Phase resolved spectral analysis of Fermi-LAT millisecond pulsars
1. Trends with energy
2. Trends with phase

2 papers

N. Renault-Tinacci

In collaboration with :
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Johnson, Q. Remy, C. Venter.

Walkthrough

WAM
1 April 2016

National Aeronautics and Space Administration

NASA

Fermi

Gamma-ray Space Telescope

www.nasa.gov/fermi

CEA – Saclay

AIM

- **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)**

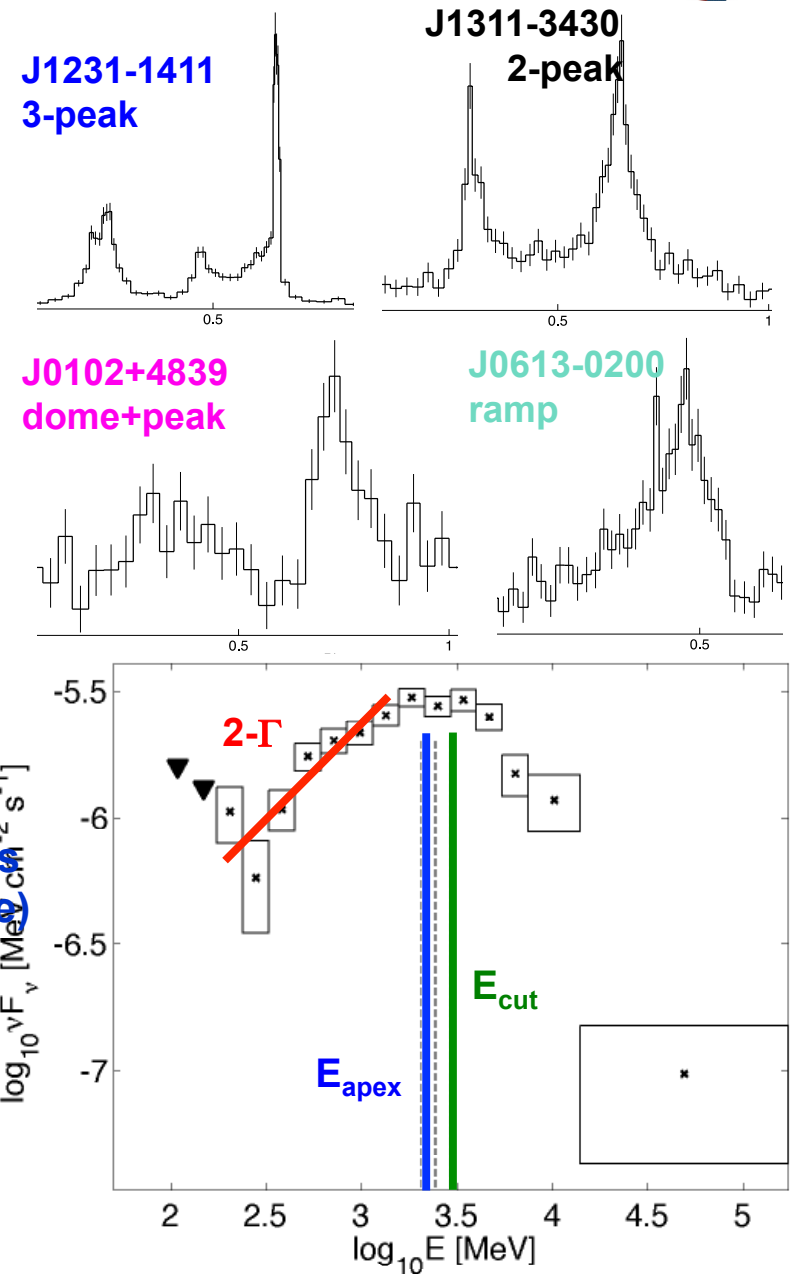# **1st systematic phase-resolved spectral analysis of γ-ray MSPs**

- **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?**

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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 θ_{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 as in gtlike)**

- **Subsequent spectral characterization:**
  - **bivariate max-likelihood fit of PL Exponential Cut-Off**
  - **local quadratic fit of SED apex energy**
  - **energy flux $G_{>50MeV}$ and luminosity L_γ above 50 MeV**

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Preliminary

J1231-1411
3-peak

J1311-3430
2-peak

J0102+4839
dome+peak

J0613-0200
ramp

2-Γ

E_{cut}

E_{apex}

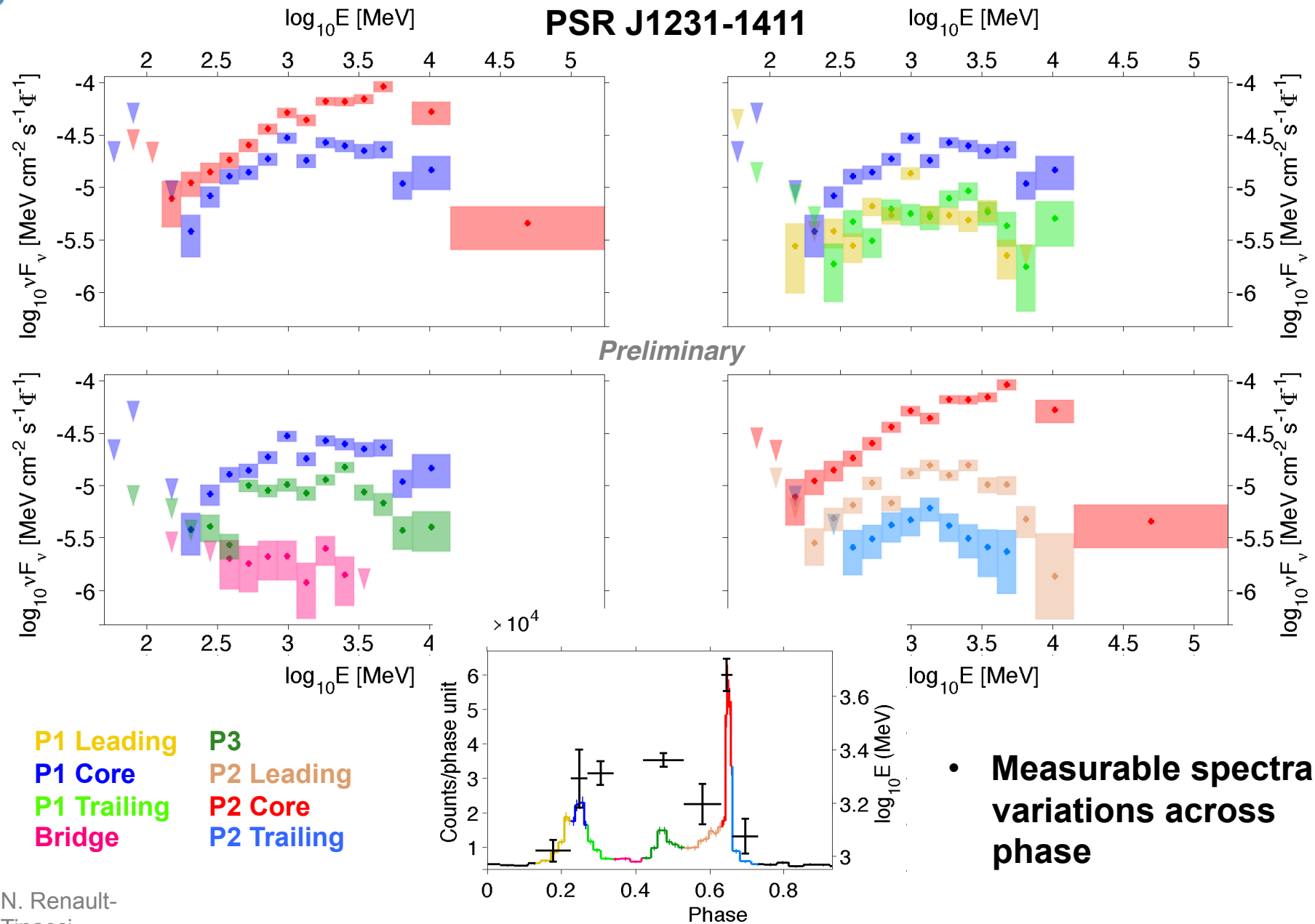$\log_{10} \nu F_\nu$ [MeV cm^{-2} s^{-1}]

$\log_{10} E$ [MeV]

- **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	b	P	$\dot{P}$	$\dot{E}$	Distance[a,b]	light-curve morphology
	(deg)	(deg)	(ms)	(10^{-20} s s^{-1})	(10^{26} W)	(kpc)	
J0030+0451	113.14	-57.61	4.87	1.06	3.62	$0.28^{0.10}_{0.06}$	3 peaks
J0034−0534†	111.49	-68.07	1.88	0.29	17.18	$0.54^{0.11}_{0.10}$	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	7.69	243.19	$2.64^{1.08}_{0.64}$	ramp
J0340+4130	153.78	-11.02	3.30	0.59	6.48	$1.73^{0.29}_{0.30}$	2 peaks
J0437−4715	253.39	-41.96	5.76	1.41	2.91	$0.156^{0.001}_{0.001}$	ramp
J0613−0200	210.41	-9.30	3.06	0.87	12.03	$0.90^{0.40}_{0.20}$	ramp
J0614−3329	240.50	-21.83	3.15	1.78	22.48	$1.90^{0.44}_{0.35}$	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	0.65	5.15	$0.44^{0.05}_{0.05}$	3 peaks
J1311−3430	307.68	28.18	2.56	2.09	49.18	1.40	2 peaks
J1514−4946	325.25	6.81	3.59	1.87	15.96	$0.94^{0.11}_{0.12}$	2 peaks
J1614−2230	352.64	20.19	3.15	0.50	6.33	$0.65^{0.05}_{0.05}$	3 peaks
J1658−5324†	334.87	-6.63	2.44	1.10	29.89	$0.93^{0.11}_{0.13}$	ramp
J1744−1134†	14.79	9.18	4.07	0.70	4.11	$0.42^{0.02}_{0.02}$	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	0.90	67.45	$1.18^{0.22}_{0.21}$	3 peaks
J1939+2134†	57.51	-0.29	1.56	10.55	1096.59	$3.56^{0.35}_{0.35}$	2 peaks
J1959+2048†	59.20	-4.70	1.61	0.81	76.33	$2.49^{0.16}_{0.49}$	dome+peak
J2017+0603	48.62	-16.03	2.90	0.83	13.44	$1.57^{0.16}_{0.15}$	3 peaks
J2043+1711	61.92	-15.31	2.38	0.43	12.65	$1.76^{0.15}_{0.32}$	2 peaks
J2124−3358	10.93	-45.44	4.93	1.12	3.67	$0.30^{0.07}_{0.05}$	ramp
J2214+3000†	86.86	-21.67	3.12	1.50	19.50	$1.54^{0.19}_{0.18}$	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	1.33	3.76	$1.19^{0.09}_{0.23}$	3 peaks

