Extreme VHE Universe Workshop
CTA Japan 2020/02/22

Dr. Giovanni Ceribella / チェリベッラ　ジョヴァンニ

The comeback of Extreme Pulsars

OUTLINE

- **INTRODUCTION**
- **PULSARS AT THE VERY-HIGH-ENERGY**

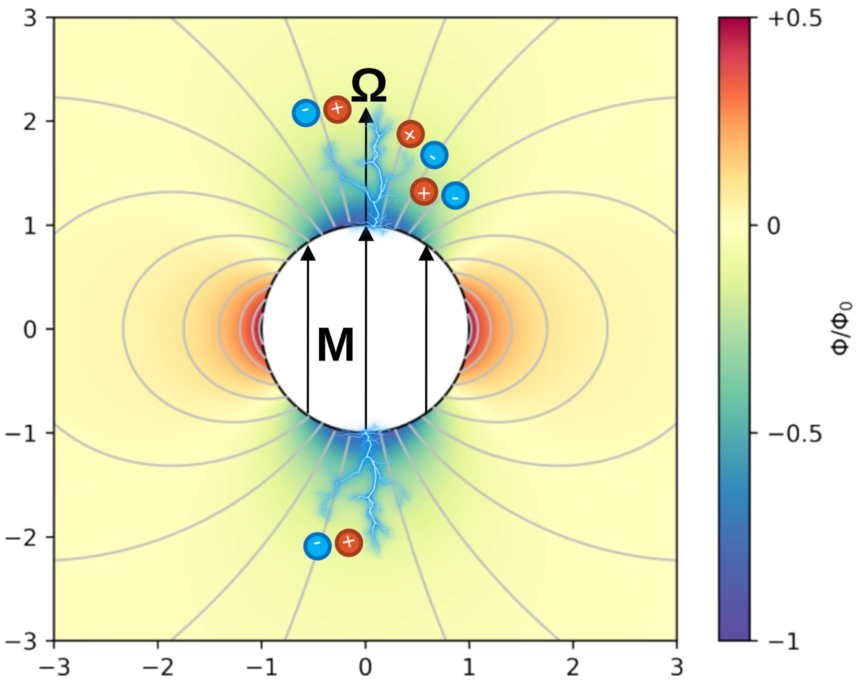
  Observational & Theoretical state of the art

  Open questions
- **PULSAR HUNTING**

  The MAGIC Sum-Trigger-II legacy
- **WHERE CTA/LST-1 CAN BE THE DIFFERENCE**

INTRODUCTION

PULSAR FUNDAMENTALS



Lengths scaled to the radius of the star, with magnetic and rotational axes parallel.

Neutron star:

Mass = 1.4 $M_\odot$ **B** field = 10^8 T
Radius = 10 km Period = 10^{-3} s – 1 s

Spinning magnet: **homopolar generator**
E + (**Ω**×**r**)×**B** = 0

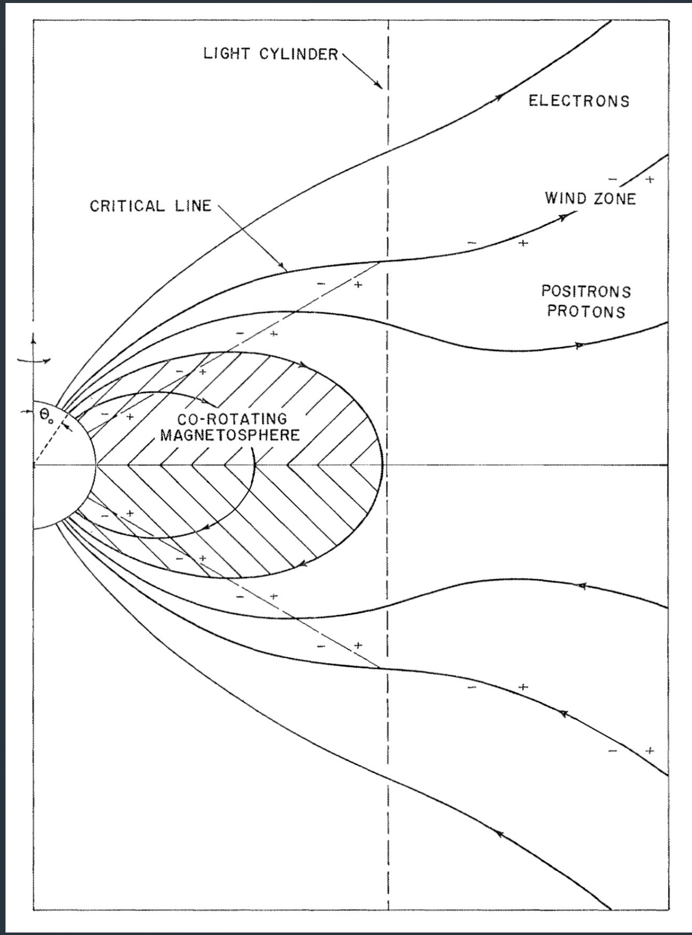
Polar Φ = 10^{16} V
E field = 10^{13} V/m

Large **E** field: **extraction of particles** from the star.

