UNIVERSITY OF AMSTERDAM

Master Astronomy and Astrophysics - 5214RAAS6Y

Radio Astronomy

Lecture 10

The Techniques of Time-Domain Radio Astronomy II: High time resolution with an interferometer

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B0.209 - May 13th, 2013

Observing Proposals

How’s it going???

The Home Stretch...

- May 13th (Today): Finish as much as possible on the data analysis project (LOFAR imaging) and start writing the report.
- May 16th: No lecture because of the NAC.
- May 21st: Lecture and practicum session. Last big chance for consultation on observing proposals.
- May 23rd: No lecture. Presentations on observing proposals.
- May 24th: Data analysis and observing proposals due.
- **May 28th: 13-16h: final exam (moved!)**

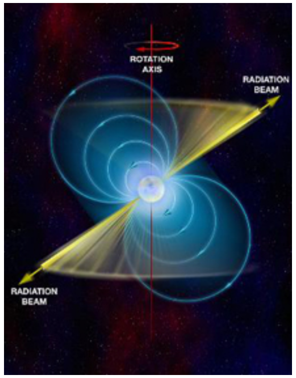
Lecture outline

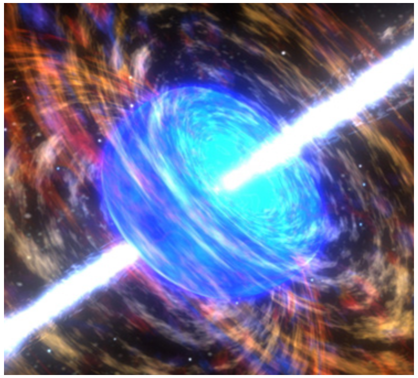
- High time resolution with an interferometer
- Beam-forming with an interferometer
- **Break**
- Pulsar and "fast transient" searches
- Fast imaging and uv-plane techniques
- Astrometry and pulsar distances

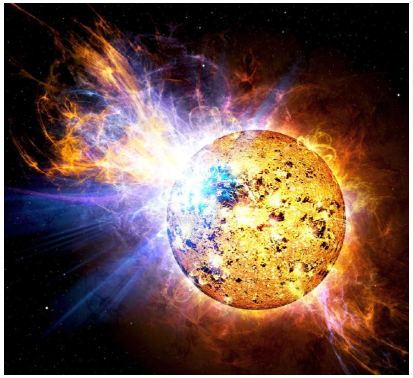
High time resolution with an interferometer

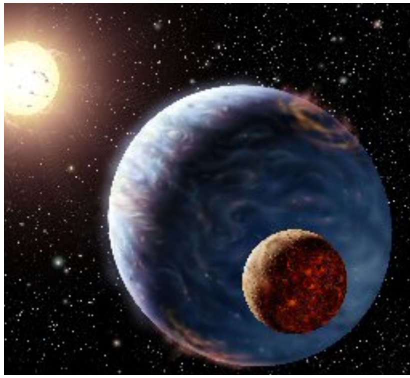
What is "high time resolution" and why do we need it?

- Here, "high time resolution" means t_samp < 1s.
- Several astronomical source classes are known to vary on this timescale, e.g.: pulsars, magnetars, the Sun, (exo)planets, flare stars.
- Explosive, dynamic events, a.k.a "fast transients".
- Huge potential discovery space for new phenomena (microsecond - second timescales not well explored).

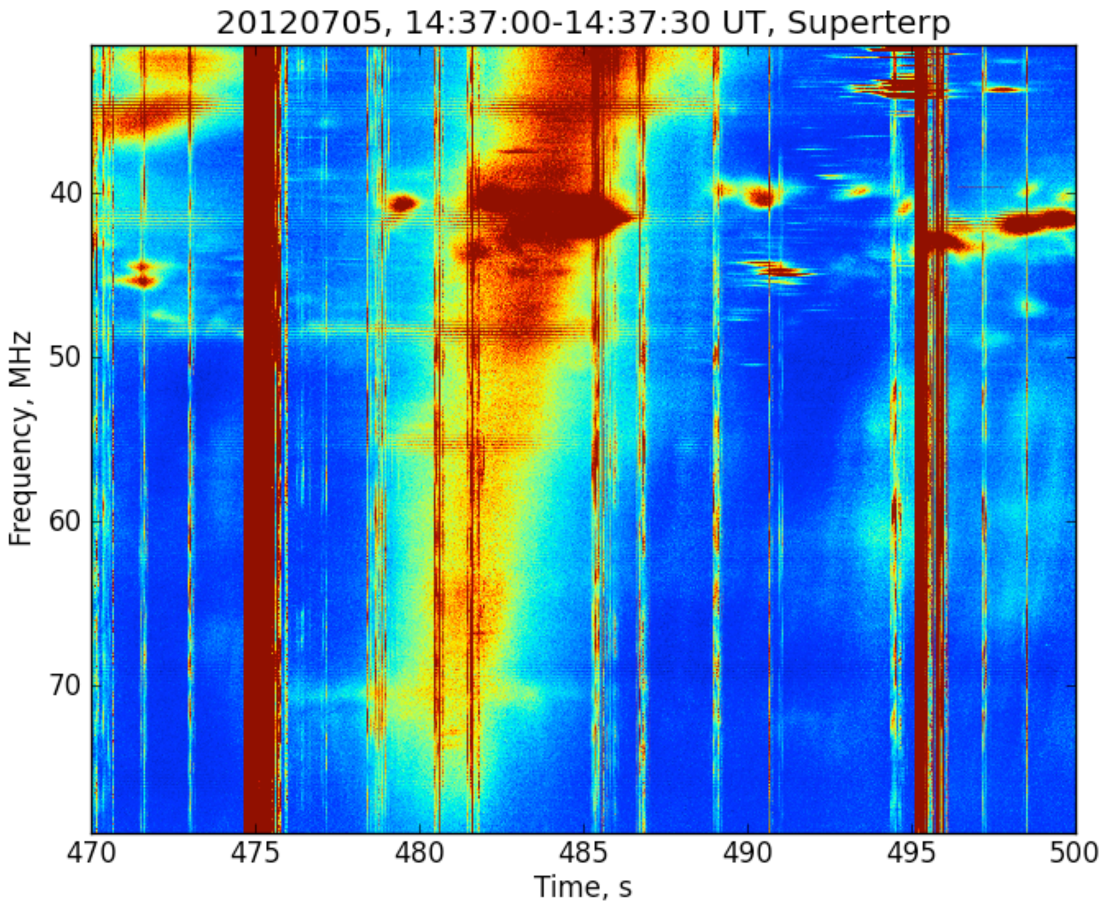








Dynamic Spectra of Solar Bursts



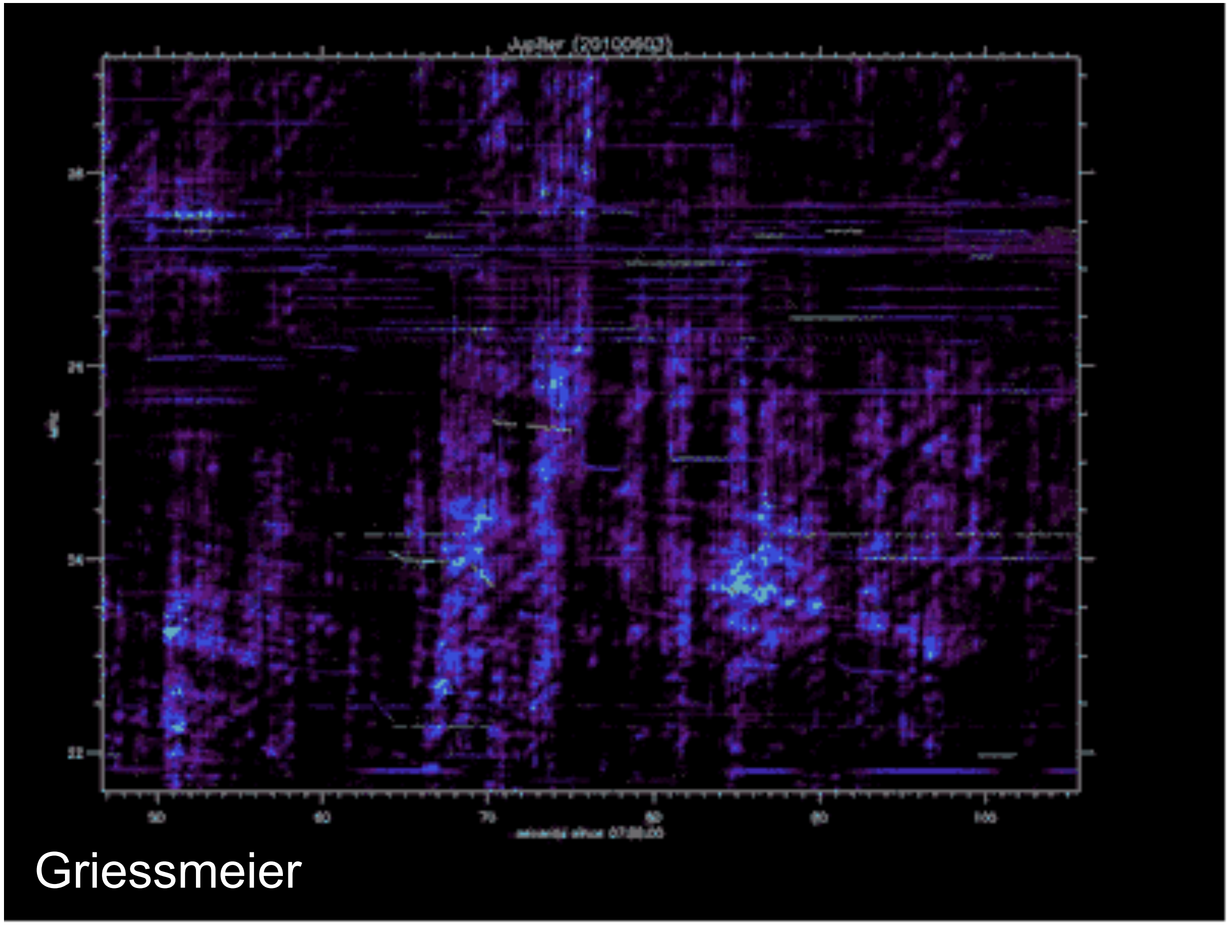
LOFAR LBA data

- "Type-III' solar radio bursts. These appear in a dynamic spectrum as a rapid drift from high to low frequencies. Their source is usually above an active region on the Sun and they arise from electrons being accelerated within a solar flare and propagating along magnetic field lines through the solar corona and sometimes out into interplanetary space.
- Also at this time, there was a powerful thunderstorm passing over the region. The strong full-bandwidth emission seen in the image is most likely to be due to lightning flashes. Evidently a thunderstorm is no barrier to observing the Sun!

Fallows

Dynamic Spectrum of Jupiter

Jupiter radio bursts

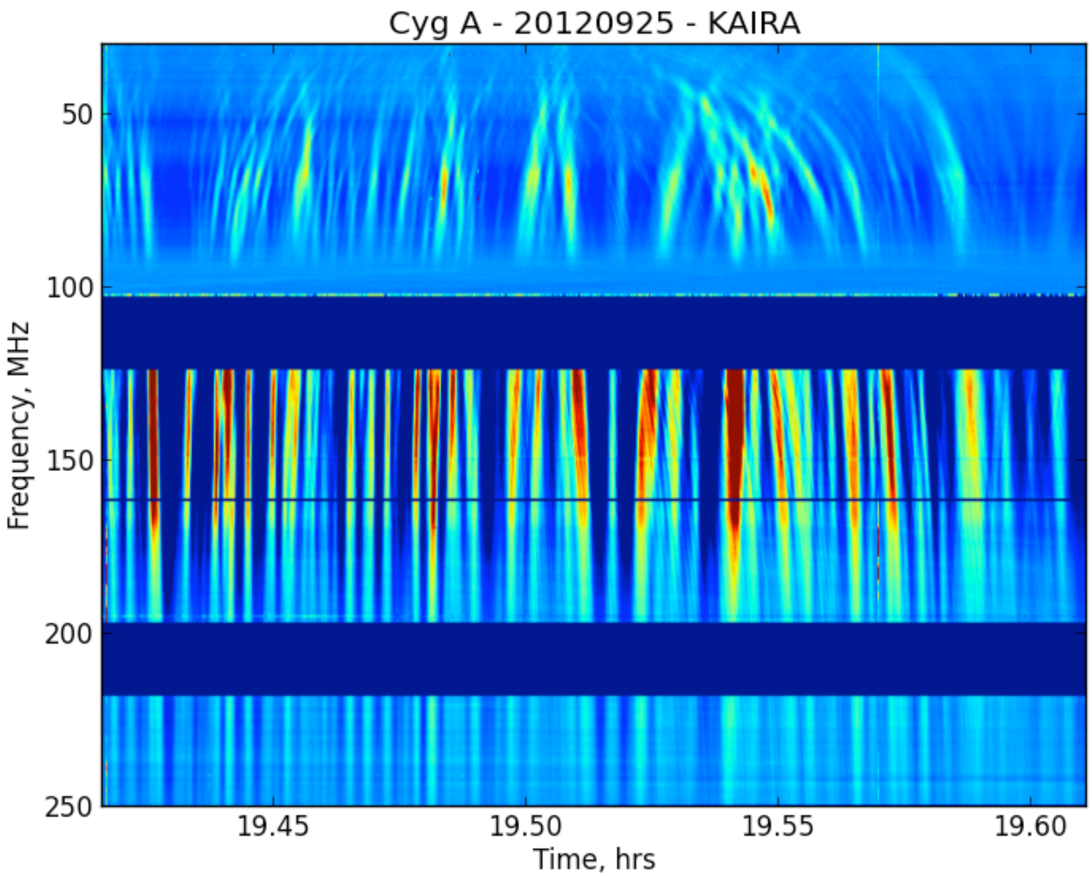


Griessmeier

LOFAR LBA data

- Probe timescales of microseconds to seconds (6 orders of magnitude!).
- Interferometer can localize the emission to a specific source region.

Ionospheric Scintillation



LOFAR LBA+HBA data

- The scintillation of point-like radio sources arises from the diffraction and refraction of light due to density variations in the line-of-sight between the source and the observer. Usually, scintillation occurs due to one or more distinct regions in the line-of-sight.
- Shown: ionospheric scintillation towards Cygnus A as seen by LOFAR.
- This offers new methods of studying the plasma structures giving rise to the scintillation.

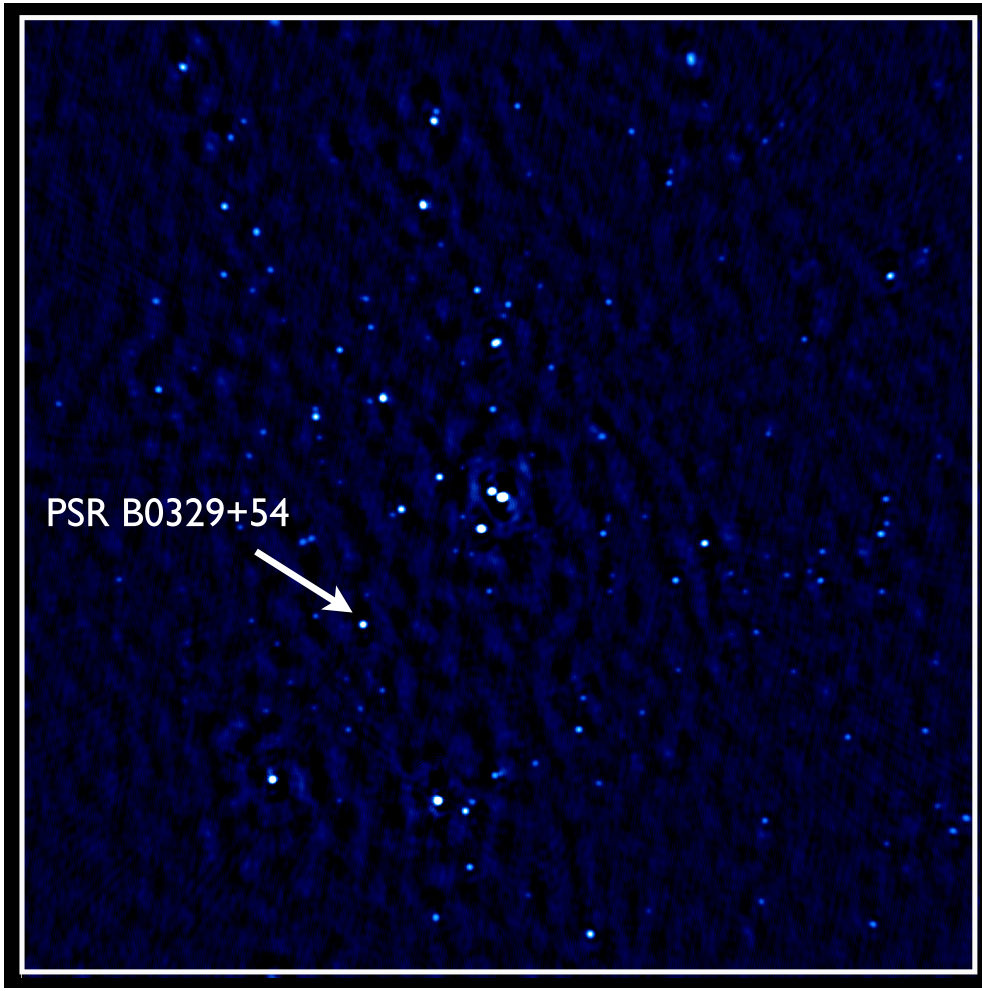
Fallows

Wait, what about imaging?

Simultaneous Imaging and Pulsar Obs.

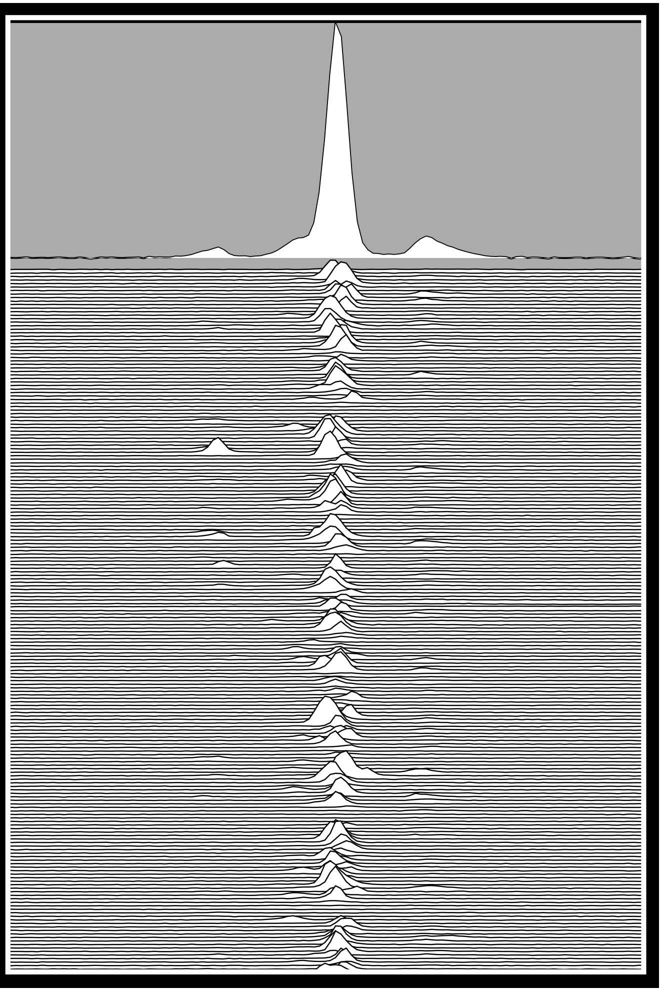
LOFAR HBA data

High angular resolution



1-second time resolution

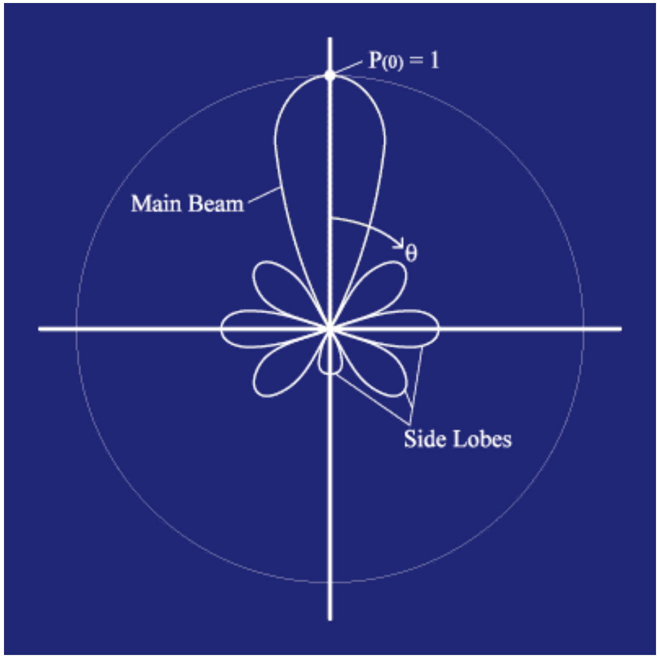
1-pixel image



1-ms time resolution

Comparison with Single Dish

- An interferometer provides a multi-pixel image with a field-of-view dictated by the primary (individual antenna) field-of-view.
- A single dish offers basically a 1-pixel image of the sky, though remember that the main-lobe and side-lobe pattern can be complicated.



- At high time resolution, we often use an interferometer as a synthesized single-dish, though many "1-pixel" images can be made within the primary field-of-view.

But why not just make a bunch of 1-ms images?

High-time resolution with an interferometer

Data rate, e.g. LOFAR

- 48 stations - i.e. 1128 baselines $N_{\text{baselines}} = \frac{N_{\text{Ant}}(N_{\text{Ant}} - 1)}{2}$
- 256 0.8-kHz chan/subband
- 488 195-kHz subbands
- 1 complex visibility represented in 64 bits (8 bytes)
- 4 polarization products
- 1-second visibility dump time

$$\text{Data rate} = \frac{N_{\text{chan}} N_{\text{sub}} N_{\text{base}} N_{\text{pol}} N_{\text{bits}}}{t_{\text{samp}}} = \frac{256 * 488 * 1128 * 4 * 64}{1} = 34\text{Gb/s}$$

High-time resolution with an interferometer

But for pulsars and other "fast transients" we need < 1ms time resolution - at least!

$$\text{Data rate} = \frac{256 * 488 * 1128 * 4 * 64}{< 0.001} > 34000\text{Gb/s}$$

Instead we form phase-array beams in particular directions:

$$\text{Data rate} = \frac{N_{\text{chan}} N_{\text{sub}} N_{\text{beam}} N_{\text{pol}} N_{\text{bits}}}{t_{\text{samp}}} = \frac{16 * 488 * 1 * 4 * 64}{0.001} = 2\text{Gb/s}$$

In a certain sense, we've traded spatial resolution for time resolution.

High-time resolution with an interferometer

Advantages

- Higher angular resolution: great for localization and rejecting sky background.
- Each element has a wide field-of-view: survey speed is high if one can process the entire field-of-view.
- Multi-beaming for interference rejection.
- Can afford to build a bigger total collecting area.

High-time resolution with an interferometer

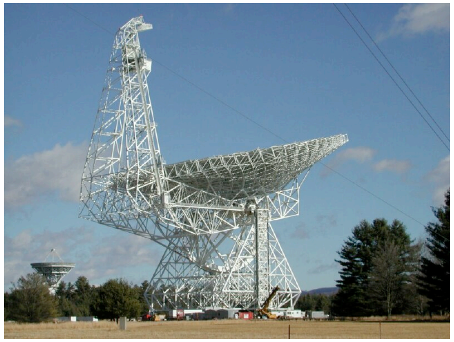
Disadvantages

- Very restricted field-of-view unless many beams can be synthesized.
- Potentially many data streams and much higher data rate.
- Careful calibration required to "phase-up" the array.
- Potentially complicated instantaneous sidelobe pattern.

But ultimately, we don’t have much choice because...

To build much bigger telescopes, we need to move to interferometers

Single Dishes



GBT

Parkes

Arecibo

Interferometers

GMRT

WSRT

LOFAR

SKA

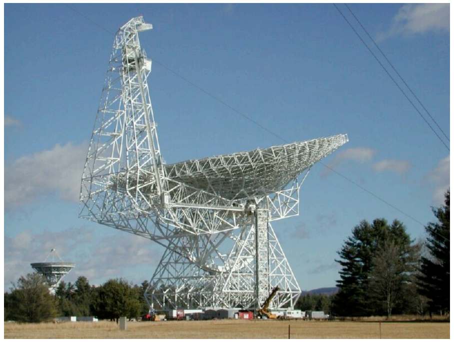
SKA Mid

SKA Low

SKA Aperture Array

This is a bit of a paradigm shift for the pulsar and high-time-resolution community

Single Dishes


GBT


Parkes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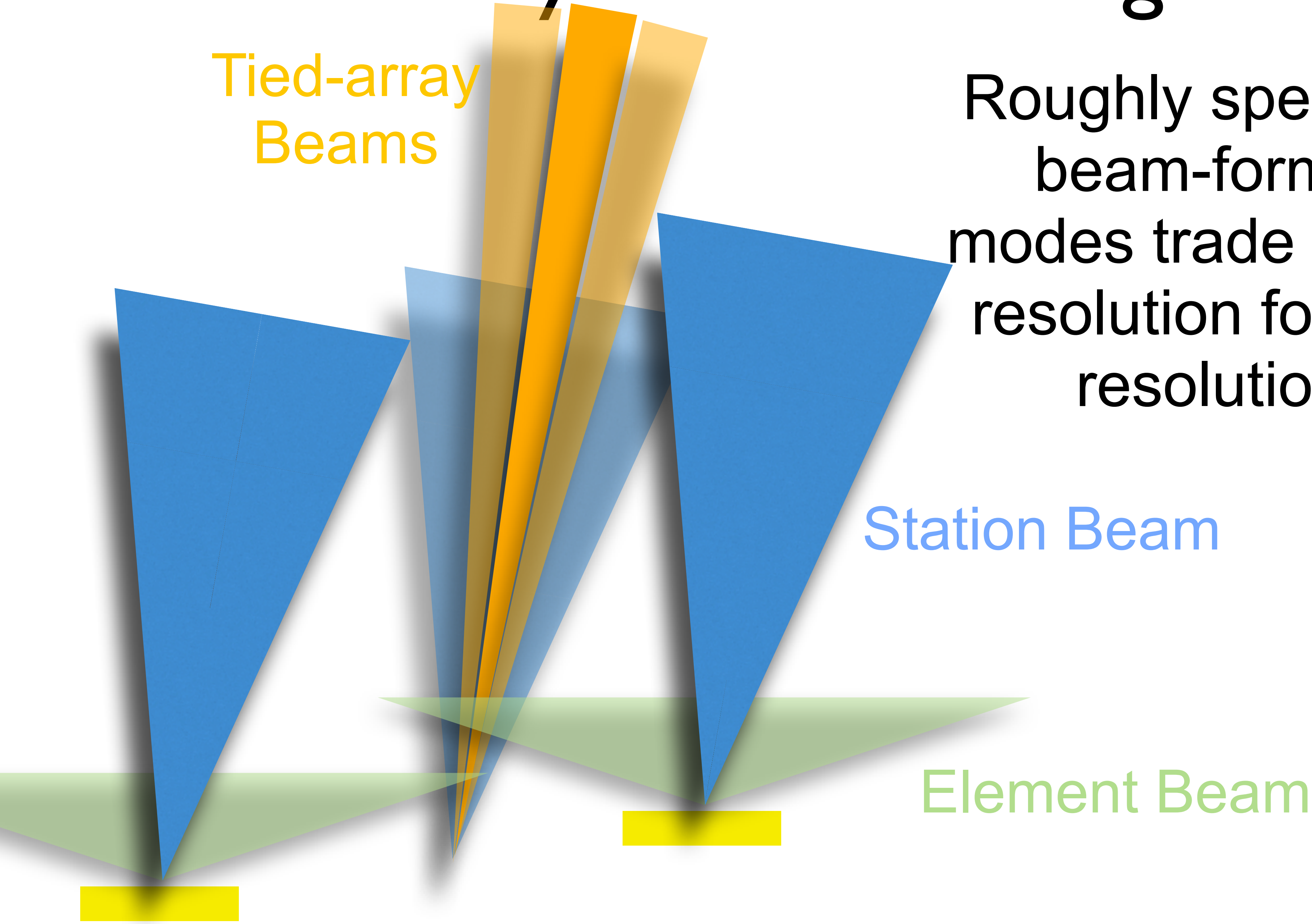
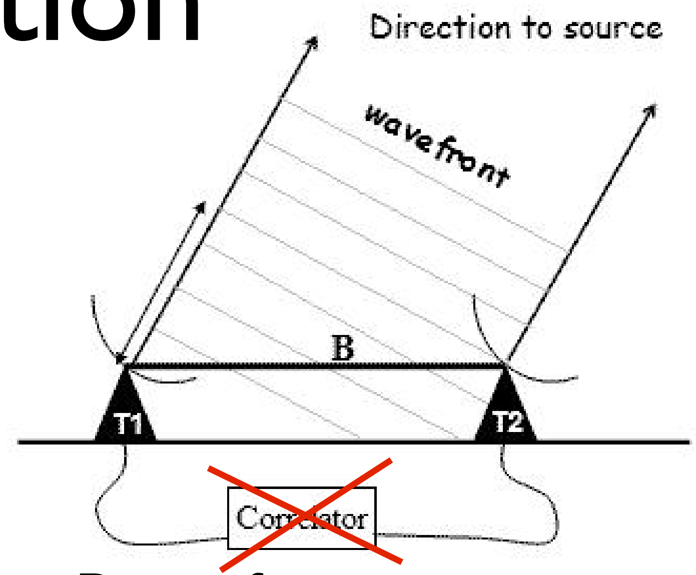
Beam-forming with an interferometer

Array Beam Forming



Roughly speaking, beam-formed modes trade spatial resolution for time resolution.

Incoherent Antenna Addition



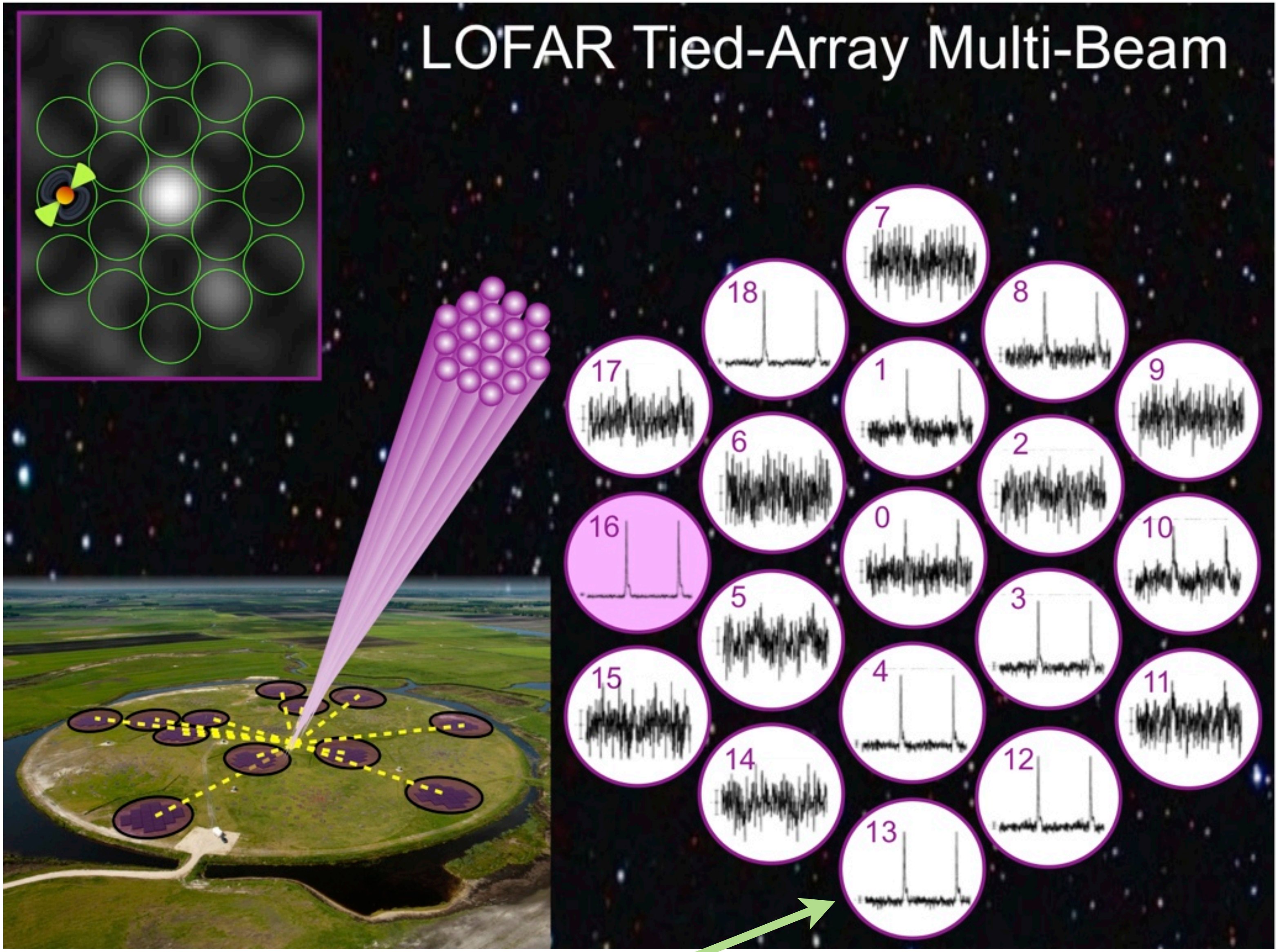
Beamformer: *sum*

- Collect the various antenna voltage streams.
- Square the signal to produce a total power timeseries from each antenna.
- Correct for geometrical delay between the antennas and the pointing direction on the sky.
- Sum the various streams.
- Produces a single field-of-view equal in size to the primary beams.
- Sensitivity scales with the square-root of the number of antennas added (assuming they are all identical).

Coherent Antenna Addition

- Collect the various antenna voltage streams.
- Correct for the geometrical delay towards a particular sky position.
- Correct for differential clock delays between the antennas.
- Correct for differential ionospheric delays along the various lines-of-sight.
- Add the calibrated, time/phase-shifted signals.
- Results in a single "tied-array" beam with a FWHM proportional to the maximum baseline.
- Can synthesize many "tied-array" beams within the primary beam.

Example: LOFAR tied-array beams

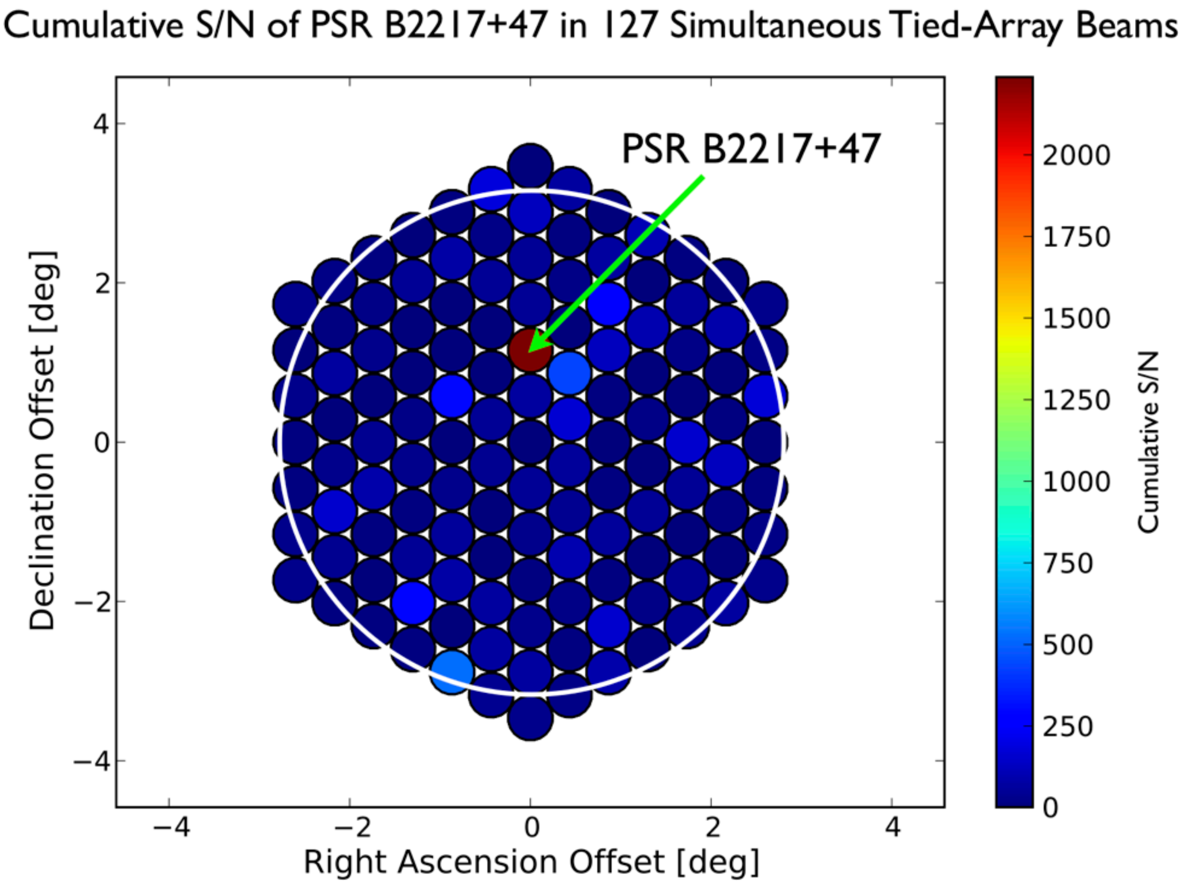


LOFAR
HBA
data

Folded and dedispersed signal

Hessels

Fill Primary Beam with Tied-Array Beams

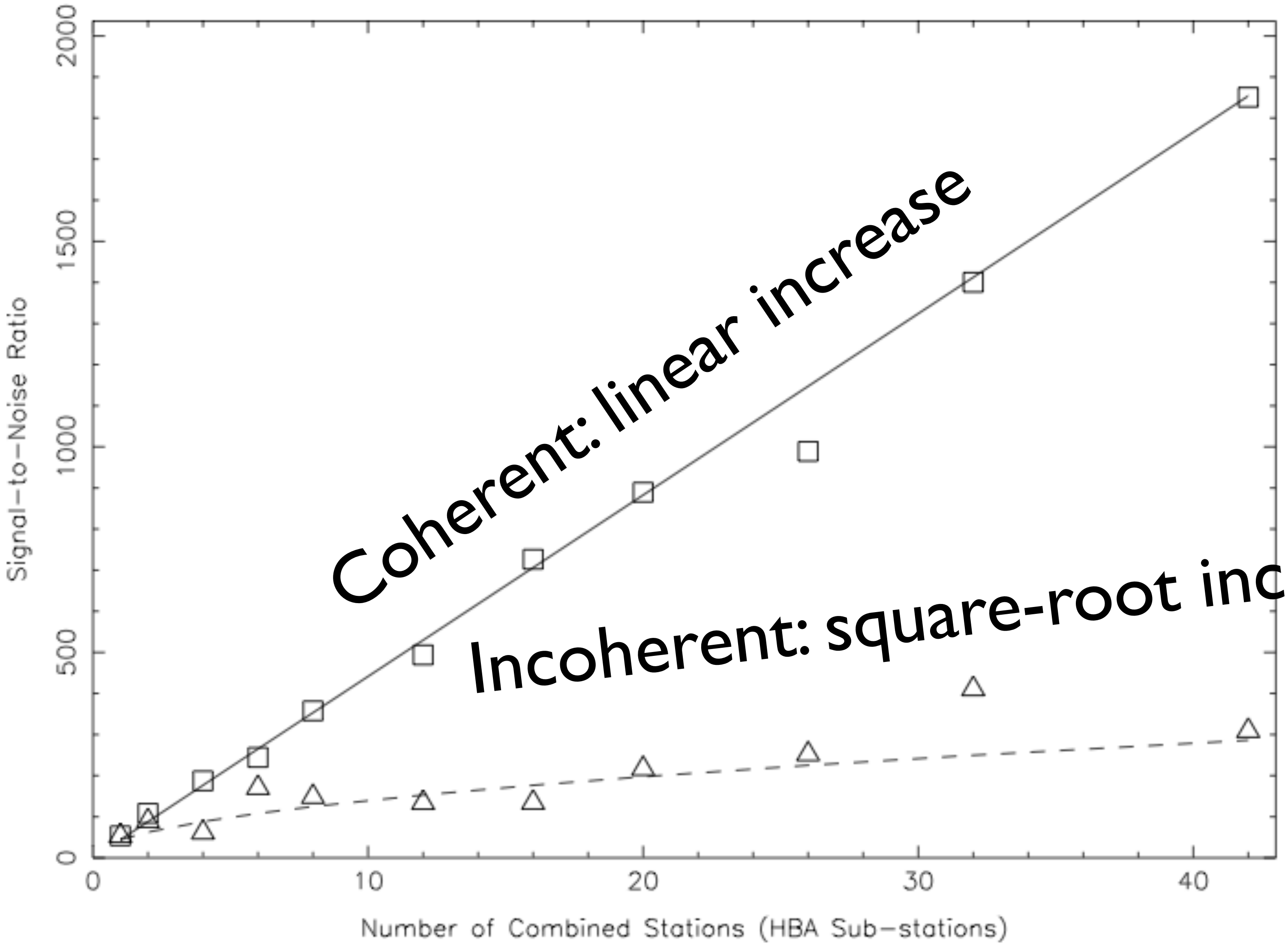


LOFAR HBA data

- White circle = station (primary) beam.
- Colored circles are the tied-array beams using the LOFAR Superterp.
- Color represents the S/N of the pulsar in each beam.

