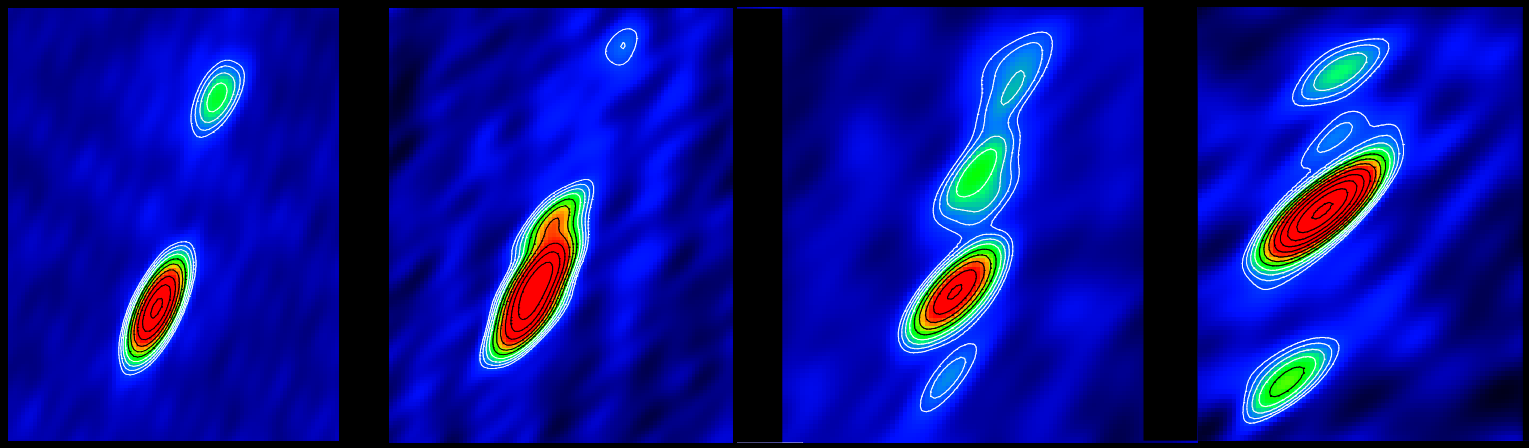

Extreme Jet Ejections from the Black Hole X-ray Binary V404 Cygni: The Unique (Sub-) Millimetre Perspective

Alex Tetarenko
University of Alberta

J.C.A. Miller-Jones (ICRAR), G.R. Sivakoff (UAlberta),
and the JACPOT XRB Team

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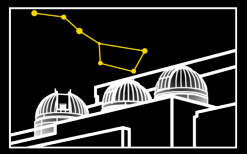
June 2015 Outburst

- On June 15, 2015 X-ray flaring detected by Swift BAT, MAXI and INTEGRAL.
- Extraordinary mutli-wavelength flaring activity followed.
- Brightest BHXB outburst in the past decade.

Rare, bright accretion state + Well-known system parameters + Close Proximity



The “Golden Data Set”

+

+

+

=

Unprecedented multi-wavelength view

(9 different frequencies!)

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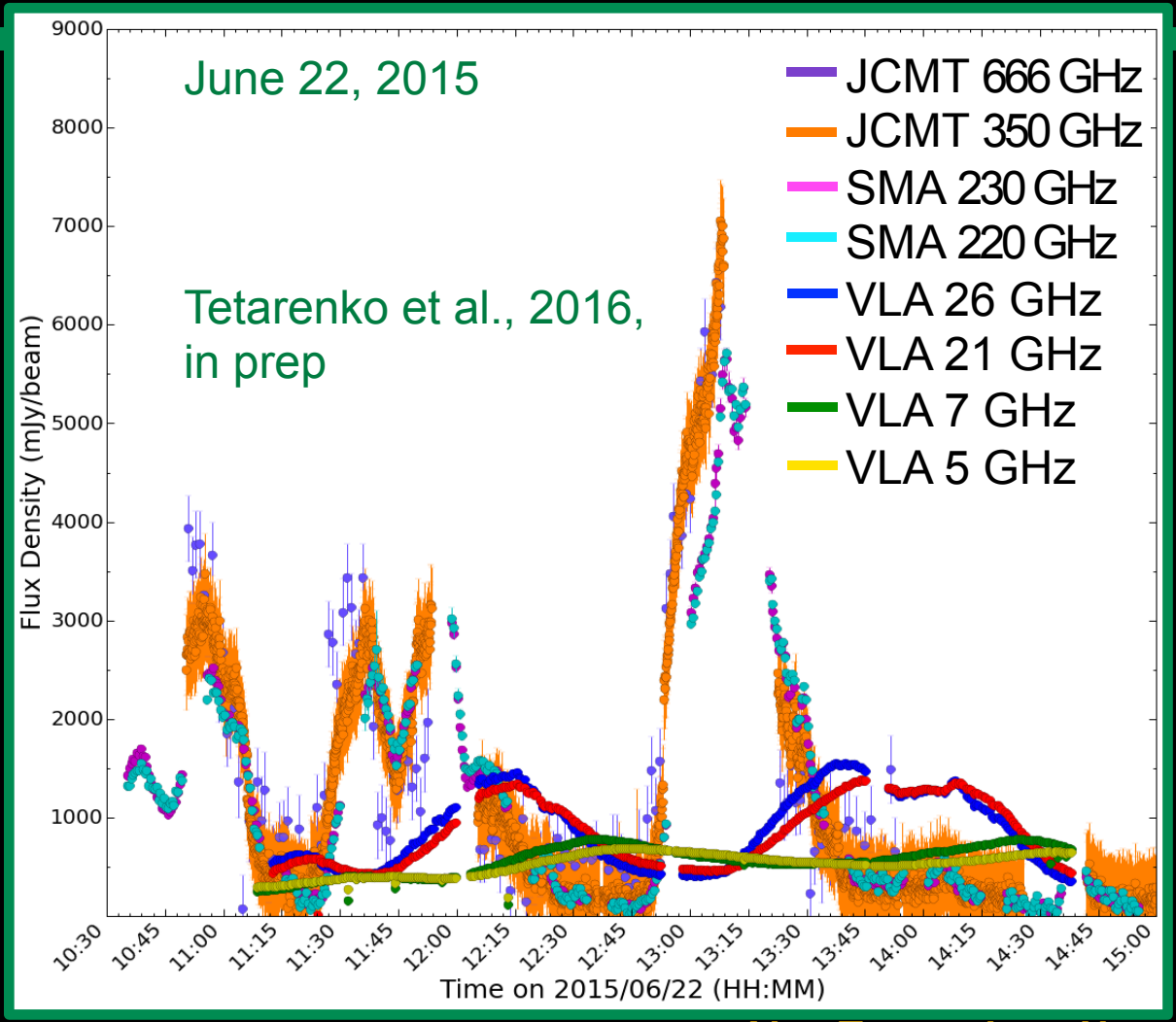
“Golden Data Set” Part 1



- Flares reach extremely bright flux levels
- Lower ν are delayed, smoothed version of higher ν
- (Sub-)mm substructure not visible in cm emission

