Phase resolved spectral analysis of Fermi-LAT millisecond pulsars

1. Trends with energy
2. Trends with phase

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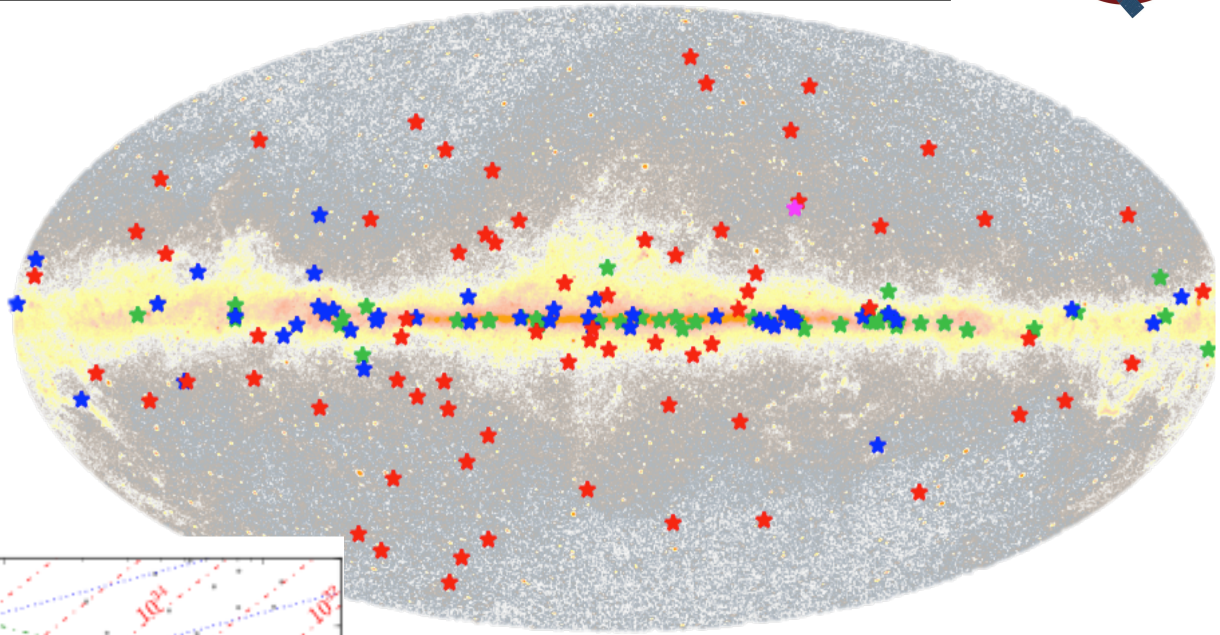
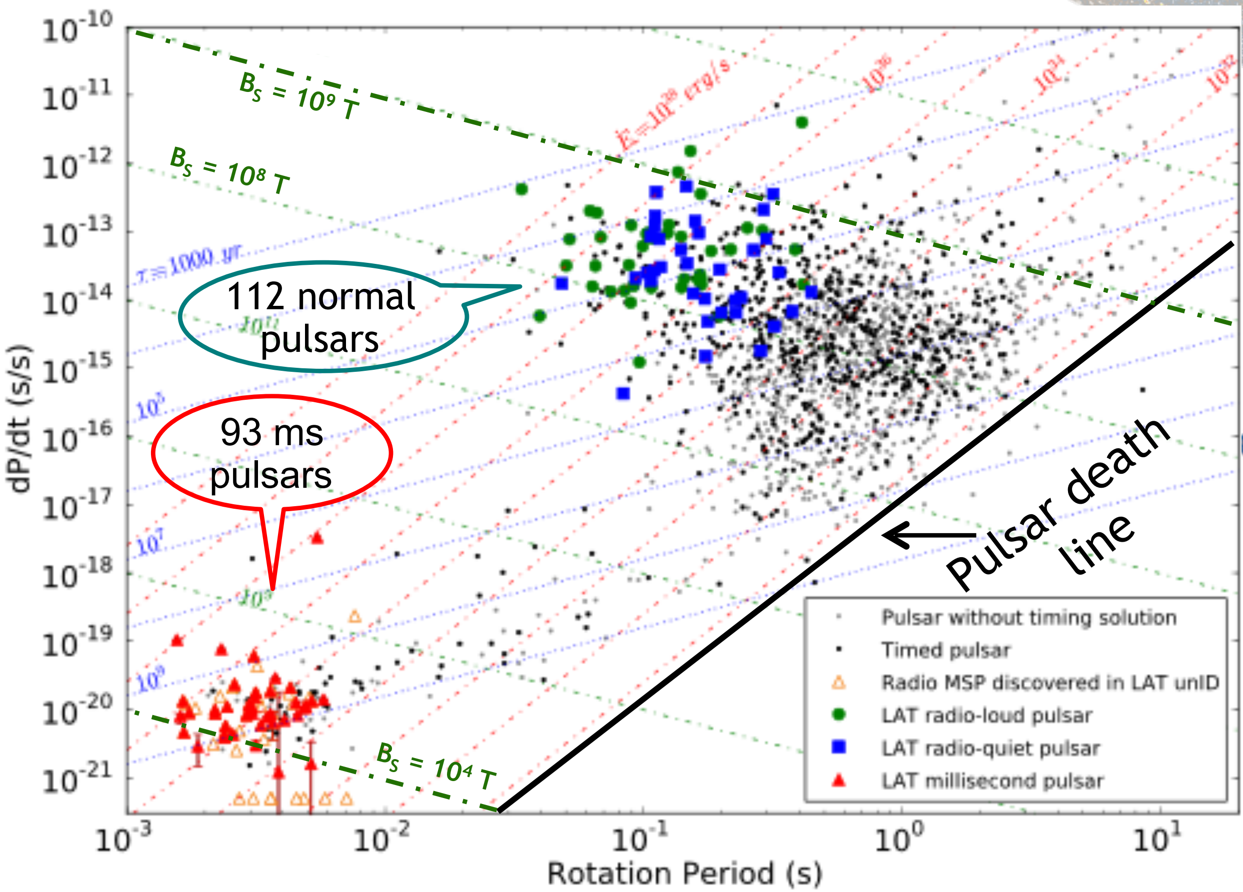
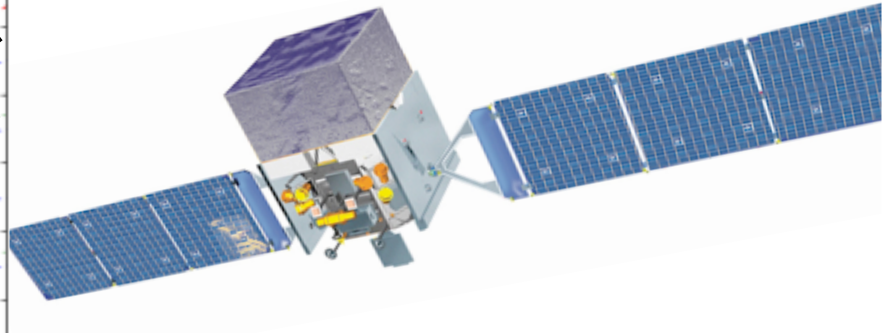
The Fermi-LAT era

- **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 : 20 MeV - 300 GeV





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

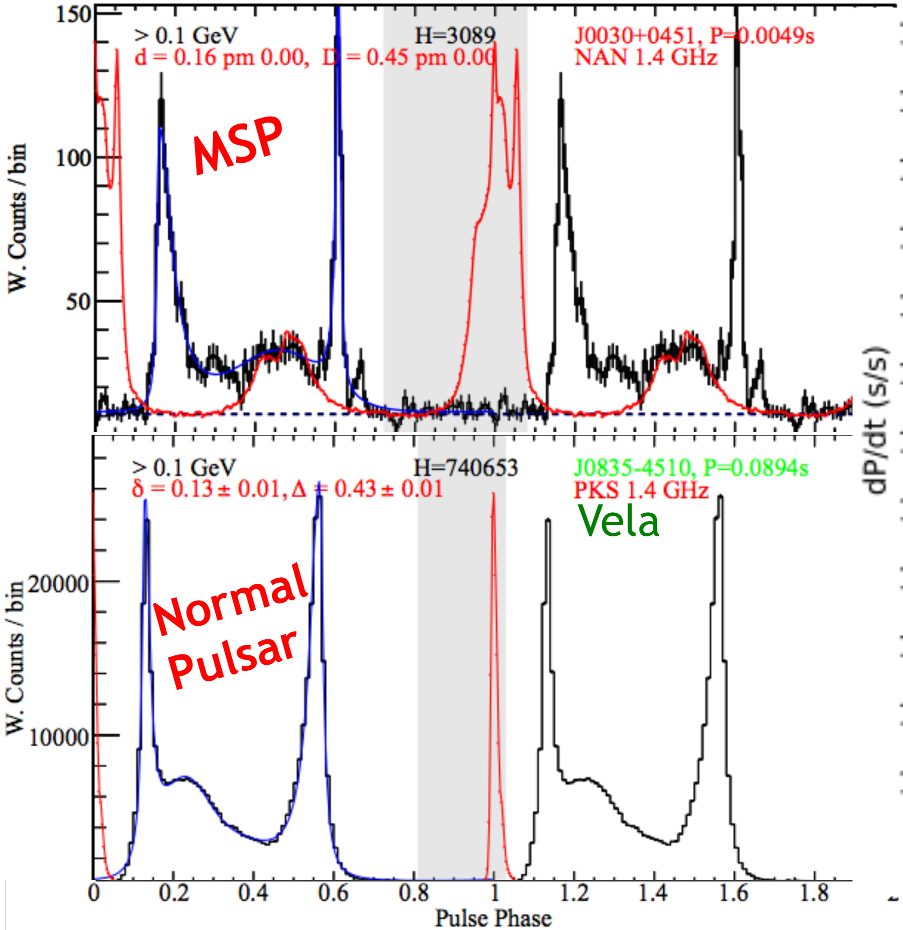


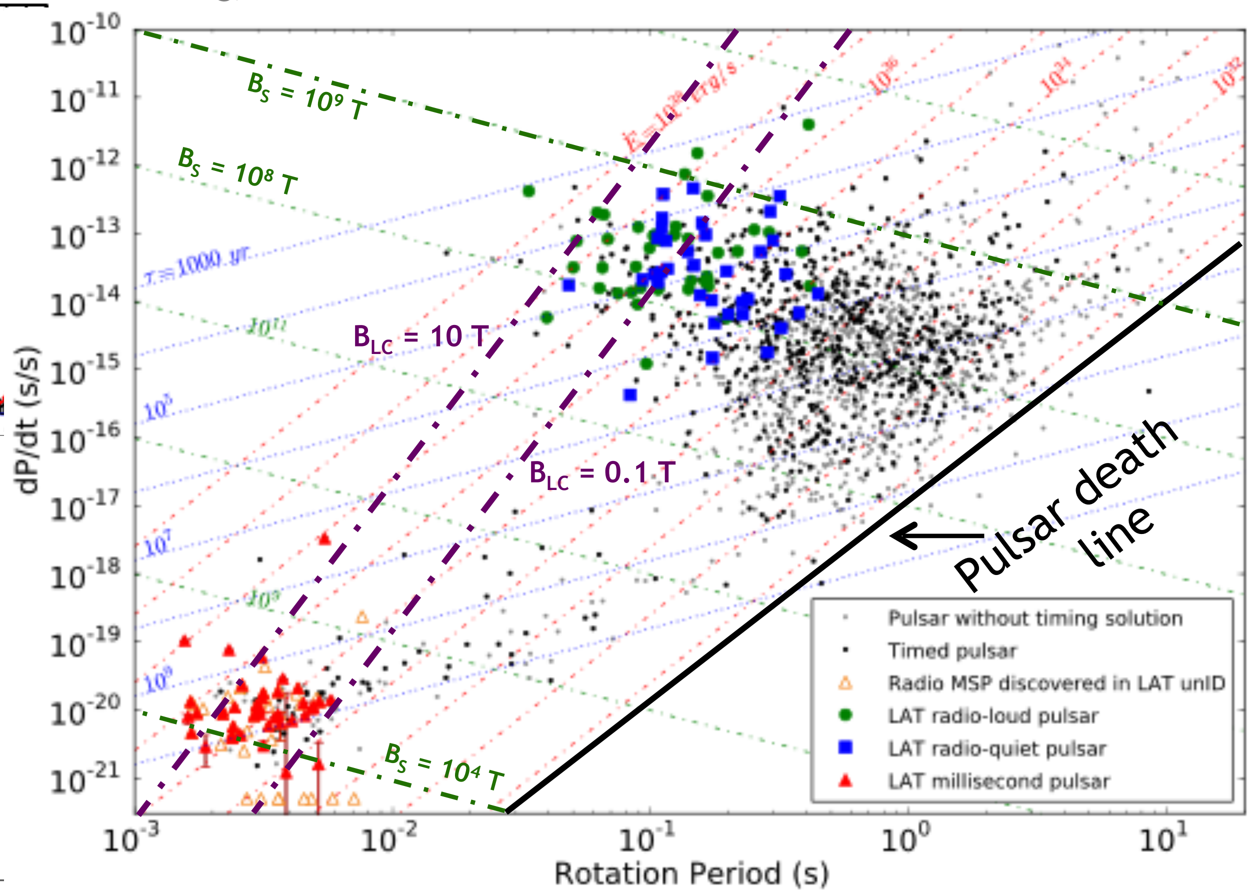
- **Highlighting millisecond pulsar (MSP) γ-ray activity**

  Unexpected !

Why MSPs ?

