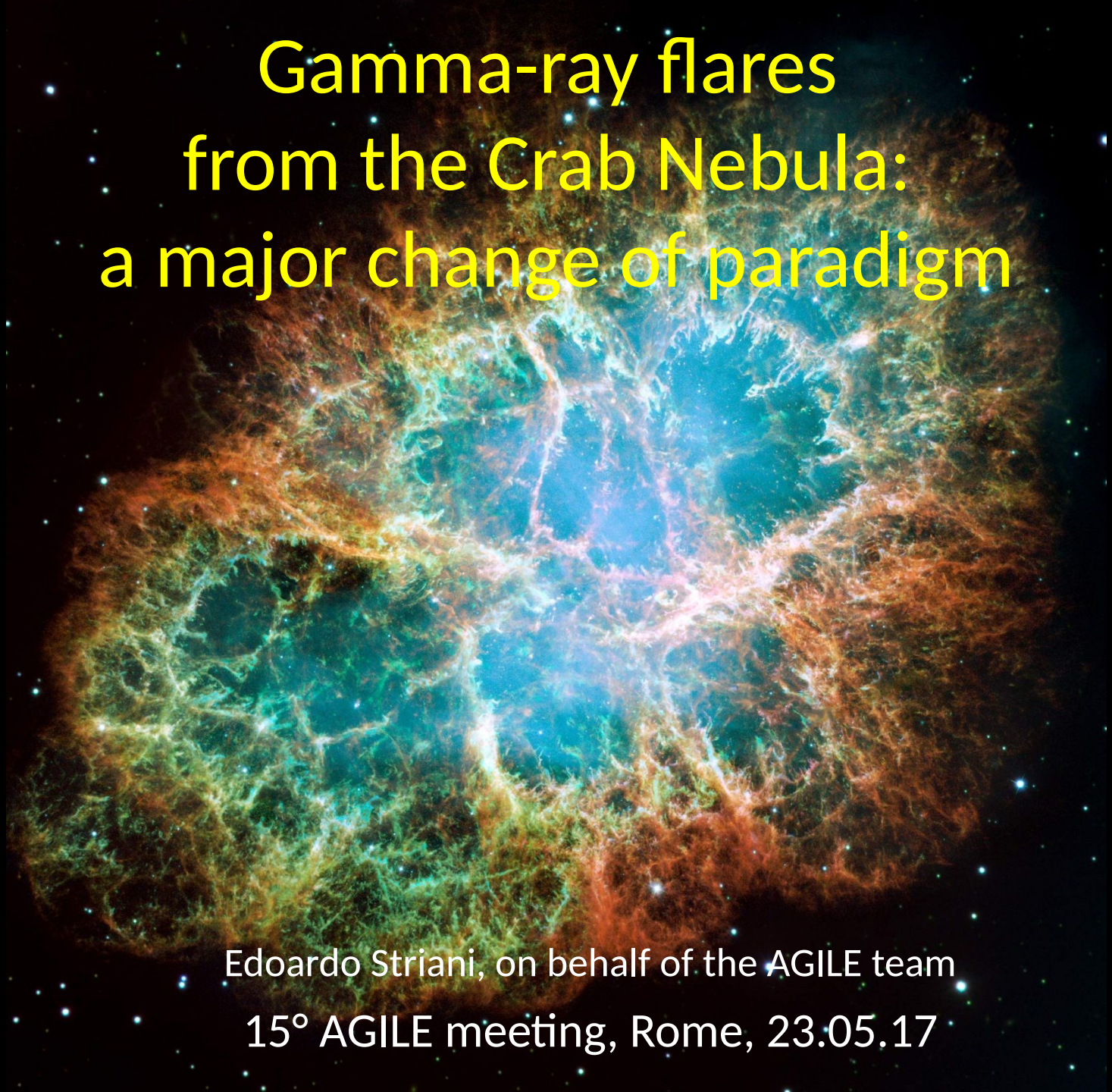
Gamma-ray flares from the Crab Nebula: a major change of paradigm



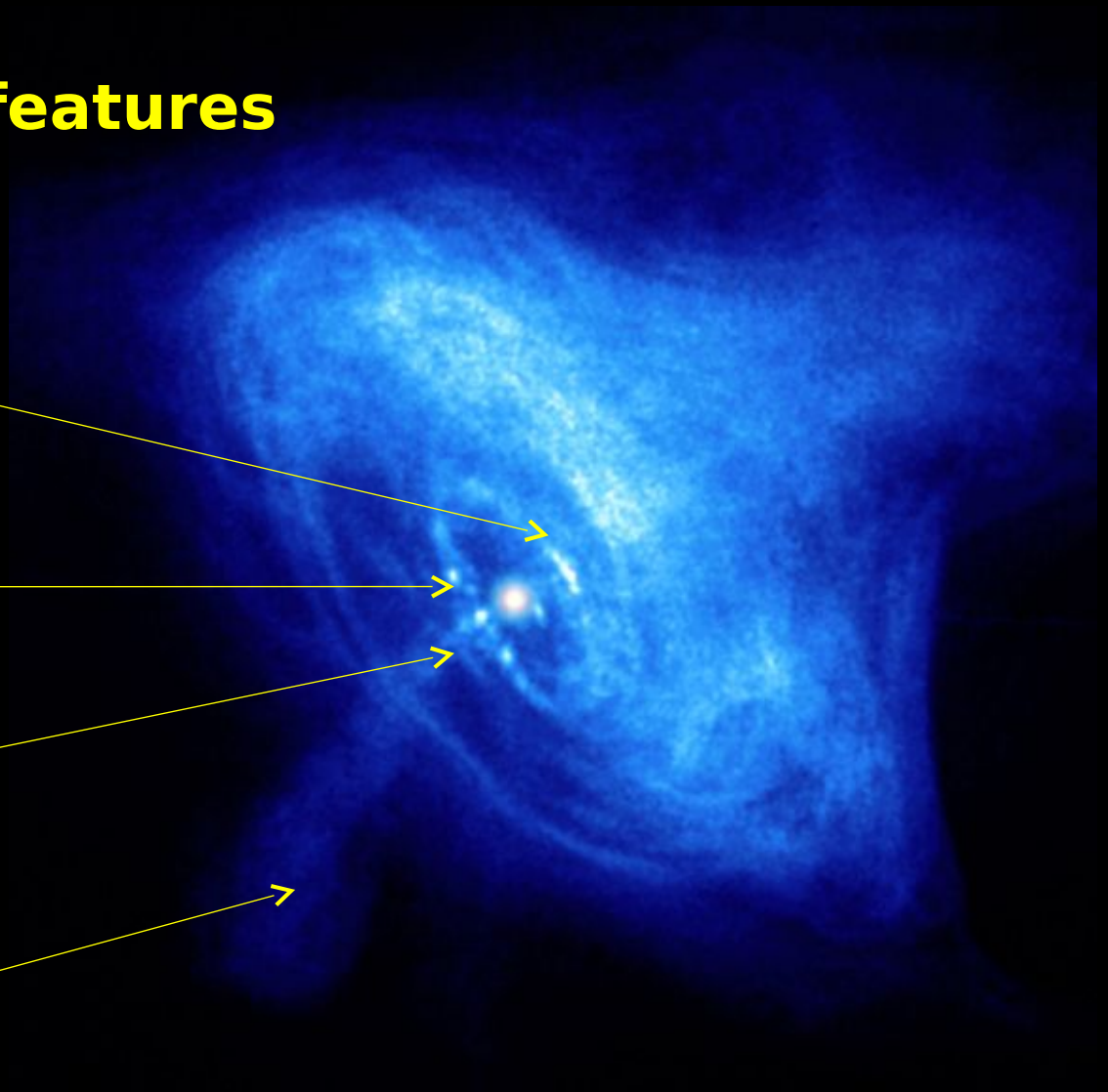
Edoardo Striani, on behalf of the AGILE team

15° AGILE meeting, Rome, 23.05.17

The Crab Nebula (M1): a wonderful laboratory

Crab Nebula: X-ray imaging (Chandra: 1-10 keV)

Several different features



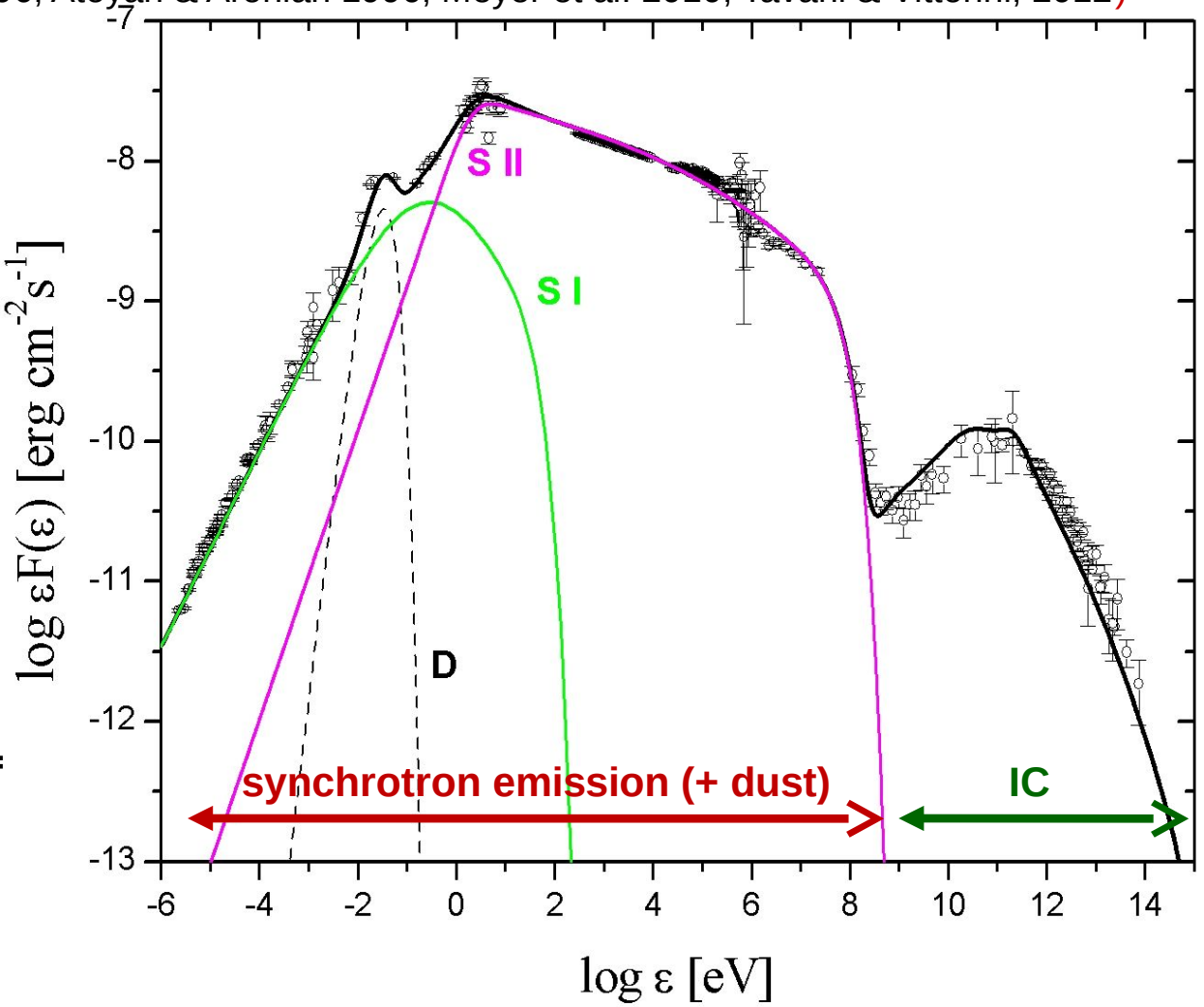
Crab Nebula spectrum from radio to TeV

(De Jager et al., 1996, Atoyan & Aronian 1996, Meyer et al. 2010, Tavani & Vittorini, 2012)

