The Crab Nebula:
History and Phenomena

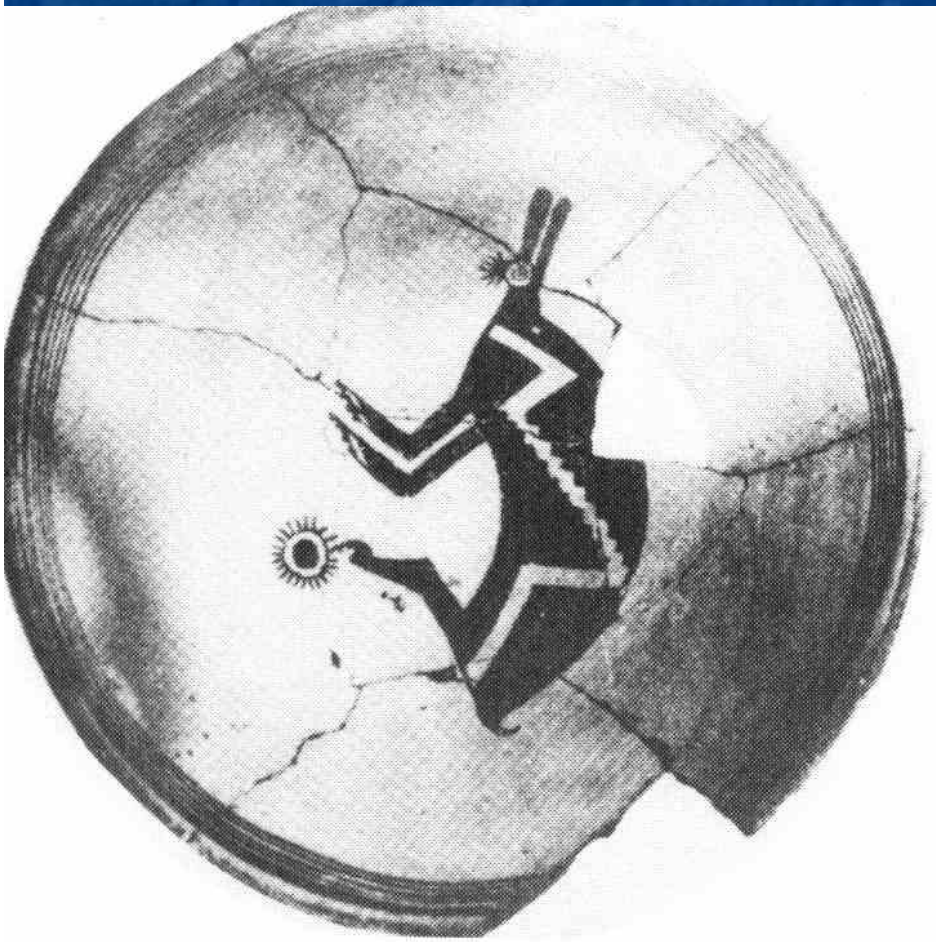
Trevor Weekes

Whipple Observatory

History

- Reference: “The Crab Nebula”,
- Simon Mitton, Cambridge University Press,1978

Mimbres Pottery



Smithsonian News Service Photo courtesy of
the University of Minnesota Museum

"Time of the Two Suns"

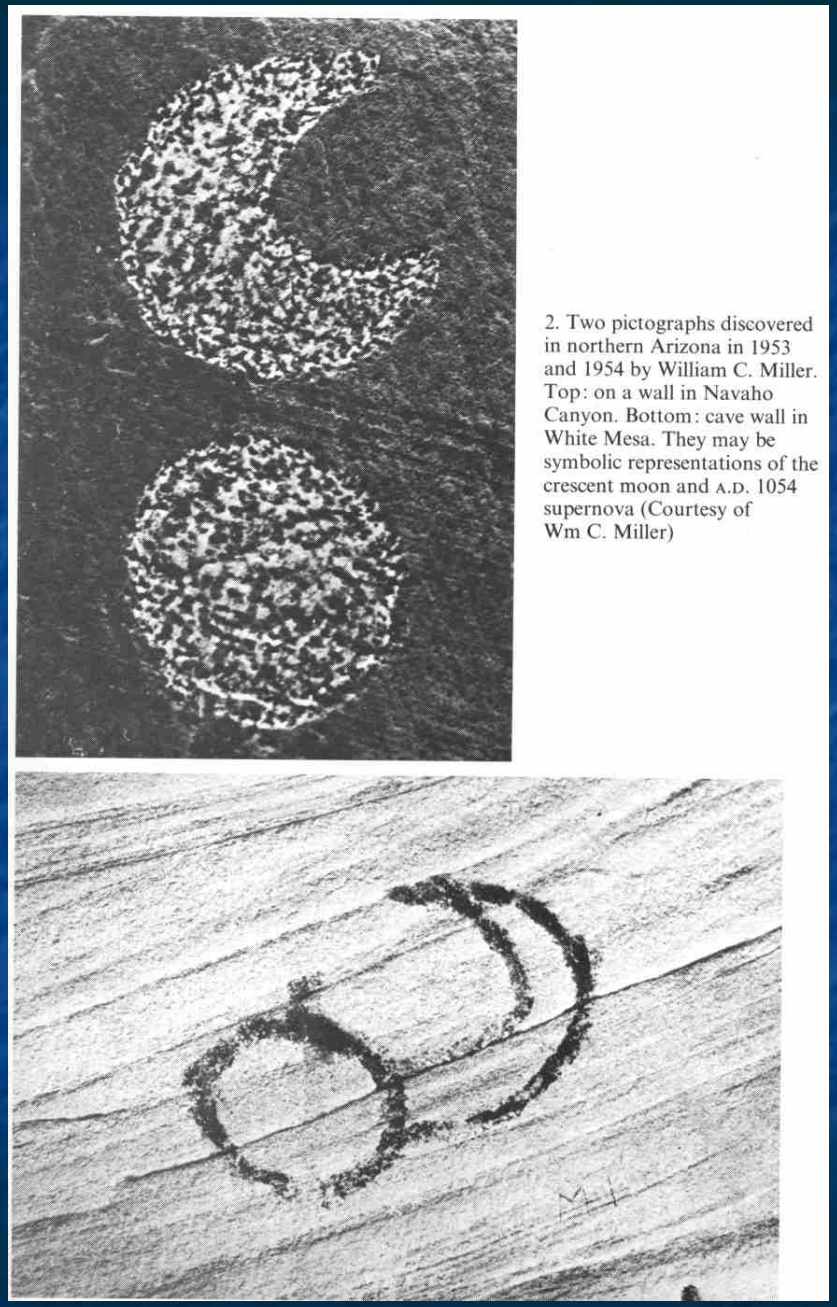
Broken Pot

Rabbit represents Moon

Mimbres Tribe in Southwest ~1000-1100 A.D.

Visible in Daylight for 23 days

When Crab Nebula exploded, it was close to waning moon



2. Two pictographs discovered in northern Arizona in 1953 and 1954 by William C. Miller. Top: on a wall in Navaho Canyon. Bottom: cave wall in White Mesa. They may be symbolic representations of the crescent moon and A.D. 1054 supernova (Courtesy of Wm C. Miller)

Other depictions of same event in Southwest

Pictographs in:

Navajo Canyon

White Mesa


FREMONT
UTAH
ARIZONA
COLORADO
NEW MEXICO
ANASAZI
HOVENWEEP
MESA VERDE
AZTEC
SAN JUAN R.
KAYENTA
CANYON DE CHELLY
GRAND CANYON
CHACO CANYON
TAOS
BANDELIER
PECOS
Albuquerque
LITTLE COLORADO R.
WUPATKI
SUNSET CRATER
WALNUT CANYON
MOGOLLON
MOGOLLON RIM
ÁCOMA
SINAGUA
TUZIGOOT
MONTEZUMA CASTLE
RIO GRANDE
PECOS R.
GRAN QUIVIRA
SALADO
Phoenix
SALT R.
TONTO
GILA CLIFF DWELLINGS
CASA GRANDE
MIMBRES
GILA R.
HOHOKAM
Tucson
MEXICO

Chaco Canyon, New Mexico

Exploding Star

Crescent Moon

Hand

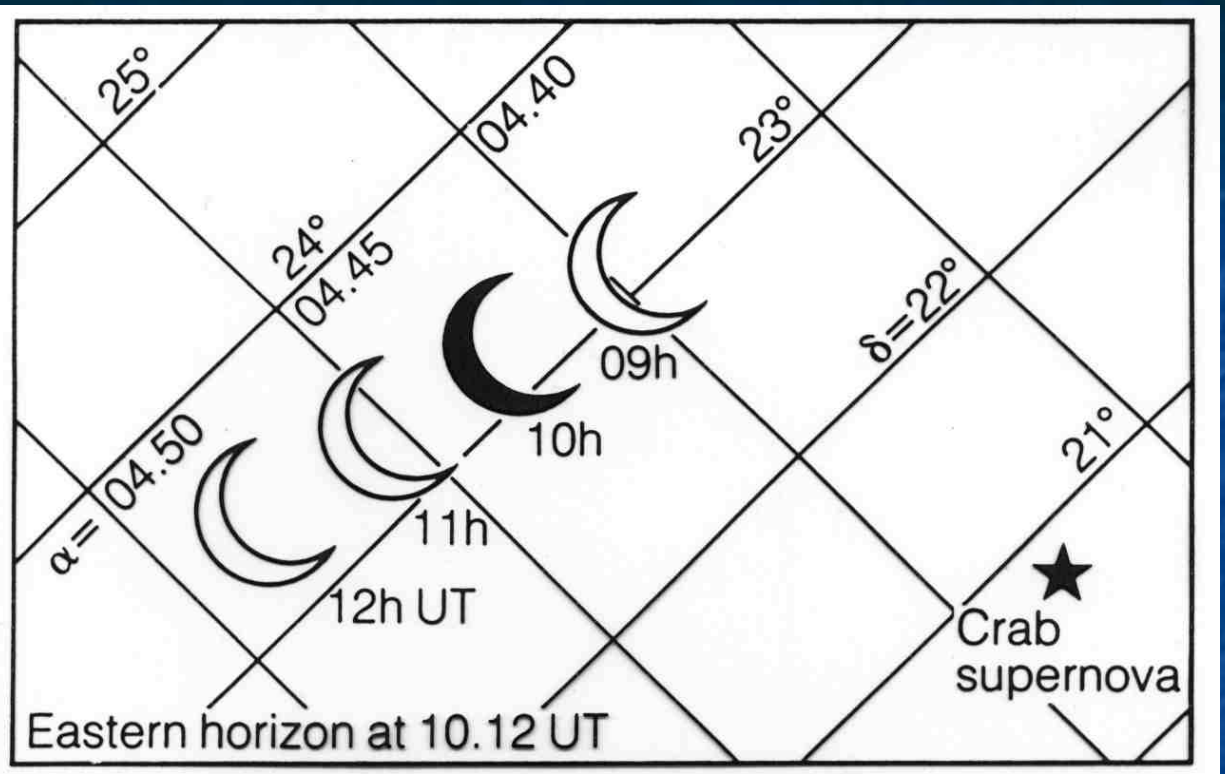


FIG. 10. *Moonrise on 1054 July 5. The Crab supernova and the Moon rose together just after 10 o'clock Universal Time on the morning of 1054 July 5, two and three quarter hours before sunrise as seen from Arizona. For at least two hours the Moon and supernova were visible in the morning twilight. Four successive hourly positions of the Moon are plotted on this diagram, of which the one at 10 h. UT most nearly represents the relative positions of Moon, supernova and horizon at moonrise.*

Supernova observed in Far East

- Chinese, Japanese and Korean emperors had court astronomers (astrologers) to observe the night-sky and report any phenomena
- Comets, nova, eclipses, etc, carefully observed and interpreted
- Interpretations had political significance
- 1n 1054 A.D. guest star reported
- Visible in day (23 days); visible at night (2 years)
- Was it seen elsewhere in world?

"...In the 1st year of the period Chi-ho, the 5th moon, the day chi-ch'ou, a guest star appeared approximately several inches south-east of Tien-Kuan [Zeta Tauri]. After more than a year, it gradually became invisible ..."

Yang Wei-Té, imperial astronomer of the Sung dynasty, in the year 935 b.T.W.

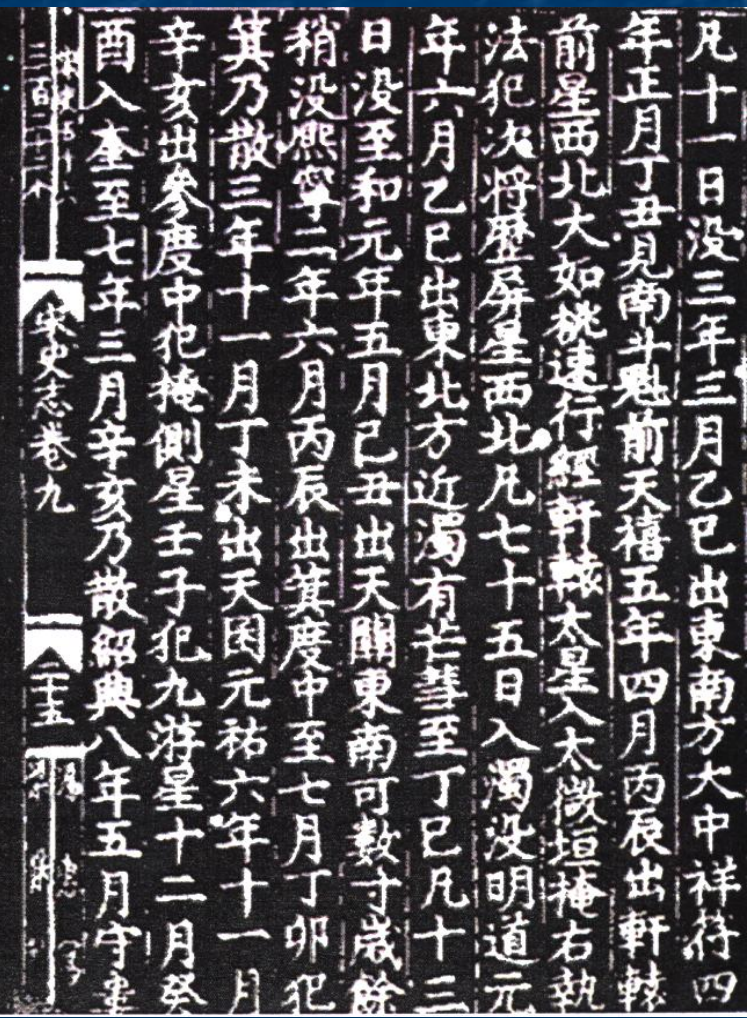


FIG. 1. *Chinese imperial astronomers. The Hsi and Ho brothers receive their commission from the Emperor Yao to organize the calendar and pay respect to the celestial bodies. Although Hsi and Ho were legendary, this late Ching representation of the court presentation illustrates the status of astronomers in China. Franz Kühnert wrote in 1888: 'Probably another reason why many Europeans consider the Chinese such barbarians as on account of the support they give to their astronomers – people regarded by our cultivated Western mortals as completely useless. Yet there they rank with Heads of Departments and Secretaries of State. What frightful barbarism!' This figure reproduced from J. Needham,* Science and Civilisation in China, *Cambridge University Press.*

