Simultaneous Multiband Observations of the Inner Crab Nebula

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Why is the Crab Nebula an important object?

– it is the bright ($L_X \sim L_{opt} \sim 10^{37}$ erg/s) and extended
(~ 2' x 2.5' in the X-rays, ~ 4' x 5' in the optical, ~ 5' x 7' in the radio)
nebula powered by the Crab Pulsar ($L_{spindown} \sim 5 \times 10^{38}$ erg/s)

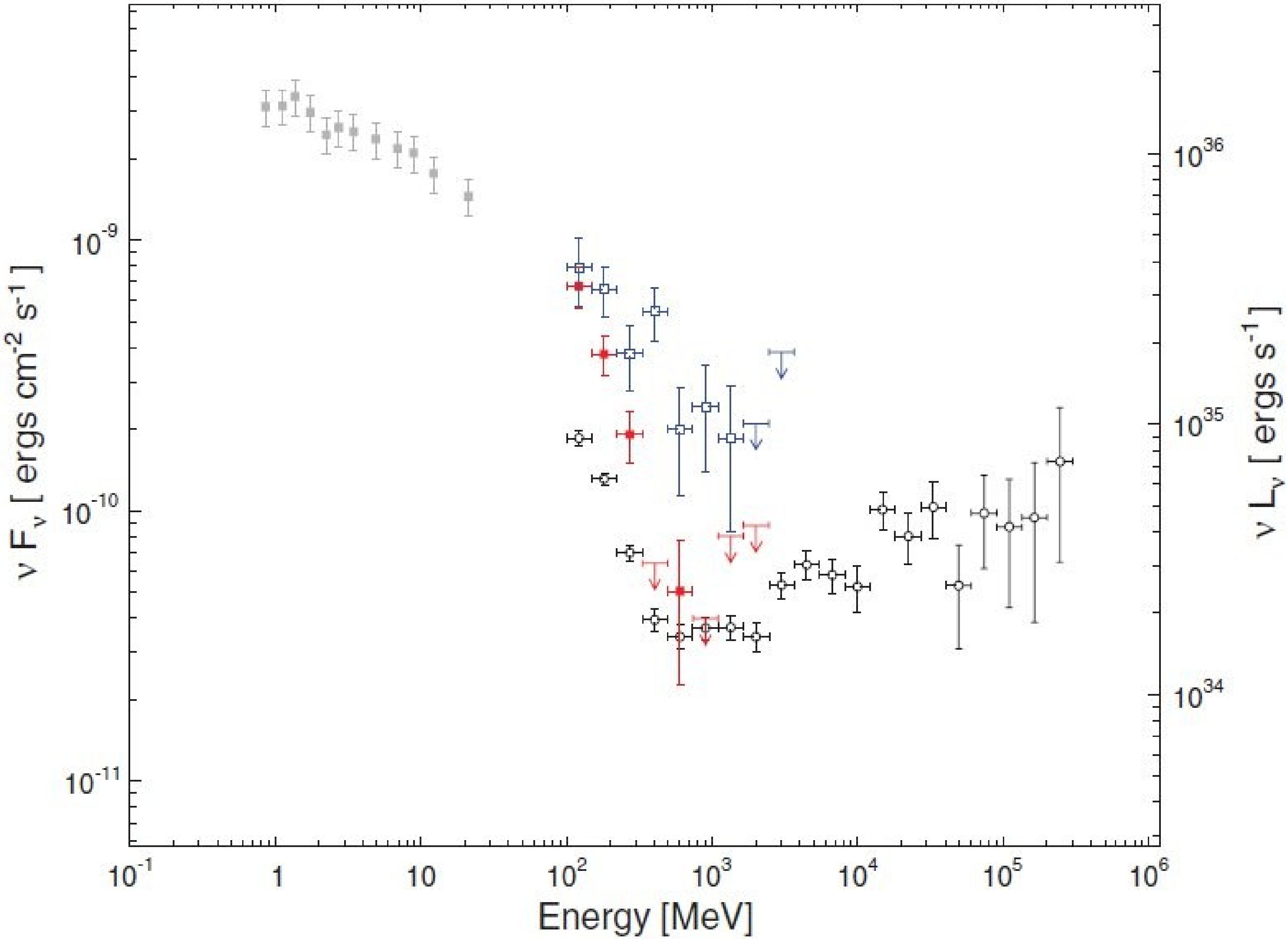
– it is the first object recognized as a remnant of a historical supernova
(E. Hubble, 1928)

– it contains one of the first discovered pulsars
(D. Staelin & E. Reifenstein, 1968)

– it is observable from radio- to the TeV gamma-ray band
(e.g., Atoyan and Aharonian 1996, Hester 2008, Buehler and Blandford 2014)

– > 2500 publications are indexed by the ADS with «Crab» in their titles

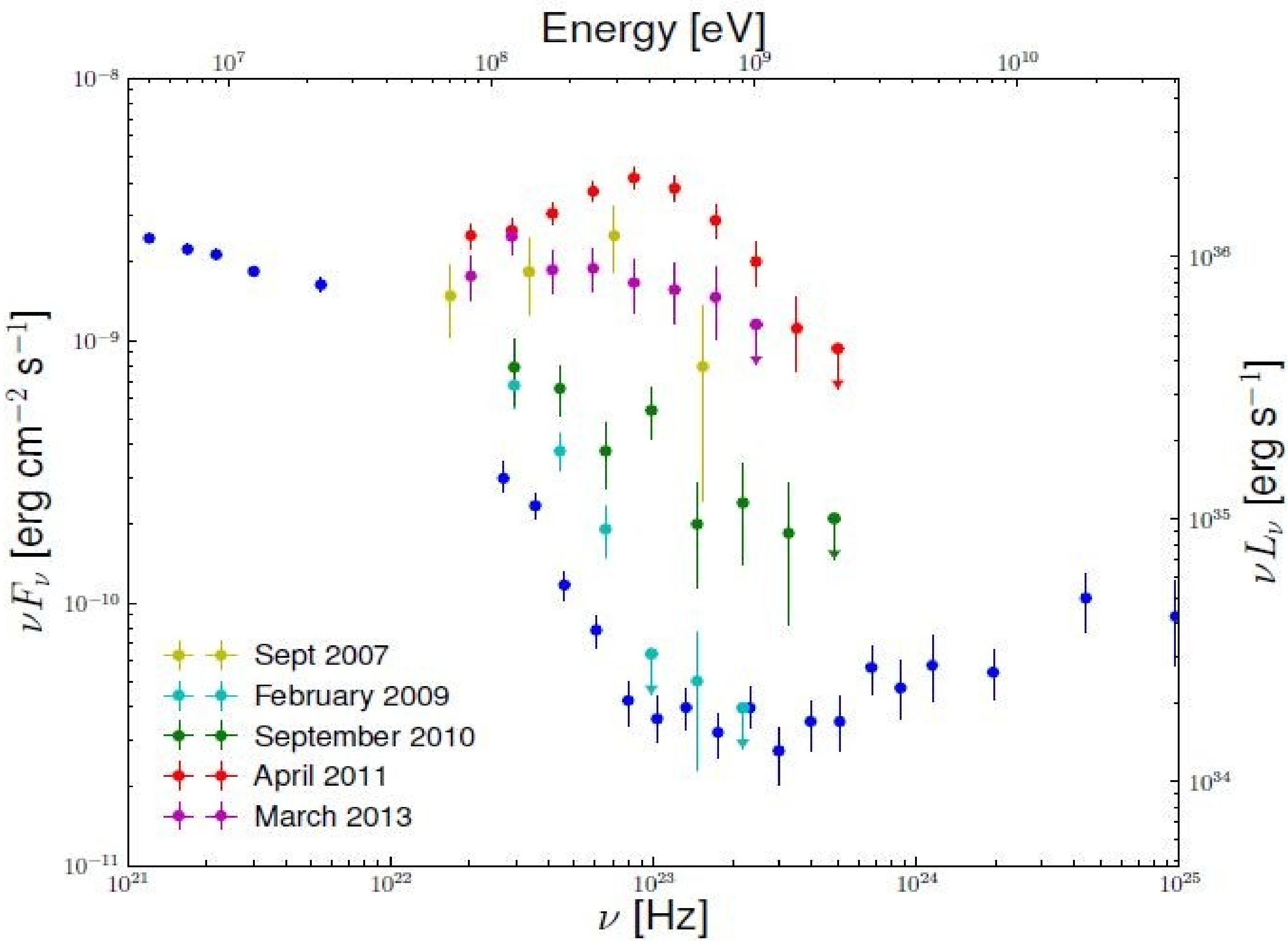
– it serves as a standard candle
for the hard X-ray and gamma-ray astrophysics
BUT: gamma-ray flares in the GeV range were discovered in 2009-2010,
their origin is still unclear