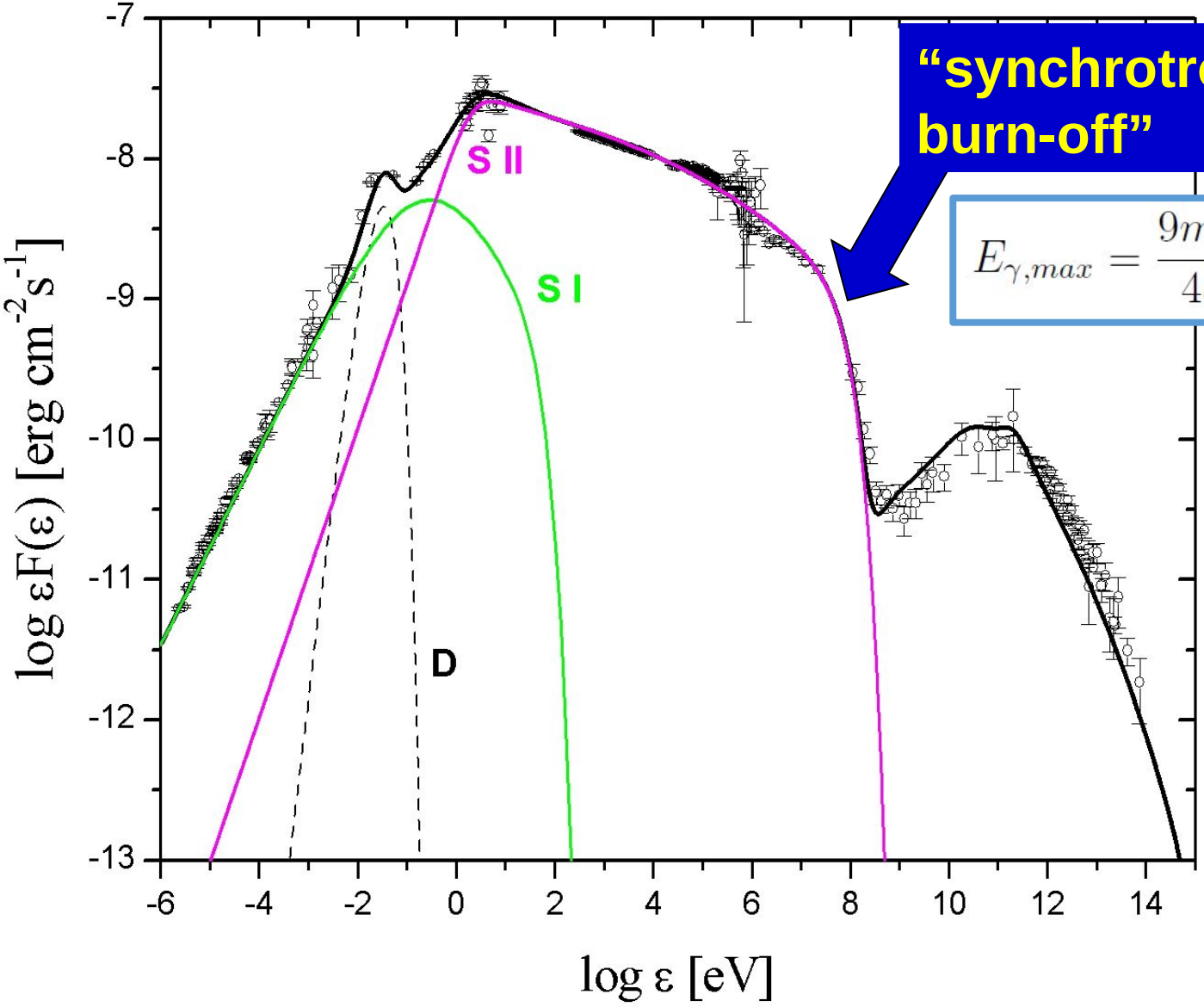
The pulsar injects **dN/dt ~ $10^{40.5}$ s^{-1}** e+/e- pairs

Particles are accelerated in many shocks sites

Interact with the average nebular magnetic field **B = 200 µG** producing Synchrotron emission



Crab Nebula average spectrum



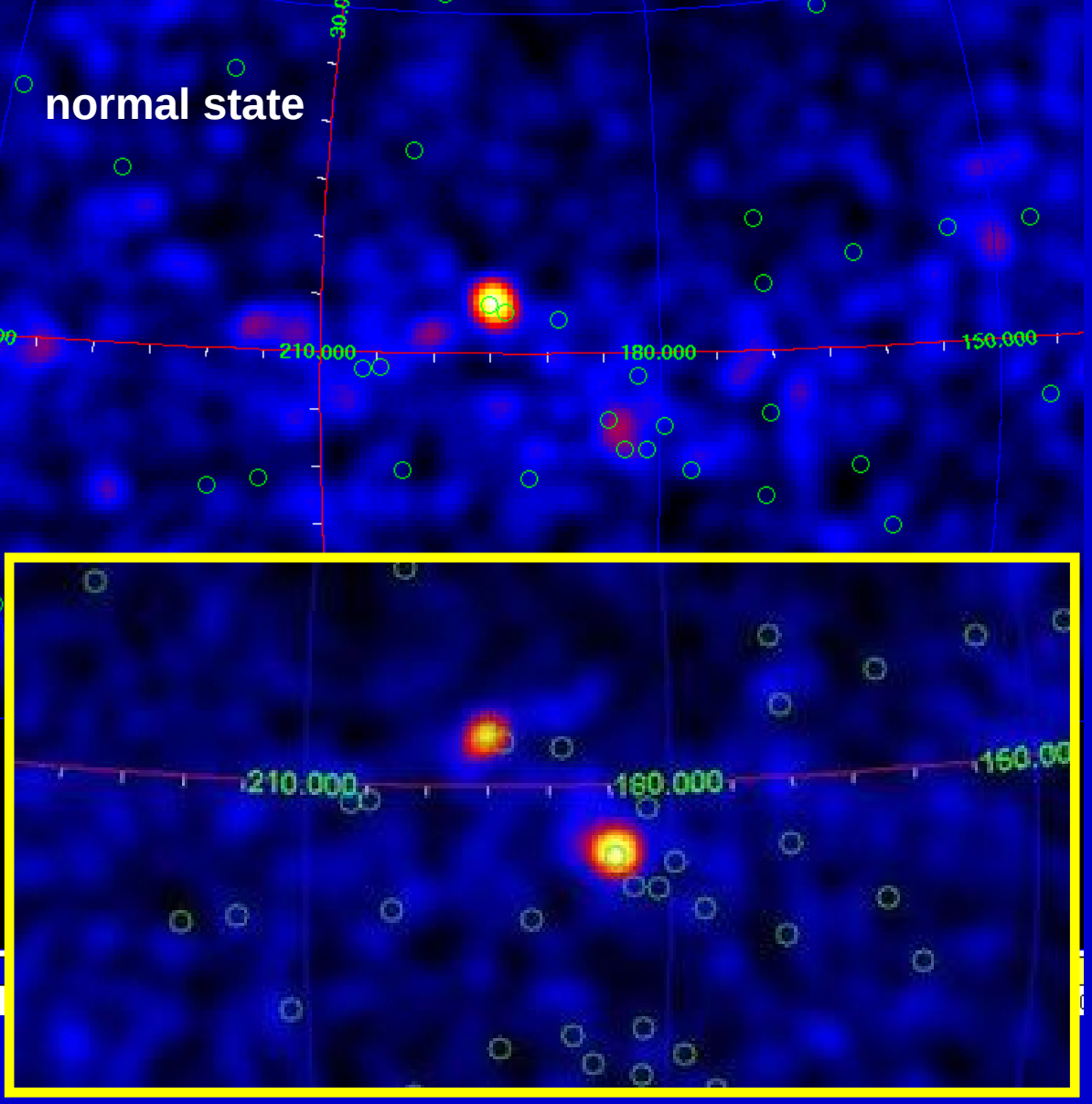
“synchrotron burn-off”

$$E_{\gamma,max} = \frac{9mc^2}{4\alpha}\frac{\mathcal{E}}{B} \simeq 160\,\mathrm{MeV}\,\frac{\mathcal{E}}{B}$$

The Crab Nebula

1. Stable (Standard candle)

2. Cut-off in the spectrum around 150 MeV



AGILE data

1-day integration

Gamma-ray flaring state: 20-21 Sept. 2010

The Discovery

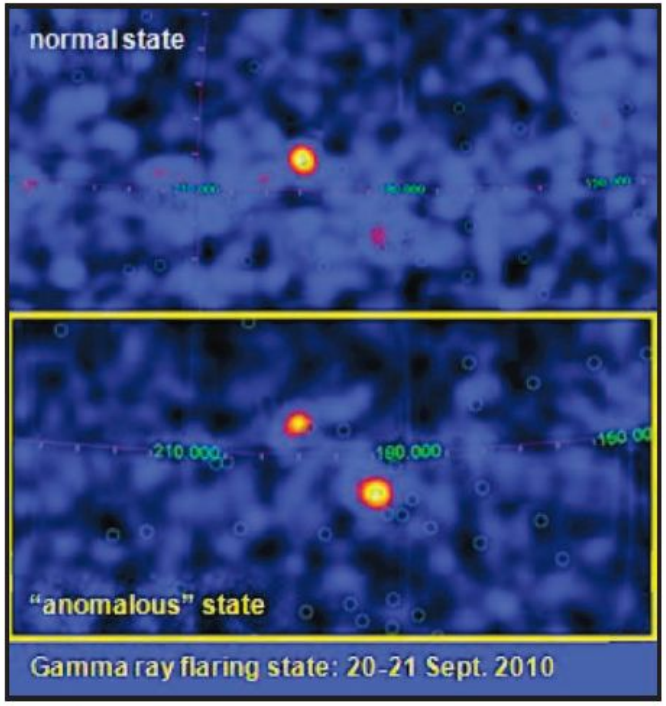
www.sciencemag.org SCIENCE VOL 341 16 AUGUST 2013
Published by AAAS

The next morning, Tavani hurried to his office at the institute, where a 2-day conference for AGILE team members was about to begin. Before the morning session, he stopped by the office of his graduate student, Edoardo Striani, who was responsible for conducting fast analyses on AGILE data, and asked Striani to take a look at the Crab.

