High-Energy Pulsar Wind Nebula Studies

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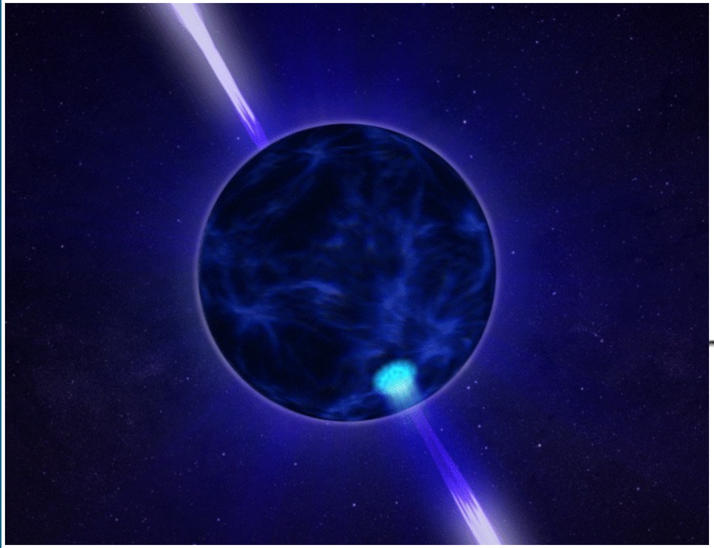
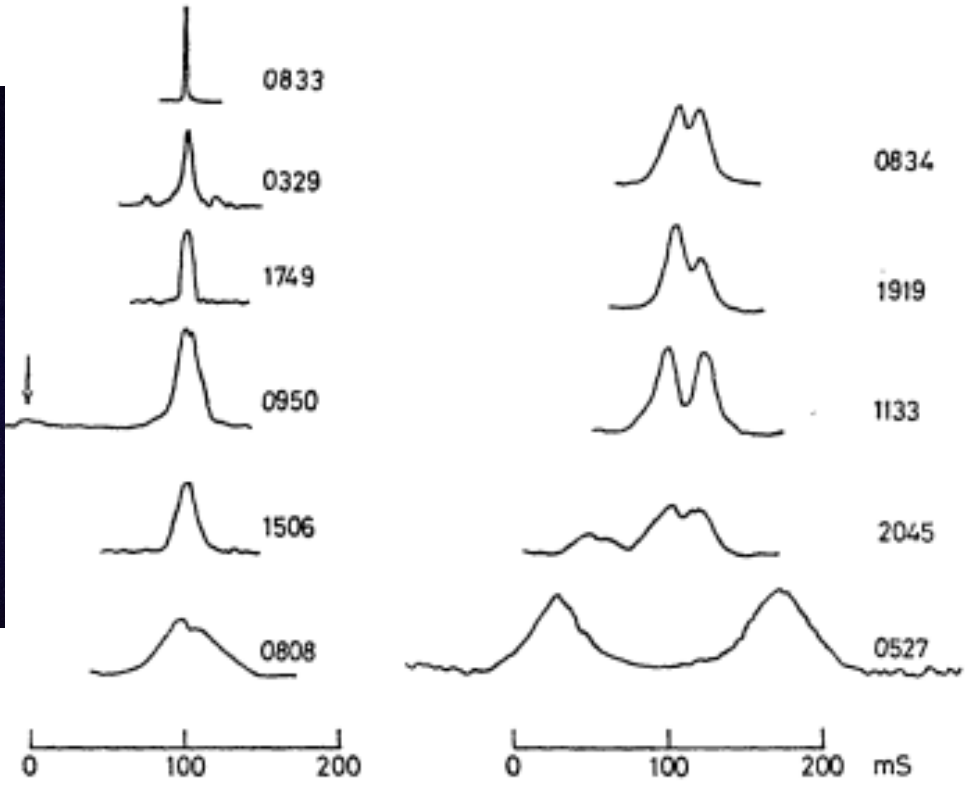
Discovery of Pulsars



Pulsar composition. Credit: NASA



Mean pulse profiles for a sample of *periodic sources* (Hewish et al., 1970)

- July 1967: constant periodic radio signal detected in sky
- Neutron stars immediately guessed to be a possible origin

“The most significant feature to be accounted for is the extreme regularity of the pulses. This suggests an origin of the pulsation of an entire star, rather than some localized disturbance in a stellar atmosphere” (Hewish et al., 1968).

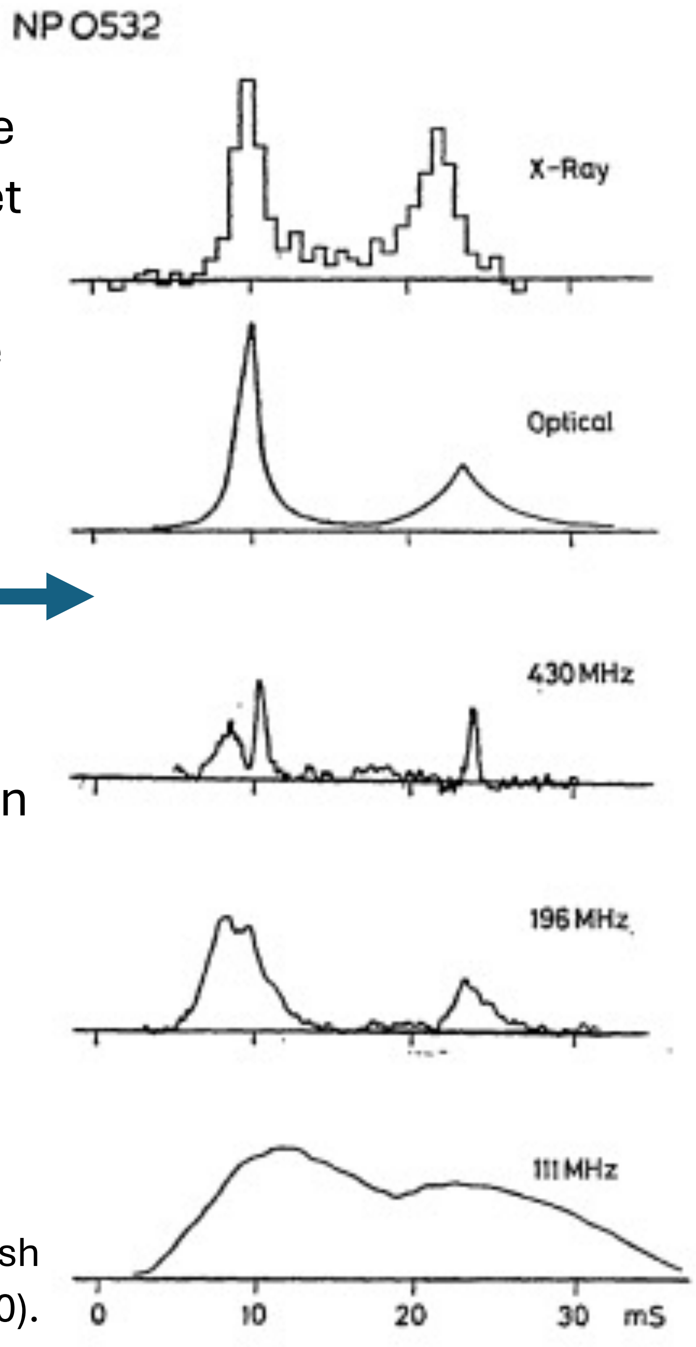
By 1969, over 50 constant periodic signals were discovered.

The Crab Nebula in X-ray (blue), optical (red), and infrared (purple). From: https://chandra.Harvard.edu/photo/2009/crab/

Discovery of Pulsars

- One such signal is discovered in the center of the Crab nebula (Staelin et al., 1969)
    - Lynds et al., 1969 confirmed the ***first ever pulsar*** in the Crab by matching optical to the radio pulse.
- The Crab is believed to be the supernova (SN) remains of a SN recorded by Chinese astronomers in 1054CE

Pulsar discovery led to improved theories on supernovae and soon, pulsar wind nebulae (PWNe)

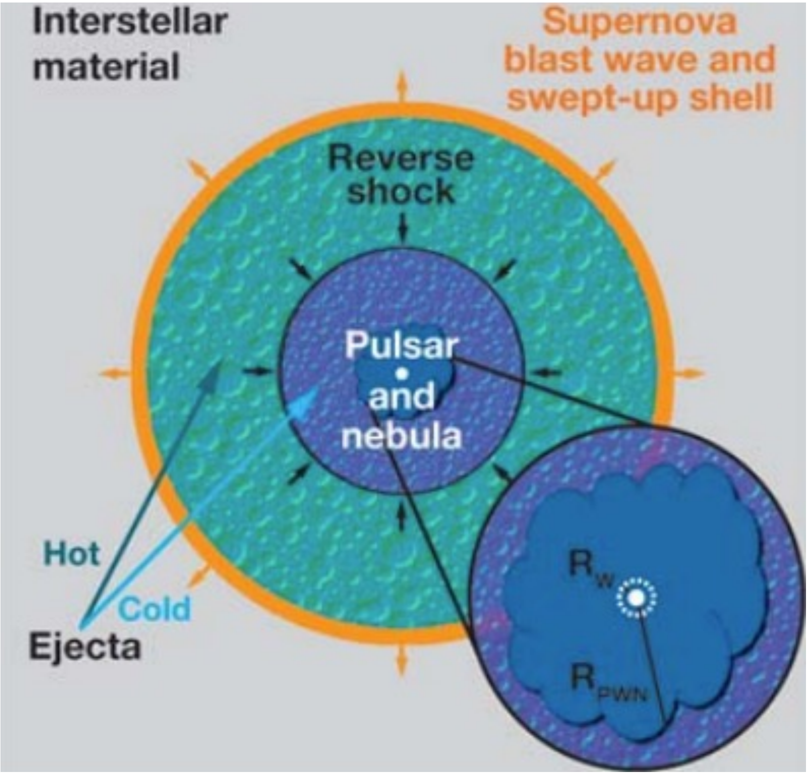


The mean pulse profiles for the Crab pulsar (Hewish et al., 1970).

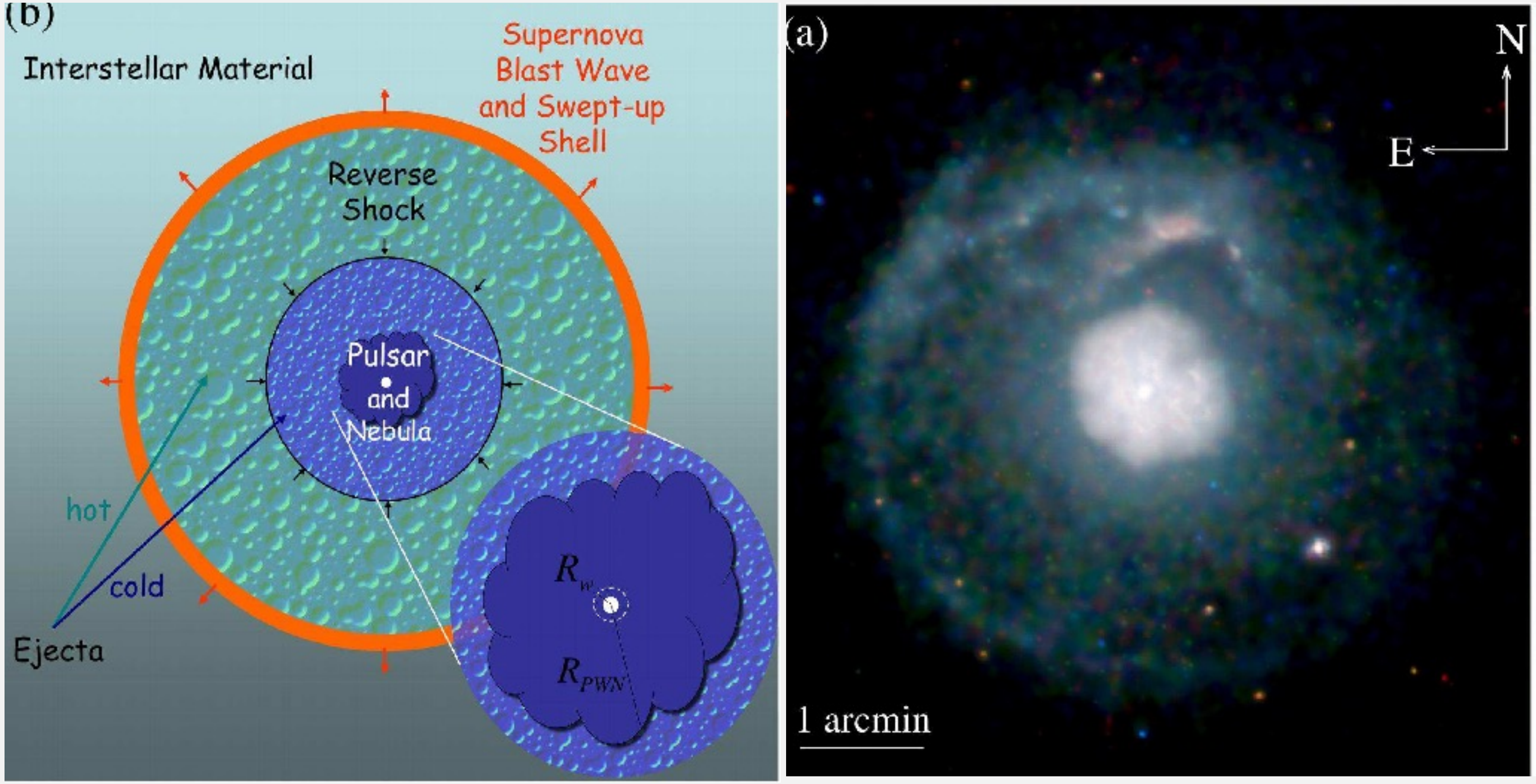
Pulsars power highly magnetic, relativistic winds

Pulsar wind nebulae (PWNe)

PWN inside host SNR, Gaensler & Slane, 2006.

