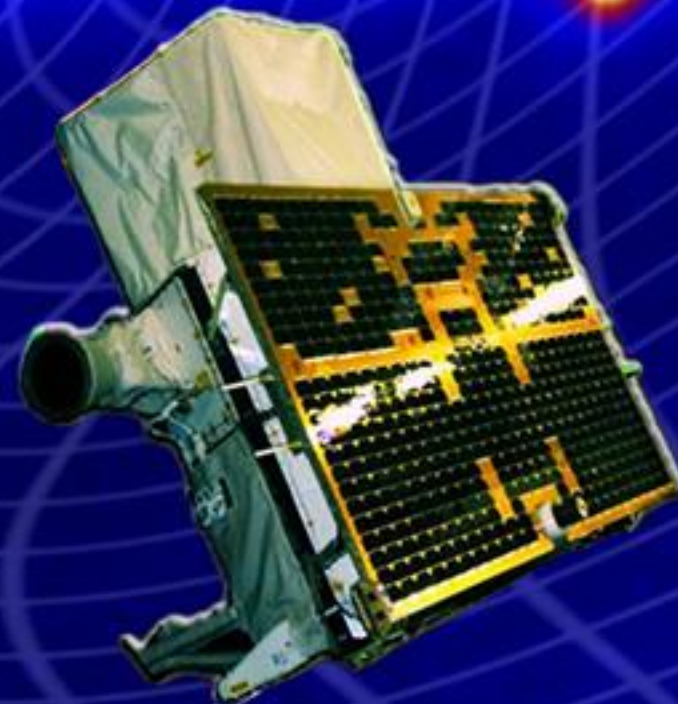
Space Science Data Center

AGILE
status and highlghts

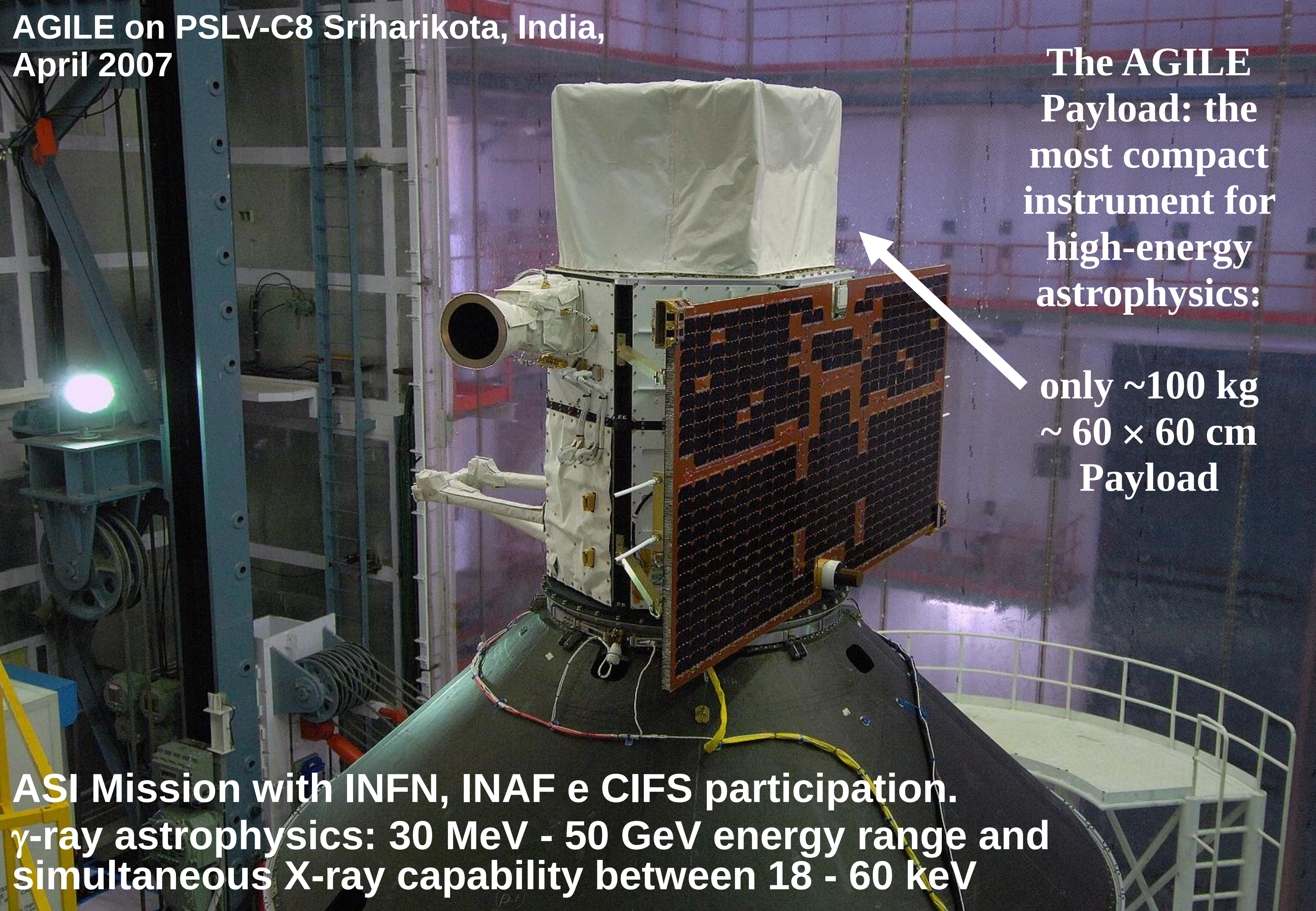
on behalf of the AGILE Collaboration



F. Verrecchia, INAF-OAR and SSDC

Roma, 5 Settembre 2018

AGILE on PSLV-C8 Sriharikota, India, April 2007



The AGILE Payload: the most compact instrument for high-energy astrophysics:

only ~100 kg
~ 60 × 60 cm
Payload

ASI Mission with INFN, INAF e CIFS participation.
γ-ray astrophysics: 30 MeV - 50 GeV energy range and simultaneous X-ray capability between 18 - 60 keV

- **first ASI ”Small Mission”**
- **goal: gamma-ray and hard X-ray astrophysics**

- **similar and very different from the *Fermi* NASA Mission**
- **optimized in the range 50 MeV – 1 GeV**
- **different exposures**

- **public data and Guest Investigator Program**

The AGILE payload

ANTICOINCIDENCE SHIELD

HARD X-RAY IMAGER (SUPER-AGILE): 18-60 keV

GAMMA-RAY IMAGER DETECTOR (GRID): 30MeV-50GeV

SILICON TRACKER

(MINI) CALORIMETER: 0.3-100MeV

GRID performances:

A_eff = 300-350 cm^2 @ 100 MeV (~500 cm^2 above 400 MeV)

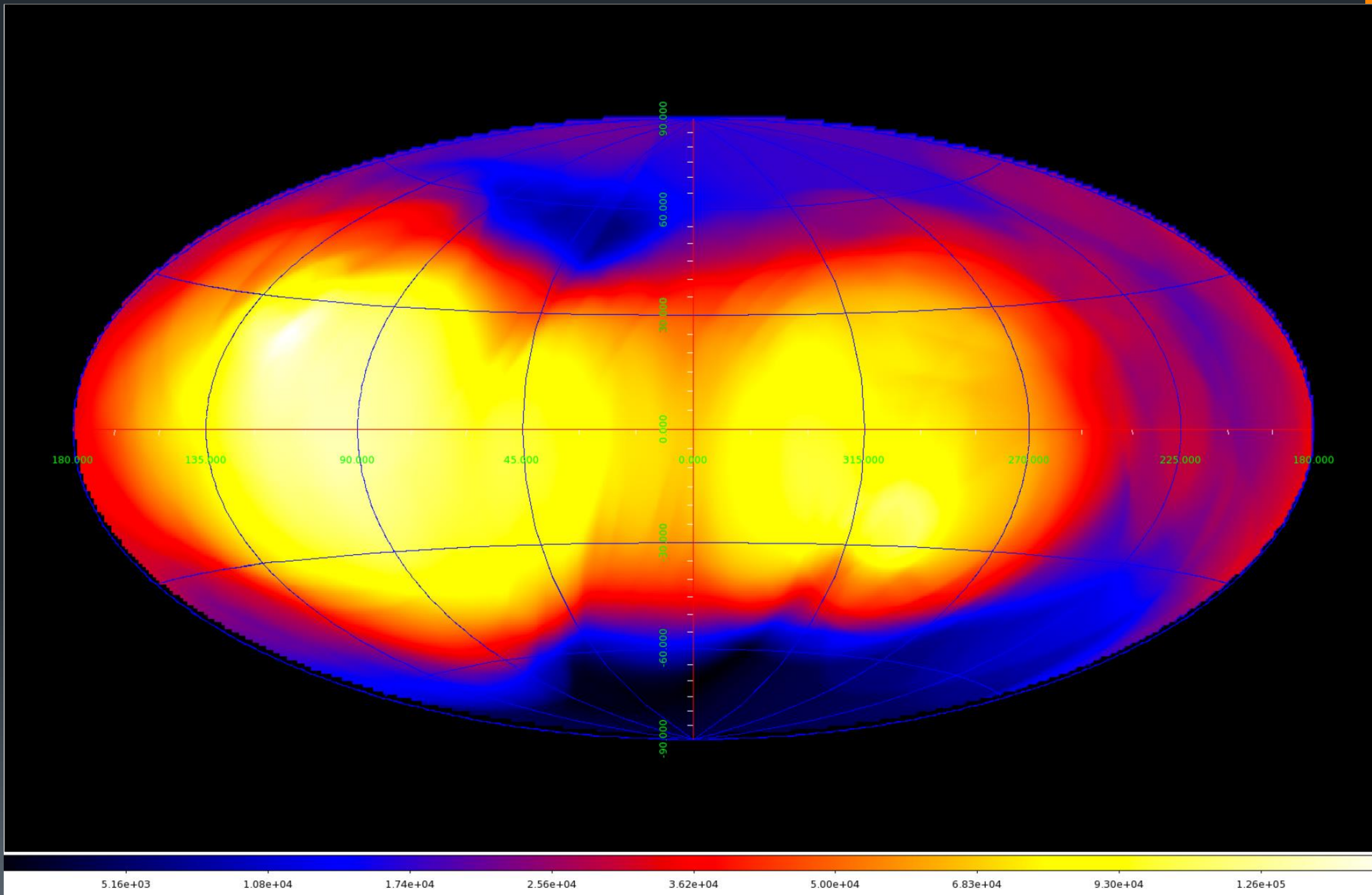
Angular Res. (68% cont.radius) = 3.5° @100 MeV (1.2° @ 400 MeV)

Two “lifes” of AGILE

	AGILE-POINT	AGILE-SPIN
time period	Jul.07 – Oct.09	Nov. 2009 - today
attitude	fixed	variable (spinning ~ 1º/sec)
sky coverage	1/5	~ 70-80 %
1-day exposure ($\leq$ 30 deg off-axis, @ 100 MeV)	~ 2×10^7 (cm^2 sec)	$(0.5-1) \times 10^7$ (cm^2 sec)

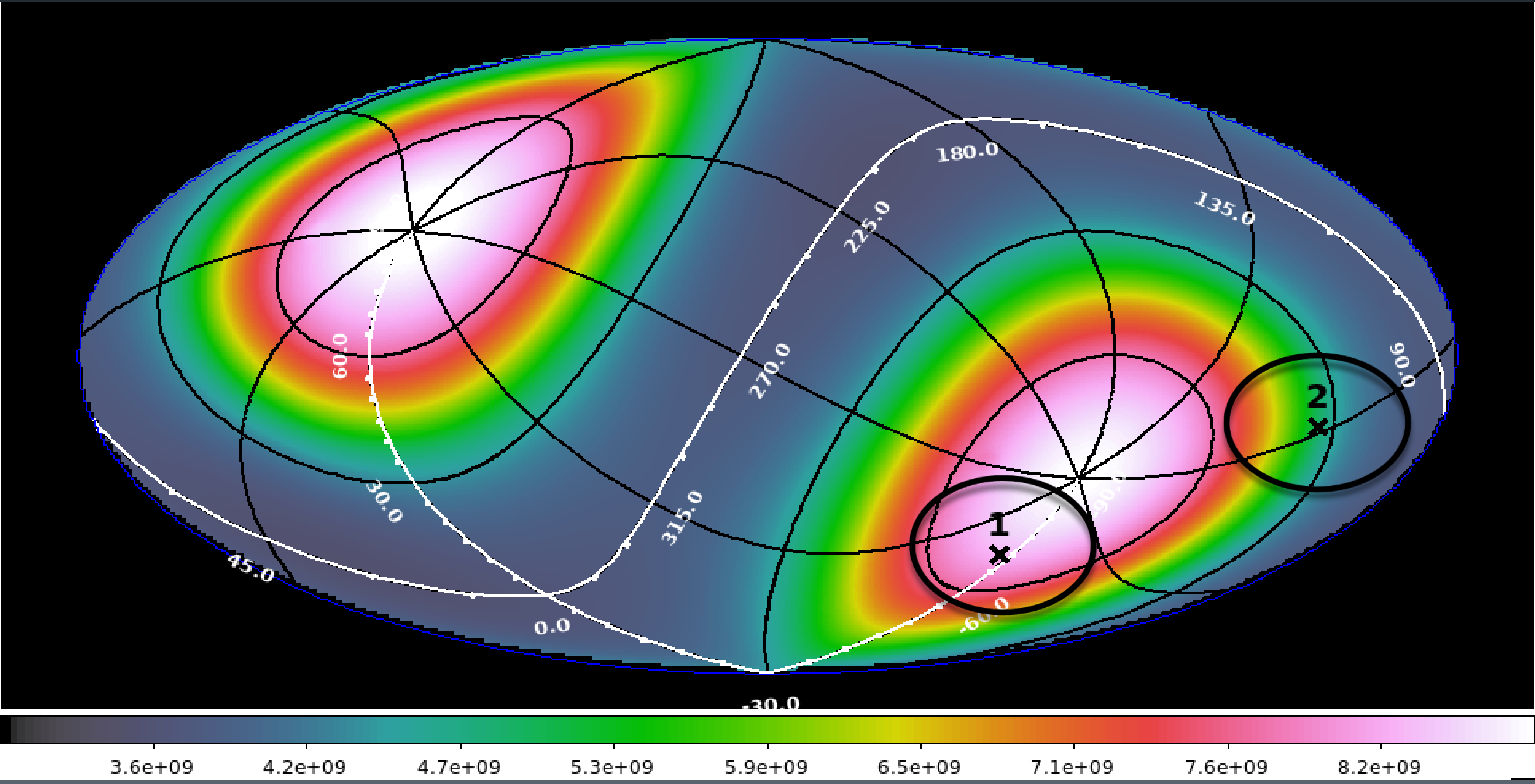
2-day Flux sensitivity in spinning (E>100 MeV, @5σ): 2÷4 x 10^{-6} ph cm^{-2} s^{-1}
1-yr Flux sensitivity in spinning (E>100 MeV, @5σ): 1÷8 x 10^{-7} ph cm^{-2} s^{-1}

AGILE pointing mode: all data exposure



AGILE spinning

~8 years of AGILE-GRID exposure in Spinning



AGILE in spinning mode

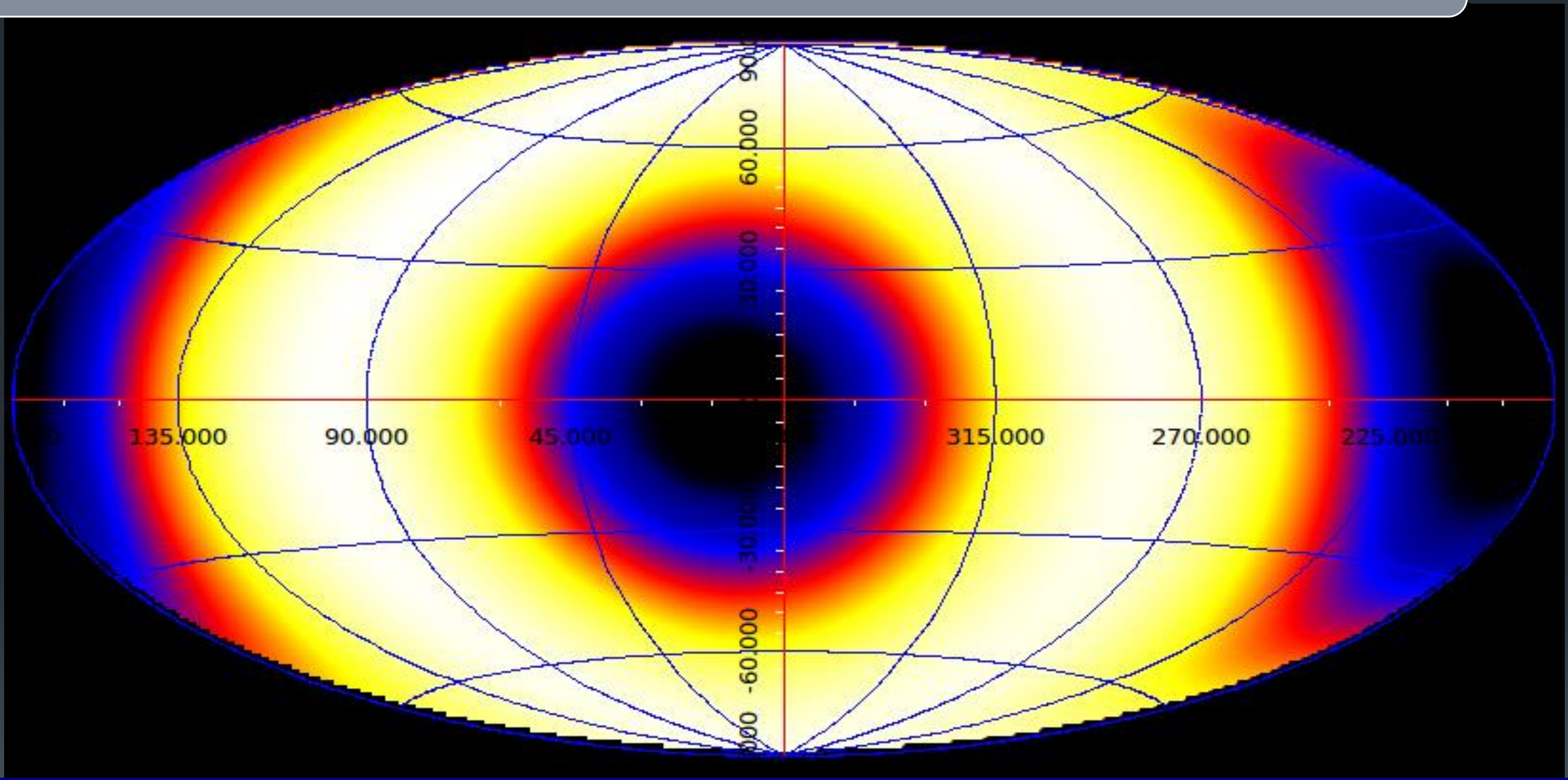
- Very large field of view (~2.5 sr).
- Coverage of 70% -- 80% of the whole sky every day.
- Very fast ground segment: first *Quick Look* analysis (on *contact* basis) available ~30 min after telemetry download.

Very suitable instrument to perform all-sky searches for short transient γ-ray sources and γ-ray counterparts to multi-messenger transients (GW and neutrinos).

