Pulsar Wind Nebulae as probes of high energy astrophysics

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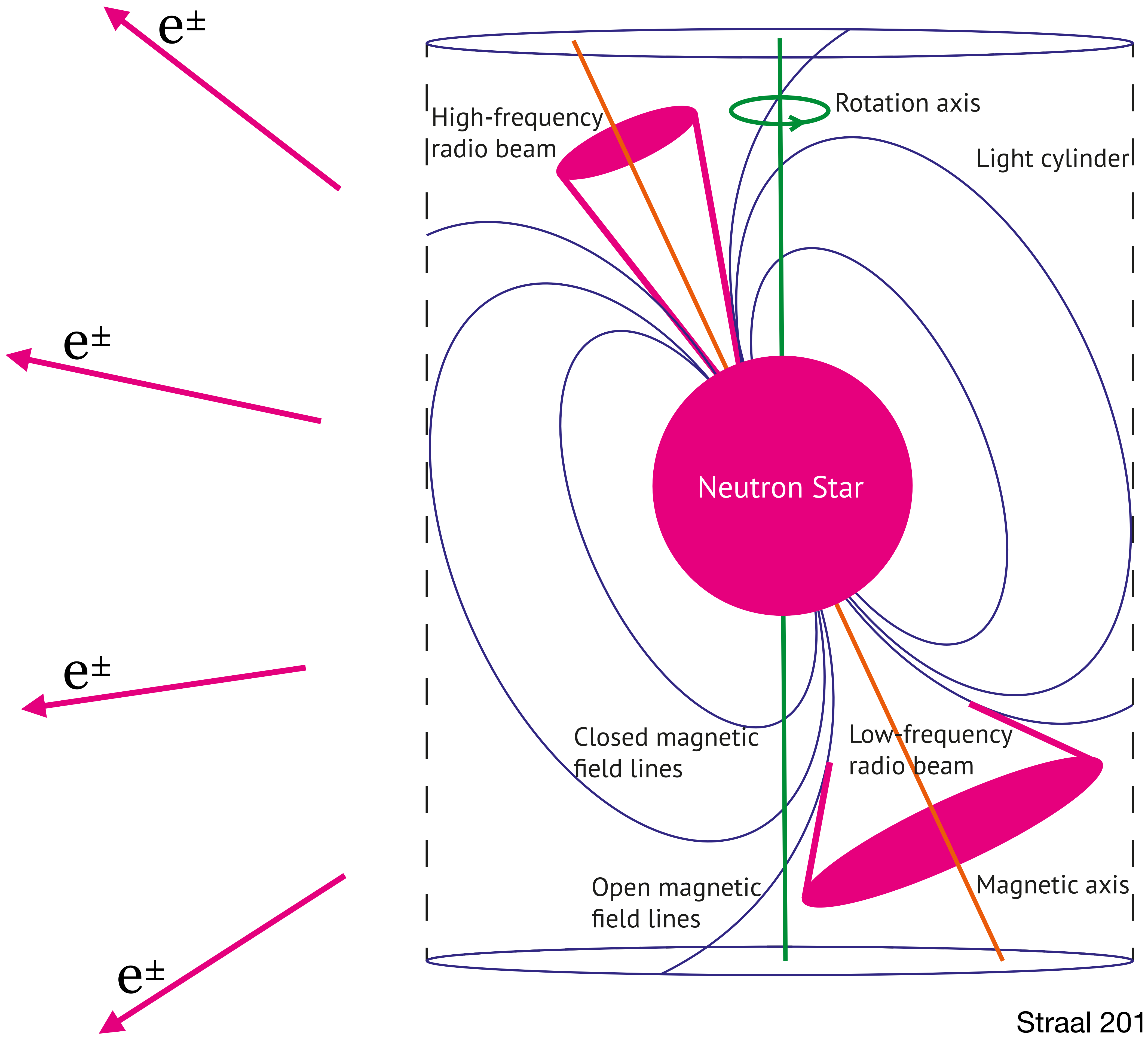
Pulsar Wind Nebulae

- Majority of CC-SNe create a neutron star (NS)
- Rotational energy of these energetic NSs power a highly relativistic e± wind
- Interaction of pulsar 'wind' and environment form the pulsar wind nebula (PWN)
- PWN act as **calorimeters** for the NS
- PWN properties depend on NS birth, SN explosion and environmental characteristics



Straal 2018

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- Rotational energy of these energetic NSs power a highly relativistic $e^{\pm}$ wind
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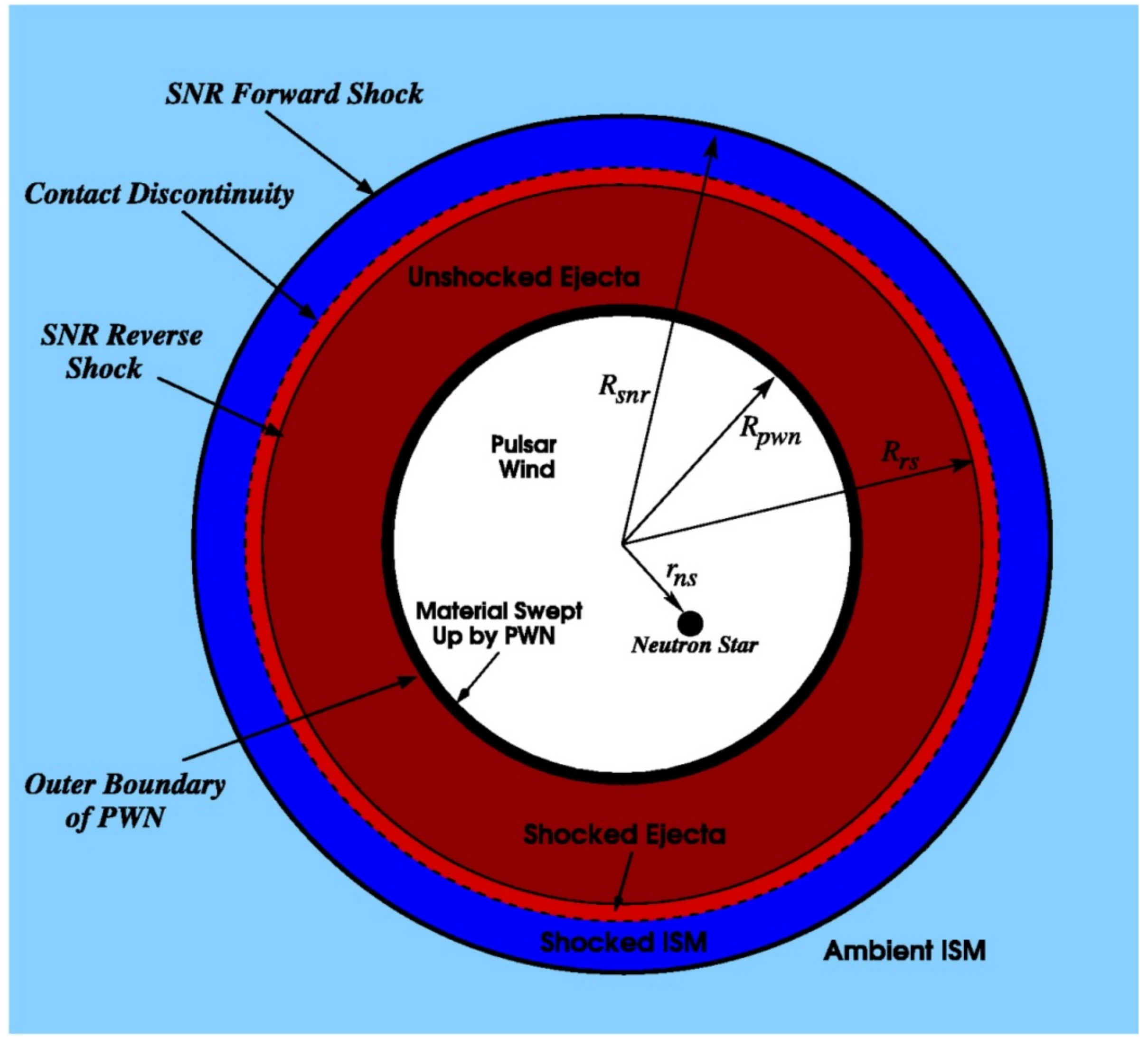
c. NASA/CXC/SAO

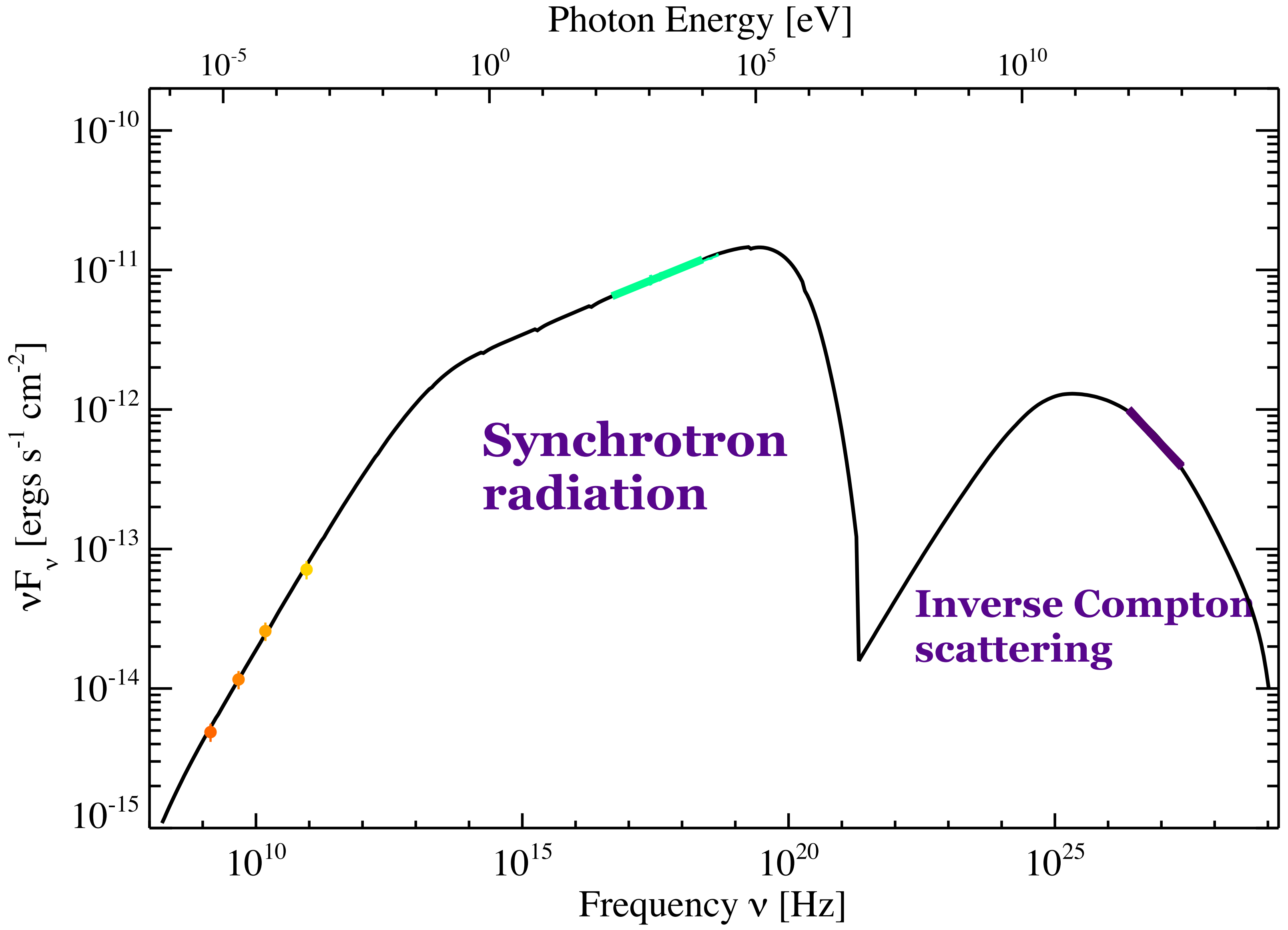
Modelling a PWN inside a SNR

- One-zone model that describes dynamic and radiative evolution (Gelfand+2009)
- Evolution depends on:
  - Initial kinetic energy of SN
  - Mass of SN ejecta
  - ISM density (n_0)
  - Pulsar wind magnetisation
  - Pulsar energy input (history)

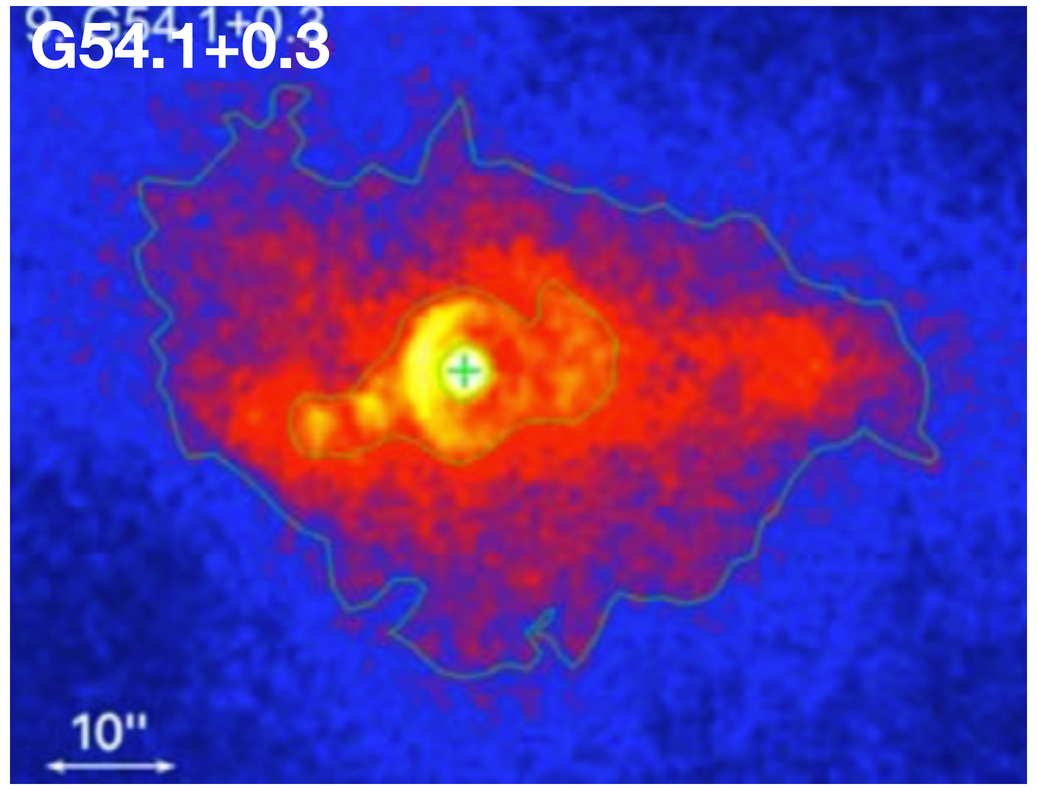
$$\dot{E}_0 = \dot{E}\left(1 + \frac{t_{\rm age}}{\tau_{\rm sd}}\right)^{\frac{p+1}{p-1}}$$

