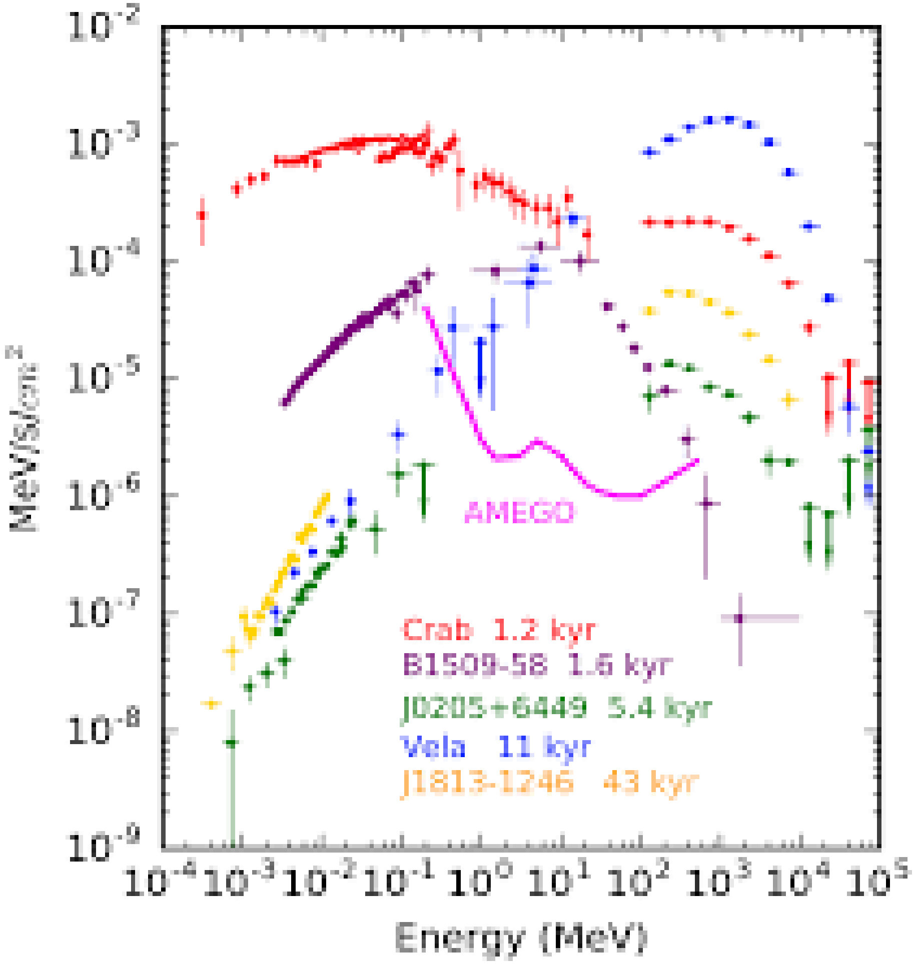
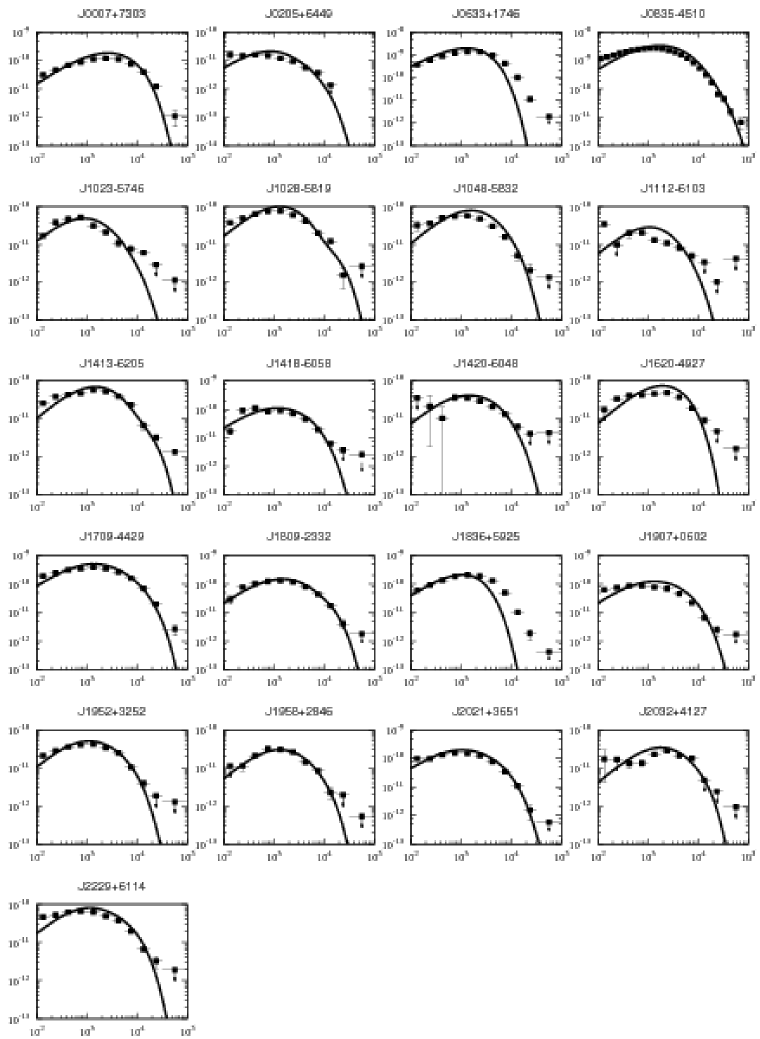
Pulsars from Afar

Views of an AGN “and accidental” pulsar theorist

Demos Kazanas, NASA/GSFC

- The discovery of over 200 LAT pulsars opened a new window in understanding the properties of pulsars.
- Though more numerous discoveries have been made in radio, the high energy (LAT and beyond) γ-ray regime is important because their peak luminosity lies in this band.
- Their increased detections allow employment of statistical studies to determine the fundamental aspects of their structure and radiation emission.
- The high energy γ-ray regime is important because there is where their peak luminosity lies.


MeV/s/cm^2
Energy (MeV)
AMEGO
Crab 1.2 kyr
B1509-58 1.6 kyr
J0205+6449 5.4 kyr
Vela 11 kyr
J1813-1246 43 kyr


J0007+7303
J0205+6449
J0633+1746
J0835-4510
J1023-5746
J1028-5819
J1048-5832
J1112-6103
J1413-6205
J1418-6058
J1420-6048
J1620-4927
J1709-4429
J1809-2332
J1836+5925
J1907+0602
J1952+3252
J1958+2846
J2021+3651
J2032+4127
J2229+6114

- In parallel, the development of *global* pulsar magnetosphere models provides the possibility of relating the observed pulsar characteristics to the physics of these global models.

- Q: *How many parameters do we need to describe the population properties of pulsars?*

For an individual pulsar these are $\alpha, \zeta, B_\star, (\Omega, P)$

While the main observables are $L_\gamma, \epsilon_{cut}, B_\star, \dot{E} \Leftrightarrow L_\gamma, \epsilon_{cut}, (\Omega, P), \dot{E}$

Q: *Are all four of the main observables independent?* (Make connection with a similar situation in galaxies where the observables (M,L), R and V, because they are related by the virial relation are on a plane, the Fundamental Plane; however this plane is almost perpendicular to the M-V plane and its projection produces the Tully-Fisher and Faber-Jackson relations).

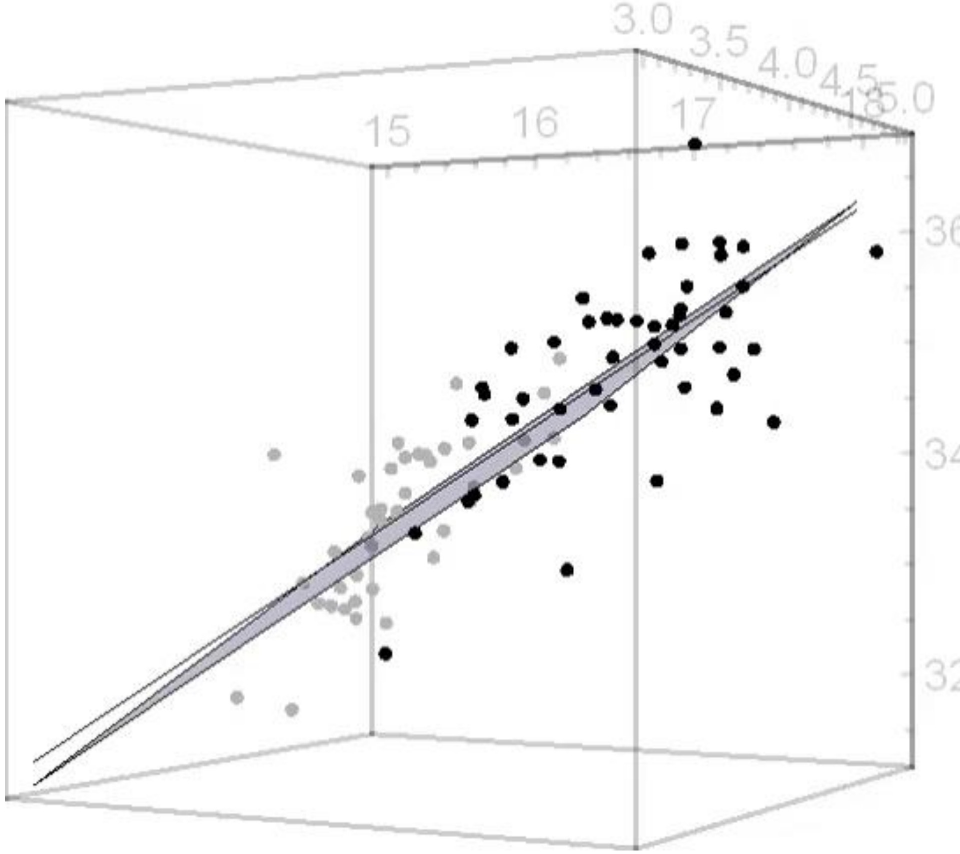
Under some simple assumptions about the maximum electron energy and their density, Kalapotharakos et al (2019) showed that

$$L_\gamma \propto \epsilon_{cut}^{4/3}\, B_\star^{1/6}\, \dot{E}^{5/12}$$

While analysis of the data has shown that the relation obeyed by these parameters is, i.e. a 3D plane in the 4D parameter space of the form

$$L_{\gamma(\mathrm{3D})} = 10^{14.2\pm2.3}\ \epsilon_{\mathrm{cut}}^{1.18\pm0.24}\ B_\star^{0.17\pm0.05}\ \ \dot{E}^{0.41\pm0.08}$$

The Fermi pulsar Fundamental Plane



$$x = B_*^{1/6} \dot{\mathcal{E}}^{5/12}$$
$$y = \epsilon_{cut}^{4/3}$$
$$z = L_\gamma$$

$$z \propto x\, y$$
(Theory)

$$z \propto x^{0.99}\, y^{0.88}$$
(Fermi data)

However, besides their main observables, the pulsar spectra are rather diverse

The Scientific Method

It is a capital mistake to theorize before one has the data. Insensibly, one begins to twist facts to suit theories, instead of theories to suit facts.

Sir Arthur Conan Doyle

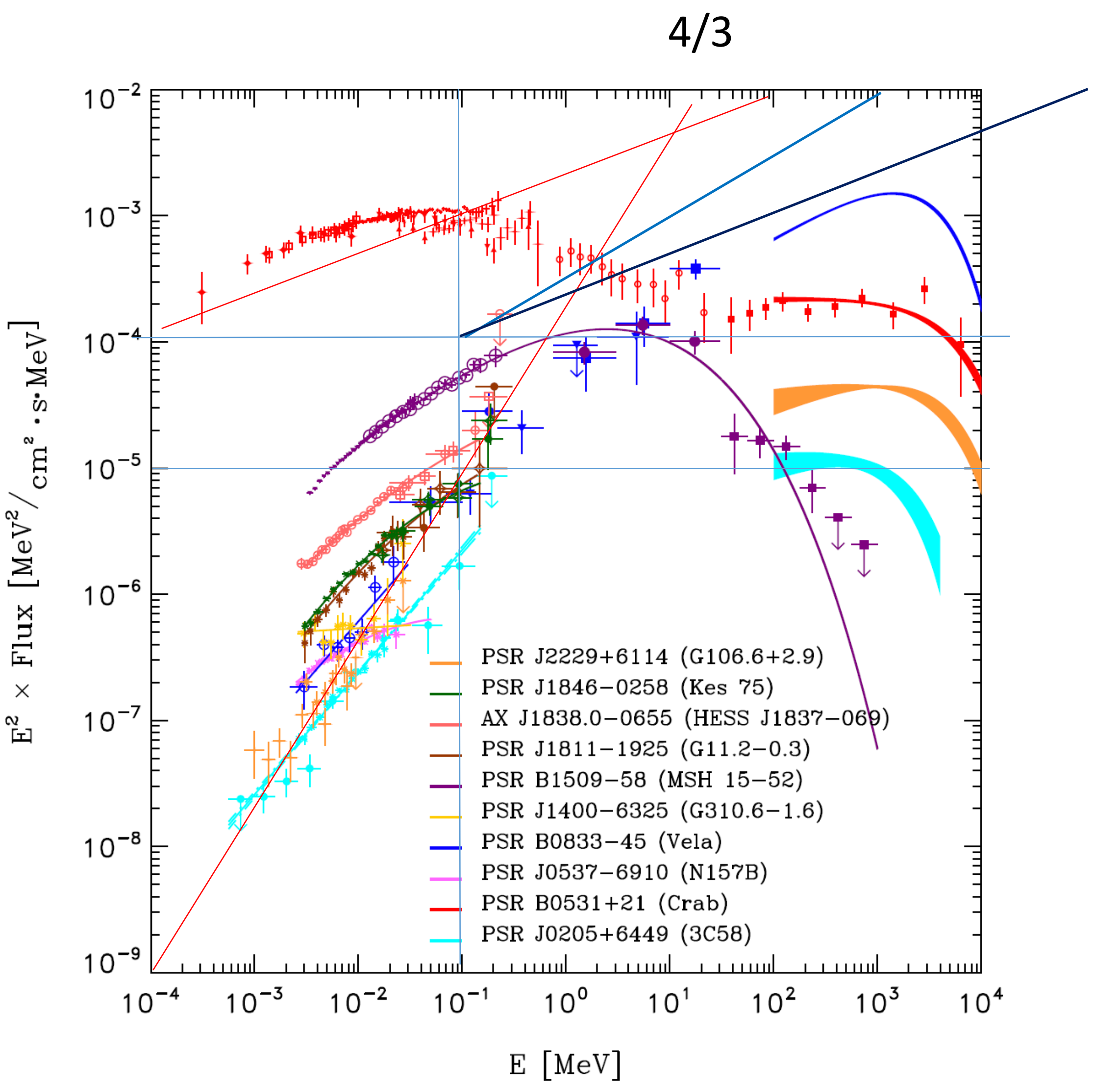
It is also a good rule not to put too much confidence in experimental results, until they have been confirmed by theory.

