LIV studies with HESS II

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Outline

LIV in Fundamental Theories

LIV tests with Cherenkov Telescopes

HESS II performance: Monte Carlo Studies

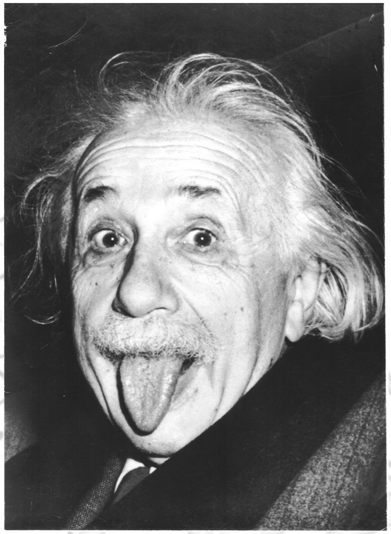
Summary and Conclusions

LIV in Fundamental Theories

- Lorentz Invariance/Symmetry: Einstein's Relativity & Standard Model

- At Planck scale~10^{-35} m (10^{19} GeV), nature of space-time needs to account for microscopic effects

→ Quantum Gravity (QG)



- Some models of QG lead to Lorentz Invariance Violation

→ D branes String model (foamy structure of space-time)

→ Non-commutative geometry

→ Spontaneous symmetry breaking (SME)

→ LQG

...

- LIV can be tested in different ways:

→ Photon decay, Vacuum Cherenkov Radiation

→ Modified GZK cutoff, and TeV γ-ray spectra of extra-galactic sources.

→ Vacuum birefringence

→ Dipersion of light in vacuum

Modification of dispersion relations in vacuum

- LIV modifies dispersion relation for the photon:

$$c^2 p^2 = E^2 \left(1 + \xi \left(E/E_{planck}\right) + \zeta \left(E/E_{planck}\right)^2 + \ldots\right)$$

- Leading order corrections to the speed of light (c) in vacuum:

$$v = \delta E / \delta p = c \left(1 - \xi \left(E/E_{planck}\right) - \zeta \left(E/E_{planck}\right)^2\right)$$

$\boxed{\xi = \frac{E_{planck}}{E_{QG}}}$ and $\boxed{\zeta = \left(\frac{E_{planck}}{E_{QG}}\right)^2}$ are LIV parameters (<0 or >0)

superluminal subluminal

- Figure of merit of LIV:

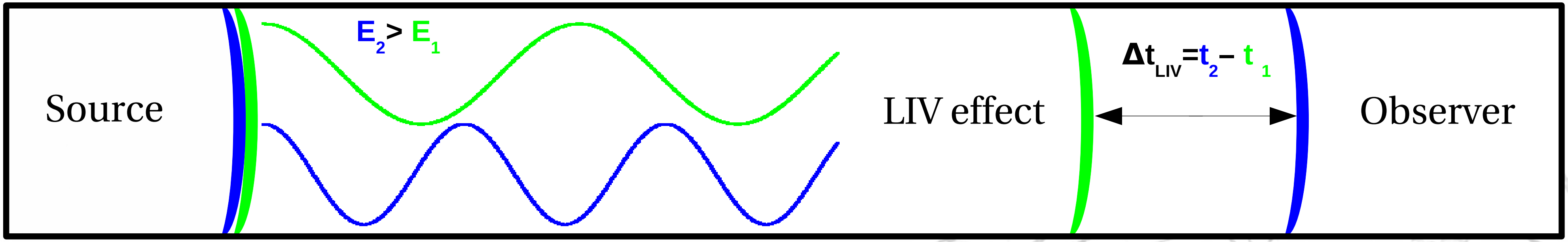
$$\xi \approx \frac{c\, E_p}{d} \frac{\Delta t}{\Delta E}$$

Best sensitivity for :
Fast variability sources
Distant sources
Energetic sources

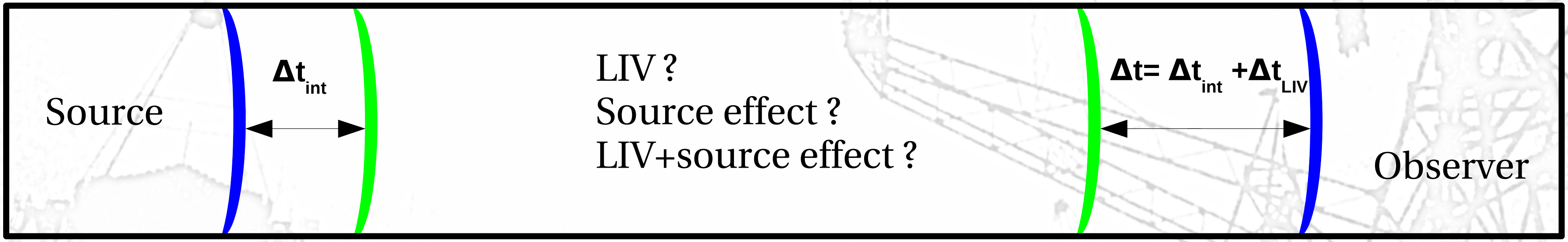
Vacuum dispersion

- 2 photons of energies $\mathbf{E_1}$ and $\mathbf{E_2}$($>\mathbf{E_1}$) emitted at time **t**

→ observed with a relative $\Delta \mathbf{t_{LIV}=t_2-t_1}$ (>0 for subluminal, <0 for superluminal)



- Possible source intrinsic delays

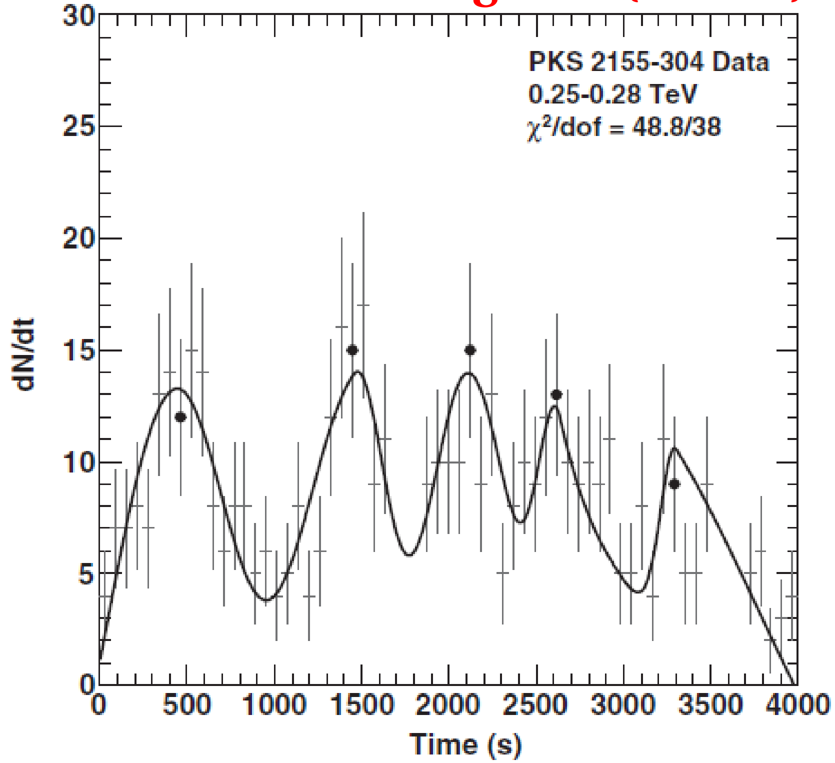


→Source effect is major caveat : only redshift dependence study can distinguish

LIV tests with Cherenkov Telescopes

- Energy dispersion of time of arrivals in observed gamma rays.

PKS2155-304 – Big flare (HESS I)

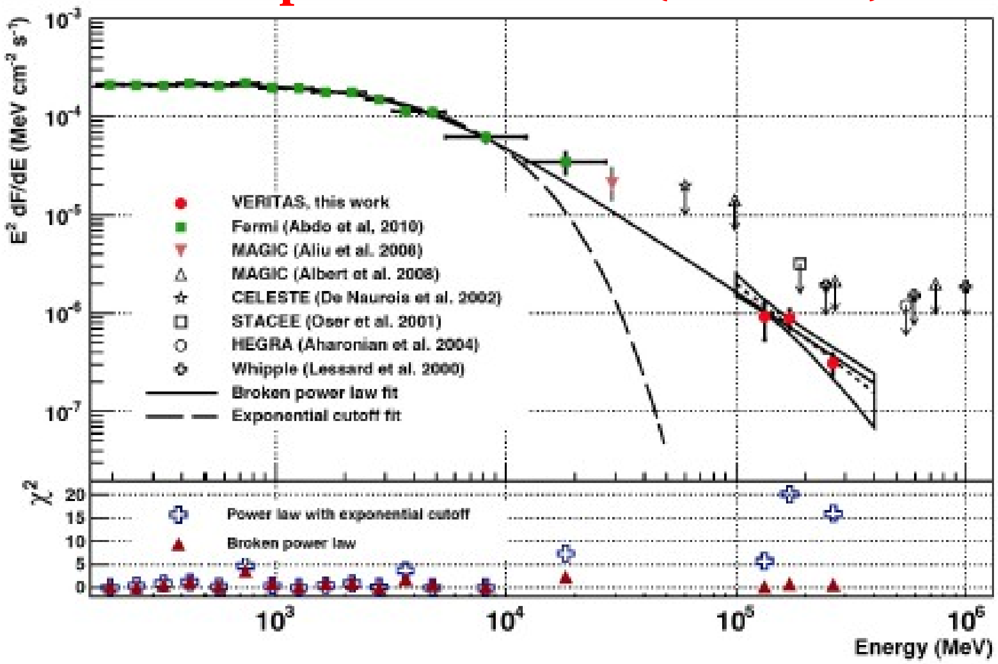


$$E_{QG,l} > 2.1 \times 10^{18}\, GeV$$

Maximum Likelihood method

Astroparticle Physics 34 (2011) 738–747

Crab-pulsed emission (VERITAS)