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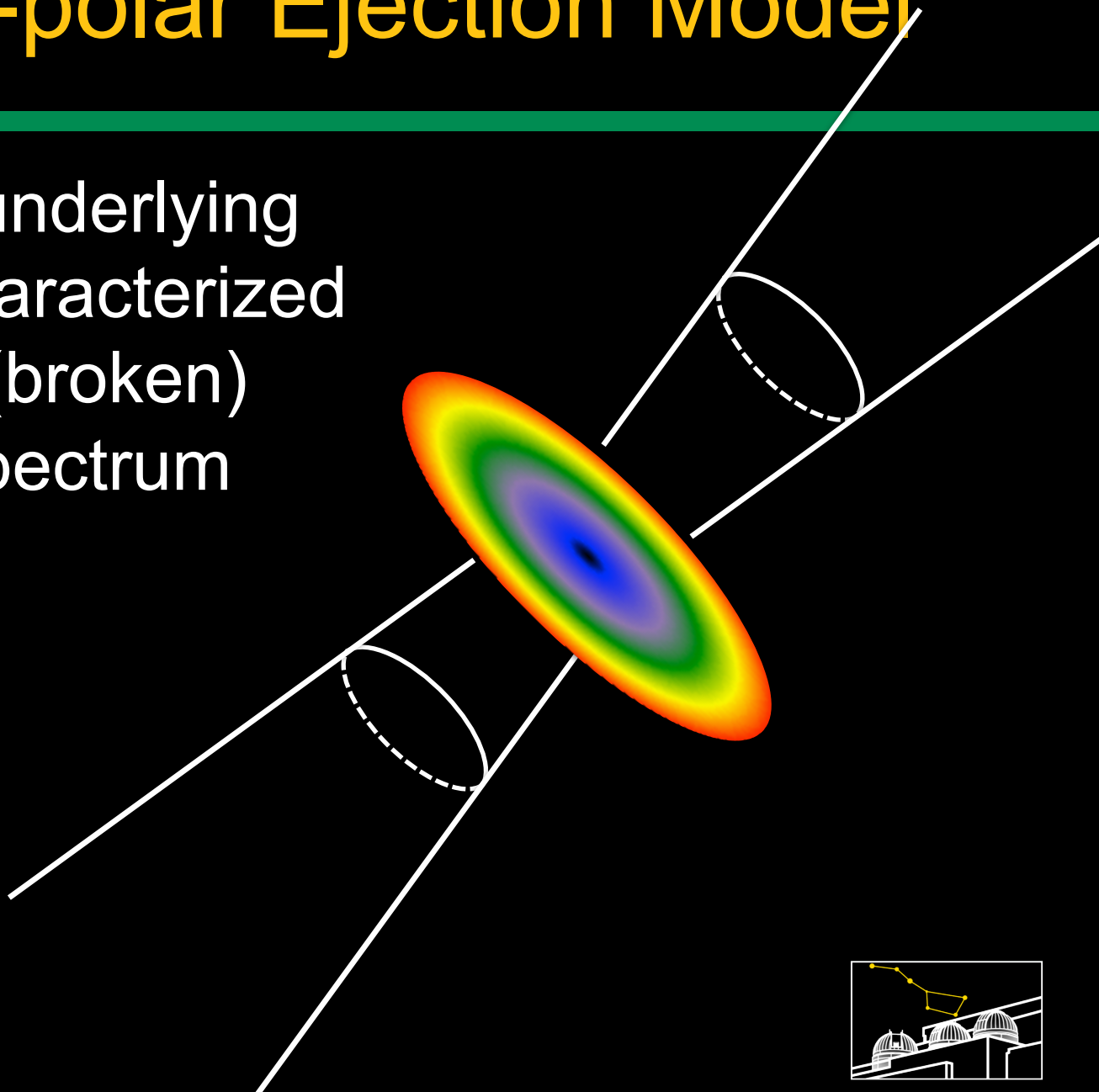
Twin Bi-polar Ejection Model

1. Assume an underlying steady jet characterized by a classic (broken) power-law spectrum



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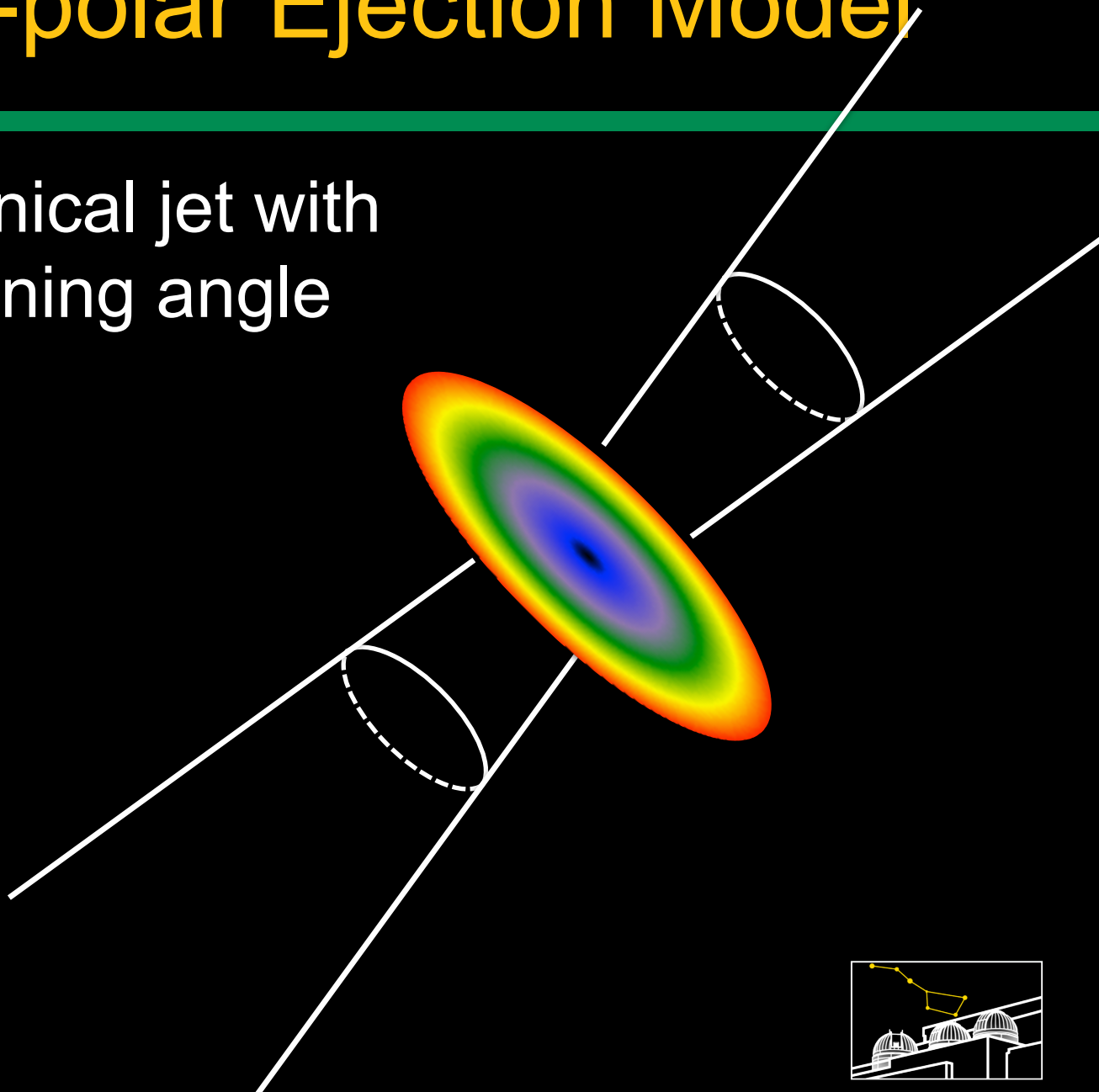
Twin Bi-polar Ejection Model

2. Assume a conical jet with constant opening angle



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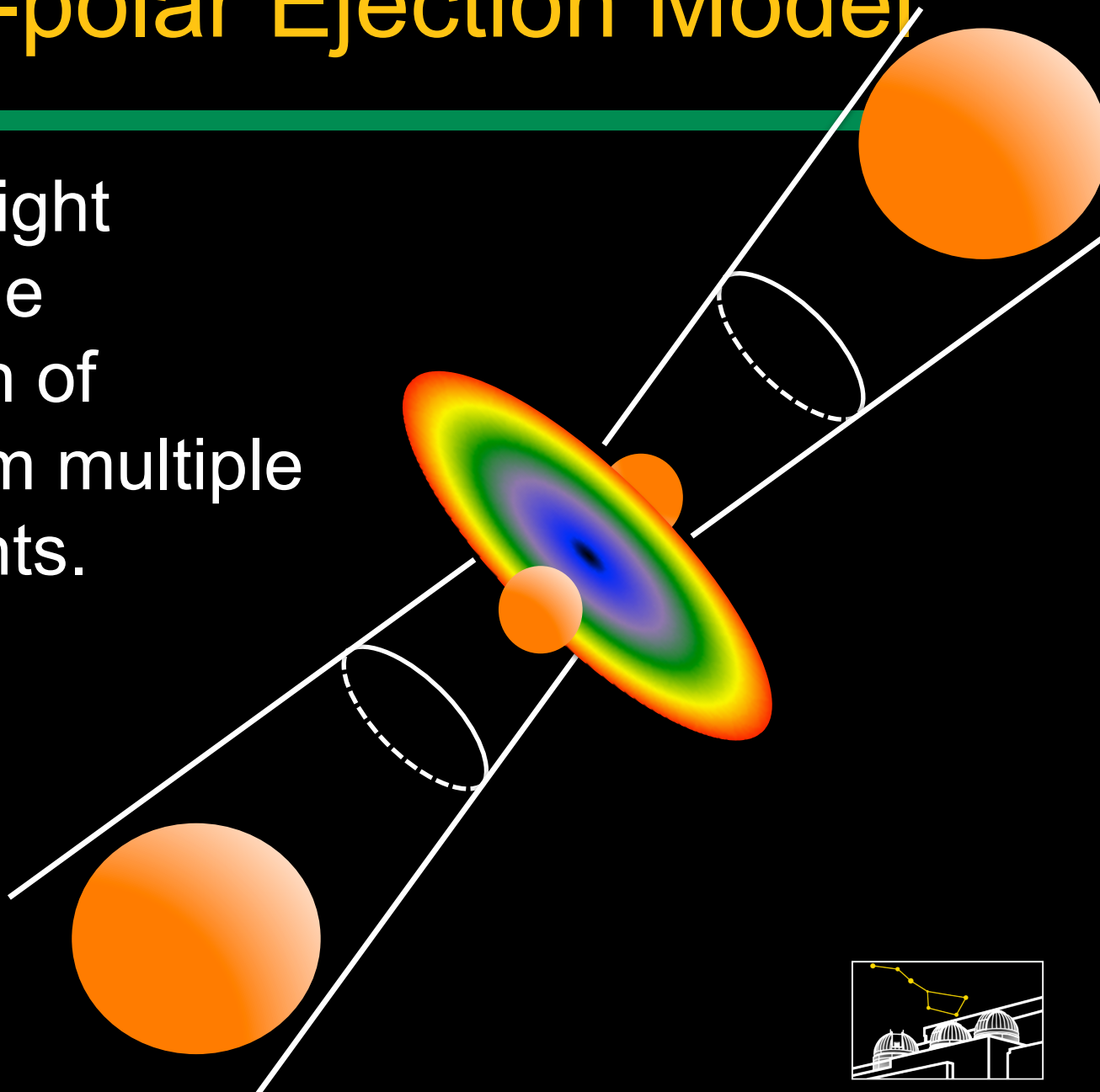
Twin Bi-polar Ejection Model

