

Time-Domain Astronomy

Jayanta Roy
NCRA-TIFR

NCRA-IUCAA Graduate School

5th May 2026

Radio Interferometers

Primary Aim: Many antennas emulate a large dish

Resolution: $\theta \approx \lambda / B_{\text{max}}$ (baseline sets resolution)

u-v coverage: Earth rotation fills Fourier plane $\rightarrow$ better images

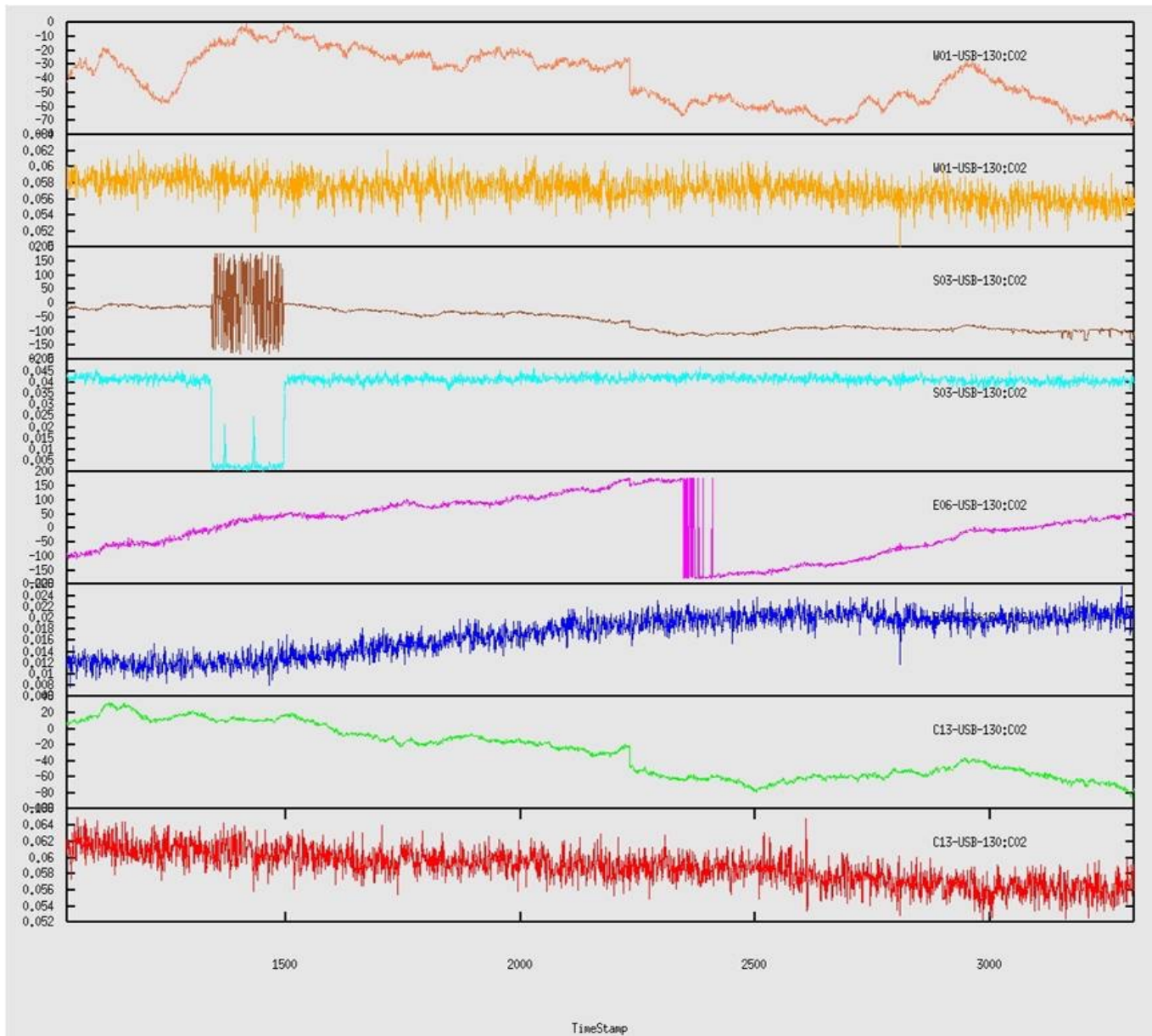
Sensitivity of a single baseline (two identical antennas)