Phase-resolved spectra

PSR J1231-1411

Preliminary

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

- **Measurable spectral variations across phase**

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Classification by Johnson et al. 2014

Preliminary

radio lead
γ–ray lead
radio/γ–ray aligned

Preliminary

radio lead
γ–ray lead
radio/γ–ray aligned
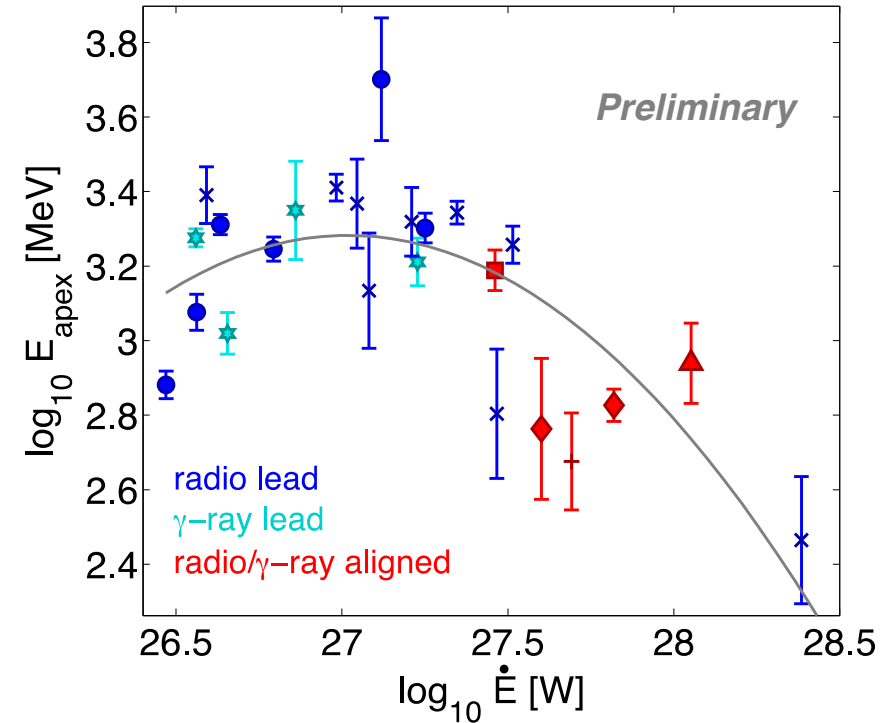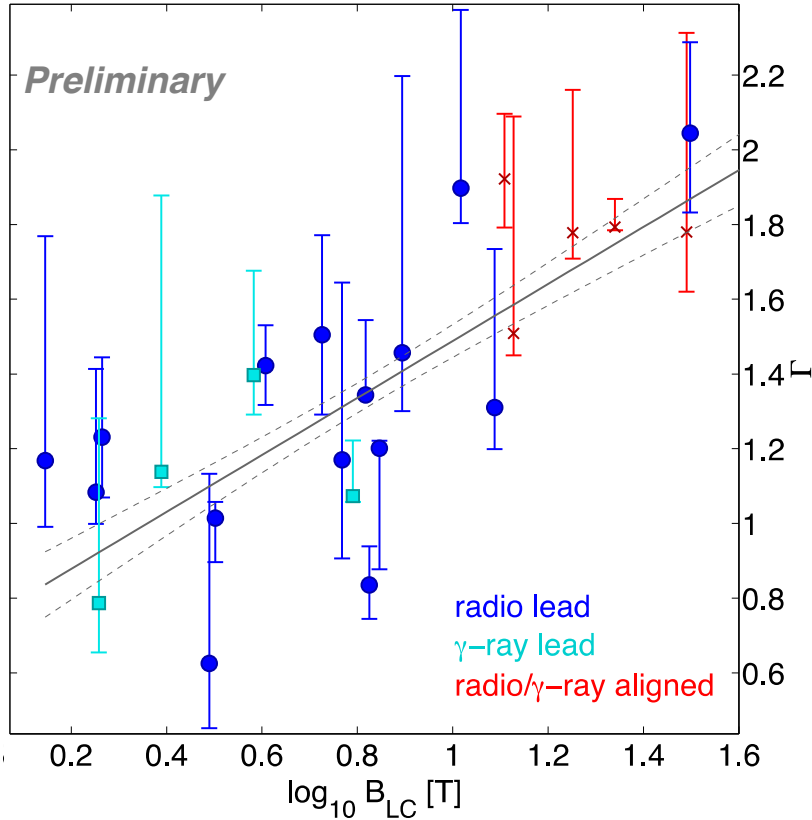
- **Softening with B_{LC} (and $\dot{E}$)**
  - Γ **constant with B_{LC} rejected at >10σ**

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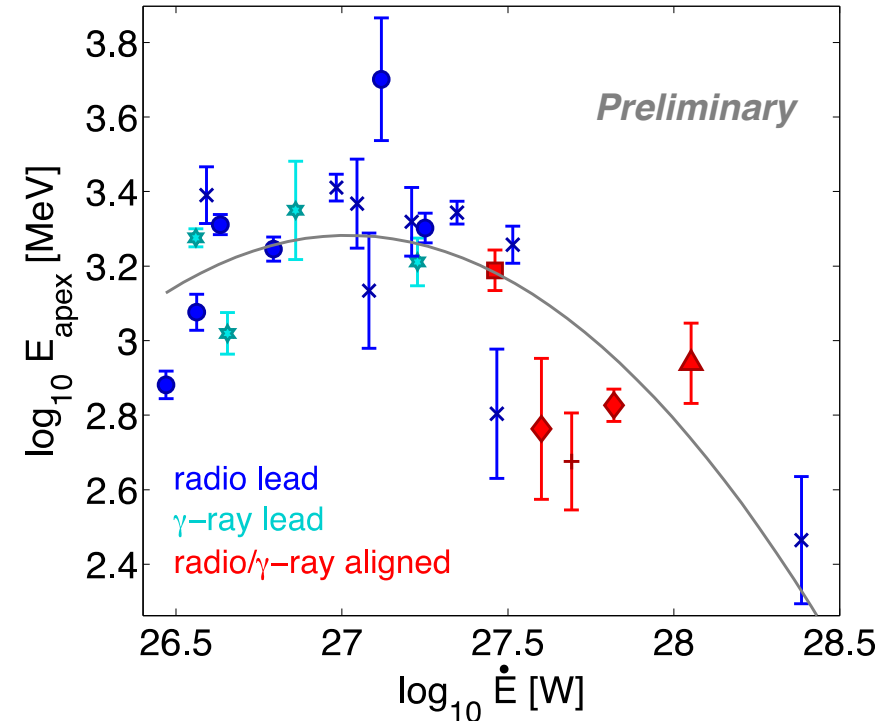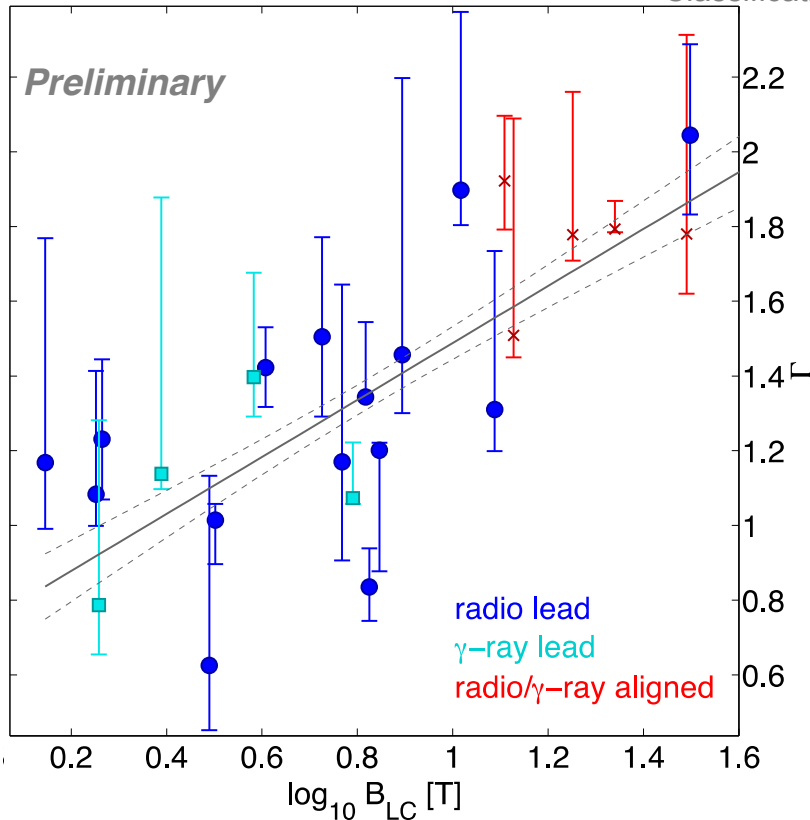
- **Toy model of curv.-radiation spectra:**
  - **primaries near the light cylinder with various Γ_{max} Lorentz factors**
  - **curv. radius = R_{LC} (Hirotani 2011)**
  - **cannot reproduce the E_{apex} vs Edot and Γ vs B_{LC} trends**
  - **➔ Additional softer component required**

