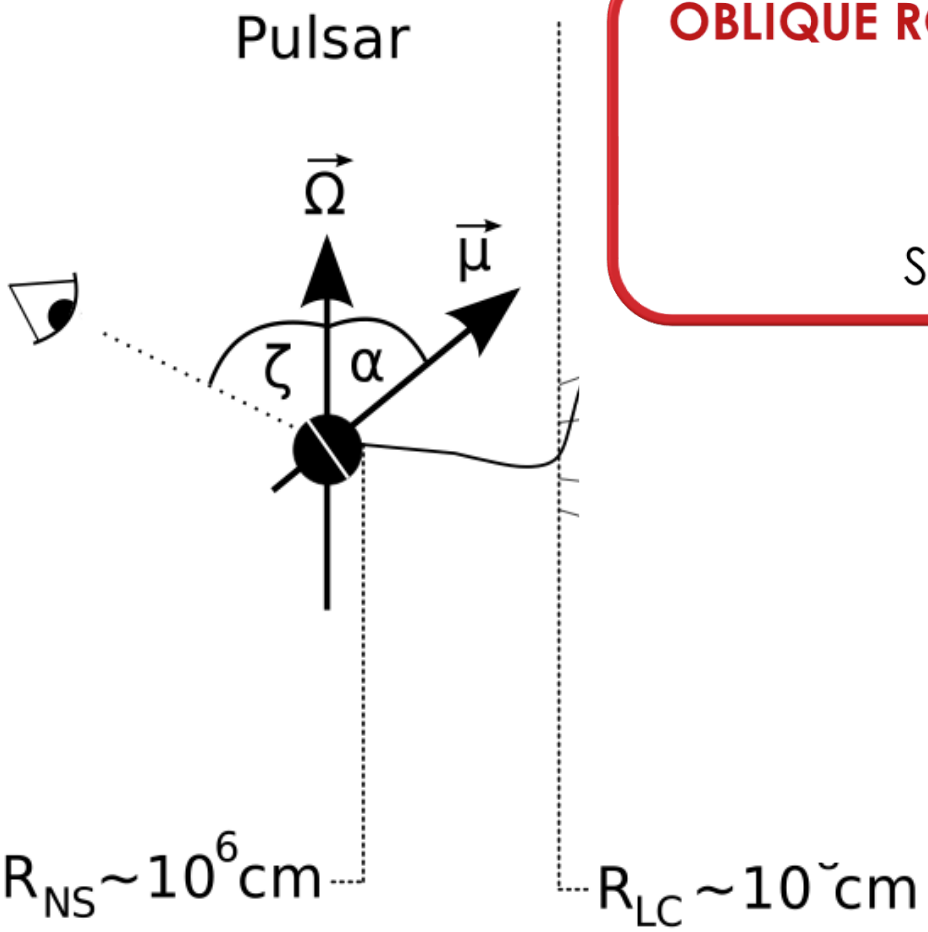
Pulsars and PWN in gamma rays

Roberta Zanin (MPIK, Heidelberg)

Outline

- State of the art knowledge of the pulsars and their environments
- Why to look at them at high energies?
- What did we learn about pulsars in the last years?
- What did we learn about PWN in the last years?

Pulsar



OBLIQUE ROTATOR IN A MAGNETIC DIPOLE FIELD

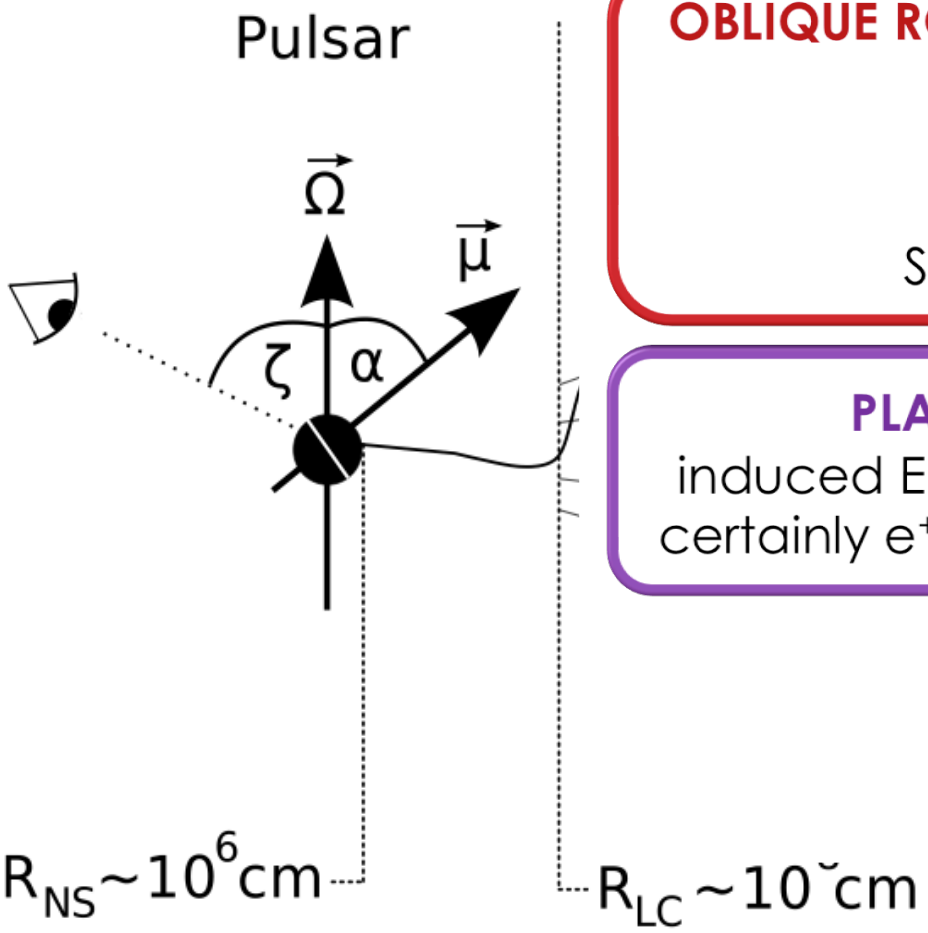
Goldreich+ 69

α→ intrinsic physics

ζ-> observed properties

So easy? everything known?

Pulsar



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PLASMA-FILLED MAGNETOSPHERE

induced E extract charges from the NS surface

certainly e^+/e^-, also ions? *Amato+ 02, Amato+ 06*

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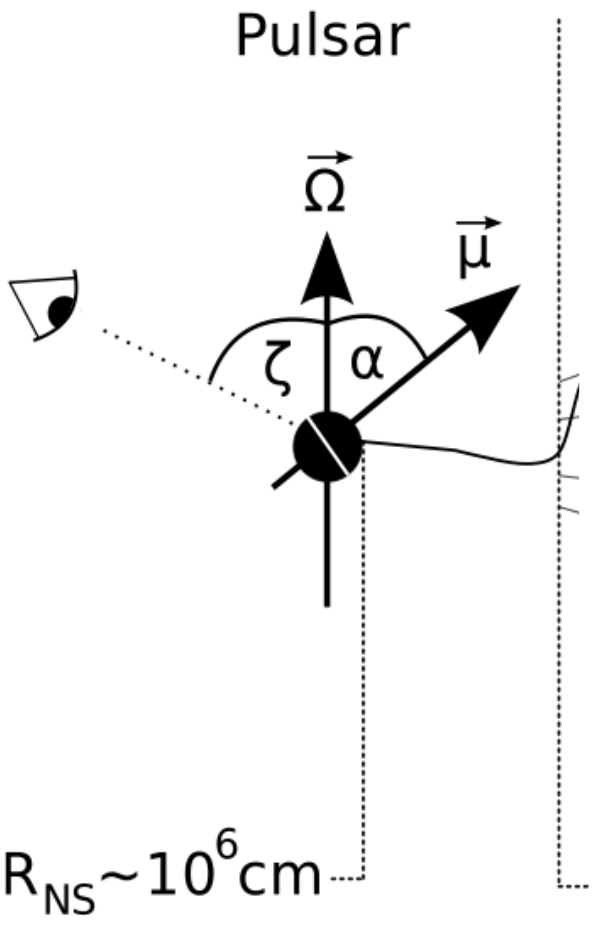

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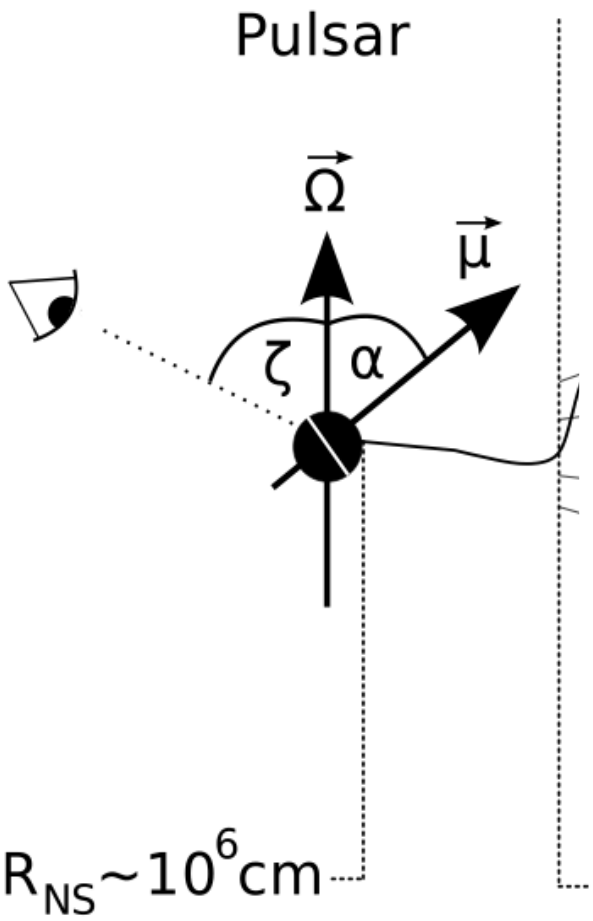
DENSE WIND due to pair production

for each e^- $10^3<k<10^7$ *Arons 2012*

Pulsar



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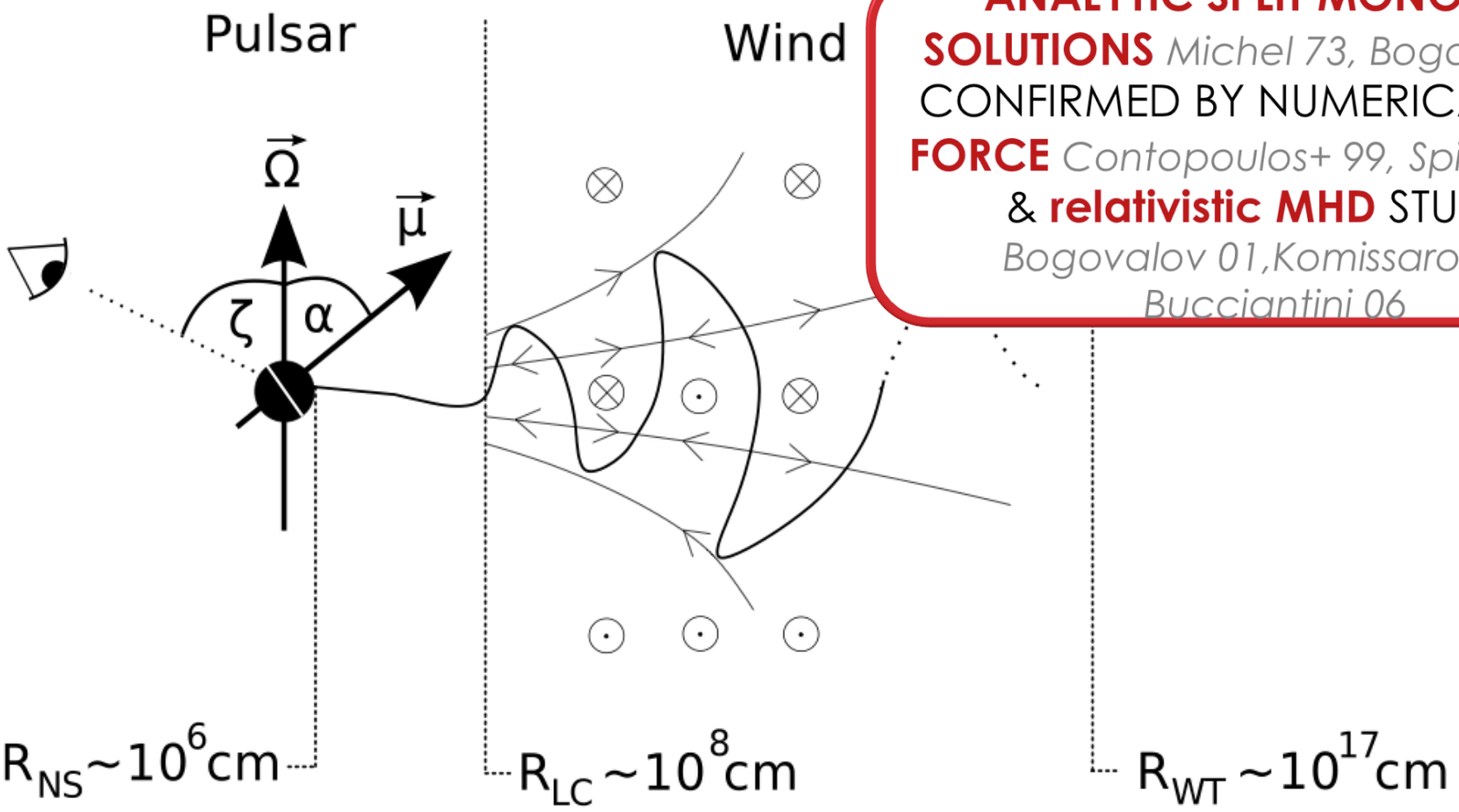
PARTICLE ACCELERATED IN UNSCREENED FIELDS (gaps)

$e^-_{primary}$ (Γ~10^7) → CURVATURE (E>50MeV)

→ $e^-_{secondary}$ (Γ~10^4)

Pulsar wind



ANALYTIC SPLIT MONOPOLE SOLUTIONS *Michel 73, Bogovalov 99*
CONFIRMED BY NUMERICAL **FREE-FORCE** *Contopoulos+ 99, Spitkovsky06*
& **relativistic MHD** STUDIES
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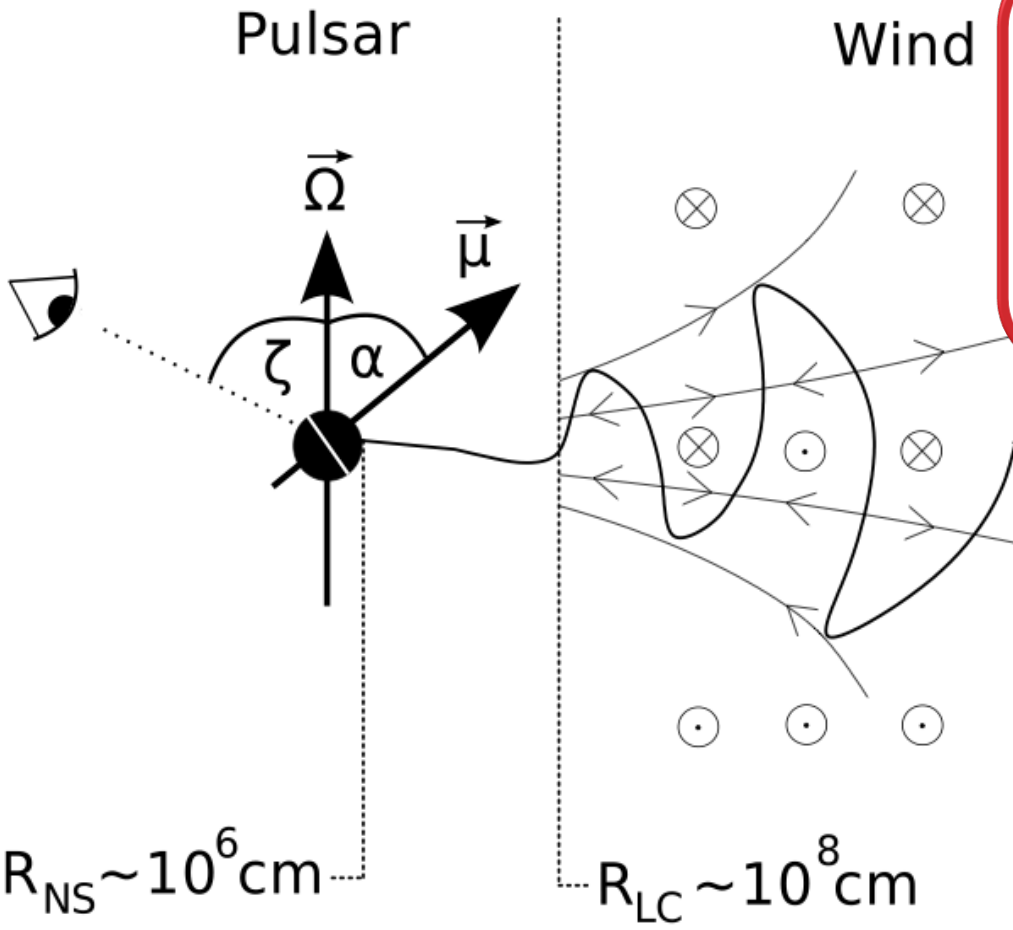

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MOST ENERGIES FLOWS AT HIGH ALTITUDES
$F \propto \sin^2(\alpha)$ *Bogovalov 99*
$F \propto \sin^4(\alpha)$ *Tchekhovsky+13,15*

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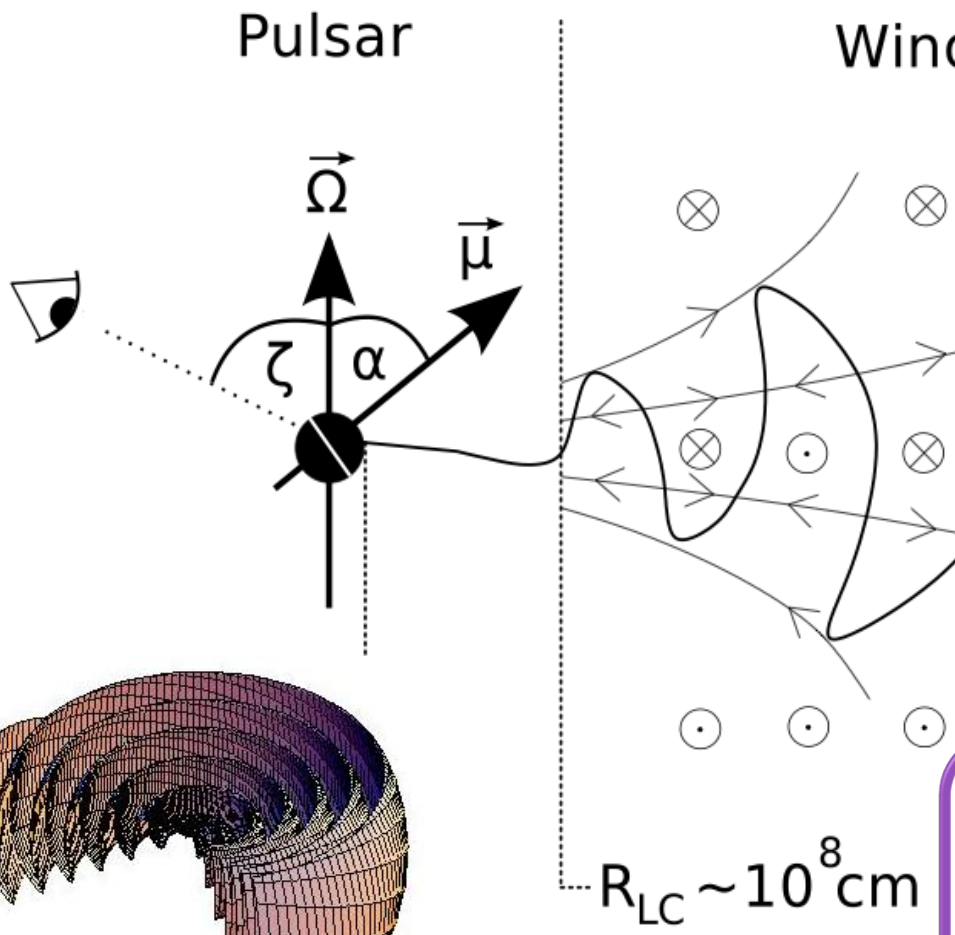

Kirk 02

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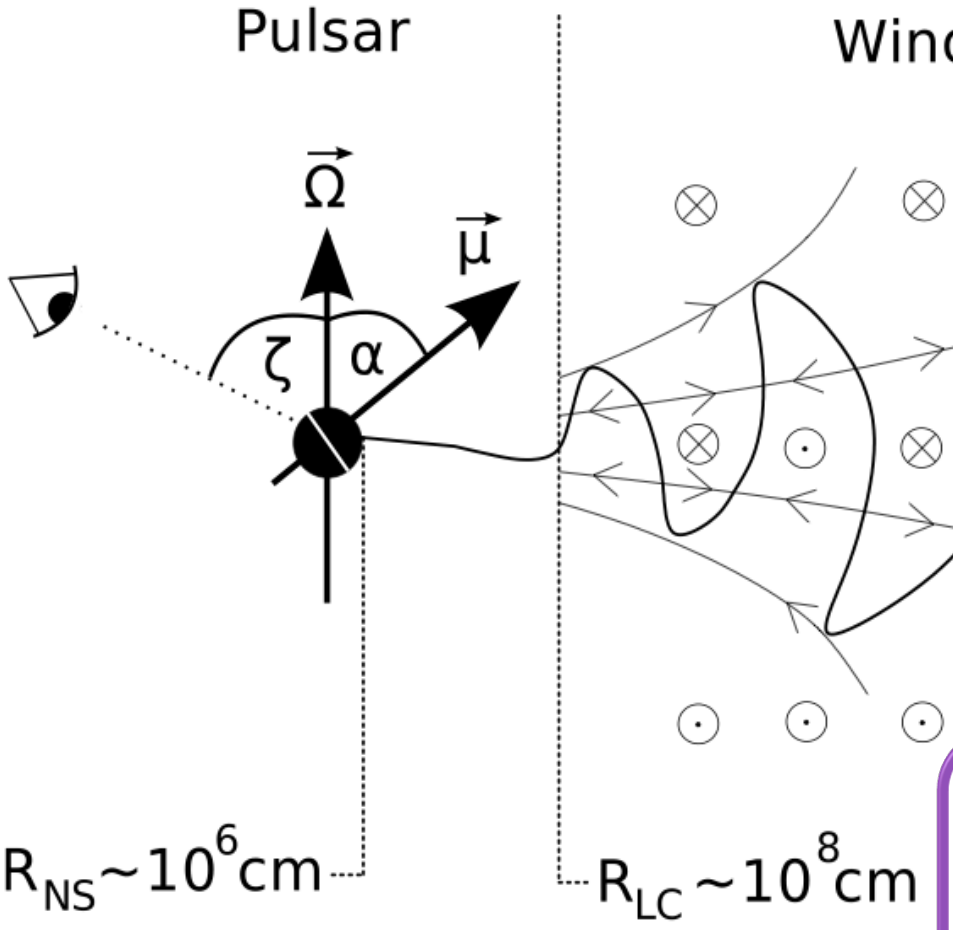
WIND IS HIGHLY MAGNETIZED (σ>>1)
WHERE MAGNETIC DISSIPATION?
STRIPED WIND → MAGNETIC RECONNECTION
Coroniti 90, Kirk 02, Sironi+ 11

Pulsar wind



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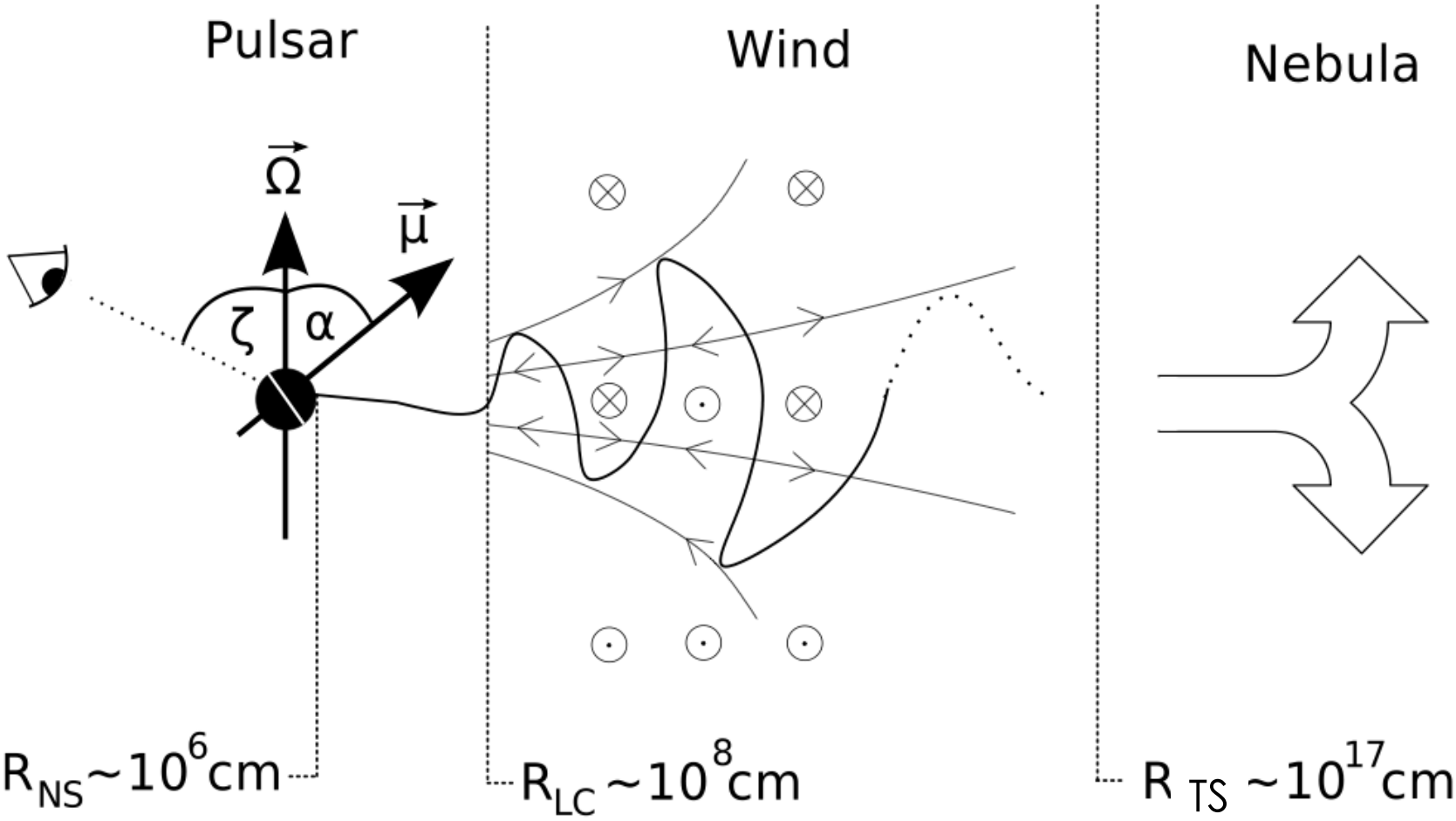
COLD RELATIVISTIC WIND
$\Gamma = 10^4$-10^6