AGILE in spinning mode

From Lucarelli F. – MG 15th Meeting

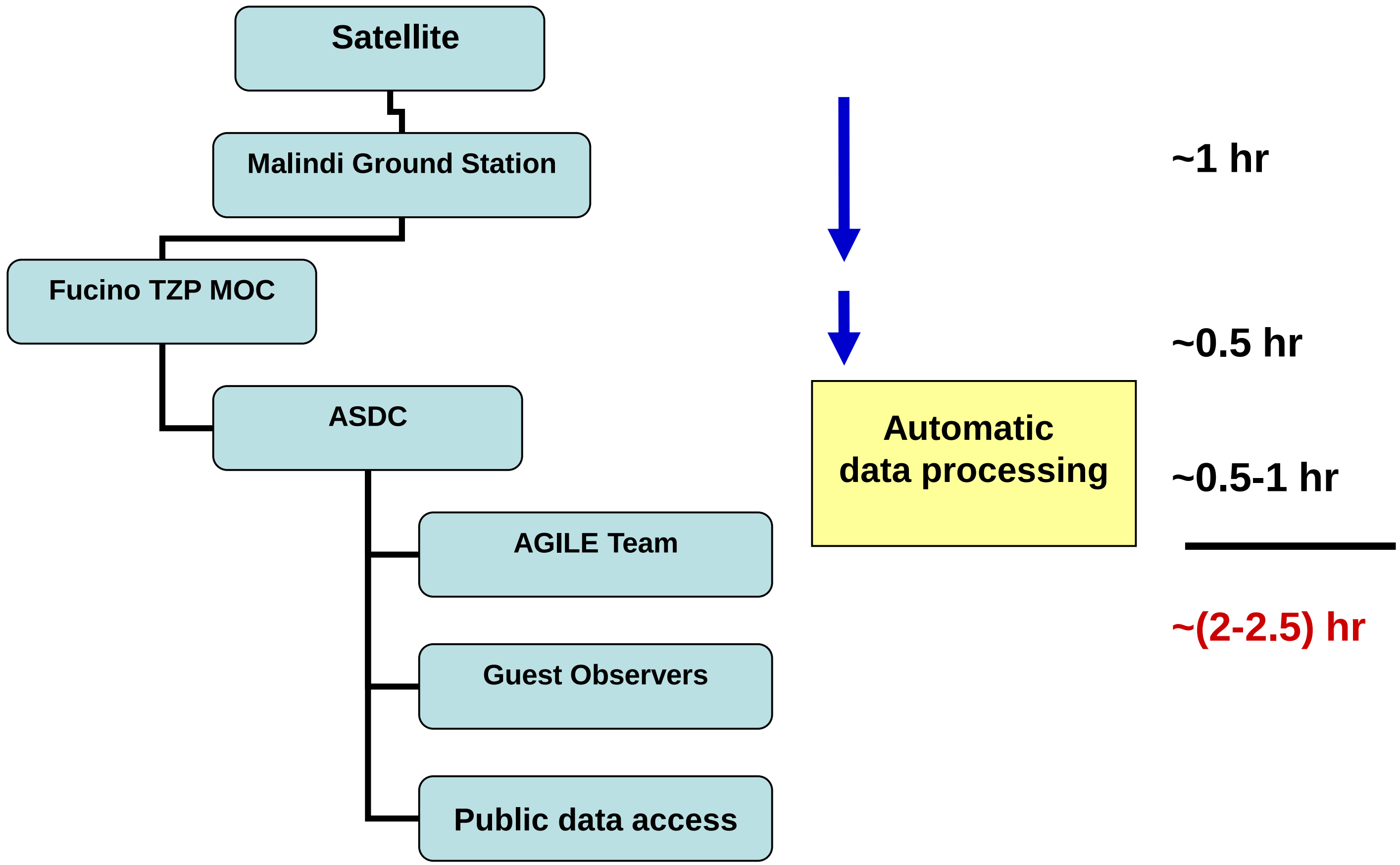
Typical AGILE *all-sky* exposure over 1÷2 days of observation



Sensitivity over 2-day time integration (E>100 MeV, 5σ): 3 ÷ 5 x 10^{-10} erg/cm^2/s

Angular resolution (100 MeV < E < 1 GeV): 1.2 ÷ 2.5 deg

AGILE: “very fast” Ground Segment



Now even faster: ~ 25 min latency. Optimized for GW counterpart hunt!

Record for a gamma-ray mission! App <u>AGILEScience</u> for mobile dev

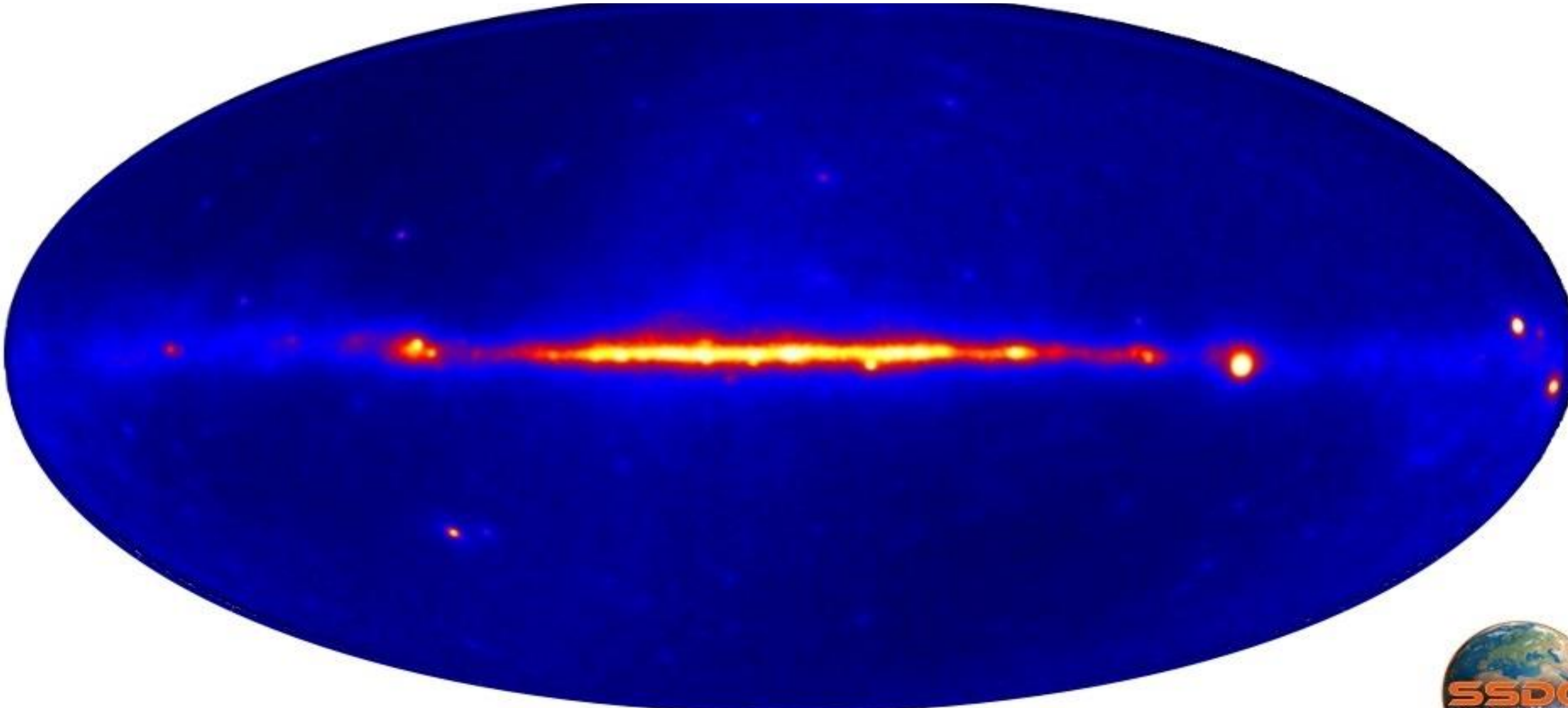
The automatic AGILE QL system

- AGILE *Quick Look* detection system searches daily for γ-ray transients above 100 MeV over predefined 2-day integration time-bins of data.
- Blind search for count excesses above the background using standard detection method (XIMAGE, spotfinder).
- Each candidate transient is then evaluated using the standard AGILE maximum likelihood (ML) algorithm.
- A refined analysis is performed to confirm the automatic detection with a dedicate Flare Advocate team.

Thanks to the QL systems, AGILE alerted the astronomical community with more than 200 ATel’s and several GCNs.

The AGILE γ-ray sky (E>100 MeV)

MORE THAN 11 YEARS OPERATING IN ORBIT!



AGILE
main scientific results

The 3 main AGILE discoveries in HE astrophysics above 100 MeV:

1. **AGILE and Gamma-ray flares E>100 MeV in Micro-QSO (Cyg X-3 with a repetitive pattern, and Cyg X-1)**

2. **AGILE and almost monochromatic gamma-ray flares from Crab Pulsar Wind Nebula**

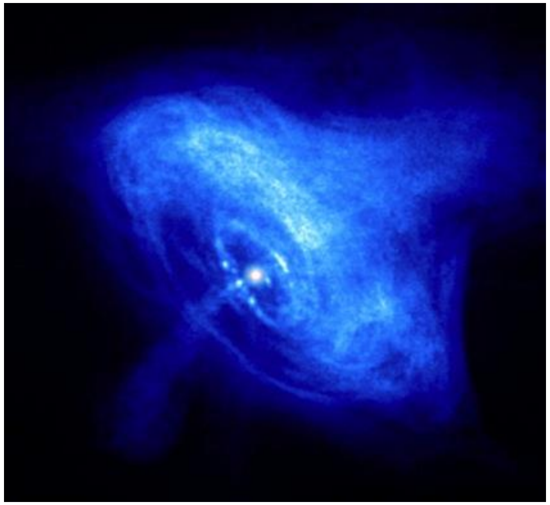
3. **First direct evidence of cosmic ray acceleration in Supernova Remnants with the AGILE observations of the SNR W44 (2017 Matteucci Medal of the National Academy of Sciences to M. Tavani)**

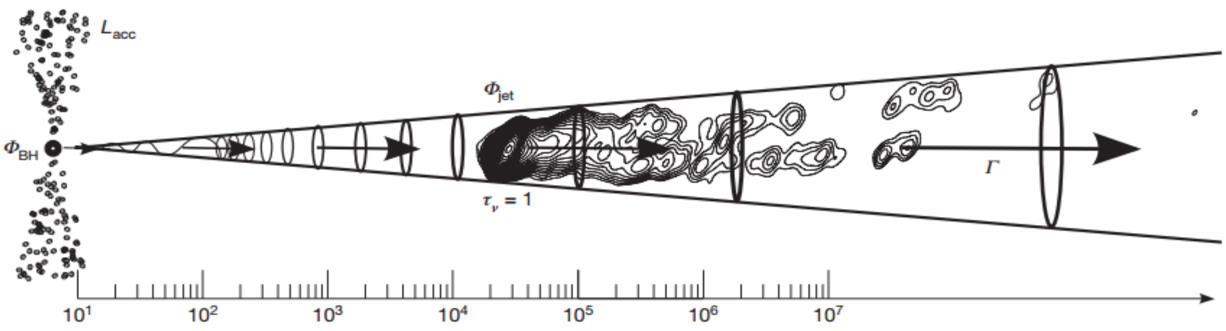
Other main AGILE results:

- **AGILE and AGNs (3C454, PKS1510, 3C279, …), with fast observed timescale variability**
- **Transient and subsequent discovery of the "hidden black hole" MCW 656 in a Be star binary**
- **η Carinae: first detection of a Colliding Wind Binary in γ-rays**
- **Surprises also from the Earth atmosphere: detection of Terrestrial Gamma-Ray Flashes (TGF) up to 100 MeV!!**

High Energy Astrophysics above 100 MeV new lesson: Gamma-ray intense transients on short timescales (< minutes, days) in different astrophysical systems:

- Role of the magnetic field
- New acceleration mechanism (e.g. Crab flares)
- Plasma instabilities
  - Galactic compact objects (e. g. Cygnus X-3)
  - Blazars and relativistic jets, GRBs





Cygnus X-3: major gamma-ray flares in special transitional states in preparation of radio flares! (Tavani et al., Nature 2009)

- **Gamma-ray flares tend to occur in the rare low-flux/pre-flare radio states.**

- **For all gamma-ray flaring episodes, the radio and hard-X-ray fluxes are low or very low, while the soft X-ray flux is large**

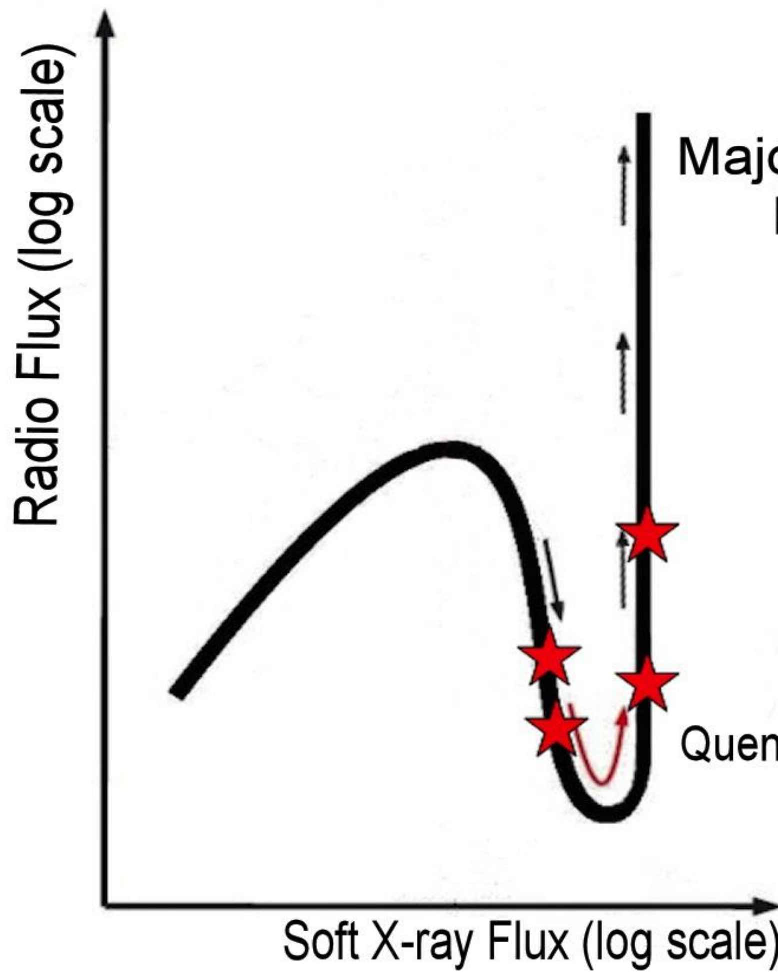
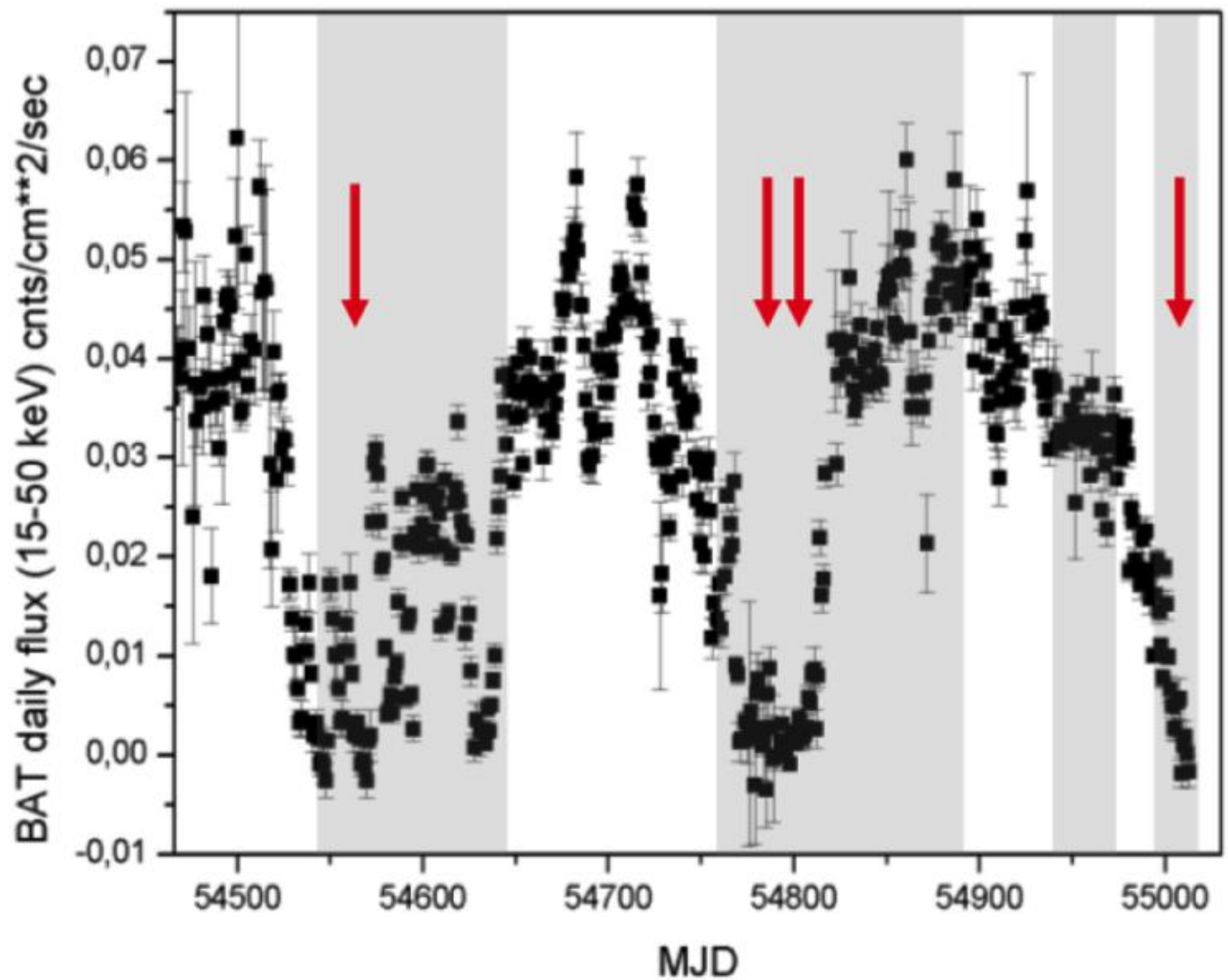


figure adapted from Szostek Zdziarski & McCollough (2008)

Cygnus X-3: major gamma-ray flares in special transitional states in preparation of radio flares! (Tavani et al., Nature 2009)

- **Gamma-ray flares** tend to occur in the rare low-flux/pre-flare radio states.
- For all gamma-ray flaring episodes, the radio and **hard-X-ray fluxes are low** or very low, while the soft X-ray flux is large



- Direct evidence that extreme particle acceleration (above 100 MeV) and non-thermalized emission can occur in microquasars with a repetitive pattern (latest gamma-ray flares in March - April 2017)

- Emission must be produced not too far away from the central object (4,8 hours orbital modulation revealed by Fermi!)

