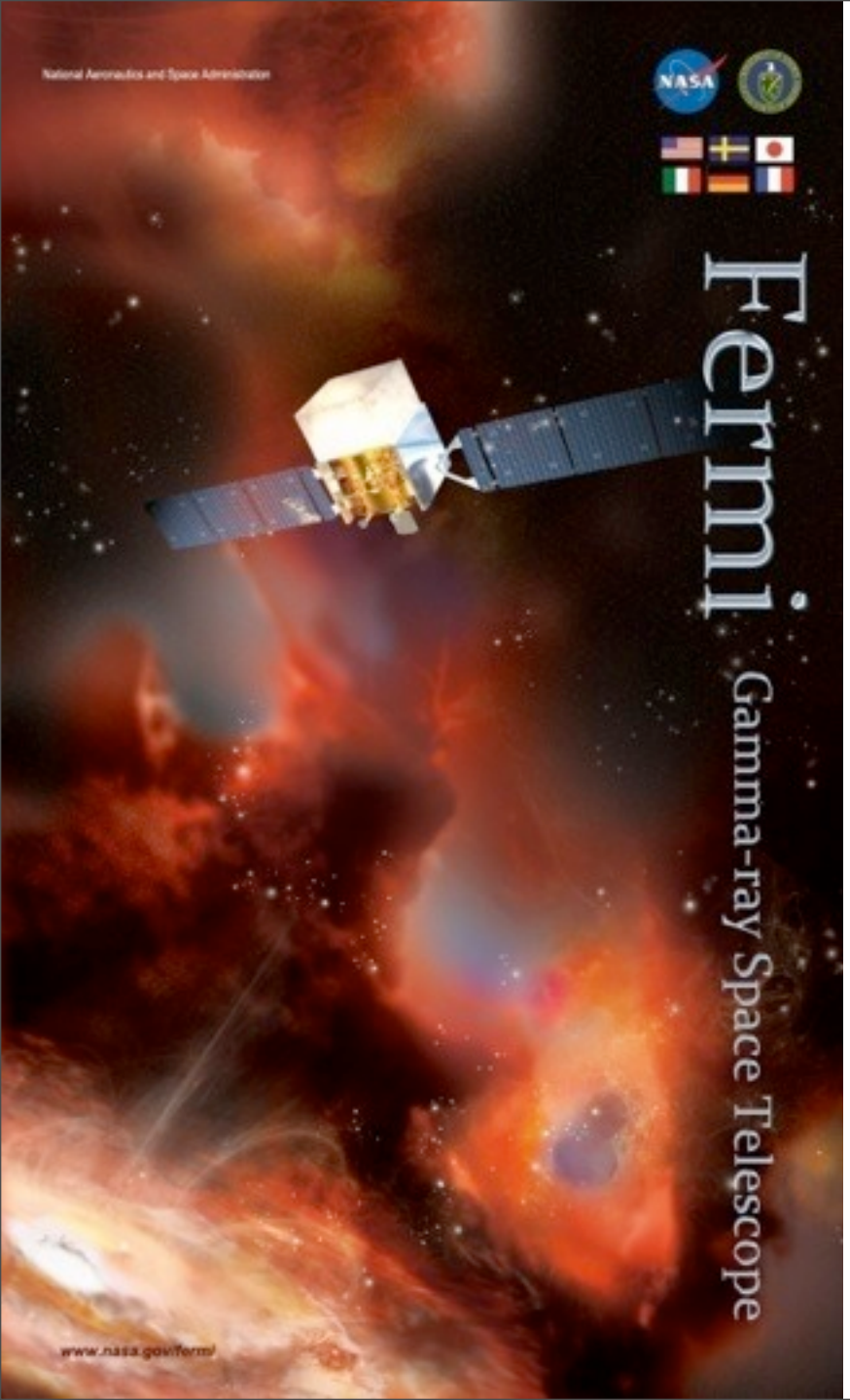

Supernova Remnant Studies with *Fermi*-LAT

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Fermi-LAT Catalog of SNRs: Key Science

- **What contribution do SNRs make to Galactic Cosmic Rays?**
  - **do all SNRs contribute equally?**
- **What variations exist between different SNRs?**
  - **Evolutionary stage**
  - **Environment**
  - **Progenitor type**
- **What can this reveal about acceleration and escape?**
- **Asking these questions requires a large (statistical) sample of SNRs, and not just a case-by-case study**

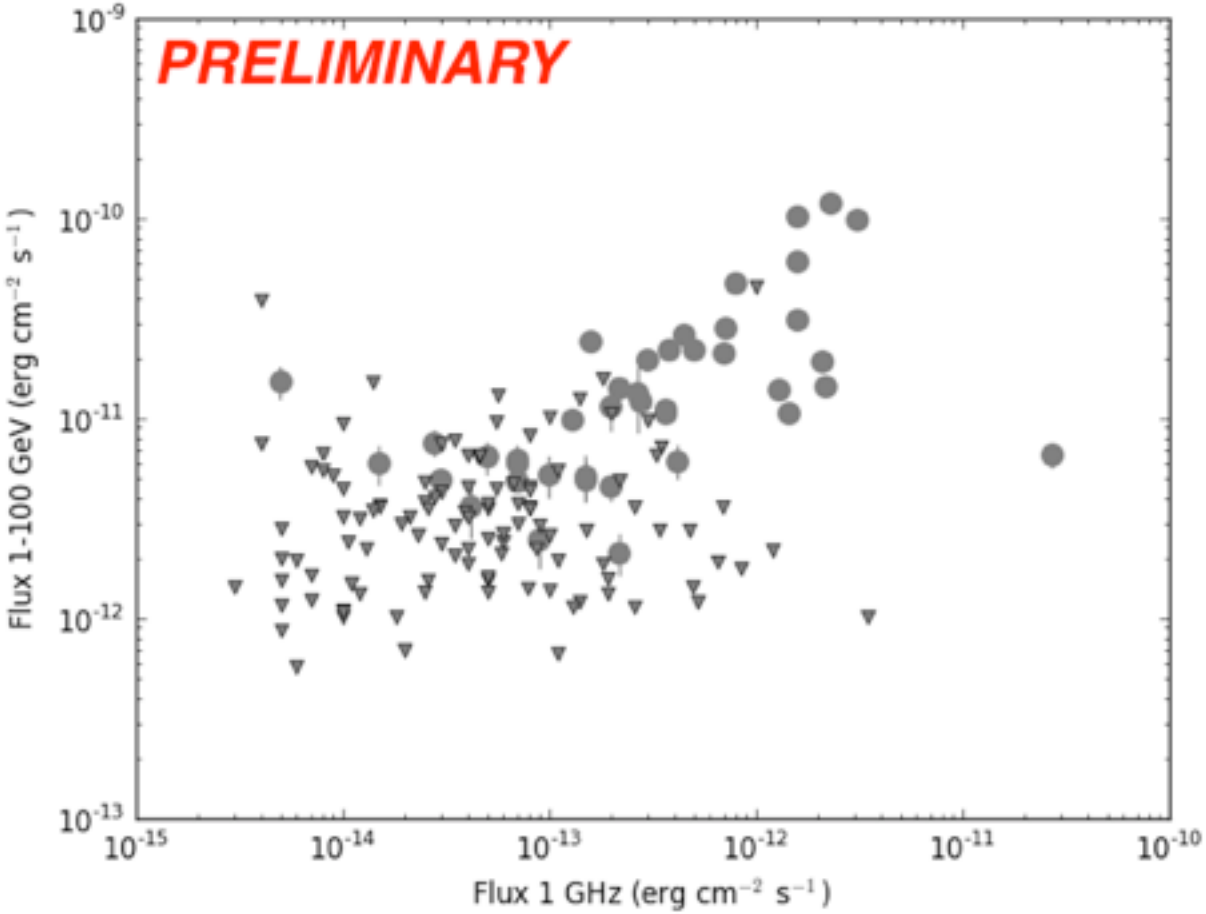
. . . now provided by the 1st Fermi-LAT SNR Catalog