Striani carried his laptop into the conference and settled down in a corner. His attention drifted in and out of the presentations. Analyzing the satellite's observations—downloaded every hour and a half by a receiver in Kenya, then relayed to the AGILE data center—he checked whether the emission from the Crab had been changing over the past few days.

By the afternoon, Striani had confirmed that the emission had been rising. He and Tavani were witnessing a flare. "It immediately occurred to me that we had seen this in 2007," Tavani says. "At that moment, I knew the phenomenon was real."

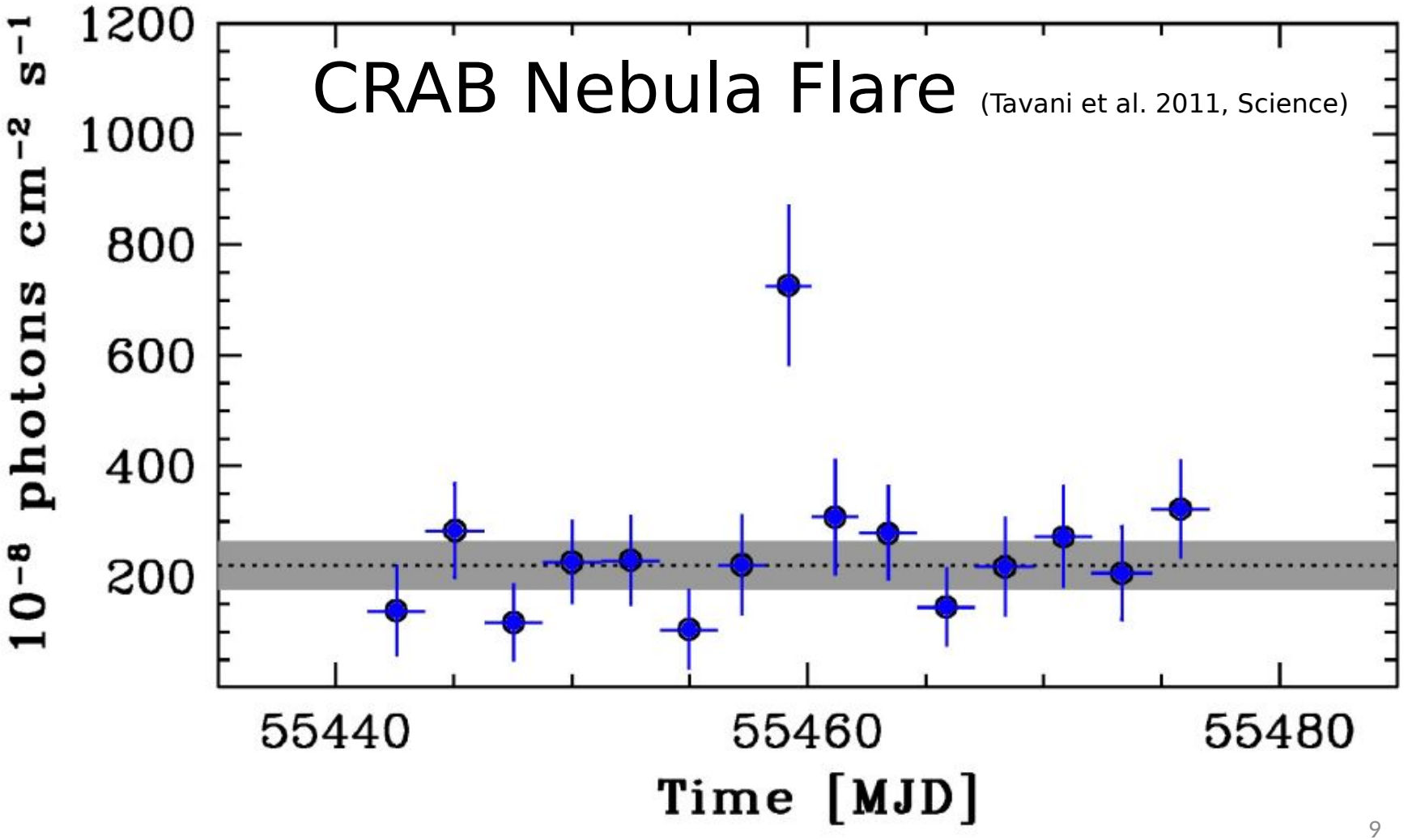
What's causing the flares is still a mystery. The data show that the pulsar doesn't emit more energy than usual during the



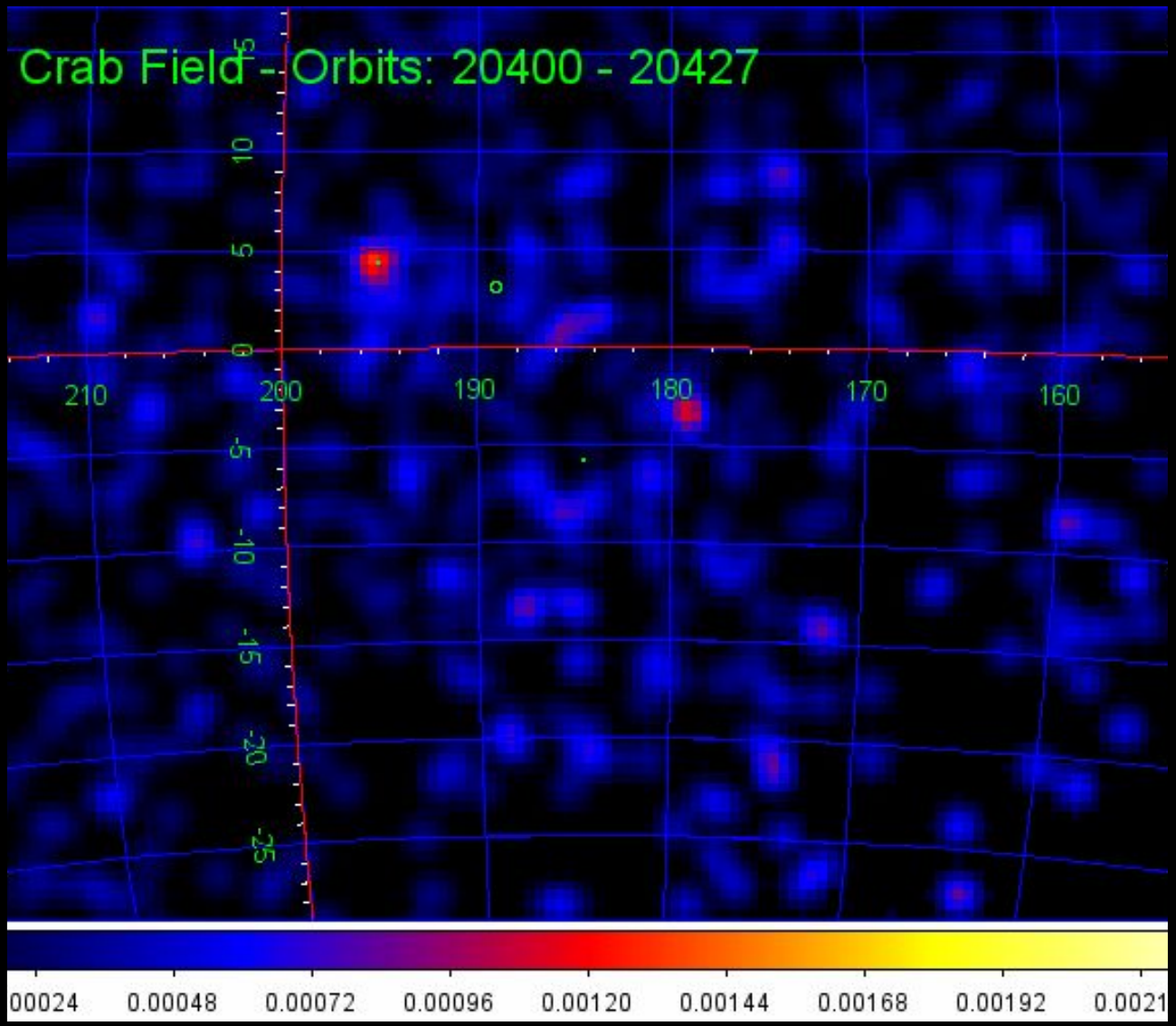
Flash! Normally (*top*) Geminga far outshines the Crab in gamma rays. But in 2010 (*bottom*), the Crab blazed forth.

