AGILE GALACTIC HIGHLIGHTS

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ON BEHALF OF THE AGILE TEAM

AGILE 16th Science Workshop

"Fast and AGILE: Multimessenger Astrophysics and Beyond"

May 18, 2018

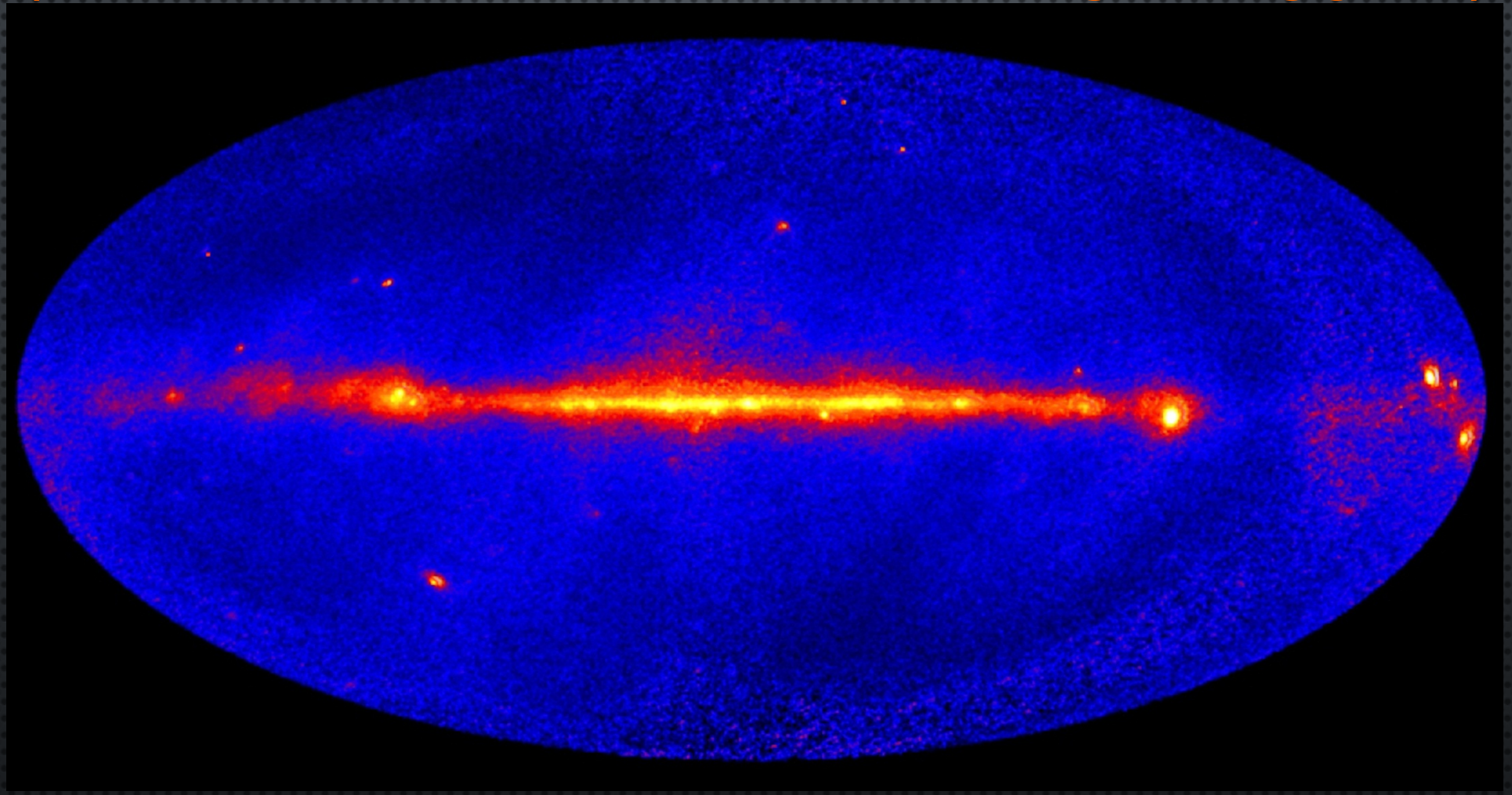
Outline → AGILE Galactic Highlights

- Variability of the Crab Nebula
- SNRs → W44: direct evidence of CR acceleration
- Gamma-ray emitting binaries
- Novae

AGILE
(Astrorivelatore Gamma a Immagini LEggero)

HST optical image of our galaxy

AGILE
(Astrorivelatore Gamma a Immagini LEggero)



AGILE γ-ray image of our galaxy (E > 100 MeV)

Pointing mode: July 2007 – July 2009

AGILE and the Crab Nebula

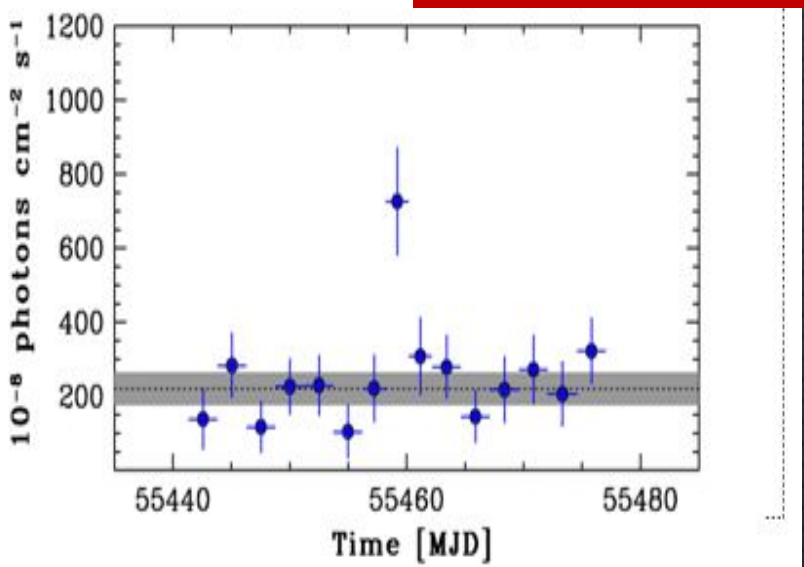
A standard candle …

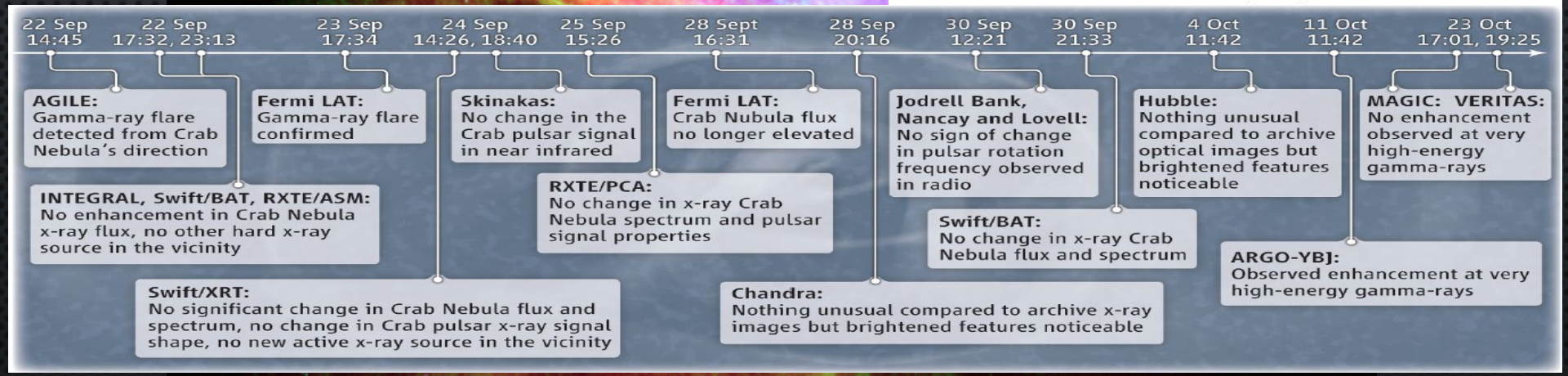
…until September 2010

AGILE and the Crab Nebula

FIRST PUBLIC ANNOUNCEMENT
Sept. 22, 2010: AGILE issues the Astronomer's Telegram #2855 announcing a gamma-ray flare from the Crab Nebula

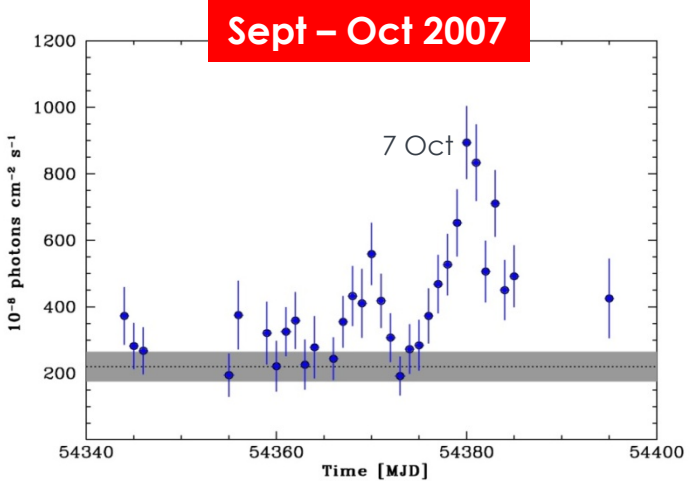
***Science Express* (6 January 2011)**

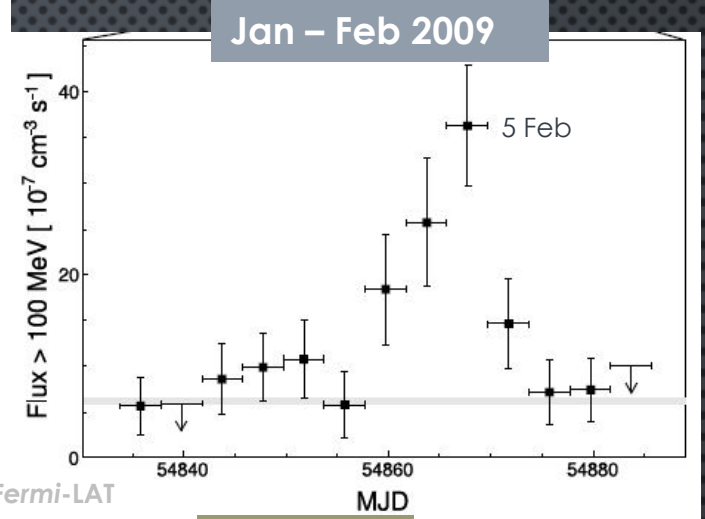


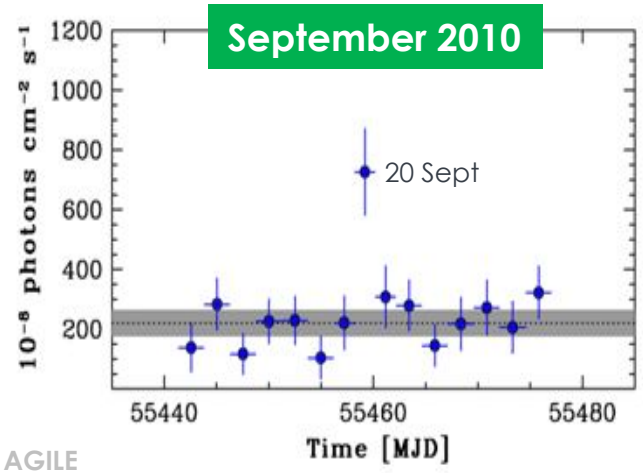


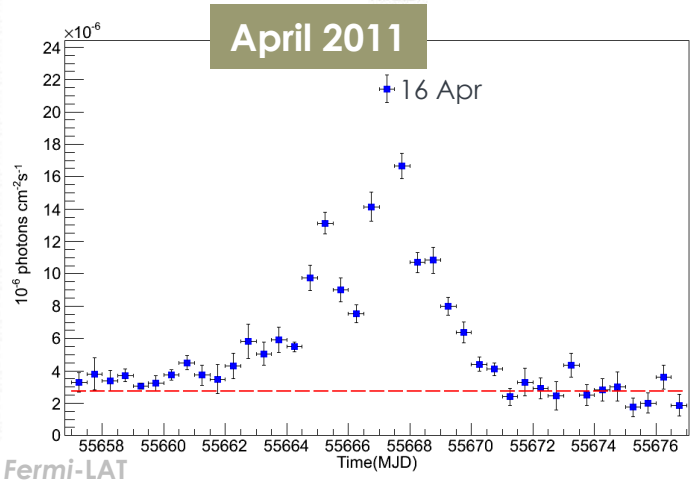
Bernardini E., 2011

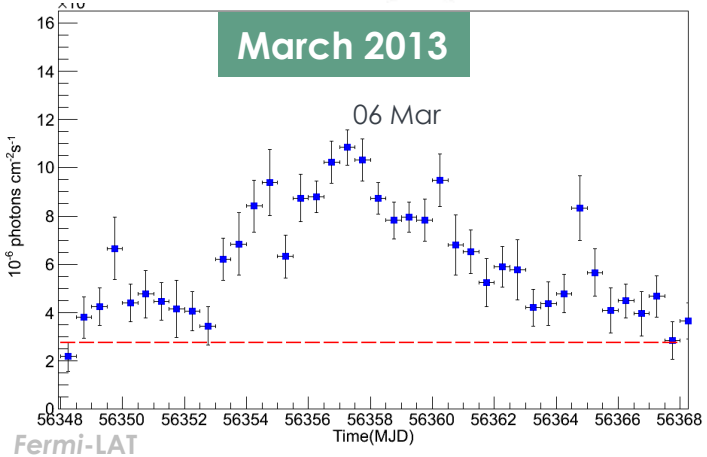
Bruno Rossi Prize from HEAD-AAS in 2012

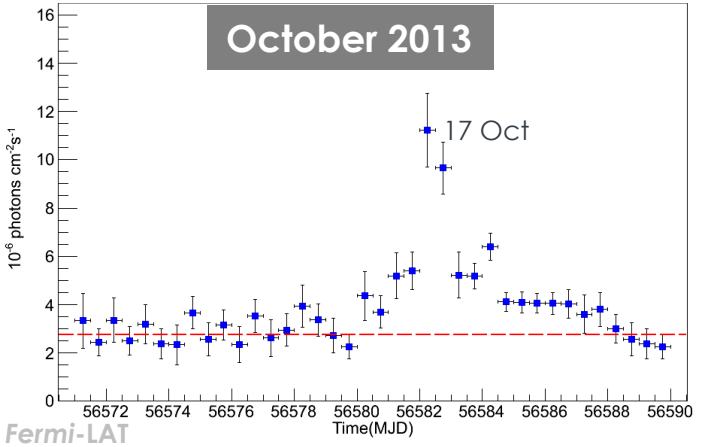




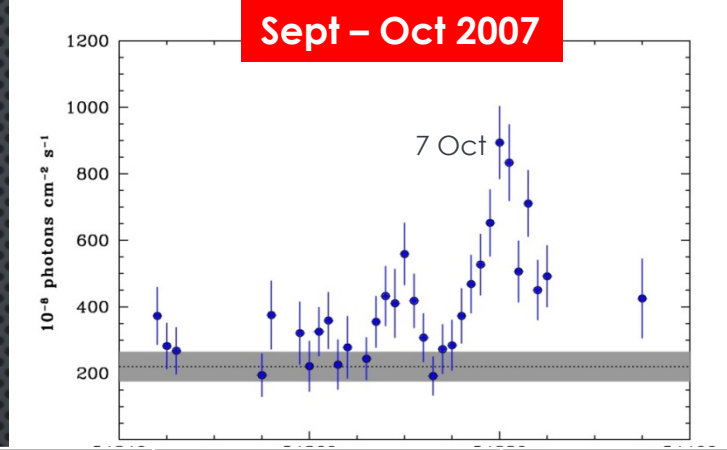


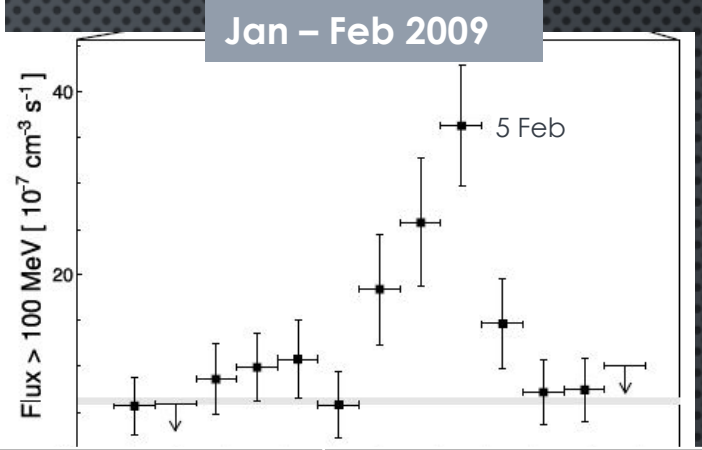




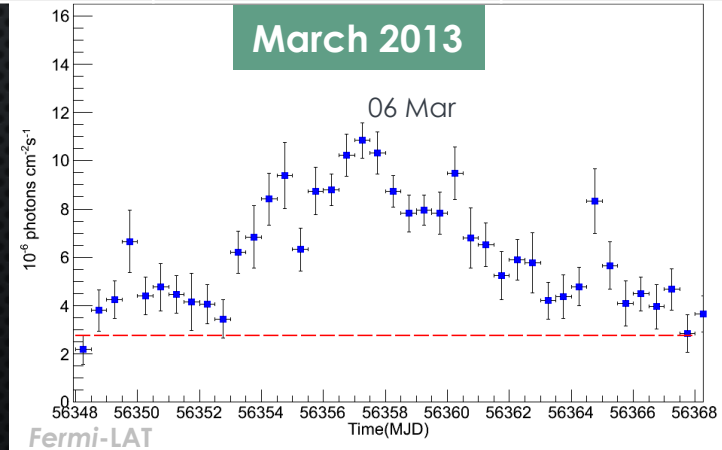


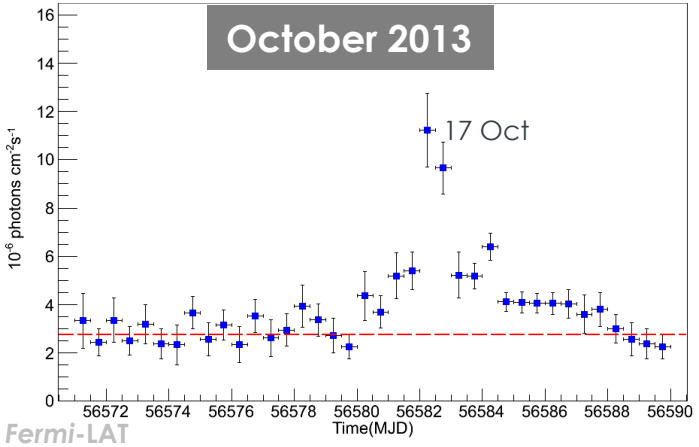
(Tavani et al., 2011)
(Striani et al., 2011)
(Striani et al., 2013)





Flare date	Duration	Peak γ-ray flux	Instruments
October 2007	~ 15 days	~ 9 ·10^{-6} ph cm^{-2} s^{-1}	AGILE
February 2009	~ 15 days	~ 4 ·10^{-6} ph cm^{-2} s^{-1}	*Fermi*-LAT
September 2010	~ 4 days	~ 7 ·10^{-6} ph cm^{-2} s^{-1}	AGILE, *Fermi*-LAT
April 2011	~ 10 days	~ 22 ·10^{-6} ph cm^{-2} s^{-1}	AGILE, *Fermi*-LAT
March 2013	~ 20 days	~ 11 ·10^{-6} ph cm^{-2} s^{-1}	AGILE, *Fermi*-LAT
October 2013	~ 7 days	~ 12 ·10^{-6} ph cm^{-2} s^{-1}	*Fermi*-LAT

