# Galactic
# γ-ray sources:
# II - pulsar activities

AIM

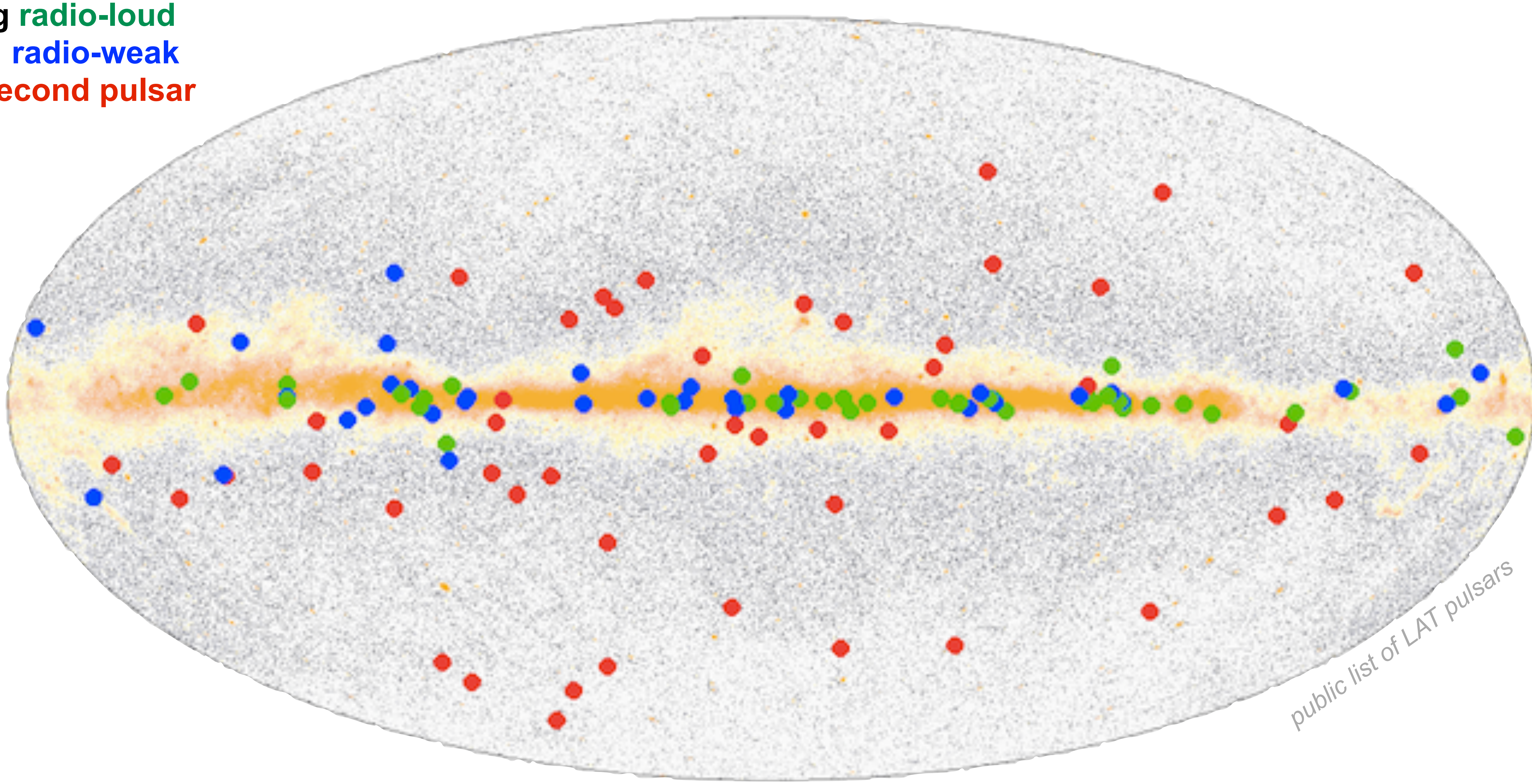
**Isabelle Grenier**

(Université Paris Diderot & CEA Saclay)

Annecy
septembre 2013

# >130 γ-ray pulsars

**γ-ray pulsars:**
**young radio-loud**
**radio-weak**
**millisecond pulsar**




Nançay (France)

GMRT (India)

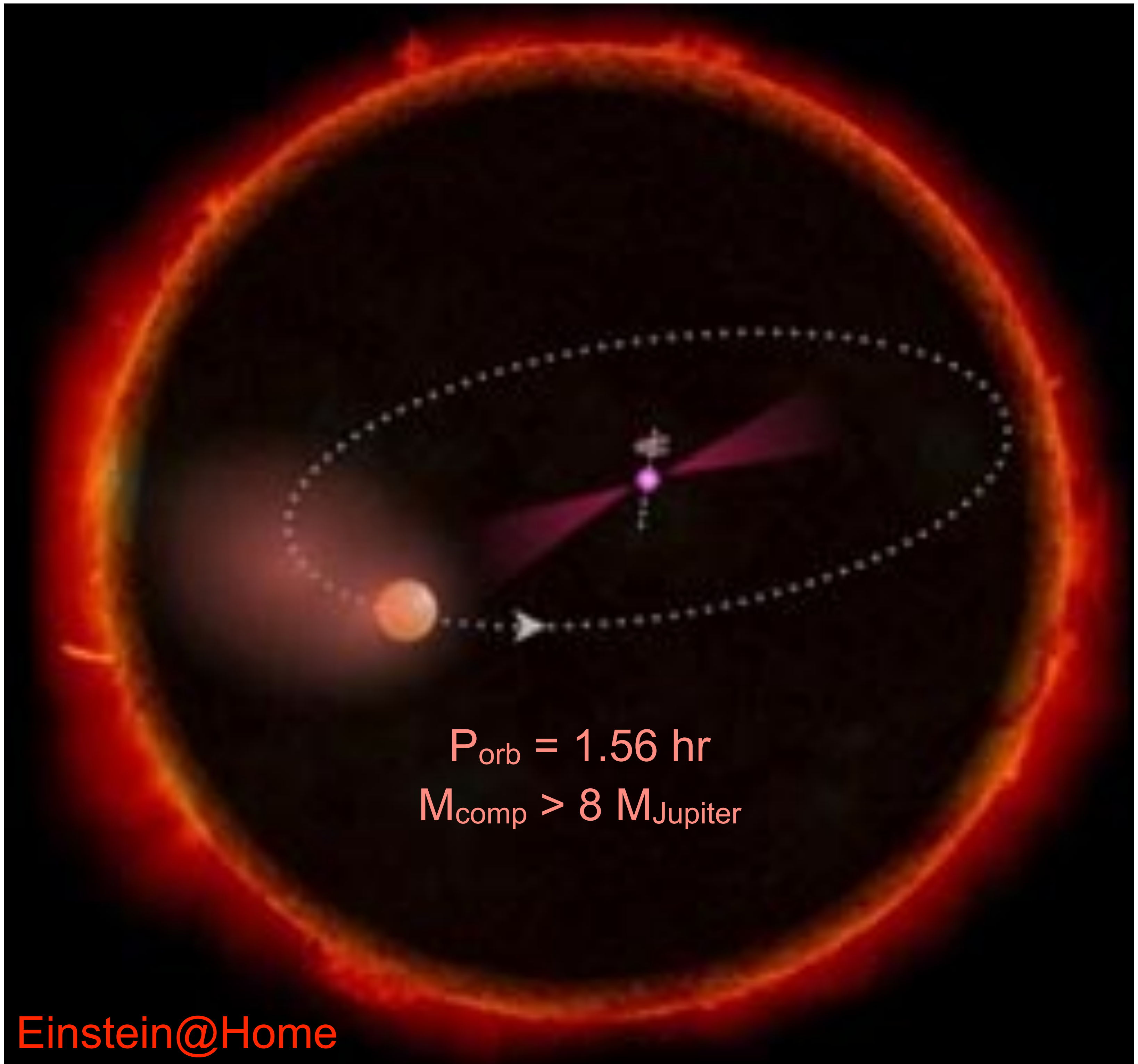
GreenBank (USA)

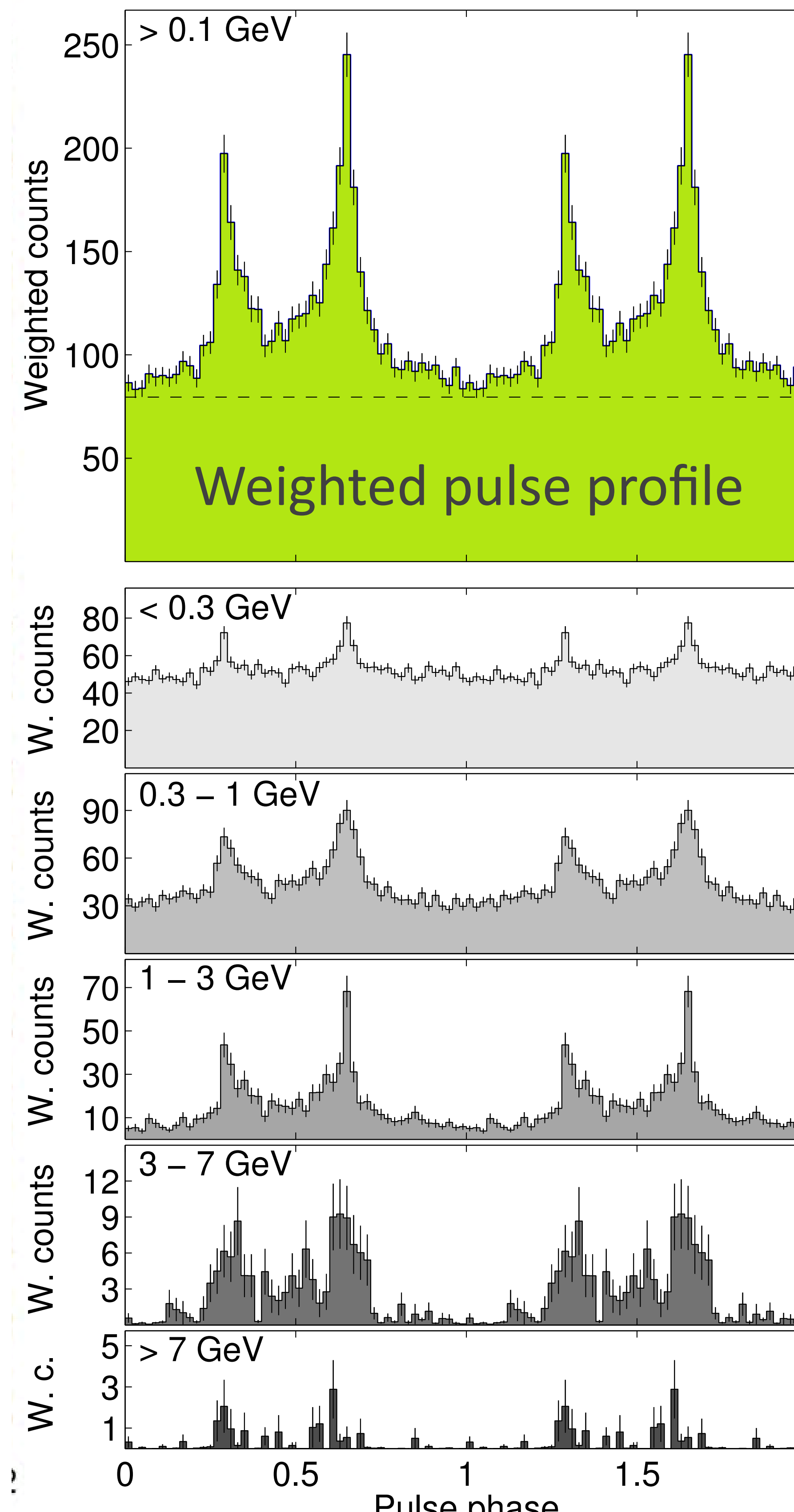
Parkes (Asutralia)

Effelsberg (Germany)

# PSR J1311-3430

- first blind-search γ-ray ms pulsar ($10^{17}$ free trials thanks to orbital info in the optical)
- extreme black widow, now seen in radio

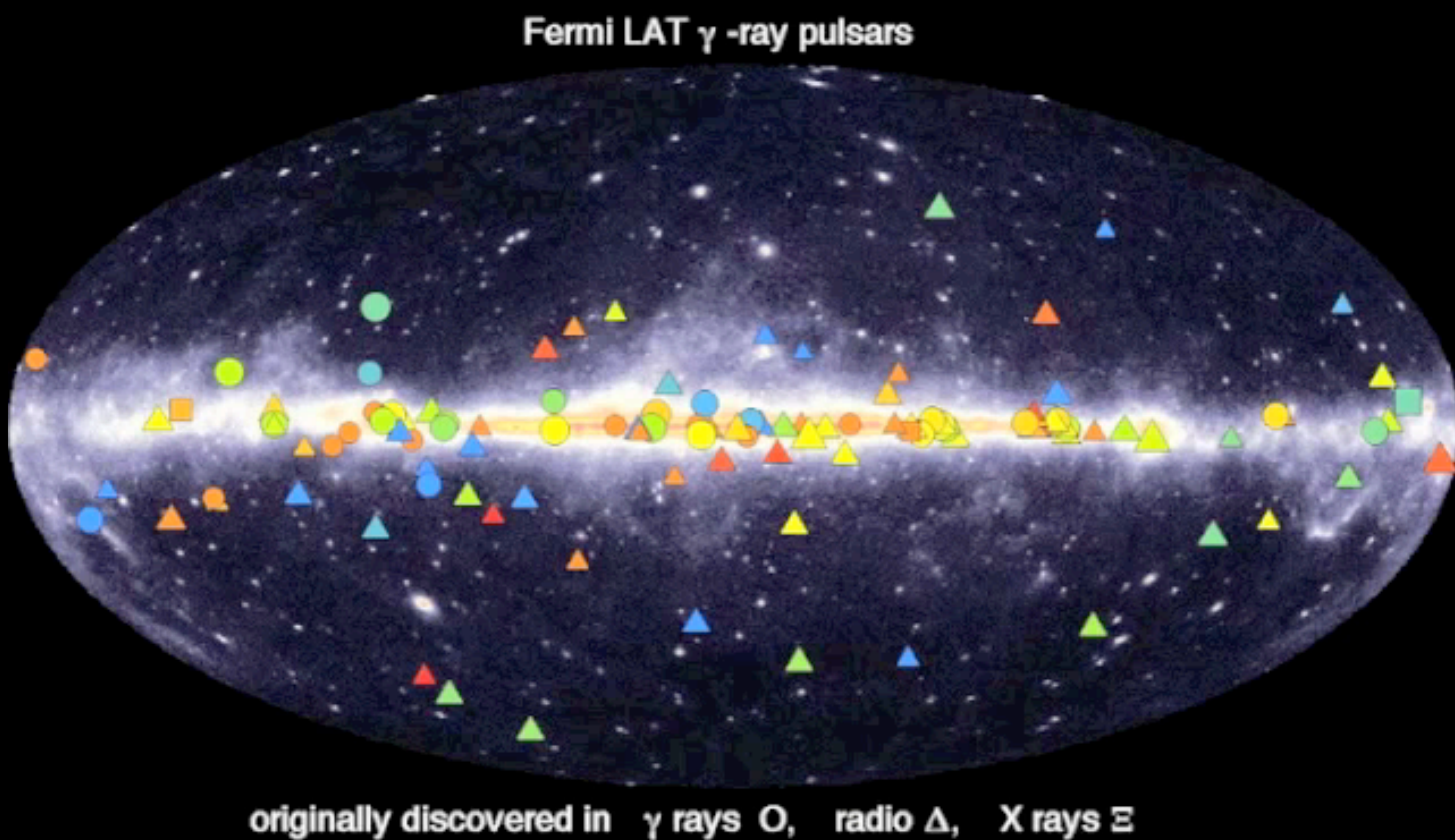



Pletsch+'2012 Science 25/10/12

# pulsations

- pulsation detection
  - folding the P and $\dot{P}$ known at other $\lambda$
  - blind search: trial and error in the P, $\dot{P}$ space



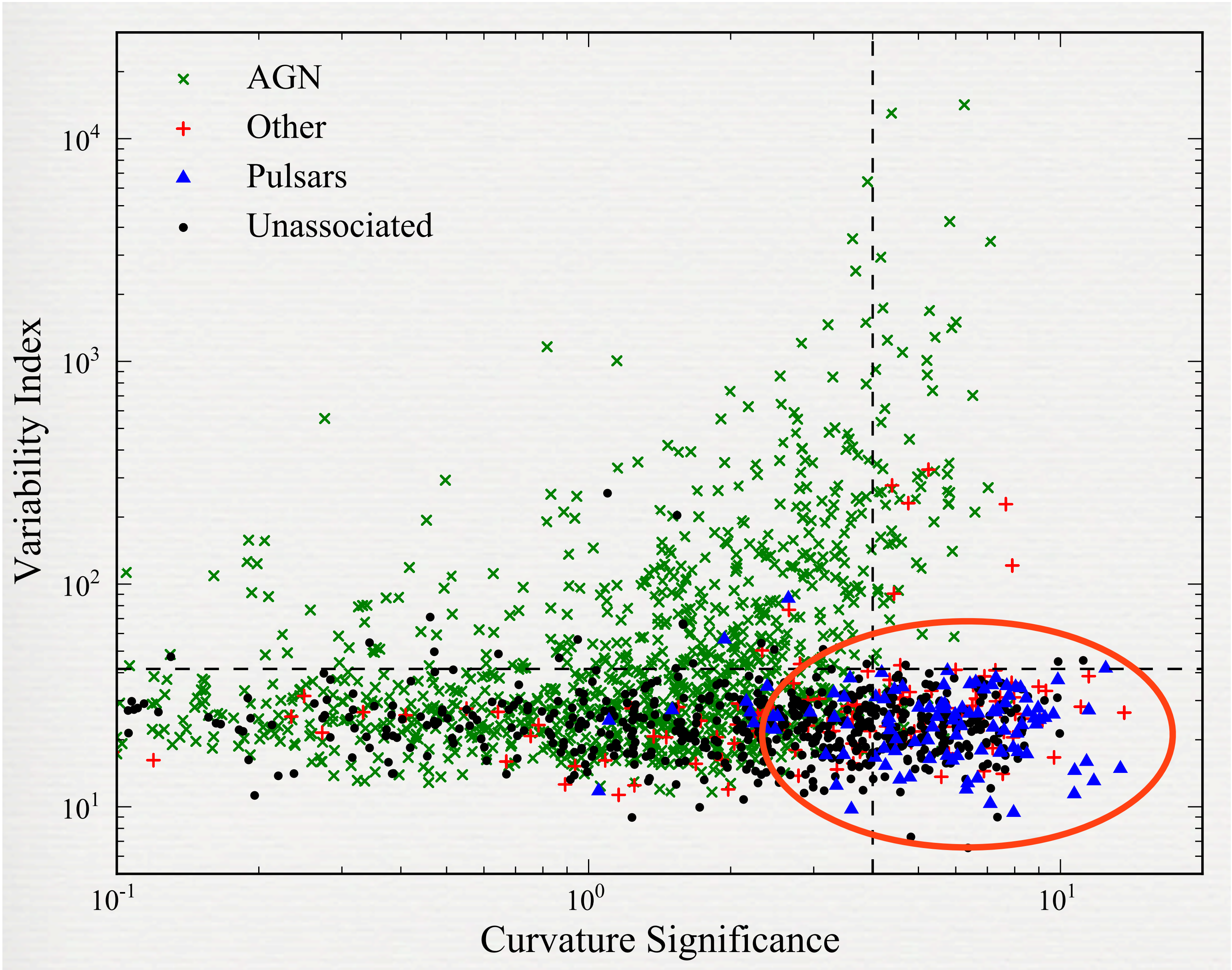
# using γ rays to find radio pulsars

- 575 unassociated 2FGL sources
- pulsar likeness
  - low variability
  - expo-cut-off spectra
  - multiple techniques for ranking sources
  - + patience ! a year to get orbit, position, $\dot{P}$, longer to proper motions (Shlovskii effect)