Hessels

Coherent vs. Incoherent Beams



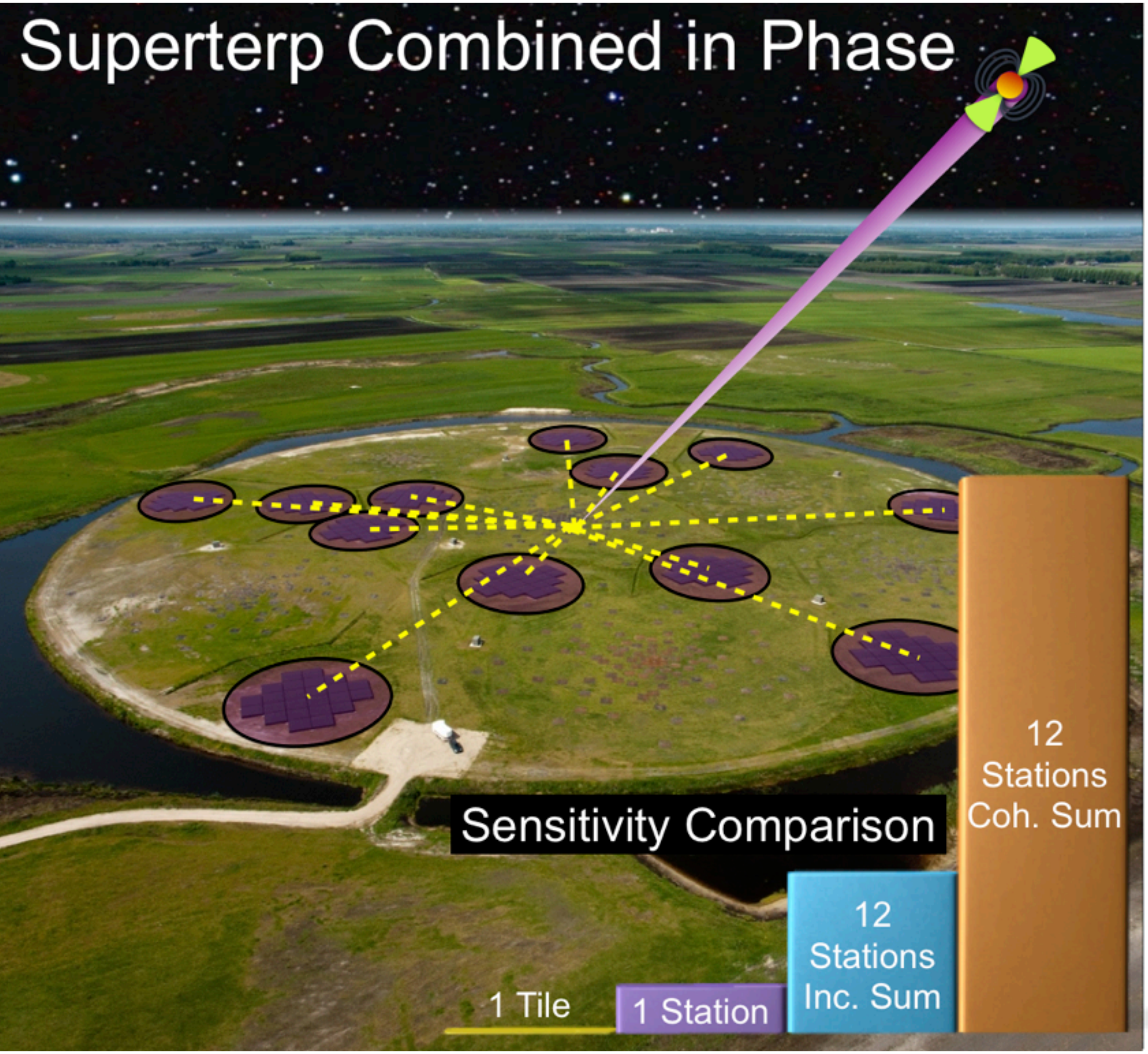
Coherent: linear increase

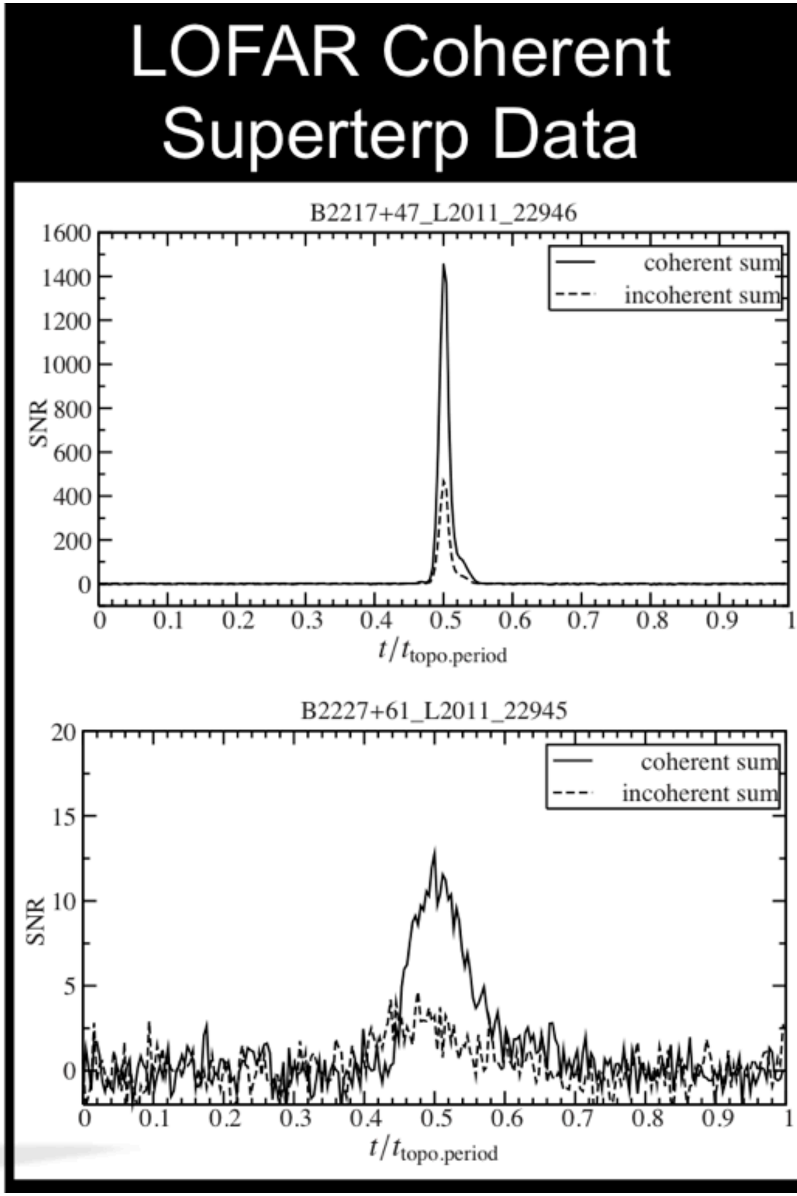
Incoherent: square-root increase

LOFAR
HBA
data

- Compromise between field-of-view and sensitivity.

Coherent vs. Incoherent Beams





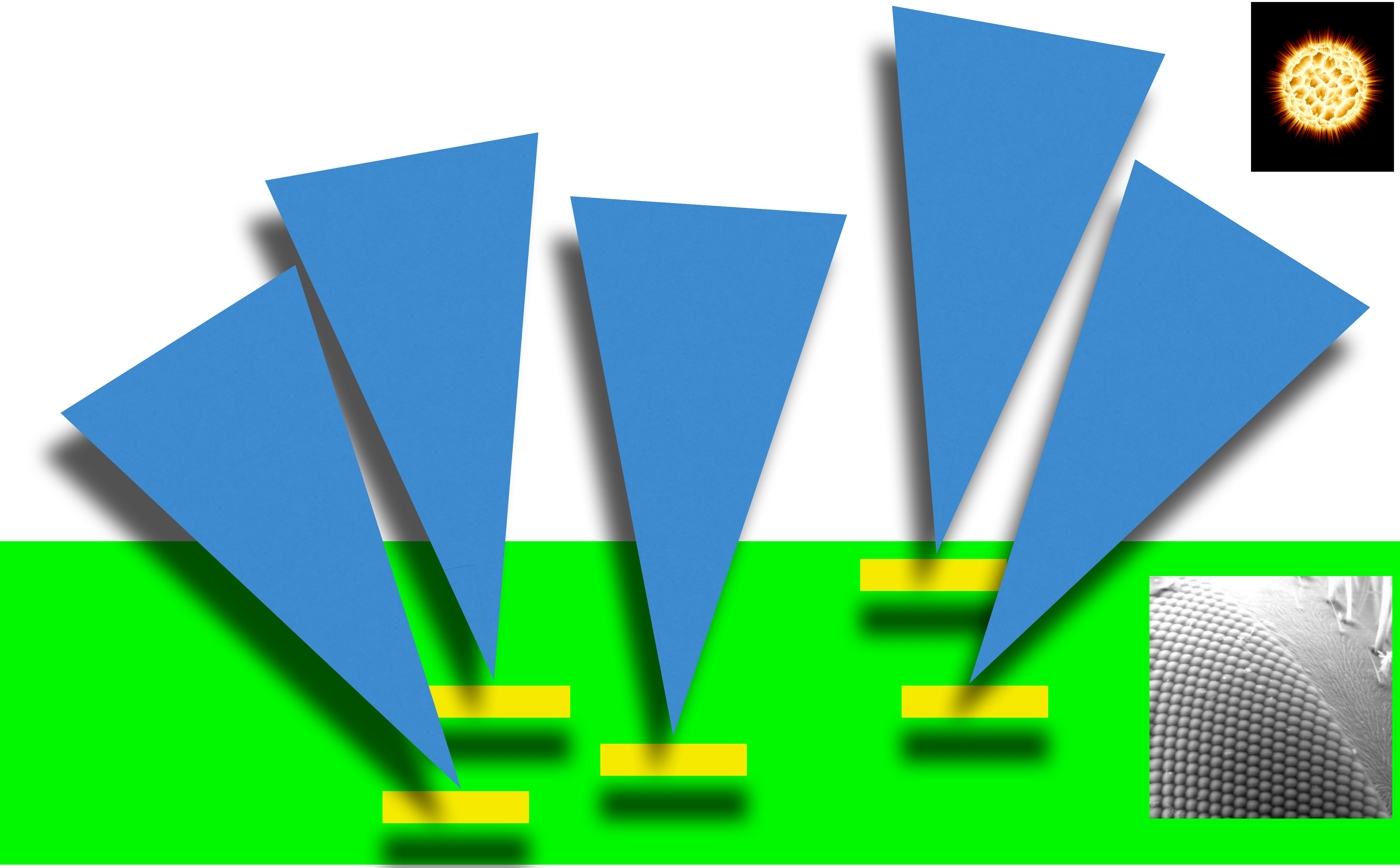
- Sensitivity gain sometimes even better than expected due to better interference rejection.

Hessels

Fly's Eye Observations

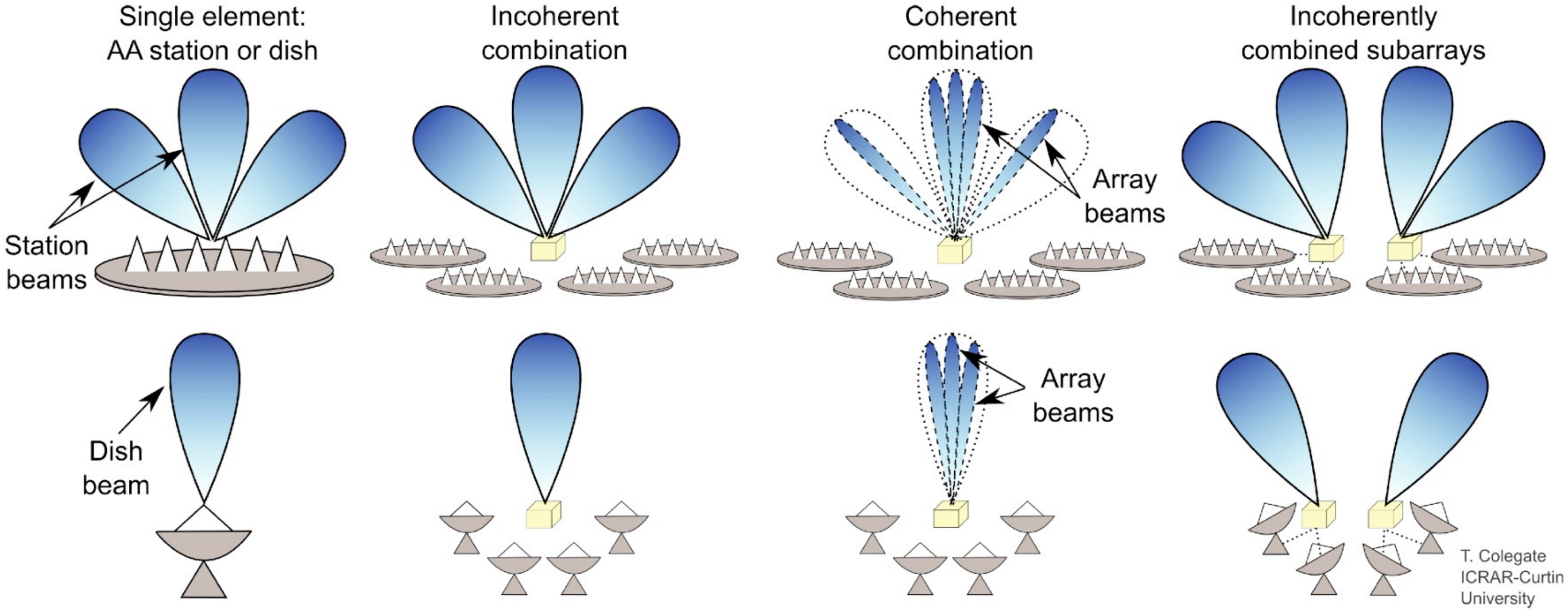
- Point each antenna is a different, complementary direction.
- Do *not* sum the individual antenna signals together (i.e. treat them as single dishes).
- Covers a large area of sky at the sensitivity of an individual antenna/station.
- Field-of-view proportional to the number of antennas times the primary beam field-of-view.
- Can employ anti-coincidence to reject interference.

“Fly’s Eye” Observations



Sub-arraying: mixing and matching what you add together

Top: aperture array like LOFAR

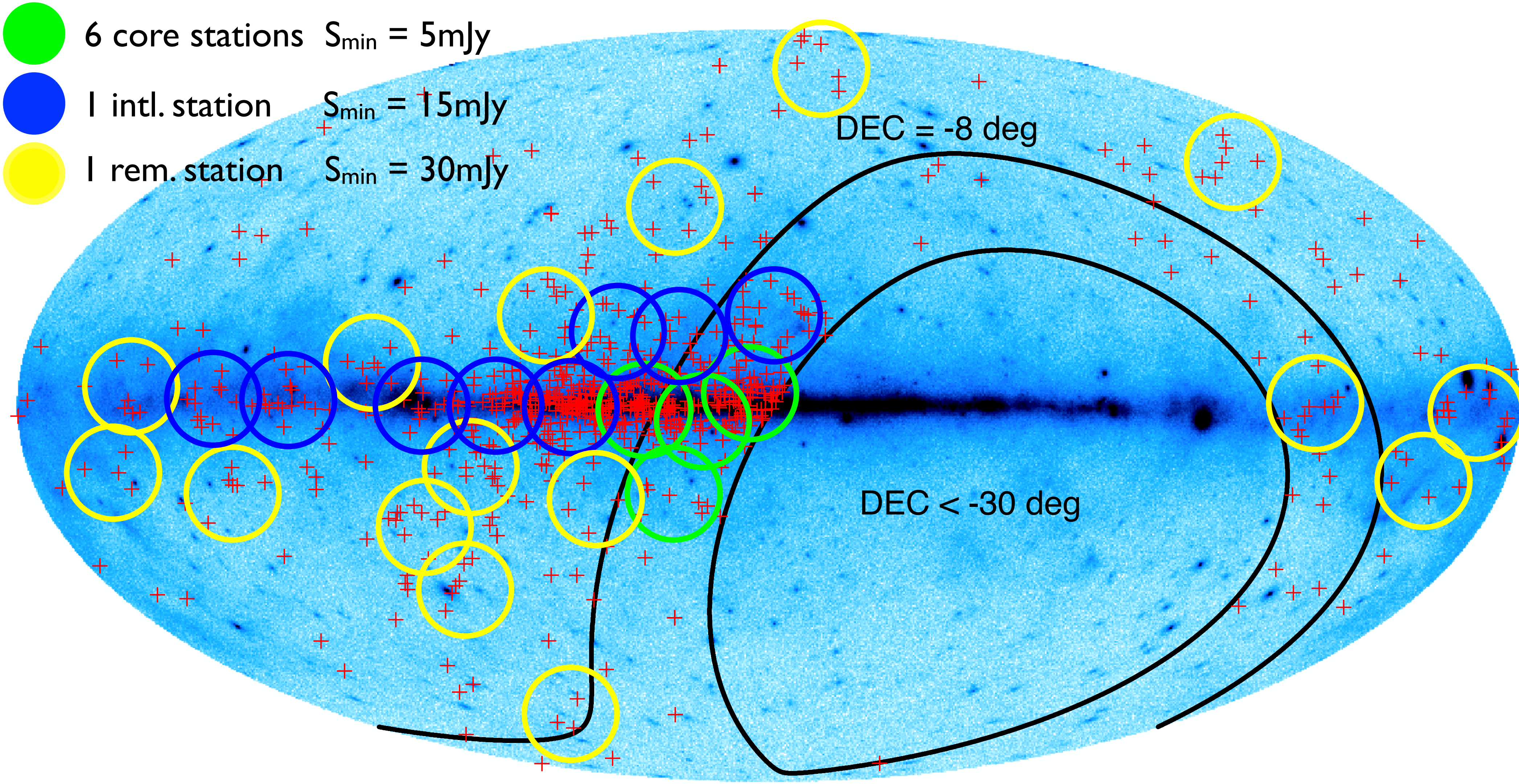


T. Colegate
ICRAR-Curtin
University

Bottom: dish array like JVLA

Colegate

Fully Flexible LOFAR



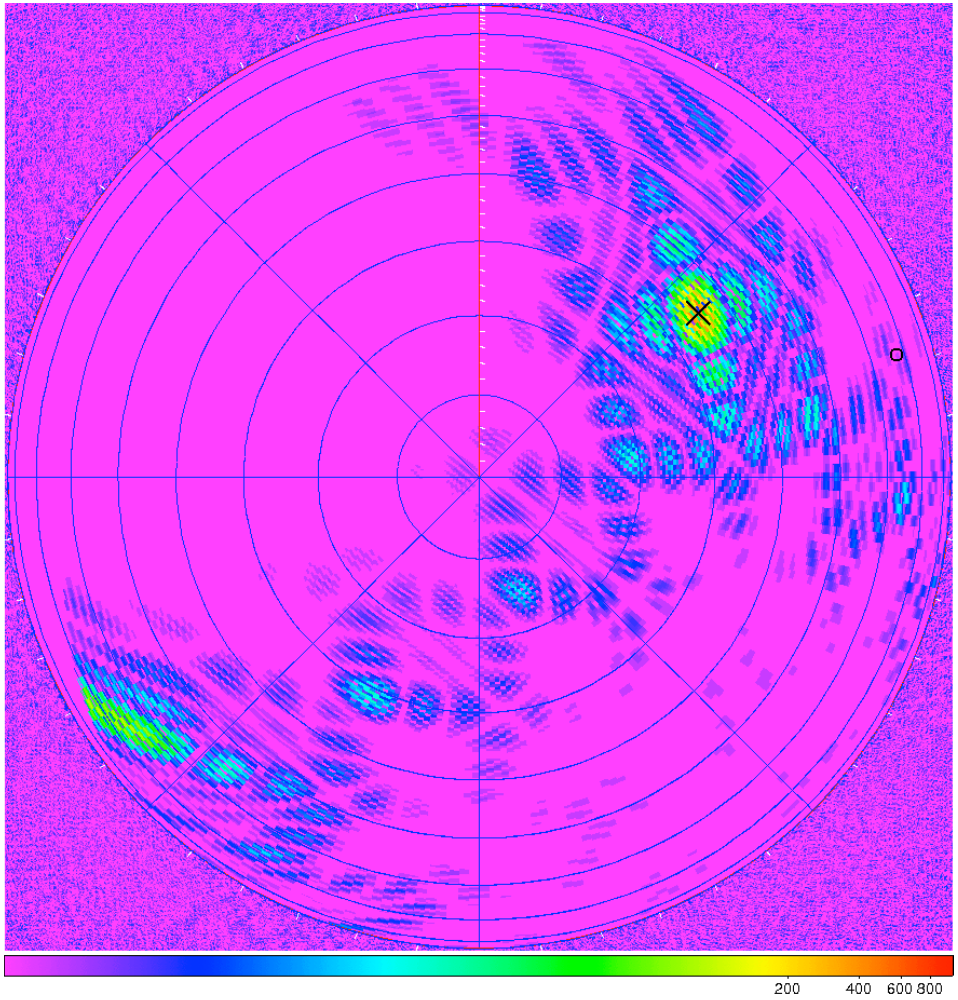
🟢 6 core stations S_{min} = 5mJy

🔵 1 intl. station S_{min} = 15mJy

🟡 1 rem. station S_{min} = 30mJy

Careful: beam patterns are sometimes very complicated

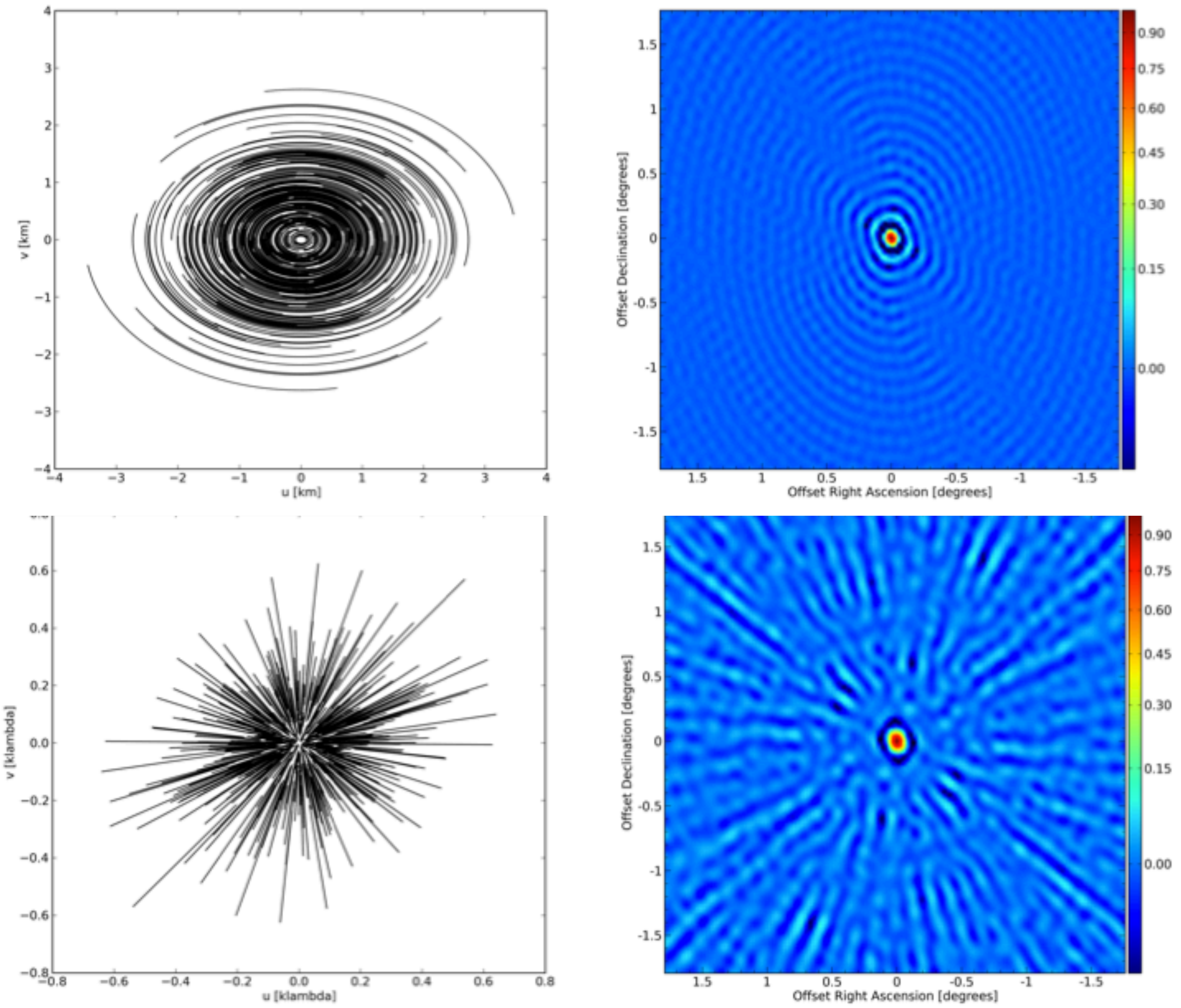
LOFAR 4-Tile Beam Pattern



Yatawatta

- Because of sidelobes, there is *some* response *across* the sky.
- Need to be careful with bright sources falling into a sidelobe.
- Potential to misidentify source direction.

LOFAR Instantaneous uv-Coverage



uv-Coverage

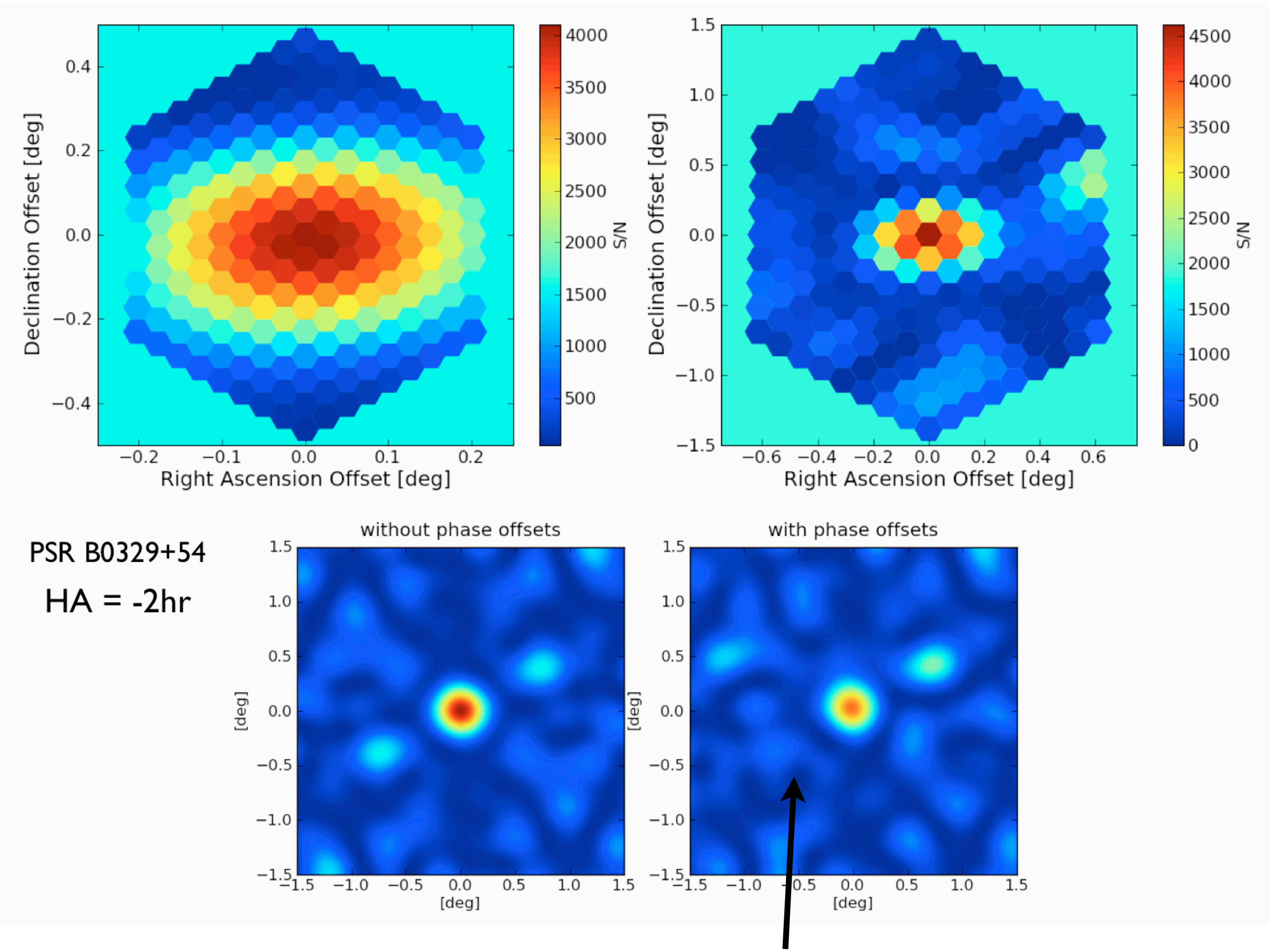
Beam shape

- 2-D array provides good instantaneous uv-coverage.
- Top: 6-hr synthesis with 24-station LOFAR core.
- Bottom: snapshot (1sec) with 24-station LOFAR core.

Heald

Superterp Tied-array Beam

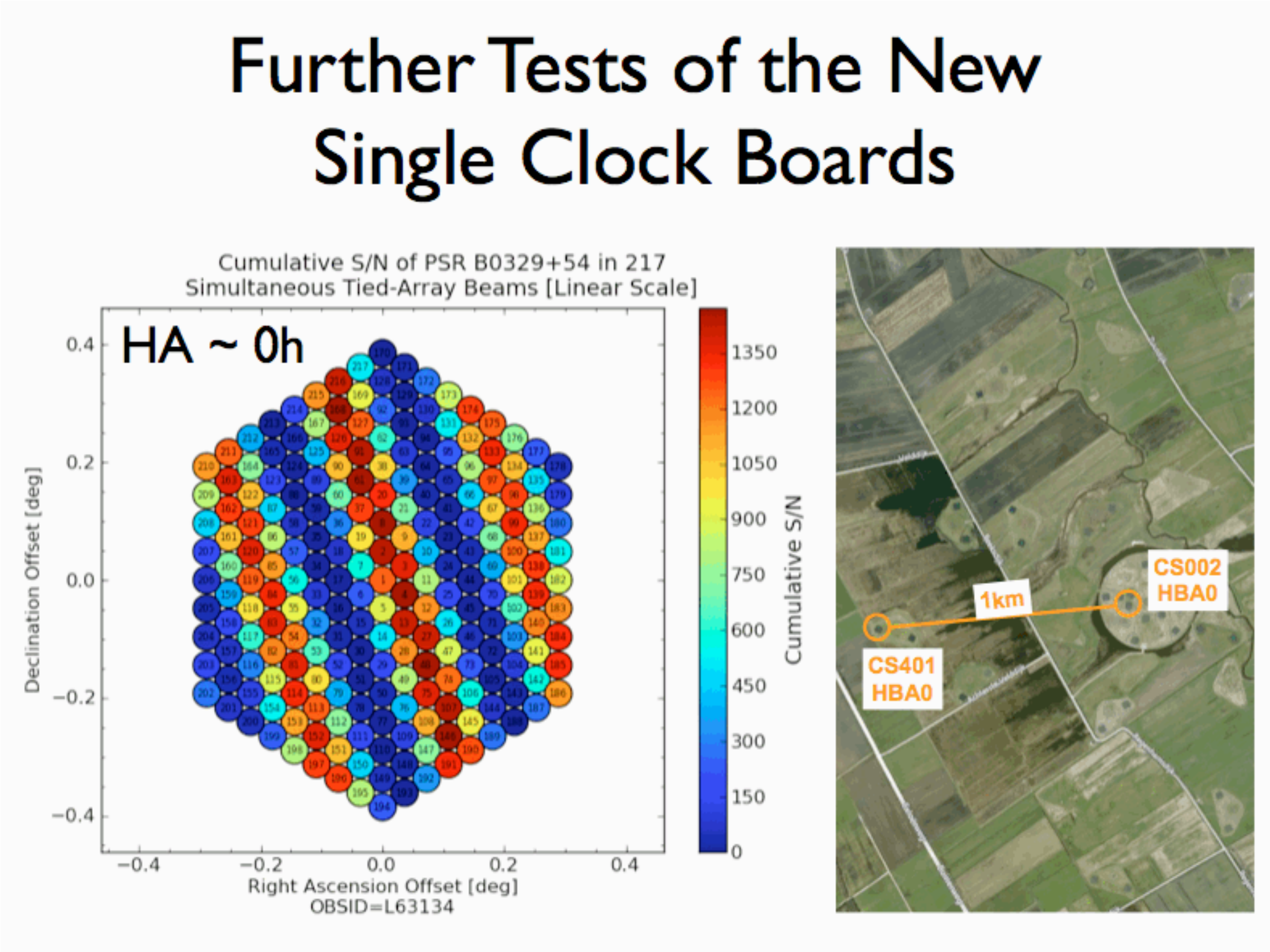
Zoom-in   Zoom-out



Imperfect calibration

- Top: real data on a bright pulsar (color indicates S/N).
- Bottom: theoretical beam shape both with and without phase offsets.
- Note asymmetric observed beam pattern.

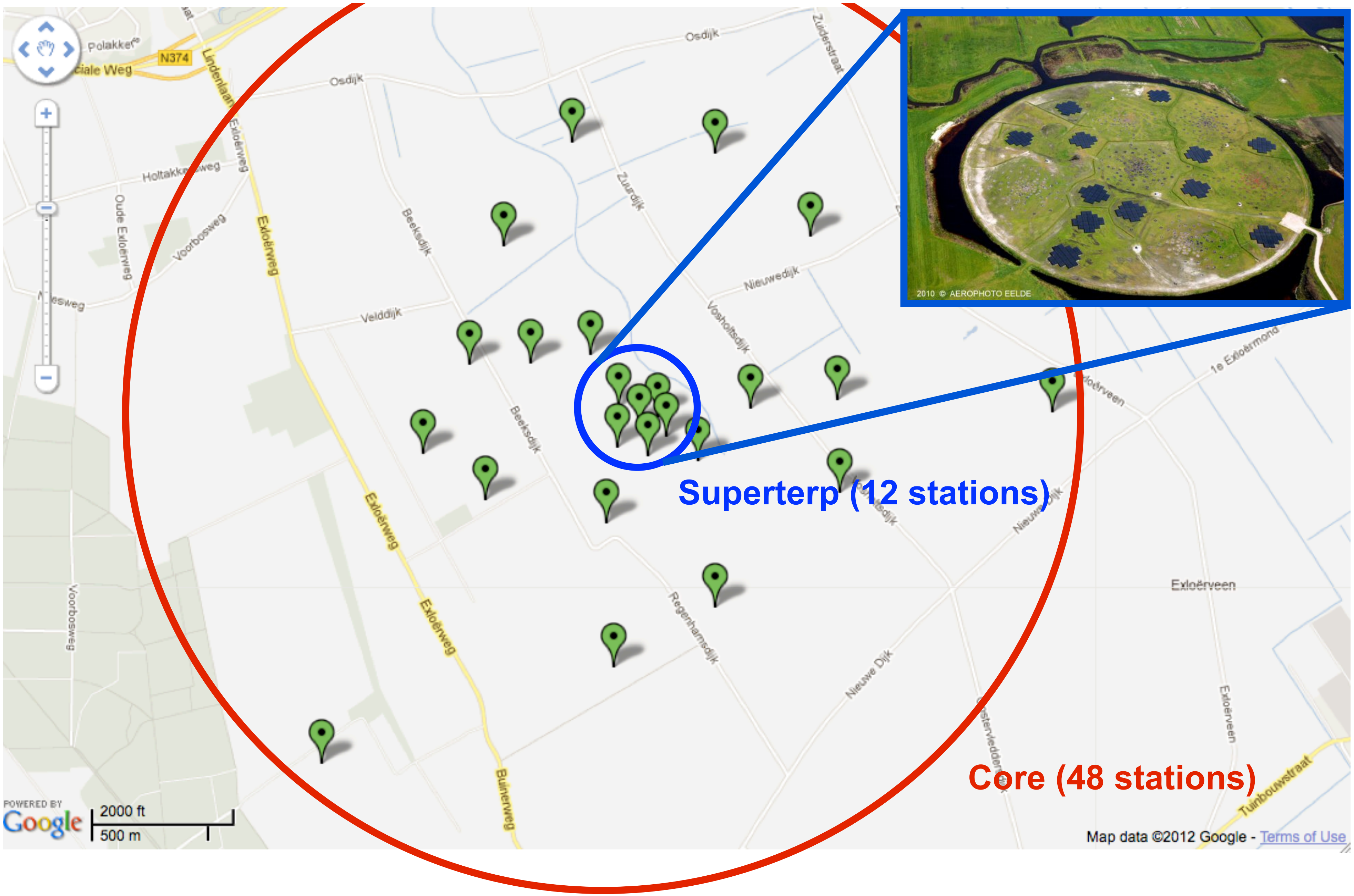
2-element Fringe Pattern



Further Tests of the New Single Clock Boards

- Late 2012 a distributed clock system was installed on the entire LOFAR core.
- Previously station clocks drifted w.r.t. each other by up to 20ns (several wavelengths).

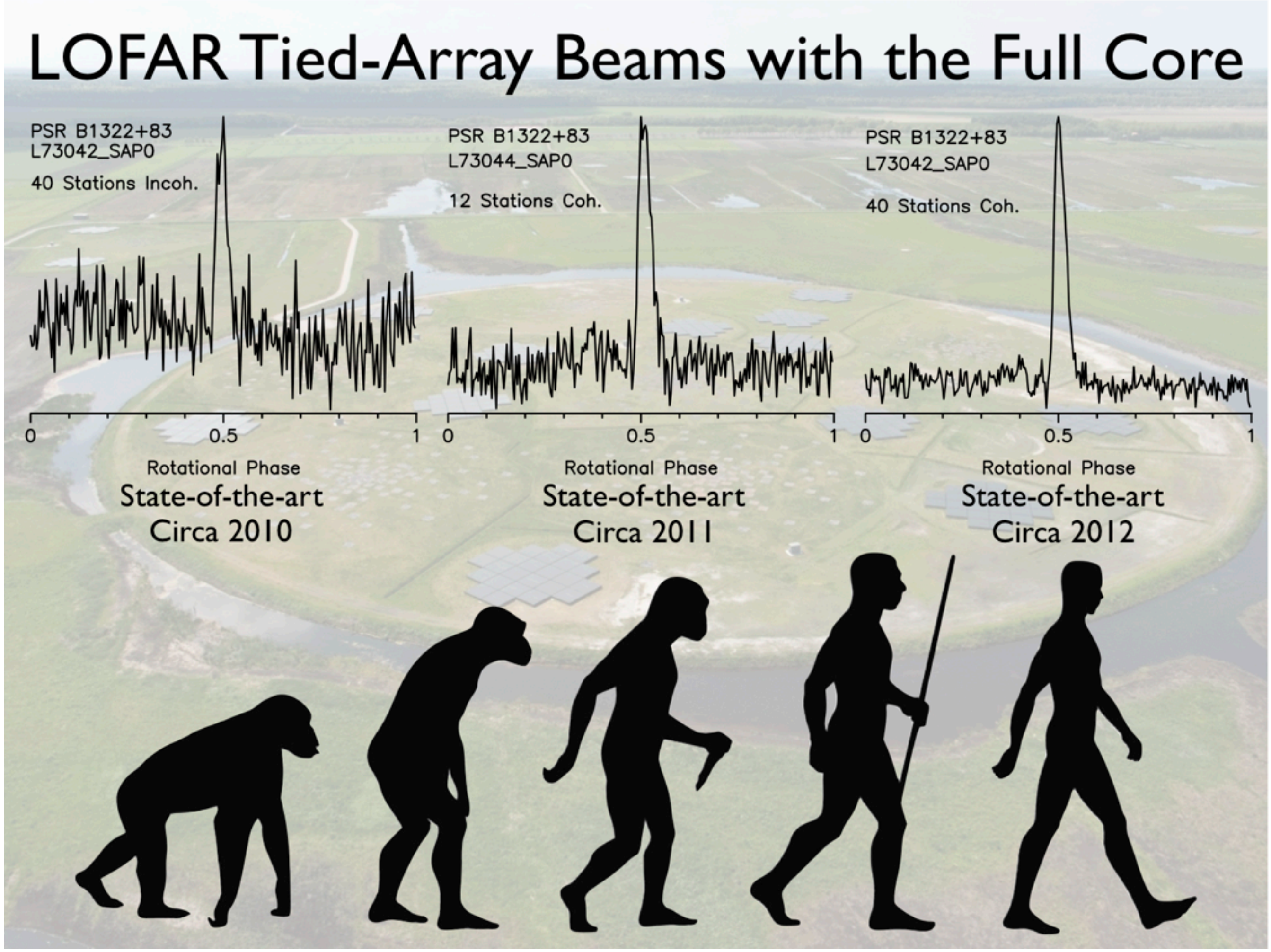
The LOFAR Core



Superterp (12 stations)

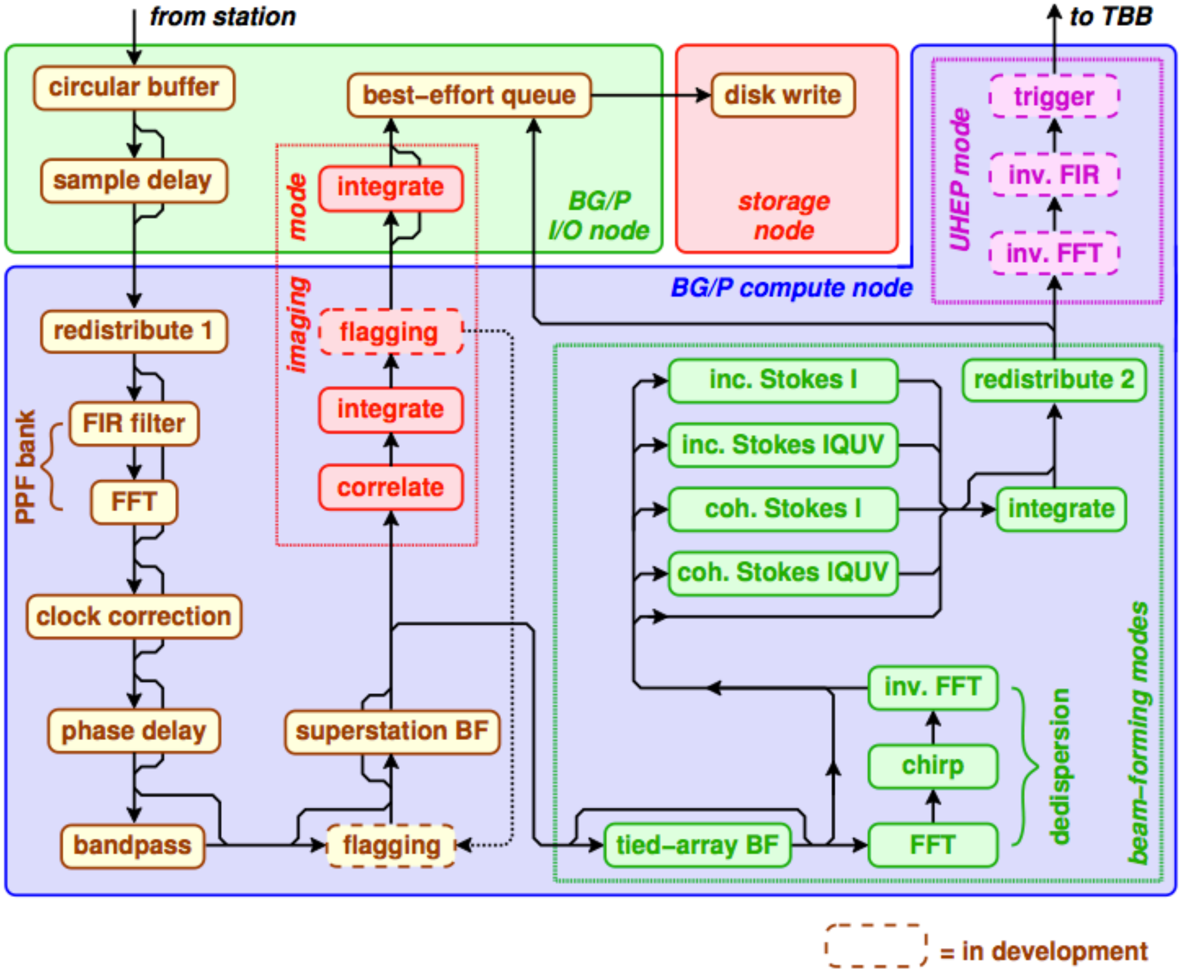
Core (48 stations)

Evolution of LOFAR's Sensitivity



- Left: incoherent core.
- Center: coherent Superterp.
- Right: coherent core.

Correlator/Beam-former

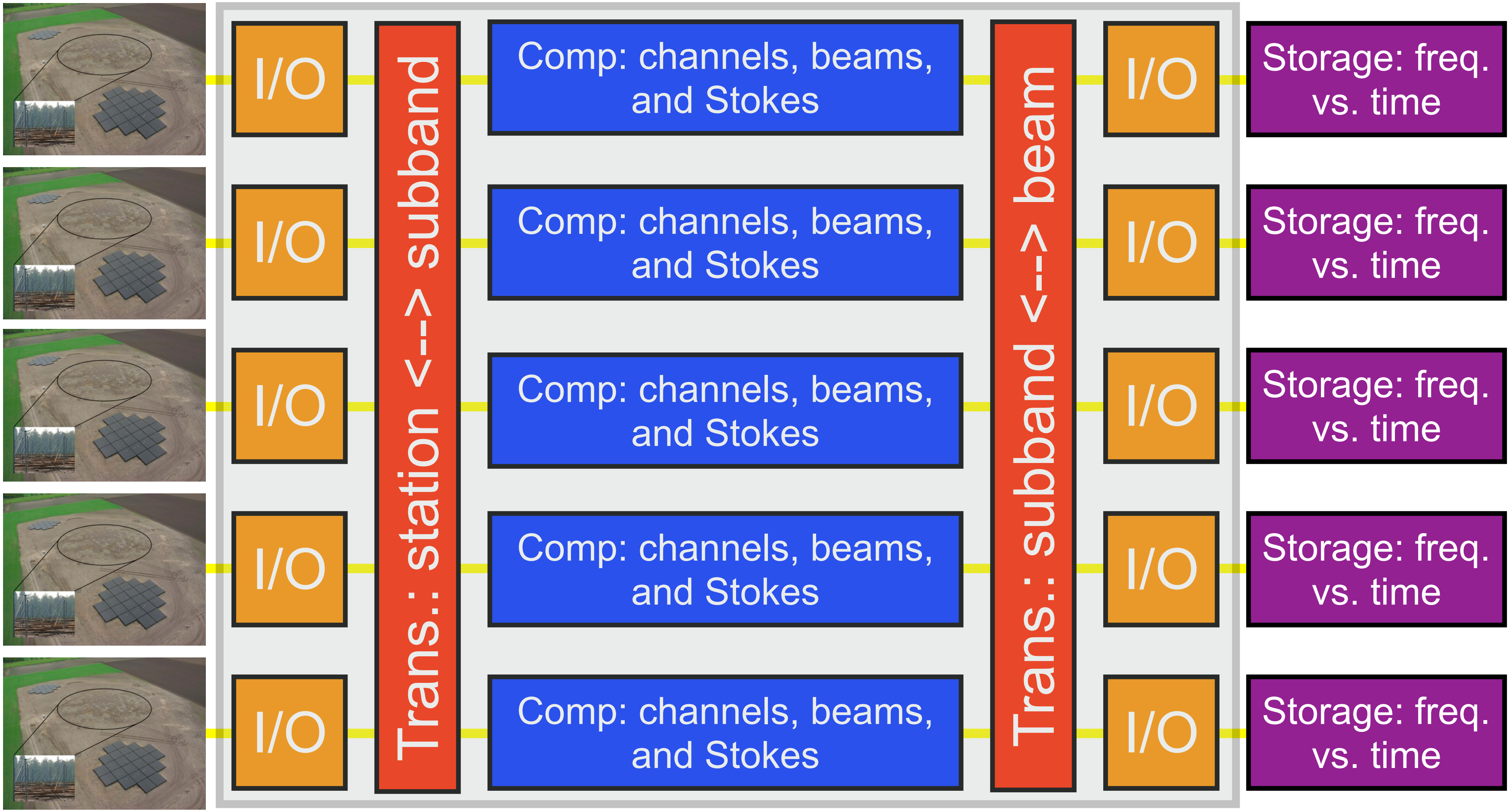


- LOFAR BG/P is both a correlator (imaging) and a "beam-former" (high time resolution).
- Many shared operations between the two main modes.

