Diversifying the Scientific Applications of the ALMA Phasing System

Lynn D. Matthews

MIT Haystack Observatory

Background: the ALMA Phasing Project (APP)

- Approved as an ALMA NA Development Project in 2012.
- **Principal Investigator:** Sheperd Doeleman (MIT Haystack Observatory)
- **Objective:** provide the hardware and software to coherently sum the 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 (sub)millimeter wavelengths.

APP Participating Organizations:

- MIT Haystack Observatory (lead)
- NRAO
- Max Planck Institut für Radioastronomie
- University of Concepción
- ASIAA
- NAOJ
- Harvard-Smithsonian Center for Astrophysics
- Onsala Observatory

Sponsors:

- ALMA North America Development Fund
- NSF Major Research Instrumentation Program
- Cost sharing partners

What Did Phasing ALMA 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 set of 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 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 ALMA Technical Notes 16-20)

Quick Summary of Phased ALMA Capabilities

Equivalent collecting area: 84-m parabolic dish
(assuming 50 phased 12-m antennas)

SEFD ~70 Jy @3 mm; 100 Jy @1 mm

Bandwidth: ~7.5 GHz

VLBI Recording: 64 Gbps aggregate (4 Mark-6 units, each 16 Gbps)

Polarization: dual pol. recording; full Stokes data sets

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

Current APP/APS Status

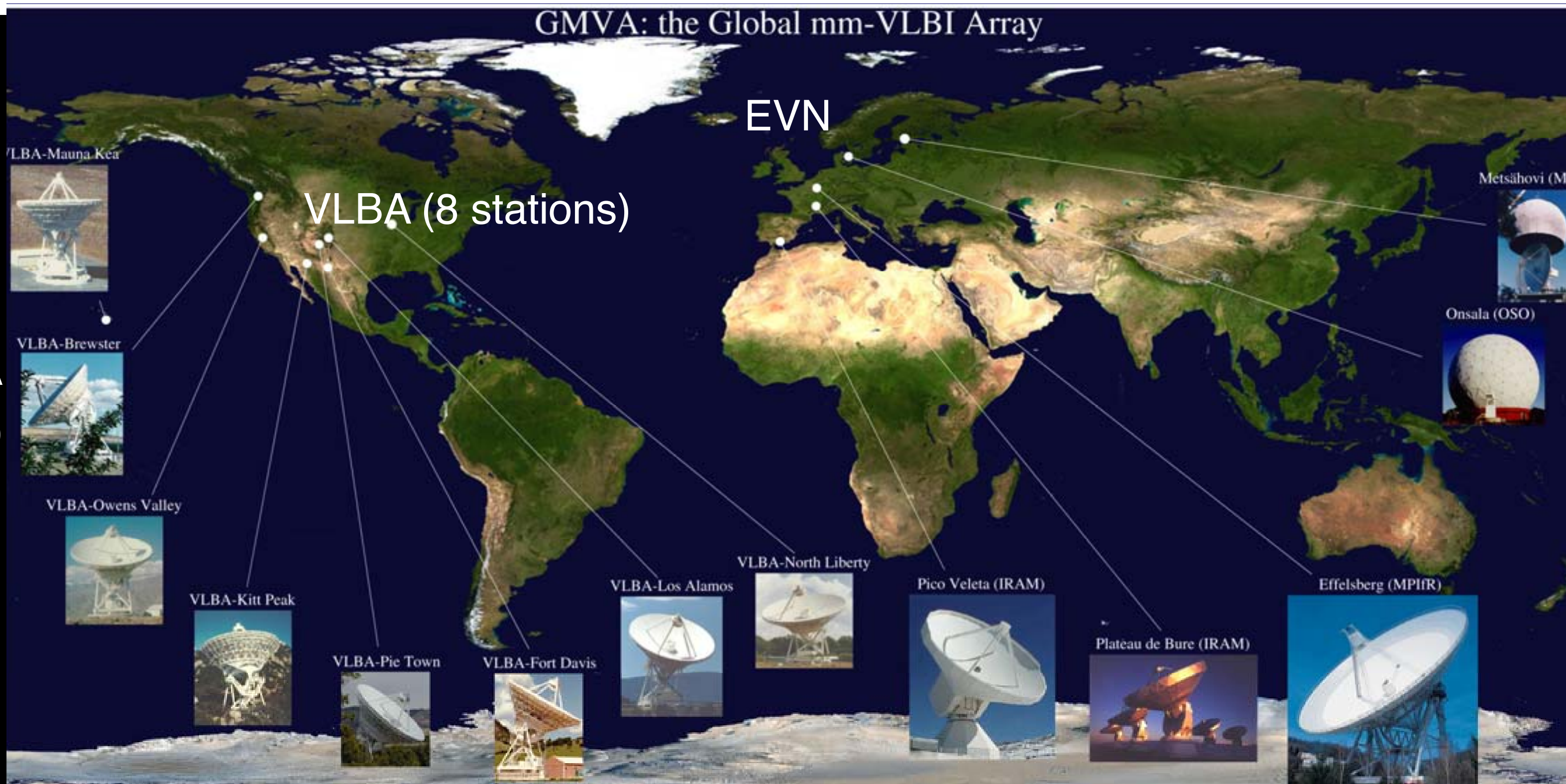
- Final stages of CSV (correlation, analysis for full “end-to-end” VLBI tests) ongoing

- VLBI with ALMA was offered to the community for the first time in Cycle 4:
  - 3-mm observations in conjunction w/ GMVA
  - 1-mm observations in conjunction w/ Event Horizon Telescope network

- Approved VLBI proposals announced August 8 (6 in Band 6; 3(?) in Band 3)

