Assessing the flaring behaviour of the **Crab pulsar wind nebula system** in high-energy γ-rays

Michelle Tsirou

Investigations conducted with

B. Reville, E. de Oňa-Wilhelmi, G. Giacinti & J. Kirk

AstroParticle Symposium 2022

Institut Pascal – Uni Paris-Saclay

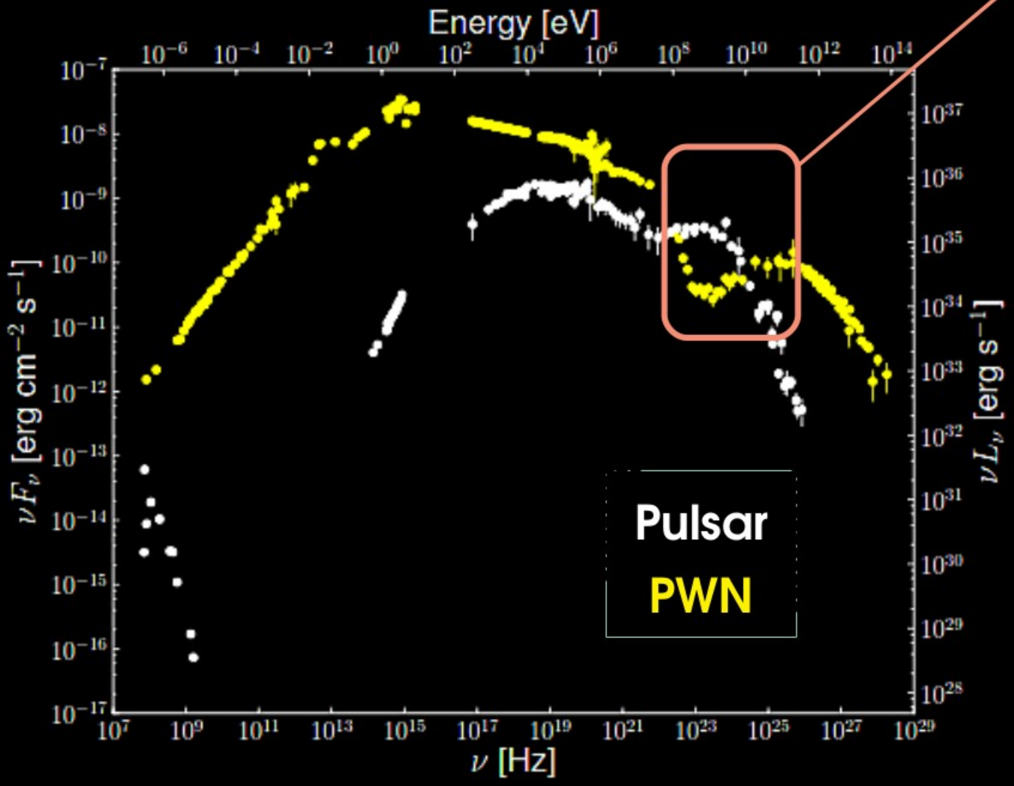
24 . 11. 2022

MAX-PLANCK-GESELLSCHAFT

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Bühler & Blandford 2014

(+ references within)

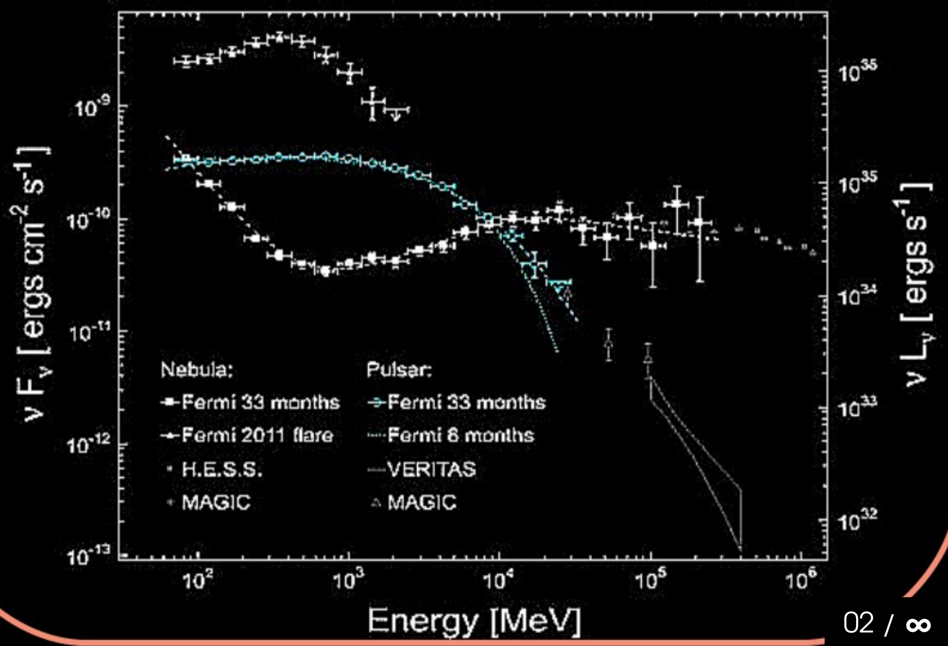


High-energy γ-ray regime :

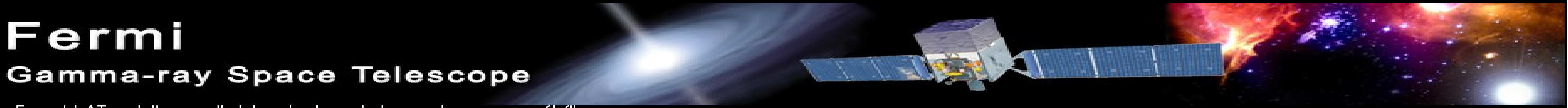
→ Fermi Gamma-ray Space Telescope

- Large Area Telescope :

~(tens/hundreds of MeV – hundreds of GeV)



Fermi-LAT : decade-long monitoring



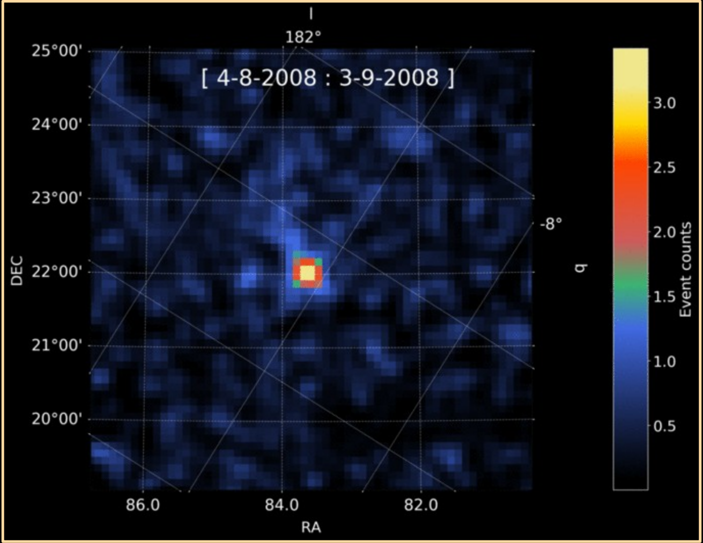
Fermi-LAT public available photon data and spacecraft files, analysed with `Fermitools` & `fermipy`:

Configuration	Selection
Event time range	August 4th 2008 – August 4th 2021
Energy	50 MeV – 500GeV 10 bins / decade
FoV	20° x 20° around the Crab
ROI	Fitting all sources within 10°
Filter	(DATA_QUAL>0) && (LAT_CONFIG==1) + Energy dispersion correction
Zenith angle	90° max (to account for Earth's limb)
Event class	128 (type : 3, front + back events)
IRFs	P8R3_SOURCE_V2
Catalogue	4FGL-8yr
Templates	Galactic diffuse + isotropic

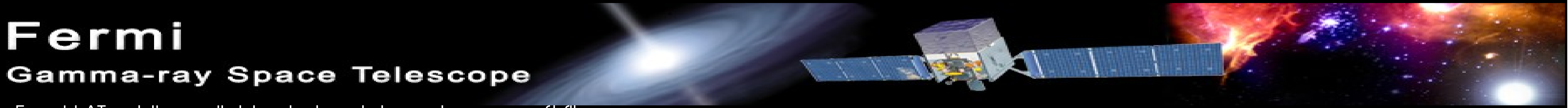
→ **13-yr** monitoring!

→ dominant radiation process **turn-over** range

→ spectro-morphological model for the Crab with **3** components (1 pulsar + **2 nebular**)



Month-long energy-stacked raw event sky map



Fermi-LAT public available photon data and spacecraft files, analysed with `Fermitools` & `fermipy`:

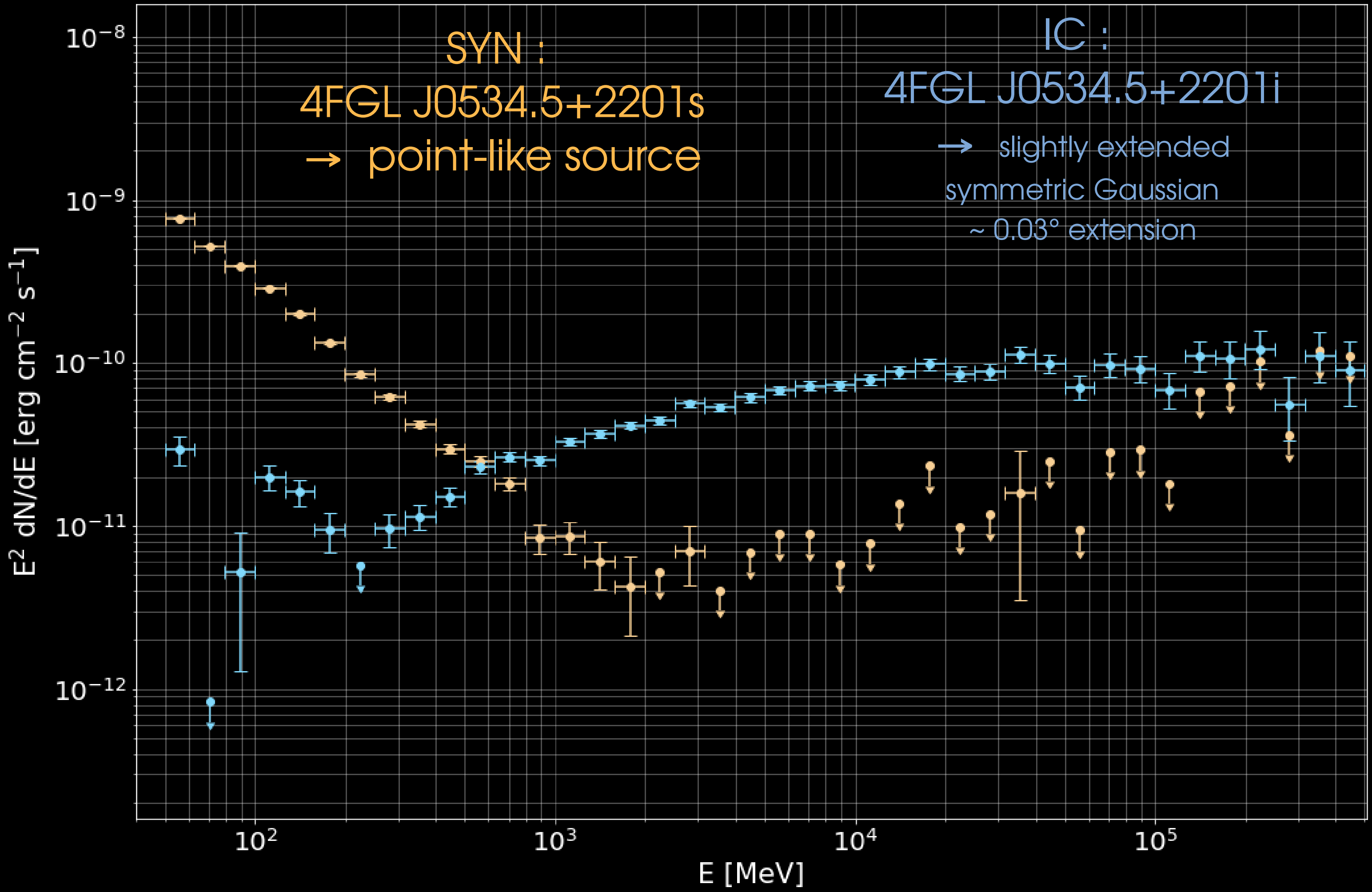
Configuration	Selection
Event time range	August 4th 2008 – August 4th 2022
Energy	50 MeV – 500GeV 10 bins / decade
FoV	20° x 20° around the Crab
ROI	Fitting all sources within 10°
Filter	(DATA_QUAL>0) && (LAT_CONFIG==1) + Energy dispersion correction
Zenith angle	90° max (to account for Earth's limb)
Event class	128 (type : 3, front + back events)
IRFs	P8R3_SOURCE_V3
Catalogue	4FGL-DR3
Templates	Galactic diffuse + isotropic

→ **14-yr** monitoring!

