Observations of the Crab Nebula and Pulsar with the MAGIC telescope

T. Y. Saito, G. Giavitto, K. Hirotani, S. Klepser,
M. Lopez, D.Mazin, T. Schweizer and R. Zanin
for the MAGIC Collaboration

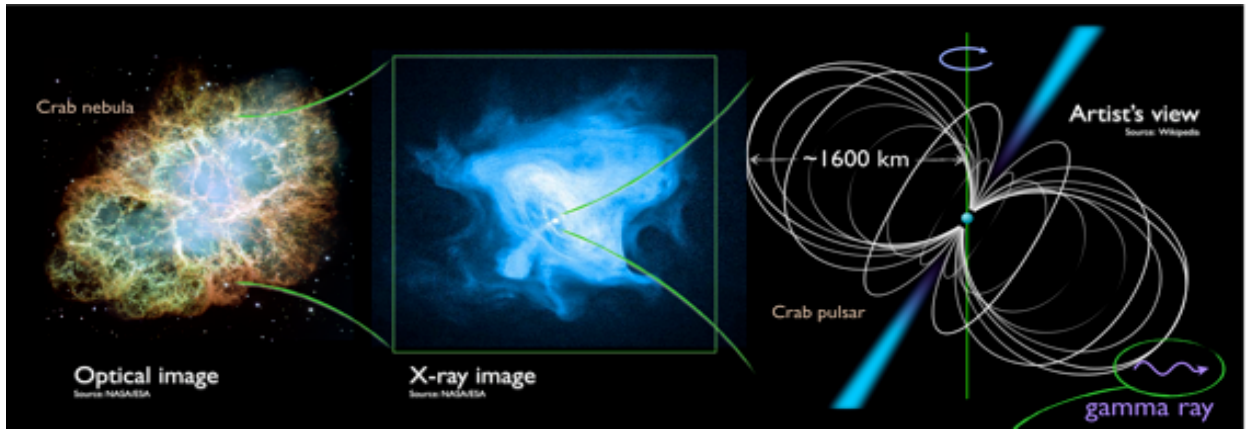
Painting of Crab

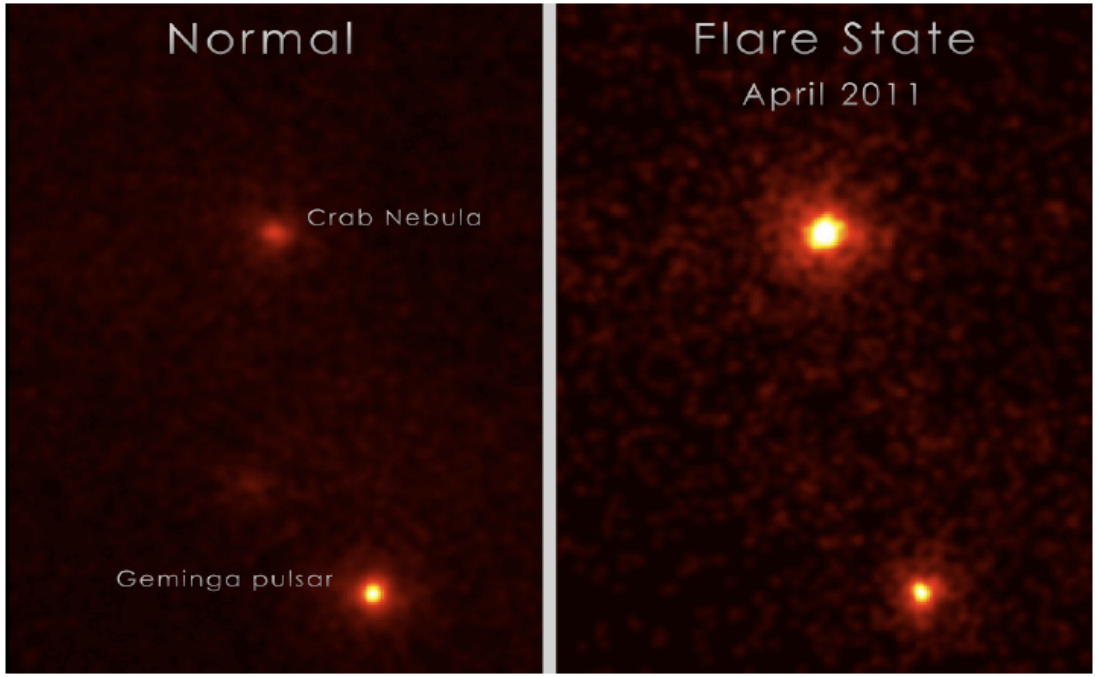
© www.Himmapan.com

Presenter: D. Paneque

the Crab

- Crab pulsar and PWN well studied across the electromagnetic spectrum
- Standard candle for gamma-ray astronomy
- **Recent surprises:**
- Nebula: Discovery of Flares at HE (>100 MeV) by AGILE (Tavani et al., 2011) and Fermi-LAT (Abdo et al., 2011)
- Pulsar: Detection of VHE emission (>100 GeV) by VERITAS (Aliu et al, 2011) and MAGIC (Aleksic et al., 2011, Aleksic et al., 2012)