3. Assume our light curves are the superposition of emission from multiple ejection events.



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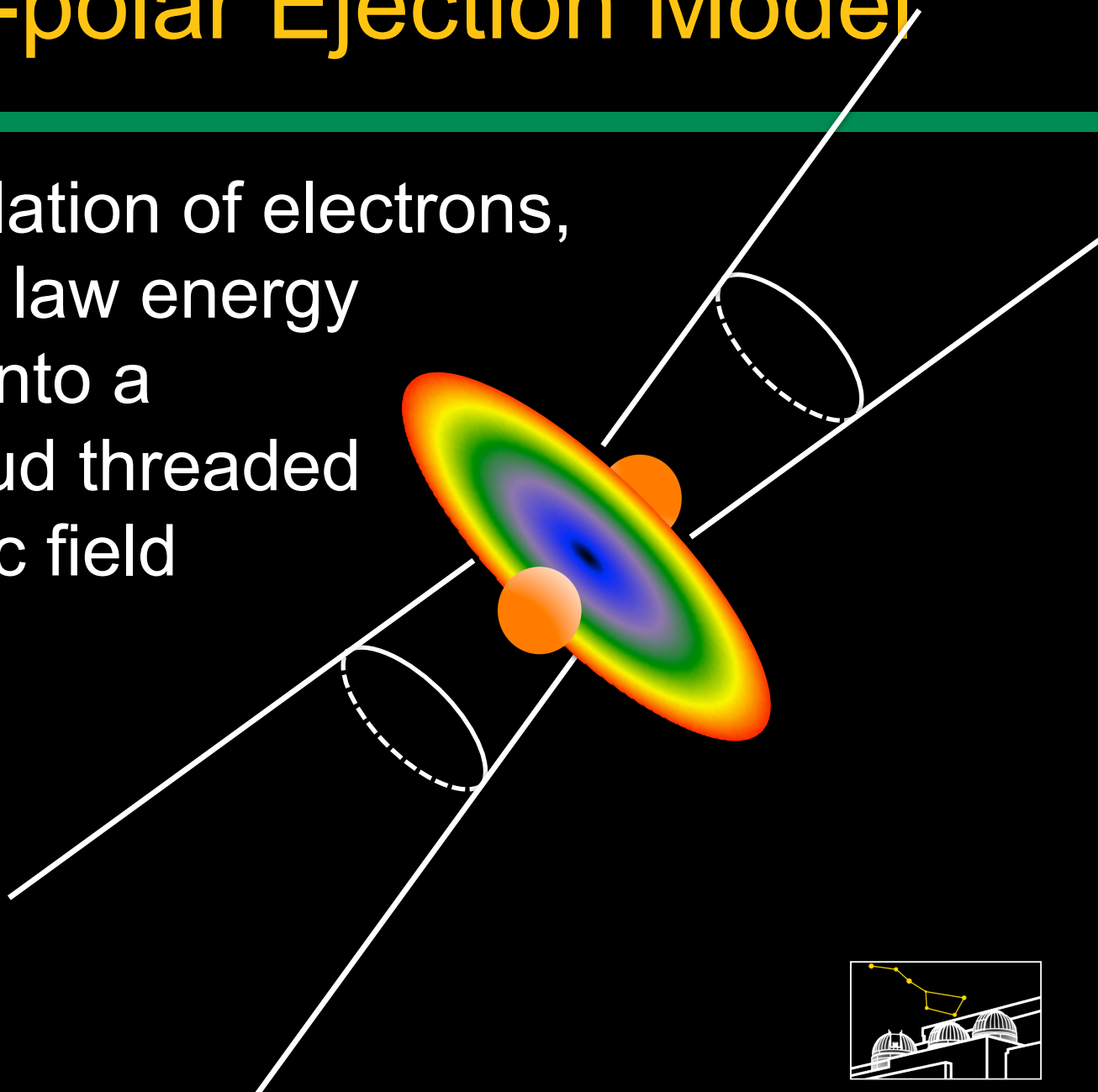
Twin Bi-polar Ejection Model

4. Inject a population of electrons, with a power law energy distribution, into a spherical cloud threaded by a magnetic field



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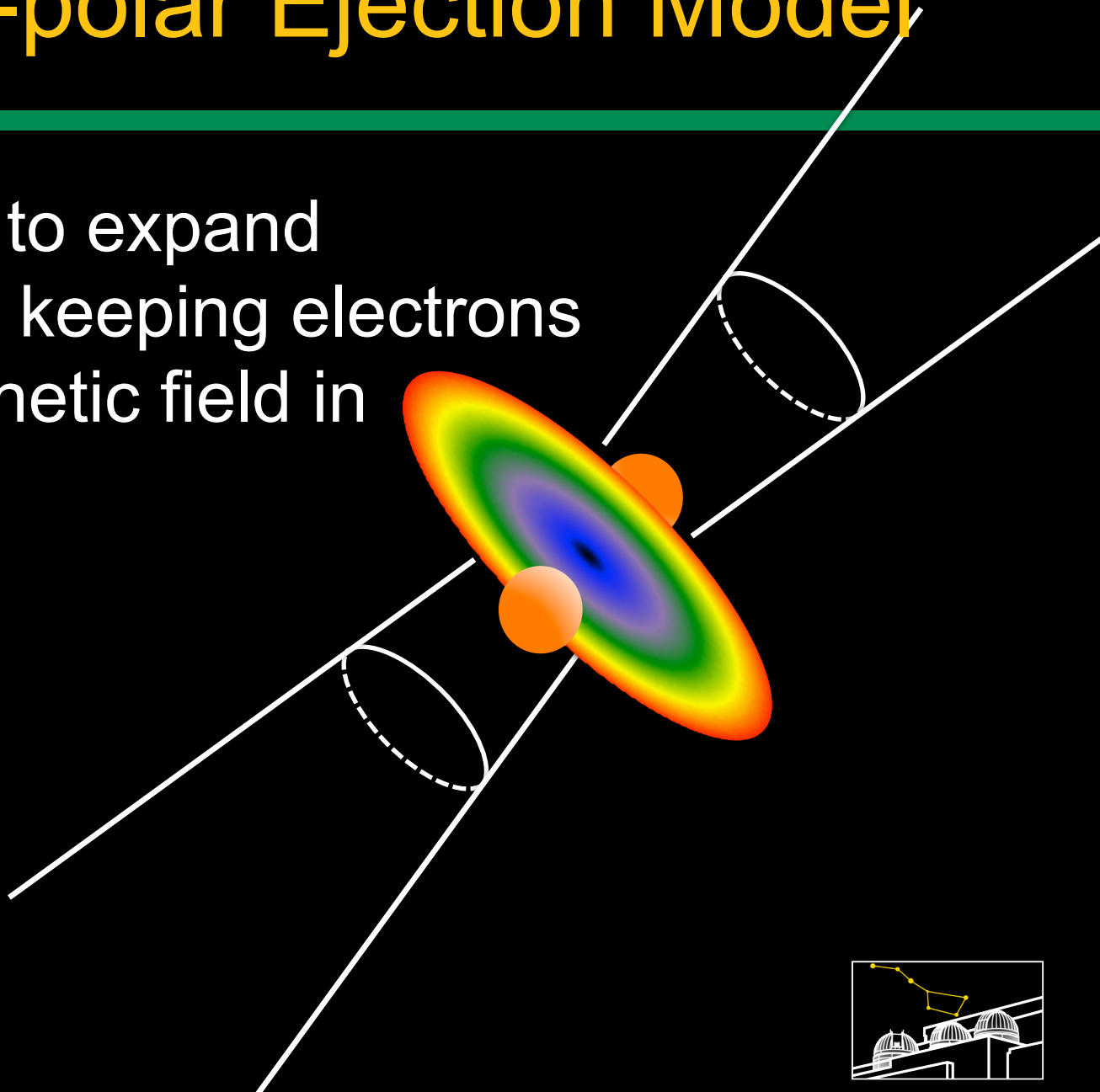
Twin Bi-polar Ejection Model