→ dominant radiation process **turn-over** range

→ spectro-morphological model for the Crab with **3** components (1 pulsar + **2 nebular**)

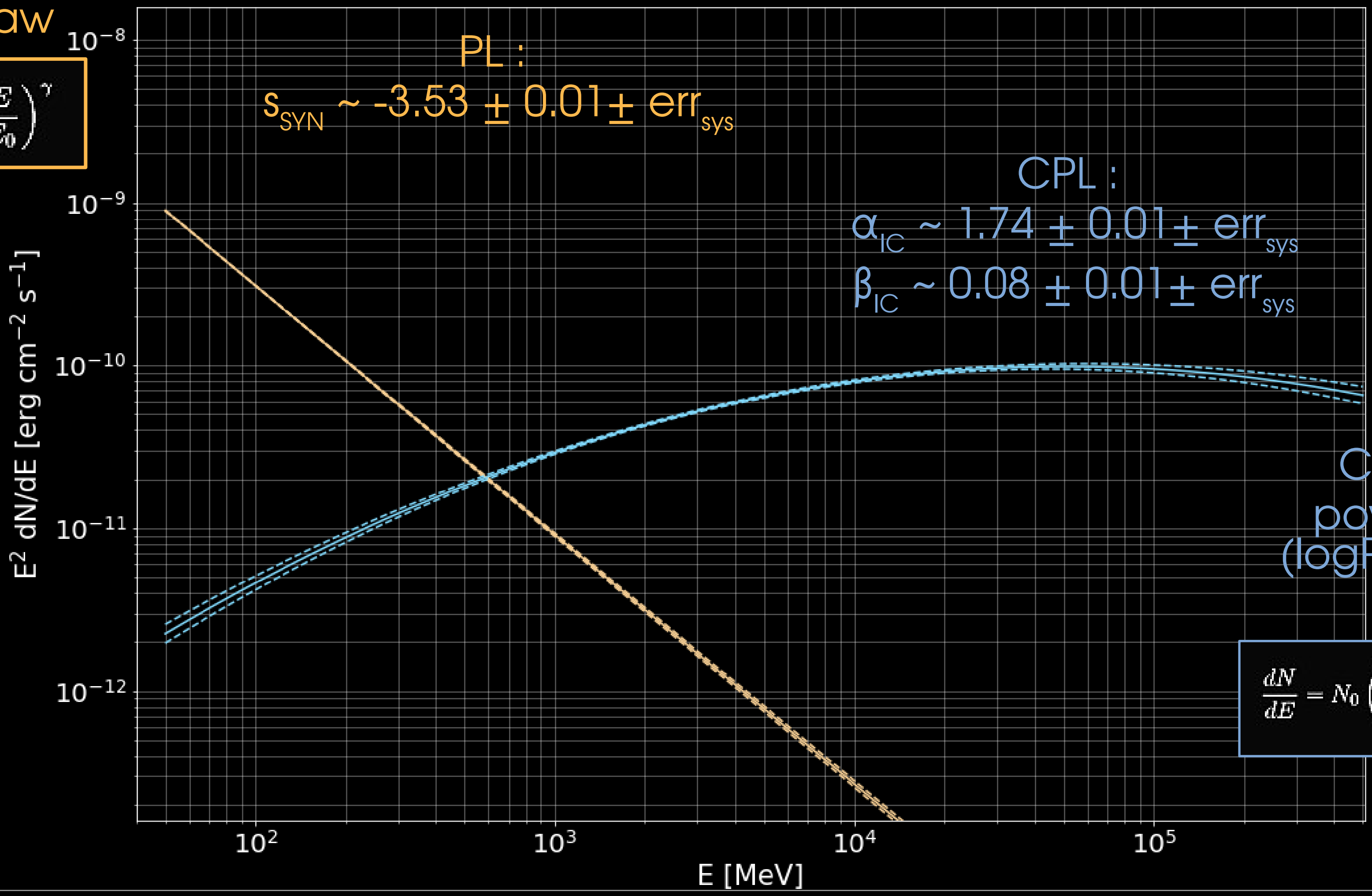
Time-averaged spectral energy distribution



Time-averaged spectral energy distribution

Power-law

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

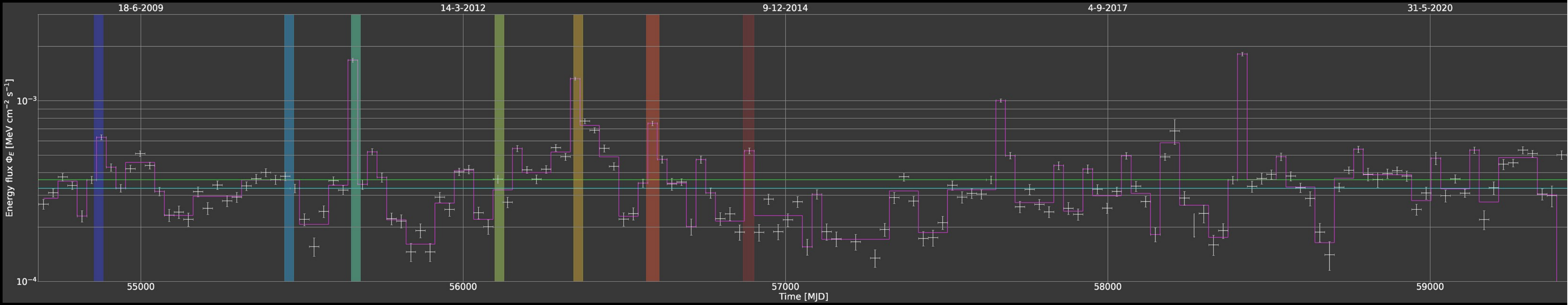


Curved power-law (logParabola)

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

+ 1-month binning

TS > 9 else 95%ULs
-
IC component
set to best-fit value from t-averaged SED
&
SYN component thawed
-
Bayesian-block analysis applied on {1 ; 3 ; 5 ; 7 ; 14 ; 30 ; 365} day-bin LCs



Previously reported flaring windows

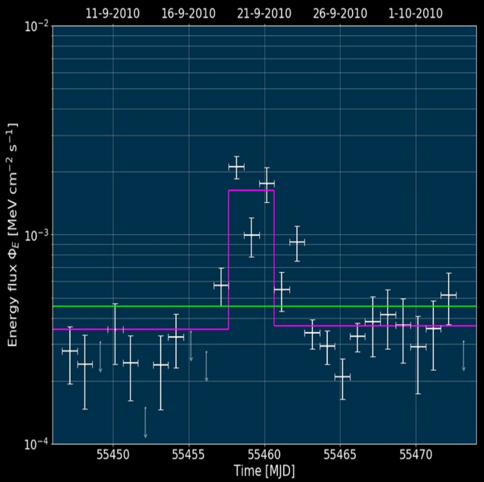
(7 flares from Mayer+15, Rudy+15)

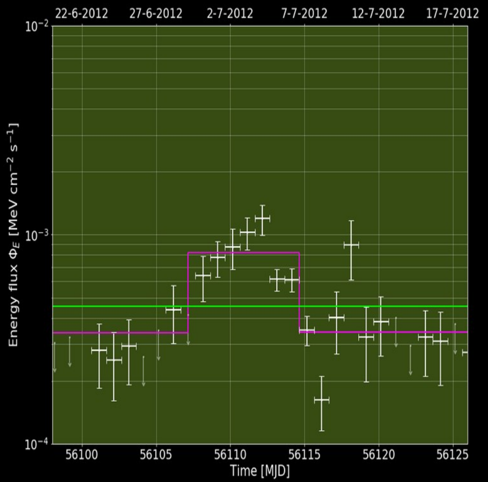
→ also in agreement with *Yeung+19, Arakawa+20, Huang+21*

