Fermi-LAT Observations of the Vela-X PWN

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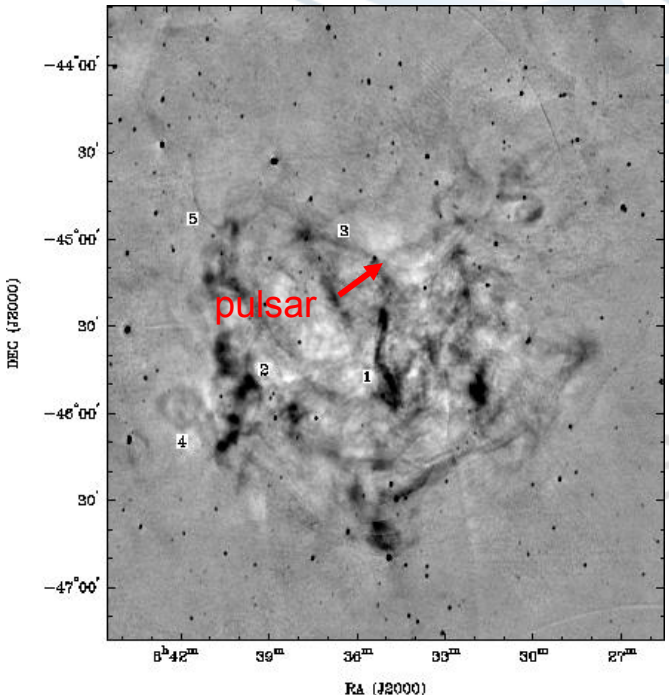
Vela-X

- **Inside the 8°-diameter Vela SNR shell, closest SNR to contain an active pulsar (D ~290 pc)**
- **G263.9-3.3 : Pulsar Wind Nebula aka « Vela-X »**
  - **Extremely bright (1000 Jy) diffuse radio structure of size 2°- 3°**
  - **Located primarily south of the pulsar**
  - **PWN formed by relativistic outflow powered by the spin-down of the Vela pulsar (Weiler & Panagia, 1980)**

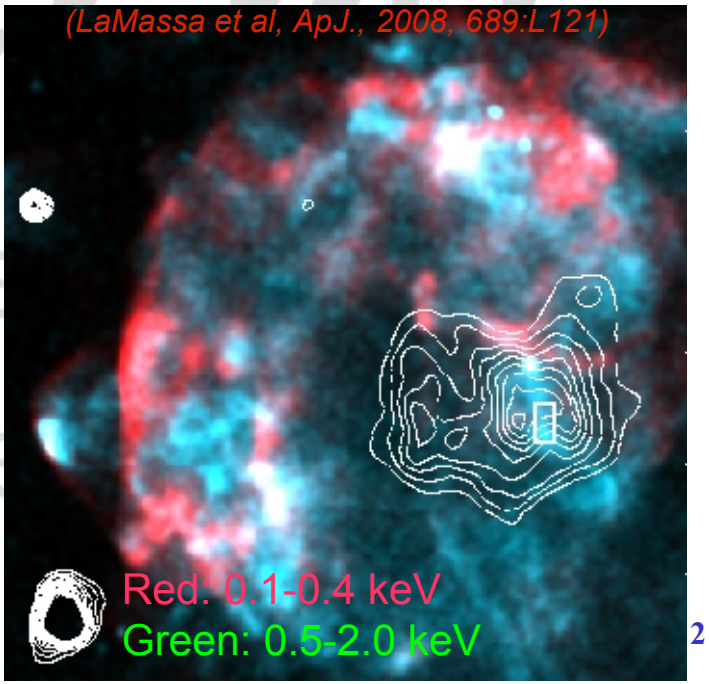
MOST observation of Vela X at 843 MHz

(Bock et al, Astronom. J. 116:1886, 1998)



Composite ROSAT-RASS image of Vela SNR with Parkes radio contours overlaid

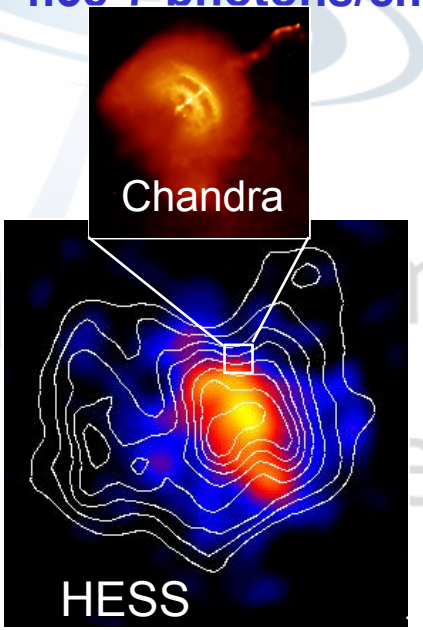
(LaMassa et al, ApJ., 2008, 689:L121)