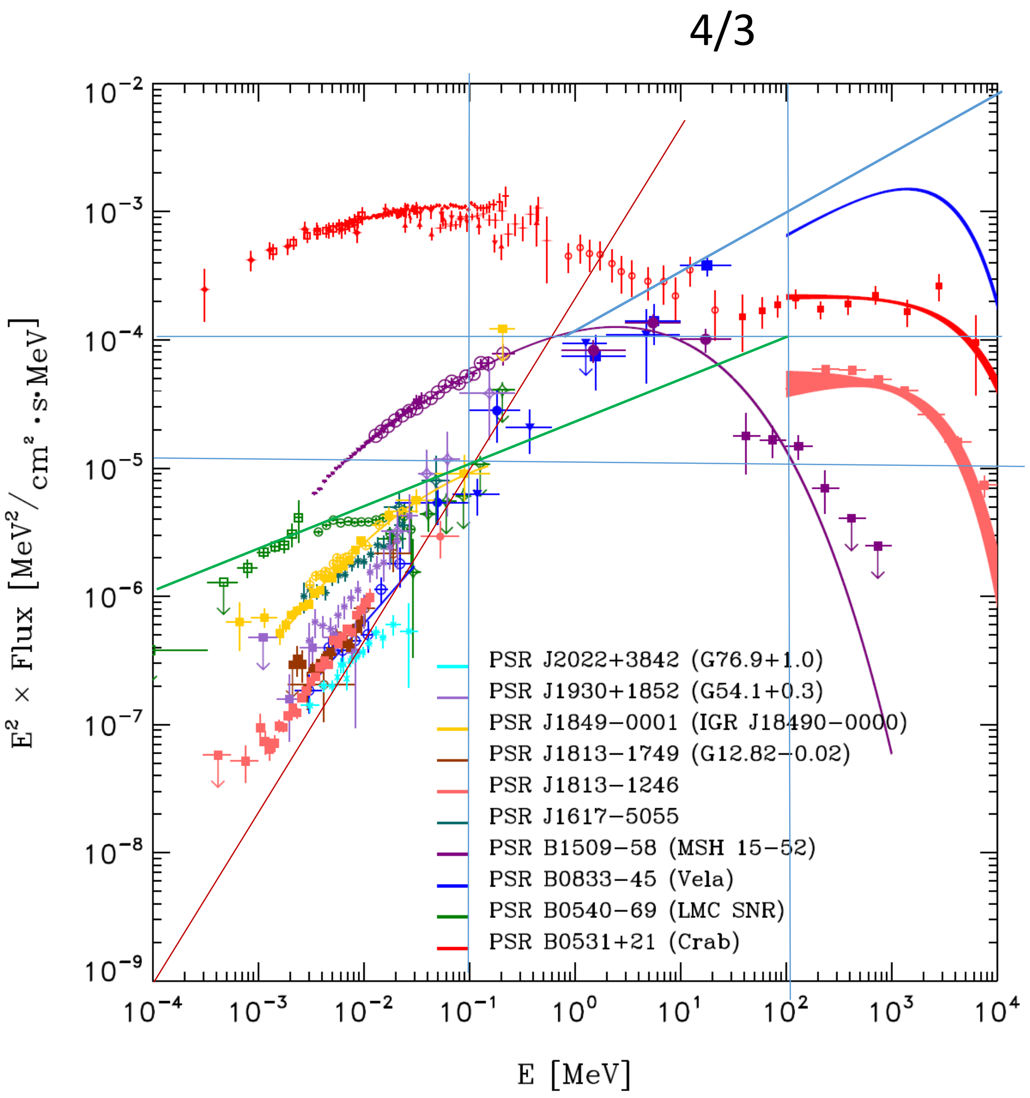
Sir Arthur Eddington

First you get your facts; then you can distort them at your leisure.

Mark Twain

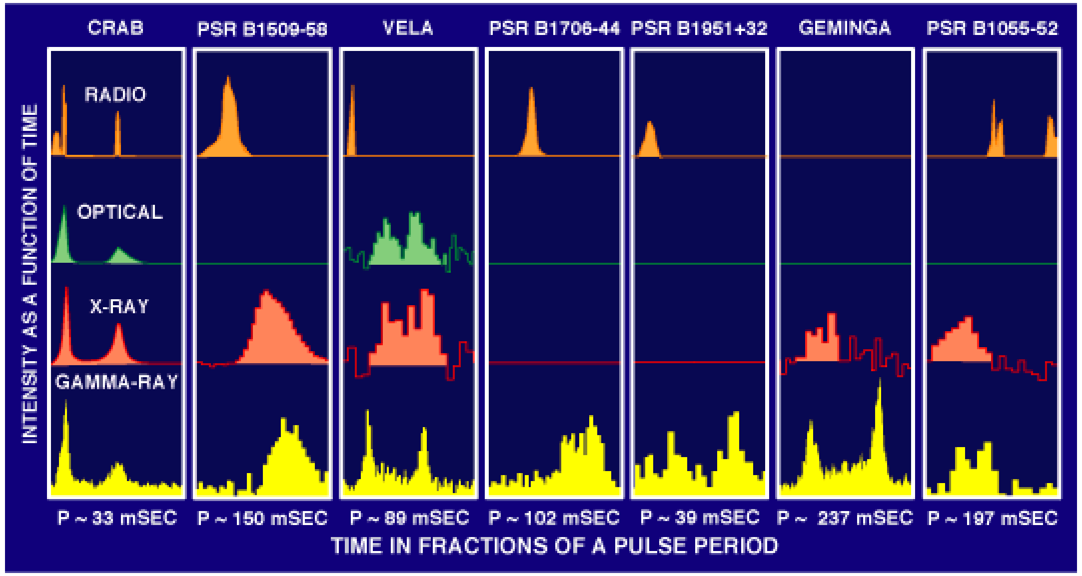
Kuiper & Hermsen 2015

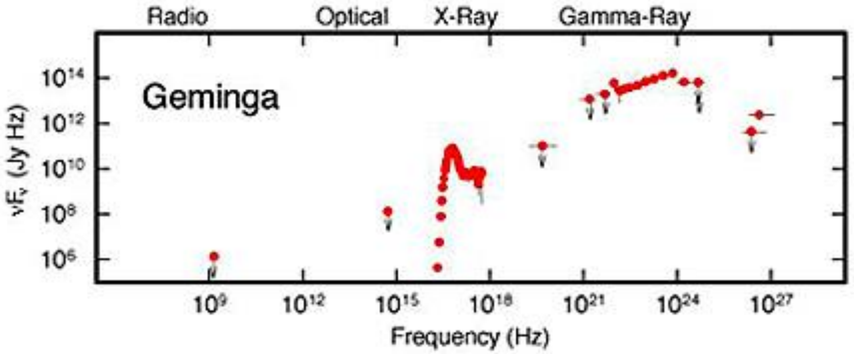


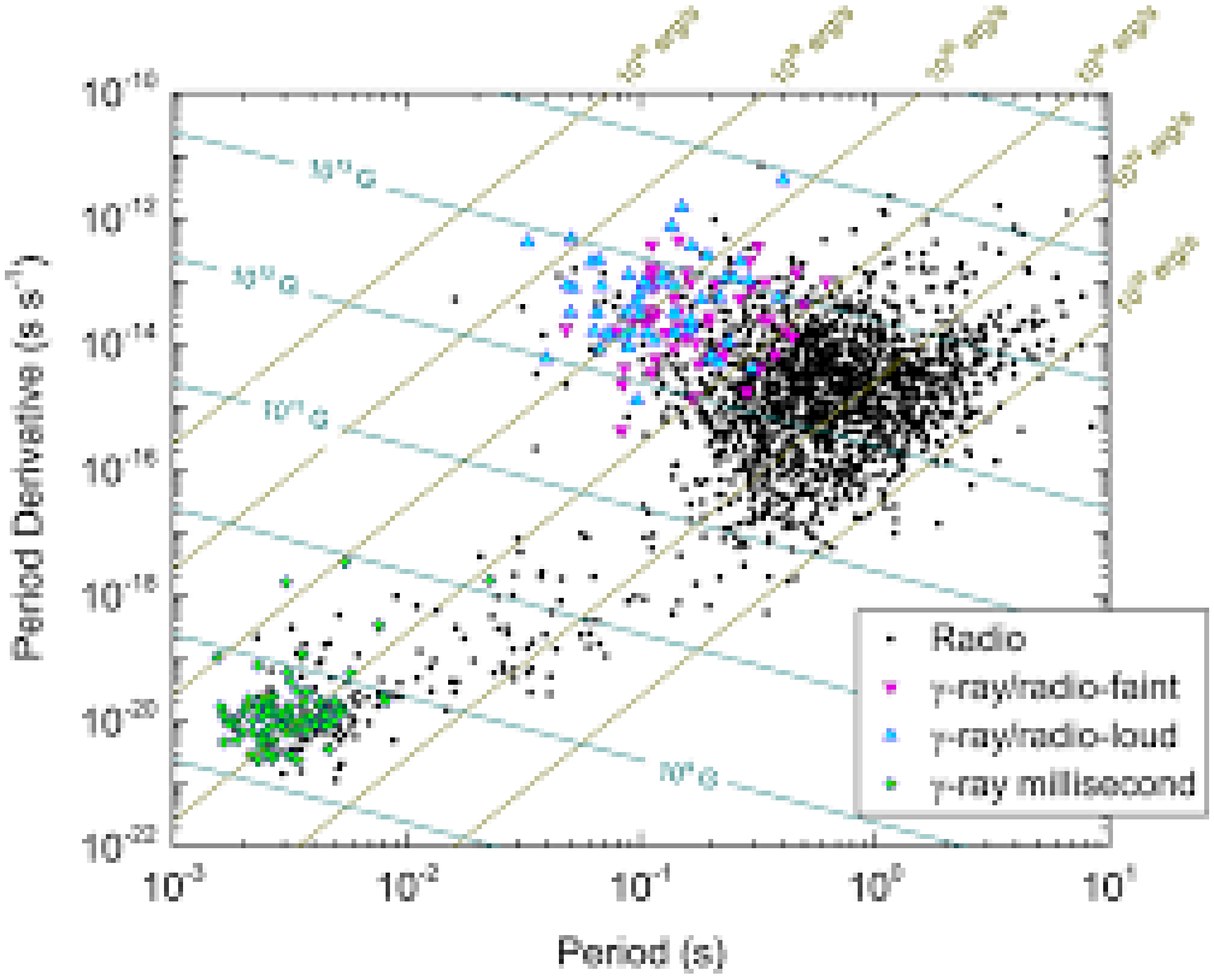


More on the Pulsar Spectra

- The detailed SED morphology (this becomes more prescient with the discovery of ~ TeV emission)
- Number of pulses per cycle
- Number of pulses as a function of energy/wavelength
- Spectral properties as a function of phase.
- Etc?



