Multiwavelength studies of pulsars

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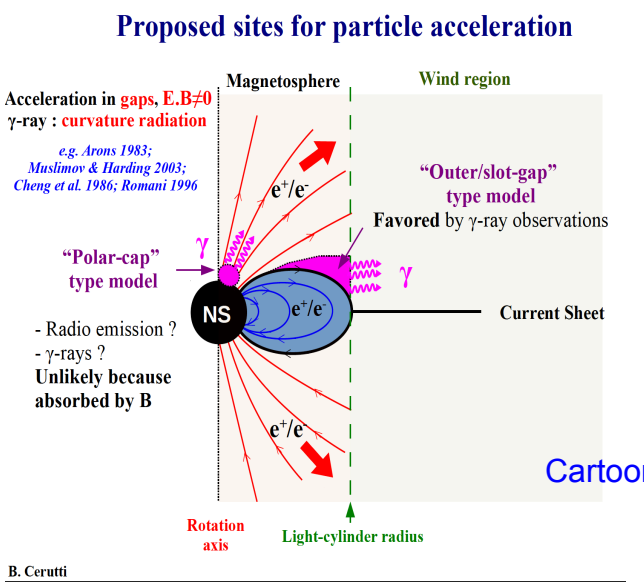
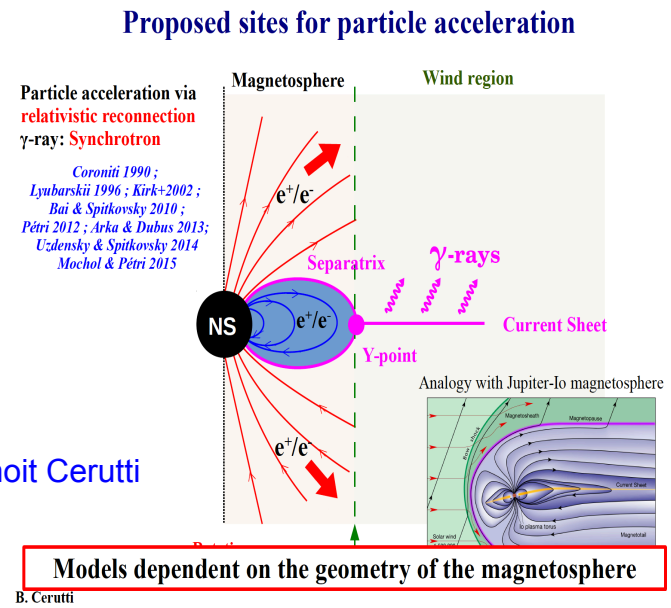
Outline

Multiwavelength properties of

- middle-aged pulsars: Vela (update), + Geminga (very old results) for comparison
- young pulsars: B0540-69 (update)

Constraints on emission regions loci in middle-aged pulsars from the lightcurves





Cartoons by Benoit Cerutti

Pulsar detections from radio to gamma rays

~ 2600 in radio

3 in mIR, 5 in nIR,

10 in optical,

10 in nUV, 4 in fUV

> 100 in X-rays (mostly Chandra and XMM Newton)

211 in gamma-rays (*Fermi* LAT, AGILE)

Cherenkov arrays:

Crab pulsar: 25 GeV – 1.5 TeV (MAGIC,VERITAS)

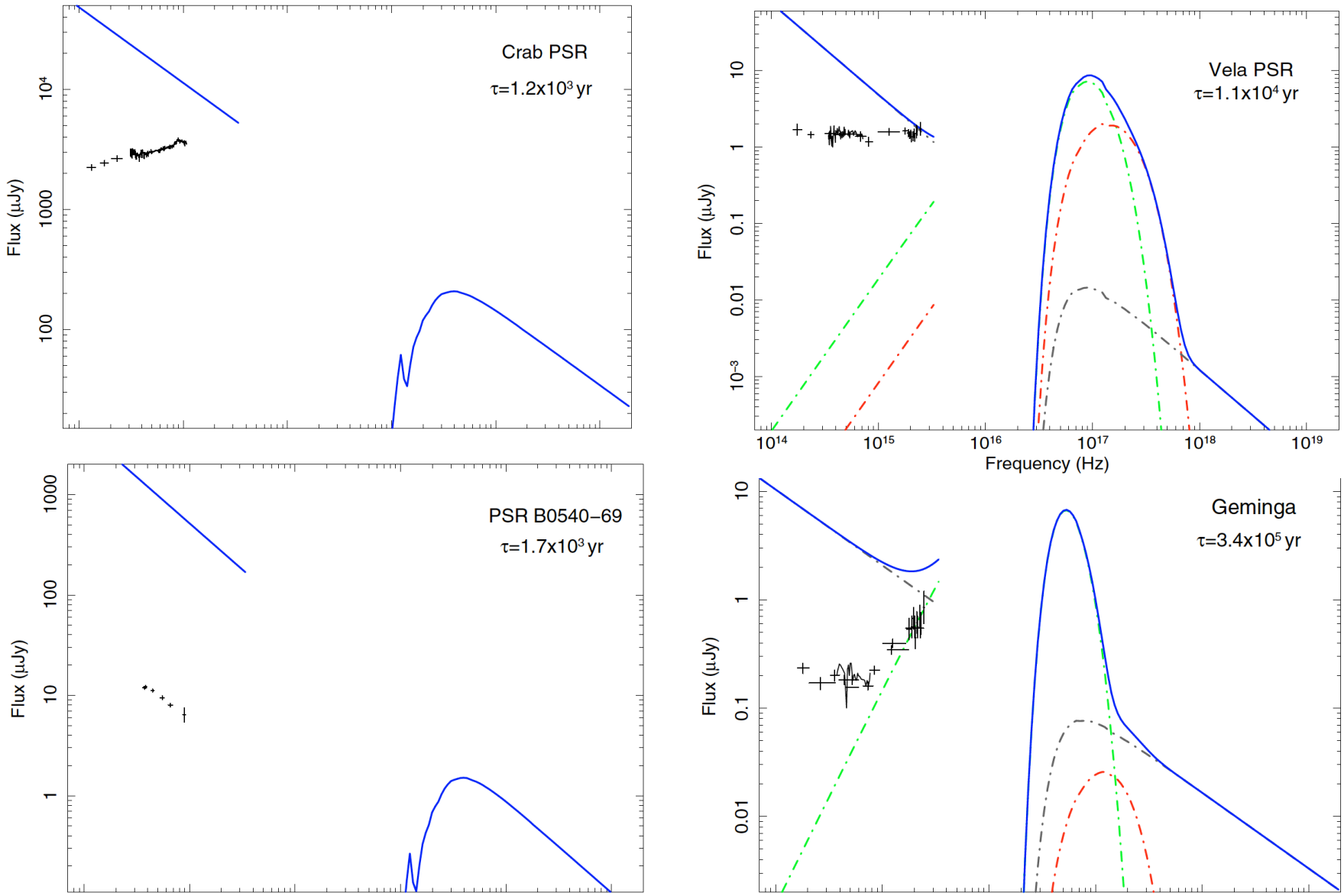
Vela pulsar: 20 – 120 GeV (H.E.S.S. II, mono), 3 TeV & 7 TeV (H.E.S.S. I, stereo)

UVOIR measurements

from compilation by Mignani et al. 2010

Young

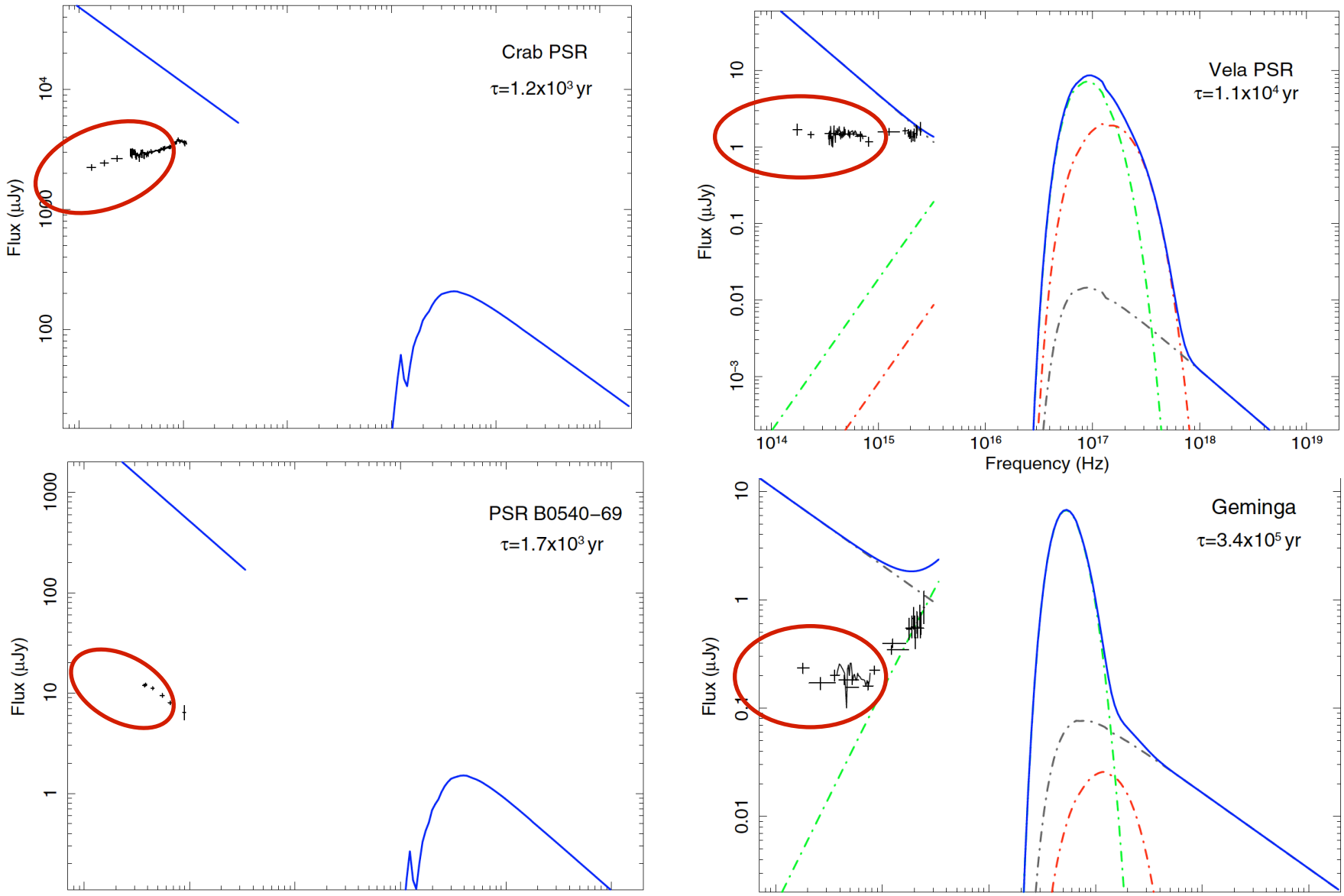
Middle aged



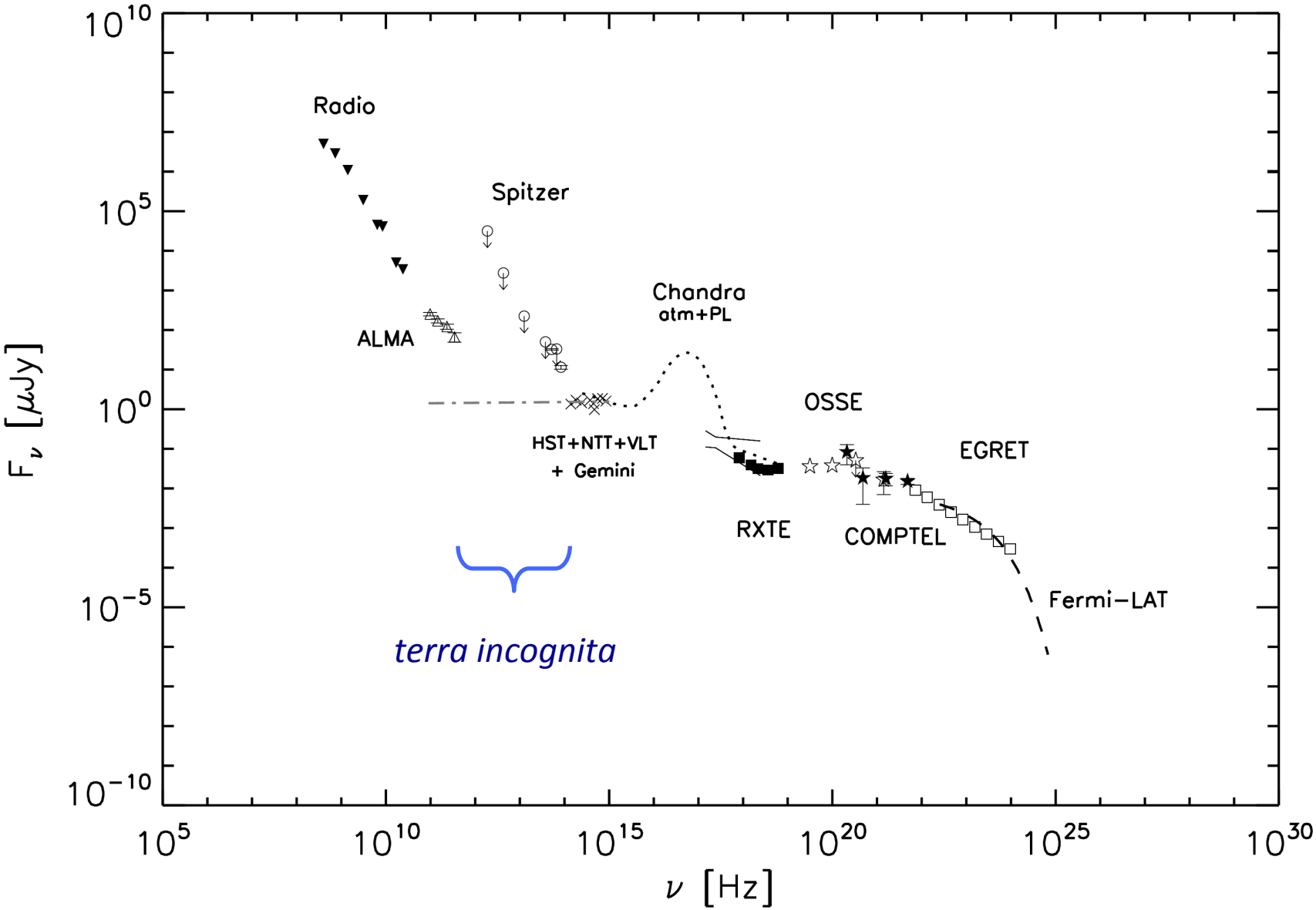
Optical and IR photon fields – potential targets for ICS -> GeV, TeV