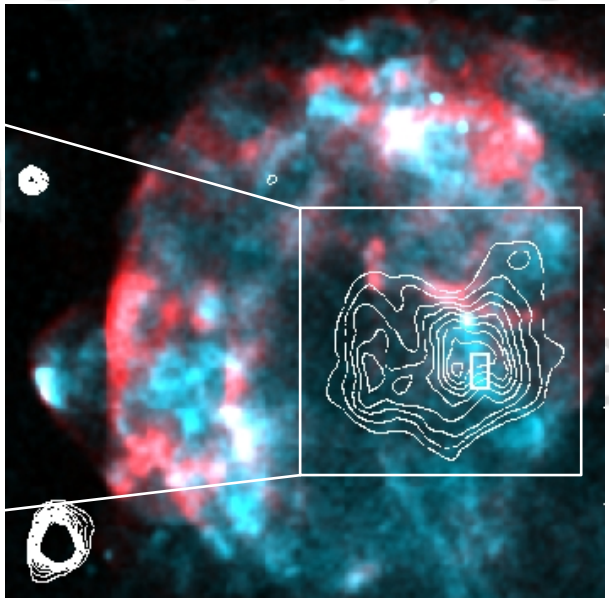


Vela-X multi-wavelength observations

- **Elongated « cocoon-like » hard X-ray structure extends southward of the Vela pulsar**
  - **This is not the pulsar jet (which is known to be directed to NW)**
  - **Apparently the result of relic PWN being disturbed by asymmetric passage of the SNR reverse shock (e.g. Blondin et al. 2001)**
  - **Clearly identified by HESS as an extended VHE structure**
  - **An upper limit assuming a point source at the position of the Vela pulsar was reported using the first 75 days of Fermi data:**