Crab light-curve

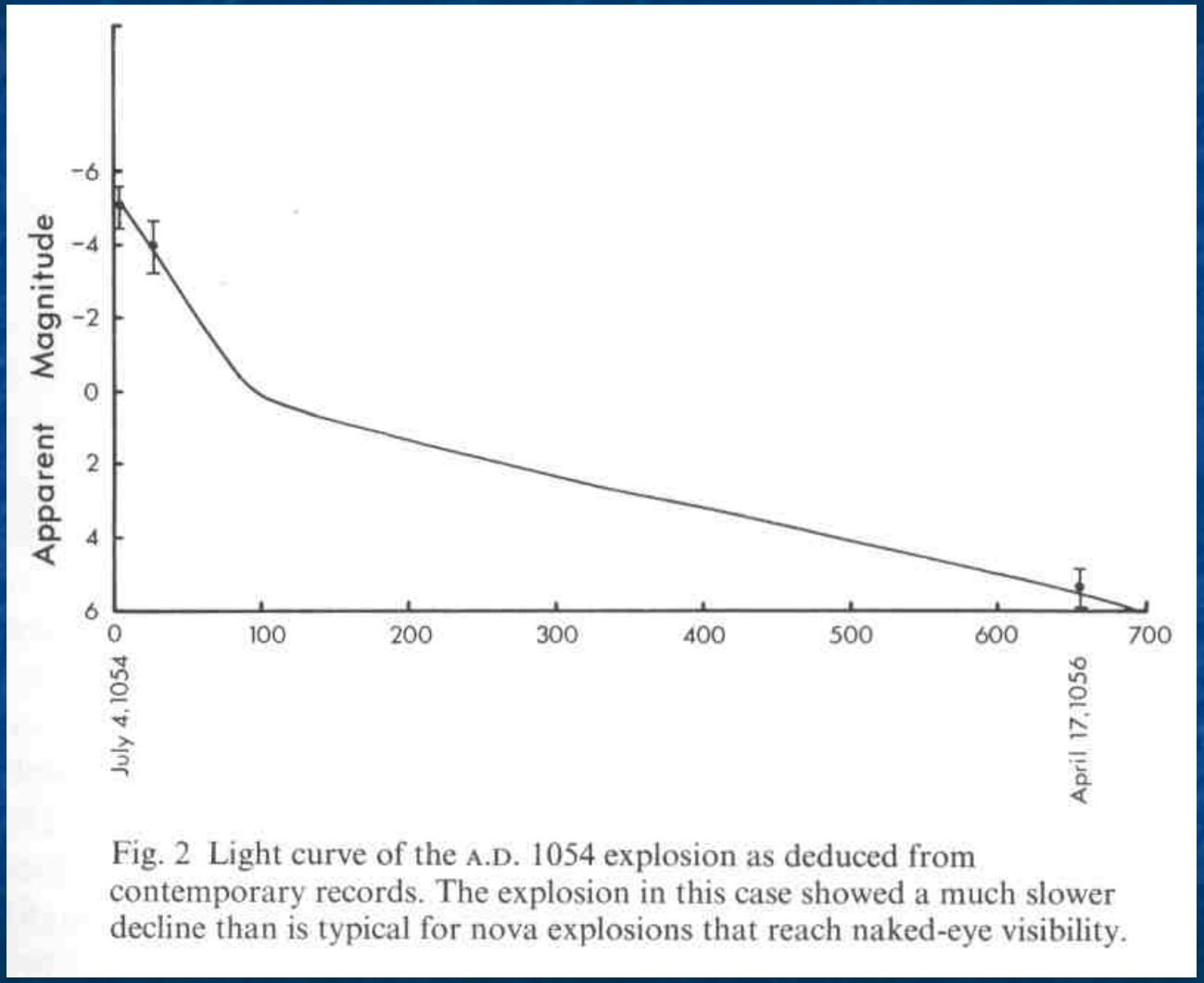


Fig. 2 Light curve of the A.D. 1054 explosion as deduced from contemporary records. The explosion in this case showed a much slower decline than is typical for nova explosions that reach naked-eye visibility.

Telescope Era

Crab rediscovered?

Rediscovery

After two years could no longer be seen with naked eye at night

- After invention of telescope, six centuries later, Crab Nebula detected as fuzzy object by Bevis
- Many Nebula had been found…origin, nature unknown

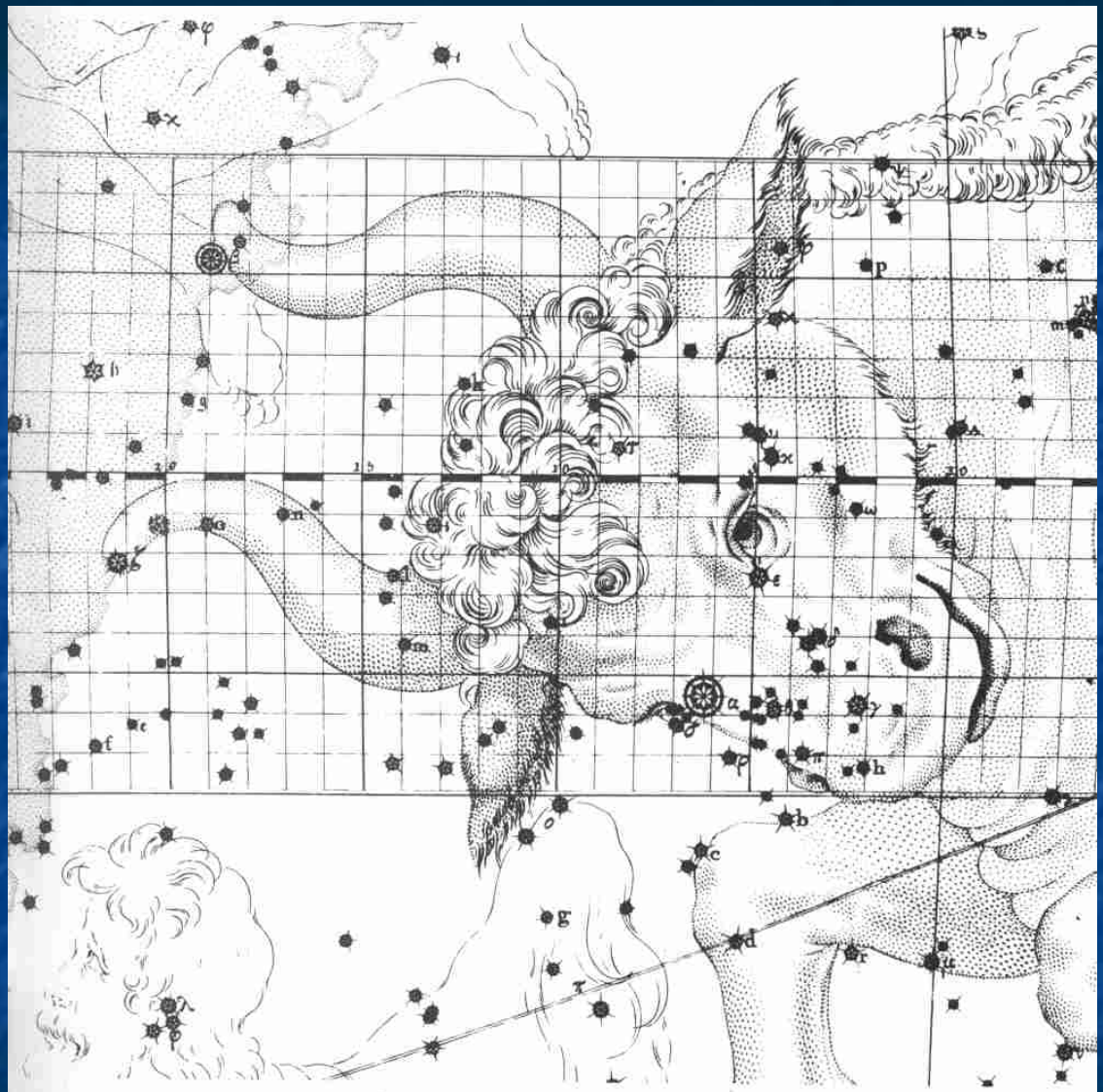
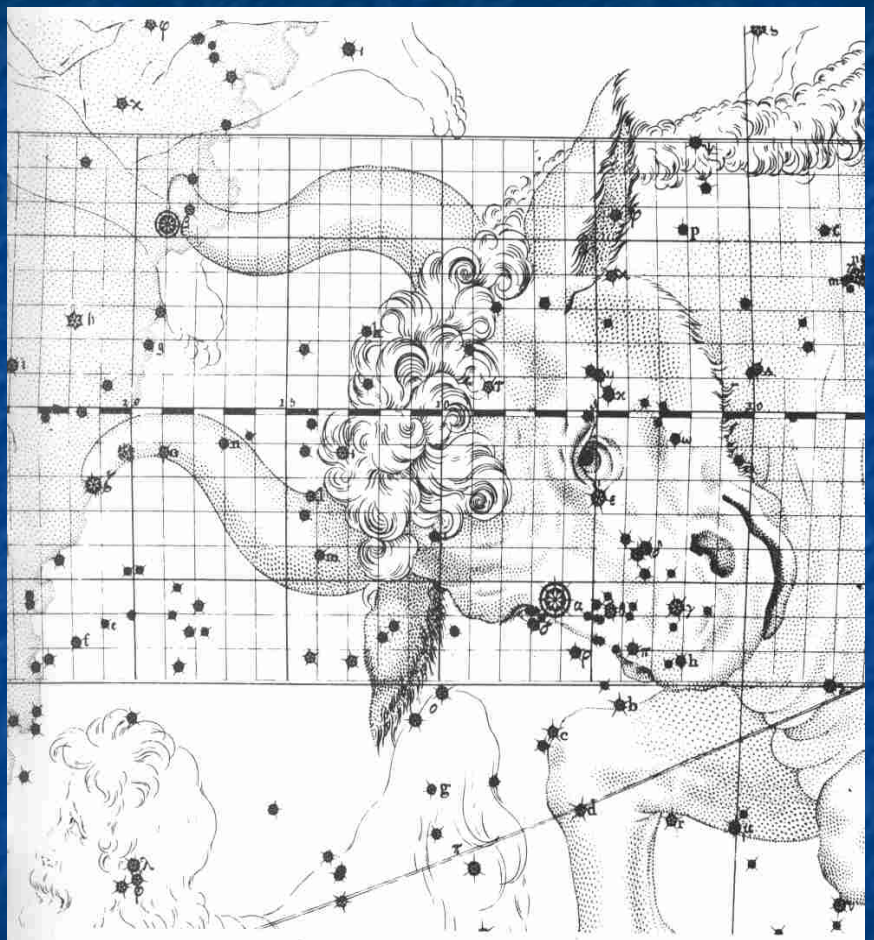


Fig. 3 Portion of Plate XXIII from John Bevis' Uranographia Britannica showing the constellation Taurus. The Crab Nebula, found by Bevis in 1731, is marked as a faint round symbol above and to the right of Zeta Tauri.

History

- 1531, 1607, 1682 Halley's comet seen; predicted to reappear between horns of Taurus in 1758
- 1758, August 28: "found the comet of 1758 below the southern horn, near Zeta Tau" Messier
- At Christmas reported by French peasant
- 1772 Messier Catalog of non-comets: M1
- 1892 First photo of Crab
- 1913-15 Slipher takes first spectra
- 1921 Lampland expansion of nebula
- Lundmark notes proximity to 1054 guest star
- Duncan wisps moving out radially
- 1953 Shklovsky proposes synchrotron origin of radio sources
- Optical polarization (13%) seen in Crab



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- 1942 Duyvendak and Mayall/0ort confirmed

The Crab Nebula: named in 1850 by Irish astronomer, the Third Earl of Rosse

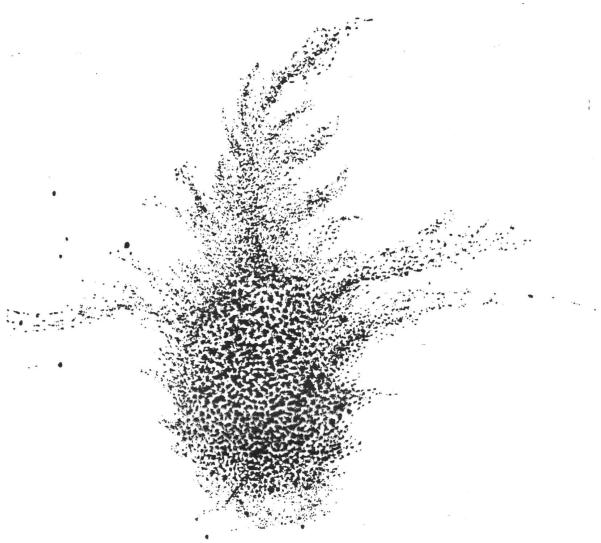


FIG. 26. *The 'Crab'. Lord Rosse's first published picture of M1 christened it with its distinctive name. Rosse later came to regret this representation of the Crab Nebula; it is nothing like his later accurate drawing.*

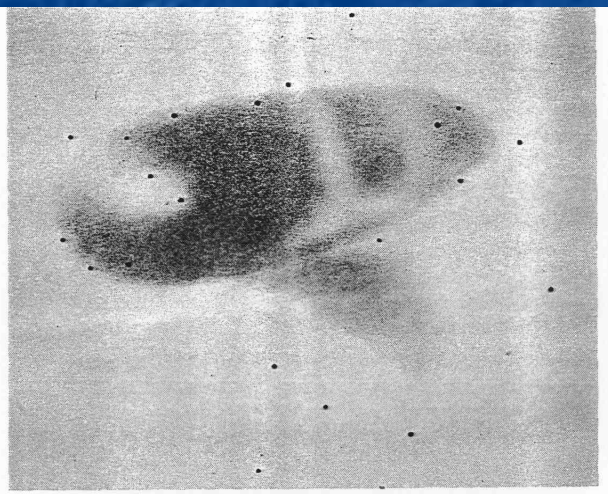
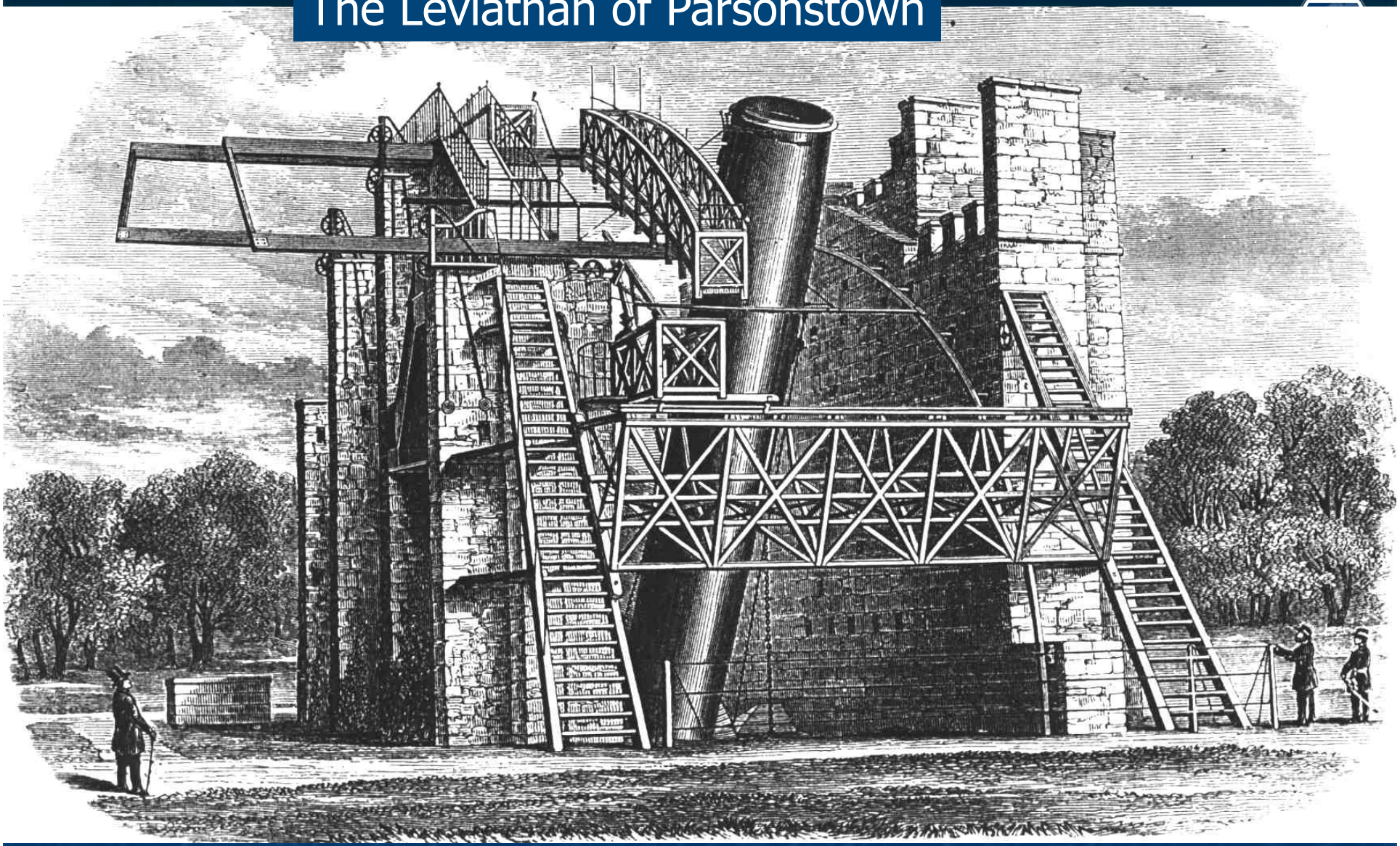


FIG. 27. *Rosse's Crab Nebula. In 1879 was published R. J. Mitchell's compilation of Rosse's observations of the Crab Nebula and the stars nearby. The accuracy of these observations can be seen by comparing the lithograph with photographs like Fig 30. The lithograph shows the bay to the east (left) and extension to the southwest (lower right) as well as recognizable internal detail. Photo by the Royal Greenwich Observatory from material provided by the Royal Astronomical Society.*

The Leviathan of Parsonstown



1845: This 72 inch telescope was to be the largest telescope built until the 100 inch on Mount Wilson, California in 1910.