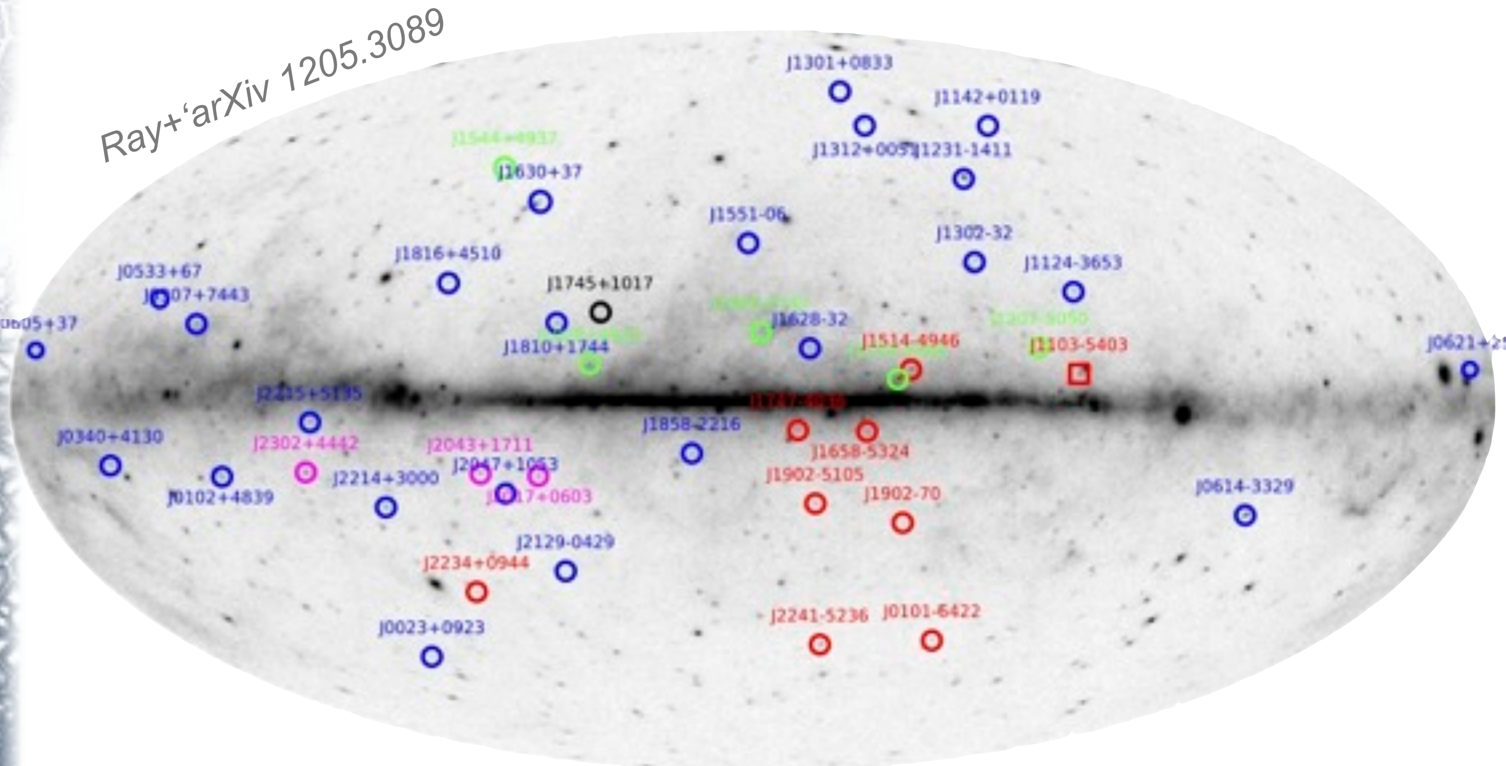
Ackermann et al., ApJ 753, 83 (2012)
Lee et al., MNRAS 424, 2832 (2012)

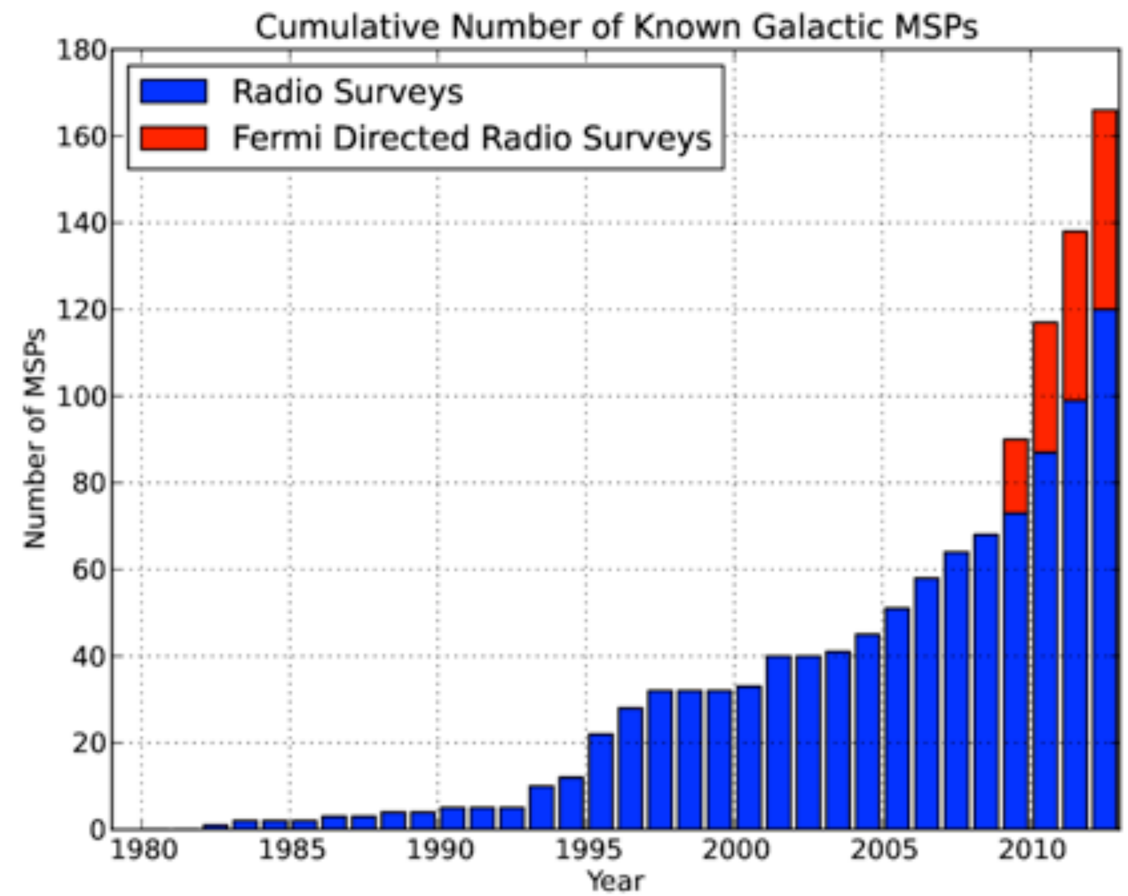
- or toward globular clusters with no known pulsar, but shining in γ rays

2FGL Catalog (Nolan et al. 2012)



# success! >48 MSPs found!

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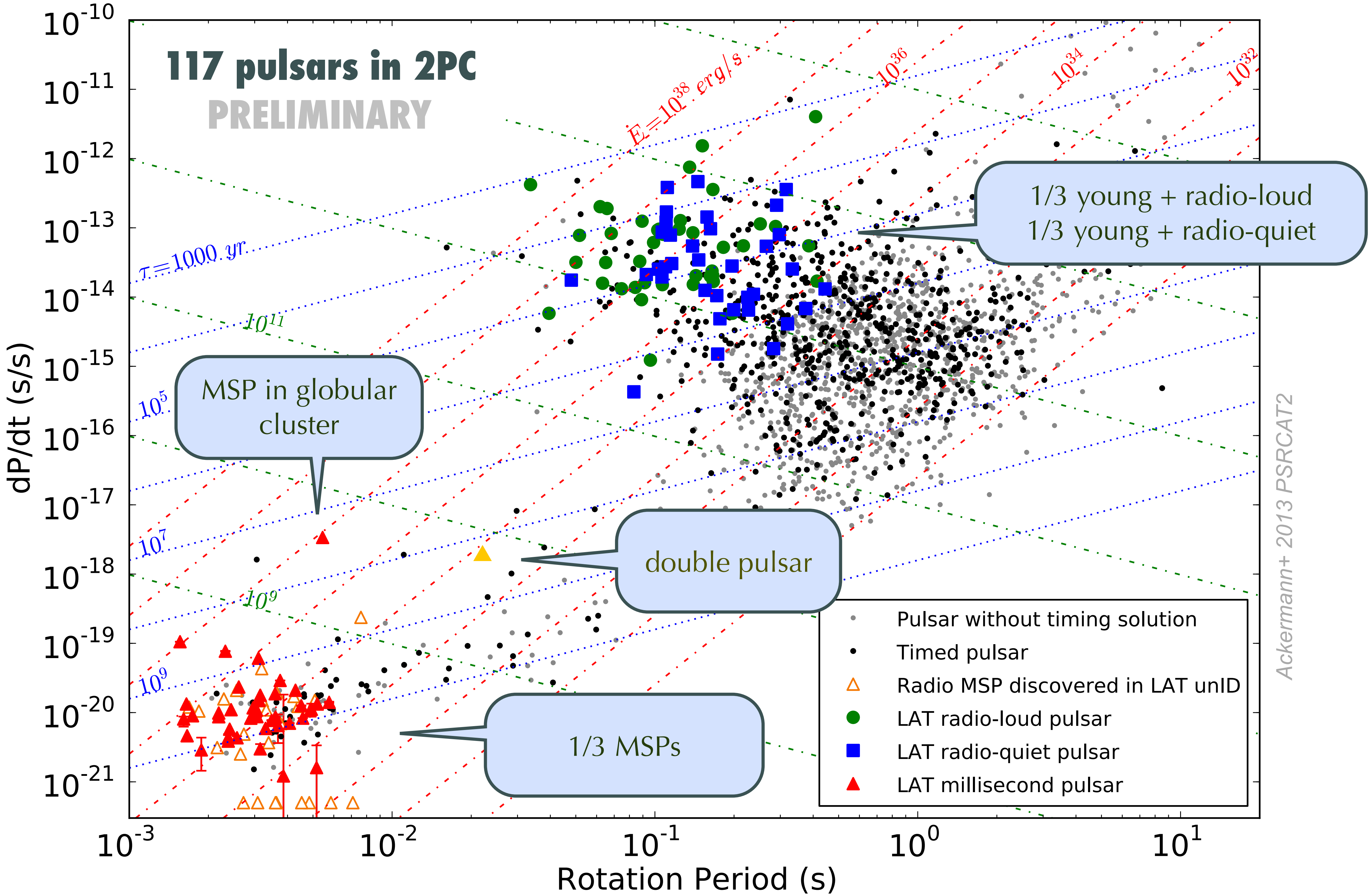
# γ-ray pulsar families



# pulsar magnetosphere

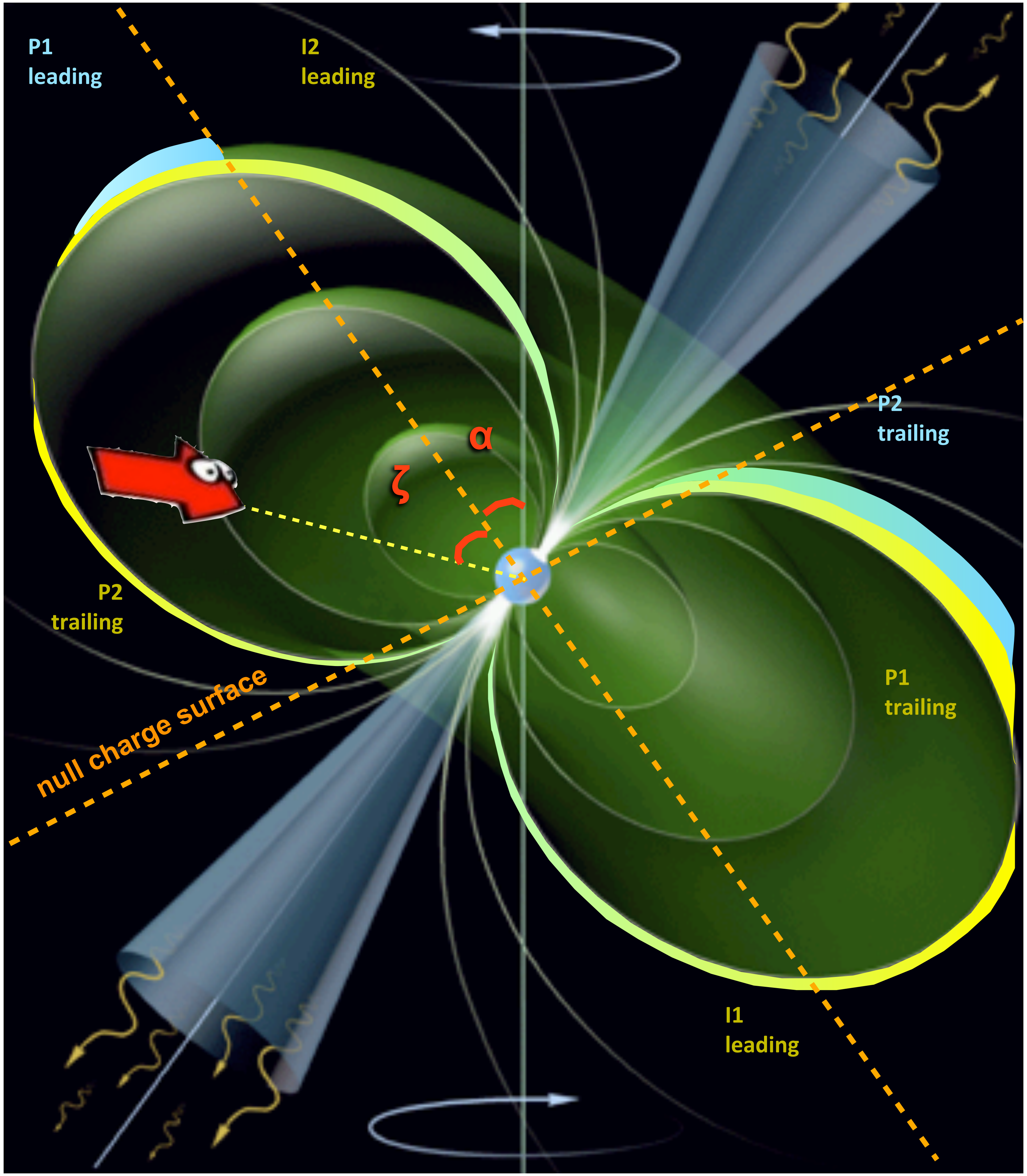
- young pulsar: $B_{NS} \sim 10^8 - 10^9$ T
- ms pulsar: $B_{NS} \sim 10^4 - 10^5$ T
- light cylinder $R_{LC}\,\mathbf{\Omega} = c$
  retarded potential near cylinder
  wave zone beyond
- unipolar induction
- magnetosphere filled with charges
  - force free plasma if
    $\rho_{GJ} = -2\epsilon_0 \vec{\Omega} \cdot \vec{B}$
    E ⊥ B (B lines = equipotential)
  - acceleration $E_{//}$ if $\rho \neq \rho_{GJ}$
- spindown power

$$\mathbf{P_{ray}} = \iint \frac{\vec{E} \wedge \vec{B}}{\mu_0} \mathbf{R^2 d\Omega}$$

$$= -\frac{\mathbf{2}\pi}{\mathbf{3}\mu_0 \mathbf{c^3}} \mathbf{B_{NS}^2 R_{NS}^6 \Omega^4} (\mathbf{1} + \sin^2 \alpha)$$

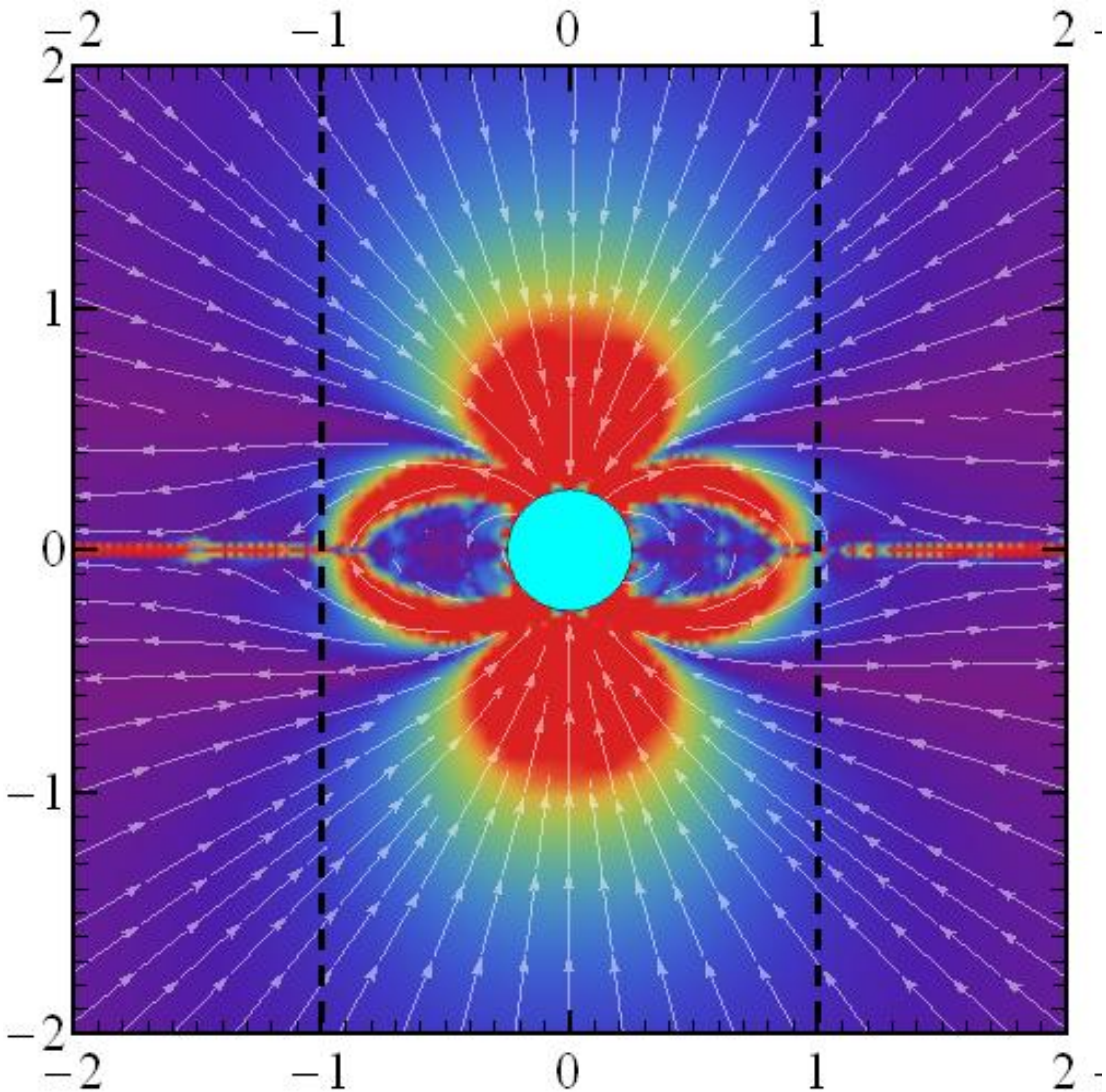
$$= \mathbf{I\Omega\dot{\Omega}} = \mathbf{\dot{E}_{psr}}$$

$$\mathbf{\dot{E}_{psr}}(\mathbf{t}) = \mathbf{\dot{E}_{ini}} \left( \mathbf{1} + \frac{\mathbf{t}}{\tau_{\mathbf{ini}}} \right)^{\mathbf{-2}}$$



# current distribution in the magnetosphere

- Kalapotharakos et al. 2011
- Spitkovsky



# 2 accelerator sites (gaps)

- polar cap + slot gap
  - above polar cap

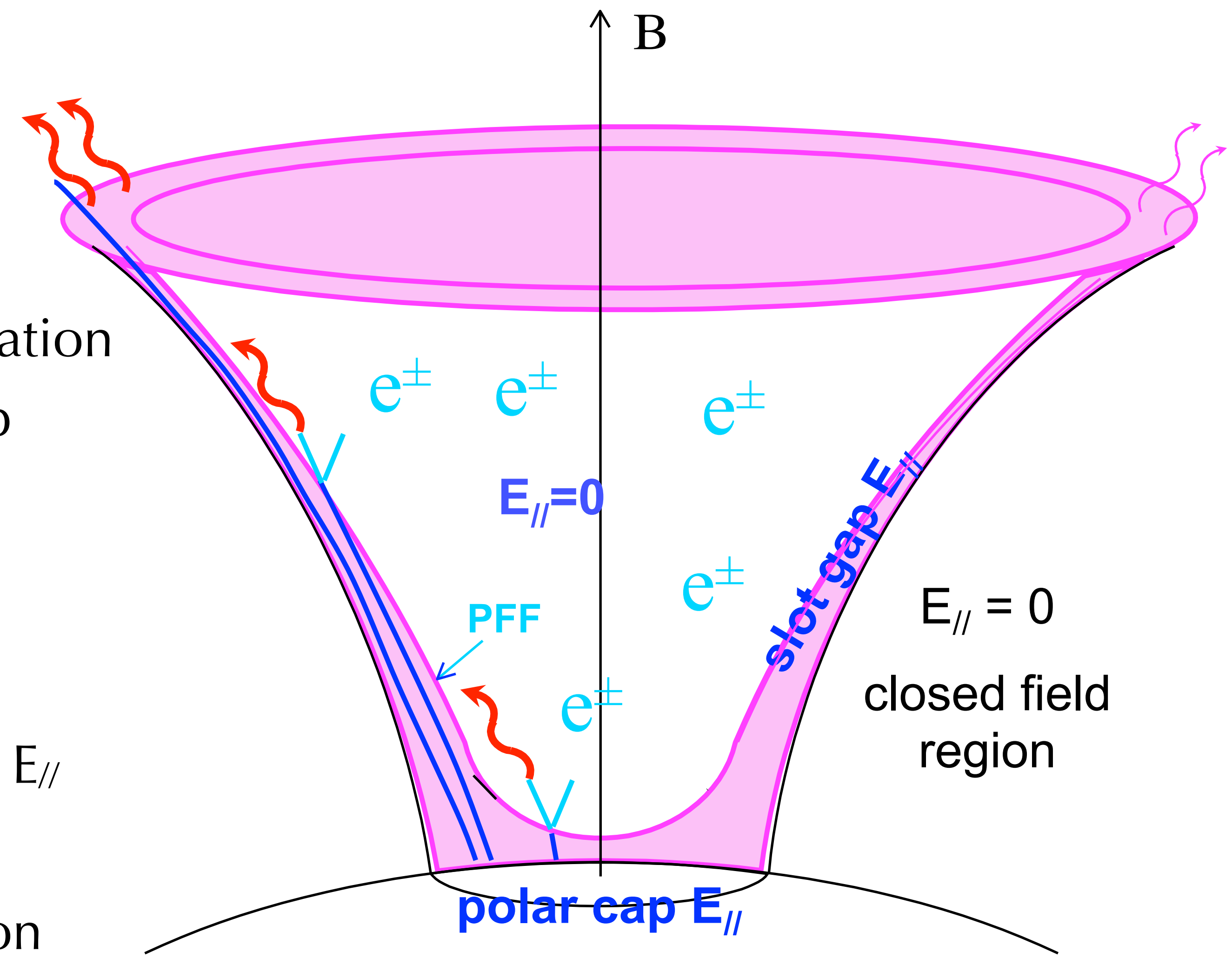
    $E_{//}$ => $e^{\pm}_1 + B_{curv} \rightarrow \gamma_1$ curvature rad.