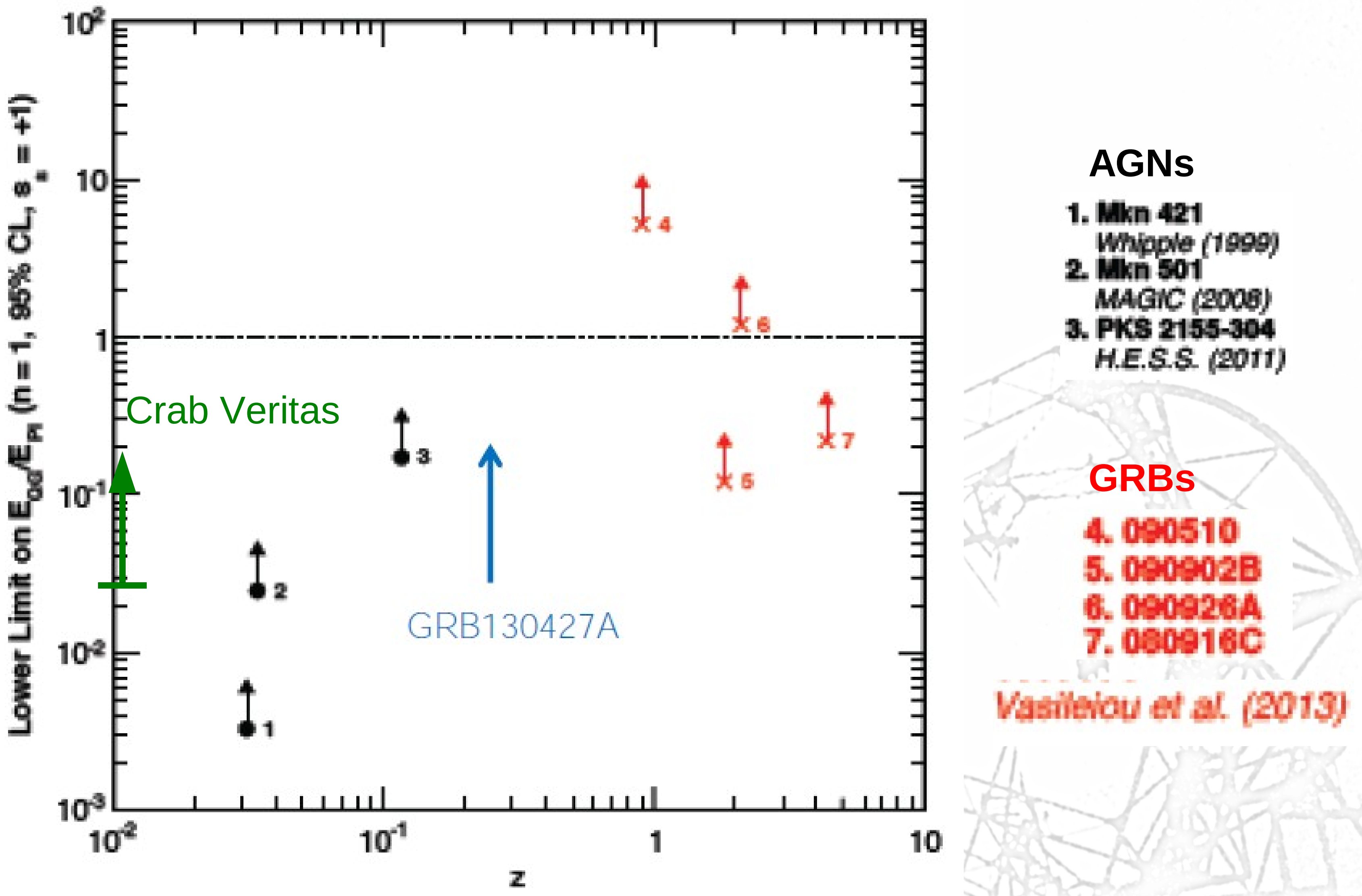


$$E_{QG,l} > 1.9 \times 10^{17}\, GeV$$

DisCan method

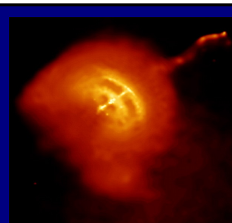
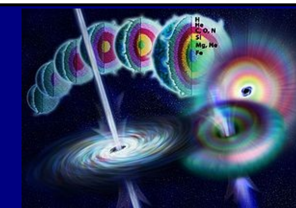
arXiv:1307.8382v1 [astro-ph.HE] 31 Jul 2013

Present QG limits on linear term



- Apart from large redshift GRBs & PKS 2155-304 , Crab pulsar good competitor.

Astrophysical probes of LIV with HESS II

	 Pulsar	 Active Galactic Nuclei	 Gamma Ray Burst
Ad.	• Permanent pulsations •Distinguish between LIV/source effects	•Extragalactic • Up to TeV	• Extragalactic •Up to TeV ?
Disad.	• Galactic • Up to 400 GeV(Crab) to be confirmed with H.E.S.S.2	• Source effects • Random transient evts	• Source effects • Obs. based on luck
HESS II running mode	• Mono → Access lower energies (crucial with pulsars)	• Hybrid → Access higher energies (crucial with AGNs)	• Hybrid

The method of time-lag measurement

- Strategy adapted from *Martinez & Errando (Astropart.Phys. 31 (2009) 226)*

$$P(E,t)=N\int_0^{\infty} A(E_s)\Gamma(E_s)G(E-E_s,\sigma(E_s))F_s(t_s-\tau_n E_s^n)dE_s$$

$A(E_s)$: Acceptance of telescope
$G(E-E_s)$: Energy smearing functon
$\Gamma(E_s)$: Spectrum at source
$F_s(t_s)$: Light curve at source

- The time-lag parameter :
(s/TeV for n=1)
(s/TeV^2 for n=2)

$$\tau_n=\frac{\Delta t}{\Delta E}\approx\frac{(n+1)\xi}{2E_p^{\ n}H_o}\int_0^z\frac{(1+z)}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}dz$$

1) Parametrize Template Light curve **$F_s(t_s)$** at low energy and spectrum **$A(E_s)$**
2) Use **Maximum Likelihood** at high energy to estimate the time lag parameter.

- The likelihood is the product of the p.d.f's over all the photons in the fit:

$$L=\prod_i P(E,t)$$

HESS II performances with pulsars
The method

- Time delay due to LIV:

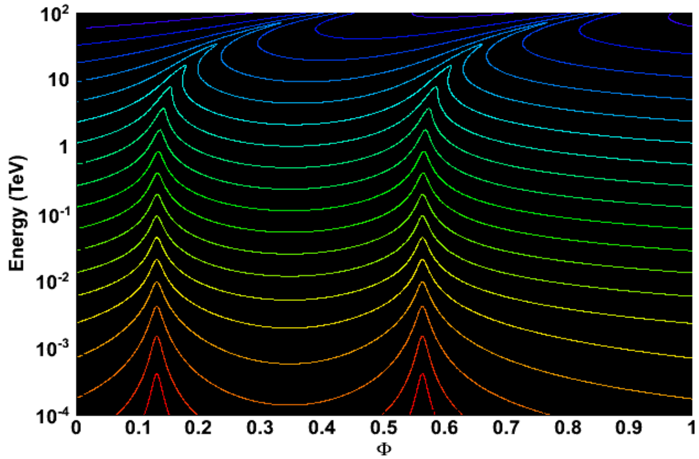
→ phase delay between photons of ≠ energies in the reconstructed phasogram.

- Define a phase-lag parameter : $\varphi_n = \dfrac{\tau_n}{P(t)}$

 (TeV^{-1} for n=1)

 (TeV^{-2} for n=2)

$P(t) \approx P + \dot{P}\, t$ For short time scale: $P(t) \approx P$



- Parametrize Template Phasogram $\mathbf{F_s}$ at low energy and spectrum $\mathbf{A(E_s)}$

$$F_s(t_s - \tau_n E_s^n) \rightarrow F_s(\Phi_s - \varphi_n E_s^n)$$

$$P(E,t) \rightarrow P(E,\Phi)$$

- **Maximum Likelihood** at high energy gives estimate on the phase-lag parameter.

$$L = \prod_i P(E,\Phi)$$

HESS II performances with pulsars

- 1 single pulse in phasogram

→ $\sigma_{pulse} = 2 \times 10^{-2}$ (rotational phases)

→ Power law spectrum $E^{-\Gamma}$ $\Gamma=3.3$

- Acceptance & energy resolution

→ H.E.S.S.2 mono

→ $\Delta E/E \sim 35\%$

- 2 studies:

→ **B1 model**: S/B=∞ (>30 GeV)

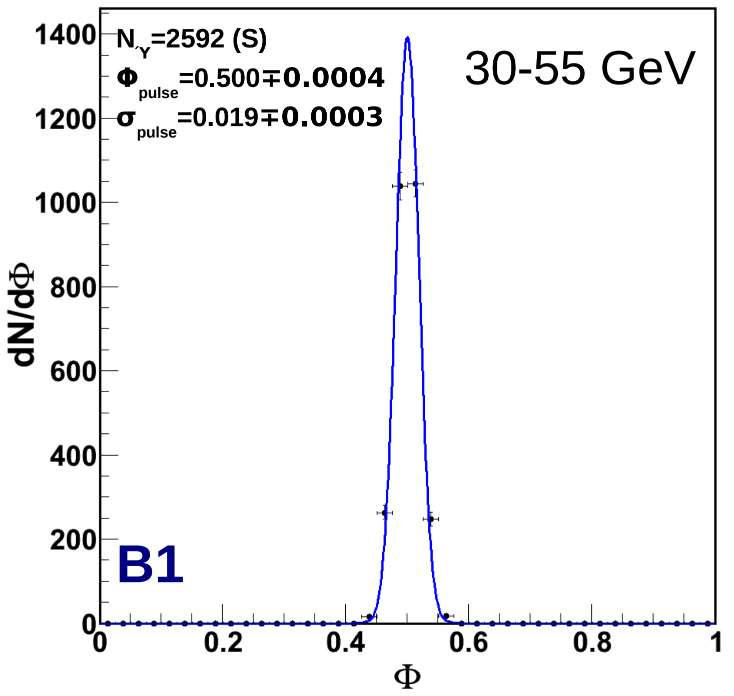
→ **B2 model**: S/B=1 (>30 GeV)

