Assessing the flaring behaviour of the Crab pulsar wind nebula system in high-energy ranges

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Investigations conducted with
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MAX-PLANCK-GESELLSCHAFT
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

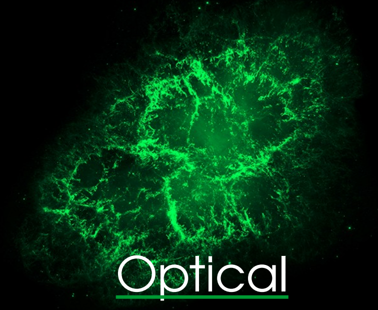
The Crab system : multi-wavelength emission

NSF/NRAO/VLA

Radio

NASA/ JPL/ Caltech

Infrared



NASA/ STScI

Optical

The Crab nebula :

{ pulsar (**PSR**)

+ pulsar wind nebula (**PWN**)

+ supernova remnant (**SNR**) evidence}

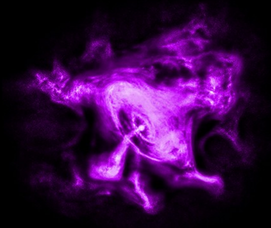
Remains of SN 1054

(records of its observation found around the world!)

Composite image taken from NASA/Chandra X-ray Observatory release

ESA/ XMM-Newton

Ultraviolet

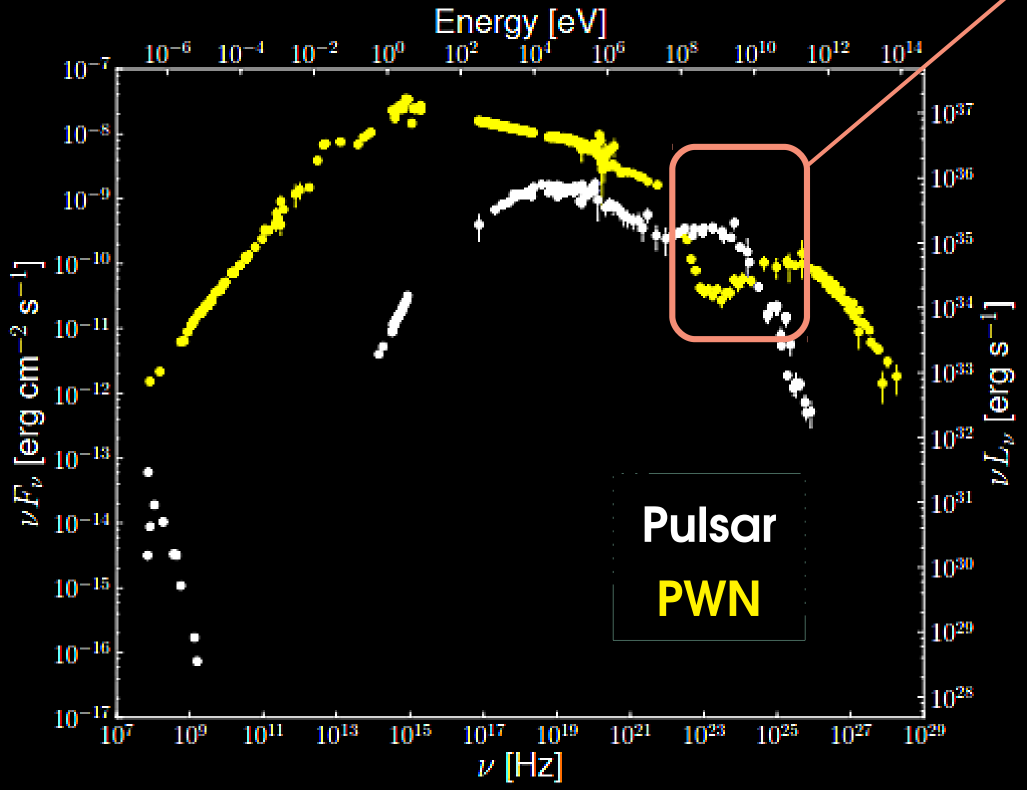


NASA/ CXC/ SAO

X-ray

Bühler & Blandford 2014

(+ references within)

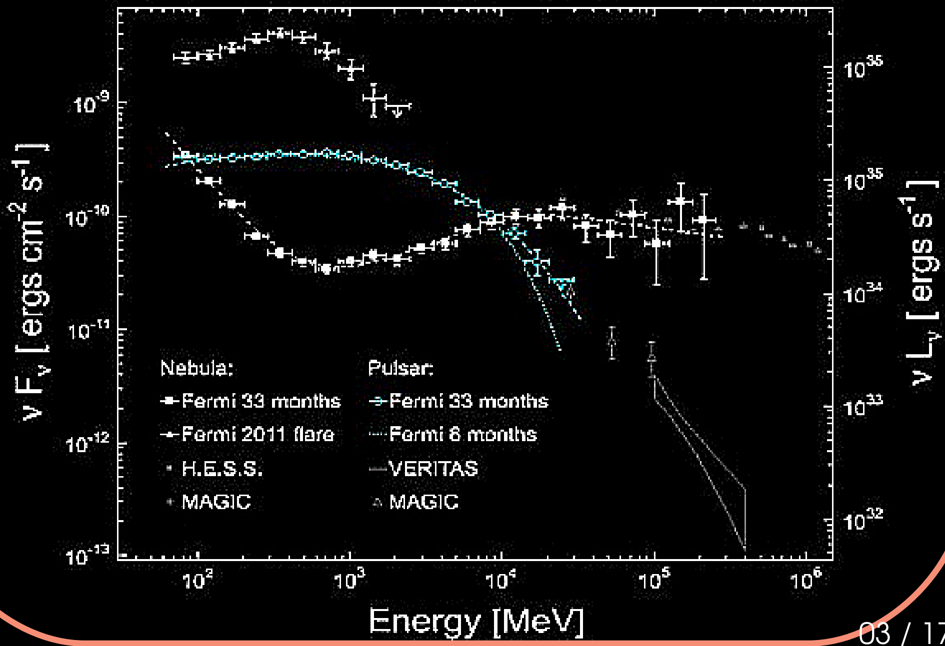


High-energy γ-ray regime :

→ Fermi Gamma-ray Space Telescope

- Large Area Telescope :

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

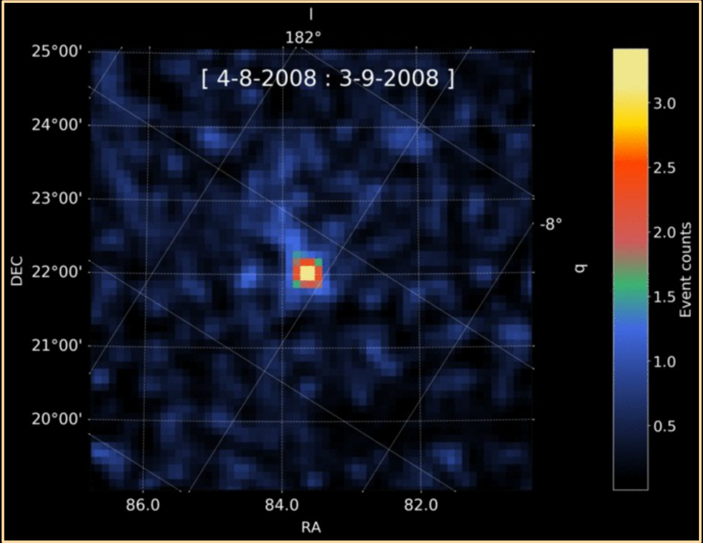


Fermi-LAT public available photon data and spacecraft files, analysed with `Fermitools` & `fermipy`:

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



Month-long energy-stacked raw event sky map

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

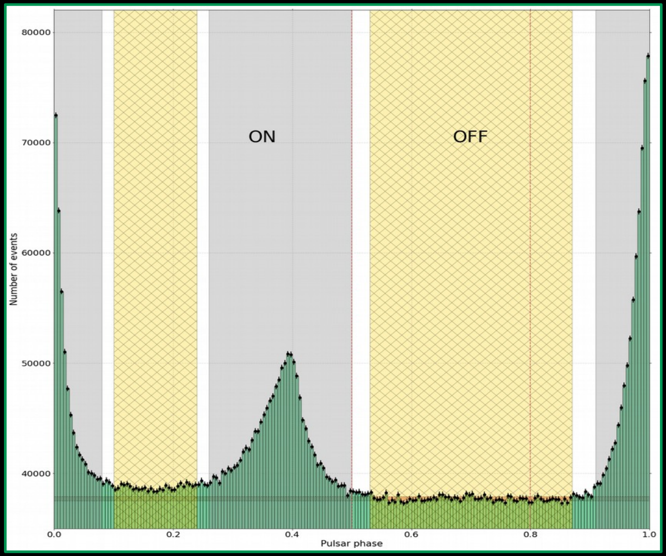
Fermi-LAT public available photon data and spacecraft files, analysed with `Fermitools` & `fermipy`.

BUT

Bright HE pulsar emission is dominant w.r.t
synchrotron (SYN) and inverse Compton (IC) nebular components,
especially for < 10 GeV ranges

→ need to "gate" the pulsar emission
by selecting the events that are in the "**OFF**" pulsar phase

Public *Jodrell-Bank Observatory* ephemerides
→ `tempo2` time analysis
+ account for both {pre & post} pulsar glitching epochs

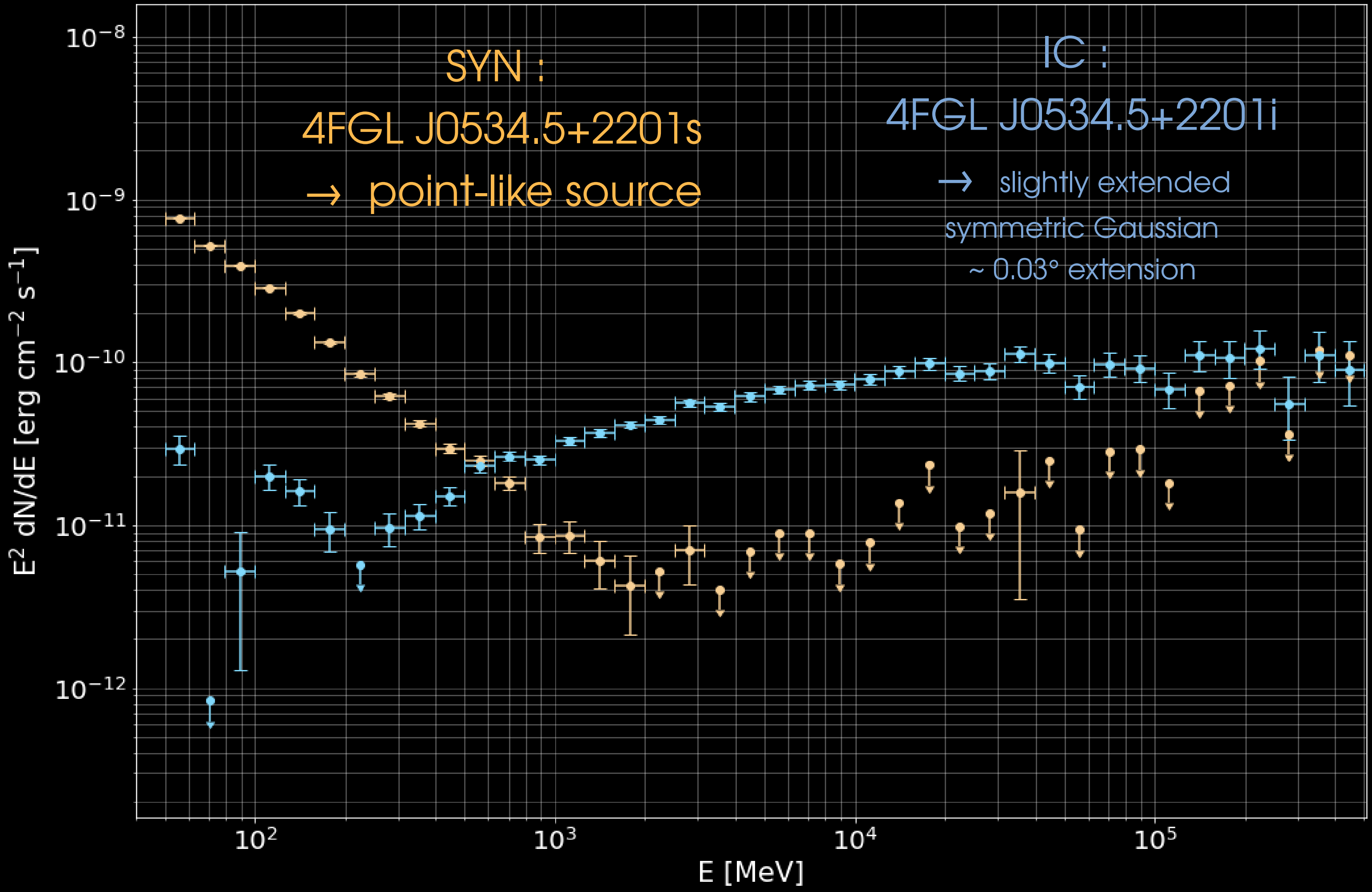


Pulsar
rotational energy ↓ steadily due to braking
BUT
sudden powerful ↑ have been observed :

31 glitches in the JB catalogue for the Crab
→ **6** during our Fermi-LAT observation span

We proceed by selecting (conservatively)
ONLY the events
in the **(0.53 – 0.87)** pulsar phase range
→ pulsar emission negligible