$$\sigma_S = \frac{T_{\text{sys}}/G}{\sqrt{2 \Delta\nu \tau}}$$

Sensitivity of an array of N identical antennas

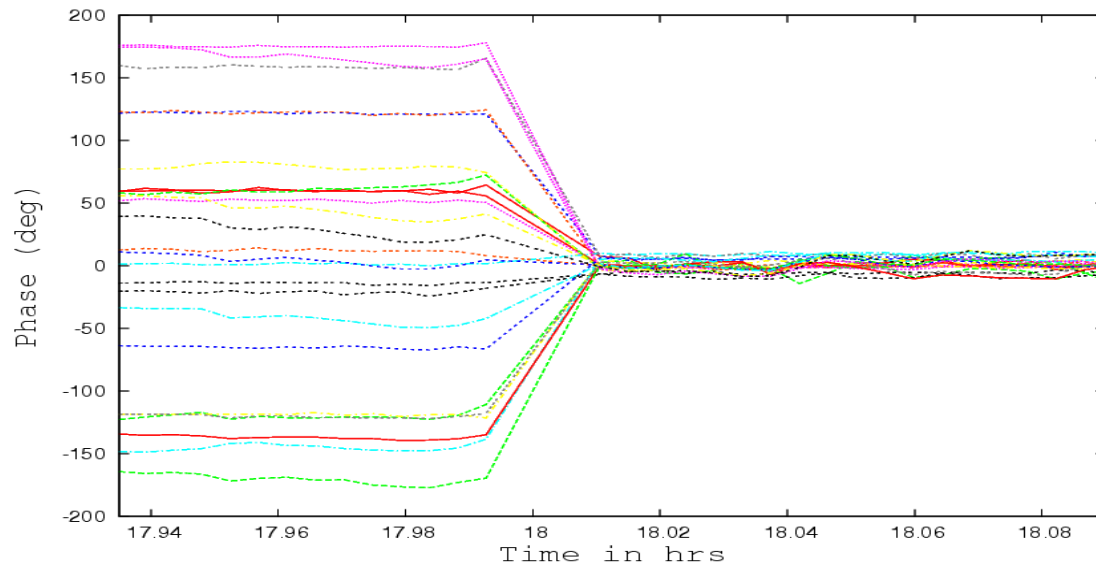
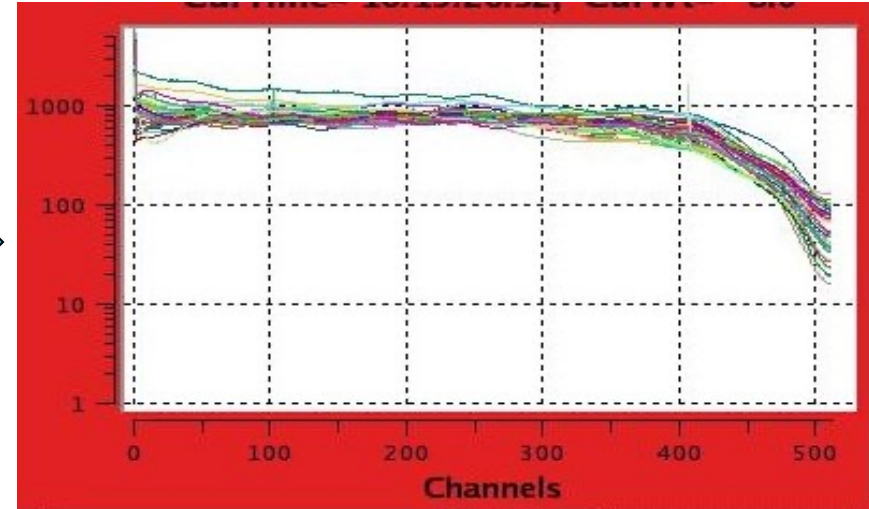
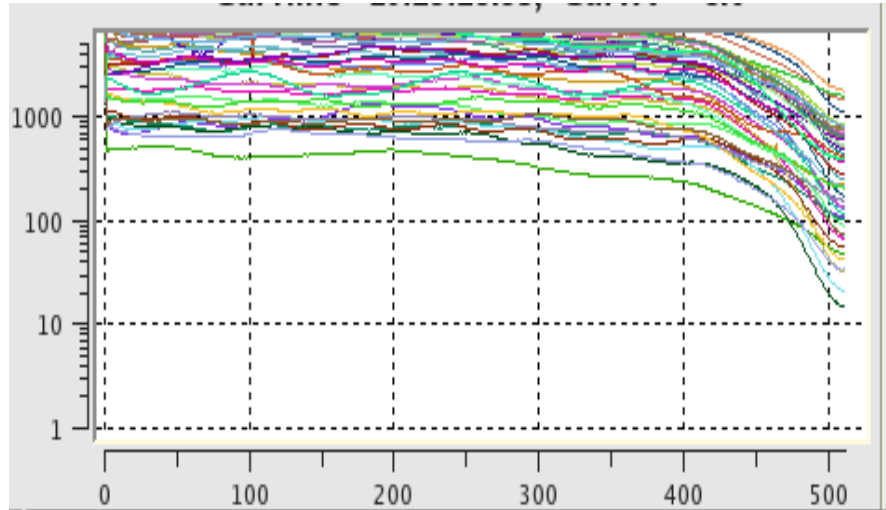
$$\sigma_S = \frac{T_{\text{sys}}/G}{\sqrt{n_{\text{pol}} N (N - 1) \Delta\nu \tau}}$$

Cross correlation output



Amplitude and phase calibration for beamformer

Antenna based gain offset correction



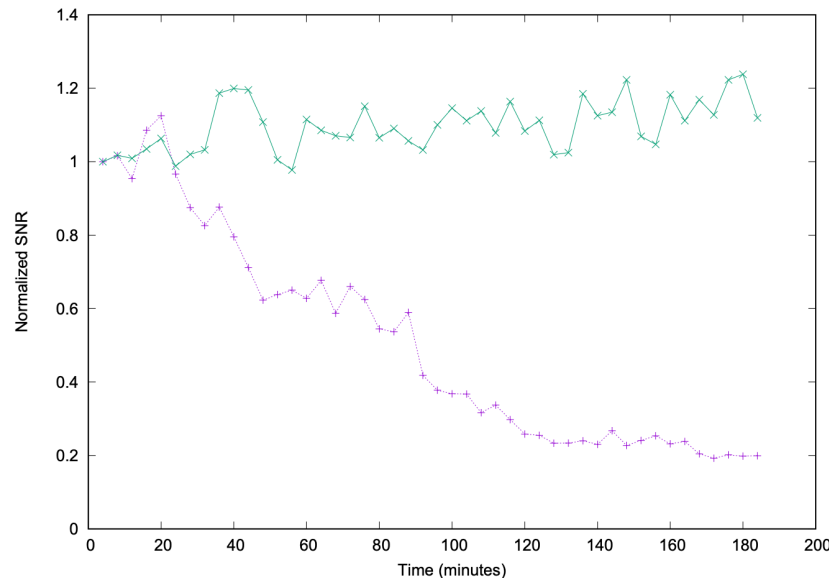
Antenna based phase offset correction

Amplitude and phase calibration for beamformer

observed visibilities V_{ij} $V_{ij} = g_i g_j^* \hat{V}_{ij}$

V_{ij} are the true visibilities $\hat{V}_{ij} = \iint \frac{\hat{I}(l, m) B(l, m) e^{-2\pi i(ul+vm+wn)}}{\sqrt{1-l^2+m^2}} dl dm$

