

# A pulsar wind nebula associated with PSR J2032+4127 as the powering source of TeV J2032+4130

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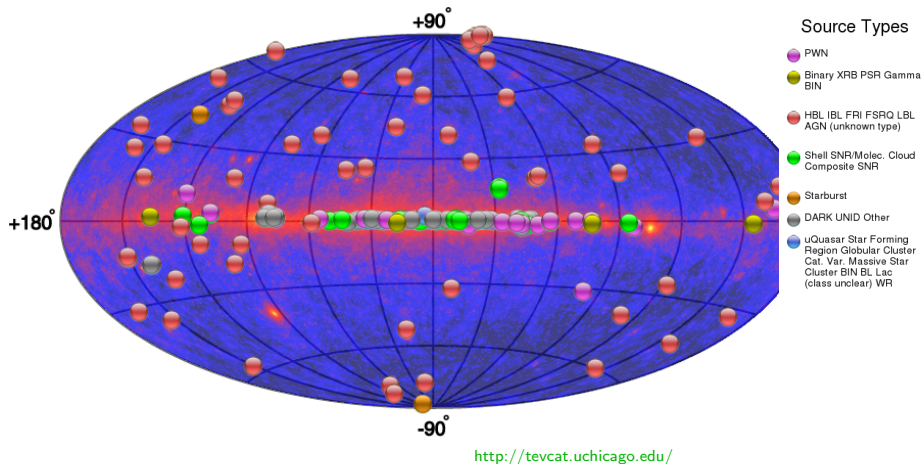
12th European VLBI Network Symposium  
Cagliari, October 10, 2014



# Collaborators

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- V. Zabalza, The University of Leicester
- V. Bosch-Ramon, Universitat de Barcelona
- M. Ribó, Universitat de Barcelona
- J. Martí, Universidad de Jaén
- M. Kramer, Max-Planck-Institut für Radioastronomie
- A. G. Lyne, Jodrell Bank Centre for Astrophysics, The University of Manchester
- B. W. Stappers, Jodrell Bank Centre for Astrophysics, The University of Manchester

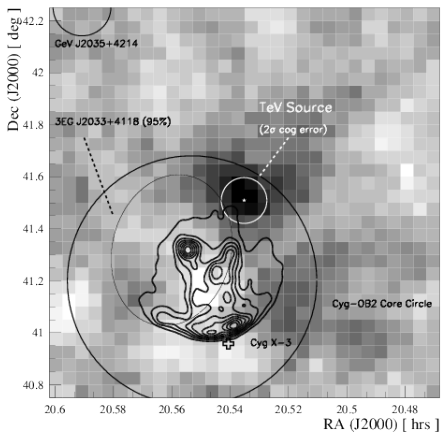
# The gamma-ray sky



- VHE ( $> 100$  GeV) sky as seen by Cherenkov telescopes.  $\sim 140$  sources
- 46 extragalactic. 61 galactic.  $\sim 30$  unidentified

# First unidentified source: TeV J2032+4130

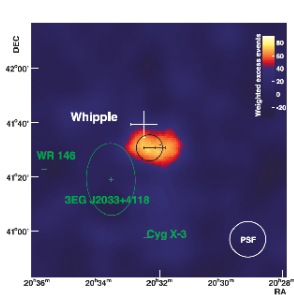
Cyg OB2 Field: HEGRA CT-System



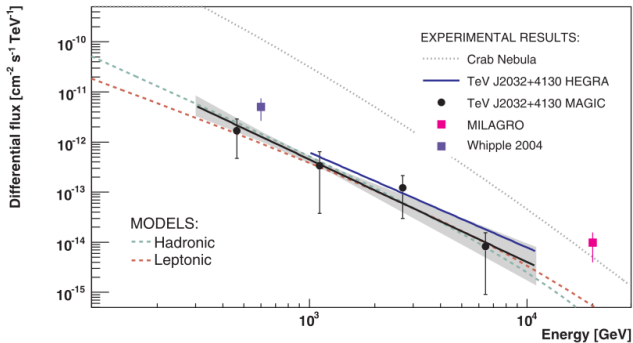
[Aharonian et al. 2002, A&A 293, L37]