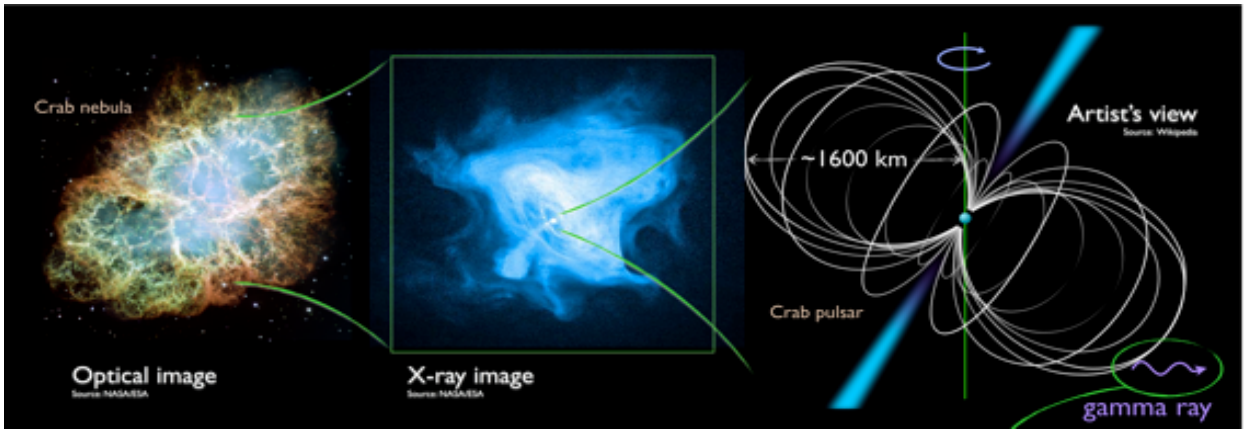


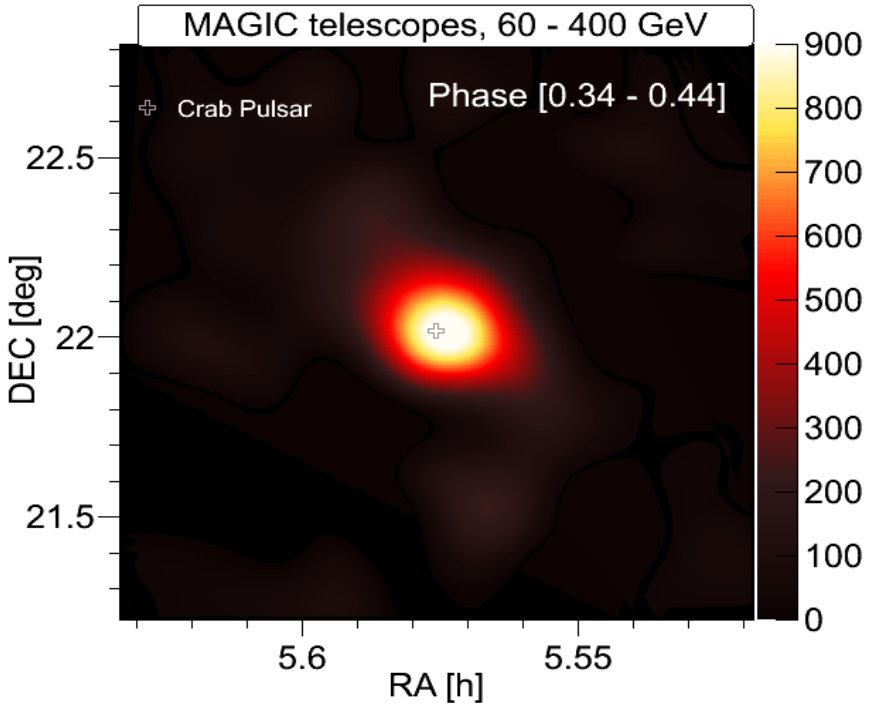


April 2011 Flare seen by Fermi-LAT
(Credit: NASA/DOE/Fermi LAT/R. Buehler)

the Crab

- Crab pulsar and PWN well studied across the electromagnetic spectrum
- Standard candle for gamma-ray astronomy
- **Recent surprises:**
- Nebula: Discovery of Flares at HE (>100 MeV) by AGILE (Tavani et al., 2011) and Fermi-LAT (Abdo et al., 2011)
- Pulsar: Detection of VHE emission (>100 GeV) by VERITAS (Aliu et al, 2011) and MAGIC (Aleksic et al., 2011, Aleksic et al., 2012)





Crab pulsar >60 GeV seen by MAGIC (Nebula subtracted)

