- SKA targeting 100 Gpc^3 (all sky up to z ~1.5) ➠1 billion HI galaxies in 2026
- Targeted regions: 10 millions up z ~3)

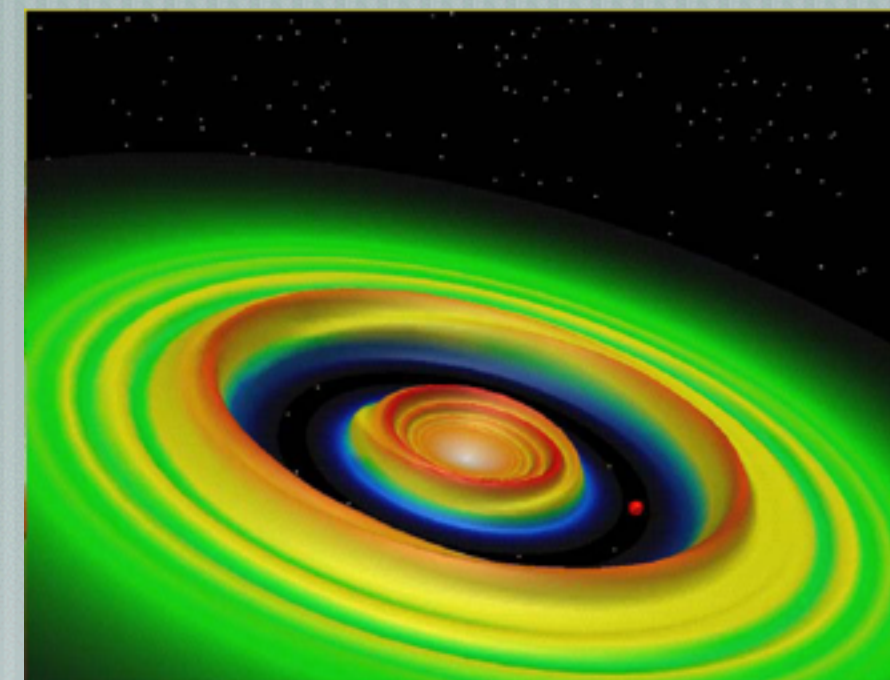
Galaxy Assembly & Evolution

- H I is the raw material for galaxies and star formation
  - How do galaxies turn gas into stars?
  - How does gas content vary with shape/size, time after the big bang, environment, mergers, feedback, ...
- Why is the expansion of the Universe accelerating ? Survey large volume:
  - Slice into redshift bins
  - Galaxies power spectrum
  - BAOs, weak lensing in each z bin
- Complementarity Planck, Euclid, LSST, JWST...

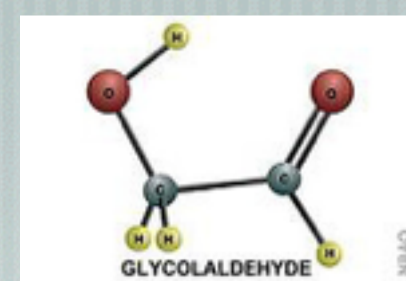
Cosmic Magnetism

- What is the origin of magnetic fields in the Universe ? Always there (primordial) or generated over the evolution of the Universe (dynamo) ? Role in the formation of structure and galaxies ?
- Synchrotron radiation: «naturally» polarised sources !
- $\theta = \theta_0 + \mathbf{RM}\ \lambda^2$ and $\mathbf{RM} = 0.81 \int n_e\, B_{//}\, dl$
- Comes for free with HI survey !! RMs towards 10^7 background sources will provide a dense grid for probing B in the MW and nearby galaxies
- $\sim$ 500 RMs per deg^2. Average separation$\sim$ 2′- 3′ vs. 2-3° now!

Astrobiology: cradle of lile



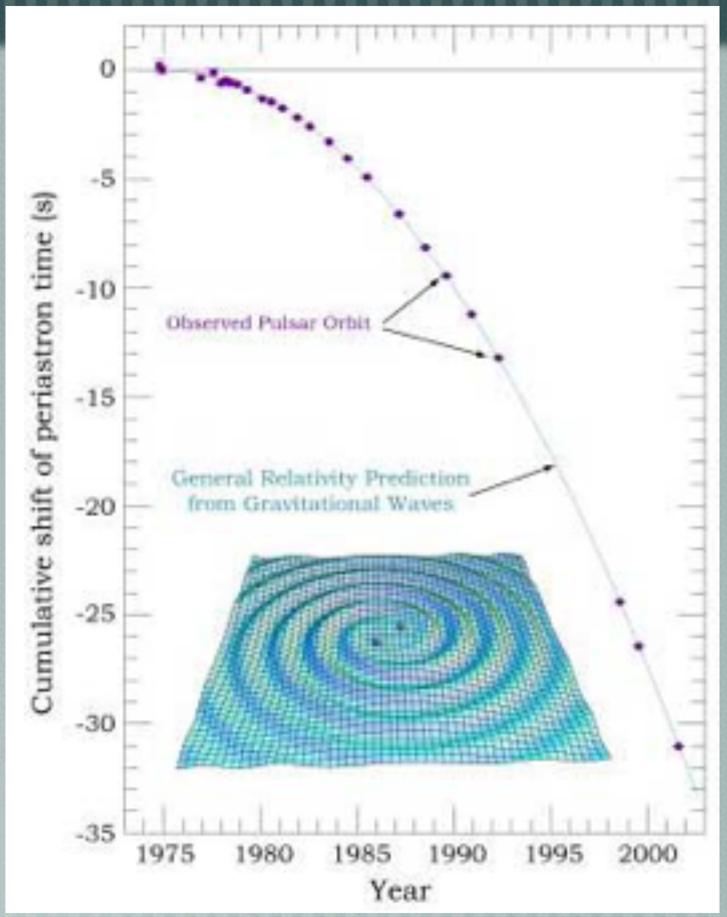
- Proto-planetary disks resolved to Earth-like orbits: 100's of proto-planetary disks at 140 pc: scales for planets is <1-10 AU, 7-70mas (only possible with SKA)

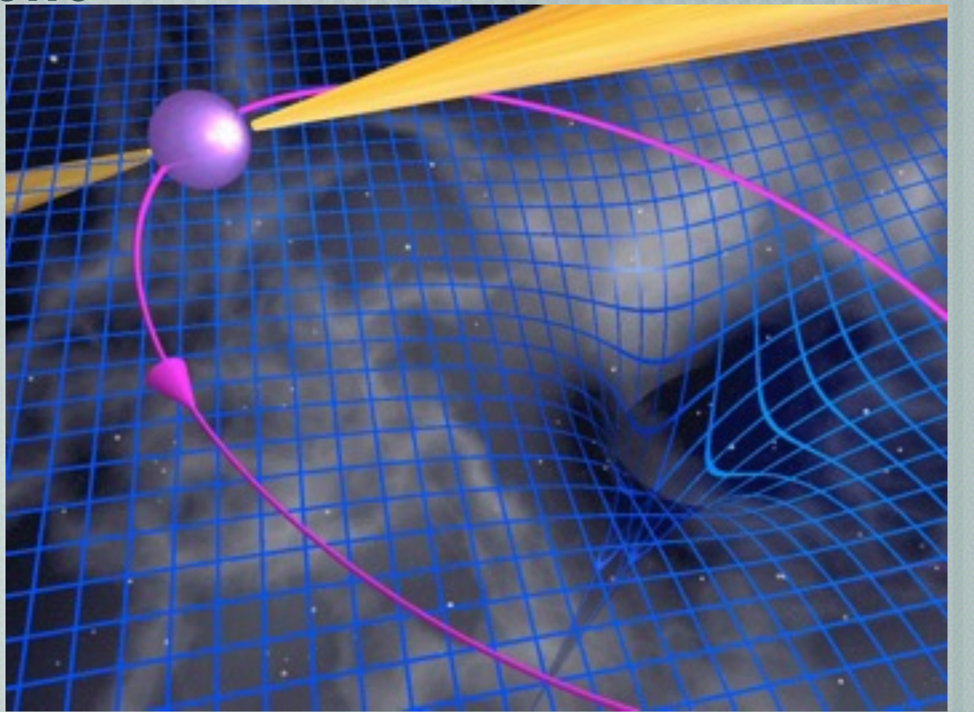


- Extrasolar planets
- Organic molecules: Low J bio-molécules
- SETI searches: «TV» leakage from exoplanets, beamed/bright radar around all stars in our Galaxy

Einstein and General Relativity

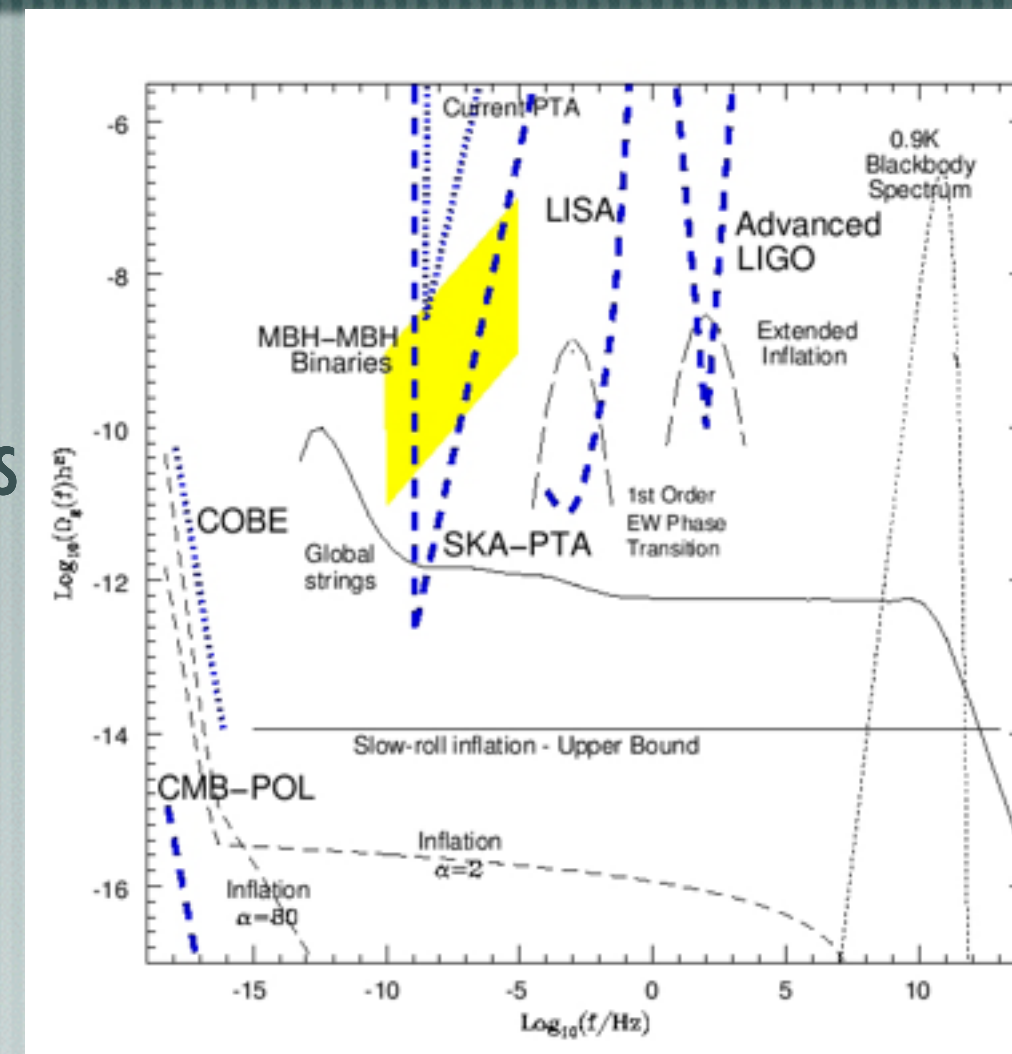
- SKA will detect up to **20 000 pulsars** in the Galaxy, incl. 1000 ms pulsar, incl at least 100 compact relatvistic binaries (almost all the population beamed toward us)
- Probing relativistic binaries:
  - Equivalence principle
  - Strong-field tests of gravity (binary orbit + relativistic effect ⇛ masses). Exple of the binary pulsar
- Full sample is certain to include the «holy grail»
  - Black hole - neutron star binaries?
  - ms pulsar around Sgr A* (massif black hole)