    **$\gamma_1 + B \rightarrow e^{\pm}_2$** $\rightarrow$ cascade + synchrotron
  - near last closed B line: E// ↓ slower acceleration

    thus pair formation front moves up: slot gap

    $e^{\pm} + B_{curv} \rightarrow \gamma$ : curvature radiation in

    radiation-reaction limit $eE_{\parallel} = \dot{\gamma}_{CR}$




- outer gap
  - current through light cylinder + Poisson => $E_{//}$

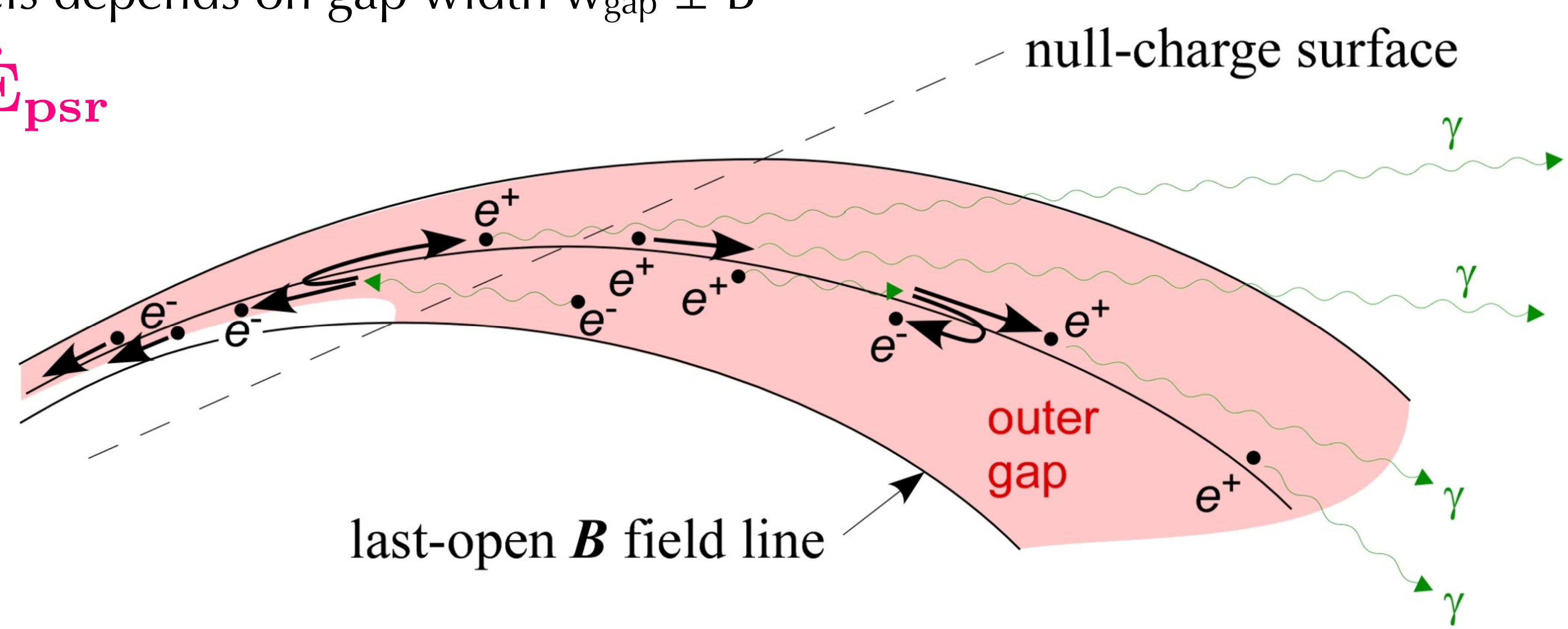
    $e^{\pm}_1 + B_{curv} \rightarrow \gamma_1$ curvature rad.

    **$\gamma_1 + \gamma_2 \rightarrow e^{\pm}_2$** $\rightarrow$ cascade + IC + synchrotron

- accelerator power in all models depends on gap width $w_{gap} \perp B$

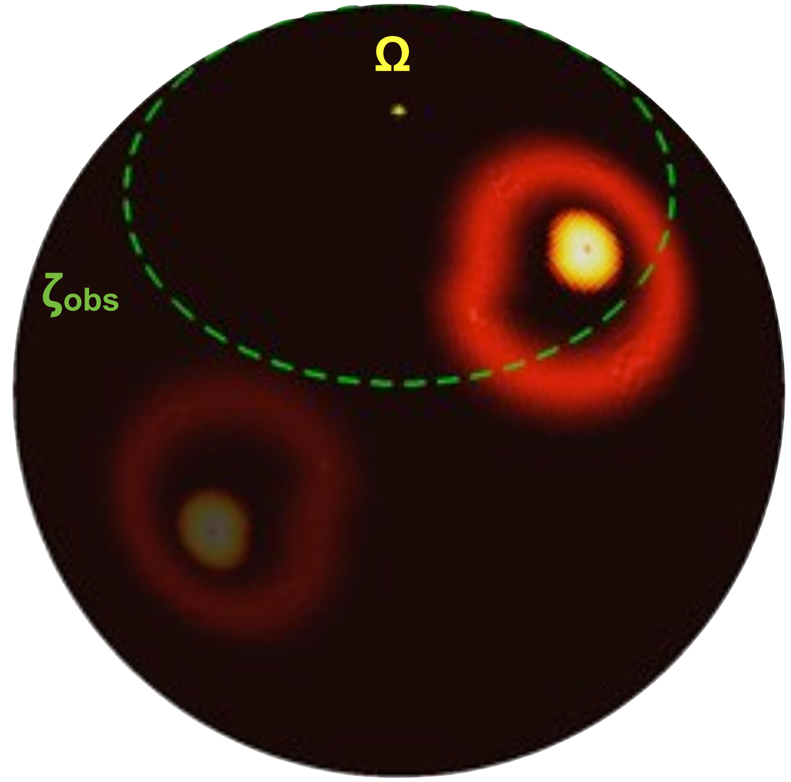
$$\mathbf{L_\gamma \propto L_{e\pm} \propto w^3_{gap} \times \dot{E}_{psr}}$$

gap widens with age

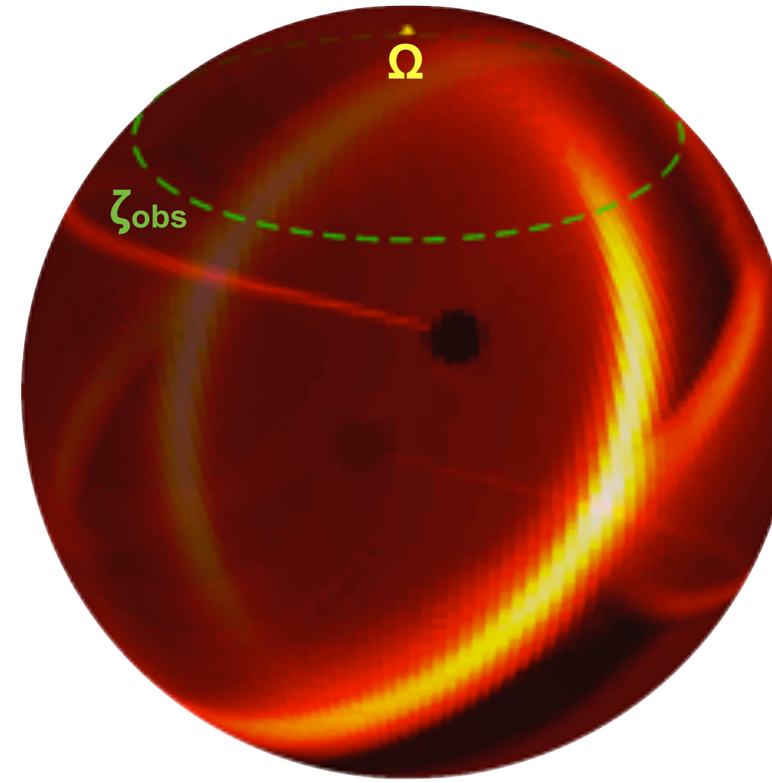


# radiation patterns

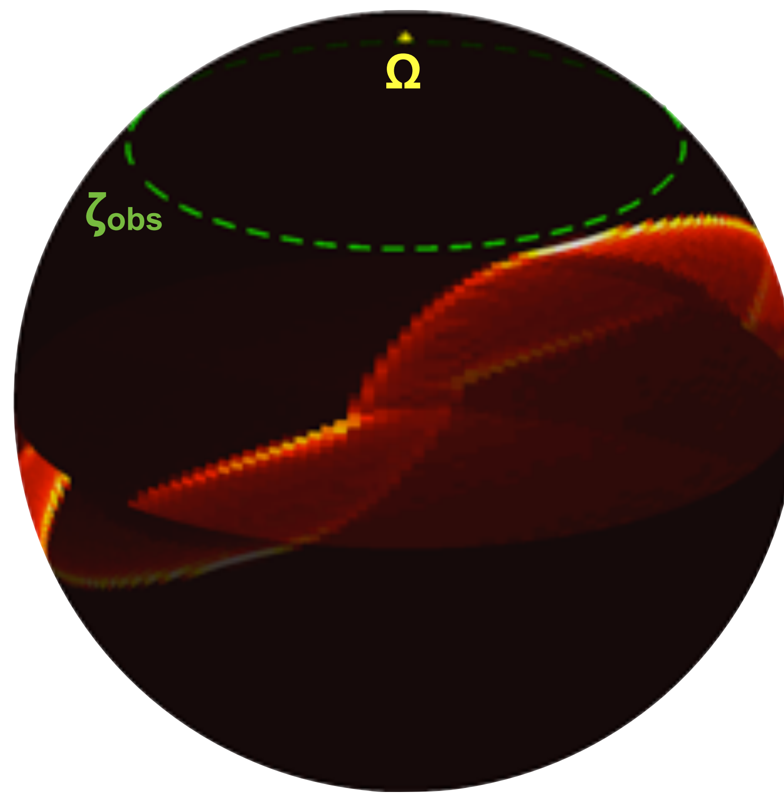
- photons emitted along B lines
- radio core + cone emission
  - $r \sim 0.05\text{-}0.1\ R_{LC}$



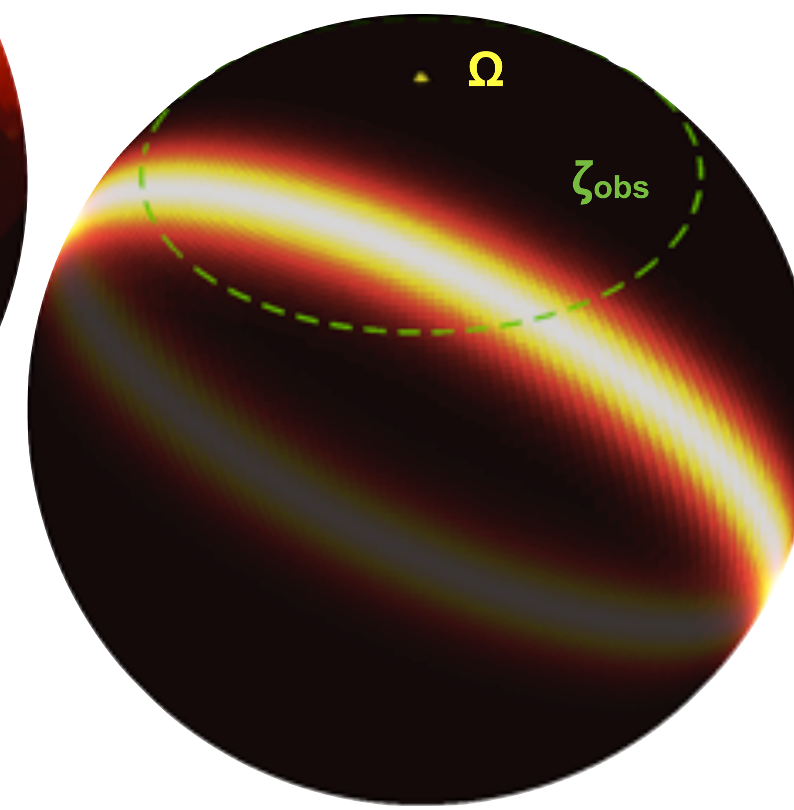

- low & high slot-gap beam
  - $r \leq 0.95\ R_{LC}$




- one-pole-outer gap
  - $R_{null} \leq r \leq 0.95\ R_{LC}$




- striped wind
  - B reconnection in wave zone
    $r \geq 5\ R_{LC} \Rightarrow E_{//}$
    => Doppler boosted synchrotron

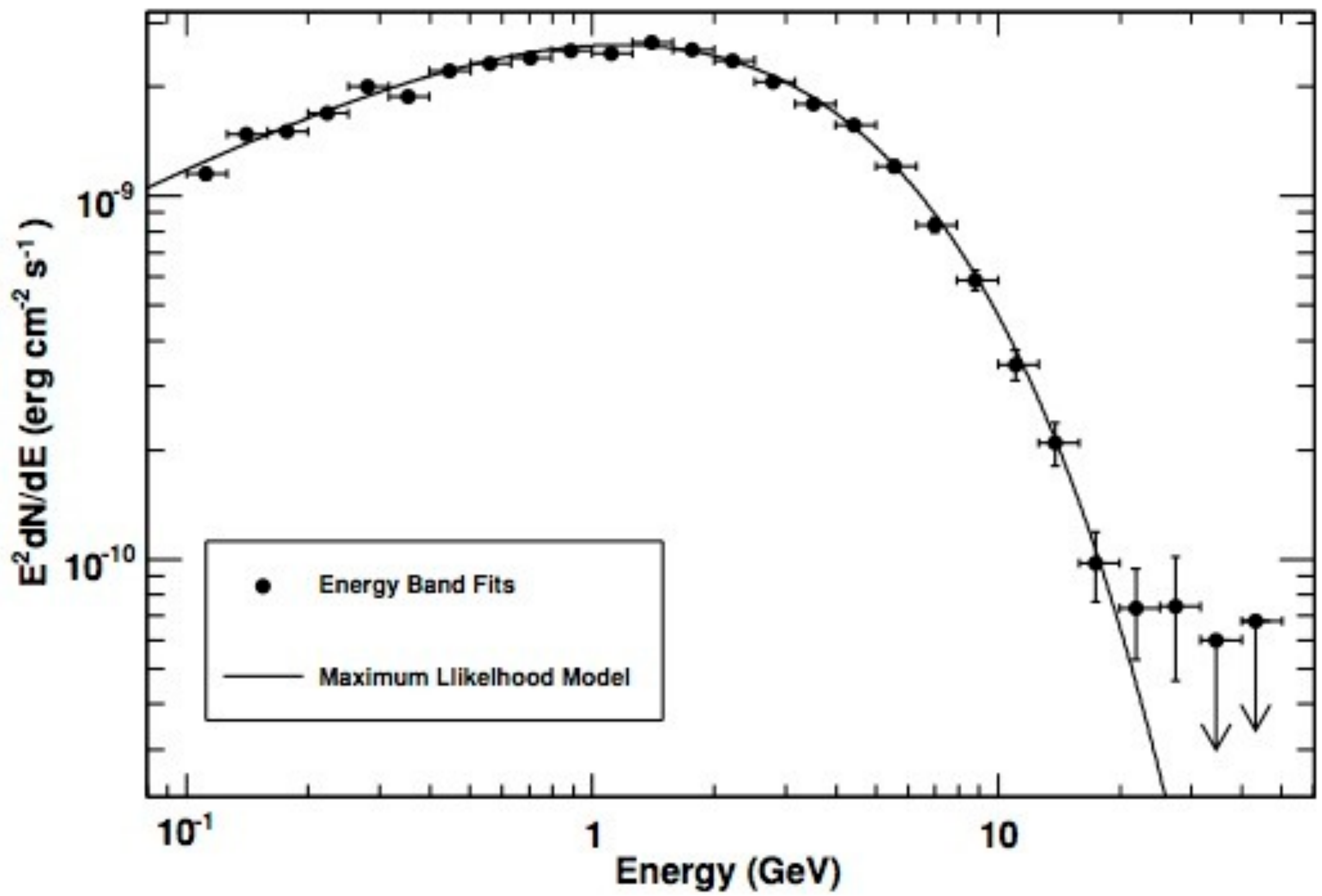



- phase shifts because of retarded potentials, time-of-flight delays, light aberration

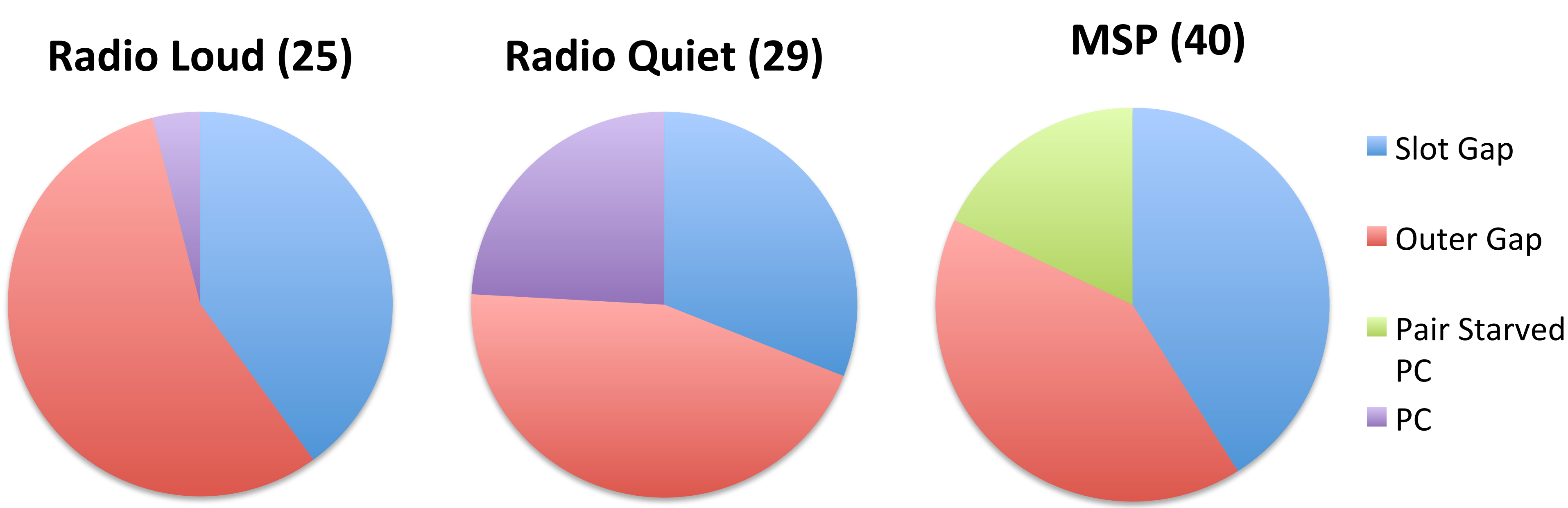
# accelerator in the outer magnetosphere