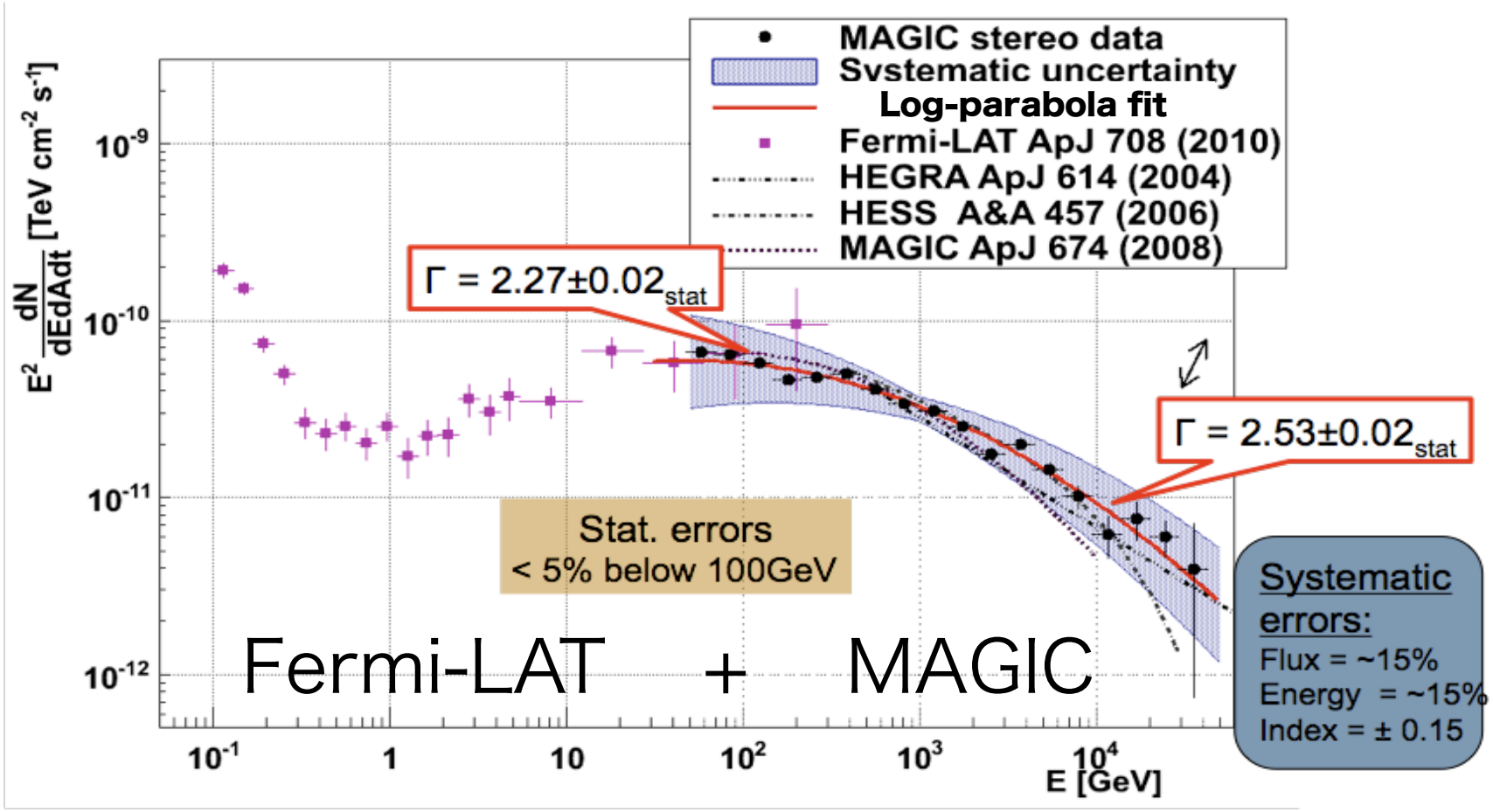
The Crab Nebula

Painting of Crab

© www.Himmapan.com

Crab Nebula: Spectrum

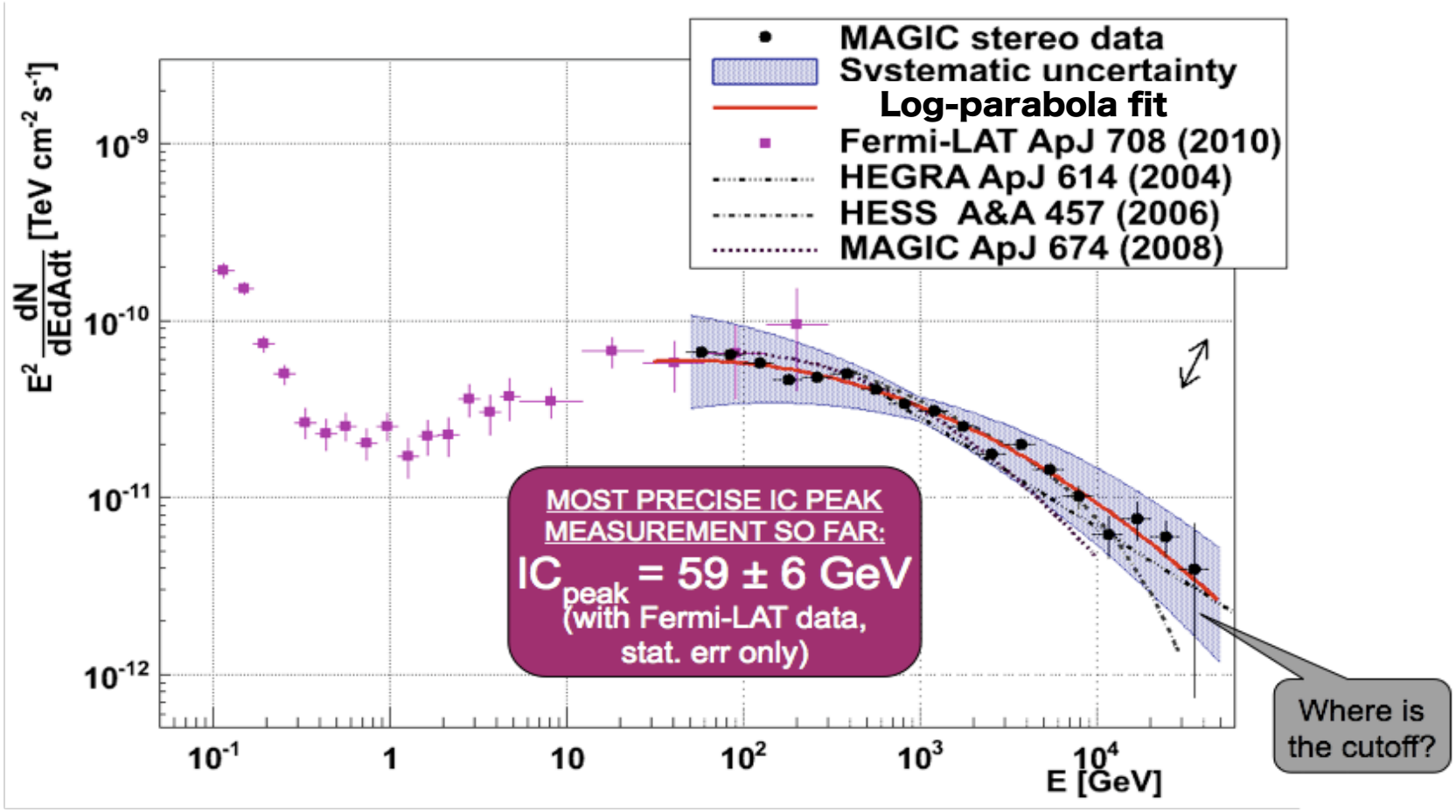
Stereo mode
2009 – 2011
T_{eff} = 48.7 h
Zenith 5°-50°



More than 5 decades in E

Crab Nebula: Spectrum

Stereo mode
2009 – 2011
T_{eff} = 48.7 h
Zenith 5°-50°



Crab Nebula: Spectrum

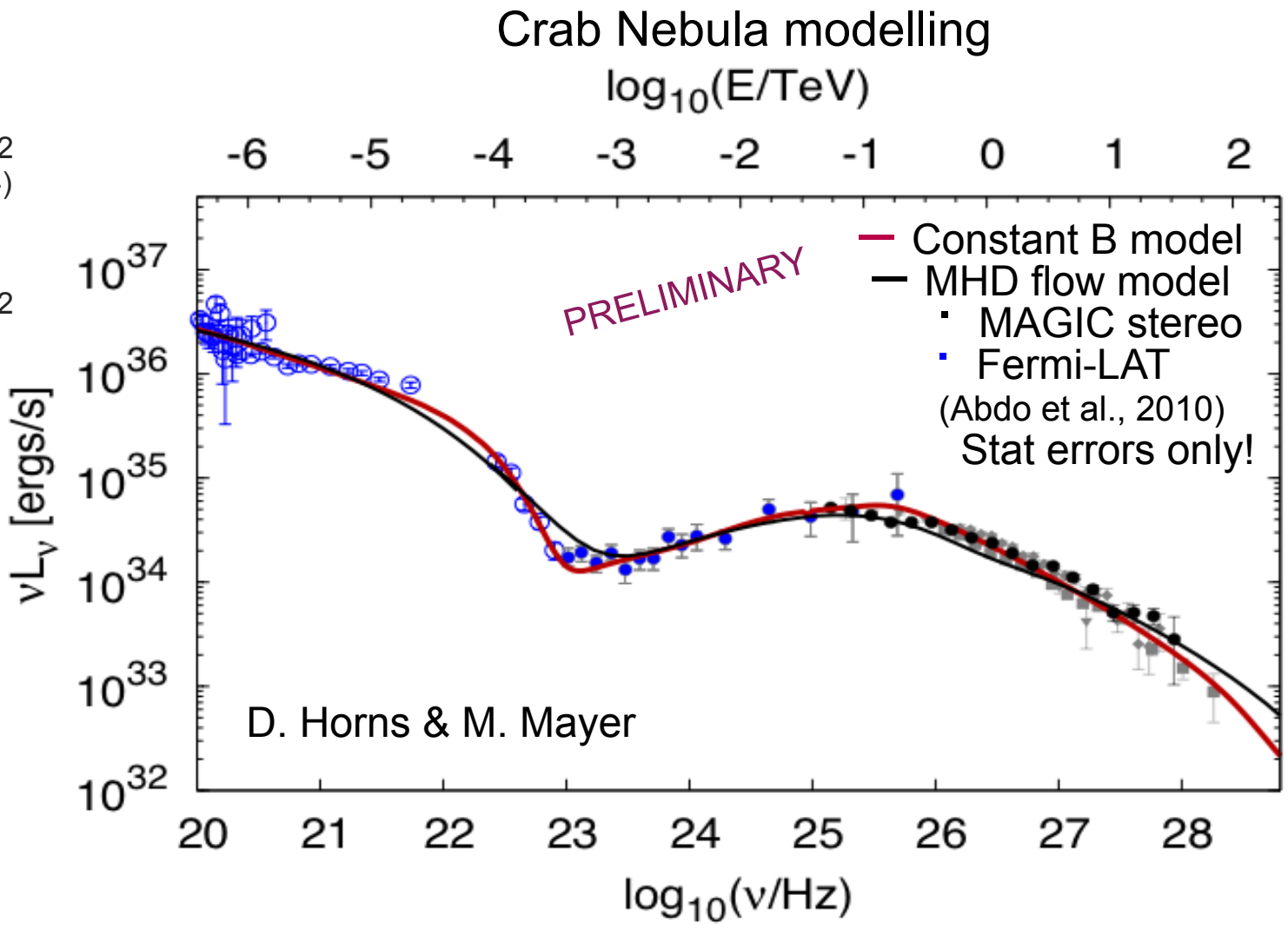
Three Models:

Constant B-field

(from Meyer et al. 2010, A&A 523:A2
as in Hillas et al. 1998, ApJ 503:744)

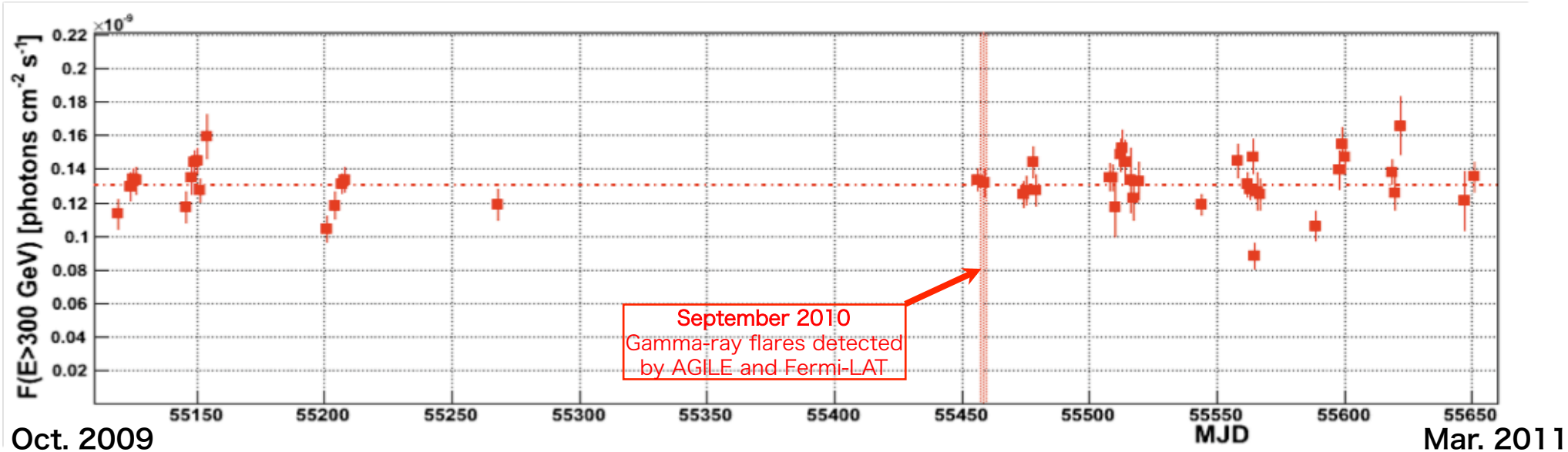
MHD flow model

(from Meyer et al. 2010, A&A 523:A2
as in K&C 1984, ApJ 283:694,
A&A 1996, MNRAS 278:525)



