The ALMA Phasing Project 'Phase 2': Extending and Enhancing the VLBI Science Capabilities of ALMA

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Very Long Baseline Interferometry (VLBI) at mm Wavelengths:

- Provides the highest angular resolution presently achievable for the study of astronomical sources (a few tens of μas)
- Can investigate sources that are self-absorbed or scatter-broadened at cm wavelengths

However, to date, scientific applications of mm VLBI have been limited:

- High receiver noise, small bandwidths
  - ⇒ limited sensitivities
  - ⇒ restricted to relatively few bright targets
- Small number of mm-equipped VLBI stations
  - ⇒ small # baselines
  - ⇒ limited *u-v* coverage
  - ⇒ not possible to image sources at $\lambda < 3$ mm

The ALMA Phasing Project (APP) was conceived to harness the enormous collecting area and sensitivity of ALMA for mm VLBI and provide a major leap in overcoming these limitations.

Background: the ALMA Phasing Project (APP) “Phase 1”

- **Goal:** turn ALMA into the world’s most sensitive station for Very Long Baseline Interferometry (VLBI) at mm wavelengths.

- **Funding:** NSF Major Research Instrumentation (MRI) and ALMA NA Development awards; approved in 2012.

- **Requirements:** Provide hardware and software to coherently sum signals from up to 61 ALMA antennas and record VLBI format data.

- **Motivation:** provide a dramatic boost in **sensitivity** (×10), ***u-v* coverage**, and north-south **angular resolution** (×2) of global VLBI networks operating at mm wavelengths.

HAYSTACK OBSERVATORY NRAO Max-Planck-Institut für Radioastronomie University of Concepcion Chile ASIAA NAOJ NSF CfA

Background: the ALMA Phasing Project (APP) “Phase 1”

Principal Investigator: Sheperd Doeleman (MIT Haystack Observatory)

Participating Organizations:

- MIT Haystack Observatory (USA, lead)
- ASIAA (Taiwan)
- Harvard-Smithsonian Center for Astrophysics (USA)
- Max Planck Institut für Radioastronomie (Germany)
- NAOJ (Japan)
- NRAO (USA)
- Onsala Observatory (Sweden)
- University of Concepción (Chile)

What Did Equipping ALMA for VLBI Entail?

Hardware:

- ✓ Install new frequency standard (***H maser***) to replace ALMA's Rb clock
- ✓ Design and install Phasing Interface Cards (***PICS)*** in ALMA correlator (2 per quadrant, 8 total) to serve as VLBI backend
- ✓ Install Mark 6 high-speed ***VLBI recorders*** at ALMA OSF
- ✓ Build and install ***optical fiber link*** system to carry data from AOS to VLBI recorders

Software:

- ✓ Implement new VLBI Observing mode (***VOM***) into existing ALMA software to coherently phase the array and operate the VLBI backend
- ✓ ***VEX2VOM*** (translates VEX to an ALMA Schedule Block)

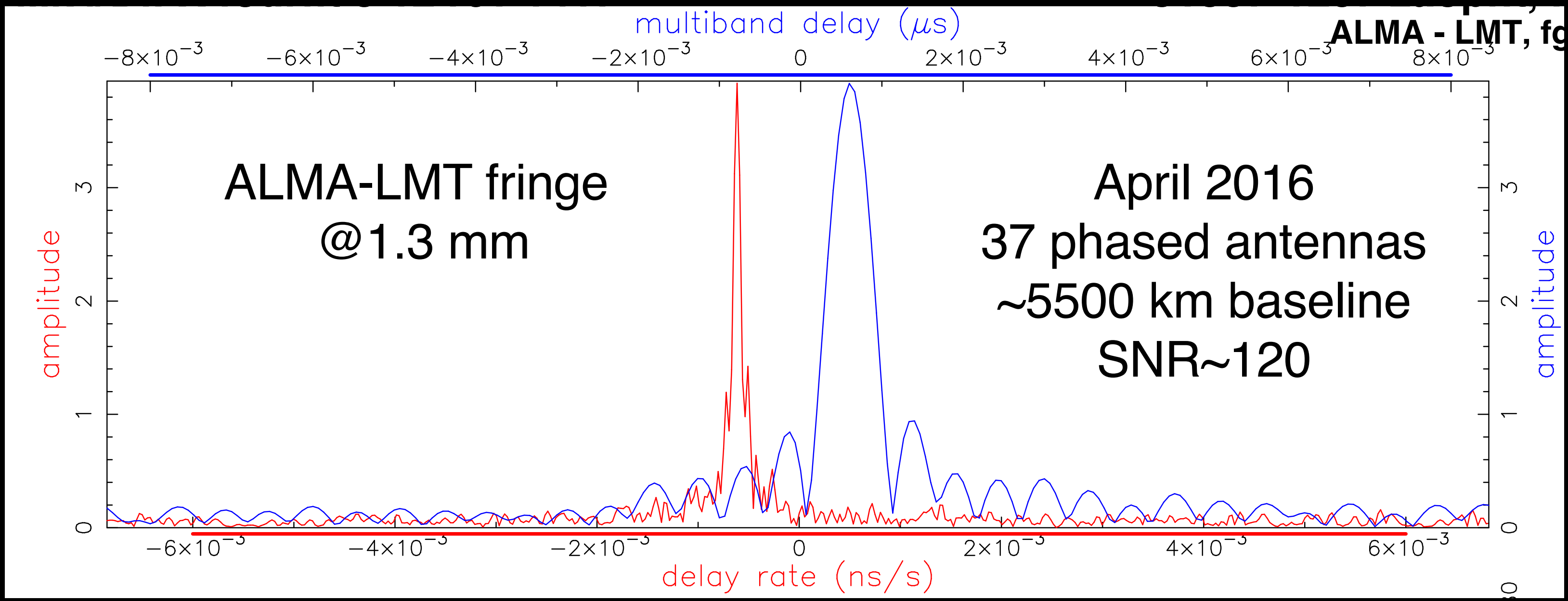
Commissioning and Science Verification (CSV):

- ✓ End-to-end, on-sky testing of the entire APS

See Matthews, Crew, Doeleman, et al. 2018 (PASP, 132, 5002) for details.

APP "Phase 1" is complete

- ALMA is now a fully functioning VLBI station.



- VLBI with ALMA offered to the community for the first time in Cycle 4

- 9 VLBI projects approved for Cycle 4

Summary of Current Phased ALMA Capabilities

Equivalent collecting area: 77 m parabolic dish
(assuming 41 phased 12 m antennas)

SEFD: **~65 Jy @3 mm; 100 Jy @1 mm**

Bandwidth: 7.5 GHz (per polarization)

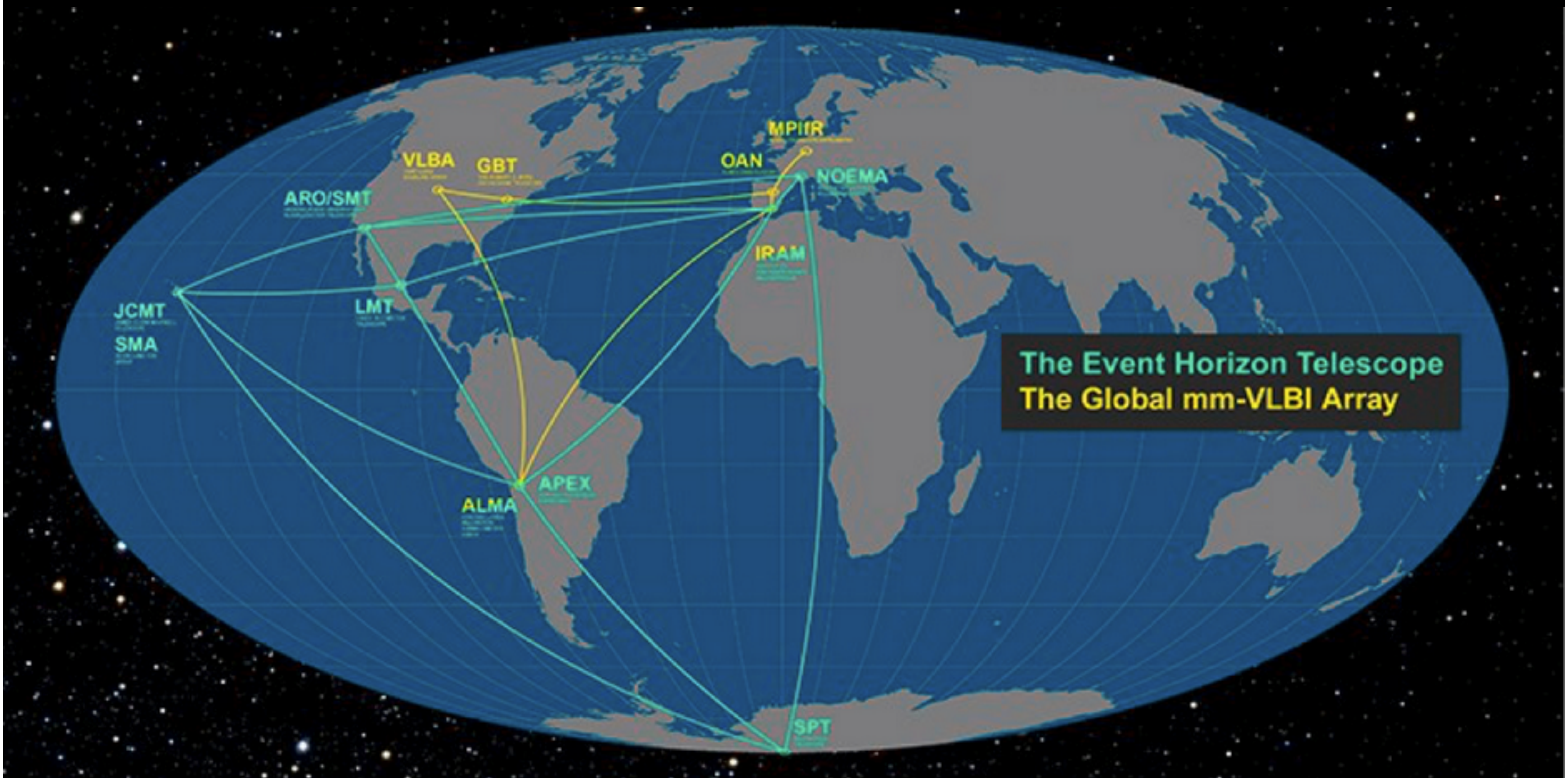
VLBI Recording: 64 Gbps (4 Mark-6 units, each 16 Gbps, 2 pol.)

Polarization: dual linear pol. recording → full Stokes data sets

Angular resolution (ALMA-Mauna Kea baseline): ~30 μas @ 1.3 mm
~70 μas @ 3 mm

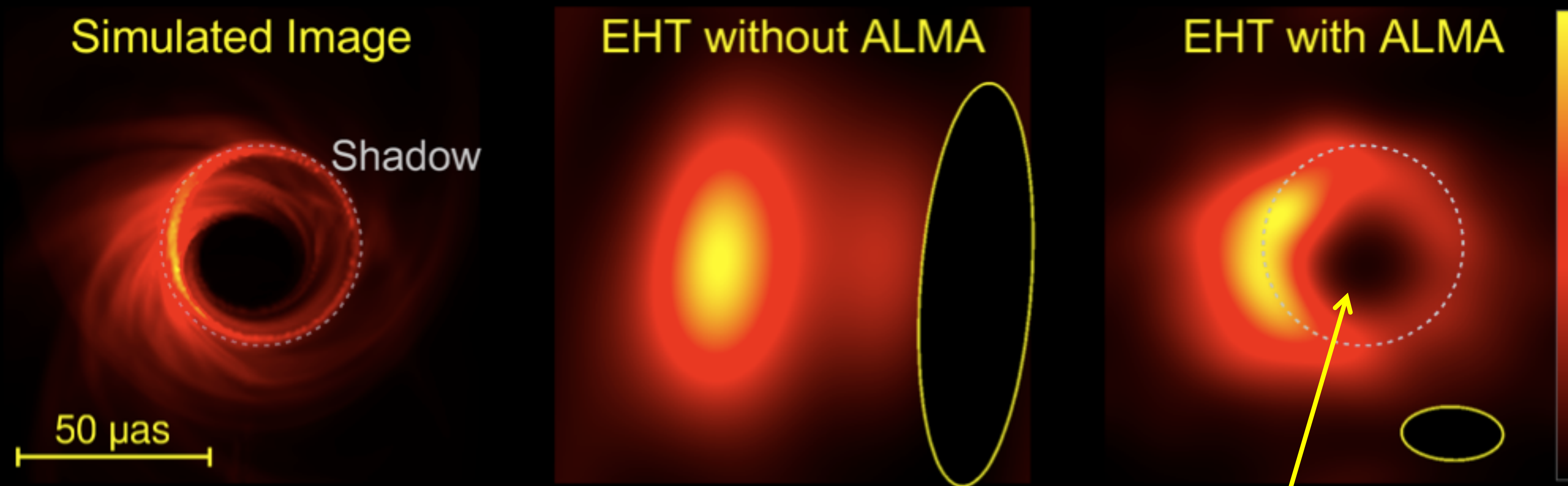
First ALMA VLBI science observations were carried out in April 2017:

- 3 mm (Band 3) in conjunction w/ GMVA (~0.2 GHz BW, dual pol.)
- 1.3 mm (Band 6) in conjunction w/ EHT network (~4 GHz BW, dual pol.)



Credit: eventhorizontelescope.org

VLBI with Phased ALMA @1 mm is expected to product the *first images of nearby black holes (Sgr A*, M87) on Event Horizon scales:*



Credit: S. Doeleman and the EHT Consortium

Black hole shadow visible

However, *the science case for Phased ALMA is broad and diverse!*
(see White Papers by Fish et al. 2013, Tilanus et al. 2014)

The APP "Phase 2"

The current implementation of APS offers only a *subset* of its fully envisioned capabilities.