Romein

LOFAR Data Flow

Synthesize 200+ beams



I/O

I/O

I/O

I/O

I/O

Trans.: station <--> subband

Comp: channels, beams, and Stokes

Comp: channels, beams, and Stokes

Comp: channels, beams, and Stokes

Comp: channels, beams, and Stokes

Comp: channels, beams, and Stokes

Trans.: subband <--> beam

I/O

I/O

I/O

I/O

I/O

Storage: freq. vs. time

Storage: freq. vs. time

Storage: freq. vs. time

Storage: freq. vs. time

Storage: freq. vs. time

Filling Factor and Beam-Formed Surveys

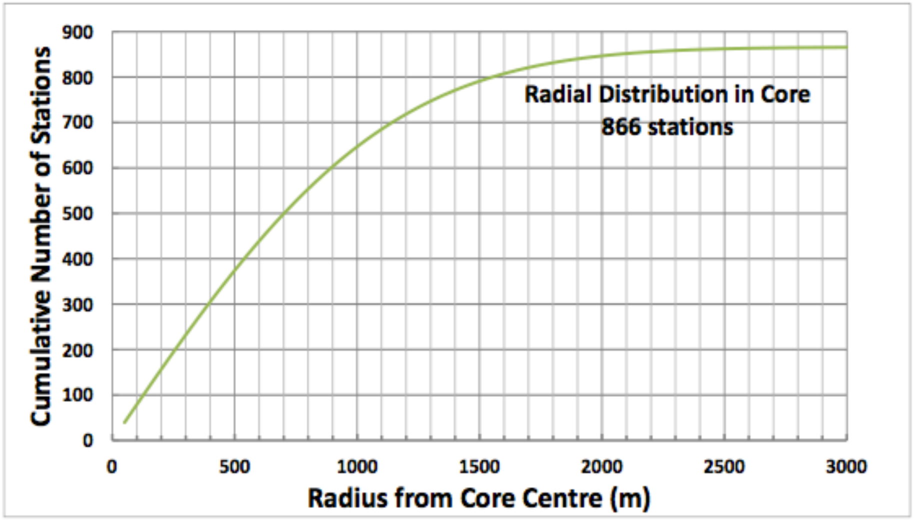


Figure 3 Cumulative collecting area as a function of core radius in the SKA1-low array.

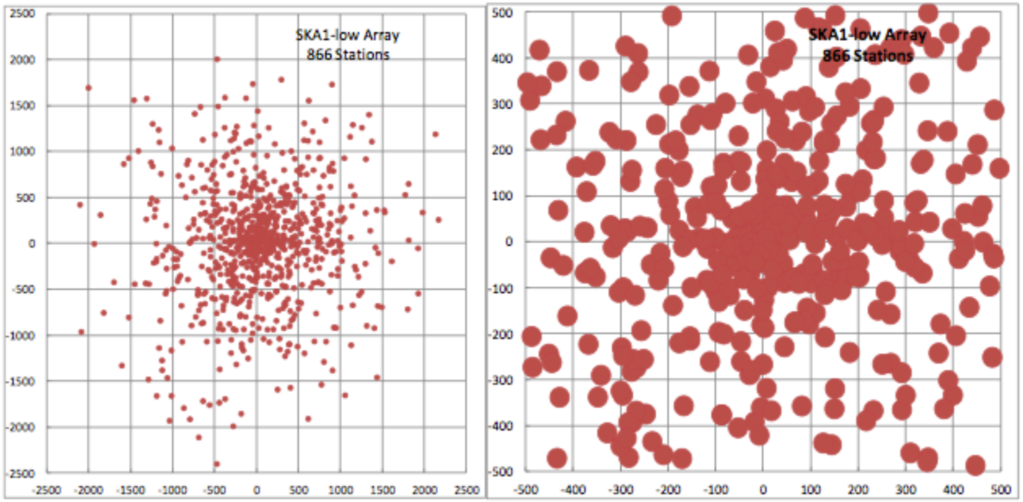
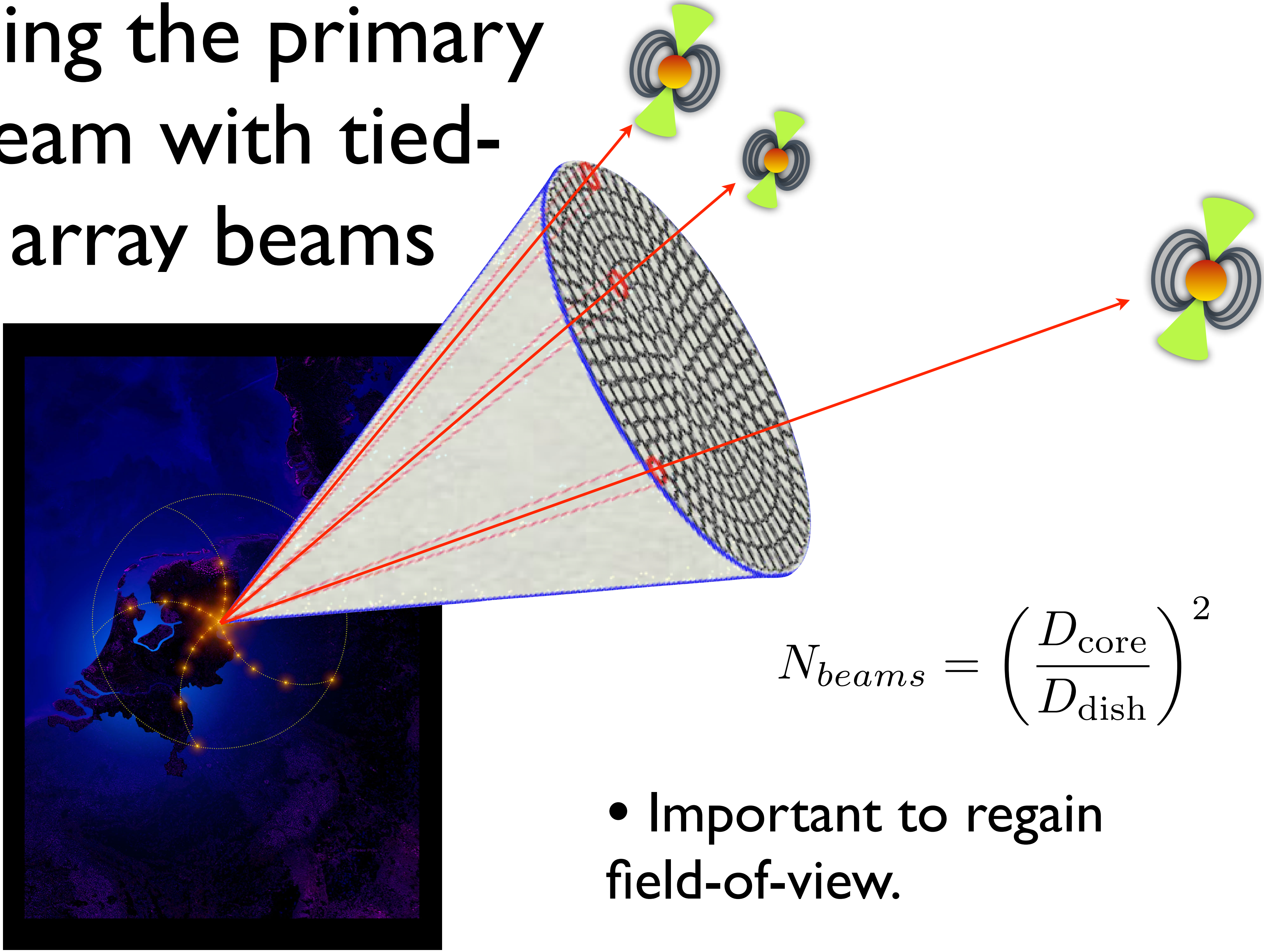


Figure 4 The SKA1-low configuration in the core (35-m diameter stations).

$$N_{ops} = F_c N_{\rm dish} N_{\rm pol} B \left(\frac{D_{\rm core}}{D_{\rm dish}}\right)^2$$

- Filling factor: area within some radius that is covered by antennas.
- Beam-formed surveys: once the filling factor starts dropping then stop including antennas.

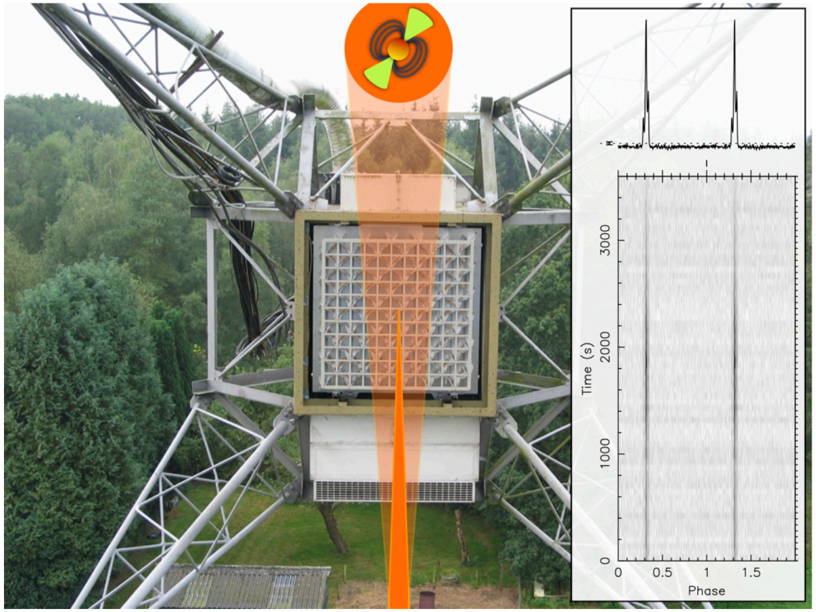
Filling the primary beam with tied-array beams

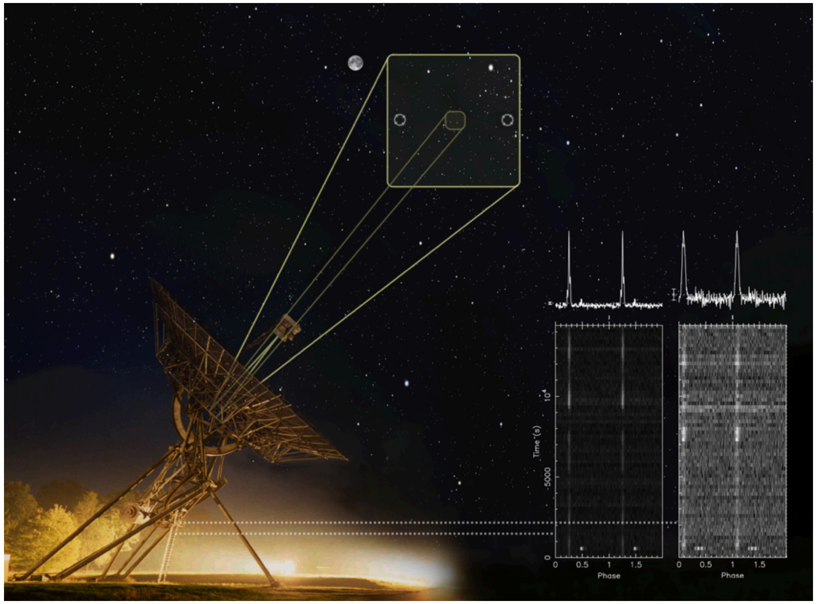


$$N_{beams} = \left(\frac{D_{\rm core}}{D_{\rm dish}}\right)^2$$

- Important to regain field-of-view.

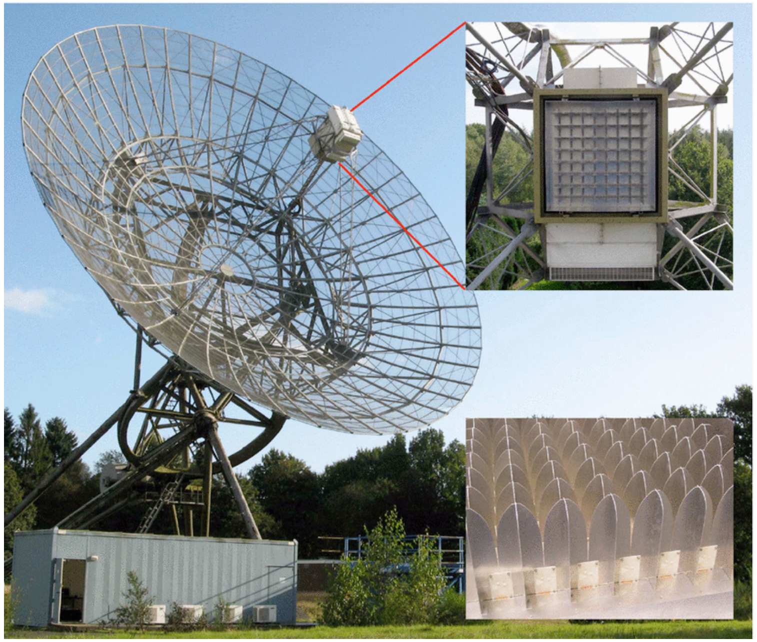
...and add a Focal Plane Array





- Focal plane arrays make wide-field surveys with dishes possible.
- APERTIF provides 37 pixels.
- The antenna beams are formed by weighting the 56 dual polarization vivaldi elements.
- Each of the 37 beams per antenna needs to be cross-correlated and beam-formed!

...and add a Focal Plane Array



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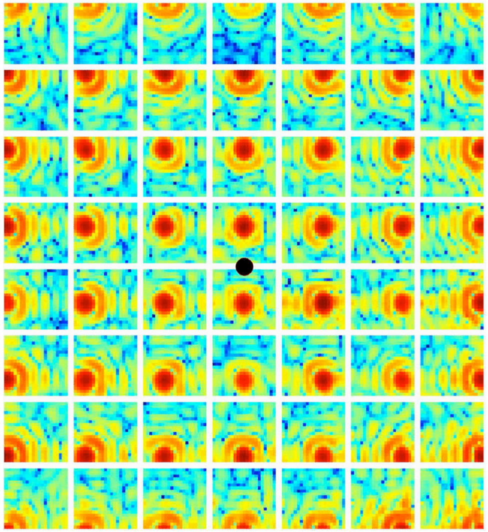
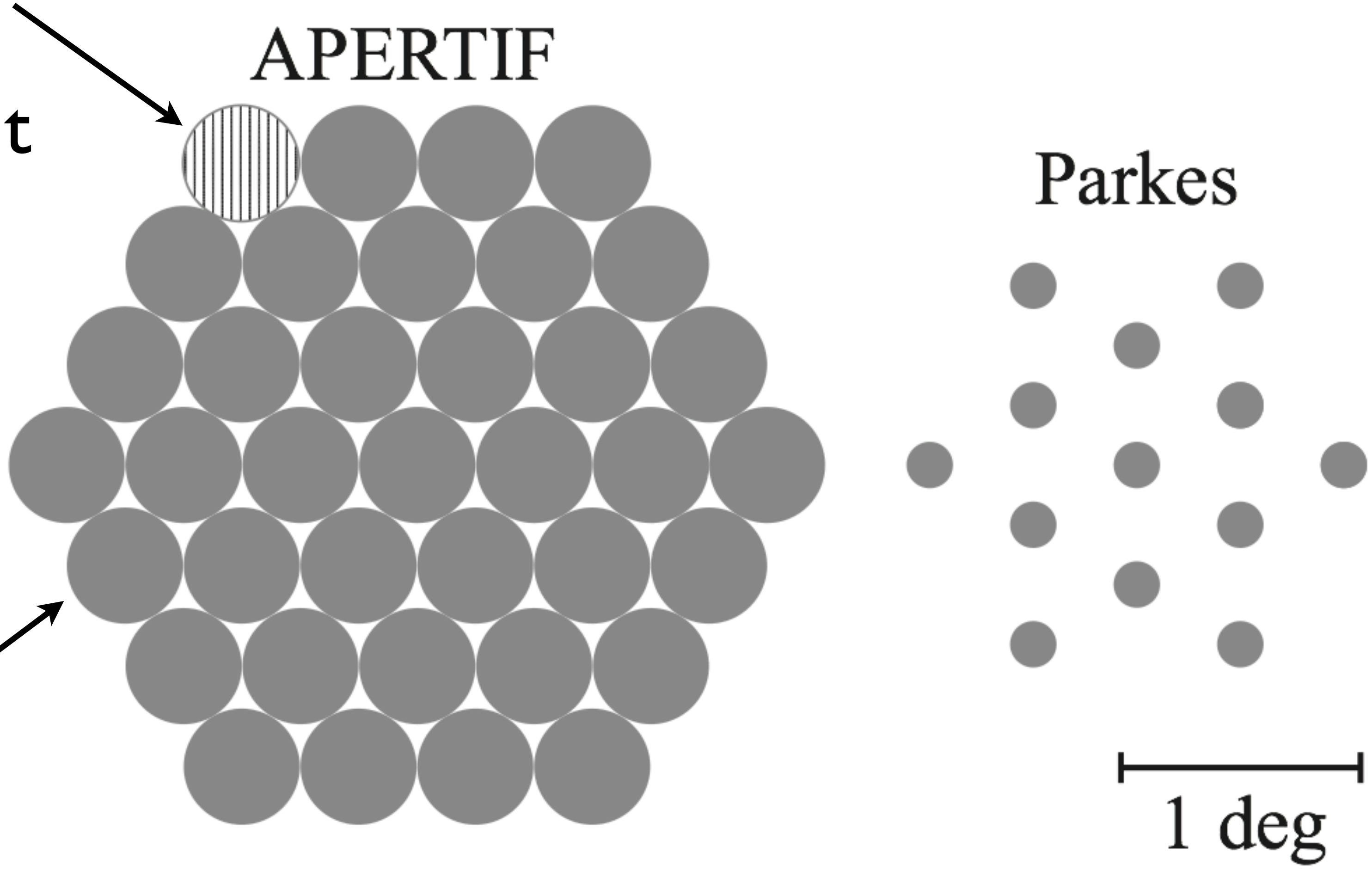
Individual element PSFs before beam-forming



APERTIF vs. Parkes

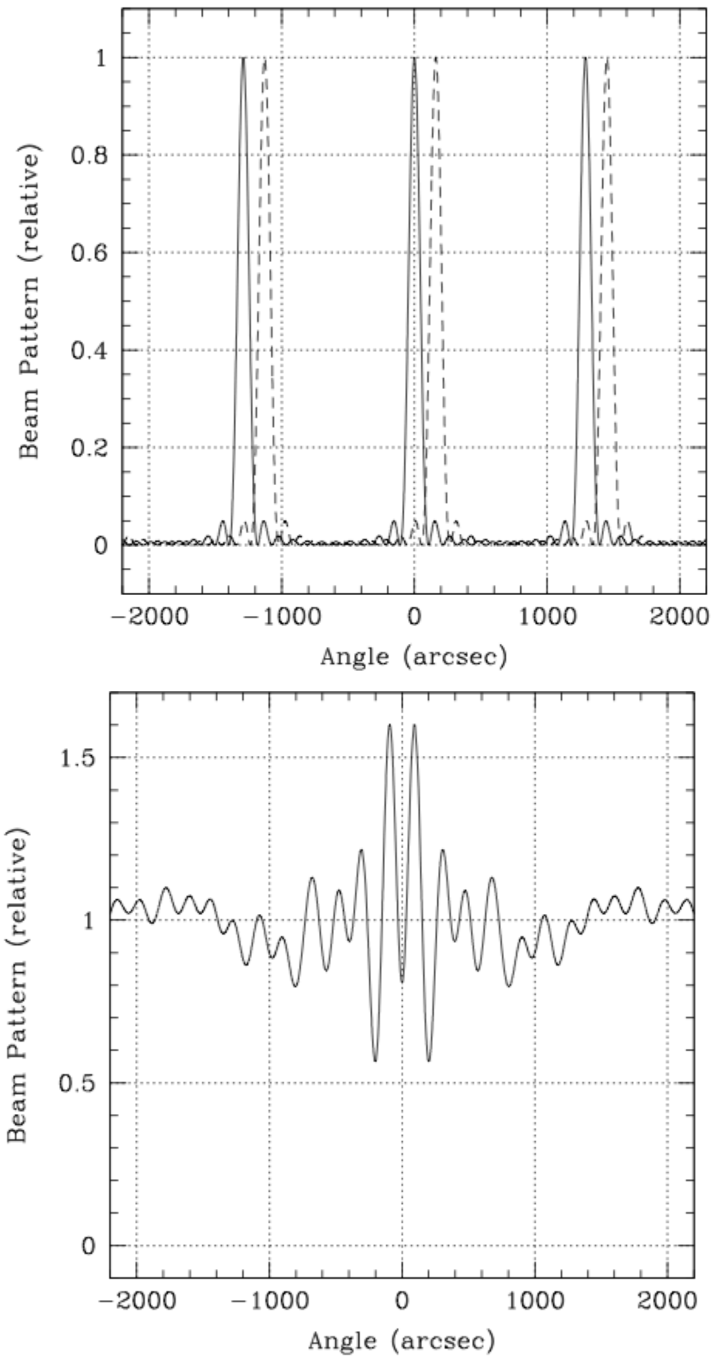


Form array beams for each element

Individual element beam

van Leeuwen

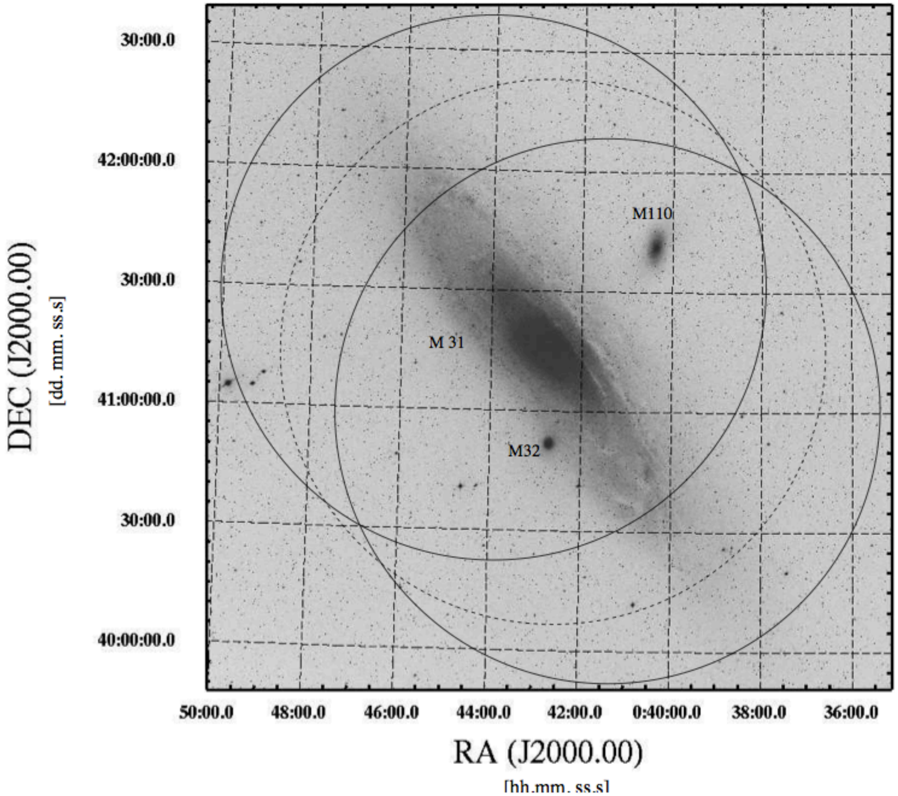
WSRT 8gr8

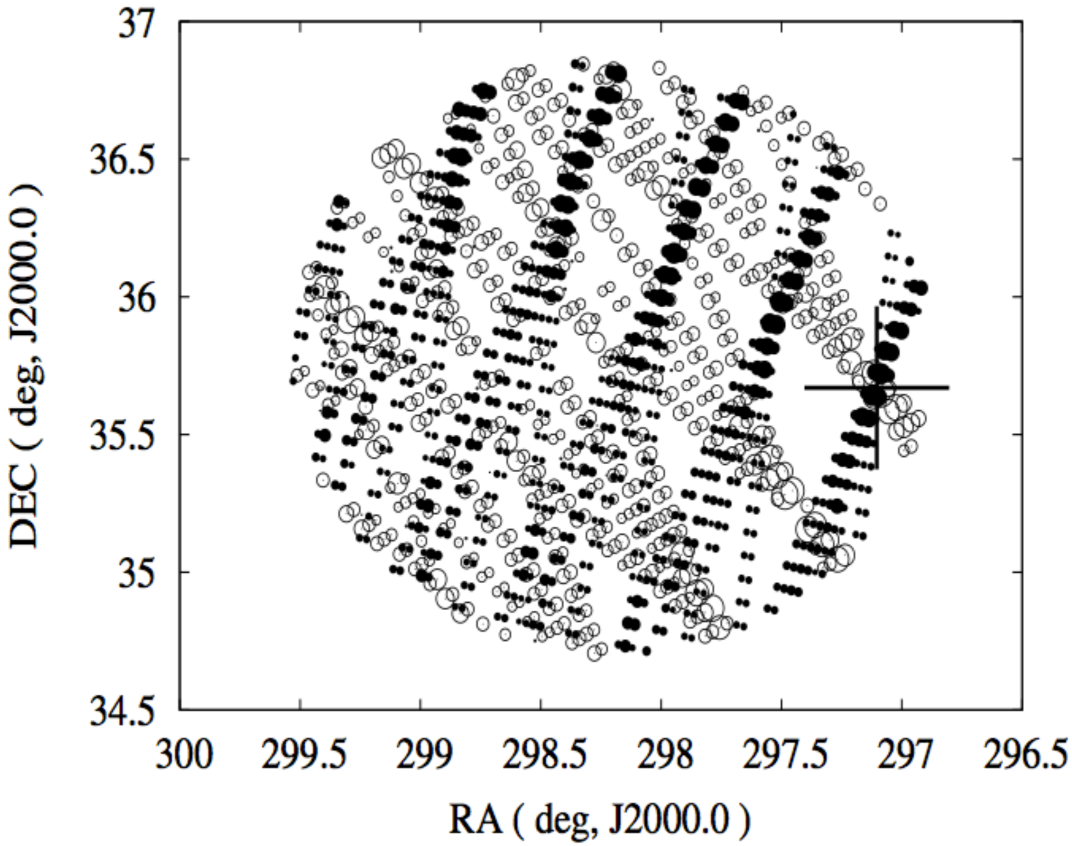


Janssen et al. 2009

- Top: the instantaneous grating fan-beam response of the WSRT telescopes RT0 through RTB, added in phase, when all have a relative baseline of 144 m.
- Bottom: the relative sensitivity across the primary beam field-of-view after a 2 h integration with a total of eight grating fan-beams. The largest oscillations are within a few beamwidths of the overall field centre. These damp out at larger distances to a constant level.

WSRT 8gr8 Andromeda Survey



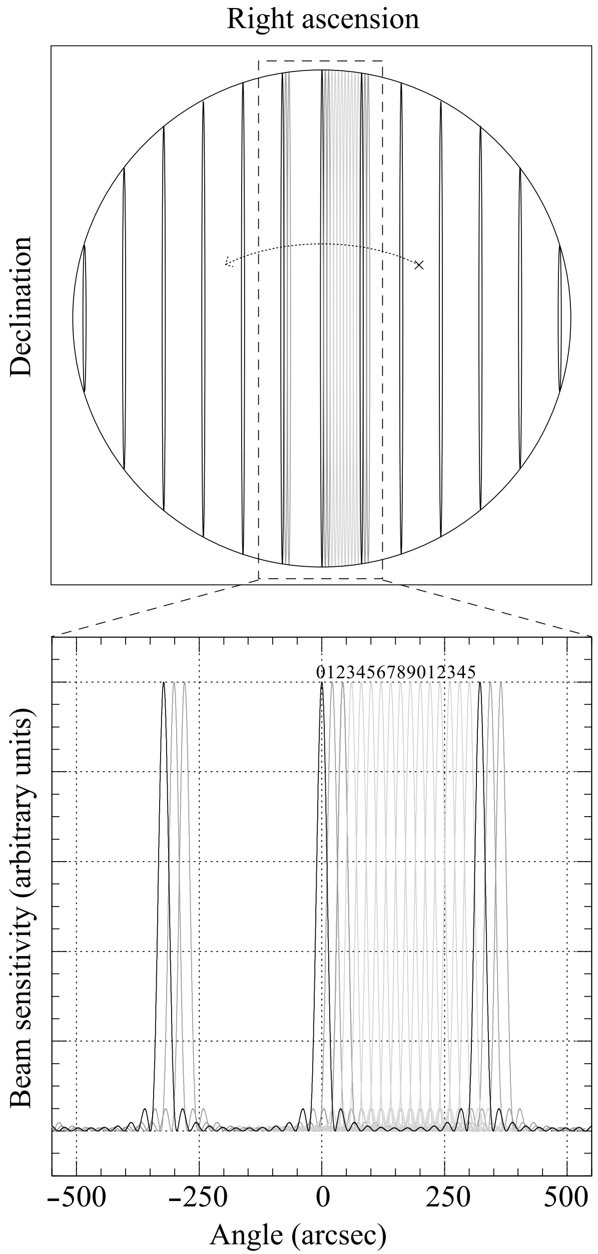


- Survey pointings: take advantage of large primary beam field-of-view.

- Localization requires detecting bursts at multiple hour angles. Circles show burst strength in the fan beams.

Rubio-Herrera et al. 2013

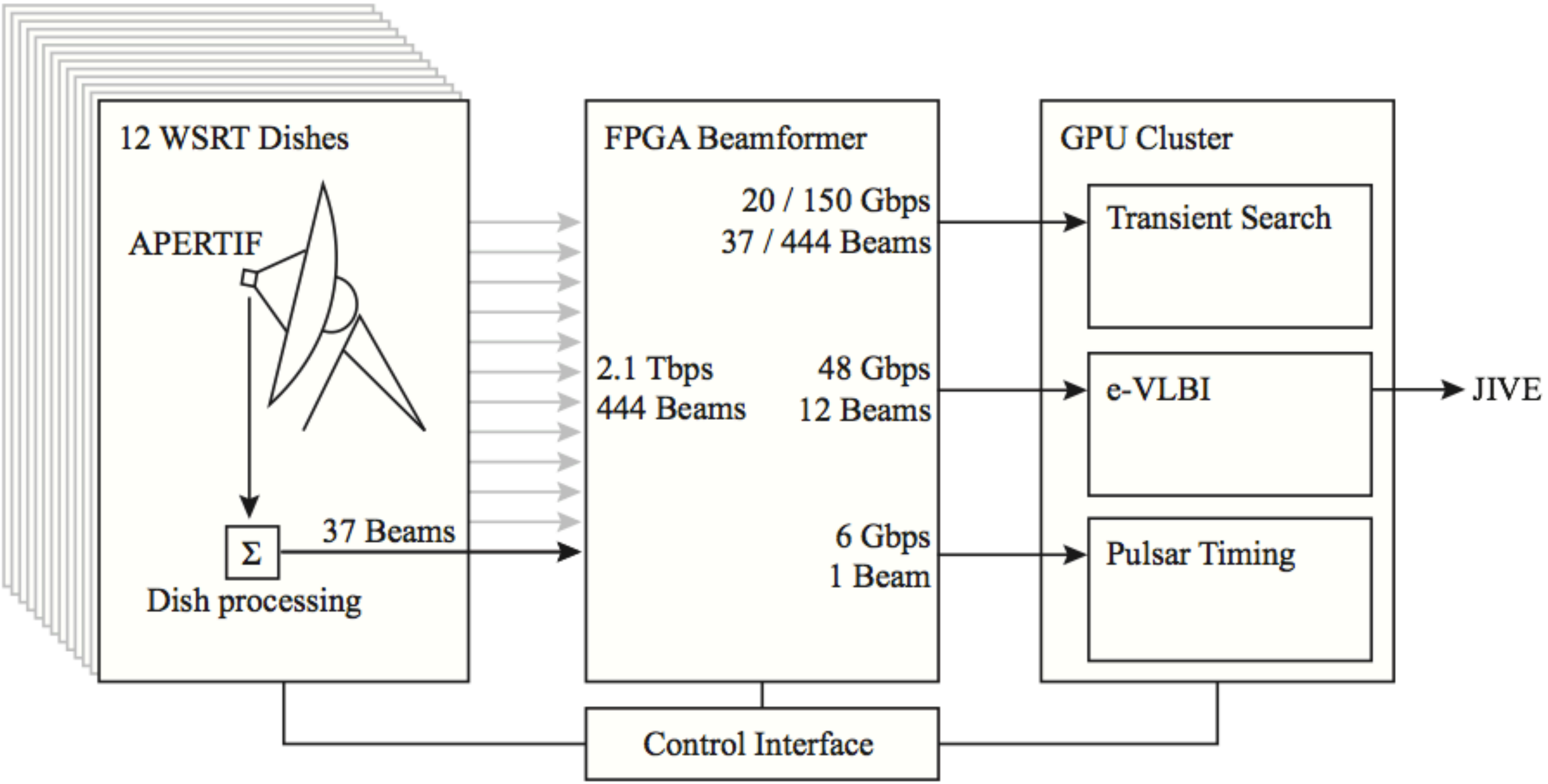
For APERTIF use 16 grating sets



van Leeuwen

- Using all 12 APERTIF dishes, 16 grating sets are required to fill the primary field-of-view.
- These will rotate with hour-angle.
- Sub-beams can be formed by linearly combining the fan beams together.
- This process needs to happen for each of the 37 APERTIF antenna beams!

2-element Fringe Pattern

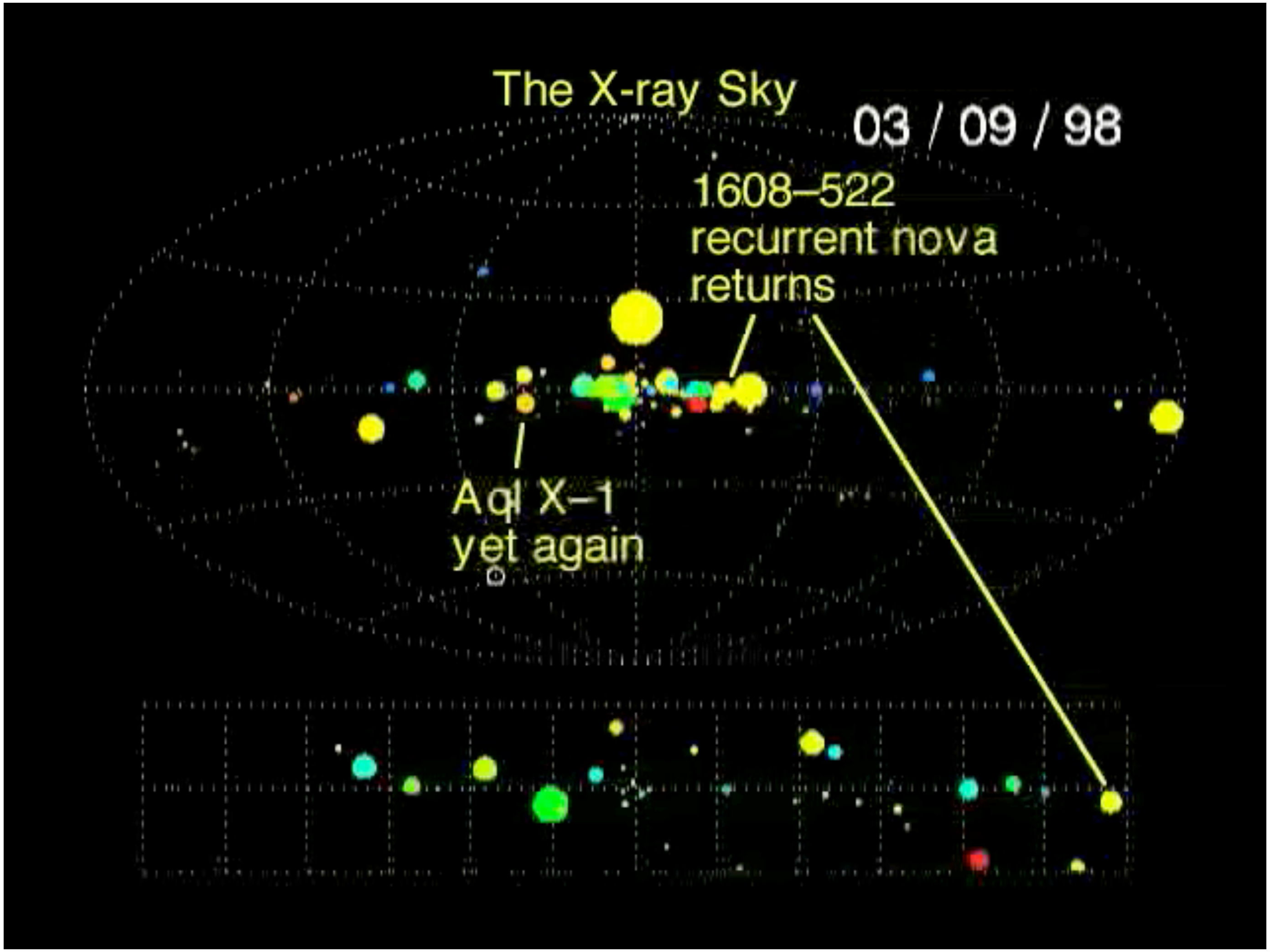


- Data rate of 2Tb/s for 444 beams
- Must form 37 x 16 sets of fan beams and detect transients in real time.

van Leeuwen

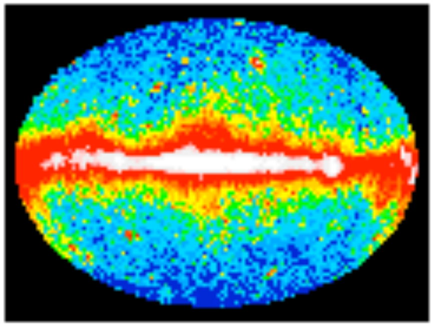
Pulsar and "fast transient" searches

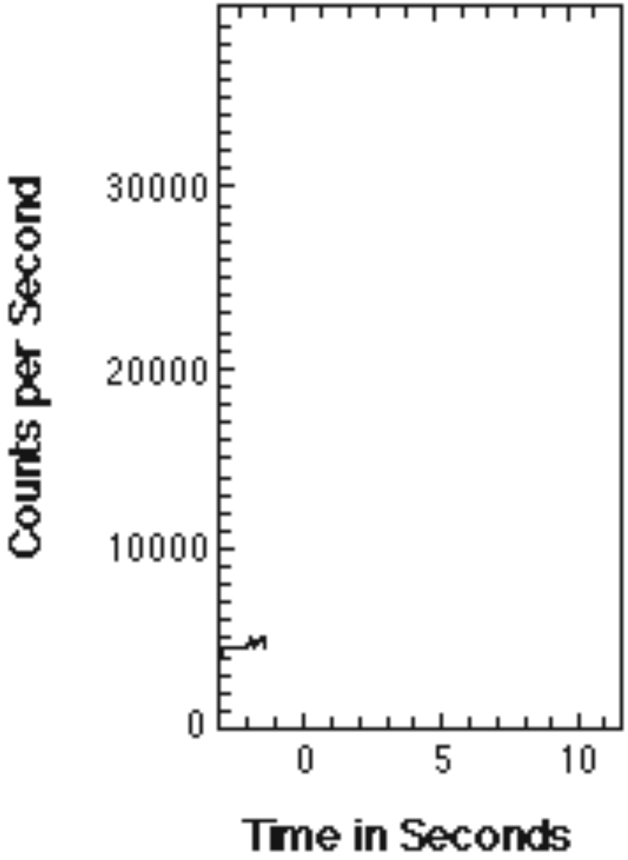
Various types of X-ray transients as seen by All-Sky Monitor onboard RXTE



The goal: do the same monitoring at radio wavelengths!

Some events are rare, but *very* bright

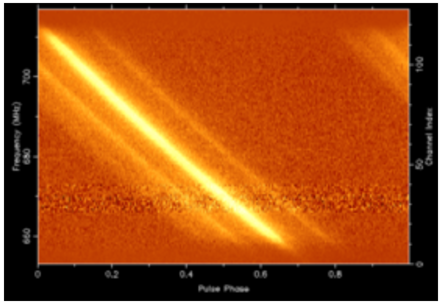




Gamma-ray burst from BATSE (Burst and Transient Source Experiment) on CGRO

Transient Radio Sky

The transient sky is a mostly unexplored domain, especially at high time resolution



Difficult to get required sensitivity *and* large field of view.

Difficult to get large field of view *and* good spatial resolution.

Much higher data rates than with photon detectors.

Propagation effects *very* important at short timescales and at low frequencies.

- F.O.M. $A^*(\Omega/\Delta\ \Omega)^*(T/\Delta T)$ should be large.