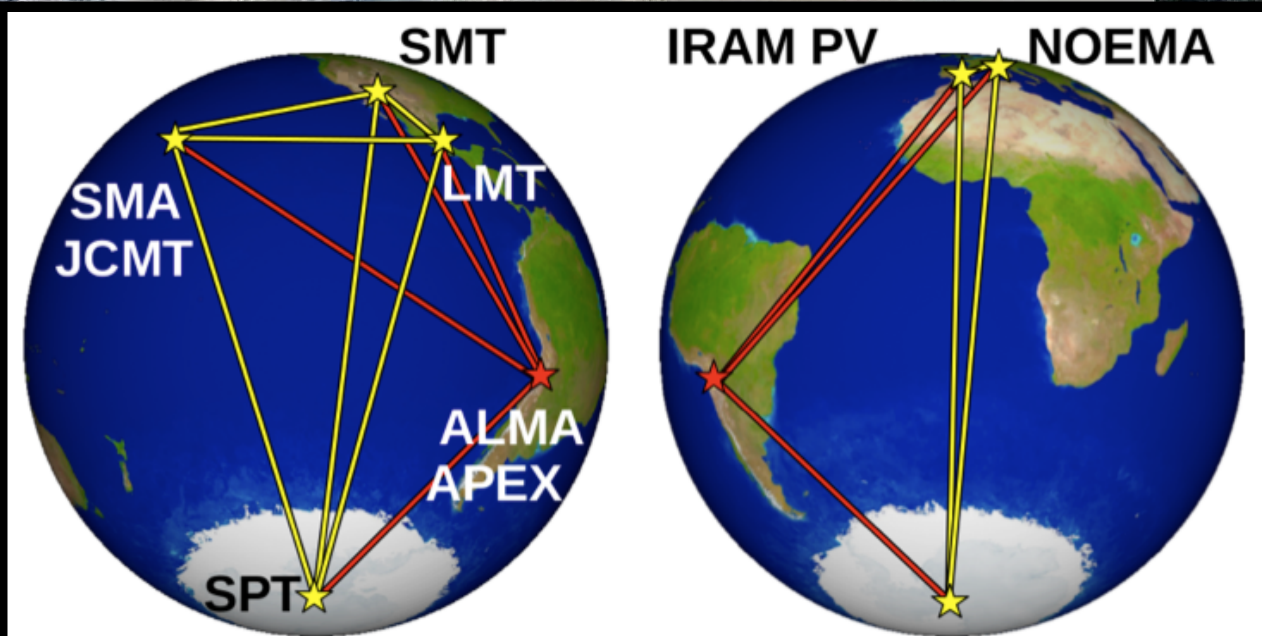
- First phased ALMA VLBI science observations will be executed in April 2017

GMVA
(3mm)

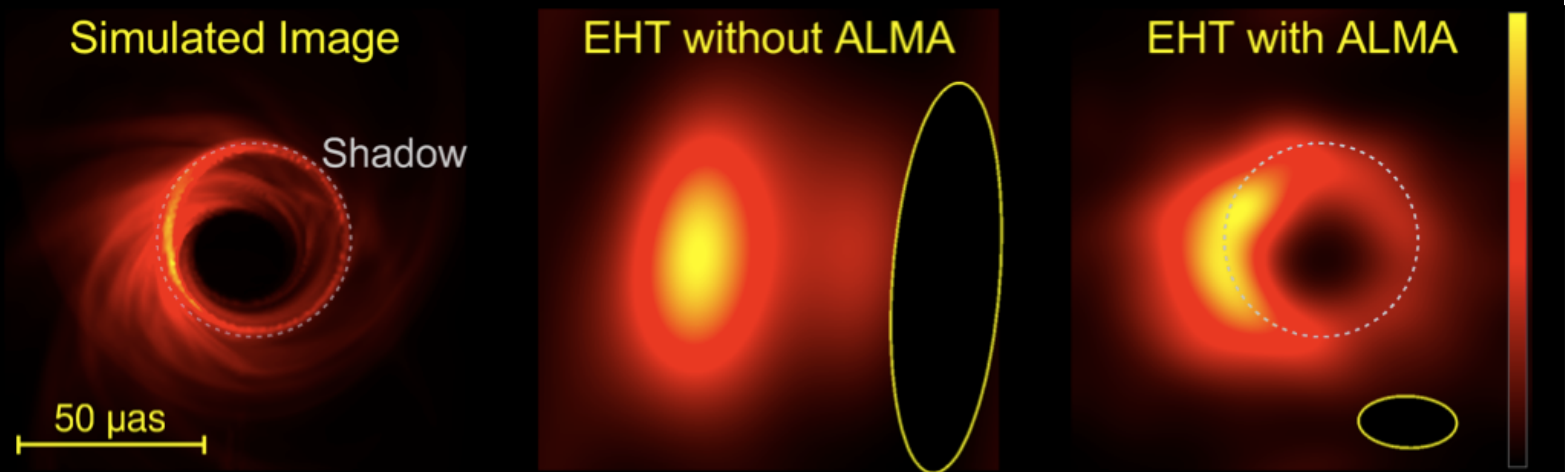


credit: T. Krichbaum

EHT
(1mm)