5. Allow sphere to expand adiabatically, keeping electrons and the magnetic field in equipartition



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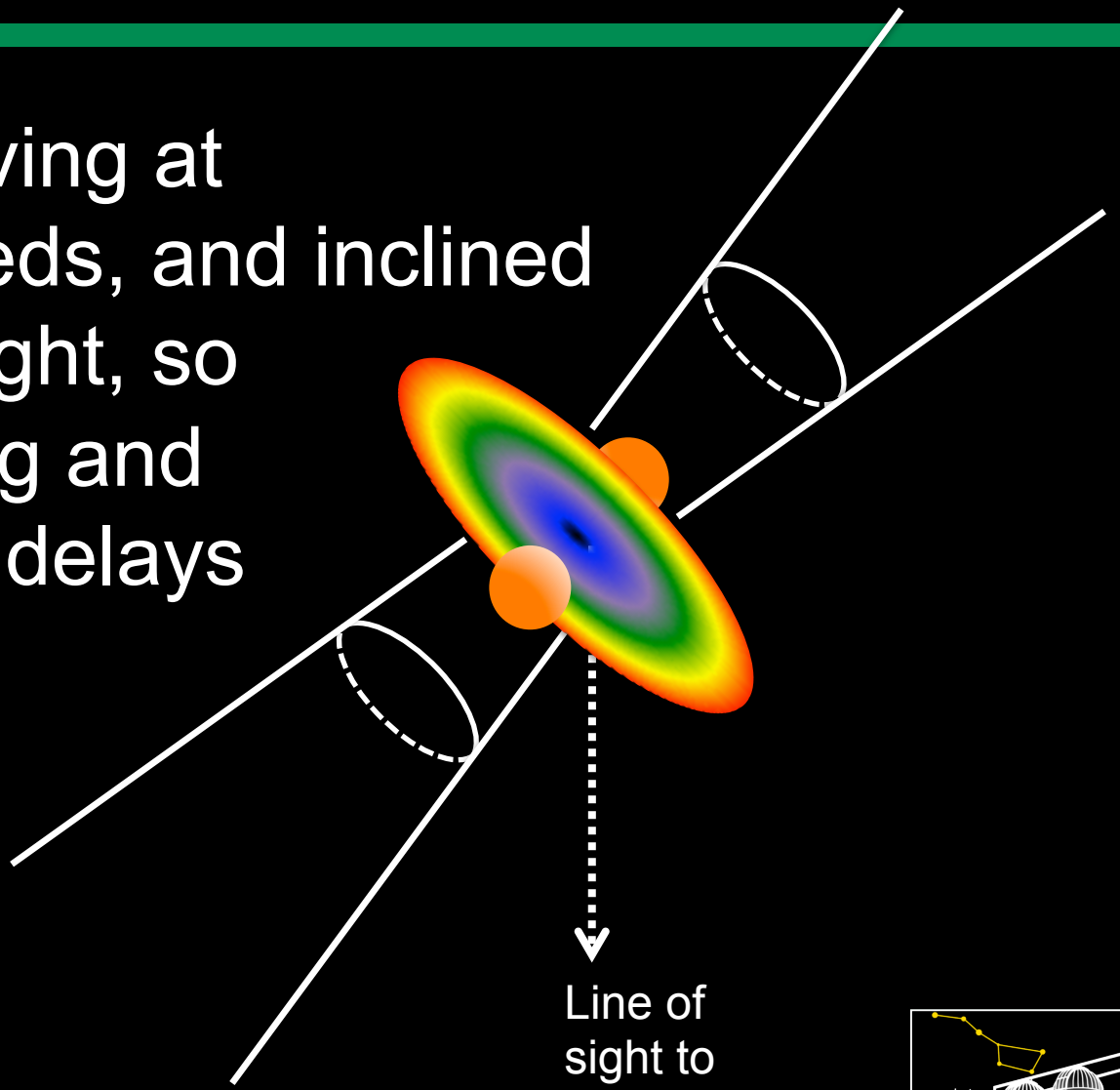
Twin Bi-polar Ejection Model

6. Clouds are moving at relativistic speeds, and inclined to our line of sight, so include beaming and geometric time delays



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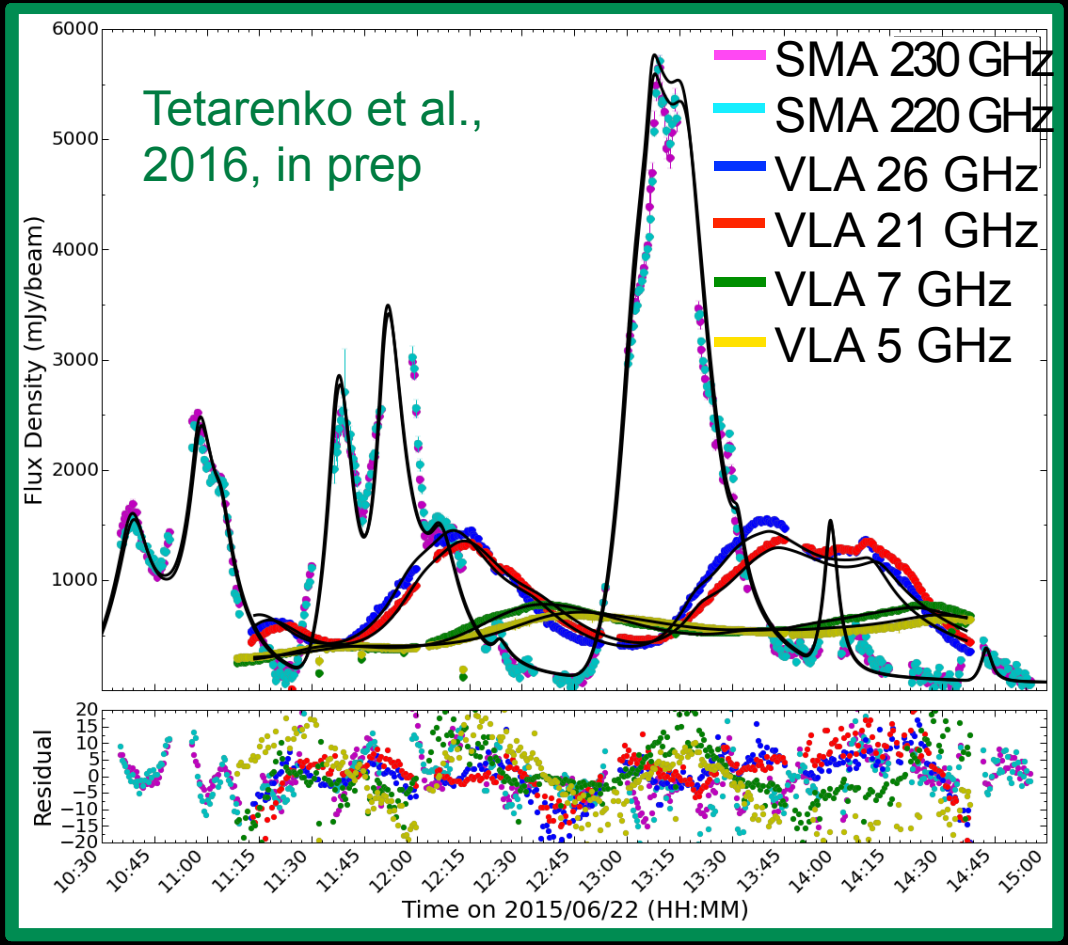
Light Curve Modeling



- Simultaneously fit all frequencies (5 - 350 GHz) with MCMC algorithm.
- 8 pairs of ejecta!
  - opening angle of 5°
  - β~0.2 - 0.6 c (Γ=1.0-1.2)
  - ejection times
- Sub-mm data is crucial in our modeling!