Pulsar wind nebula



@ TS: PITCHING ANGLE RANDOMIZED & PARTICLE ACCELERATED

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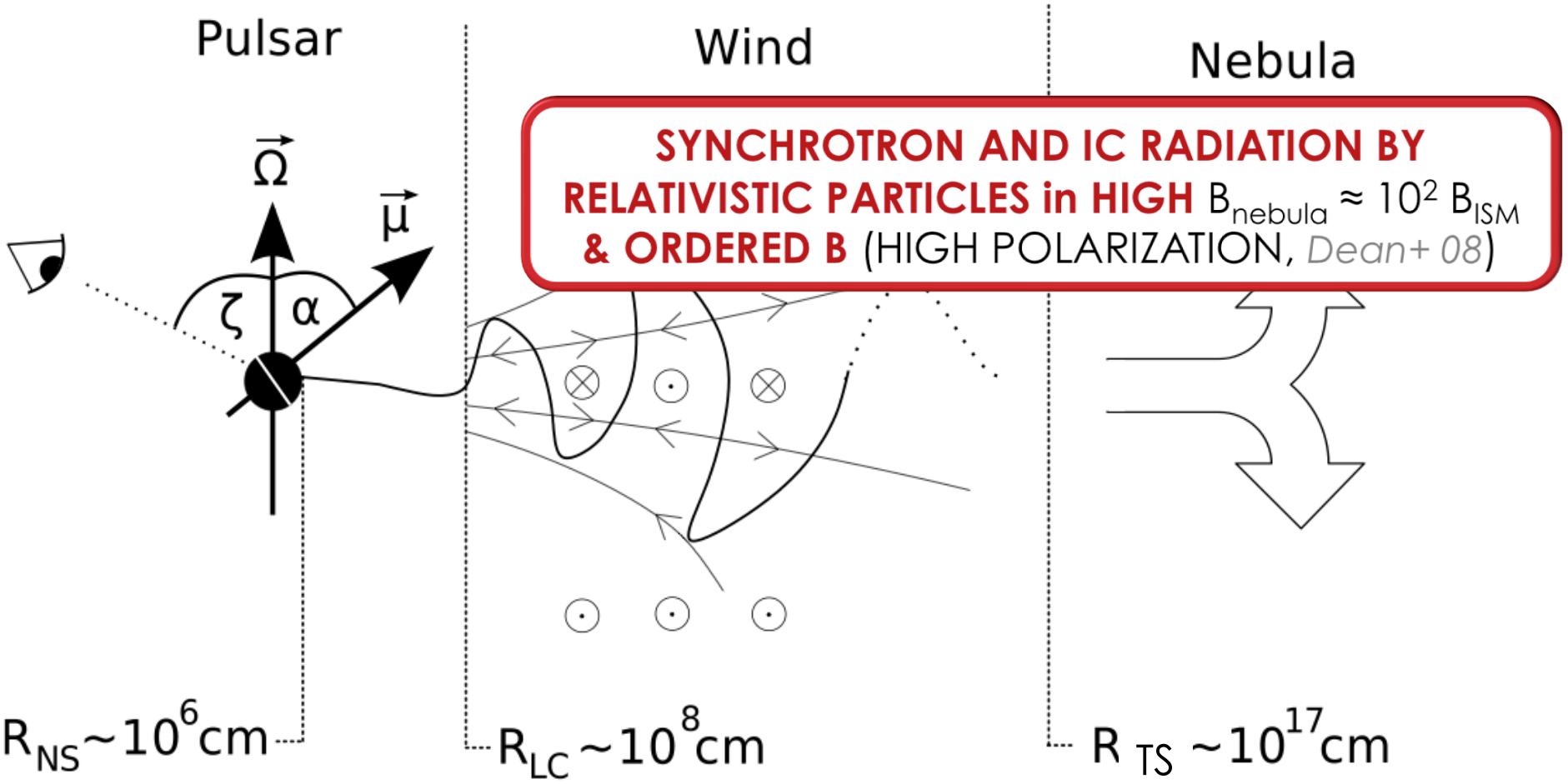

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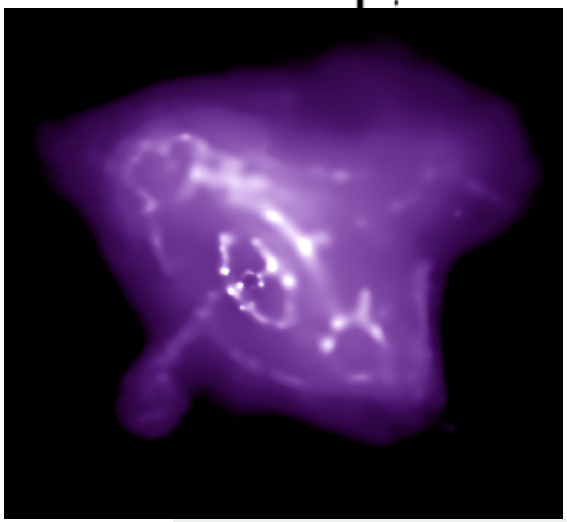


Pulsar

Wind

Nebula

$\vec{\Omega}$

$\vec{\mu}$

ζ

α

SYNCHROTRON AND IC RADIATION BY RELATIVISTIC PARTICLES in HIGH $B_{nebula} \approx 10^2 B_{ISM}$ **& ORDERED B** (HIGH POLARIZATION, *Dean+ 08*)

JET-TORUS
from spin-B misalignment (α)
Bogovalov+02, Komissarov+03, Del Zanna+04

$R_{LC} \sim 10^8$ cm

$R_{TS} \sim 10^{17}$ cm

@ TS: PITCHING ANGLE RANDOMIZED & PARTICLE ACCELERATED

Some energetics

PULSED EMISSION ONLY A FRACTION OF THE RELEASED ENERGY

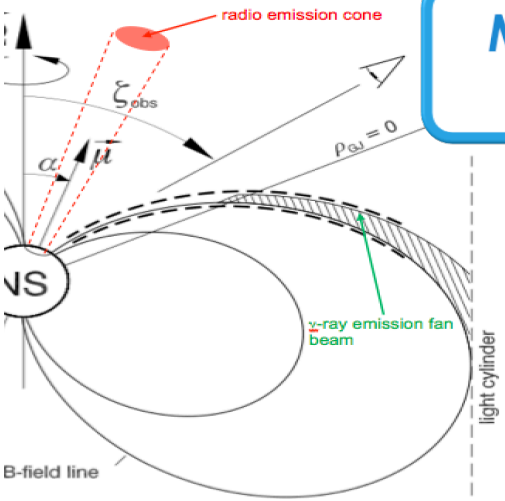
$L_{radio} \leq 10^{-10}\,\dot{E}$

$L_{\gamma} \leq 10^{-2}\,\dot{E}$

$L_{PWN} \geq 0.1\,\dot{E}$

THE ENERGY GOES TO THE PWN!!

Why high energies? Theoretically..



MAGNETOSPHERIC γ RAYS TRACK THE B STRUCTURE
HIGHEST ENERGIES OF ELECTRONS

SYNCHROTRON EMISSION
COMBINED INFO ON n_e (electron spectrum)
& B

$$L_{syn} \propto n_e B^2$$

IC EMISSION
COMBINED INFO ON n_e (electron spectrum)
& RADIATION PHOTON FIELD

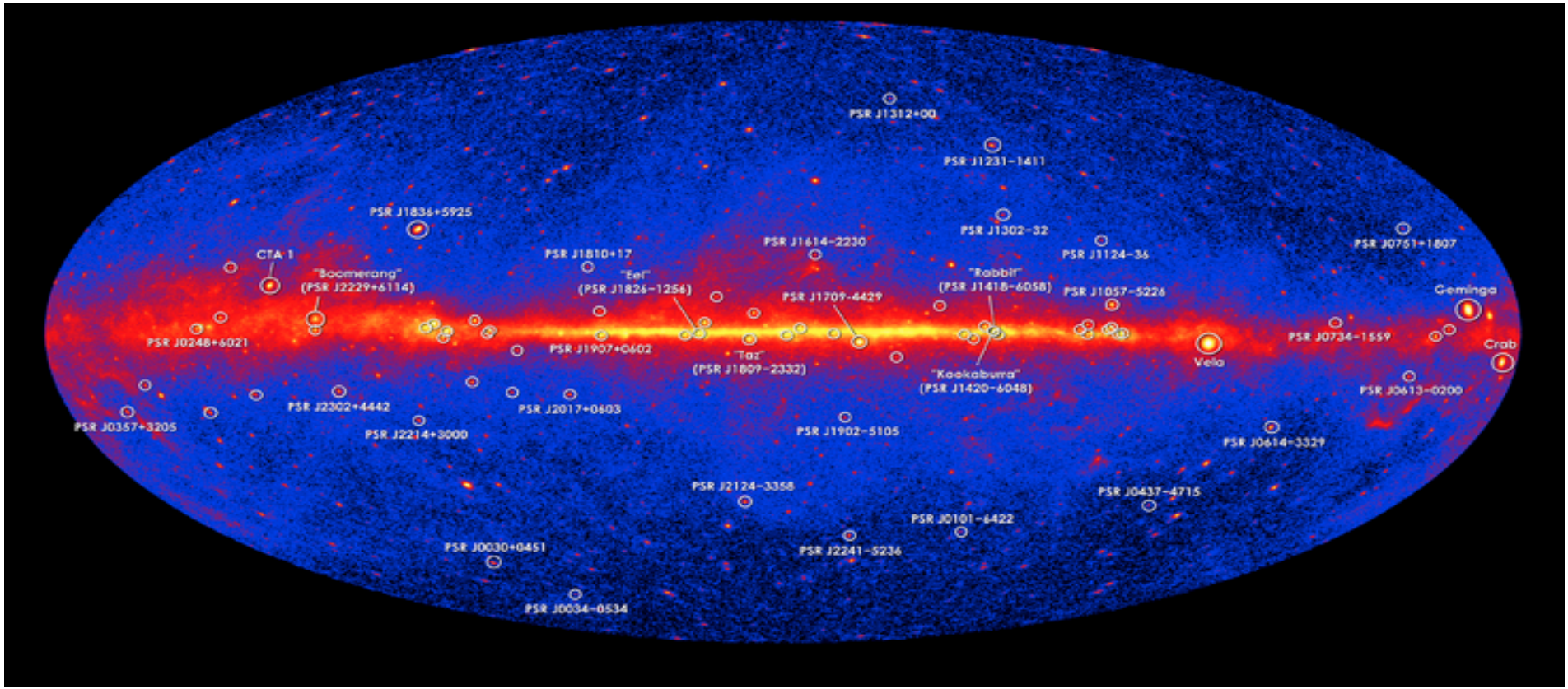
$$L_{IC} \propto n_e U_{ph}$$

PULSAR WIND DIRECT DETECTION

Why high energies? Observationally..

Caraveo 14

~ 150 γ-RAY PULSARS



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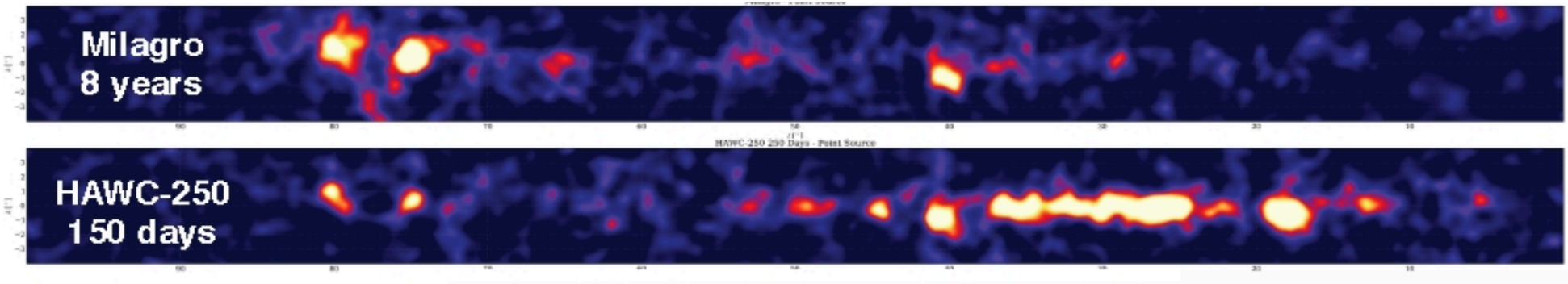
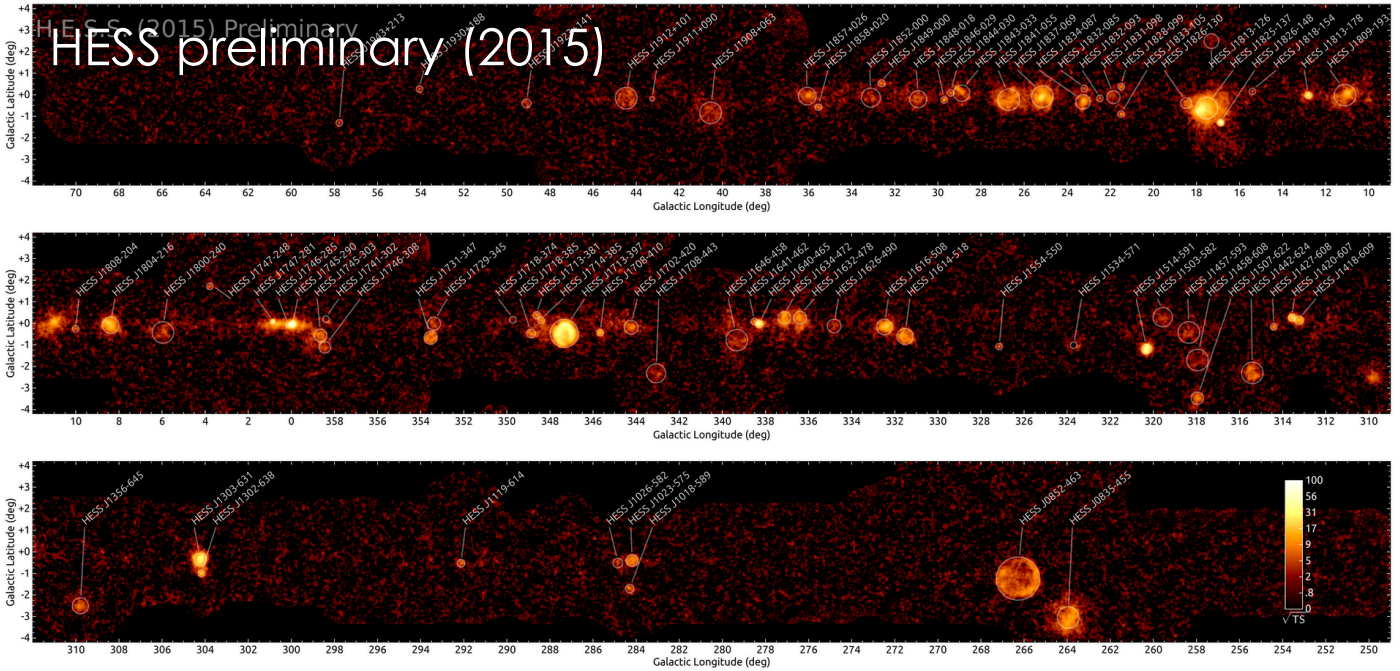


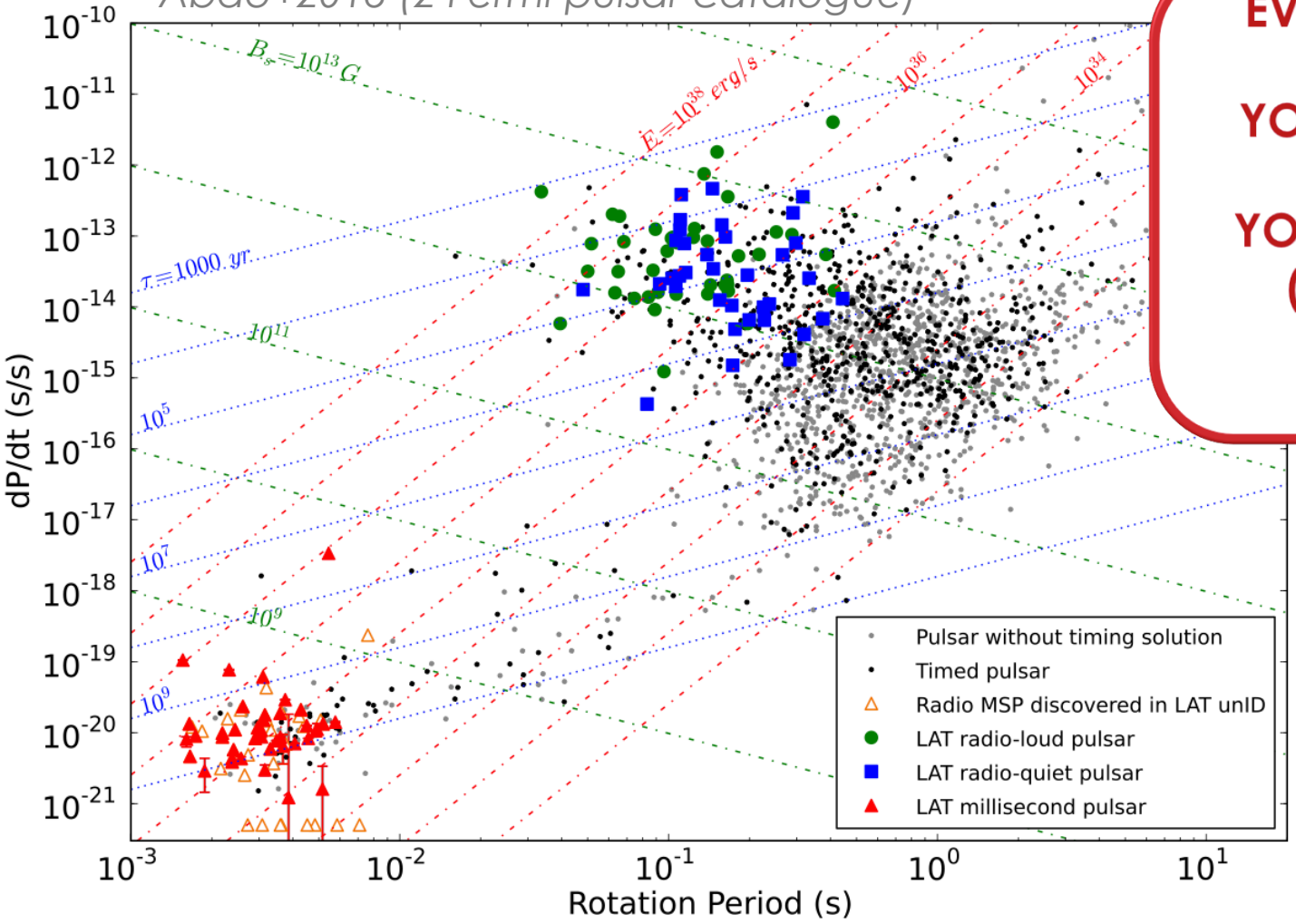


What did we learn about pulsars?

LOW ALTITUDE MODELS:
POLAR CUPS
Harding+
HIGH ALTITUDE MODELS:
OUTER GAP
Cheng 86, Romani+ 96, Hirotani 06
SLOT GAP
Harding+ 04

Three populations

Abdo+2013 (2 Fermi pulsar catalogue)



EVENLY DISTRIBUTED:

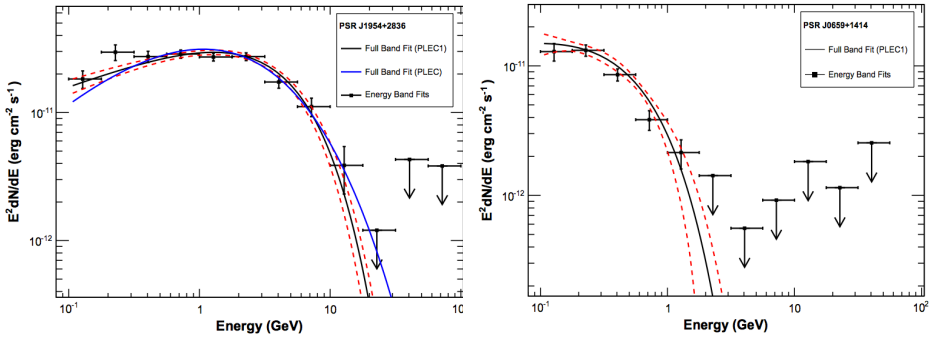
YOUNG RADIO LOUD

YOUNG RADIO-QUIET (GEMINGA-LIKE)

MSP

γ rays from outer magnetosphere

EXPONENTIAL SPECTRA CUTOFFS EVEN HARDER FOR BRIGHT PULSARS



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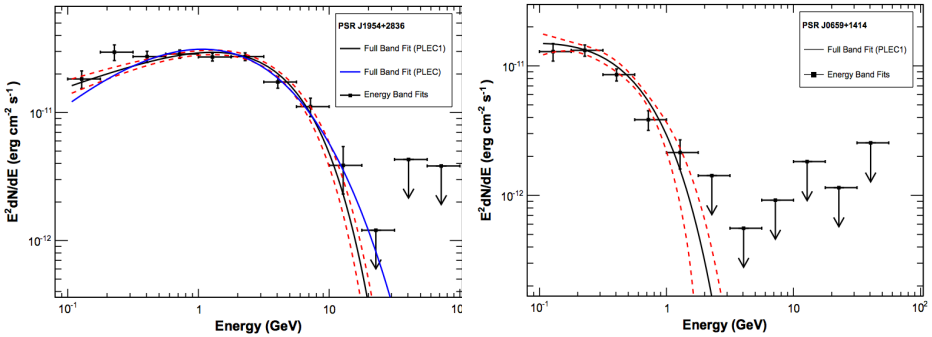
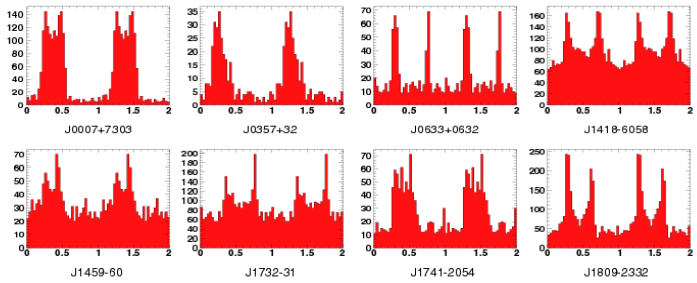


PULSE PROFILES

Watter+ 09,11, Takata+ 11, Pierbattista+ 10, 12, 15



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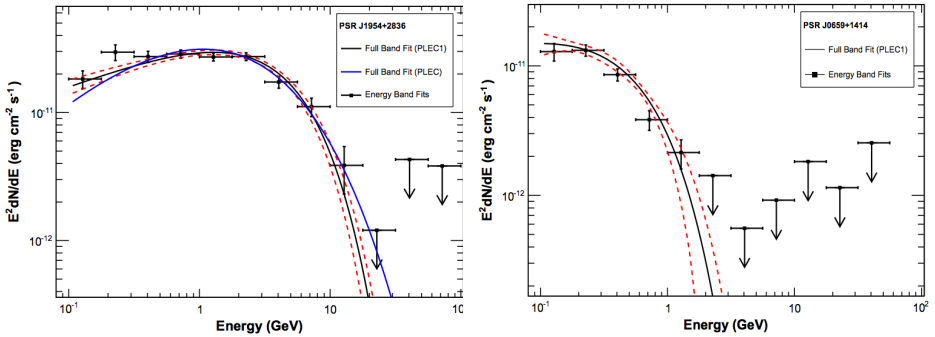
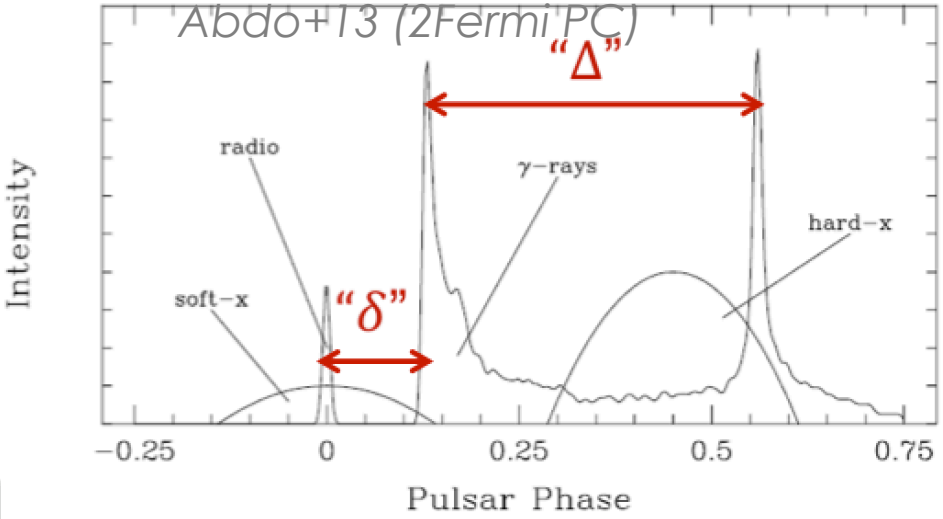


