# VHE detection and monitoring of the radio galaxy 3C 264

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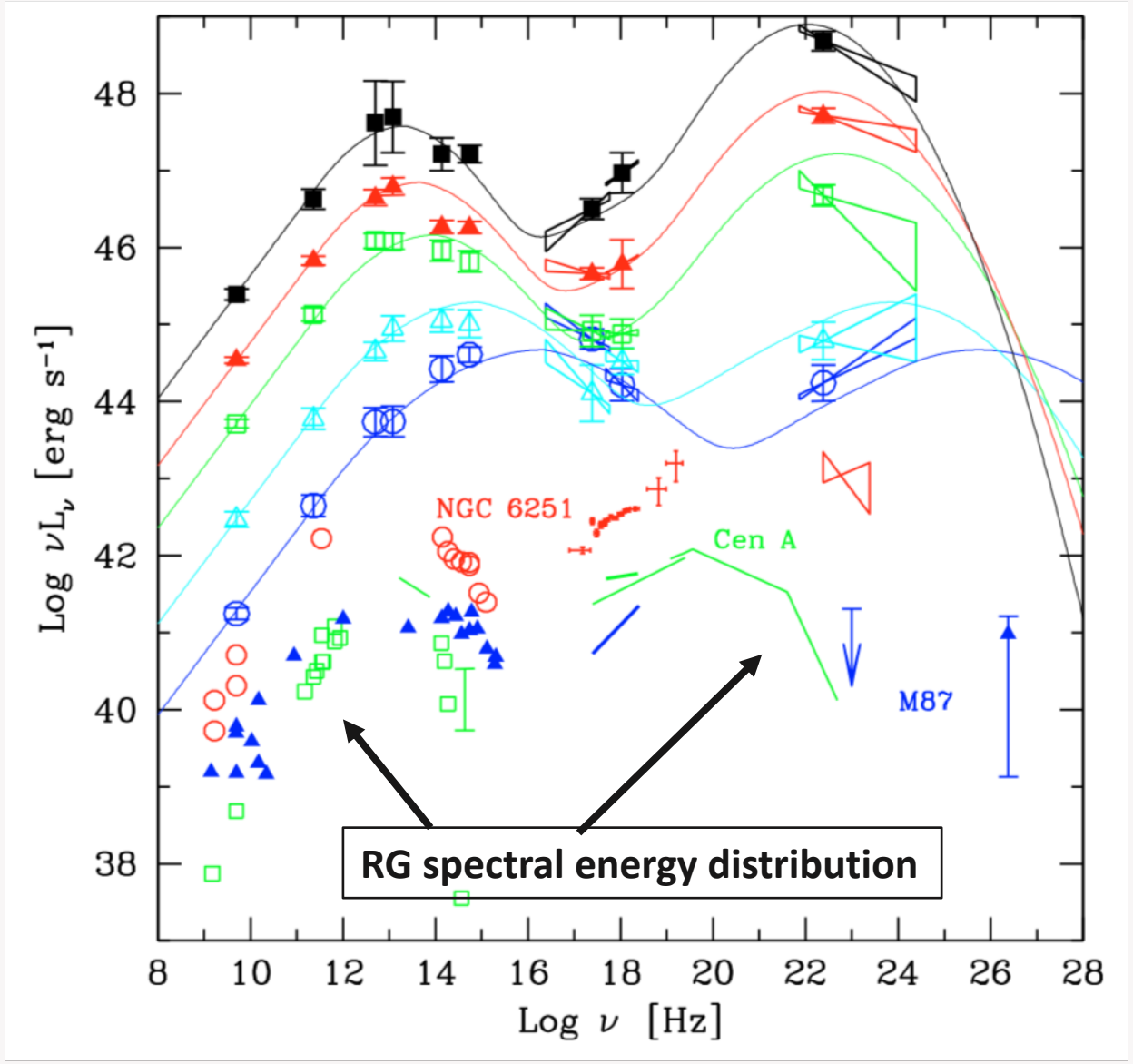
# Radio Galaxies, a different view of an AGN

- Radio Galaxies are identified by an extended jet feature in radio observations.
- Jet morphology may also be observed in optical and X-ray.
- VHE Acceleration is associated with the core and/or knots.
- Mis-aligned AGN, inclination $\gtrsim 15°$ makes Doppler beaming less likely.
- VHE emission is only detected for nearby sources.
- About 70 Blazars have been identified with VHE emission compared to 5 or possibly 6 radio galaxies.
- Viewed through external photon fields. Leads to complex SED.
- Emission from the Core can be highly variable. Larger features like knots are generally steady state.



# 3C 264

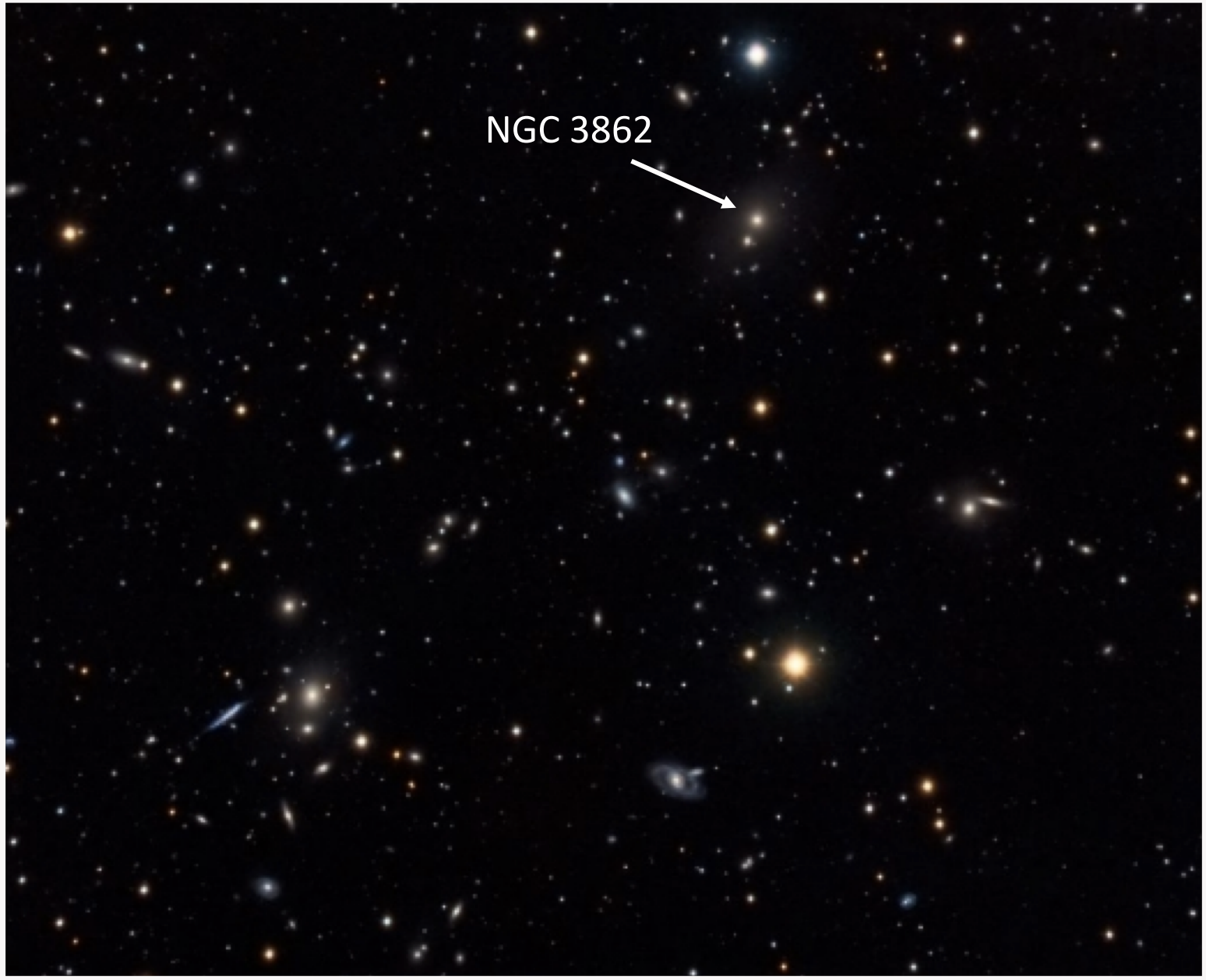
The most recent addition to the VHE emitting Radio Galaxies.

