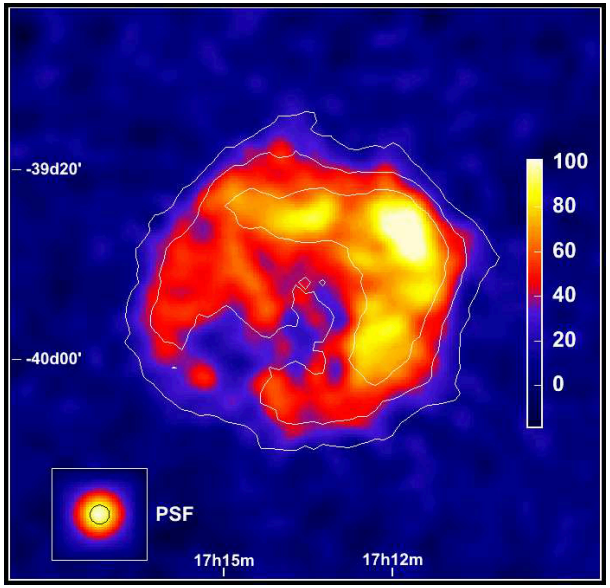
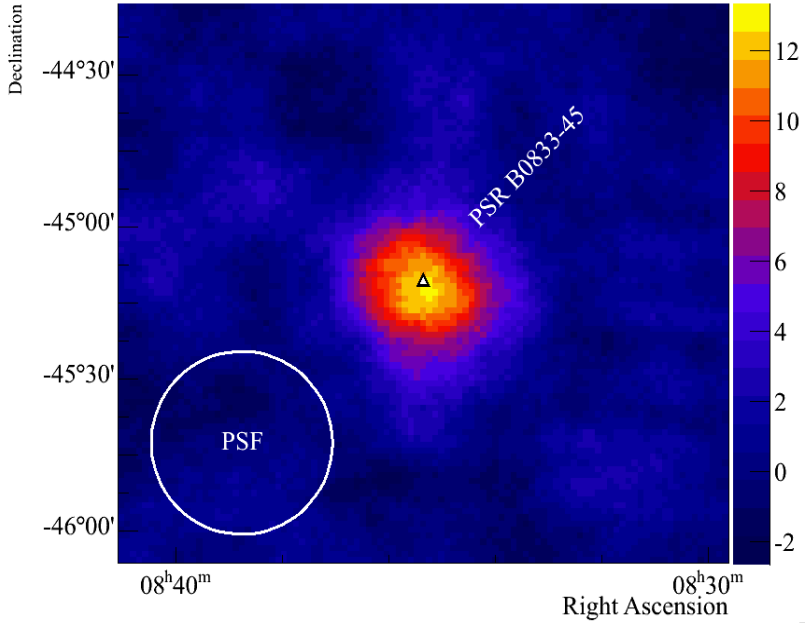
Gamma-ray emission from pulsars and pulsar wind nebulae

Bronisław Rudak

CAMK PAN





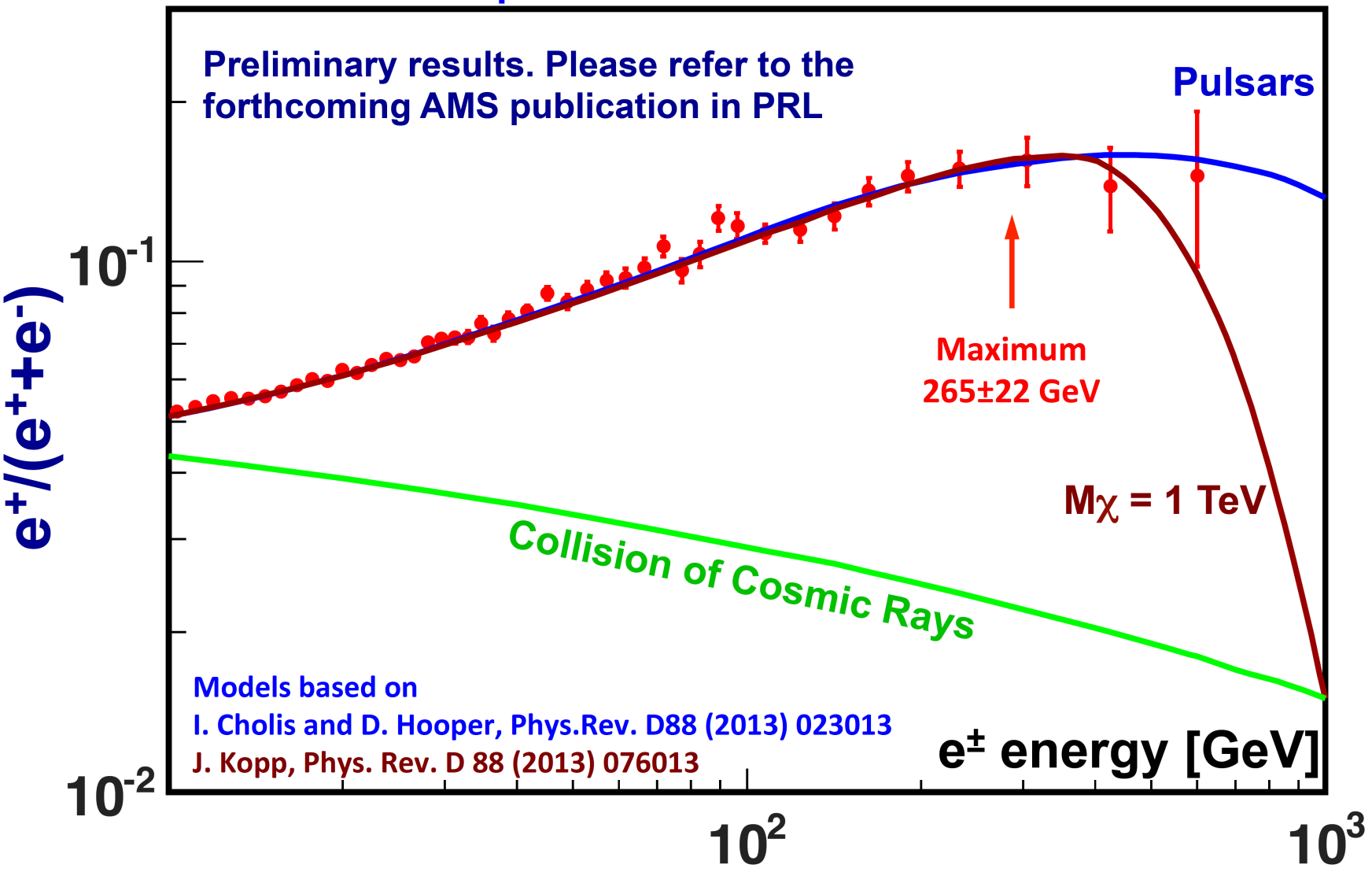
KRAC, 20-22 Oct 2017

Pulsars and PWNe are powerful tools to study/test

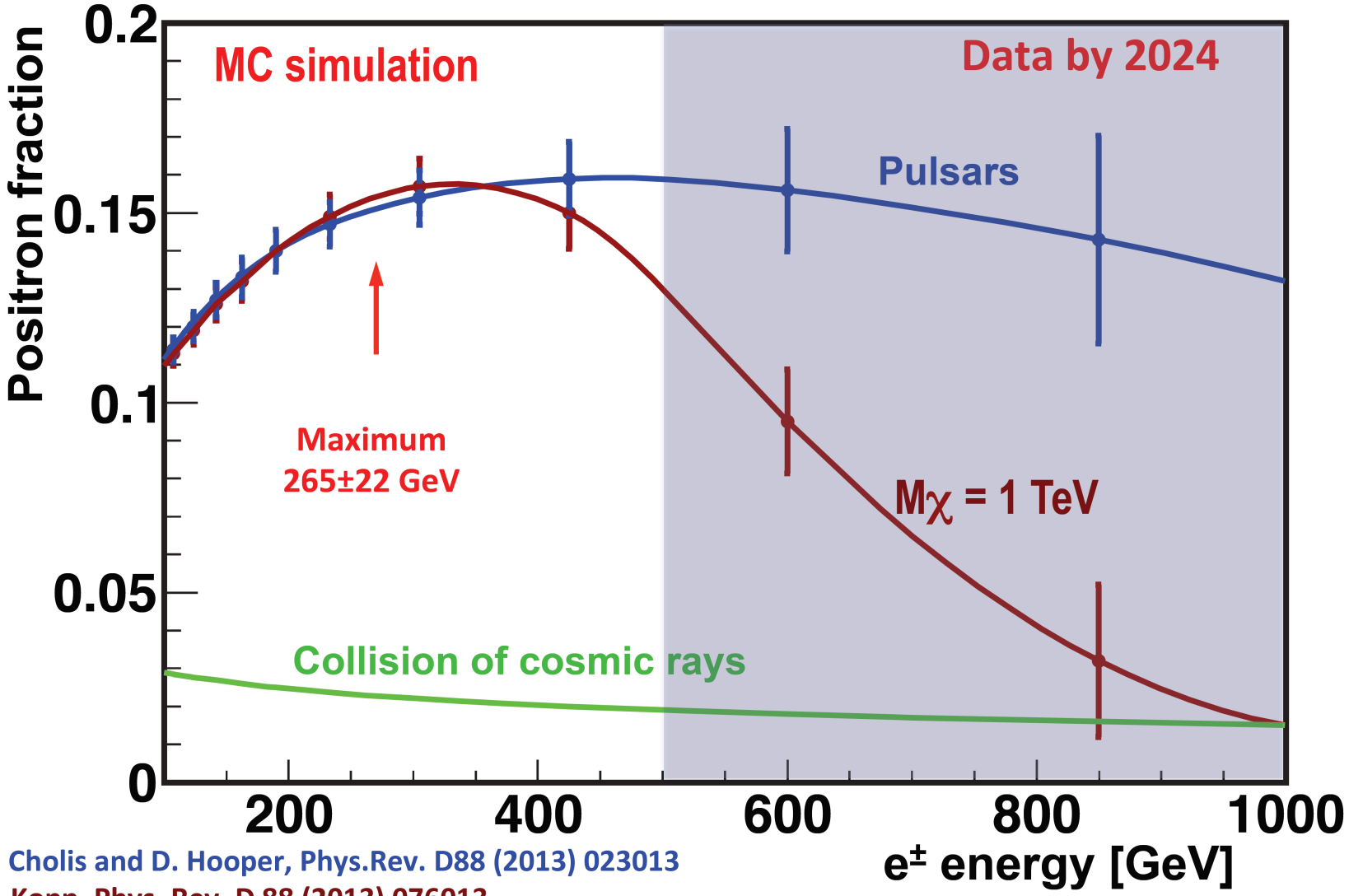
- EOS of ultradense matter
- QED in strong magnetic fields
- theories of gravitation in strong-field limits
- supernova outburst mechanisms
- interstellar medium
- low-frequency gravitational waves
- relativistic MHD flows and shocks
- origin of primary $e^{\pm}$-pairs in Cosmic Rays (justifies my talk at KRAC mtg.)

Behavior of the positron fraction at high energies

Comparison with theoretical Models

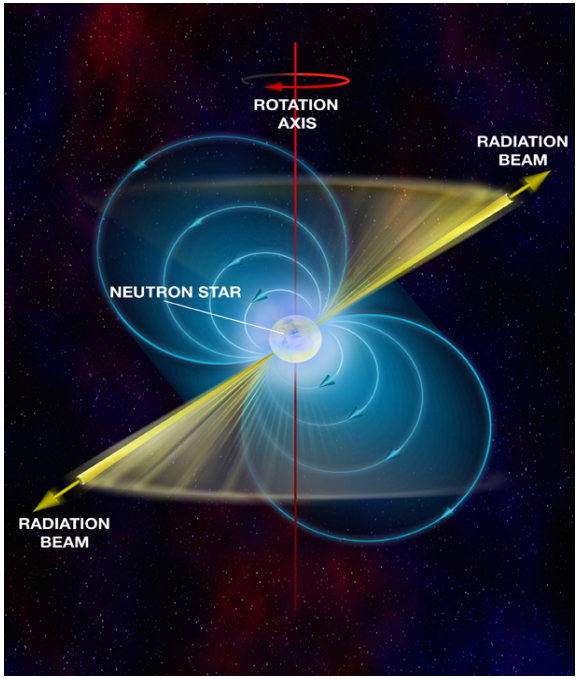


The expected rate at which it falls beyond the turning point.



I. Cholis and D. Hooper, Phys.Rev. D88 (2013) 023013

J. Kopp, Phys. Rev. D 88 (2013) 076013



Pulsars

Rotating, strongly magnetized neutron stars acting as unipolar inductors.

Maximum potential drop (voltage):

$V_{max} \approx 6 \times 10^{12}\ (B/10^{12}\ G)\ P^{-2}$ Volts.