- **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)**

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- **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) ?**
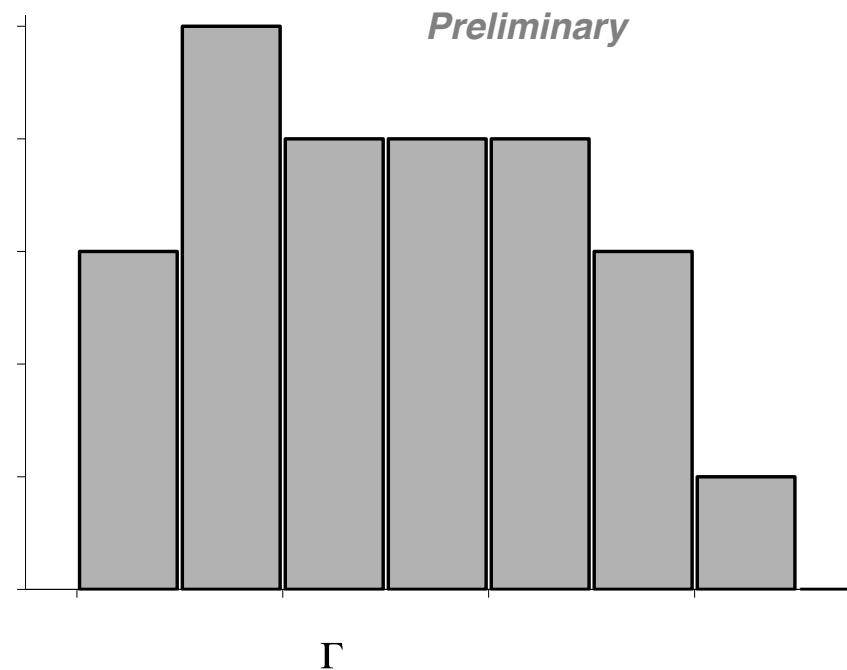
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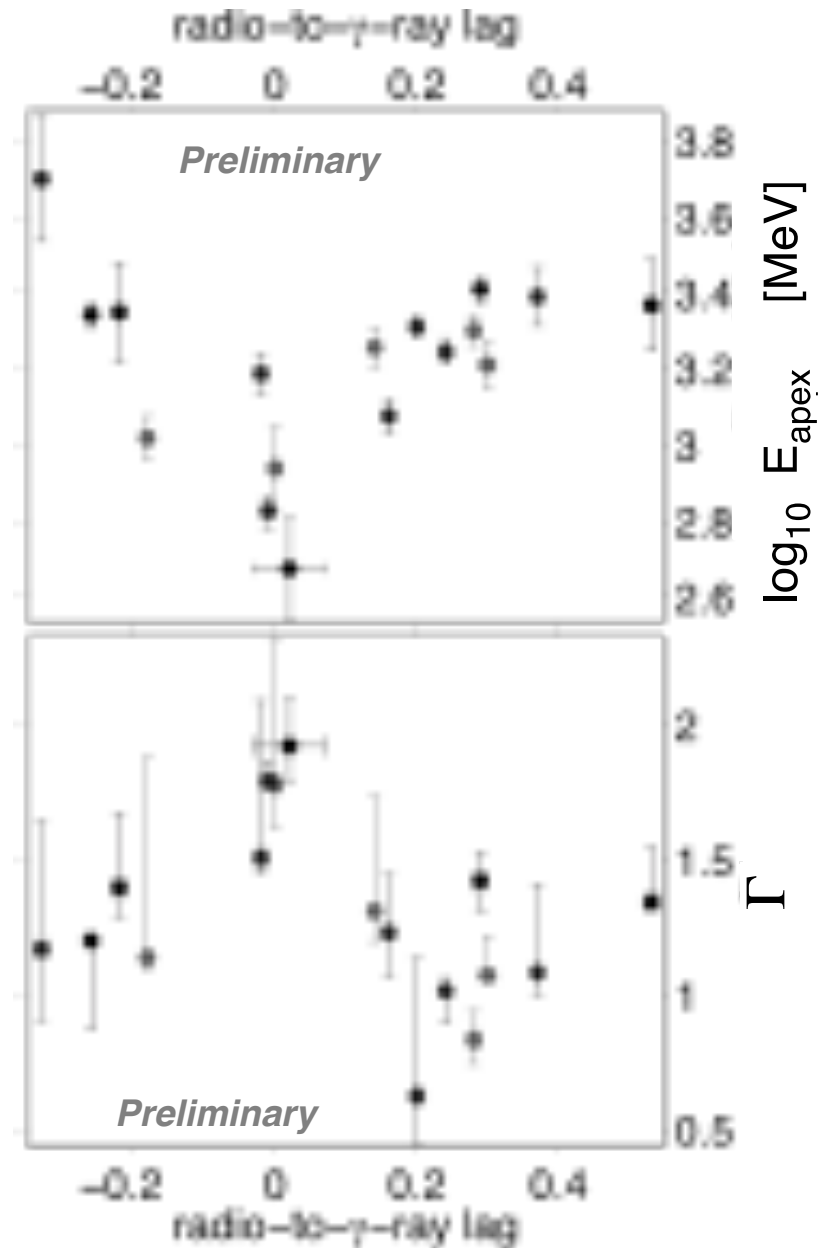
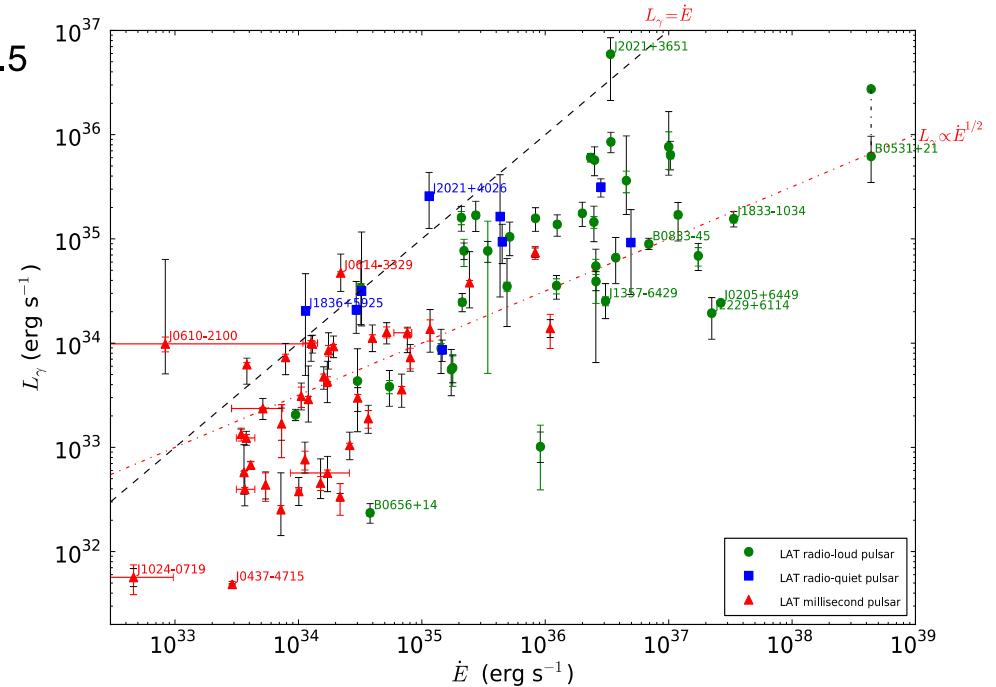- **Maximum Lorentz factor estimation from E_{cut}**
  - **for the total emission**
  - **assuming curv. radiation**
  - **with curv. radius = R_{LC}**
  (Hirotani 2011)

