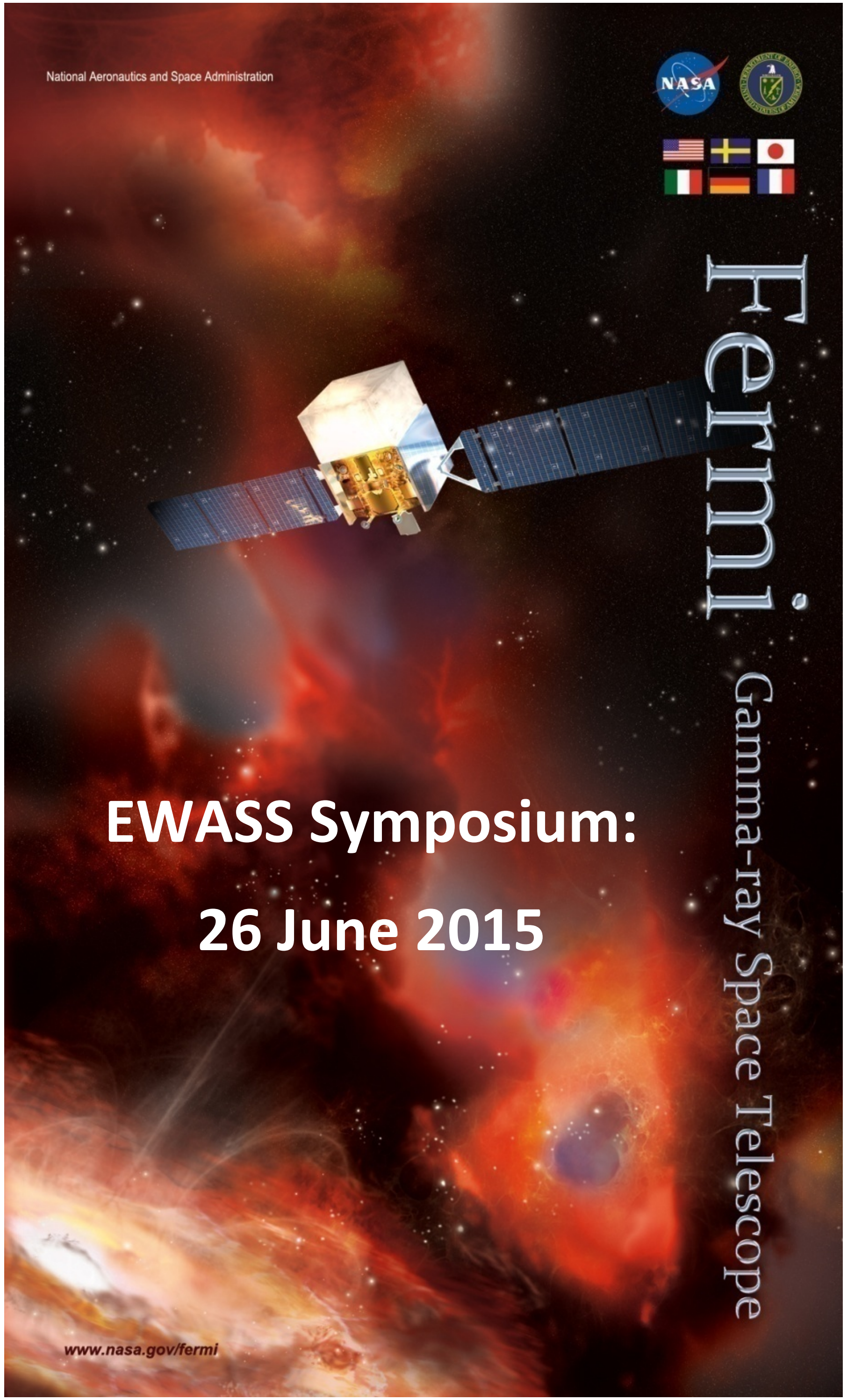


EWASS Symposium:

26 June 2015

Spectral evolution of 25 millisecond γ-ray pulsars with Fermi-LAT

2 papers in preparation

Alice Harding
N. Renault-Tinacci

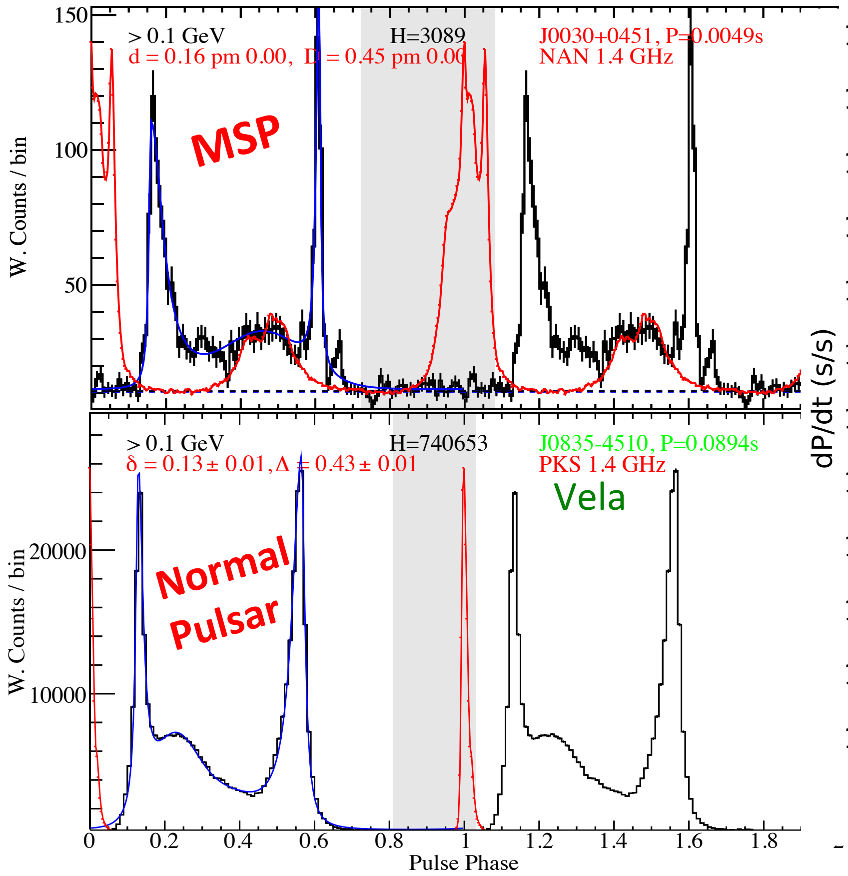
On behalf of the Fermi-LAT Collaboration

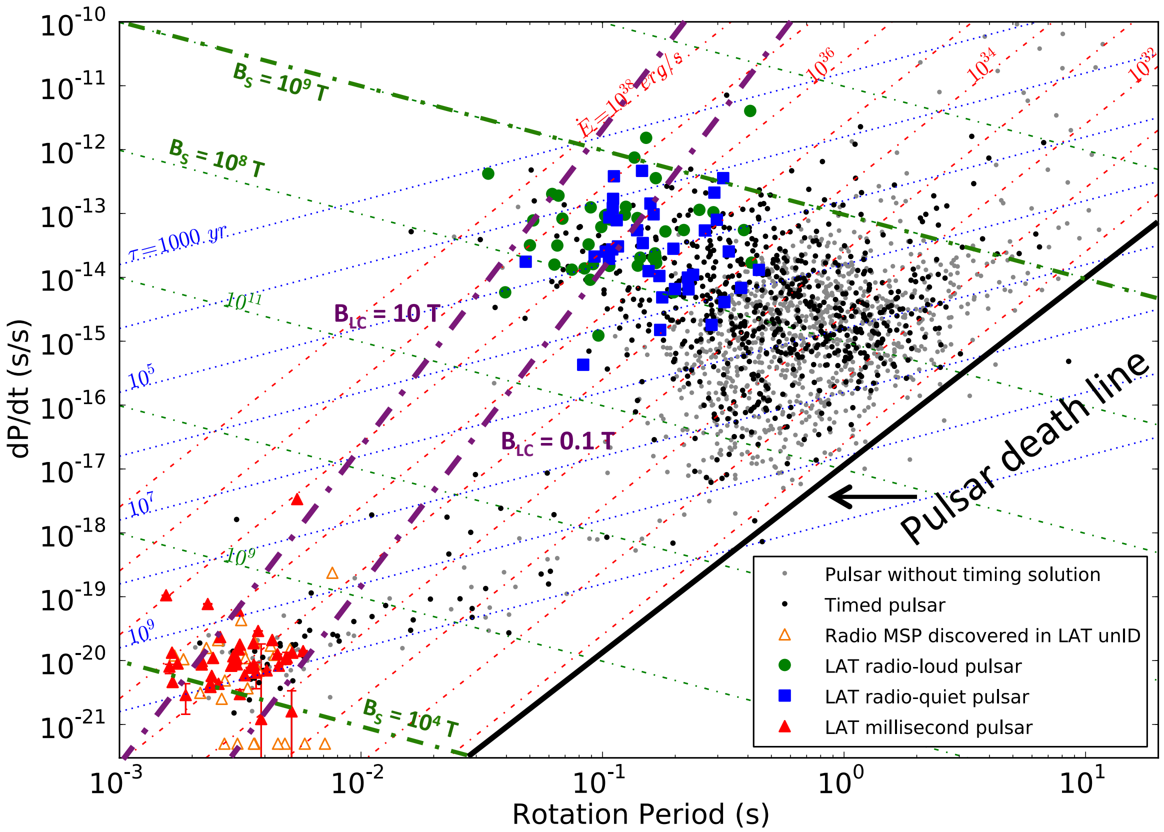
In collaboration with :
I. Grenier, L. Guillemot, C. Venter.

CEA - Saclay

Why MSPs ?

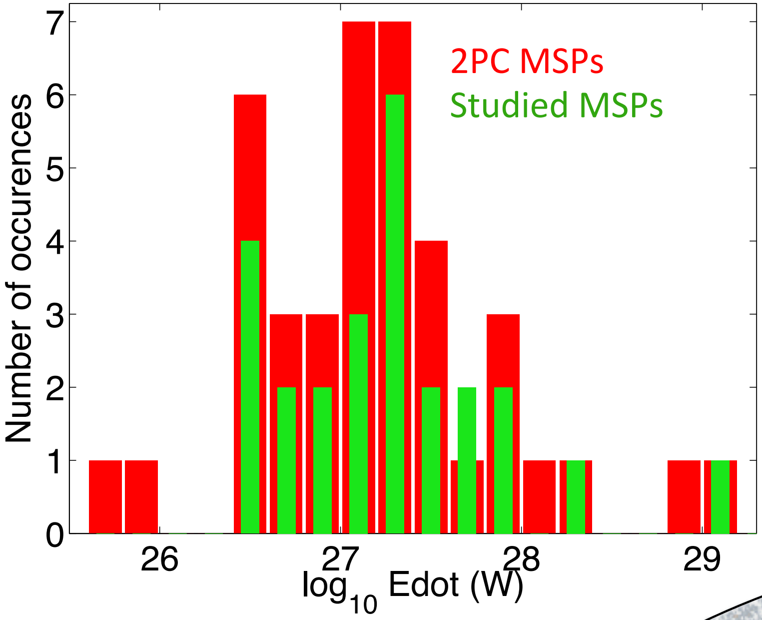
Second Fermi-LAT Pulsar Catalog, Abdo et al. 2013





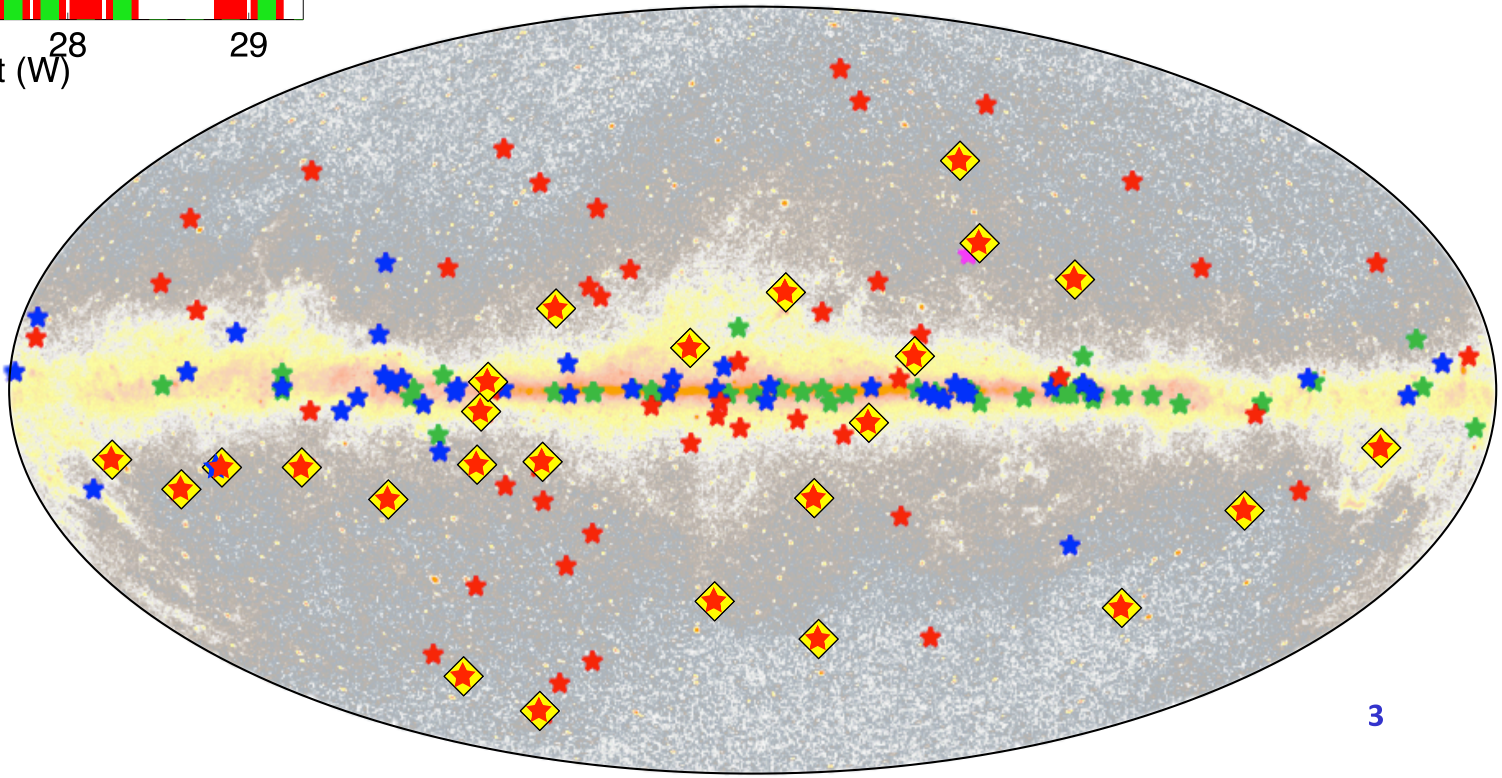
- **Growing γ-ray pulsar class**
  - (≈50% of detected pulsars)
- **Sharp MSP γ-ray profiles**
  - ➔ thin gaps ➔ high pair densities
  - similar to young pulsars
- **More compact magnetospheres :**
  - same B_{LC} ➔ similar acceleration & radiation processes
- **MSPs larger stability**
- **But MSPs are fainter pulsars**
  ➔ spectral analyses more difficult