δ–Δ ANTICORRELATION

Romani+ 95

Abdo+13 (2Fermi PC)



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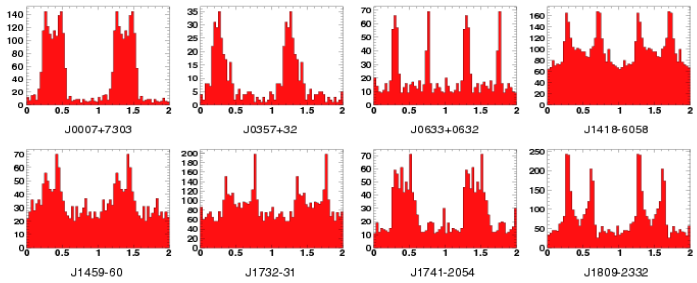

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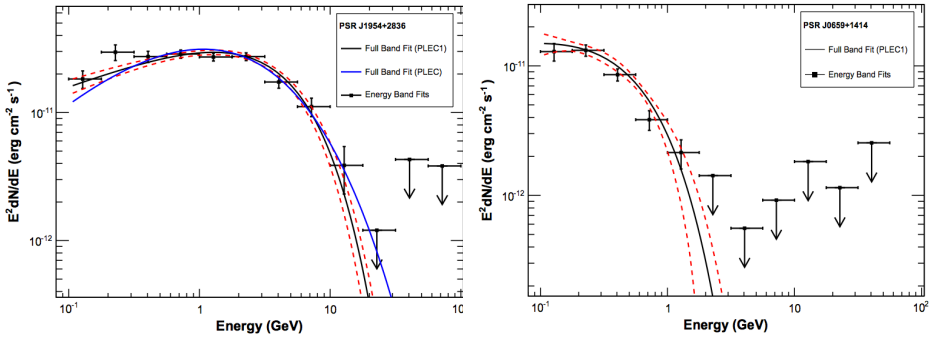

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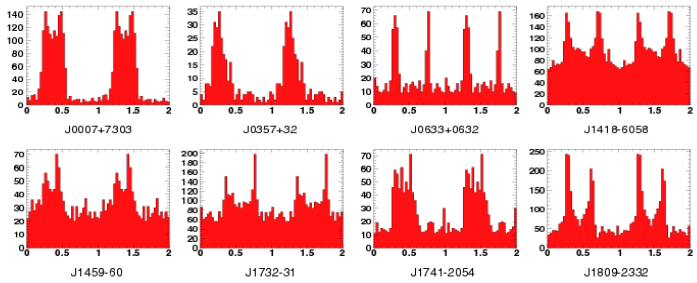

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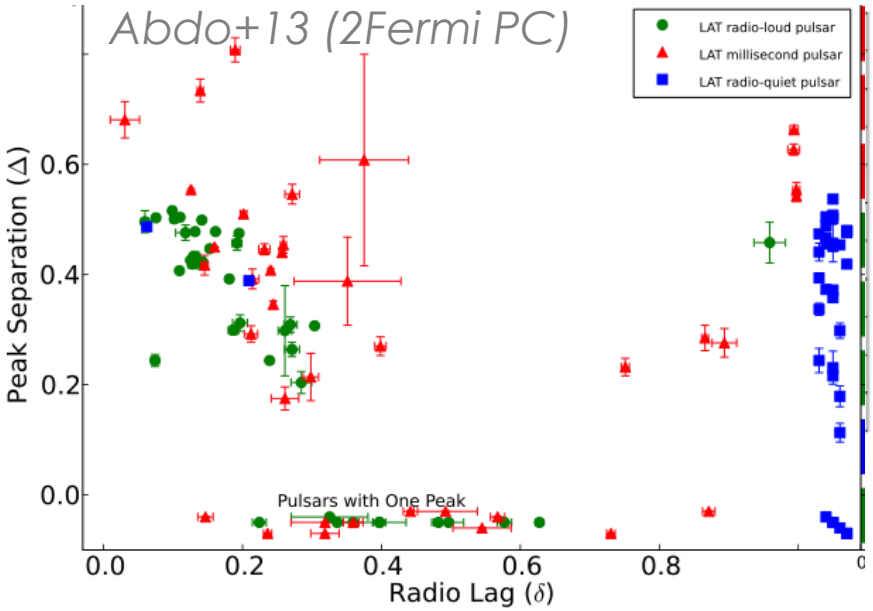

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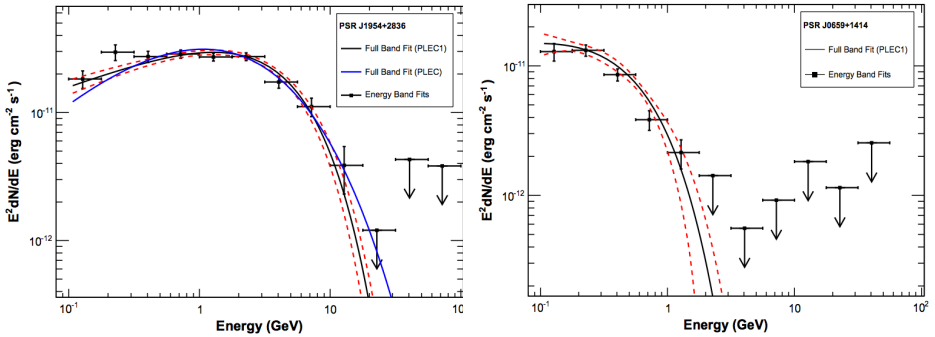

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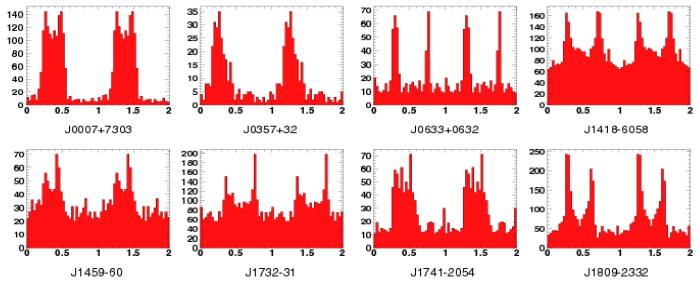

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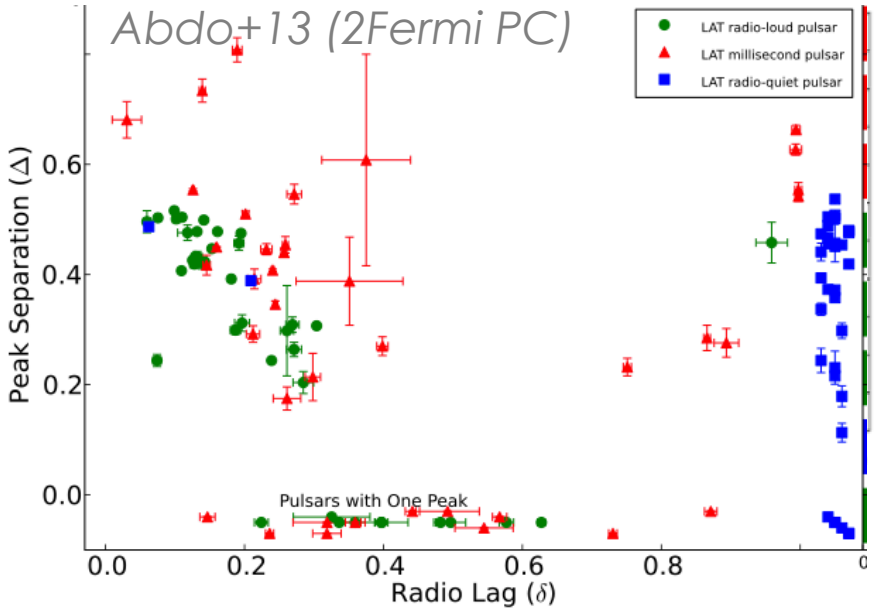
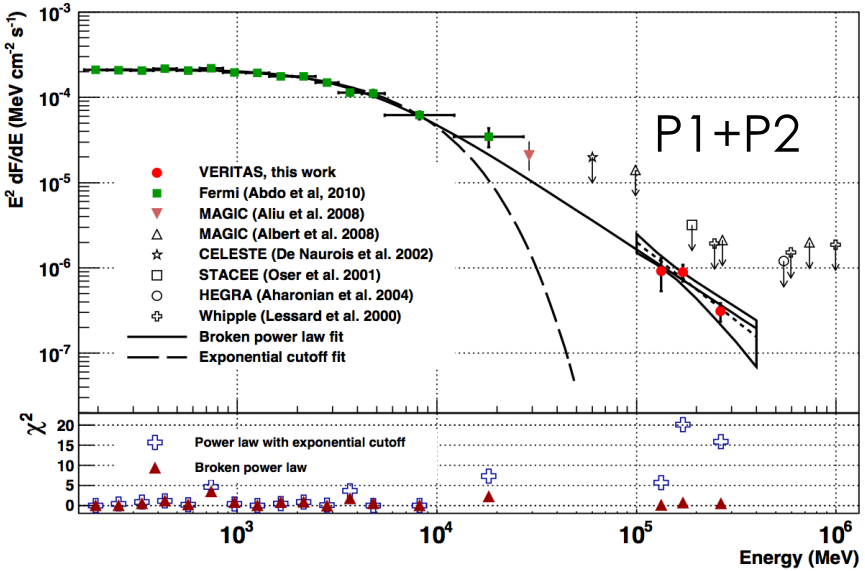


MOST OF PULSARS DO NOT SHOW DC EMISSION

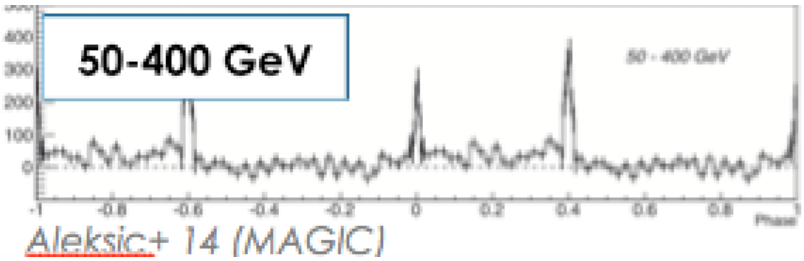
Cheng+ 86, Fermi-LAT 13

An exception(?): the Crab

Aliu+ 11 VERITAS



P1 P2



Aleksic+ 14 (MAGIC)

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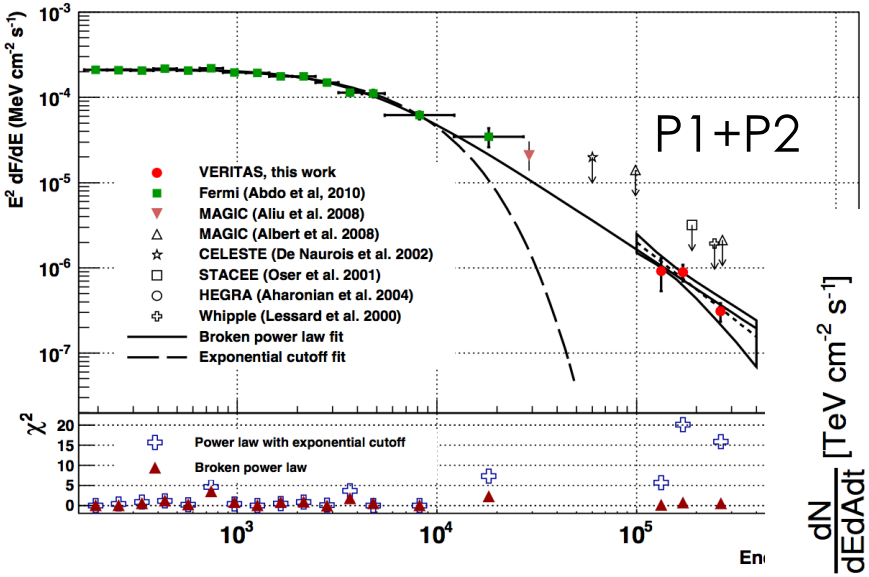
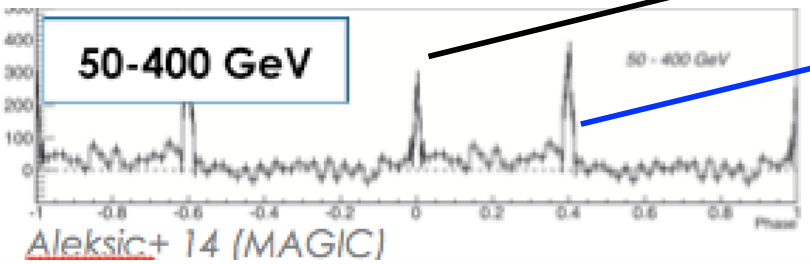


SINGLE POWER LAW FROM 0.01-1 TeV

P1 SOFTER THAN P2: $\Delta\alpha$ =0.5±0.1

P1 P2



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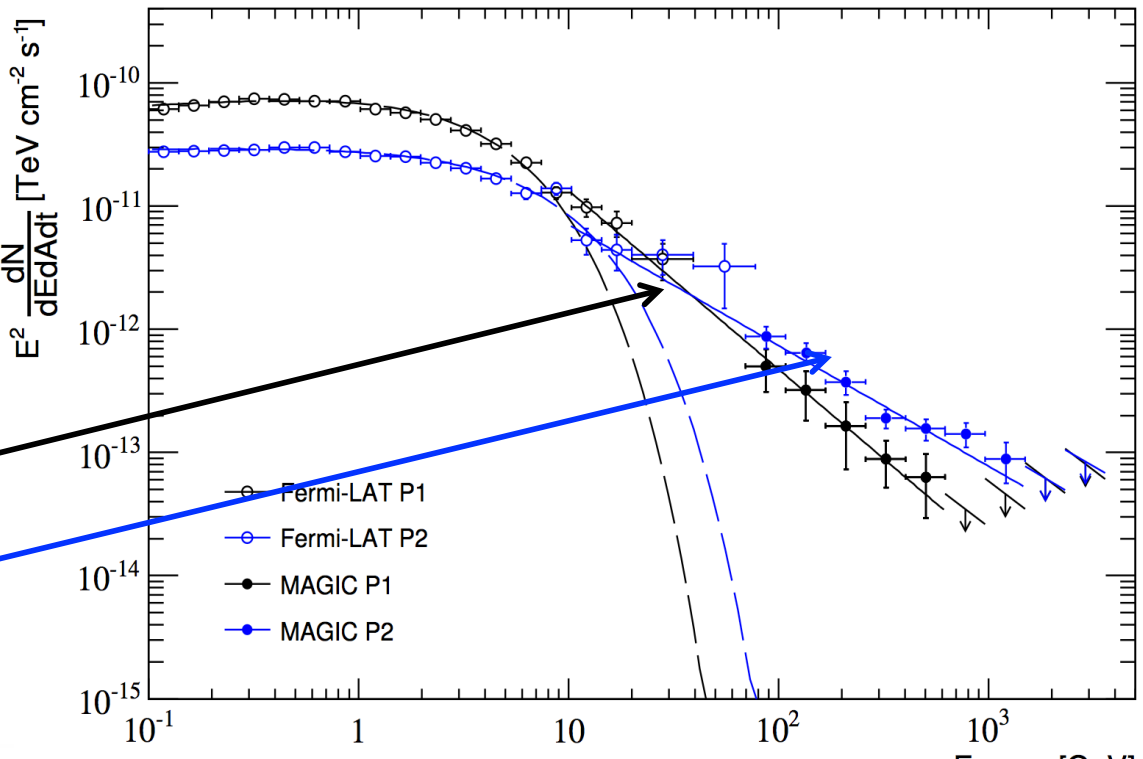

MAGIC accepted by A&A, arXiv: 1510.07048

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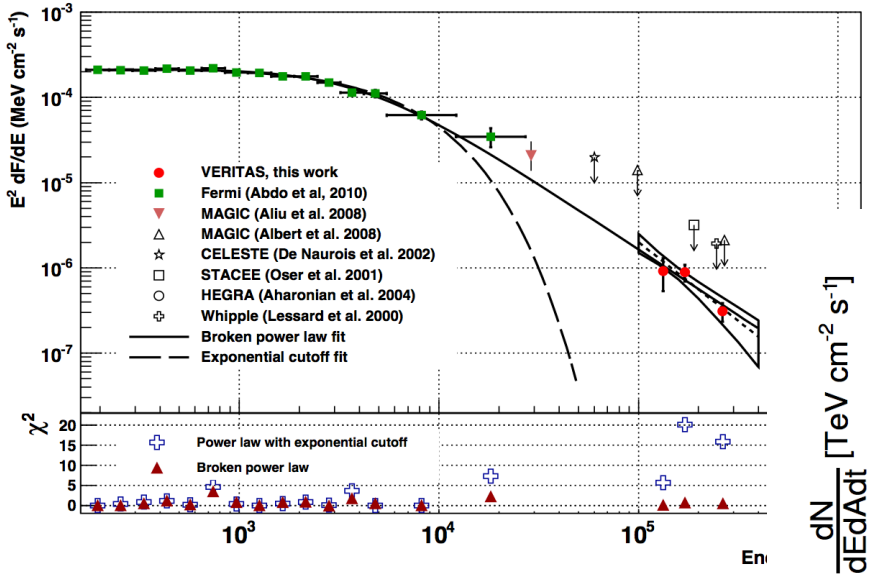

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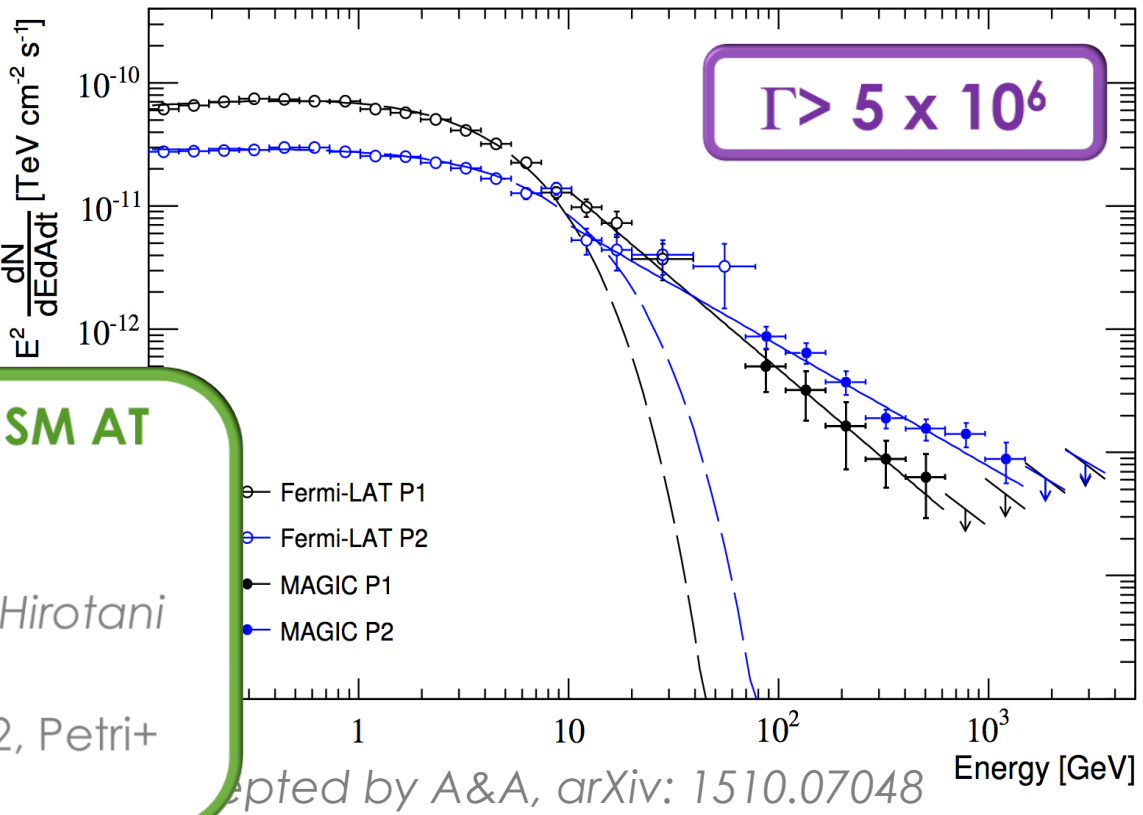


IC MOST PROBABLE MECHANISM AT WORK BUT WHERE?

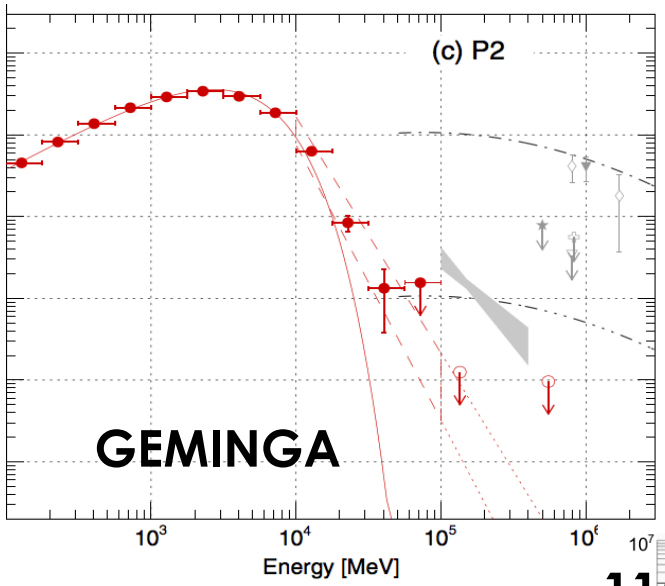
MAGNETOSPHERE *Lyutiikov+,12 Hirotani 15*

PULSAR WIND Aharonian+ 02, 12, Petri+ 2012, Mochol+ 15

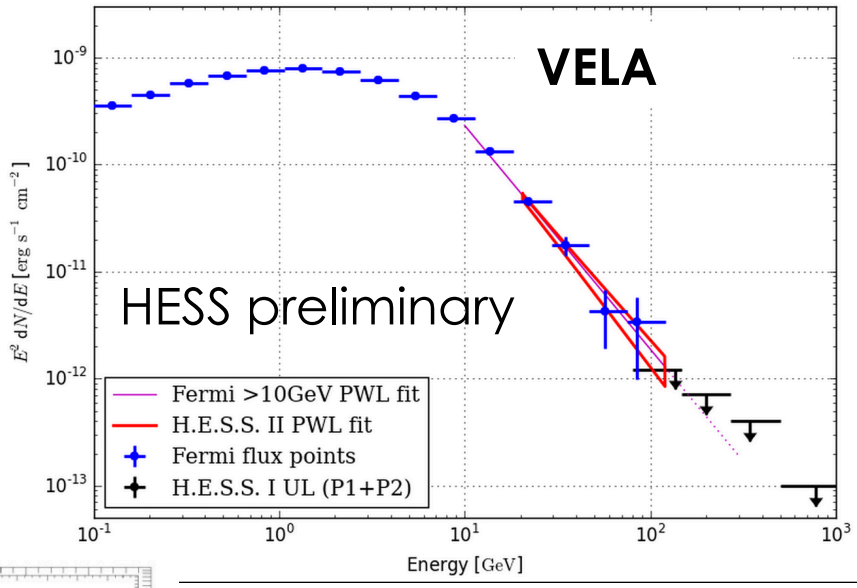
epted by A&A, arXiv: 1510.07048

Some more?