Crab Nebula: Variability and Flares

- **MAGIC light curve above 300 GeV**



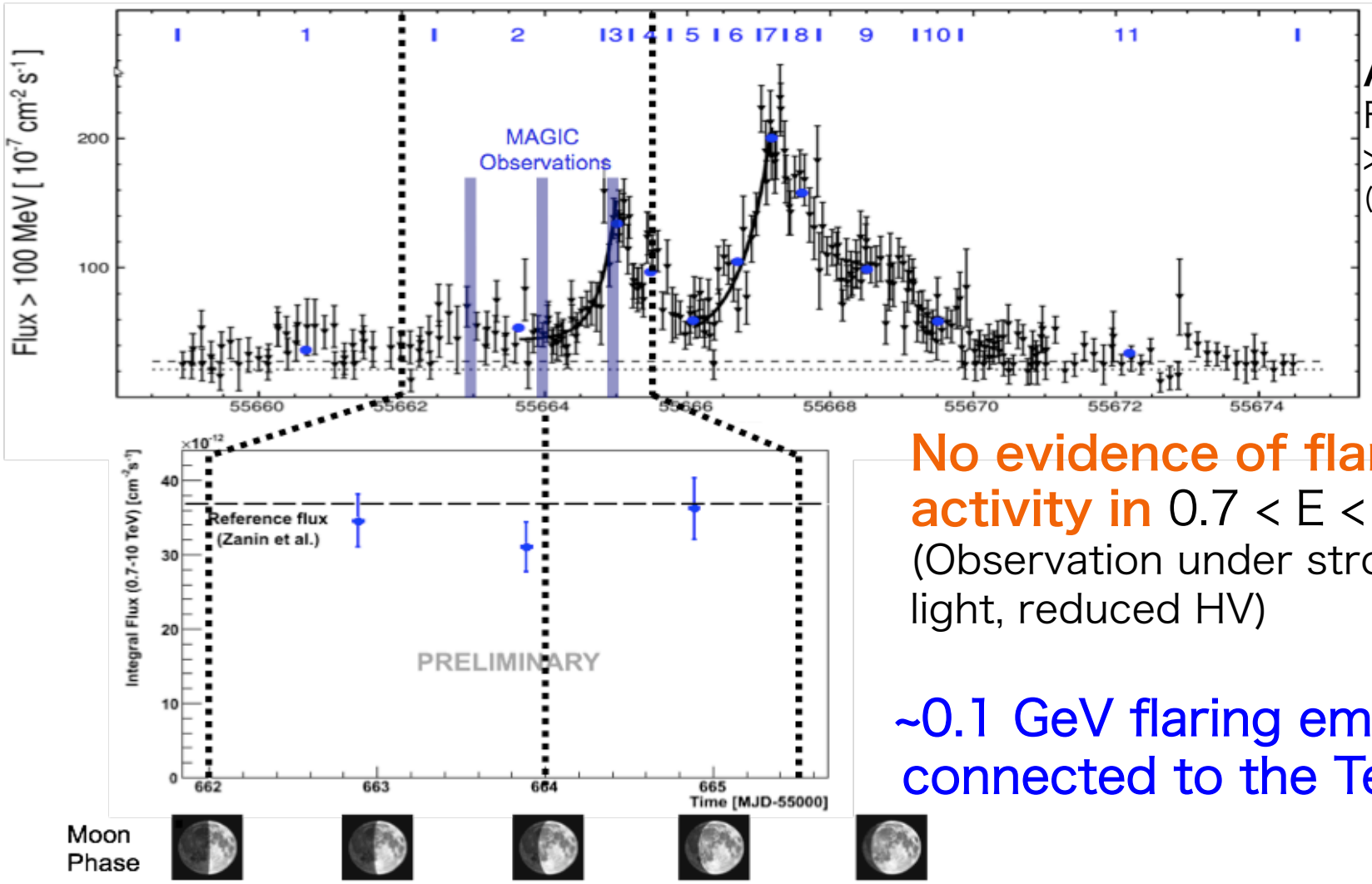
$$\text{Flux } (E > 300 \text{ GeV}) = (1.31 \pm 0.03_{\text{stat}} \pm 0.17_{\text{sys}}) \times 10^{-10} \text{ ph. cm}^{-2} \text{ s}^{-1}$$

MAGIC measures constant flux above 300 GeV

within systematic error of 13%

・During the GeV flares in Sep. 2010, ARGO reported a γ-ray excess at 4σ level, corresponding to a flux 3-4 times higher than usual at a median energy of 1 TeV (ATel 2921), while VERITAS reported no significant enhancement between 200 GeV and 3 TeV (ATel 2968)

Crab Nebula: Variability and Flares



April 2011 Flare
Fermi Light curve
> 100 MeV
(Buehler et al. 2011)

No evidence of flaring activity in 0.7 < E < 10 TeV
(Observation under strong moon light, reduced HV)

~0.1 GeV flaring emission is not connected to the TeV emission

・During the GeV flares in April. 2011, ARGO reported a γ-ray excess at 3.5σ level in corresponding to a flux few times higher than usual at a median energy of 3 TeV (I. De Mitri, Taup 2011)

The Crab Pulsar

Painting of Crab

© www.Himmapan.com

Crab Pulsar: Recent VHE history

2008-2010:

- MAGIC (mono) discovery at 25GeV rules out Polar Cap model
  (Aliu et. al 2008, Science 322:1221)

-Fermi-LAT measures exp. cutoff at ~6 GeV. It is not super-exponential and hence it also rules out the polar cap model
-(Abdo et al, 2010)

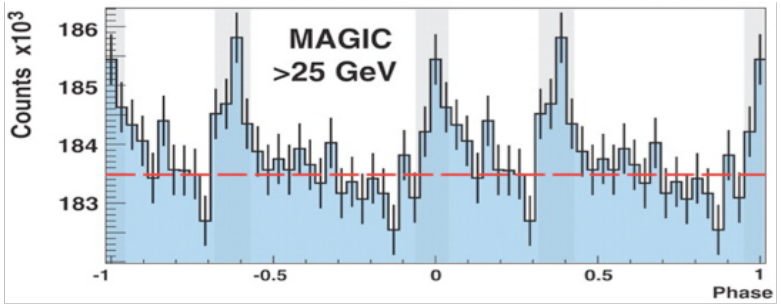
2010: PhD thesis, Takayuki Saito

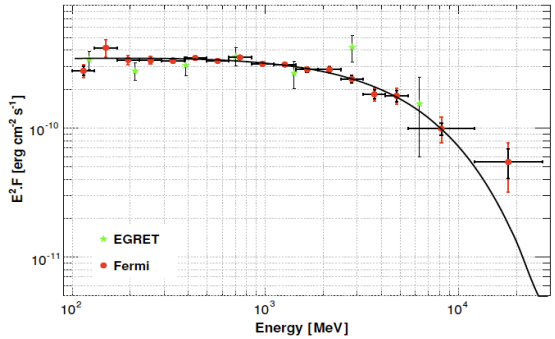
2011:

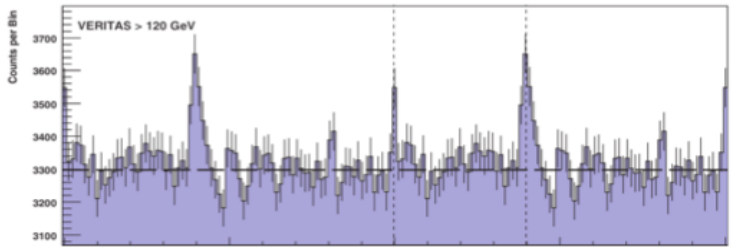
- VERITAS detect emission >100 GeV excludes exponential cutoff
  (Aliu et. al 2011, Science 334:69)

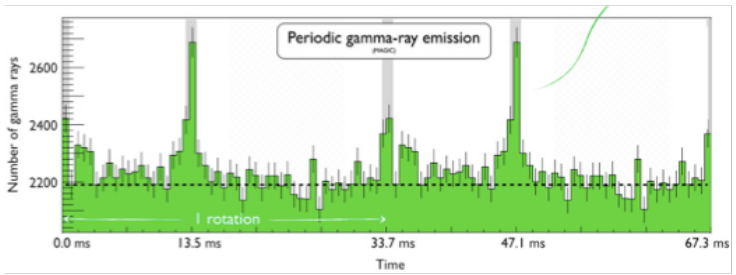
- MAGIC mono measures phase resolved spectrum at 25-100 GeV excludes exponential cutoff
  (Aleksić et. al 2011, ApJ 742:43)

· MAGIC stereo measures phase resolved spectrum at 50 - 400 GeV(Aleksić et. al 2012, A&A 540:A69)









Crab Pulsar: Mono Observations

PhD thesis of T. Saito (2010)

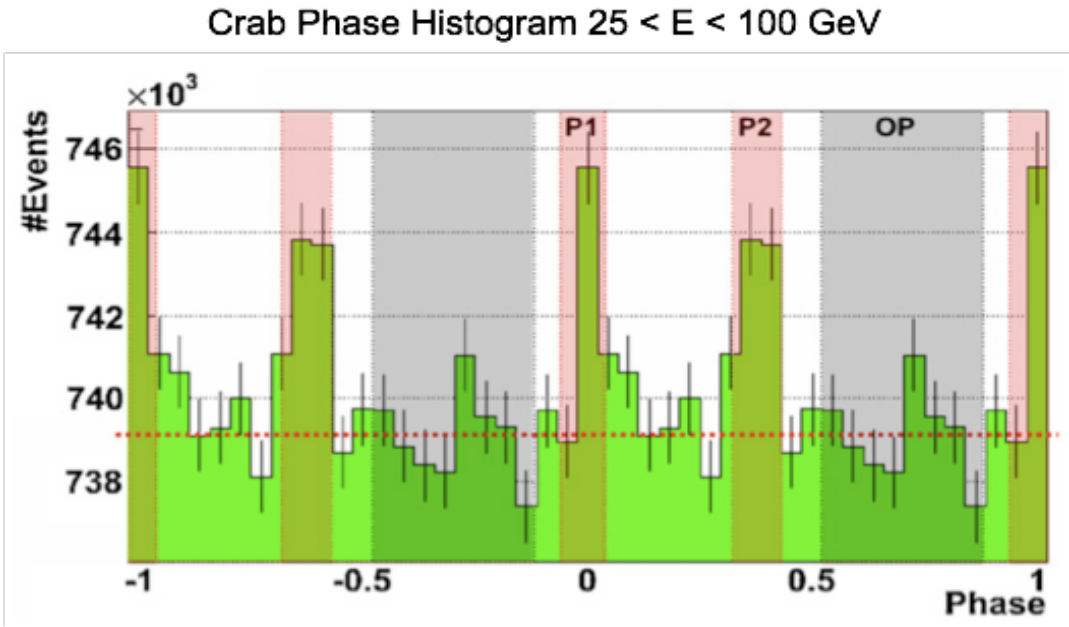
- 59 hrs of data (Oct. 2007 - Feb.2009)
  (Aleksić et. al 2011, ApJ 742:43)

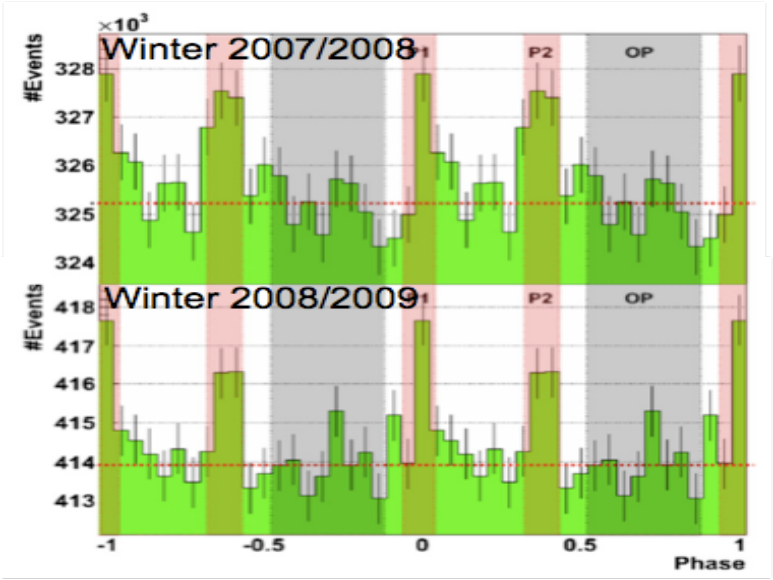
- Sum-trigger: threshold at 25 GeV
- EGRET – era peak definitions:
  (from Fierro et al., 1998, ApJ 494:734)
  21% of the whole phase

- Pulsation detected at 7.5σ (P1+P2)