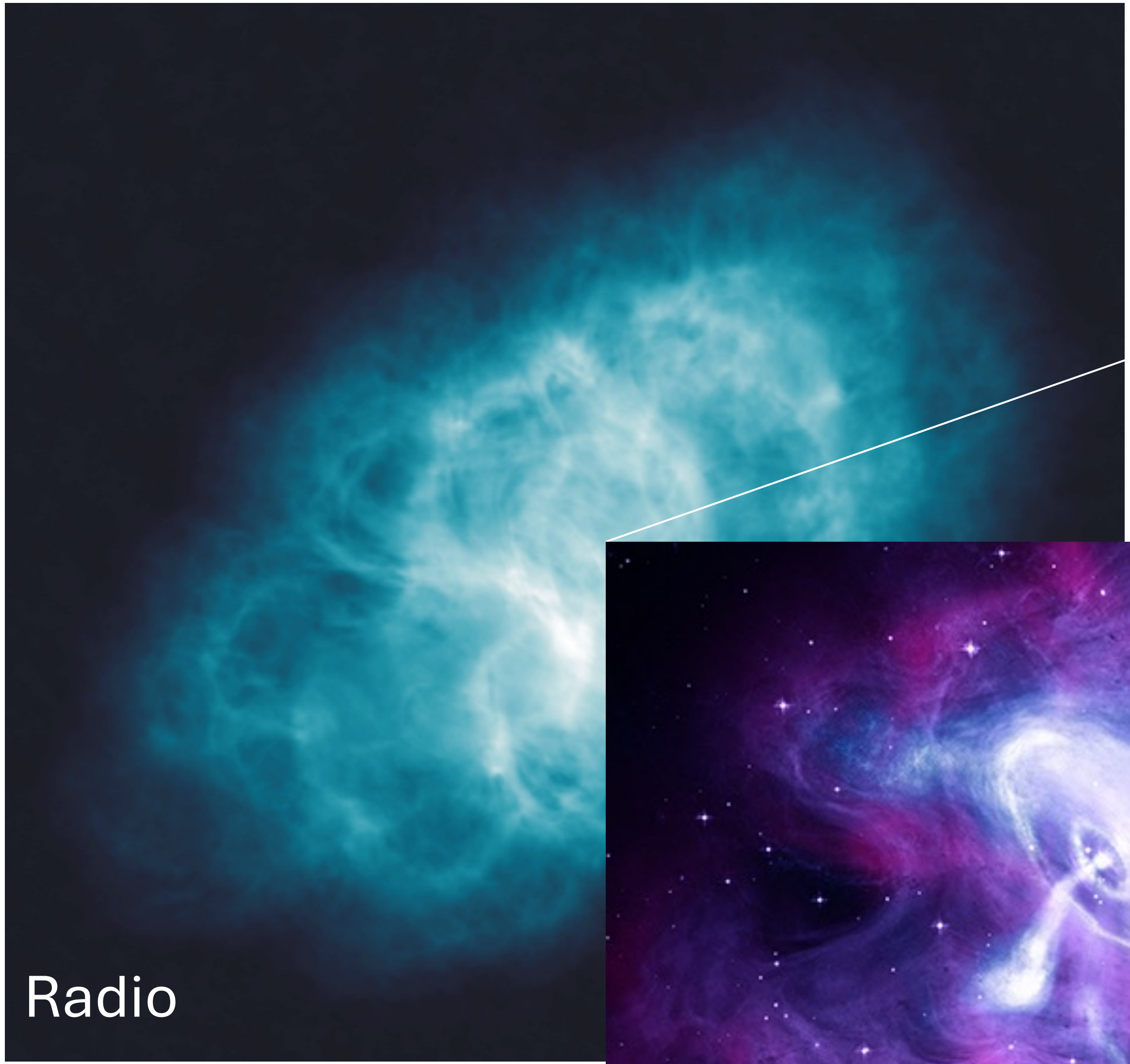


X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Infrared: NASA-JPL-Caltech

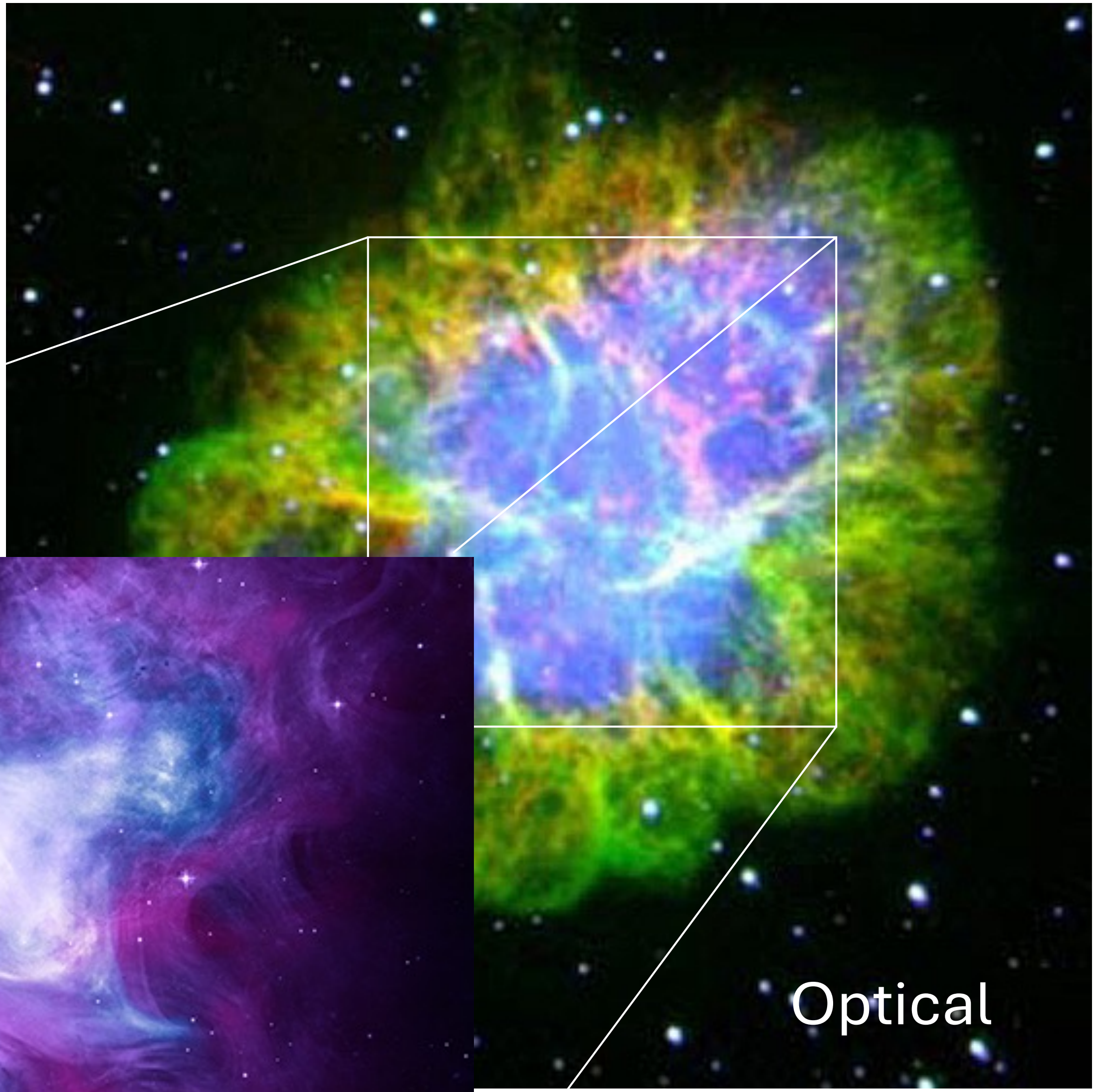


Instagram versus reality

Gaensler and Slane, 2006, ARAA



NRAO/AUI and M. Bietenh



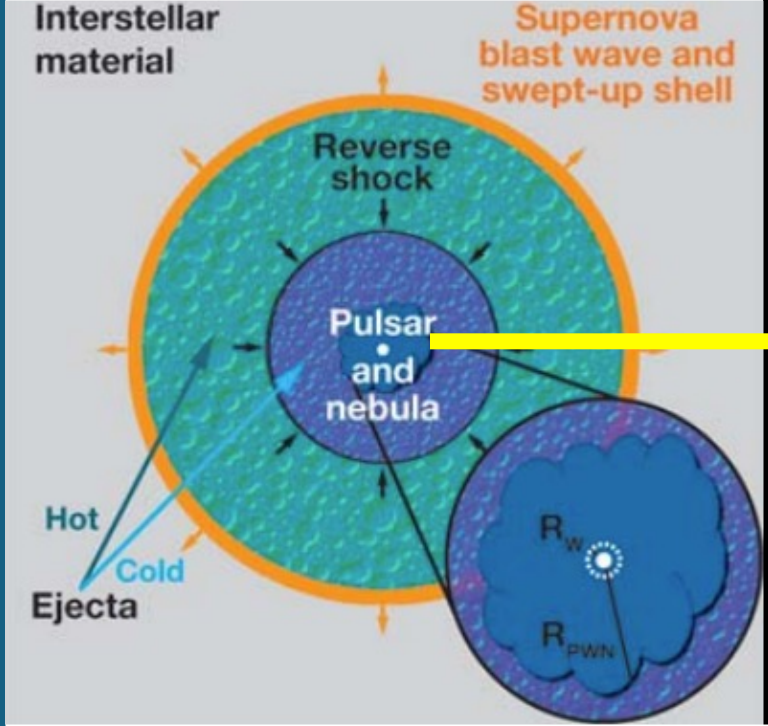
SA/ASU/J.Hester & A.Loll)

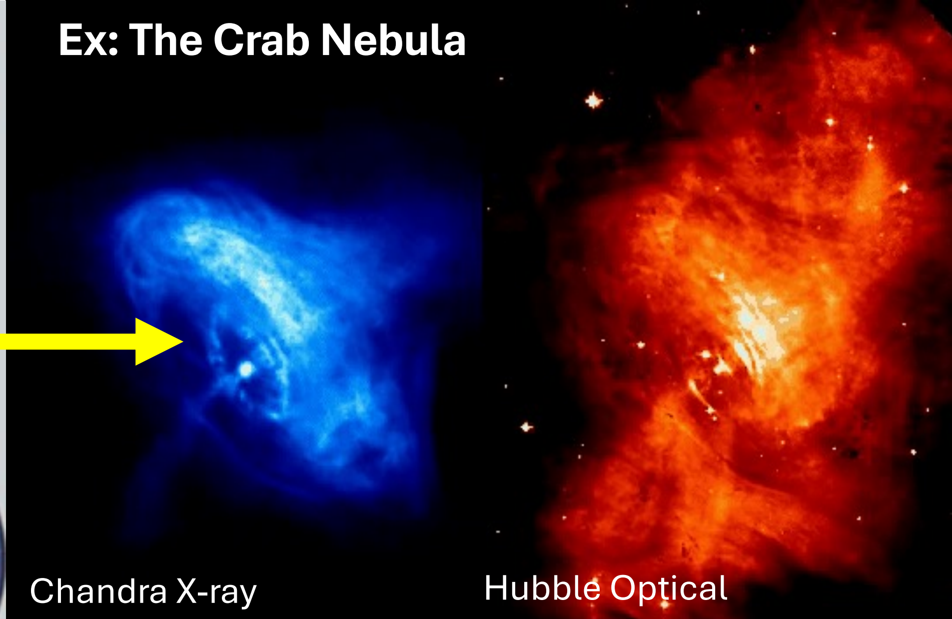
NASA/CXC/ASU/J.Hester et al.

Review: Hester, J. J., 2008, ARA&A, 46, 127

From Liz‘s 2023 Crab Flare Lecture!

PWN inside host SNR, Gaensler & Slane, 2006.



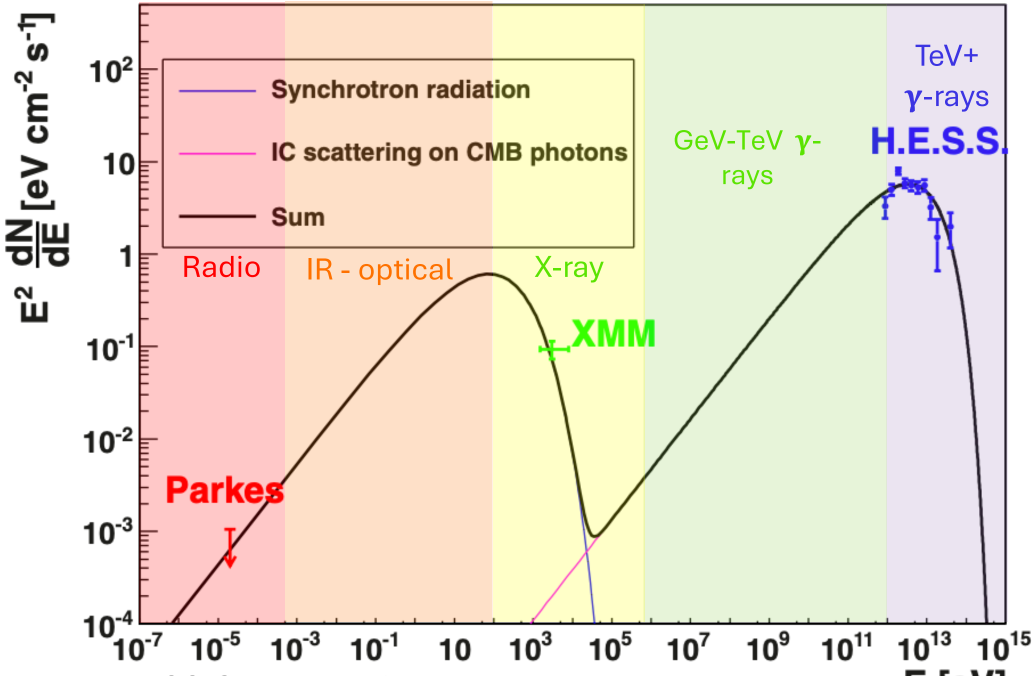


Credits: X-ray: NASA/CXC/ASU/J.Hester et al.; Optical: NASA/HST/ASU/J.Hester et al.

Pulsar Wind Nebulae (PWNe)

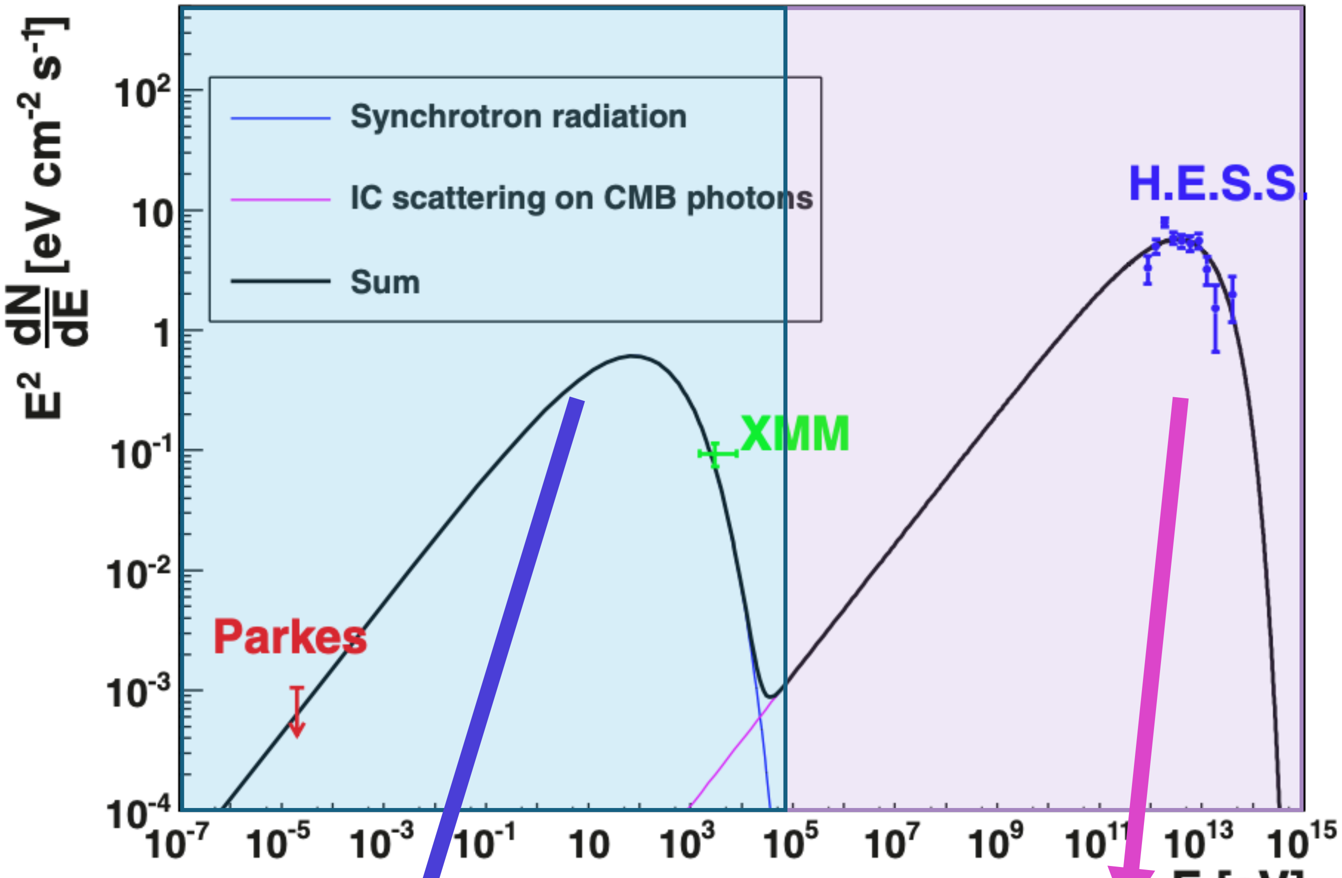
A highly relativistic, magnetic particle wind

- Descendants of core collapse supernovae (CC SNe)
- Powered by the central pulsar
- Mostly **electrons and positrons** radiating synchrotron and Inverse Compton Scattering (ICS) emission

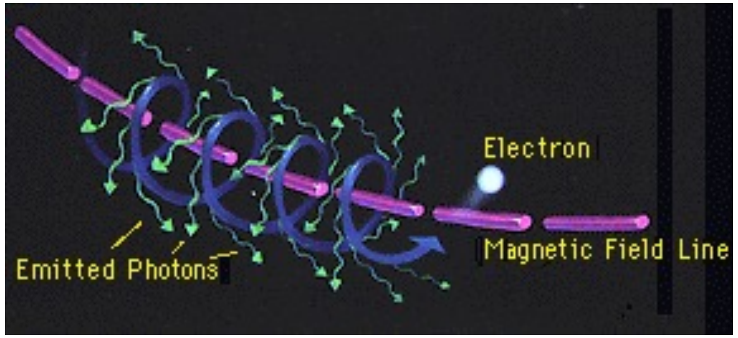


HESS Collaboration et al., 2012

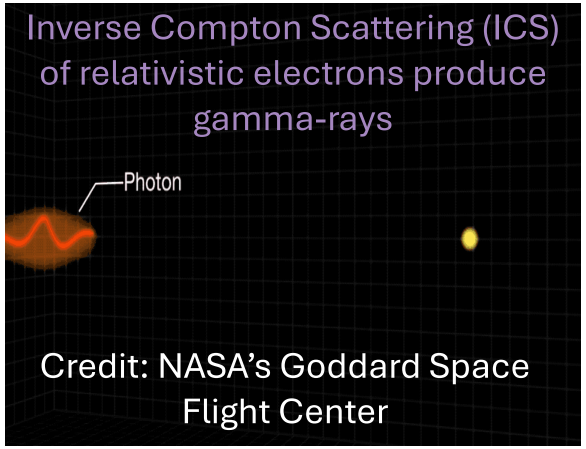
Broadband emission from PWNe



HESS Collaboration et al., 2012



From: https://imagine.gsfc.nasa.gov/science/toolbox/xray_generation_el.html



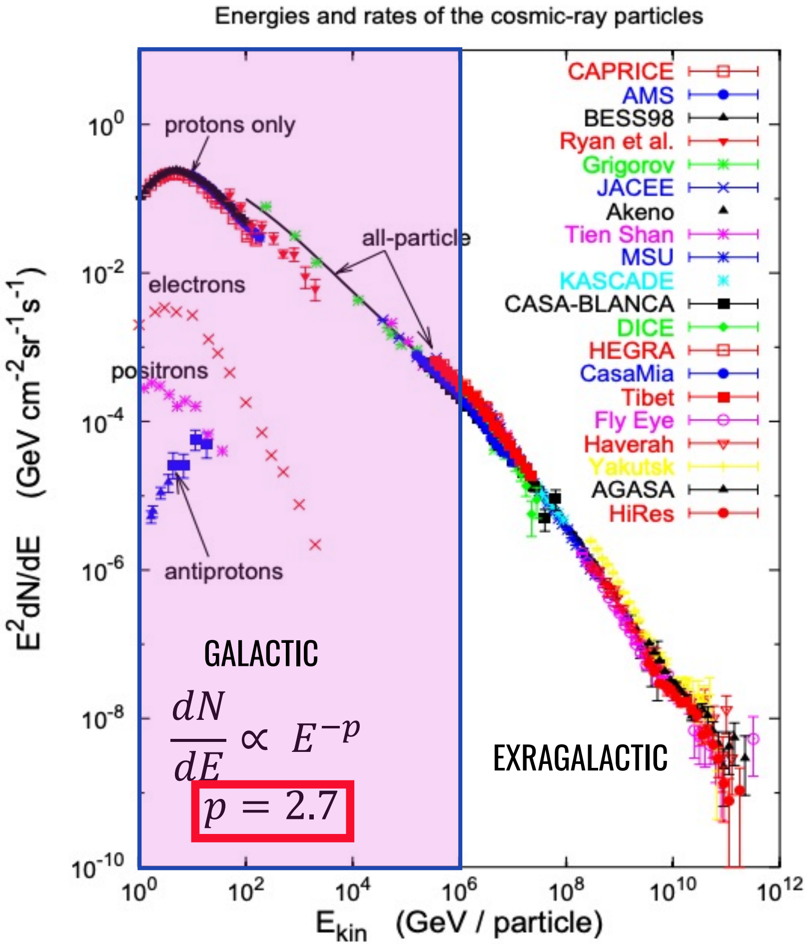
Credit: NASA's Goddard Space Flight Center

The High-Energy Domain

Short answer:

Long answer (still cosmic rays):

The CR flux as observed on Earth (Hillas, 2006).