Ideal Magnetohydrodynamic plus axial symmetry:

$\vec{u} = \vec{\Omega} \times \vec{r} + g_{(r,z)} \vec{B}$

PULSAR FUNDAMENTALS



Plasma-filled **magnetosphere**

Ohm's law: **j** = σ (**E** + **u**×**B**)

Ideal plasma (infinite conductivity):

E + **u**×**B** = 0 **E**·**B** = 0

Magnetic field lines are **electric equipotential**

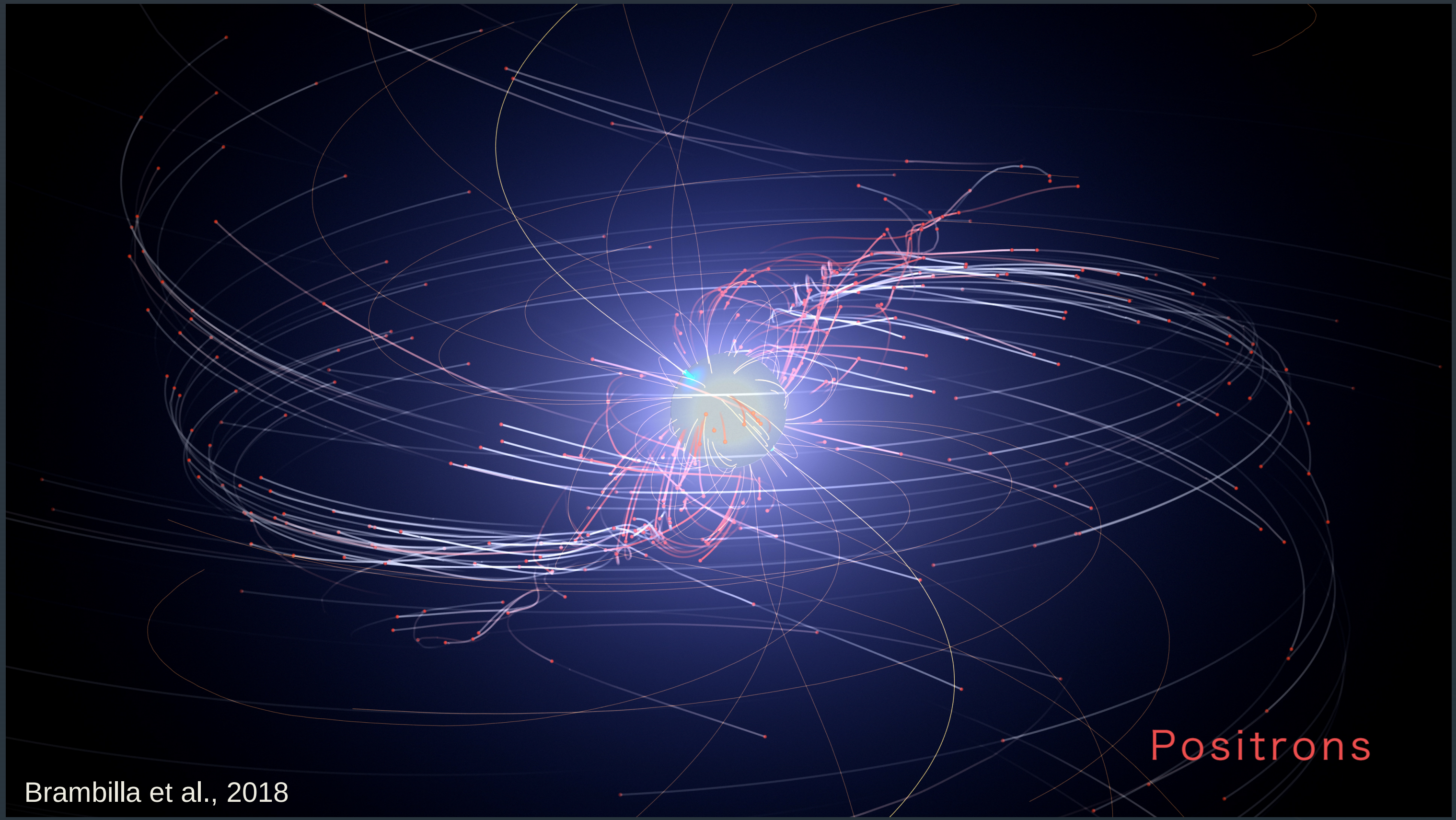
Particles **bound to the field lines** and in **co-rotation** with the neutron star

Co-rotation radius limited by the speed of light. **Light cylinder** R = c/Ω

Open magnetosphere !

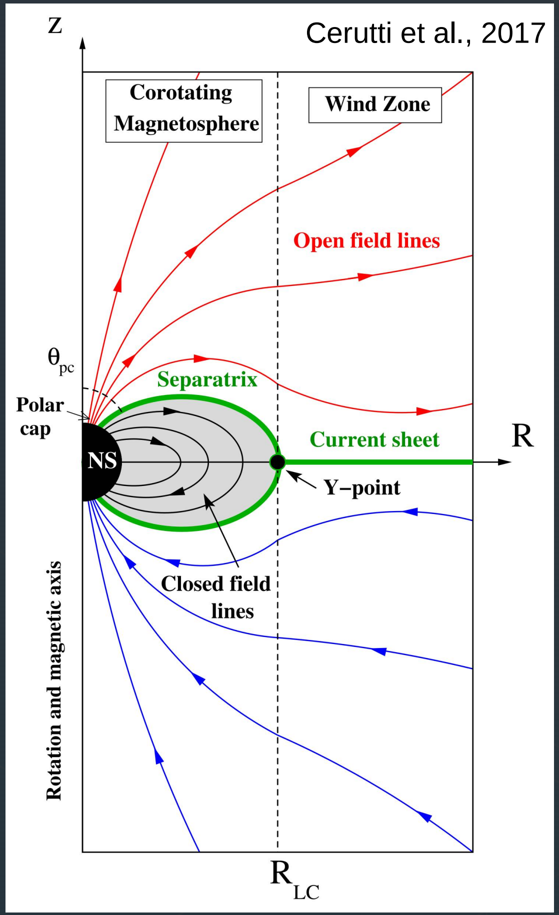
Particles stream away **leaving the star**
Loss of energy: **pulsar spins down**