Young

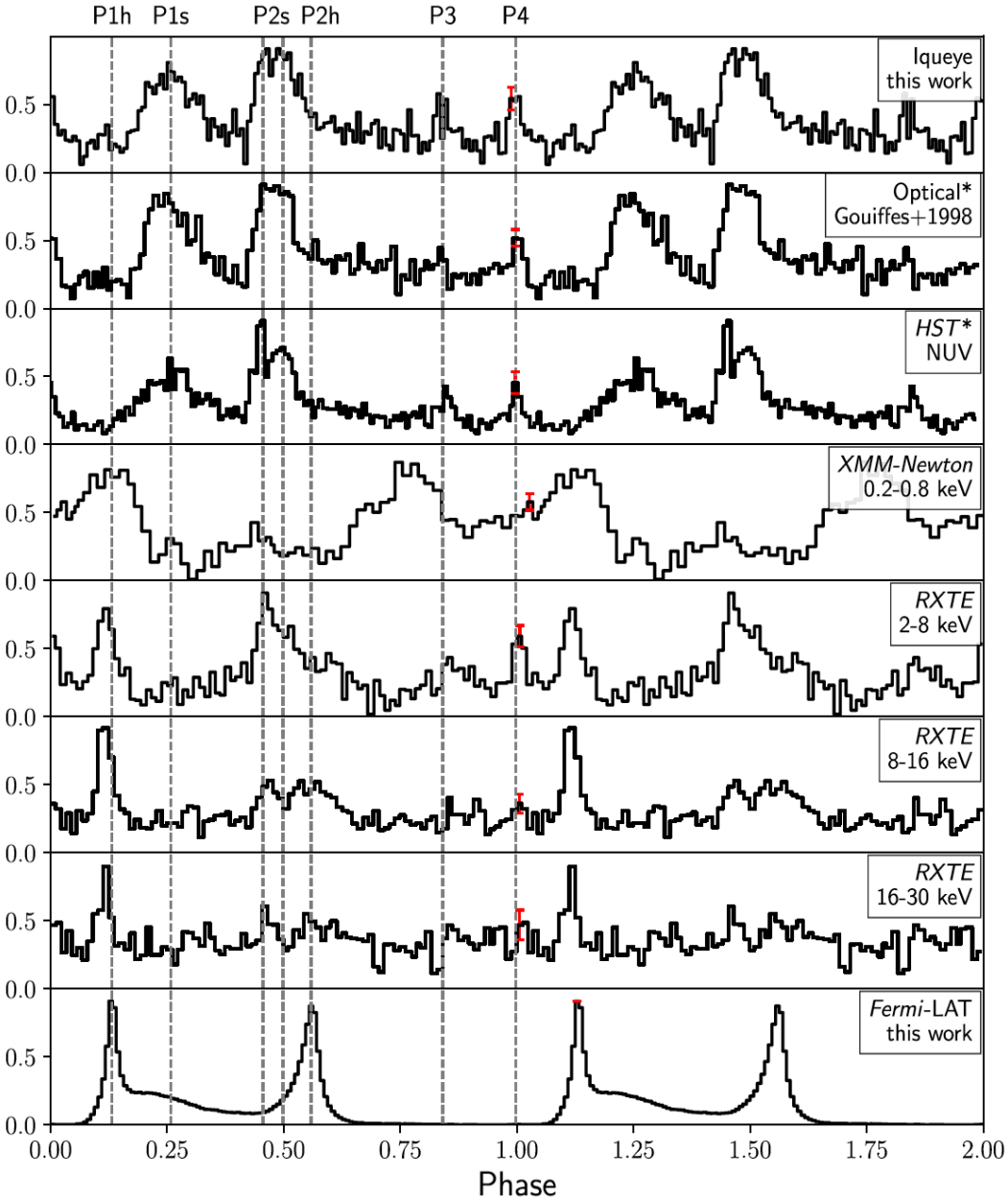
Middle aged



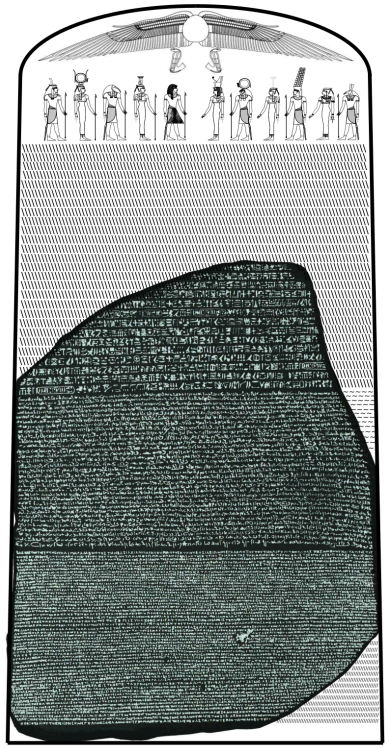
The SED of Vela



The Vela lightcurves



Spolon et al. 2019



See Strickman et al. 2001 for details

Sub-mm range - the yet unxeplored land

Transition region between coherent and incoherent emission

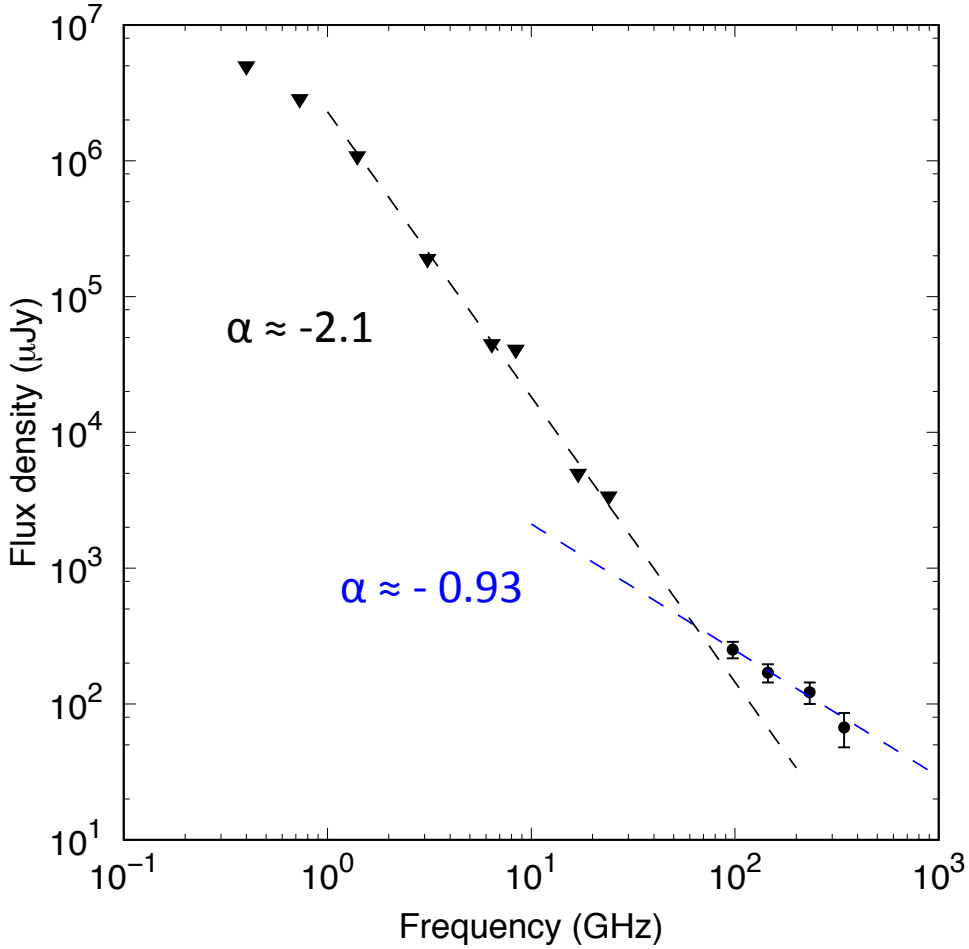
At what frequency does the transition occur?

How does the lightcurve change?

Are the radio spectrum and the IR-O-UV spectrum disconnected?

Vela is the first pulsar detected with ALMA (Mignani et al. 2017)

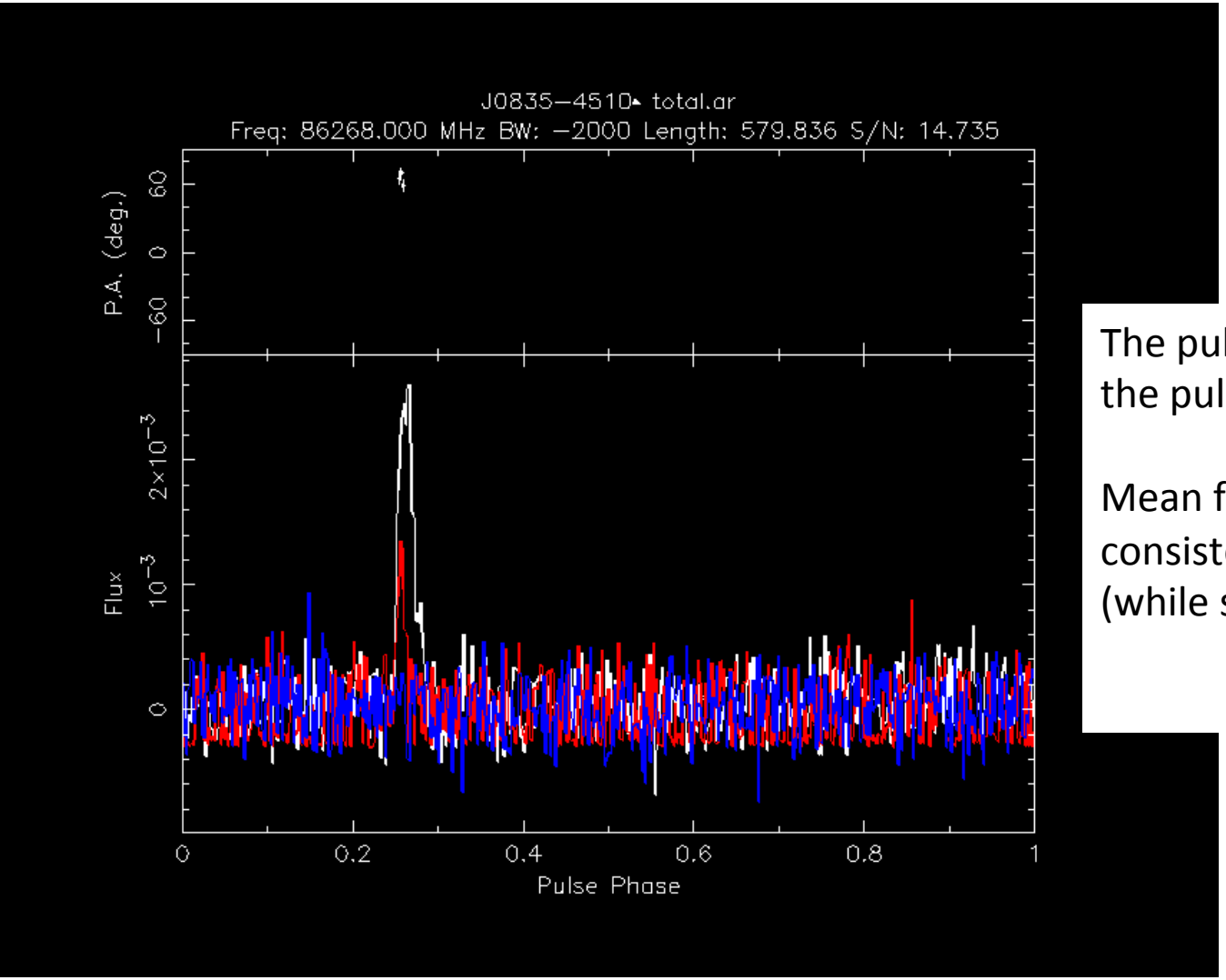
Radio spectrum of Vela



The ALMA fluxes: pulsed or not?