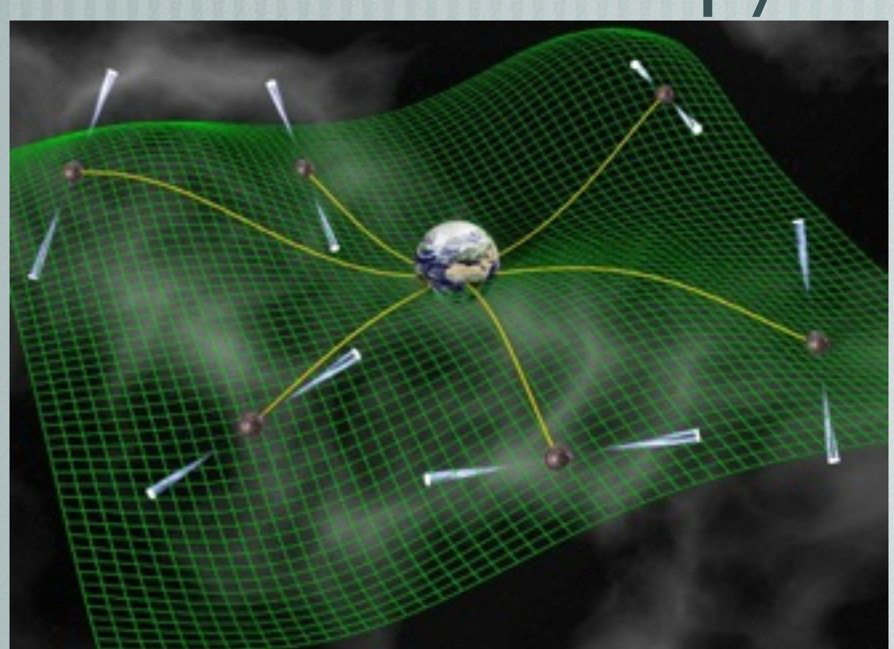




A Gravitational Wave Detector

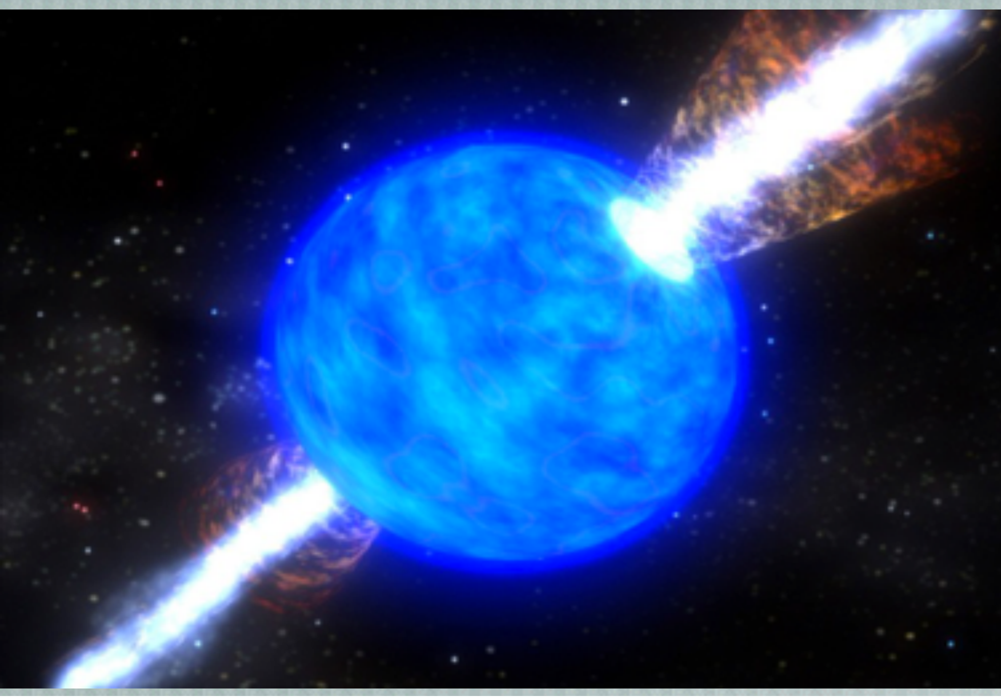
- **LIGO** = suspended mirrors
- **LISA** = freely-falling masses in spacecraft
- **Pulsar Timing Array** = freely-falling ms pulsars
- SKA should detect the signal of a **stochastic background of GW emission** produced by a large number of unresolved indpt/uncorrel events

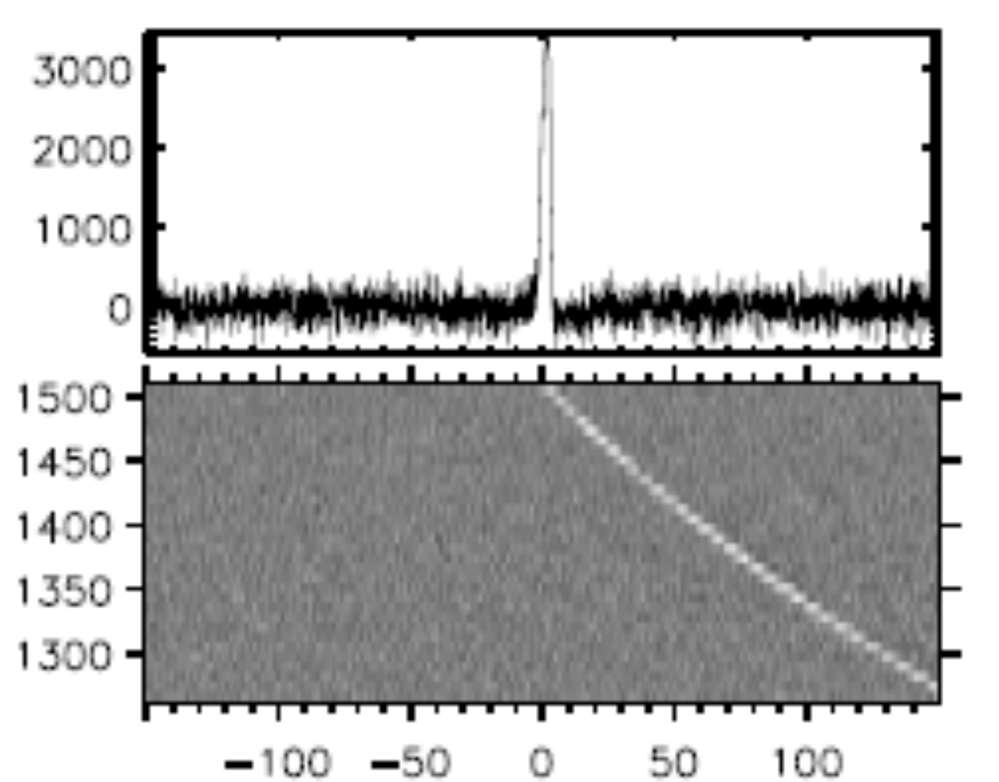




Complementary in Frequency with other GW detector

The Dynamic Radio Sky





- Transient radio signals of any duration (ns to weeks)
- Neutron stars: Magnetars, Giant pulses, Short GRBs?
- GRBs: Afterglows, Prompt emission?
- Sub-stellar objects: Brown dwarfs, Extrasolar planets?
- Microquasars, BH collision at cosmological distance
- ETI
- The Unknown !!!! Remember the wise word of DR

Classes of radio transients

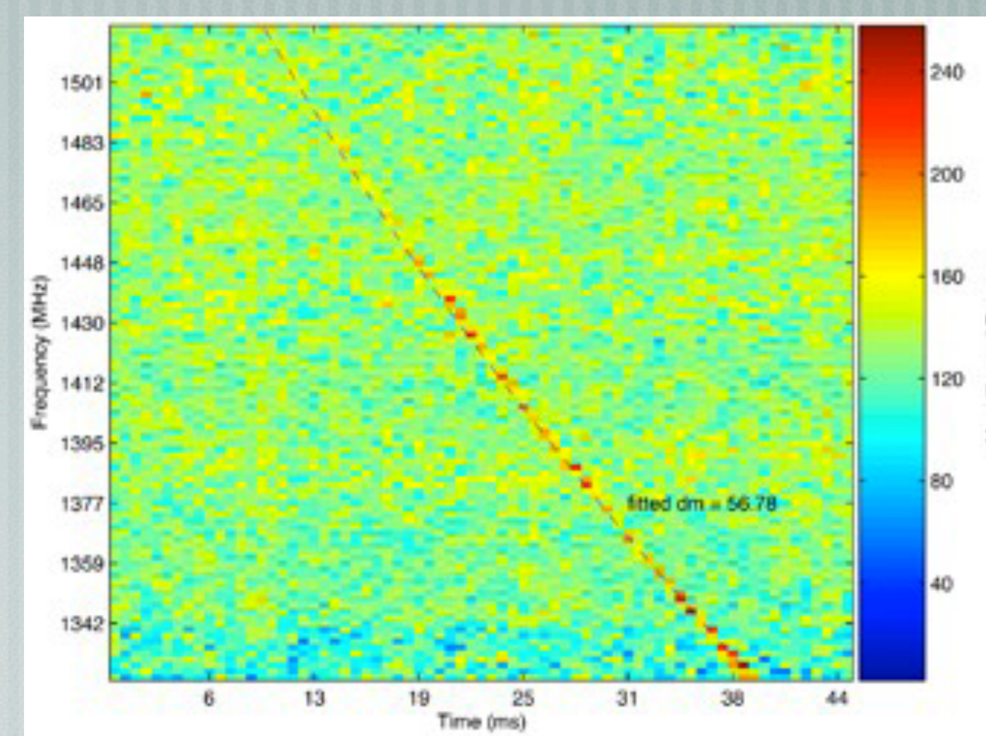
- Well-studied sources («**known knowns**») such as a radio flare from a microquasar (e.g. Cyg X-3 the brightest transient radio source in our Galaxy)
- Many new types of source discovered in recent years («**known unknowns**»)
  - Burpers: e.g. GCRT J1745-3009, Rotating Radio Trantsients (RRATs) : Neutron star phenomena
  - Tidal disruption events (e.g. Swift J1644+57) : capture (?) of a star by a BH
- But most exciting prospect is to find the «**unknown unknowns**»
- Separate by timescale and duration (Frail et al. 2011):
  - Short (< few s): coherent emission (high T_B)
  - Long (> few s): incoherent (synchrotron) emission

Two flavours of transients

- Incoherent synchrotron emission
  - Relatively slow variability
  - Brightness temperature limited (10^{12} K)
  - Associated with all explosive events
  - Strong potential for MW astronomy