- Observed by HEGRA in 1999-2001
- Significance of  $6.1\sigma$
- **Steady** flux on yr timescales
- **Extended** with radius  $6.2 \pm 1.2 \pm 0.9$  arcmin
- **Hard spectrum** with index  $-1.9 \pm 0.1_{\text{stat}} \pm 0.3_{/rmsys}$
- **Integral flux**  $> 1$  TeV at the level of  $\sim 5\%$  Crab

# TeV counterpart (MAGIC)

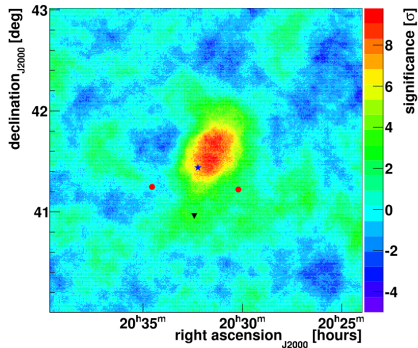


[Albert et al. 2008, ApJ, 675, L25]



- Extension of the energy spectrum down to 400 GeV. No spectral break
- Extension of the source:  $\sim 5$  arcmin (assuming Gaussian shape)
- No flux variability over several yr, compatible with HEGRA (not Whipple)

# TeV counterpart (VERITAS)



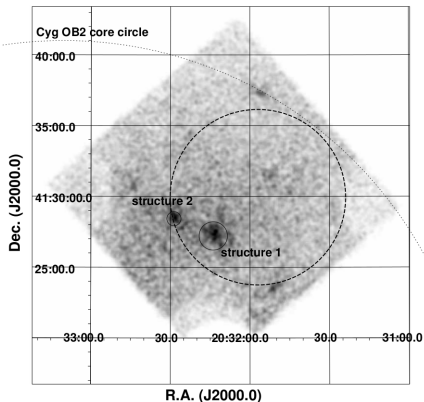
Summary of VHE Detections, Measured Positions, and Extensions for Each Experiment Prior to VERITAS Observations

Experiment	R.A.	Error in R.A. <i>Stat(Sys)</i> (arcmin)	Decl.	Error in Decl. <i>Stat(Sys)</i> (arcmin)	Reported Extension $\pm$ <i>Stat(Sys)</i> (arcmin)
HEGRA	20 <sup>h</sup> 31 <sup>m</sup> 57 <sup>s</sup>	6.2(13.7)	+41°29'57"	1.1(1.0)	6.2 ± 1.2(0.9)
Whipple	20 <sup>h</sup> 32 <sup>m</sup> 27 <sup>s</sup>	21(23)	+41°39'17"	5(6)	<6.0
MAGIC	20 <sup>h</sup> 32 <sup>m</sup> 20 <sup>s</sup>	11(11)	+41°30'36"	1.2(1.8)	5.0 ± 1.7(0.6)
Milagro	20 <sup>h</sup> 28 <sup>m</sup> 43 <sup>s</sup> .2	25	+41°07'48"	16	66
ARGO	20 <sup>h</sup> 32 <sup>m</sup> 24 <sup>s</sup> .0	...	+41°45'00"	...	12 <sup>+24</sup> <sub>-12</sub>

[Aliu et al. 2014, ApJ 783, 16]