PULSAR FUNDAMENTALS



PULSAR FUNDAMENTALS

- **Particle acceleration** possible only in **defects** of the ideal **plasma:**
  - **Where** are they? **What** sustains them?
- **Gamma rays** via **synchro-curvature** (SC) radiation or **inverse-Compton** scattering (ICS):
  - Competition with **absorption** in the **strong B** field
  - Spectral **cut-offs** due to maximum electron energy
- **No analytical** solution!
  - Theoretical modeling **limited** by **computational methods** and power



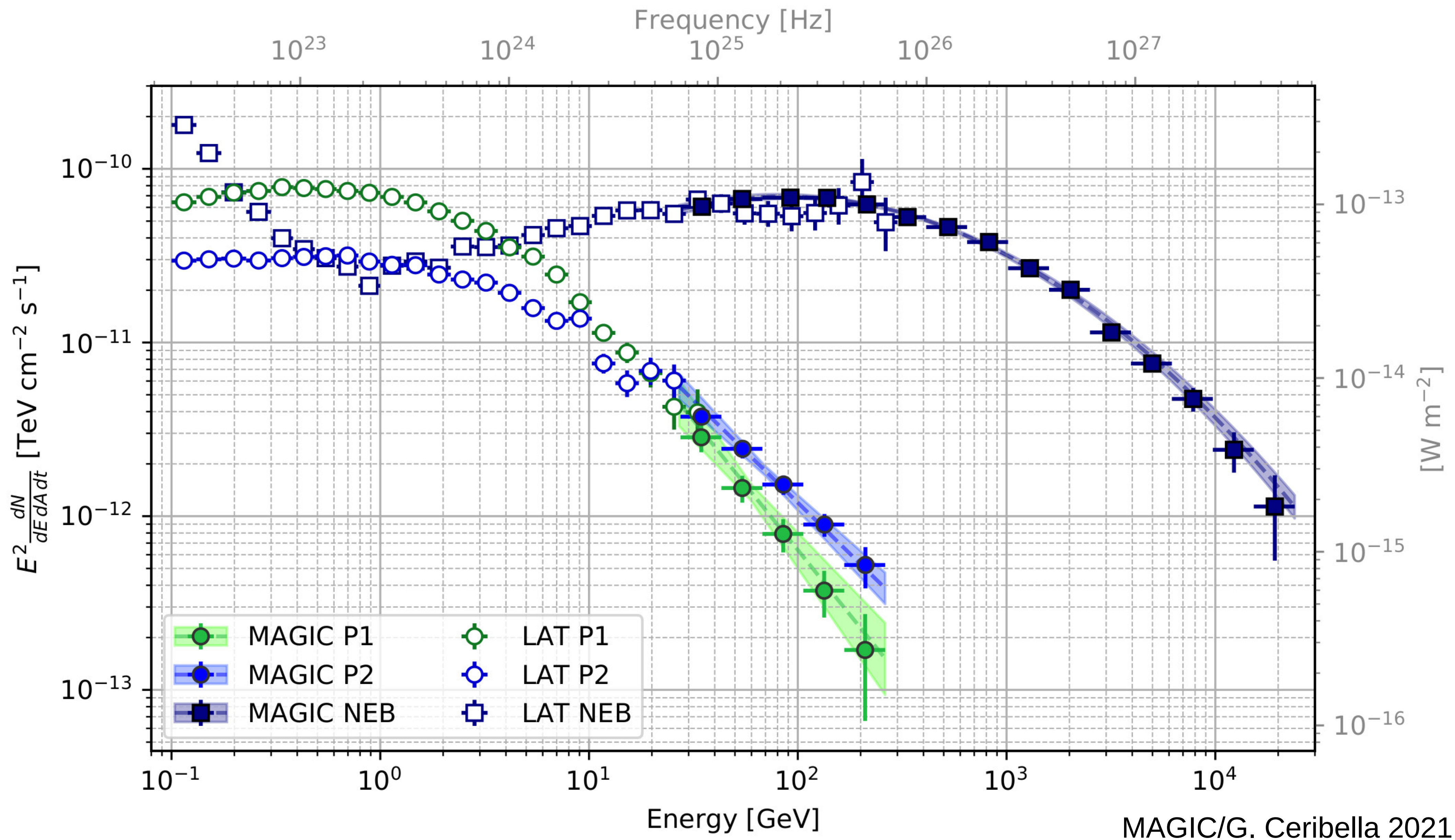
VERY-HIGH-ENERGY PULSARS

DETECTED PULSARS

Four very-high-energy pulsars (one still unconfirmed), all young and spin-powered.
Two (one still unpublished) of them reach TeV energies (inverse-Compton component).