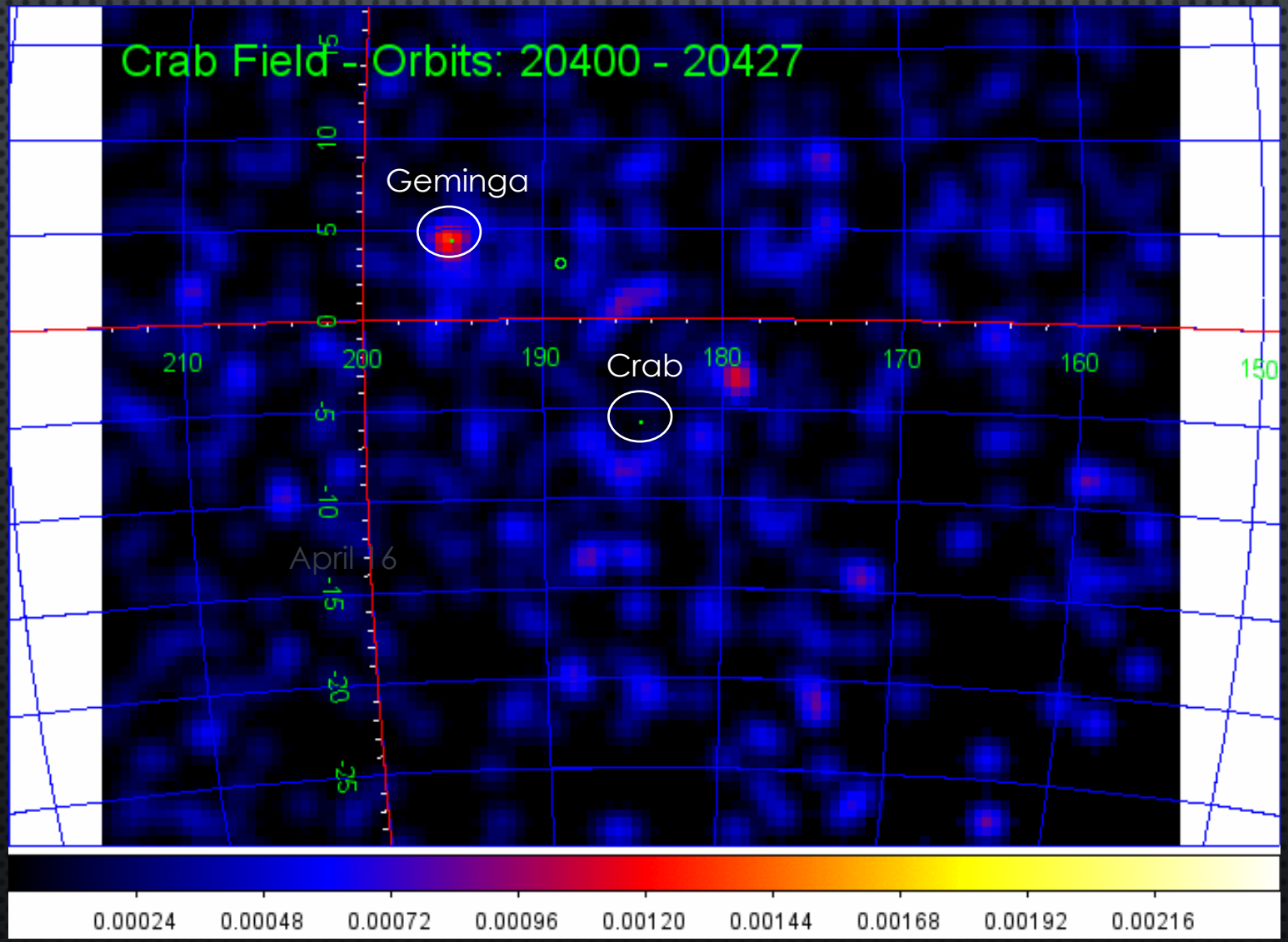




(Tavani et al., 2011)
(Striani et al., 2011)
(Striani et al., 2013)

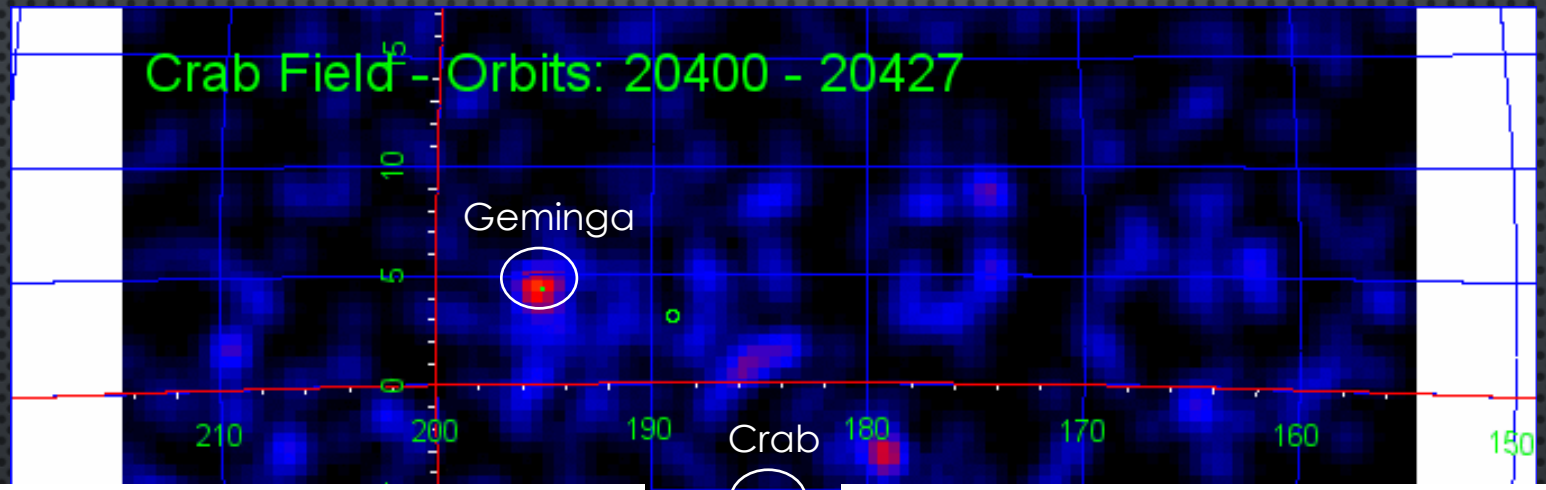
AGILE and the Crab Nebula

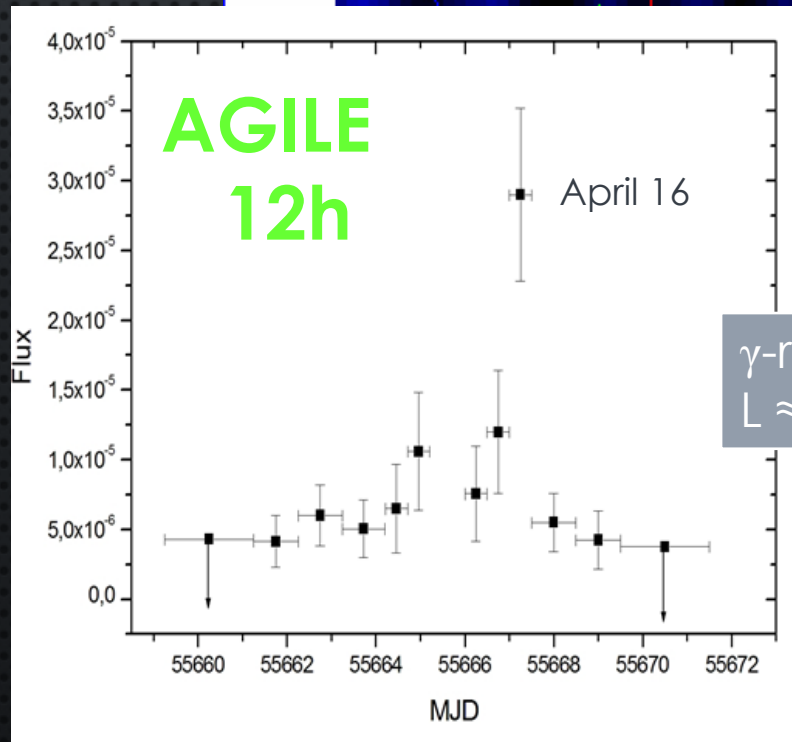
γ-ray monitoring: April 2011



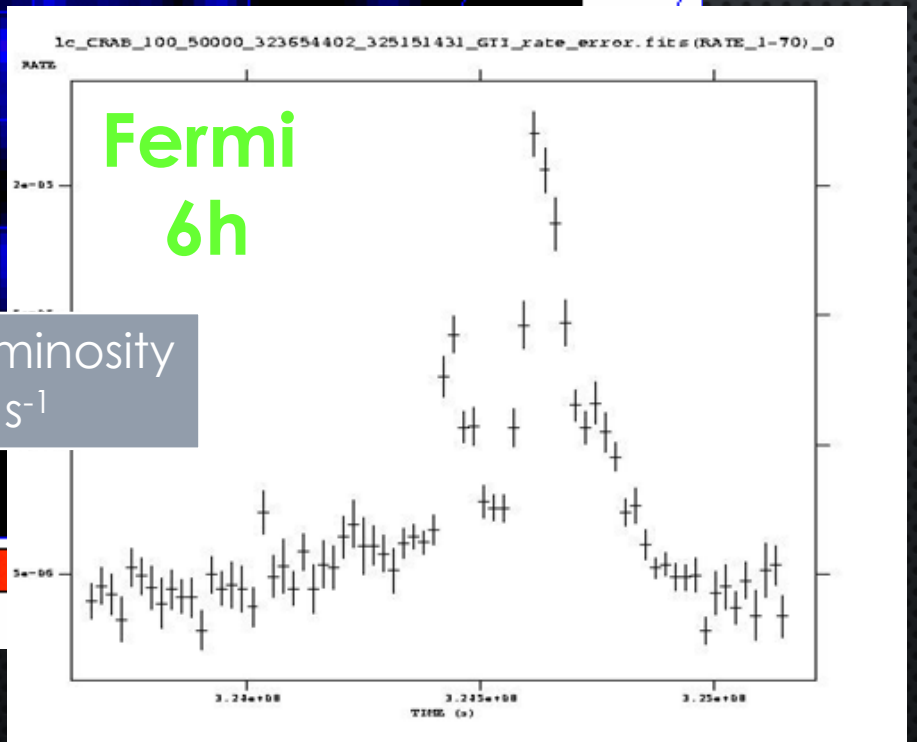
AGILE and the Crab Nebula

γ-ray monitoring: April 2011



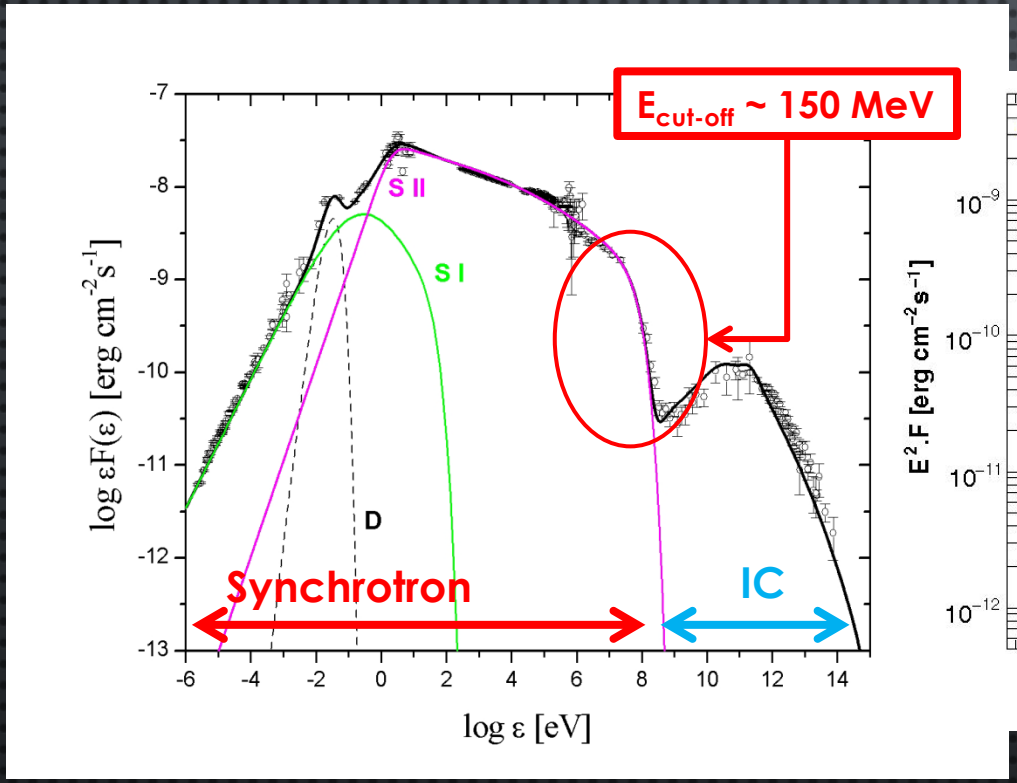


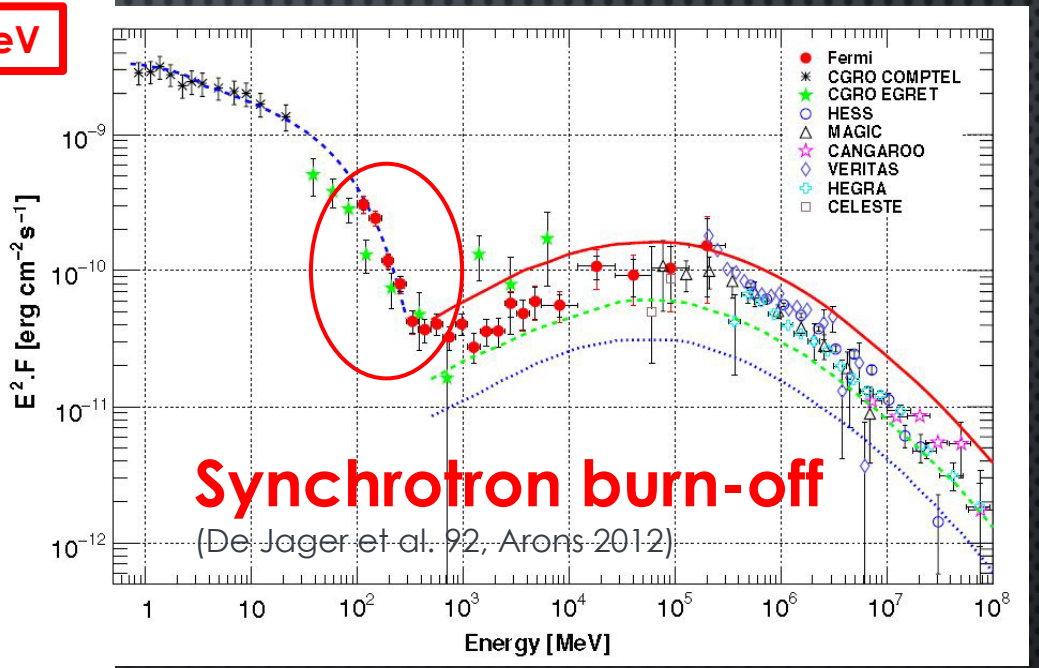
γ-ray peak luminosity
$L \approx 2 \cdot 10^{36}$ erg s^{-1}



AGILE and the Crab Nebula

The Crab Nebula steady spectrum





Linear accelerator in ideal MHD framework

$$t_{acc} = \frac{\gamma}{\omega_B}\frac{B}{E} \qquad t_{synch} = \frac{3m^3c^5}{2e^4B^2\gamma}$$

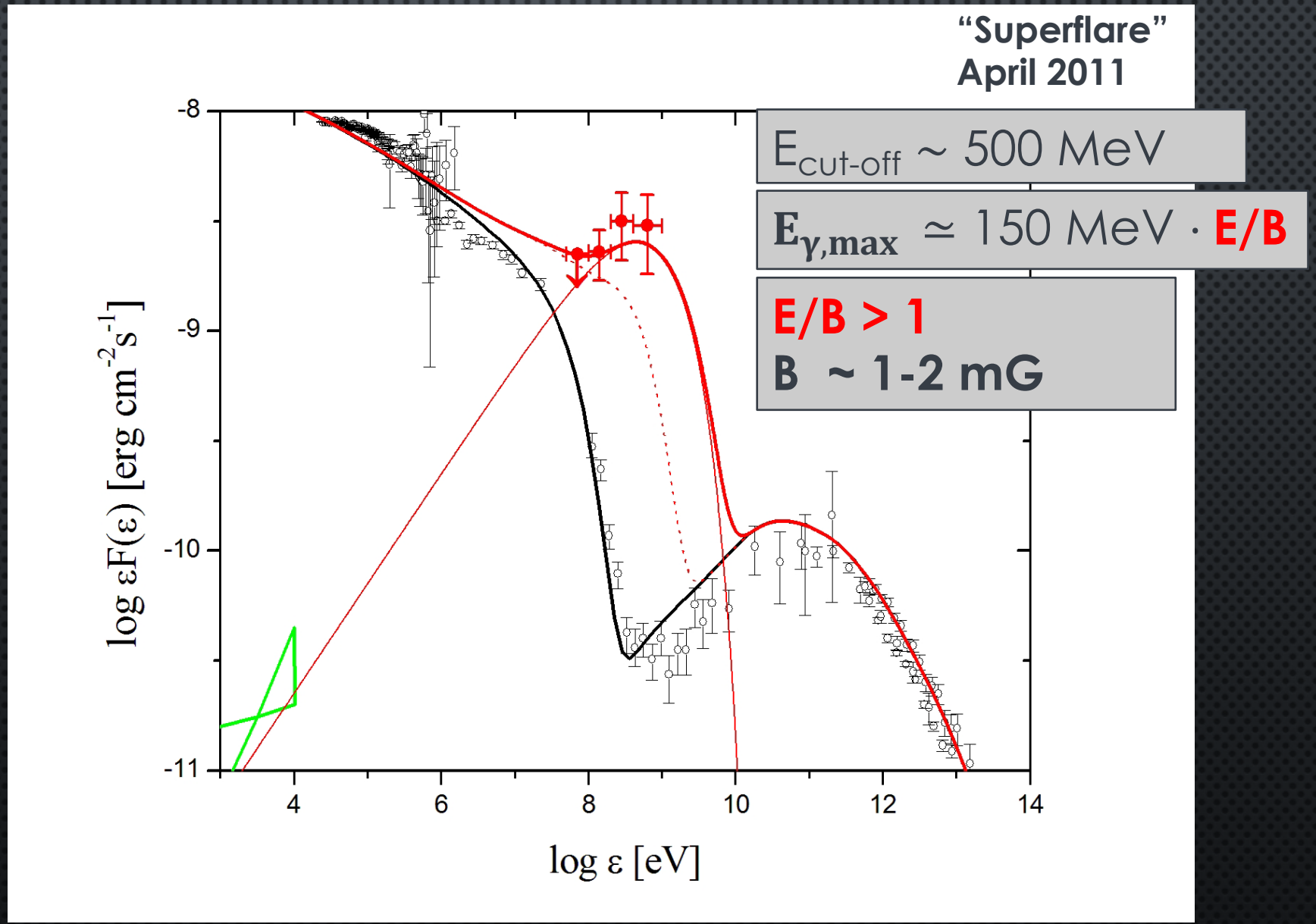
$$E_{\gamma,max} = \frac{9}{4}\frac{mc^2}{\alpha}\cdot \mathbf{E/B} \simeq \mathbf{150\ MeV}\cdot \mathbf{E/B}$$

Nebula → B = 200 μG

E/B ≤ 1 (ideal MHD)