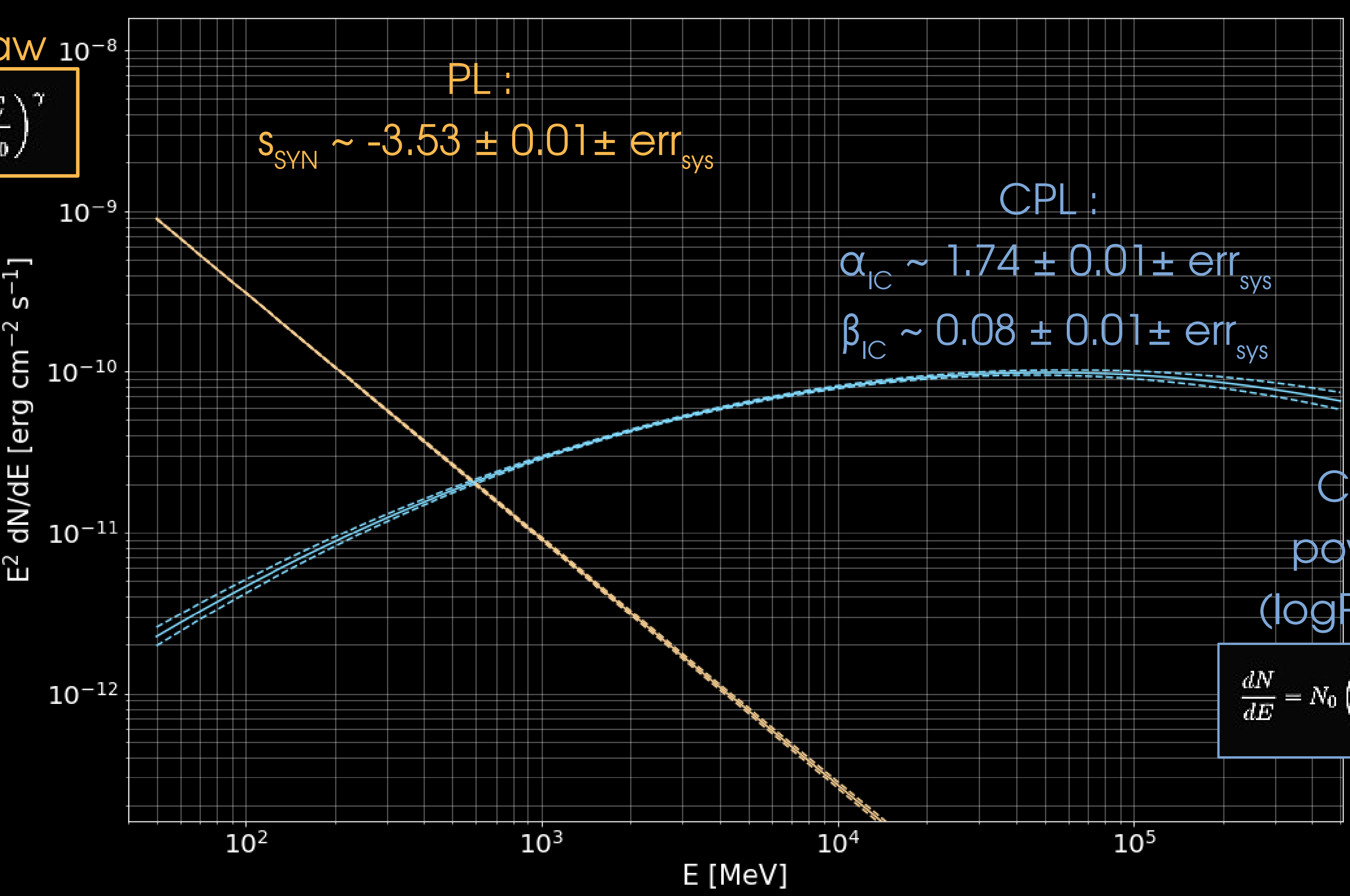
Time-averaged spectral energy distribution



Time-averaged SED

Power-law

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



PL :

s_{SYN} ~ -3.53 ± 0.01± err_{sys}

CPL :

α_{IC} ~ 1.74 ± 0.01± err_{sys}

β_{IC} ~ 0.08 ± 0.01± err_{sys}

Curved power-law (logParabola)

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

+ 1-month binning

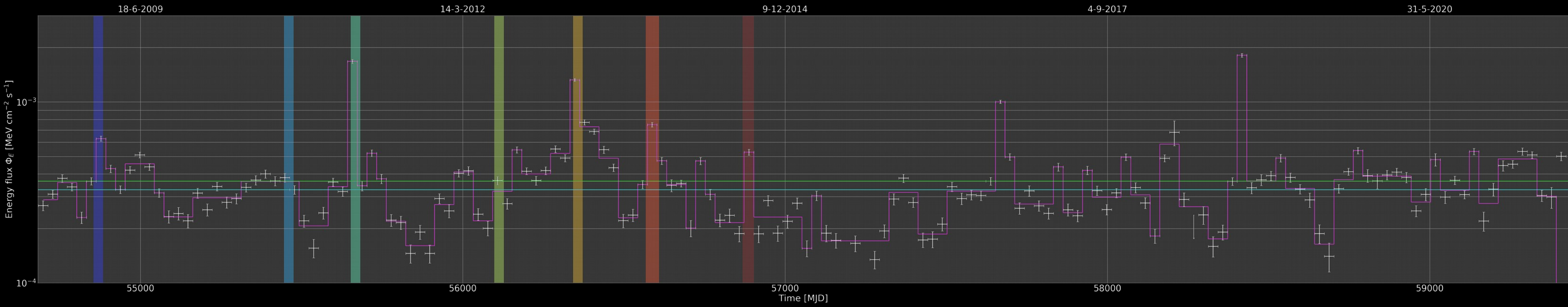
TS > 9 else 95%ULs

-

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

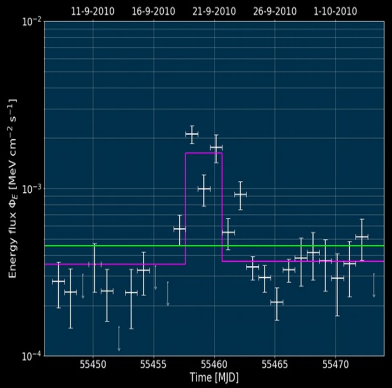
(7 flares from Mayer+15, Rudy+15)

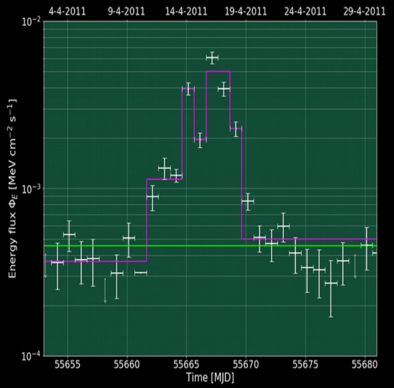
→ also in agreement with *Yeung+19, Arakawa+20, Huang+21*

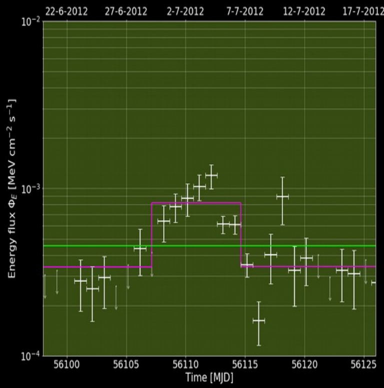
Crab flare studies

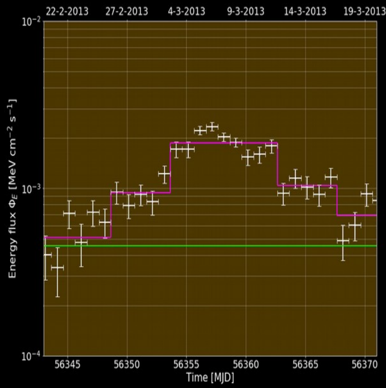
- mean $\Phi_E \sim 3.7\ 10^{-4}$ MeV. cm^{-2}.s^{-1}
- median $\Phi_E \sim 3.3\ 10^{-4}$ MeV. cm^{-2}.s^{-1}

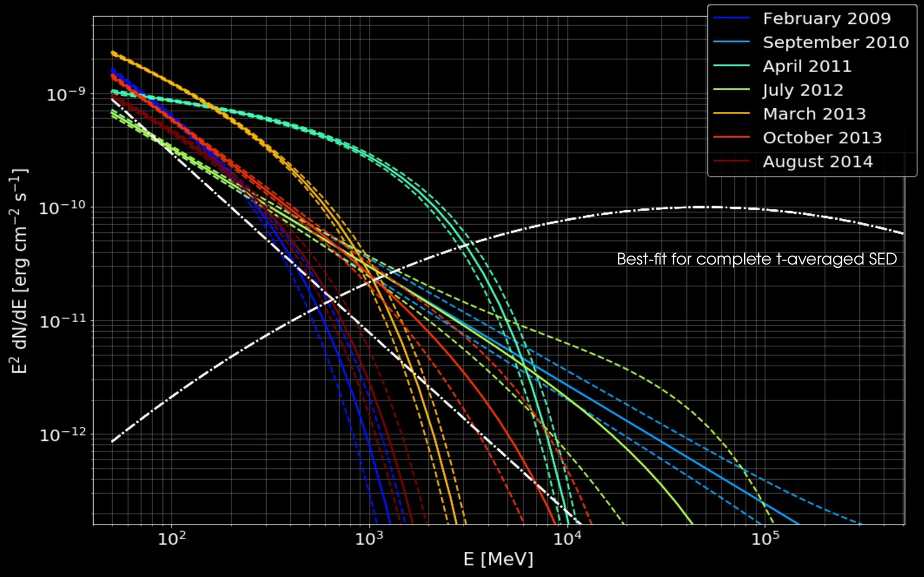
Flare characterisation : light curve











Investigations for (here 7) flaring windows

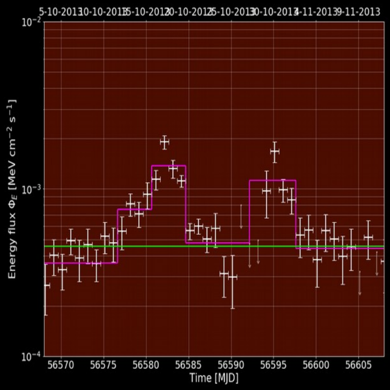
→ **IC** fixed

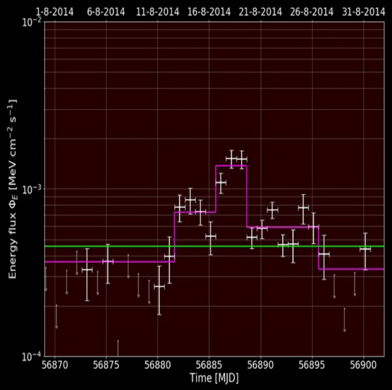
→ **SYN** fitted

as an exponential cut-off PL **(ECPL)**

Compared to PL assumption (Δ d.o.f = 1, so $\sqrt{TS} \sim \sigma$)

- For 2 : PL is preferred (with <2σ)
- For 1: both shapes are equivalent
- For 2: slight preference for ECPL (2.5σ< . < 3σ)
- For 2: clearly an ECPL is significant



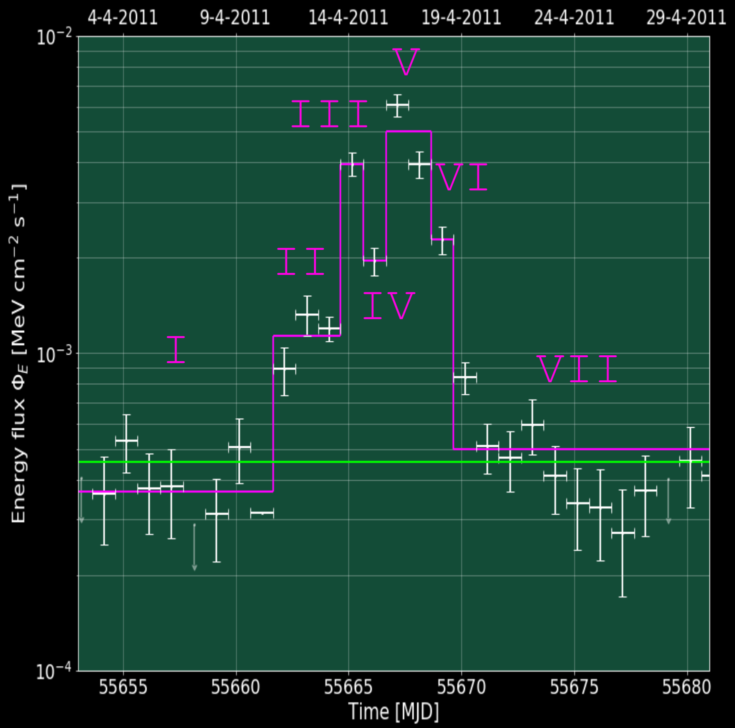


+ 1-day binning

mean

Bayesian blocks

flaring windows (pre-2015)



+ 1-day binning

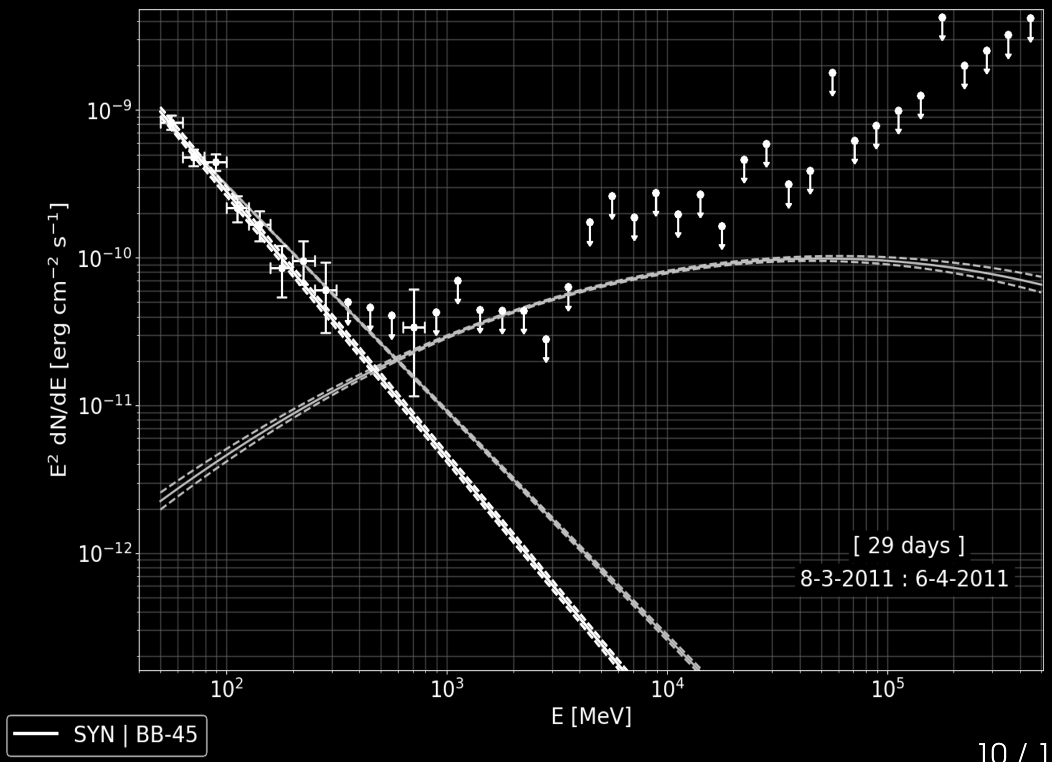
mean

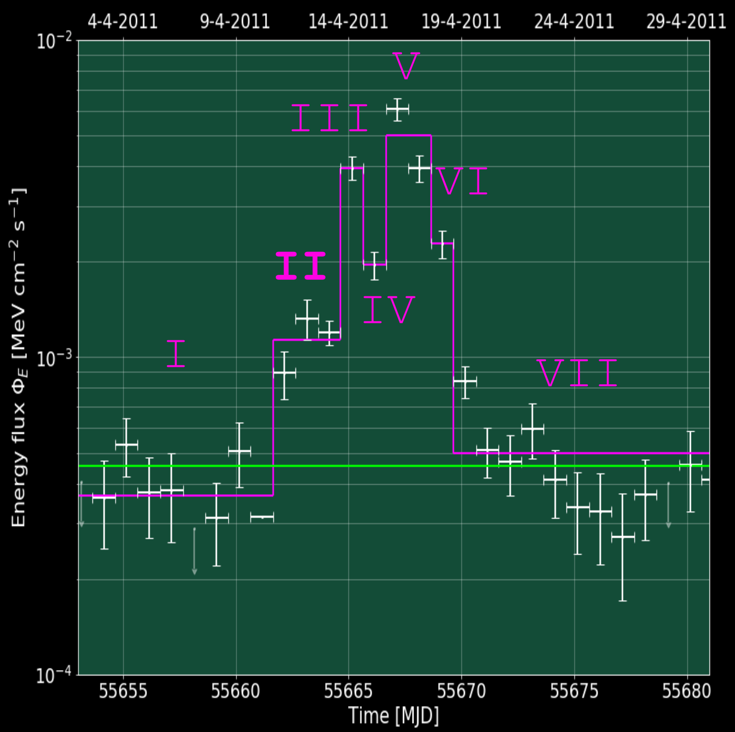
Bayesian blocks

flaring windows (pre-2015)