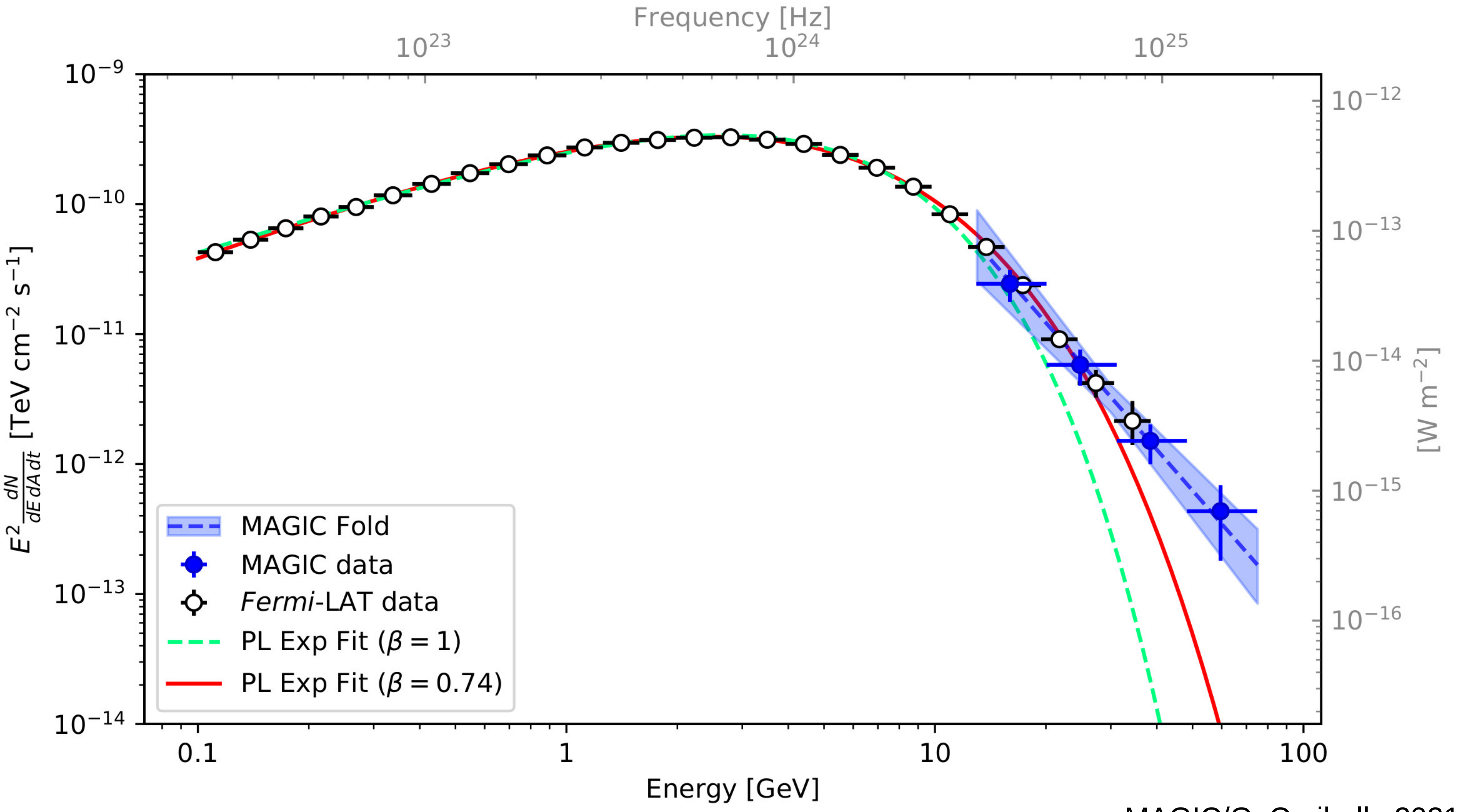
		Crab	Geminga	Vela*	B1706-44*
Catalog name		J0534+2200	J0633+1746	J0835-4510	J1709-4429
Age	[a]	967	$3.4 \cdot 10^5$	$1.1 \cdot 10^4$	$1.8 \cdot 10^4$
Distance	[kpc]	2.00	0.25	0.28	2.6
Radio?		Yes	No	Yes	Yes
Period	[ms]	33.4	237.1	89.3	102.5
Period derivative		$4.2 \cdot 10^{-13}$	$1.1 \cdot 10^{-14}$	$1.2 \cdot 10^{-13}$	$9.3 \cdot 10^{-14}$
Luminosity	[W]	$4.5 \cdot 10^{31}$	$3 \cdot 10^{27}$	$7 \cdot 10^{29}$	$3 \cdot 10^{29}$
Polar *B*	[T]	$3.8 \cdot 10^8$	$1.6 \cdot 10^8$	$3.4 \cdot 10^8$	$3.1 \cdot 10^8$
Light-cylinder *B*	[T]	9.55	0.12	4.45	2.70
Gamma efficiency		0.14%	97%	1.3%	25%
Energy range	[GeV]	27 – 1500	15 – 75	$<$ 20 – 110	10 – 65
Spectral index		~3.2	~5.4	~4.1	~3.8

CRAB PULSAR



MAGIC/G. Ceribella 2021

GEMINGA PULSAR



MAGIC/G. Ceribella 2021

DETECTED PULSARS

- **Common features:**
  - **Power-law-like** tail, overshooting expectations of basic theoretical models (IC component?)
  - Large evolution of the **pulse ratio** with the energy
- **Where** and **how** is the emission really **produced**?
- Are we observing the **aging** of **spin-powered pulsars**?
- Is there any **large-scale time variability** in their flux?

THEORETICAL PERSPECTIVE

Different models try and explain the emission with completely **different mechanisms**:

Classical **Outer Gap** model (Hirotani 2013): electrons **linearly accelerated** in an inner **magnetospheric gap,** radiating **synchro-curvature** and **SSC radiation:**

- **Extension** required to explain the **Crab** emission at **~1 TeV**.
- Interprets the **Geminga emission** as **inverse-Compton** off X-rays.

