Accretion-ejection morphology of the microquasar SS 433 resolved at sub-au scale with VLTI/GRAVITY

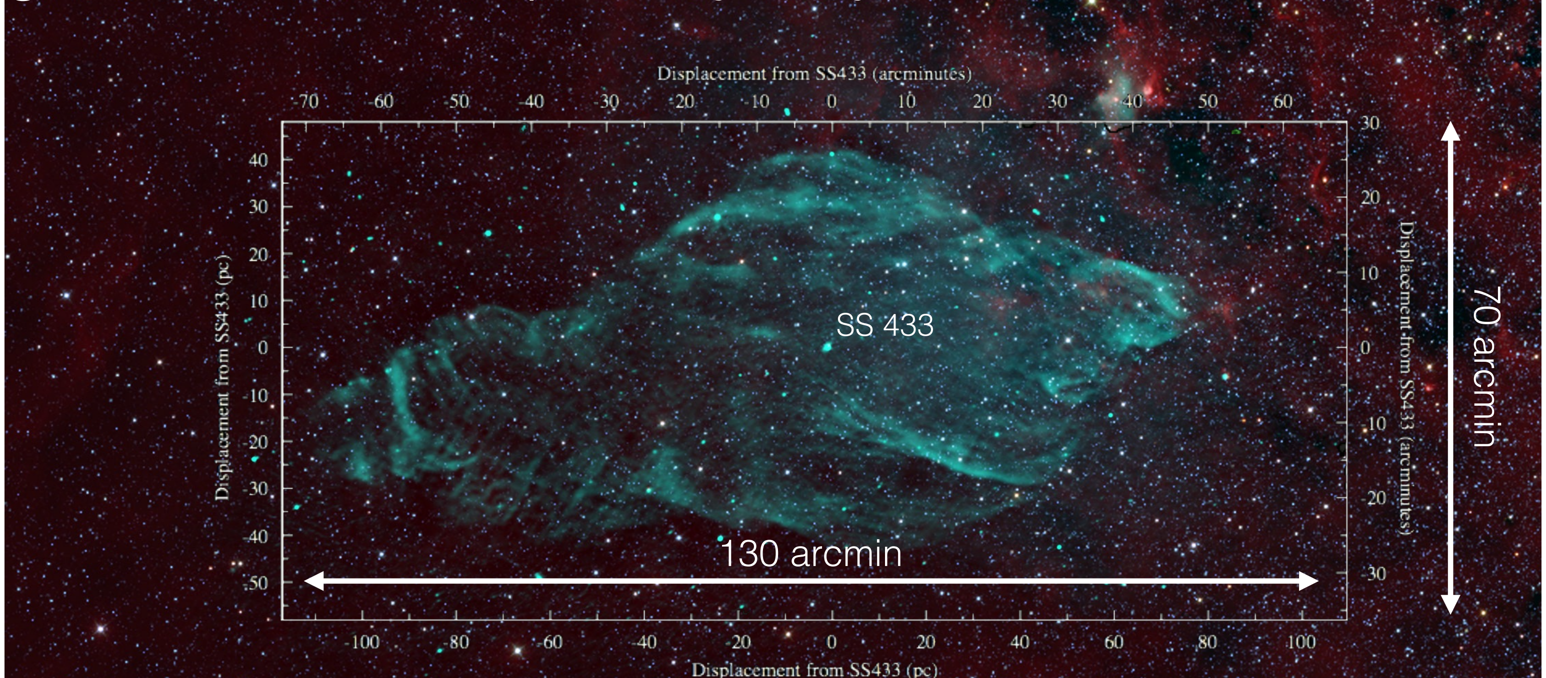
P.-O. Petrucci[1], I. Waisberg[2], J.-B Lebouquin[1], J. Dexter[2], G. Dubus[1], K. Perraut[1], F. Eisenhauer[2] and ***the GRAVITY collaboration***

[1] **I**nstitute of **P**lanetology and **A**strophysics of **G**renoble, France
[2] **M**ax **P**lanck Institute fur **E**xtraterrestrische Physik, Garching, Germany

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

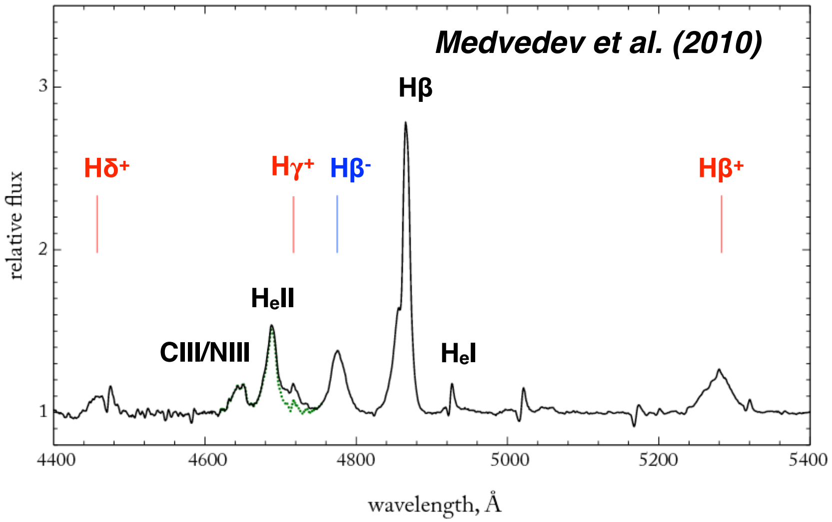
What is SS 433?

- SS 433 discovered in the 70’s. In the galactic plane. K=8.1!
- At a distance of 5.5 kpc, embedded in the radio nebula W50
- Eclipsing binary with Period of ~13.1 days, the secondary a A-type supergiant star and the primary may be a ~10 M_{sun} BH.



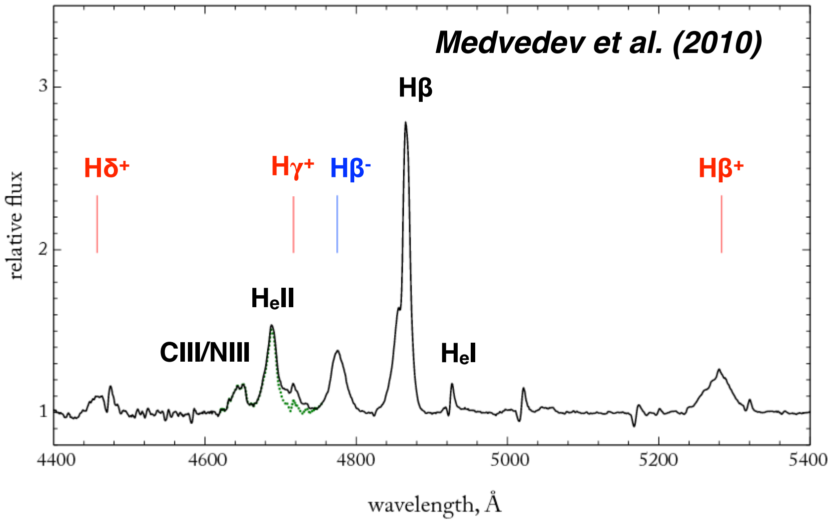
W50 supernova remnant in radio (green) against the infrared background of stars and dust (red).

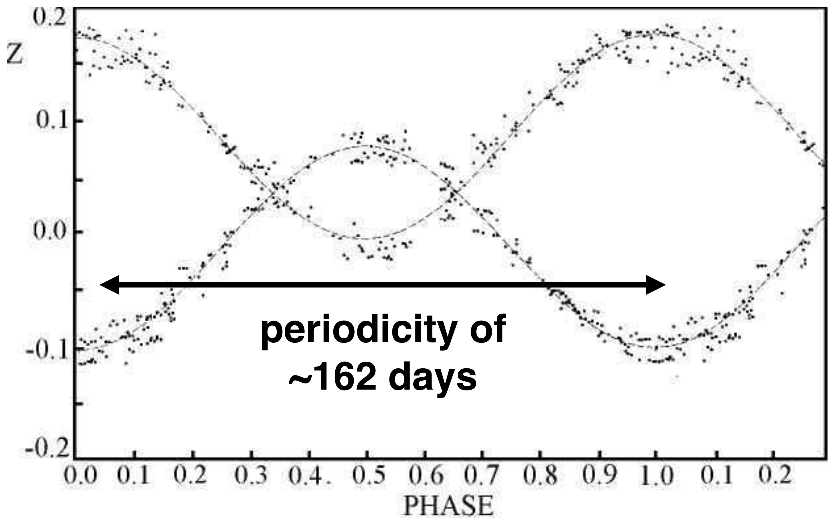
Moving Lines: Jet Signatures



- Optical/IR spectrum:
  - Broad emission lines (**stationary lines**)
  - Doppler (blue and red) shifted lines (**moving lines**)

Moving Lines: Jet Signatures



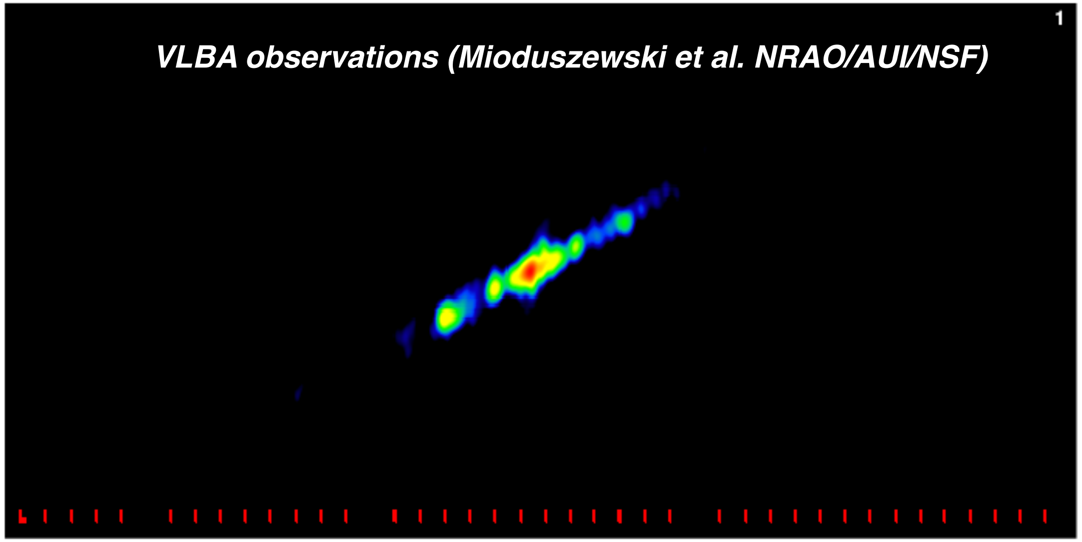


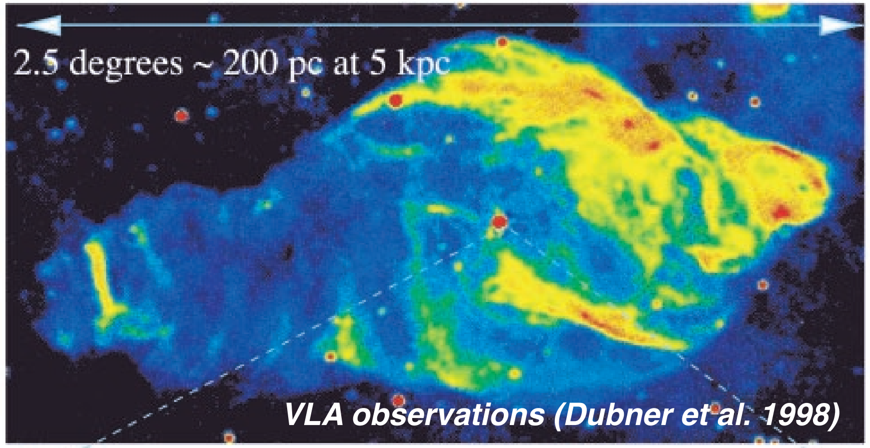
- Optical/IR spectrum:
  - Broad emission lines (**stationary lines**)
  - Doppler (blue and red) shifted lines (**moving lines**)

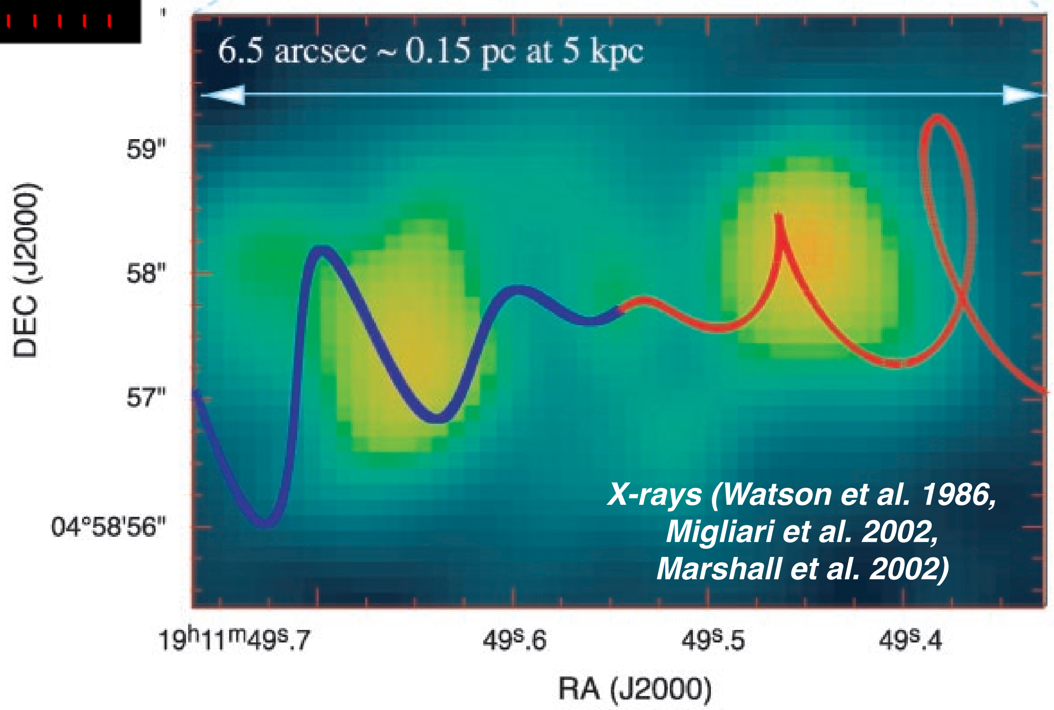
- Variable, periodic, Doppler shifts reaching ~50000 km/s in redshift and ~30000 km/s in blueshift

- Rapidly interpreted as signature of collimated, oppositely ejected jet (v~0.26c) precessing (162 days) and nutating (6.5 days)

