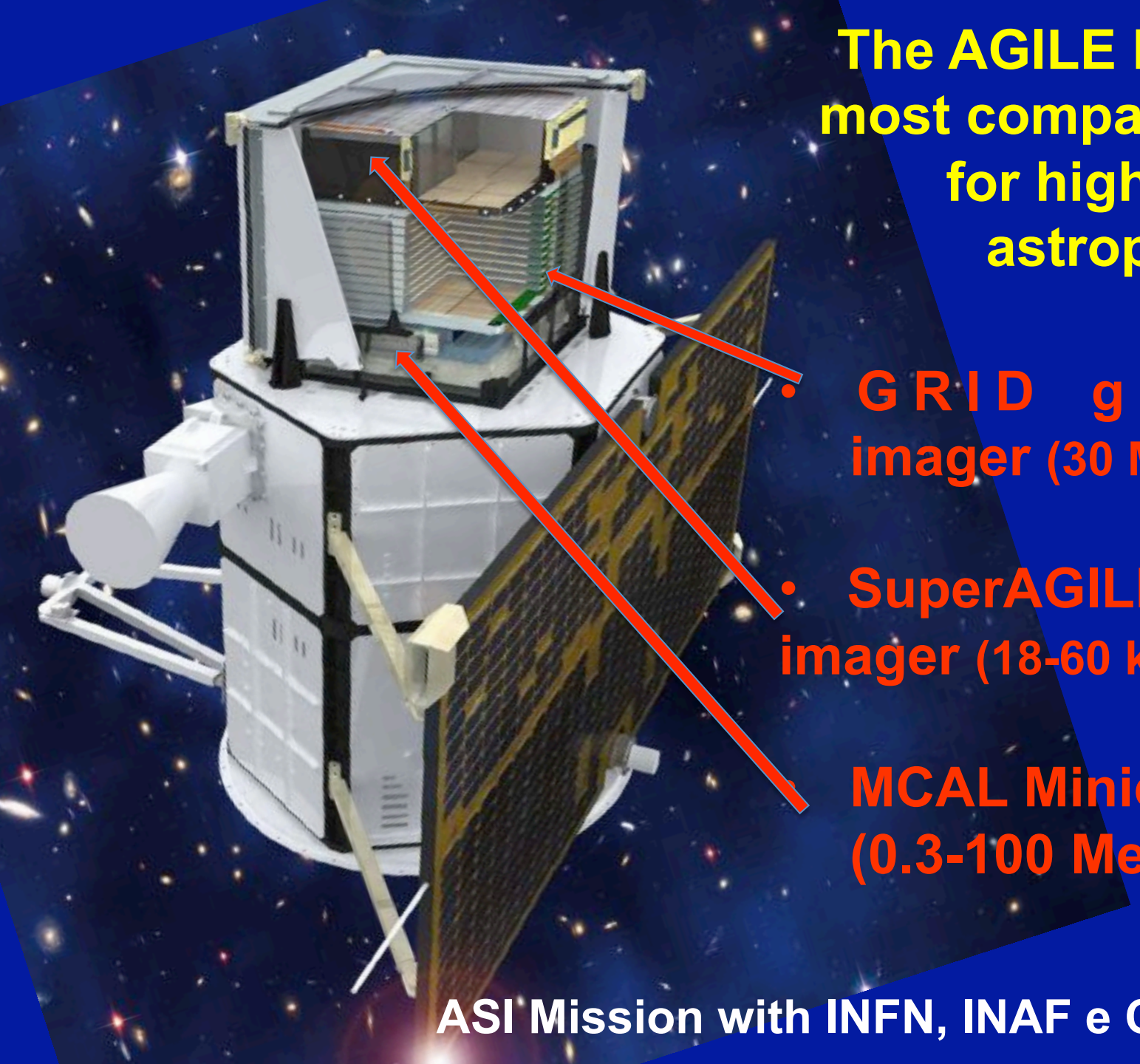
γ-ray emission and variability of the Crab Nebula above 100 MeV: theoretically challenging AGILE observations

Carlotta Pittori
AGILE Data Center at ASDC,
on behalf of the AGILE *Collaboration*
Vulcano, 18-24 May 2014



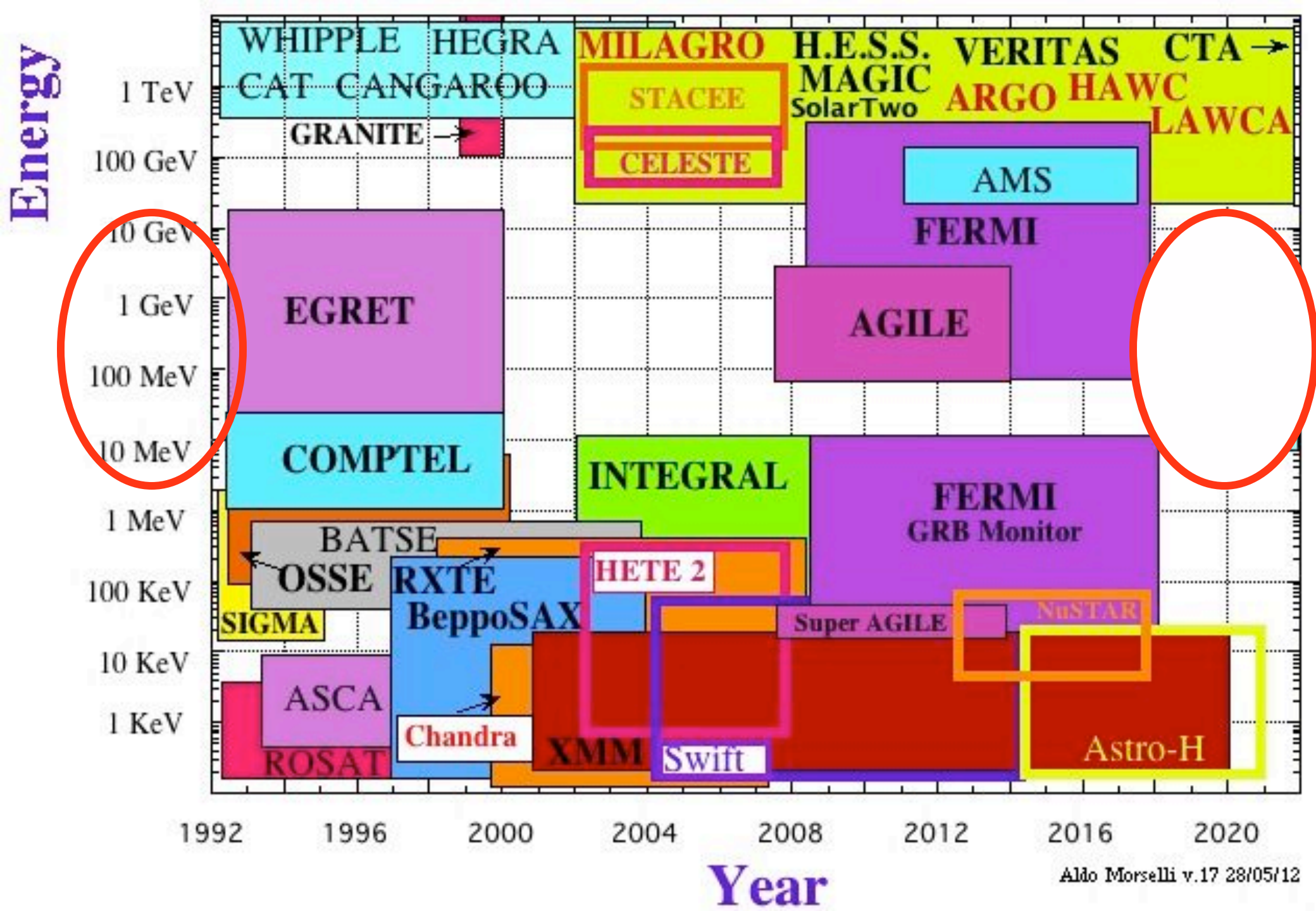
The AGILE Payload: the most compact instrument for high-energy astrophysics

- **GRID gamma-ray imager (30 MeV- 30 GeV)**
- **SuperAGILE hard X-ray imager (18-60 keV)**
- **MCAL Minicalorimeter (0.3-100 MeV)**

ASI Mission with INFN, INAF e CIFS participation

April 23, 2007: Launch!

Equatorial orbit: 550 Km, < 3º inclination angle


Energy
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
100 KeV
10 KeV
1 KeV
WHIPPLE
HEGRA
CAT
CANGAROO
GRANITE
MILAGRO
STACEE
CELESTE
H.E.S.S.
MAGIC
SolarTwo
VERITAS
CTA
ARGO
HAWC
LAWCA
AMS
FERMI
EGRET
AGILE
COMPTEL
INTEGRAL
FERMI
GRB Monitor
BATSE
OSSE
RXTE
BeppoSAX
HETE 2
SIGMA
Super AGILE
NuSTAR
ASCA
Chandra
XMM
Swift
Astro-H
ROSAT
1992
1996
2000
2004
2008
2012
2016
2020
Year
Aldo Morselli v.17 28/05/12


TZP
FUCINO
Malindi
(Kenya)
ASI Science Data
Center

- The ADC, based at ASDC (ASI HQ), is in charge of all the scientific o… …rchiving of AGILE dat…

From scientifi…

- ✓ Preproce…
- ✓ Quick-Lo…
- ✓ Standard … (photon li…)
- ✓ Scientific analysis (source detection, diffuse gamma-ray background)
- ✓ Archiving and distributing all scientific AGILE data

Different kinds of users:

- **Internal ADC operators**
- **AGILE Team scientists**
- **AGILE Guest Observers**
- **Scientific Community**

…ta

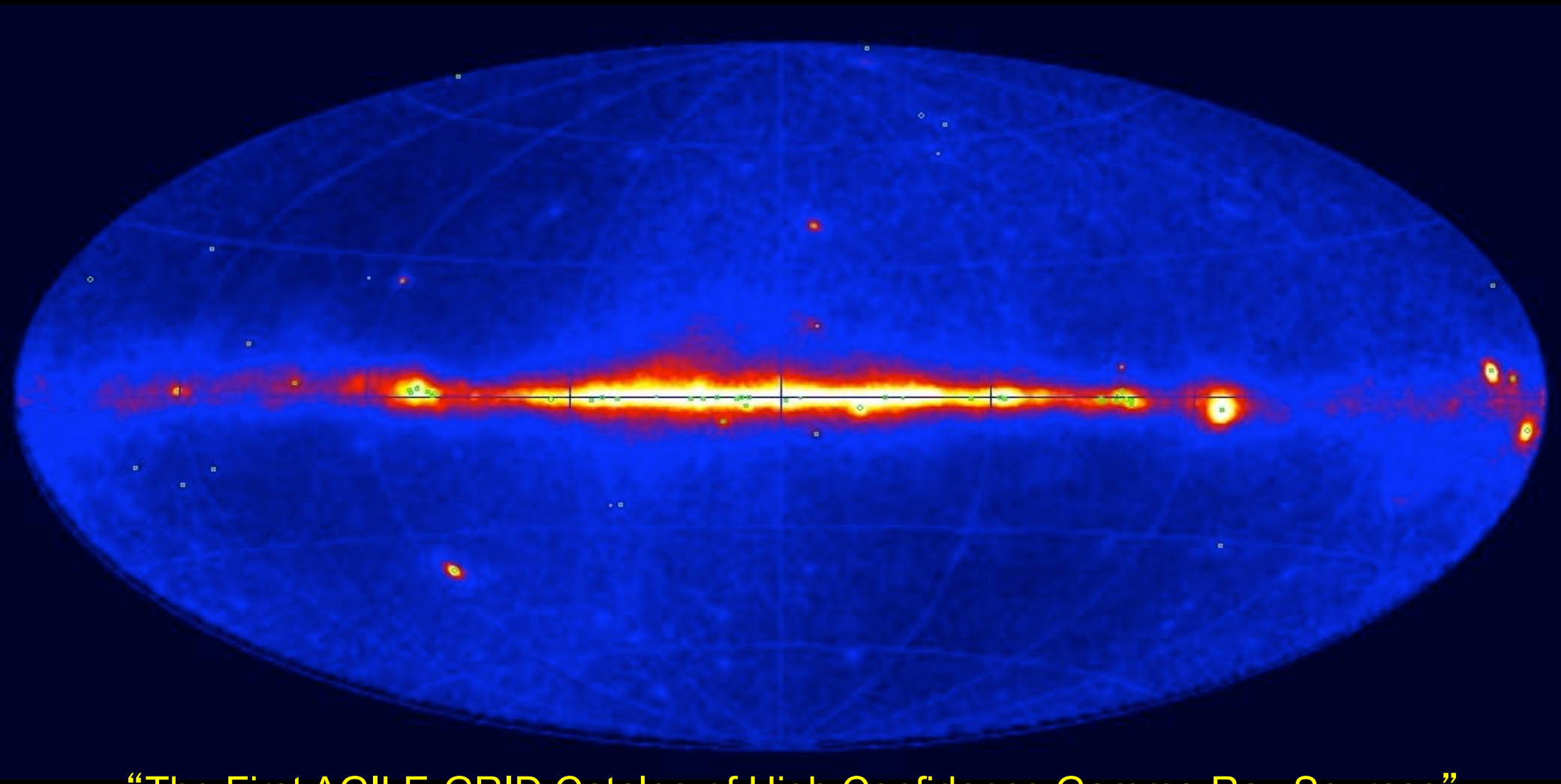
…:

…Quicklook &
…Level-2 data
(photon list and logfile)

Scientific analysis:
Level-3 data
OUTPUT: High level data products
(count maps, spectra, light curves…)

AGILE Total Intensity Map (E > 100 MeV)

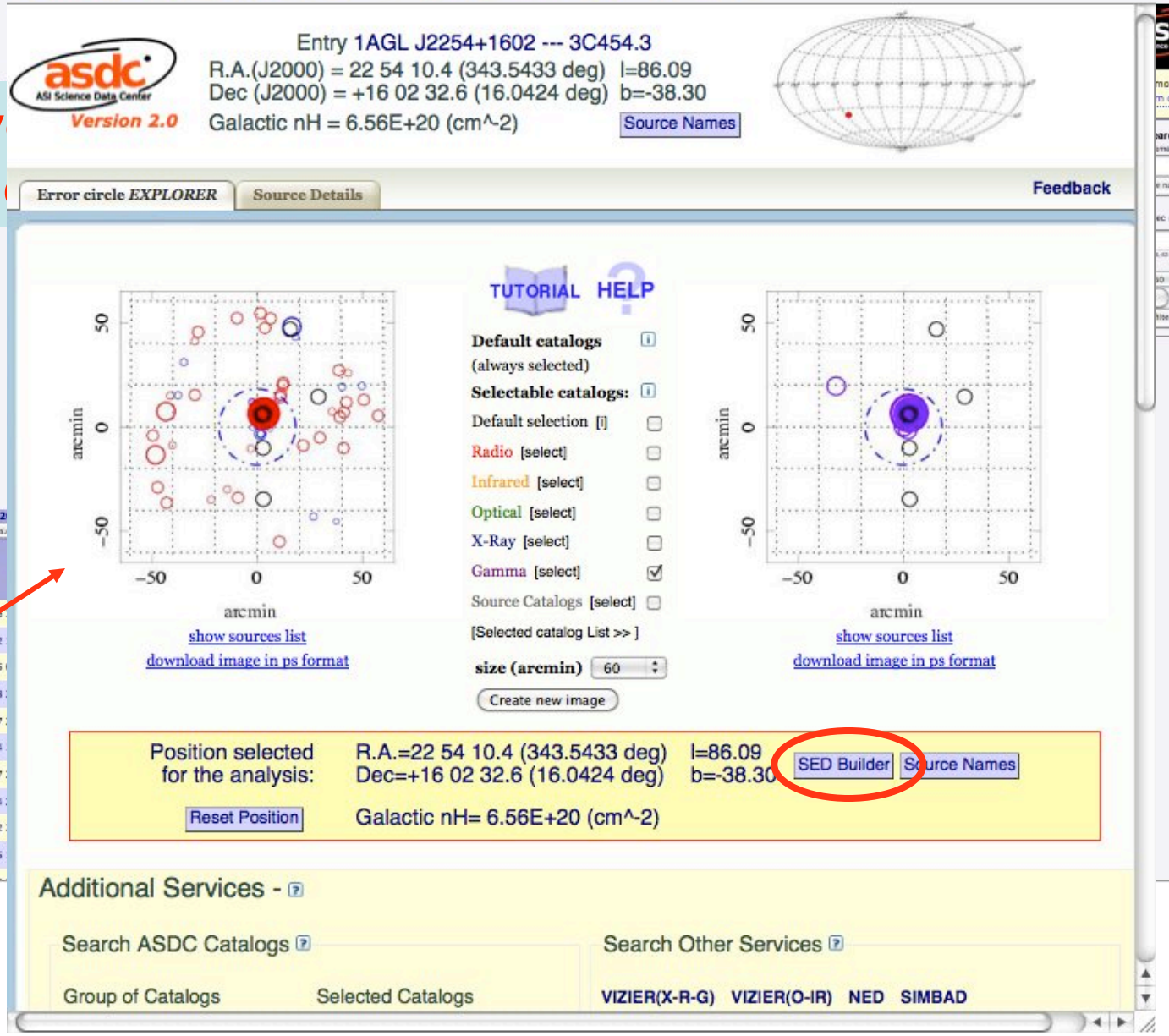
Pointing + Spinning (up to Dec 25, 2012)