SNRs Radio vs GeV Flux

- **"Radio-Gamma correlation" has been proposed**

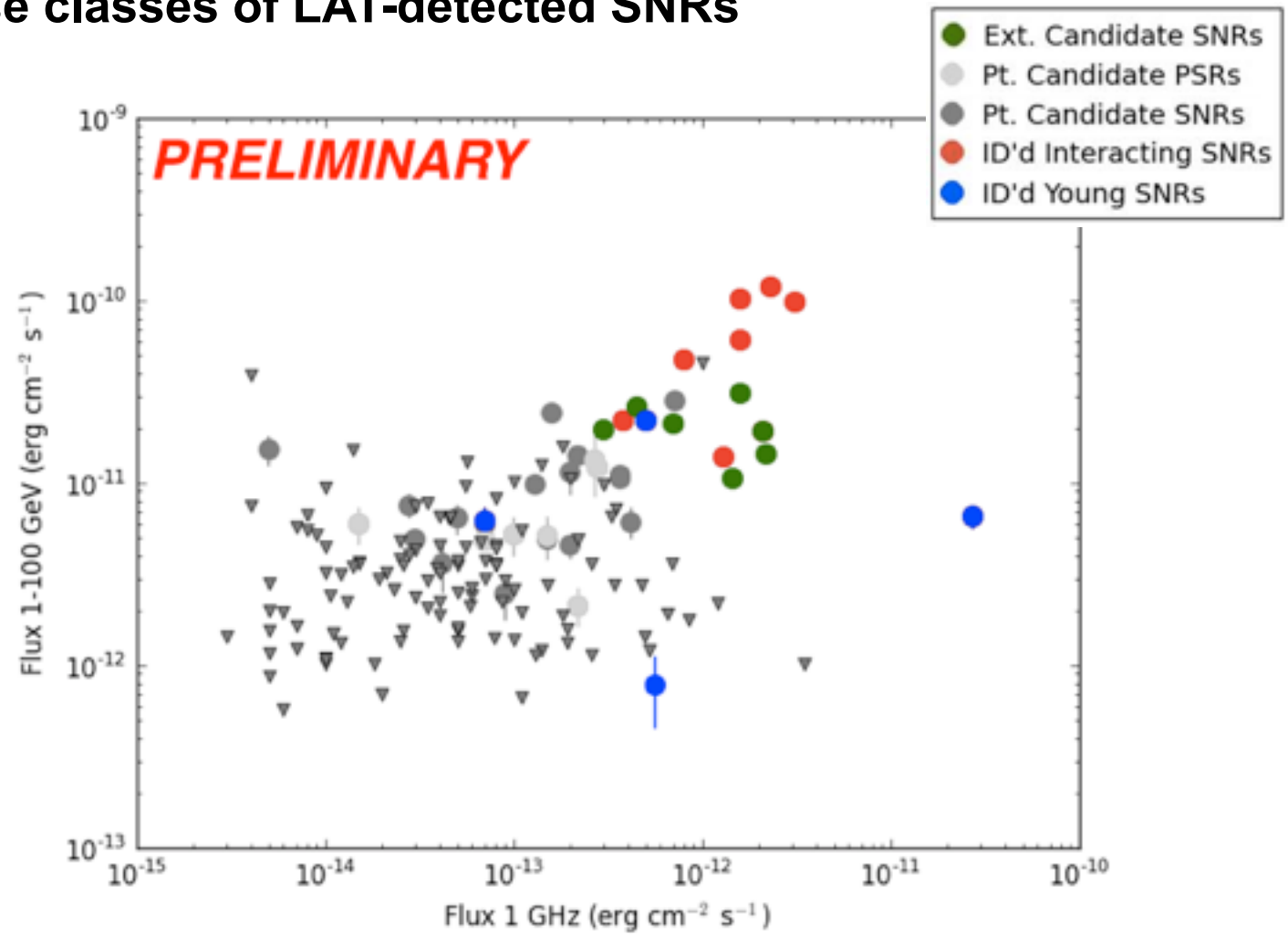
All SNR candidates detected >1 GeV

99% CL calculated, assuming Radio size and Γ=2.5



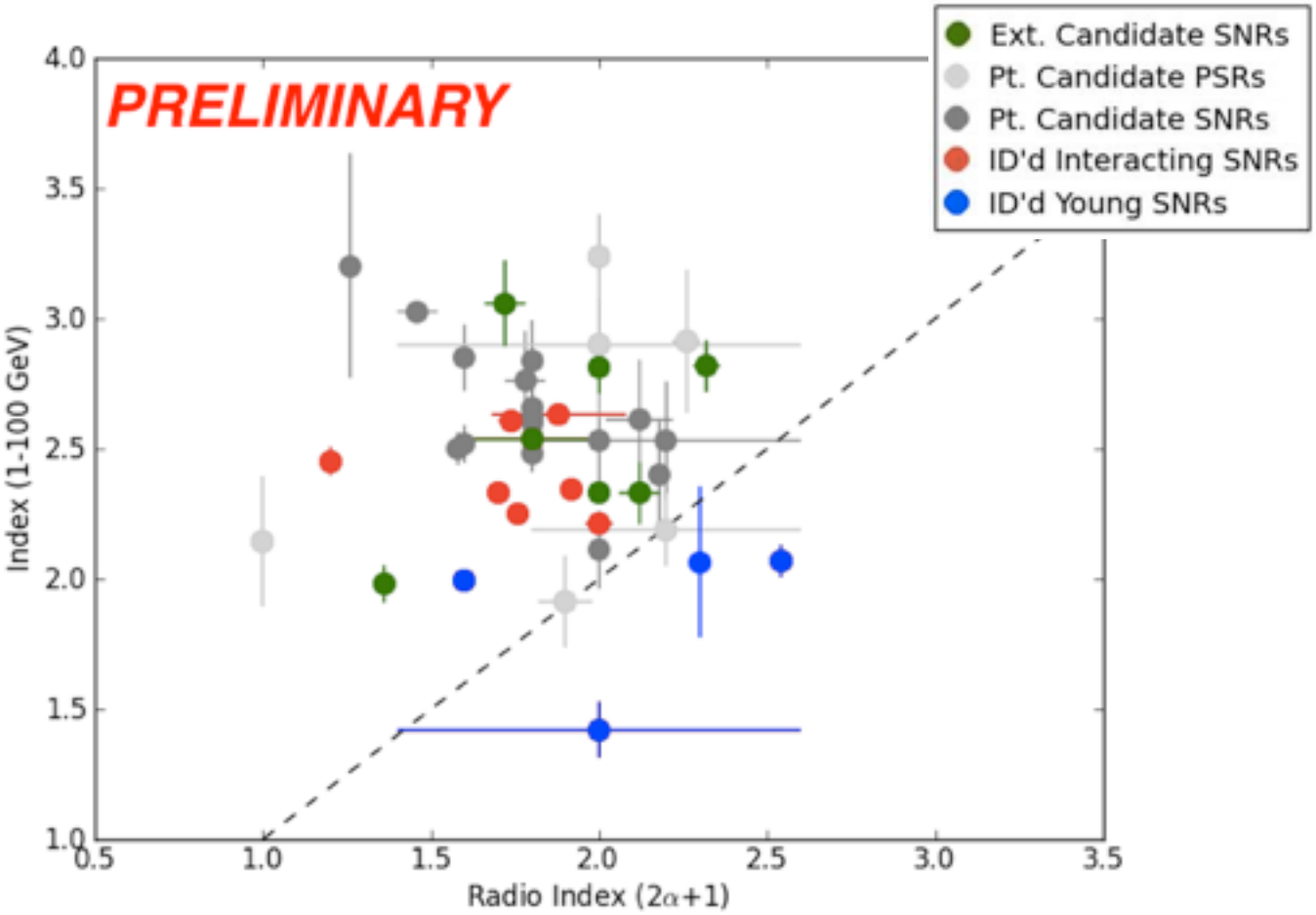
SNRs Radio vs GeV Flux

- **Plots throughout this talk will keep this color-scheme based on these classes of LAT-detected SNRs**