Precessing Jets

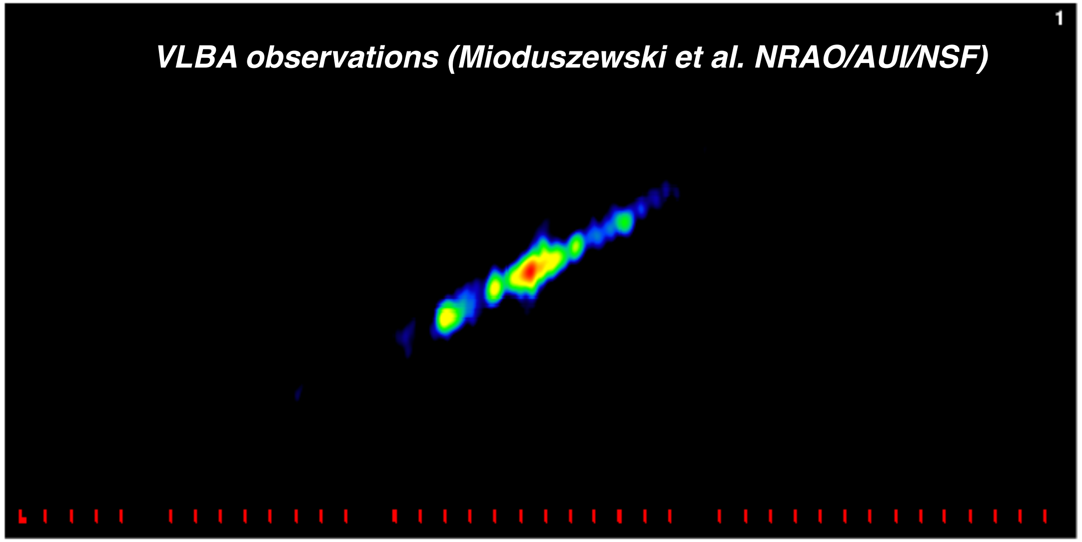


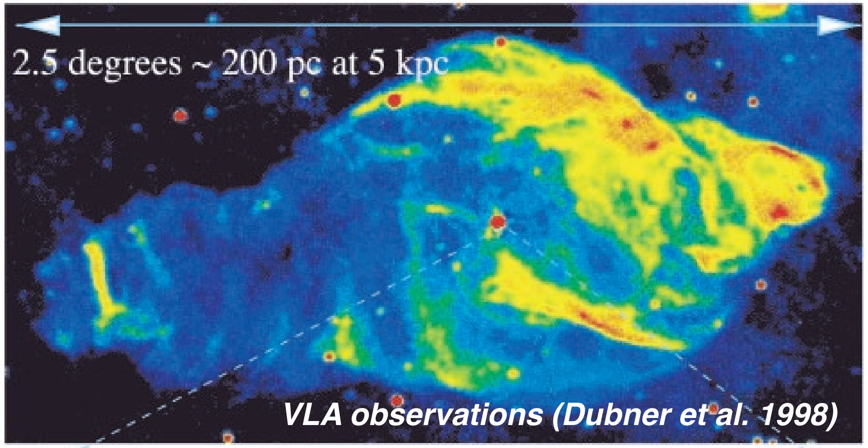


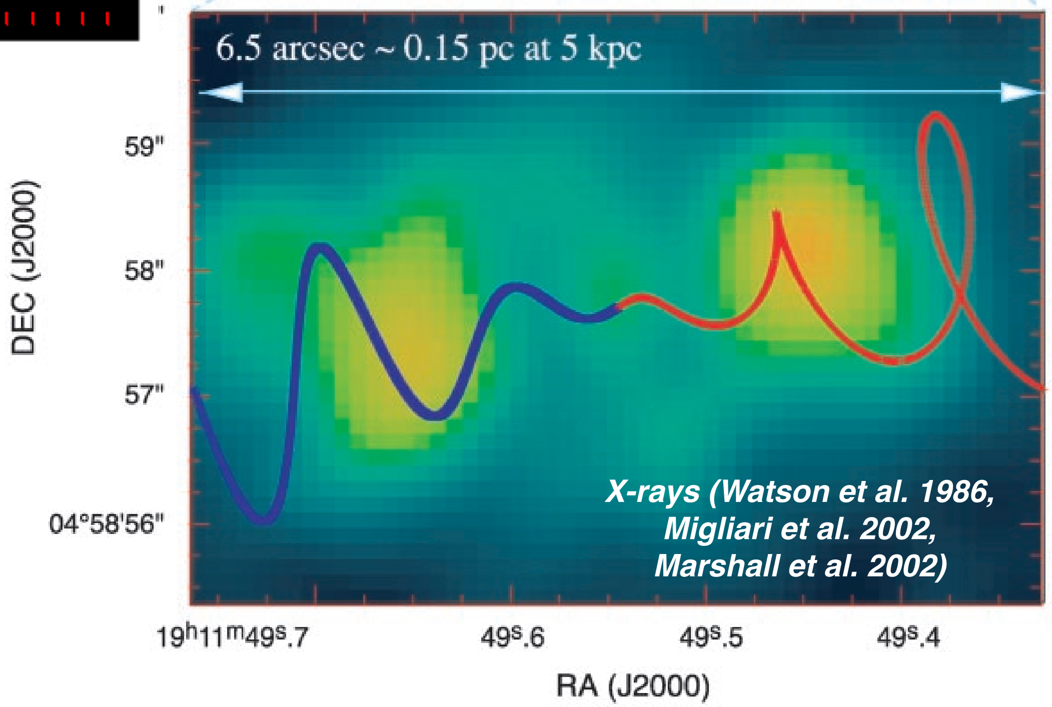


- Collimation with opening angle ~1°
- Jets mass-loss rate $>10^{-6}\ M_\odot\ yr^{-1}$
- $L_{kin} > 10^{39}$ erg s^{-1} > 1000 $L_{2\text{-}10\ keV}$. ($L_{X,intrinsic}$ may be much larger)
- They interact in a helical pattern with W50
- Presence of ionized heavy elements

Precessing Jets

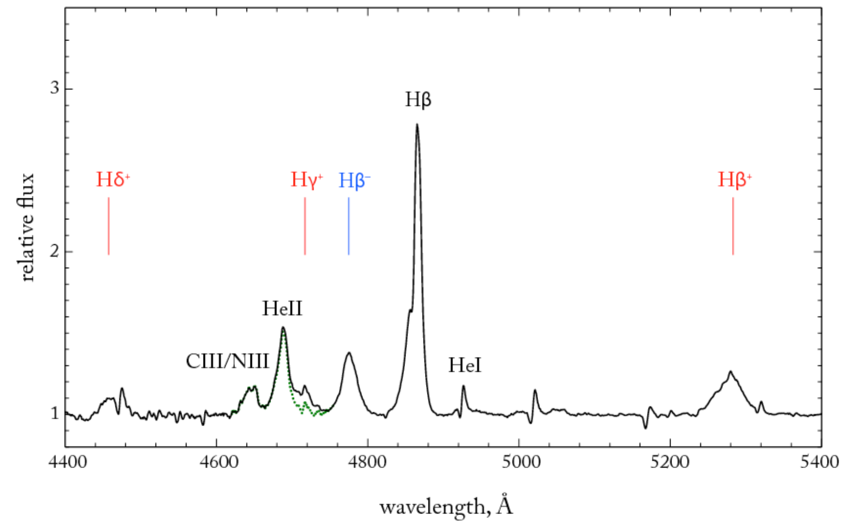






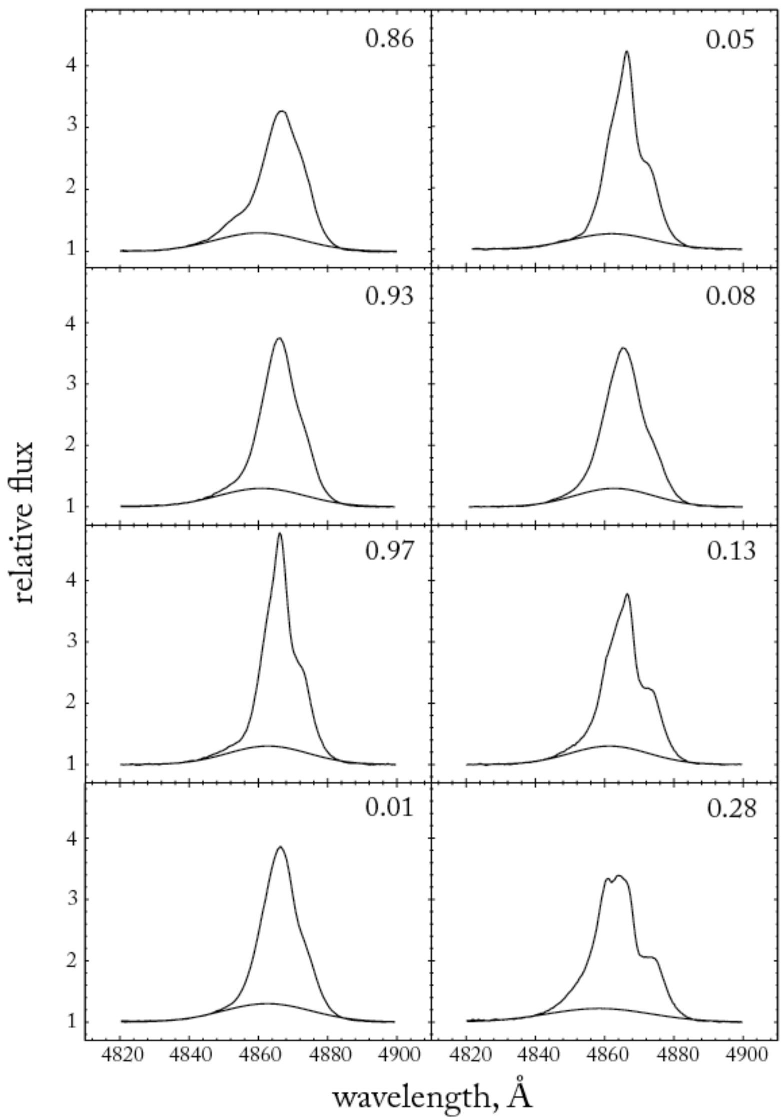
- Collimation with opening angle ~1°
- Jets mass-loss rate >10^{-6} $M_\odot$ yr^{-1}
- L_{kin} >10^{39} erg s^{-1} > 1000 $L_{2\text{-}10\ keV}$. ($L_{X,intrinsic}$ may be much larger)
- They interact in a helical pattern with W50
- Presence of ionized heavy elements

Stationary Lines



- Lines that do not share the large periodic Doppler shifts are called « stationary » lines
- The « stationary » lines vary in strength and profile shape during the orbital phase
- Fits with multiple-gaussians model reveal different components

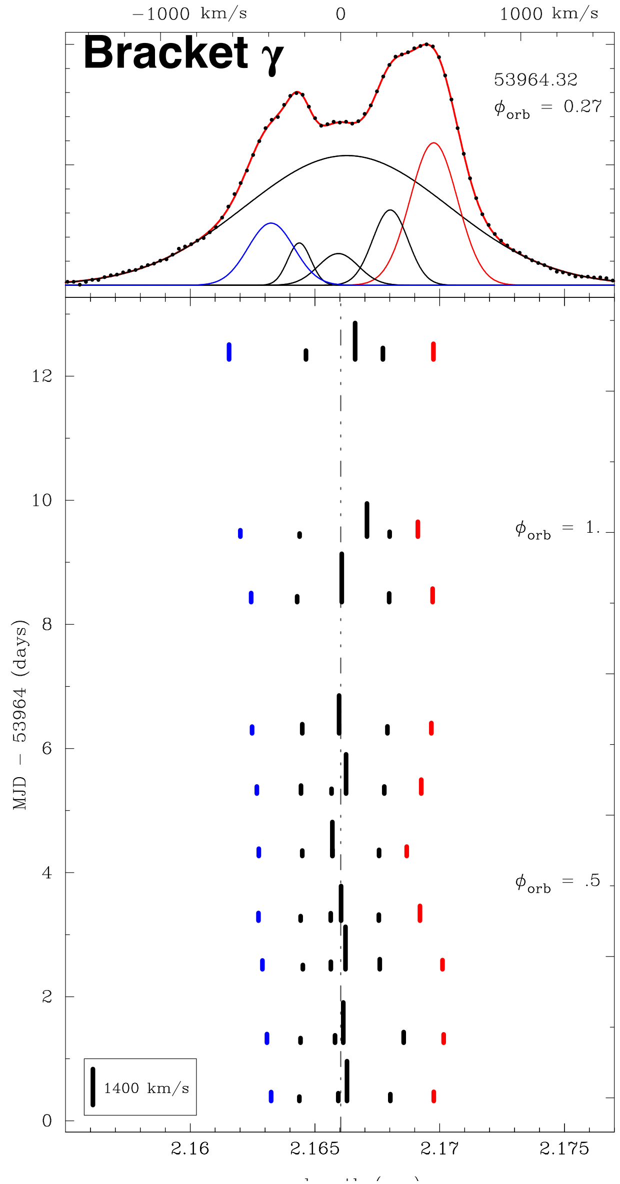
Hβ profiles



Medvedev et al. 2013

Wind, accretion and Circumbinary discs

Stationary lines generally consist of three components:

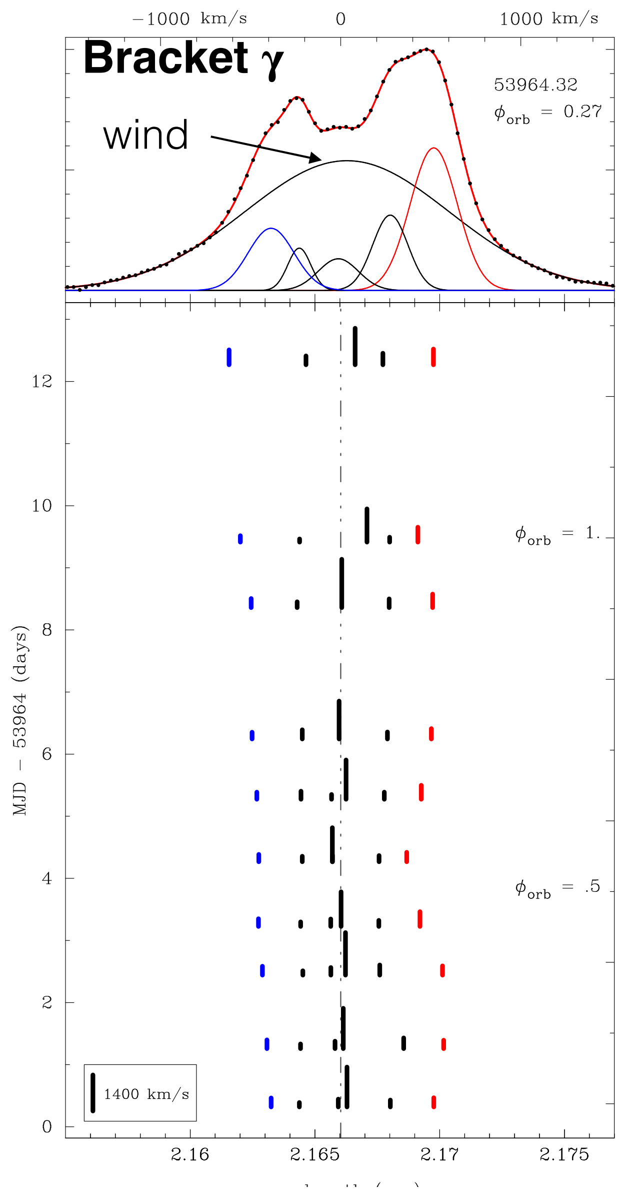


Perez & Blundell (2009)

Wind, accretion and Circumbinary discs

Stationary lines generally consist of three components:

- A broad component is identified as emitted in that **wind from the accretion disc.**

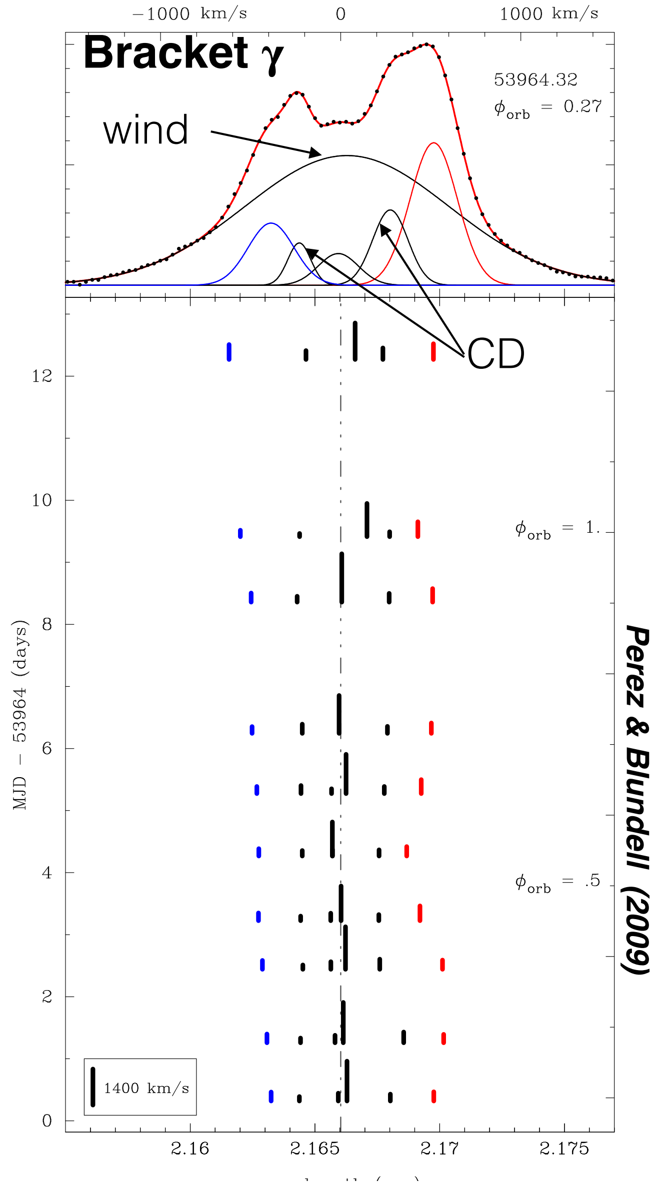


Perez & Blundell (2009)

Wind, accretion and Circumbinary discs

Stationary lines generally consist of three components:

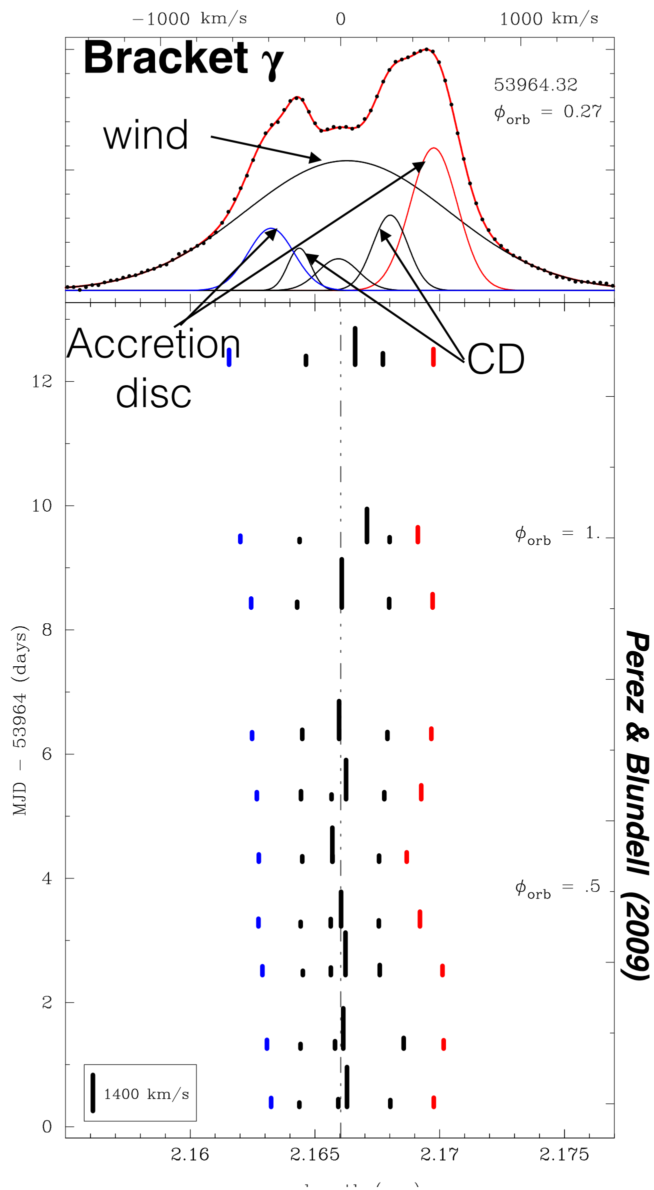
- A broad component is identified as emitted in that **wind from the accretion disc.**
- Two narrow remarkably constant components, one permanently redshifted and the other permanently to the blue signature of a **circumbinary ring** (the inner rim of an excretion disc?)