"The First AGILE-GRID Catalog of High Confidence Gamma-Ray Sources"
C. Pittori et al., A&A 506, 2009 (green circles, first year of operations)

The First AGILE-GRID Catalog of High Confidence Gamma-Ray Sources

ASDC interactiv
catalogs webpag



ASDC Data Explorer Tool

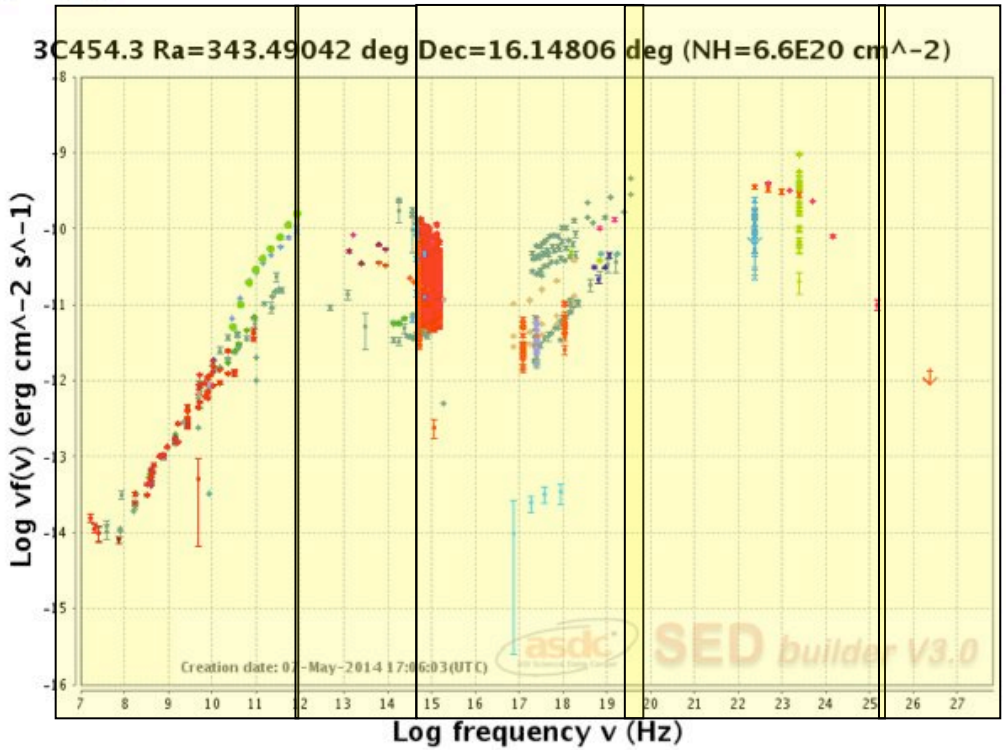
The new ASDC SED Builder

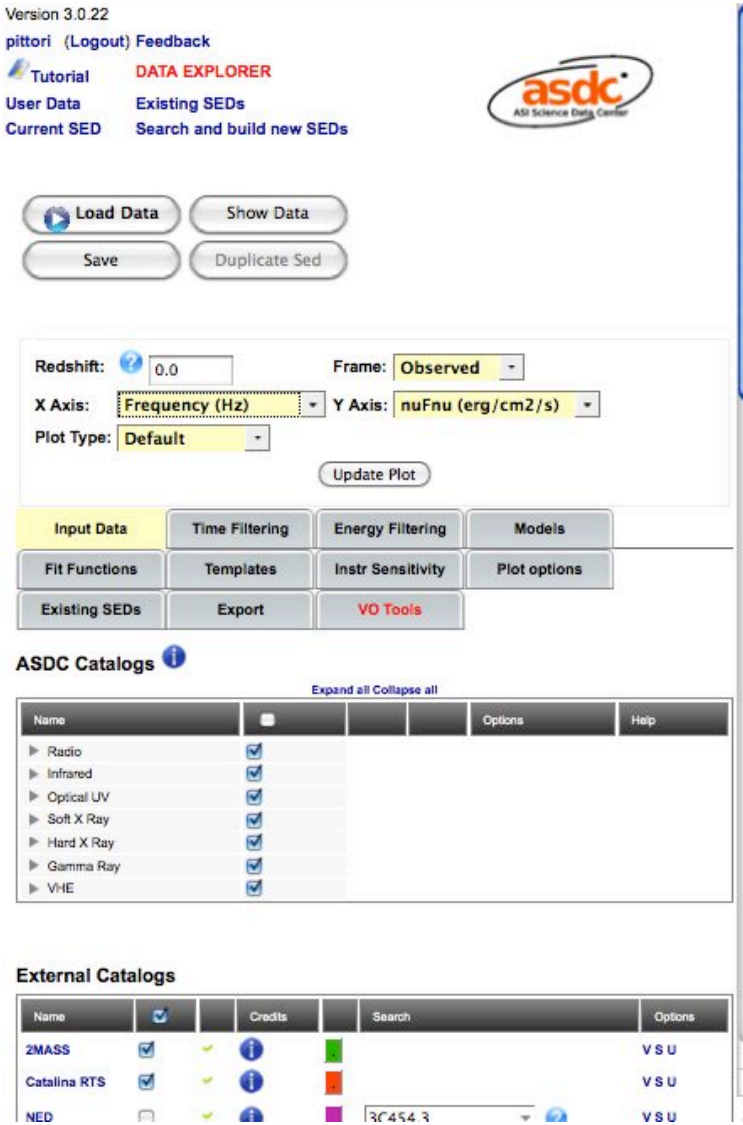
VO tools and TIME domain

SED(t) builder V3.0

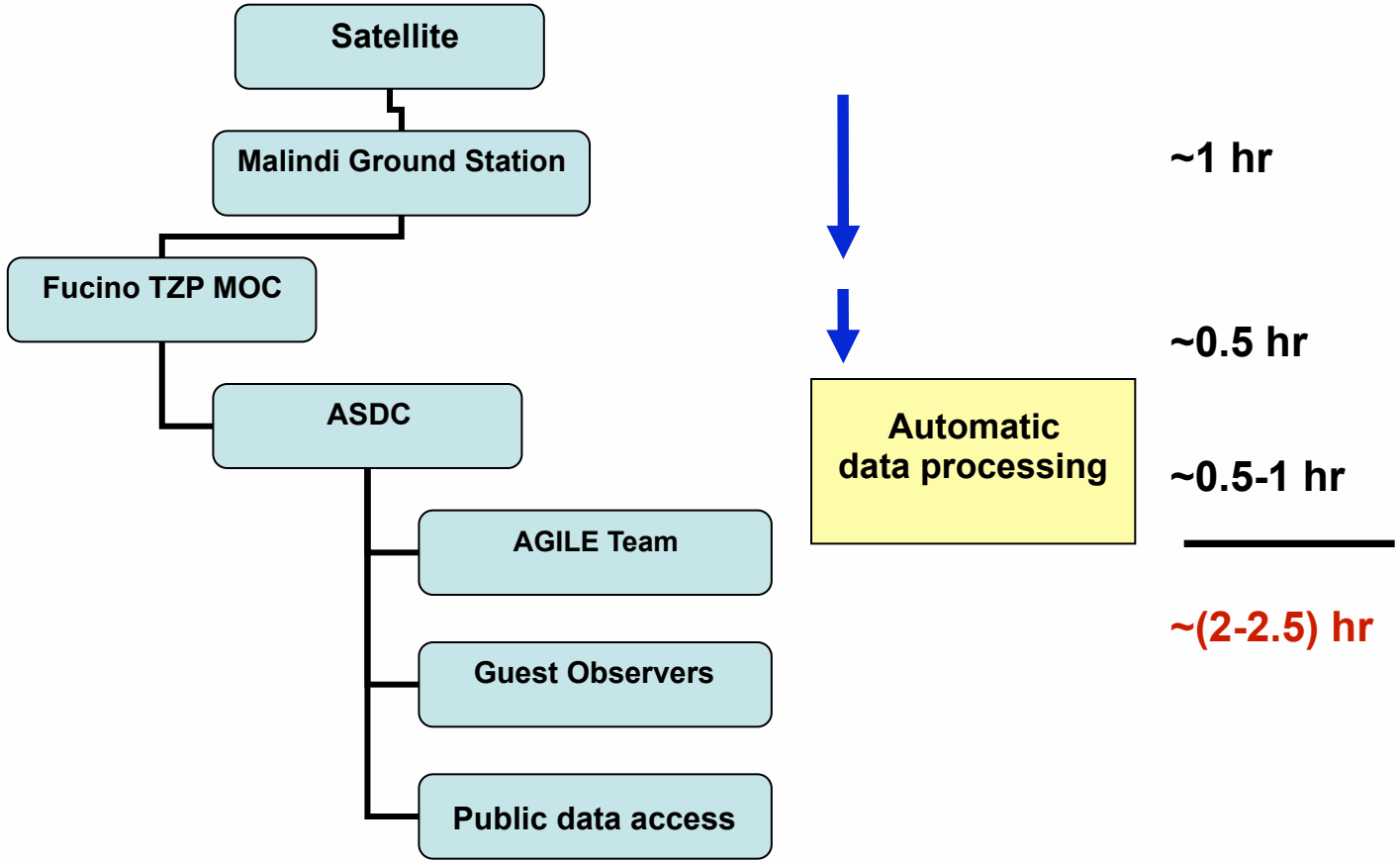
Radiotelescopes and Planck AGILE and TeV/CTA

A tool to build and handle Spectral Energy Distributions, time-resolved SEDs and multi-frequency light-curves



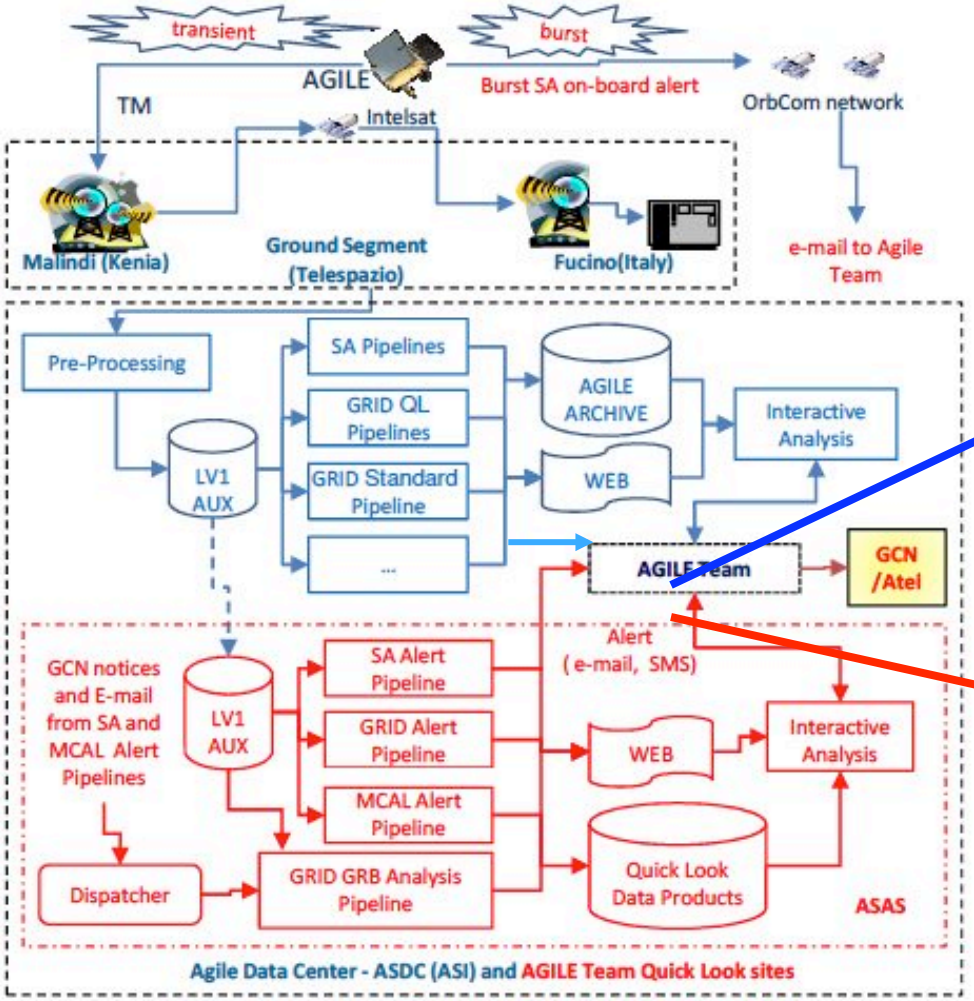


AGILE: “very fast” Ground Segment (with contained costs)

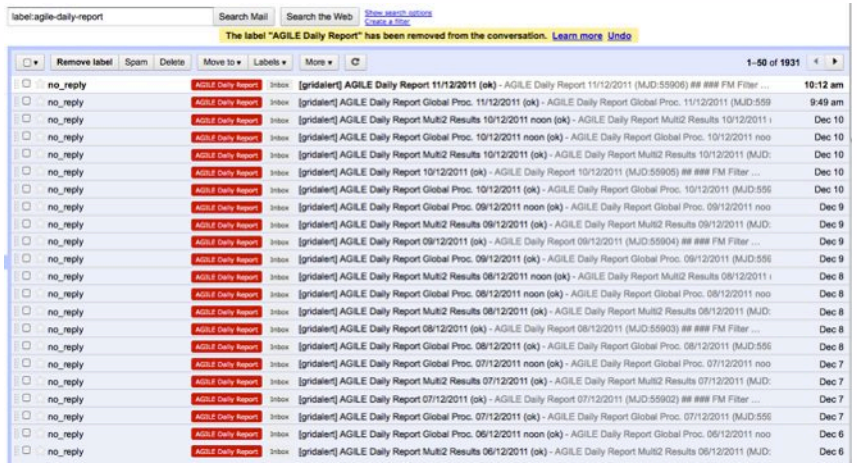


Record for a gamma-ray mission!

Selected **alerts** sent via email, sms

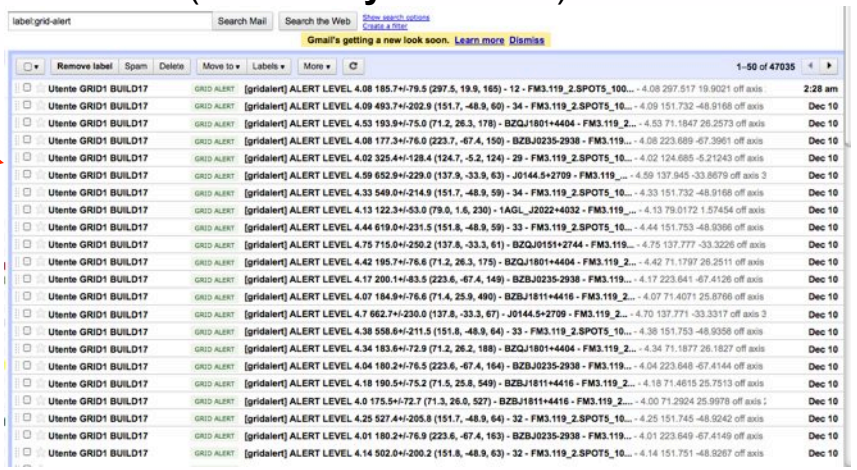


(Figure adapted from M. Trifoglio et al.)



Daily reports on a 48h time scale (**sent twice a day**) FAST

Contact-by-contact alerts on a 48h time scale (**sent every ~100 min**) VERY FAST



New: App for mobile devices!

The variable Crab Nebula!