Analysis sample



- **25 millisecond pulsars**
  - **Bright**
  - **Bright enough wrt background**
- **Good sampling of the MSP population**
  - **Spatial (l, b)**
  - **Timing (P, Pdot)**
  - **Energetics ($\dot{E}$, B_{LC}, …)**
  - **Obliquities (α, ζ)**

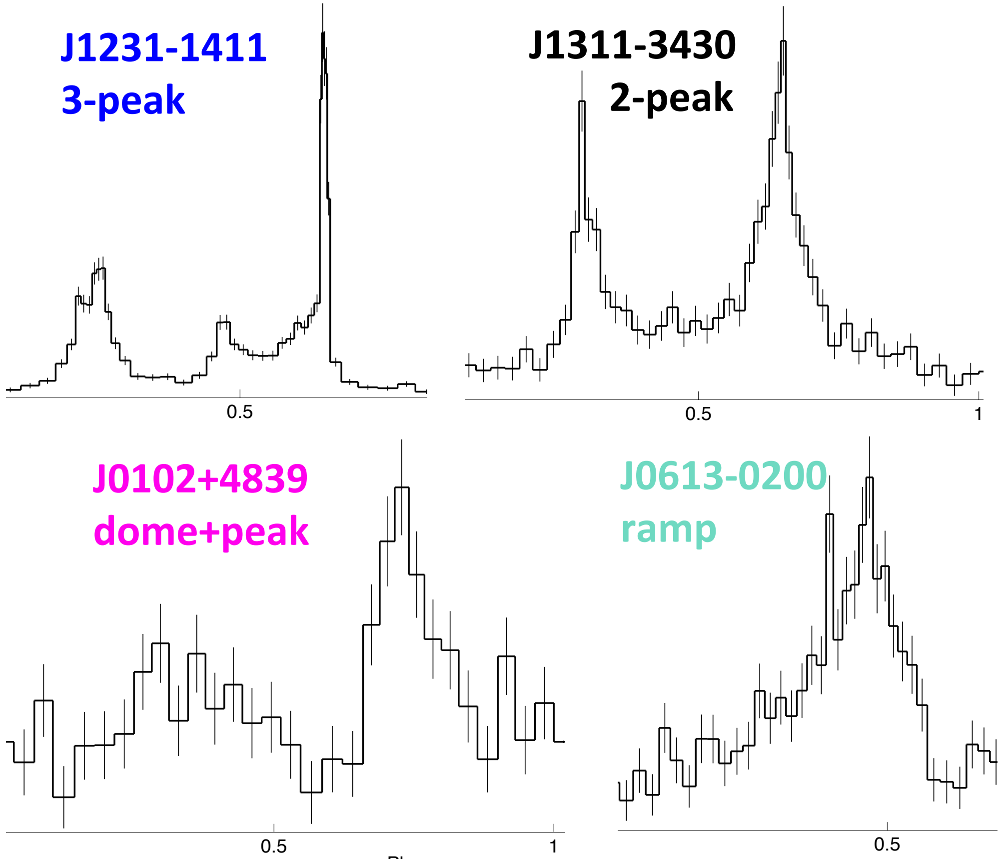
Millisecond pulsars •
Young pulsars •
Studied MSPs ◇



Second Fermi-LAT Pulsar Catalog, Abdo et al. 2013

Dataset & Analysis

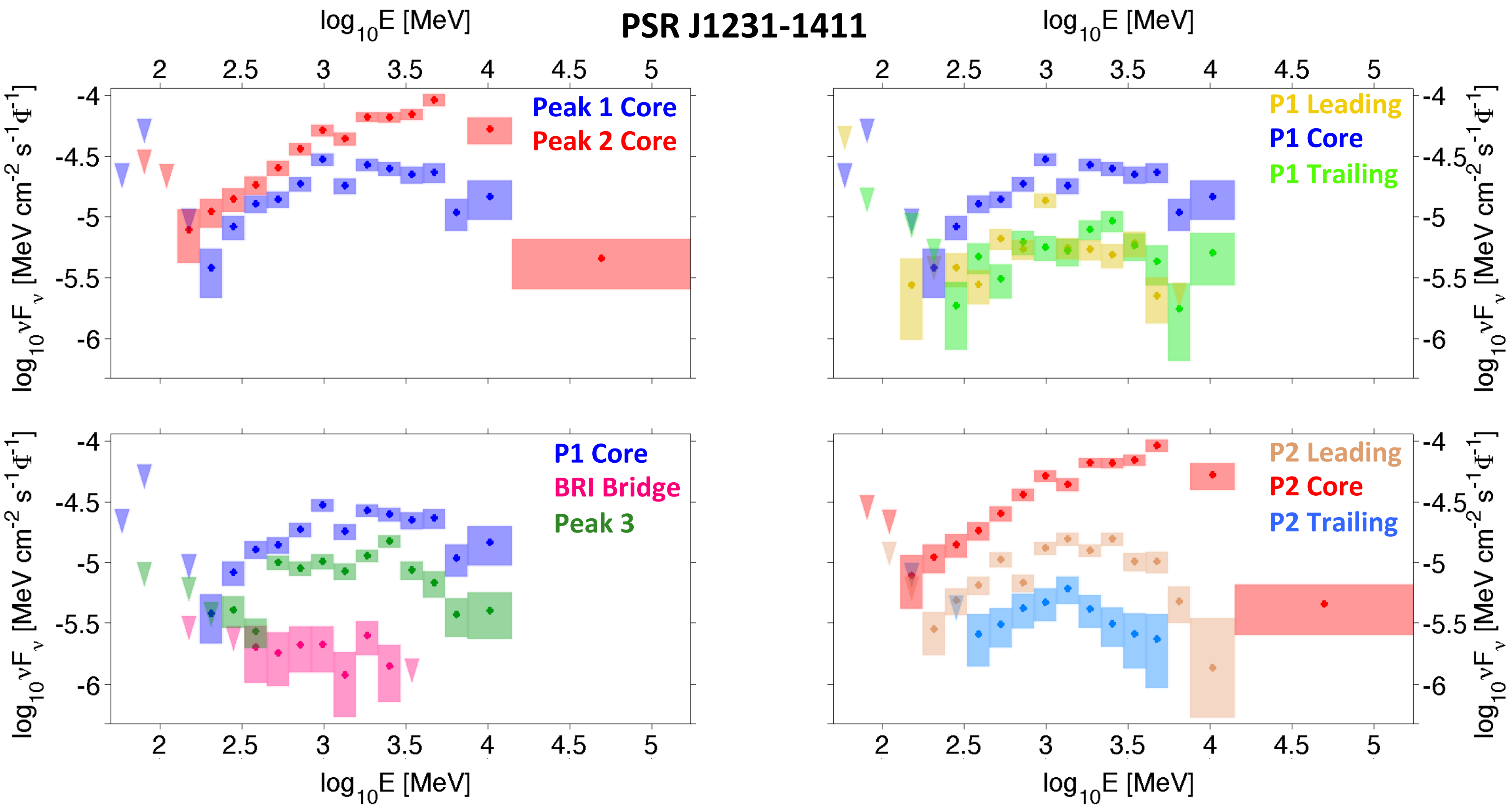
- **Data selection :**
  - Pass 7 Reprocessed Fermi-LAT data
  - 60 months (August 2008 – August 2013)
  - 50 MeV < E_{phot} < 172 GeV
- **Fixed-count binned lightcurves :**
  - E_{phot}> 200 MeV
  - 4 MSPs classes based on morphology
  - Phase interval definition
- **Spectral analysis :**
  - Total emission and from phase intervals
  - Pulsed flux extraction in energy bins (no need for an input spectral shape)
- **Subsequent spectral characterisation**
  - Power law with exponential cut-off
  - SED apex energy
  - γ-ray luminosity above 50 MeV, L_γ
  - …



$$\frac{dN}{dE} = N\left(\frac{E}{E_0}\right)^{-\Gamma} \exp\left(-\frac{E}{E_{cut}}\right)$$

Phase-resolved spectra

PSR J1231-1411



Phase-resolved spectra

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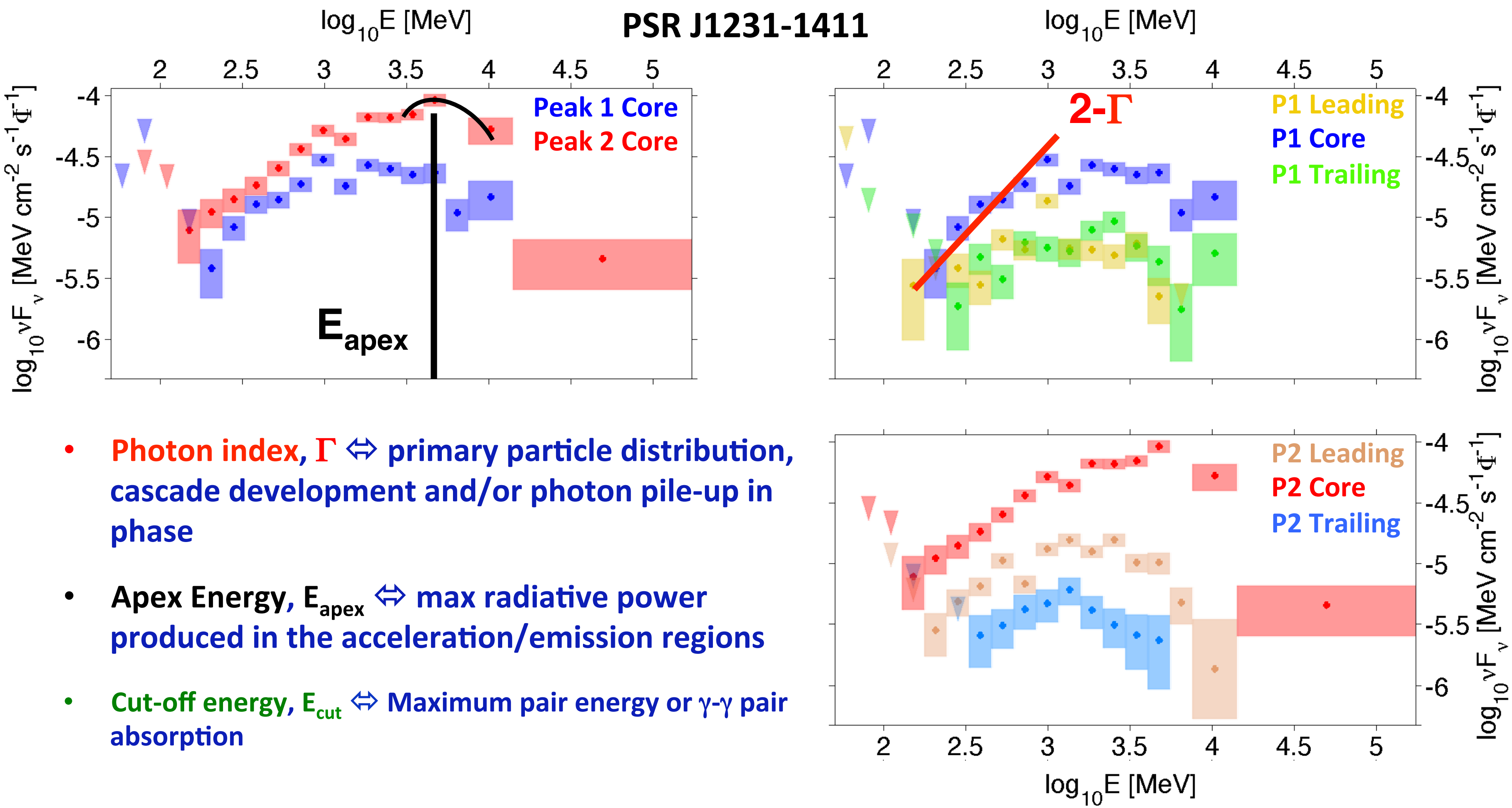
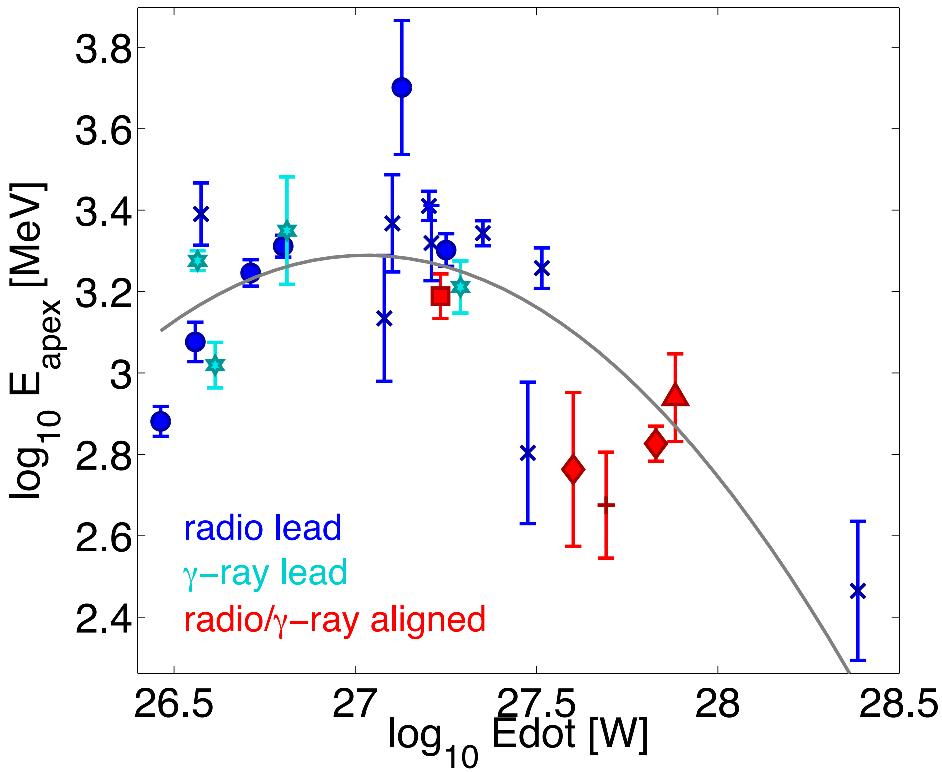