- Fanaroff-Riley type I radio galaxy,
- Optically associated with elliptical galaxy NGC 3862
- in the Leo Cluster (Abell 1367)

Relatively close

- z = 0.02
- 91 Mpc.

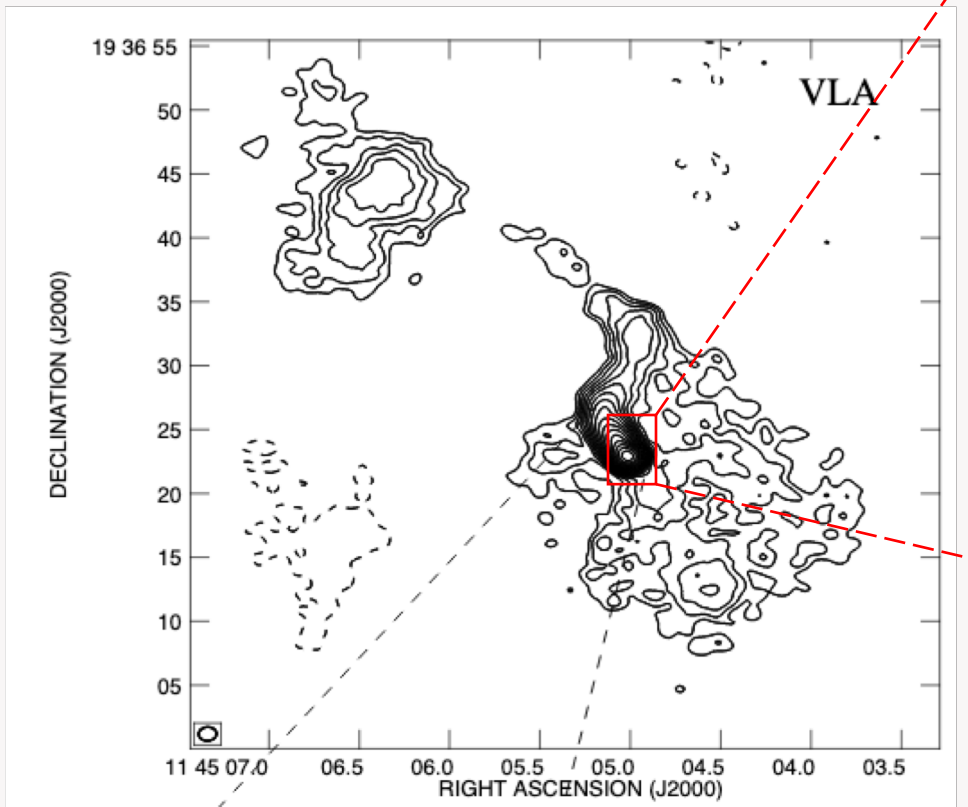
Leo Cluster

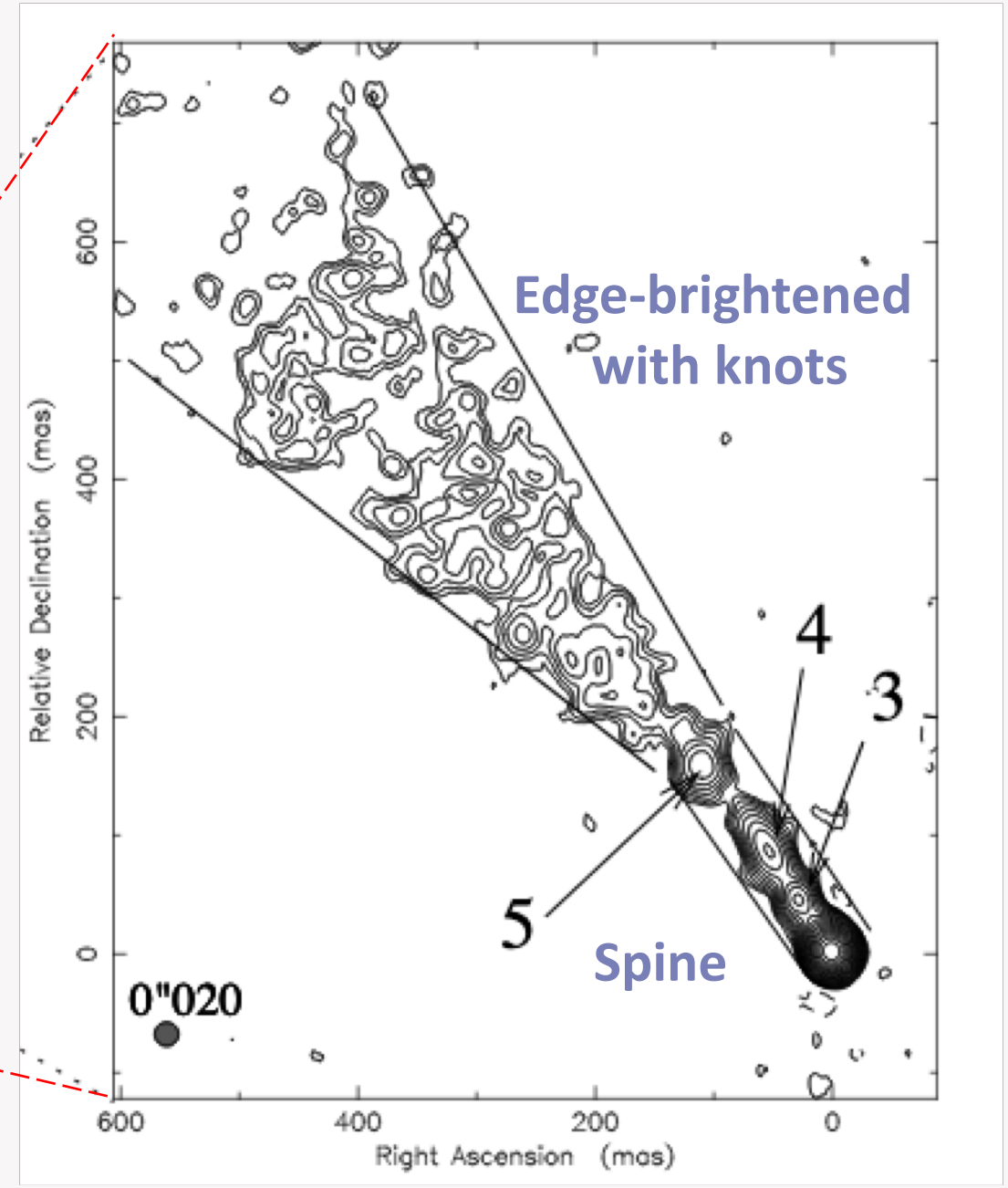