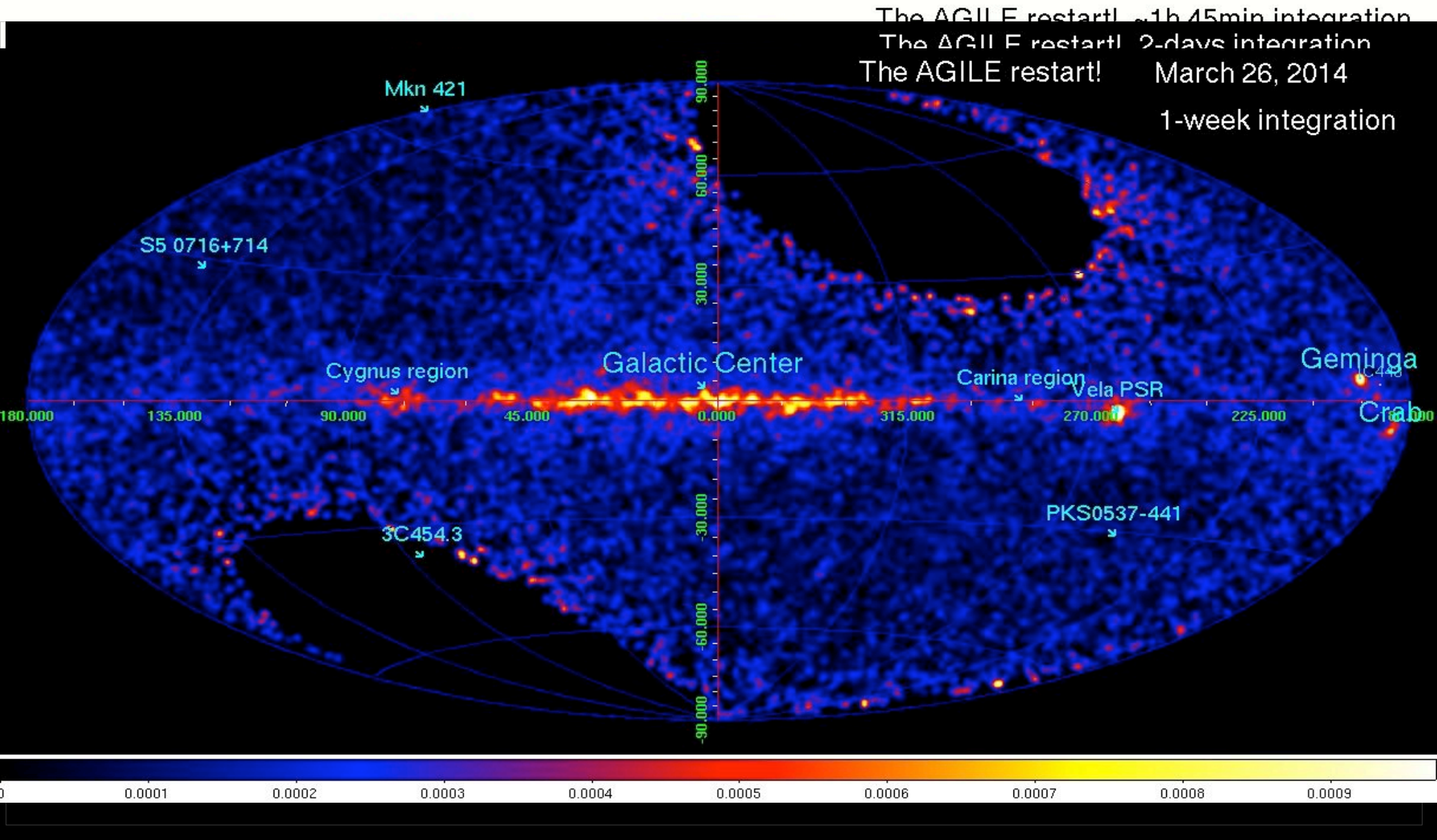
Tavani et al., *Science 331* (2011)

AGILE: 7th year in orbit

- AGIL… of the entire …ngular resoluti…
- AGIL… of its gamma…
- **> 356…**
- **Poi…** and **spinni…**
- **Very …V**
- **Gues…ty:**
  - **4 AS…**
  - **Cycl…**
  - **Cycl…**

The AGILE restart: data acquisition animation

(1 day final integration, the 2d and 1week)



UNEXPECTED DISCOVERY FROM THE γ-RAY SKY:

AGILE DISCOVERY OF THE CRAB NEBULA VARIABILITY IN γ-RAYS

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

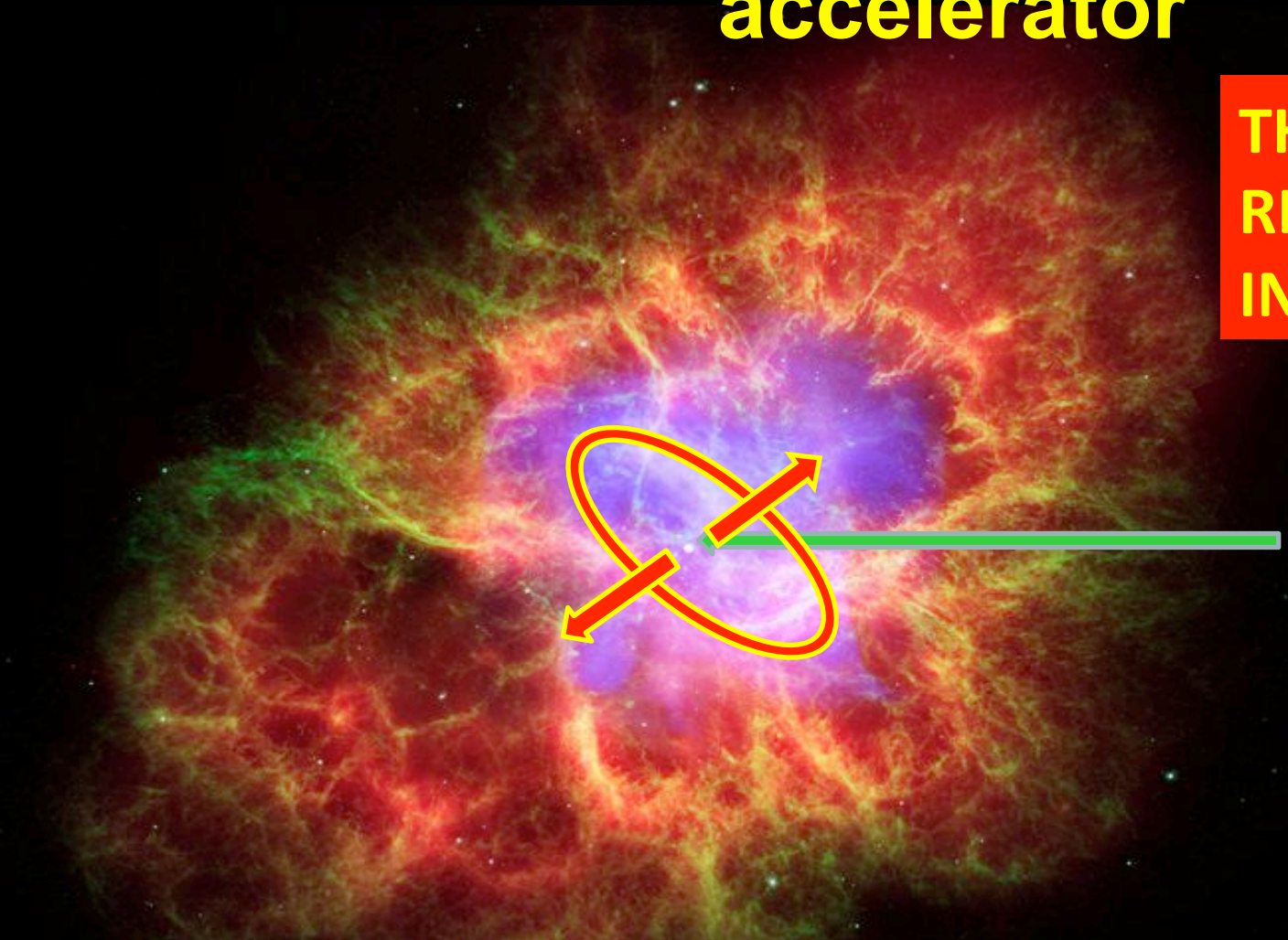
Fermi confirmation:

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

The Crab Nebula: a spectacular cosmic accelerator

Crab Nebula: a remnant of a supernova that exploded in AD 1054 (Chinese astronomers). X-ray data from Chandra (light blue), visible light data from Hubble (dark blue and green) and infrared data from Spitzer (red), 31/1/2001

The Crab Nebula: a spectacular cosmic accelerator



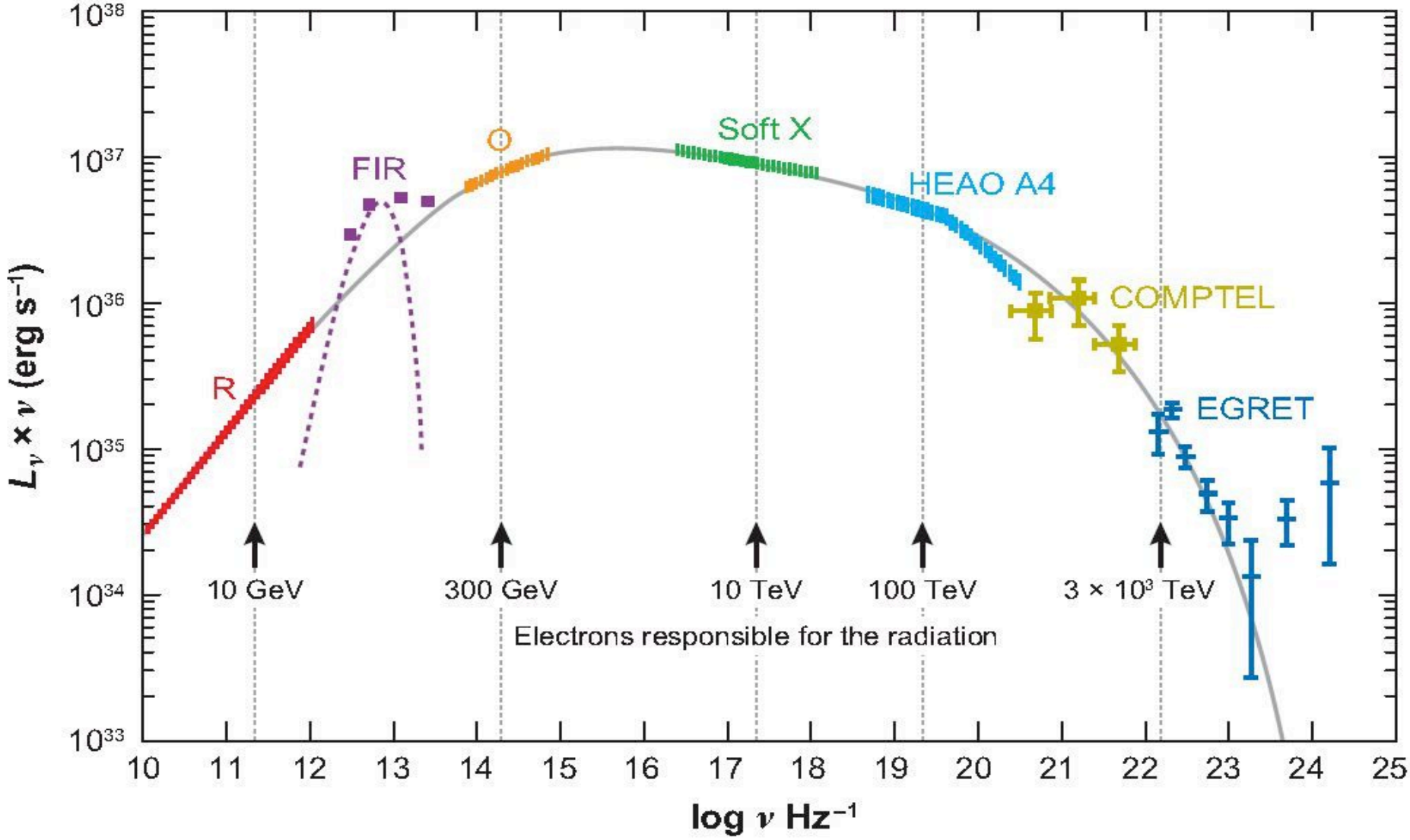
THE STANDARD REFERENCE SOURCE IN ASTROPHYSICS

POWERFUL PULSAR (Neutron Star rotating 30 times a sec)

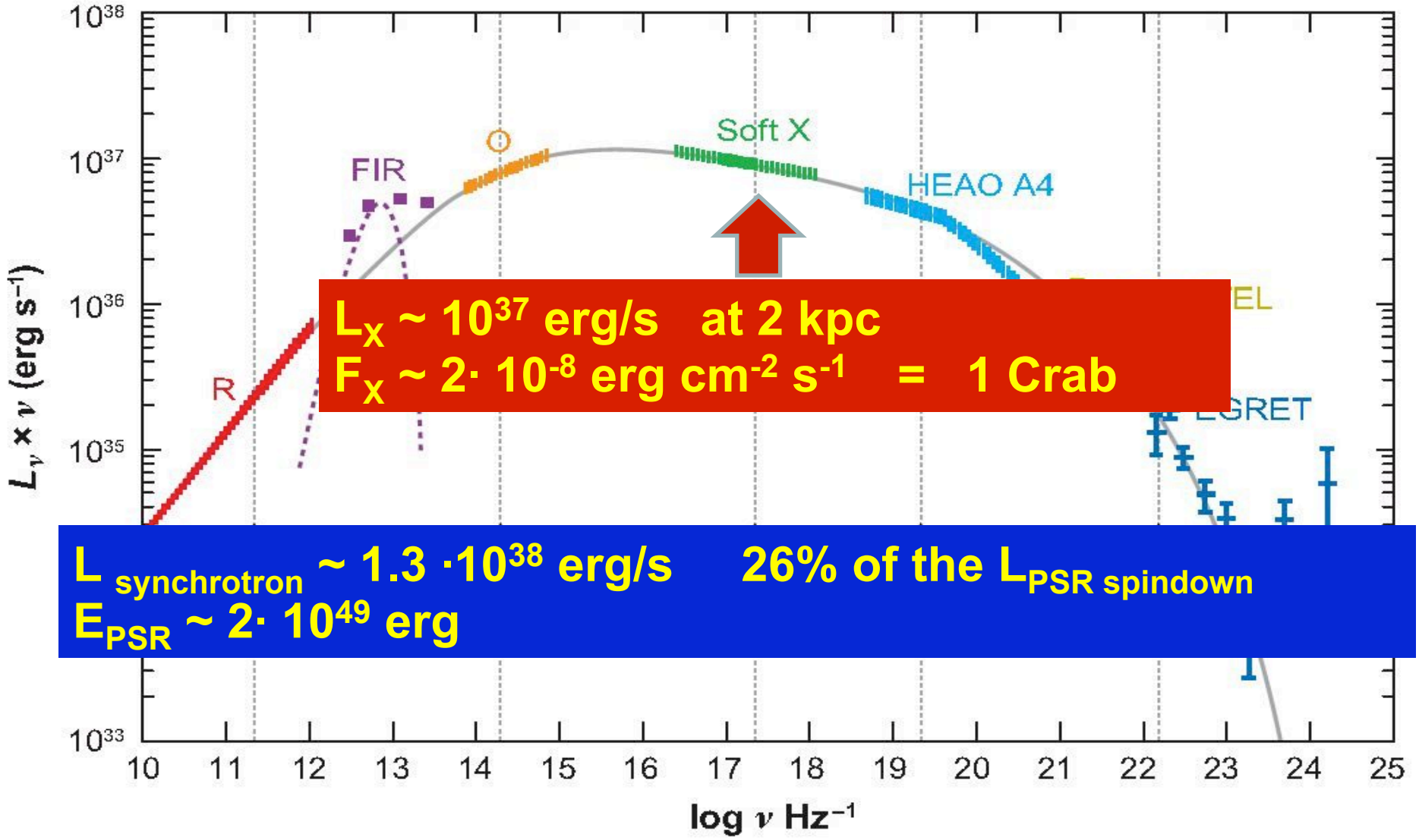
NEBULA SHOCKED BY THE PULSAR WIND

Crab Nebula: a remnant of a supernova that exploded in AD 1054 (Chinese astronomers). X-ray data from Chandra (light blue), visible light data from Hubble (dark blue and green) and infrared data from Spitzer (red), 31/1/2001

Crab Nebula spectrum (Hester 2008)



Crab Nebula spectrum (Hester 2008)