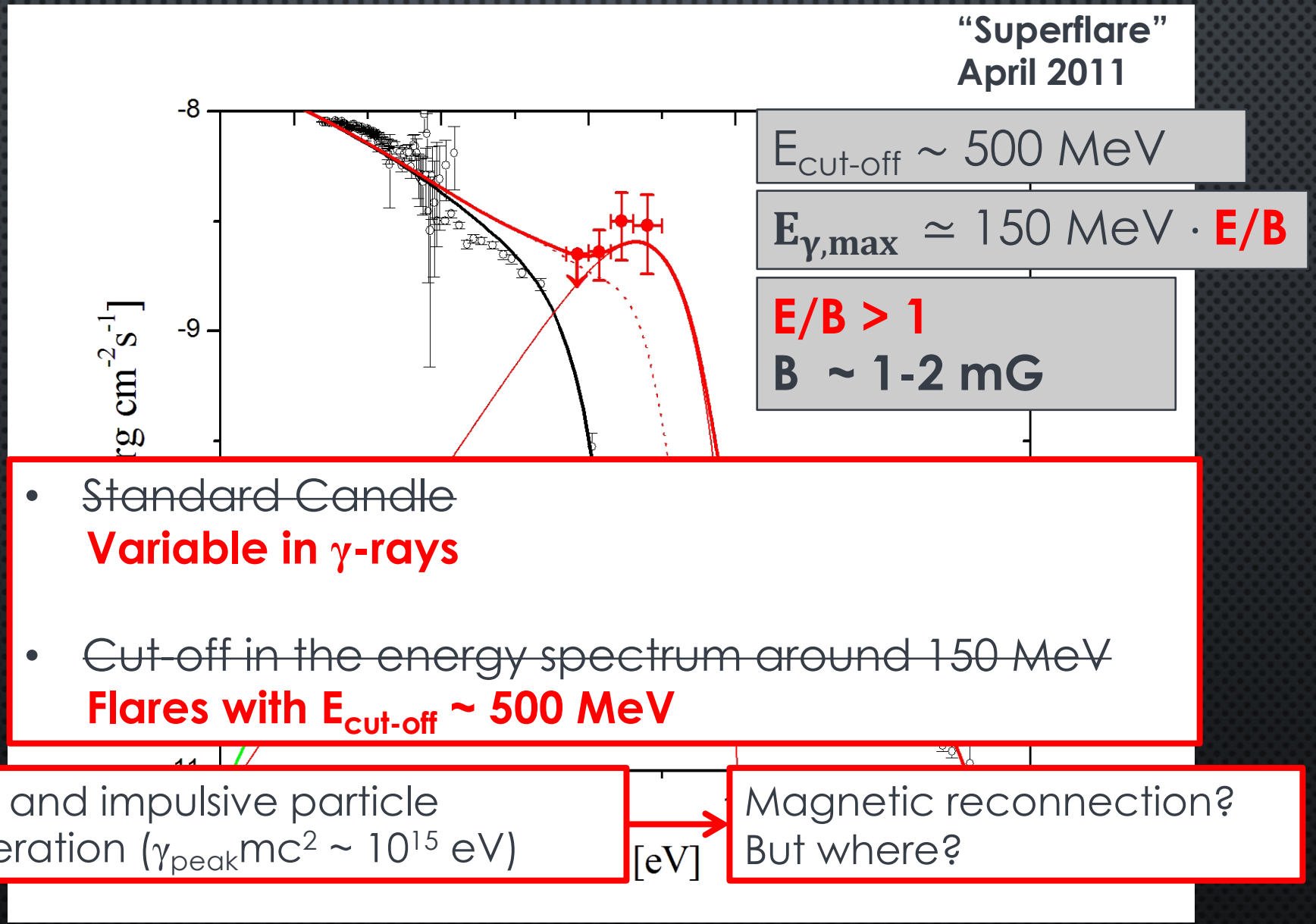
AGILE and the Crab Nebula

The Crab Nebula γ-ray flaring spectrum



AGILE and the Crab Nebula

The Crab Nebula γ-ray flaring spectrum

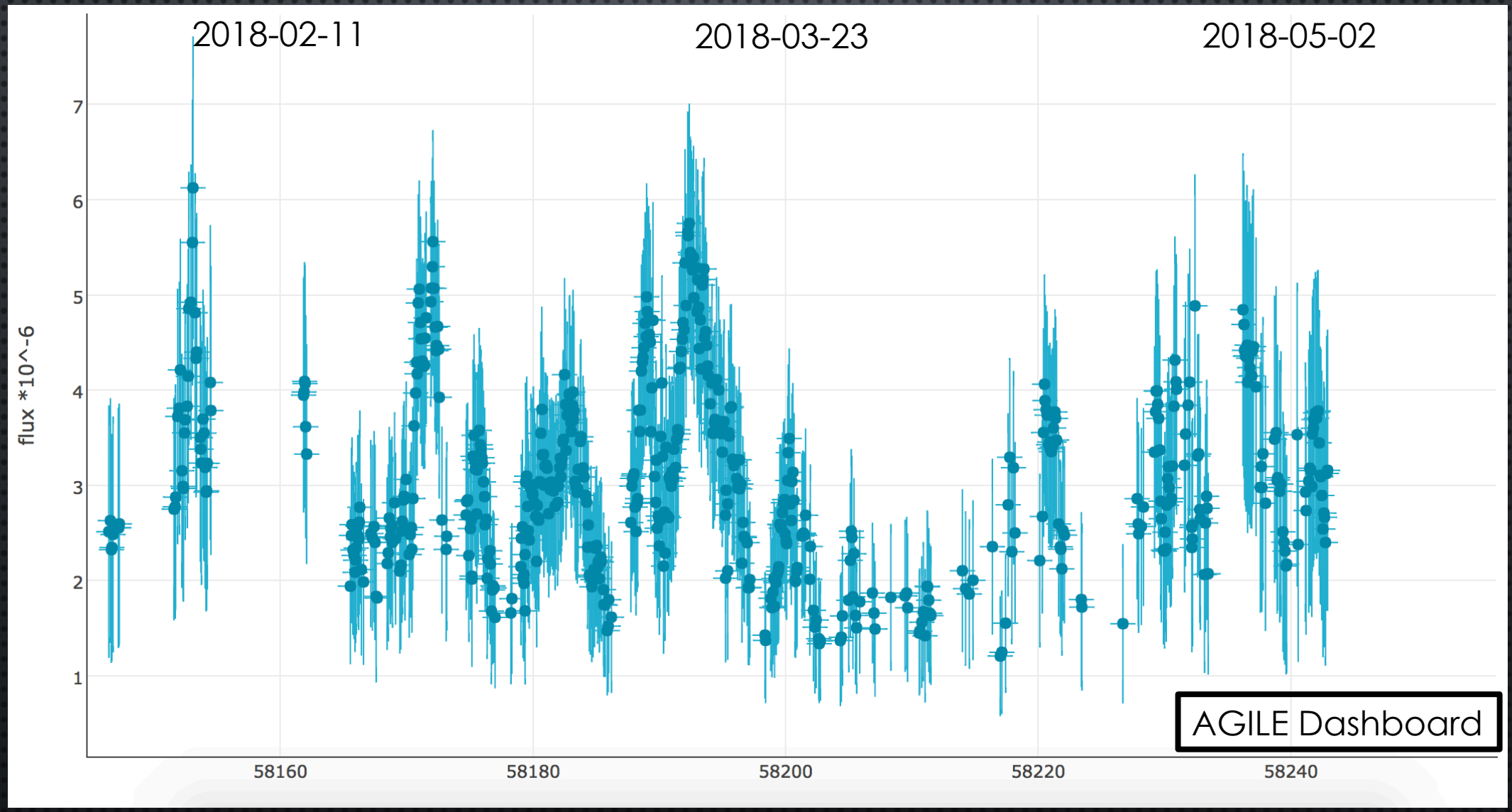


- ~~Standard Candle~~
  Variable in γ-rays
- ~~Cut-off in the energy spectrum around 150 MeV~~
  Flares with $E_{cut\text{-}off}$ ~ 500 MeV

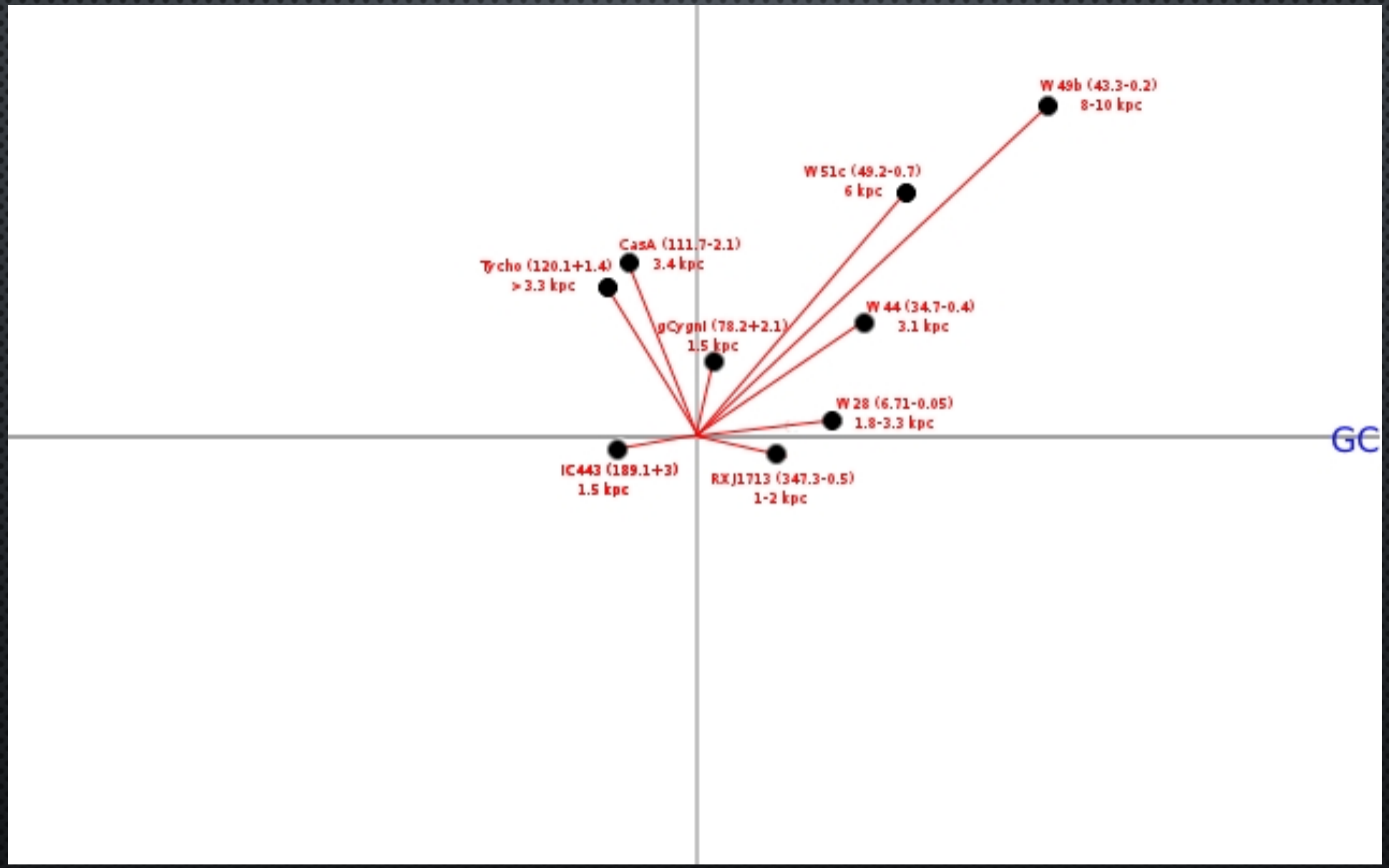
Strong and impulsive particle acceleration ($\gamma_{peak} mc^2 \sim 10^{15}$ eV) → Magnetic reconnection? But where?

AGILE and the Crab Nebula

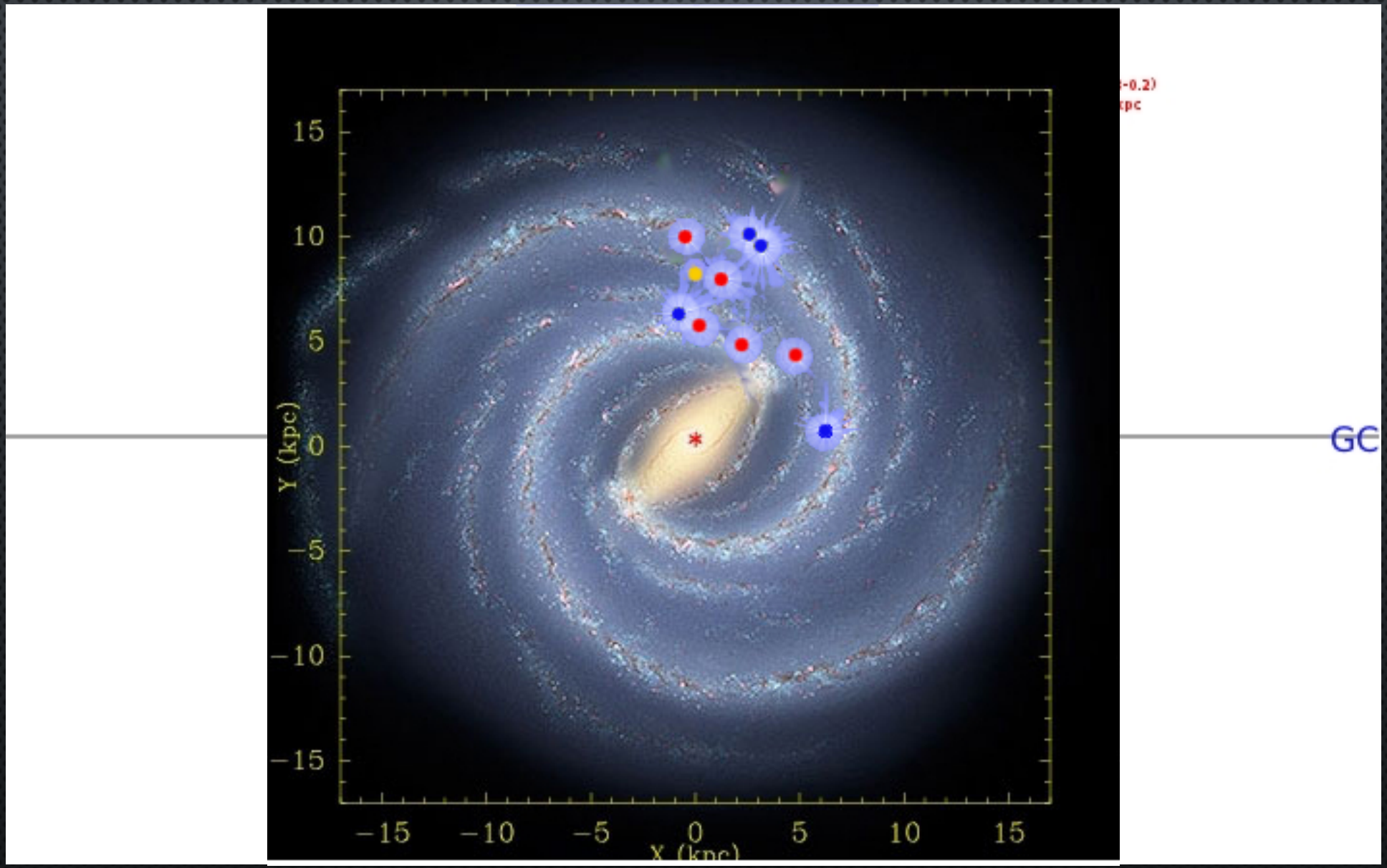
Recent γ-ray activity



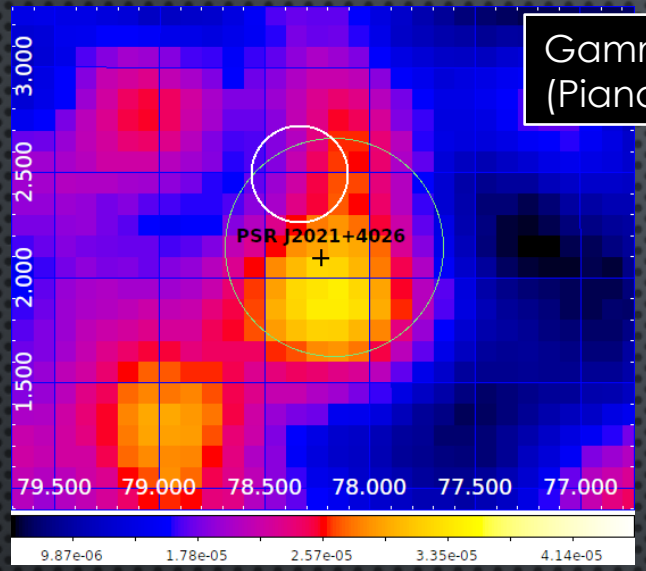
SNRs in gamma-rays



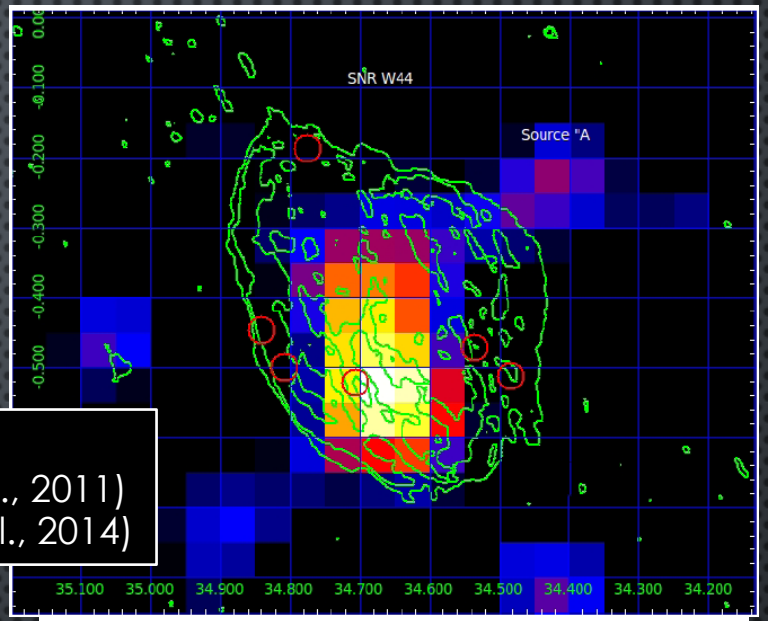
SNRs in gamma-rays



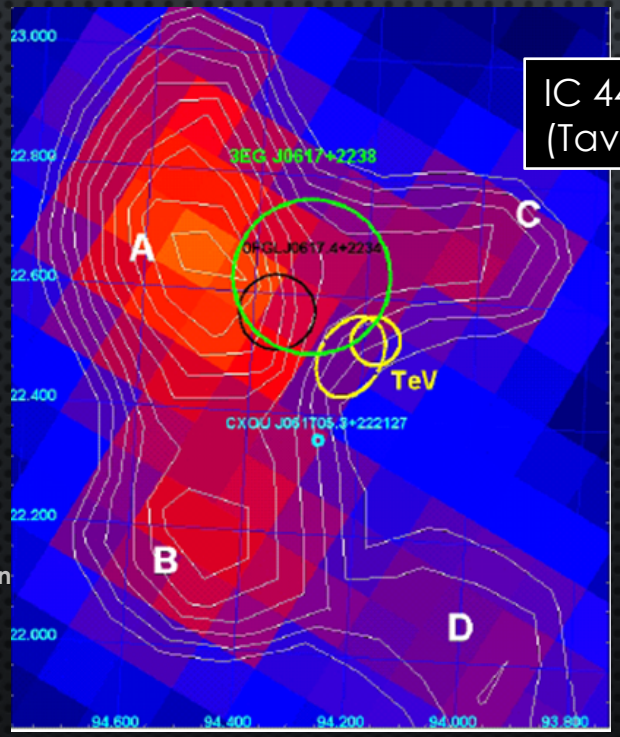
AGILE and SNRs



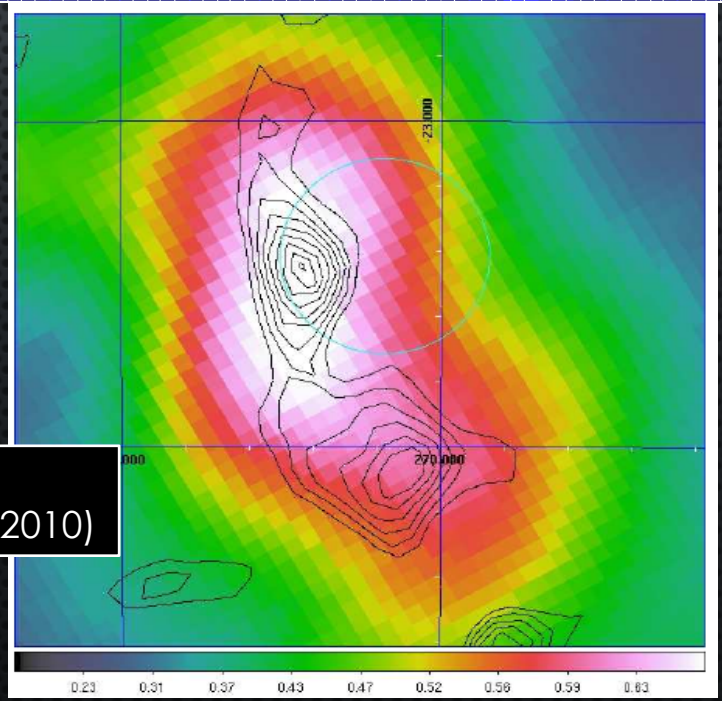
Gamma Cygni
(Piano et al., in preparation)



W44
(Giuliani et al., 2011)
(Cardillo et al., 2014)



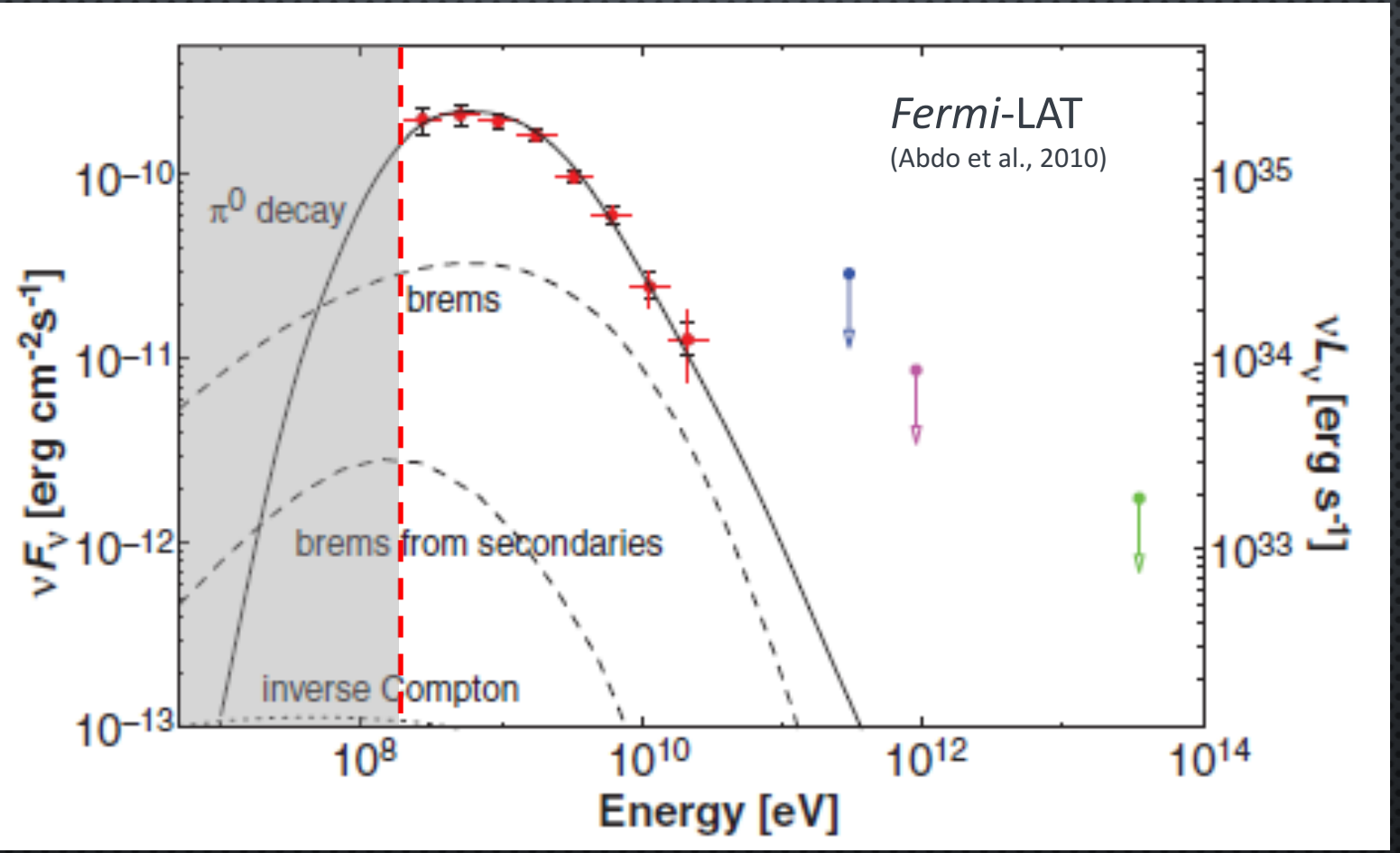
IC 443
(Tavani et al., 2010)