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





- Growing γ-ray pulsar class
  - (≈45% 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
- MSP larger stability
- But MSPs are fainter pulsars

Motivations, Goals, Questions

- Why MSPs ?
  - Growing γ-ray pulsar class
  - Clues indicating same acceleration/radiation processes in MSPs as in young pulsar magnetospheres (similar γ-ray profiles, same B near the light cylinder)
  - More stable (but fainter)

1^{st} systematic phase-resolved spectral analysis of γ-ray MSPs

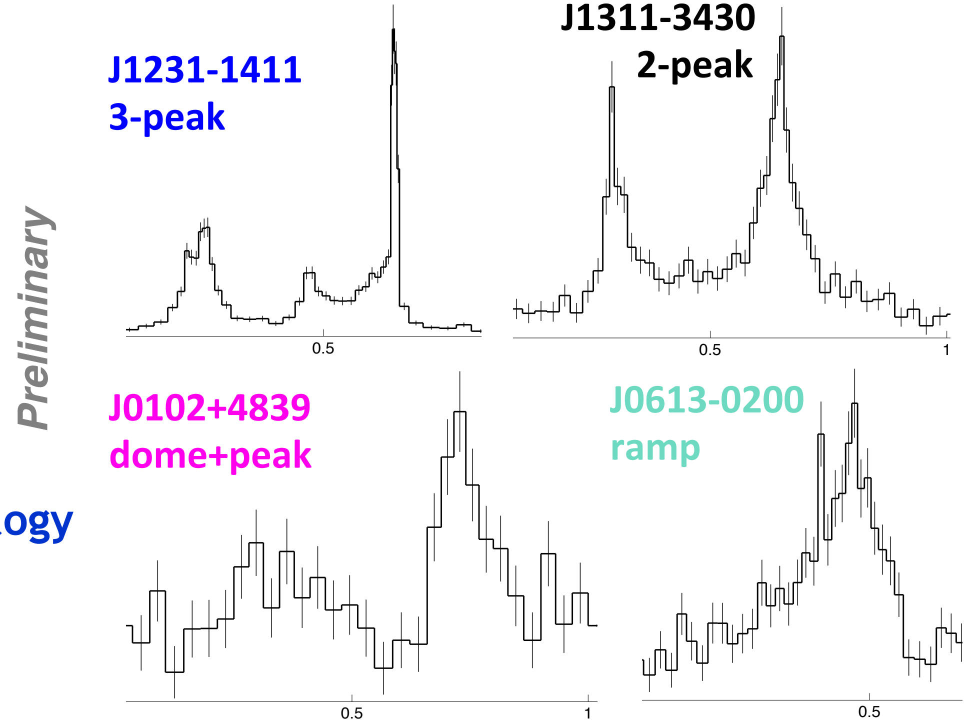
- Where do the acceleration and γ-ray emission originate in the magnetosphere ?
- Acceleration in thin screened gaps or in thick, pair-starved zones?
- Which γ radiation processes involved?

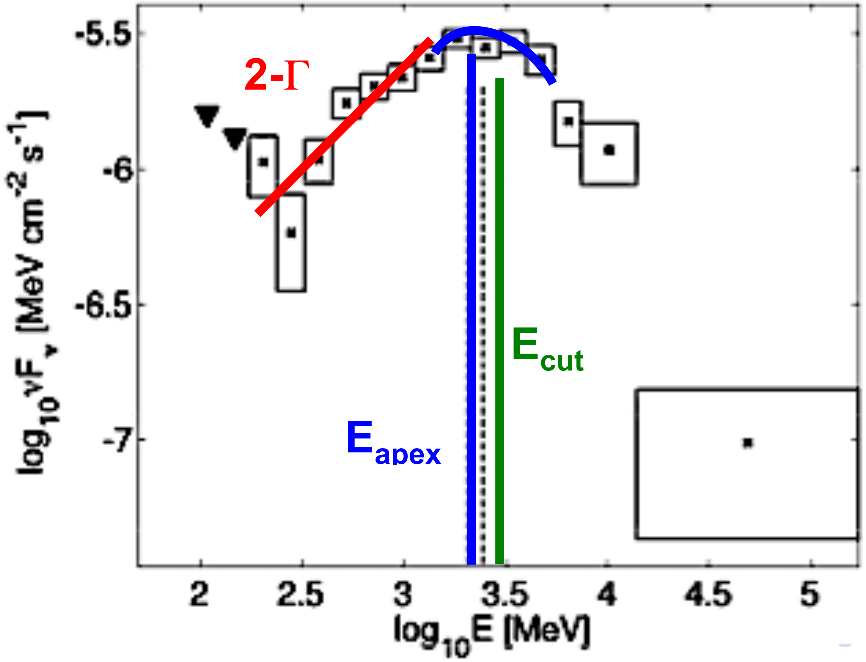
Data & Analyses

- **Data selection :**
  - Pass 7 Reprocessed Fermi-LAT data
  - 60 months (August 2008 - August 2013)
  - 50 MeV < E_{phot} < 170 GeV
- **Fixed-count binned lightcurves :**
  - Tempo2
  - photon selection
    - E_{phot} > 200 MeV and $\theta_{phot} < PSF_{68\%}(E_{phot})$
  - separation of 4 MSP classes based on morphology
  - phase interval definition (Peak cores, wings, bridge,...)
- **Spectral analysis :**
  - total emission and in phase intervals
  - iterative extraction of pulsed flux in energy bins (no need for an input spectral shape)
- **Subsequent spectral characterization:**
  - bivariate max-likelihood fit of PL Exponential Cut-Off

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

  - local quadratic fit of SED apex energy
  - energy flux $G_{>50MeV}$ and luminosity $L_\gamma(E>50\ MeV)$



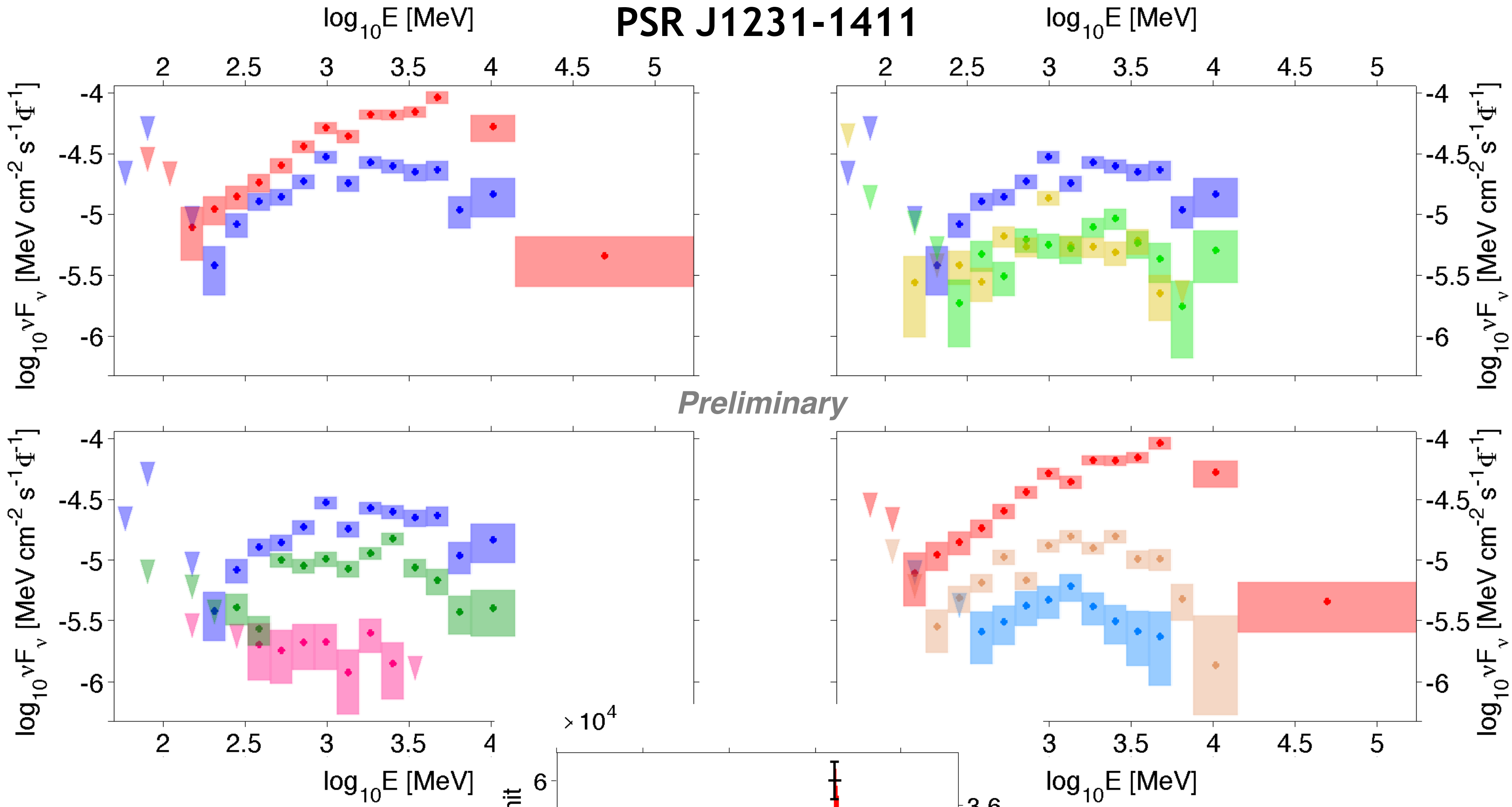


MSP sample

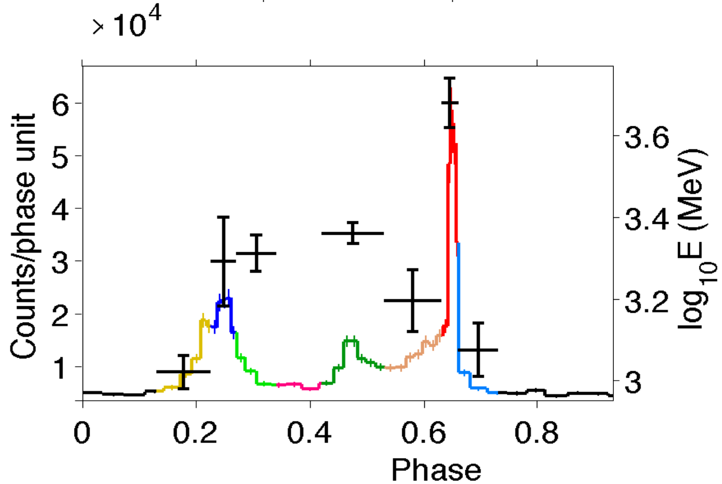
- **25 millisecond pulsars**
  - bright
  - bright enough wrt background
- **Good sampling of the MSP population in**
  - direction (l, b)
  - P & Pdot
  - energetics ($\dot{E}$, B_{LC}, …)
  - geometry (α_B, ζ_{view})

Pulsar name	l (deg)	b (deg)	P (ms)	$\dot{P}$ (10^{-20} s s^{-1})	$\dot{E}$ (10^{26} W)	Distance (kpc)	light-curve morphology
J0030+0451	113.14	-57.61	4.87	1.07	3.65	$0.28^{0.10}_{0.06}$	3 peaks
J0034-0534	111.49	-68.07	1.88	0.49	28.93	$0.54^{0.11}_{0.10}$	3 peaks
J0102+4839	124.87	-14.17	2.96	1.17	17.81	$2.32^{0.50}_{0.43}$	dome+peak
J0218+4232	139.51	-17.53	2.32	7.66	242.31	$2.64^{1.08}_{0.64}$	ramp
J0340+4130	153.78	-11.02	3.30	0.66	7.25	$1.73^{0.29}_{0.30}$	2 peaks
J0437-4715	253.39	-41.96	5.76	1.43	2.95	$0.156^{0.001}_{0.001}$	ramp
J0613-0200	210.41	-9.30	3.06	0.88	12.07	$0.9^{0.4}_{0.2}$	ramp
J0614-3329	240.50	-21.83	3.15	1.76	22.22	$1.90^{0.44}_{0.35}$	2 peaks
J1124-3653	284.10	22.76	2.41	0.58	16.22	$1.72^{0.43}_{0.36}$	ramp
J1231-1411	295.53	48.39	3.68	0.79	6.22	$0.44^{0.05}_{0.05}$	3 peaks
J1311-3430	307.68	28.18	2.56	2.09	49.18	$1.4^{0.3}_{0.3}$	2 peaks
J1514-4946	325.25	6.81	3.59	1.13	9.62	$0.94^{0.11}_{0.12}$	2 peaks
J1614-2230	352.64	20.19	3.15	0.34	4.30	$0.77^{0.05}_{0.05}$	3 peaks
J1658-5324	334.87	-6.63	2.44	1.08	29.28	$0.93^{0.11}_{0.13}$	ramp
J1744-1134	14.79	9.18	4.07	0.77	4.52	$0.42^{0.02}_{0.02}$	dome+peak
J1810+1744	44.64	16.81	1.66	0.46	39.93	$2.00^{0.31}_{0.28}$	ramp
J1902-5105	345.65	-22.38	1.74	0.88	66.00	$1.18^{0.22}_{0.21}$	3 peaks
J1939+2134	57.51	-0.29	1.56	10.68	1110.82	$3.56^{0.35}_{0.35}$	2 peaks
J1959+2048	59.20	-4.70	1.61	1.19	112.74	$1.4^{1.0}_{0.5}$	dome+peak
J2017+0603	48.62	-16.03	2.90	0.81	13.14	$0.9^{0.4}_{0.4}$	3 peaks
J2043+1711	61.92	-15.31	2.38	0.38	11.10	$1.76^{0.15}_{0.32}$	2 peaks
J2124-3358	10.93	-45.44	4.93	1.10	3.63	$0.30^{0.07}_{0.05}$	ramp
J2214+3000	86.86	-21.67	3.12	1.30	16.89	$0.60^{0.31}_{0.31}$	dome+peak
J2241-5236	337.46	-54.93	2.19	0.87	32.70	$0.51^{0.08}_{0.08}$	dome+peak
J2302+4442	103.40	-14.00	5.19	1.38	3.91	$1.19^{0.09}_{0.23}$	3 peaks