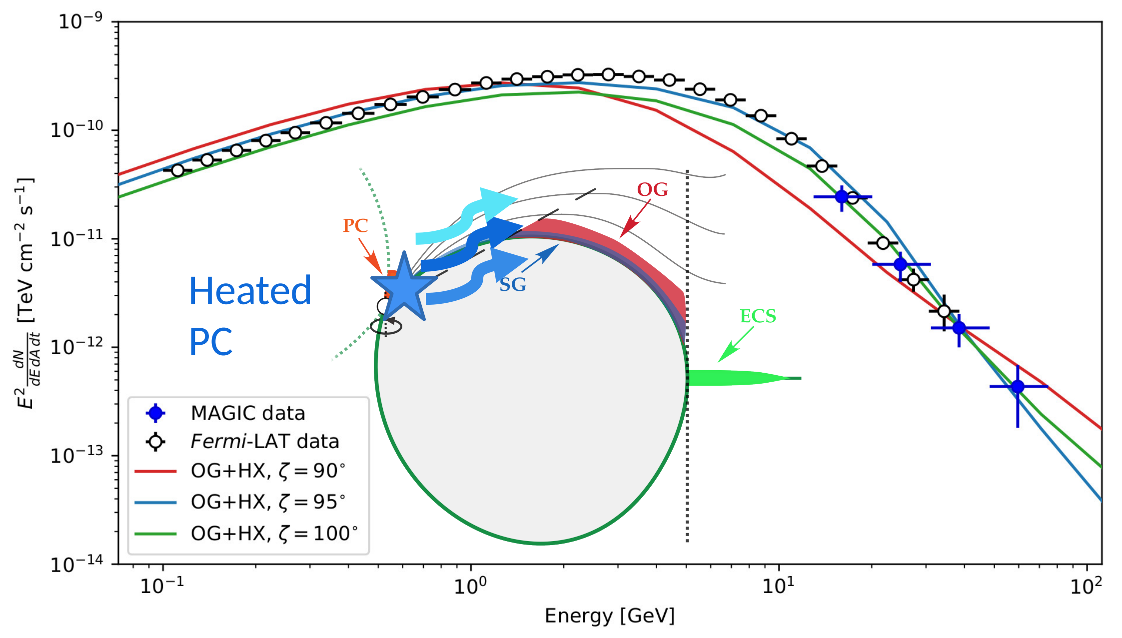
Novel **Current Sheet** model (Harding 2021): electrons accelerated at the **junction between inner** and **outer magnetosphere**, at the light cylinder:

- **Crab** emission resulting from **multiple components**, potentially extended in the **>10 TeV regime**.
- **Geminga** interpreted as **synchro-curvature**.

THEORETICAL PERSPECTIVE

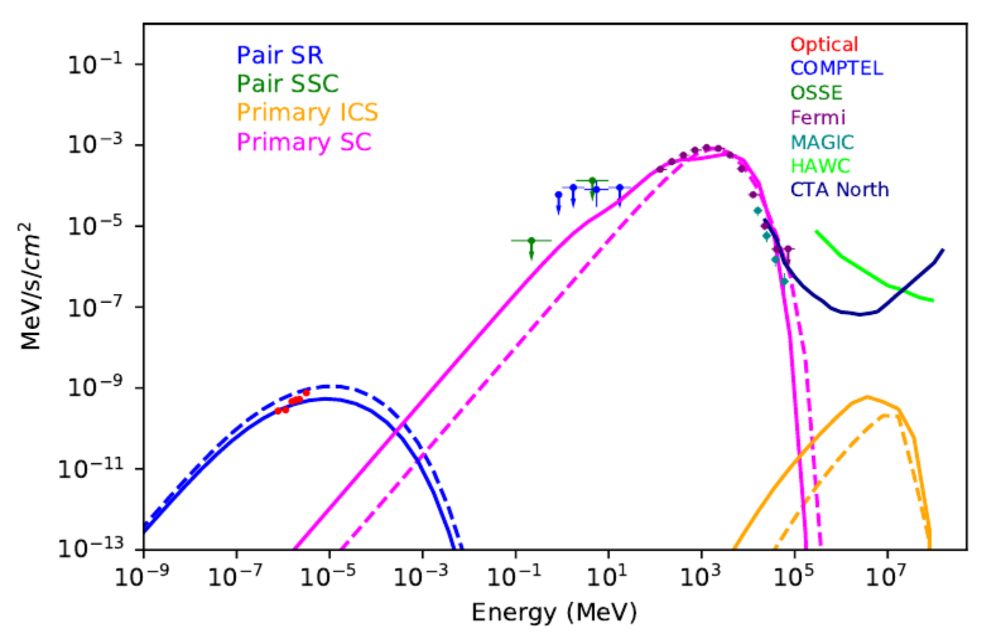
GEMINGA VERY-HIGH-ENERGY EMISSION PUZZLE

INVERSE-COMPTON?