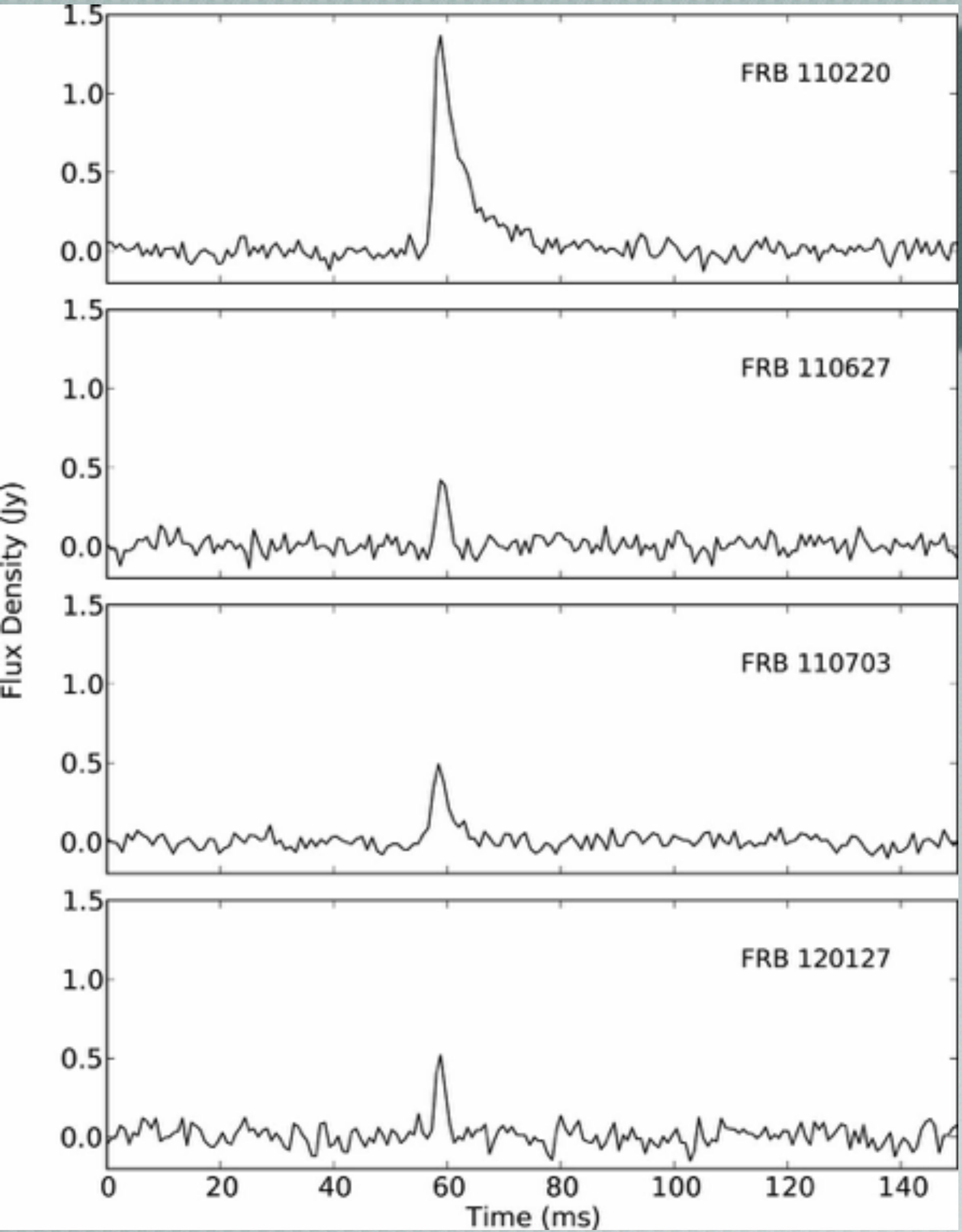
Detection: images

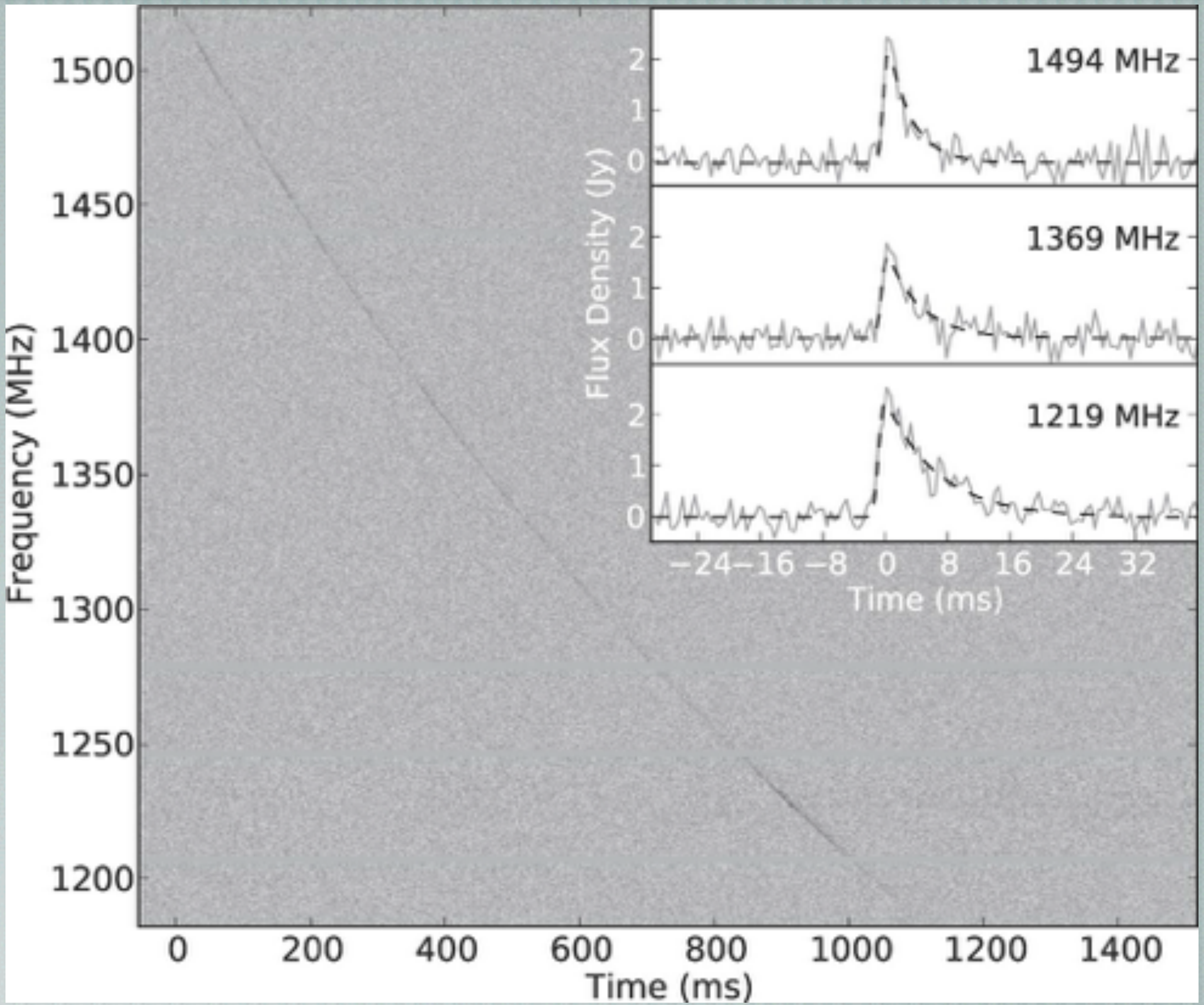
- Coherent emission
  - Relatively fast variability
  - High brightness temperature
  - Often highly polarised



Detection: time series

A pop. of fast radio burst at cosmological distance

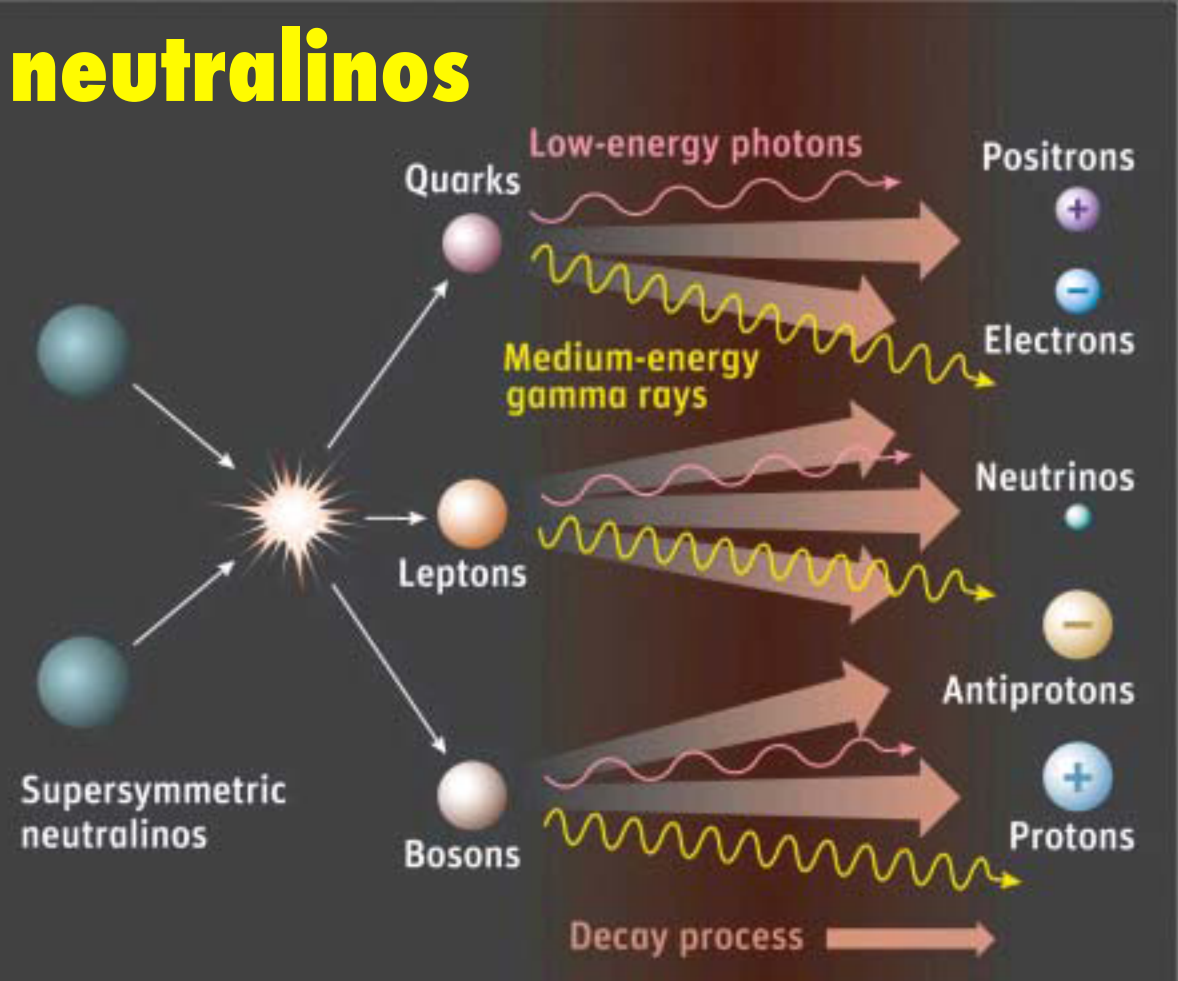




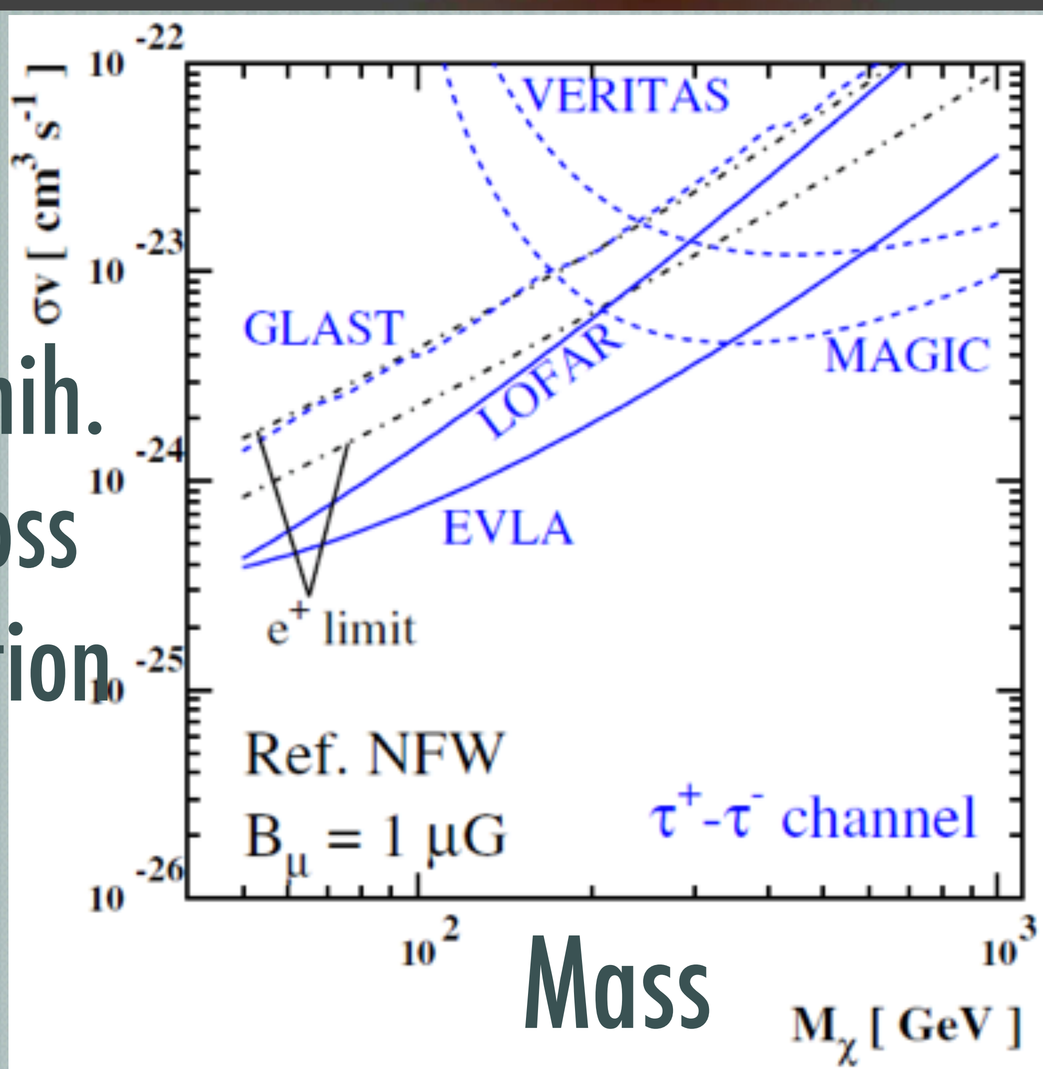
- Four celestial "FRB" events now detected (after first "Lorimer" burst): S = 0.5 –1.3 Jy, Δt = 1–6 msec, DM= 550–1100 cm^{-3} pc
- Estimated event rate: 1×10^4 sky^{-1} day^{-1}. Detection rate = 5 per day with SKA1-LOW

Fundamental physics with the SKA

- Extensions of standard model ⇛ existence of a «hidden» sector of particles as promising candidates for DM and DE particles:
  - supersymmetry/supergravity: WIMP (neutralinos, gravitinos) with $m_c > 100$ GeV
  - string theory: ultralight weakly interacting particles: WISP like axions, hidden photons, ... with $m_g < 1$ meV
- Direct detection of WIMP/WISP or limits on their properties: crucial for cosmology and particle physics



- **Neutralinos annihilation**: EM signature in γ-ray (IC or in the radio (synchrotron from e^-/e^+)
- Compact source in γ-ray, but a **smooth/extended halo in radio**
- **SKA targets**: dwarf galaxies (less EM contamination from astrophysical sources), Galactic center, globular clusters, ...
- DM signal detectable.