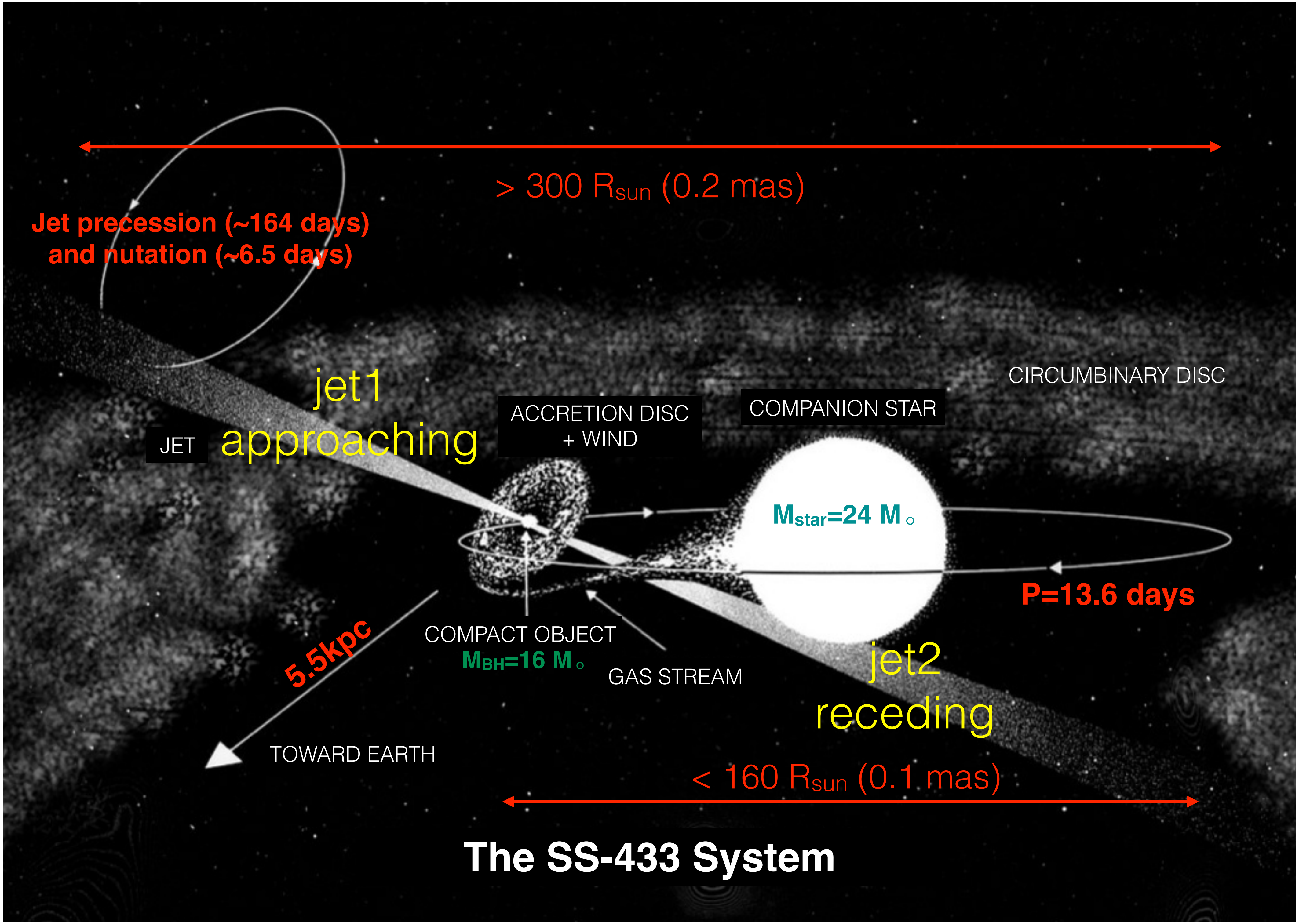


Wind, accretion and Circumbinary discs

Stationary lines generally consist of three components:

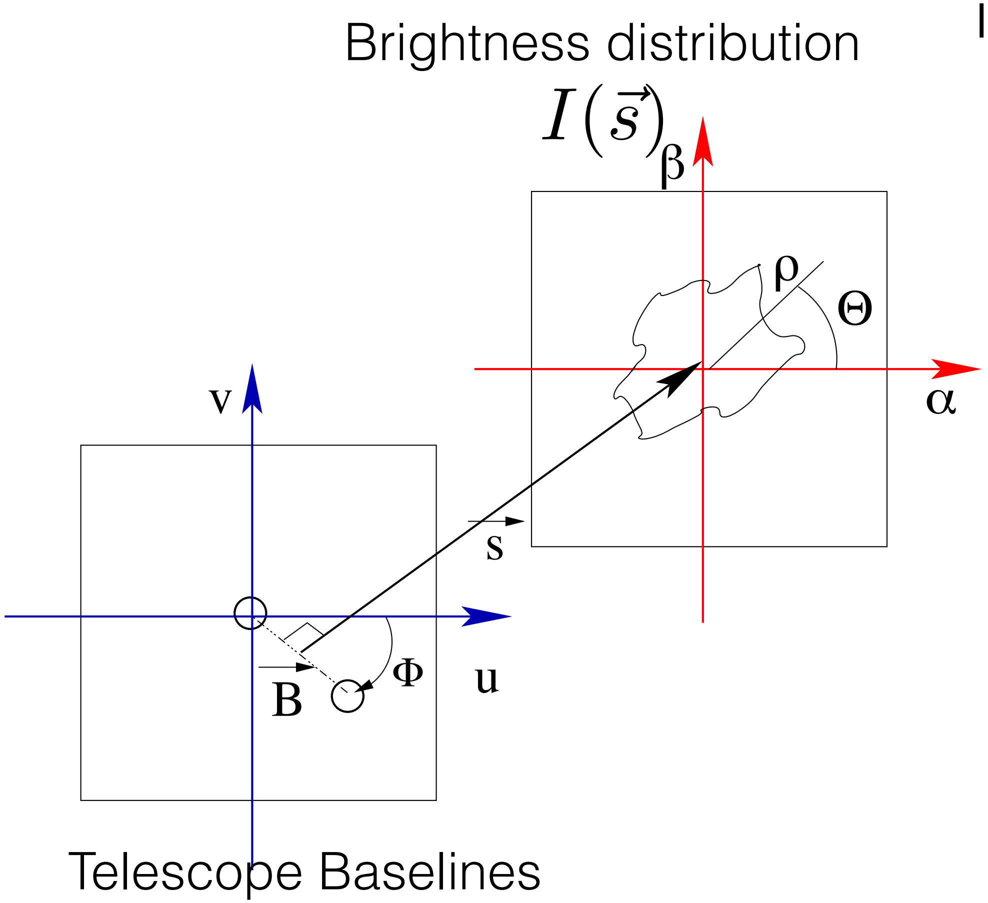
- A broad component is identified as emitted in that **wind from the accretion disc.**
- Two narrow remarkably constant components, one permanently redshifted and the other permanently to the blue signature of a **circumbinary ring** (the inner rim of an excretion disc?)
- Some « extra » broadening can be due to the presence of two narrow components at comparatively extreme excursions in velocity signature. Signature of a ring or **disc orbiting the compact object itself.**



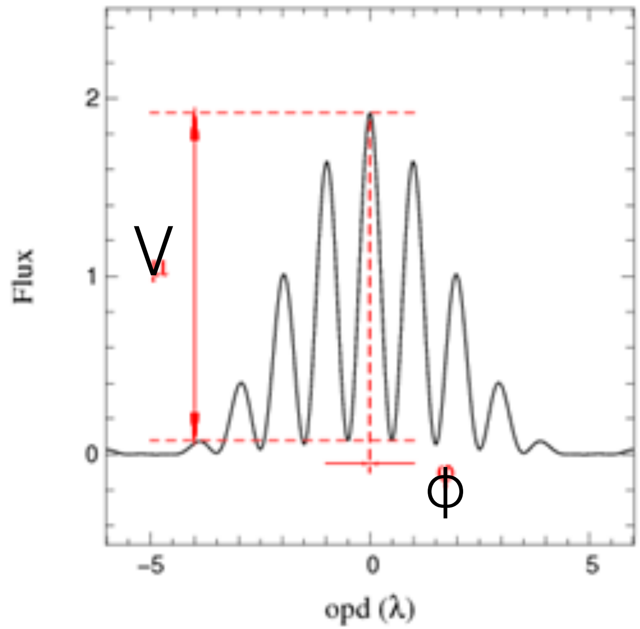


> 300 Rsun (0.2 mas)
Jet precession (~164 days)
and nutation (~6.5 days)
jet1
approaching
JET
ACCRETION DISC
+ WIND
COMPANION STAR
CIRCUMBINARY DISC
Mstar=24 M☉
P=13.6 days
5.5kpc
COMPACT OBJECT
MBH=16 M☉
GAS STREAM
jet2
receding
TOWARD EARTH
< 160 Rsun (0.1 mas)
The SS-433 System

Basics of Interferometry

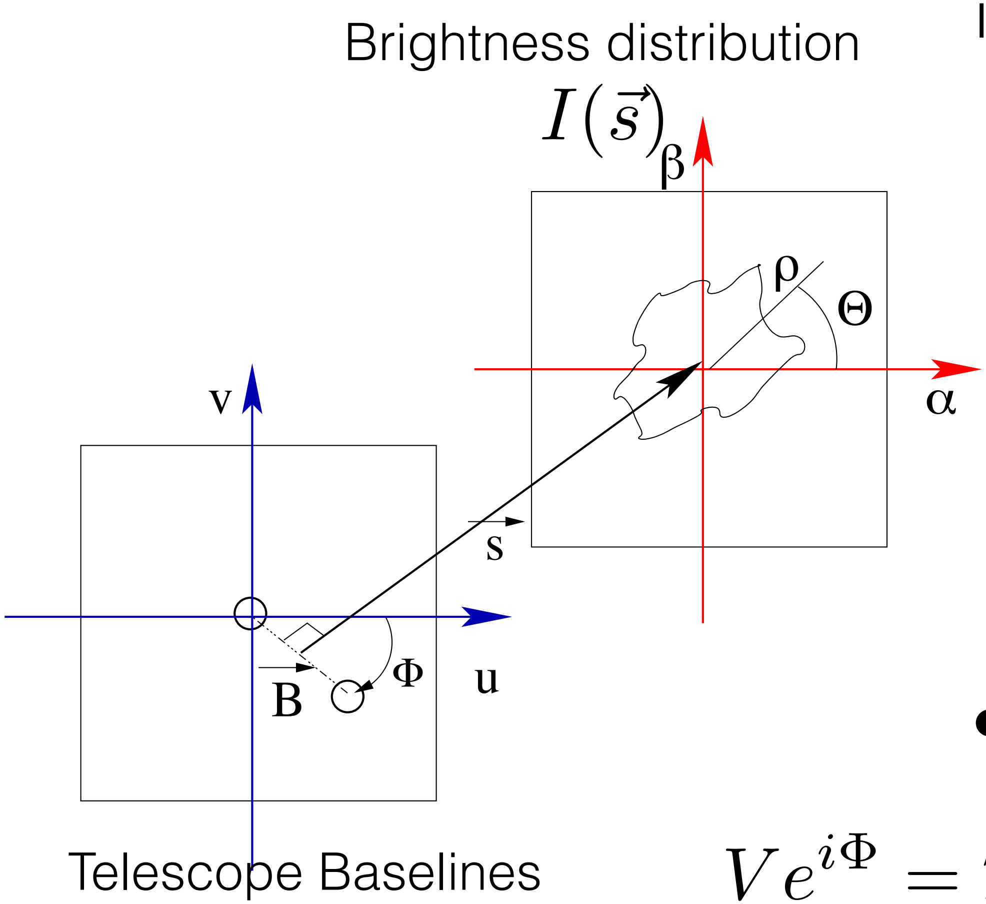


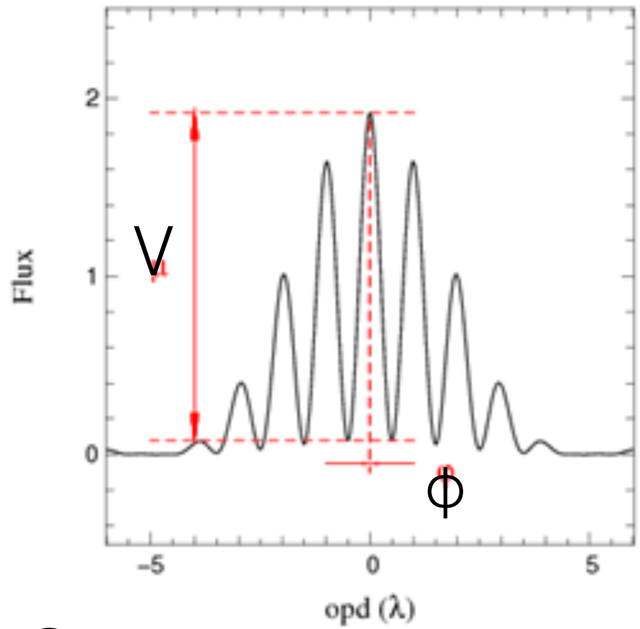
- In optical range we observe interference fringe patterns



Basics of Interferometry

- In optical range we observe interference fringe patterns



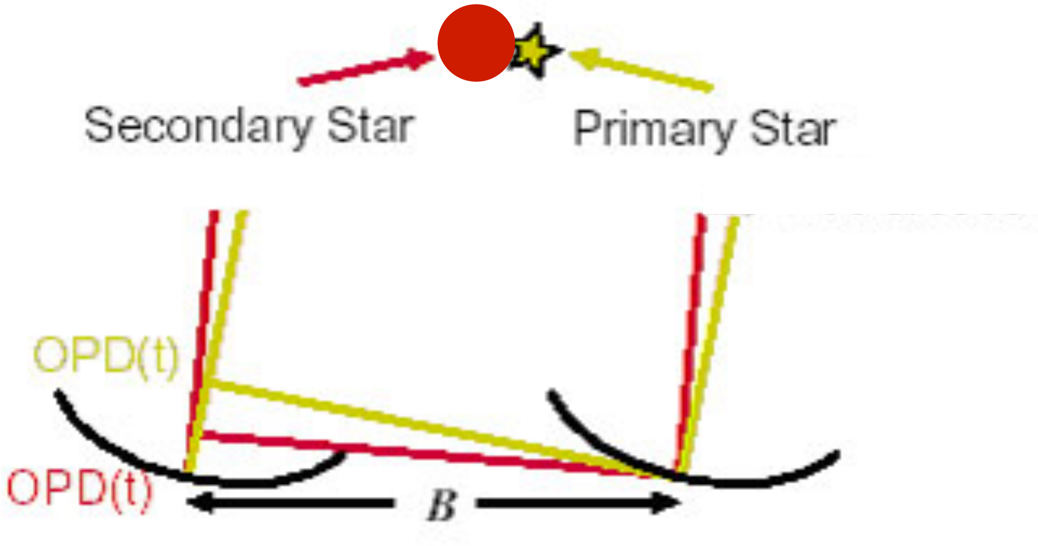


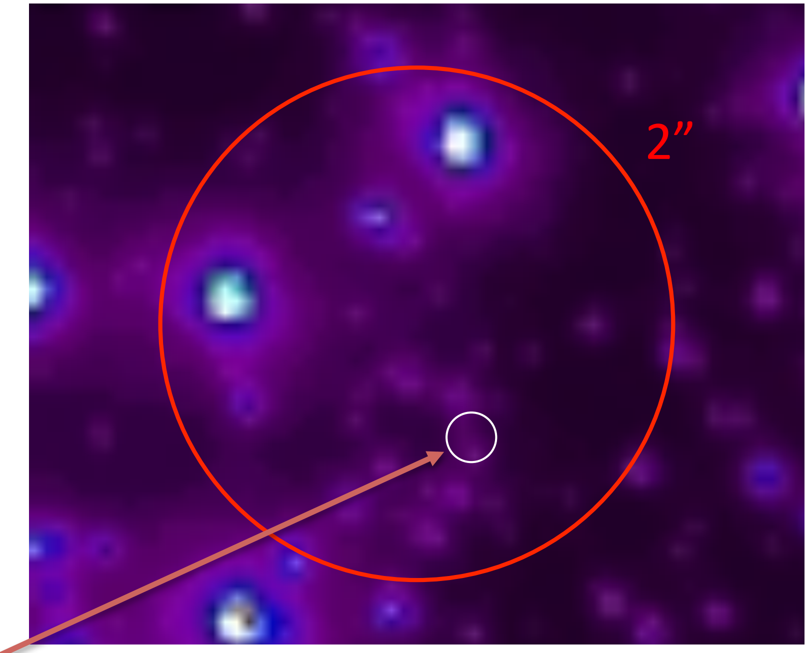
- van Cittert-Zernike Theorem:

$$Ve^{i\Phi} = TF\{Object\}(B/\lambda) \qquad \Phi = 2\pi\frac{\vec{B}}{\lambda}.\vec{s}$$

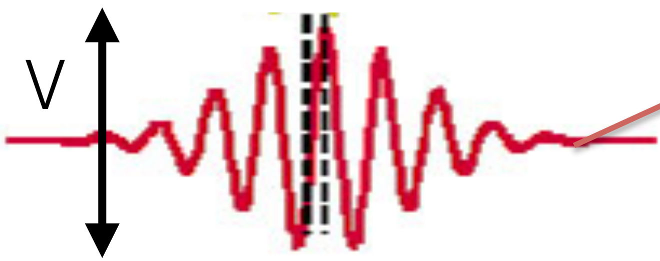
If we collect enough V and ϕ (for different $\vec{B}$) we can reconstruct $I(\vec{\alpha})$