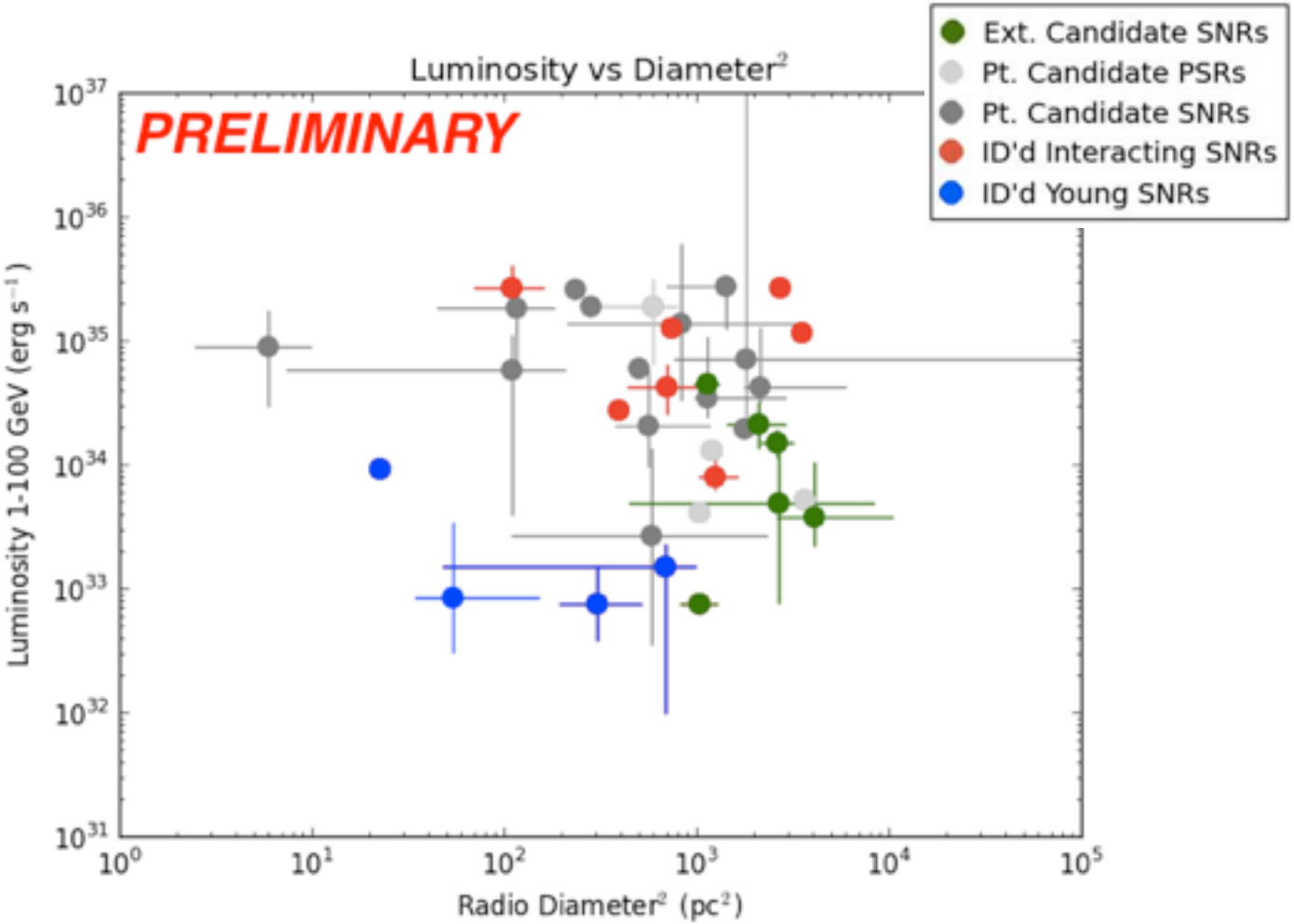
Radio vs GeV Index

- **Young SNRs RX J1713 and Vela, Jr have harder GeV index than inferred from radio (Γ = 2α+1), possibly suggesting an IC origin**
- **Many SNRs show soft GeV index suggesting a ~GeV break.**