Crab Nebula: rename?

M1—THE IRISH NEBULA

By W. B. Somerville
Department of Physics and Astronomy, University College London

It is suggested that The Crab Nebula is a poor name for an object that much more resembles a shaggy dog. The name The Irish Nebula is proposed instead, in honour of Lord Rosse.

In all the extensive and continuing discussion[1,2] of the object known as *The Crab Nebula*, one simple fact is rarely mentioned—in its appearance, the object does not remotely look like a crab. Moreover, unlike others such as the Orion nebula and the Andromeda nebula, the Crab nebula is not in the constellation of the same name, a potential cause of confusion. Taking these points together prompts the idea that a more suitable name should be found.

An obvious approach is to examine the appearance in modern photographs. Good high-resolution black-and-white photographs, showing the filaments, have always reminded me very much of the structure seen in very-short-exposure ($\sim 10^{-5}$ sec) spark photographs of the shattering of a jug of milk[3,4], consistent with the violent motions known to be present, although on a very different time-scale. A possible name might therefore be *The Spilt Milk Nebula*. The essential objection to such a name is that it is totally shapeless.

Not only does it not resemble a crab, the nebula also clearly does not resemble a pineapple[5]. It is possible, however, that the Birr Castle observers thought of their first drawing not as a pineapple but as some creature of the sea, perhaps even an elongated crustacean like a lobster or crayfish. In many of the old drawings of constellation figures[6], Cancer the Crab appears as a lobster.

To be fair to the name, in the Palomar Sky Survey photographs the Crab does have some similarity to a crab, albeit rather a small one. However, the image there is heavily overexposed, so this doesn't count. In any case, it actually looks much more like a small spider, squashed onto the print. This would make for an unattractive name. The idea of something animate is appealing, however; and indeed a very good representation can be found without any difficulty. If in its photographs the nebula looks like any creature at all, it surely is a shaggy dog. This is seen particularly clearly in the well-known colour picture from the Hale Observatories[11], oriented to have East downwards. The dog even appears to be wearing a collar. I hesitate, however, to propose the name *The Shaggy Dog Nebula*, for fear that the suggestion might not be taken seriously.

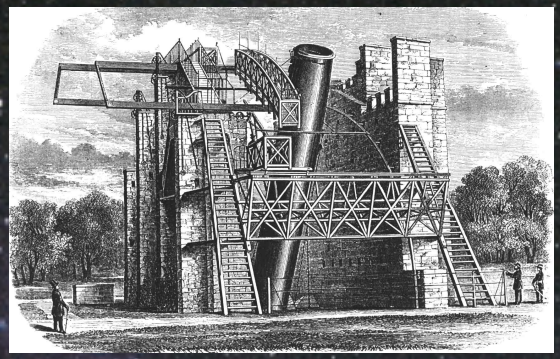
Indeed, a better name can be found. The shape of the nebula M1 not only is like a shaggy dog, it also is very much like the map of Ireland. This comes about, of course, because Ireland itself is like a shaggy dog: with East upwards, Ulster is the

The Irish Nebula ?

Footnote: Better Name for Crab Nebula?

The Irish Nebula!

2009: Irish Post Office marks Astronomy Year with image of Crab



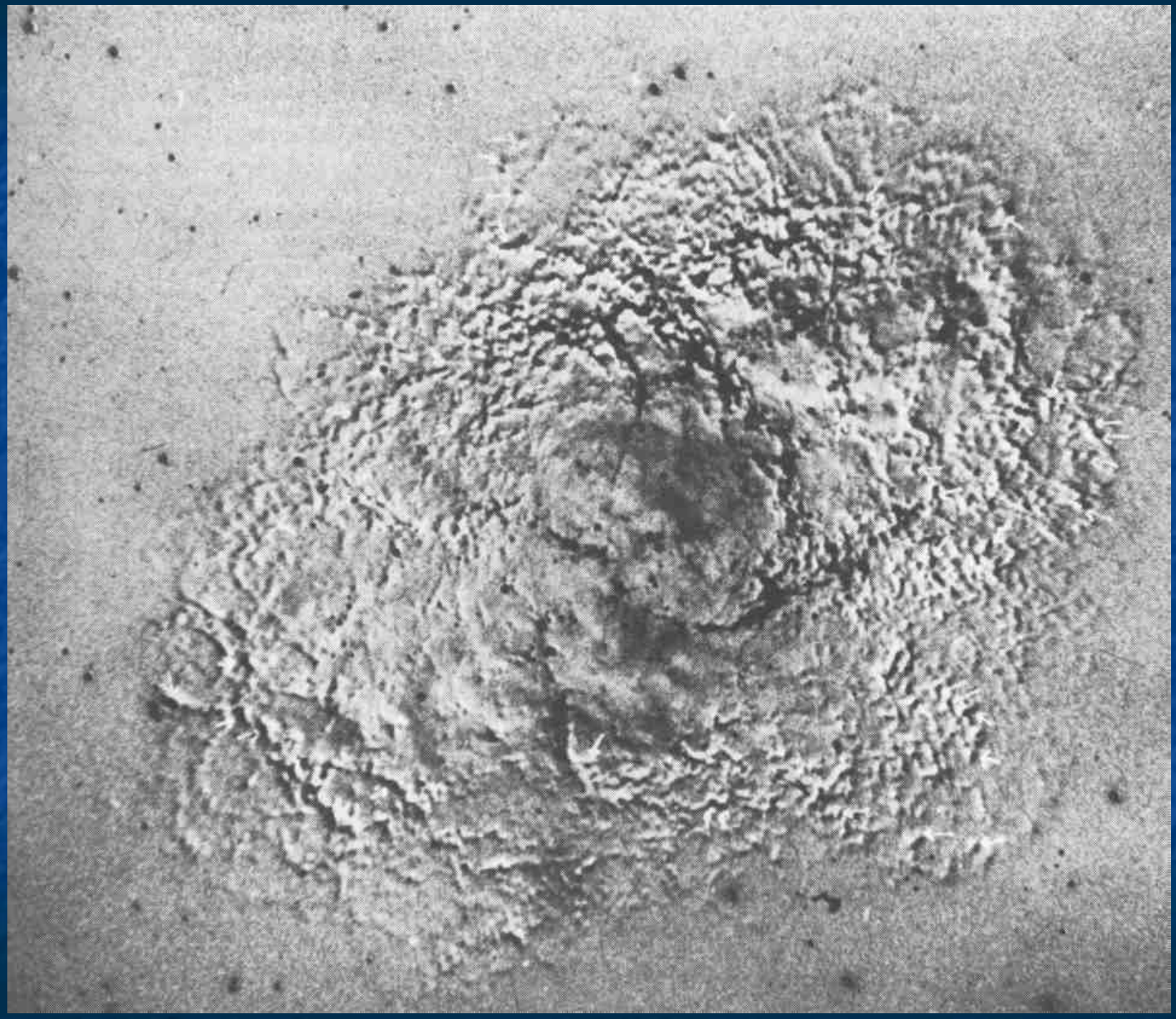
Crab Astrophysics

- Reference:
- "The Crab Nebula: An Astrophysical Chimera", J.J. Hester, Ann.Rev.Astron.Astrophys., 2008

- "You can divide astronomy into two parts: the of Crab Nebula and the astronomy of everything else" Burbidge

- "Most observed object in the sky (beyond the Solar System). ..> 5,000 references."

The Crab Nebula: still alive!



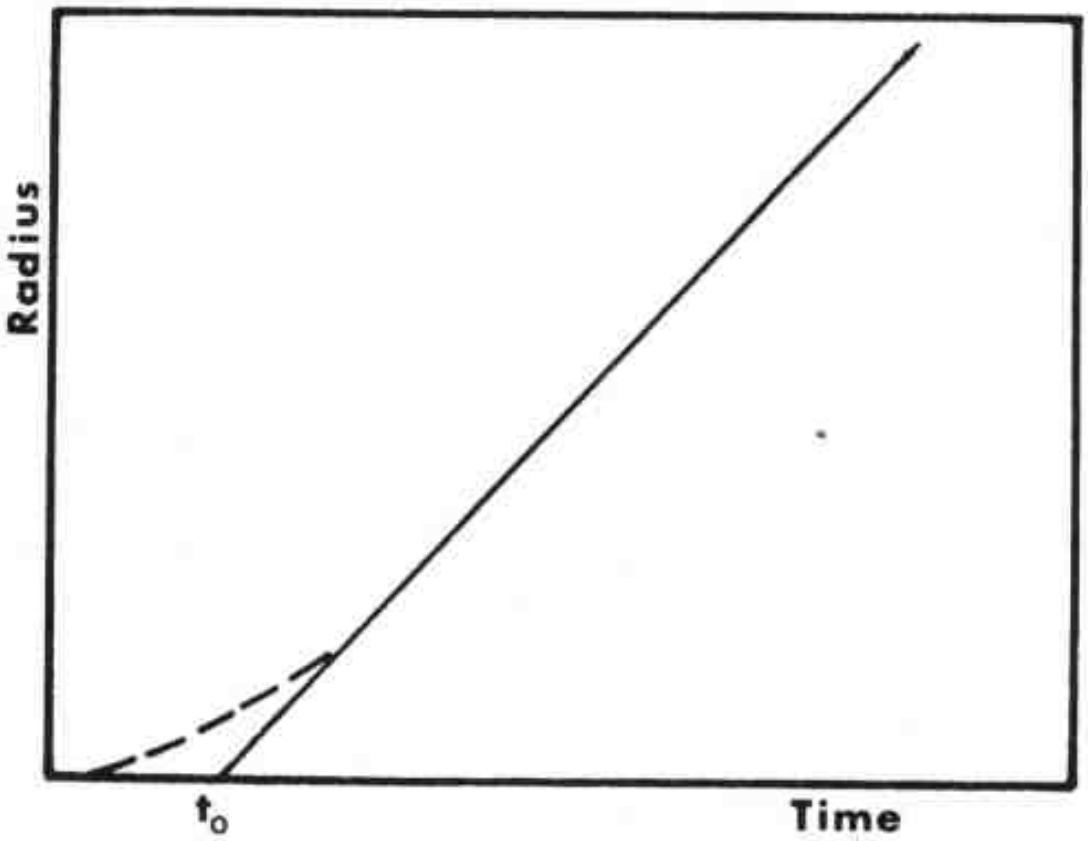
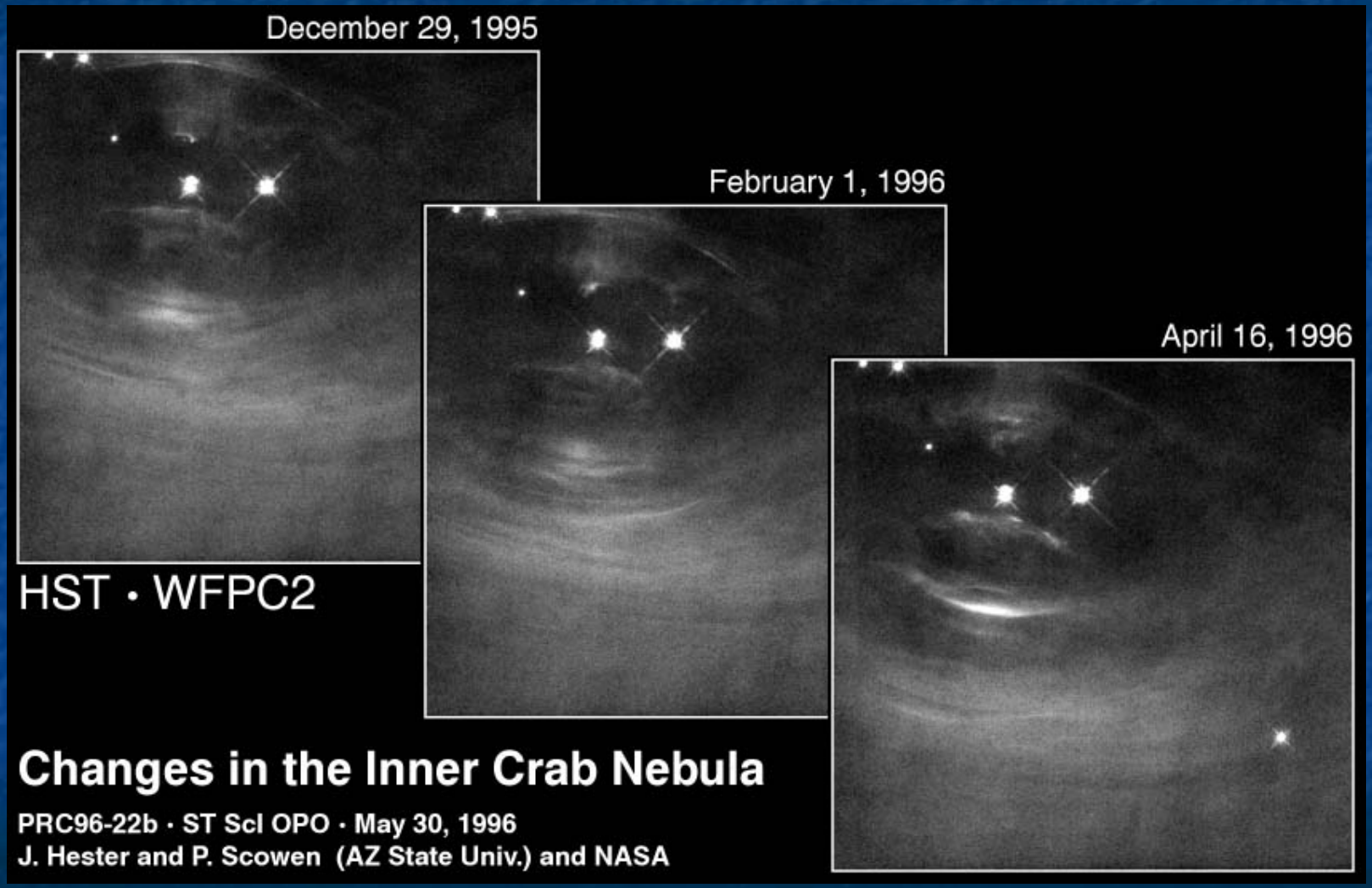


Fig. 15 Schematic illustration of the time behaviour of the Crab Nebula expansion. The presently-observed expansion rate gives an age that is too young. This indicates that the nebular expansion must have accelerated in the past.