# 3C 264 Radio Features

## Prominent jet (Lara 1999)

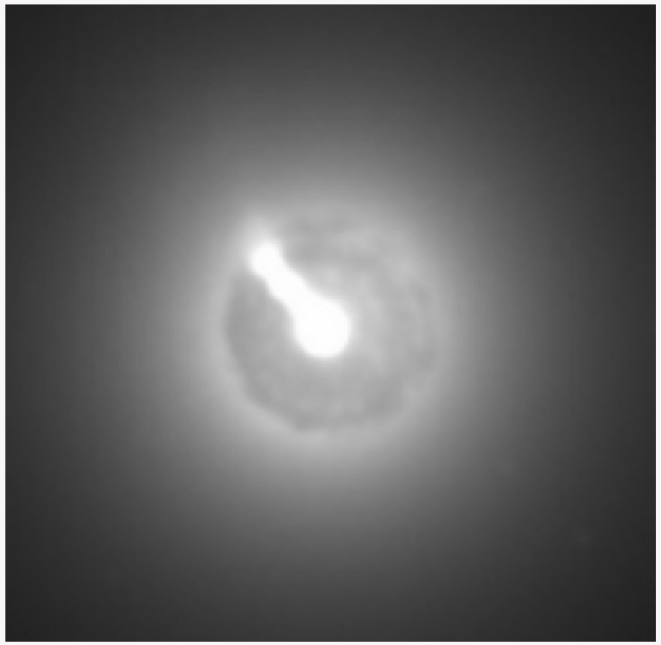
- Spine brightened jet at the Core
- Edge-brightened jet with knots after 10° bend
- Wiggling jet
- Terminal blob 28’’ from the core.



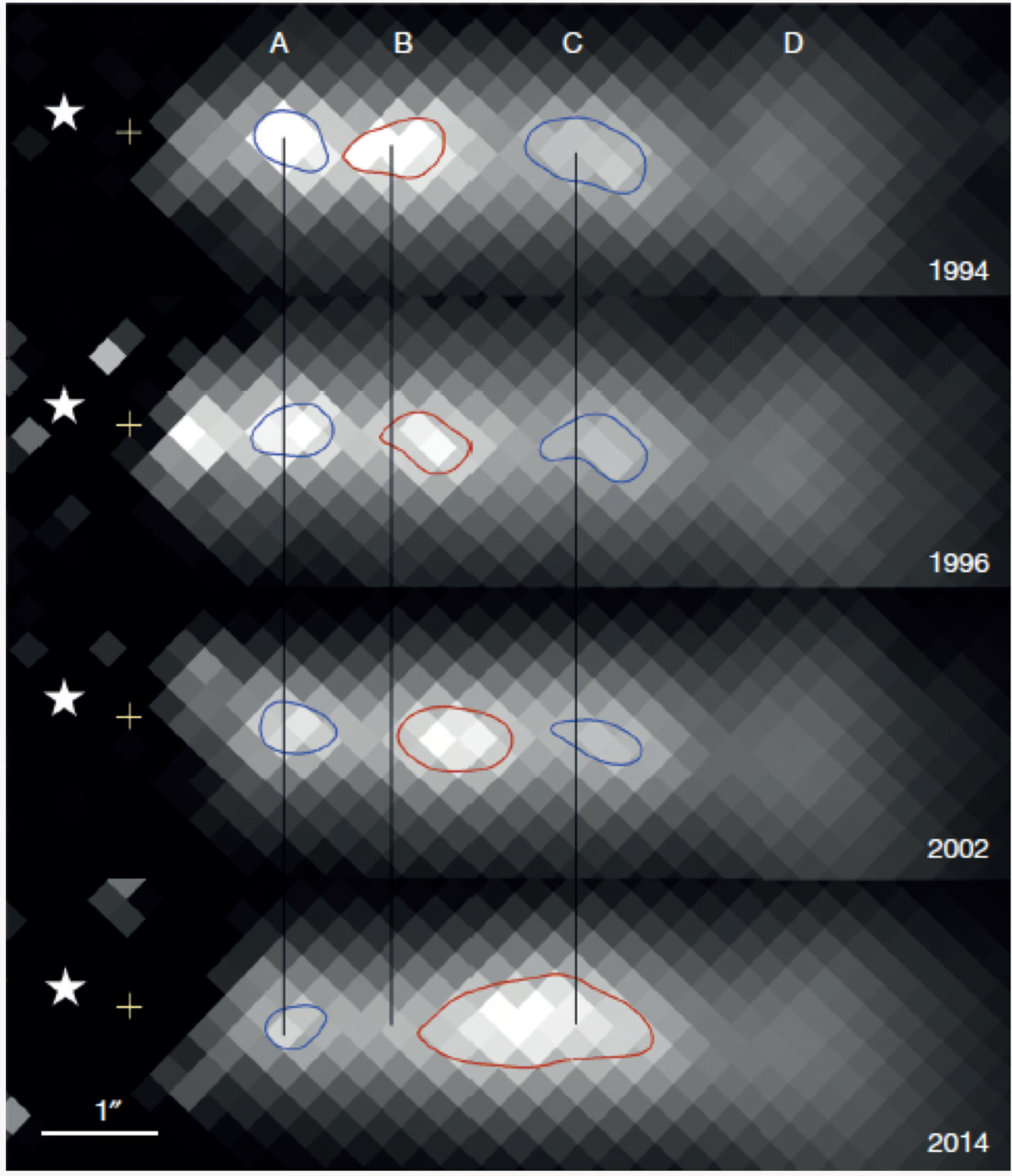



# 3C 264 Optical Features

- HST ACS/WFC
  Meyer (2015)