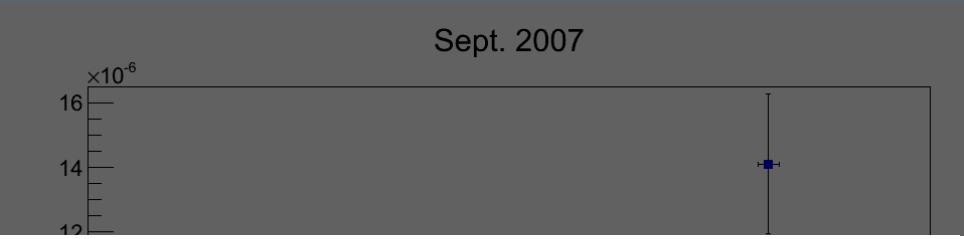
The story of the dramatic moments leading to the discovery of the Crab Nebula flares was described in *Science* on August 16, 2013

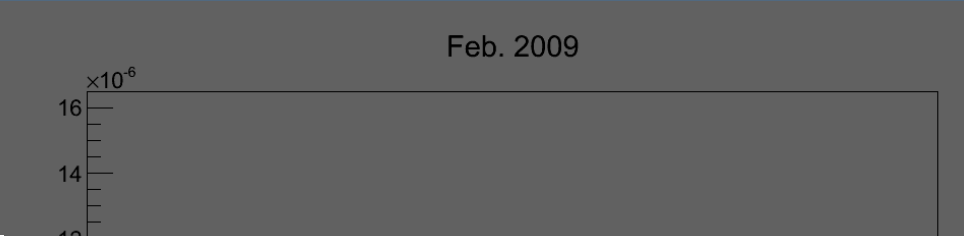
The Discovery

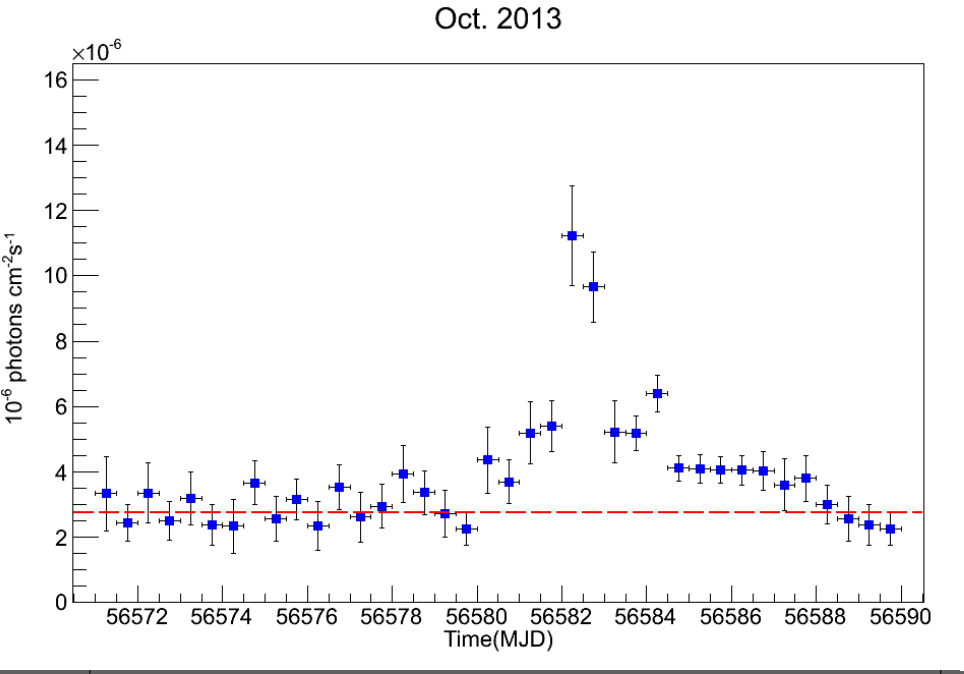


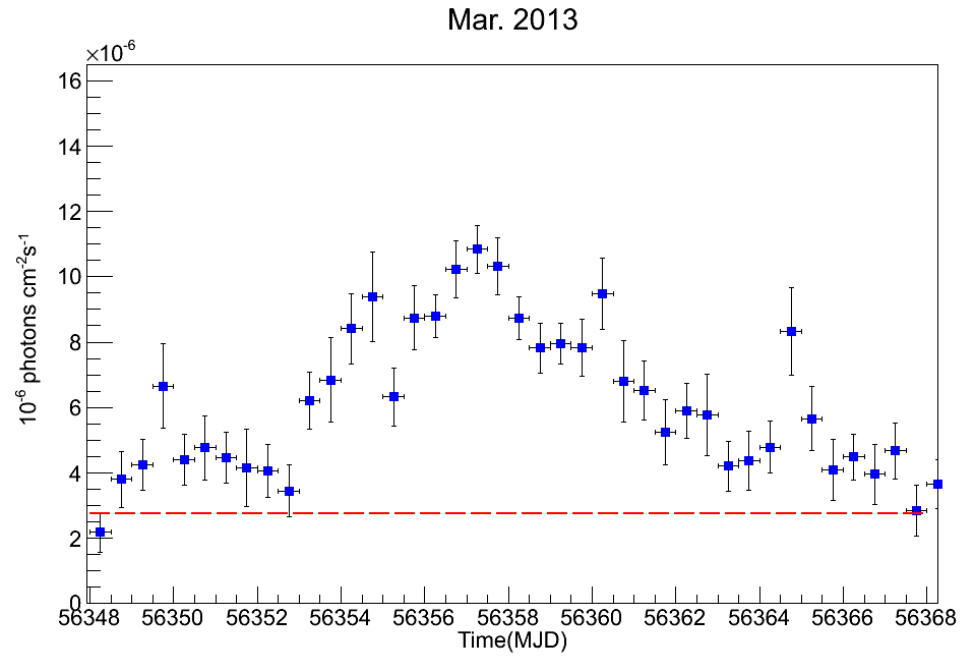
AGILE monitoring of the Crab (April 2011)

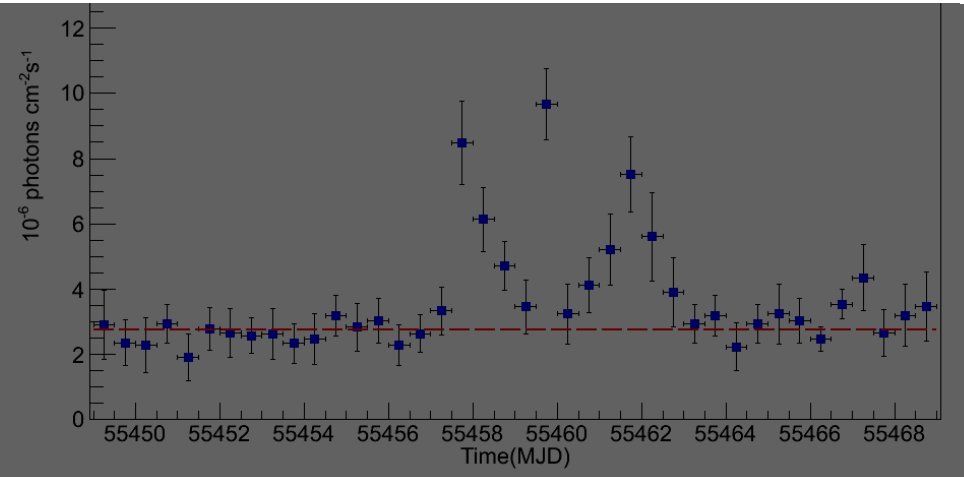


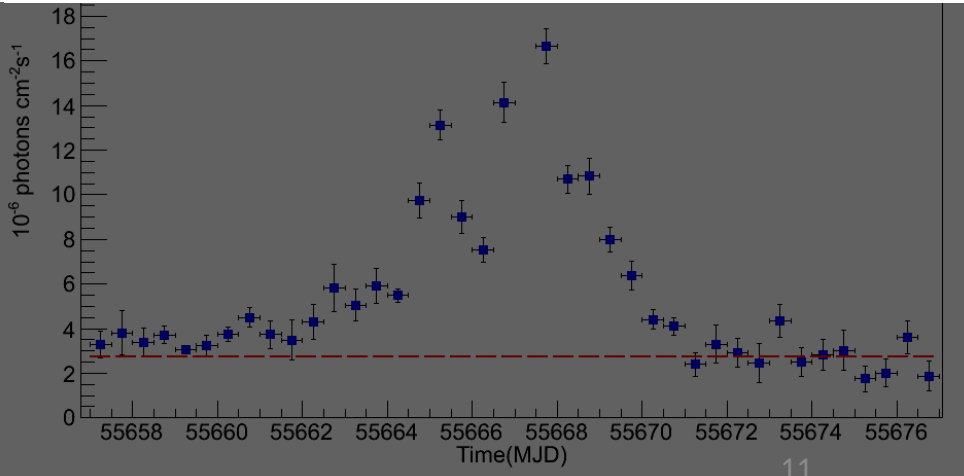

Sept. 2007
×10⁻⁶
16
14


Feb. 2009
×10⁻⁶
16
14


Oct. 2013
×10⁻⁶
10⁻⁶ photons cm⁻²s⁻¹
Time(MJD)
56572 56574 56576 56578 56580 56582 56584 56586 56588 56590


Mar. 2013
×10⁻⁶
10⁻⁶ photons cm⁻²s⁻¹
Time(MJD)
56348 56350 56352 56354 56356 56358 56360 56362 56364 56366 56368


10⁻⁶ photons cm⁻²s⁻¹
Time(MJD)
55450 55452 55454 55456 55458 55460 55462 55464 55466 55468


10⁻⁶ photons cm⁻²s⁻¹
Time(MJD)
55658 55660 55662 55664 55666 55668 55670 55672 55674 55676

Major gamma-ray flaring episodes (up to 2013)

Flare date	$\Delta t_{E > 400\ MeV}$	$\Delta t_{E > 650\ MeV}$	Peak γ-ray flux (ph cm^{-2} s^{-1})	E_{TOT} (erg)	E_{peak} (erg)
Oct. 2007	~ 15 days	~ 6 days	~ $14 \cdot 10^{-6}$	~ 10^{42}	~ $7 \cdot 10^{41}$
Feb. 2009	~ 11 days	~ 5 days	~ $7 \cdot 10^{-6}$	~ $6 \cdot 10^{41}$	~ $4 \cdot 10^{41}$
Sept. 2010	~ 5 days	~ 5 days	~ $7 \cdot 10^{-6}$	~ $6 \cdot 10^{41}$	~ $6 \cdot 10^{41}$
Apr. 2011	~ 11 days	~ 5 days	~ $24 \cdot 10^{-6}$	~ $2 \cdot 10^{42}$	~ 10^{42}
Mar. 2013	~ 18 days	~ 8 days	~ $12 \cdot 10^{-6}$	~ $2 \cdot 10^{42}$	~ 10^{42}
Oct. 2013	~ 6 days	~ 4 days	~ $10 \cdot 10^{-6}$	~ $5 \cdot 10^{41}$	~ $4 \cdot 10^{41}$

major flare rate: ~ 1/year

Fermi LAT detection of enhanced gamma-ray emission from the Crab Nebula region

ATel #5971; *D. Gasparrini (ASDC/INAF), R. Buehler (DESY) on behalf of the Fermi LAT Collaboration*
on 11 Mar 2014; 20:40 UT
Credential Certification: Dario Gasparrini (dario.gasparrini@asdc.asi.it)

F = (5.7 +- 0.5) x 10^-6 ph cm^-2 s^-1

F= (7.5+/-0.6) 10^-6 ph cm^-2 s^-1

Fermi LAT detection of enhanced gamma-ray emission from the Crab Nebula region

ATel #6401; *J. Becerra (NASA/GSFC/UMD/CRESST), R. Buehler (DESY), E. Hays (NASA/GSFC), on behalf of the Fermi LAT Collaboration*
on 19 Aug 2014; 14:51 UT
Credential Certification: Josefa Becerra Gonzalez (josefa.becerra@nasa.gov)