Phase-resolved spectra



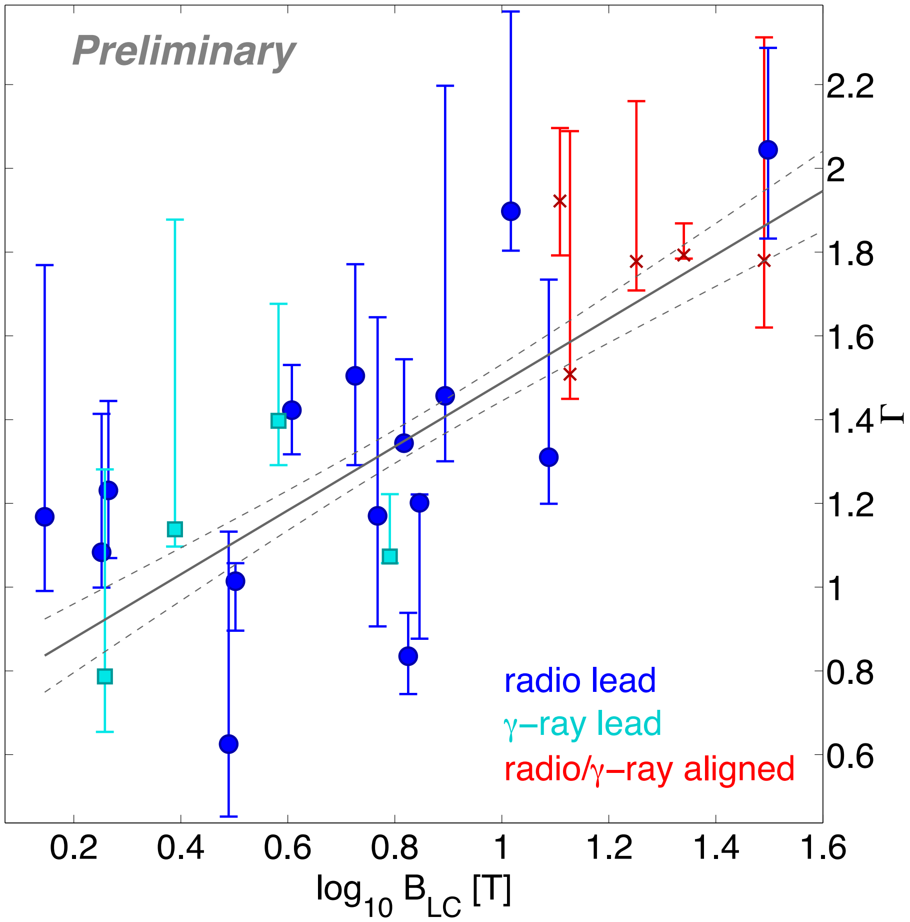
P1 Leading
P1 Core
P1 Trailing
Bridge
P2 Leading
P2 Core
P2 Trailing
P3

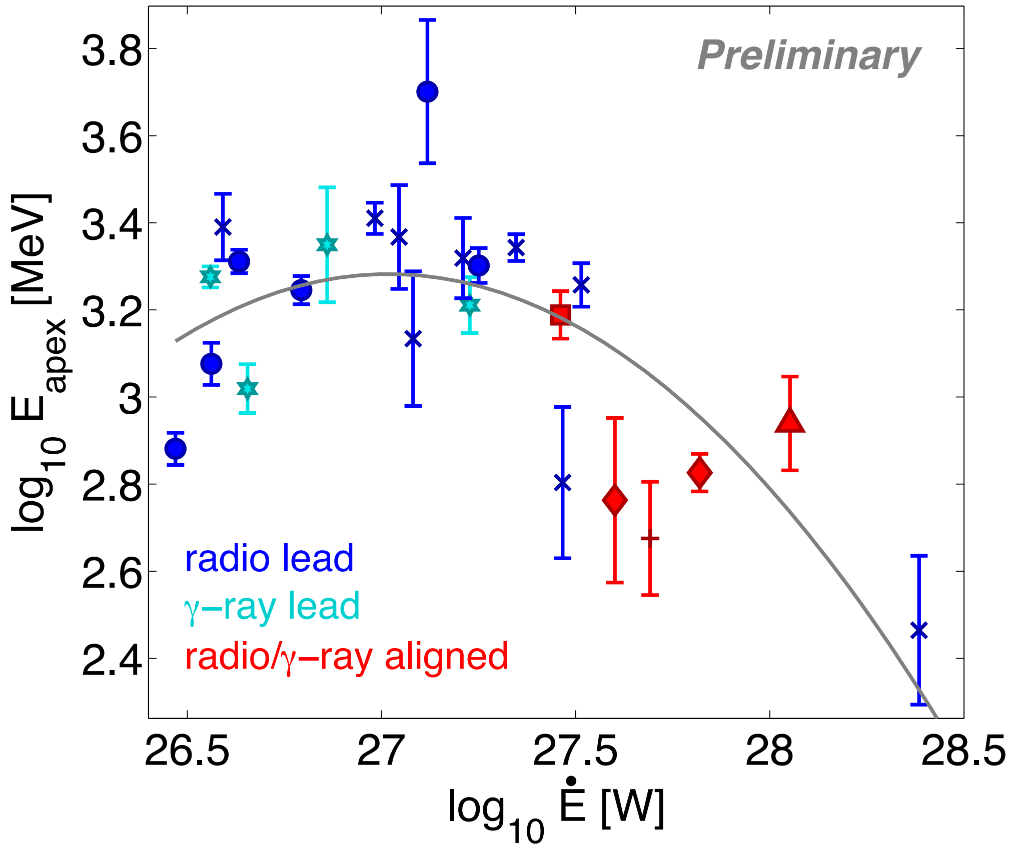


- **Measurable spectral variations across phase**

MSP spectral sequence

Classification by Johnson et al. 2014



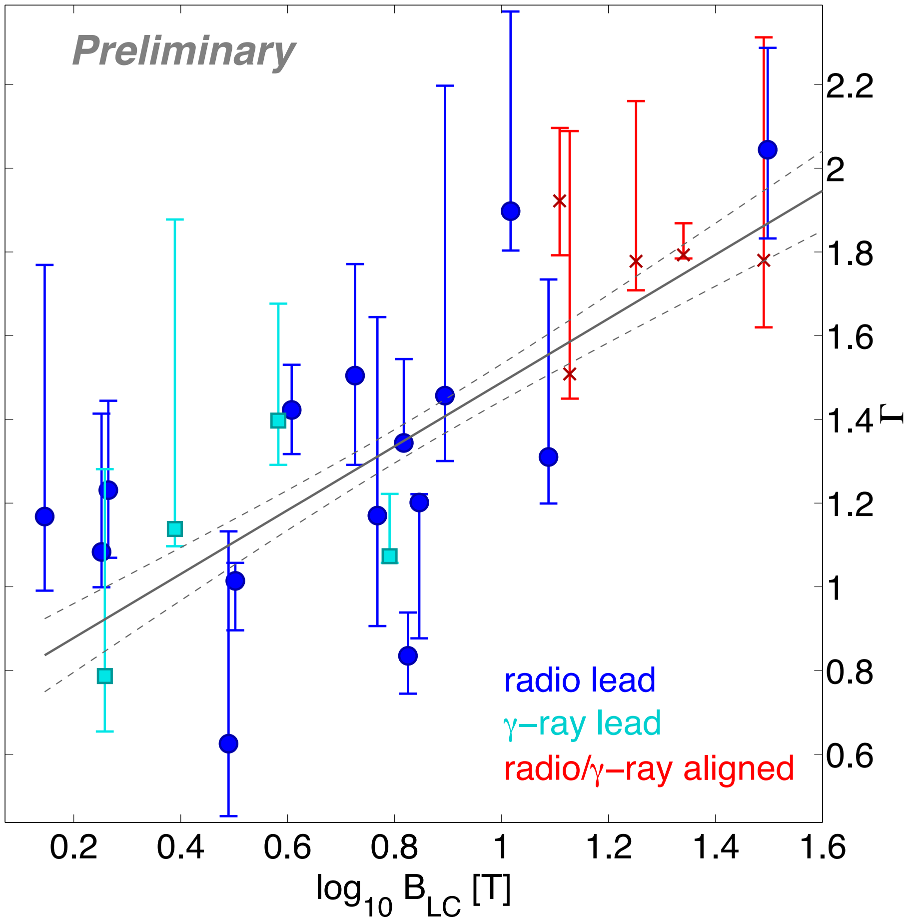


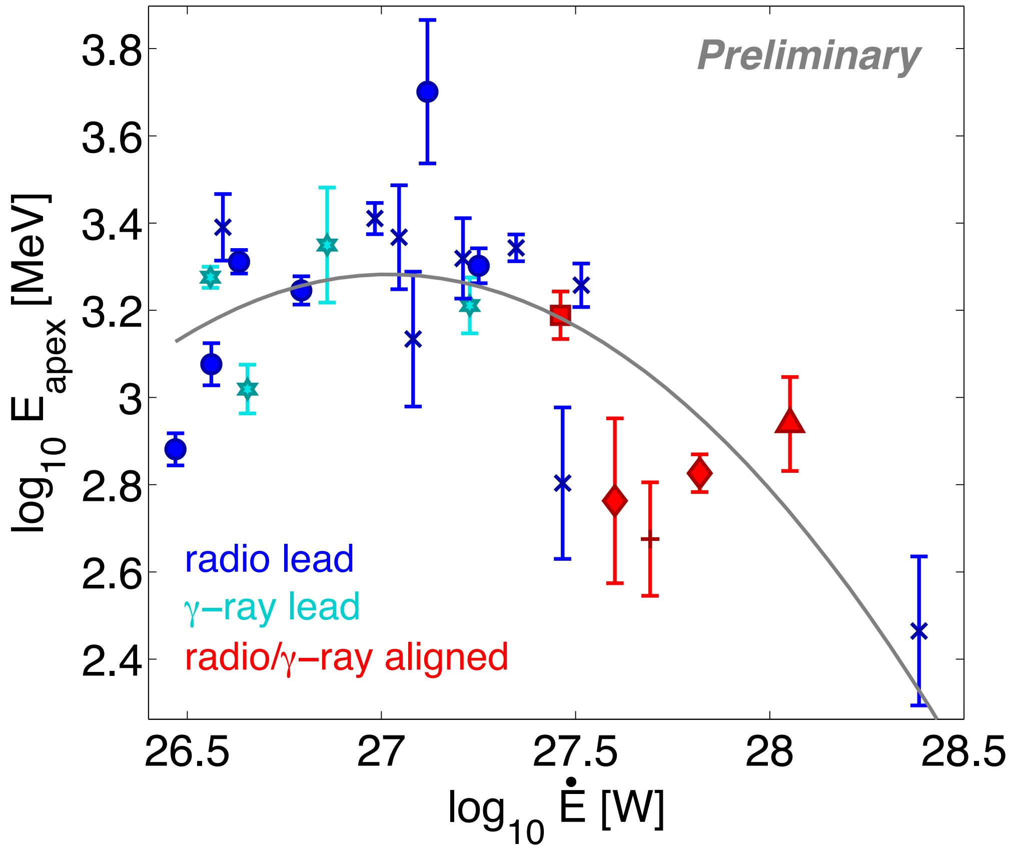
- **Softening with B_{LC} (and $\dot{E}$)**
  - **Γ constant with B_{LC} rejected at >10σ**
- **Shift in E_{apex} with $\dot{E}$ (and B_{LC})**
  - **Curvature testing (« pairwise slope statistics », Abrevaya et Jiang 2003)**