Current limitations include:

- Phasing only in Band 3 (3 mm) or Band 6 (1 mm)
- Fixed tunings
- Continuum mode only (no spectral line science)
- Targets must be bright enough for direct phase-up (≥500 mJy on baselines <1 km).

These factors prevent phased ALMA from achieving its full scientific promise (see Fish et al. 2013, Tilanus et al. 2014).

$\Rightarrow$ Motivation for an APP "Phase 2"

ALMA Cycle 3 Study:
"Extensions and Enhancements of the ALMA Phasing System"
(Status: *Concluded Sept. 2017*)

ALMA Cycle 4 Study:
"Diversifying the Scientific Applications of the ALMA Phasing System"
(Status: *Concludes Jan. 2018*)

Team:
L. D. Matthews (PI), G. B. Crew, M. H. Hecht, V. L. Fish (*MIT Haystack*)

Proposed new capabilities include:

1. Extension of phasing capabilities to the sub-mm (Band 7)
2. Procedures for use of APS on weaker sources
3. Development of spectral line VLBI capabilities

***Implementation* will be carried out as part of a recently approved Cycle 5 ALMA NA Development Project.**

ALMA NA Cycle 5 Development Project:
"Enabling New Science with the ALMA Phasing System 'Phase 2'"

Status: *Approved*

Expected duration: *January 31, 2018 – June 30, 2020*

Delivery of capabilities: *ALMA Cycle 7 (or Cycle 8)*

Team:

L. D. Matthews (PI), G. B. Crew, M. H. Hecht, V. L. Fish

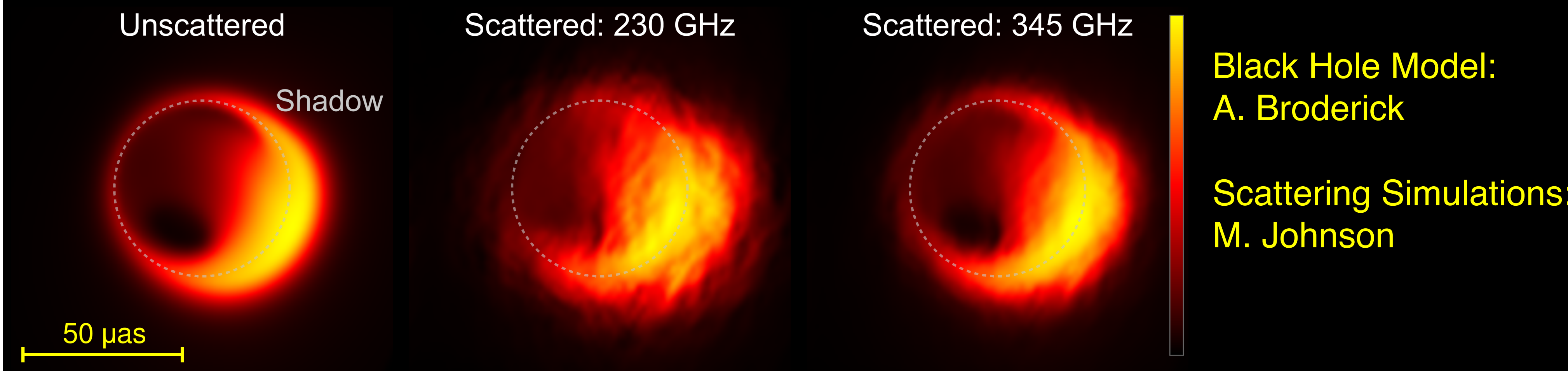
(*MIT Haystack Observatory*)

1. Extension of phasing capabilities to the <u>sub-mm</u> (Band 7)
2. Procedures for use of APS on <u>weaker sources</u>
3. Development of <u>spectral line</u> VLBI capabilities

Topic 1: Extension of Phasing Capabilities to the Submillimter

Phasing/VLBI capabilities at higher frequencies offer 2 key advantages:

- Higher spatial resolution: ~20µas @0.8 mm (Band 7)
- Reduced impact of interstellar scattering ⇒ enhanced ability to reconstruct images (Johnson & Gwinn 2015).



Anisotropic scattering ⇔ Gaussian convolution
FWHM ~22µas @1.3mm (Band 6; 230 GHz)
vs.
FWHM ~10µas @0.8mm (Band 7; 345 GHz)

Extension of Phasing Capabilities to Band 7

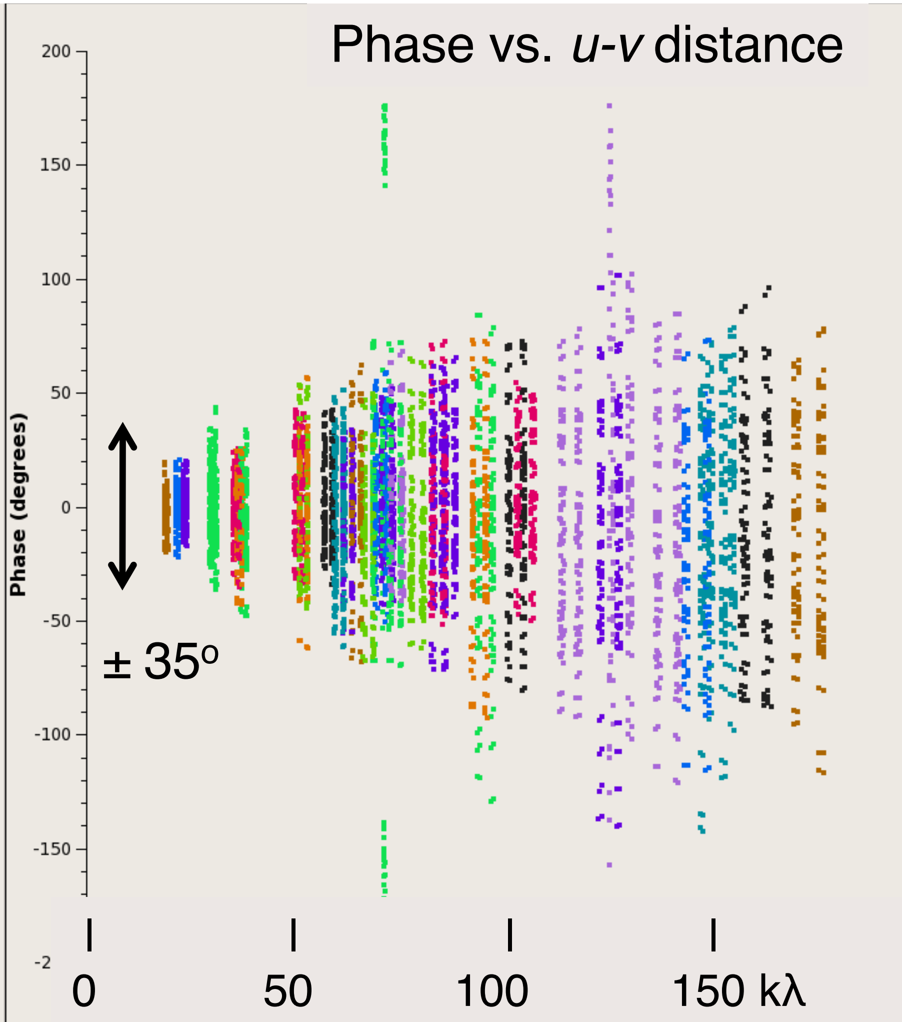
The ALMA Phasing System (APS) is designed to work at any band.

But in practice, shorter coherence timescales at higher frequencies mean additional considerations:

- Optimizing trade-offs between array size and phasing efficiency

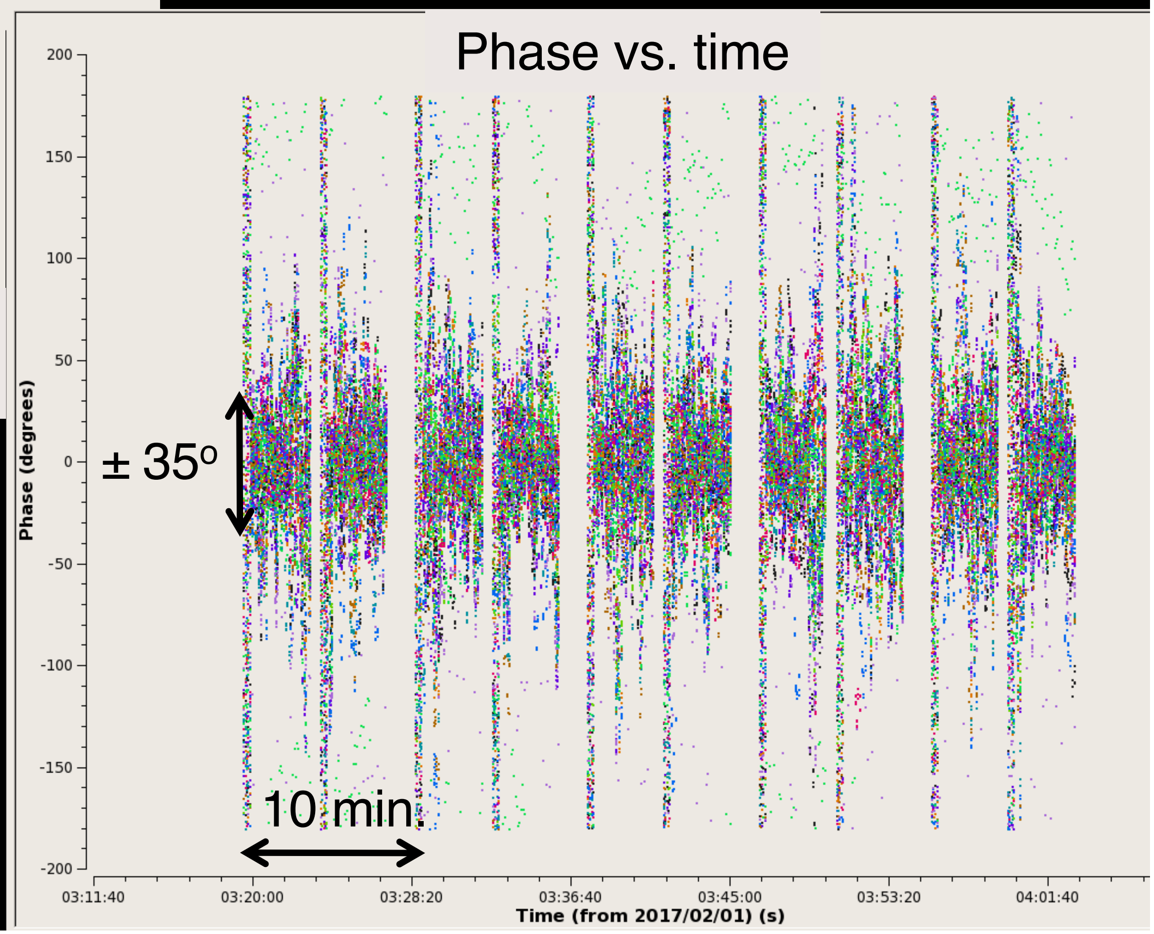
- Judicious application of “fast” (WVR-based) phasing corrections to complement “slow” (TelCal-based) solutions

- Commissioning to demonstrate VLBI fringes at sub-mm wavelengths.



Band 7 phasing tests (Feb. 2017):

- Phase RMS ~35° w/ PWV~1.6 mm
- Acceptable phasing efficiency (~83%) on baselines up to ~300m.



Topic 2: Improved Flux Density Thresholds for the APS

Current flux density requirement for the APS: S_ν >500 mJy on baselines <1 km.