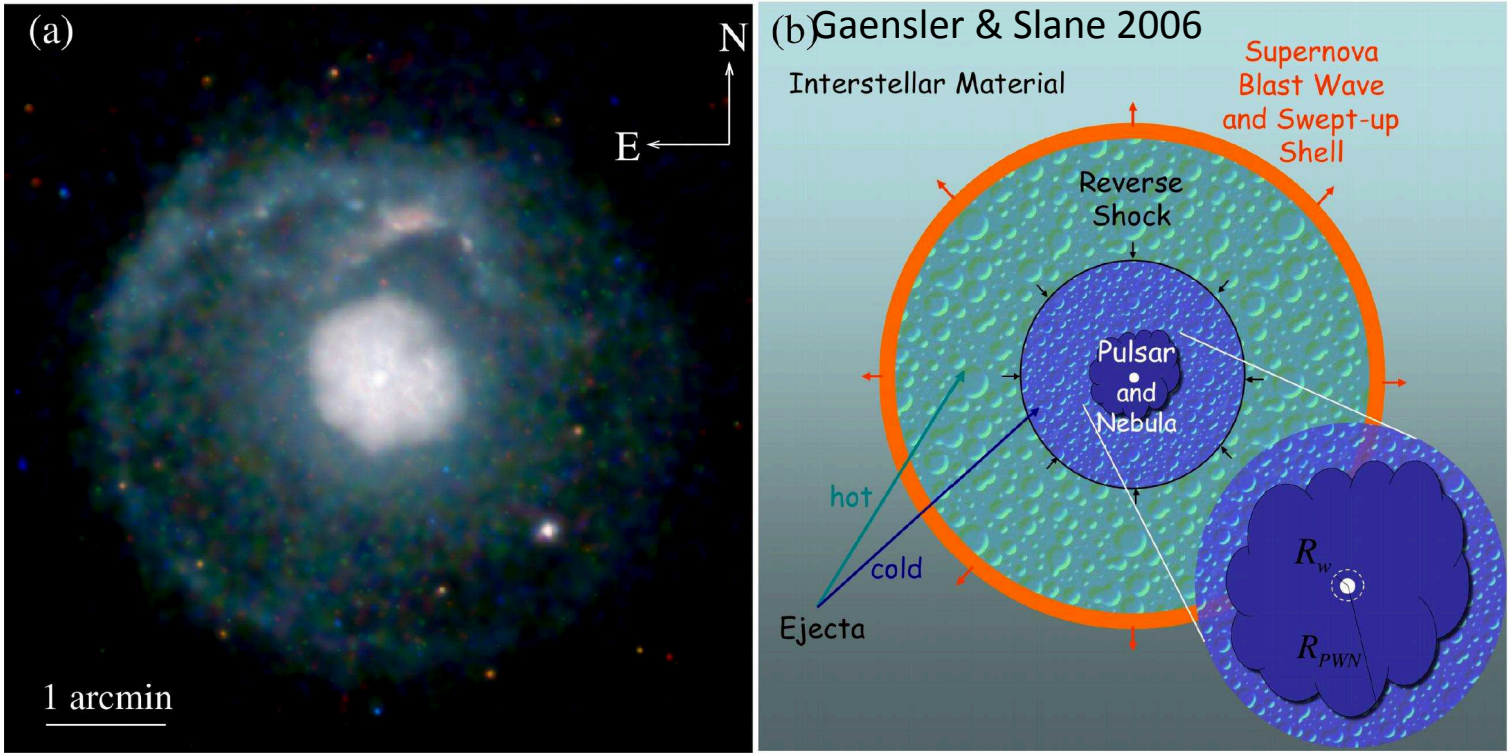
Realistic potential drops - much smaller, but high enough to accelerate particles to ultrarelativistic energies.

Pulsed radiation spectra

from radio to gamma-rays (across 16 decades!):

- curvature and synchrotron emission

- Inverse Compton scattering



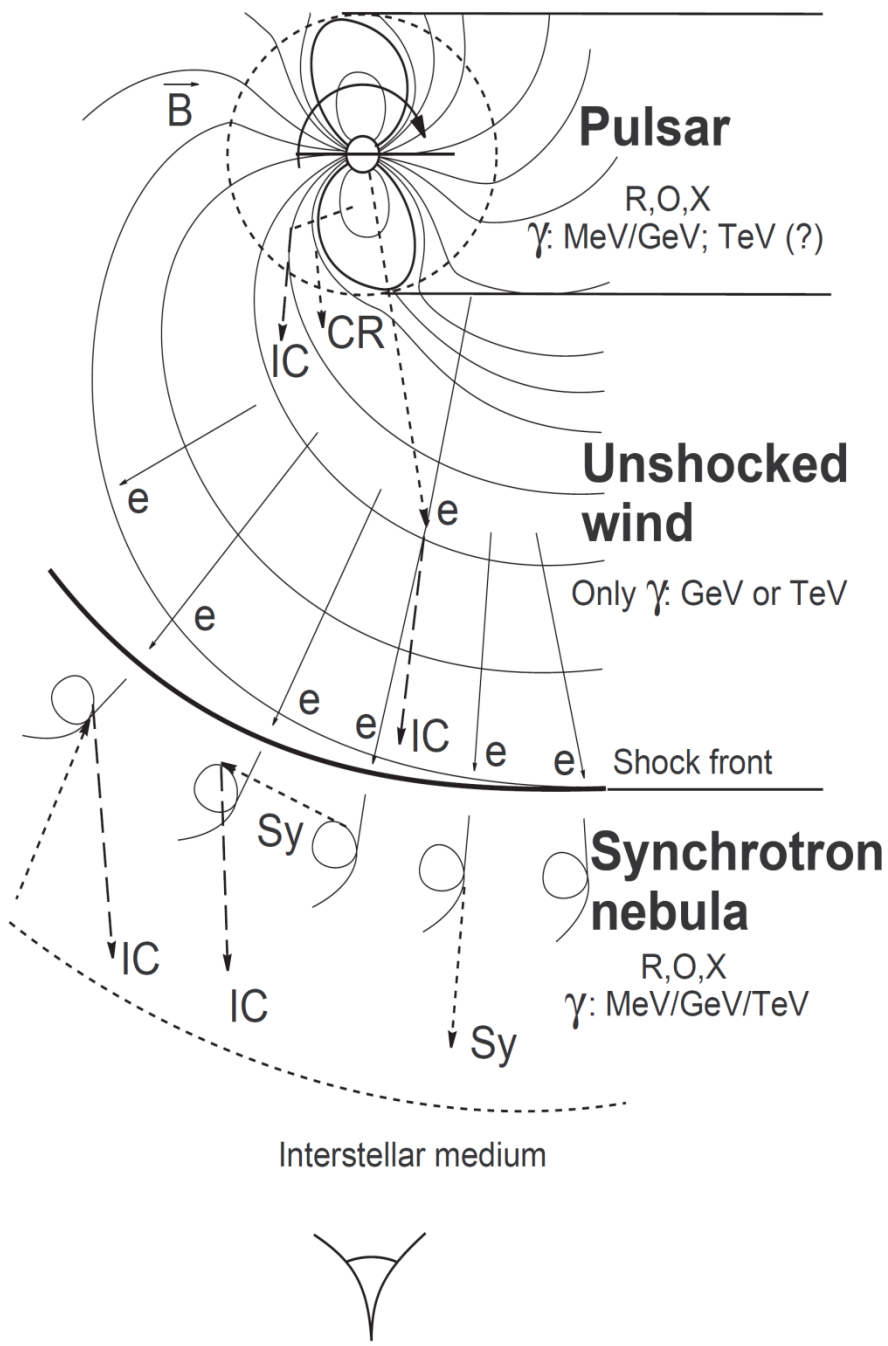
Pulsar Wind Nebulae

- extended sources

- powered by relativistic magnetized wind from pulsar

- radiation spectra from radio to gamma-rays: synchrotron emission from shocked pulsar wind and Inverse Compton scattering

Radiation from a **Pulsar-wind-nebula** complex

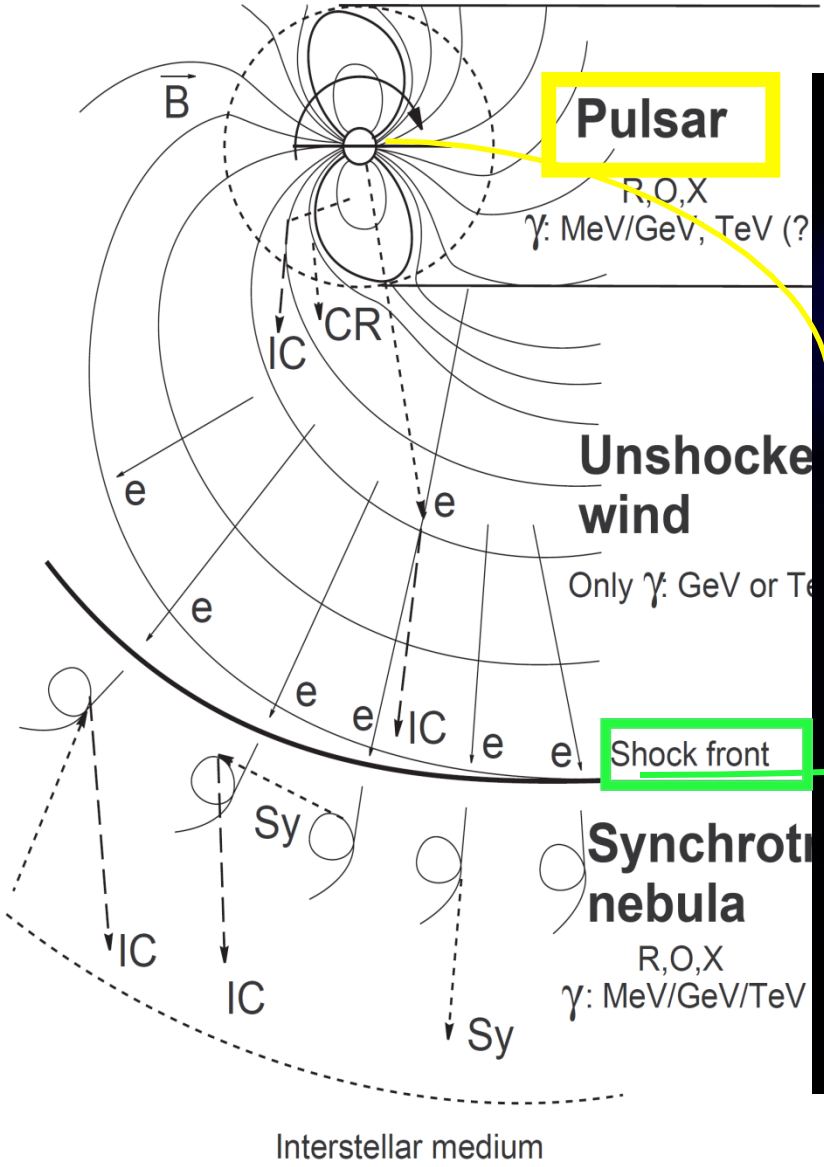


Pulsed inside LC

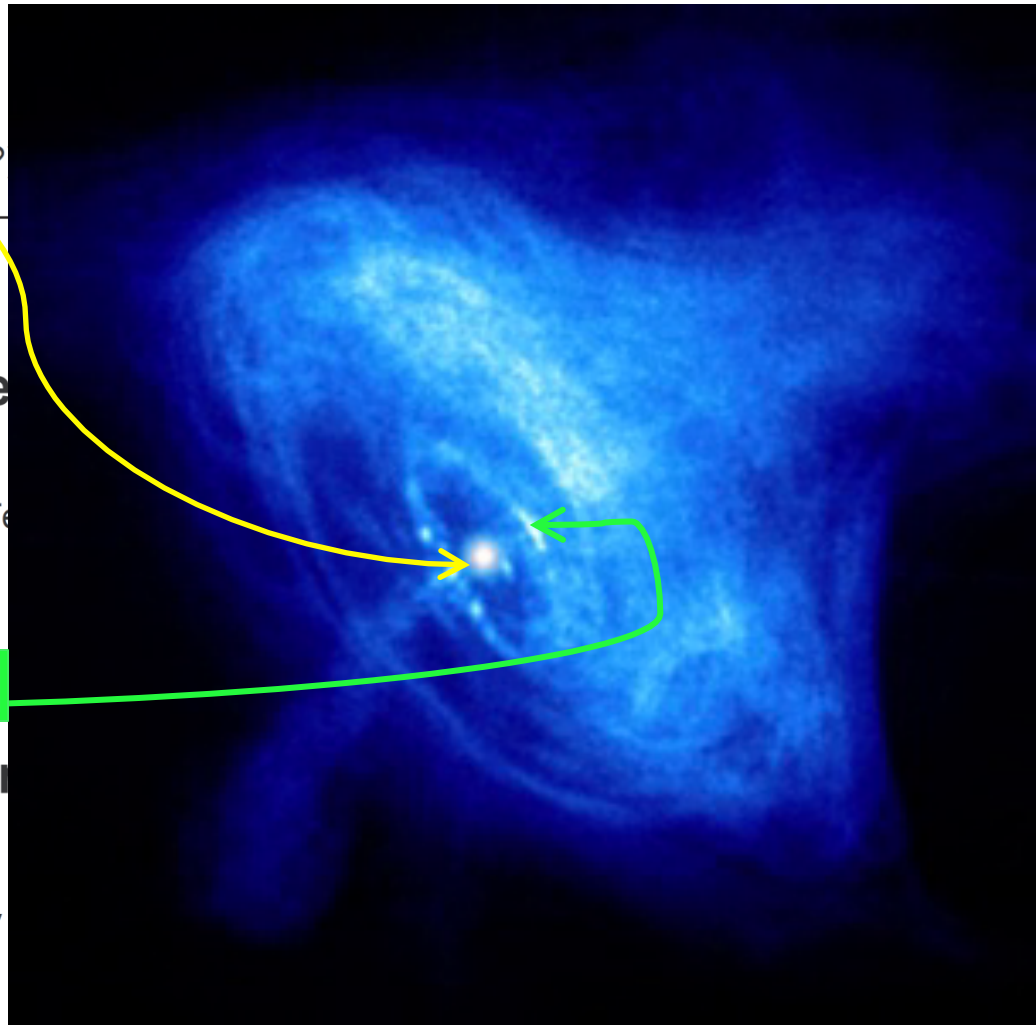
Pulsed outside LC

Unpulsed

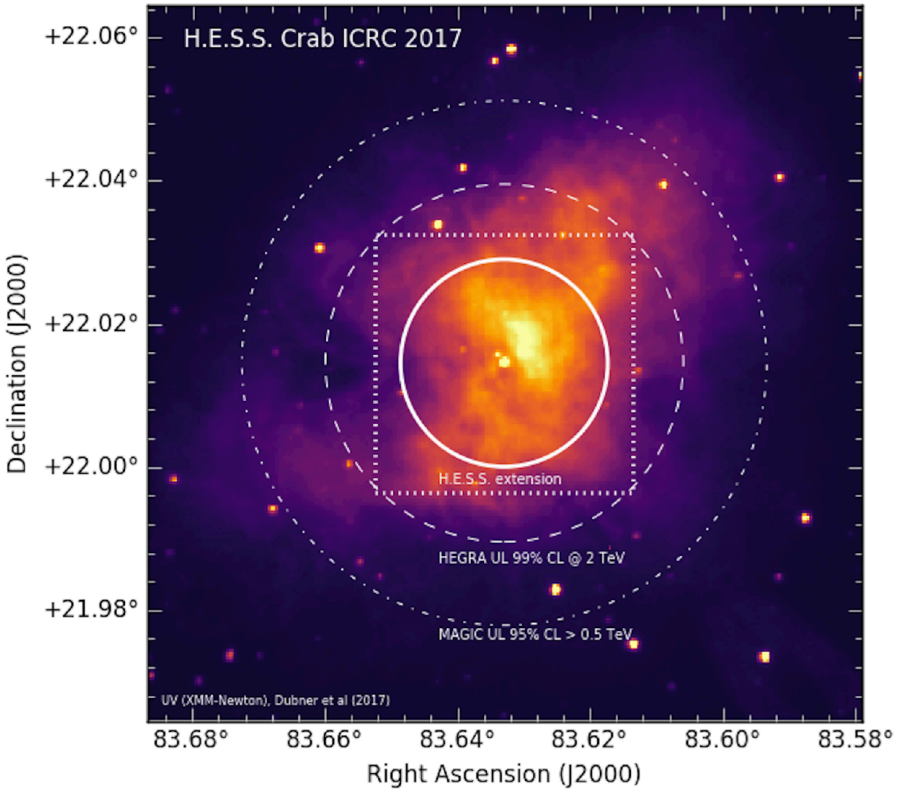
Radiation from a **Pulsar-wind-nebula** complex