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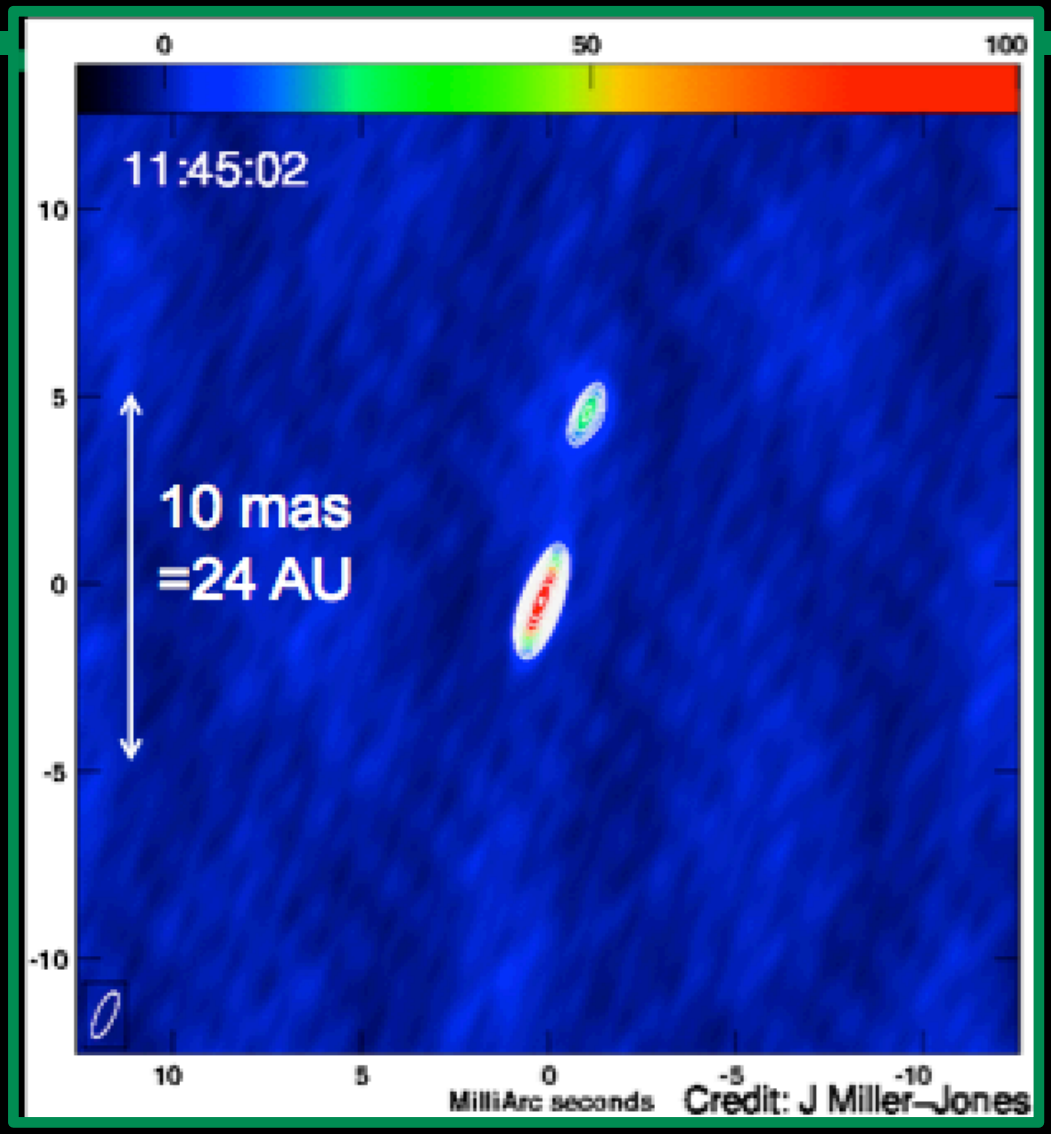
“Golden Data Set” Part 2



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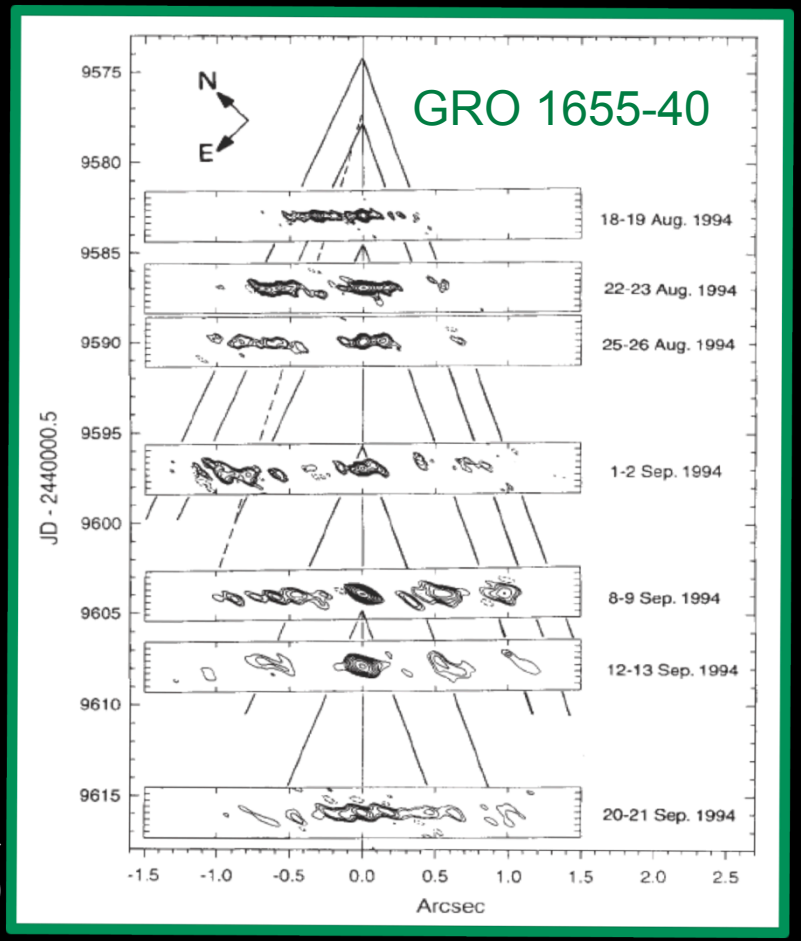
“Golden Data Set” Part 2

The state of the art: 1990s
Daily observations of
bright outbursts



Hjellming &
Rupen (1995)