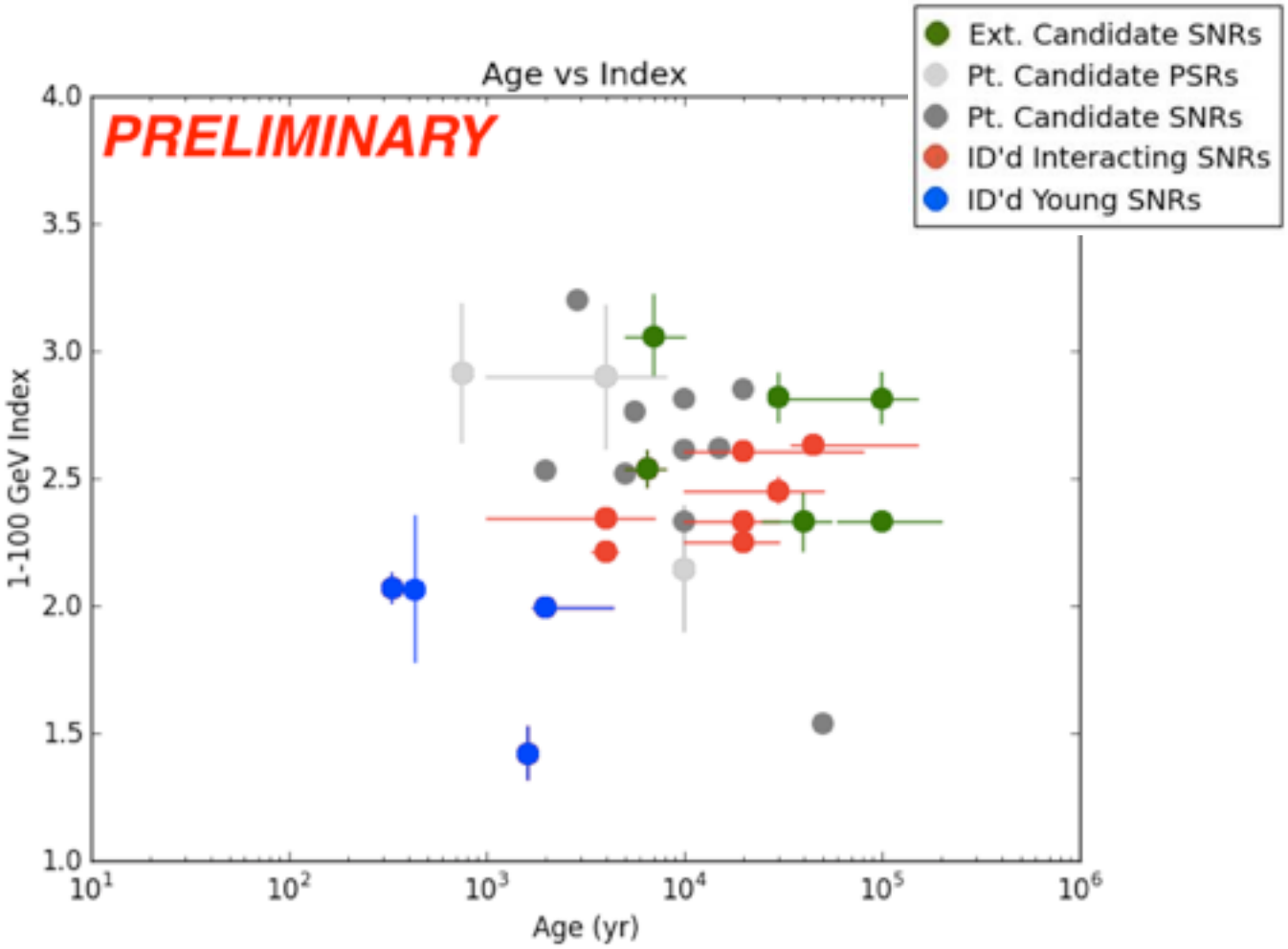
Effect of Environment?

- **Diameter traces SNR evolution (in Sedov stage $R \propto t^{2/5}$)**
- **Interacting SNRs generally show higher L(GeV) than young SNRs**



Effect of Age?