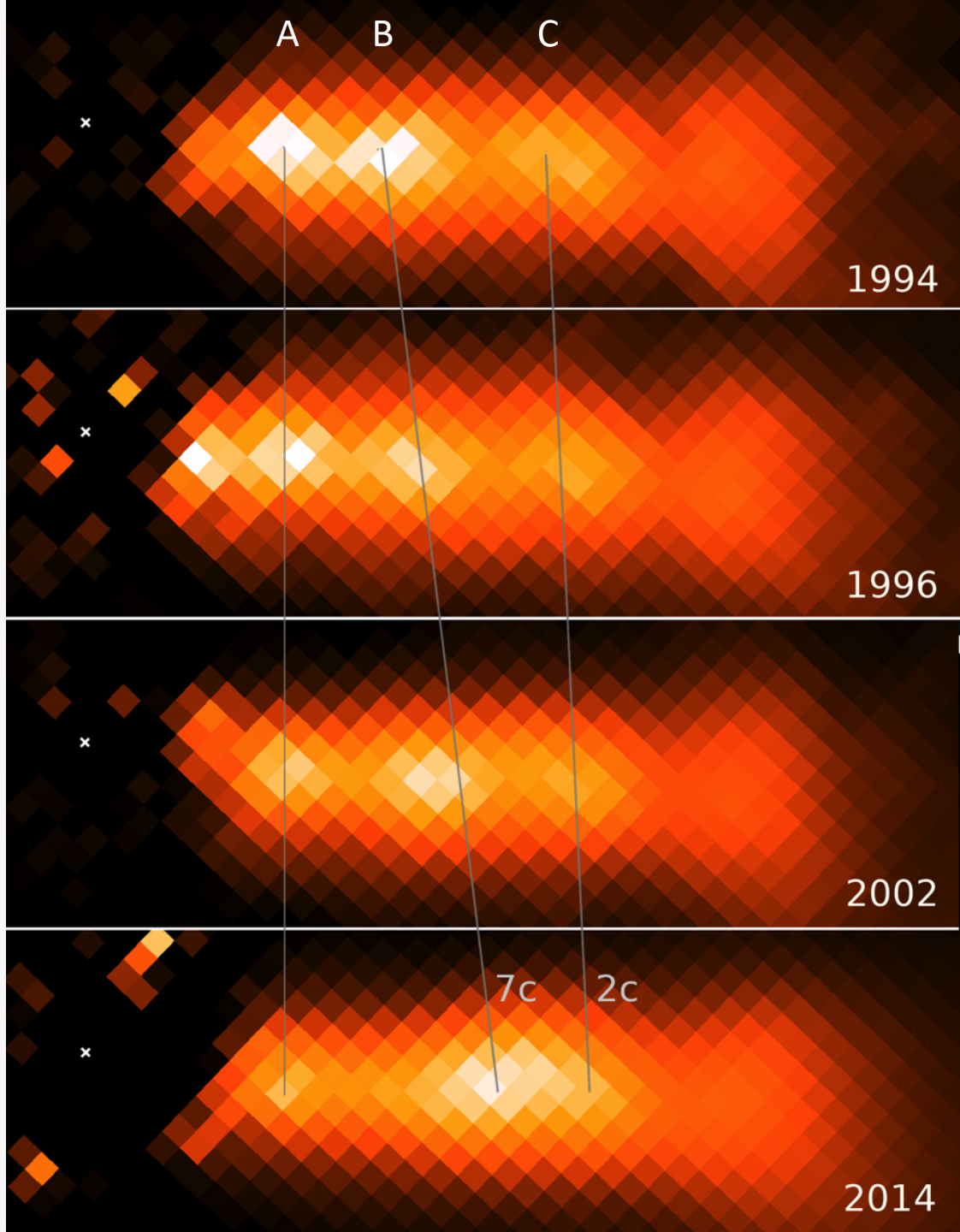
- Knots are synchrotron emission located just past the 10° bend in the jet.
- Bubble or possibly disk
- First ~90° wiggle in the radio jet is at the radius of the bubble.



# 3C 264 Superluminal Knots

- VERITAS observations were motivated by the HST proper motion study (Meyer 2015)
- Knot A is stationary, possibly a reconfinement shock where the jet pressure drops below that of the external environment.
- Knot B has apparent speed of $(7 \pm 0.8)c$
- Colliding with Knot C in final epoch. Significant brightening is observed.
- 30 years for collision to go to completion.
- Assume cooling time << collision time.

- VERITAS:
  - ~9.2 h observation in 2017 yielded no detection
  - ~3 h observation in 2018 yielded $> 3\sigma$ excess.
    + 35 h follow-up.
  - ~ 10.3 h observation in 2019



# 3C 264 VERITAS Discovery of VHE emission

## VERITAS discovery of VHE emission from the FRI radio galaxy 3C 264

ATel #11436; ***Reshmi Mukherjee (Barnard College) for the VERITAS Collaboration***
*on **17 Mar 2018; 00:25 UT***
*Credential Certification: Reshmi Mukherjee (muk@astro.columbia.edu)*

Subjects: Gamma Ray, TeV, VHE, Request for Observations, AGN, Blazar



We report the VERITAS discovery of very-high-energy emission (VHE; >100 GeV) from the FRI radio galaxy 3C 264, also known as NGC 3862. Nearly 12 hours of quality selected data, collected by VERITAS between 09 February 2018 and 16 March 2018 (UTC), were analyzed. Preliminary results yield an excess of 60 gamma-ray events above background at the position of the source, corresponding to a statistical significance of 5.4 standard deviations. Our preliminary flux estimate (E>300 GeV) is (1.3 ± 0.2)e-12 cm^-2 s^-1, or approximately 1% of the Crab Nebula flux above the same threshold. The Fermi-LAT 3FHL catalog (Ackermann et al. 2017 ApJS 232, 18) lists a photon index of 1.65 ± 0.33 for 3C 264 which, when extrapolated to the VHE band, is consistent with the VERITAS detection. At a redshift of 0.0217, 3C 264 is a

**Follow-Up Observations Scheduled:**

VLA (DDT - April 2018)
HST (GO, PI: Meyer – Mar 2018, Jan 2019)
VLBI (MOJAVE + DDT – Mar 2018)
Chandra (DDT– April 2018)
Swift & Ground-based Optical