pre-flare epoch : < I

- - - Best-fit for complete t-averaged SED

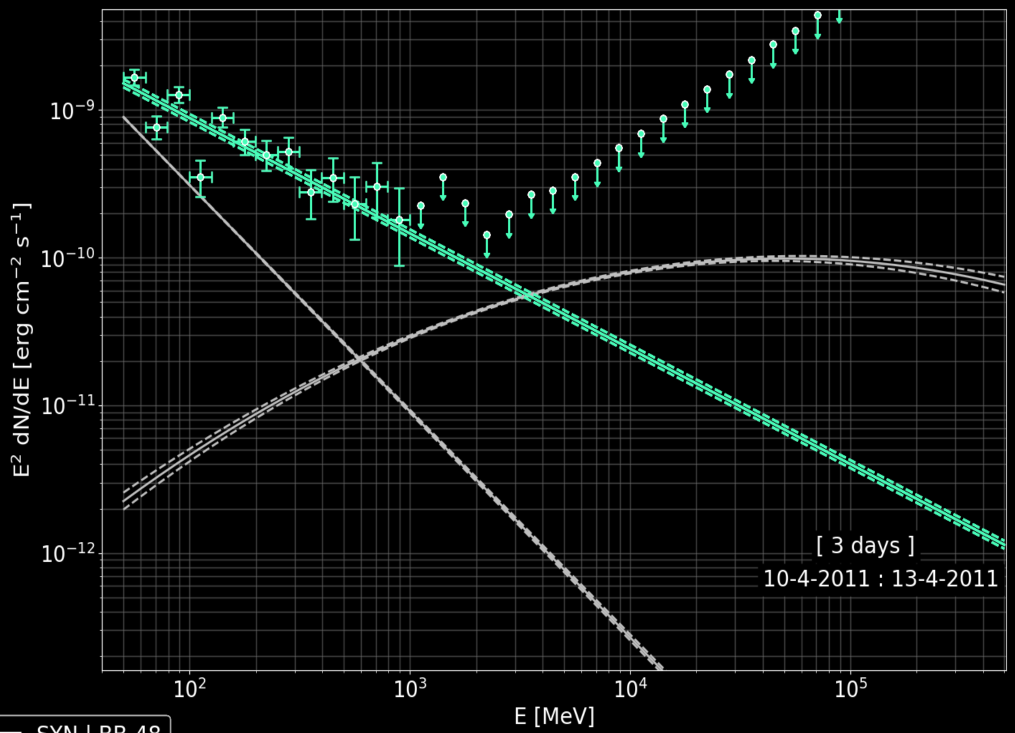




+ 1-day binning
mean
Bayesian blocks
flaring windows (pre-2015)

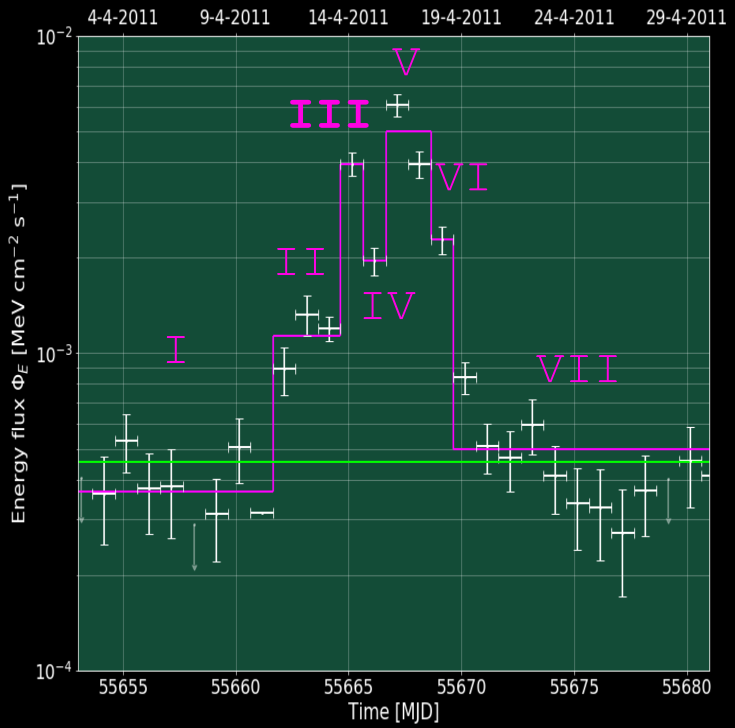
flare epoch : II

- - - Best-fit for complete t-averaged SED



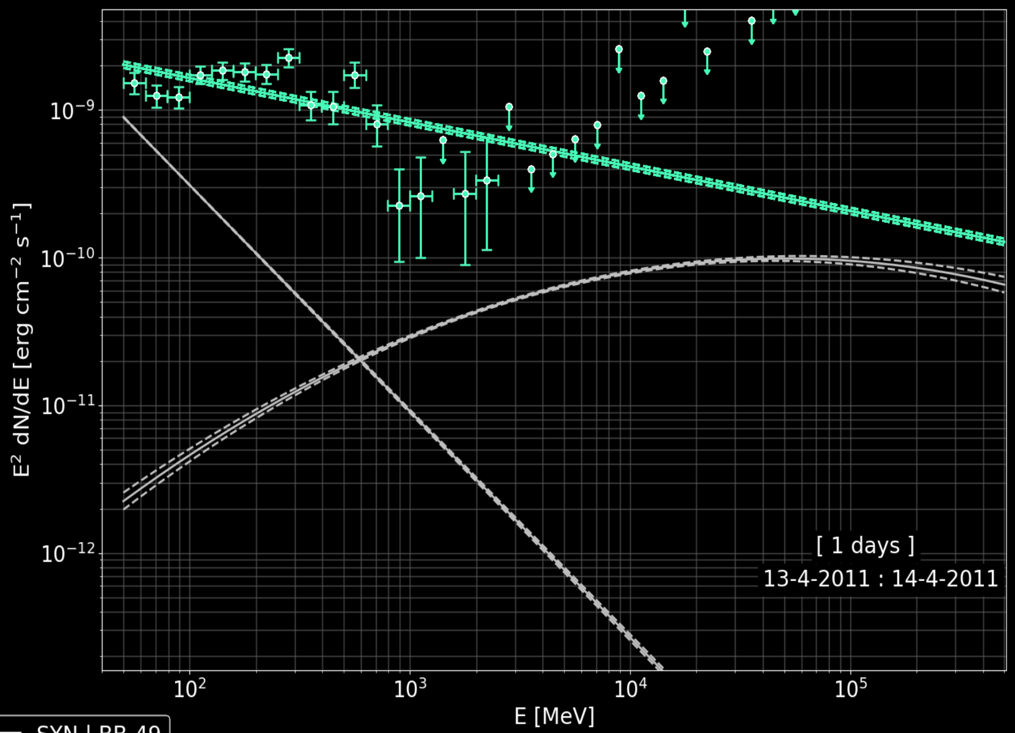
SYN | BB-48

Bright flares : April 2011



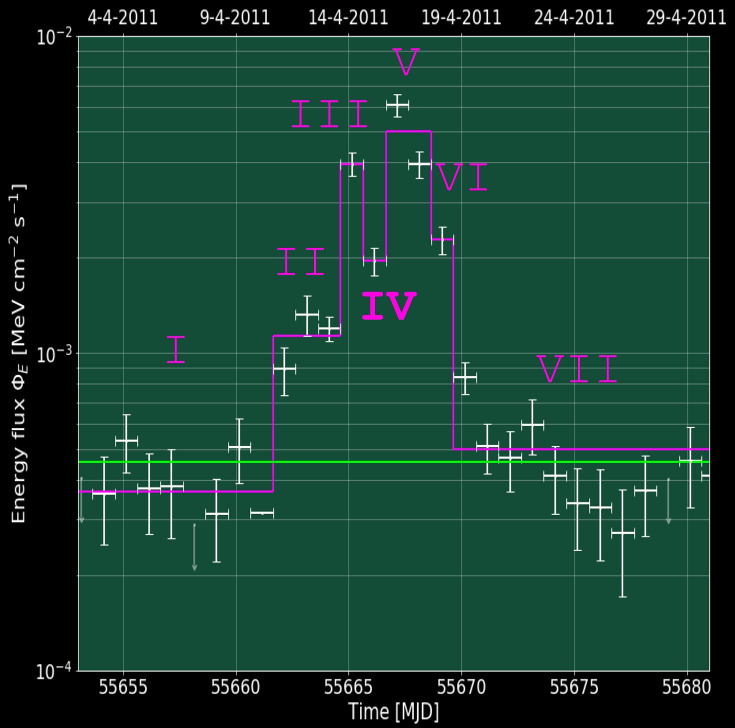
flare epoch : III

- - - Best-fit for complete t-averaged SED



SYN | BB-49

+ 1-day binning
mean
Bayesian blocks
flaring windows (pre-2015)

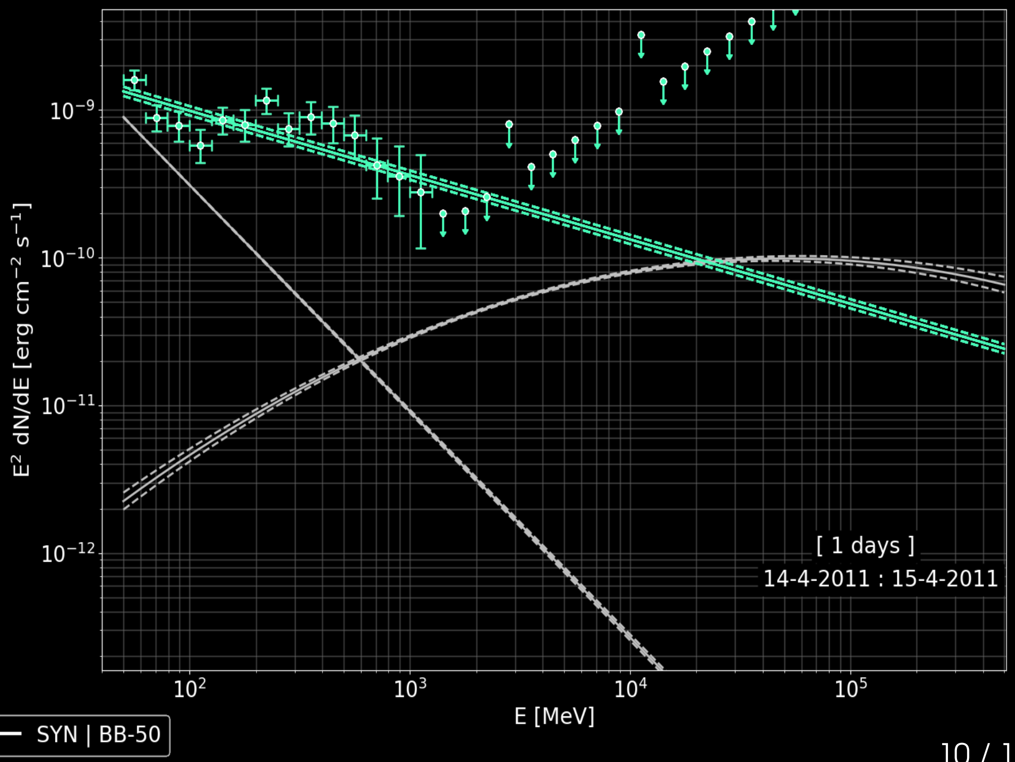


+ 1-day binning
mean
Bayesian blocks

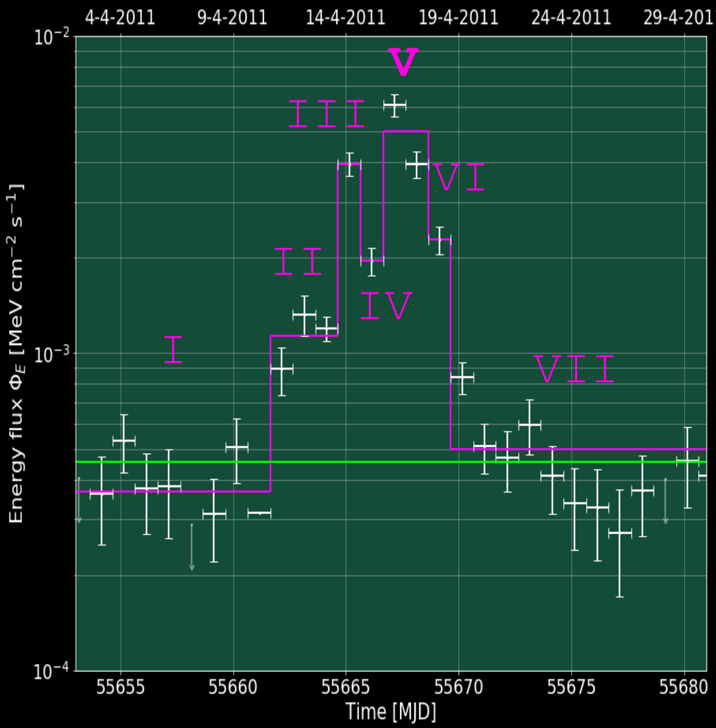
flaring windows (pre-2015)