  ➔ P_{curv} = 99,97 %

MSP spectral sequence

Classification by Johnson et al. 2014

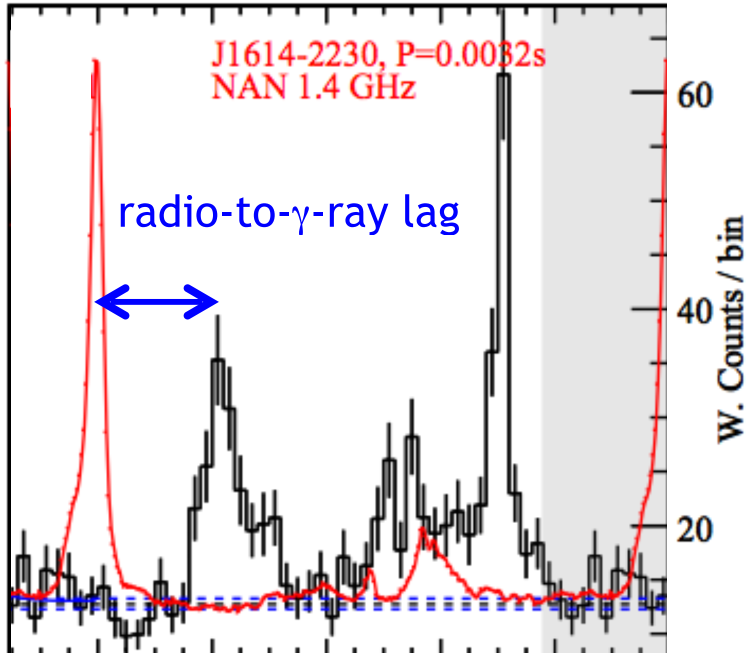


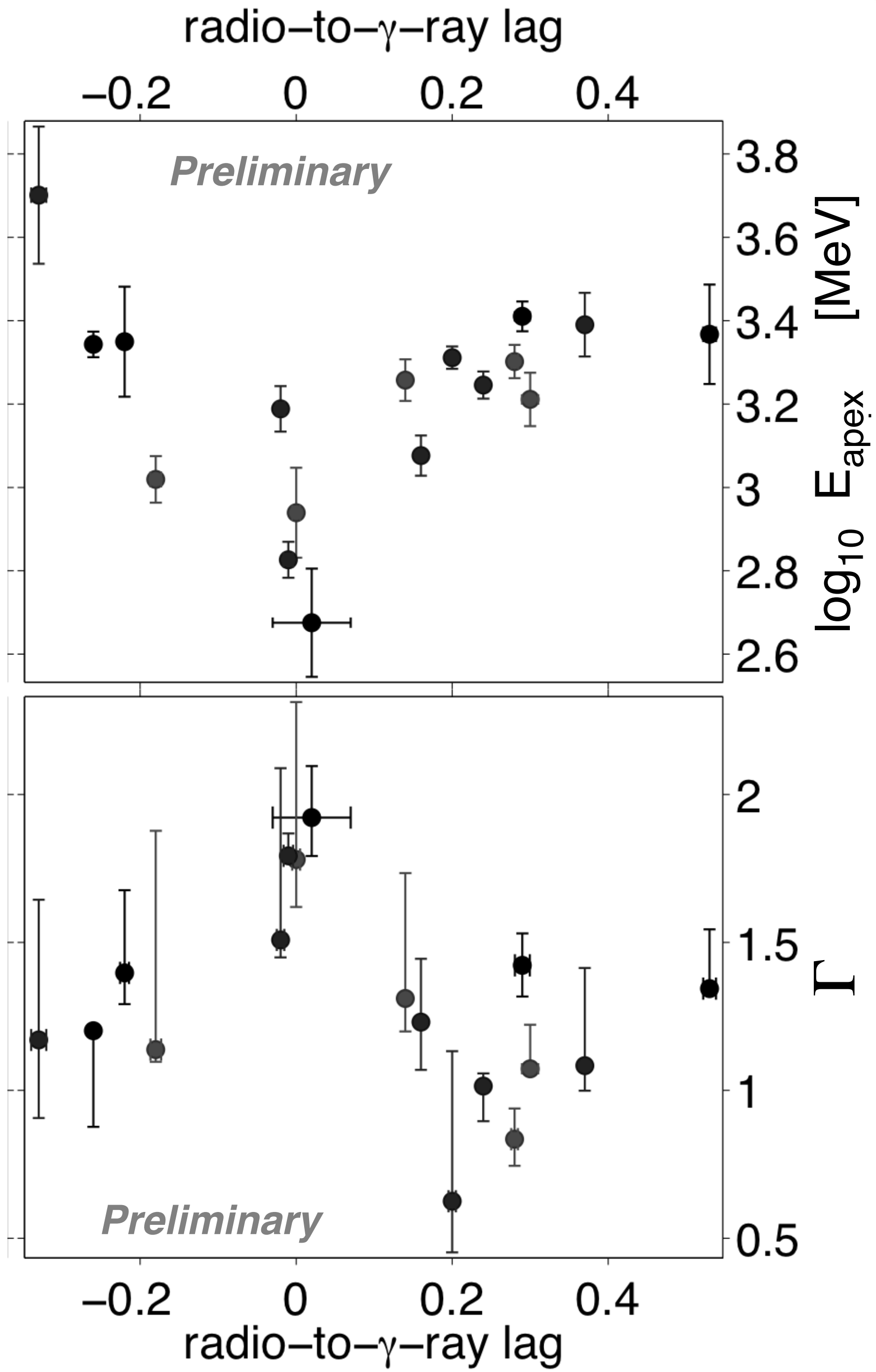


- **Toy model of curv.-radiation spectra:**
  - **primaries near the light cylinder with various Γ_{max} Lorentz factors**
  - **curv. radius = R_{LC} (Hirotani 2011)**
  - **cannot reproduce the E_{apex} vs Edot and Γ vs B_{LC} trends**
  - **➔ Additional softer component required**

- **Synchroton component from primary pairs**
  - **too high energy γ rays for secondary pairs**
  - **for the SG (Harding et al. 2008) or OG models (Takata et al. 2008)**
- **Smooth transition layer from $E_{//}\neq 0$ to $E_{//}=0$ ➔ CR at a few hundred MeV**
  - **for the OG (Wang et al. 2010) or FIDO models (Kalapotharakos 2014)**

radio and γ-ray alignment





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

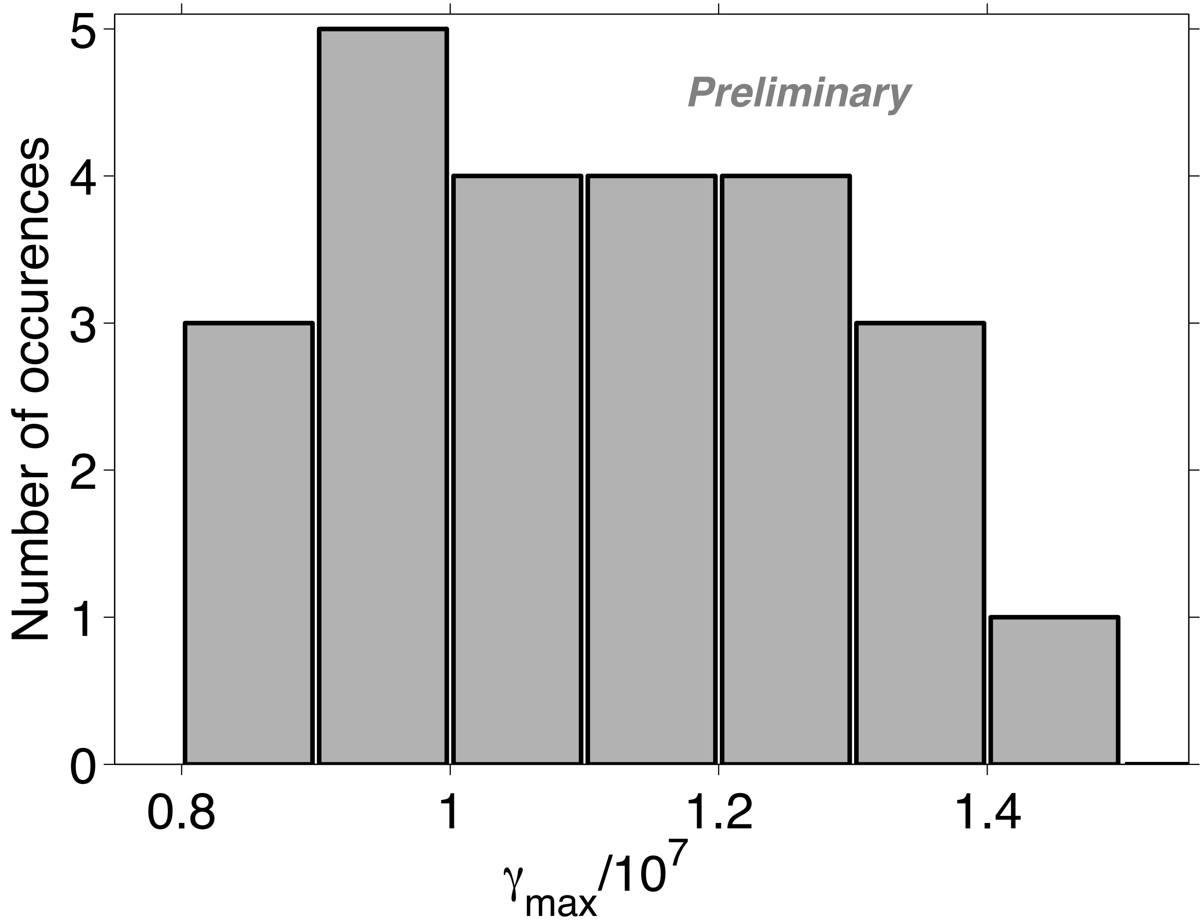
➔ **Synchrotron component from pairs gaining pitch angle by cyclotron resonant absorption of co-located radio photons (Harding et al. 2008) ?**

Saturation of Lorentz factors

- Maximum Lorentz factor estimation from E_{cut}
  - for the total emission
  - assuming curv. radiation
  - with curv. radius = R_{LC}

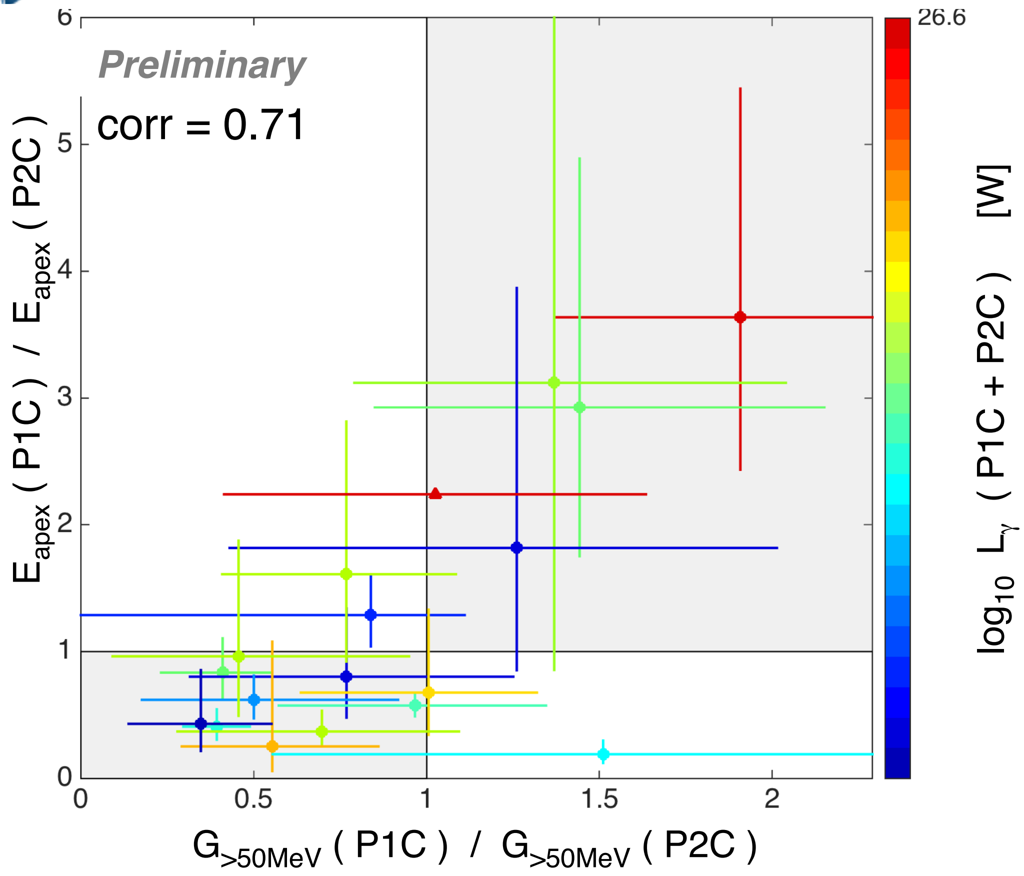
    (Hirotani 2011)

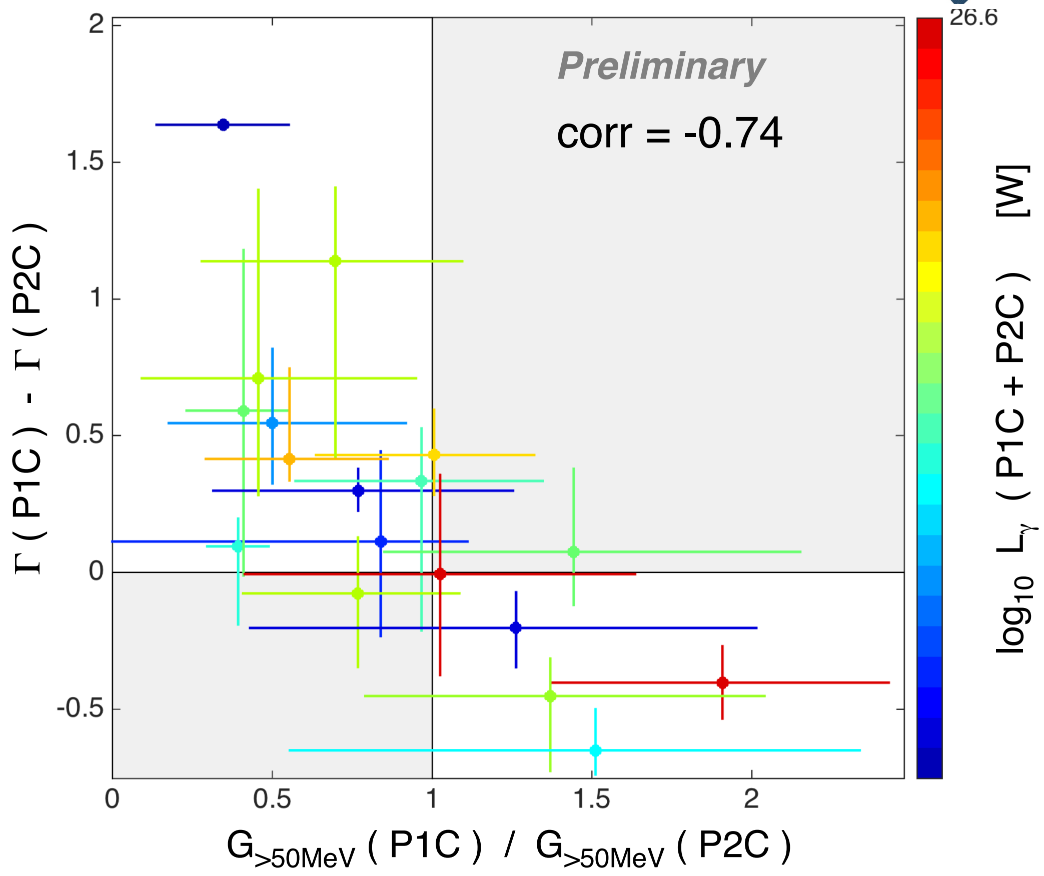
$$\Gamma_{max} = \left(E_{cut} \frac{2}{3} \frac{R_{LC}}{\hbar c} \right)^{1/3}$$