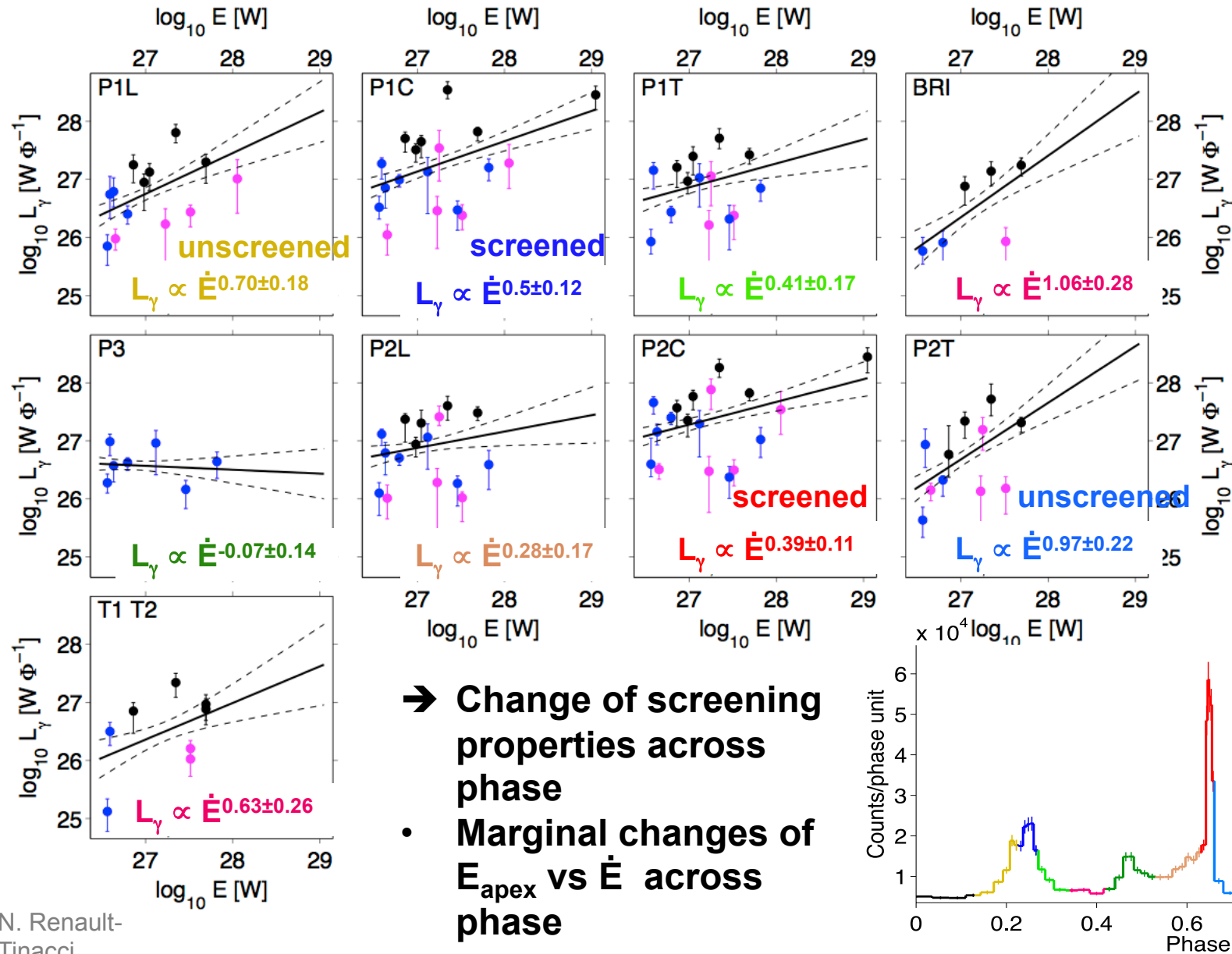$$\Gamma_{max} = \left(E_{cut} \frac{2}{3} \frac{R_{LC}}{\hbar c} \right)^{1/3}$$

Preliminary

- **Narrow Γ_{max} distribution around 10^7**

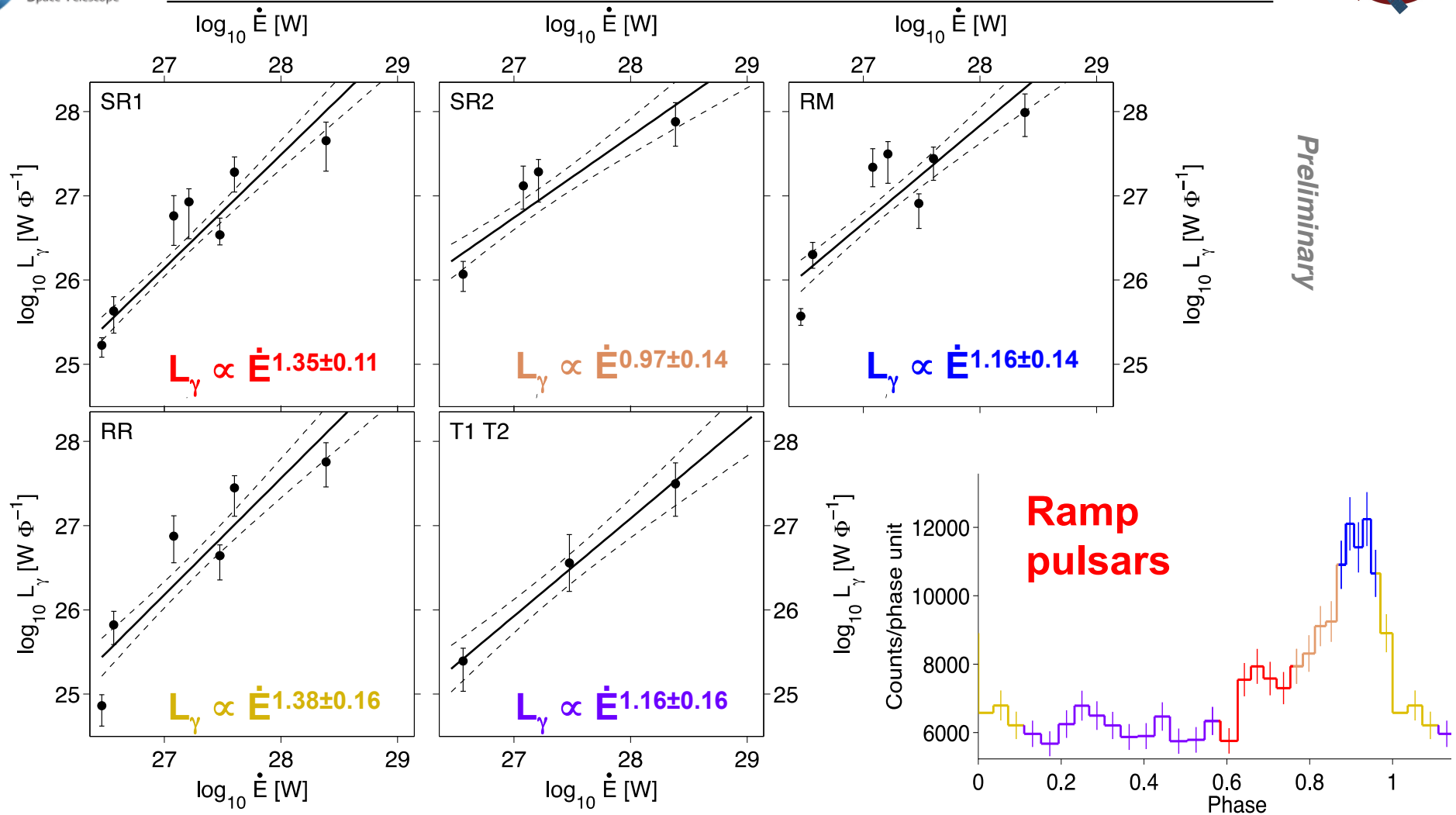Γ

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

- **Total emission**
  - **Trend & 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**

P1L unscreened $L_\gamma \propto \dot{E}^{0.70\pm0.18}$

P1C screened $L_\gamma \propto \dot{E}^{0.5\pm0.12}$

P1T $L_\gamma \propto \dot{E}^{0.41\pm0.17}$

BRI $L_\gamma \propto \dot{E}^{1.06\pm0.28}$

P3 $L_\gamma \propto \dot{E}^{-0.07\pm0.14}$

P2L $L_\gamma \propto \dot{E}^{0.28\pm0.17}$

P2C screened $L_\gamma \propto \dot{E}^{0.39\pm0.11}$

P2T unscreened $L_\gamma \propto \dot{E}^{0.97\pm0.22}$

T1 T2 $L_\gamma \propto \dot{E}^{0.63\pm0.26}$

➔ **Change of screening properties across phase**

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

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Preliminary

SR1: $L_\gamma \propto \dot{E}^{1.35 \pm 0.11}$

SR2: $L_\gamma \propto \dot{E}^{0.97 \pm 0.14}$

RM: $L_\gamma \propto \dot{E}^{1.16 \pm 0.14}$

RR: $L_\gamma \propto \dot{E}^{1.38 \pm 0.16}$

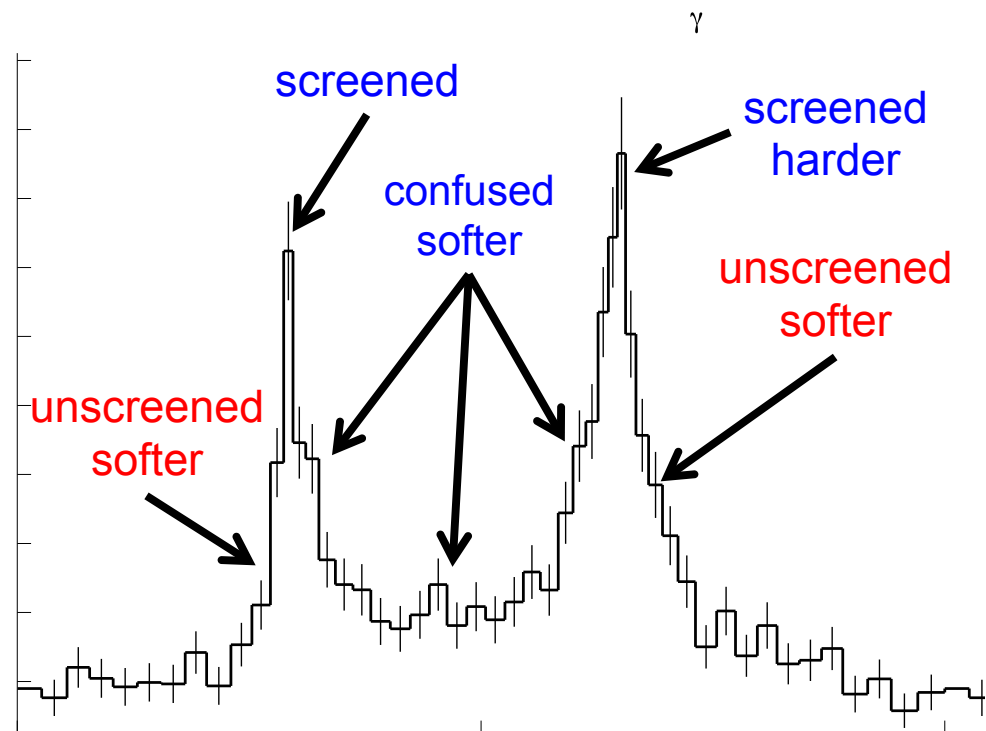T1 T2: $L_\gamma \propto \dot{E}^{1.16 \pm 0.16}$