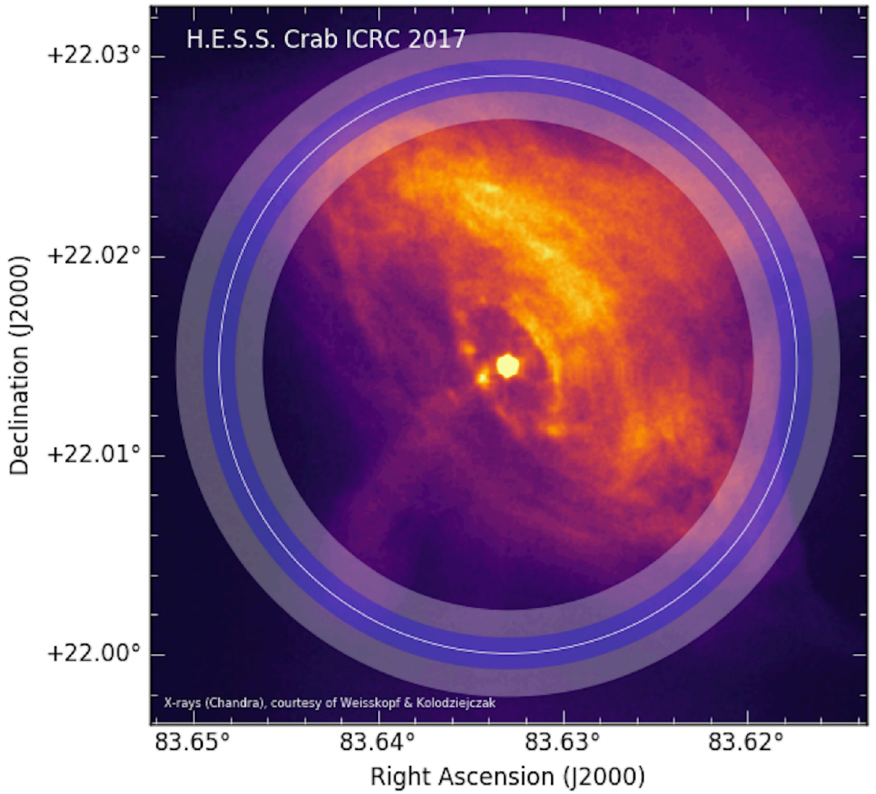


Crab Nebula in X-rays



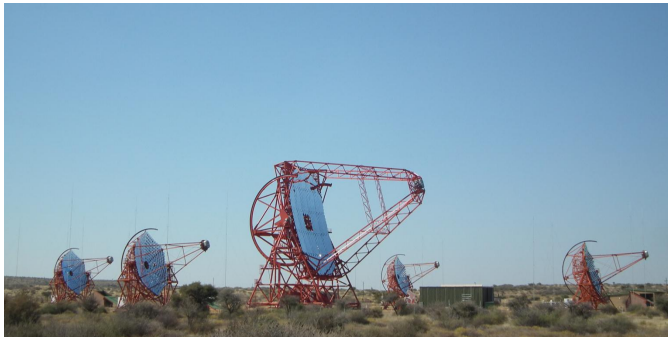
First measurement of the extension of the Crab Nebula at TeV energies



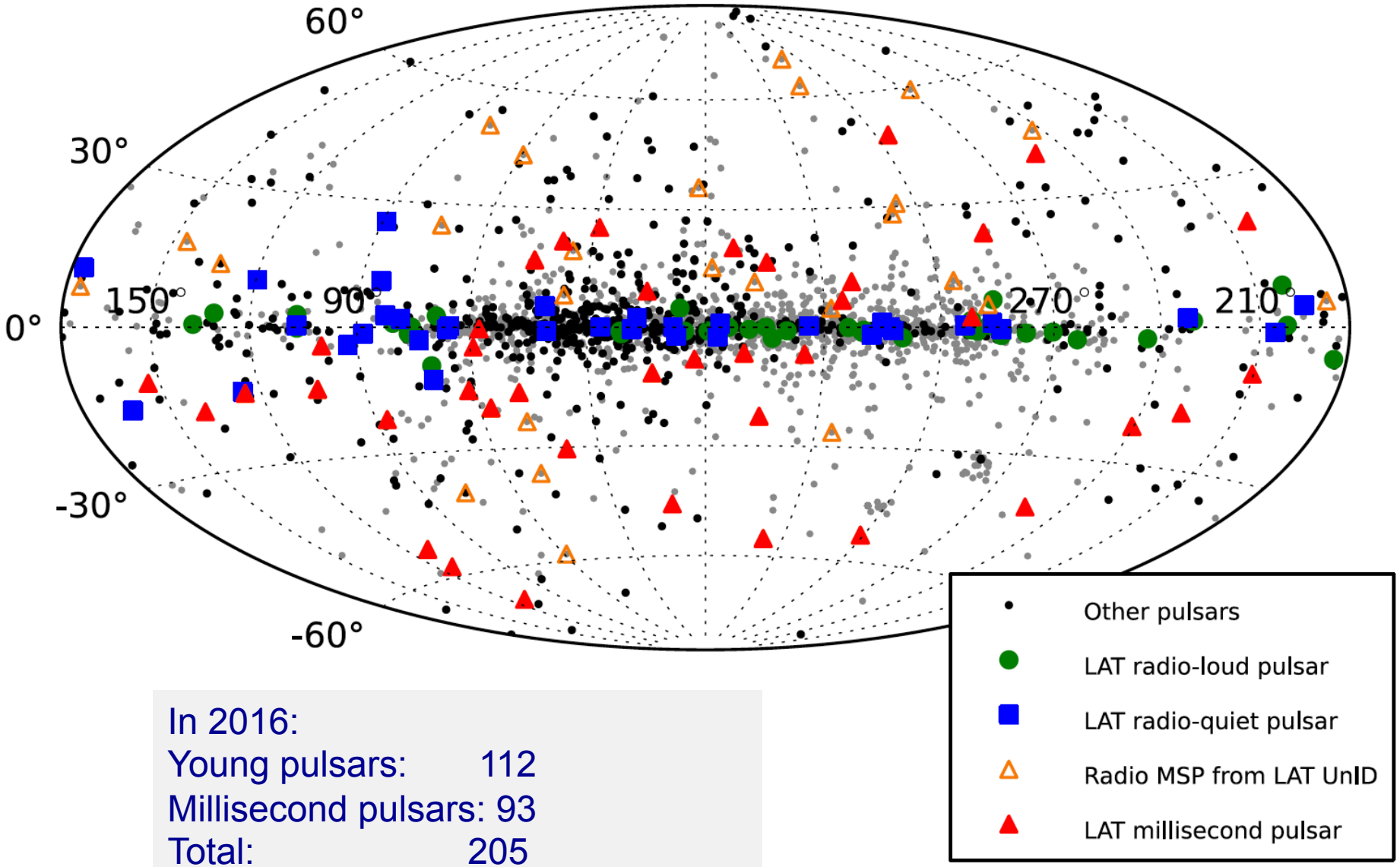


Gamma-ray pulsars – dominant class of Galactic GeV sources (due to Fermi LAT)

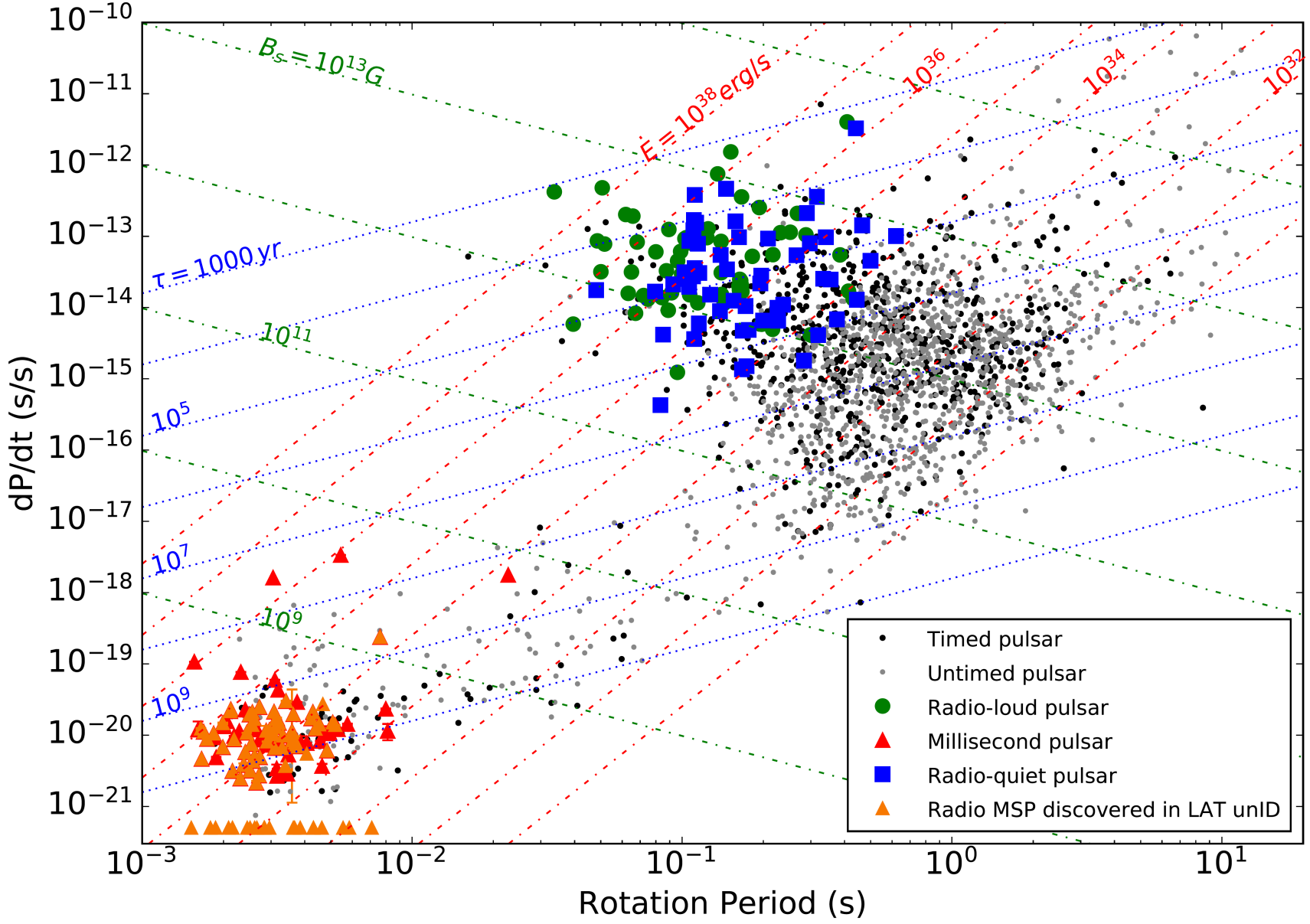
Pulsar Wind Nebulae – dominant class of Galactic TeV sources (H.E.S.S., VERITAS)