F(>100 MeV) < 4.5e-7 photons/cm^2/s ***(Abdo et al.,2009, ApJ, 696, 1084)***

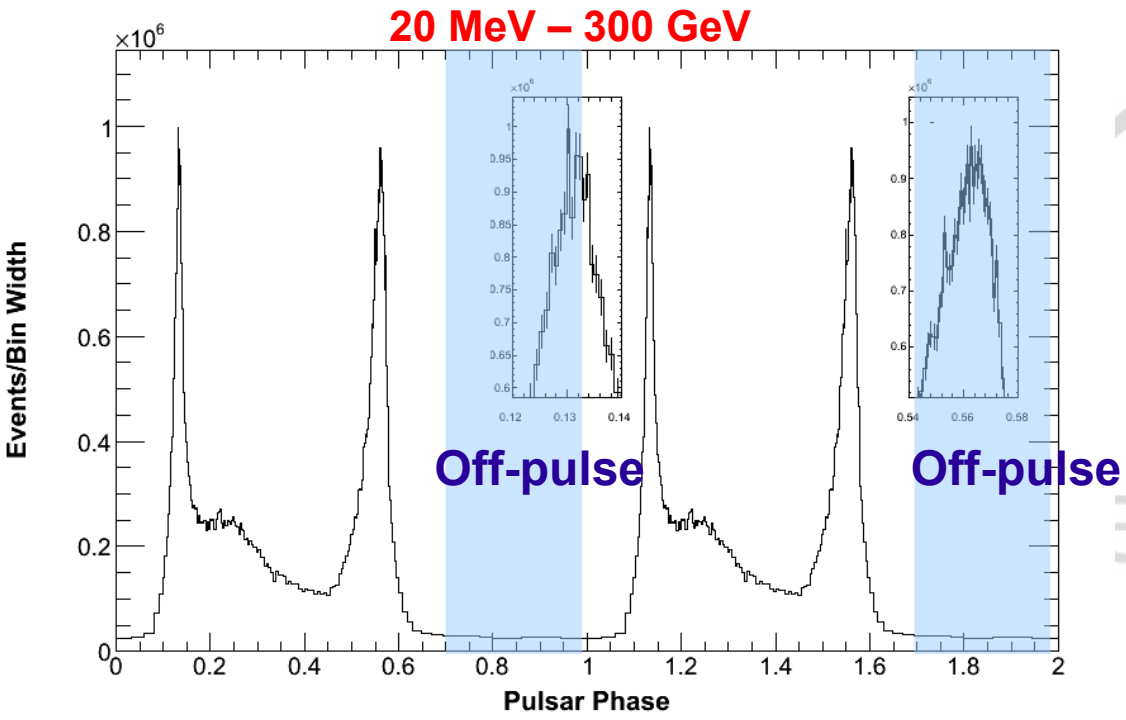




The Vela pulsar: very bright in gamma-rays !

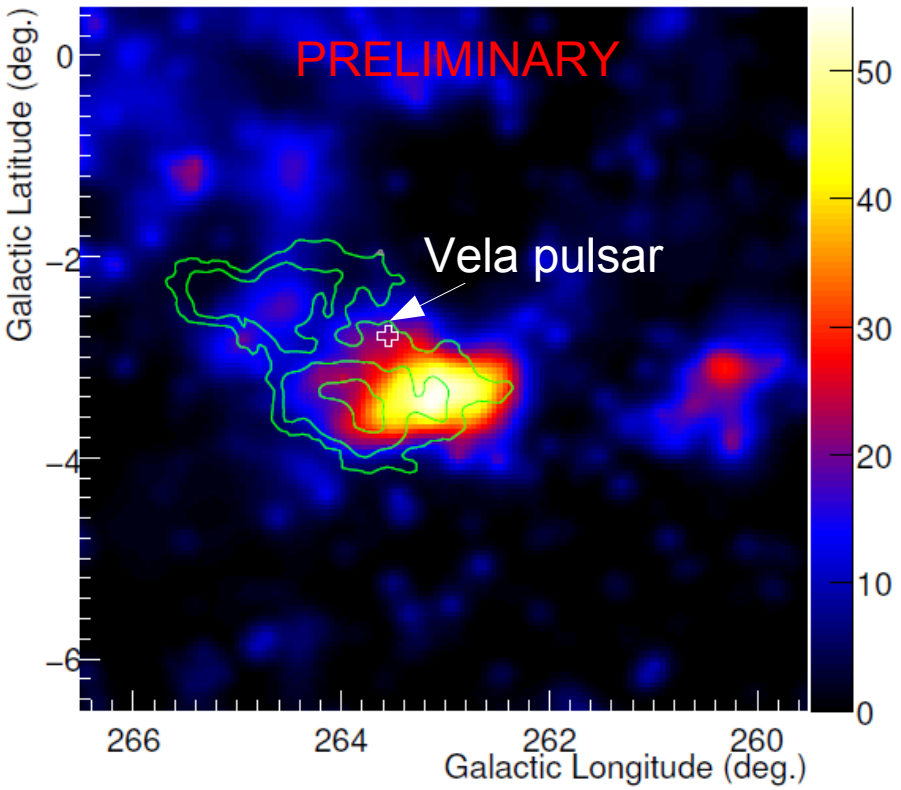
- **Timing model derived purely from LAT observations**
- **RMS residuals of the TOAs with respect to the fitted model= 63μs**
- **Data from August 4, 2008 to July 4, 2009: 127019 photons above background !**
  - **restrict to phase interval [0.7 – 1.0] to study the nebula**

Vela pulsar phase histogram (2 cycles are shown)
Poster P2-93 (T. Johnson et al. for the Fermi-LAT Collaboration)



Significant detection by Fermi-LAT

- **11 months of survey data (08/04/2009 – 07/04/2009):**
  - **Diffuse class events**
  - **E > 800 MeV**
  - **Off-pulse interval only**
- **Bright emission South of the Vela pulsar + fainter emission to the East**
- **Gamma-ray complex lies within Vela-X**
- **Additional source coincident with the SNR Puppis A**