Basics of Interferometry

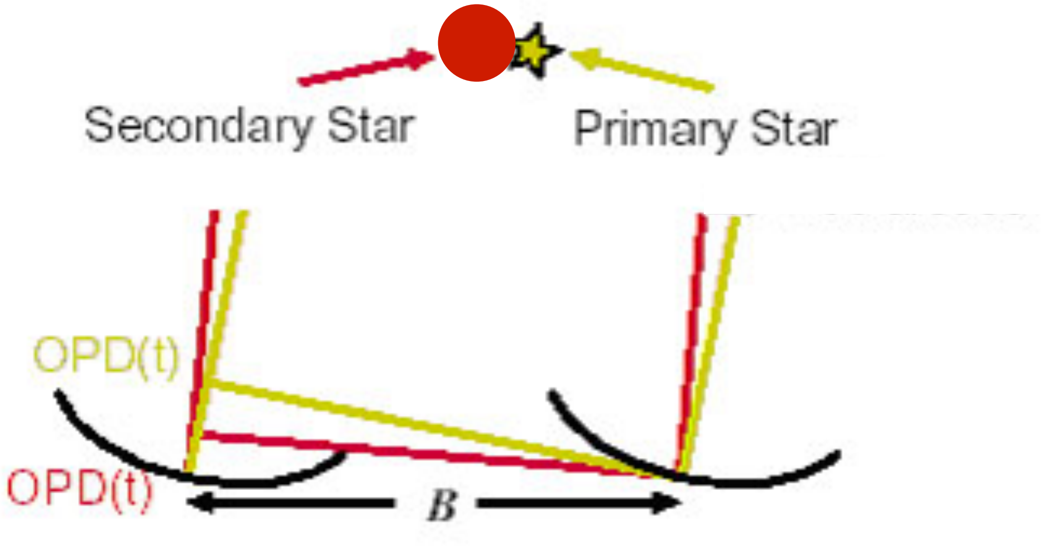


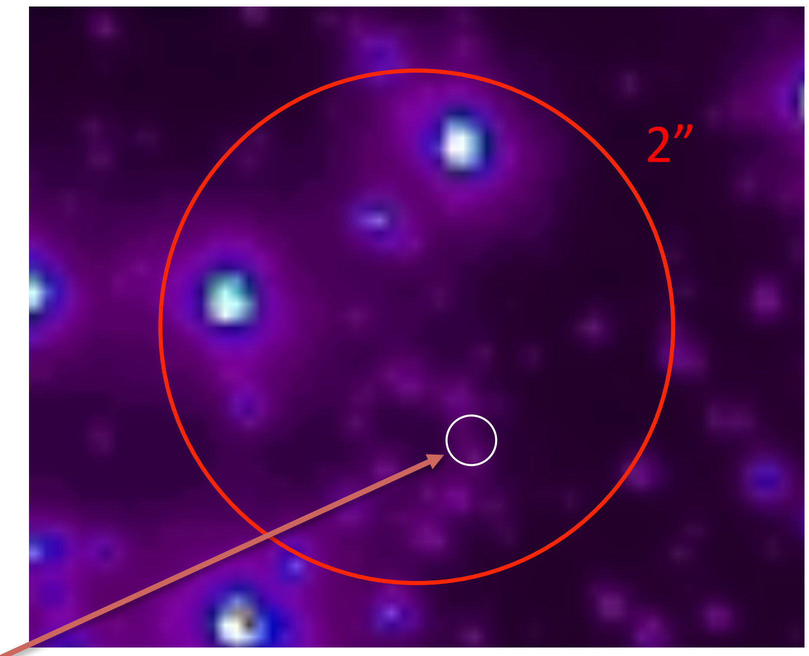


The smaller the V amplitude, the more resolved the object is!



Basics of Interferometry

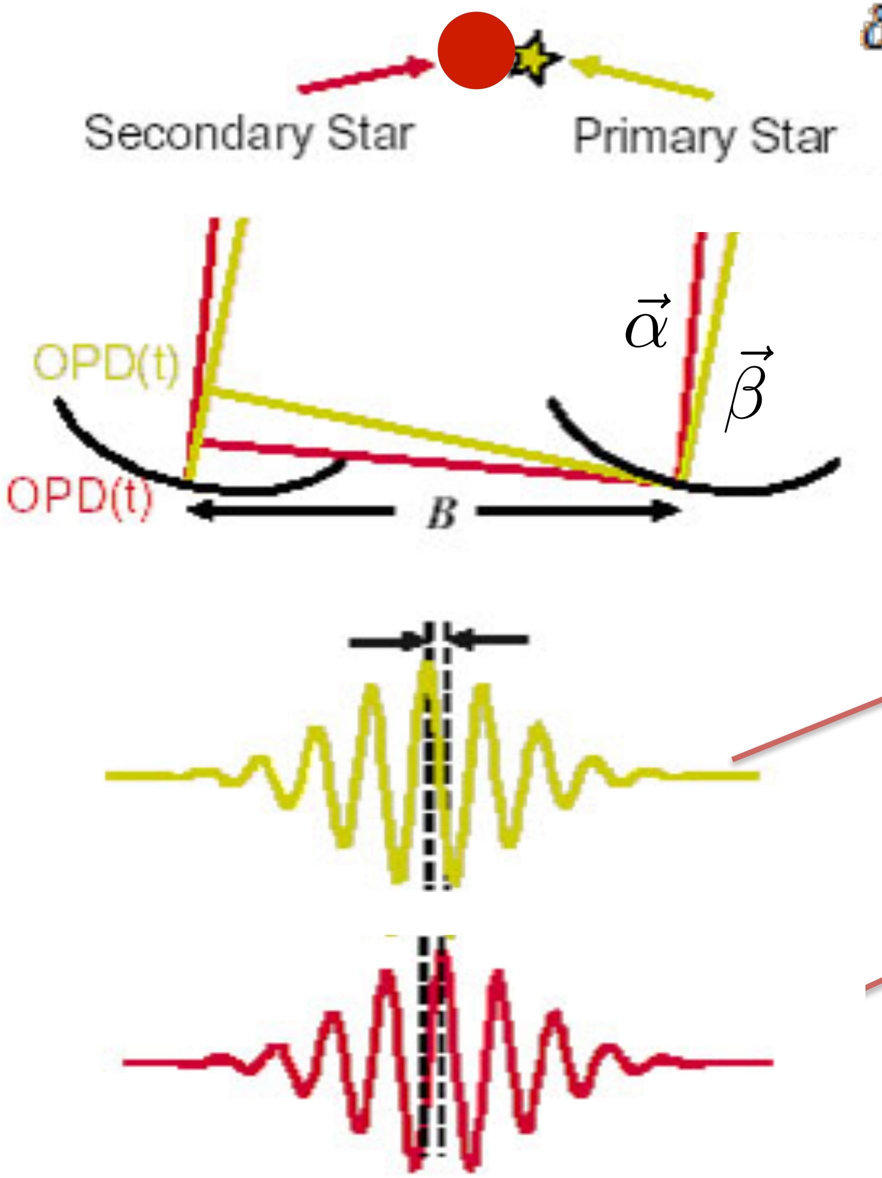


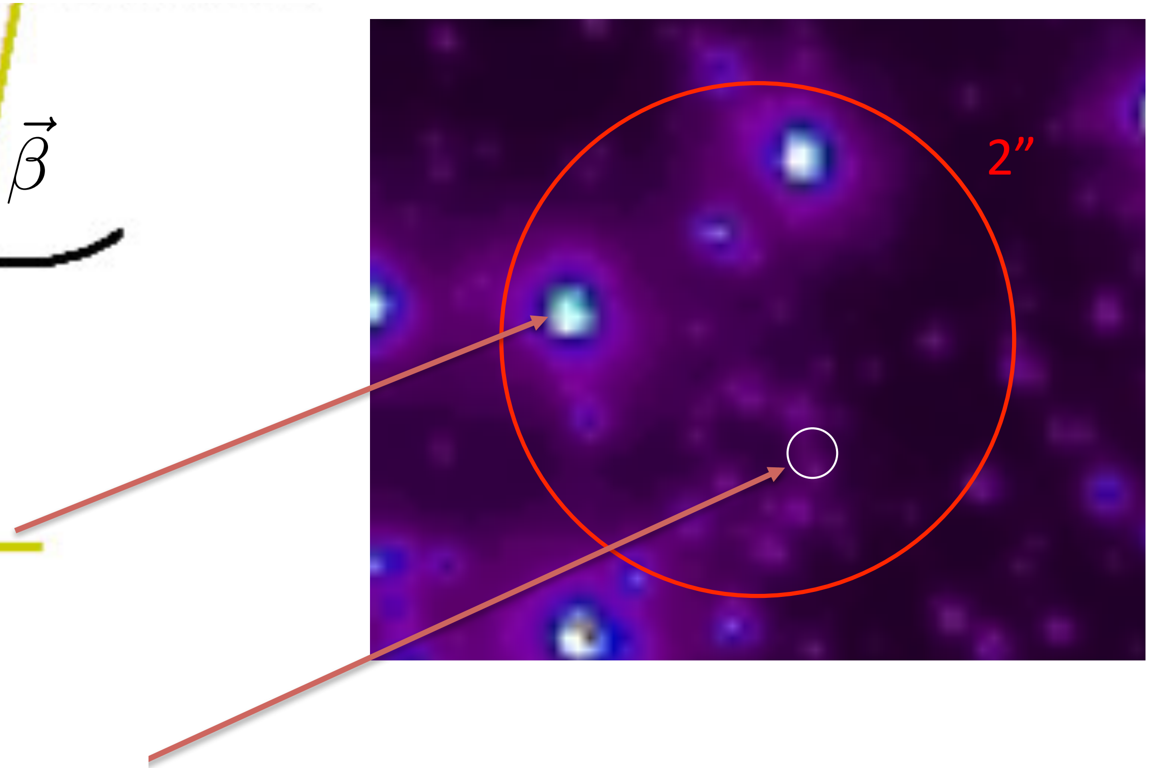


The smaller the V amplitude, the more resolved the object is!

Basics of Interferometry

$$\delta OPD = \vec{B}.\vec{\alpha} - \vec{B}.\vec{\beta} = \vec{B}.(\vec{\alpha} - \vec{\beta})$$

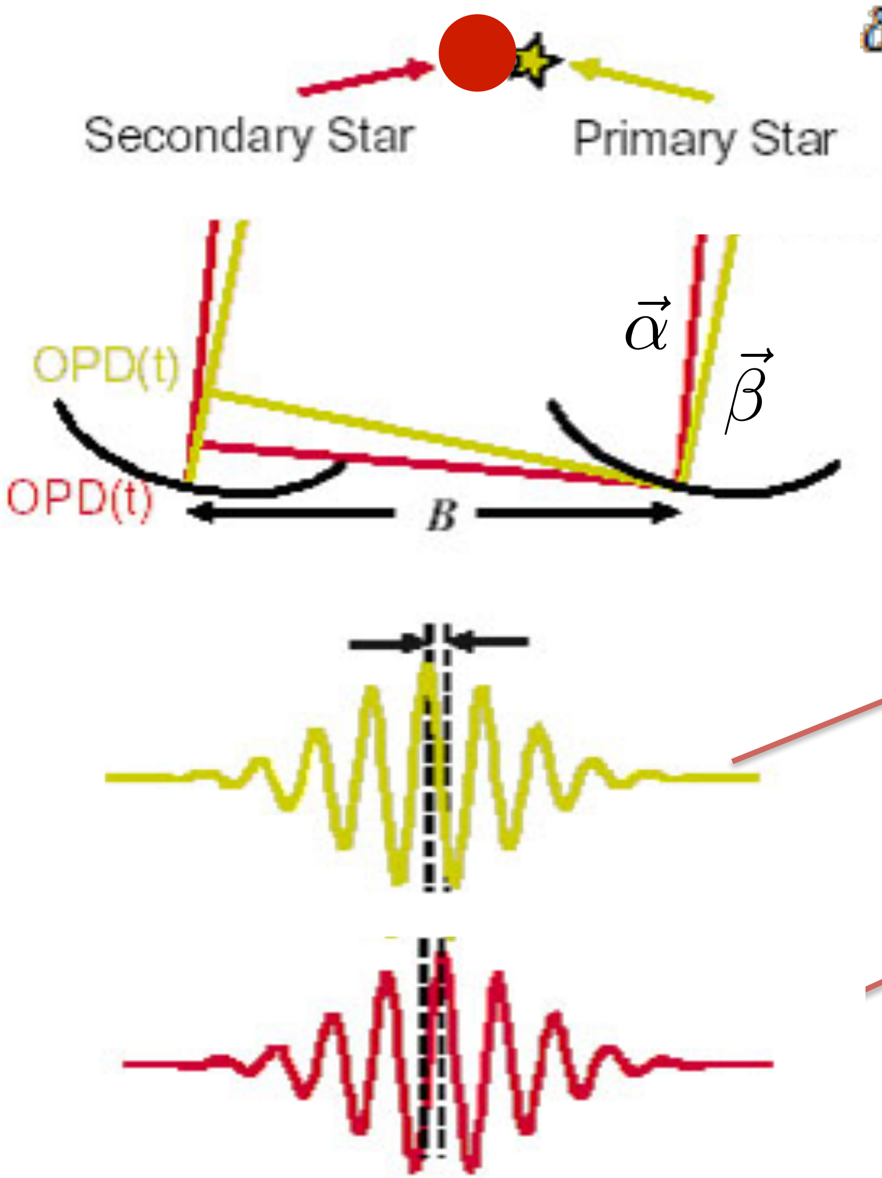


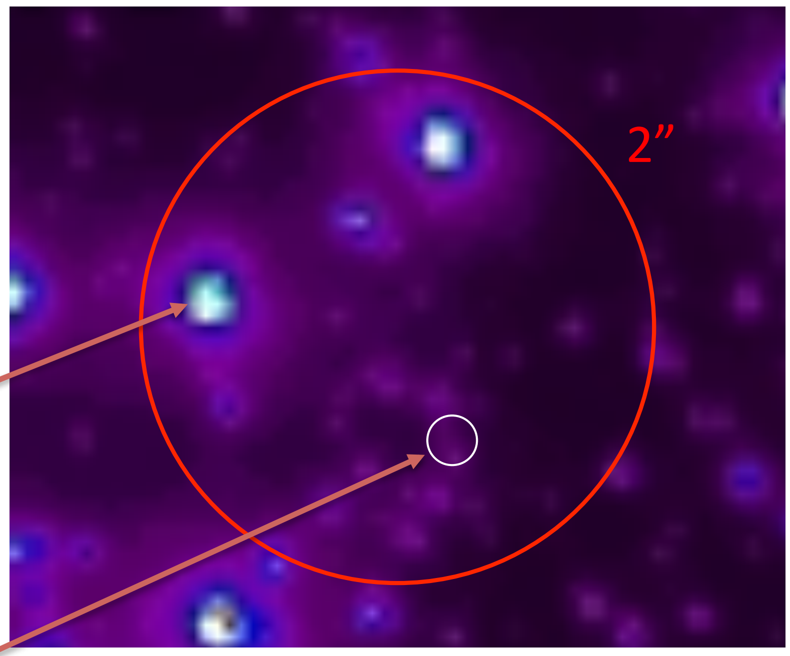


The larger the Φ phase, the more dissymetric the object is!

Basics of Interferometry

$$\delta OPD = \vec{B}.\vec{\alpha} - \vec{B}.\vec{\beta} = \vec{B}.(\vec{\alpha} - \vec{\beta})$$





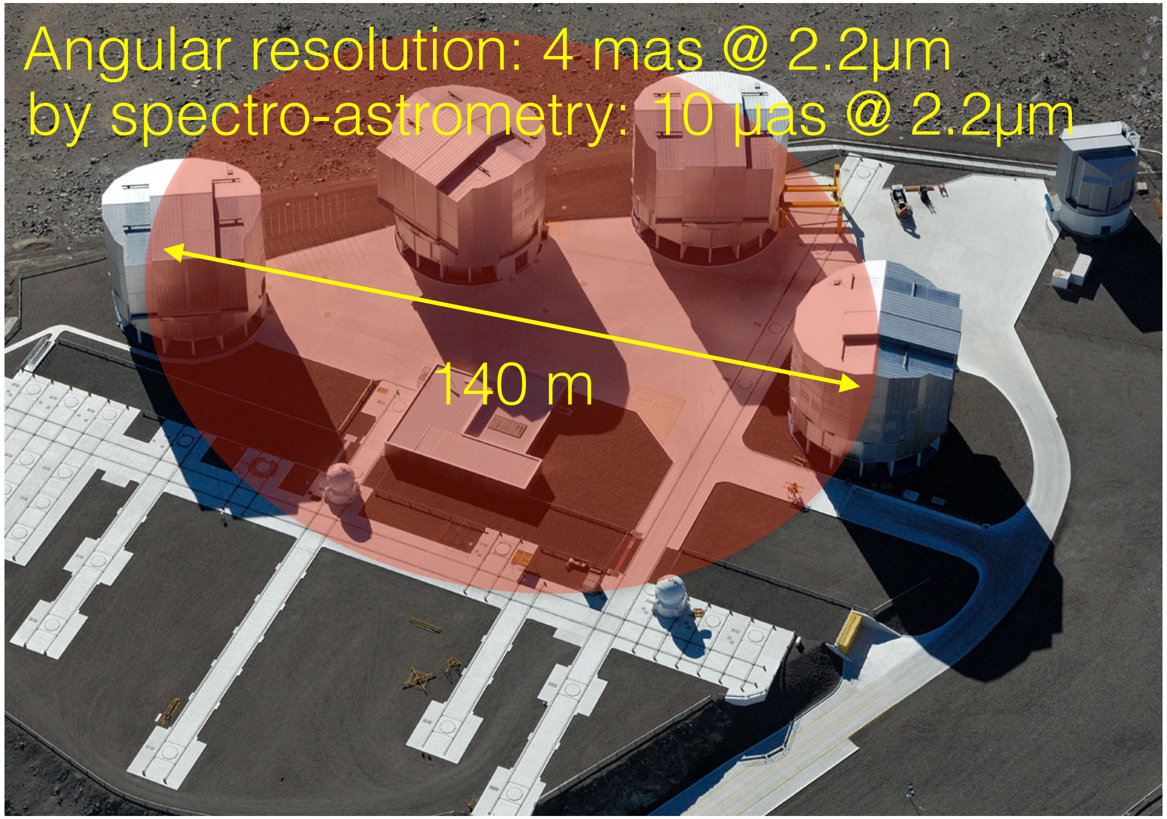
The larger the Φ phase, the more dissymetric the object is!