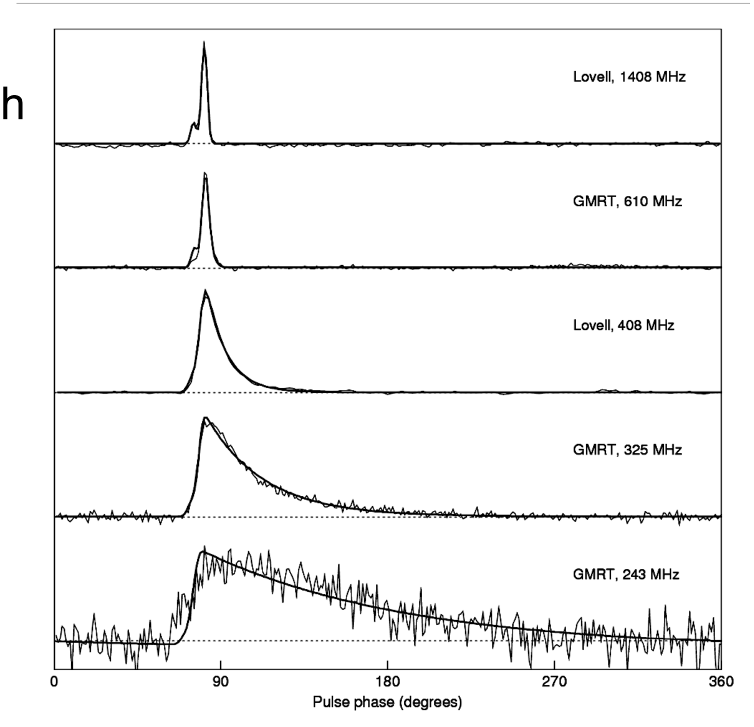
Propagation effects in the ionized interstellar medium

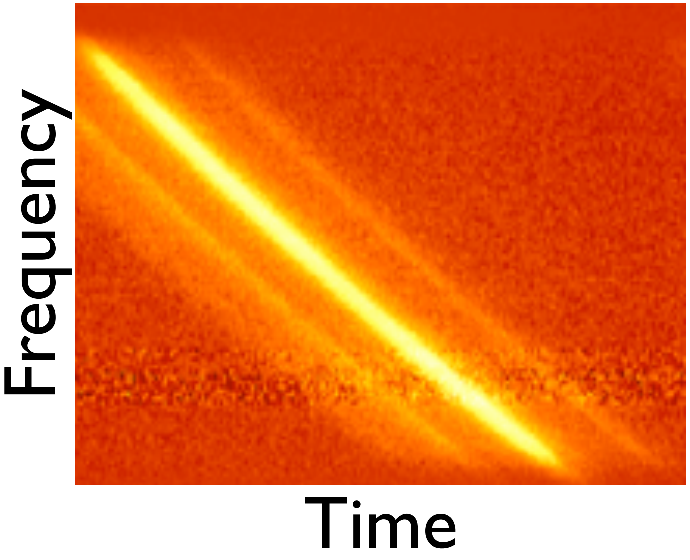
$$I(t) = g_r g_d S(t) * h_{\mathrm{DM}}(t) * h_d(t) * h_{\mathrm{Rx}}(t) + N(t)$$

Scattering: multi-path propagation

Dispersion: freq. dependent arrival time

Scintillation: const./dest. interference





Not pure evil: show that the signal is astronomical

Propagation effects in the ionized interstellar medium

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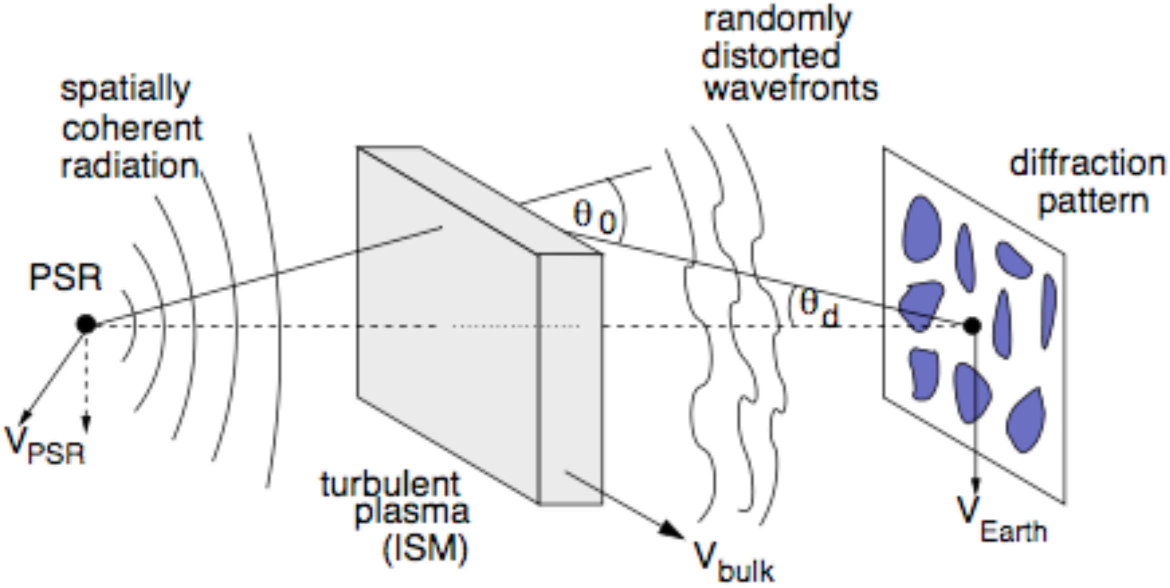


Kramer, Lorimer

Not pure evil: show that the signal is astronomical

“Fast Transients”

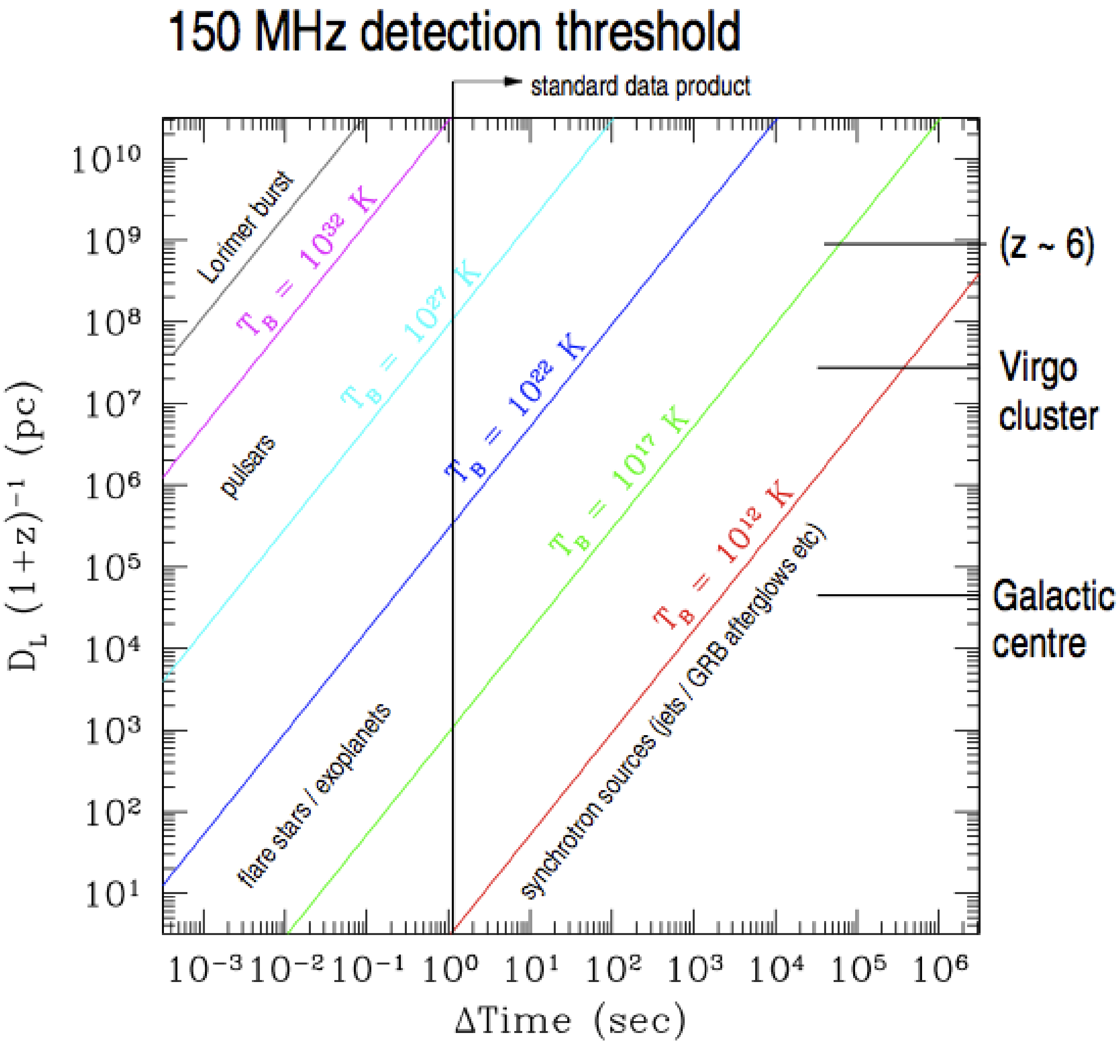
- Timescales of ns - seconds.

- Internal source variability and singular bursts.

- Probed only by non-imaging (timeseries) techniques.

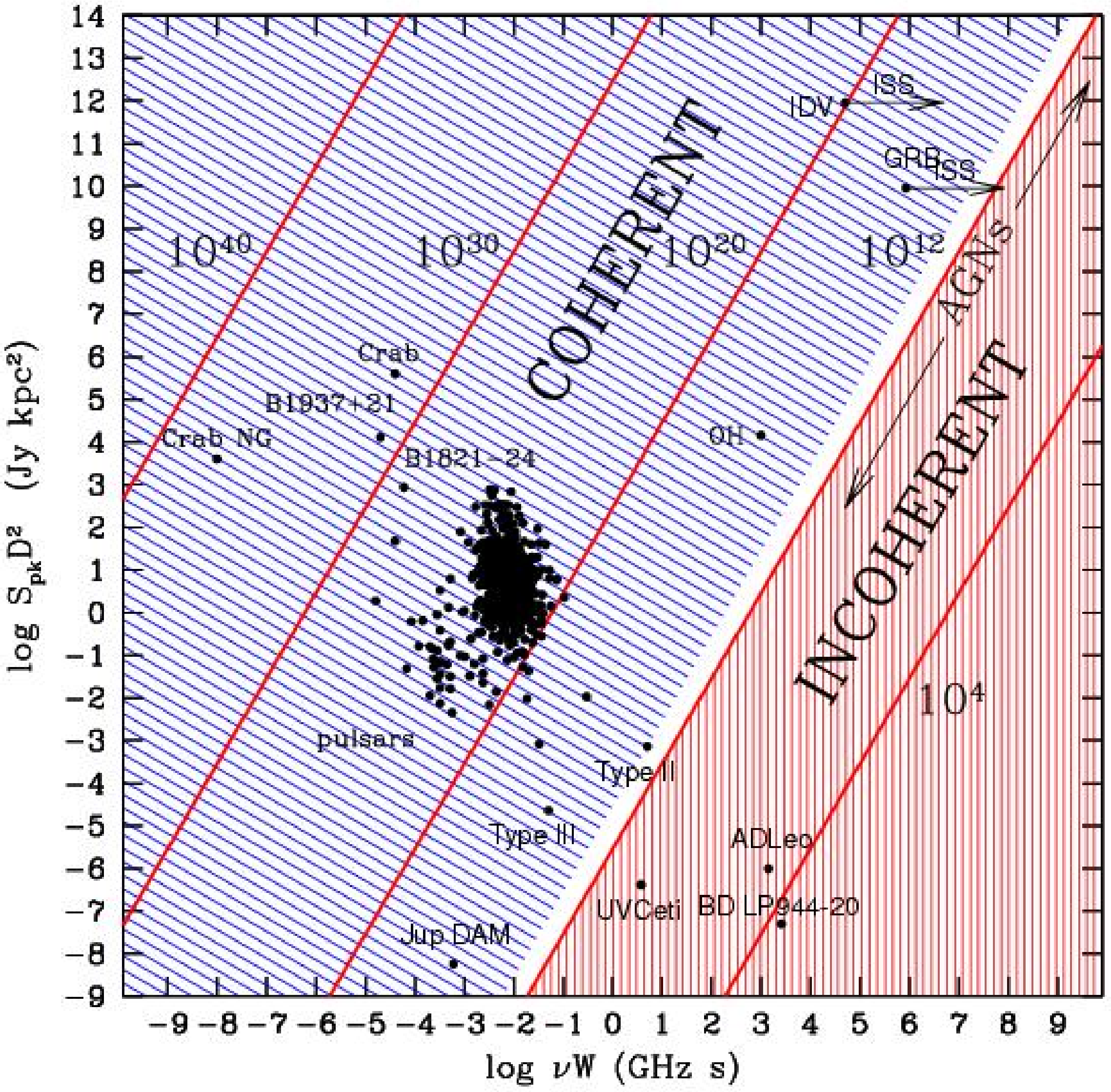
- Propagation effects in ISM (e.g. scattering and dispersion) *very* important.

- More susceptible to RFI contamination.



Fender et al. 2008

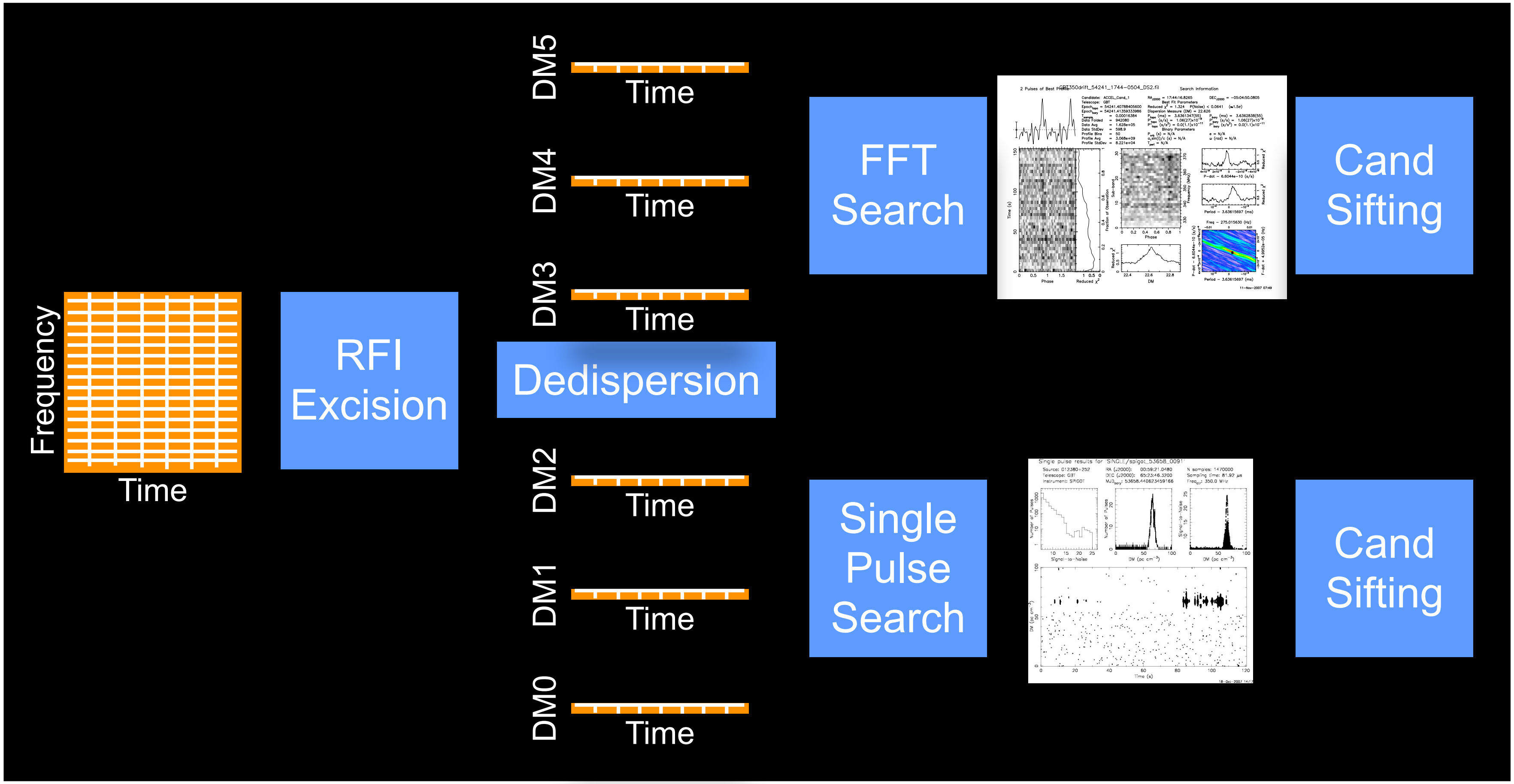
Transient Parameter Space



$$(\mathrm{W}\nu)^2 \propto \frac{\mathrm{SD}^2}{T_b}$$

Cordes et al. 2004

Standard Pulsar/Fast Transient Search



RFI Excision

Dedispersion

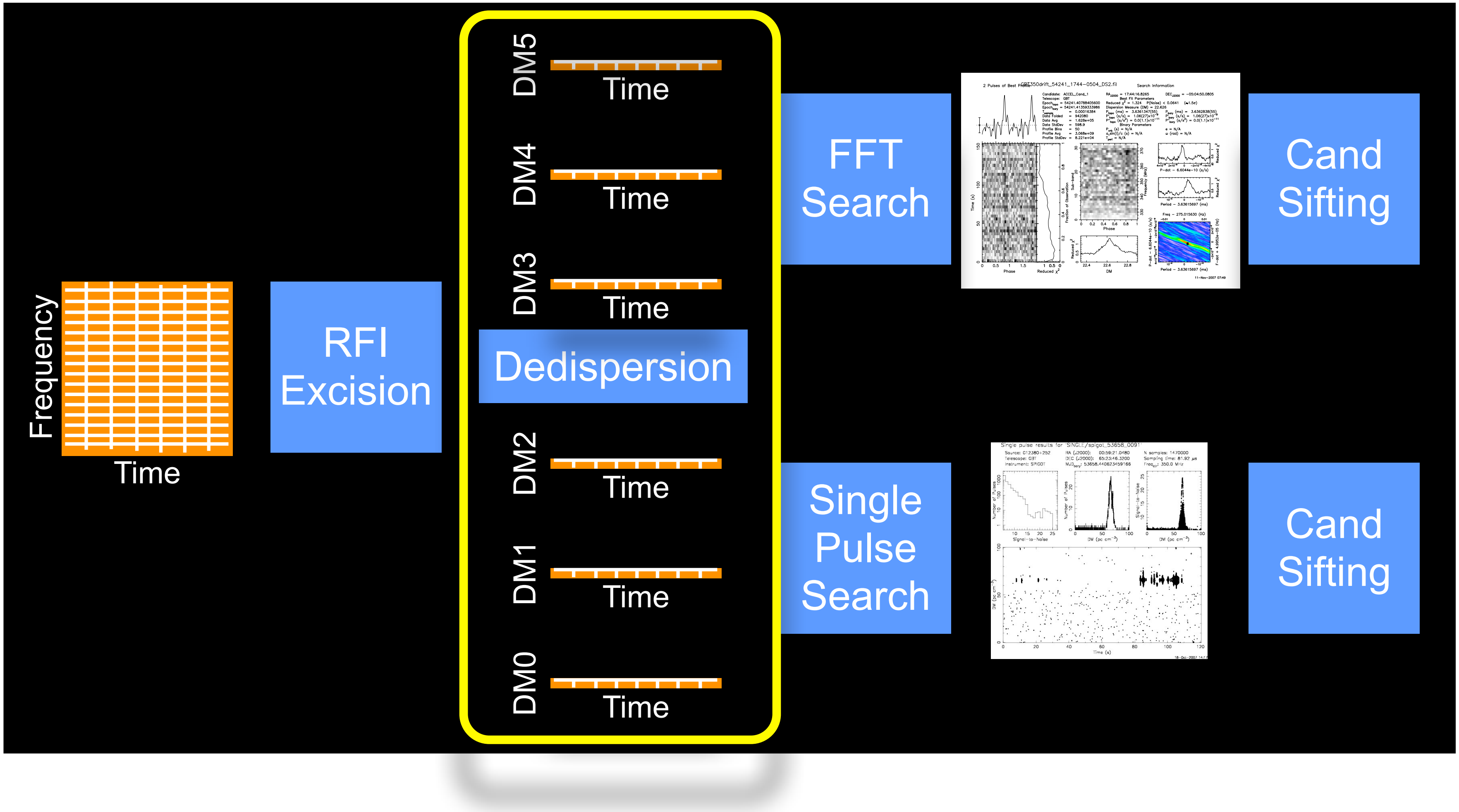
FFT Search

Cand Sifting

Single Pulse Search

Cand Sifting

Standard Pulsar/Fast Transient Search



Frequency

Time

RFI Excision

DM5 Time

DM4 Time

DM3 Time

Dedispersion

DM2 Time

DM1 Time

DM0 Time

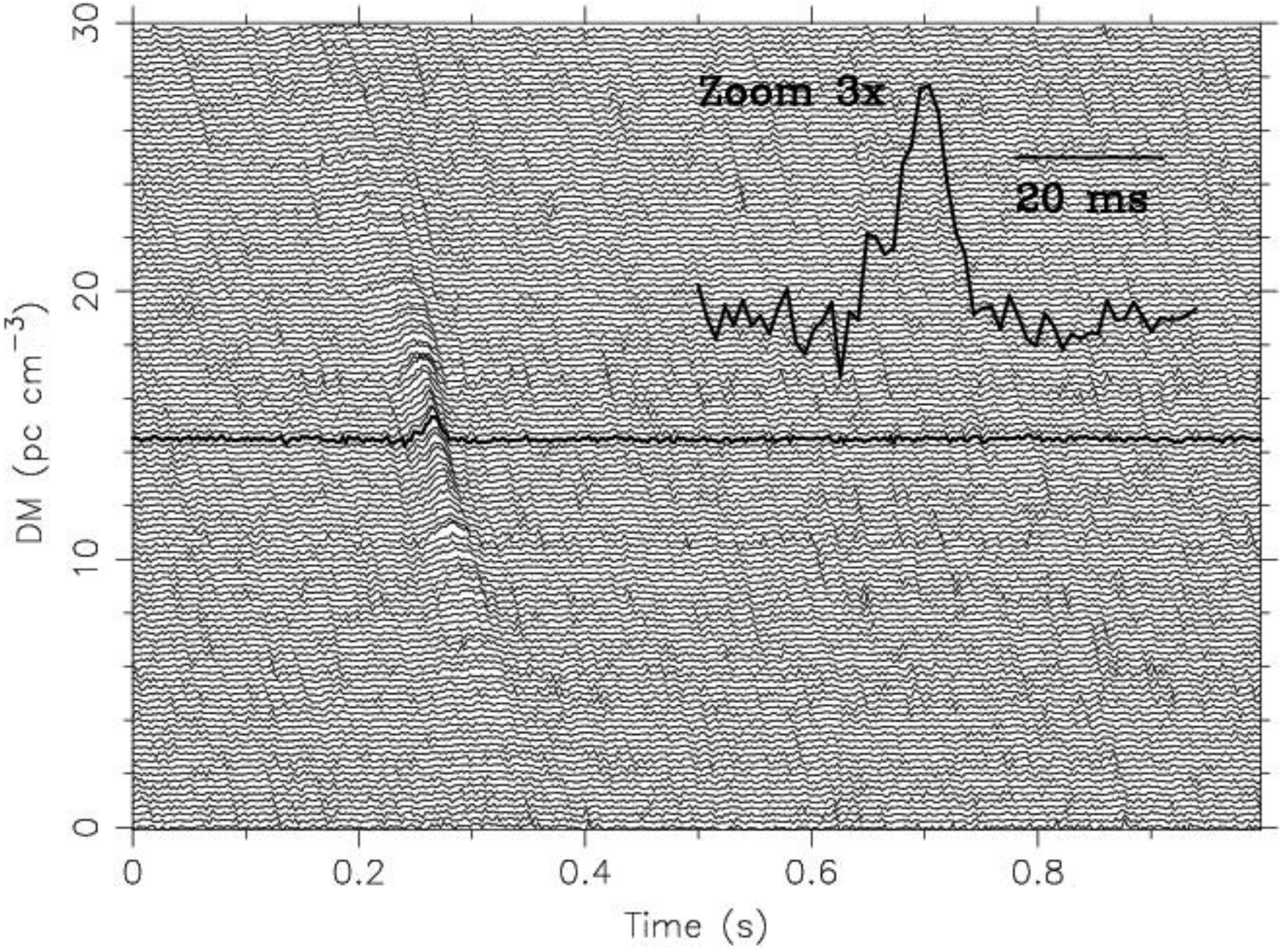
FFT Search

Cand Sifting

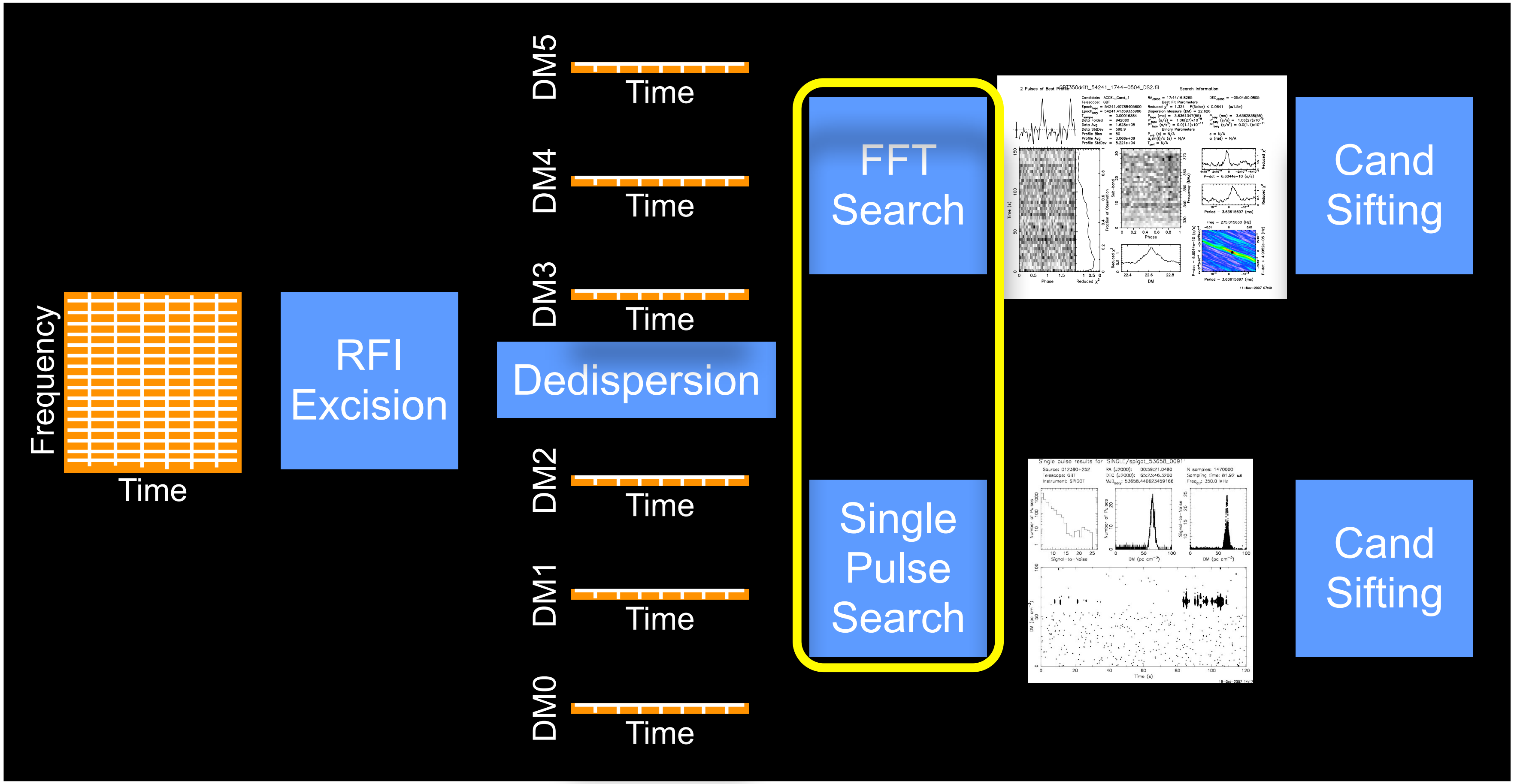
Single Pulse Search

Cand Sifting

Searching over Dispersion Measure



Standard Pulsar/Fast Transient Search



RFI Excision

Dedispersion

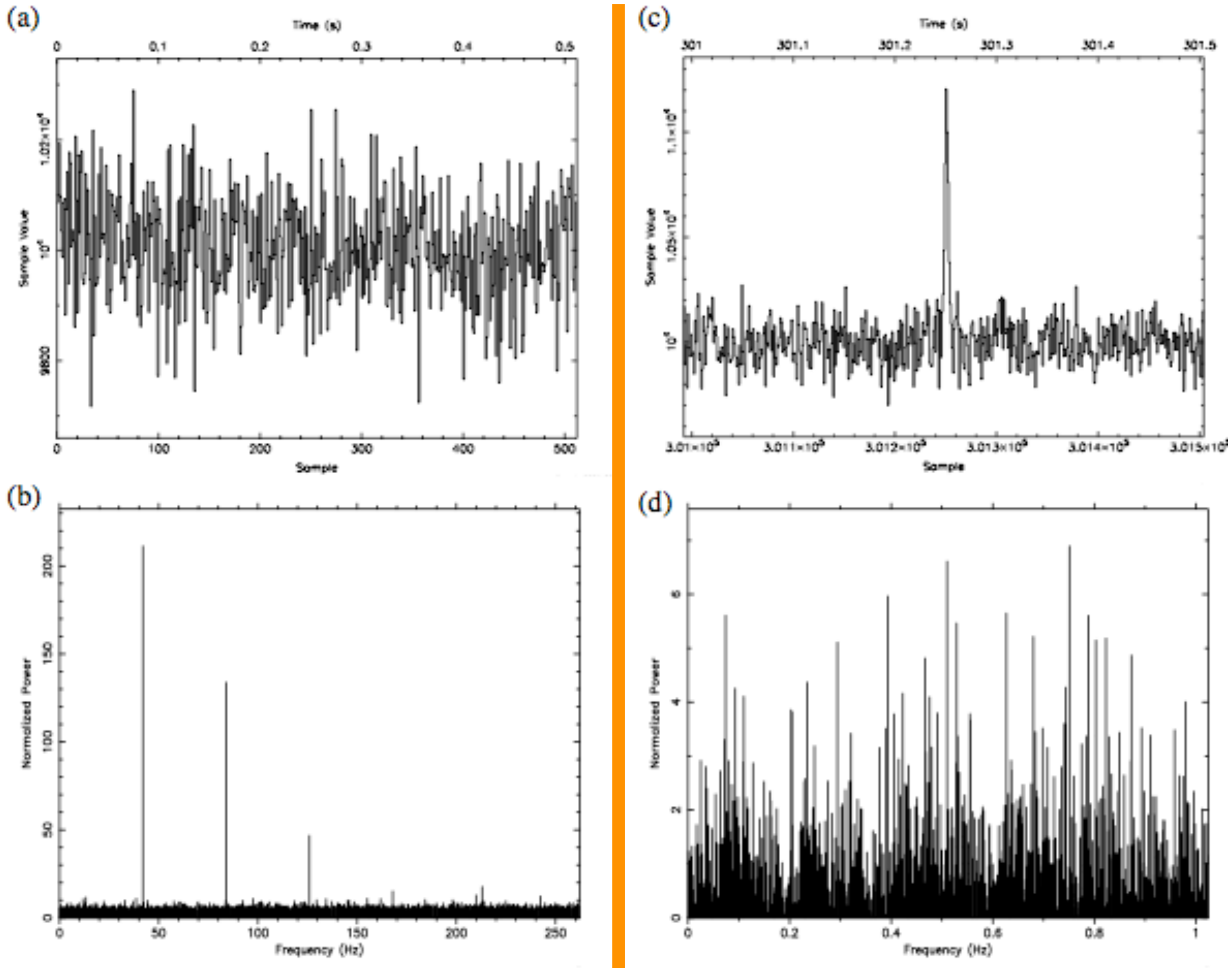
FFT Search

Single Pulse Search

Cand Sifting

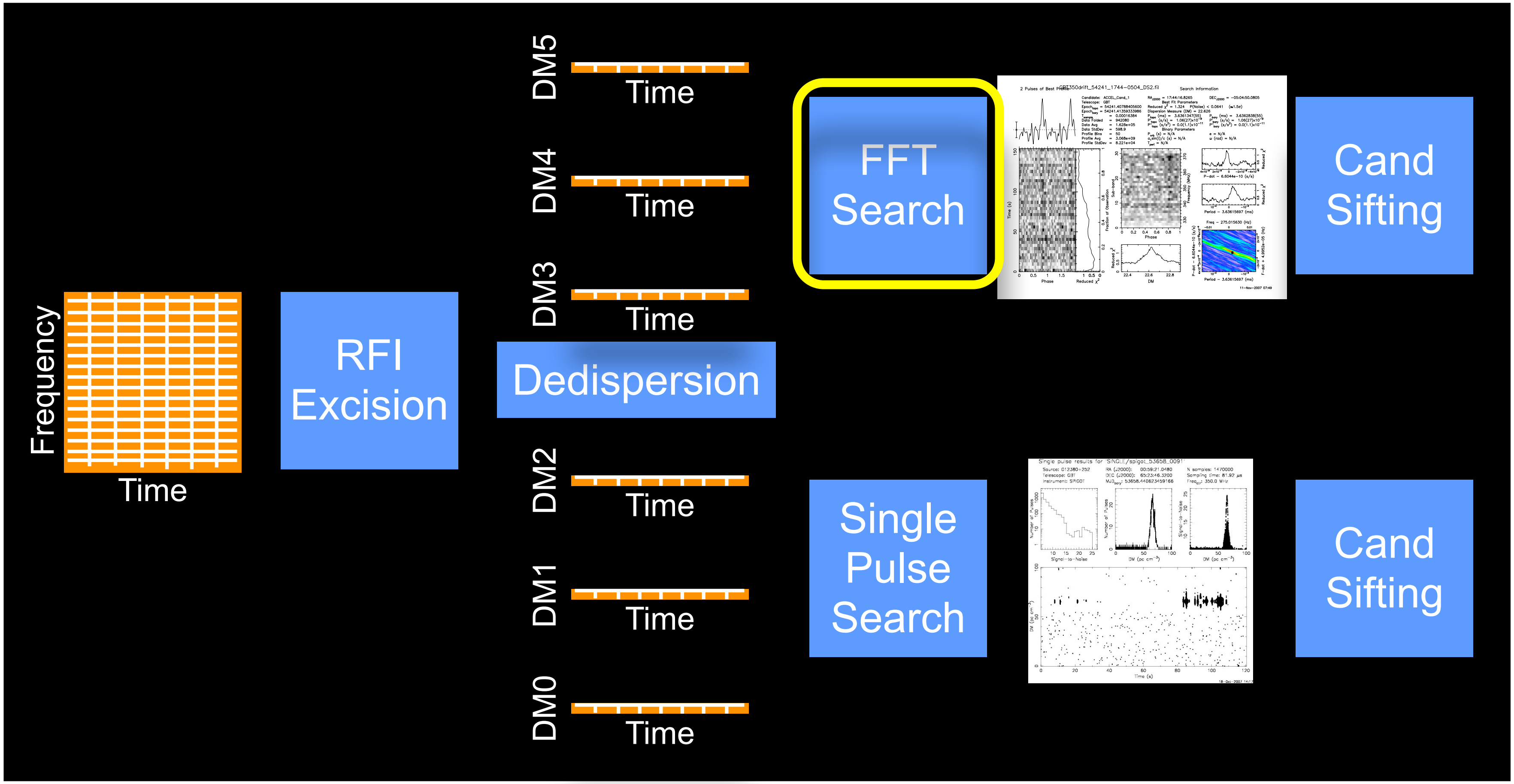
Cand Sifting

Periodic Signals vs. Bursts



Fourier techniques | Time-series techniques

Standard Pulsar/Fast Transient Search



RFI Excision

Dedispersion

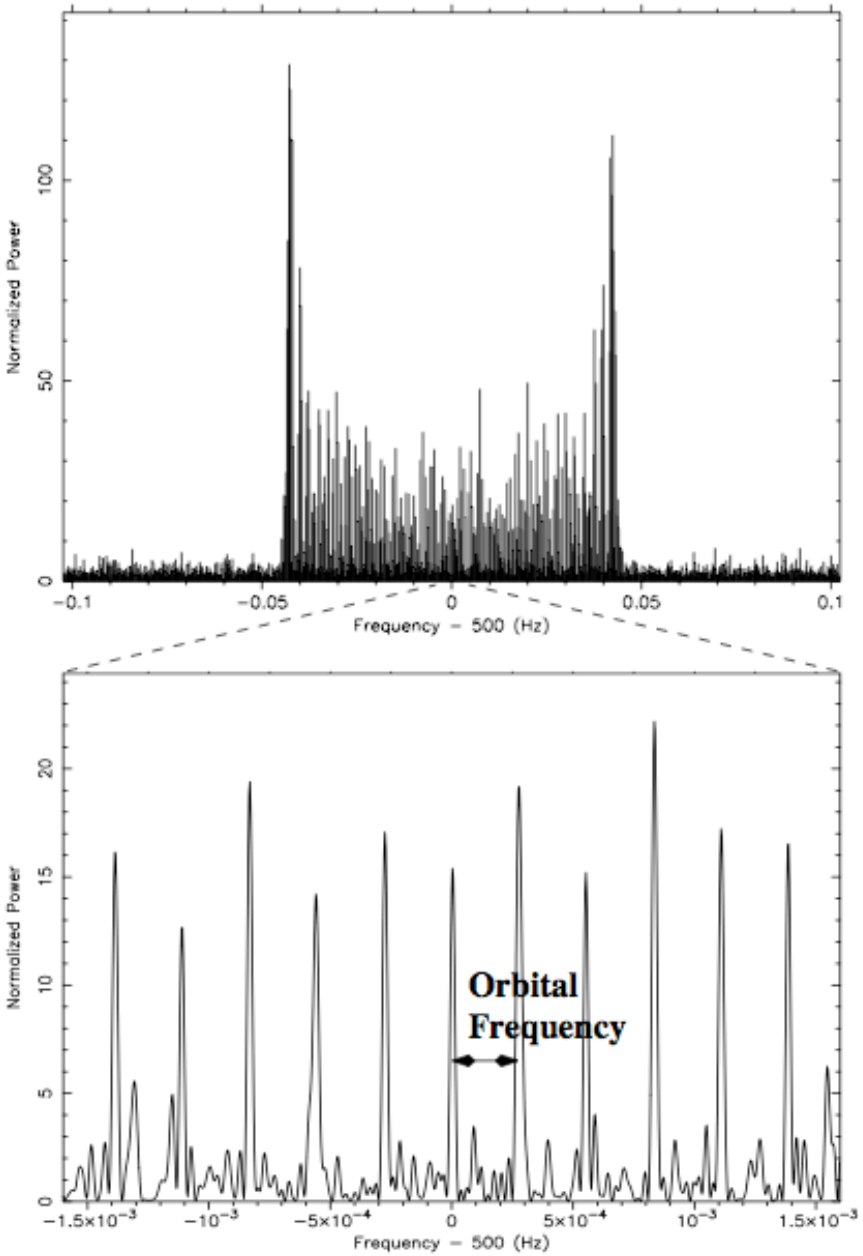
FFT Search

Cand Sifting

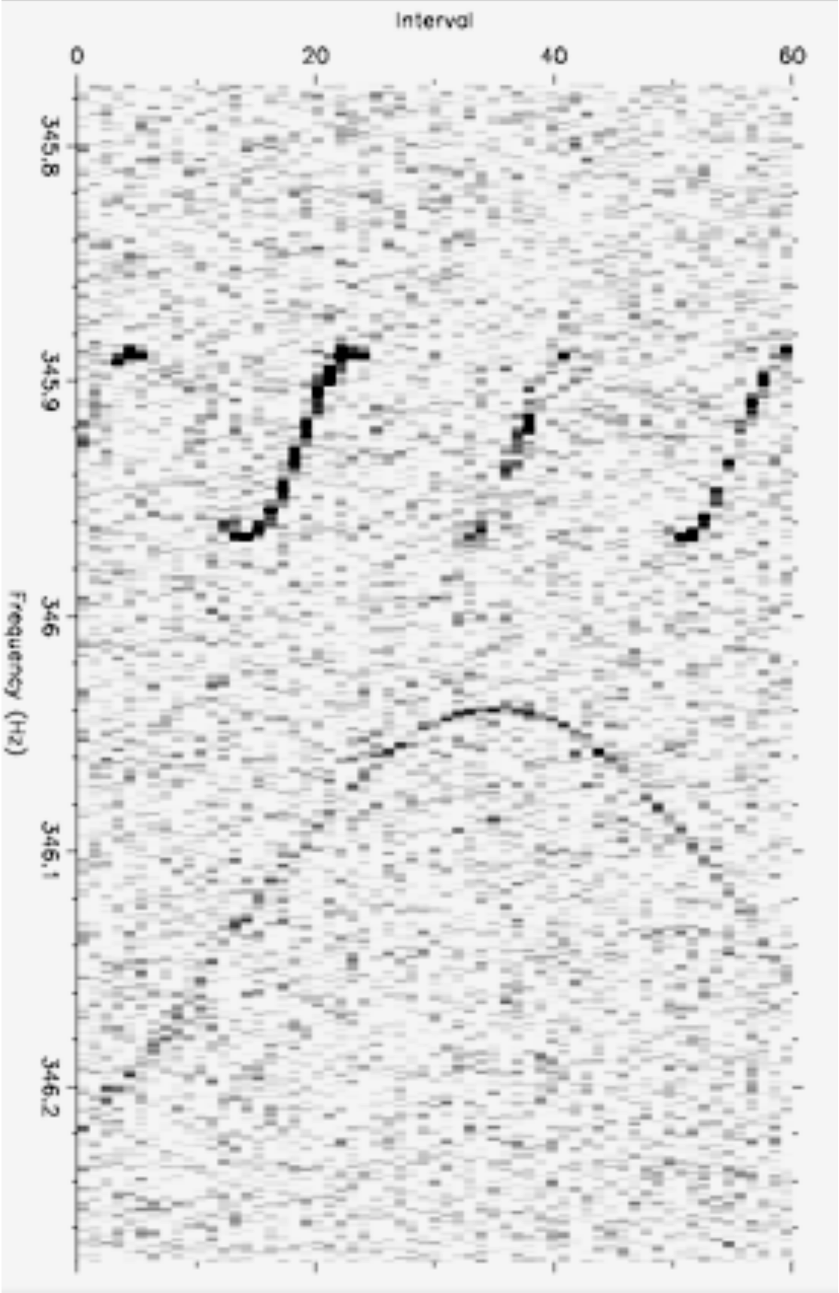
Single Pulse Search

Cand Sifting

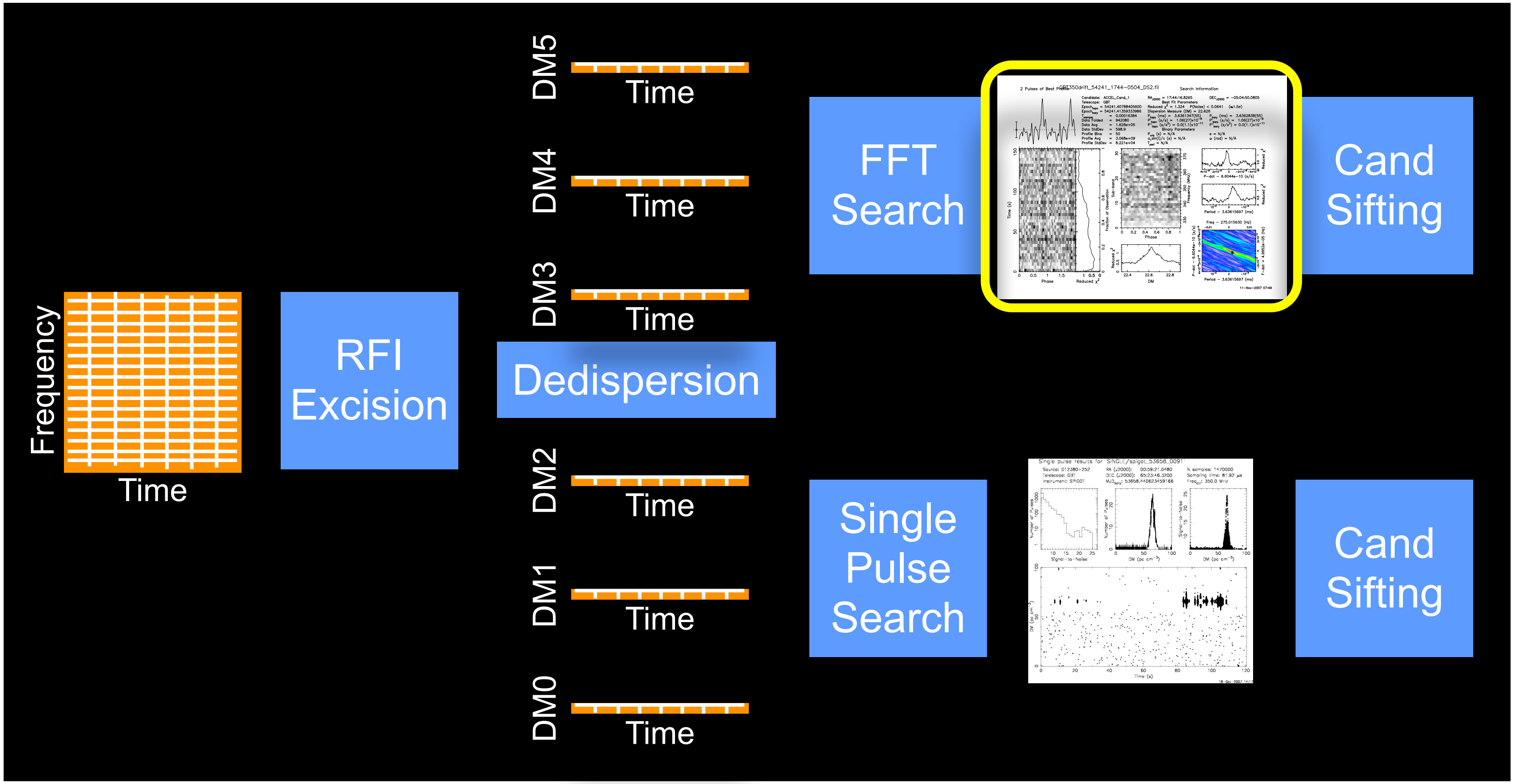
Detecting Binary Pulsars



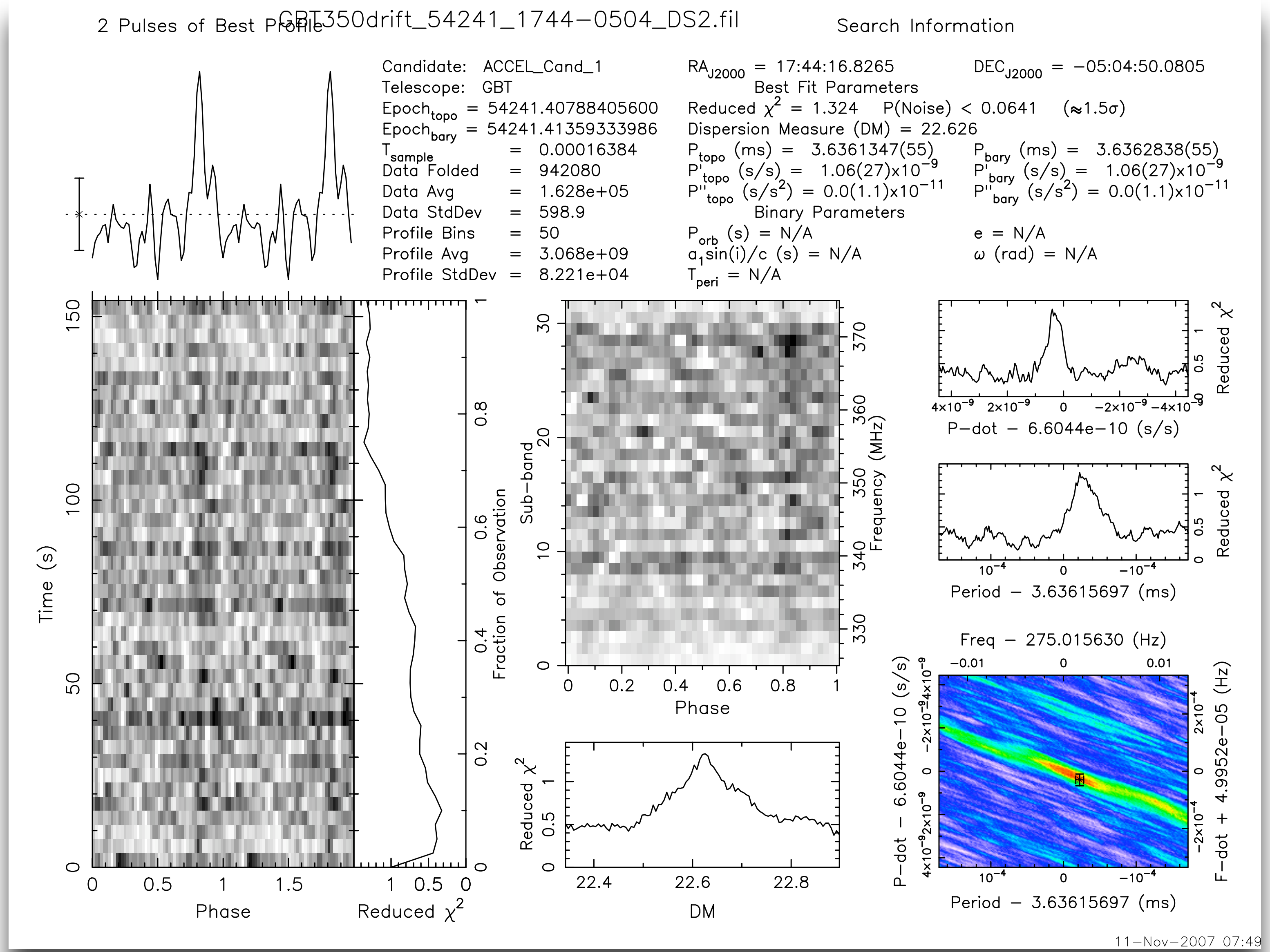
Orbital Frequency



Standard Pulsar/Fast Transient Search



FFT (acceleration) searches



GBT350drift_54241_1744−0504_DS2.fil

Search Information

Candidate: ACCEL_Cand_1
Telescope: GBT
$\mathrm{Epoch_{topo}}$ = 54241.40788405600
$\mathrm{Epoch_{bary}}$ = 54241.41359333986
$\mathrm{T_{sample}}$ = 0.00016384
Data Folded = 942080
Data Avg = 1.628e+05
Data StdDev = 598.9
Profile Bins = 50
Profile Avg = 3.068e+09
Profile StdDev = 8.221e+04