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“Golden Data Set” Part 2

The state of the art 2000s:
2-3 hrs per epoch over 42 days

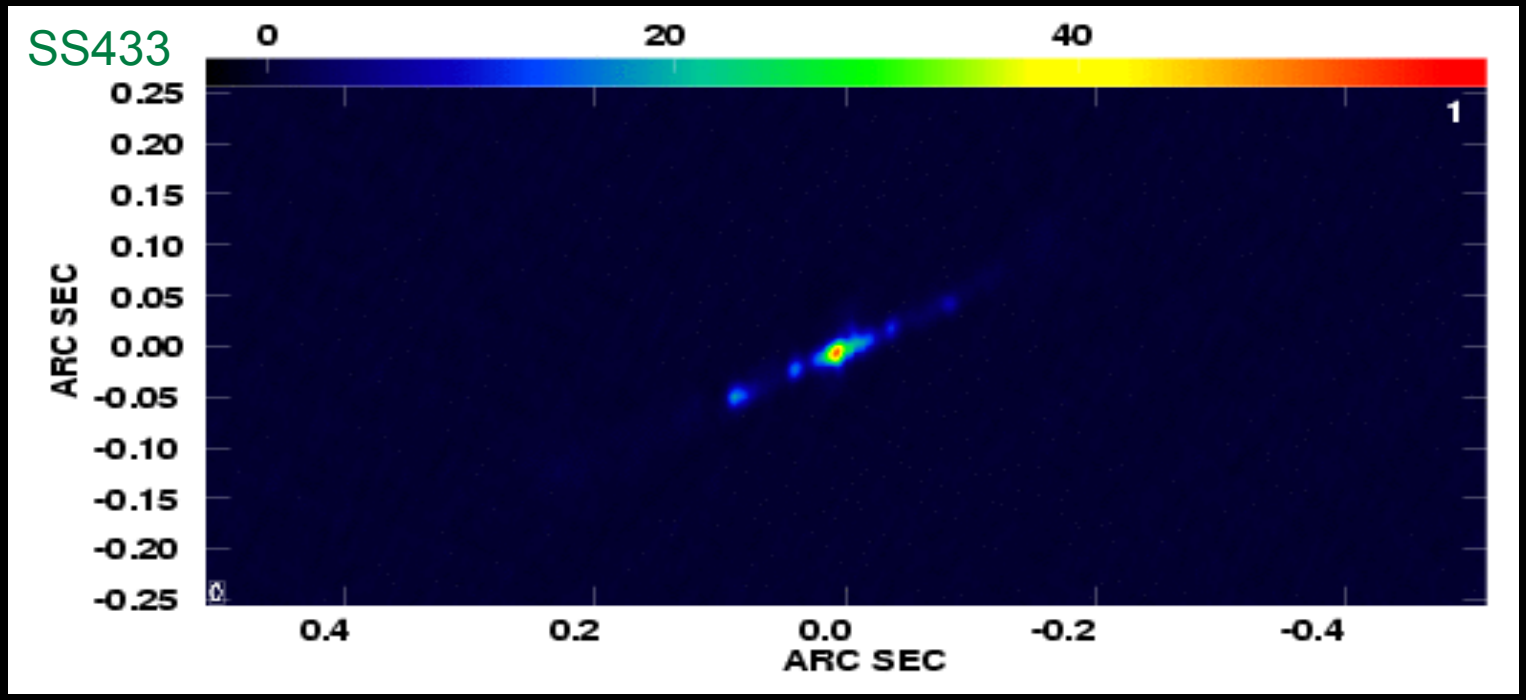
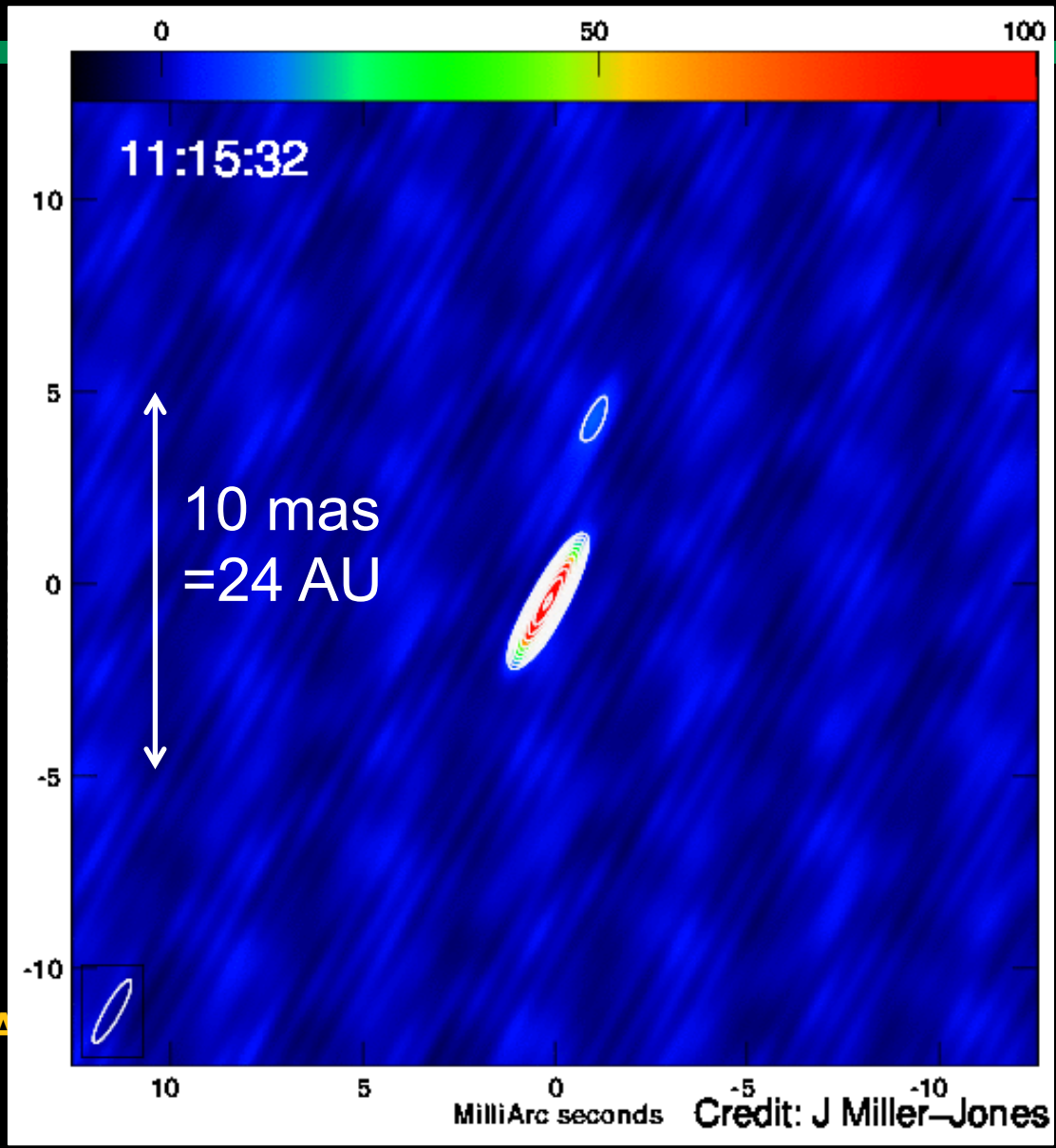


Image credit: Rupen, Mioduszewski, Walker & Taylor

“Golden Data Set” Part 2

Real time VLBI!

- Rapid evolution on minute timescales
- 2 min epochs over 5 hours of observation (>100 frames!)



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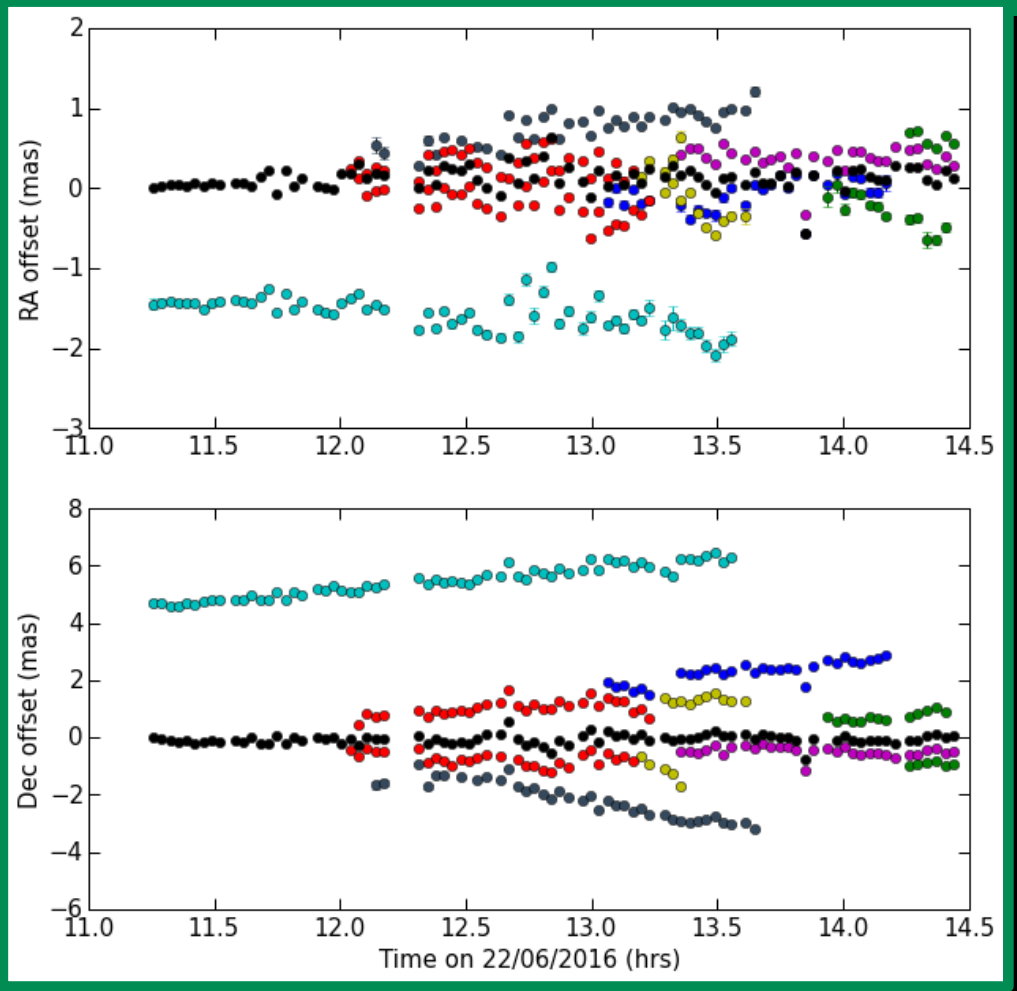
Tracking the Ejecta Motion