Aliu+ 15 VERITAS

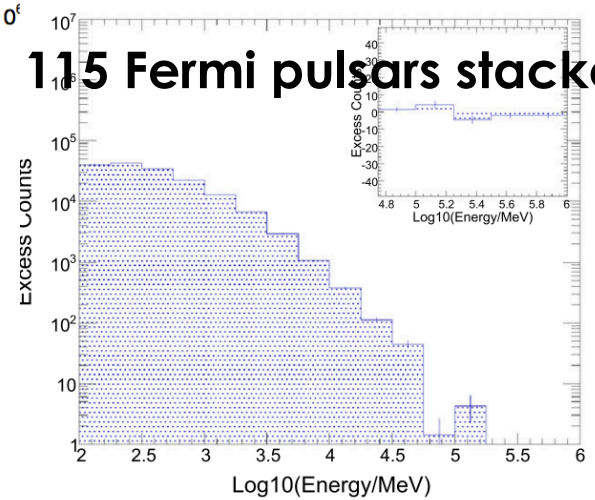


Gajdus+15



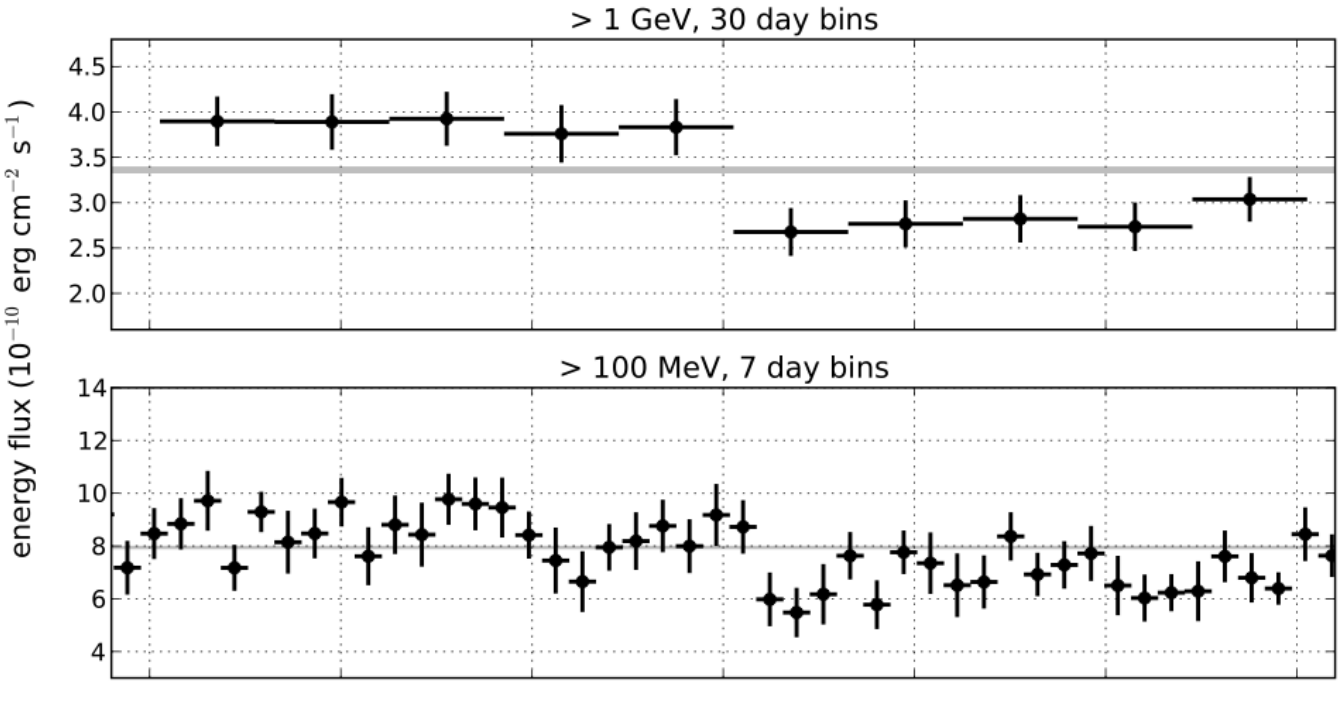
McCann+15

115 Fermi pulsars stacked



Not stable sources

PSR J2021+4026 — *Fermi-LAT 13*



FLUX DECREASE BY 20%, 5σ CHANGE IN THE PULSE PROFILE & 3σ CHANGE IN SPECTRAL VARIABILITY
CHANGE IN EMISSION BEAMING? *Fermi-LAT 13*

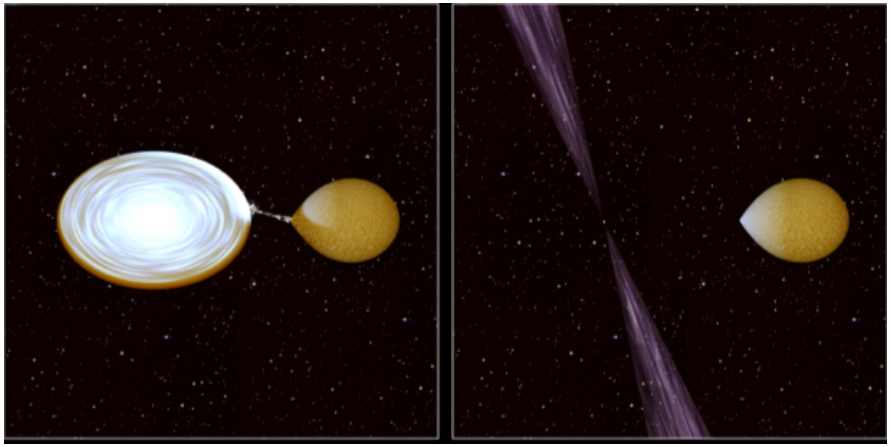
MSP: a new population

ONLY RADIO LOUD
RADIO EMISSION AT HIGHER ALTITUDES AND WIDER BEAMS
Abdo+ 13 (Fermi 2PC)

ROTATION-POWERED AND ACCRETION-POWERED SWING
Papitto+13, 14, Roy+14, Ferrigno+14, Bassa+14, Patruno+14, Archibald+15…

NEEDED AN HYBRID MODEL TO FIT MSP LC

RADIO & γ-RAY ALIGNED
RECALLING LOW ALTITUDE MODELS
Venter+ 12, Johnson+ 14

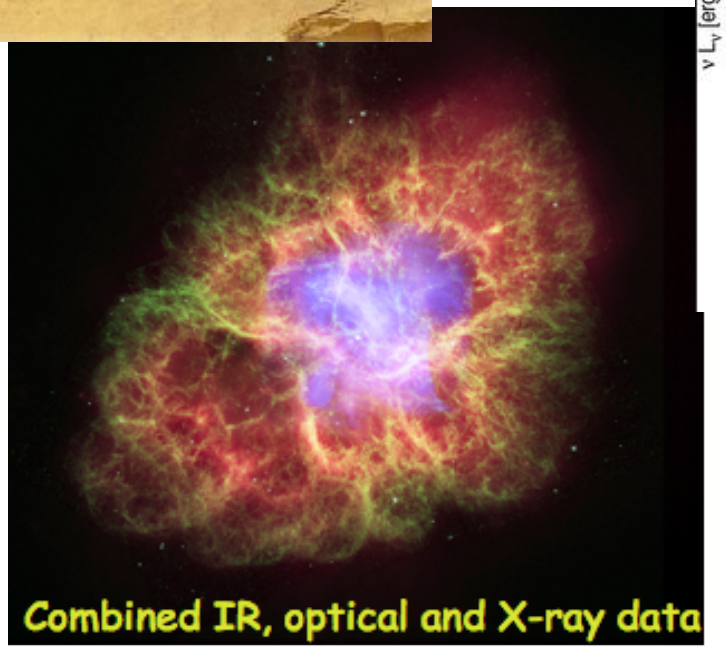


What did we learn about PWN?

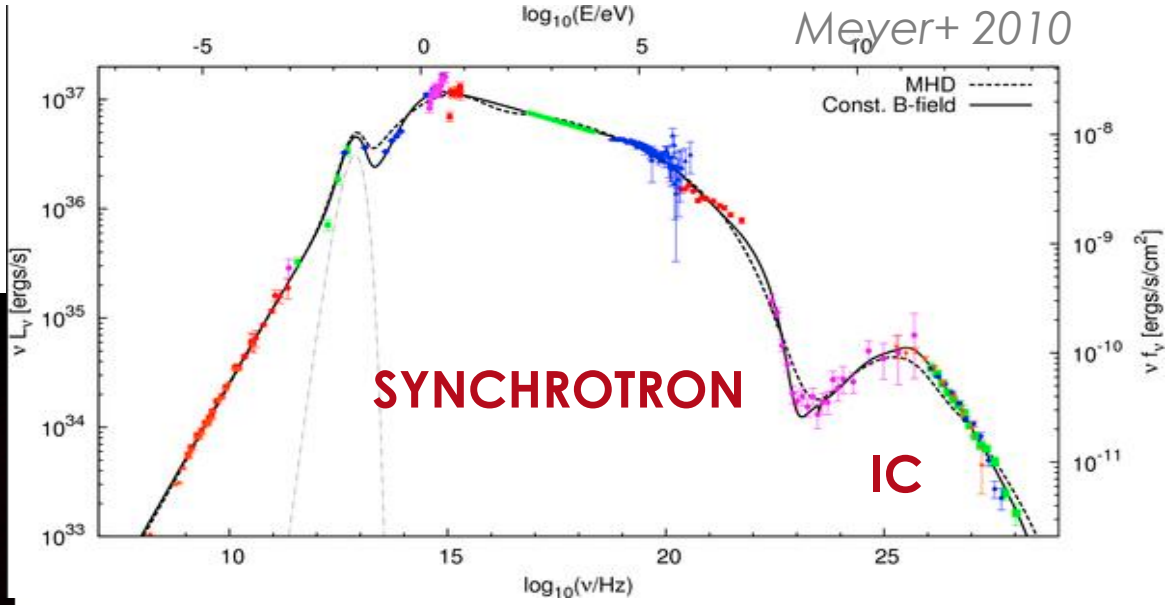
- ~100 known PWN
- 70 detected in X-ray
- 35 detected at VHE (26 in the HESS GPS)

Most of what we know from the Crab

LEFTOVER OF SN 1054



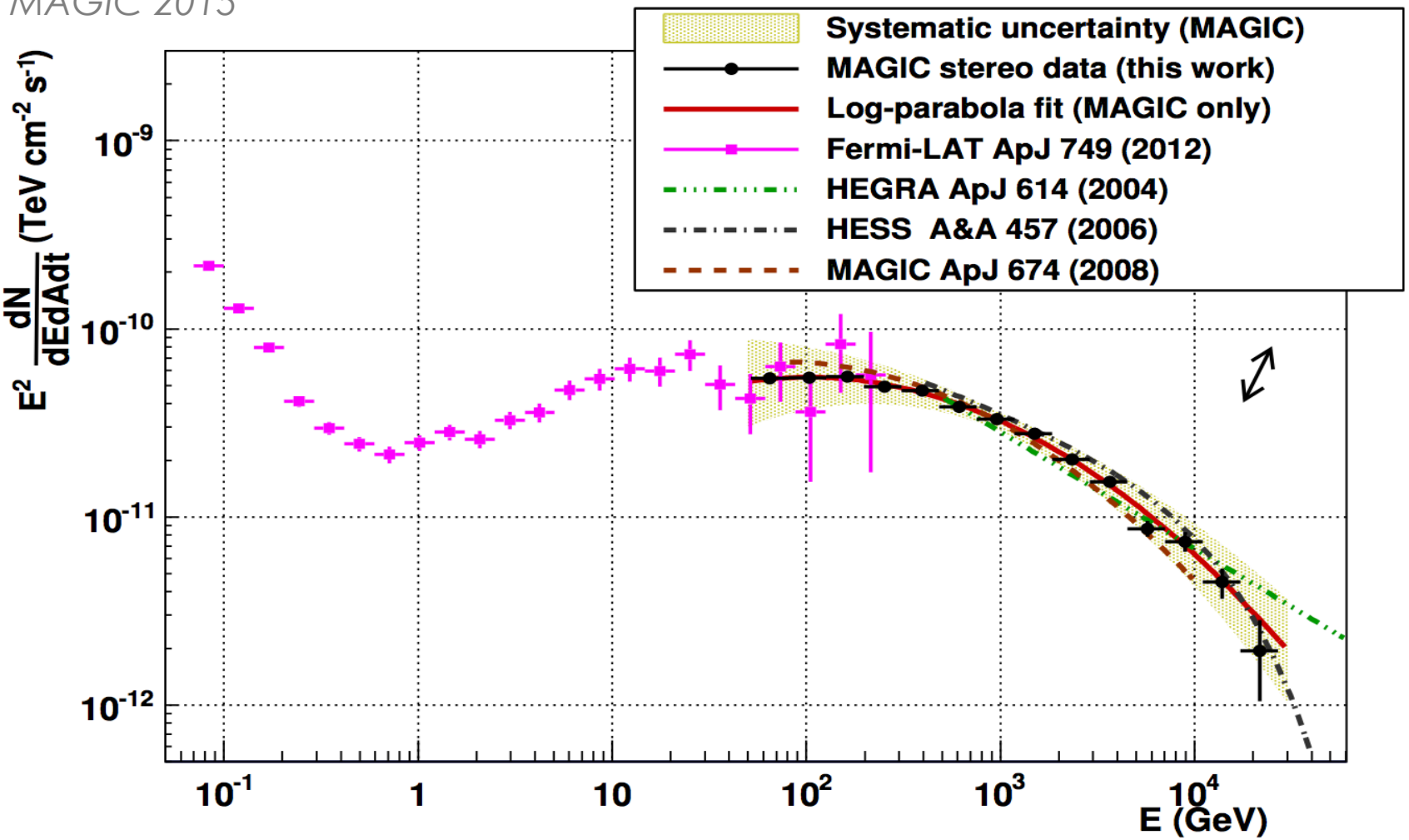
BROAD-BAND SPECTRUM



Meyer+ 2010

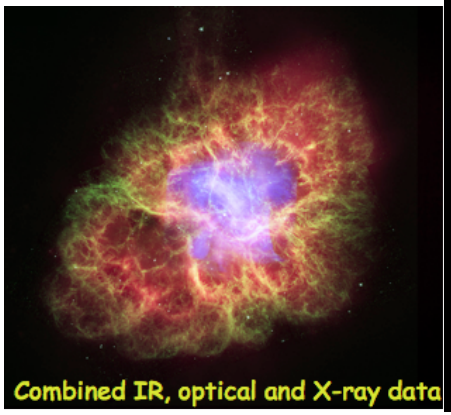
Most of what we know from the Crab

MAGIC 2015

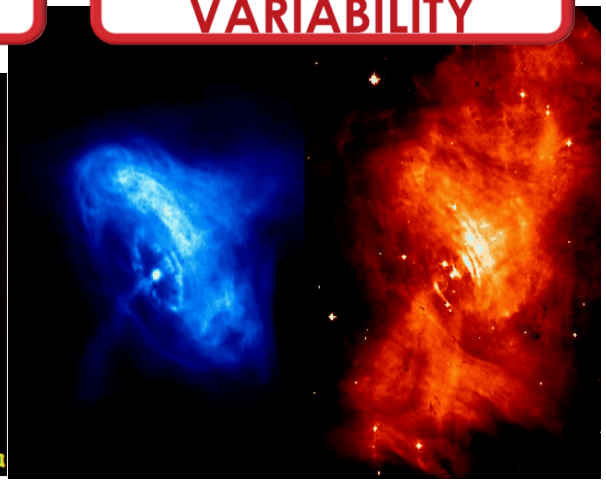


Most of what we know from the Crab

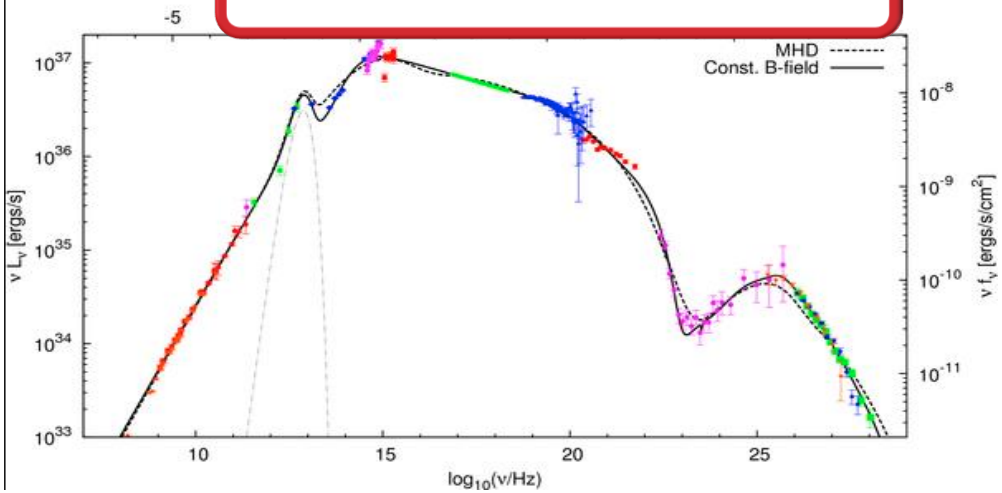
MORPHOLOGY



SUBSTRUCTURE VARIABILITY

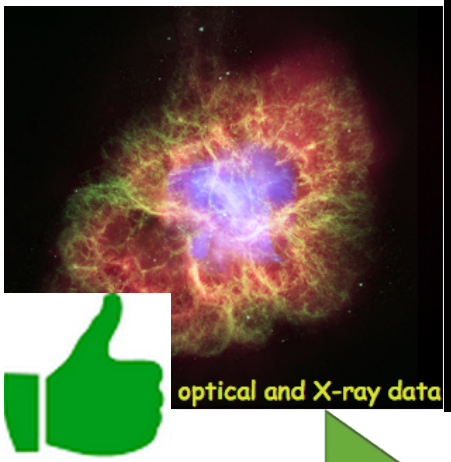


BROAD BAND SPECTRUM



Most of what we know from the Crab

MORPHOLOGY



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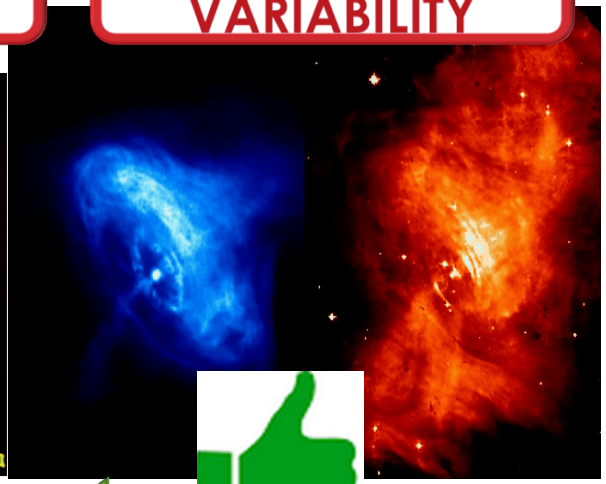

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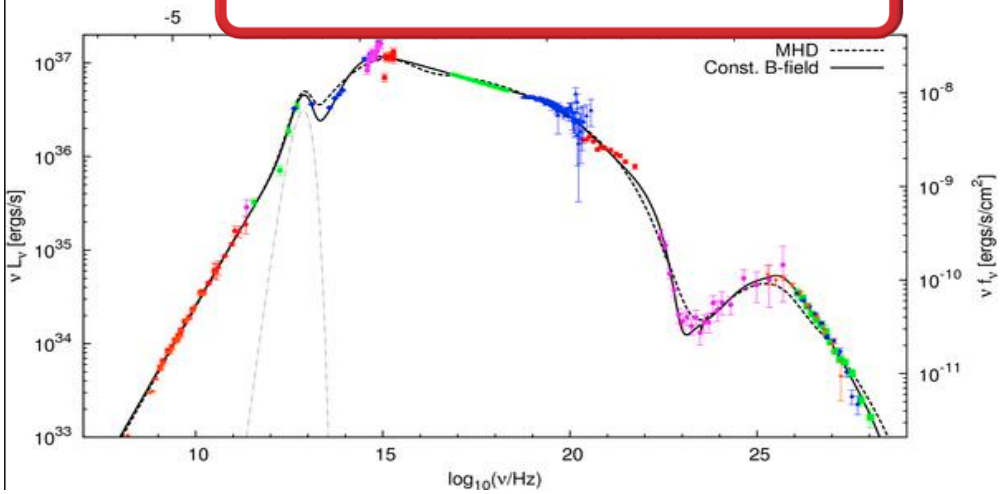
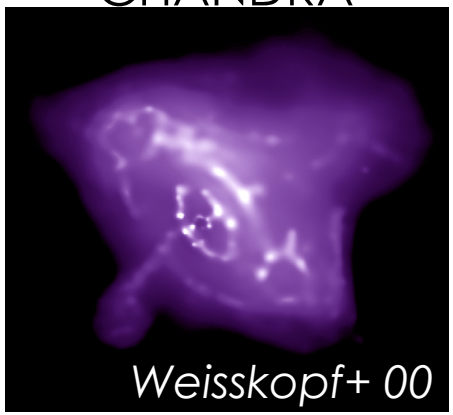