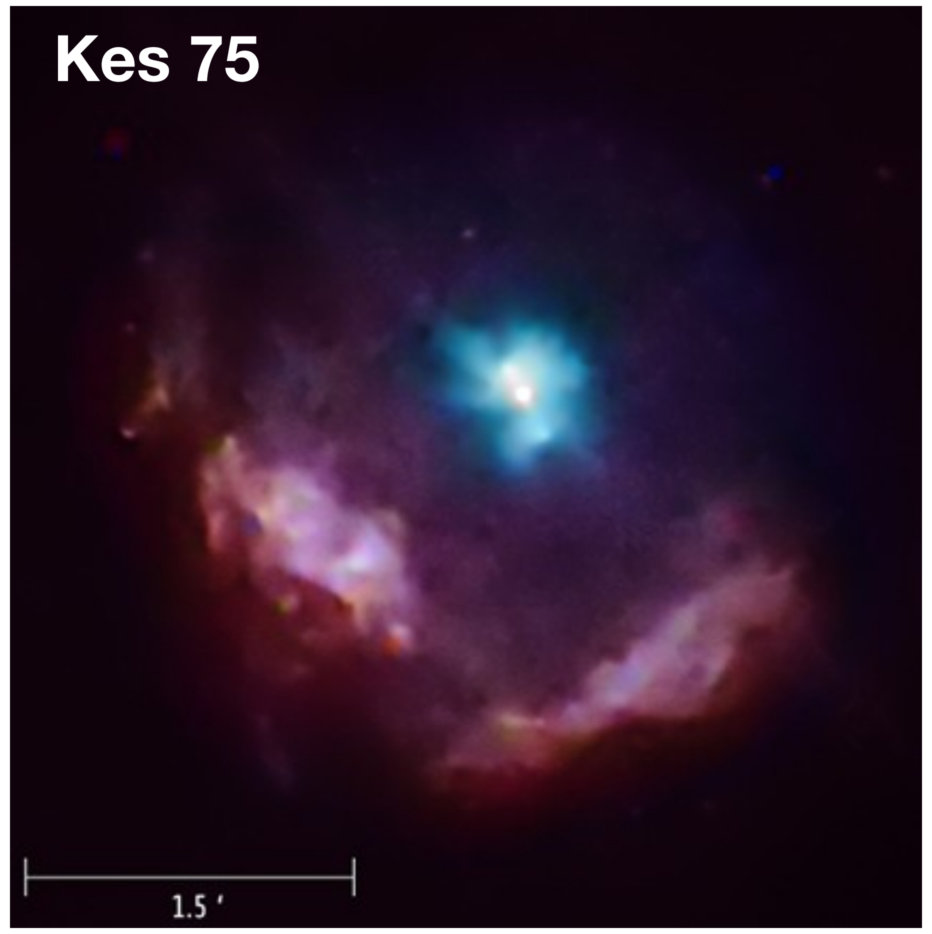


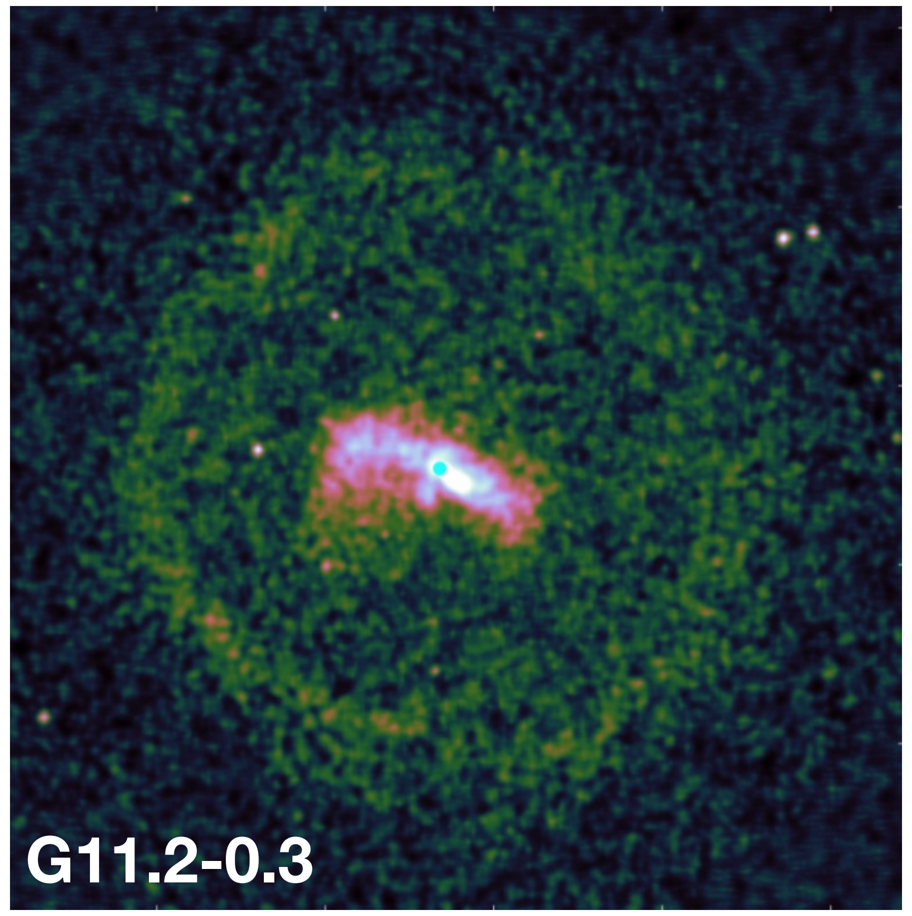
Gelfand+ 2007 (ApJ, 663, 468)

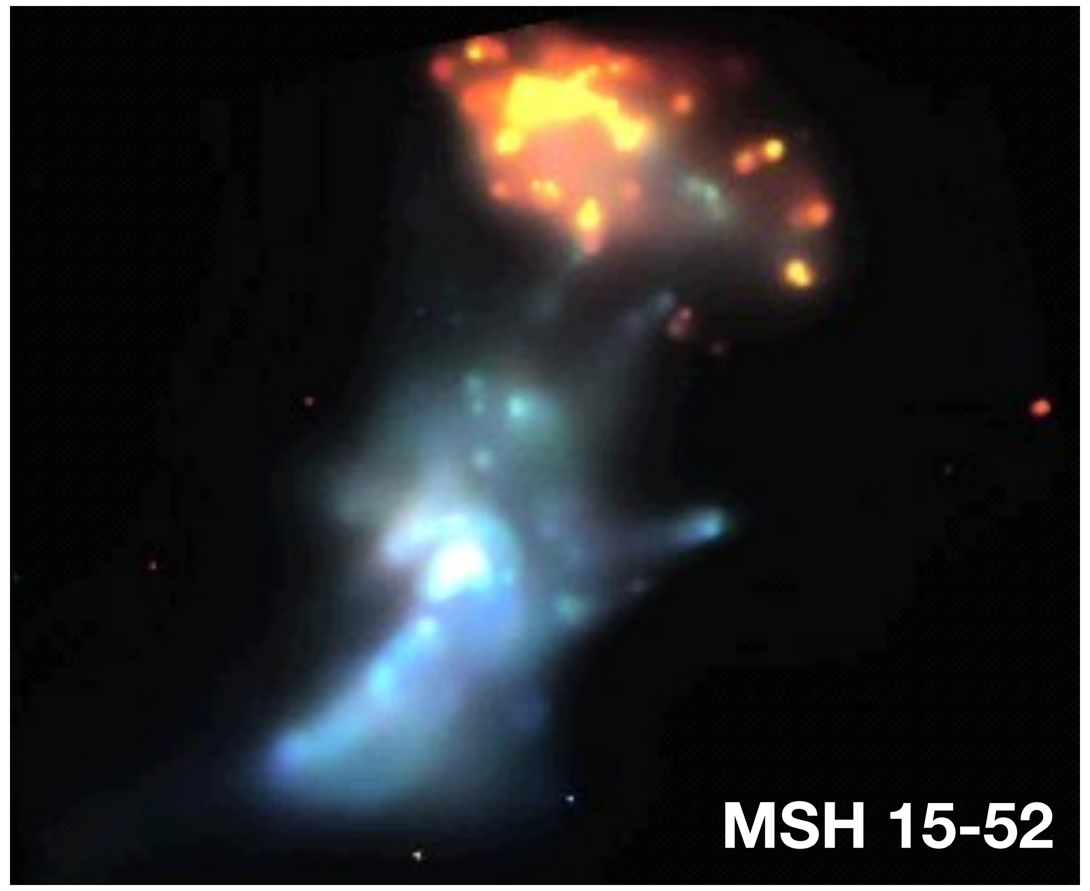


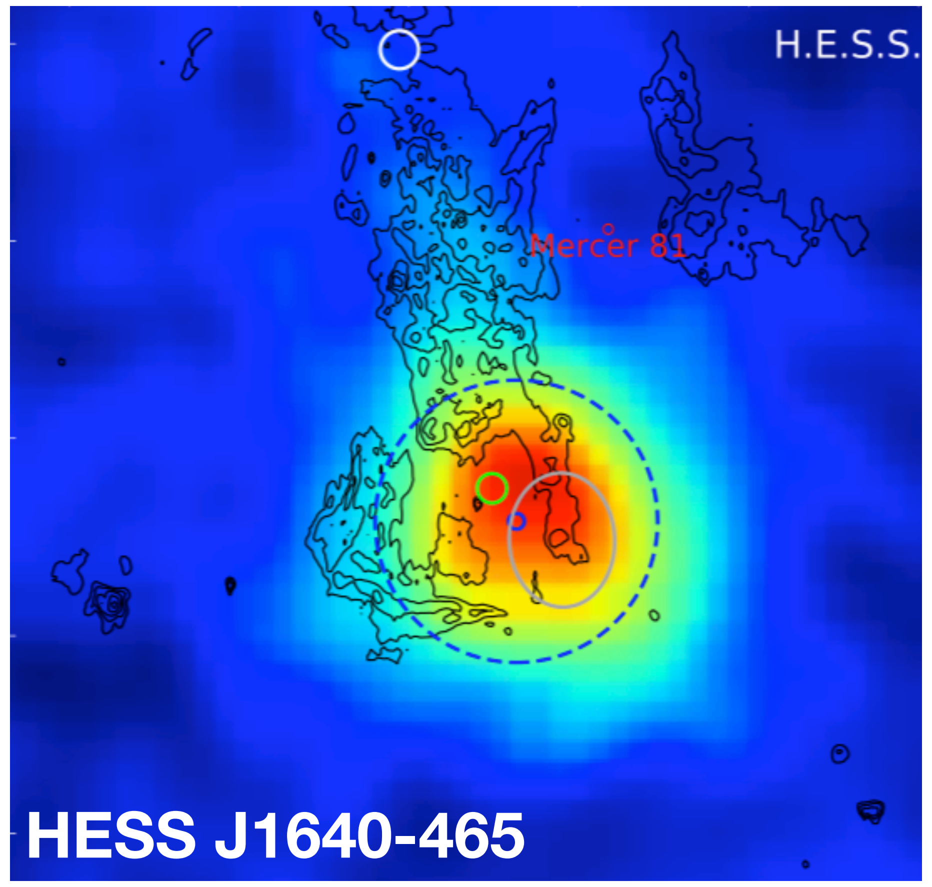
Current sources (being) studied



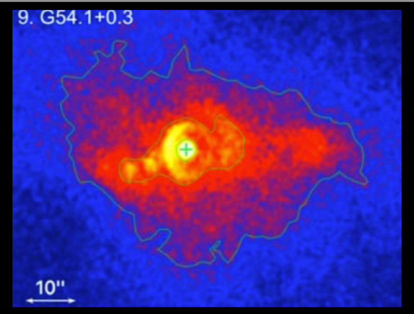
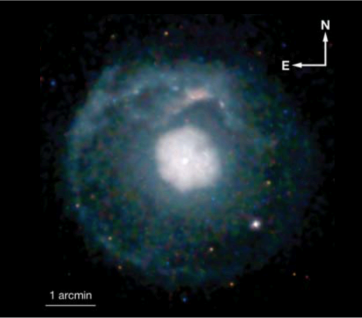
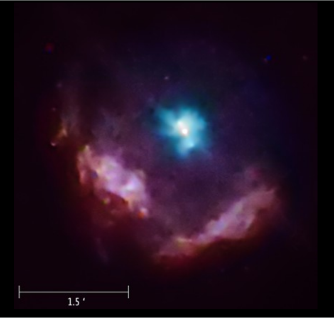
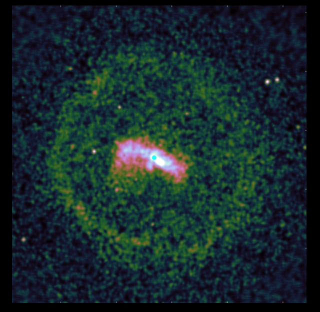
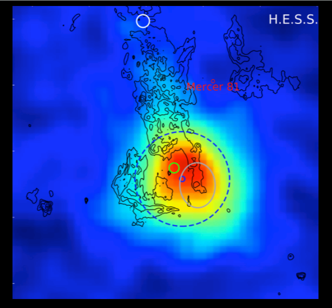