W28
(Giuliani et al., 2010)

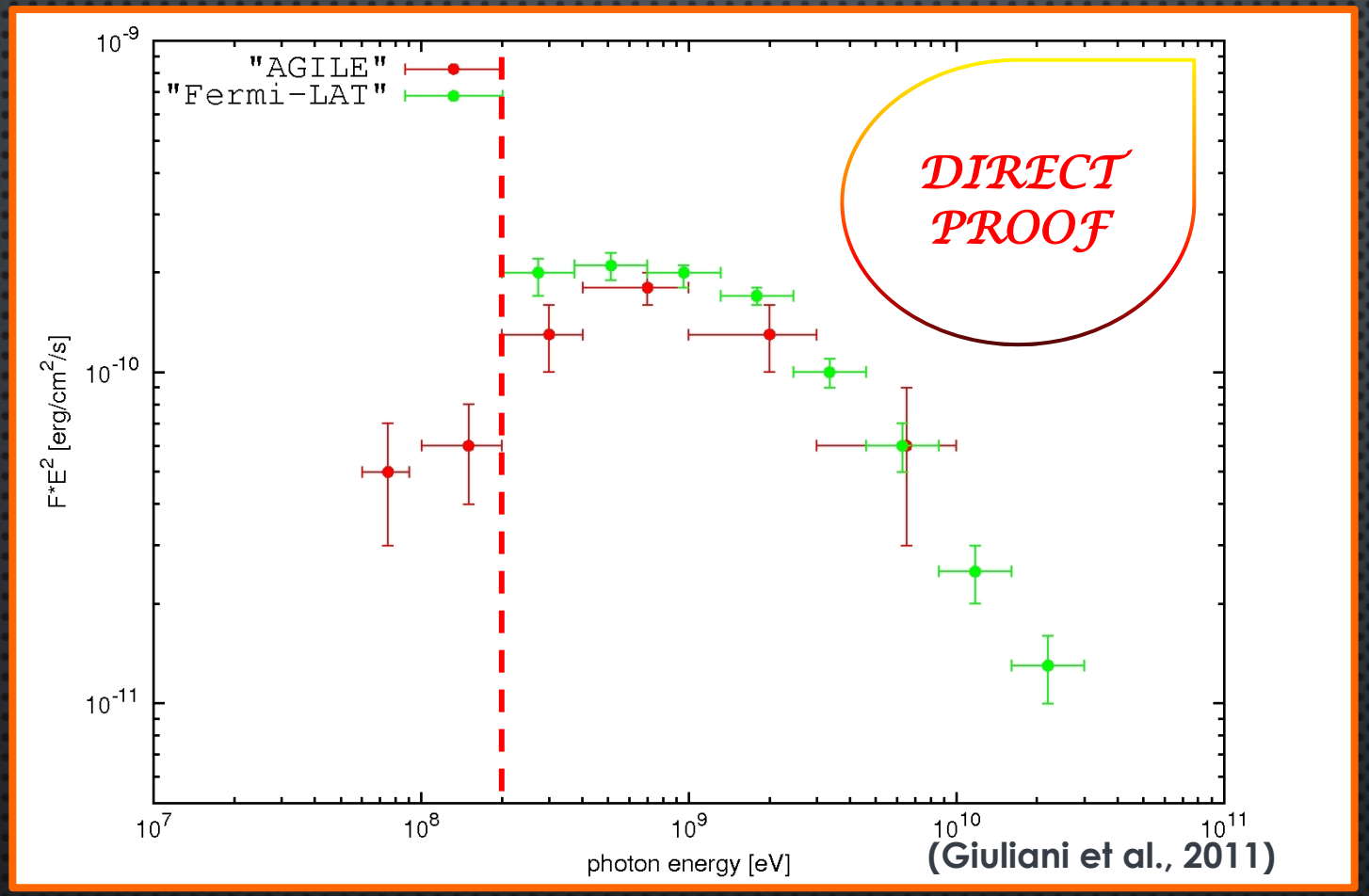
Giovan

AGILE and SNRs: W44



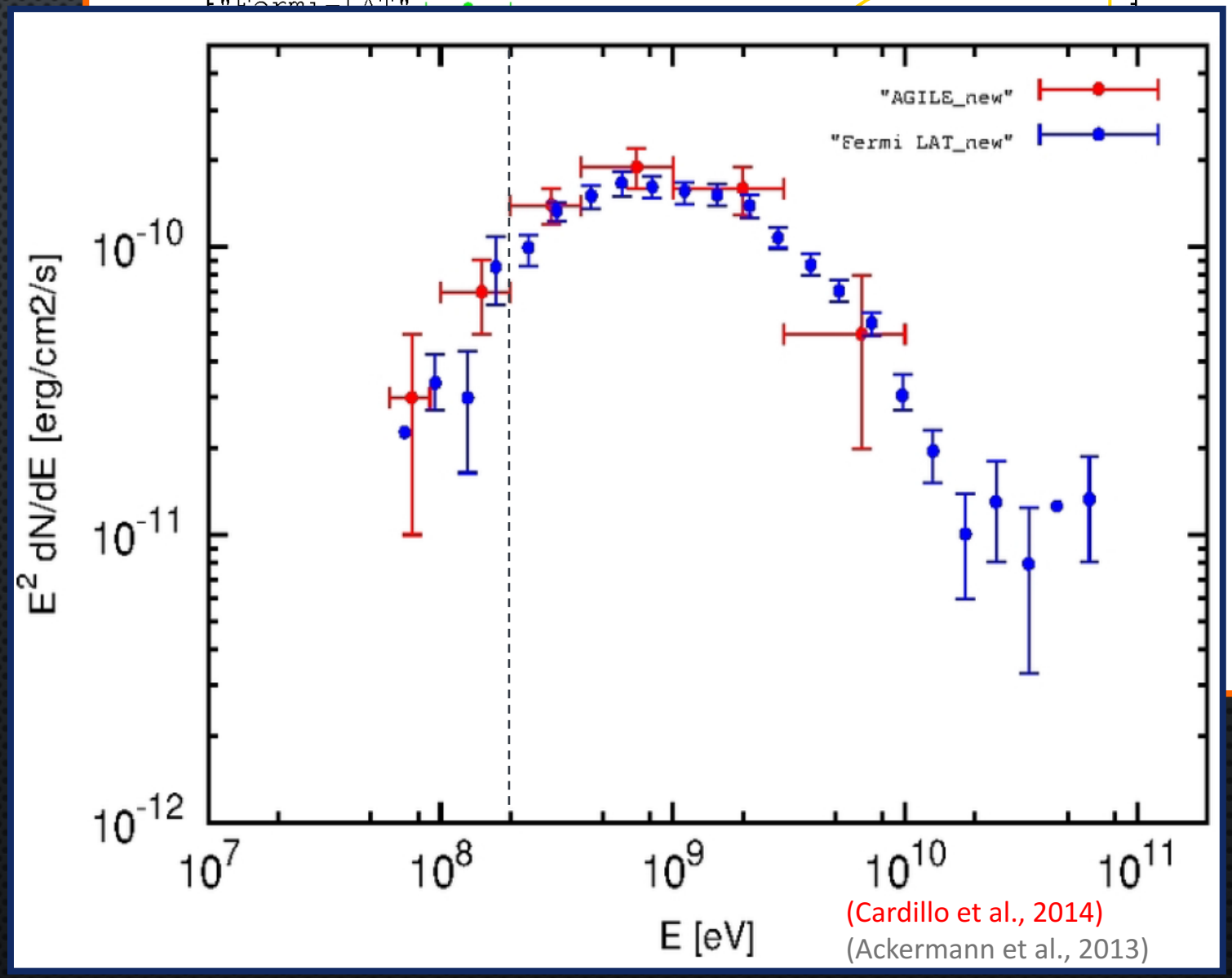
- Strong evidence supporting the hadronic scenario (neutral pion decay)
- No data below 200 MeV (→ π^0 "signature": fast steepening spectrum)

AGILE and SNRs: W44



(Giuliani et al., 2011)

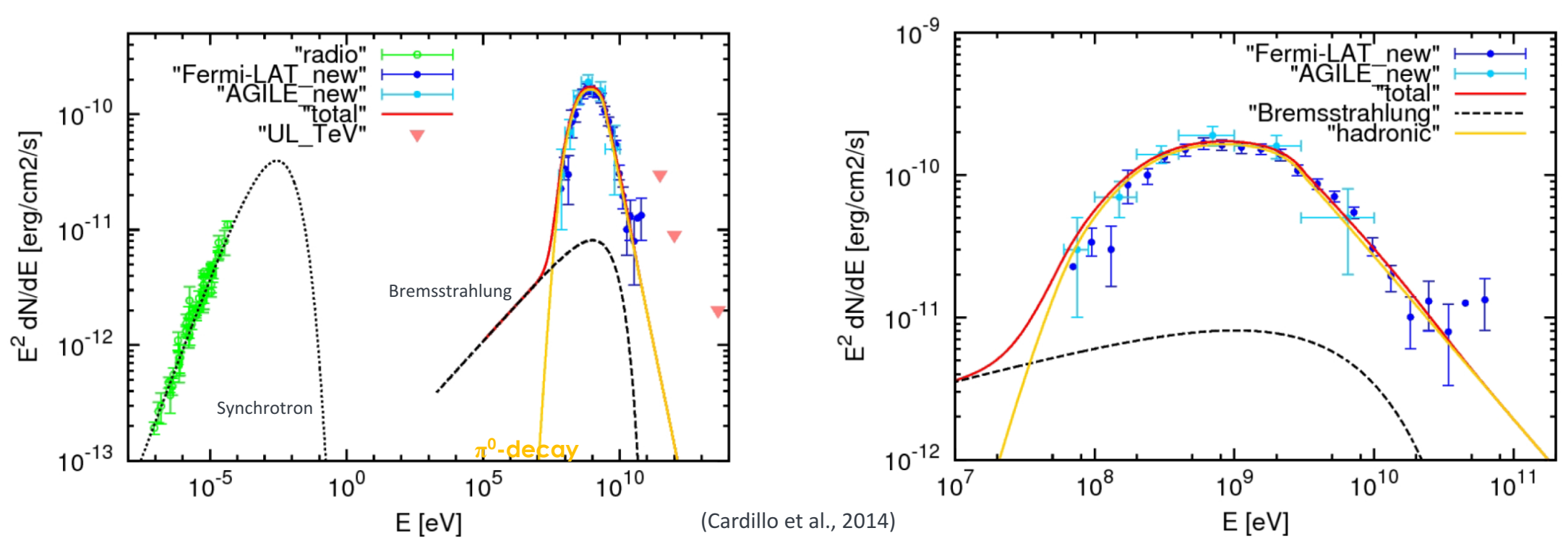
AGILE and SNRs: W44



(Cardillo et al., 2014)

(Ackermann et al., 2013)

AGILE and SNRs: W44



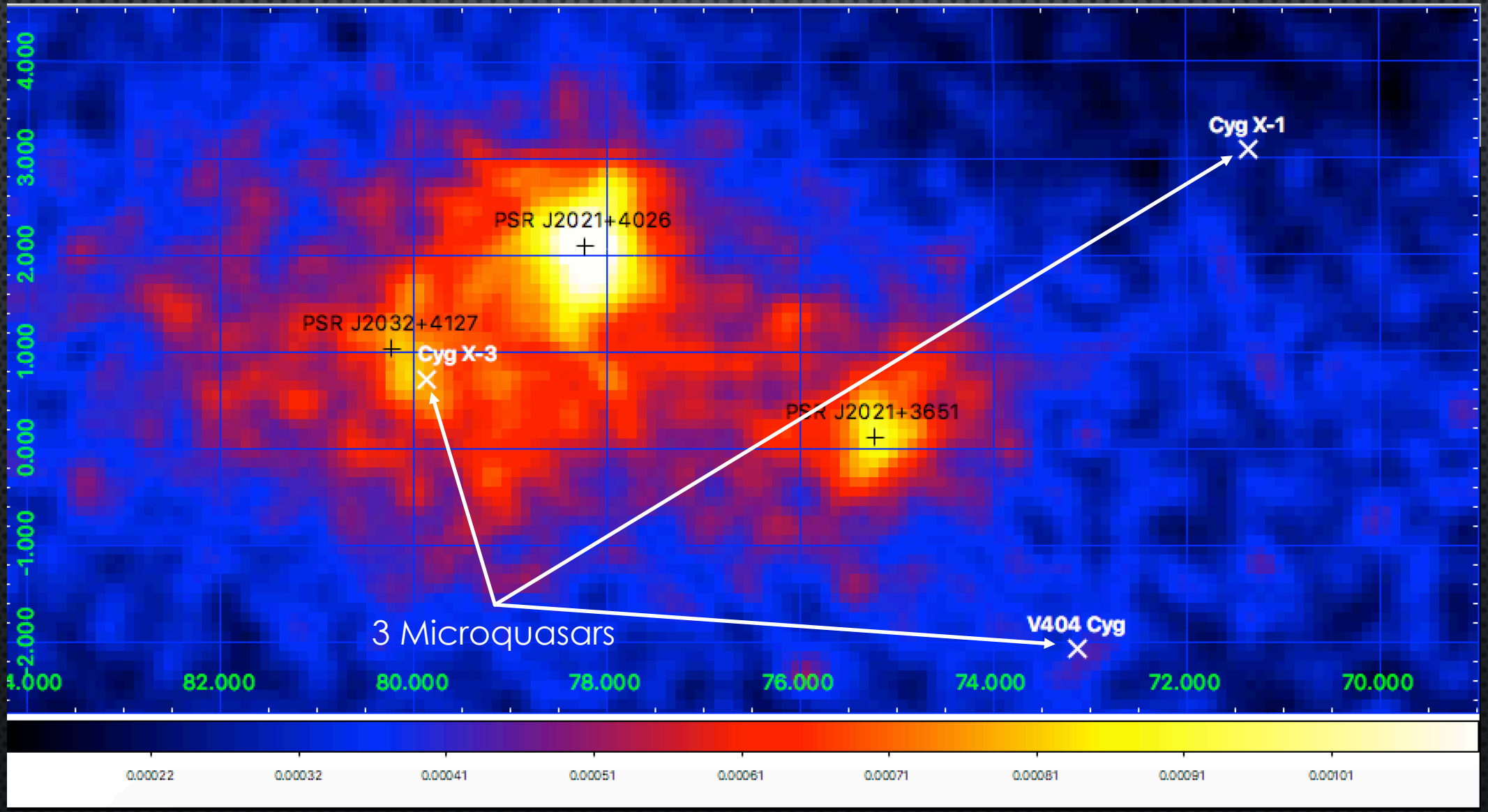
(Cardillo et al., 2014)

- A dominant leptonic contribution is excluded for W44
- Direct proof of π^0 "bump" → accelerated hadrons
- "Smoking gun" of CR acceleration process in a Galactic source

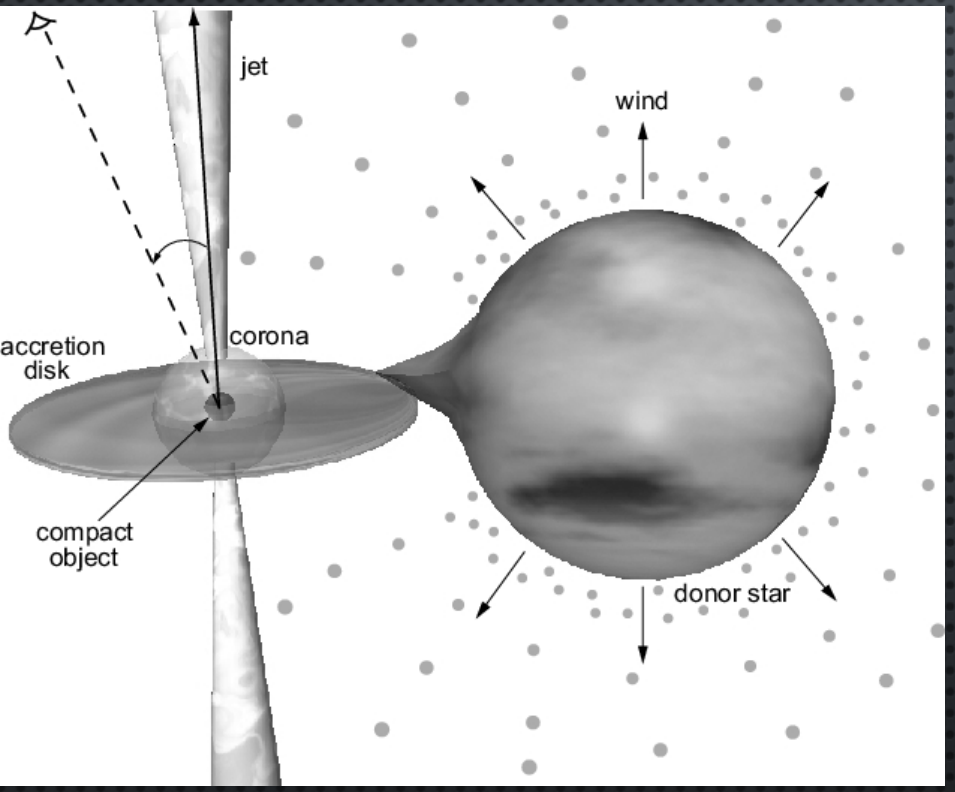
γ-ray binaries detected by AGILE

- Microquasars in the Cygnus Region
  - Cygnus X-1
  - Cygnus X-3
  - V404 Cygni
- η Carinae: a colliding wind binary
- AGILE Sources Possibly Associated with Binary Systems

THE CYGNUS REGION AS DETECTED BY AGILE (E > 100 MeV)



Microquasar



- X-ray binary systems: accreting NS or BH + jets
- Variable X-ray emission
- Radio emission: variable low-level flux + giant flares (Cyg X-3)
- Typically, correlated radio/soft X-ray/hard X-ray emission

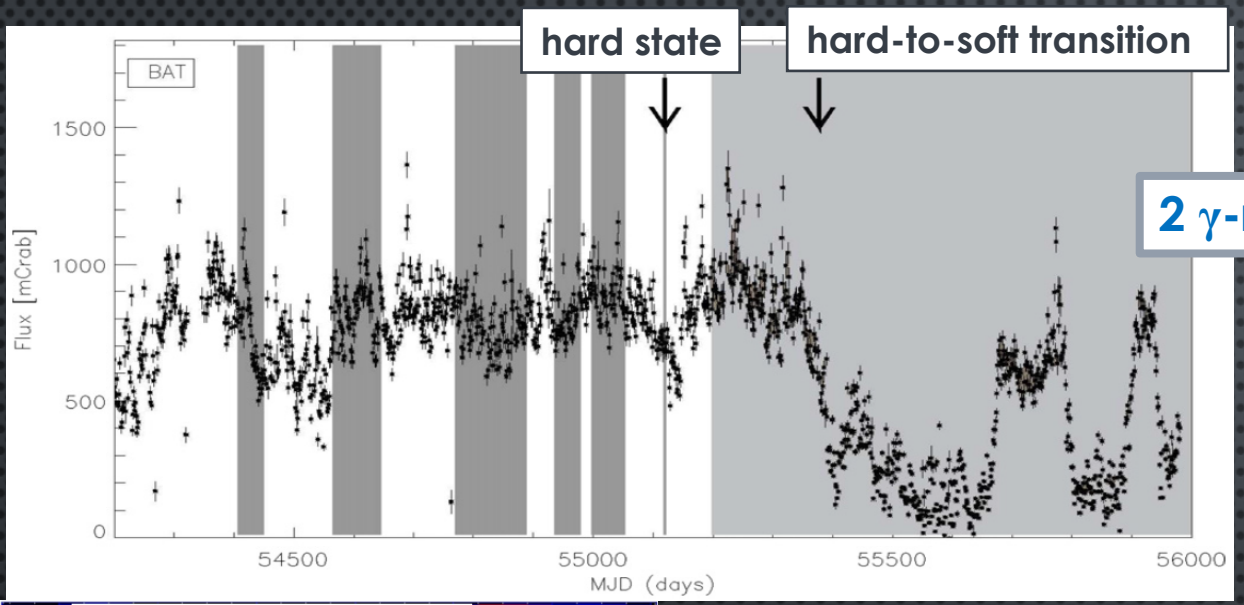
Open question (pre-AGILE/Fermi):