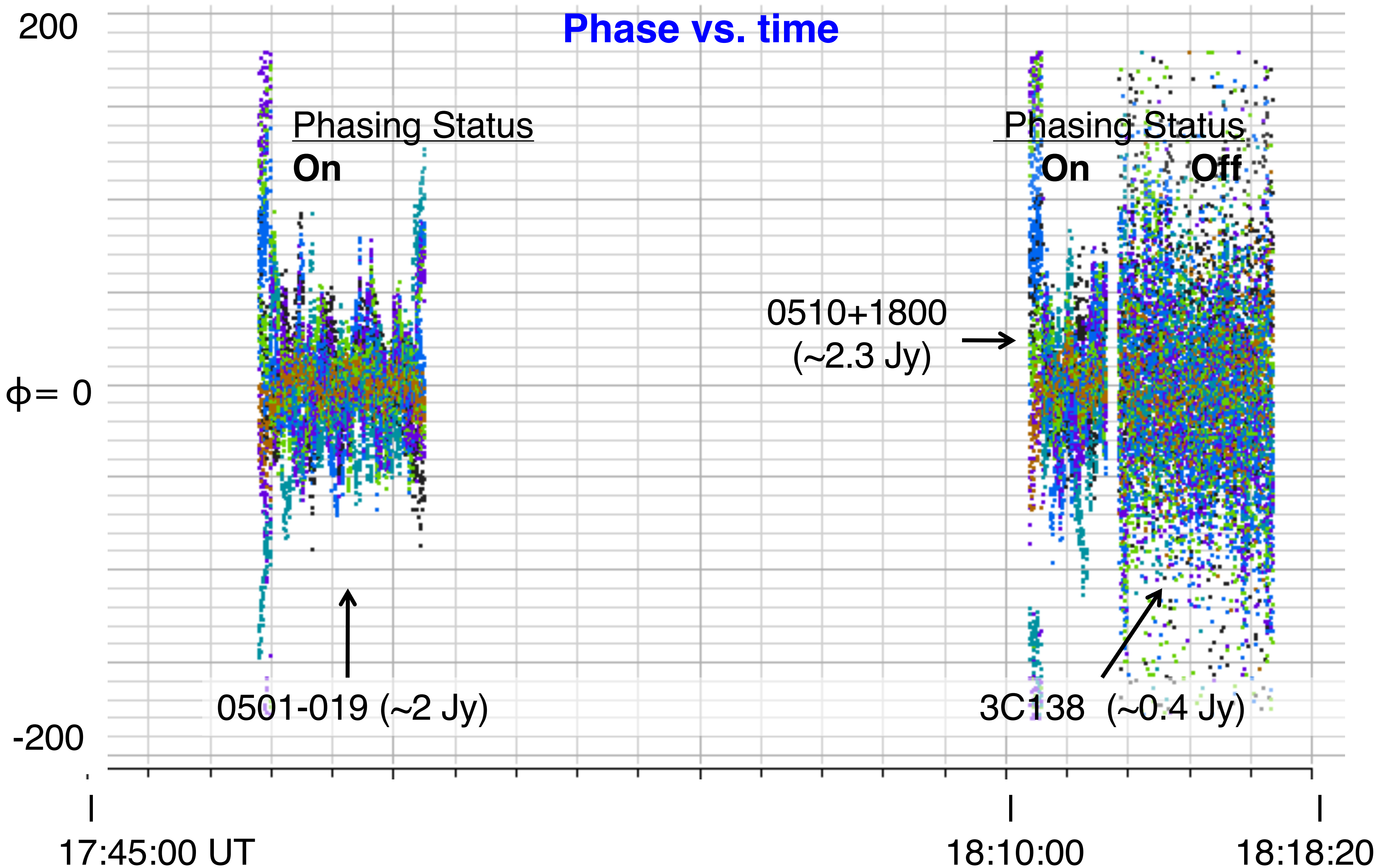
Constraint arises from:

- Theoretical considerations (sensitivity, phasing efficiency)
- Requirement to phase up on the science target itself

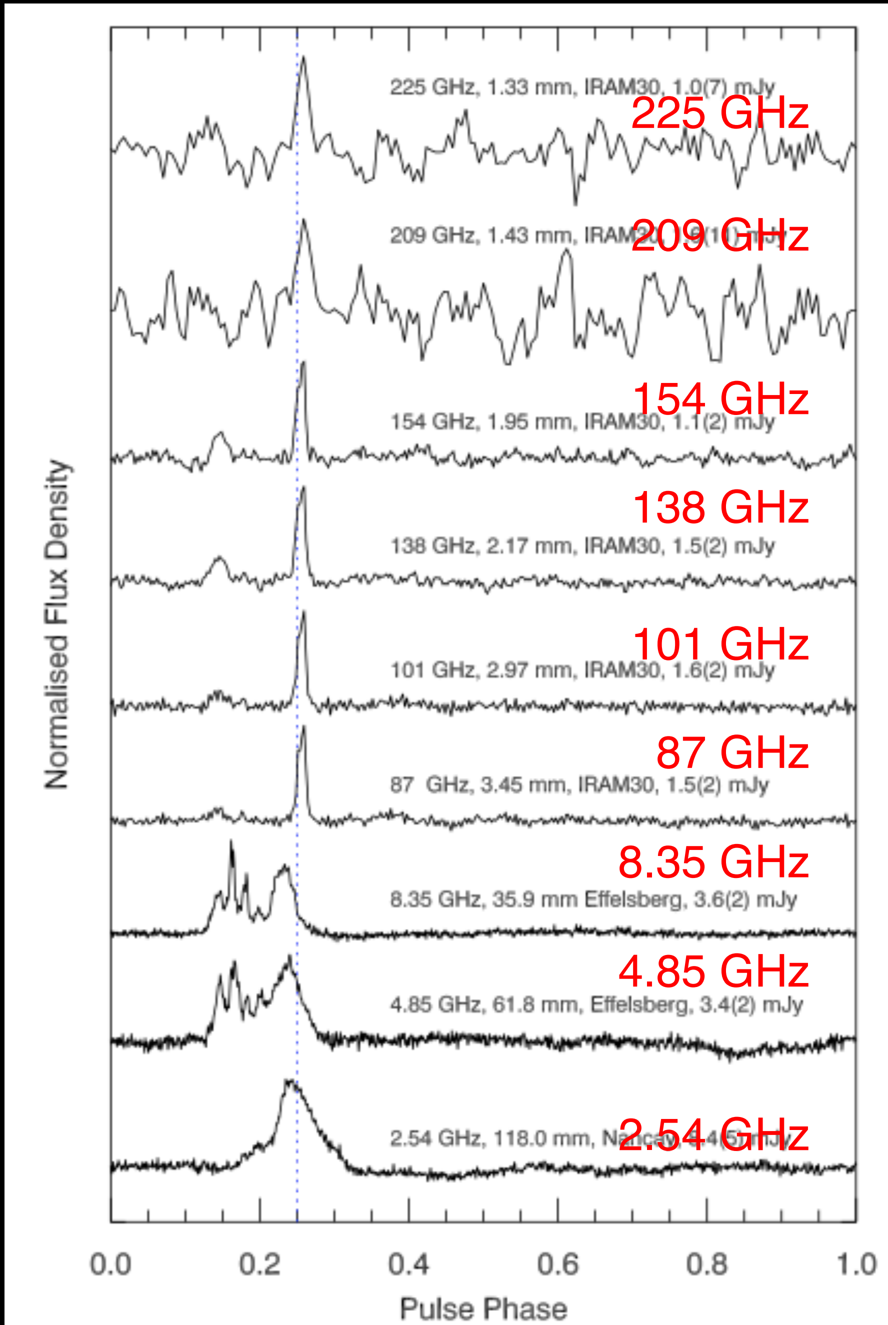
APP 'Phase 2' implementation will enable:

1. Direct phase-up on weaker sources: improved handling of baseband delays $\Rightarrow$ higher SNR on phasing solutions.
2. "Passive" phasing: phase up on a bright source close in angular distance to a weaker target.

Preliminary demonstration of “passive” phasing in Band 3 (July 10, 2016)

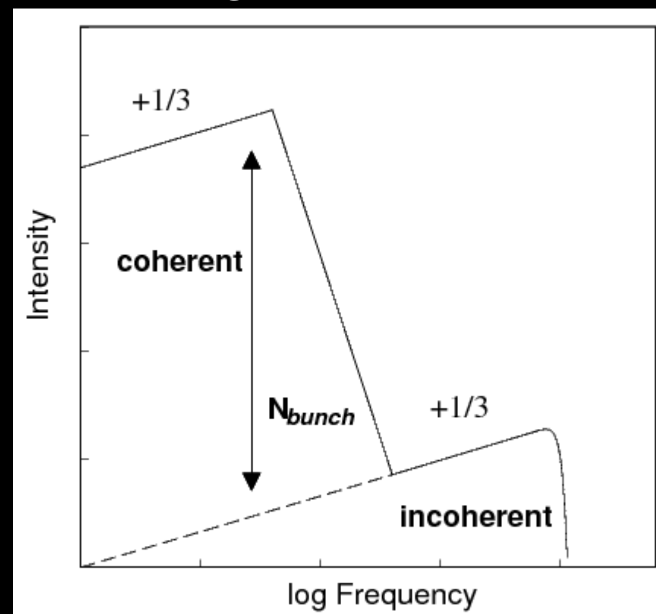


Application of Passive Phase-Up: Pulsar Studies

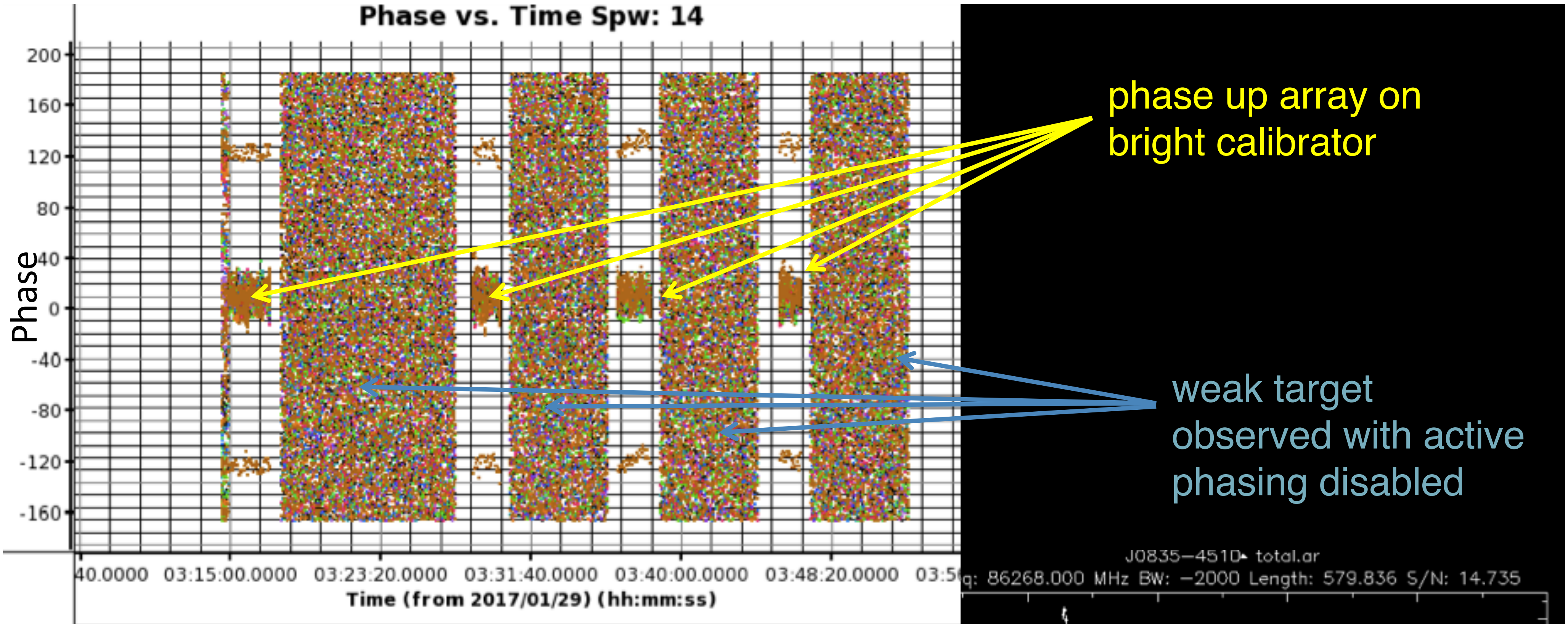


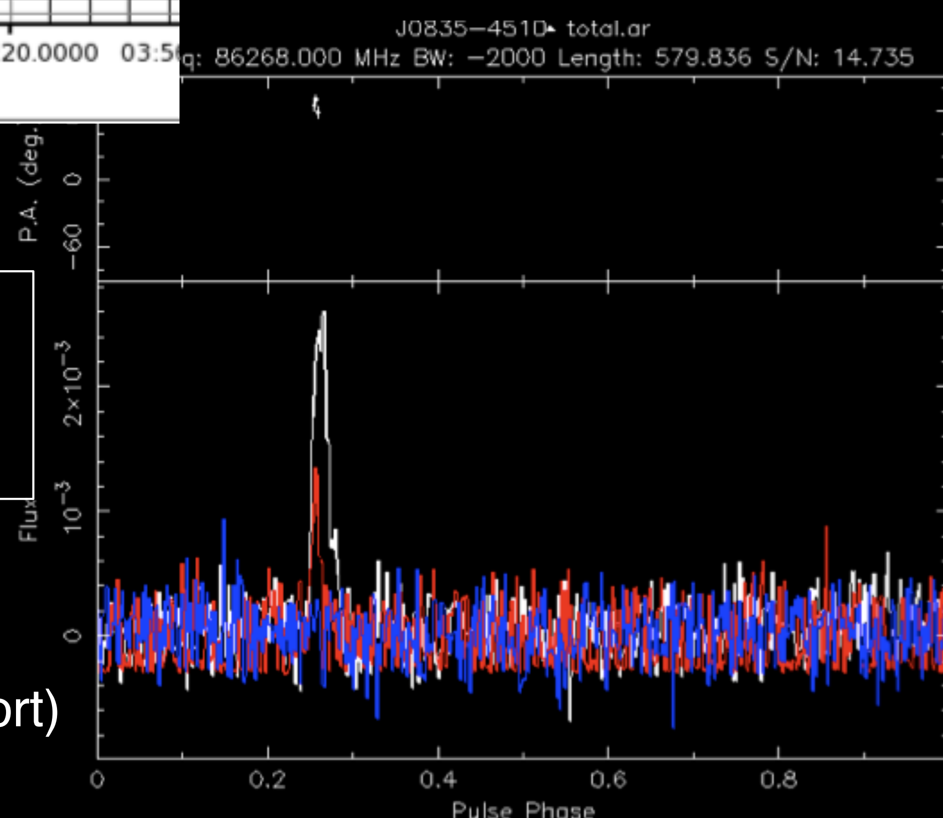
Torne et al. (2015)

- Pulsars become weaker at higher frequencies, but effects of scattering become smaller.
- High-freq. observations probe SED changes (Kramer 1995).



← Sequence of profiles from magnetar near Sgr A*, J1740-2900





Successful detection of the Vela pulsar with Phased ALMA at 86 GHz during “passive phasing” test (January 2017).

from Cordes et al. 2017 (Cycle 3 Study Report)

Topic 3: Enabling Spectral Line Science with the APS

Fundamental principles of using the APS for spectral line work are the same as for continuum. But there are additional requirements:

- Spectral window matching: phase-up possible on a bright line, but spectral window for phasing calculations must be judiciously selected.