flare epoch : **IV**

- - - Best-fit for complete t-averaged SED



Bright flares : April 2011



+ 1-day binning

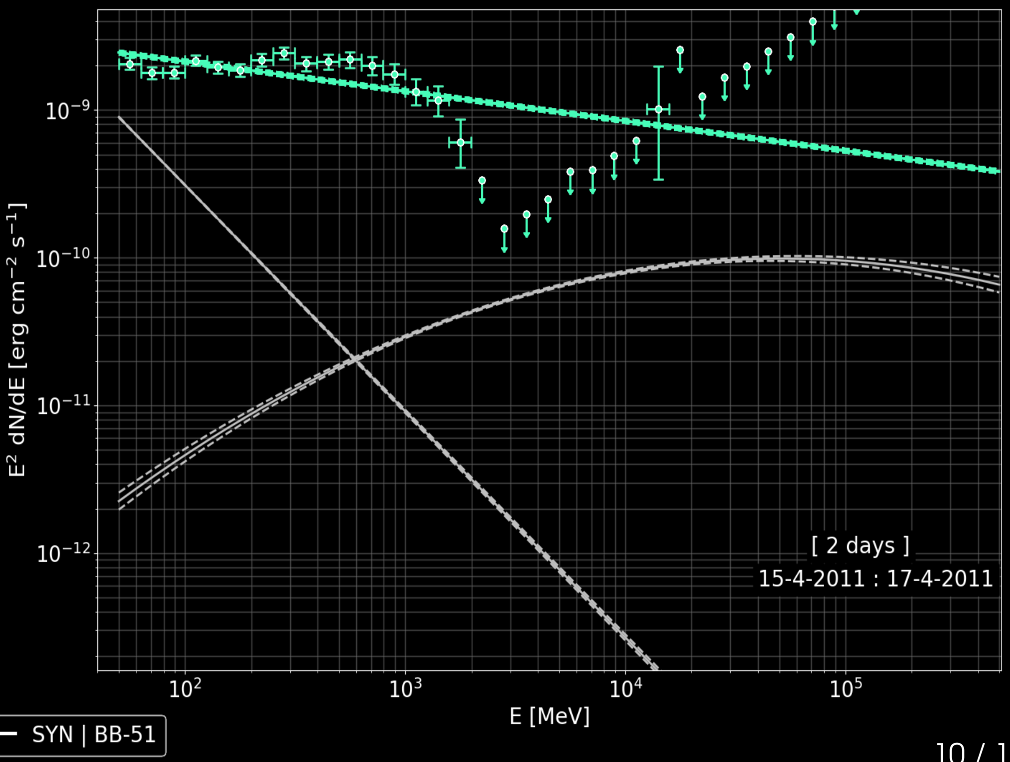
mean

Bayesian blocks

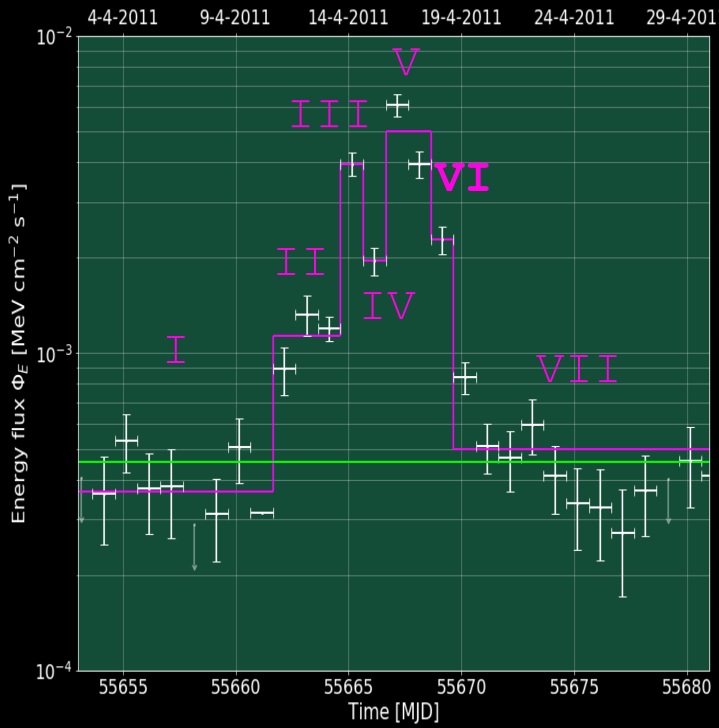
flaring windows (pre-2015)

flare epoch : V

- - - Best-fit for complete t-averaged SED



Bright flares : April 2011



+ 1-day binning

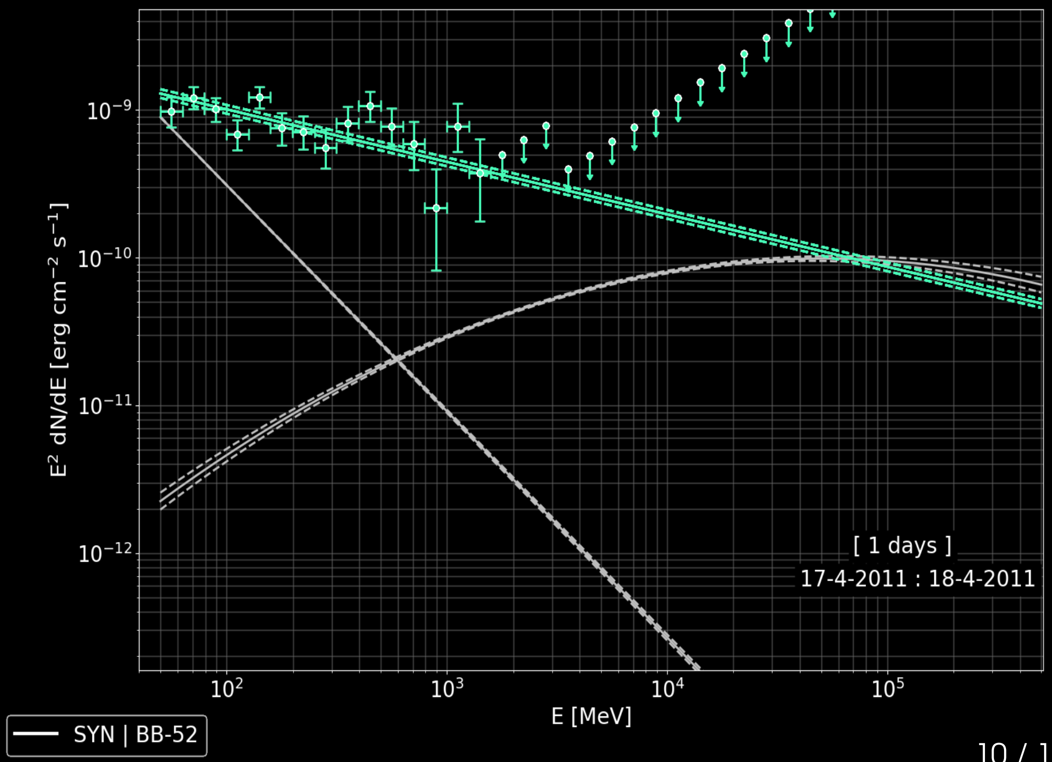
mean

Bayesian blocks

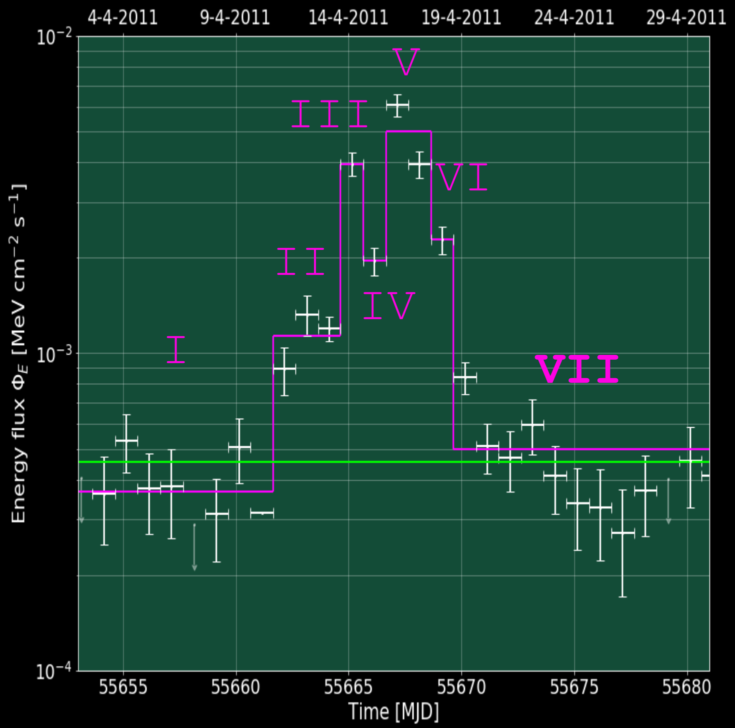
flaring windows (pre-2015)

flare epoch : VI

- - - Best-fit for complete t-averaged SED



Bright flares : April 2011



+ 1-day binning

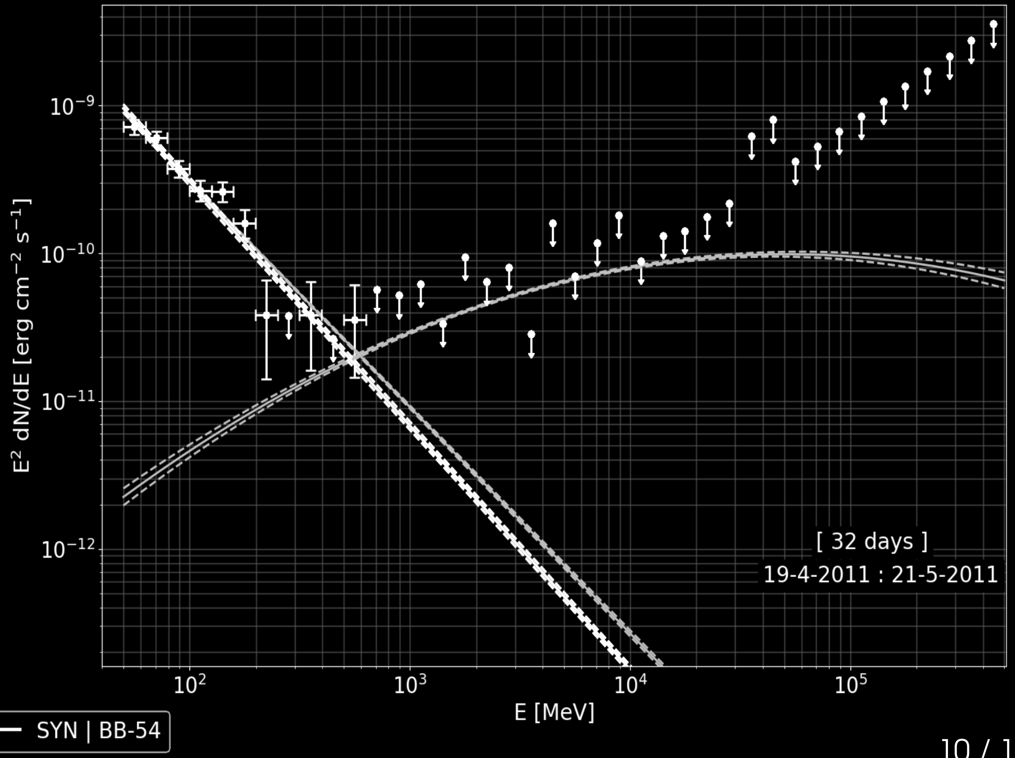
mean

Bayesian blocks

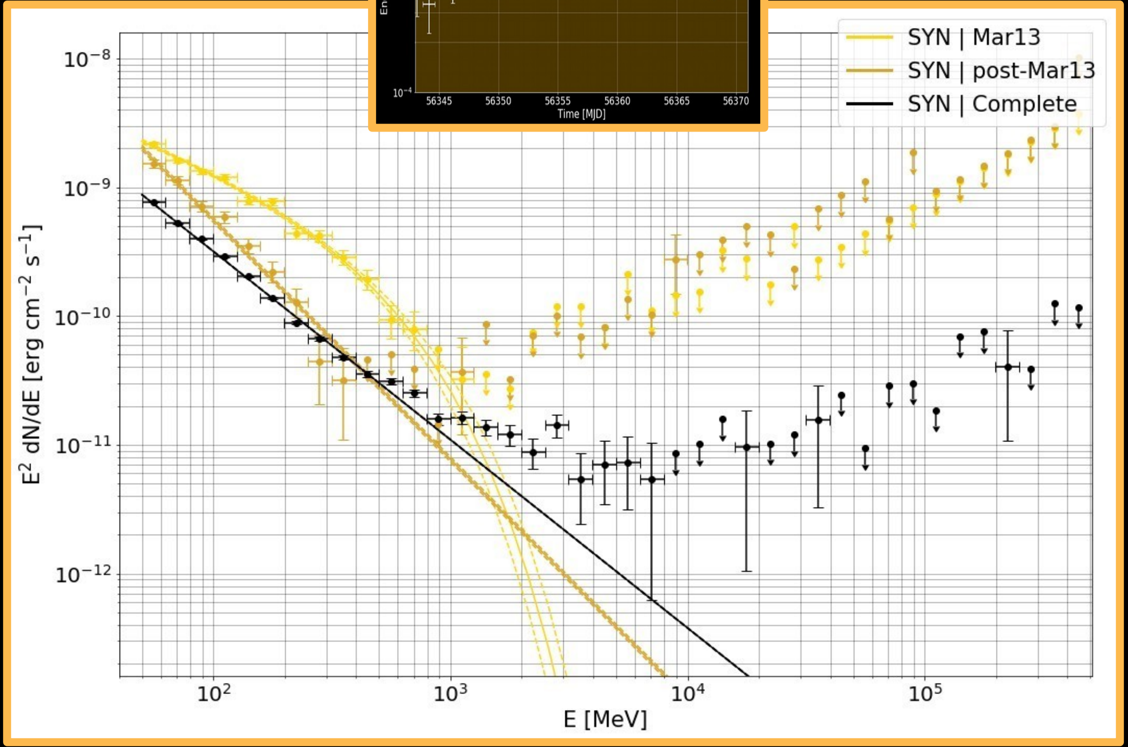
flaring windows (pre-2015)

Post-flare epoch : VII

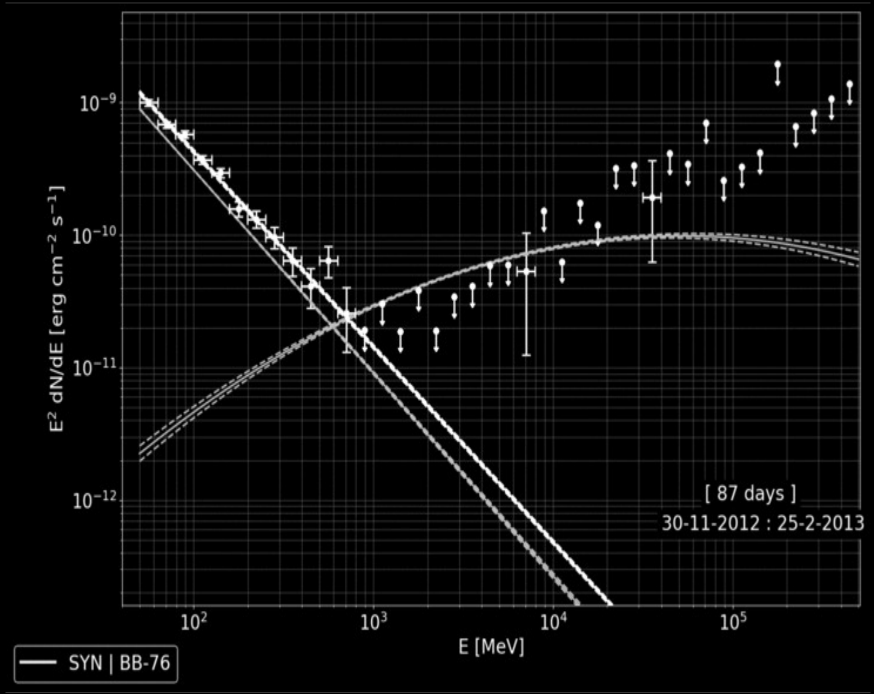
- - - Best-fit for complete t-averaged SED

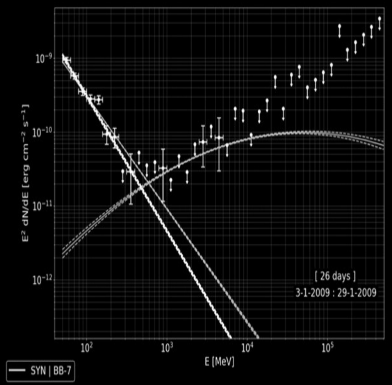


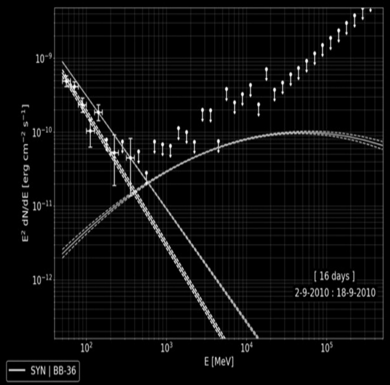
+ 1-day binning
mean
Bayesian blocks
flaring windows (pre-2015)