The flares were also detected with AGILE (Tavani et al., Science, v. 331)

Fig. 1. Spectral energy distribution of the Crab Nebula. Black open circles indicate the average spectrum measured by the LAT in the first 25 months of observations. Red squares indicate the energy spectrum during the flare of February 2009 (MJD 54857.73 to 54873.73), and blue open squares indicate the spectrum in September 2010 (MJD 55457.73 to 55461.73). Gray squares indicate historical long-term average spectral data from the COMPTEL telescope, with 15% systematic errors (*41*). Arrows indicate 95% confidence flux limits.

Fermi/LAT spectra of gamma-ray flares from the Crab [Abdo et al., Science, v. 331 (2011)]



Since 2009
at least 6 GeV flares
have been observed
(about 1/year)

Figure 9. Spectral energy distribution at the maximum flux level for five of the six Crab nebula flares detected as of September 2013 (Abdo et al. 2011, Buehler et al. 2012, Striani et al. 2013, Mayer et al. 2013). No spectrum has been published for the low intensity flare of July 2012 (Ojha et al. 2012). The blue points show the average nebula flux values referenced in Fig. 2.

Buehler & Blandford, Reports on Progress in Physics, v. 77 (2014)

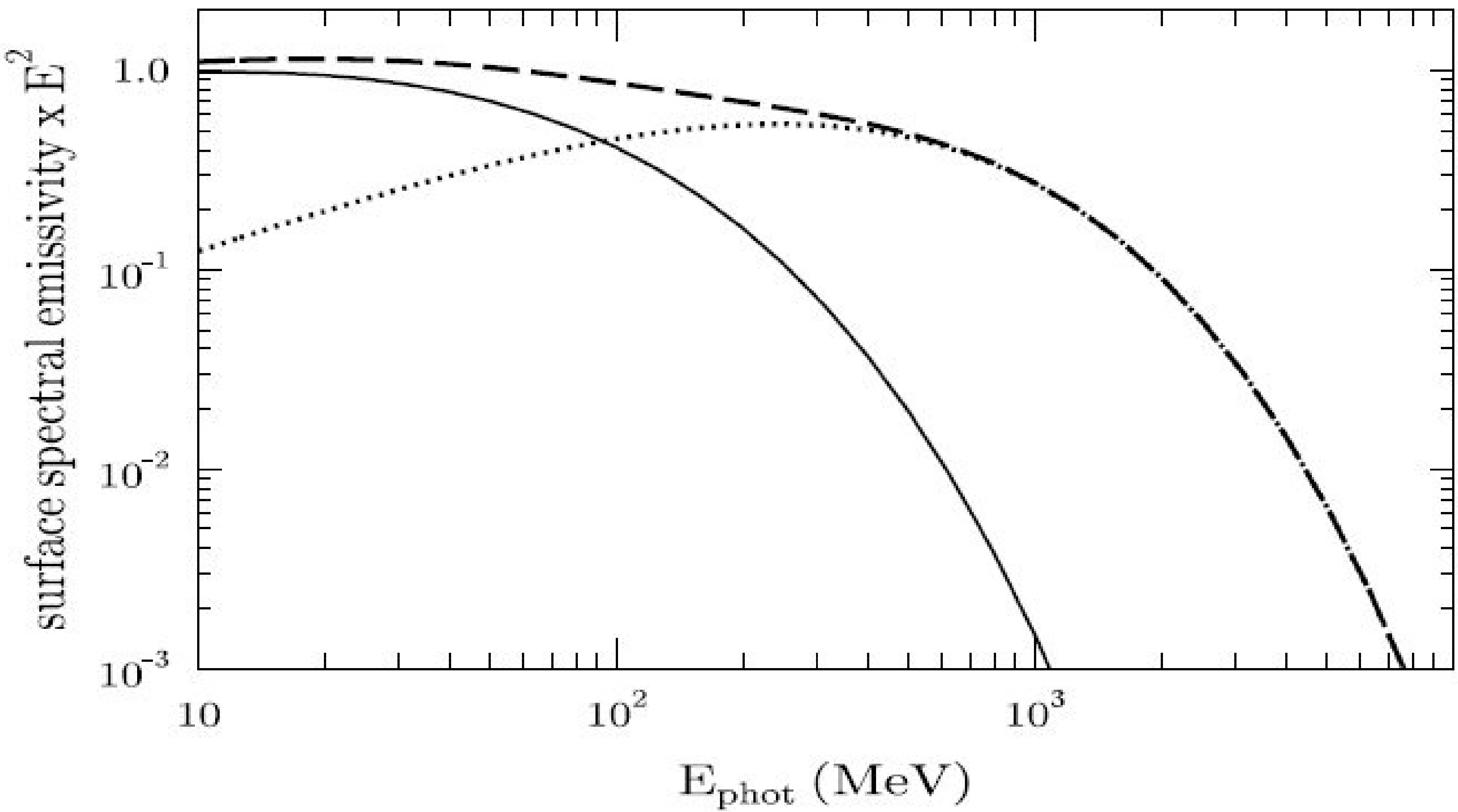
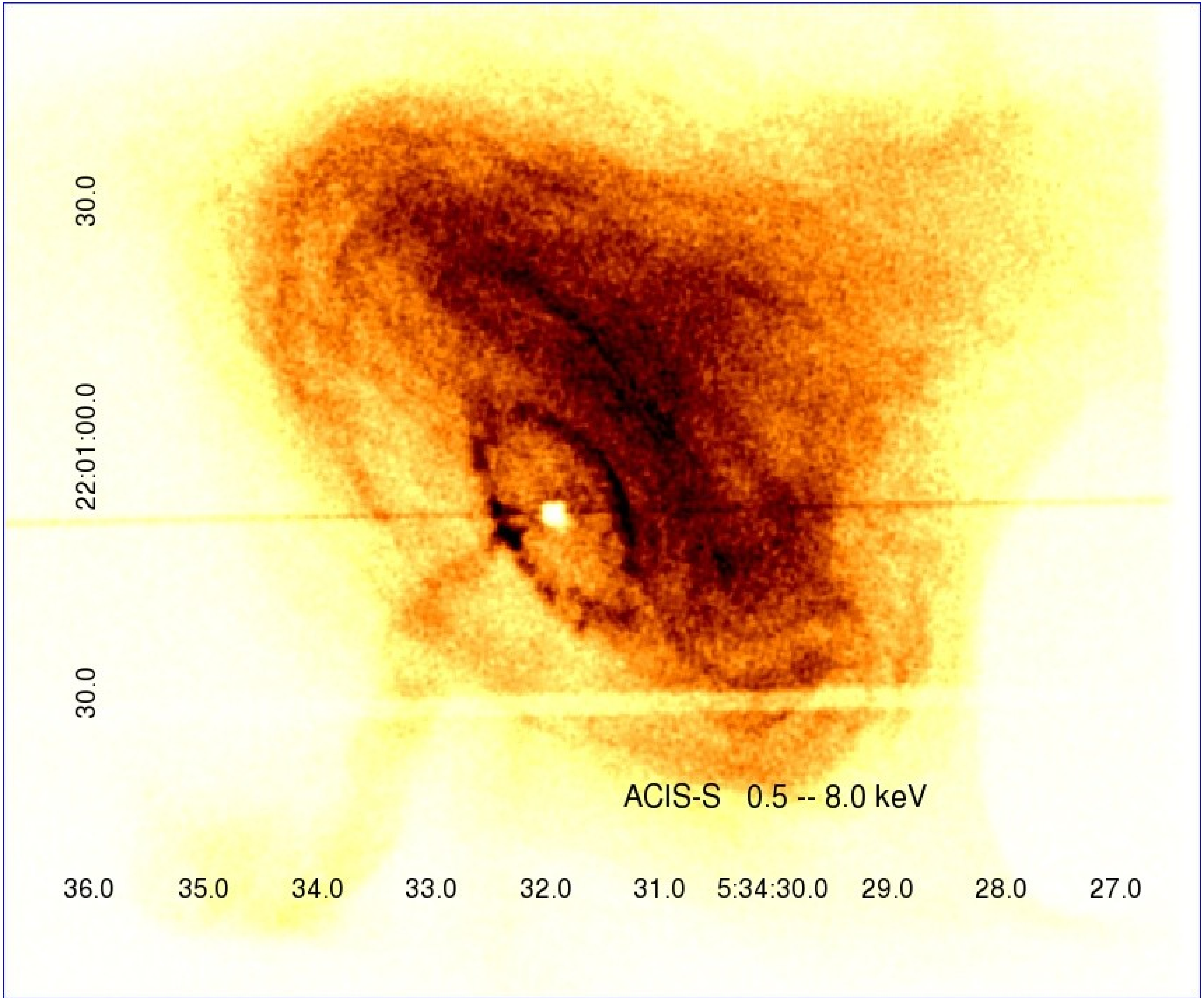


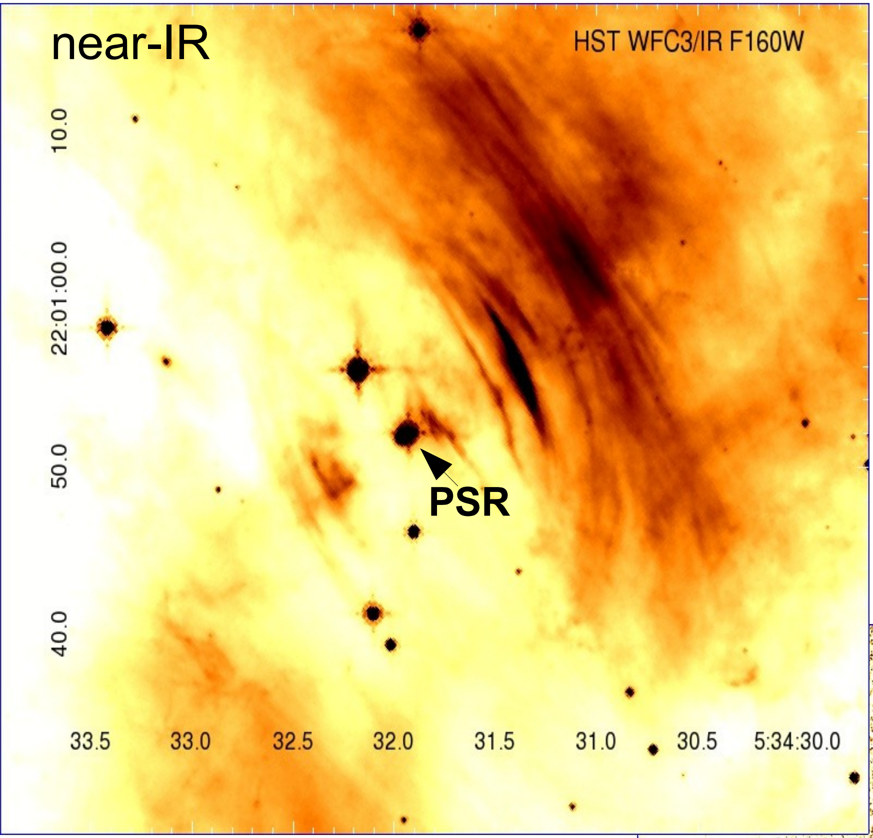
Figure 2. Normalized spectra of synchrotron radiation at two different time-moments, $ct/\Delta_0 = 0.2$ (solid line) and 0.6 (dashed line), which model the quiescent and flare spectra, respectively (see Fig. 1). The dotted curve shows the contribution of the variable magnetic field. The power emitted in the GeV flare is about 2×10^{36} erg s^{-1}, for the Crab Nebula parameters.