Annih. cross section

Mass

Colafrancesco et al. 2007

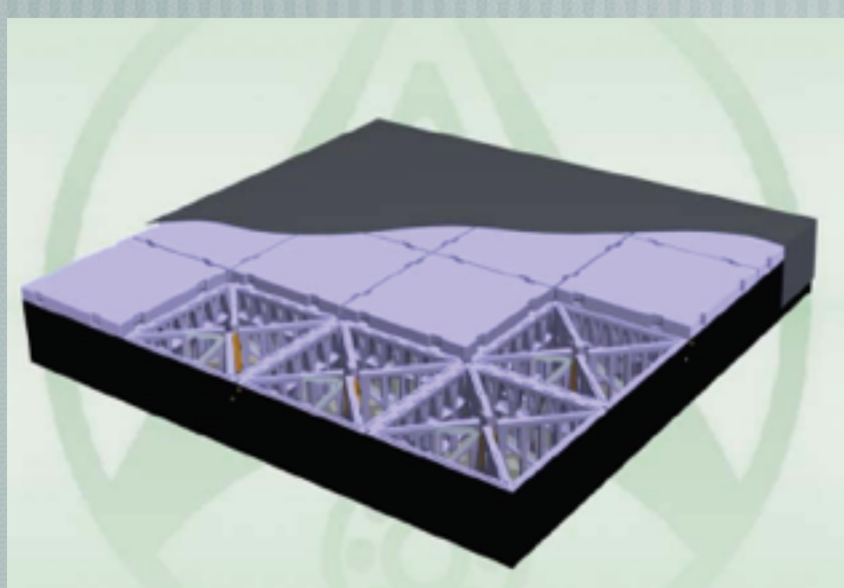
The current generation and the SKA precursors/pathfinders

SKA precursors/pathfinders

- **LOFAR** : already working (fully completed)
- Two main precursors:
  - **ASKAP** (Australia) 3600 m^2 30 deg^2
  - **MeerKAT** (South Africa) 8000 m^2 1 deg^2
- Renovation of Westerbork:
  - APERTIF (Netherland) 7000 m^2 8 deg^2
- Instruments fully operational in 2016
- Don't forget the major VLA upgrade finished in 2012

LOFAR

Low band antenna: 30 – 80 MHz
48/96 antennas per station



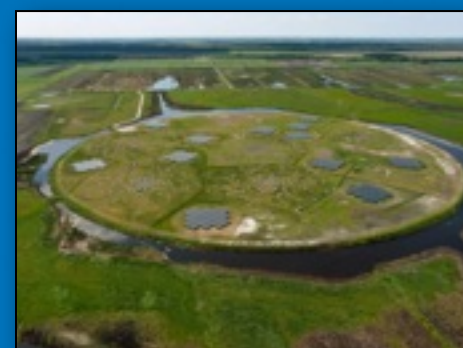
High band tiles:120 – 240 MHz
48/96 tiles/station, 4x4 antennas/tile

- Operational: 24 Core Stations + 10 Remote Stations + 8 International Stations (Nançay)
- Planned: 1 more Dutch remote station + 1 German station (Hamburg)
- 3 Polish stations? 1 Irish station?
- ➠ The International LOFAR Telescope
- Sciences + technology pathfinders for SKA low. 2nd open call for proposals in 2013.
- 6 Key projects + MSSS survey

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

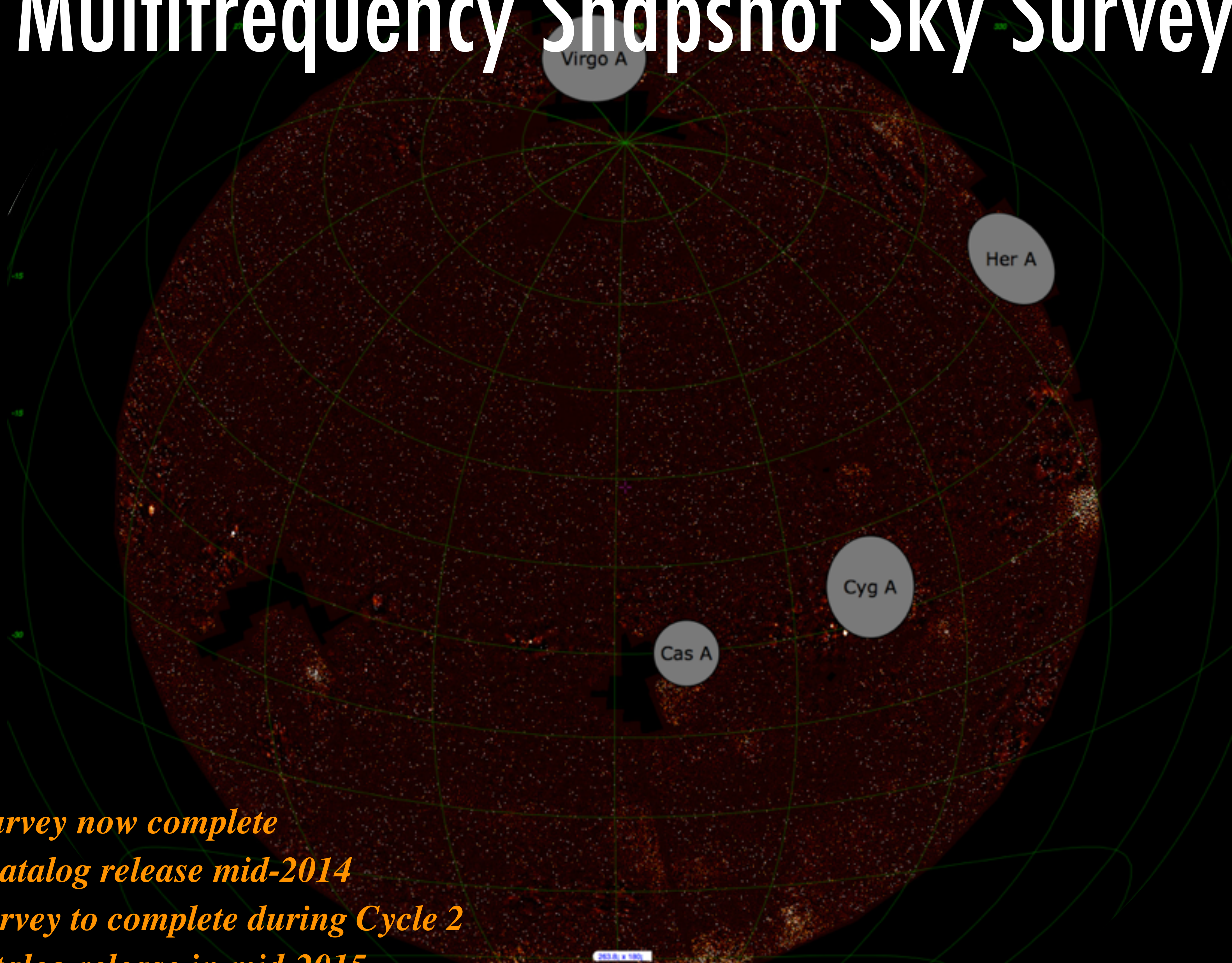
Tautenburg

Nançay

Unterweilenbach

Lofar @ Nançay +LSS (Zarka et al.)