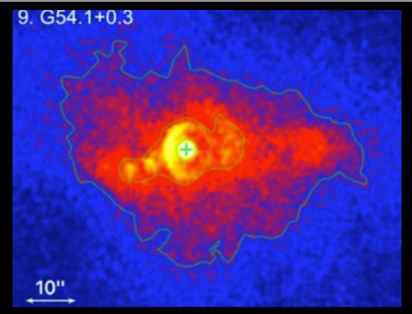
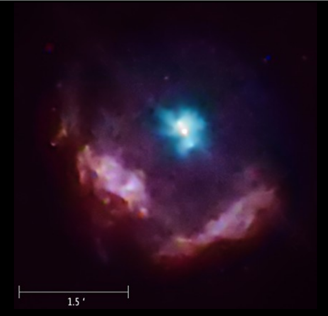
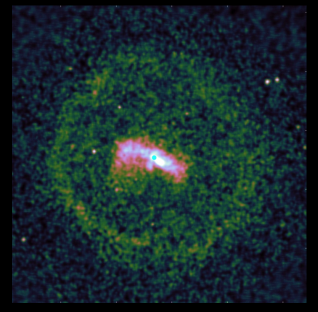
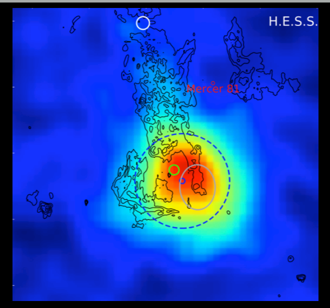




Supernova and environment parameters

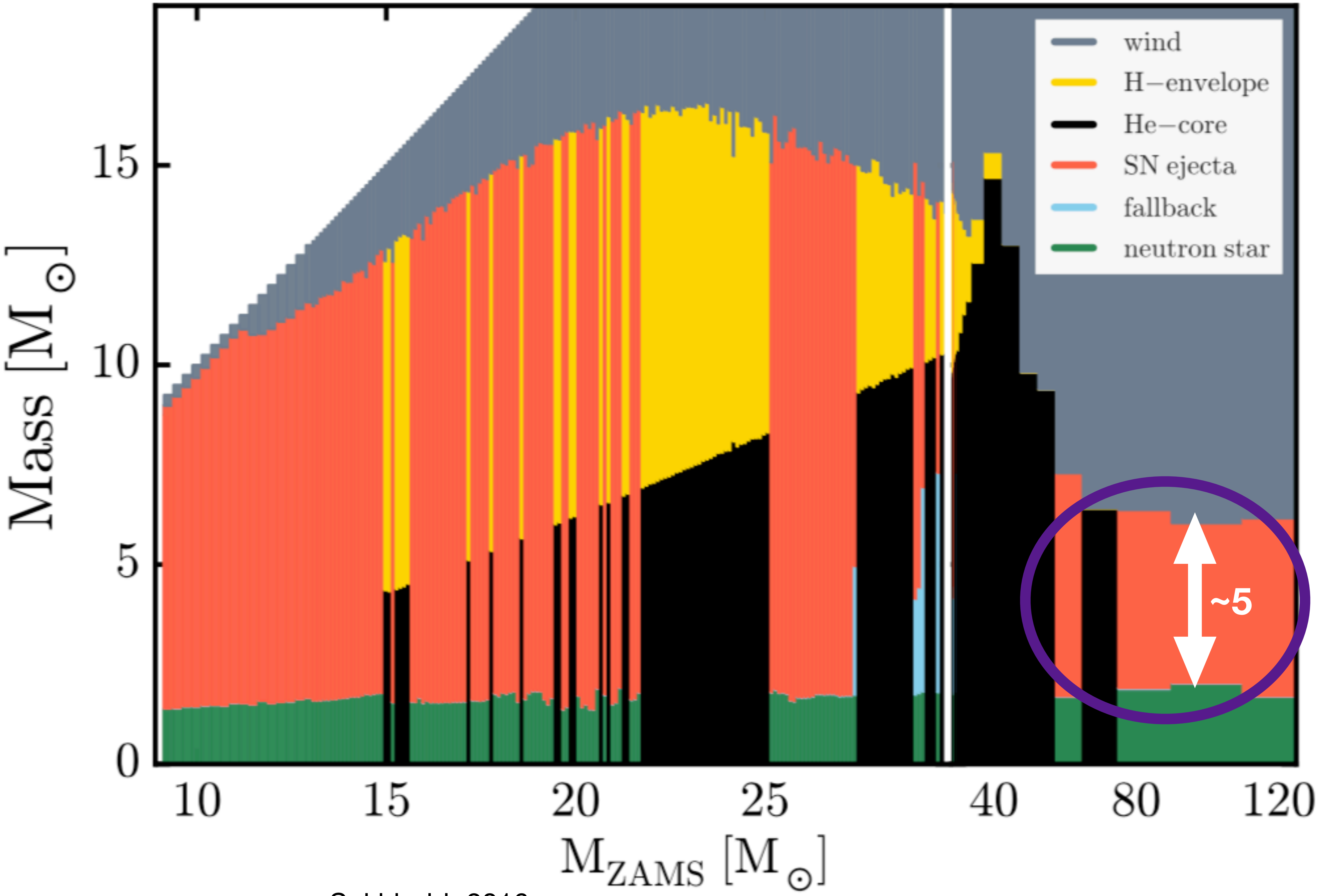
Source		~ E_{sn} (10^{51}ergs)	~ M_{ej} ($M_{\odot}$)	Progenitor mass ($M_{\odot}$)	*n* ism (cm-3)	T photon background (K)
G54.1+0.3 Gelfand+2015		~0.08 - 0.3	10 - 15	~15 - 20	(0.03 - 6) x10^{-3}	-
G21.5-0.9 Hattori, **Straal,** 2020		~0.12	~11.3	~15	~0.2	~1700
Kes 75 Gotthelf et al, 2021 **Straal** et al, in prep		~0.12 - 0.6	~0.5 - 1.4	Stripped star	~0.4	~30-40
G11.2-0.3		0.03 - 0.3	~8 - 16	~15 - 20	1.5 - 2	(2.5-10) x10^{6}
HESS J1640-465		~1	~10	~10 - 15	~0.002	T1 ~5, T2 ~12000
MSH 15-52		~2	~5.5	> 60	~1	T1 ~165, T2 ~50000

Wide range in explosion energy and ejecta mass

Source		~ E_{sn} (10^{51}ergs)	~ M_{ej} ($M_{\odot}$)	Progenitor mass ($M_{\odot}$)	*n* ism (cm-3)	T photon background (K)
G54.1+0.3 Gelfand+2015		~0.08 - 0.3	10 - 15	~15 - 20	(0.03 - 6) x10^{-3}	-
G21.5-0.9 Hattori, **Straal,** 2020		~0.12	~11.3	~15	~0.2	~1700
Kes 75 Gotthelf et al, 2021 **Straal** et al, in prep		~0.12 - 0.6	~0.5 - 1.4	Stripped star	~0.4	~30-40
G11.2-0.3		0.03 - 0.3	~8 - 16	~15 - 20	1.5 - 2	(2.5-10) x10^{6}
HESS J1640-465		~1	~10	~10 - 15	~0.002	T1 ~5, T2 ~12000
MSH 15-52		~2	~5.5	> 60	~1	T1 ~165, T2 ~50000

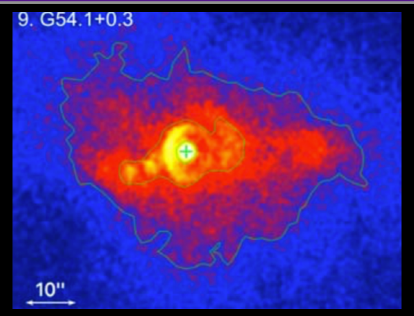
Massive star progenitor

- Final mass = M_{ej} + M_{ns}
- Final mass ranges obtained agree with "lower mass star" or massive star with strong wind mass-loss
- Note: schematic for $E_{sn} = 10^{51}$ ergs
  - Lower E_{sn} increases chance for BH formation
- *Not including binary star evolution



Sukhbold+2016

Progenitor mass derivation

Source		~ E_{sn} (10^{51}ergs)	~ M_{ej} ($M_{\odot}$)	Progenitor mass ($M_{\odot}$)	n ism (cm-3)	T photon background (K)
G54.1+0.3 Gelfand+2015		~0.08 - 0.3	10 - 15	~15 - 20	(0.03 - 6) $\times 10^{-3}$	-
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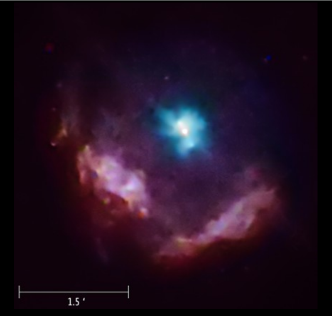
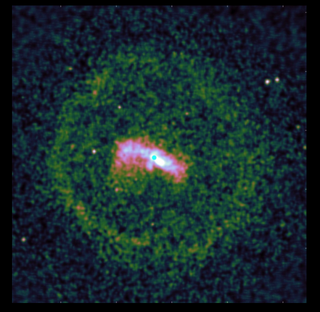
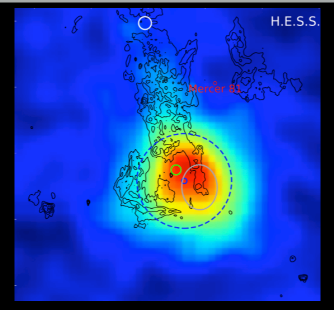
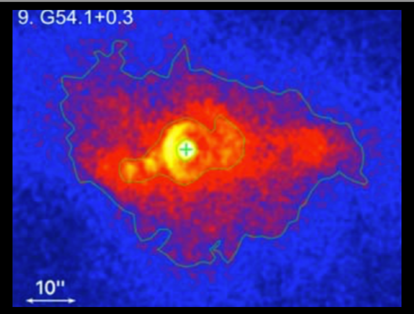
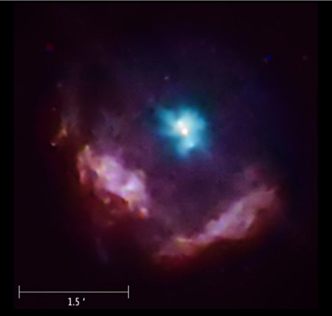
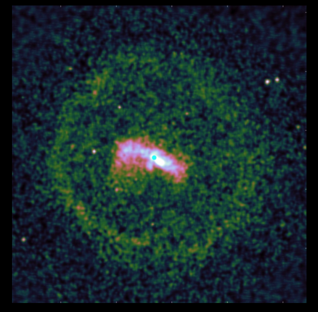
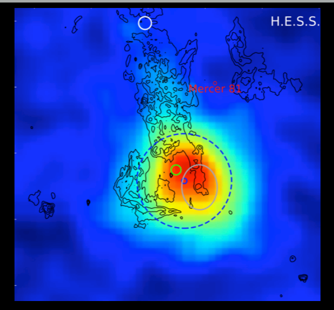
Kes 75 Gotthelf et al, 2021 **Straal** et al, in prep		~0.12 - 0.6	~0.5 - 1.4	Stripped star	~0.4	~30-40
G11.2-0.3		0.03 - 0.3	~8 - 16	~15 - 20	1.5 - 2	(2.5-10) $\times 10^{6}$
HESS J1640-465		~1	~10	~10 - 15	~0.002	T1 ~5, T2 ~12000
MSH 15-52		~2	~5.5	> 60	~1	T1 ~165, T2 ~50000