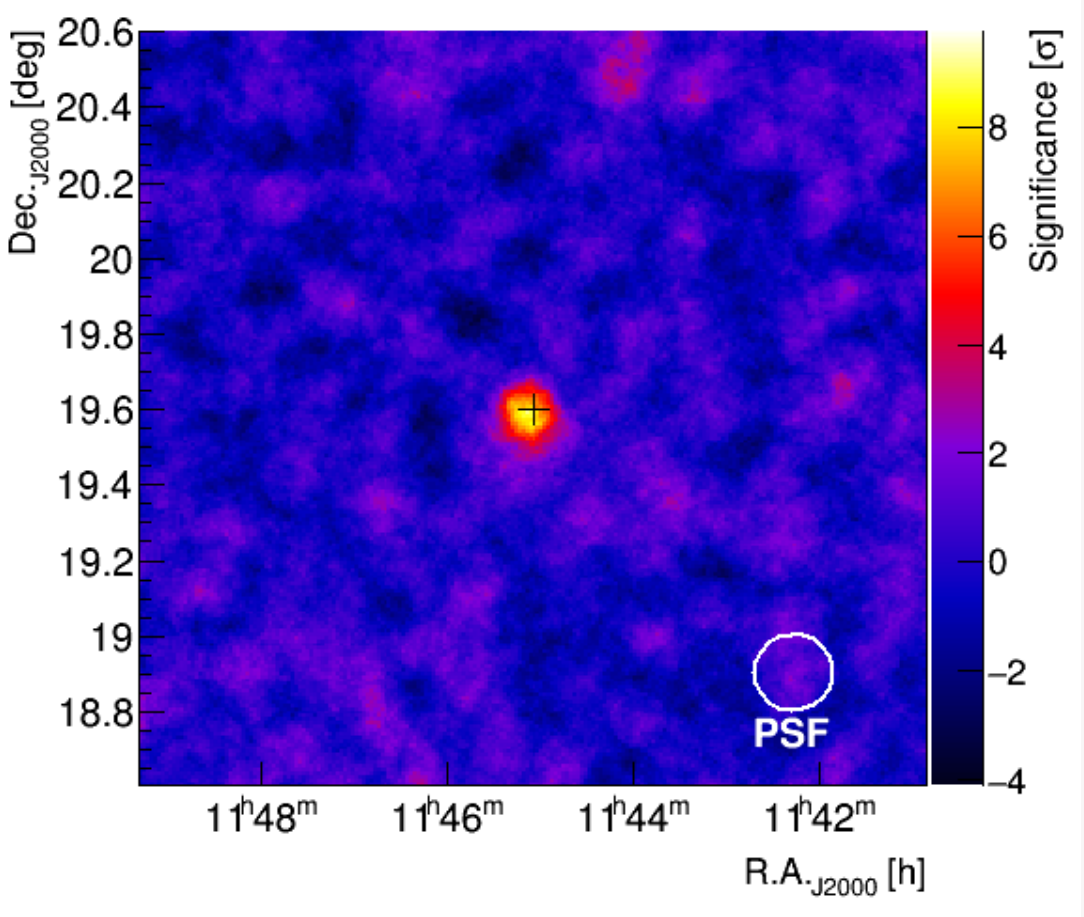
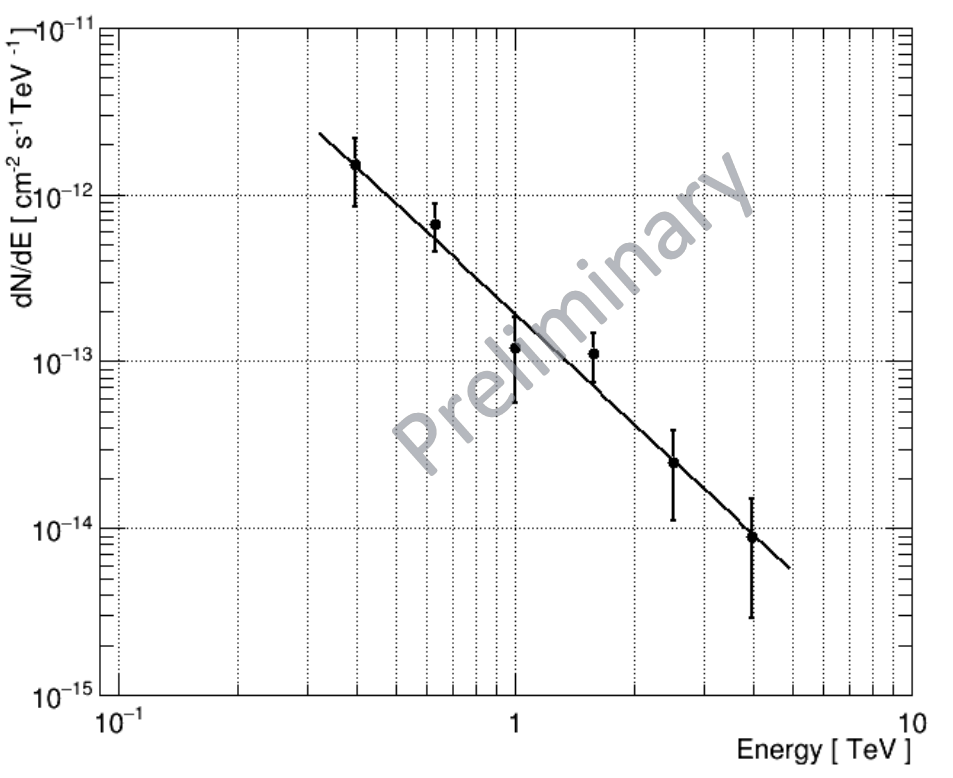


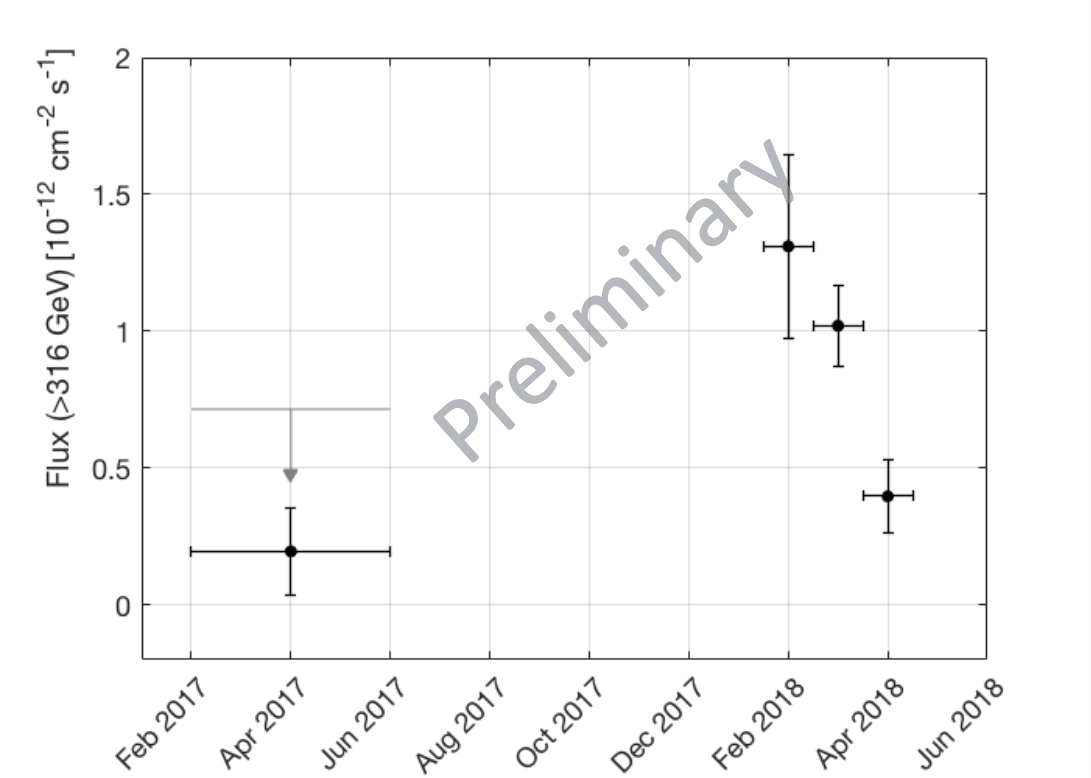

Image-Template Analysis (ITM): 7.8$\sigma$ detection
ITM PSF is 20% smaller than the standard Hillas PSF resulting in a 30% increase in sensitivity.