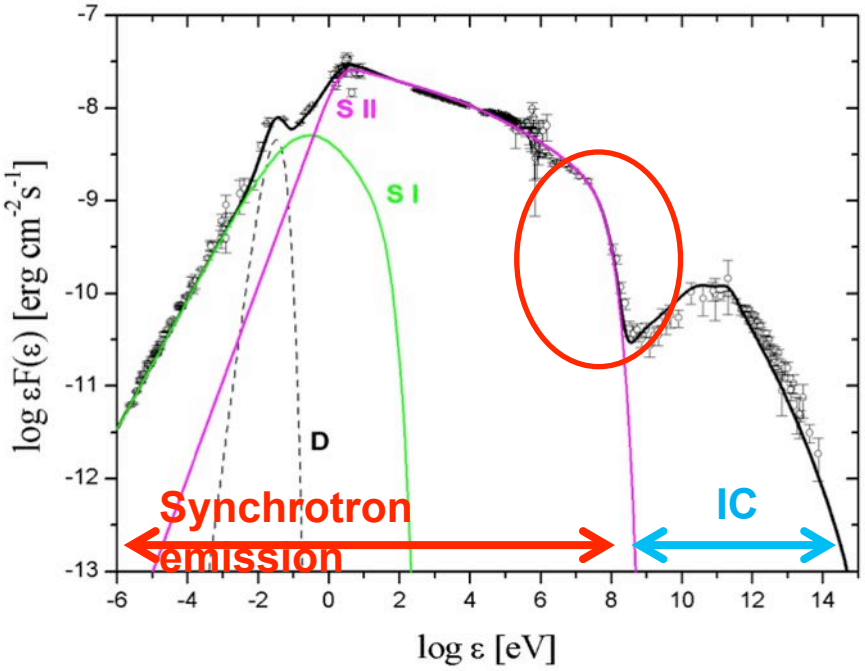
$L_X \sim 10^{37}$ erg/s at 2 kpc

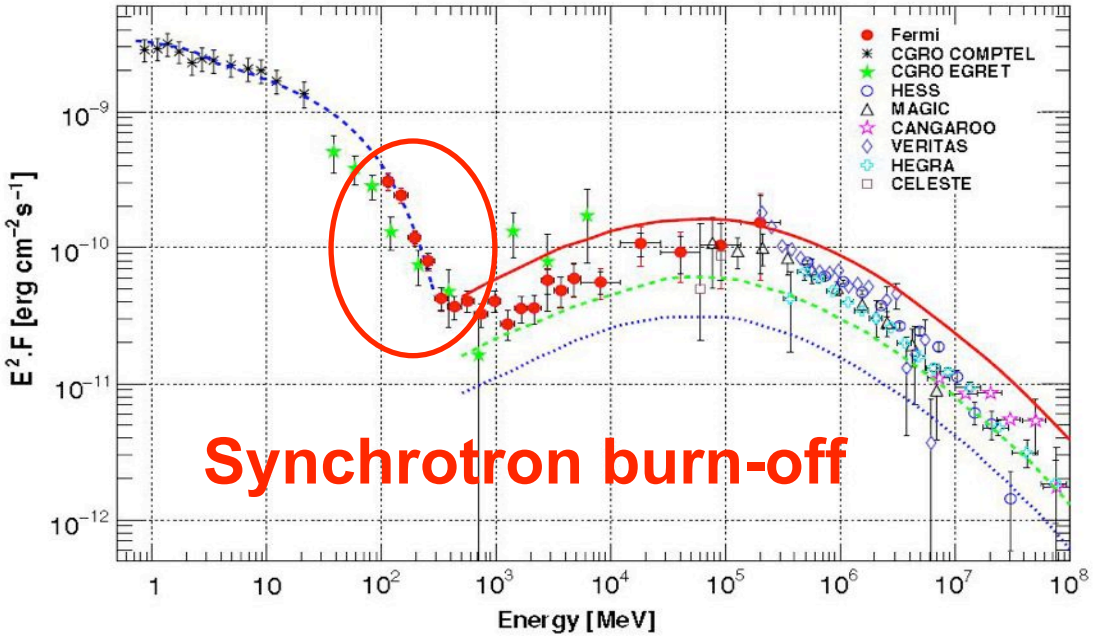
$F_X \sim 2 \cdot 10^{-8}$ erg cm^{-2} s^{-1} = 1 Crab

$L_{synchrotron} \sim 1.3 \cdot 10^{38}$ erg/s 26% of the $L_{PSR\ spindown}$

$E_{PSR} \sim 2 \cdot 10^{49}$ erg

Updated Crab Nebula spectrum from radio to TeV





Diffusive acceleration

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

Linear accelerator in ideal MHD framework

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

Synchrotron burn-off (E/B<1)

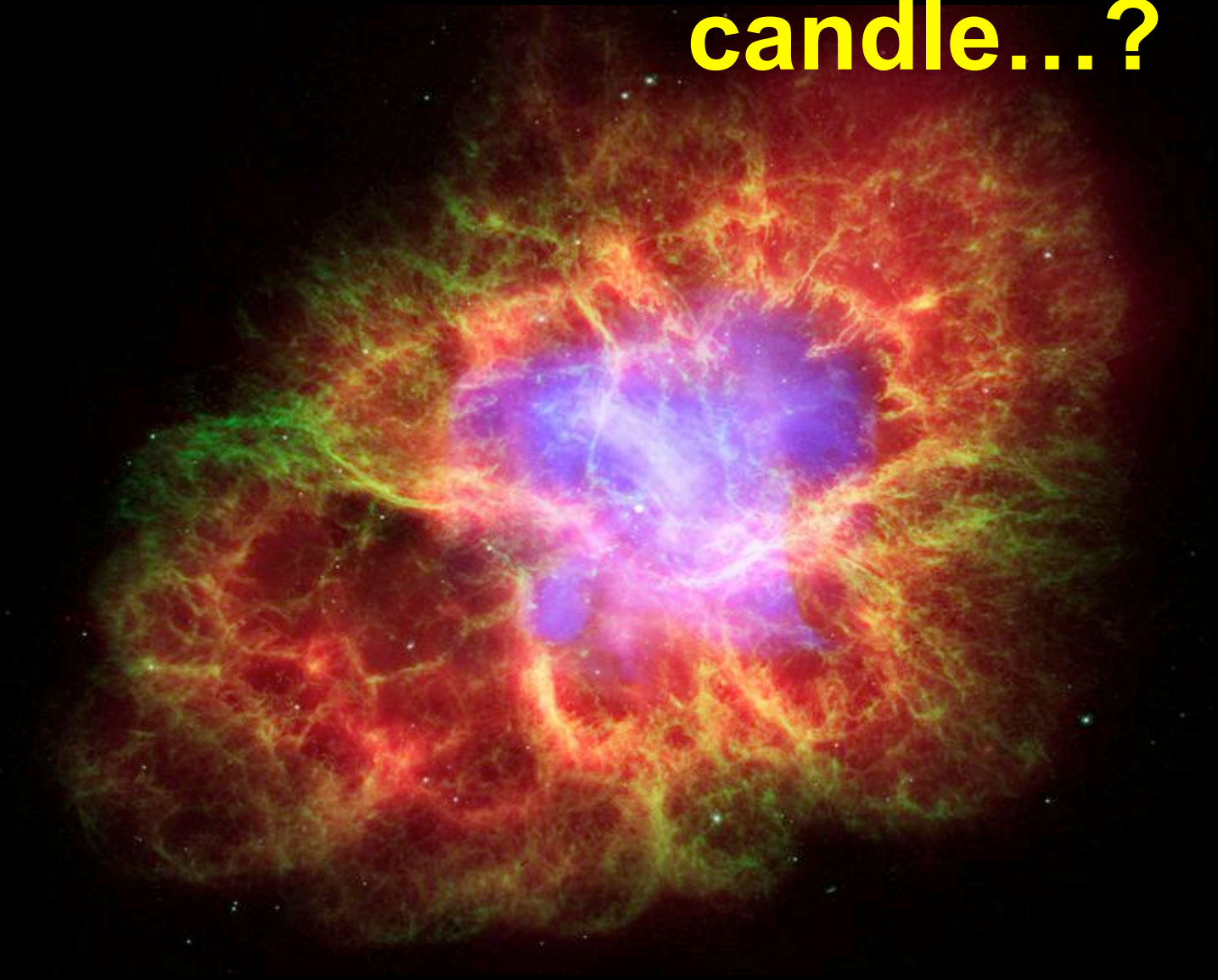
(De Jager et al. 92, Arons 2012)

(Slide adapted from E. Striani, PhD Thesis)

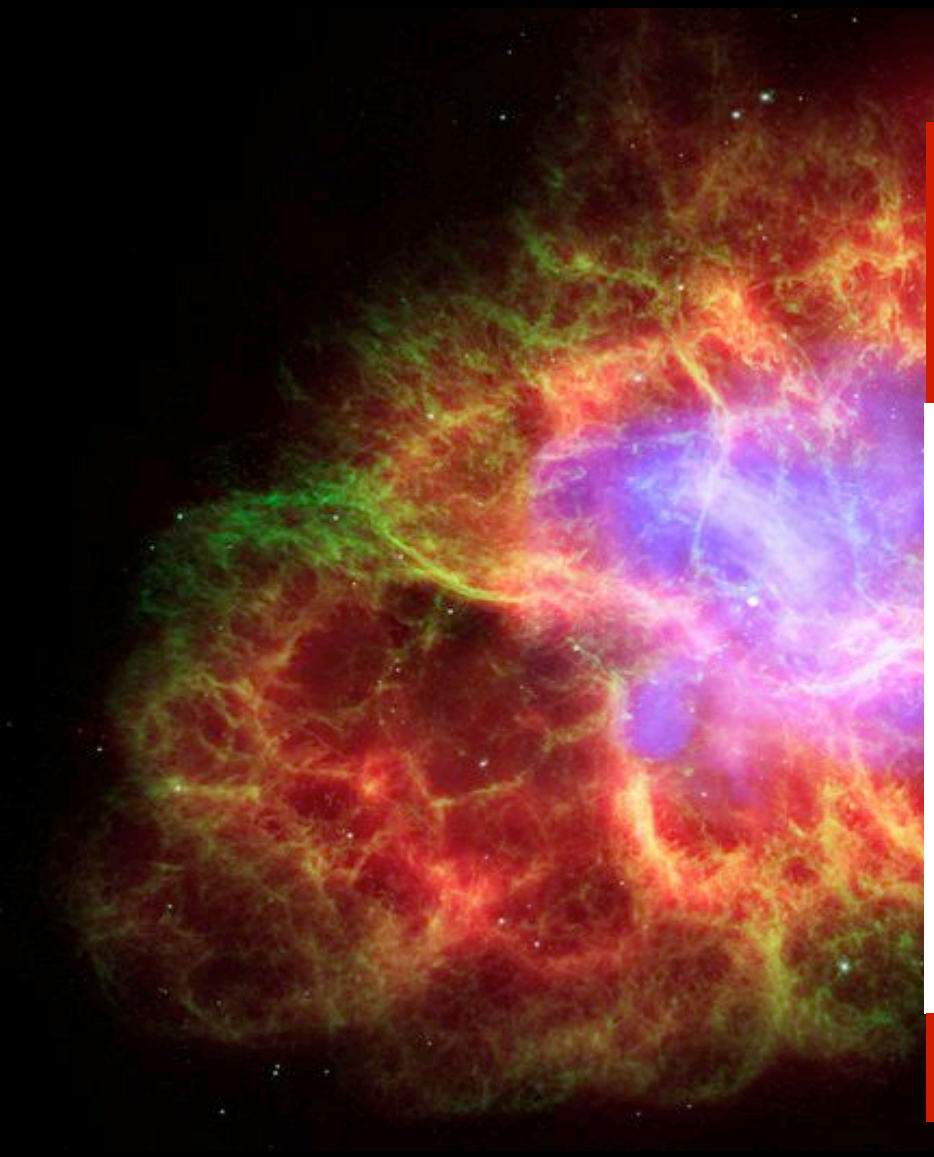
Crab Nebula “standard” modelling

- Average nebular magnetic field B = 200 μ G
- PSR-injected particles dN/dt ~ $10^{40.5}$ s^{-1}
- Total emitting particles, N ~ 2 ·10^{51}
- Many shock accelerating sites in the Nebula
- Inner Nebula variability (weeks-months)
  - **Toroidal structures (wisps)**
  - **Jet-like structures (knots)**

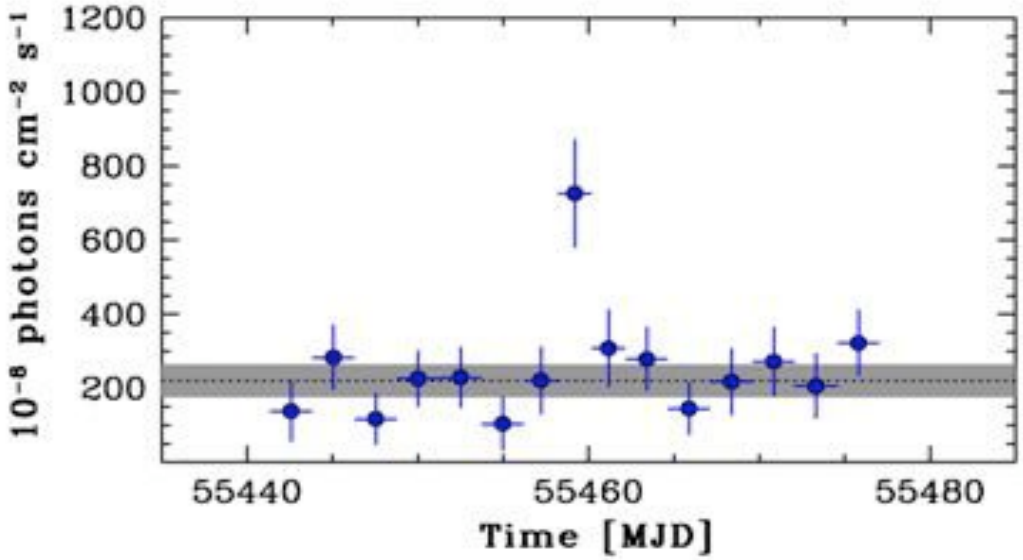
The Crab Nebula: a standard candle…?



The variable Crab Nebula!



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



Science Express **(6 January 2011)**

AGILE first detection of a strong gamma-ray flare in Oct. 2007 reported in the First AGILE source catalog as possible short unexpected flux increase

A&A 506, 1563–1574 (2009)
DOI: 10.1051/0004-6361/200911783

Astronomy & Astrophysics

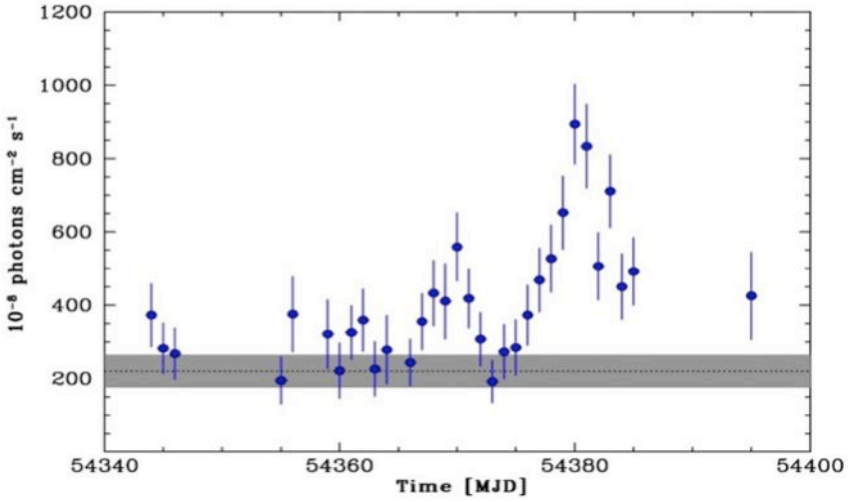
First AGILE catalog of high-confidence gamma-ray sources

C. Pittori[1], F. Verrecchia[1], A. W. Chen[2,3], A. Bulgarelli[4], A. Pellizzoni[5], A. Giuliani[2,3], S. Vercellone[6], F. Longo[7,8], M. Tavani[9,10,11,3], P. Giommi[1,12], G. Barbiellini[7,8,3], M. Trifoglio[4], F. Gianotti[4], A. Argan[9], A. Antonelli[13], F. Boffelli[14], P. Caraveo[2], P. W. Cattaneo[14], V. Cocco[10], S. Colafrancesco[1,12], T. Contessi[2], E. Costa[9], S. Cutini[1], F. D'Ammando[9,10], E. Del Monte[9], G. De Paris[9], G. Di Cocco[4], G. Di Persio[9], I. Donnarumma[9], Y. Evangelista[9], G. Fanari[1], M. Feroci[9], A. Ferrari[3,15], M. Fiorini[2], F. Fornari[2], F. Fuschino[4], T. Froysland[3,11], M. Frutti[9], M. Galli[16], D. Gasparrini[1], C. Labanti[4], I. Lapshov[9,17], F. Lazzarotto[9], F. Liello[9], P. Lipari[18,19], E. Mattaini[2], M. Marisaldi[4], M. Mastropietro[9,21], A. Mauri[4], F. Mauri[14], S. Mereghetti[2], E. Morelli[4], E. Moretti[7,8], A. Morselli[11], L. Pacciani[9], F. Perotti[2], G. Piano[9,10,11], P. Picozza[10,11], M. Pilia[22,2,5], C. Pontoni[3,8], G. Porrovecchio[9], B. Preger[1], M. Prest[8,22], R. Primavera[1], G. Pucella[9], M. Rapisarda[20], A. Rappoldi[14], E. Rossi[4], A. Rubini[9], S. Sabatini[10], P. Santolamazza[1], E. Scalise[9], P. Soffitta[9], S. Stellato[1], E. Striani[10], F. Tamburelli[1], A. Traci[4], A. Trois[9], E. Vallazza[8], V. Vittorini[9,3], A. Zambra[2,3], D. Zanello[18,19], and L. Salotti[12]

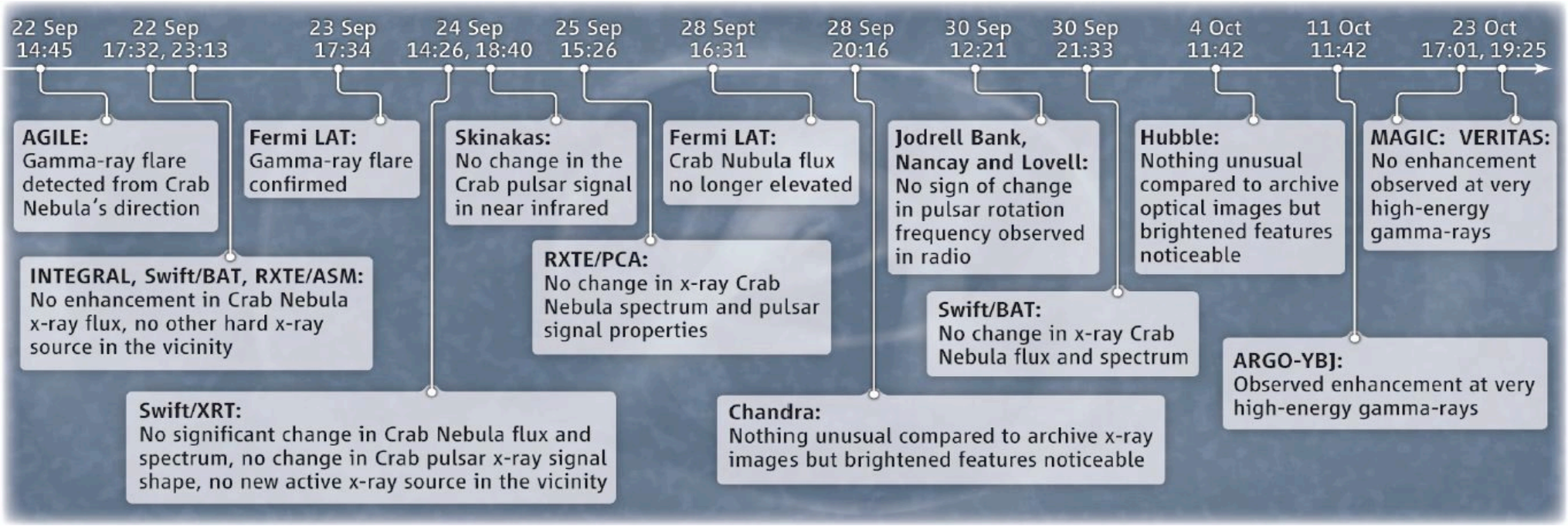
Sect. 6.1
Notes on individual sources:

1AGL J0535+2205 and 1AGL J0634+1748 (Crab and Geminga). These two well known strong γ-ray pulsars, together with the Vela pulsar, were used for in-flight AGILE calibrations. We report the flux values obtained during calibration subperiods. These values agree with pulsed flux values reported in (Pellizzoni et al. 2009). We note, however, that we observed higher flux values, over 1σ from the reported mean flux, for both sources when merging all the data, including shorter (1 day) integration periods during 2007. This point is under investigation.