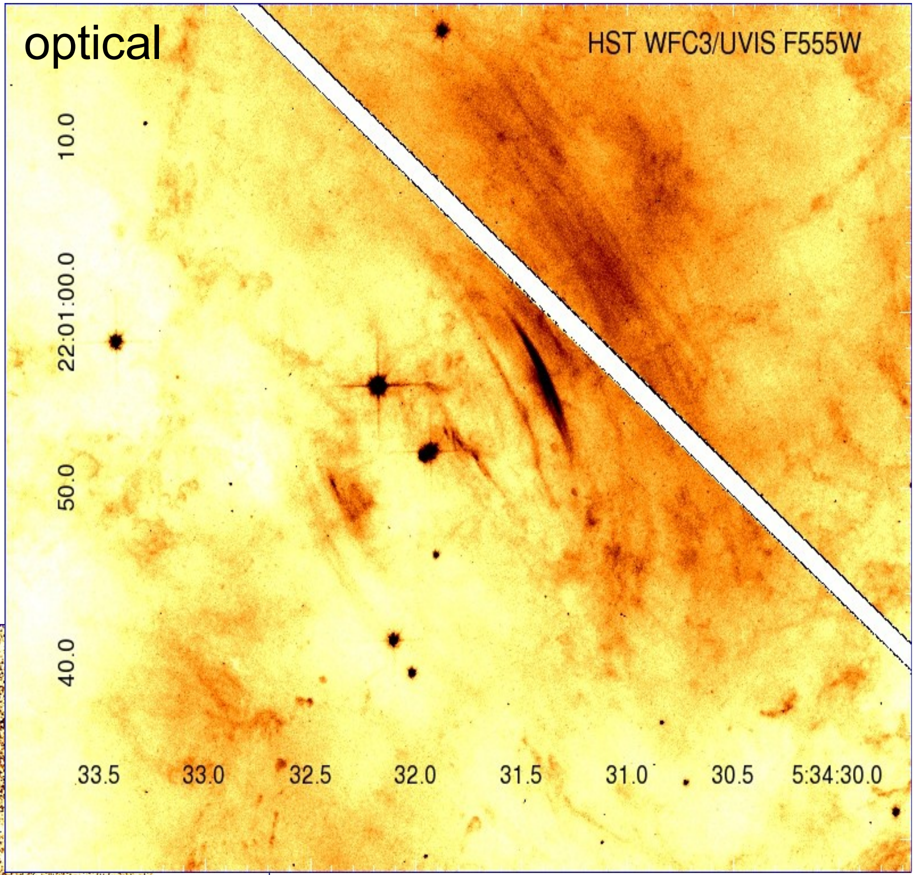
A model of gamma-ray flares in the Crab [Bykov, Pavlov, Artemiev, Uvarov, MNRAS, v. 421 (2012)]:
the observed flaring sub-GeV emission comes from the wisp-bearing part of the PWN
Δ_0 = 2 x 10(16) cm for E ~ 1 GeV, τ ~ 10(5) s ~ days