- Cyg X-3 is capable of accelerating particles by a very efficient mechanism leading to photon emission at energies thousands of times larger than the max energy previously detected (E ~ 300 keV)

- Comptonization models (thermal and non-thermal) that reproduce the spectral states up to 300 keV must take into account the data above 100 MeV

MOST UNEXPECTED DISCOVERY FROM THE γ-RAY SKY:

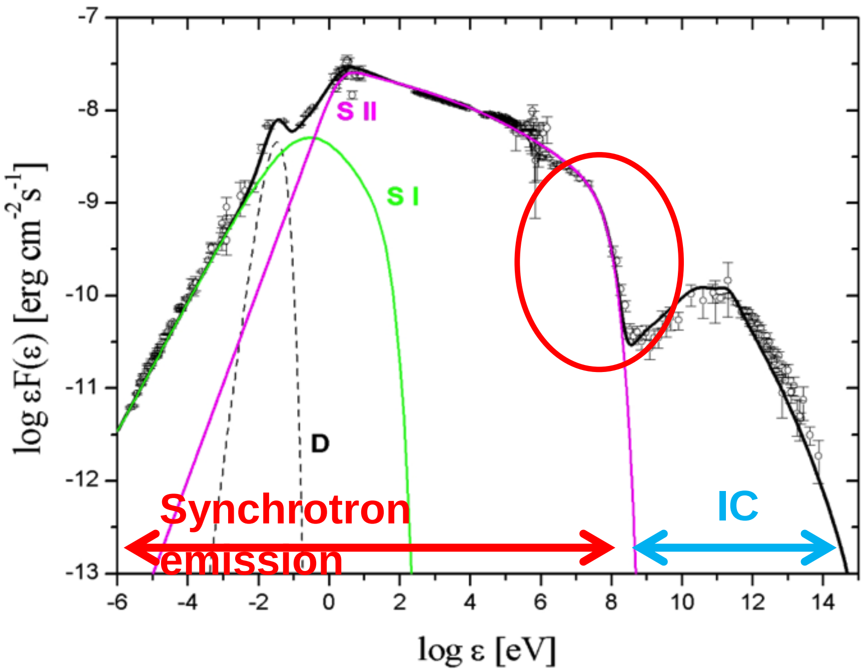
AGILE DISCOVERY OF THE CRAB NEBULA VARIABILITY IN γ-RAYS

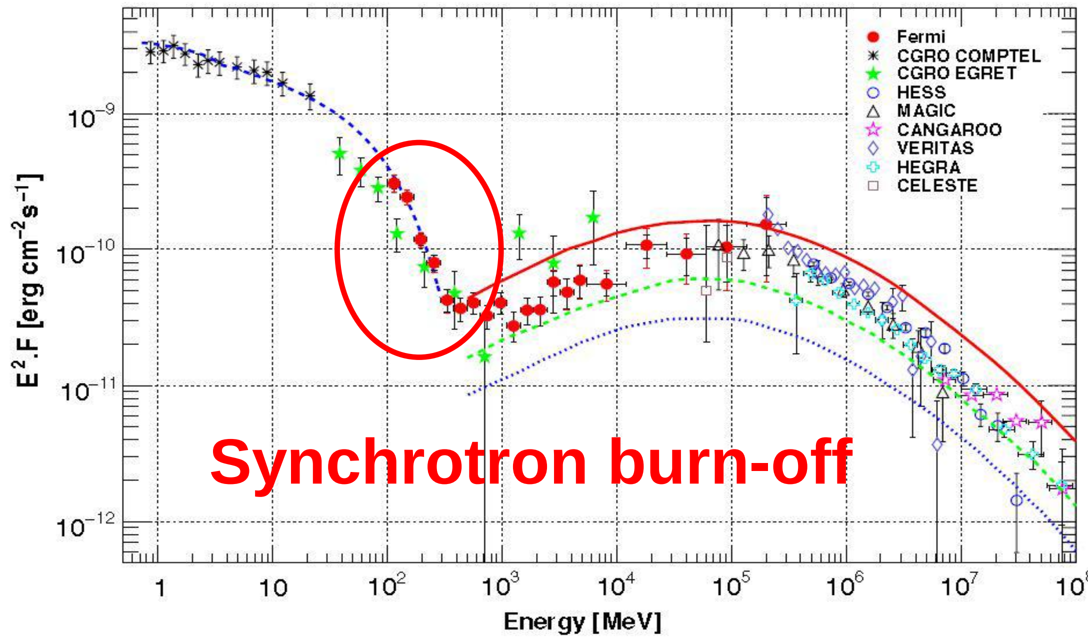
Tavani et al., Science, 331, 736 (2011)

Fermi confirmation:

Abdo et al., Science, 331, 739 (2011)

Crab Nebula spectrum from radio to TeV





Diffusive acceleration

$E_{\gamma,max} \approx 25$ MeV

Linear accelerator in ideal MHD framework

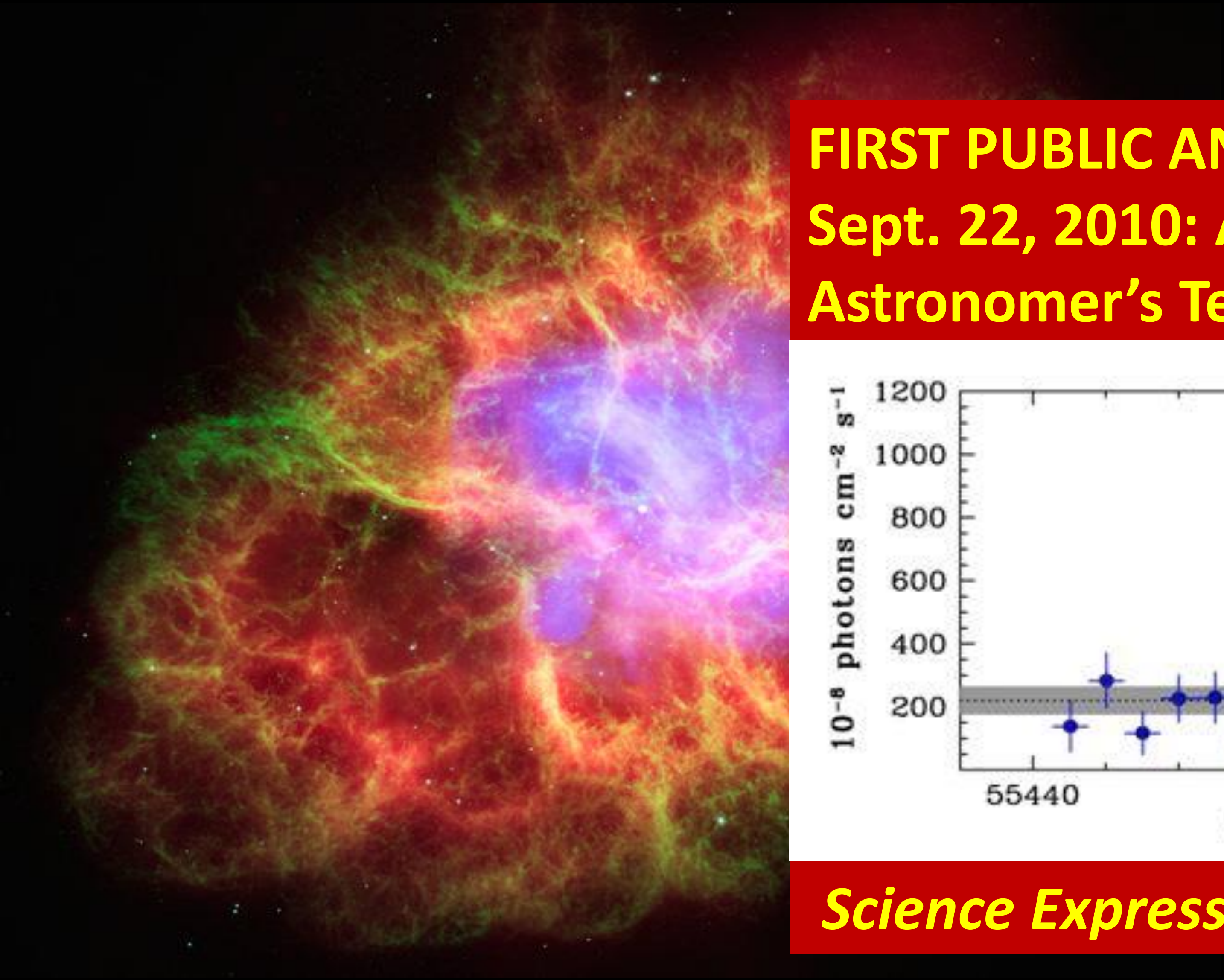
$E_{\gamma,max} = 9/4\ mc^2/\alpha\ \mathbf{E/B} \approx 150\ \text{MeV}\ \mathbf{E/B}$

Synchrotron burn-off (E/B<1)

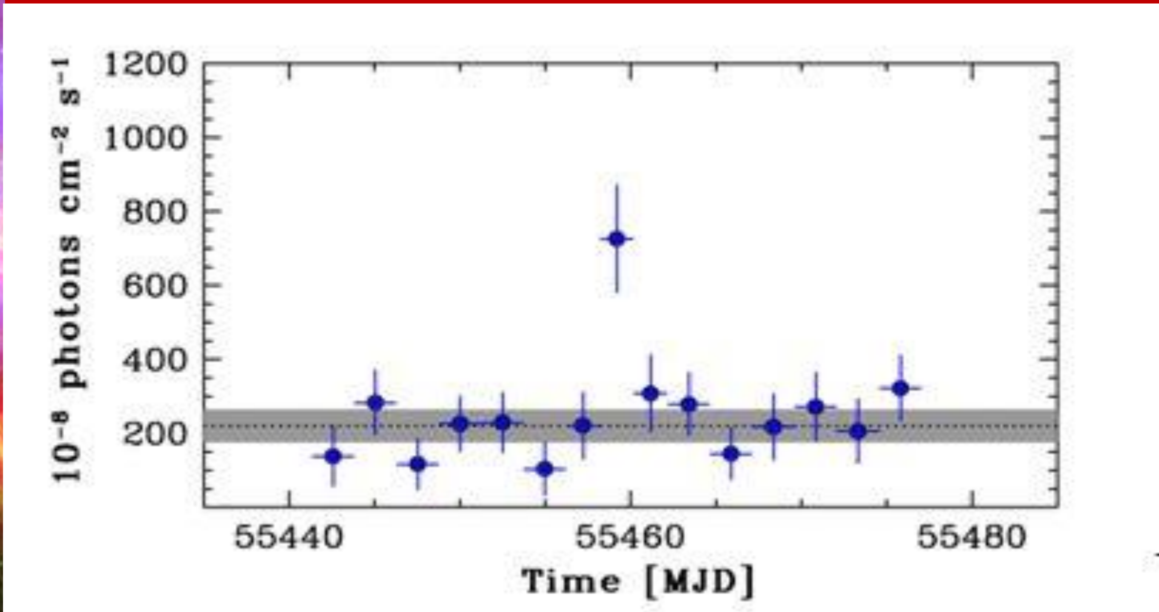
(De Jager et al. 92, Arons 2012)

(Slide adapted from E. Striani, PhD Thesis)

The variable Crab Nebula!



FIRST PUBLIC ANNOUNCEMENT
Sept. 22, 2010: AGILE issues the Astronomer's Telegram n. 2855



Science Express **(6 January 2011)**

Marco Tavani, "AGILE Discovery of Gamma-Ray flares from the Crab Nebula"

Crab Sept. 2010 flare:

- gamma-ray flare peak luminosity

$$L \approx 5 \cdot 10^{35} \text{ erg cm}^{-2} \text{ s}^{-1}$$

- kin. power fraction of PSR spindown L_{sd},

$$\varepsilon \approx 0.001\ (\eta_{-1}/0.1) \approx 0.01$$

- timescales:
  - risetime: $\leq$ 1 day
  - decay: ~ 2-3 days

very efficient acceleration !

fast cooling, B, Lorentz γ

Flare date	Duration	Peak γ-ray flux	Instruments
October 2007	**~ 15 days**	**~ $6 \cdot 10^{-6}$ ph cm^{-2} s^{-1}**	**AGILE**
February 2009	**~ 15 days**	**~ $4 \cdot 10^{-6}$ ph cm^{-2} s^{-1}**	***Fermi***
September 2010	**~ 4 days**	**~ $5 \cdot 10^{-6}$ ph cm^{-2} s^{-1}**	**AGILE, *Fermi***
April 2011	**~ 2 days**	**~ $30 \cdot 10^{-6}$ ph cm^{-2} s^{-1}**	***Fermi*, AGILE**

Other γ-ray flaring states seen by Fermi and AGILE:

Mar and Oct 2013, Aug 2014, Oct 2016, March 2018 ...

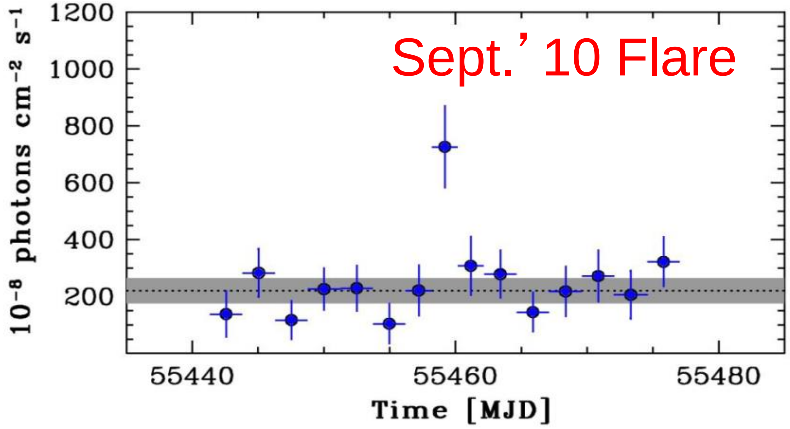
Rate: ≈ 1/year

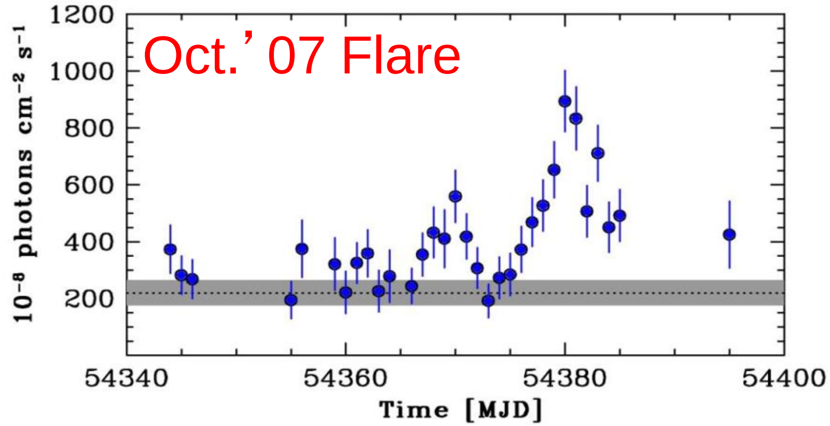
Big theoretical challenge:

the Crab Nebula is not a standard candle in gamma-rays!