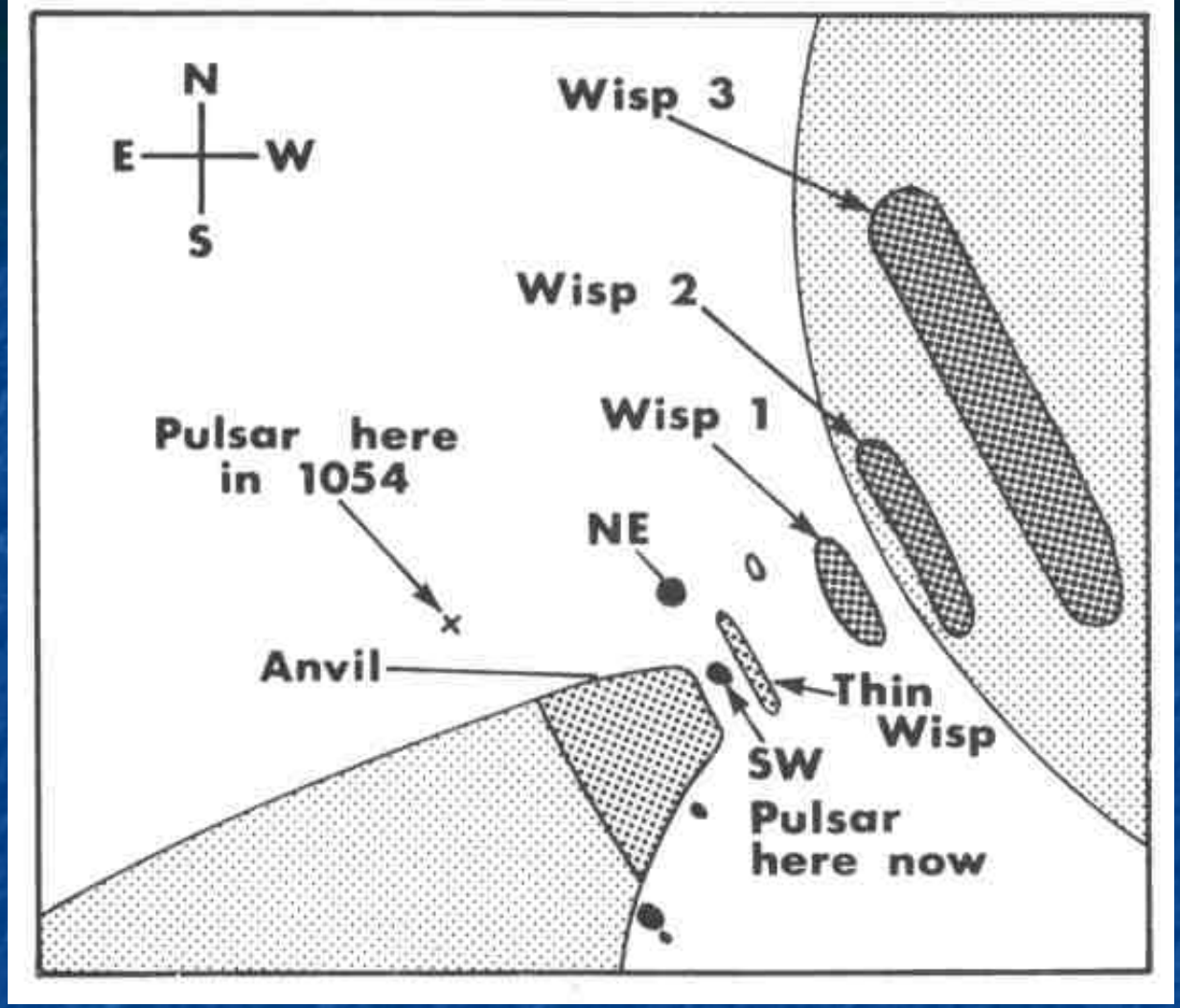
Center of Nebula

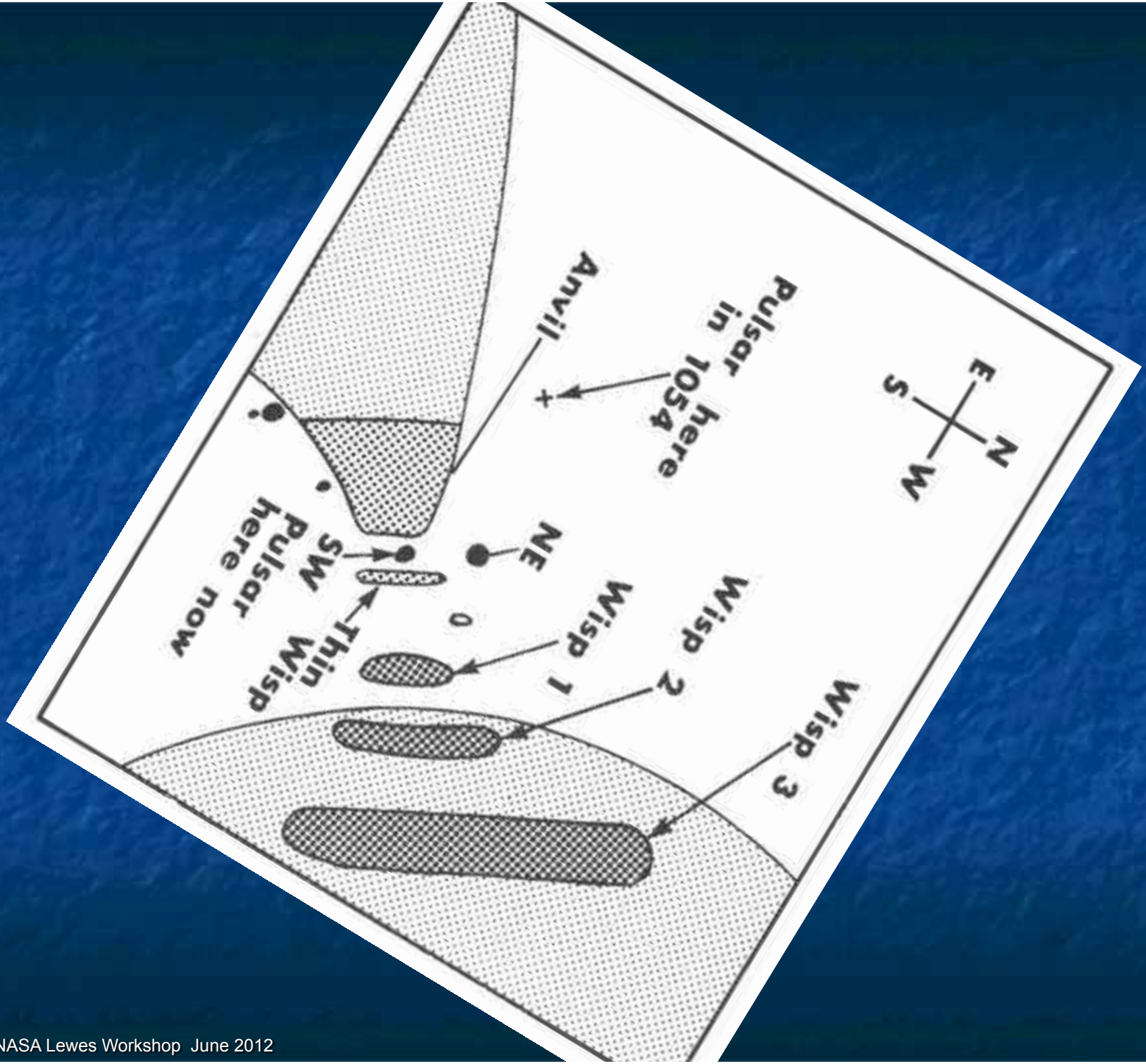
- “Two stars at center; neither of them is anyway unusual” nearly Weekes, 1969

Crab Nebula

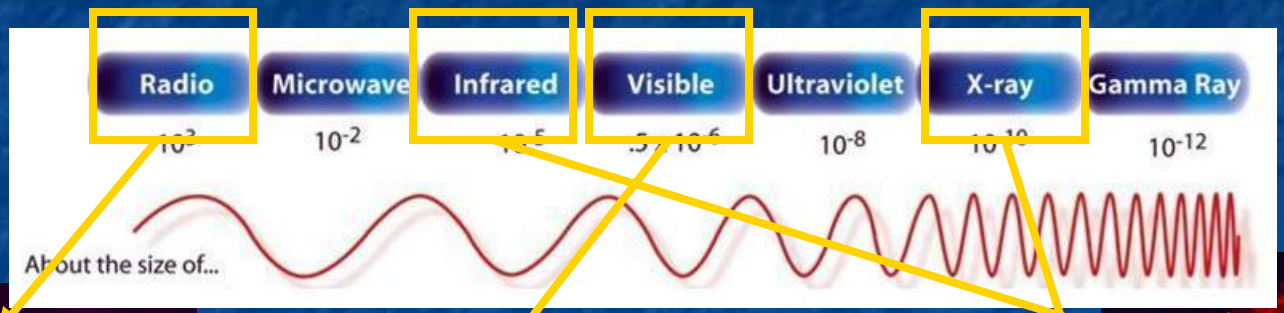


Some have said they could see the pulsar pulsing


N
E
W
S
Wisp 3
Wisp 2
Wisp 1
Pulsar here
in 1054
NE
Anvil
Thin
Wisp
SW
Pulsar
here now

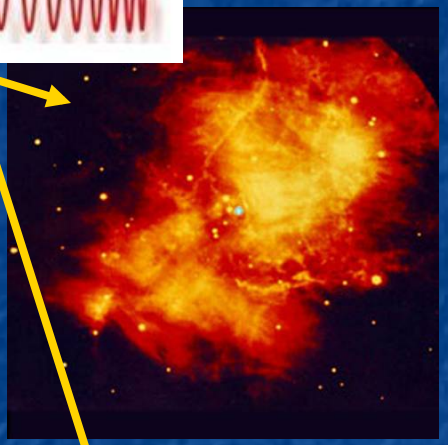

Anvil
Pulsar here in 1054
E
S
N
W
NE
SW Pulsar here now
Thin Wisp
Wisp 1
Wisp 2
Wisp 3

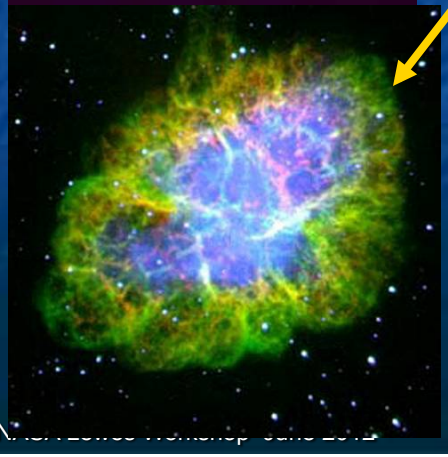
Crab – brightest object in the sky at many energies:



← Radio Image
… cool gas from stellar explosion

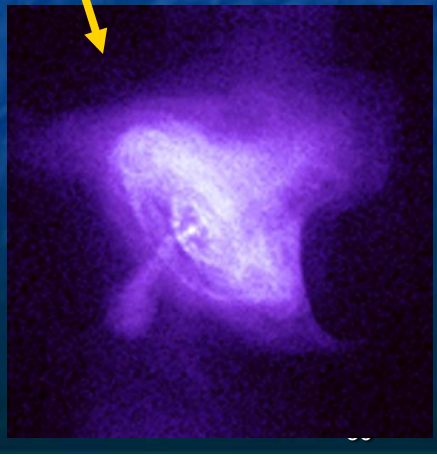
Infra-red Image →
… warm gas and dust





←Optical Image
… hot gas and energetic particles

X-ray Image →
… jets and shells of energetic particles



Ion pictures

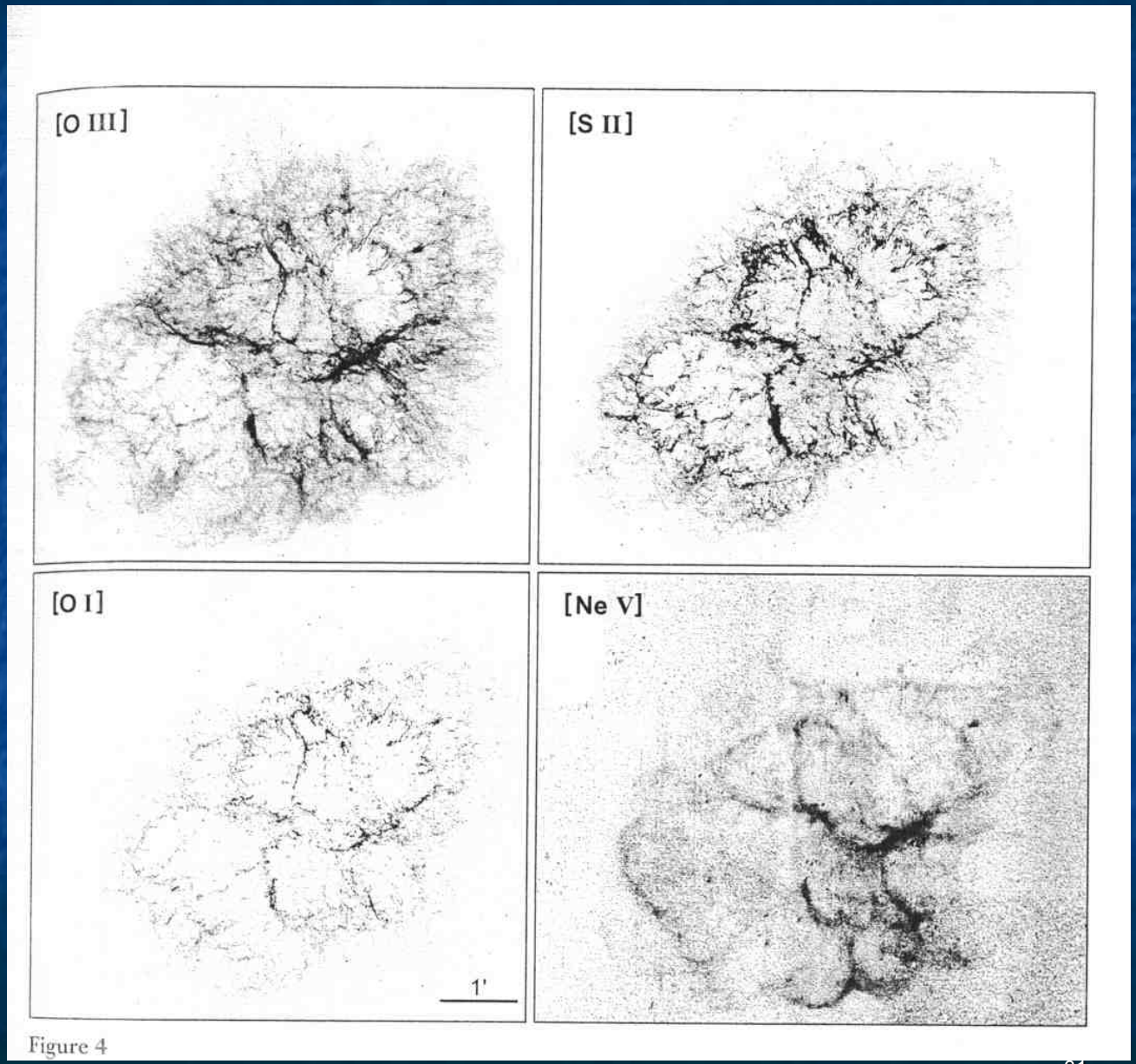
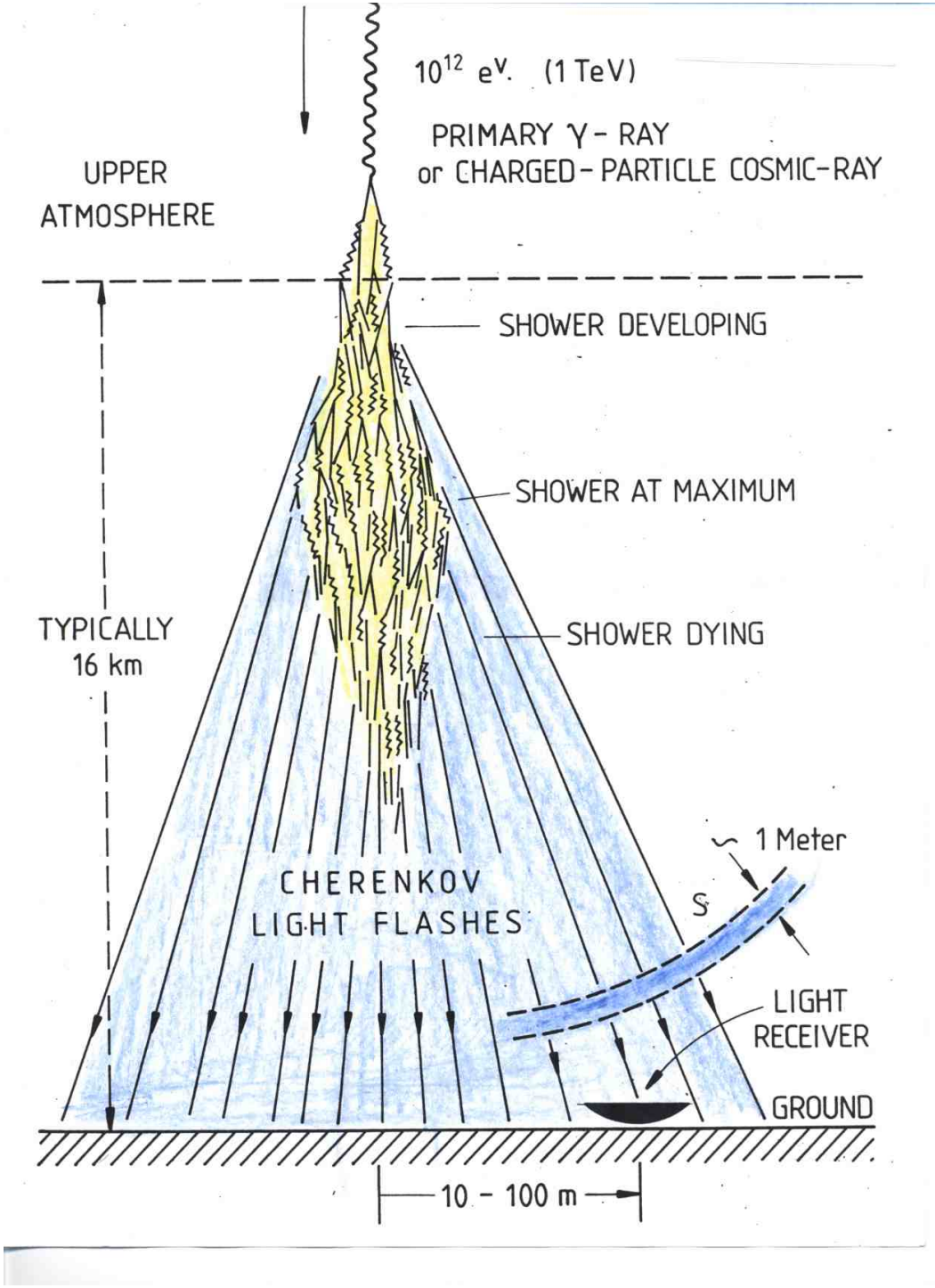