$$RA_{ij} = \mu_{RA,j}\left(t_i - t_{eject}\right) + Offset_{RA,i}$$

$$Dec_{ij} = \mu_{Dec,j}\left(t_i - t_{eject}\right) + Offset_{Dec,i}$$

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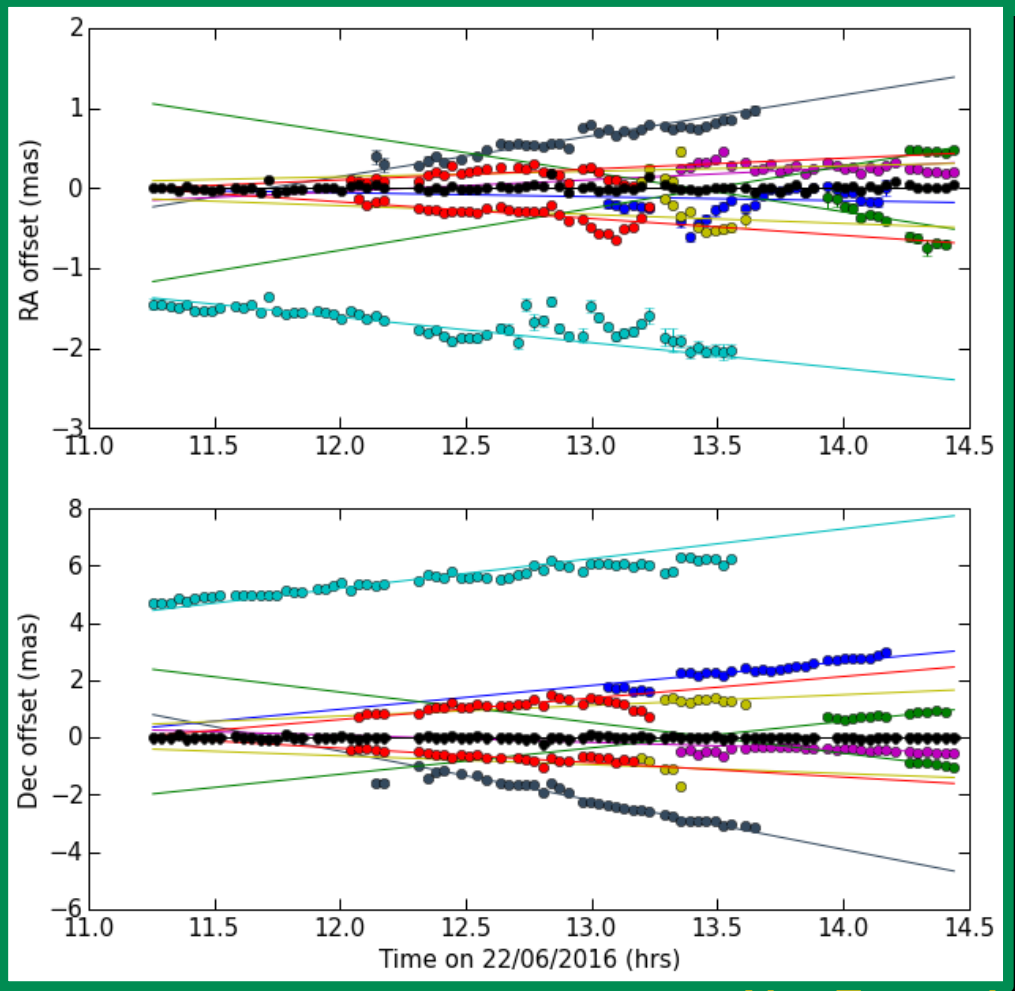

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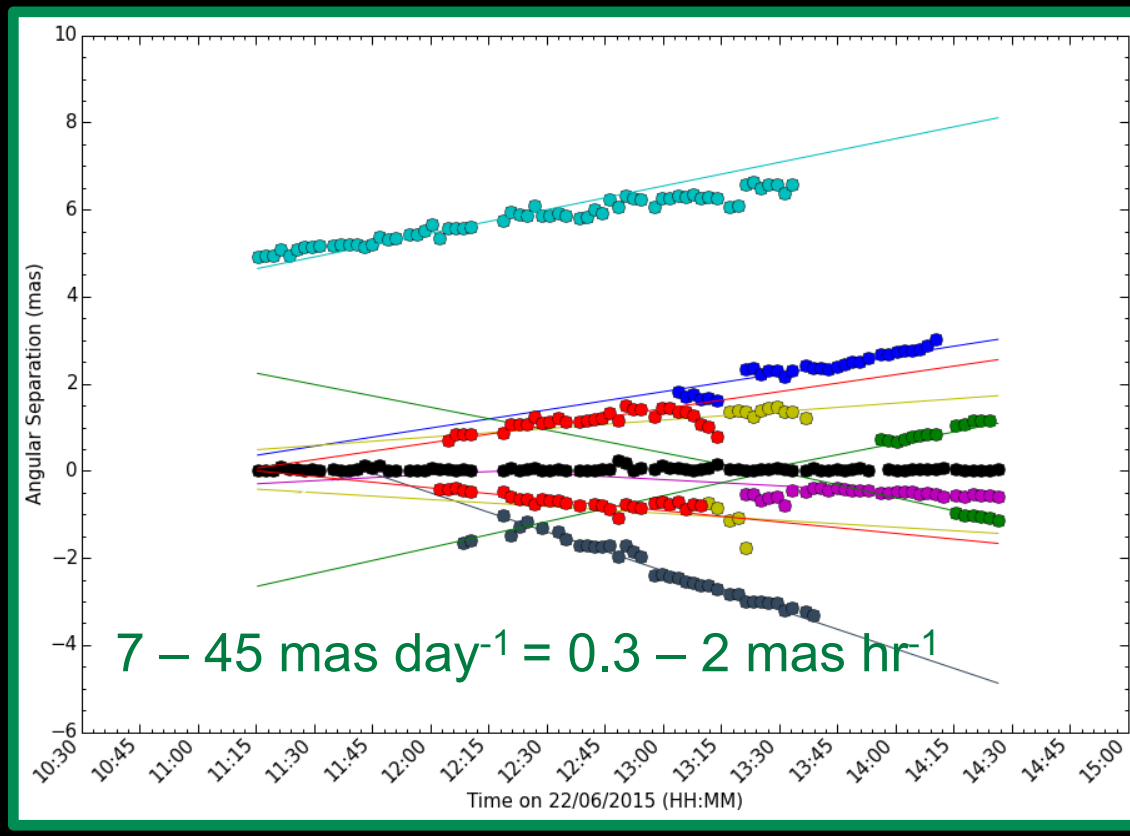
Tracking the Ejecta Motion

1. Identify pairs
2. Measure proper motions
3. Estimate ejection times
4. Uniquely solve for β,i

$$\beta = 0.33^{+0.18}_{-0.09}$$
$$i = 37.1^{+10.0}_{-15.9}$$

$$\beta = 0.2^{+0.4}_{-0.2}$$
$$i = 80.0^{+5.9}_{-12.8}$$

$$\beta = 0.2^{+0.1}_{-0.1}$$
$$i = 50.1^{+14.0}_{-11.3}$$



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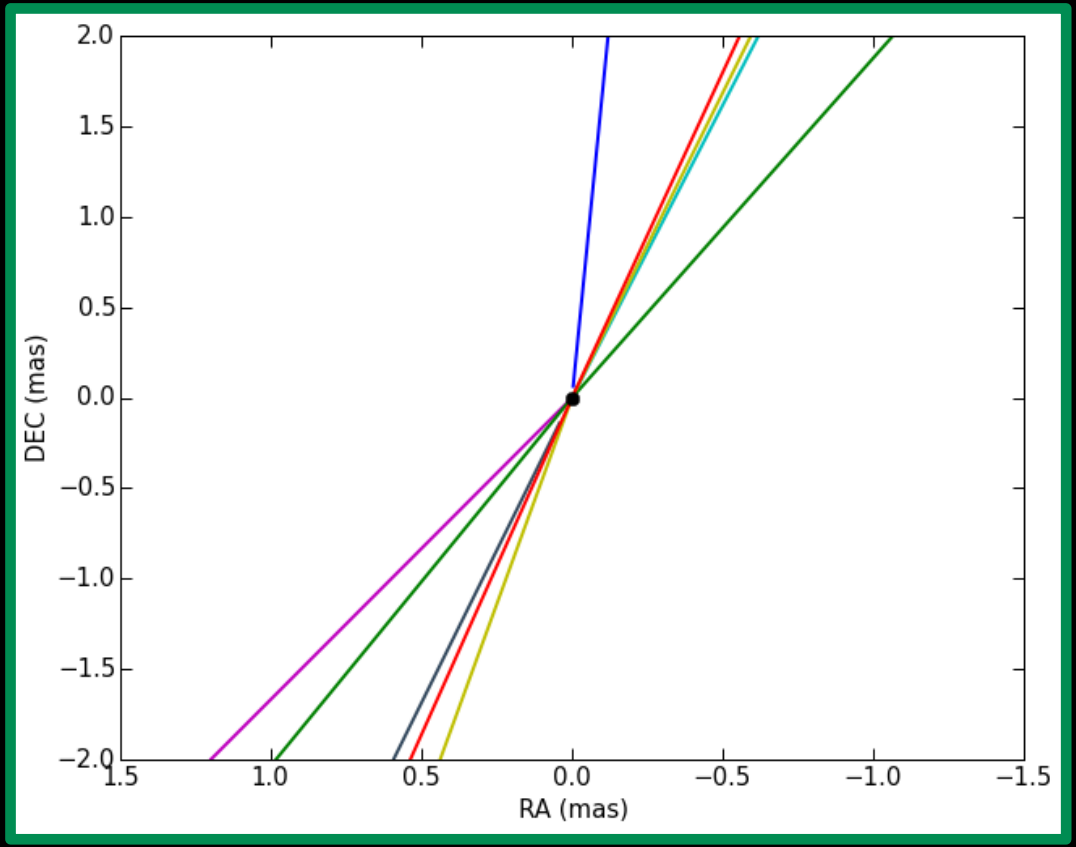