Enhanced gamma-ray activity from the Crab nebula

ATel #8519; *R. Buehler (DESY) and S. Ciprini (ASDC Rome and INFN Perugia, Italy) on behalf of the Fermi LAT Collaboration*
on 9 Jan 2016; 03:35 UT
Credential Certification: Elizabeth Hays (elizabeth.a.hays@nasa.gov)

F = (4.7 +/- 0.5) x 10^-6 ph cm^-2 s^-1

F = (5.9 +/- 1.3) x 10^-6 ph cm^-2 s^-1

Enhanced gamma-ray emission from the Crab Nebula detected by AGILE

ATel #9586; *A. Bulgarelli (INAF/IASF-Bo), G. Piano, P. Munar-Adrover (INAF/IAPS), F.*
on 3 Oct 2016; 13:36 UT
Credential Certification: Andrea Bulgarelli (bulgarelli@iasfbo.inaf.it)

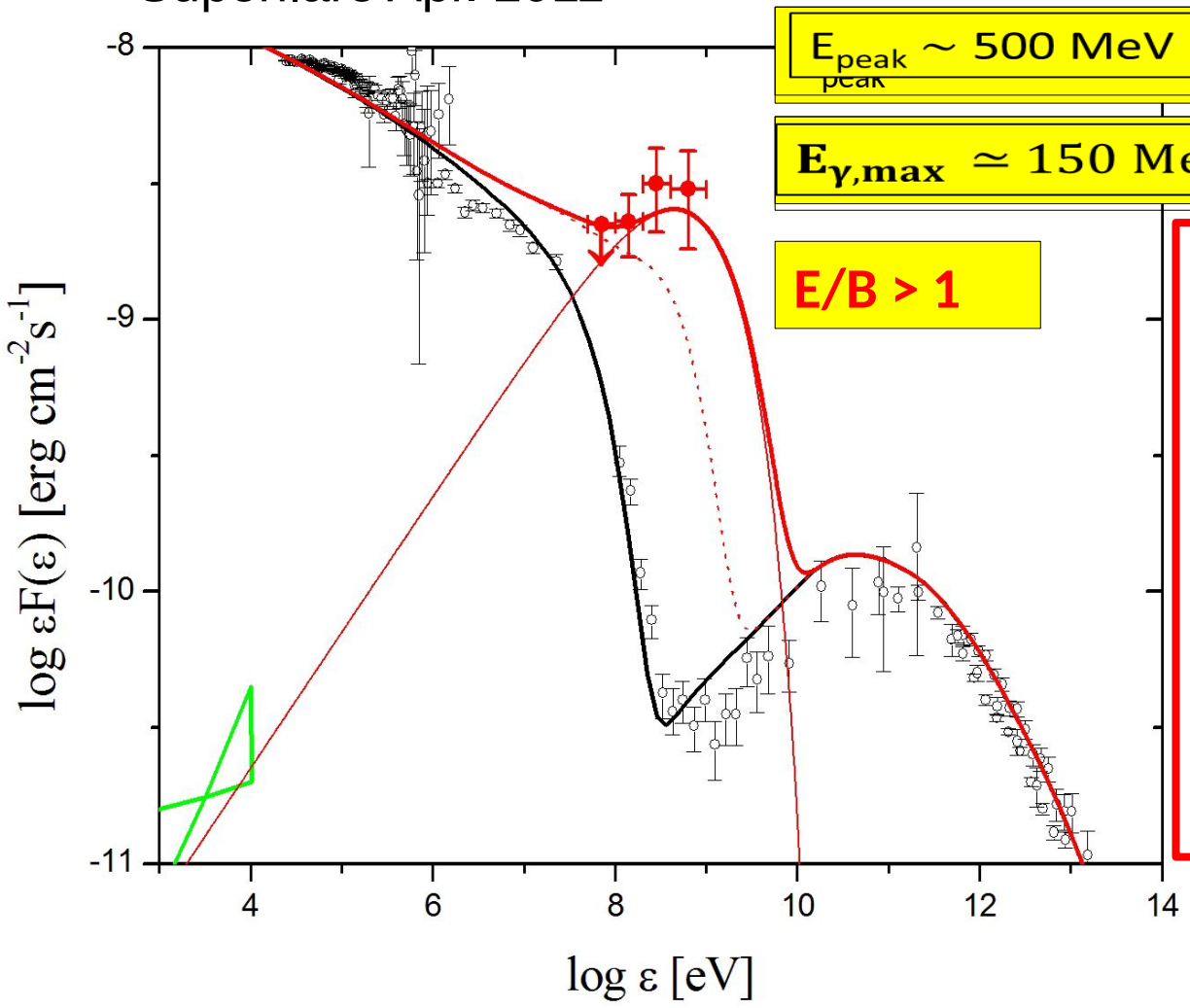
New episode of enhanced gamma-ray emission from the Crab Nebula detected by AGILE

ATel #9617; *P. Munar-Adrover (INAF/IAPS), F. Verrecchia, C. Pittori, (ASDC and*
on 12 Oct 2016; 12:44 UT
Credential Certification: Pere Munar-Adrover (pere.munar@iaps.inaf.it)

F = (6.9 +/- 1.3) x 10^-6 ph cm^-2 s^-1

AGILE Spectrum at the peak (12 hr) (ES et al. 2011)

Superflare Apr. 2011



Surprising features of the flares

- The gamma-ray emission from the nebula can be tens of time larger than the average nebular emission: the Crab is not stable
- The emission is peaked much beyond the synchrotron burnoff.

The Crab Nebula

1. Stable

2. Cut-off in the spectrum around 150 MeV

The Crab Nebula

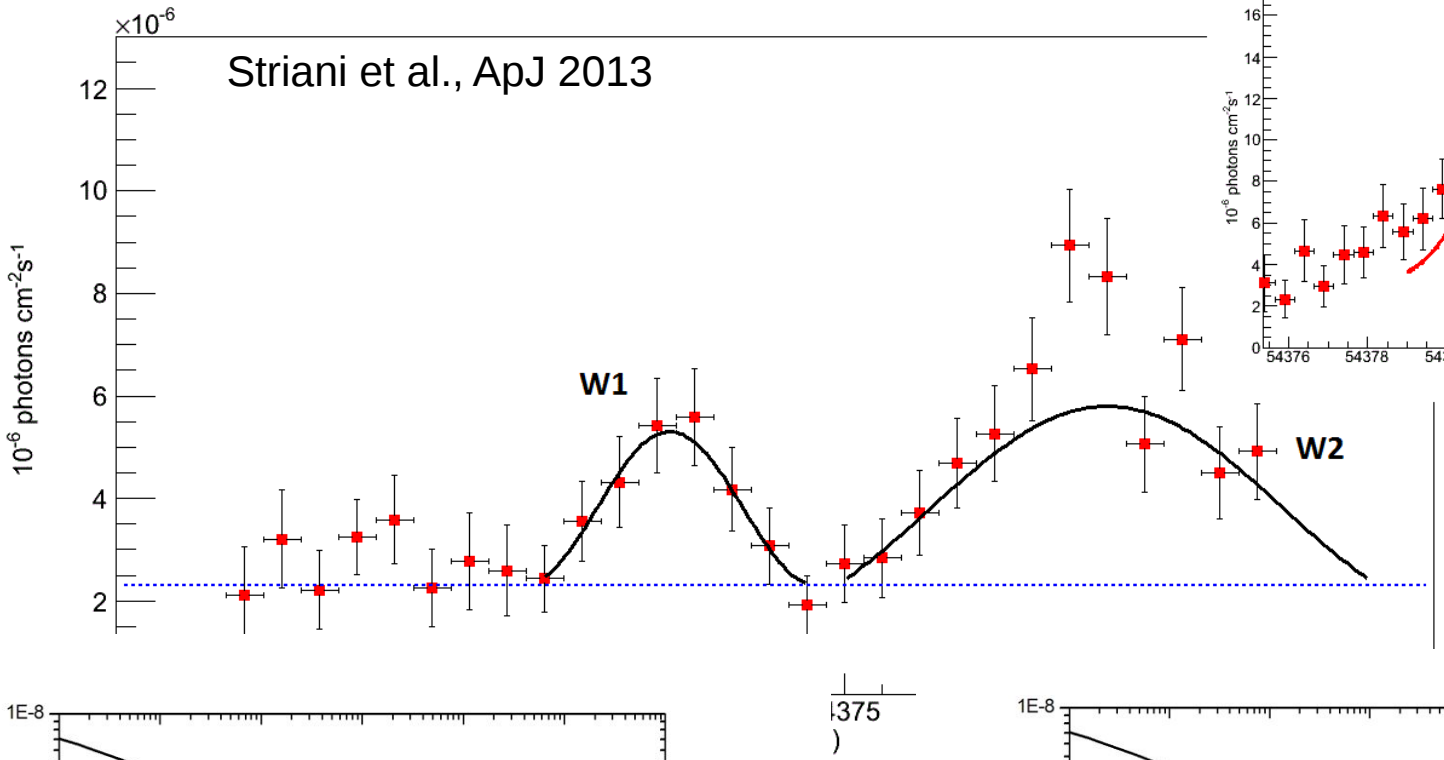
~~1. Stable~~

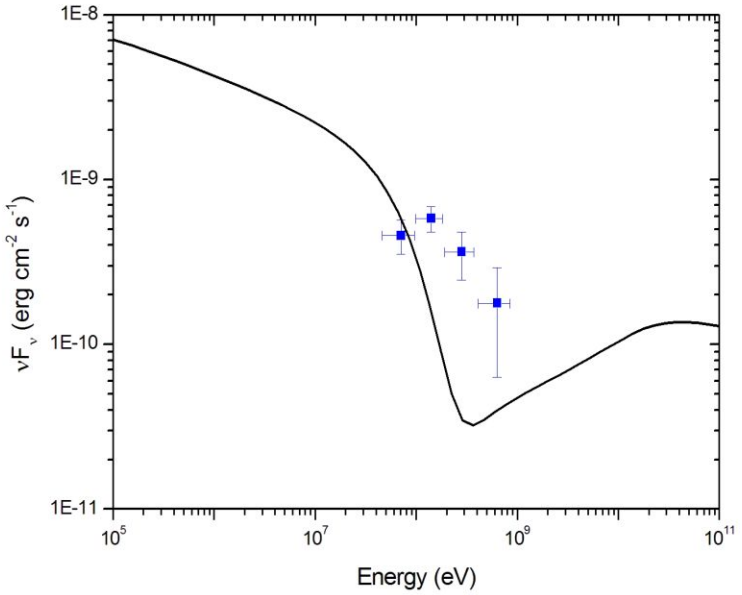
The Crab is **variable** in gamma rays.