Figure 4

Crab as Gamma Ray Source

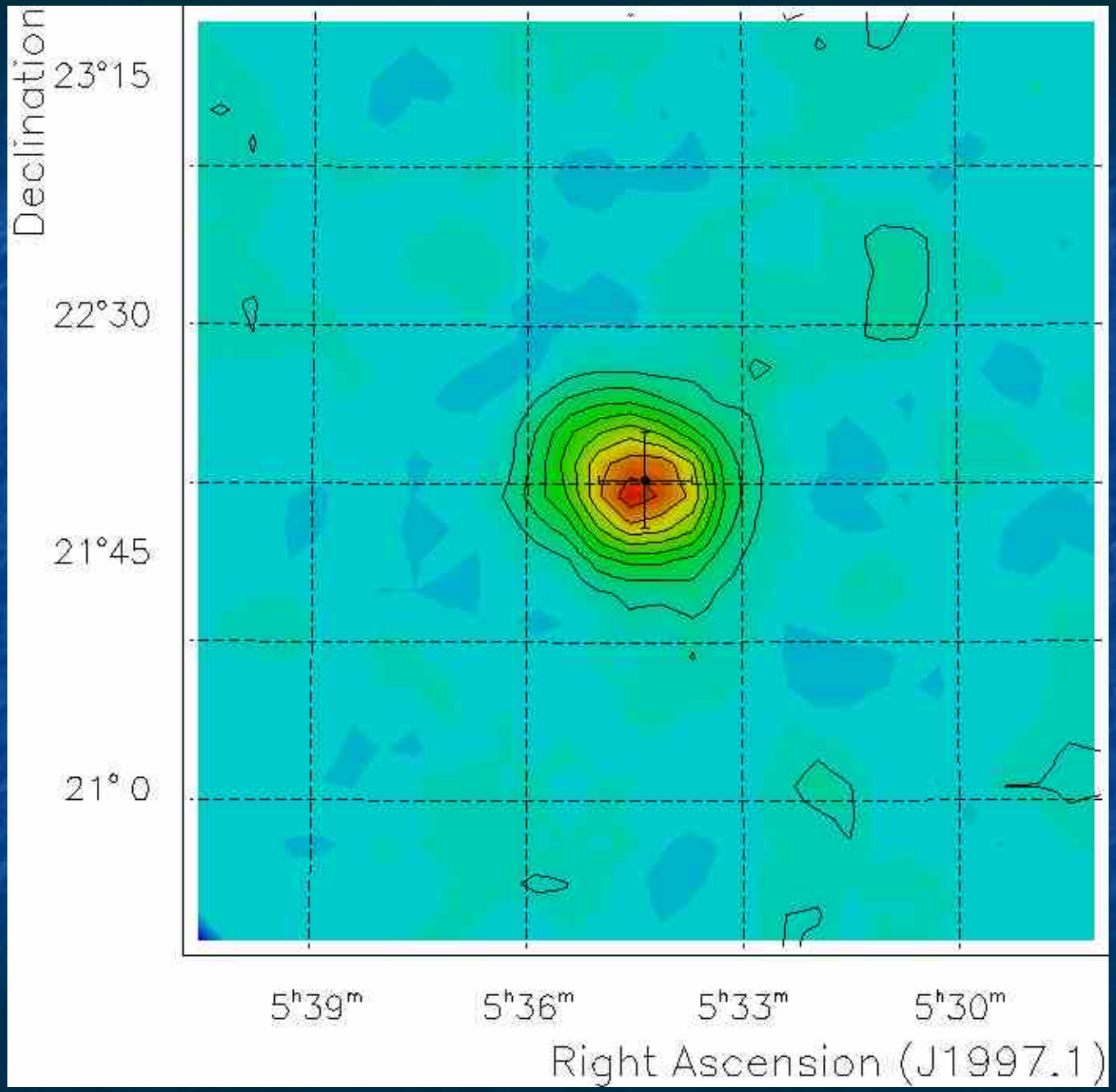
- Detected as 100 MeV source in 1965-72 in balloon experiments
- Pulsar signal dominated
- Predicted to be TeV source
- Until 1985 unsuccessful attempts using Cherenkov technique



THE ATMOSPHERIC CHERENKOV TECHNIQUE IS USED TO DETECT SMALL COSMIC RAY SHOWERS

Simple Technique,
Simple Detectors,
Low costs

Whipple 10m



First Credible TeV Source. 1989

Publication

THE ASTROPHYSICAL JOURNAL, 342:379–395, 1989 July 1

OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

T. C. WEEKES,[1] M. F. CAWLEY,[2] D. J. FEGAN,[2] K. G. GIBBS,[1] A. M. HILLAS,[4] P. W. KWOK,[1] R. C. LAMB,[5] D. A. LEWIS,[2] D. MACOMB,[5] N. A. PORTER,[2] P. T. REYNOLDS,[1,3] AND G. VACANTI[5]

Received 1988 August 1; accepted 1988 December 9

ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the 9.0 σ level, corresponding to a flux of 1.8×10^{-11} photons cm^{-2} s^{-1} above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuum emission from the pulsar cannot be ruled out, it seems more likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula.

Subject headings: gamma rays: general — nebulae: Crab Nebula — pulsars — radiation mechanisms

I. INTRODUCTION

The observation of polarization in the radio, optical, and X-ray emission from the Crab Nebula is usually taken as confirmation of the synchrotron origin of the radiation and is a strong indication of the presence in the nebula of a reservoir of relativistic electrons with energies up to 1 TeV. The presence of the radio pulsar, PSR 0531, near the center of the nebula provides a source for the on-going injection of relativistic electrons into this reservoir. The collision of the synchrotron-radiating electrons with synchrotron-radiated photons within the nebula inevitably results in a hard photon spectrum (at some level) that extends from the X-ray into the gamma-ray energy range; the shape of the spectrum mirrors that of the soft photon spectrum but with greatly reduced intensity. The Compton synchrotron model of the nebula was first developed by Gould (1965) and was refined by Rieke and Weekes (1969) and by Grindlay and Hoffmann (1971). A strong flux of gamma rays was predicted with maximum luminosity in the 0.1–1.0 TeV energy range. The gamma-ray flux level depends on the strength of the nebular magnetic field, which is a free parameter in the model and is little constrained by observations at other wavelengths. However, based on equipartition arguments, it is estimated to be $\sim 10^{-3}$ G.

Subsequent to the discovery of PSR 0531 in the nebula, TeV gamma-ray observations concentrated on the pulsar because greater sensitivity could be achieved by the assumption of synchronization of the gamma-ray emission with the periodic radio emission. Several detections were reported at very high energies (Grindlay 1972; Jennings *et al.* 1974; Grindlay Helmken, and Weekes 1976; Porter *et al.* 1976; Erickson Fickle, and Lamb 1976; Vishwanath 1982; Vishwanath *et al* 1985; Gupta *et al.* 1977; Gibson *et al.* 1982*b*; Dowthwaite *et al* 1984; Turner *et al.* 1985; Bhat *et al.* 1986), but the statistica significance was not high, and upper limits were also presente which appeared to be in conflict with the reported fluxe (Helmken *et al.* 1973; Vishwanath *et al.* 1986; Bhat *et al.* 1987 At energies above 1 TeV there were also reports of emissio from the direction of the Crab (Mukanov 1983; Boone *et a* 1984; Dzikowski *et al.* 1981; Kirov *et al.* 1985), but, because o the limited angular resolution and the absence of accurat timekeeping, it was not possible to identify the source of th observed signal with the nebula or the pulsar. Again there ma be conflicting upper limits (Craig *et al.* 1981; Watson 1985). A 100 MeV energies (which are accessible to study by spar chambers on satellites), both a pulsed and steady componen were detected (Kniffen *et al.* 1977; Hermsen *et al.* 1977; Clea

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It is customary for the senior author to sign the publication!

The Brightest TeV Object in the High Energy Sky

Simple Picture:

- Pulsar left behind = Core of Star
- Spinning Neutron Star; rotation 30 times per second
- Optical pulsar discovered
- Expanding Nebula: contains outer layers of star
- Electrons from pulsar collide in Nebula to produce gamma-rays

Crab Nebula

TeV Gamma-ray energy spectrum confirms equipartition magnetic field as 300 microgauss

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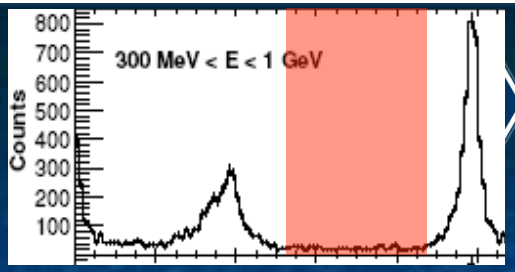
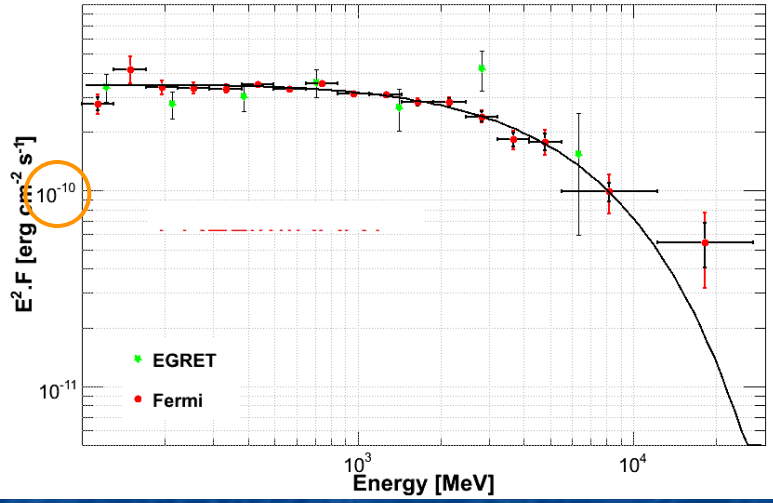
Strongest steady TeV source in the sky; standard candle

The Crab above 100 MeV



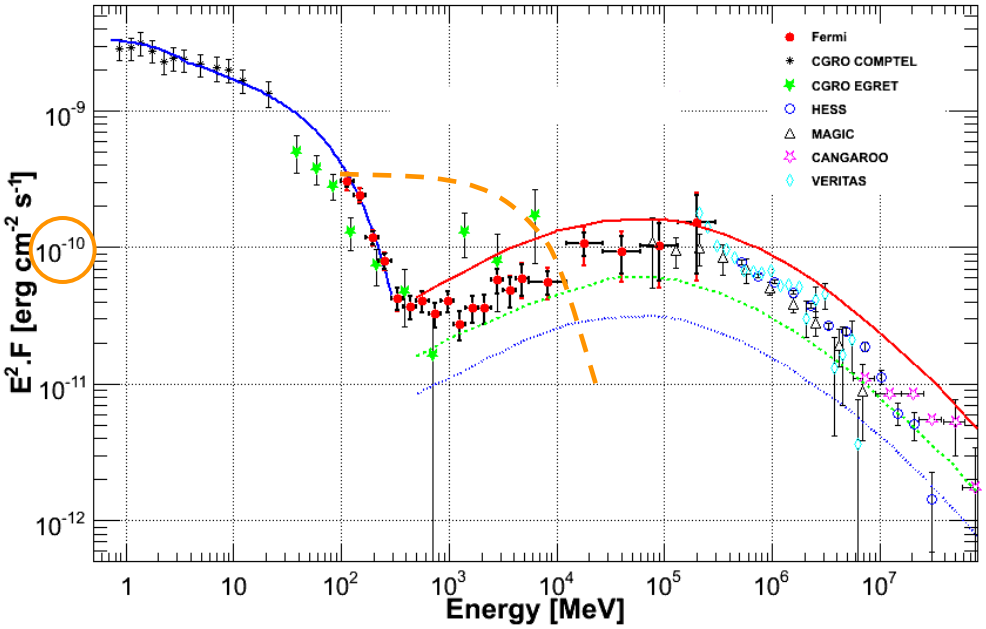
Pulsar 100 MeV to 20 GeV



Hyper-exponential cutoff excluded in phase-averaged spectrum.

WARNING: Phase matters!

Nebula from MeV to TeV

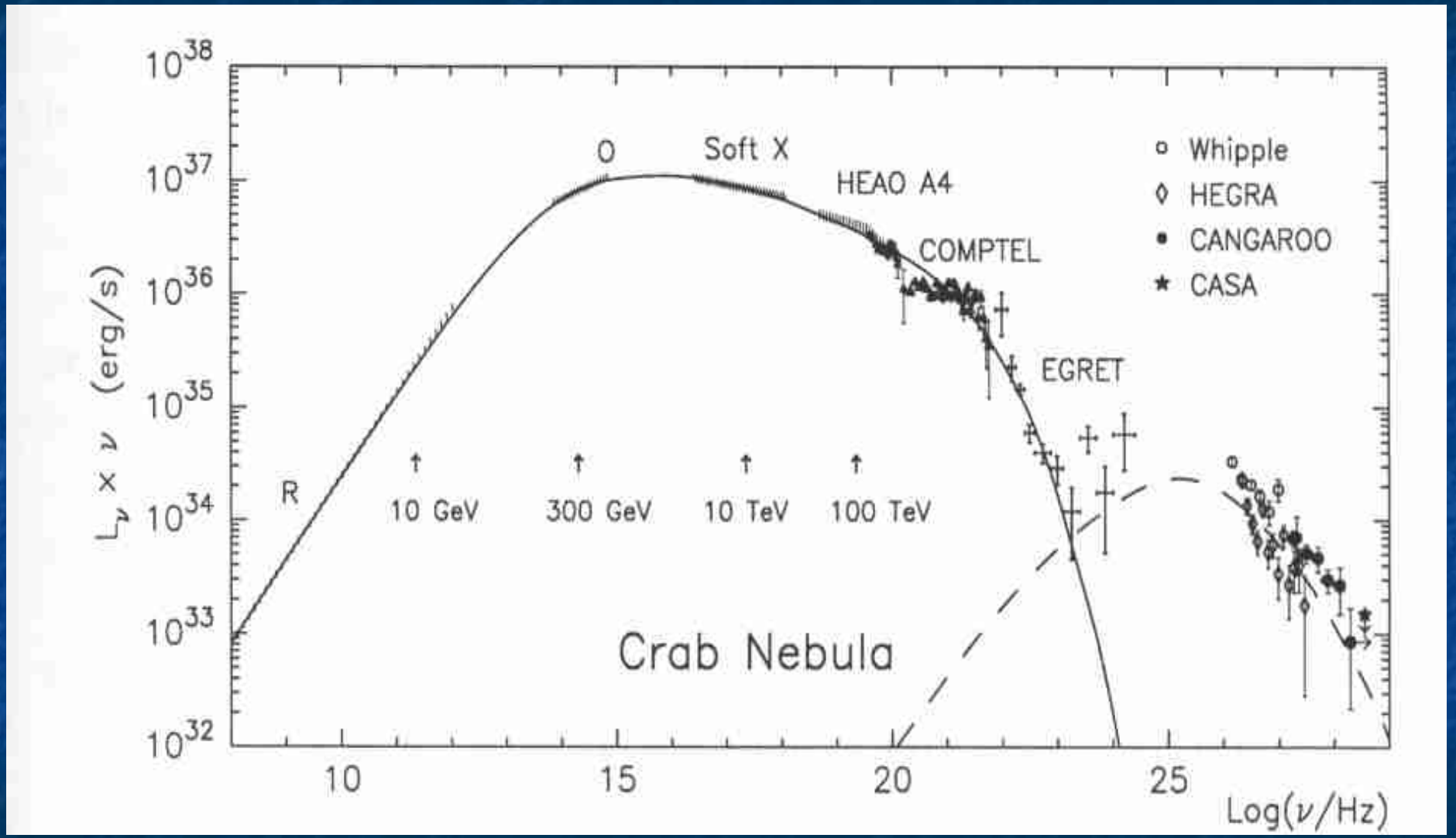


2 components: Synchrotron + Inverse Compton extending to TeV.

Mean B field in nebula 100 to 200 μG.