→ Indication that peaks become narrower than at MeV energies

→ No significant yearly variability

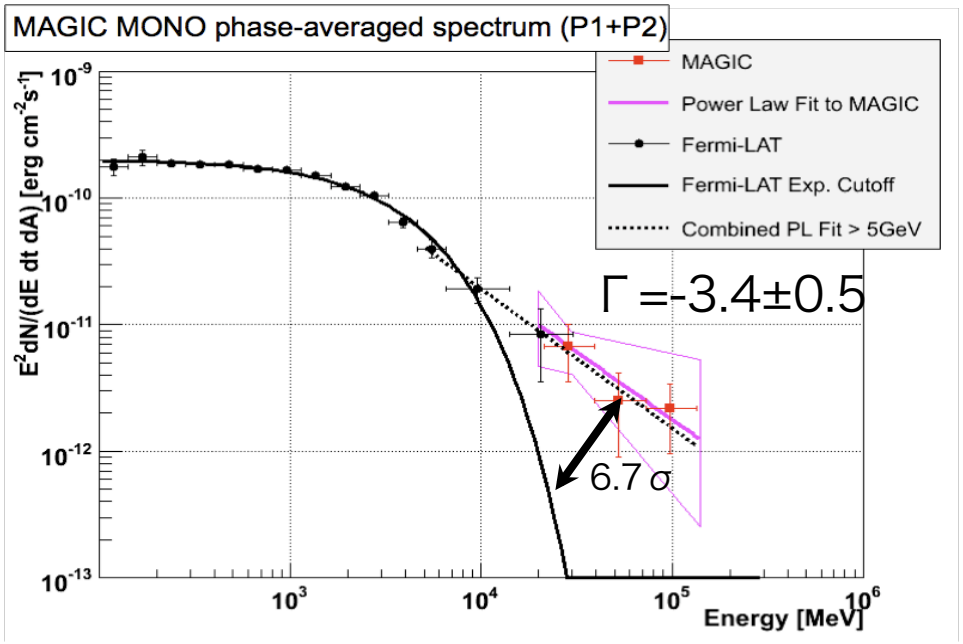




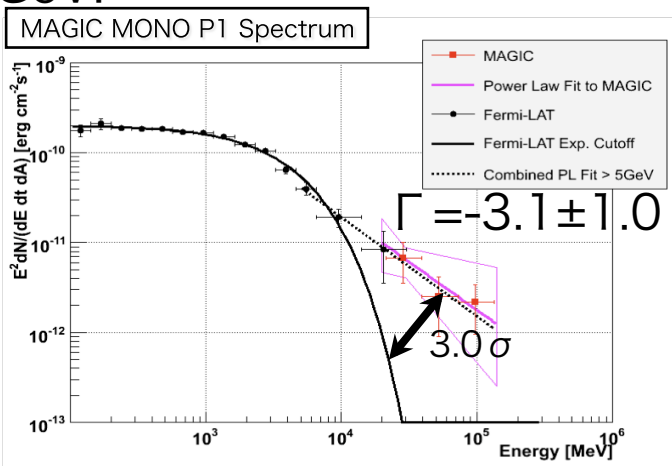
Crab Pulsar: mono observations

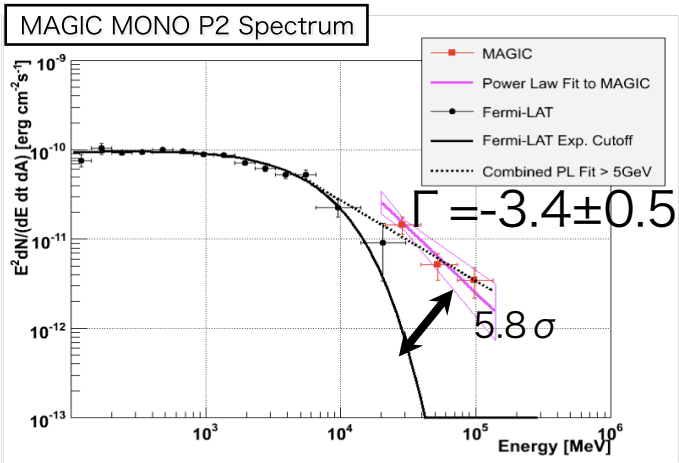
PhD thesis of T. Saito (2010)

- Phase averaged (P1+P2) and P1, P2 spectra are power-laws above ~5 GeV
- **Exclude the spectrum with an exp. cutoff reported by Fermi**
  - P1+P2 with 6.7 σ (5.8 σ with sys. err)
  - P1 with 3.0 σ (2.5 σ with sys. err)
  - P2 with 5.8 σ (4.7 σ with sys. err)



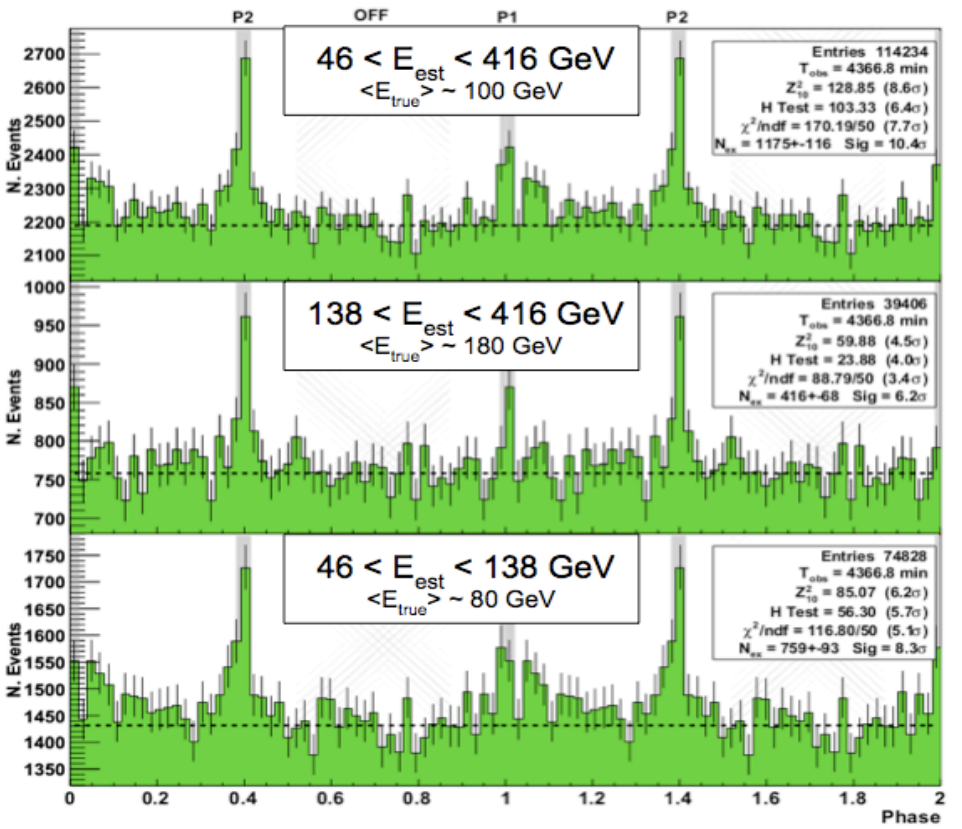
- Fermi-LAT + MAGIC fit > 5 GeV: PL with Γ = -3.0 ± 0.1
- Syst. uncertainties:
  - 20% on energy scale
  - 20% on flux
  - 0.3 on photon index





Crab Pulsar: Stereo Observations

- 73 hrs of data (Oct. 2009 - Mar. 2011)
  (Aleksić et. al 2012)
- Energy range: E > 50 GeV
- Pulsation firmly detected
  - H-Test (unbinned) : 6.4 σ
  - EGRET-peaks (a-priori) : 7.7 σ
- **Peaks get narrower w/energy**
- New peak definitions ±2 σ FIT:
  - 8.8% of the whole phase
  - P1+P2:10.4 σ, P1 5.5 σ, P2 9.9 σ
- 3.4 σ hint at TW1 [0.04:0.14]