Background photon field

Source		~ E_{sn} (10^{51}ergs)	~ M_{ej} (M_o)	Progenitor mass (M_o)	*n* ism (cm-3)	T photon background (K)
G54.1+0.3 Gelfand+2015		~0.08 - 0.3	10 - 15	~15 - 20	(0.03 - 6) x10^{-3}	-
G21.5-0.9 Hattori, **Straal,** 2020		~0.12	~11.3	~15	~0.2	~1700
Kes 75 Gotthelf et al, 2021 **Straal** et al, in prep		~0.12 - 0.6	~0.5 - 1.4	Stripped star	~0.4	~30-40
G11.2-0.3		0.03 - 0.3	~8 - 16	~15 - 20	1.5 - 2	(2.5-10) x10^6
HESS J1640-465		~1	~10	~10 - 15	~0.002	T1 ~5, T2 ~12000
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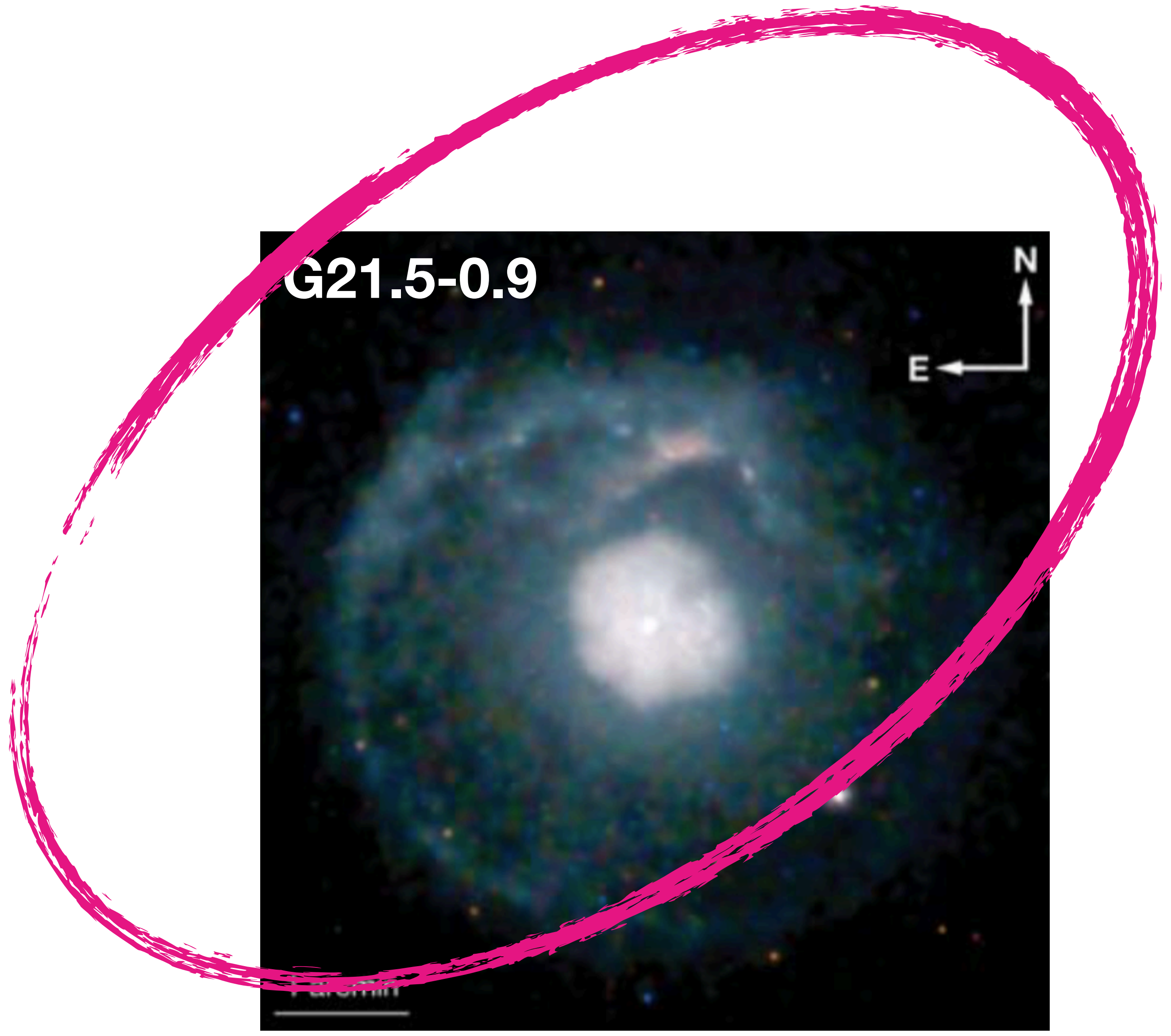
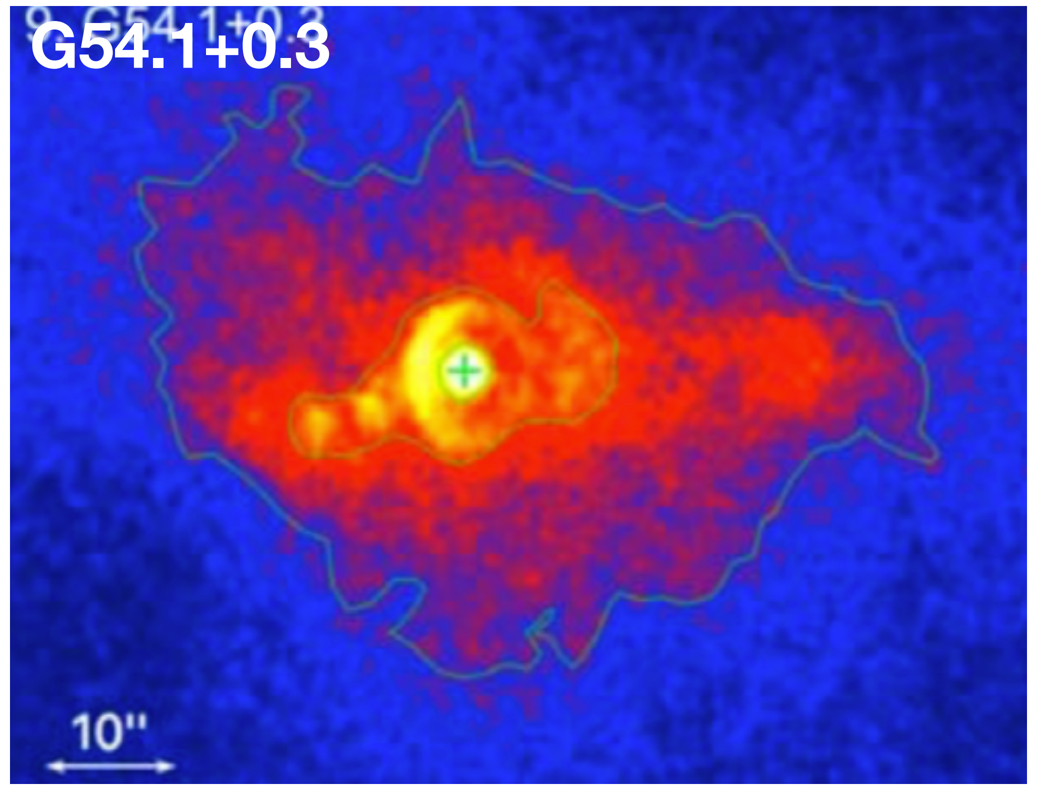
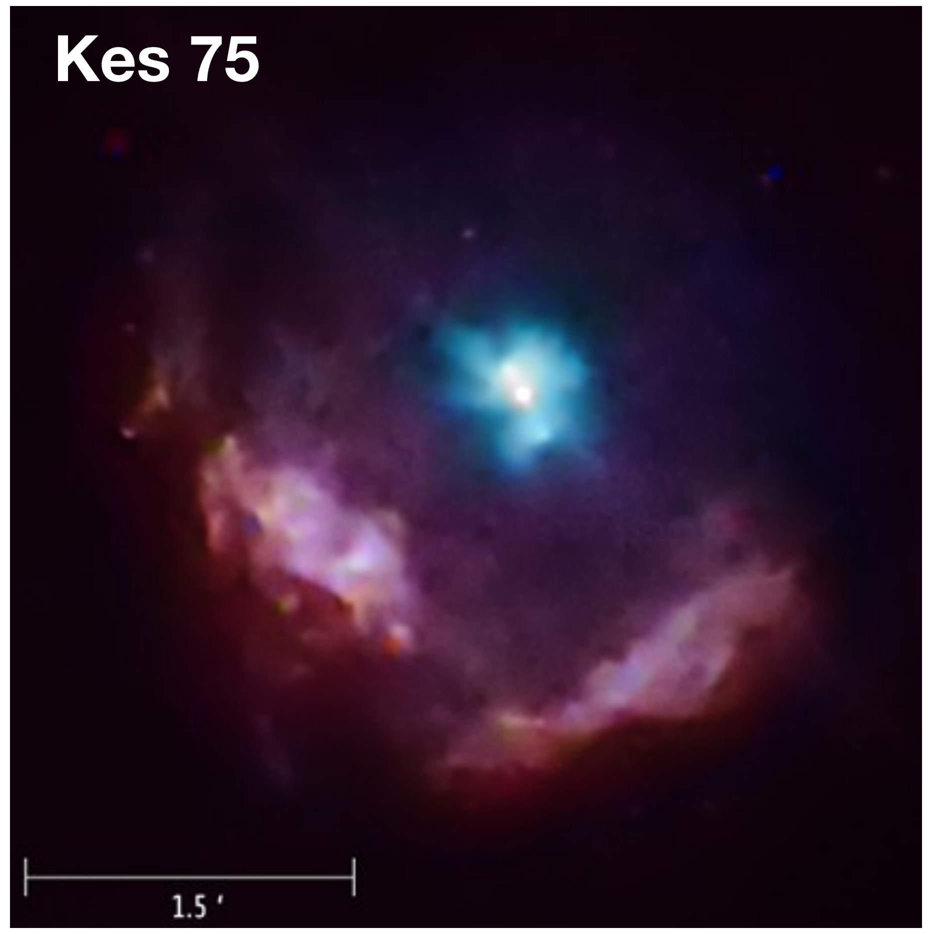
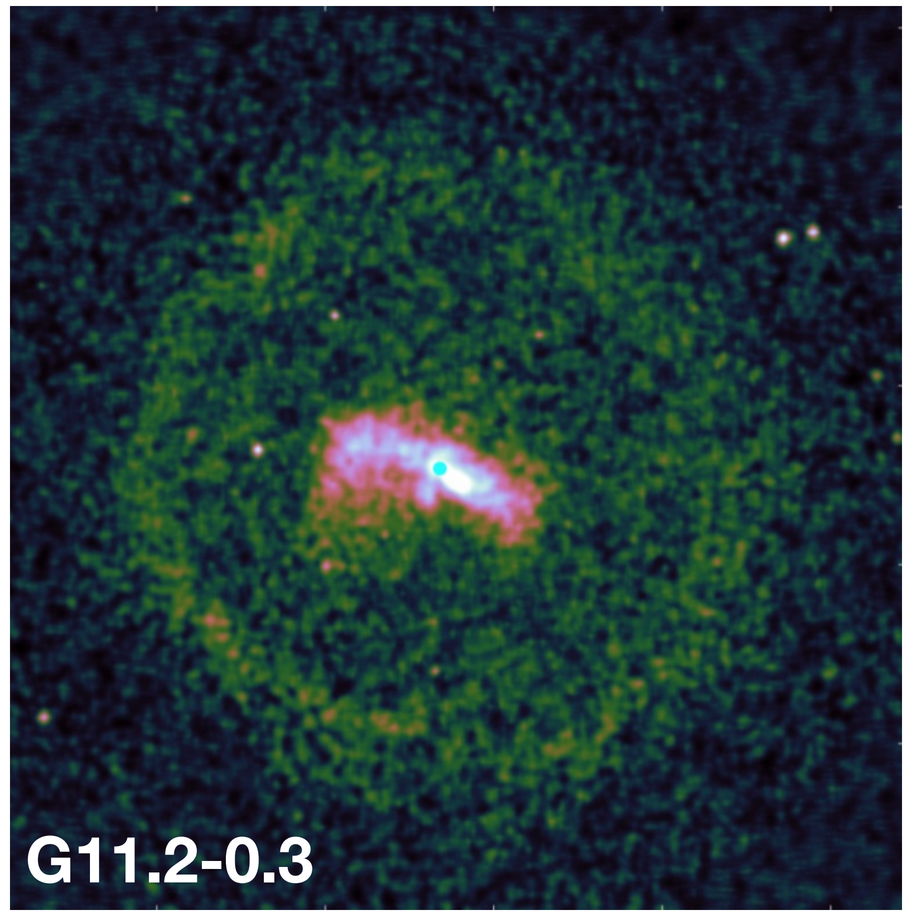
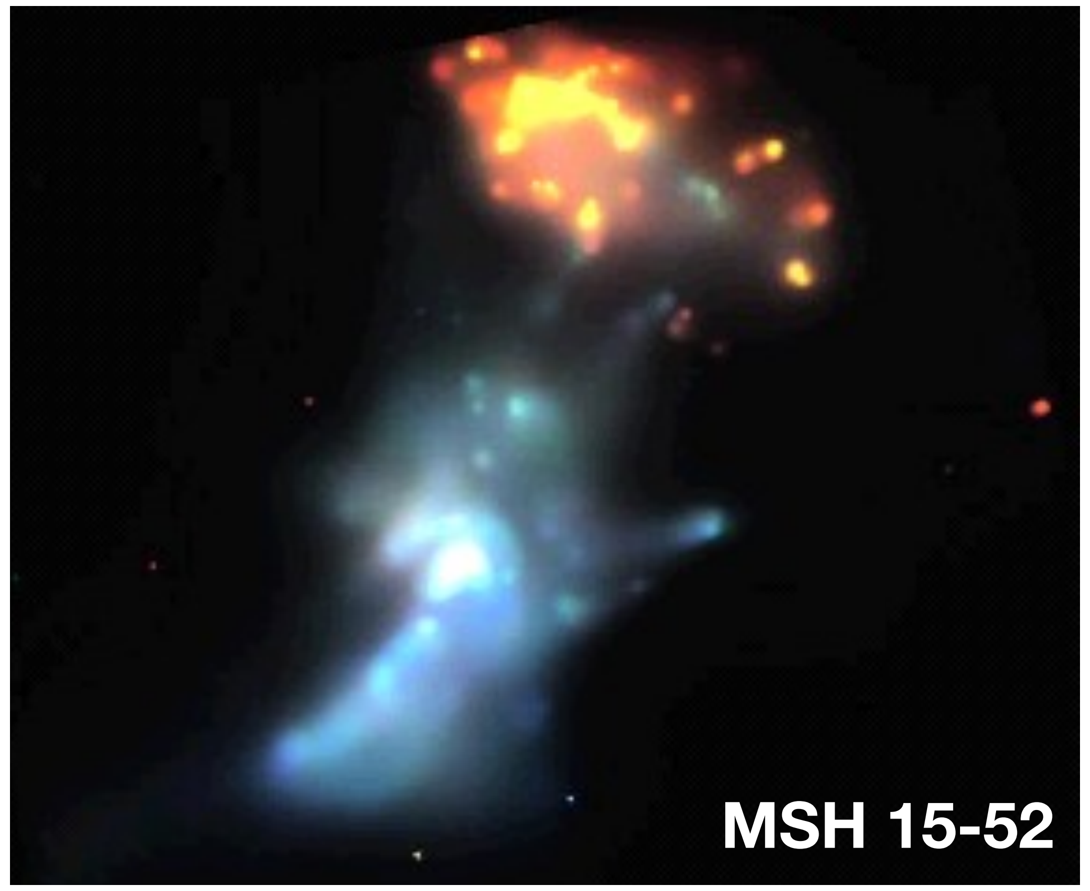
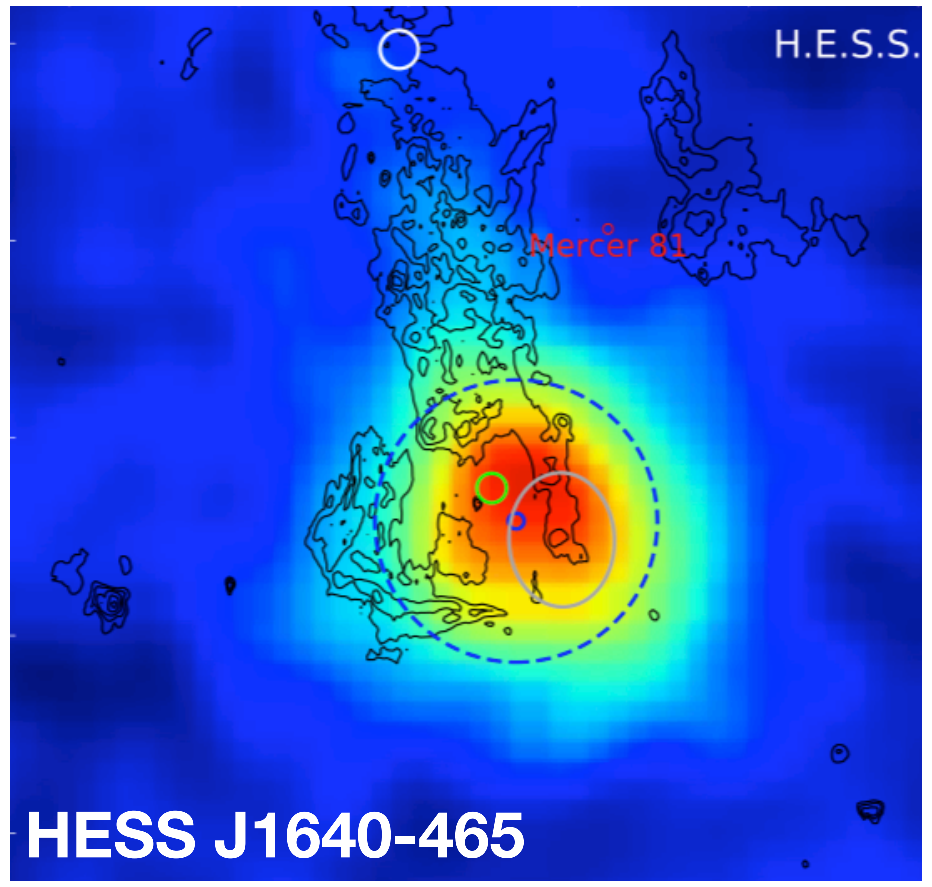