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

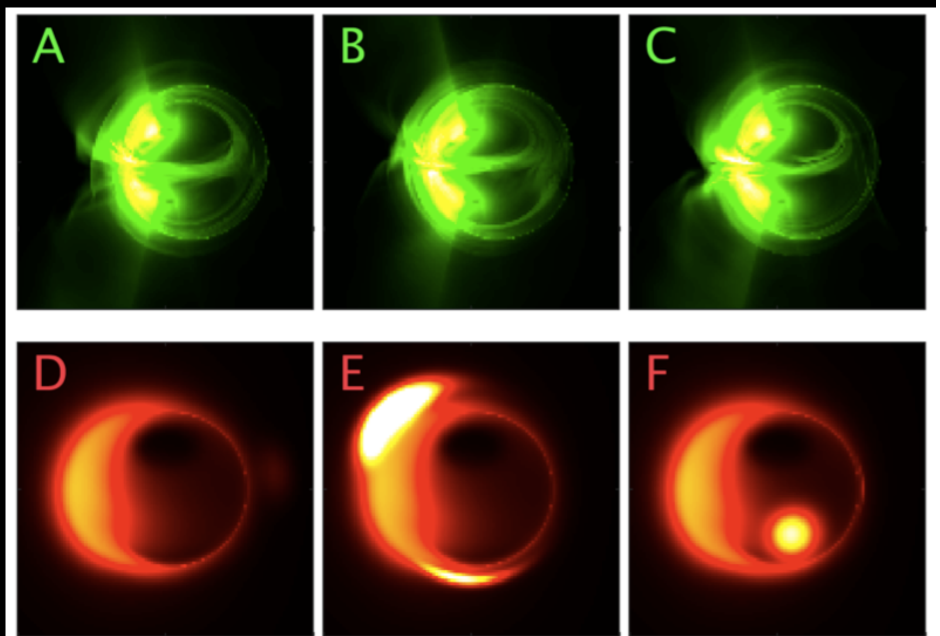


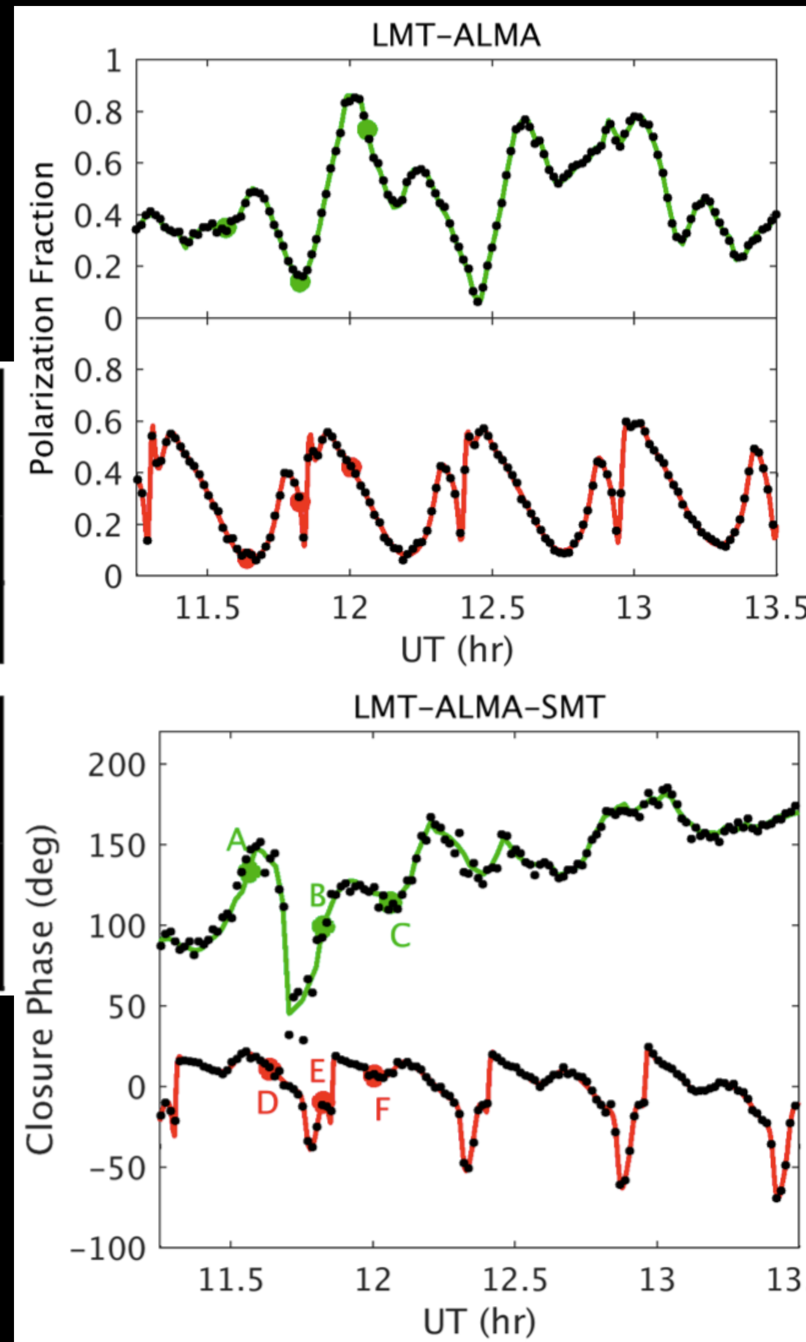
Credit: M. Johnson

- 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.





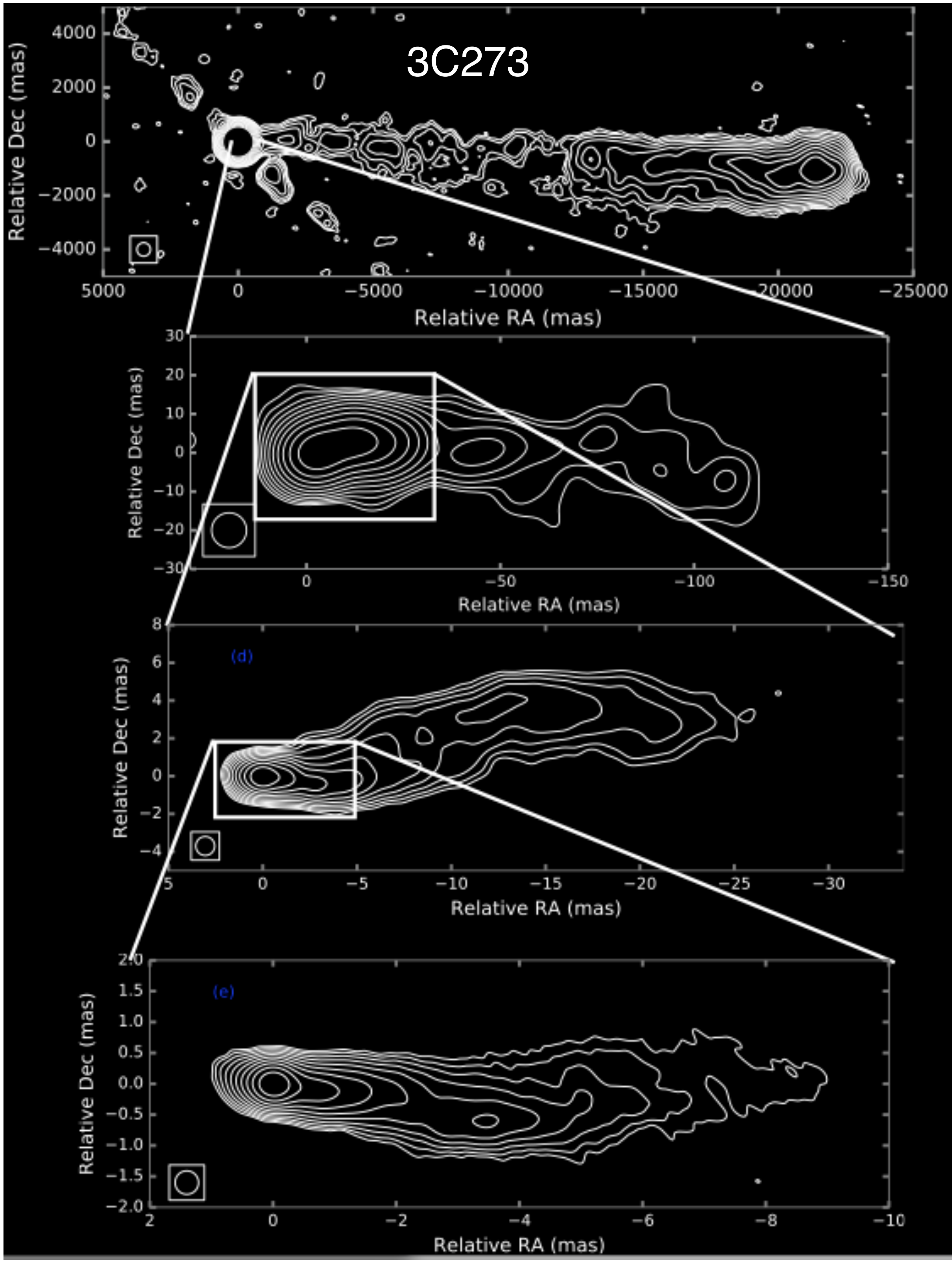
Credits:
Images: Michael Johnson
Models: Gold et al. (2016; top);
Broderick & Loeb (2006),
Doeleman et al. (2009) (bottom)

Approved APS Science for Cycle 4:
Probing the Active Collimation Regions of the Relativistic Jet in 3C273 at 3mm
Team: K. Akiyama et al.