2nd Pulsar Fermi LAT Catalog, 2013

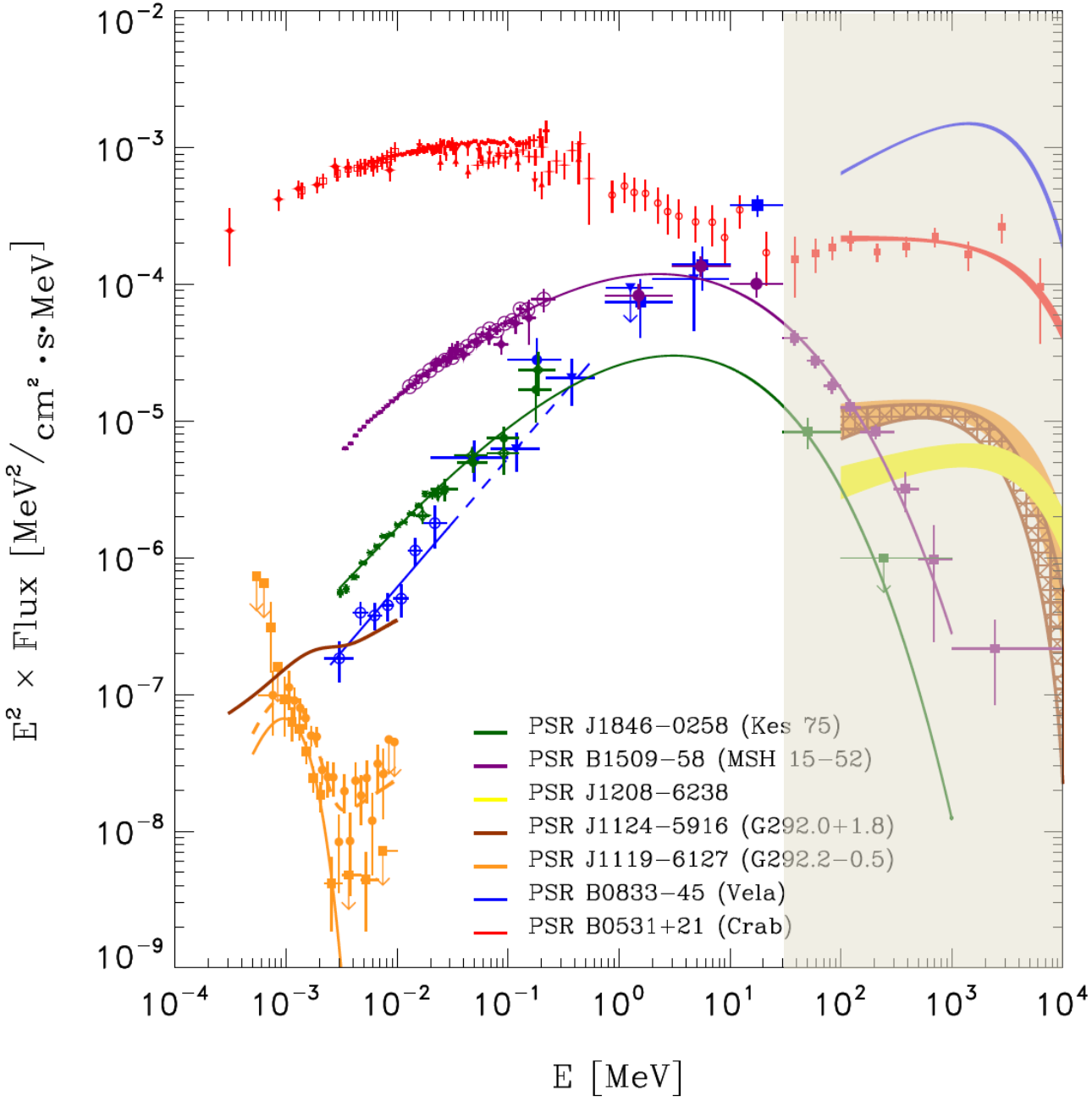


In 2016:
Young pulsars: 112
Millisecond pulsars: 93
Total: 205


dP/dt (s/s)
Rotation Period (s)
$B_s = 10^{13}$G
10^{11}
10^9
10^7
10^5
$\tau = 1000$ yr
$\dot{E} = 10^{38}$ erg/s
10^{36}
10^{34}
10^{32}
Timed pulsar
Untimed pulsar
Radio-loud pulsar
Millisecond pulsar
Radio-quiet pulsar
Radio MSP discovered in LAT unID

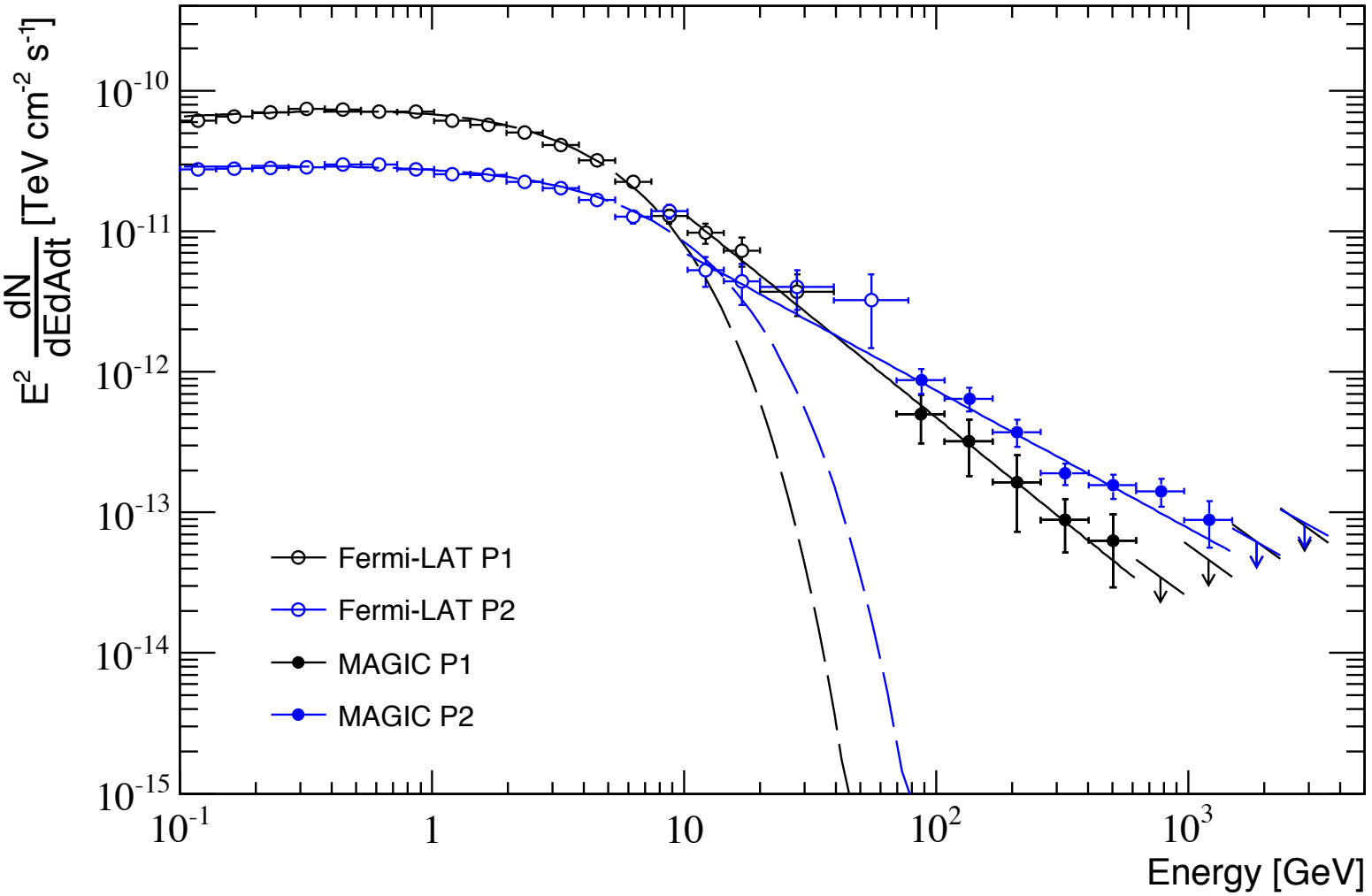
Phased-averaged spectral energy distributions

Kuiper + 2017



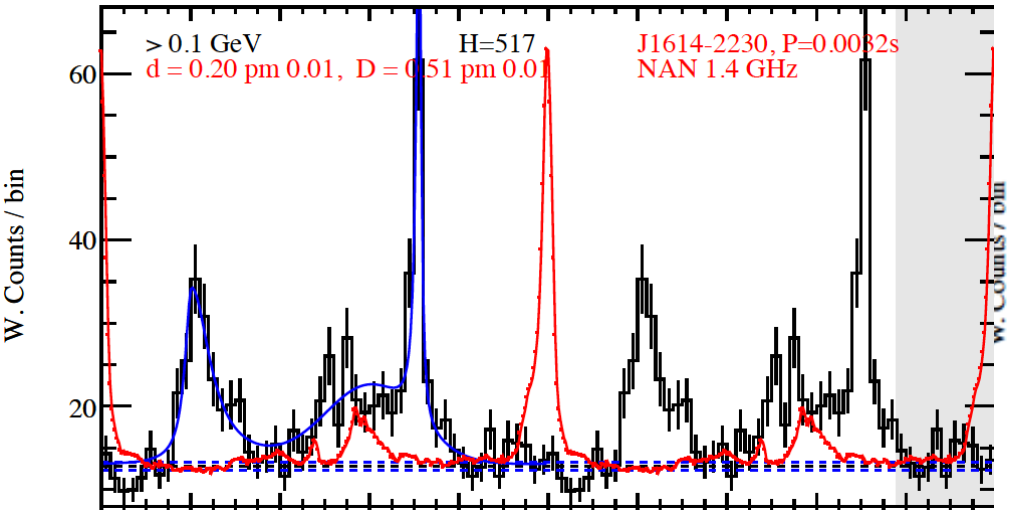
TeV pulsed emission from the Crab pulsar detected by MAGIC

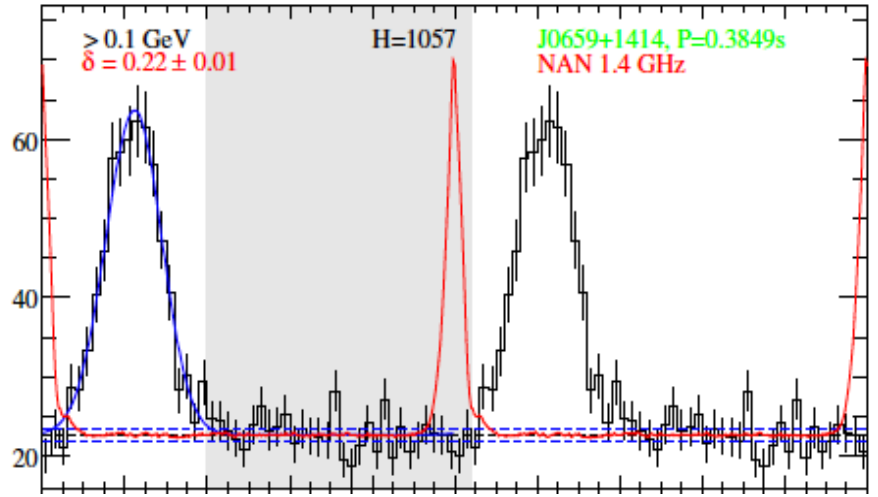
(Ansoldi et al. 2015)

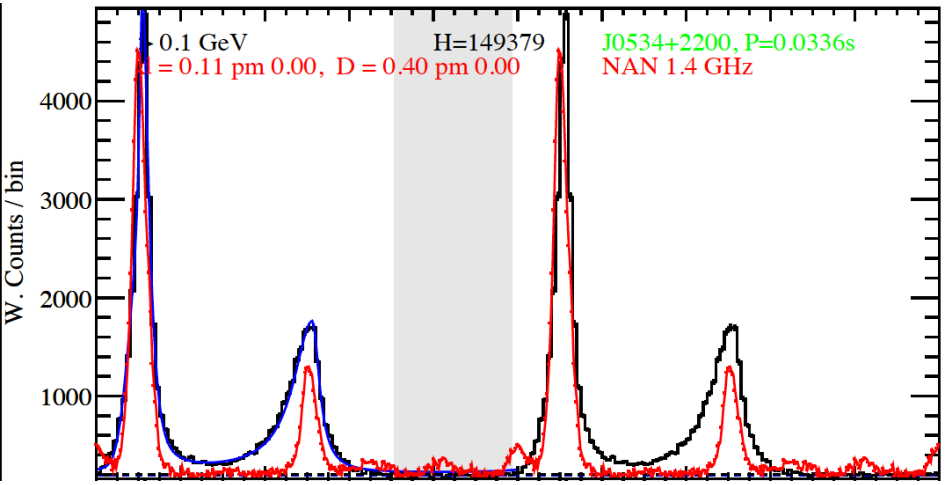


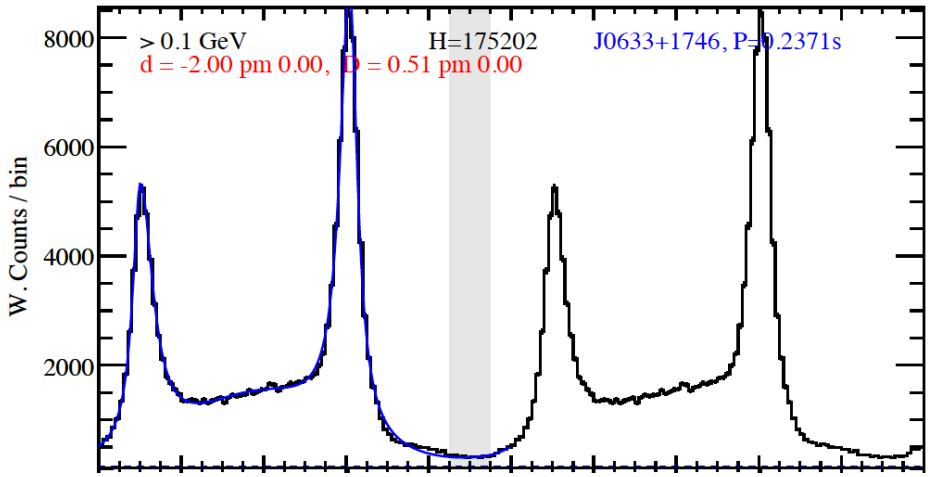
Examples of pulse profile morphology

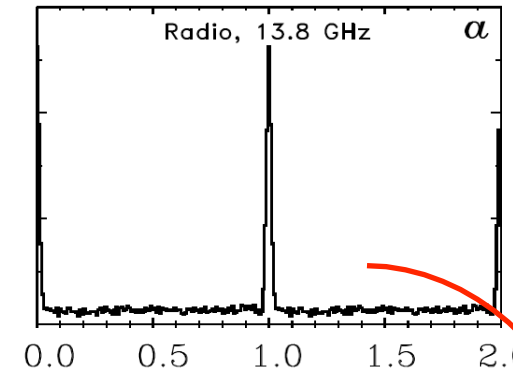
(2nd Fermi LAT Pulsar Catalog, 2013)