The ALMA fluxes imply high brightness temperatures $T_b \sim 10^{17}$ - 10^{15} K for 10km x 10km

Vela- test observations in the Phased ALMA Pulsar Mode at 86 GHz

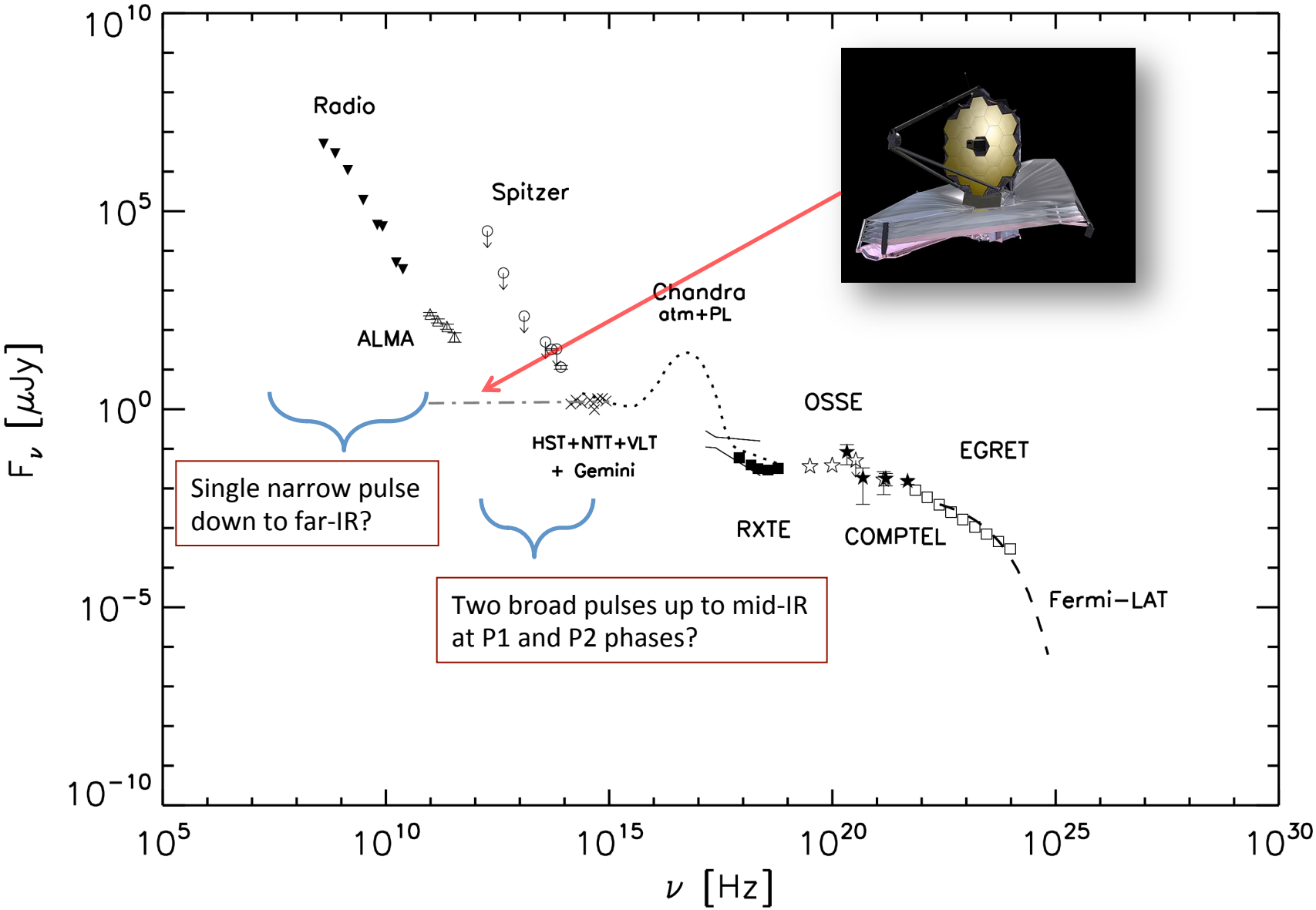


The pulse is in phase with the pulse at low frequencies.

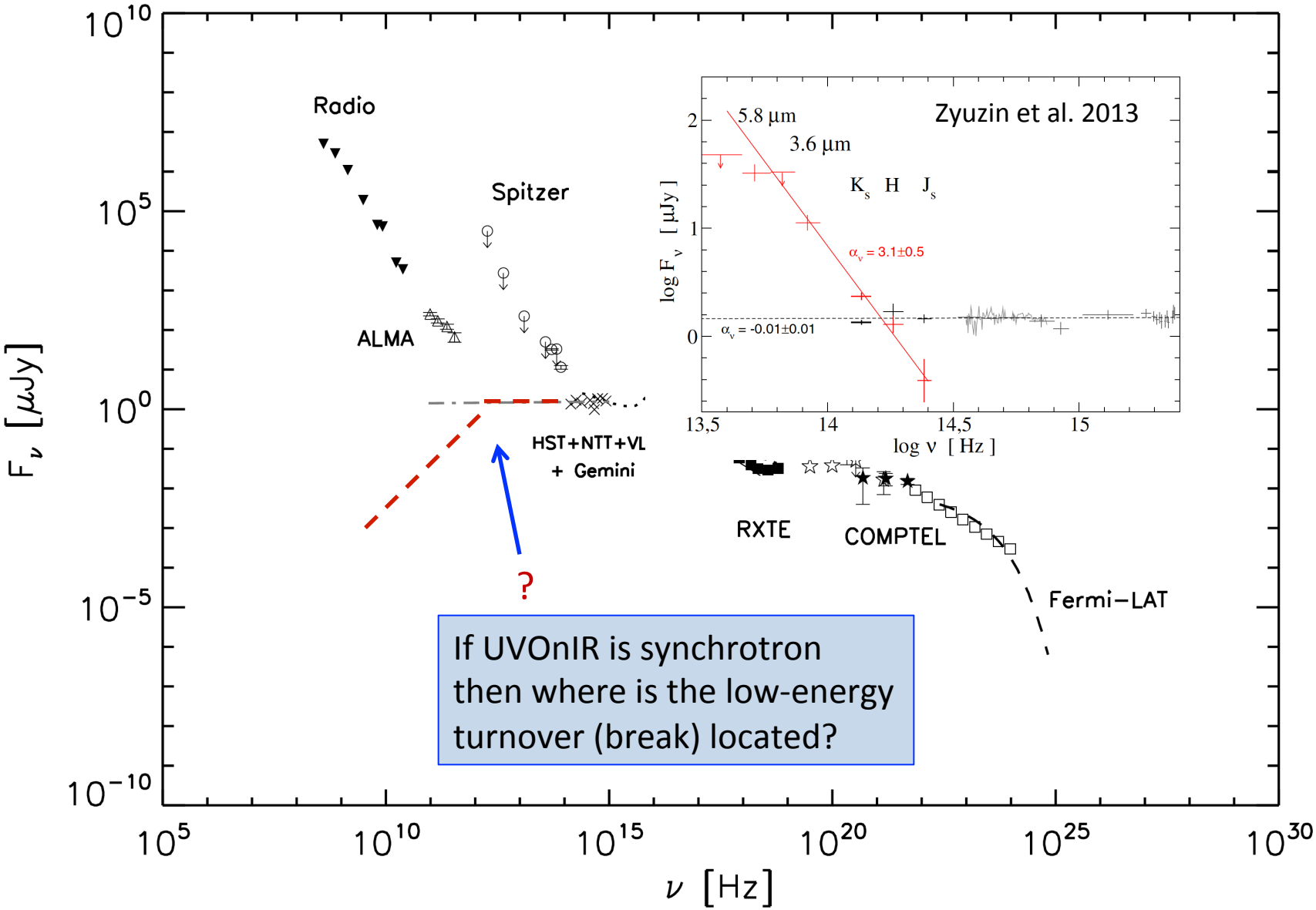
Mean flux density „in general consistent with Mignani et al. 2017 (while slightly higher)".

Kuo Liu et al. in prep.

mid-IR observations of Vela in the future (2021+)

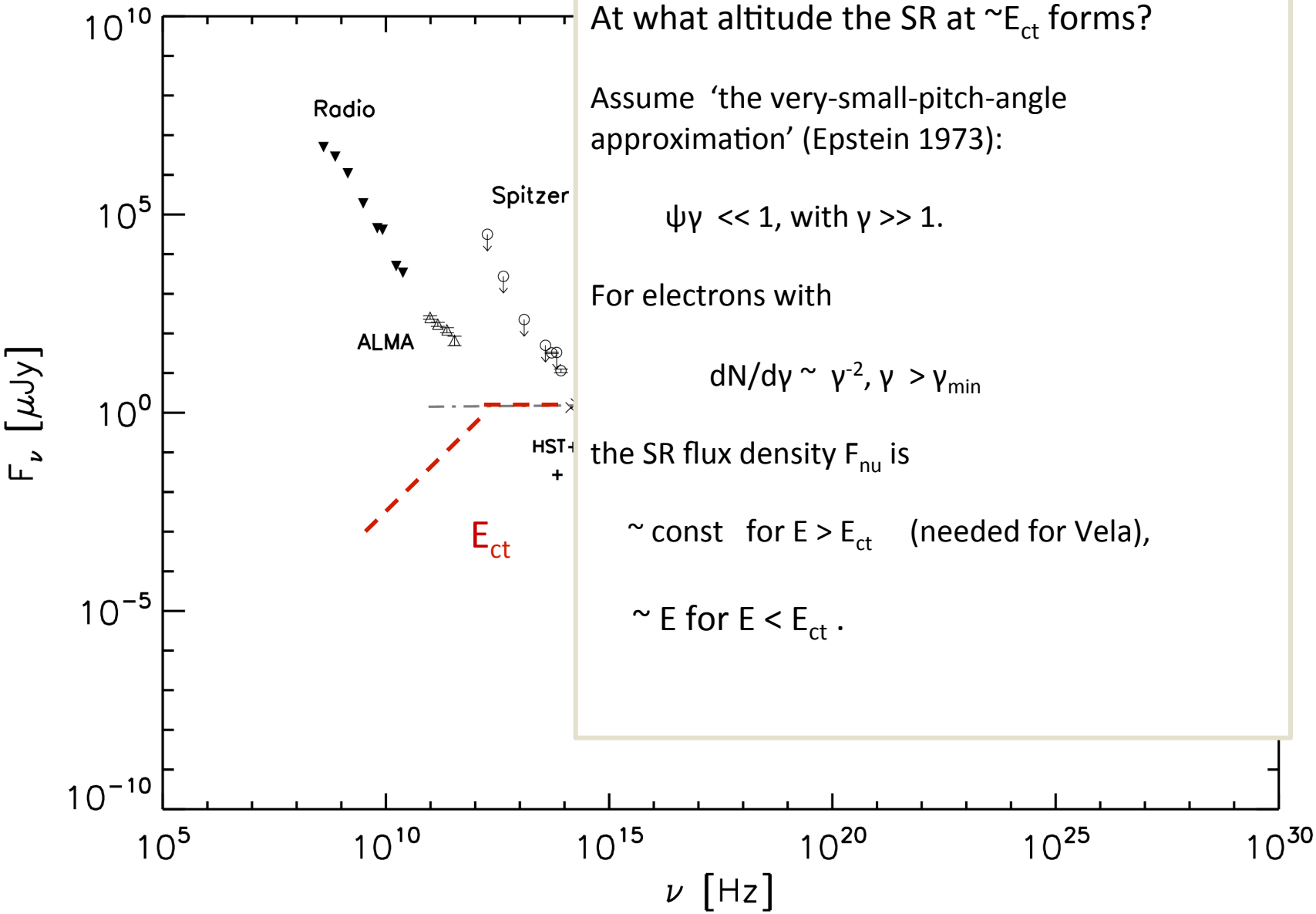


The SED of Vela



If UVOnIR is synchrotron then where is the low-energy turnover (break) located?

The spectrum of Vela



At what altitude the SR at ~E_{ct} forms?

Assume 'the very-small-pitch-angle approximation' (Epstein 1973):

$\psi\gamma \ll 1$, with $\gamma \gg 1$.

For electrons with

$dN/d\gamma \sim \gamma^{-2}, \gamma > \gamma_{min}$

the SR flux density F_{nu} is

~ const for $E > E_{ct}$ (needed for Vela),

~ E for $E < E_{ct}$.

Low-energy break E_{ct} in SR spectrum of Vela – why does it matter?

$$E_{ct} = 2\,\gamma_{min}\;\; h\,e\,B\,/2\pi\,m_e\,c$$

For the vacuum dipole it yields a lower boundary of the radius r_{ct} where the densest soft-photon field is located.