- Updates to the Observing Tool (OT): tuning flexibility required; must respect tuning limitations of peer observatories.

- Data rate issues: currently ALMA SFI data binned to coarse (~8 MHz) spectral resolution to avoid data rate bottlenecks; need to explore ways to overcome while preserving high spectral resolution.

- Correlation: need to refine strategies for spectral line modes;
  - ALMA has non-power-of-two sampling rate
  - Power is concentrated in freq. making the delay function broad
  - Atmospheric effects can introduce spurious peaks in the fringe rate

Spectral Line Science with the APS

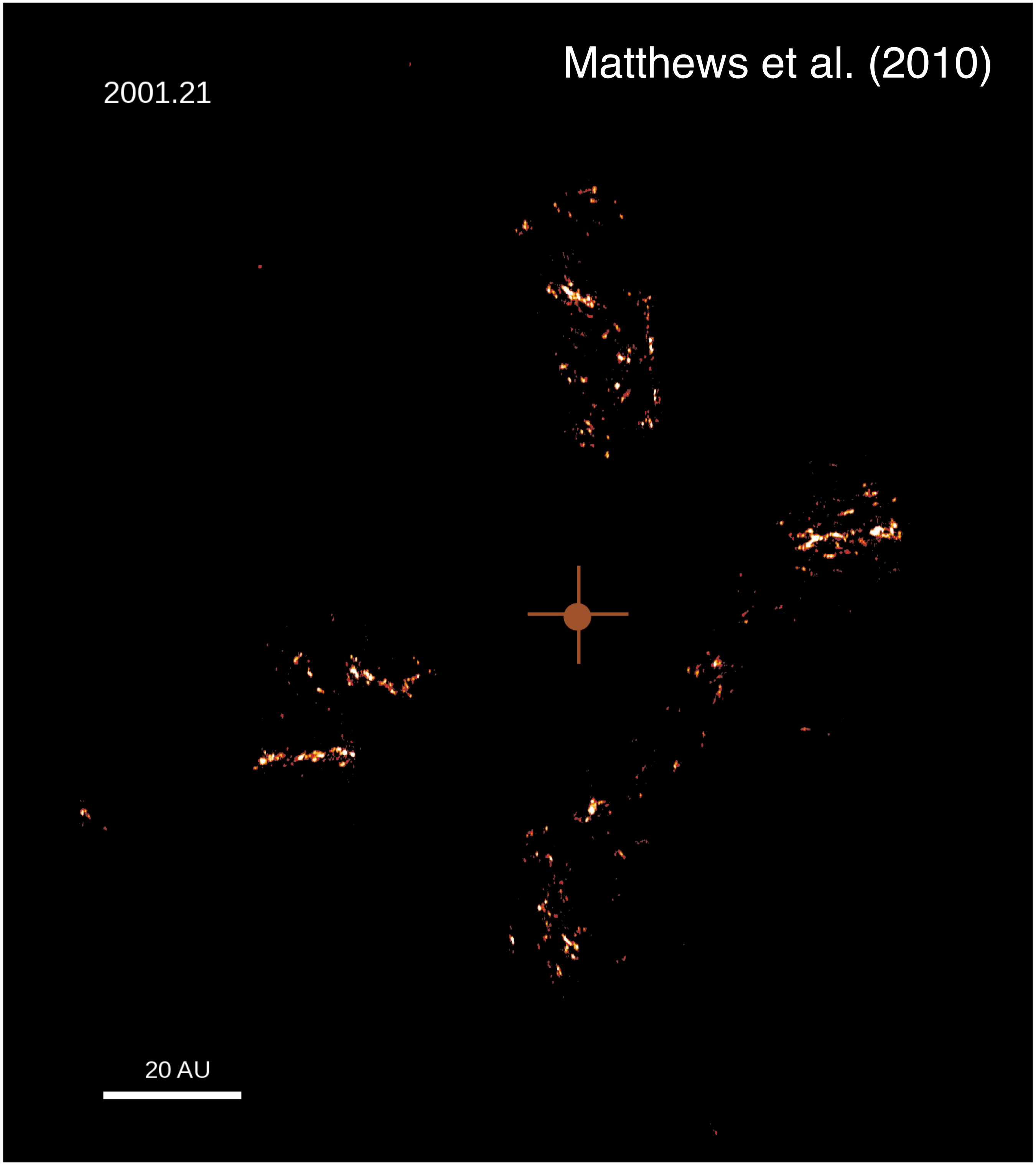
- High-redshift absorption lines: lines such a HCN, HCO+ could be used to map chemical evolution of the universe with redshift; measure isotopic abundance ratios, CMB temperature, variation in fundamental constants.

- Maser mapping: compact sizes (~1 AU) and high brightness temperatures of masers (up to 10^{17} K) make them prime targets for VLBI; masers trace kinematics, physical conditions, magnetic fields in evolved stars, star-forming regions, nuclear regions of external galaxies.

- Astrometry of masers: map rotation curve and spiral structure of MW; dynamical masses of black holes; trace outflows from YSOs...

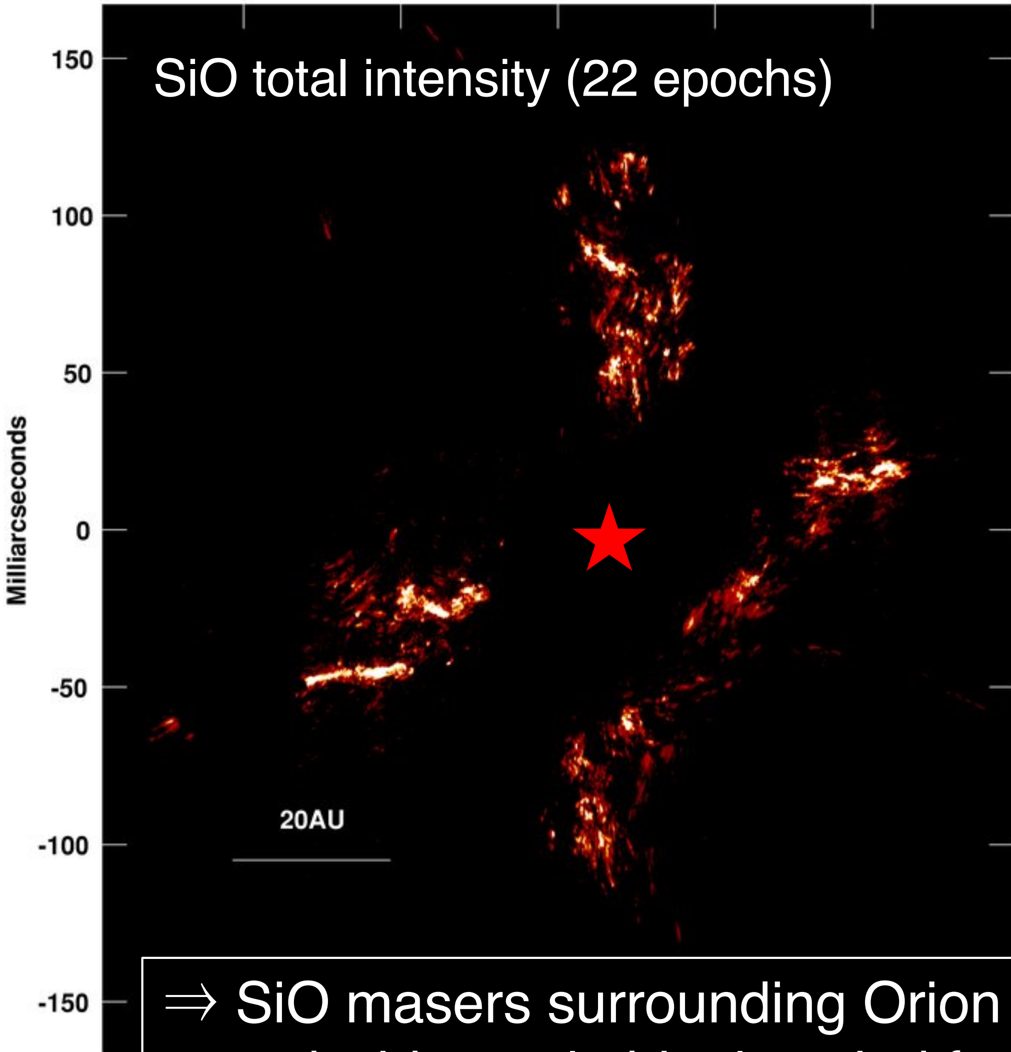
See White Papers by Fish et al. (2013); Tilanus et al. (2014)

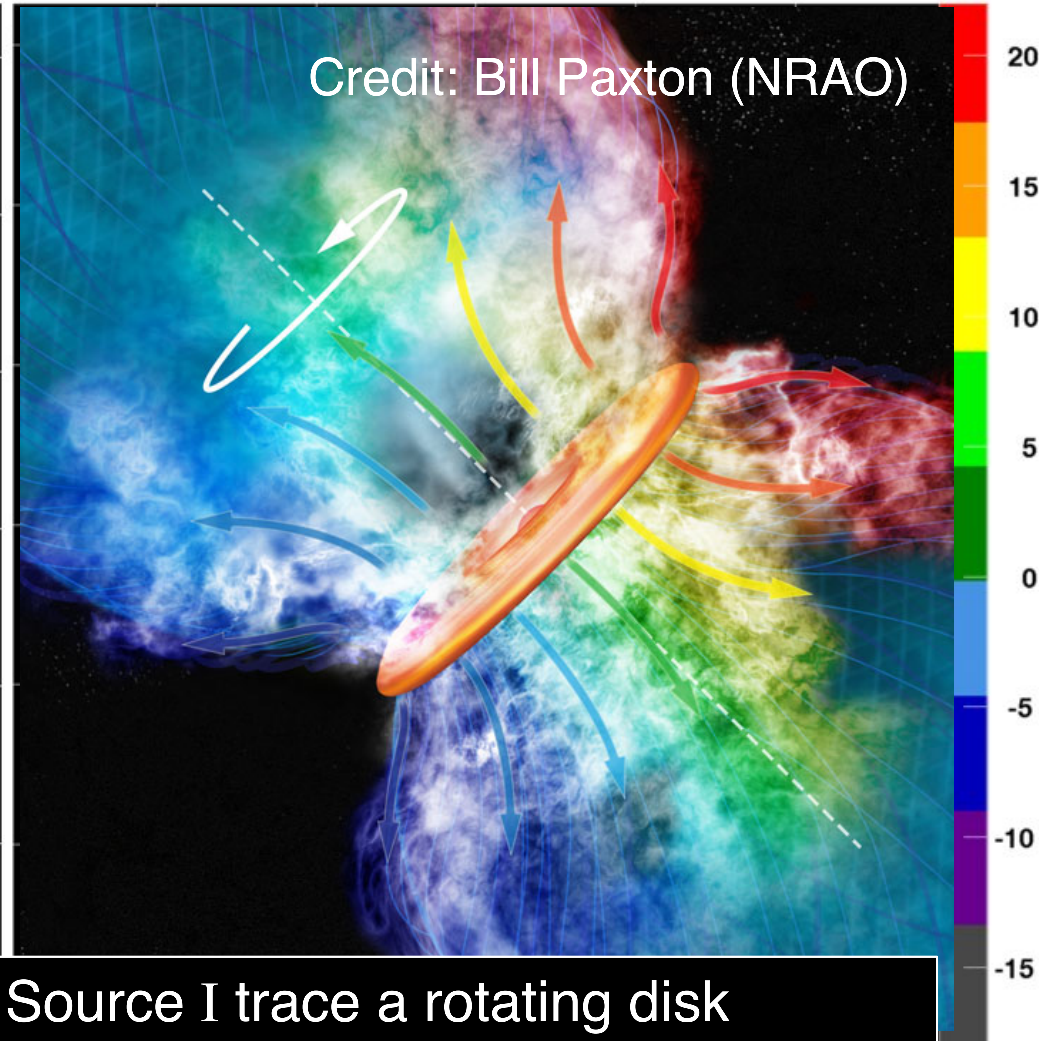
VLBA time series movie of SiO v=1, J=1-0 (7 mm) masers surrounding the massive YSO Orion Source I.