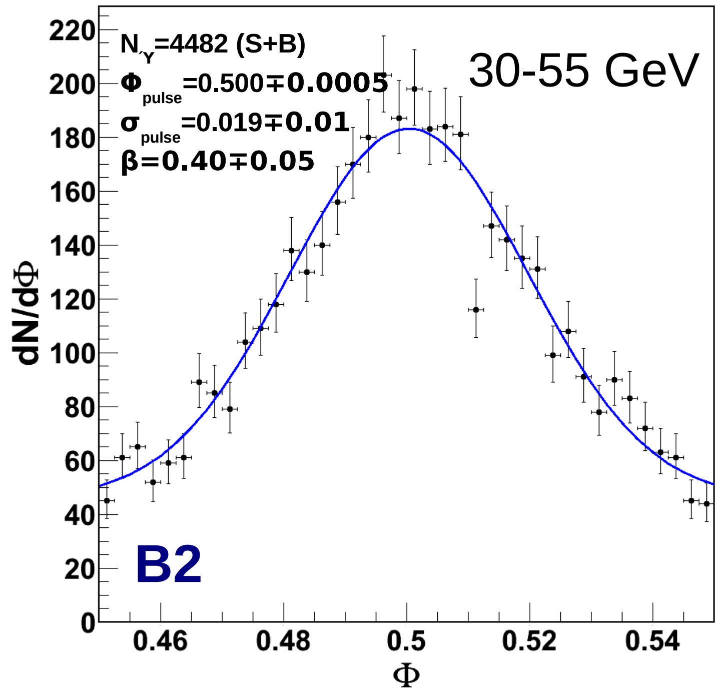
<u>Model is optimistic:</u>

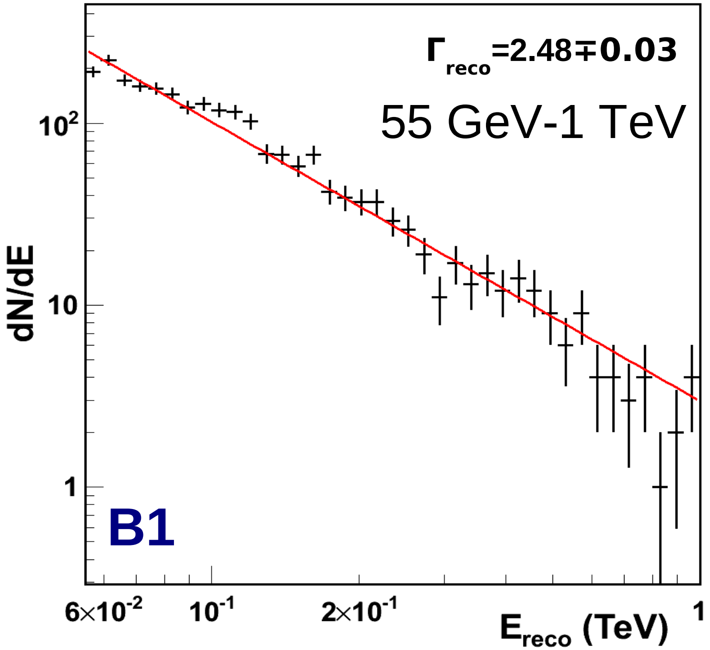
→Pulse shape not Gaussian

→S/B could be >1 due to hadron bckg suppression problems

HESS II performances with pulsars
Template phasogram and spectrum



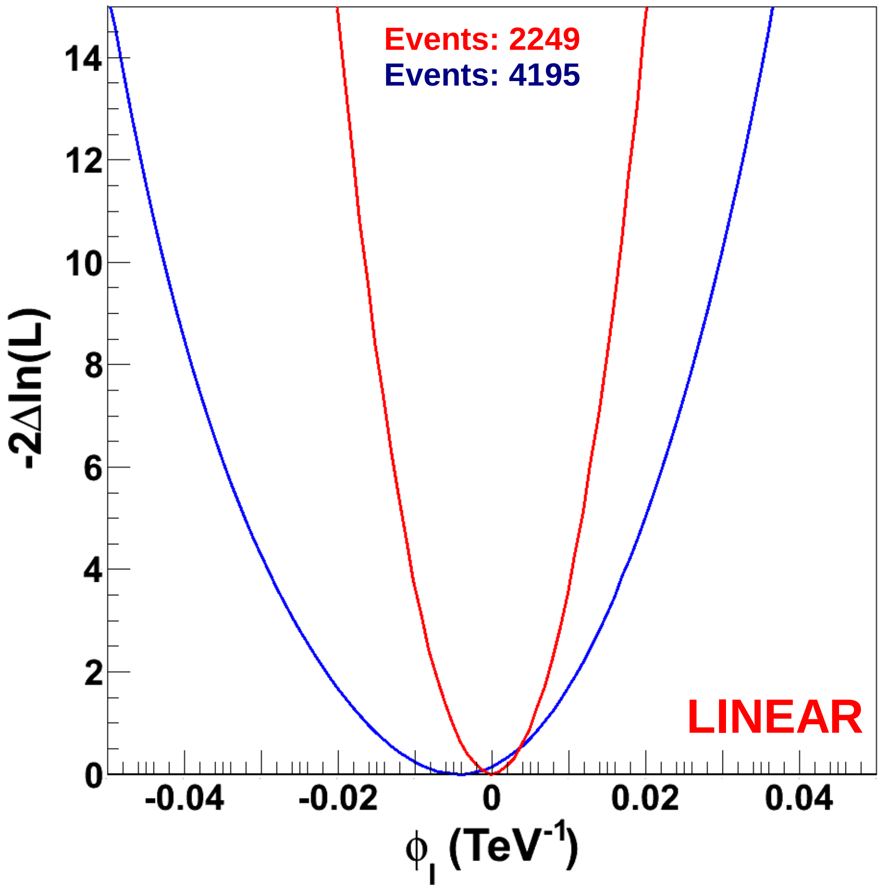


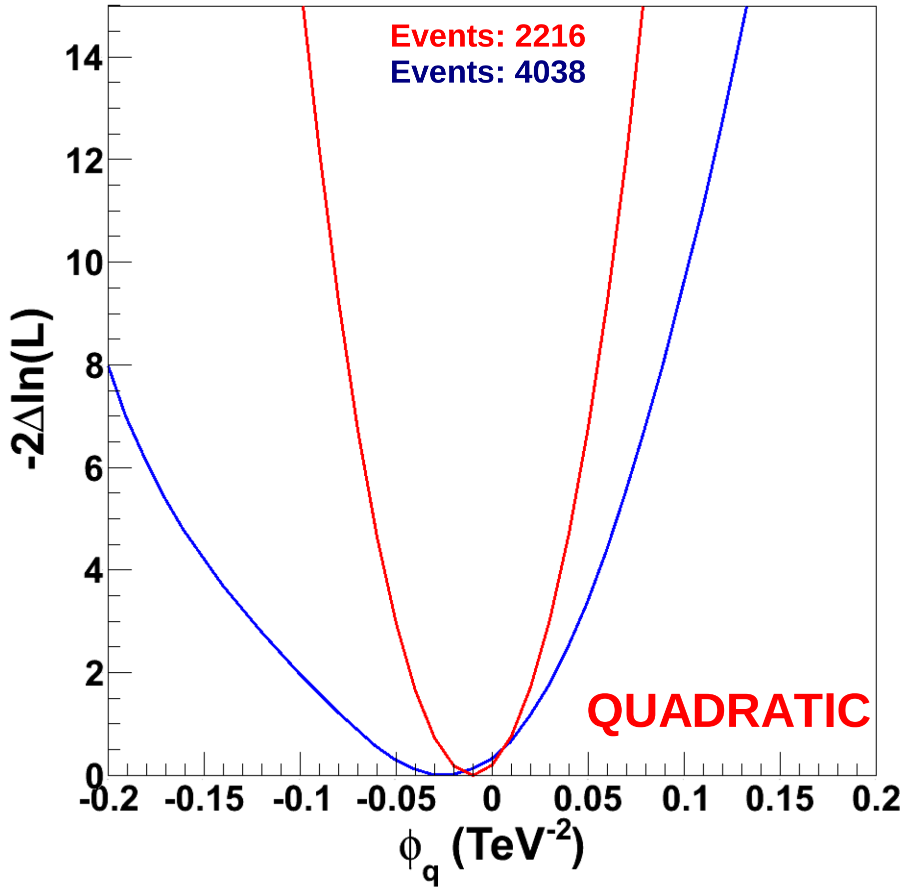


- **B1: S/B=∞**:
  - →Fit phasogram using Gaussian pulse.
  - →Fit spectrum with power law (>55GeV)
- **B2: S/B=1**:
  - →Fit phasogram using (1-β) x Gaussian(Φ) + β x Uniform (Φ)

HESS II performances with pulsars
Results

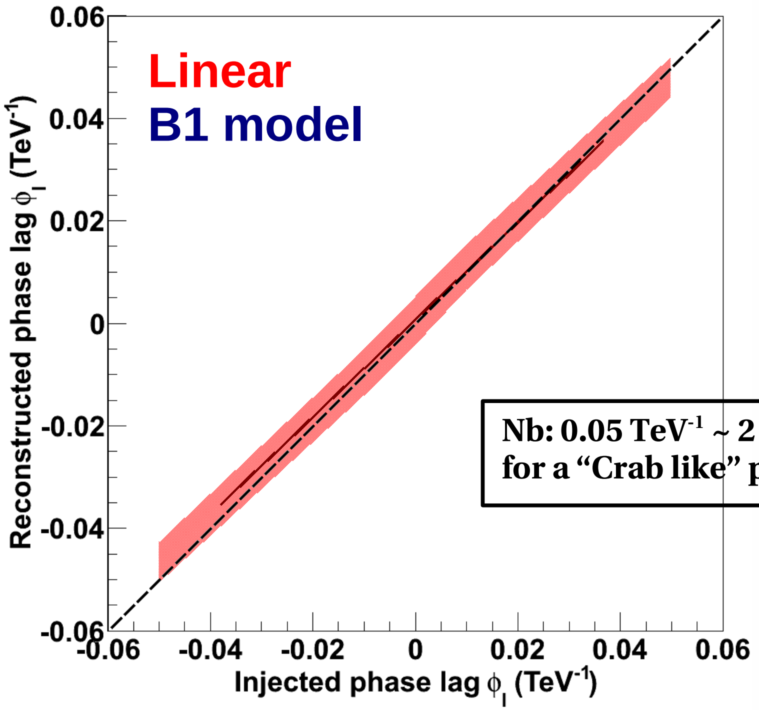
- Estimate on phase-lag parameter given by minimum of -2Δln(L).



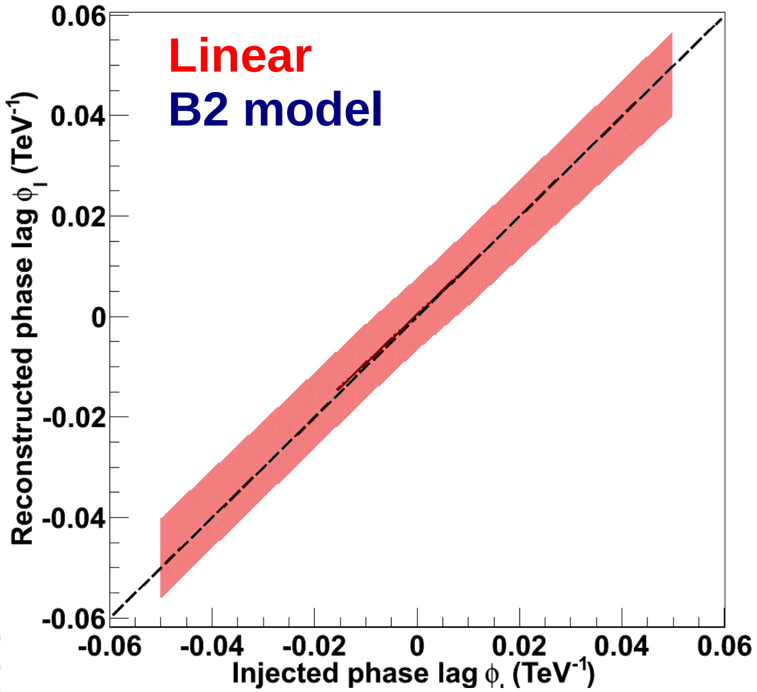


- **Red** : B1 model (no background)
- **Blue**: B2 model (S/B=1)
- Wider “parabola” due to background contamination.

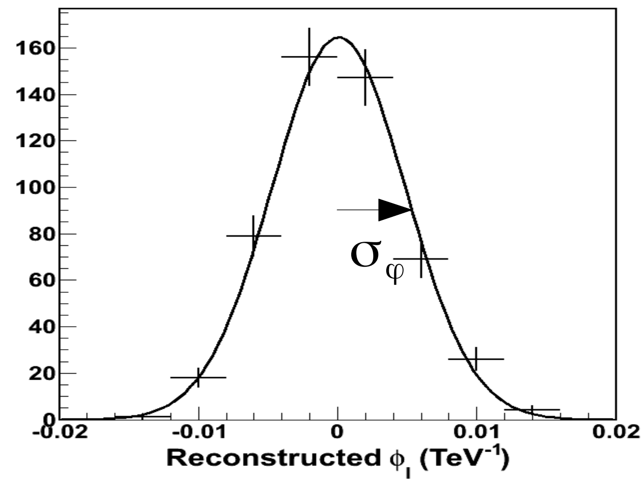
HESS II performances with pulsars
Calibration of the method



Nb: 0.05 TeV^{-1} ~ 2 ms/TeV^{-1} for a "Crab like" pulsar.

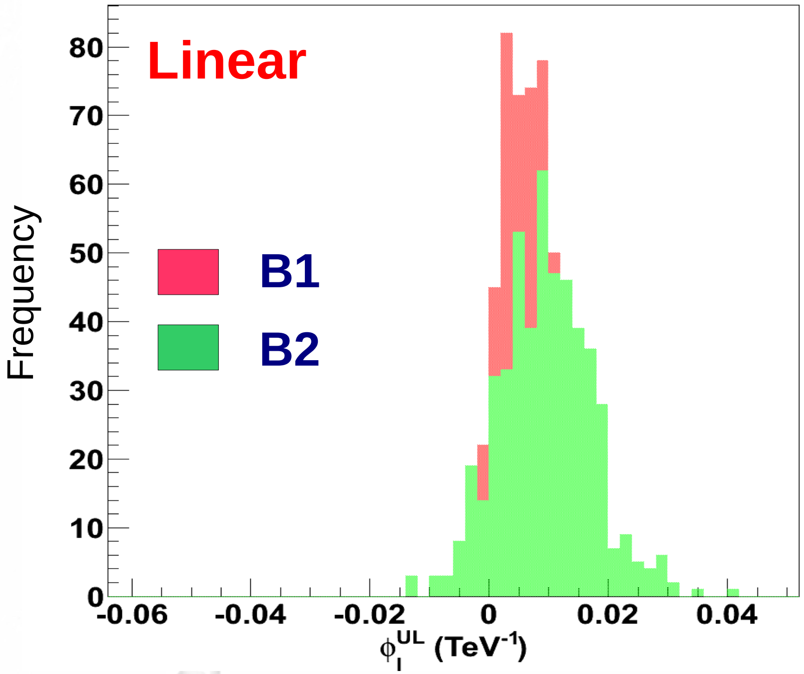


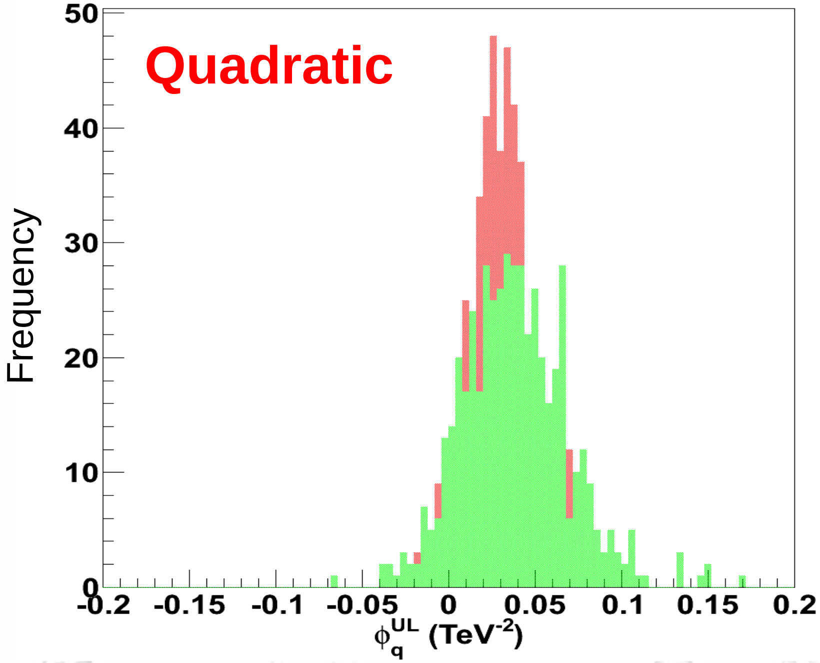
	N_{evt}	Calibrated error σ_φ (φ_{inject}=0)	Remarks
Linear S/B=∞	2449	0.0047 ± 0.0001 TeV^{-1}	-
Linear S/B=1	4195	0.0072 ± 0.0002 TeV^{-1}	~35% deterioration
Quadratic S/B=∞	2216	0.0193 ± 0.0006 TeV^{-2}	-
Quadratic S/B=1	4038	0.0285 ± 0.0006 TeV^{-2}	~32% deterioration



HESS II performances with pulsars
Calibration of confidence intervals

- 95% CL upper/lower limits on phase lag parameter are derived from -2Δln(L).