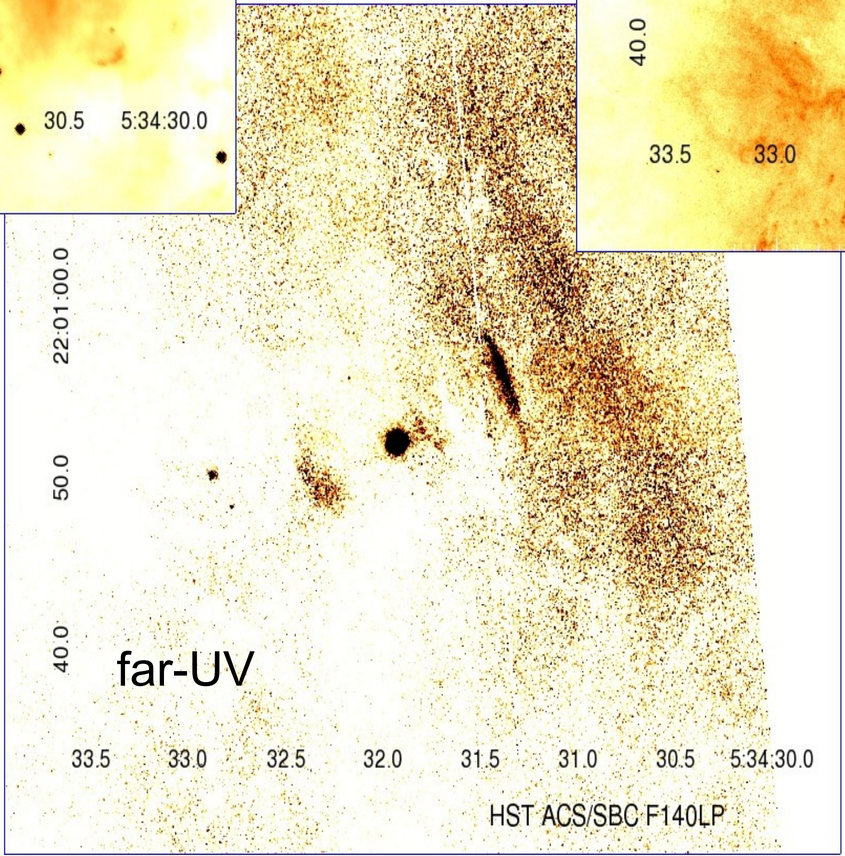
Observations with Chandra ACIS



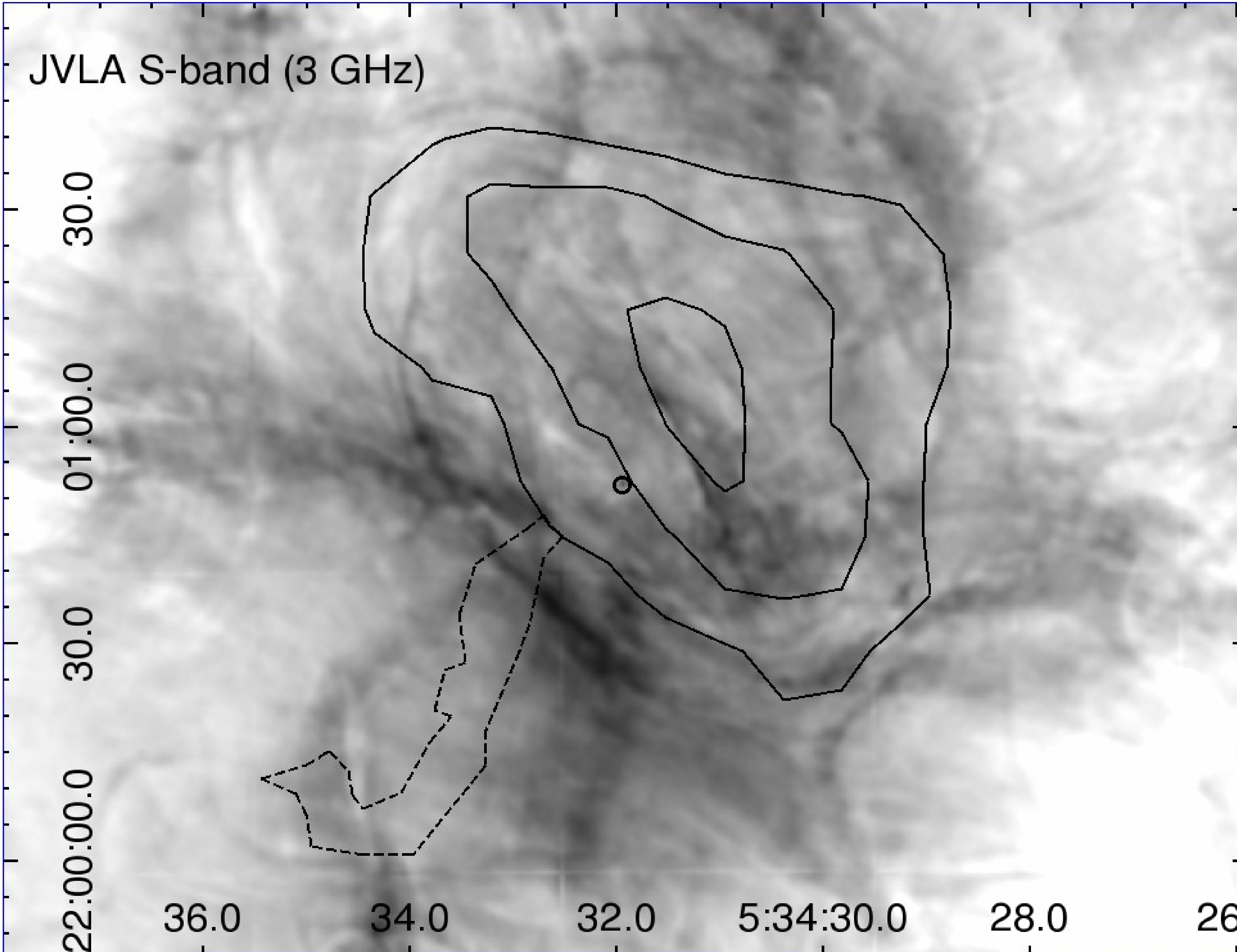
Observations with the Hubble Space Telescope (WFC3 and ACS)