GRAVITY Instrument

http://www.mpe.mpg.de/ir/gravity

First light paper: GRAVITY Collaboration: Abuter et al. (2017)

- Combines the 4 UT (8,20 m) or the 4 AT (1,80 m) since 2016



GRAVITY Instrument

http://www.mpe.mpg.de/ir/gravity

First light paper: GRAVITY Collaboration: Abuter et al. (2017)

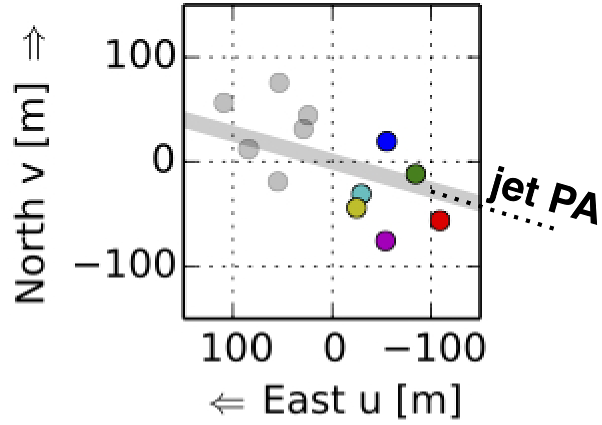
- Combines the 4 UT (8,20 m) or the 4 AT (1,80 m) since 2016

- Devoted to the observation of the very close environment of the black hole at the galactic center

- Room for other science (AGN, stars, binaries, …): open to ESO proposals!

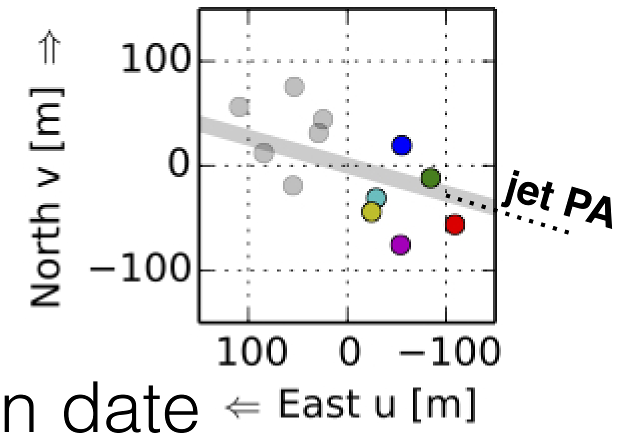
The SS 433 Observation

- 3.5h with the 4 UTs, the 16th July 2016
- uv-plane (coincidentally) aligned with the jet PA

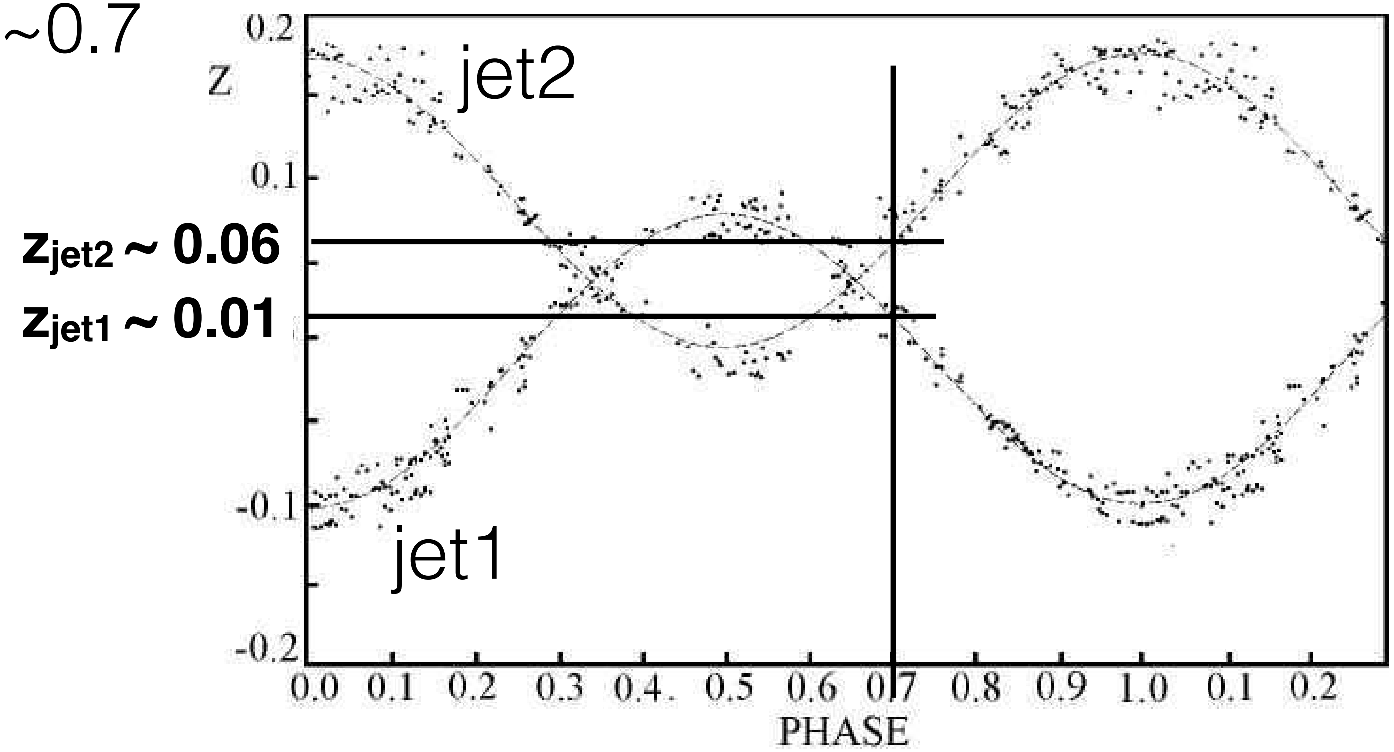


The SS 433 Observation

- 3.5h with the 4 UTs, the 16th July 2016
- uv-plane (coincidentally) aligned with the jet PA



- The jet precession phase at the observation date is ~0.7

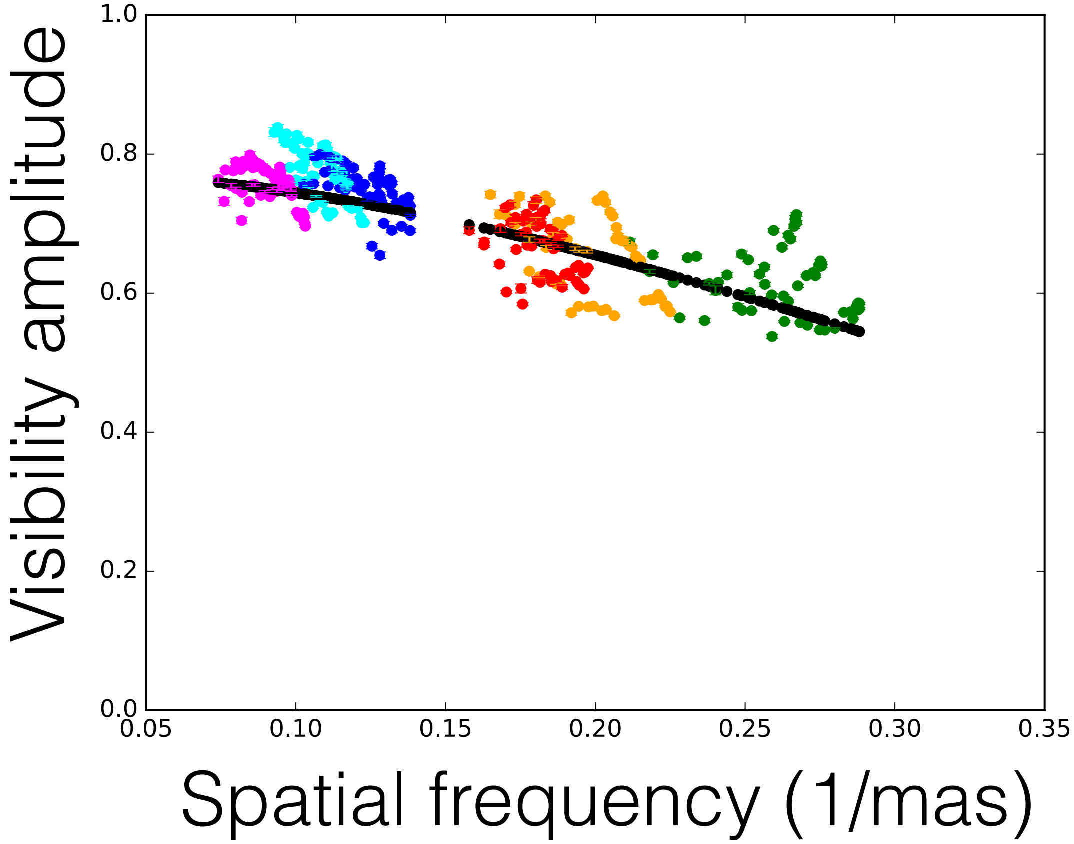


Continuum Visibility

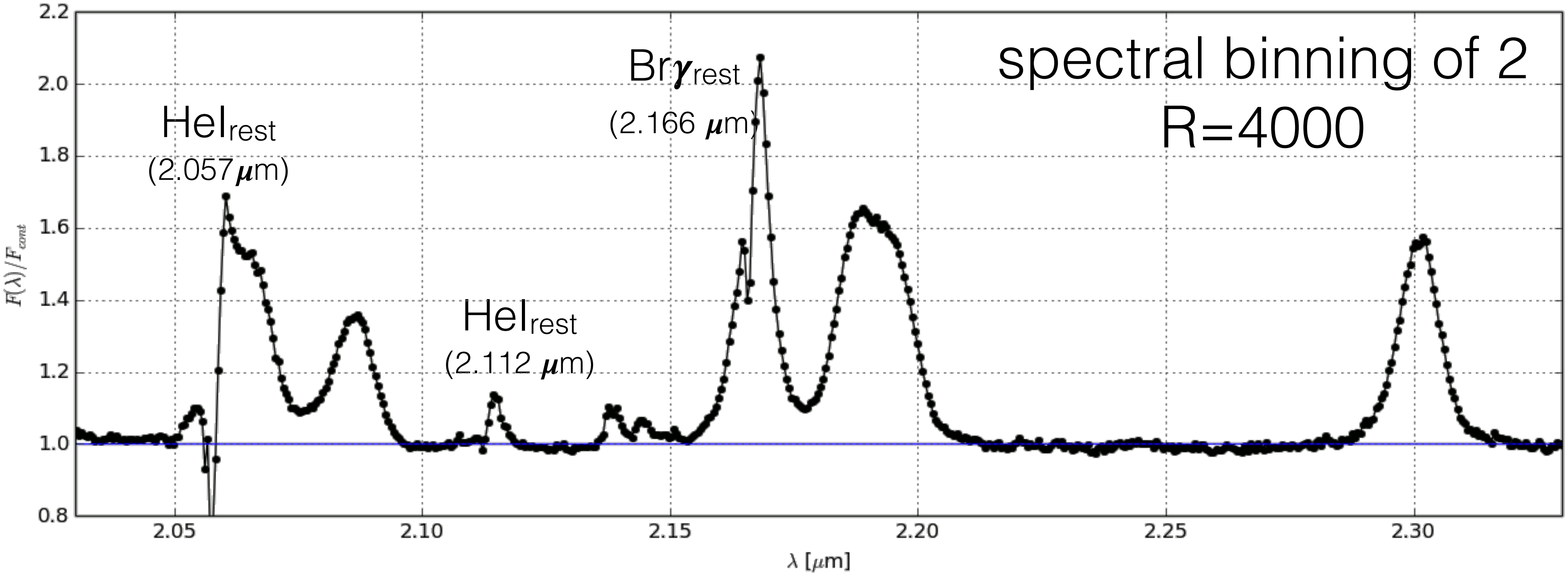
- Systematic drop versus baseline length

- No closure phase measurable

- Simple modeling with a Gaussian disk:
  - 90% from emitting region of 0.8mas
  - 10% from diffuse background (>15mas)



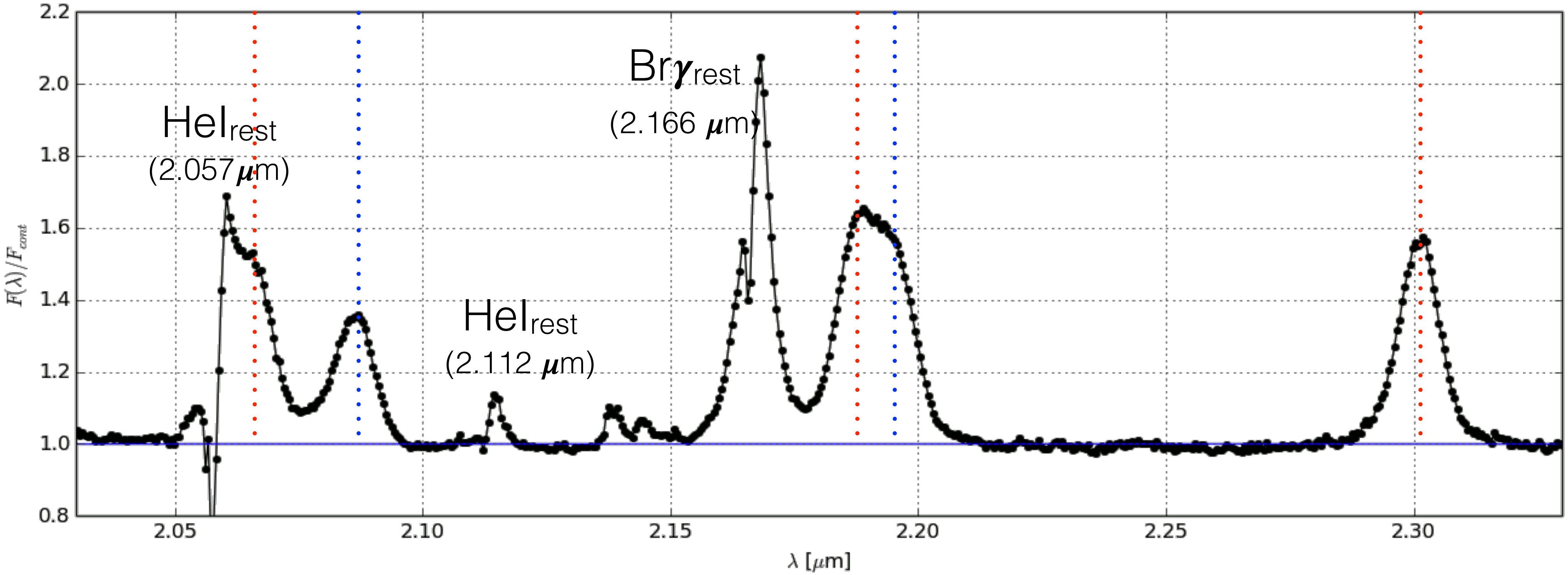
The GRAVITY Spectrum



<u>Stationary lines</u>

- Brγ is double-peaked
- HeI with P Cygni profile

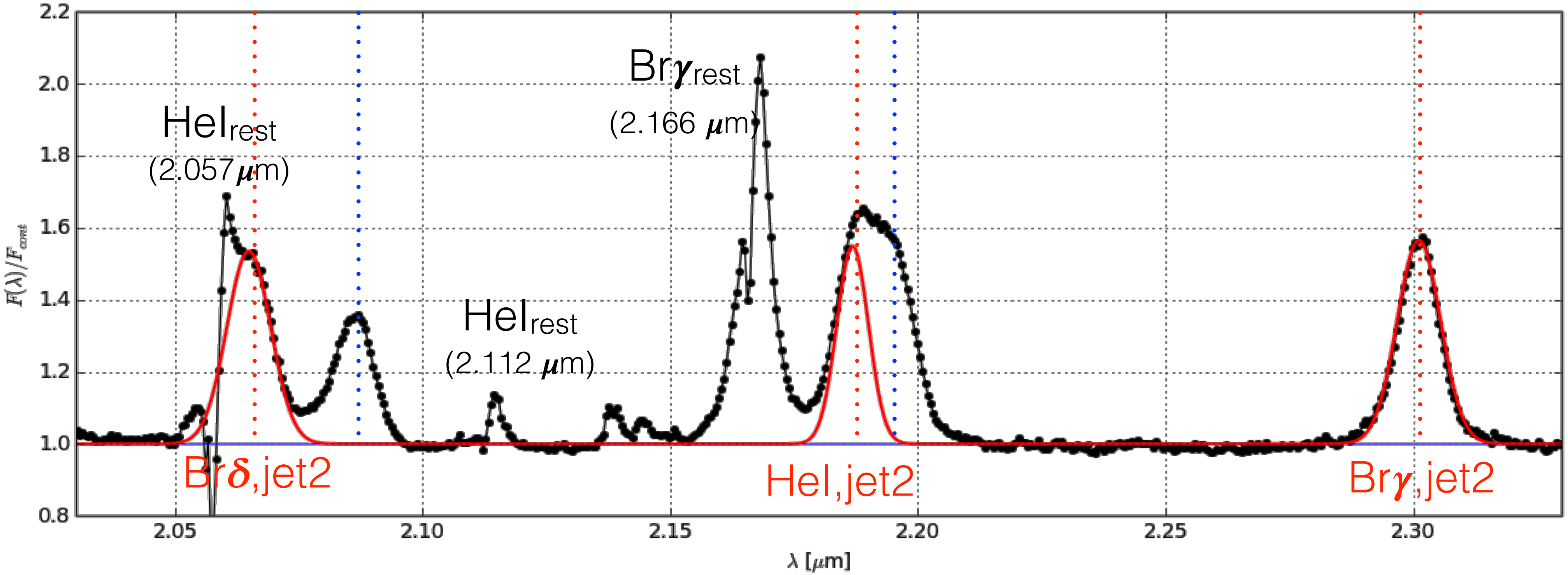
The GRAVITY Spectrum



<u>Jet lines</u>

- Emission features agree with the jet line shifts expected at the observation date
- Br$\boldsymbol{\gamma}$, HeI from jet1 and jet2 and Br$\boldsymbol{\delta}$ from jet1

