

Gamma-Ray Pulsars as probes for Lorentz Invariance Violation with CTAO


Lina Breton-Zaourat

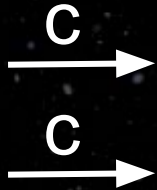
Sami Caroff
Vincent Poireau


Gamma-Ray Pulsars as probes for Lorentz Invariance Violation with CTAO

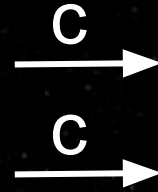



Lorentz Invariance Violation
through time lag effect

 LIV effect : Case without LIV



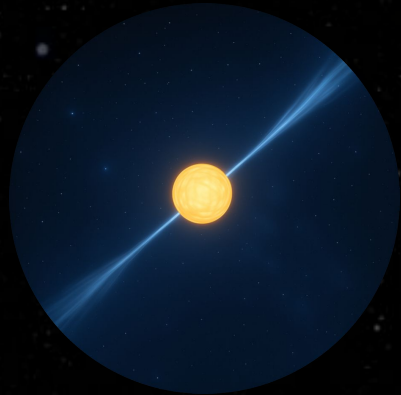
 LIV effect : Case without LIV





 LIV effect : Case with LIV

$$E_{\gamma 2} > E_{\gamma 1}$$

$$c \longrightarrow v_{\gamma}(E_{\gamma}, E_{LIV})$$




$$v_{\gamma 1}(E_{\gamma 1})$$


$$v_{\gamma 2}(E_{\gamma 2})$$


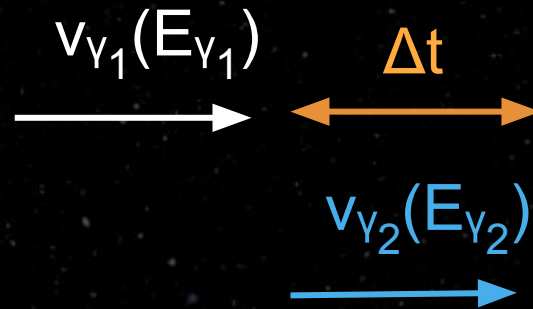


$$v_{LIV} = c \cdot \left(1 + \sum_{n=1}^{\infty} \left(\frac{E}{E_{LIV,n}} \right)^n \right)$$

 LIV effect : Case with LIV

$$E_{\gamma 2} > E_{\gamma 1}$$

$$c \longrightarrow v_{\gamma}(E_{\gamma}, E_{\text{LIV}})$$



$$\Delta t = \frac{(n+1)}{2} \frac{d}{c} \left(\frac{\Delta E}{E_{\text{LIV},n}} \right)^n$$

Gamma-Ray Pulsars as probes for Lorentz Invariance Violation with CTAO



Lorentz Invariance Violation
through time lag effect

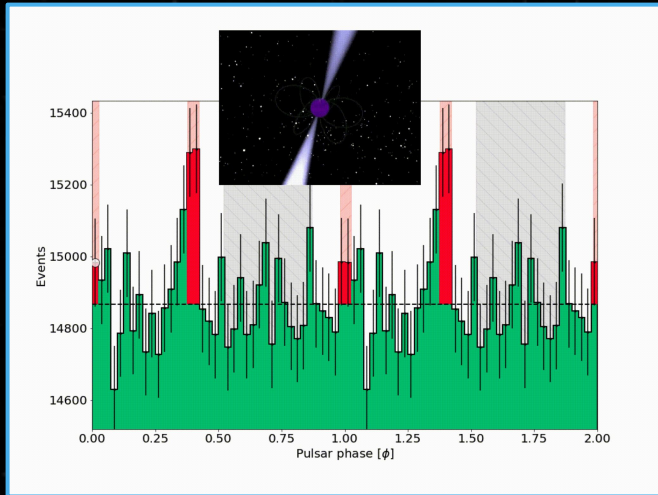


Pulsars and millisecond
pulsars

Pulsars

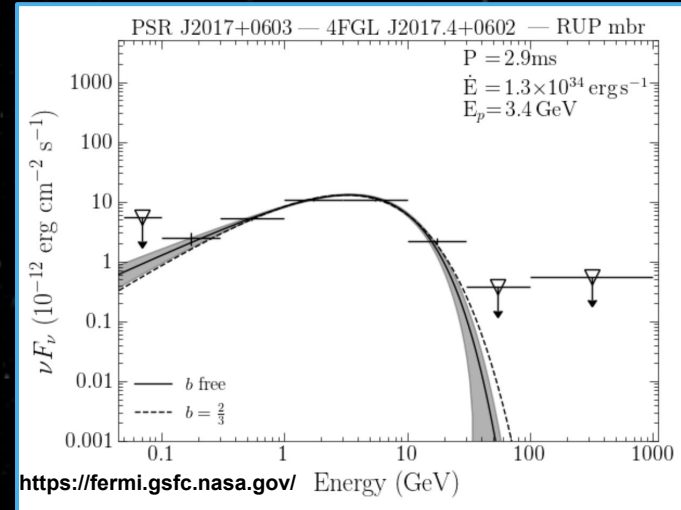
- Rapidly rotating neutron stars
- Extremely dense ! (\approx a solar mass contained within a sphere with a diameter of 20 km)

Phasogram



- Generally the same pattern: P1, P2 and Bridge

Spectral energy distribution (SED)



- The emission of the pulsar VS energy fitted by a specific model

Pulsars : good candidates for LIV



Periodic nature of pulsar :

- Deterministic and almost stable variability
- Data accumulation for a long time

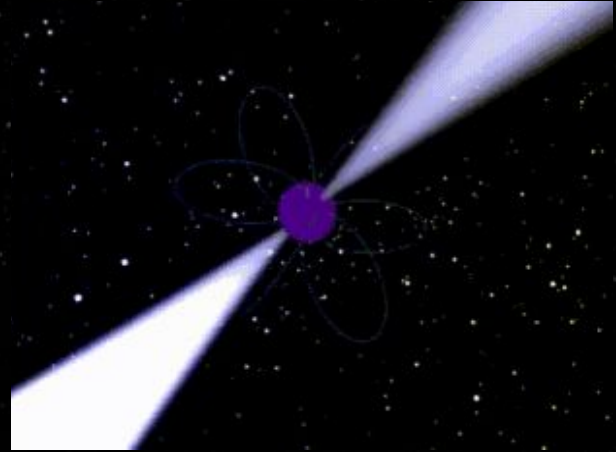


Galactic origin:

- Avoids cosmological effect on the time lag propagation (better model independence)



Combined pulsars analysis necessary to disentangle LIV (propagation effect) from intrinsic effect





best pulsar candidates for LIV

The higher the energy difference, the **higher $\Delta\Phi$**

➔ **High energy emission component (Inverse Compton)**

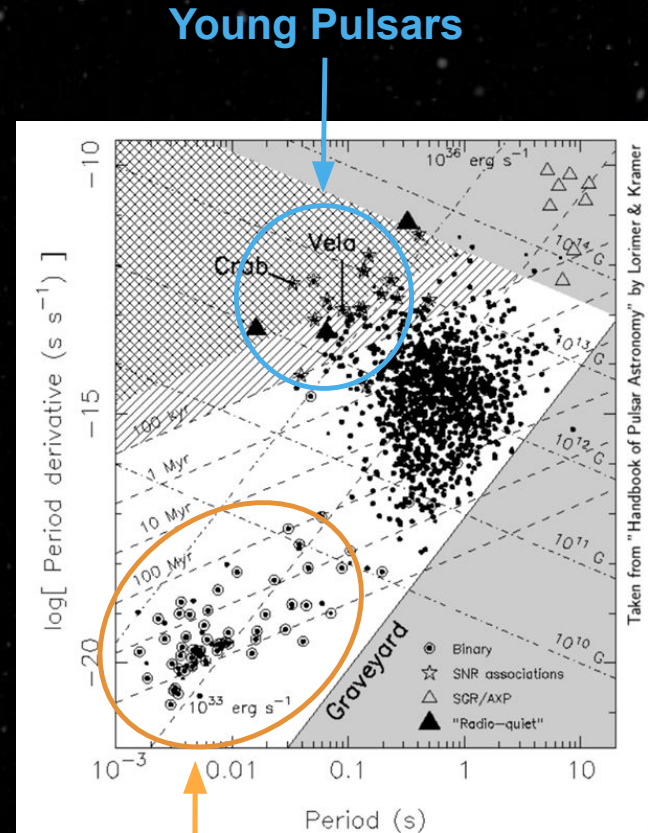
The higher the distance, the **higher $\Delta\Phi$**

➔ **Very far pulsars**

$$\Delta\phi = \frac{\Delta t}{P} = \frac{1}{P} \frac{(n+1)}{2} \frac{d}{c} \left(\frac{\Delta E}{E_{\text{LIV},n}} \right)^n$$

The shorter the **rotation period**, the **higher $\Delta\Phi$**

➔ **Very fast rotating pulsars**



Millisecond Pulsars

Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Gamma-Ray Pulsars as probes for Lorentz Invariance Violation with **CTAO**



Lorentz Invariance Violation
through time lag effect



The CTA observatory



Pulsars and millisecond
pulsars



The CTA observatory



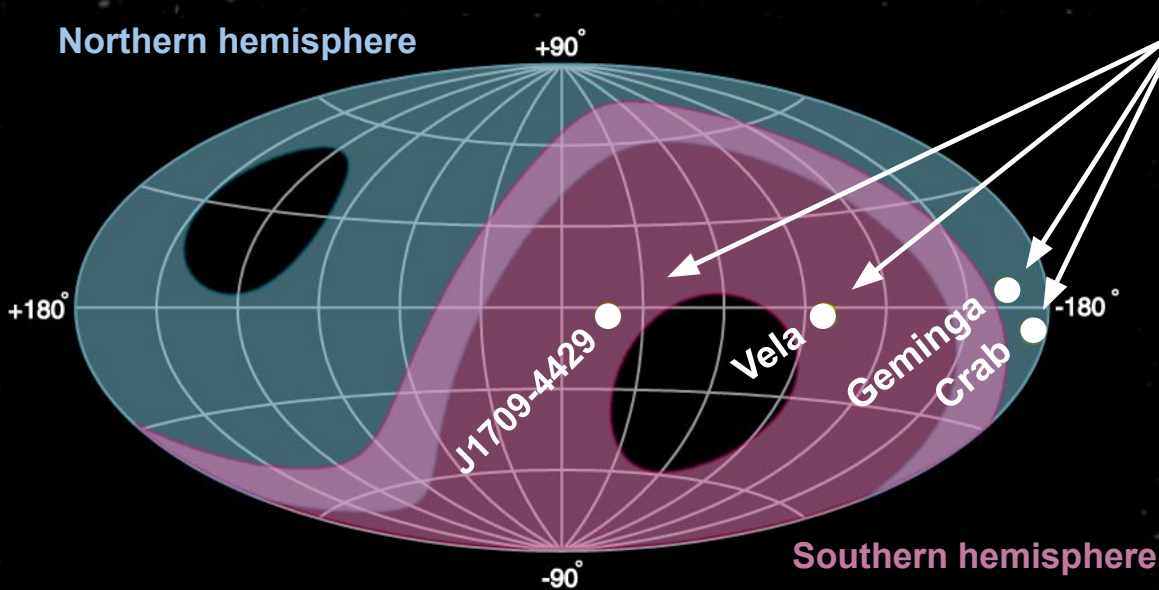
Cherenkov Telescope Array

- 2 sites : La Palma & Chile
- 3 different types of telescopes:
LST, MST, SST
- Cherenkov Light detection emitted by
the electromagnetic showers
- 3 future LST telescopes in 2027

The Large Sized Telescope (LST)



Current state of the art



- 4 pulsars detected by the IACTs (HESS, LST, VERITAS, MAGIC)
- No millisecond pulsars have been detected yet by the IACTs
- LIV application only for the Crab and Vela among pulsars
(<https://iopscience.iop.org/article/10.3847/1538-4357/ac5048/pdf>)

Next steps :

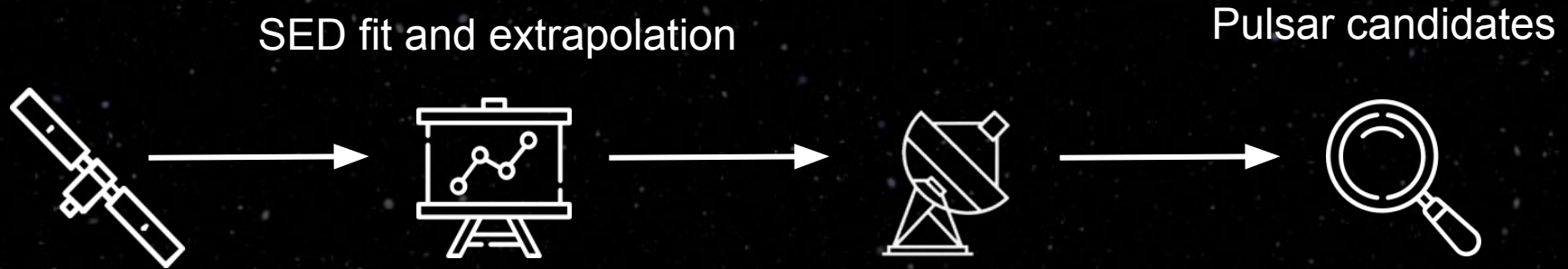
- ➔ What are the best pulsar candidates to detect with CTAO ?
- ➔ What are the best pulsar candidates to probe LIV ?