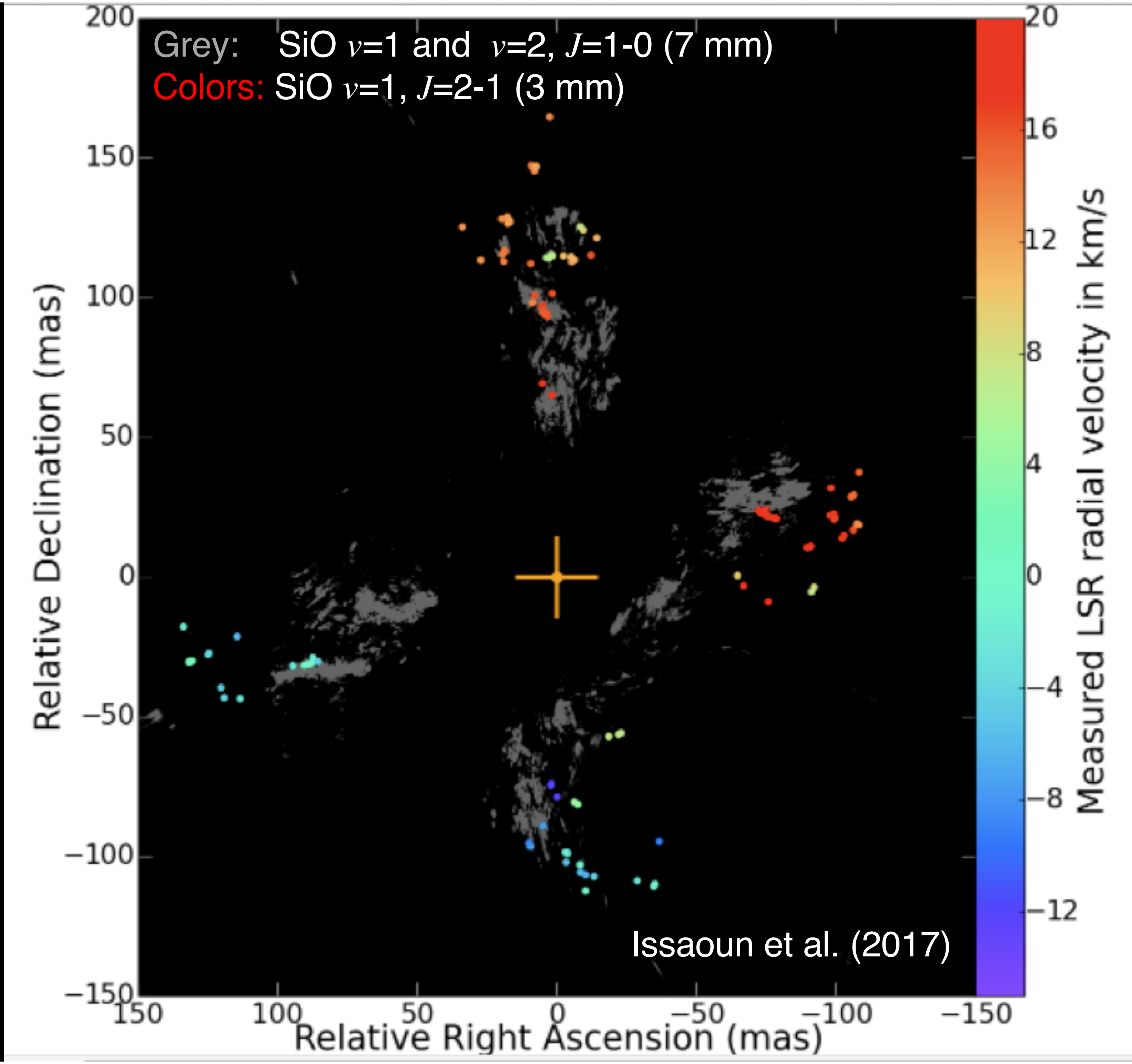
Multi-epoch observations of the SiO v=1 & 2, J=1-0 masers (7 mm) surrounding the massive YSO Orion Source I

Matthews et al. (2010)



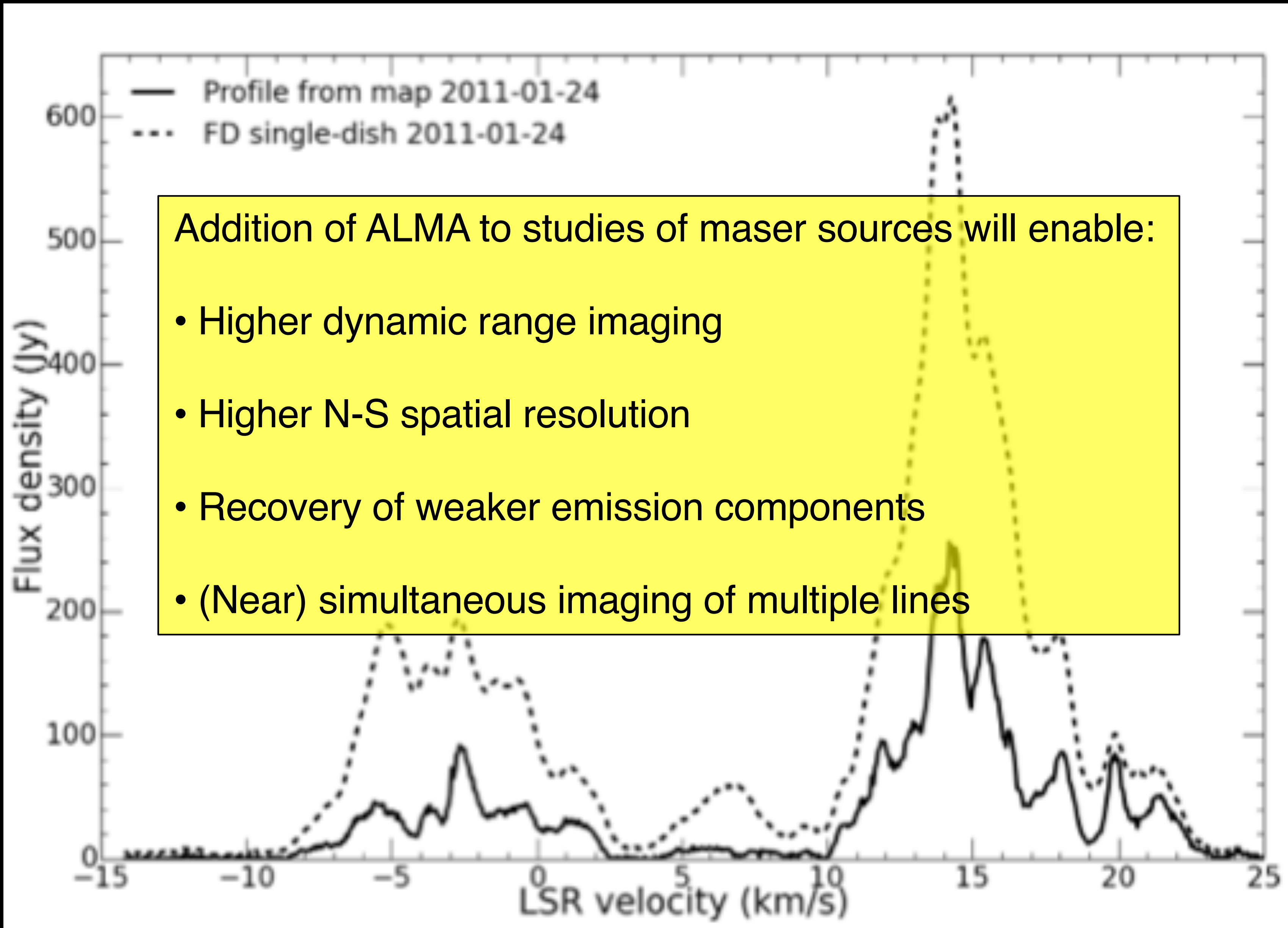


⇒ SiO masers surrounding Orion Source I trace a rotating disk and wide-angle bipolar wind from this massive young stellar object.



Grey: SiO v=1 and v=2, J=1-0 (7 mm)
Colors: SiO v=1, J=2-1 (3 mm)
Issaoun et al. (2017)
Relative Declination (mas)
Relative Right Ascension (mas)
Measured LSR radial velocity in km/s
200
150
100
50
0
−50
−100
−150
150
100
50
0
−50
−100
−150
20
16
12
8
4
0
−4
−8
−12

SiO v=1, J=2-1 spectra of Orion Source I: single-dish vs. VLBI data



Addition of ALMA to studies of maser sources will enable:

- Higher dynamic range imaging
- Higher N-S spatial resolution
- Recovery of weaker emission components
- (Near) simultaneous imaging of multiple lines

Issaoun et al. (2017)

Spectral Line Science with the APS

VLBI studies of masers to date have mainly focused on cm-wavelength maser transitions.

But numerous maser lines are also founds in the mm/submm regime:

Table 4. ALMA bands with known masering lines

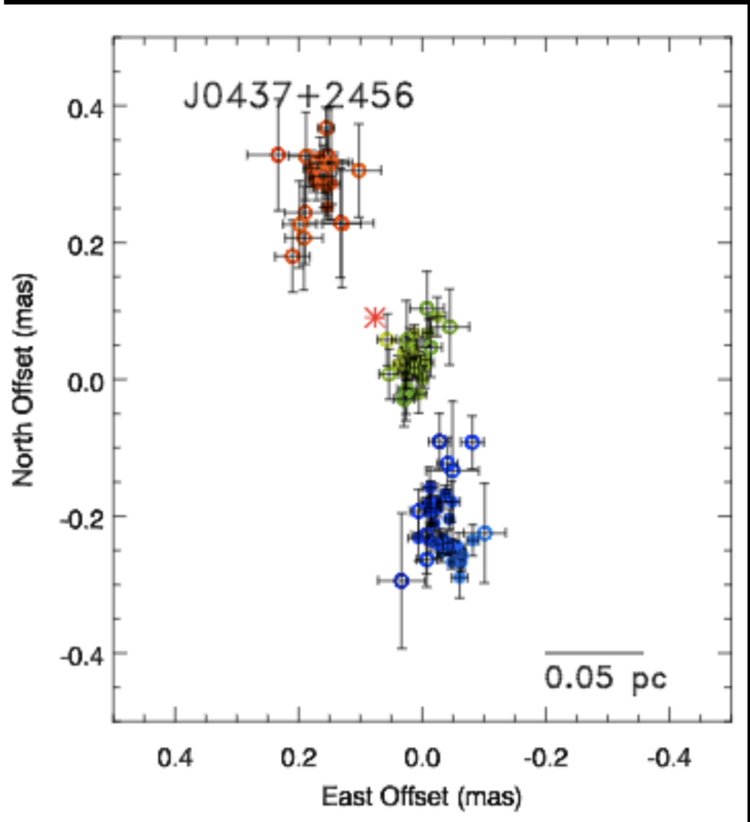
Array	**12m** and **Compact (ACA)**
Species	Bands
H_2O	B3, B5, B6, B7, B8, B9
CH_3OH	B1, B3, B4, B6
SiO	B1, B2, B3, B4, B5, B6, B7
HCN	B3, B5, B6, B7, B9
Etc: H$n\alpha$, SiS	B3, B4, B6, B7, B9

from
Wootten 2007

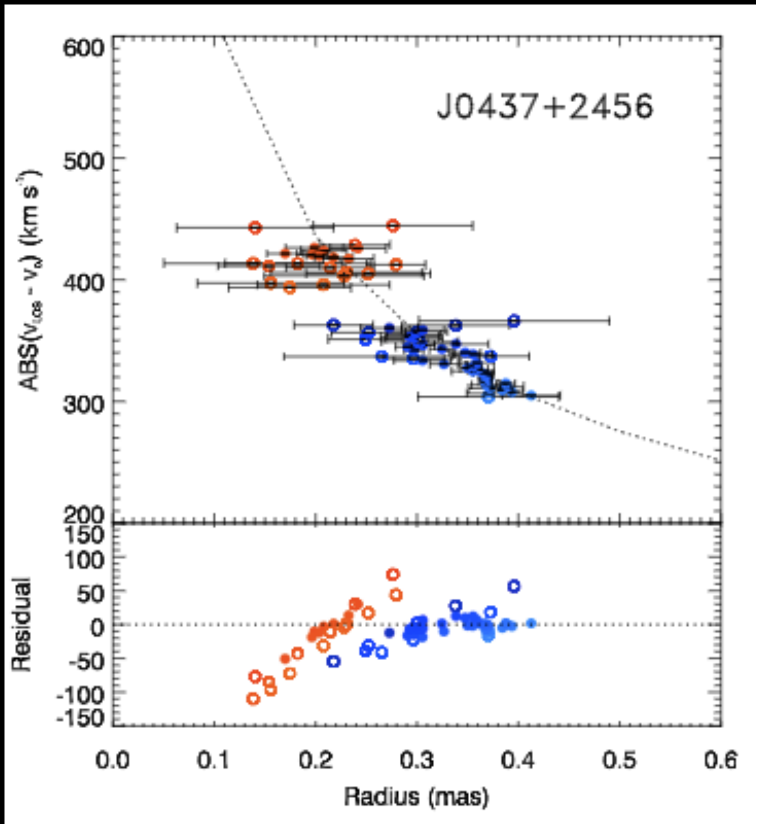
Different maser species, and different maser transition of a given molecule, can probe different different physical conditions and spatial scales.

VLBI observations of H_2O maser disk at center of galaxy J0437+2456 (D≈7 Mpc)

22 GHz H_2O Maser velocity map



P-V diagram



⇒BH mass
(2.9±0.3) × 10^6 $M_\odot$

from Gao et al. 2016

Future observations of high frequency transitions could allow:
- improved resolution
- observations of back side of maser disk (owing to smaller optical depth).

Summary

- “Phase 1” of the ALMA Phasing Project (APP) has created a powerful new facility for VLBI science at mm wavelengths.

- An approved APP “Phase 2” is poised to further enhance and diversify the scientific potential of ALMA for VLBI.