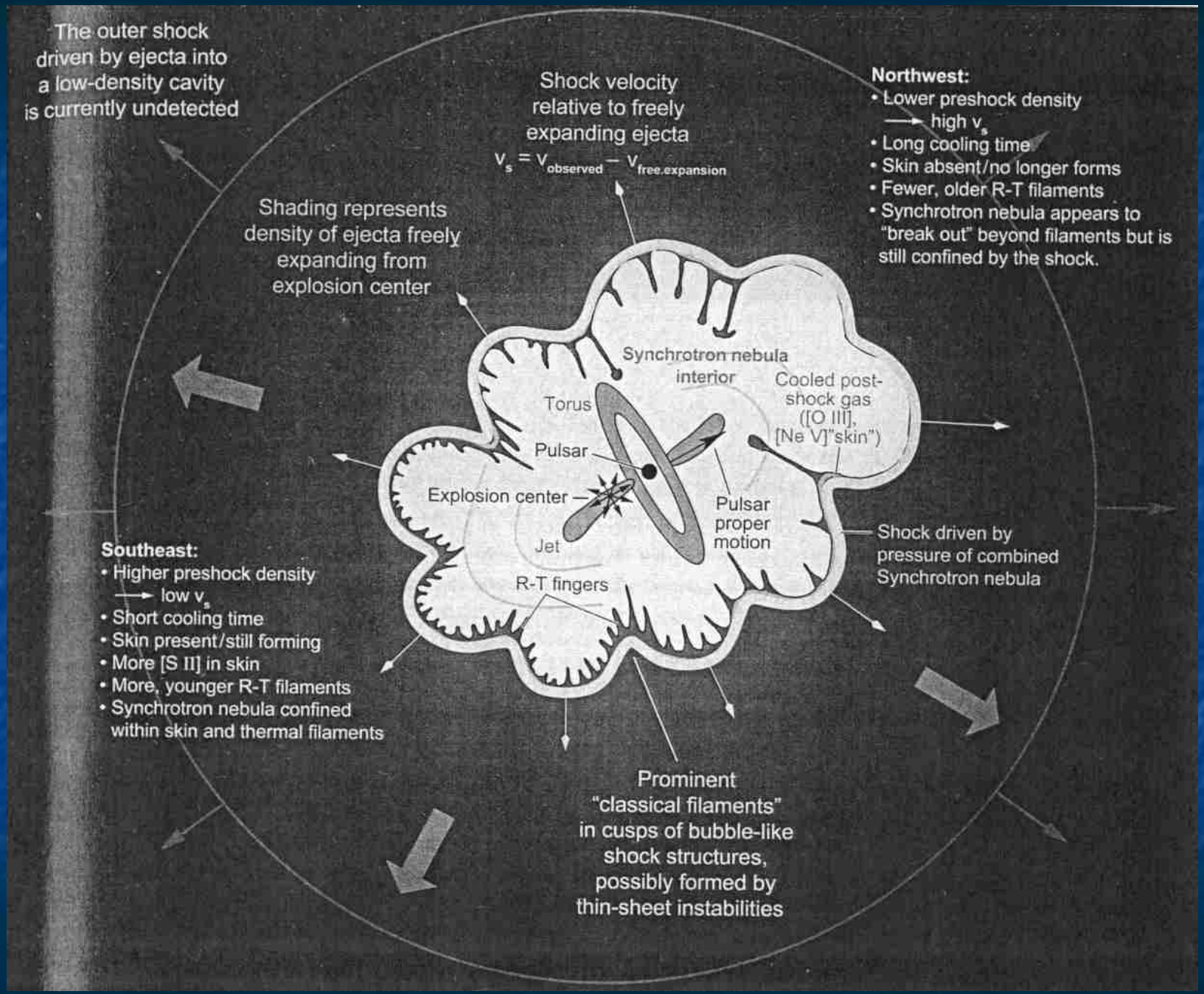
Abdo et al. 2010, ApJ, 708, 1254

Hays. 2012


10^{38}
10^{37}
10^{36}
10^{35}
10^{34}
10^{33}
10^{32}
$L_\nu \times \nu$ (erg/s)
O
Soft X
HEAO A4
COMPTEL
EGRET
R
10 GeV
300 GeV
10 TeV
100 TeV
Whipple
HEGRA
CANGAROO
CASA
Crab Nebula
10
15
20
25
Log(ν/Hz)

The Four Components

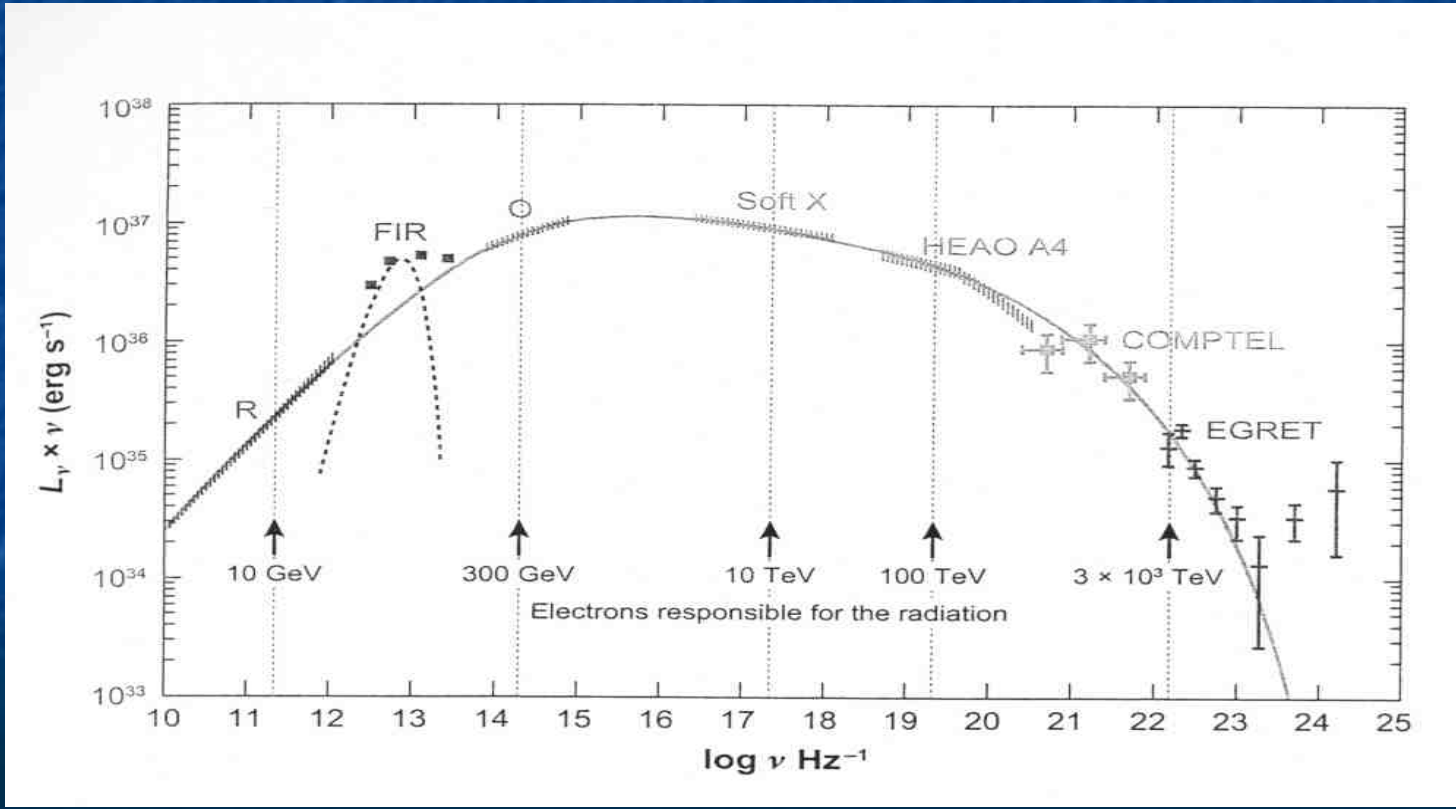
- (1) The Pulsar
- (2) The Synchrotron Nebula
- (3) Thermal Filaments
- (4) Freely Expanding Ejecta


The outer shock driven by ejecta into a low-density cavity is currently undetected
Shock velocity relative to freely expanding ejecta
$v_s = v_{observed} - v_{free.expansion}$
Shading represents density of ejecta freely expanding from explosion center
Northwest:
• Lower preshock density → high v_s
• Long cooling time
• Skin absent/no longer forms
• Fewer, older R-T filaments
• Synchrotron nebula appears to "break out" beyond filaments but is still confined by the shock.
Synchrotron nebula interior
Cooled post-shock gas ([O III], [Ne V]"skin")
Torus
Pulsar
Explosion center
Pulsar proper motion
Jet
R-T fingers
Shock driven by pressure of combined Synchrotron nebula
Southeast:
• Higher preshock density → low v_s
• Short cooling time
• Skin present/still forming
• More [S II] in skin
• More, younger R-T filaments
• Synchrotron nebula confined within skin and thermal filaments
Prominent "classical filaments" in cusps of bubble-like shock structures, possibly formed by thin-sheet instabilities

By the Numbers:

- (1) “The Crab Pulsar powers the Nebula”
- First pulsar in visible
- Period 33 msec
- If r=10km, mass 1.4=Mo, I=1.1x10^45 erg-cm^2, then spin-down luminosity= 4x^38 erg/s ~ 130,000Lo
- If braking index n=2.51, original period =19msec
- (2) “The Shocked Pulsar a Wind fills the Crab Synchrotron Nebula”
- Shock between cold fast wind and thermal ejecta at 3x10^17cm, about distance to wisps
- Electrons to 10 PeV
- Magnetic field = 3x10^-4 gauss
- Nebula size decreases with energy

- "The very highest energy emission from the Crab above frequencies of ~ 10^23 Hz is thought to be due to inverse Compton radiation"

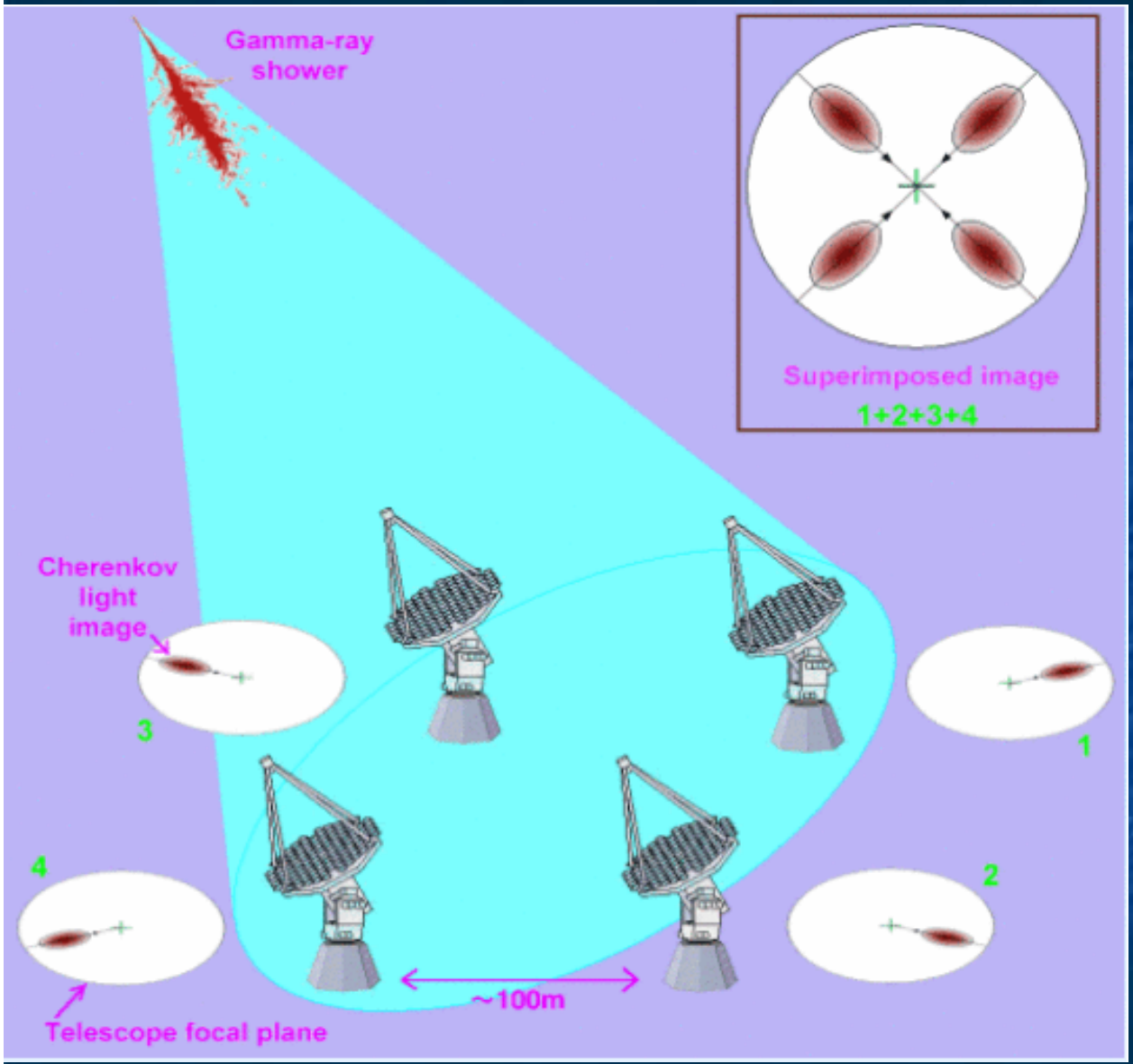


By the Numbers (cont.)

- (3) “Thermal Filaments form a Cage around the Synchrotron Nebula”
- Network of filaments form cage around synchrotron neb.
- Filaments have velocity ~ 700-1800 km/s
- Proper motion gives distance of Crab as 2kpc
- Helium prominent
- Photoionisation by hard synchrotron continuum
- Dust
- (4) “There is freely Expanding Ejecta around the easily visible Crab”
- Only recently recognised
- Missing mass; should be 10^51 erg; only 3x10^49 erg obs.
- Shock outside outside edge, e.g. OIII line
- Also CIV lines in absorption (~1550A)

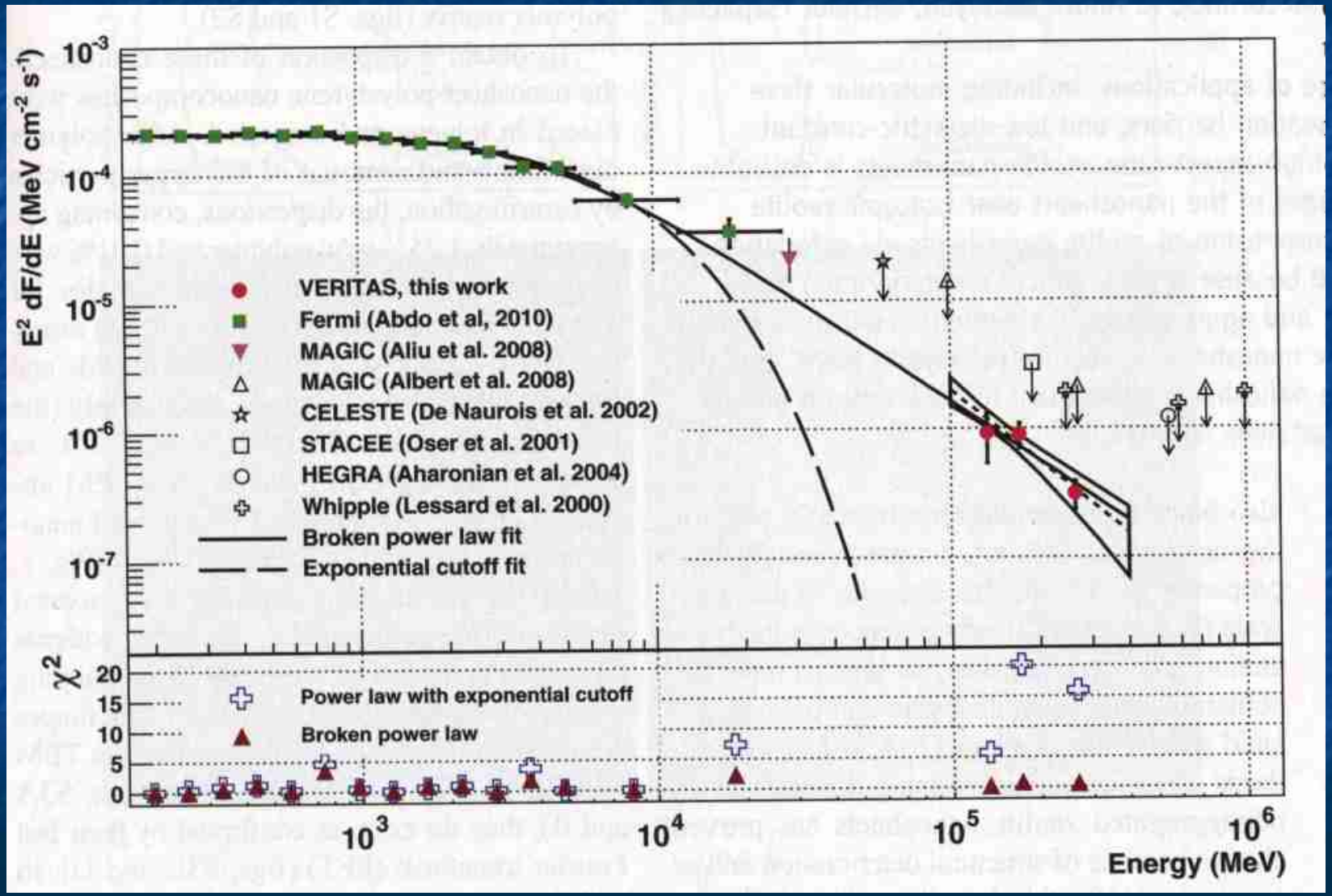
The Crab Pulsar

VERITAS: Array Imaging



Multiple Telescopes:
- improve angular resolution
- improve energy resolution
- reduce background