1AGL J0617+2236. This AGILE detection provides an improved positioning compared to the 3EG J0617+2238 error box. This source is positionally coincident with the SNR IC443



post-flare excitement



Bernardini E., 2011

Crab Sept. 2010 flare

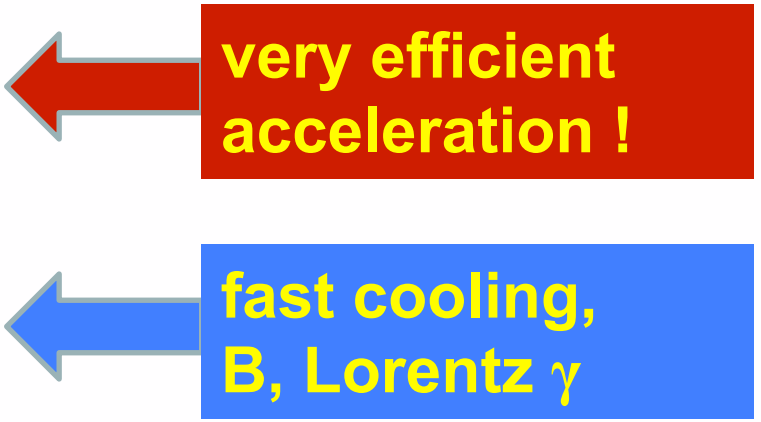
- gamma-ray flare peak luminosity

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

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

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

- timescales:
  - risetime: ≤ 1 day
  - decay: ~ 2-3 days



- **Crucial constraints on shock particle acceleration theory !**
  - **e-/e+ shock acceleration by magnetic turbulence (diffusive vs. non-diffusive)**
  - **ion cyclotron absorption (e.g., J. Arons et al.)**

- **Crab Nebula *shocks* able to accelerate electrons/positrons at $\gamma \sim 10^9$ (PeV) !?**
  - **already inferred from "static" Nebula models (e.g., deJager & Harding, Atoyan & Aharonian)**
  - **never observed before within a 1-day timescale !**

AGILE first detection of a strong gamma-ray flare in Oct. 2007 reported in the First AGILE source catalog as possible short unexpected flux increase

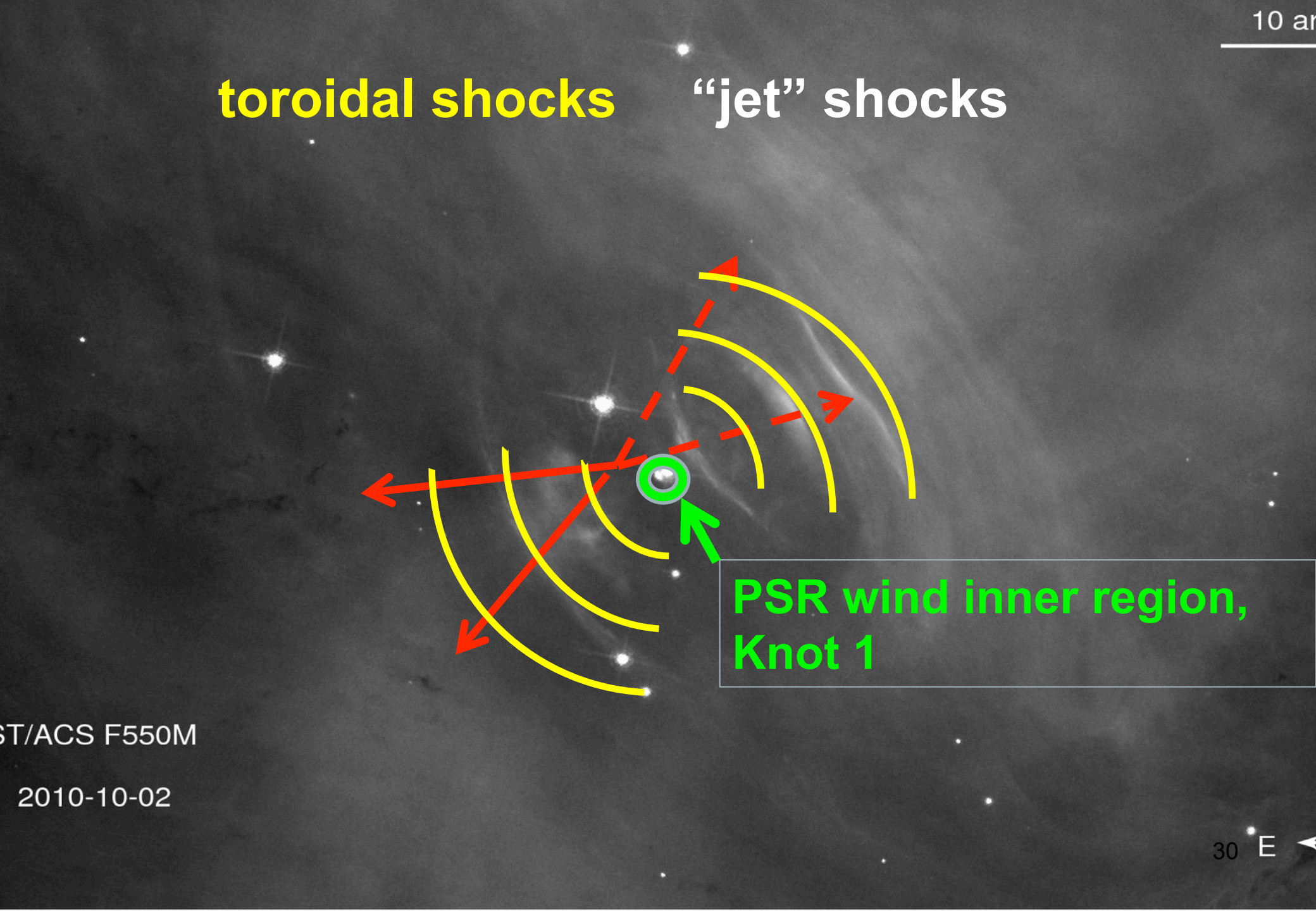
Flare date	Duration	Peak γ-ray flux	Instruments
October 2007	~ 15 days	~ $6 \cdot 10^{-6}$ ph cm^{-2} s^{-1}	AGILE
February 2009	~ 15 days	~ $4 \cdot 10^{-6}$ ph cm^{-2} s^{-1}	*Fermi*
September 2010	~ 4 days	~ $5 \cdot 10^{-6}$ ph cm^{-2} s^{-1}	AGILE, *Fermi*
April 2011	~ 2 days	~ $30 \cdot 10^{-6}$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

March and Oct 2013: **new** γ-ray flaring states detected by Fermi and AGILE

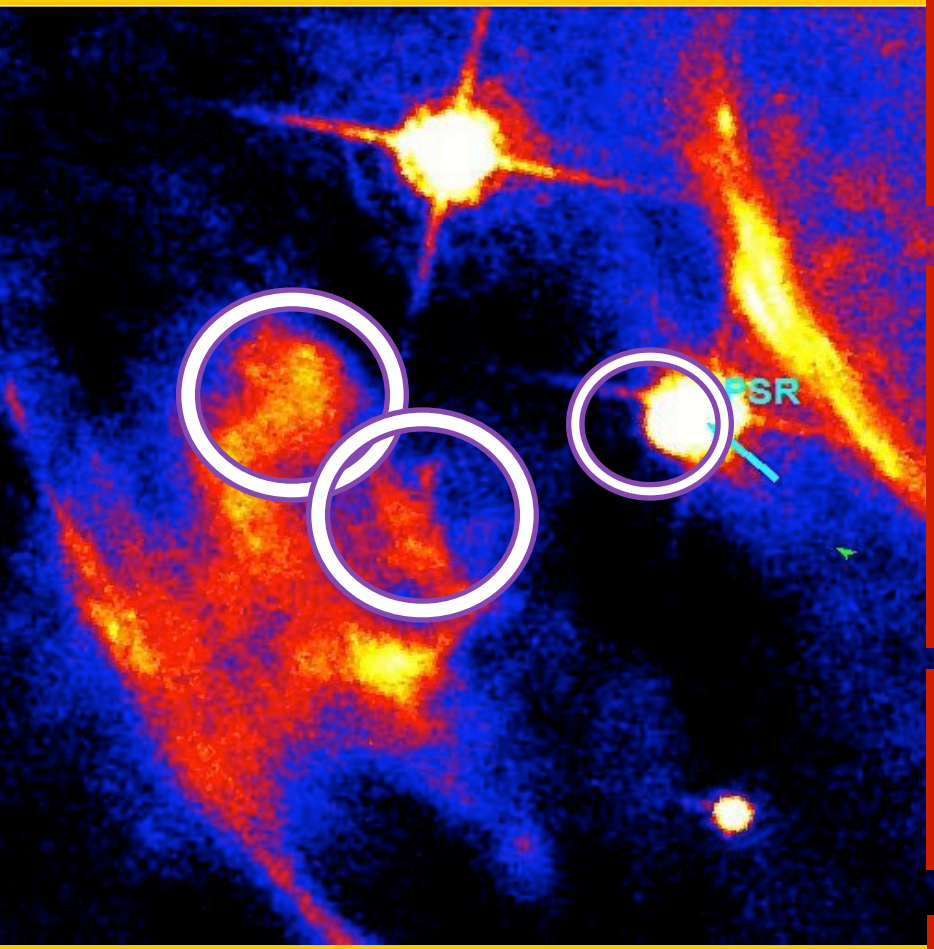
Rate: ≈1/year

- **a big theoretical challenge: the Crab Nebula is not a standard candle in gamma-rays!**


Where is the site of PeV e- acceleration? Very small size (day-light). Beyond MHD limit of about 200 MeV. MHD origin unlikely (achromatic effects). Very strong localized magnetic fields? Magnetic field reconnection, relax the E< B condition. Kink instabilities in the South East Jet? **Polarization?**


10 ar
toroidal shocks
"jet" shocks
PSR wind inner region,
Knot 1
ST/ACS F550M
2010-10-02
30
E

Hubble (optical) Oct. 2, 2010



PUZZLING ACCELERATION:

- fast flares imply VERY EFFICIENT particle acceleration at shocks, and "small" emission sites

source A

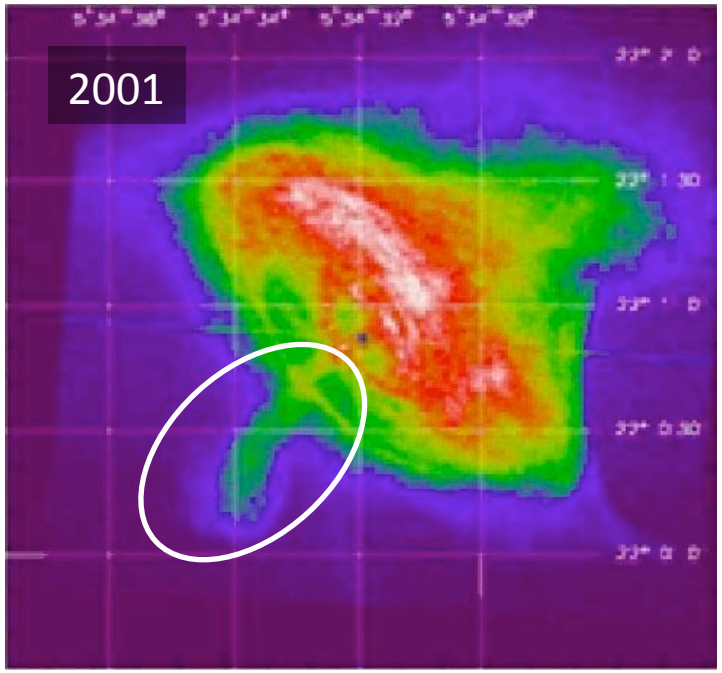
- *FAST ACCELERATION inconsistent with "slow" diffusion processes, a challenge to shock acceleration theory !*

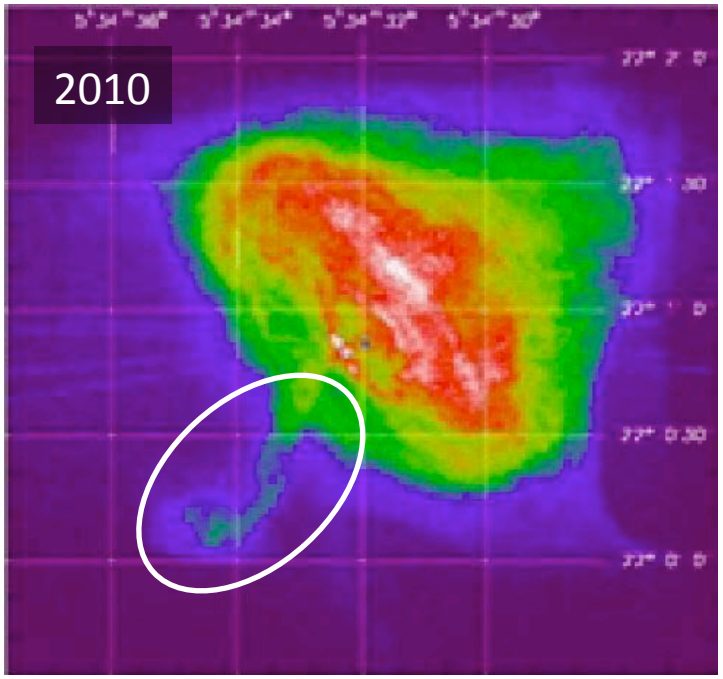
- acceleration up to 10^{15} eV, 1000 times larger than Tevatron or LHC

- shock structures might be the sites of transient gamma-rays, HST and Chandra candidates

(Slide adapted from
E. Striani, PhD Thesis)