- In a subset of galaxies that host supermassive black holes, accretion onto the BH drives powerful radio jets.

- A key to understanding the origin of these relativistic jets is constraining competing models for their *collimation*.

- The nearby AGN 3C273 ($z=0.158$) is a prime object for solving the puzzle.



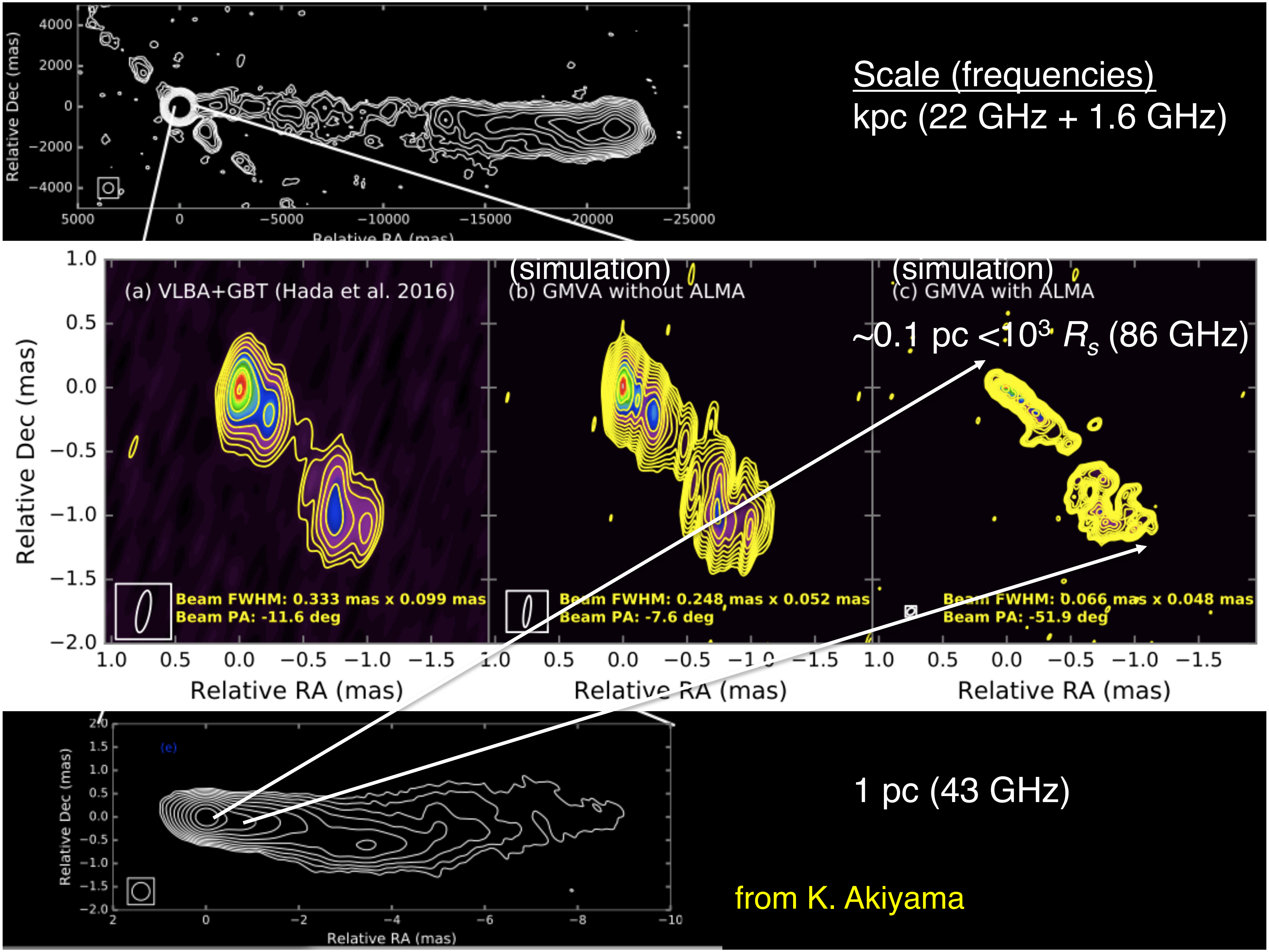
Scale (frequencies)
kpc (22 GHz + 1.6 GHz)

100 pc (1.6 GHz)

10 pc (15 GHz)

1 pc (43 GHz)

from K. Akiyama



Scale (frequencies)
kpc (22 GHz + 1.6 GHz)
(simulation)
(simulation)
(a) VLBA+GBT (Hada et al. 2016)
(b) GMVA without ALMA
(c) GMVA with ALMA
~0.1 pc <10^3 R_s (86 GHz)
Beam FWHM: 0.333 mas x 0.099 mas
Beam PA: -11.6 deg
Beam FWHM: 0.248 mas x 0.052 mas
Beam PA: -7.6 deg
Beam FWHM: 0.066 mas x 0.048 mas
Beam PA: -51.9 deg
Relative Dec (mas)
Relative RA (mas)
1 pc (43 GHz)
from K. Akiyama

What's Next for the APP/APS?

The "Phase 1" APS offered in Cycle 4 includes only a subset of its fully envisioned capabilities.