- Photon index, Γ ⇔ primary particle distribution, cascade development and/or photon pile-up in phase
- Apex Energy, E_{apex} ⇔ max radiative power produced in the acceleration/emission regions
- Cut-off energy, E_{cut} ⇔ Maximum pair energy or γ-γ pair absorption

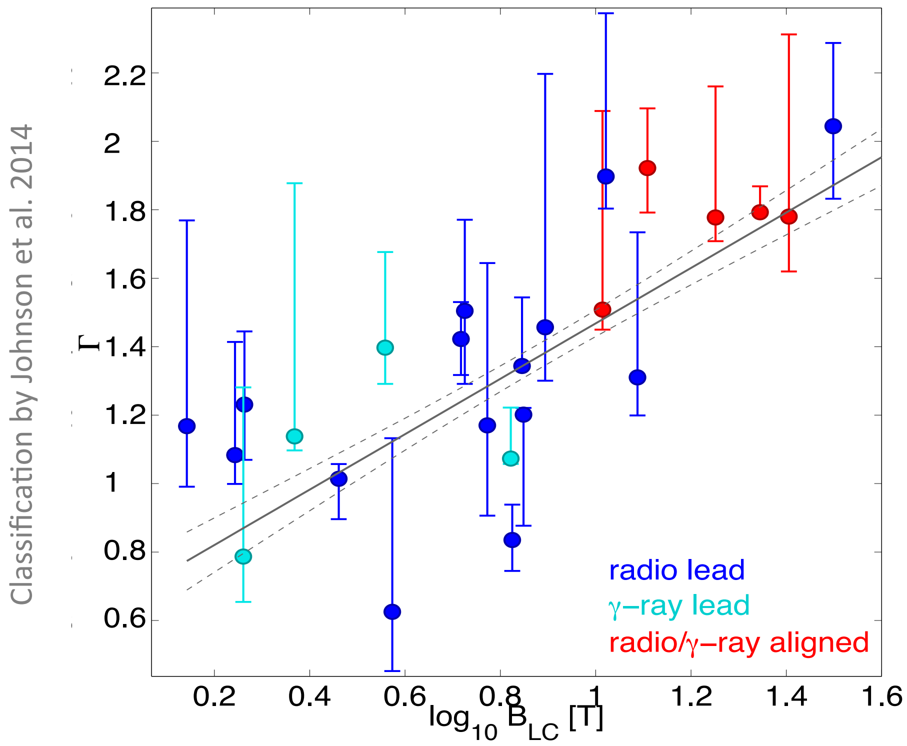
MSP spectral sequence

- **Shift in E_{apex} with $\dot{E}$ (and B_{LC})**
- **Curvature testing (« pairwise slope statistics », Abrevaya et Jiang 2003) ➔ P_{curv} = 99,97 %**



- **Toy model of curvature radiation spectra :**
  - **From primaries near the light cylinder**
  - **$\rho_c = R_{LC}$ (Hirotani 2011)**

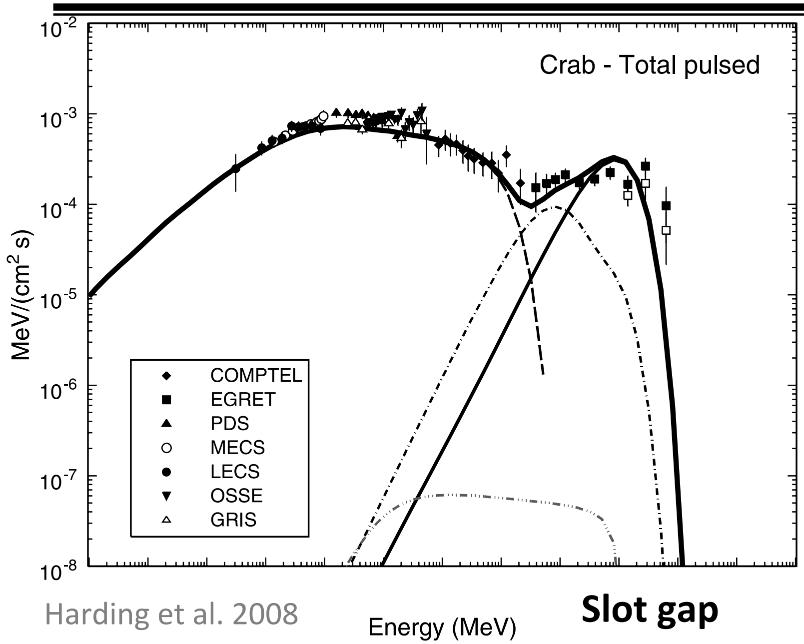
- **Softening with B_{LC} (and $\dot{E}$)**
- **Γ constant with B_{LC} rejected at >11σ**



  - **Test with different Γ_{max} distributions**

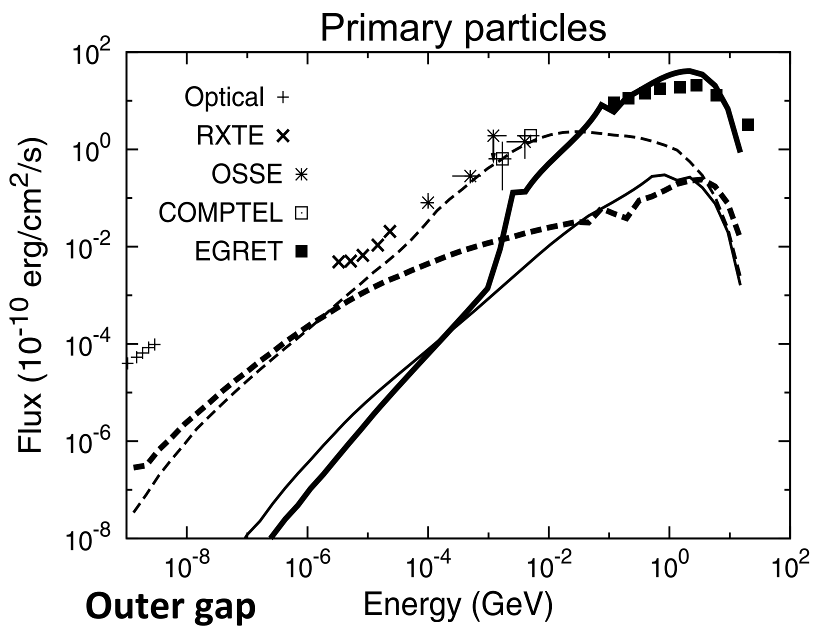
- **Softer component required to reproduce the evolution in the sample**

MSP spectral sequence

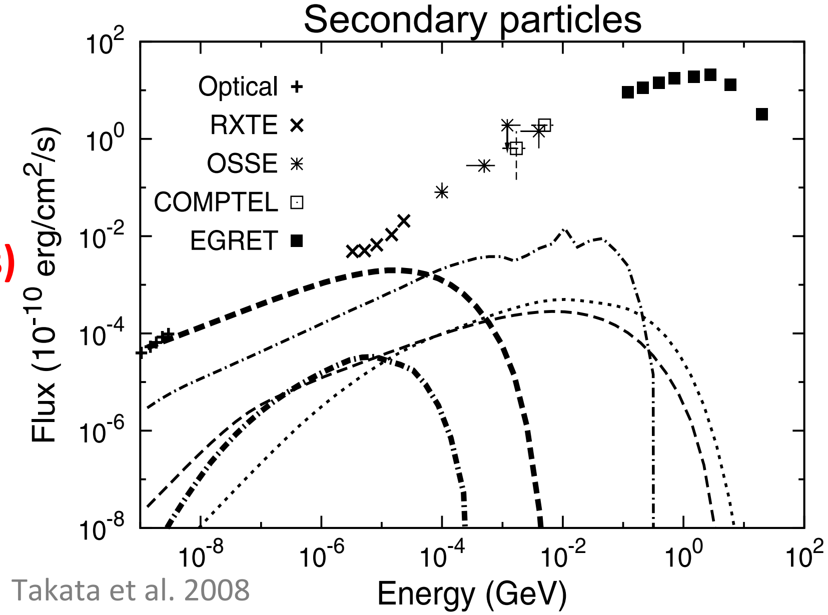


Harding et al. 2008

Slot gap



Outer gap



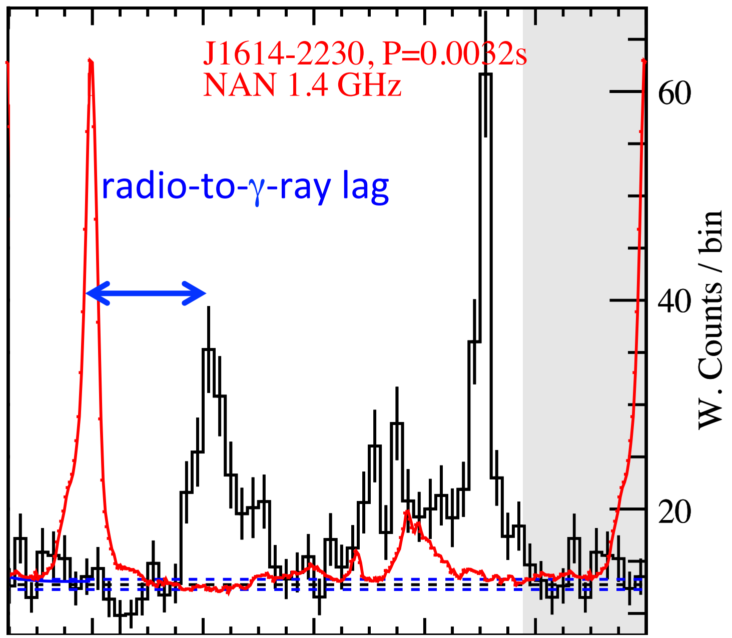
Takata et al. 2008

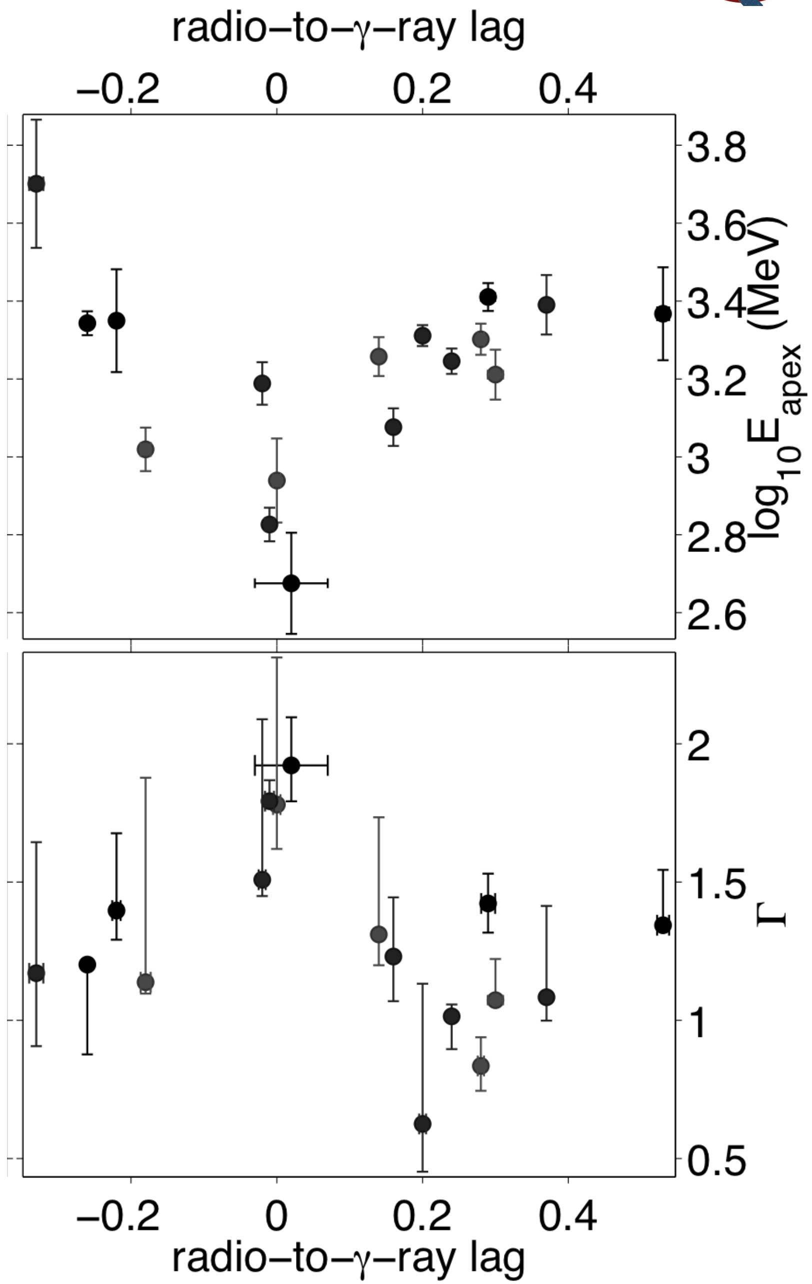
- **For the Slot Gap (Harding et al. 2008) or Outer Gap models (Takata et al. 2008)**
  - **Synchroton component (cyclotron resonant absorption of radio photons)**
    - **from primaries (not possible from secondaries)**
- **For the Outer Gap (Wang et al. 2010) or the FIDO models (Kalapotharakos 2014)**
  - **Transition from $E_{//} \neq 0$ to $E_{//} = 0$ not abrupt**