Efficient Particle Acceleration

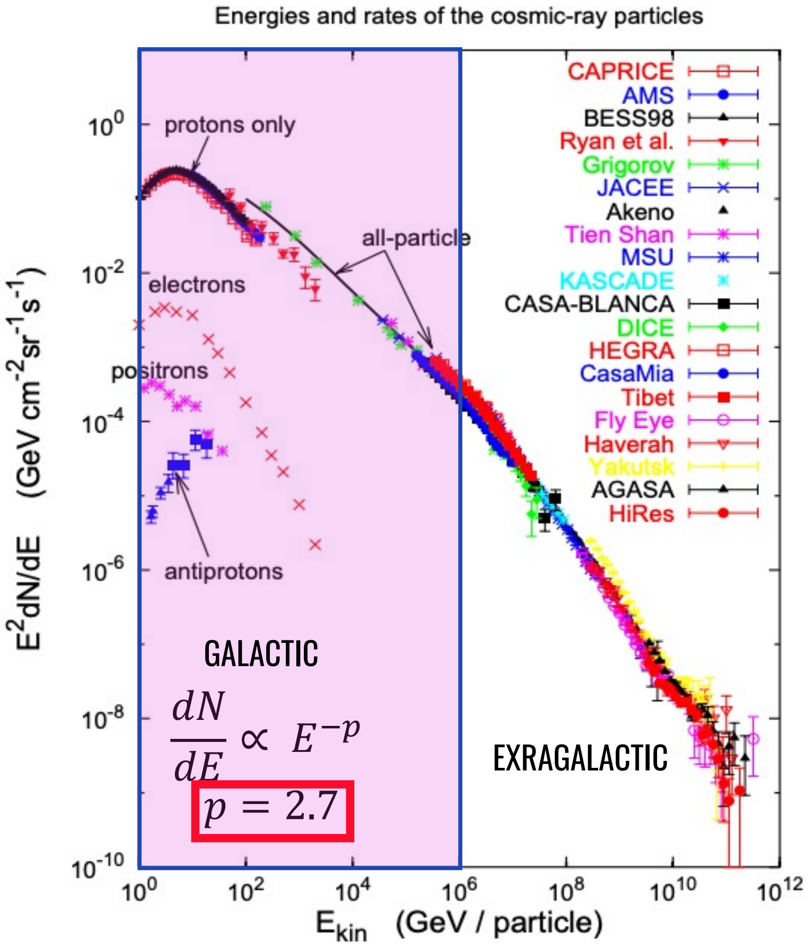
CR particle spectrum follows a power law where p ≥ 2

$$\frac{dN}{dE} \propto E^{-p}$$

High-energy observations of several PWNe imply p ~ 2 for the underlying particle spectra

The observed CR spectrum from Earth

(Hillas, 2006).



PWNe as efficient particle accelerators

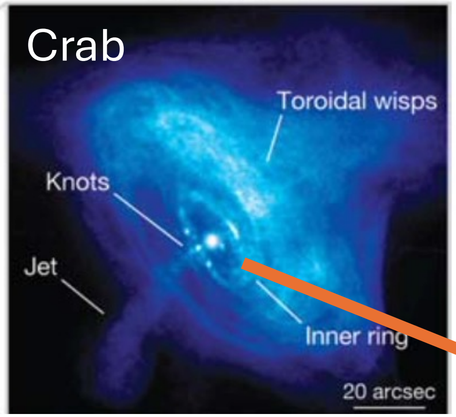
Galactic Cosmic Ray Production

- Where there are shockwaves (PWNe, SNRs, AGN, etc.) there is possibly ***diffuse shock acceleration (DSA)*** that is efficiently accelerating particles to cosmic ray (CR) energies

Enrico Fermi

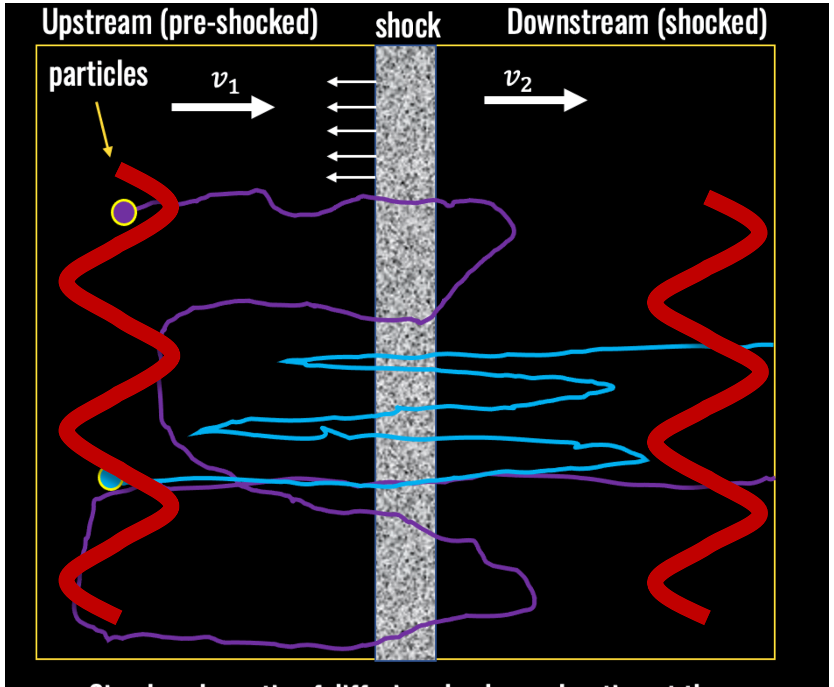
WikiCommons

X-ray (CXC)



Gaensler & Slane 2006

Diffuse Shock Acceleration (DSA)



Simple schematic of diffusive shock acceleration at the shock boundary.

Inner ring = termination shock (TS) – is DSA occurring here?

High-energy observatories

Disclaimer: Not an exhaustive list!

X-ray

- **Chandra (<10keV)**
- **XMM-Newton (<10keV)**
- **NuSTAR (<78keV)**

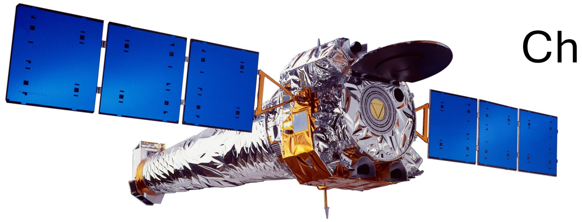
Low-energy gamma-ray

- **The least explored!**
- **COSI (2027 🤞, 200keV-1MeV)**
- **AMEGO-X (2028 🤞, 100keV-1GeV)**

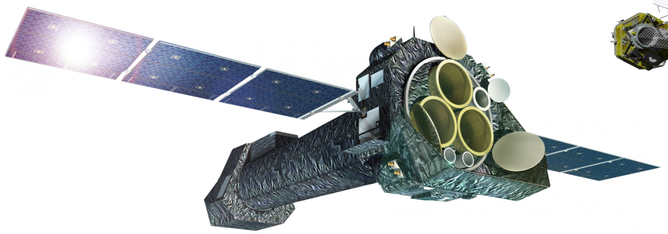
High-energy Gamma-ray

- **Fermi-LAT (50MeV to >300GeV)**
- **IACTs (+water Cherenkov, >1TeV)**

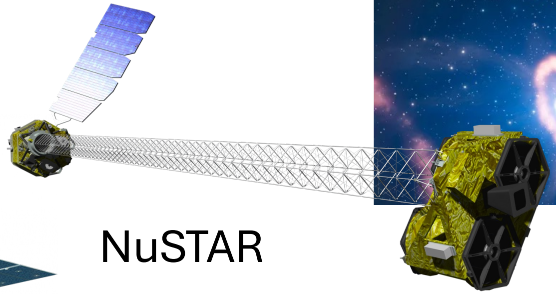
e.g., MAGIC, VERITAS, HAWC, HESS, LHAASO



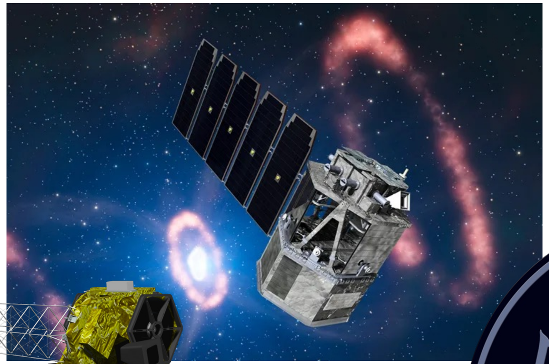
Chandra



XMM-Newton

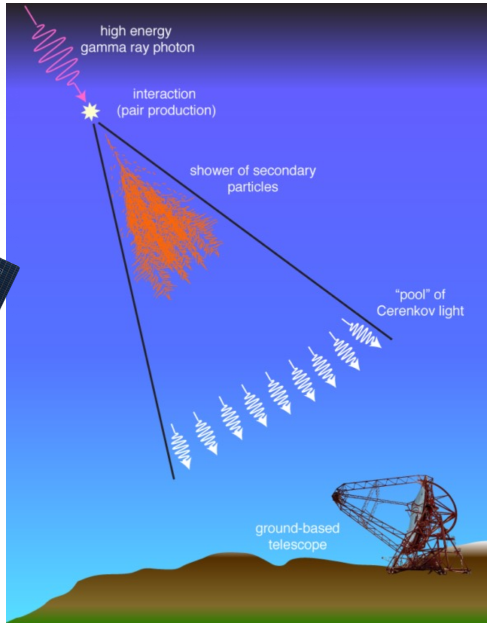


NuSTAR

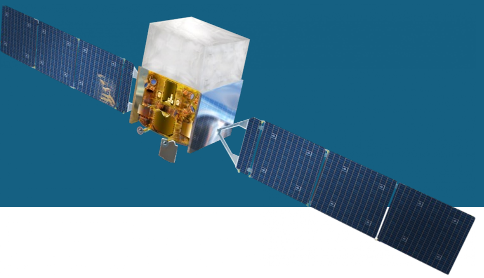


COSI

Fermi-LAT



IACTs



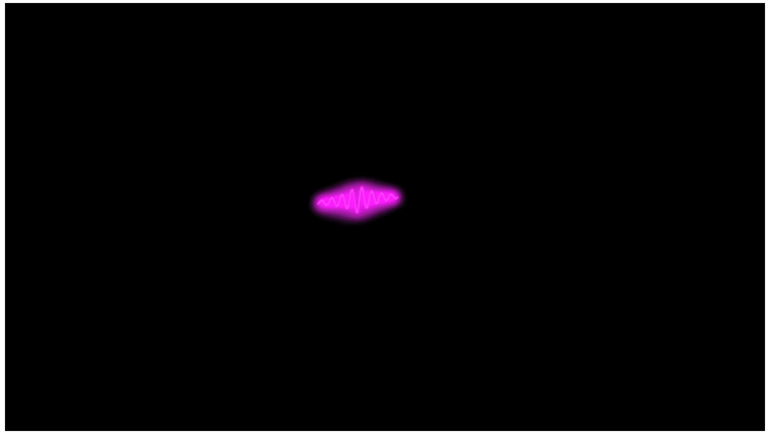
The Fermi- Large Area Telescope (LAT)

Instrument Design:

- **“Indirect” imaging via process called pair conversion**

Pair conversion process animation

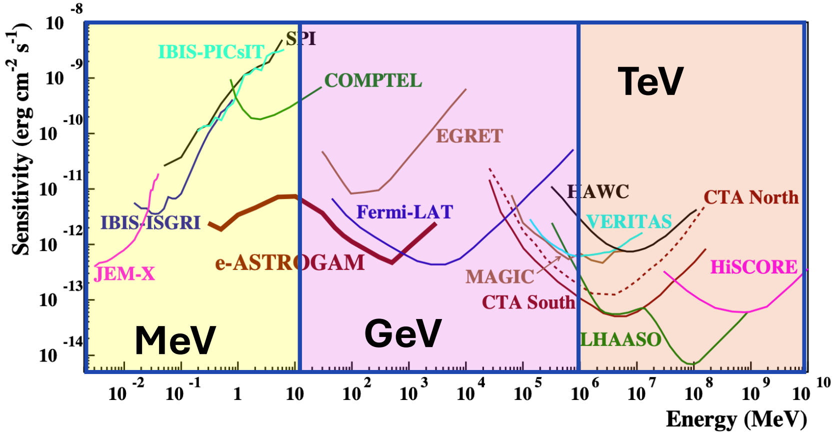
Credit: NASA/Goddard Space Flight Center



Sensitivity:

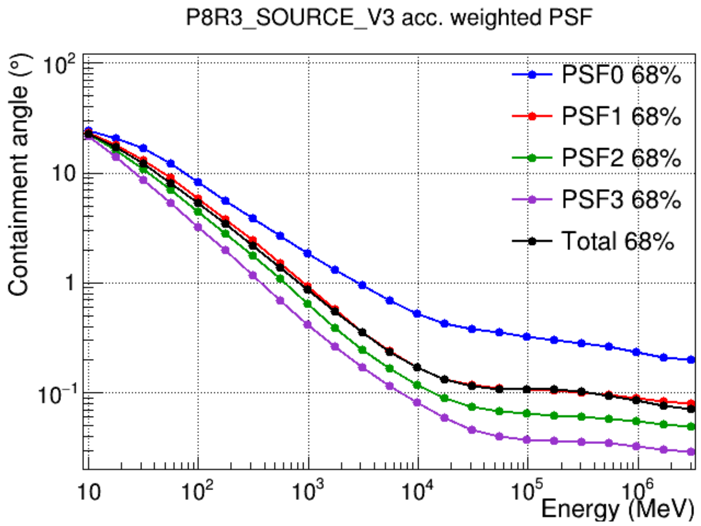
- **The most sensitive instrument operating between 50 MeV to > 300GeV gamma-ray energies**

De Angelis+2017



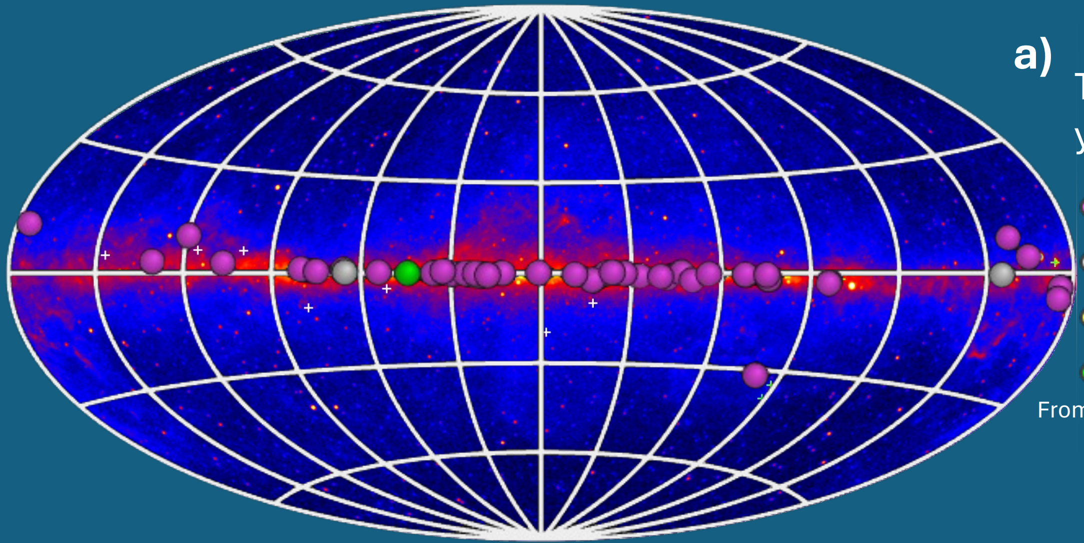
Resolution:

- **Energy-dependent**
- **Optimal at ~ 10GeV**



From: https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

High-Energy Pulsar Wind Nebula Studies

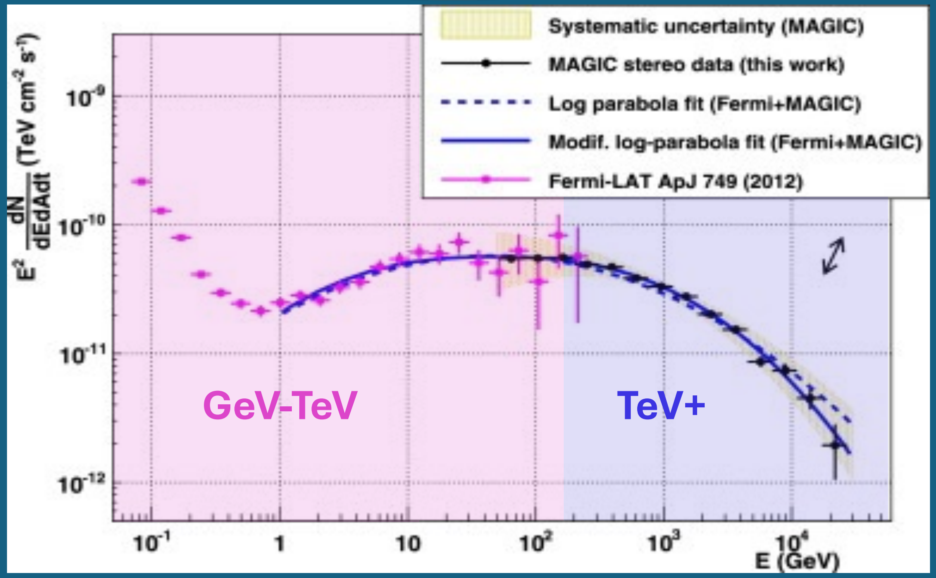


a)

The Fermi-LAT 12-year sky E > 1 GeV

- TeV PWNe
- TeV Halo, UNID
- PSR
- TeV Halo Cand

From: http://tevcat.uchicago.edu/



b)

SED of the Crab from 100 MeV to 30 TeV obtained by Fermi-LAT and MAGIC. Aleksić, et al., 2015.