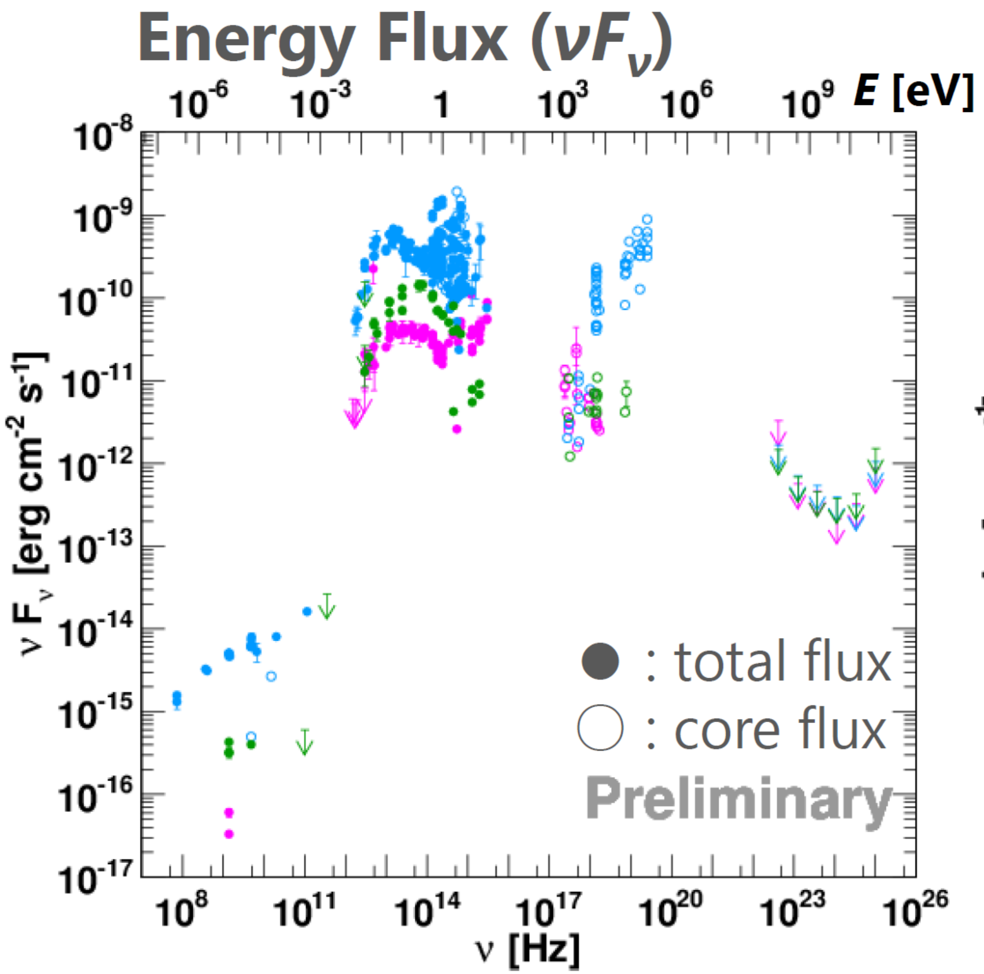


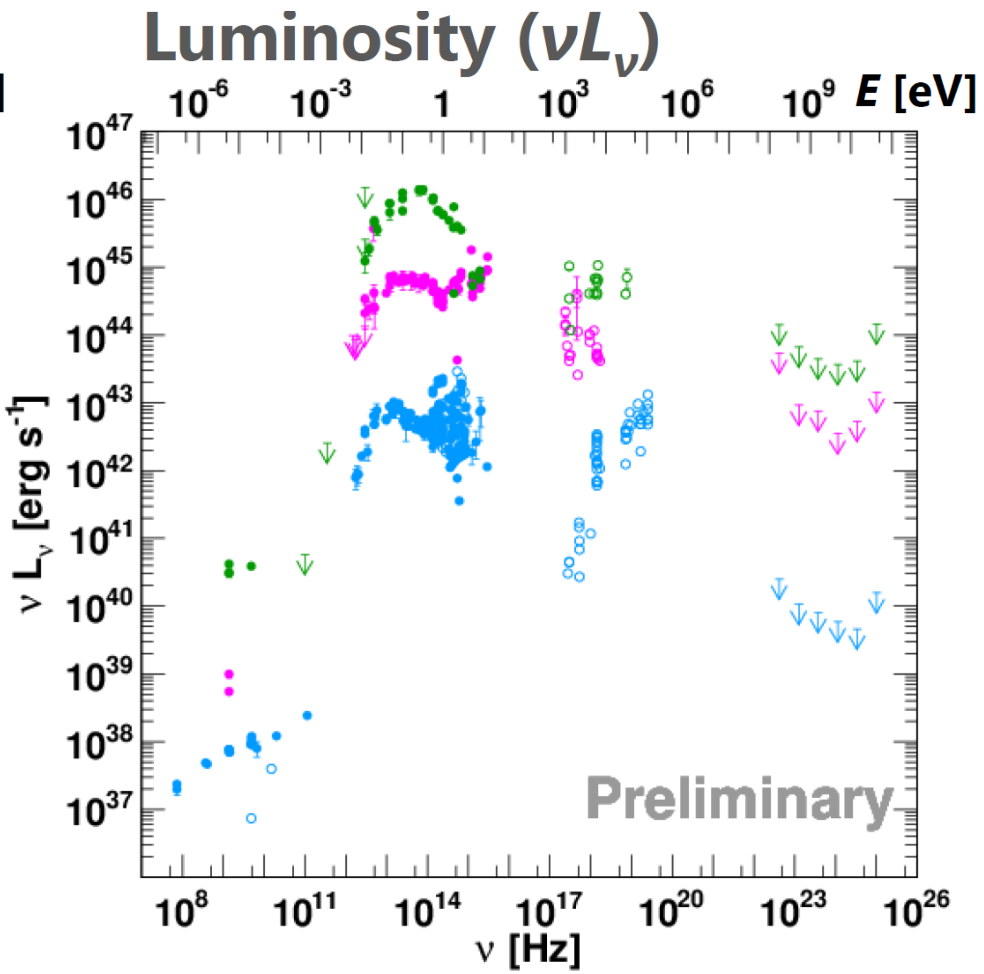


Examples of multi-wavelength observations (EGRET). We need a similar compilation for the pulsars of Fermi-LAT.

- The situation is not unlike another class of astrophysical high energy population, namely AGN.
- AGN have myriads of facts at a wide range of frequencies which somehow obey some general relations.
- It may be instructive to make comparisons and borrow tools that can be applied across the disciplines, considering they both involve high energy emission.
- Here is a list comparing properties of these very separate classes:

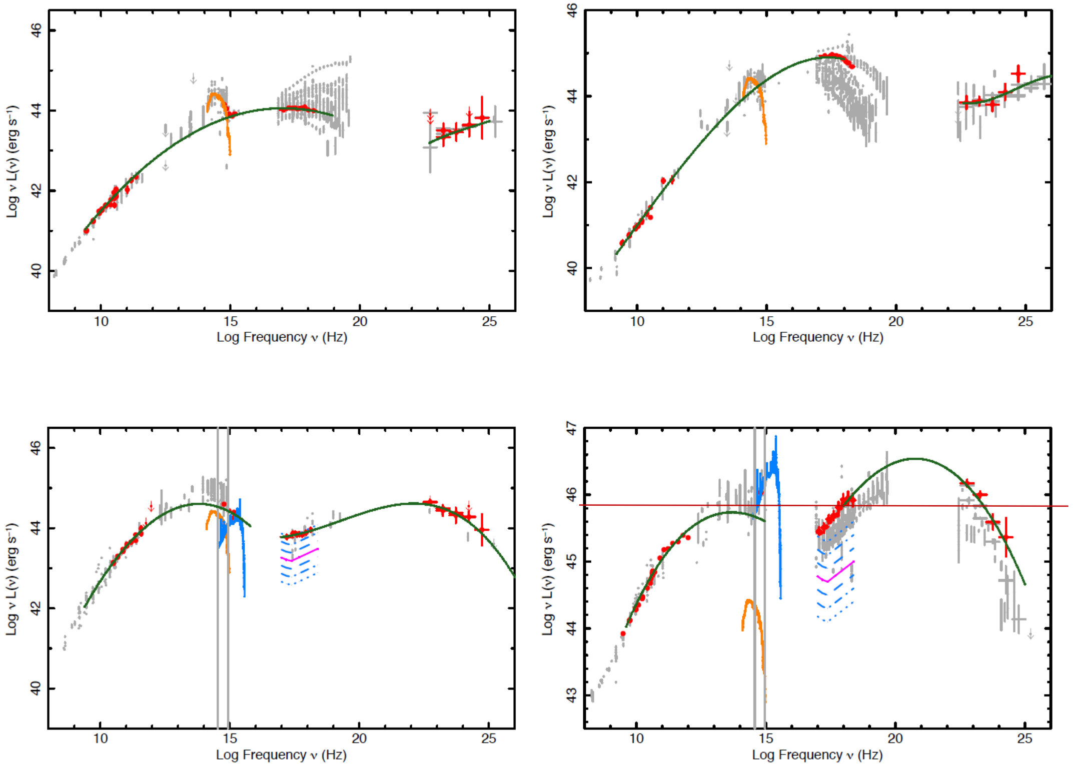
	Pulsars	AGN
• Multiwavelength spectra	Yes	yes
• 3D Geometry	Yes	yes
• Non-thermal emission	Yes	yes, no
• Rotation Powered	Yes	no ??





PDS 456 PG 1211+143 NGC 4151 **3 Radio Quiet AGN**

4 Radio Loud AGN



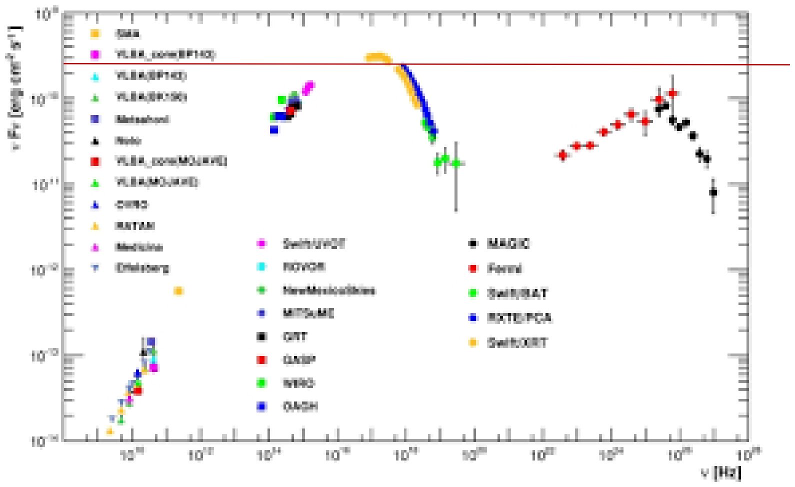
Mkn 501

Mkn 421

BL Lac

3C 273

IC dominance



S-dominance

Mkn 421

Synchrotron (?)

SSC, EC

Synchr., Curvat. (?)

Synchr., Curvature
SSC, EC (?)