$\mathrm{RA_{J2000}}$ = 17:44:16.8265
$\mathrm{DEC_{J2000}}$ = −05:04:50.0805

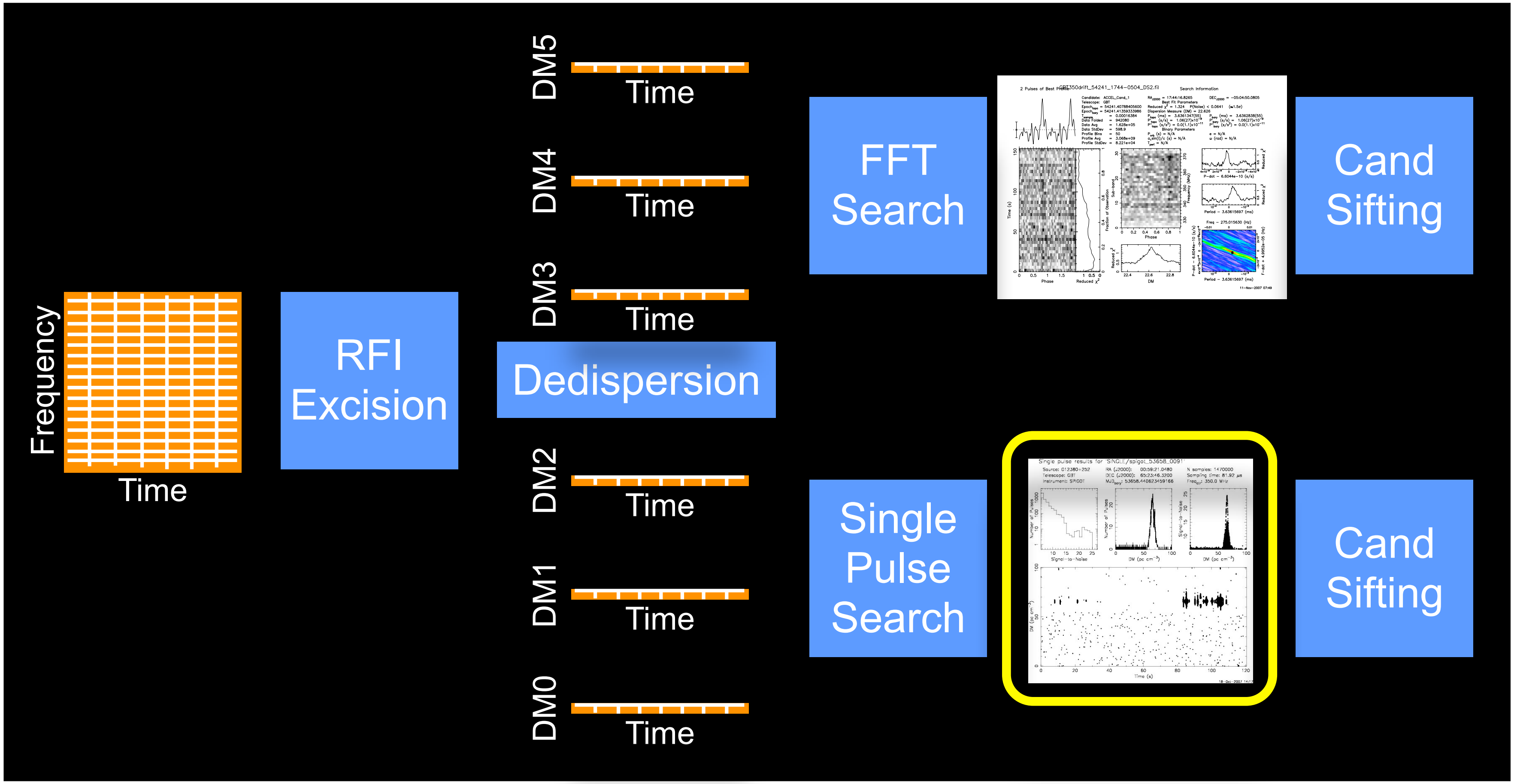
Best Fit Parameters

Reduced χ^2 = 1.324 P(Noise) < 0.0641 (≈1.5σ)
Dispersion Measure (DM) = 22.626
$\mathrm{P_{topo}}$ (ms) = 3.6361347(55)
$\mathrm{P'_{topo}}$ (s/s) = $1.06(27)\times10^{-9}$
$\mathrm{P''_{topo}}$ ($\mathrm{s/s^2}$) = $0.0(1.1)\times10^{-11}$
$\mathrm{P_{bary}}$ (ms) = 3.6362838(55)
$\mathrm{P'_{bary}}$ (s/s) = $1.06(27)\times10^{-9}$
$\mathrm{P''_{bary}}$ ($\mathrm{s/s^2}$) = $0.0(1.1)\times10^{-11}$

Binary Parameters

$\mathrm{P_{orb}}$ (s) = N/A
$a_1\sin(i)/c$ (s) = N/A
$\mathrm{T_{peri}}$ = N/A
e = N/A
ω (rad) = N/A

Standard Pulsar/Fast Transient Search



Frequency

Time

RFI Excision

Dedispersion

DM5 Time

DM4 Time

DM3 Time

DM2 Time

DM1 Time

DM0 Time

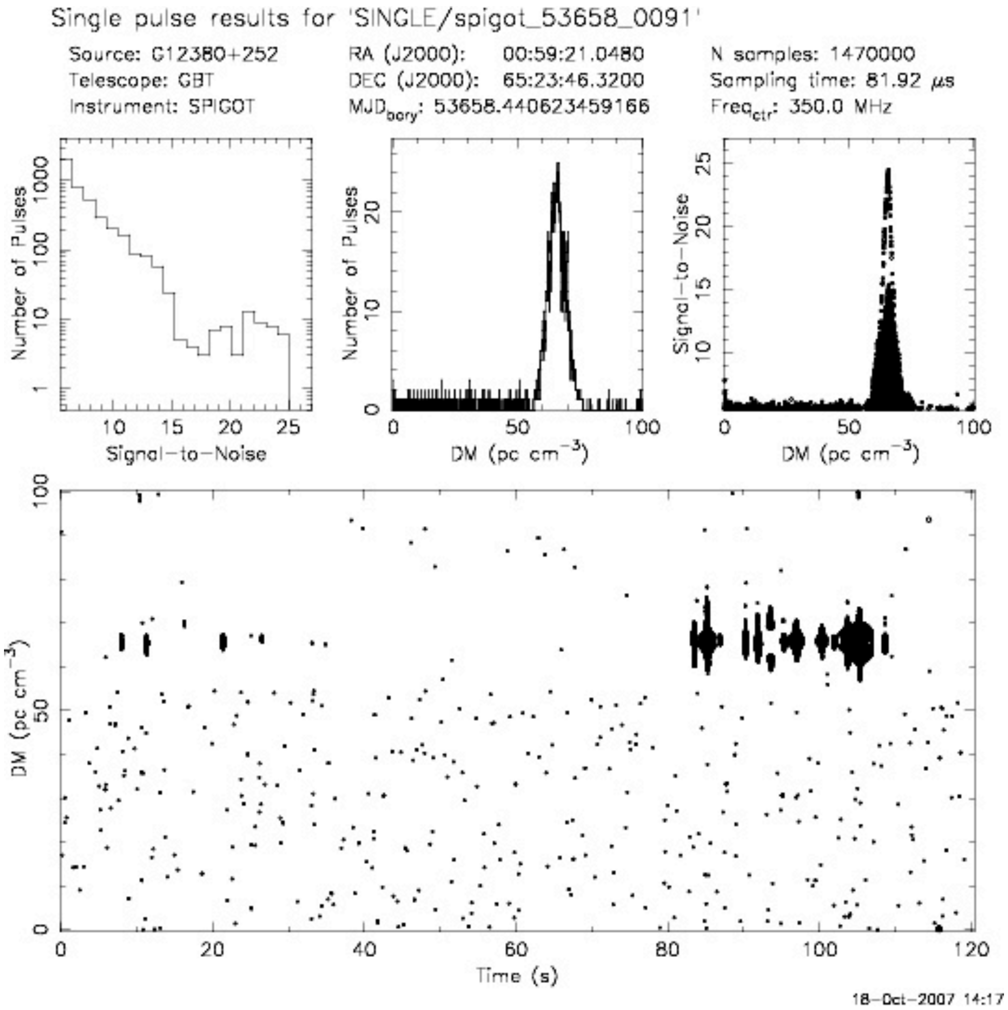
FFT Search

Cand Sifting

Single Pulse Search

Cand Sifting

Single-Pulse Search



Single pulse results for 'SINGLE/spigot_53658_0091'

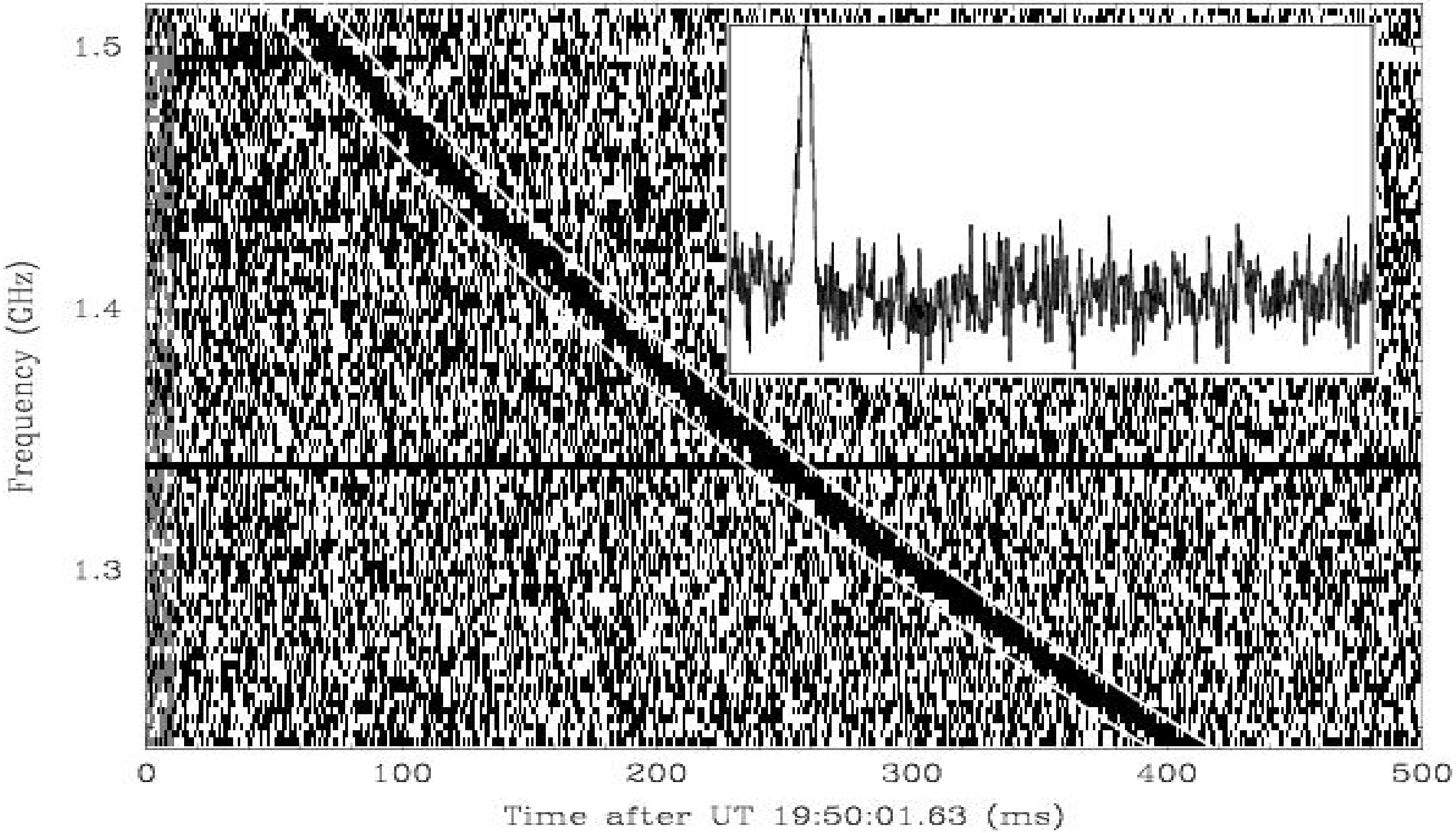
Source: G12380+252
Telescope: GBT
Instrument: SPIGOT

RA (J2000): 00:59:21.0480
DEC (J2000): 65:23:46.3200
MJD$_{bary}$: 53658.440623459166

N samples: 1470000
Sampling time: 81.92 μs
Freq$_{ctr}$: 350.0 MHz

The Lorimer Burst

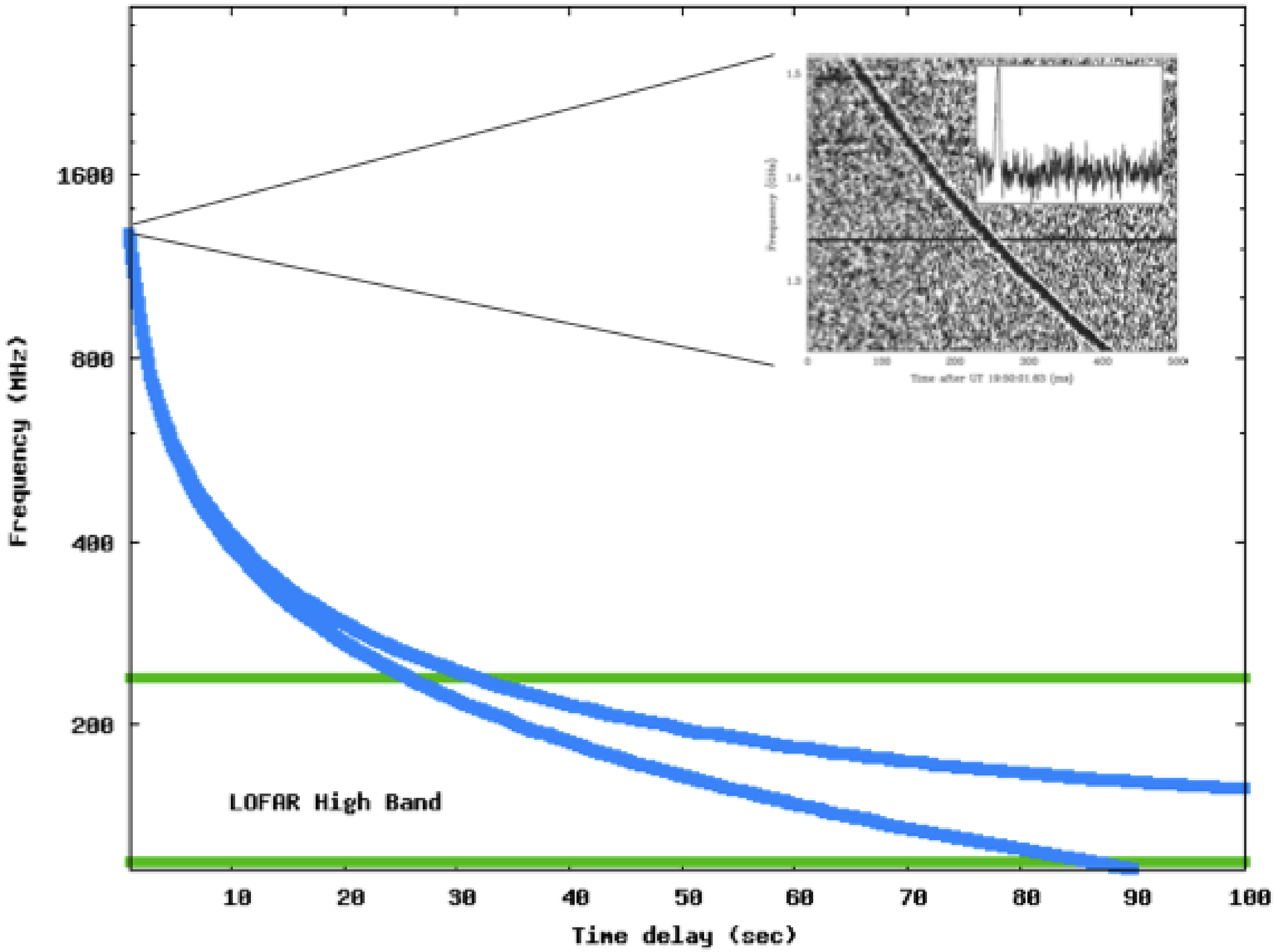
Lorimer et al. 2007



A bright radio burst of apparent extra-galactic origin

Dispersion Delay with LOFAR

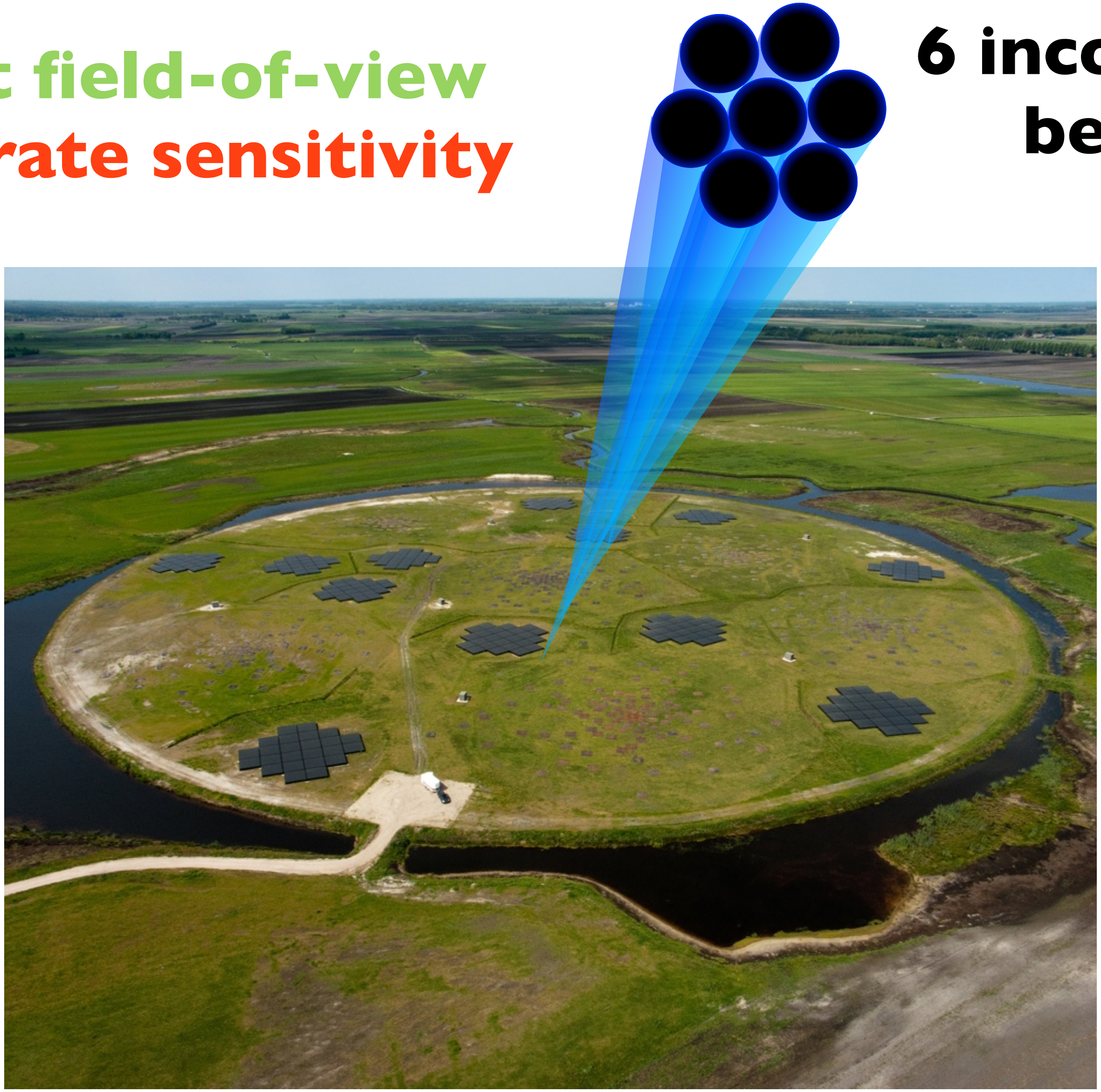
$$\Delta t_{\rm disp} \propto \nu^{-2}$$



Fender

LOFAR Pulsar Surveys

Great field-of-view
Moderate sensitivity



6 incoherent beams

Pilot Incoherent Survey

Hessels

LOFAR Pulsar Surveys

Moderate field-of-view

Great sensitivity

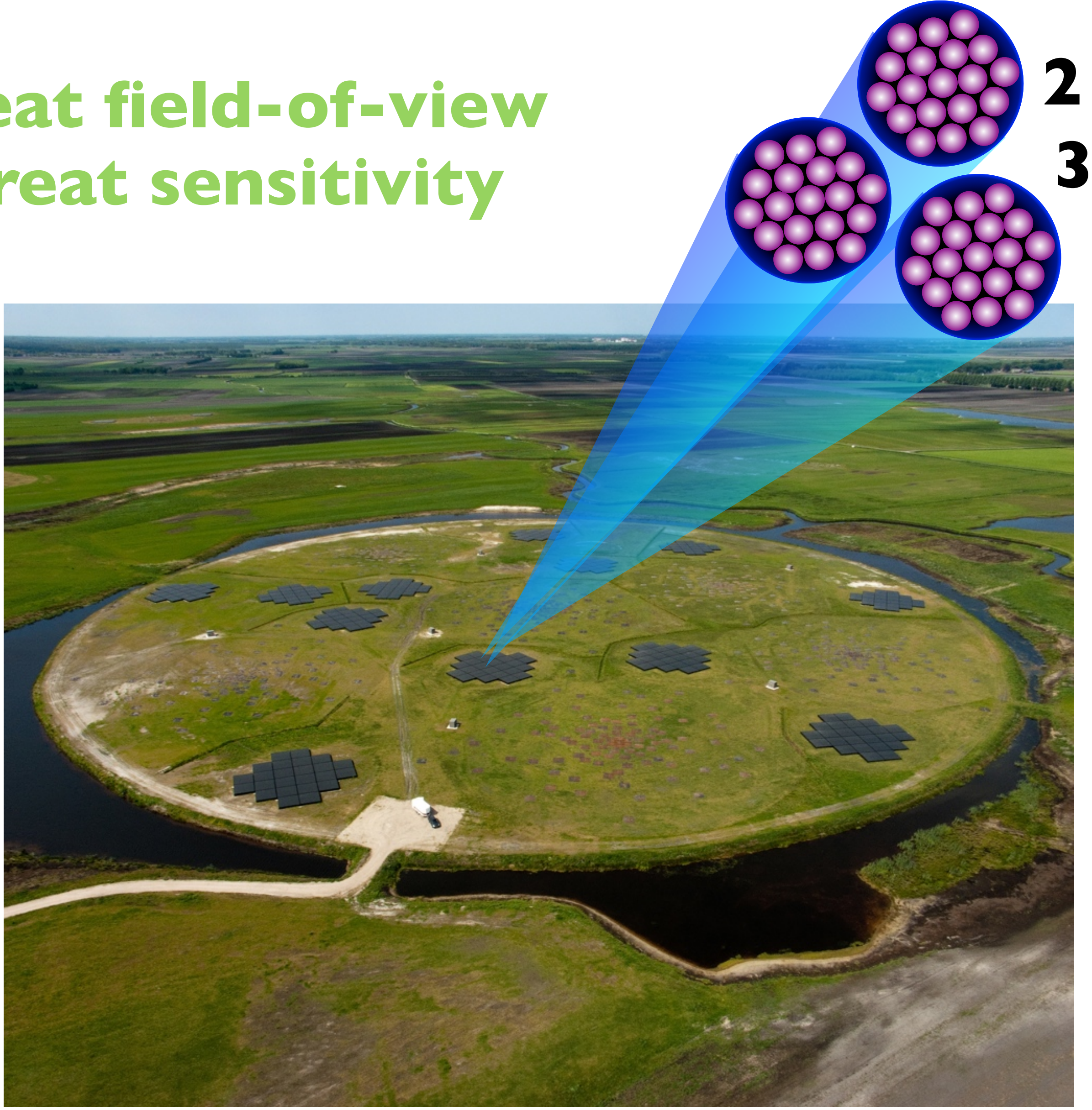
19 coherent beams

Pilot Coherent Survey

Hessels

LOFAR Pulsar Surveys

Great field-of-view
Great sensitivity

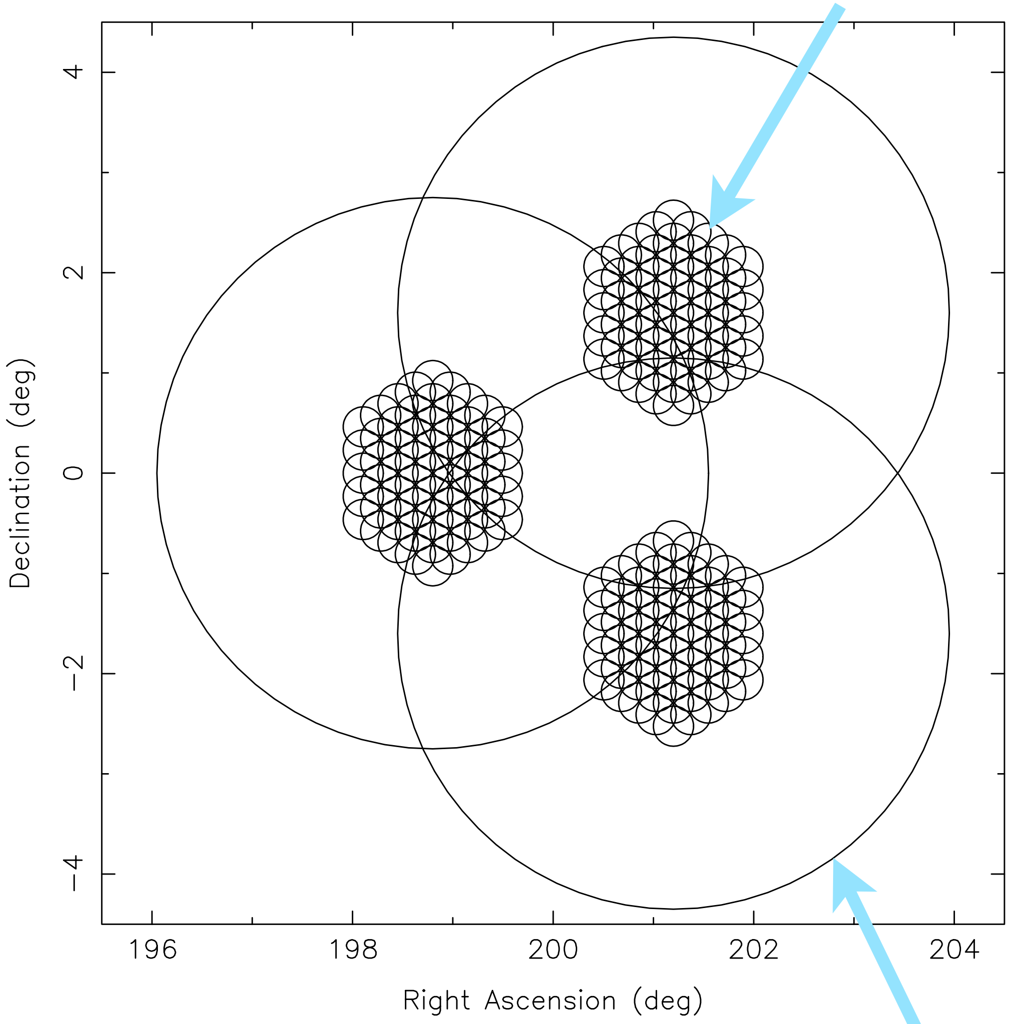


219 coh. beams
3 incoh. beams

LOTAAS (Full Survey)