Research Work

First focus of my research:

Evaluate Fermi pulsar detectability with CTAO/LST

Analysis steps



Fermi pulsar catalog

<https://fermi.gsfc.nasa.gov/>

CTAO/LST detectability
evaluation



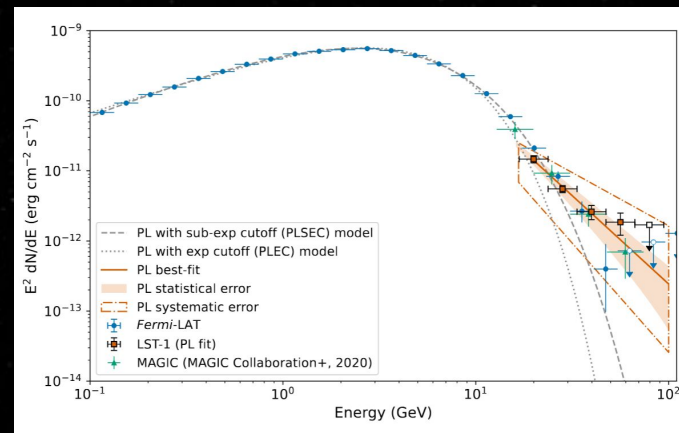
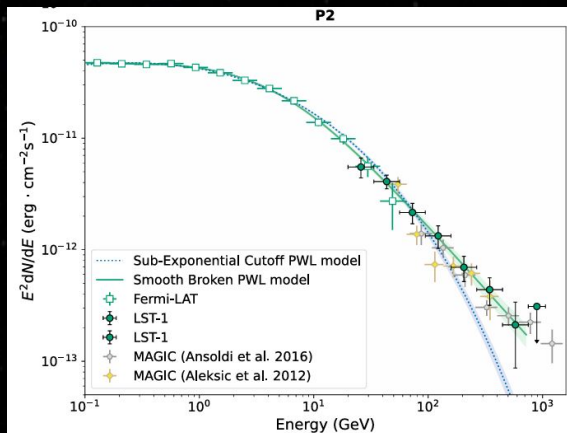
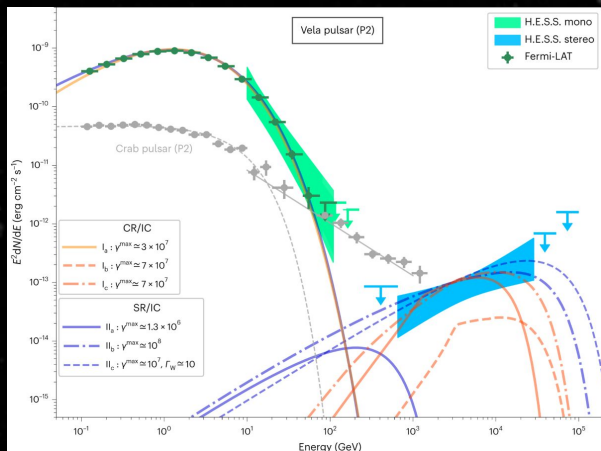
SED fit and extrapolation

Models

Power Law Exponential Cut-Off
(ExpCutOff)

Smooth Broken Power Law (SBPL)

Geminga-like



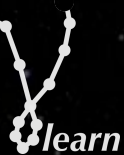
Fitted SED & sensitivities

SED of the Fermi pulsar J2032+4127 (gray points) fitted with SBPL shown in blue. The sensitivity curve of the LST telescope (for different configurations) are also shown in pink and purple

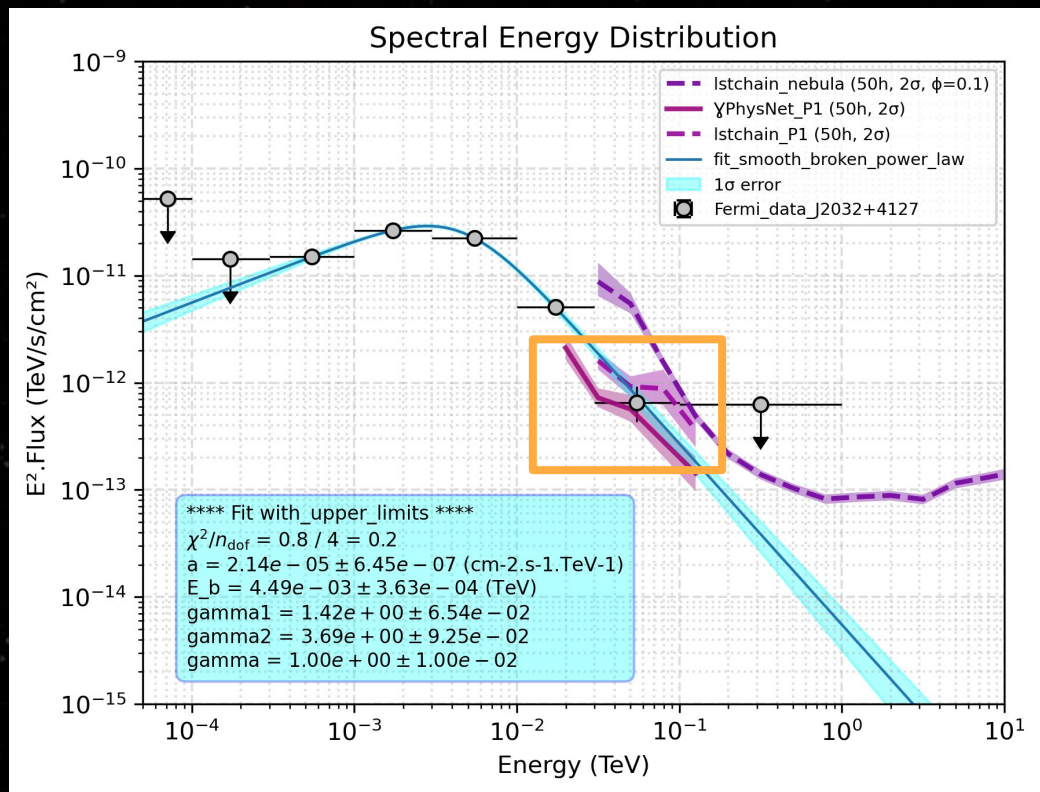


Istchain

New method of reconstruction !



gammalearn



→ A significant improvement in LST sensitivity at low energy (\approx tens of GeV) !



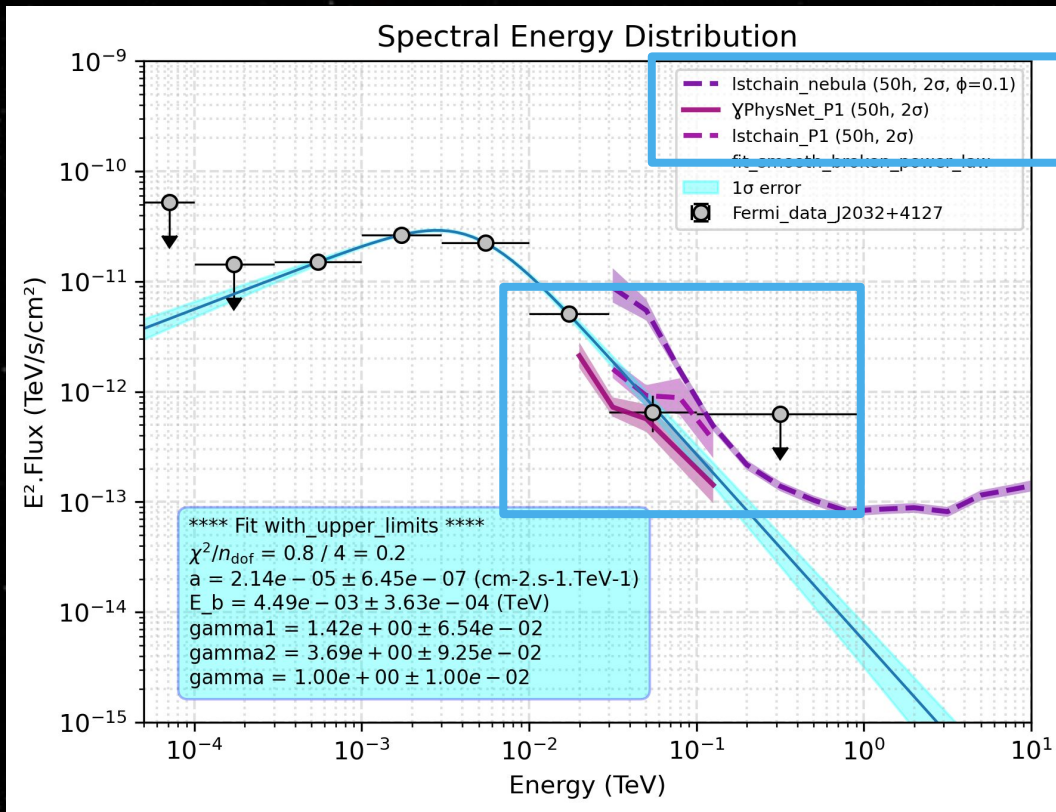
CTAO/LST detectability evaluation: ratio method

Sensitivity rescale

Sigma evaluation by energy bin

$$\frac{F_{fitted}}{F_{sens}} = \frac{\sigma_{fitted}}{\sigma_{sens}}$$

Total significance sum



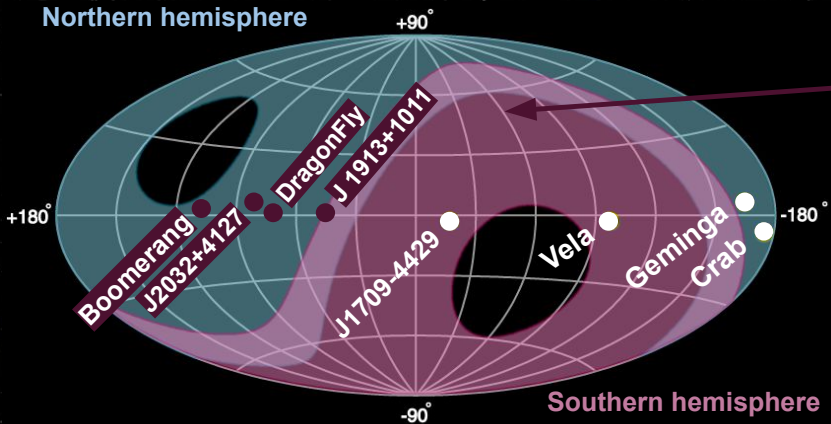


Results for pulsars

Parameter

● Observation time : 50h

● In the very short term, 1 LST North (current CTAO configuration) :



4 new pulsars that had not previously been detected by the lstchain analysis (or that had not yet been analysed) are now potentially detectable thanks to a gammalearn analysis!

Next step :

→ Perform a gammalearn analysis of the data already available

LST Data available

Name	RA (°)	DEC (°)	Rot Period (ms)	Distance (kpc)
Crab	83.6	22.0	34	1.9
Geminga	98.5	17.8	237	0.25
DragonFly	305	36.8	104	1.8
Boomerang	337	61.2	52	3.00
J2032+4127	308	41.5	36	4.61
J1913+1011	288	10.2	143	1.80



Results for millisecond pulsars

Parameter

● Observation time : 50h

● The best candidates are mostly observable by the Southern hemisphere

→ In the long term with one LST South (~2030) : two millisecond pulsars (J1536-4948, J0614-3329) detectable according to the estimations

● The best candidate for the North is J2017+0603

→ In the very short term with 1 LST North (current CTAO configuration): not detectable except in a very optimistic scenario :(

↳ Results of this analysis motivated a observation proposal for LST on Feb 2026 : declined

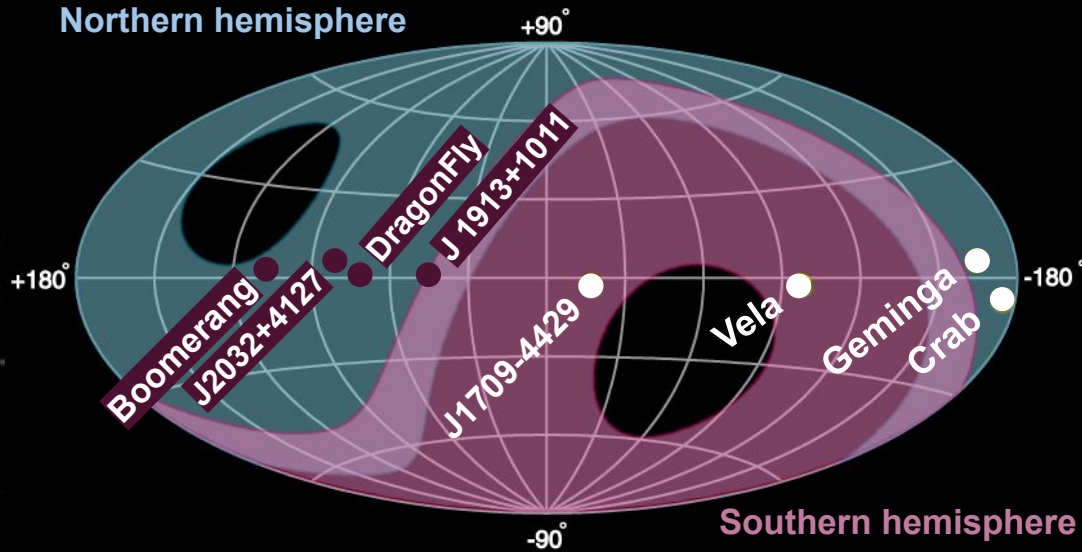
→ In the medium term with 4 LSTs North (~2027) : potentially detectable (at least a strong hint at 3σ)