VERITAS detects pulsar above 100 GeV



Variability; the flares

Crab Nebula: standard candle

The Crab Nebula as a standard candle in very high-energy astrophysics

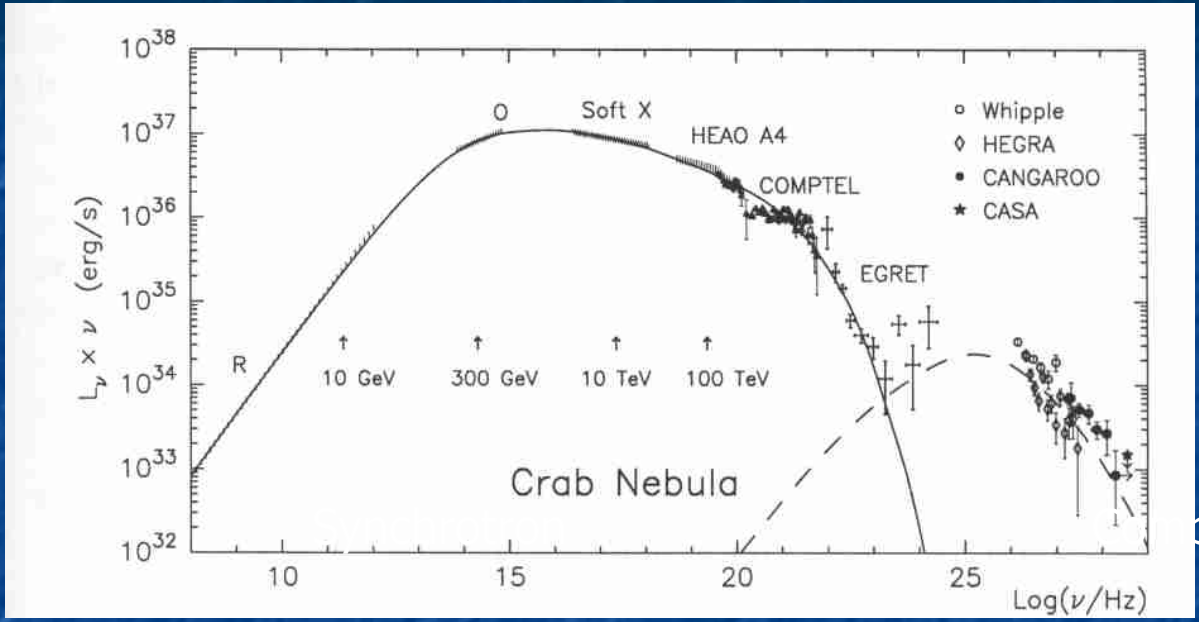
M. Meyer,* D. Horns, H.-S. Zechlin
Institut für Experimentalphysik, University of Hamburg, Luruper Chaussee 149, D-22761 Hamburg, Germany

(Dated: August 27, 2010– Accepted in *Astronomy & Astrophysics*, July 18, 2010)

The continuum high-energy gamma-ray emission between 1 GeV and 10^5 GeV from the Crab Nebula has been measured for the first time in overlapping energy bands by the Fermi large-area telescope (Fermi/LAT) below ≈ 100 GeV and by ground-based imaging air Cherenkov telescopes (IACTs) above ≈ 60 GeV. To follow up on the phenomenological approach suggested by Hillas et al. (1998), the broad band spectral and spatial measurement (from radio to low-energy gamma-rays < 1 GeV) is used to extract the shape of the electron spectrum. While this model per construction provides an excellent description of the data at energies

Very important in X-ray and gamma ray to have a standard candle as calibration.

Crab Nebula detected as a TeV source in 198



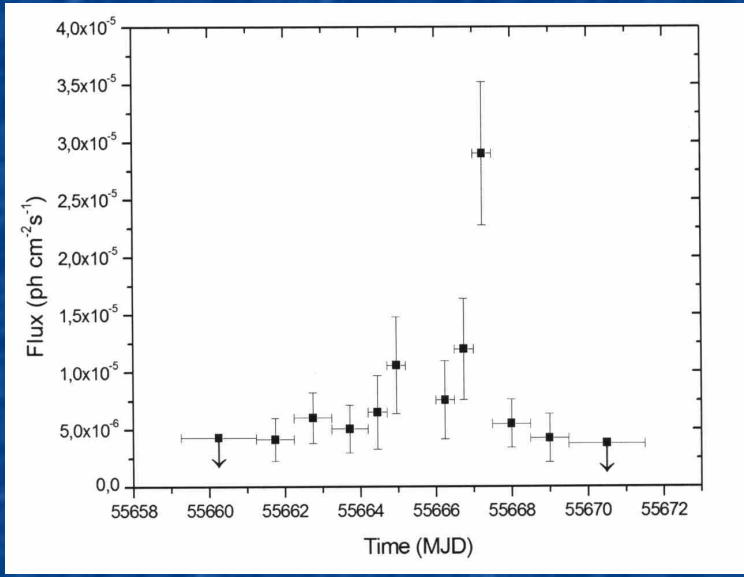
bton

Since then has been regarded as the Standard Candle for TeV Astronomy.

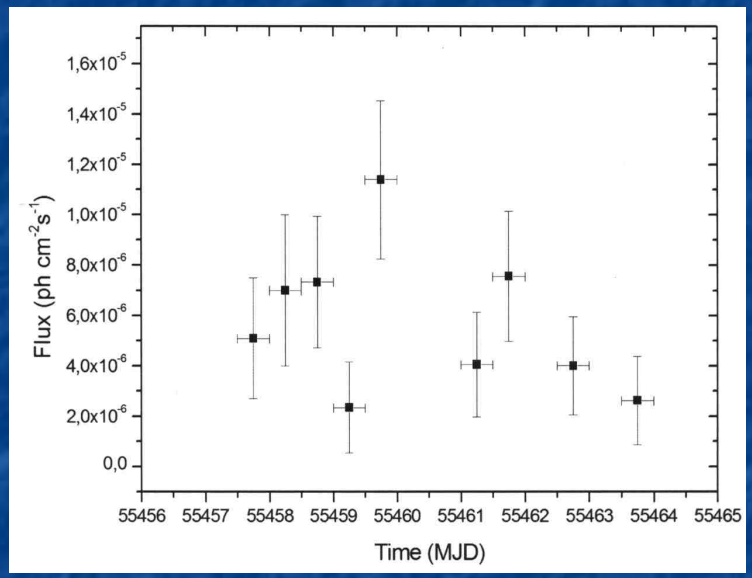
At Whipple Observatory it has been observed at least once per night since 1985 and all other sources are referenced to it.

AGILE, 2010
Discovery of flares at 1-300 MeV energies from the Crab

Flare #1



Flare #3 (discovery flare)



Confirmed by Fermi

Is the Crab Nebula really a Standard Candle at all gamma-ray energies?

Inner Crab Nebula:
As seen by Hubble a few days after flare

Flare Summary

Flare	Year	Telescope	Duration
(1)	Oct., 2007	AGILE	15 days
(2)	Feb. 2009	Fermi	15 days
(3)	Sept. 2010	AGILE/Fermi	4 days
(4)	April 2011	AGILE/Fermi	10 days

Summary of Flare Properties: 1-2 flares per year

Hard Spectrum

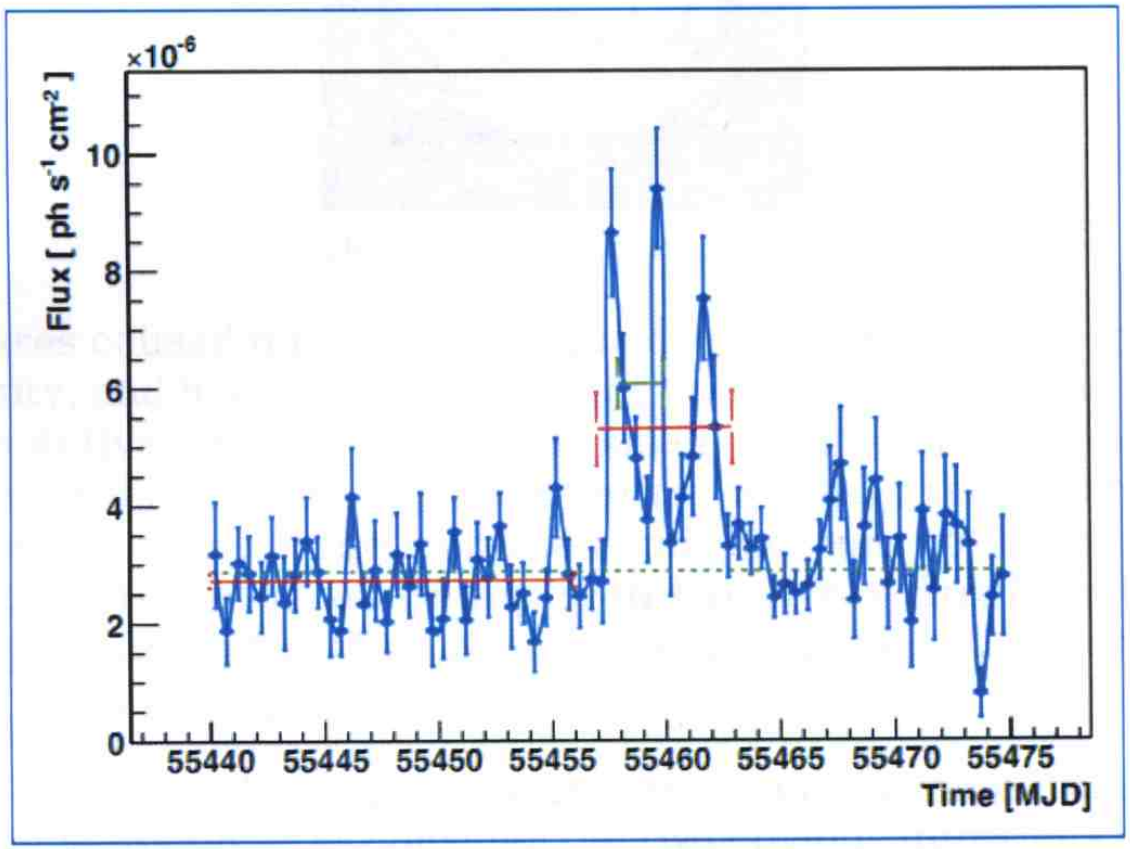
Size >x3 to>x10 Rise time

Duration 4 to 14 days Structure

September 19-21, 2010
Crab is Standard Candle no more

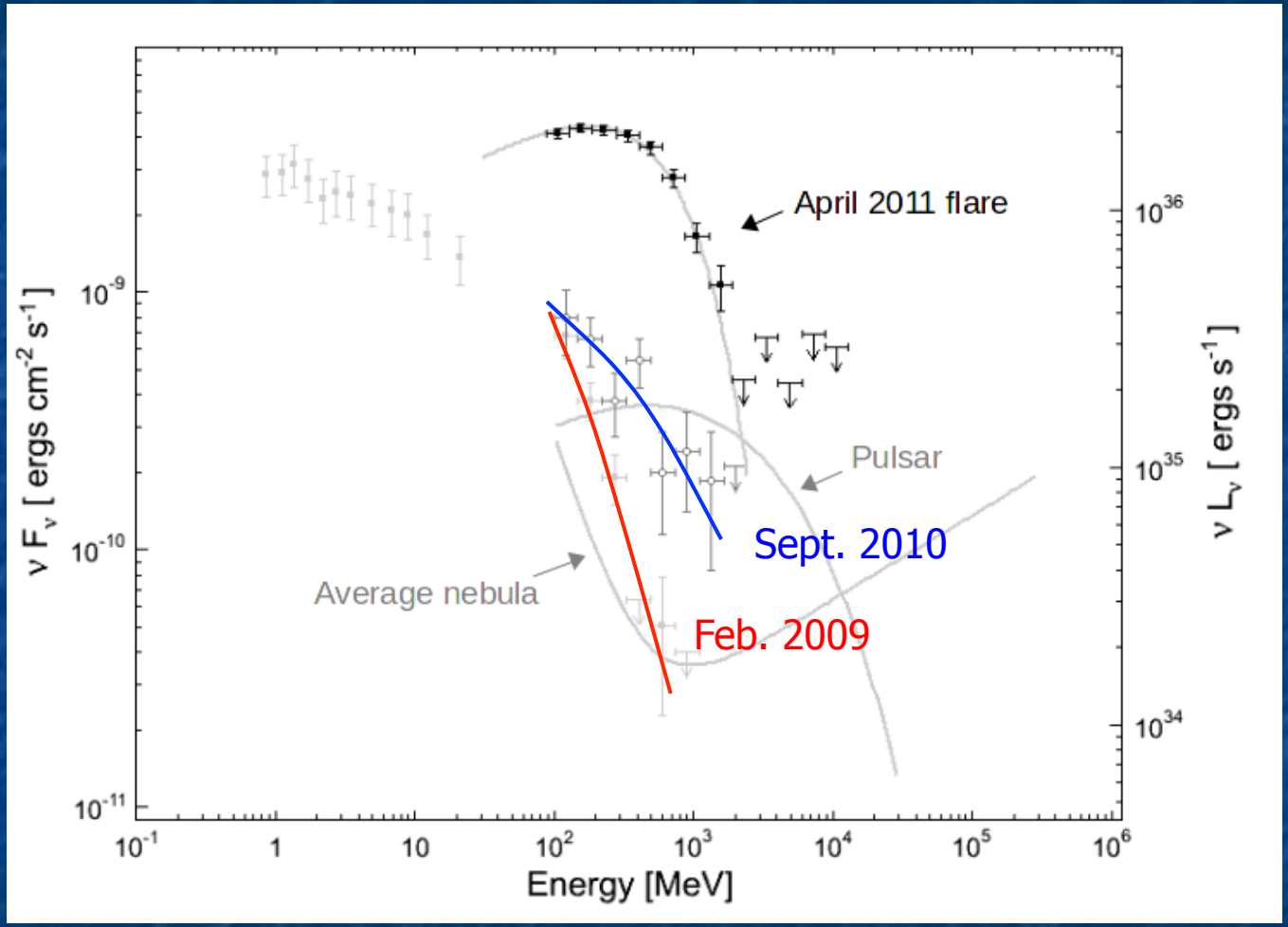
Gamma-ray signal seen by gamma-ray telescopes on satellites is seen to double

- No change in pulsar
- No change in total signal at radio, optical or X-ray



Observations of the light curve of the Crab Nebula in the range 0.1 to 300 GeV showing the three observed flares. Each horizontal unit represents a 12h time bin. The red lines represent the average flux before and during the flares (image: Balbo et al. 2011).