Ramp pulsars

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

- $L_\gamma \propto \dot{E}$ ➔ **unscreened gaps**

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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
- **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**
- **Softer emission and lower E_{apex} outside the main peaks**
- **Perspectives**
  - confirm trends with 8 years of data and with larger MSP sample
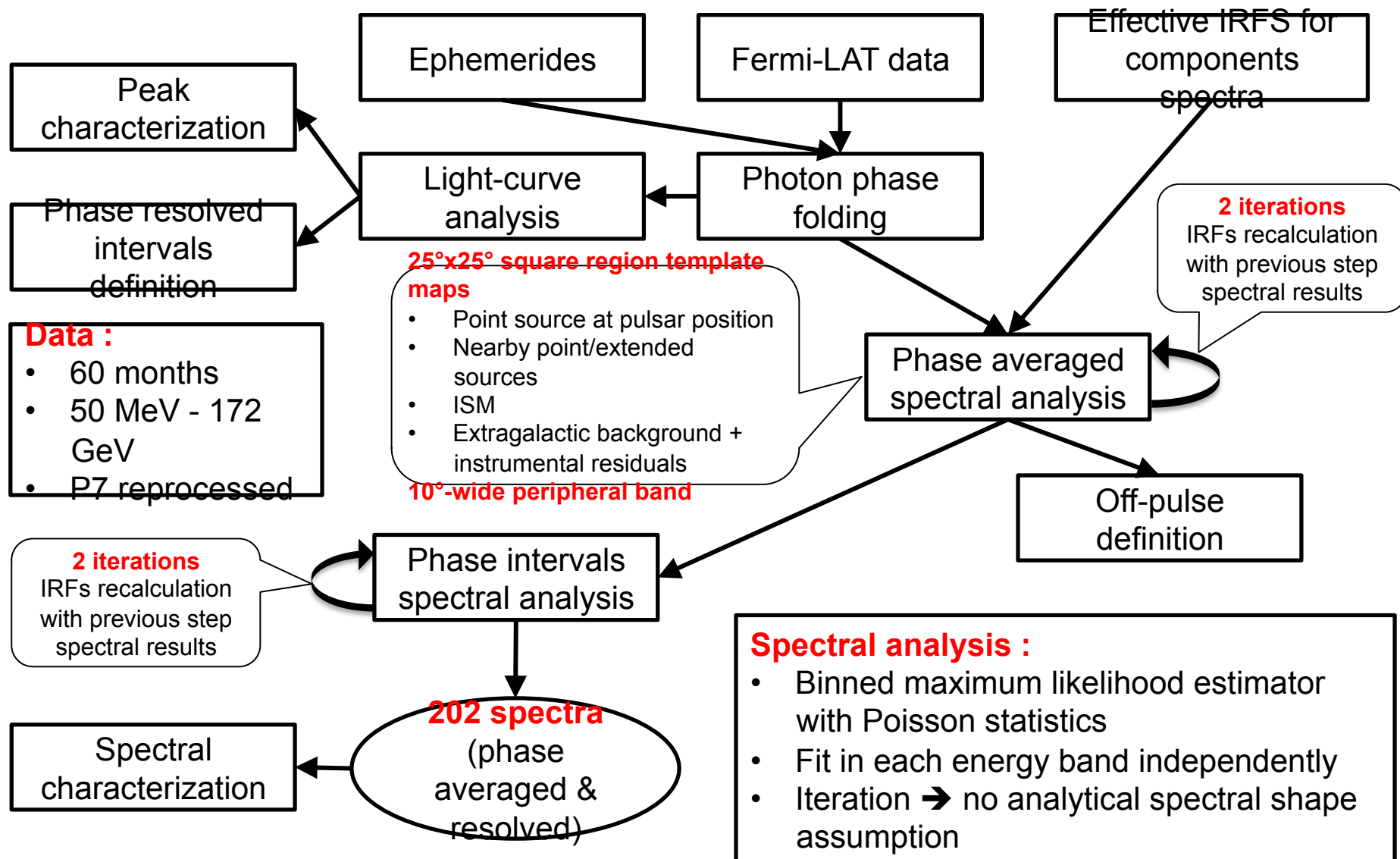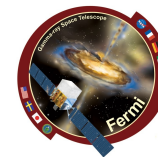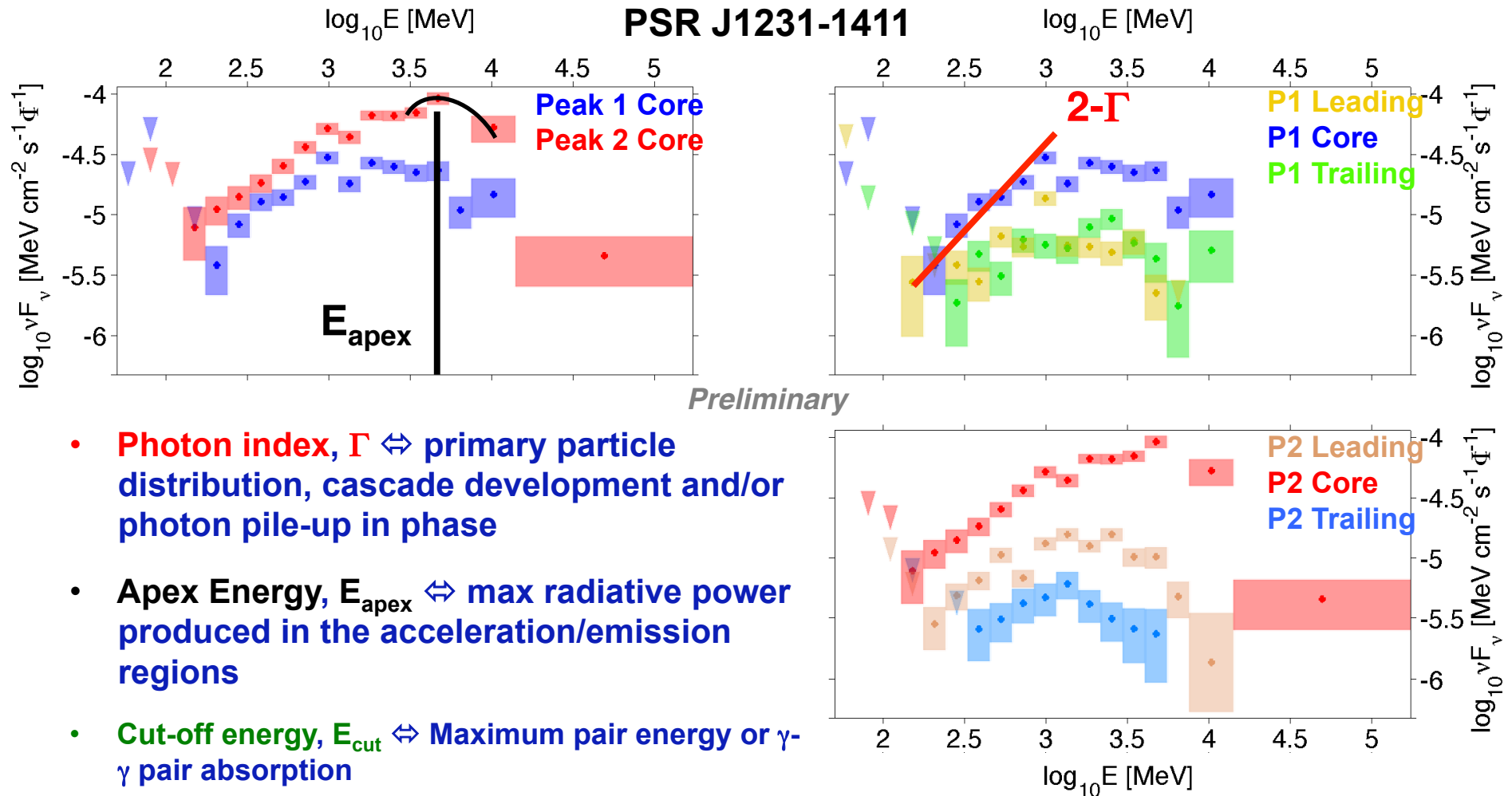 - same analyses for young pulsars to accompany 3PC