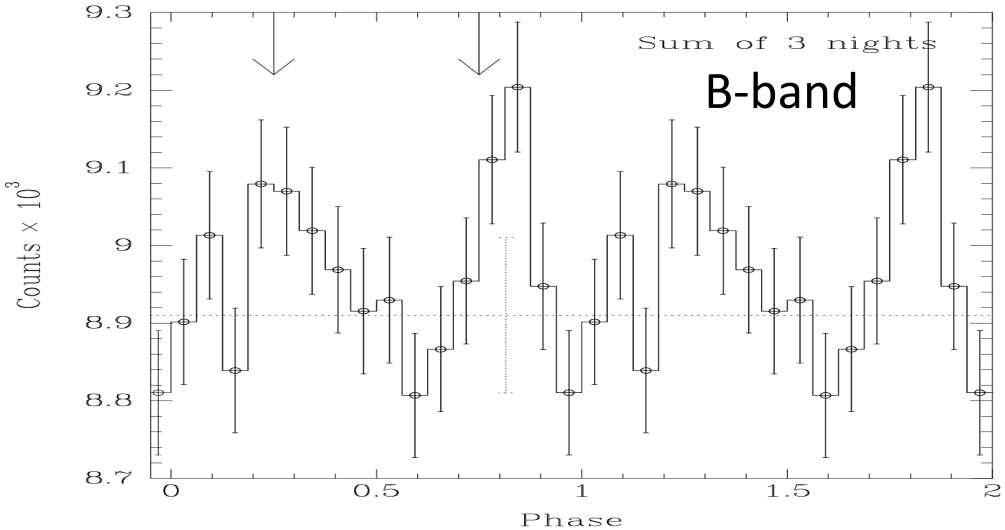
$$\frac{r_{\rm ct}}{r_{\rm ns}} \approx 130 \left[\frac{B_0({\rm TG})}{E_{\rm ct}({\rm eV})}\frac{\gamma_\pm}{100}\right]^{1/3}$$

For E_{ct} = 0.1 eV (mid-IR), γ_{min} = 100, B_0 = 4 TG

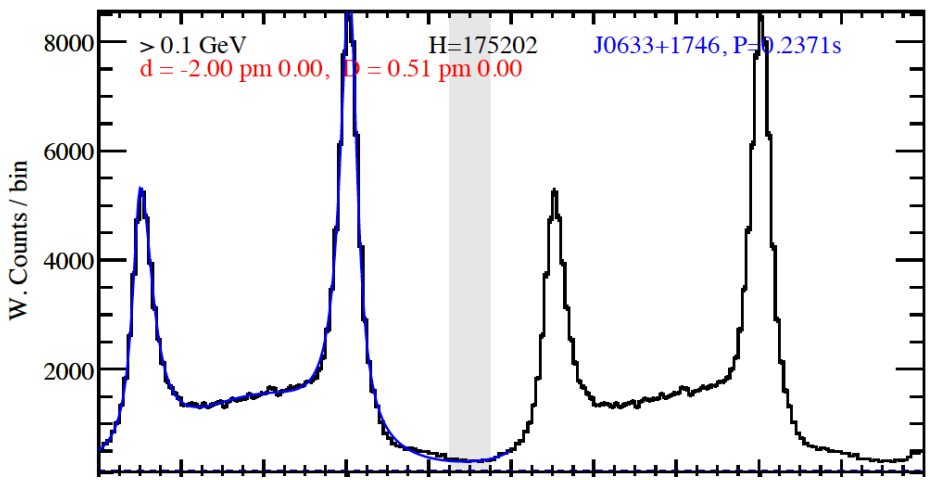
$r_{ct} \approx r_{LC}$.

Location suitable for ICS process generating GeV-TeV emission

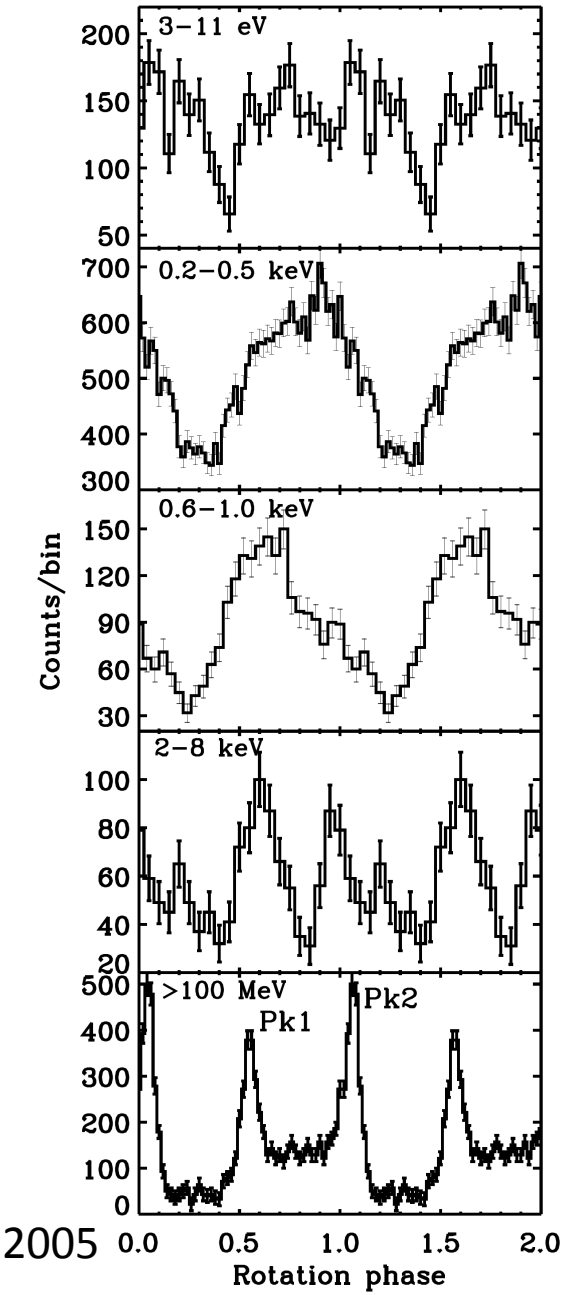
Geminga – is it similar to Vela?



Shearer 1998



Fermi-LAT



Kargaltsev et al. 2005

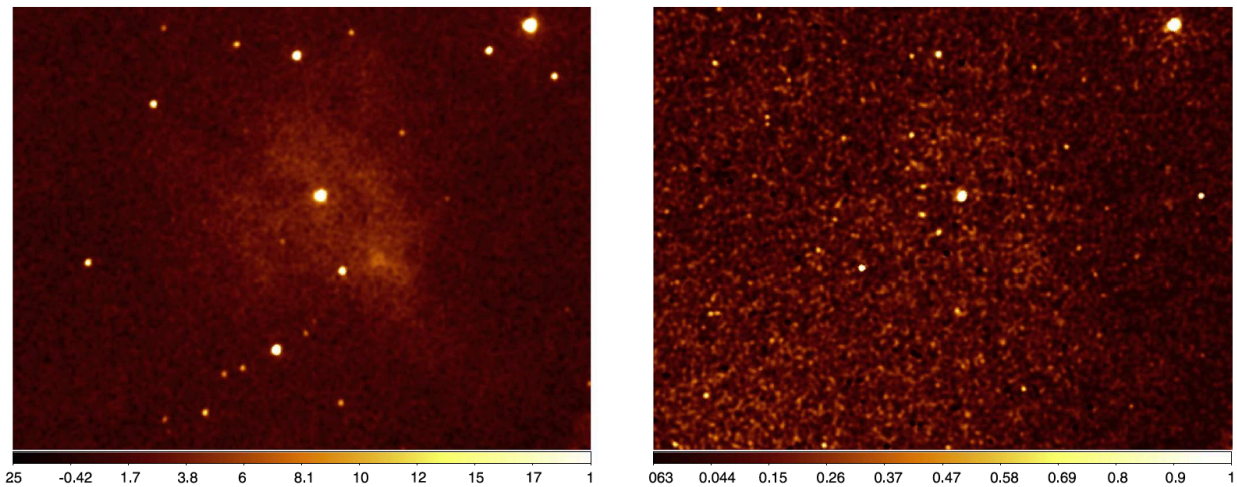
The first UV detection of PSR B0540-69 in LMC

Mignani et al. 2019

Observations with the *HST* :

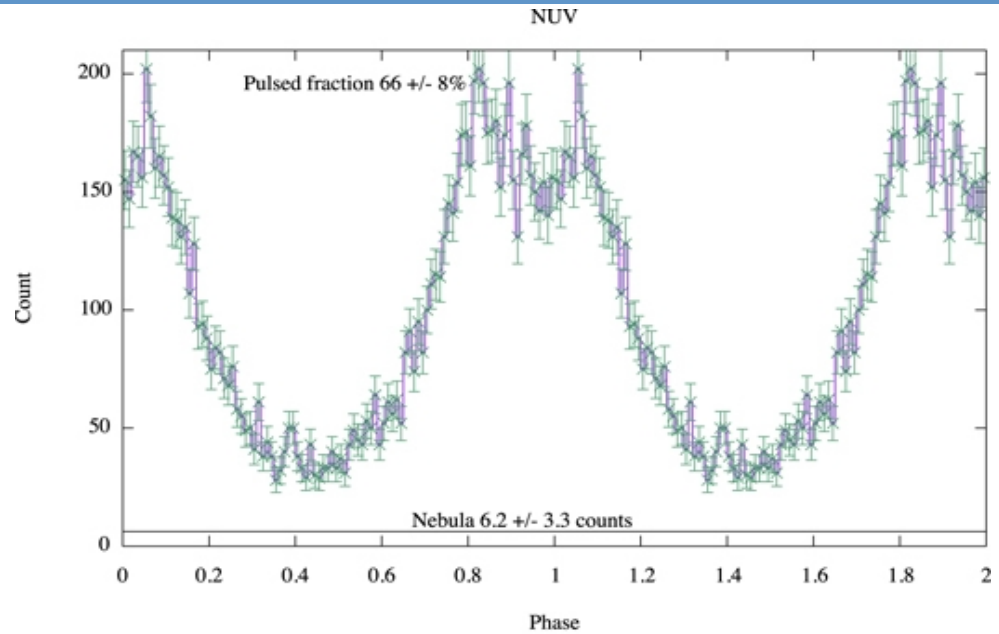
Space Telescope Imaging Spectrograph,
NUV- and FUV-MAMA in the TIME-TAG mode with a net total integration time of 9650 s

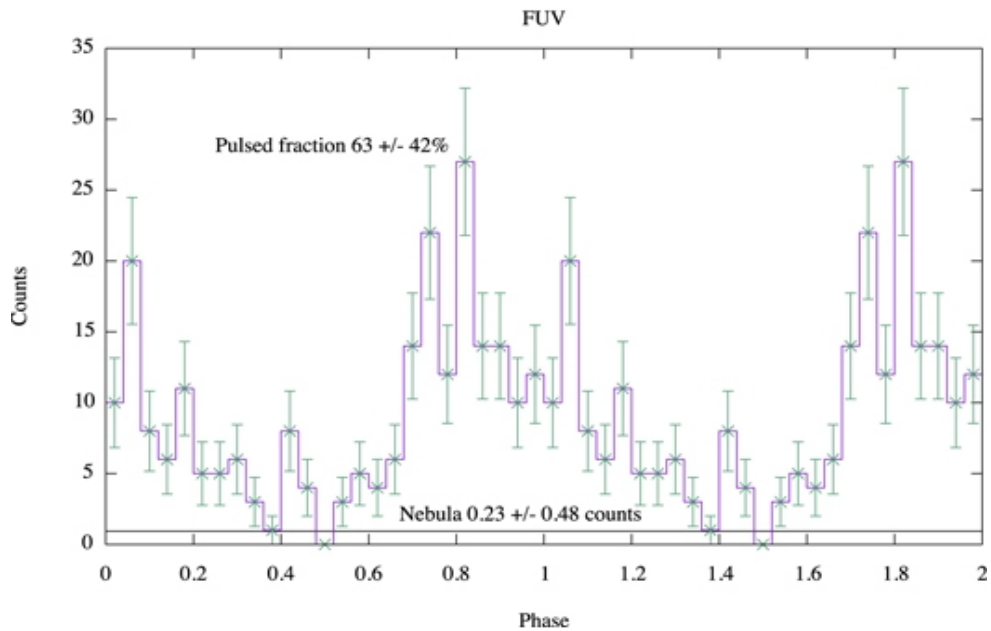
NUV (~2350 Å) 9” x 9” FUV (~1590 Å)