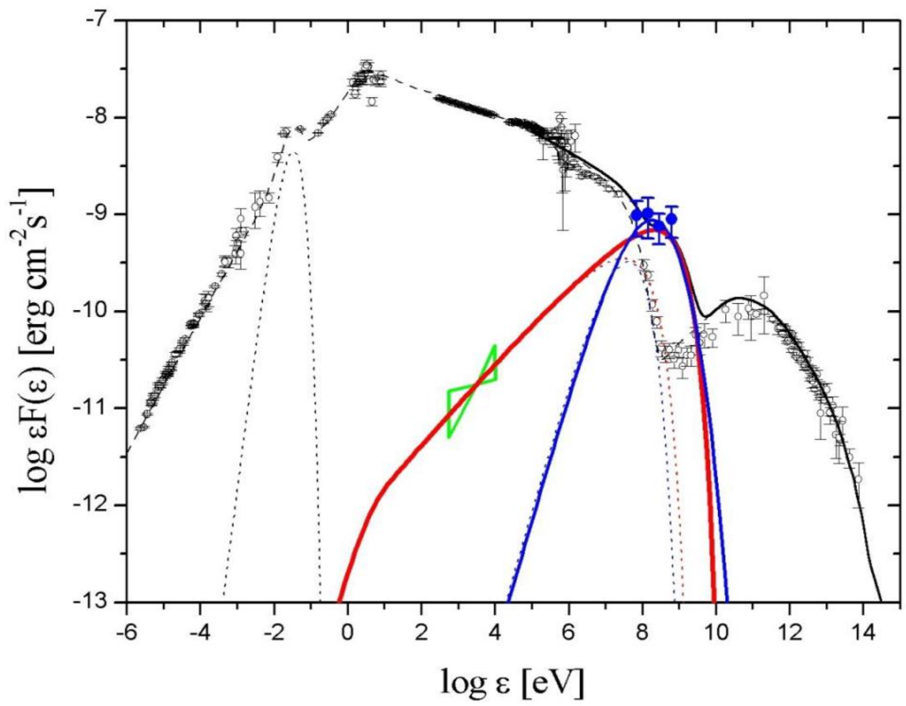
AGILE and TeV Galactic Sources IV

Crab Nebula

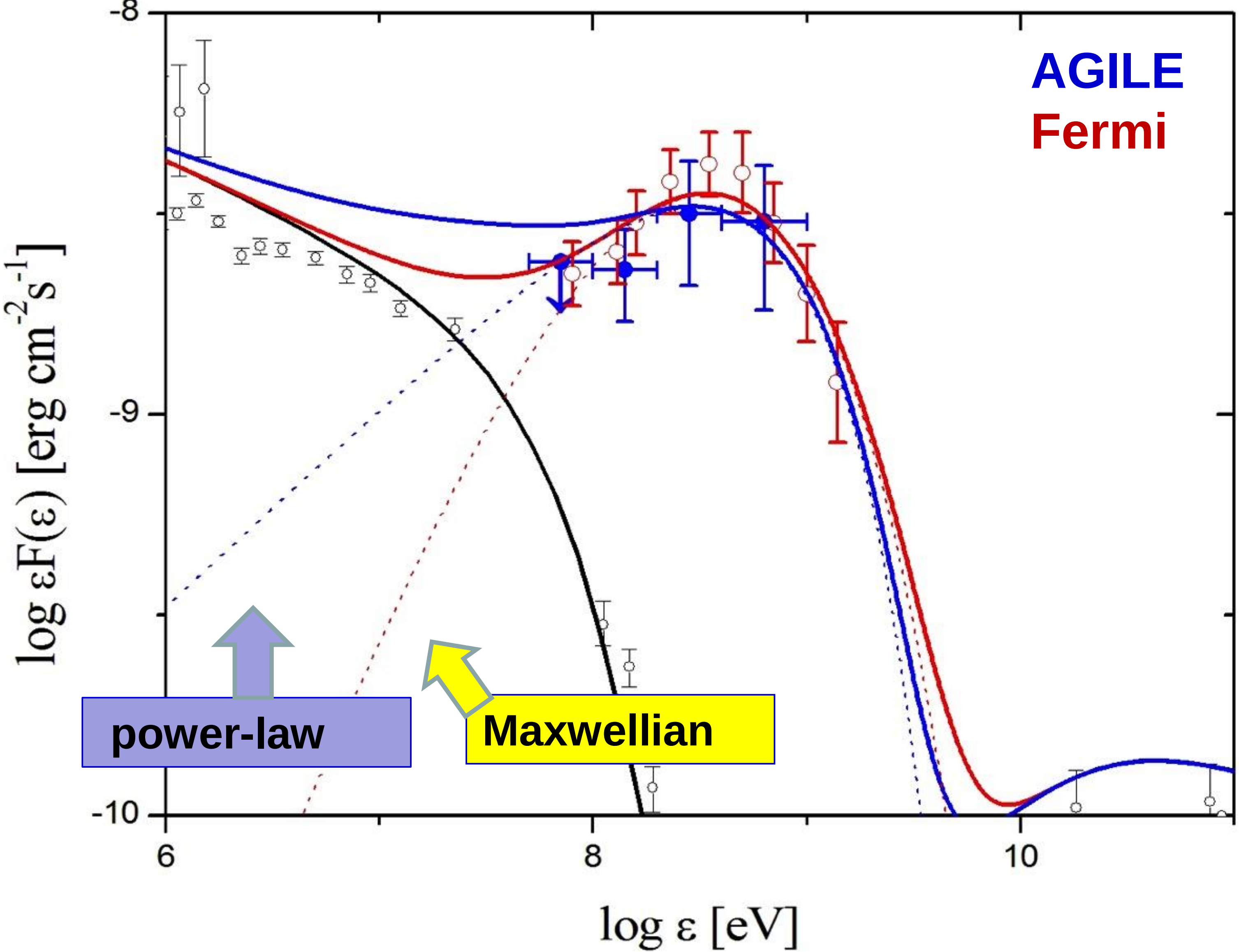




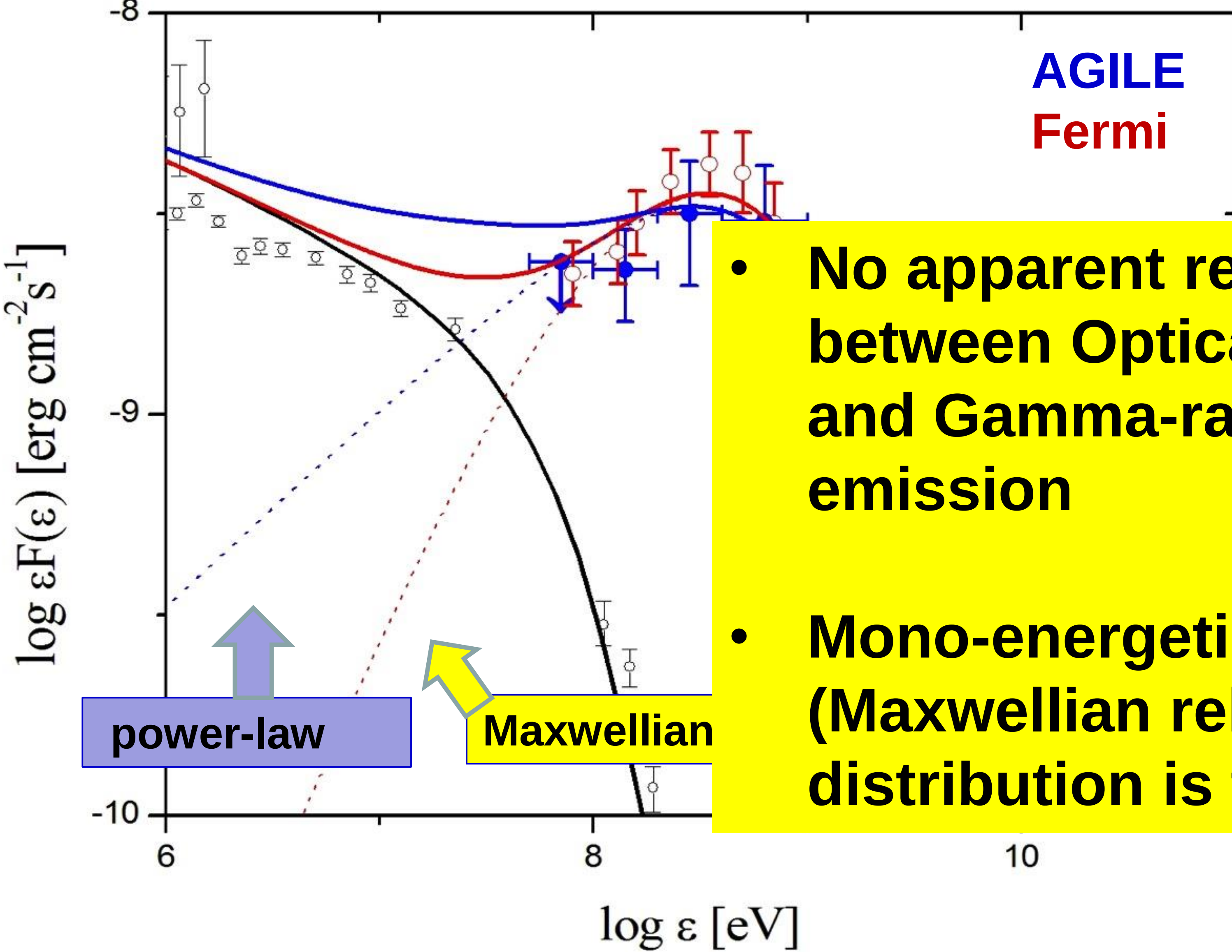
Tavani et al. 2011, Science 311



Modelling of the April 2011 super-flare



Modelling of the April 2011 super-flare



- No apparent relation between Optical, X-ray and Gamma-ray flaring emission
- Mono-energetic (Maxwellian relativistic) distribution is favored

Crab lessons:

- **Crab Nebula shocks able to accelerate electrons/positrons at $\gamma \sim 109$ (PeV) !**

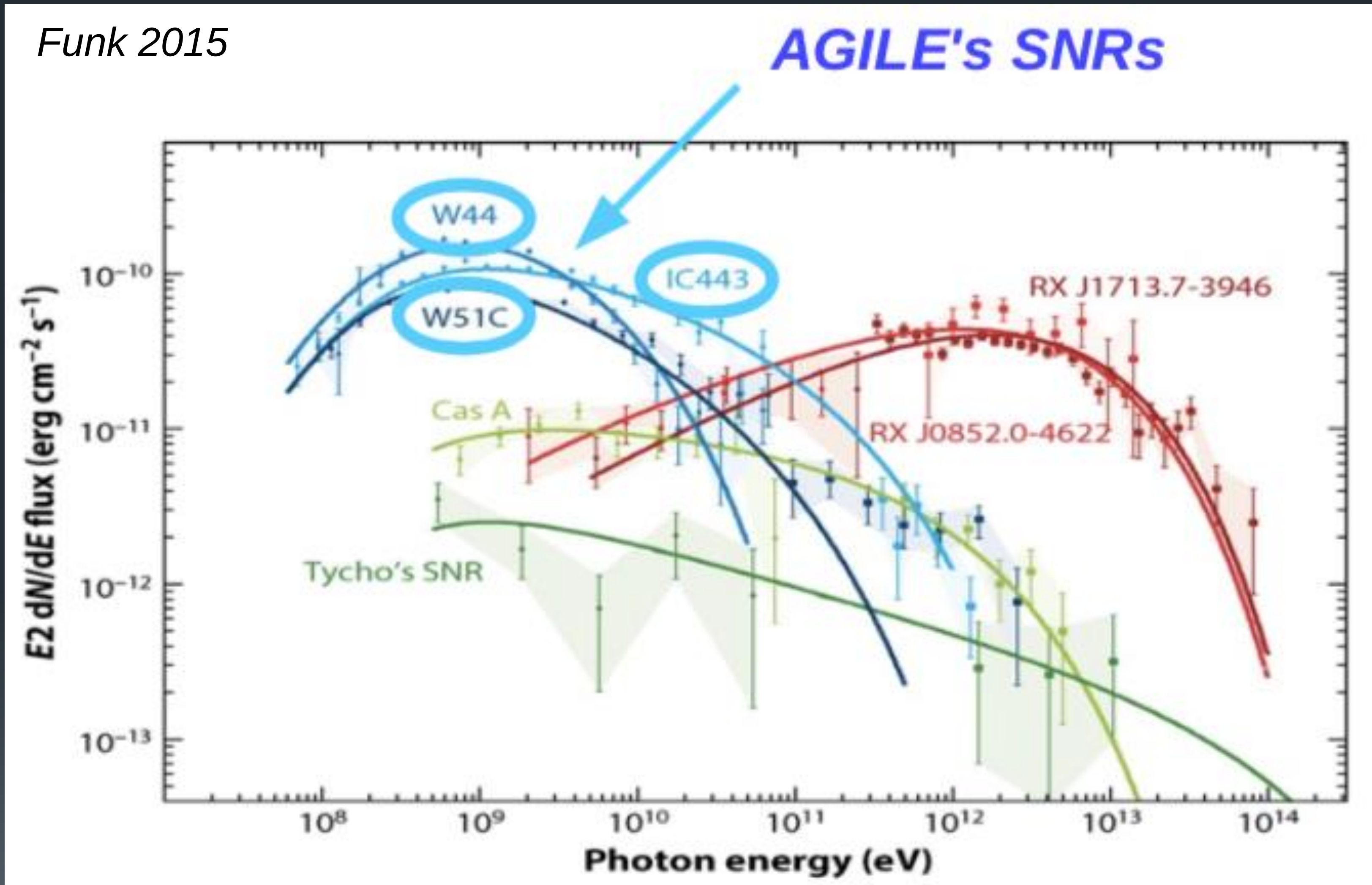
- **We “lost” the stability of an ideal reference source, but gained tremendous information about the fundamental process of particle acceleration**

- **Big theoretical challenge, crucial feedback with laboratory plasma physics**

- **The ultimate source of particle enhancements in the pulsar wind needs to be established: future surprises**

AGILE and SNRs

AGILE and SNRs

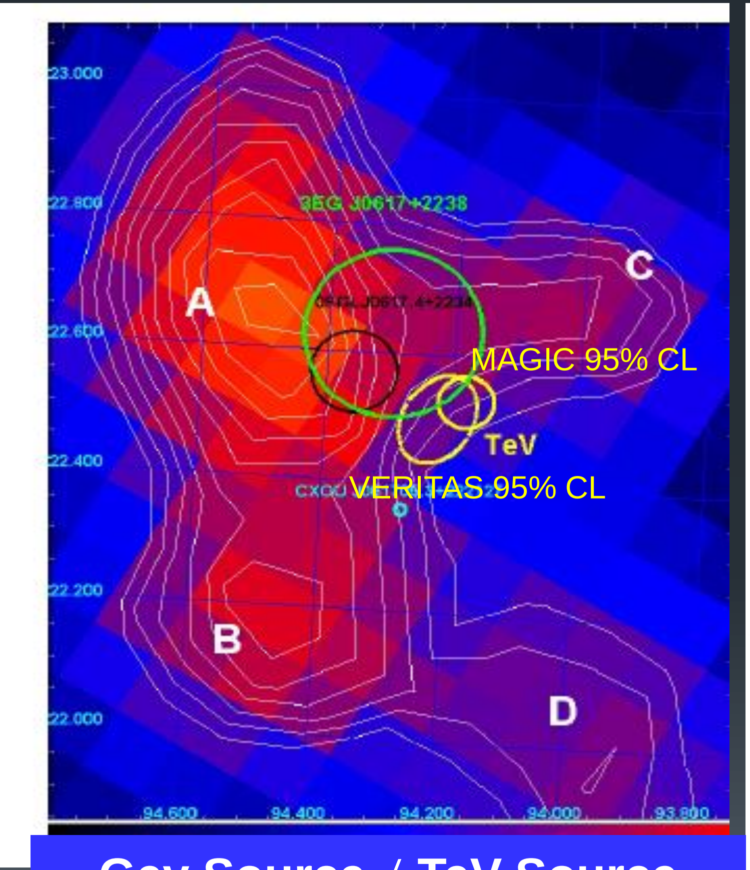


<u>All of them are middle-age (~10^4 yrs), interacting with GMCs</u>

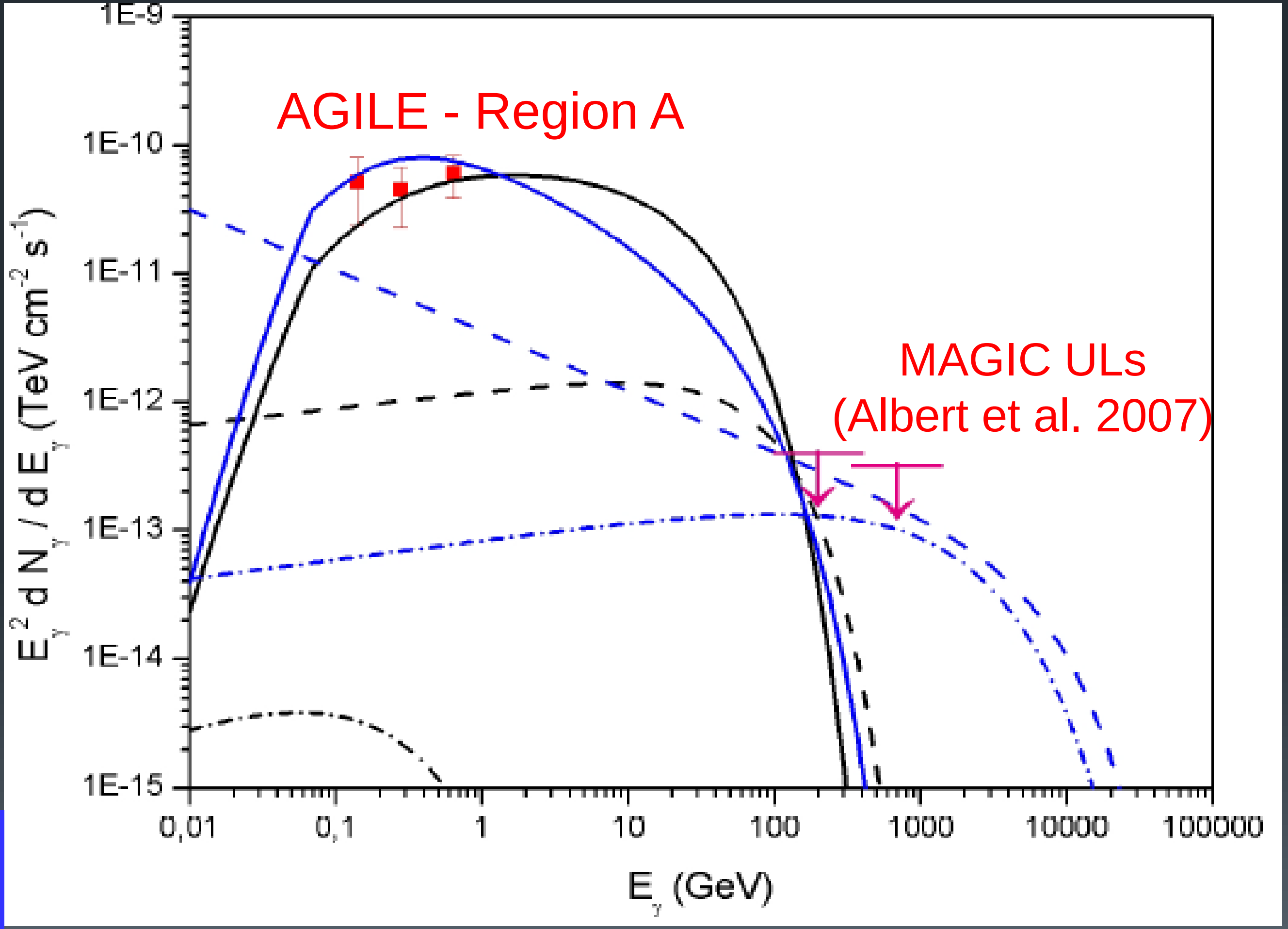
First detection of GeV photons from SNR

IC 443

Tavani et al. 2010, ApJL 710



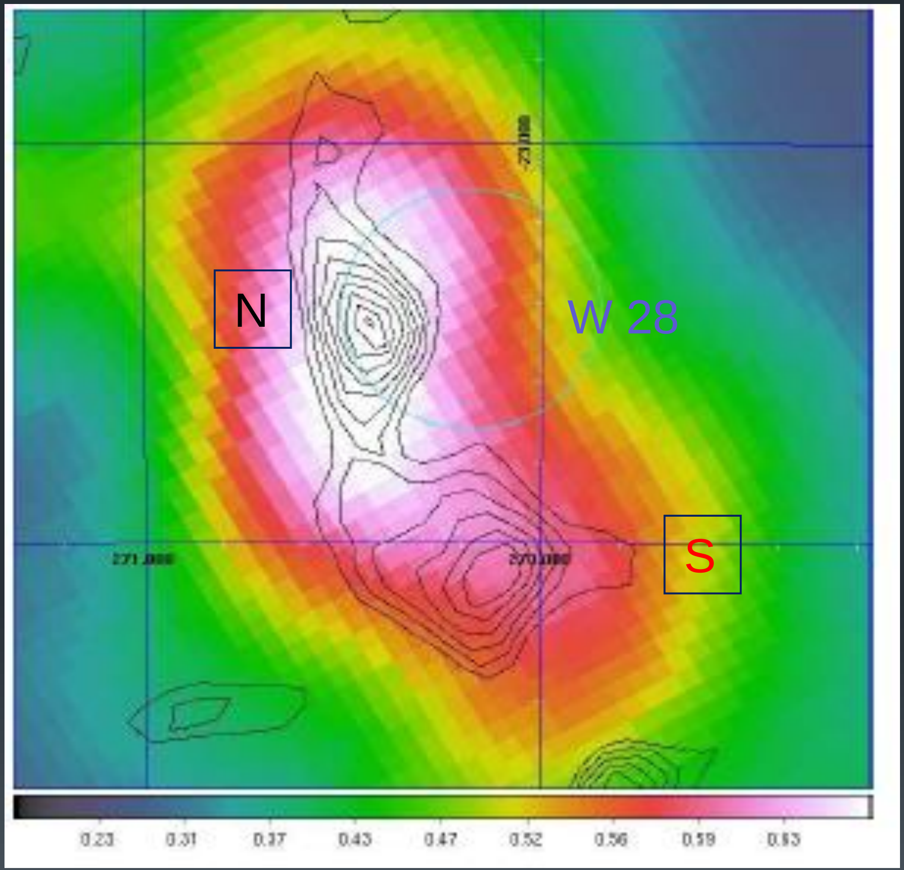
Gev Source ≠ TeV Source
Extended Source (Shell)