Current (Cycle 4) limitations include:

- Phasing in Band 3 (3mm) and Band 6 (1mm) only
- Fixed tunings at both 3mm and 1mm
- Targets must be bright (≥500 mJy on baselines <1 km)
- Continuum mode only (no spectral line science)

⇒ Two new ALMA NA Studies to address these areas

ALMA Cycle 3 Study:
"Extensions and Enhancements of the ALMA Phasing System"
(Status: *Ongoing*)

ALMA Cycle 4 Study:
"Diversifying the Scientific Applications of the ALMA Phasing System"
(Status: *Recommended for funding*)

Team:

L. D. Matthews (PI), G. Crew, S. Doeleman, V. Fish, M. Hecht
(*MIT Haystack Observatory*)

Topics include:

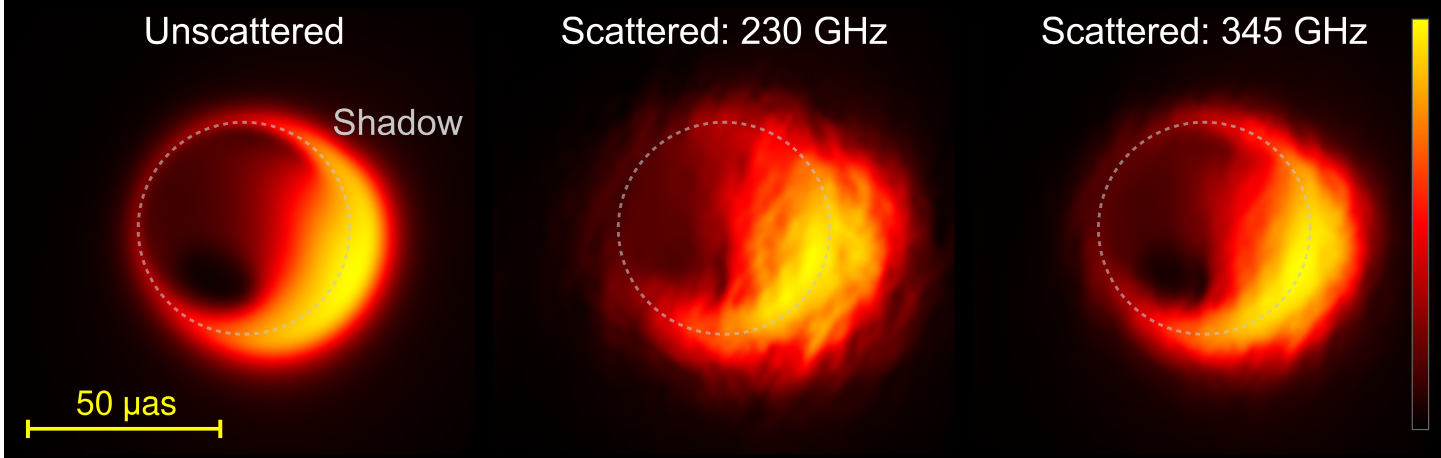
1. Extension of Phasing Capabilities to Band 7
2. Explore procedures for use of APS on weaker sources
3. Development of spectral-line VLBI capabilities

To avoid strain on ALMA resources, all target full implementation in ALMA Cycle 6.

Extension of Phasing Capabilities to Band 7

Taking phasing capabilities to higher frequencies offers key advantages:

- Enables higher spatial resolution: ~20μas @0.8mm (Band 7)
- Lessens impact of interstellar scattering, thereby enhancing ability to reconstruct images (see Johnson & Gwinn 2015).



Credits:
Black Hole Model:
Avery Broderick
Scattering Simulations:
Michael Johnson

Anisotropic scattering ⟺ Gaussian convolution
FWHM ~22μas @1.3mm (230 GHz)
vs.
FWHM ~10μas @0.8mm (345 GHz)

Extension of Phasing Capabilities to Band 7

The APS is in principle designed to work at any band, but in practice, greater coherence loss at higher frequencies results in additional factors to consider:

- How does phasing efficiency change with increasing frequency?

- What is the optimal balance between “fast” and “slow” phasing corrections?

- Is there an optimal array size for Band 7 observations (i.e., trading sensitivity loss by discarding outer stations to gain stability and/or allow more efficient use of computing resources)?

Flux Density Thresholds for the APS

For Cycle 4, imposed flux density requirement for the APS: S_ν >500 mJy on baselines <1 km.

These constraints are based on:

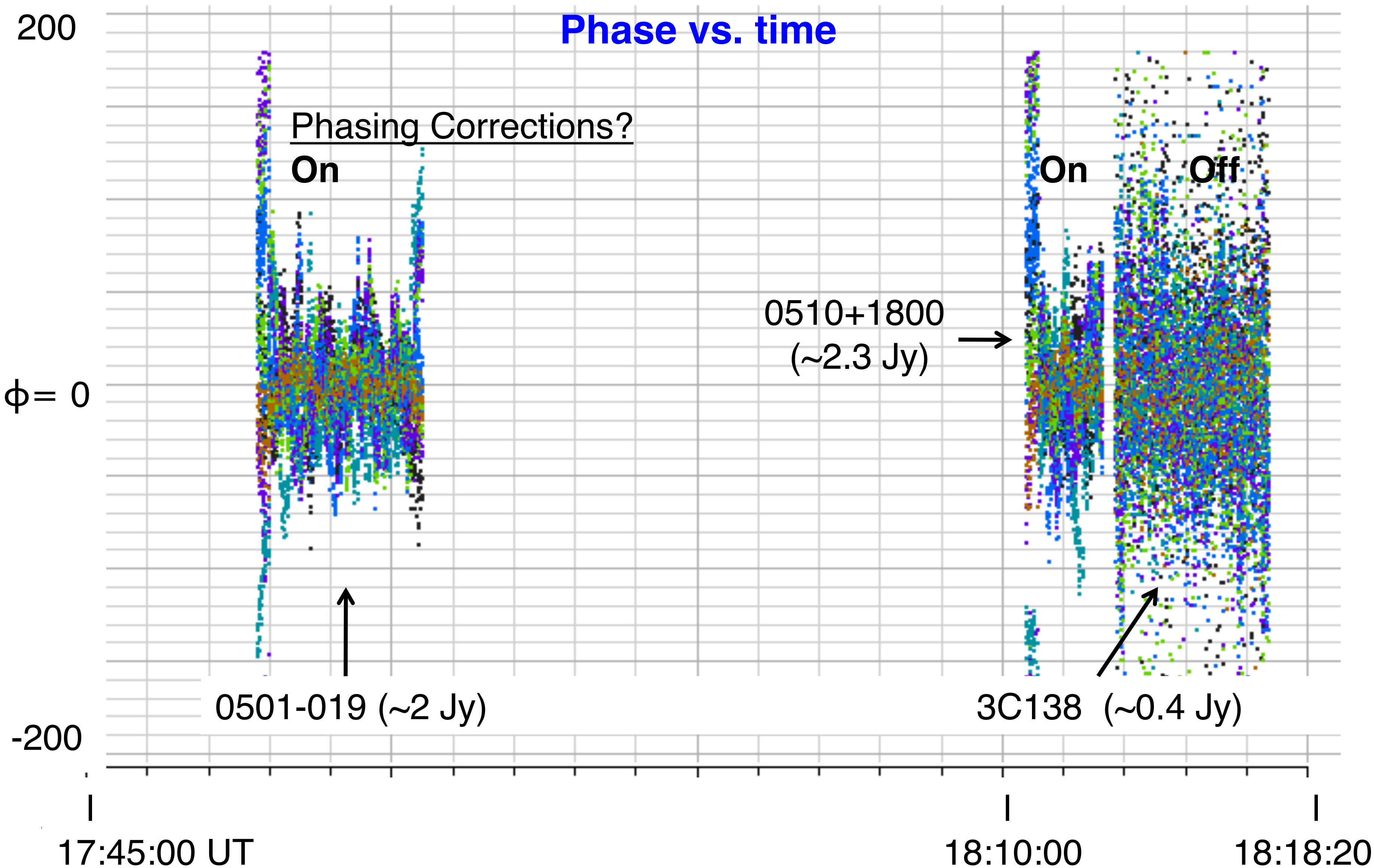
- Theoretical considerations (sensitivity, phasing efficiency)
- Current requirement to phase up on the science target itself