- **Young SNRs have generally harder GeV indices, but no clear trends for interacting SNRs**



Emerging Classes

- **With 12 previously identified SNRs and 6 new extended candidates, we clearly see at least two classes emerging**

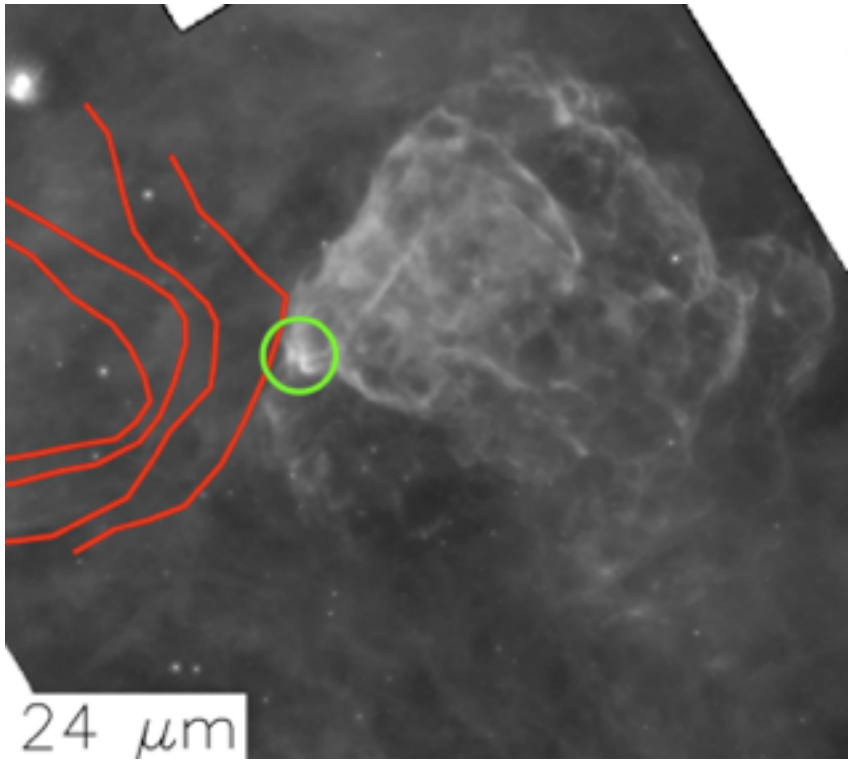
- **Interacting SNRS**
  - **Spectral break from GeV to TeV emission**
  - **Higher density clouds act as target for high L_{GeV}**

- **Young SNRs**
  - **GeV to TeV emission**
  - **No GeV spectral break**
  - **Lower density ISM/CSM**

- **When does transition occur?**
- **How is CR acceleration effected?**

Puppis A: Proto-SNR/MC or a YSNR?

- Puppis A (G260.4-3.4) is a well-studied SNR in a well-known environment:
  - Distance of 2.2±0.3 kpc
  - Age of 4,000±400 years
  - Physical diameter of 30 pc
  - Sedov phase
- Has overtaken any progenitor wind-blown bubble, and is evolving into the ISM in the vicinity of a molecular cloud
- Non-radiative shock, except at some "knots", small shocked clumps
- X-ray/IR modeling indicates n_e~4 cm^{-3}
- Central compact object identified as X-ray PSR J0821-4300



from Arendt, et al. (2011)

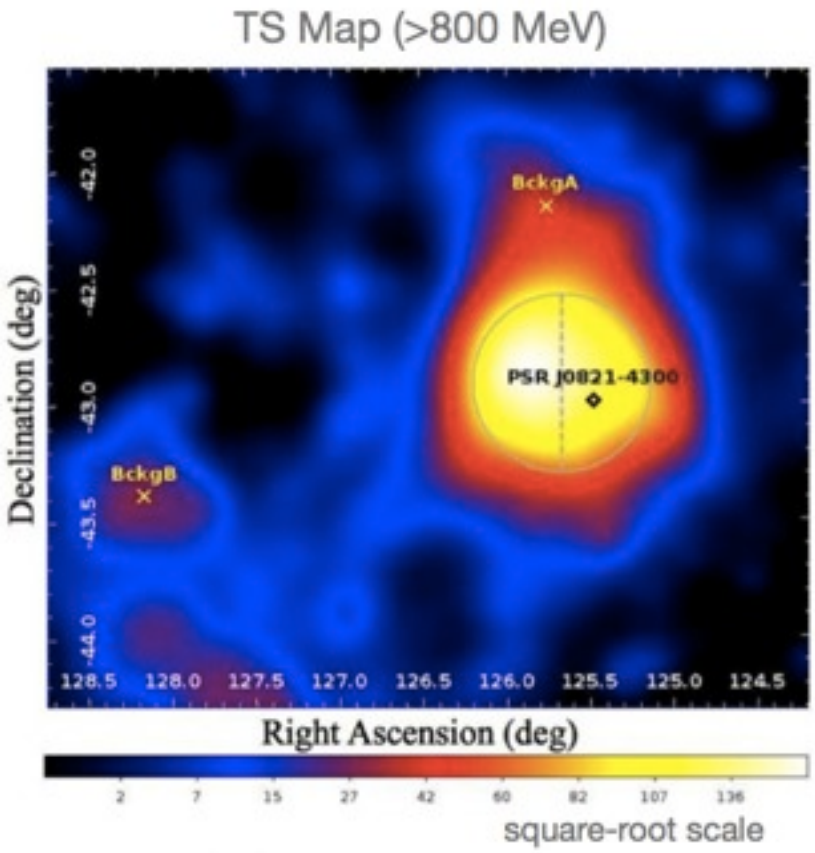
Shocked dust as Puppis A expands towards a nearby molecular cloud (CO contours). Interaction with a dense clump is indicated.

Puppis A: Extended LAT source

- SNR appears as an extended source (Lande, et al. 2012) above 800 MeV
- Comparison of different spatial models

Spatial Model	$-2\ln(L_0/L)$	Ndf
Null hypothesis	0	0
Point Source ($PS1$)	120	4
Three Point Sources (2FGL)	160	12
Radio Template	166	2
X-ray Template	170	2
Uniform Disk ($D1$)	172	5
Two Hemispheres Disk (E, W)	180	7
Two Hemispheres X-ray (E, W)	178	4

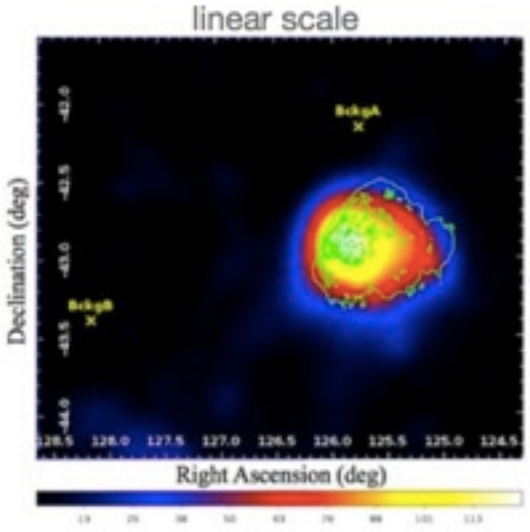
- Best-fit spatial model is Uniform Disk with R=0.38±0.04° (TS_{ext}~7σ)
- Two nearby background sources Bckg A,B (TS=48, 89) are not associated with the SNR