Spectrum during the April 2011 flare



Flare is well described by additional power-law component that cuts off with energy

Photon index ~1.3

Energy of peak 375 ± 26 MeV

Energies above ~250 MeV exceed expected maximum for the electron synchrotron process

Hays, 2012

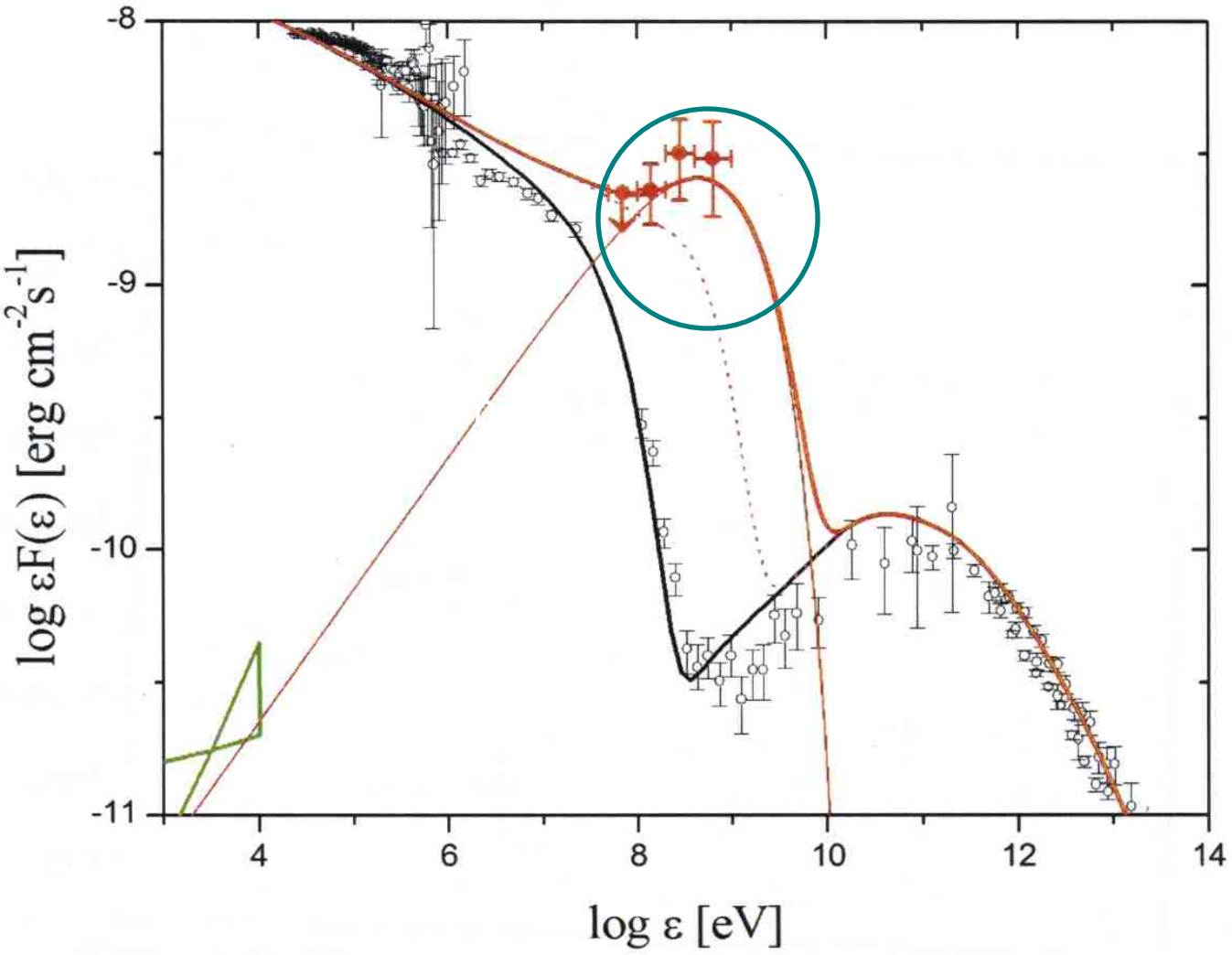
Summary

- Fast, high-energy flares from the Crab nebula appear to be uniquely gamma-ray phenomena
- Rapid variability and high energy suggest relativistic beaming of electron synchrotron radiation
- Time scale and small region imply electrons accelerated through electrostatic acceleration or magnetic reconnection
- Nebula is highly dynamic over the spectrum, but not yet clear how to connect features and timescales
- Future observations of large flares may help further pinpoint the emission site

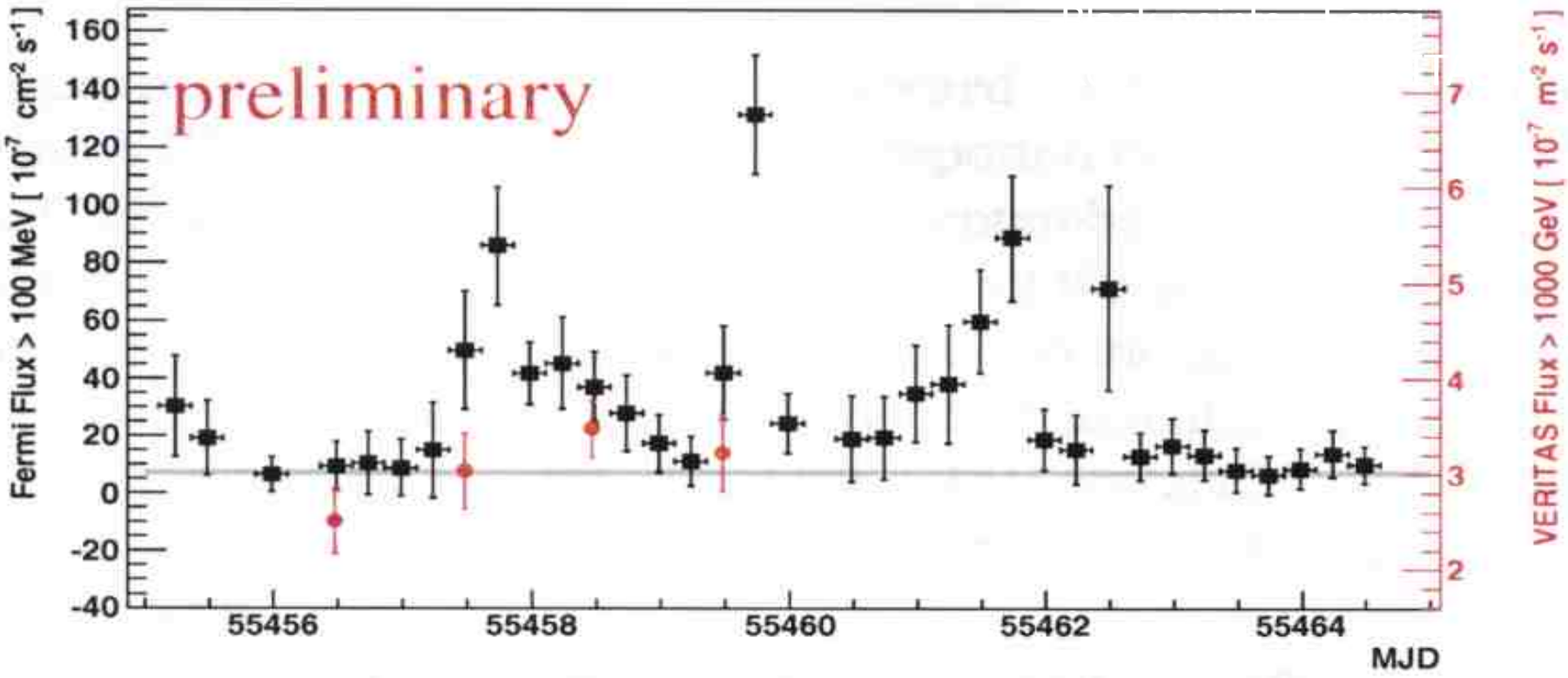
http://fermi.gsfc.nasa.gov

Hays, 2012

Spectrum from AGILE



Best Overlap with VERITAS of Flare #3

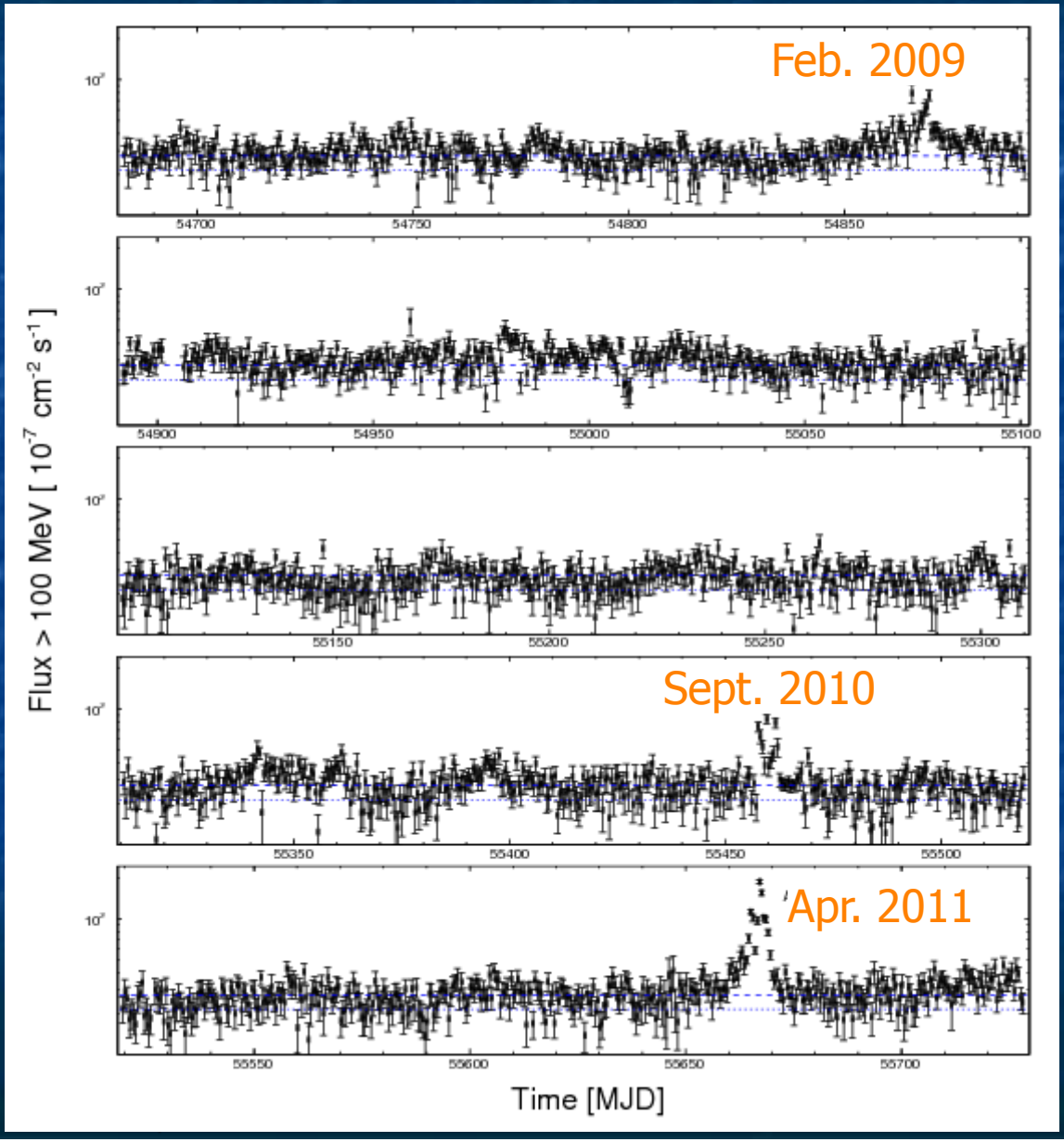


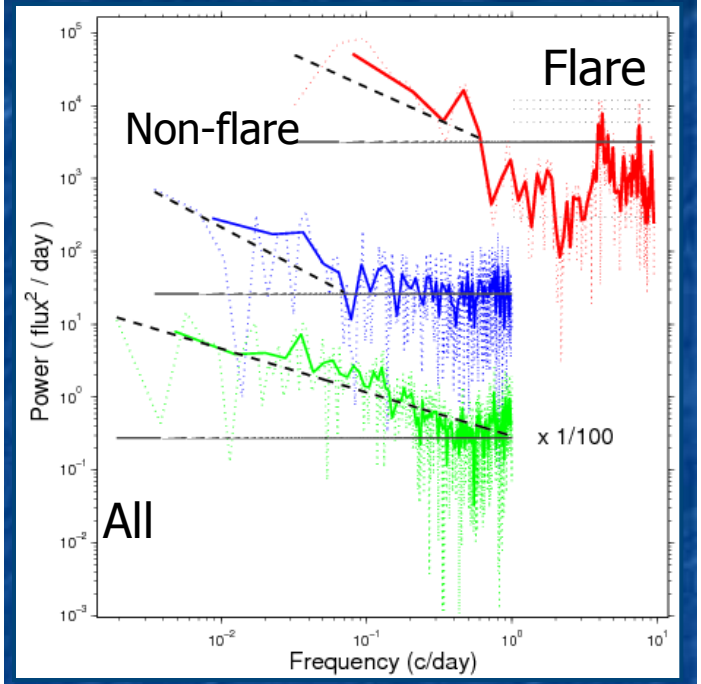
No evidence for TeV signal.

Crab Observations now High Priority ToO with VERITAS.

Notification of flare within six hours of detection by Fermi

Persistent Variability





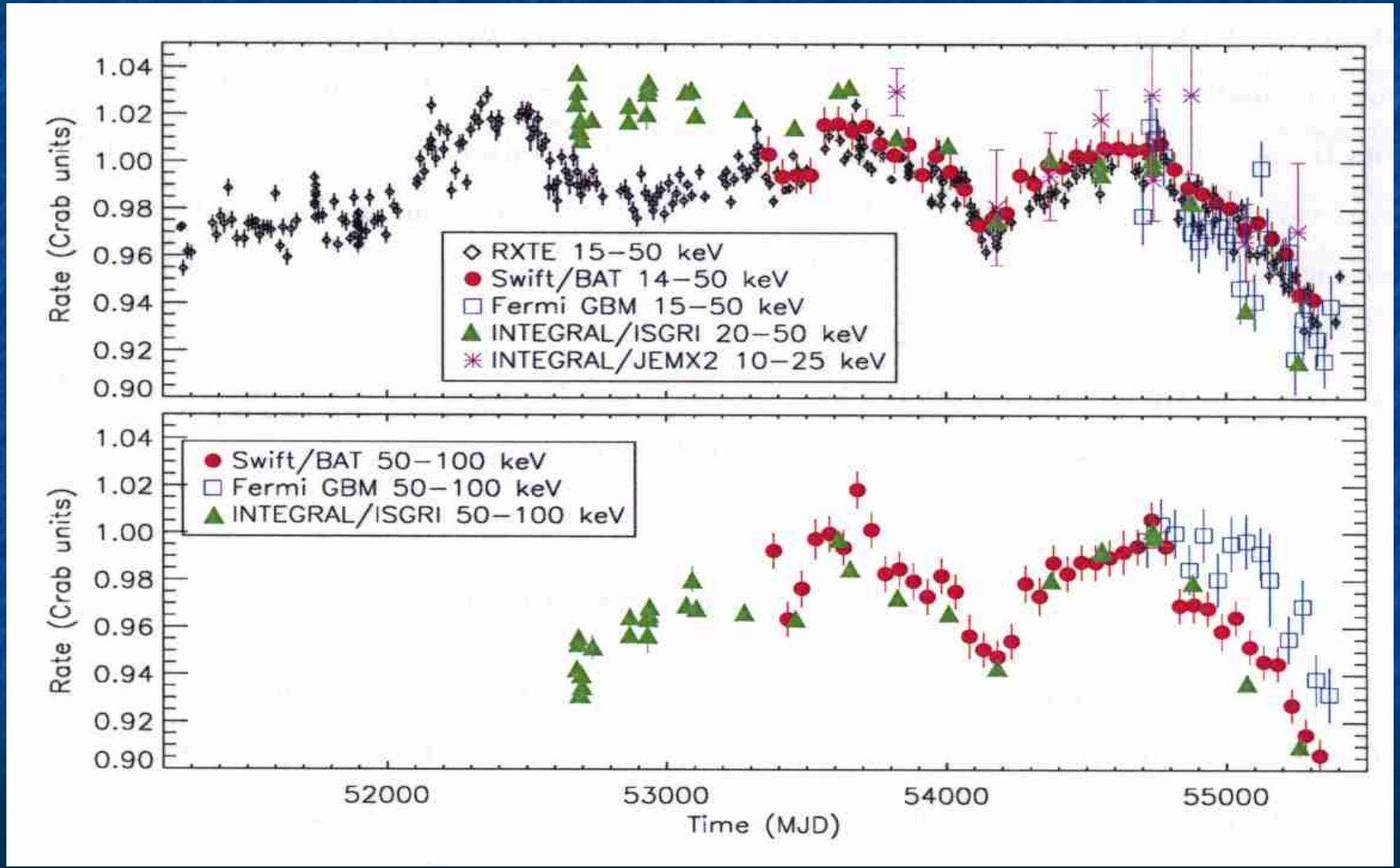
LAT data show variability (weeks to years) over full lightcurve and outside of flare periods.

Summary of Flare Phenomena

- Fast, high-energy flares from the Crab nebula appear to be uniquely gamma-ray phenomena
- Rapid variability and high energy suggest relativistic beaming of electron synchrotron radiation
- Time scale and small region imply electrons accelerated through electrostatic acceleration or magnetic reconnection
- Nebula is highly dynamic over the spectrum, but not yet clear how to connect features and timescales
- Future observations of large flares may help further pinpoint the emission site

http://fermi.gsfc.nasa.gov

Is the Crab fading away?



- Crab continues to provide surprises
- Sufficient Variety of Phenomena to demonstrate anything you want to!