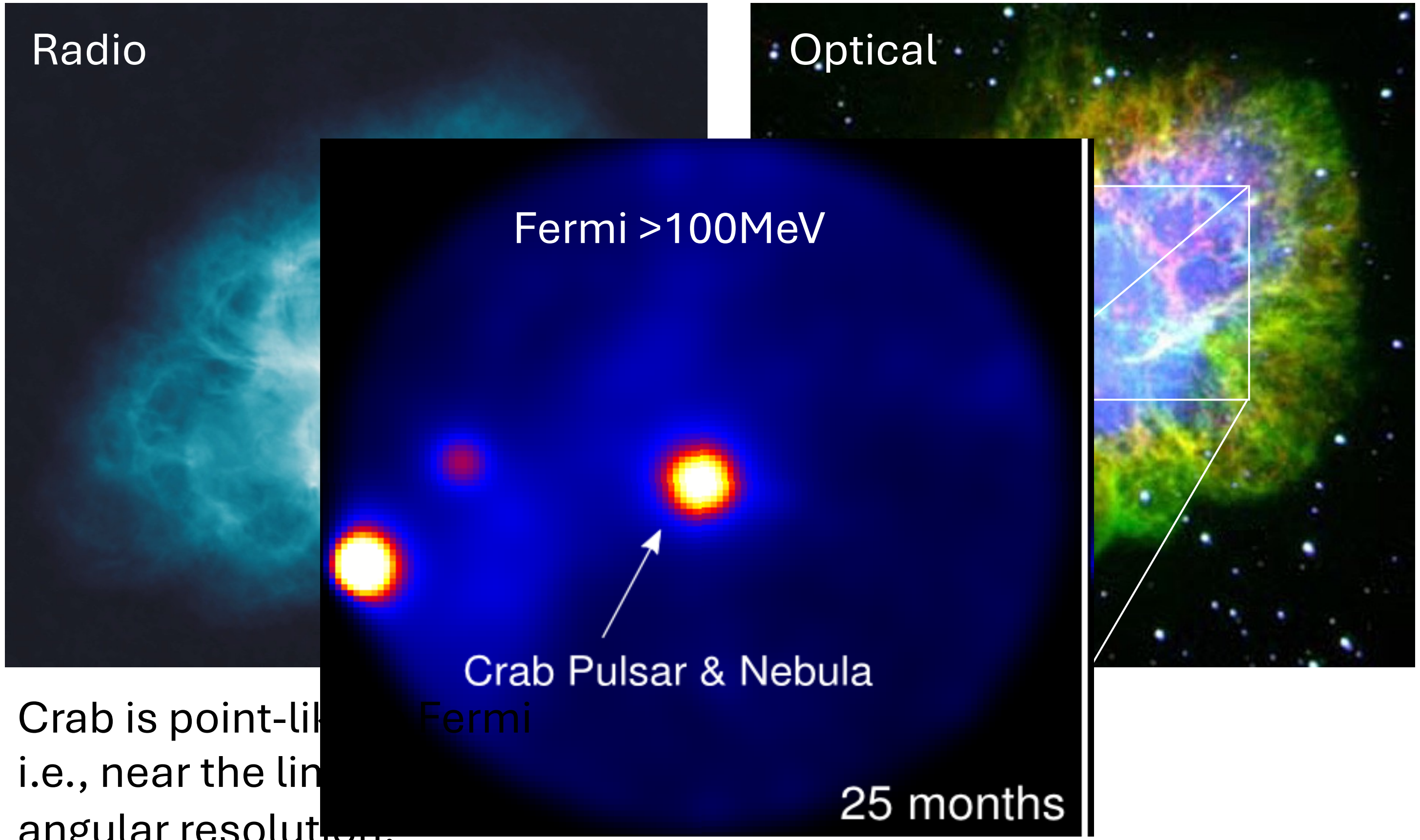
Fermi-LAT PWNe

a) Majority (~38) of Galactic TeV sources are PWNe

b) Spectra of many TeV PWNe indicate ICS peak occurs in lower-energy γ-rays (i.e., MeV – GeV <u>where Fermi is most sensitive</u>)

c) Only 11 PWNe are firmly identified by the Fermi-LAT in the MeV - GeV band!

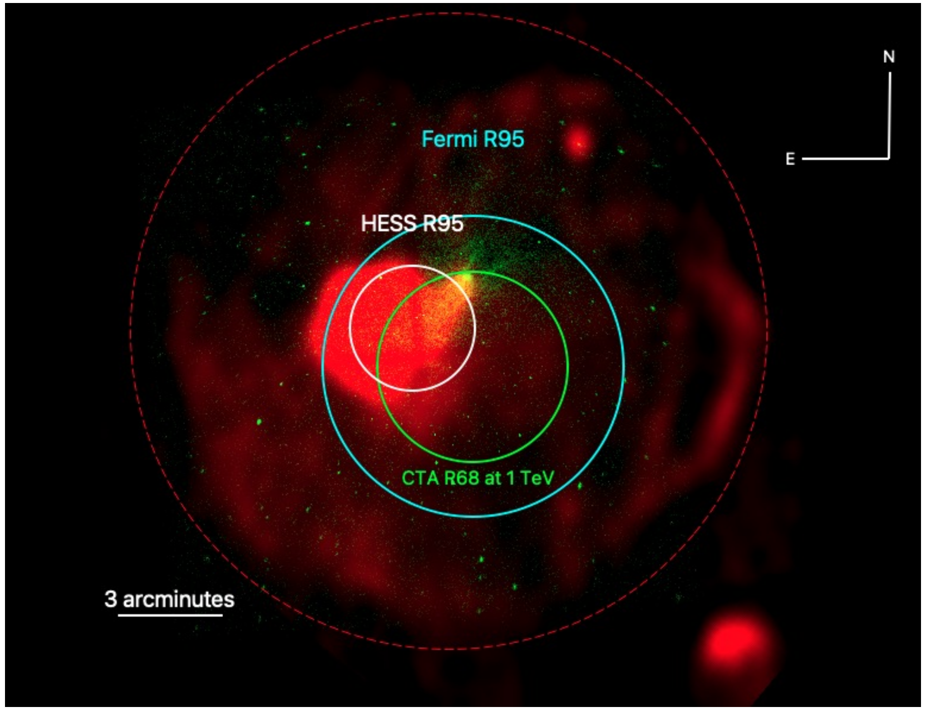
What I focus on: completing a systematic search for the γ-ray counterparts to known+candidate PWNe identified in radio, X-ray or TeV



Crab is point-lik Fermi
i.e., near the lin
angular resolution.

G327.1—1.1 Observation

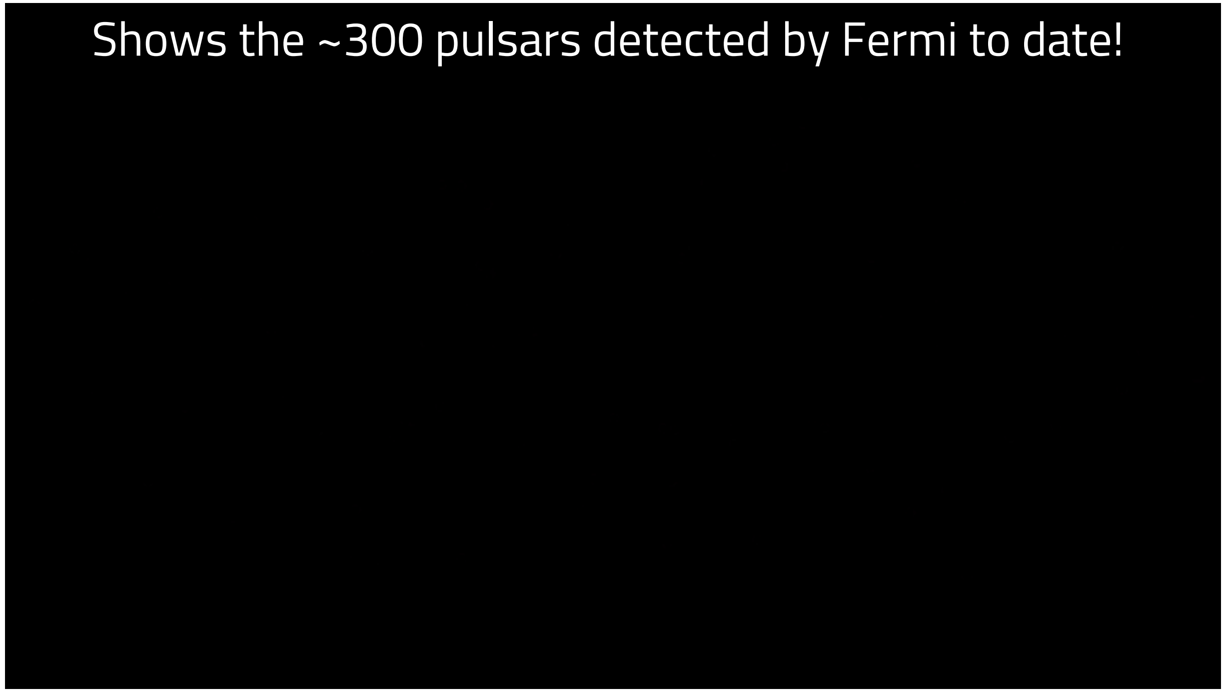
red = 843MHz radio
green = *Chandra* X-ray



Current gamma-ray telescopes have limited angular resolution

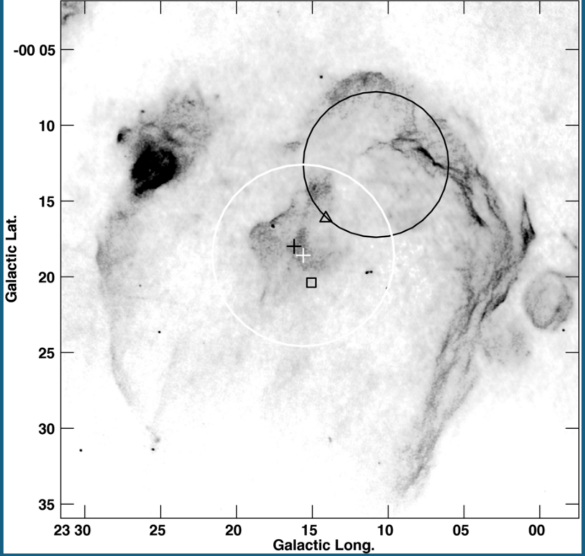
To identify γ-ray PWNe, we rely on multiwavelength (MWL) studies

We must also consider PSR or SNR contributions…



Credit: NASA's Goddard Space Flight Center

- Pulsars are the **largest** Galactic source population detected by the Fermi-LAT
- Typically "soft" spectral nature i.e., Fermi emission becomes insignificant by a few GeV

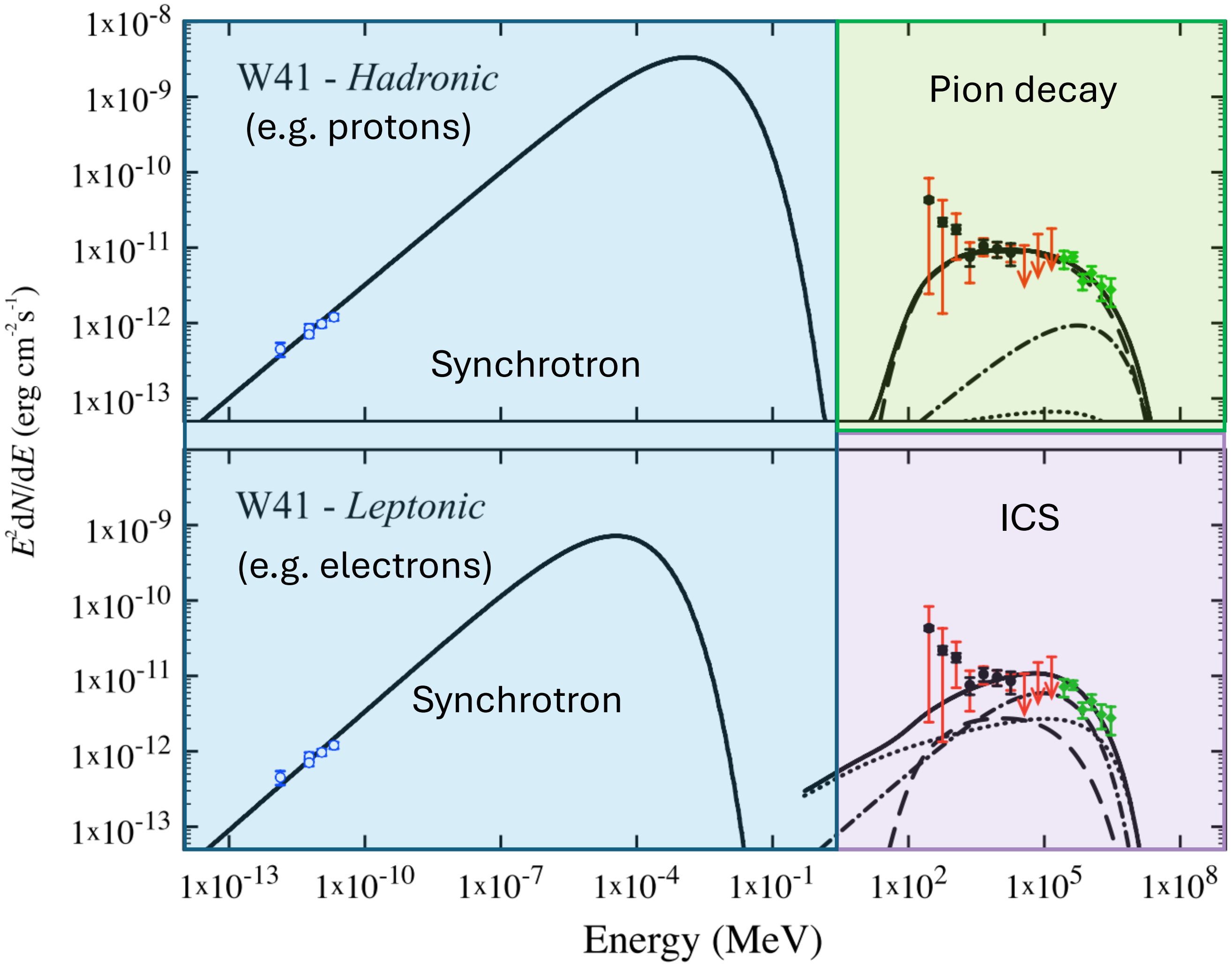


Supernova Remnants (SNRs)

- SNRs can also emit γ-rays
- Outnumber PWNe in Fermi catalogs (by nearly double)