    ➔ **CR at few hundreds MeV**

MSP spectral sequence

Second Fermi-LAT Pulsar Catalog, Abdo et al. 2013

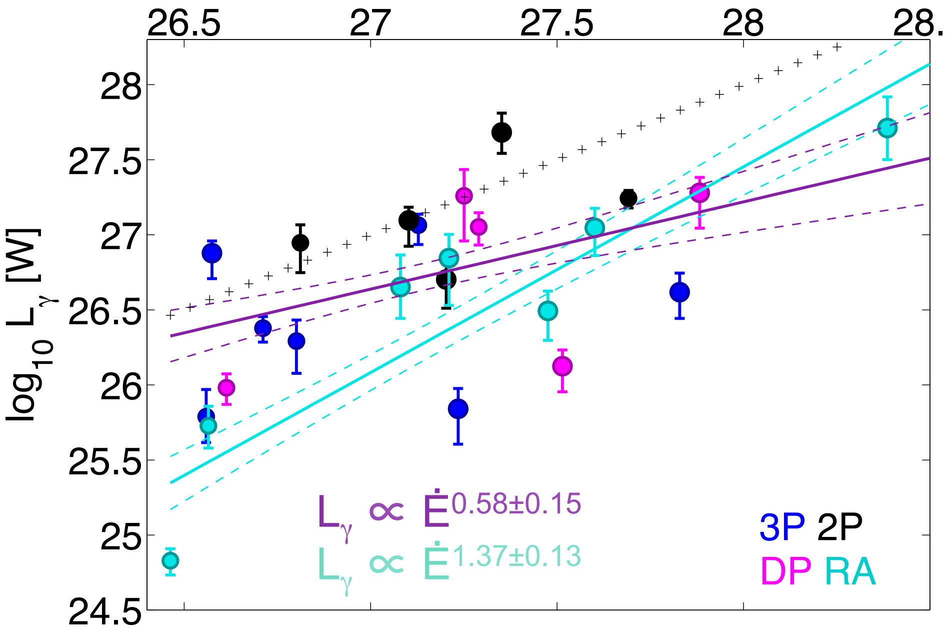




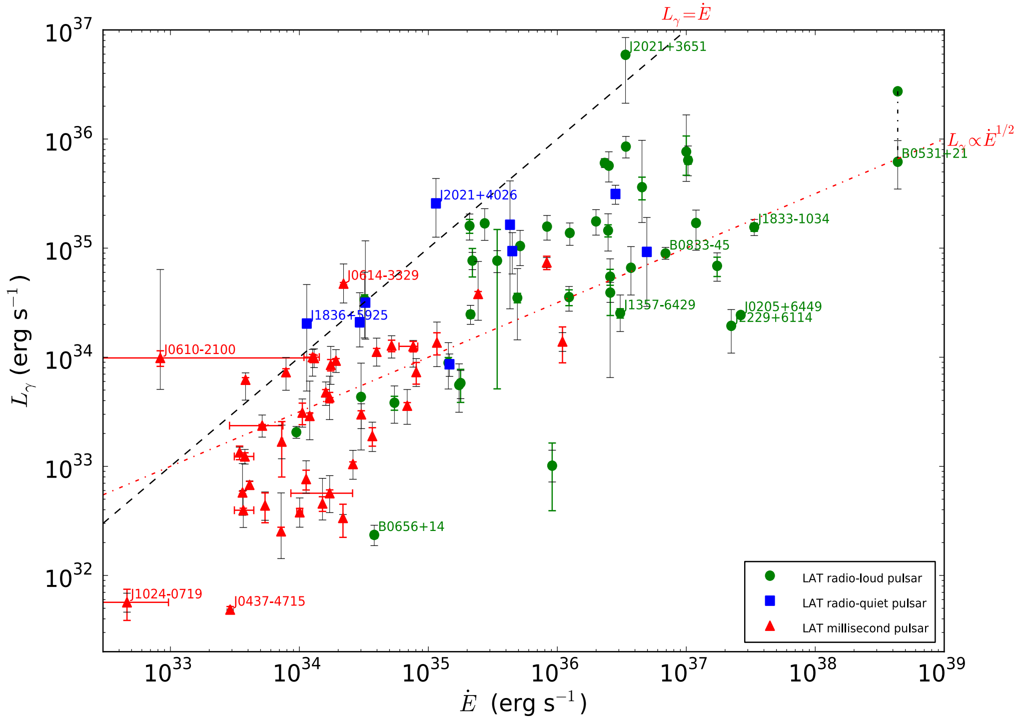
- **Multi-peak pulsars : softening when radio and γ-ray aligned**

➔ **Synchrotron component from pairs gaining pitch angle by cyclotron resonant absorption of co-located radio photons (Harding et al. 2008)**

Different emission regions/regimes

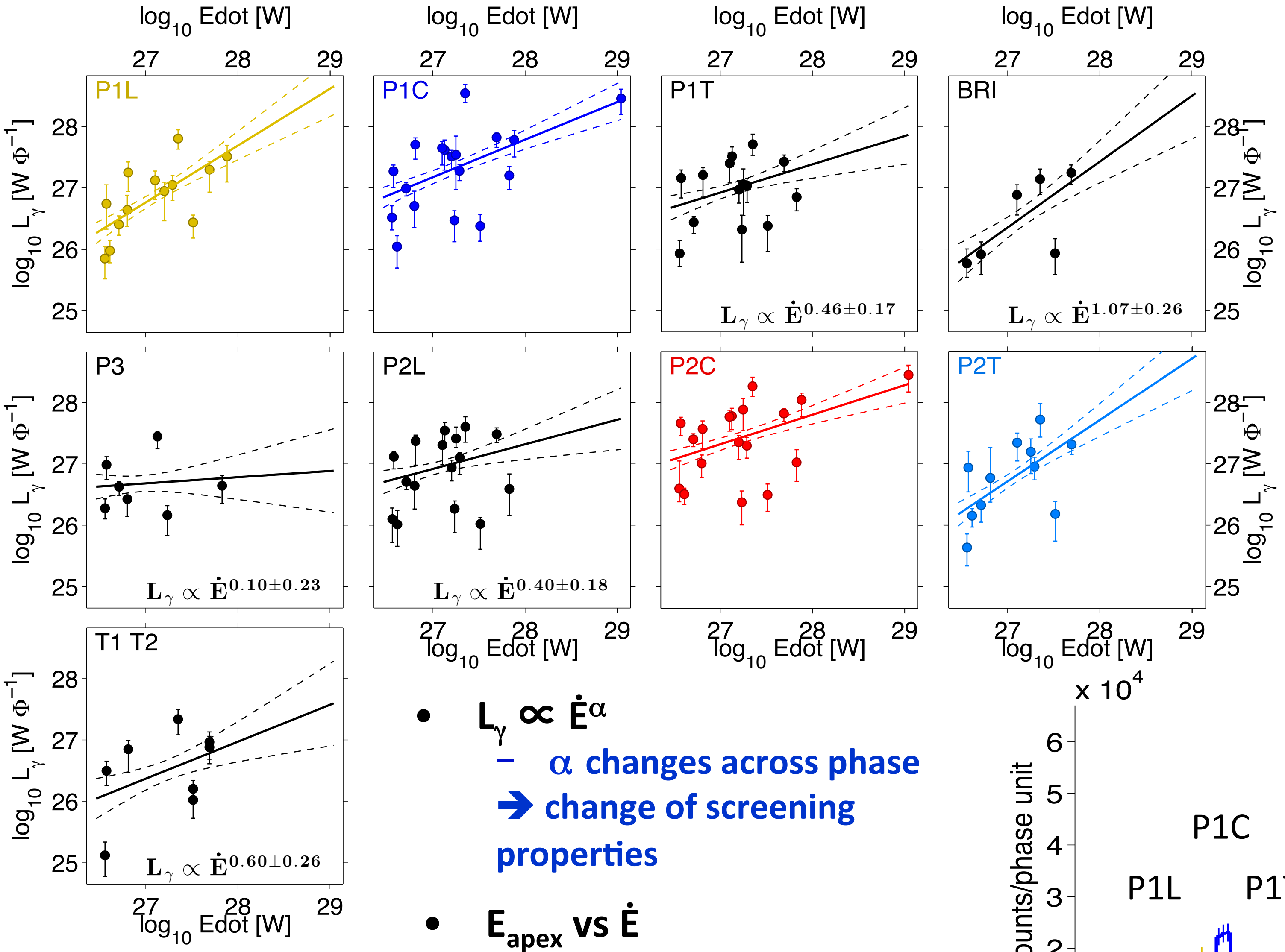


Second Fermi-LAT Pulsar Catalog, Abdo et al. 2013



- **Total emission**
- **Trend consistent with the Second Fermi-LAT Pulsar Catalog (Abdo et al. 2013)**
- **$L_\gamma \propto \dot{E}$ ➔ unscreened gaps**
- **But :**
  - **Multi-peaks : $L_\gamma \propto \sqrt{\dot{E}}$ ➔ screening**
  - **Ramps : $L_\gamma \propto \dot{E}$ ➔ no screening**

Different emission regions/regimes



$L_\gamma \propto \dot{E}^{0.93\pm0.16}$

$L_\gamma \propto \dot{E}^{1.0\pm0.19}$

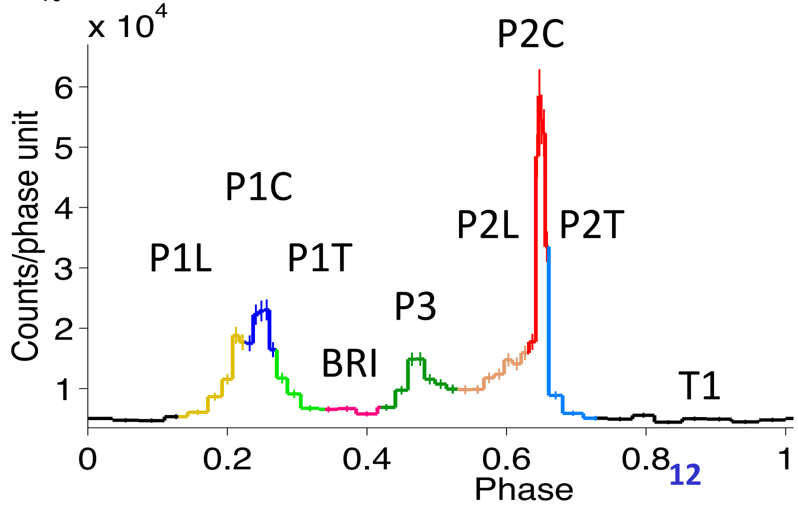
➔ ~ **unscreened**

$L_\gamma \propto \dot{E}^{0.61\pm0.12}$

$L_\gamma \propto \dot{E}^{0.48\pm0.11}$

➔ ~ **screened gaps**

- $L_\gamma \propto \dot{E}^{\alpha}$
  - α changes across phase
  - ➔ change of screening properties
- E_{apex} vs $\dot{E}$
  - Change across phase
  - ➔ Change of accelerating properties