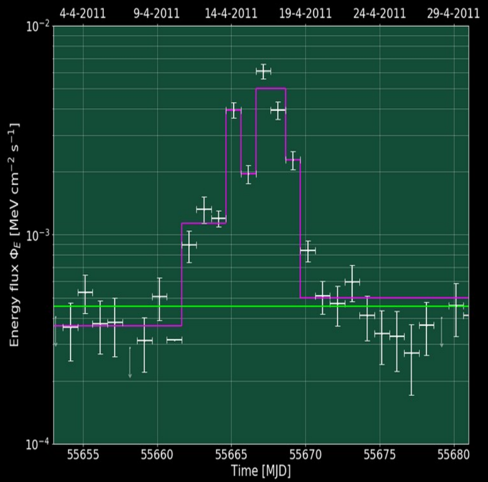
- mean Φ_E ~ 3.7 10^{-4} MeV. cm^{-2}.s^{-1}
- median Φ_E ~ 3.3 10^{-4} MeV. cm^{-2}.s^{-1}

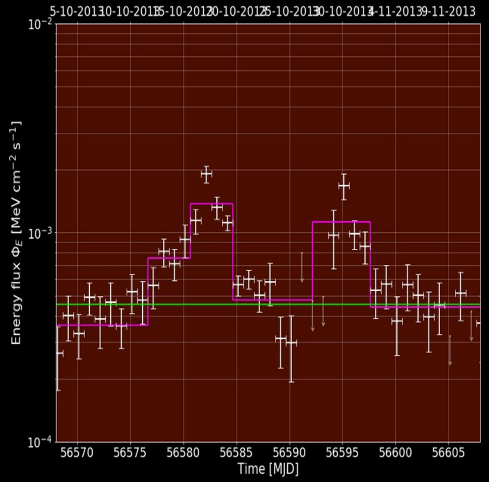
Crab flare studies

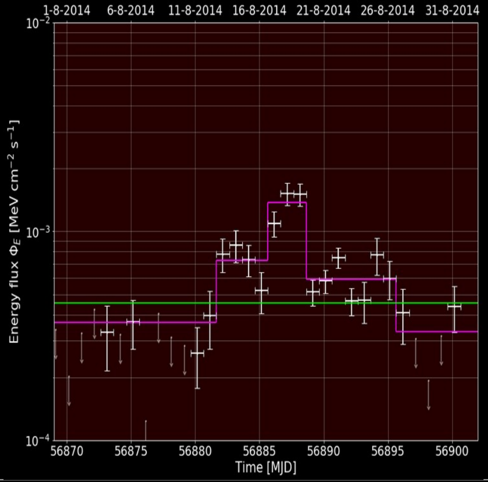
Sample of flares : LCs





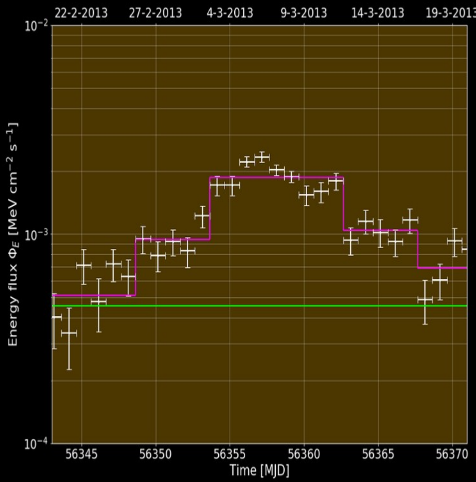




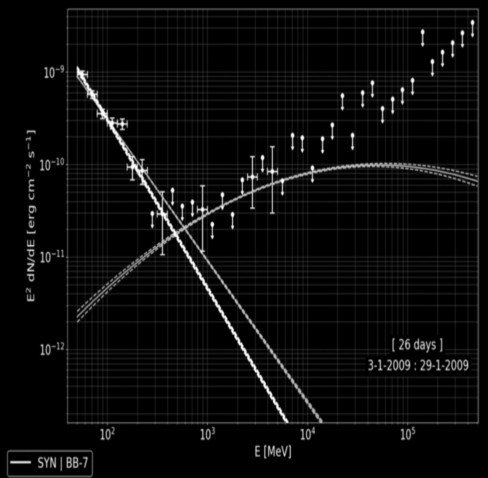


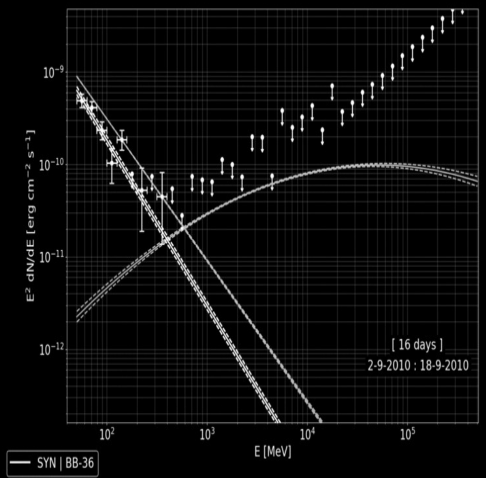
+ 1-day binning
- mean
- Bayesian blocks

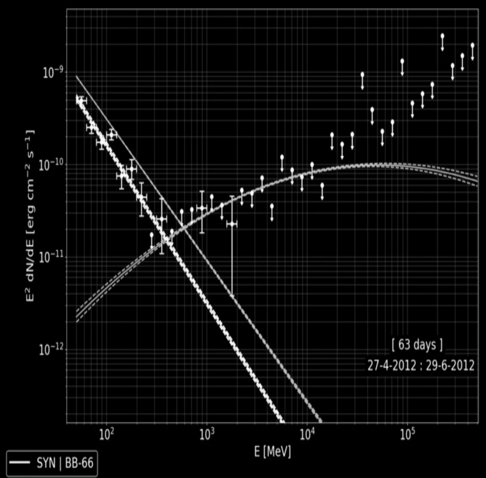
flaring windows
(pre-2015)

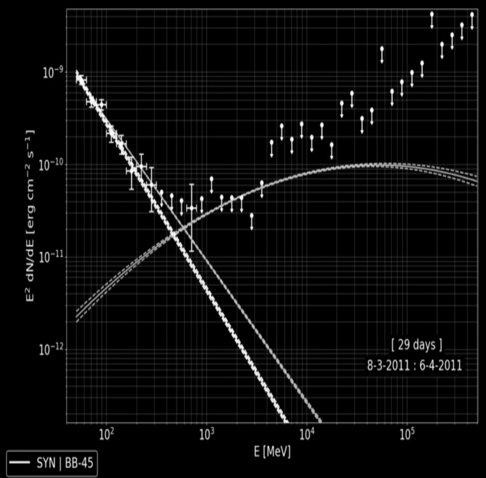


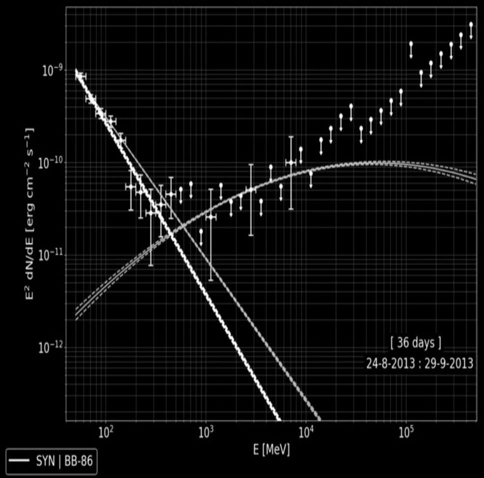
Sample of flares : SEDs during Bayesian blocks