MAGIC Collaboration, 2020

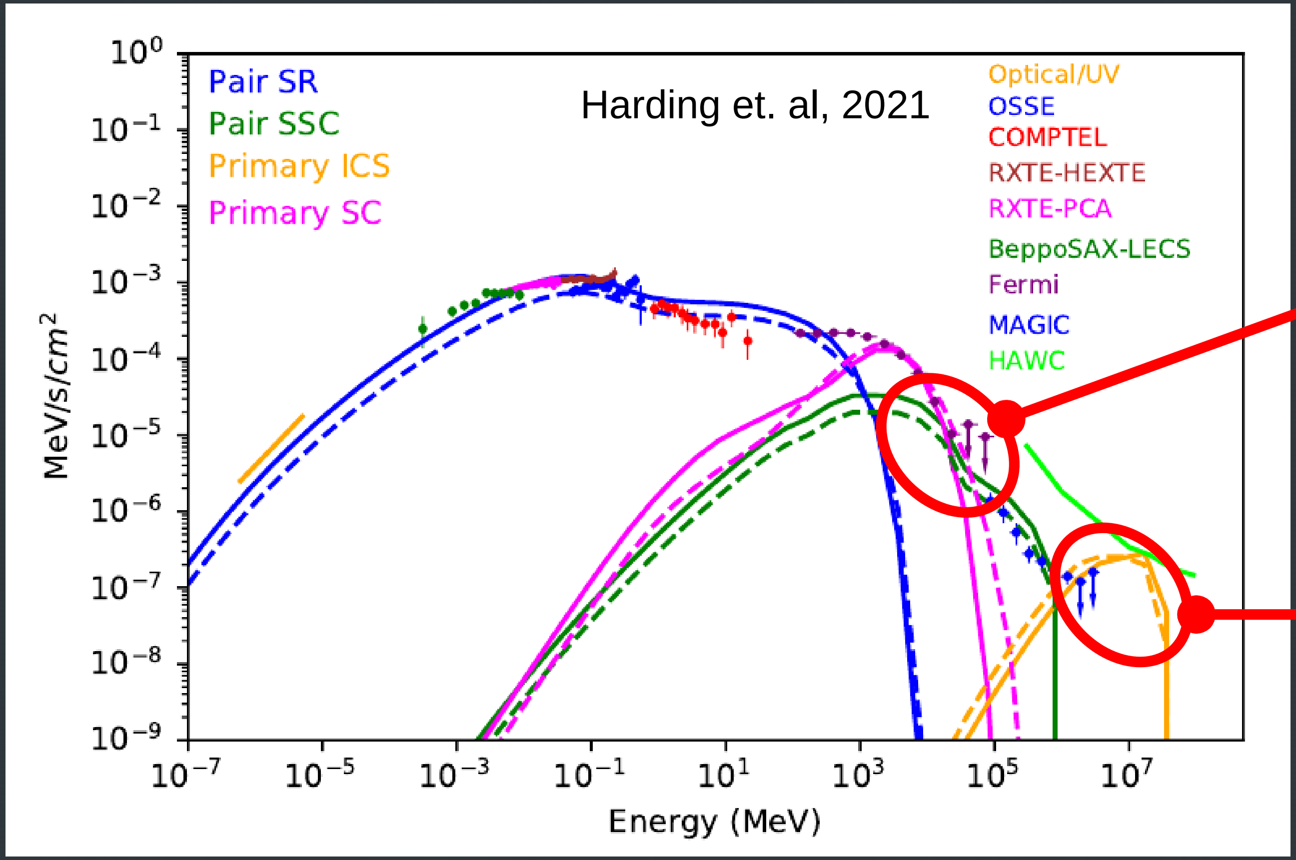
SYNCHRO-CURVATURE?



Harding et. al, 2021

THEORETICAL PERSPECTIVE

CRAB VERY-HIGH-ENERGY EMISSION



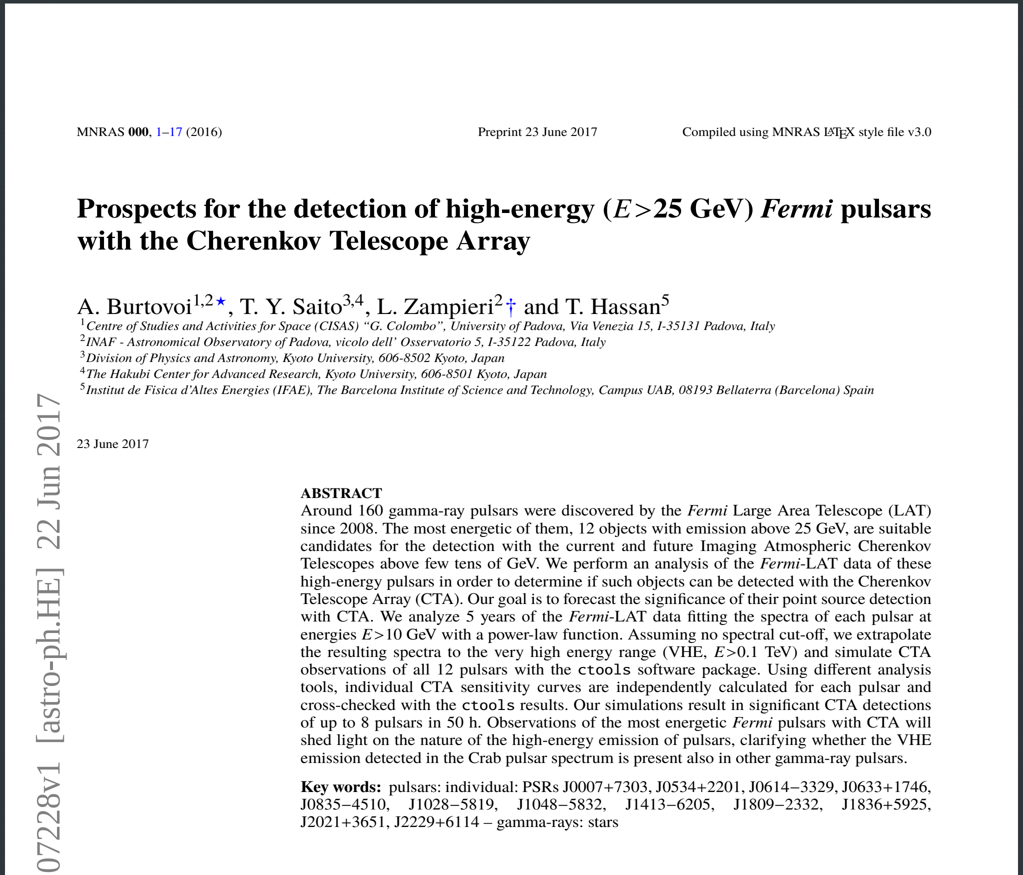
Transition between **two different components** at **few tens of GeV**