The pulsar: $m_{NUV} = 21.45$, $m_{FUV} = 21.83$

The NUV and FUV lightcurves of PSR B0540-69

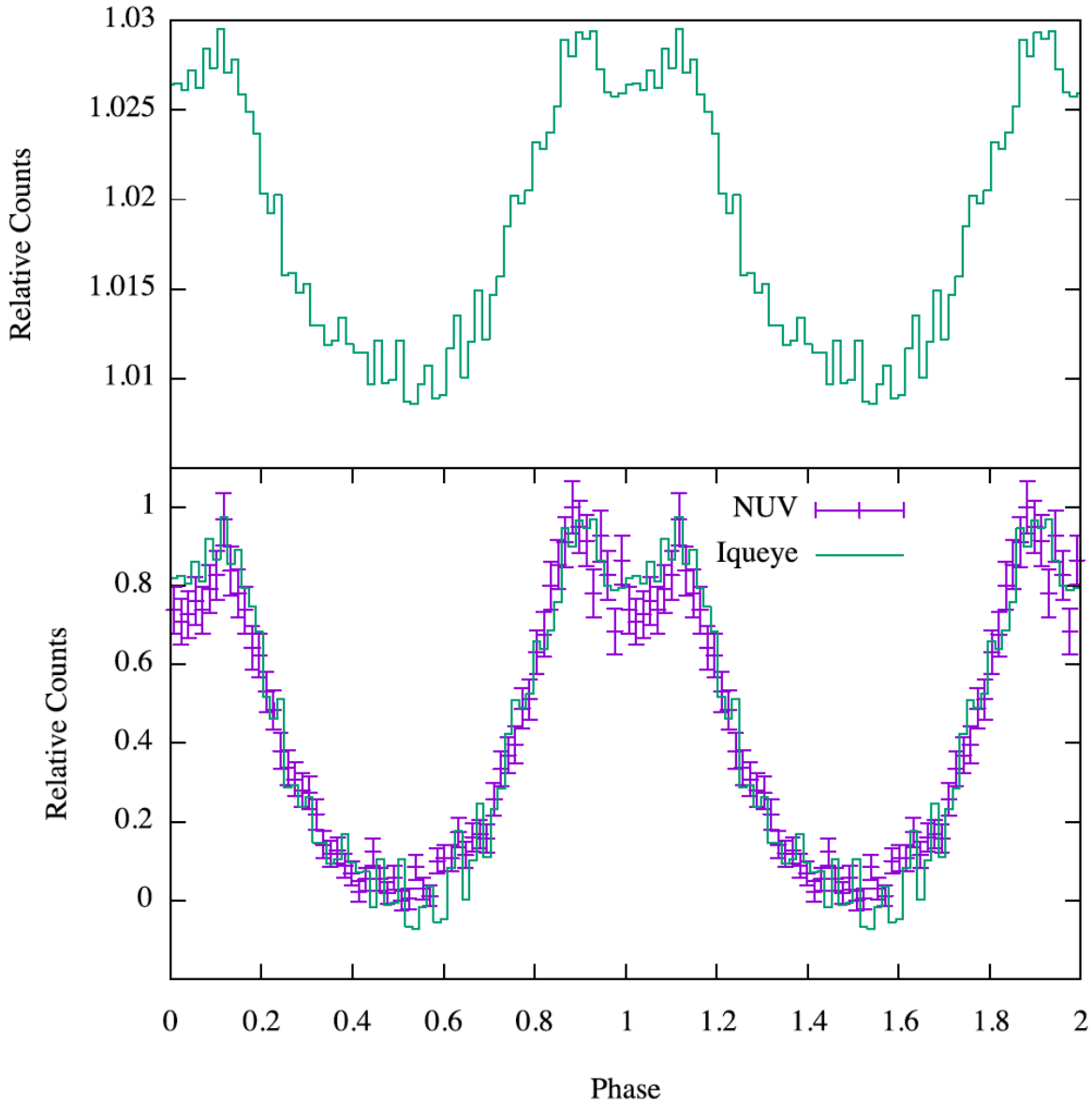




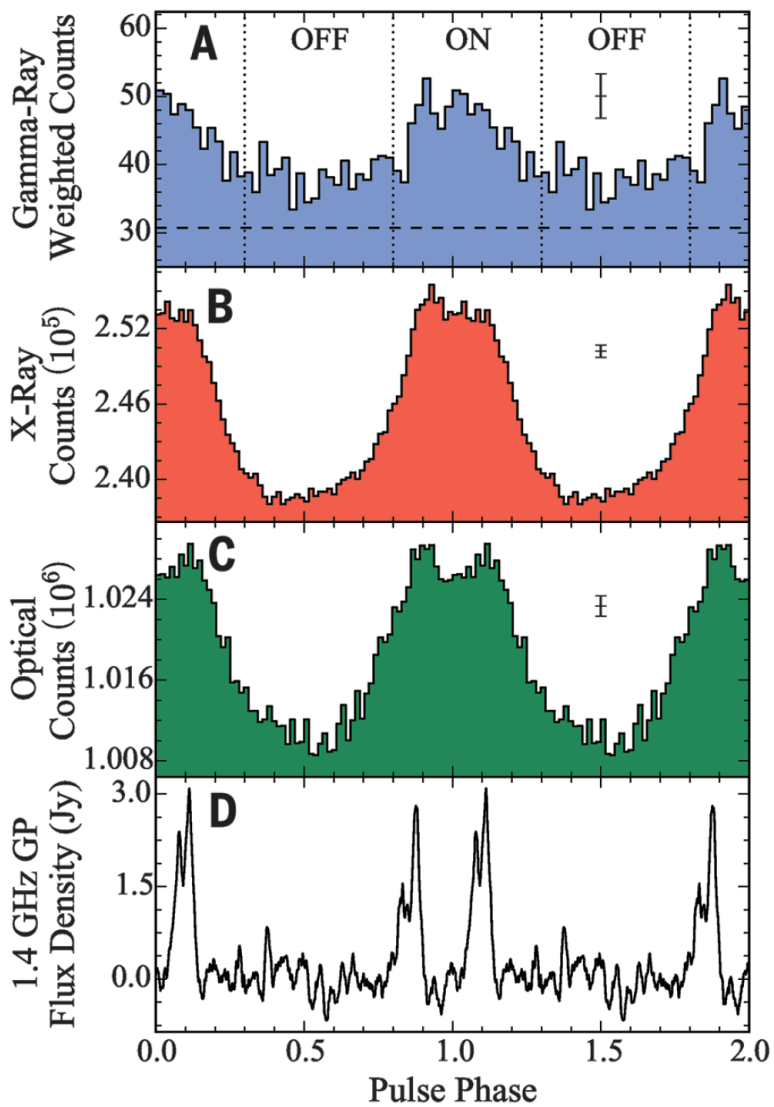
Mignani et al. 2019

PSR B0540-69

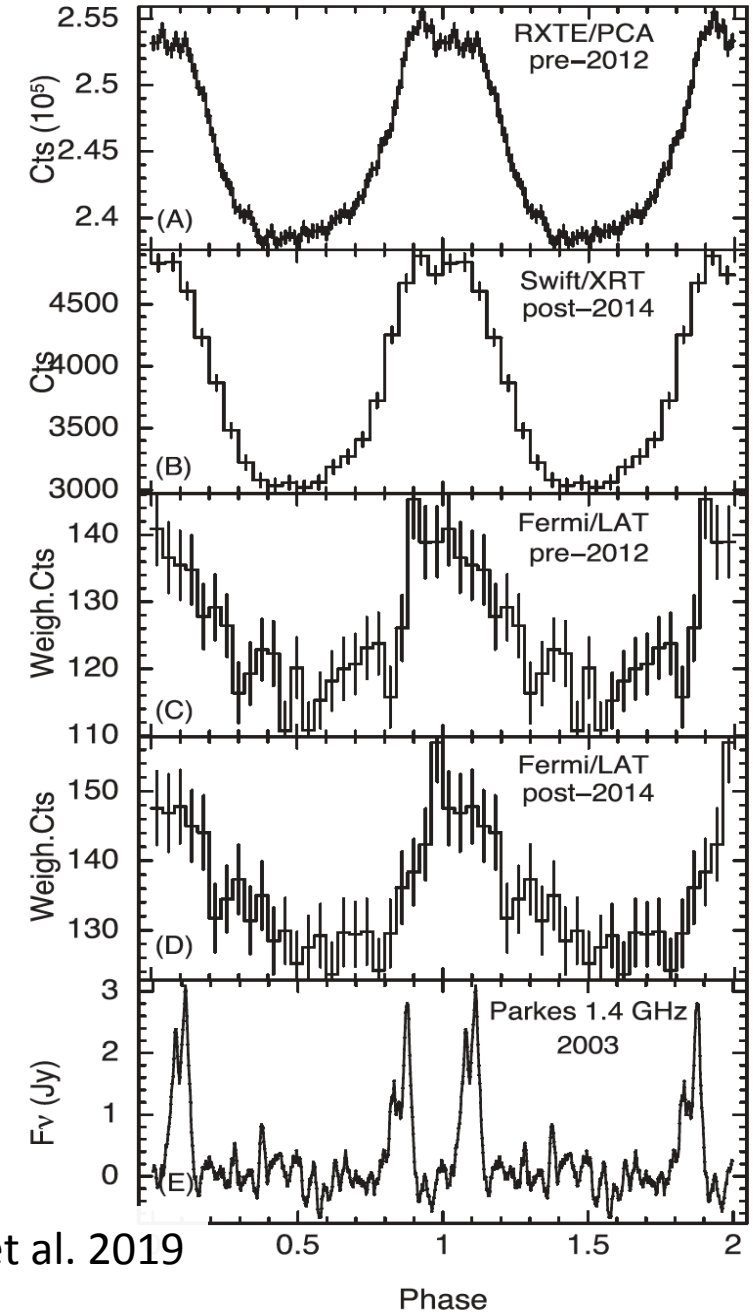
Mignani et al. 2019



PSR B0540-69 multi-epoch lightcurves

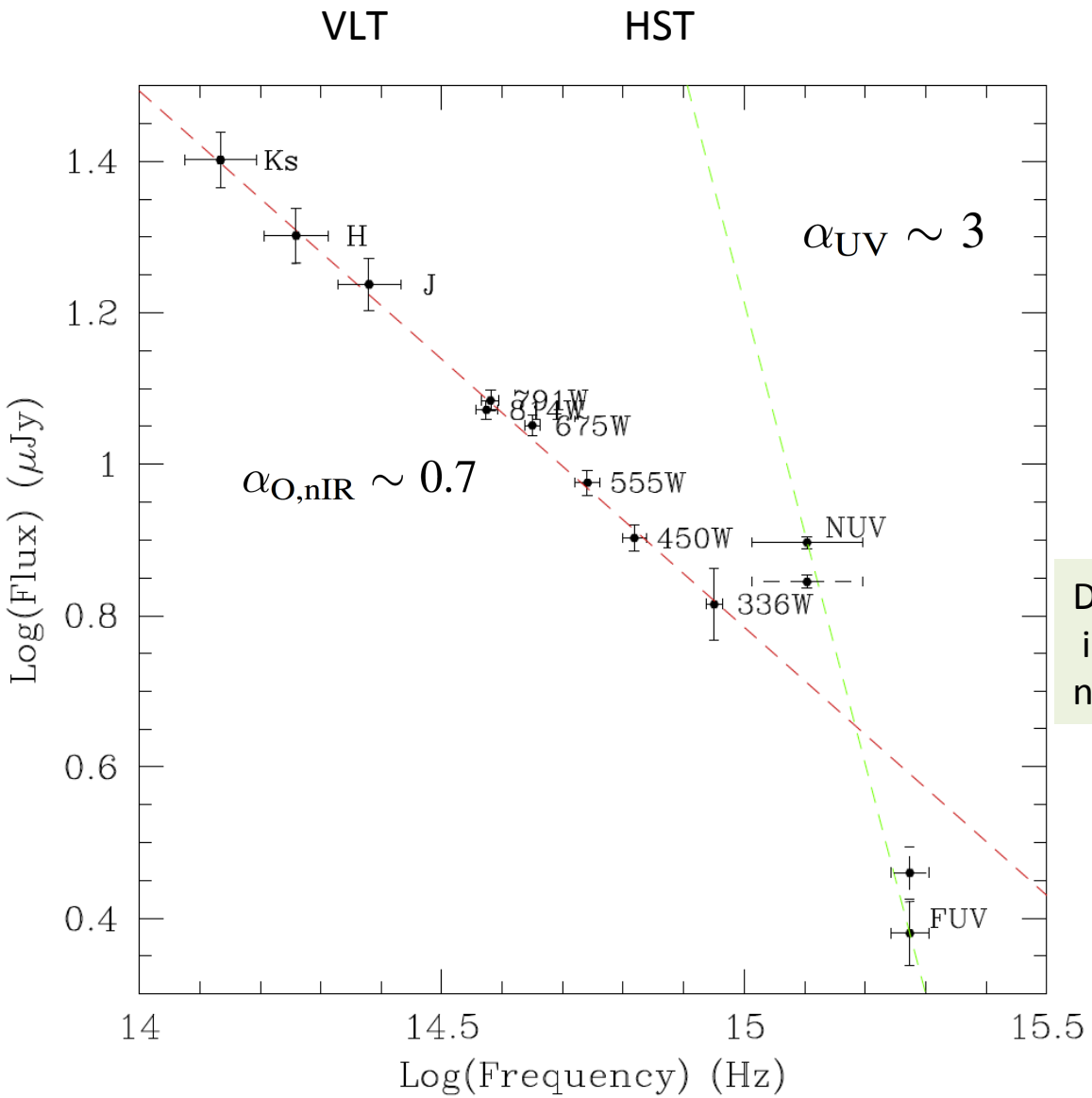


Fermi LAT Collab. 2015



Mignani et al. 2019

The UVOIR spectrum of PSR B0540-69

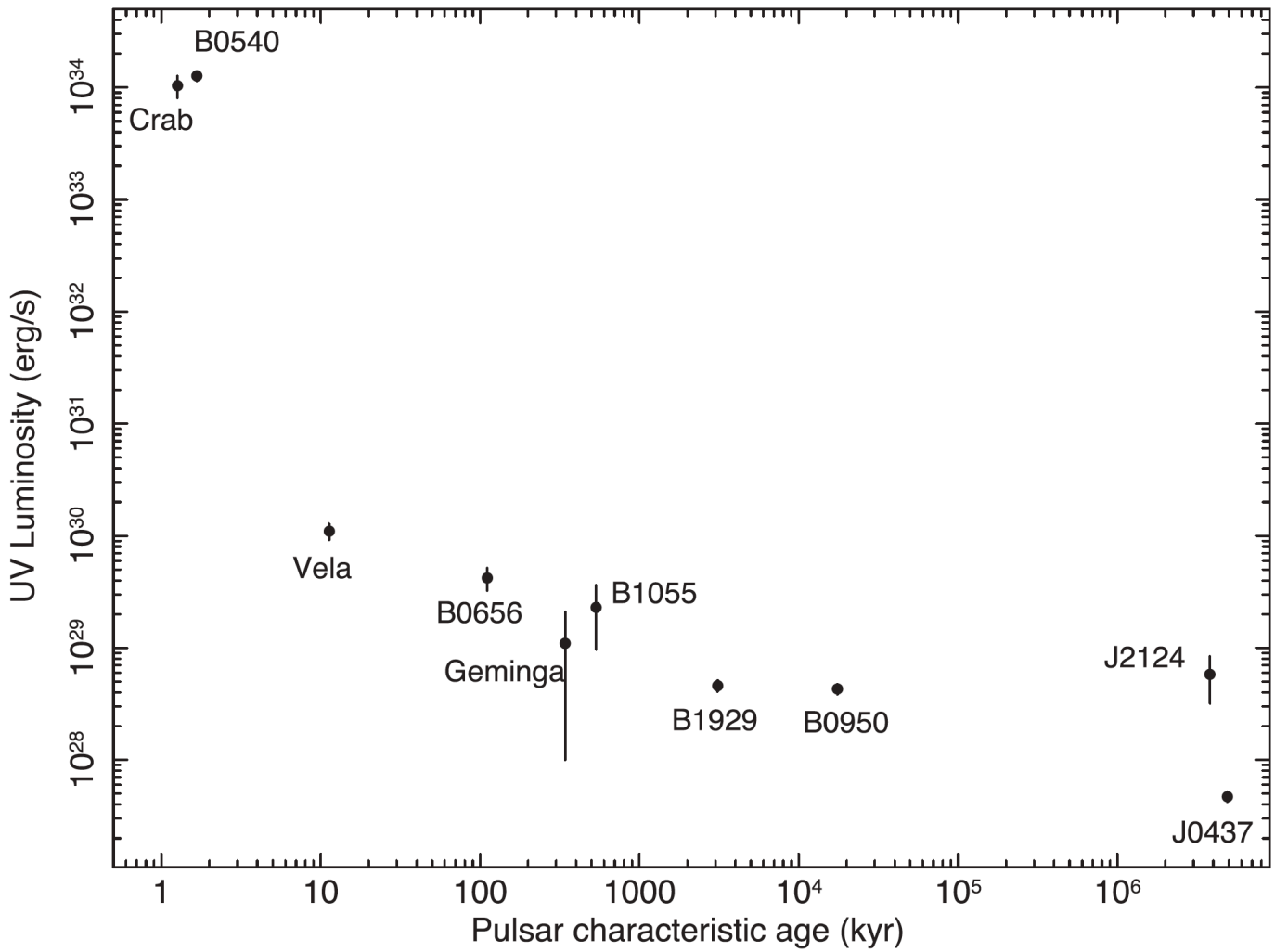