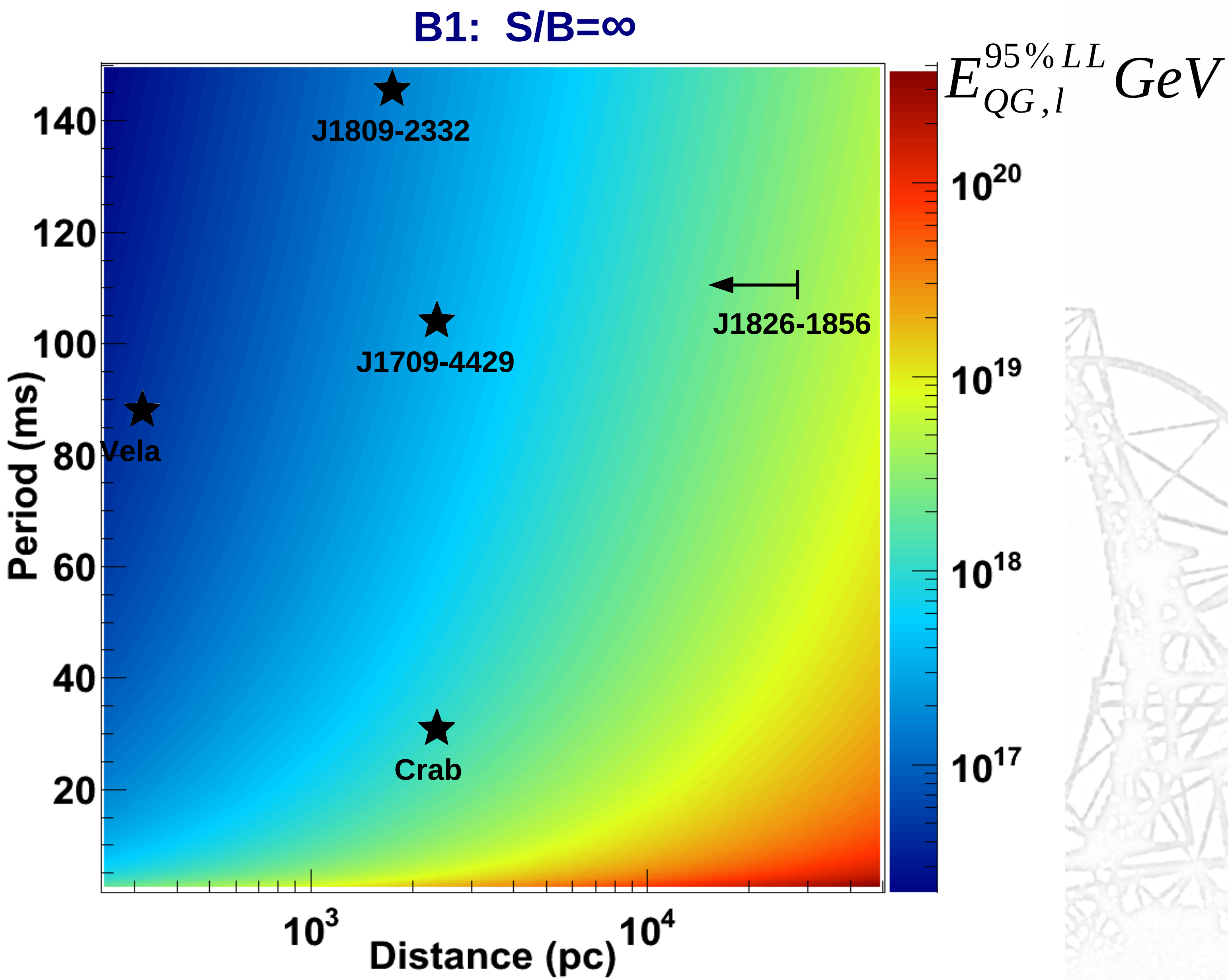


- **Improper coverage**, mainly due to:
  - Template phasogram uncertainties
  - Spectrum parametrization

- **Refine threshold** on -2Δln(L) to get proper coverage.
  - Derive mean upper/lower limits on linear and quadratic phase lag parameter
  - Lower limits on quantum gravity scale E_{QG}

HESS II performances with pulsars

Sensitivity (linear correction, subluminal)



HESS II performances with pulsars

$E_{QG}^{95\% LL}$ (GeV) for H.E.S.S.2 pulsar candidates	Linear		Quadratic	
	S/B=∞	S/B=1	S/B=∞	S/B=1
Crab	1.04×10^{18}	5.47×10^{17}	1.74×10^{10}	1.48×10^{10}
PSR J1826-1256*	$< 3.18 \times 10^{18}$	$< 1.83 \times 10^{18}$	$< 3.19 \times 10^{10}$	$< 2.72 \times 10^{10}$
PSR J1709-4429	3.19×10^{17}	1.84×10^{17}	1.01×10^{10}	8.63×10^{9}
PSR J1809-2332	1.64×10^{17}	9.5×10^{16}	7.25×10^{9}	6.20×10^{9}
Vela	4.69×10^{16}	2.71×10^{16}	3.87×10^{9}	3.31×10^{9}

* *from published upper limit on distance (Fermi 2nd year catalog), distance to the Galaxy's edge*

HESS II performances with AGNs
Toy MC simulations

Modest flare from PKS 2155-304:

- 1 gaussian pulse in 25 min
- → 1000 events > 0.3 TeV
- → σ_{flare} = 250 s
- → Power law spectrum $E^{-\Gamma}$ Γ=3.2

Acceptance and resolution: HESS II hybrid/mono

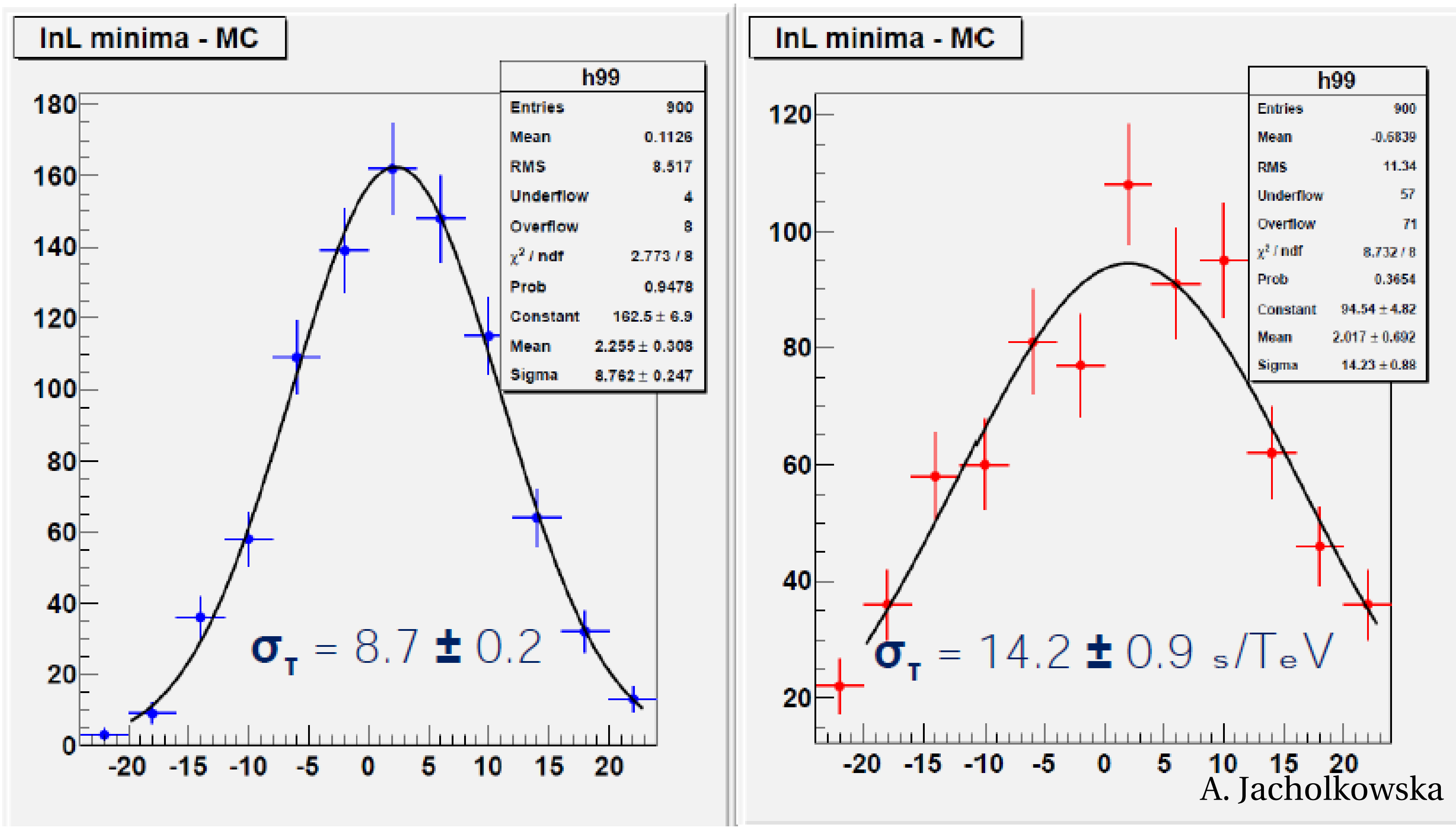
- → Estimation of no of events in the low energy range for a Template LC

- → HESS I/ HESS II sensitivity ratio in 0.15 – 1.0 TeV range ~ 2
- → Safe range for likelihood fit (> 0.15 TeV) with respect to:
  Efficient background suppression
  Assuming a power law spectrum reconstruction