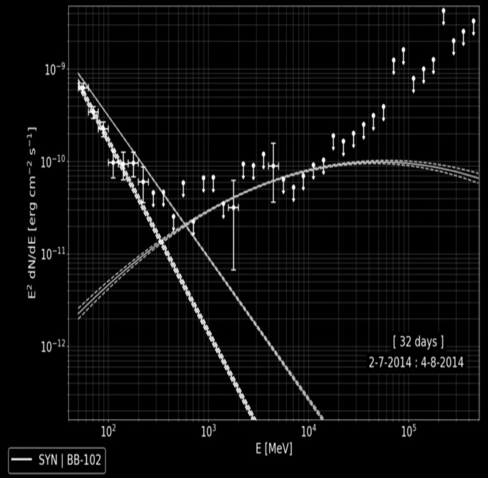






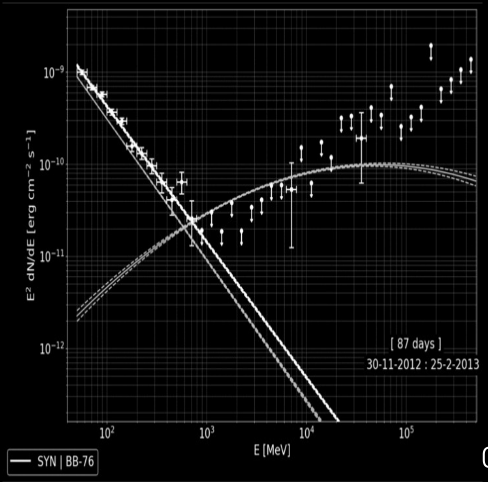


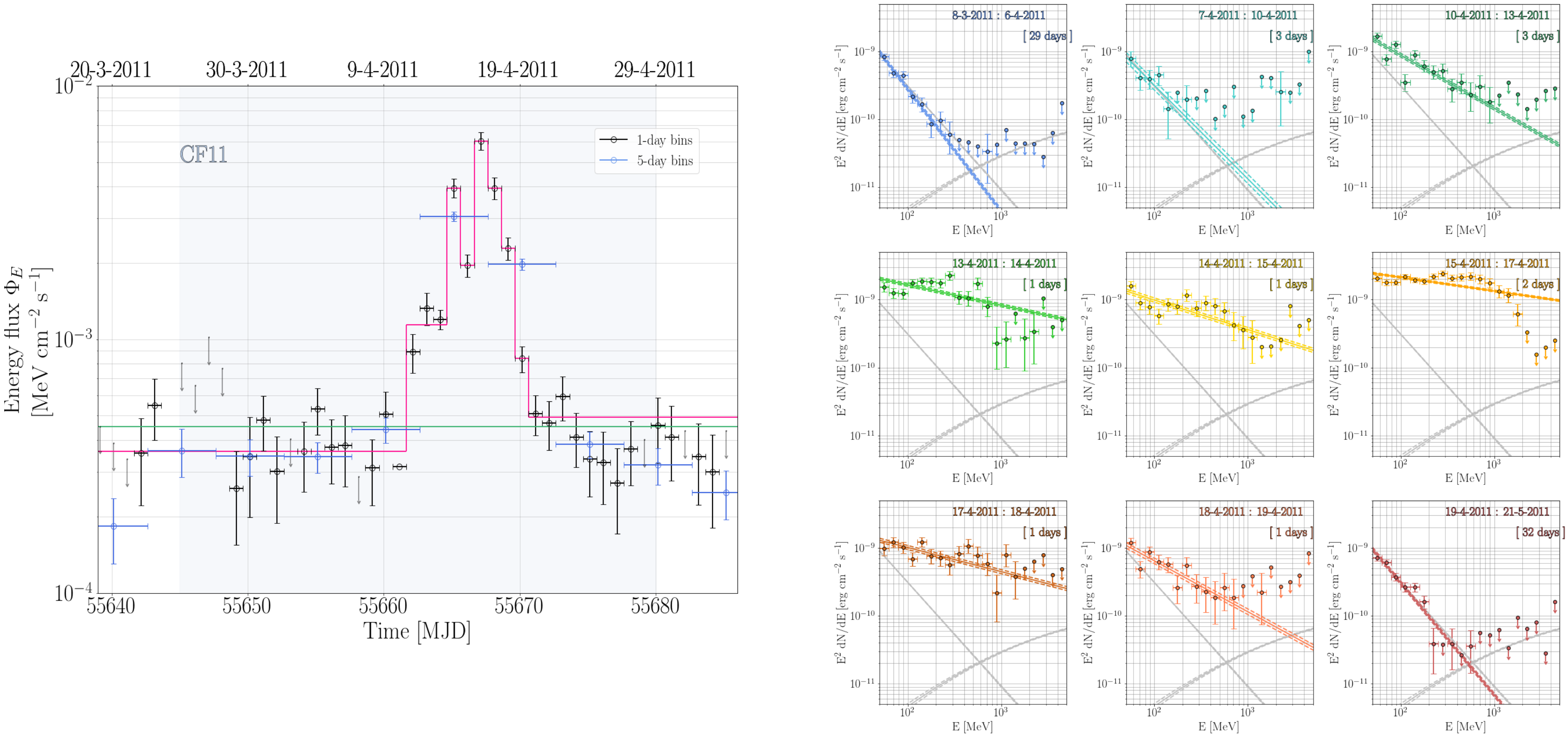




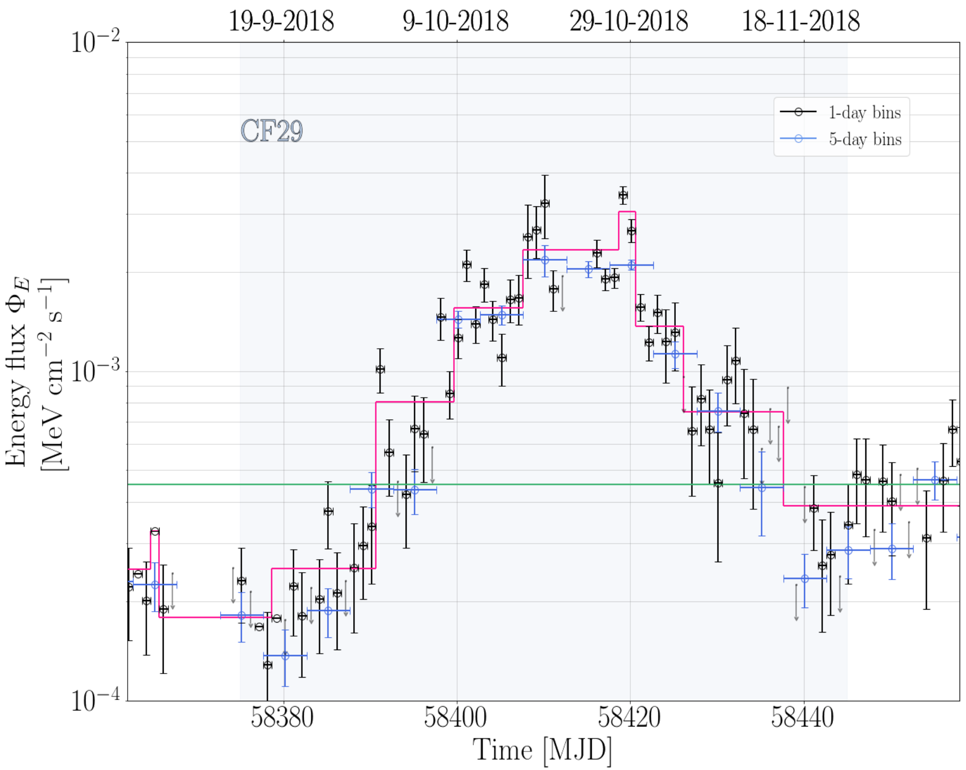
- t-averaged SED best-fit values for nebular components