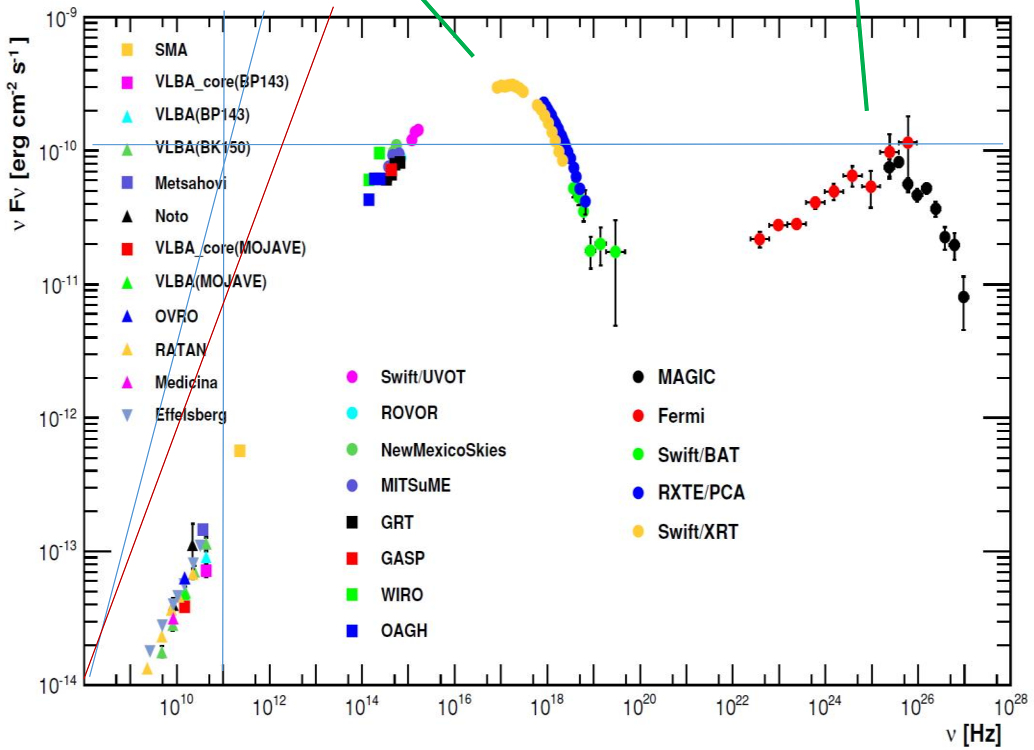
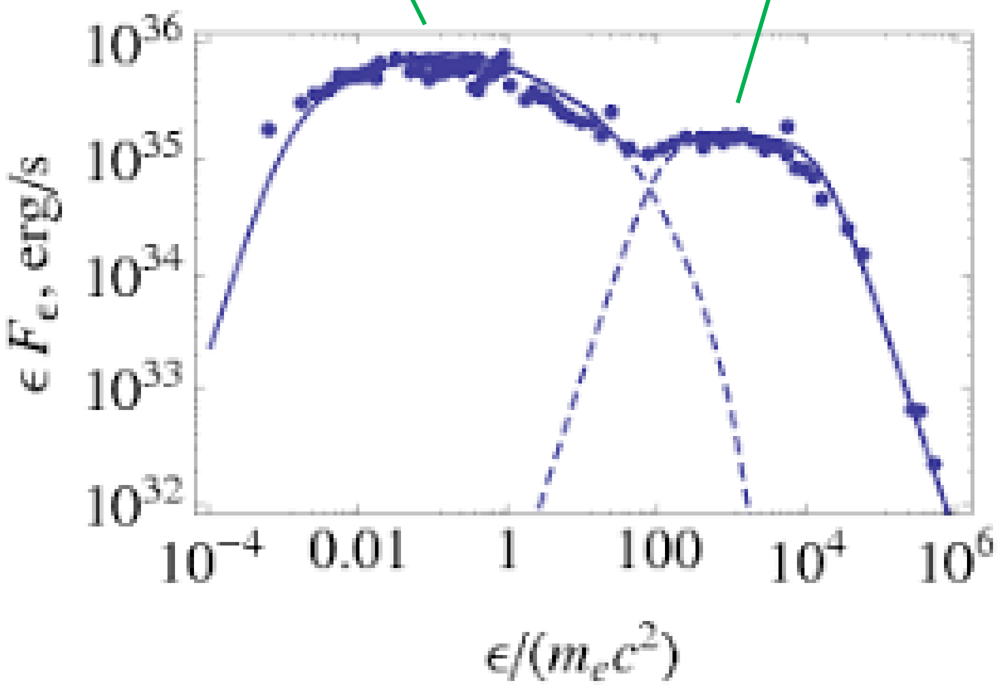
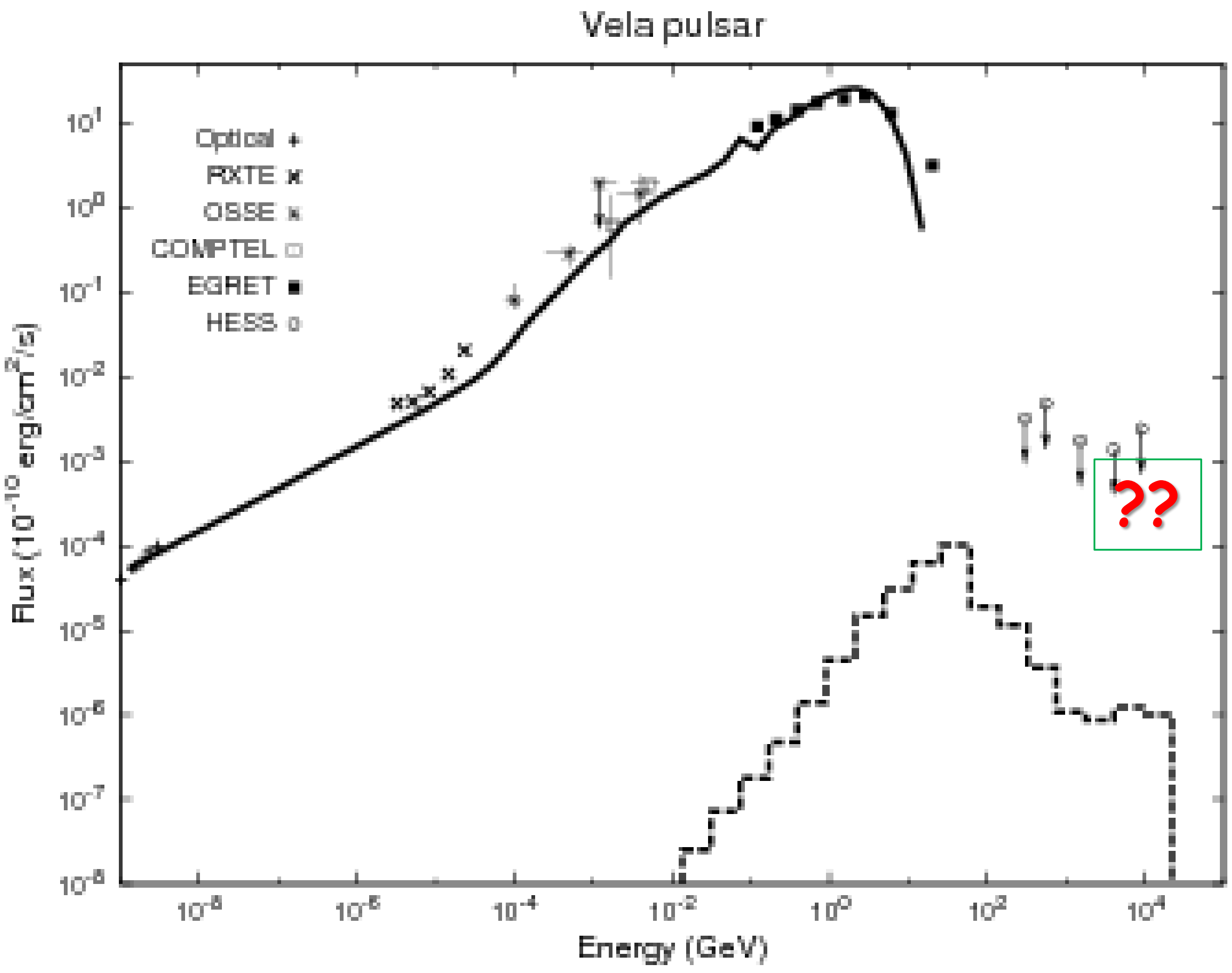
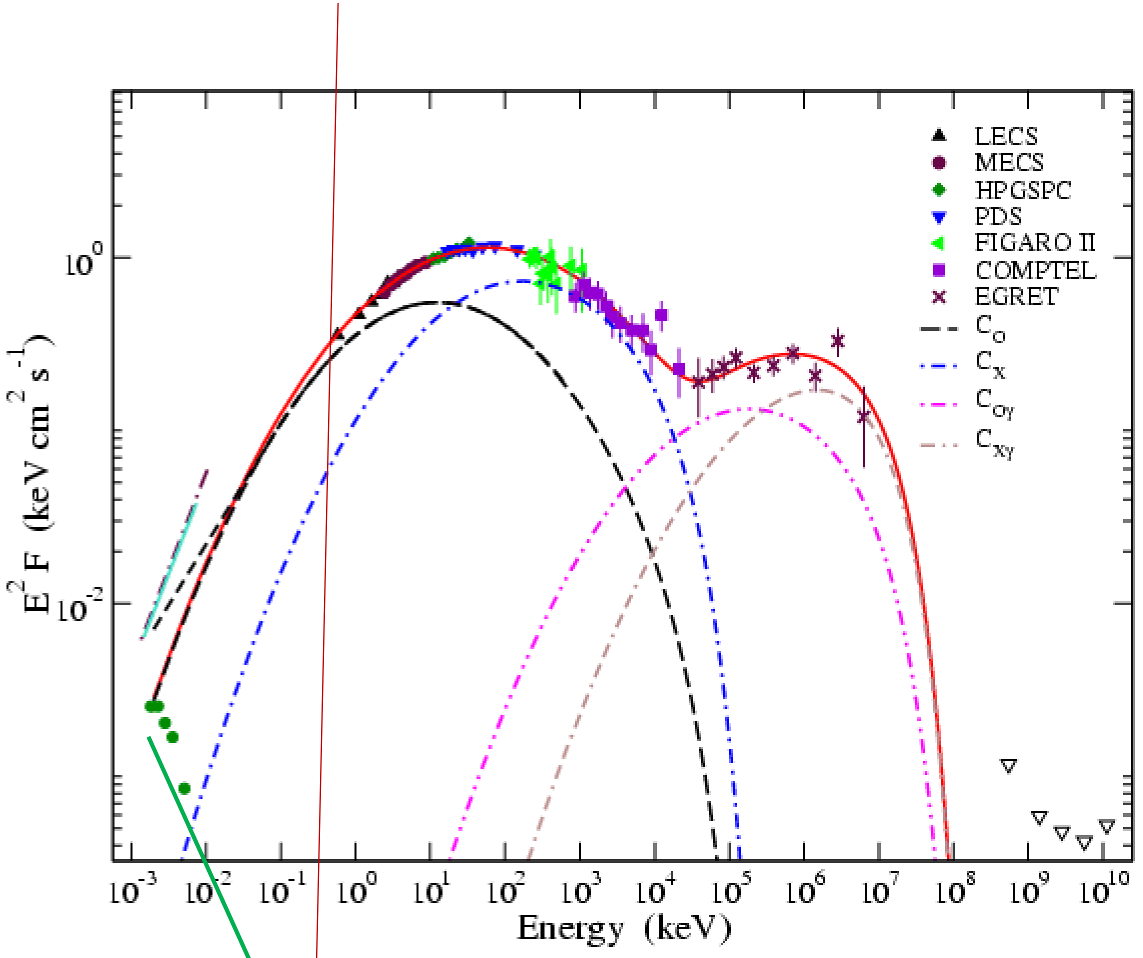


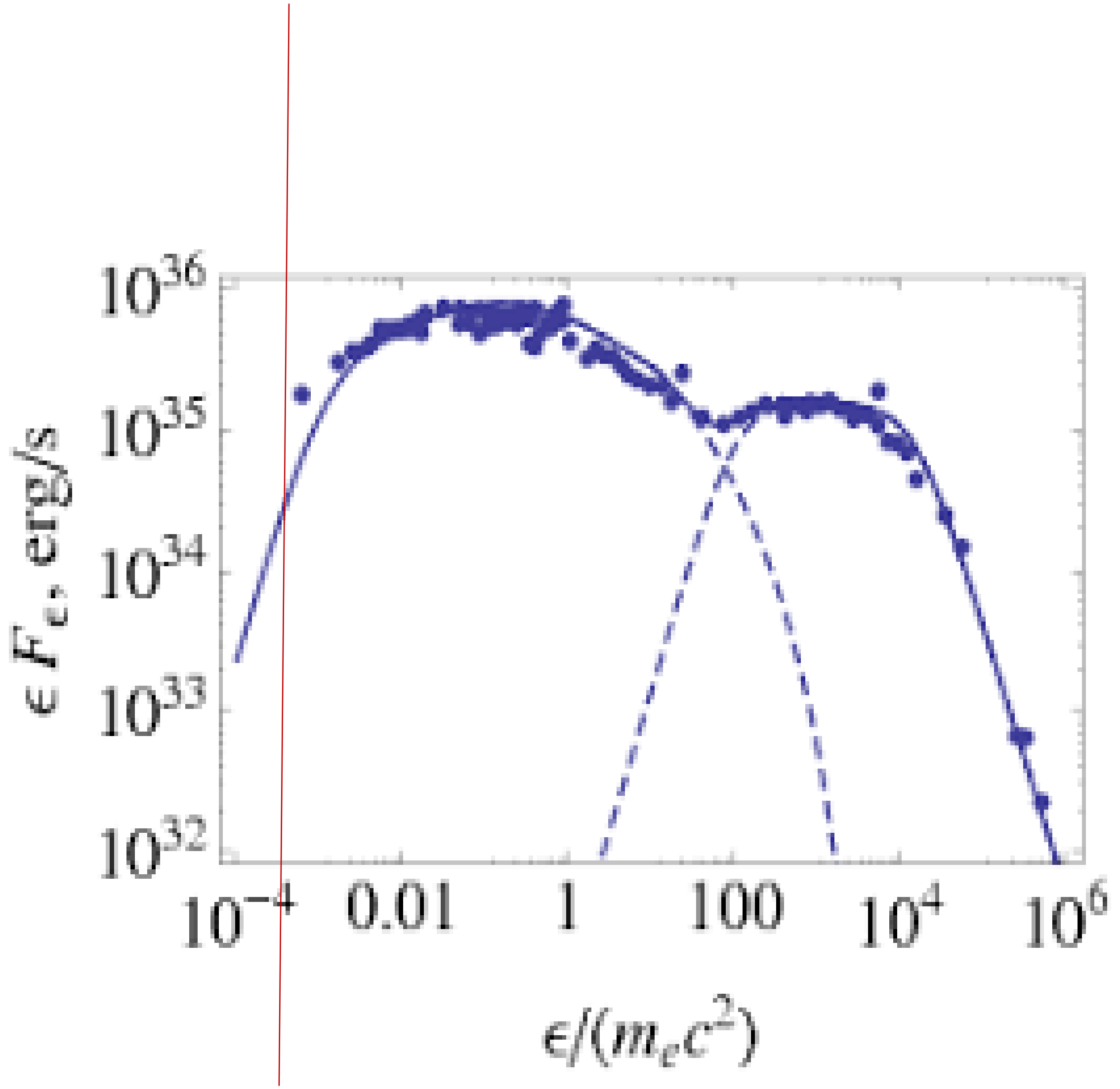
Figure 8. Spectral energy distribution of Mrk 421 averaged over all the observations taken during the multifrequency campaign from 2009 January 19 (MJD 54850) to 2009 June 1 (MJD 54983). The legend reports the correspondence between the instruments and the measured fluxes. The host galaxy has been subtracted, and the optical/X-ray data were corrected for the Galactic extinction. The TeV data from MAGIC were corrected for the absorption in the EBL using the prescription given in Franceschini et al. (2008).