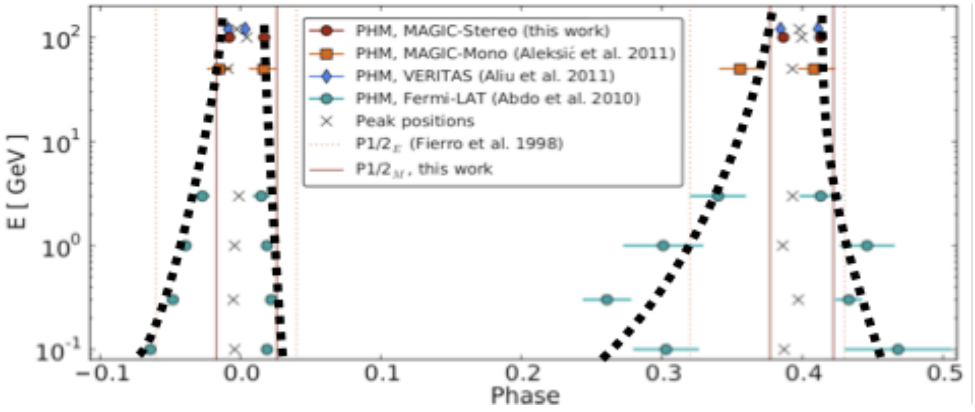


- P1/P2 ratio ~ 0.4 ± 0.2
  at 100 GeV
- No significant yearly
  variability

100 GeV

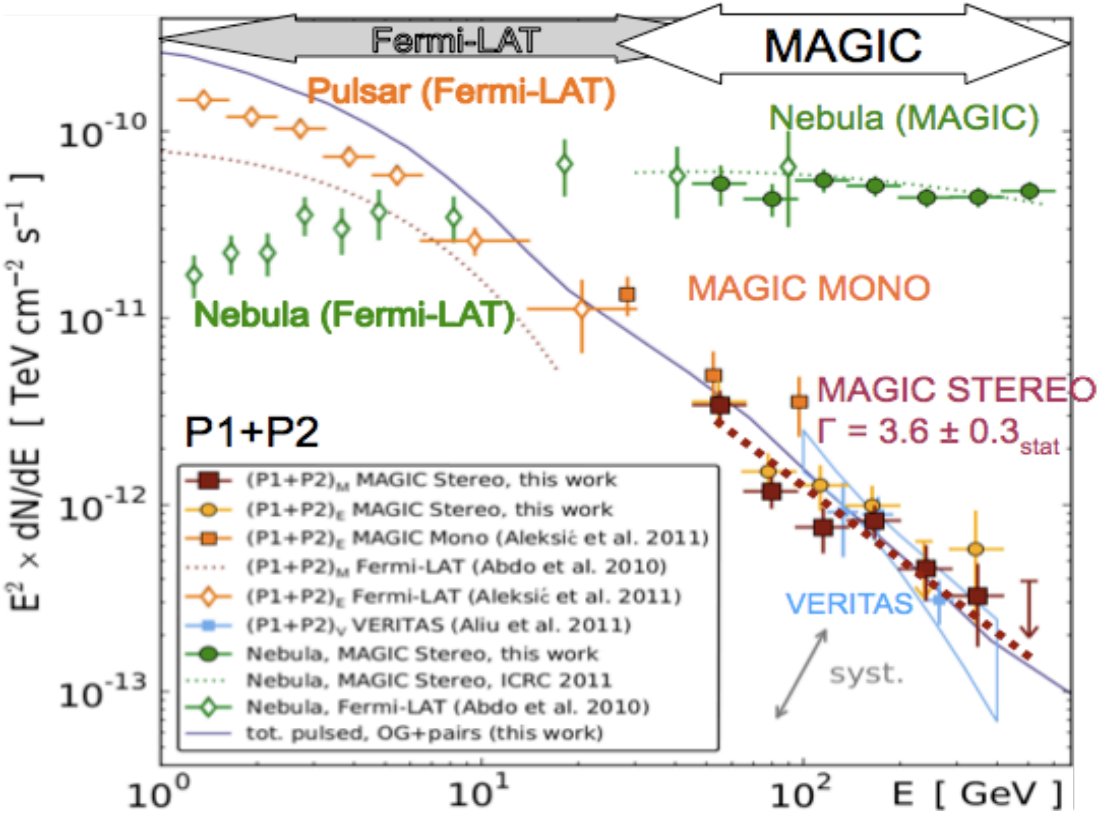
10 GeV

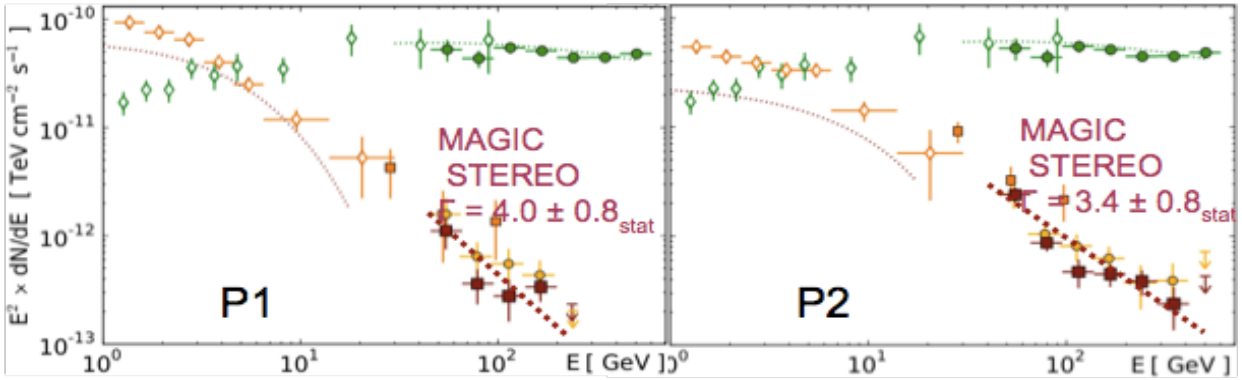
1 GeV



Crab Pulsar: Stereo Observations

- Stereo spectrum: Power law, joins Fermi-LAT, MAGIC mono and VERITAS
- *Double-checked with Nebula spectrum: ok down to 50 GeV*
- Phase-averaged index :
  - P1+P2 : Γ = -3.6 ± 0.3
  - P1 : Γ = -4.0 ± 0.8
  - P2 : Γ = -3.4 ± 0.3
- Systematic uncertainties:
  - 17% energy scale
  - 19% flux normalization
  - 0.2 photon index