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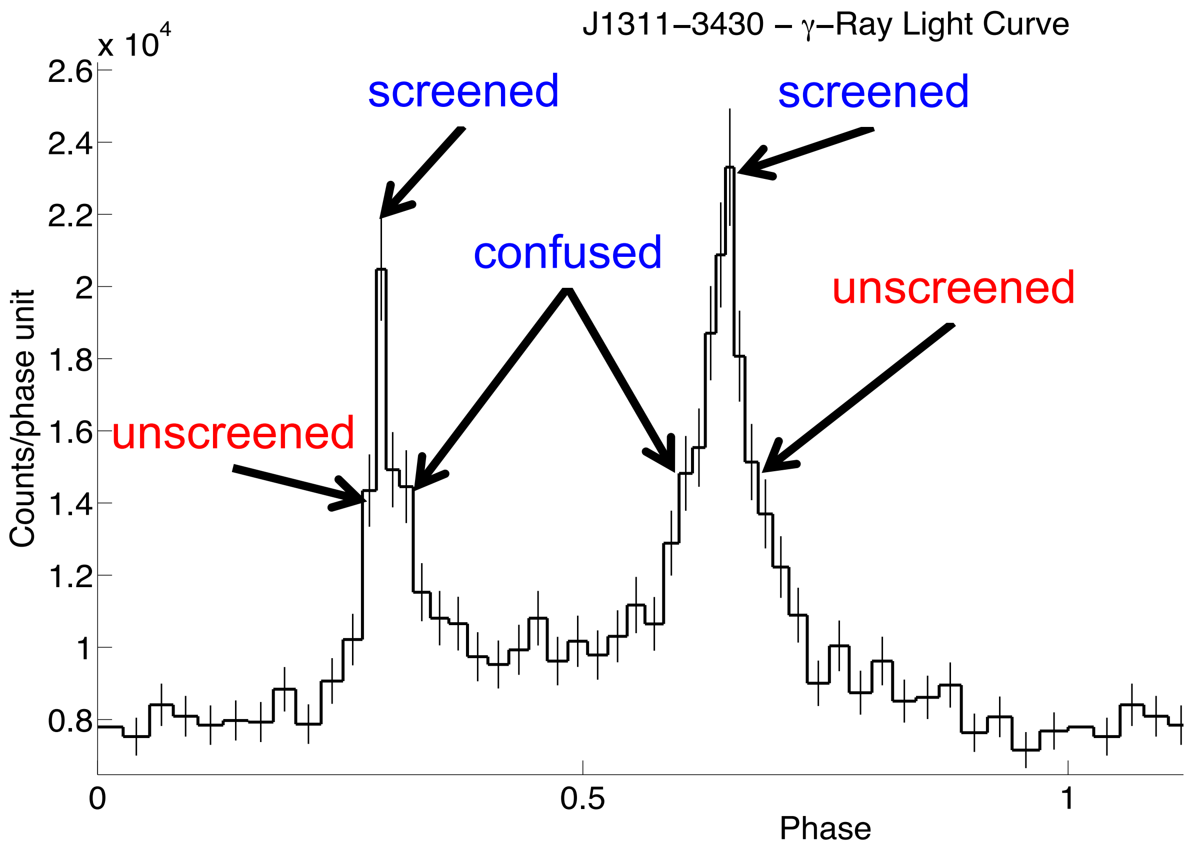
Conclusion

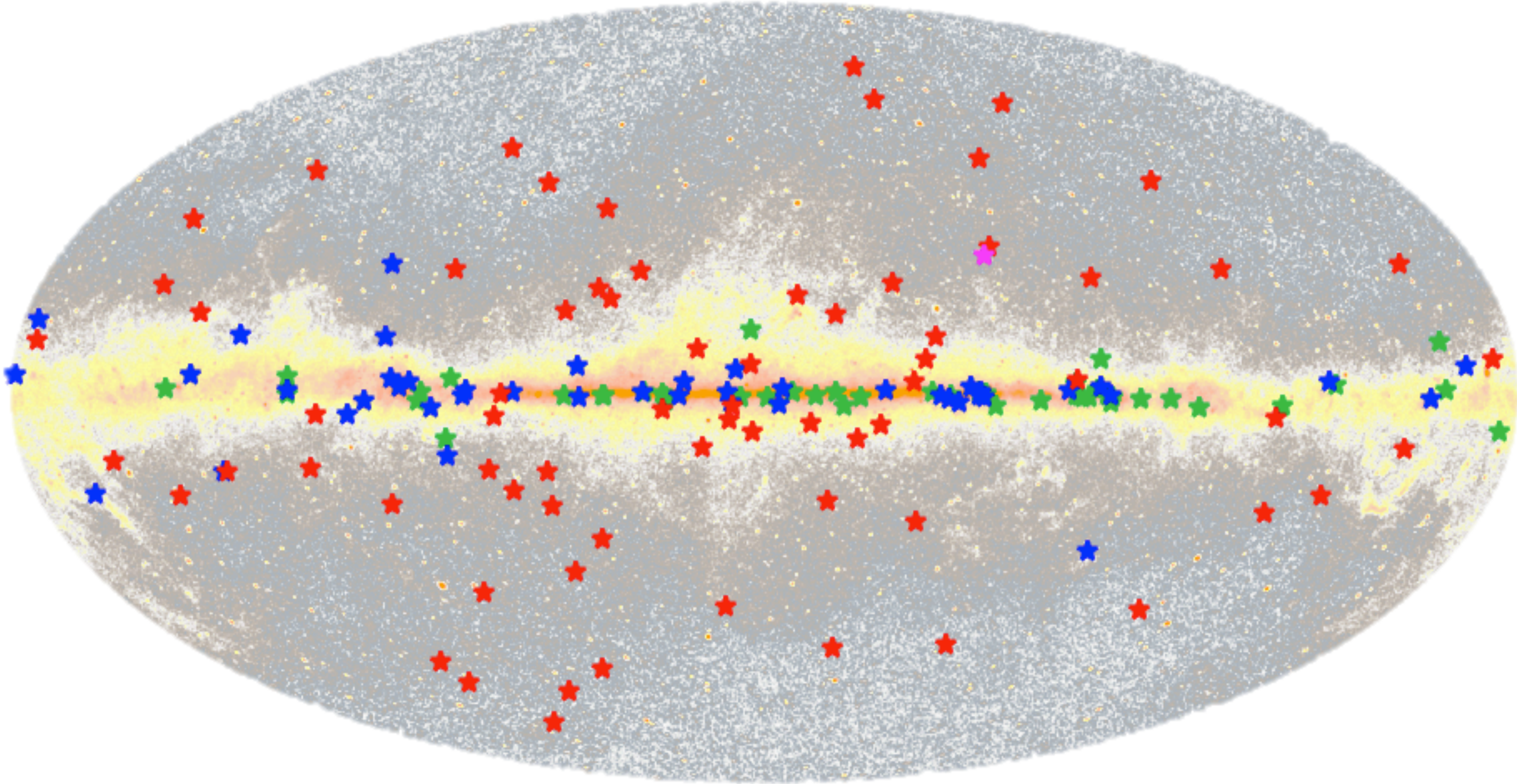
- **Need to re-think the classical picture of thin caustic gaps/wide unscreened regions**
  - **Evolution across rotational phase of accelerating and screening regimes**
    - **Emission from multiple regions with different electrodynamic properties**
      - **Lightcurve = Combination of emissions from different zones of a single accelerator and/or from different magnetospheric regions**

- **MSP spectral sequence with $\dot{E}$:**
  - **Potential influence of radio emission**
  - **Consistent with the onset of an additional component at lower energy**
    - **Synchrotron radiation of primaries**
  - **And/or smooth transition in $E_{//}$**

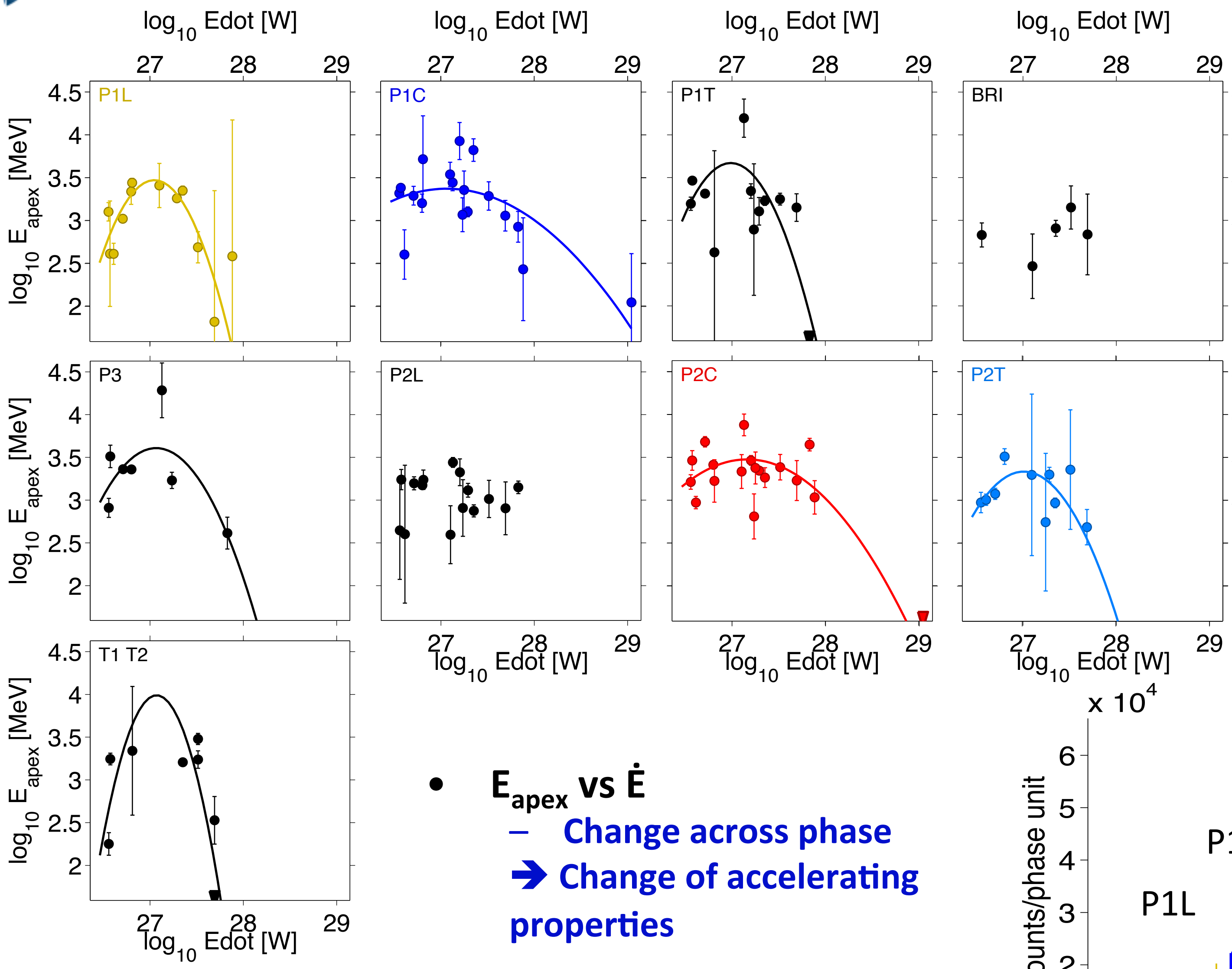


Thank you for your attention !

BACK-UP



Different emission regions/regimes



P_{curv} = 96,4 %

P_{curv} = 90,7 %

➔ **Correlation E_{apex} with $\dot{E}$**

P_{curv} = 99,7 %

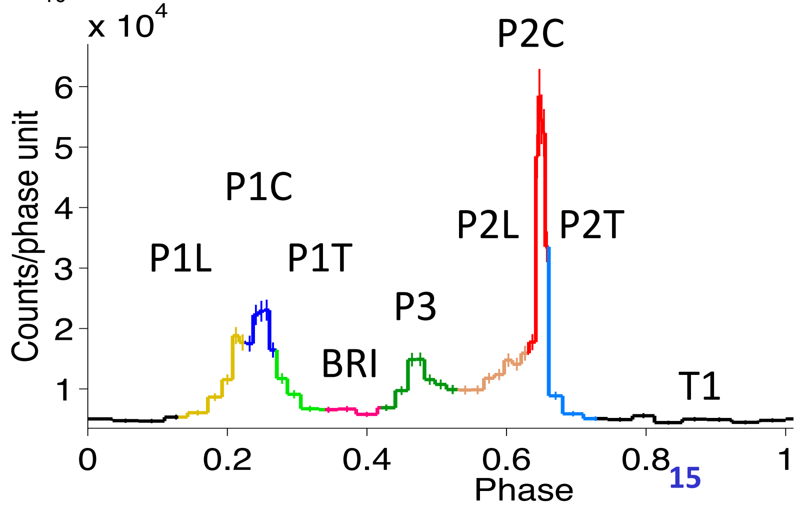
➔ **Correlation E_{apex} with $\dot{E}$**

P_{curv} = 80,7 %

➔ **Possible correlation**

- **E_{apex} vs $\dot{E}$**
  - **Change across phase**

  ➔ **Change of accelerating properties**



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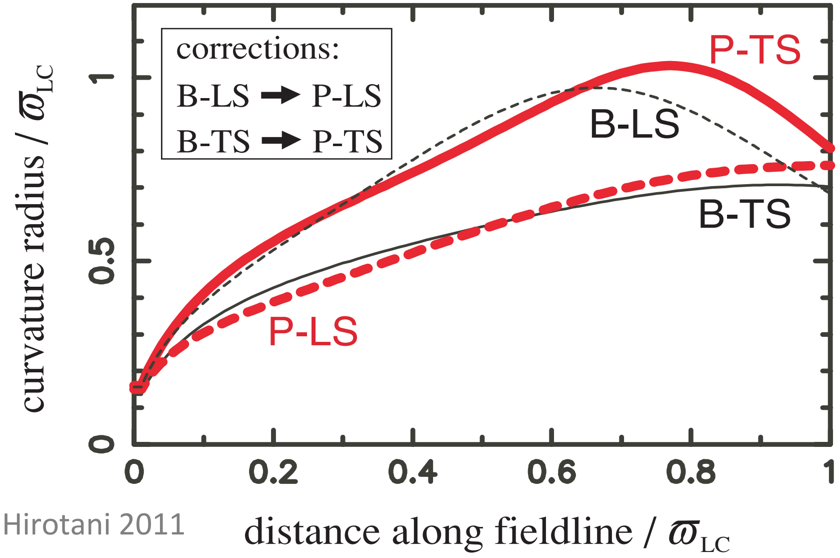
Saturation of Lorentz factors