- spectral evidence : no spectral cutoff from magnetic pair production
  - => 10 TeV accelerator in the slot gap or outer gap

- radiation patterns : fits of γ-ray and radio lightcurves with the different mode
  - no single model can reproduce the variety of lightcurves despite large choice of α and ζ



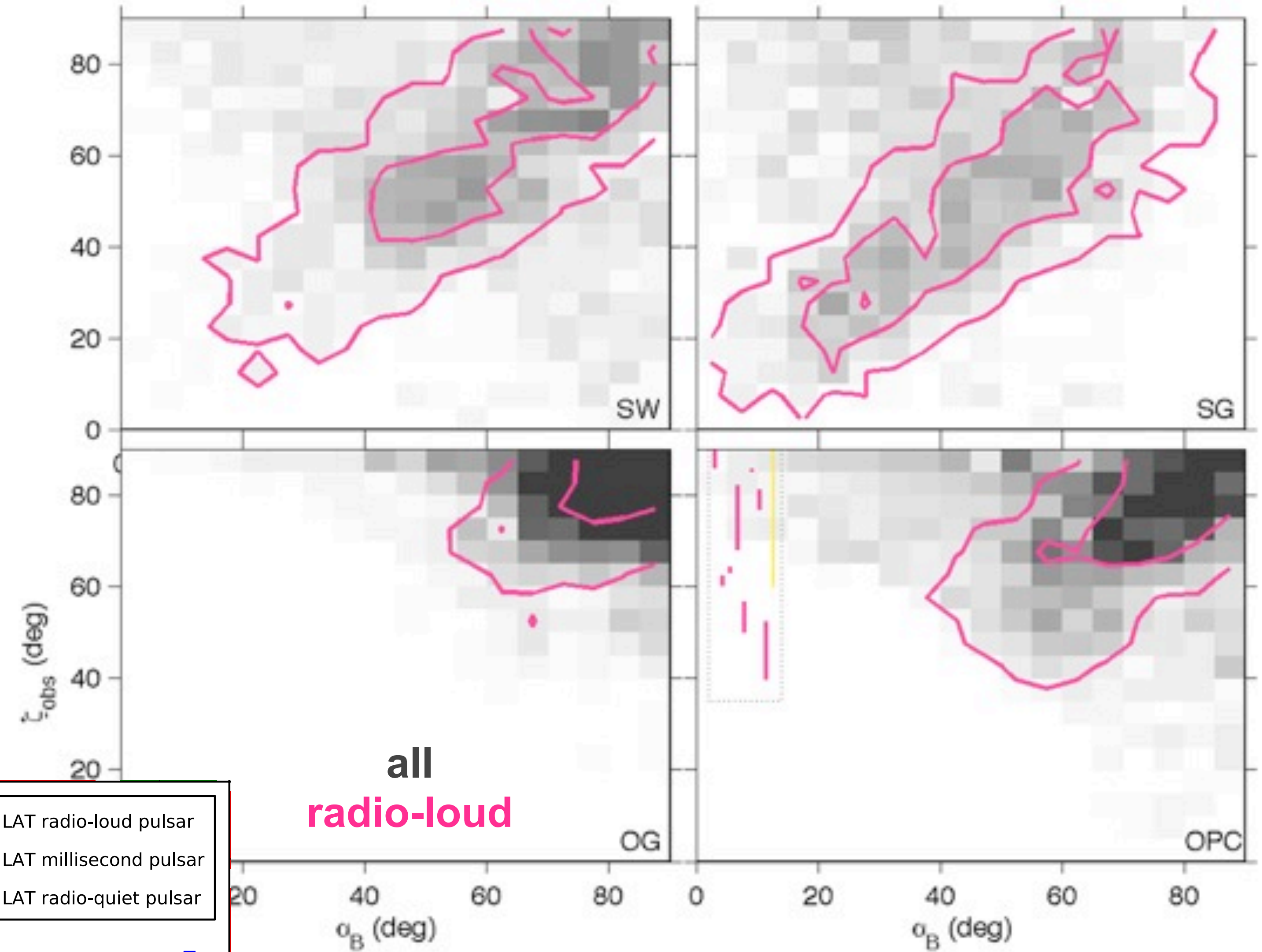

*Abdo+2010, ApJ 713, 154*



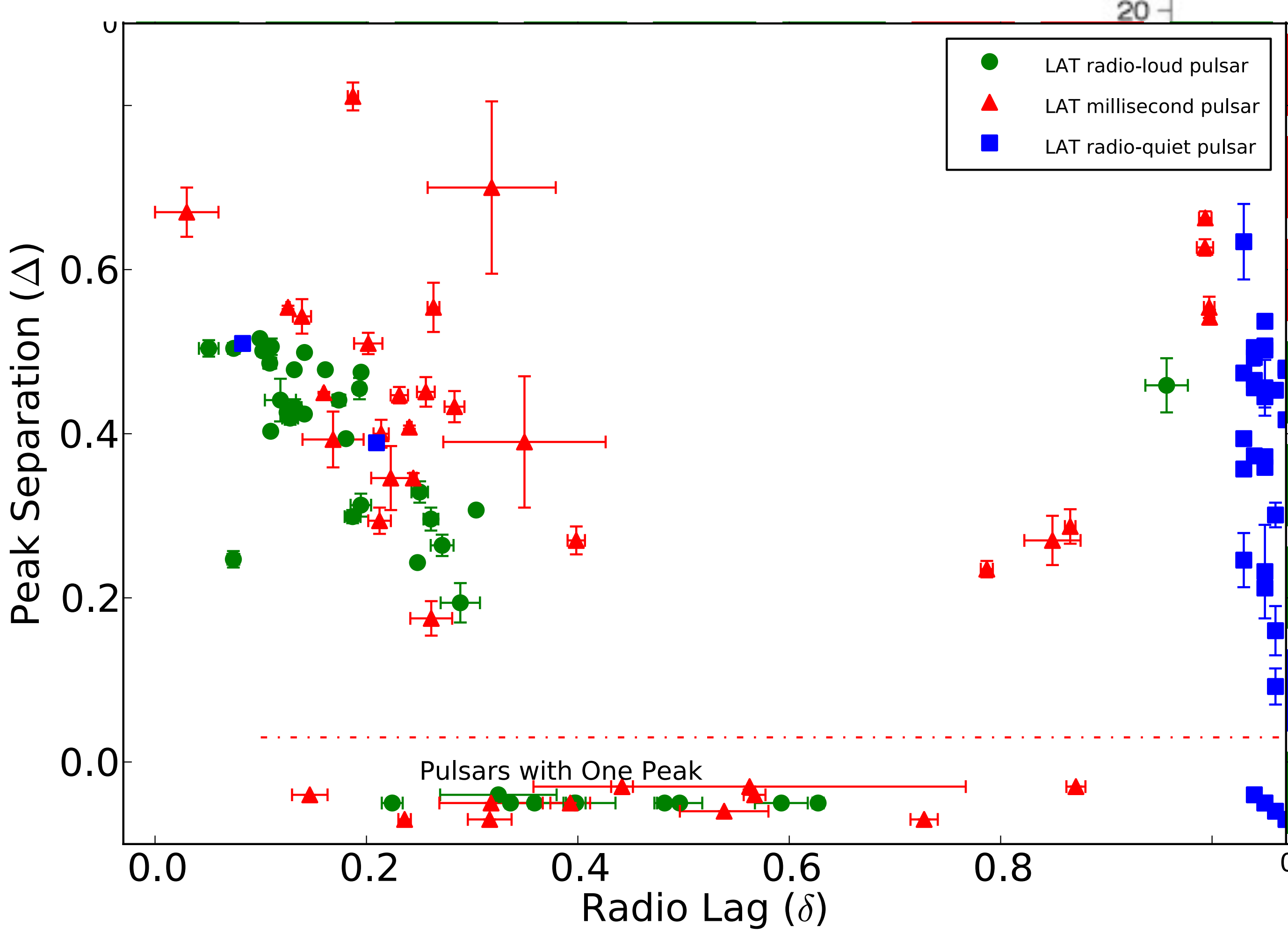

*Pierbattista+ 2013, Johnson+ 2013*

# opposite poles shining in γ rays & radio ?

- preferred viewing geometries
  - radio-loud objects for α ~ ζ
  - radio-quiet objects
    large |α - ζ] for the striped wind and
    skewed to ζ > α for the slot gap
- suggestion of
  - one pole seen in γ rays
  - opposite pole seen in radio
- little evolution of peak separation with $\dot{E}$




Pierbattista+ 2012



# pulsar orientations

- lightcurve fits using the radiation patterns of the different models
  $\Rightarrow$ pulsar orientation $\zeta$ and magnetic obliquity $\alpha$

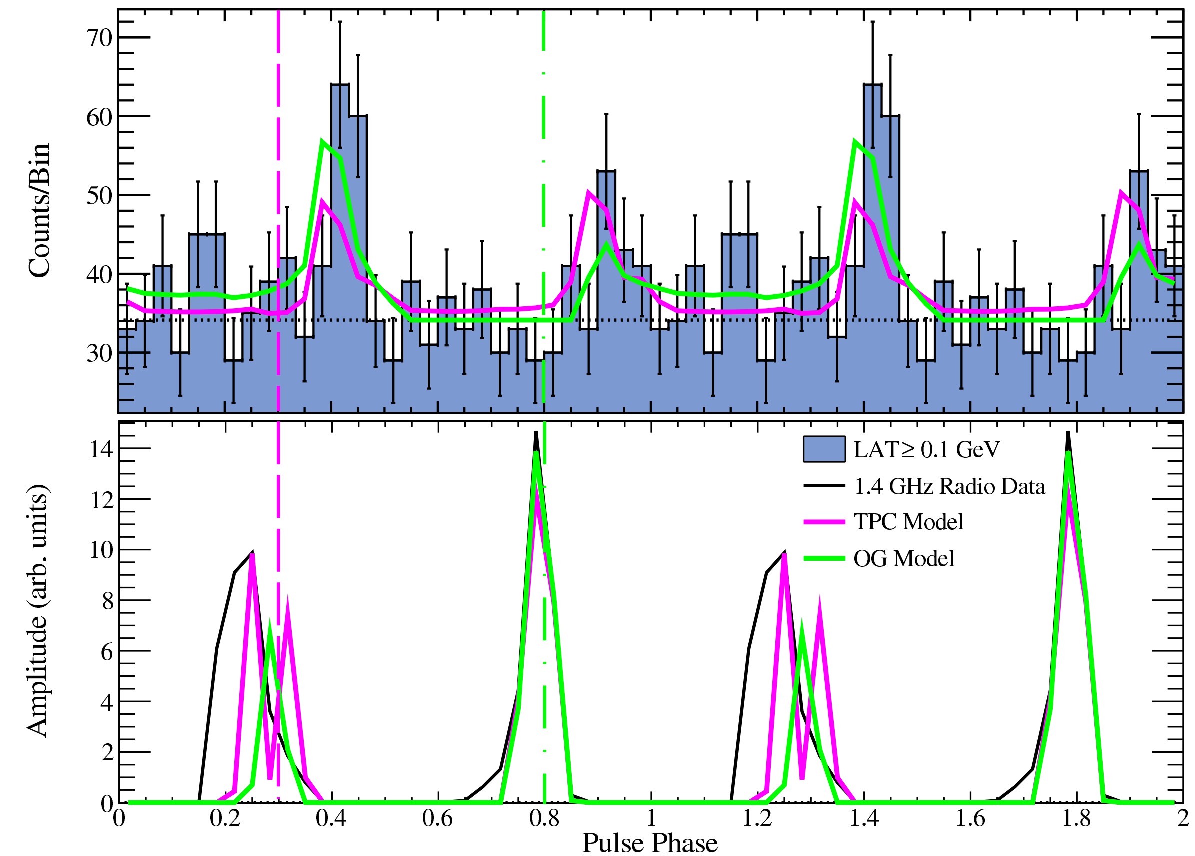
- ex: double pulsar J0737-3039
  $\Rightarrow$ orientation consistent with polarisation data
  - radio + γ-ray profile fits

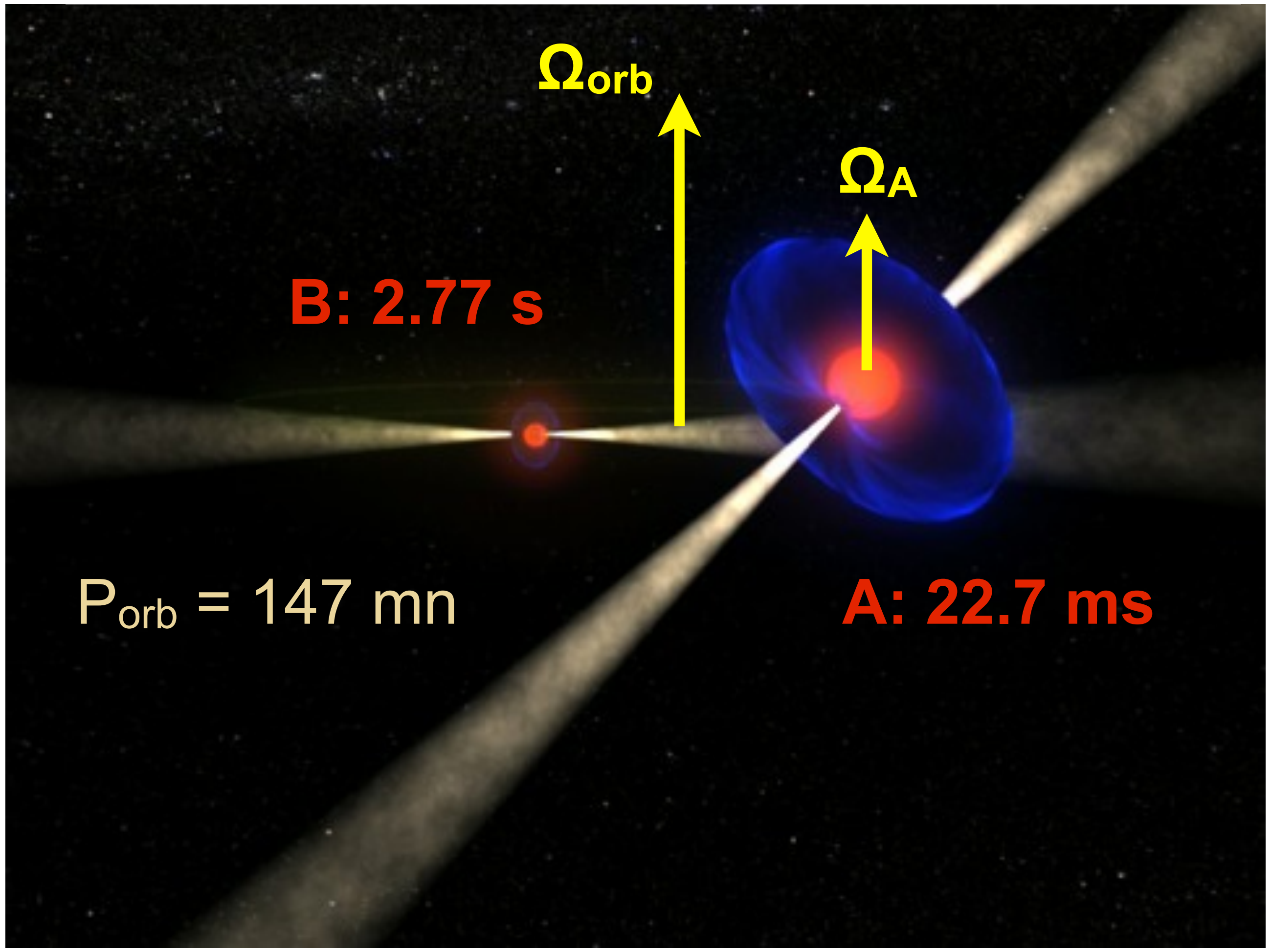
| | TPC | OG |
|---|---|---|
| $\alpha$ (°) | $80^{+9}_{-3}$ | $88^{+1}_{-17}$ |
| $\zeta$ (°) | $86^{+2}_{-14}$ | $74^{+14}_{-4}$ |

  - polar + RVM fit

| | |
|---|---|
| $\alpha$ (°) | $98.8^{+8-1.5}$ |
| $\zeta$ (°) | $95.8^{+13.2}_{-4.3}$ |