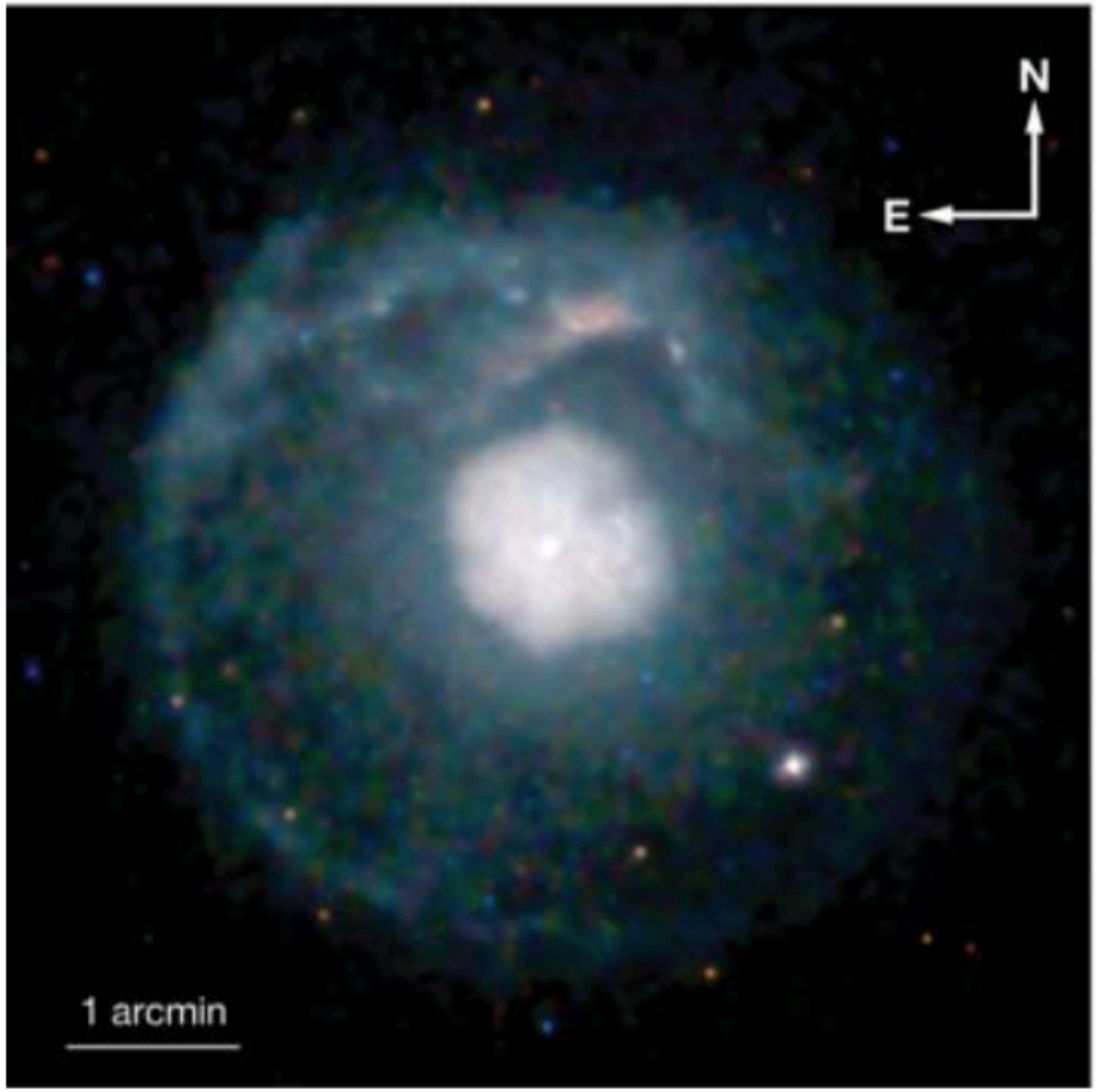






PWN G21.5-0.9

- Powered by PSR J1833-1034
  - Radio pulsar
  - t_{char} = 4850 years
  - Age ~ 870 years
  - $\dot{E}$ = 3.3E37 erg/s
- PWN detected in radio, IR, X-ray, TeV energies



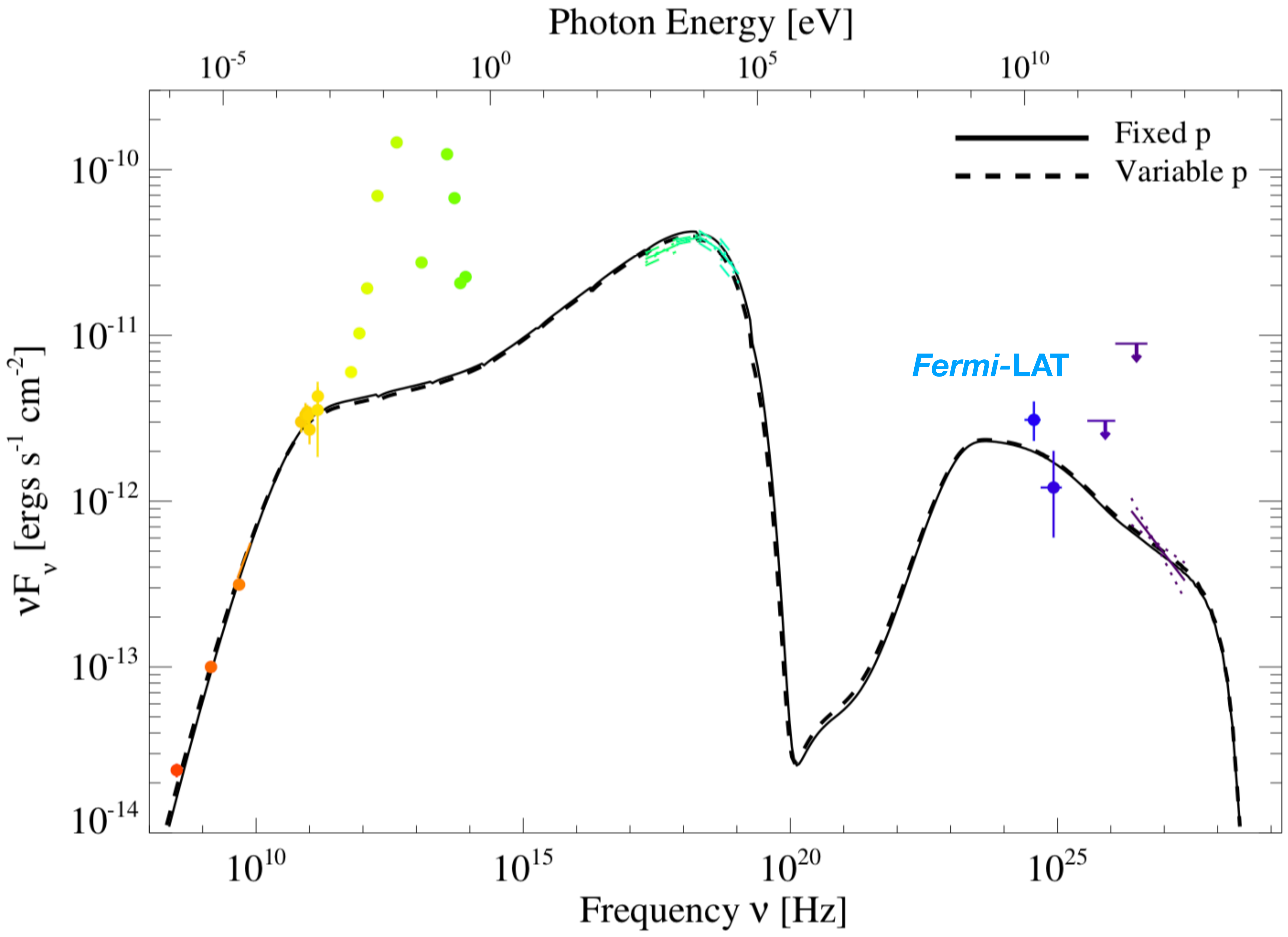
Matheson & Safi-Harb 2005

Modelling results:
(Hattori, Straal et al. 2020)

- M_{ej} = 11.3 $M_{\odot}$
- E_{sn} = 1.2 E50 erg
- Progenitor: ~ 15 $M_{\odot}$

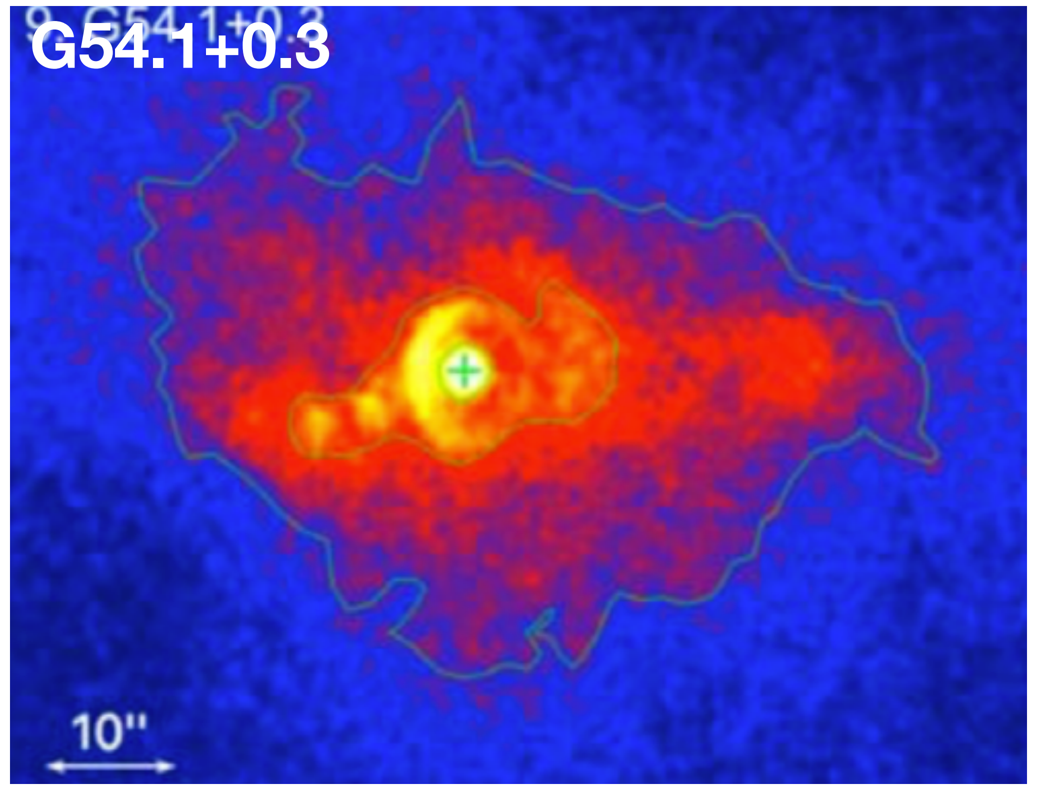
PWN G21.5-0.9 - highlight

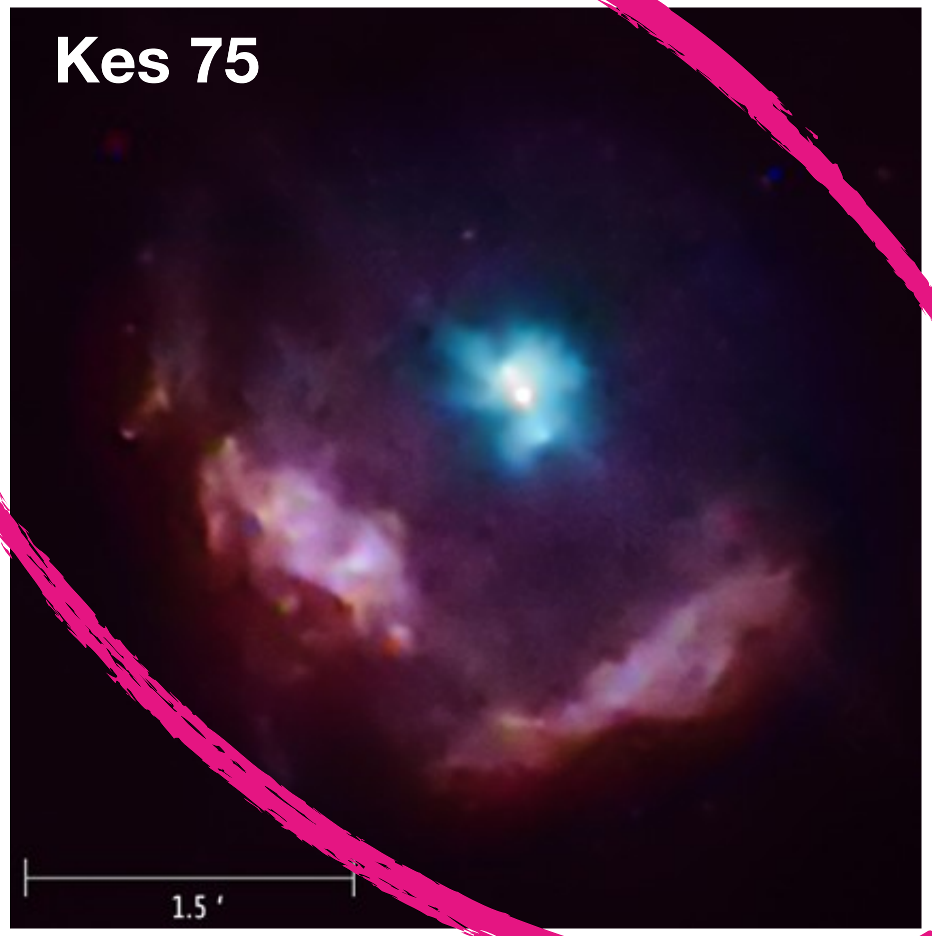
- Model the source with a fixed (p=1.8569, Roy et al. 2012) and free braking index
- Particle Injection spectrum:
  - Low energy particle index: p1 = 2.86
  - High energy particle index p2 = 2.15
- Both low and high energy particles accelerated via fermi acceleration
- Particles accelerated/injected at two sites
  - Could explain spatial variations in spectral index observed near the center of the PWN (e.g. Guest at al. 2019)