We are exploring two extensions of this:

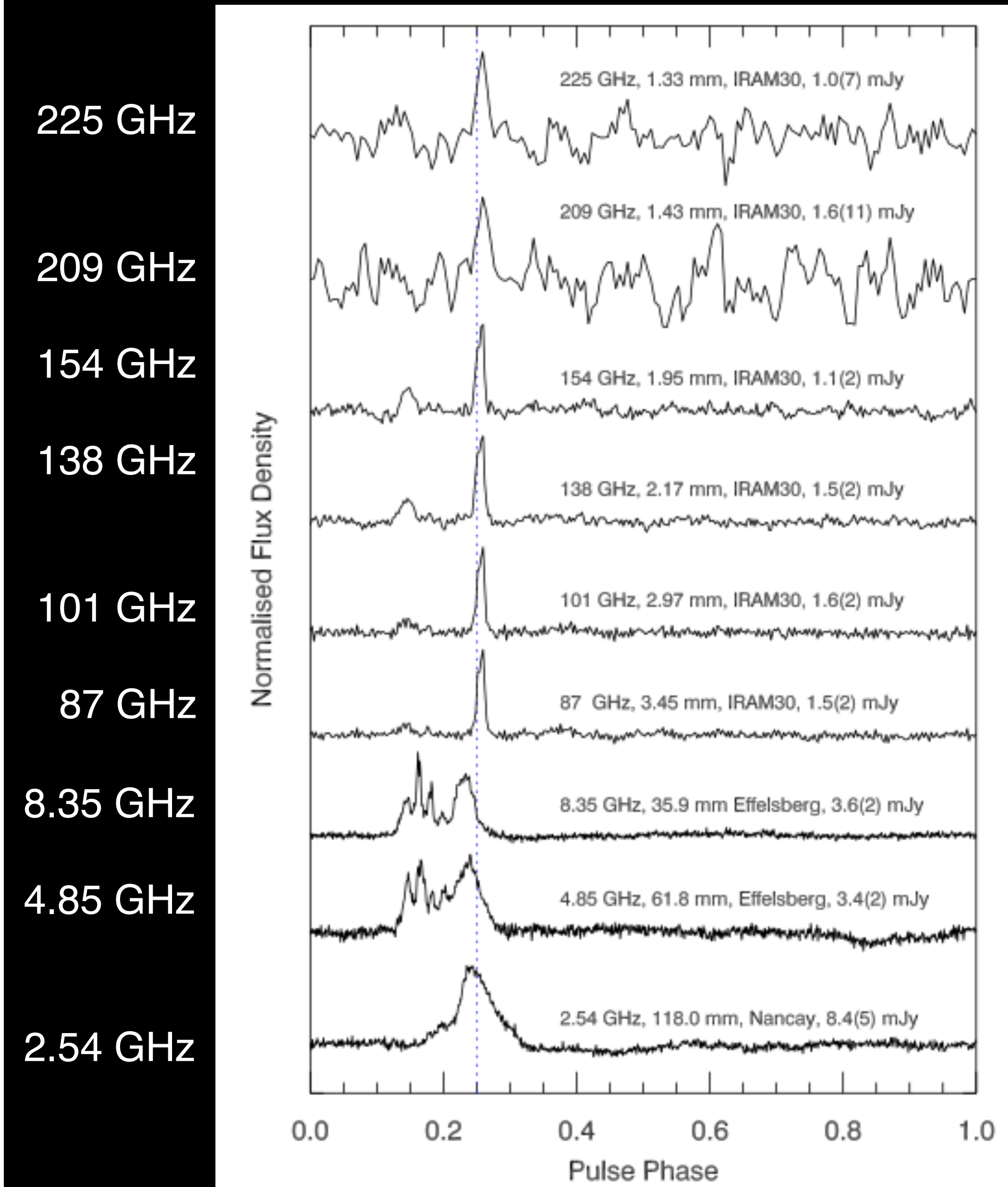
1. Direct phase-up on weaker sources: what is the empirical limit?
2. "Passive" phase-up (phase up on a brighter source close in angular distance to the target).

Variations of "passive phase-up" commonly used in VLBI already—but not at ALMA—and never at λ<3 mm.

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



Application of Passive Phase-Up: Pulsar Studies



from Torne et al. (2015)

Pulsars become weaker at higher frequencies, but effects of scattering become smaller.

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

⇒ Detectable at ALMA frequencies

Enabling Spectral Line VLBI

Fundamental principles of using the APS for spectral line work are the same as for continuum. But in practice, there are additional complications to consider:

- Spectral window matching: phasing up on a bright line is possible, but the spectral window used for the phasing calculation must be judiciously selected.

- Updates to the Observing Tool (OT): tuning flexibility required; may also need to impose tuning limitations of peer observatories.