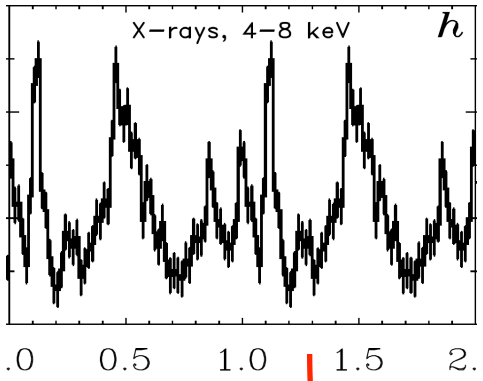


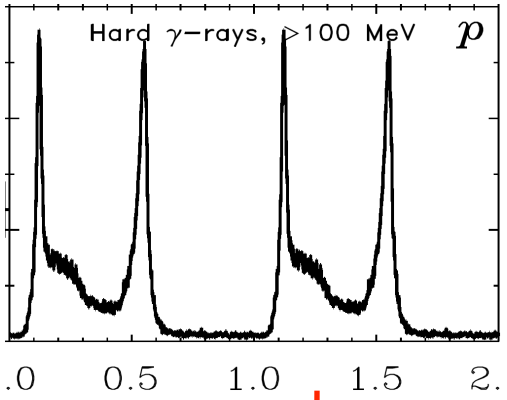


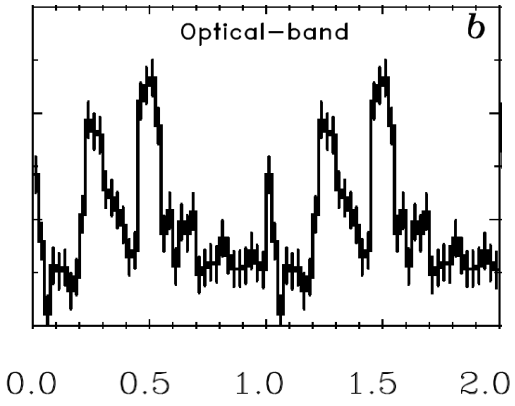


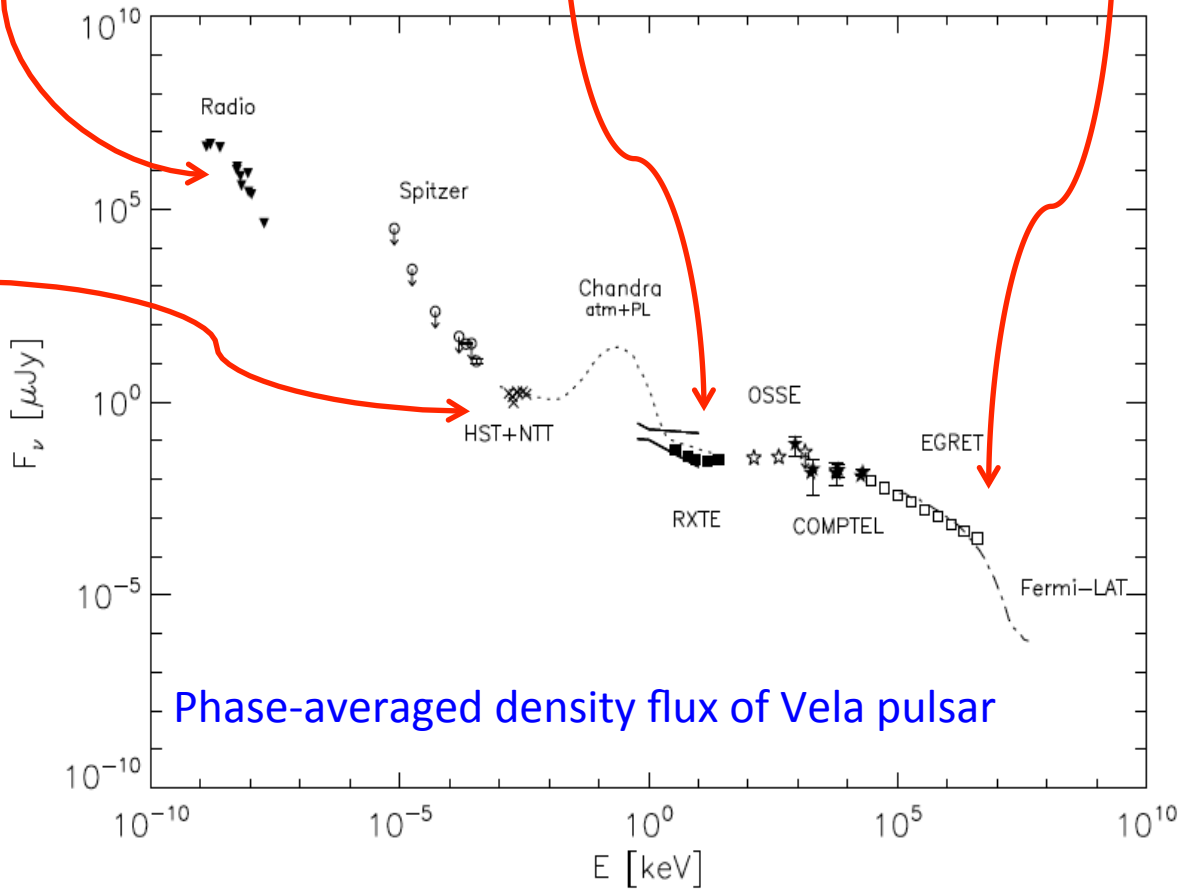










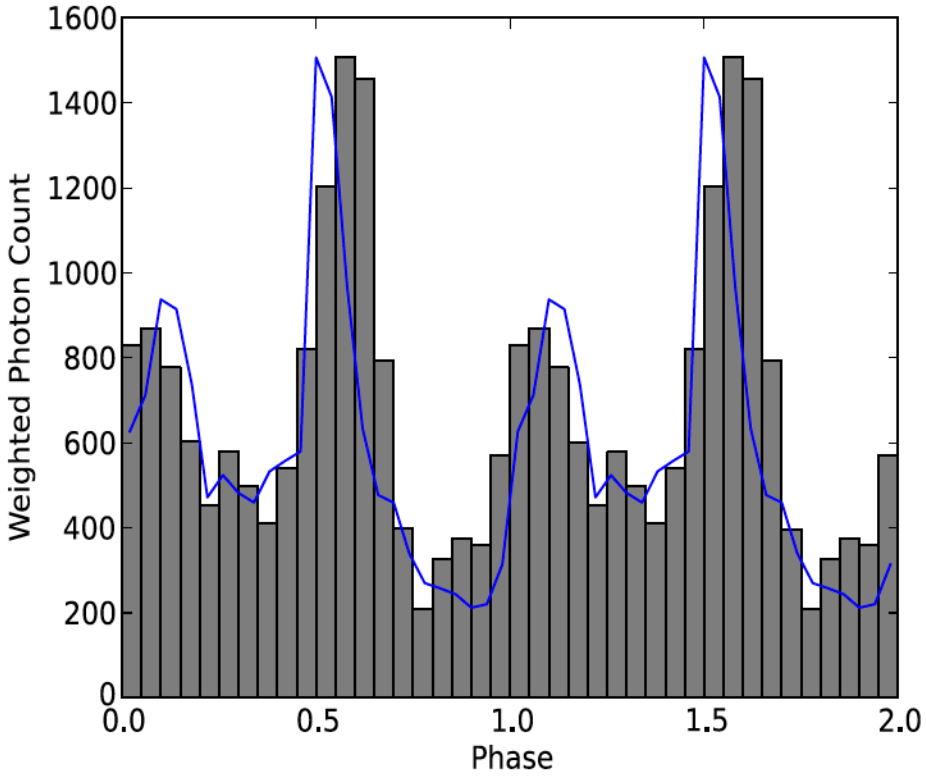


Phase-averaged density flux of Vela pulsar

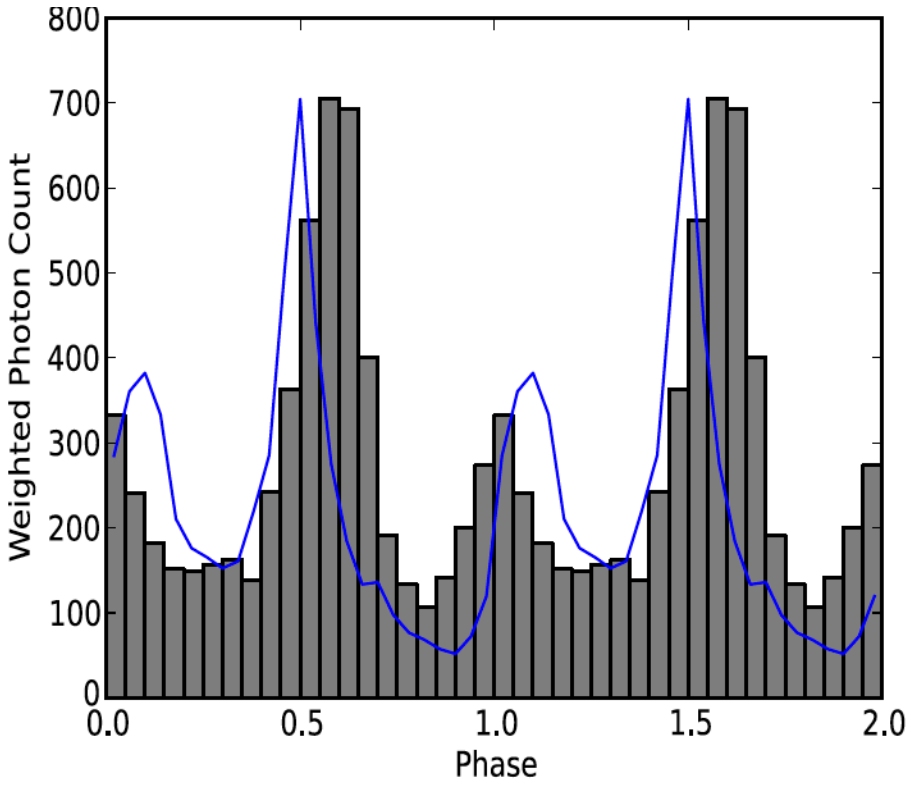
Ng+ 2016

PSR J2021+4026
Pulse profile above 100 MeV

Before the glitch

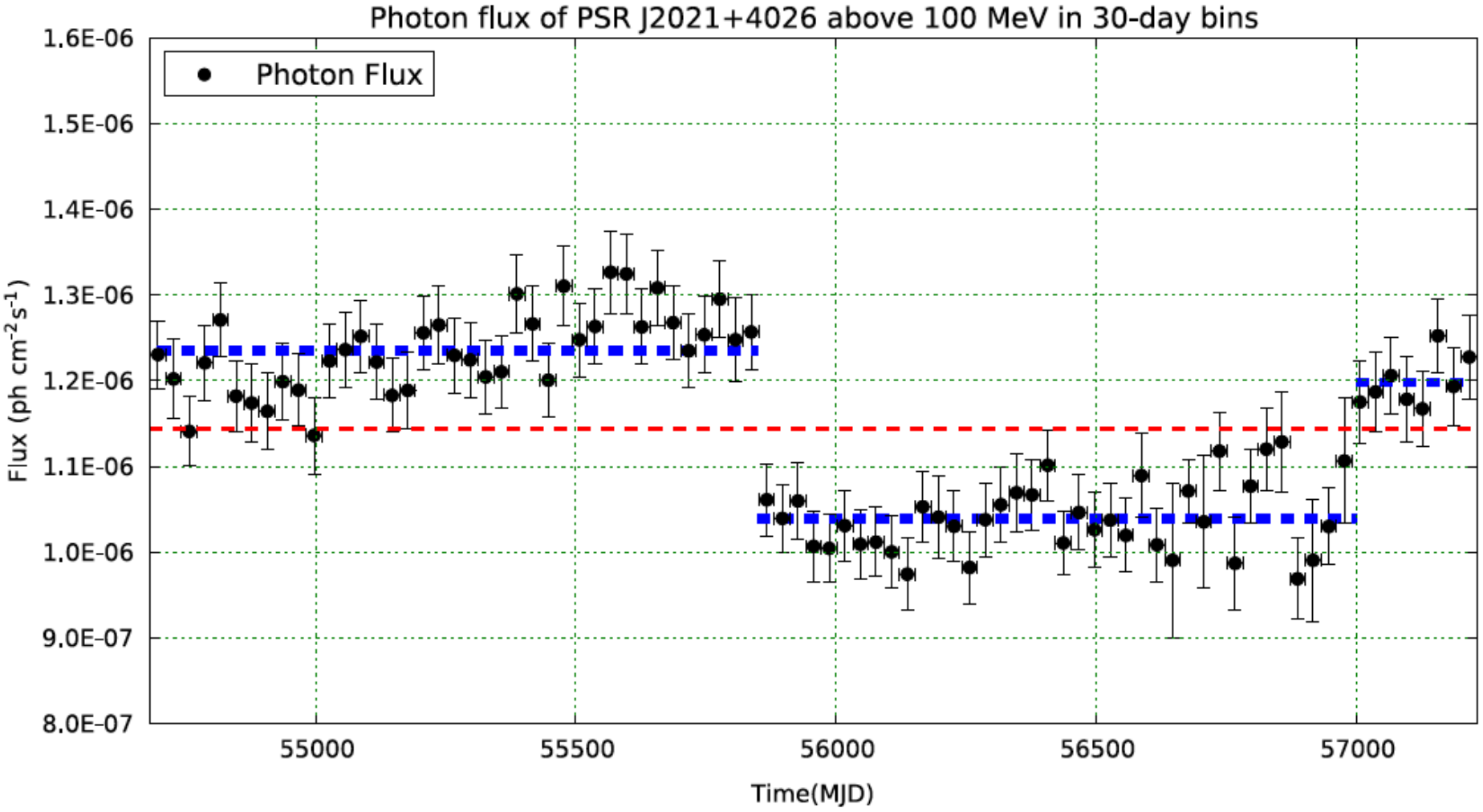


after



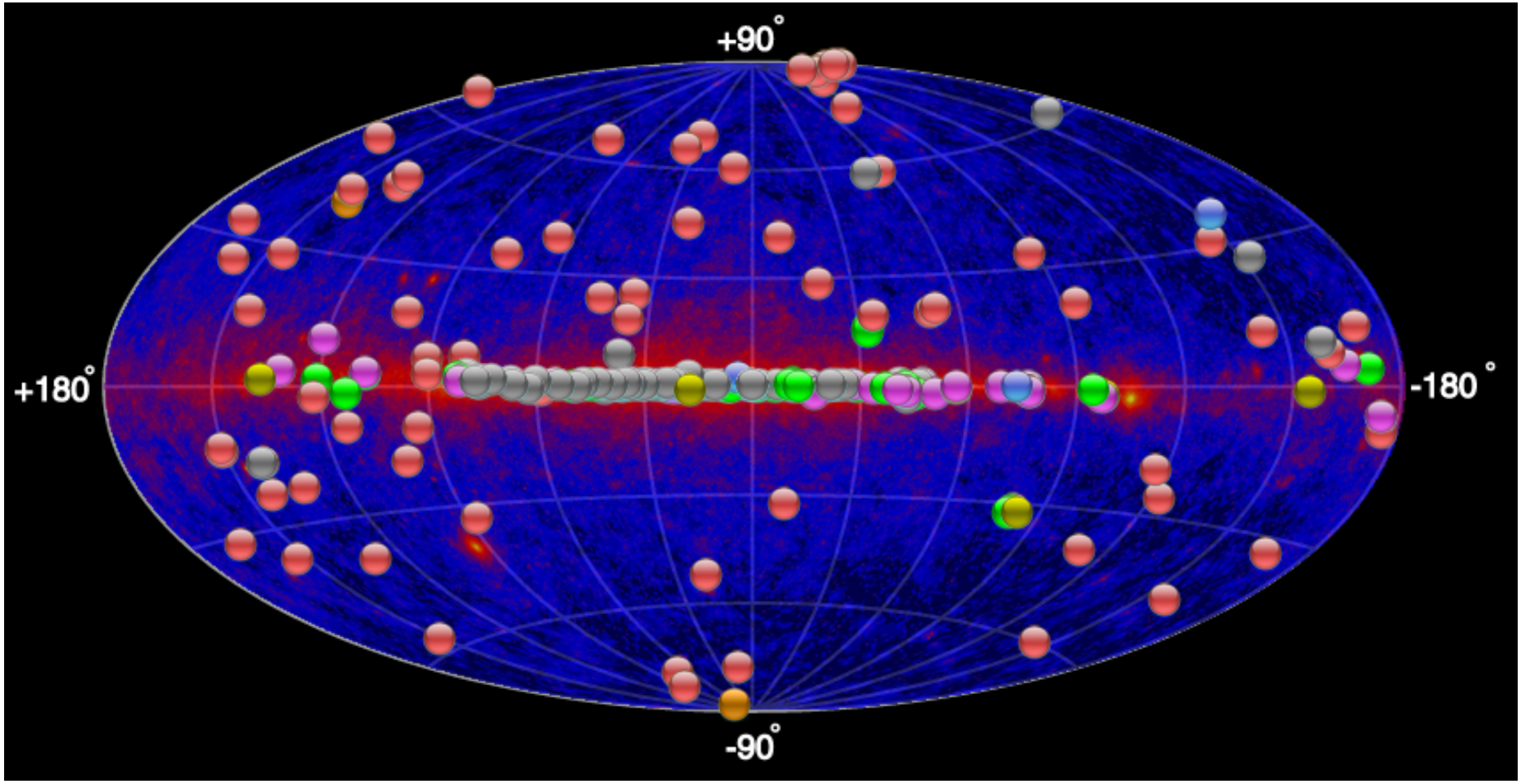
Ng+ 2016

Drop in photon flux above 100 MeV



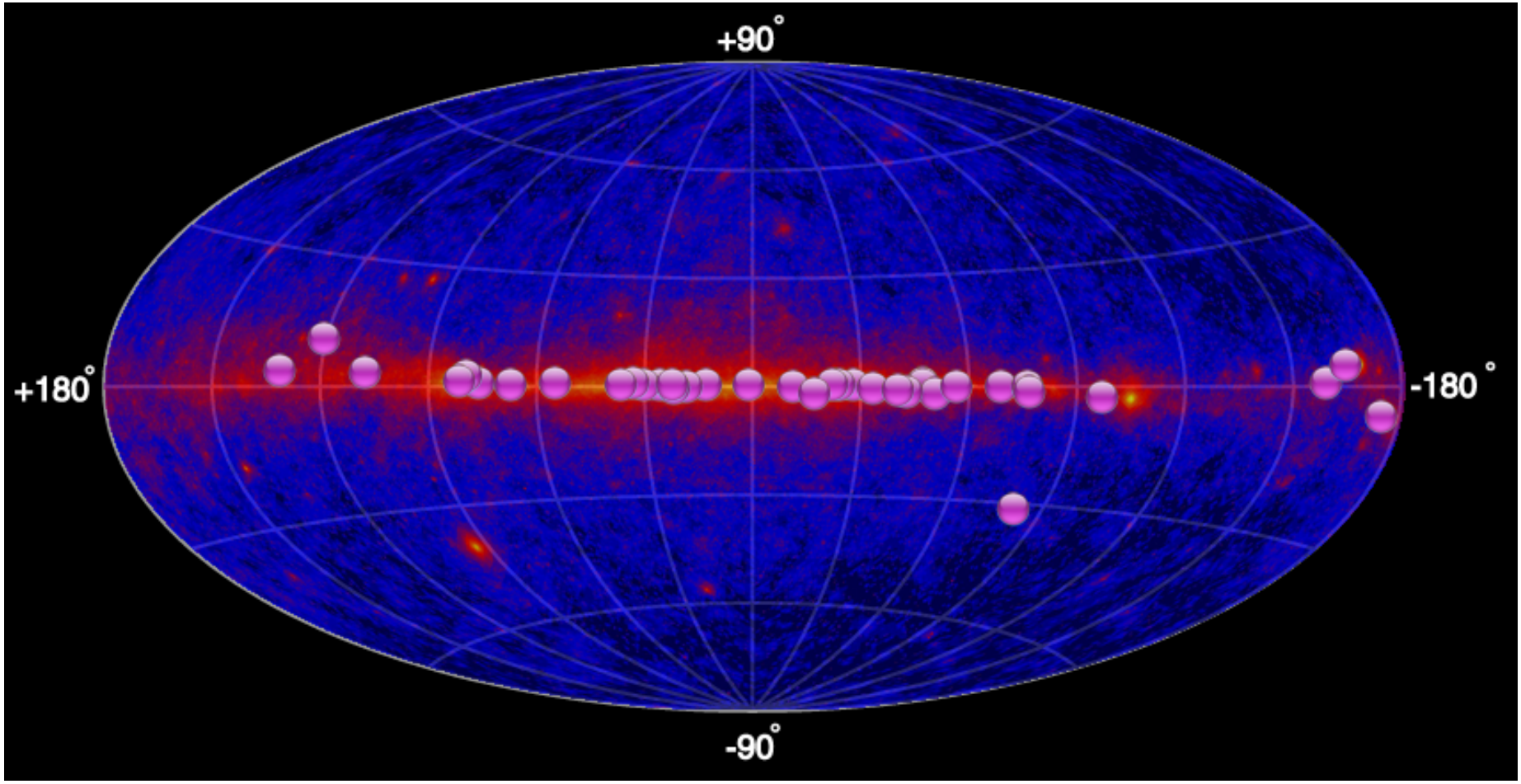
Very High Energy gamma-ray Sky

In 1989 - 1 source, in 2017 – 220 sources
Expectations for CTA ~ 1000 sources

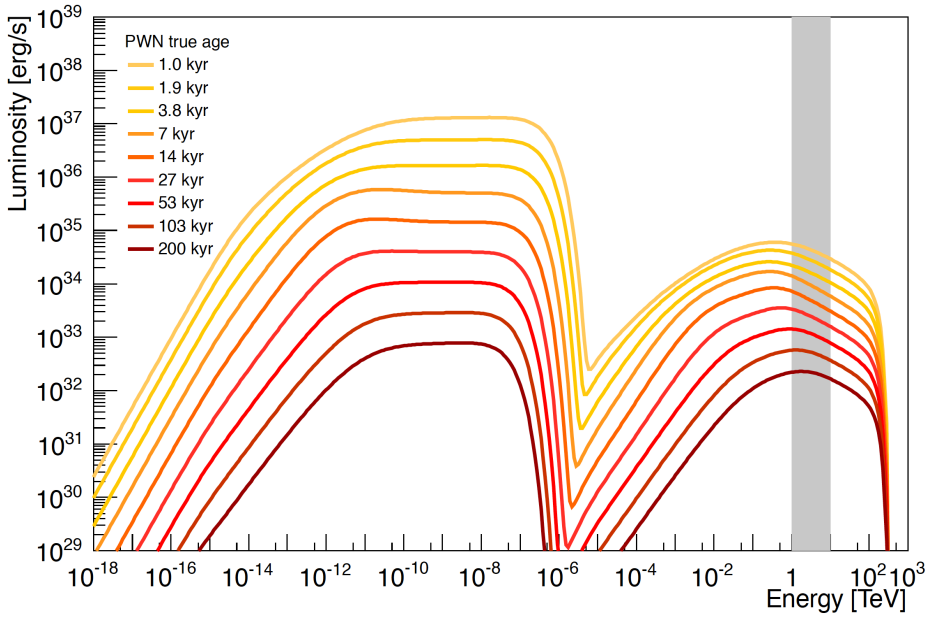