W41 in radio. Frail et al., 2013

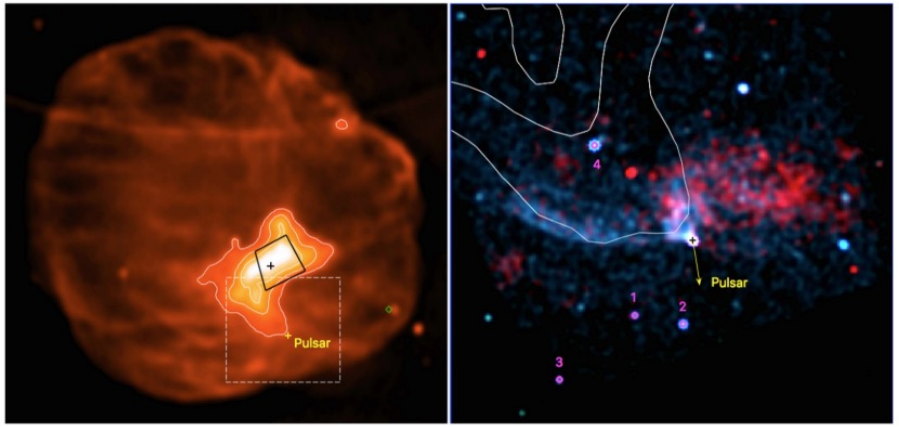
Broadband emission



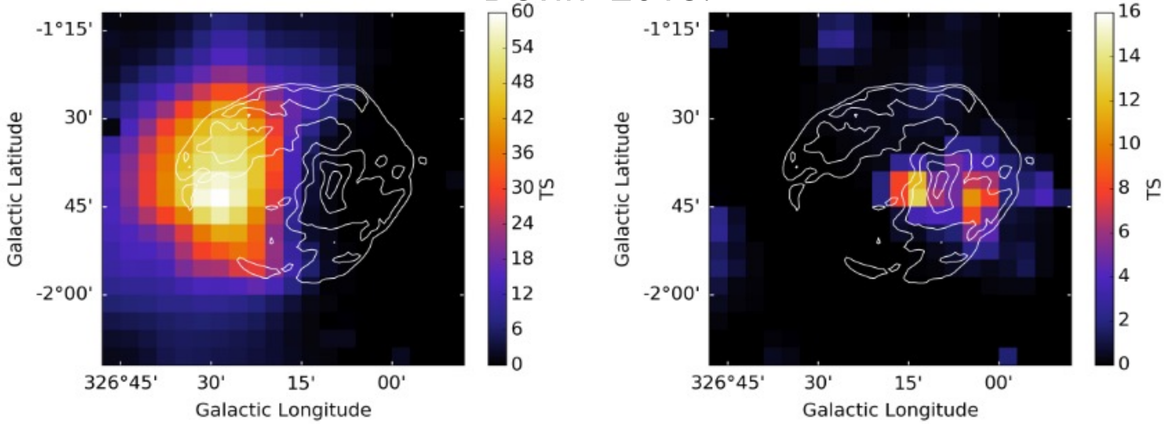
Castro et al., 2013.

Identifying Fermi PWNe

MSH 15-56 in radio (left) and in X-ray (right) from Temim+2017.



MSH 15-56 SNR (left) and PWN (right) in 1-300GeV with Fermi from Devin+2018.

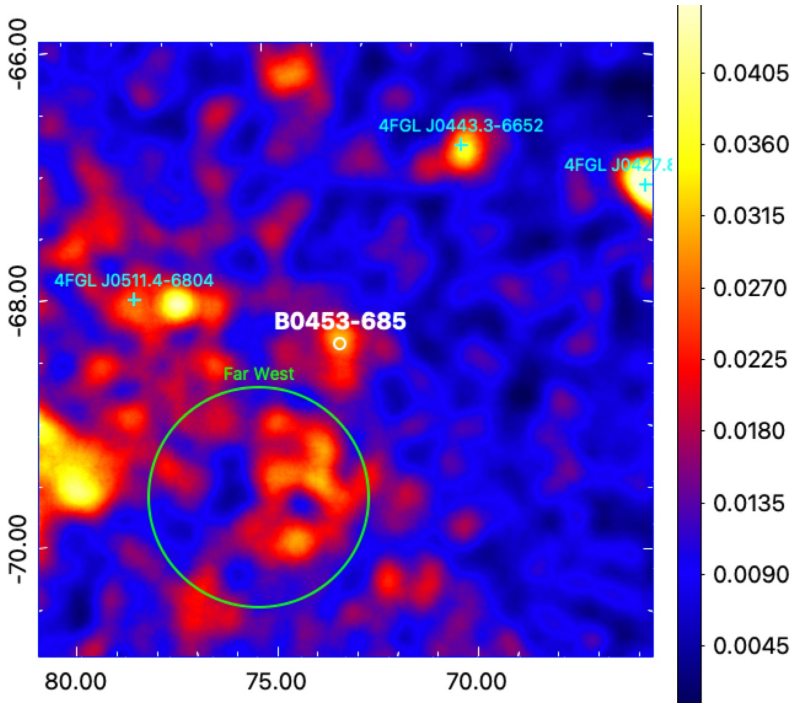


- Remove pulsed γ-ray signal → detect off-pulse signature not from pulsar (Crab, Vela-X, 3C 58)
- Flaring (Crab)
- Spatial and spectral studies in broadband (MSH 15-56)

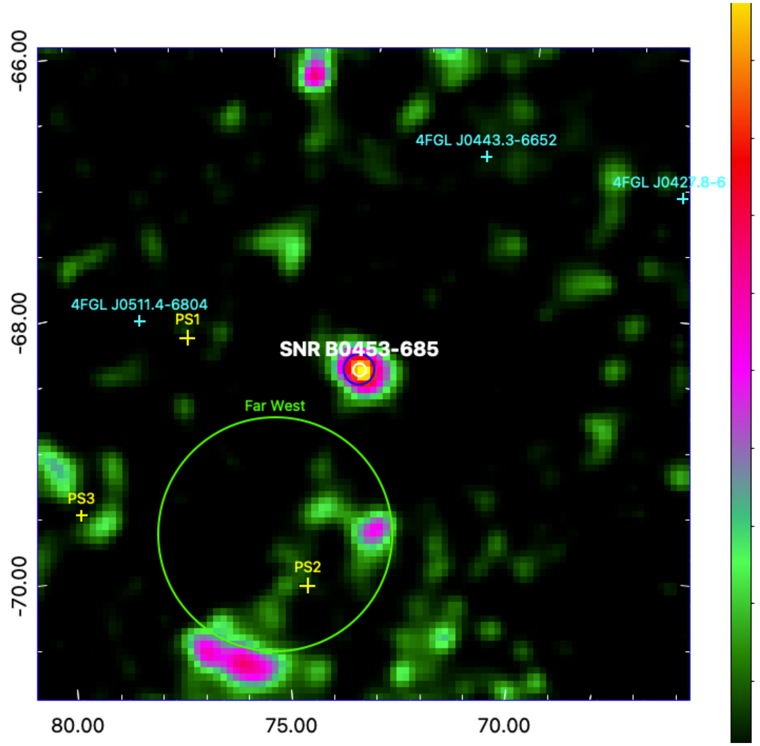
B0453-685 Fermi-LAT detection

- Point-like γ-ray emission discovered coincident to B0453-685
  - B0453-685 has angular size < 0.05 °
    - << than the Fermi optimal PSF ~ 0.1°
  - Detected at ~4σ (TS = 23 for 2 DOF)
  - Has soft spectral index $\Gamma_\gamma = 2.3 \pm 0.2$

1-10GeV *Fermi* γ-ray event map



1-10GeV *Fermi* γ-ray significance map

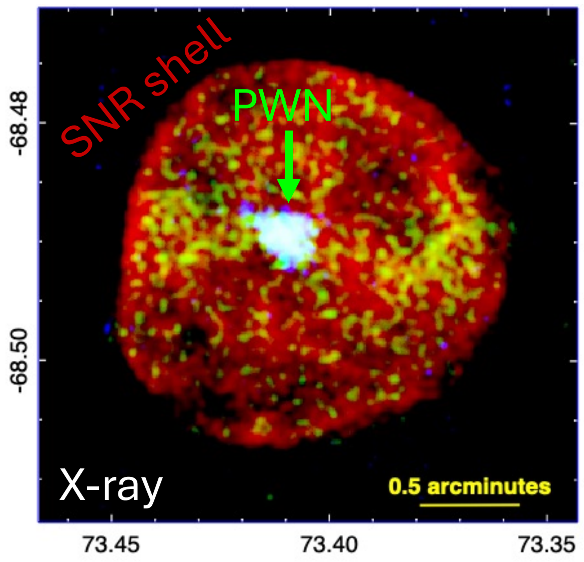


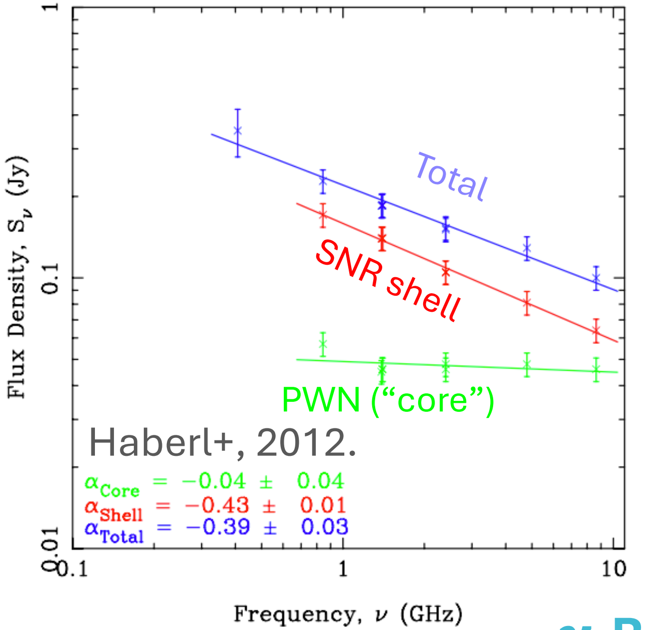
1 < E< 10GeV 5x5 ° TS map. Max TS at location of B0453-685 = 28.

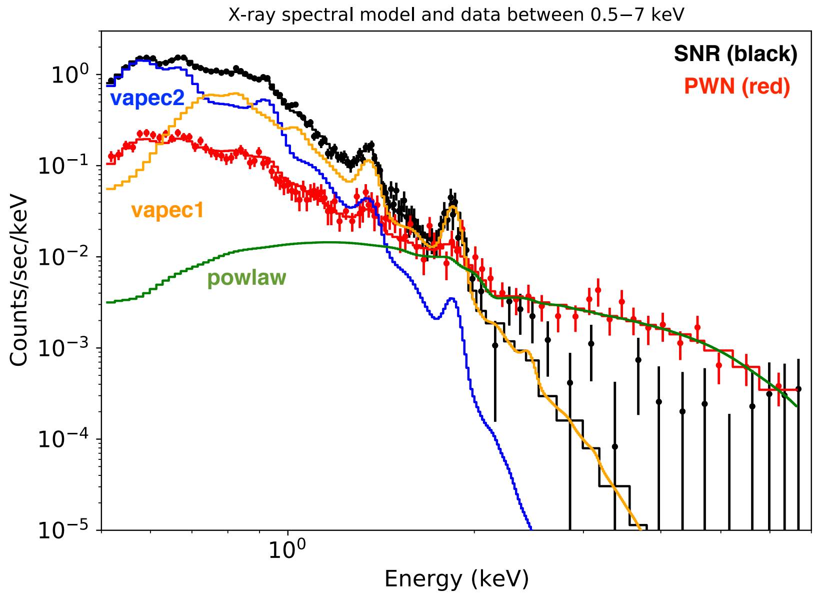
Spatial and spectral studies in broadband

RADIO

X-RAY



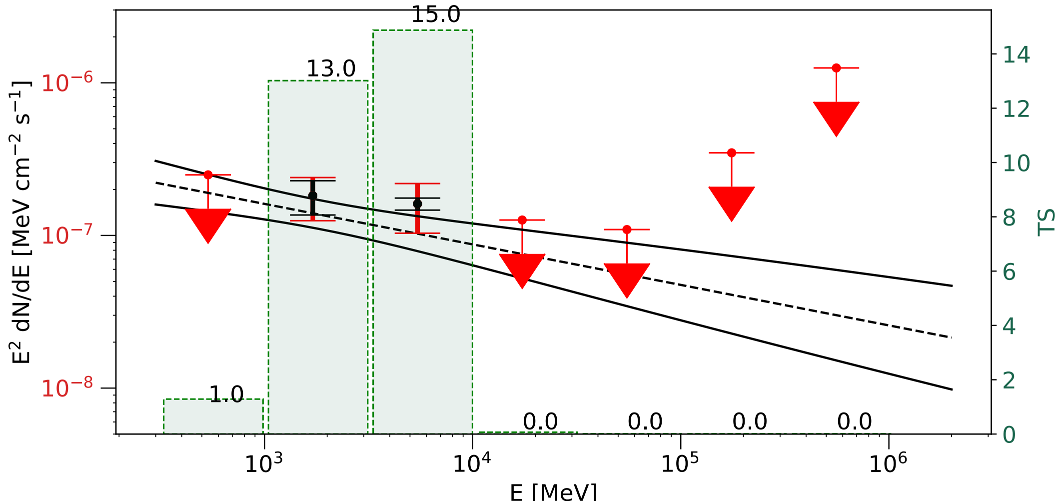




Chandra X-ray spectral data and models. The PWN is best-fit as a simple power law ($\Gamma_X \sim 1.7$).

- No non-thermal X-ray emission is detected from the SNR
- Combine the newfound γ-ray data with available radio and X-ray data to determine a most likely origin for the γ-rays

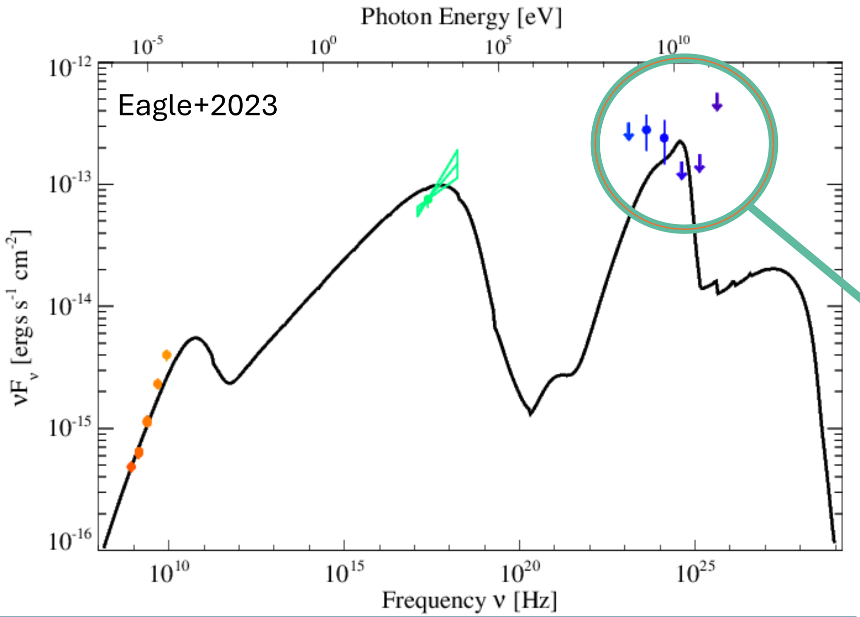
γ-RAY



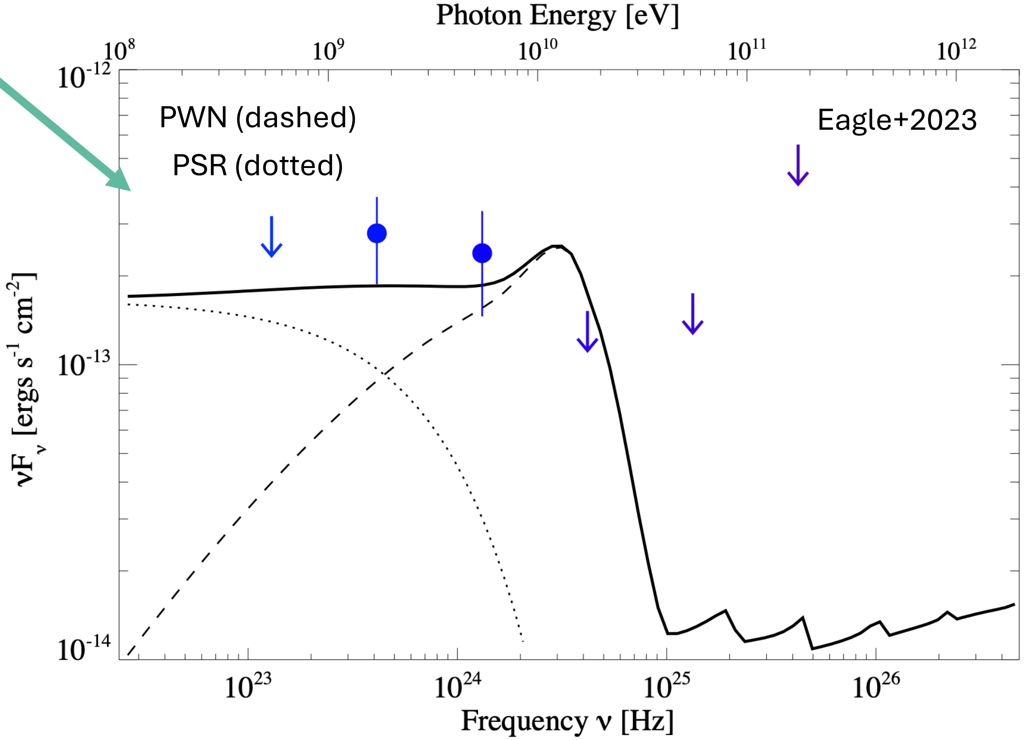
1-σ statistical errors

total systematic error from diffuse LMC model and LAT effective area

Spectral modeling



Best-fit results of the radiative evolution code for a PSR+PWN γ-ray origin.