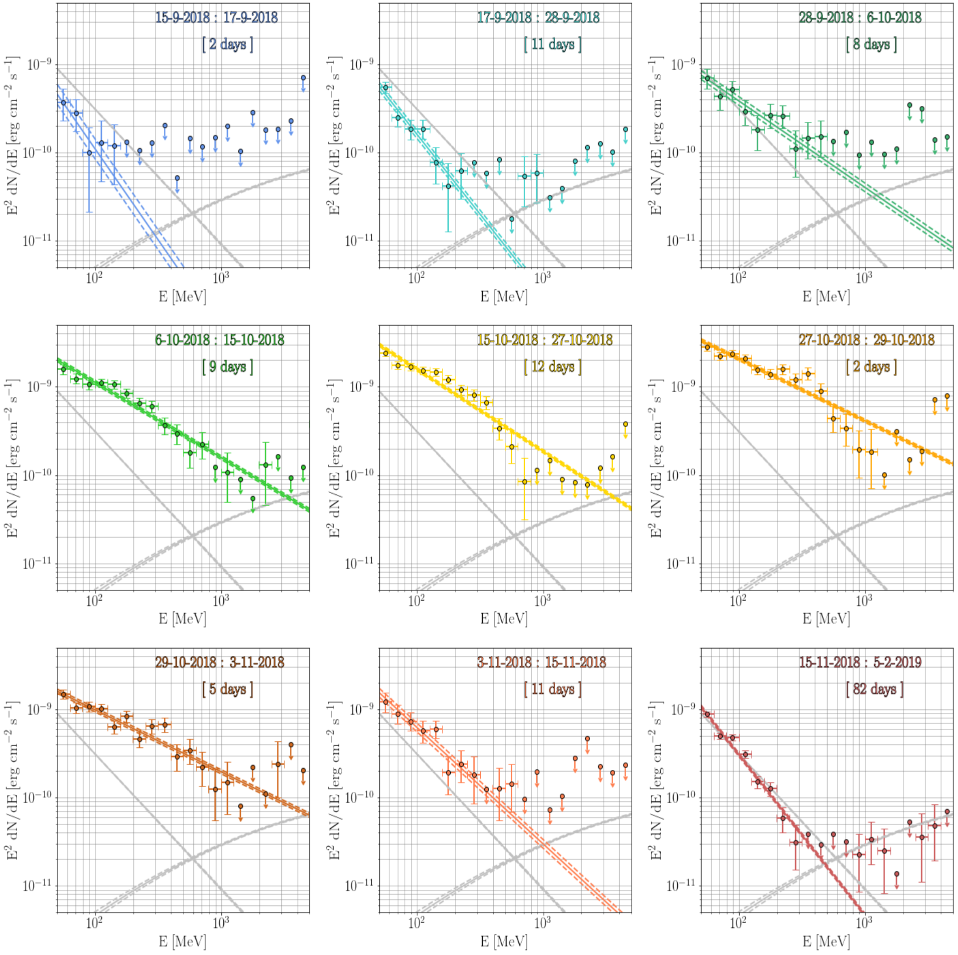
flaring windows (pre-2015)




20-3-2011
30-3-2011
9-4-2011
19-4-2011
29-4-2011
CF11
1-day bins
5-day bins
Energy flux Φ_E [MeV cm^{-2} s^{-1}]
Time [MJD]
8-3-2011 : 6-4-2011 [29 days]
7-4-2011 : 10-4-2011 [3 days]
10-4-2011 : 13-4-2011 [3 days]
13-4-2011 : 14-4-2011 [1 days]
14-4-2011 : 15-4-2011 [1 days]
15-4-2011 : 17-4-2011 [2 days]
17-4-2011 : 18-4-2011 [1 days]
18-4-2011 : 19-4-2011 [1 days]
19-4-2011 : 21-5-2011 [32 days]
E^2 dN/dE [erg cm^{-2} s^{-1}]
E [MeV]

October 2018 flare : long & bright





Are all flares similar in their behaviour?

Flare	features	rise	peak	decay	$E_{max,\varphi}$	$E_{max,e\pm}$ (B = 0.15mG)
Feb09	1	~ 1 week	3 days	~ 5 days	~ 500 MeV	~ 7.2 PeV
Sep10	~ 1?	-	3 days	-	~ 1 GeV	~ 10 PeV
Apr11	~ 2 at least	~ 3 days	< 1 day ~ 2 days	~ 2 days	> 1 GeV	> 10 PeV
Jul12	~1?	-	1 week	-	~ 800 MeV	~ 9.5 PeV
Mar13	~ 1	> ~ 5 days	> 1 week	5 days	~ 700 MeV	~ 8.4 PeV
Oct13	2	> 1 week	~ 3 days 5 days	~ 5 days	~ 650 MeV	~ 8 PeV
Aug14	~ 1 ?	> ~ 1 week	~ 3 days	~ 1 week	~ 400 MeV	~ 6.4 PeV