  New capabilities to be implemented in Cycle 7 are expected to include:

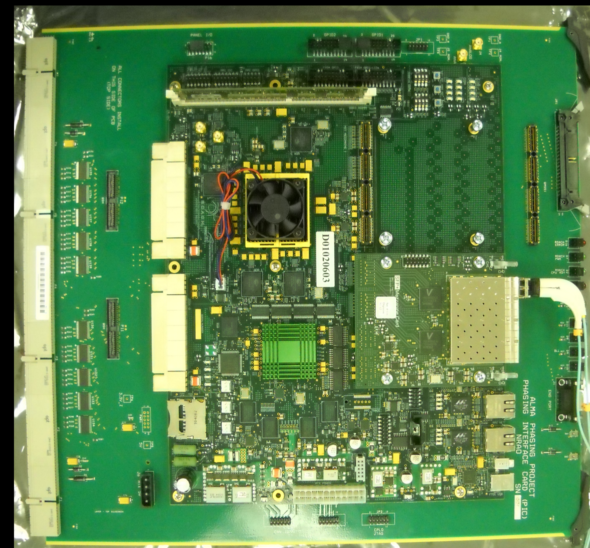
  1) Extension of phasing to the sub-mm (Band 7)
  2) VLBI on weaker sources (<0.5 Jy)
  3) Spectral line VLBI

[redacted]

APP hardware components

(Half of)
Optical Fiber
Link System

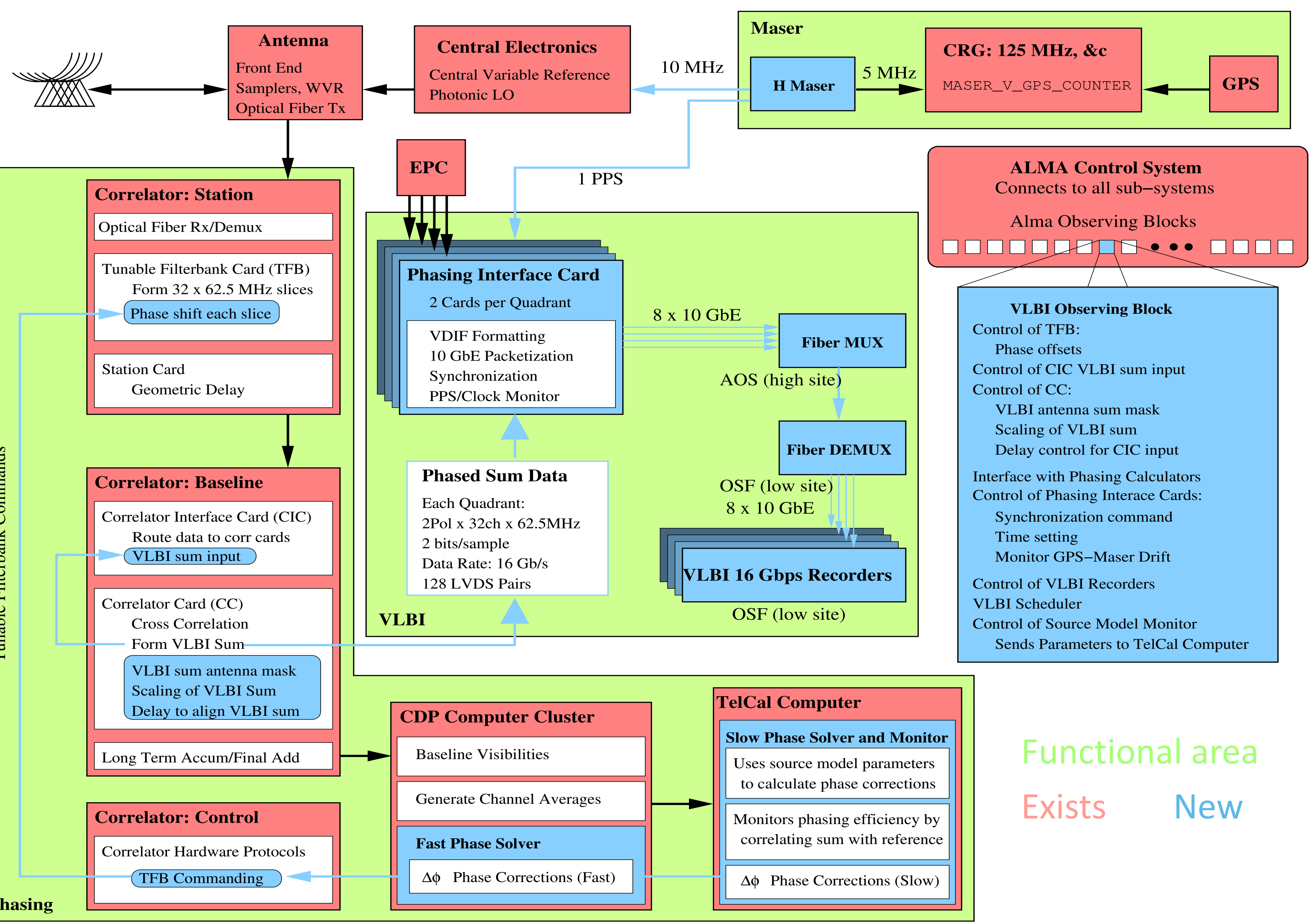
Mark 6
VLBI
Recorders

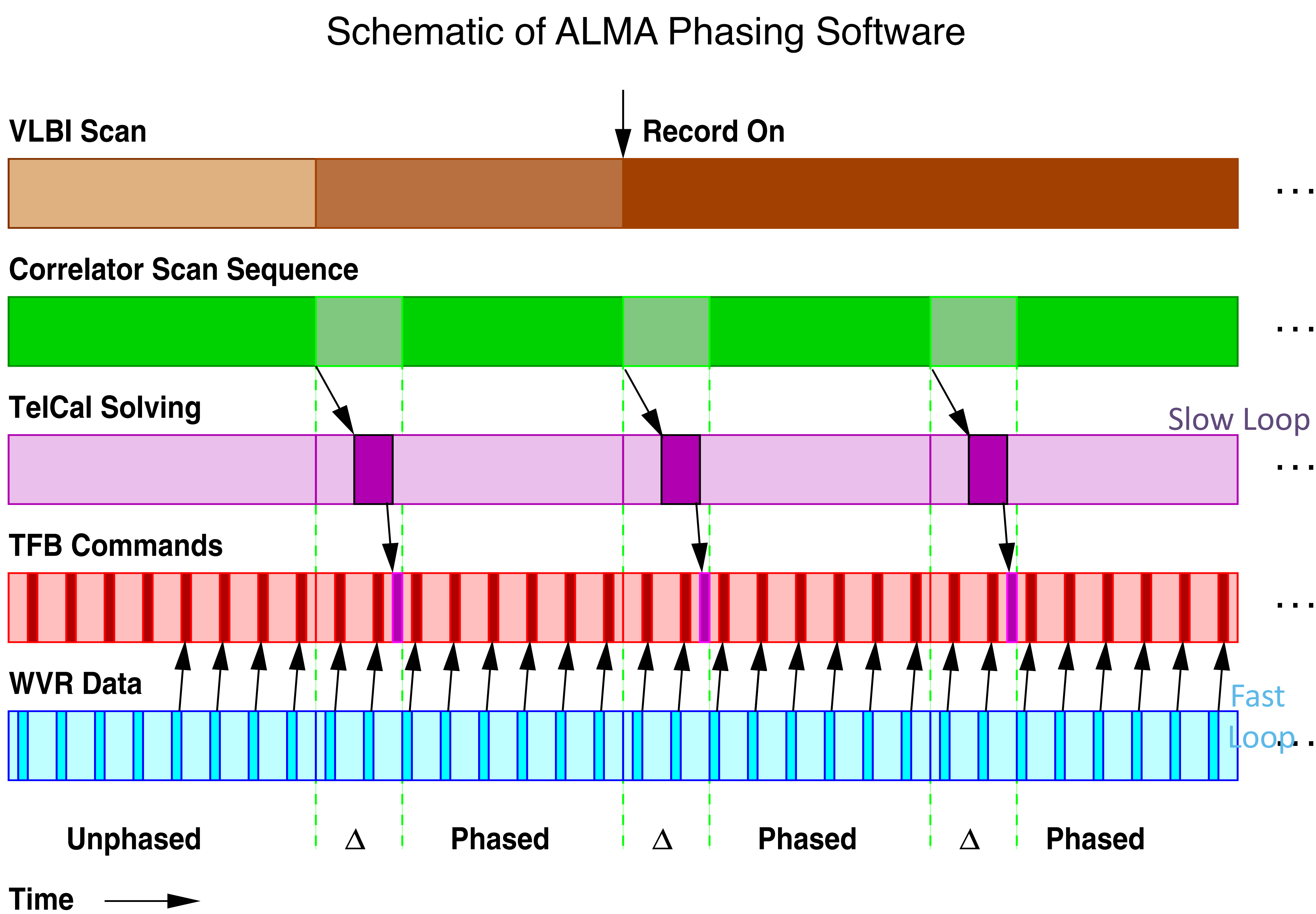


Phasing
Interface
Cards (PICs)

Hydrogen
Maser

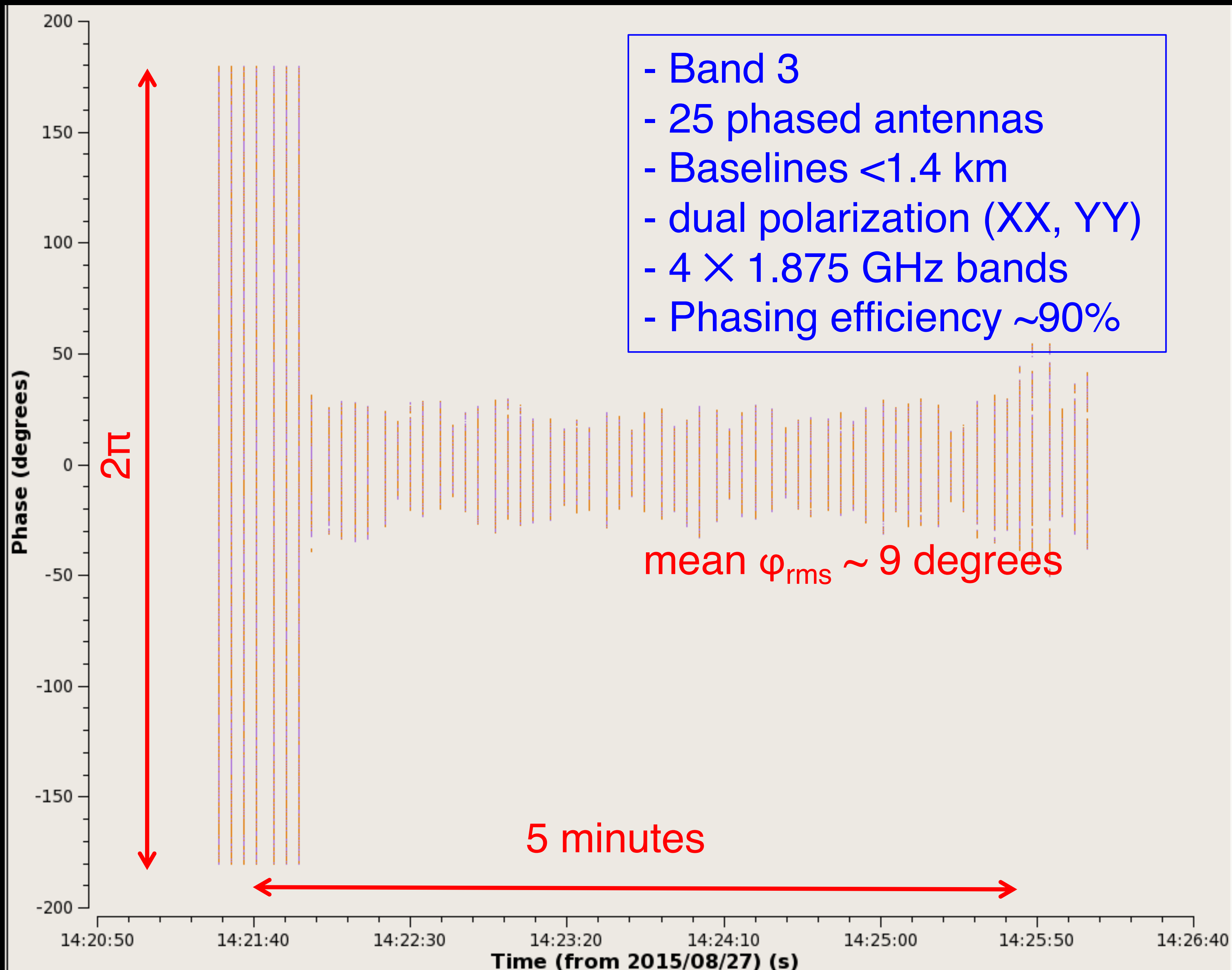
APP System Block Diagram



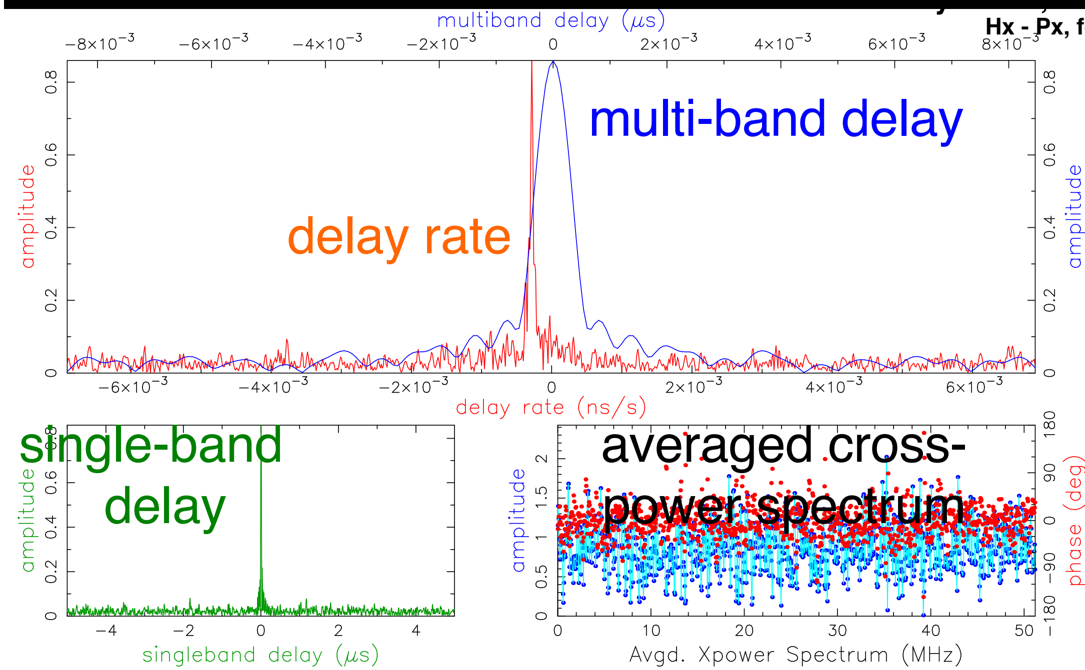


Schematic of ALMA Phasing Software
VLBI Scan
Record On
Correlator Scan Sequence
TelCal Solving
Slow Loop
TFB Commands
WVR Data
Fast Loop
Unphased
Δ
Phased
Δ
Phased
Δ
Phased
Time