Yet unobserved **multi TeV component**

PULSAR HUNTING

CANDIDATE NEW PULSARS

- **Crab** (detected)
- **Geminga** (detected)
-  **Dragonfly** (J2021+3651)
- **Boomerang** (J2229+6114)
- **J0007+7303** (CTA1)
- **J1836+5925** (γ Cyg)
- **J0218+4232** (non-detected)



MNRAS 000, 1–17 (2016) Preprint 23 June 2017 Compiled using MNRAS LATEX style file v3.0

Prospects for the detection of high-energy (E>25 GeV) *Fermi* pulsars with the Cherenkov Telescope Array

A. Burtovoi[1,2]*, T. Y. Saito[3,4], L. Zampieri[2]† and T. Hassan[5]
[1] *Centre of Studies and Activities for Space (CISAS) "G. Colombo", University of Padova, Via Venezia 15, I-35131 Padova, Italy*
[2] *INAF - Astronomical Observatory of Padova, vicolo dell' Osservatorio 5, I-35122 Padova, Italy*
[3] *Division of Physics and Astronomy, Kyoto University, 606-8502 Kyoto, Japan*
[4] *The Hakubi Center for Advanced Research, Kyoto University, 606-8501 Kyoto, Japan*
[5] *Institut de Fisica d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, 08193 Bellaterra (Barcelona) Spain*

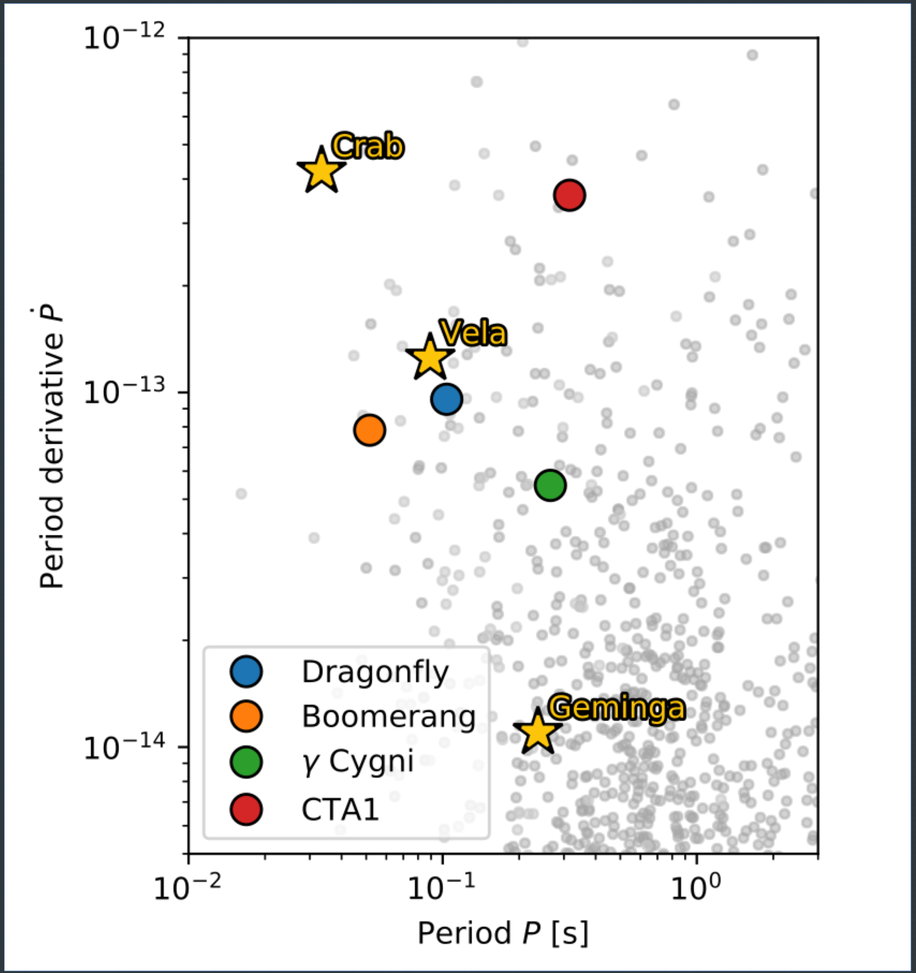
23 June 2017

ABSTRACT
Around 160 gamma-ray pulsars were discovered by the *Fermi* Large Area Telescope (LAT) since 2008. The most energetic of them, 12 objects with emission above 25 GeV, are suitable candidates for the detection with the current and future Imaging Atmospheric Cherenkov Telescopes above few tens of GeV. We perform an analysis of the *Fermi*-LAT data of these high-energy pulsars in order to determine if such objects can be detected with the Cherenkov Telescope Array (CTA). Our goal is to forecast the significance of their point source detection with CTA. We analyze 5 years of the *Fermi*-LAT data fitting the spectra of each pulsar at energies E>10 GeV with a power-law function. Assuming no spectral cut-off, we extrapolate the resulting spectra to the very high energy range (VHE, E>0.1 TeV) and simulate CTA observations of all 12 pulsars with the `ctools` software package. Using different analysis tools, individual CTA sensitivity curves are independently calculated for each pulsar and cross-checked with the `ctools` results. Our simulations result in significant CTA detections of up to 8 pulsars in 50 h. Observations of the most energetic *Fermi* pulsars with CTA will shed light on the nature of the high-energy emission of pulsars, clarifying whether the VHE emission detected in the Crab pulsar spectrum is present also in other gamma-ray pulsars.