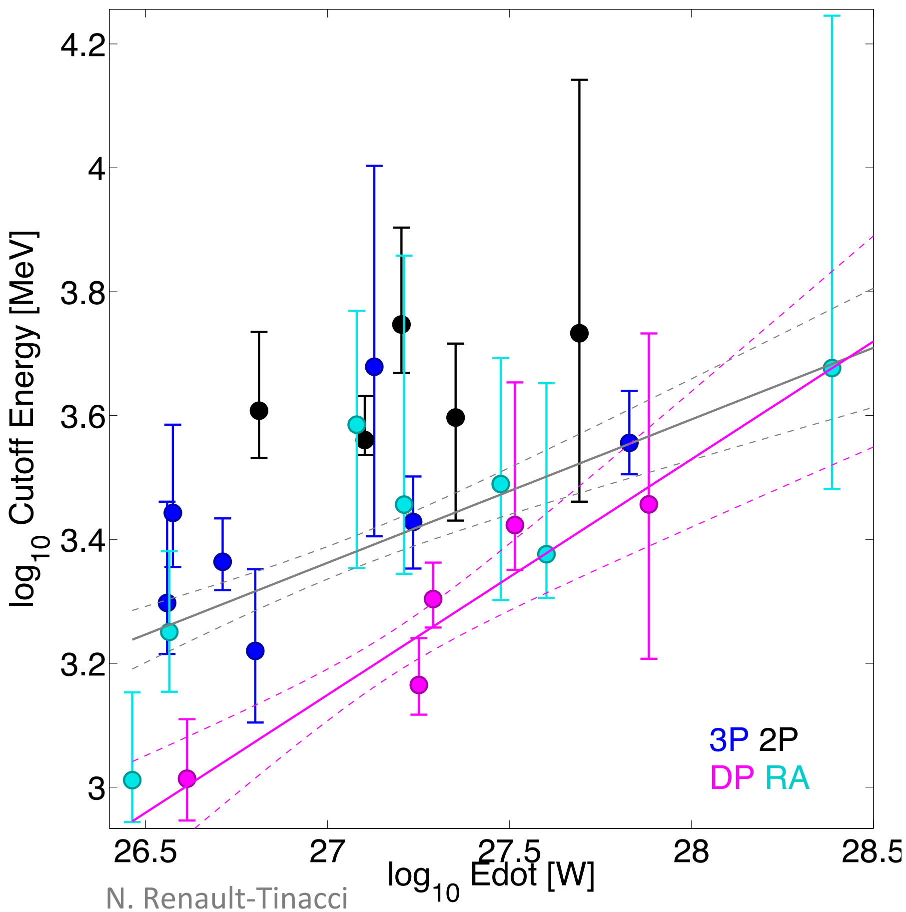
- **Γ_{max} estimation from E_{cut}**

$$\Gamma_{max} = \left(E_{cut} \frac{2}{3} \frac{R_{LC}}{\hbar c} \right)^{1/3}$$

- **Narrow Γ_{max} distribution**



Hirotani 2011



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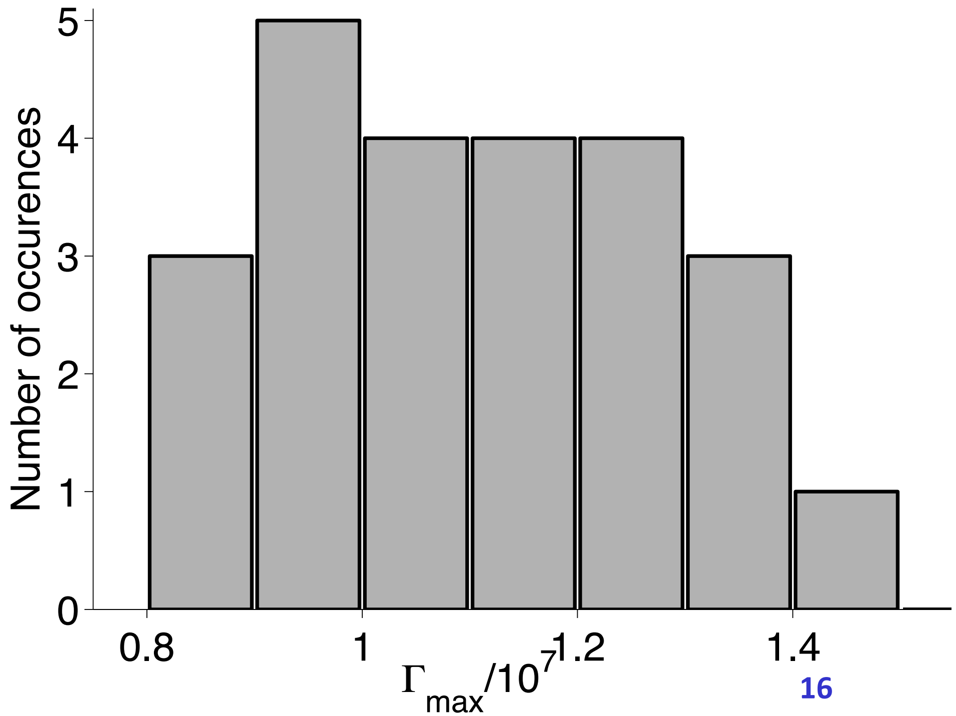
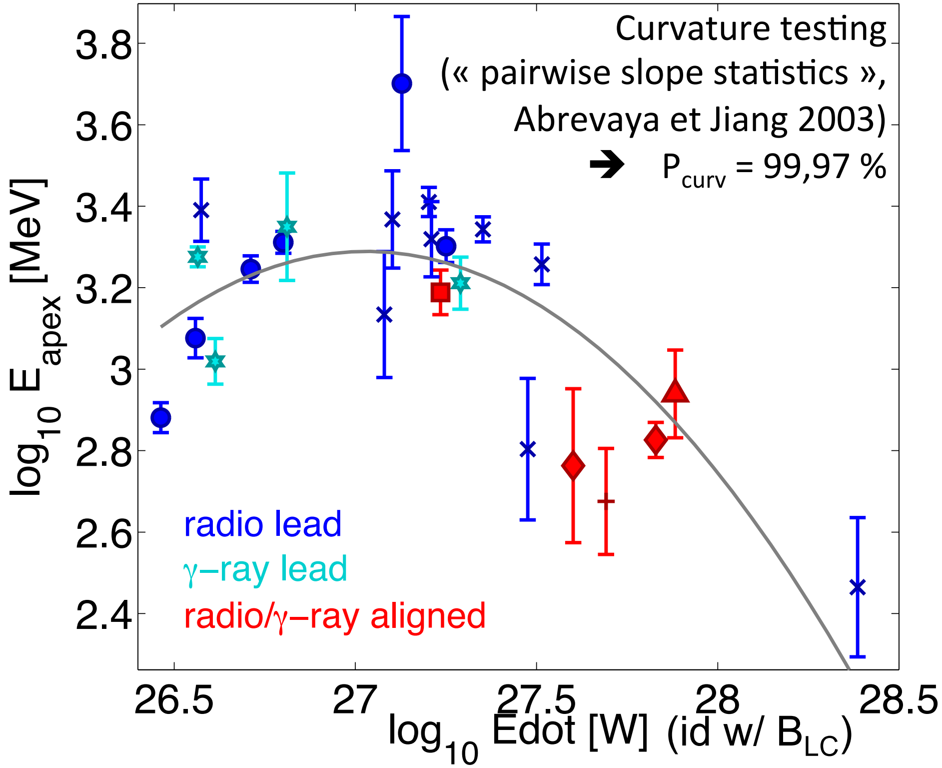
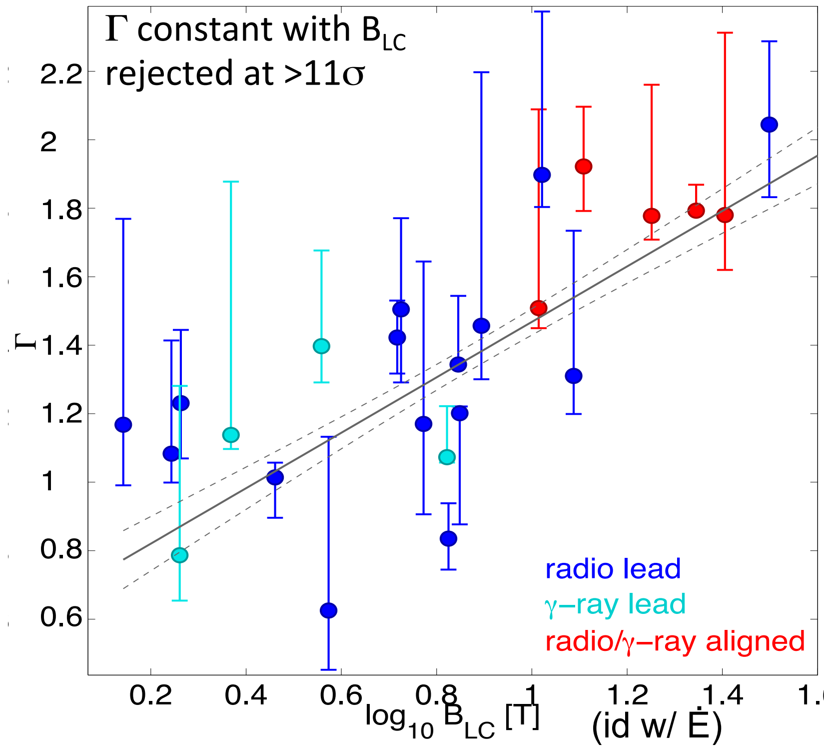


MSP spectral sequence

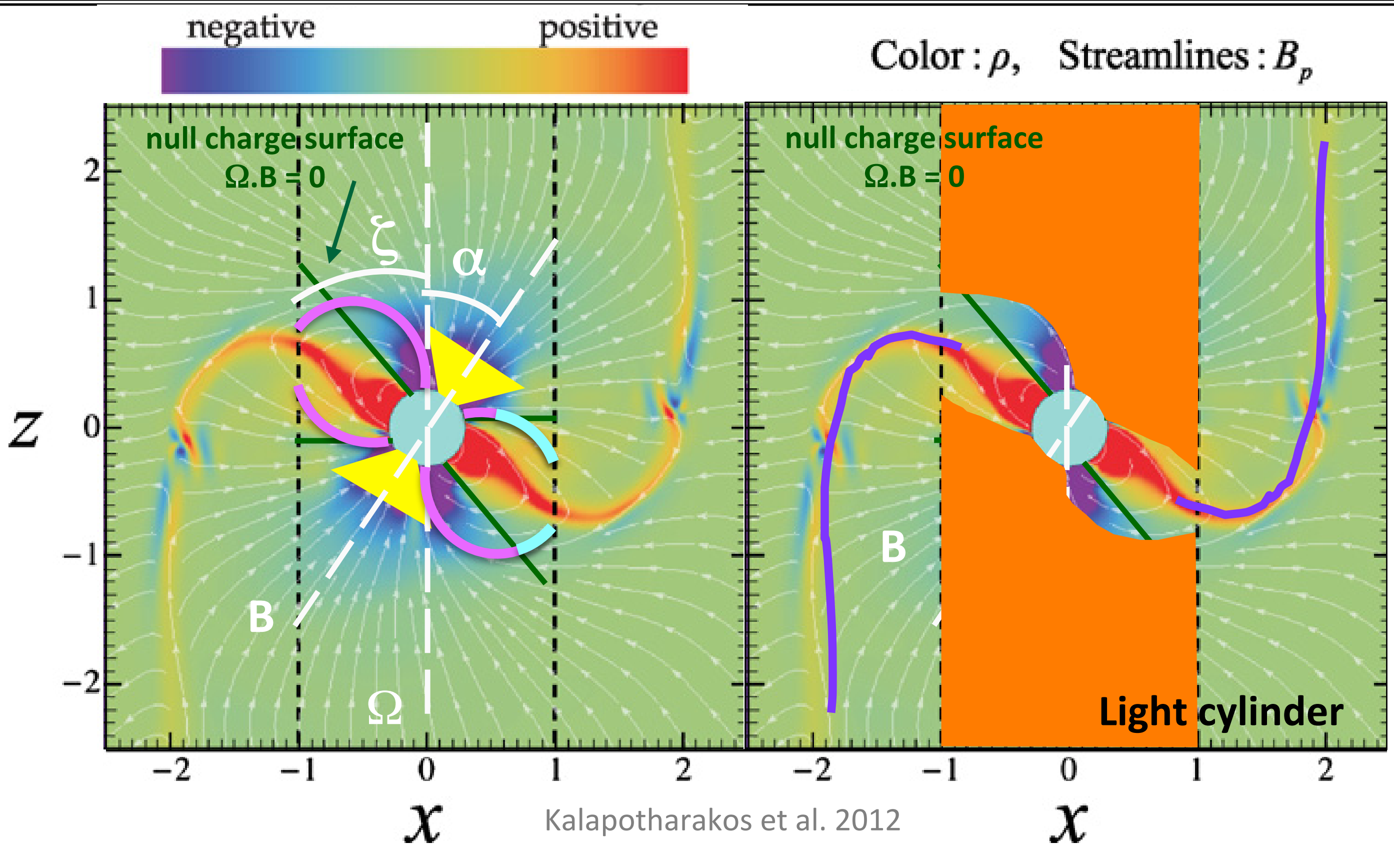


Classification by Johnson et al. 2014



- **Toy model of curvature radiation spectra :**
  - **From primaries near the light cylinder**
  - **$\rho_c = R_{LC}$ (Hirotani 2011)**
  - **Test with different Γ_{max} distributions**
- **Inability of a single CR component to reproduce the evolution in the sample**
  - **With pure CR : ➚ E_{apex} & ➘ Γ**
  - ➔ **Softer component required**
- **For the Slot Gap (Harding et al. 2008) or Outer Gap models (Takata et al. 2008)**
  - **Synchroton component (cyclotron resonant absorption of radio photons)**
    - **from primary pairs**
- **For the Outer Gap (Wang et al. 2010) or the FIDO models (Kalapotharakos 2014)**
  - **Transition from $E_{//} \neq 0$ to $E_{//} = 0$ not abrupt**
    - ➔ **CR at few hundreds MeV**