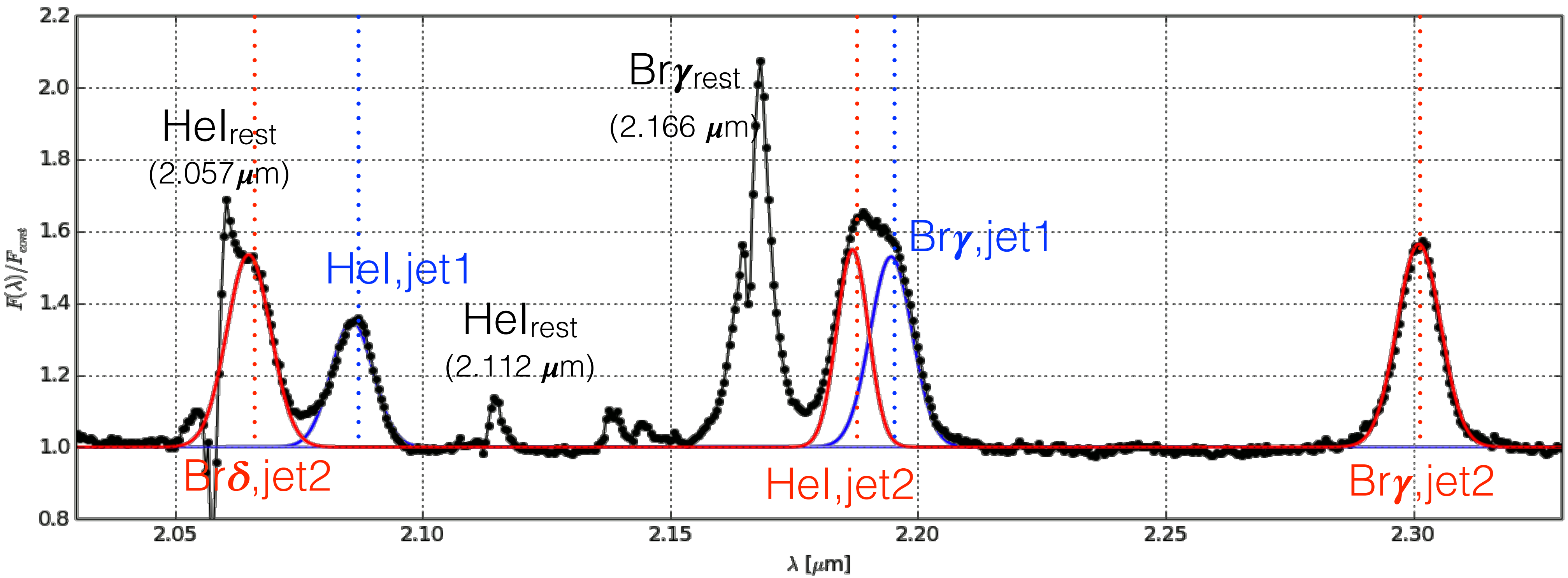
The GRAVITY Spectrum



<u>Jet lines</u>

- Emission features agree with the jet line shifts expected at the observation date
- Brγ, HeI from jet1 and jet2 and Brδ from jet1

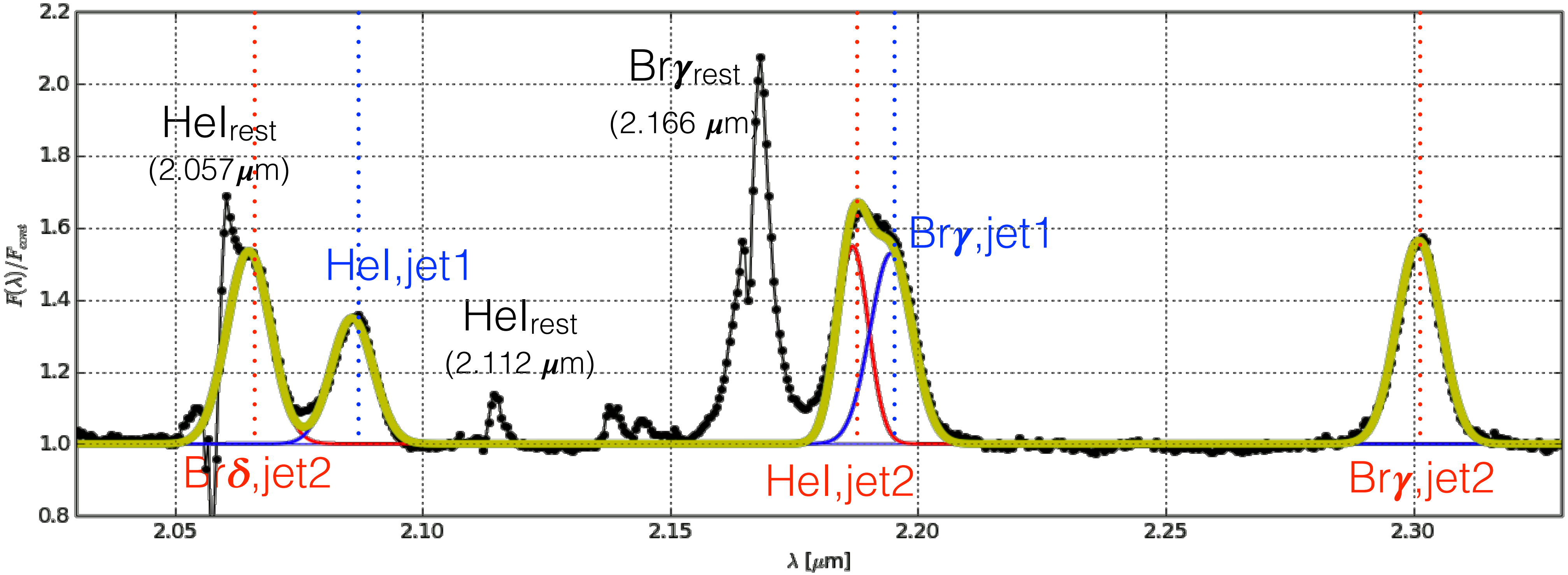
The GRAVITY Spectrum



Jet lines

- Emission features agree with the jet line shifts expected at the observation date
- Brγ, HeI from jet1 and jet2 and Brδ from jet1

The GRAVITY Spectrum

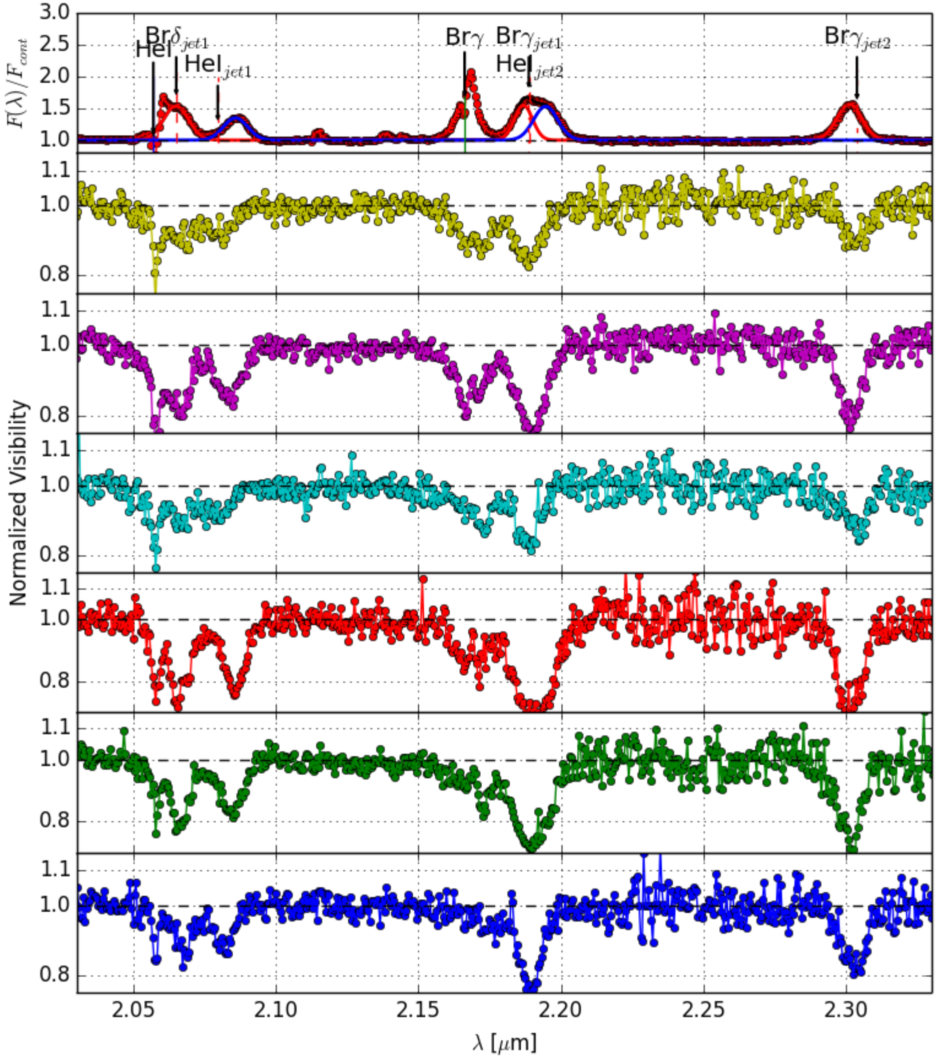


Jet lines

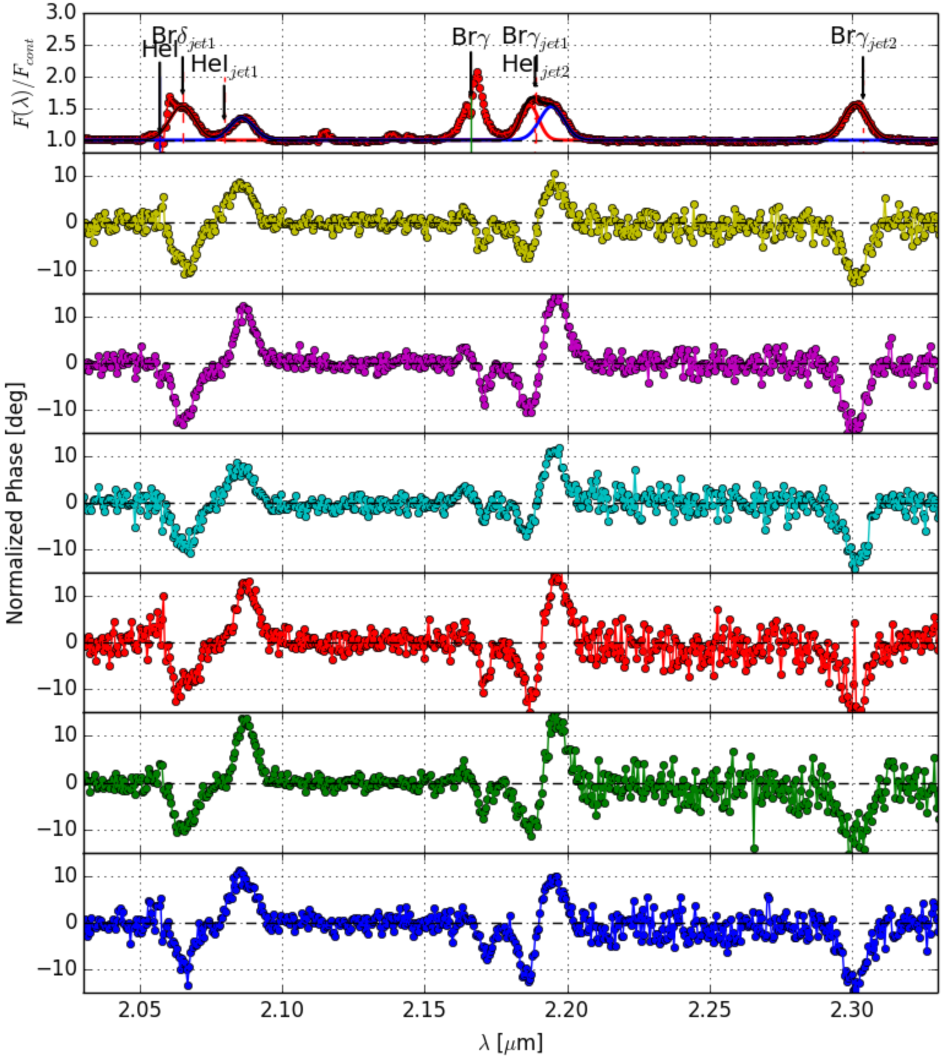
- Emission features agree with the jet line shifts expected at the observation date
- Brγ, HeI from jet1 and jet2 and Brδ from jet1

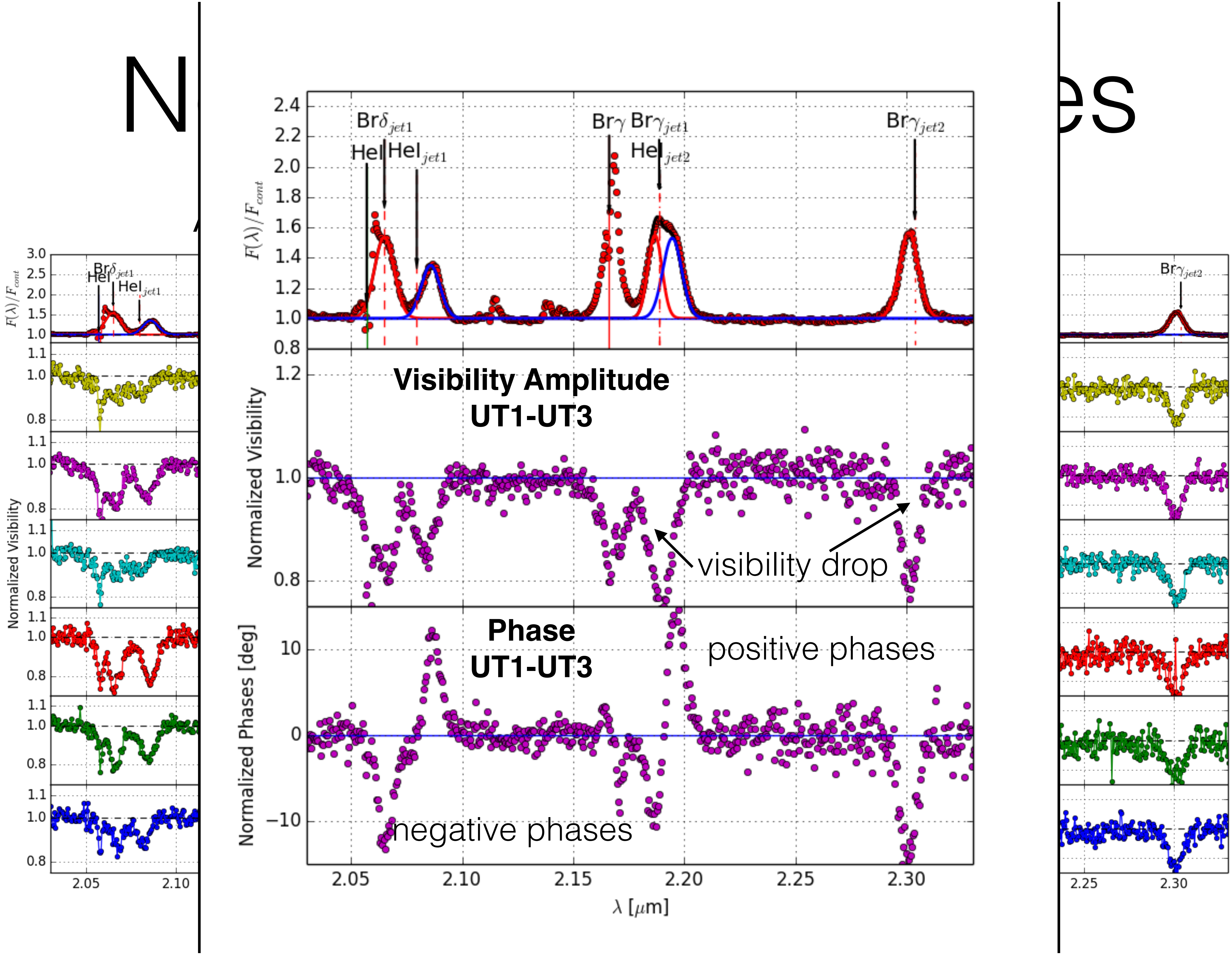
Normalized Visibilities

Amplitudes



Phases





N
es
Brδ jet1
HeI
HeI jet1
Brγ
Brγ jet1
HeI jet2
Brγ jet2
F(λ)/F cont
Visibility Amplitude
UT1-UT3
Normalized Visibility
visibility drop
Phase
UT1-UT3
positive phases
negative phases
Normalized Phases [deg]
λ [μm]