➢ **Can the jet emit γ-rays above 100 MeV?**

Microquasars in the Cygnus region

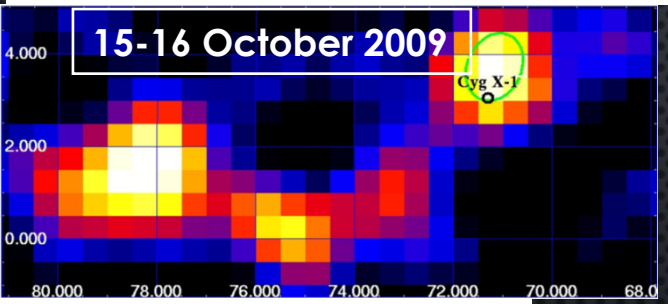
	Cygnus X-1	Cygnus X-3	V404 Cygni
type	HMXB	HMXB	LMXB
compact object	BH (4.8-14.8 $M_\odot$)	BH or NS (?)	BH (9 $M_\odot$)
companion star	09.7 Iab (17-31 $M_\odot$)	WR (> 7 $M_\odot$)	K3 III (0.7 $M_\odot$)
distance	1.9 kpc	7-10 kpc	2.39 kpc
orbital period	5.6 days	4.8 hours	6.47 days

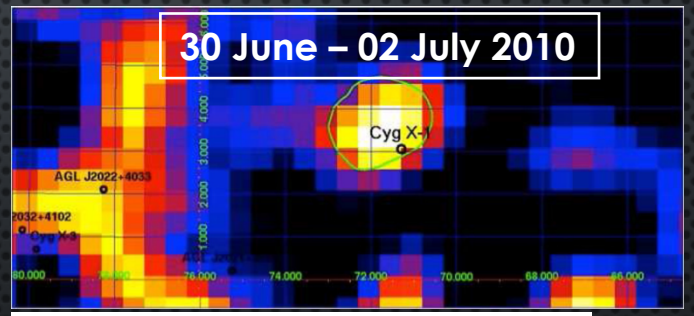
Cygnus X-1

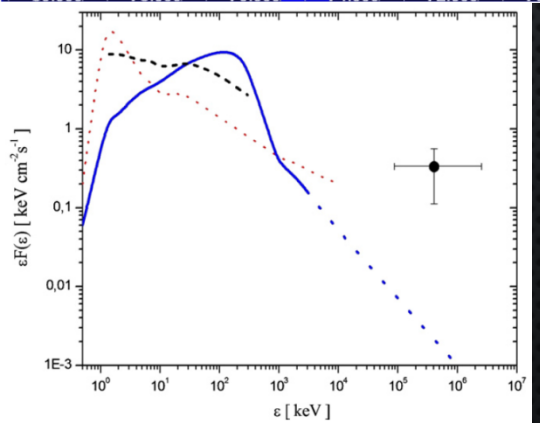


2 γ-ray flares detected by AGILE

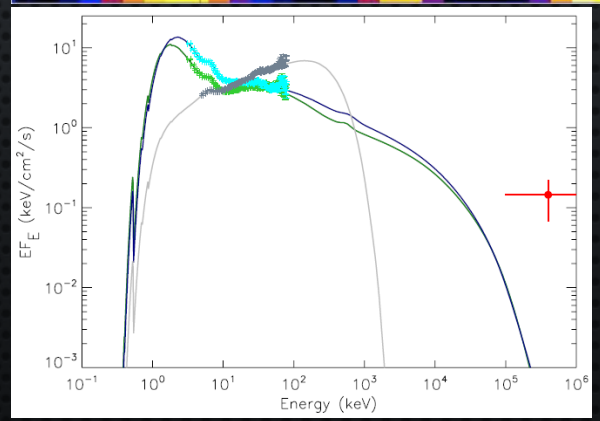
Sabatini et al., ApJL, 712, L10 (2010)
Sabatini et al., ApJ, 766, 83 (2013)







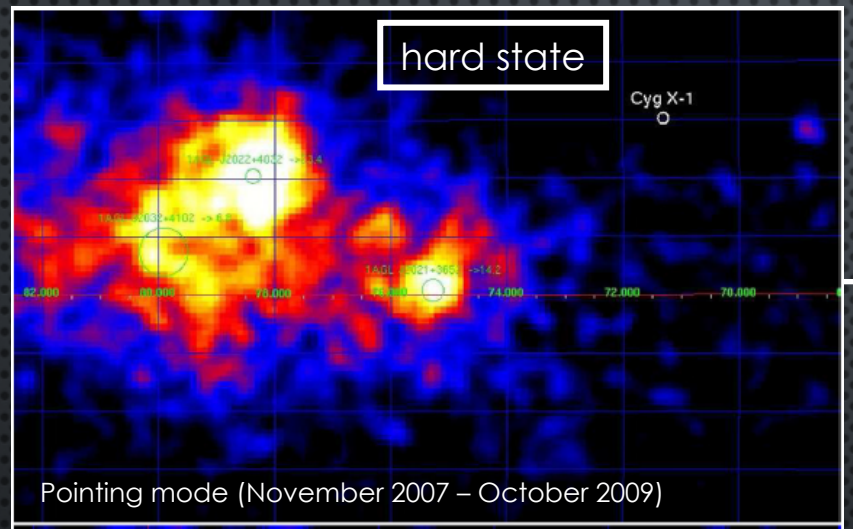
significance = 5.3σ
$F_\gamma = (232 \pm 66)\ 10^{-8}$ ph cm^{-2} s^{-1}

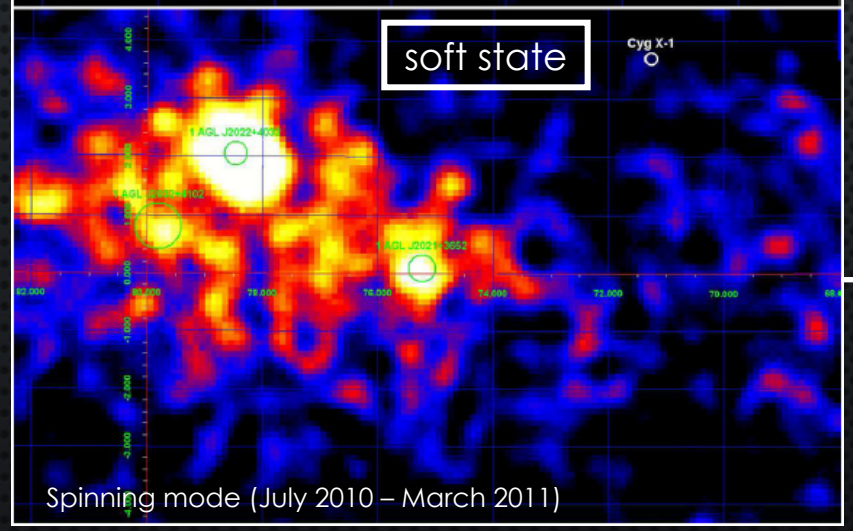


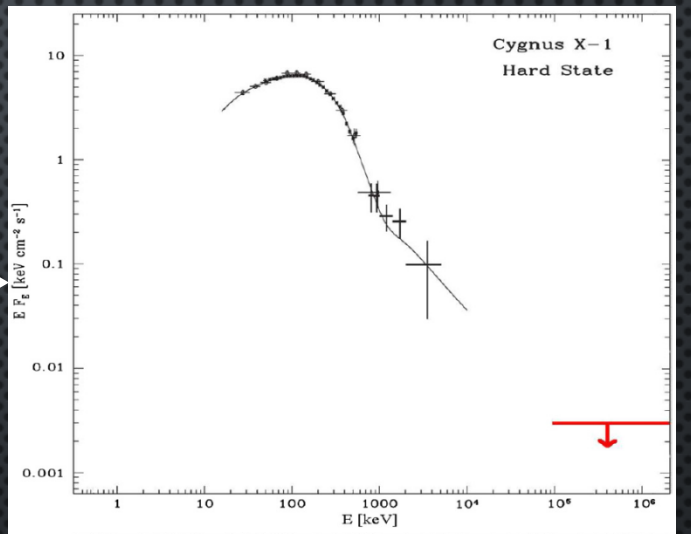
significance = 3.0σ
$F_\gamma = (145 \pm 78)\ 10^{-8}$ ph cm^{-2} s^{-1}

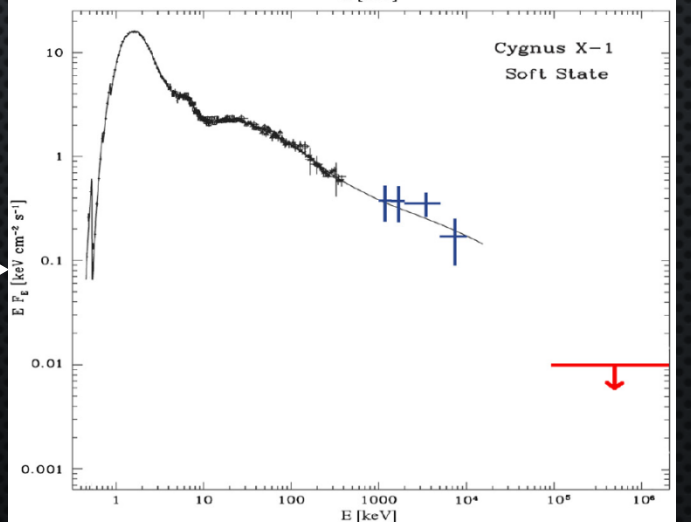
Cygnus X-1

Comptonization models: spectral ULs from long-term integration in the γ-ray energy band both for hard and soft states









Sabatini et al.,
ApJ, 766, 83 (2013)

Cygnus X-3

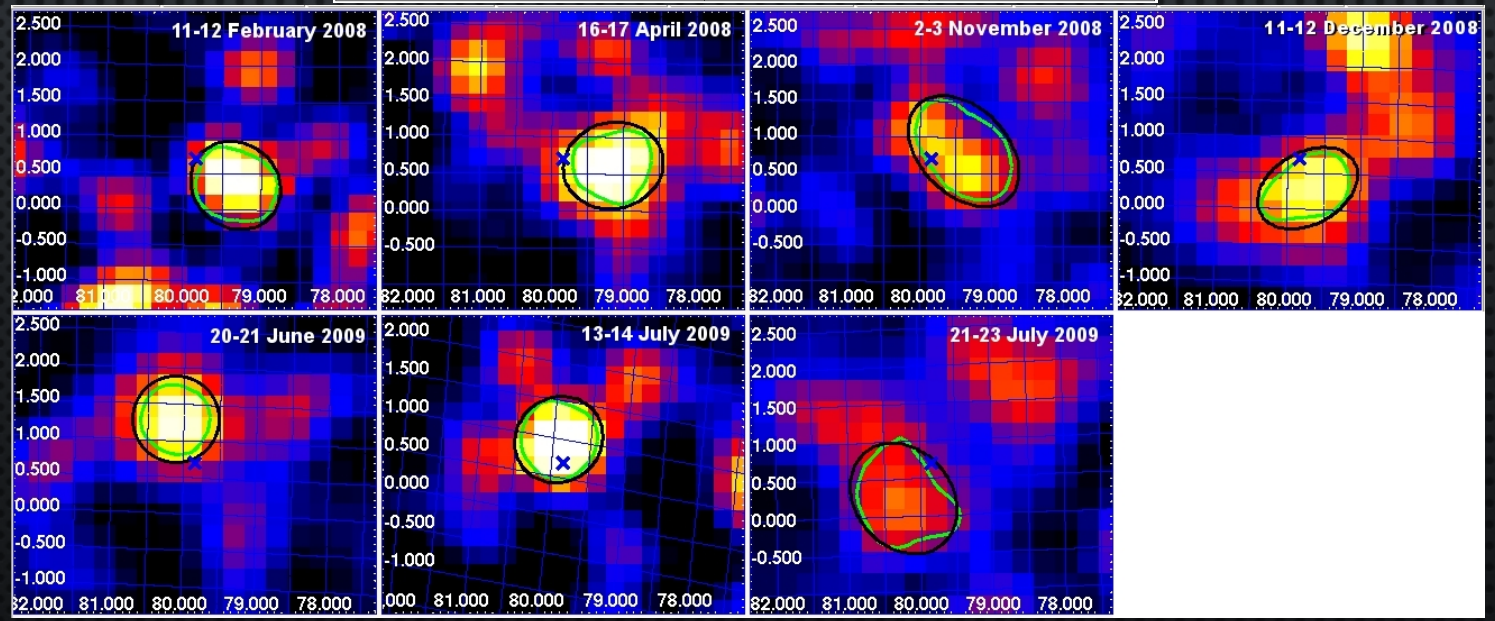
γ-ray activity discovered in late 2009

AGILE → (Tavani et al, *Nature*, 2009); *Fermi*-LAT → (Abdo et al., Science, 2009)

7 γ-ray flares have been detected between November 2007 and July 2009:

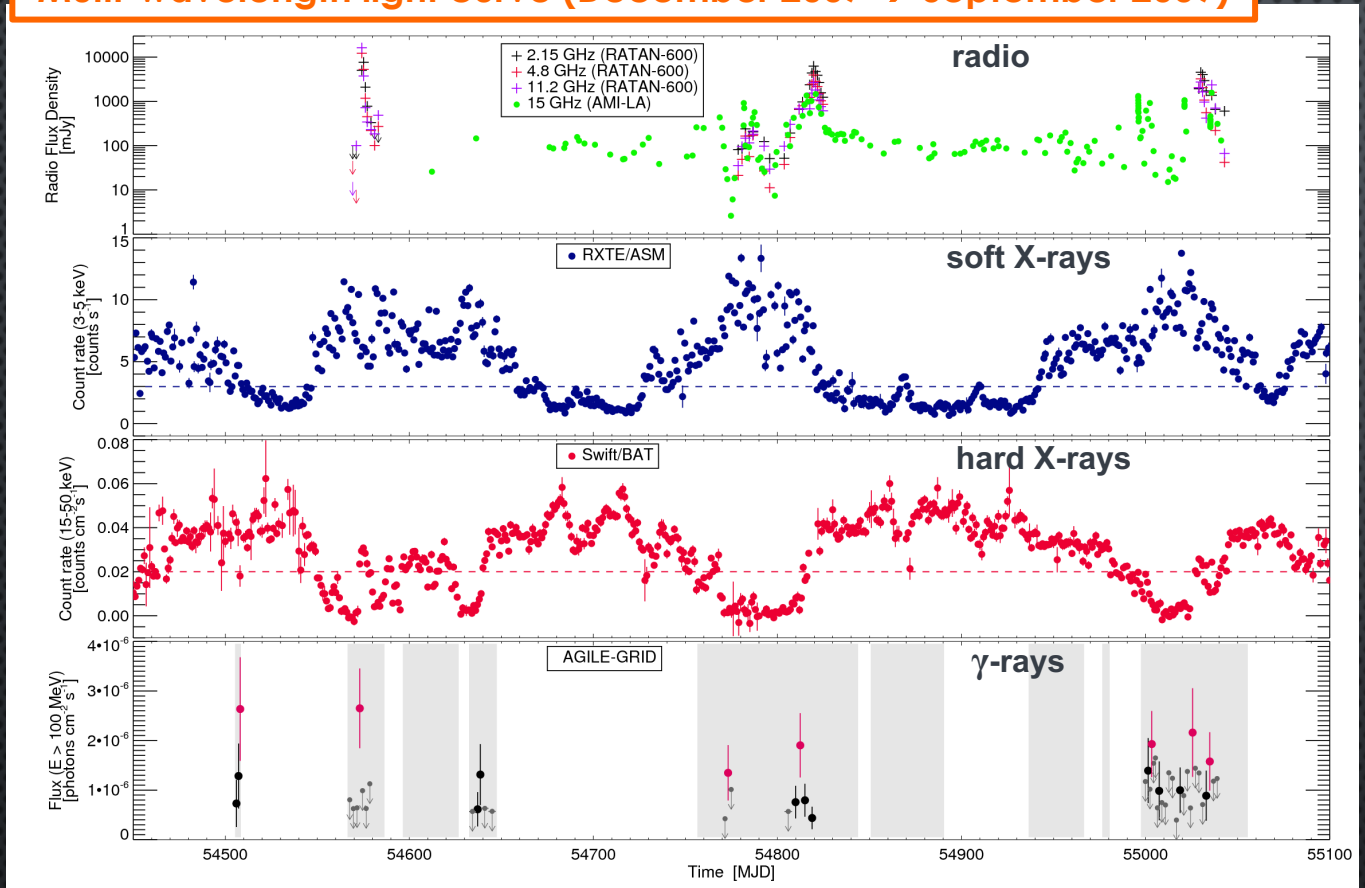
- significance ≥ 3σ
- γ-ray fluxes more than 10 times the steady flux [F_{steady} = (14 ± 3) x 10^{-8} ph cm^{-2} s^{-1}]

Period	MJD	√TS	Flux [10^{-8} photons cm^{-2} s^{-1}]
2008 Feb 11 (18:07:28) - 2008 Feb 12 (11:07:44)	54507.76 - 54508.46	3.7	264 ± 104
2008 Apr 16 (13:59:12) - 2008 Apr 17 (13:48:00)	54572.58 - 54573.58	4.5	265 ± 80
2008 Nov 2 (13:01:05) - 2008 Nov 3 (19:01:05)	54772.54 - 54773.79	3.1	135 ± 56
2008 Dec 11 (19:50:40) - 2008 Dec 12 (23:02:40)	54811.83 - 54812.96	4.0	190 ± 65
2009 Jun 20 (21:04:48) - 2009 Jun 21 (20:53:04)	55002.88 - 55003.87	3.8	193 ± 67
2009 Jul 13 (01:11:60) - 2009 Jul 14 (00:59:44)	55025.05 - 55026.04	3.2	216 ± 89
2009 Jul 21 (21:07:12) - 2009 Jul 23 (21:07:12)	55033.88 - 55035.88	3.6	158 ± 59



Cygnus X-3

Multi-wavelength light curve (December 2007 → September 2009)



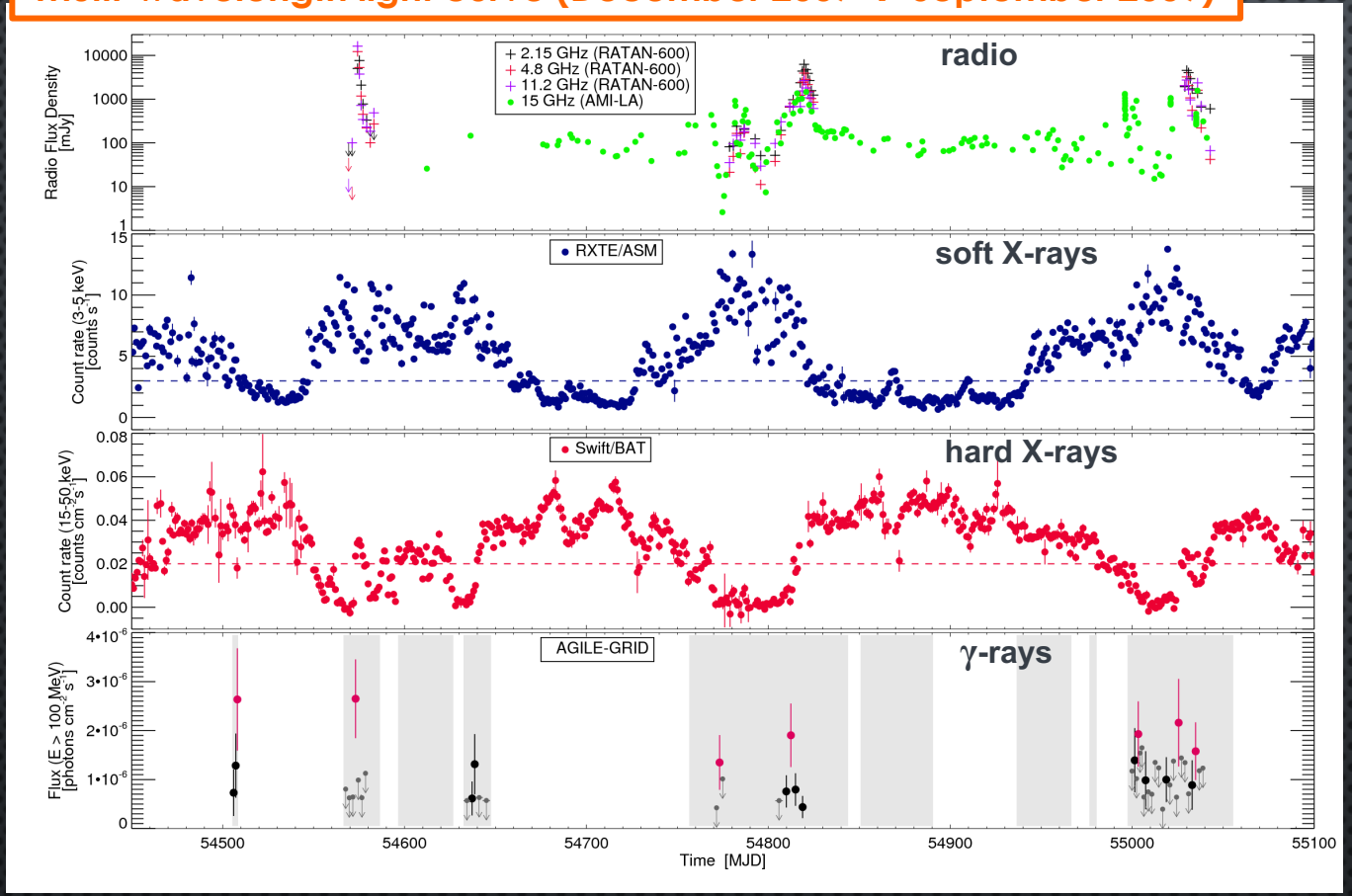
Repetitive multi-frequency emission pattern:

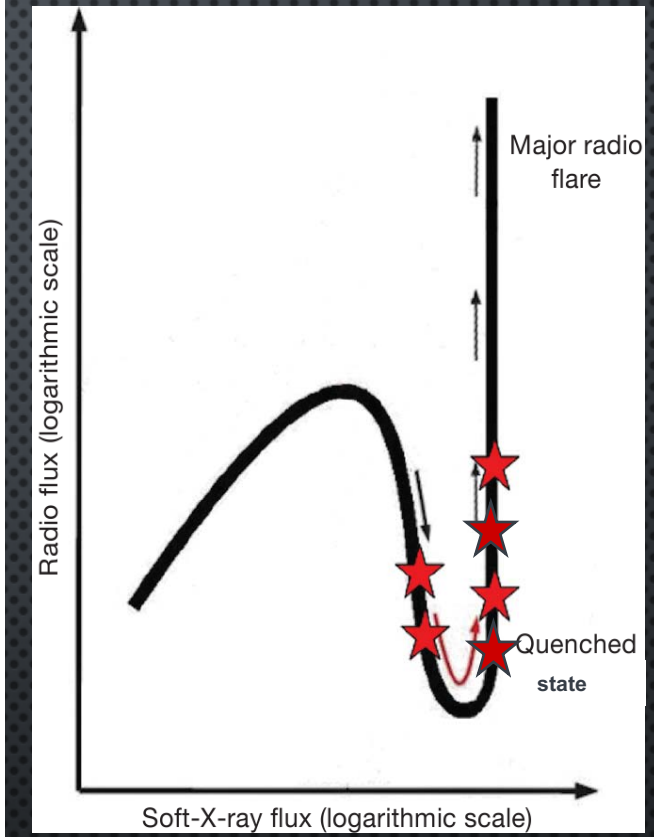
- **STRONG ANTICORRELATION** between hard X-ray and γ-ray emission: γ-ray activity associated with sharp/local minima in the hard X-ray light curve (*Swift*/BAT count rate ≤ 0.02 counts cm^{-2} s^{-1})
- γ-ray flares coincident with soft spectral states (*RXTE*/ASM count rate ≥ 3 counts s^{-1})
- γ-ray flares around hard-to-soft or soft-to-hard spectral transitions
- γ-ray flares a few days before major radio flares

Piano et al., A&A, 545, A110 (2012)

Cygnus X-3

Multi-wavelength light curve (December 2007 → September 2009)





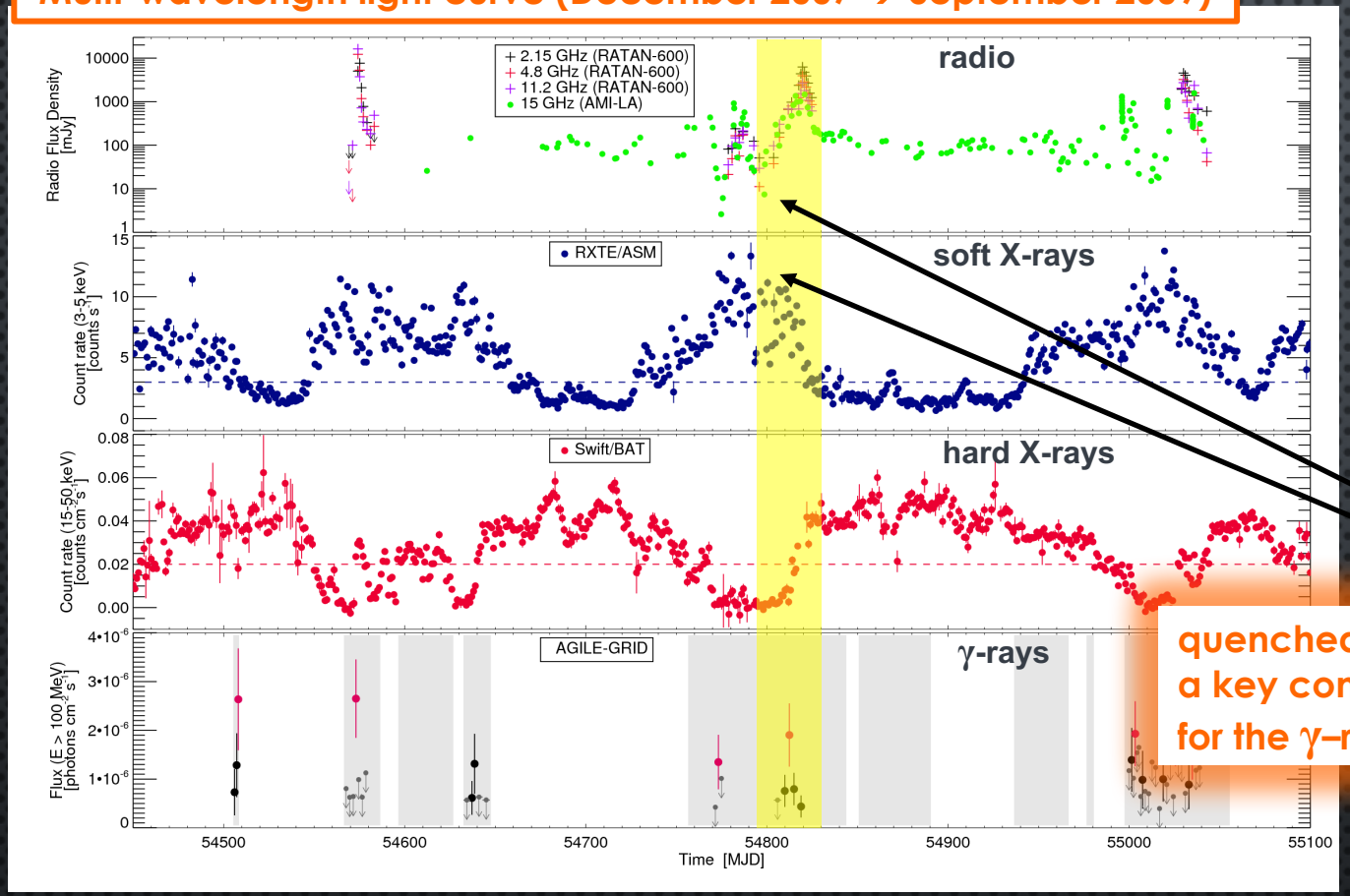
Repetitive multi-frequency emission pattern:

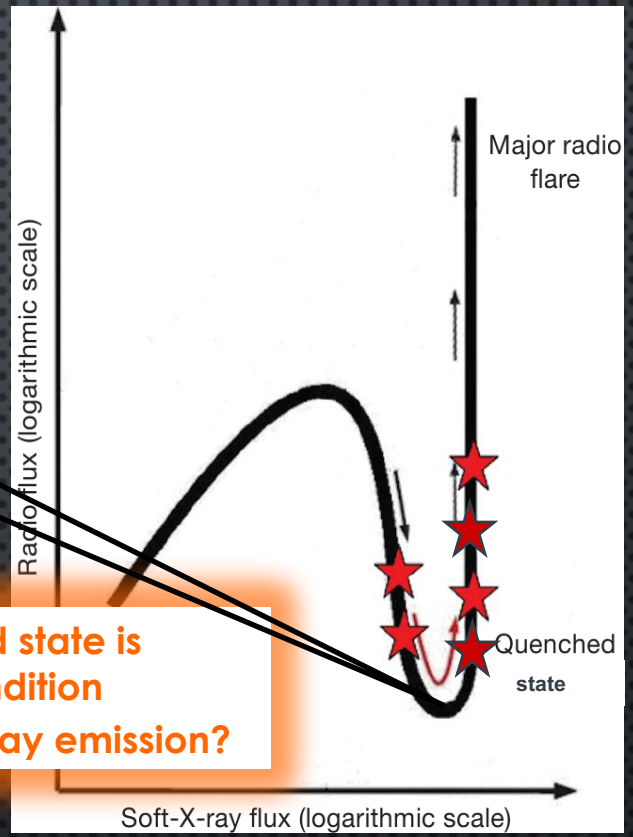
- **STRONG ANTICORRELATION** between hard X-ray and γ-ray emission: γ-ray activity associated with sharp/local minima in the hard X-ray light curve (*Swift*/BAT count rate ≤ 0.02 counts cm^{-2} s^{-1})
- γ-ray flares coincident with soft spectral states (*RXTE*/ASM count rate ≥ 3 counts s^{-1})
- γ-ray flares around hard-to-soft or soft-to-hard spectral transitions
- γ-ray flares a few days before major radio flares

Piano et al., A&A, 545, A110 (2012)

Cygnus X-3

Multi-wavelength light curve (December 2007 → September 2009)





quenched state is a key condition for the γ–ray emission?

Repetitive multi-frequency emission pattern:

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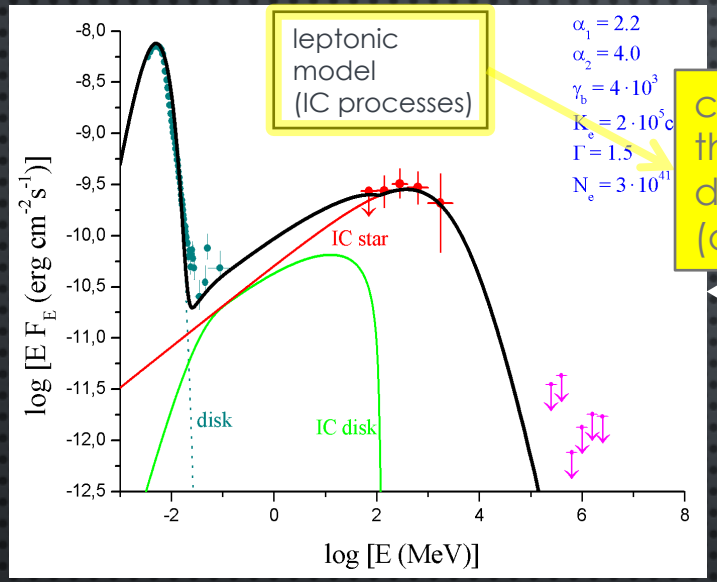
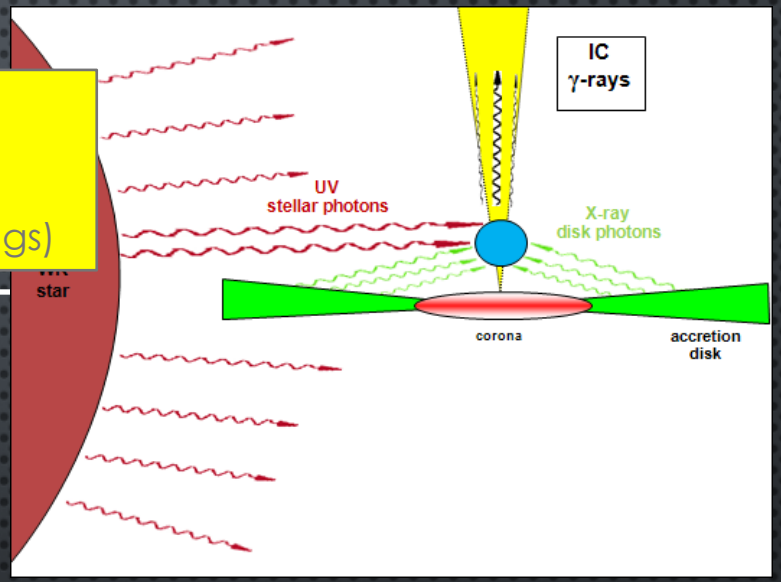
Piano et al., A&A, 545, A110 (2012)

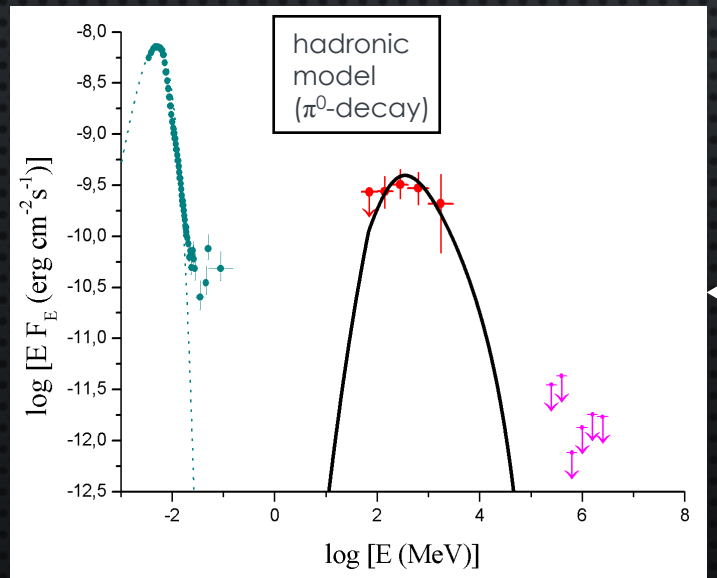
Cygnus X-3

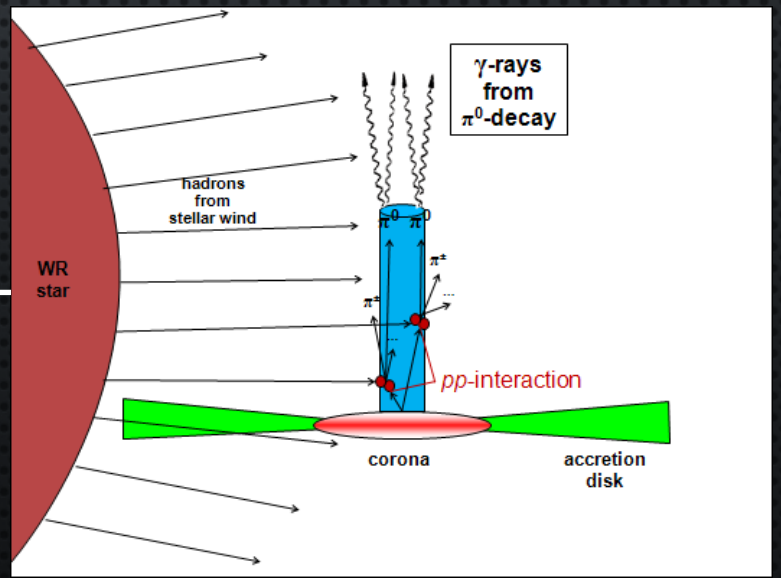
Both leptonic and hadronic emission models
can account for the γ-ray flaring spectrum detected by AGILE



can easily accounts for the γ-ray modulation detected by *Fermi*-LAT (anisotropic IC scatterings)



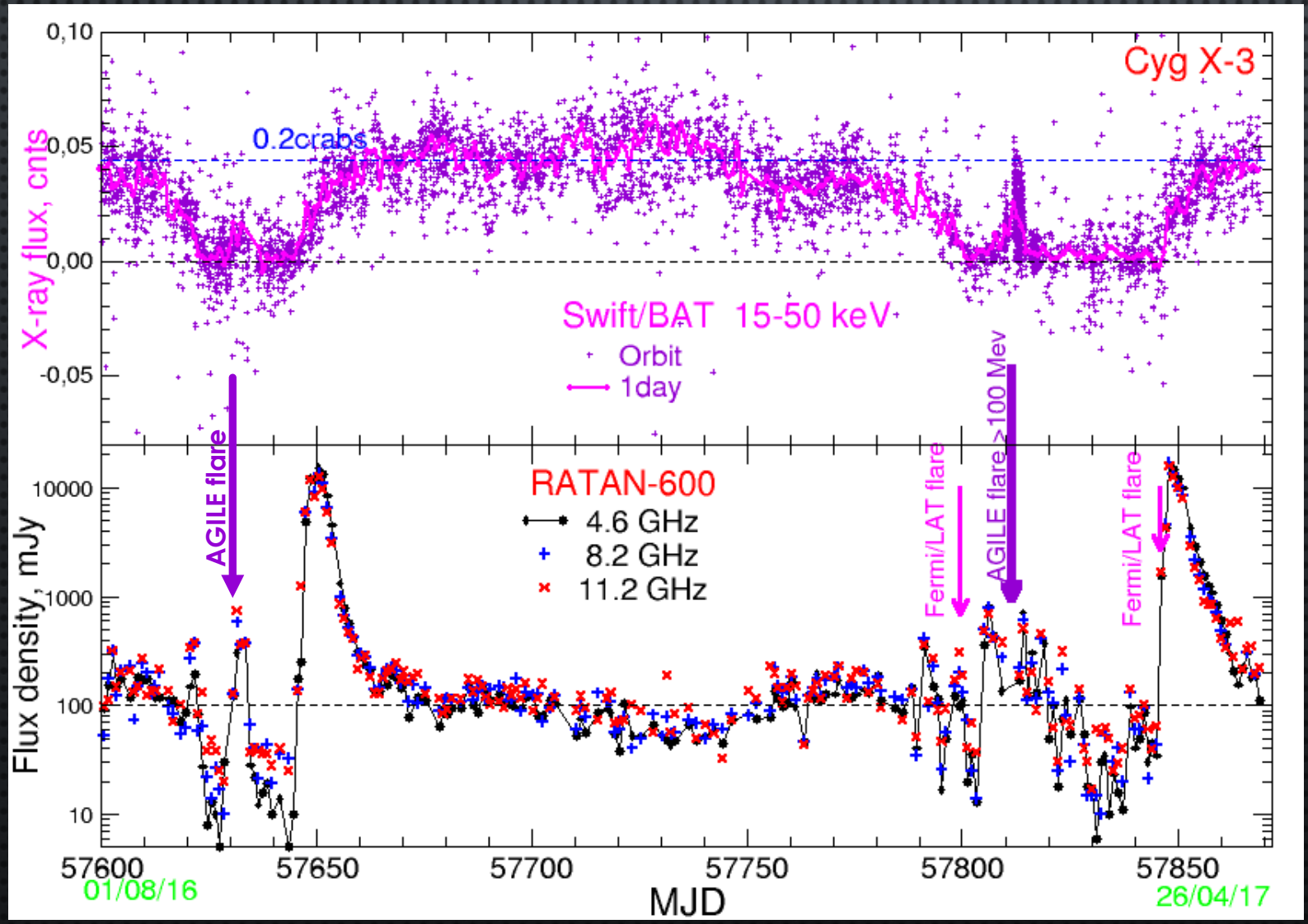




Piano et al.,
A&A, 545, A110 (2012)

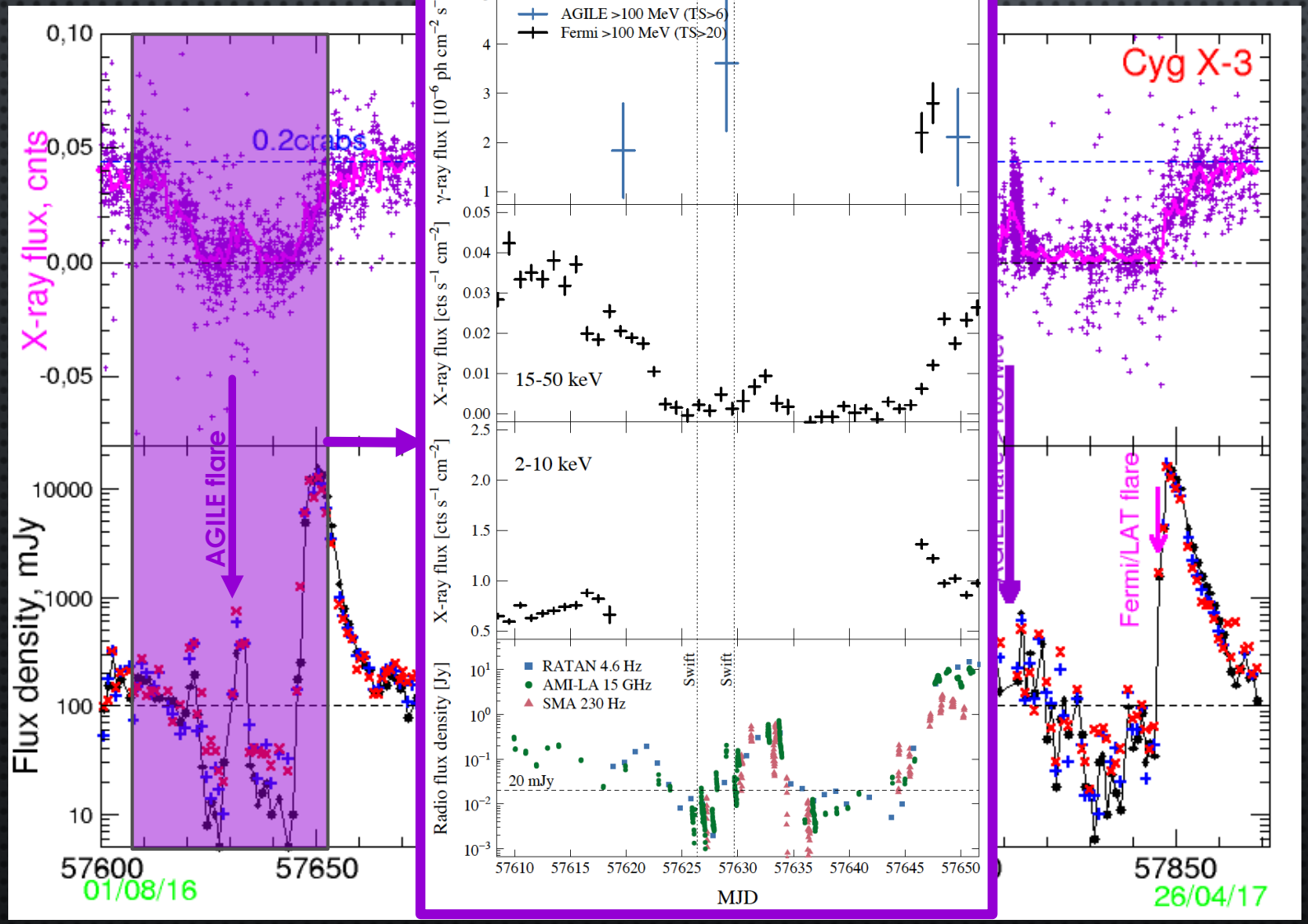
Cygnus X-3

Recent γ-ray activity → 2016 – 2017 (Koljonen et al., A&A 612, A27, 2018)