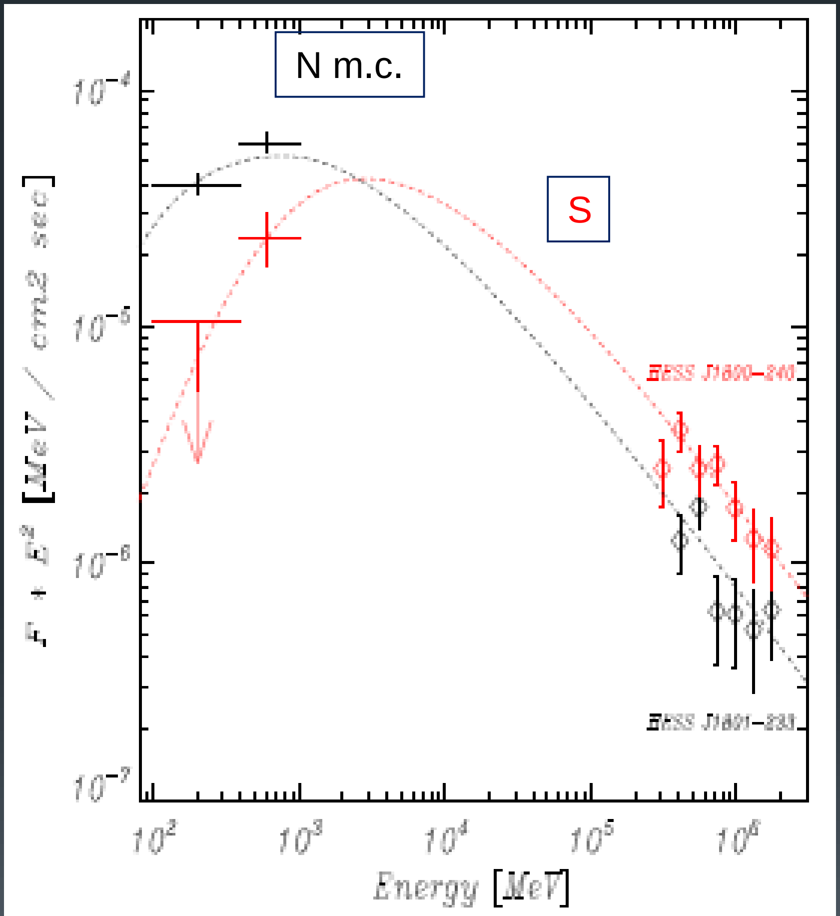
First measure of diffusion coefficient

W28

Giuliani et al. 2010



AGILE map + TeV contour: main GeV emission ≠ TeV one

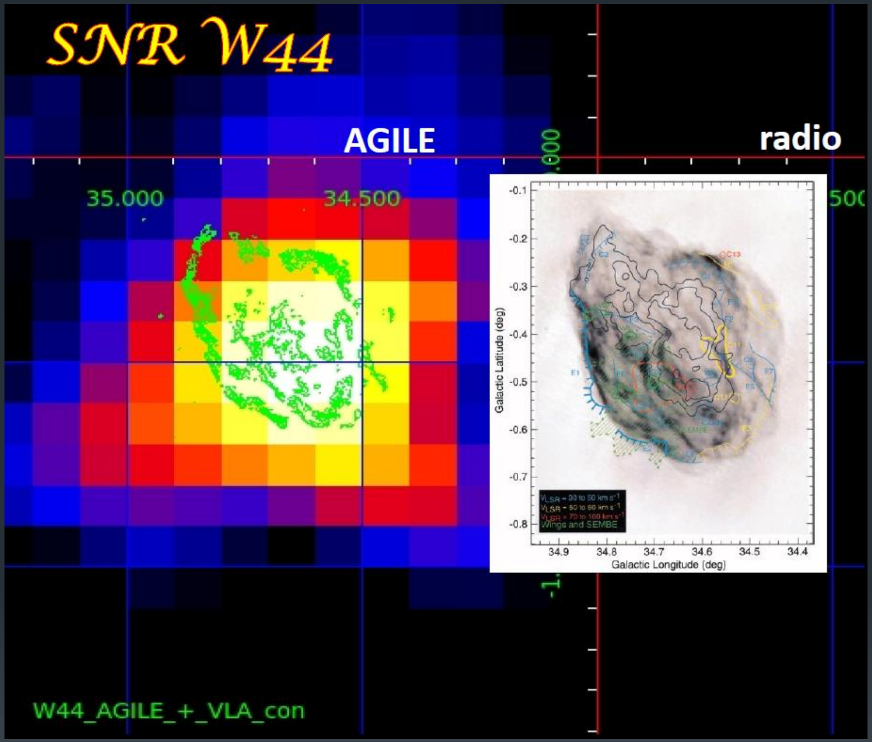


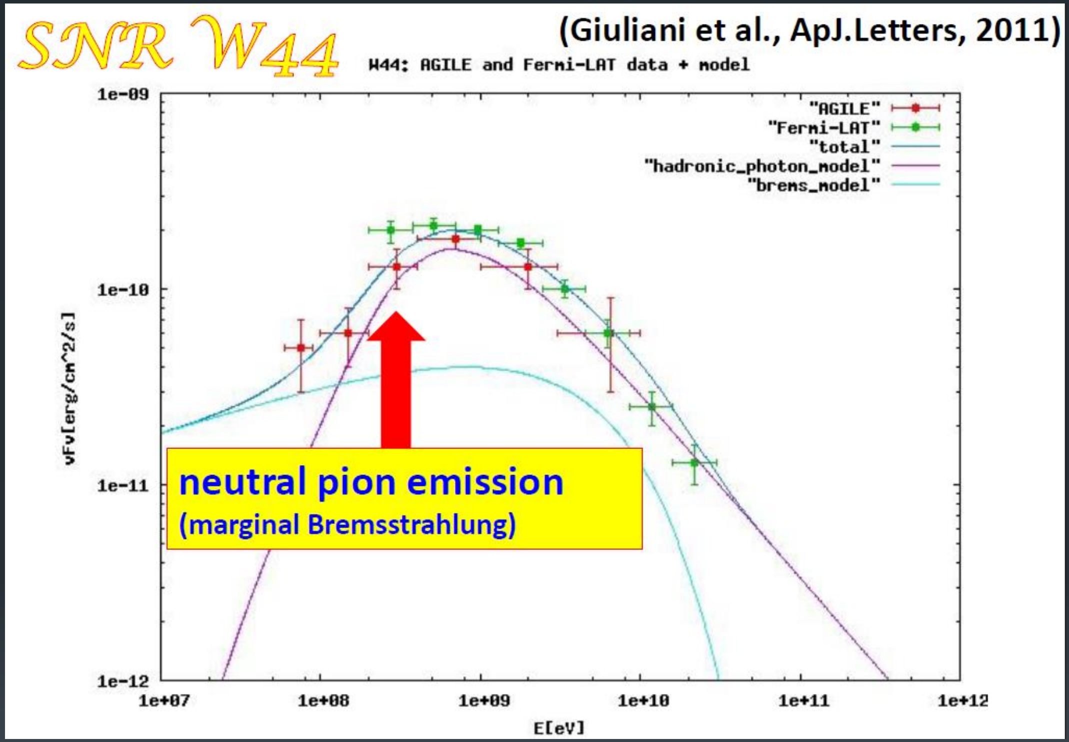
CR diffusion model (hadronic): different distances from W28

First detection of the *pion bump*

Giuliani et al. 2011
Cardillo et al. 2014

W44



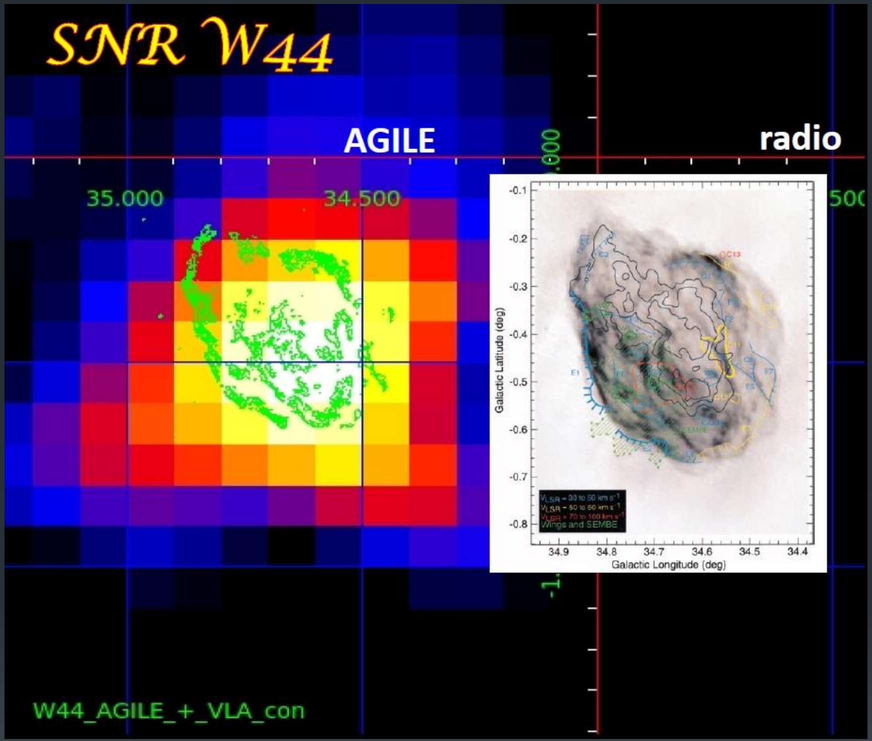


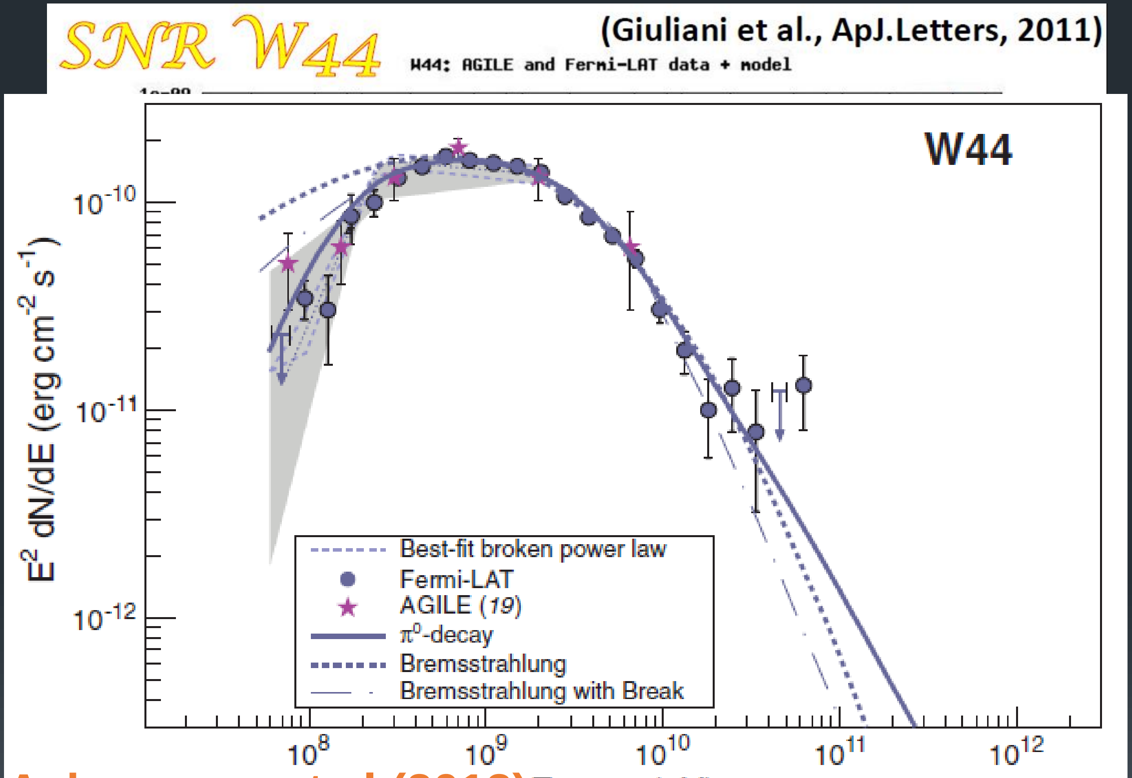
Spectral modeling: hadronic signature->spectrum compatible with pion bump

First detection of the *pion bump*

W44

Giuliani et al. 2011
Cardillo et al. 2014





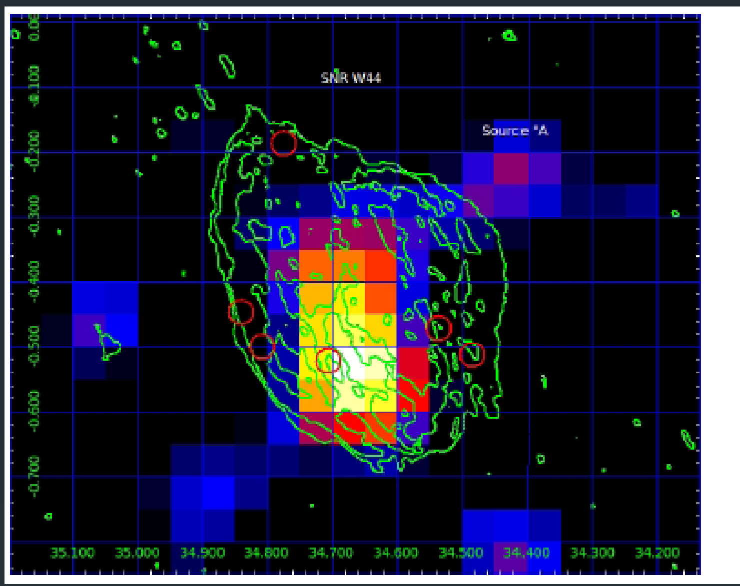
Ackermann et al.(2013)

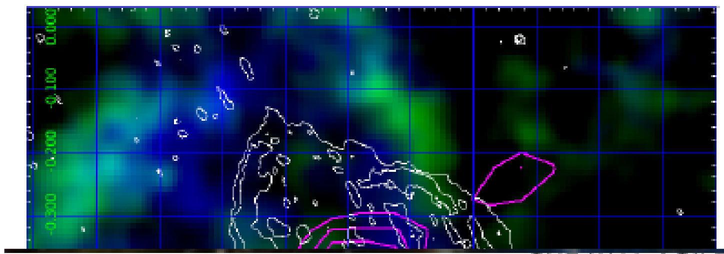
Spectral modeling: hadronic signature->spectrum compatible with pion bump

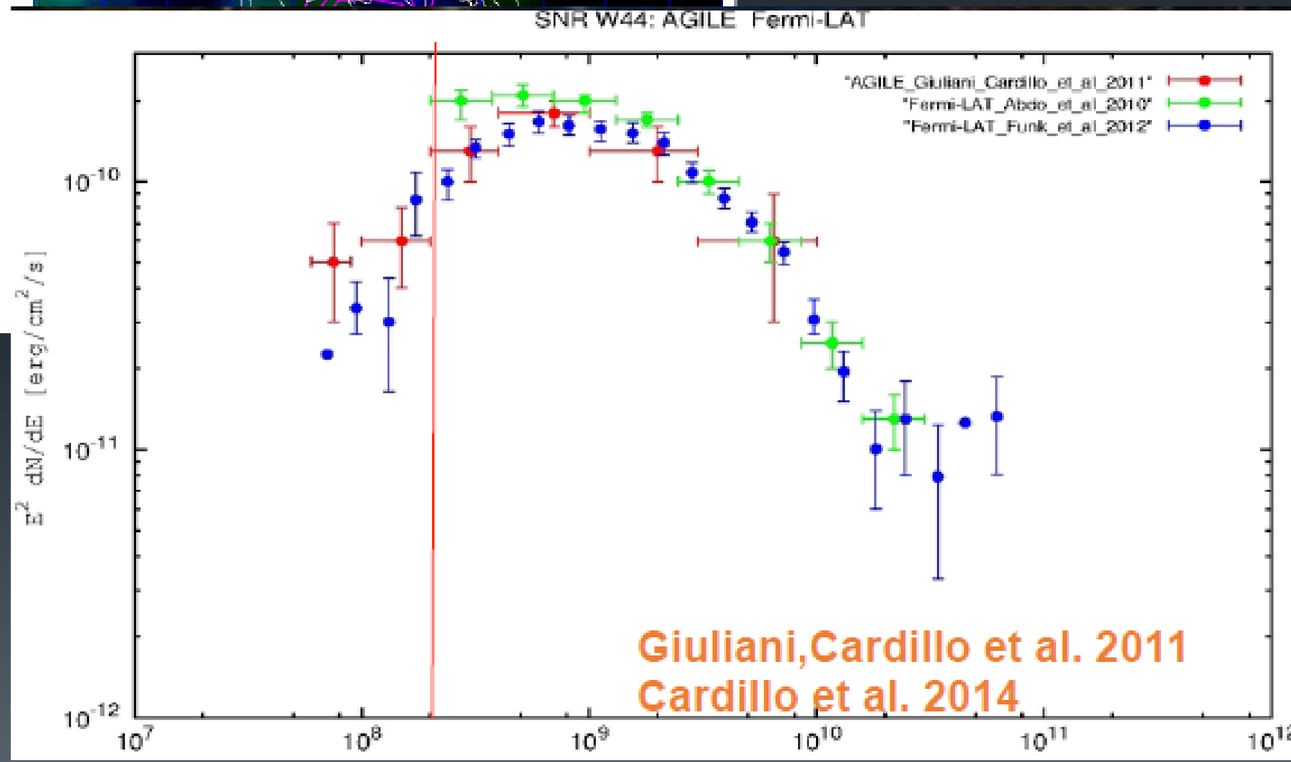
First detection of the *pion bump: updated*

W44

Cardillo et al. 2014







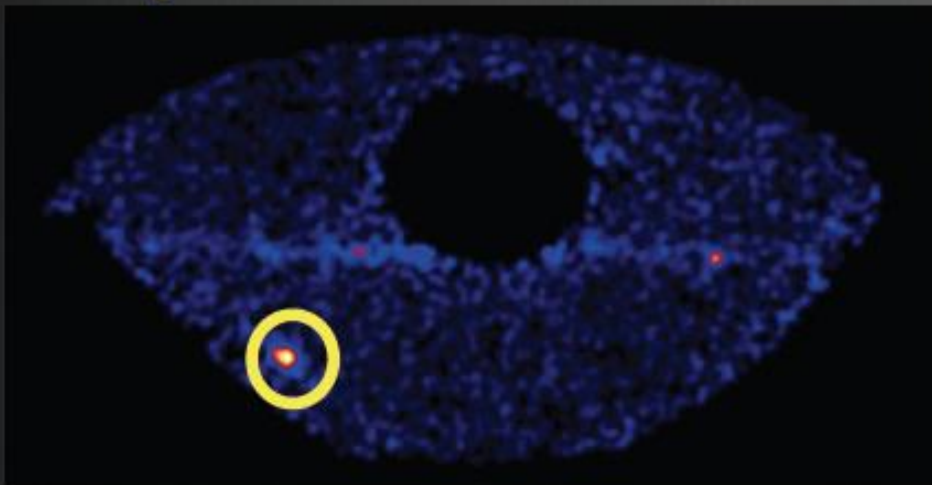
New AGILE and Fermi data

Gamma-ray flaring blazars: 3C 454.3, 3C 279

- Ratios between optical and γ-rays variation factors may be > 2 or more. Compton dominance varies
- Gamma-ray only "orphan" flares. The Compton dominance attains values of 100 or more.
- Very fast variability: γ-flux shows doubling times of few minutes
- High energy spectrum can be unusually hard