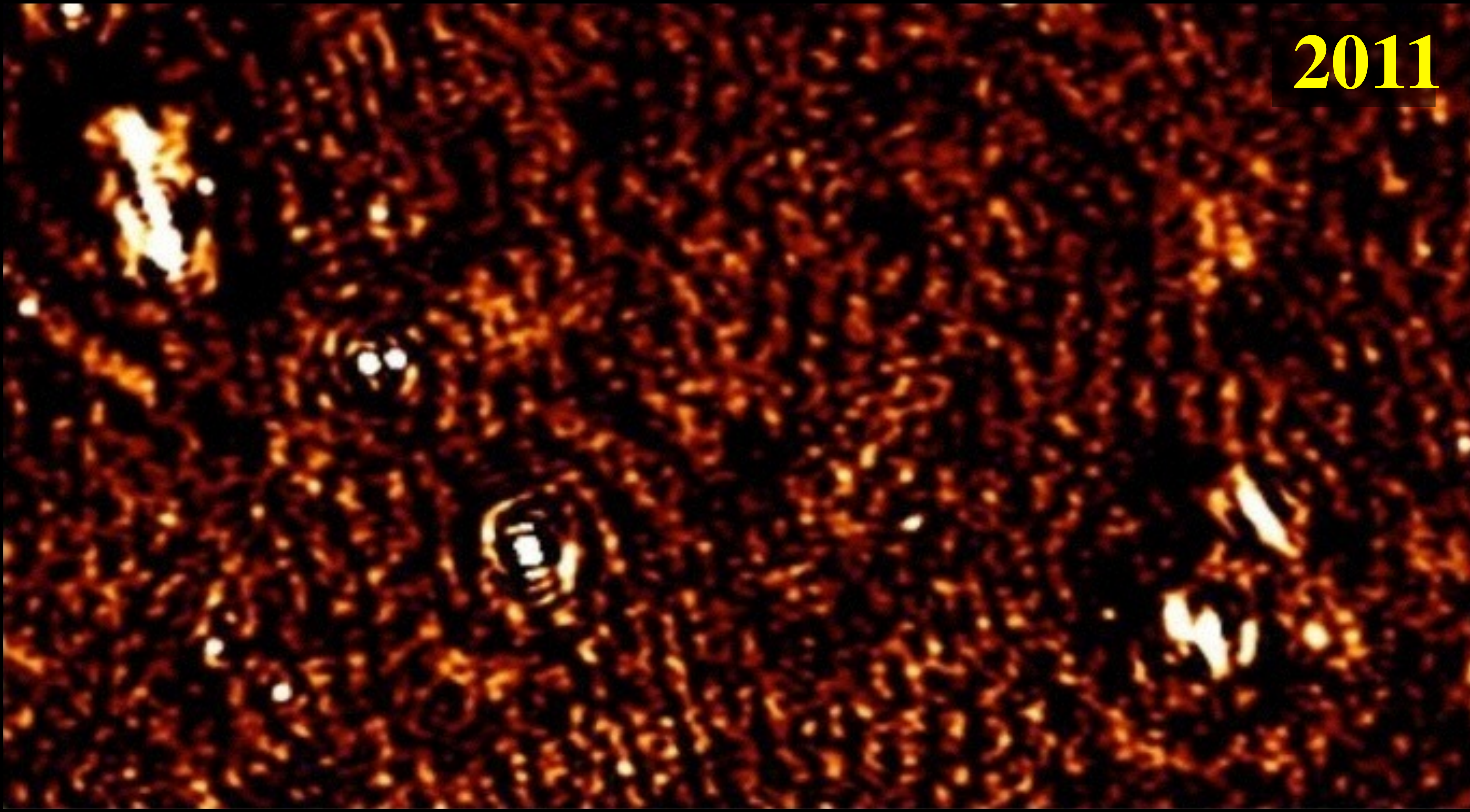
Multifrequency Snapshot Sky Survey



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

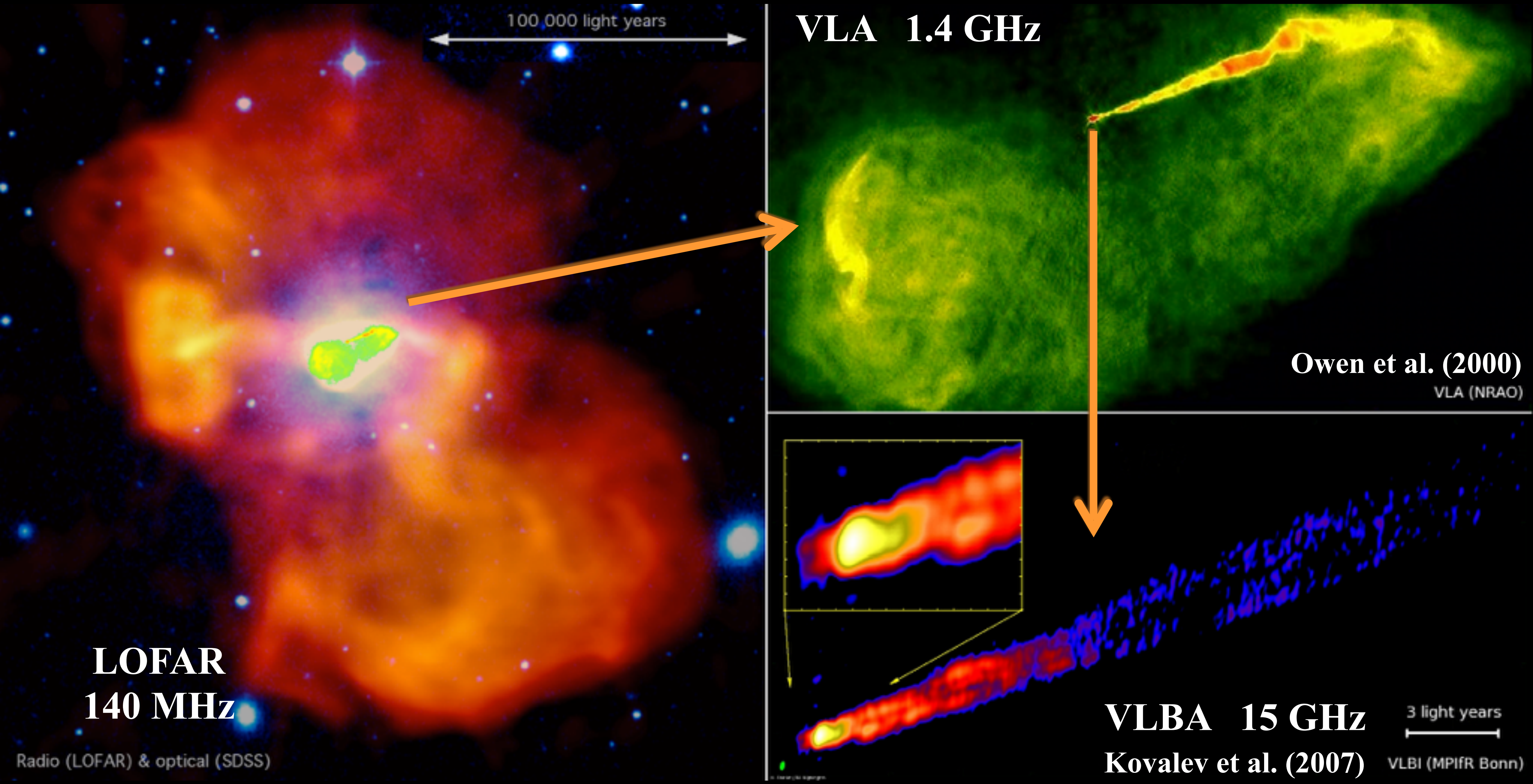
NCP field ≈ 180 μJy / beam *(image courtesy S. Yatawatta)*



NCP field ≈ 30 μJy / beam

(image courtesy S. Yatawatta)

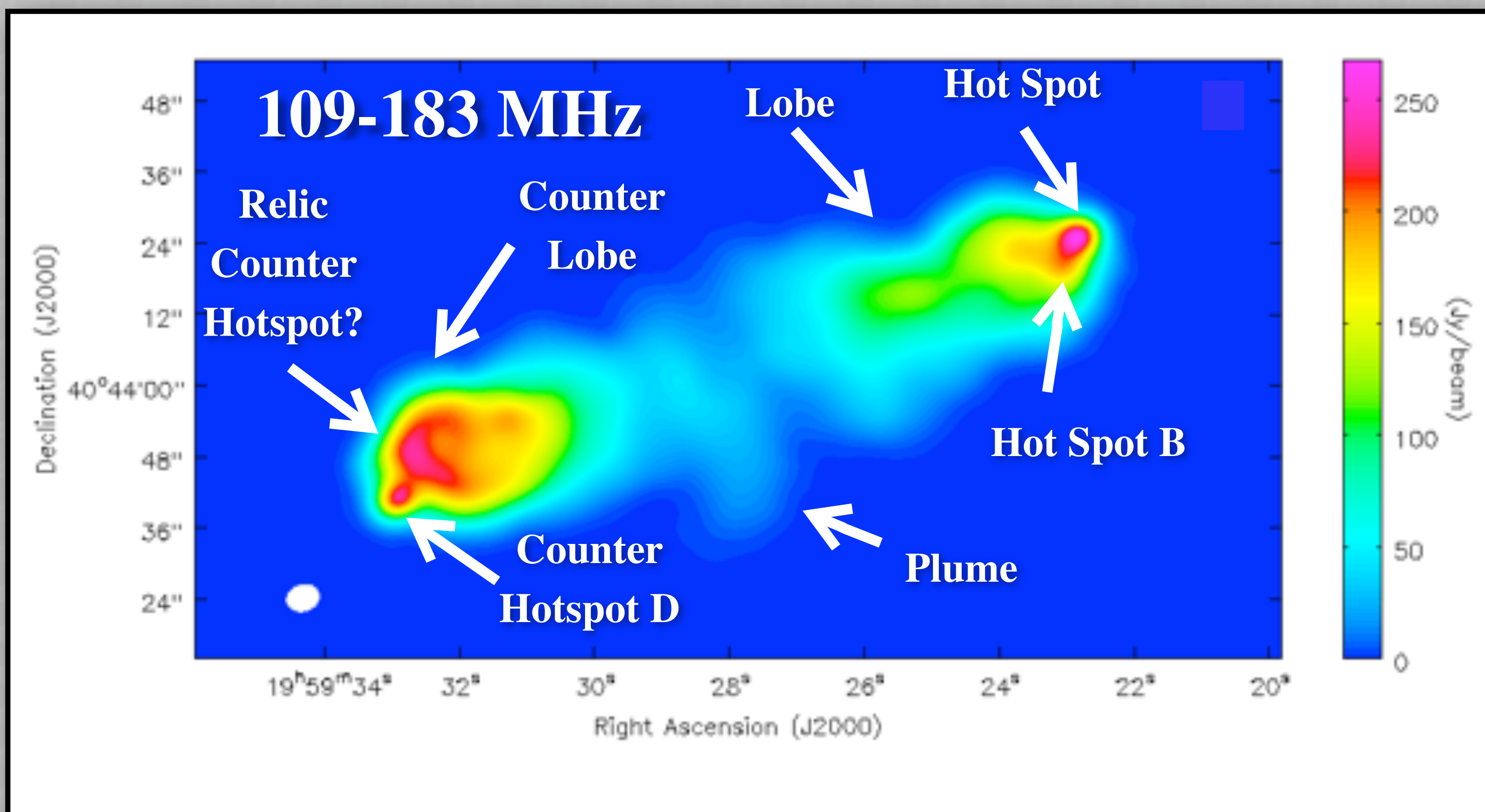
M87 at Low Frequencies



de Gasperin et al. (2012)

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

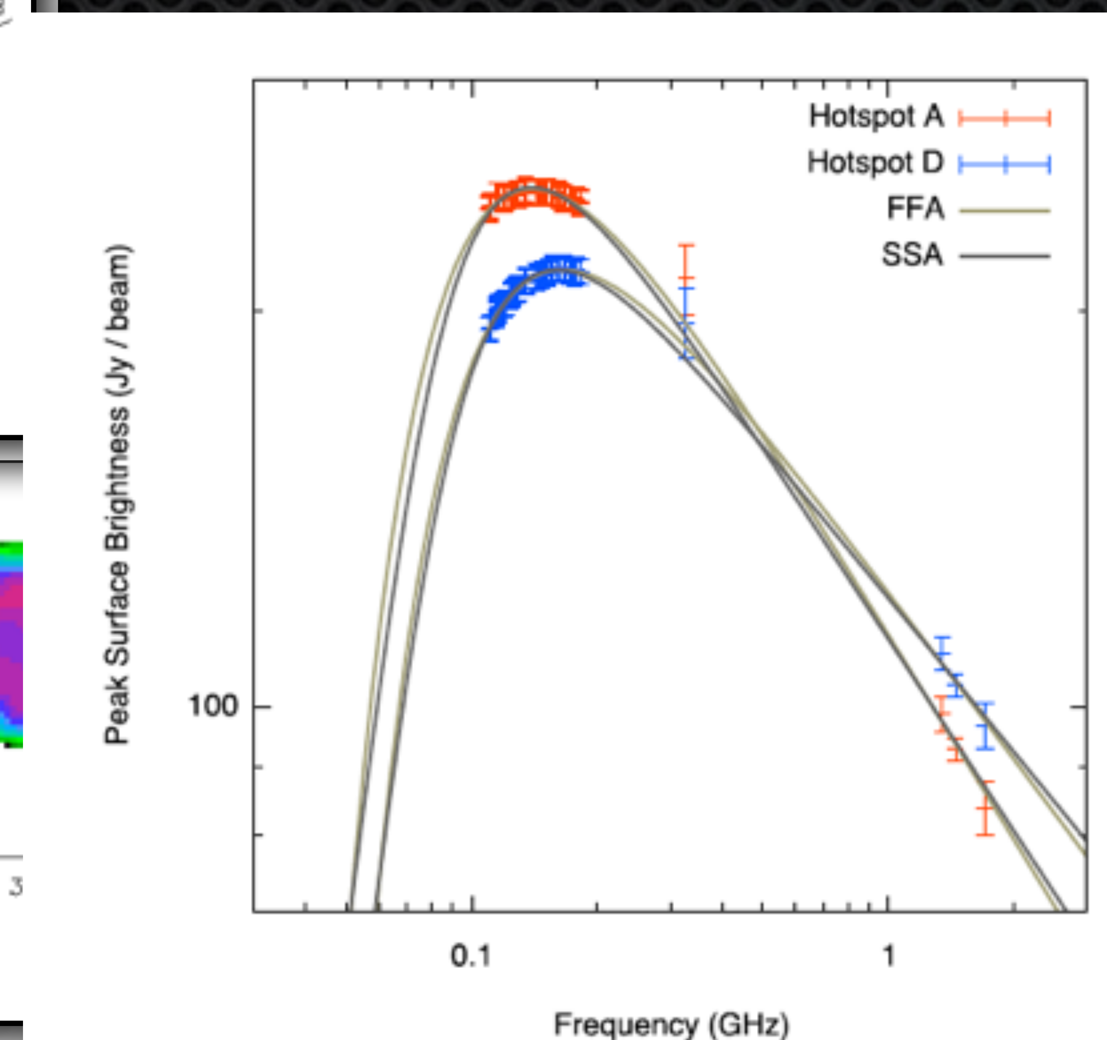
Cygnus A in the Low-Frequency Radio



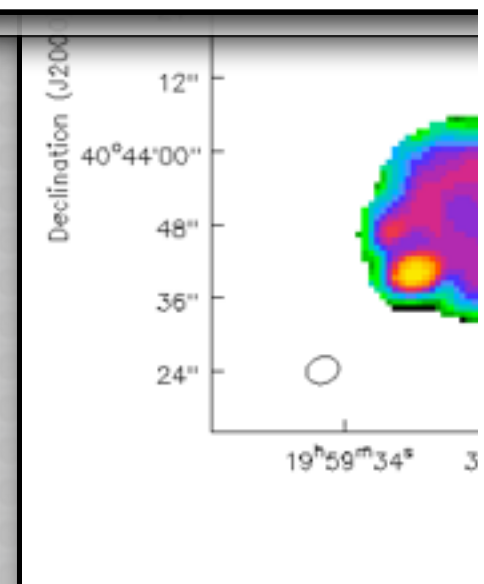
Spectral aging analysis consistent with higher frequency (Carilli et al. 1991)