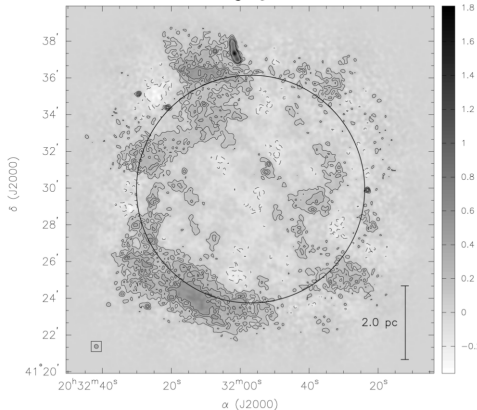
# Field around PSR J2032+4127

## Suzaku



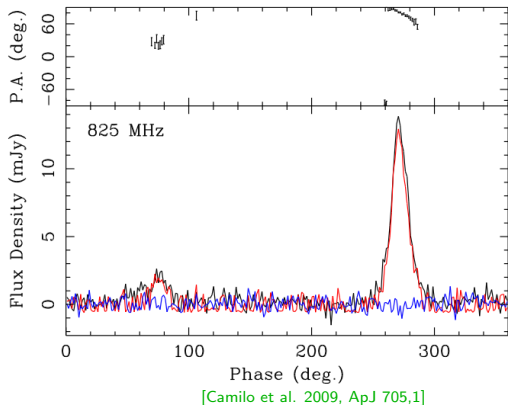
[Murakami et al. 2011, PASJ, 63, 873]

## VLA 6 cm



[Butt et al. 2008, MNRAS 385, 1764]

# PSR J2032+4127



- Fermi: GeV pulsar LAT PSR J2032+4127 [Abdo et al. 2009, Sci 325, 840]
- $P = 143$  ms,  $\tau_c = 0.11$  Myr,  $\dot{E}_{\text{sp}} = 2.7 \times 10^{35}$  erg s $^{-1}$
- GBT: radio pulsar same position and period GeV pulsar, and a Be star



# Observations

- VLA
  - June 28, 2010
  - Two frequency bands centered at 4.4 and 7.8 GHz
  - D configuration
- EVN
  - Observations on 2010, 2011, and 2014
  - 1.6 GHz
  - Pulsar gating
- *Chandra*
  - Archival data, 0.5-10 keV band, 48.7 ks observation on 2004 July 12 with the Advanced CCD Imaging Spectrometer (ACIS) detector.



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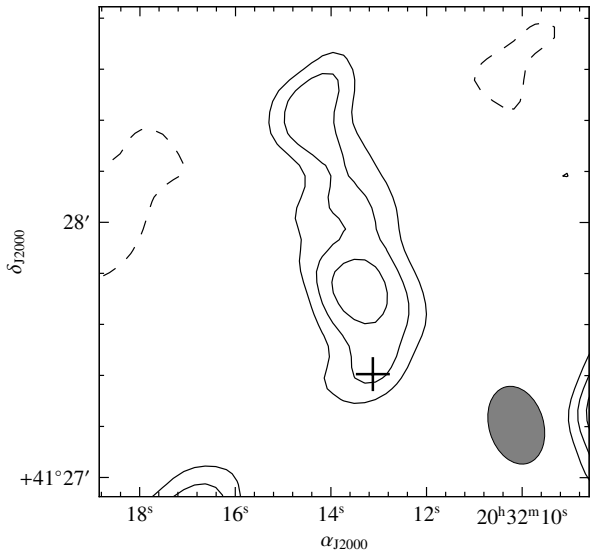
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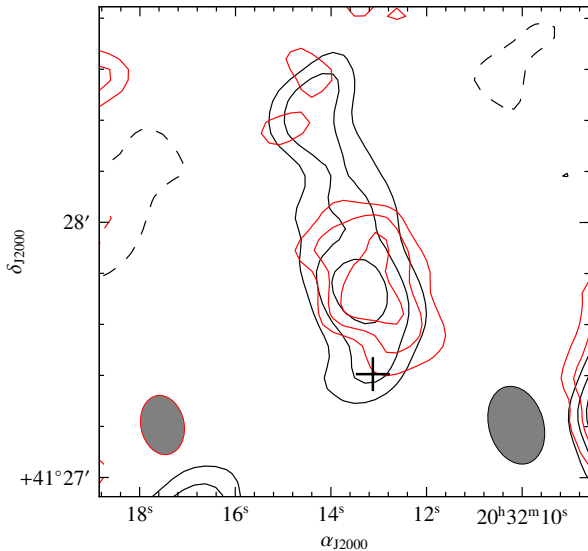
VLA: Extended radio emission