Cygnus X-3

Recent γ-ray activity → 2016 – 2017 (Koljonen et al., A&A 612, A27, 2018)



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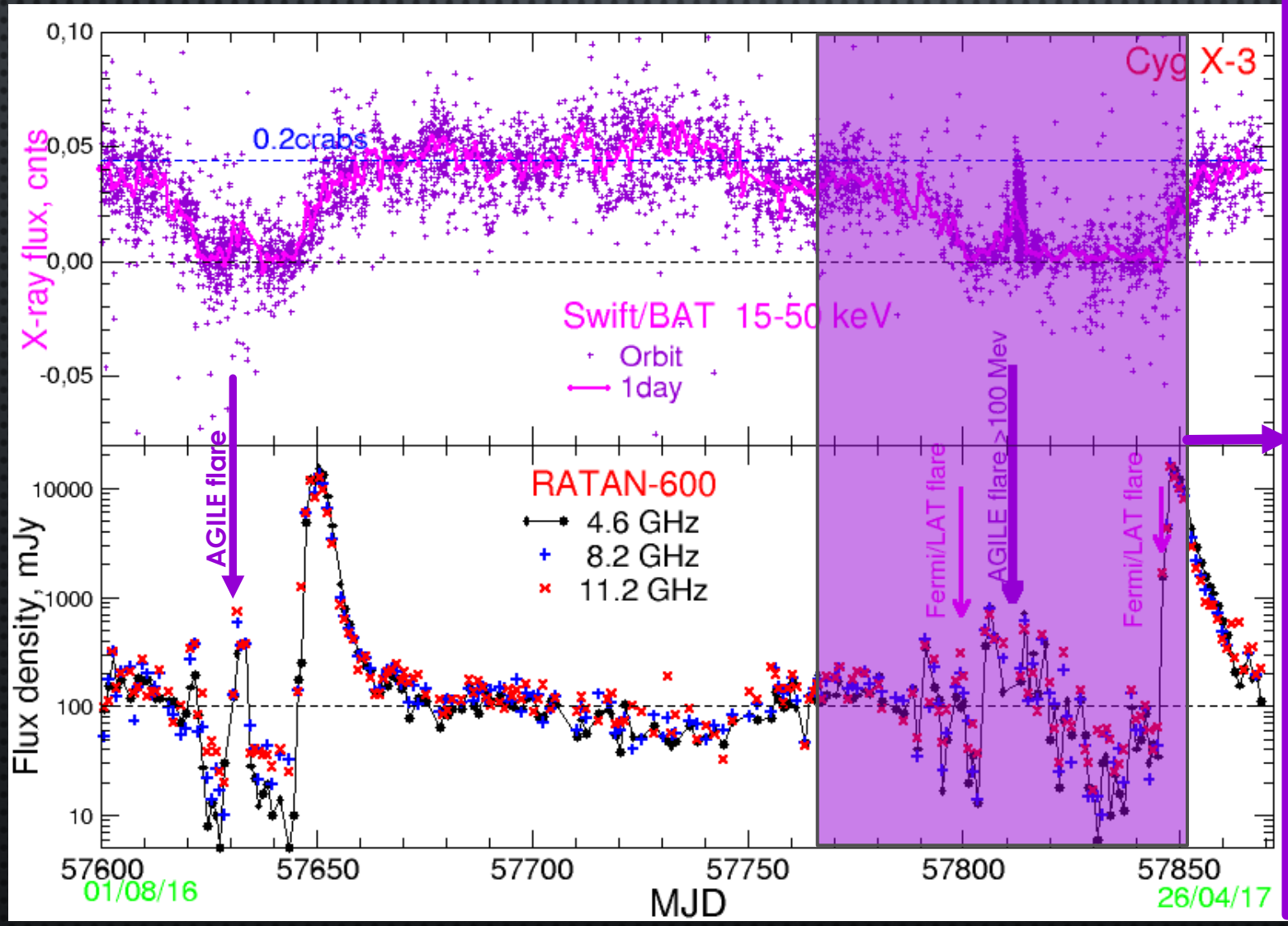
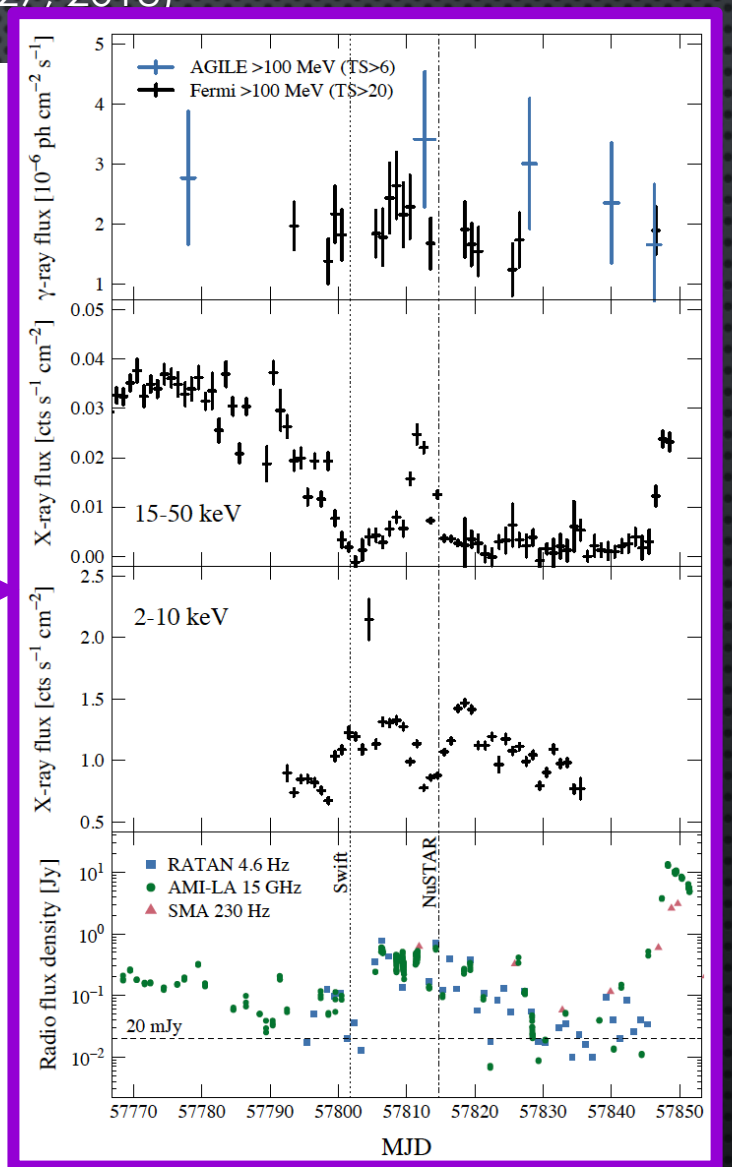


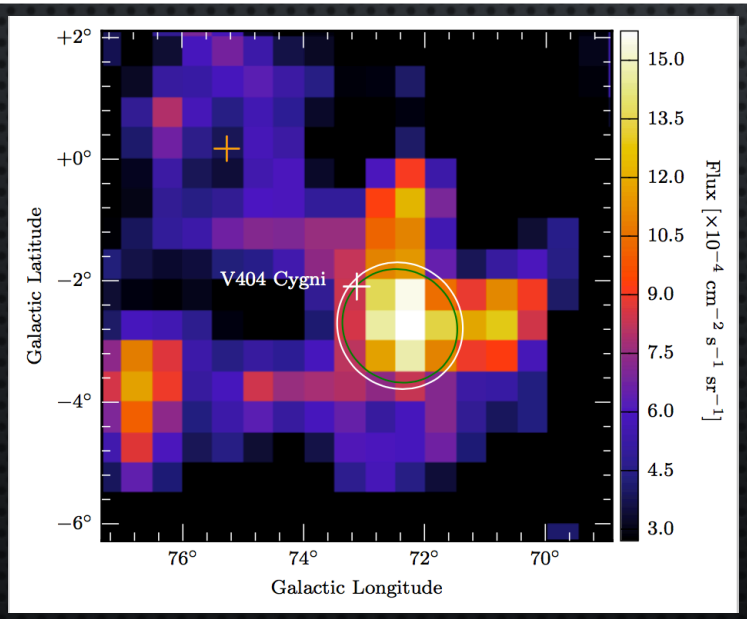


V404 Cygni

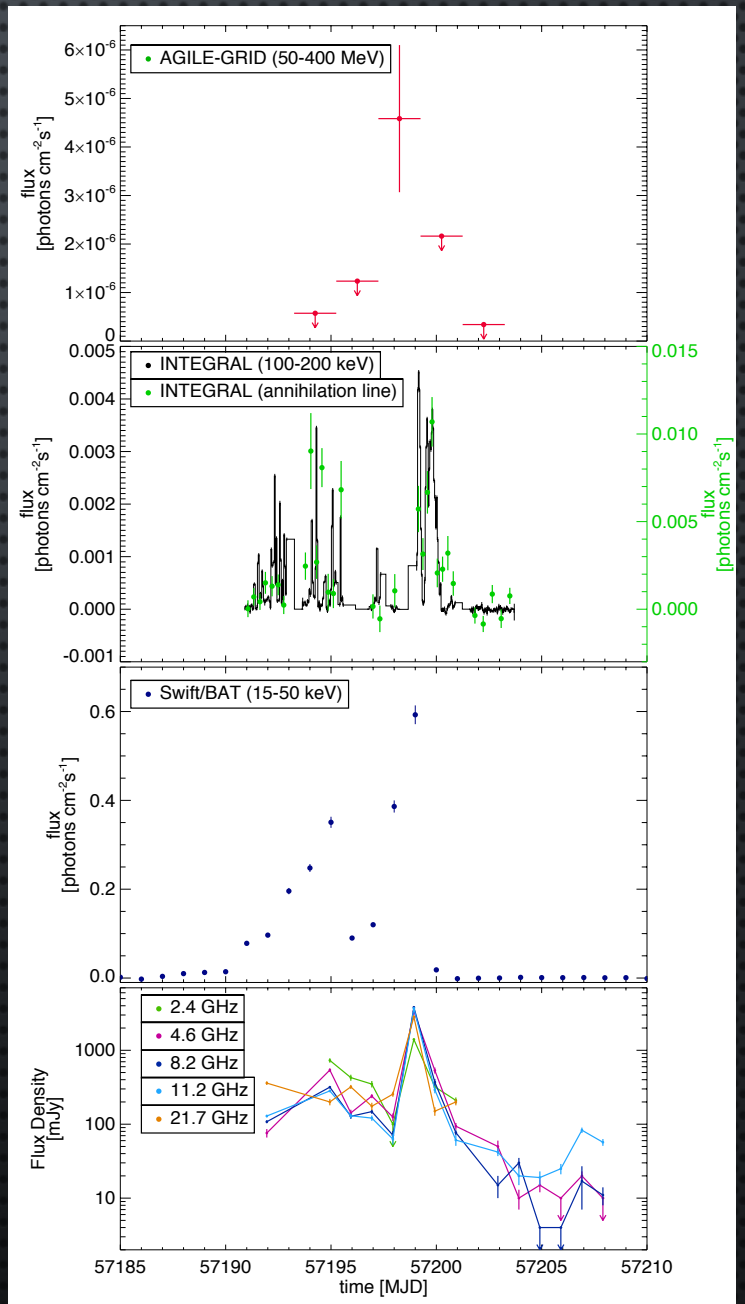
After ~26 years of quiescence → active phase in June 2015

High Energy γ-ray flare (50-400 MeV) coincident with outbursts in:
- radio
- X-ray
- soft γ-rays (continuum & 511 keV annihilation line)

AGILE 2-day intensity map (50-400 MeV)

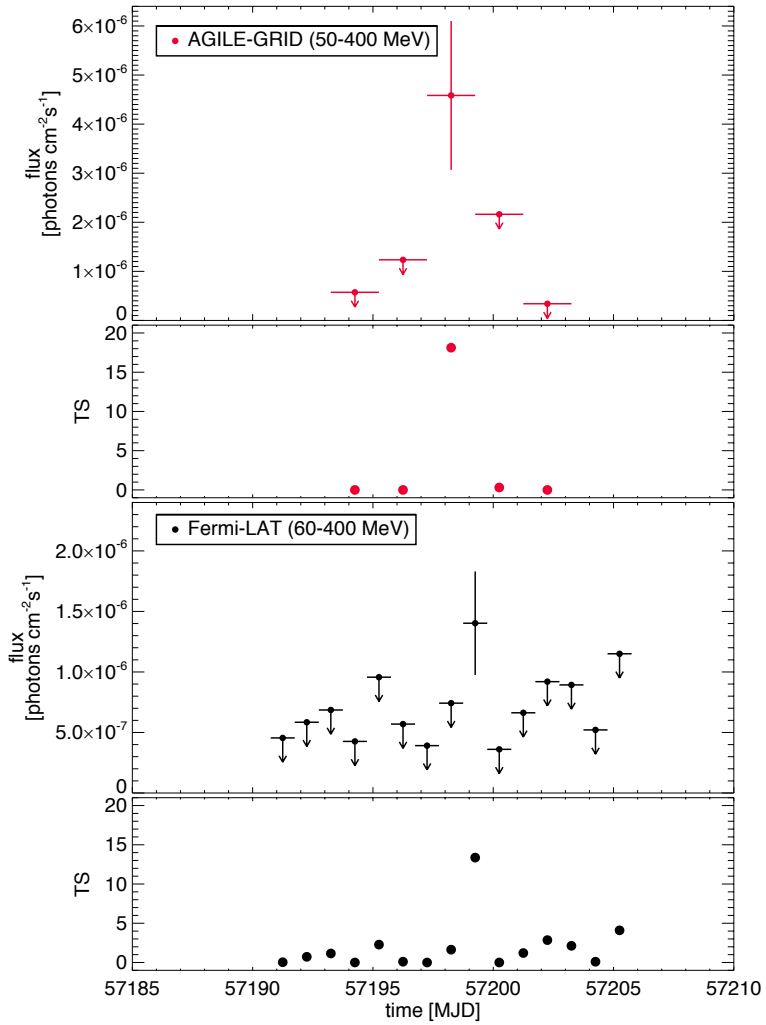


Piano et al., ApJ, 839, 84 (2017)

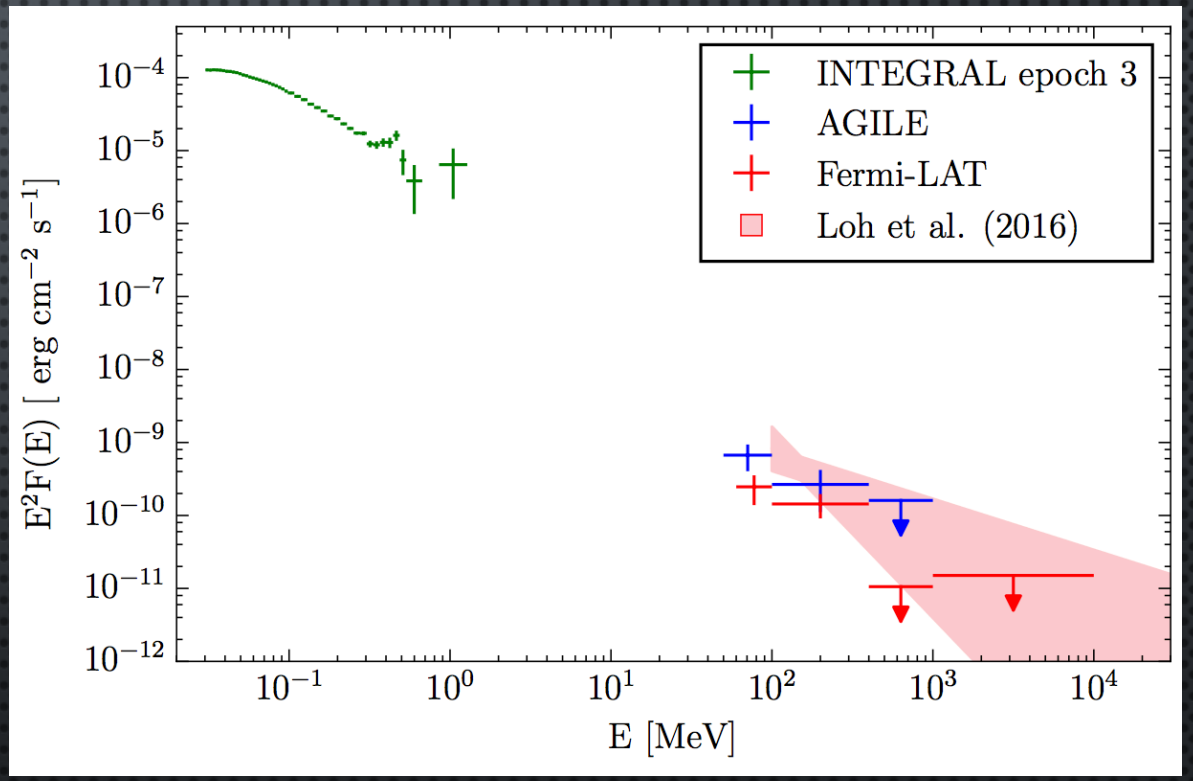


V404 Cygni

AGILE (50-400 MeV) simultaneous with Fermi-LAT (60-400 MeV)



Simultaneous flaring SED



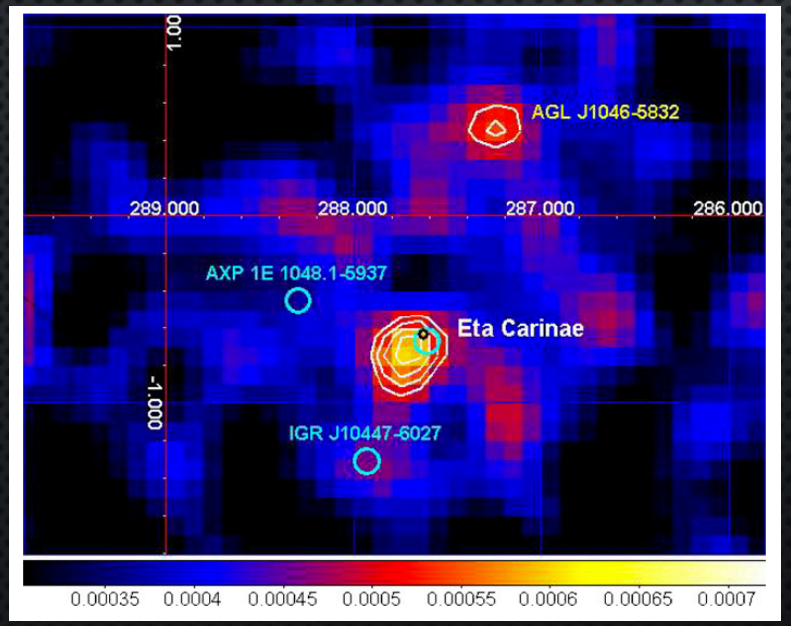
Soft emission in HE γ-rays:
no detected activity above 400 MeV