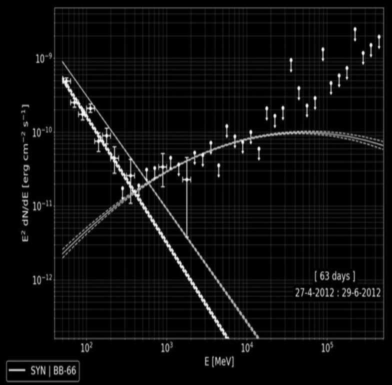


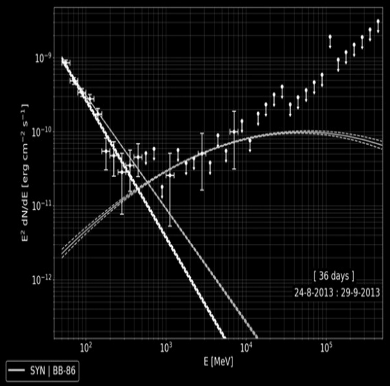
Increased synchrotron flux-levels
for **> 1 month beyond the flaring window...**

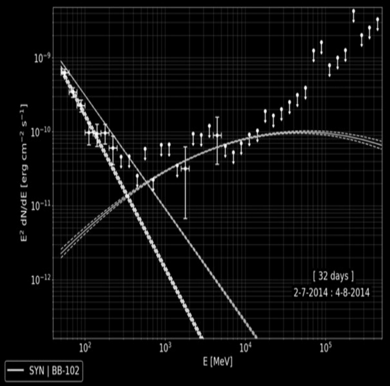












Flare	features	rise	peak	decay	$E_{max, \varphi}$	$E_{max, e\pm}$ (B = 0.15mG)
Feb09	1	~ 1 week	3 days	~ 5 days	~ 500 MeV	~ 7.2 PeV
Sep10	~ 1?	-	3 days	-	~ 1 GeV	~ 10 PeV
Apr11	~ 2 at least	~ 3 days	< 1 day ~ 2 days	~ 2 days	> 1 GeV	> 10 PeV
Jul12	~1?	-	1 week	-	~ 800 MeV	~ 9.5 PeV
Mar13	~ 1	> ~ 5 days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

- - - Best-fit for complete t-averaged SED

+ SEDs with SYN PL assumption for all Bayesian blocks during flaring windows (pre-2015)

- radiated

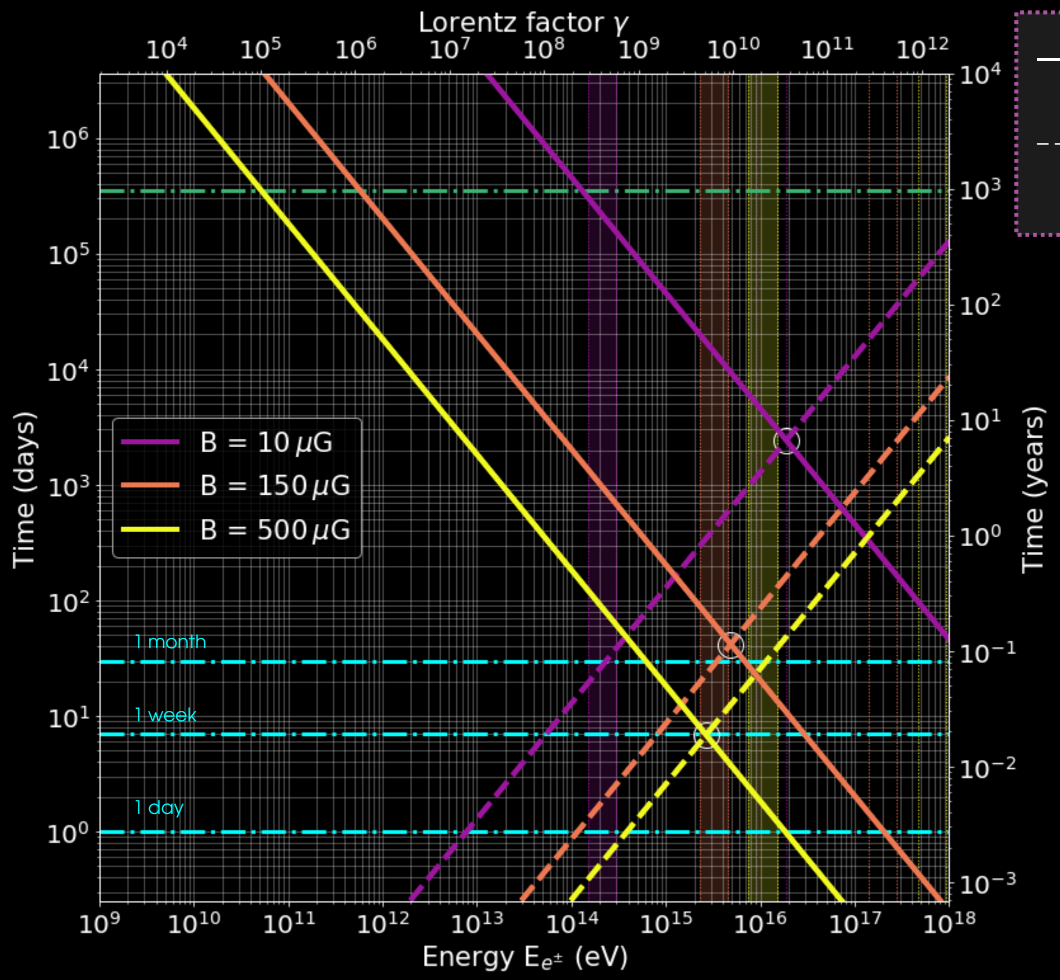
$E_{max, \varphi} >> E_{SYN, burn-off}$

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"

Timescales



—— $t_{SYN, cool}$

- - - - t_{gyro}

Vertical lines → the Hillas criterion

.... : for R_{PWN} (1 – 2 pc)

shades : for R_{PW} *

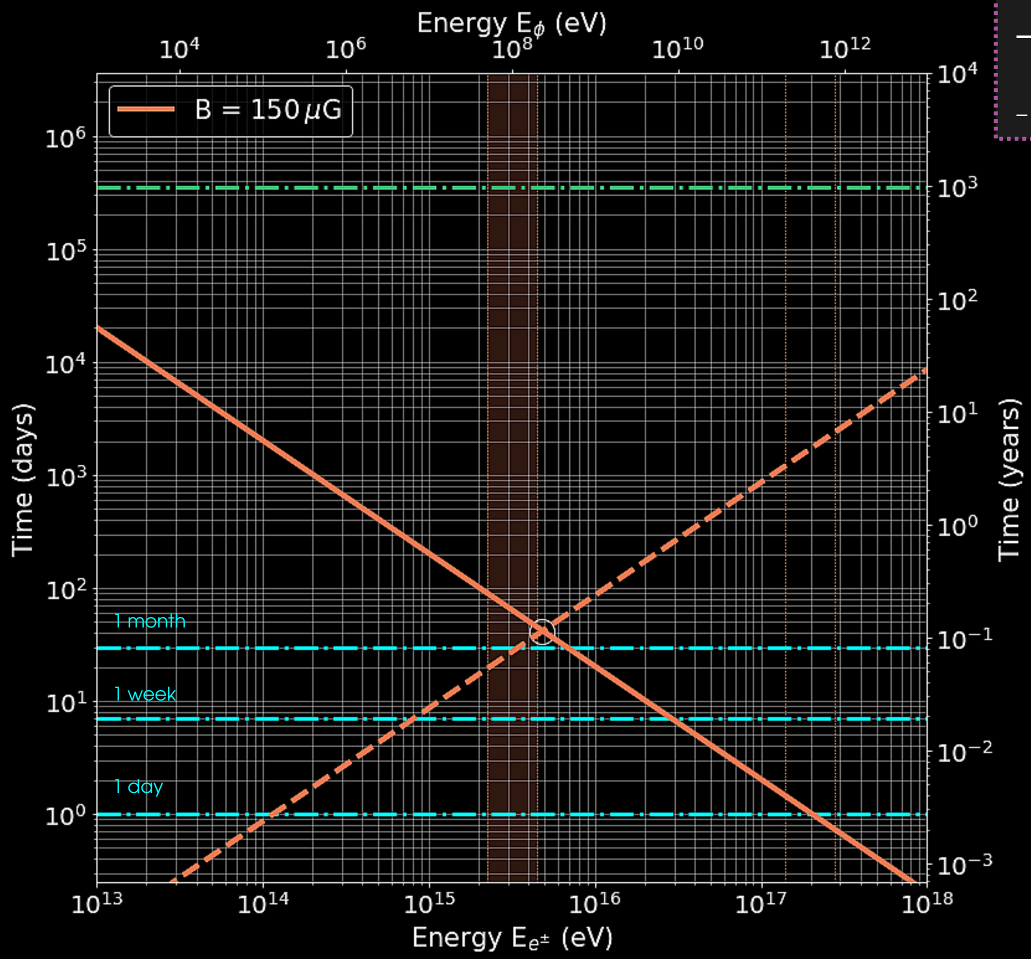
*(estimated by balancing wind ram pressure P_{PW} with the nebula pressure P_{PWN})

For “low” B :

$e^\pm$ ~ TeV range → $E_{max,\varphi}$ << MeV

For very high B :

synchrotron losses would dominate



—— $t_{SYN, cool}$

- - - - t_{gyro}

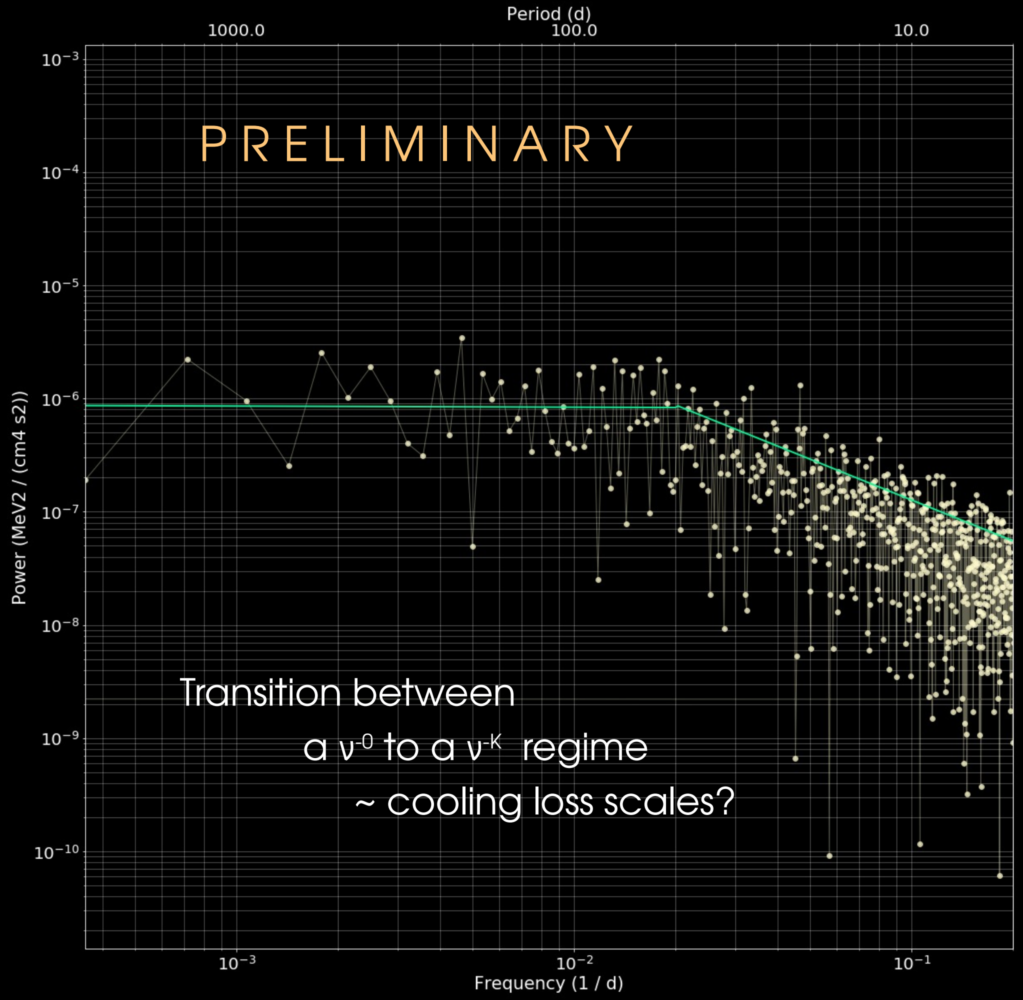
Vertical lines → the Hillas criterion
.... : for R_{PWN} (1 – 2 pc)
shades : for R_{PW} *

*(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 days**

Frequency domain



Power spectrum for the complete 13-yr dataset LCs

- Using Fourier space to investigate emerging scales for several sub-samples

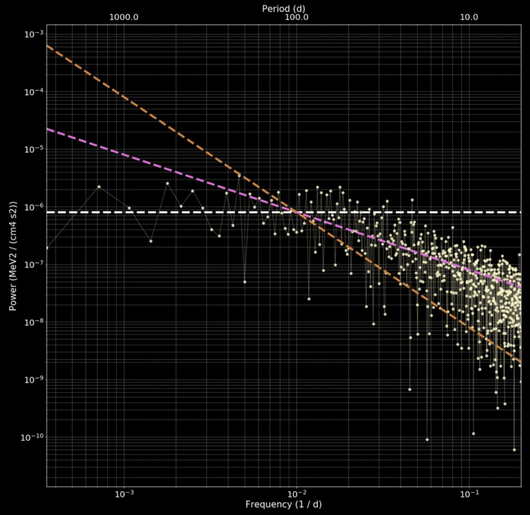
- Noise
  → filter signal (low-pass)
  → **white** (ν^{-0}) +
  pink (ν^{-1}) (+ **Brownian** (ν^{-2})) noise?