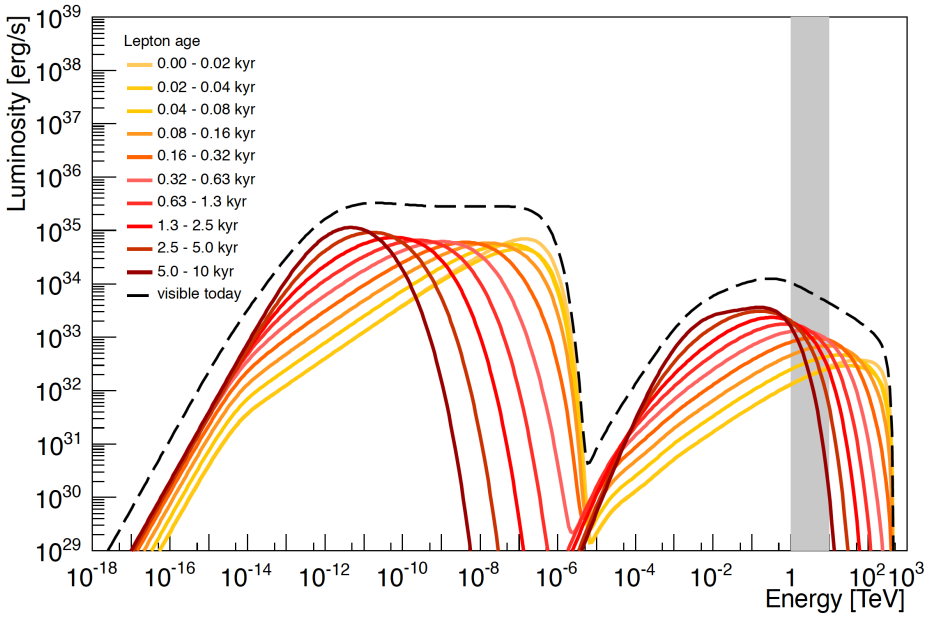
PWNe in VHE

In 1989 - 1 source, in 2017 – 37 sources



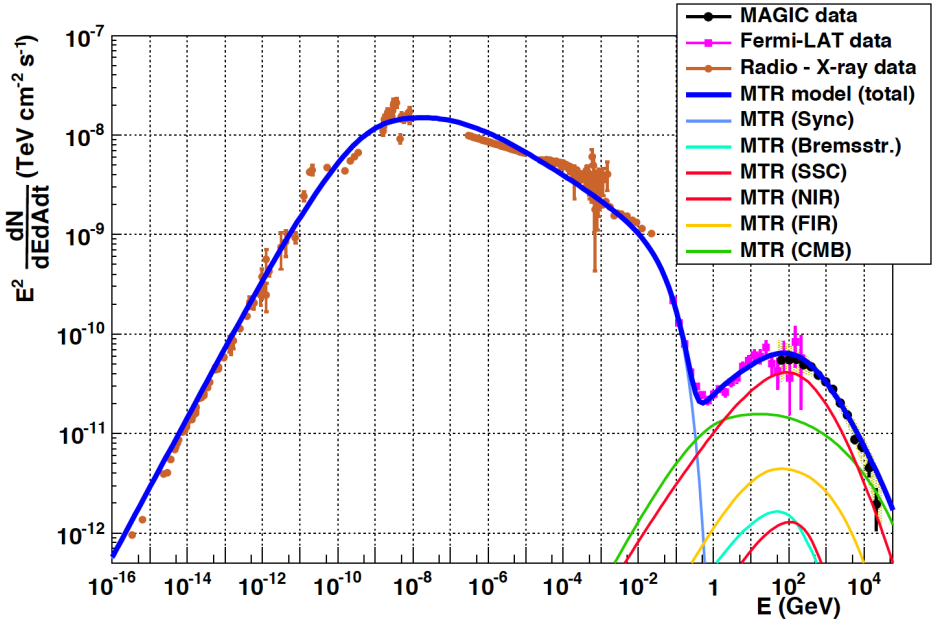
Modelled SED of a generic PWN

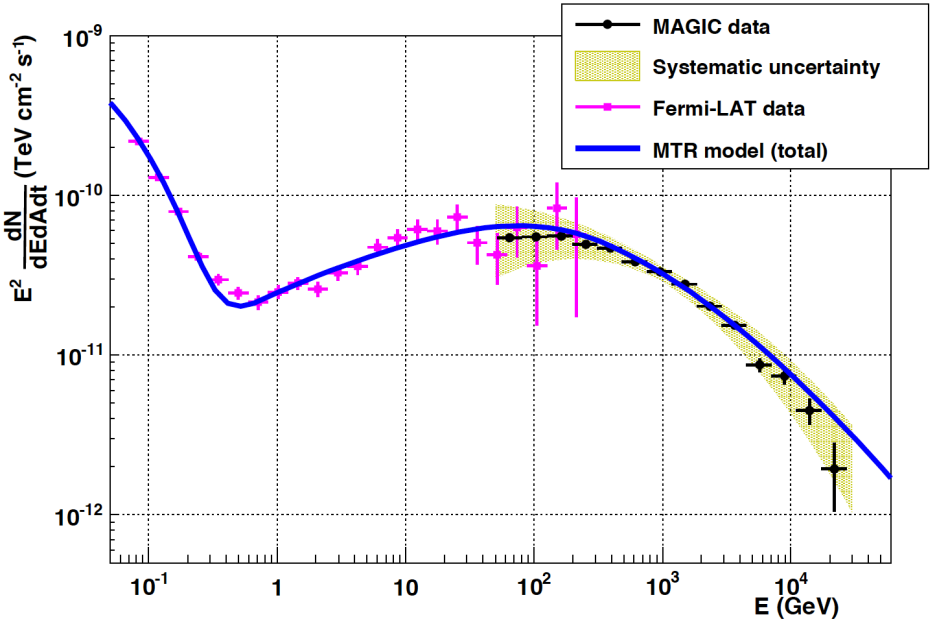




SED of the Crab Nebula

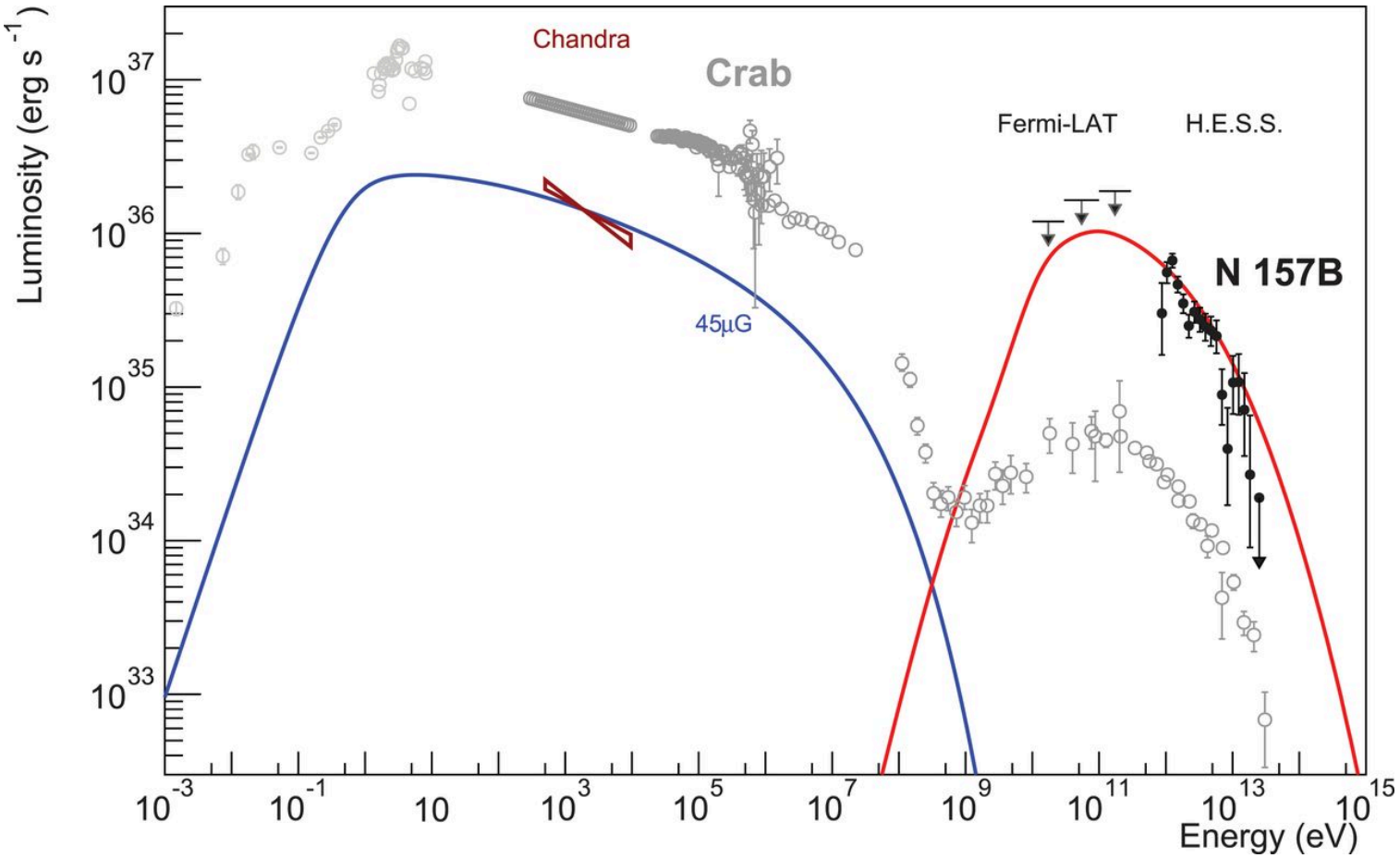
Aleksic+ 2015 (MAGIC Coll.)



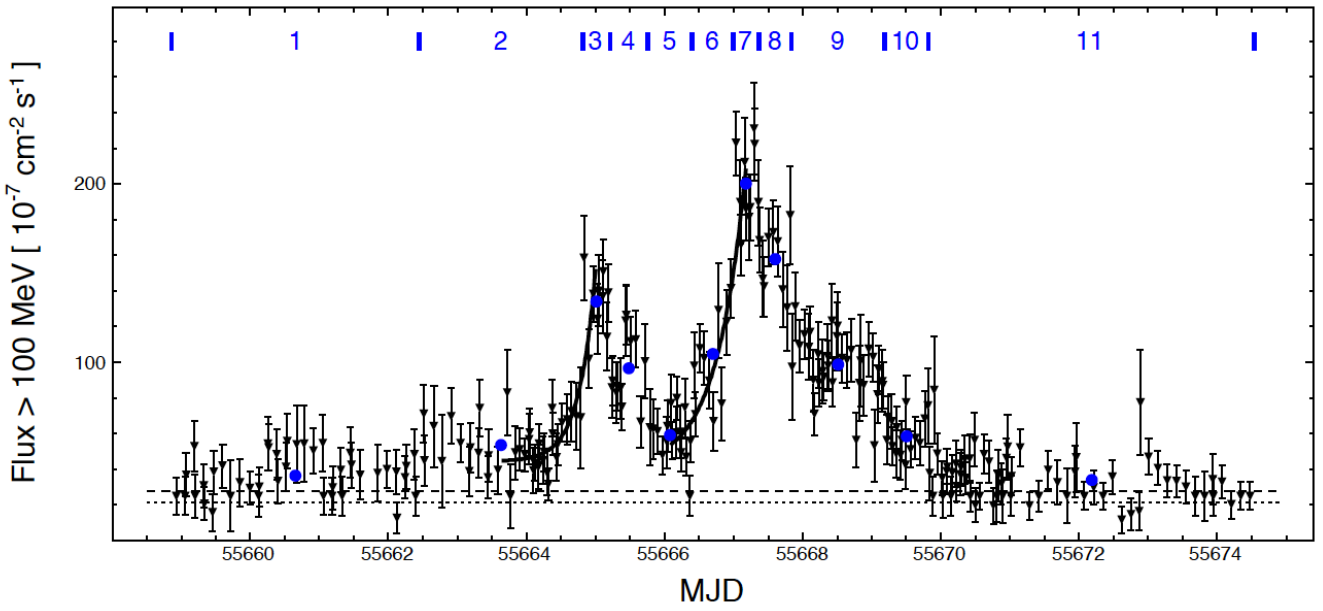


The H.E.S.S. Collab. 2015

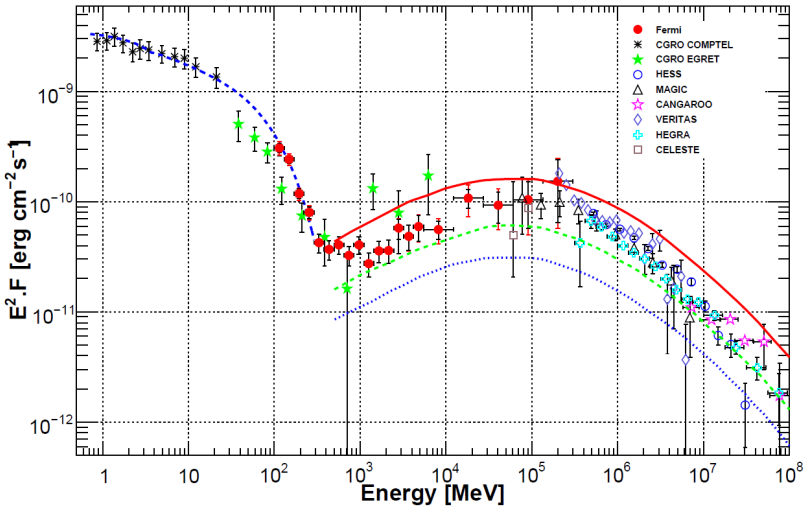
PWN N 157B in Large Magellanic Cloud

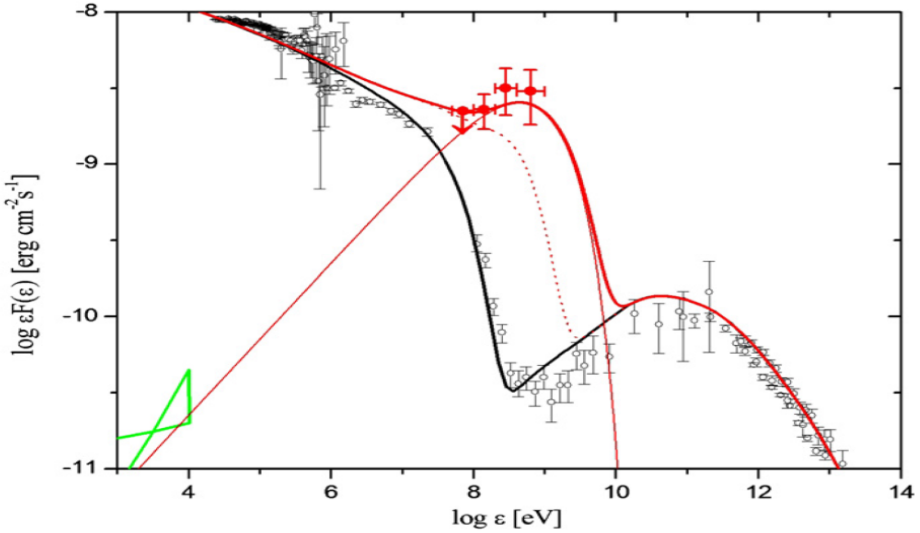


The Crab Nebula is not a standard candle at MeV-GeV



Flaring of the Crab Nebula





Super-flare on 2011 April 15-16
AGILE

Is magnetic reconnection responsible for flares in Crab Nebula ?