Name	RA (°)	DEC (°)	Rot Period (ms)	Distance (kpc)
J0614-3329	93.5	-33.5	3	0.63
J1536-4948	234	-49.8	3	0.98
J1231-1411	188	-14.2	4	0.42
J1514-4946	229	-49.7	4	0.91
J2017+0603	304	6.05	3	1.40

— Southern hemisphere

— Northern hemisphere

Current state of the art



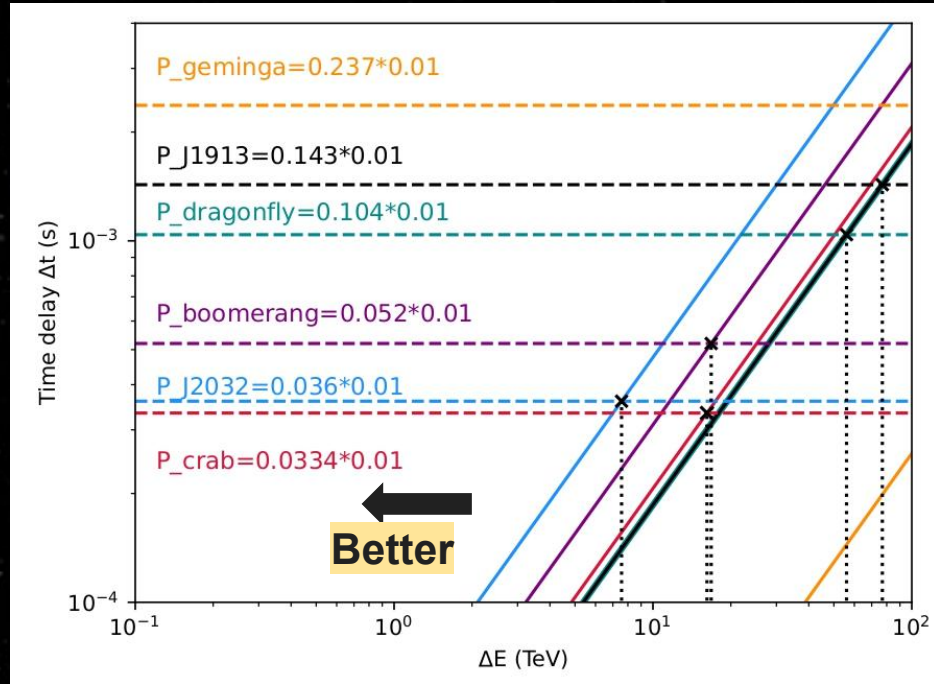
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Next steps :

➔ What are the best pulsar candidates to detect with CTAO ?

➔ What are the best pulsar candidates to probe LIV ?

Best pulsar candidates to probe LIV



● Interpretation :

→ The intersection point is the key information : allows us to determine approximately the minimal energy where we could find a time lag effect

→ The idea is to minimize this energy because the higher the energy of the emitted photons, the more difficult - or even impossible - it will be for LST to detect them

● Conclusion :

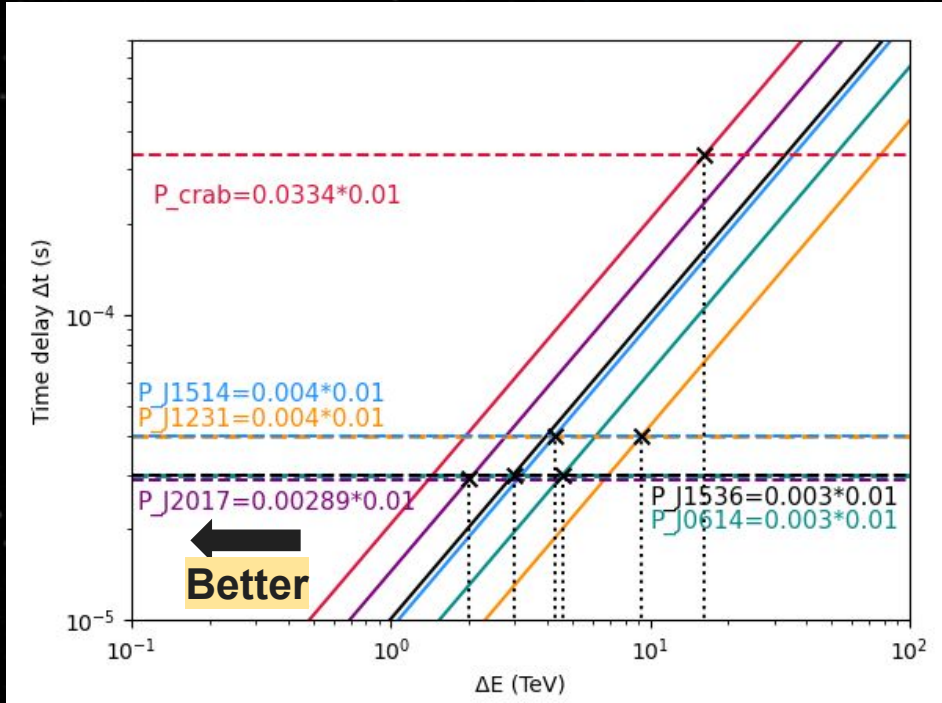
→ best pulsar candidates for LIV : **Crab** and **J2032+4127** and in second time **Boomerang** and **DragonFly**

$$\Delta t = \frac{(n+1)}{2} \frac{d}{c} \left(\frac{\Delta E}{E_{\text{LIV},n}} \right)^n$$



$$\Delta t = \frac{d}{c} \left(\frac{\Delta E}{E_{\text{Planck}}} \right)$$

Even better candidates : **millisecond pulsars** to probe LIV



● Interpretation :

- around **17 TeV** gamma to detect for LIV (with the Crab: the best pulsar for the normal population)
- at the order of **the TeV** gamma to detect for millisecond pulsars !

● Conclusion :

- best millisecond pulsar candidates for LIV in order of priority :

- **J2017+0603**
- **J1536-4948**
- **J1514-4946**
- **J0614-3329**
- **J1231-1411**

- Southern hemisphere
- Northern hemisphere

$$\Delta t = \frac{(n+1)}{2} \frac{d}{c} \left(\frac{\Delta E}{E_{\text{LIV},n}} \right)^n$$



$$\Delta t = \frac{d}{c} \left(\frac{\Delta E}{E_{\text{Planck}}} \right)$$

Conclusion & Perspectives

- Pulsar and millisecond pulsar detectability estimation for:

- LST North ✓
- LST 1-4 North ✓
- LST South ✓

- Rank the pulsars from best to worst for the LIV ✓

} Presented at the general LST meeting, Padova, June 2026

→ Conduct an analysis with gammalearn in order of priority:

- Crab, Geminga
- DragonFly , J2032+4127 (first detection ?)
- Boomerang (difficult due to high zenith)
- J1913+1011 (observation proposal ?)

→ In long term, use of this analysis to motivate the future proposals (for the northern millisecond pulsars J2017+0603) and as tool for the Southern pulsars detectability estimation

Second research focus :

Crab analysis to probe LIV through time lag effects

Analysis steps





Crab LST data analysis

● Data selection :

- First data cleaning to remove data affected by light pollution and atmospheric variations
- Second data selection related to gamma-hadron discrimination

● Add the phases

- ephemeris: a radio telescope specifically dedicated to observing the Crab Pulsar (<https://www.jb.man.ac.uk/~pulsar/crab.html>)
- Add the pulsar phase with PulsarTimingAnalysis code

Data selection

Add the phases

High level analysis

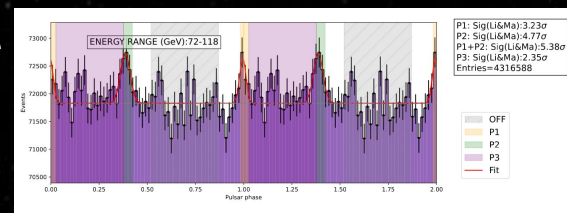
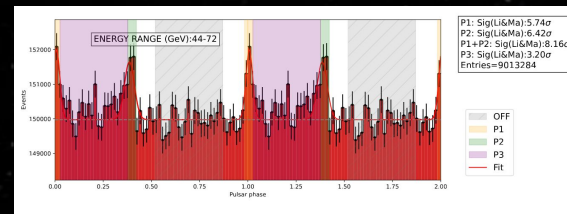
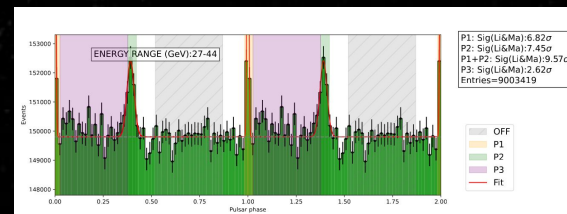
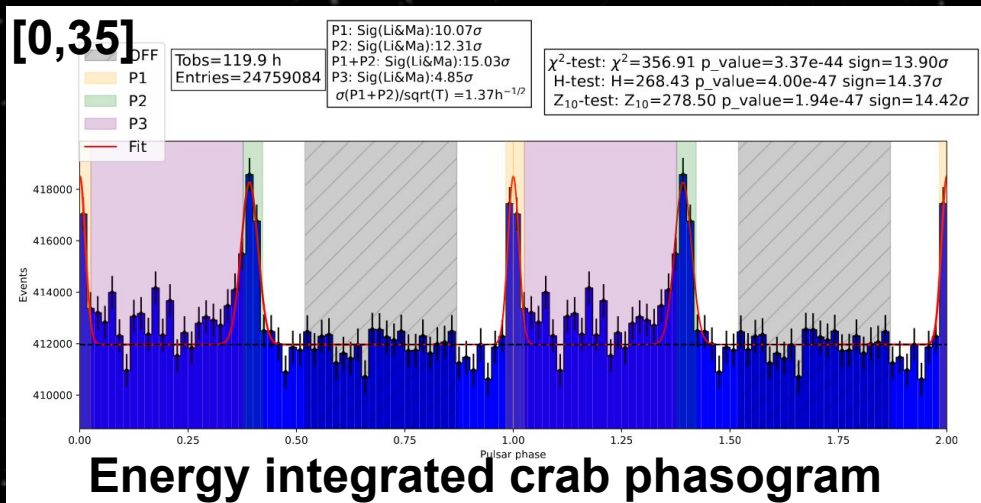




Crab Phasogram analysis

→ Energy binning from 10 GeV to 10 TeV

→ Double gaussian phasogram fitting





LIV effect constraints evaluation

- **MeanPhase VS Energy : $\Delta\Phi=f(\Delta E)$**

- Determine the Mean phase from the fitted P1 and P2 for each energy bin
- Linear fit of the plot to estimate approximately constraints on E_{LIV}

$$\Delta\phi = \frac{\Delta t}{P} = \frac{1}{P} \frac{(n+1)d}{2c} \left(\frac{\Delta E}{E_{LIV,n}} \right)^n$$

Fixed parameters

LIV parameter to constrain

Conclusion & Perspectives

● Crab analysis for LIV : work in progress

- Data selection done : 192 hours of Crab data to analyse ✓
- Pipeline that allows us to perform high level analysis (SED and Phasogram construction) ✓
- multi-zenith study to research a potential emission at high energy : no such component was detected ✓
- simple double gaussian fit performed for the phasogram ✓
- estimation of the LIV constraints (in progress)

Presented at the
general LST meeting,
Padova, June 2026

- Gammalearn re-analysis (an estimate of **+10 σ** compared to the standard analysis for the Crab !)
- Other pulsars LIV analysis thanks to the Crab analyse code (DragonFly, 2032+4127 and boomerang)
- Use of LIVelihood code for a more rigorous LIV constraints

Future work for the next year

- Conduct an analysis with `gammalearn` in order of priority:
 - Crab, Geminga (an estimate of **+10 σ** compared to the standard analysis for the Crab !)
 - DragonFly , J2032+4127 (first detection ?)
 - Boomerang (difficult due to high zenith)
 - J1913+1011 (observation proposal ?)
- Use of the the detectability estimation analysis to motivate the future proposals (northern millisecond pulsars [J2017+0603](#)) and as tool for the Southern pulsars detectability estimation
- Other pulsars LIV analysis (Istchain and `gammalearn`) thanks to the Crab analyse code (DragonFly, 2032+4127 and boomerang)
- Use of `LIVelihood` code for a more rigorous LIV constraints
- Technical task : provide the softwares (detectability estimation, LIV analysis) documented to the CTA collaboration
- LST Shift in La Palma ?