Could the flares be a signature of …

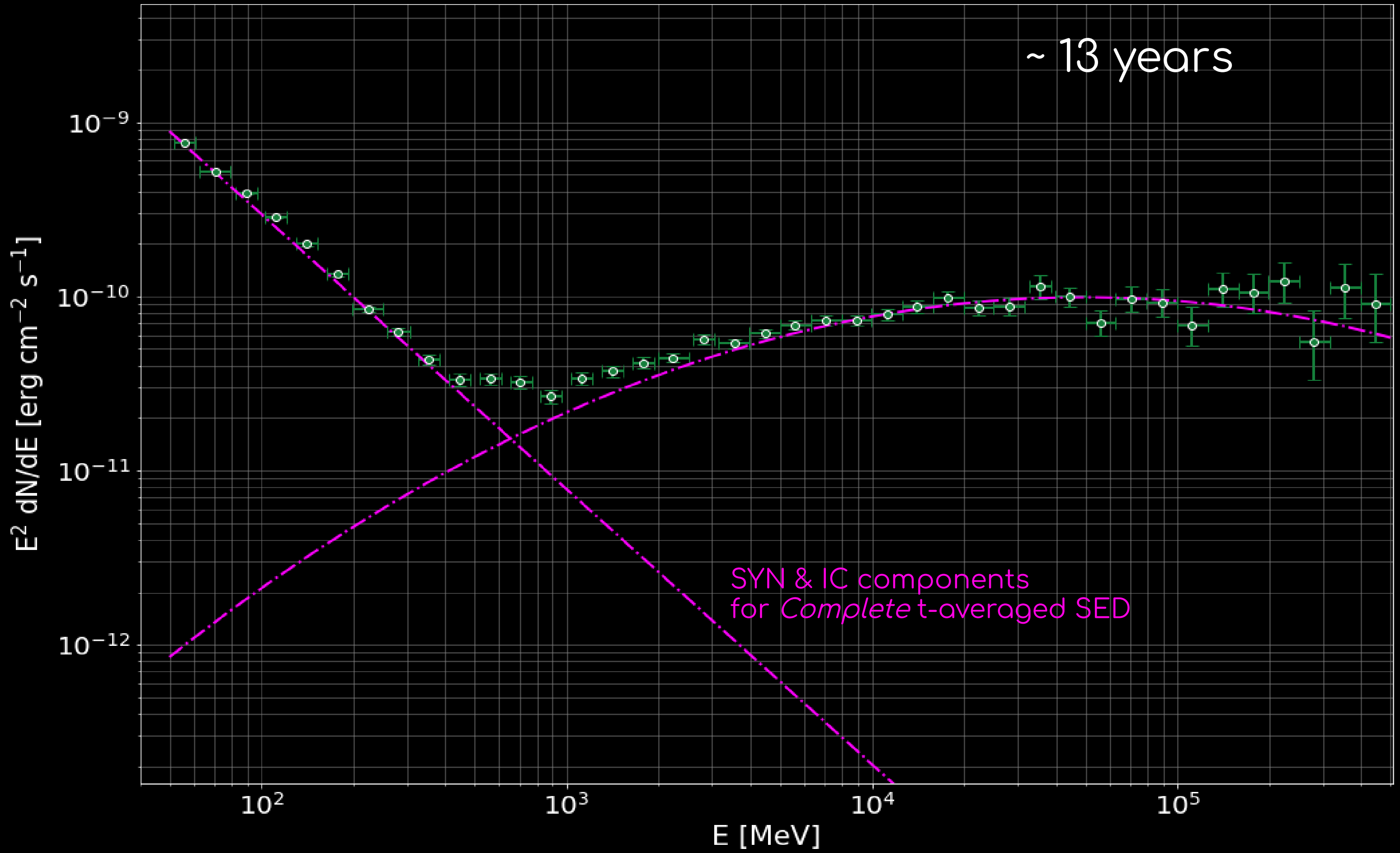
- highly efficient acceleration in the PW

  \+

- nebular emission process ?



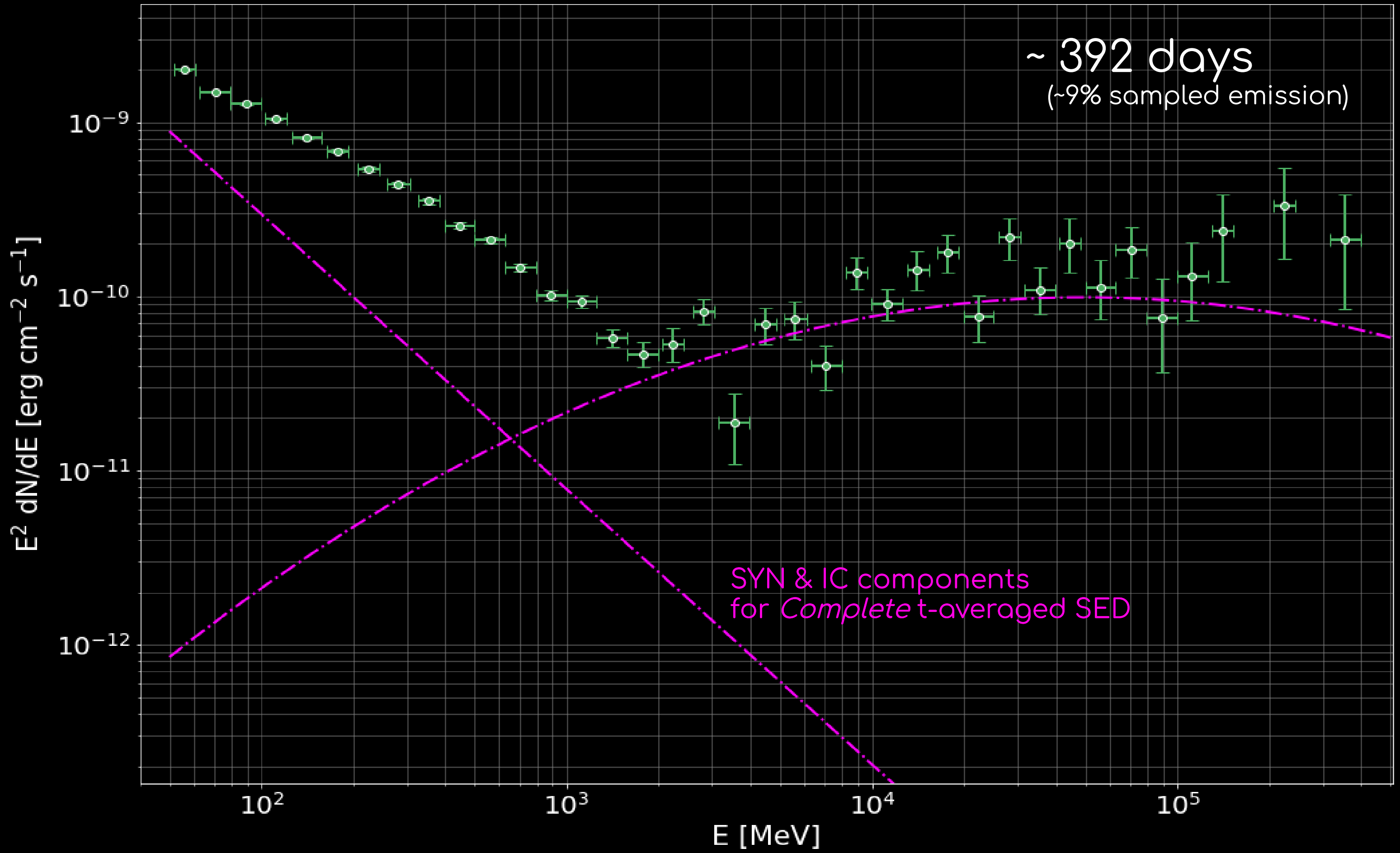
SYN + IC



Complete :
Unabridged emission in the OFF phase

Time-averaged total SED : emission states

SYN + IC

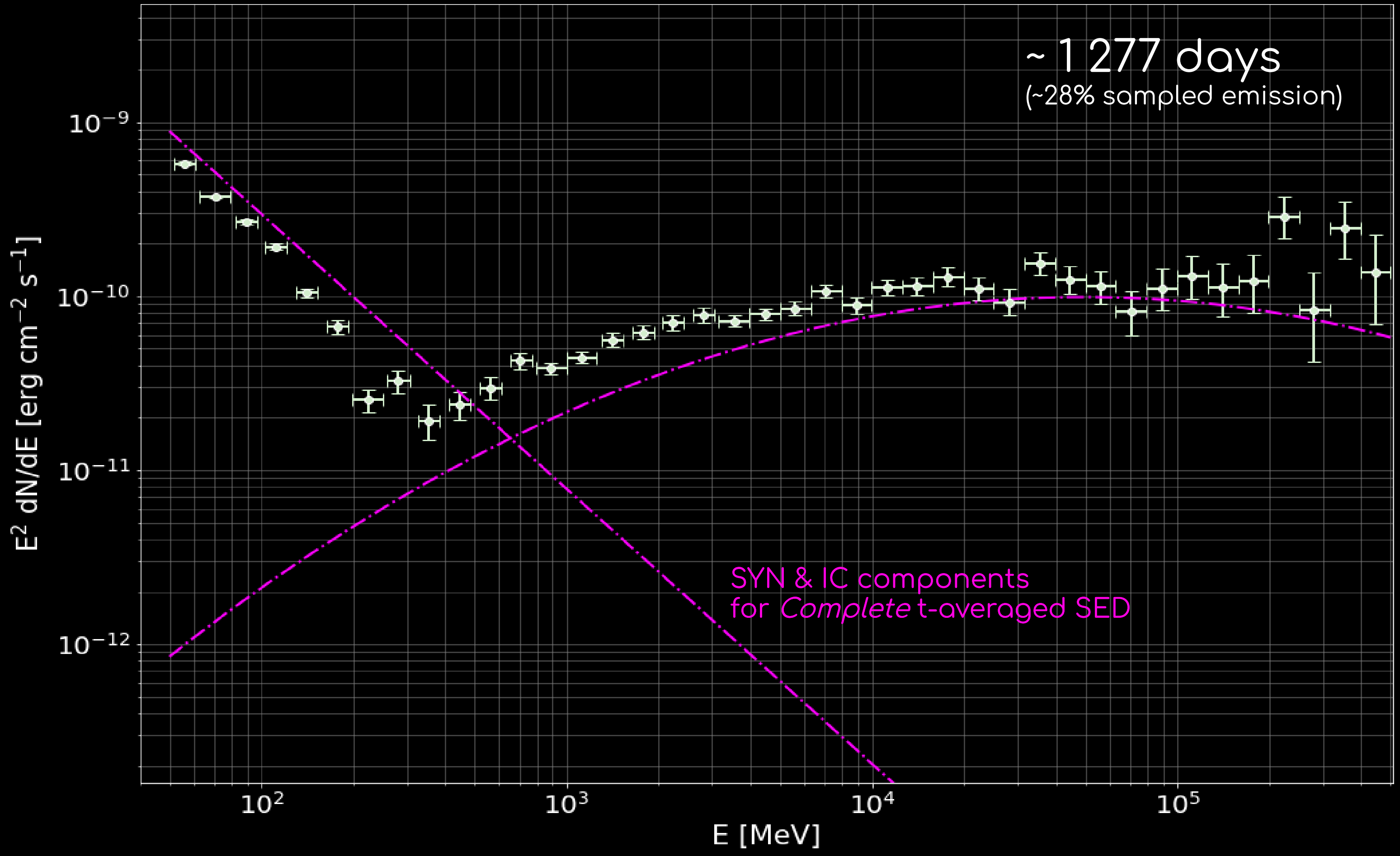


Complete :
Unabridged emission in the OFF phase

State selection :

High :
Φ_E > 6e-4 MeV.cm^{-2}.s^{-1}
(> 3/2 mean flux)

SYN + IC

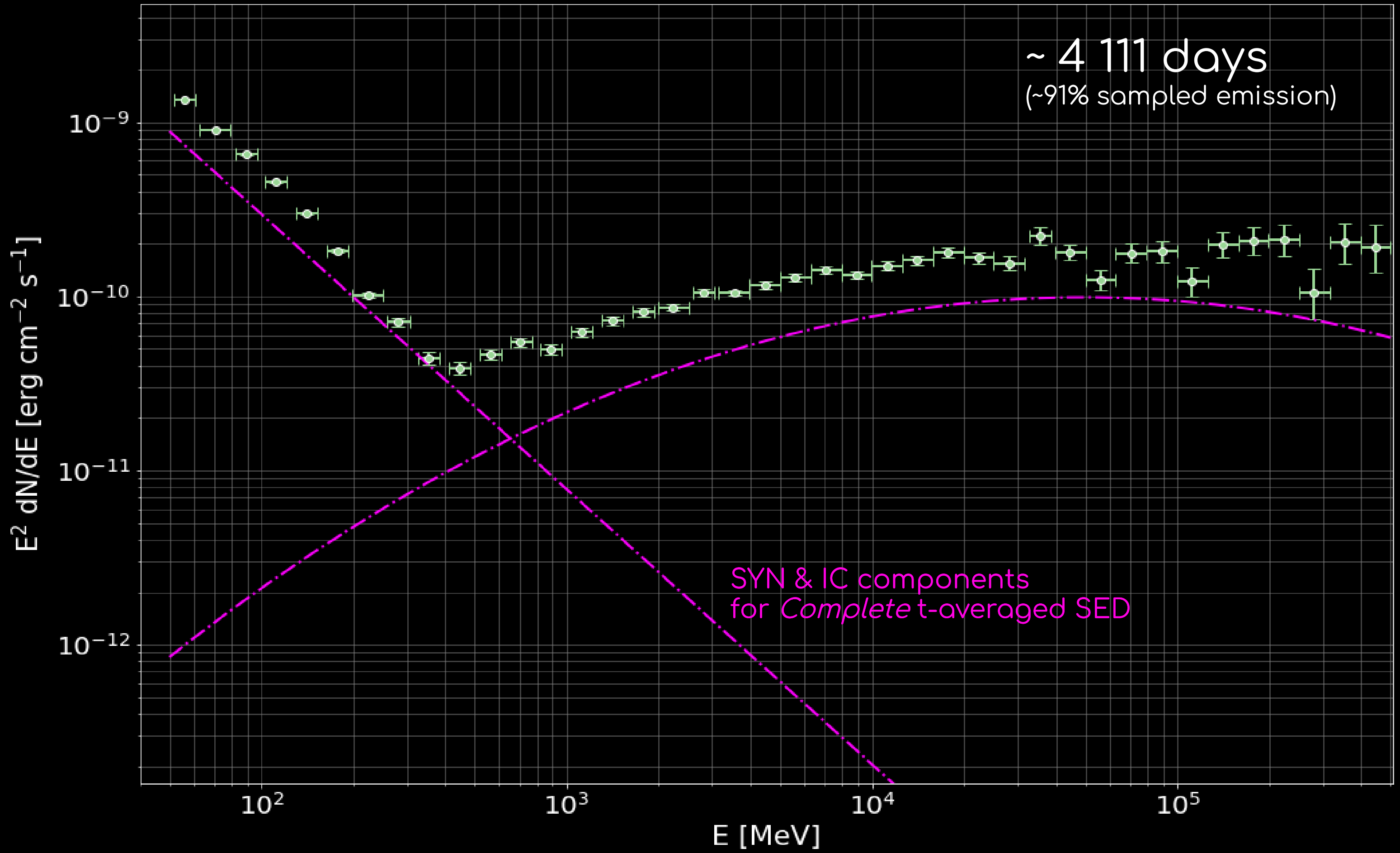


Complete :
Unabridged emission in the OFF phase

State selection :

Faint :
Φ_E < 2e-4 MeV.cm^{-2}.s^{-1}
(< 1/2 mean flux)

