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# Highlights from the VERITAS Radio Galaxy Observation Program



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University of Minnesota

31<sup>st</sup> Rencontres de Blois  
June 2-7, 2019

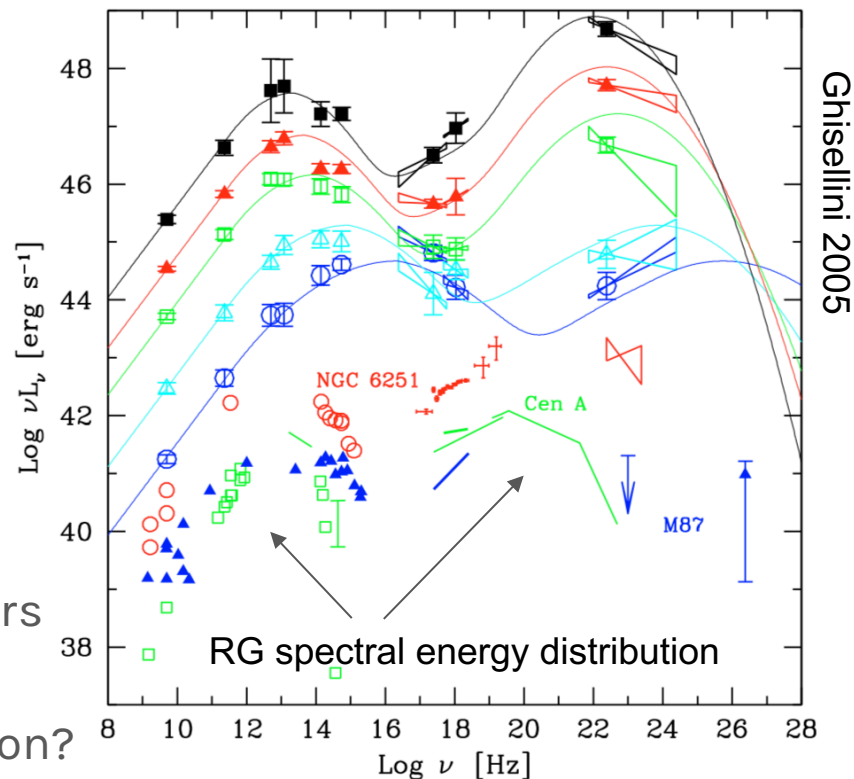
# Radio Galaxies as “mis-aligned” AGN



Blazars are majority class of gamma-ray loud extra-galactic sources



- Radio galaxies “parent population” of blazars
- Doppler factor drops with viewing angle
- Low power SEDs explained by blazar emission?



**OR... new angle on jet physics?**

# Current VHE catalog of Radio Galaxies

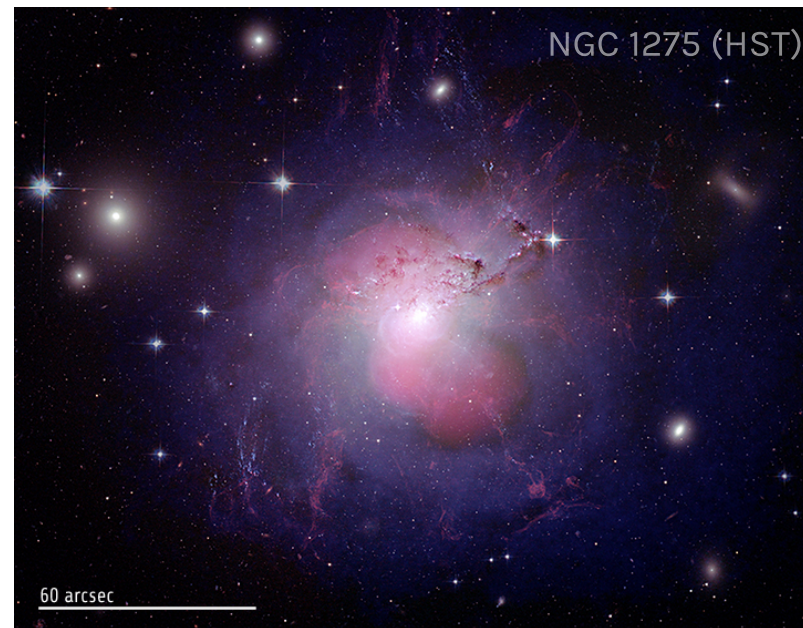


Name	Cross-ID	Type	Distance	BH mass [10 <sup>8</sup> Msun]
Cen A	NGC 5128	FR 1	3.7 Mpc	(0.5-1)
M87	NGC 4486, Virgo A	FR 1	16 Mpc	(20-60)
NGC 1275	3C84, Perseus A	FR 1	70 Mpc	3-4
IC 310	B0313+411	FR I/BL Lac	80 Mpc	3 [0.3?]
3C 264	NGC 3862	FR I	95 Mpc	4-5
PKS 0625-35	OH 342	FR I/BL Lac	220 Mpc	~10

Rieger & Levinson 2018

**VERITAS detected** ←

**Presentation focus on NGC 1275 & 3C 264**



# NGC 1275

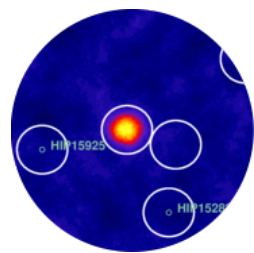
Observations on NGC 1275 and neighboring IC 310 part of regular VERITAS monitoring program.