Activities

● Presentations

- LST General meeting, Padova, *June 2026*
- Bridging high and low energies in search of quantum gravity - 2026 Cost Action CA23130 Second Annual Conference, *Varna, July 2026*


● Schools

- 2nd Cherenkov Astronomy Data School – *November 2025*
- School : Sustainable Scientific Software School 2026 – *January 2026*
- 2nd UNDARK School : The multi-messenger non-thermal universe – *March 2026*

● Teaching


- Enseignement de TP d'informatique, 1ère année Licence Physique – *15 heures*
- Enseignement de TP de mathématiques, 1ère année IUT spécialité GEII – *14 heures*

● Doctoral school (~ 120 h)

→ Catégorie professionnelle (~90h) 

→ Catégorie professionnelle (50h) 

- MOOC Doctorat et poursuite de carrière/ PhD and career development (24h)
- Encadrer efficacement des TD + TP (16h)
- Career Development Day for PhD Students (10h)

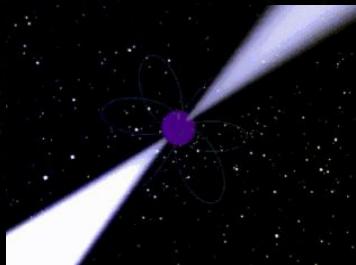
→ Catégorie transversale (48h) 

- S'initier à la vulgarisation ; Raconter, expliquer, et partager sa recherche (20h)
- Journée de Rentrée des Doctorantes et doctorants 2025 (3h)
- Éthique de la recherche (15h)
- Outreach : Fête de la Science 2025, FIRST, Mercredi du LAPP, présentations Eutopia (10h)

Thank you for your attention !

BACK UP

Pulsars : good candidates for LIV



$$\Delta\phi = \frac{\Delta t}{P} = \frac{1}{P} \frac{(n+1)}{2} \frac{d}{c} \left(\frac{\Delta E}{E_{\text{LIV},n}} \right)^n$$



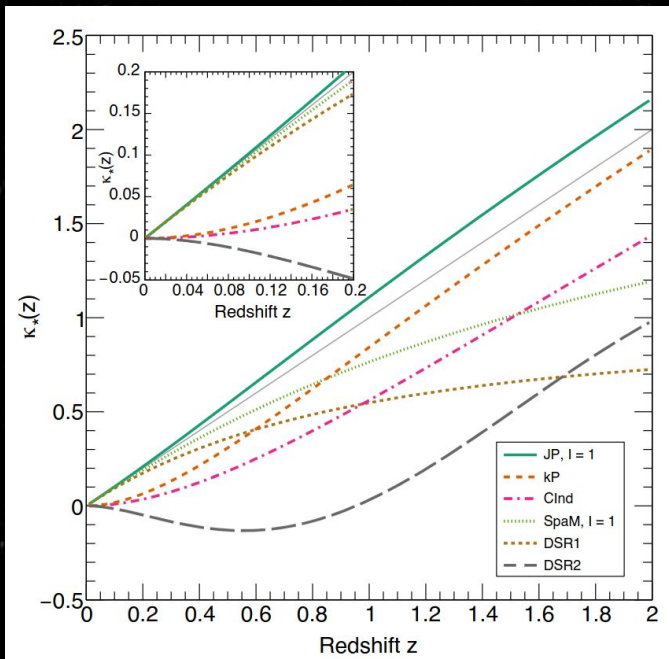
Periodic nature of pulsar :

- Deterministic and almost stable variability
- Data accumulation for a long time



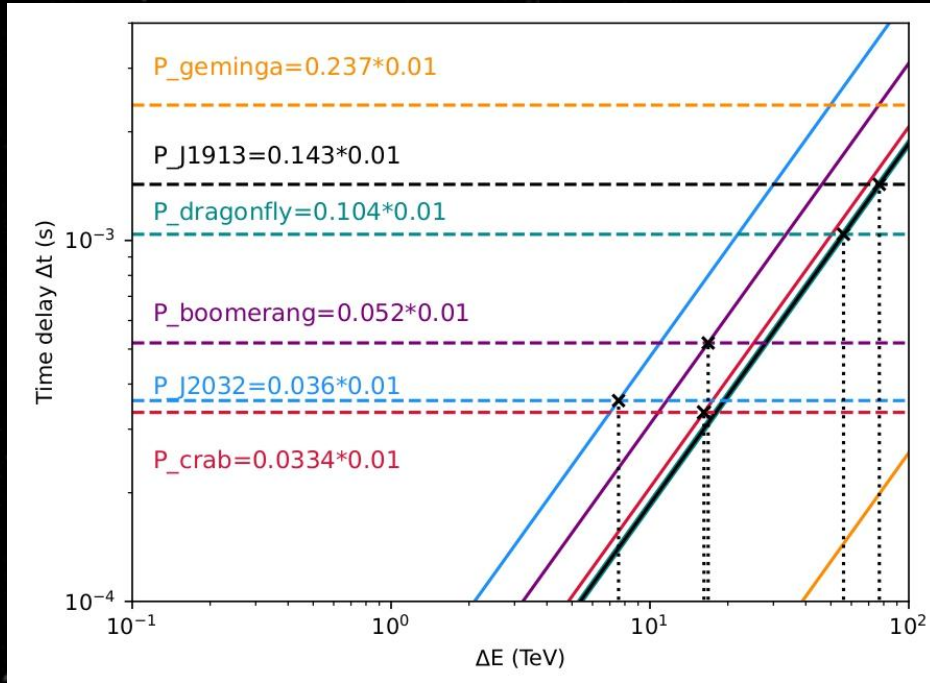
Galactic origin:

- Avoids cosmological effect on the time lag propagation (better model independence)
- Pulsar counterbalance small distance with high variability



Combined pulsars analysis necessary to disentangle LIV (propagation effect) from intrinsic effect

Best pulsar candidates to probe LIV



$$\Delta\phi = \frac{\Delta t}{P} = \frac{1}{P} \frac{(n+1)}{2} \frac{d}{c} \left(\frac{\Delta E}{E_{\text{LIV},n}} \right)^n$$

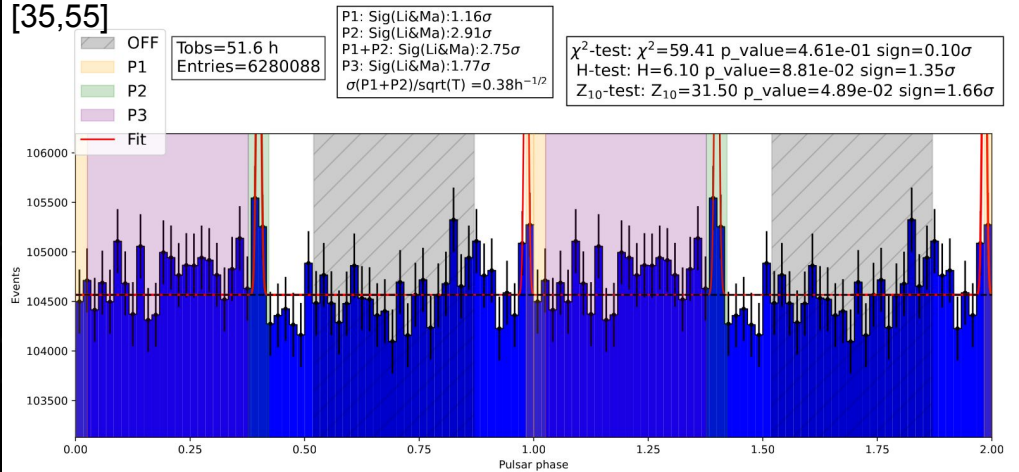
Assumptions :

- one of the energy photons is zero : $\Delta E = E - E_0$ with $E_0 = 0$
- First order hypothesis : $n=1$
- $E_{\text{LIV},1} \approx E_{\text{Planck}} \approx 10^{19} \text{ GeV}$
- Rotation period multiplied by 0.01 : represents in first approximation the position error at high energy of Crab peak P1

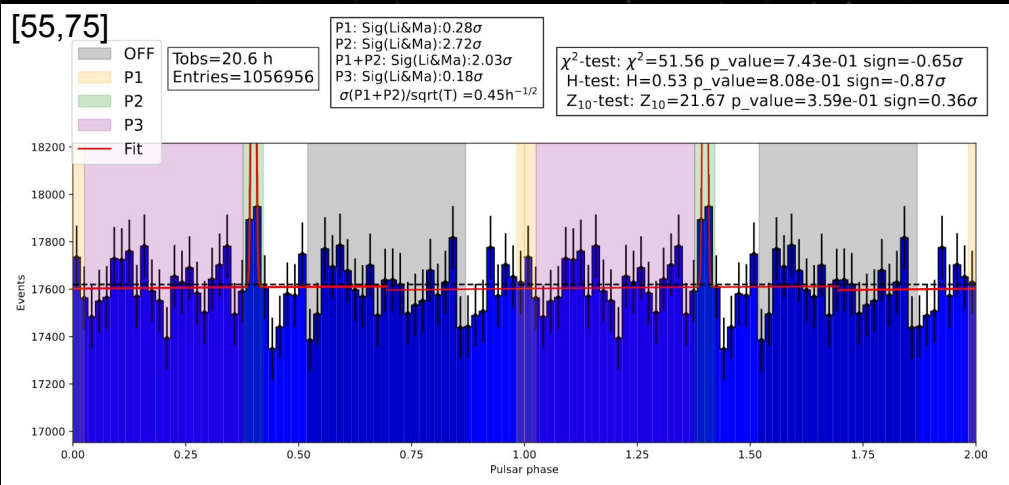
Limitation :

- This plot doesn't take into account the statistics for each pulsars

[35,55]

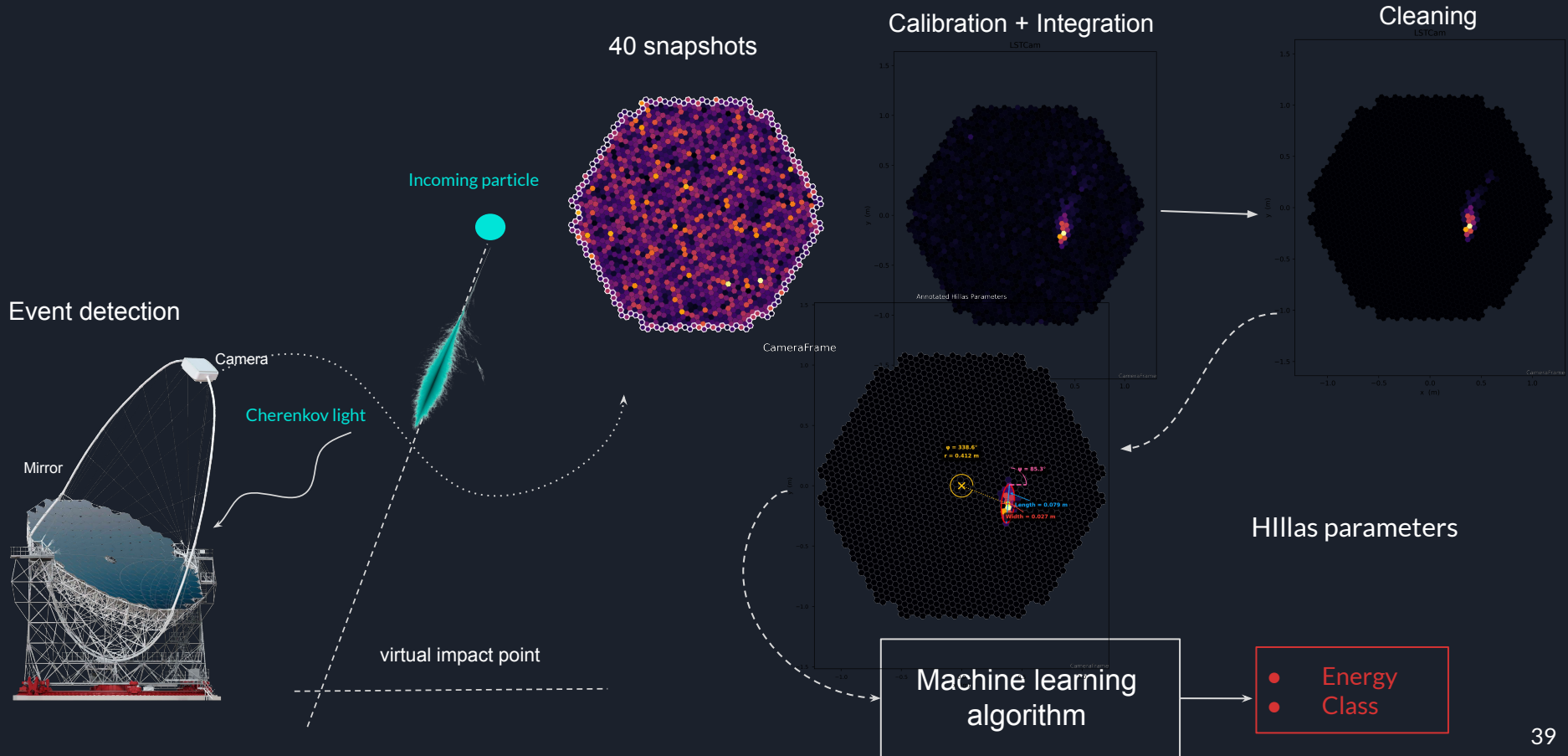


[55,75]