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

No diffusion of plasma to large radii



McKean et al. (2014)



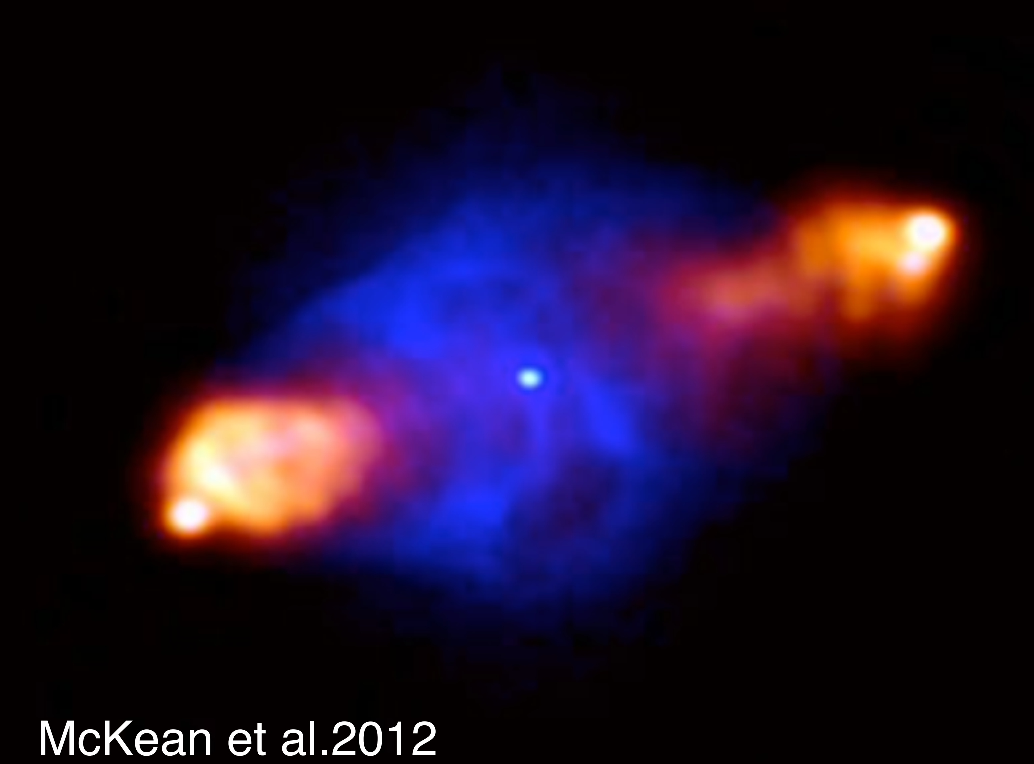
LOFAR HBA

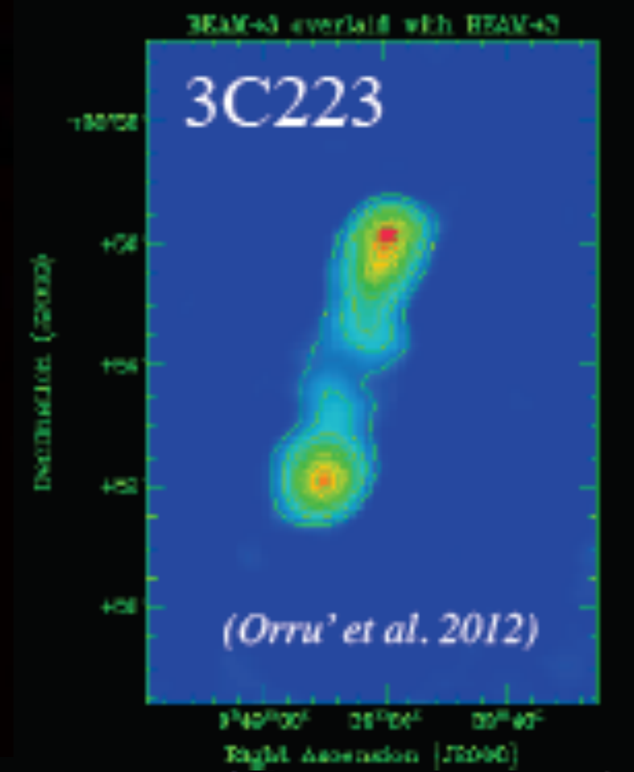
6 hr / 109 - 183 MHz / 28 MHz

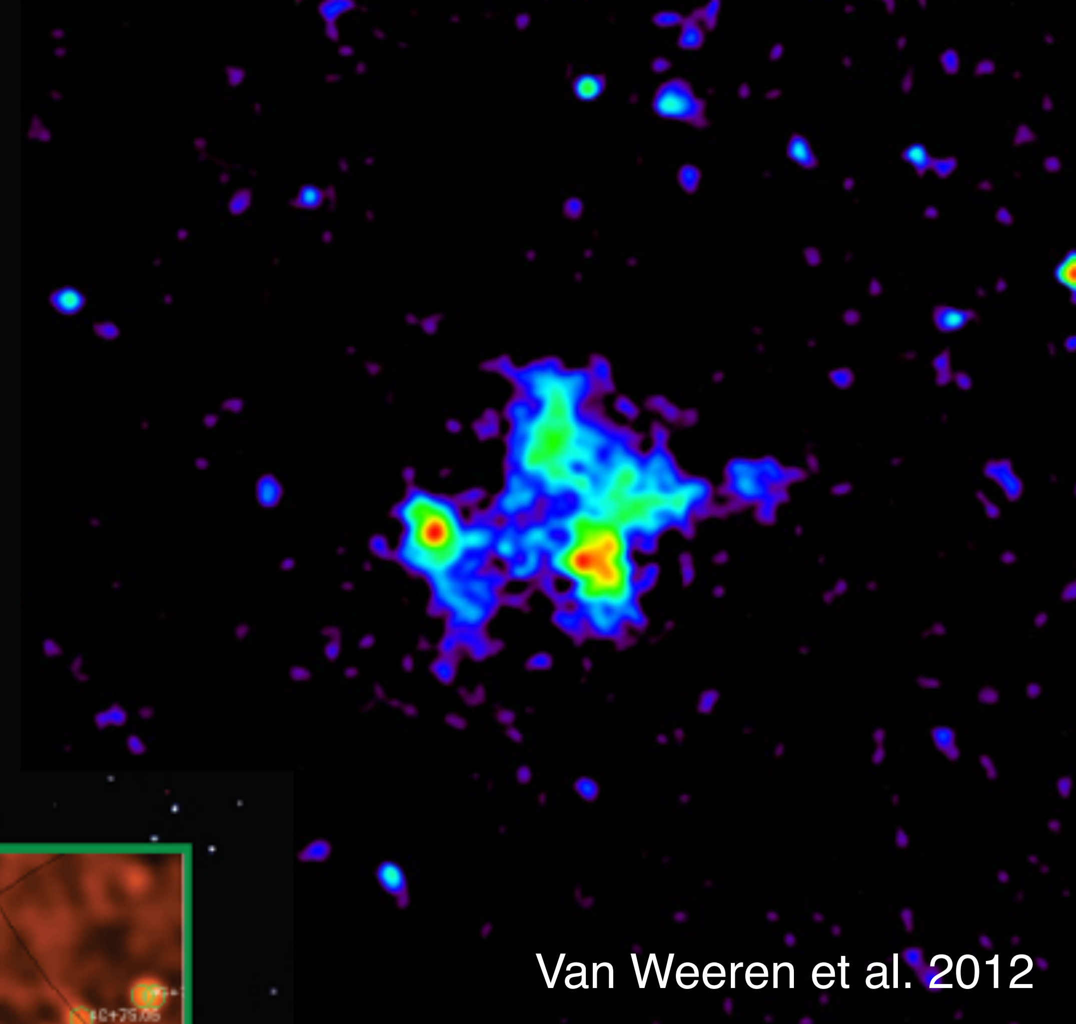
σ ~ 43 mJy / DR ~ 5000

NL baselines only

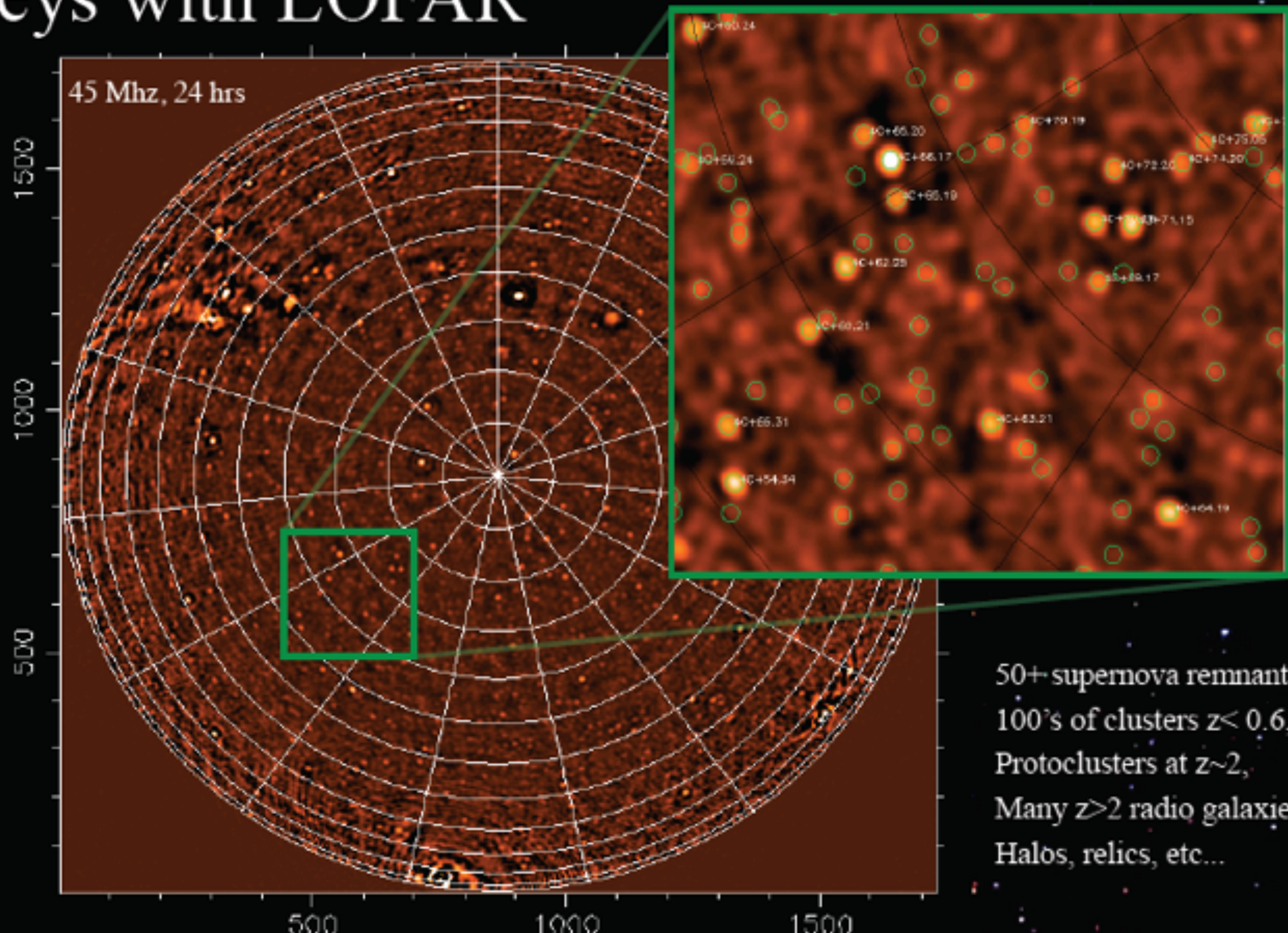
3.8 x 2.7 arcsec beam





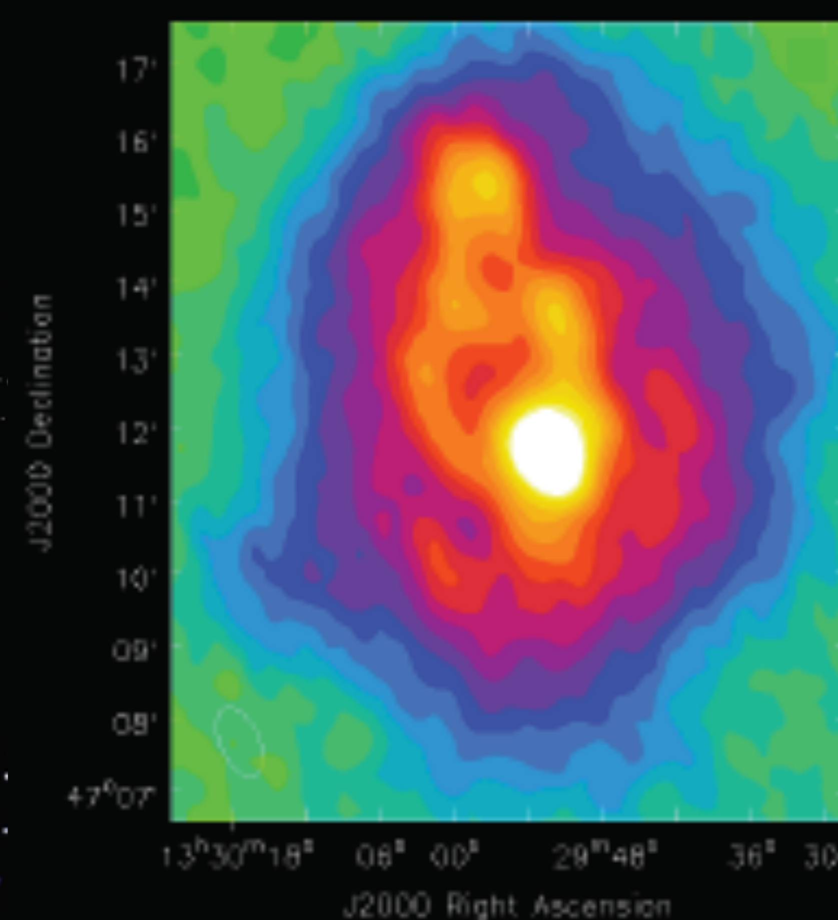


Surveys with LOFAR



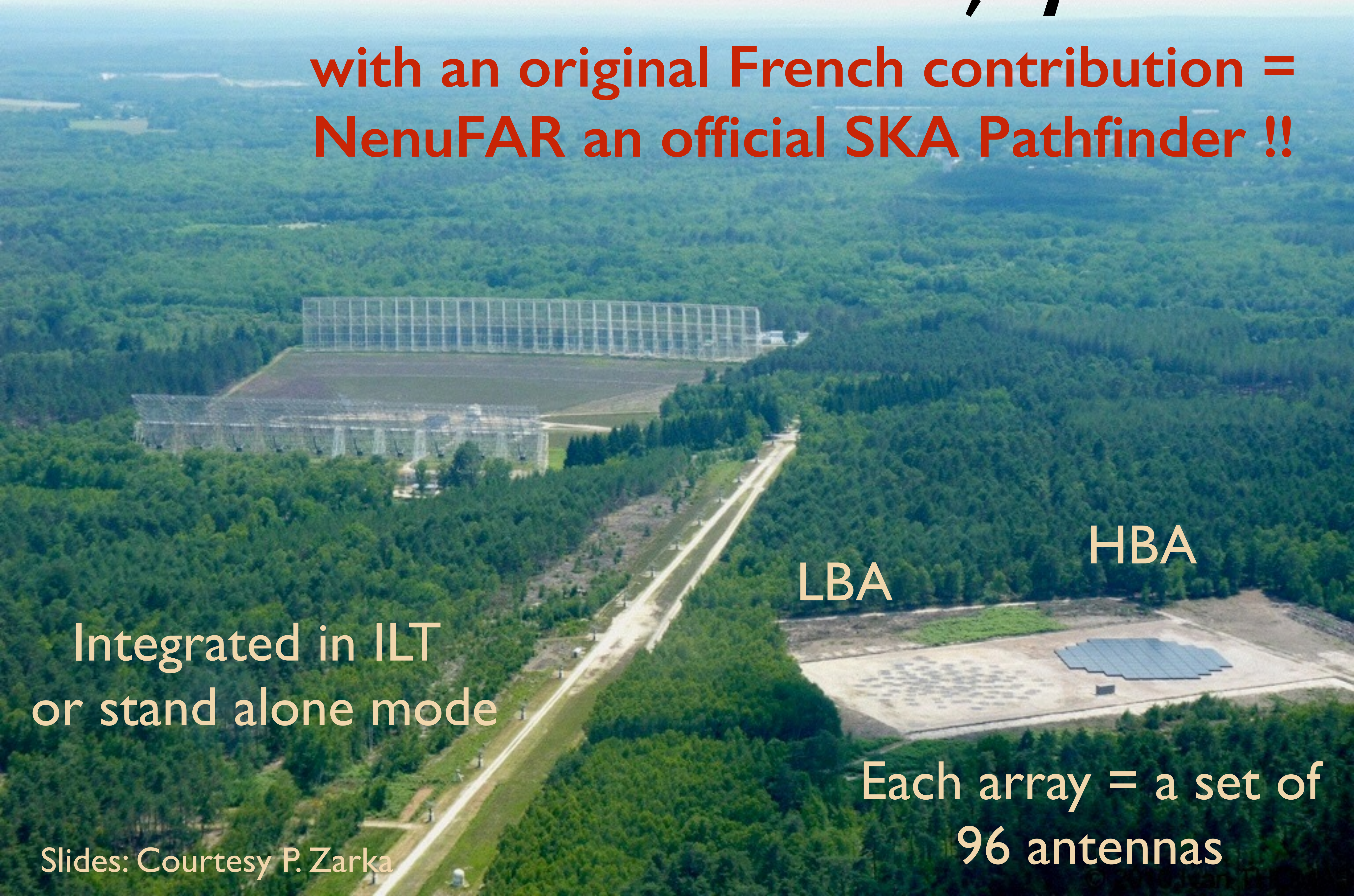