- Paper in prep on data since Jan 2009 including 3 flares
- Good MWL data around flare periods

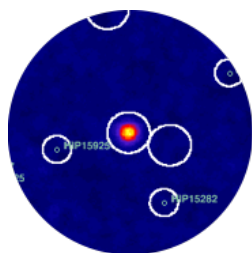
Oct 30, 2016

Jan 2, 2017

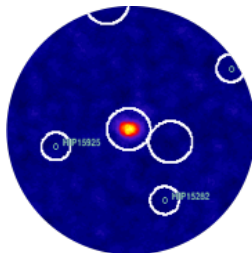
Jan 3, 2017



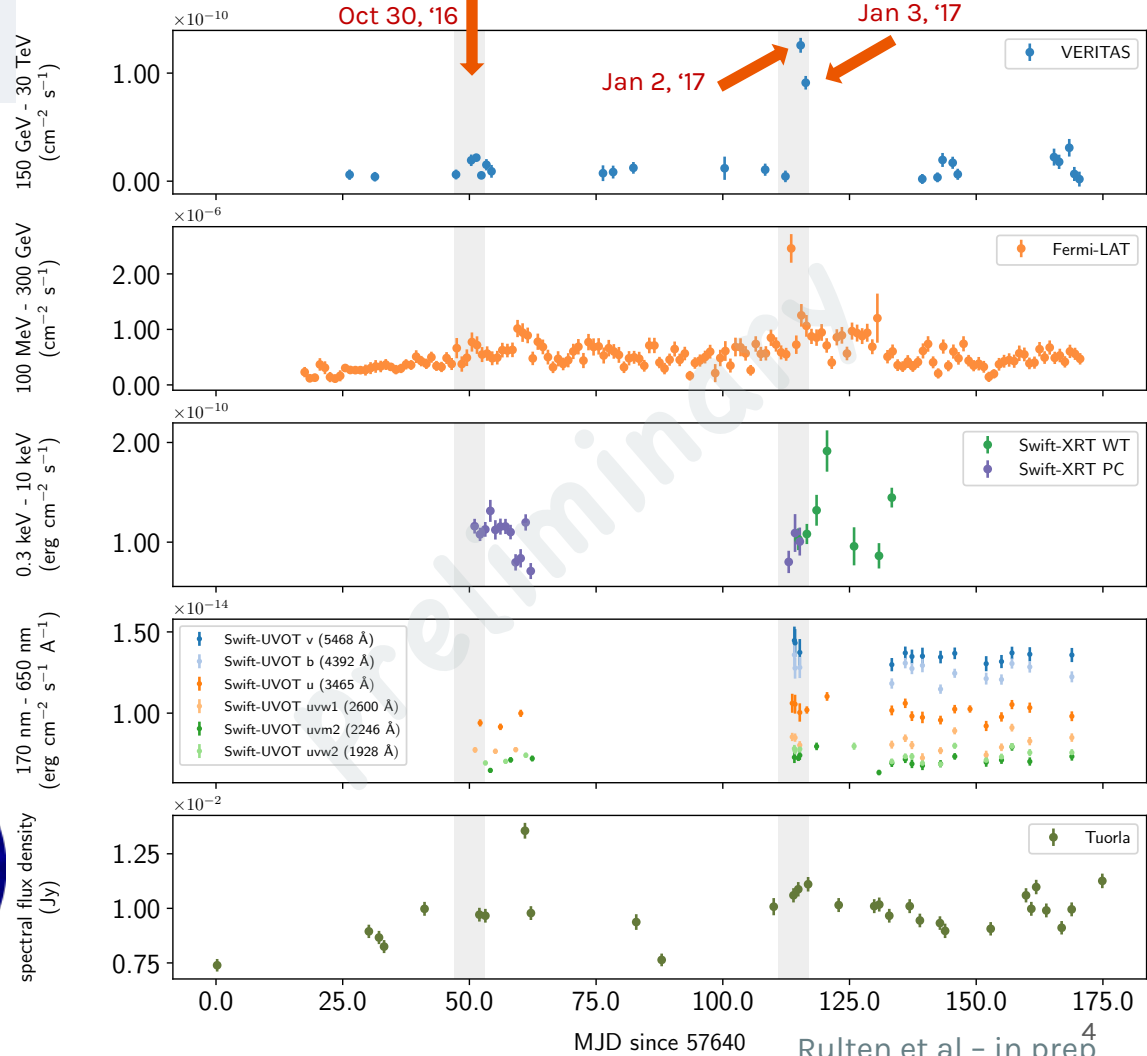
~15% Crab



~65% Crab



~60% Crab

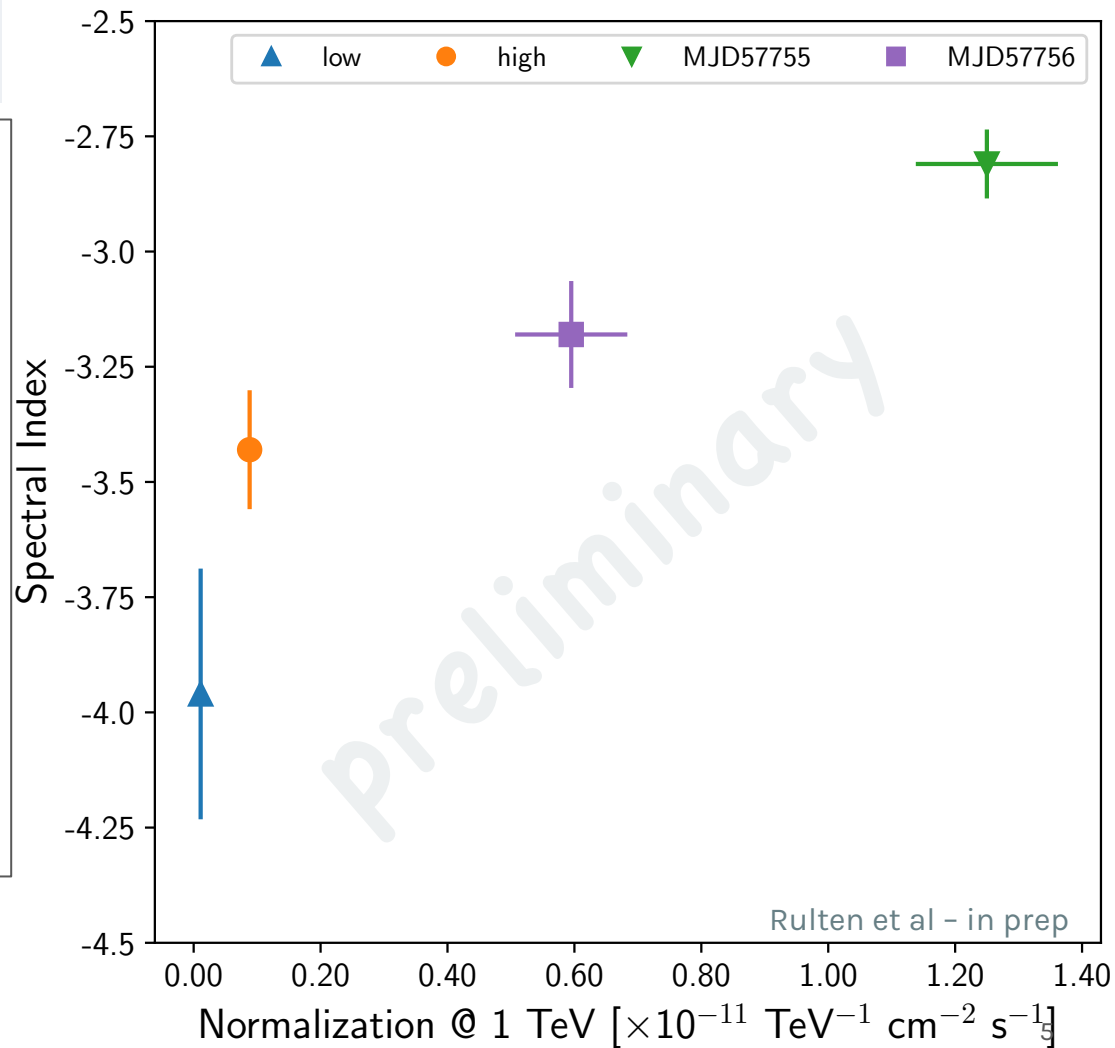


# NGC 1275

VERITAS analysis separated into four states based on 8 year lightcurve:

- Low state:  $< 3\sigma$  mean flux
- High:  $> 3\sigma$  mean flux (without below flares)
- Jan 2, 2017 flare
- Jan 3, 2017 flare decline
- **Observed events  $> \text{TeV}$**
- Low state very soft
- Trend to harder when brighter
- Joint Log P fit between Fermi-LAT and VERITAS spectra

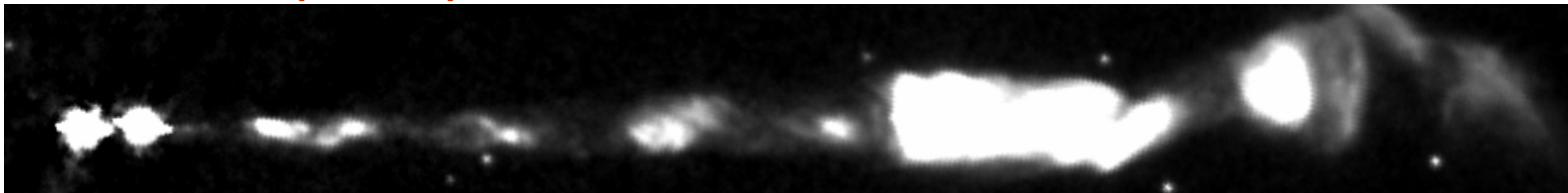
**Some evidence for softer-when-brighter evolution during Jan 2, 2017 flare night.**