Solution of g_i can be found by minimising
$$L = \sum_{i=1}^N \sum_{j=i+1}^N w_{ij} |V_{ij} - g_i g_j^* \hat{V}_{ij}|^2$$



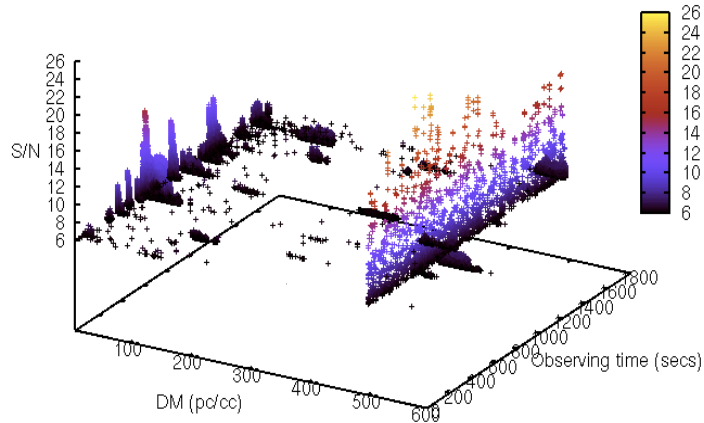
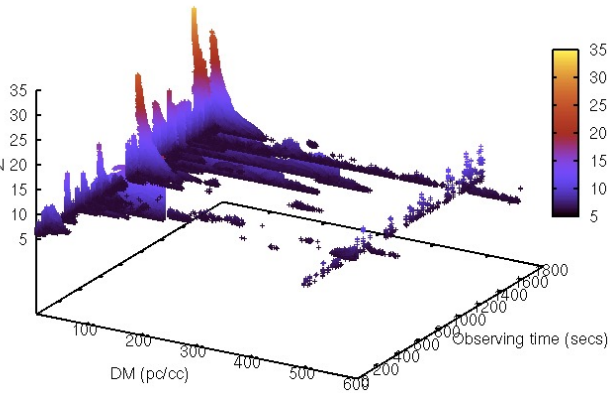
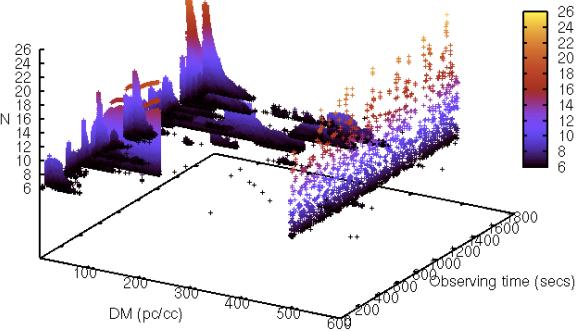
Beamforming

$$P_{\text{IA}} = \sum_{i=0}^{N-1} |V_i|^2$$

$$(S/N)_{\text{IA}} = \frac{GS\sqrt{2N_a\Delta\nu\tau}}{T_{\text{sys}}}$$

$$P_{\text{PA}} = \left| \sum_{i=0}^{N-1} V_i e^{-i\phi_i} \right|^2$$

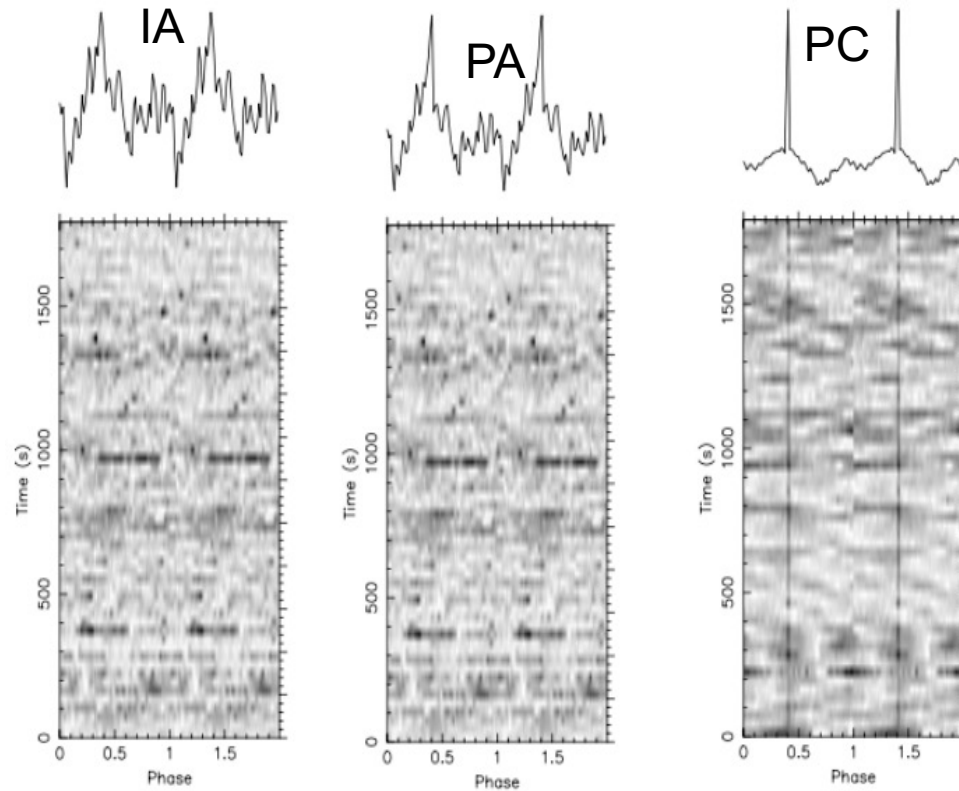
$$(S/N)_{\text{PA}} = \frac{GSN_a\sqrt{2\Delta\nu\tau}}{T_{\text{sys}}}$$