- Narrow Γ_{max} distribution around 10^7

Spectral trends for peaks

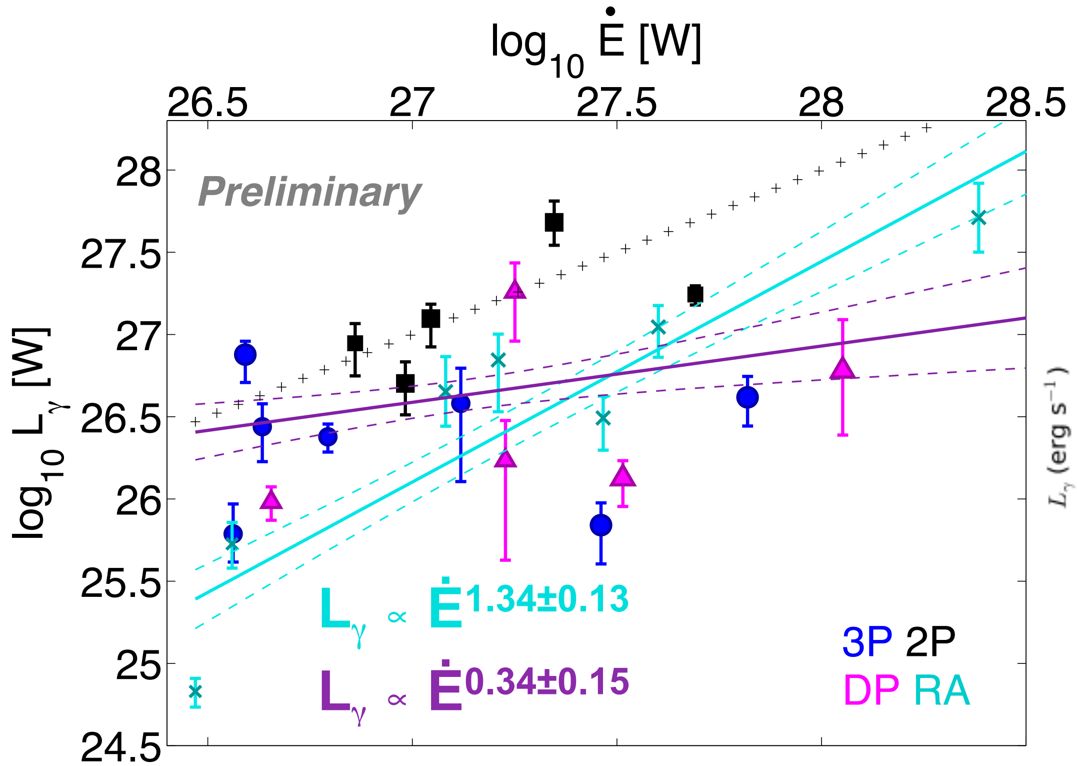




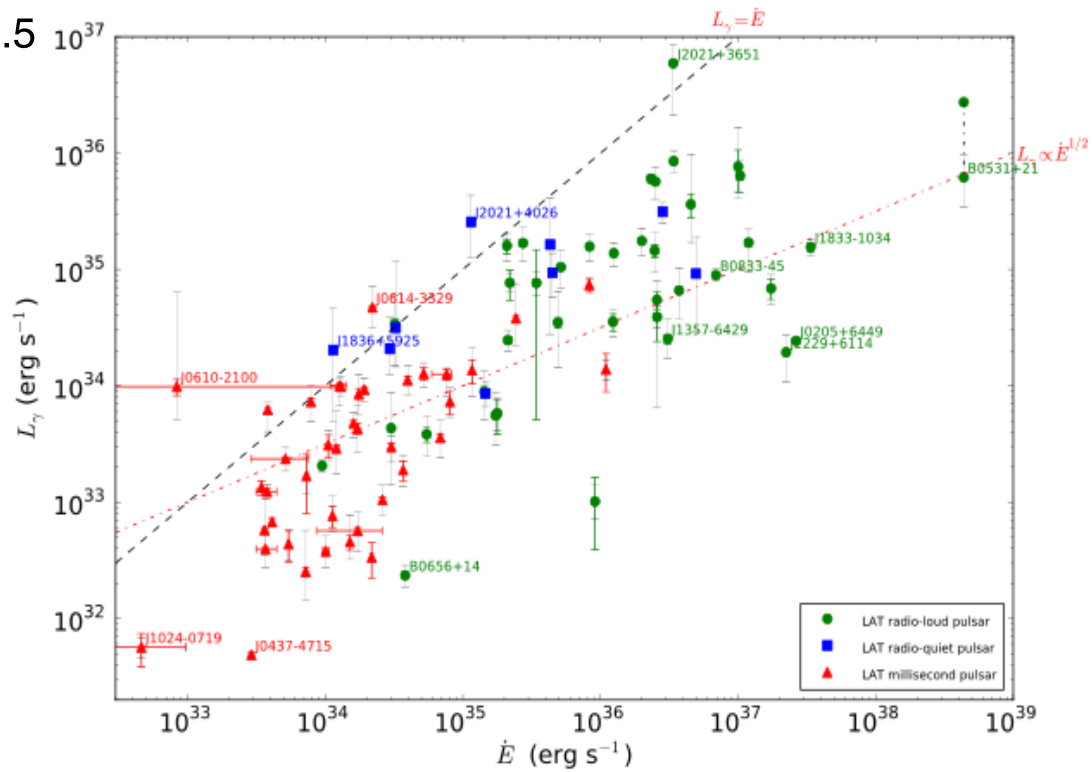
- **The brighter the core, the harder the SED (lower Γ), the higher the apex energy**
  - **Irrespective of the peak order**
- **Expected if dominant curv. radiation**

- **Inconsistent with classical OG/SG models (harder 2nd peak)**
- **Consistent with new FIDO model** (Kalopotharakos et al. 2014)
- **Potential diagnostic to discriminate 1- vs 2-pole emission models**

Different emission regions/regimes



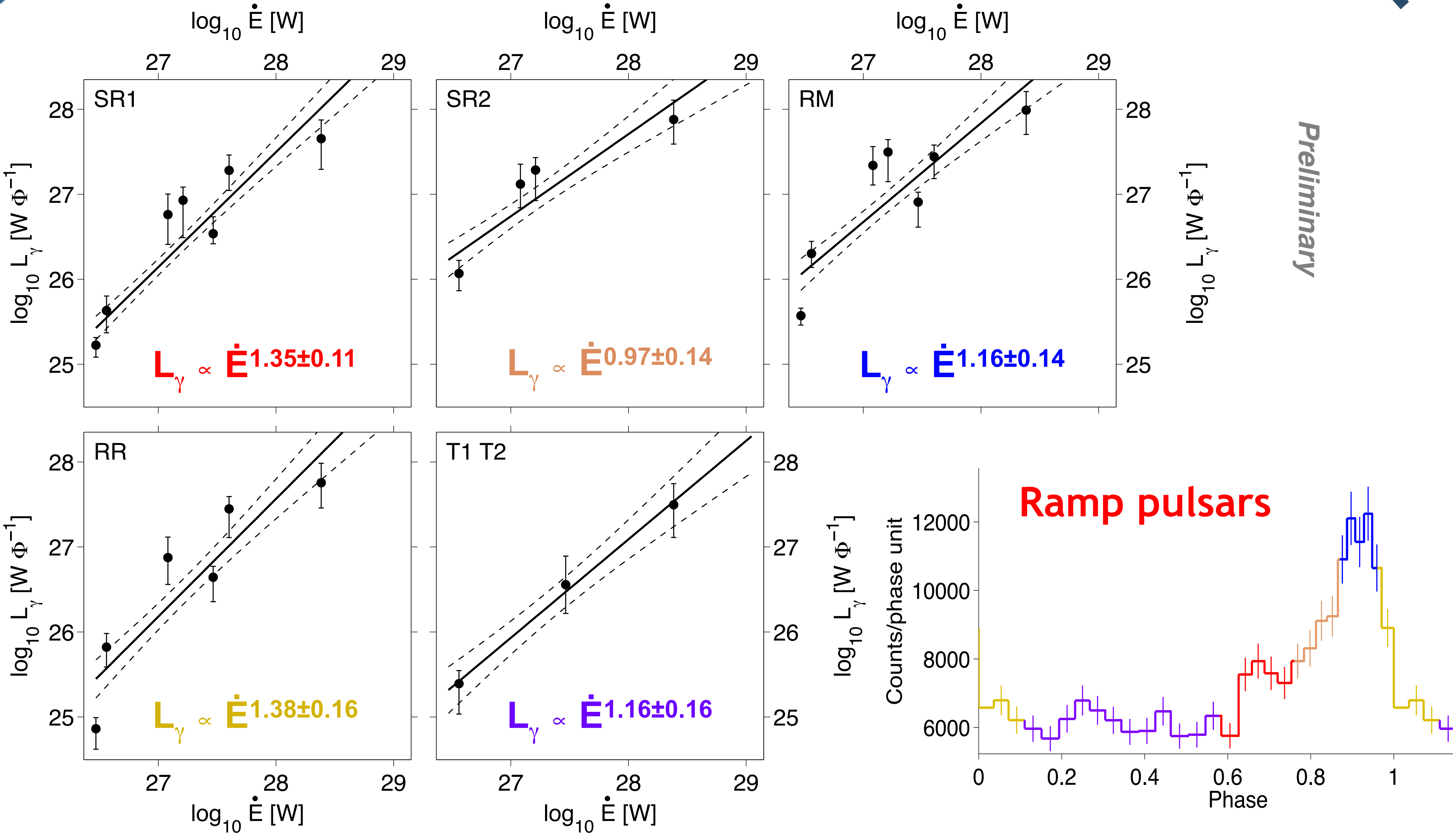
Second Fermi-LAT Pulsar Catalog, Abdo et al. 2013



$$L_\gamma = 4\pi G_{>50\mathrm{MeV}} d^2$$

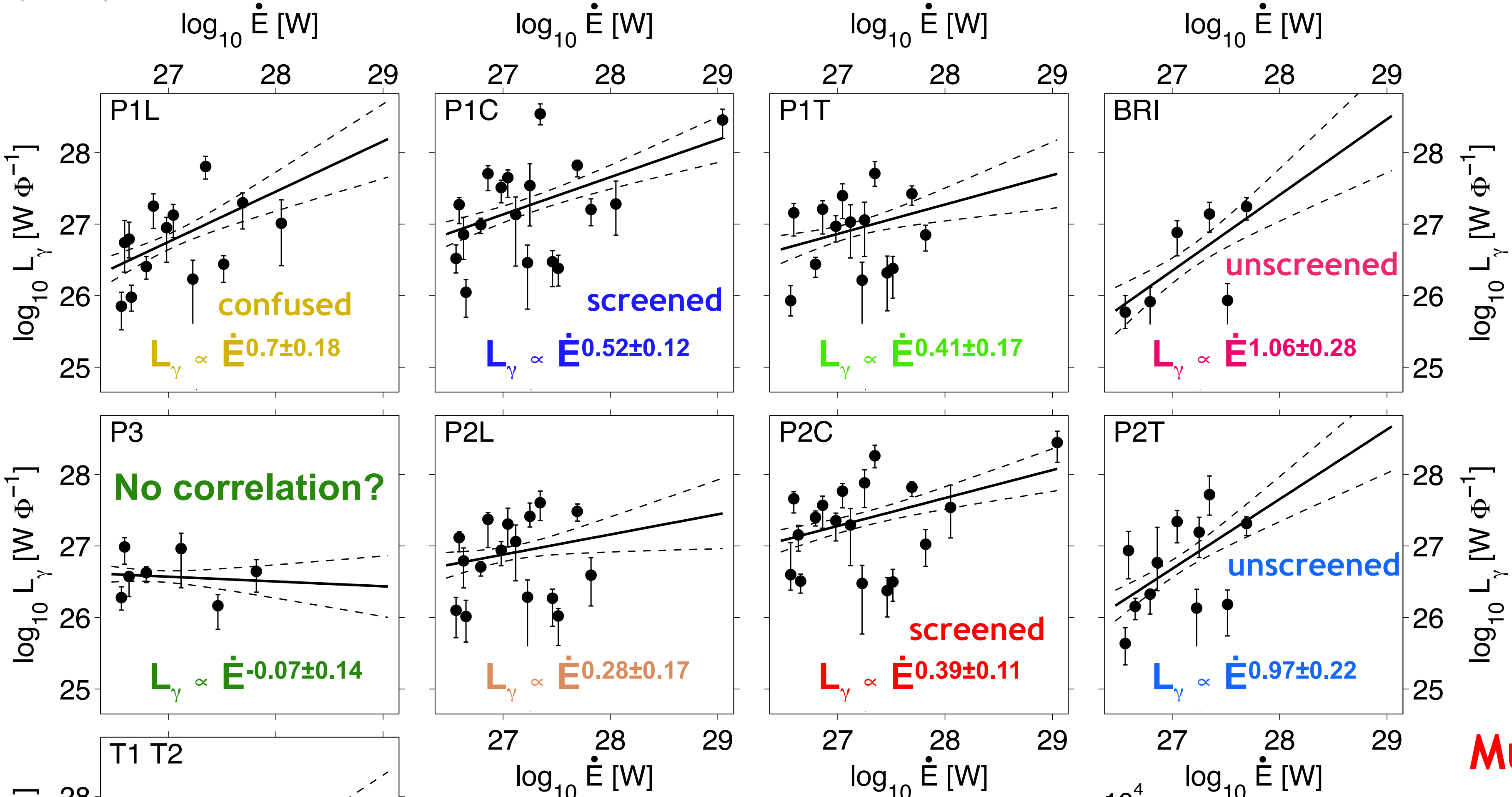
- **Total emission**
  - **Trend and dispersion consistent with 2PC**
- **But :**
  - **Multi-peaks : $L_\gamma \propto \sqrt{\dot{E}}$ ➔ screened thin gap near last closed B line dominates the output**
  - **Ramps : $L_\gamma \propto \dot{E}$ ➔ unscreened thick region partially (?) filling the open magnetosphere**