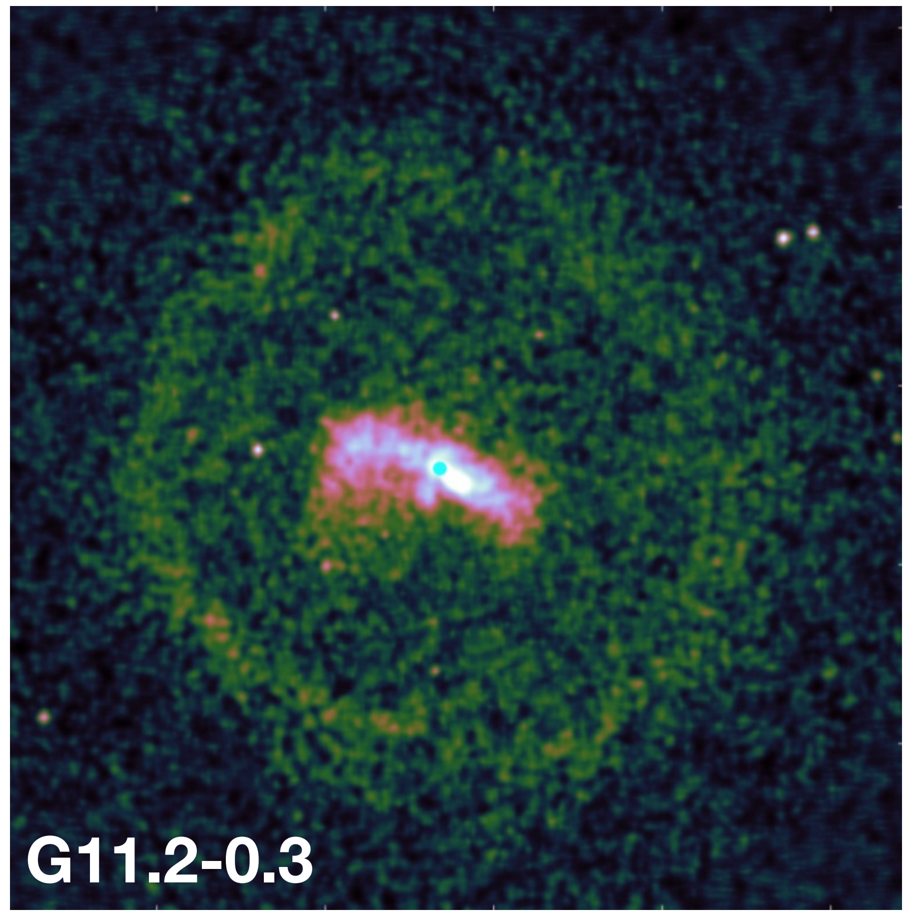


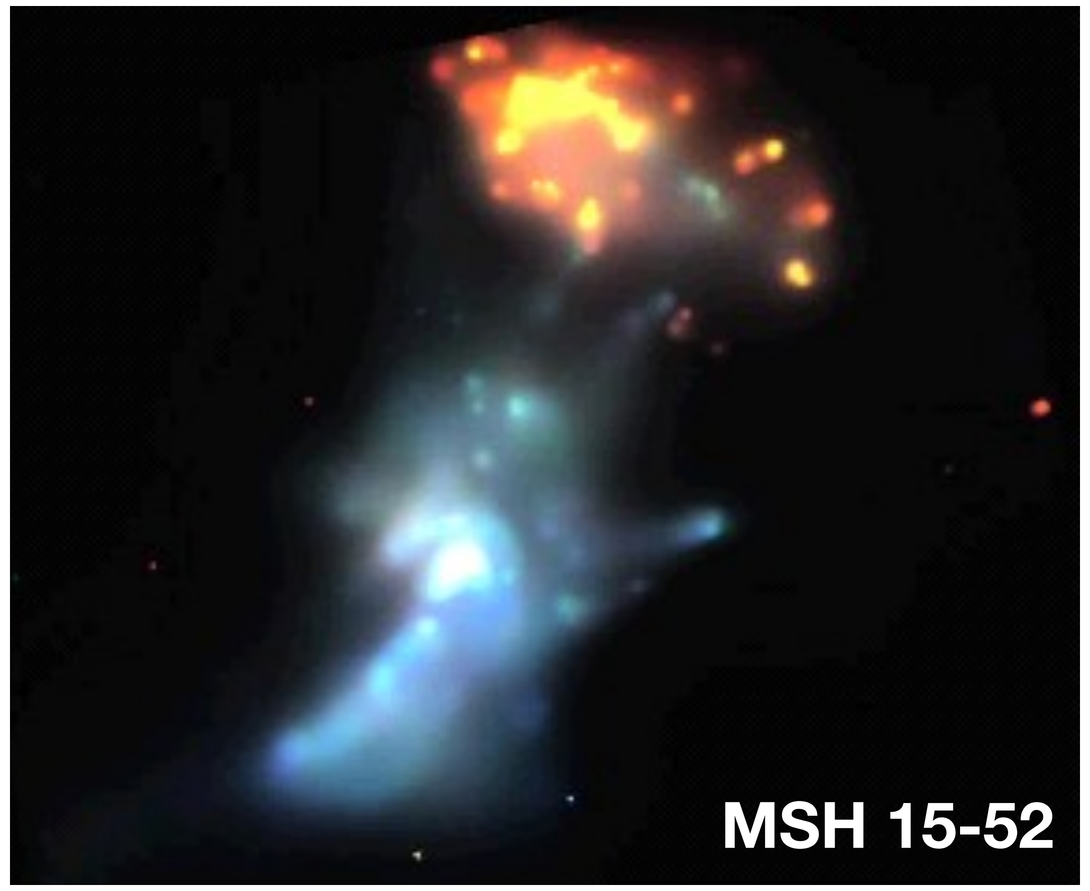
Hattori, Straal et al. 2020

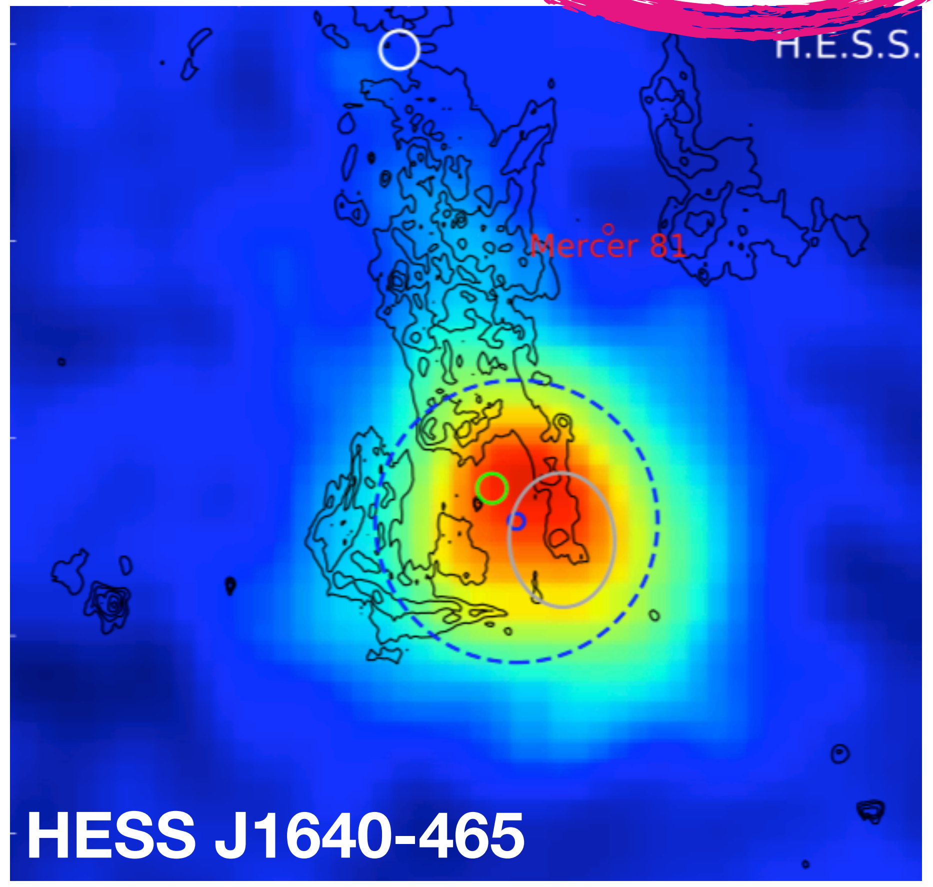
Current sources (being) studied





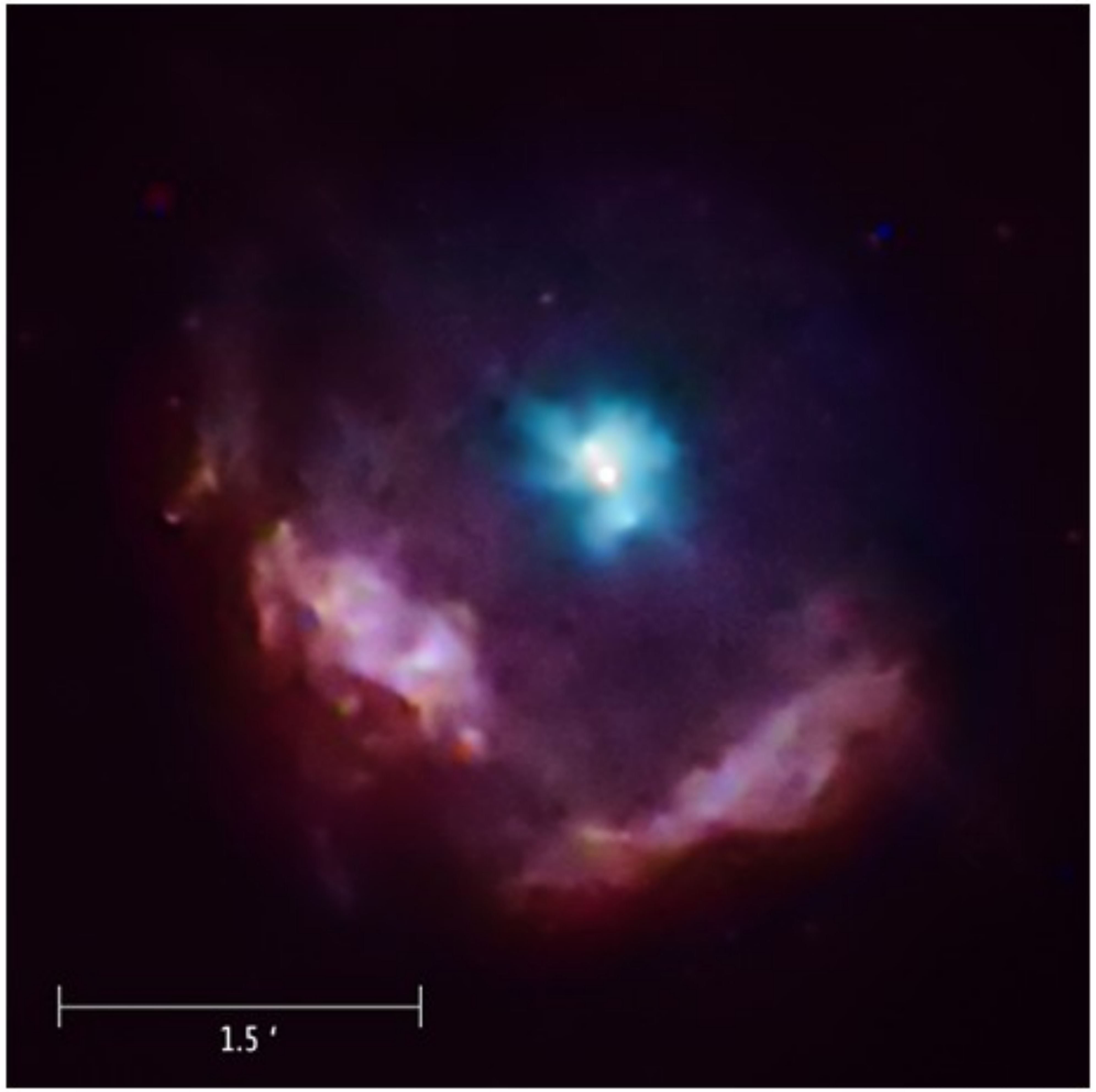






PWN Kes 75

- Powered by PSR J1846-0258
  - P = 325 ms, $\dot{E}$ = 8.3 x 10^{36} erg s^{-1}, B = 4.9 x 10^{13} G
  - 2006: Pulsar showed magnetar-like behaviour;
    X-ray bursts, glitch, X-ray brightness increase
    (Gavriil et al. 2008; Kumar & Safi-Harb 2008; Ng et al. 2008)
  - Braking index changed from p=2.65 to p=2.16
    (Livingstone+2006, Livingstone+2011)
- PWN detected in radio, X-ray, TeV energies
  - Not yet at GeV energies
  - PSR J1846-0258 is detected at 30-100 MeV
    (Kuiper at al. 2018)
- PWN size = 30”; SNR size = 1.5’