HESS II performances with AGNs
Error calibration

- Statistical precision measurement: calibrated error p.d.f.s

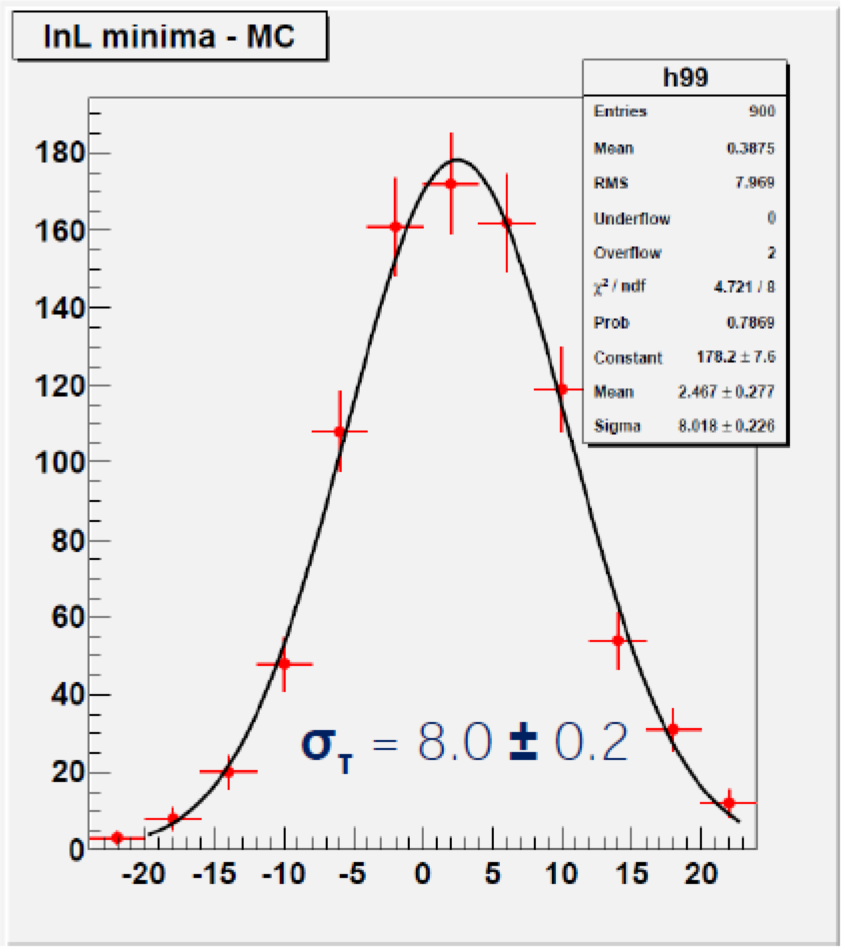
HESS 1 E > 0.3 TeV HESS 2 mono E > 0.15 TeV



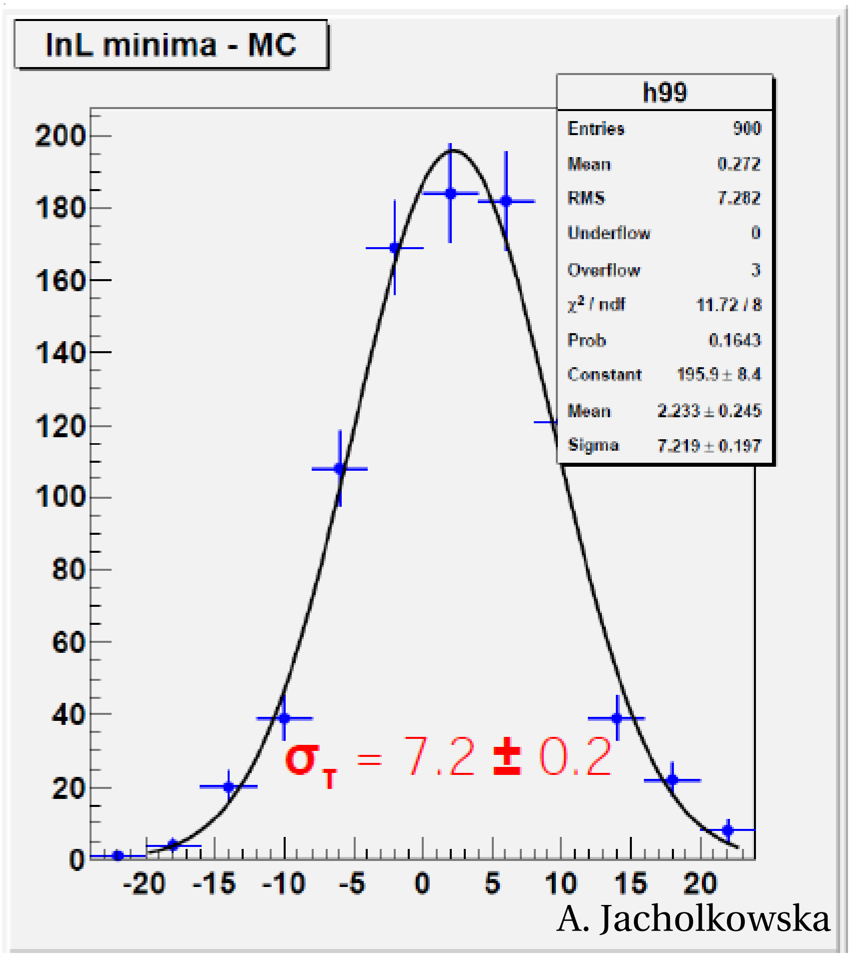
HESS II performances with AGNs

Error calibration

HESS 1 + HESS 2 mono



HESS 2 hybrid E > 0.2 TeV



A. Jacholkowska

HESS II performances with AGNs

Summary

A. Jacholkowska

Mode	N_{evt}	Calibrated error σ_T (s/TeV)	Template LC range (TeV)	Remarks
HESS 1 E > 0.3 TeV	1000	8.7 ± 0.2	0.15 – 0.25	Low intensity flare BF calibration: 5.5 s/TeV
HESS 2 mono E > 0.15 TeV	1100	14.2 ± 0.9	0.05 – 0.12	Not competitive alone
HESS 1 + HESS 2 mono E > 0.3 E > 0.15 TeV	2100	8.0 ± 0.2	0.15 – 0.25 0.05 – 0.12	Suitable for tests: 2 template LCs
HESS 2 hybrid E > 0.2 TeV	3600	7.2 ± 0.2	0.05 – 0.12	error: 25% improvement

With systematics $\sigma_{syst} \approx \sigma_{stat}$

$\boxed{E_{QG}^{1} > 3.50 \times 10^{18}\ \text{GeV}\ \ (95\%\ \text{CL})}$

Summary and Conclusions

- **Overall:**
  - → Increase in sensitivity <0.2 TeV, better Template at low energy
  - → Larger statistics

- If pulsars confirmed with HESS II (Mono running mode)
  - → Permanent pulsations, low systematics
  - → "Crab like" competitors to AGNs
  - → With millisecond pulsars, could reach the Planck scale.

- With AGNs (PKS 2155-304)
  - → Hybrid running mode
  - → 25% improvement on statistical error compared to HESS I

- With GRBs
  - → Work is ongoing, preliminary result (z=0.5): $E_{QG}^{1} > 1.02 \times 10^{20}$ GeV

- White paper before end of the year

Thanks

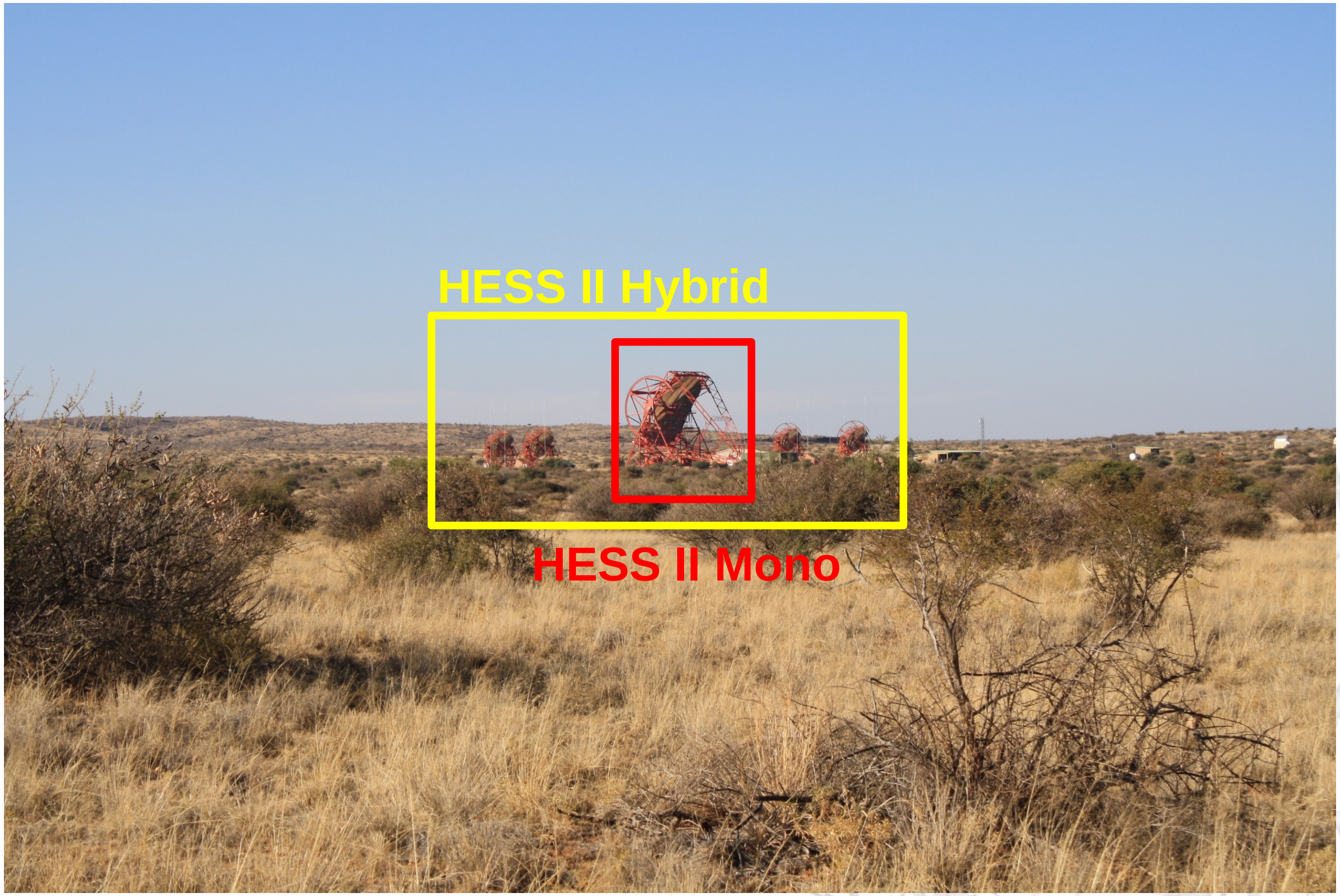
Tack!

“That's a violation of the law of Lorentz invariance, baby”
Futurama, “Law and Oracle” (2011)

Backup slides

HESS II telescope running modes

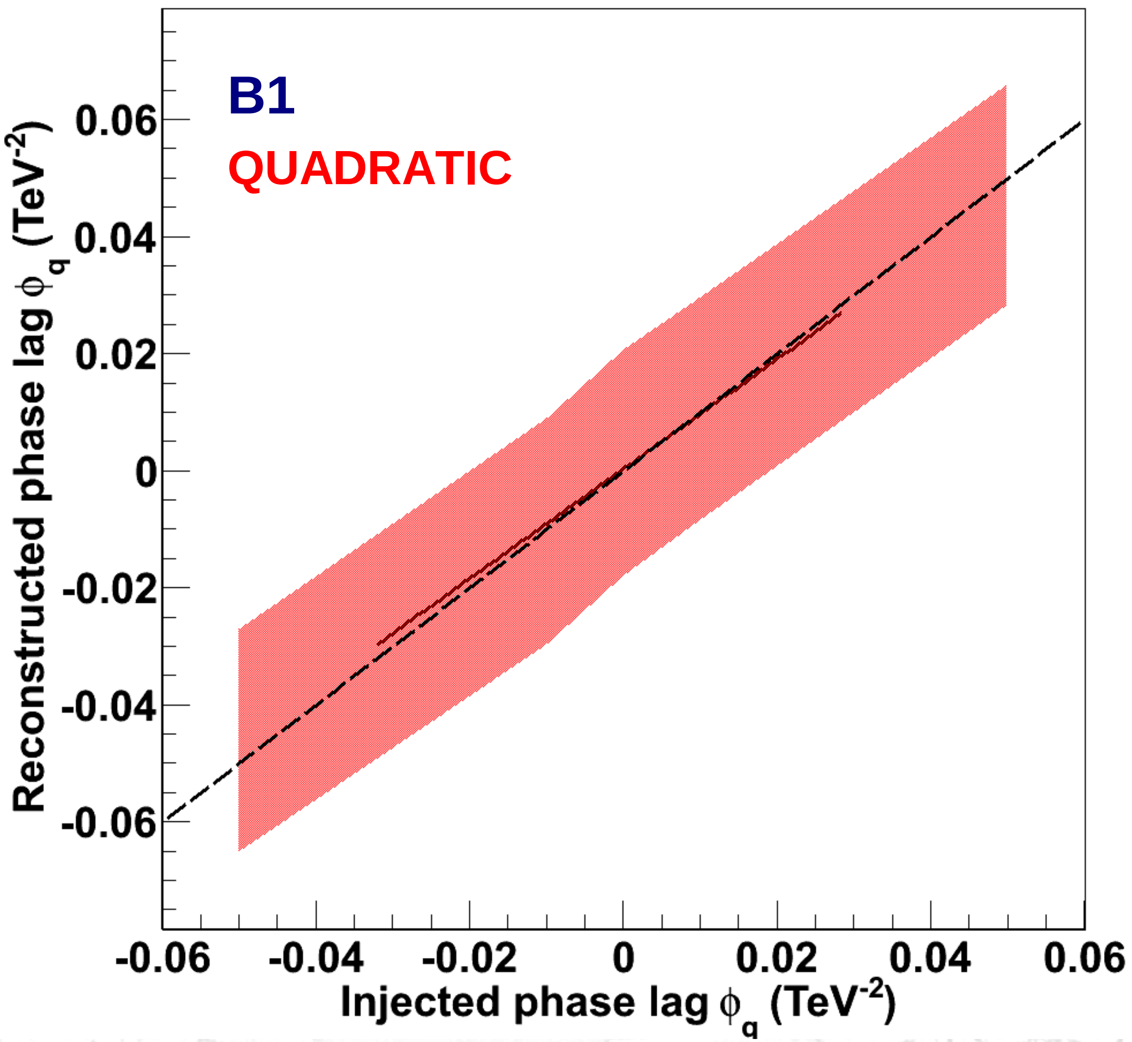
- Hybrid
  - → Higher energy threshold
  - → Access higher energies