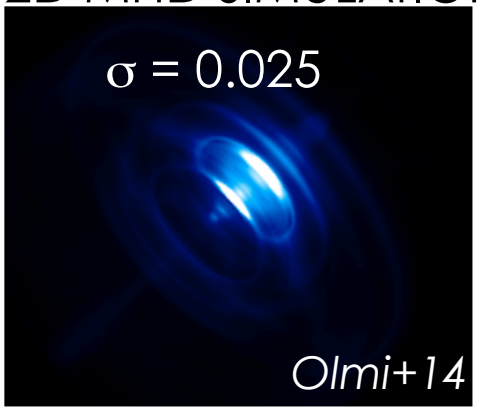
2D MHD MODELS SUCCESSFUL ASSUMING A LOW MAGNETIZATION

Komissarov+04, Del Zanna+04, Volpi+08,

CHANDRA



2D MHD SIMULATION

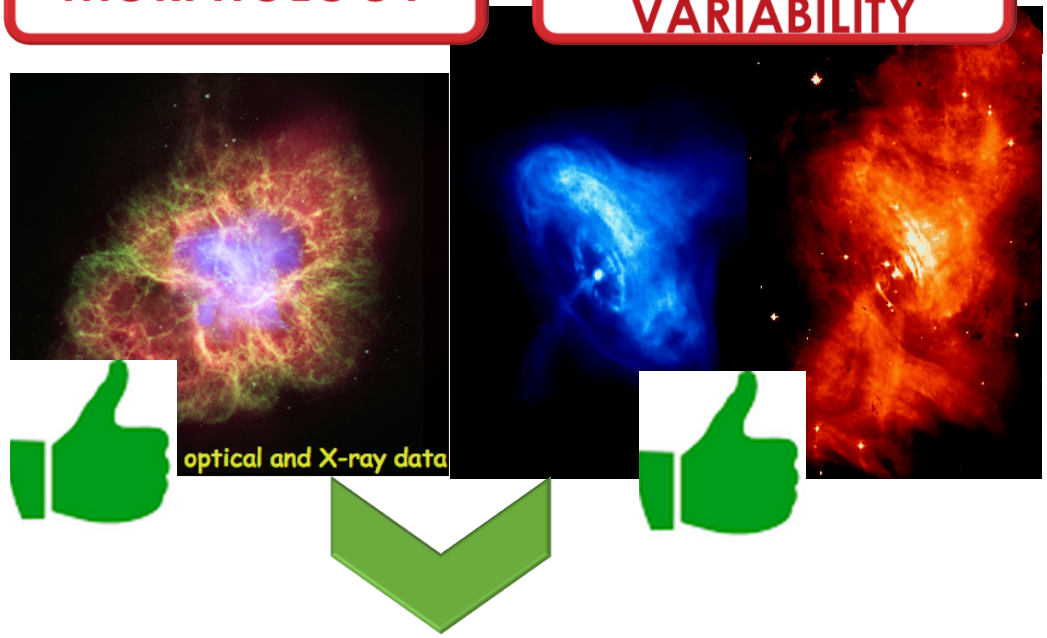


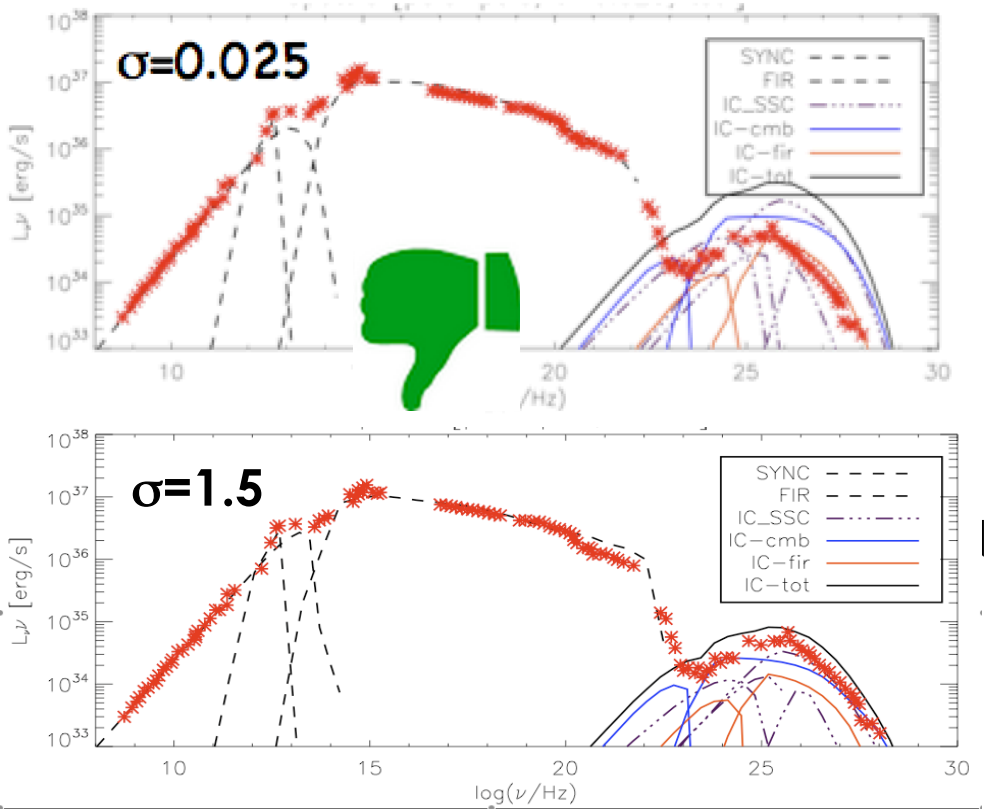
Most of what we know from the Crab

MORPHOLOGY

SUBSTRUCTURE VARIABILITY

BROAD BAND SPECTRUM





2D MHD MODELS SUCCESSFUL ASSUMING A LOW MAGNETIZATION

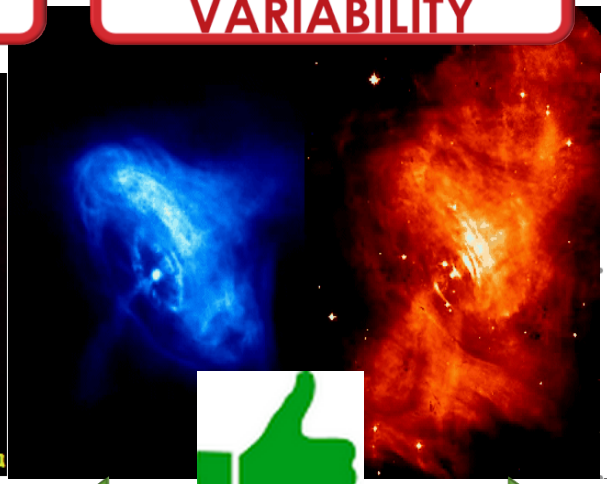
Komissarov+04, Del Zanna+04, Volpi+08,

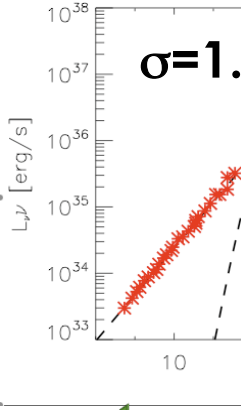
Credit to E. Amato

Most of what we know from the Crab

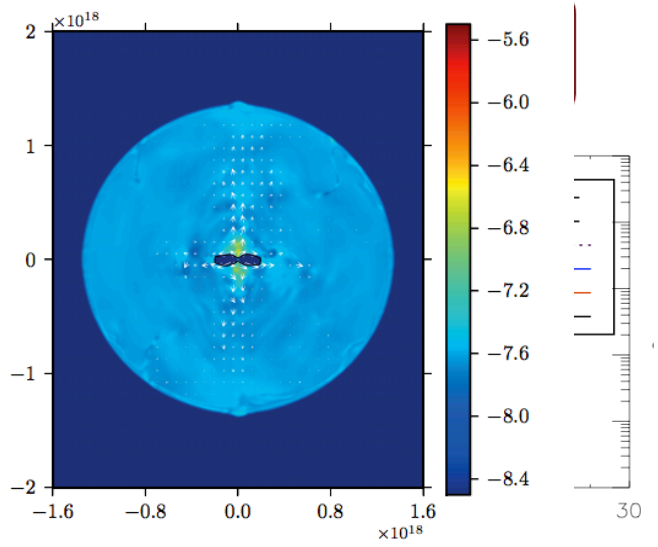
MORPHOLOGY

SUBSTRUCTURE VARIABILITY



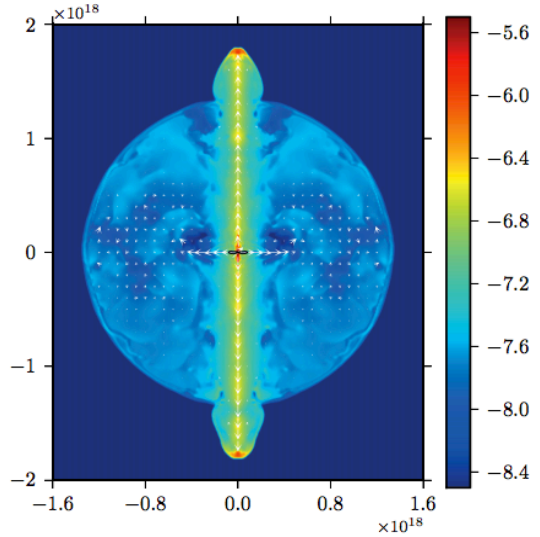


3D



to

2D



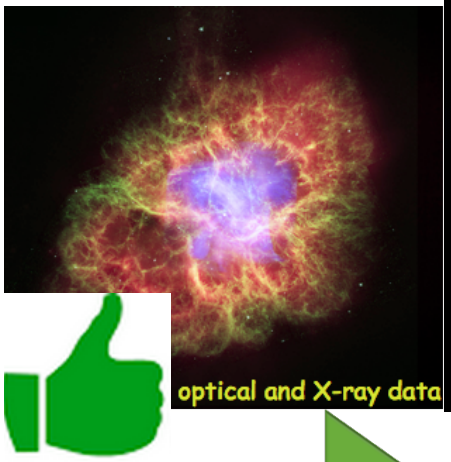
3D MHD SOLVES THE MAGNETIZATION PROBLEM

kink instability relaxes the hoop stress

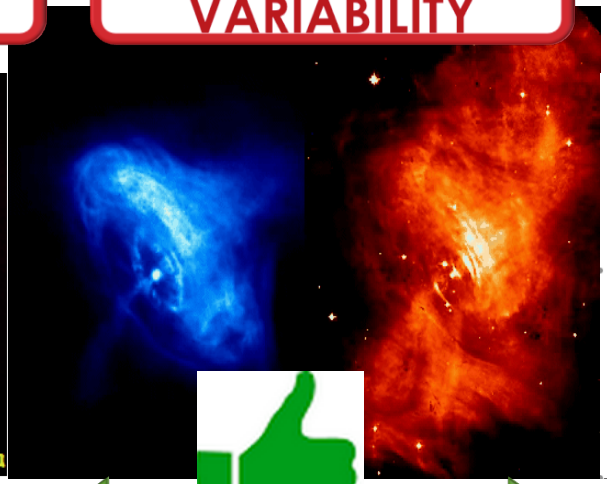
Begen 98, Porth+ 14

Most of what we know from the Crab

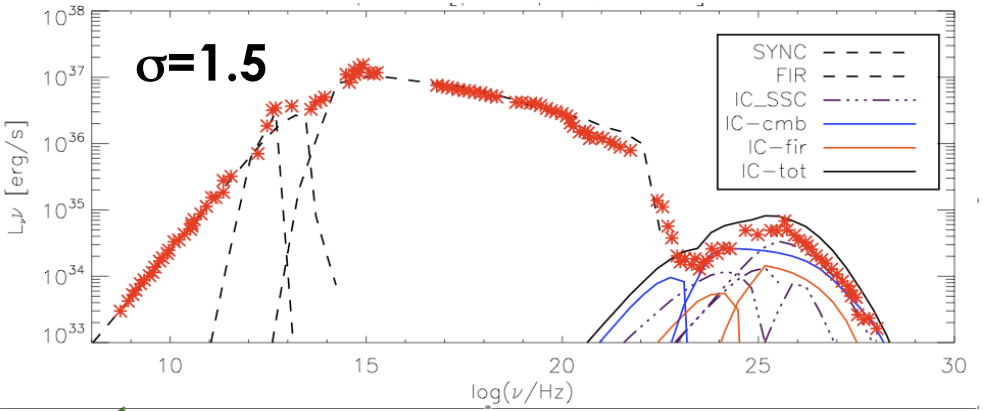
MORPHOLOGY



SUBSTRUCTURE VARIABILITY



BROAD BAND SPECTRUM



3D MHD SOLVES THE MAGNETIZATION PROBLEM

kink instability relaxes the hoop stress

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WHICH ACCELERATION MECHANISM AT WORK?

DSA UNLIKELY

MAGNETIC RECONNECTION

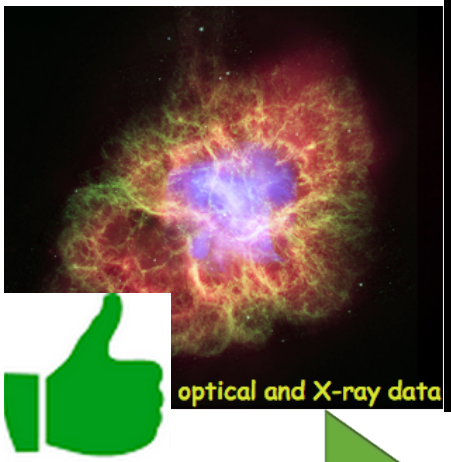
Bucciantini+ 11, Sironi+ 11

RESONANT ABSORPTION OF IONS-CYCLOTRON WAVES

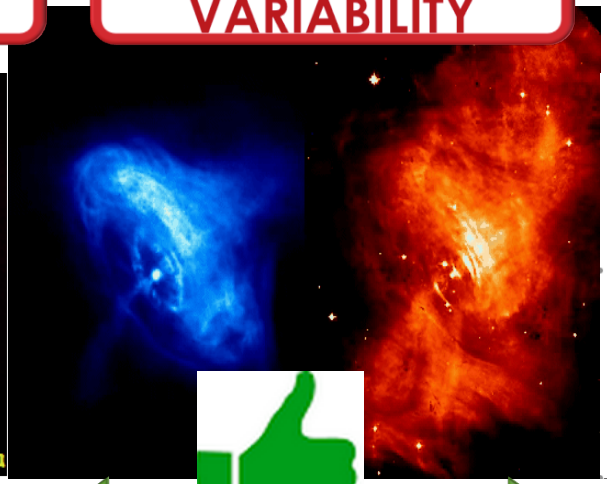
Amato 14

Most of what we know from the Crab

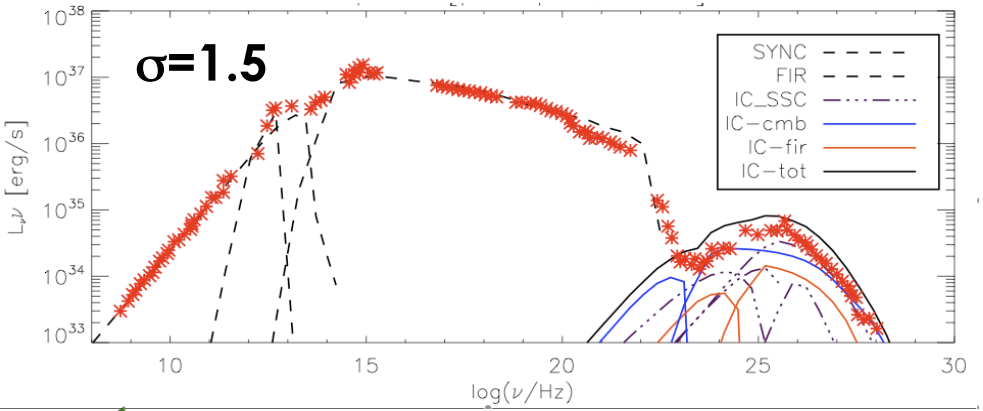
MORPHOLOGY



SUBSTRUCTURE VARIABILITY



BROAD BAND SPECTRUM



3D MHD SOLVES THE MAGNETIZATION PROBLEM

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Bucciantini+ 11, Sironi+ 11

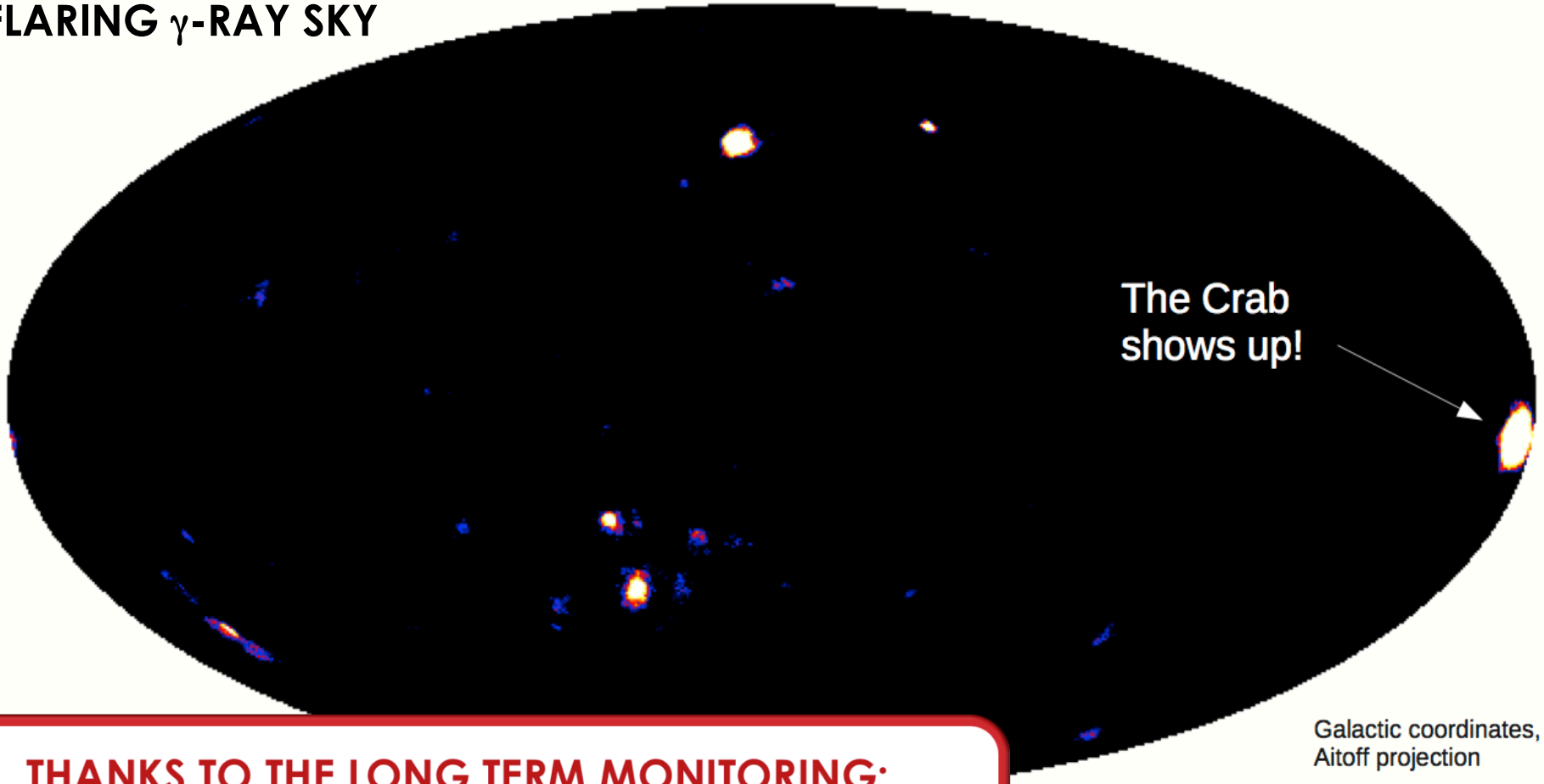
ABSORPTION OF CYCLOTRON WAVES

Amato 14

Rolf Buhler's talk

Not std candel anymore

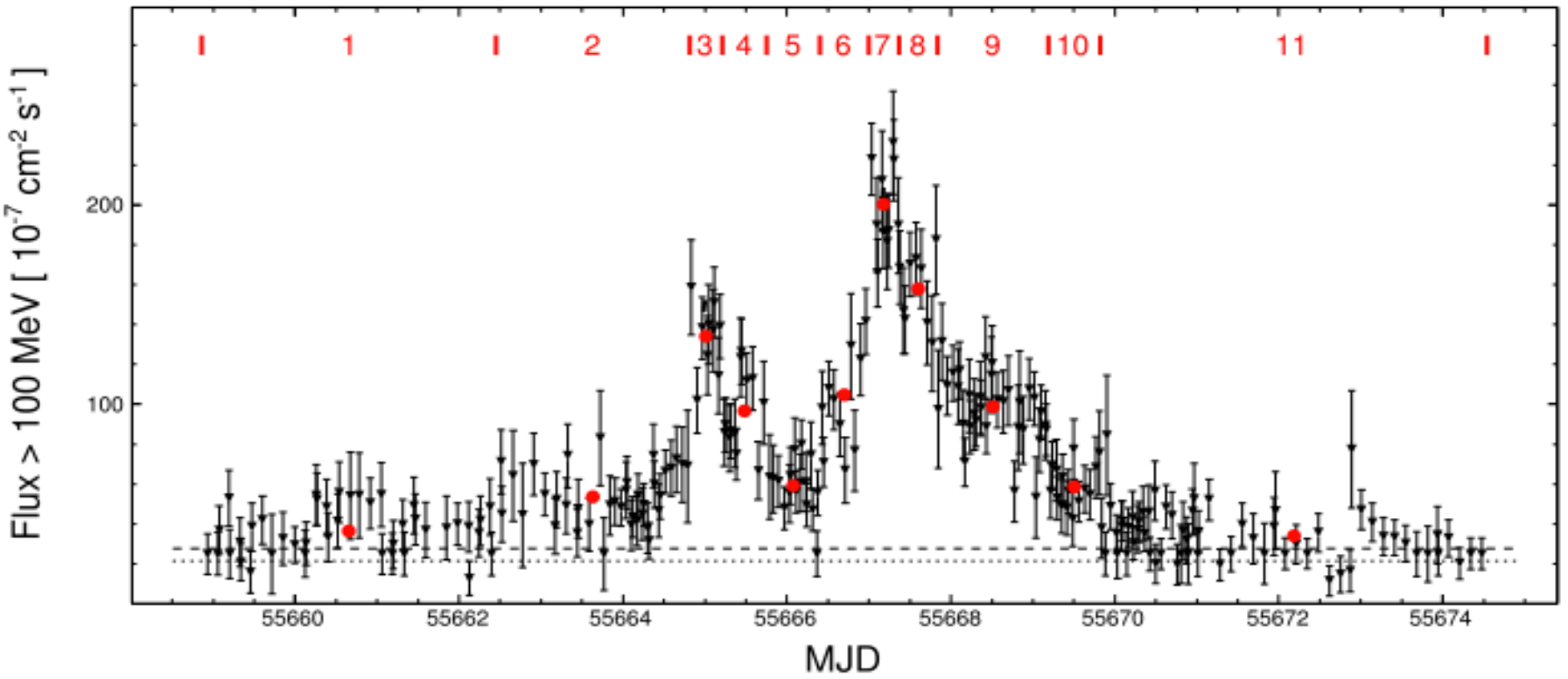
THE FLARING γ-RAY SKY



THANKS TO THE LONG TERM MONITORING:
6 EVENTS in 8 YEARS LASTING DAY/WEEKS
Abdo+ 11, Tavani+ 11, Buhler+ 12, Striani+ 13

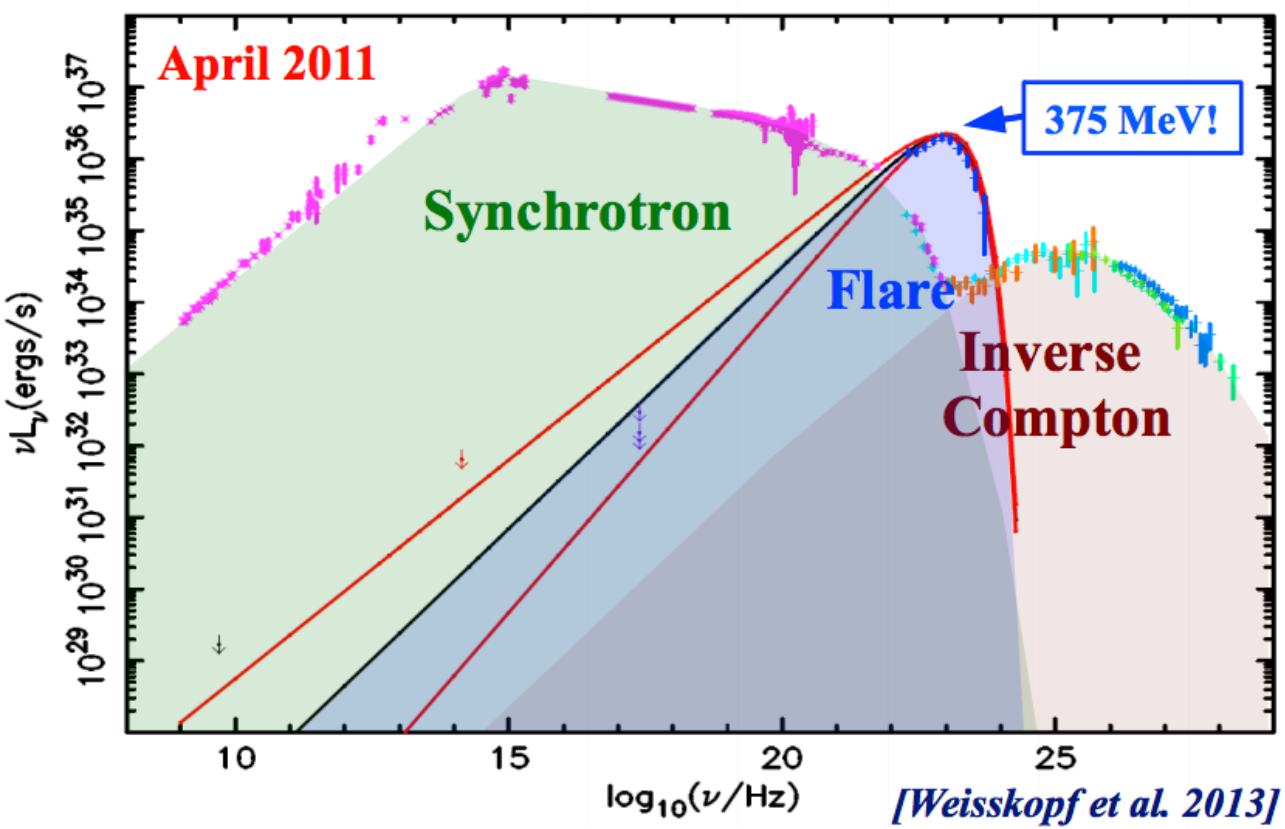
The April 2011 Crab flare

Buhler+ 12



FLUX DOUBLING IN < 8 hrs →
COMPACT EMISSION REGION $<ct_{flare}=10^{-3}$pc

The Crab γ-ray flares



NO OBVIOUS COUNTER PART AT OTHER WAVELENGTHS

NO IC FLARING COMPONENT

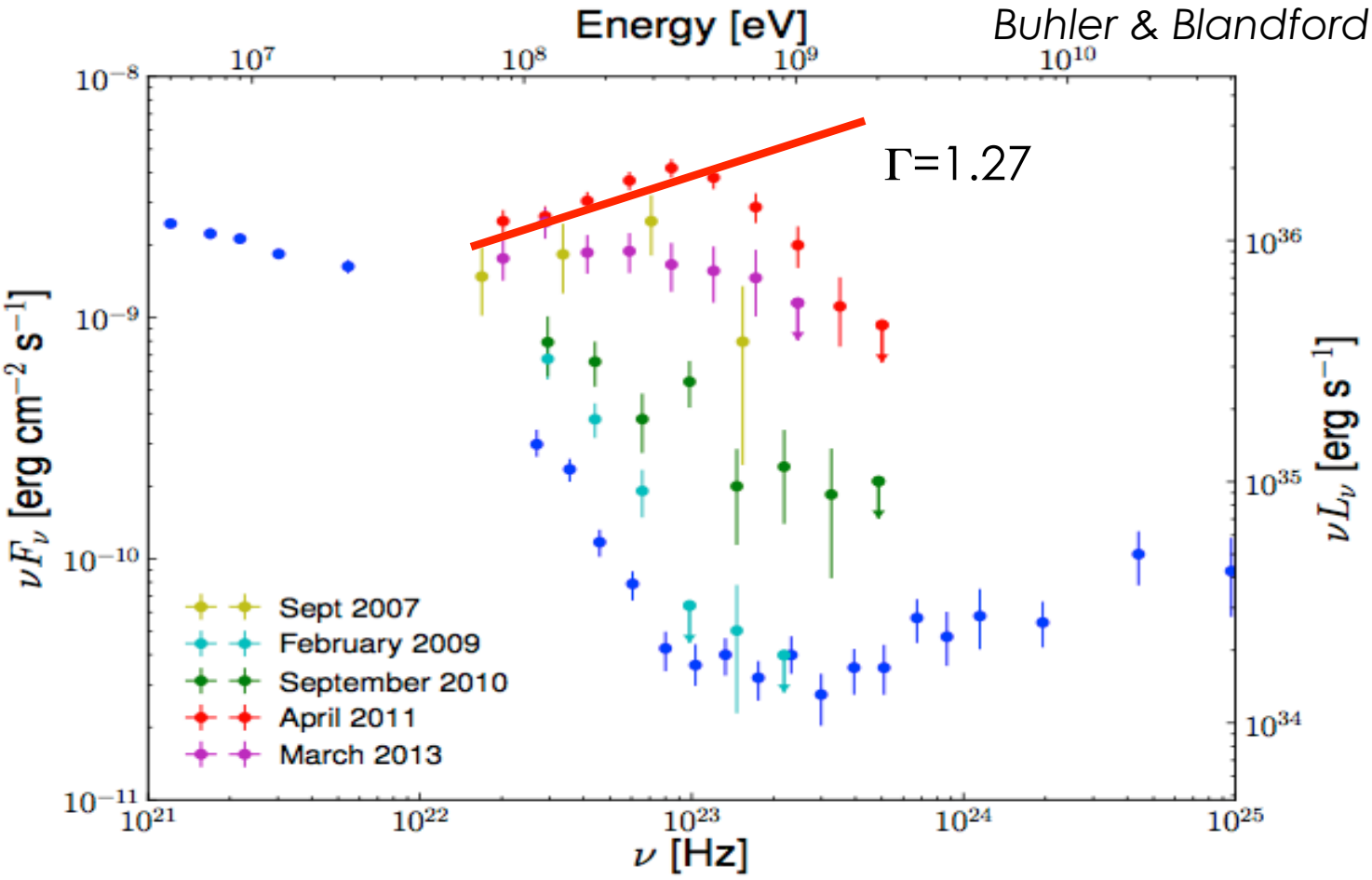
HESS 13, VERITAS 14

NEW SYNCHROTRON COMPONENT ABOVE 160 MeV

Buhler+ 12,14; Weisskopf+ 13

The Crab γ-ray flares

Buhler & Blandford 14



HARD SPECTRUM, INCOMPATIBLE WITH DSA

Possible explanations

DOPPLER BEAMING:

ε_{max}=D×160 MeV → D≈3-4

Yuan+11, Bednarek+11, Komisarrov+ 11, Lyutikov+12 Clausen-Brown+ 12

RELATIVISTIC FLOW ONLY AT HIGH LATITUDES *Komissarov 13*

→ INNER KNOT

Tavani+ 11, Lobanov+ 11, Weisskopf+ 13

NO VARIATIONS CORRELATED WITH THE FLARES

Rudy+ 15

Possible explanations

DOPPLER BEAMING:

ε_{max}=D×160 MeV → D≈3-4

Yuan+11, Bednarek+11, Komisarrov+ 11, Lyutikov+12 Clausen-Brown+ 12

RELATIVISTIC FLOW ONLY AT HIGH ALTITUDES *Komissarov 13*

→ INNER KNOT

Tavani+ 11, Lobanov+ 11, Weisskopf+ 13

MAGNETTIC RECCONECTION

Sironi+ 11, Cerutti+ 12,13, 14

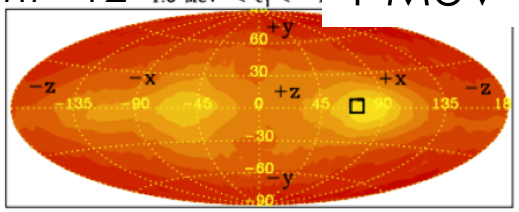
BEAMING OF HIGH_ENERGY PARTICLES, CONSISTENT WITH 6-8 hrs VARIATIONS *Cerutti+ 12*