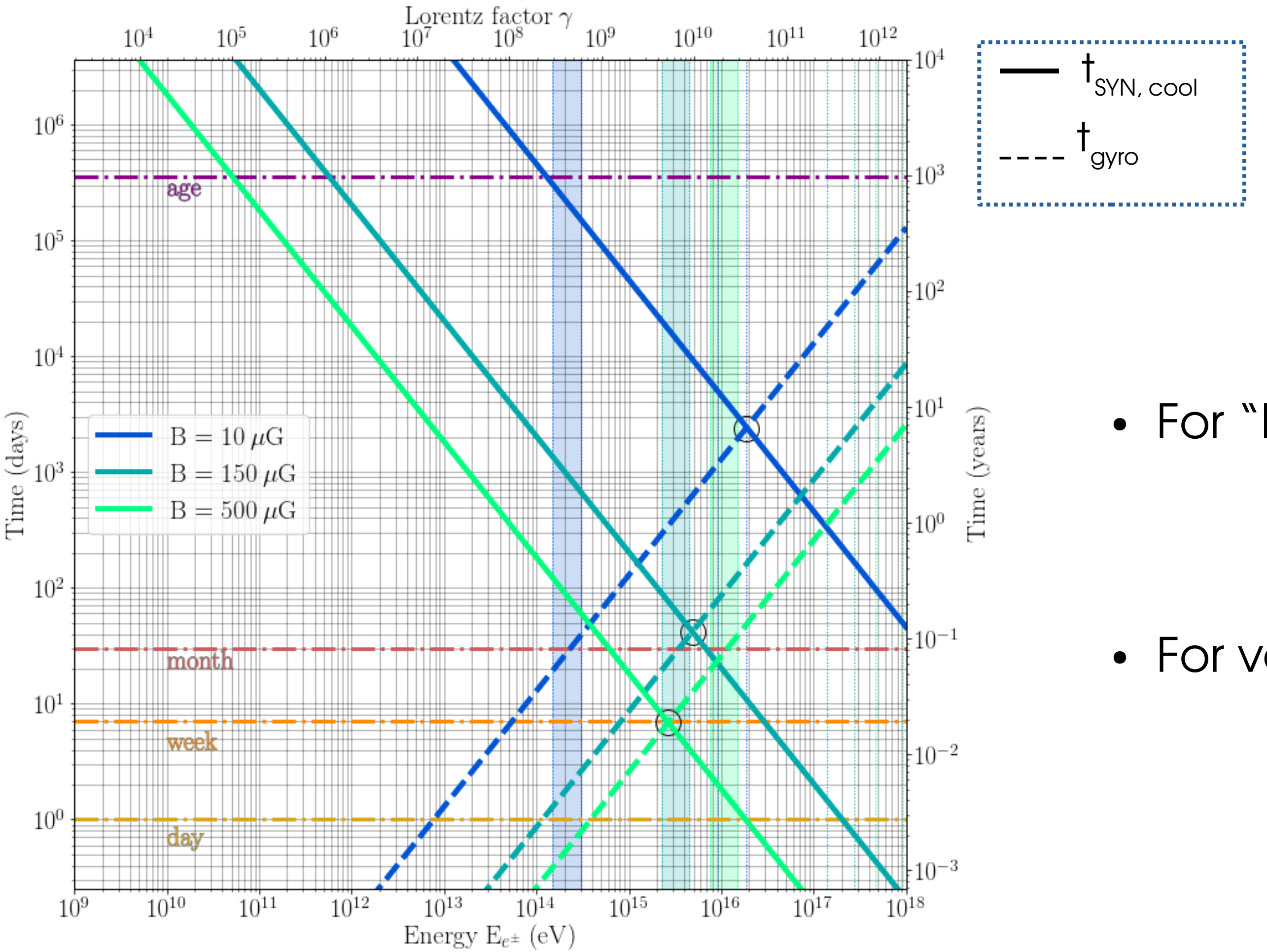
Investigations for (here 7) flaring windows

Differences for :

- Pre- and post-flaring epochs show trends
- **Duration** of flaring event
- **Variability** scale
- Features within a given flare window : "flare sub-structures"

- radiated $E_{max,\varphi} >> E_{SYN\ burn\text{-}off}$

!



Vertical lines → the Hillas criterion

.... : for R_{PWN} [1 – 2 pc]

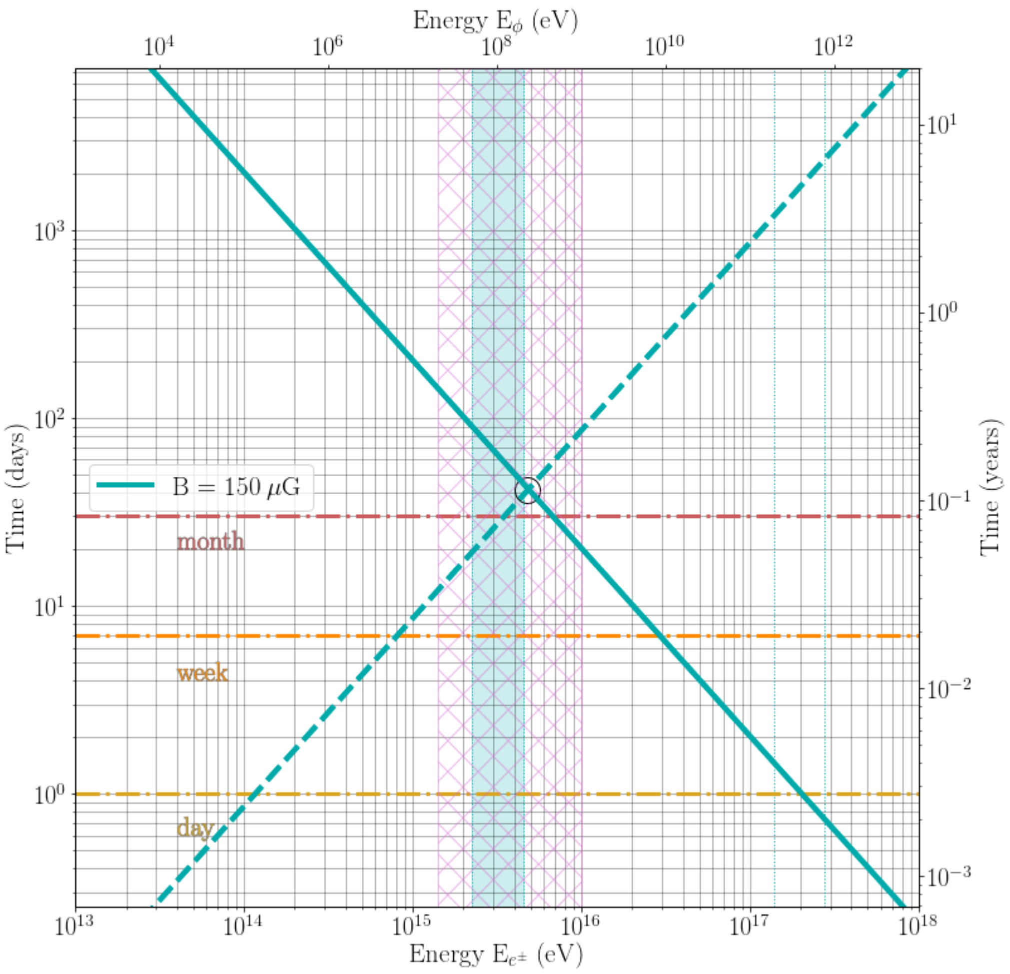
shades : for R_{PW} *

*(estimated by balancing wind ram pressure P_{PW} with the nebula pressure P_{PWN})