- Mono
  - → Lower energy threshold (smaller effective area)
  - → Access lower energies (~<100 GeV)

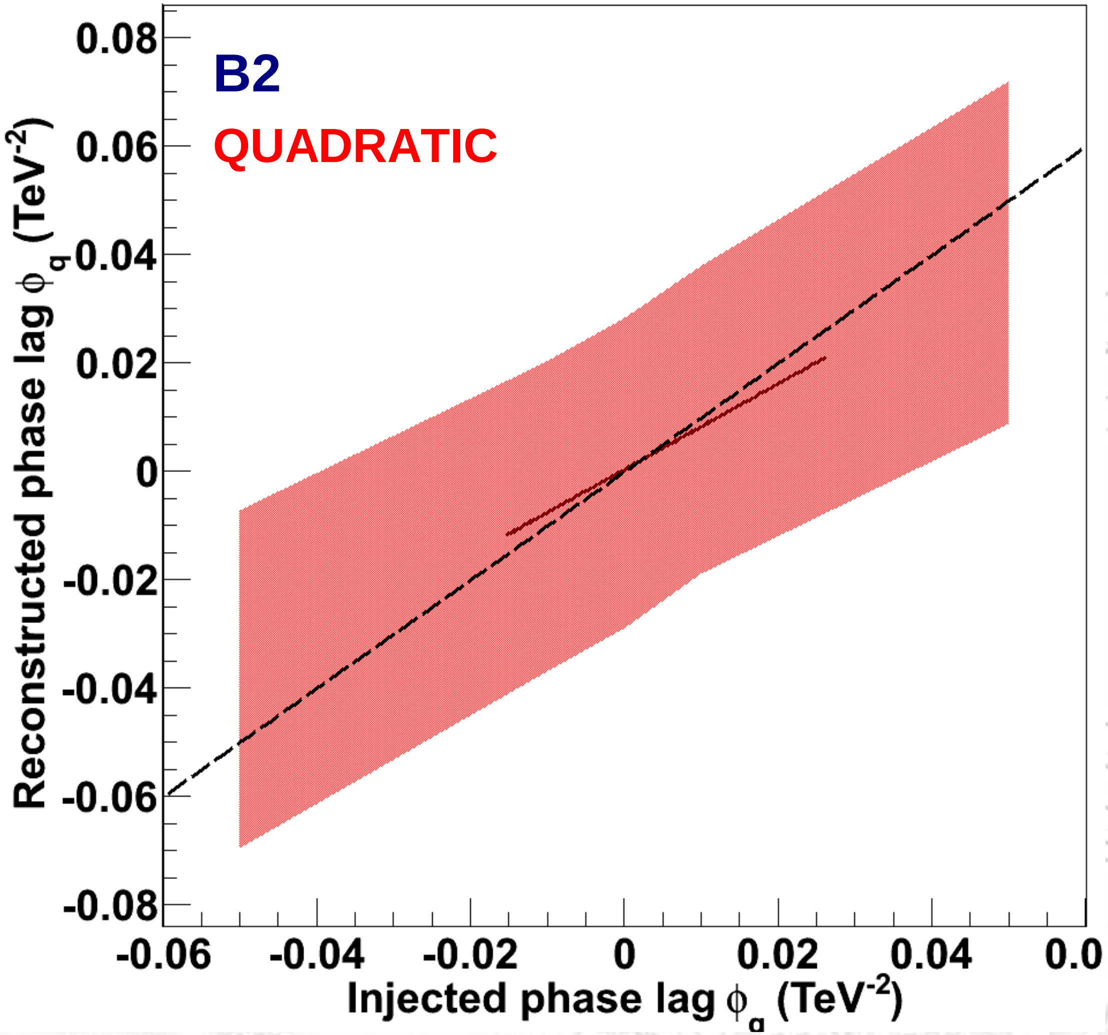
Backup slides

Calibration curves



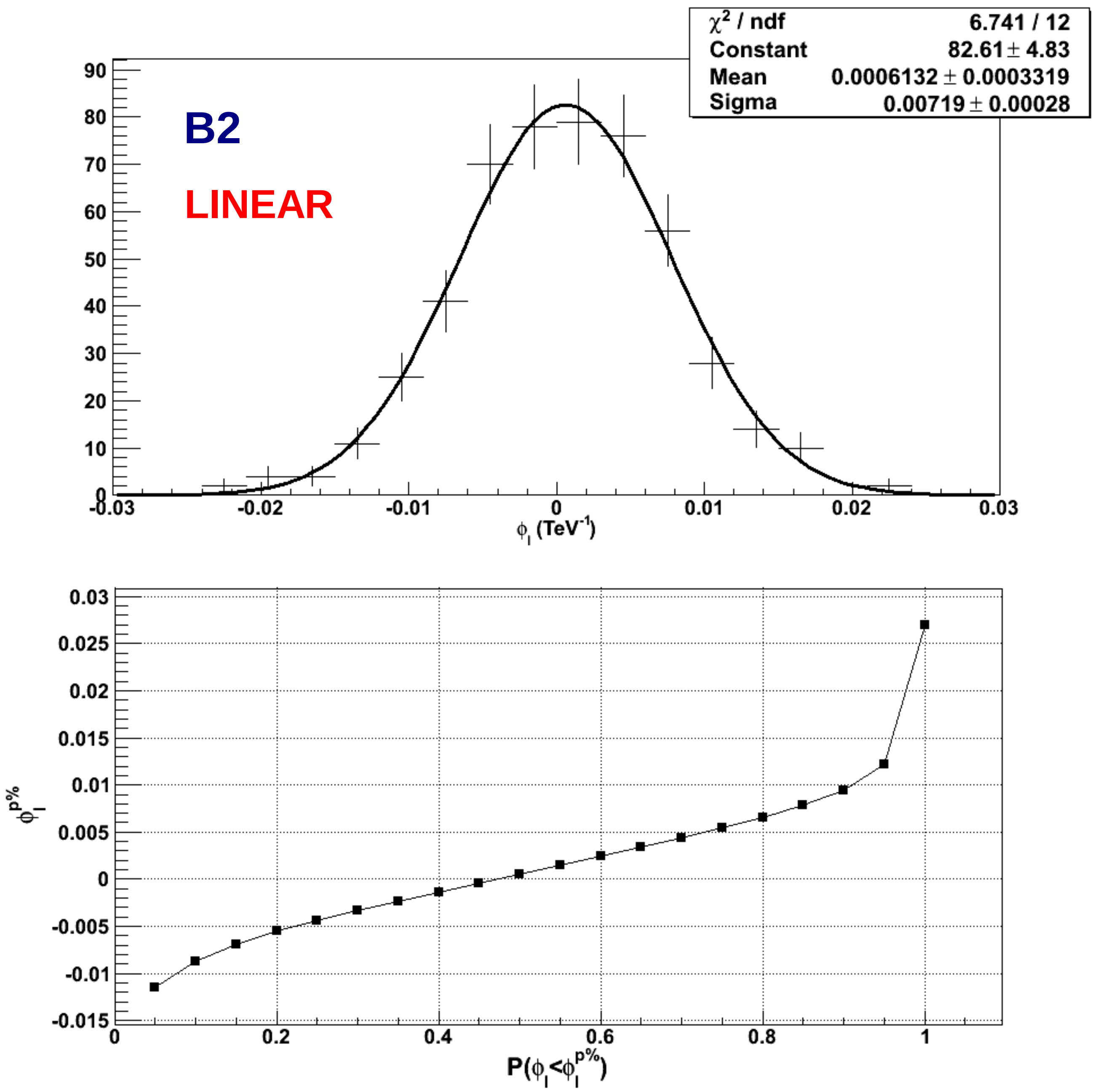
Backup slides

Calibration curves



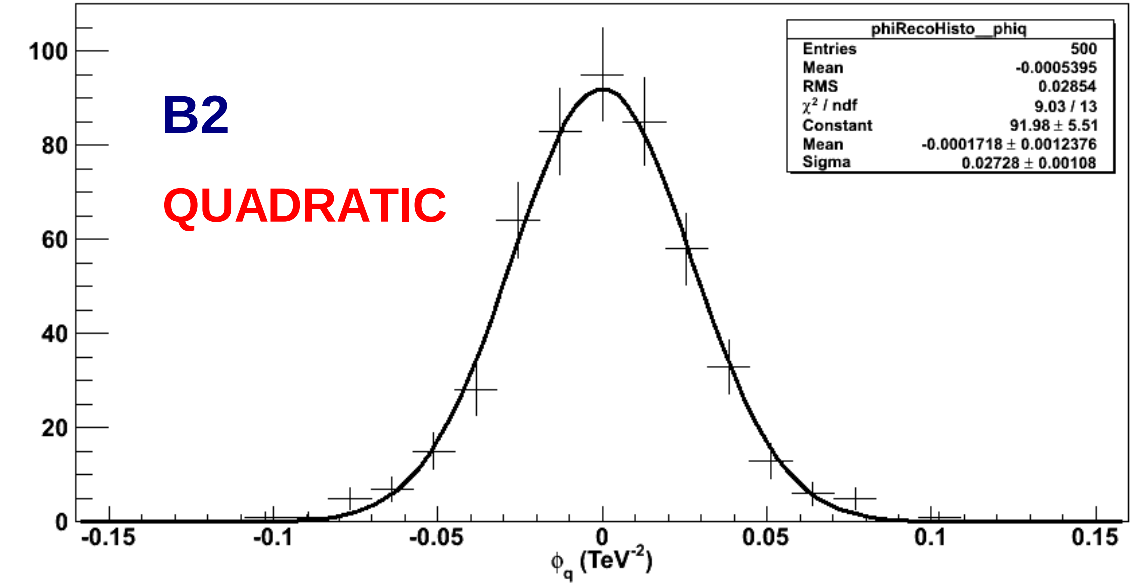
Backup slides

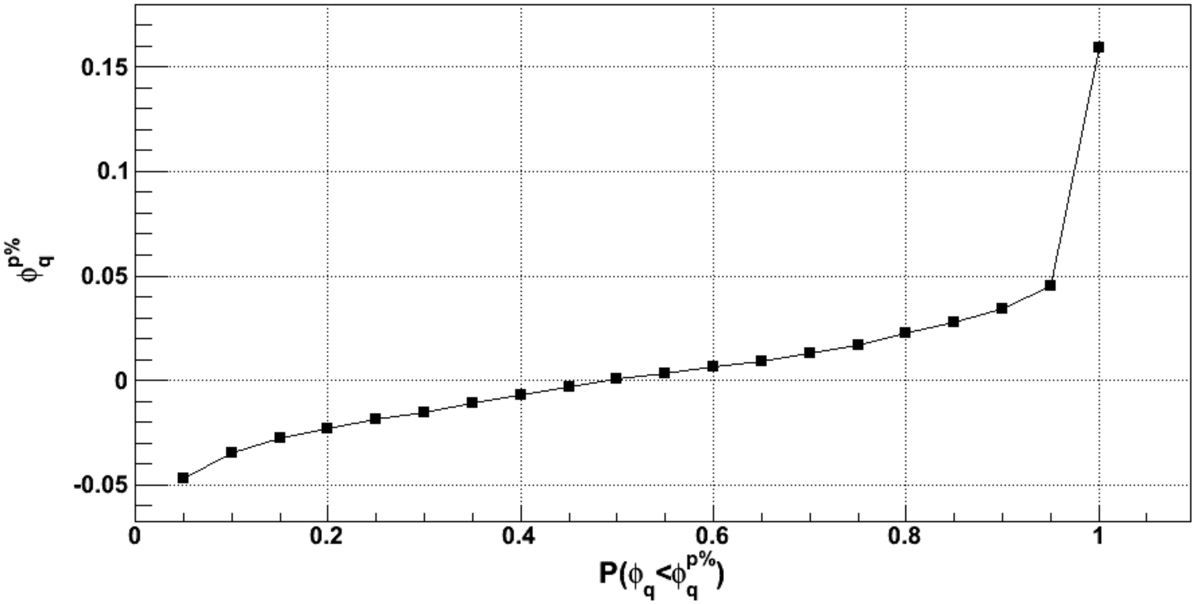
Distribution of reconstructed phase lag (no LIV)