Accelerator/emission geometries



Kalapotharakos et al. 2012

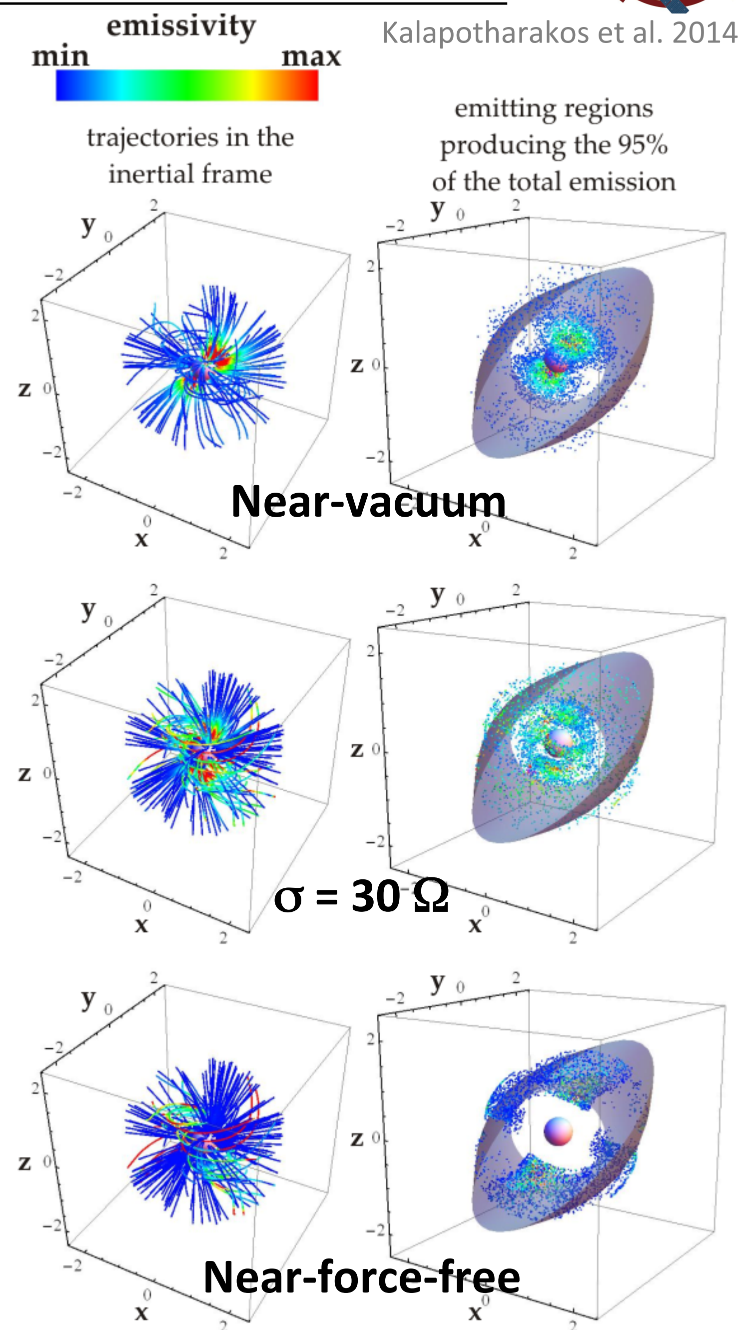
- Slot Gap (Arons 1983), Polar Cap (Sturrock 1971), Outer Gap (Cheng et al 1986, Romani 1996), FIDO (Kalapotharakos et al. 2014, dissipative magnetosphere simulations, in current sheet) ➔ screened regime ➔ Thin gaps ➔ $L_\gamma \propto \sqrt{\dot{E}}$
- Pair Starved Polar Cap (Harding & Muslimov 2004b) ➔ unscreened regime ➔ acceleration in the open field line region ➔ CR ➔ $L_\gamma \propto \dot{E}$
- Striped wind (Kirk et al. 2009, Pétri 2012) ➔ outside light cylinder (>5 R_{LC}), synchrotron, $L_\gamma \propto \sqrt{\dot{E}}/P$

Force-free Inside Dissipative Outside

- **Dissipative magnetosphere**
- **Time-dependent Maxwell equation numerical resolution**
  - Ohm's law relating current and EM fields

$$\vec{J} = c\rho \frac{\vec{E} \wedge \vec{B}}{E_0^2 + B^2} + \sigma E_{||}$$

  - σ is fixed
  - Curvature radiation
- **Increasing σ ➔ decreasing $E_{||}$ ➔ longer acceleration distance ➔ outer magnetosphere emission**
- **To reproduce Fermi-LAT observations**
  - FIDO, force free inside, dissipative outside
  - Current sheet emission
- **In reality need a variable σ (Philippov 2014)**



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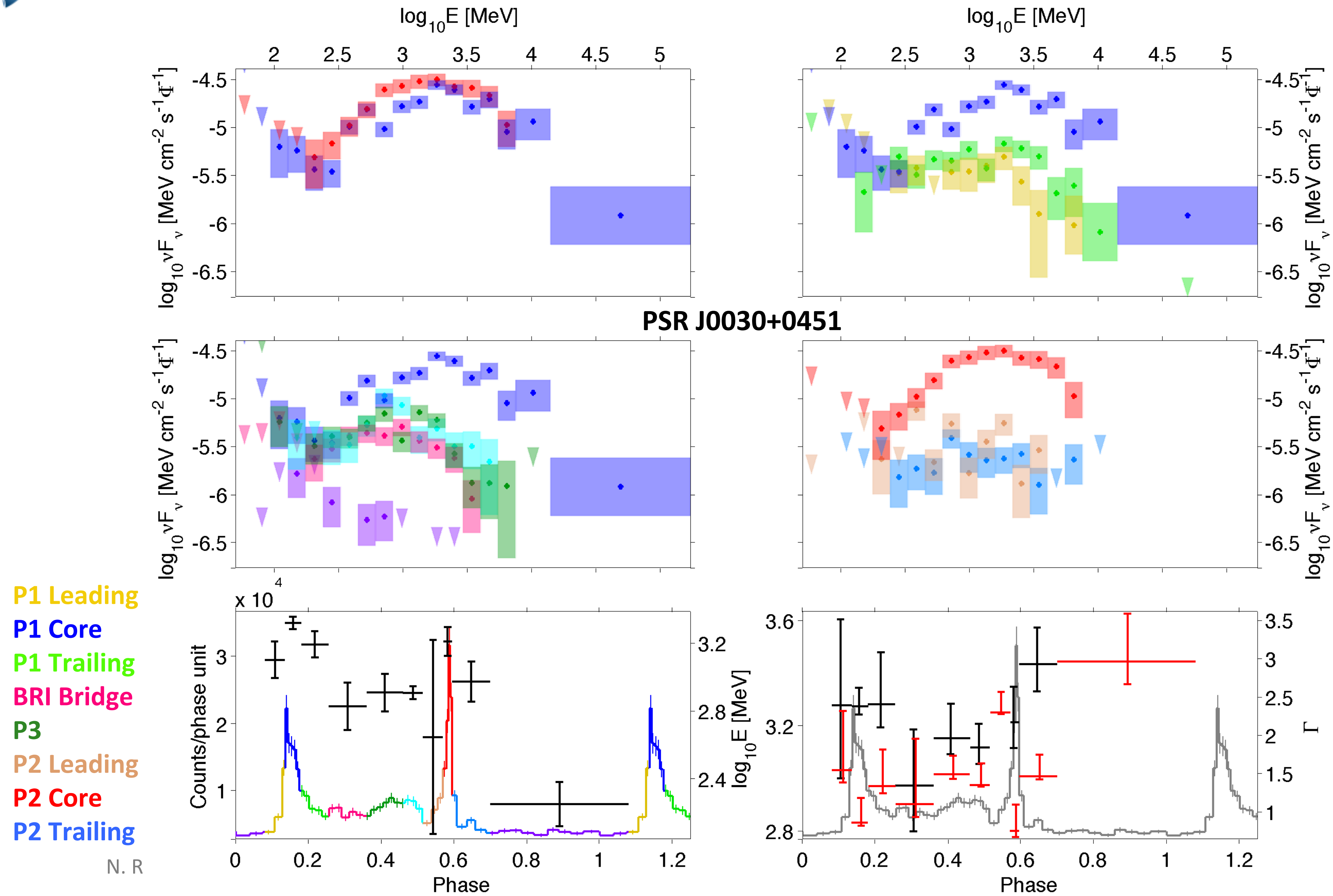
Spectral behaviour across phase (multi-peak)

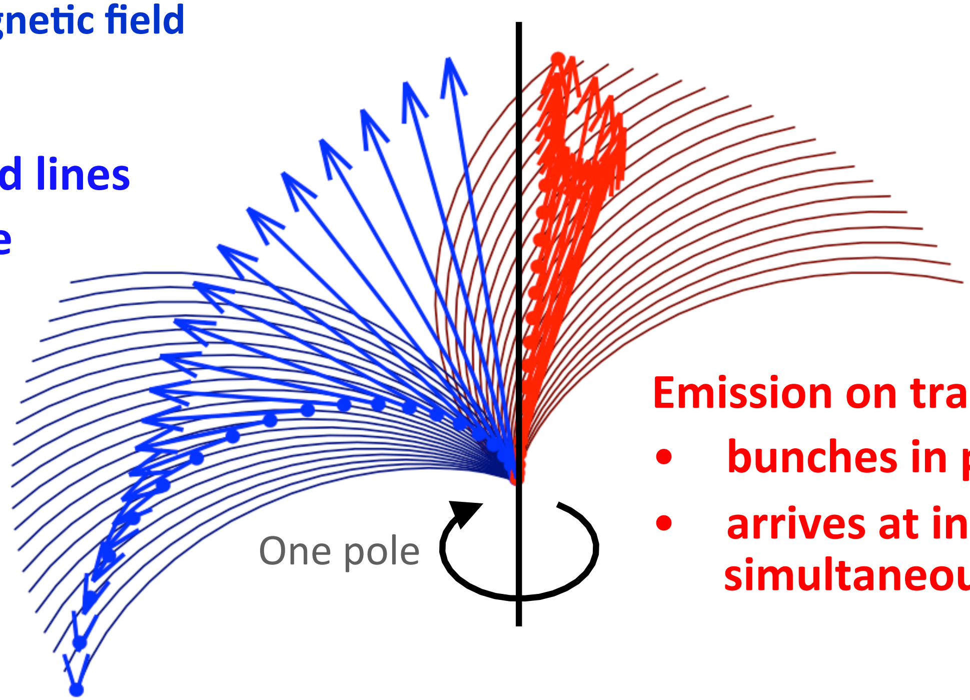


N. R

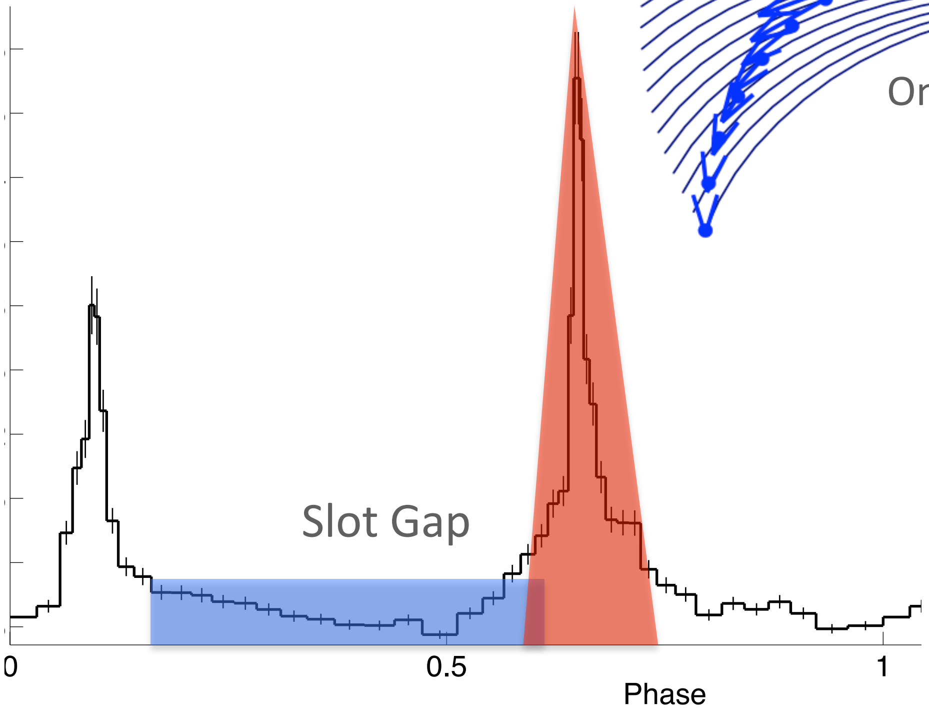
Why "phase-resolved spectroscopy" ?