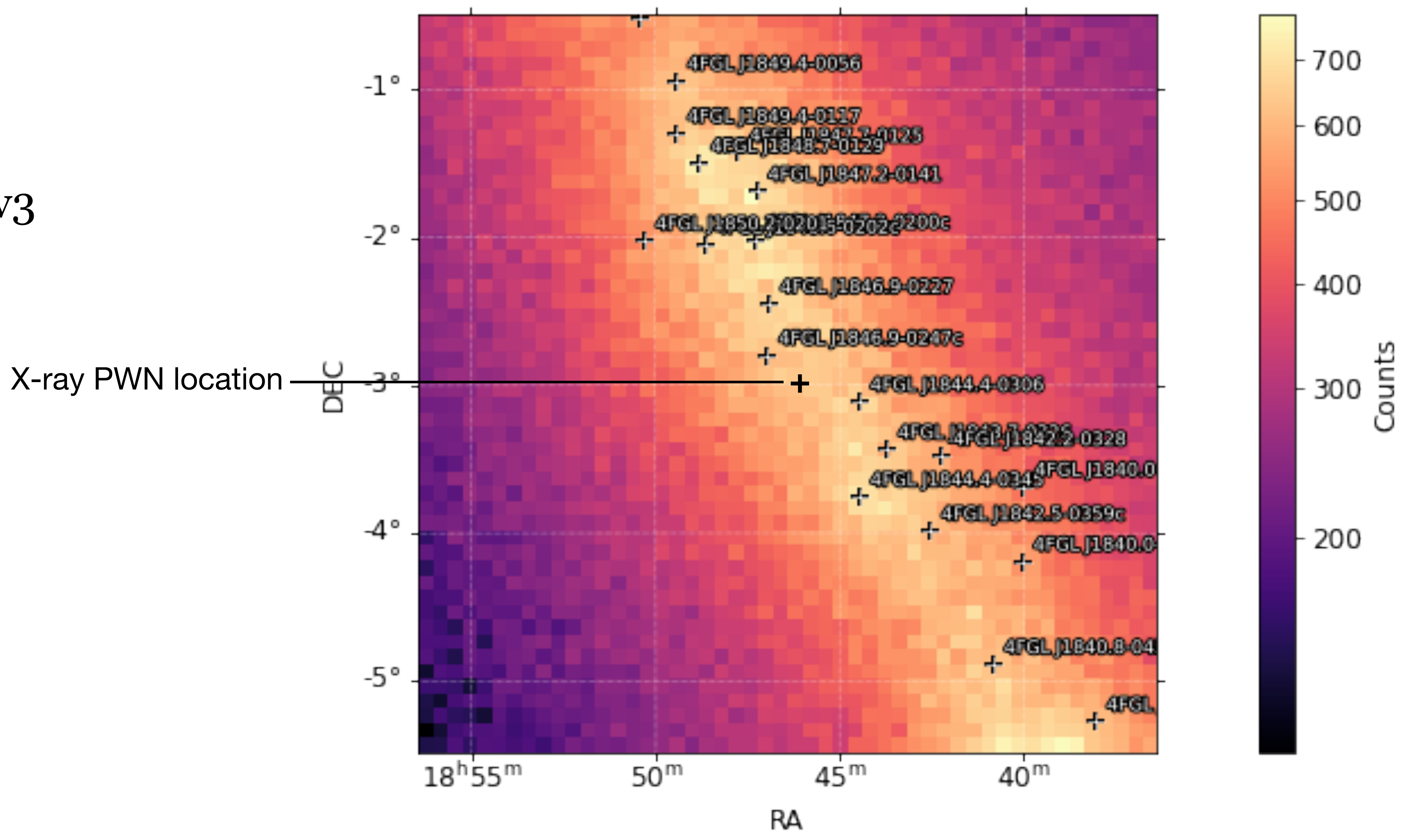


NASA/CXC/GSF/F.P.Gavrill et al.

Fermi analysis of Kes 75

- 12.3 yrs of *Fermi*-LAT data, Pass 8, Source Class
  - Source in the Galactic Plane
  - Analysed at 100 MeV - 500 Gev
  - 4FGL-DR2 with irf P8R3_SOURCE_v3

- Fit data for 3 scenarios:
  - PWN only
  - PWN + PSR
  - Pulsar only



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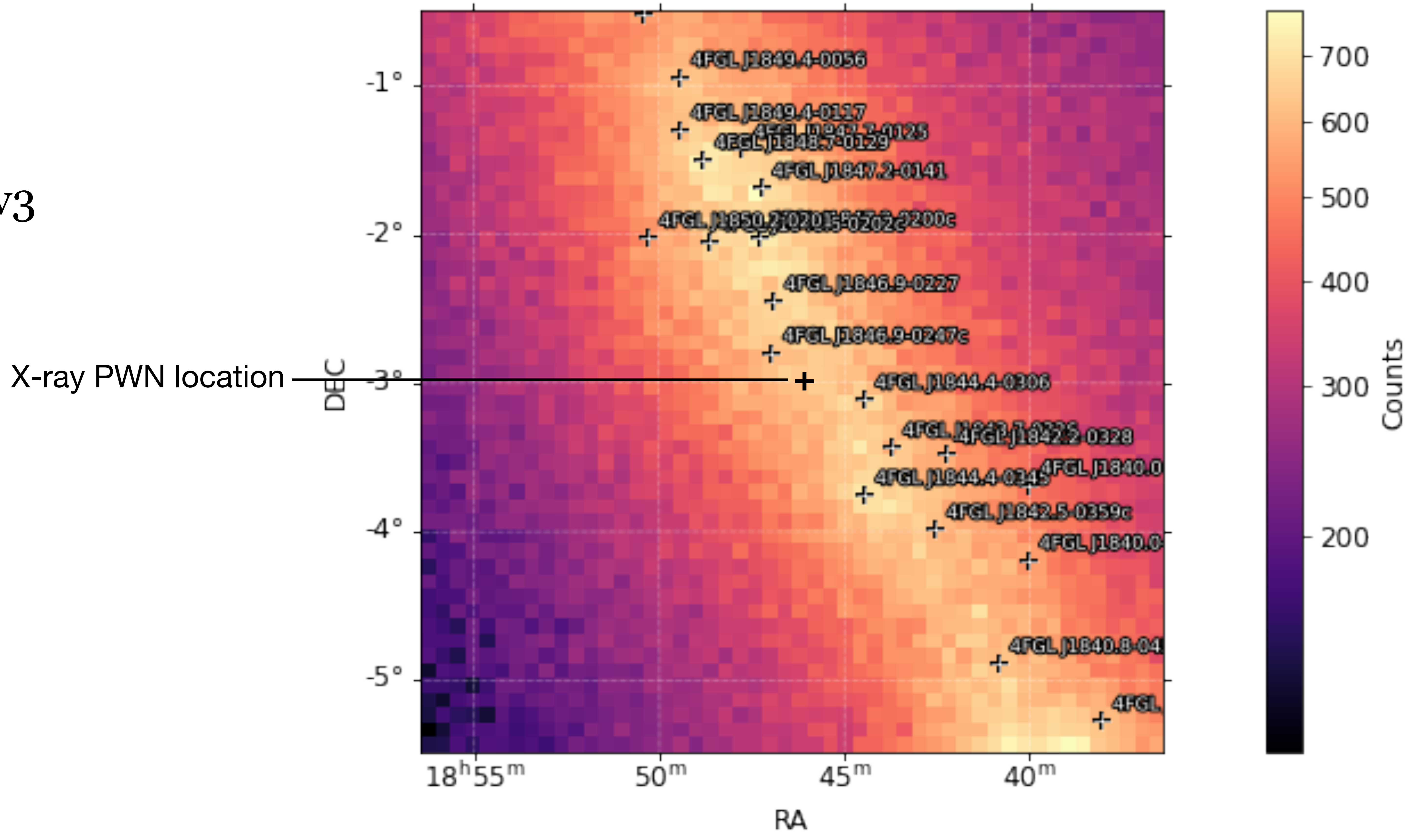
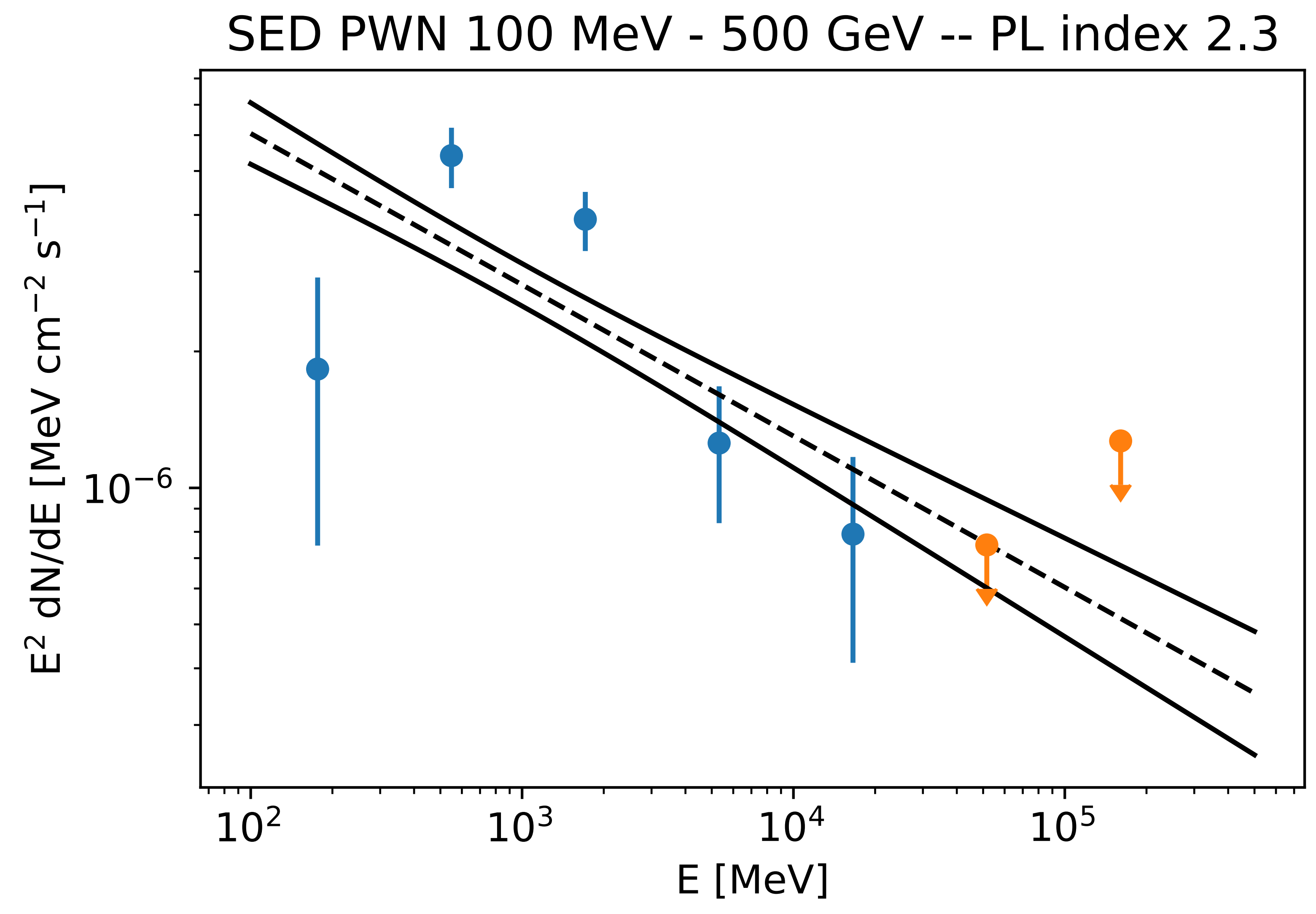
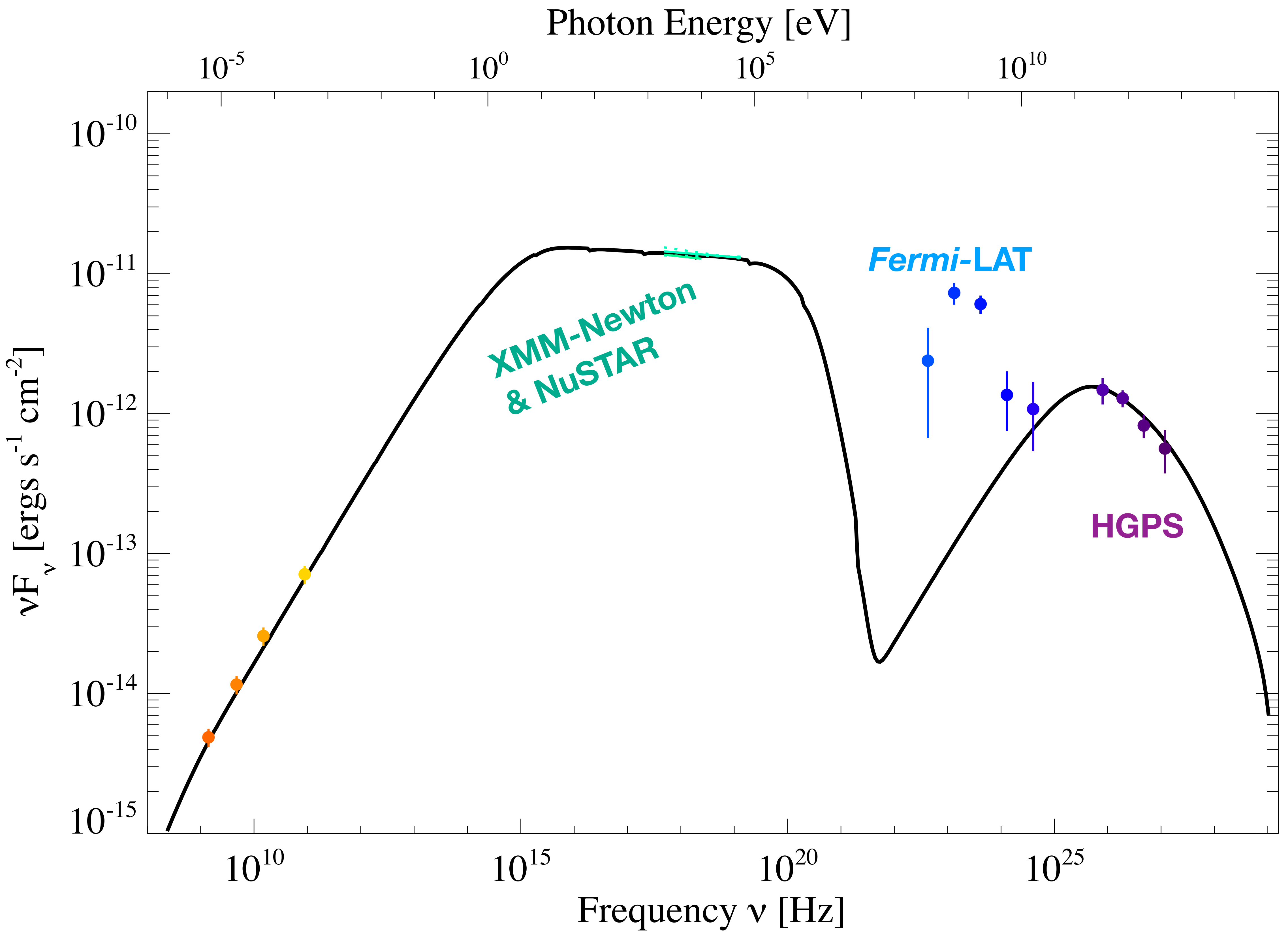