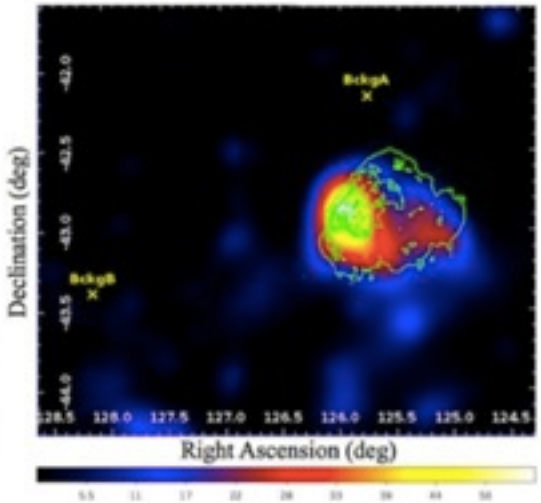
Puppis A: Changing with Energy

TS Maps

>0.8 GeV
off-pulse



>5 GeV
all-phase

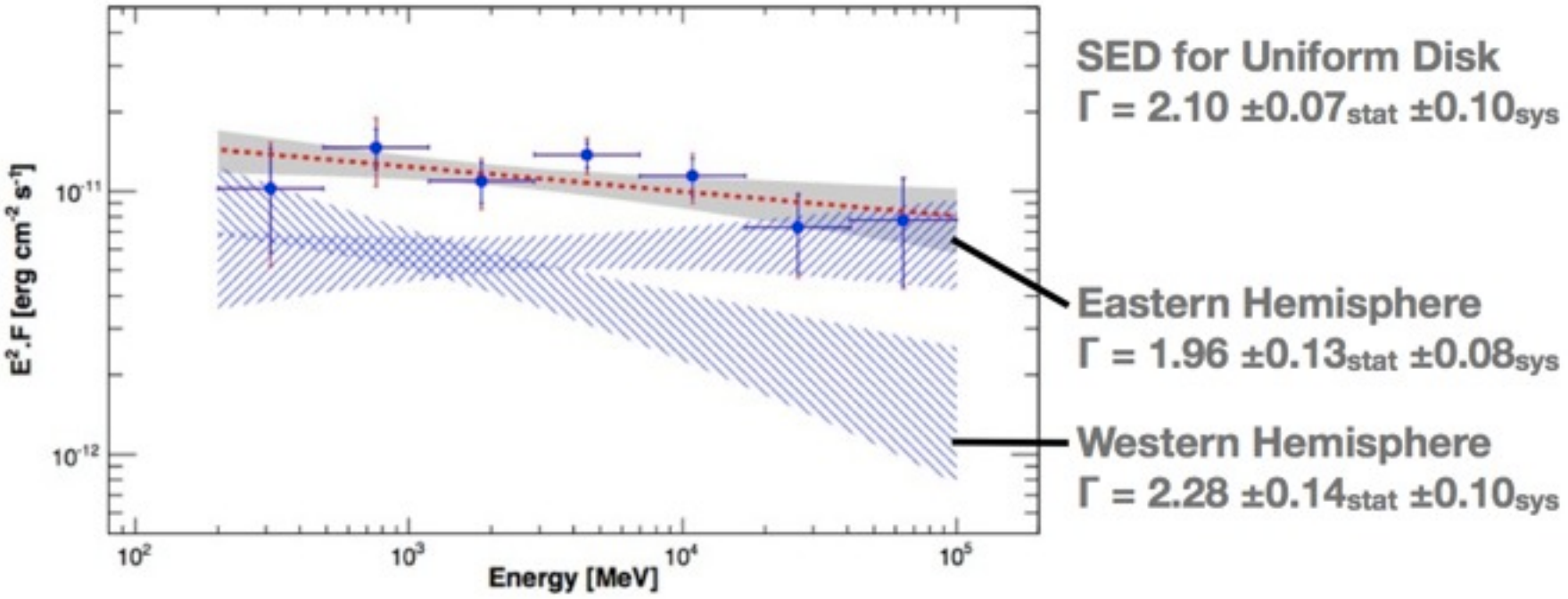


- Excellent correlation with X-rays (ROSAT) and Radio (VLA 1.4 GHz) which show enhancement to the East, due to an increasing density gradient toward the MC.
- Going from lower to higher energy the fitted radius decreases, and centroid shifts to East, but effect is marginal.

Spatial Model	Energy (GeV)	Radius (°)	TS_{ext}
Point Source	0.8 – 100		
Disk	0.8 – 100	0.38 ± 0.04	46
Point Source	0.8 – 5		
Disk	0.8 – 5	0.47 ± 0.08	14
Point Source	5 – 100		
Disk	5 – 100	0.32 ± 0.03	26

Puppis A: Changing with Energy

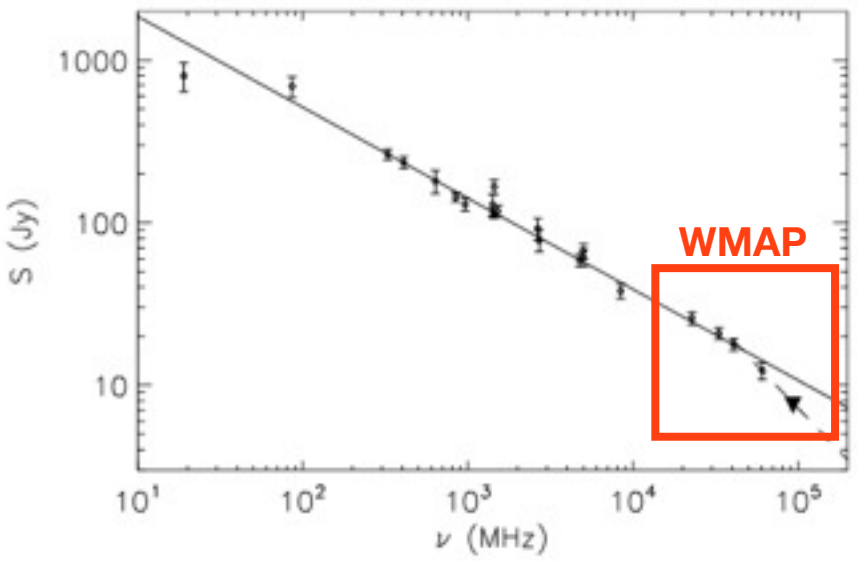
- Best-fit by simple power-law, index=2.1 (using off-pulse data from 0.2-100 GeV). SED points from all-phase (>3 GeV) and off-pulse (<3 GeV) for best statistics. No evidence of curvature or cutoff.