South-East jet





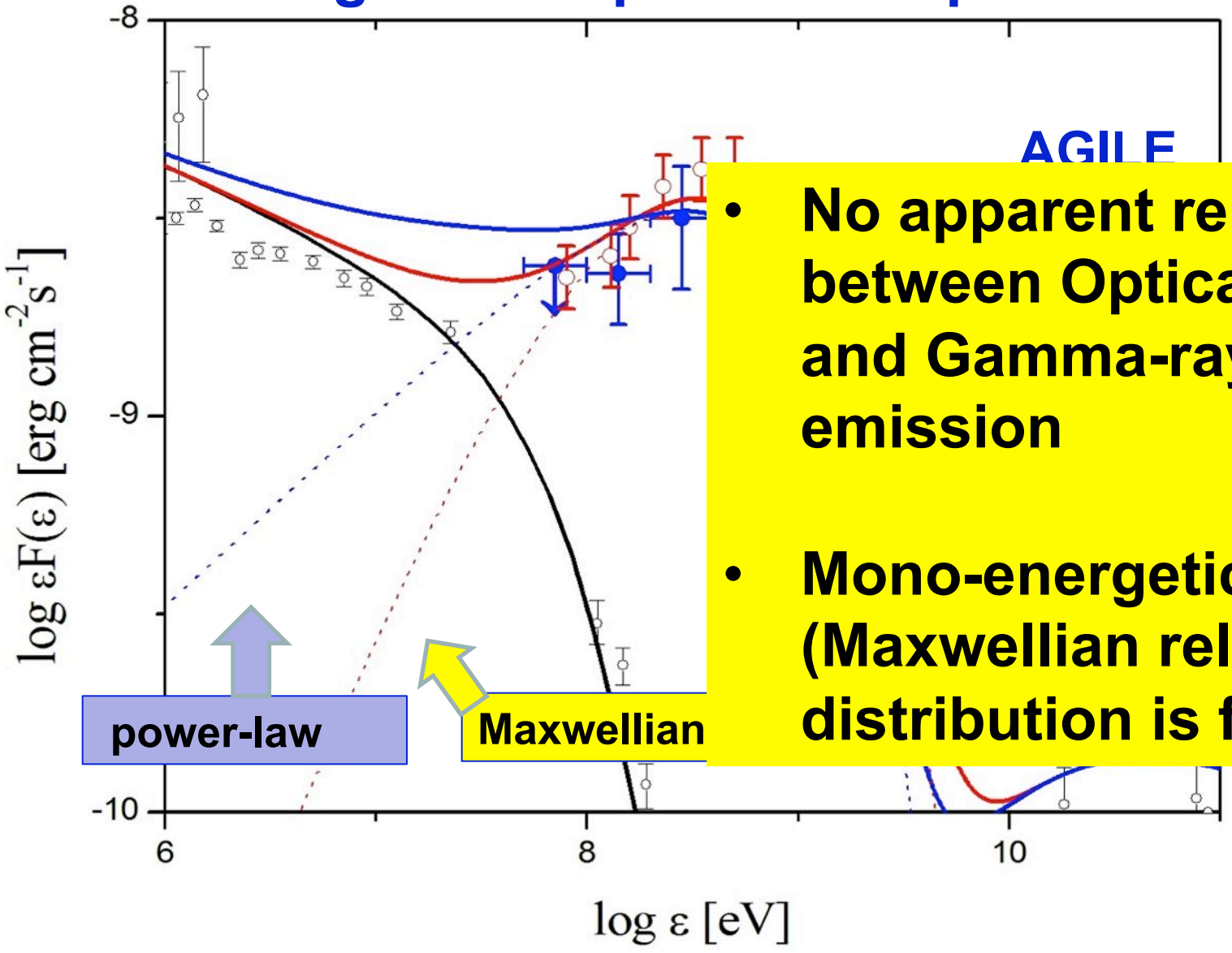
Promising candidate for the gamma-ray flaring site?:

- Remarkable time variability and jet wiggling
- High X-ray variability
- Highly magnetized plasma

Kink instability in the jet could be responsible for the observed jet wiggling and trigger magnetic reconnection and particle acceleration.

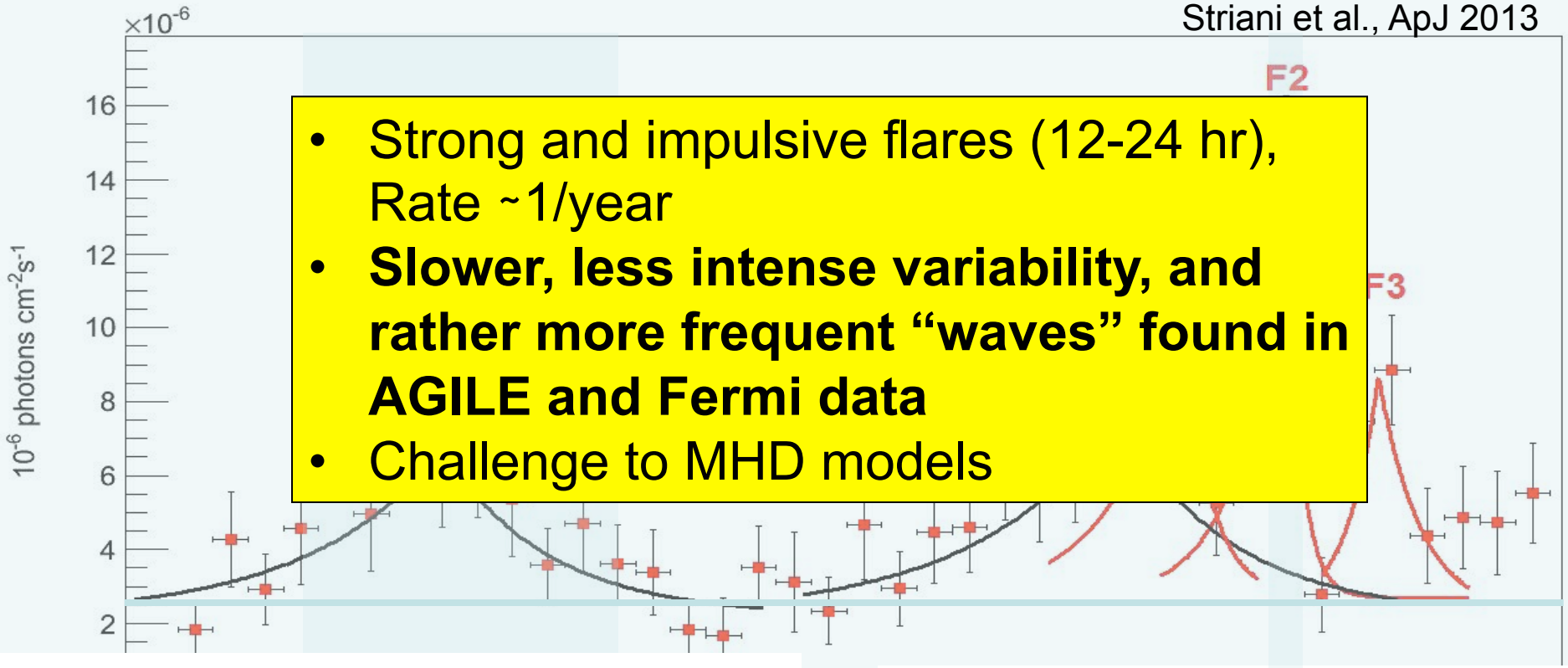
(3D rel. MHD simulations + resistivity , Mignone, Striani, et al. 2013, 2014 in progress)

Modelling of the April 2011 super-flare

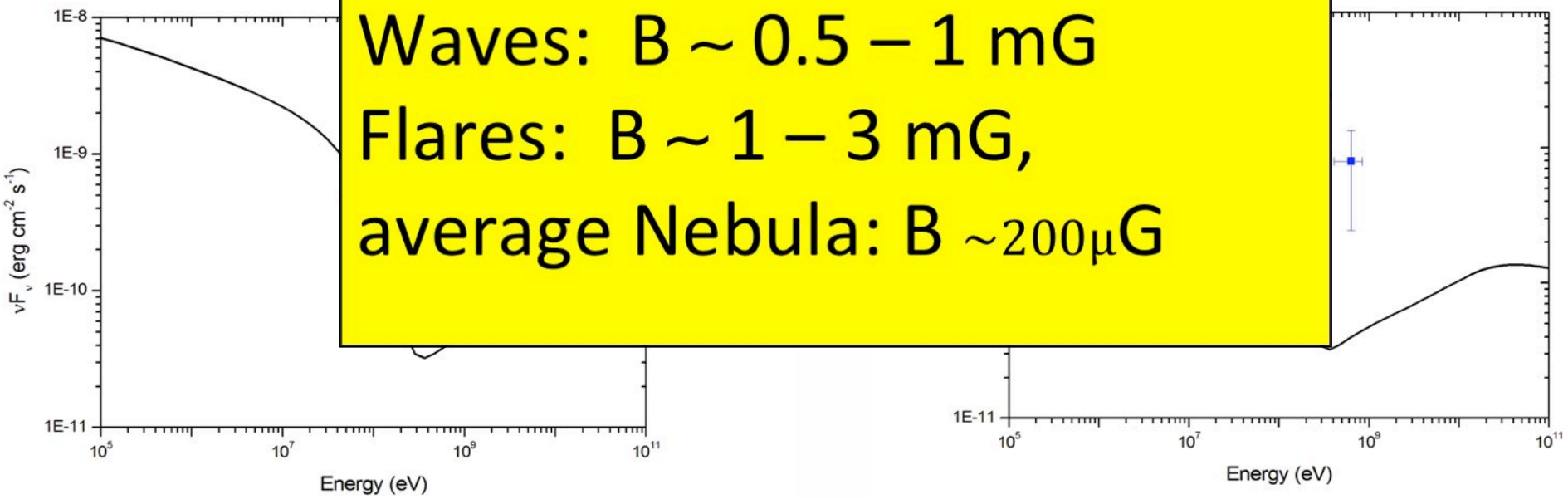


- **No apparent relation between Optical, X-ray and Gamma-ray flaring emission**
- **Mono-energetic (Maxwellian relativistic) distribution is favored!**

Striani et al., ApJ 2013



- Strong and impulsive flares (12-24 hr), Rate ~1/year
- **Slower, less intense variability, and rather more frequent "waves" found in AGILE and Fermi data**
- Challenge to MHD models



Waves: B ~ 0.5 – 1 mG

Flares: B ~ 1 – 3 mG,

average Nebula: B ~200μG

Summing up

- **very exciting: the Crab Nebula is not a standard candle in gamma-rays**

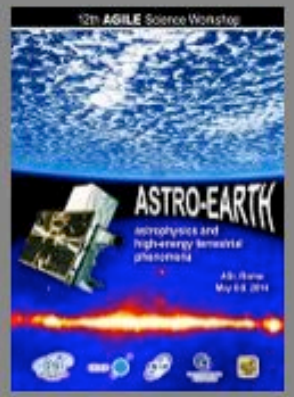
- **we "lost" the stability of an ideal reference source, but gained tremendous information about the fundamental process of particle acceleration**

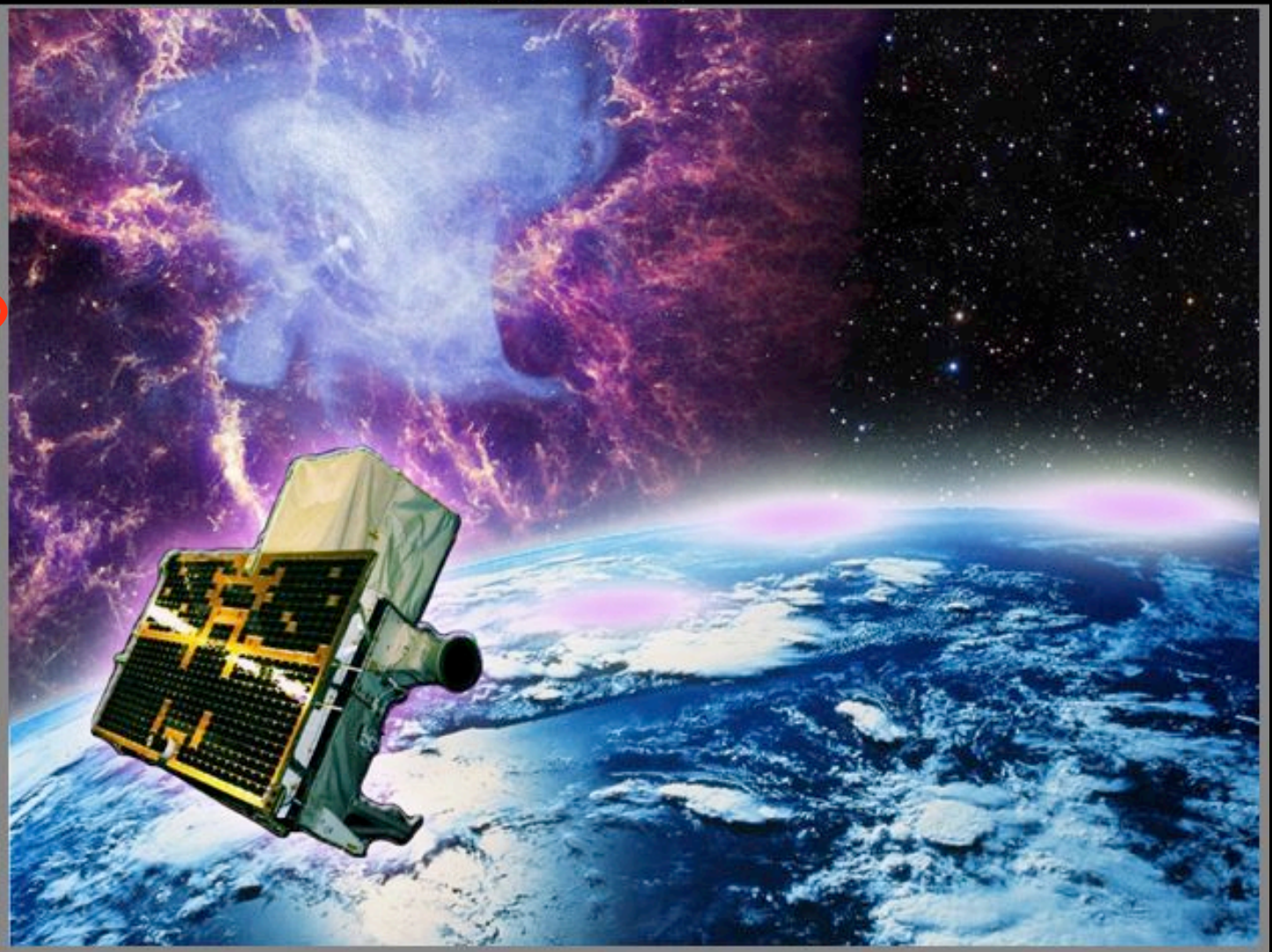
- **a big theoretical challenge. Theoretical models of particle acceleration based on the ideal MHD approximation fail: the observed variability timescales and energy peaks are not compatible with diffusive acceleration.**

- **the ultimate source of particle enhancements in the pulsar wind needs to be established: future surprises**
  (study of vacuum energy in extreme gravity conditions?)

12th AGILE Science Workshop
"ASTRO-EARTH: astrophysics and high-energy terrestrial phenomena"
May 8 and 9, 2014
ASI Headquarters, Via del Politecnico, Rome

- Home Page
- Organization
- Registration
- Participants
- Announcement
- Program and online presentations
- Location
- Contacts





BACKUP SLIDES

Table 3: AGILE Scientific Performance

Gamma-ray Imaging Detector (GRID)		
Energy Range	30 MeV – 50 GeV	
Field of view	~ 3 sr	
Sensitivity at 100 MeV (ph cm^{-2} s^{-1} MeV^{-1})	6×10^{-9}	(5σ in 10^6 s)
Sensitivity at 1 GeV (ph cm^{-2} s^{-1} MeV^{-1})	4×10^{-11}	(5σ in 10^6 s)
Angular Resolution at 1 GeV	36 arcmin	(68% cont. radius)
Source Location Accuracy	$\sim$5–20 arcmin	S/N$\sim$10
Energy Resolution	ΔE/E$\sim$1	at 300 MeV
Absolute Time Resolution	$\sim 1\,\mu$s	
Deadtime	$\sim 200\,\mu$s	
Hard X–ray Imaging Detector (Super-AGILE)		
Energy Range	10 – 40 keV	
Field of view	107°$\times$68°	FW at Zero Sens.
Sensitivity (at 15 keV)	$\sim$5 mCrab	(5σ in 1 day)
Angular Resolution (pixel size)	~ 6 arcmin	
Source Location Accuracy	$\sim$2-3 arcmin	S/N$\sim$10
Energy Resolution	ΔE$<$4 keV	
Absolute Time Resolution	$\sim 4\,\mu$s	
Deadtime (for each of the 16 readout units)	$\sim 4\,\mu$s	
Mini-Calorimeter		
Energy Range	0.3 – 200 MeV	
Energy Resolution	~ 1 MeV	above 1 MeV
Absolute Time Resolution	$\sim 3\,\mu$s	
Deadtime (for each of the 30 CsI bars)	$\sim 20\,\mu$s	

Main galactic AGILE discoveries

- **Carina region:** γ-ray detection of the colliding wind massive binary system η-Car with AGILE

  Tavani et al., ApJ, 698, L142, 2009 (arXiv:0904.2736)

- **Cygnus region microquasars:**
  - AGILE observations of Cygnus X-1 gamma-ray flares

    Sabatini et al., ApJ 2010, Del Monte et al., A&A 2010

  - AGILE detects several gamma-ray flares from Cygnus X-3, and also weak persistent emission above 100 MeV

    Tavani et al., Nature 462, 620, 2009 (arXiv:0910.5344)