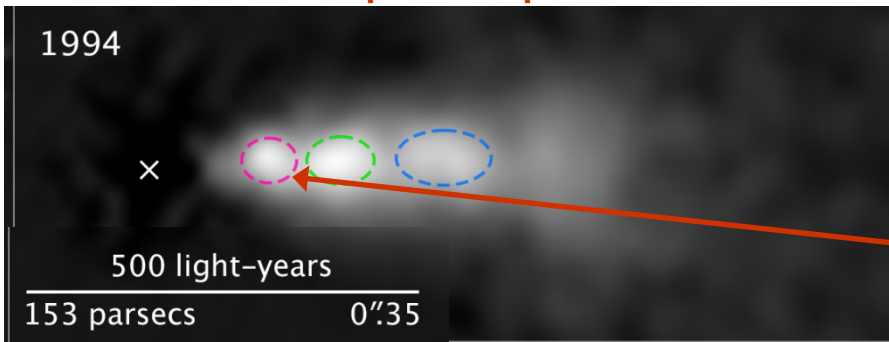
# 3C 264 - Analog to M87



M87 -  $d=22$  Mpc,  $106$  pc/''



3C264 -  $d=91$  Mpc,  $442$  pc/''



- More distant ( $\sim 5x$ ) "M87 analog"
- FR-I radio galaxy,  $z = 0.0216$

**Stationary shock/feature**

← M87 at equivalent scale to 3C 264

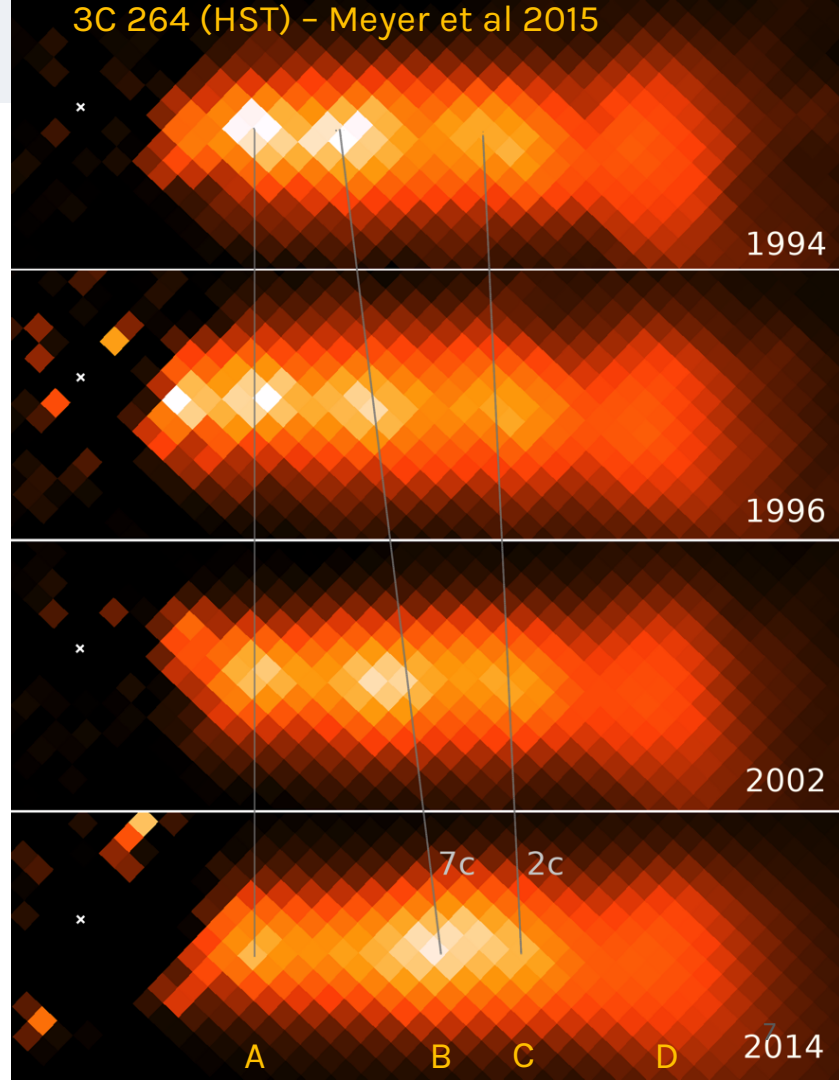
# 3C 264 – VERITAS motivation

## HST Proper Motion Study (Meyer 2015)

- Jet is 0.4 kpc in length
- Rapidly evolving knot-structure
  - Knot B has apparent speed of  $7 \pm 0.8 c$  (highest ever measured at these distances)
  - Colliding with Knot C in final epoch
  - Significant Brightening Observed

## Included in 2017 VERITAS RG Targets

- Clearest M87 analog
- MeV-GeV source: 3FGL, 2FHL & 3FHL
- $\Gamma_{3FHL} \sim 1.65 \Rightarrow F(>200 \text{ GeV}) \sim 1.6\% \text{ Crab}$
- VERITAS  $\sim 10$  h observation in 2017
- $\sim 2\sigma$  excess: 2018 follow-up (10 h + 15 h)