Hessels

LOTAAS Single Pointing



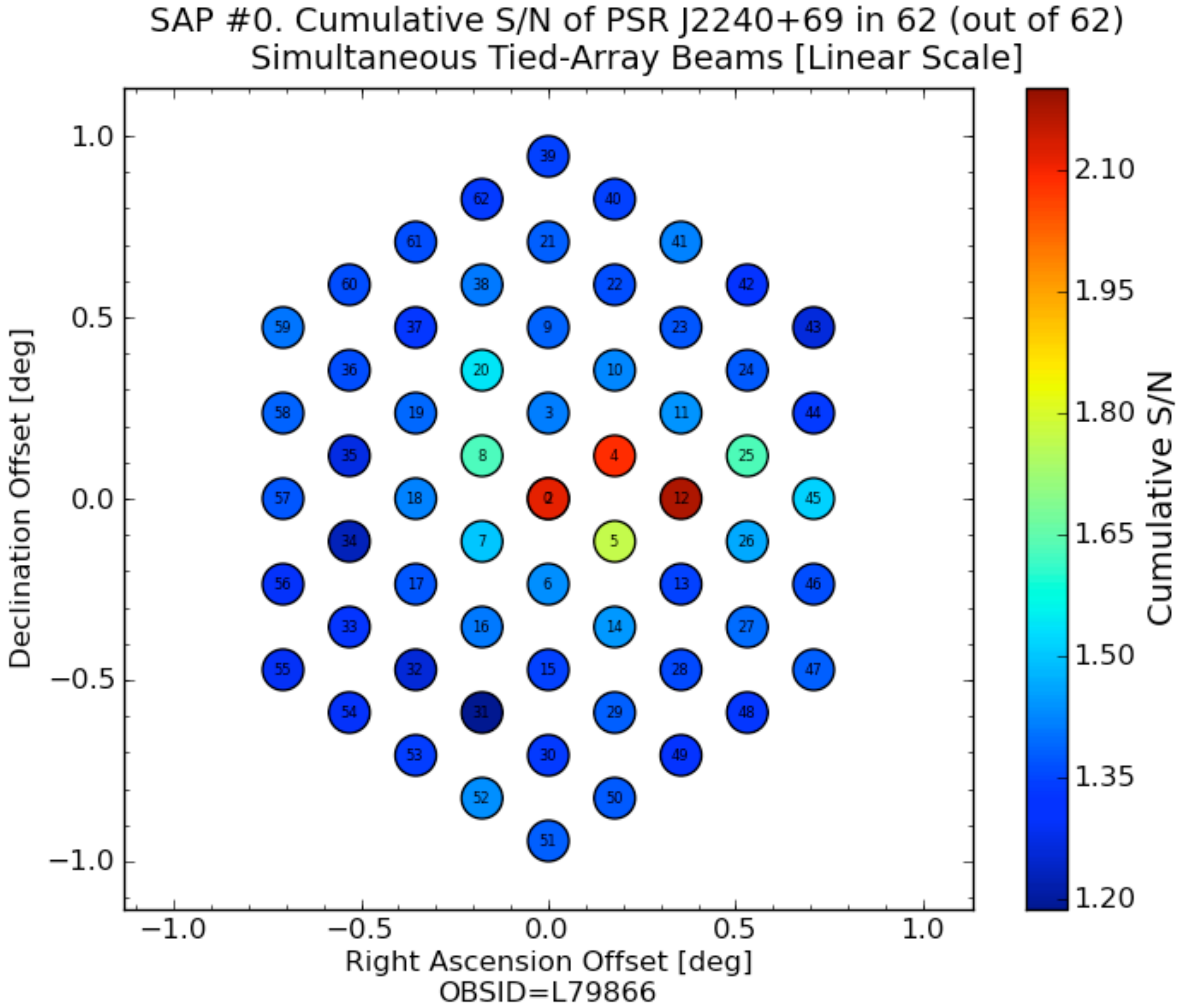
Coherent "tied-array" beams

Incoherent "station" beam

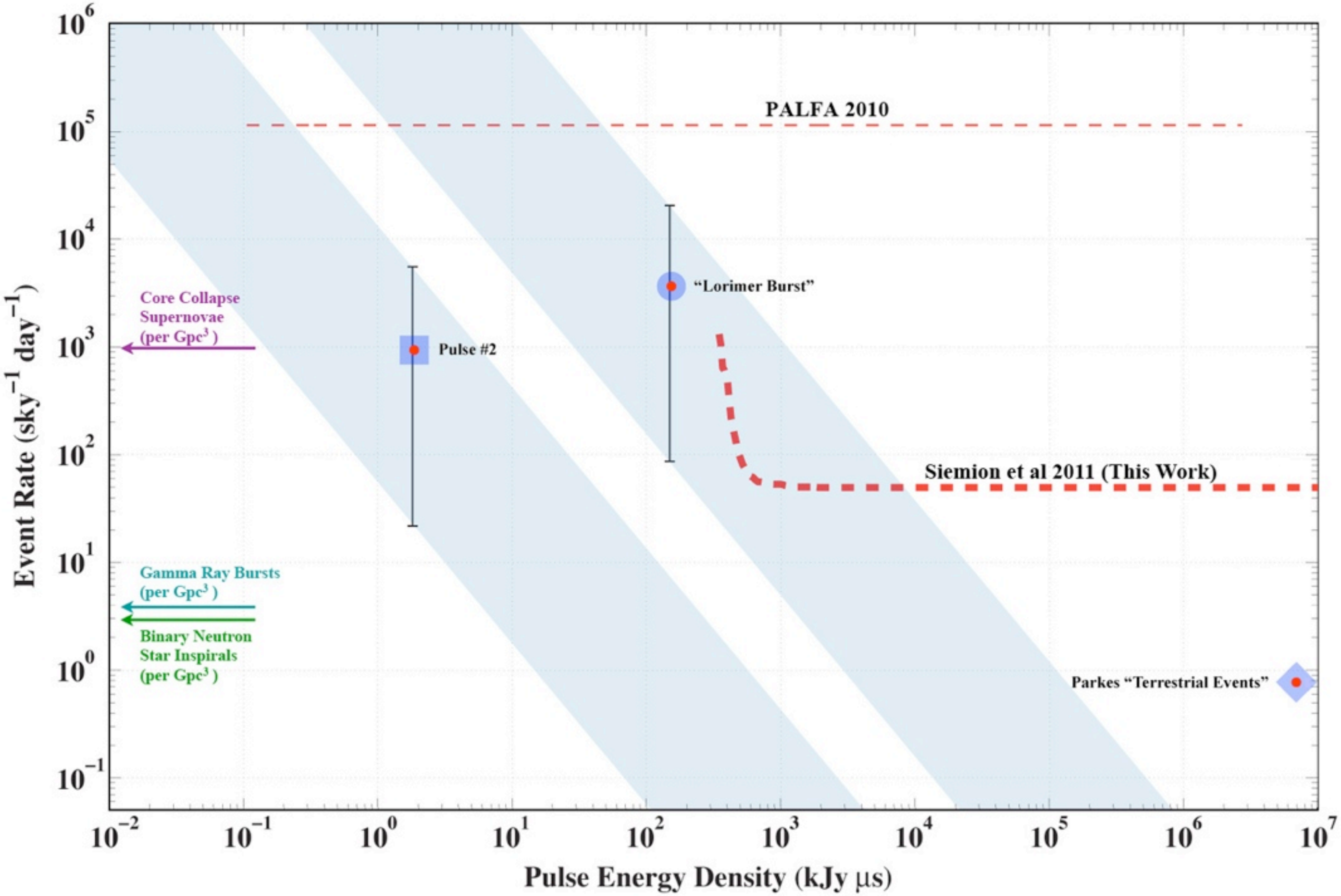
222 beams (FoVs) at once

First SKA-like pulsar survey

Localization of Transients

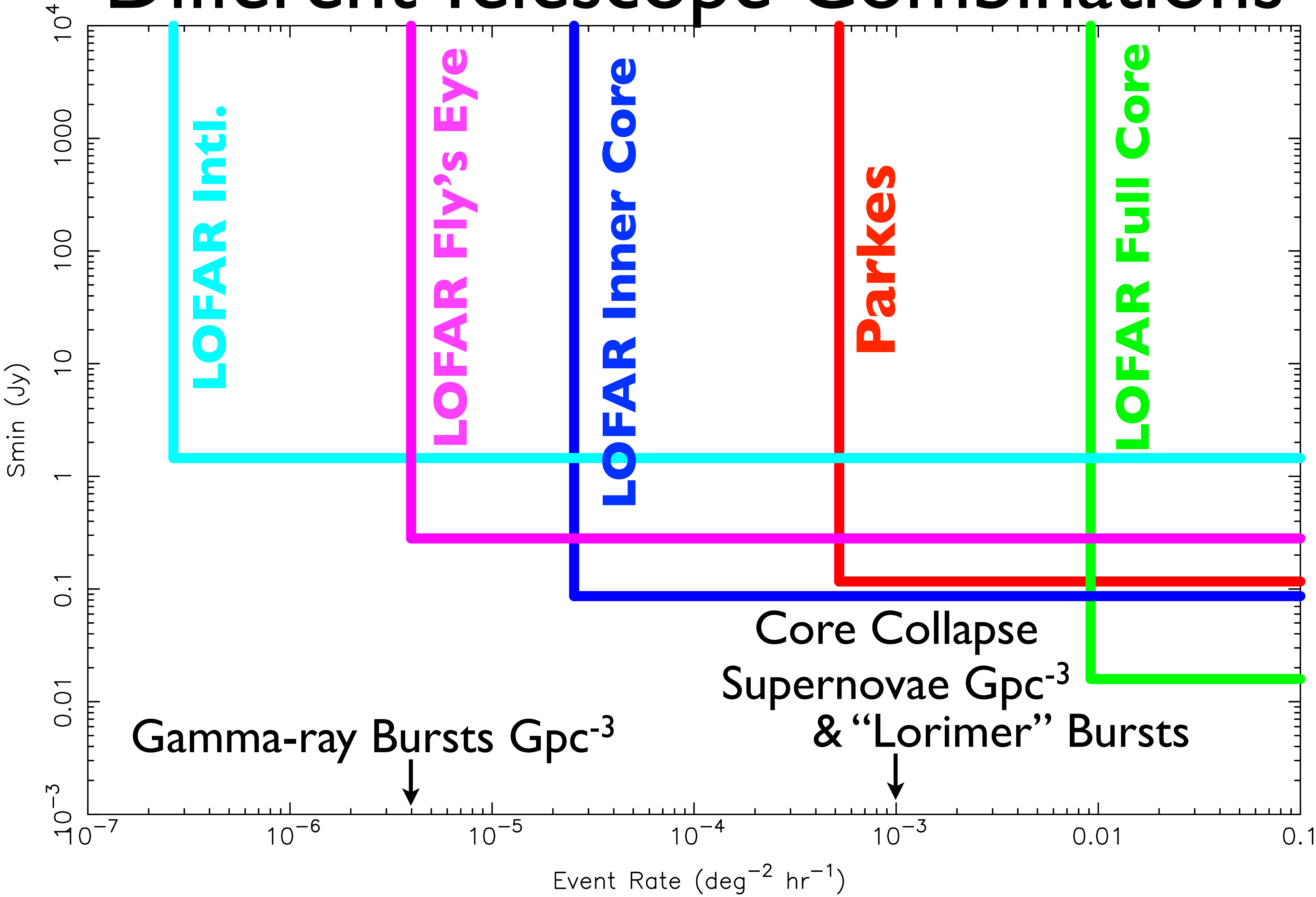


Constraints on Transient Parameter Space



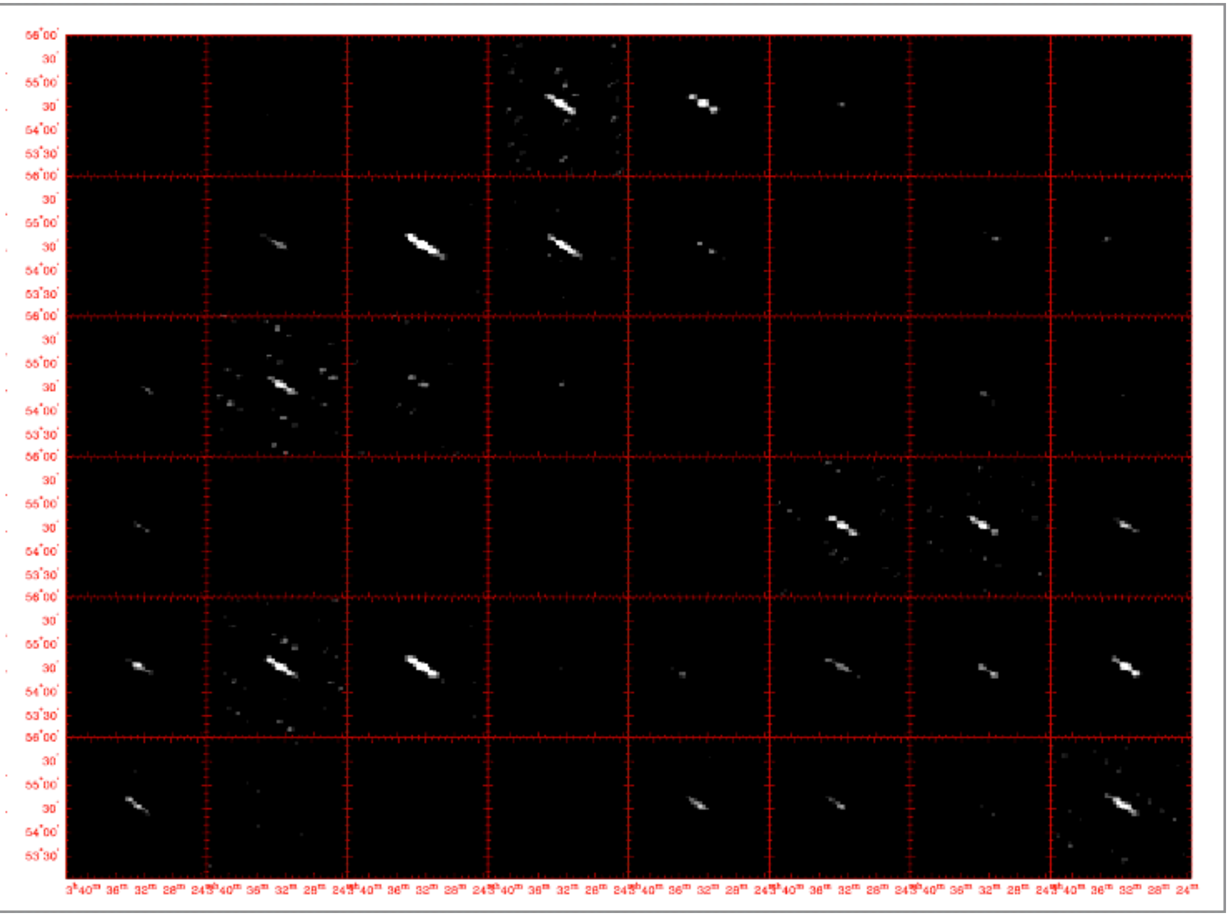
Siemion

Different Telescope Combinations



Fast imaging and uv-plane techniques

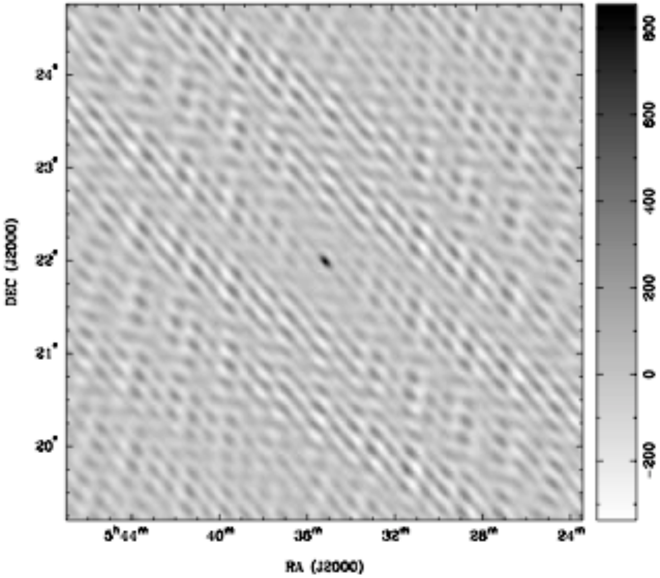
Fast Imaging: B0329+54

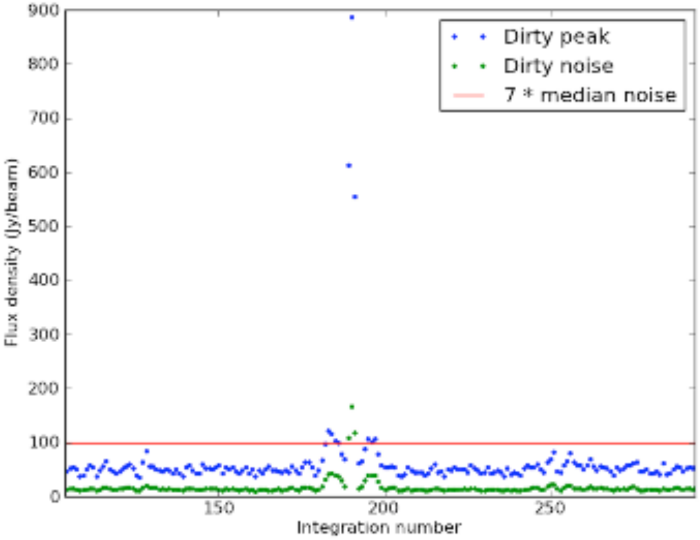


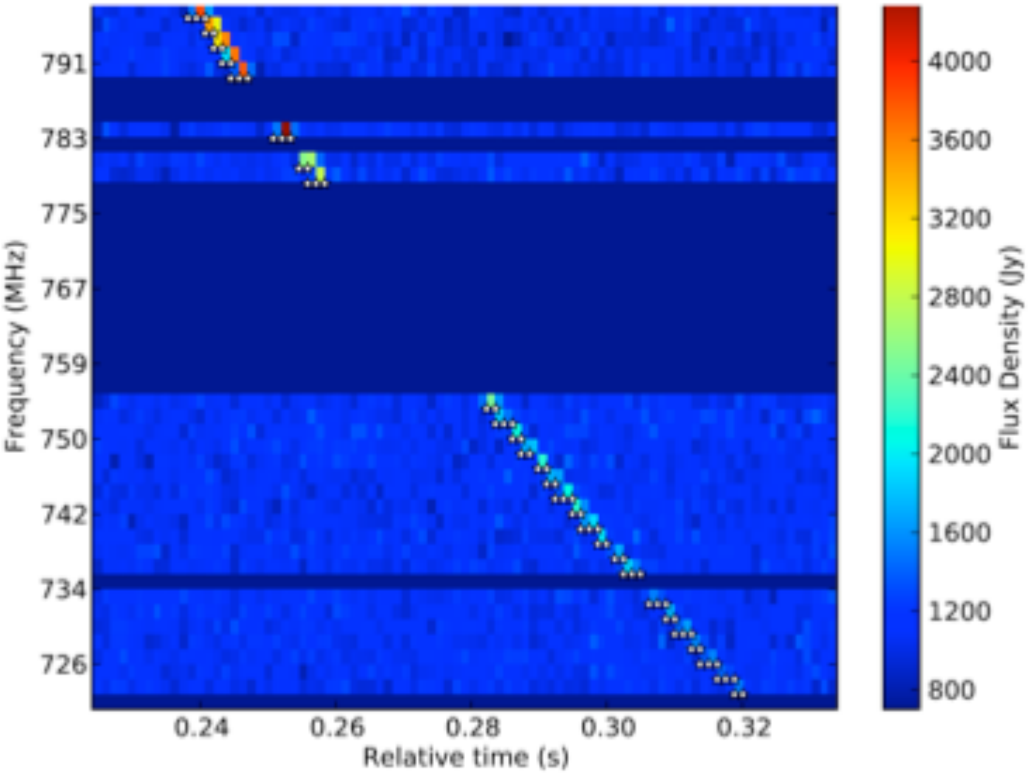
- Series of 100-ms images made with the Allen Telescope Array.
- Repeating, pulsed signal from B0329+54 can be seen.

Law

Fast Imaging: Crab Giant Pulse

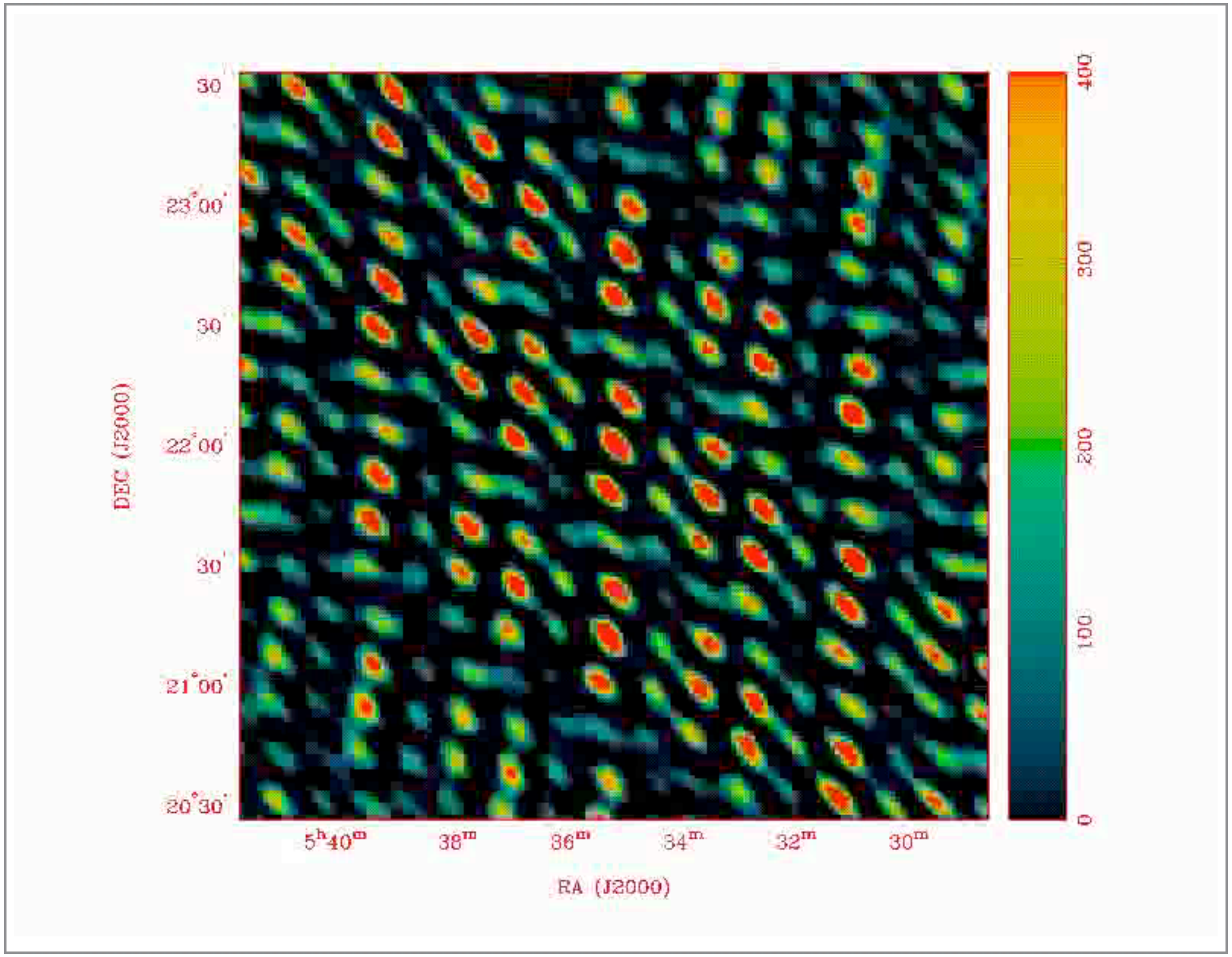






Law

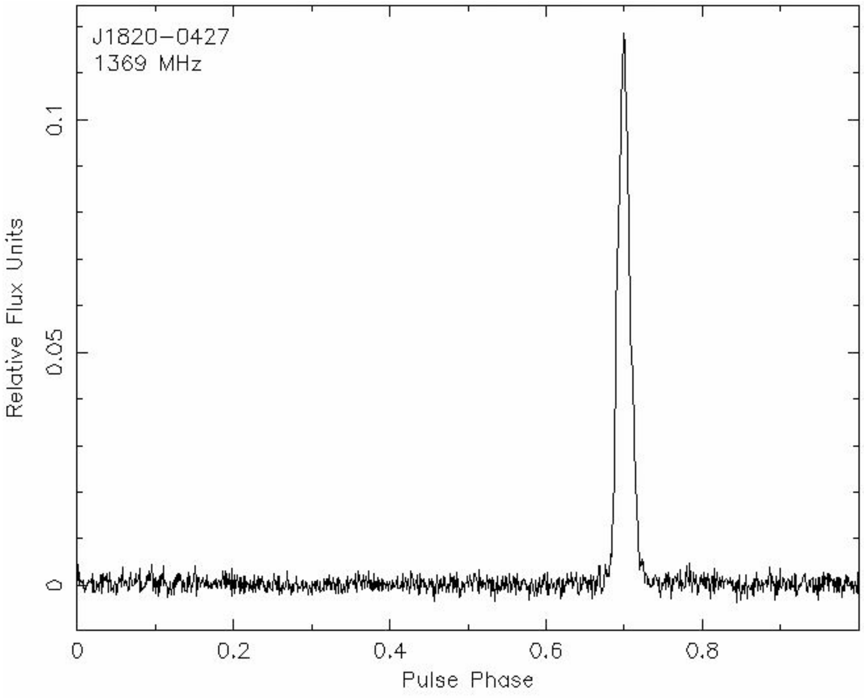
Fast Imaging: Crab Giant Pulse



- Movie showing imaging of a Crab giant pulse at 1/40th of the actual speed.
- Dedispersion required.

Law

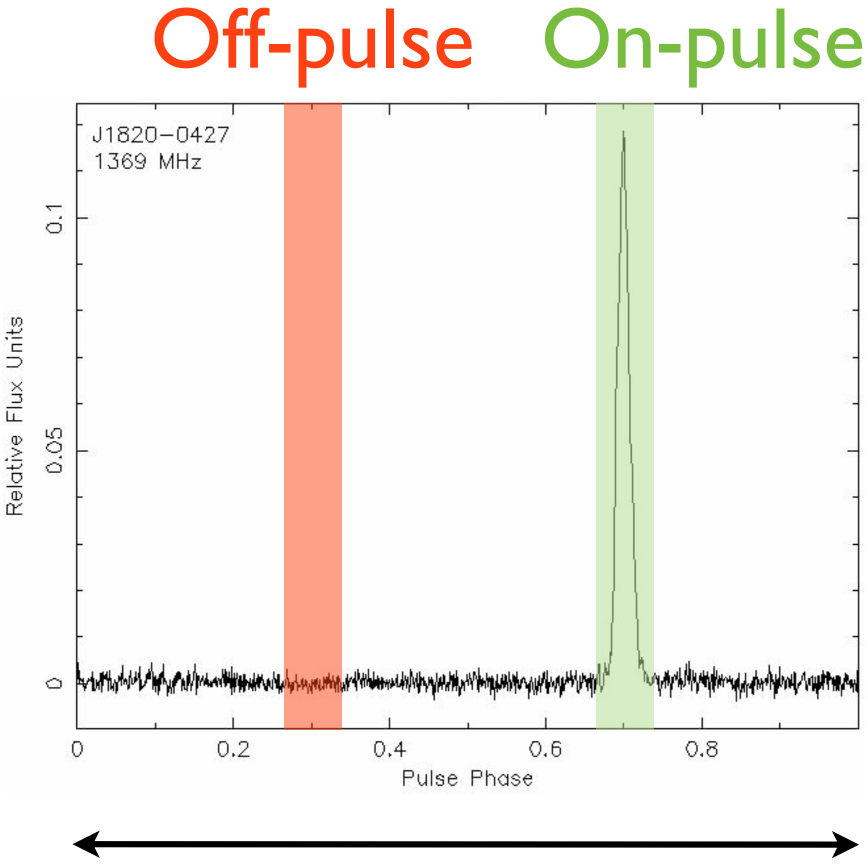
Pulse Gating



~1 second

- Pulsars typically have narrow duty cycles (~5% for slow pulsars, ~20% for millisecond pulsars).
- Need tsamp < spin period in order to see pulsations.
- S/N is also poor if pulse is not resolved.
- Problem: can't dump correlator fast enough. Also, lots of the data is uninteresting because the pulsar is mostly off.

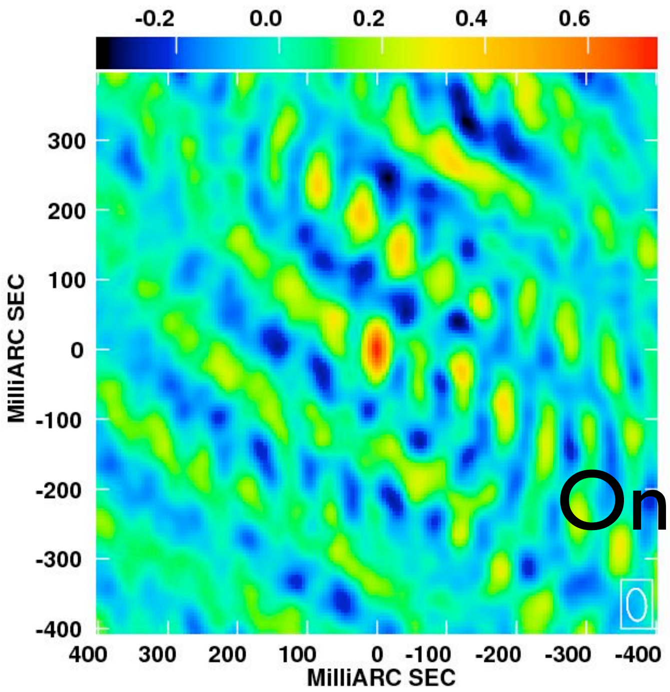
Pulse Gating



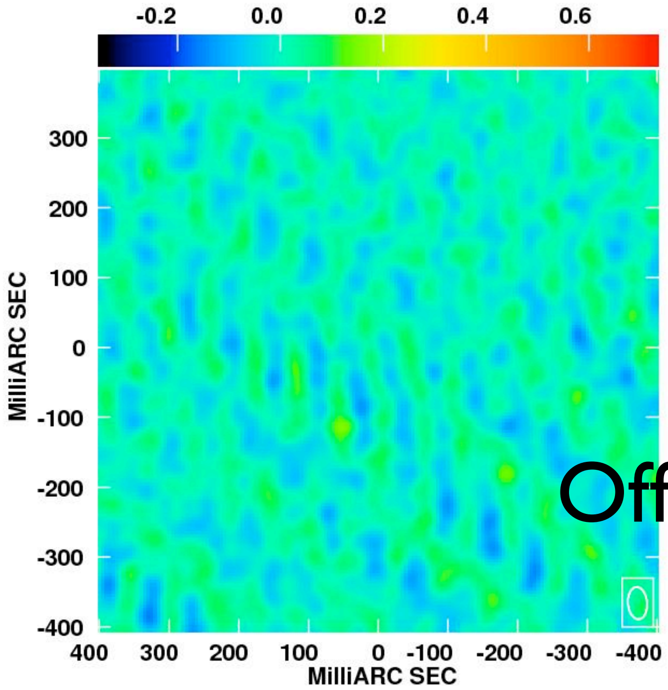
~1 second

- Solution: use the pulsar timing ephemeris to predict which bits of data the pulsar is on and only write out those integrations.
- Can also use binning to give a coarse image of the pulse with time.

Pulse Gating



On-pulse

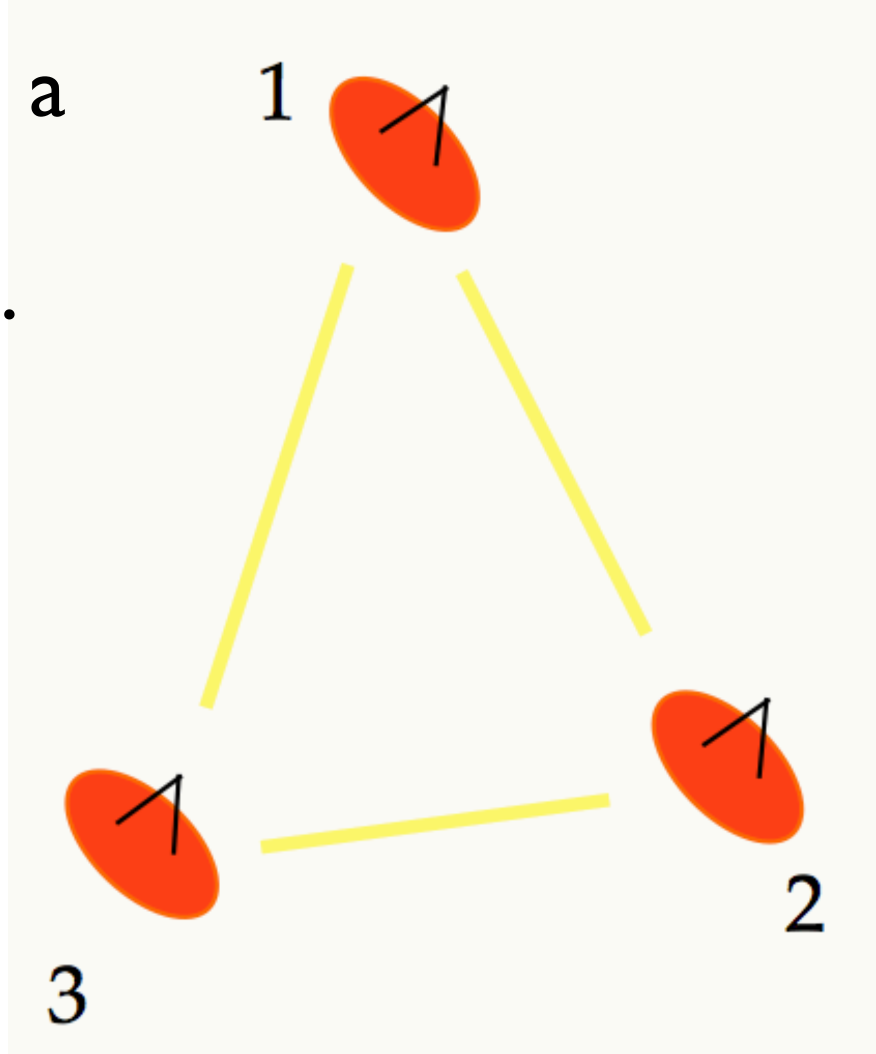


Off-pulse

- Preliminary images of PSR J2032+4127 obtained with 6 stations of the EVN at 1.6 GHz. The data were correlated with the new DiFX correlator in Bonn using pulsar gating, which improved the signal-to-noise ratio by a factor of 2. The left image corresponds to the data correlated during on-pulse (0.1 phase bin), and the right image during off-pulse (for a 0.1 phase bin as well).

Closure quantities

- Combination of visibilities on a closed loop is independent of source location and calibration.

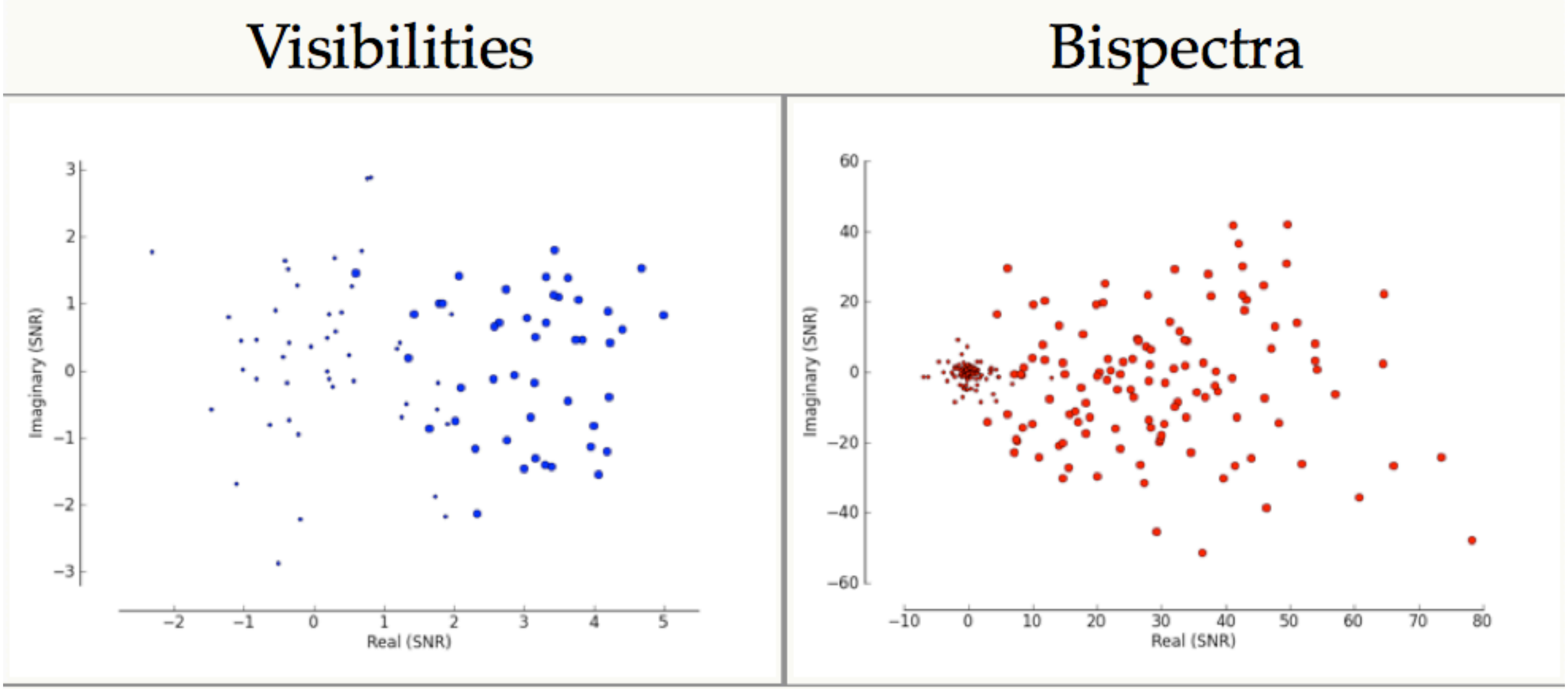


$$\Theta_{12} + \Theta_{23} + \Theta_{31}$$

$$V_{12} * V_{23} * V_{31}$$

Law

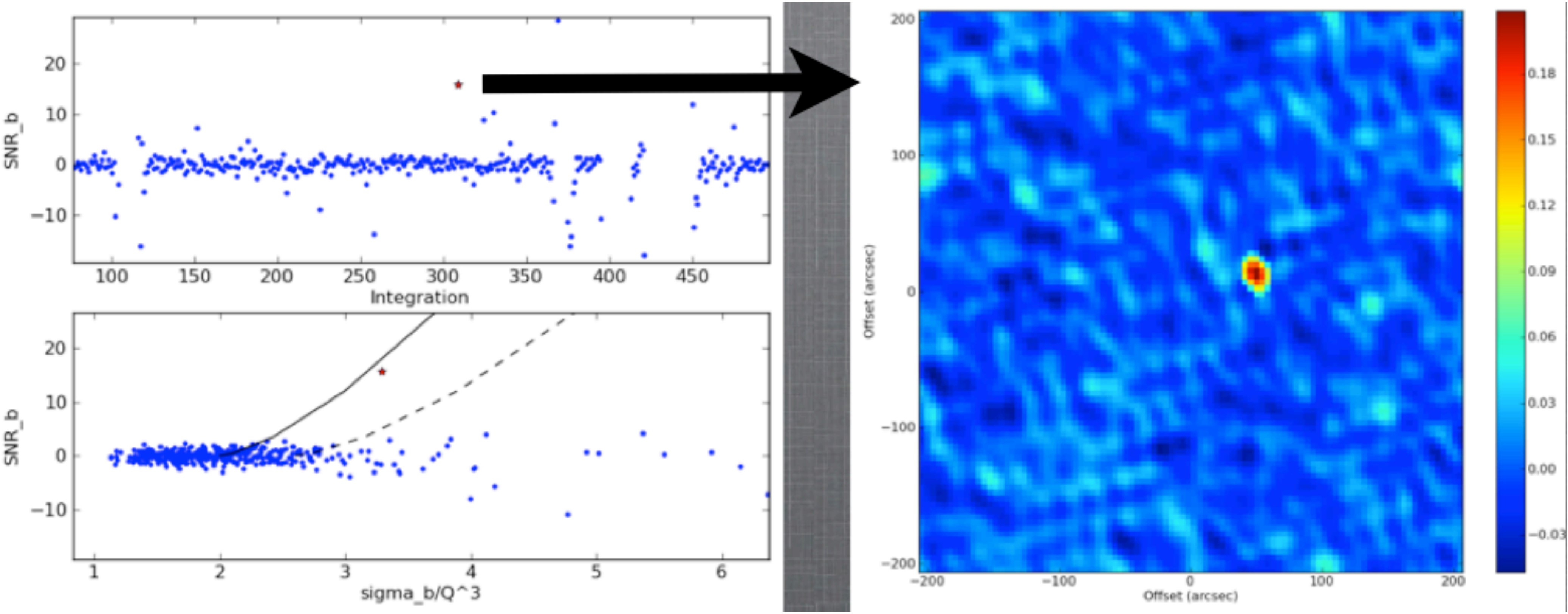
Bi-spectrum detection method



Real-imaginary values for noise (points) and SNR_bl=3 (circles) for n_a=10.

Law

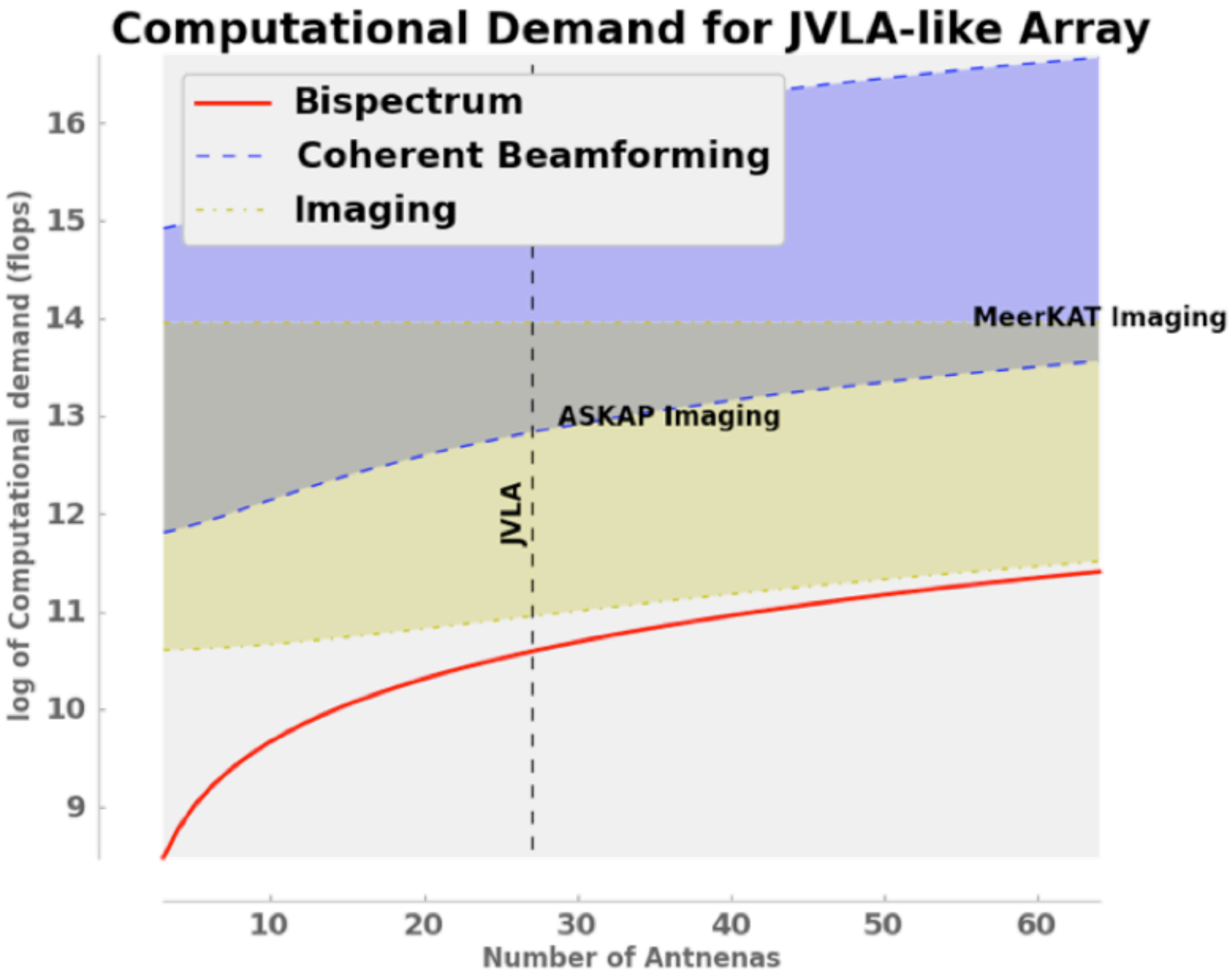
Bi-spectrum detection method



- Transient astronomical signal sticks out like a sore thumb.
- Save those data and image the pulse.

Law

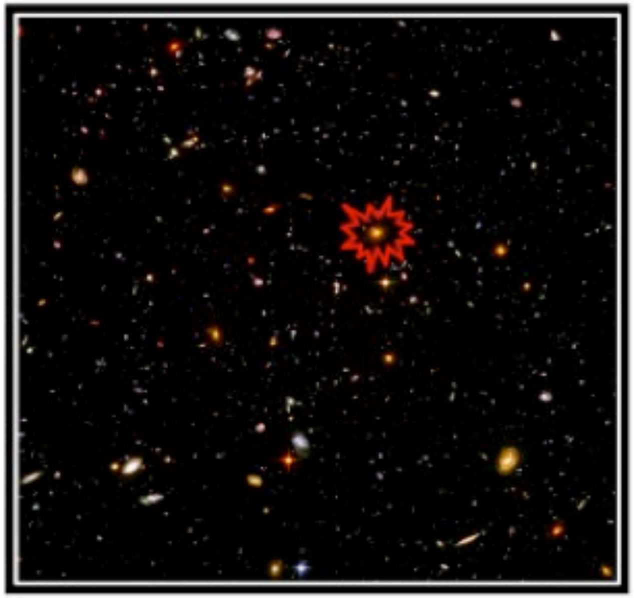
Bi-spectrum detection method

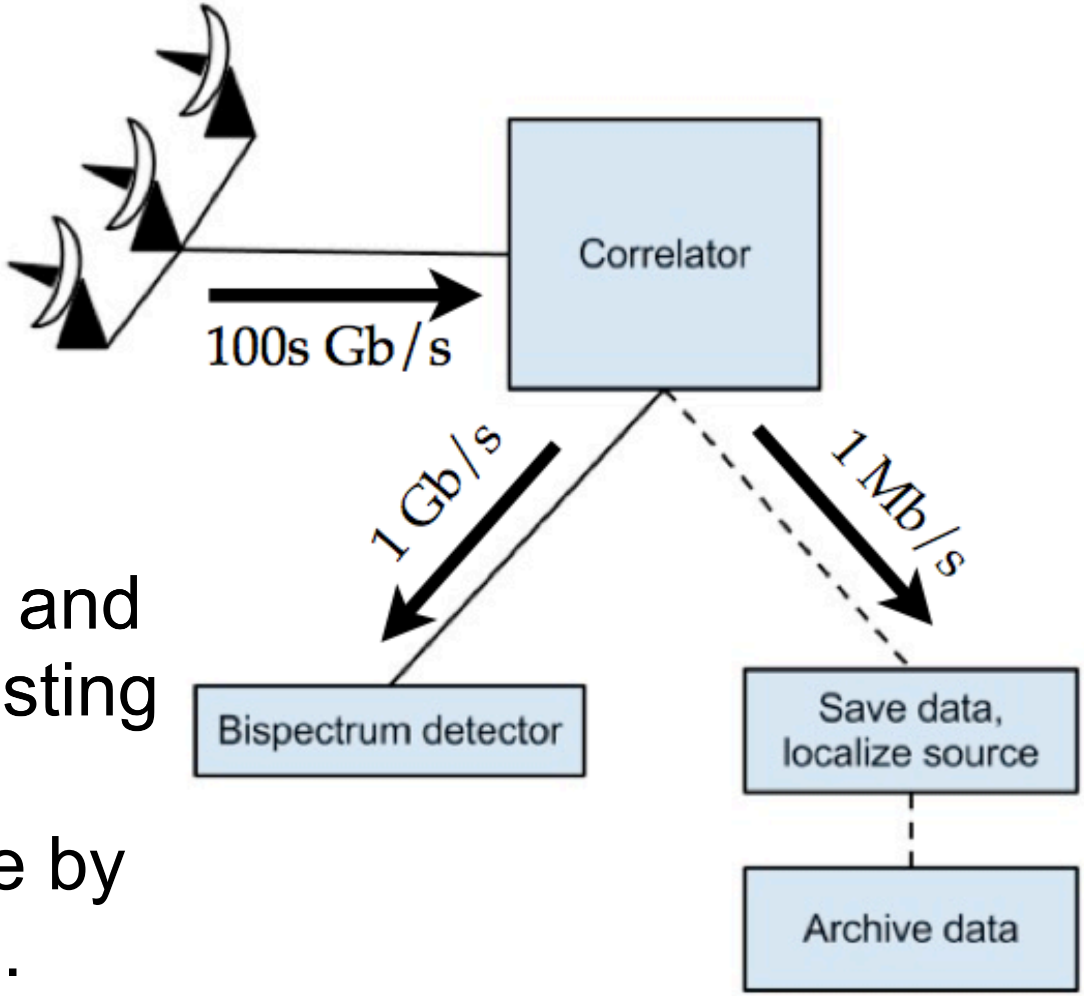


- Computational demand *much* lower than traditional beam-forming.

Law

Bi-spectrum detection method

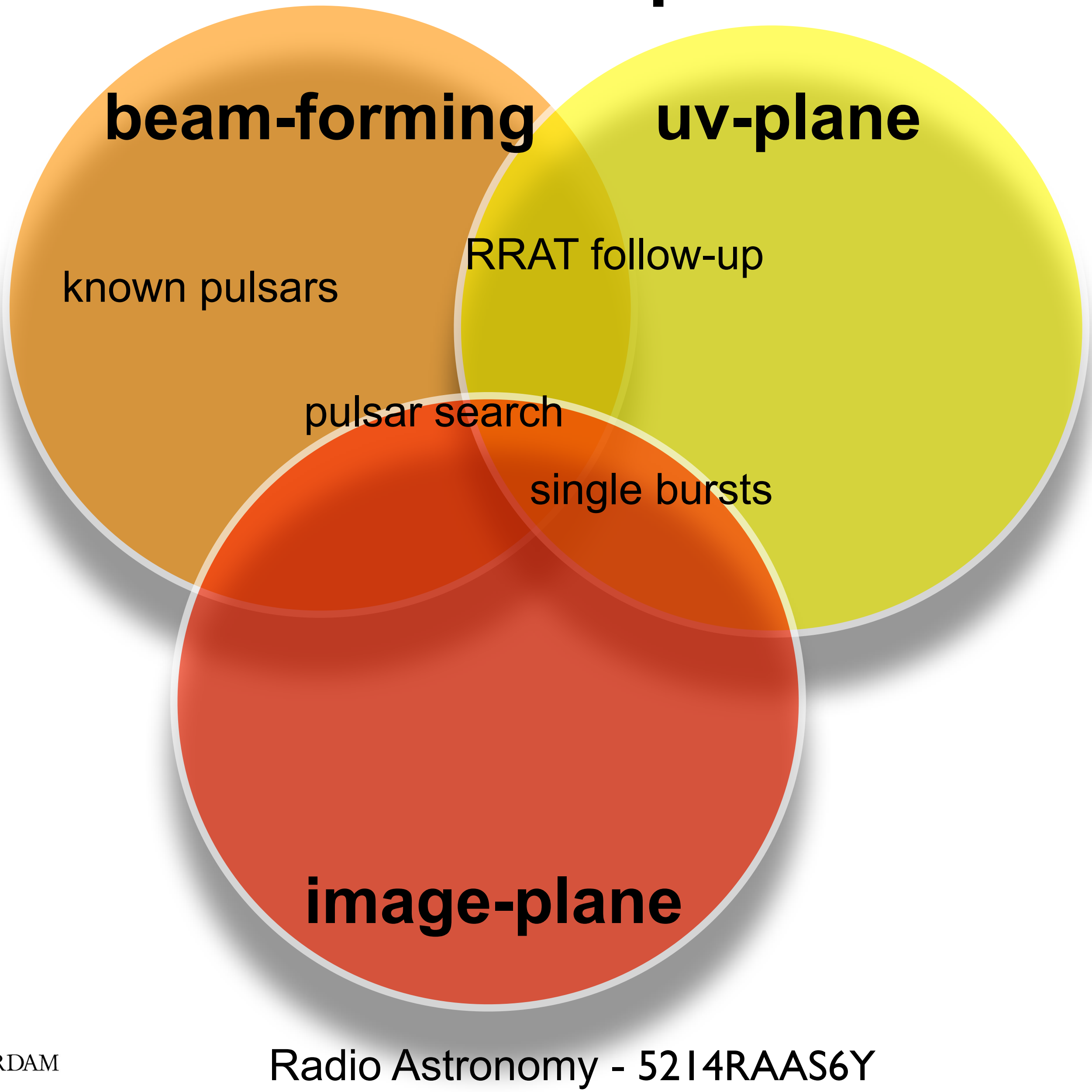




- Perform detection online and then dump the most interesting data.
- Reduces output data rate by many orders of magnitude.

Law

Fast Transient Detection Techniques



beam-forming

uv-plane

image-plane

known pulsars

RRAT follow-up

pulsar search

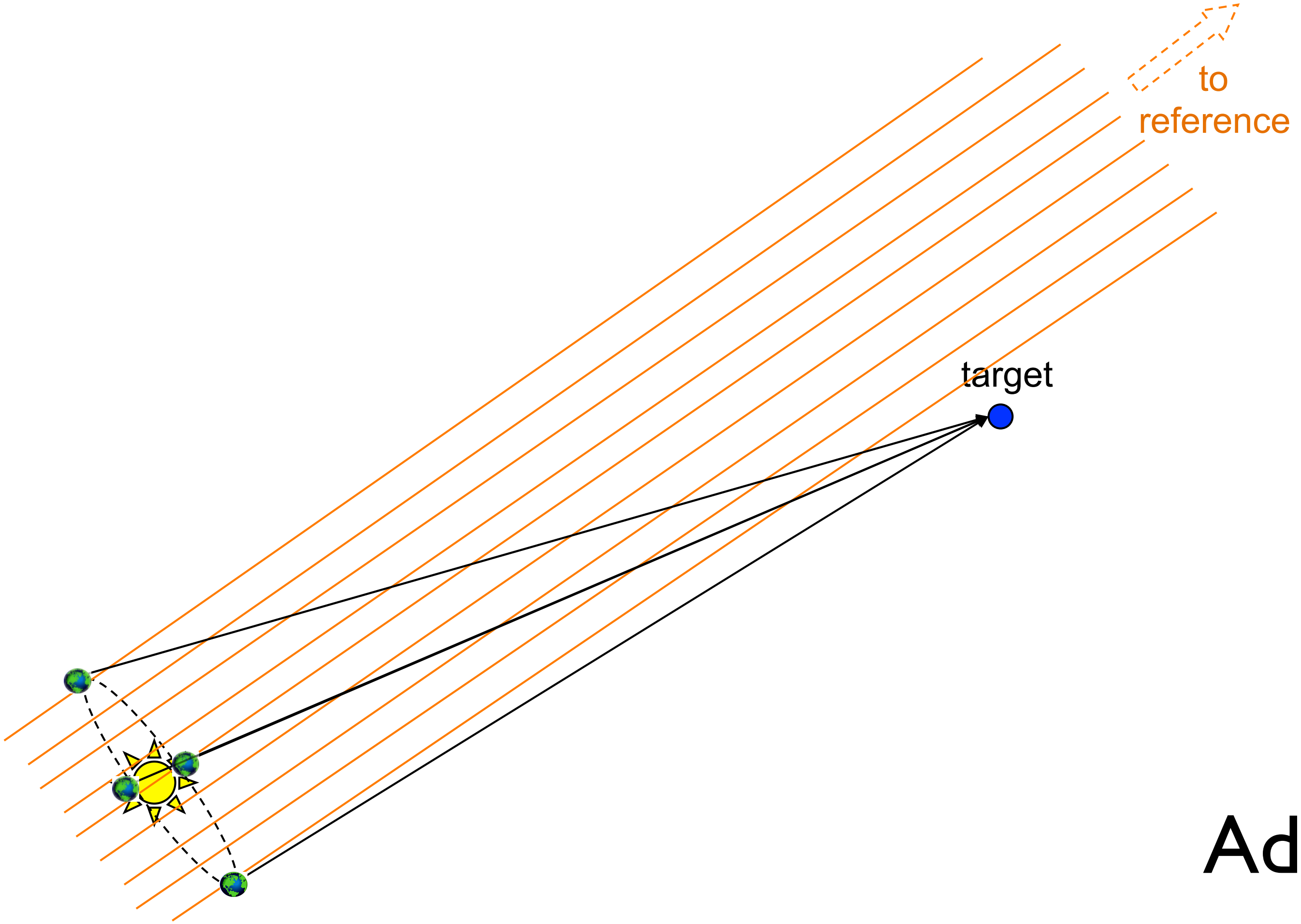
single bursts

Astrometry and pulsar distances

Astrometry

- Astrometry is the concrete base supporting all distance models.
- Distance ladder reaches from precision parsec-level measurements in our Galaxy out to inferred Gpc cosmological distances.
- Incredibly important because the scientific consequences of distance are far-reaching (e.g. luminosity is proportional to distance squared).