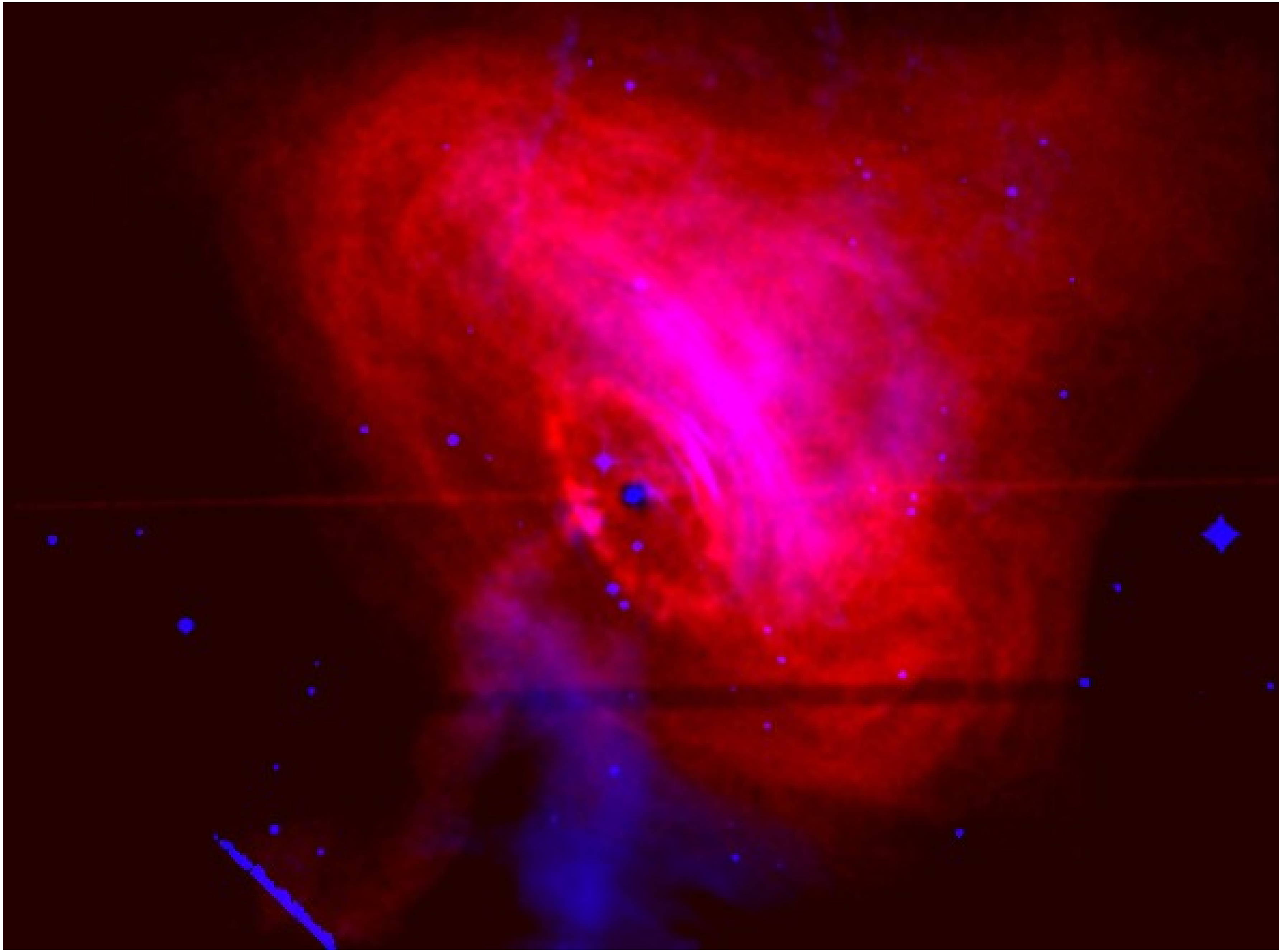






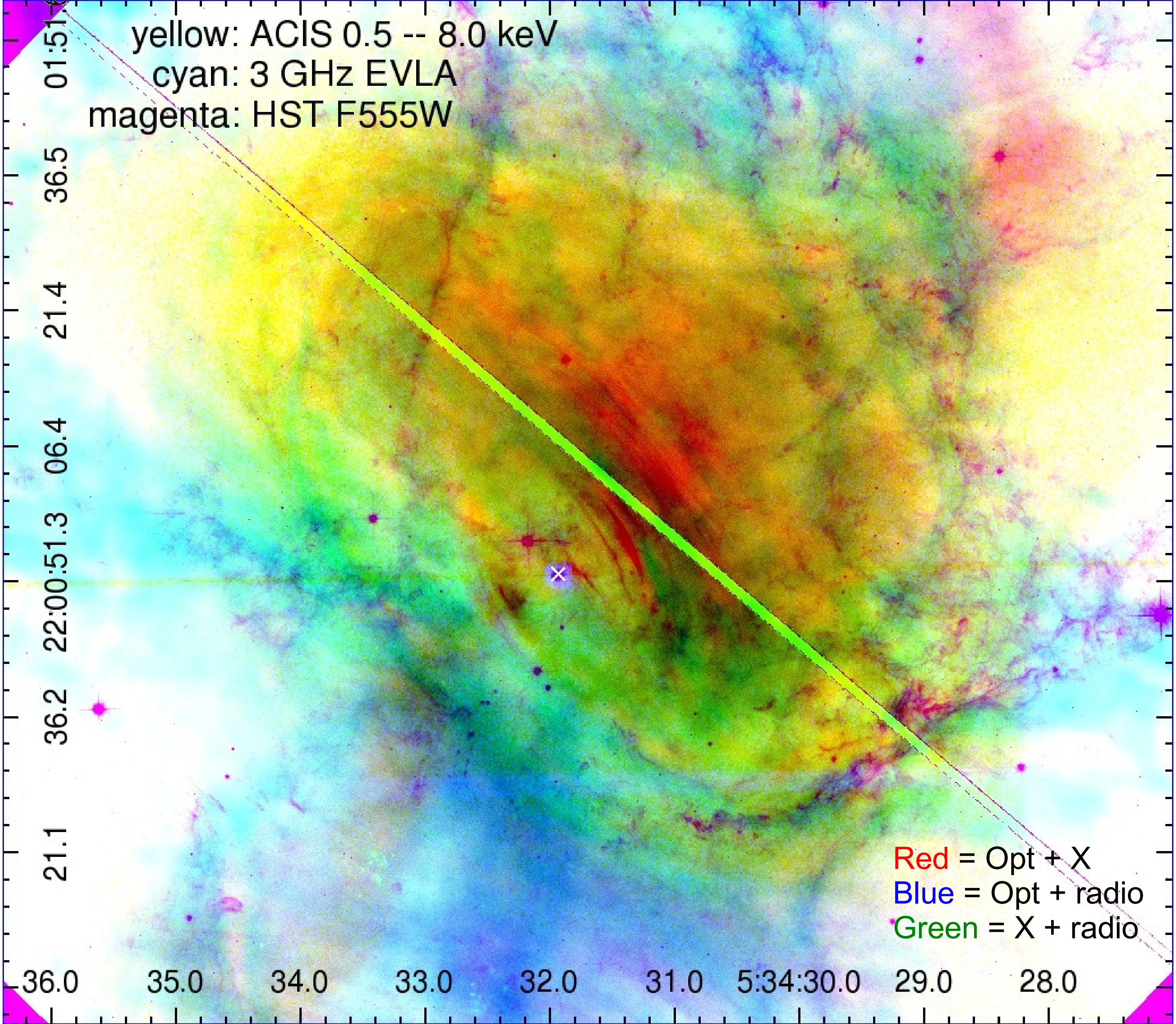
Observations with the