$$P_{\text{PC}} = \left| \sum_{i=0}^N V_i e^{-i\phi_i} \right|^2 - \sum_{i=0}^N |V_i|^2$$

$$(S/N)_{\text{PC}} = \frac{GS\sqrt{2N_a(N_a-1)\Delta\nu\tau}}{T_{\text{sys}}}$$

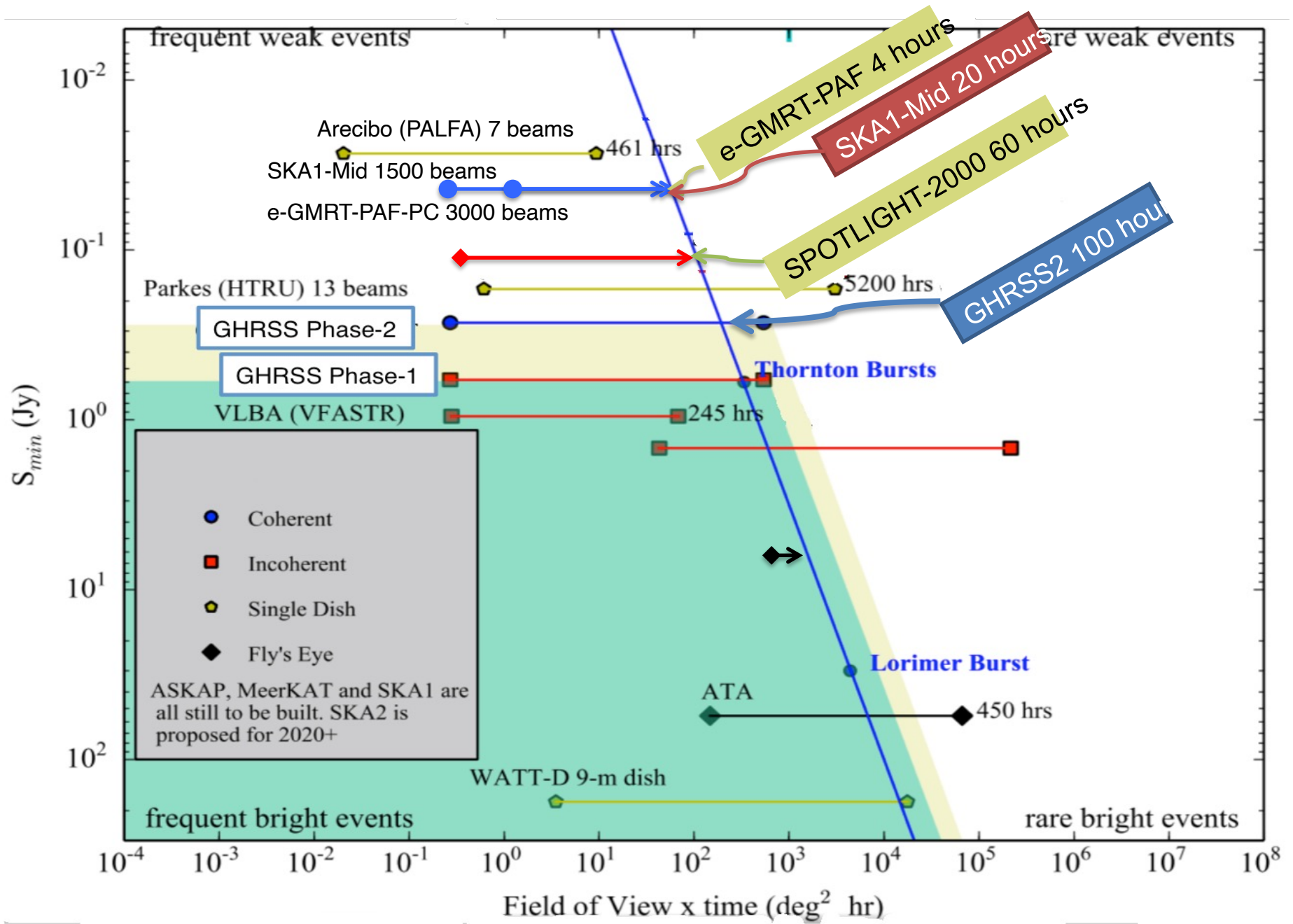
Beamforming



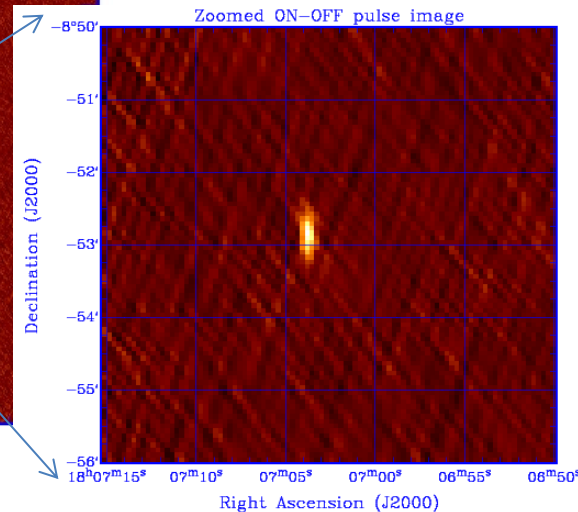
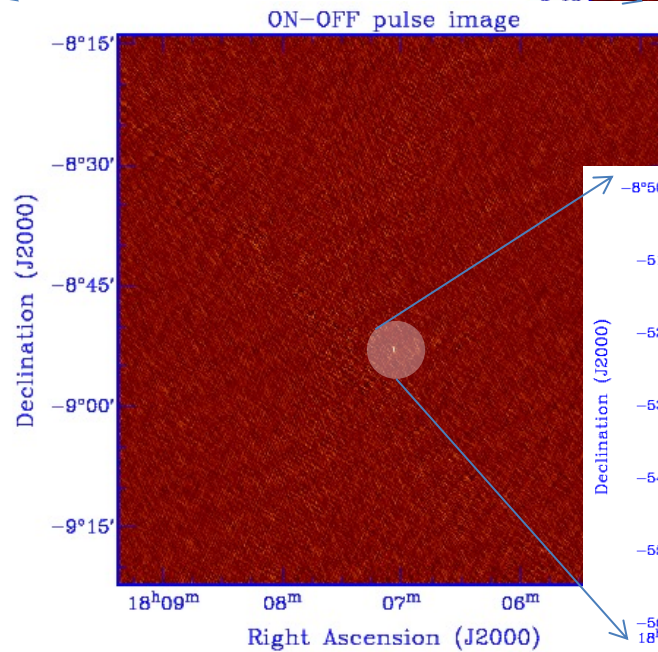