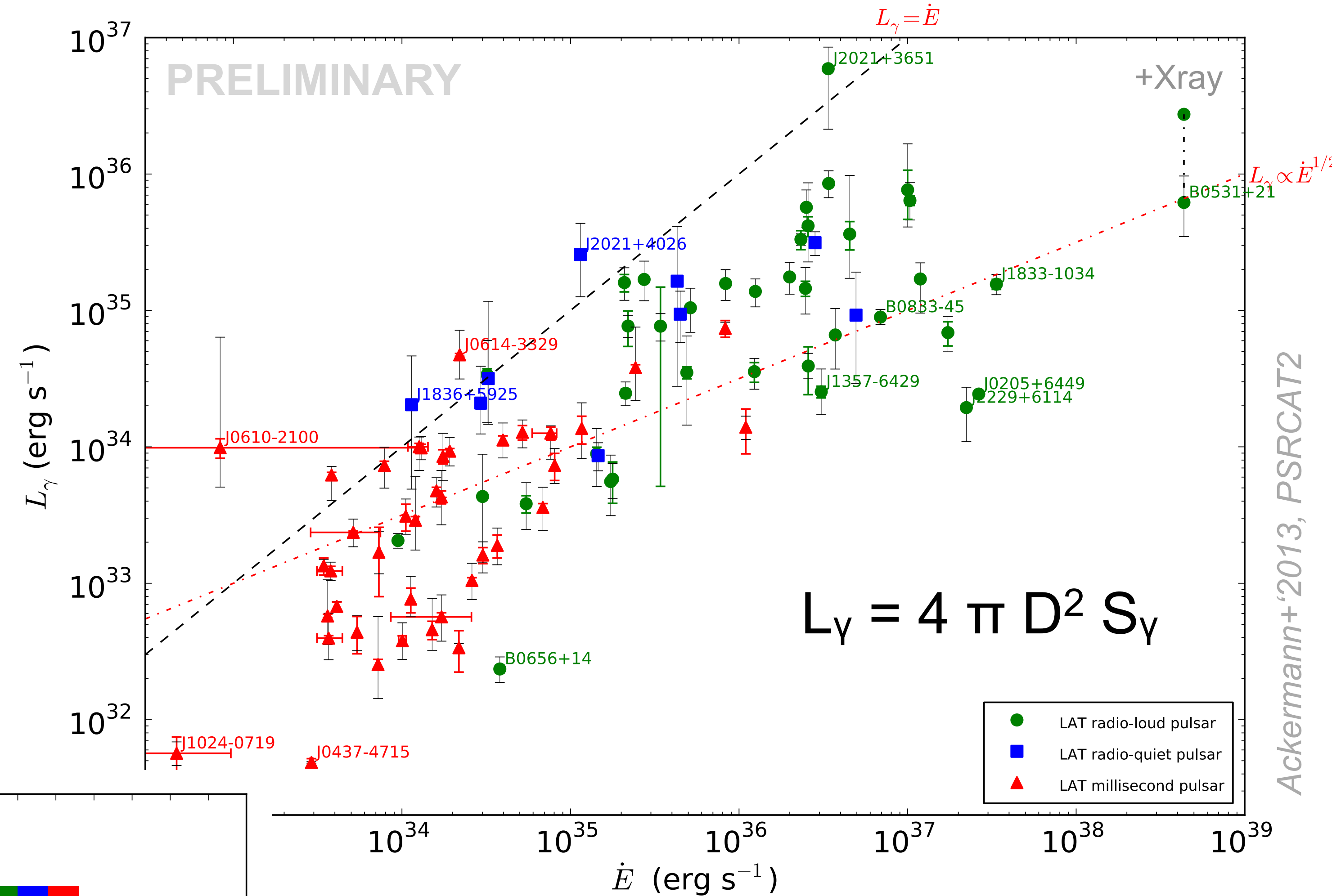
Guillemot+. 2013, arXiV:1303.7352v2

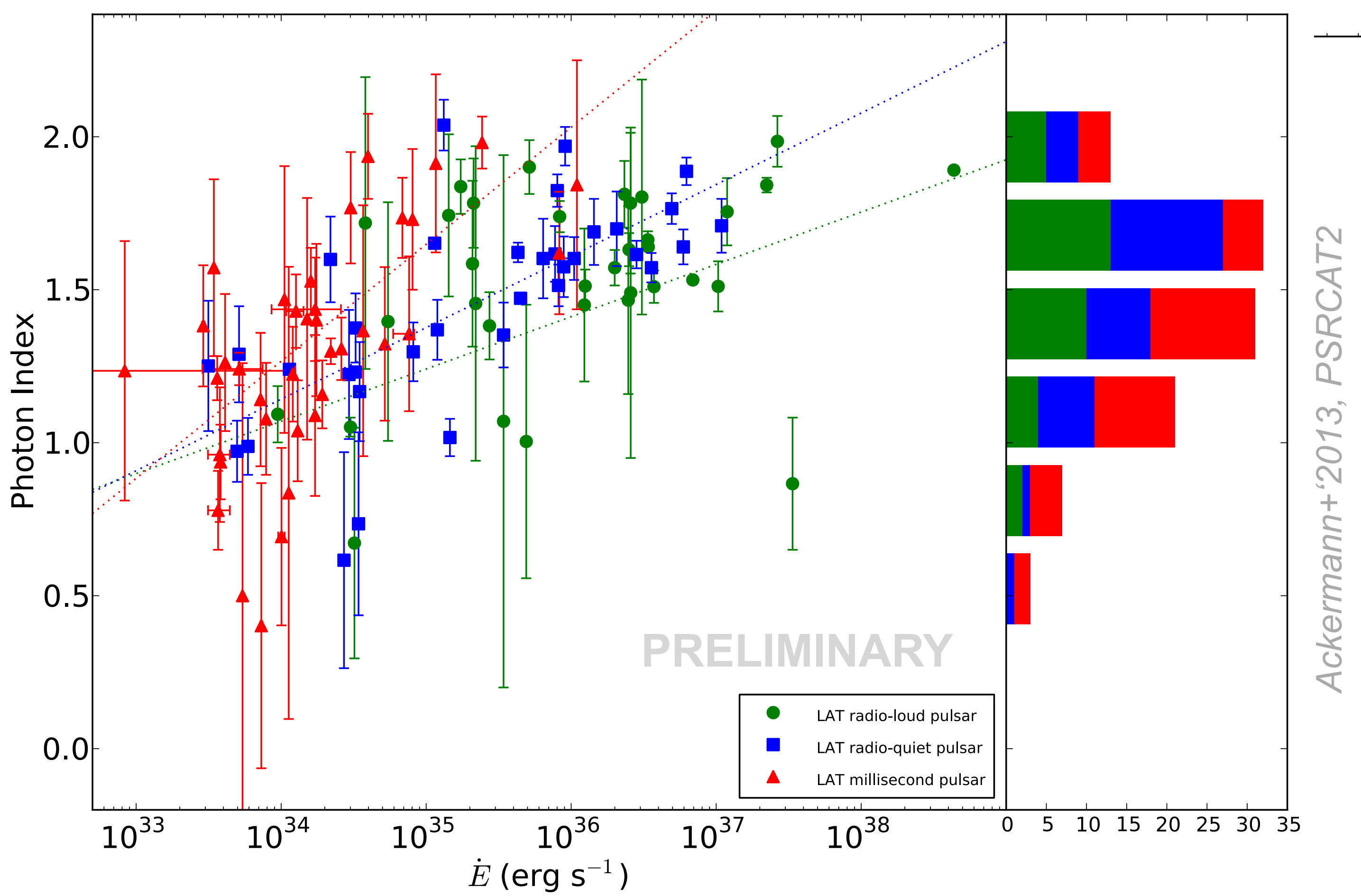


# evolutionary trends

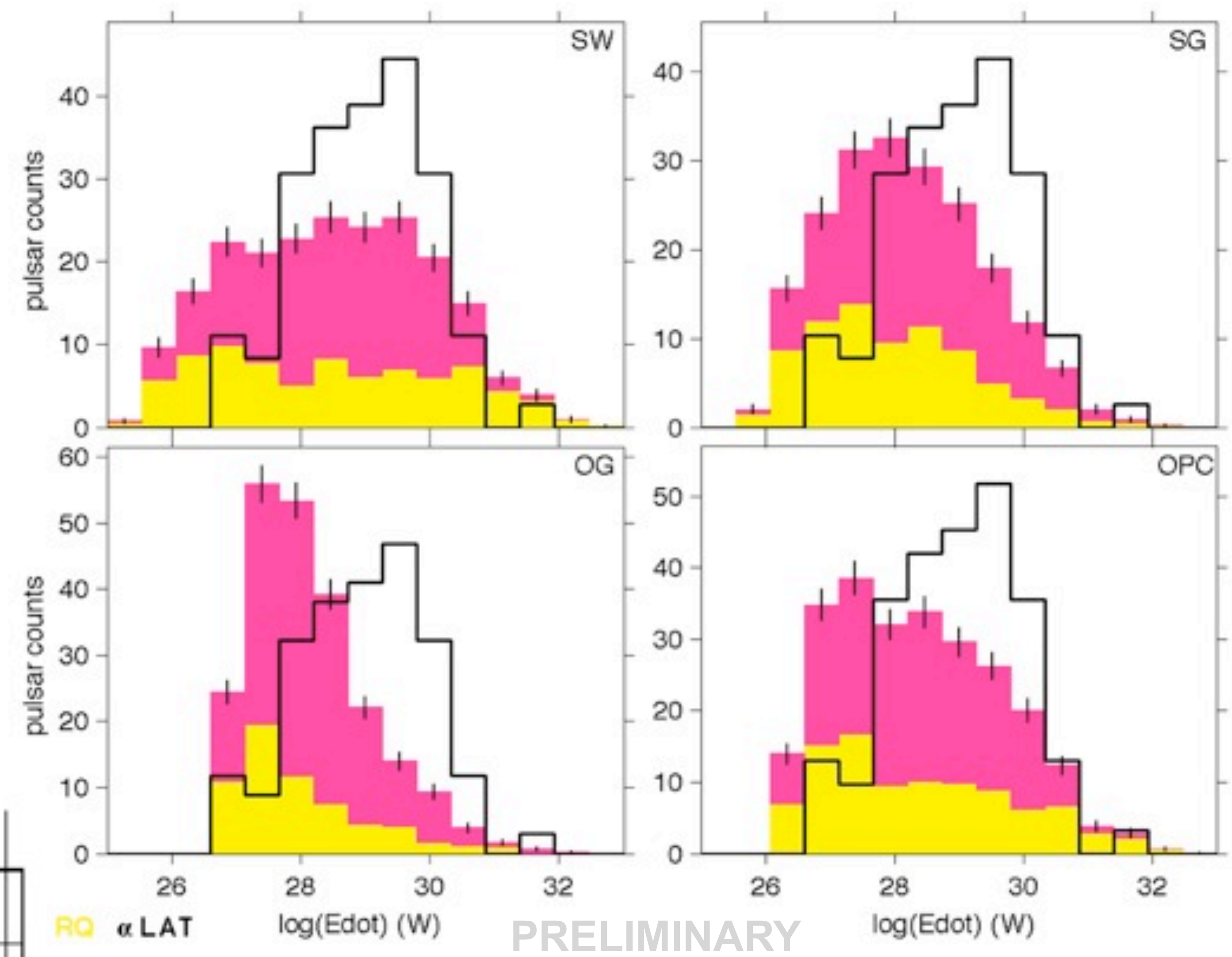
- large dispersion in isotropic luminosities dominated by
  - distance uncertainties
  - $\neq$ beaming factors
  - roughly consistent with slot-gap and outer-gap predictions
- the older, the harder in γ rays, the more efficient in $L_\gamma/\dot{E}$



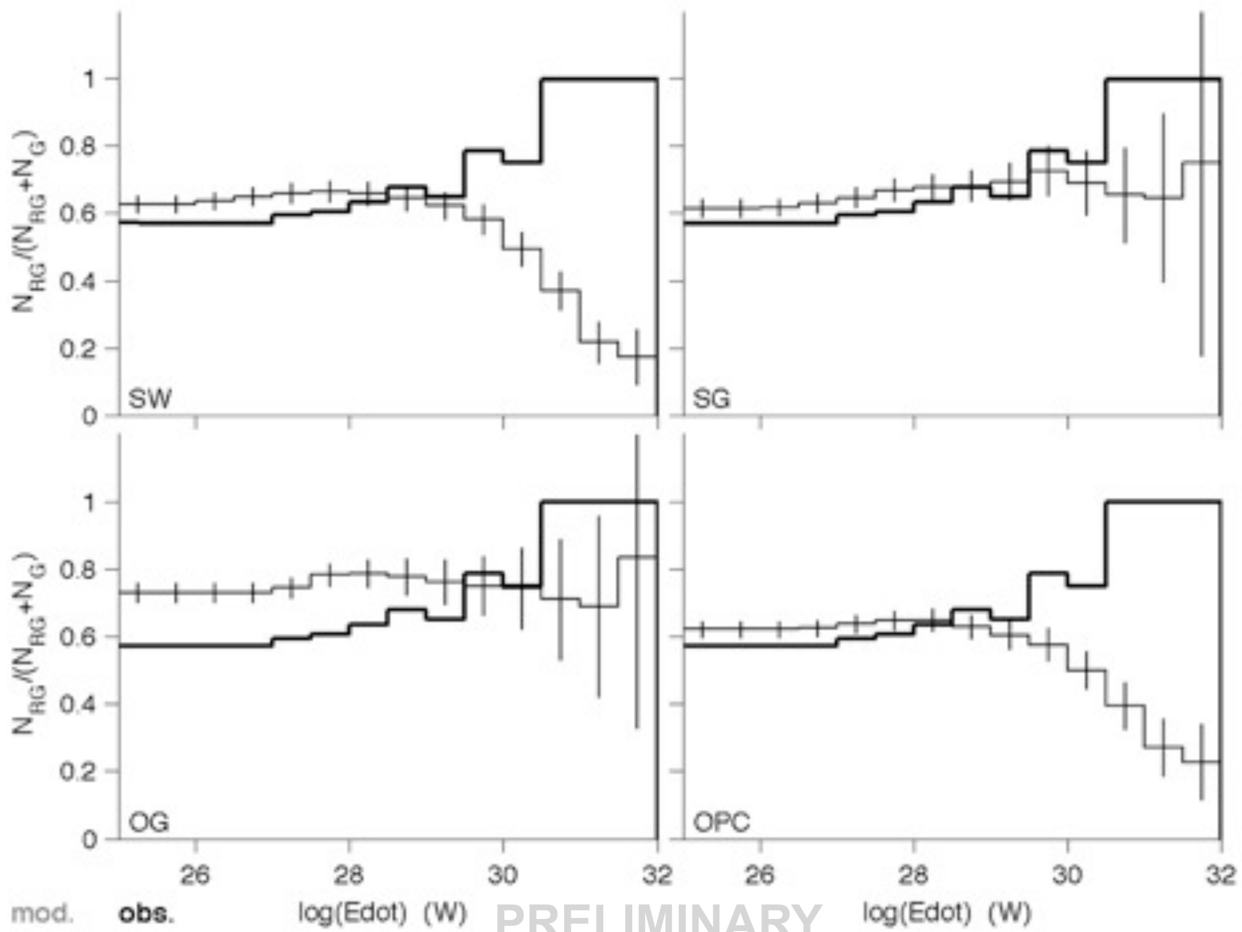



# lack of high Ė simulated pulsars

- all models fail to reproduce
  - the abundance of LAT pulsars with ages < 100 kyr => unexplained evolution in the extraction of the dynamo power as the pulsar slows down, i.e. in the evolution of the starvation gap width
  - the high probability of observing both the radio and γ beams at high Ė




RL RQ
LAT scaled

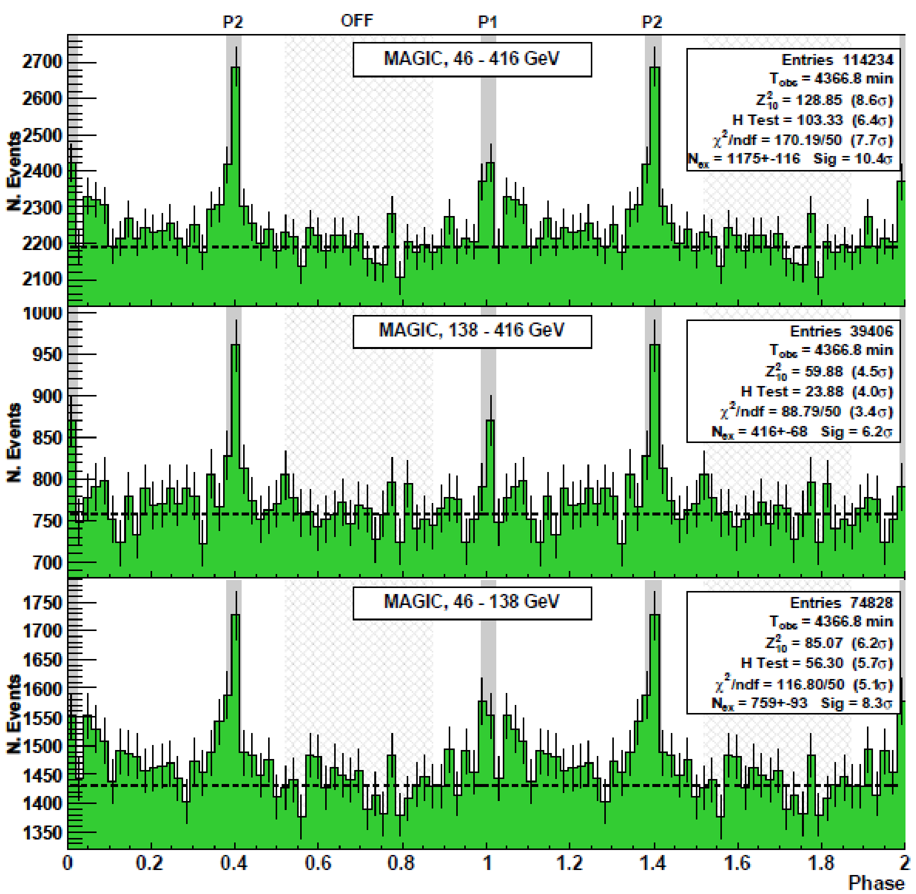


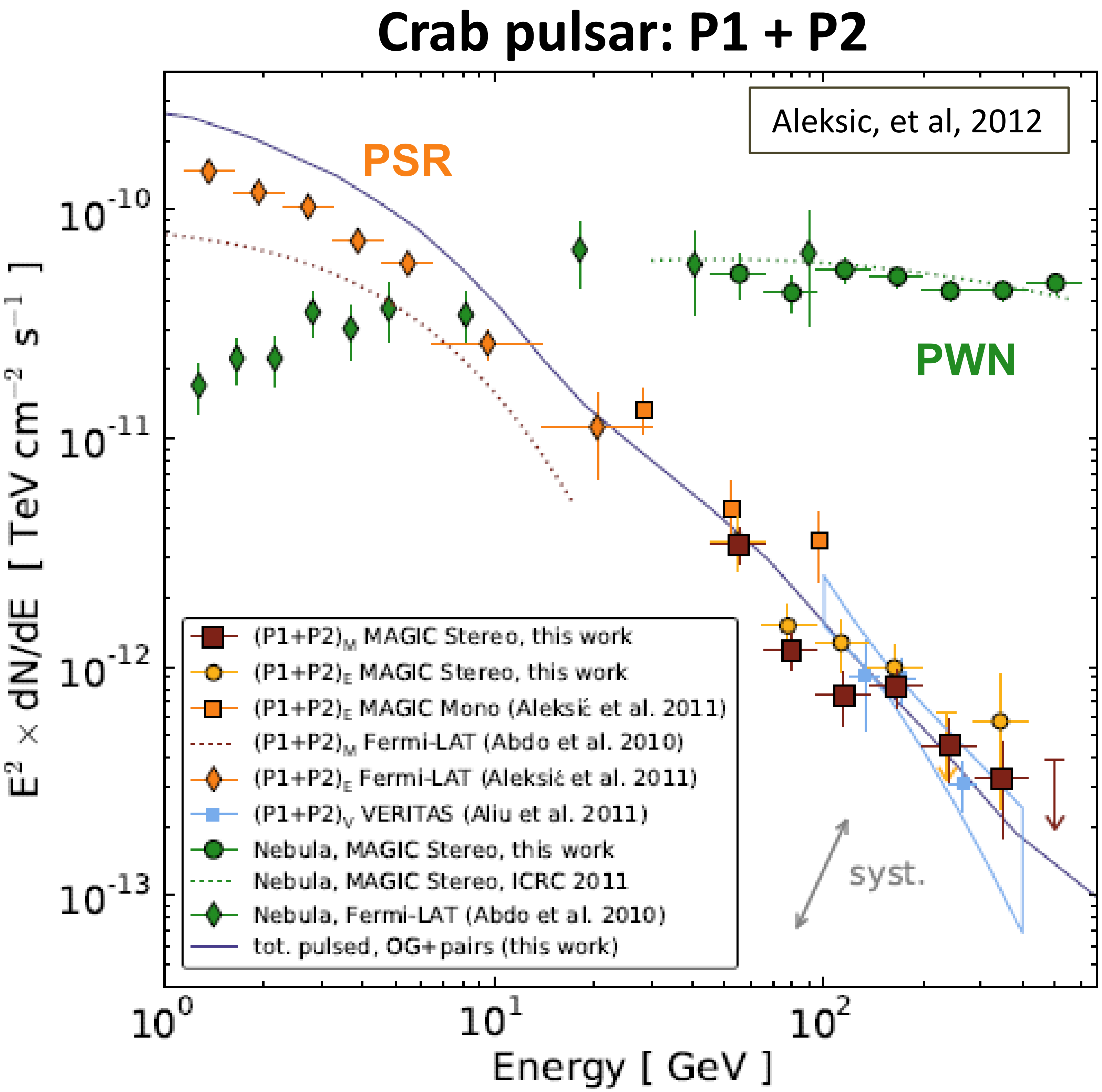

radio-loud fraction among γ pulsars

Grenier+. 2014, in preparation

# Crab TeV pulsations

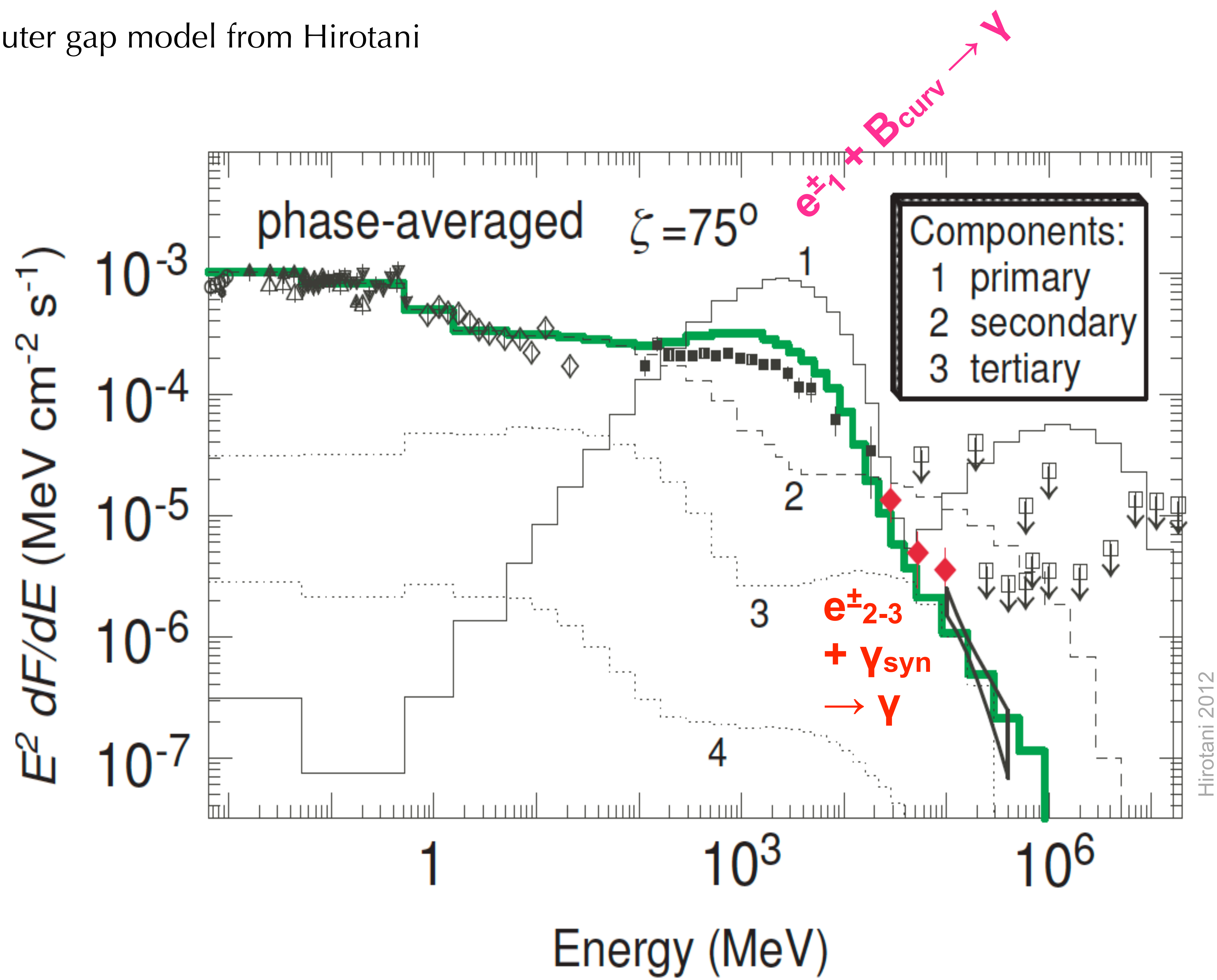
- MAGIC detection of 100 GeV pulsations
  likely SSC origin