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

- Correlation: mismatch of sampling rates between ALMA and peer stations necessitates special approaches to correlation; need to further refine these for spectral line set-ups

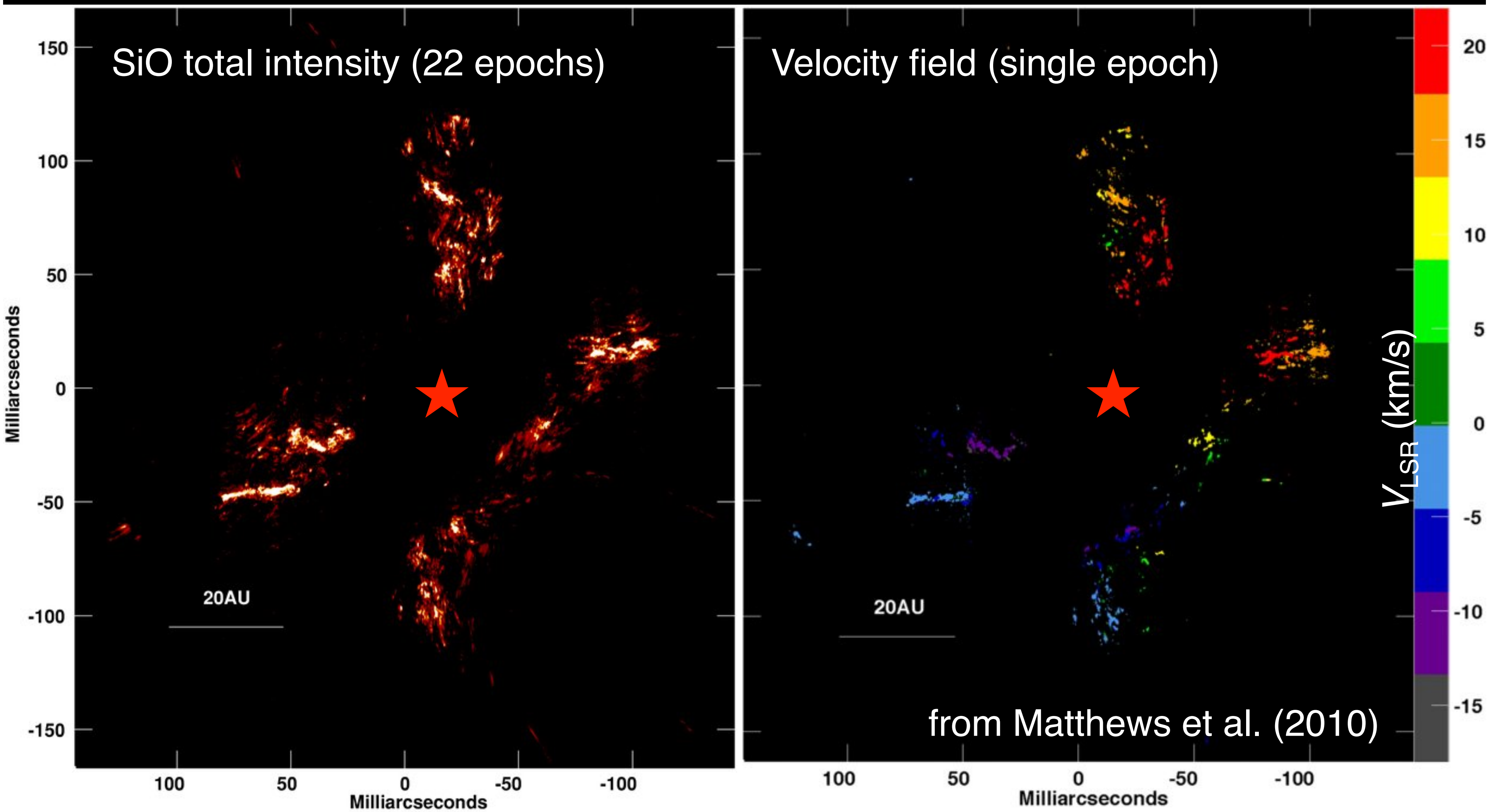
Spectral Line Science with the APS: Masers

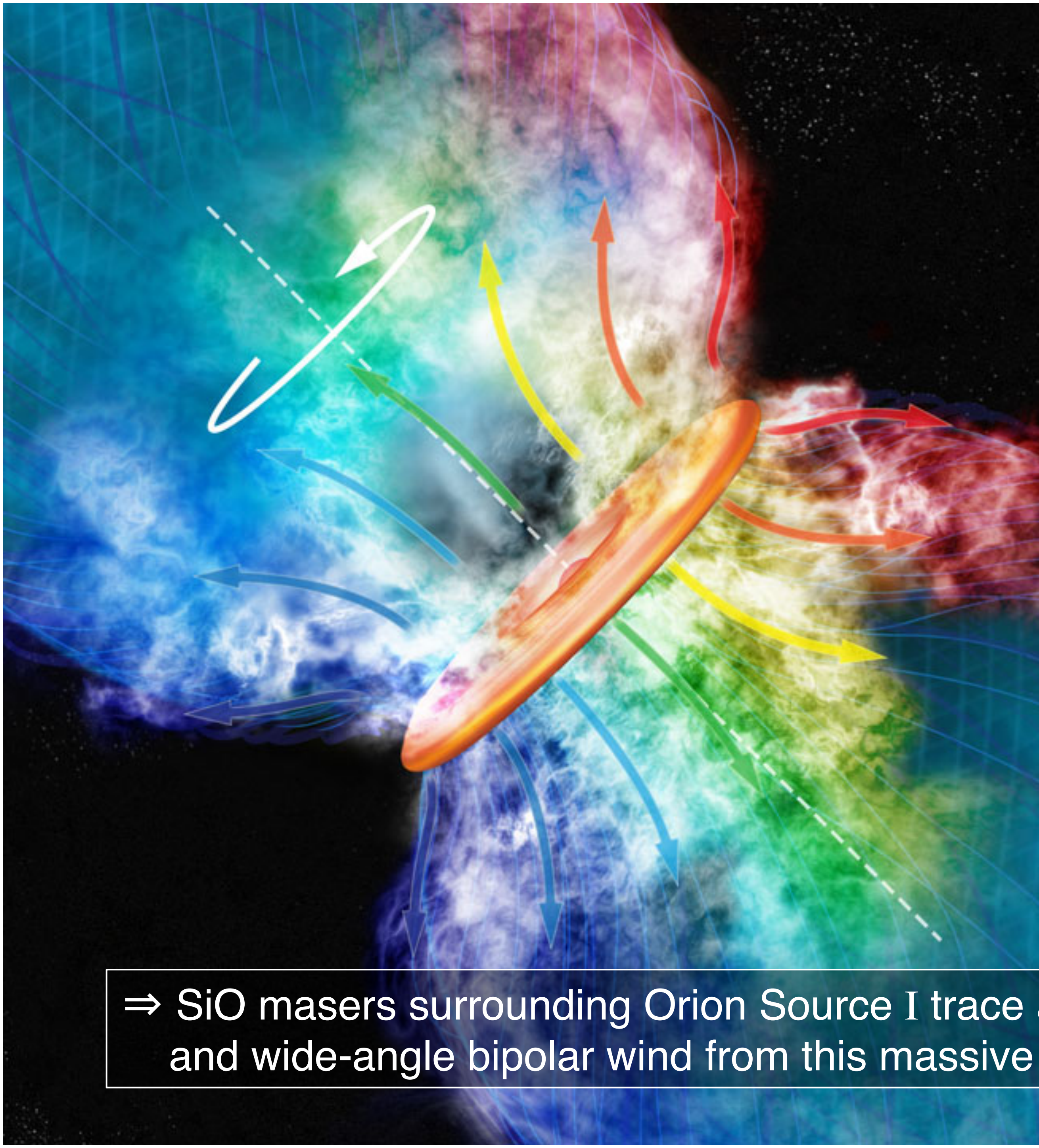
Astrophysical masers probe a variety of astrophysical environments:
- star-forming regions
- envelopes of evolved stars
- stellar/PN outflows
- circumnuclear disks of galaxies