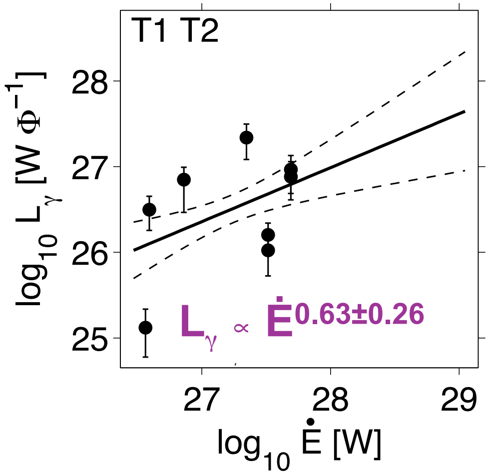
Ramps: uniform emission region/regime



- **No evolution across phase → single emission region?**

Different emission regions/regimes

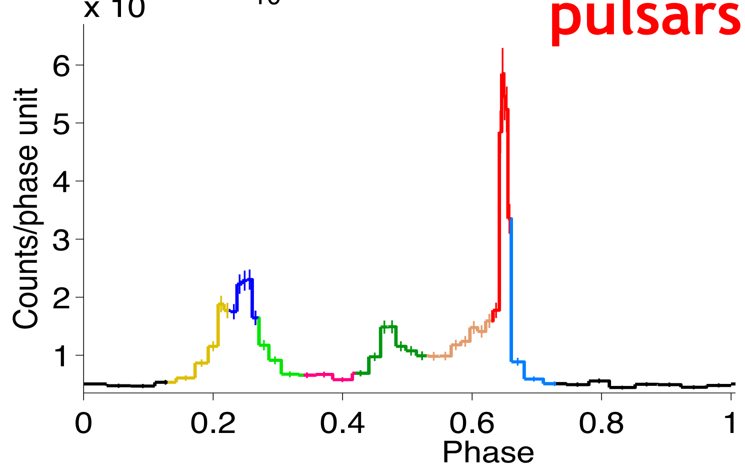




Preliminary

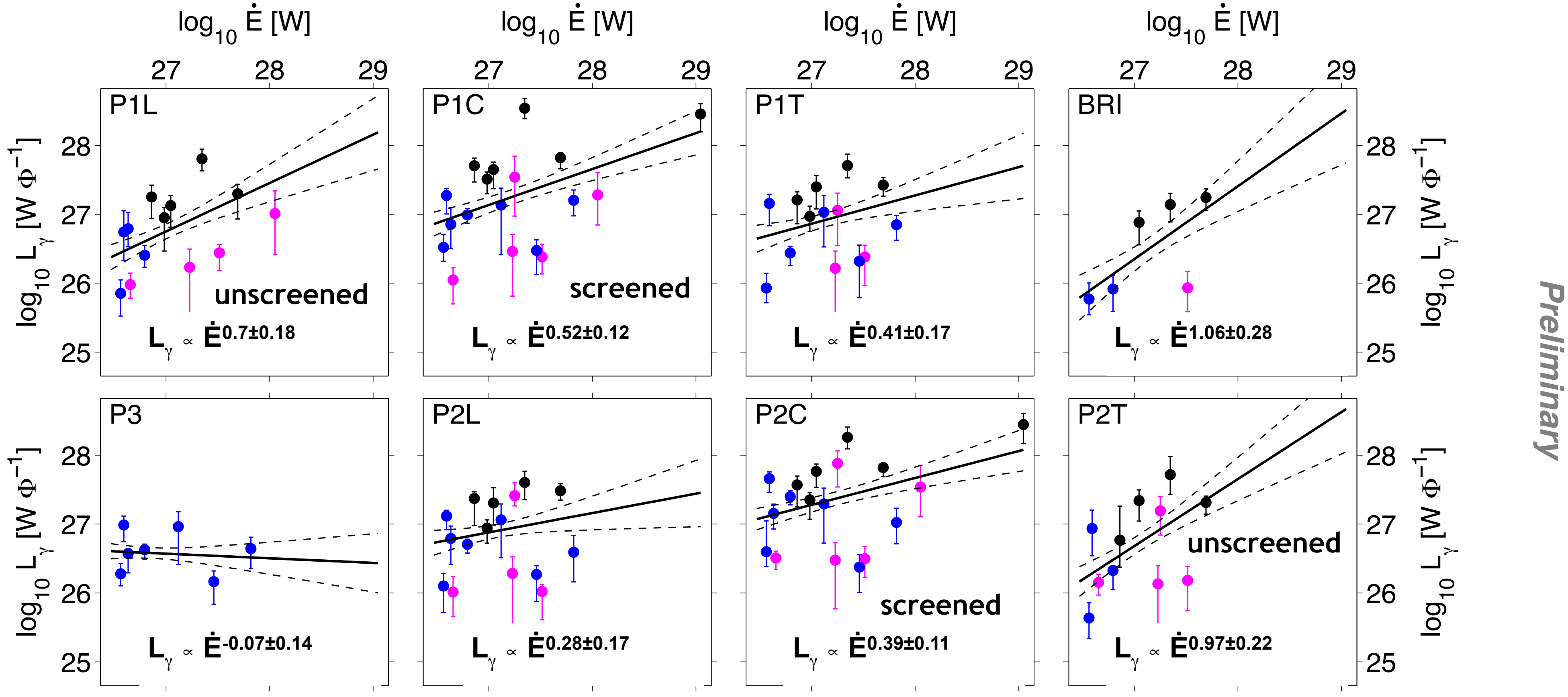
→ **Change of screening properties across phase**

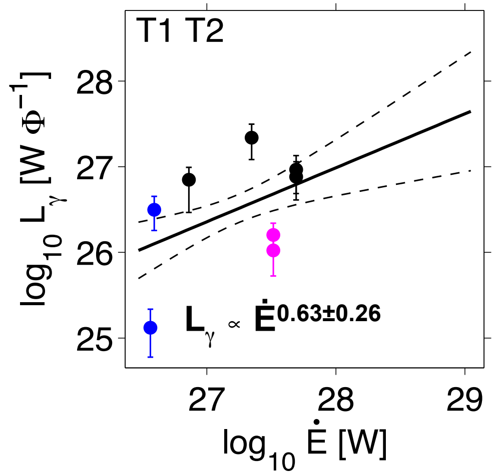
- **Marginal changes of E_{apex} vs $\dot{E}$ across phase**



Multi-peak pulsars

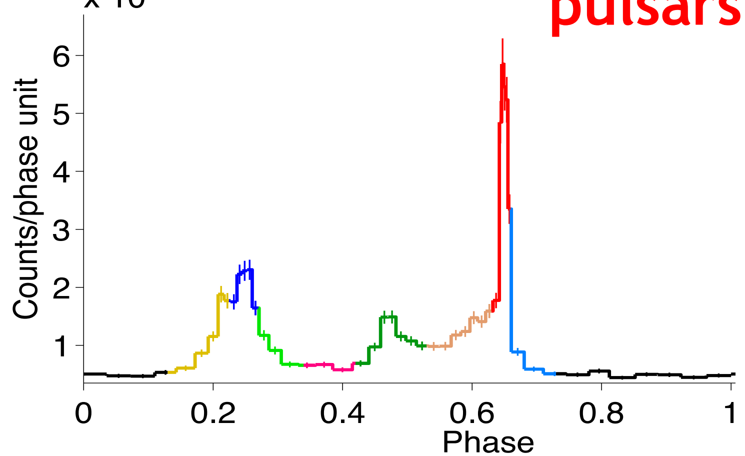
Different emission regions/regimes





→ **Change of screening properties with the morphology ?**

Multi-peak pulsars

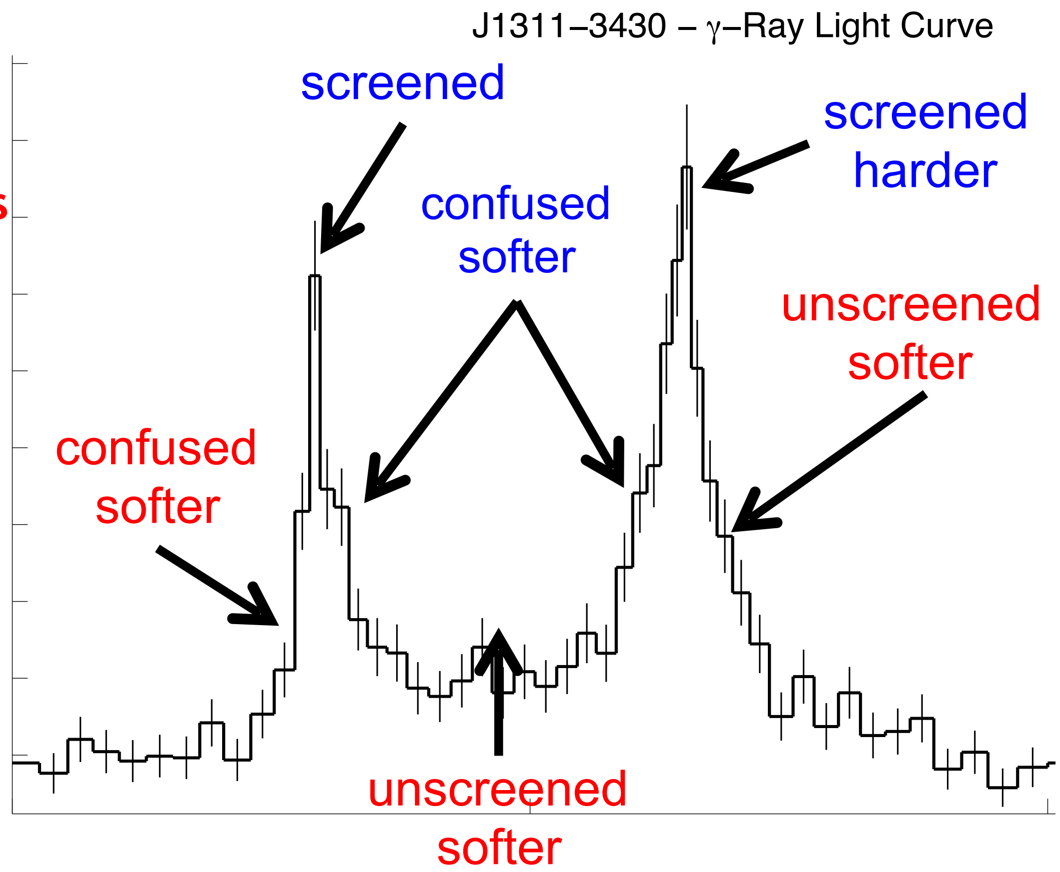


Conclusions

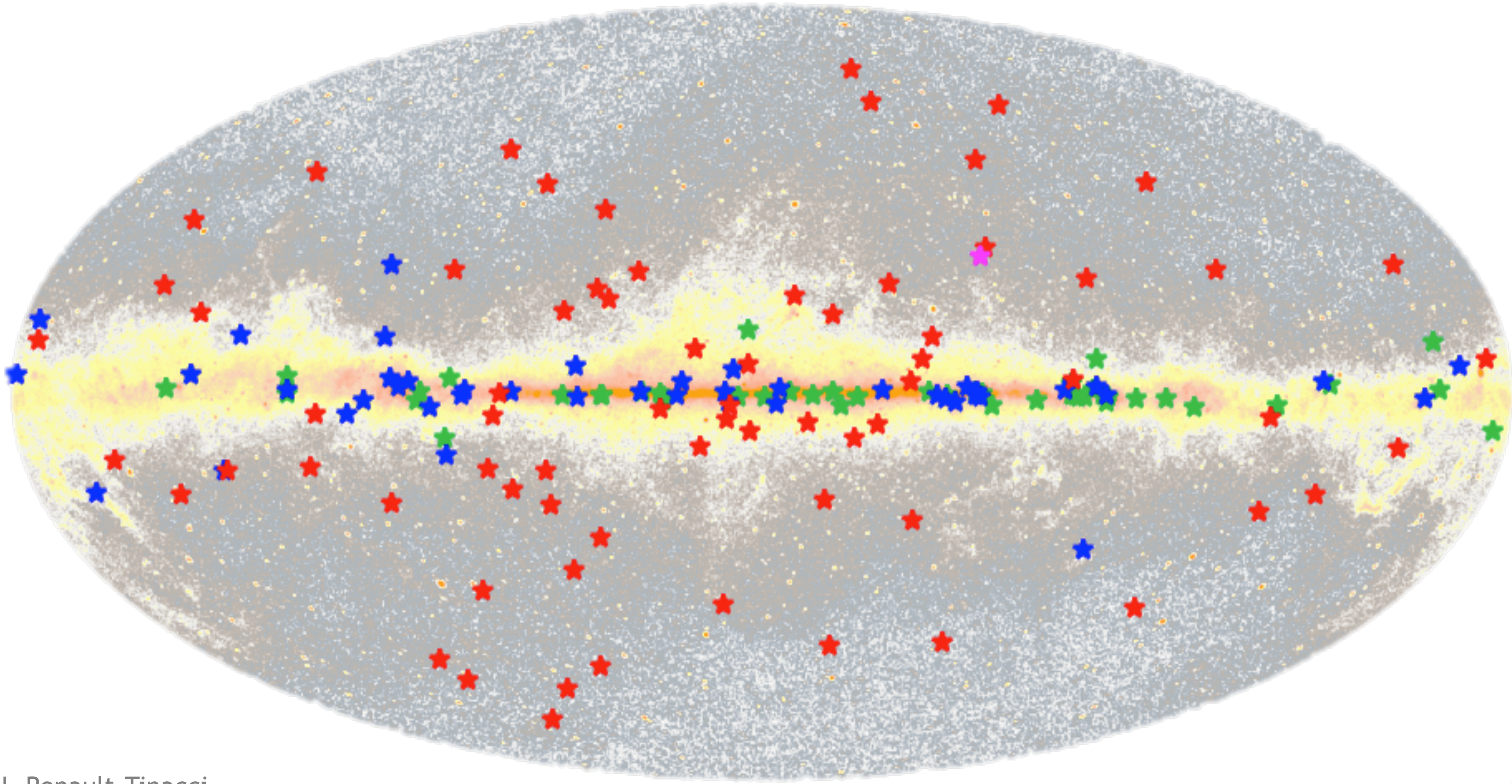
- Need to re-think the classical picture of thin caustic gaps/wide unscreened regions
  - possibly co-existing in the magnetosphere and both contributing to the observed pulsed emission
  - Impact of the morphology/geometry ?