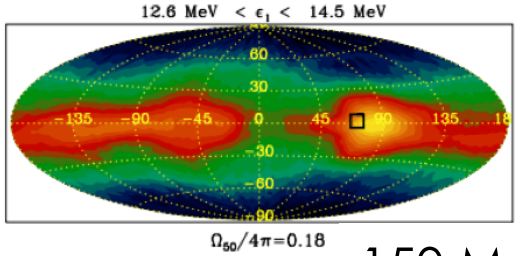
HARD SPECTRA *Sironi+ 11*

WORKS BEST IN HIGHLY MAGNETIZED FLOW → HIGH LATITUDES → JETS

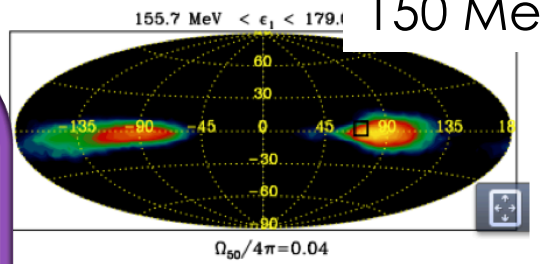
Cerutti+ 12

1 MeV





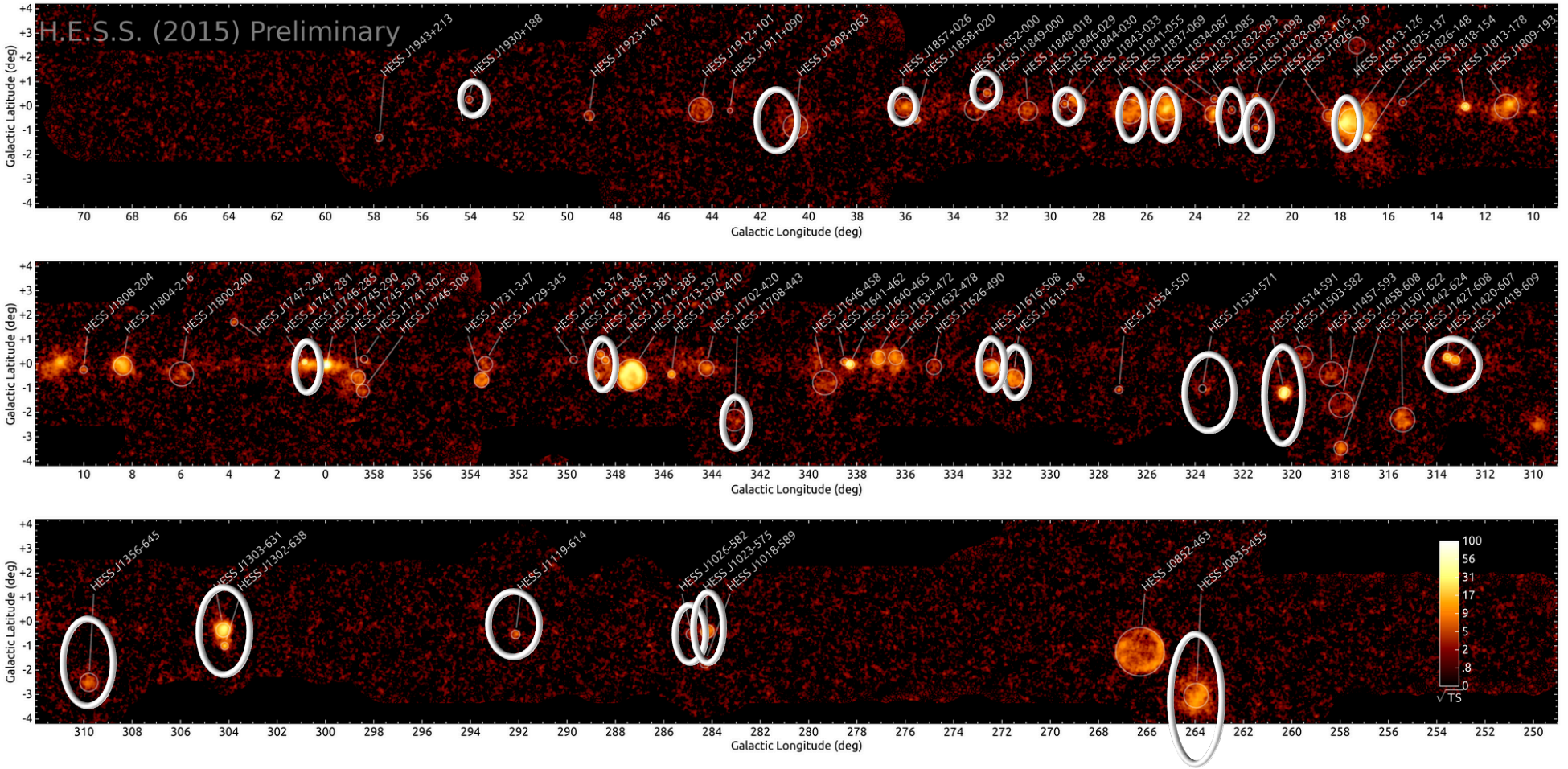
150 MeV



Rolf Buhler's talk

The TeV PWN population

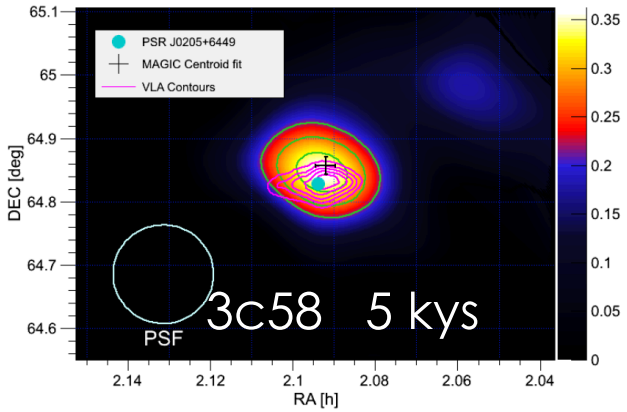
H.E.S.S. preliminary (2015)

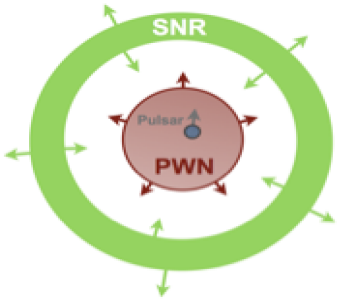


PWN evolution

MAGIC 14

YOUNG PWN IN FREE EXPANSION





PWN evolution

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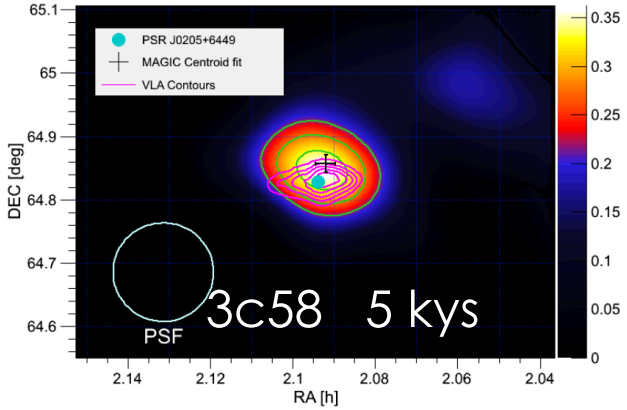
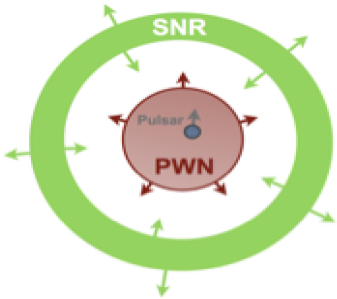
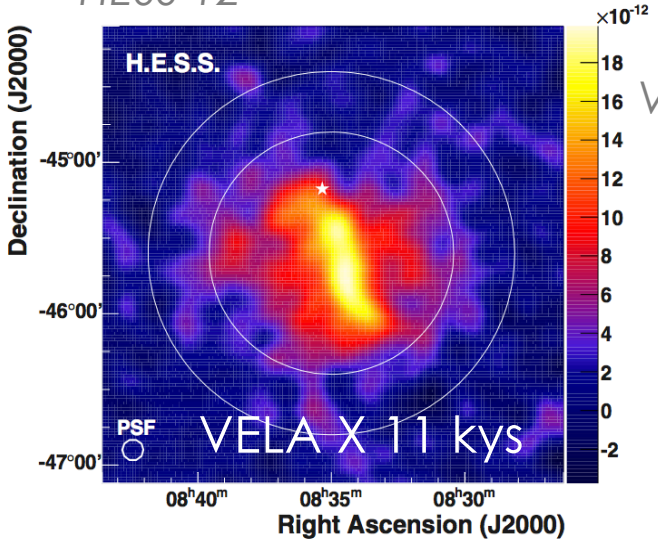
MAGIC 14

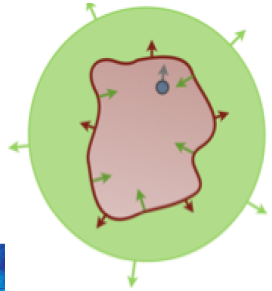




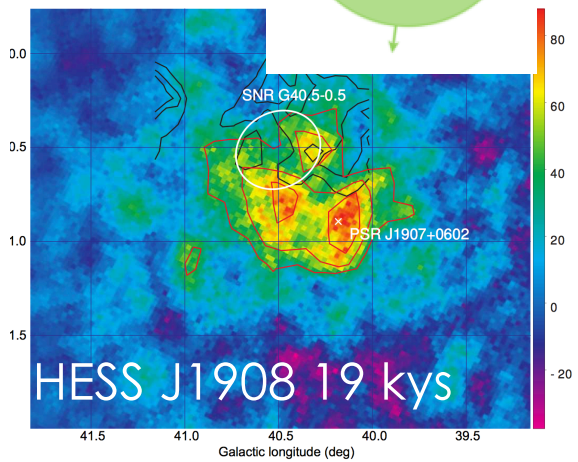
MIDDLE-AGE PWN

HESS 12





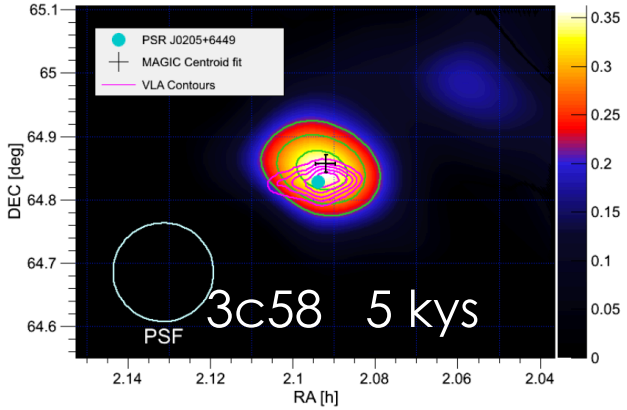
VERITAS 14

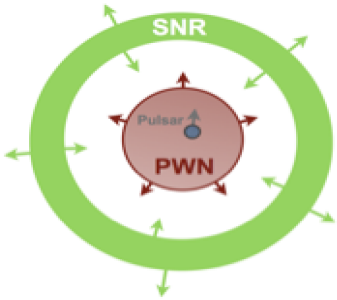


PWN evolution

YOUNG PWN IN FREE EXPANSION

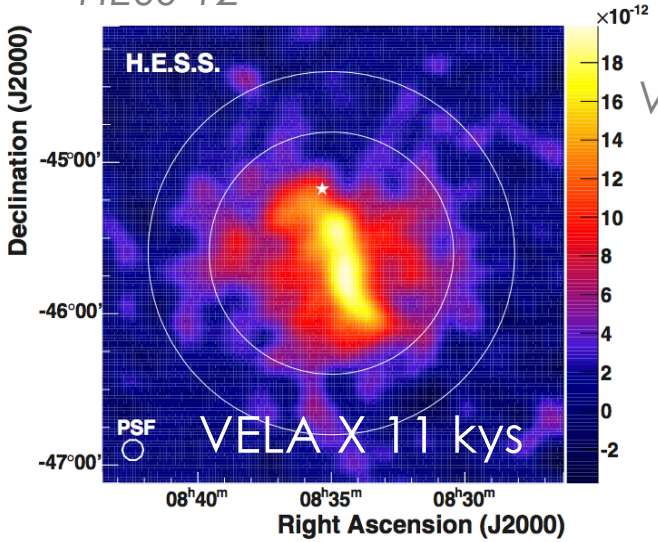
MAGIC 14

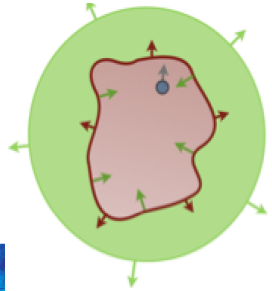




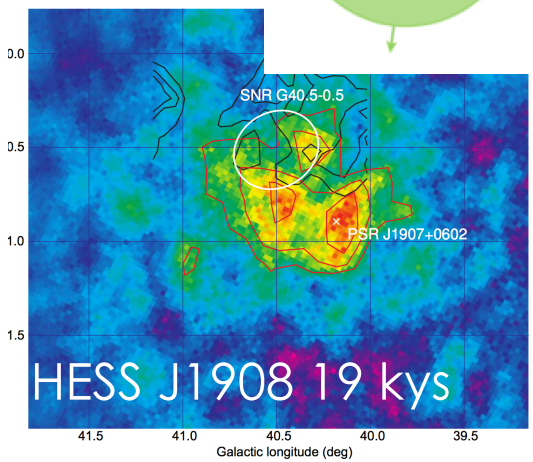
MIDDLE-AGE PWN

HESS 12

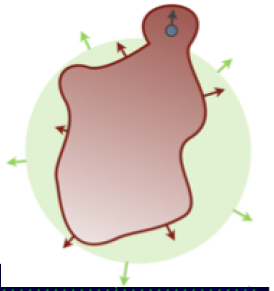




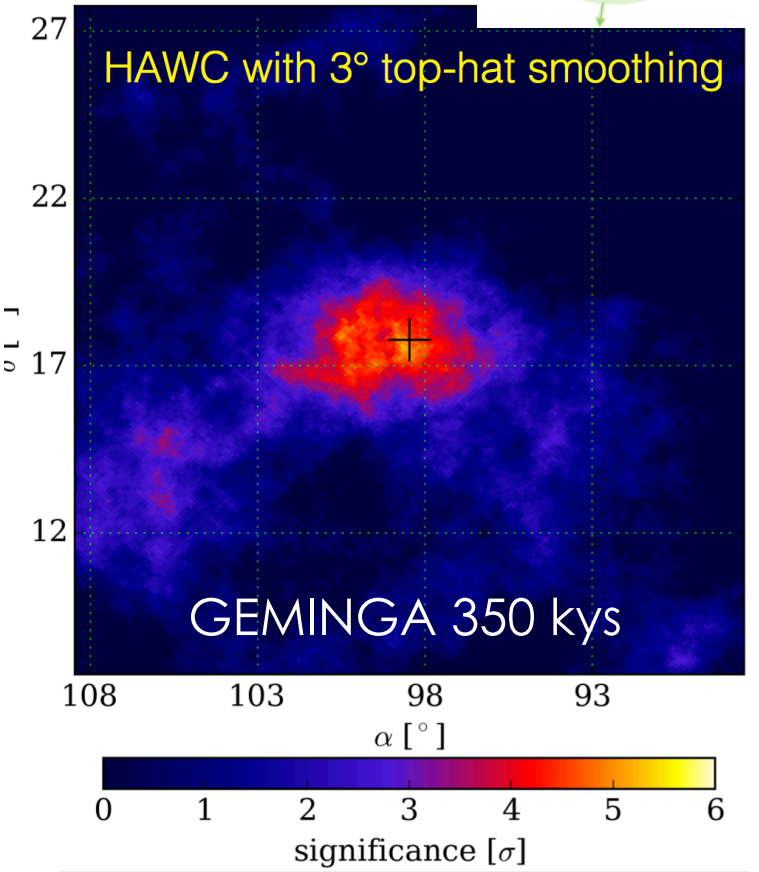
VERITAS 14



RELIC PWN

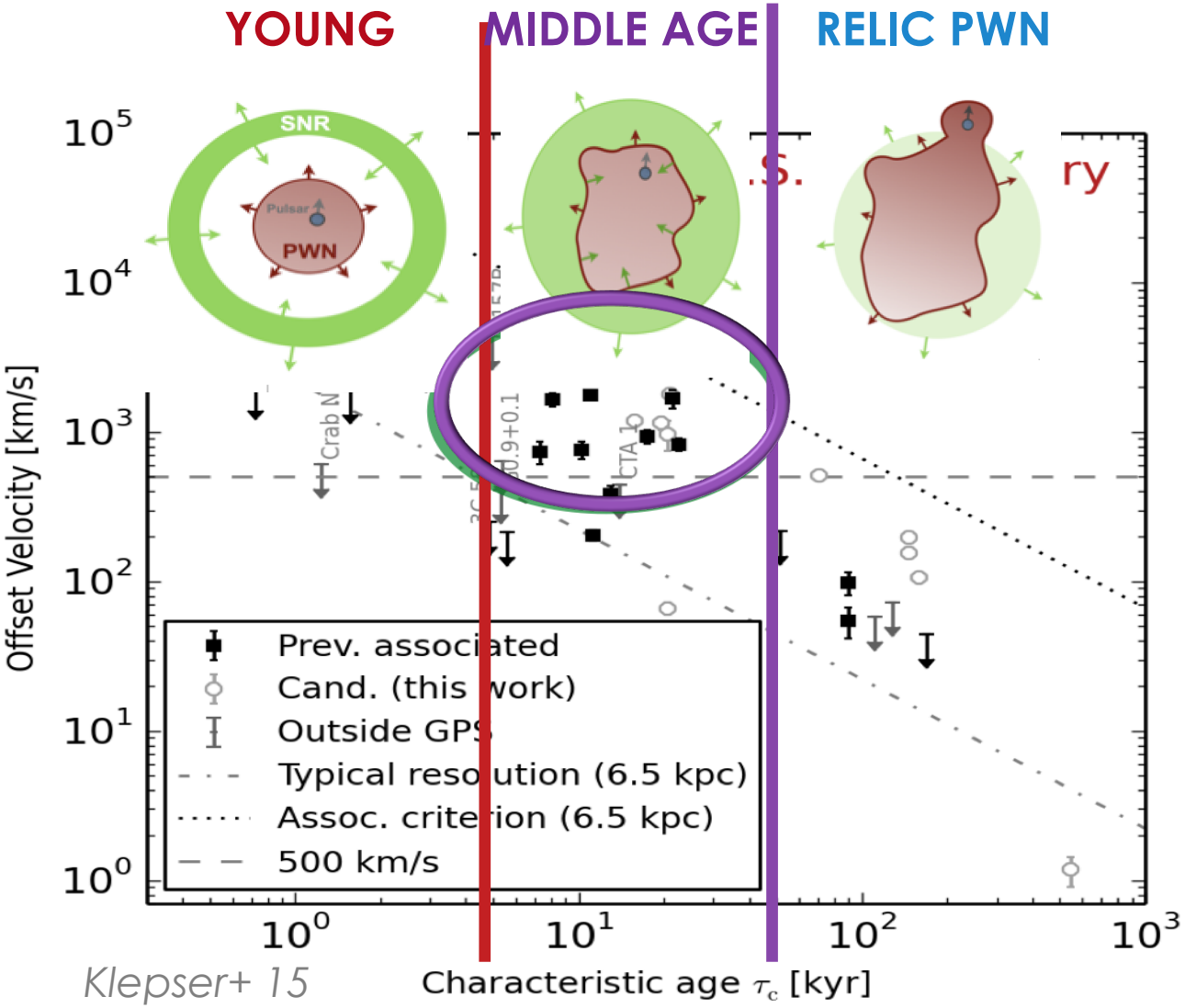


HAWC 15



PWN evolution

POPULATION STUDIES CONFIRM THE EXPECTED EVOLUTION SIGNATURES:
EXTENSION, PULSAR OFFSET
Mattana+09, Meyer +12, Fermi-LAT 13, Kargaltsev+ 13, 15, H.E.S.S. in preparation



Klepser+ 15

Conclusions

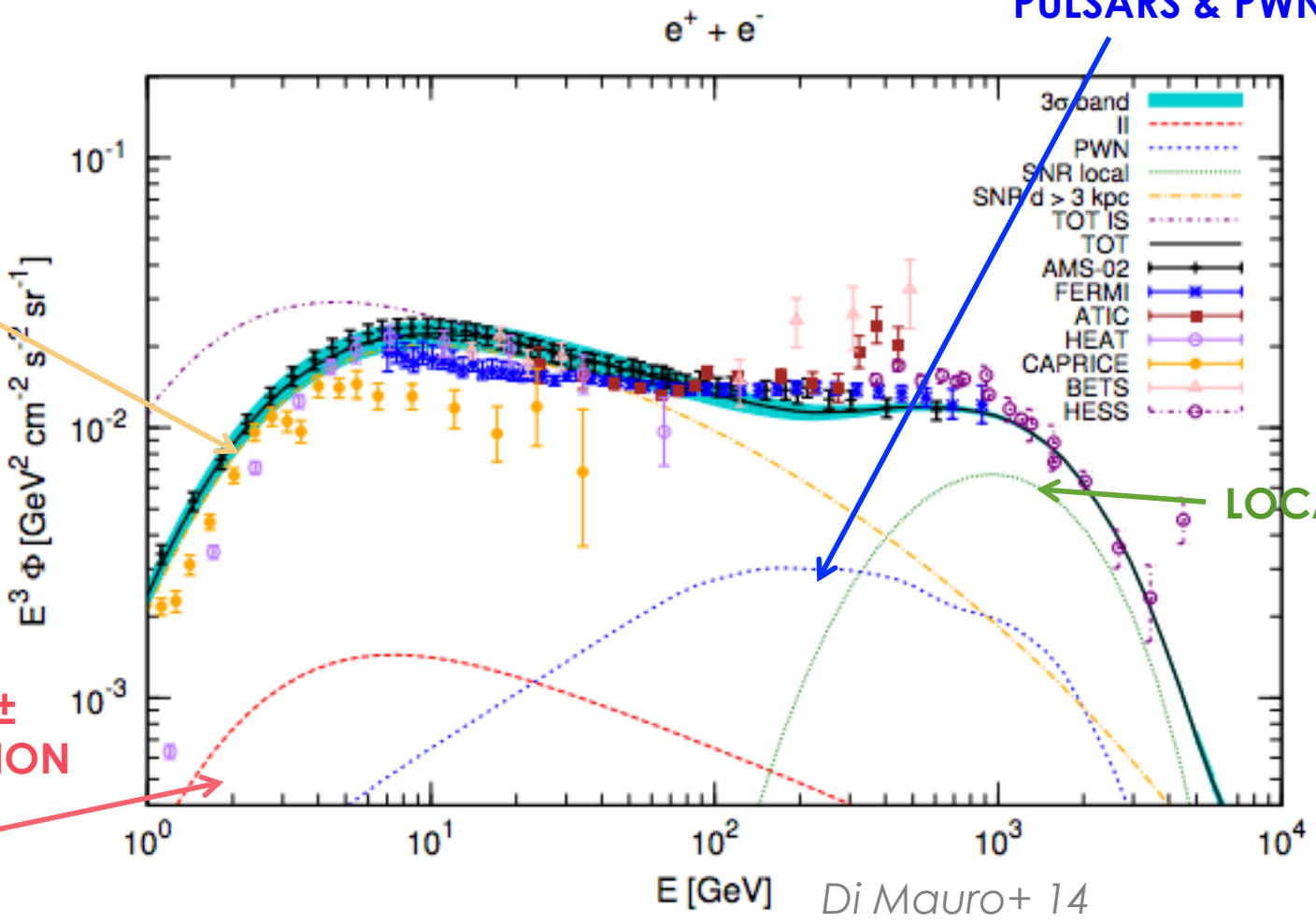
- Three evenly distributed γ-ray pulsar populations
- In young pulsars γ rays comes from high altitudes, in MSP probably a mixture of low and high altitudes
- MSP in spiders showed swing between rotation- and accretion-powered states
- 1st PULSAR SURPRISE: Crab is showing an IC(?) tail above the curvature cutoff up to TeV energy: so far the only one
- 2nd PULSAR SURPRISE: PSR J2021+4026 is variable
- 3D MHD could be able to describe the whole Crab picture (morphology, broad-band spectrum, sub-structure variability)
- 1st PWN SURPRISE: Crab Nebula flares: synchrotron emission above the critical energy, with no counterpart in any wavelength, & hard spectra → magnetic reconnection?
- The TeV PWN population confirm most of the expected evolution signatures (pulsar offset, extension)