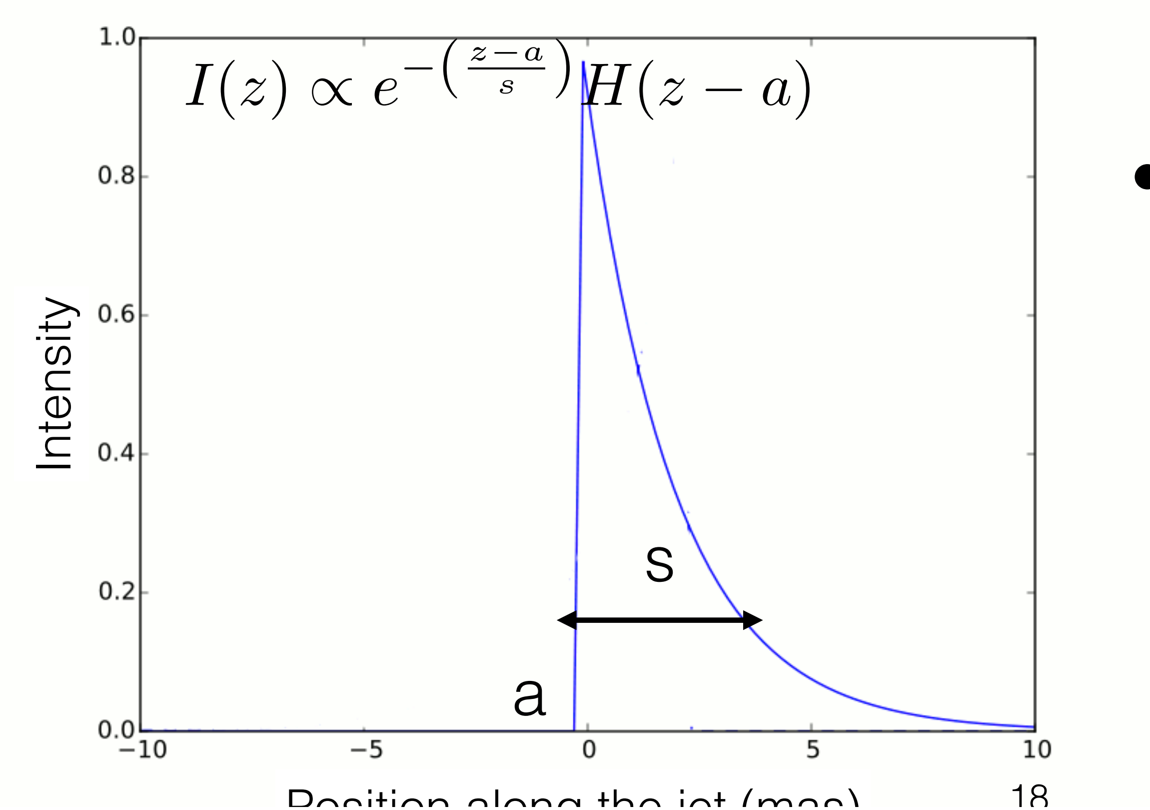
Jet line Model

Method: fit all jet lines (flux, vis. amplitude and phase) together assuming the same jet intensity profile moving at 0.26c

Jet line Model

Method: fit all jet lines (flux, vis. amplitude and phase) together assuming the same jet intensity profile moving at 0.26c

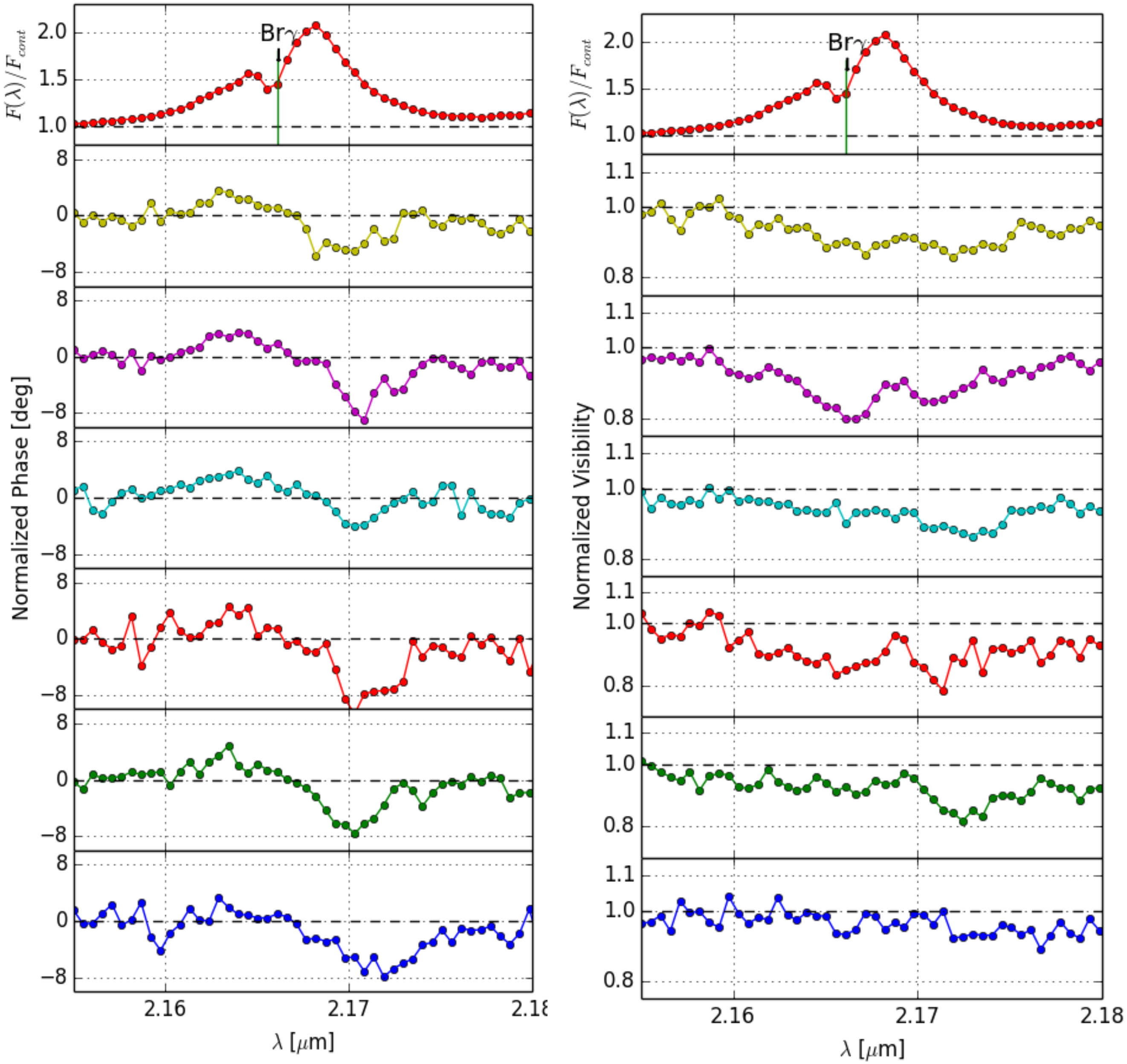
- An exponentially decreasing intensity profile preferred to a gaussian one ($\Delta\chi^2 > 36$ for 57 dof)



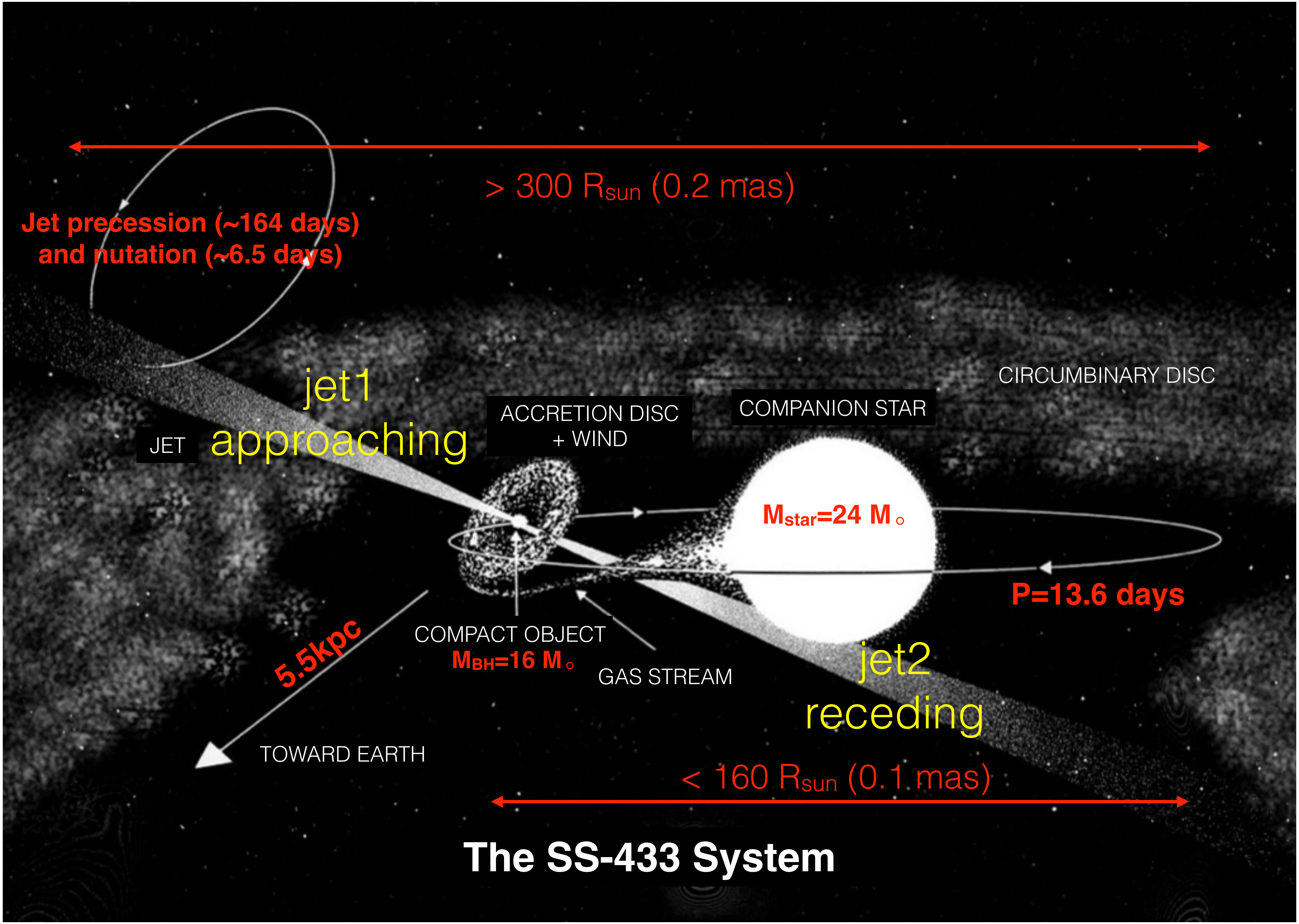
- Best fit with:
  - PA=75°±20° (3$\boldsymbol{\sigma}$ error)
  - s=1.7±0.6 mas,
  - a=-0.15±0.34 mas

- Transverse size < 1.2 mas

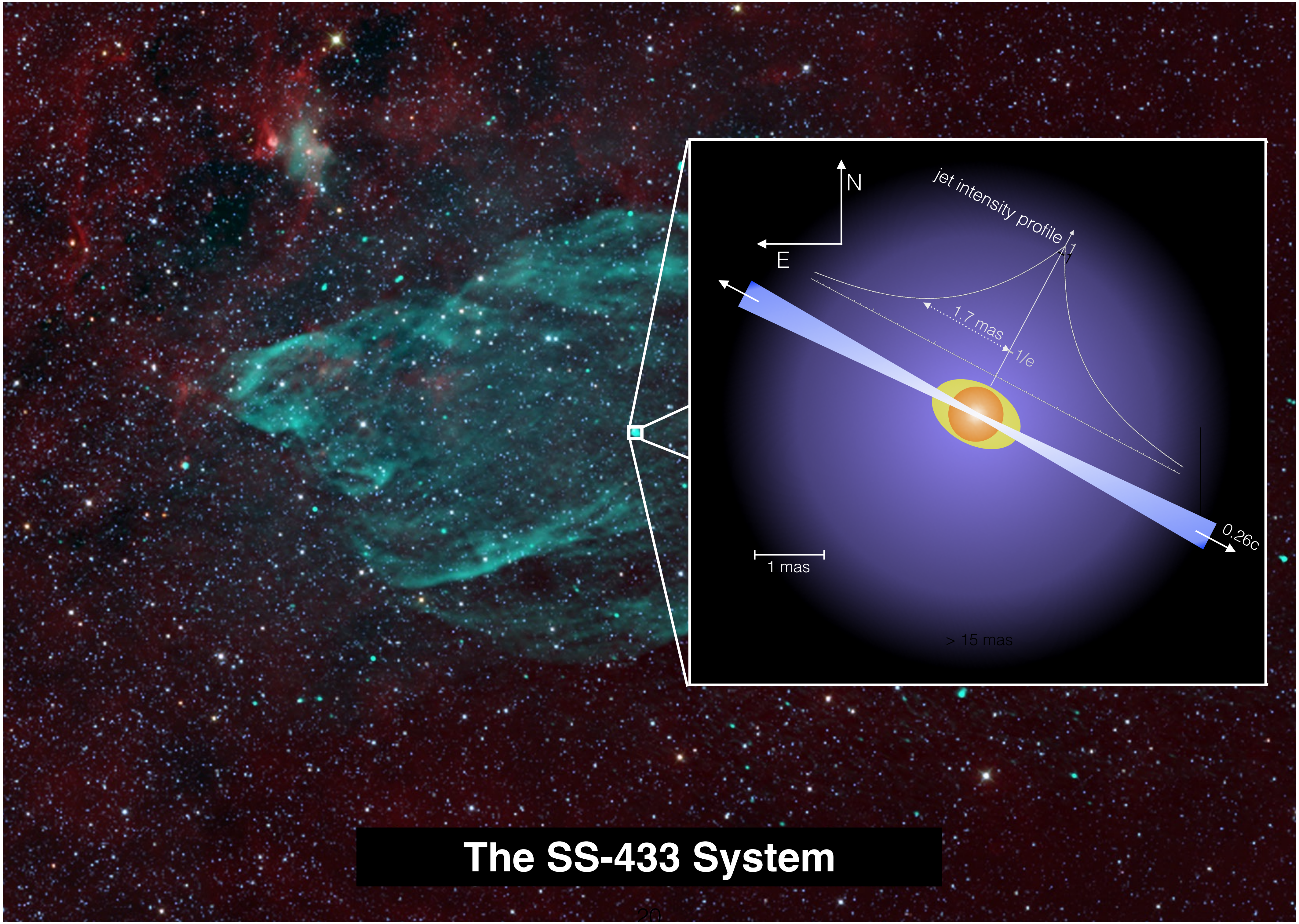
Stationary line: Brγ



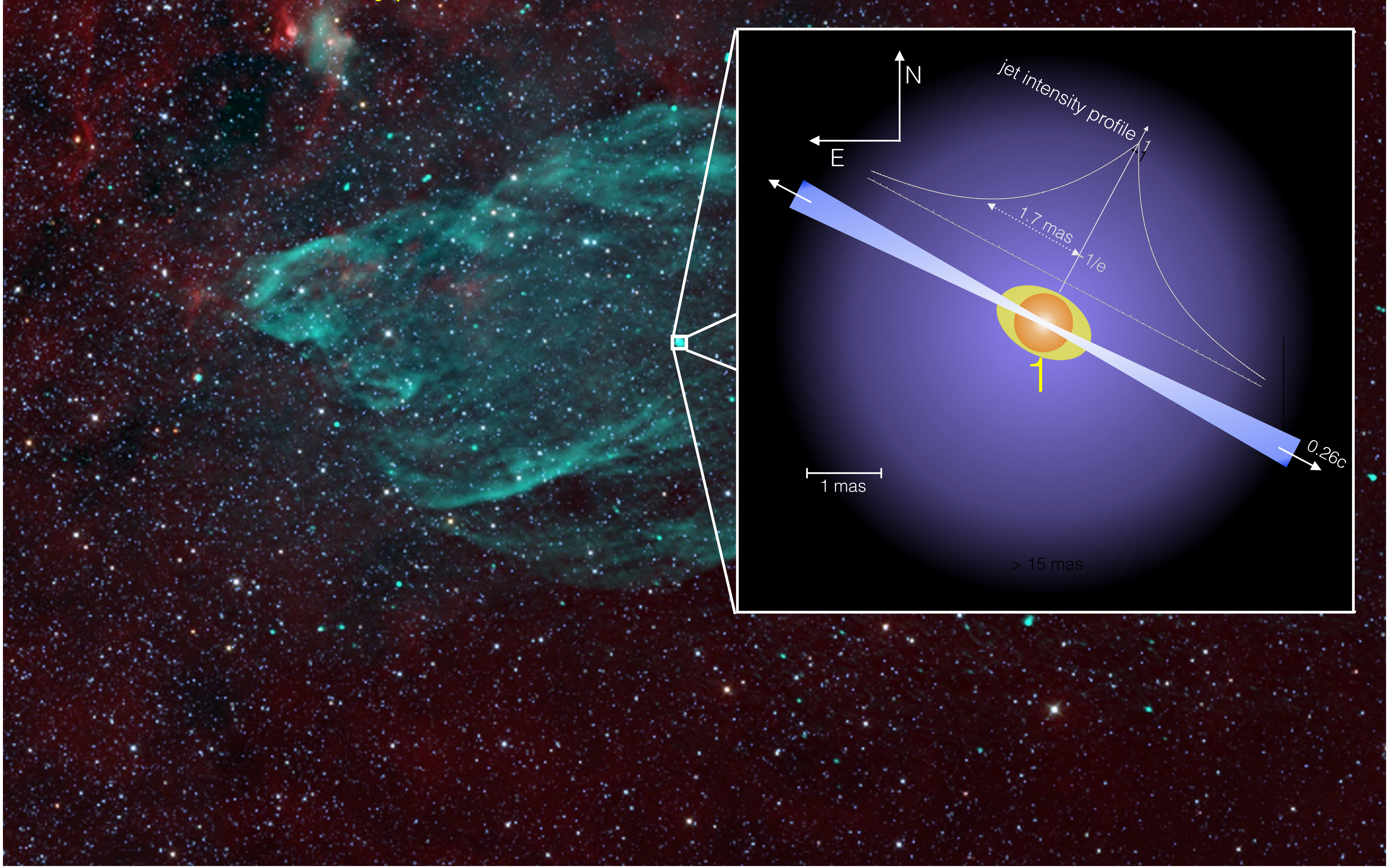
- Visibilities clearly drop across the line for all the baselines
- Deeper for longer baselines.
- Emitting region size is found to be ~1 mas
- Phases behavior suggest East-West oriented geometry, i.e., in a direction similar to the jet one