Energy (GeV)	μ_1	FWHM ₁ ($\cdot 10^{-2}$)	μ_2	FWHM ₂ ($\cdot 10^{-2}$)
20 - 33	0.999 ± 0.003	3.1 ± 0.6	0.389 ± 0.004	5.4 ± 1.1
33 - 55	1.0000 ± 0.0018	2.2 ± 0.4	0.387 ± 0.003	4.4 ± 0.8
55 - 92	0.994 ± 0.005	4.0 ± 1.1	0.388 ± 0.006	5.5 ± 1.3
92 - 153	1.0020 ± 0.0022	1.5 ± 0.5	0.402 ± 0.004	3.6 ± 1.0
153 - 253	1.015 ± 0.009	3.7 ± 2.2	0.3981 ± 0.0017	1.9 ± 0.7

Event reconstruction





Results : Smooth Broken power law and power exp cut off

Parameters	
●	Observation time : 50h
●	ON phase : 0.1 & 0.05



« famous » pulsars detected (Geminga, Vela) as expected



With LST1 only, no millisecond pulsar detectable with ExpCutOff and SBPL



With LST1-4 some millisecond pulsars can be detected

SBPL

Name	Sigma	
	$\Phi_{on} = 0.05$	$\Phi_{on} = 0.1$
J0614-3329	29.3	20.7
J1536-4948	12.3	8.69
J1231-1411	5.36	3.79
J1514-4946	4.54	3.21
J2017+0603	4.46	3.16

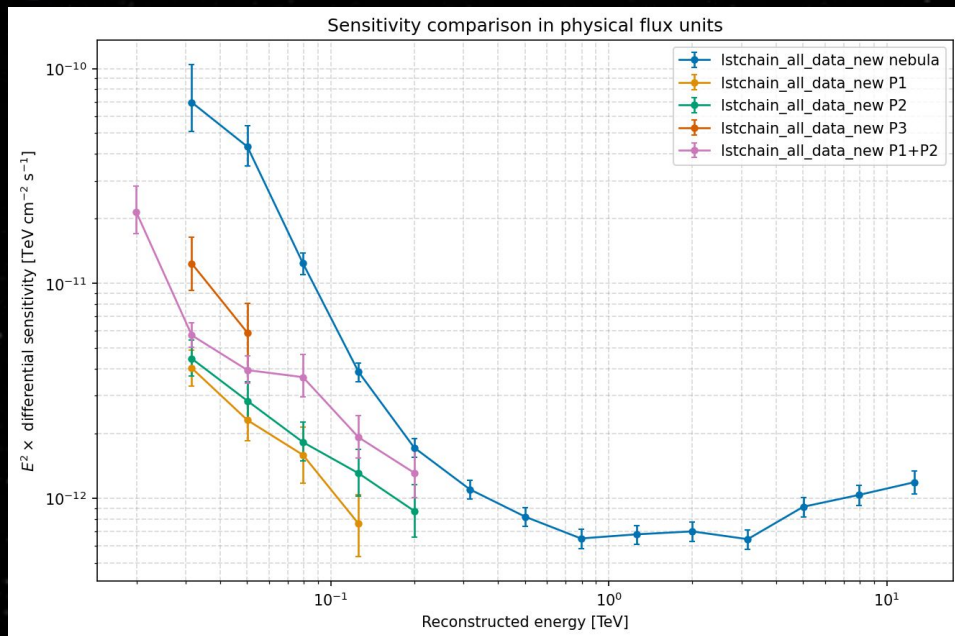
Name	Sigma	
	$\Phi_{on} = 0.05$	$\Phi_{on} = 0.1$
J0614-3329	12.4	8.75
J1536-4948	11.1	7.87
J2017+0603	3.1	2.19

ExpCutOff



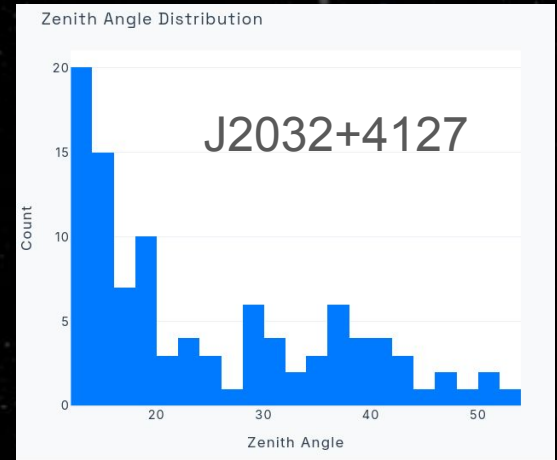
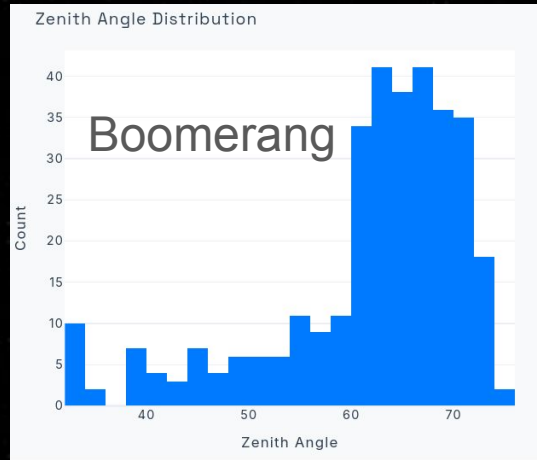
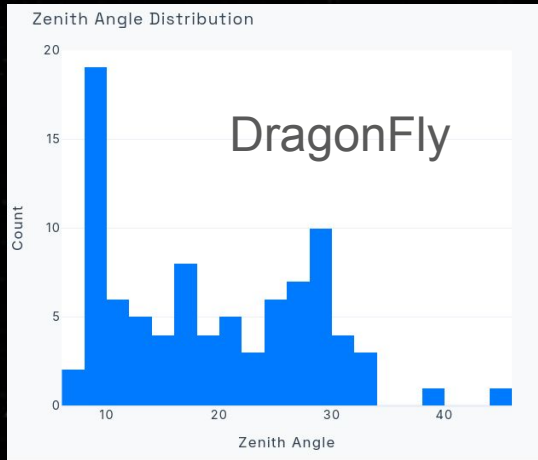
Sensitivities used

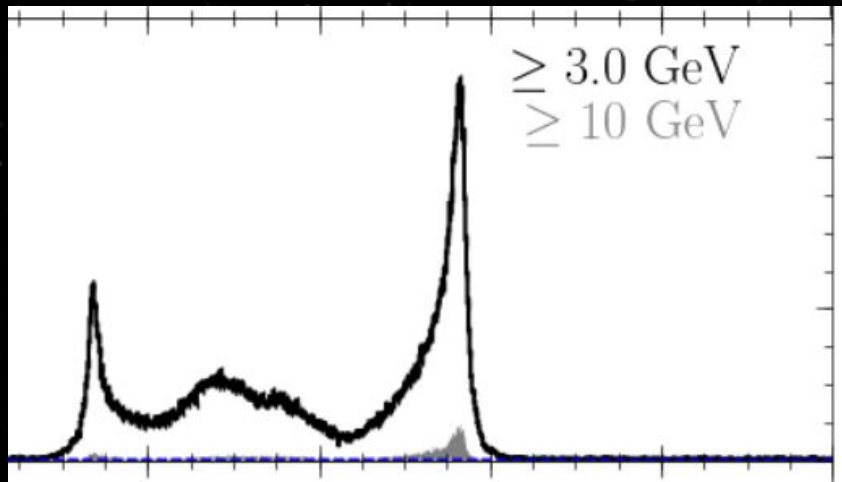
New LST **pulsar phase-selected** sensitivities based on the Crab data (P1,P2 and P1P2) and deep learning approach **gammalearn** (cf : Sami's and Guillaume's presentation tomorrow)



- P1, P2, and P1P2 selected via a Φ_{on} region in the phasogram
- P1, P2 present nearly the same sensitivity curves ($\Phi_{\text{on,P1}} \approx \Phi_{\text{on,P2}} \approx 0.05$)
➔ **Signal concentrated in a single peak**
- P1+P2 region is more broader ($\Phi_{\text{on,P1+P2}} \approx 0.1$)
➔ **Signal is spread across two peaks**

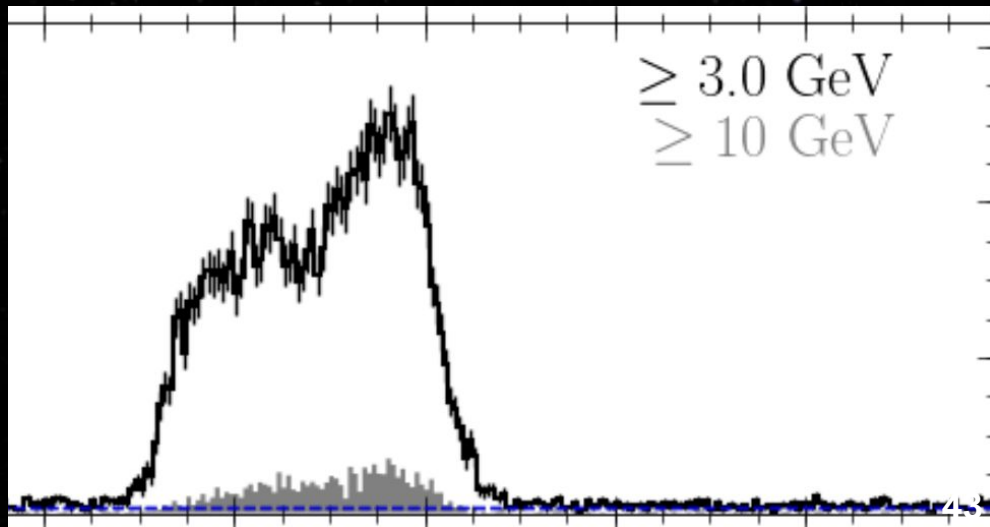
Zenith angle distributions



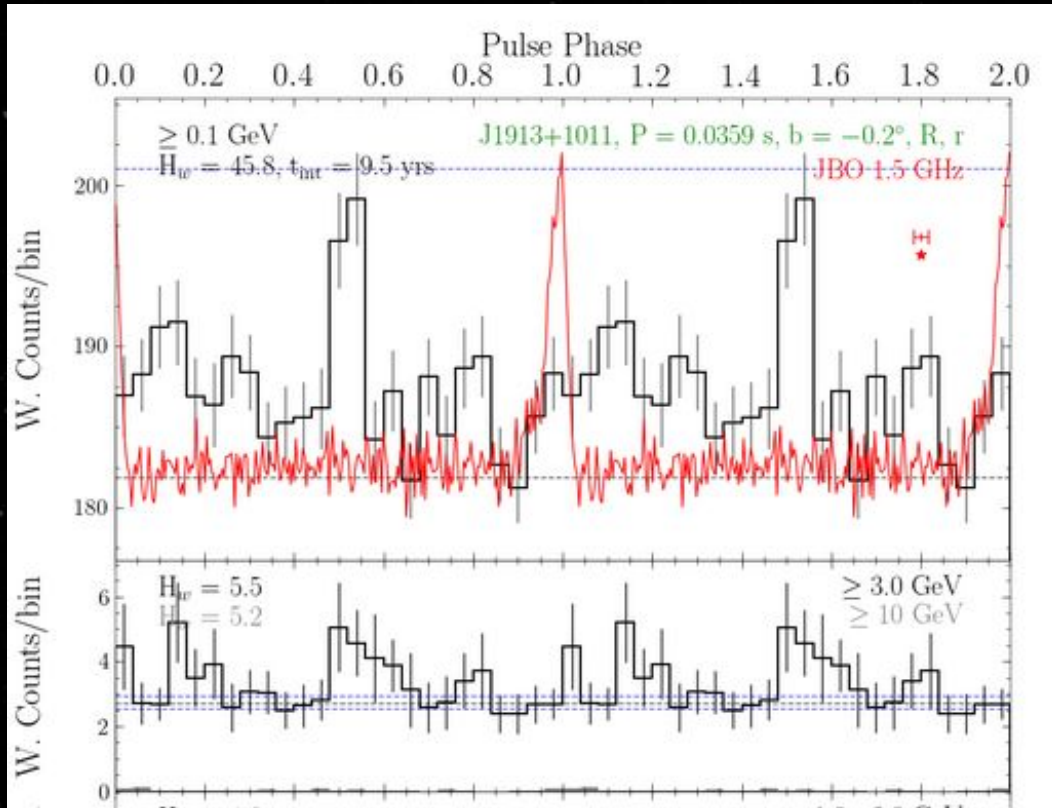


Single Peak concentrated

A more spread_out Peak



J1913+1011 fermi phasogram





LST simulations: Ist-chain



A precise method to simulate a specific pulsar



Allows us to simply implement a personalized SED model



Only a simulator for LST 1 (based on the technical parameters of the telescope)