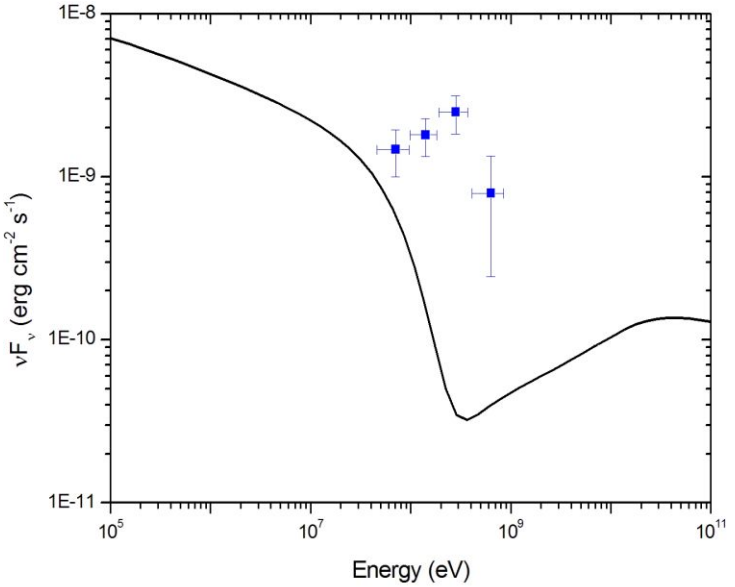
~~2. Cut-off in the spectrum around 150 MeV~~

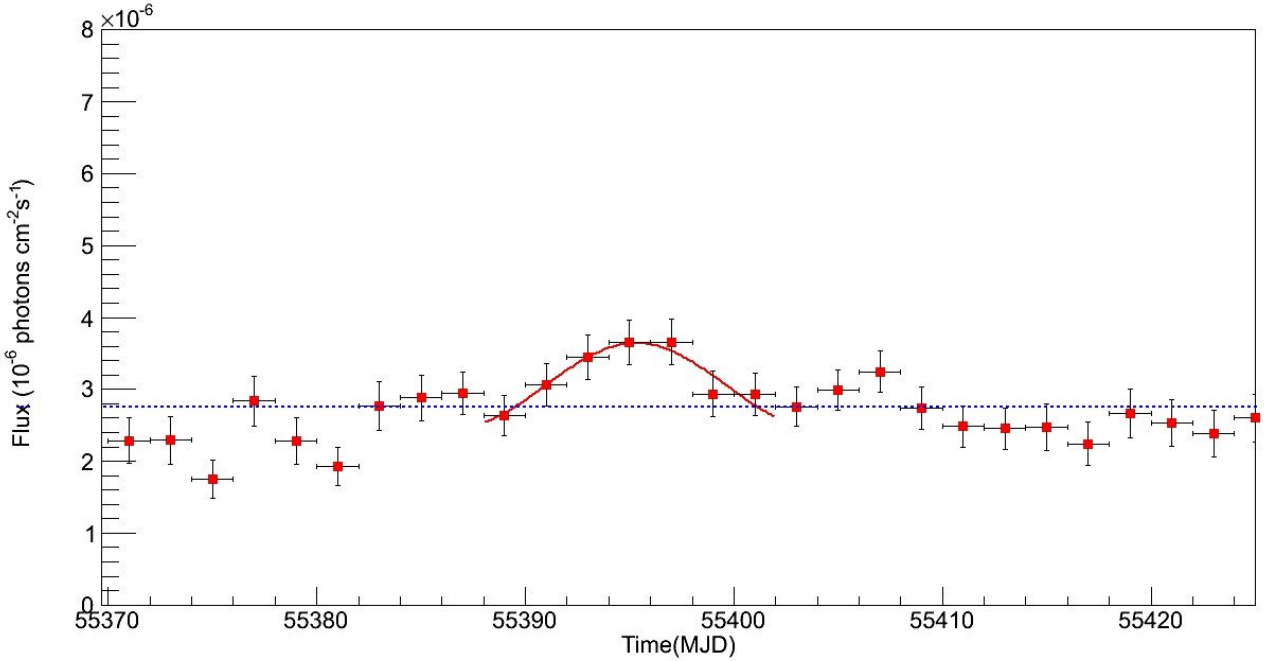
Flares peaking around 500 MeV

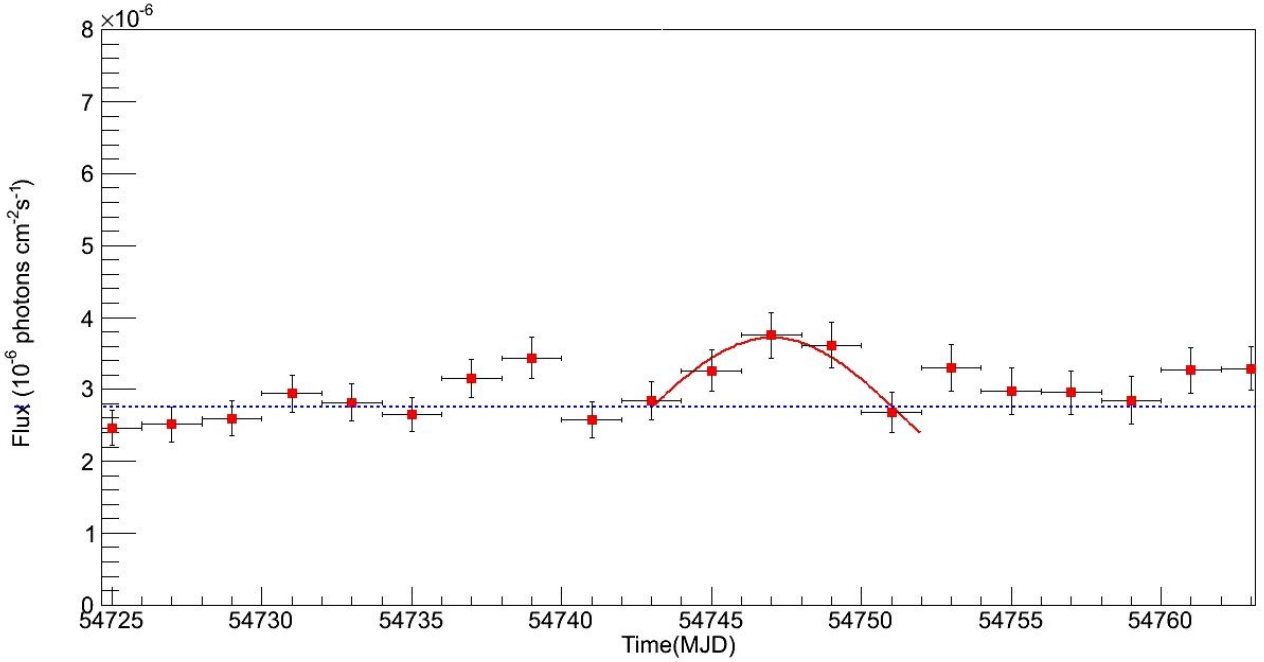
AGILE 1-day bin lightcurve of the 2007 event: *WAVES*








×10^-6
Flux (10^-6 photons cm^-2 s^-1)
Time(MJD)
55370
55380
55390
55400
55410
55420


×10^-6
Flux (10^-6 photons cm^-2 s^-1)
Time(MJD)
54725
54730
54735
54740
54745
54750
54755
54760

More *WAVES*

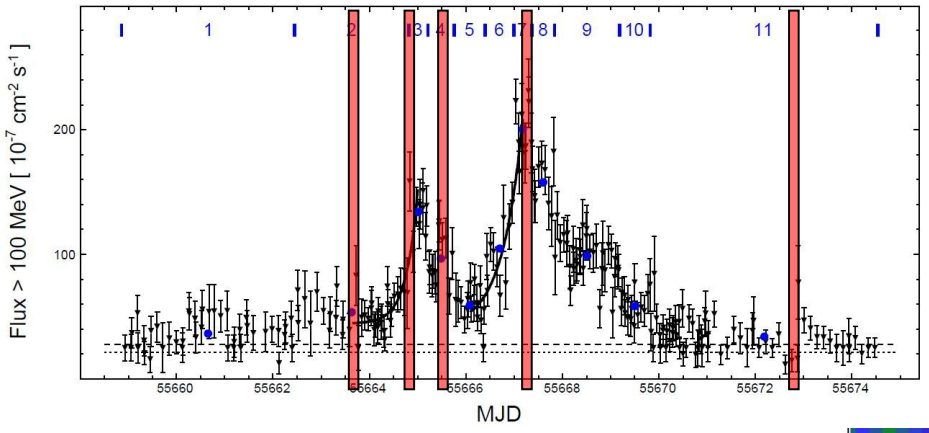
Features

Flares

- Intense gamma-ray flares ~ 1/year
- $t_{variability}$ ~ 6-12 hr to 1 day
- Peak energies ~ 500 MeV
- Structured, frequent flux variation at different intensities and time scales
- Gamma-ray flare radiated energy ~ 10^{42} erg
- B ~ 2 mG, R ~10^15 cm