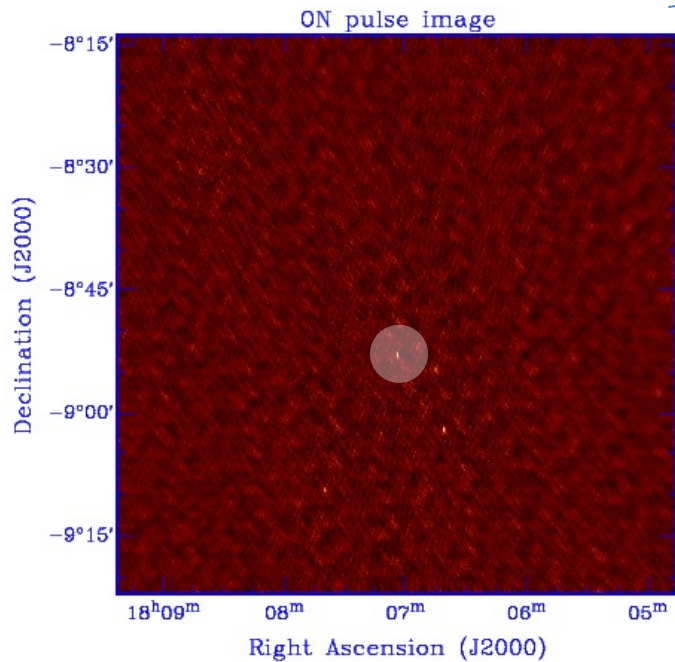
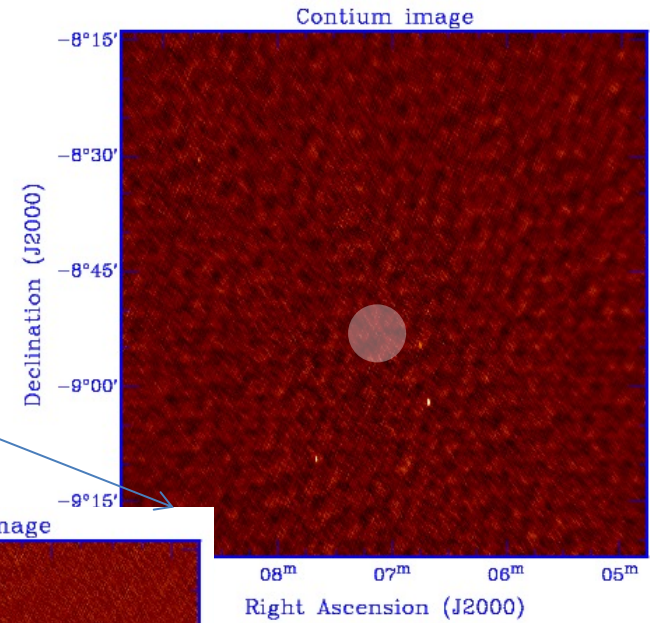
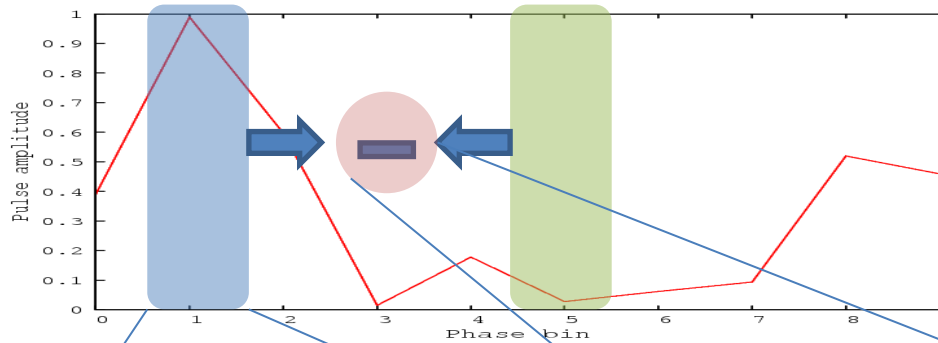
Incoherent Combination of Phased Arrays

$$(S/N)_{\text{LOFAR}} = \frac{GS N_{\text{element}} \sqrt{M_{\text{station}}} \sqrt{2\Delta\nu\tau}}{T_{\text{sys}}}$$