Heavy (Contain a lot of parameters to set), not adapted to a first global analysis

Crab Pulsar P1+P2

● Observation time : 103h

Parameters

● Comparison between the method and the real data (LST Paper)

→ P1+P2 sensitivity curve

→ simulation with the power-law of $\Gamma = 3.2$ from the LST paper for P1+P2

		Significance σ	
		paper	gammalearn pulsar
P1P2	12.5	13.9	24.9

Geminga pulsar

Parameters

● Observation time : 60h

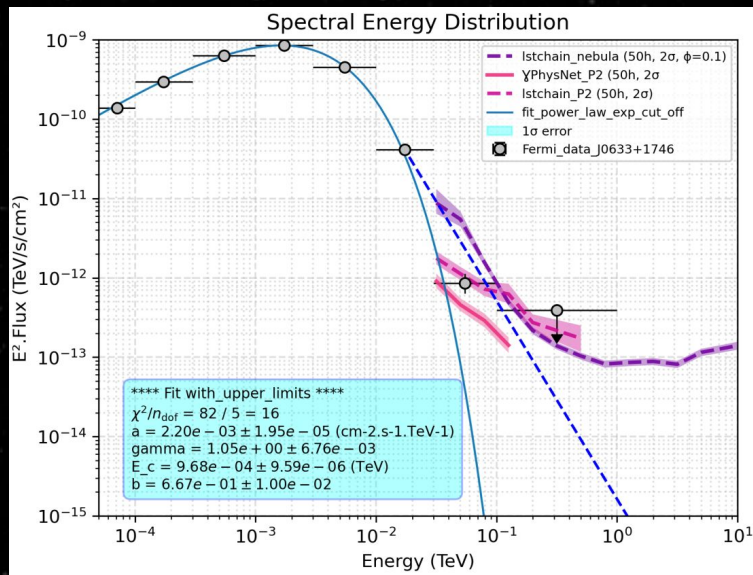
● Comparison between the method and the real data (LST Paper)

→ P2 sensitivity curve

→ geminga-like model used to simulate the power-law of $\Gamma = 4.5$ from the LST paper

		Significance σ	
		paper	gammalearn pulsar
P2	12.2	12.9	27.3

● Major expected significance improvement with gammalearn

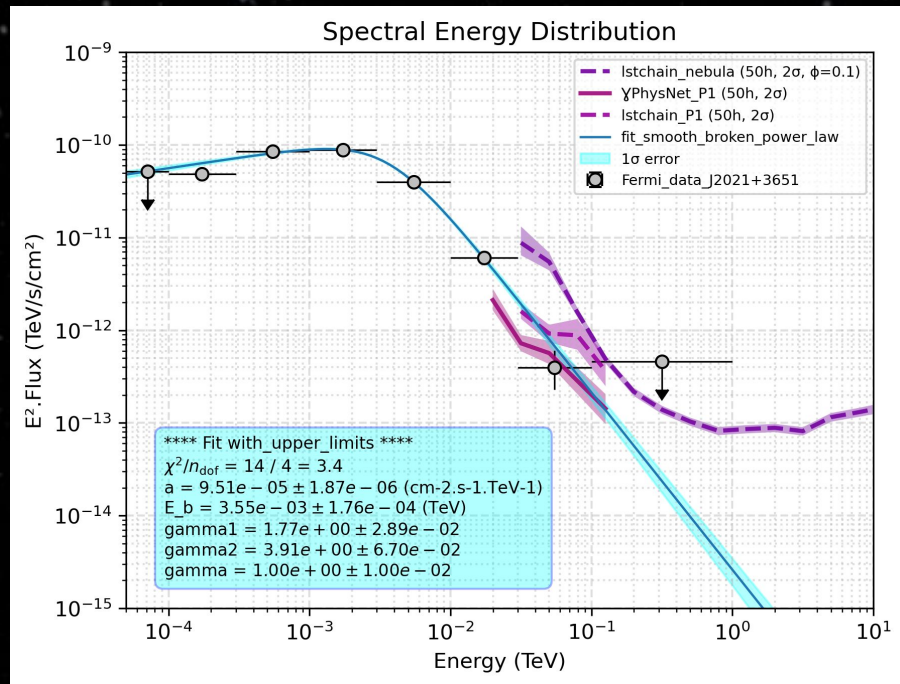


DragonFly pulsar

Potentially a first detection ?

- data available with LST (88 runs) to analyse
- Smooth Broken Power Law model used
- Observation time : 50h

Sensitivity	Significance σ	
	Istchain pulsar	gammalearn pulsar
P1	3.14	7.63
P2	2.81	6.24
P1P2	2.32	4.04



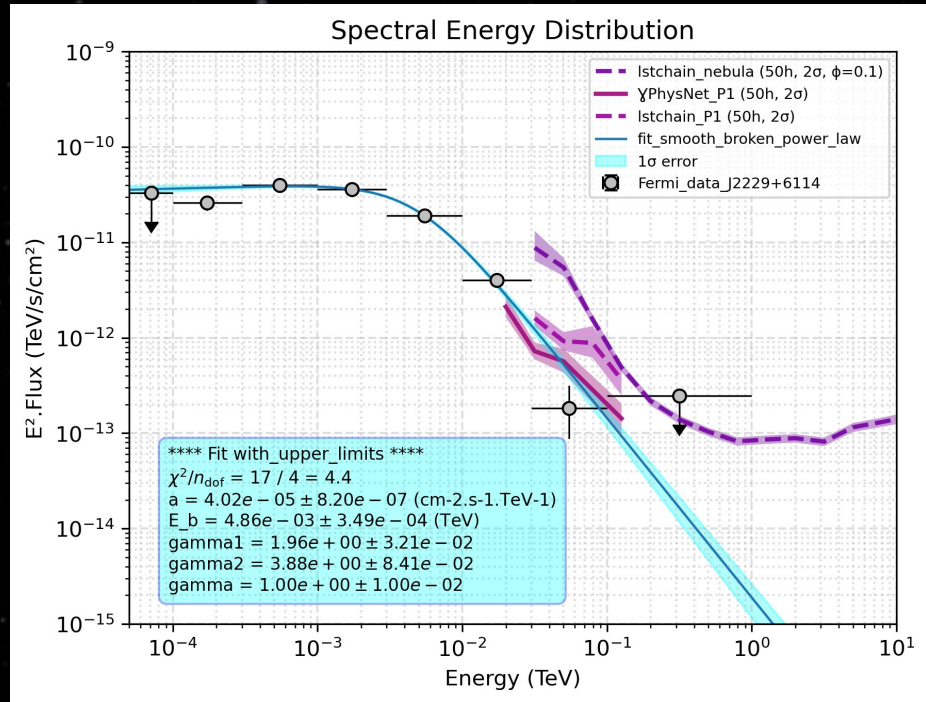
Expected detection if signal is concentrated in one peak, strong hint if two peaks

Boomerang pulsar

Potentially a first detection ?

- ➔ data available with LST (331 runs) **but** mostly at high zenith (not adapted yet to current sensitivity curves used)
- ➔ Smooth Broken Power Law model used
- ➔ Observation time : 50h

Sensitivity	Significance σ	
	Istchain pulsar	gammalearn pulsar
P1	2.04	4.87
P2	1.82	4.07
P1P2	1.49	2.58



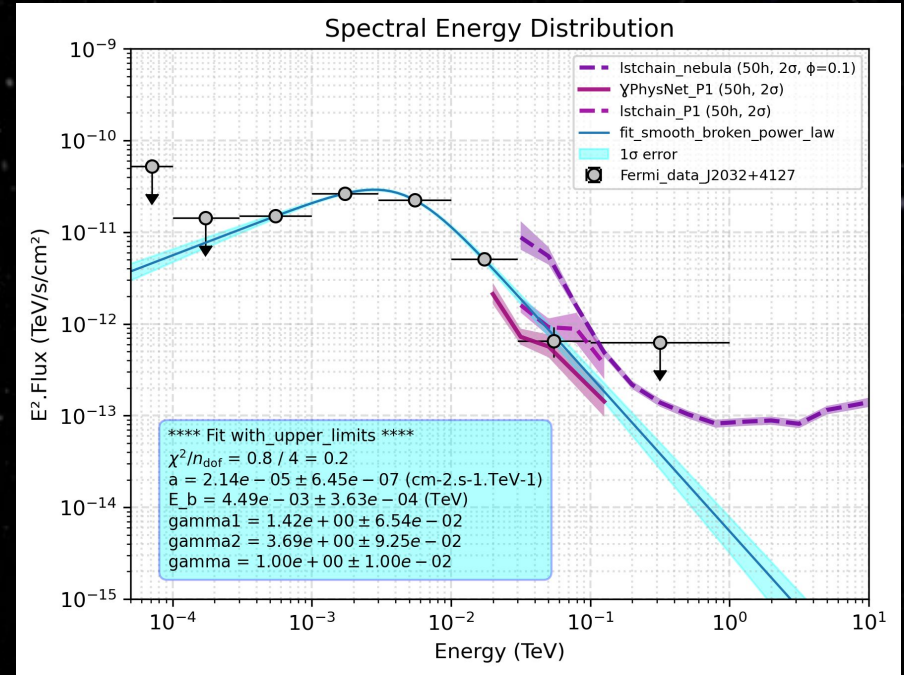
J2032+4127 pulsar

Potentially a first detection ?

→ data available with LST (102 runs) to analyse

→ Smooth Broken Power Law model used

Sensitivity	Significance σ	
	Istchain pulsar	gammalearn pulsar
P1	3.29	7.54
P2	2.96	6.74
P1P2	2.35	4.11



The last fermi data point is detectable directly by gammalearn without any model assumption

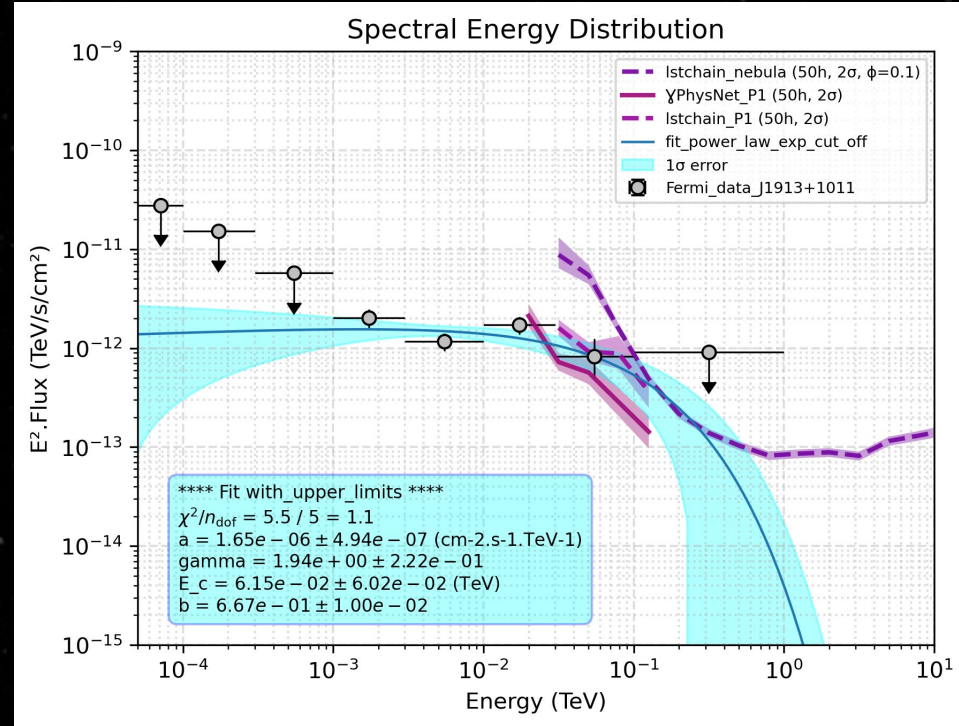
J1913+1011 pulsar

Potentially a first detection ?