$$F_\nu \propto \nu^{-\alpha}$$

Dramatic break
in the UVOIR spectrum,
not seen in other pulsars

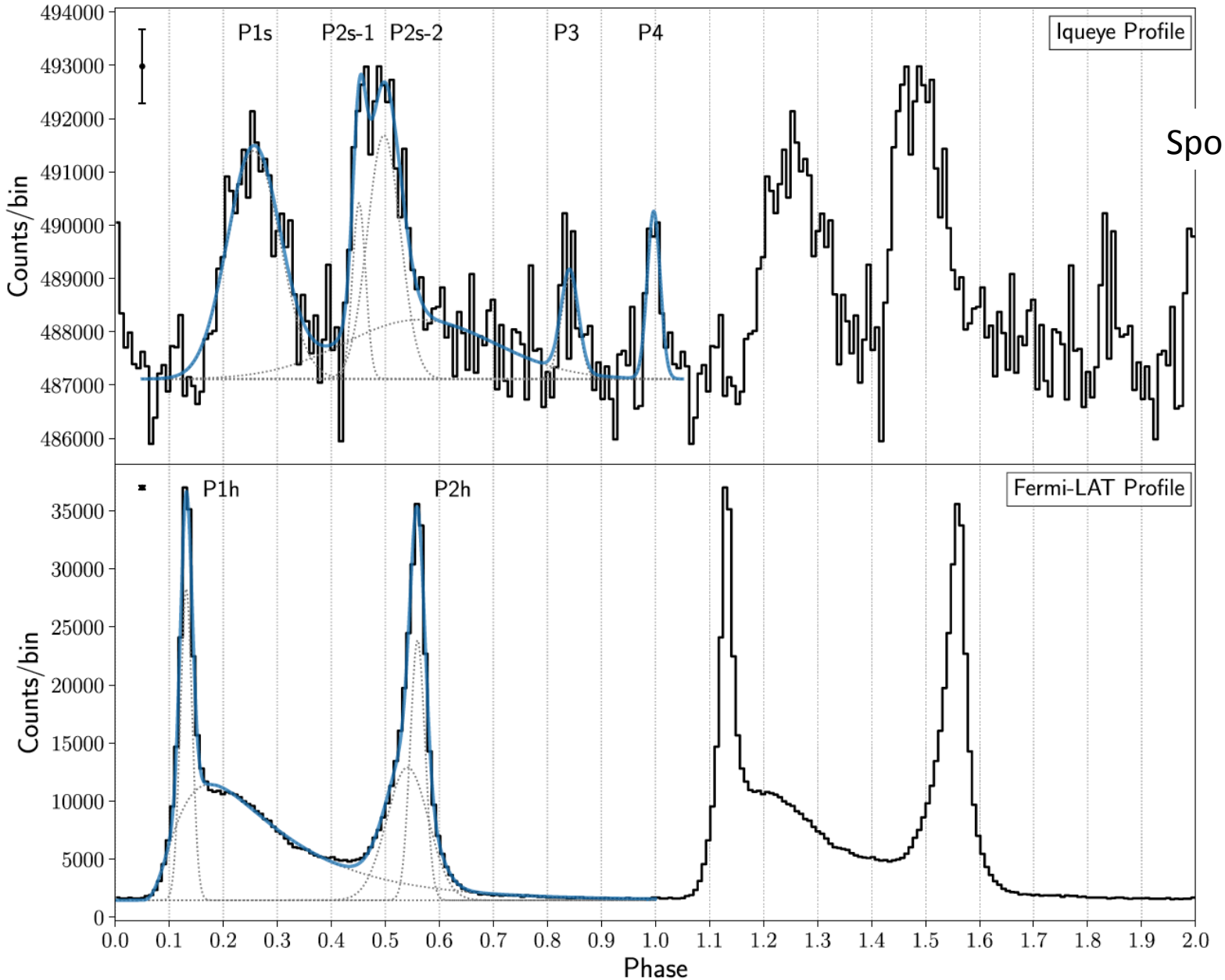
Mignani et al. 2019

PSR B0540-69 in UV



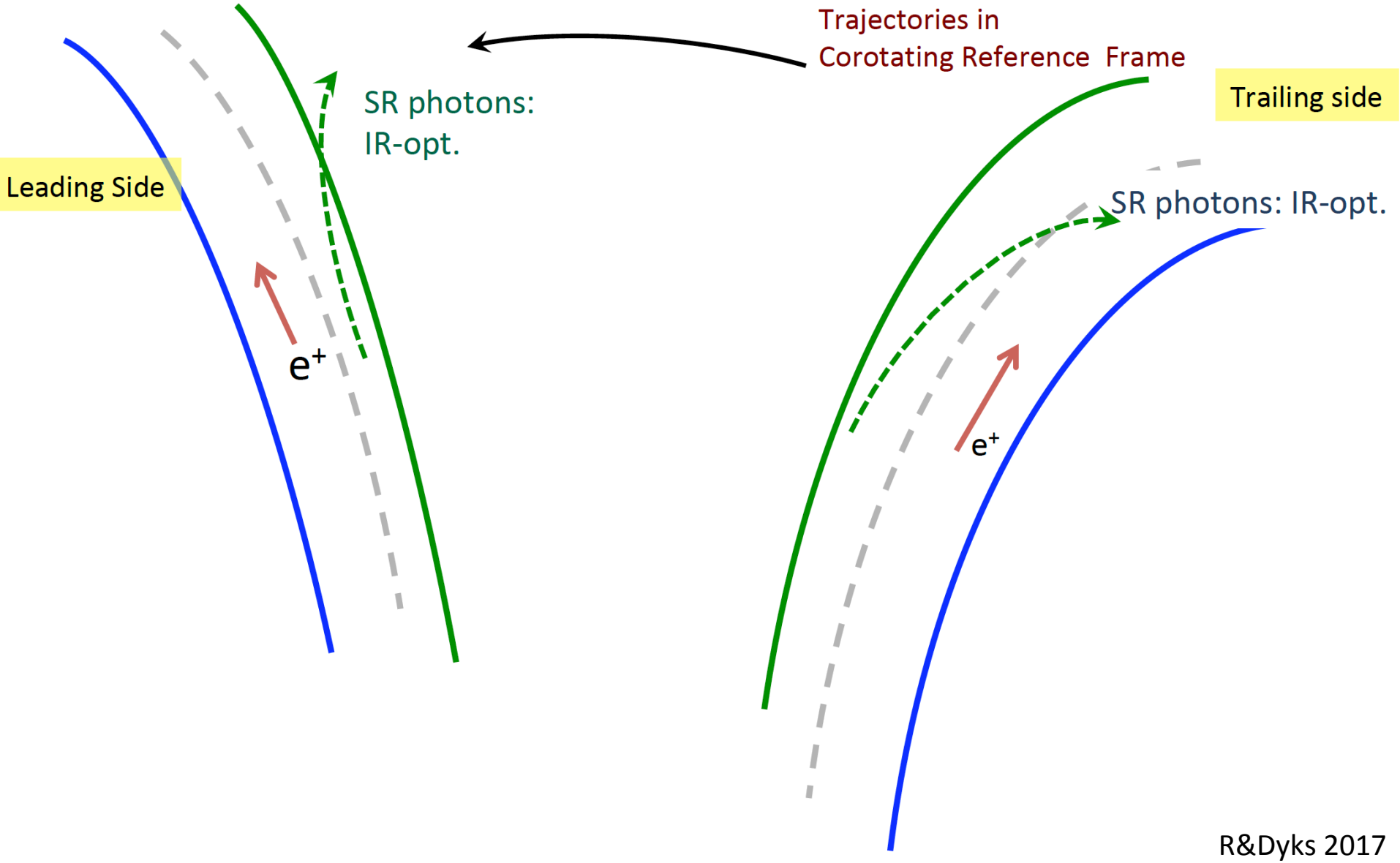
Mignani et al. 2019

Vela lightcurve in the optical band vs gamma

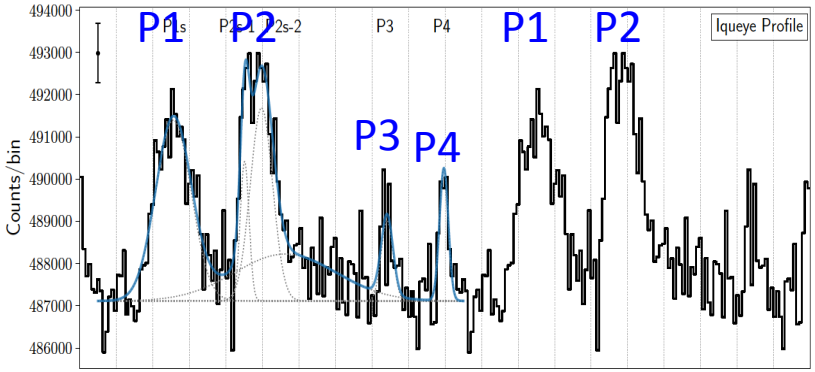


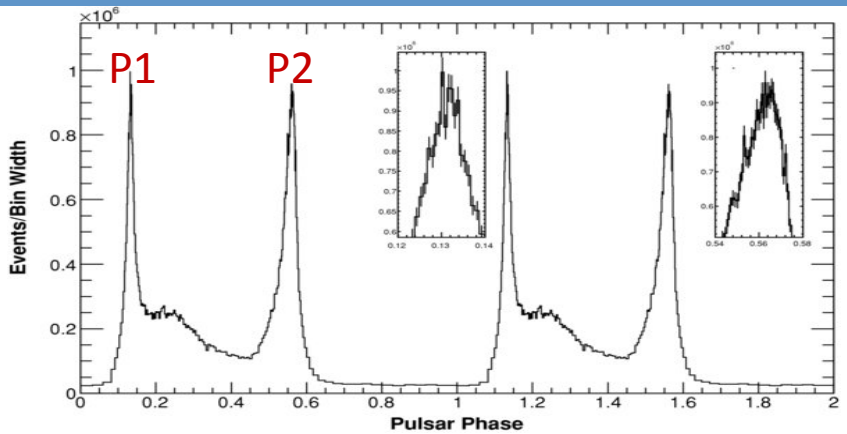
Spolon et al. 2019

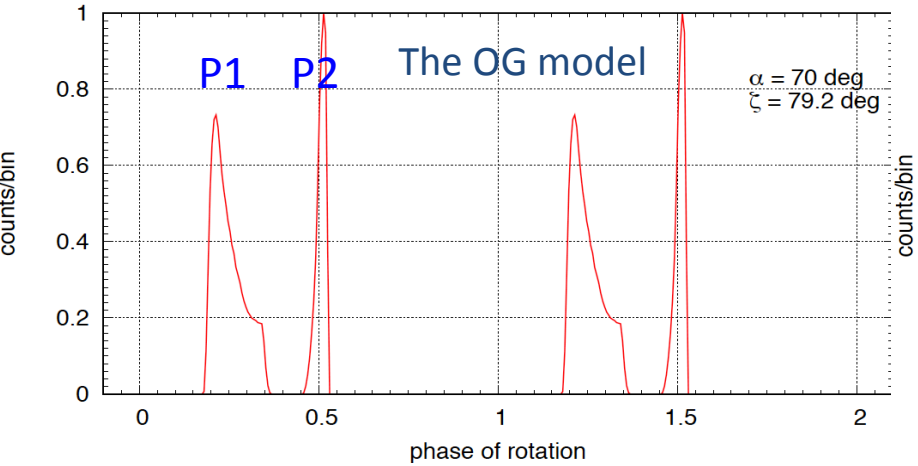
Vela: optical and gamma-ray emission in an 'old-fashioned' simplified OG model