- MSP spectral sequence with $\dot{E}$:
  - potential influence of radio emission
  - need for an additional soft radiation component
  - synchrotron radiation from primary pairs and/or CR smooth transition layer in $E_{//}$

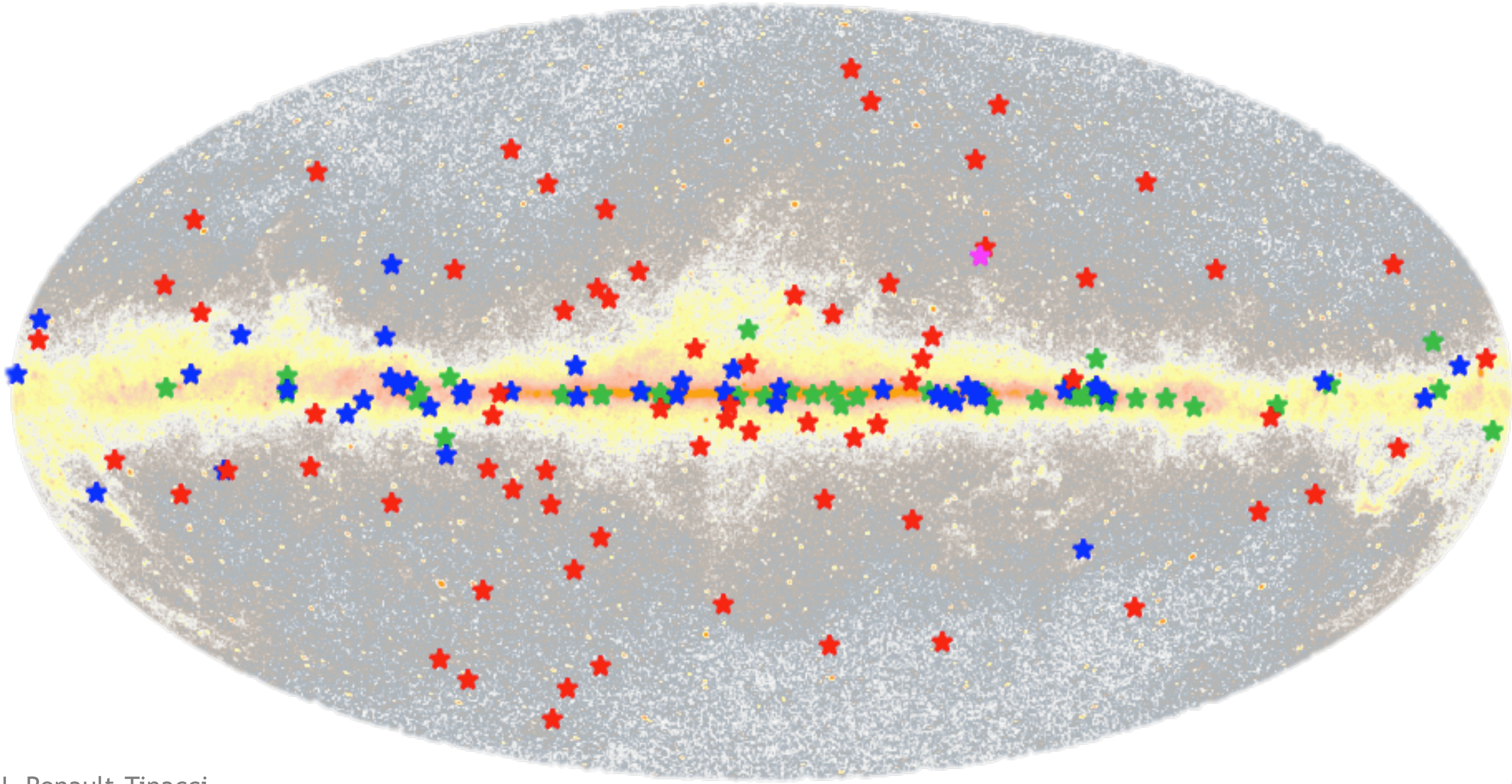
- The brighter the core, the higher the apex energy, the harder the SED
  - CR dominant and potential diagnostic for 1 or 2 emission poles
- Softer emission and lower E_{apex} outside the main peaks
- Perspectives
  - confirm trends with 8 years of Pass 8 data and with larger MSP sample
  - same analyses for young pulsars to accompany future pulsar catalog



Thank you for your attention



BACK-UP

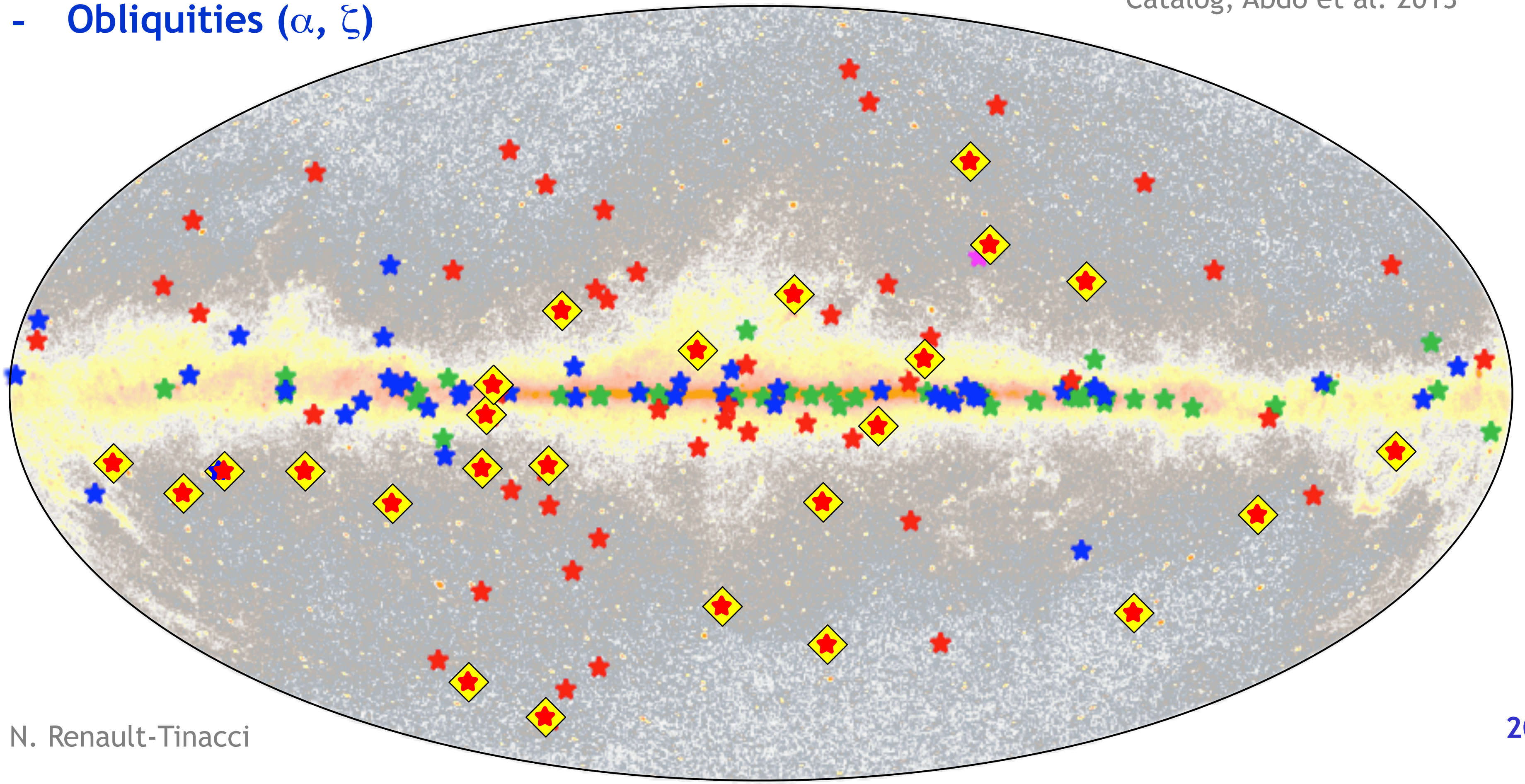


MSP sample

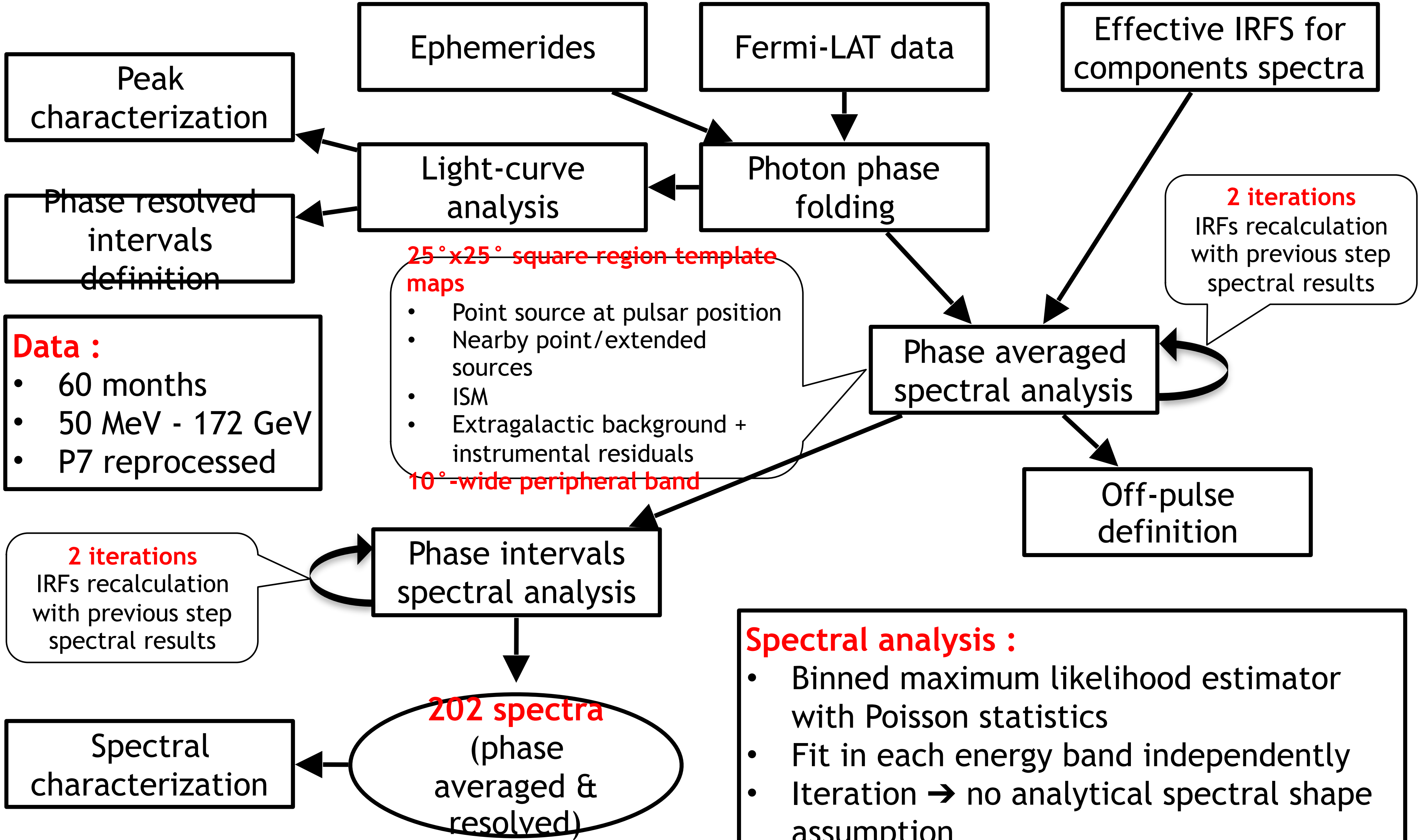
- 25 millisecond pulsars
  - Bright
  - Bright enough wrt background
- Good sampling of the MSP population in
  - Spatial (l, b)
  - Timing (P, Pdot)
  - Energetics ($\dot{E}$, B_{LC}, …)
  - Obliquities (α, ζ)