Waves

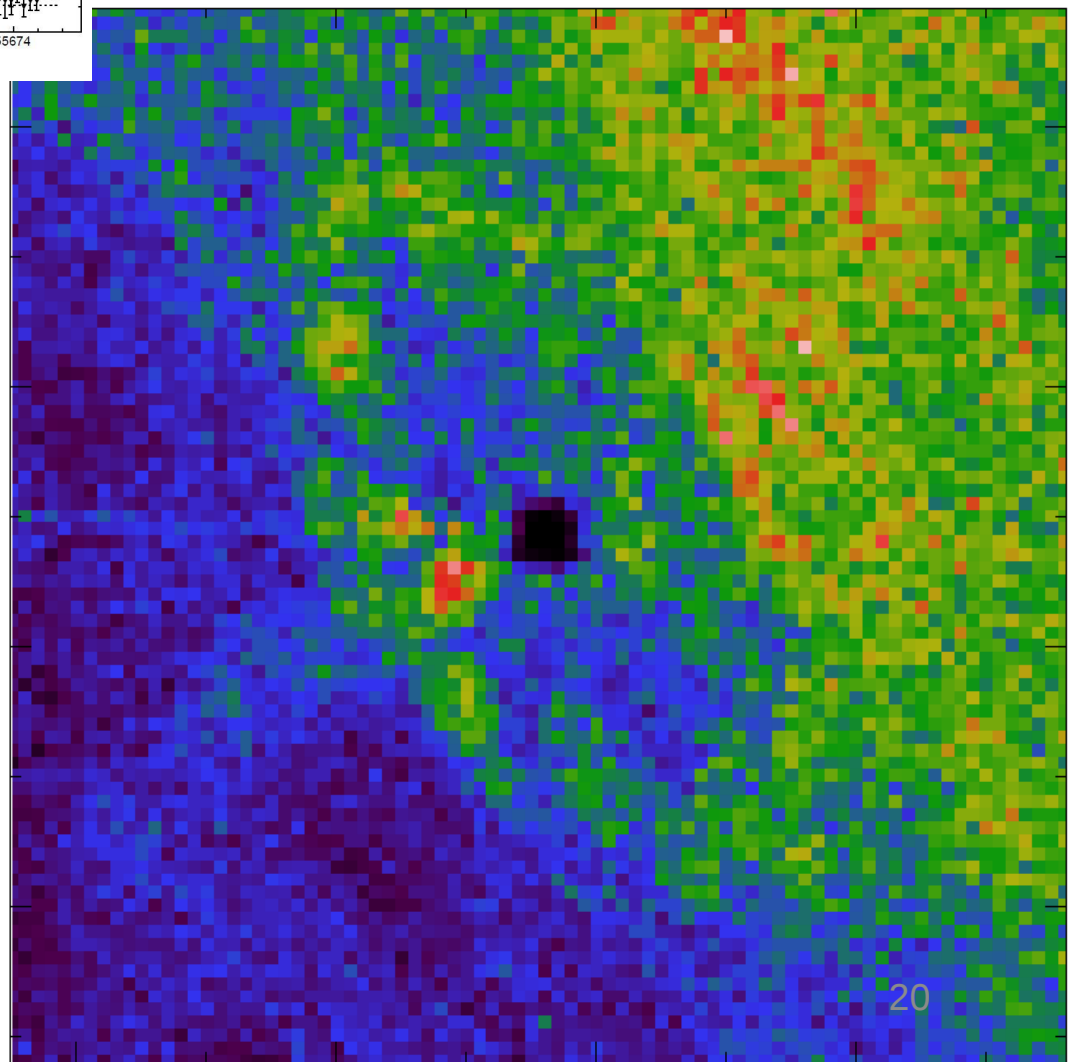
- Waves ~ few/year
- $t_{variability}$ ~ 2-10 days
- Peak energies ~ 200 MeV
- Alone or overlapped with fast flares
- Gamma-ray flare radiated energy ~ 10^{41} erg
- B ~ 1 mG, R ~10^16 cm



Crab super-flare: Chandra monitoring

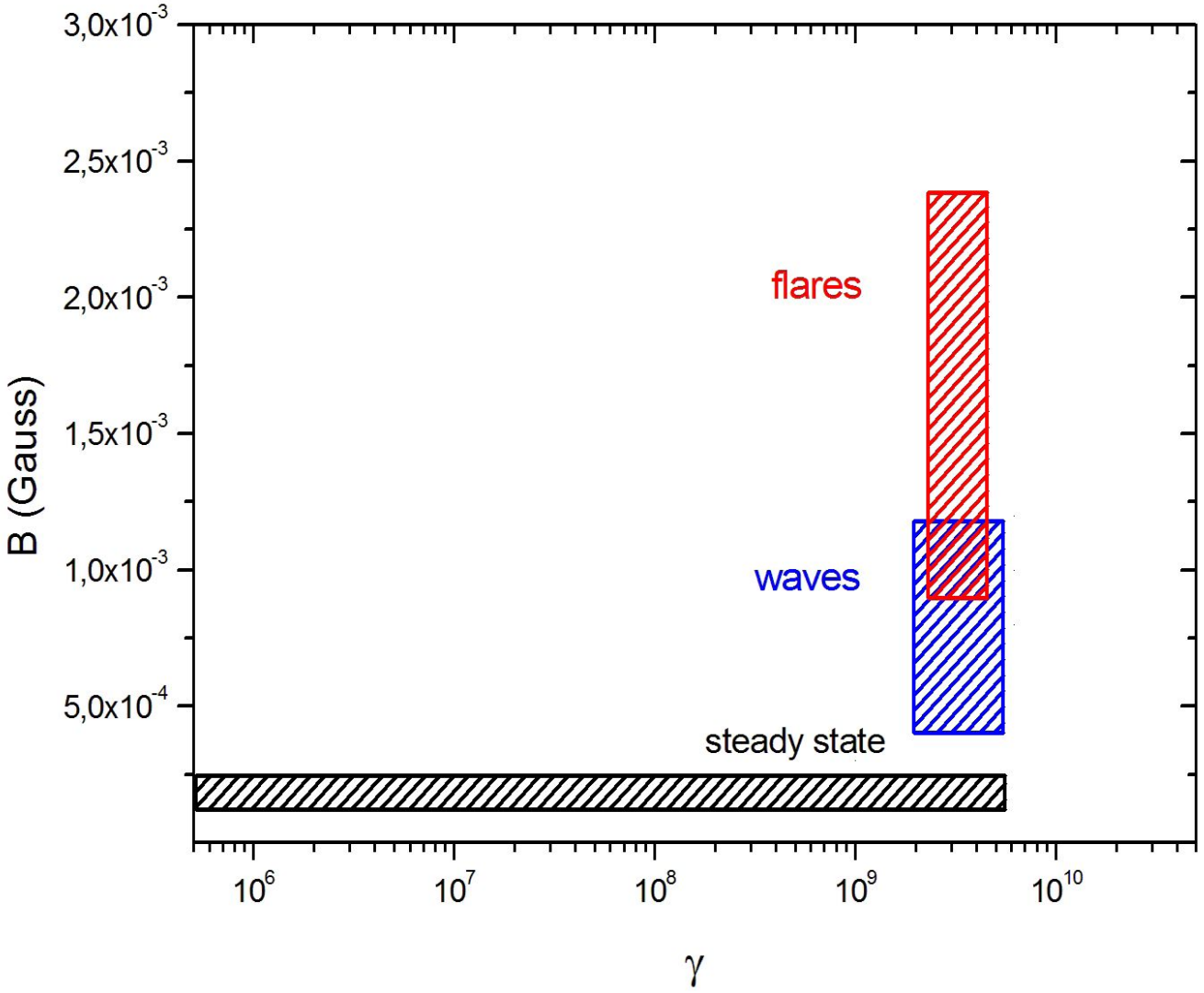
(12, 13, 14, 16, 21 Apr. 2011: A. Tennant, M. Weisskopf)

07 (2011−04−12)



- **No clear smoking gun**
- **No demonstrated relation between simultaneous X-ray and gamma-ray emission.**
- **Mono-energetic (e.g., relativ. Maxwellian) distribution is favored.**

Crab Nebula ***super-acceleration***



It defies synchrotron burnoff (E_parallel)

It defies ideal MHD ($E/B \gtrsim 3$)

It produces "mono-energetic" spectrum

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Theoretical interpretations (2011/13)

- Bednarek & Idec (2011)
- Komissarov & Lyutikov (2011)
- Yuan et al. (2011)
- Uzdensky et al. (2011)
- Bykov, Pavlov, Artemyev, Uvanov (2011)
- Clausen-Brown & Lyutikov (2012)
- Lyutikov et al. (2012)
- Arons (2012)
- Kohri et al. (2012)
- Teraki et al. (2012)
- Sturrock & Aschwanden (2012)
- Lyubarsky (2012)
- Cerutti et al. (2012, 2013a, 2013b)
- Komissarov (2013)
- Baty, Petri, Zenitani (2013)
- Porth et al. (2013a, 2013b)
- Mignone et al. (2013)
- Giannios (2013)
- Weisskopf et al. (2013)

What we recently learnt about Crab: structure of the wind, the shock, flares and reconnection

Maxim Lyutikov

Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907-2036, USA

...ation from RRMHD simulations ...reconnection - Application to

doi:10.3847/0004-637X/823/1/39

CrossMark

...E THE PULSAR STRIPED WIND

...lerator Laboratory, Menlo Park, CA 94025, USA

...2016 May 20

...rth[3,4]

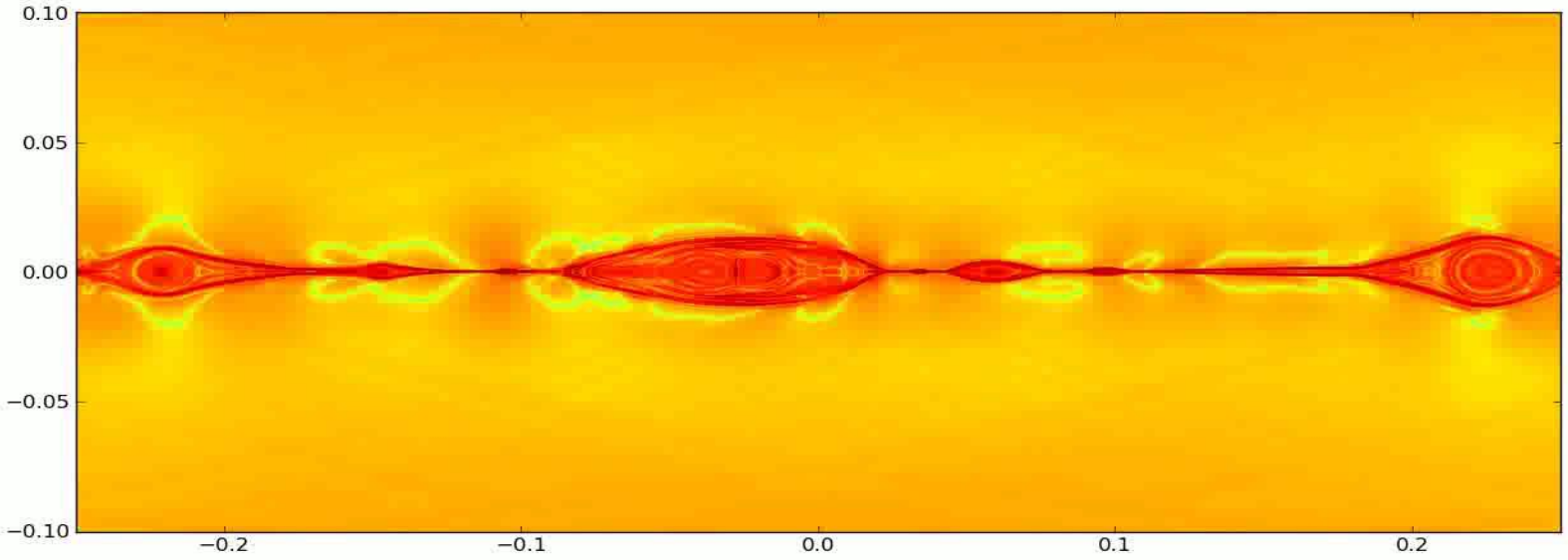
THE ASTROPHYSICAL JOURNAL, 823:39 (7pp), 2...