The spectrum of the Vela pulsar





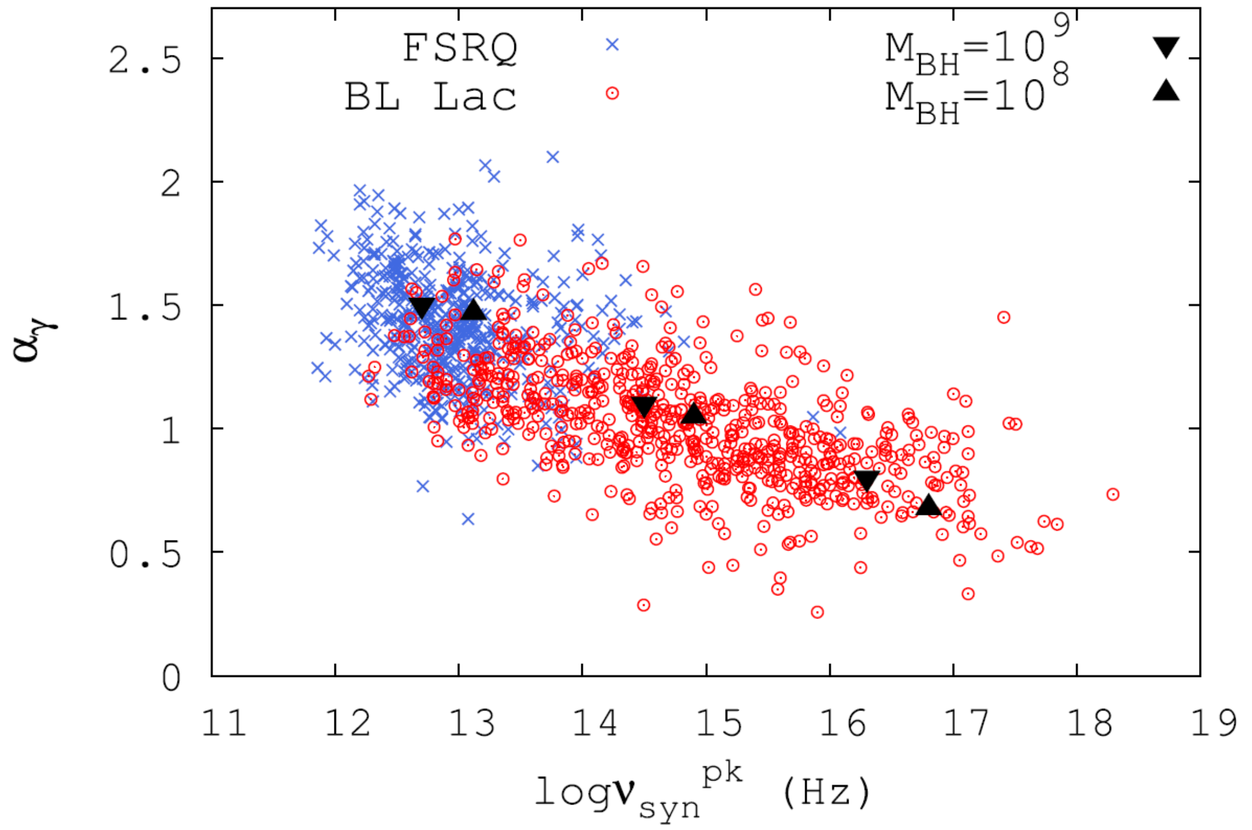


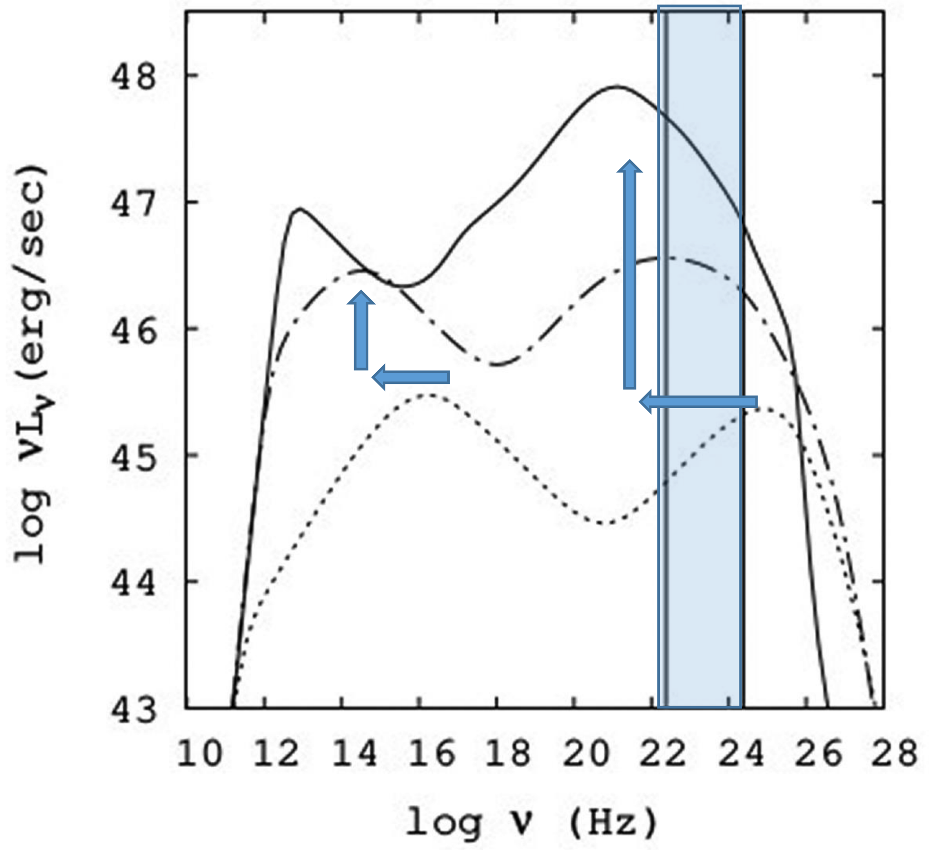
Optical Emission

The pulsed Crab emission (ignoring the radio) spans 13 decades

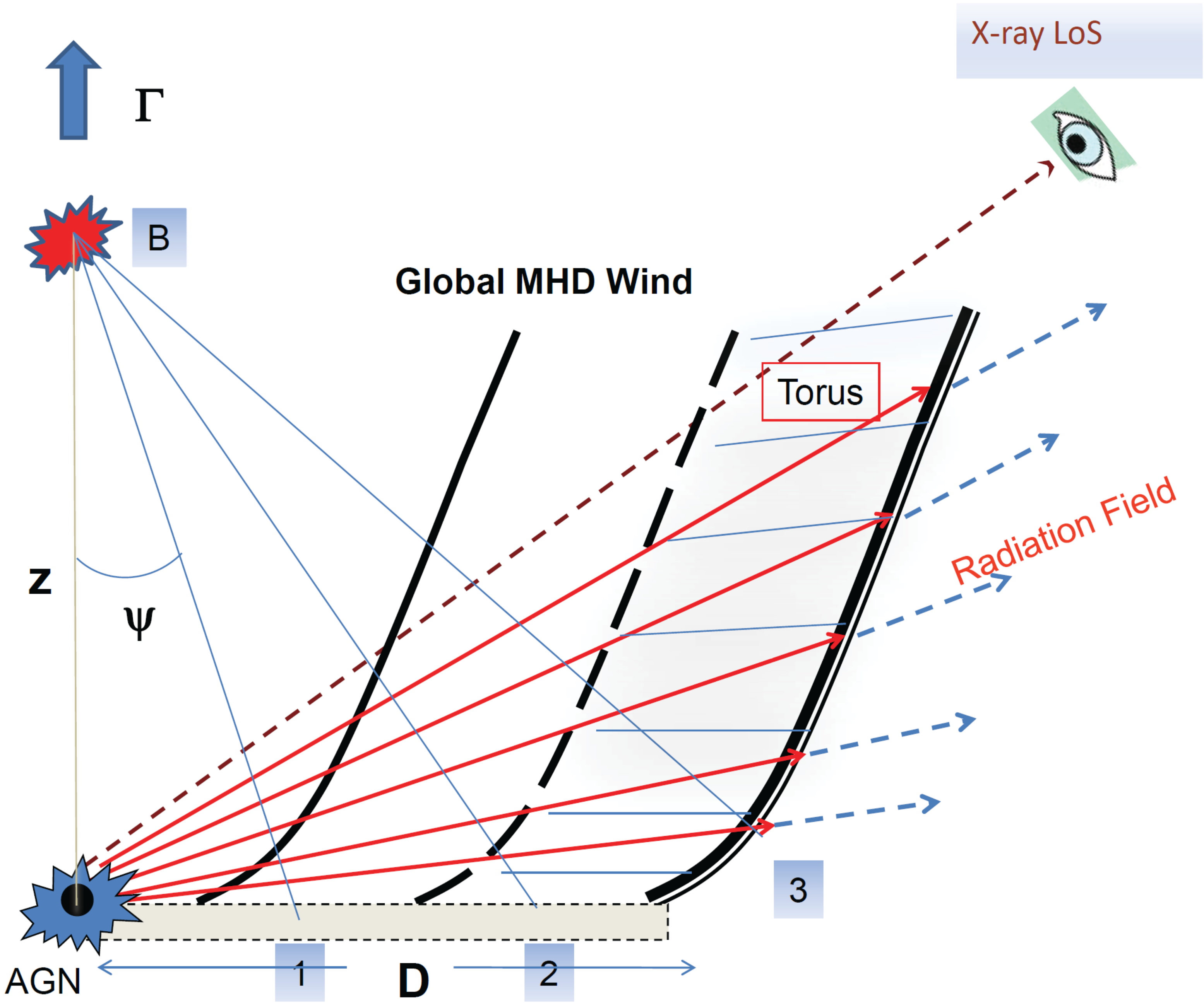
- Given the similarity of the spectra the following questions arise:
  - 1. Does the spectral similarity in the two classes imply similarity between the corresponding emission processes?
  - 2 Is the blazar non-thermal emission powered also by rotation (of a black hole than a neutron star)?
  - 3. Do we have to reconsider our views on the process responsible for the pulsar γ-rays or the blazar synchrotron?

While fitting individual blazar spectra requires *4-6 parameters*, the LAT *ensemble* is effectively a *one parameter* family, the dimensionless accretion rate (which relates also to the density of the surrounding wind as given in ***Contopoulos & Lovelace 1994***, critical to produce the EC normalization)



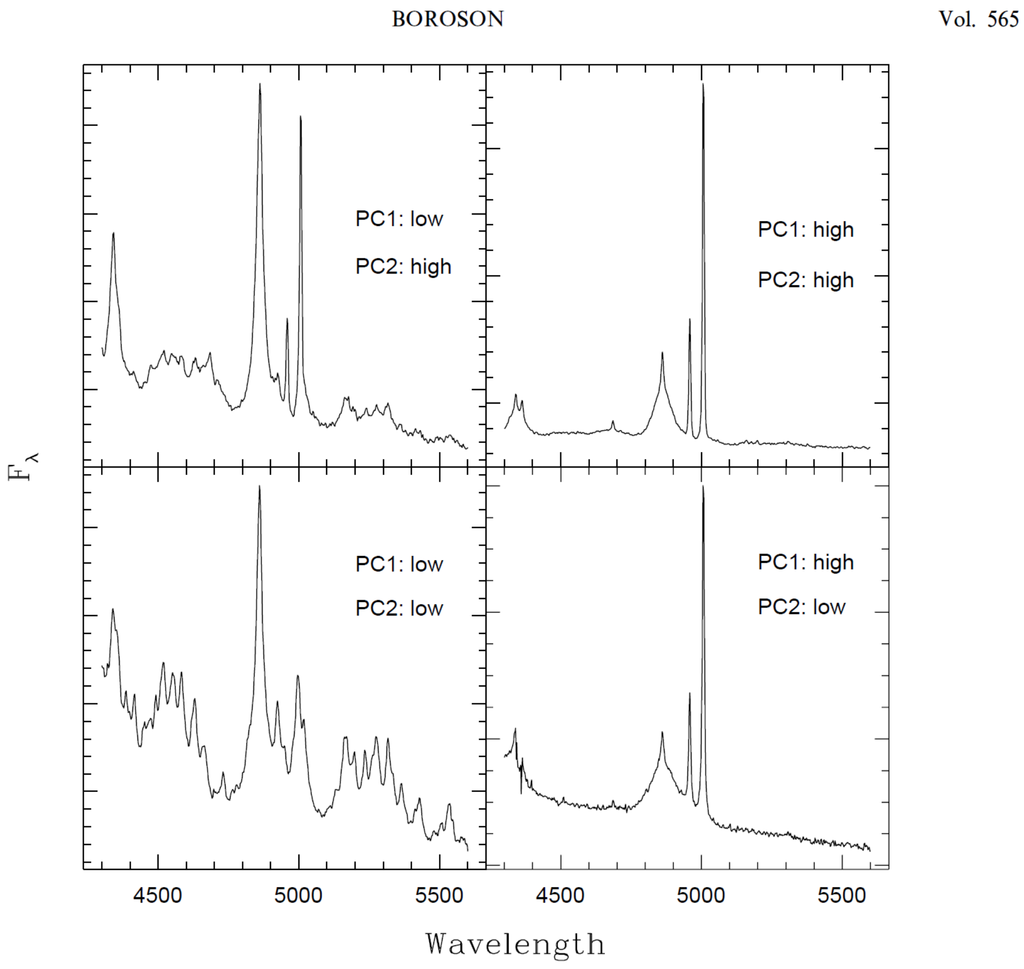


Boula, DK, Mastichiadis 2018



X-ray LoS
Γ
B
Global MHD Wind
Torus
Radiation Field
z
ψ
3
AGN
1
D
2

Multi-parameter situation in AGN (optical spectra, X-ray and radio properties)



In AGN Principal Component Analysis has been employed to determine the eigenvectors of the correlation matrix of the multitude of the AGN properties (Boroson & Green 1992; Boroson 2002)

Is something similar possible with the pulsar with the multitude of the pulsar properties ?