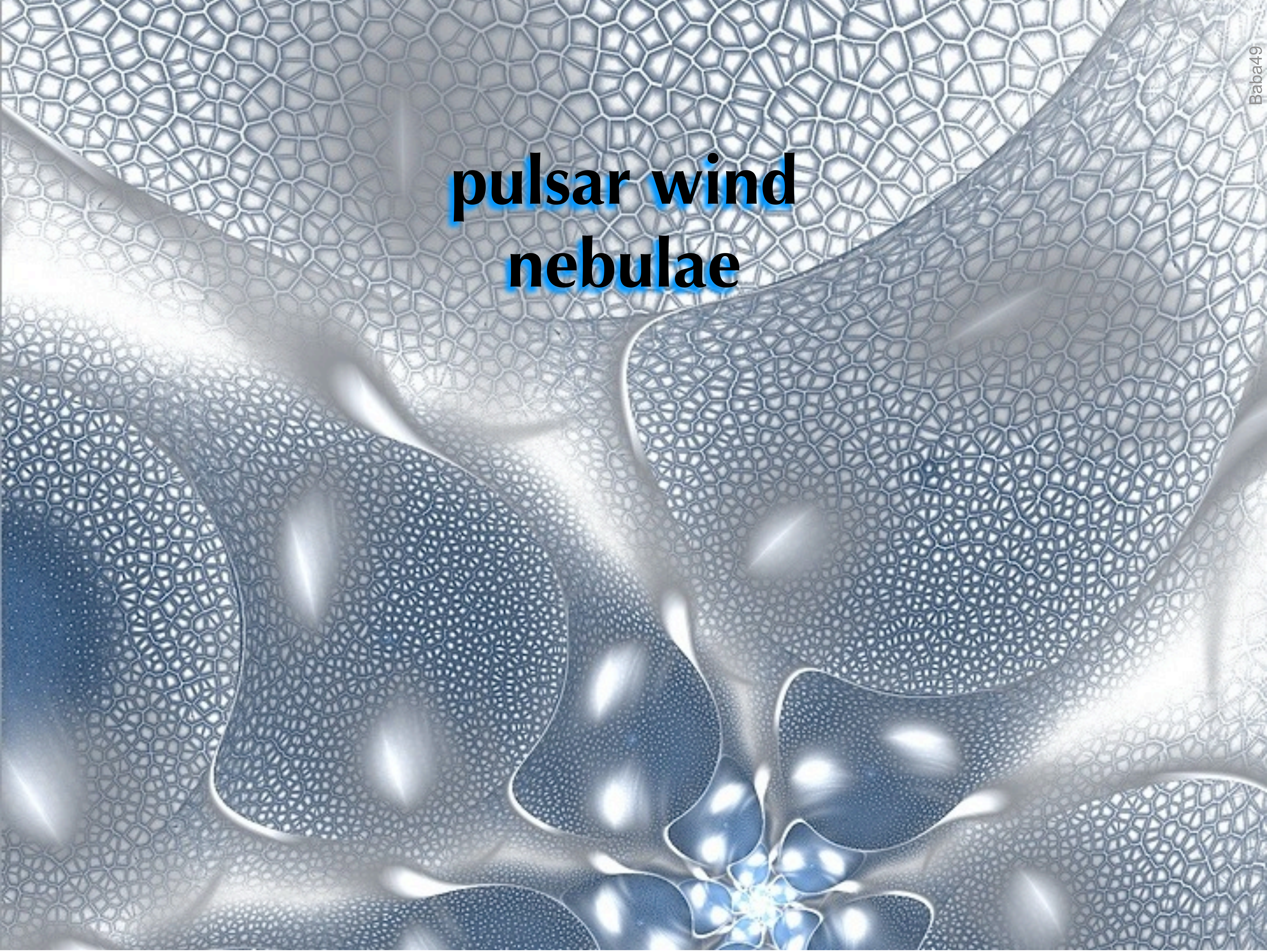



# Crab pulsed spectrum

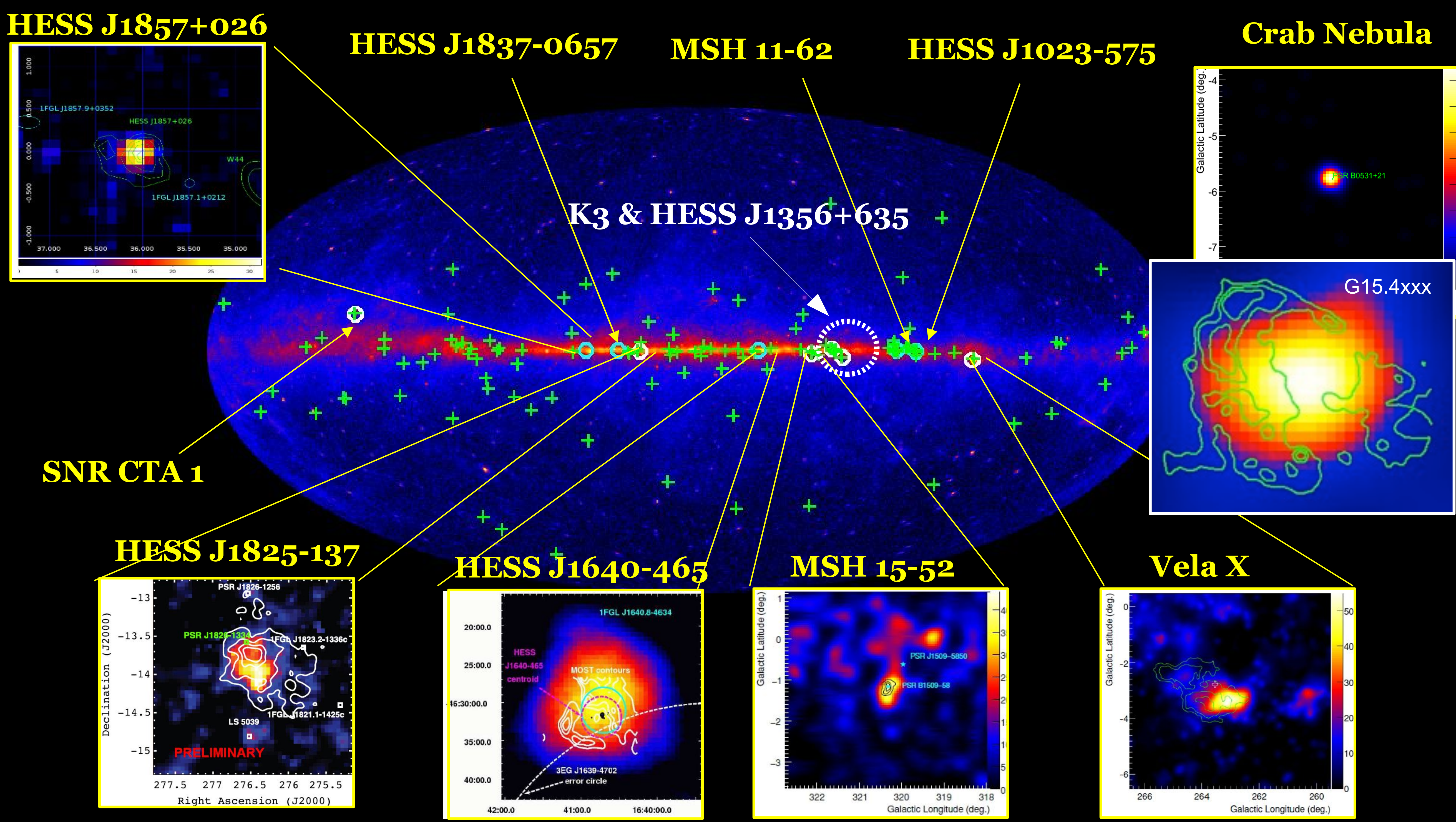
- γ rays at sub-TeV energies from inverse Compton scattering (SSC or on stellar radiation)
- ex: outer gap model from Hirotani



# pulsar wind nebulae



# pulsar wind nebulae




- extended PWNe dominate the Galactic TeV source population: confusion threat for CTA

# pulsar wind

- retarded potentials => elmgn. wave outside the light cylinder
- wind = toroidal (wound up) field frozen to a $e^{\pm}$- ion plasma
- $\sigma$ ratio = Poynting flux / particle energy flux (Rees & Gunn '74, Kennel & Coroniti '84)

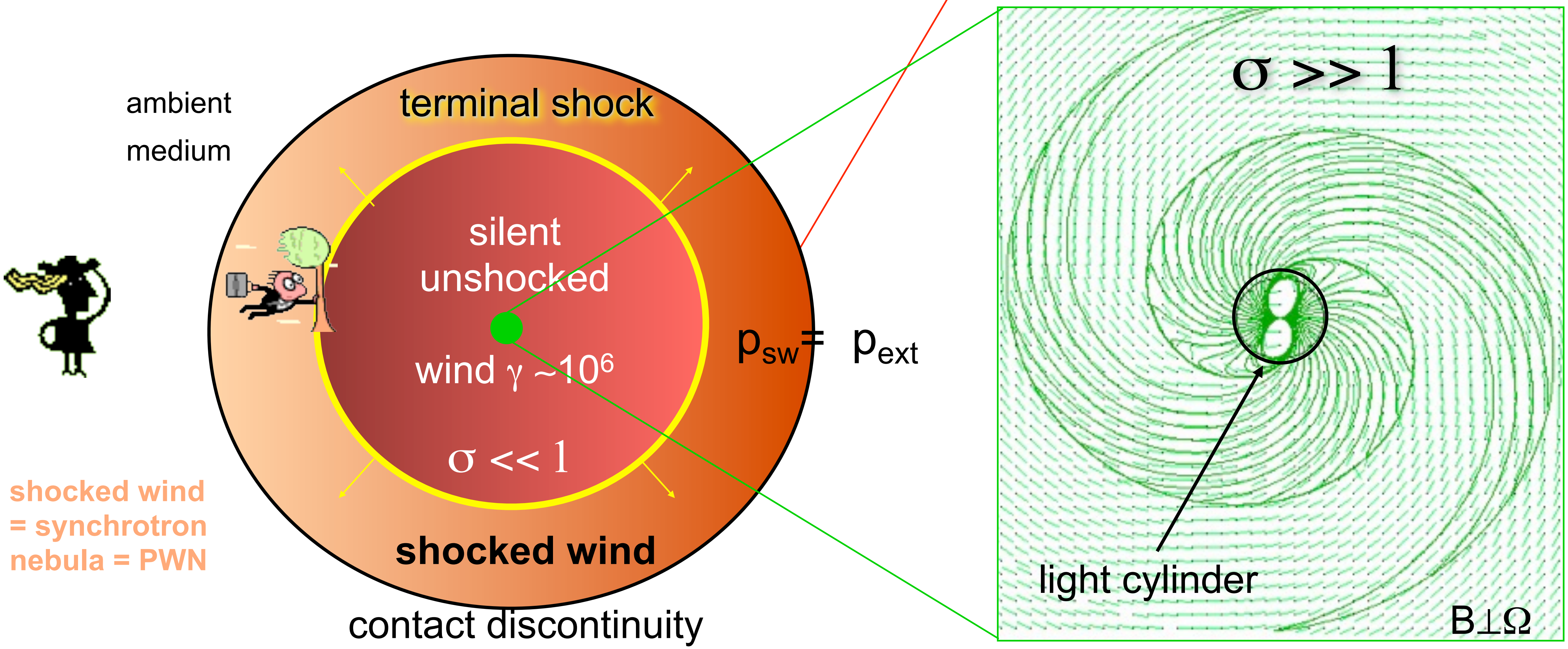
$$\sigma = \frac{B_{1w}^2 c/\mu_0}{n_{1w} v_{1w} (\gamma_{1w} m c^2)}$$

$$\dot{E}_{psr} = \dot{E}_w + \dot{E}_{EB} \Rightarrow \dot{E}_w = \frac{\dot{E}_{psr}}{1+\sigma} \qquad \dot{E}_{EB} = \frac{\dot{E}_{psr}}{1+1/\sigma}$$

$\sigma >> 1$ EM wave takes the pulsar energy away (near light cylinder)

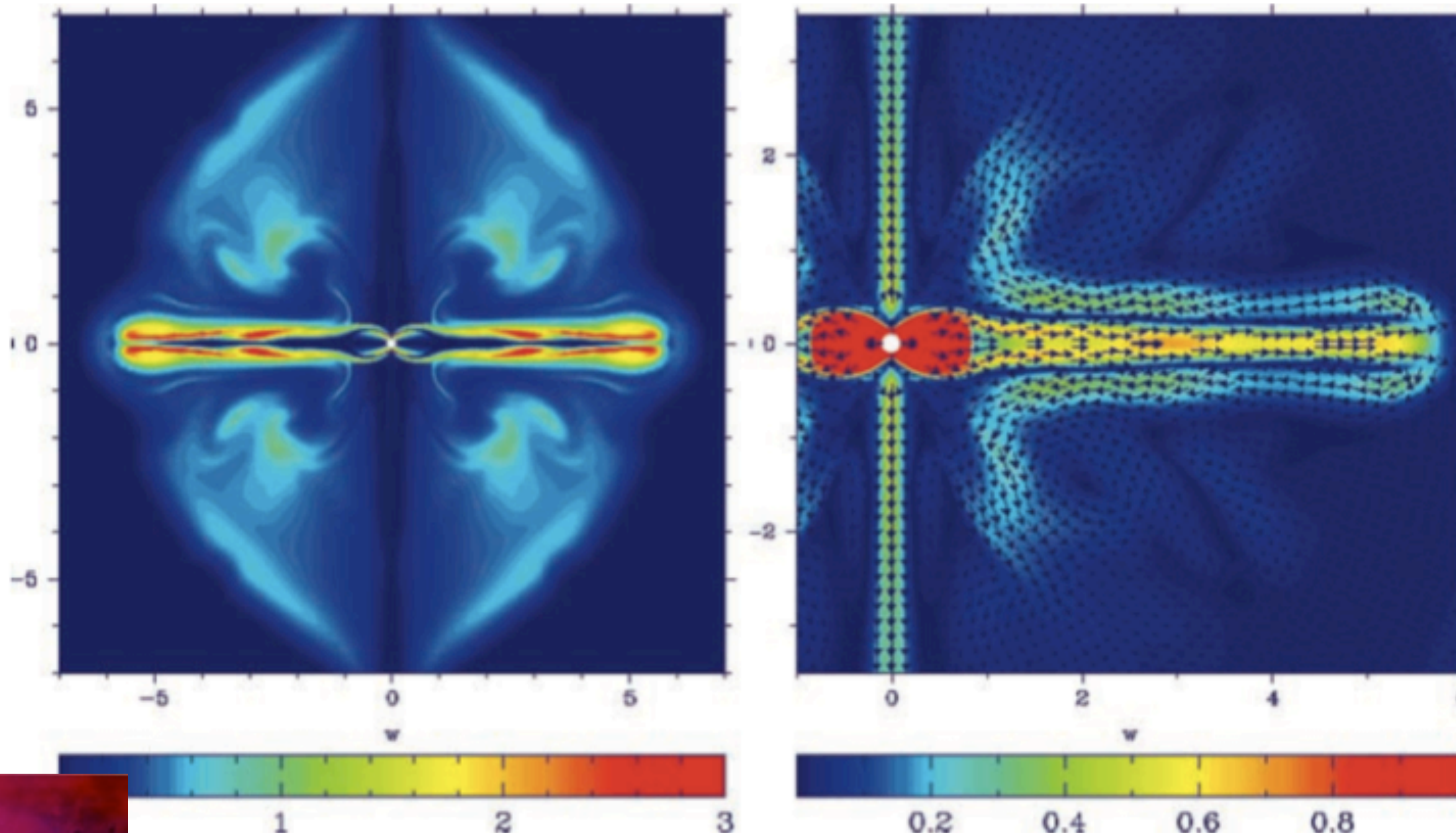
$\sigma << 1$ pulsar energy transferred to wind particles (near terminal shock)

shocked wind => pitch angle for $e^{\pm}$ => synchrotron + IC nebula

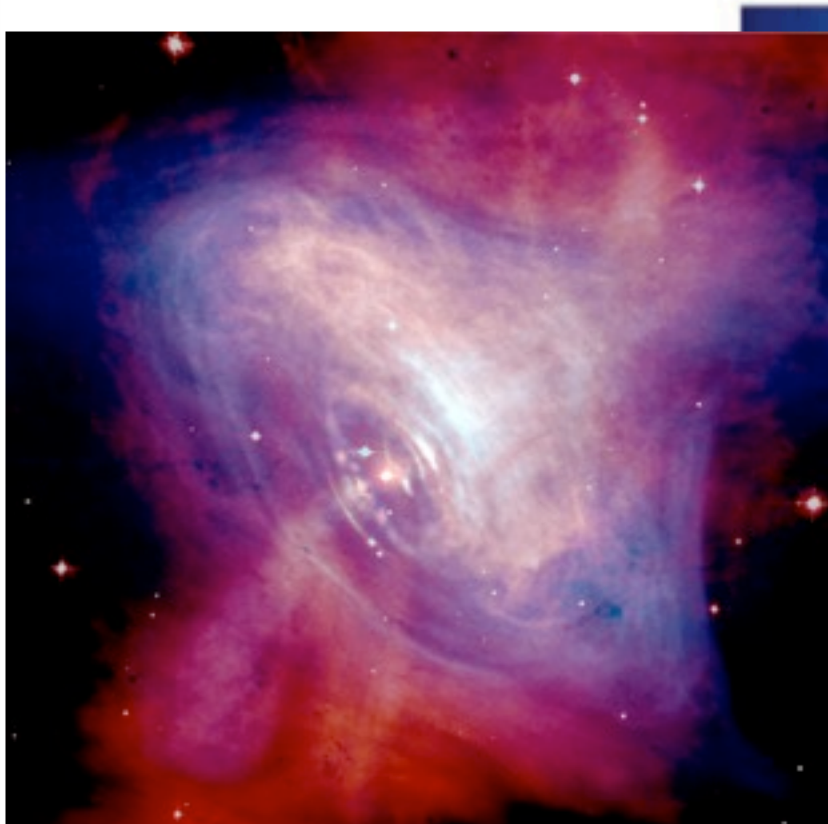


# torus & jet

- MHD simulations (Komissarov 2004+ Bucchiantini 2005+…)
- Doppler de/boosting & red/blue shift of the observed flux in the inner torus & jet




2. The $\xi = 0.3$ model at $t = 190$. Left panel: Ratio of magnetic to gas pressures, $p_m/p_g$. Right panel: Magnitude and direction of velocity.