3C 454.3
The monster flare in 2010

16-19 Nov 2010→ 10σ in 5,8 days



Most intense gamma-ray source ever detected: 3C 454.3

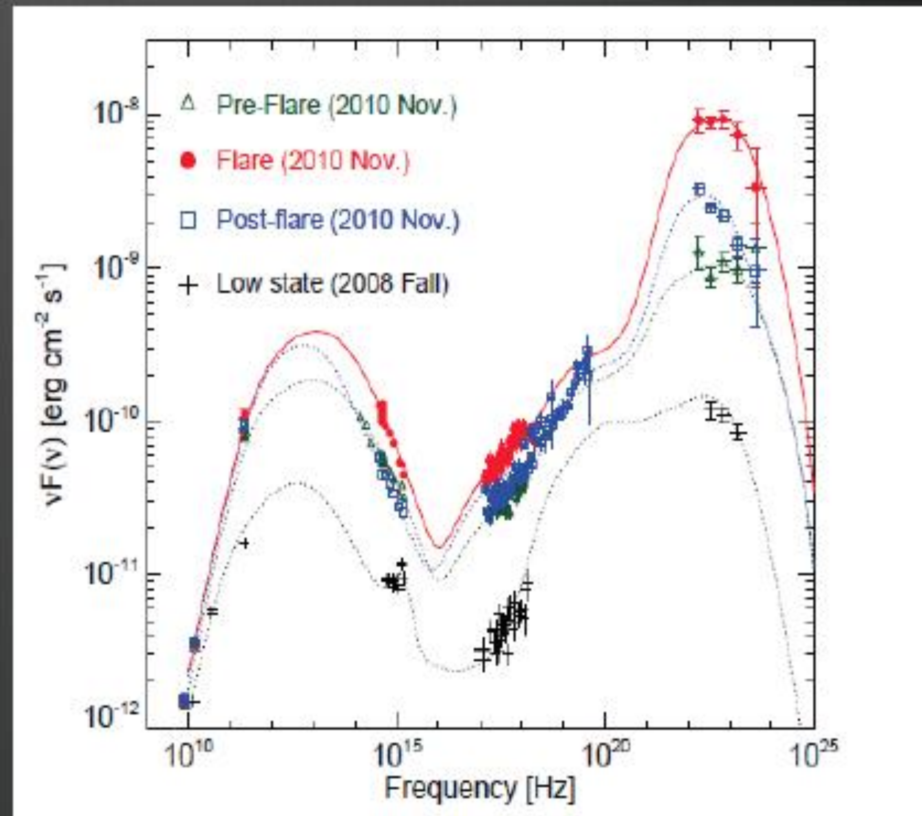
z=0.859,

F_γ > 8000 10^{-8} ph. cm^{-2} s^{-1},

L_{iso}= 2×10^{50} erg s^{-1},

for δ = 10, $L_{jet} \approx$1 Earth/sec)

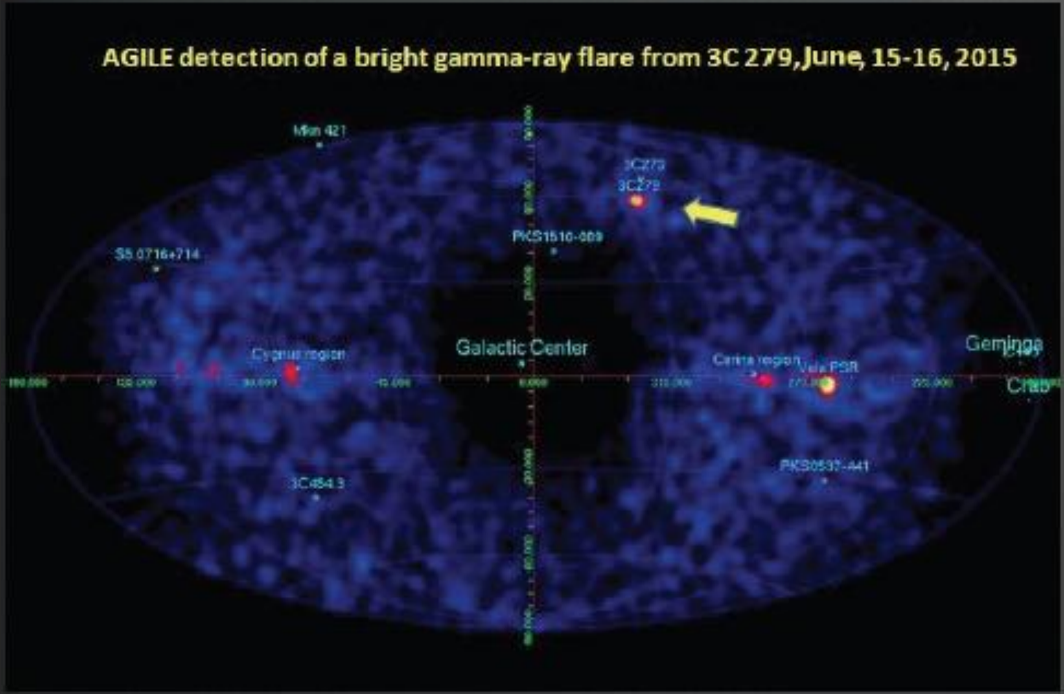
Superflare may require two electron populations (see Pacciani et al., 2010)

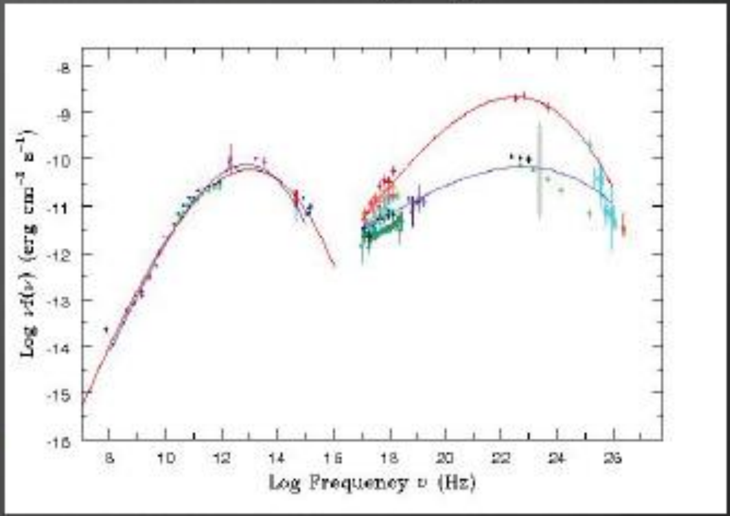


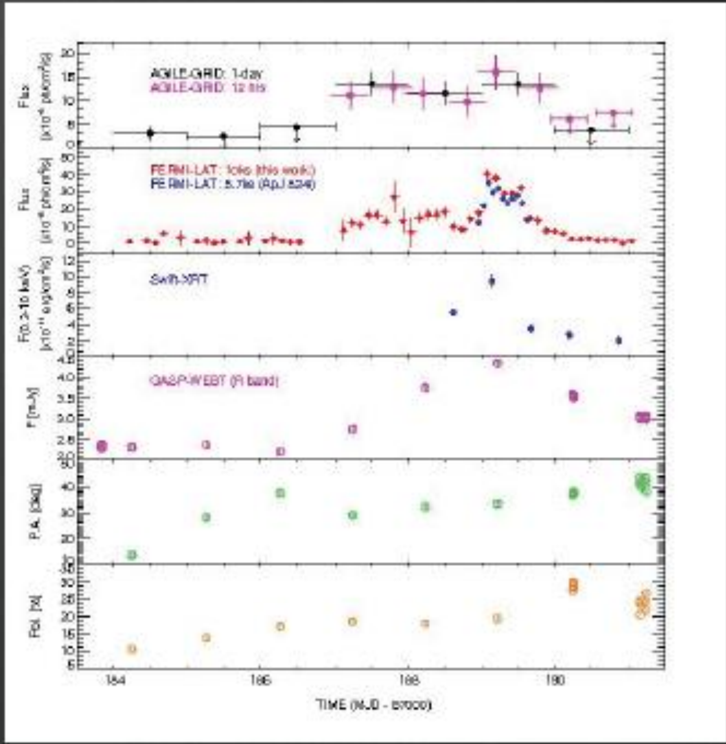
Vercellone et al., 2010, 2011

3C 279
The monster flare in June 2015

Pittori et al., ApJ 856 (2018)







z=0.536,

$F_\gamma > 3000\ 10^{-8}$ ph. cm^{-2} s^{-1},

γ-ray emitting region at the outer edge of the broad line region or farther out from it

Minute timescale observed by Fermi

Many challenges for theory

All the phenomenology challenges the standard models

- **Where is the γ-ray dissipation region and what is the nature of seed photons in IC emission?**

- **How many electron populations responsible for the Sync emission?**

- **What is the dominant particle acceleration mechanisms to simultaneously account for far emitting regions and rapid variability (even minute timescale)?**

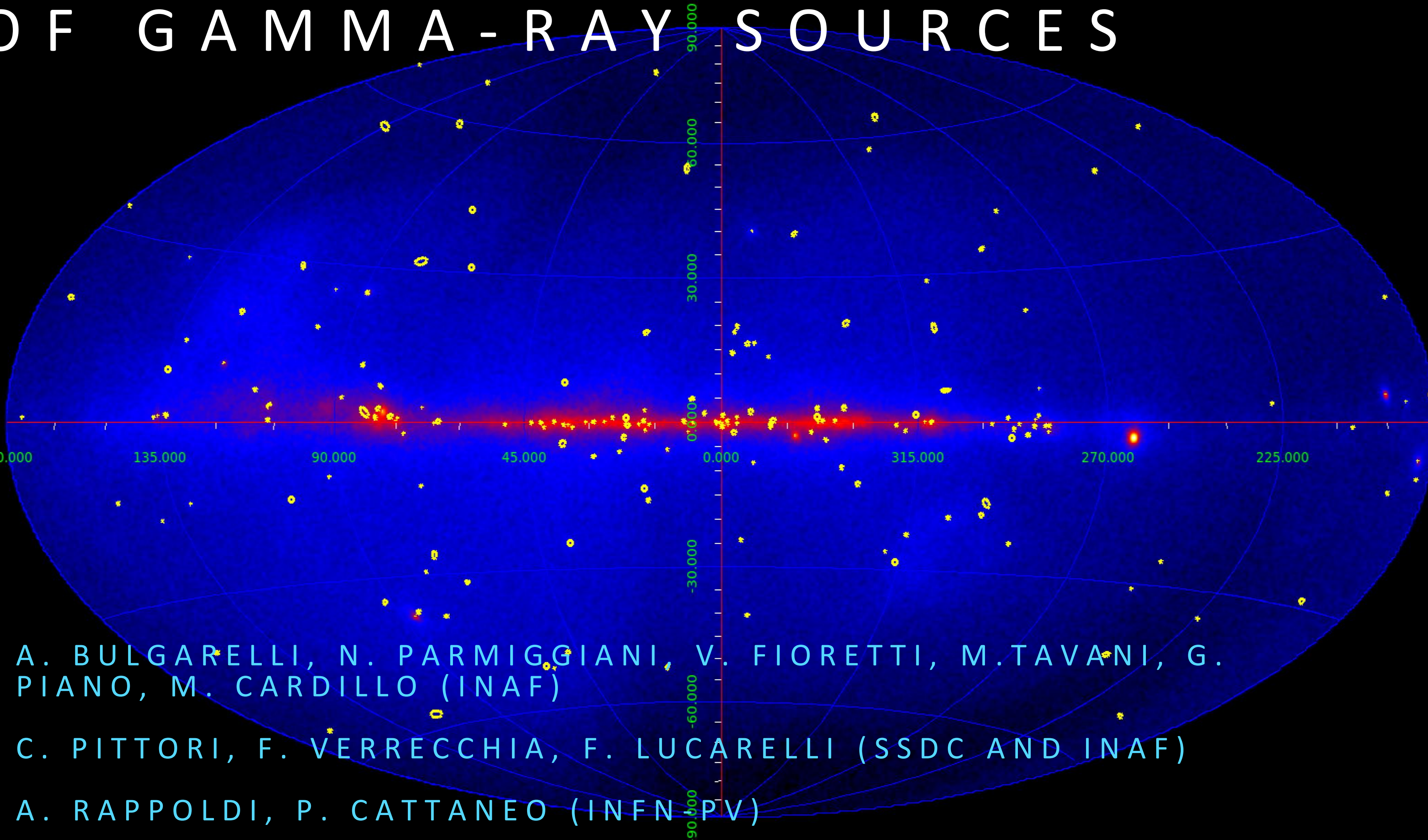
Lessons learned from the CRAB flare discovery

adapted from I. Donnarumma

Many challenges for theory

Variations required in the external photon field seen by the moving blobs:
mirrowing effect between plasmoids?
(See Vittorini et al., ApJL 2017)

THE SECOND AGILE CATALOG OF GAMMA-RAY SOURCES



A. BULGARELLI, N. PARMIGGIANI, V. FIORETTI, M.TAVANI, G. PIANO, M. CARDILLO (INAF)

C. PITTORI, F. VERRECCHIA, F. LUCARELLI (SSDC AND INAF)

A. RAPPOLDI, P. CATTANEO (INFN-PV)

A. ABOUDAN (CISAS)

- The 2th AGILE Catalog of gamma-ray sources: final review
- AGILE/GRID observations covering the time period July 4, 2007, to October 15, 2009 (the AGILE POINTING MODE).
- The analysis is based on data in the
  - 100 MeV to 50 GeV energy range
  - A check in the "*low*" energy range 30 MeV - 100 MeV has been performed for the most significant sources
- Source detection is based on the integrated data set, i.e., sources are detected according to their average fluxes over about 27 months.

UPDATES

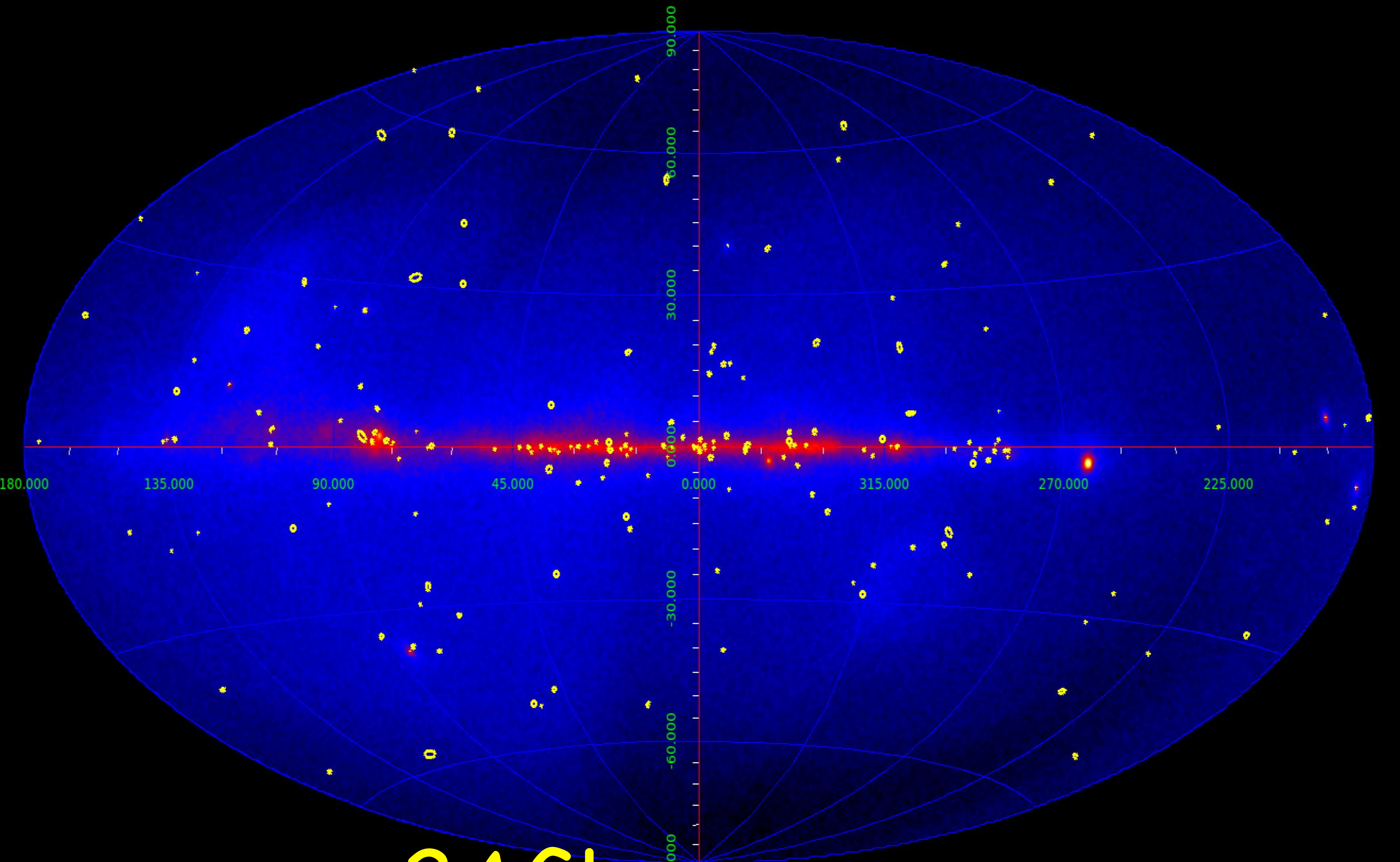
- A long path… Updates from last Workshop:
  - The catalog adopts now different spectral shapes
    - Simple Power Law
    - Power Law with exponential cutoff
    - Power Law with super exponential cutoff
    - Log Parabola
  - The NEW BUILD25 (AGILE/GRID Science Tools) has been used, that ~~include also the~~ energy dispersion correction factor (EDP)
  - New Instrument Response Functions: H0025 -> energy range 100-300, 300-1000, 1000-3000, 3000-10000, 10000-50000 MeV
  - Variability and spectral curvature indices

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{\gamma}$$

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{\gamma_1} \exp\left(-\left(\frac{E}{E_c}\right)\right)$$

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{\gamma_1} \exp\left(-\left(\frac{E}{E_c}\right)^{\gamma_2}\right)$$

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_b}\right)^{-(\alpha+\beta\log(E/E_b))}$$



2AGL sources

PRELIMINARY ASSOCIATIONS

- Positional coincidence only
- These associations are not in general to be taken as firm identifications: a physical relationship is not established between gamma-ray sources and sources in other wavelenghts.
- 29 AGILE-only (no 3FGL) sources