Backup slides

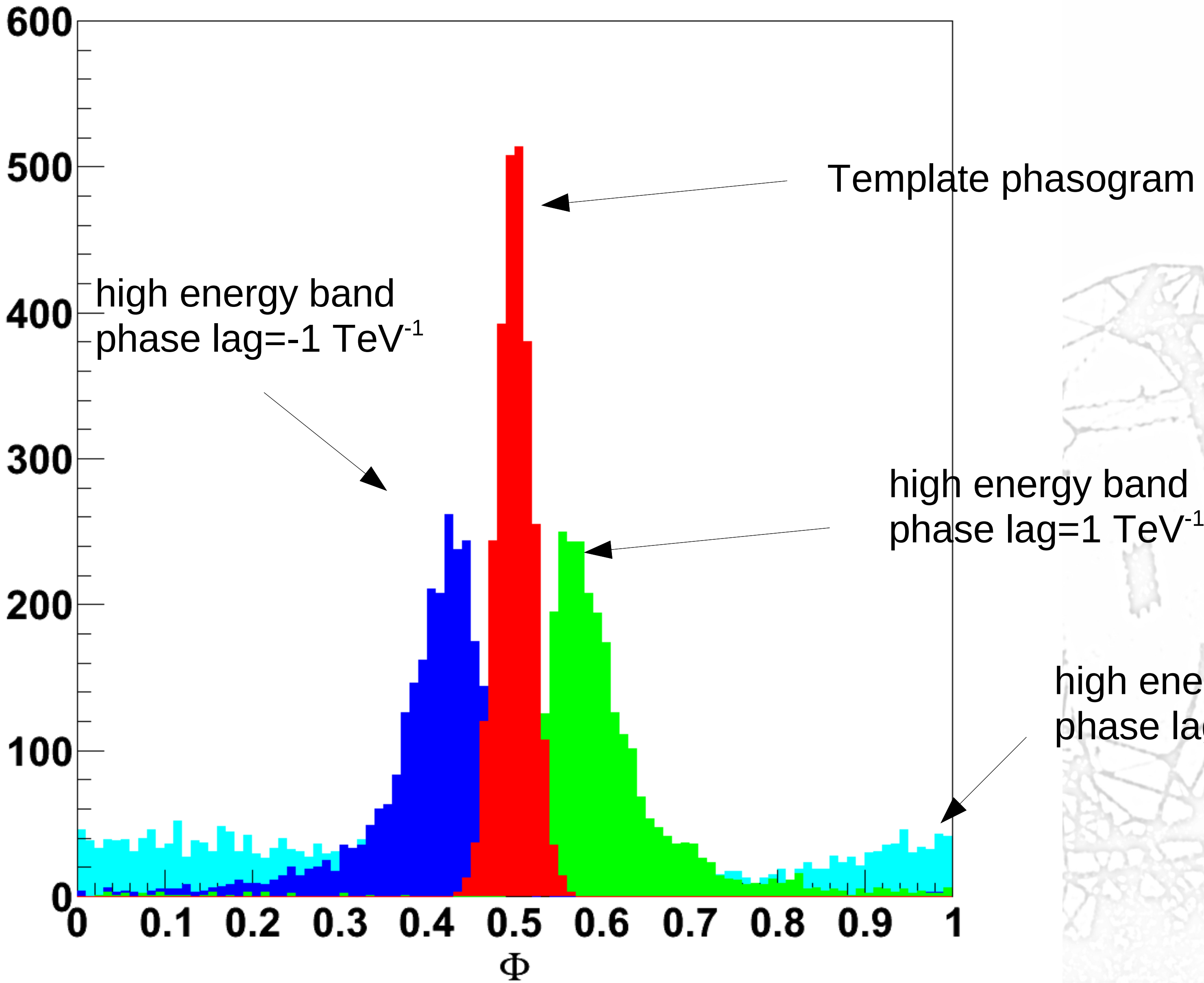
Distribution of reconstructed phase lag (no LIV)





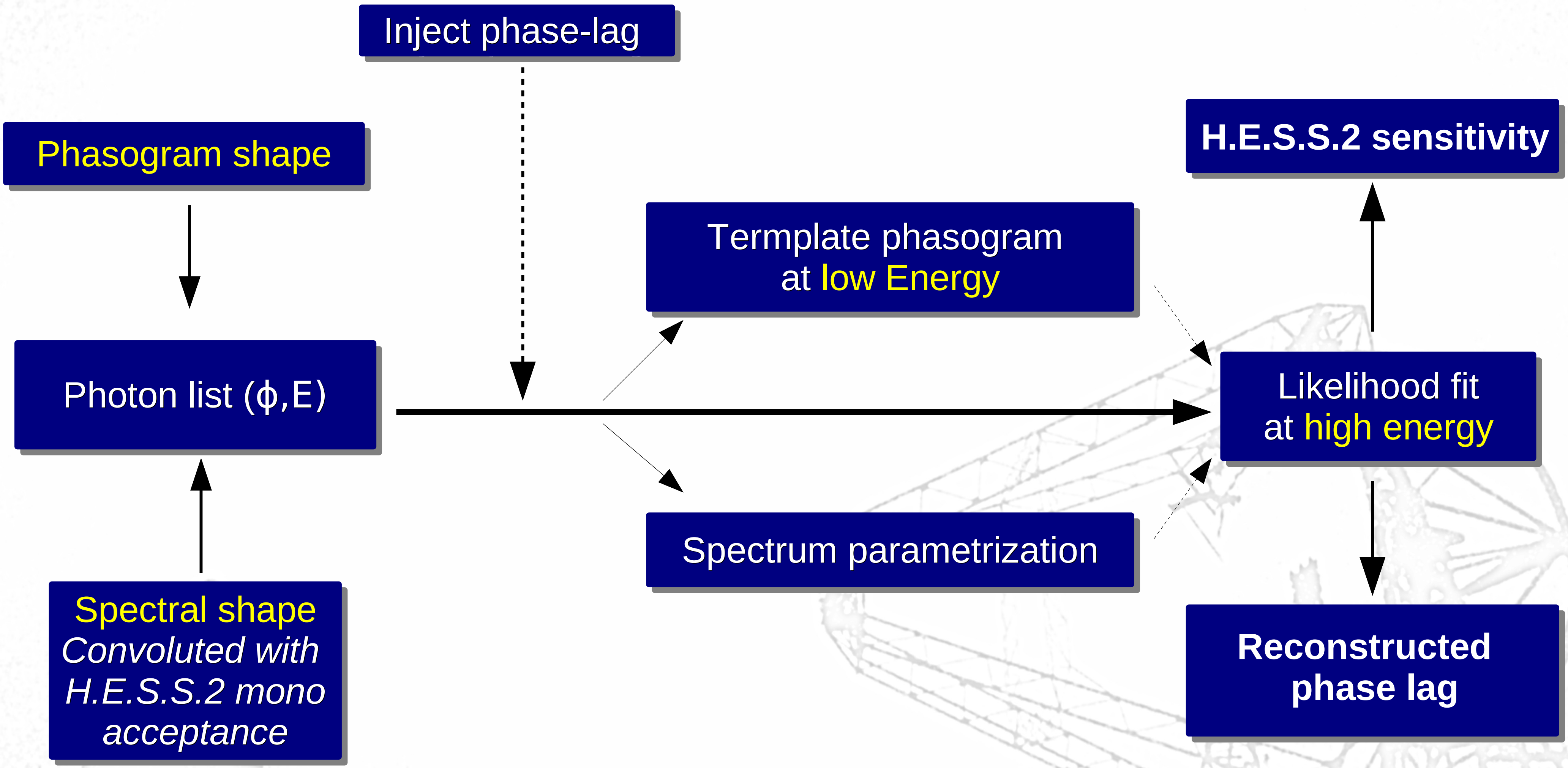
Backup slides

Effect of LIV on phasogram



Backup slides

Toy Monte Carlo (pulsars)



- Generate 500 realizations.
- Inject phase-lag parameter from -0.05 to 0.05 TeV^{-1} ($^{-2}$).
- 2 energy intervals: low energy (30 – 55 GeV) and high energy (55 GeV – 1 TeV)

Backup slides
Pulsar candidates for HESS II

Name (PSR)	zenith_{culm} (°)	$\log10(F_{10-100GeV})$ ($cm^{-2}s^{-1}$)	$\log10(F_{1-100GeV})$ ($cm^{-2}s^{-1}$) [2]	$\Delta\beta$
J0835-4510*	22	-8.01	-5.87	—
J1709-4429	21	-8.63	-6.72	3.20-3.70
J1809-2332	0	-9.28	-7.16	3.50-3.70
J1907+0602	29	-9.47	-7.42	2.90-3.50
J1826-1256	10	-9.51	-7.27	3.00-3.60
J1732-3131	8	-9.57	-7.43	3.10-3.50
J1833-1034	13	-9.63	-7.99	2.30-2.70
J0633+0632	30	-9.72	-7.81	3.00-3.10
J1614-2230	1	-10.11	-8.34	2.60-2.70
J2124-3358	11	-10.16	-8.13	2.10-2.30

Table 1: Top-ten list of the best candidates to reach 5σ in 100 hours for observation zenith angles $<30°$. The columns represent (by left-right order): the source culmination zenith angle, the logarithm of the energy flux between 1 and 100 GeV ($F_{1-100\,GeV}$ for Crab pulsar is 1.8×10^{-7} $cm^{-2}s^{-1}$) and the range of values in β allowed in our simulation for each pulsar. The asterisk (*) following Vela pulsar's name indicates that it is the top-ten list besides of having a strong indication of an exponential cut-off at high energies, since it is the most energetic one in the Southern hemisphere.