facteur Doppler du jet : $\mathcal{D} = \Gamma_{jet}(1 + \beta_{jet} \cos \varphi_{jet})$

décalage spectral : $h\nu_{obs} = \mathcal{D}.h\nu_{jet}$

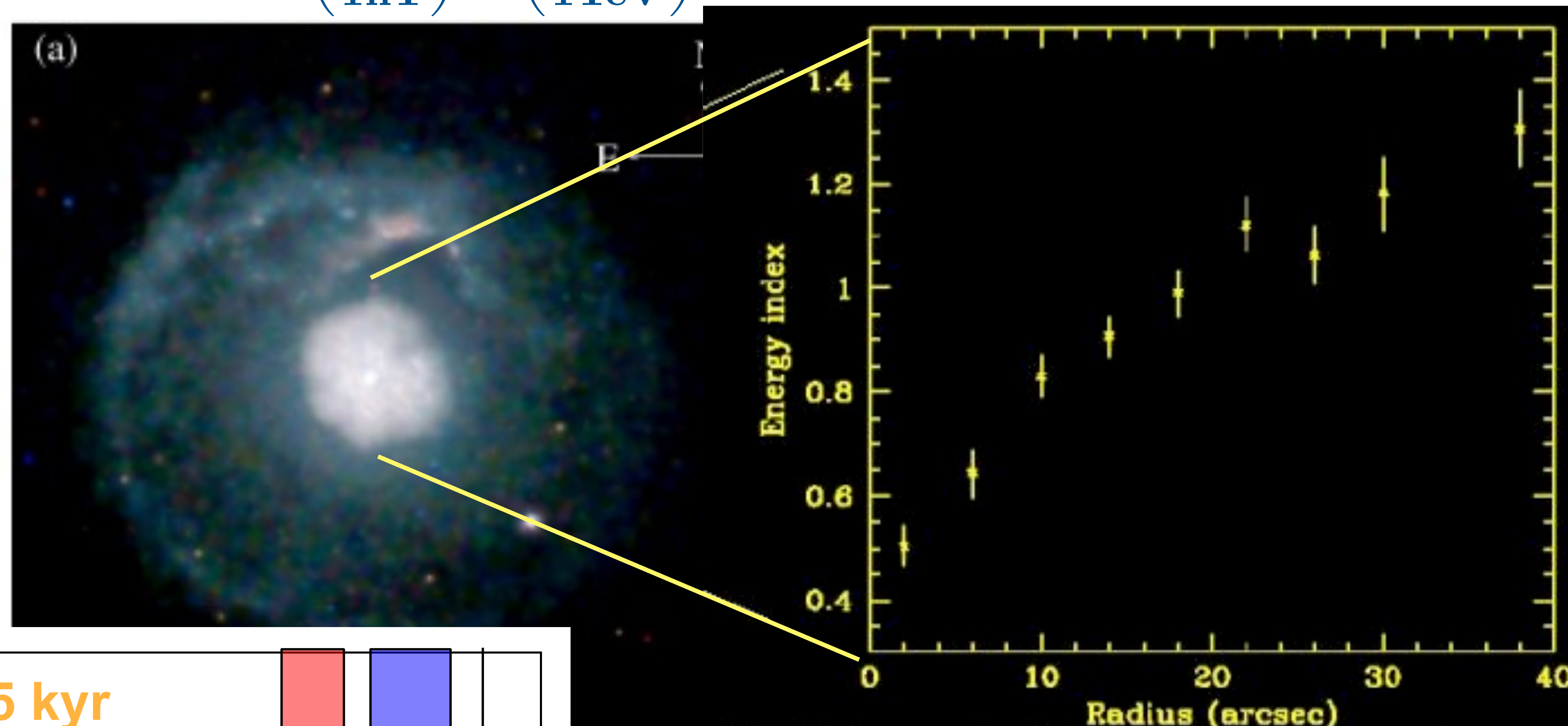
"surintensité" : $I_{obs} = \mathcal{D}^{\alpha_s + 1} I_{jet}$

# pair burn-off

- synchrotron losses dominate
  => $D_{max}$ ↑ with Ee ↓

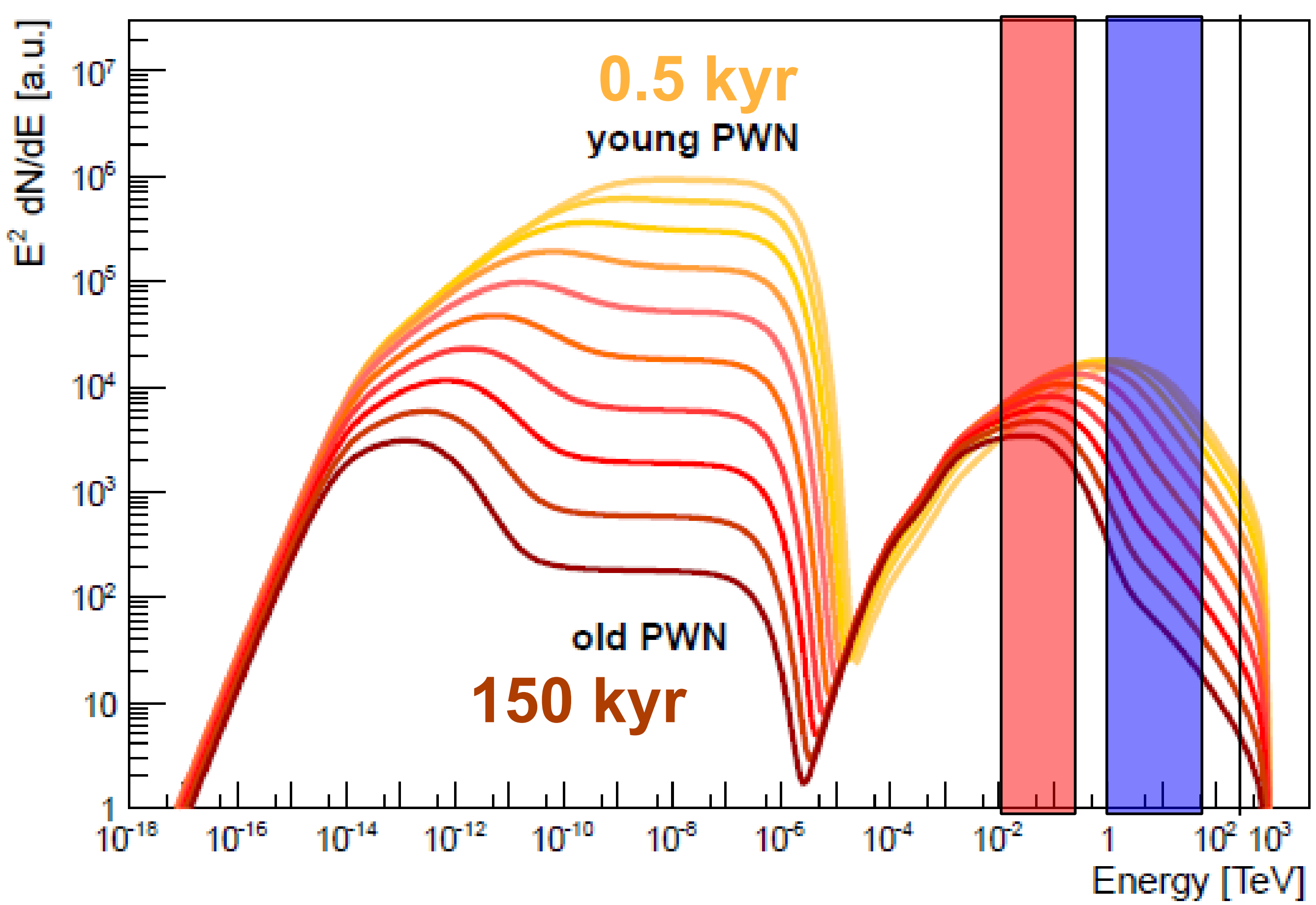
$$t_{syn} = 55.8\ \mathrm{kyr} \left(\frac{\bar{B}}{1\mathrm{nT}}\right)^{-2} \left(\frac{E}{1\mathrm{TeV}}\right)^{-1} \propto E^{-1}$$

Slane et al. 2000




- syn + IC losses and $\dot{E}(t)$

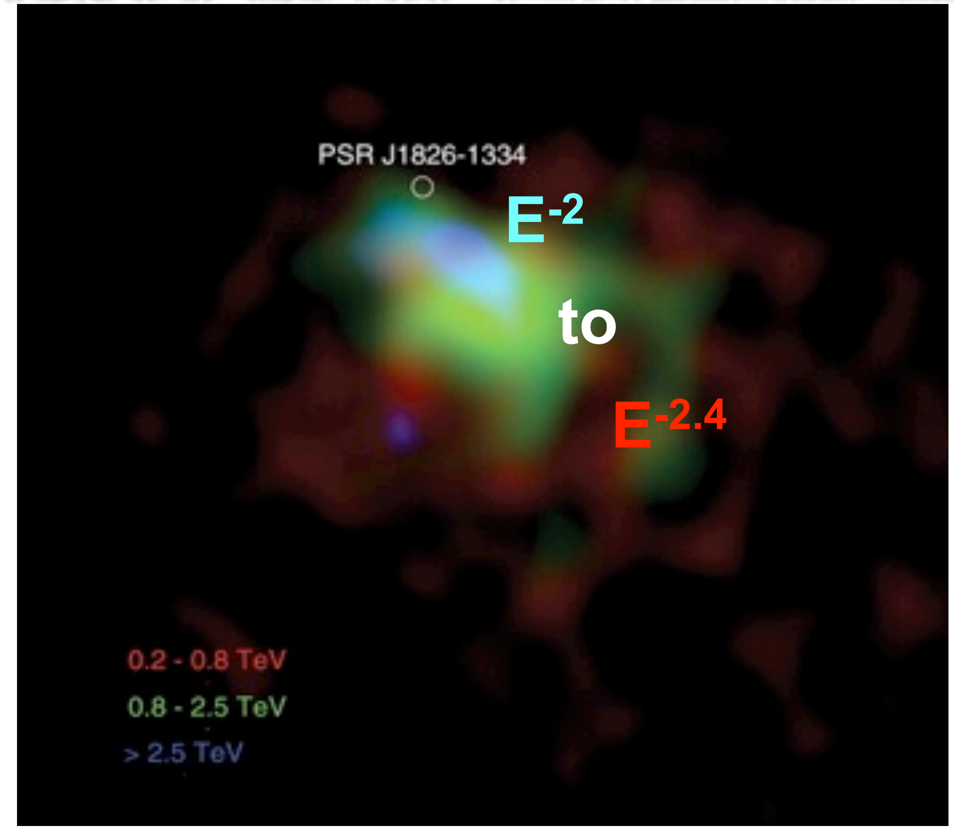
Mayer et al. 2012



# extended IC TeV tails

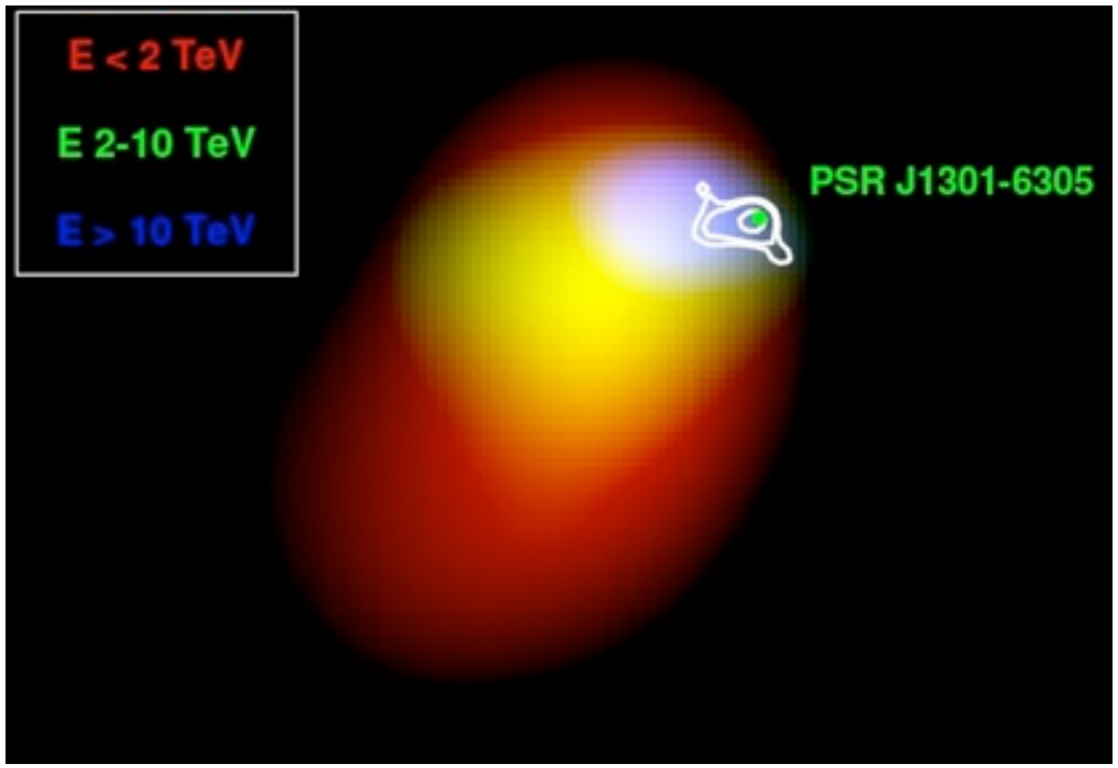
- ex: HESS J1825-137
  - TeV tail $L_{TeV}$ ~ 50 pc: $e^{\pm}$(TeV) + CMB-IR → $\gamma$(≥ 200 GeV)
  - X-ray tail $L_X$ ~ 5 pc: $e^{\pm}$(200 TeV) + $B_{equip}$(1 nT) → X

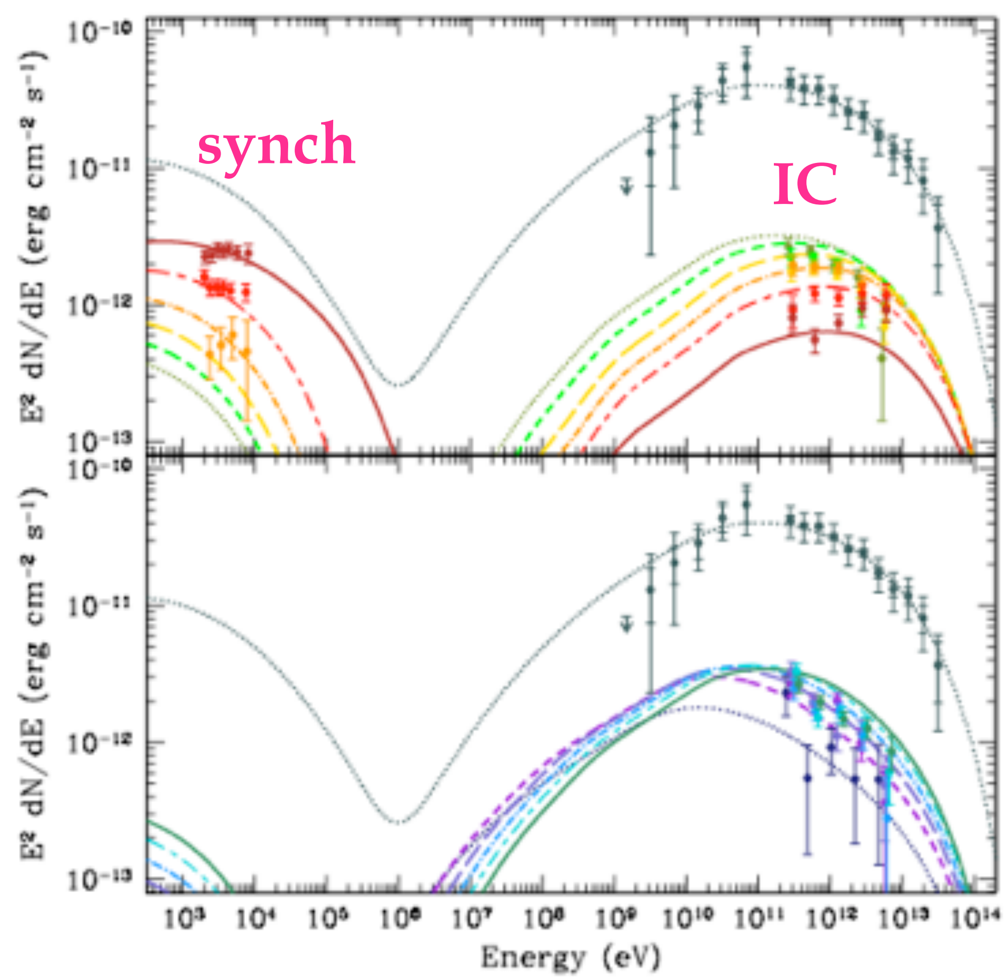
  multi-layer model => rapid diffusion of pairs to 80 p




Aharonian+ 2006

- autre ex:



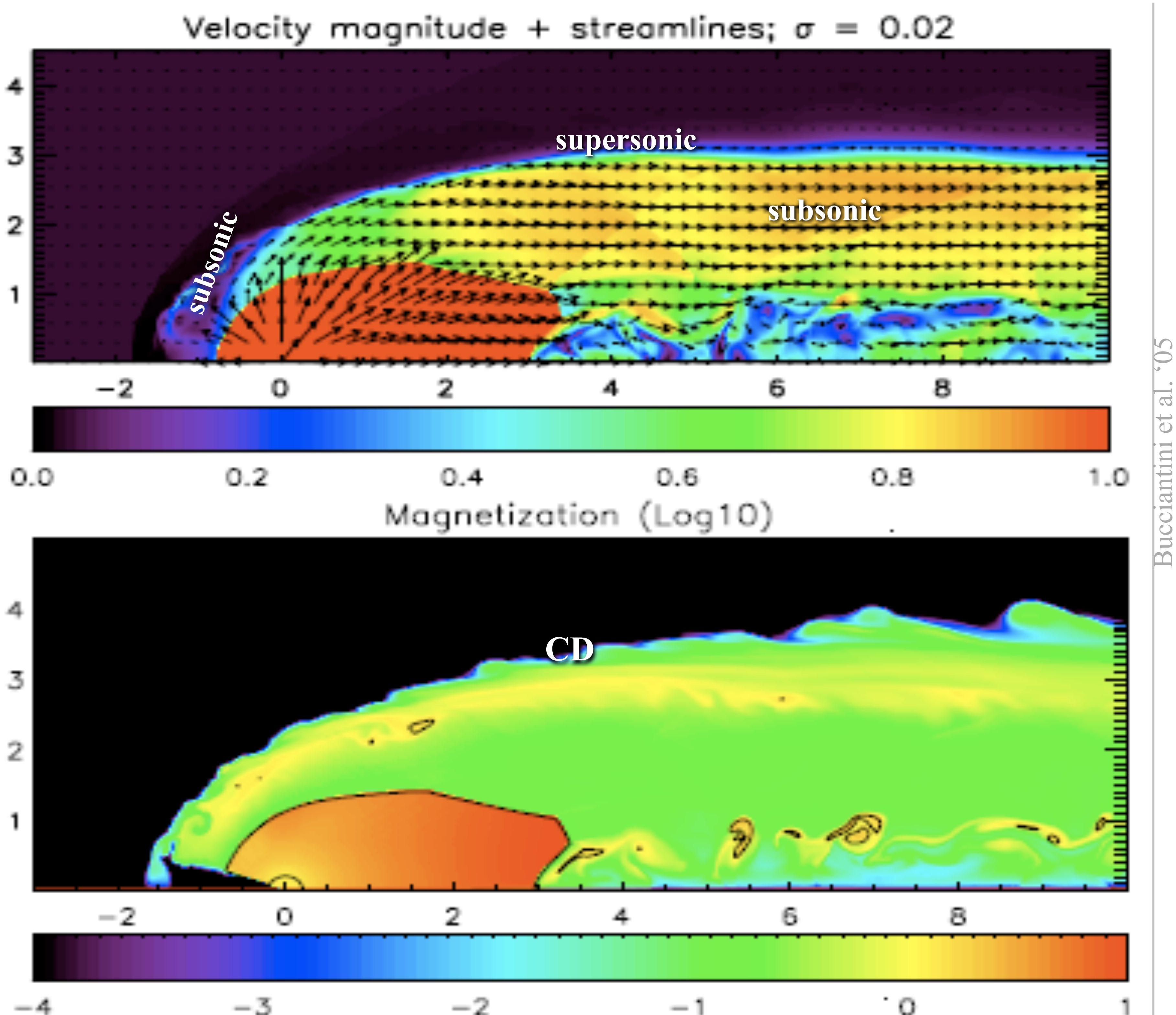




Van Etten & Romani 2011

- current models too crude wrt the B structure in the tail, thus wrt the pair losses in the tail
  => coupling MHD with radiation yield necessary
  (O. de Jagger, Bucchiantini)