AGN

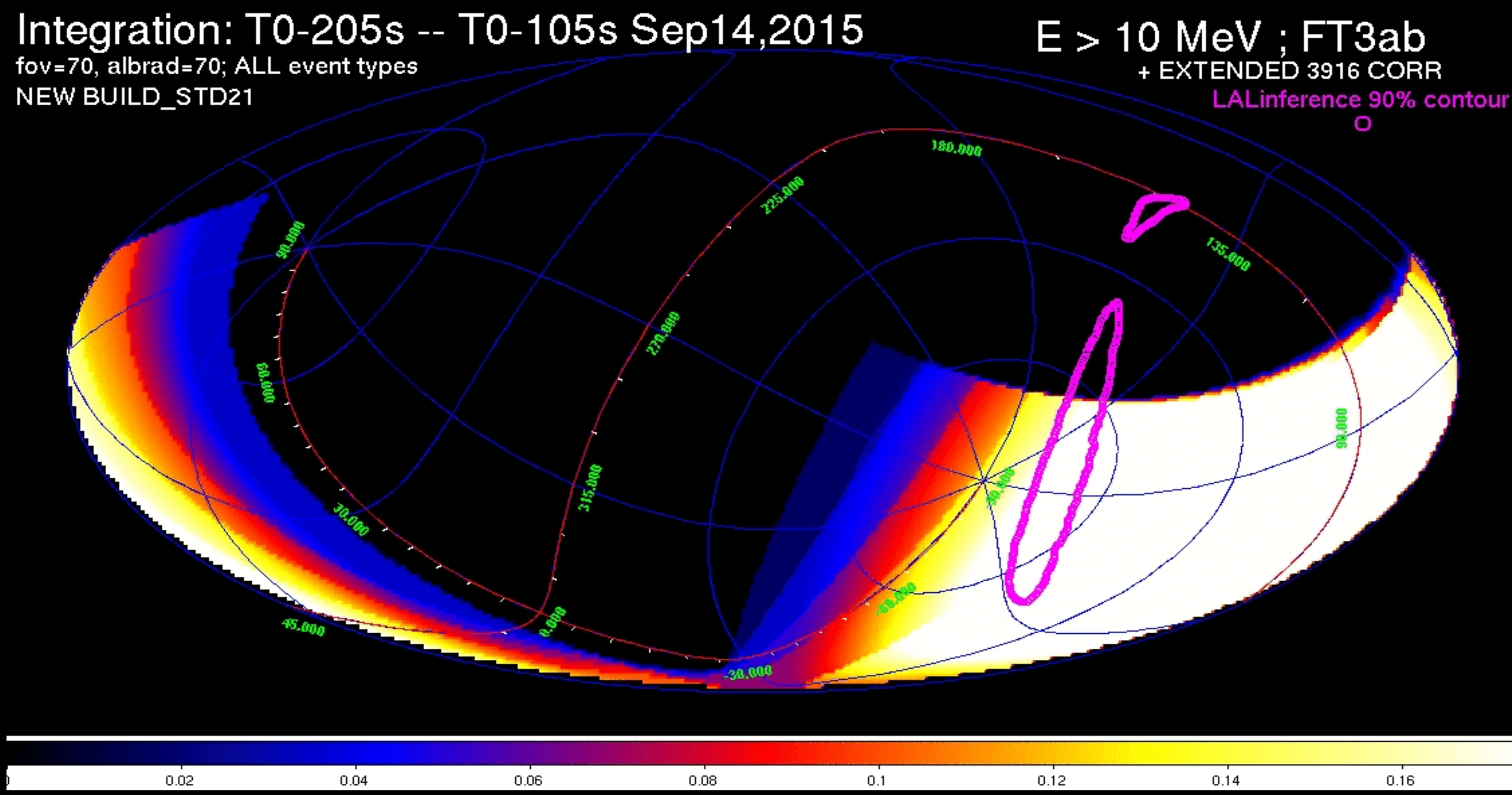
Description	number
BCU (Blazar candidate of uncertain type)	10
BLL (BL Lac type of blazar)	17
FSRQ (FSRQ type of blazar)	31
RDG (Radio galaxy)	2 (CenA, NGC1275)
BIN (Binary)	1 (Eta Carinae)
GLC (Globular cluster)	1 (Terzan 5)
HMB (High-mass binary)	3
PSR (positional only)	50
PWN	3
SNR	9
SPP	7
	134

HMB (High-mass binary)	LSI+61 303, 1FGLJ1018.6-5856, Cygnus X-3
SNR	IC443, CTB37A, W28, W30, W44, W49B, W51, GammaCygni, HB21
PWN	Crab Nebula, HESSJ1632-478, PWNG0.13-0.11)

AGILE and GW astrophysics

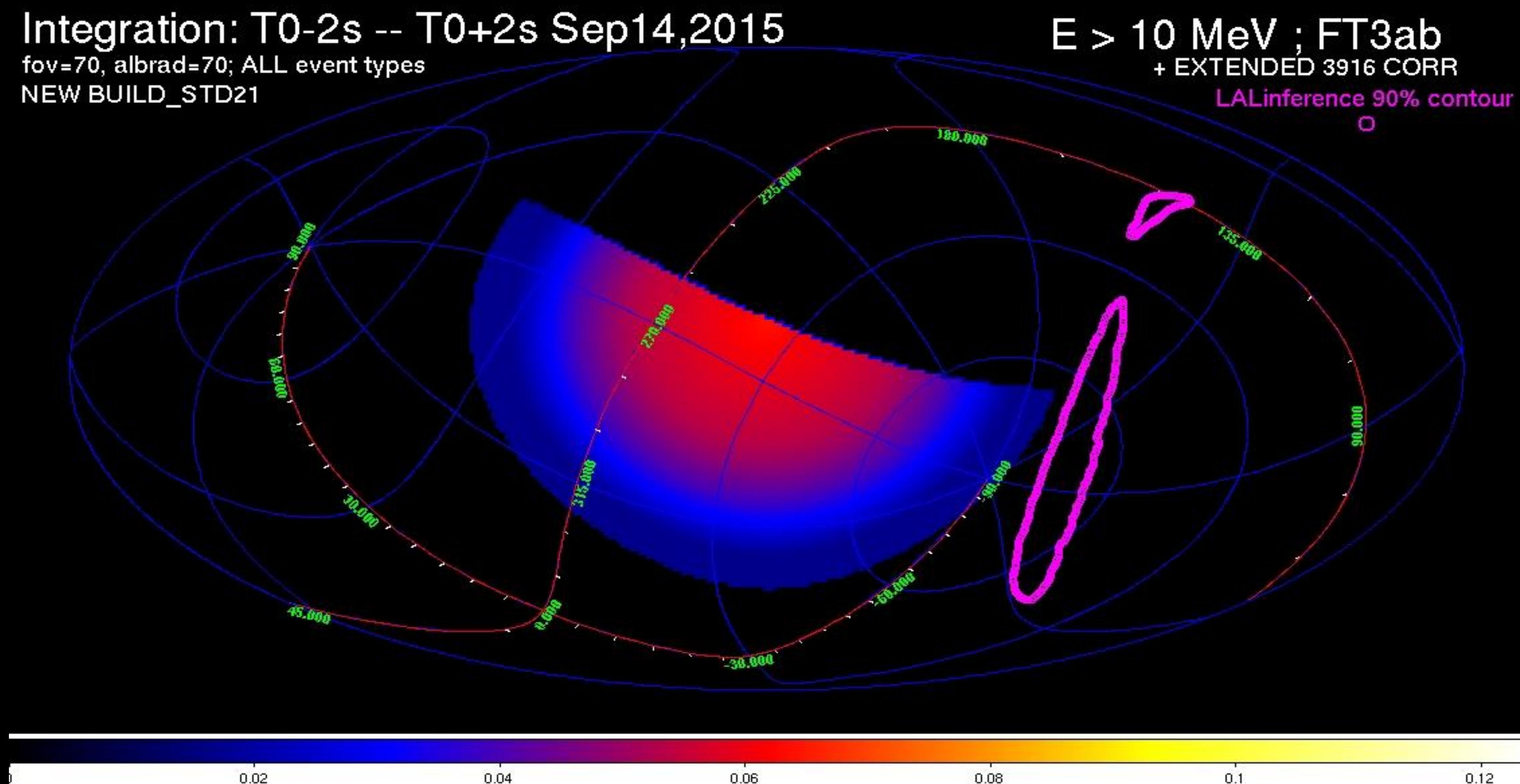
- very fast reaction to external GW trigger: AGILE real-time analysis pipeline @OAS Bologna and SSDC
- new processing pipelines for “sub-threshold events”
- great potential for fast discovery of gamma-ray transients associated with NS-NS, NS-BH and BH-BH (if any) coalescences
- AGILE GW-Team monitoring shifts (24/7) during the O2 GW LIGO-Virgo observing run.

AGILE-GRID in spinning: revolution including T_0 of GW150914



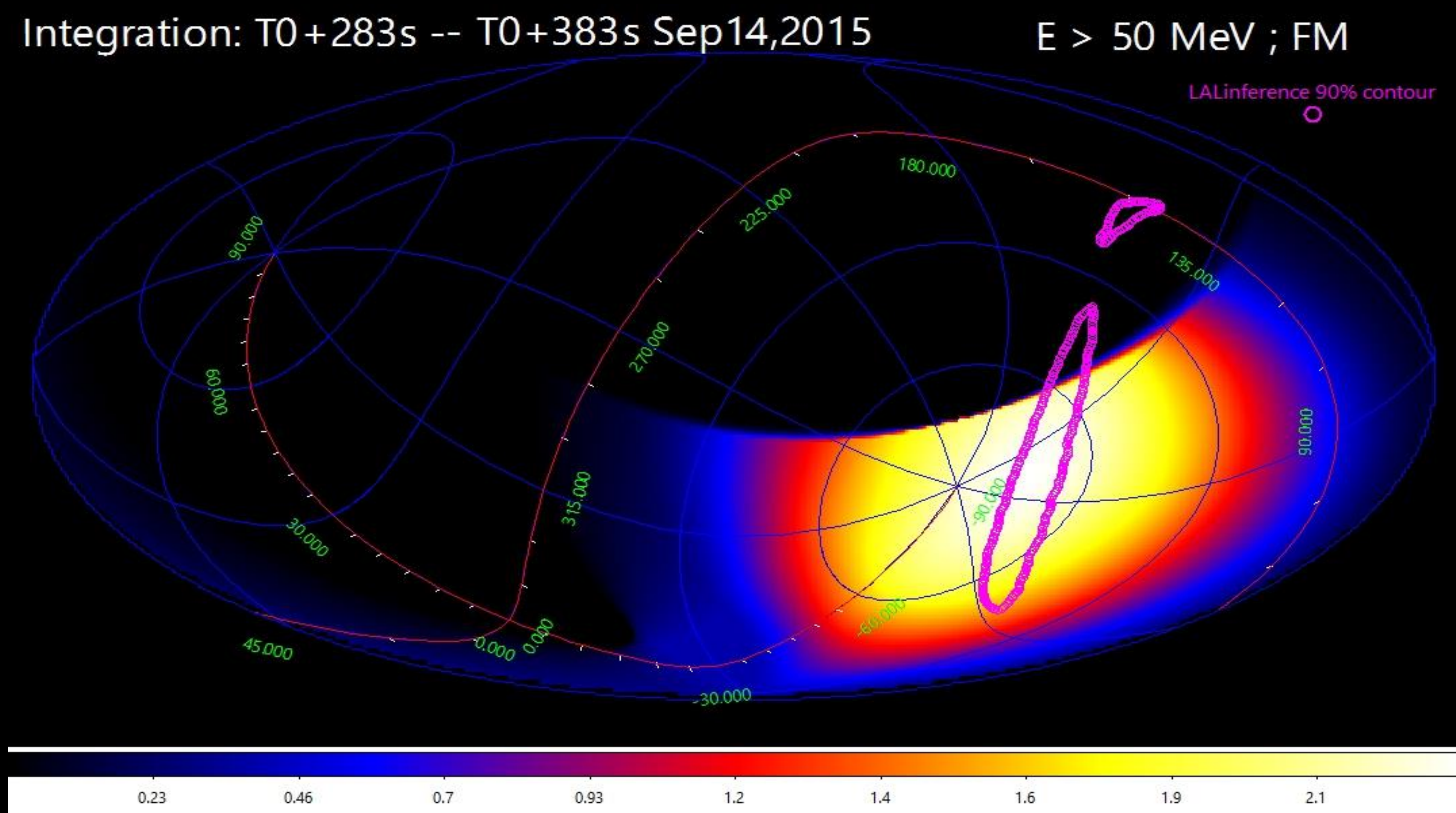
Adapted from F. Verrecchia

AGILE just missed the T0 !

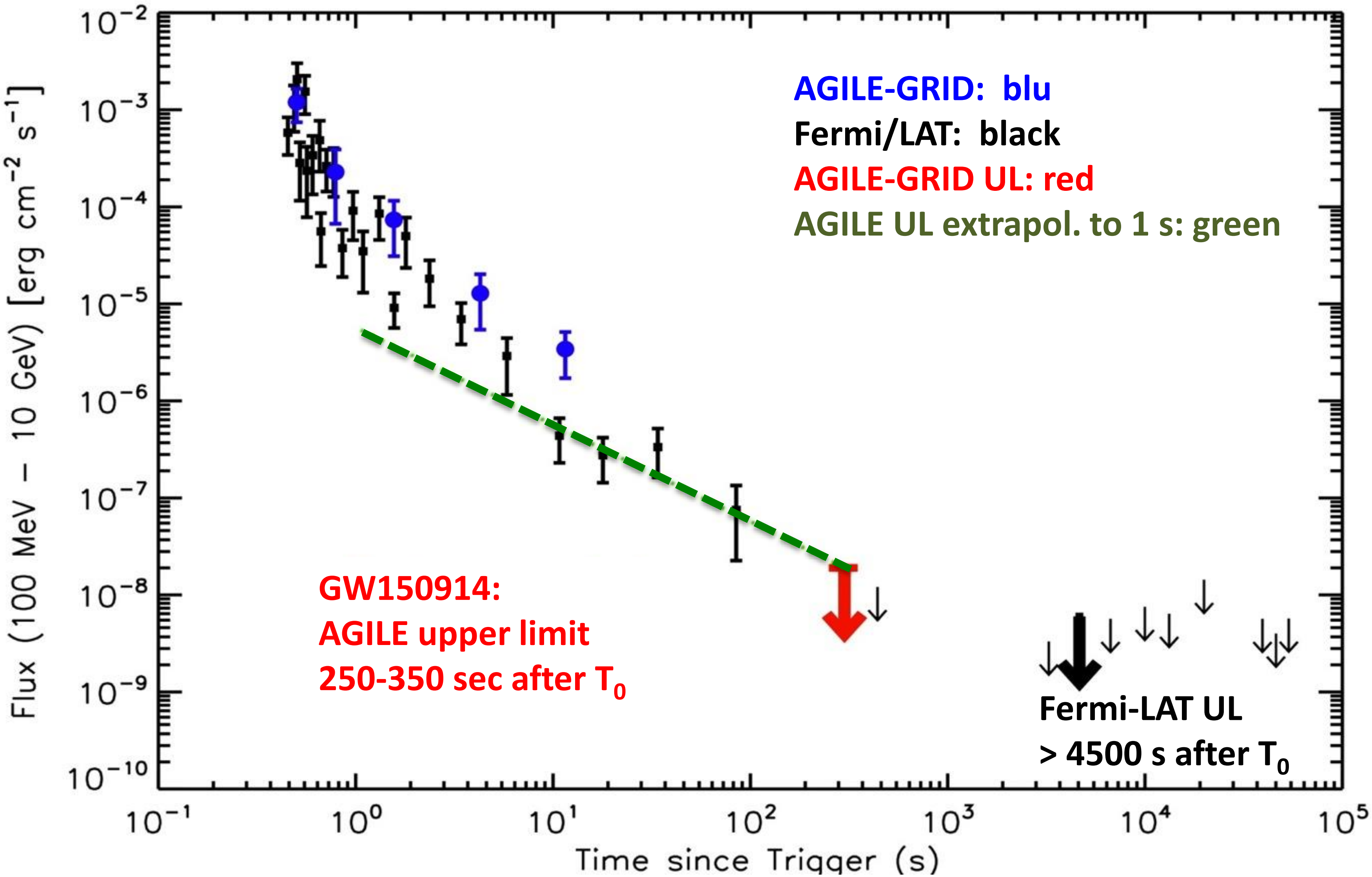


but only ~300 sec later…

AGILE exposure 330 sec (+/- 50 sec)



AGILE and Fermi-LAT upper limits in the GRB 090510 light curve used as a template for GW events (scaled at z = 0.1)



Summary 2016-2017:

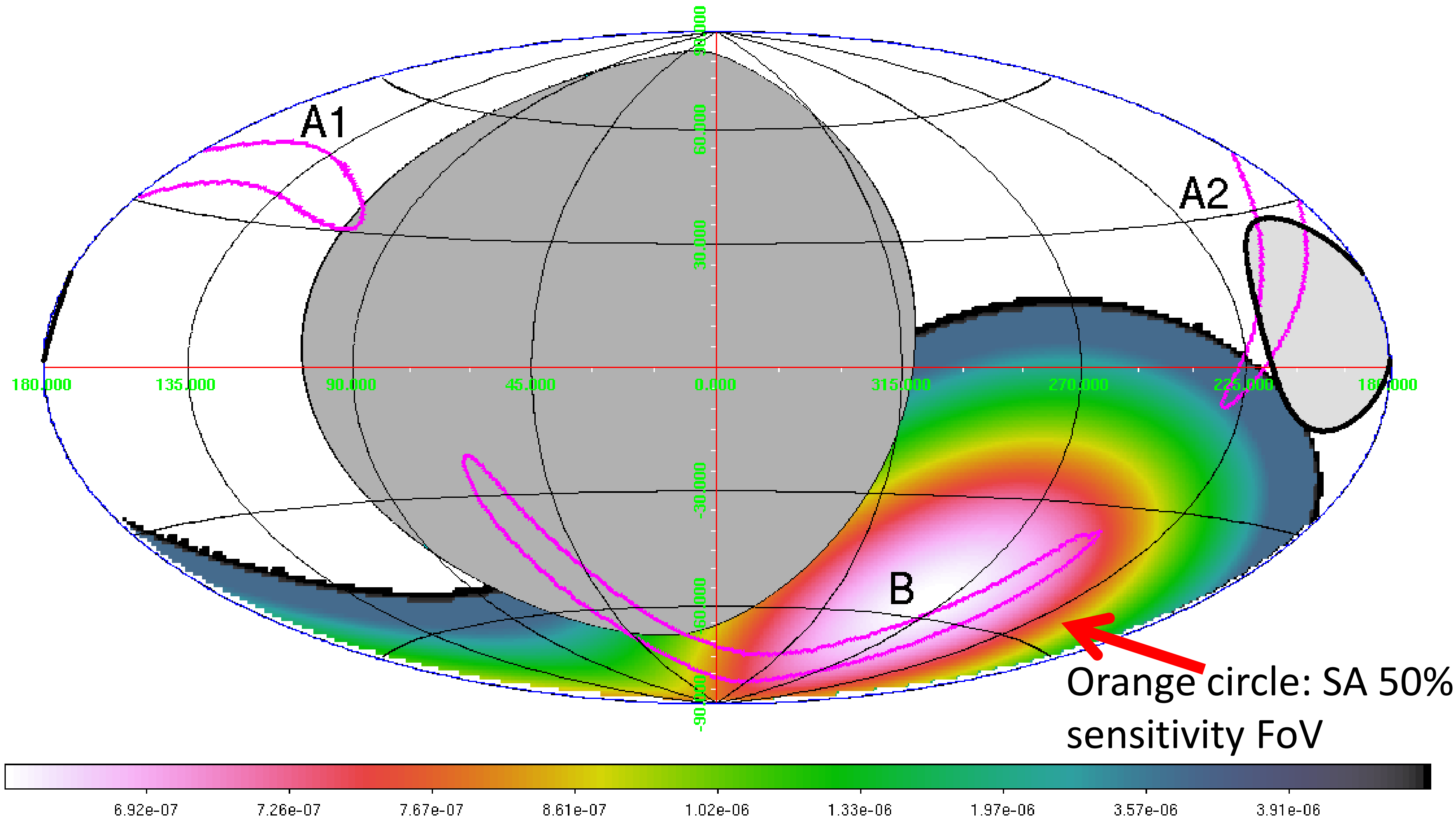
- AGILE in the MoU since Nov 2016 promptly reacted to all GW candidate events communicated by LIGO-Virgo in O2 with reaction time of 2-3 hrs (including manual refined validation)