Where? Close to the termination shock ?

A brief history of pulsar models in three stages

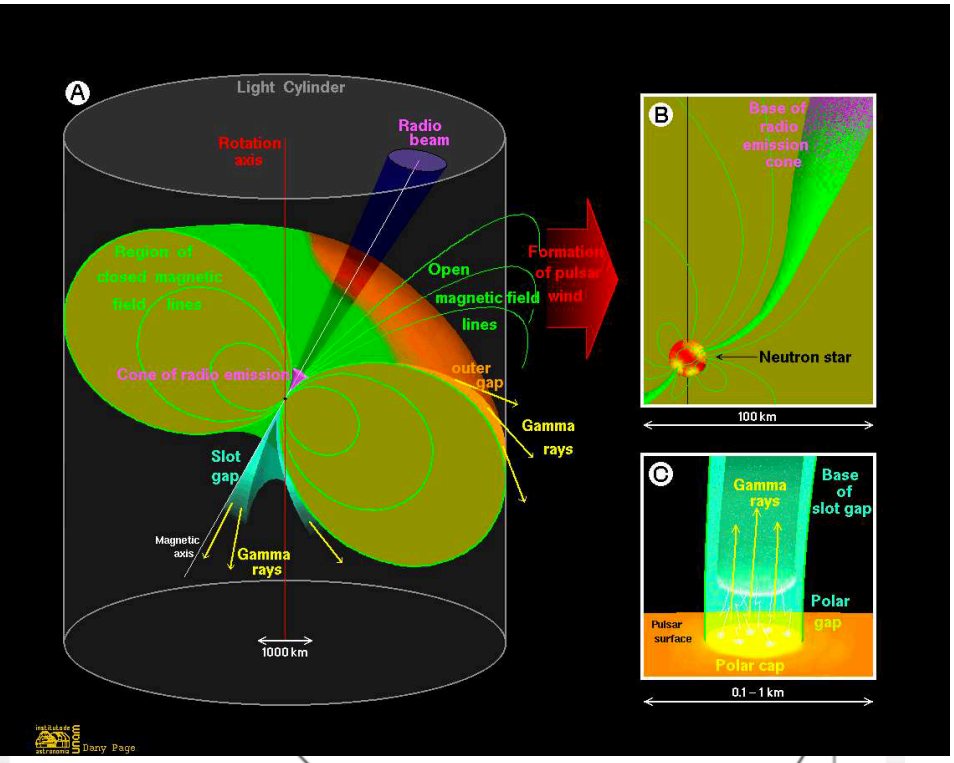
Stage 1 The vacuum magnetic dipole model

passé, but some features still in use

Stage 2 The co-rotating magnetosphere models
in low-density, charge-separation limit (next slide)

still in use (many papers in 2016, 2017)
but their days are numbered

3D magnetospheric accelerators (gaps) – local approach



To be solved simultaneously in a magnetosphere:

- non-vacuum Poisson equation,
- Boltzmann equation for pairs,
- radiative transfer

Boundary conditions (taken ad hoc => many flavours of the model)

The global current closure issue – ignored.