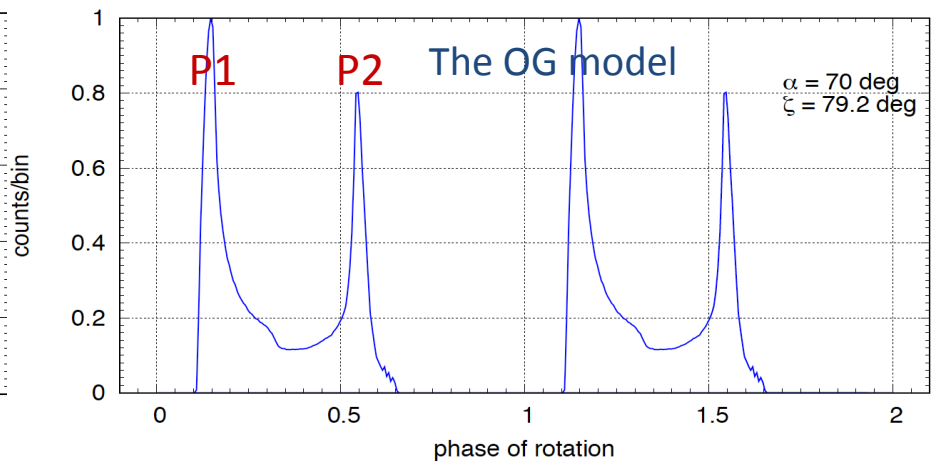


Vela: P1 & P2 shapes and phases in optical and gamma reproduced with an 'old-fashioned' simplified OG model by R & Dyks 2017



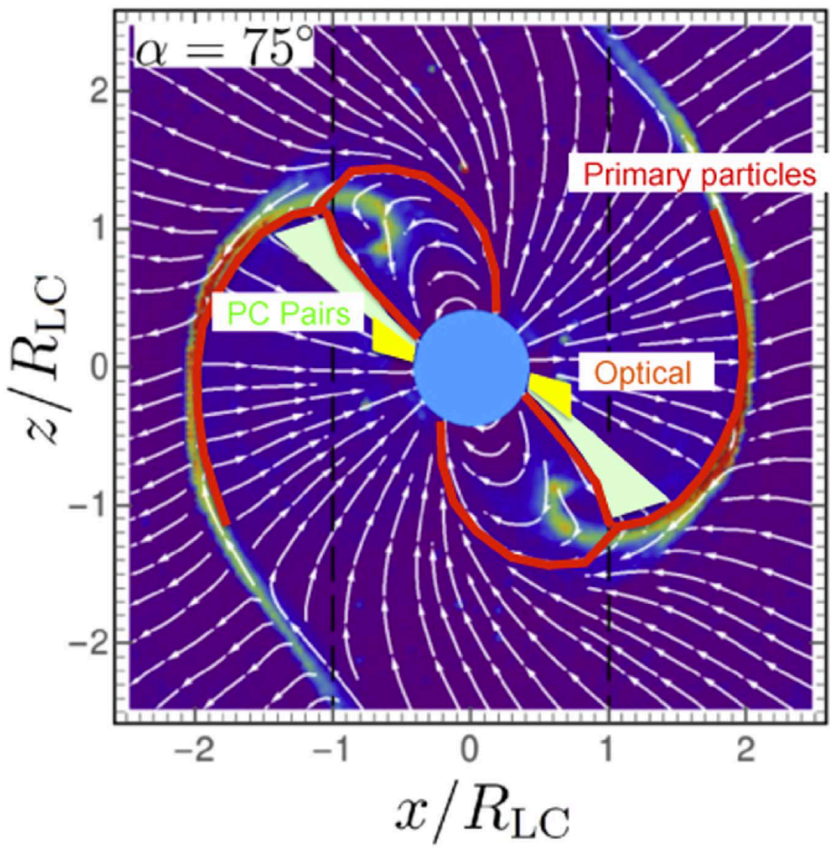


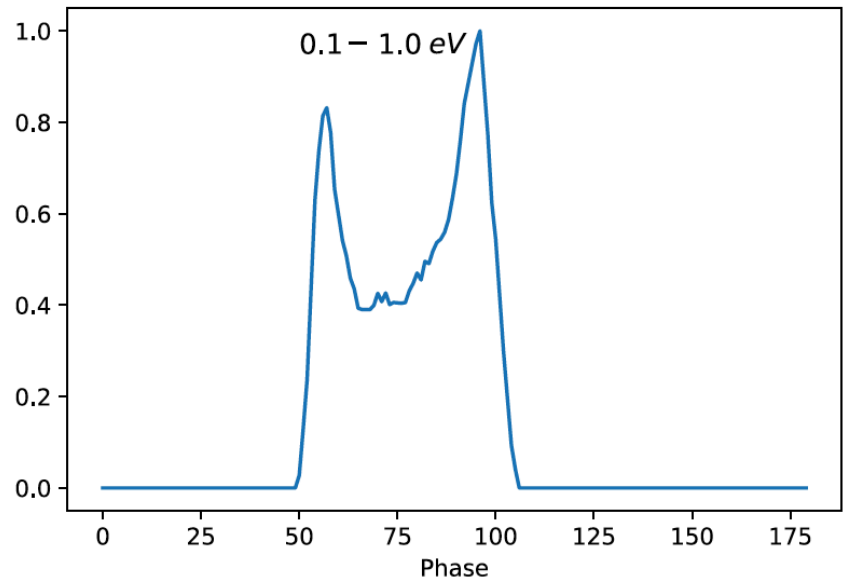


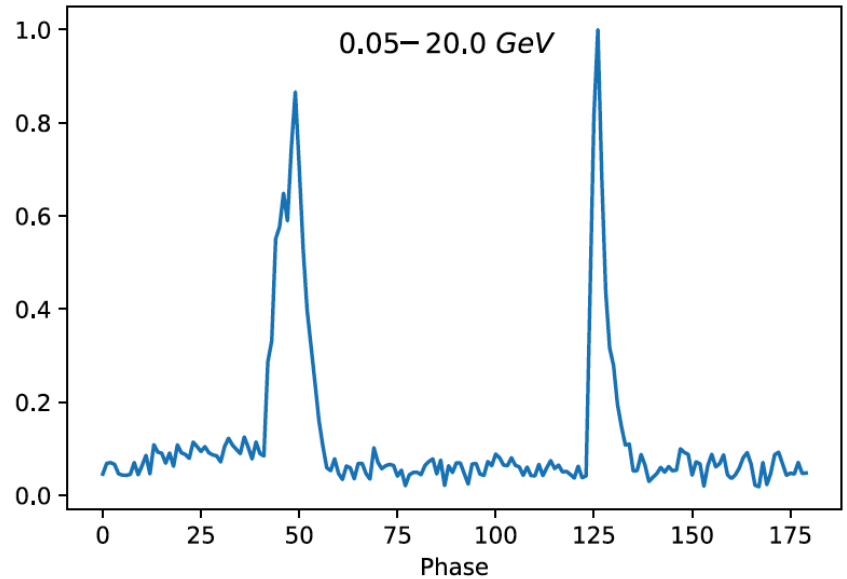


P1 and P2 pulses in optical and gamma rays
and their reconstruction in the *uniform-emissivity* version of the OG model,
obtained for
inclination angle $\alpha = 70^{o}$, viewing angle $\zeta = 79^{o}$

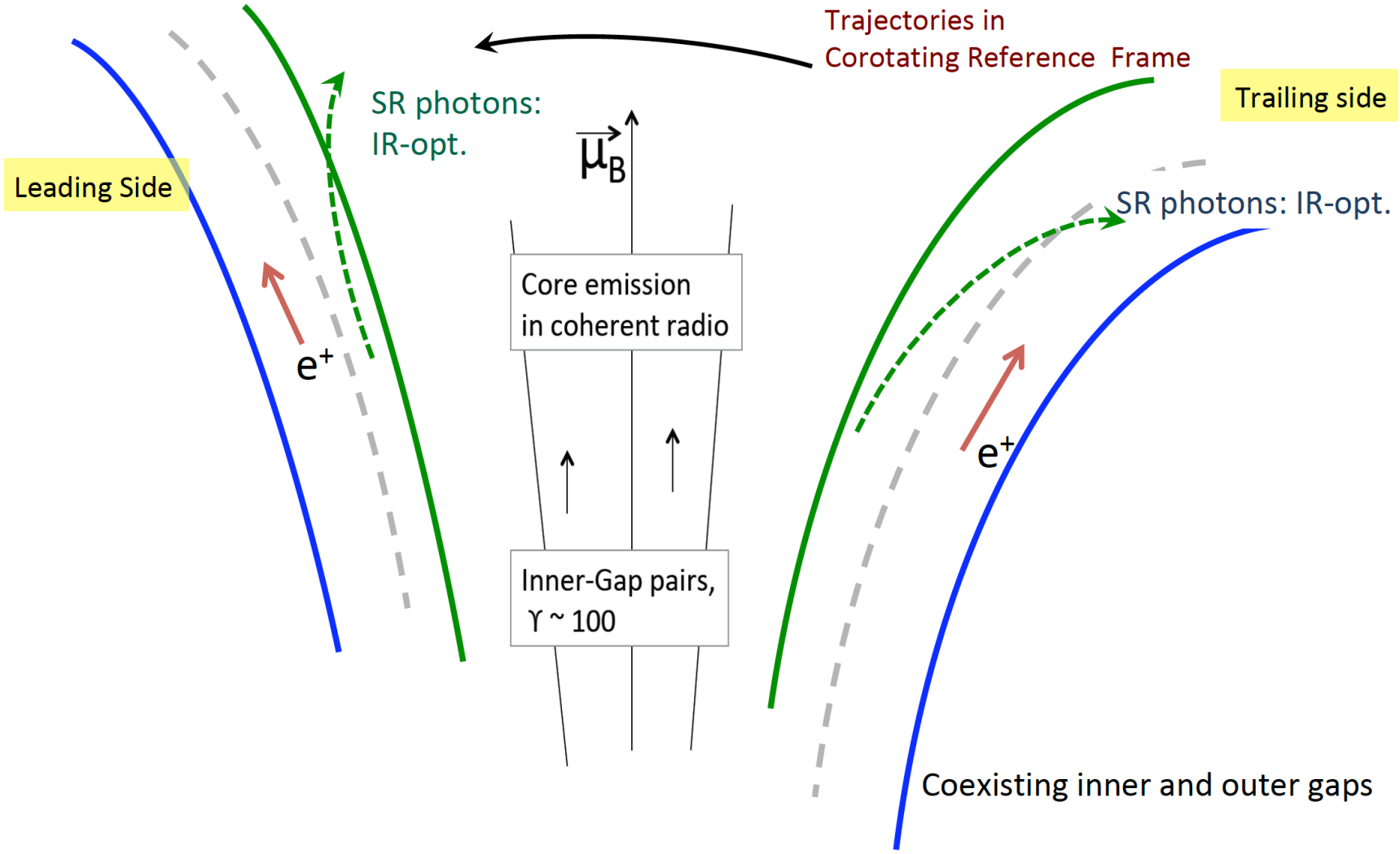
Vela: P1 & P2 shapes and phases in optical and gamma reproduced with the model of Harding at al. 2018

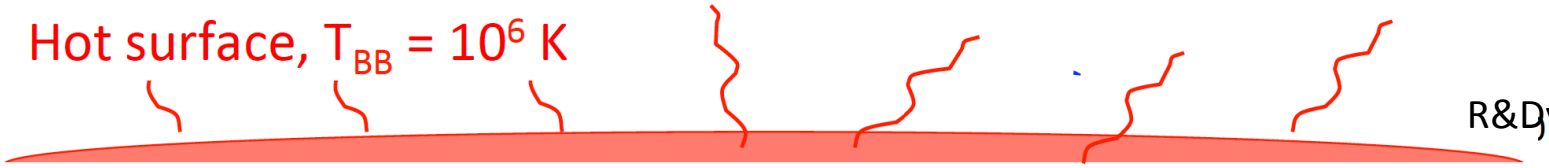






Vela: what is the origin of P4 at the radio phase in optical-UV-hard Xrays?