Jansky Very Large Array



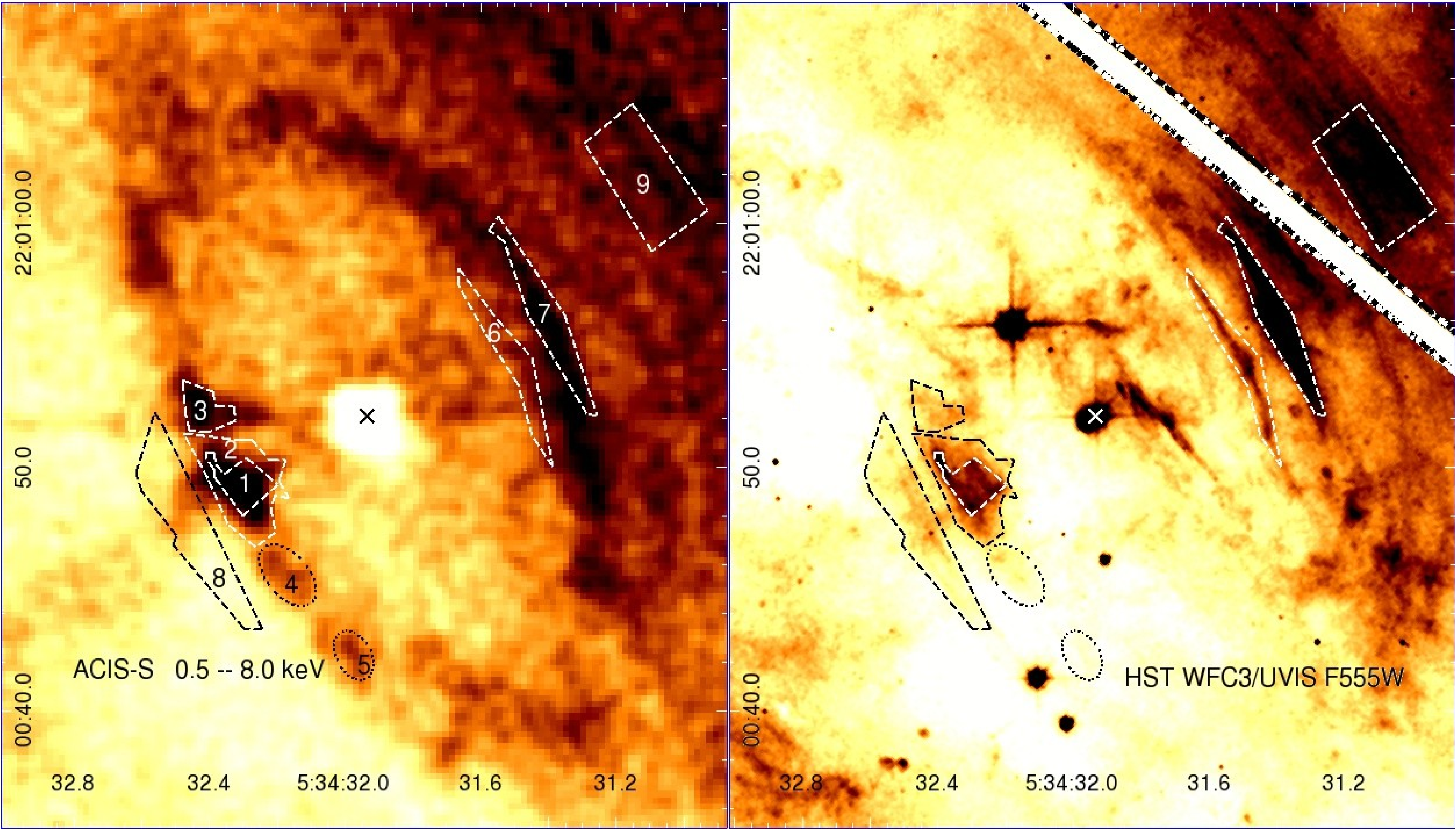


Red – X-rays (Chandra)
Blue – near-IR (HST)