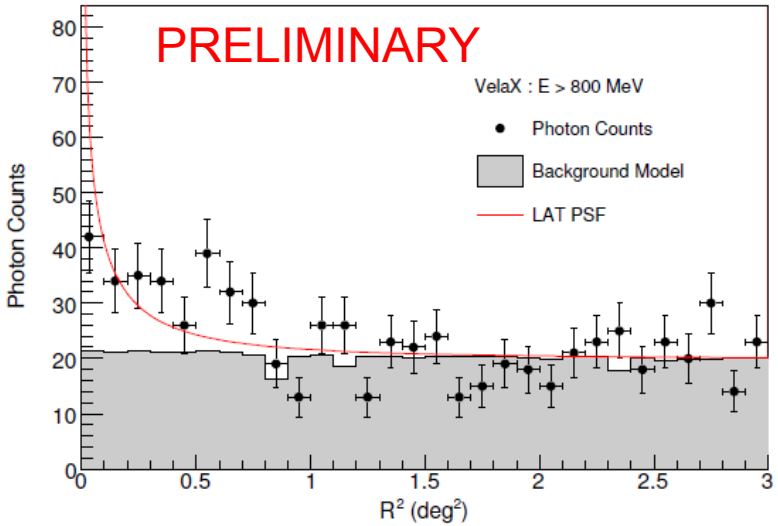
Fermi-LAT TS map (E > 800 MeV)
WMAP radio contours at 61 GHz superimposed (green solid line)

An extended source

- **E > 800 MeV**
- **Fit using different spatial templates**
  - **Fitting a disk to the data improves the TS by 40.4**
    - **Best fit with a disk of radius 0.88° ± 0.12°**
  - **Replacing the disk with the HESS spatial template decreases the TS**
  - **Using the radio contours improve the TS by 11.7 wr to the disk**

Model	Name	TS
Point Source	PS	44.0
Disk	D	84.4
HESS		53.1
WMAP 41 GHz		96.1
WMAP 61 GHz		94.0

Gamma-ray source significantly extended
Best match with radio morphology but simple disk is not rejected at high significance



Fermi-LAT radial profile (E > 800 MeV)
Fermi-LAT PSF overlayed (red solid line)

Fermi-LAT spectrum of Vela-X

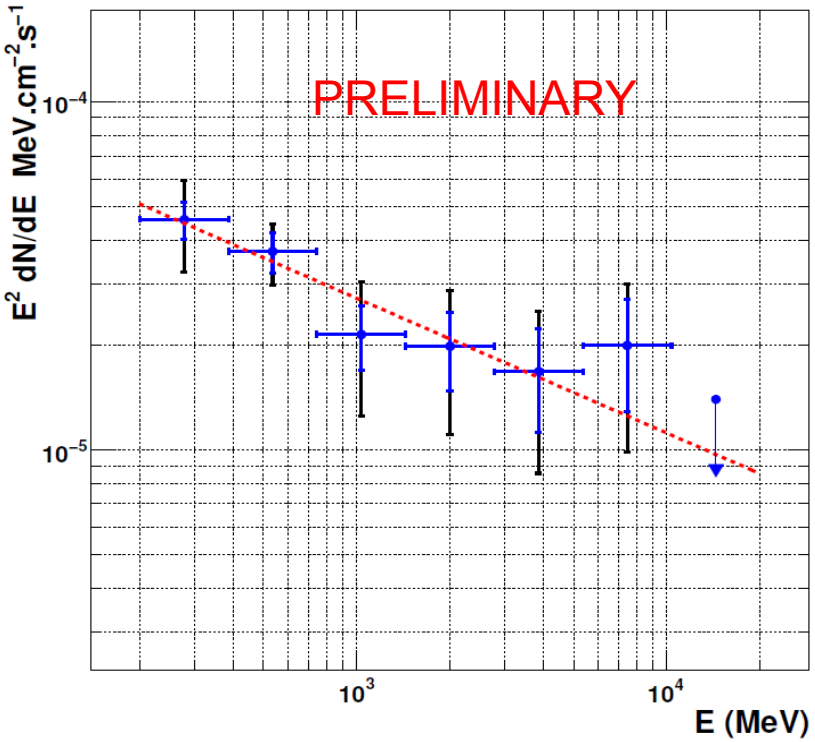
- **Analysis in the off-pulse window; 200 MeV < E < 20 GeV**
- **Spatial template used: uniform disk**
- **Vela-X spectral parameters (renormalized):**
  - **Spectral index: $2.41 \pm 0.09_{stat} \pm 0.15_{syst}$**
  - **Integral flux (>100 MeV): $(4.73 \pm 0.63_{stat} \pm 1.32_{syst}) \times 10^{-7}$ cm^{-2} s^{-1}**
- **No indication of a spectral cut-off at high energy detected**