# 3C 264 VERITAS Discovery



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

ATel #11436; **Reshmi Mukherjee (Barnard College) for the VERITAS Collaboration**

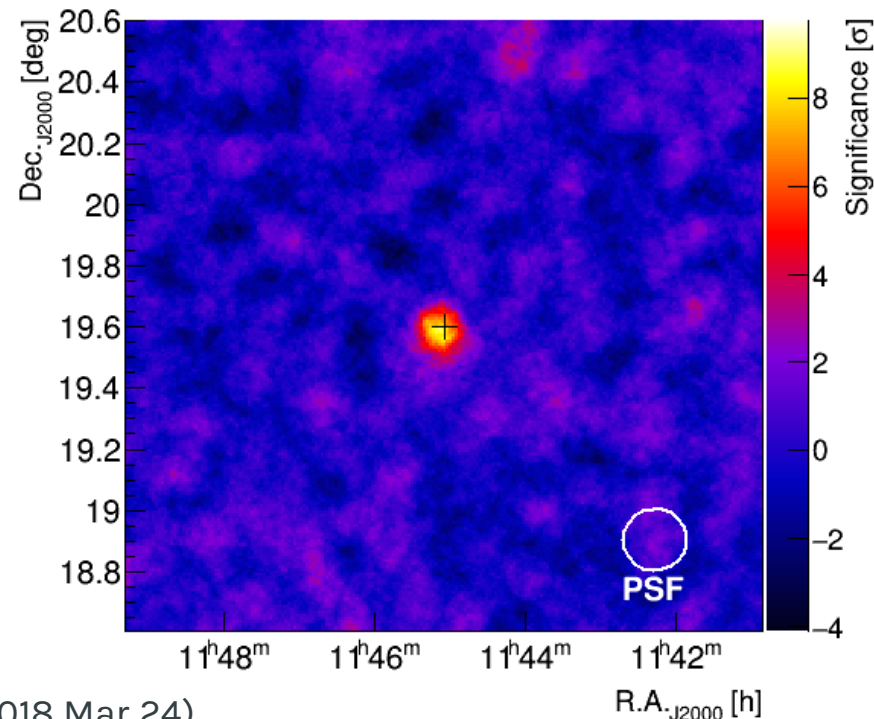
on **17 Mar 2018; 00:25 UT**

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  $(1.3 \pm 0.2) \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1}$ , 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  $1.65 \pm 0.33$  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 (DD - 2018 April 02)

HST (GO, PI: Meyer - 2018 Mar 24)

VLBI (MOJAVE + DD - 2018 Mar 30)

Chandra (DD - 2018 April 04)