ALMA Phasing System observation from August 2015:

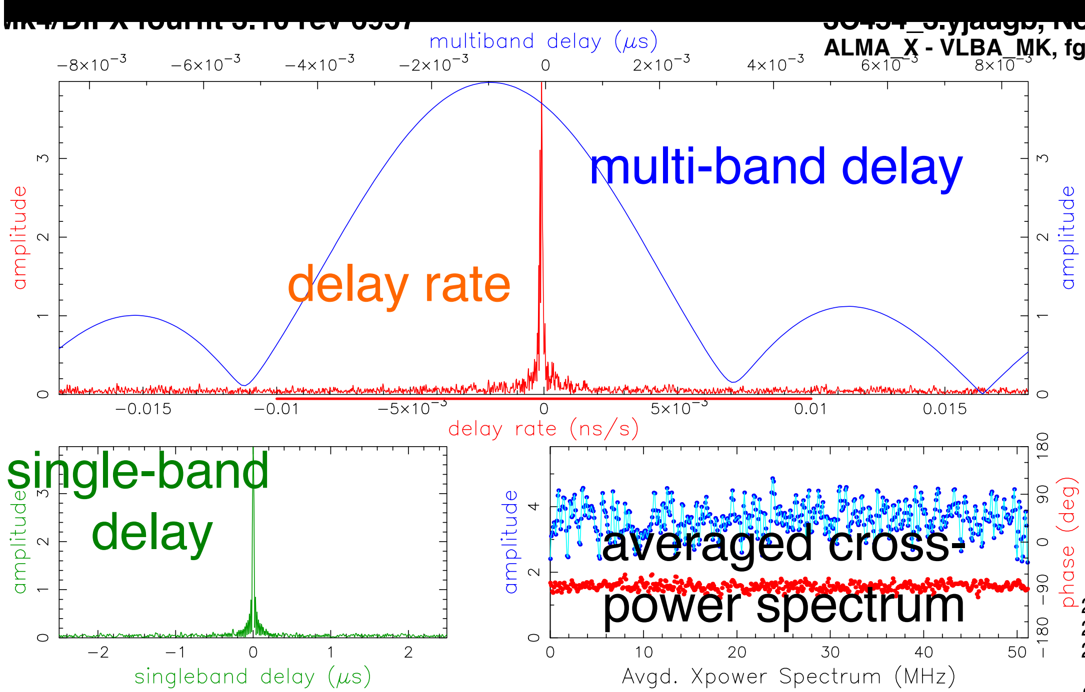


First Intercontinental VLBI Fringes with ALMA



Phased ALMA – IRAM 30m:
March 30, 2015

- Band 6 (λ1.3 mm)
- Source 3C273
- 9770 km baseline



Phased ALMA – VLBA (MK):
August 1, 2015

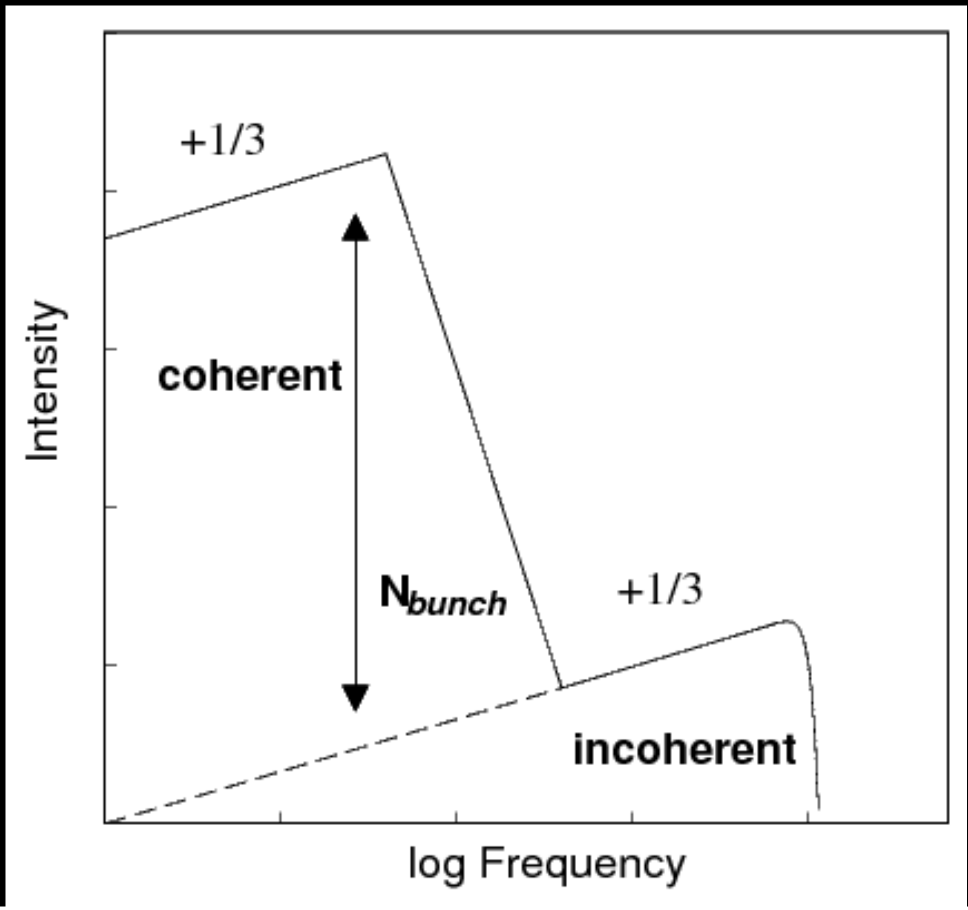
- Band 3 (λ3 mm)
- Source 3C454.3
- 9446 km baseline

Pulsars

• A number of pulsars and magnetars have now been detected at mm wavelengths (32-86 GHz).

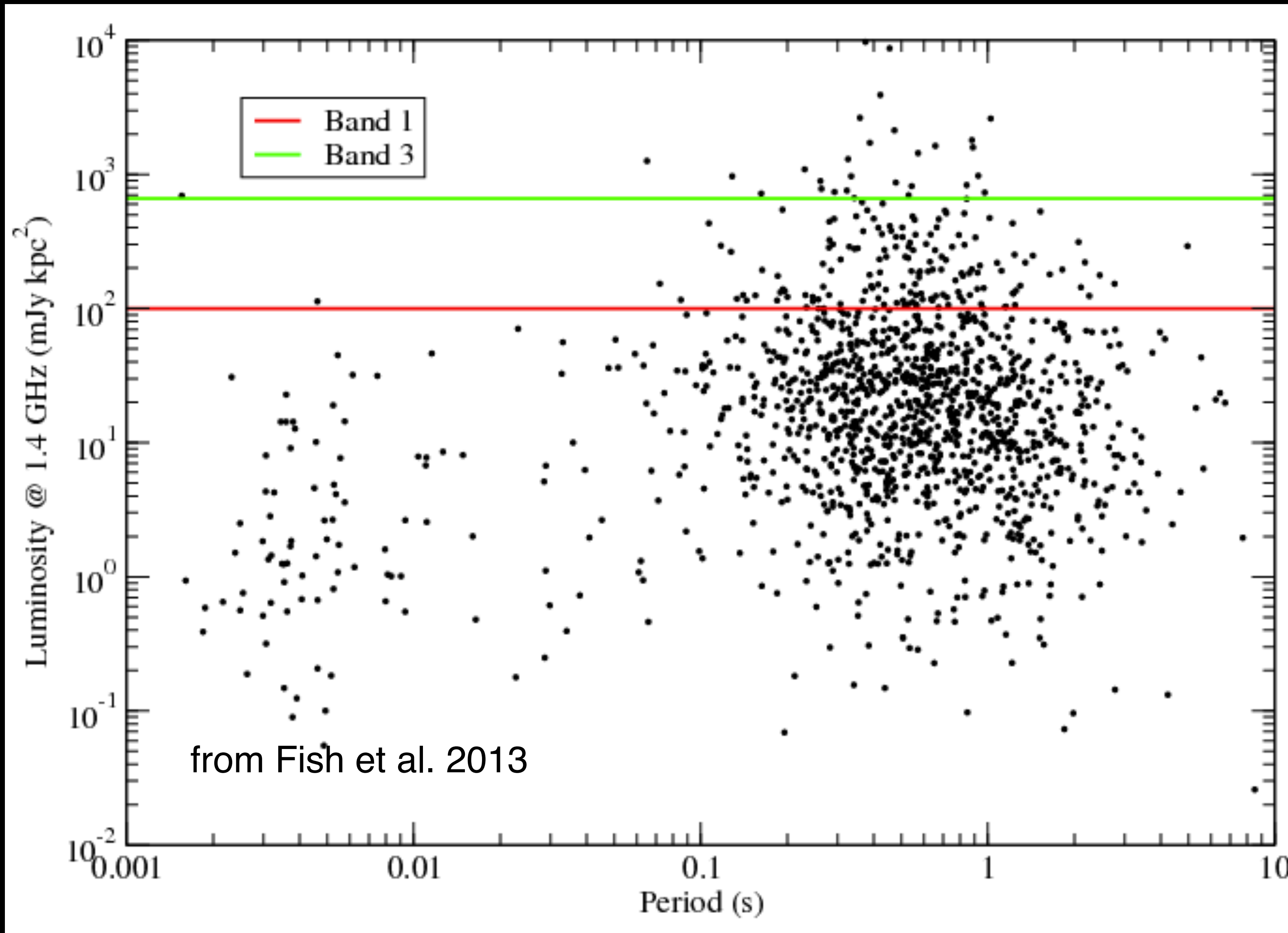
• Evidence for turnover at high frequency ⇒different emission mechanism?

• 72% of known pulsars lie in the Southern Hemisphere; detection of ~100 more at mm wavelengths predicted with ALMA.



credit: M. Kramer

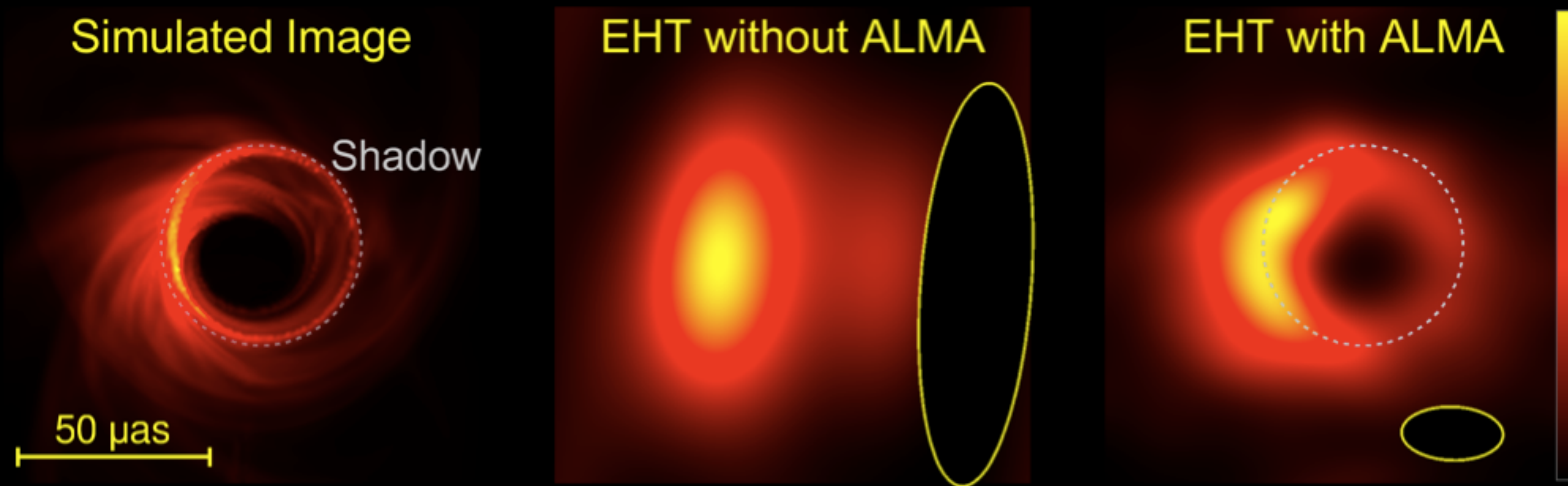
Application of Passive Phase-Up: Pulsar Searches



- Searches for pulsars toward the Galactic Center are of particular interest for precise tests of general relativity