- The Principal Components (the eigenvectors of the correlation matrix) contain most of the variance of line and continuum properties

TABLE 3

LINE AND CONTINUUM CORRELATION MATRIX

	z	M_V	Log R	α_{ox}	EW Hβ	EW λ5007	EW λ4686	EW Fe II	R λ5007	R λ4686	R Fe II	Peak λ5007	Hβ FWHM	Hβ shift	Hβ shape	Hβ asymm	$M_{[OIII]}$
z		−0.871	0.252	0.238	−0.083	−0.180	−0.419	−0.128	−0.156	−0.442	−0.134	0.098	0.307	0.031	0.228	−0.171	−0.554
M_V	−0.871		−0.376	−0.229	0.053	0.289	0.588	0.050	0.267	0.612	0.098	0.025	−0.275	−0.076	−0.191	0.104	0.650
Log R	0.252	−0.376		−0.088	−0.145	0.200	−0.146	−0.404	0.292	−0.128	−0.319	0.364	0.303	0.237	0.052	−0.273	−0.540
α_{ox}	0.238	−0.229	−0.088		−0.318	−0.413	−0.358	0.132	−0.261	−0.301	0.209	−0.319	−0.086	0.165	0.328	0.225	0.075
EW Hβ	−0.083	0.053	−0.145	−0.318		0.363	0.324	0.142	−0.103	−0.010	−0.425	0.065	0.181	−0.149	−0.088	−0.185	−0.188
EW λ5007	−0.180	0.289	0.200	−0.413	0.363		0.488	−0.389	0.803	0.311	−0.462	0.716	0.136	−0.029	−0.197	−0.239	−0.345
EW λ4686	−0.419	0.588	−0.146	−0.358	0.324	0.488		−0.077	0.355	0.876	−0.222	0.271	−0.199	−0.120	−0.167	−0.119	0.165
EW Fe II	−0.128	0.050	−0.404	0.132	0.142	−0.389	−0.077		−0.529	−0.084	0.766	−0.670	−0.436	−0.155	0.122	0.454	0.494
R λ5007	−0.156	0.267	0.292	−0.261	−0.103	0.803	0.355	−0.529		0.347	−0.365	0.827	0.139	0.010	−0.113	−0.288	−0.361
R λ4686	−0.442	0.612	−0.128	−0.301	−0.010	0.311	0.876	−0.084	0.347		−0.042	0.181	−0.288	−0.053	−0.140	−0.039	0.270
R Fe II	−0.134	0.098	−0.319	0.209	−0.425	−0.462	−0.222	0.766	−0.365	−0.042		−0.635	−0.548	−0.001	0.198	0.591	0.604
Peak λ5007	0.098	0.025	0.364	−0.319	0.065	0.716	0.271	−0.670	0.827	0.181	−0.635		0.508	−0.003	−0.121	−0.472	−0.555
Hβ FWHM	0.307	−0.275	0.303	−0.086	0.181	0.136	−0.199	−0.436	0.139	−0.288	−0.548	0.508		−0.068	−0.146	−0.316	−0.450
Hβ shift	0.031	−0.076	0.237	0.165	−0.149	−0.029	−0.120	−0.155	0.010	−0.053	−0.001	−0.003	−0.068		0.130	0.119	−0.011
Hβ shape	0.228	−0.191	0.052	0.328	−0.088	−0.197	−0.167	0.122	−0.113	−0.140	0.198	−0.121	−0.146	0.130		0.066	−0.028
Hβ asymm	−0.171	0.104	−0.273	0.225	−0.185	−0.239	−0.119	0.454	−0.288	−0.039	0.591	−0.472	−0.316	0.119	0.066		0.481
$M_{[OIII]}$	−0.554	0.650	−0.540	0.075	−0.188	−0.345	0.165	0.494	−0.361	0.270	0.604	−0.555	−0.450	−0.011	−0.028	0.481	

Boroson 2002

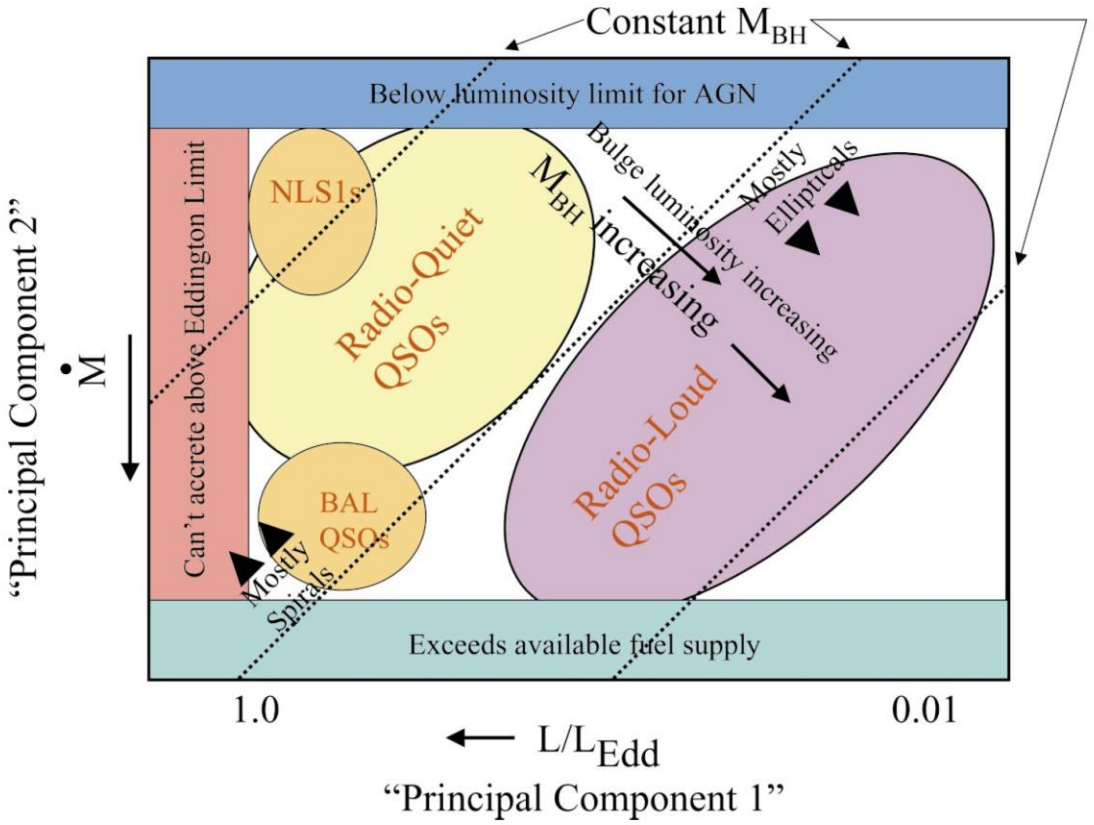


FIG. 7.—Interpretive diagram showing how PC1-PC2 plane provides basis for classification of AGNs

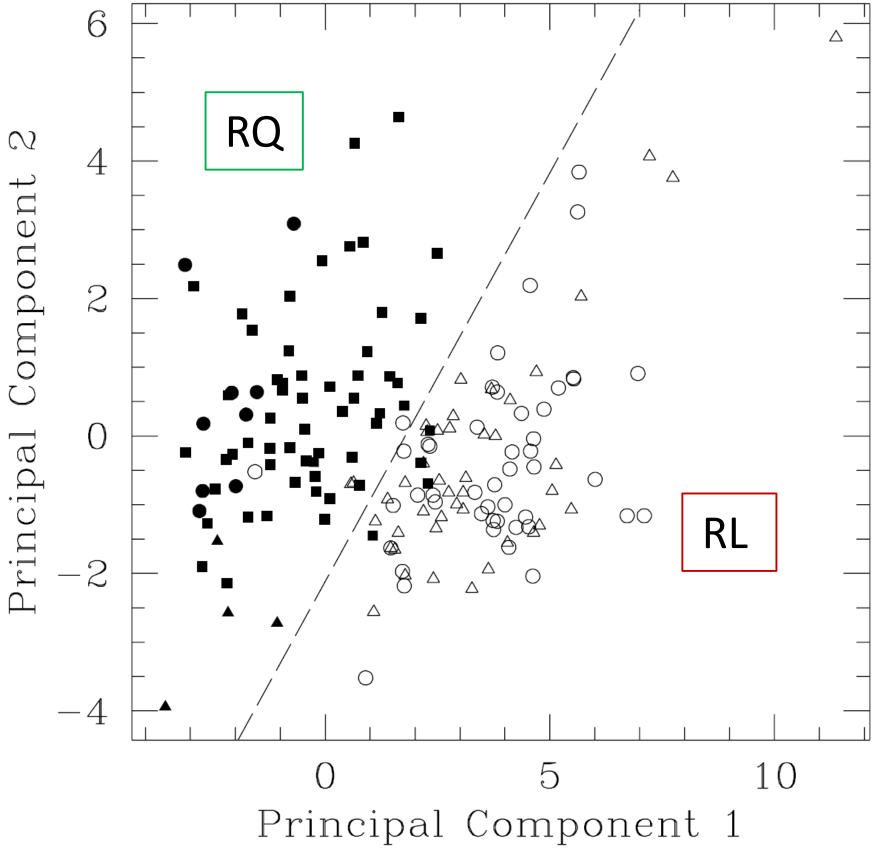
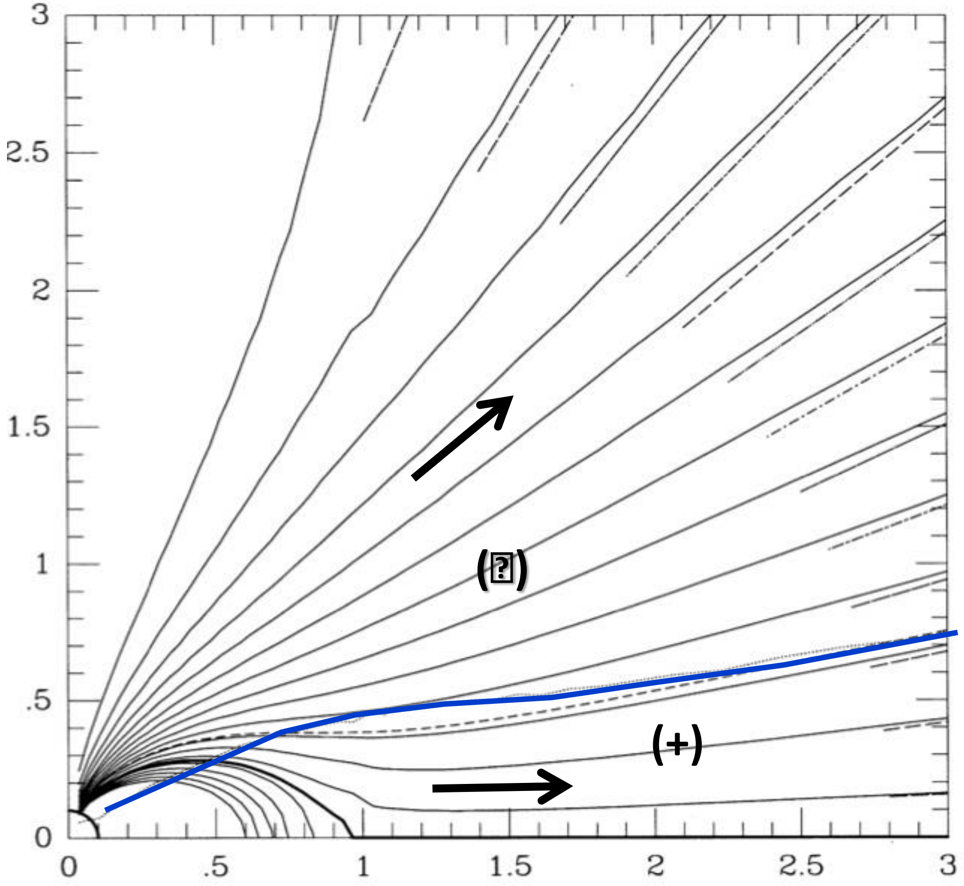