CRAB FLARES DUE TO TU...

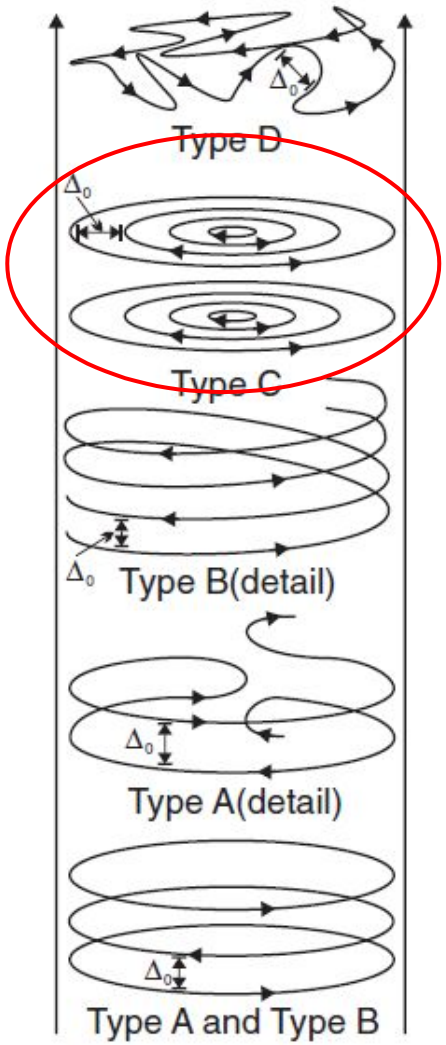
Received 2015 Decembe...

Kavli Institute for Particle Astrophysics and Cosmology,

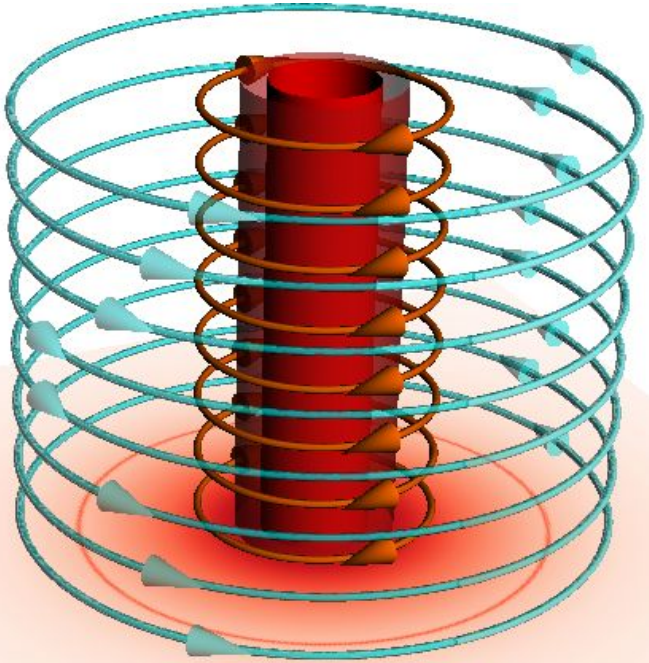
...Lyutikov,[1] Lo... Becker


0.10
0.05
0.00
−0.05
−0.10
−0.2
−0.1
0.0
0.1
0.2

(J. McKinney and D. Uzdensky 2012)



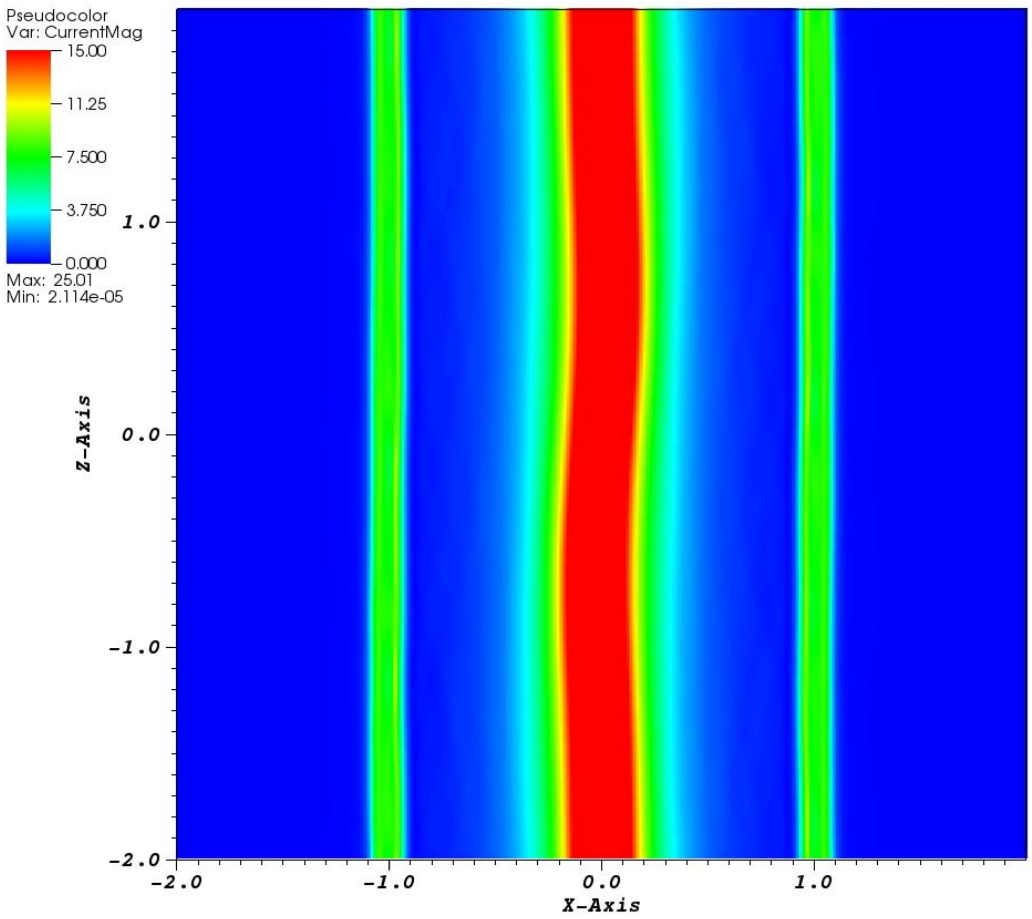
B_{phi} reversal along r



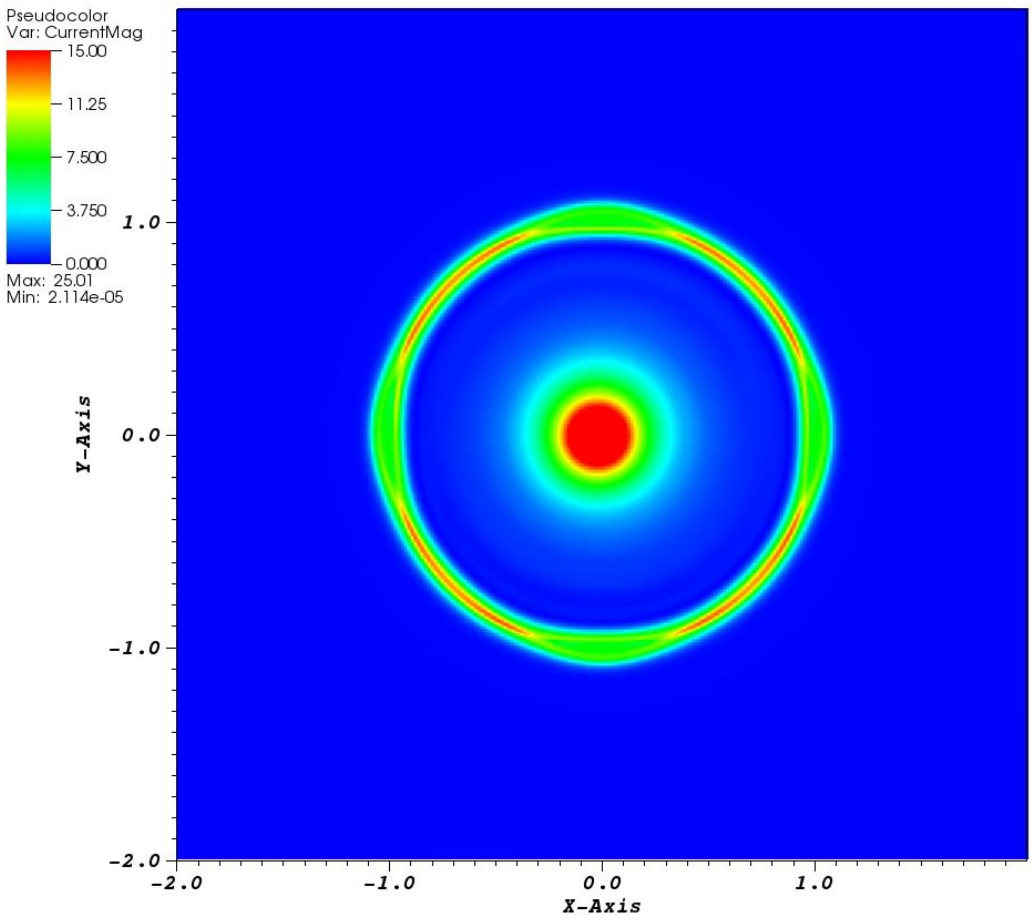
Magnetic reconnection in a plasma column

- pressure-balanced equilibrium (pressure-driven instabilities)
- force-free equilibrium (current-driven instabilities)

How magnetic reconnection is affected by 3D instabilities?



slice on the x-z plane



slice on the x-y plane

Particle acceleration in explosive relativistic reconnection events and Crab Nebula gamma-ray flares

Maxim Lyutikov,[1] Lorenzo Sironi[2], Sergey Komissarov[1,3], Oliver Porth[3,4] (140 pages)

"Particles producing Crab flares, and possibly most of the Crab Nebula high energy emission, are accelerated via magnetic reconnection events, and not at shock via Fermi mechanisms, **a major change of paradigm**."

Conclusions

- The discovery of the Crab Nebula variability **challenged** theoretical models of particle acceleration based on the ideal MHD approximation: the observed variability timescales and energy peaks are **not compatible** with diffusive acceleration.

- **Magnetic reconnection** may be a dominant process in the Crab Nebula and other astrophysical sources.

- Triggered a large number of investigations on particle acceleration and especially magnetic reconnection.

- Large impact on a variety of other objects

Thank you and

Happy birthday Agile!