- 1 possible AGILE-MCAL gamma-ray transient candidate found as counterpart of GW170104 (Verrecchia et al., ApJL 847, 2017)

- AGILE and GW170817: first γ-ray instrument with exposure on the localization region starting at ~ T_0 + 930s (Verrecchia et al., ApJL 850,2017)

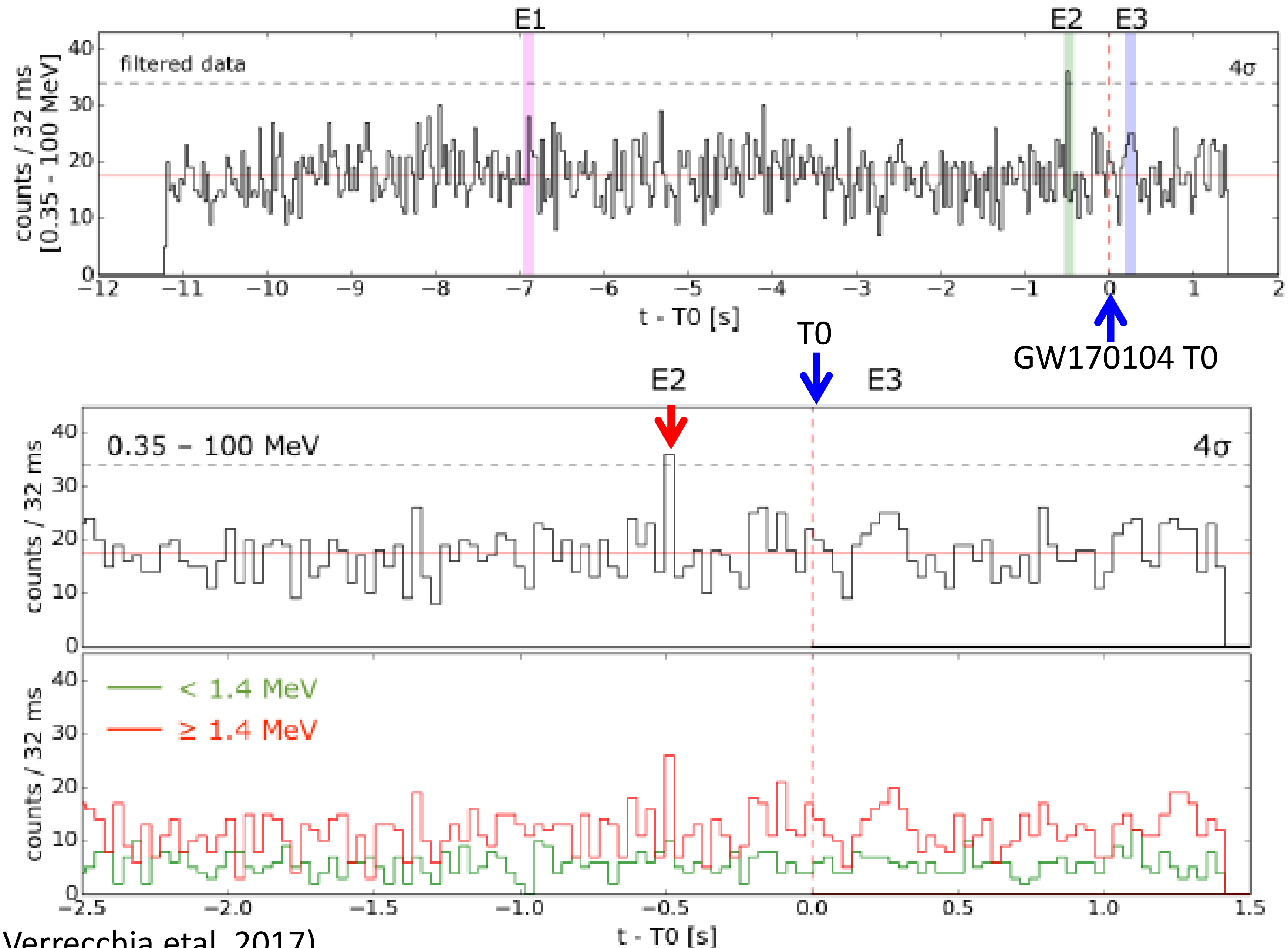
- AGILE observations provided the fastest response and the most significant upper limits above 100 MeV to all GW events detected up to now!!

AGILE gamma-ray exposure at trigger time (-2 / +2 sec)



3-sigma upper limit (E > 50 MeV) = 2.9 x 10^{-8} erg cm^{-2} s^{-1}

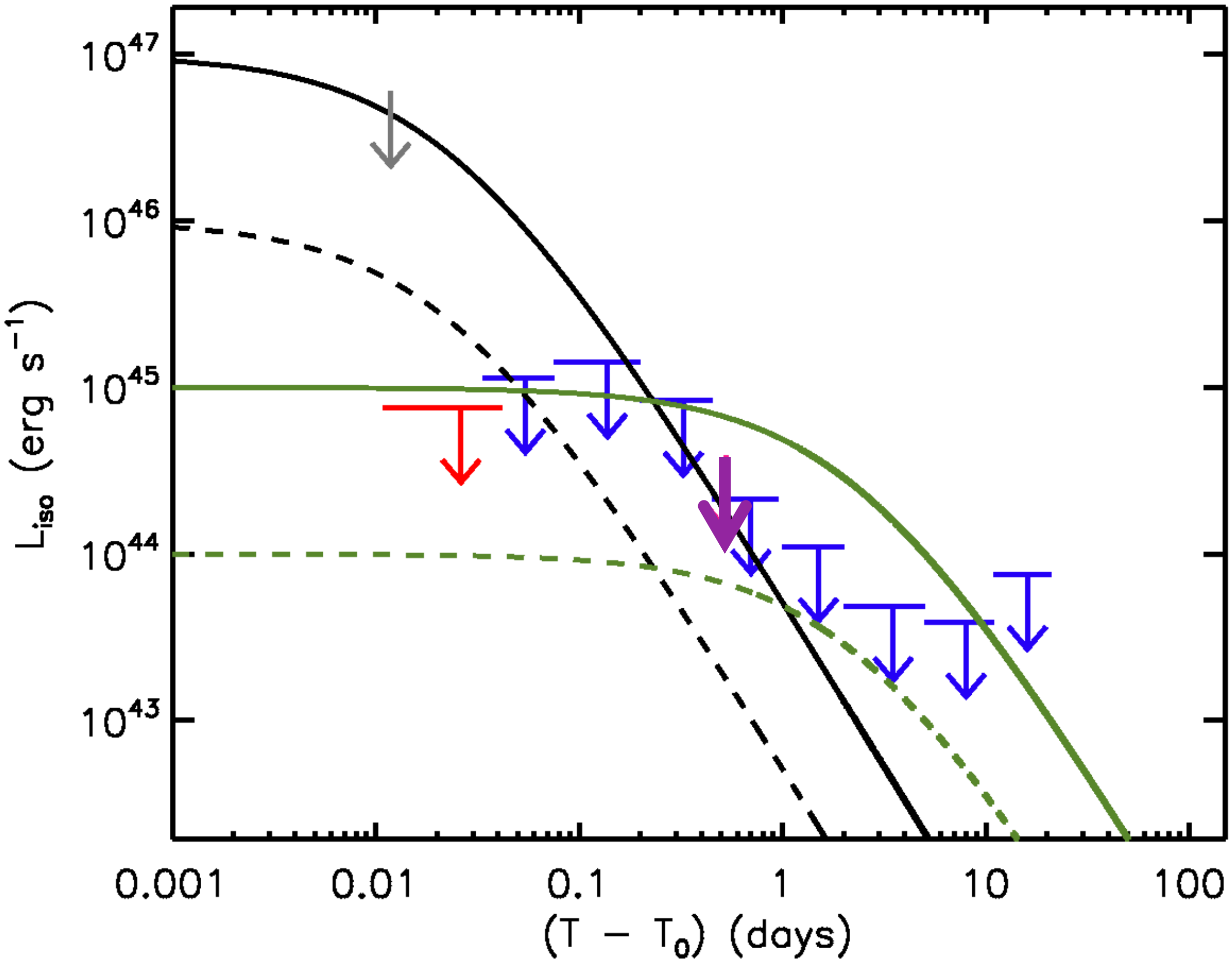
GW170104: an MCAL candidate event



(Verrecchia etal. 2017)

GW170817: AGILE crucial limits on magnetar emission:

HE emission from a magnetar remnant left by NS-NS coalescence model:



Radiation efficiency
ξ = 0.01 -> solid
ξ = 0.001 -> dashed

B = 10^{14} G (green)
B = 10^{15} G (black)

Magenta: SA U.L.

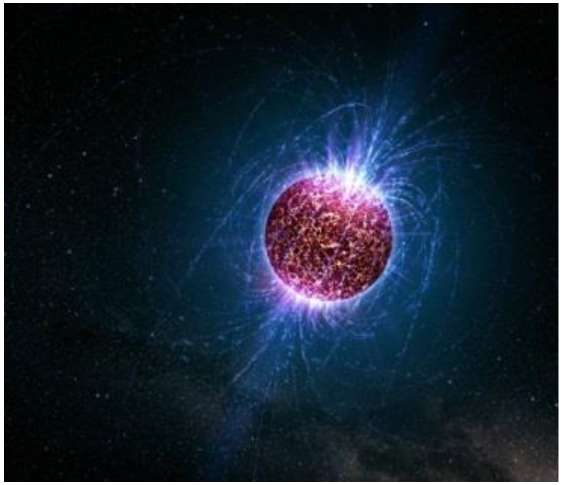
Gray: MCAL U.L

(Verrecchia et al. 2017)

(GBM GRB170817A spectrum cutoff out of MCAL band)

Space Science Data Center

AGILE limits on magnetar emission:



AGILE UL set important constraints in the early phases to exclude a highly magnetized magnetar for the remnant of GW170817- GRB170817A

Future GW hunt:

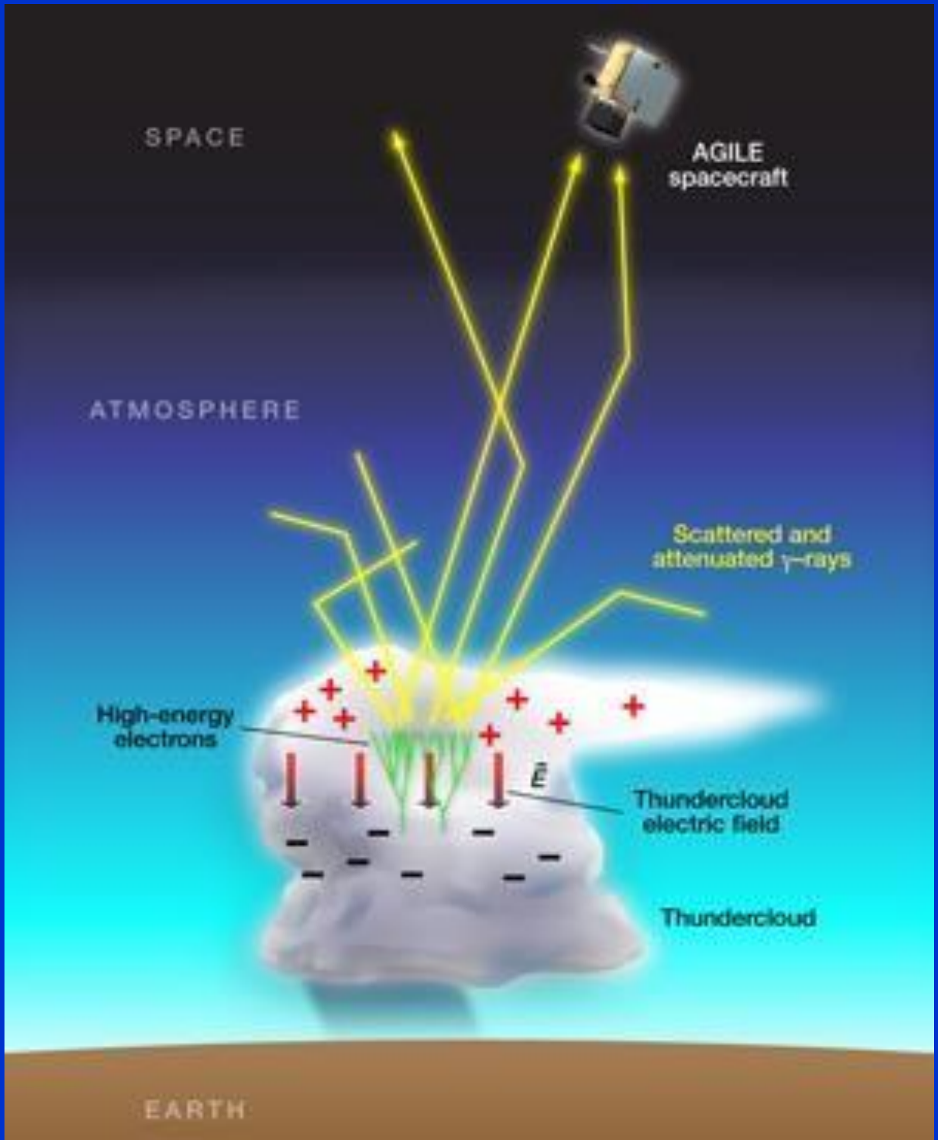
- **AGILE fast and unique hard X/γ-ray coverage**
- **Improved performance with NEW MCAL pipeline developed for "sub-threshold events" btw 4 ÷ 5 sigma pre-trial significance**
- **Alerts will be issued to LVC for AGILE-detected events (new channel)**
- **Can play an important role in the new astronomy of gravitational waves. Waiting for Ligo-Virgo O3 run!**

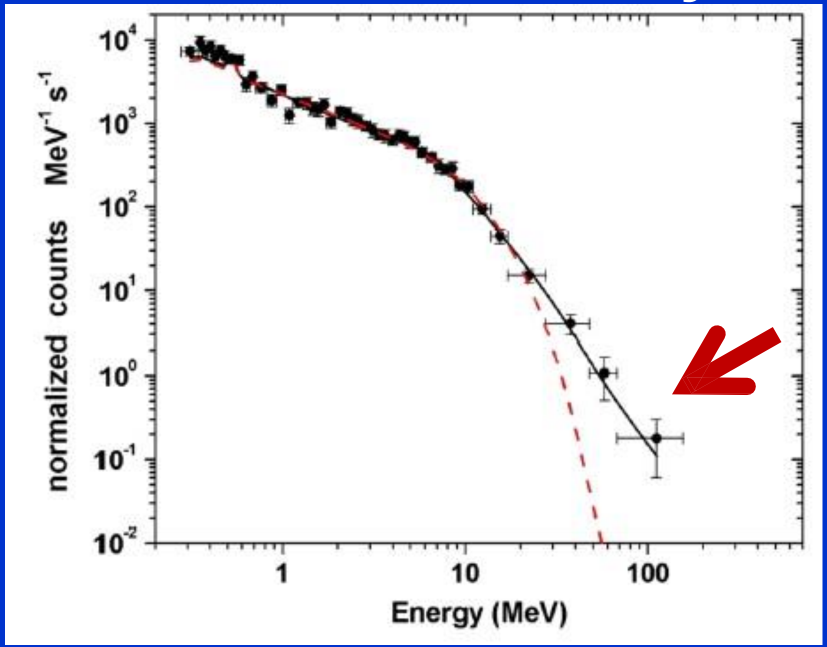

AGILE and
Terrestrial Gamma-Ray Flashes

Tavani et al., Phys. Rev. Letters 106, 018501 (2011).
Marisaldi et al. (2010), Fuschino et al. (2012), Ursi et al. (2016).

AGILE detection of Terrestrial Gamma-Ray Flashes (TGFs)

- surprising detections up to > 30 MeV;
- hundreds of events/year localized by AGILE in the equatorial region;
- TGF impacts for environment and aircraft under study.



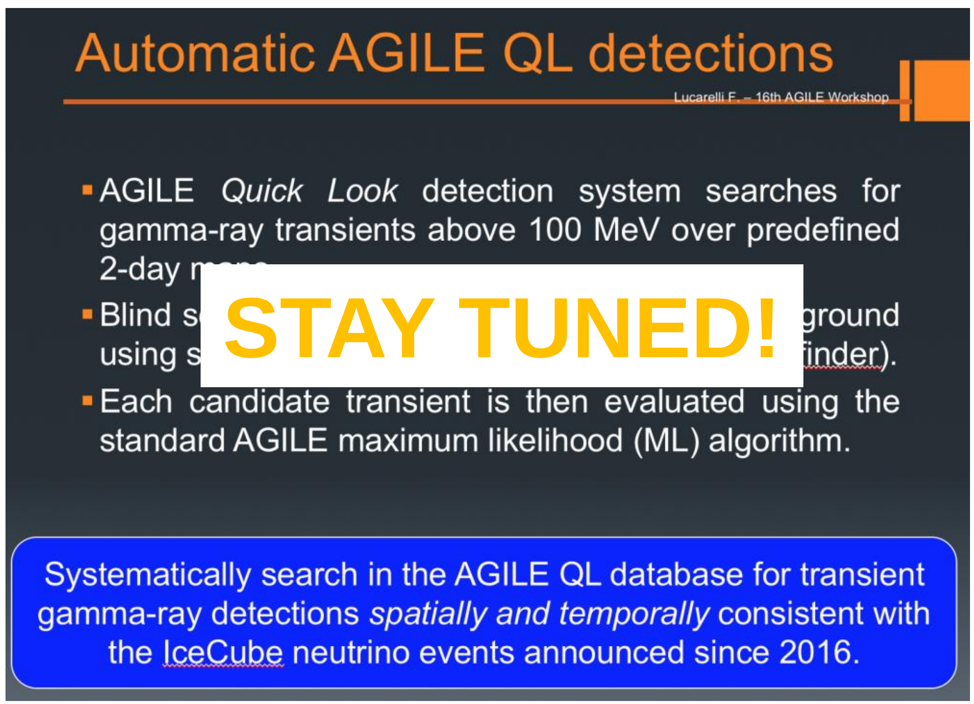


Last (but not least): AGILE and neutrinos

- **AGILE and IC-160731**: Gamma-ray emission announced by AGILE in ATel #9265 and further investigated in **ApJ 846 (Lucarelli et al. 2017)**

- **AGILE and IC-170922**: Gamma-ray emission **observed by both Fermi-LAT and AGILE** (ATel #10791 and **ATel #10801**) from the direction of the BL Lac blazar TXS 0506+056

- In progress:



F. Lucarelli talk at the 16th AGILE Workshop

AGILE keeps going…

- AGILE continues its journey…
- fully integrated in a network of multi-frequency observers from ground and space.
- enhanced detection capabilities of short (and long) transients, especially for GW events (and neutrinos).
- check also the AGILE APP ("AGILEScience")!