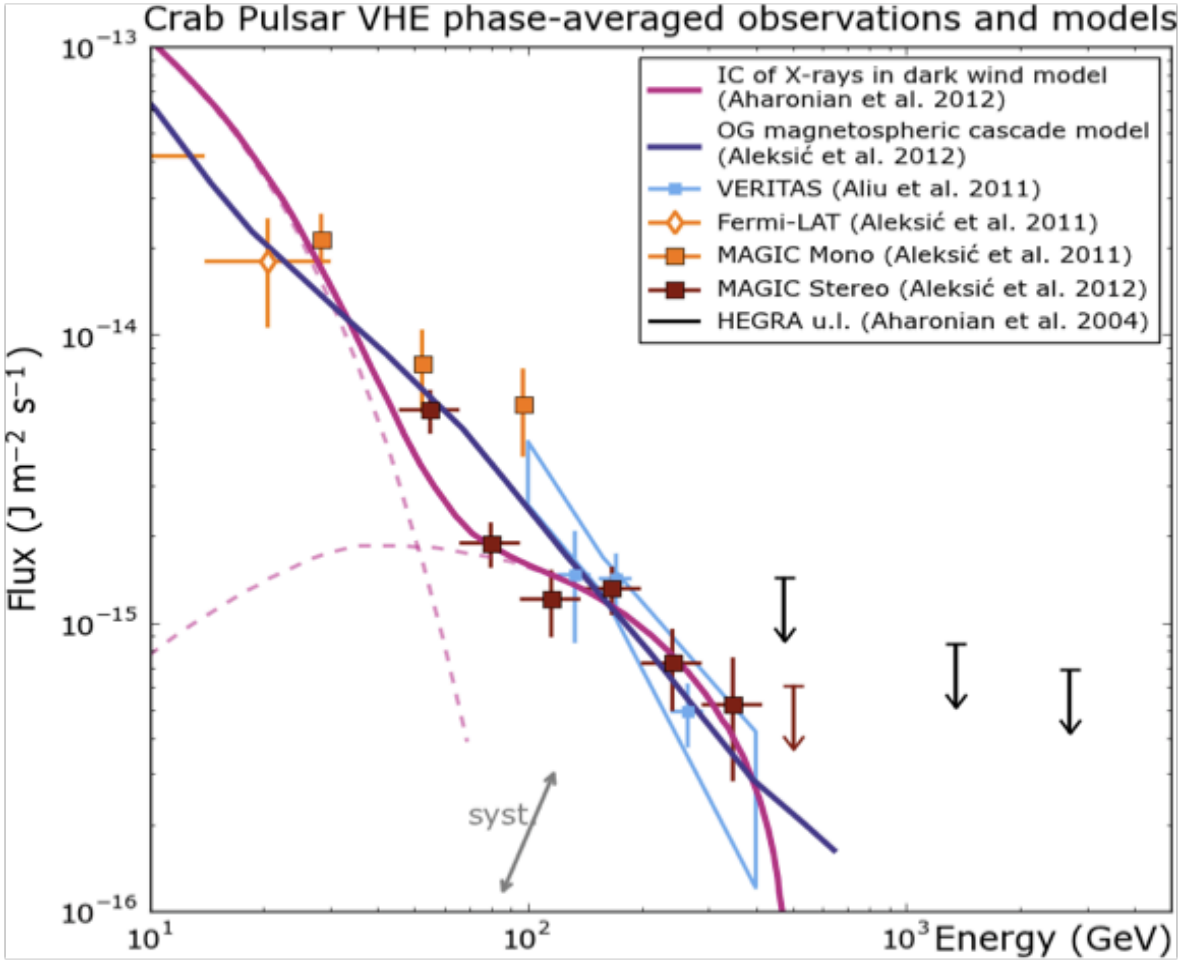


Crab Pulsar: Models

- Curvature radiation from the outer gap (OG) cannot explain the VHE spectrum measured with MAGIC and VERITAS

- Proposed extension of OG model:
  - Self-consistent 3D solution of Poisson and Radiative Transfer: (as in Hirotani, K. 2006, Mod. Phys. Lett. A, 21:1319)
  - VHE pulsed γ-rays are produced via Inverse compton on magnetospheric IR-UV photons by secondary and tertiary pairs at >0.5 light cylinder (LC) radius

- Other possibilities exists:
  - IC upscattering of pulsed X-ray photons in "Dark wind region" outside LC (Aharonian et al. 2012, Nature letters)
  - Synchrotron emission or Curvature emission near LC (Chkheidze et al., 2011,ApJ 730:62) (Bednarek W., 2012, MNRAS 424. 2079)
  - IC of secondary pairs in Annular gap(Du et al., 2012 ApJ 748:84)



Is there a 2nd component or a cutoff?

crucial points now structures at ~100 GeV emission at > 500 GeV

Conclusion

- MAGIC has observed both the Crab Nebula and the Pulsar with an unprecedented accuracy
- Nebula IC peak determined to be at 59 ± 6 GeV. (Fermi-LAT + MAGIC)
- No evidence of flux variability at TeV energies during the GeV flares from 2010 and 2011

  → *Agreement with VERITAS, but controversy with ARGO-YBJ*

- First VHE Pulsar phase-resolved spectrum, from 25 to 400 GeV. Power-law extension of Crab pulsar spectrum confirmed.

  → *Agreement with VERITAS (average phase) spectrum above 100 GeV*

  → *Fermi + IACTs can resolve the spectrum of the Crab pulsar from 0.1 to 400 GeV without any gap*

- These experimental observations pose some challenges to conventional pulsar emission theories.

  → *Is the Crab pulsar unique ? Or are there other VHE pulsars ?*

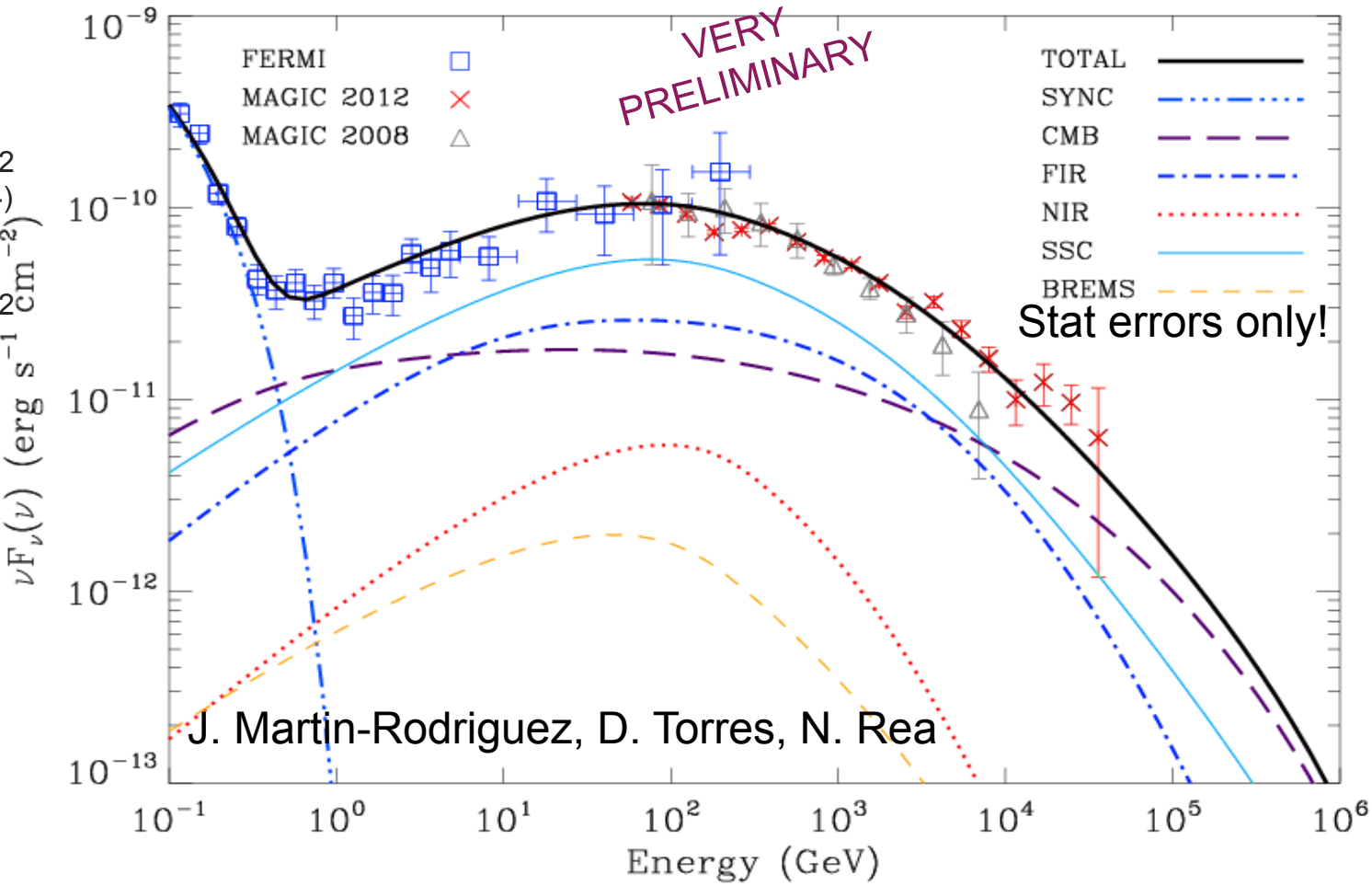
- The completion of the upgrade of the MAGIC telescopes (involving an improved camera, readout system, and the stereo-sumtrigger) will boost the performance of MAGIC telescopes to study these extreme objects.

- Backup

Crab Nebula: Spectrum

Three Models:

Constant B-field
(from Meyer et al. 2010, A&A 523:A2
as in Hillas et al. 1998, ApJ 503:744)

MHD flow model
(from Meyer et al. 2010, A&A 523:A2
as in K&C 1984, ApJ 283:694,
A&A 1996, MNRAS 278:525)

Time-dependent
(as in Martin-Rodriguez et al.,
in prep.)