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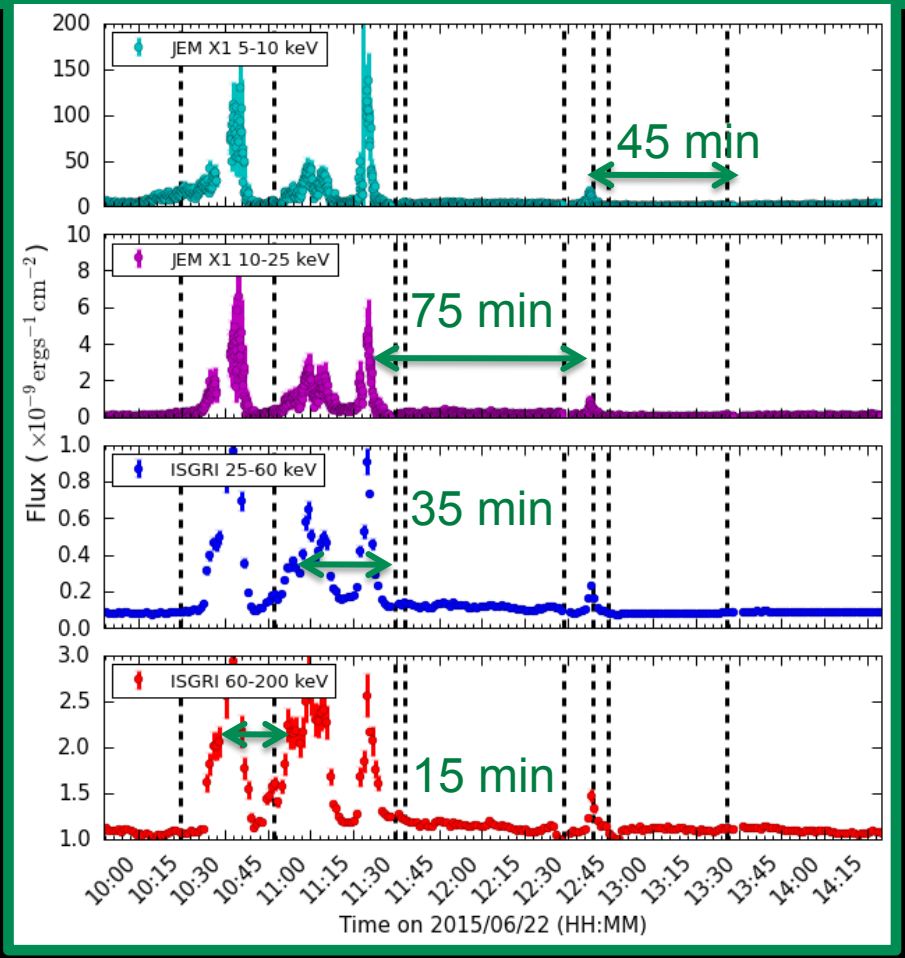
Relationship to X-ray Emission



Data from Rodriguez et al., 2015

- Predicted ejection times do not appear to correlate well with X-ray emission
- Ejections could lag X-ray peaks?

Tetarenko et al., 2016, in prep

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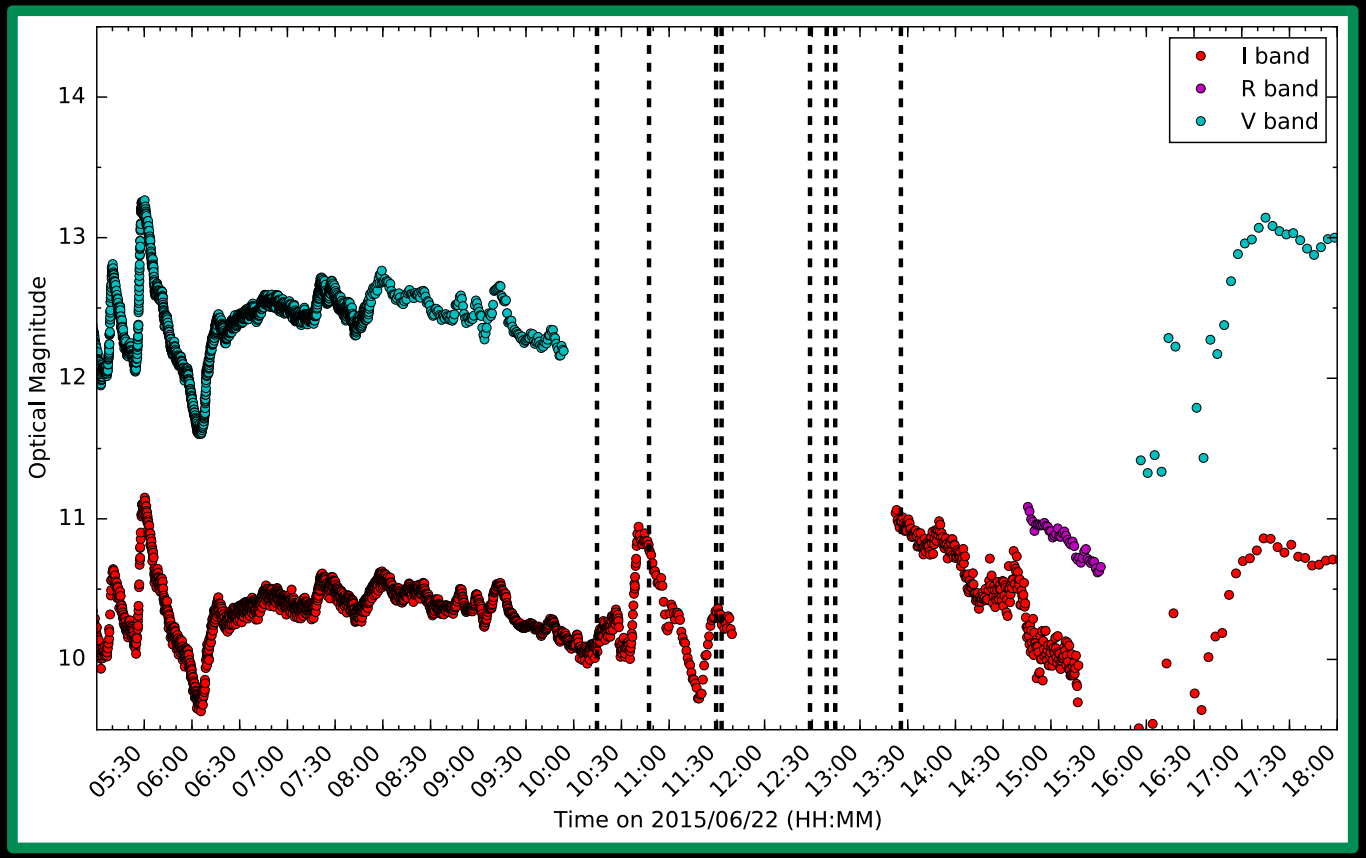
Relationship to Optical Emission

Hints of correlation, but unfortunate holes in coverage



Mariko Kimura, et al. 2015

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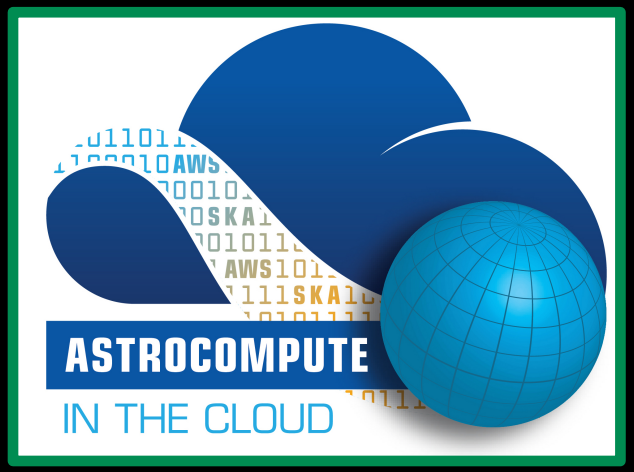
High Time Resolution Measurements

- Our team has developed custom timing scripts for interferometric data that runs in CASA on Amazon Web Services
- Produces light curves on user specified time bin
- Many customizable options:
  - UV or image plane
  - Object detection
  - And many more…
- Will be available soon, stay tuned!

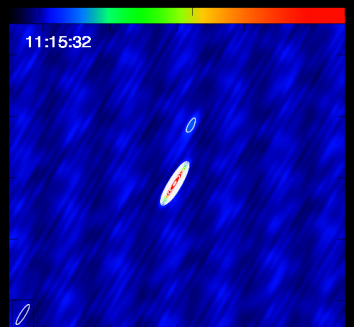


https://github.com/Astroua/AstroCompute_Scripts

Summary

- Analysis is ongoing
- Simultaneous multi-wavelength coverage essential to unlocking complicated physics.
- Rapid response and specialized observing techniques, like sub-arrays and VLBI, make this possible.
- mm/sub-mm data provides a unique, more detailed view of the jet compared to cm.

Thank you!



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