Key words: pulsars: individual: PSRs J0007+7303, J0534+2201, J0614−3329, J0633+1746, J0835−4510, J1028−5819, J1048−5832, J1413−6205, J1809−2332, J1836+5925, J2021+3651, J2229+6114 – gamma-rays: stars

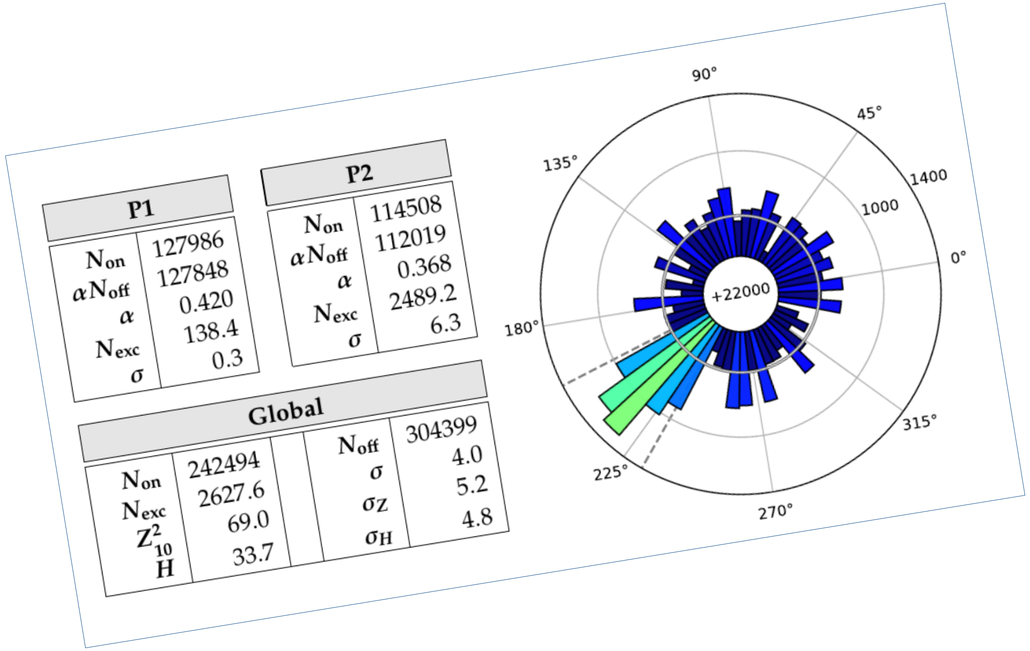
CANDIDATE NEW PULSARS

- **Crab** (detected)
- **Geminga** (detected)
- **Dragonfly** (J2021+3651)
- **Boomerang** (J2229+6114)
- **J0007+7303** (CTA1)
- **J1836+5925** (γ Cyg)
- **J0218+4232** (non-detected)



MAGIC Sum-Trigger-II maturity: Geminga P2

- **IRF model:** LogAeff_zd10-30_Geminga_size20_eest25-100_t75h90fine.root
  (*incorporating the estimated-energy cuts, tailored MCs, with zenith distribution similar to the data*)
- **Assumed spectrum:** $A\cdot(x/x_0)^{-\Gamma}$ *x0 = 32.15 GeV* *$A = 2.3\cdot10^{-8}$ GeV^{-1} m^{-2} s^{-1}* *Γ=5.2*
- Estimated **excess rate:** $\mathbf{R_{ex}}$ **= 7.2 mHz**
- **Background rate:**
  $\alpha\ N_{off,0} = 112019$ $t_{eff} = 80h$ $\mathbf{R_{off}}$ **= 389.0 mHz**
- **Detection ratio:** **s** **= 0.69 σ/h$^{0.5}$**
- **Real** detection ratio: **s** **= 0.70 σ/h$^{0.5}$**
- **Predicted significance** (80h): **6.2σ**



Possible new pulsars

Name	*Excess rate [Hz]*	*SDR [$\sigma/h^{0.5}$]*	*Detection time [h]*
J0007+7303	$1.27 \cdot 10^{-3}$	0.13	1600
Crab	**$3.03 \cdot 10^{-2}$**	**2.49**	**4**
Geminga	**$9.93 \cdot 10^{-3}$**	**0.60**	**70**
J1836+5925	$5.57 \cdot 10^{-4}$	0.03	27000
 Dragonfly	$2.20 \cdot 10^{-3}$	0.15	1150
Boomerang	$1.98 \cdot 10^{-3}$	0.20	600

LST & PULSARS

LST & PULSARS

Open questions:

- Disentanglement of **different emission models**. **Spectral features** in the **Crab**; Solution of **Geminga's puzzle**.
- **Time variability** of pulsars?
- **Expansion of the set** of VHE pulsars: **pulsar hunting**. **Evolution** of VHE pulsars?

LST & PULSARS

Topics of work:

- Study of p**ulsar detection feasibility** with **LST** and **LST+MAGIC** (special Monte-Carlo productions).
- Integration and testing of the **very-low-energy analysis pipeline** of MAGIC (MaTaJu) in **LST.**
- Integration of the l**ow-energy MAGIC Sum-Trigger-II** in the **MAGIC+LST** efforts.
- … and of course, observing possible new VHE pulsars!