Eb (GeV)	Index1 (E < Eb)	Index2 (E > Eb)	Max E (PeV)
70	1.3	2.4	0.73

Particle Properties

$\dot{E}$ (erg/s)	$\Gamma_{\gamma,psr}$	$E_{cut,psr}$ (GeV)	B (μG)	W_e (erg)	η ($\frac{L_\gamma}{\dot{E}}$)
8e35	2.0	3.2	6	5e48	0.32

Pulsar and PWN Properties

Inferred properties from X-ray:

τ (kyr)	n_0 (cm-3)	E_{SN} (erg)
13	0.4	7e50

Gaensler+,2003

Semi-analytic model results

τ (kyr)	n_0 (cm-3)	E_{SN} (erg)
14	1.0	5e50

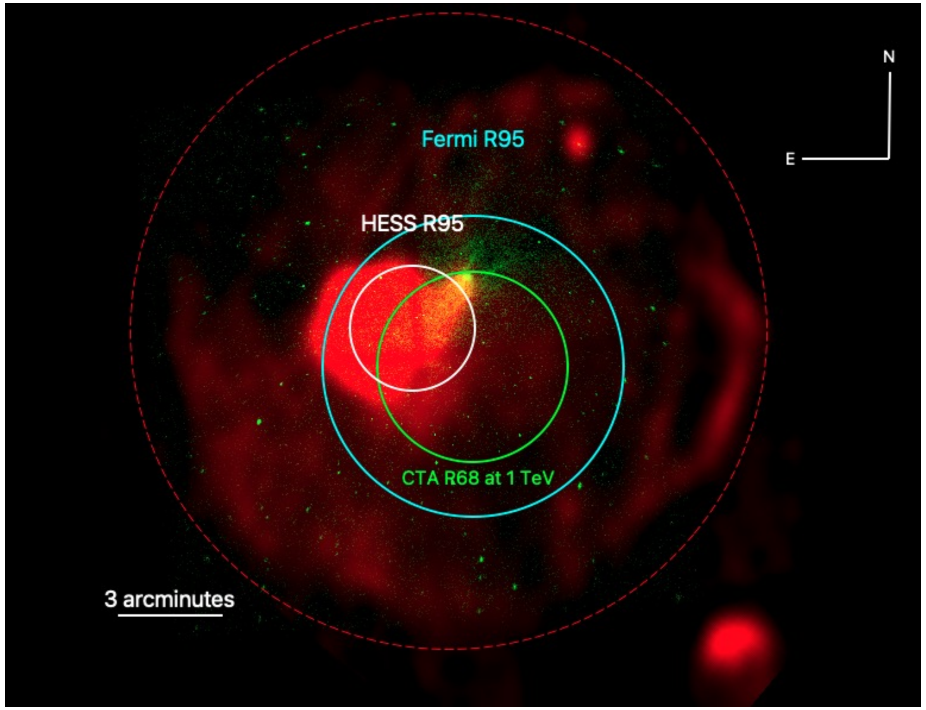
Another example... G327.1-1.1

Spatial and spectral modeling

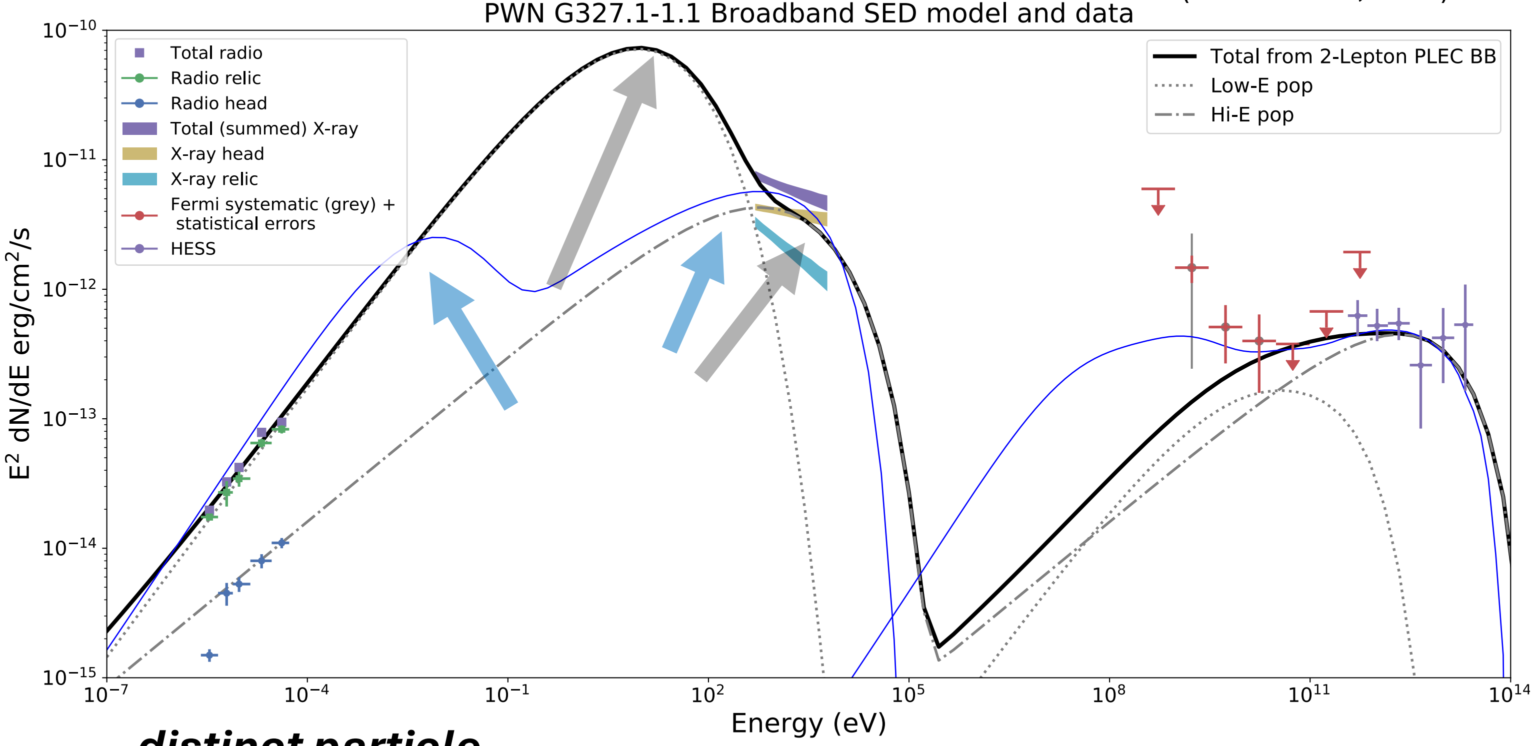
G327.1—1.1 Observation

red = 843MHz radio

green = *Chandra* X-ray



blue = broadband model derived from a radiative evolution code (Temim et al., 2015).



distinct particle populations manifest as double-peak structures

From Eagle et al., 2022

We can learn about the acceleration mechanisms of the underlying particles

Particle Properties	Eb (GeV)	Index1 (E < Eb)	Index2 (E > Eb)	Max E (PeV)
B0453-685	70	1.3	2.4	0.73
G327.1-1.1 (Temim+2015)	300	1.48	2.2	0.5
G327.1-1.1 (Eagle+2022)	1000-41000	1.61	2.15	0.2

Similar to the Crab which also requires two electron populations:

Comp-I particle injection index **p = 2.2**
- Accelerated via diffusive shock acceleration (DSA)
- Dominate in MeV-GeV γ-ray band

Comp-II particle injection index **p = 1.6**
- Not likely to be undergoing DSA, but instead ***turbulence-driven**** particle acceleration
- Dominates majority of radio emission

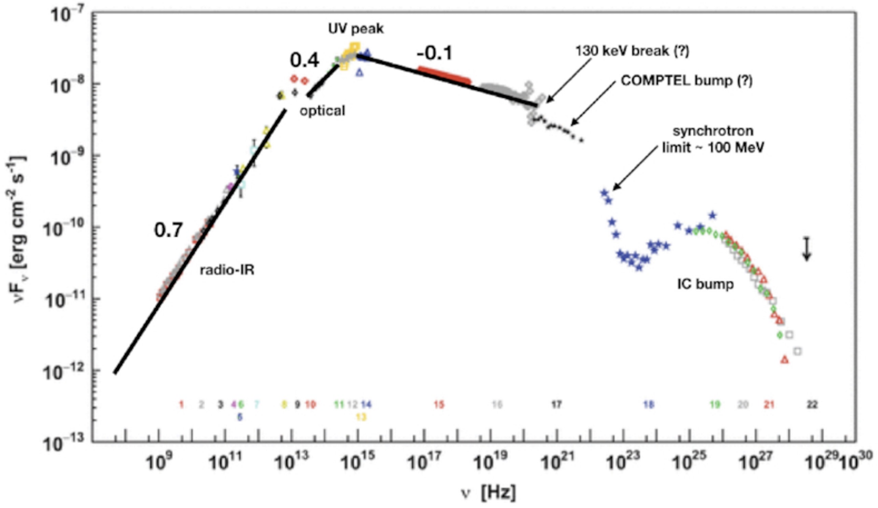


Fig. 1 of Lyutikov, 2019

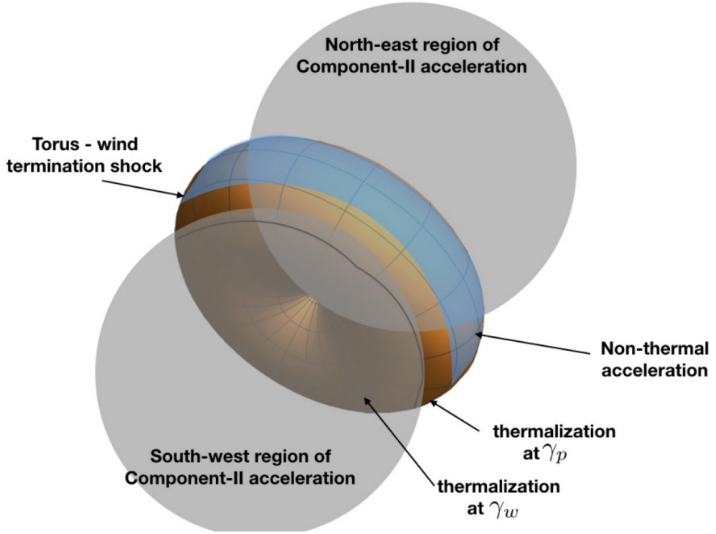


Fig. 4 of Lyutikov, 2019

* Such as magnetic reconnection and/or Weibel instability (Sironi & Spitzkovsky, 2011)

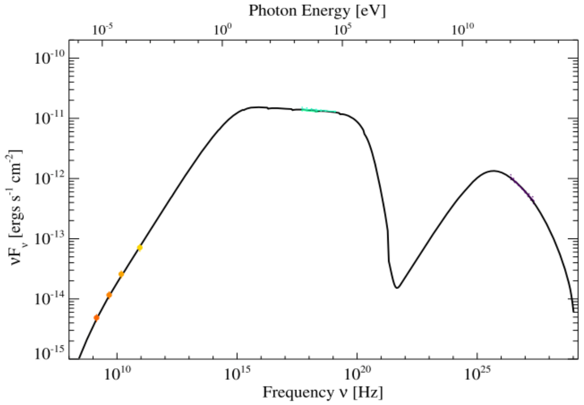
Lyutikov+, 2019

High-energy PWN population

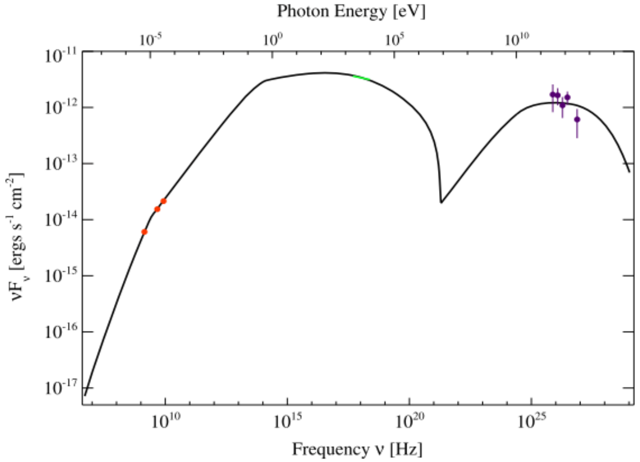
Kes 75	G54.1+0.3	B0453-685	G327.1-1.1
Young PWN ($\tau \sim 300\ yr$)	Young PWN ($\tau \sim 2.5\ kyr$)	Middle-aged/evolved PWN ($\tau \sim 14\ kyr$)	Old/evolved PWN ($\tau \sim 18\ kyr$)

dominated by earliest injected particles (i.e., old) at all energies

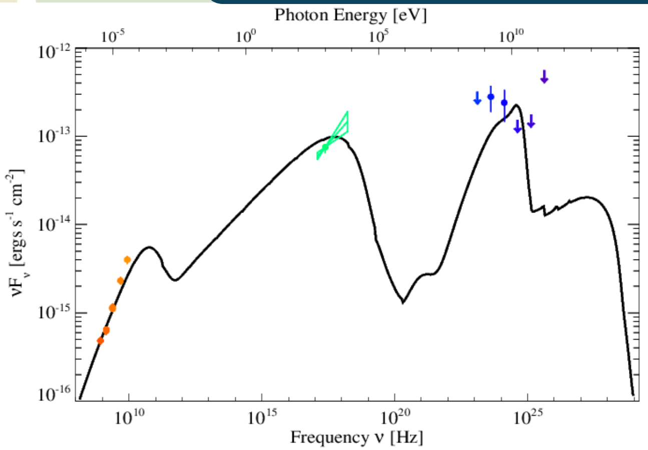
distinct particle populations manifest as PWN evolves + PSR continues to inject new high-energy particles



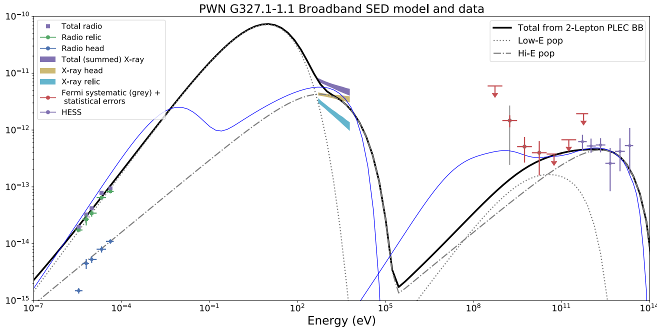
Gotthelf et al., 2021



Gelfand et al., 2015



Eagle et al., 2023



Eagle et al., 2022

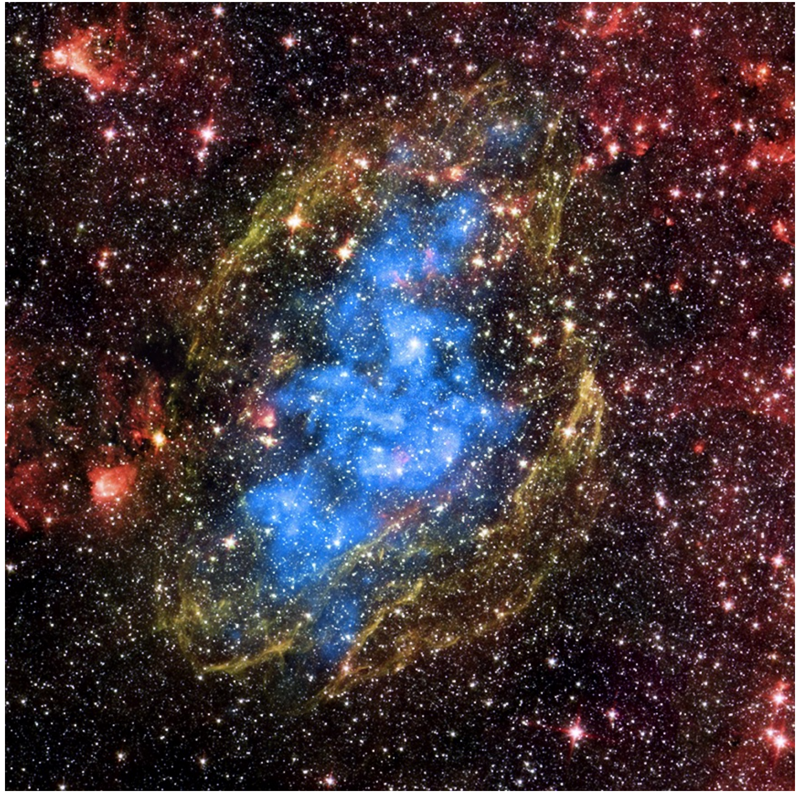
Summary

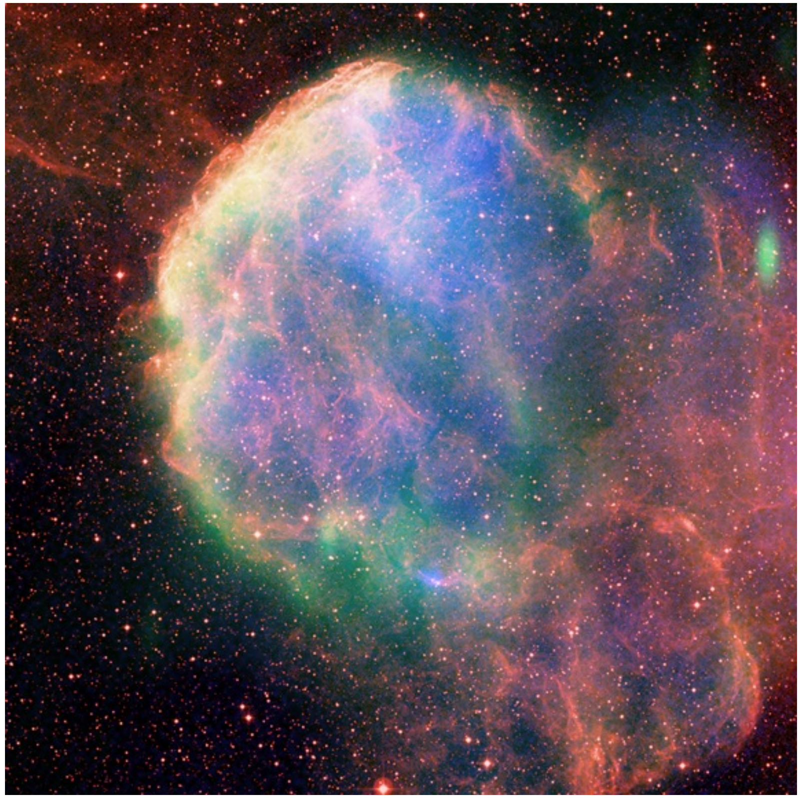
- The Crab Nebula is the prototype of PWNe (for good reason!)
- Where there are gamma-rays there may be cosmic rays
- PWNe are candidates for Galactic CR acceleration
  - Most Galactic TeV sources = PWNe
  - High-energy PWN observations imply CR acceleration capabilities
  - Great laboratories for studying acceleration mechanisms,required conditions, and particle properties