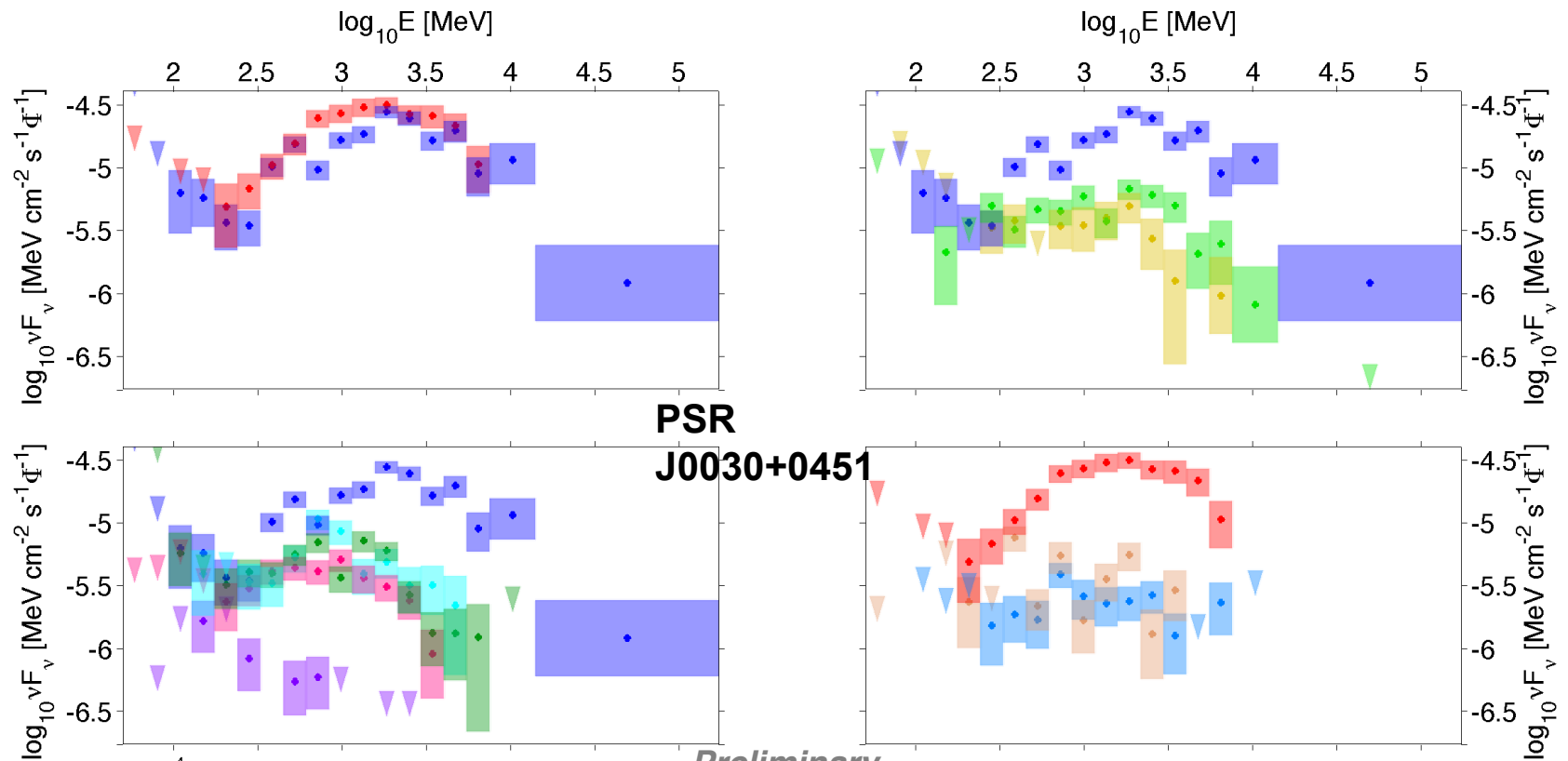# Thank you for your attention
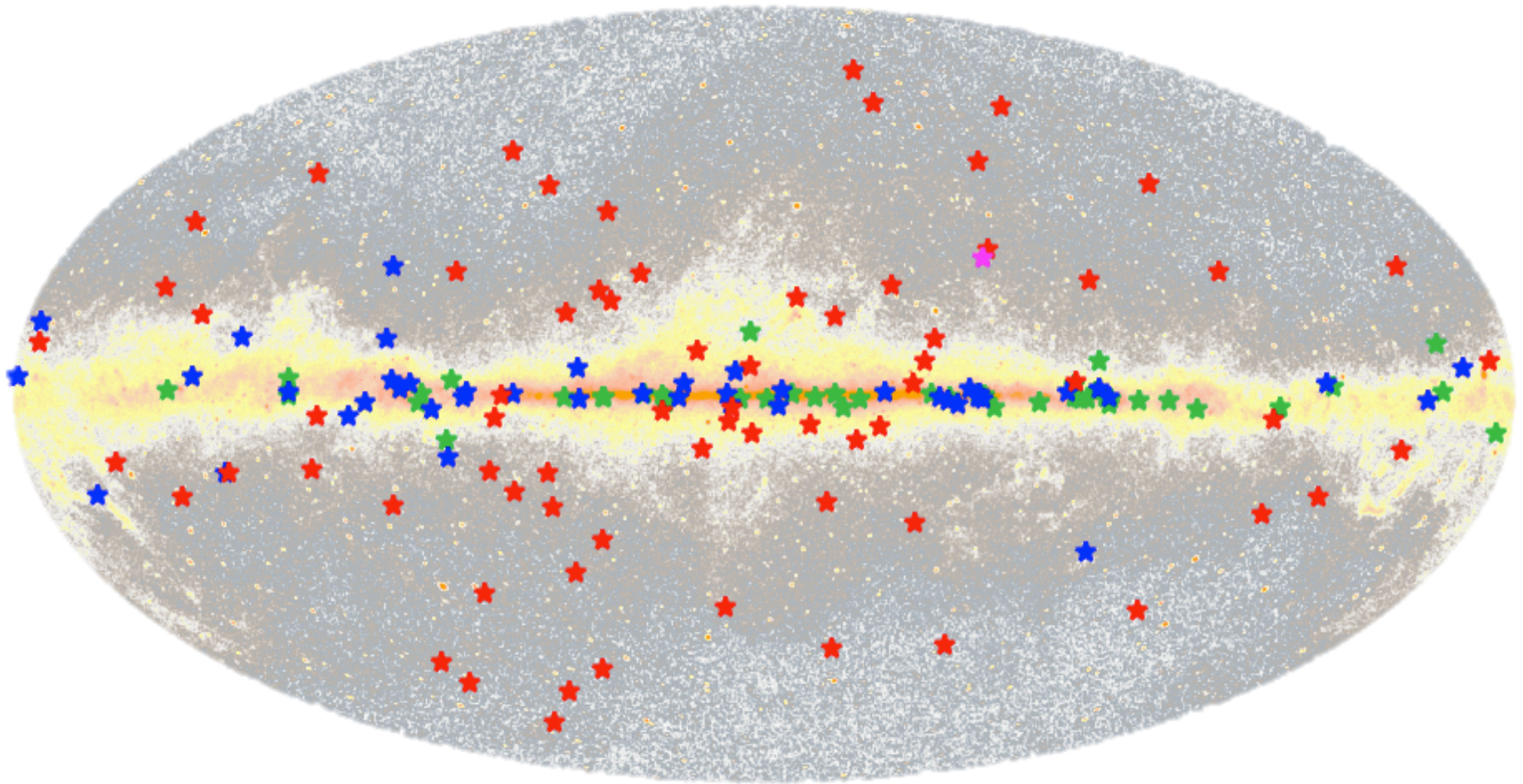
BACK-UP
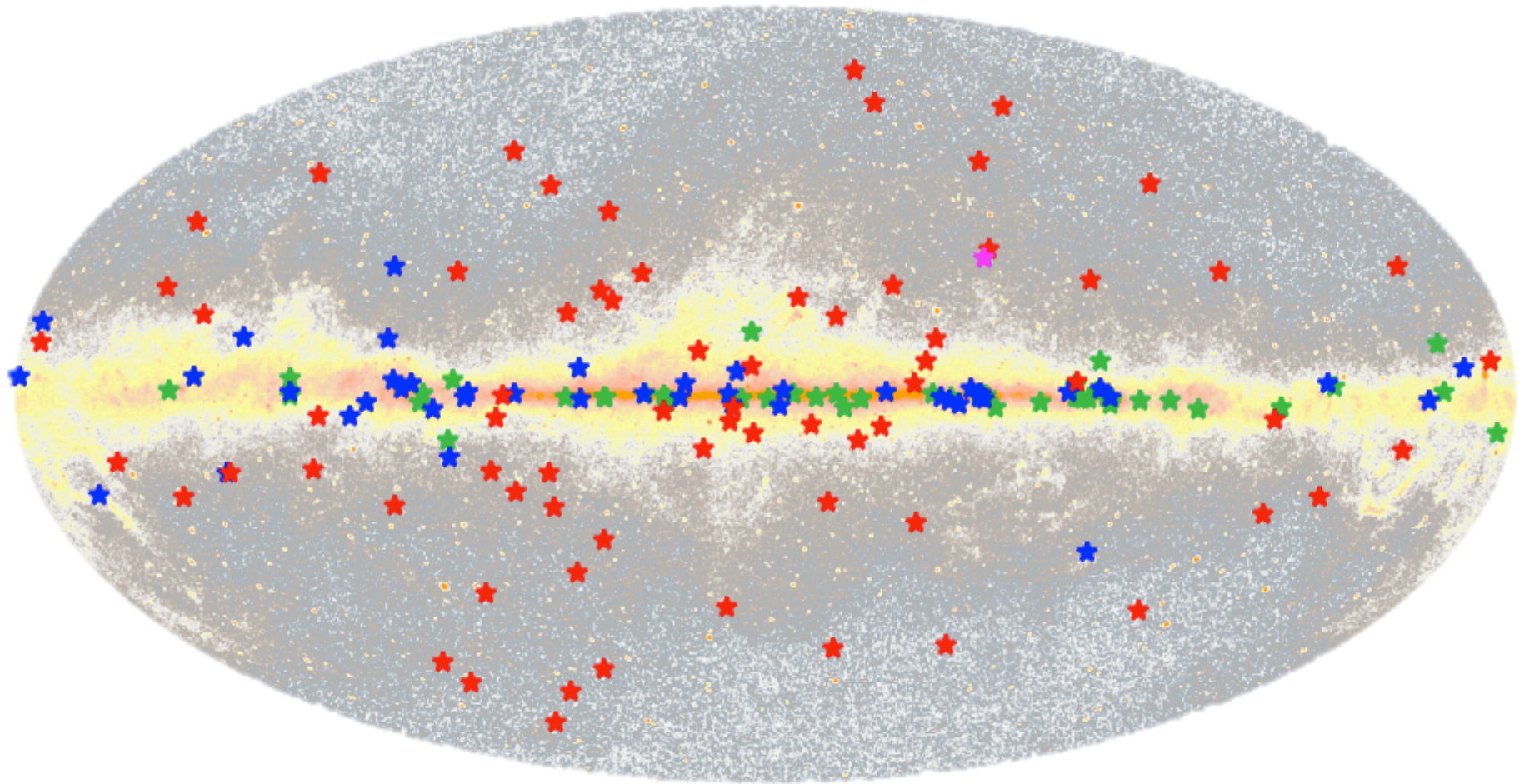
Detailed analysis protocol