- Interestingly, the two hemispheres appear different, but more statistics are needed (~2.4σ in 3 years), or TeV observations may confirm spectral/spatial differences

Puppis A: WMAP Detection

- Previous radio spectrum from 20 MHz to 8 GHz (Castelletti et al. 2006)
- Puppis A detected as a point source in WMAP 7-year all-sky data across 5 bands, from 23-93 GHz
- Template-fit using 1.4 GHz image + sloping-planar baseline
- χ^2 fit of the radio spectrum
  $S_\nu = (141 \pm 3 \text{ Jy}) \nu^\alpha$
  $\alpha = -0.56 \pm 0.01$
- Bands >40 GHz show decreasing flux fit, suggesting a possible high-frequency break



Band	ν_{eff} (GHz)	Flux Density (Jy)	FWHM (°)
K	22.7	25.8±2.3	0.93
Ka	33.0	20.8±1.7	0.68
Q	40.6	17.8±1.5	0.53
V	60.5	12.3±1.5	0.35
W	93.0	3.0±2.3[a]	0.23

[a]Not detected. 2σ upper limit of 7.6 Jy.

Puppis A: SED Models

- Assume particle population with cutoff. Impulsively injected at t=0, and account for energy losses in t=3,700 years.
- All mechanisms are viable, requiring W_{CR} ~ (1-5)x10^{49} erg but **π^0-decay** is most reasonable
- **Brems.** dominates over **π^0-decay** for **e/p > 0.1** (for n_H=4 cm^{-3})
- **IC** photons from CMB (50%), hot dust (35%) and stars (15%); requires **n_H < 0.3 cm^{-3}**
- One-zone models have great difficulty explaining a radio break (if confirmed)

$$E = 14.7(\nu_{\rm GHz}/B_{\mu\rm G})^{1/2}\ \rm GeV.$$

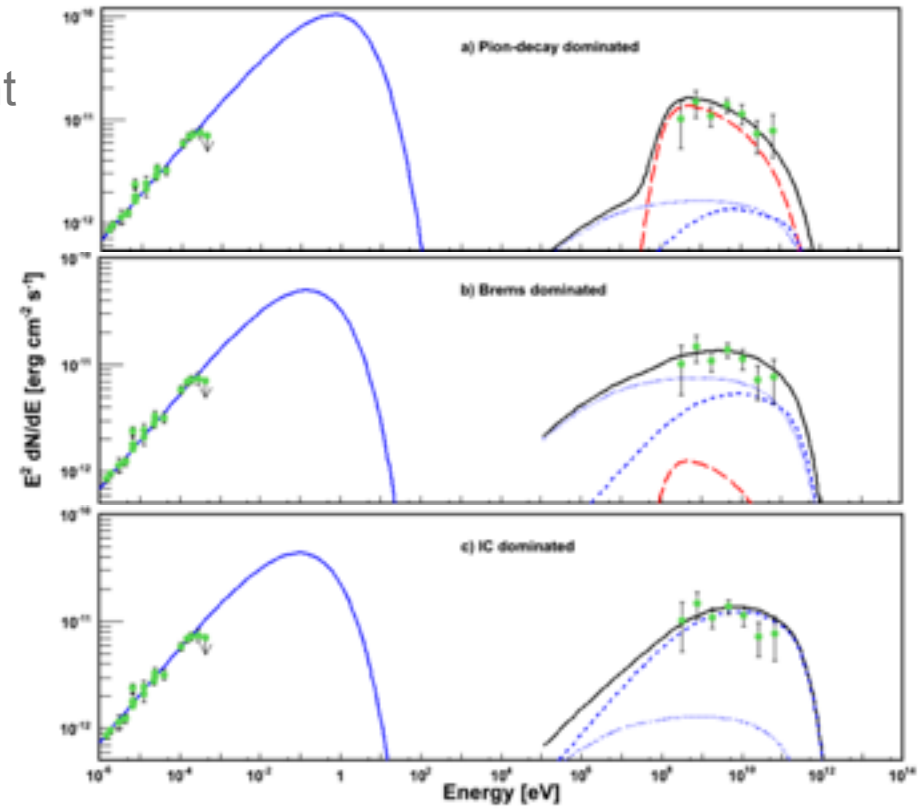


Table 5. One-Zone Model Parameters

Model	Index	E_{max} [TeV]	n_H [cm^{-3}]	B_{tot} [μG]	η_e/η_p	W_p [erg]	W_e [erg]
π^0-decay	2.1	0.8	4	35	0.02	4.0×10^{49}	2.8×10^{48}
Brems.	2.1	0.5	4	13	1	3.5×10^{48}	1.3×10^{49}
IC	2.1	0.5	0.3	8	1	8.0×10^{48}	2.9×10^{49}

Summary

- **Fermi-LAT SNR Catalog**
  - Emerging classes of gamma-ray-detected SNRs
  - Radio-gamma correlation apparent, but not universal (SNR upper limits are interesting constraint)
  - Luminosity and Index show correlation with age/environment (but this degeneracy needs to be broken)

- **Puppis A identified by Fermi-LAT**
  - Extended source, D_{GeV}~0.8°, with power-law index ~2.1
  - SED models require $E_{CR}=(1\text{-}5)\times10^{49}$ erg
  - Possible radio break ~40 GHz
  - Indications of spatial/spectral variations need to be confirmed

    - **Puppis A (and a growing number of SNRs) are interesting future targets for radio, TeV, and *Fermi*-LAT!**