The compact sizes (~1 AU) and high brightness temperatures of maser-emitting regions (up to 10^{17} K) makes them prime targets for VLBI.

Such studies can provide key insights into gas distributions, kinematics, and physical conditions on spatial scales that cannot be probed any other way.

Multi-epoch observations of the SiO v=1 & 2, J =1-0 masers (43 GHz) surrounding the massive YSO Orion Source I





Credit:
Bill Paxton (NRAO)

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

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 (see also Humphreys 2007).

Table 4. ALMA bands with known masering lines

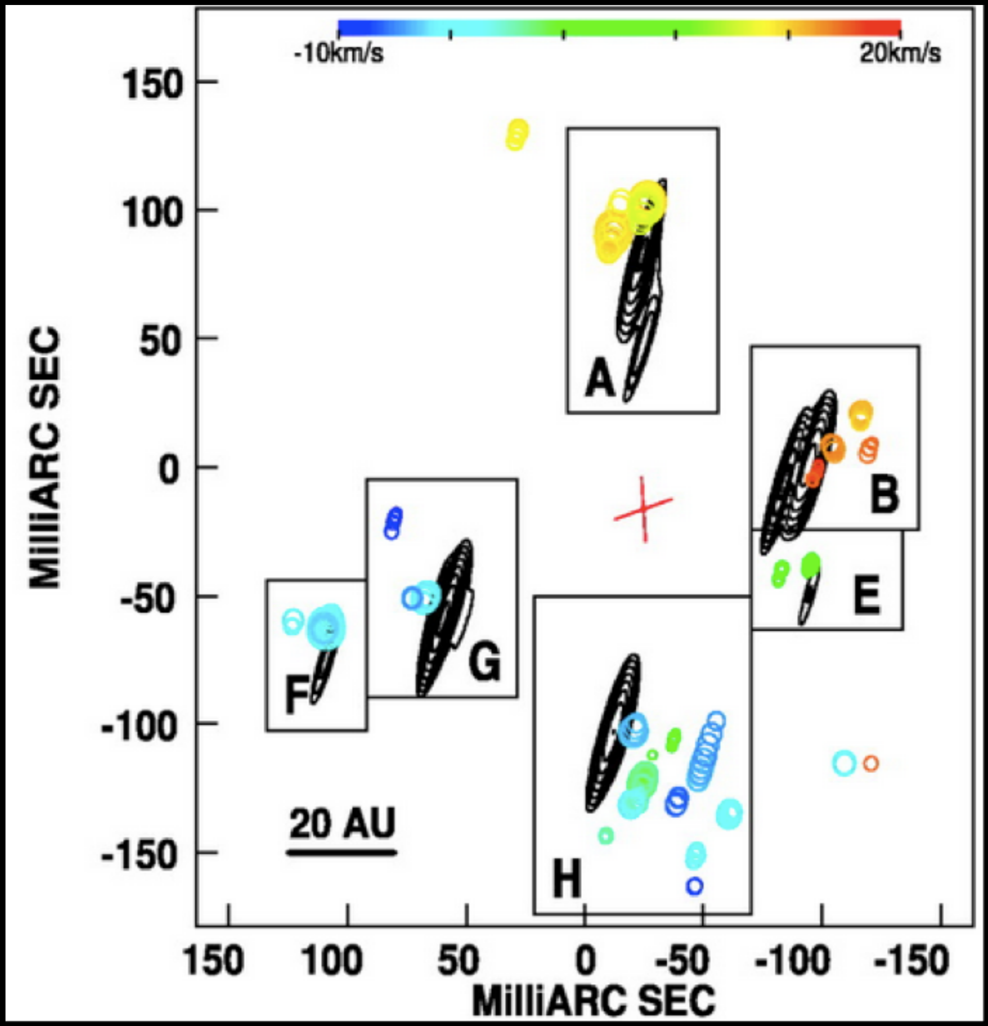
Array	**12m** and **Compact (ACA)**
Species	Bands
H_2O	B3, B5, B6, B7, B8, B9
CH_3OH	B1, B3, B4, B6
SiO	B1, B2, B3, B4, B5, B6, B7
HCN	B3, B5, B6, B7, B9
Etc: H$n\alpha$, SiS	B3, B4, B6, B7, B9

from Wootten 2007

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

Single-baseline VLBI map of Source I suggests SiO v=1,J =2-1 (3mm) forms *closer* to the YSO than SiO v=1, J=1-0 (7mm).

Future imaging with GMVA+ALMA could provide exquisitely detailed kinematic comparisons.



Doeleman et al. (2004)

SiO v=1,J=2-1
(86 GHz: black contours)

SiO v=1,J=1-0
(43 GHz; colored contours)

Spectral Line Science with the APS: Other Applications

- Astrometry of masers: measure rotation curve of MW; compare to other tracers (e.g., CO)

- Masers as tracers of magnetic fields: star-forming regions, atmospheres of evolved stars

- 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, and fundamental constant variation at cosmological distances.

See also White Papers by Fish et al. (2012); Tilanus et al. (2013)

Summary

- The ALMA Phasing Project has implemented the capability to coherently phase up ALMA, creating a sensitive new aperture for (sub)mm science for ALMA Cycle 4.

- Phased ALMA significantly increases the sensitivity and resolution of high-frequency VLBI arrays, enabling a diverse array of new ultra high-resolution science.

- Enhancements to the APS enabled by the ALMA NA Development program are poised to further enhance and diverisfy the scientific promise of ALMA and VLBI.