FRBs with GMRT



What is pulsar gating?

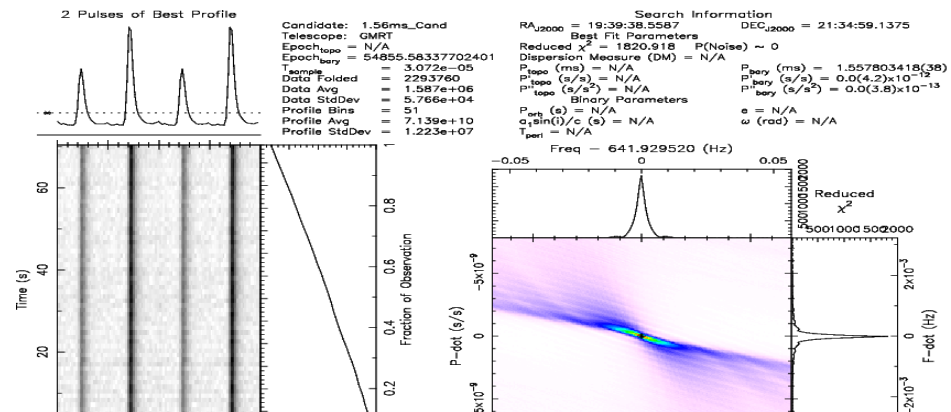
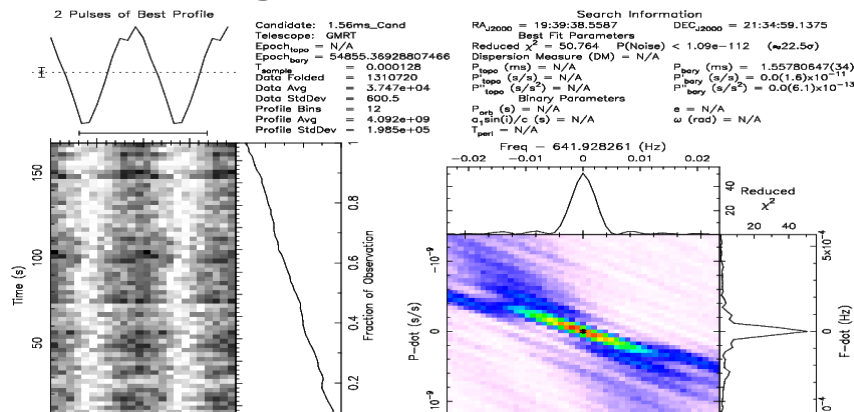


Coherently dedispersed gating correlator

1st instance of coherently dedispersed gating correlator for binary MSPs
(Roy, J. & Bhattacharyya, B., 2013, ApJ Letters, 765, 45)

(Improvement of S/N by 3-6 on the gated image plane)

- MSP gating correlator is implemented off-line using the recorded base-band data
 - ✓ Antenna based coherent dedispersion to reconstruct intrinsic pulse width to avoid the reduction of effective gates at low frequency due to incoherent dispersion error
 - ✓ For 2 ms MSP with 5% duty cycle dispersion error can be 5x of pulse width
 - ✓ Antenna based CD can be cheaper than baseline based ID for future arrays with large no. of elements