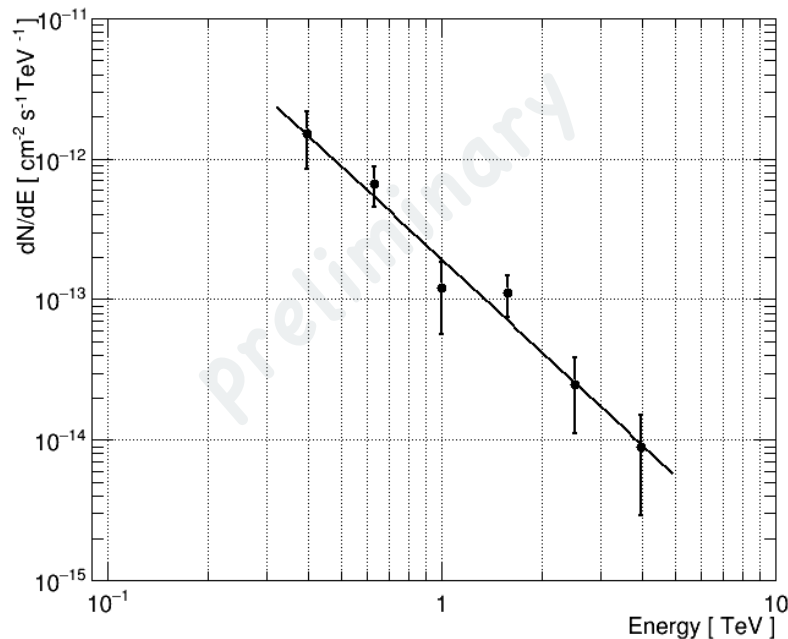
Swift & Ground-based Optical



# 3C 264 - VERITAS Preliminary results



## VERITAS Energy Spectrum

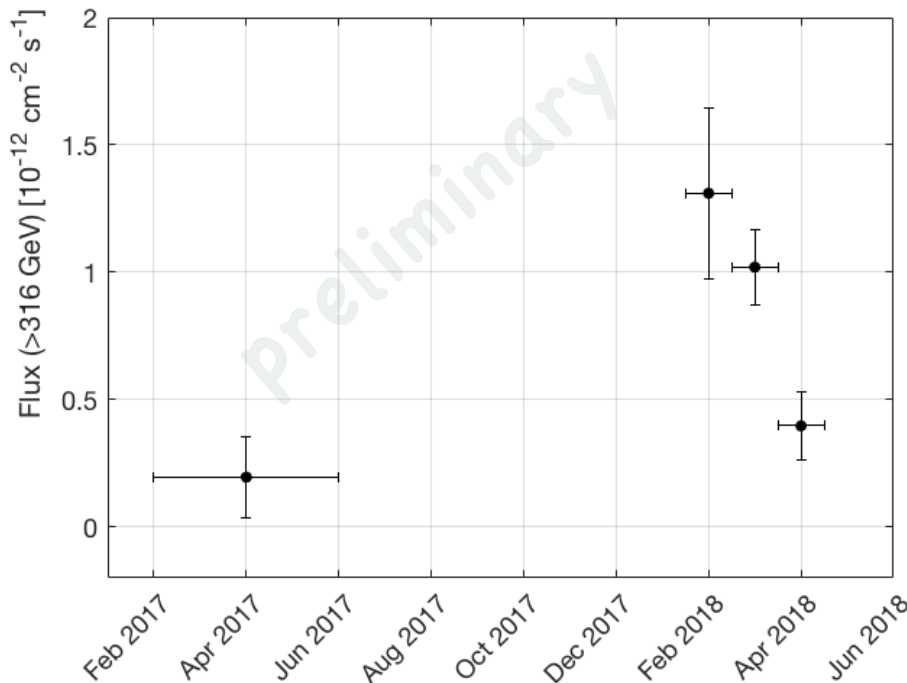


**2018: 37.9 h live time, 8.6  $\sigma$  detection**

**Hard spectrum**

- $\Gamma = 2.20 \pm 0.27$  at  $\sim 0.5\%$  Crab

## VERITAS Light Curve



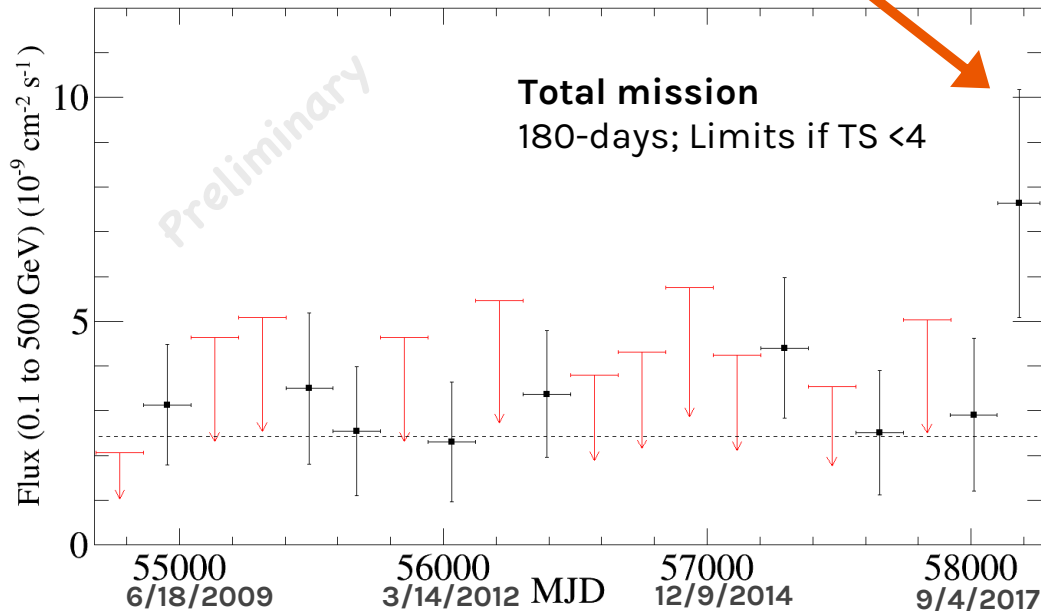
# 3C 264 - MWL Data



## Fermi LAT Data

- Brighter in early 2018 (3x,  $\sim 2\sigma$ )
  - Overall lightcurve consistent with constant
- Hard spectrum (10-yr):  $\Gamma = 1.9 \pm 0.1$ 
  - $F(0.1 - 500 \text{ GeV}) \sim 2.4 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1}$
  - Consistent with FL8Y, 3FGL (flux a bit lower)
- Fermi solar panel issues:
  - Safe mode began: March 16, 2018
  - Nominal operations resumed: April 8, 2018