Spectral energy distribution of Vela-X

(renormalized to total phase)

blue line: Statistical errors

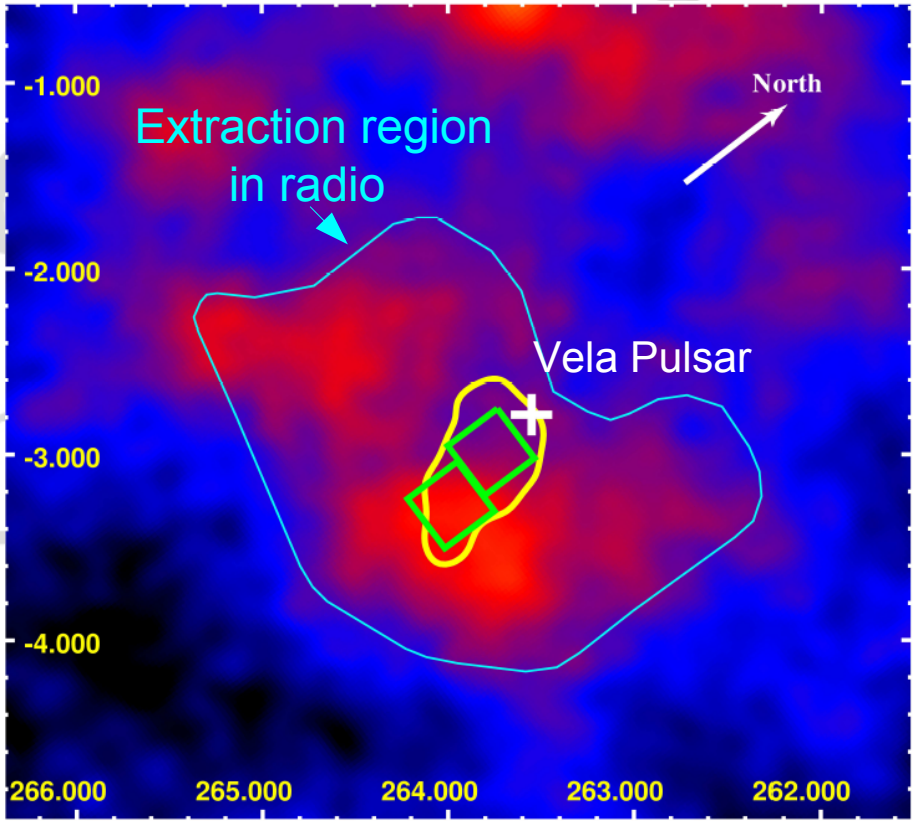
black line take into account both systematic and statistical errors



Analysis of radio data

- **Archival 5-year WMAP all-sky images at 23-, 33-, 41-, 61- and 94-GHz**
  - **As the resolution increases to higher frequencies, it is increasingly separated into eastern and western sub regions**
  - **We measured a flux for each energy band and estimated a flux error**
    - **Flux density spectral index of 0.5 ± 0.05**

WMAP sky map of the Vela-X region at 61-GHz



Analysis of ASCA data

For the cocoon:

- Data sets 23043000 and 23043010 cover the southern region
- Data set 25038000 cover the northern region
- Fit to the combined region:
  - Average index of 2.06 $\pm$ 0.05
  - 2-10 keV flux of (6.7 $\pm$ 0.4)$\times$ 10^{-11} erg cm^{-2} s^{-1}

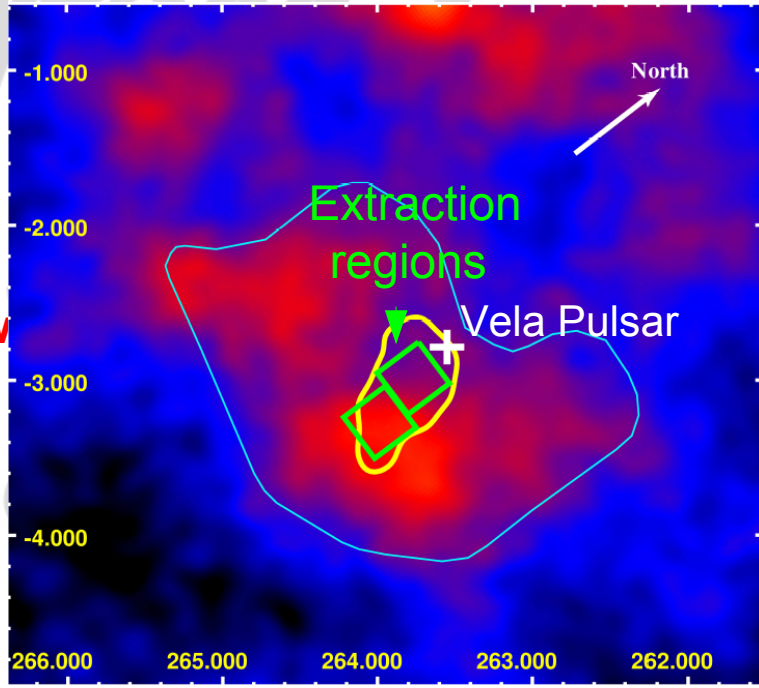
For the halo covered by the radio/LAT component:

Large region only well covered by the ROSAT All Sky Survey

Measured counts in this region in the hard-band 0.5-2.0 keV image

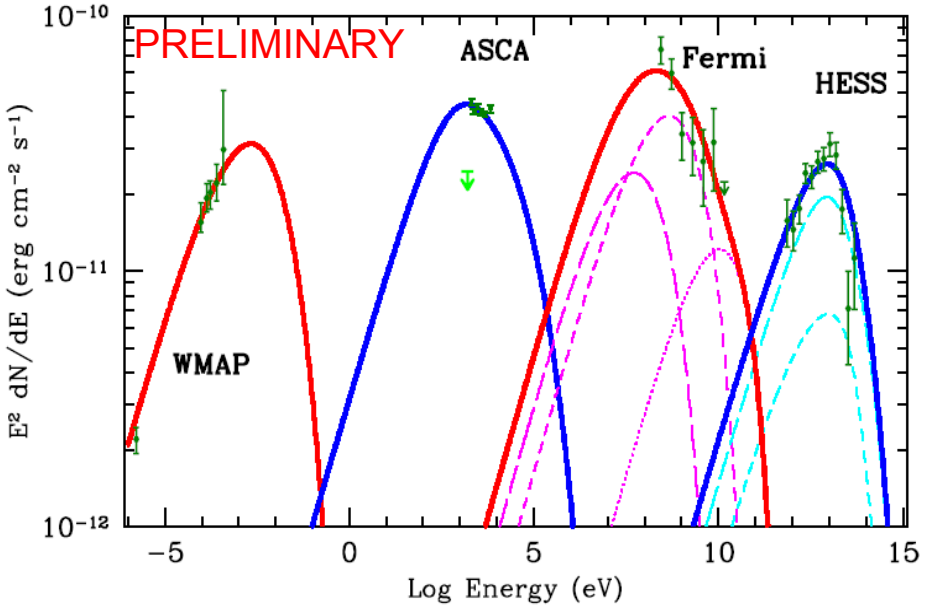
No significant excess counts found:

Upper limit on the flux of a Γ=2 power-law component of 2.5$\times$ 10^{-11} erg cm^{-2} s^{-1}



Discussion

- As noted by de Jager et al. (2008), the SED strongly favors a two-component leptonic model
- Hadronic model is disfavoured
- We have computed the SEDs from evolving power-law electron populations, one each for the X-ray/VHE-peak *cocoon* and radio/MeV-peak *halo:*
  - *Synchrotron/Compton peak ratio of the cocoon implies a B=4μG with small uncertainty*
  - *Cocoon region requires a 600 TeV exponential cut-off controlled by the cooling break*
  - *Halo region requires a 130 GeV exponential cut-off controlled by the cut-off of the injected spectrum*



Summary

- Significant gamma-ray emission contained within Vela-X
- The LAT flux is signicantly spatially extended with a best fit radius of 0.88 ± 0.12 for an assumed uniform disk
- LAT spectrum well described by a power-law with a spectral index of $2.41 \pm 0.09_{stat} \pm 0.15_{syst}$
- We are now testing the plausible injection spectrum of the Vela-X PWN:
  - Cocoon emission evidently represents significantly cooled electrons
  - Halo component represents old electrons produced over the lifetime of the pulsar
- Extension of the radio spectrum through the mm band promises to constrain the high energy cut-off of the halo electron spectrum
- For the *cocoon* component, scheduled *XMM* mapping of this region may extend to low enough energy to probe the synchrotron peak