SYN + IC

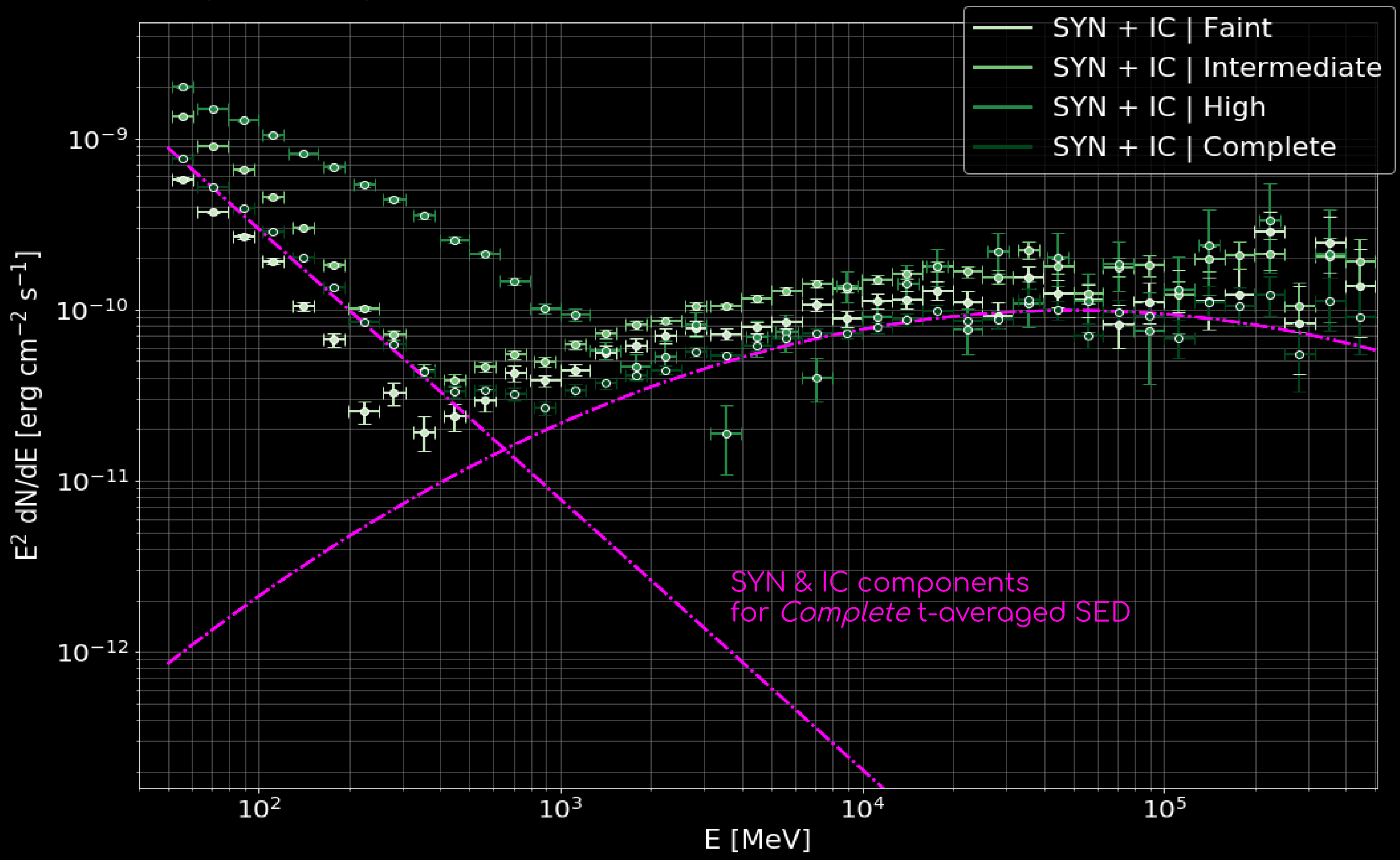


Complete :
Unabridged emission in the OFF phase

State selection :

Intermediate :
Φ_E < 6e-4 MeV.cm^{-2}.s^{-1}
(< 3/2 mean flux)

SYN + IC



Complete :
Unabridged emission in the OFF phase

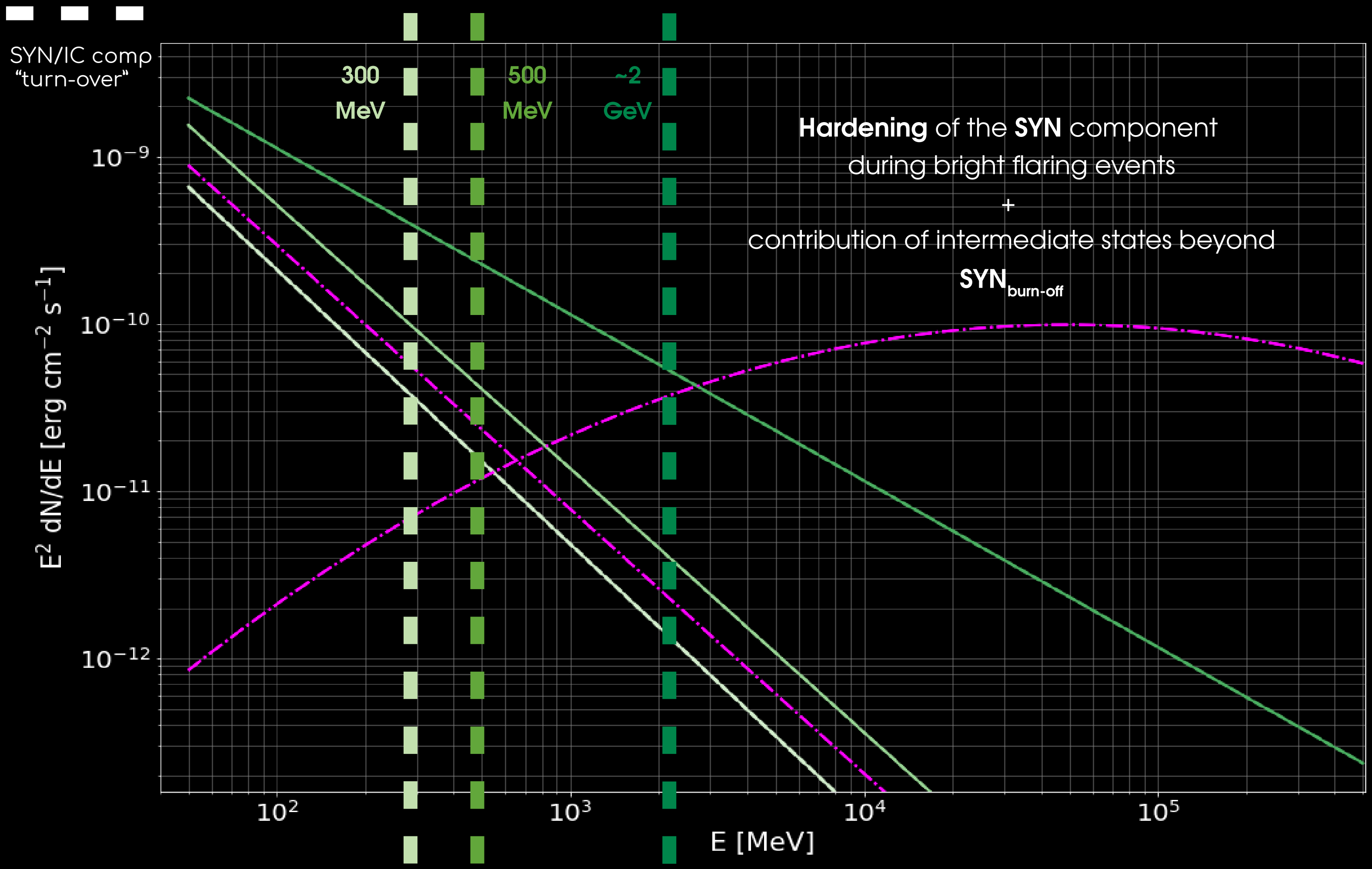
State selection :

Faint :
Φ_E < 2e-4 MeV.cm^{-2}.s^{-1}
(< 1/2 mean flux)

High :
Φ_E > 6e-4 MeV.cm^{-2}.s^{-1}
(> 3/2 mean flux)

Intermediate :
Φ_E < 6e-4 MeV.cm^{-2}.s^{-1}
(< 3/2 mean flux)

Time-averaged SED : synchrotron emission states



Complete :
Unabridged emission in the OFF phase

State selection :

Faint :

(< 1/2 mean flux)

High :

(> 3/2 mean flux)

Intermediate :

(< 3/2 mean flux)

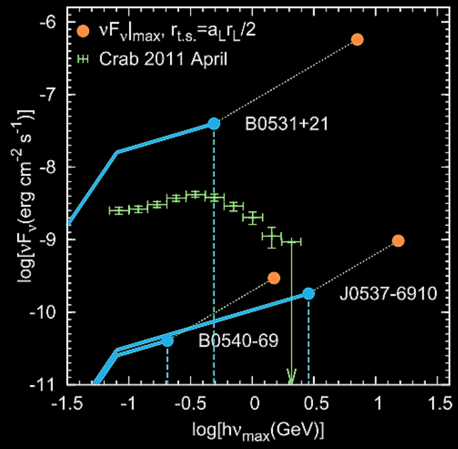
Open questions :

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?

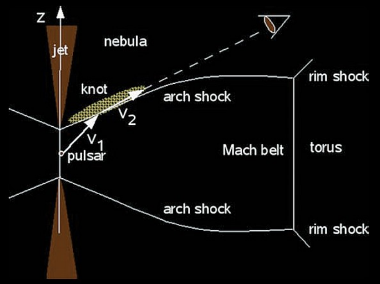
Models rely on system conditions
(B-field strength, bulk Lorentz factor, topology, anisotropy, ...)

? Inductive acceleration model
Kirk & Giacinti 2017

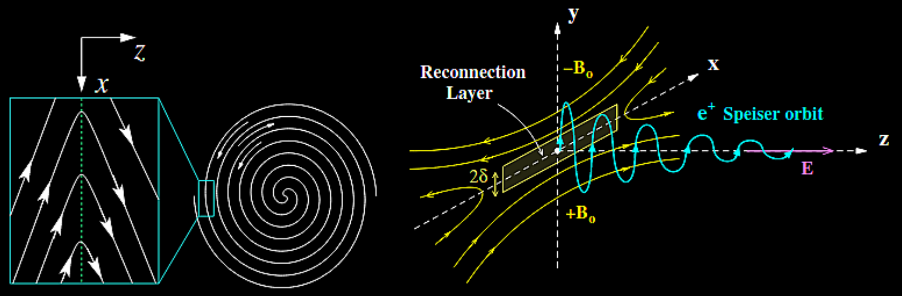
Drop in ρ_e with R
→ possible origin
of "inductive" spikes
via low-density pockets
injected radially as a beam
by the PW into the PWN



? 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

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

Paper in prep

- 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 for 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 and 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 slides

.. / ..

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

Bayesian analysis + screening yield →

~ 34 candidate flaring windows (2008 - 2021) with :

- 7 / 7 pre-reported ← Mayer+15, Rudy+15 and ref therein (pre-2015)
- 6 / 7* *small-flares* ← Arakawa+20 (pre-2015)
- 7 / 8* *flares* ← Huang+21 (pre-mid 2019)
- 7 / 7 *dimming-states* ← Yeung & Horn 2019 (pre-mid 2018)

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

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Light curve : time-dependence

+ 1-week binning

mean $\Phi_E \sim 3.5\ 10^{-4}$ MeV. cm^{-2}.s^{-1}

Bayesian blocks

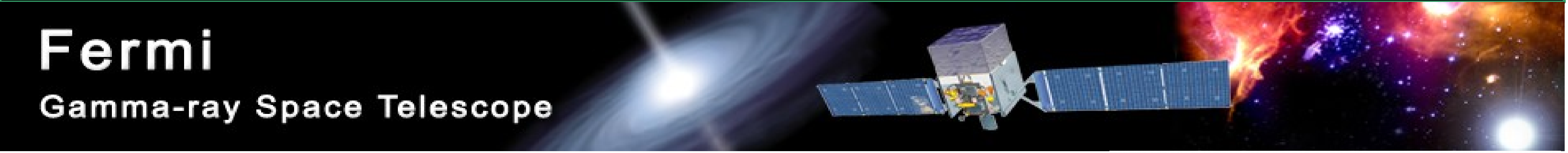
flaring windows (pre-2015)

Time window selection

+

binning

→ flare features : **time-dependent** behaviour



Fermi-LAT public available
photon data and spacecraft files :

Some technical notes

Event time range :

from August 4th 2008 – August 4th 2021 → **13-year** monitoring!

FoV : 20 deg x 20 deg around

Energy binning : 10 bins / decade

3 spectro-morphological components for the Crab

(1 for PSR + 2 for PWN)

Pass 8 data : P8R3

Event class : 128 (and type : 3, front + back events)

IRFs : P8R3_SOURCE_V2

Apparent zenith : 90° max

(selection to account for the Earth's limb)

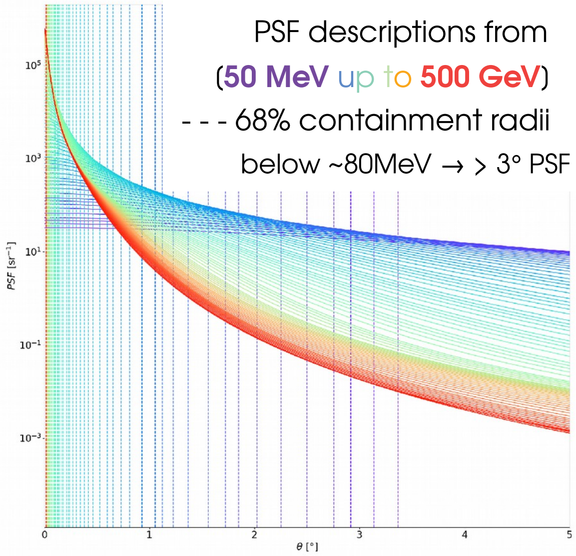
Filtering : (DATA_QUAL>0) && (LAT_CONFIG==1)

Energy dispersion correction enabled

One of the aims of our study :

"characterise the e-dependence of the synchrotron Crab flares"

Illustration of the point spread function (PSF) dependence with energy →



PSF descriptions from
(**50 MeV** up to **500 GeV**)
- - - 68% containment radii
below ~80MeV → > 3° PSF