Another «relic» jet in the near-IR?


yellow: ACIS 0.5 -- 8.0 keV
cyan: 3 GHz EVLA
magenta: HST F555W
Red = Opt + X
Blue = Opt + radio
Green = X + radio
01:51.5
36.5
21.4
06.4
51.3
22:00:51.3
36.2
21.1
36.0
35.0
34.0
33.0
32.0
31.0
5:34:30.0
29.0
28.0

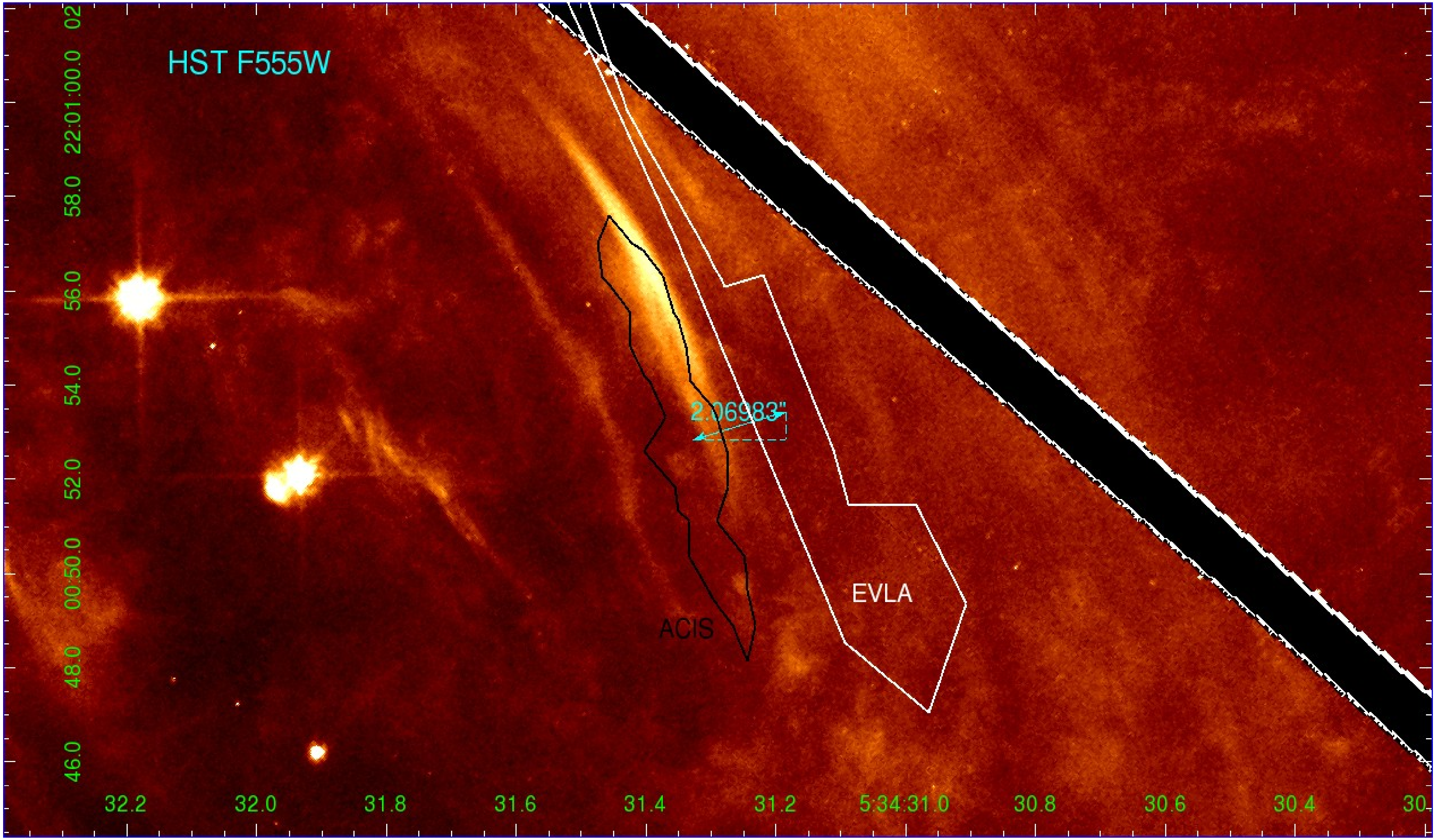
Small-scale features chosen for detailed analysis



1,2 – anvil, 3 – knot, 4 – knot1, 5 – knot2,
6 – wisp1, 7 – wisp2, 8 – wisp1s, 9 – wisp3

Wisp2 position in 3 bands

evolution of the stochastic magnetic field rather than partcile distributions?