# 3C 264 VERITAS Preliminary Results

## VERITAS Spectrum




## VERITAS Light Curve




Hard spectrum in 2018

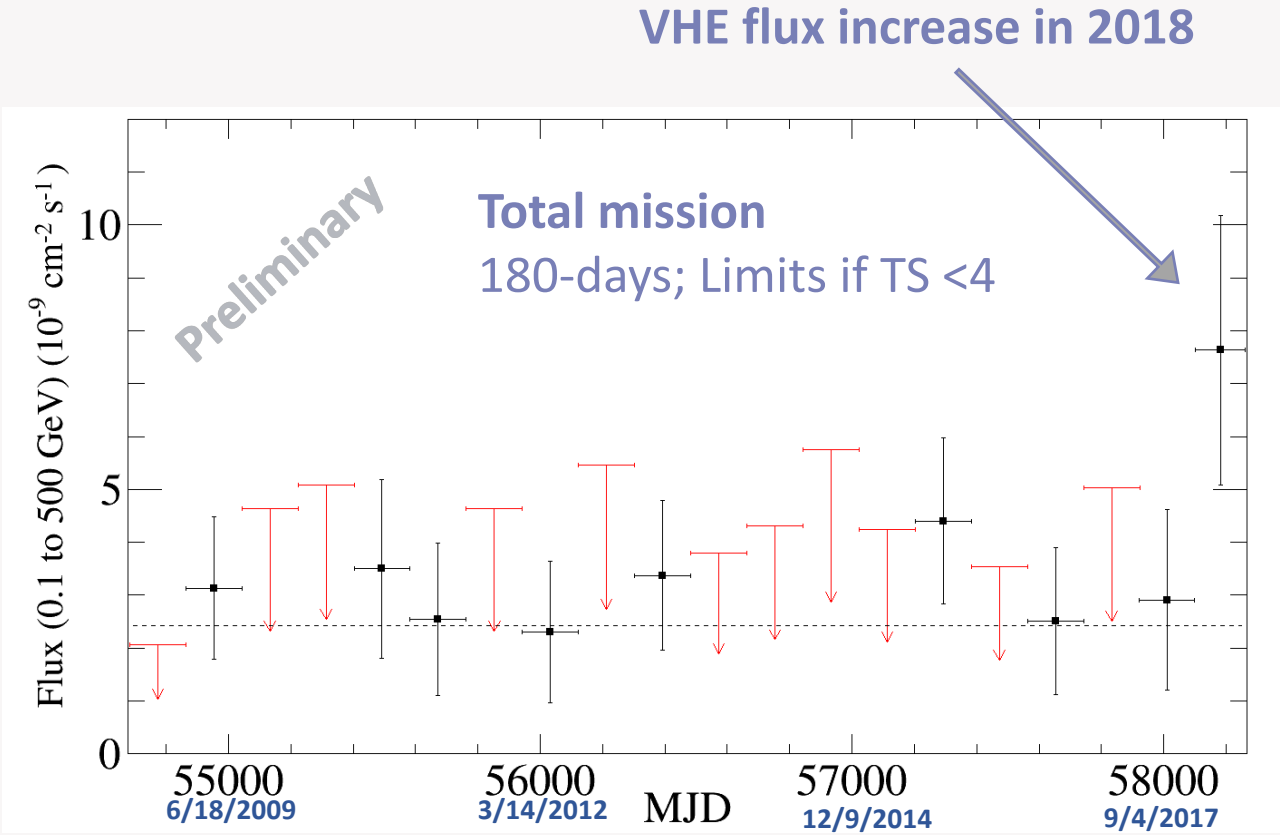
$\Gamma = 2.20 \pm 0.27$ at ~0.5% Crab

Elevated flux in Feb/March 2018

# 3C 264 MWL Data, Gamma-ray

**Fermi LAT**

- Brighter in early 2018 (3x, ~2σ)
  Fermi solar panel issues resulted in lower statistics in 2018.
  - Safe mode began on March 16, 2018
  - Normal operations resumed on April 8, 2018
- Hard spectrum (10-yr):
  $\Gamma = 2.0 \pm 0.2$
  $F \sim 2.4 \times 10^{-9} / cm^2 s$ from 0.1 to 500 GeV




Tyrel Johnson (NRL), Fermi-LAT collaboration

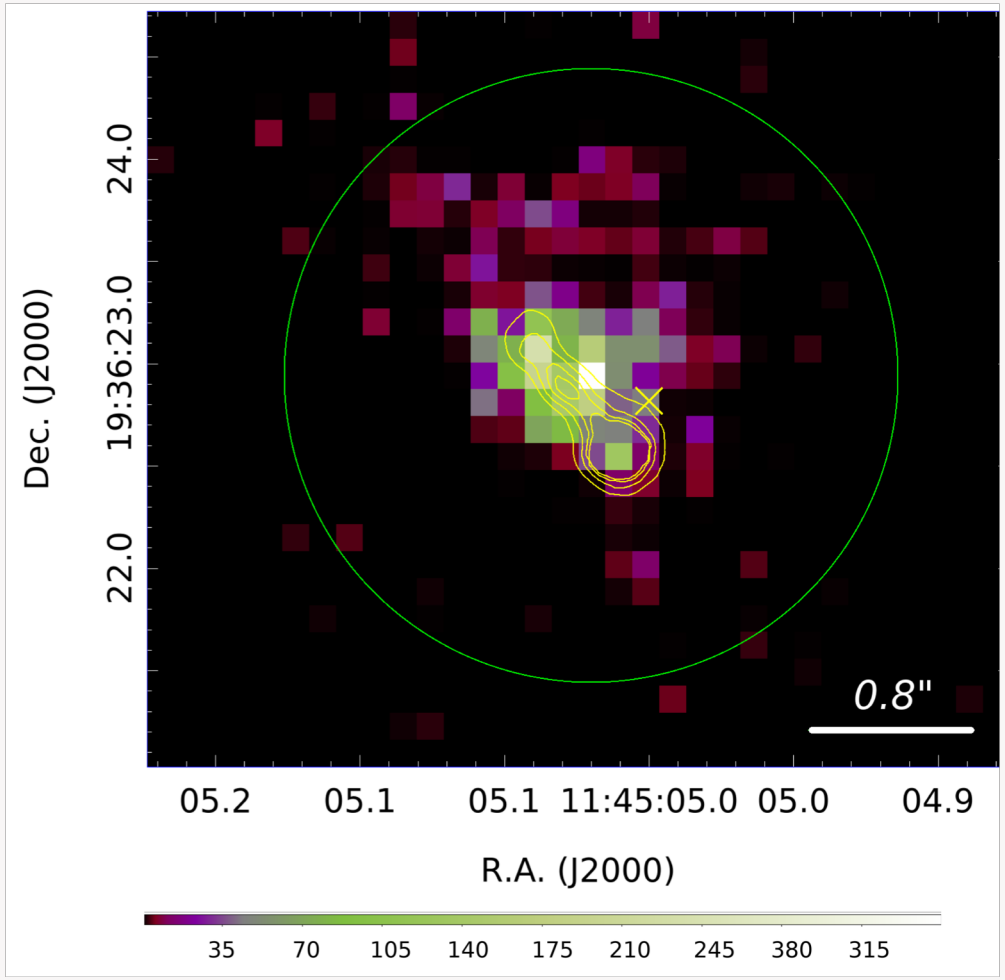
# 3C 264 MWL Data, X-ray

**Chandra DDT (15 ks, 30'x30', April 4, 2018)**

- Extended emission detected.
- Core astrometry difficult as absolute pointing accuracy of both HST and Chandra ~0.8". Reasonable agreement.
- Factor 2 brightening compared to Perlman 2010 (2004 ACIS data)

**Swift XRT**

- Steady emission from 17-24 Mar 2018 and 8-20 Apr 2018.