- Detection of Gamma-Ray Emission from the Vela Pulsar Wind Nebula with AGILE

  Pellizzoni et al., Science 327, 2010

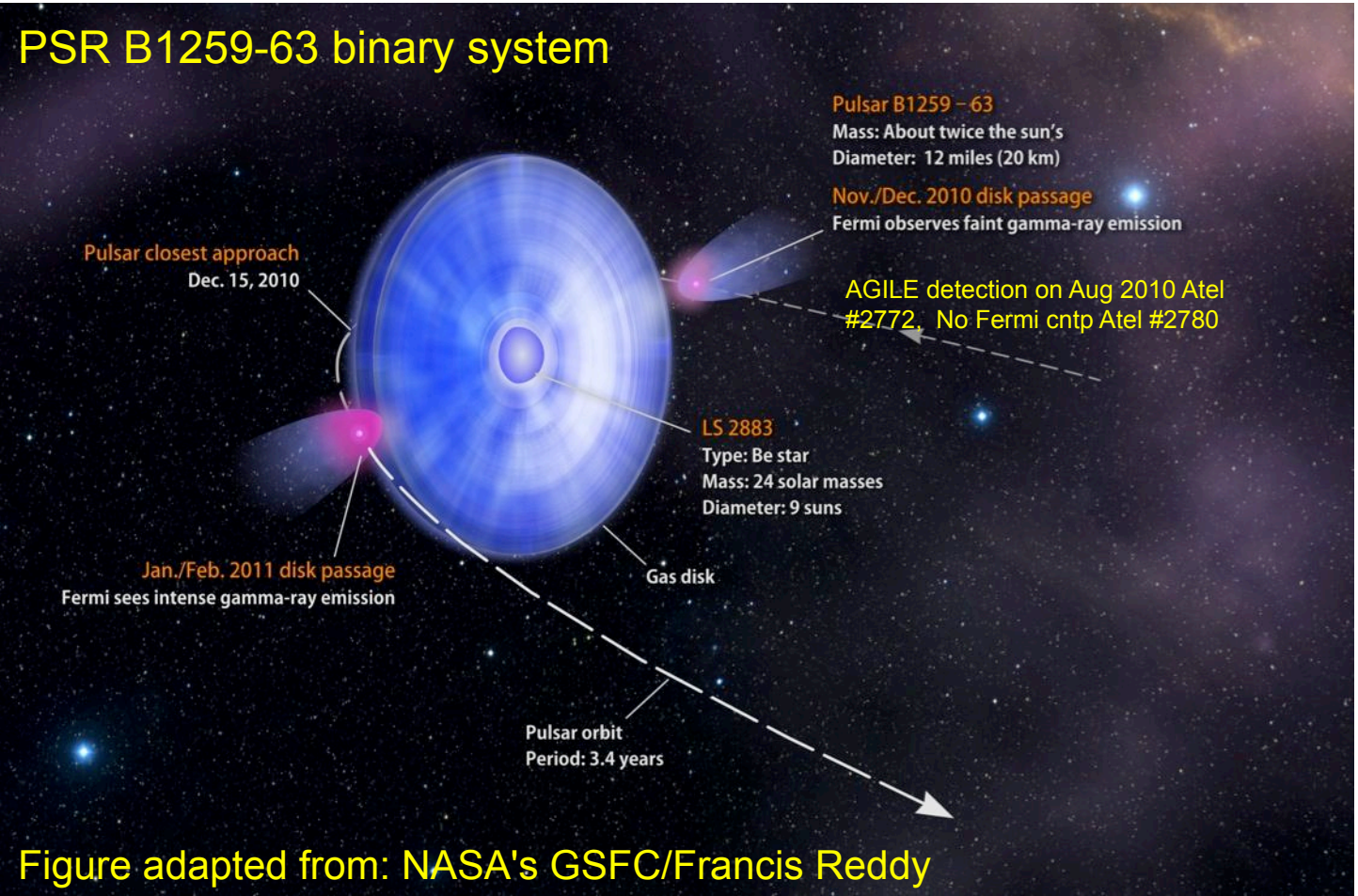
- Neutral pion emission from accelerated protons in the SNR W44

  Giuliani et al., ApJ, 742, 2011

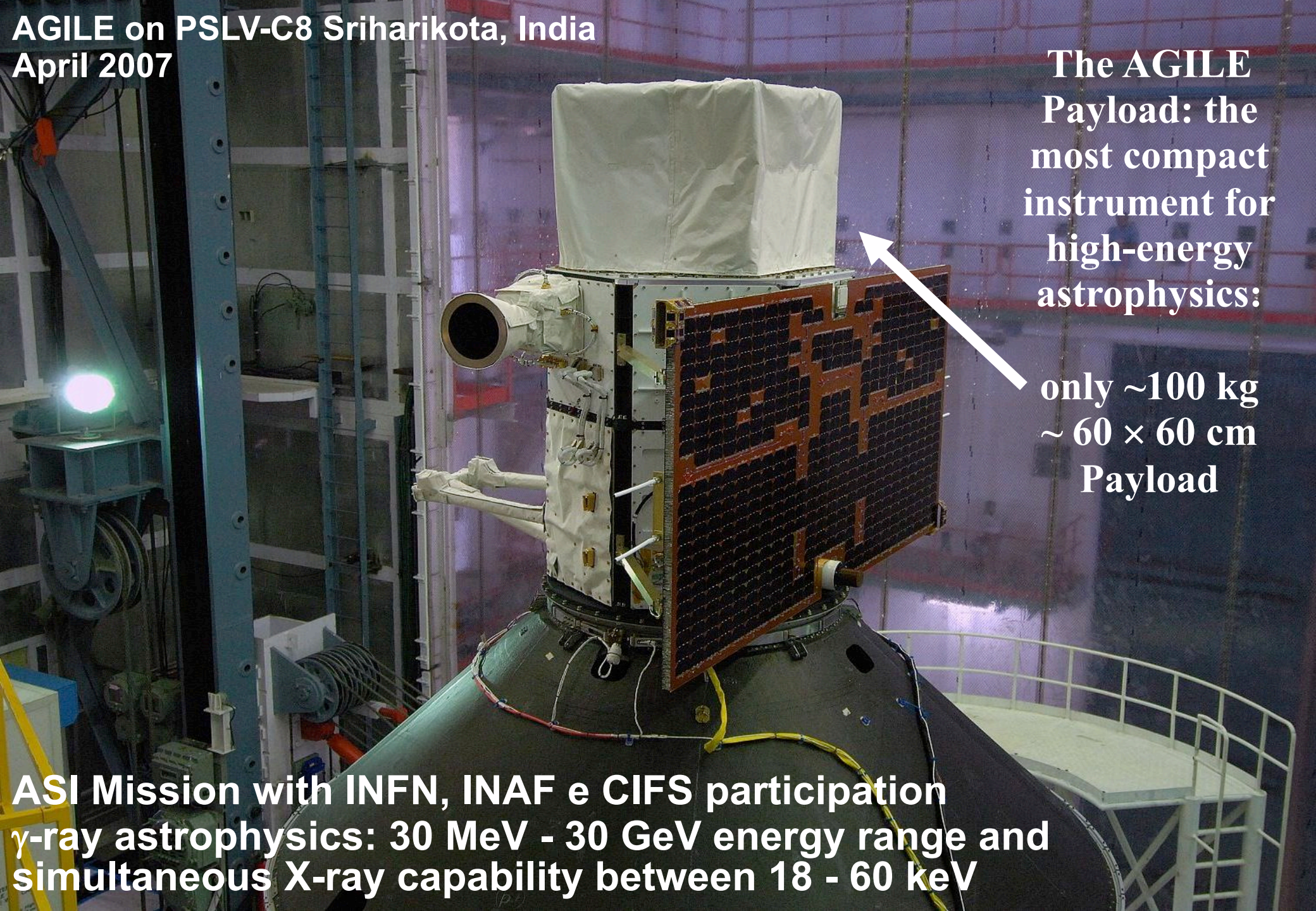
AGILE Announcement of Opportunity: AO4

Multimessenger analysis of possible gravitational wave emitters

F. Garufi et al., proposal ID93. On-going analysis



Look for interesting periods in AGILE gamma-ray data above 100 MeV, possibly with simultaneous X-ray monitoring with Swift/XRT, for seven compact binary systems (including PSR B1259-63) to be correlated with the LIGO and VIRGO GW detectors

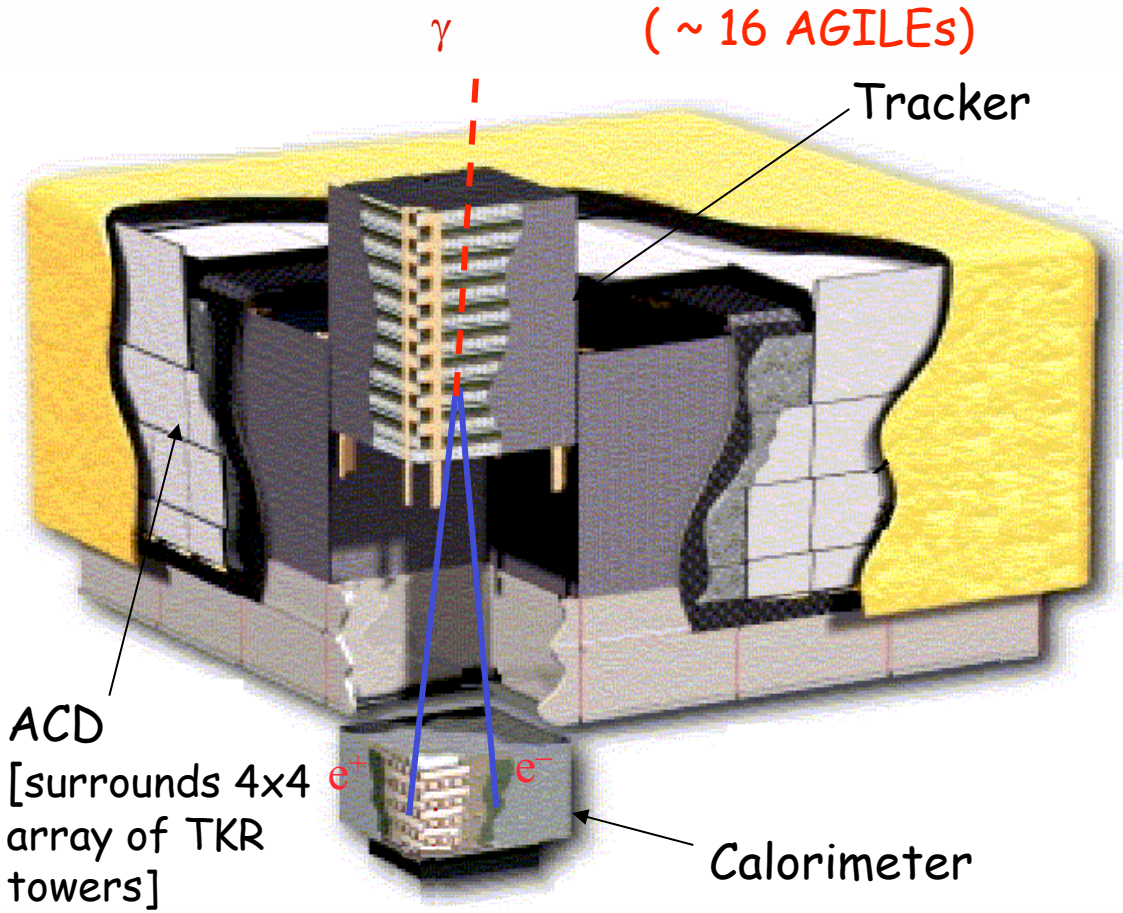

AGILE on PSLV-C8 Sriharikota, India
April 2007
The AGILE Payload: the most compact instrument for high-energy astrophysics:
only ~100 kg
~ 60 × 60 cm
Payload
ASI Mission with INFN, INAF e CIFS participation
γ-ray astrophysics: 30 MeV - 30 GeV energy range and simultaneous X-ray capability between 18 - 60 keV

AGILE: inside the cube…

Fermi (formerly GLAST):
launched June 11, 2008

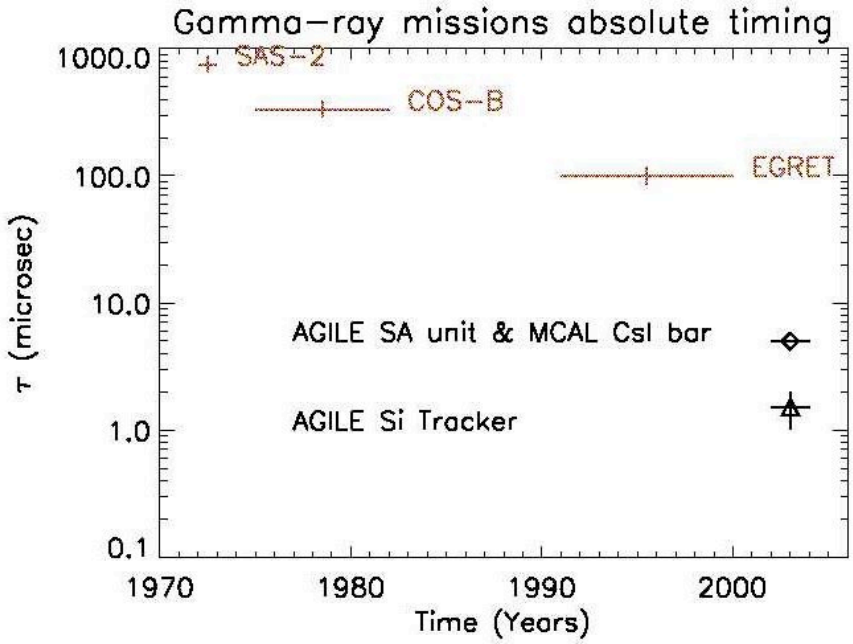
Fermi Large Area Telescope LAT:

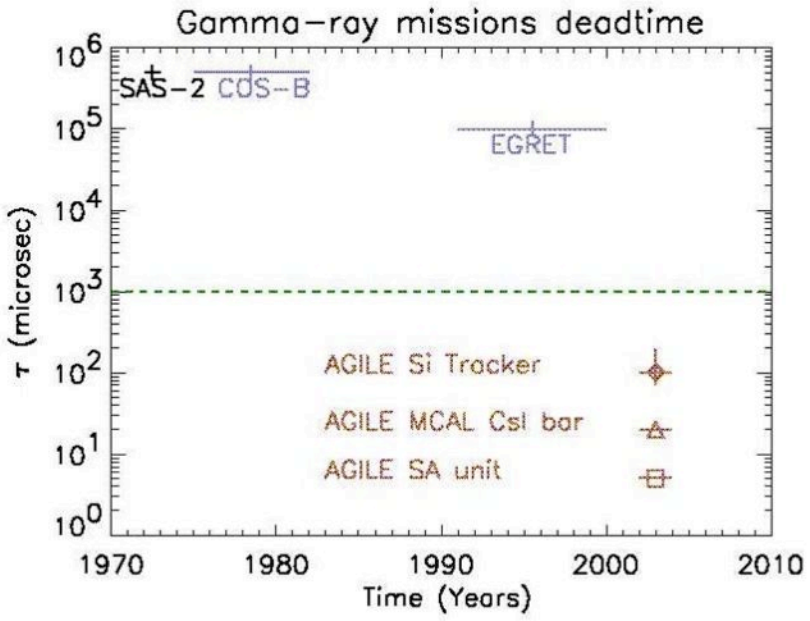
- **Precision Si-strip Tracker (TKR)**
  70 m² of silicon detectors arranged in 36 planes. 880,000 channels.
- first 12 x y planes with 0.03 X_0 (thin part)
- 4 x y planes with 0.18 X_0 (thick part)
- last 2 planes without converter
- **Hodoscopic CsI Calorimeter(CAL)**
  1536 CsI(Tl) crystals in 8 layers, total mass 1.5 tons.
- **Segmented Anticoincidence Detector (ACD) 89 plastic scintillator tiles.**
- **Electronics System Includes flexible hardware trigger and onboard computing.**