L_{GeV} vs D^2 and Radio-Gamma

- **Plots using only published sources**
  from Thompson, Baldini & Uchiyama, 2012 (arXiv:1201.0988)

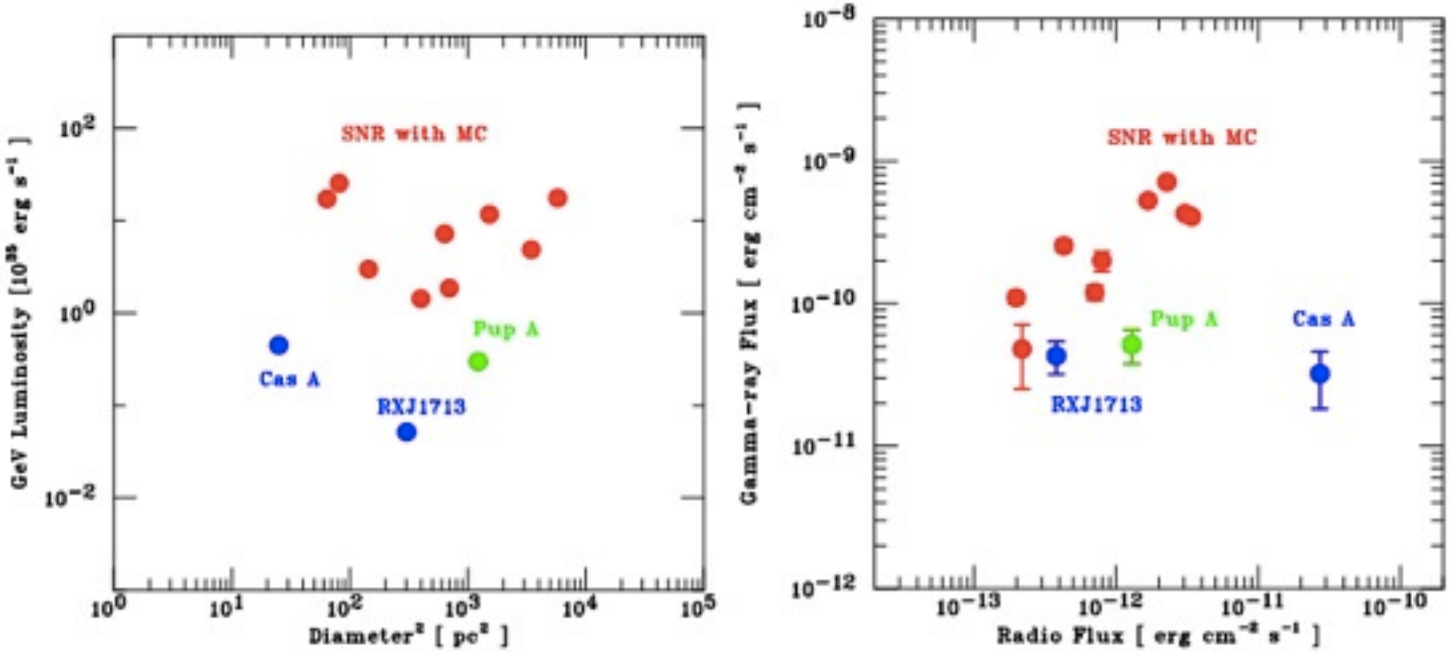
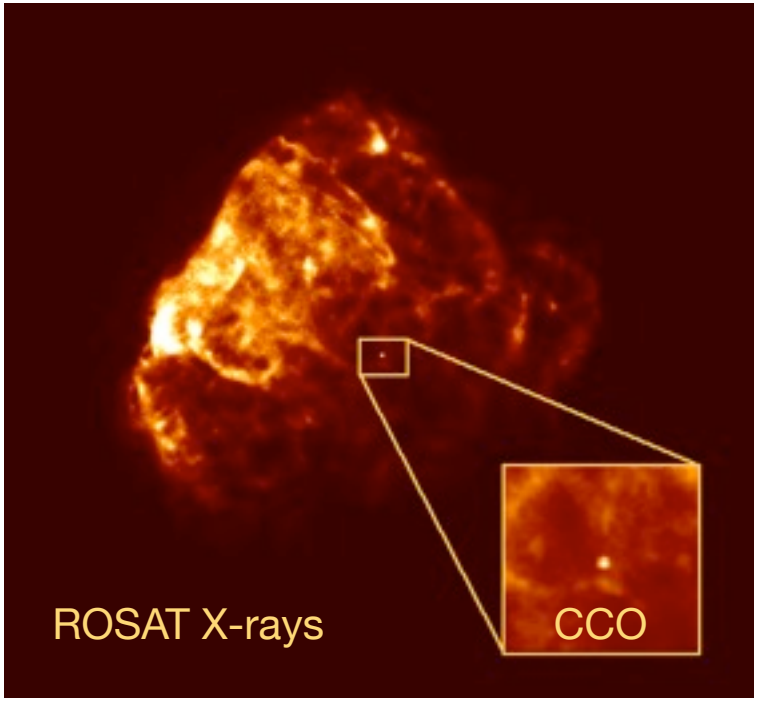


Figure 7: (Left) GeV luminosity (0.1-100 GeV) in units of 10^{35} erg s^{-1} is plotted as a function of diameter squared. (Right) Synchrotron radio flux vs GeV γ-ray flux for SNRs. The γ-ray energy flux integrated over 0.1–100 GeV and the radio flux, νf_ν at 1 GHz, are shown.

- **Note: different energy range than SNR Catalog (>100 MeV vs >1 GeV)**

Pulsation search

- Could the CCO explain soft-spectrum emission in the West?
- PSR J0821-4300
  112 ms X-ray pulsar, “anti-magnetar”
  (Gotthelf+ 2009, 2010)
- Proper motion gives projected velocity of ~1500 km/s (quite a kick!) placing it at the dynamical center of SNR at t=0.
- Not a good γ-ray PSR candidate
  $P_{dot} < 3.5 \times 10^{-16}$
  $E_{dot} < 2.3 \times 10^{35}$ erg/s
  $B_S < 2 \times 10^{11}$ G



- Blind search unfeasible (low TS; few counts)
  No significant pulsations using Xray timing solution (H-test=13.5, 2.8σ)
- Conclude PSR J0821-4300 is **unlikely** to provide soft-spectrum emission seen in the Western hemisphere