Pulse smearing ~ 1.1 ms for spectral res ~ 62.5 KHz

Pulse smearing $\sim$ Nyquist res for spectral res ~ 1.9 Hz

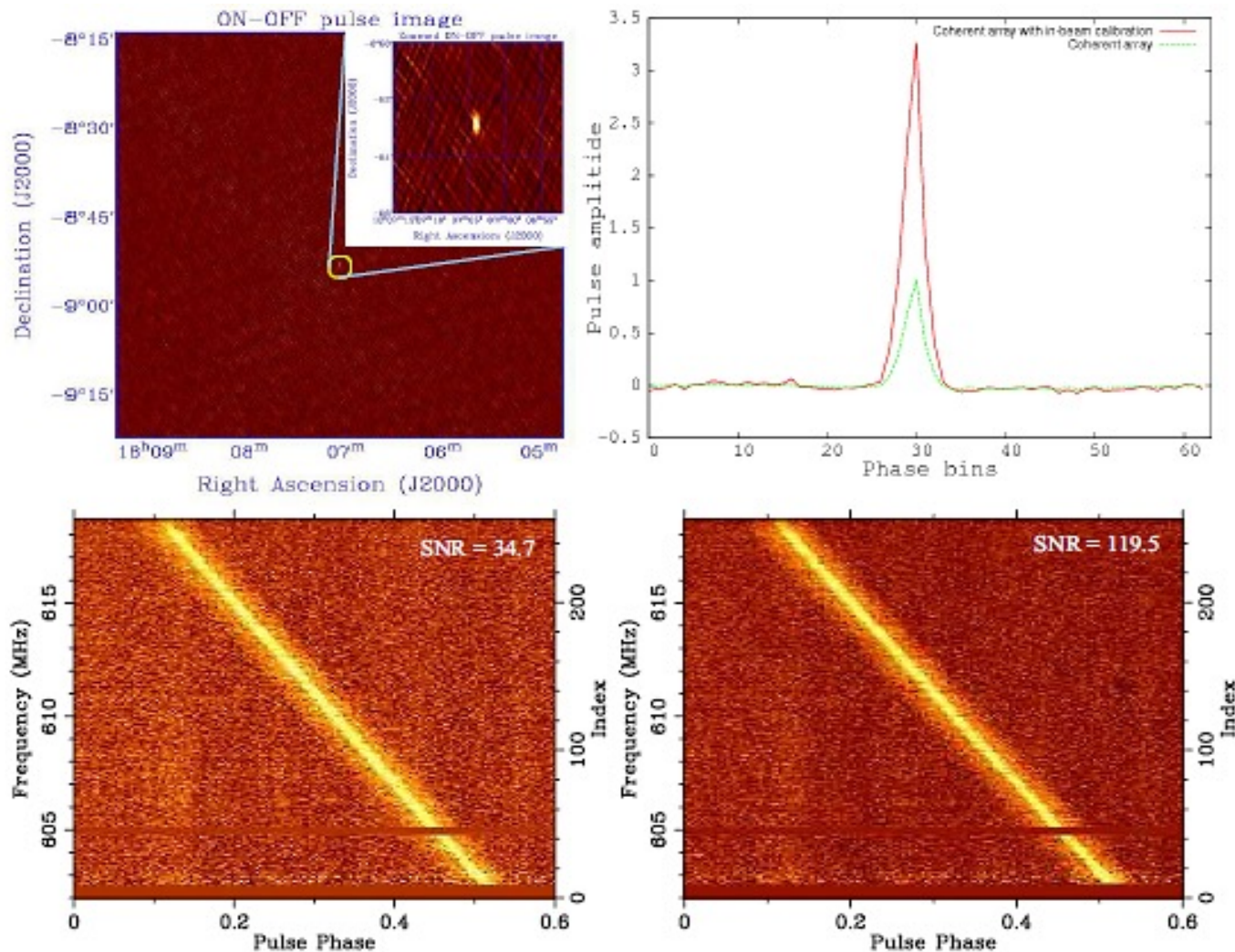
Coherently dedispersed gated imaging

- ✓ correlation and folding in visibility plan with best-fit topocentric model
- ✓ Best-fit topocentric model for newly discovered MSPs consists of acceleration and jerk along with period
- ✓ Best-fit topocentric model for known MSPs (with timing ephemerides) generates from TEMPO based predictions
- ✓ For optimal gating (gate window = pulse width), MSP period is required to be accurate upto 7 significant digit (for 2 ms MSP in 1 hr of gating observation)
- ✓ ON gate is identified using the simultaneously generated incoherent beamformer data
- ✓ ON-OFF gated image is generated to unambiguously localise the MSP at an accuracy of $\pm 1'' [\approx FWHM / (2 \times SNR)]$

In-beam phasing using pulsar

- Coherent array sensitivity degrades due to temporal decoherence caused by instrumental and ionospheric phase fluctuations
- Special decoherences caused by approximating phase from distant calibrator to pulsar field, due to the underlying ionospheric inhomogeneity
- ON-OFF gated image of target pulsar can be used to solve for antenna based residual phase errors (stochastic and broad-band) in self-calibration
- Background subtracted ON-OFF gated image provides better model, where the instrumental and RFI artefacts are subtracted out
- Very useful methodology for up-coming array telescopes (e.g. LOFAR, MWA, ASKAP, MeerKAT, SKA)

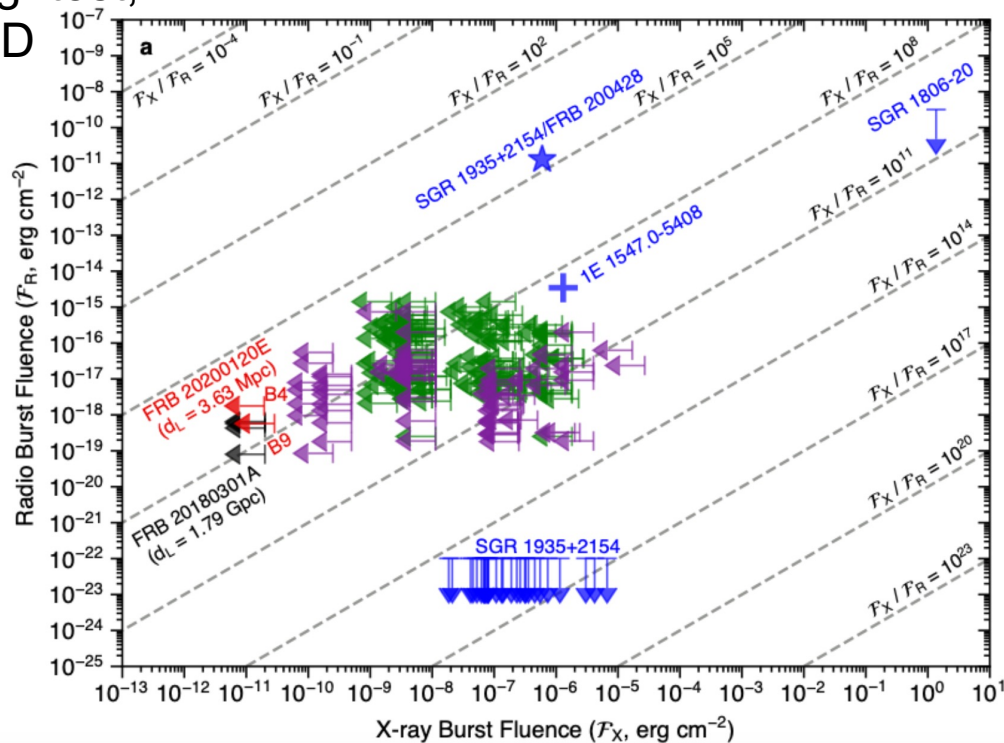
Optimal sensitivity of coherent array



➤ 3.5X sensitivity improvement along with 12% reduction in noise rms is achieved for in-beam calibration on B1804-08 using 1 min of data