Backup slides

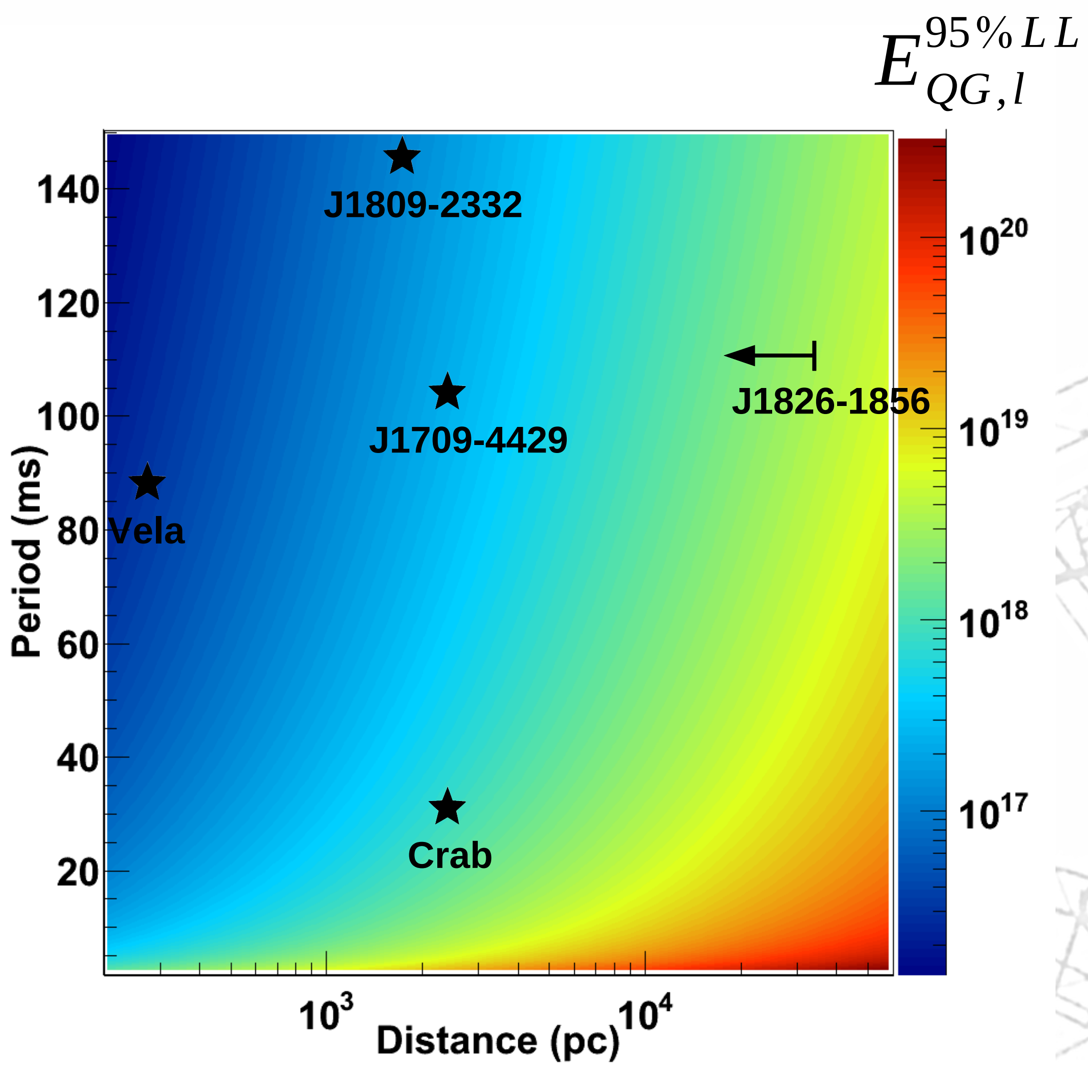
6 Fermi millisecond pulsars

Pulsar name	l, b	P (ms)	d (pc)	Log $\dot{E}$ (ergs s^{-1})	δ	Δ	Photon flux >0.1 GeV (10^{-8} photons cm^{-2} s^{-1})	Energy flux >0.1 GeV (10^{-11} ergs cm^{-2} s^{-1})	Spectral index	Exponential cutoff energy (GeV)	η (%)
J0030+0451	113.1°, −57.6°	4.865	300 ± 90	33.54	0.16	0.45	5.5 ± 0.7	4.9 ± 0.3	1.3 ± 0.2	1.9 ± 0.4	15 ± 9
J0218+4232 (b)	139.5°, −17.5°	2.323	2700 ± 600*	35.39	0.50	—	5.6 ± 1.3	3.5 ± 0.5	2.0 ± 0.2	7 ± 4	13 ± 6
J0437−4715 (b)	253.4°, −42.0°	5.757	156 ± 2	33.46	0.45	—	4.4 ± 1.0	1.9 ± 0.3	2.1 ± 0.3	2.1 ± 1.1	1.9 ± 0.3
J0613−0200 (b)	210.4°, −9.3°	3.061	480 ± 140	34.10	0.42	—	3.1 ± 0.7	3.1 ± 0.3	1.4 ± 0.2	2.9 ± 0.7	7 ± 4
J0751+1807 (b)	202.7°, 21.1°	3.479	620 ± 310	33.85	0.42	—	2.0 ± 0.7	1.7 ± 0.2	1.6 ± 0.2	3.4 ± 1.2	11 ± 11
J1614−2230 (b)	352.5°, 20.3°	3.151	1300 ± 250*	33.7	0.20	0.48	2.3 ± 2.1	2.5 ± 0.8	1.0 ± 0.3	1.2 ± 0.5	100 ± 80
J1744−1134	14.8°, 9.2°	4.075	470 ± 90	33.60	0.85	—	7.1 ± 1.4	4.0 ± 1.0	1.5 ± 0.2	1.1 ± 0.2	27 ± 12
J2124−3358	10.9°, −45.4°	4.931	250 ± 125	33.6	0.85	—	2.9 ± 0.5	3.4 ± 0.3	1.3 ± 0.2	2.9 ± 0.9	6 ± 6

A. A. Abdo *et al.*
Science **325**, 848 (2009);

Backup slides

Sensitivity (linear correction)

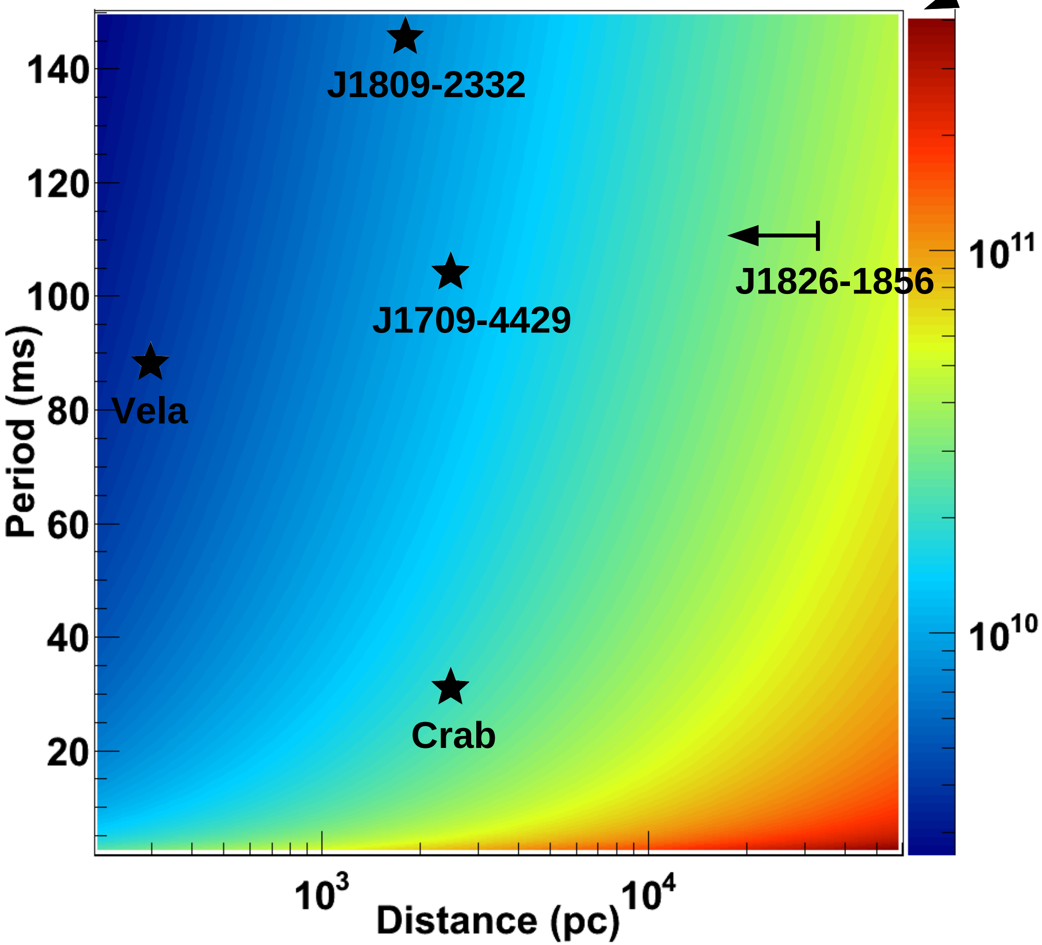


B2: S/B=1

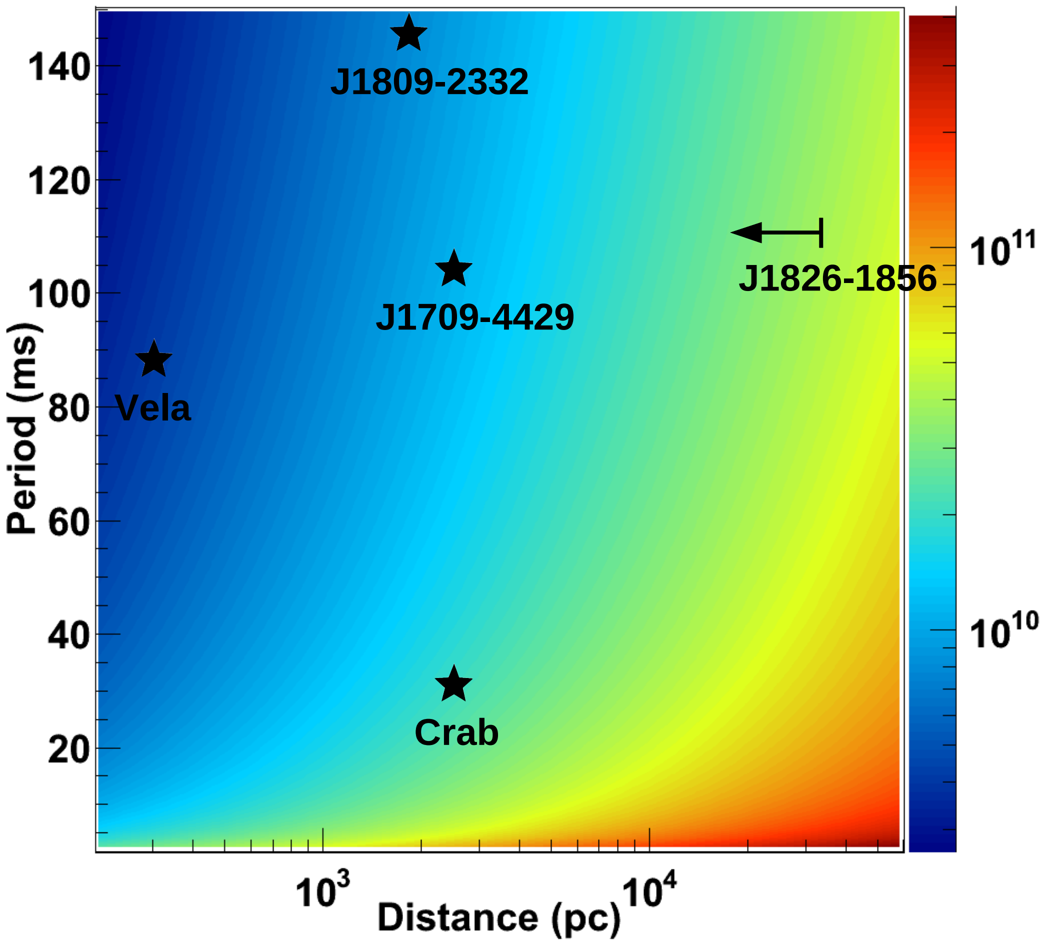
Backup slides

Quadratic term

$E_{QG,q}^{95\% \, LL}$



B1: S/B=∞



B2: S/B=1

Backup slides

Distinguish between LIV and source intrinsic delays

- **LIV delay**:
  - P(t)=P+ dP/dt t and ΔΦ(t)=Δt/P(t) in pulsar frame
  - ΔΦ decreases with time for LIV delays.
- **Source Intrinsic delay:**
  - ΔΦ=Constant in pulsar frame (if not correlated with period increase)
  - No change with time