50+ supernova remnants,
100's of clusters z< 0.6,
Protoclusters at z~2,
Many z>2 radio galaxies,
Halos, relics, etc...

M51



A Lofar station in Nançay

with an original French contribution = NenuFAR an official SKA Pathfinder !!

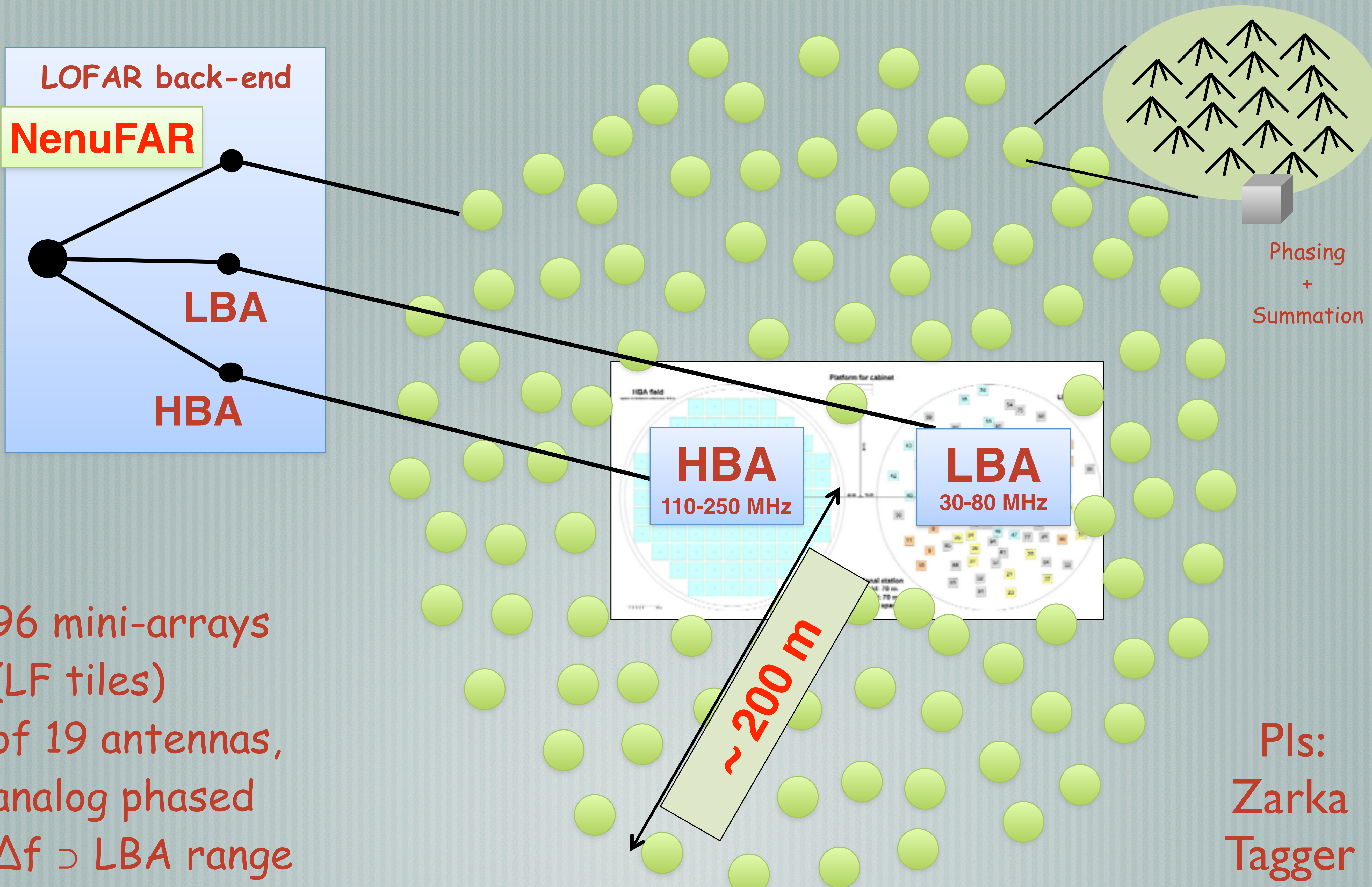


Integrated in ILT
or stand alone mode

Each array = a set of
96 antennas

Slides: Courtesy P. Zarka

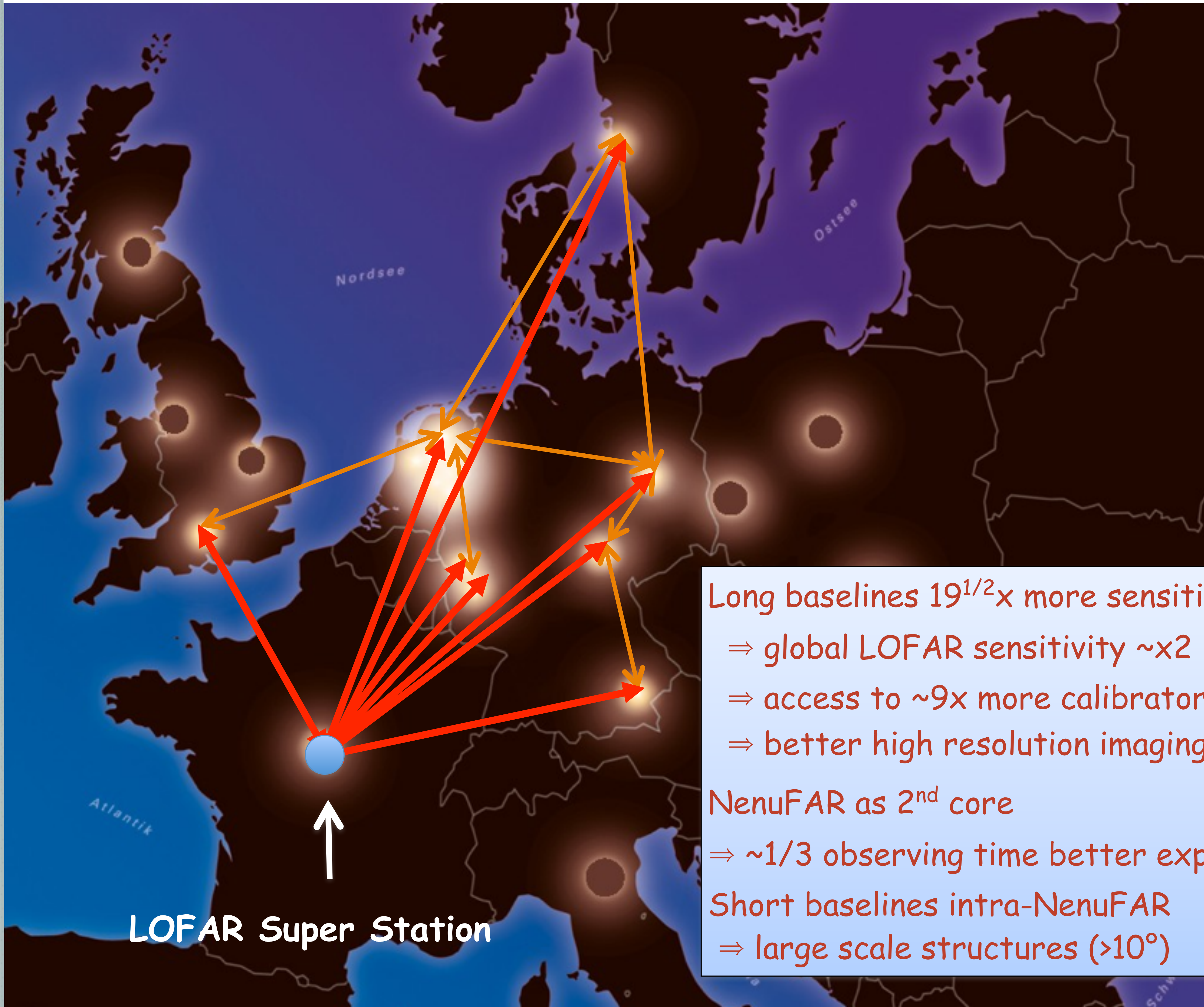
The NenuFAR concept : giant local phased array + interferometer