Multi-wavelength association of Fast Radio Transients

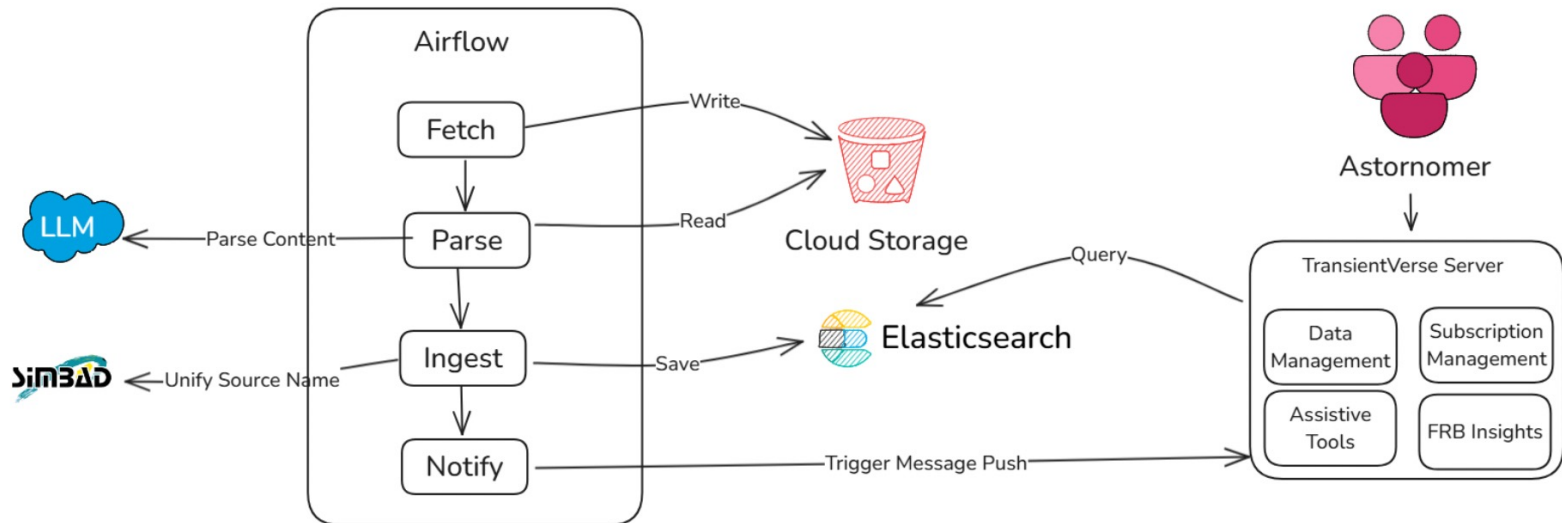
- Multi-wavelength, multi-messenger signals associated with any of these sources would shed light on their possible origins.
- Only case of FRB 20200428D and Galactic magnetar SGR J1935+2154 association
- Bursts simultaneously detected by a few X-ray missions coinciding with the MJy radio millisecond bursts
- Various X-ray/γ-ray fluence upper limits for cosmological FRBs suggest M81 globular cluster upper limit is the tightest, but is still above of FRB 20200428D
- Coordinated radio-X-ray follow-up of hyperactive repeaters
- Search for spatially associated GRB-FRB or SN-FRB pairs, with the GRB or the SN leading the FRB
- Coherent radio flash with the LOFAR telescope at 76.6 min after the short-duration GRB 201006A (Rowlinson A, et al. 2023)



Multi-messenger association of Fast Radio Transients

- Three scenarios of FRB generation and proton acceleration (to produce neutrino) with different emission sites: inside the magnetosphere, in the current sheet region beyond the light cylinder, and in relativistic shocks (Qu Y, Zhang B. 2022)
- The neutrino flux is many orders of magnitude below the IceCube sensitivity even for the Galactic FRB 20200428D
- Neutron stars carrying magnetospheres would induce additional interactions before the merger → a brief electromagnetic chirp would also accompany the gravitational wave chirp
- Active repeaters could be interacting neutron stars that are close to merging, and some nearby systems may be detected as gravitational wave sources by future space-borne gravitational wave detectors such as LISA
- FRB 20190425A occurred about 2.5 hours after GW190425 (BNS merger)
- Probing for GW-sGRB-FRB tripple association
- Red-shift estimation of one-off FRBs are important as a primary aim of SPOTLIGHT

Real-time multi-wavelength, multi-messenger follow-up



Fang et al. 2025

- Transient astronomical alert message collection and integration
- Integrating real-time alerts from multiple sources (e.g., ATel, VOWEvent, and GCN)
- Support for multi-wavelength, multi-messenger time-domain astronomy and astrophysics studies of transients
- Establishing internal and external transient alert system for SPOTLIGHT