R&Dyks 2017

Pulsed emission due to Inverse Compton Scattering

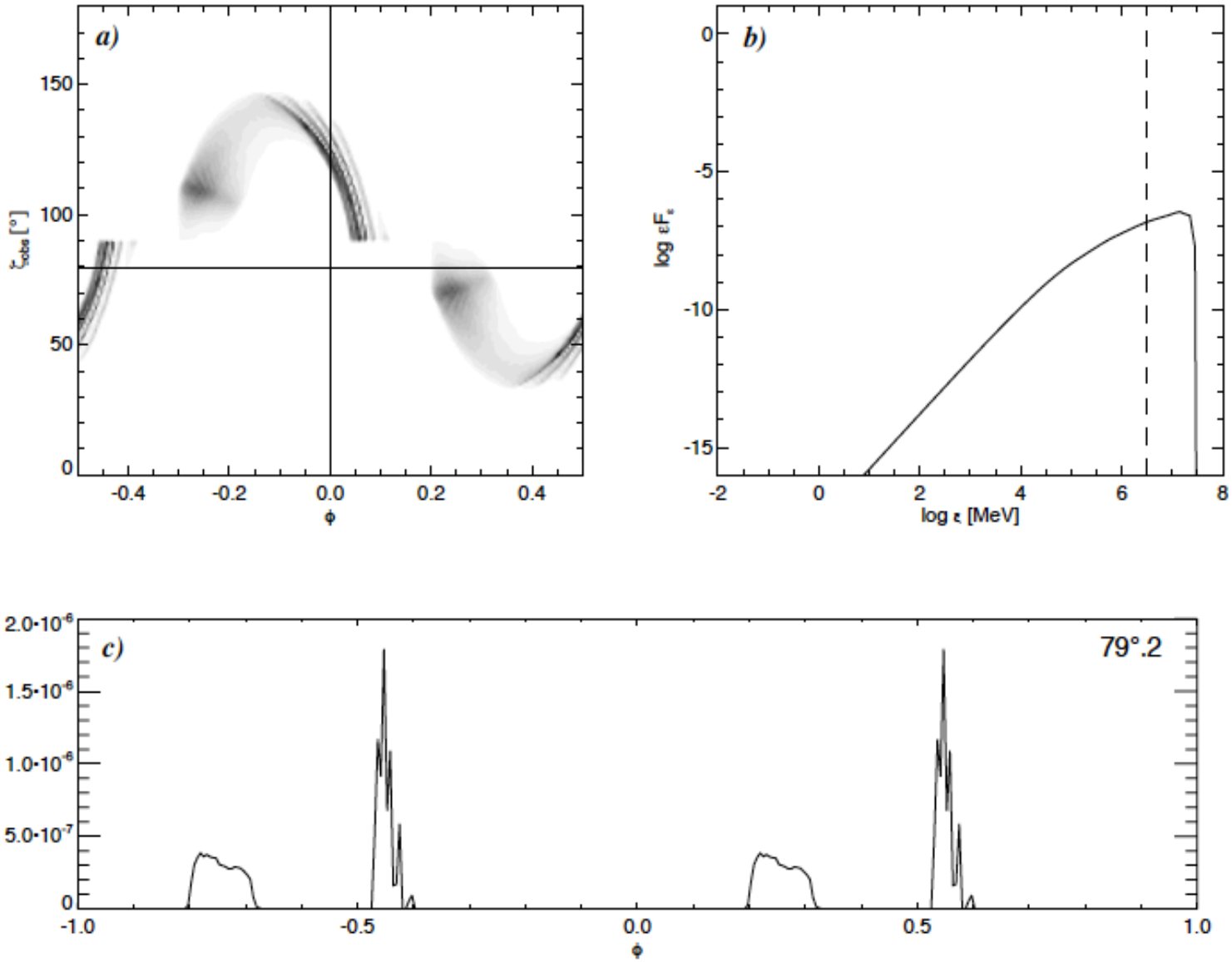
1. Primary OG pairs + IR photons (synchrotron photons) → pulsed VHE component

2. Inner Gap pairs + optical-IR photons (synchrotron photons) → P4 in optical-UV

3. Inner Gap pairs + thermal X-ray photons → P4 in hard X-rays

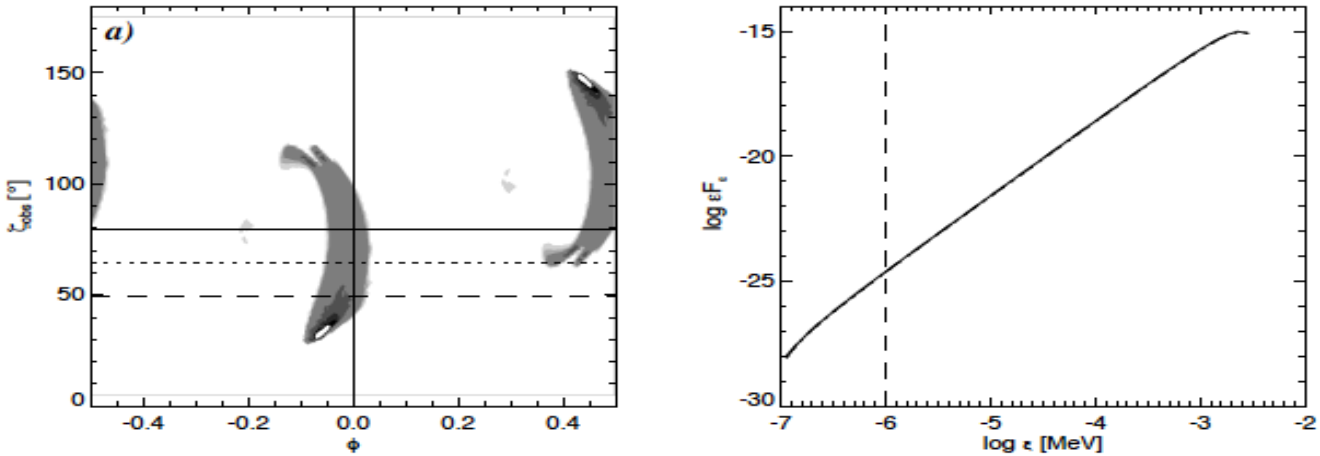
The ICS component in VHE

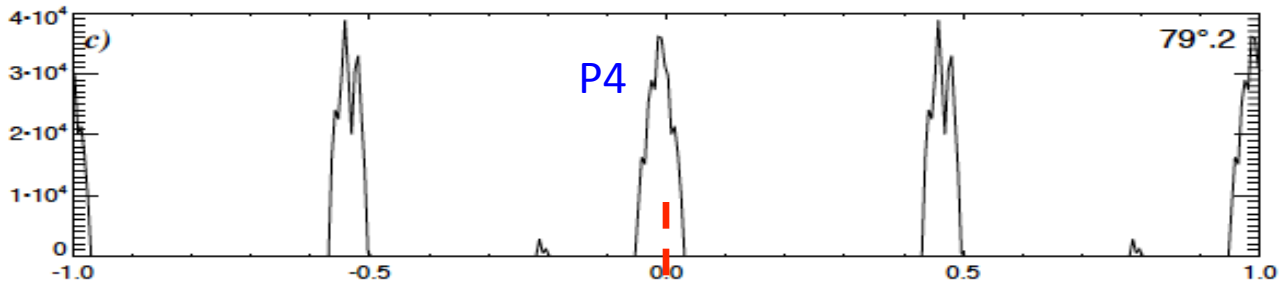
$\alpha = 70^{o}$

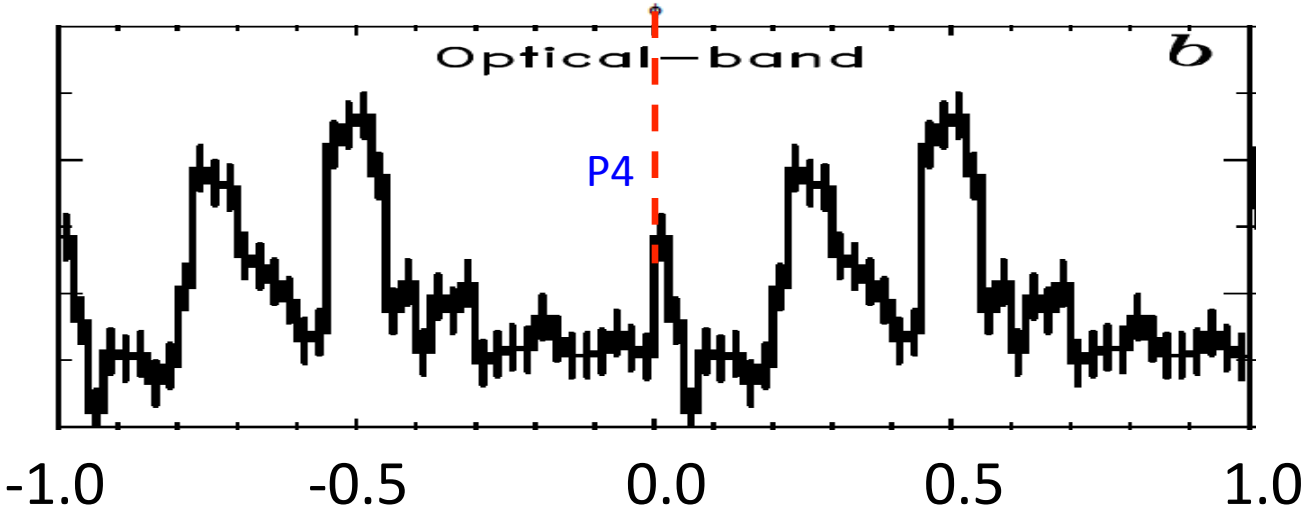


The ICS core component in optical-UV

$\alpha = 70^{o}$

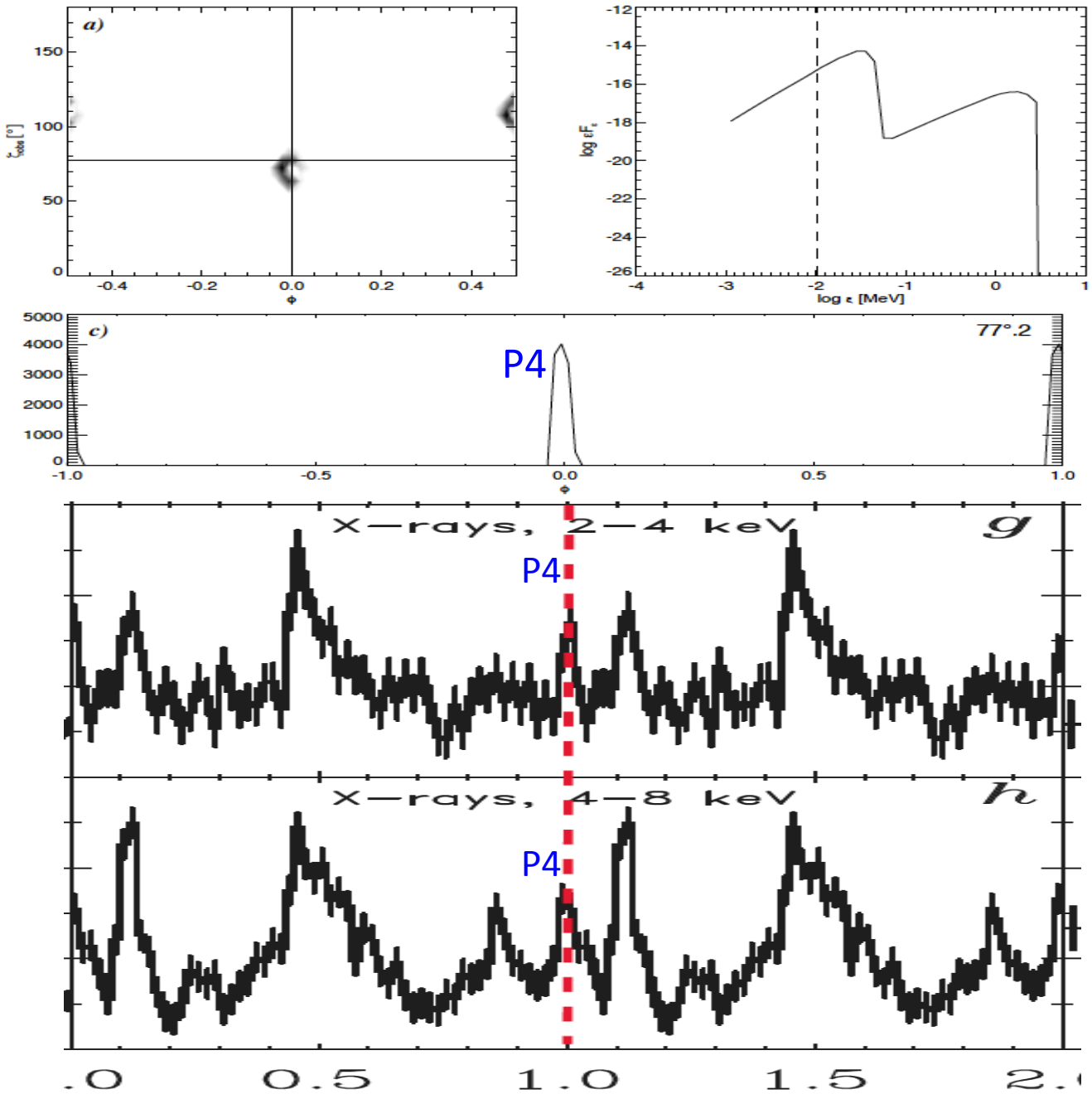






The ICS core component in hard X-rays

$\alpha = 70^{o}$



Conclusions

1. Multiwavelength properties of Vela suggest that its magnetosphere contributes significantly to formation of its radiation (unlike in young pulsars, where ECS zone seems to dominate)

2. Realistic magnetospheric models should contain gaps similar to the gaps of corotating low-density magnetosphere models.

   2a. Hints for coexistence of outer gaps and inner gaps in the magnetosphere of Vela:

   - the main optical pulses wrt the gamma-ray pulses

   - the core-like pulses in optical, UV and in hard X-rays, aligned in phase with the core-like radio pulse