Extras

Image/gif credit: Goddard Med

W44 in X-ray (blue), IR (green and red). X-ray: NASA/CXC/Univ. of Georgia/R.Shelton & NASA/CXC/GSFC/R.Petre; Infrared: NASA/JPL-Caltech

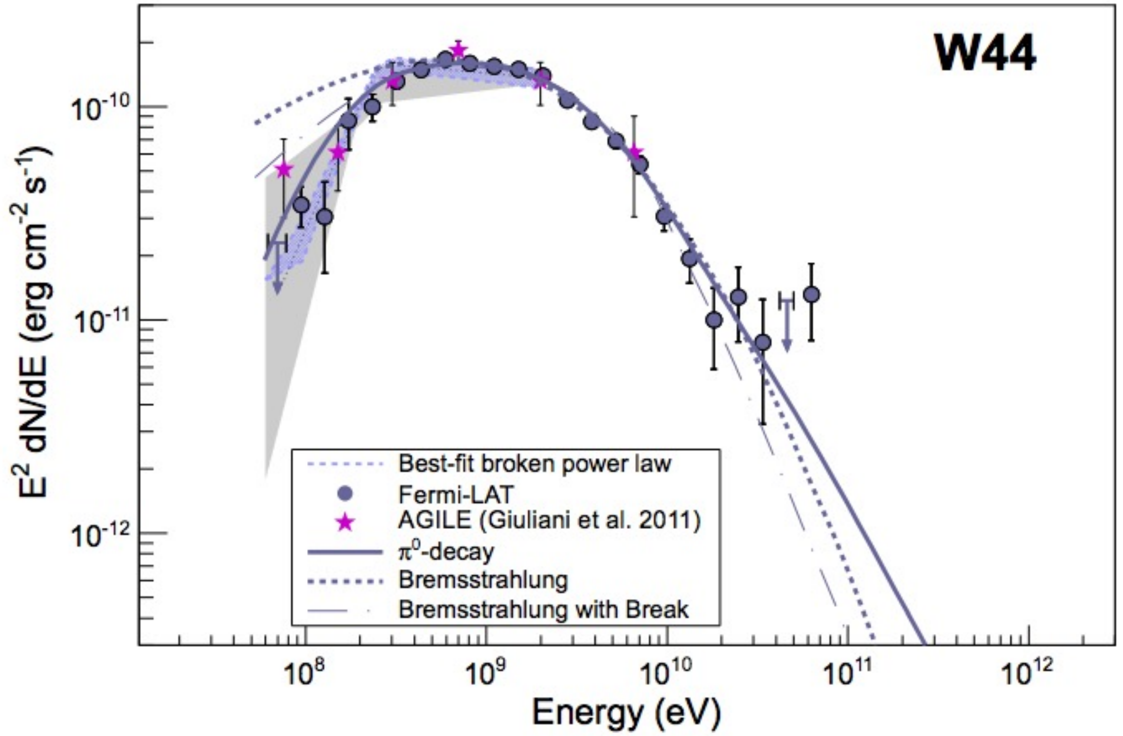


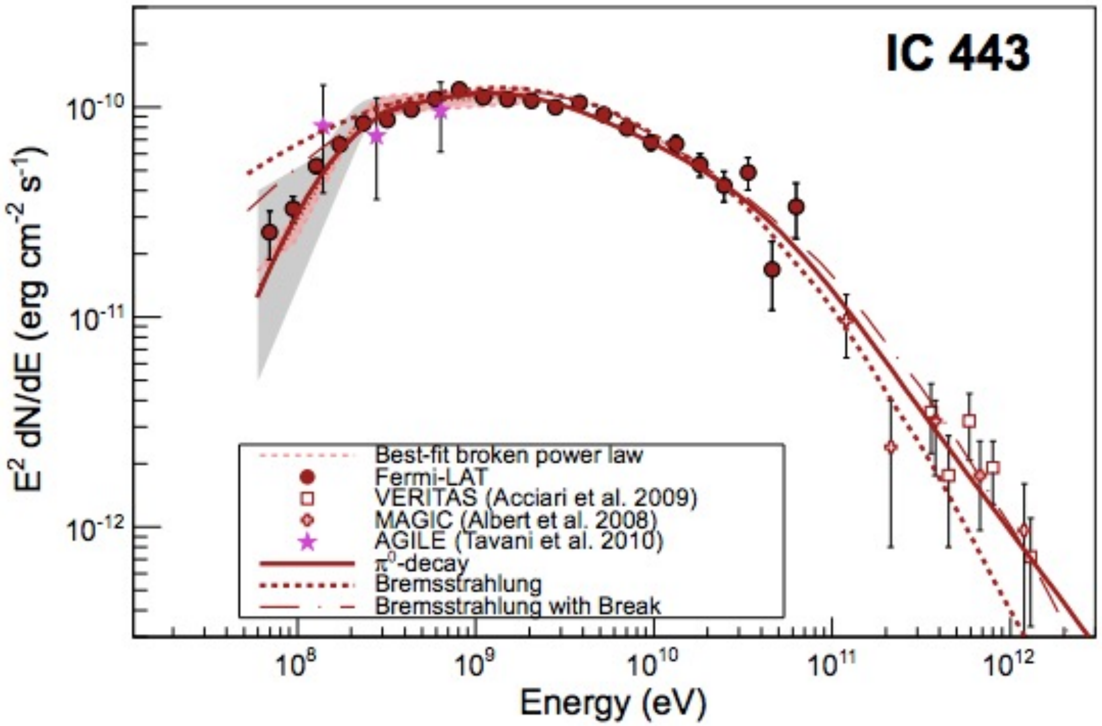


IC 443 in X-ray (blue), radio (green), and optical (red). Credit: Chandra X-ray: NASA/CXC/B.Gaensler et al; ROSAT X-ray: NASA/ROSAT/Asaoka & Aschenbach; Radio Wide: NRC/DRAO/D.Leahy; Optical: DSS

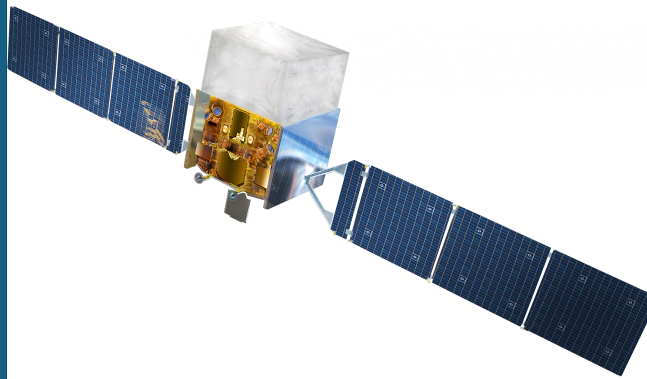
Fermi-LAT Supernova remnants W44 and IC443

High-Energy Pulsar Wind Nebula Studies



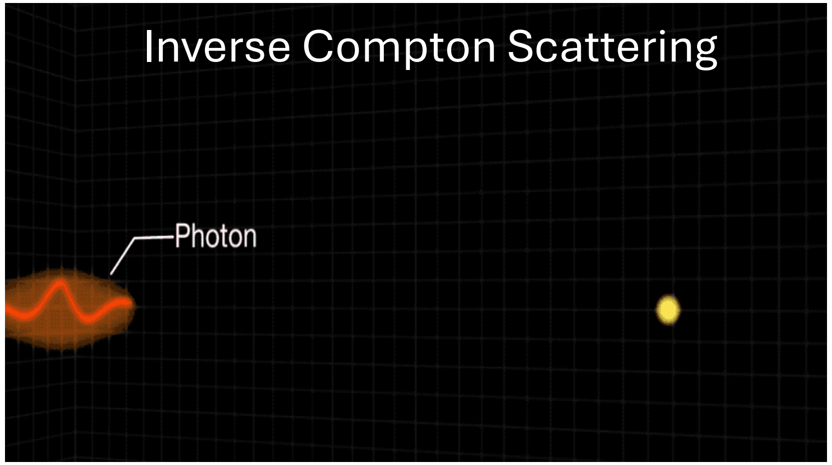


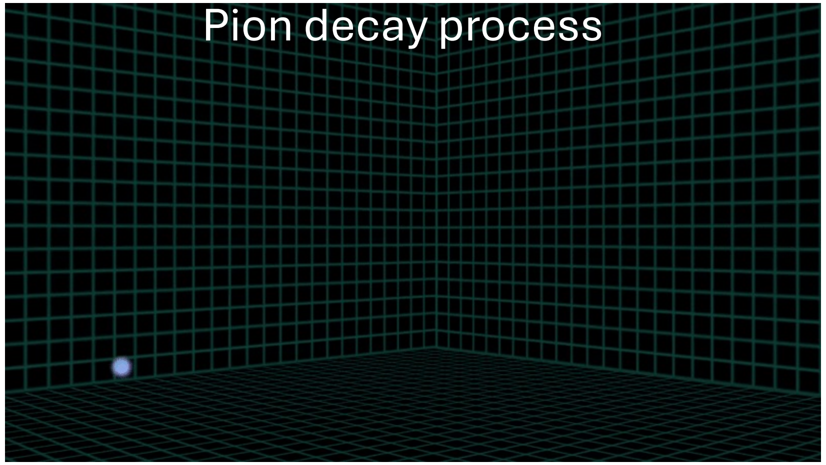
Ackermann et al., 2013.

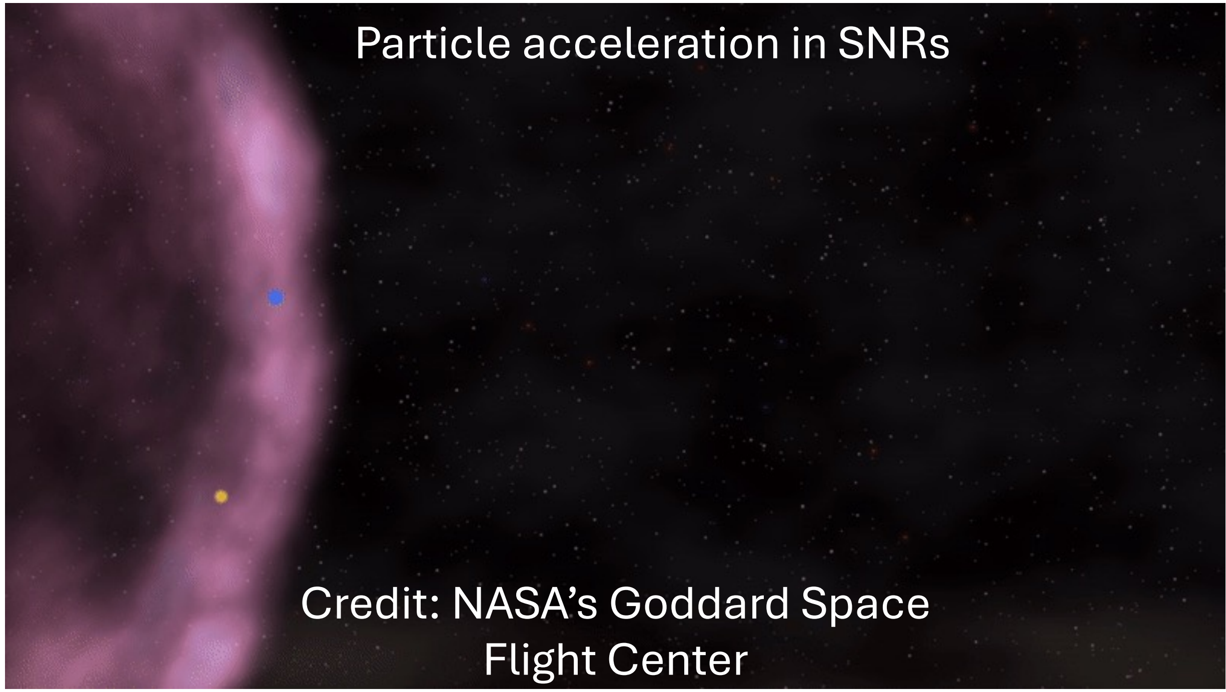


Signature pion-decay “bump”

High-Energy Pulsar Wind Nebula Studies







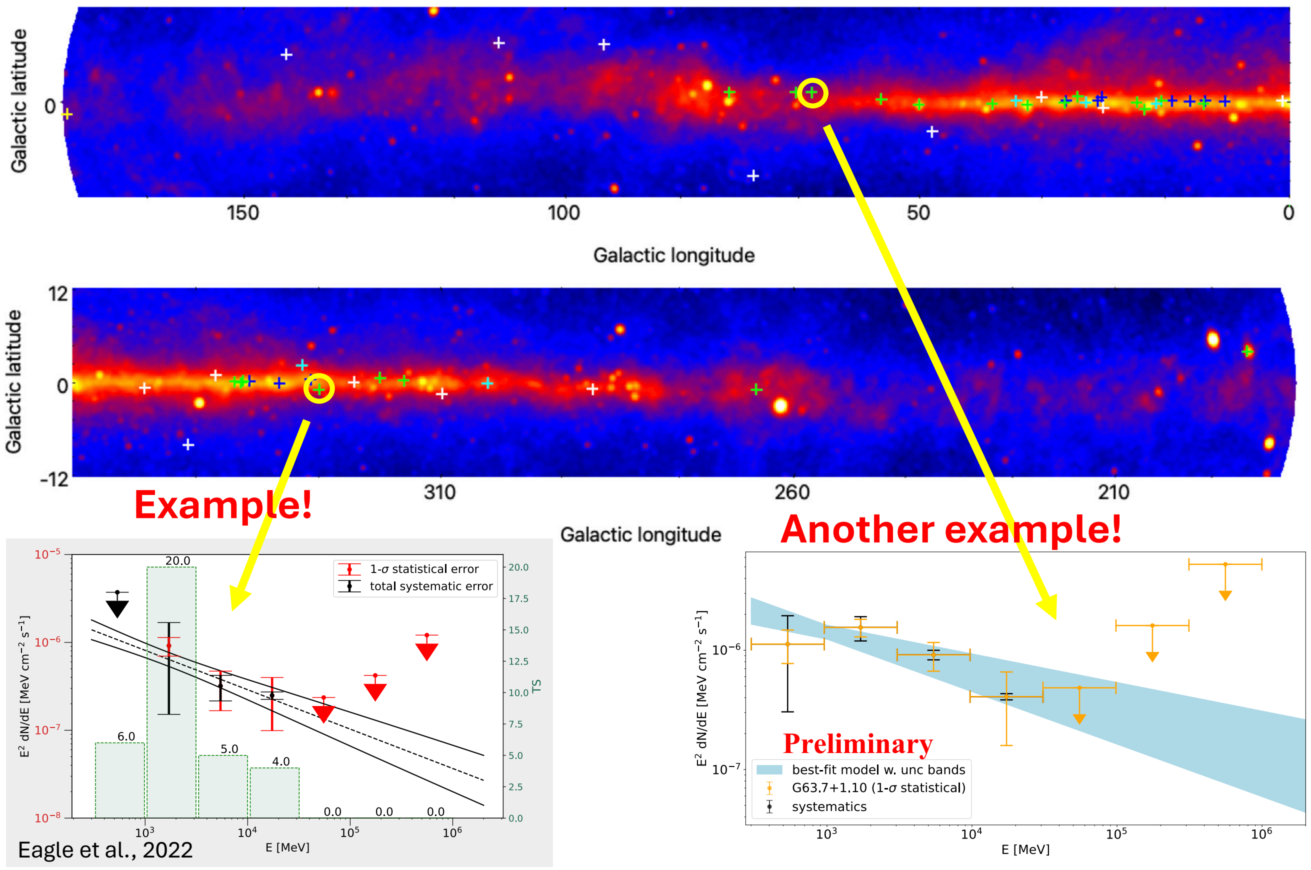
Both electrons and protons can be accelerated in the shockwaves of SNRs