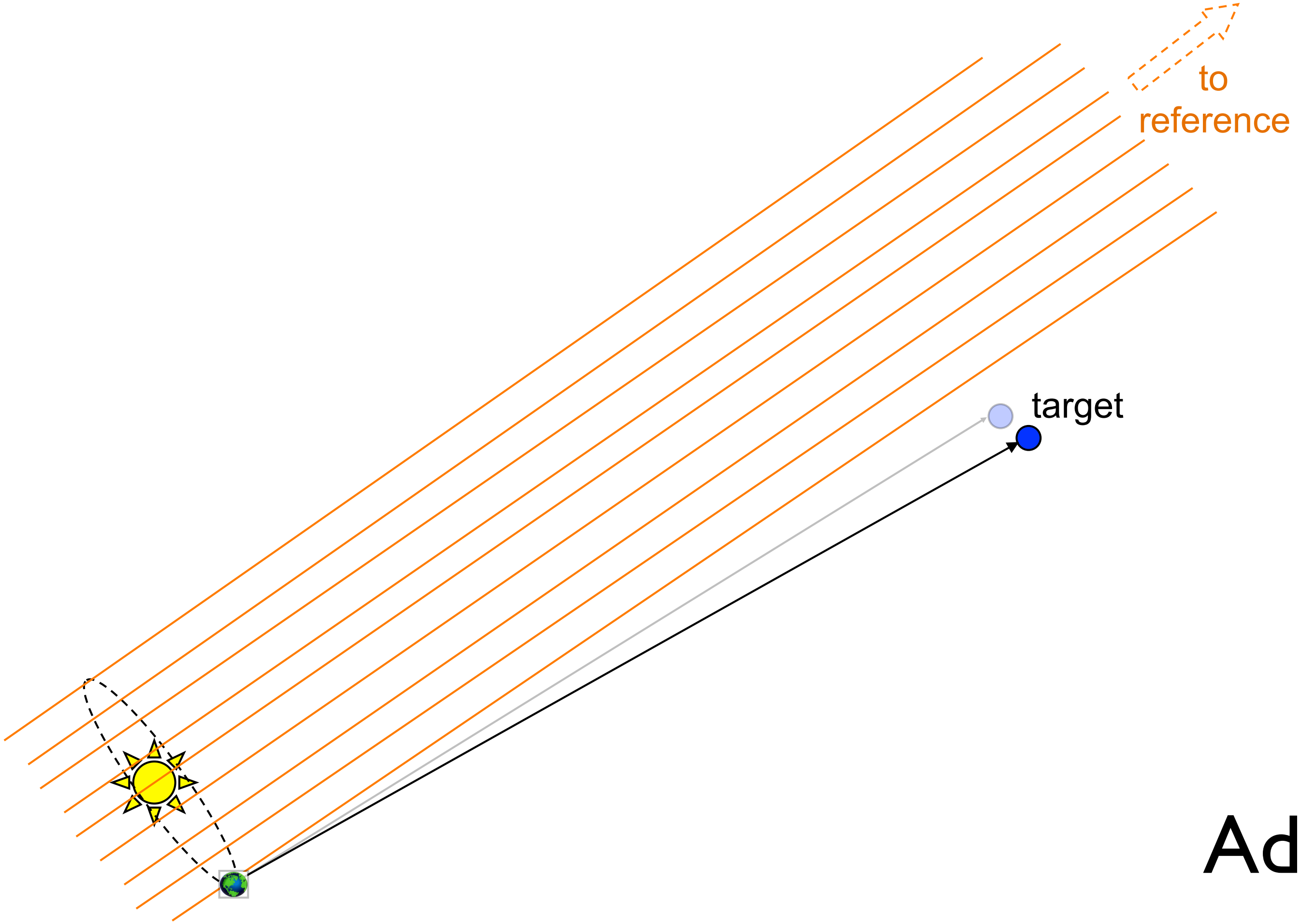
Distance and Velocity via Astrometry



Adam Deller

- Measure positions over time with respect to a fixed reference frame.

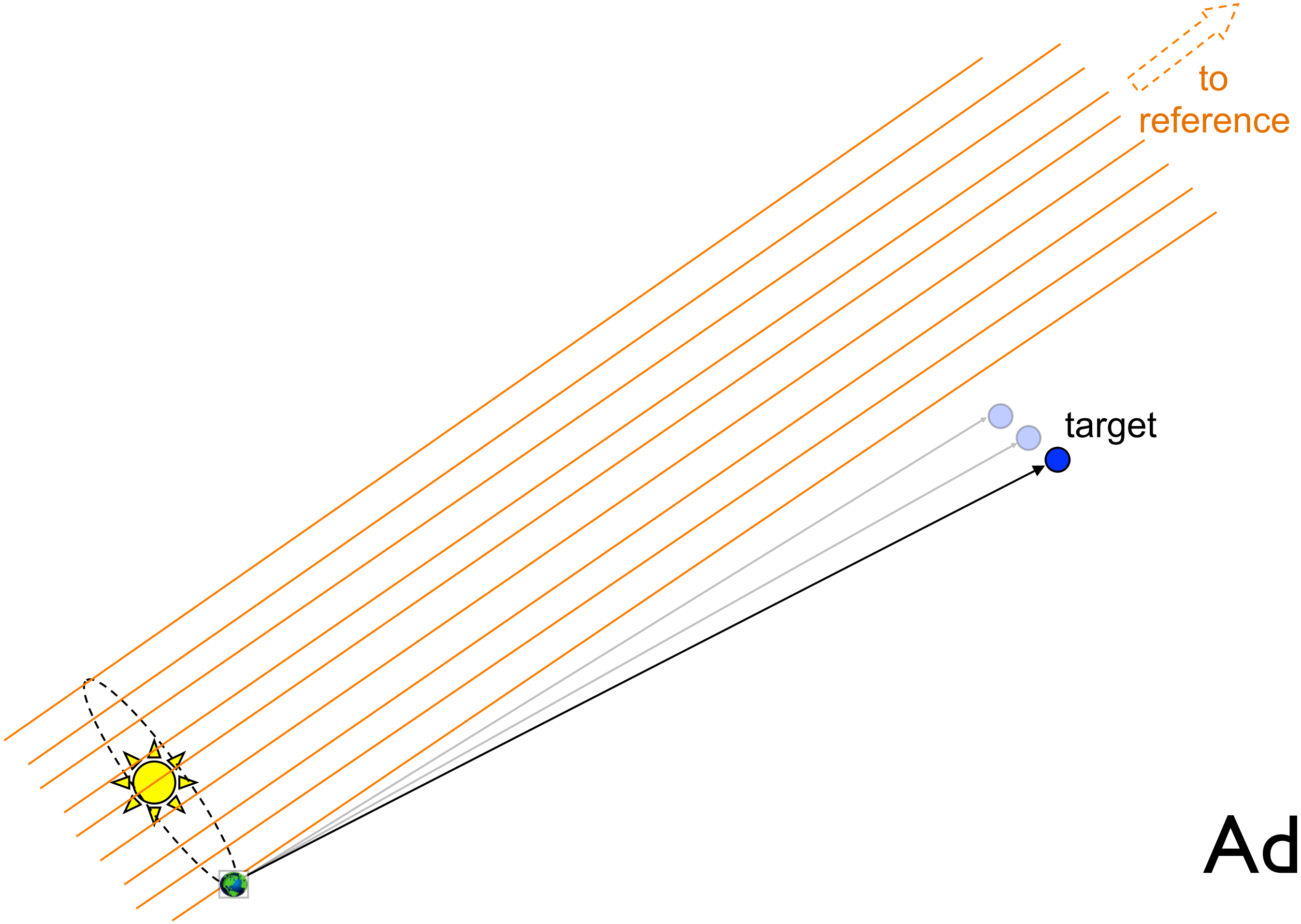
Distance and Velocity via Astrometry



Adam Deller

- Measure positions over time with respect to a fixed reference frame.

Distance and Velocity via Astrometry



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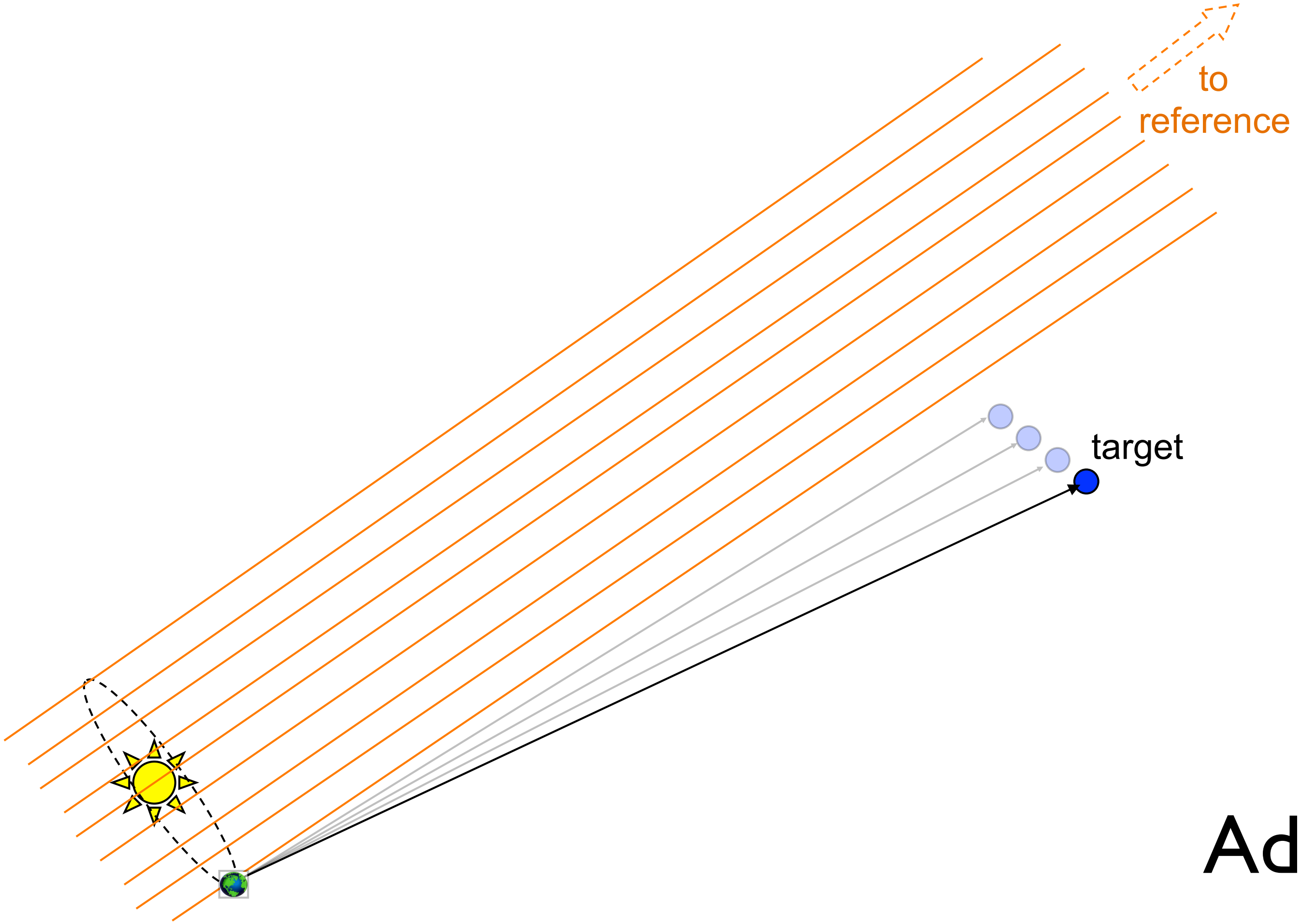
Distance and Velocity via Astrometry

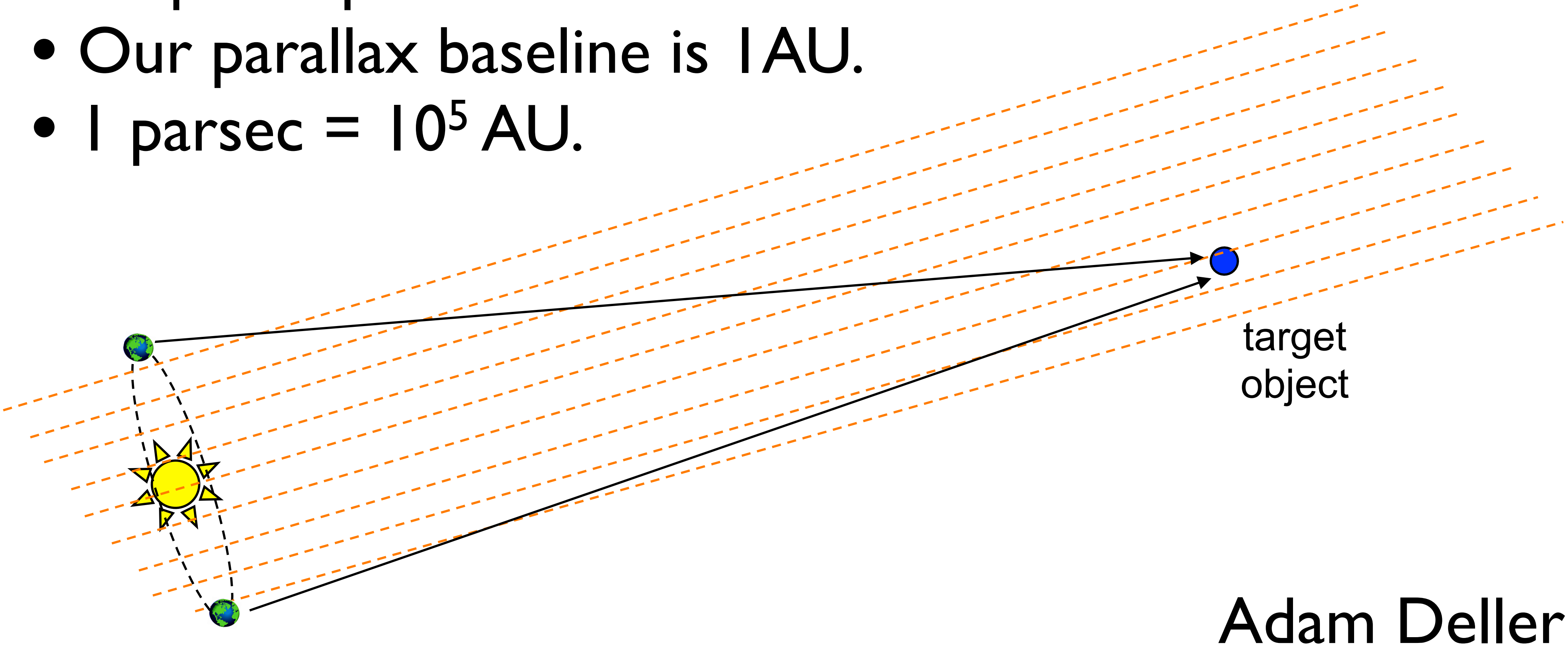


Adam Deller

- Measure positions over time with respect to a fixed reference frame.

Distance and Velocity via Astrometry

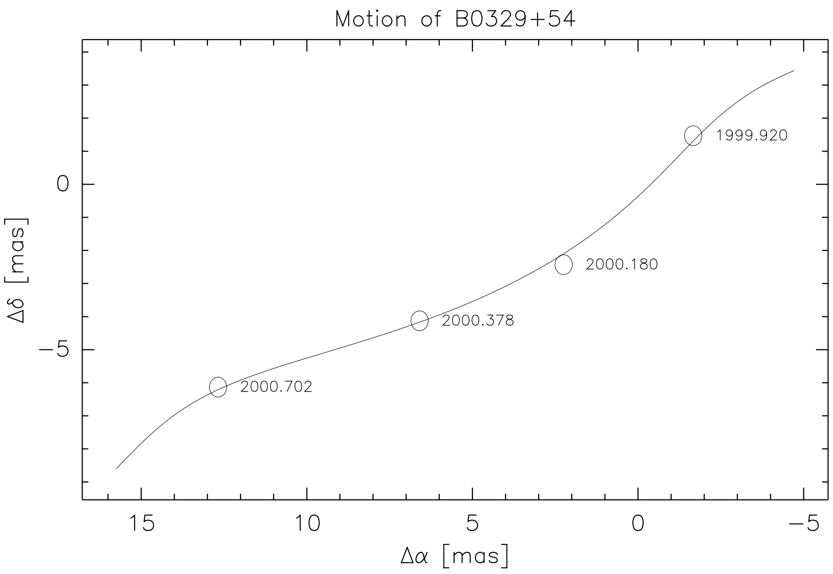
- Required precision is extreme.
- Our parallax baseline is 1AU.
- 1 parsec = 10^5 AU.

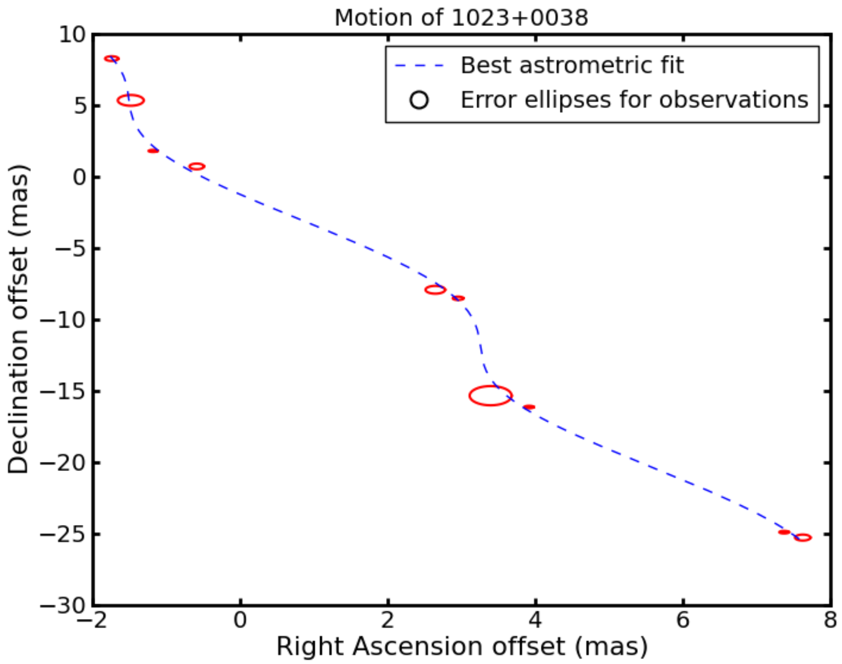


Adam Deller

- Distance scale in Galaxy (~kpc) is foreshortened by a factor of 10^8!

Pulsar Astrometry with VLBI





- Very Long Baseline Interferometry (VLBI) has the precision to measure both the proper motion and distance to pulsars given multi-year monitoring campaigns.
- Linear trend is the proper motion. Extra "squiggle" is from parallax.

Chatterjee, Deller

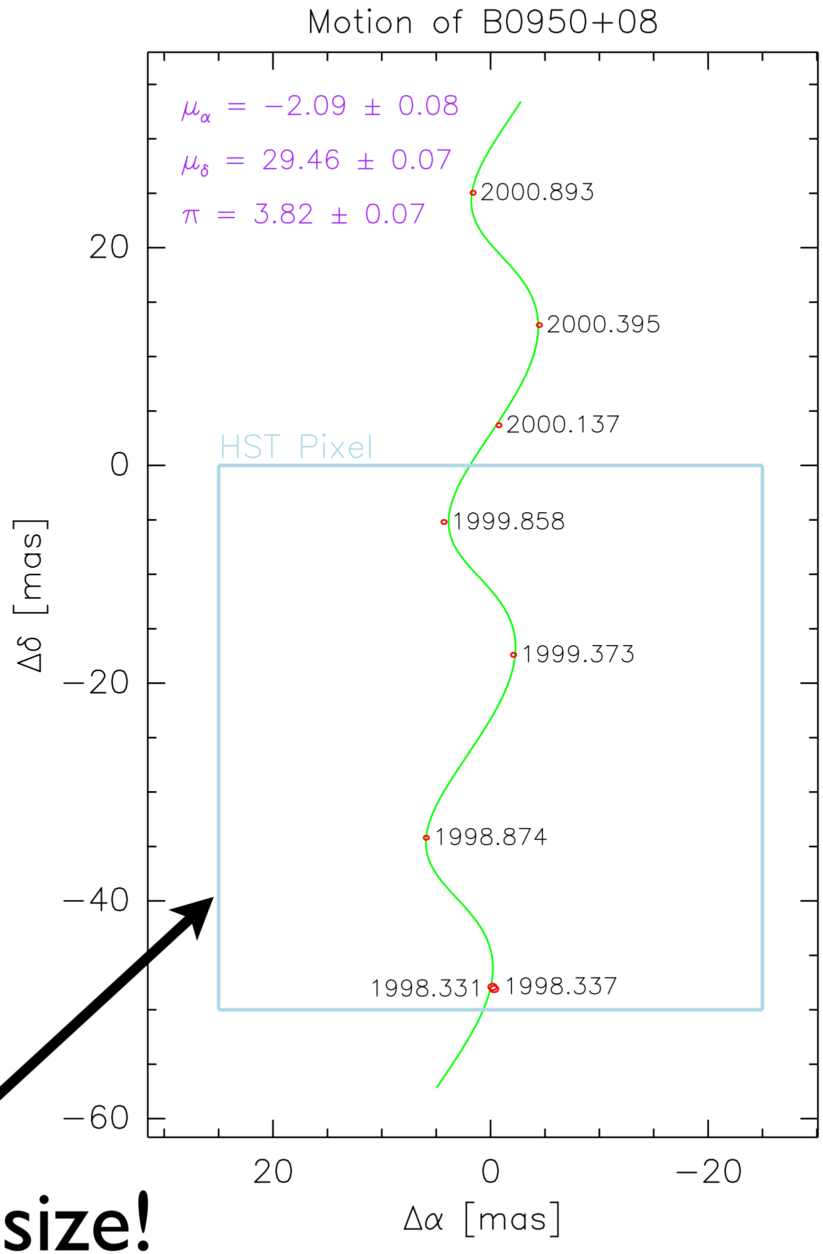
Pulsar Astrometry with VLBI

Distance (kpc)	**Velocity** (km/s)	**Parallax** (mas)	**Proper motion** (mas/yr)
0.1	10	10	21.1
10	200	0.1	4.2
770	100	0.0013	0.027

Current Galactic applications

Tiny fractions of a resolution element, even for e.g. Hubble (50+ mas)

- Need 10's-100 *micro*-arcsecond precision on the position at each epoch.



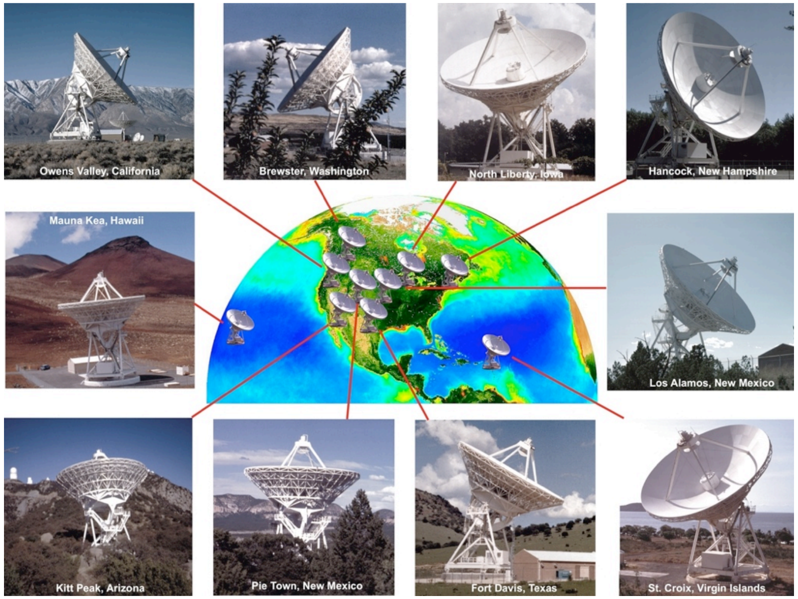
Hubble pixel size!

Adam Deller

Astrometry with VLBI

$$\Theta = \frac{\lambda}{D}$$

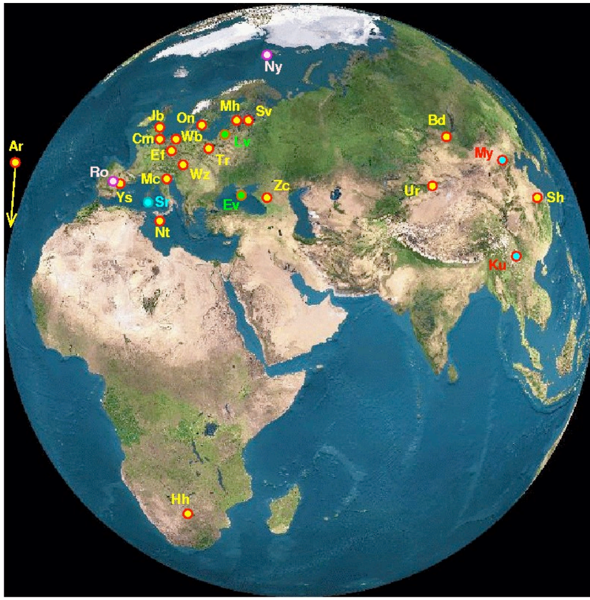
$$\lambda \sim \mathrm{cm}$$
$$D \sim 1000\mathrm{km}$$
$$\Theta \sim \mathrm{mas}$$



VLBA, USA

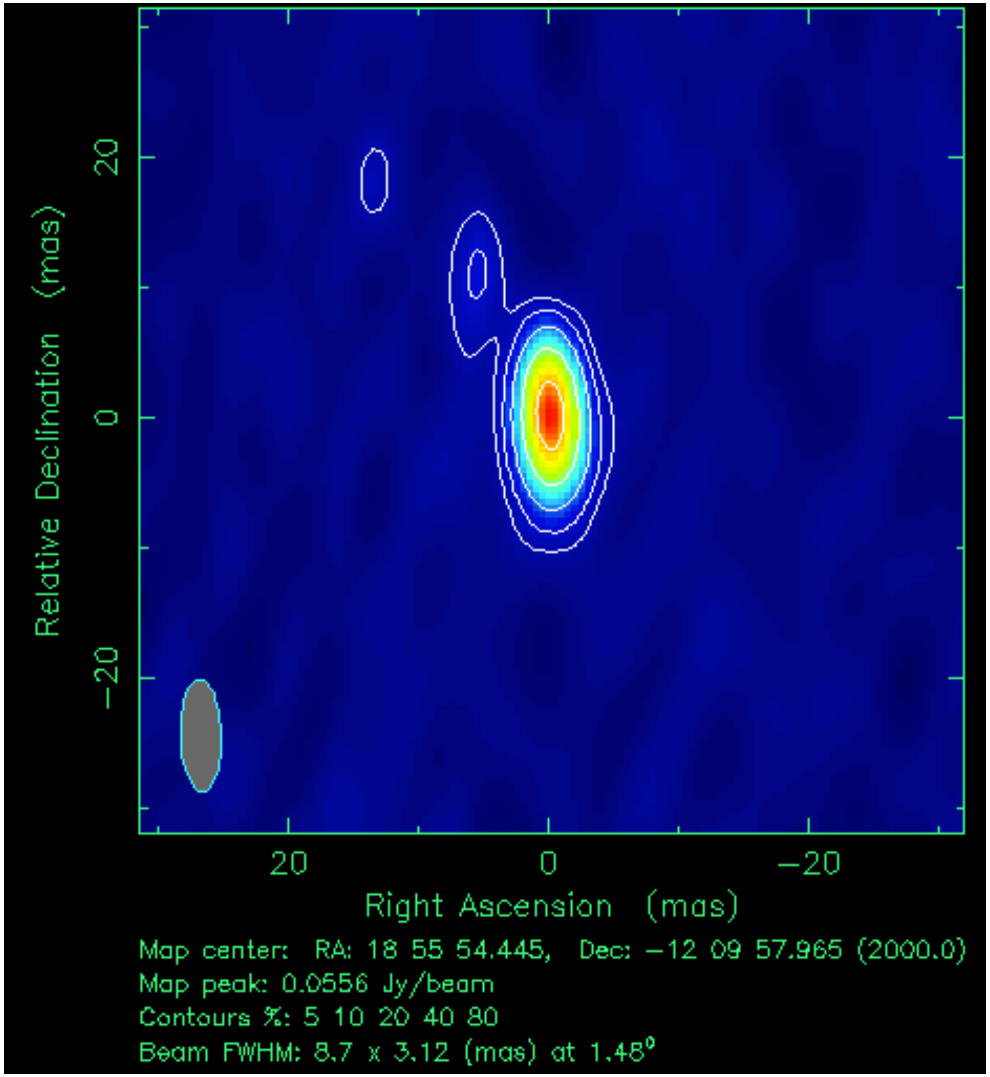
Image by Paul Boven (boven@jive.nl), satellite image by NASA Visible Earth (visibleearth.nasa.gov)

EVN, Europe



Global VLBI

Astrometry with VLBI



$$\delta(\mathrm{Position}) \sim \frac{\mathrm{PSF}}{2 \times \mathrm{S/N}}$$

- With proper calibration the beam size (PSF) is very stable and depends only on the antenna positions.

- Need to do better than just the beam size (PSF).

Astrometry with VLBI

Ideal situation

Take a short observation with the VLBA @ 8 GHz, with 1.25 hours on target:

- Beam size is 1 x 2 mas
- Image sensitivity is 35 Jy
- Say your source is 1 mJy (faint!), giving you a modest S/N ~ 30
- Your limiting positional accuracy will be 1/60 mas = **16 micro-as**!
- With more integration time/more sensitive arrays/brighter sources it is trivial to do many times better

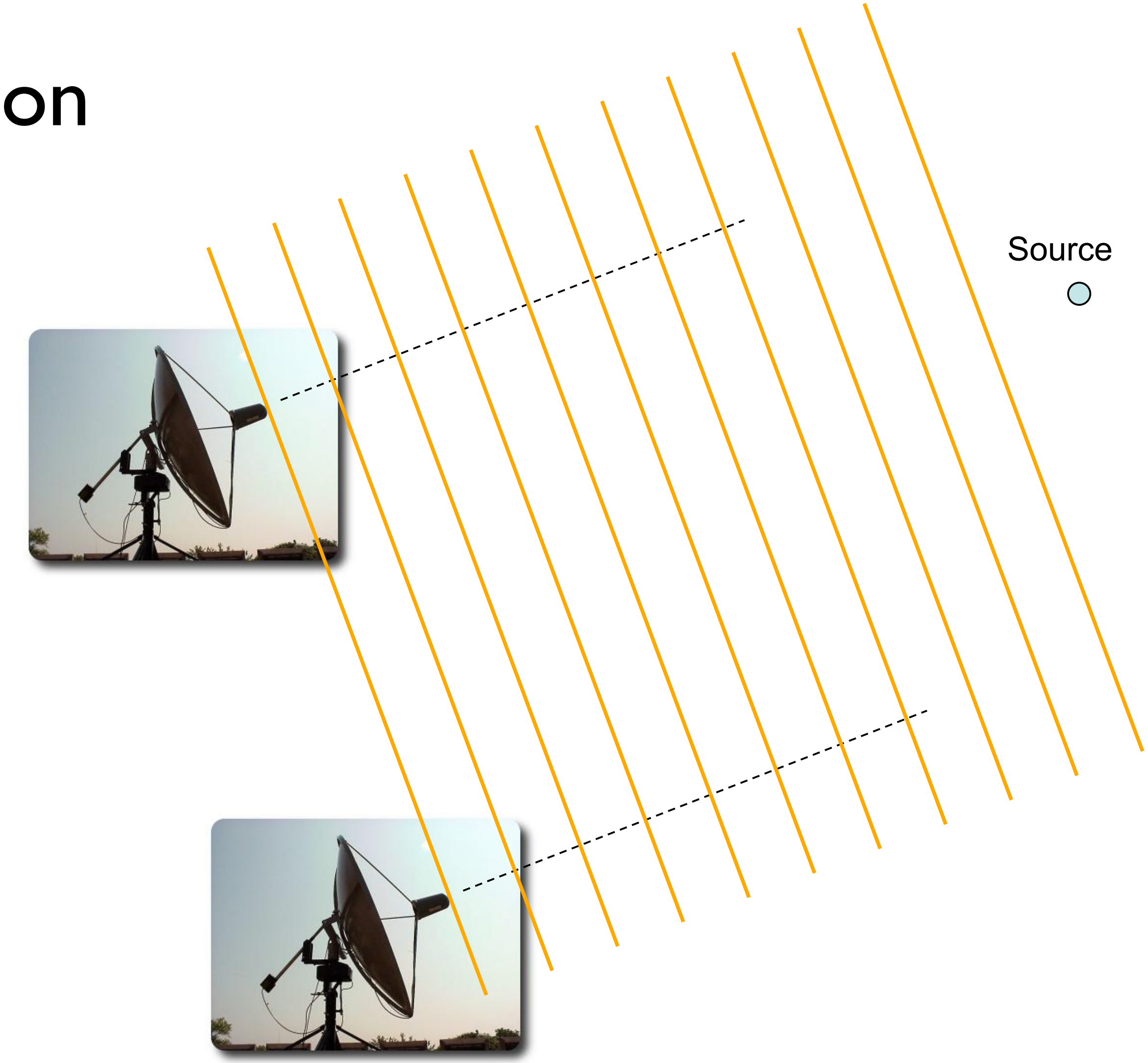
…in theory

Real world situation

Anything which causes relative delays in the arrival time of the signal will lead to errors in positional estimation

Astrometry with VLBI

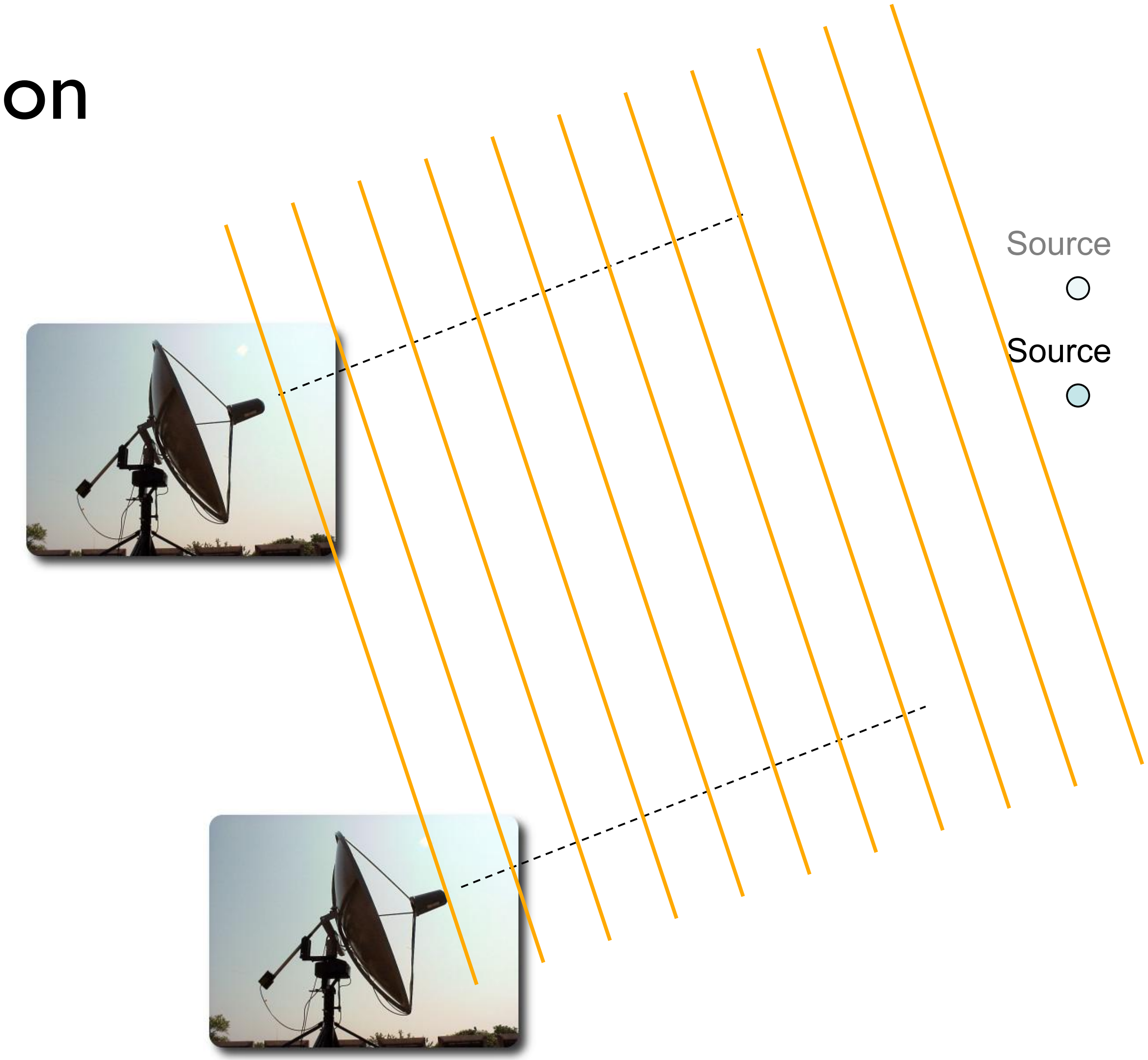
Ideal situation



Minute change in source position will cause a minute but measurable differential arrival time

Astrometry with VLBI

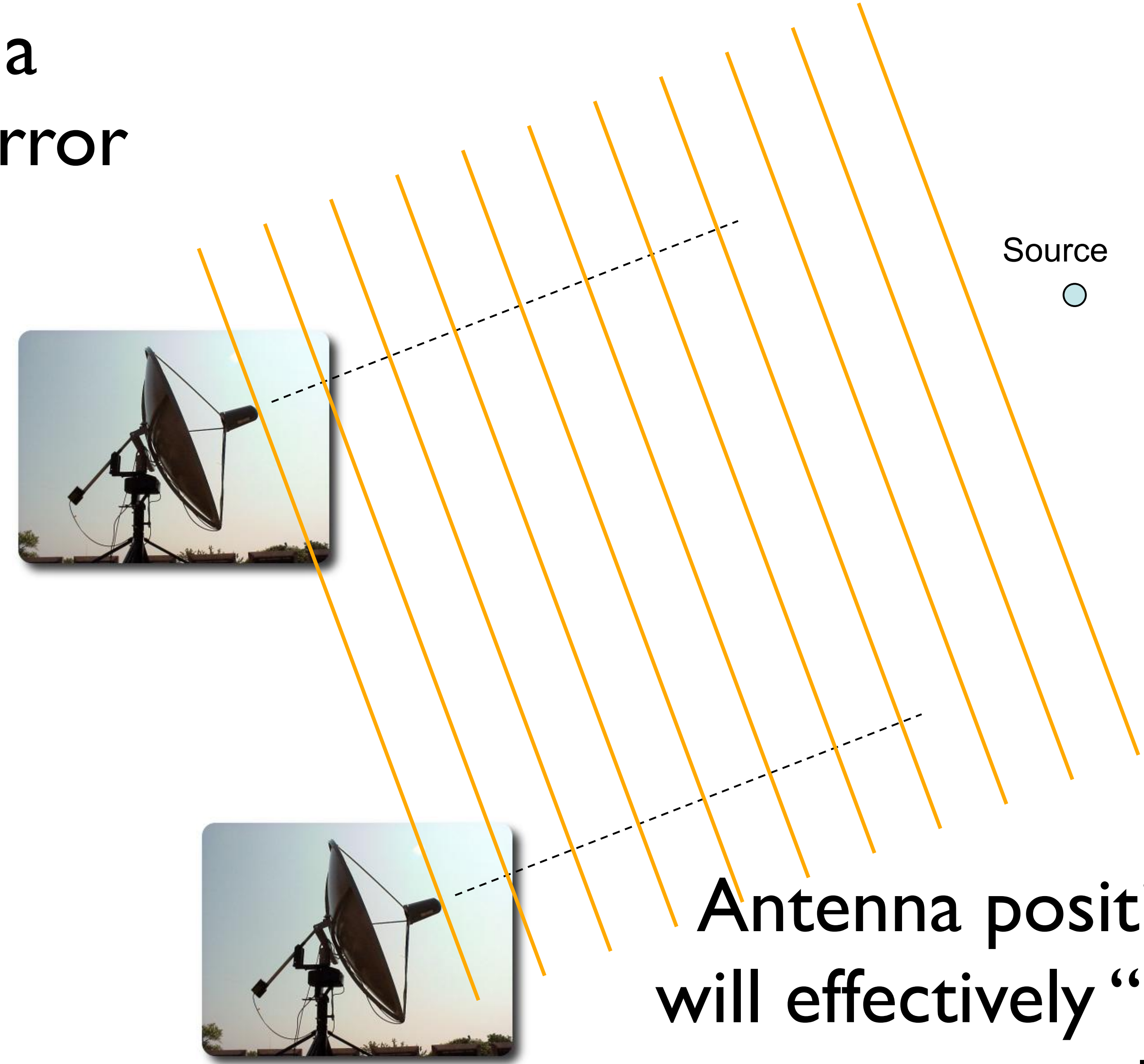
Ideal situation



Long baselines are critical for getting the "lever arm" necessary to see the small position change

Astrometry with VLBI

Antenna position error

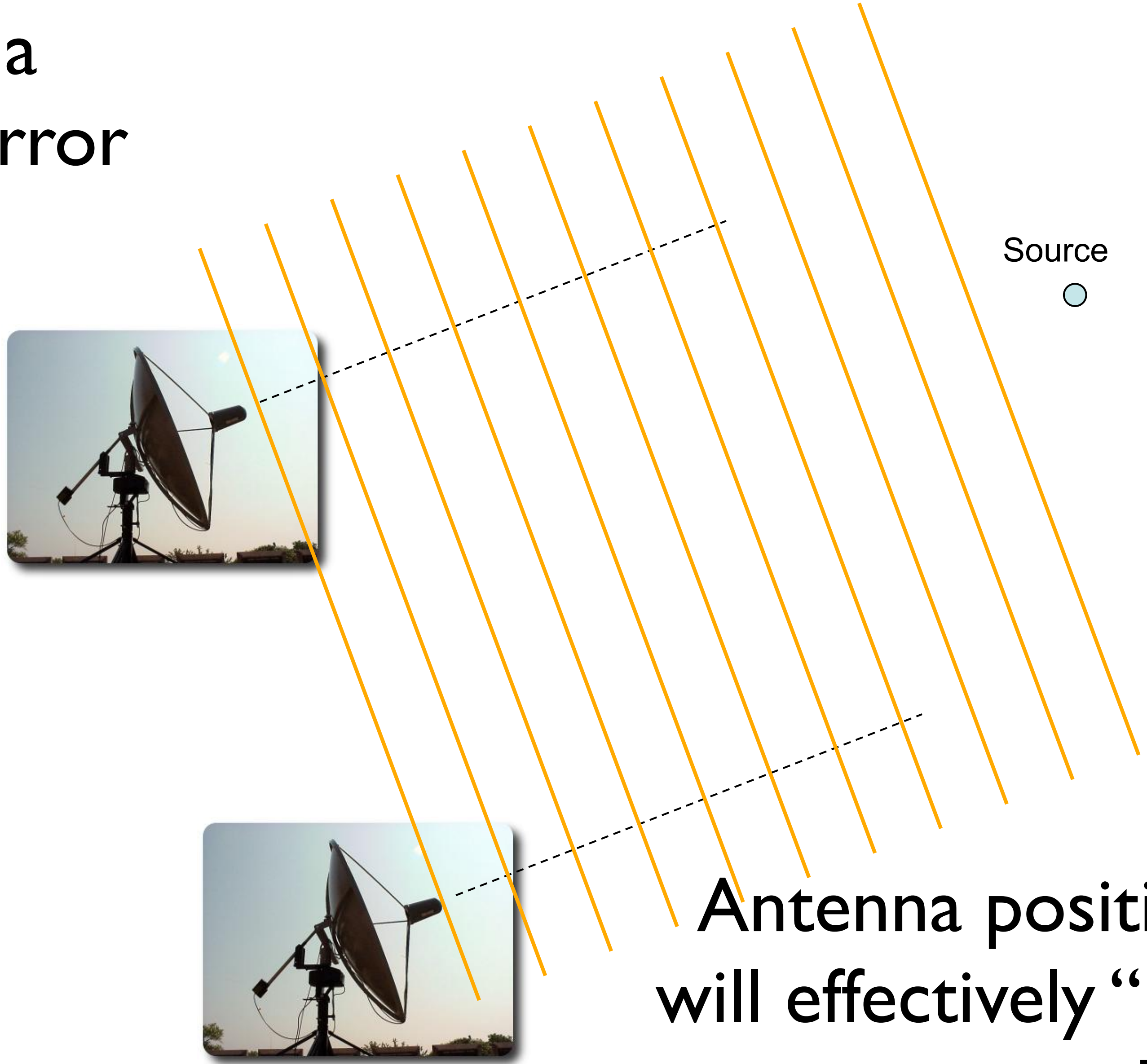


Correct position

Antenna position error will effectively “move” the source on the sky!