> 300 R_{sun} (0.2 mas)
Jet precession (~164 days)
and nutation (~6.5 days)
jet1
approaching
JET
ACCRETION DISC
+ WIND
COMPANION STAR
CIRCUMBINARY DISC
M_{star}=24 $M_\odot$
P=13.6 days
5.5kpc
COMPACT OBJECT
M_{BH}=16 $M_\odot$
GAS STREAM
jet2
receding
TOWARD EARTH
< 160 R_{sun} (0.1 mas)
The SS-433 System

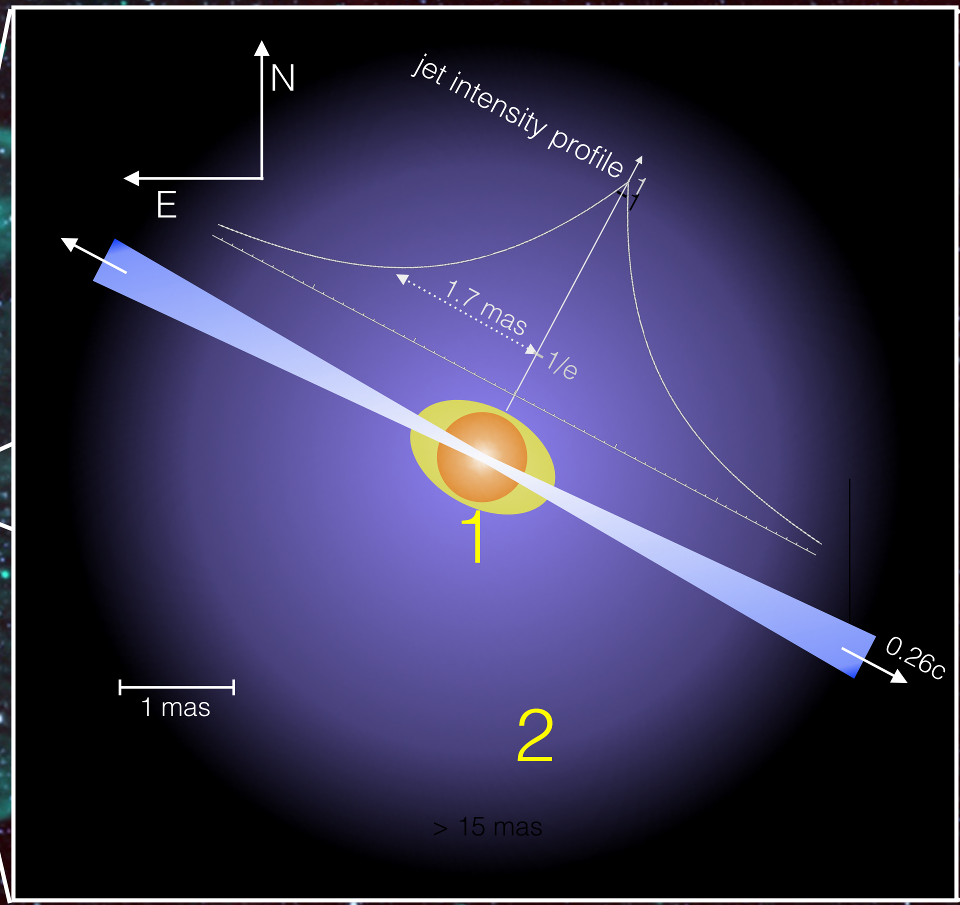

N
E
jet intensity profile
1
1.7 mas
1/e
0.26c
1 mas
> 15 mas
The SS-433 System

1. Most (90%) of the infrared continuum comes from a partially resolved central source of typical size ~0.8 mas



1. Most (90%) of the infrared continuum comes from a partially resolved central source of typical size ~0.8 mas

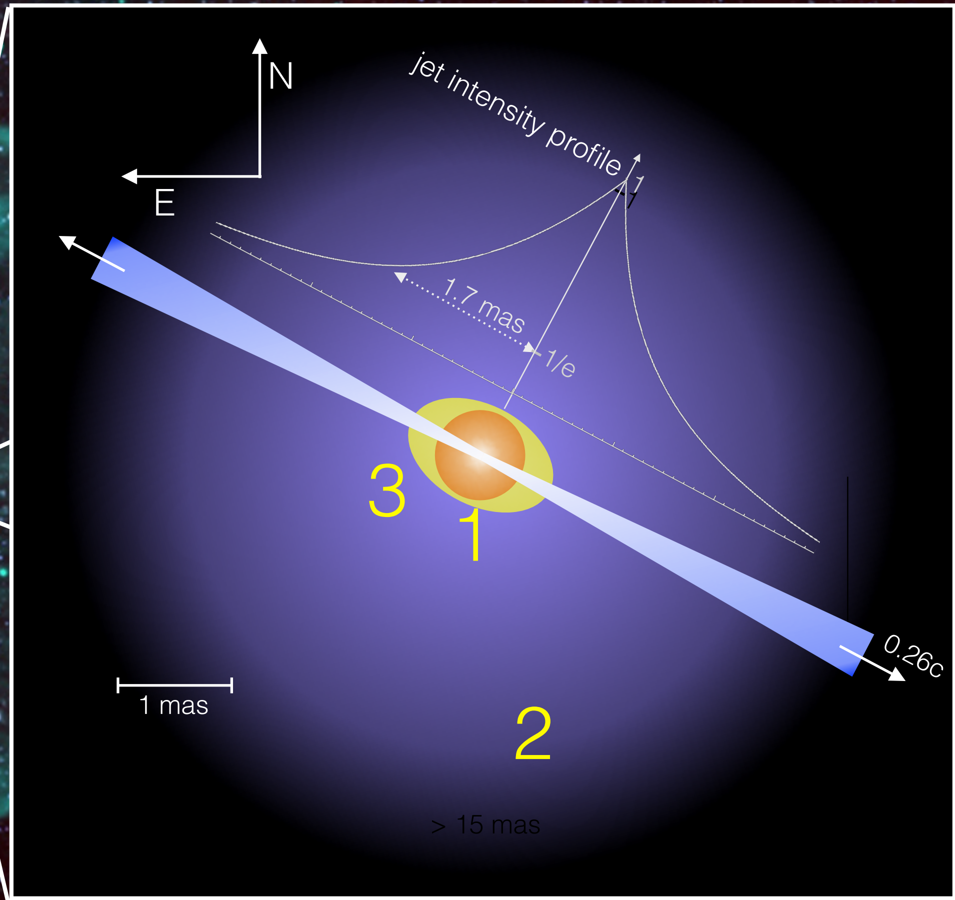
2. 10% continuum flux left over produced by a completely resolved background on a larger scale (>15mas).



1. Most (90%) of the infrared continuum comes from a partially resolved central source of typical size ~0.8 mas

2. 10% continuum flux left over produced by a completely resolved background on a larger scale (>15mas).

3. The Brγ emitting region has a typical size of 1 mas with an East-West elongation, along the jet axis

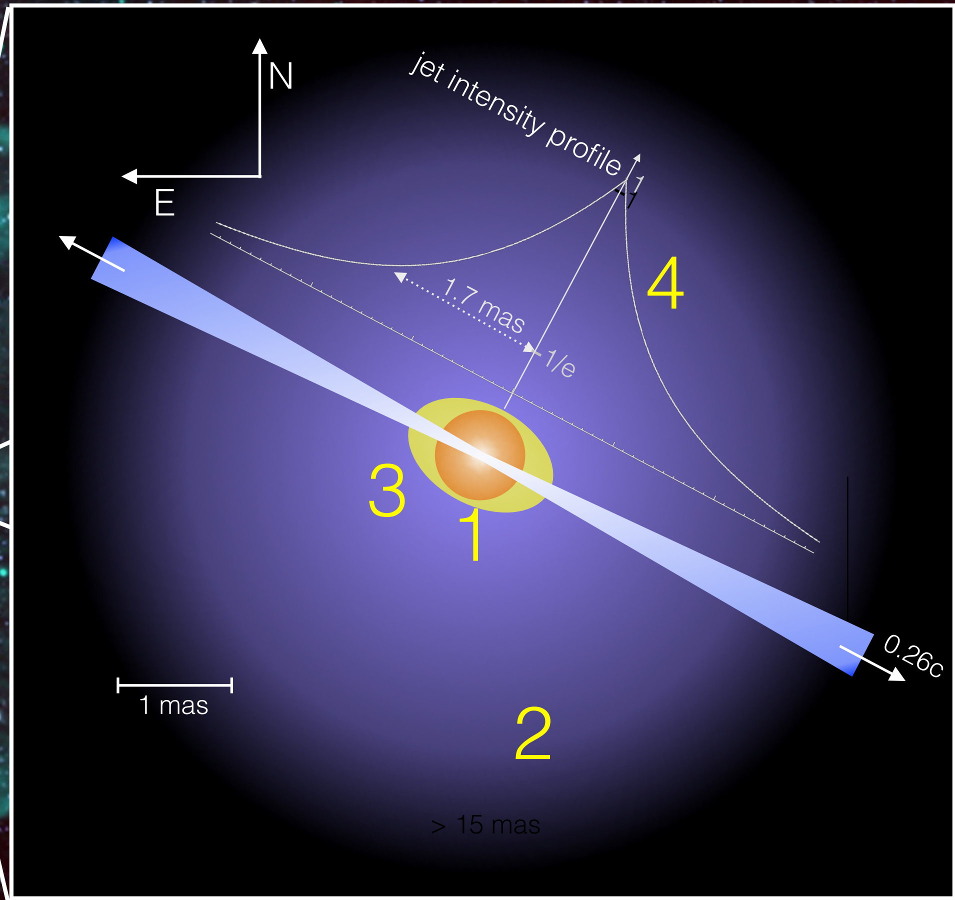


1. Most (90%) of the infrared continuum comes from a partially resolved central source of typical size ~0.8 mas

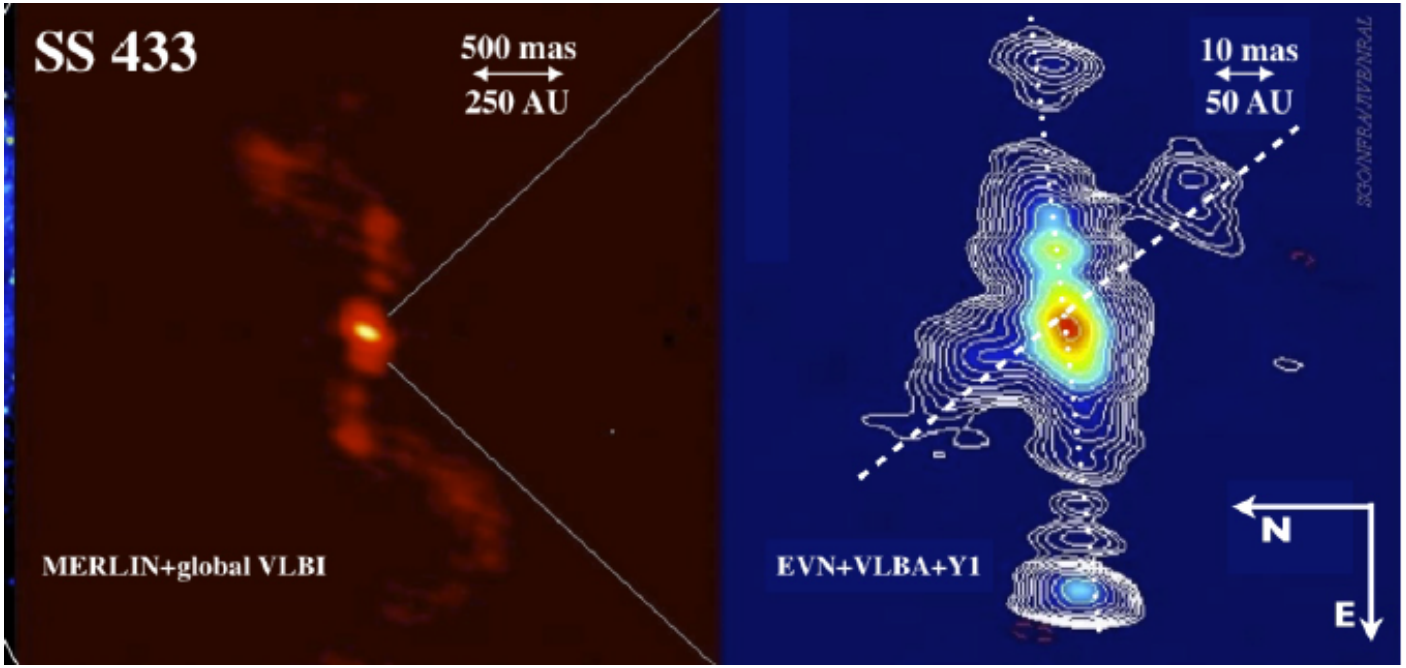
2. 10% continuum flux left over produced by a completely resolved background on a larger scale (>15mas).

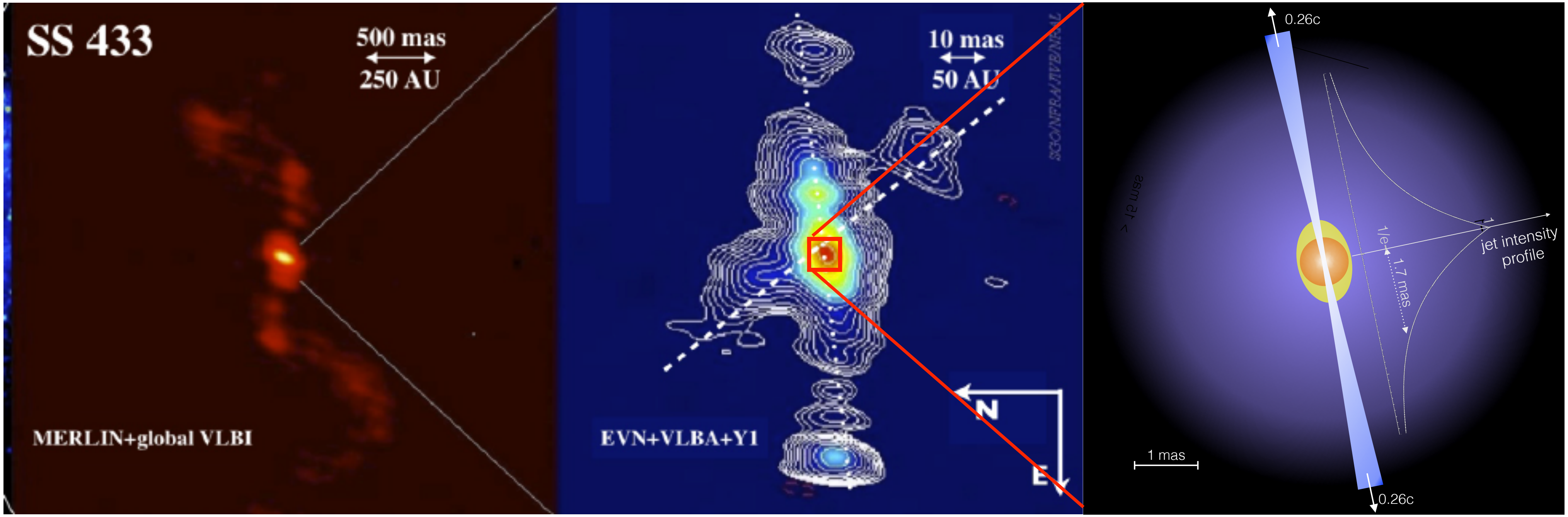
3. The Brγ emitting region has a typical size of 1 mas with an East-West elongation, along the jet axis

4. Jet with a continuous (exponentially decreasing) emitting profile. No signature of moving blobs.



Jet already at 0.26c at <0.2mas (1.6 10^{13} cm) from the binary (line locking process on hydrogenoid ions for jet acceleration)


SS 433
500 mas
250 AU
MERLIN+global VLBI
10 mas
50 AU
EVN+VLBA+Y1
N
E


SS 433
500 mas
250 AU
MERLIN+global VLBI
10 mas
50 AU
EVN+VLBA+Y1
N
E
0.26c
jet intensity
profile
1/e
1.7 mas
1 mas
0.26c

Perspectives

- Improve the uv coverage
- Days/Week/Month monitoring to follow the source on different time scales (orbital period, jet precession period)

➞ jet stability, ejection phenomena, line substructure origin (e.g. Brγ)

New data

- A GRAVITY (5h) + XSHOOTER (2h) observation accepted for P99 in A priority (PI: I. Waisberg): **data analysis in progress…**
- VLBA (15-86 GHz) (PI: I. Waisberg)

Thanks!