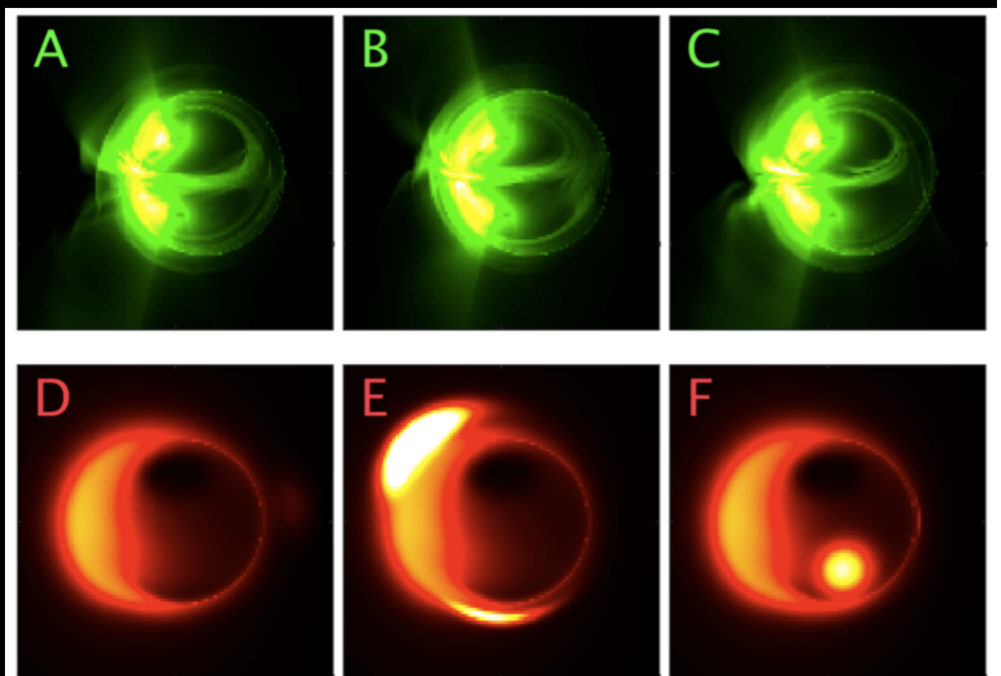
- Although pulsars get weaker with high freq., scattering effects decrease

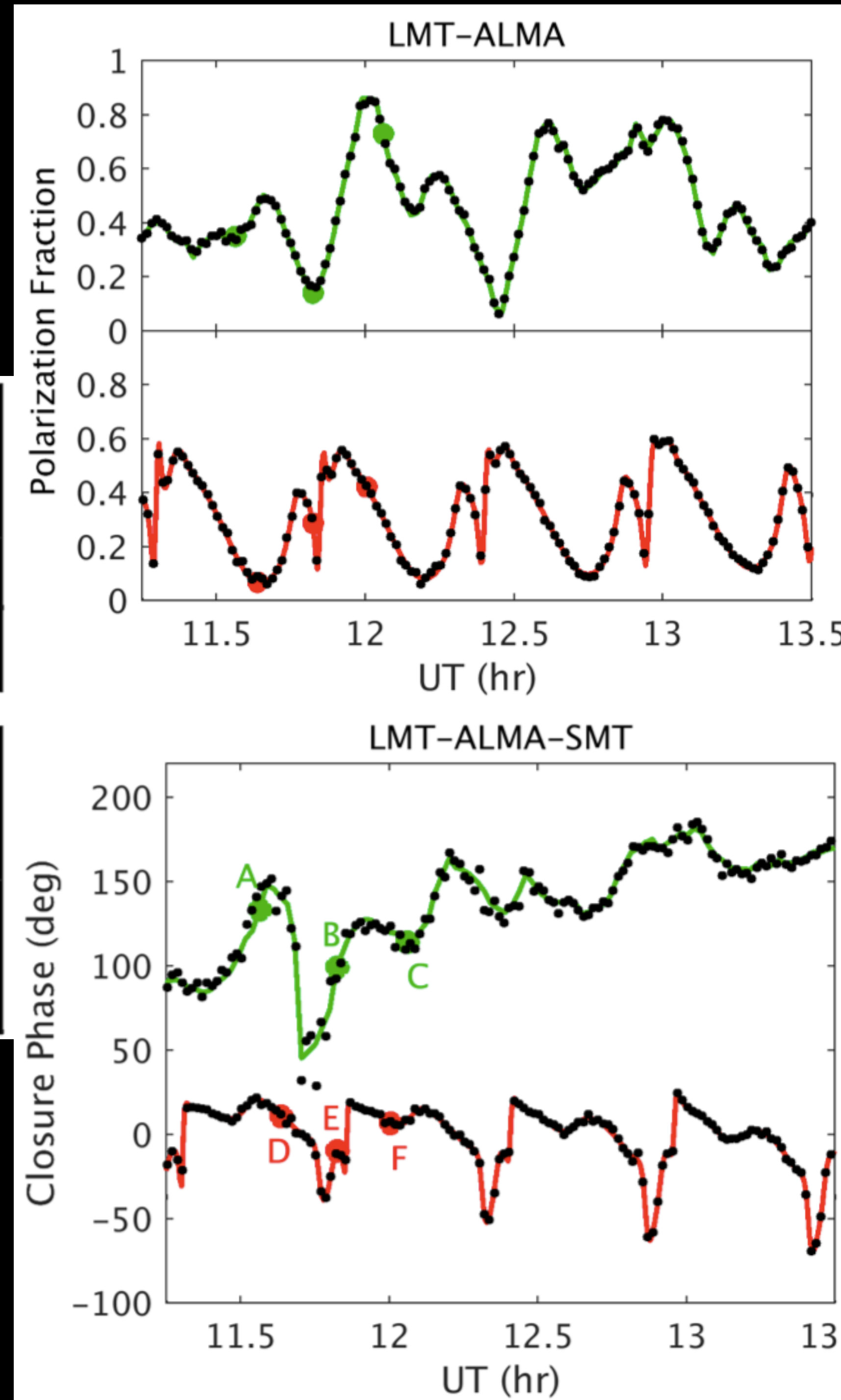
Approved APS Science for Cycle 4:
Imaging the Shadow of a Supermassive Black Hole: Sgr A* at 1.3mm
Team: EHT Consortium, S. Doeleman PI



- Observations with an earth-sized telescope at λ~1 mm are needed to resolve structures around Sgr A* on event horizon scales (~30µas).
- The boost in sensitivity of phased ALMA, coupled with its geographical location, will be key to recovering predicted signatures of strong field gravity—including the “shadow” cast by the BH on the surrounding plasma.

Time-variable phenomena associated with Sgr A* should also be readily detectable with Cycle 4 ALMA+EHT VLBI observations.





Credits:
Gold et al. (2016; top); Broderick & Loeb (2006), Doeleman et al. (2009) (bottom)

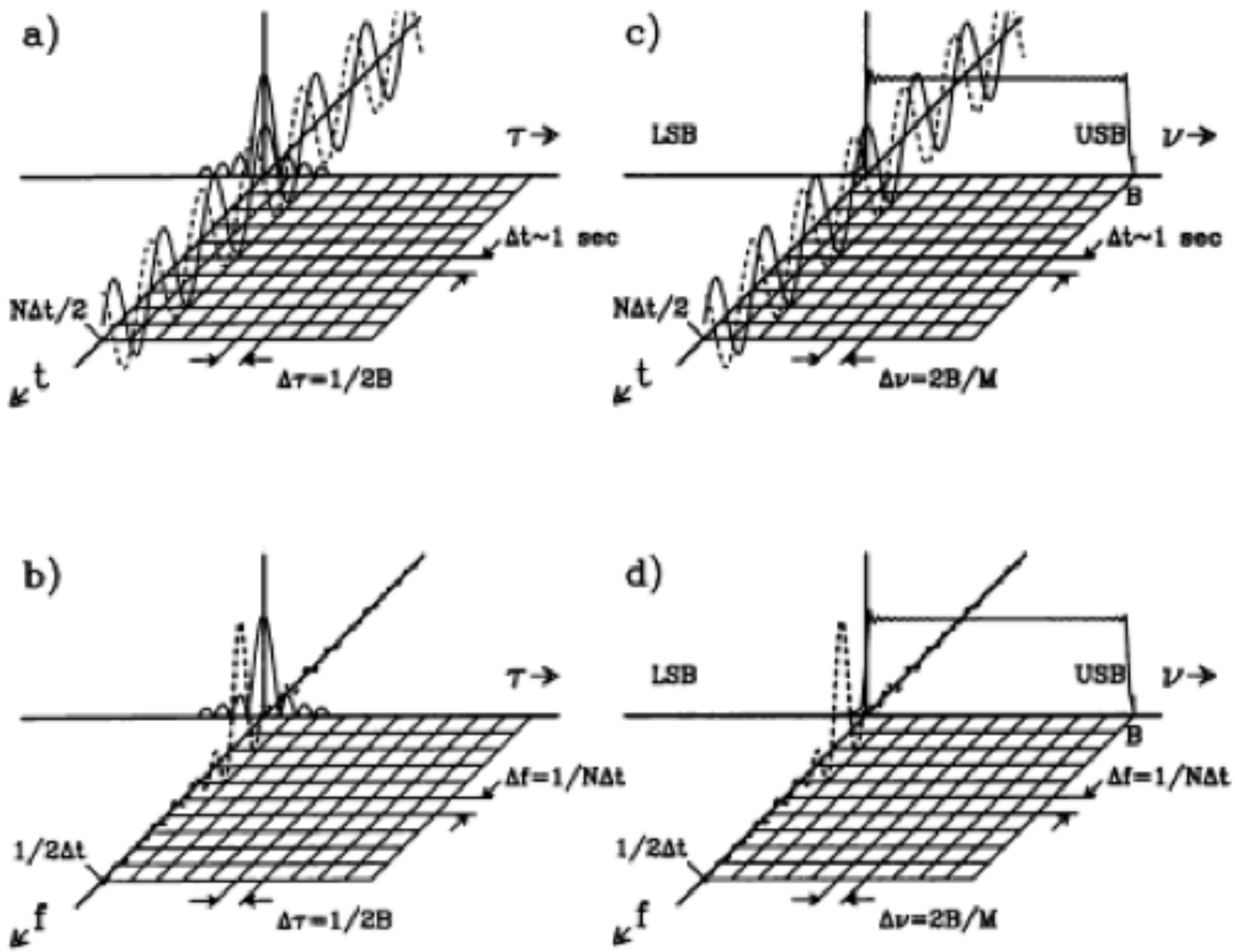


Figure 11.1: Fringe visibilities for a continuum source *(see text)*.

Reid 1995

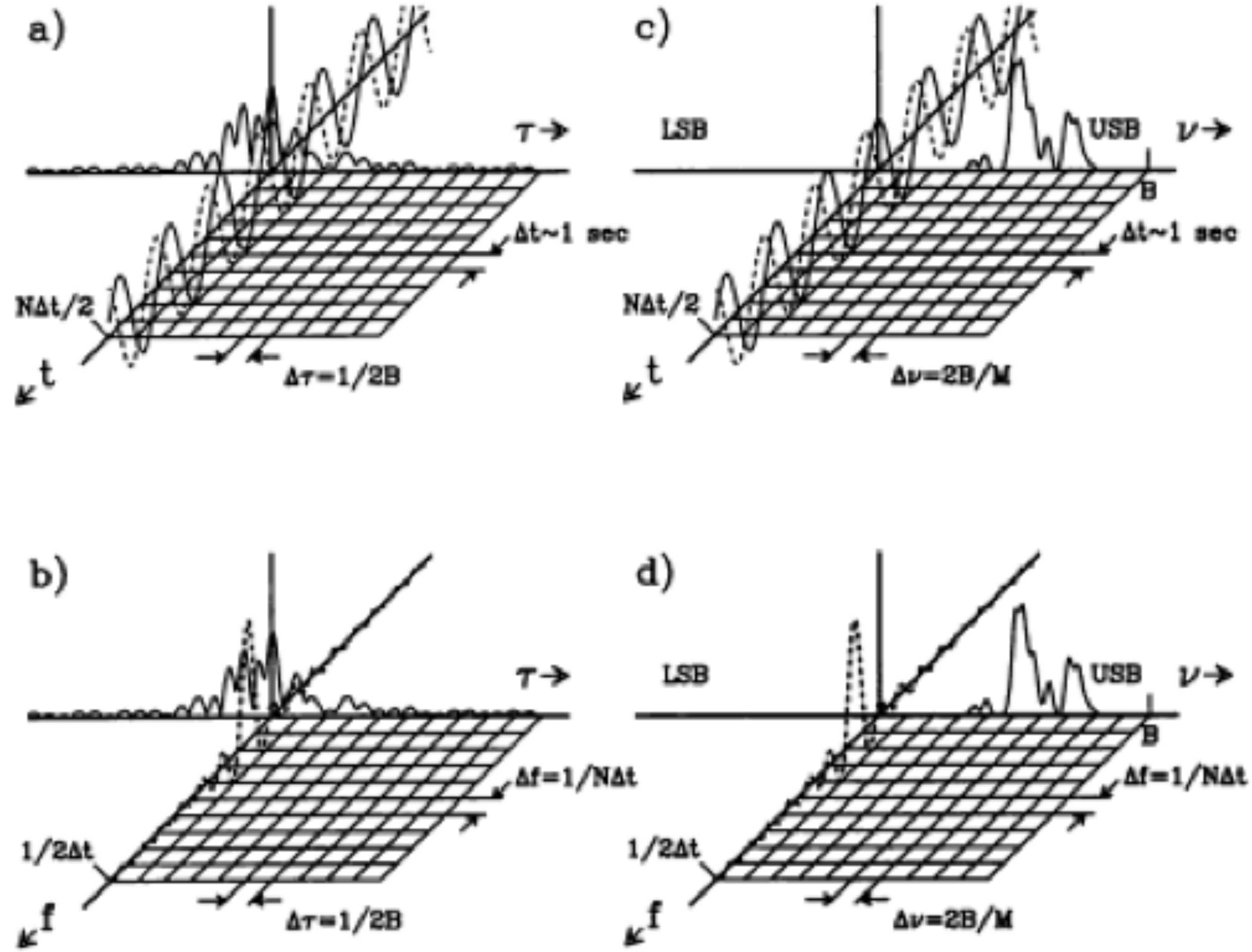


Figure 11.2: Fringe visibilities for a spectral-line source *(see text)*.

Reid 1995