γ-ray Emission in SNRs

High-Energy Pulsar Wind Nebula Studies

Systematic Studies

Below: The Fermi-LAT 12-year sky E > 1 GeV. The 58 ROIs are indicated. Green = point-like detections, blue = extended detections, white = nondetections



High-Energy Pulsar Wind Nebula Studies

Systematic error from choice of IEM

IEM: the interstellar emission model

Must consider uncertainties from diffuse gamma-ray Galactic background model

- aIEM prescription first outlined in the SNR catalog
- We adopt the same 8 alternative IEMs (aIEMS) from FGES to measure systematics from choice of IEM

Systematic error from IRF

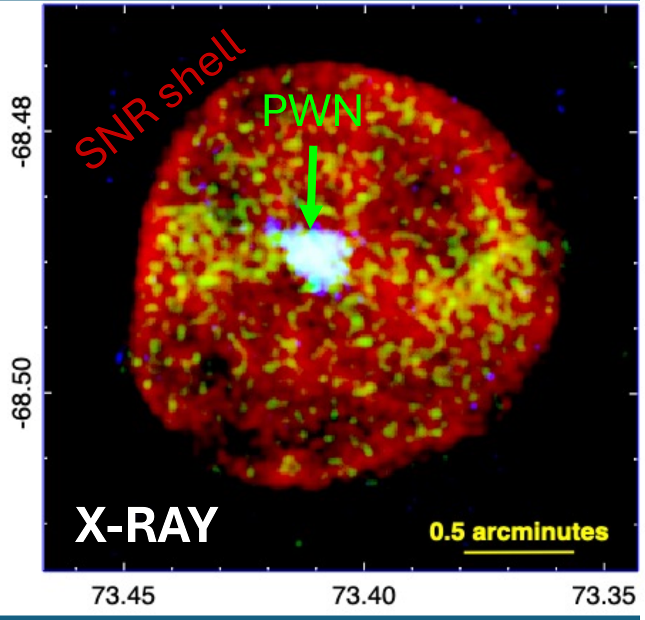
IRF: Instrument response function

Must consider uncertainties from instrument performance

- Analysis enables energy dispersion
- IRF systematics estimated as follows:
  - +/- 3% for E < 100 GeV
  - +/- 4.5% for E = 175 GeV
  - +/- 8% for E = 556 GeV

For more info:
https://fermi.gsfc.nasa.gov/ssc/data/analysis/LAT_caveats.html

γ-ray origin investigation through MWL modeling



Estimated values for LMC:

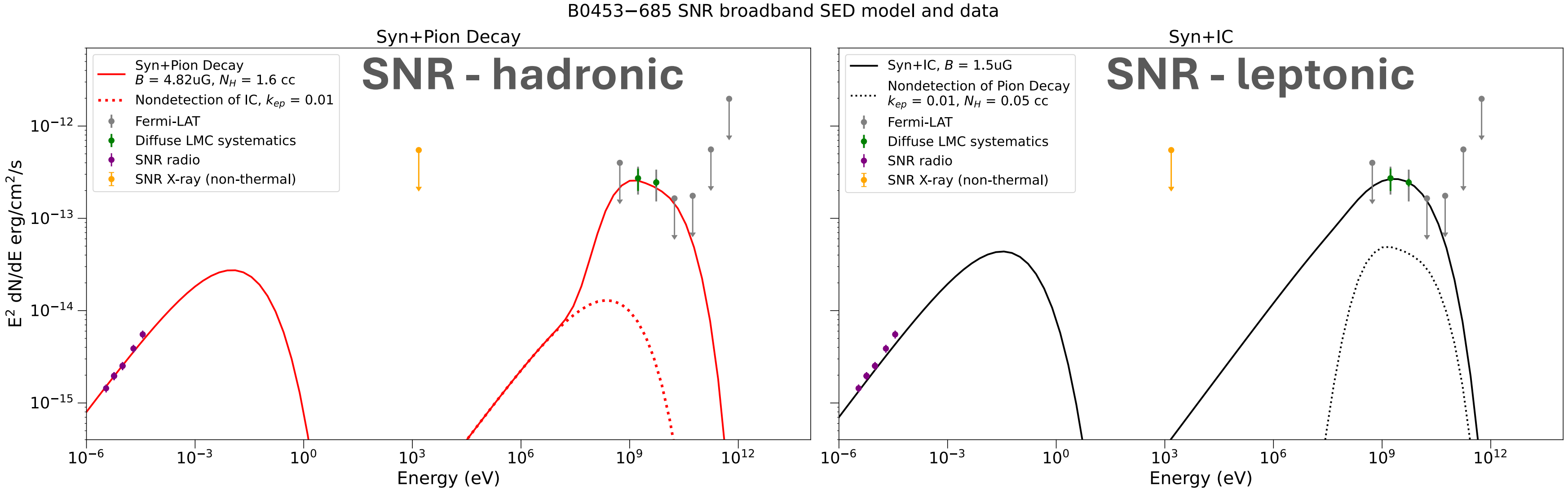
B (uG)	Nh (cm-3)
~ 1.0 (3)	8 (1)

Observational constraints

Inferred SNR properties from X-ray:

τ (kyr)	Nh (cm-3)	v_s (km/s)
13 (2)	1.6 (2)	$\lesssim$ 500 (4)

(1) Kim+, 2003
(2) Gaensler+,2003
(3) Gaensler+,2005
(4) Castro+, 2011



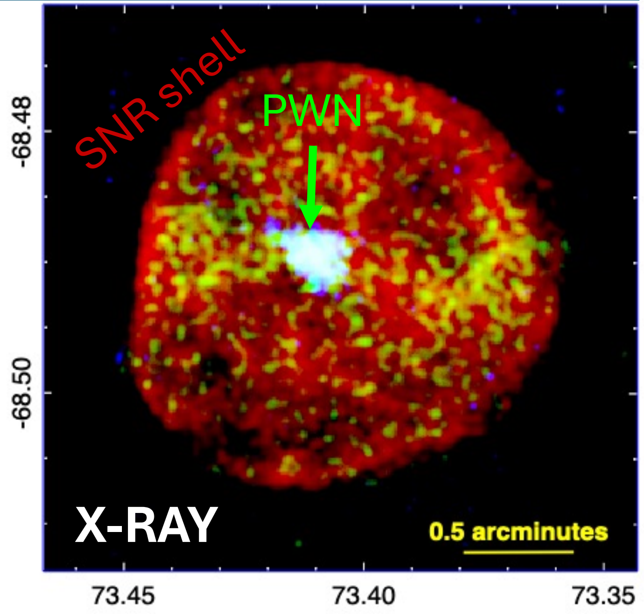
Model	We or Wp (erg)	B (μG)	Nh (cm-3)
SNR (hadronic)	4e51	4.8	1.6
SNR (leptonic)	3e50	1.5	0.05

Modeling results

- The **age** of the SNR inferred from X-rays, **lack of non-thermal X-rays** from SNR, and the **MWL modeling** results **do not support** an SNR origin

High-Energy Pulsar Wind Nebula Studies

γ-ray origin investigation through MWL modeling



High-Energy Pulsar Wind Nebula Studies

Estimated values for LMC:

B (uG)	Nh (cm-3)
~ 1.0 (3)	8 (1)

Observational constraints

Inferred SNR properties from X-ray:

τ (kyr)	Nh (cm-3)	v_s (km/s)
13 (2)	1.6 (2)	≲ 500 (4)

(1) Kim+, 2003
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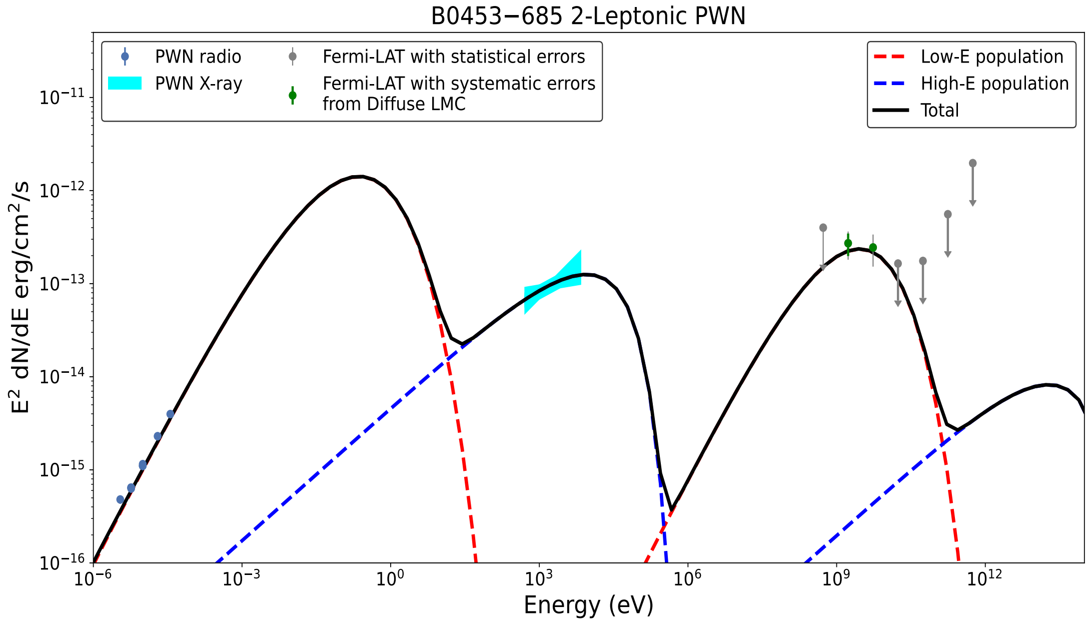
(3) Gaensler+,2005
(4) Castro+, 2011

PWN - leptonic



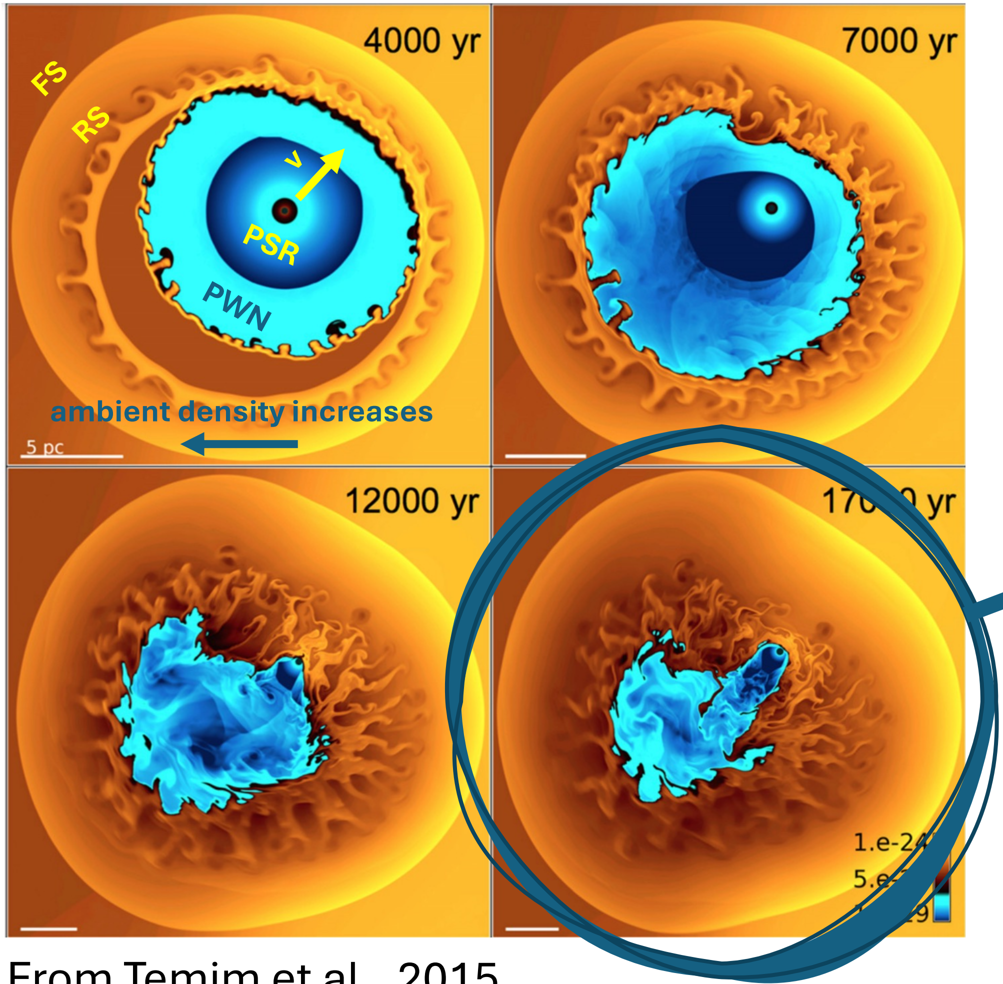
Model	We or Wp (erg)	B (μG)	Nh (cm-3)
PWN (leptonic)	3e49	8.2	--

Modeling results

Summary: Simple radiative modeling favors PWN γ-ray origin

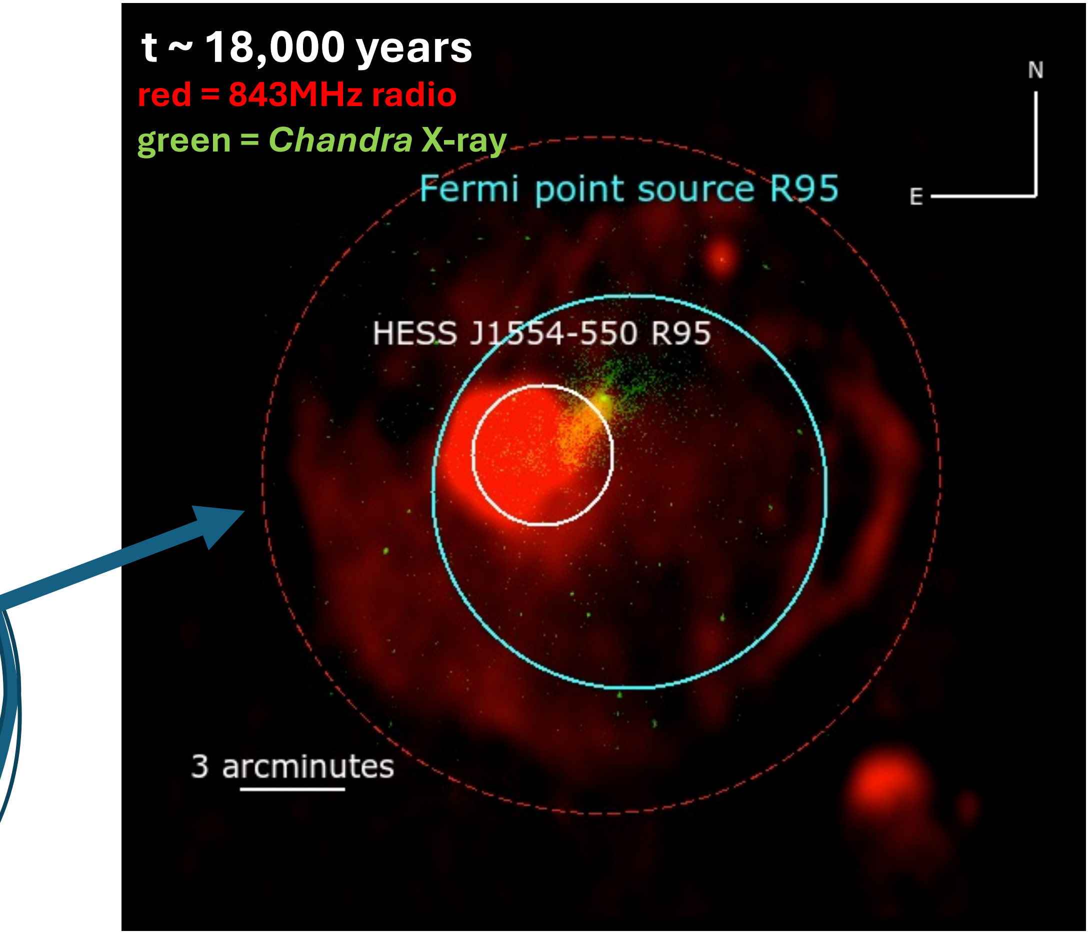
PWN Evolution through Broadband Studies

G327.1—1.1 Simulation



From Temim et al., 2015

G327.1—1.1 Observation



From Eagle et al., 2022