96 mini-arrays
(LF tiles)
of 19 antennas,
analog phased
$\Delta f \supset$ 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°)

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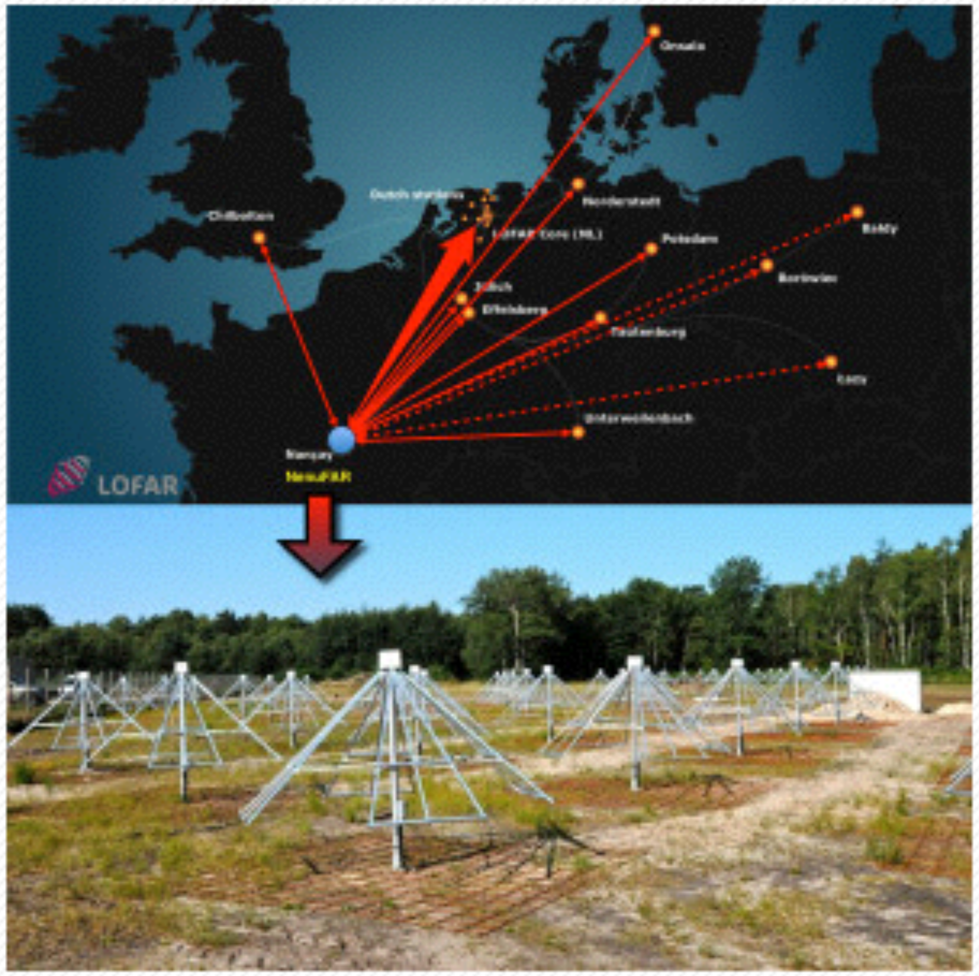
French NenuFAR Telescope Granted SKA Pathfinder Status

The SKA Organisation has officially recognised NenuFAR, a French radio telescope, as a Pathfinder Project of the SKA telescope.



The NenuFAR instrument in France and the international LOFAR telescope array

NenuFAR, which stands for New Extension in Nançay Upgrading LOFAR, is a new low-frequency radio telescope under construction at the Nançay Observatory near Orleans to extend the existing international LOFAR radio telescope, an array of low frequency antennas spread across eight European countries and centred in the Netherlands.

"With this announcement, NenuFAR is recognised as an instrument concept paving the way for the new science to be done with the SKA", said Gilles Theureau, Director of the Nançay Observatory. "It's excellent news for the project, as well as for the Nançay Observatory."

The SKA officially has three precursor telescopes, MeerKAT, ASKAP and MWA. Located at SKA sites in South Africa and Western Australia, these precursors are and will be carrying out scientific studies related to future SKA activities, as well as helping the development and testing of new crucial SKA technologies.

MeerKAT

- The most sensitive radio interferometer in the Southern hemisphere
- A wide range of observing mode: deep continuum, polarisation and spectral line imaging, pulsar timing, and transient searches

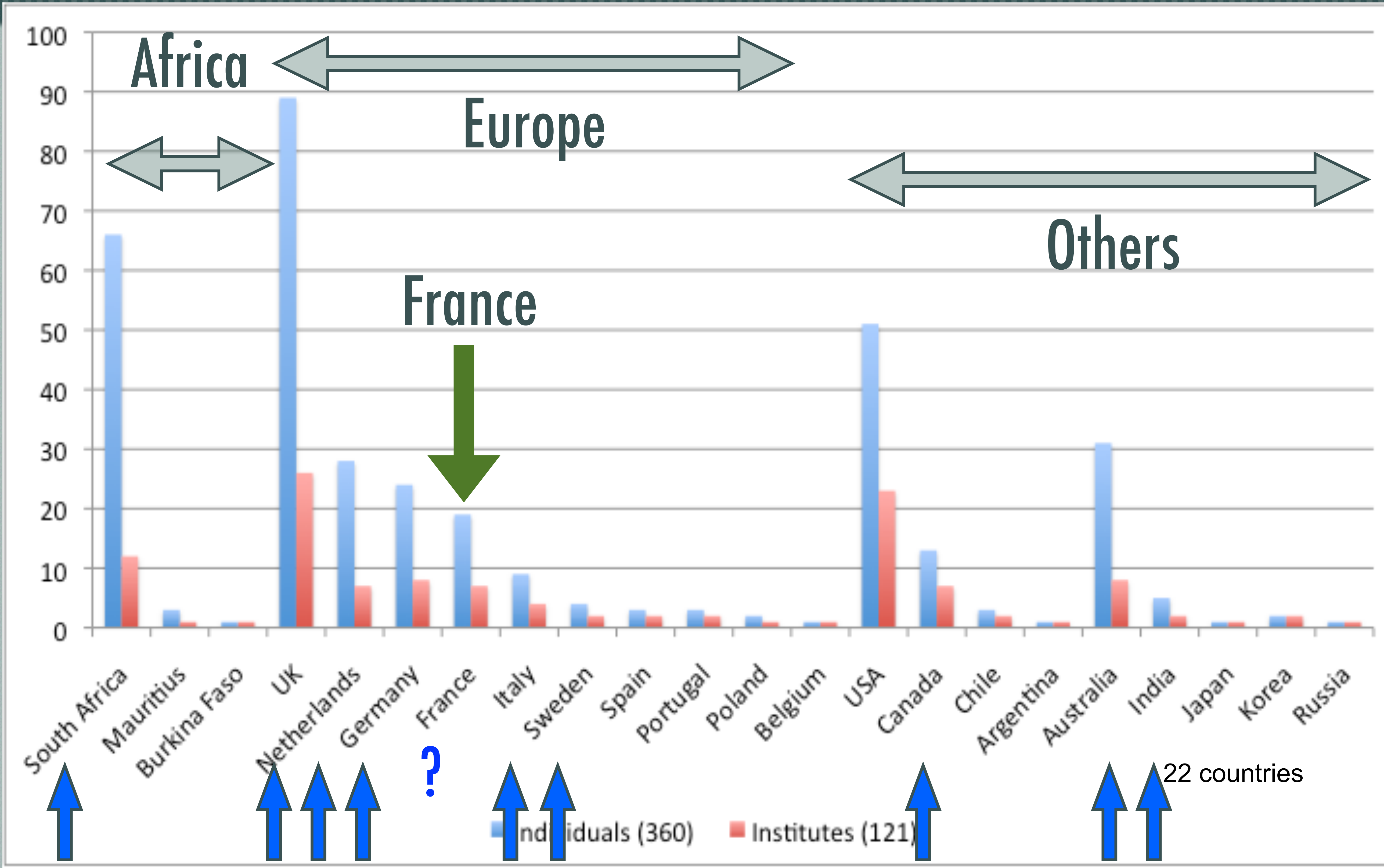
- 64 x 13.5 m gregorian offset antennas in 580 MHz - 15 GHz (~SKA-mid+)
- Baseline out to ~ 8 km (70% in a 1 km core)

- Phase 1 (2016): 1-1.75 GHz cryogenic single-pixel receiver (L-band)
- Phase 2 and 3 (2018):
  - 580-1000 MHz + 8 - 14.5 GHz (wide-band receiver)
  - 7 additional antennas and 20+ km baselines

MeerKAT Key Projects

- **Radio Pulsar Timing**: Testing Einstein's theory of gravity and gravitational radiation
- LADUMA**:** Looking at the Distant Universe with the MeerKAT Array - An **ultra-deep survey of neutral hydrogen** gas in the early universe.
- MESMER: MeerKAT Search for Molecules in the Epoch of Re-ionisation - Searching for **CO at high redshift (z>**7) to investigate the role of molecular hydrogen in the early universe.
- MeerKAT **Absorption Line Survey** for atomic hydrogen and OH lines in absorption against distant continuum sources
- MHONGOOSE: MeerKAT **HI Observations of Nearby Galactic Objec**ts: Observing Southern Emitters - Investigations of different types of galaxies; dark matter and the cosmic web.
- TRAPUM: **Transients** and **Pulsars** with MeerKAT - Searching for, and investigating new and exotic pulsars.
- A MeerKAT HI Survey of the **Fornax Cluster** - Galaxy formation and evolution in the cluster environment.
- MeerGAL: MeerKAT **High Frequency Galactic Plane Survey** - Galactic structure and dynamics, distribution of ionised gas, recombination lines, interstellar molecular gas and masers.
- MIGHTEE: MeerKAT International GigaHertz Tiered Extragalactic Exploration Survey - **Deep continuum observations of the earliest radio galaxies**
- ThunderKAT: The Hunt for Dynamic and **Explosive Radio Transients** with MeerKAT - e.g. gamma ray bursts, novae and supernovae, plus new types of transient radio sources

MeerKAT Large Surveys



ASKAP

- 36 x 12 m antennas located in the radio quiet zone of Western Australia outback. Completion 2013 (early science 2014).
- Designed to be the world's premier survey telescope.
- 700 - 1800 MHz. Maximum baseline of 6 km (resol. ~30'')
- Phase array feeds (PAF) allowing multiple (94) synthetic beams on the sky. **Wide field of view** ~30 deg^2
- BETA sub-array (6 antennas) in commissioning with PAF.

Conclusions

- **Radio Astronomy** is undergoing a massive expansion with SKA and the precursors/ pathfinders: LOFAR, MeerKAT, ASKAP, etc..
- **Complementary** to new facilities: ALMA, JWST, Euclid, SVOM, LSST... and **CTA** !!
- Many **open questions** to be addressed by **SKA** : Fundamental physics (gravitational waves, pulsars, dark energy, ...), Exploration of the Unknown, Origin and evolution of the Universe
  - SKA at **SPP** ? Cosmology, high en. transients, fundamental physics, synergy with CTA, ...
  - SKA at **SAp**: Cosmology, transients, pulsars, HI and galaxy evolution, etc + new developments in algorithmic with JL Starck
- **SKA operational for 50 years !**

How to get precise information ?

- The most recent updates on the SKA scientific case:
  - https://indico.skatelescope.org/conferenceCFA.py?confId=270
- or type : Advancing astrophysics with the SKA (conference in Italy, June 2014)
- Presentations online + the new SKA book to come.

Thank You !

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