➔ No LST data available

➔ Power Law ExpCutOff used

Sensitivity	Significance σ	
	Istchain pulsar	gammalearn pulsar
P1	2.79	7.45
P2	2.38	5.40
P1P2	1.79	2.7



The last fermi data point is detectable directly by gammalearn without any model assumption

Results

Smooth Broken Power Law

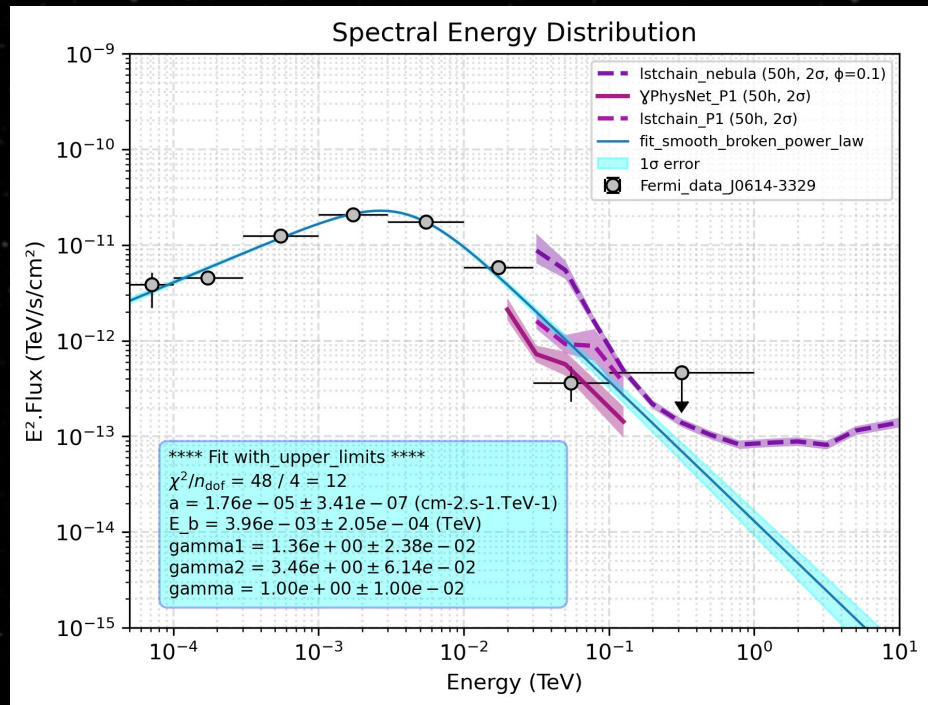
LST 1

- Observation time : 50h

Name	Sigma	
	Istchain	gammalearn
J0614-3329	3.85	8.44
J1536-4948	1.55	3.70
J1231-1411	0.64	1.65
J1514-4946	0.56	1.39
J2017+0603	0.55	1.37

■ Southern hemisphere

■ Northern hemisphere



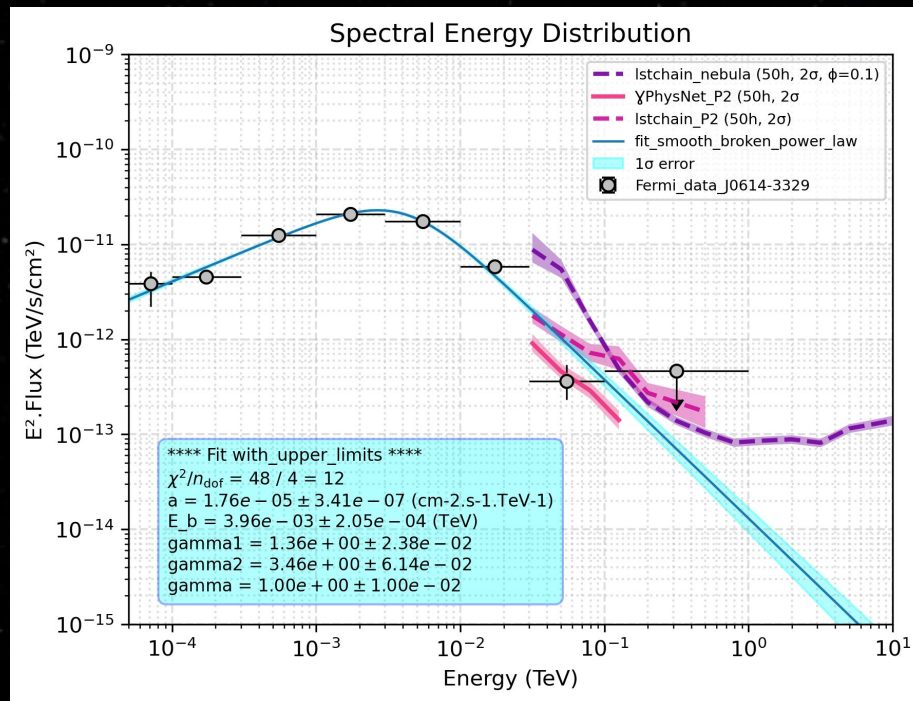
P2 sensitivity

SBPL

Parameter

● Observation time : 50h

Name	Sigma	
	Istchain	gammalearn
J0614-3329	3.53	8.20
J1536-4948	1.39	3.09
J1231-1411	0.57	1.25
J1514-4946	0.50	1.09
J2017+0603	0.49	1.07



■ Southern hemisphere

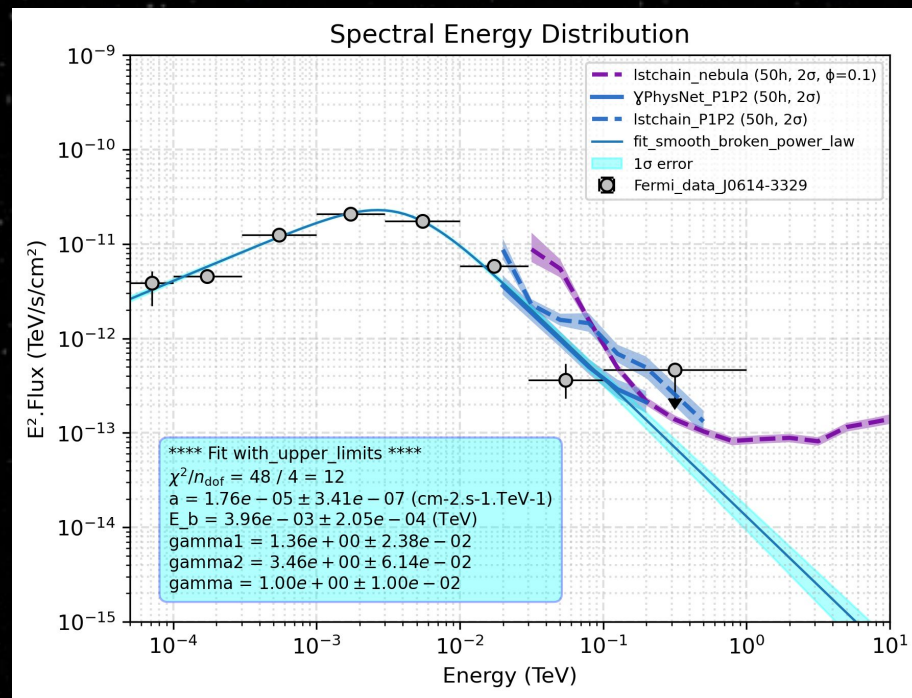
■ Northern hemisphere

● Observation time : 50h

Name	Sigma	
	Istchain	gammalearn
J0614-3329	2.71	4.83
J1536-4948	1.13	1.96
J1231-1411	0.49	0.86
J1514-4946	0.42	0.73
J2017+0603	0.41	0.72

■ Southern hemisphere

■ Northern hemisphere



Results

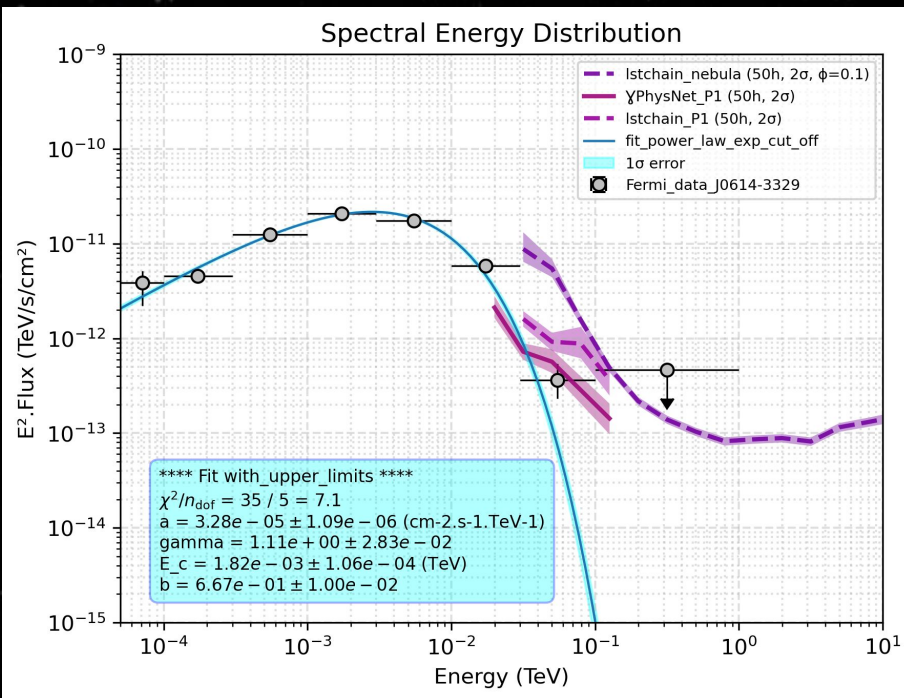
**Power Law Exp Cut Off
LST 1**

● Observation time : 50h

Name	Sigma	
	Istchain	gammalearn
J0614-3329	1.11	4.03
J1536-4948	1.16	3.50
J2017+0603	0.24	1.05
J1514-4946	0.21	0.92
J2339-0533	0.16	0.66

■ Southern hemisphere

■ Northern hemisphere



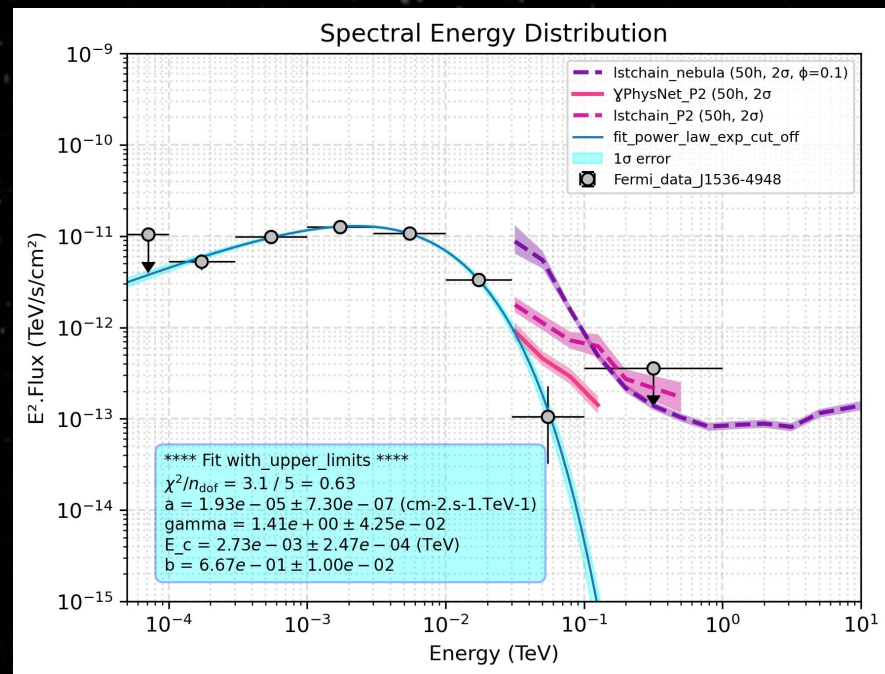
PLExpCutOff

● Observation time : 50h

Name	Sigma	
	Istchain	gammalearn
J1536-4948	1.04	2.09
J0614-3329	1.00	1.98
J2017+0603	0.22	0.43
J1514-4946	0.19	0.38
J2339-0533	0.14	0.28

■ Southern hemisphere

■ Northern hemisphere



P1P2 sensitivity

PLExpCutOff

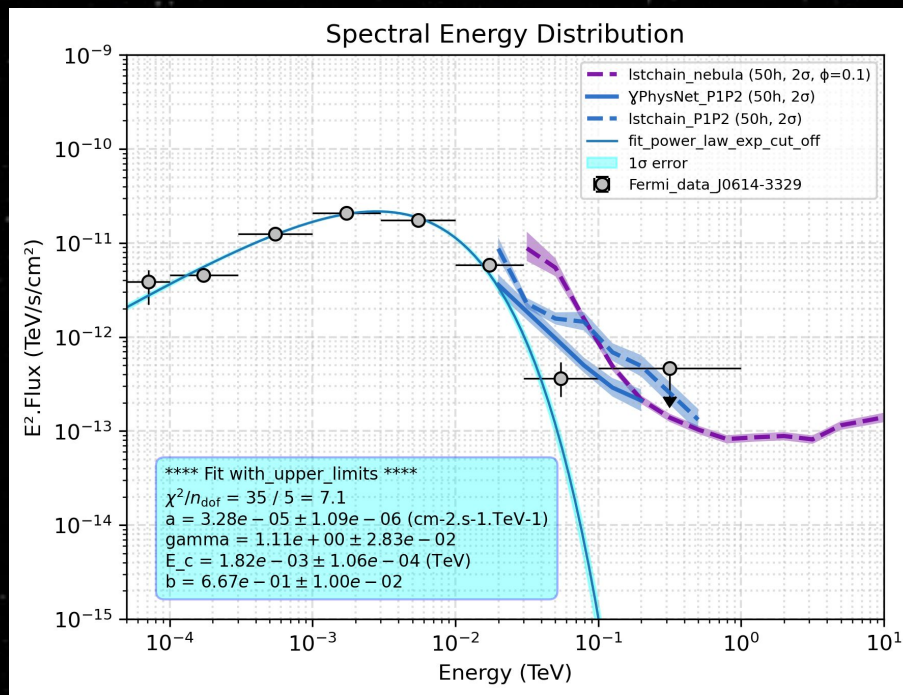
Parameter

● Observation time : 50h

Name	Sigma	
	Istchain	gammalearn
J0614-3329	1.10	2.12
J1536-4948	1.00	1.76
J2017+0603	0.28	0.57
J1514-4946	0.24	0.50
J2339-0533	0.17	0.35