Time period corresponding to VHE flux increase



Tyrel Johnson (NRL), Fermi-LAT collaboration

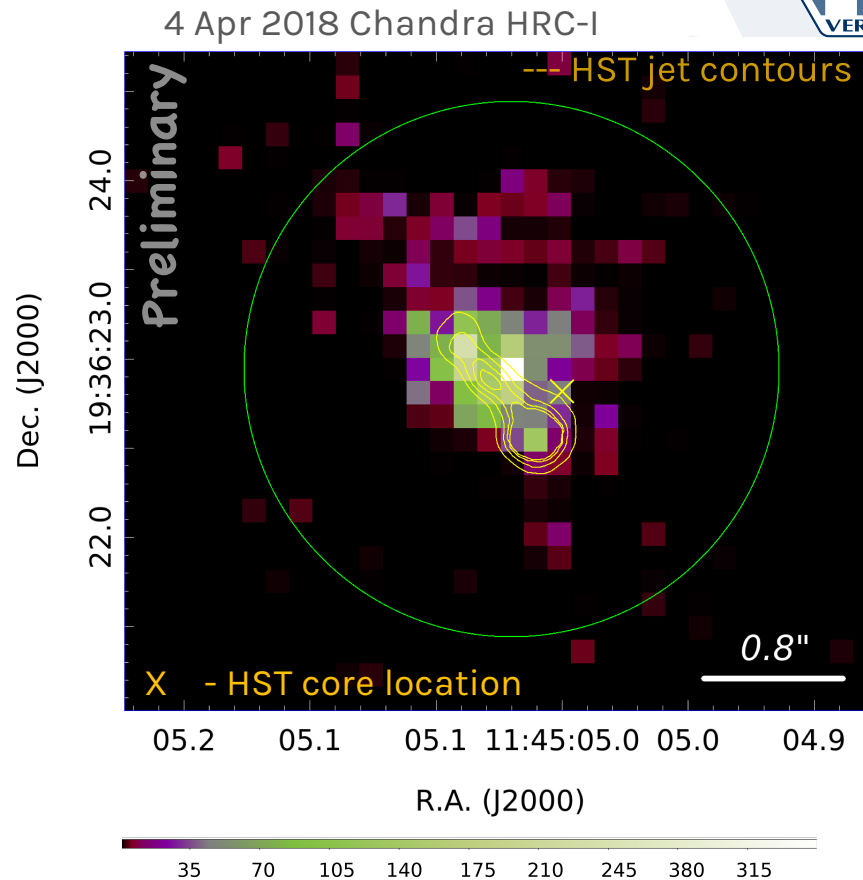
- Full SED in progress - preliminary broad synchrotron peak

# 3C 264 - MWL Data



## X-ray data

- 15 ks Chandra DDT (30'x30' FoV)
  - ~2000 cts
  - Factor 2 brightening compared to Perlman 2010 (2004 ACIS data)
  - Extended emission detected
  - Core astrometry difficult as absolute pointing accuracy of both HST and Chandra ~0.8"
    - HST jet contours on "reasonable" core location agrees with Chandra extended emission
- Swift XRT
  - Steady emission seen over 17-24 Mar 2018; and 8-20 Apr 2018



# 3C 264 - MWL Data



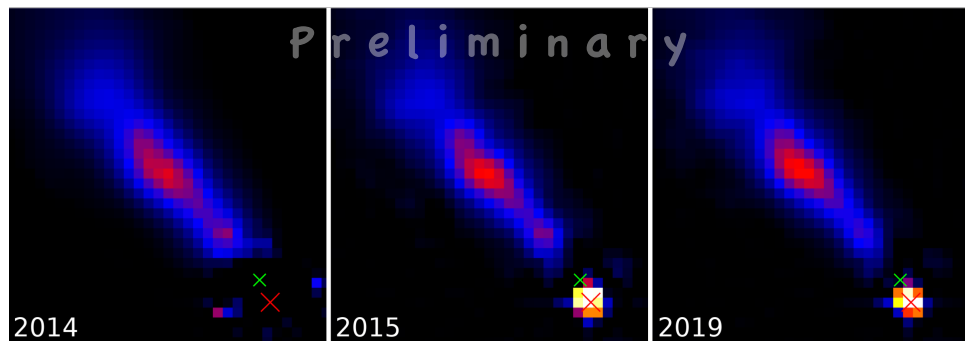
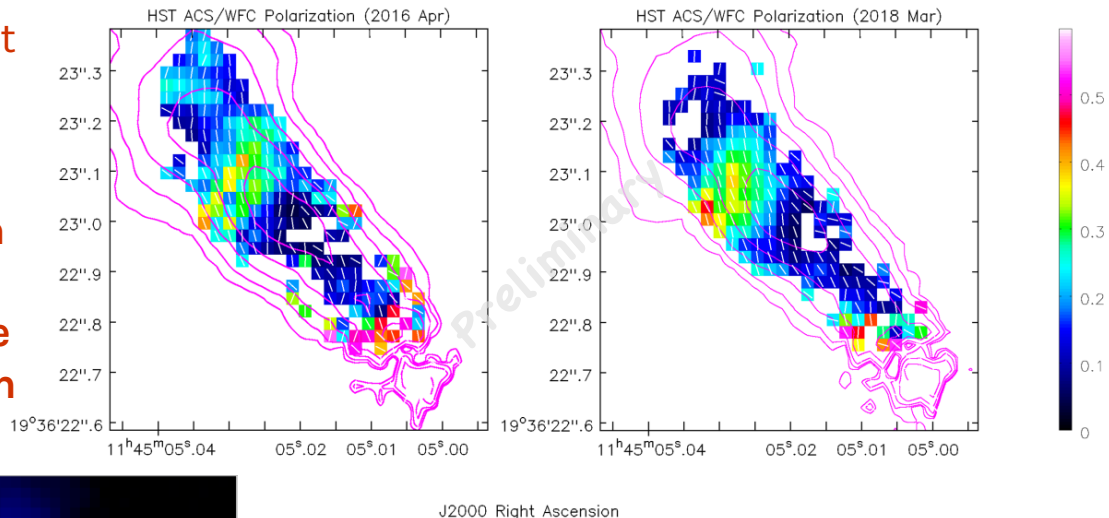
## HST