- Special relativistic effects → phase shifts (Morini 1983)
  - time-of-flight delays, light aberration
  - retardation of magnetic field

Emission on leading field lines
- spreads out in phase
- arrives at inertial observer at different times

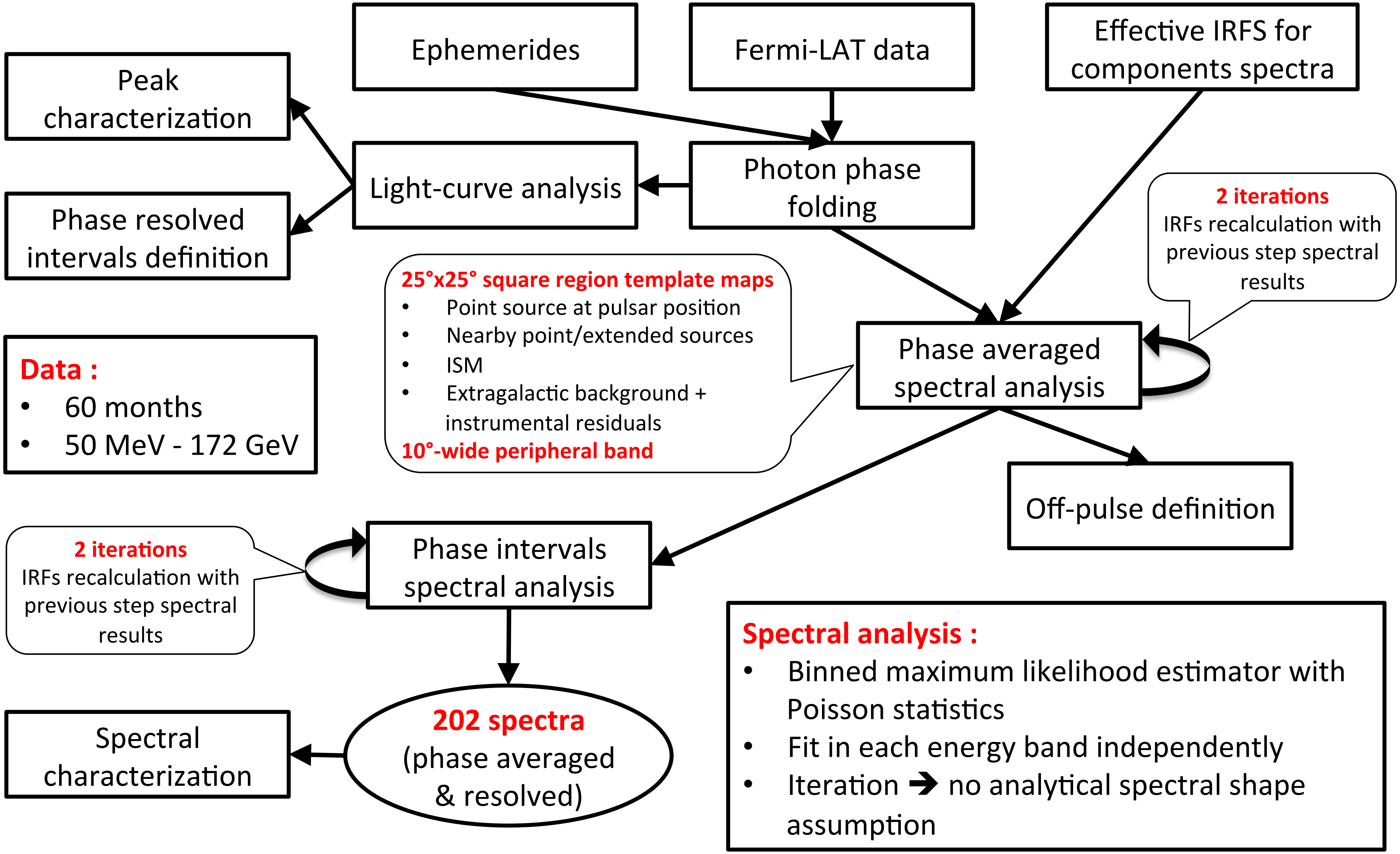


Emission on trailing field lines
- bunches in phase
- arrives at inertial observer simultaneously



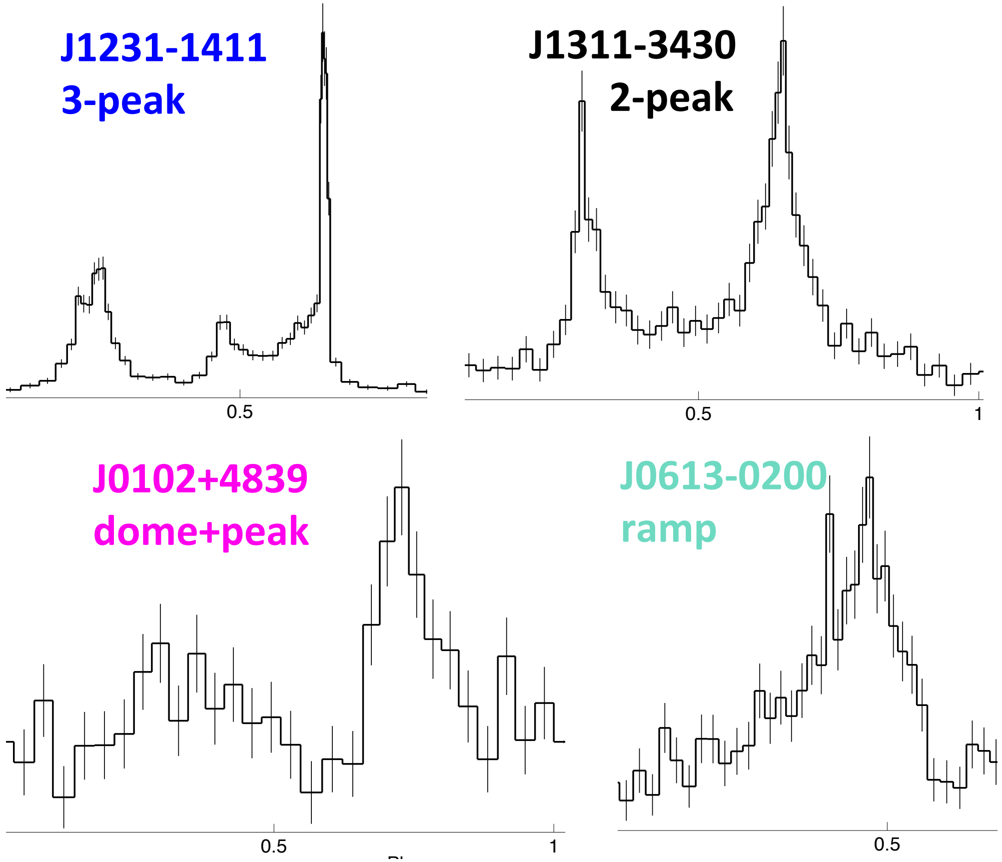
- Peaks = caustics
- Phased resolved spectral analysis
  - mapping (in a complex way) processes with altitude and azimuth

Analysis protocol



Dataset & Analysis

- **Data selection :**
  - Pass 7 Reprocessed Fermi-LAT data
  - 60 months (August 2008 – August 2013)
  - 50 MeV < E_{phot} < 172 GeV
- **Fixed count binned lightcurves :**
  - Photon selection
    - E_{phot} > 200 MeV
    - $\theta_{phot} < \theta_{68\%}(E_{phot})$
    - 30 or 50 bins
  - 4 MSPs classes based on morphology
  - Phase resolved interval definition

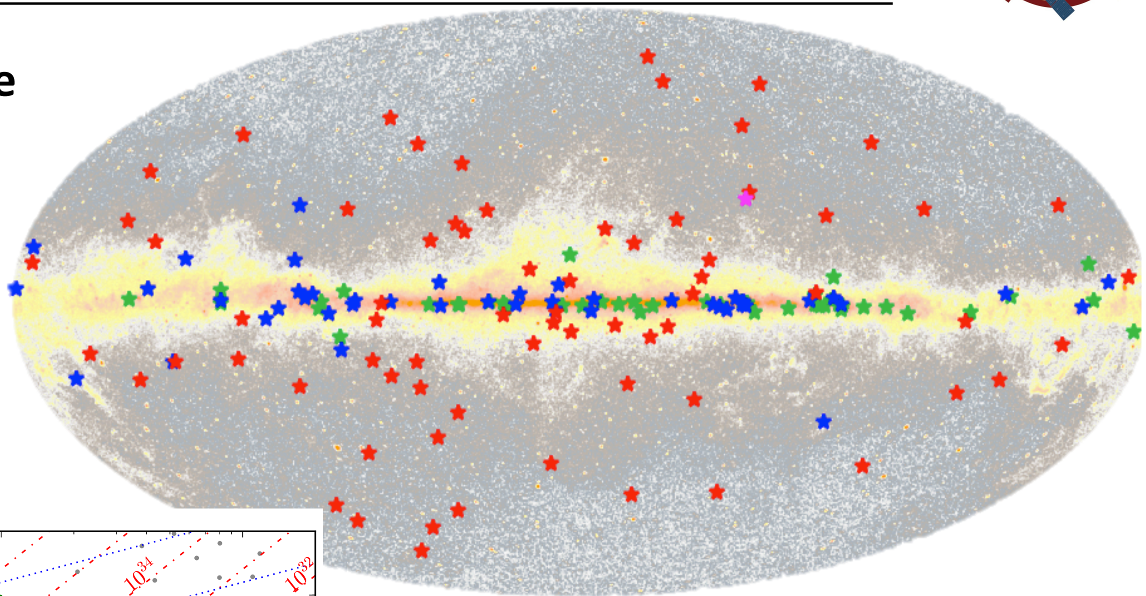


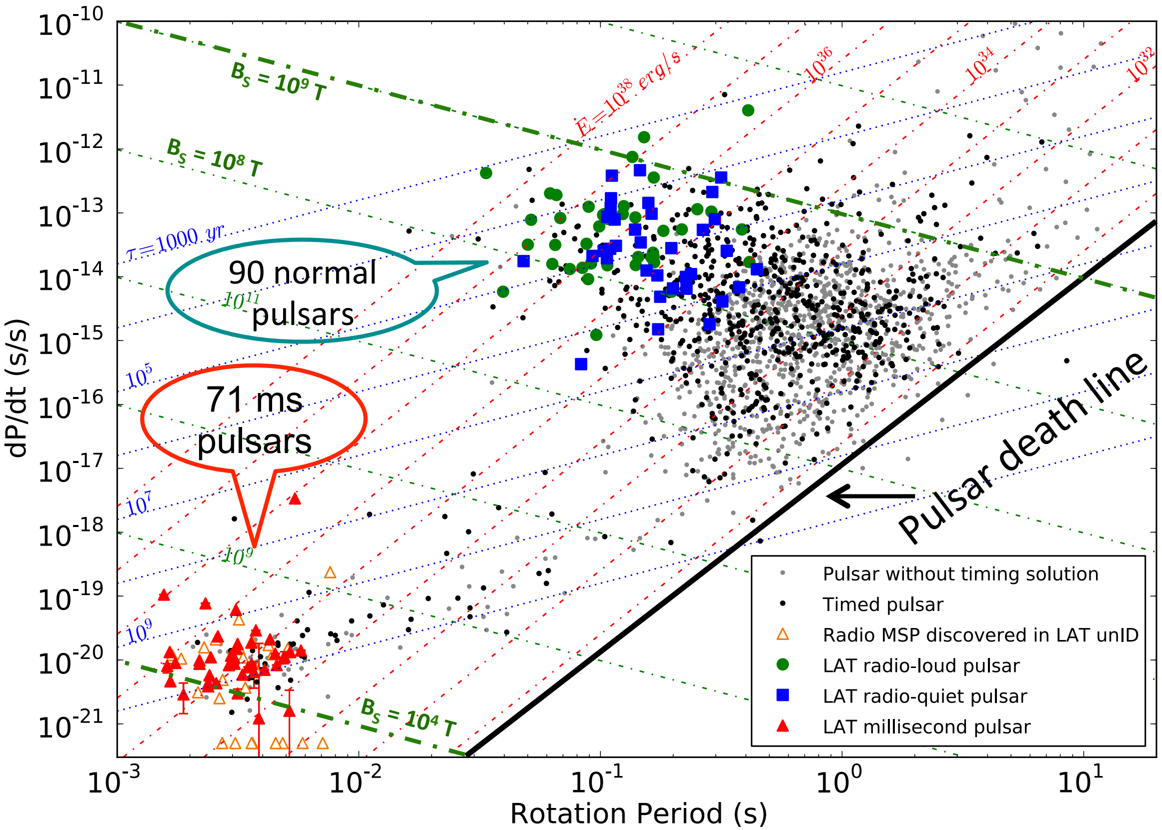
- **Spectral analysis method :**
  - Binned maximum likelihood estimator with Poisson statistics
  - Fit in each energy band independently
  - Iterations ➔ no analytical spectral shape assumption
- **Spectral charactrisation**
  - Bivariate maximum likelihood estimator➔
  - Local quadractic regression (χ^2)

Spectral shape : $$\frac{dN}{dE} = N\left(\frac{E}{E_0}\right)^{-\Gamma} \exp\left(-\frac{E}{E_{cut}}\right)$$

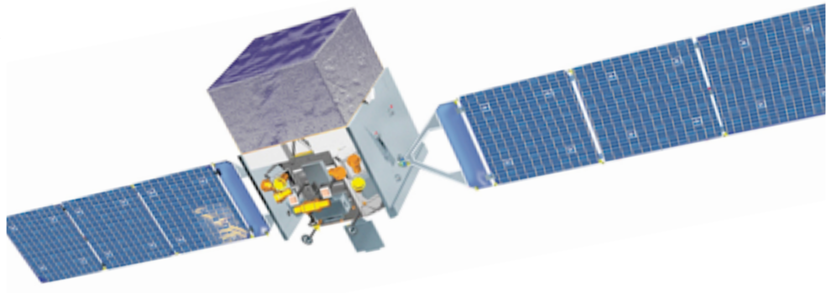
The Fermi-LAT era

- **Pair conversion γ-ray space telescope launched in 2008 :**
  - **Large FoV : 20% of the sky at any instant**
  - **Full sky coverage every 3 hours**
  - **Energy : 20MeV - 300 GeV**





Second Fermi-LAT Pulsar Catalog,
Abdo et al. 2013



- **Highlighting millisecond pulsars (MSPs) γ-ray activity**

Unexpected !