Results: model spectra and emission directionalities ->

-> 'observed' characteristics depend on the inclination angle and the line of sight angle

Stage 3 Electrodynamics with the plasma

in development:

1. Force-free (FF) magnetospheres:

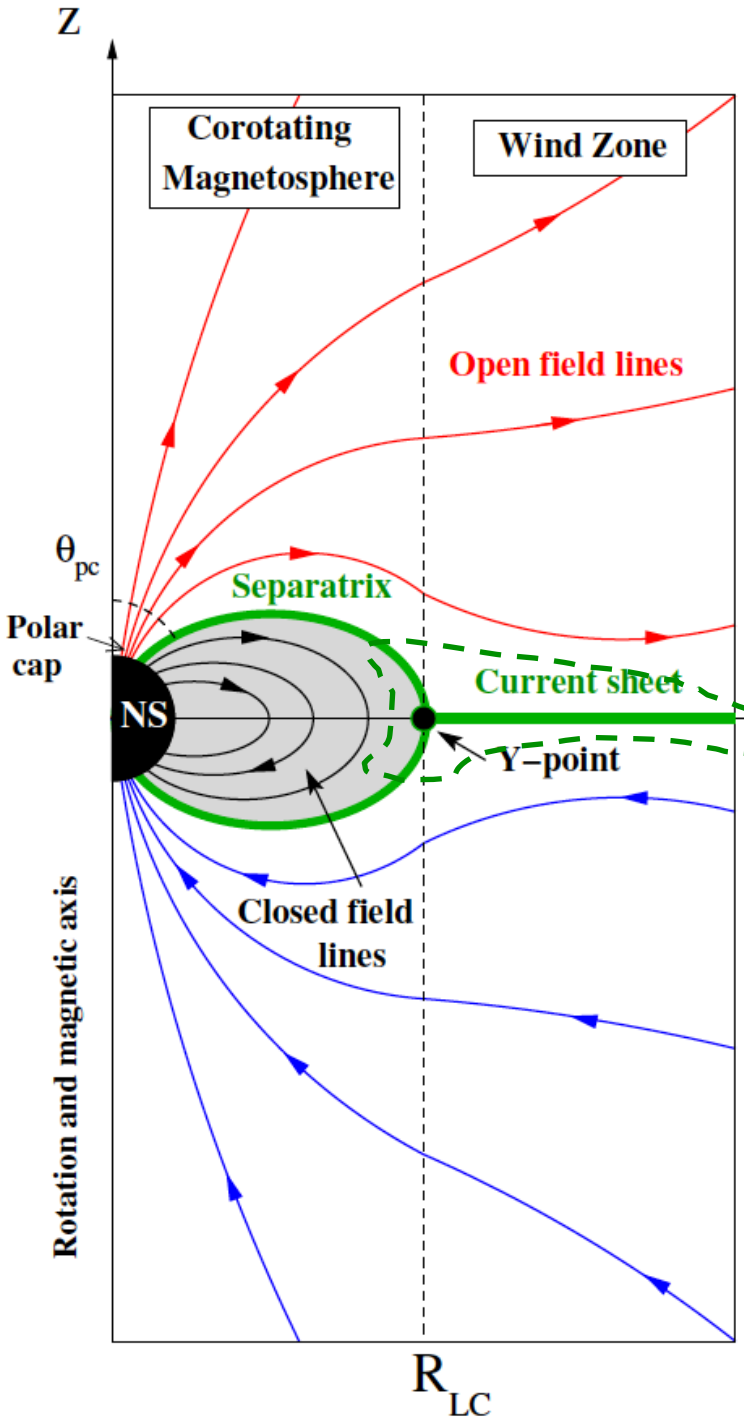
- ideal MHD (no dissipation => no radiation).

2. Dissipative magnetospheres and winds:

- many versions of 'FF' with macroscopic conductivity,

2a. Particle-In-Cell (PIC) simulations
- include particle inertia and acceleration,
but only low-resolution calculations possible so far.

Lyubarskii 1990, … ,
Cerutti & Beloborodov 2016

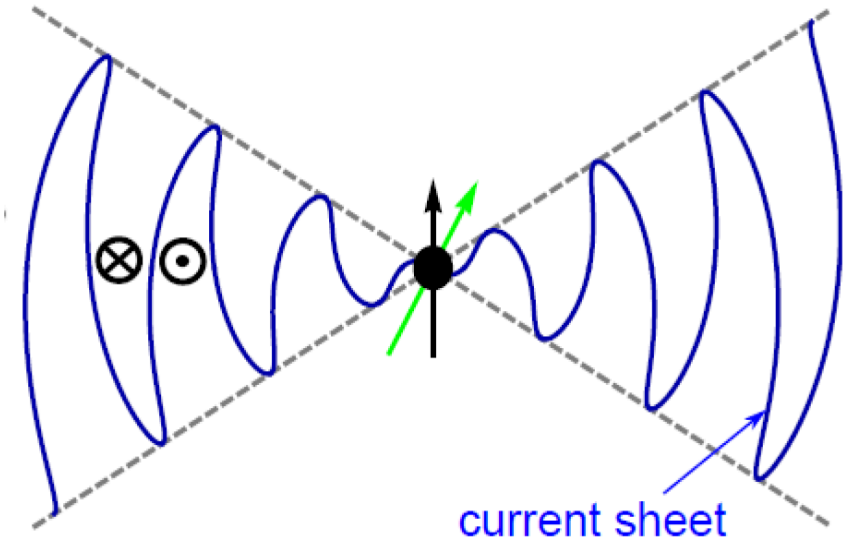


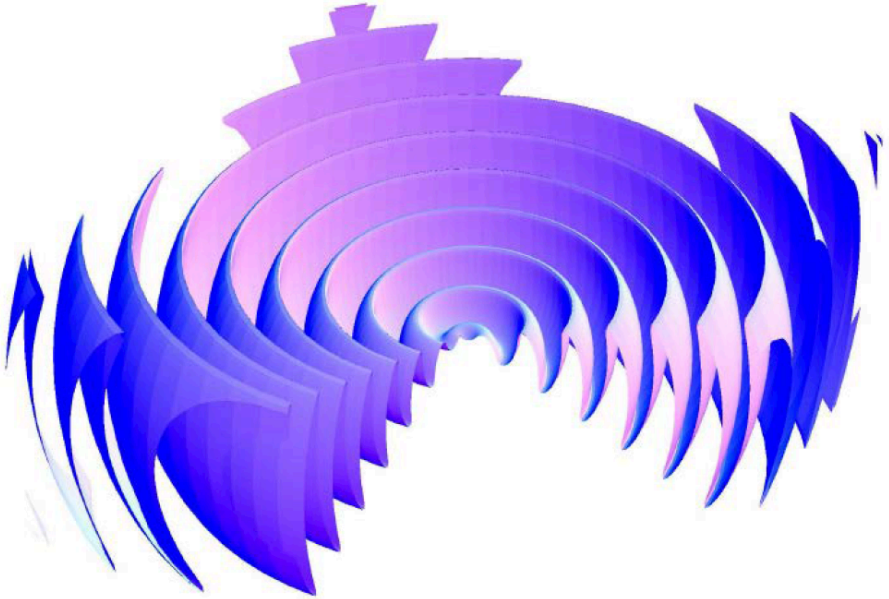
Aligned rotator with a force-free magnetosphere:

- dense (n > n_GJ) plasma outflow,
- split monopole magnetic field at r >> R_LC
- current sheet forms.

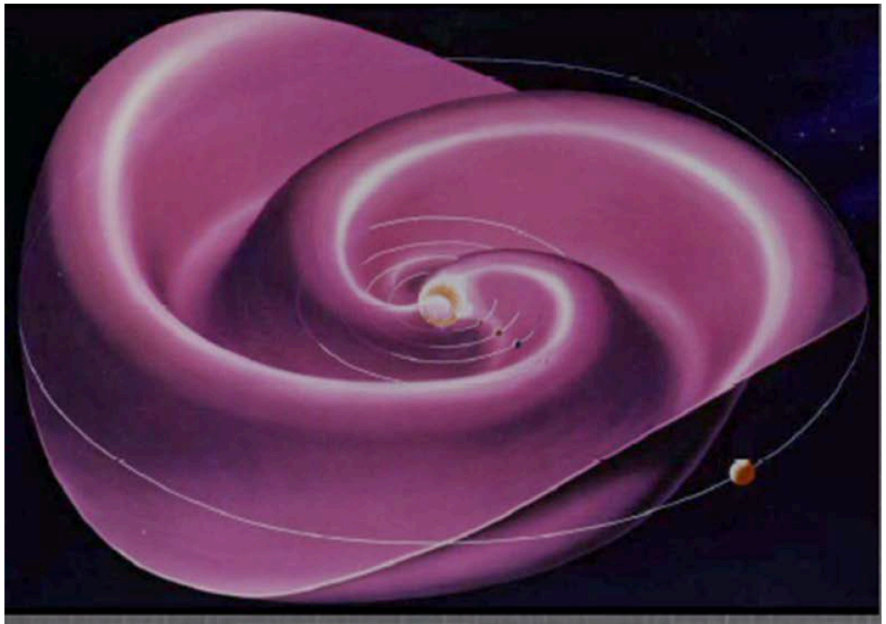
Strong non-thermal emission can be produced in the CS and in the separatrix sheets inside the light cylinder.

Oblique rotator => current sheet becomes corrugated; striped wind forms



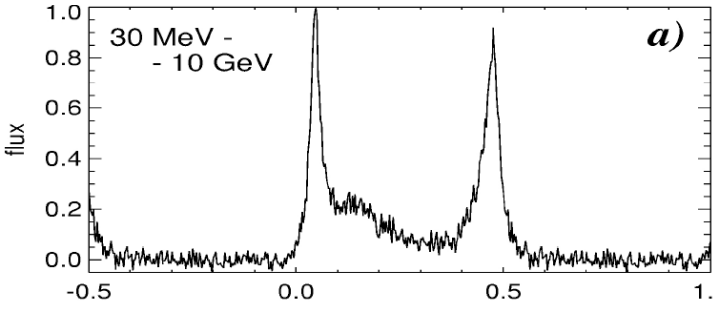


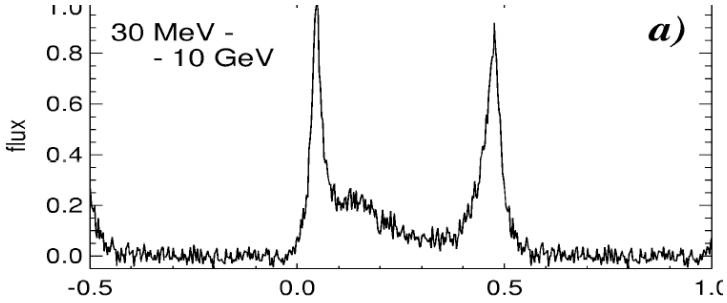
„a ballerina skirt”

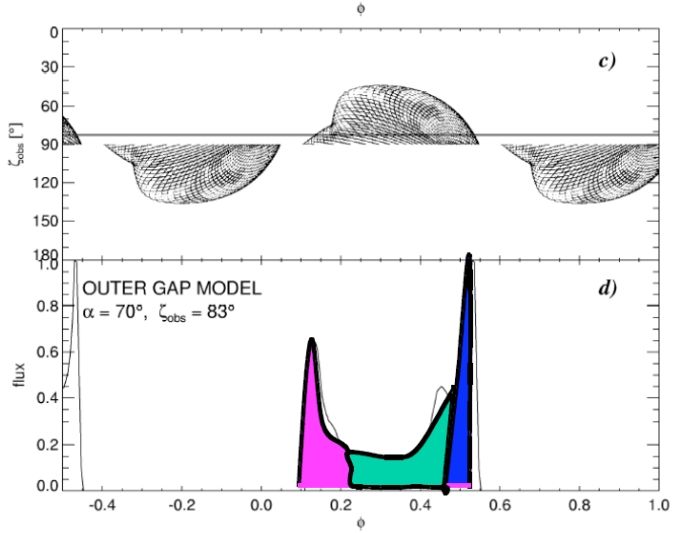


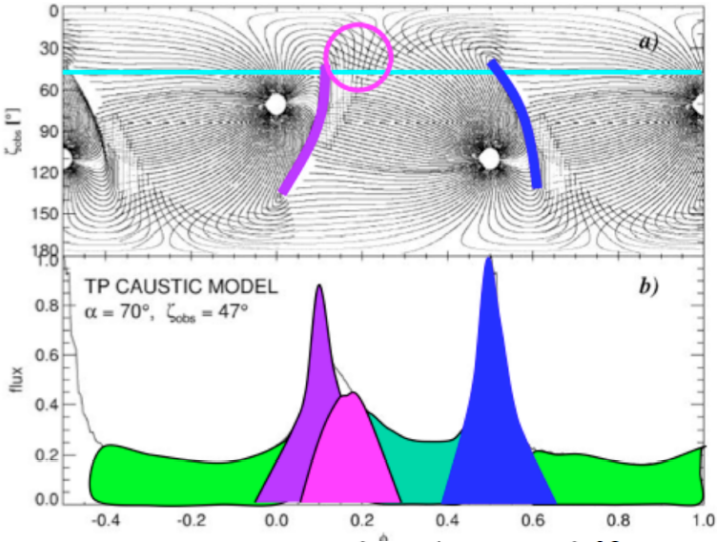
Back-up slides

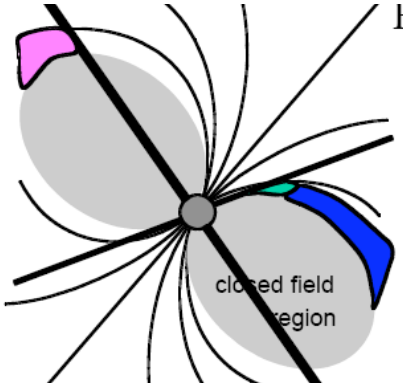
Outer Gap and TPC emission models for the Vela pulsar

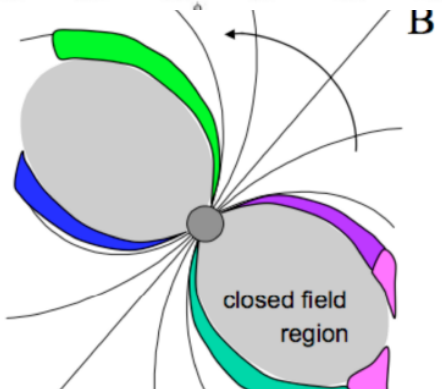












Morphology of PWNe in X-rays