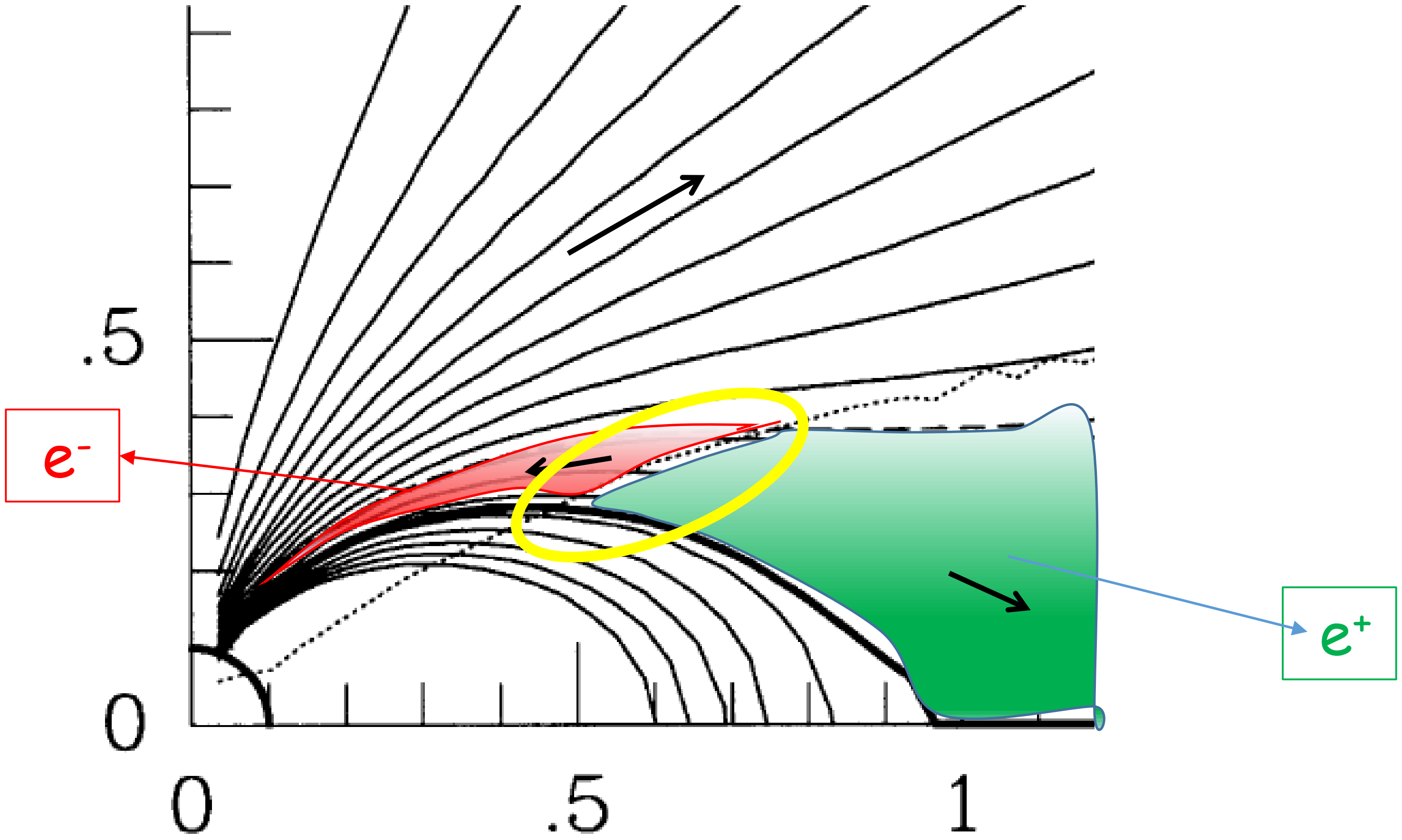
FIG. 4.—Distribution of the enlarged sample of 162 objects with respect to the two principal components. *Filled triangles*: BALQSOs, *filled circles*: NLS1s, *filled squares*: other radio-quiet QSOs, *open triangles*: flat-spectrum radio-loud QSOs, *open circles*: steep-spectrum radio-loud QSOs. The dashed line (drawn by eye) separates radio-loud and radio-quiet objects.

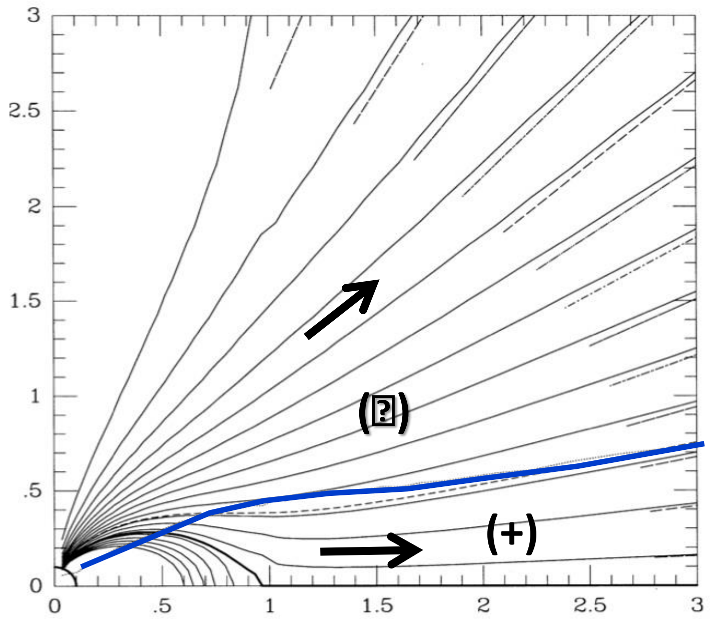
Eventual classification of the entire AGN pop in terms of the two eigenvector values

Need a source of pairs!!



Where and How??





A Radiative Instability Reaction Network

Applied to AGN and GRB (DK, Mastichiadis, Georganopoulos 02, 06, 09)

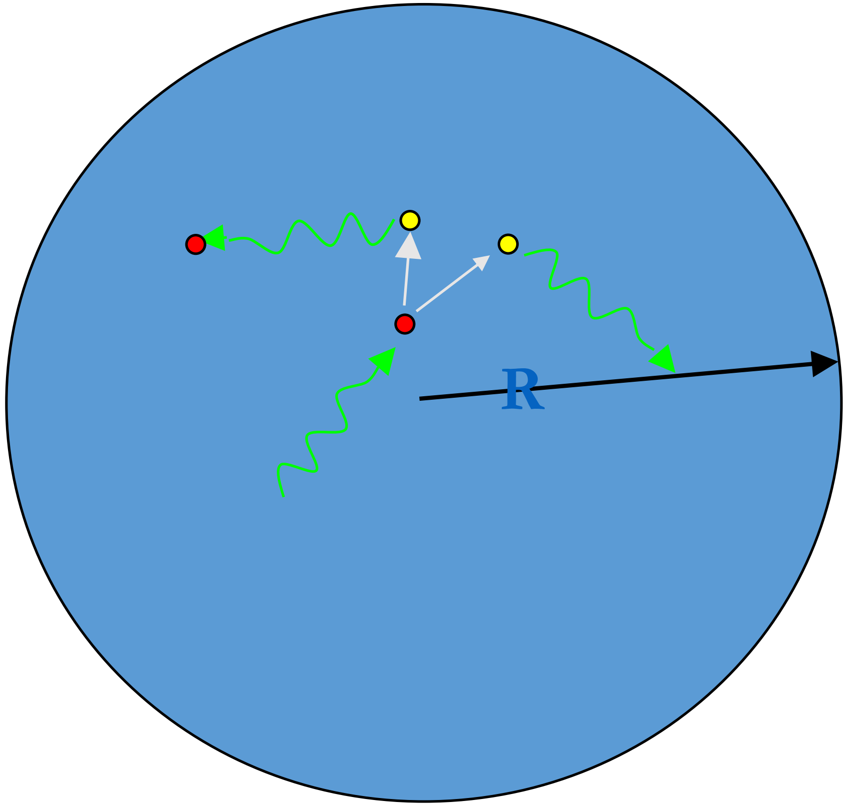
ε in $m_e c^2$ units, $b = B/B_{cr}$

● Proton

● e^+ or e^-

$P\gamma \rightarrow e^+e^-$

$eB \rightarrow B\gamma$



Photons produce *e+e-* of energy $\varepsilon \sim b\gamma^2$ interacting with relativistic ***p***

e+e- produce $N = \gamma/b\gamma^2 = 1/b\gamma$ *photons* by synchrotron

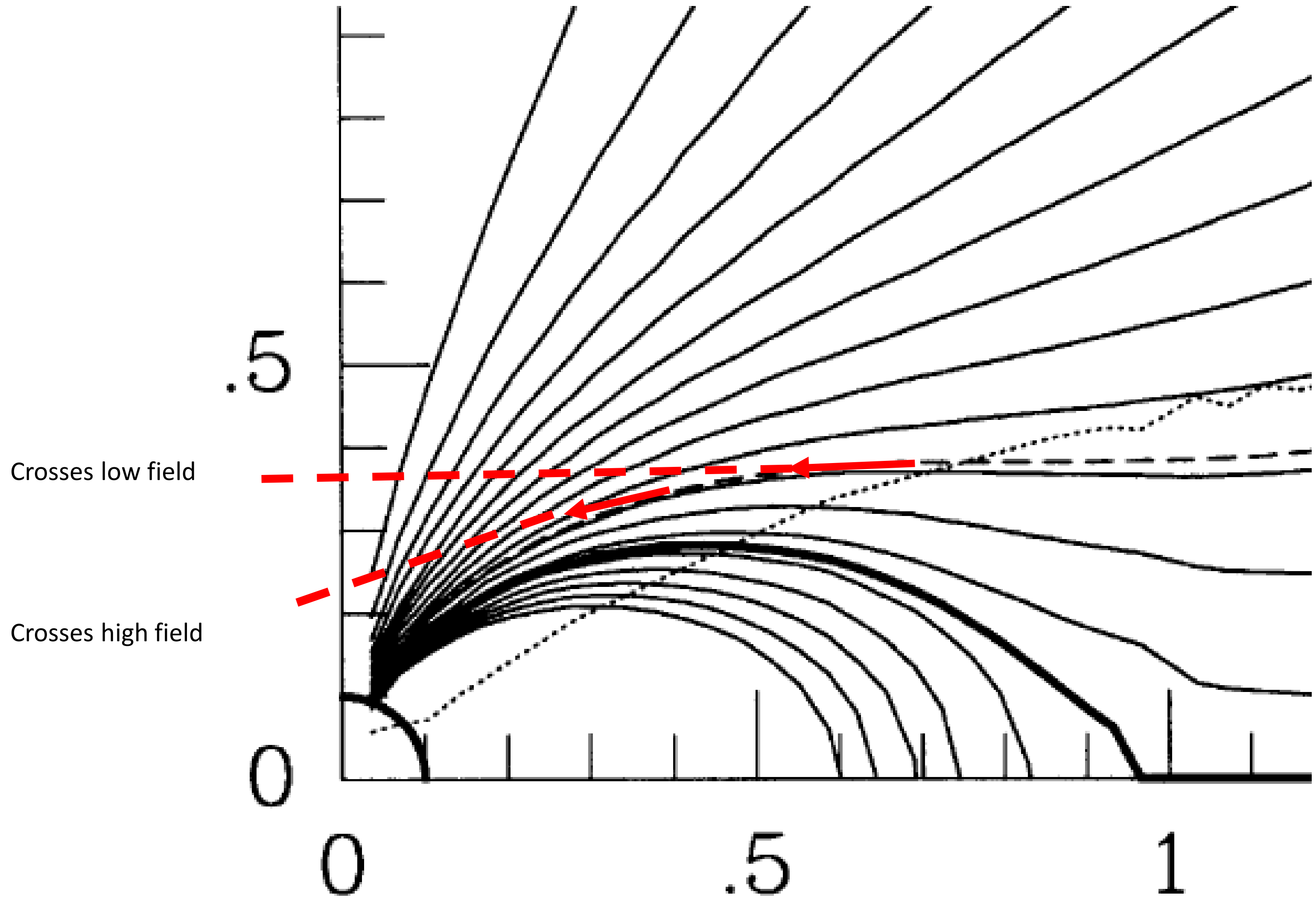
The photons of energy $\varepsilon \sim b\gamma^2$ can *e+e-* produce on the ***p frame*** if $b\gamma^3 > 2$ *(kinematic threshold)*

The situation becomes *supercritical* if the blob column of $p\gamma$ to *e+e-* is grater than $1/N$ or $n\sigma R > 1/N \sim b\gamma$. *Then the entire energy in p's is converted to photons on time scales R/c .*

- A similar instability is possible in a unscreened electric field (Voltage), which plays the role of the proton free energy and the B-γ or γ-γ opacity providing the criticality condition.