Fermitools : v1.2.23
fermipy : v0.19.0
tempo2 : core code with fermi plugin

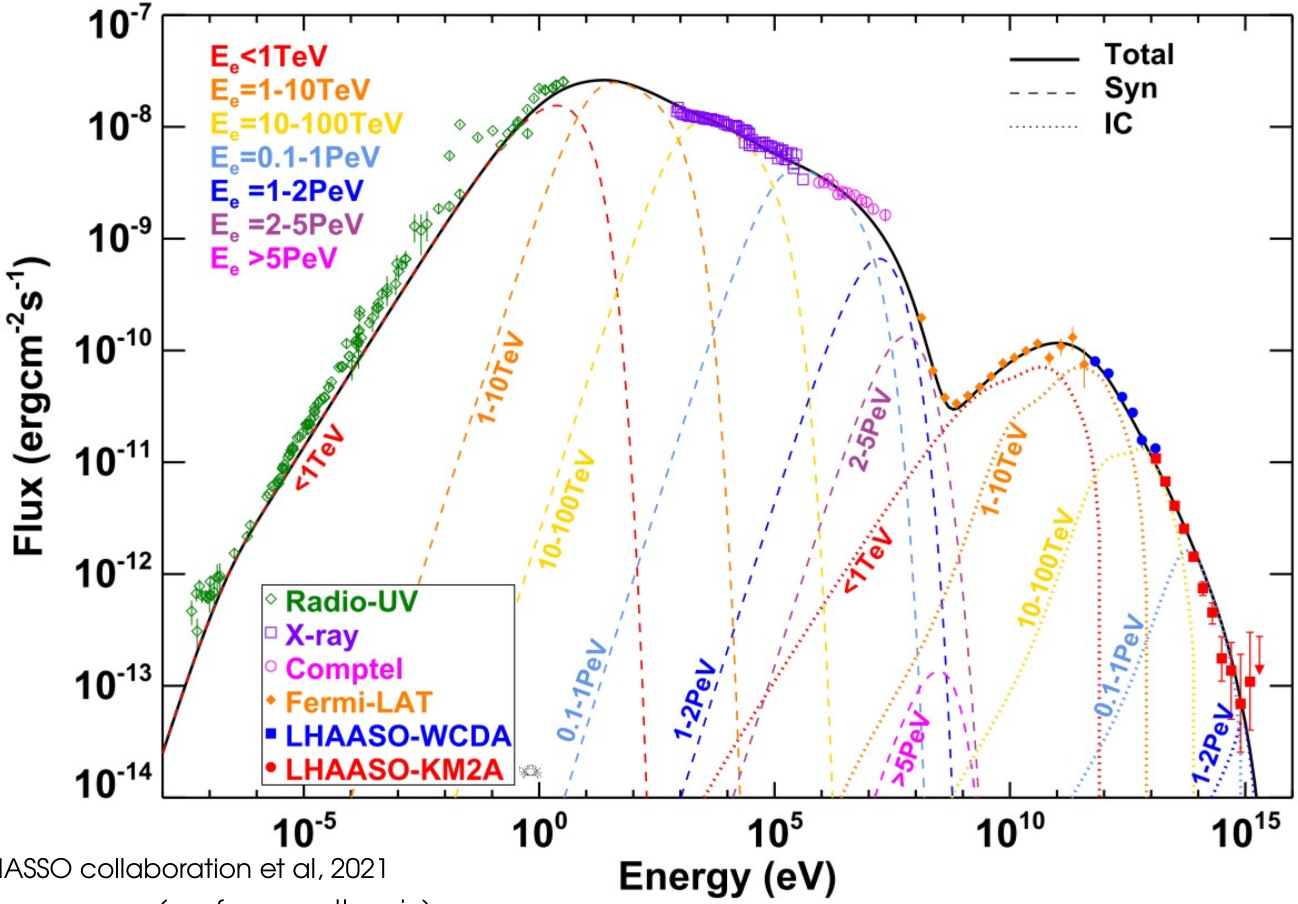
Galactic diffuse emission template : gll_iem_v07.fits
Isotropic spectral template : iso_P8R3_SOURCE_V2_v1.txt

4FGL -8yr catalogue : gll_psc_v21.fit

(hyperlinks to material of interest

.. / ..

PWN with detected emission ranging from ~ tens of MHz up to PeV photons!



LHASSO collaboration et al, 2021

(+ references therein)

In the last two decades, **γ-ray** experiments have contributed to the discovery of exciting and surprising features from the Crab!

E.g :

In the high-energy range (**HE**)
(~ tens MeV to ~ hundreds GeV)
→ Fermi-LAT, AGILE

Very high energy range (VHE)
(hundreds of GeV to ~ tens of TeV)
→ H.E.S.S., MAGIC, VERITAS, HAWC, Tibet As-γ, LHAASO

→ dawn of the ultra-high-energy range (UHE)
(~ hundreds TeV - ~ PeV)
era?

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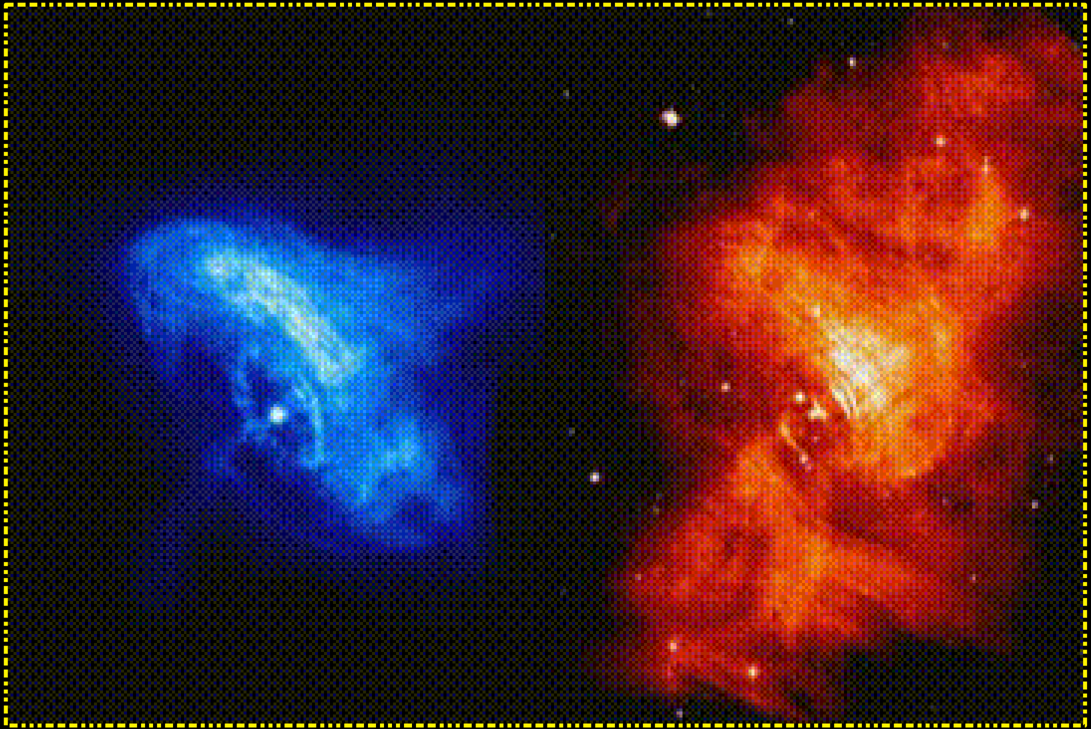
- "Wisps" : systematic brightness variability in radio, optical and X-ray bands → propagating plasma waves?

Observations :
(Nov 2000 - April 2001)

scale : inner ring ~ 0.3 pc



X-rays (Chandra) and optical light (Hubble)
Credits: NASA/CXC/ASU/J.Hester et al. and NASA/HST/ASU/J.Hester et al.

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The Crab system : a unique source in the Milky Way

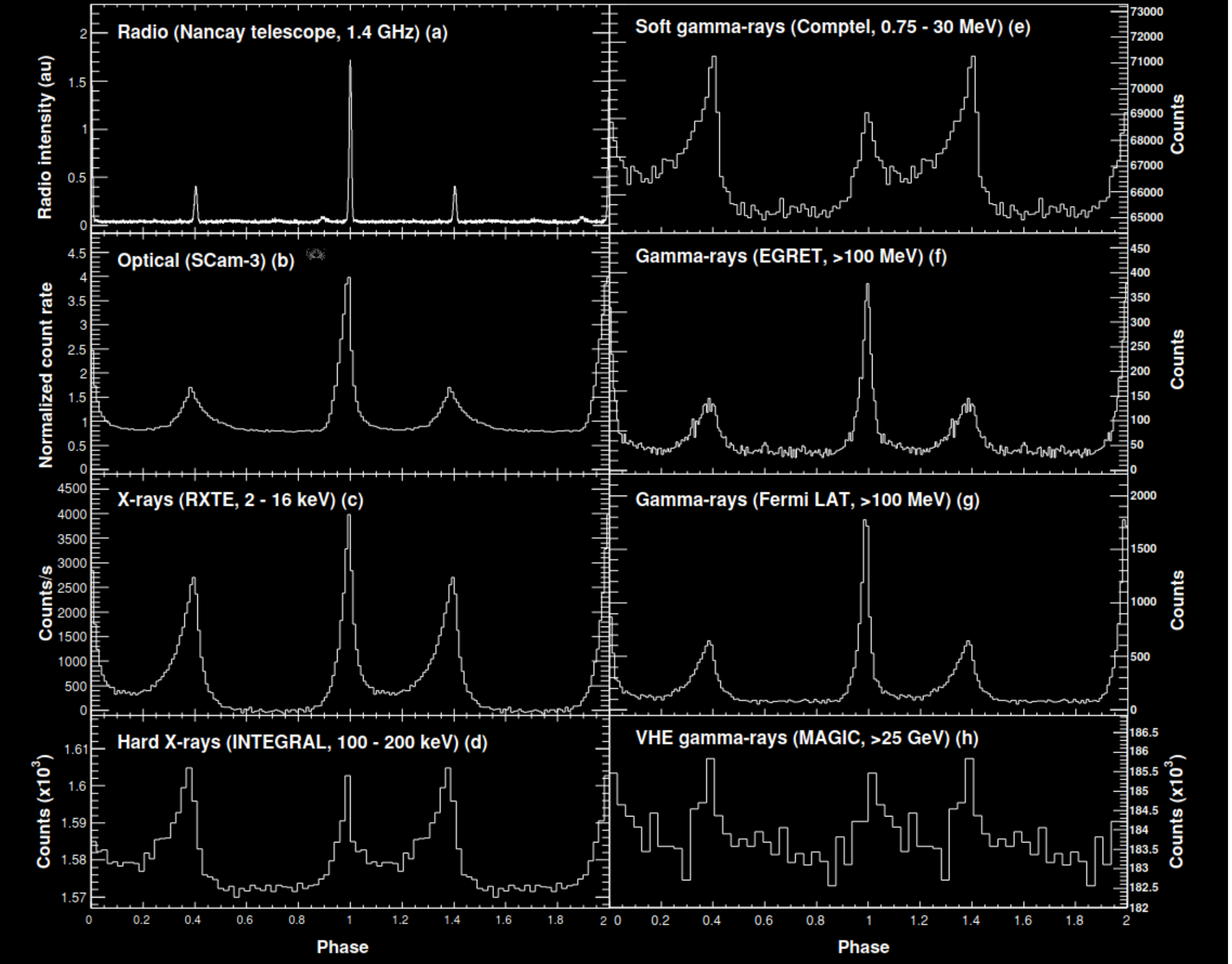

Figure 2. Light curves at different wavelengths. Two cycles are shown. References: (a) from the Nançay radio telescope; (b) Oosterbroek et al. 2008; (c) Rots et al. 2004; (d) Mineo et al. 2006; (e) Kuiper et al. 2001; (f) EGRET, Kuiper et al. 2001; (g) This paper; (h) Aliu et al. 2008.

- With a central young and energetic pulsar B0531+21 (or 4FGL J0534.5+2200)

  - estimated distance ~ 2 kpc
  - age ~ 1 kyr
  - spin-down power ≈ 4.5×10^{38} erg.s^{-1}
  - period ~33ms
  - $B_{light\text{-}cylinder} \sim 10^{6}$ G
  - $B_{surf} \sim 10^{12}$ G

with firmly discovered pulsations seen in the radio band and all the way up to VHE ranges!

Hear the pulsation!

Fermi-LAT collaboration et al, 2010
(+ references therein)

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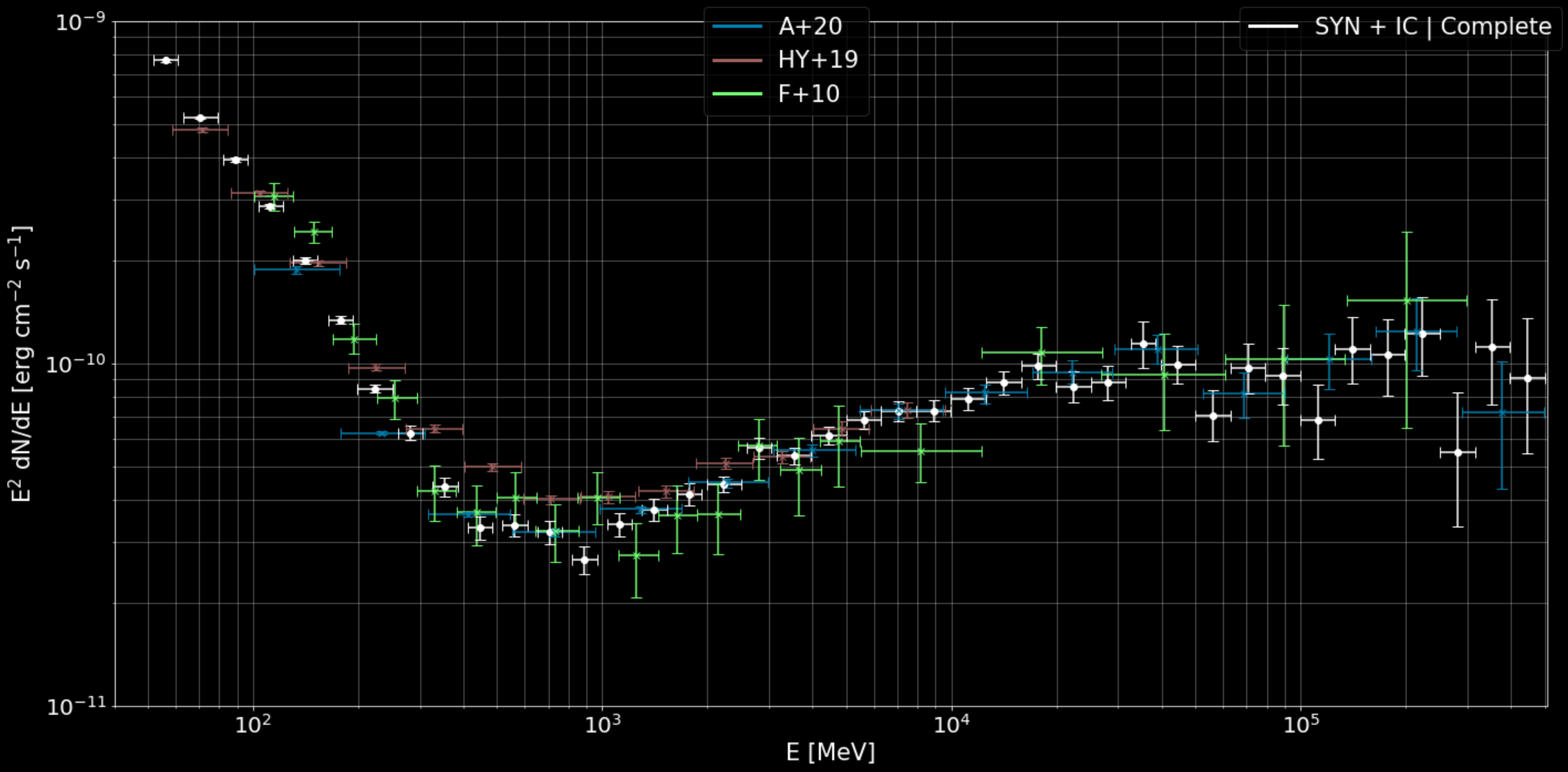
Time-averaged SED comparison



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Time-averaged SED comparison