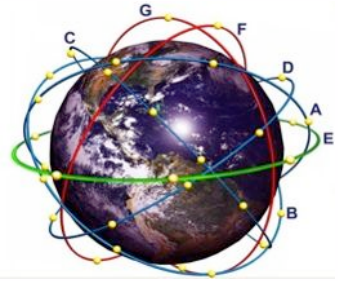
Total power 650 W
Total mass 2,789 kg

AGILE Temporal Resolution

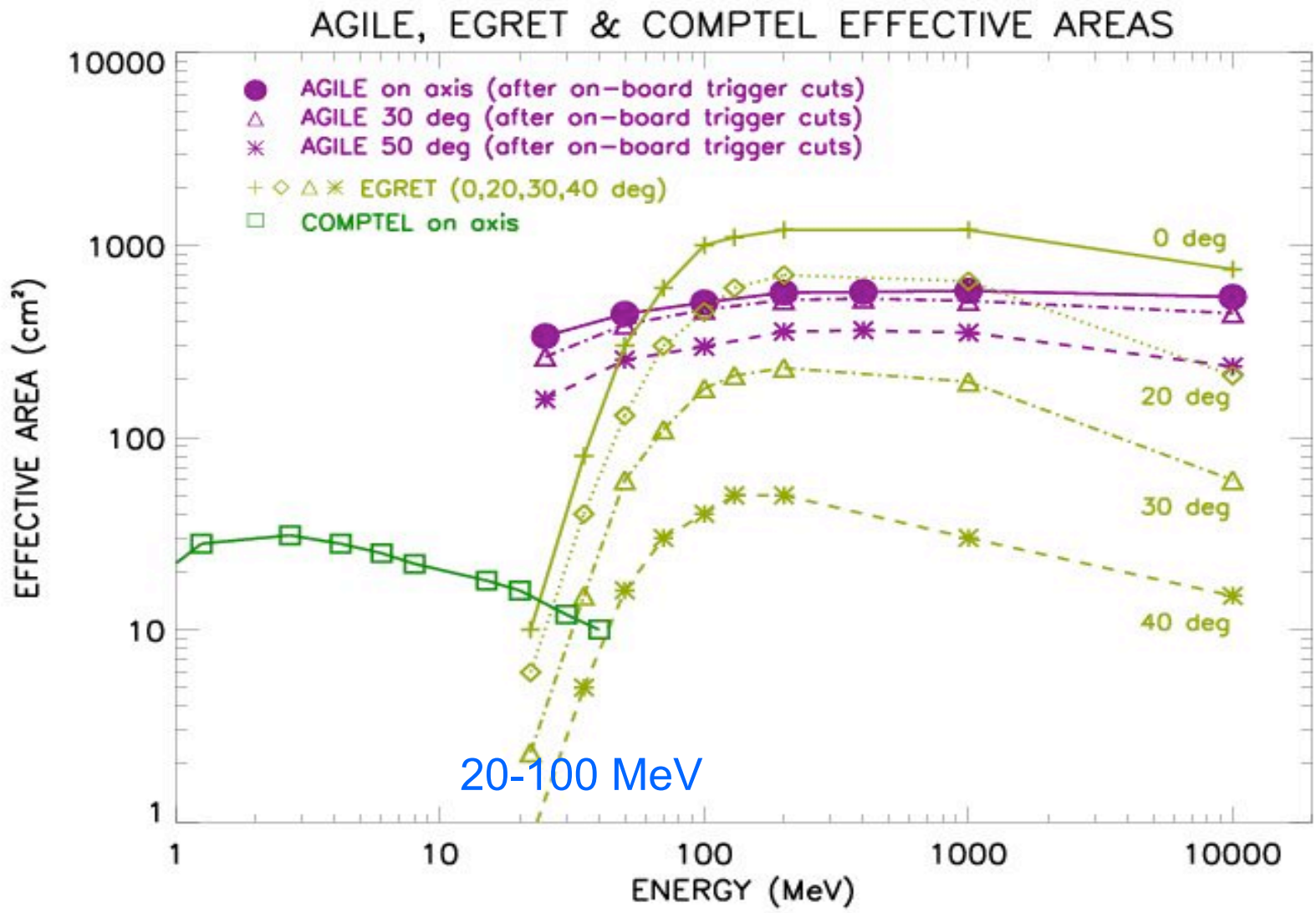


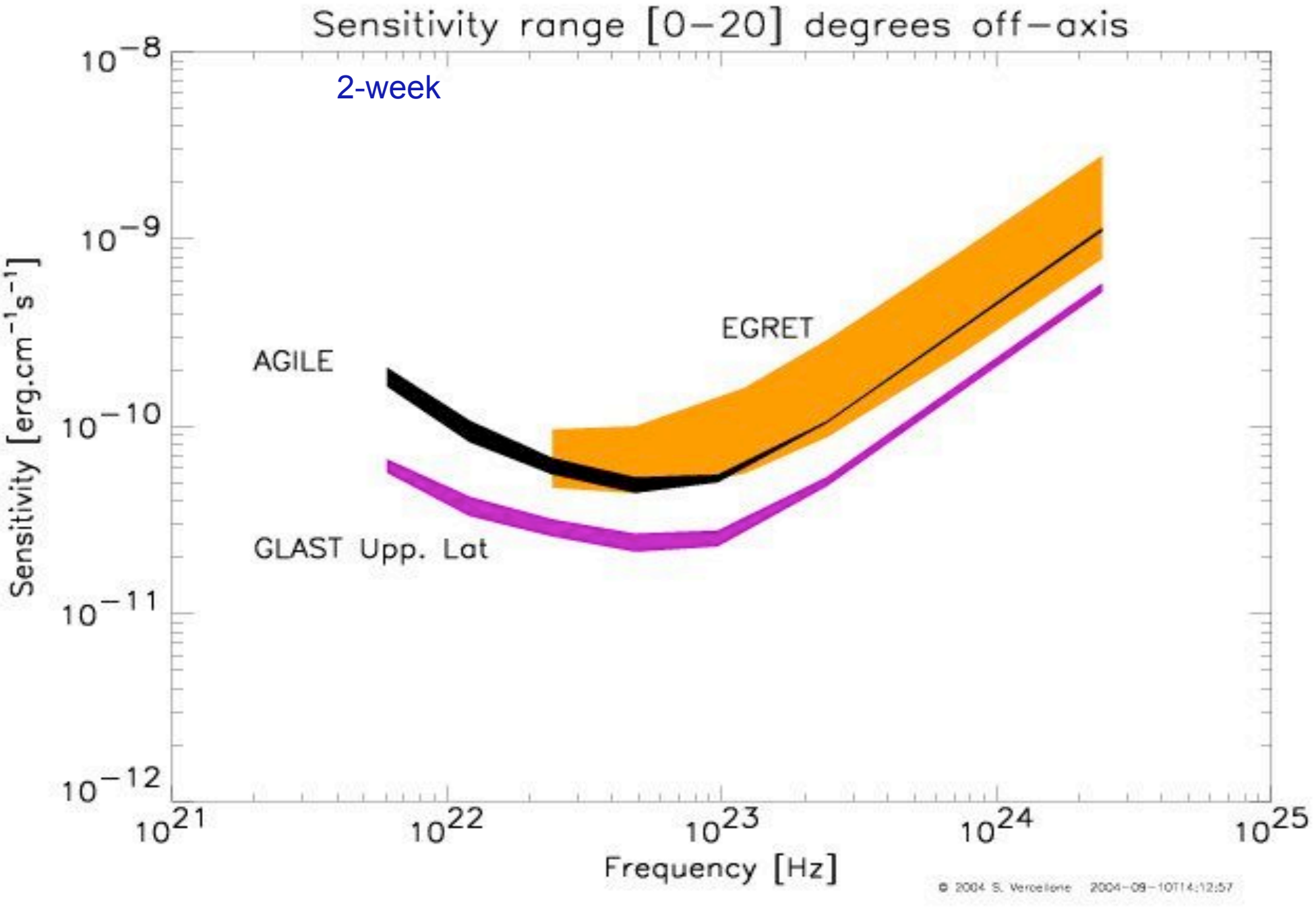


AGILE fast timing allows, for the first time, a search for sub-millisecond transients in the γ-ray energy range.

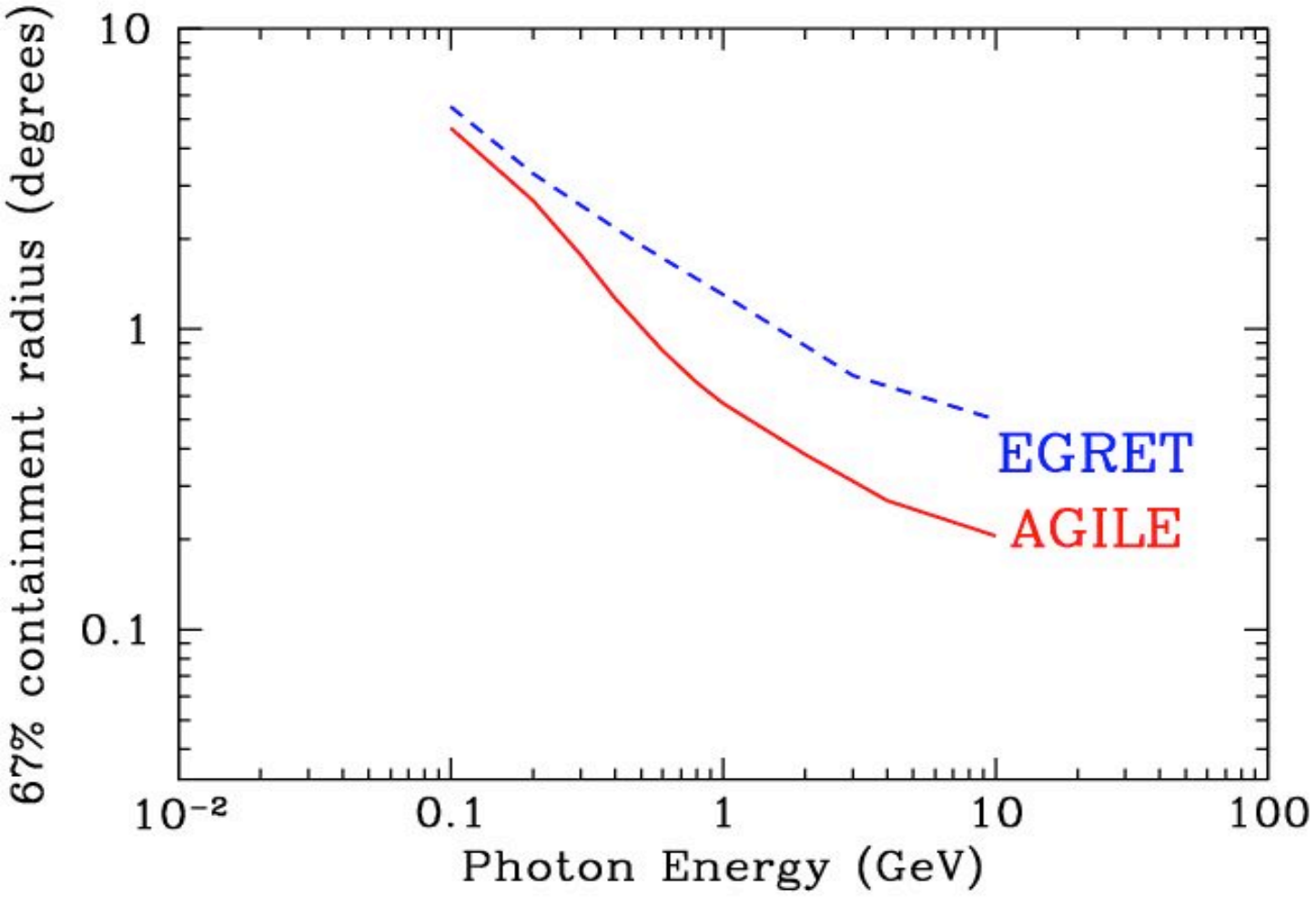


ORBCOMM *AGILE* Fast Link


AGILE, EGRET & COMPTEL EFFECTIVE AREAS
AGILE on axis (after on-board trigger cuts)
AGILE 30 deg (after on-board trigger cuts)
AGILE 50 deg (after on-board trigger cuts)
EGRET (0,20,30,40 deg)
COMPTEL on axis
0 deg
20 deg
30 deg
40 deg
20-100 MeV
EFFECTIVE AREA (cm²)
ENERGY (MeV)
10000
1000
100
10
1
1
10
100
1000
10000


Sensitivity range [0−20] degrees off−axis
2-week
AGILE
EGRET
GLAST Upp. Lat
Sensitivity [erg.cm^{-1}s^{-1}]
Frequency [Hz]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{21}
10^{22}
10^{23}
10^{24}
10^{25}
© 2004 S. Vercellone 2004-09-10T14:12:57

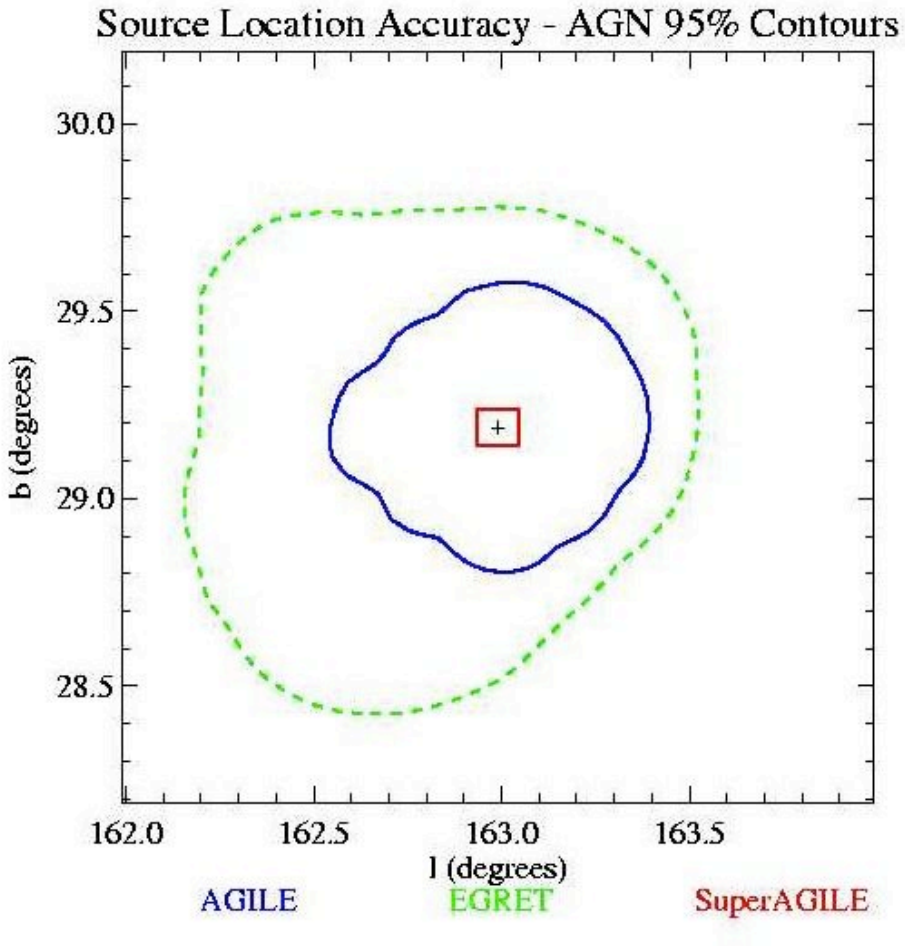
AGILE-GRID angular resolution



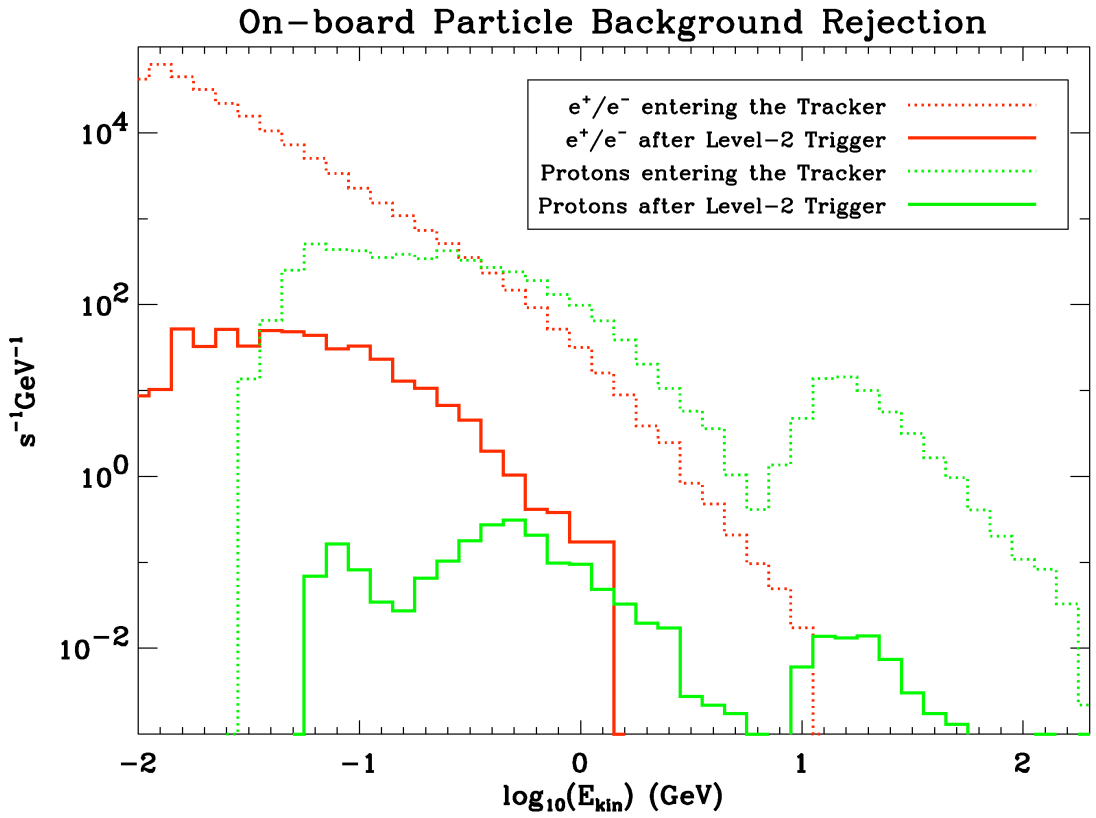
AGILE Source Location Accuracy:

AGILE ~ 5-20 arcmin (S/N ~ 10)

Super-AGILE: ~ 2-3 arcmin



On-board GRID Background Rejection:



Particle background rates :

- e+/e-:
reduced by a factor ~ 100

- Protons:
reduced by a factor ~ 1000

- Earth albedo γ-ray flux :
reduced by a factor ~ 30

The GRID on-board background rejection is quite efficient, reducing the total charged-particle rate from ~ 2000 Hz to ~ 20 Hz.