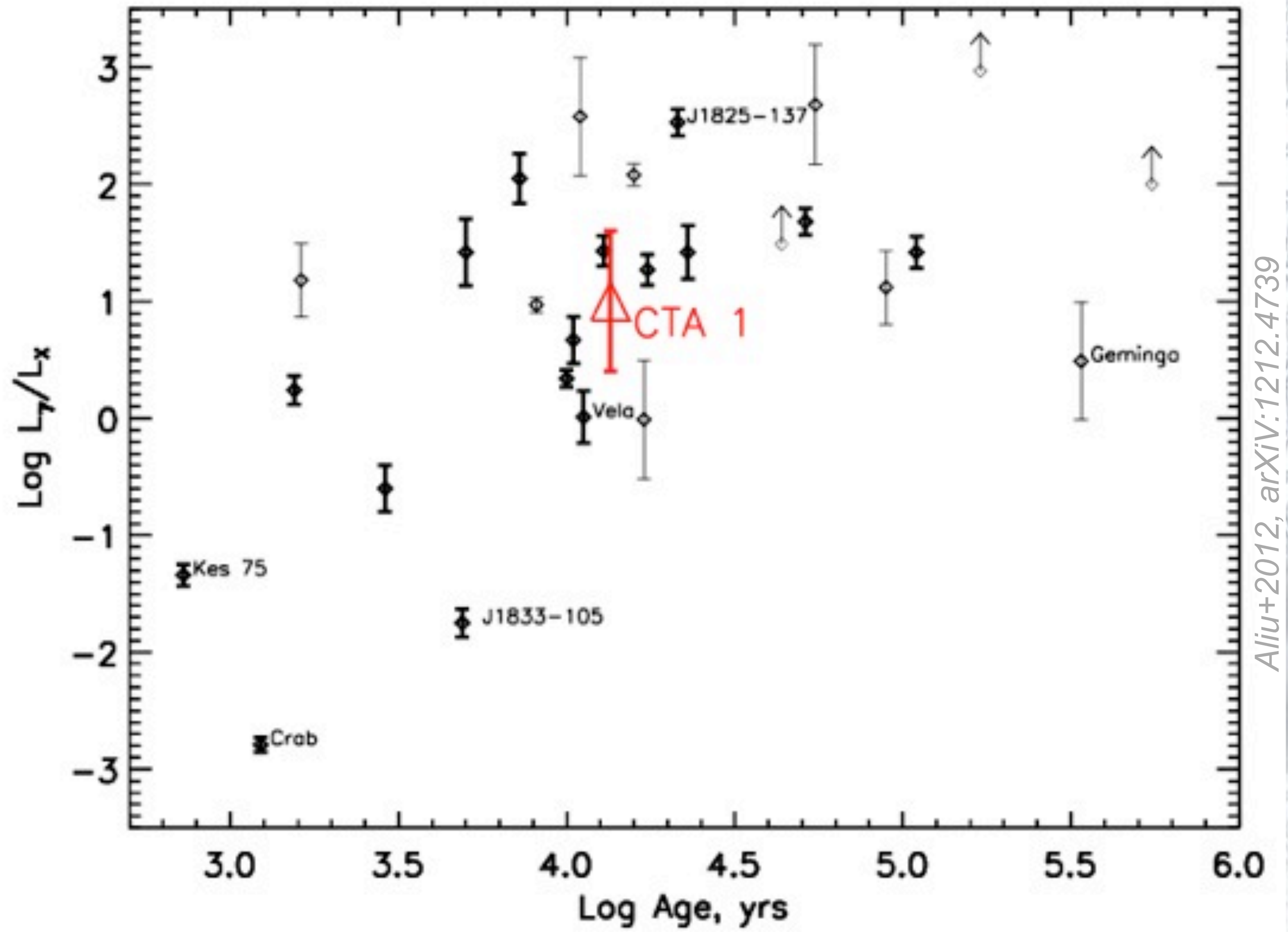
# bow shock PWNe

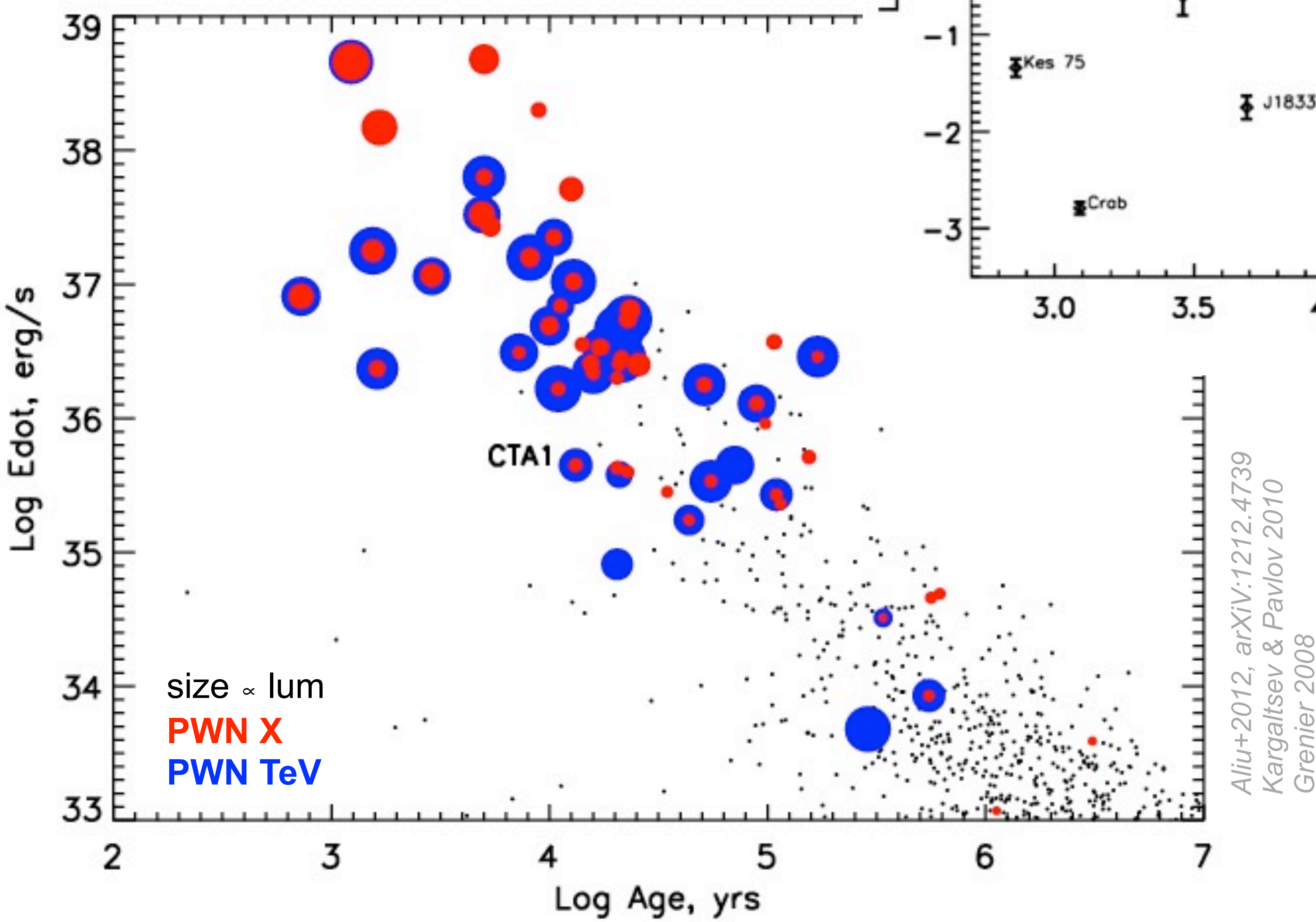
- advected flow ⇒ large variations in velocity, density, B intensity => strong impact on X-ray + γ yield
- ⇒ detailed MHD modelling to understand population trends



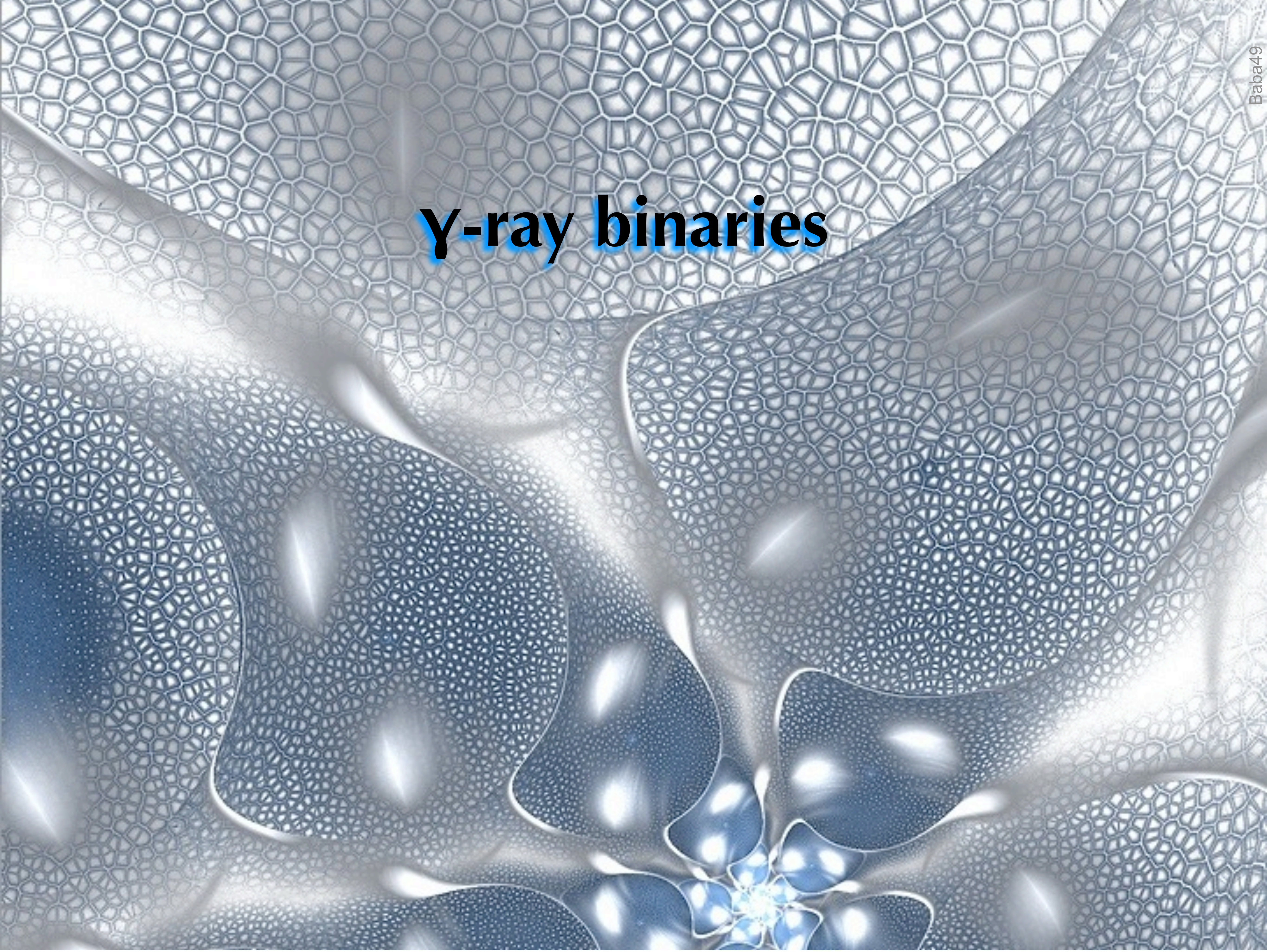
# TeV population trends

- the long-lived TeV tail trails farther & farther behind the running pulsar
- young & energetic pulsars favoured

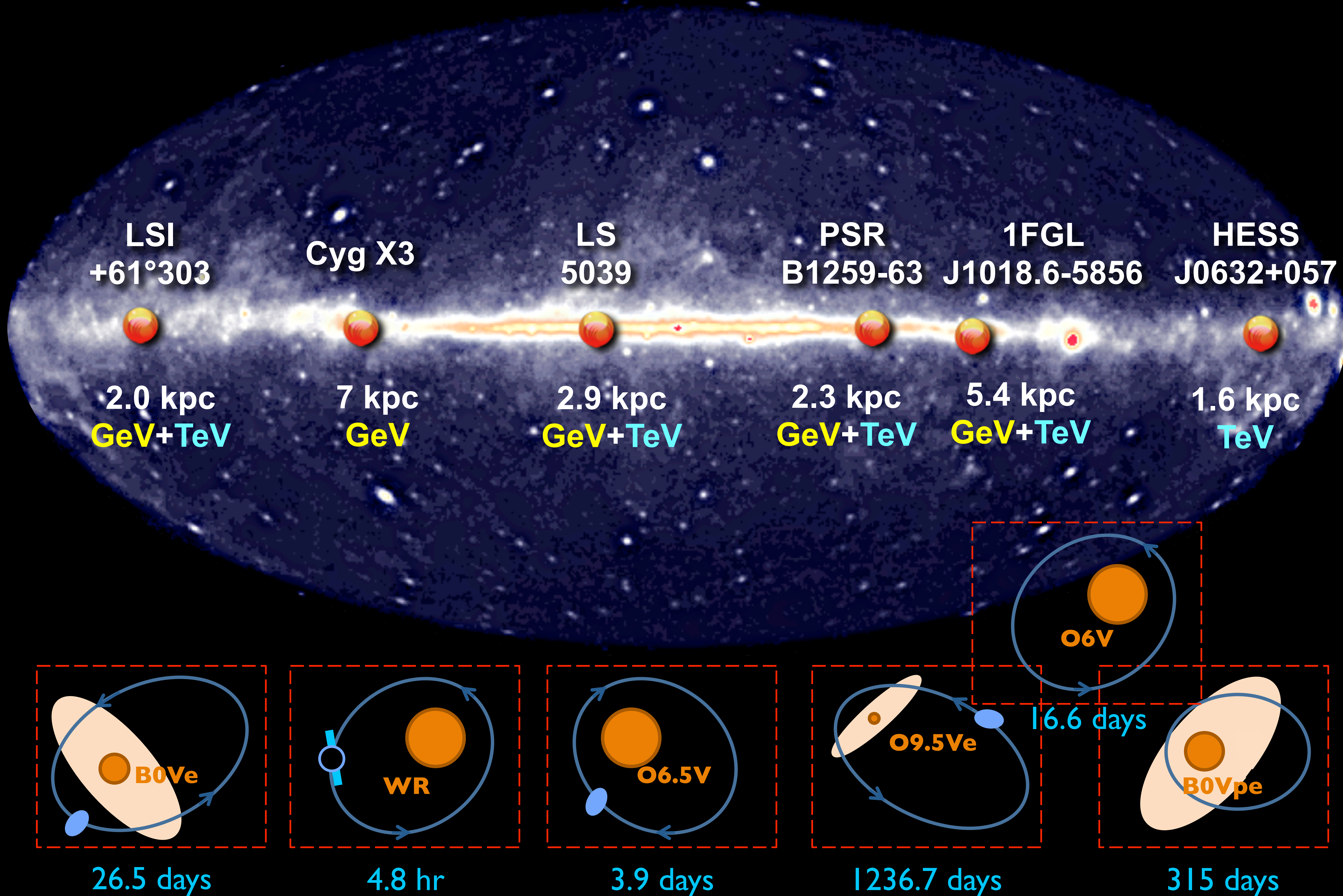


# γ-ray binaries



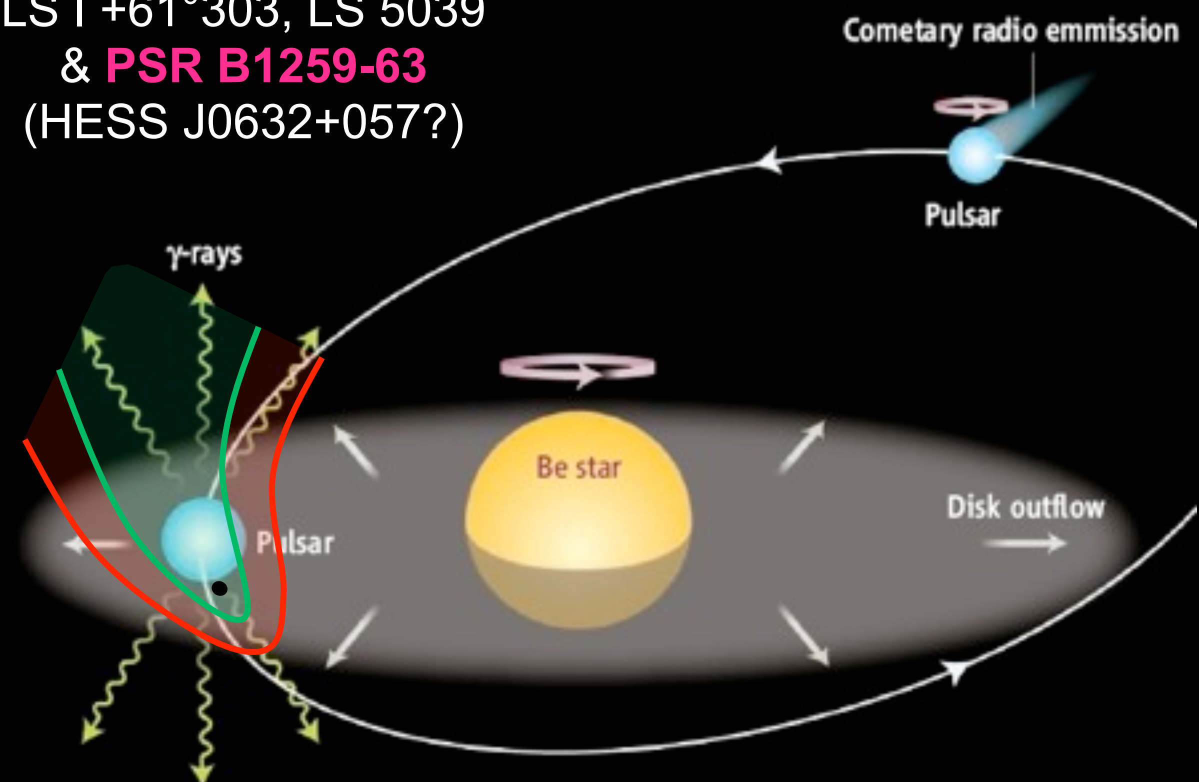
# γ-ray stellar binaries



# rotation powered

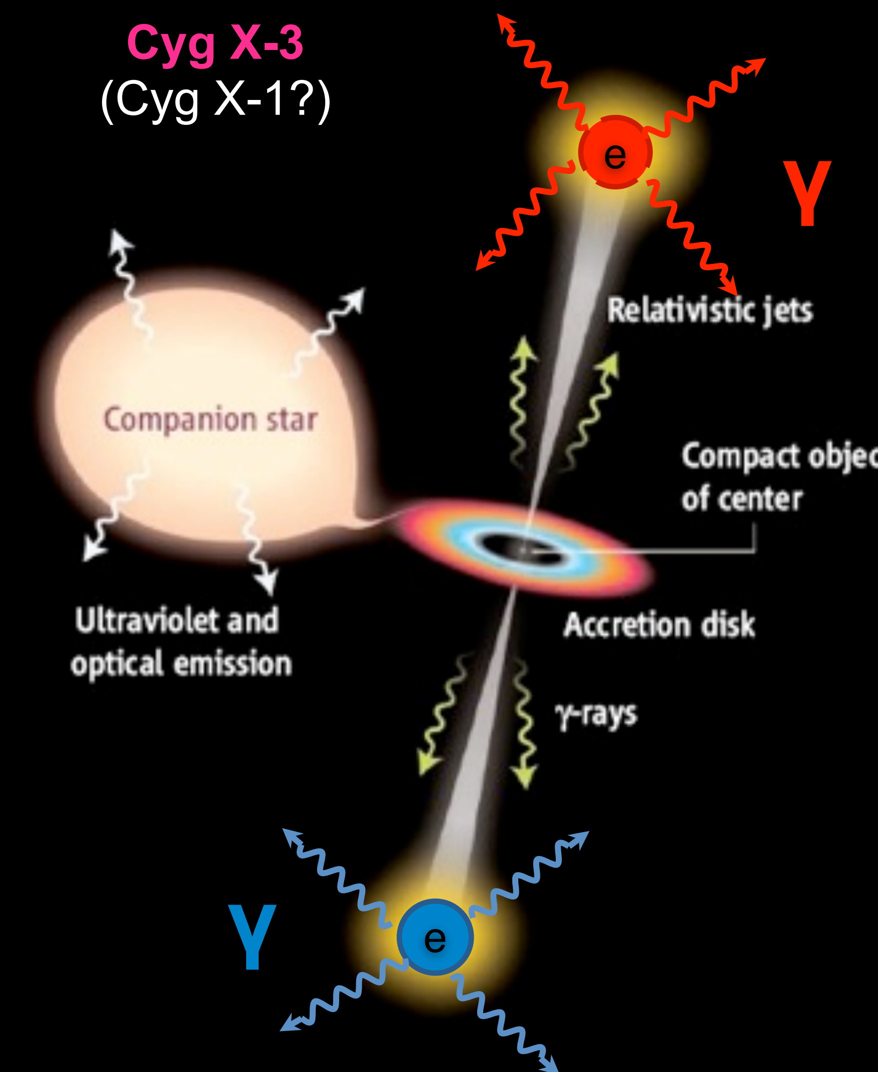
# accretion powered

LS I +61°303, LS 5039
& PSR B1259-63
(HESS J0632+057?)




anisotropic IC + anisotropic e$^{\pm}$ cascades
ok for TeV modulation in LS5039
not ok for the others
B1259 flare at odd orbital phase
Doppler boosting
ok for TeV+X modulation of LSI
origin of pulsar-like GeV emission ??
use of PWN compression along the orbit to probe the wind physics

Cyg X-3
(Cyg X-1?)




GeV+radio activity
Doppler boosting of IC
in jet and counter-jet
ok for GeV+X modulation if μ-blazar
use of the γ rays to probe the launch of the jet from the corona

see Dubus A&AR 2013 arXiV:1307.7083 and Dubus Ecole Cargèse 2013