THANK YOU

Primary positron factories

PRIMARY e± FROM PULSARS & PWN

FAR SNRs: e⁻
d>3 kpc

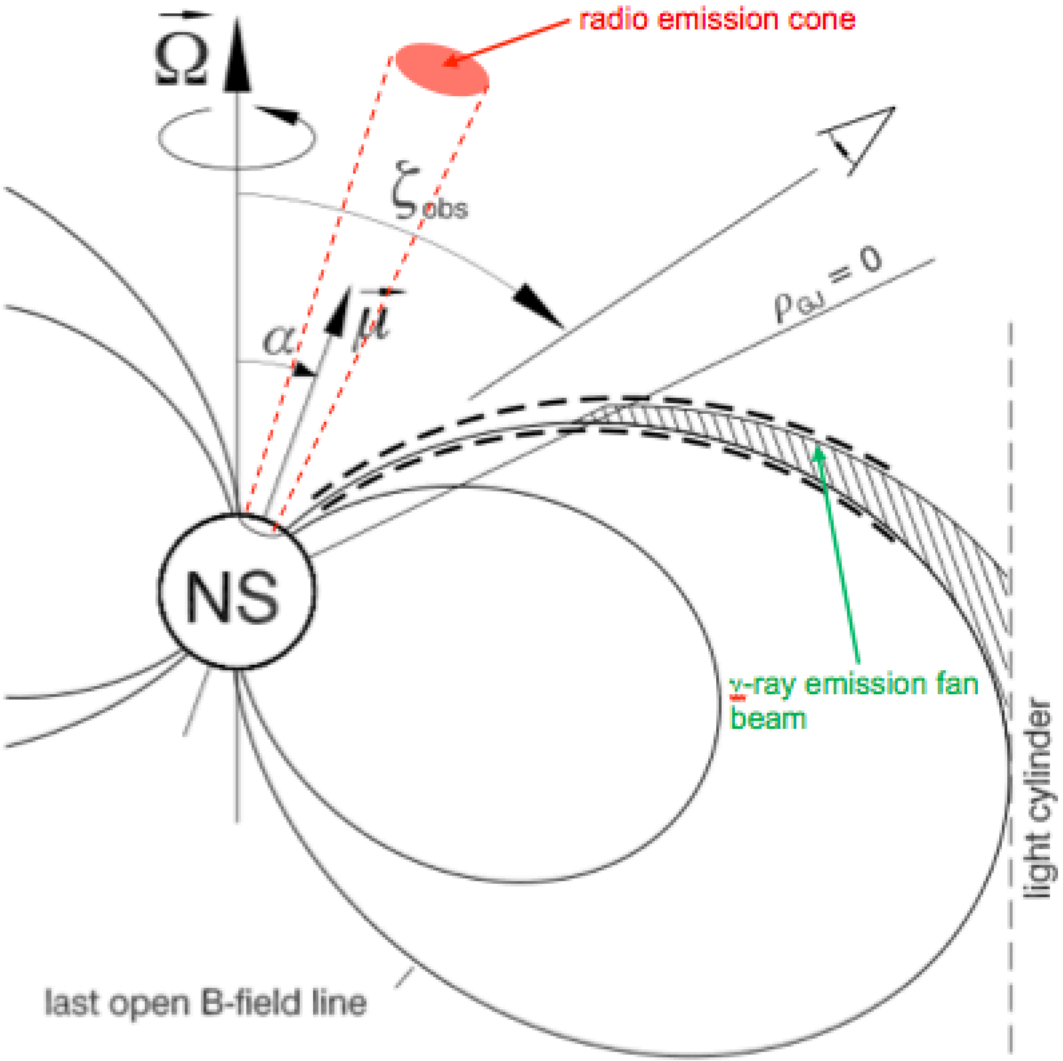


LOCAL SNRs: e⁻

SECONDARY e± FROM SPALLATION REACTION OF HADRONIC CR WITH ISM

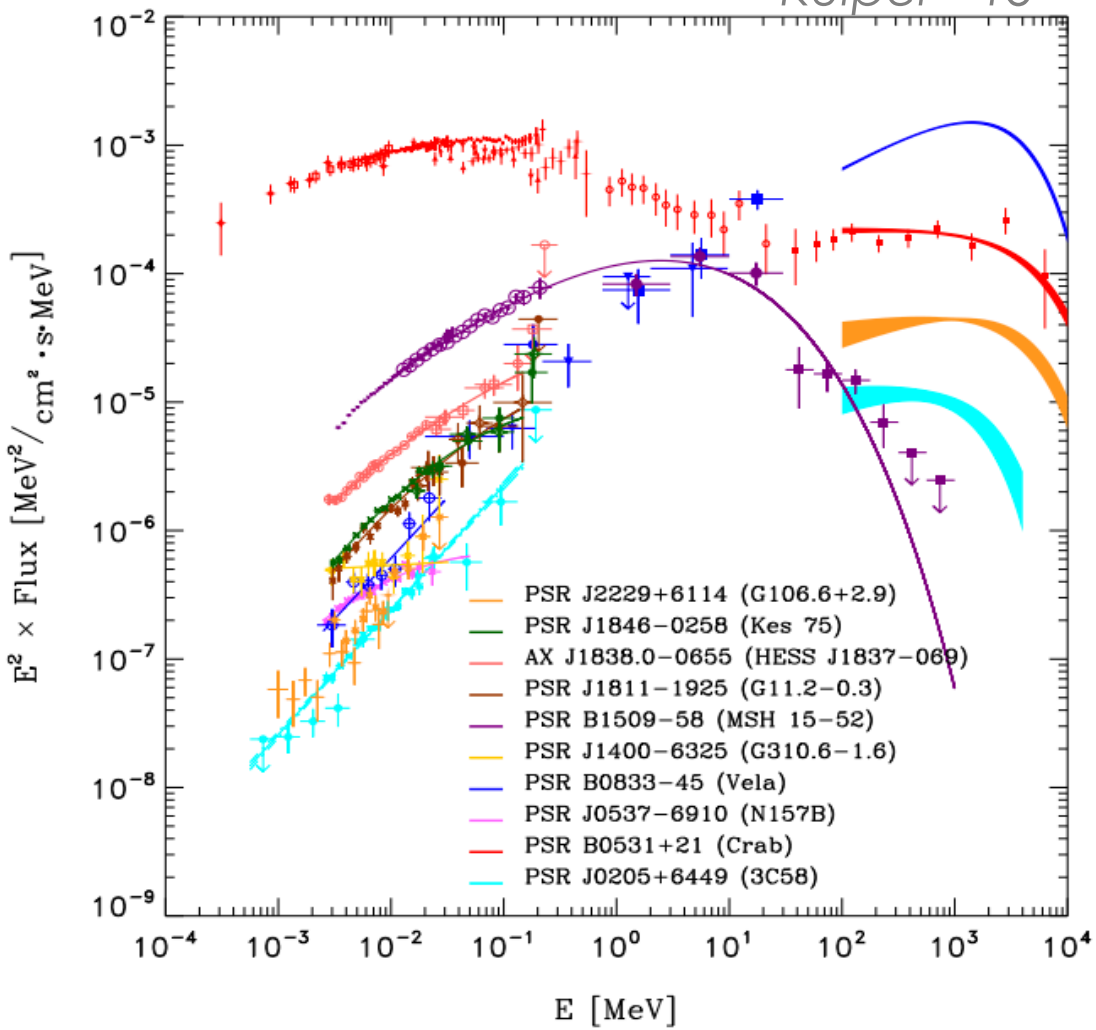
Di Mauro+ 14

Pulsars – Emission models

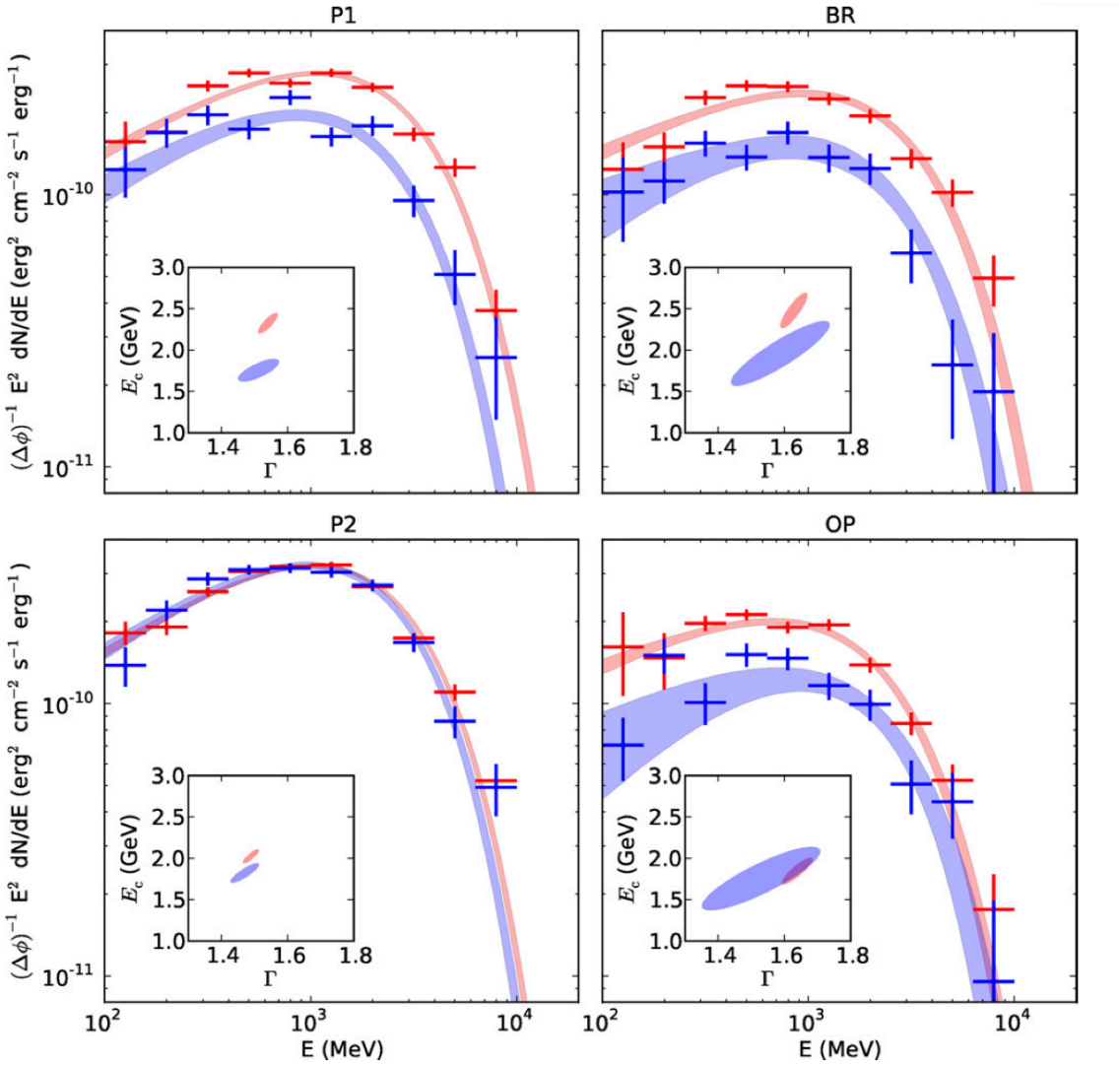


So strange that the Crab is an exception?

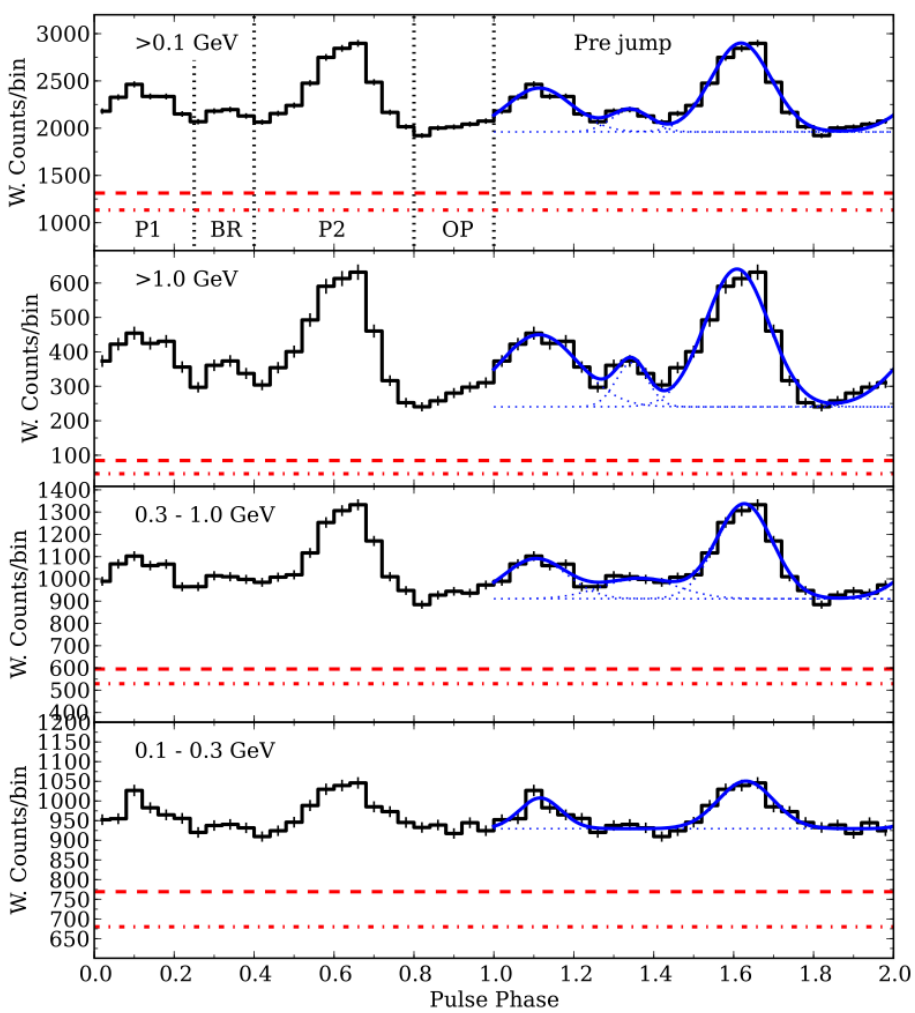
Kuiper+ 15

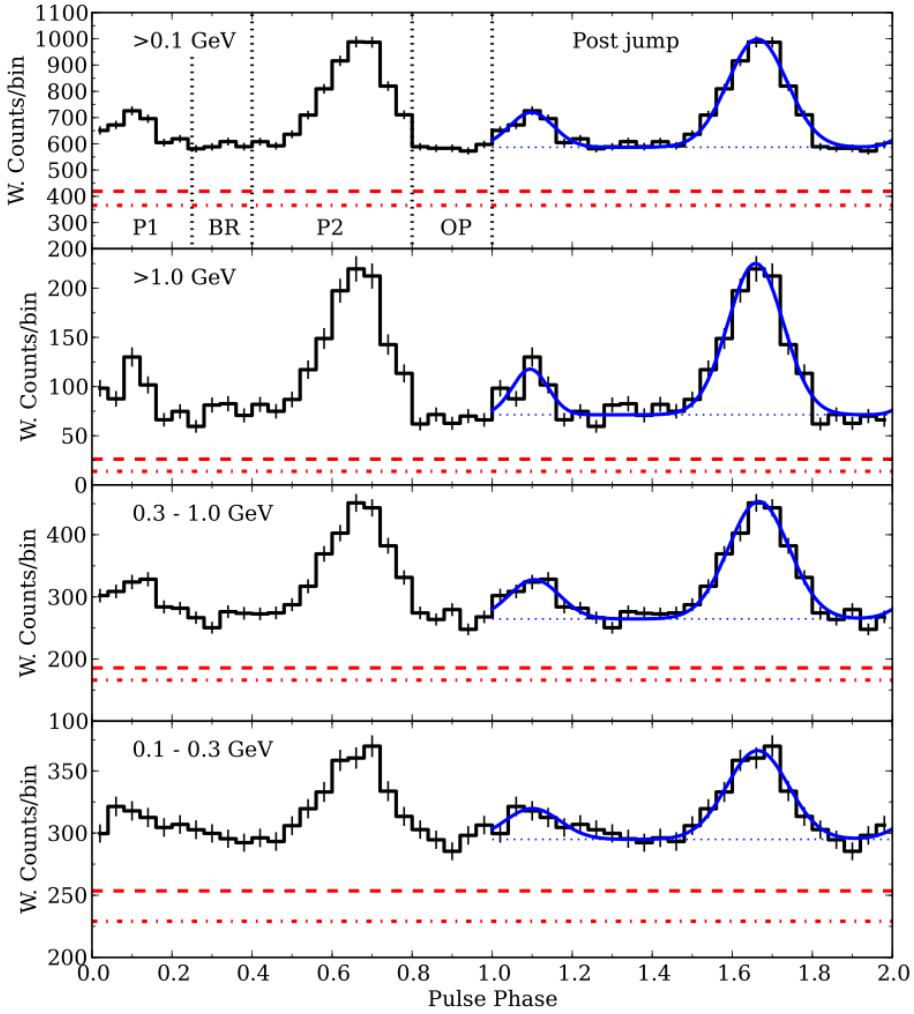


Variable pulsar: J2021+4026

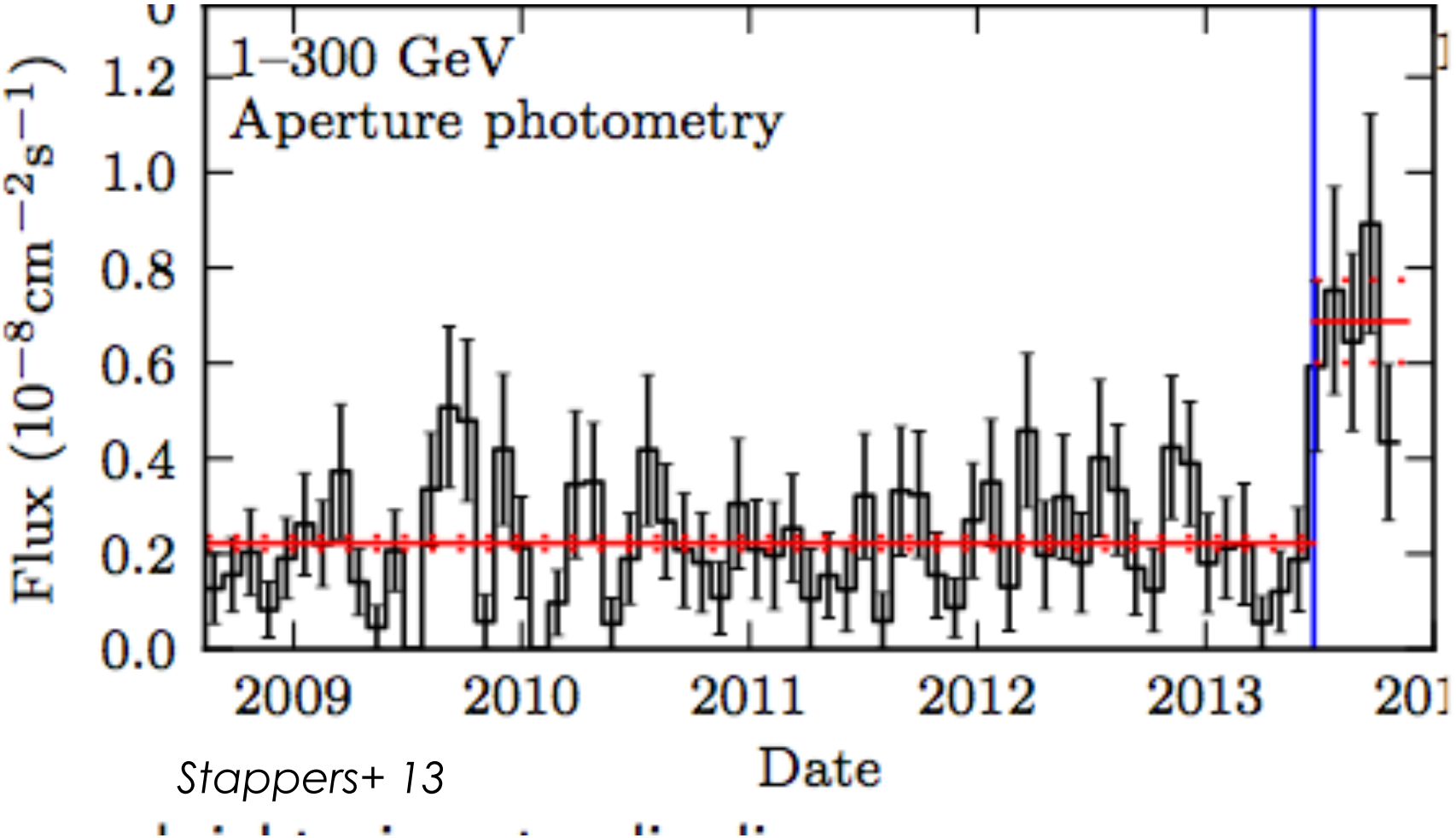


Variable pulsar: J2021+4026





Transitional pulsars



Stappers+ 13

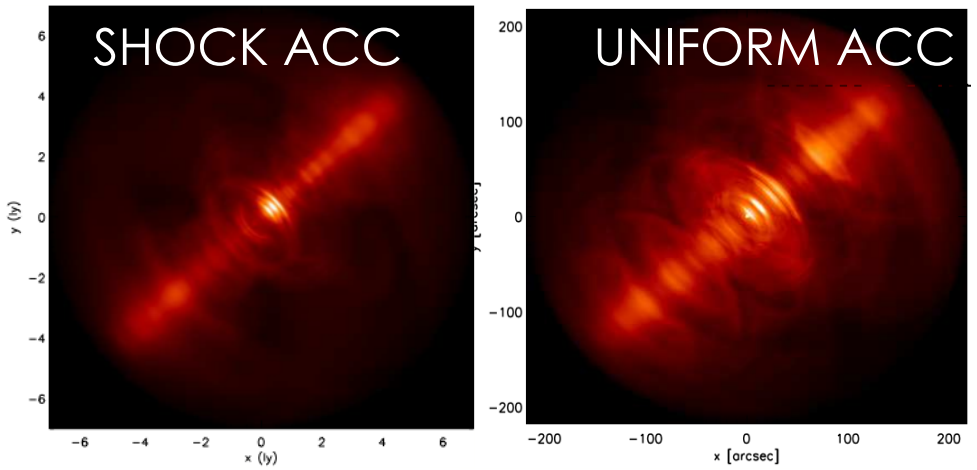
Most of what we know from the Crab

PAIR MULTIPLICITY MODELING PWN

FROM **RADIO** EMISSION **k ~ 10^6**
Bucciantini+ 11
FROM **X-RAY** EMISSION **k ~ 10^4**
Kennel & Coroniti 84

RADIO ORIGIN

- RELIC POPULATION excluded!
- CONTINUOSLY INJECTED AT THE TS
- UNIFORM DISTRIBUTION (re-accelerated in turbolence)



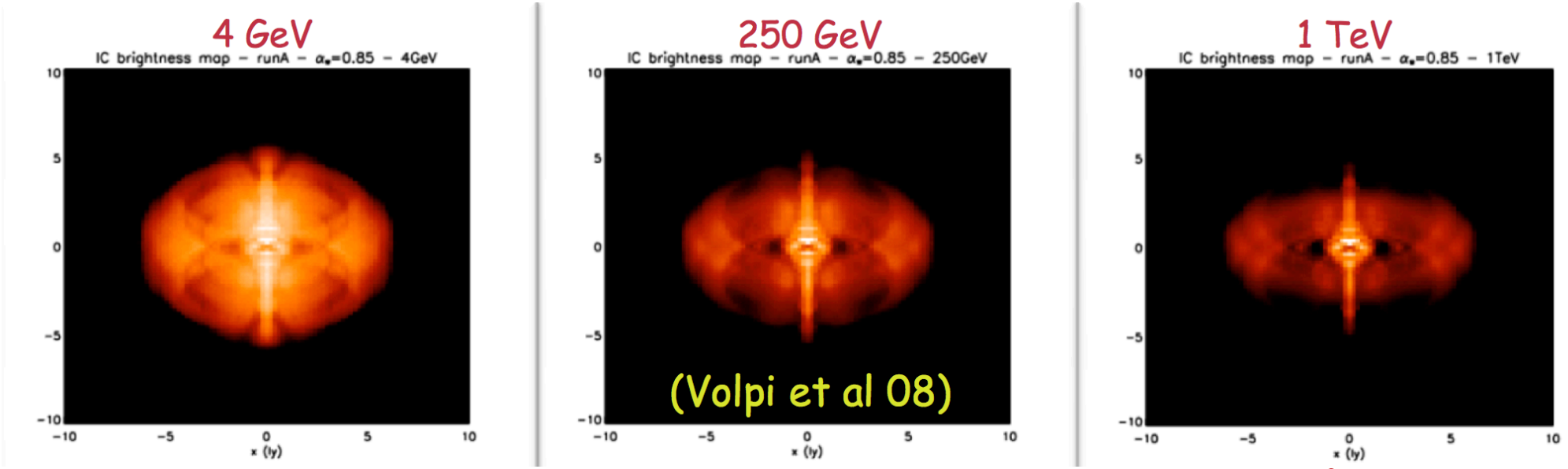
SIMILAR MAPS *Olmi+ 14*

Extension

Gamma rays resembling X-rays due to electron distribution

radio e-

X-ray e-

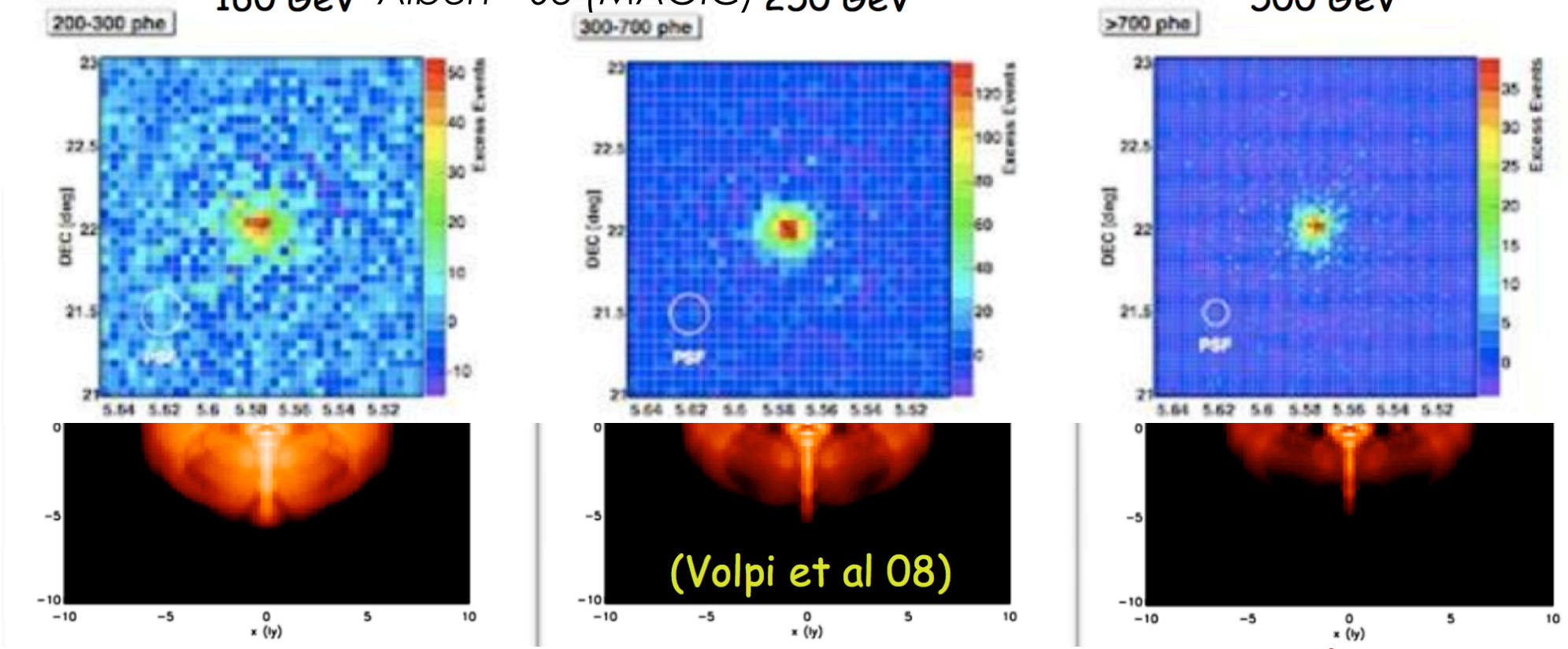


r(GeV) ~ r(GHz)= 5'