Peak characterization

Ephemerides

Fermi-LAT data

Effective IRFS for components spectra

Phase resolved intervals definition

Light-curve analysis

Photon phase folding

2 iterations
IRFs recalculation with previous step spectral results

25°x25° square region template maps
- Point source at pulsar position
- Nearby point/extended sources
- ISM
- Extragalactic background + instrumental residuals

10°-wide peripheral band

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

Phase averaged spectral analysis

Off-pulse definition

2 iterations
IRFs recalculation with previous step spectral results

Phase intervals spectral analysis

202 spectra
(phase averaged & resolved)

Spectral characterization

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

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PSR J1231-1411

Preliminary

- **Photon index, Γ $\Leftrightarrow$ primary particle distribution, cascade development and/or photon pile-up in phase**

- **Apex Energy, E_{apex} $\Leftrightarrow$ max radiative power produced in the acceleration/emission regions**

- **Cut-off energy, E_{cut} $\Leftrightarrow$ Maximum pair energy or γ-γ pair absorption**

PSR J0030+0451

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

Preliminary

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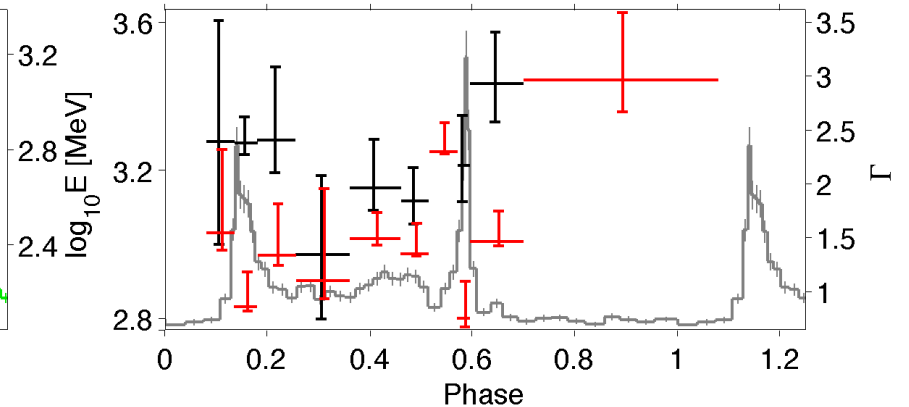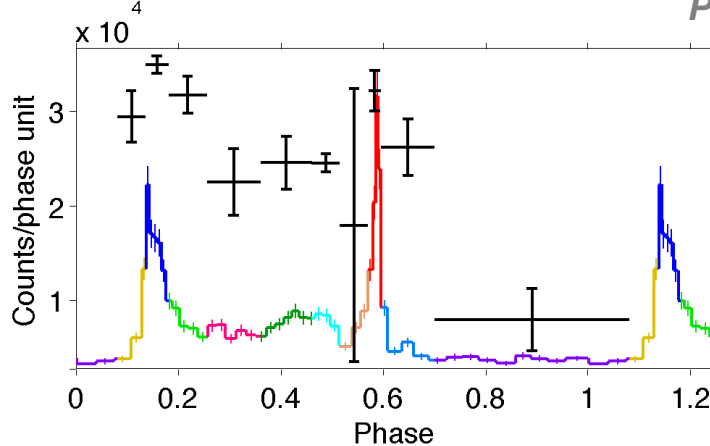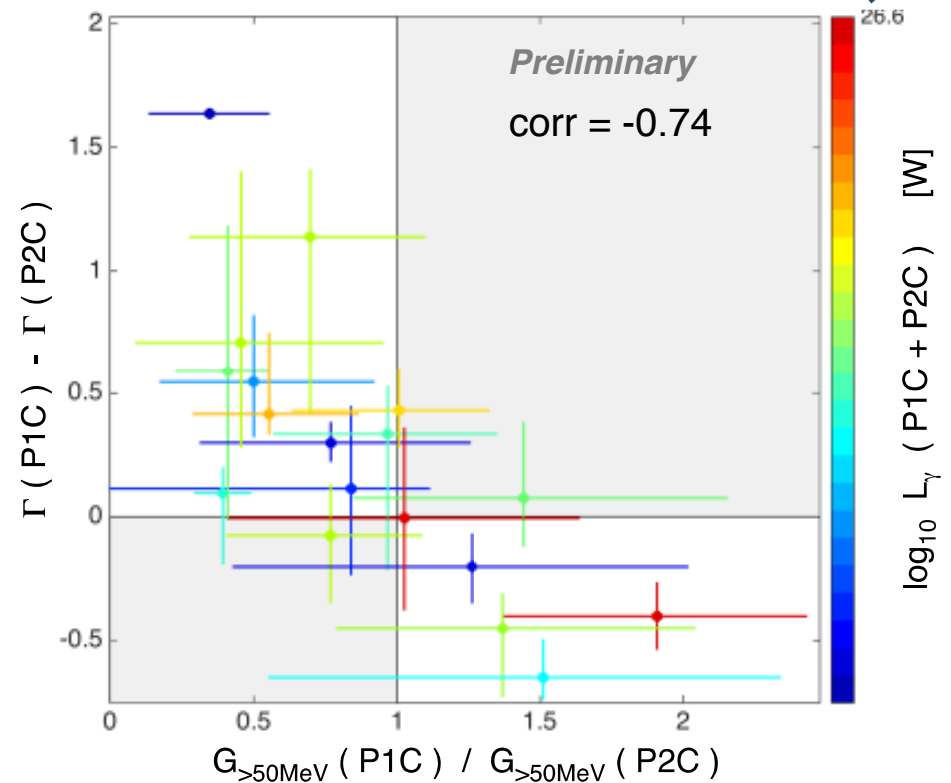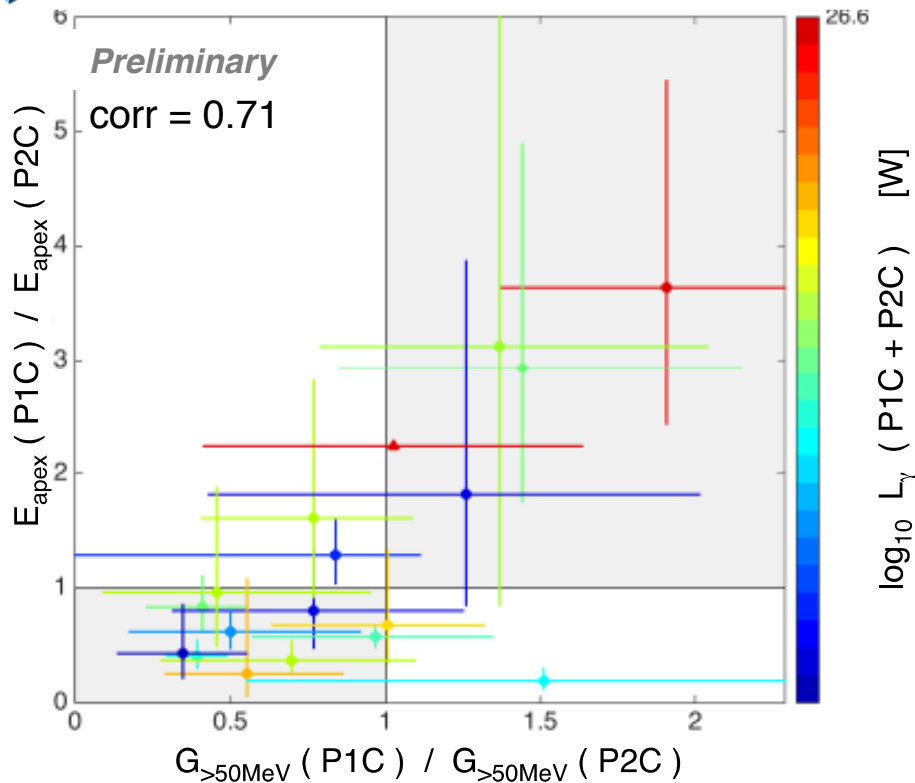
- **The brighter the core, the harder the SED (lower Γ), the higher the apex energy**
  - **Irrespective of the peak order**
- **Expected if dominant curv. radiation**