# Extended radio emission: a PWN



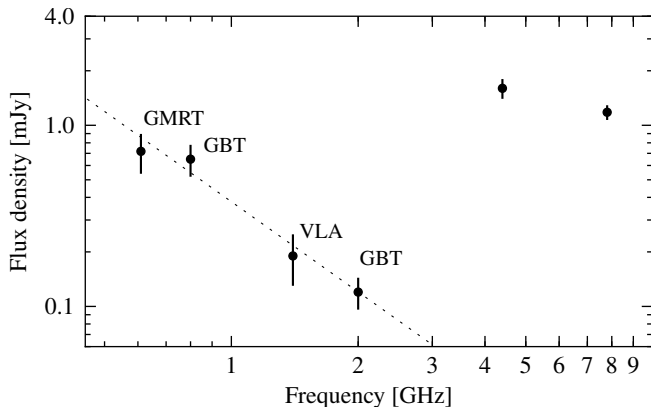
+ PSR J2032+4127  
VLA 4.4 GHz

# Extended radio emission: a PWN



+ PSR J2032+4127  
VLA 4.4 GHz  
VLA 7.9 GHz

# Radio spectrum

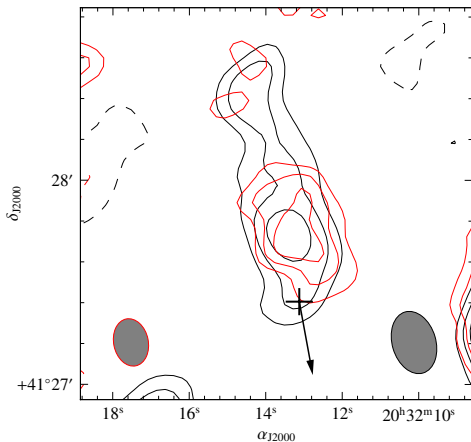


- Pulsar spectrum:  $S_\nu = (0.36 \pm 0.02)(\nu/\text{GHz})^{-1.6 \pm 0.1}$  mJy
- Insignificant contribution from the pulsar:  $\alpha = -0.4 \pm 0.4$

EVN: Pulsar proper motion



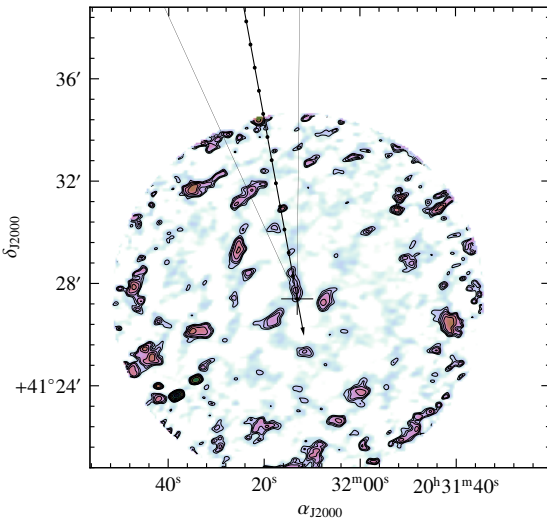
# PSR J2032+4127 proper motion



$$\mu_{\alpha} \cos \delta = -2.0 \pm 2.0 \text{ mas yr}^{-1}$$
$$\mu_{\delta} = -10.8 \pm 2.0 \text{ mas yr}^{-1}$$

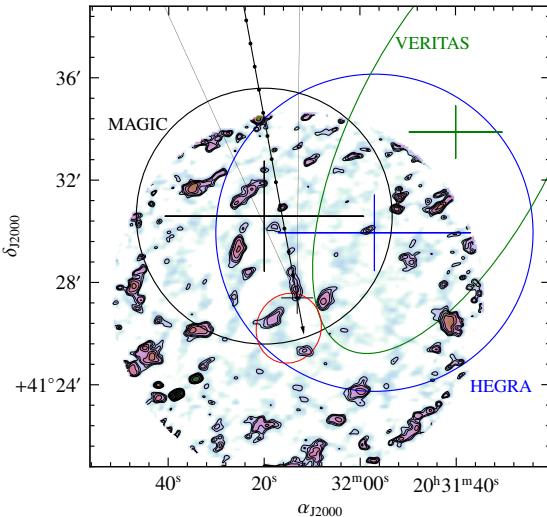
2D velocity:  $90\text{--}190 \text{ km s}^{-1}$   
at  $1.7\text{--}3.6 \text{ kpc}$