- For "low" B :
  $e^\pm$ ~ TeV range
  → $E_{max, \varphi}$ << MeV

- For very high B :
  synchrotron losses would dominate

Synchrotron burn-off limit



— $t_{SYN,\,cool}$

- - - - t_{gyro}

Vertical lines → the Hillas criterion

………. : for R_{PWN} [1 – 2 pc]

shades : for R_{PW} *

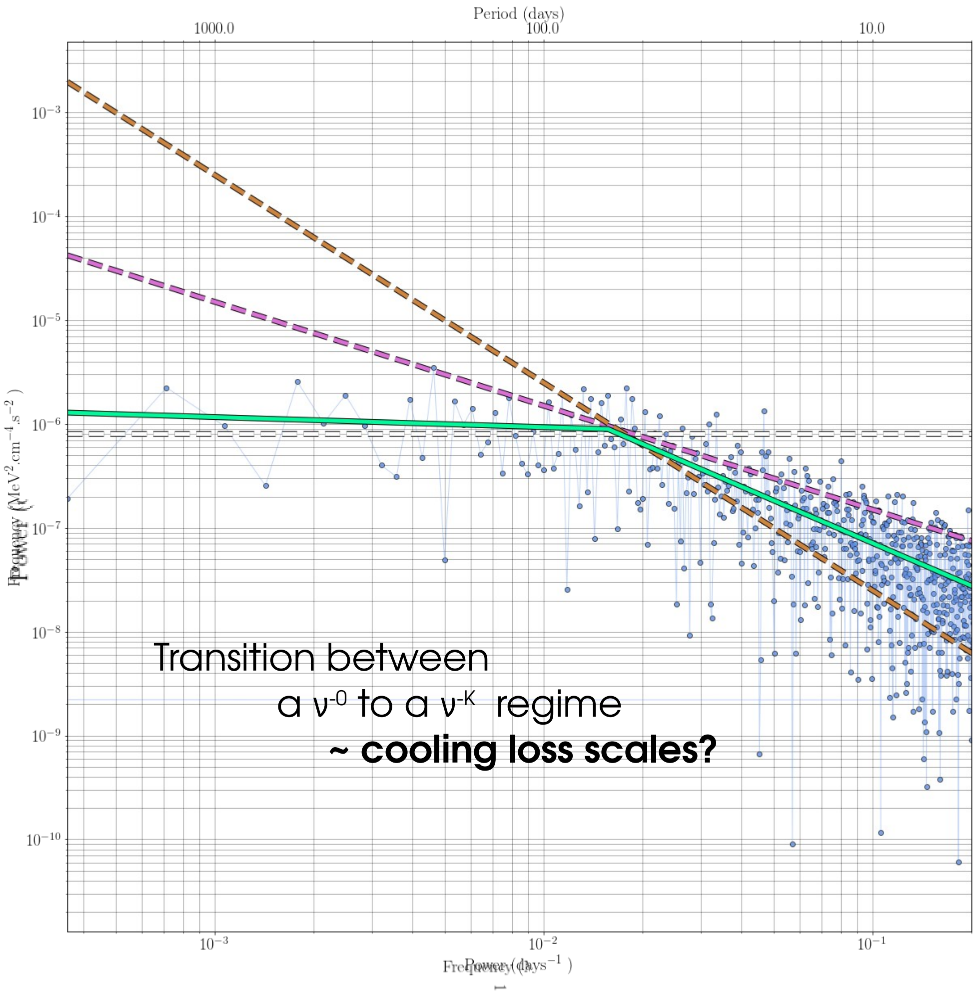
*(estimated by balancing wind ram pressure P_{PW} with the nebula pressure P_{PWN})

Assuming B ~ 150 μG
→ leptons accelerated
up to ~ **5 PeV**
in a synchrotron
MHD flow :

→ $\mathbf{E_{max}}$ ~ [70 MeV – 230 MeV]

&

synchrotron variability would be expected
for timescales
of ~ **40-50 days**



Power spectrum for the complete 13-yr dataset LCs

- Using Fourier space to investigate emerging scales for several sub-samples
- Noise
  → filter signal (low-pass)
  → **white** (ν^{-0}) +
  pink (ν^{-1}) [+ **Brownian** (ν^{-2})] noise?

Could the flares be a signature of ...

highly efficient acceleration in the PW

+

nebular emission process ?

Unraveling origin(s) & acceleration mechanism(s) ?

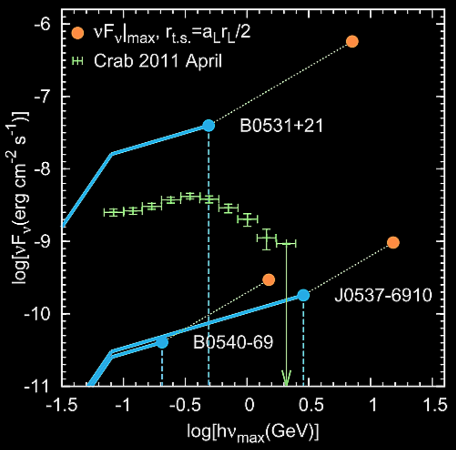
Open questions :

o Origin of the flares? Universality ?
o Acceleration site
(light-cylinder vicinity, inner-knot, close to TS, shock interface?)
o Which mechanism at play for the short-timescale variability?

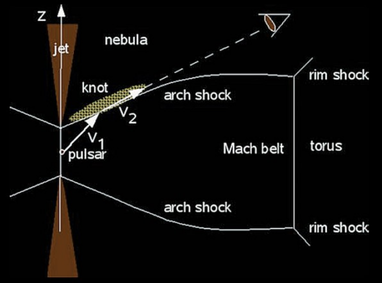
Models rely on system conditions
(B-field strength, bulk Lorentz factor, topology, anisotropy, ...)

? Inductive acceleration model
Kirk & Giacinti 2017

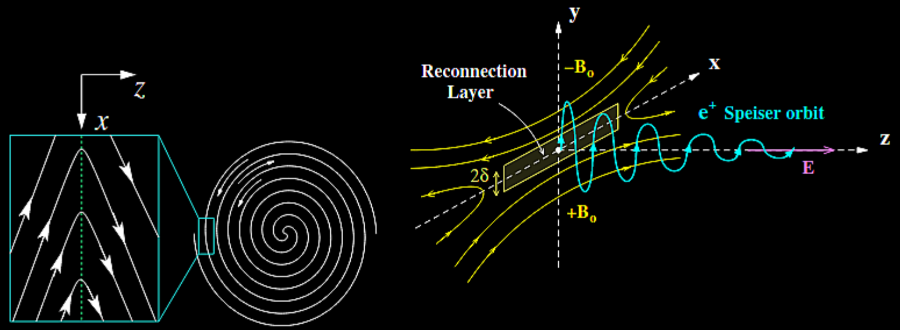
Drop in ρ_e with R
→ possible origin
of "inductive" spikes
via low-density pockets
injected radially as a beam
by the PW into the PWN



? High Doppler boosting
(relativistic beaming downstream)
e.g : *Komissarov & Lyutikov 2011*, ++



? Magnetic reconnection
in the PW + boosting
i.e : *Kirk 2004, Cerutti et al 2013*, ++



? Acceleration in TS + 2-zone model
? other

The flaring behaviour of the system in HE γ-rays

Study based on the 13-year-long monitoring of Crab PWN emission detected in [50 MeV – 500 GeV] :

- Gated pulsar emission with observed glitches taken into account
- Spectro-morphological model of both nebular components
- Investigation for day-week-month timescales via Bayesian analysis

Power spectra examination + selected flux-level samples
& samples of candidate flaring epochs

~ 34 candidate flaring windows [2008 - 2021]

Flaring behaviour:
Not driven by a single mechanism?

→ flare characteristics pointing to different observational signatures!

Interpretation relying on the observed
energy-dependence & time variability of the synchrotron associated emission

→ intense flaring contributes to the unabridged Crab PWN spectrum **?**
→ possible nebular origin of the flares **?**
(→ acceleration ~ TS and anisotropic injection then cooling in the PWN?)

Back-up