- **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**
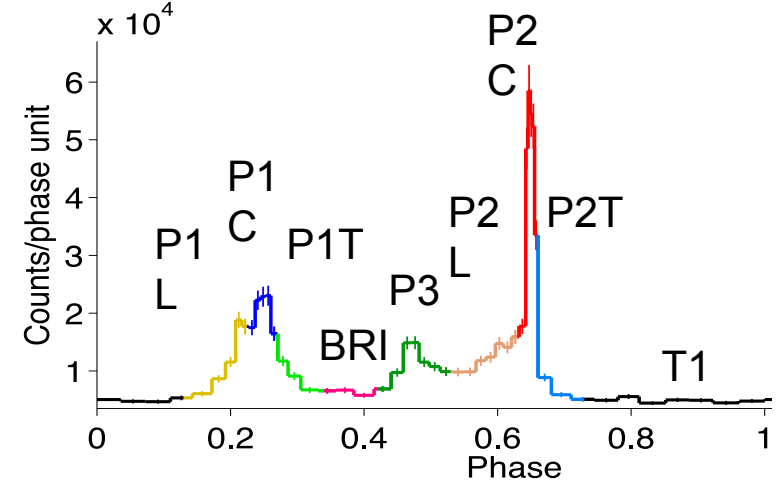
Different emission regions/regimes
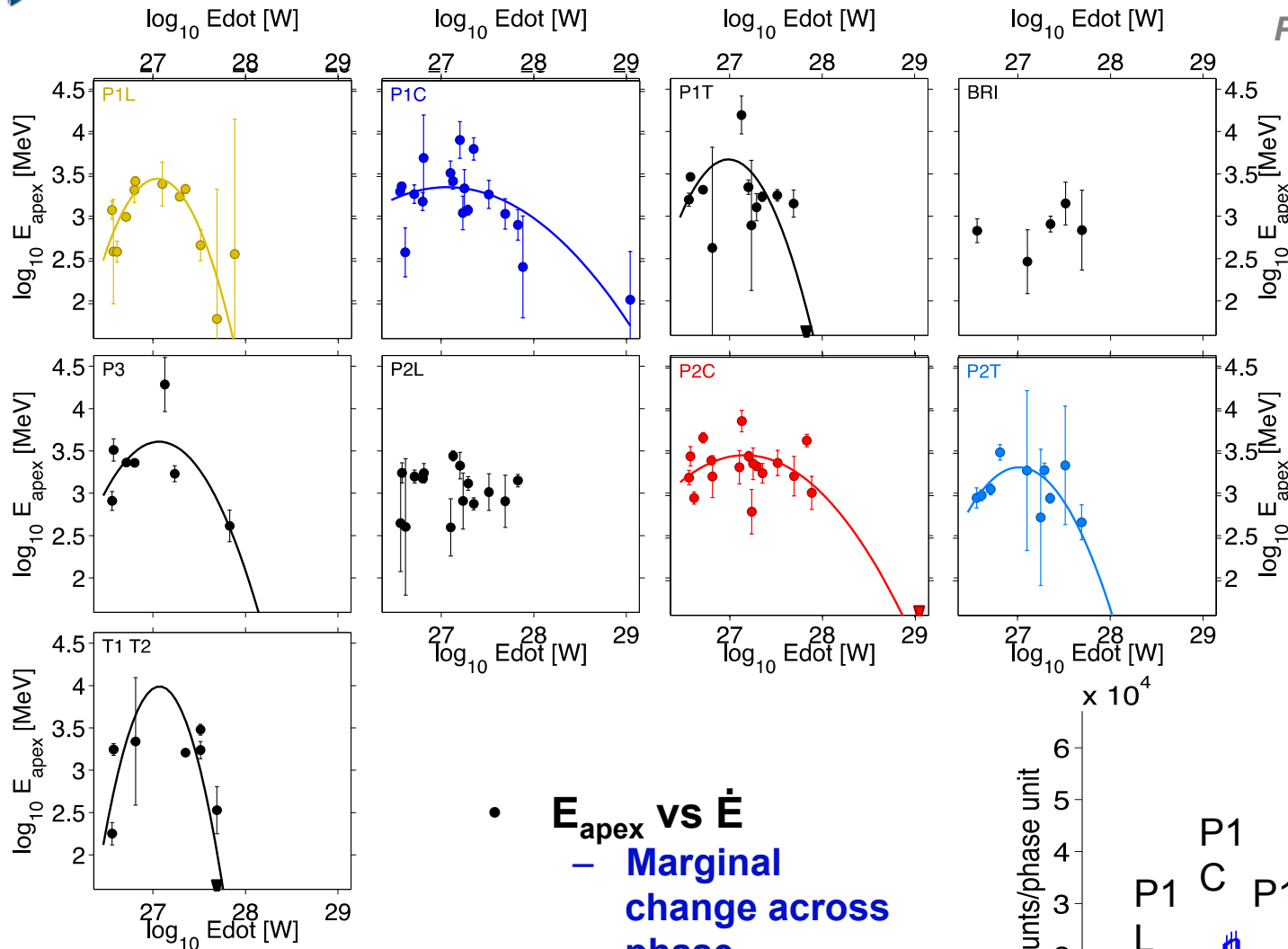
P$_{curv}$ = 96,4 %
P$_{curv}$ = 90,7 %
→ **Correlation E$_{apex}$ with $\dot{E}$**

P$_{curv}$ = 99,7 %
→ **Correlation E$_{apex}$ with $\dot{E}$**

P$_{curv}$ = 80,7 %
→ **Possible correlation**

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

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Different emission regions/regimes
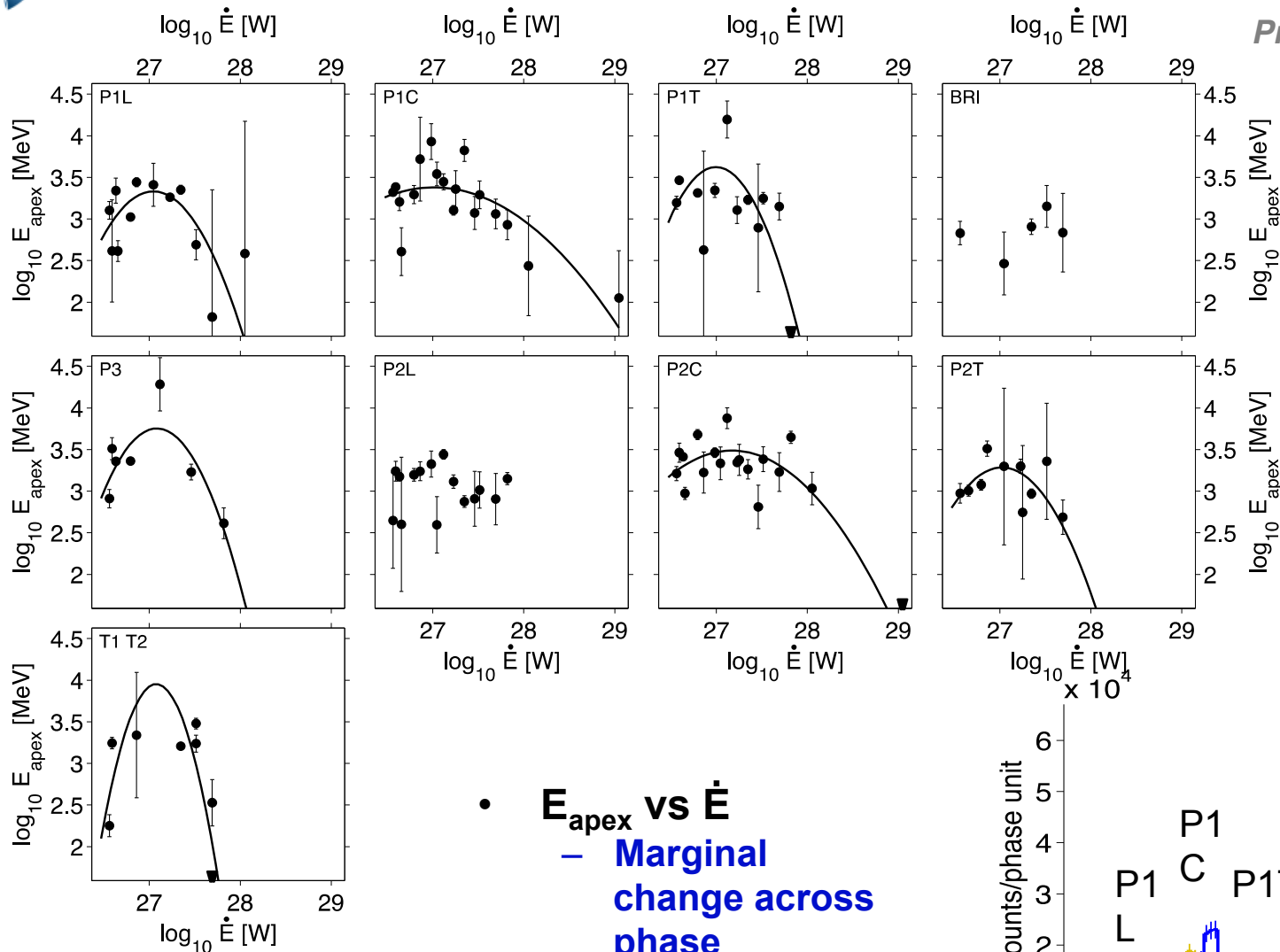
P$_{curv}$ = 96,5 %
P$_{curv}$ = 95,9 %
➜ **Correlation E$_{apex}$ with Ė**

P$_{curv}$ = 99,9 %
➜ **Correlation E$_{apex}$ with Ė**

P$_{curv}$ = 83,2 %
➜ **Possible correlation**

- **E$_{apex}$ vs Ė**
  – **Marginal change across phase**

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