- ACS/WFC Polarization
  - Polarization structure consistent between 2016 and 2018
- Imaging
  - WFC3/UVIS F814W from 2019 Jan and 2015 compared to 2014 ACS/WFC F606W show **very little change except expected shift in B/C knot location**

## Optical Polarization

2016 Apr HST

2018 Mar HST



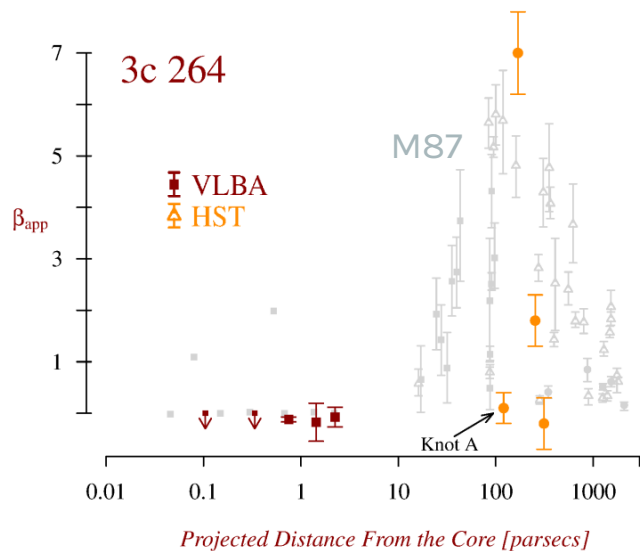
← HST imaging: light from galaxy & inner dust disk subtracted

# 3C 264 - MWL Data

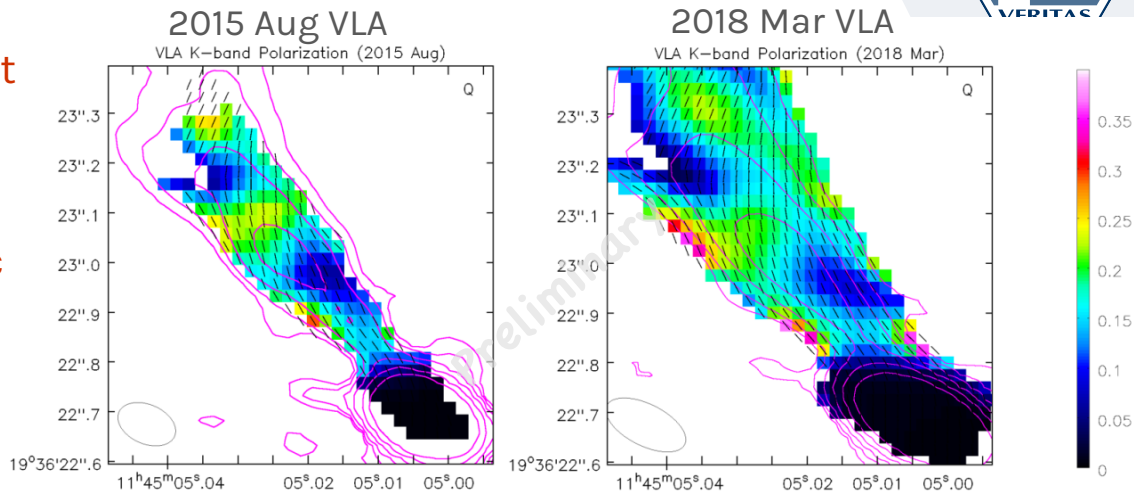


## Radio

- VLA Polarization
  - Polarization structure consistent between 2016 and 2018
- VLBI kinematics
  - Knot A projected distance 100 pc from core similar to M87



## Radio Polarization



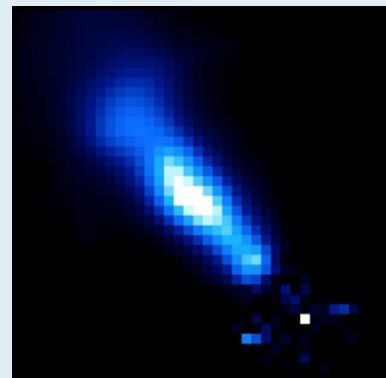
State of system at lower bands during VHE “flare” shows little change from previous epochs.

- Little evidence in polarization for strong shock
- x2 brightening in Chandra X-ray at time of VHE
- VHE emission location unclear

# Summary



- VERITAS has an active Radio Galaxy observation program with strong MWL participation
  - Source monitoring component for all (northern) RGs
    - long-term program on NGC 1275
    - special campaigns on e.g. M87
  - Discovery component
    - Led to discovery of 3C 264
- Goal to understand RGs as mis-aligned “blazars” or a new view on jet physics



3C 264 (HST) - Meyer et al 2015