# 3C 264 MWL Data, Optical

## Hubble Space Telescope

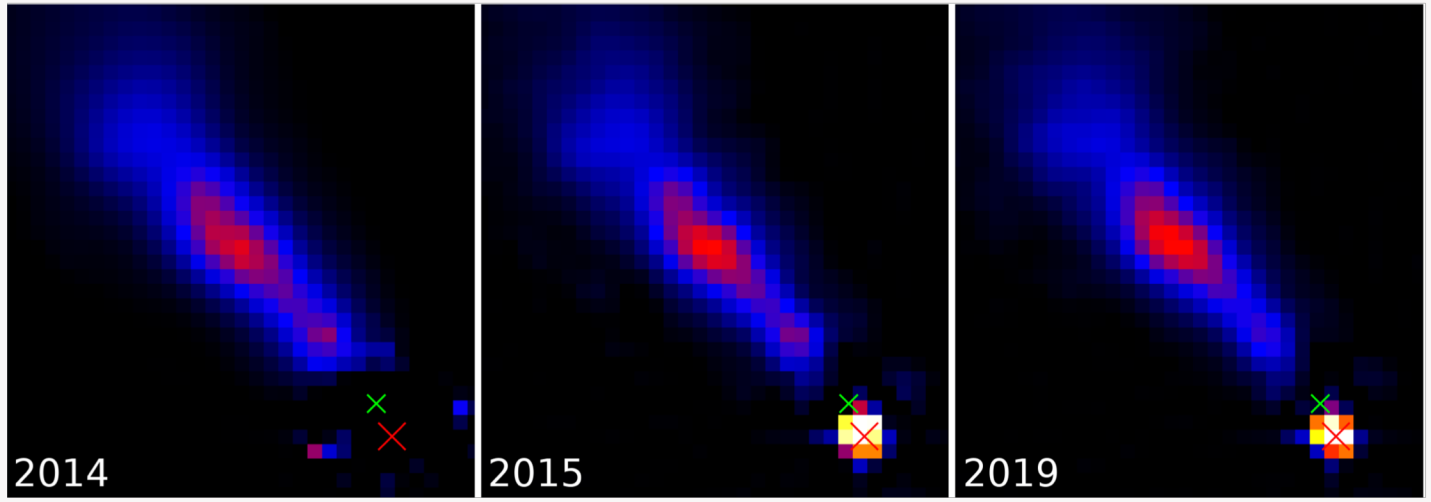
### Imaging

- WFC3/UVIS F814W from 2015 & 2019 compared to 2014 ACS/WFC F606W
- Light from galaxy & inner disk/bubble is subtracted.
- Linear brightening
- Change in shape expected shift in B/C knot location.

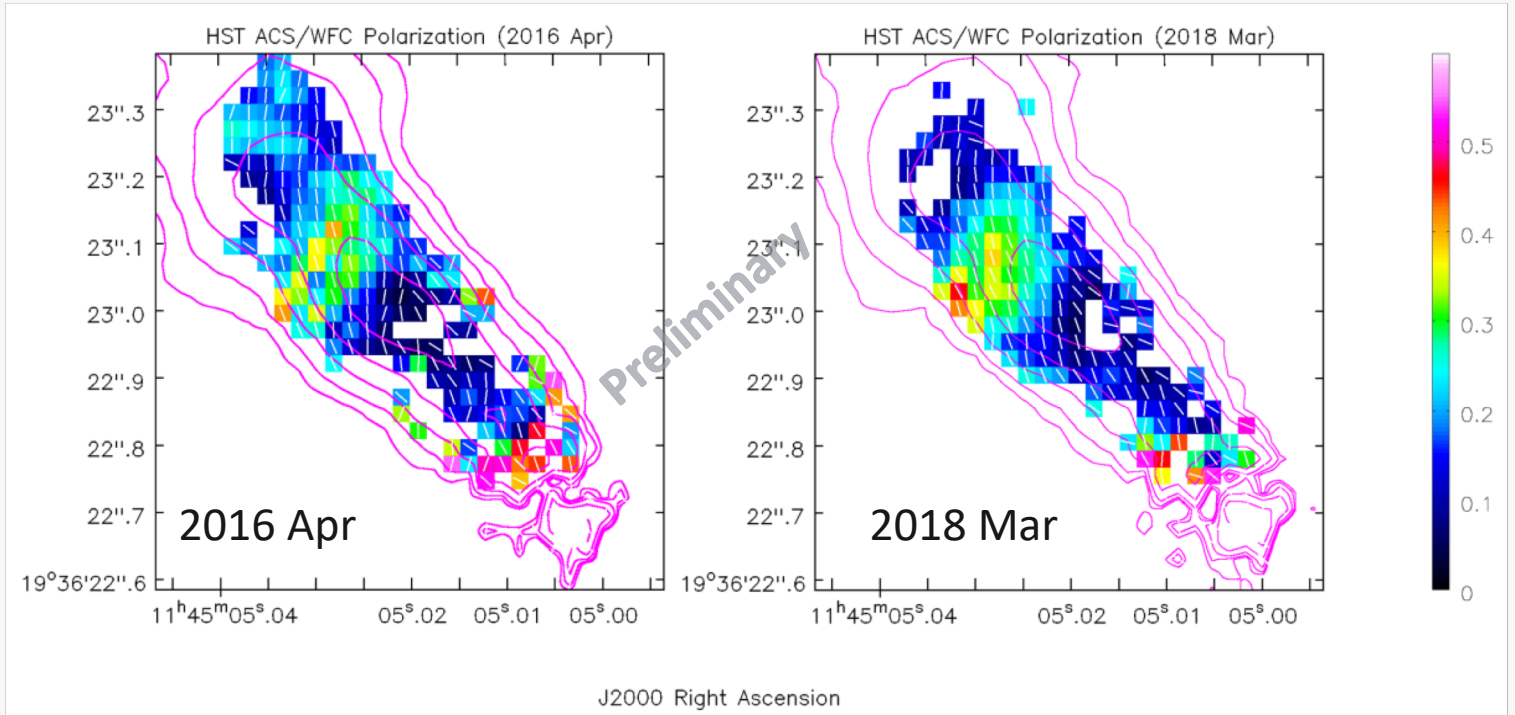
### ACS/WFC Polarization

- Polarization structure consistent between 2016 and 2018.
- Higher polarization downstream of knot B/C collision zone in 2018.