■ Southern hemisphere

■ Northern hemisphere



Results

Geminga-like

LST 1

P1 sensitivity

Geminga-like

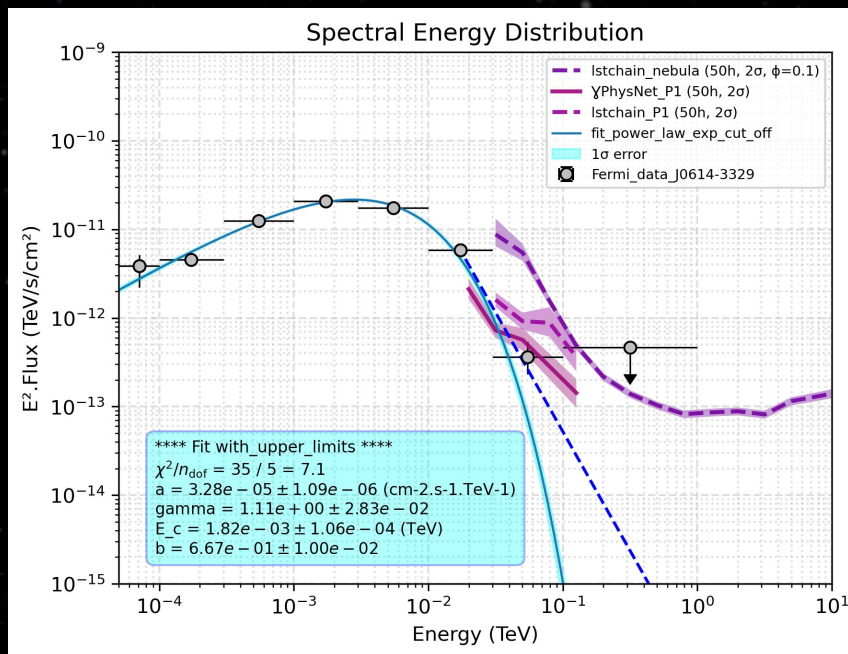
Parameters

- Observation time : 50h
- Sigma condition: 5σ
- Energy pivot : 0.017 TeV

Name	Spectral index	
	Istchain	gammalearn
J0614-3329	3.34	4.69
J1536-4948	2.82	3.55
J2017+0603	2.31	2.76
J1231-1411	2.31	2.72
J1514-4946	2.21	2.62

■ Southern hemisphere

■ Northern hemisphere



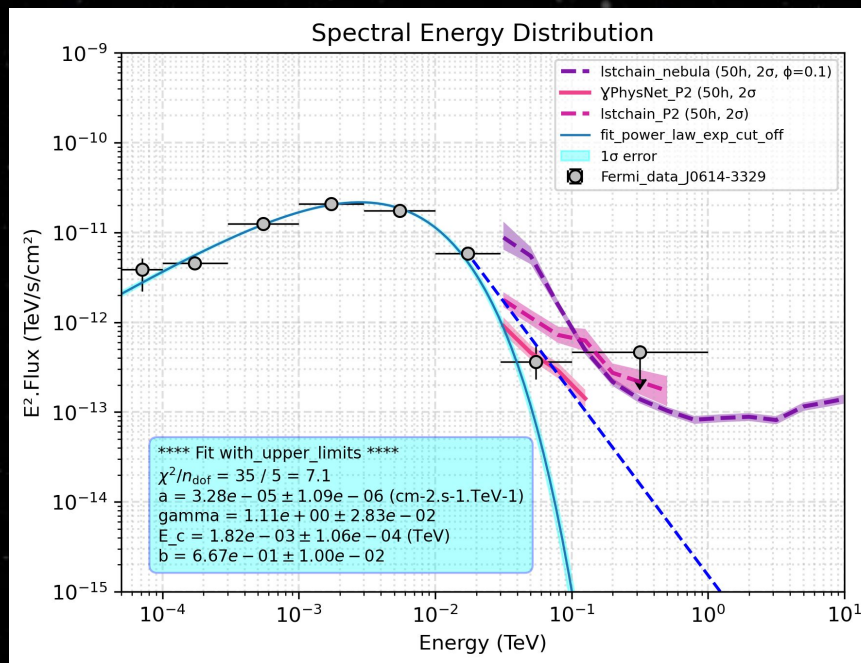
P2 sensitivity

Geminga-like

Parameters

- Observation time : 50h
- Sigma condition: 5σ
- Energy pivot : 0.017 TeV

Name	Spectral index	
	Istchain	gammalearn
J0614-3329	3.24	4.03
J1536-4948	2.83	3.55
J1231-1411	2.41	2.83
J2017+0603	2.41	2.83
J1514-4946	2.41	2.72



■ Southern hemisphere

■ Northern hemisphere

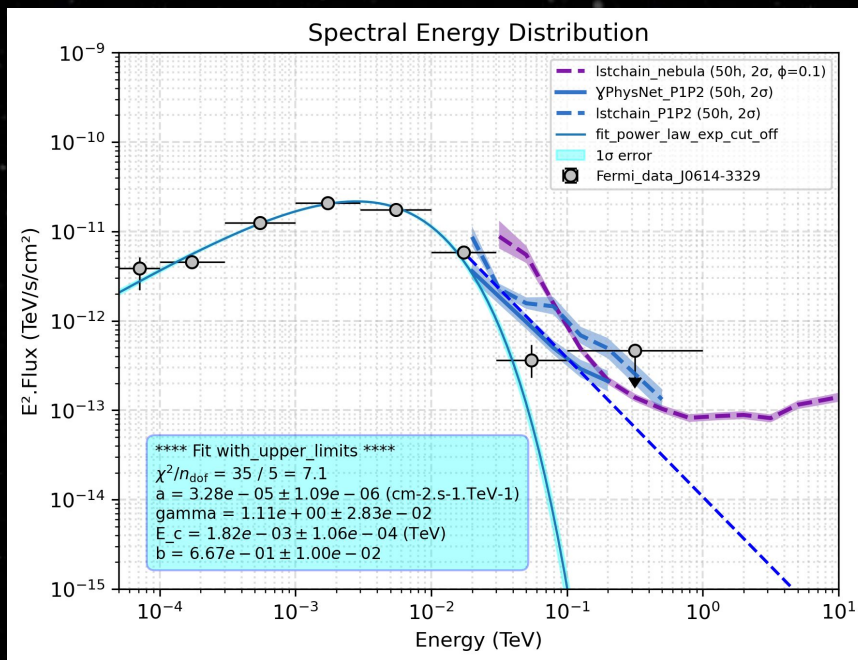
P1P2 sensitivity

Geminga-like

Parameters

- Observation time : 50h
- Sigma condition: 5σ
- Energy pivot : 0.017 TeV

Name	Spectral index	
	Istchain	gammalearn
J0614-3329	3.03	3.55
J1536-4948	2.72	3.14
J1231-1411	2.41	2.52
J2017+0603	2.41	2.52
J1514-4946	2.41	2.41

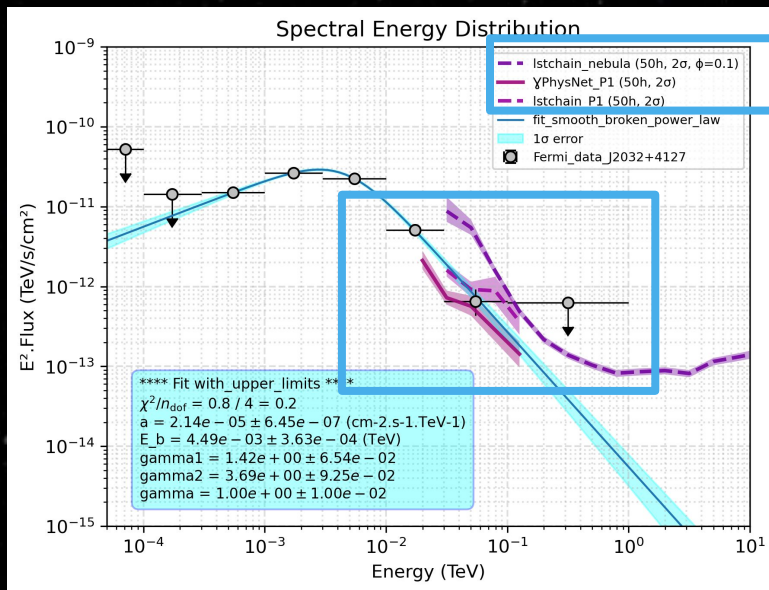


■ Southern hemisphere

■ Northern hemisphere



CTAO/LST detectability evaluation : ratio method



$$\frac{F_{fitted}}{F_{sens}} = \frac{\sigma_{fitted}}{\sigma_{sens}}$$

Sensitivity rescale

Total significance sum



Sigma evaluation by energy bin



Results for millisecond pulsars

Parameter

- Observation time : 50h

- In the very short term : 1 LST North (current CTAO configuration)

- The best candidate is **J2017+0603** but it will not be detectable by only one LST

- In the medium term : 4 LSTs North (≈ 2027) :





- The stereoscopic configuration LST1-4 will improve the sensitivity and will probably make **J2017+0603** detectable (at least a strong hint $\approx 3\sigma$)

- In the long term : CTAO South (≈ 2030) :

- At least two millisecond pulsars (**J1536-4948**, **J0614-3329**) potentially detectable by one LST South

Conclusion & Perspectives

● Crab analysis for LIV : work in progress

- Data selection done : 192 hours of Crab data to analyse 
- Pipeline that allows us to perform high level analysis (SED and Phasogram construction) 
- multi-zenith study to research a potential emission at high energy : no such component was detected 
- simple double gaussian fit performed for the phasogram 
- estimation of the LIV constraints (in progress)

→ Analysis for the source dependent and optimized cuts data

→ Taking into account the Bridge in the phasogram fit (global fit P1,P2 and Bridge)

→ Use of LIVelihood code for a more rigorous LIV constraints

→ Other pulsars LIV analysis thanks to the Crab analyse code (DragonFly, 2032+4127 and boomerang)

Sensitivities used



Istchain

New method of reconstruction !



gammalearn

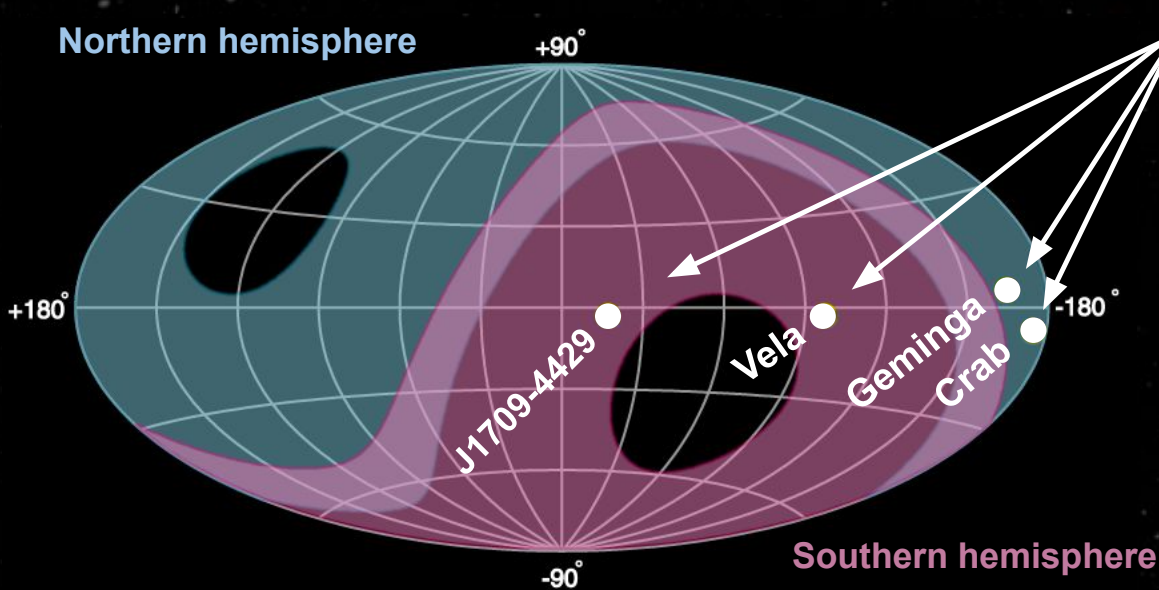


- Based on a random forest

- Based on deep learning

→ **A significant improvement in LST sensitivity at low energy (\approx tens of GeV) !**

Current state of the art



- 4 pulsars detected by the IACTs (HESS, LST, VERITAS, MAGIC)
- No millisecond pulsars have been detected yet by the IACTs
- LIV application only for the Crab and Vela among pulsars
(<https://iopscience.iop.org/article/10.3847/1538-4357/ac5048/pdf>)

Next steps :

- ➔ What are the best pulsar candidates to detect with CTAO ?
- ➔ What are the best pulsar candidates to probe LIV ?