Millisecond pulsars •
Young pulsars •
Studied MSPs ◆

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



Detailled analysis protocol

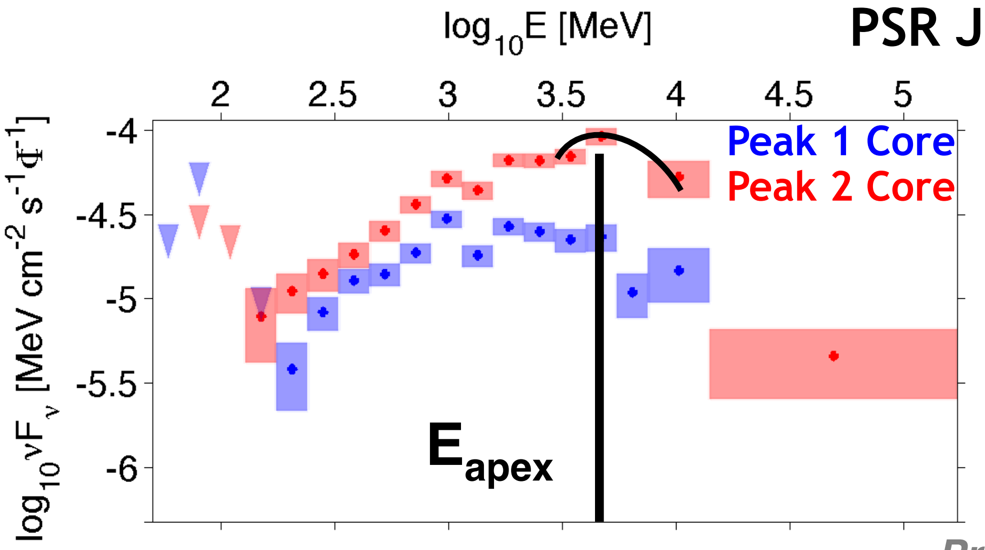


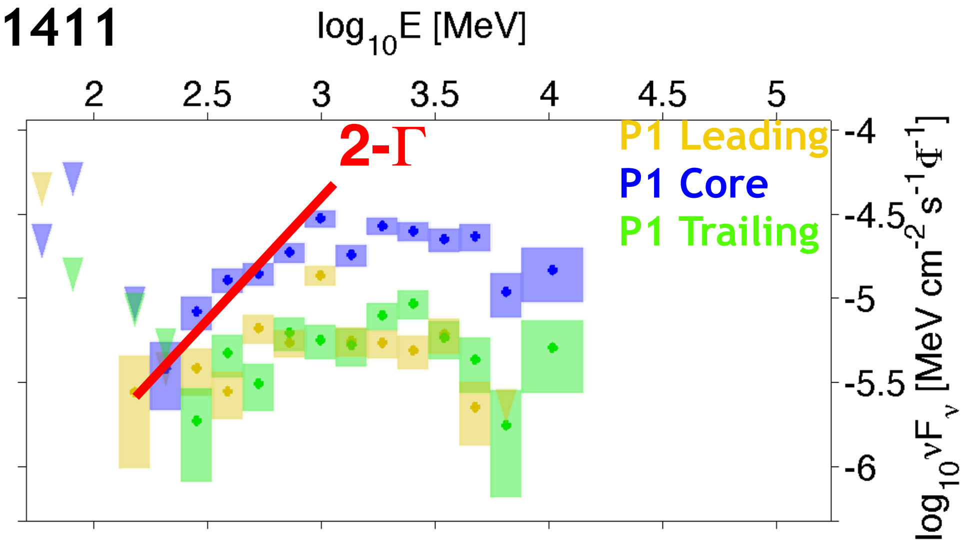
Data :
- 60 months
- 50 MeV - 172 GeV
- P7 reprocessed

Spectral analysis :
- Binned maximum likelihood estimator with Poisson statistics
- Fit in each energy band independently
- Iteration → no analytical spectral shape assumption

Phase-resolved spectra

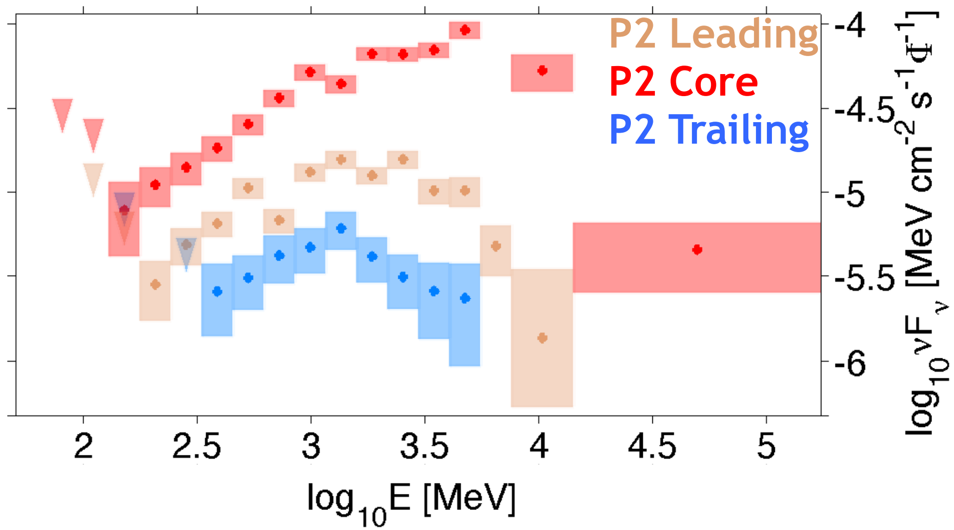
PSR J1231-1411



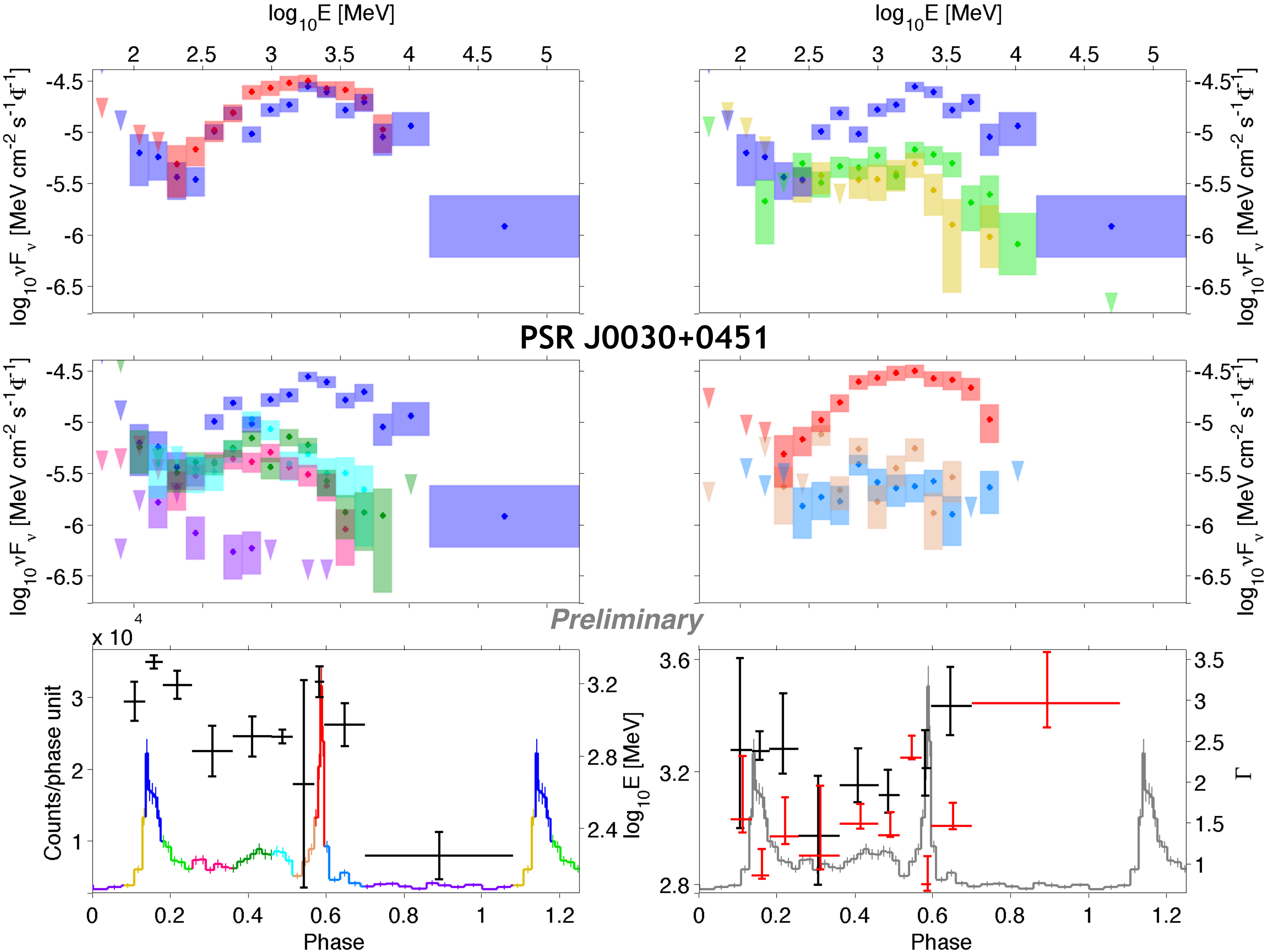


Preliminary

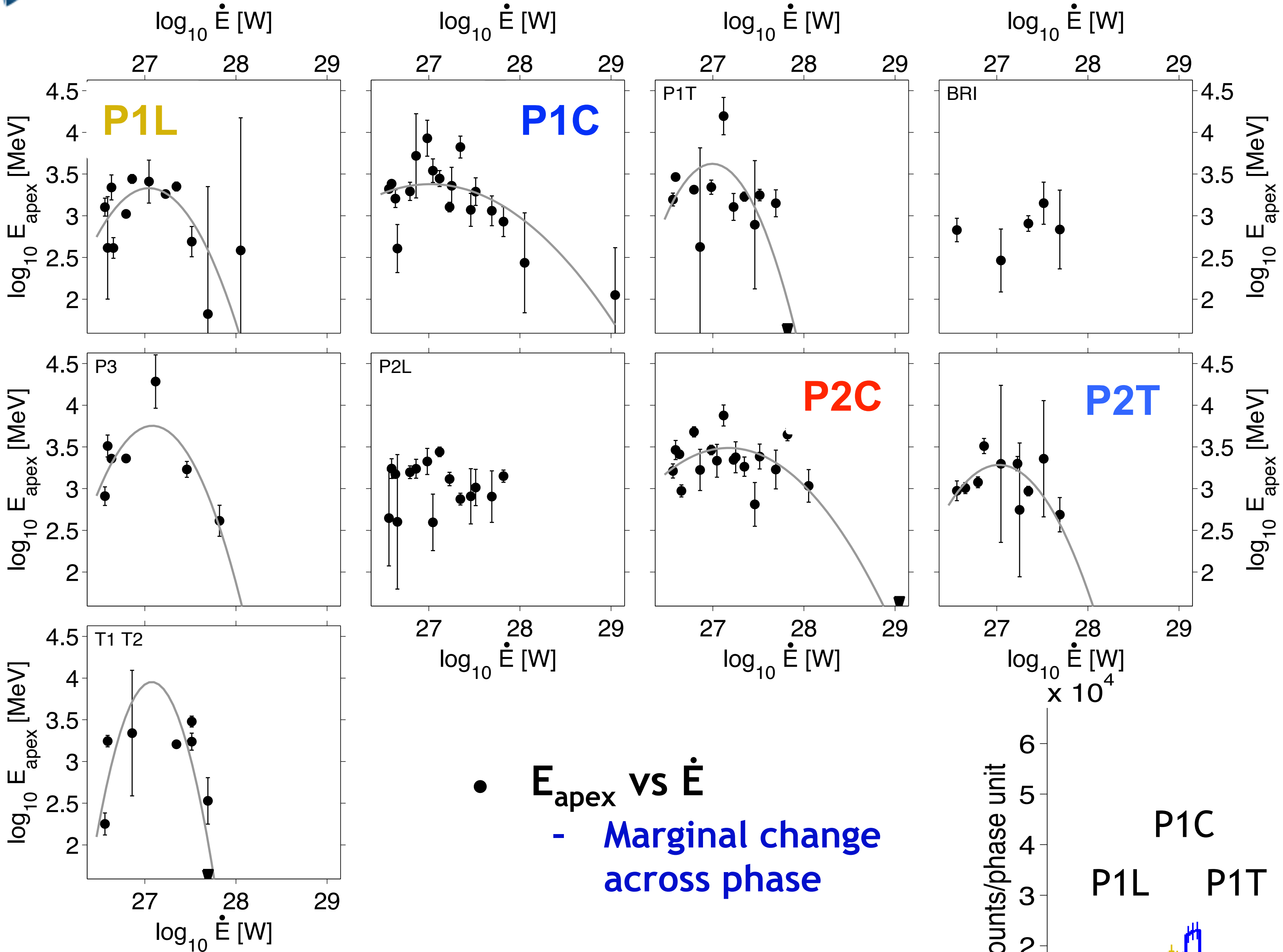
- Photon index, Γ ⇔ primary particle distribution, cascade development and/or photon pile-up in phase
- Apex Energy, E_{apex} ⇔ max radiative power produced in the acceleration/emission regions
- Cut-off energy, E_{cut} ⇔ Maximum pair energy or γ-γ pair absorption



Spectral behaviour across phase (multi-peak)



P1 Leading
P1 Core
P1 Trailing
BRI Bridge
P3
P2 Leading
P2 Core
P2 Trailing



P_{curv} = 96,5 %

P_{curv} = 95,9 %

➔ Correlation E_{apex} with $\dot{E}$

P_{curv} = 99,9 %

➔ Correlation E_{apex} with $\dot{E}$

P_{curv} = 83,2 %

➔ Possible correlation

- E_{apex} vs $\dot{E}$
  - Marginal change across phase