**HST Images**




**HST Polarization**



# 3C 264 MWL Data, Radio

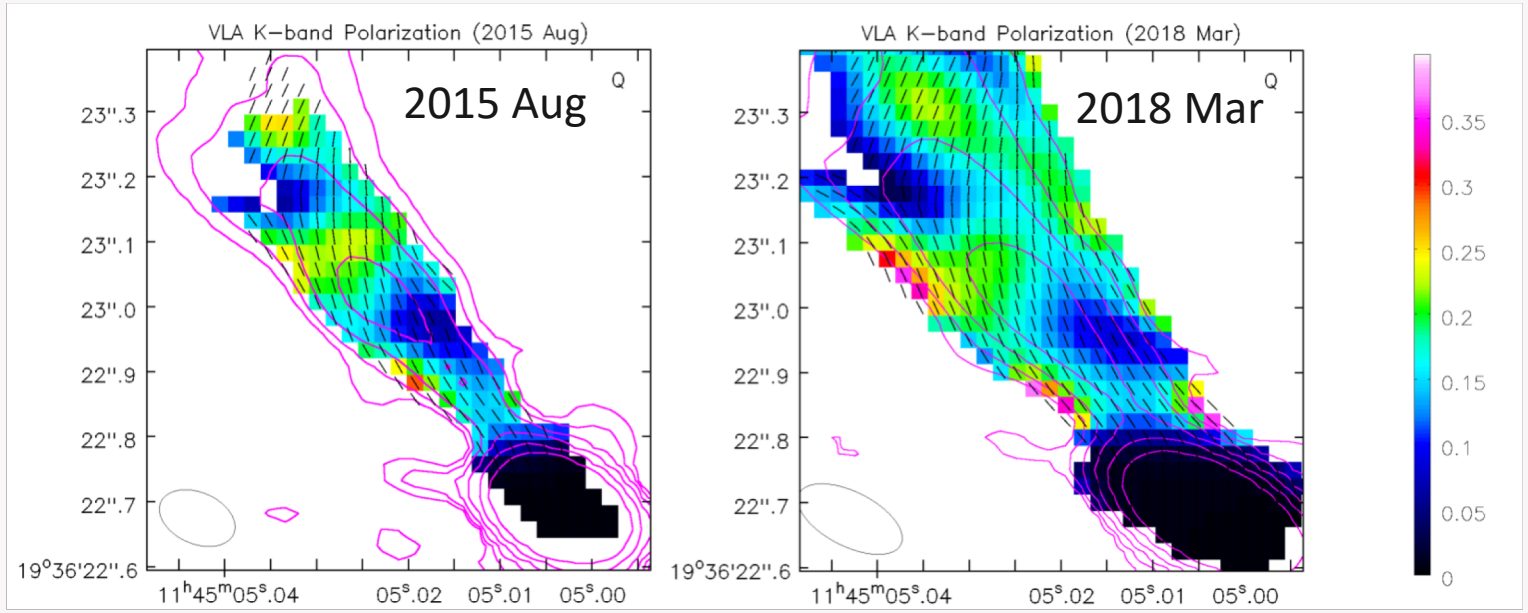
## VLA DDT (Jet with Knots)

- Polarization structure consistent between 2015 and 2018
- No evidence in polarization for a strong shock.

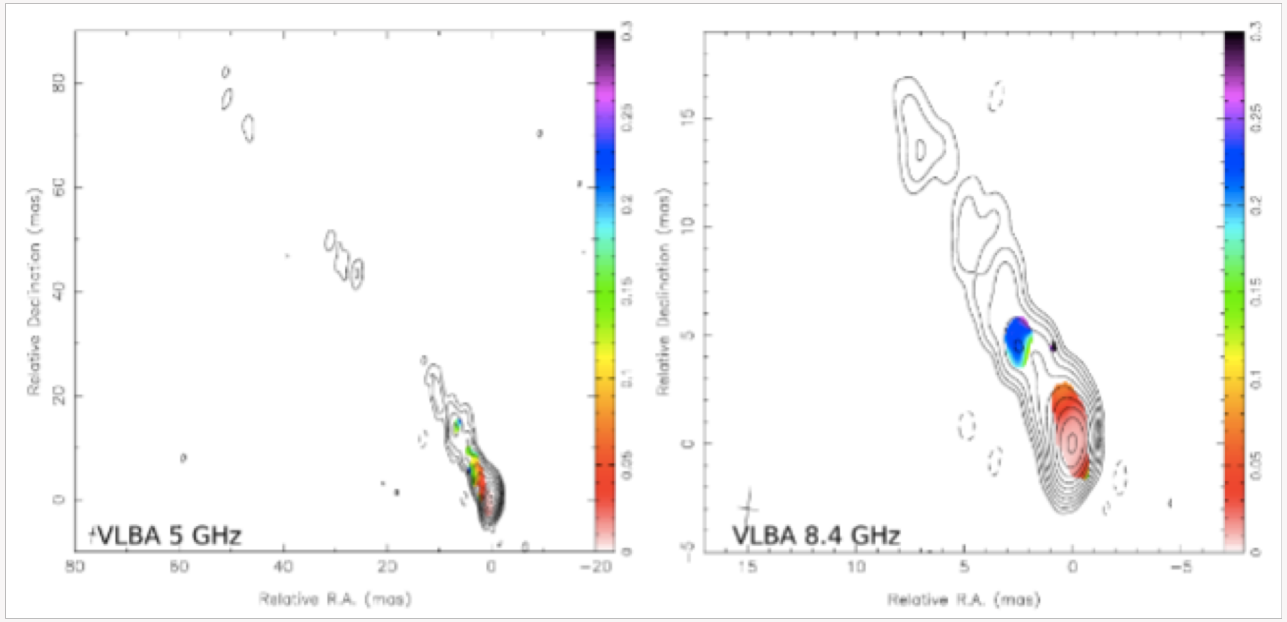
## VLBI DDT (Jet at Core)

- March 2018
- Core becomes optically thin 4 mas (13 pc) from the core.
- At 11 mas (36 pc) there is an inverted spectrum.
- High fractional linear polarization may be indicative of a transverse shock that is accelerating e-.

### VLA Polarization Maps




### VLBI (9 participating telescopes)



# Is 3C 264 an analog to M87?

- Classes of VHE Radio galaxies have not been defined with so few candidates, but M87 and. 3C 264 have several features in common.
    1. FRI with optical jet and superluminal knots.
    2. First optical knot is ~100 pc from the core and stationary.
    3. Knot speeds slow as they move down the jet.
    4. Similar viewing angle.
    5. Blazar-like (BL-Lac, HBL) emission from the core.
    6. M87 has shown short intense flares, 3C 264 was discovered in an elevated state.

| | BH mass | distance | stationary knot proj. dist. from core | Max optical knot App. Speed | Inclination |
|---|---|---|---|---|---|
| M87 | $\sim 4\times10^{9} M_{\odot}$ | 16.4 Mpc | ~100 pc | *4.5c* | $< 20°$, Likely ~9.5° |
| 3C 264 | $\sim 5\times10^{8} M_{\odot}$ | 91 Mpc | ~ 125 pc | *7c* | $< 20°$, Likely ~8° |

- IC 310 also exhibits blazar-like emission and is sometimes classified as a BL-Lac.
- In contrast Cen A and NGC 1275 are misaligned two-sided radio jets without superluminal motion.

# Summary

- 3C 264 has a complex jet morphology, kinematics, and SED.
- The jet inclination is likely ~8° which allows for moderate blazar-like beaming of the core.
- The elevated Gamma-ray emission in 2018 is likely produced in the Core.
- Provides a new observational angle to study the physics of BL-Lacs.
- 3C 264 may be a more distant analog to M87.

- The interaction of knots B and C has so far only enhanced the optical and x-ray emission.
- No significant brightening in radio, or gamma-rays.
- No significant change in polarization in radio or optical.