# Widefield



Contours: JVLA 4.4 GHz  
Black Cross: EVN, pulsar  
Black dots every 5000 yr

# Widefield

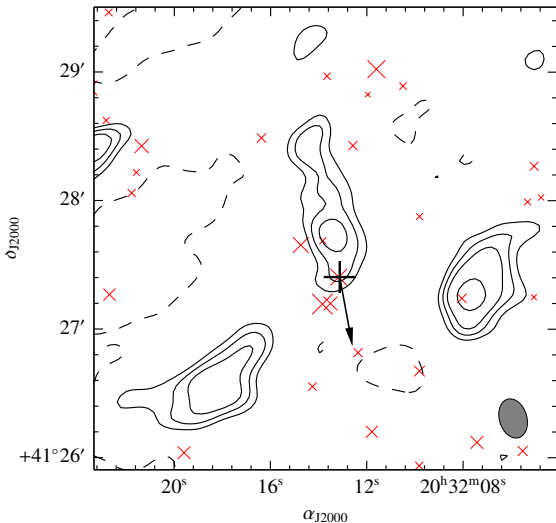


Contours: JVLA 4.4 GHz  
Black Cross: EVN, pulsar  
Black dots every 5000 yr  
Red ellipse: *Fermi*

The past trajectory of PSR J2032+4127 coincides with the measurement of the CoG of the TeV emission measured with MAGIC, which is compatible with the measured positions from HEGRA and VERITAS

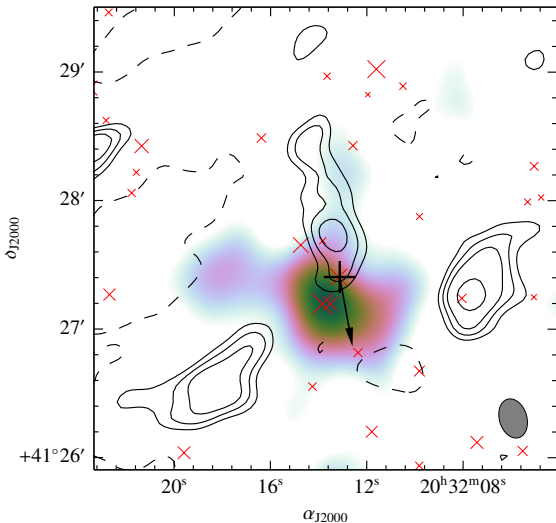
*Chandra*: diffuse X-ray emission

# Diffuse X-ray emission



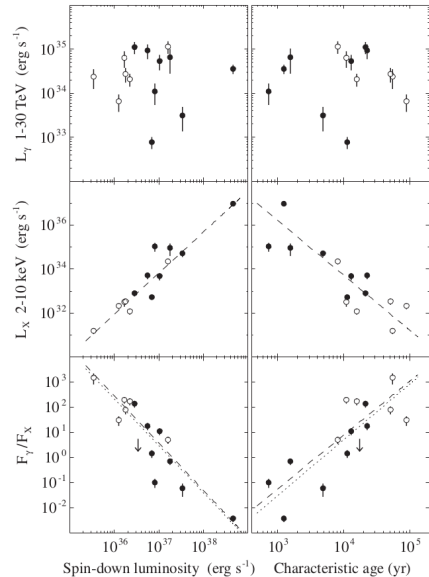
Contours: JVLA 4.4 GHz  
Cross: EVN, pulsar  
Red Crosses: *Chandra*

# Diffuse X-ray emission



Contours: JVLA 4.4 GHz  
Cross: EVN, pulsar  
Red Crosses: *Chandra*  
Color scale: diffuse *Chandra*