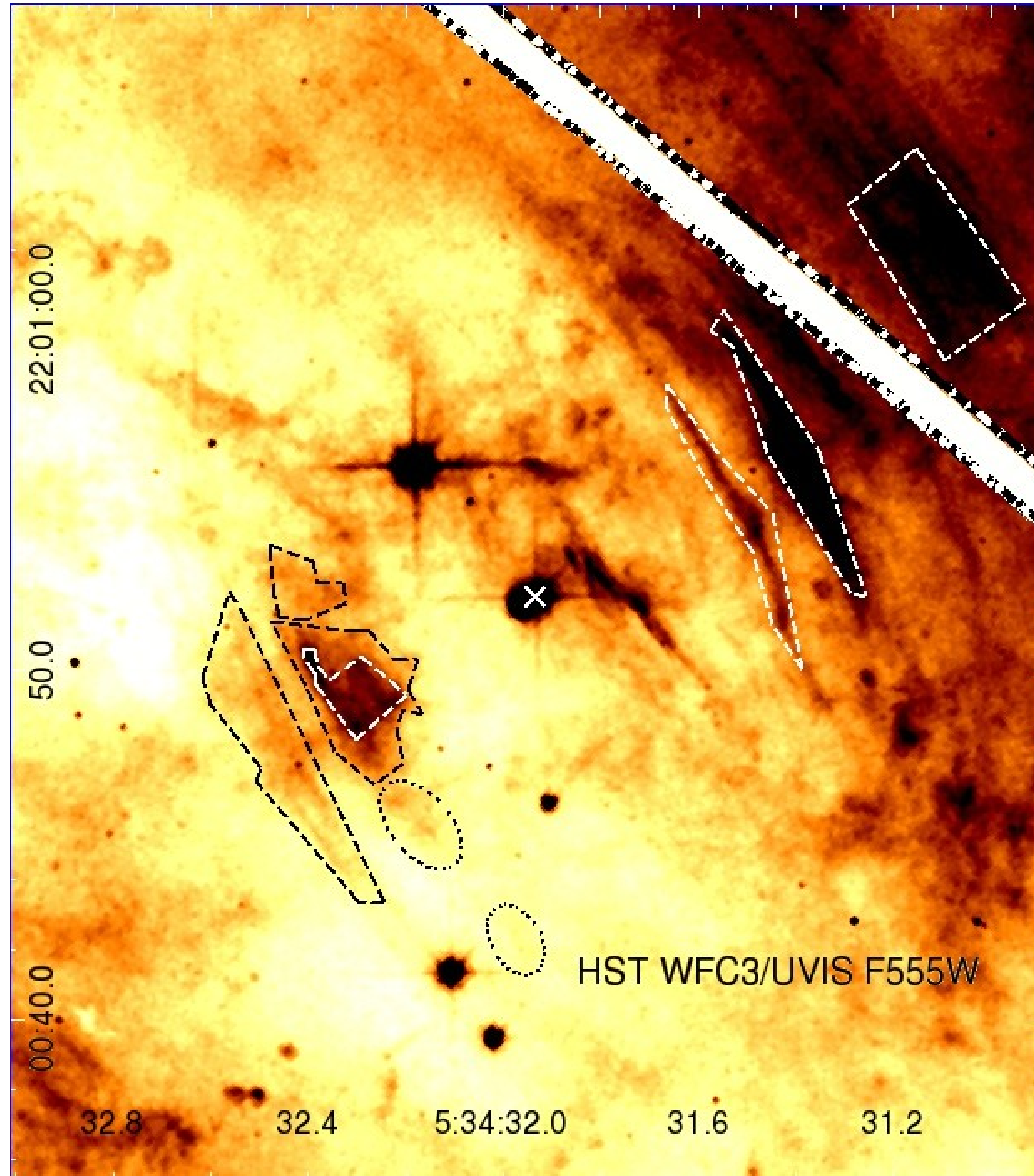


Modeling of magnetic field evolution in the PWN:
Korteweg — de Vries soliton-like solutions
A.E. Petrov and A.M. Bykov (JPhCS 2014, 2015)

Spectral indices

PRELIMINARY

	Γ_{opt} (dereddened)	Γ_X (unpiled)
anvil	1.23 +/- 0.18	$1.46^{+0.22}_{-0.07}$
knot	1.18 +/- 0.29	$1.61^{+0.14}_{-0.20}$
knot1	1.25 +/-0.38	$1.62^{+0.13}_{-0.08}$
knot2	1.26 +/- 0.50	$1.68^{+0.08}_{-0.26}$
wisp1	1.24 +/- 0.23	$1.61^{+0.17}_{-0.07}$
wisp2	1.25 +/- 0.16	$1.74^{+0.14}_{-0.13}$
wisp3	1.25 +/- 0.17	$1.56^{+0.09}_{-0.05}$
wisp1s	1.33 +/- 0.31	$1.70^{+0.13}_{-0.05}$



$$\Gamma_X \sim \Gamma_{opt} + (0.3\text{-}0.4)$$

a spectral break ?

Summary

* The small-scale features of the inner Crab Nebula
are morphologically similar in the optical and X-ray bands,
but in general the structure does not coincide

* The NIR – FUV parts of individual features' spectra
appear systematically harder than the X-ray ones

* No certain interpretation of the observed spatial structure
and spectral behavior is suggested, it might be due to
a) specific mechanisms of particle acceleration,
b) energy-dependent diffusion in the nebula or
c) nonlinear evolution of magnetic field perturbations

* Additional simultaneous high-resolution multiband observations
are required to study spectral shapes (and variability)
of individual emitting regions in the Crab Nebula
and to conclude on their nature

* The existence of simultaneous multiband data
implies that any model of the Crab PWN structure and emission
has to reproduce and explain them

Thank you for your attention!

Why do we need **simultaneous** observations of the Crab?

– the structure of the Crab Nebula has shown **variability on days to weeks scale**
– PWNe are dynamical structures by their nature

the Crab Nebula is ~ 2 kpc away (V. Trimble, 1968)
1'' ~ 3.3×10^{16} cm
may change on 0.1'' scales in ~ 10^5 s ~ 1 day

Simultaneous observations in 2001 and in 2012

A set of simultaneous observations (Δt ~ 1 day => ~ 2.5×10^{15} cm scale) with Chandra, HST, and VLA was performed in 2001 (**J.J. Hester, M. Bietenholz** et al., published in 2002, 2004):
– only 1 HST band (F547M)
– 5 GHz VLA-B band – 1.4'' resolution
– only morphological studies, no spectra were produced
– conclusions: a) some structures are matched, some are not
b) the structures evolve on 1-2 weeks scale

We have performed **a new set of observations** (Δt < 13 hrs => $\Delta x < 1.4 \times 10^{15}$ cm scale) with Chandra, HST, and JVLA on 2012 Nov 26:
– 3 HST bands (F140LP, F555W, F160W)
– 3 GHz EVLA-A band – 0.9'' resolution
– spectral studies of individual features

Data reduction and spectral analysis issues

- HST data reduction: AstroDrizzle 1.1.8
- Chandra data reduction: CIAO 4.5 + XSpec 12
- JVLA data reduction: NRAO CASA 4.2
- $N_H \approx 0.3 \times 10^{22}$ cm^{-2} +/- 8% across the PWN
  agrees with Mori et al. (2004)
- $A_V \approx 1.61$
  extinction curve measurements of Sollerman et al. (2000)
  agrees with the $N_H \rightarrow A_V$ relation (e.g., Tian et al. 2013)
- $A_V \rightarrow A_\lambda$ transformation according to Cardelli et al. (1989)
- Pileup effects in Chandra ACIS were accounted for
  with the model of Davis (2001)

instrument	*HST* ACS F140LP	*HST* WFC3 F555W	*HST* WFC3 F160W	*Chandra* ACIS-S	JVLA-A band S
band	140 – 170 nm	450 – 650 nm	1.4 – 1.7 μm	0.3 – 10 keV	2.5 – 3.5 GHz
observation id	13043	13043	13043	14458	12B-380
start time, MJD	56257.673416	56257.738460	56257.751070	56257.873616	56257.132951
end time, MJD	56257.706155	56257.748980	56257.771880	56258.018533	56257.296331
exposure, s	2592	774	1612	10000	11967
resolution (PSF FWHM), $''$	0.06	0.07	0.15	0.49	0.9