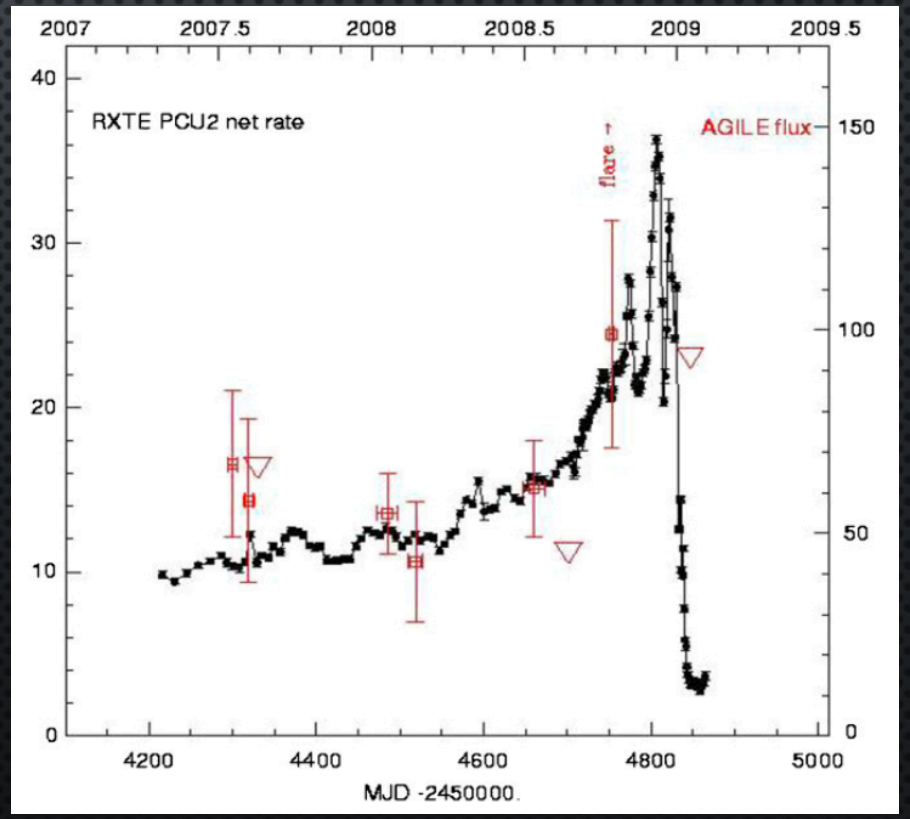
Piano et al., ApJ, 839, 84 (2017)

η Carinae

- Luminous Blue Variable + O Star
- Orbital period ~ 5.54 years
- First detection of a Colliding Wind Binary in γ-rays (Tavani et al., ApJ, 698, L142, 2009)
- Shock acceleration mechanism in a wind-wind interaction scenario
  ($\dot{M}_1 \approx 2 \times 10^{-4}\ M_\odot$ yr^{-1}, $\dot{M}_2 \approx 2 \times 10^{-5}\ M_\odot$ yr^{-1}, $v_1 \approx 600$ km/s, $v_2 \approx 3000$ km/s)

AGILE map
(July 2007 – October 2008)



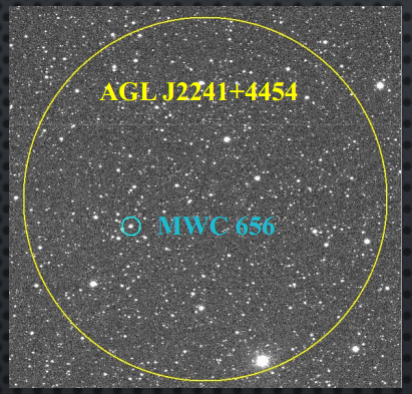


AGILE AND GALACTIC GAMMA-RAY SOURCES POSSIBLY ASSOCIATED WITH BINARY SYSTEMS

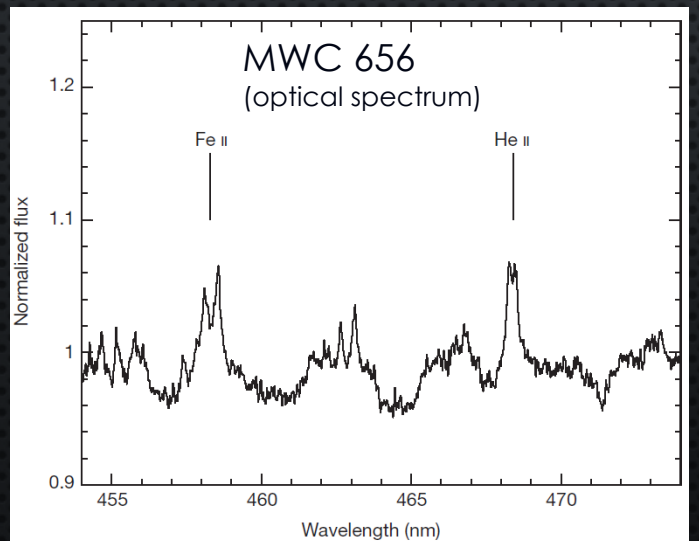
AGILE source	binary system	binary type	orbital period
1AGL J0242+6111	LS I +61 303	Be + ? (HMXB)	26.5 days
1AGLR J1822-1456	LS 5039	O + ? (HMXB)	3.9 days
AGL J1734-3310	IGR J17354−3255	SFXT (HMXB)	8.45 days (Sguera et al., 2011)
AGL J2022+3622	IGR J20188+3647	SFXT (HMXB) ?	? (ATel #1313; Sguera et al., 2006)
AGL J1037-5708	4U 1036-56	Be-NS (HMXB)	61.0 days (Cusumano et al., 2013)
AGL J2241+4454	MWC 656	Be-BH (HMXB)	60.37 days (Casares et al., 2014; P. Munar-Adrover et al., 2016)

AGILE AND GALACTIC GAMMA-RAY TRANSIENTS: AGL J2241+4454

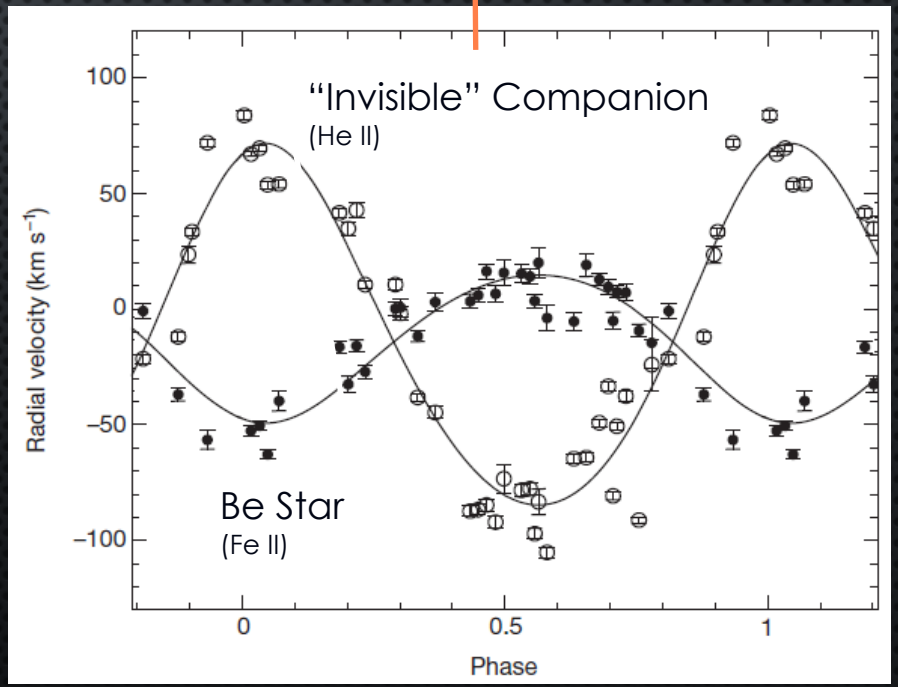
- Transient γ-ray activity detected in July 2010 (ATel #2761).
- AGILE detection → discovery of the first Be-HMXB hosting a Black Hole: MWC 656 (Casares et al., 2014 → optical data)



Casares et al.,
"A Be-type star with a black-hole companion",
Nature 505, 378 (2014)



Black Hole
(M = 3.8 – 6.9 $M_\odot$)



AGL J2241+4454: AGILE OBSERVATIONS

- Blind search in 2-day bin lightcurve (Pointing and Spinning)
- 10 flaring events observed by AGILE between 2007 and 2013

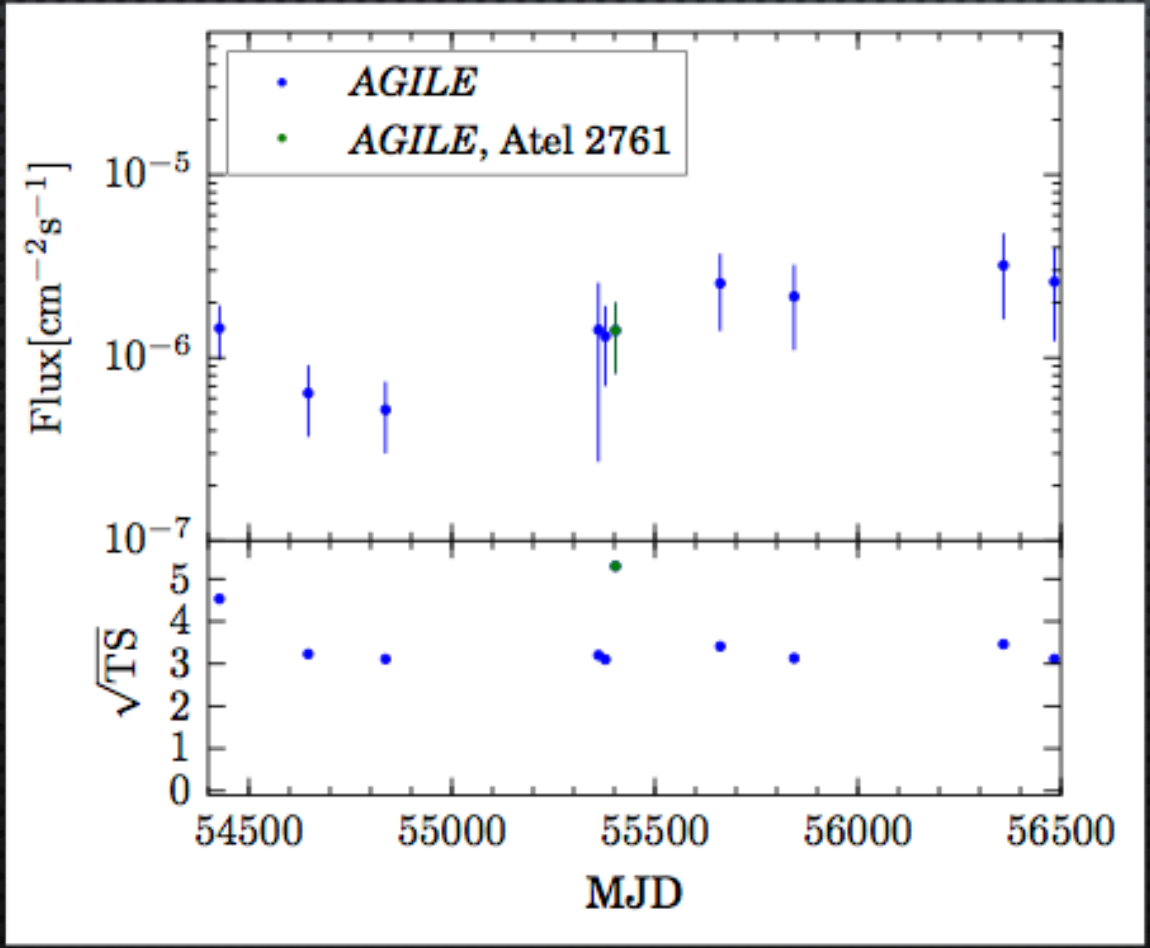
AGILE GAMMA-RAY TRANSIENT DETECTIONS AROUND THE POSITION OF MWC 656.

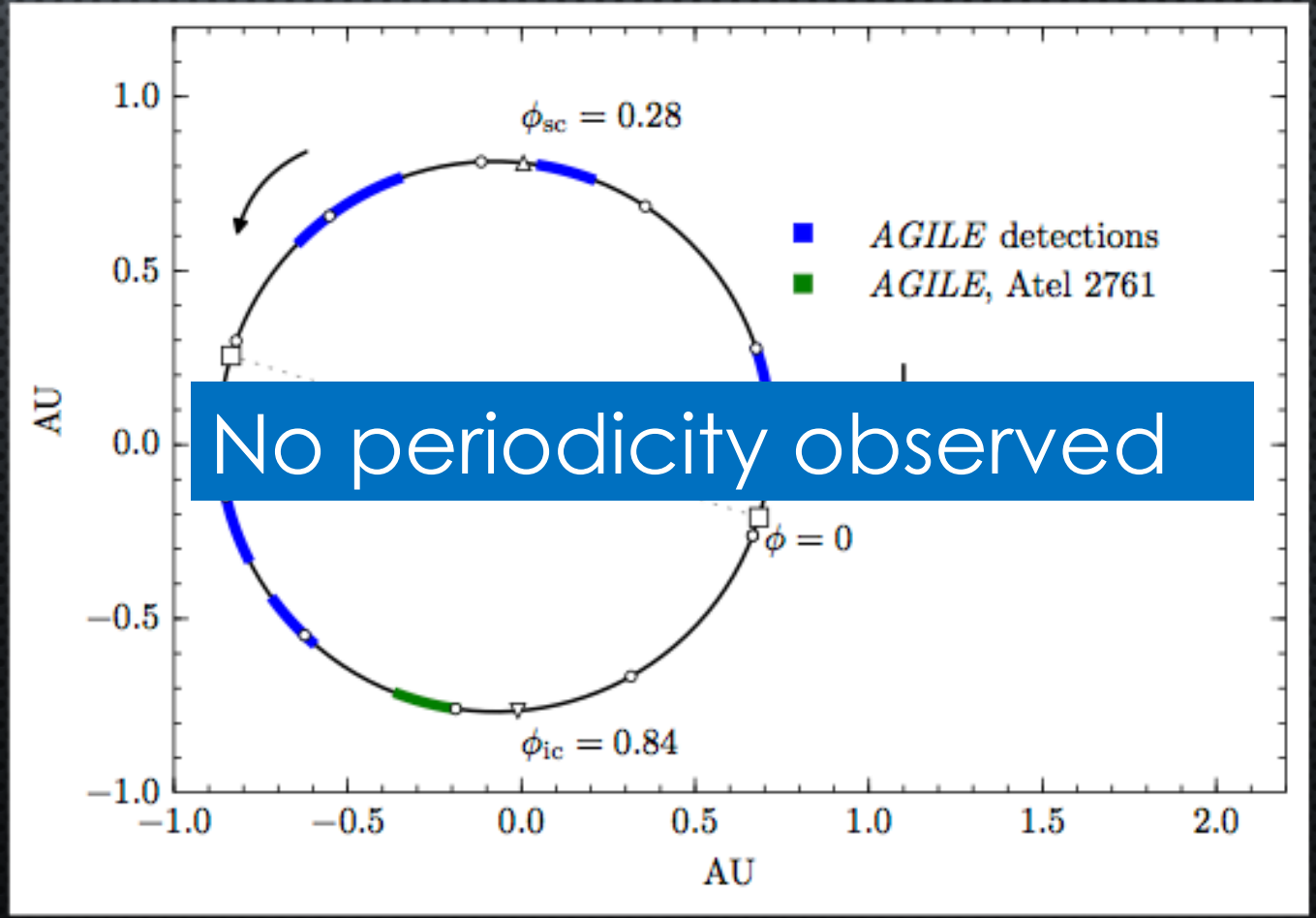
t_{start} [UT]	t_{end} [UT]	Flux [$\times 10^{-6}$ cm^{-2} s^{-1}]	$\sqrt{TS}$
2007-11-23 UT00:00:00	2007-11-24 UT00:00:00	1.5 ± 0.5	4.5
2008-06-28 UT00:00:00	2008-06-30 UT00:00:00	0.6 ± 0.3	3.2
2009-01-04 UT00:00:00	2009-01-07 UT00:00:00	0.5 ± 0.2	3.1
2010-06-13 UT00:00:00	2010-06-14 UT00:00:00	1.4 ± 1.1	3.2
2010-06-30 UT00:00:00	2010-07-02 UT00:00:00	1.3 ± 0.6	3.1
2010-07-25 UT00:00:00	2010-07-27 UT00:00:00	1.4 ± 0.6	5.3
2011-04-09 UT00:00:00	2011-04-11 UT00:00:00	2.2 ± 1.1	3.1
2011-10-08 UT00:00:00	2011-10-10 UT00:00:00	2.5 ± 1.1	3.4
2013-03-07 UT00:00:00	2013-03-08 UT09:00:00	2.6 ± 1.4	3.1
2013-07-10 UT00:00:00	2013-07-12 UT00:00:00	3.2 ± 1.6	3.5

Munar-Adrover et al., ApJ, 829, 101 (2016)

AGL J2241+4454: AGILE OBSERVATIONS

- Searching for periodic γ-ray emission
- Folding data with 60.37 day period



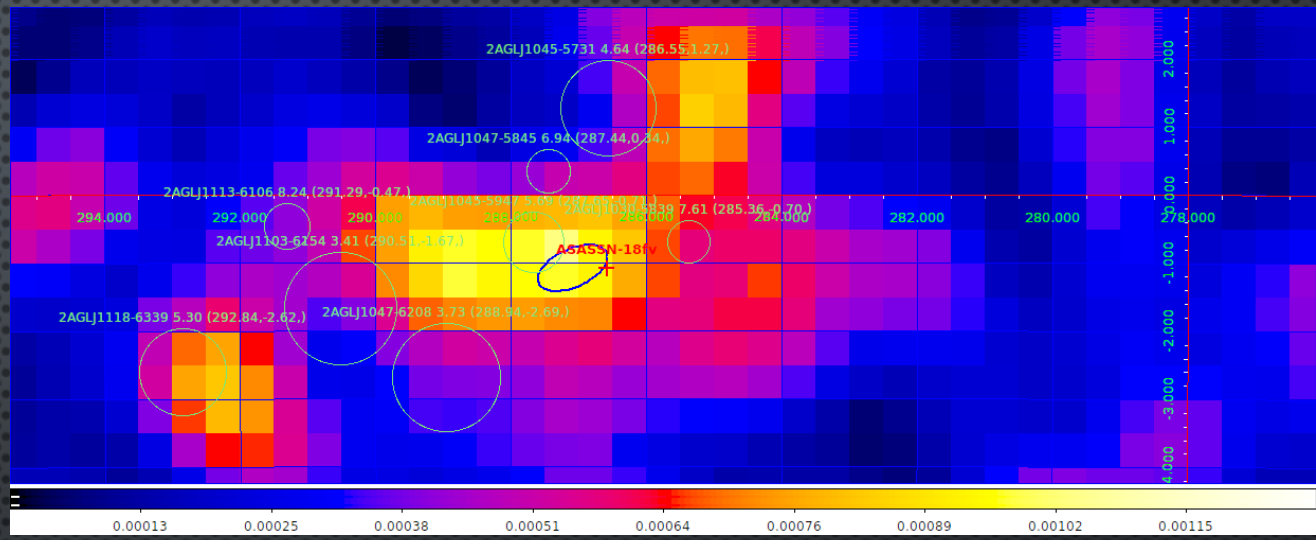


Munar-Adrover et al., ApJ, 829, 101 (2016)

NOVAE DETECTED IN GAMMA RAYS

	Active phase	Fermi-LAT [photons cm^{-2} s^{-1}]	AGILE [photons cm^{-2} s^{-1}]
V679 Car 2008	December 2008 – January 2009	$(1.9 \pm 0.5)\ 10^{-7}$	Outside the FoV
V407 Cyg 2010	March 2010	$(3.47 \pm 0.44)\ 10^{-7}$	UL = $7.7\ 10^{-7}$
V1324 Sco 2012	June-July 2012	$(4.40 \pm 0.85)\ 10^{-7}$	Outside the FoV
V959 Mon 2012	June-July 2012	$(2.64 \pm 0.45)\ 10^{-7}$	Outside the FoV
V339 Del 2013	August-September 2013	$(1.45 \pm 0.19)\ 10^{-7}$	Outside the FoV
V1369 Cen 2013	December 2013 – January 2014	$(2.51 \pm 0.52)\ 10^{-7}$	UL = $3.7\ 10^{-7}$
V745 Sco 2014	February 2014	$(3 \pm 1)\ 10^{-7}$	Outside the FoV
V1535 Sco 2015	February 2015	$(1.0 \pm 0.3)\ 10^{-7}$	Outside the FoV
V5668 Sgr 2015	March-May 2015	$(0.61 \pm 0.13)\ 10^{-7}$	UL = $3.1\ 10^{-7}$
V407 Lup 2016	September 2016	$(1.8 \pm 0.6)\ 10^{-7}$	UL = $2.3\ 10^{-6}$
V5855 Sgr 2016	October-November 2016	$(2.6 \pm 0.7)\ 10^{-7}$	Outside the FoV
V5856 Sgr 2016	November 2016	$(6.1 \pm 0.5)\ 10^{-7}$	UL = $1.5\ 10^{-6}$
V549 Vel 2017	October-November 2017	$(8.0 \pm 3.5)\ 10^{-8}$	UL = $1.9\ 10^{-7}$
Nova Mus 2018	January 2018	$2.4\ 10^{-7}$	UL = $1.7\ 10^{-6}$
ASASSN-18fv	April-May 2018	$(3.6 \pm 0.3)\ 10^{-6}$	$(3.0 \pm 0.9)\ 10^{-6}$
V392 Per 2018	April-May 2018	$(3.47 \pm 0.44)\ 10^{-7}$	Outside the FoV

NOVA ASASSN-18FV



$\sqrt{TS} = 4.5$

Flux = $(3.0 \pm 0.9)\ 10^{-6}$ ph/cm^2/s

Novae:
new class of gamma-ray binary sources

(See Domitilla's talk)

Thanks for your attention