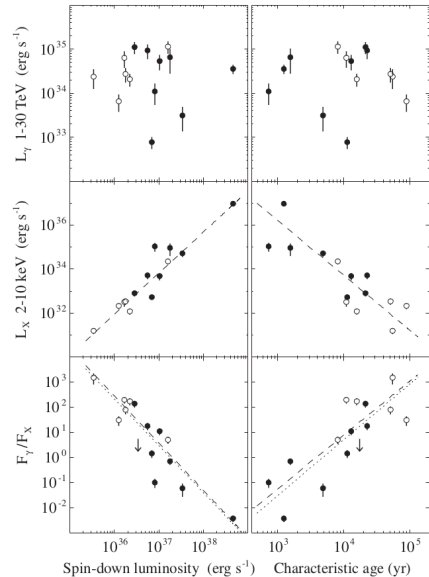
# X-ray/gamma-ray correlation



- Correlations of the X-ray and gamma-ray fluxes with  $\dot{E}$  and  $\tau_c$ :
- $\dot{E}_{sp} = 2.7 \times 10^{35} \text{ erg s}^{-1} \Rightarrow$   
 $L_X = 7.4 \times 10^{30} \text{ erg s}^{-1}$  or  
 $F_X = 2.2 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$
- $\tau_c = 0.11 \text{ Myr} \Rightarrow F_\gamma/F_X \sim 1000 \Rightarrow$   
 $L_\gamma = 7.4 \times 10^{33} \text{ erg s}^{-1}$

[Mattana et al. 2009 ApJ 694 12]

# X-ray/gamma-ray correlation

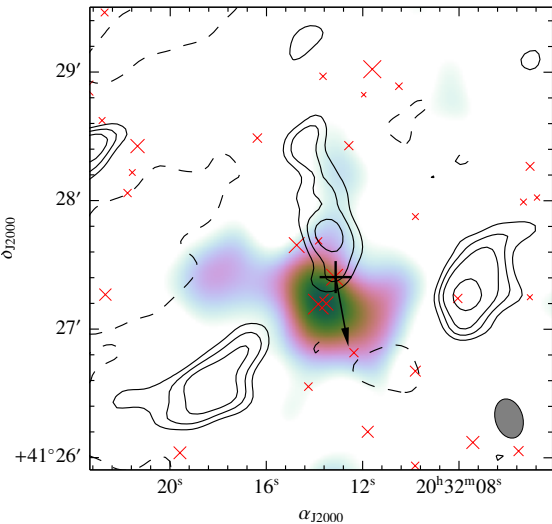


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[Mattana et al. 2009 ApJ 694 12]



# Diffuse X-ray emission



The diffuse emission could be:

- Partially from the PWN itself.
- Unrelated source. Field young stars?
- $e^-$  escaping from the shock?

# Scenario

- High speed pulsar forms a shock at  $\sim 1''$ .
- High energy particles are accelerated and escape the shock region.
- If leptonic, they could be the responsible of the TeV source through IC in the Thomson regime off CMB and IR galactic photons with energy density  $u_{\text{CMB-IR}} \sim 1 \text{ eV}$ .
- Diffusion coefficient of  $D \sim 10^{26} \text{ cm}^2 \text{ s}^{-1}$ ,  $t_{\text{diff}} \sim 30 - 50 \text{ kyr}$ .
- Particles are advected by the shocked flow in the opposite direction to the pulsar motion. These relativistic particles produce radio (detected) and X-ray emission (not detected yet).
- The size of the TeV source is compatible with a projected velocity of  $\sim 100 \text{ km s}^{-1}$ .

# Conclusions

- The radio morphology strongly resembles that of a PWN.
- The positional coincidence between the pulsar and the origin of this elongated radio structure suggests a physical association.
- This is supported by the proper motion of the pulsar, opposite to the radio structure.
- The pulsar space velocity is not compatible with the Galactic rotation. Probably formed with a kick.
- The absence of diffuse X-ray emission overlapping the elongated radio structure could be explained by the low flux expected.
- The extended X-ray emission detected with *Chandra* and *Suzaku* remains unclear. (Associated with the Be stars in the field?).