shrinking with the energy only in one direction

Extension

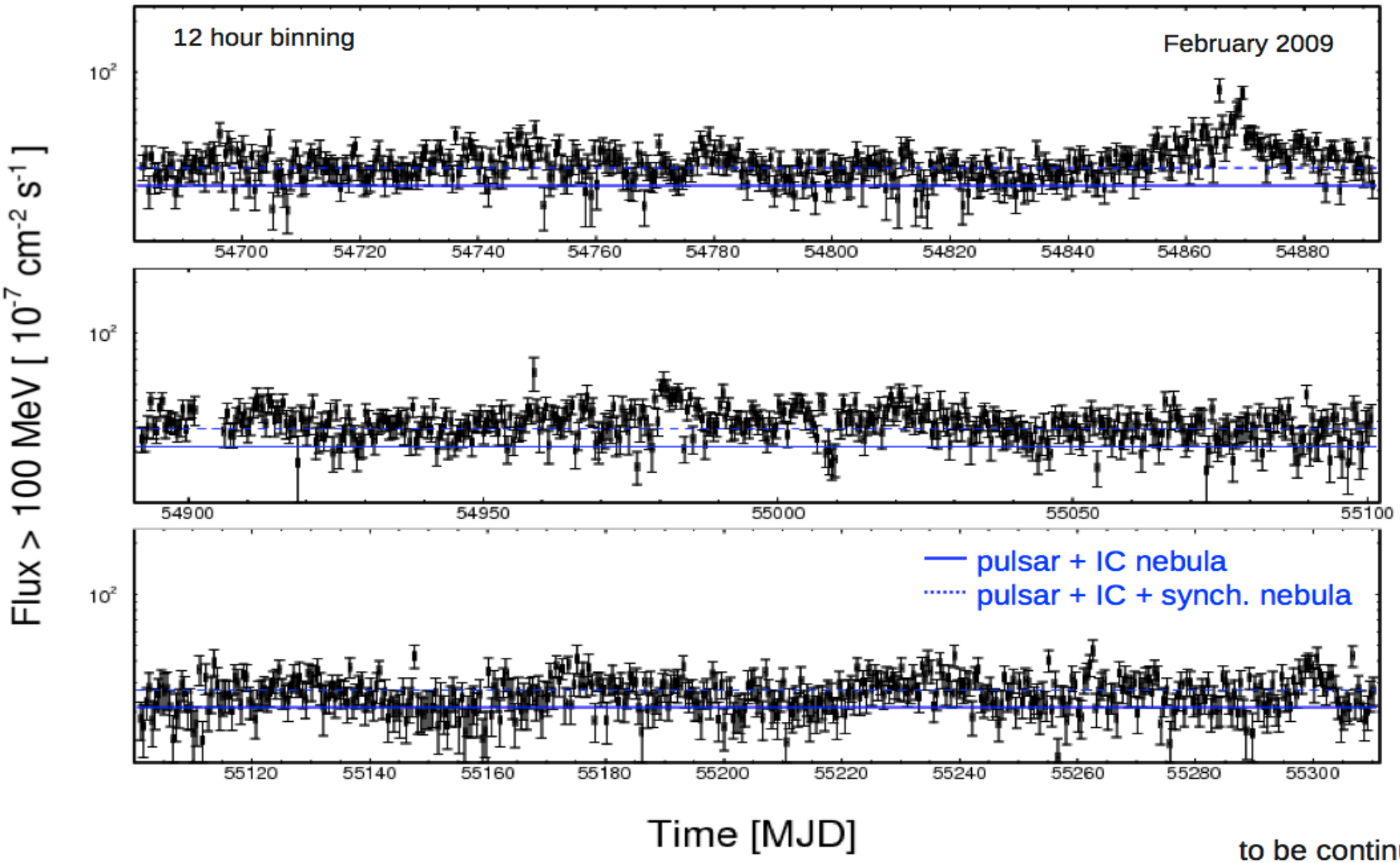
160 GeV *Albert+ 08 (MAGIC)* 250 GeV 500 GeV



r(GeV) ~ r(GHz)= 5'

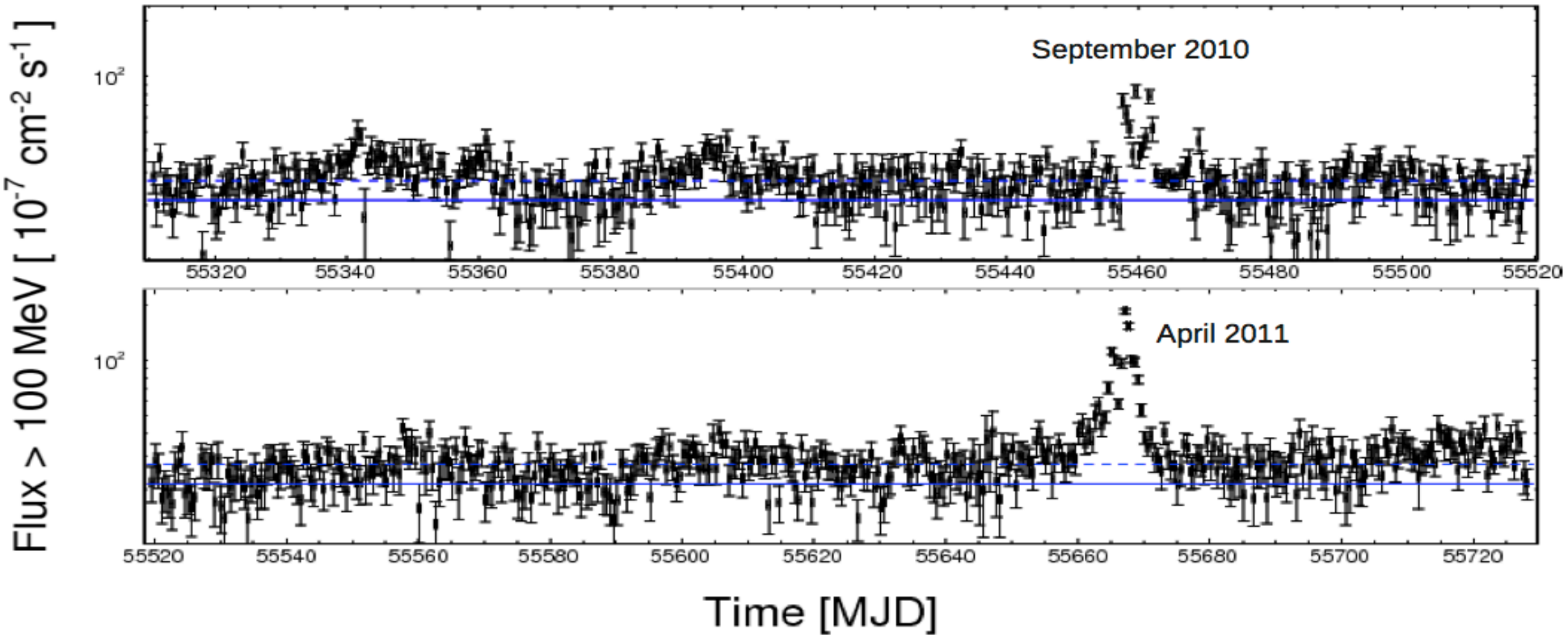
shrinking with the energy only in one direction

The Crab γ-ray flares

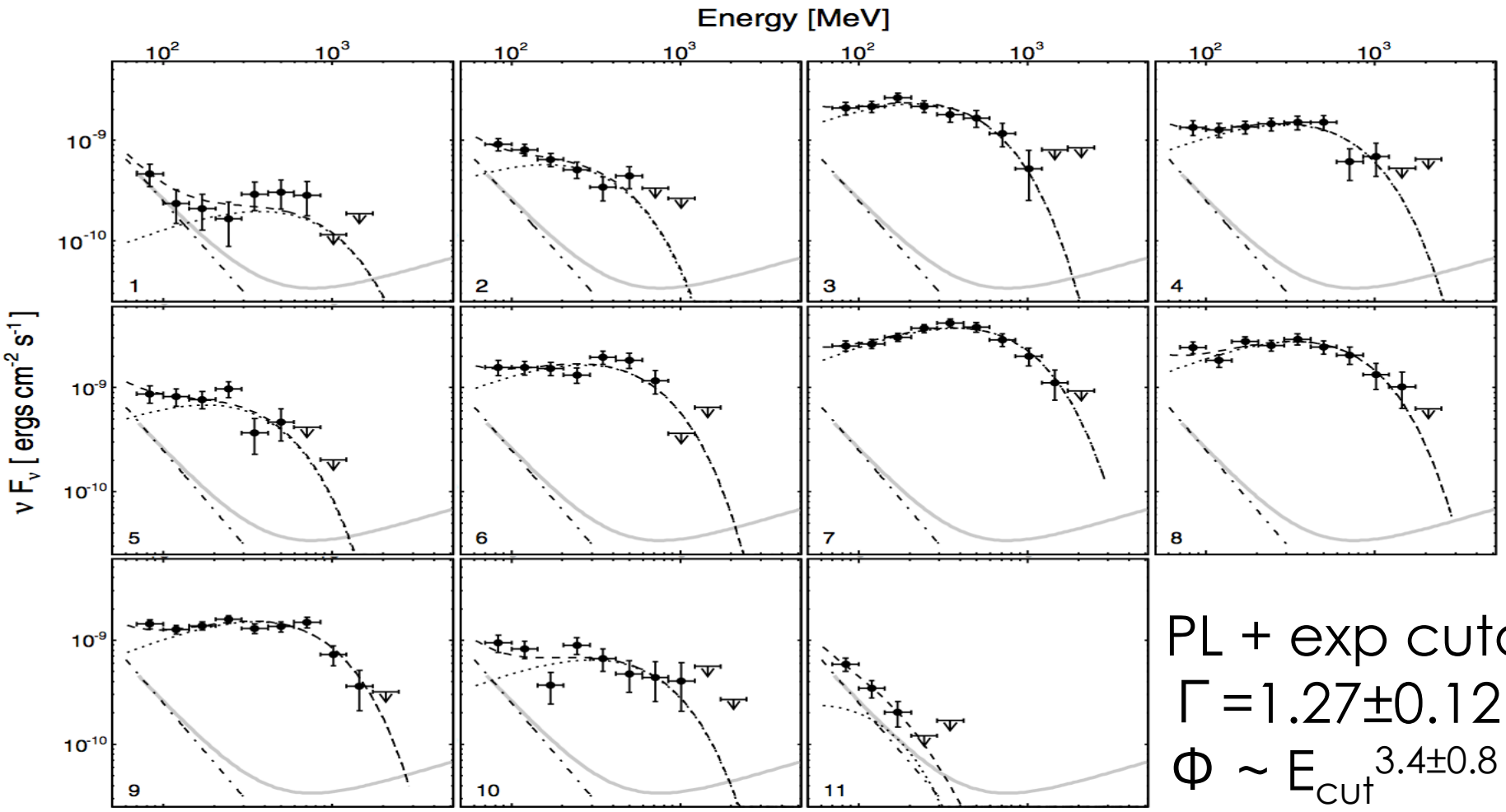


to be continued....

The Crab γ-ray flares



The Crab γ-ray flares



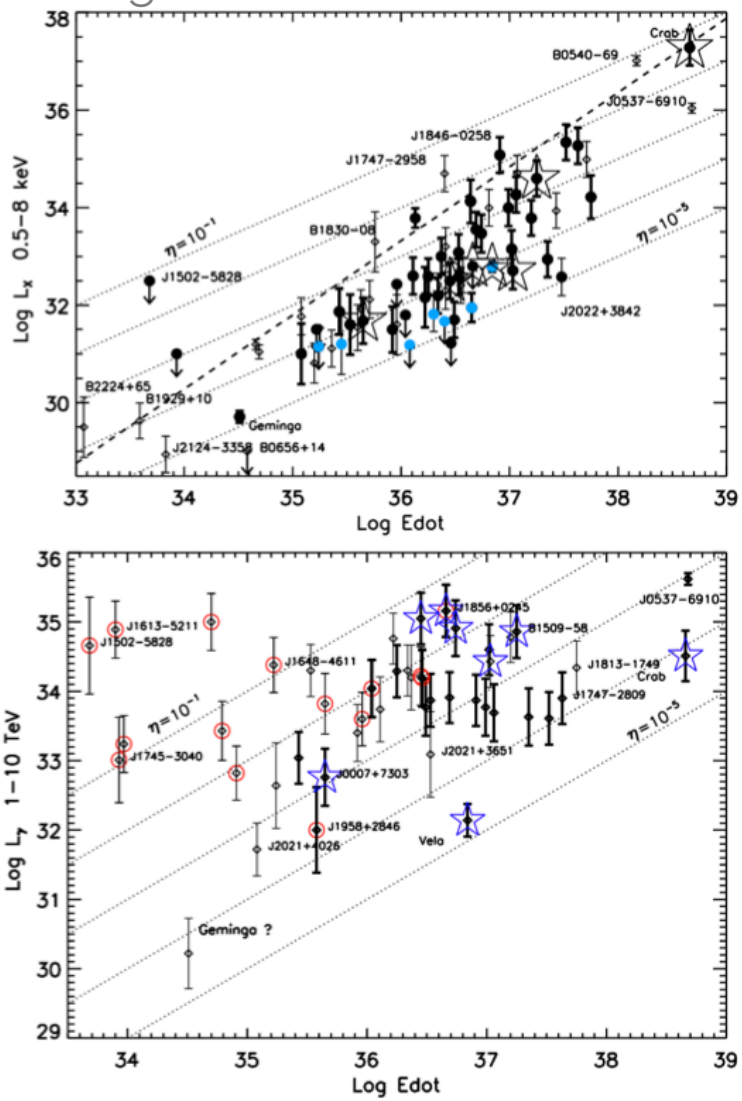
PL + exp cutoff

$\Gamma = 1.27 \pm 0.12$

$\Phi \sim E_{cut}^{3.4 \pm 0.8}$

TeV PWN a cumulative story

Kargaltsev+ 15



L_X-$\dot{E}$ CORRELATION
Kargaltsev 13,15, Acero+ 13

X-RAY by FRESH ENERGETIC e^-

THE UNDERLUMINOUS OUTLIERS RELATED TO SMALL B INCLINATION ANGLE *Rookyard+14*

NOT SO CLEAR CORRELATION L_γ-$\dot{E}$
Kargaltsev 13,15, Acero+ 13, HESS in preparation

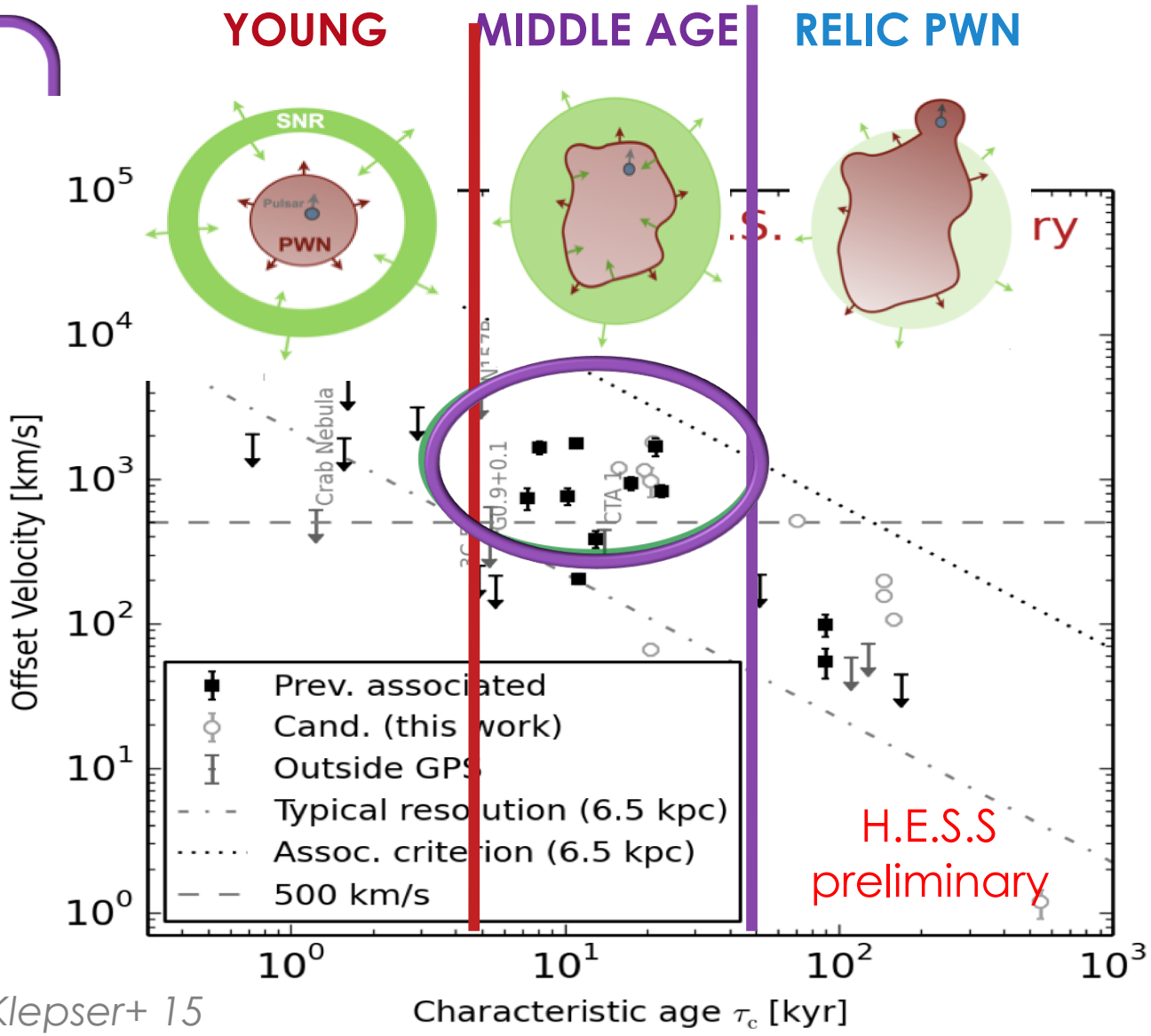
TeV = CUMULATIVE PWN STORY

SEVERAL low $\dot{E}$ (high τ) ONLY DETECTED AT TeV

PWN evolution

INTERACTION WITH SNR
GROWS slower
($R \sim t^{0.3}$ *Reynold 84*)
PULSAR OFFSET

FREE EXPANSION
PWN GROWS FAST
($R \sim t^{0.2}$ *Chevalier 77*)
UP to ~10 pc



Klepser+ 15

PWN evolution

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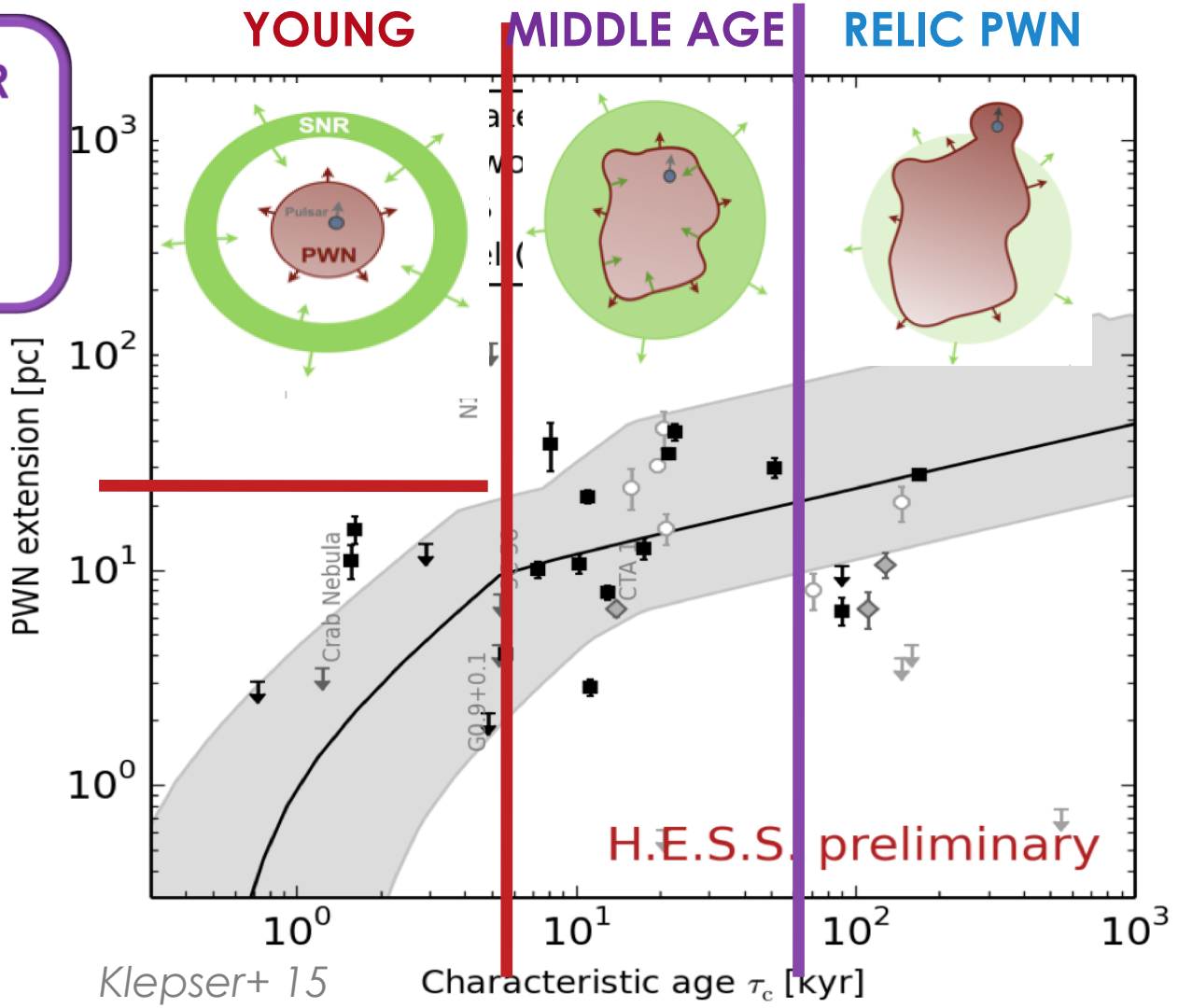
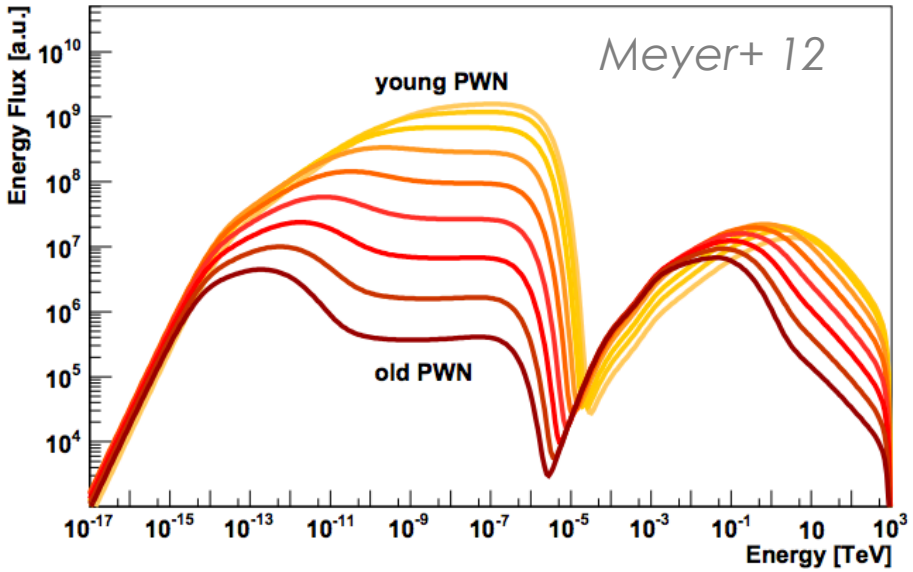


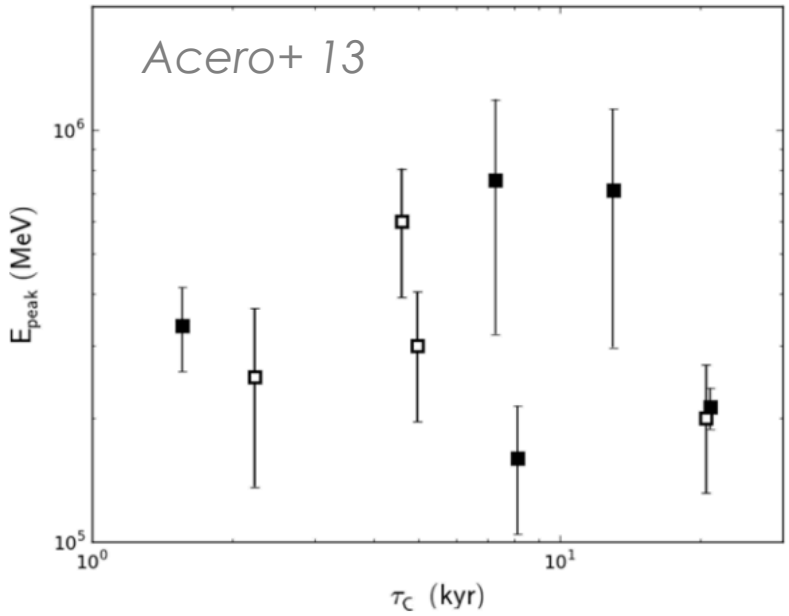
Klepser+ 15

PWN evolution

IC BECOMING DOMINANT



THE PEAK CONTRIBUTION SHIFTS TO LOWER ENERGIES WITH TIME
→ NOT SUPPORTED BY OBSERVATIONS SO FAR *Acero+ 13*



Why interesting?

PRIMARY POSITRON FACTORIES

Di Mauro+ 14, 15, Venter+ 15

COSMIC RAY PHYSICS: MOST RELATIVISTIC SHOCKS

($10^4<\Gamma<10^7$)

PEVATRONS

GRAVITATIONAL WAVES DETECTORS