Astrometry with VLBI

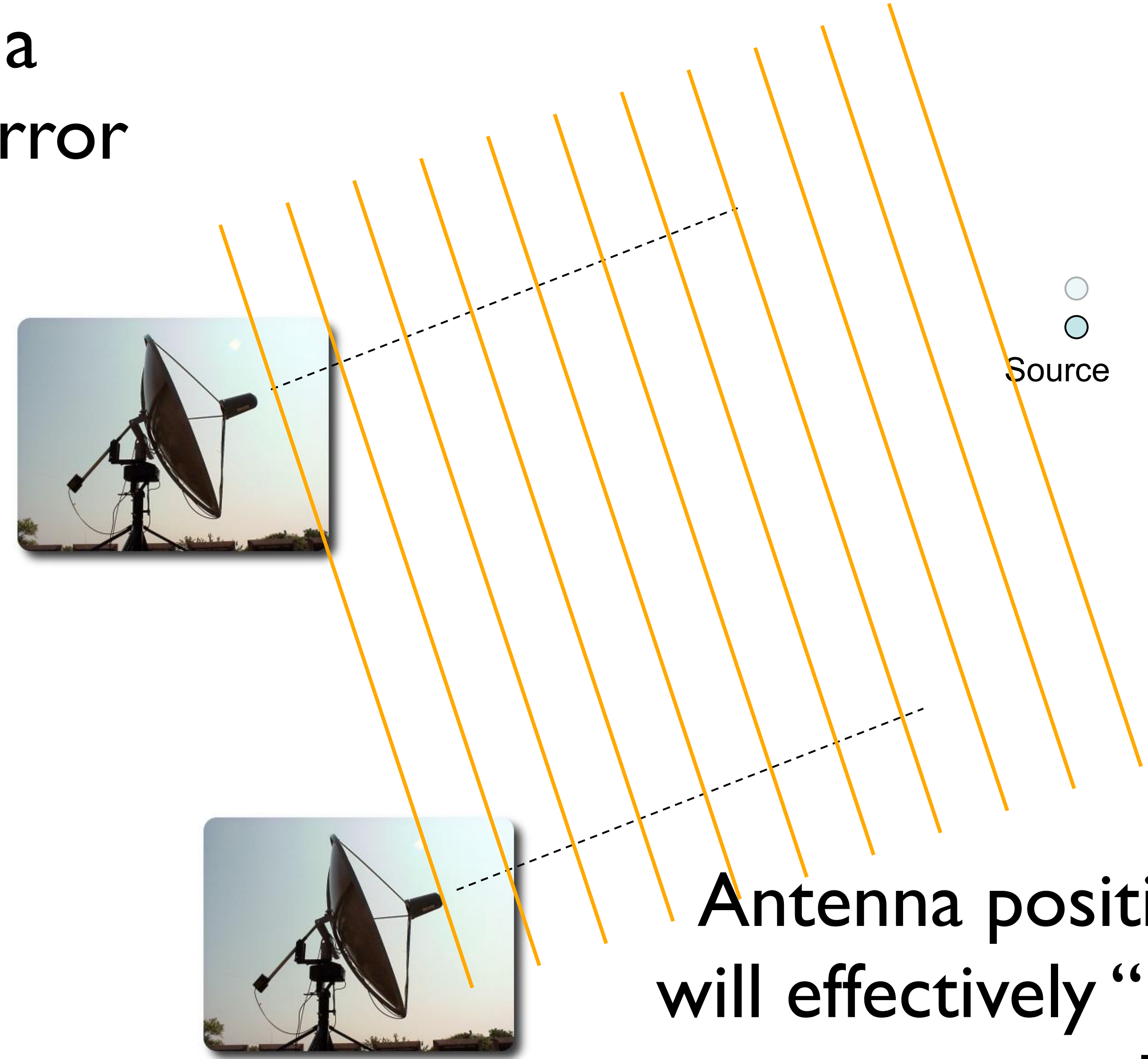
Antenna position error



Incorrect position

Antenna position error will effectively “move” the source on the sky!

Astrometry with VLBI



Antenna position error

Incorrect position

Incorrect source position

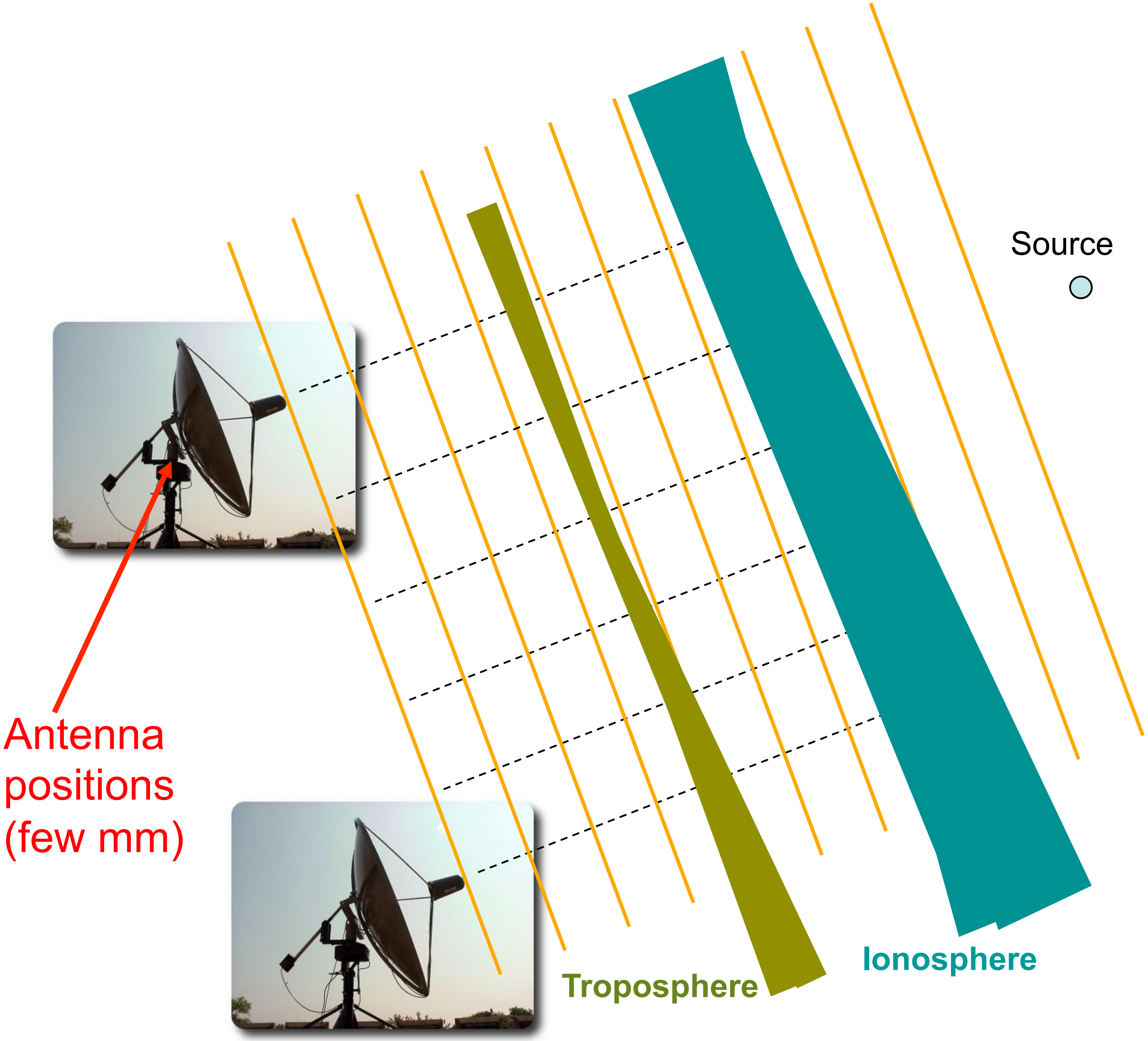
Antenna position error will effectively “move” the source on the sky!

Astrometry with VLBI

Real world situation

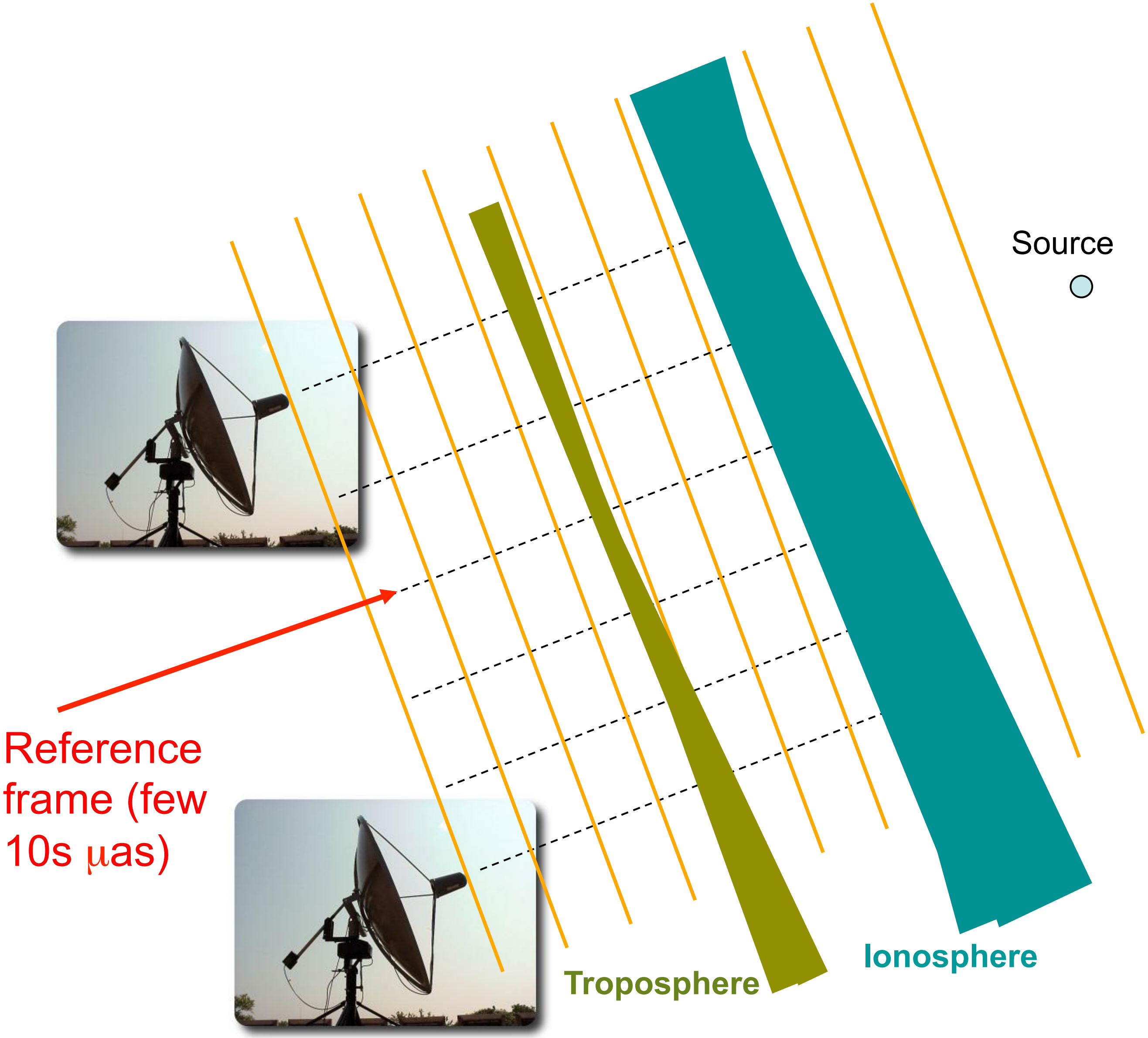
- **Anything** which causes relative delays in the arrival time of the signal will lead to errors in positional estimation
- The control of systematics has to be phenomenal:
  - 10 as angular change (5 x 10^{-11} radians) induces differential delay ~ **1 picosecond** on a 5000 km baseline
  - Equivalently, a path length error of 0.3 mm

Astrometry with VLBI



- Relative antenna positions (w.r.t. each other) are known to a few mm precision.
- These are constantly changing due to continental drift.

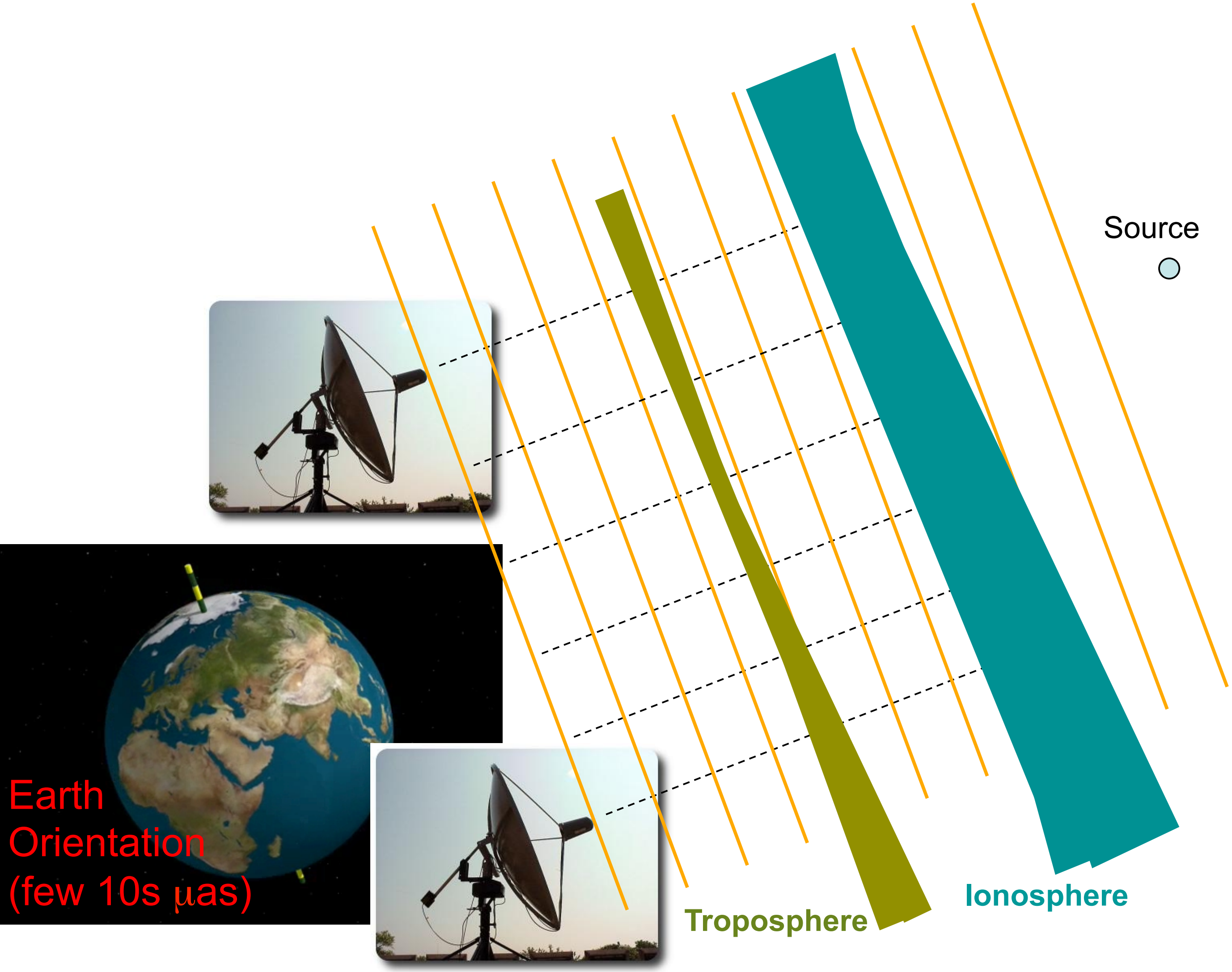
Astrometry with VLBI



Reference frame (few 10s μas)

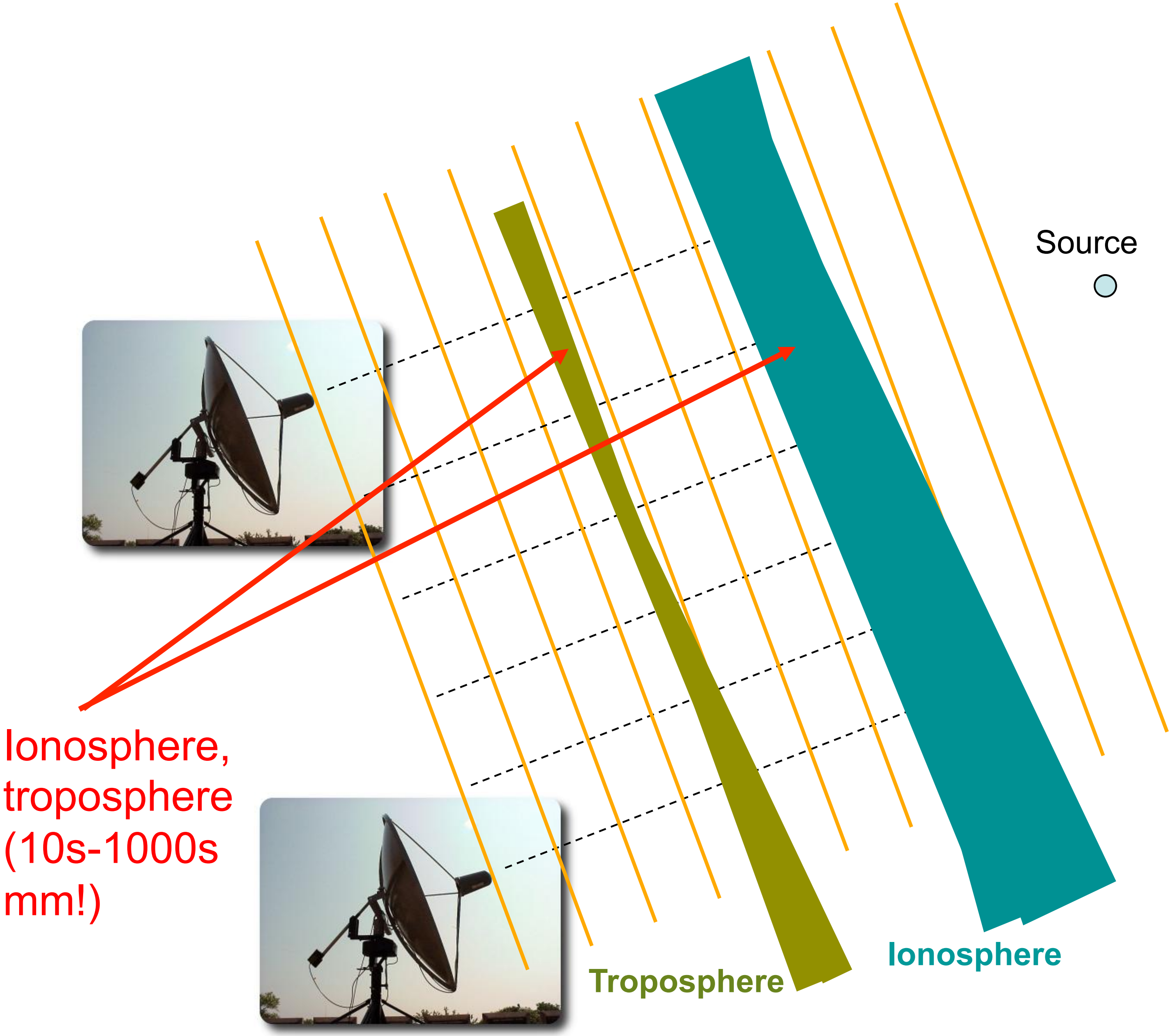
- Reference frame (e.g. J2000) itself is good to ~10s microarcseconds.

Astrometry with VLBI



- Earth orientation changes with time due to precession and nutation. This also introduces inaccuracies on the 10s microarcsecond level.

Astrometry with VLBI



- Ionosphere and troposphere are highly dynamic, even on a few minute timescale.
- Depends on latitude, season, time of day, Solar activity, etc.
- Ionosphere a big problem at low frequencies.

Atmospheric Effects

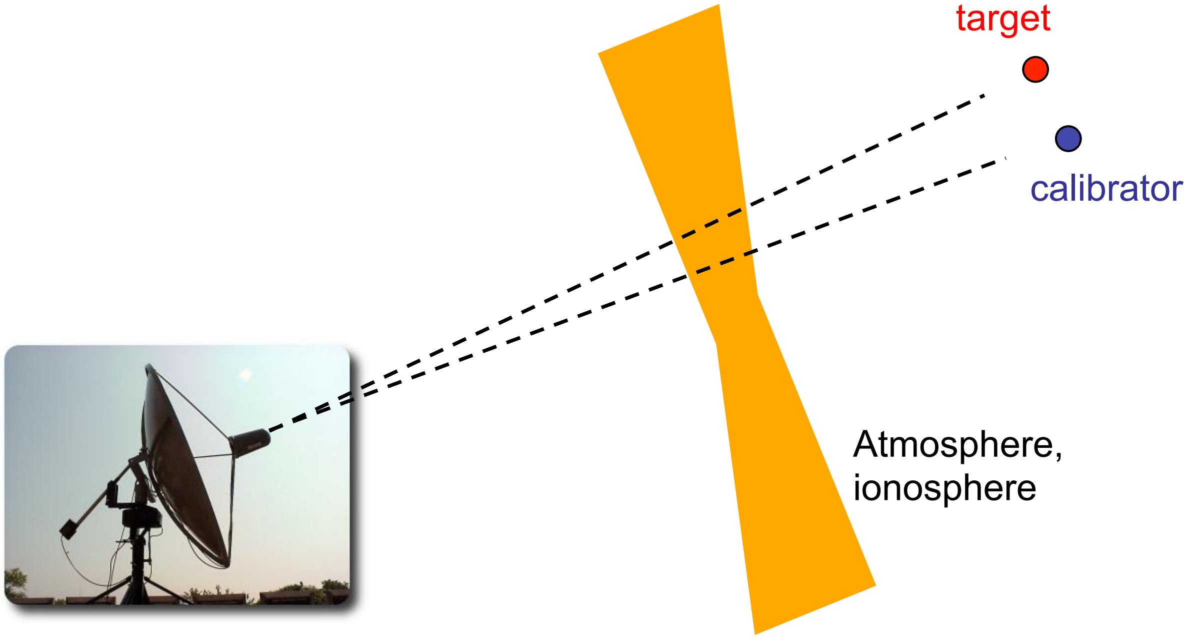
Troposphere: bulk of atmosphere mass

- Non-dispersive (freq. independent) delay
- Depends on latitude, weather etc but predictable; with good model error ~50 mm

Ionosphere: charged particles, higher

- Ionised -> dispersive delay
- Highly dependant on solar weather, much less smooth than troposphere
- 1.6 GHz, good model + good day, error ~500 mm!

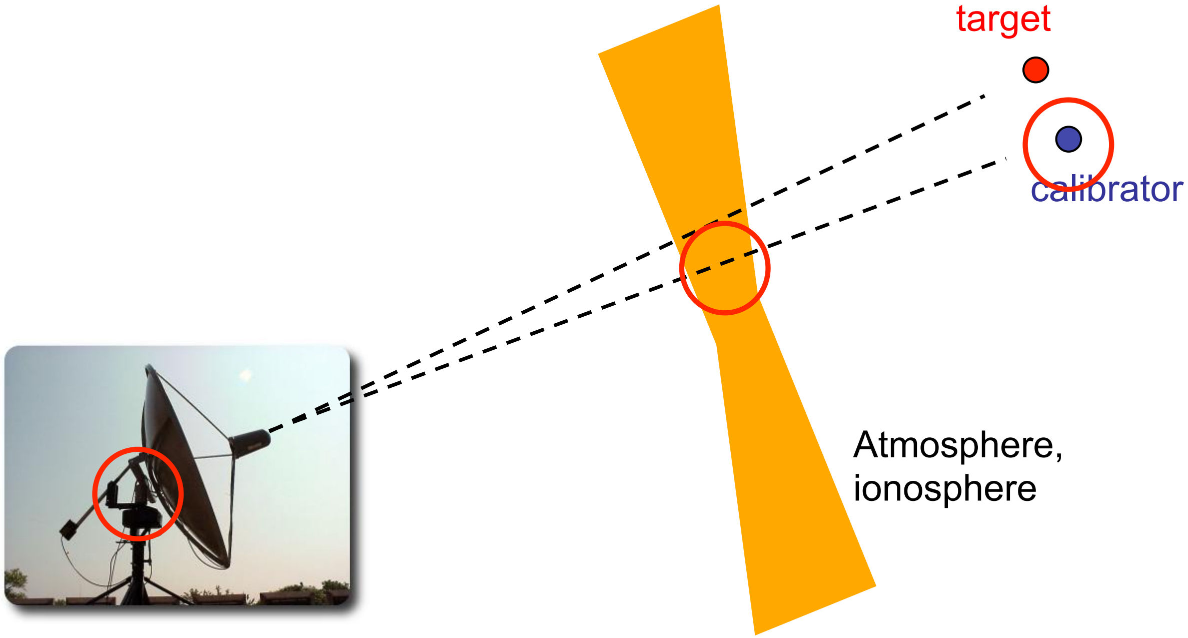
Relative Astrometry



Calibrate: nearby astronomical source

- Solve for and remove sum of all delays; residual will be of order sin(separation).
- Accuracy is seriously limited if a good nearby calibrator cannot be found.

Relative Astrometry



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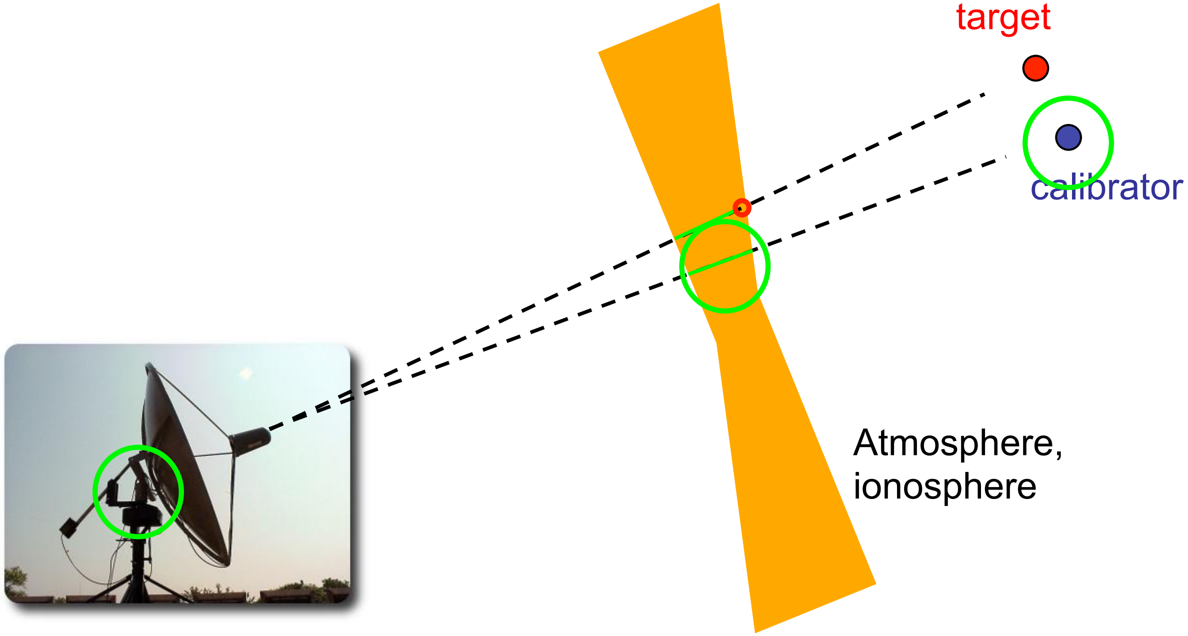
Relative Astrometry



- Very important that the calibrator is unresolved and stable. It's the reference point after all...

Relative Astrometry

Getting ultimate positional accuracy of 20 microarcsec requires each measurement to have an accuracy of ~50 microarcsec

Corresponds to a path length of ~1.5 mm

High frequency (≥ 8 GHz, troposphere dominates):

Need a calibrator source within ~2°

Low frequency (~1.6 GHz, ionosphere dominates):

Need a calibrator source within ~10’

Pulsar Astrometry

Radio pulsars tick every box as interesting astrometric targets:

1) Compact
2) Hugely scientifically interesting: as gravitational wave detectors, probes of strong field gravity, dense nuclear matter, high energy emitters…
3) And: mostly, distance precision is appalling!

Pulsar Astrometry

(Refine distances to) the
same objects we search for

Exotic objects

Triple system,
pulsars with PWN...

Population analysis

Shklovskii corrections,
velocities...

Multiwavelength observations

Get an accurate luminosity
(e.g. FERMI sources)

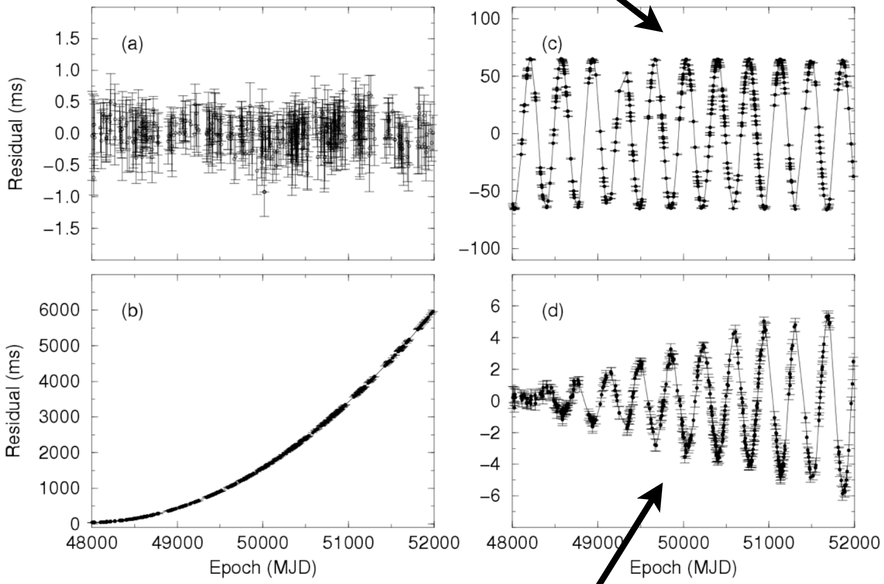
Tools for fundamental physics

PSR B1913+16

- Accurate and precision distance aids almost all areas of pulsar science.

Pulsar Astrometry

Signature of incorrect position

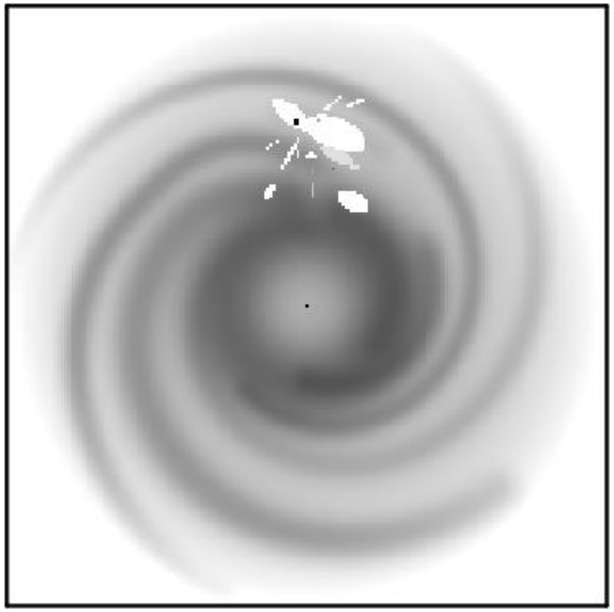


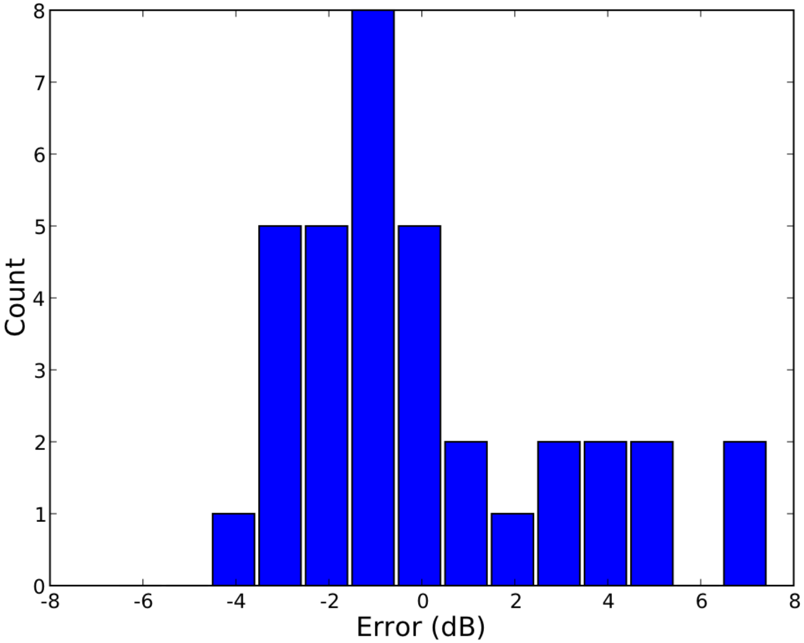
Proper motion signature

Pulsar timing residuals

- Recall that pulsar timing can give milliarcsecond positions and proper motions.
- Getting distance is only possible in a few extreme cases (need to see the curvature in the wave front from the arrival times!).

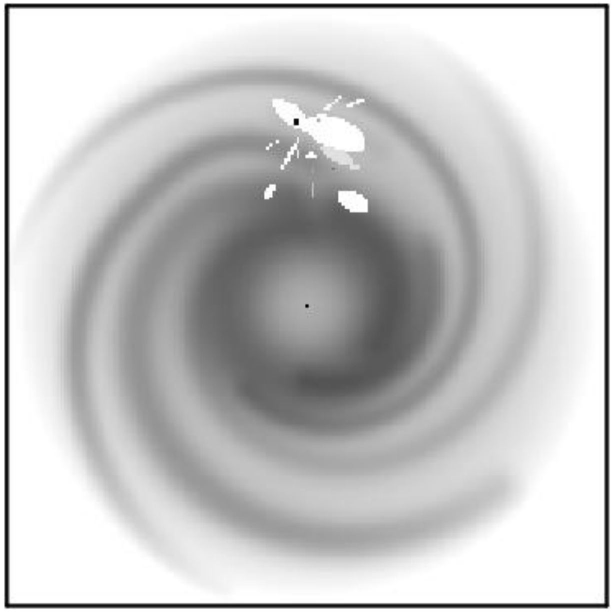
Pulsar Distances





- Top: the NE2001 electron density distribution model (Cordes & Lazio, 2002).
- Given a pulsar DM, can use NE2001 to get the distance.
- Problem: these are good to only about a factor of 2.
- Bottom: NE2001 distance errors compared with accurate astrometry measurements.

Pulsar Distances



The NE2001 model is anchored by just **112** distance measurements (plus some scattering measurements)

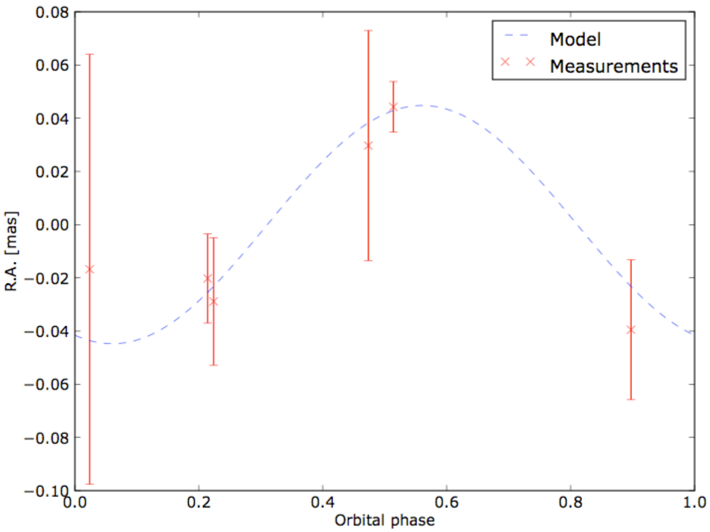
- Heavily concentrated in the solar neighbourhood
- Many are themselves model-dependent (HI plus Galactic rotation)
- Many are low quality - just **8** are model-independent with error of 10% or less

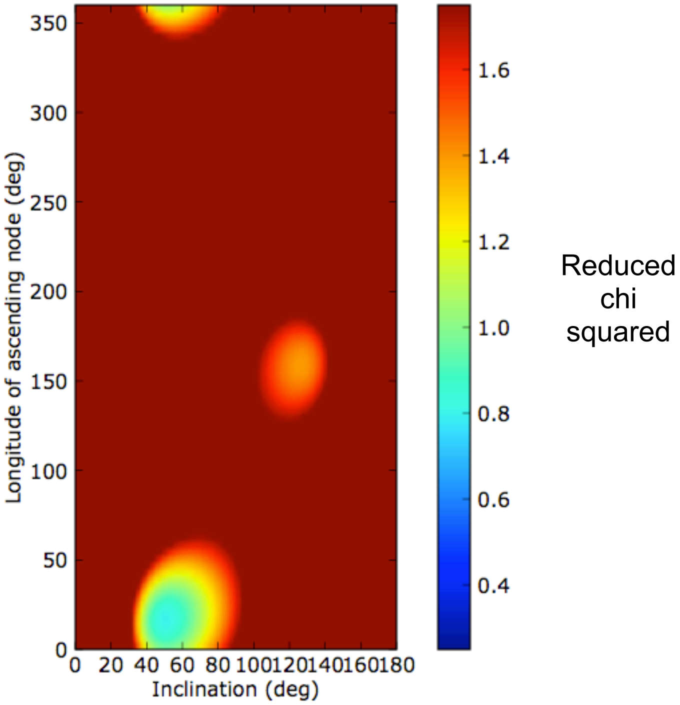
Binary Pulsar Astrometry

Example: PSR J1022+1001

- Observed by PPTA and EPTA
- 7.8 day binary, recycled (P=16 ms)
- Massive WD companion
- DM distance: relatively near (~600 pc)
  - Projected orbital motion ~ 50 microarcsecond
- Observational details:
  - 7 epochs (of 9 total) in hand
  - Pulsar is moderately bright, ~3 mJy

Binary Pulsar Astrometry





Full orbital solution:
- 39deg < inclination < 63deg
- -5deg < Omega < 40deg

Parallax 1.438 +/- 0.010 milliarcsec
- Distance 695 +/- 4 pc
- Transverse velocity 52.5 +/- 0.3 km/s

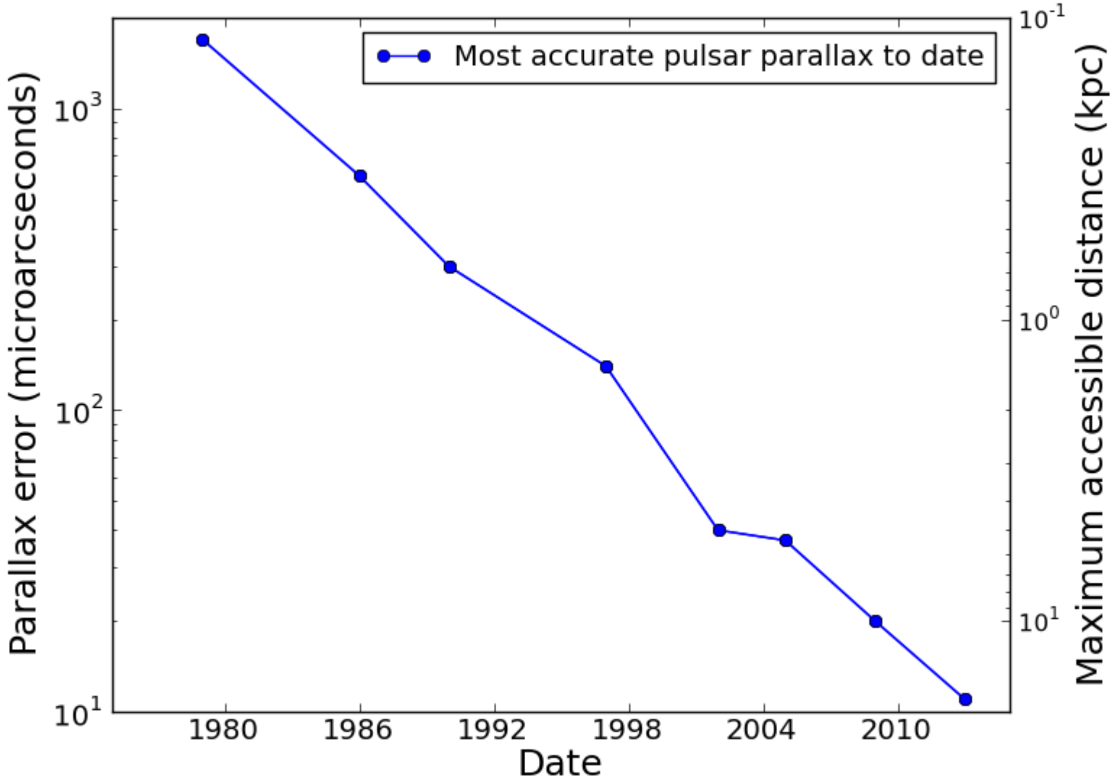
Needed just ~10 hours of VLBA time

Refined timing solution to come

Precise white dwarf constraints

Similar results for J2145-0750

VLBI Precision



- VLBI astronometry with the SKA will likely be a big business.

Sources

Figures from Adam Deller, Casey Law, and other (cited on slide)

Other course slides (see links on course wiki page):

http://www.astron.nl/astrowiki/doku.php?id=uva_msc_radioastronomy_2013