- The increase in carrier density reduces the voltage and hence the photon energy. The lowering of photon energy allows reduction of pair formation, reducing the carrier density, increasing the voltage, to find eventually a steady solution.

- The magnetic field structure plays a role in this respect because the curvature photons are emitted along the field tangent.



Crosses low field
Crosses high field
.5
0
0
.5
1

Harding & Lai 2006

- The B-γ mean free path is given by: 1/L ~ $R^{\rm pp}_{1\gamma}(\chi) = \frac{\alpha}{2\lambda} B' \sin\theta \;\; T(\chi),$

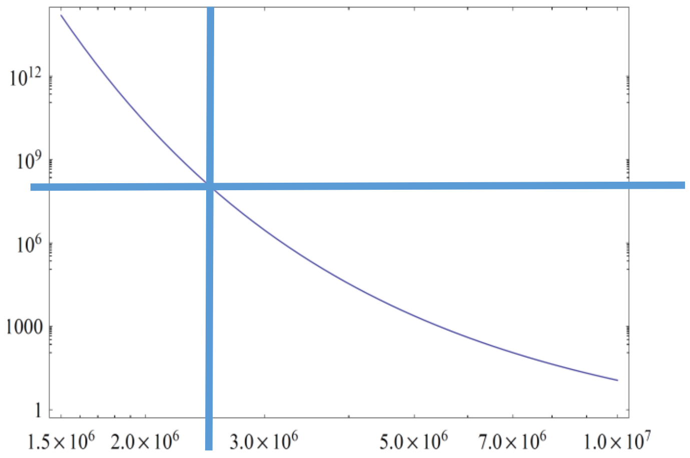
$$T(\chi) \approx 4.74\chi^{-1/3}\mathrm{Ai}^2(\chi^{-2/3}) = \begin{cases} 0.377\exp\left(-\frac{4}{3\chi}\right) & \chi \ll 1 \\ 0.6\chi^{-1/3} & \chi \gg 1 \end{cases}$$

$$\chi \equiv \epsilon B' \sin\theta/2,$$

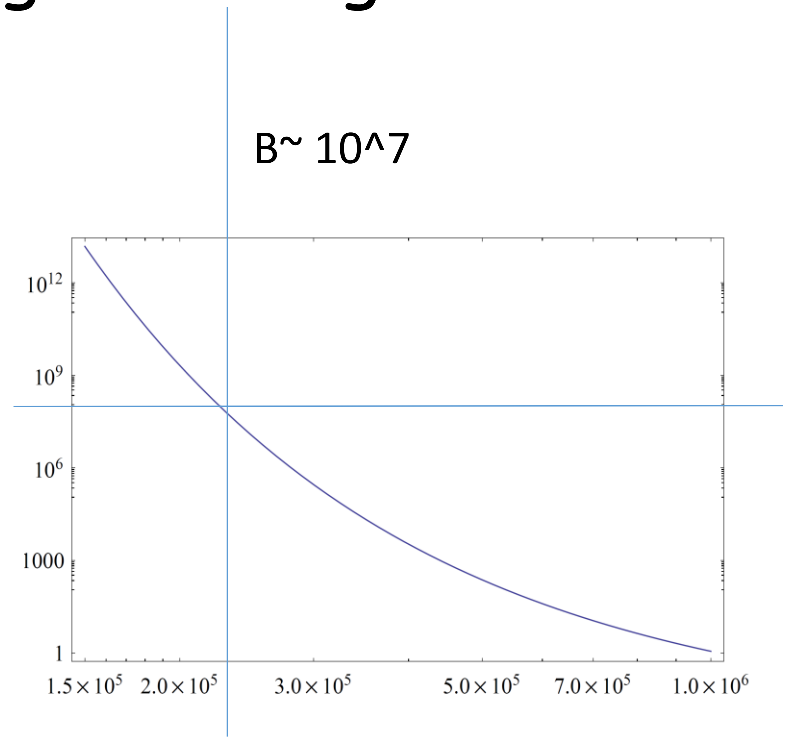
- The energy ε in units of $m_e c^2$ and of B' in B_{cr}

- For the Crab the LC field is ~ 10^6 G. We can ask the question of what γ-ray energy will have mfp $L \sim R_{LC}$, in direction perpendicular to the rotation axis. Directions of higher inclination go thru higher B-field and have shorter mfp.

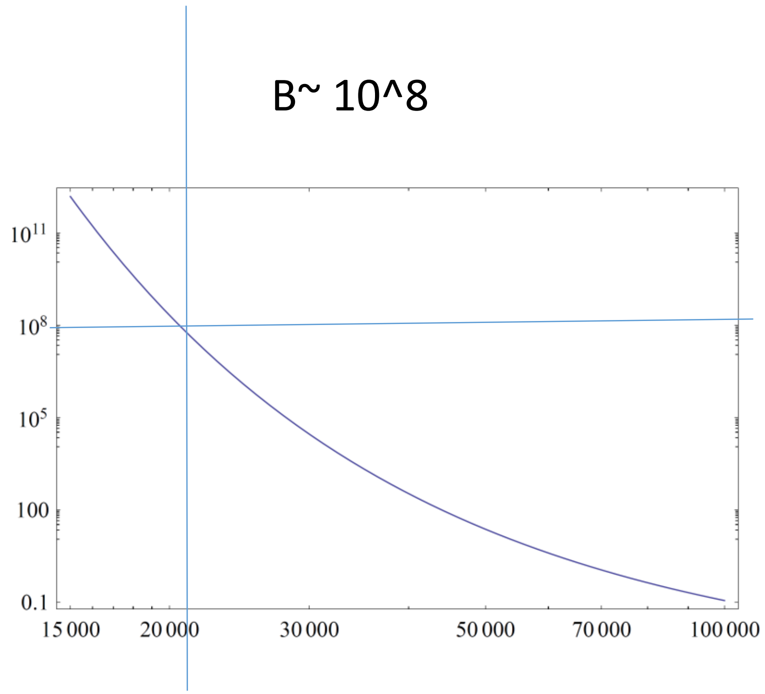
B~ 10^6



B~ 10^7



B~ 10^8



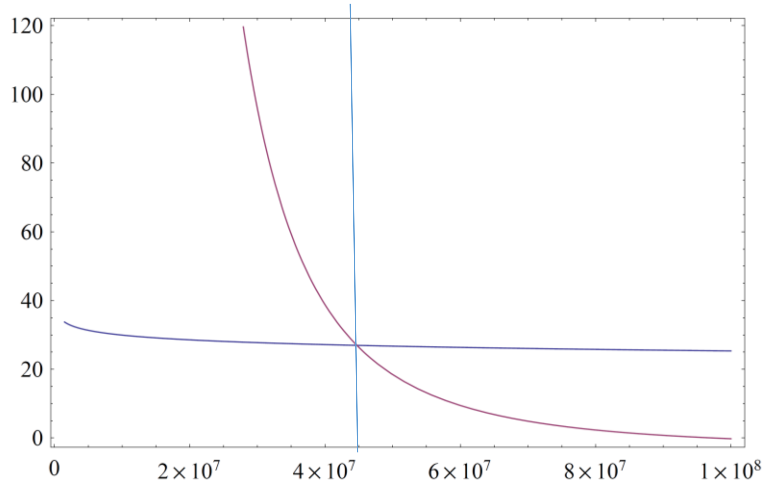
$m_e c^2$

- However, we need the mfp to be $(1/N)R_{LC}$ where N is the number of curvature photons

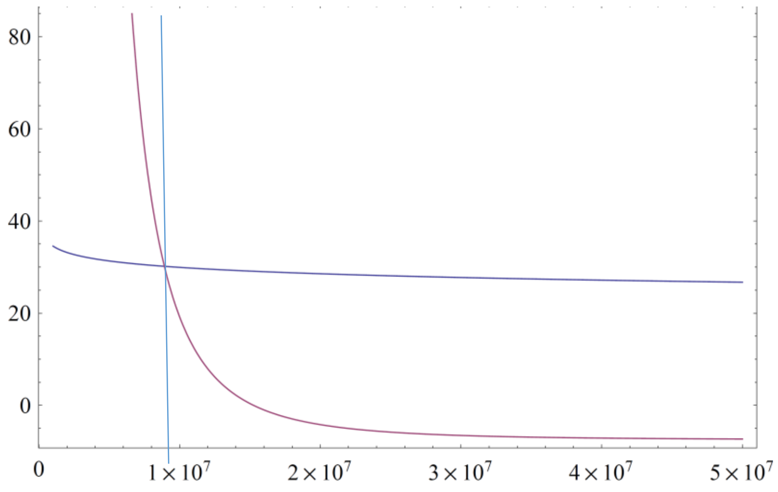
$$N \sim \gamma\, m_e c^2/\gamma^3\, h\Omega \sim m_e c^2/\gamma^2\, h\Omega \sim 10^{19}/\gamma^2 \quad \textit{for the Crab}$$

Solving graphically we obtain the critical γ values for which their curvature photons will obey the dynamical threshold i.e. they can initiate a cascade to produce the necessary pairs

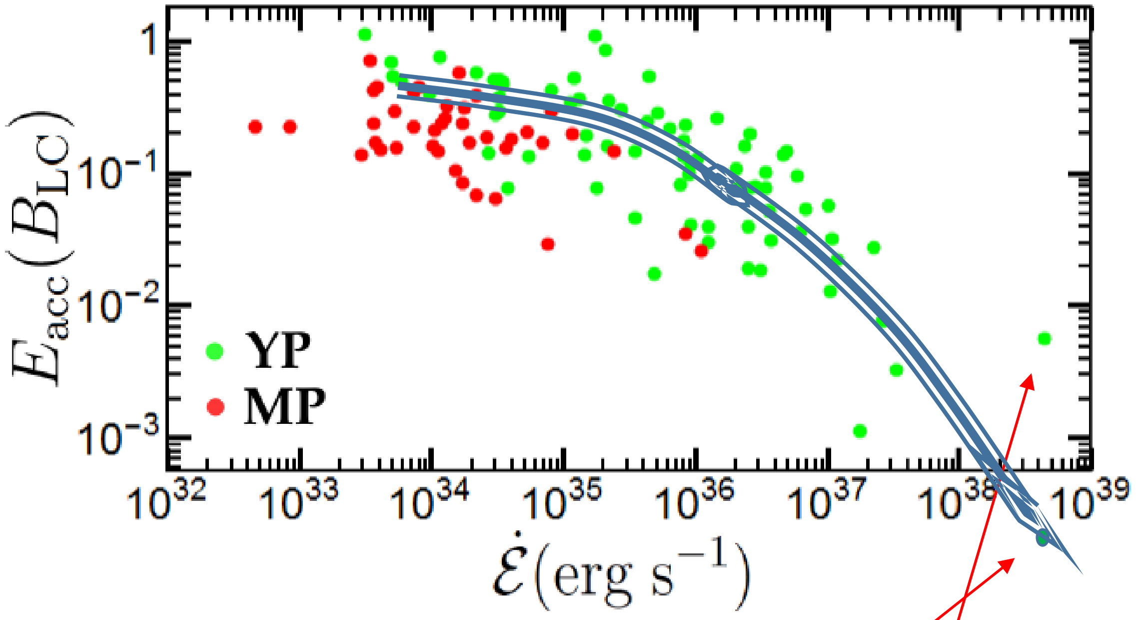
B~ 10^6, $\gamma \sim 4\ 10^7$

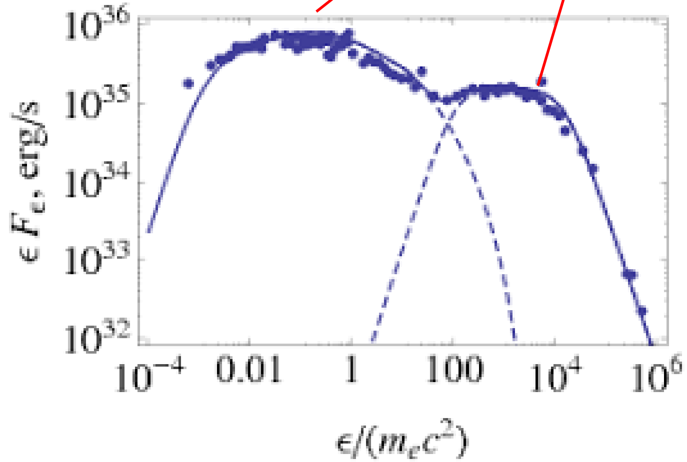


B~ 10^8, $\gamma \sim 10^7$



- It is opacity to pair production (either on photons or B-field that determines the number of pairs produced, which in turn determines the value of the accelerating E-field and the particle energy.
- This was estimated in K+2017 demanding that the accelerated particle produce the observed Fermi cut-off energies by curvature radiation.





Summary - Conclusions – Questions (personal)

- Great progress in understanding the dynamics and structure of pulsar magnetospheres!
- Q1: Does this suffice to explain the observed phenomenology? Do we need only minor adjustments in our models and more detailed calculations (more of whether this is feasible the next days).
- Q2: With global magnetospheric models at hand, have we been asking the right questions? Can we calculate breaking indices?
- Q3: How many parameters we need to describe the pulsar phenomenology? How many would be satisfied with?
- Thank you!!