Fermi analysis of Kes 75 PWN Only (Preliminary)

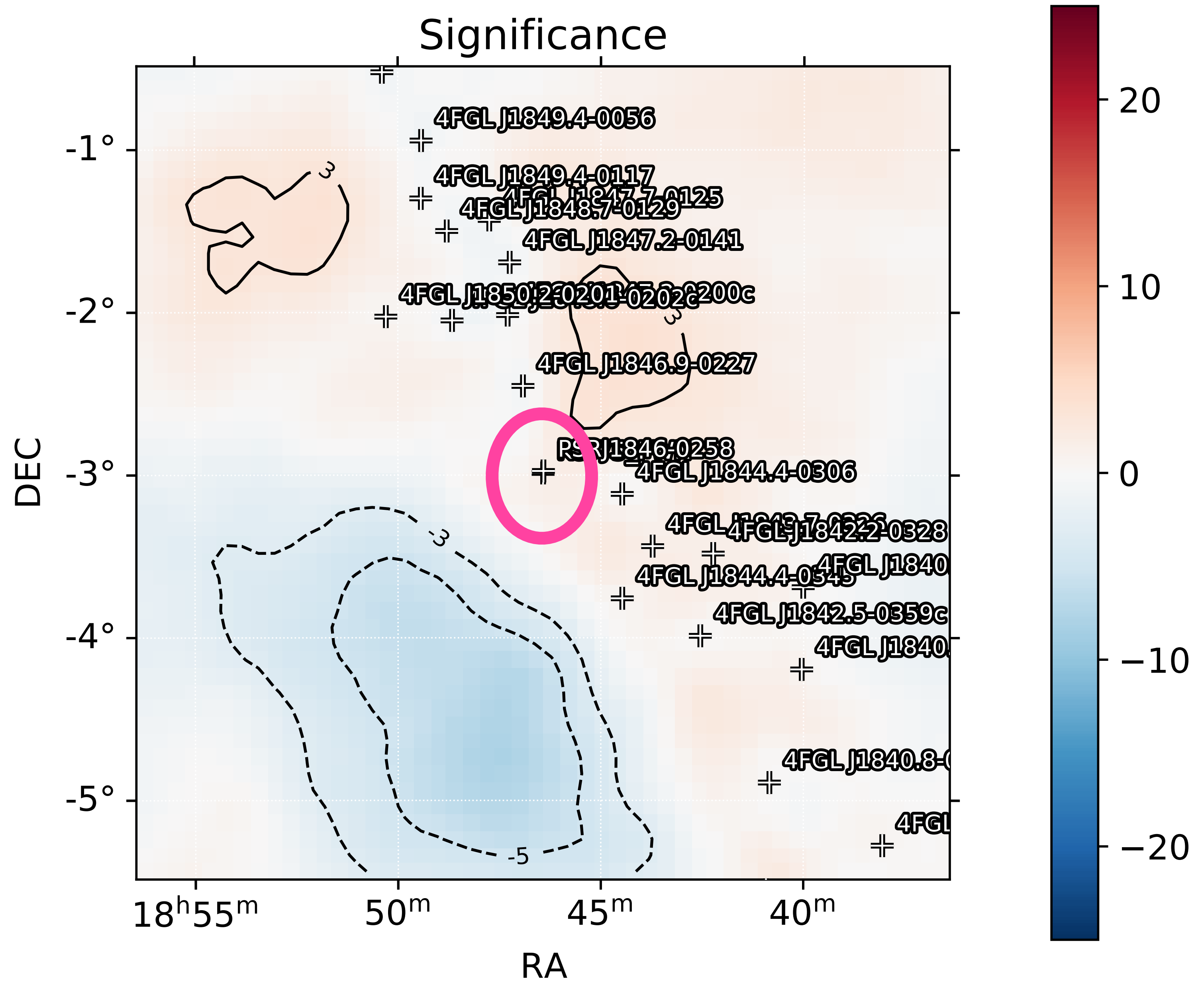
- Fit as point source with Powerlaw spectrum, typical for PWNe, index = 2.3
- Best-fit location at 0.375 deg
- TS = 85

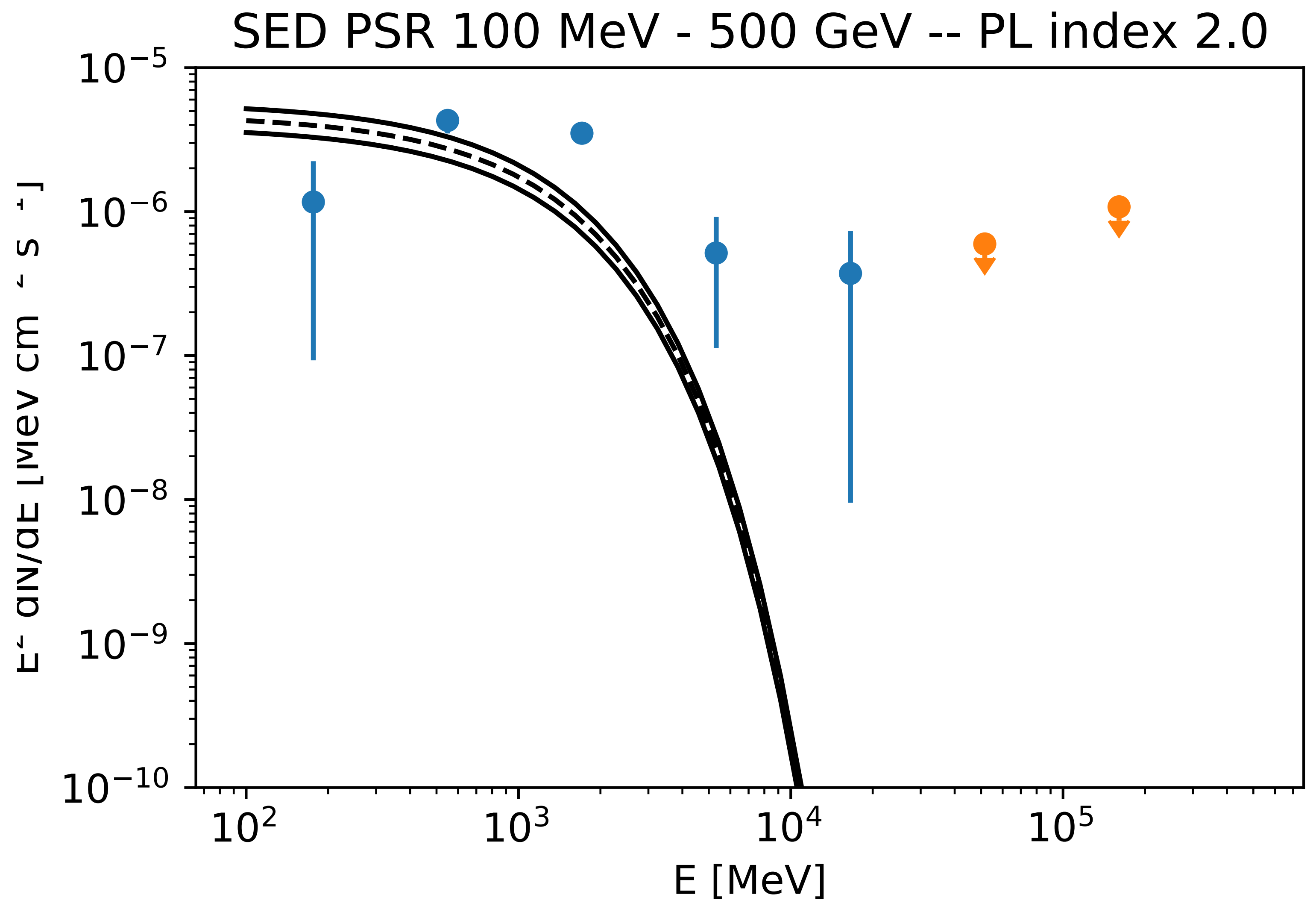


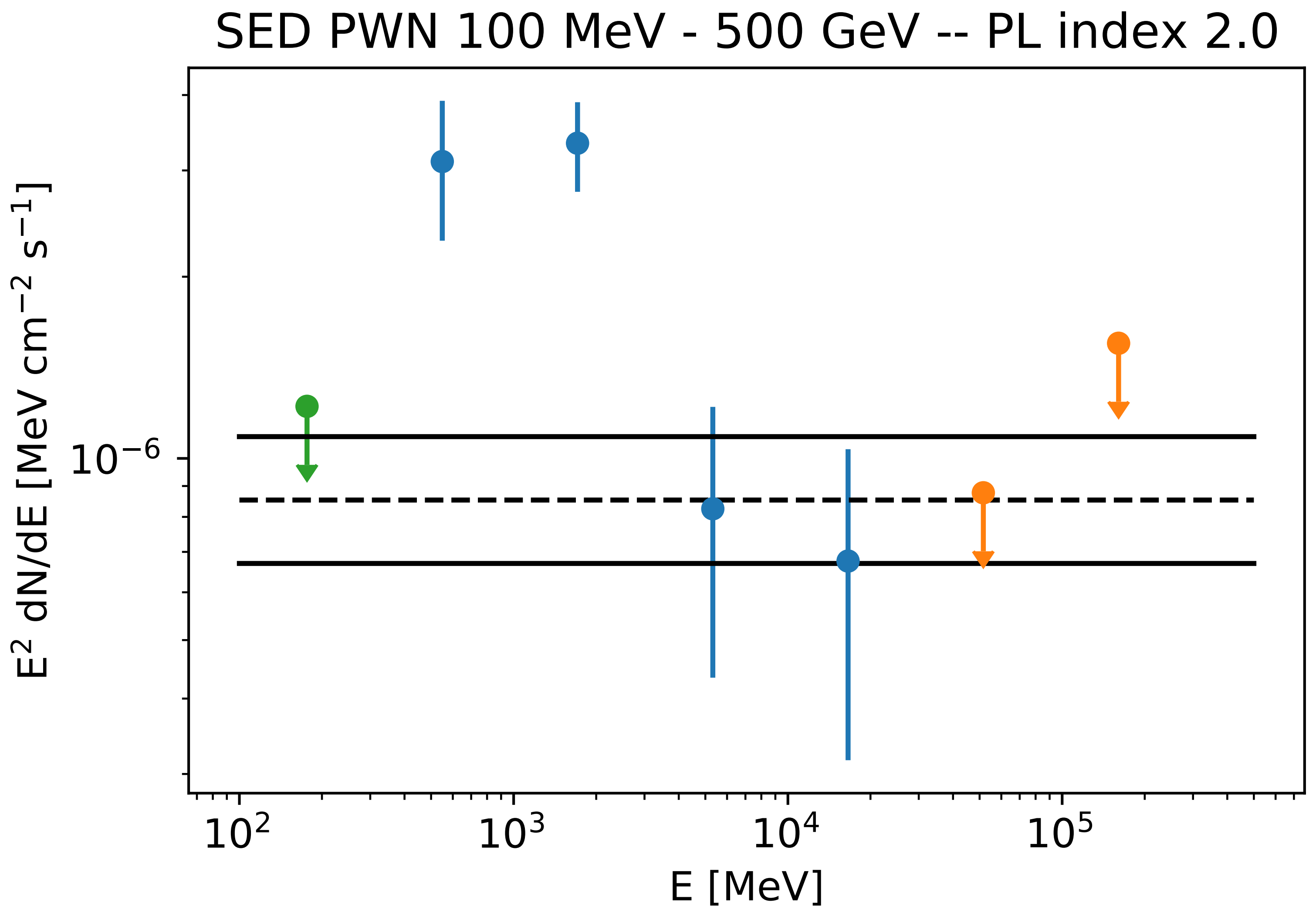


Fermi analysis of Kes 75 PWN + PSR (Preliminary)

- PWN fit with Powerlaw spectrum
- PSR fit with Powerlaw Exponential Cutoff
- Source location fixed
- $TS_{PWN} = 17.4$, $TS_{PSR} = 27.2$







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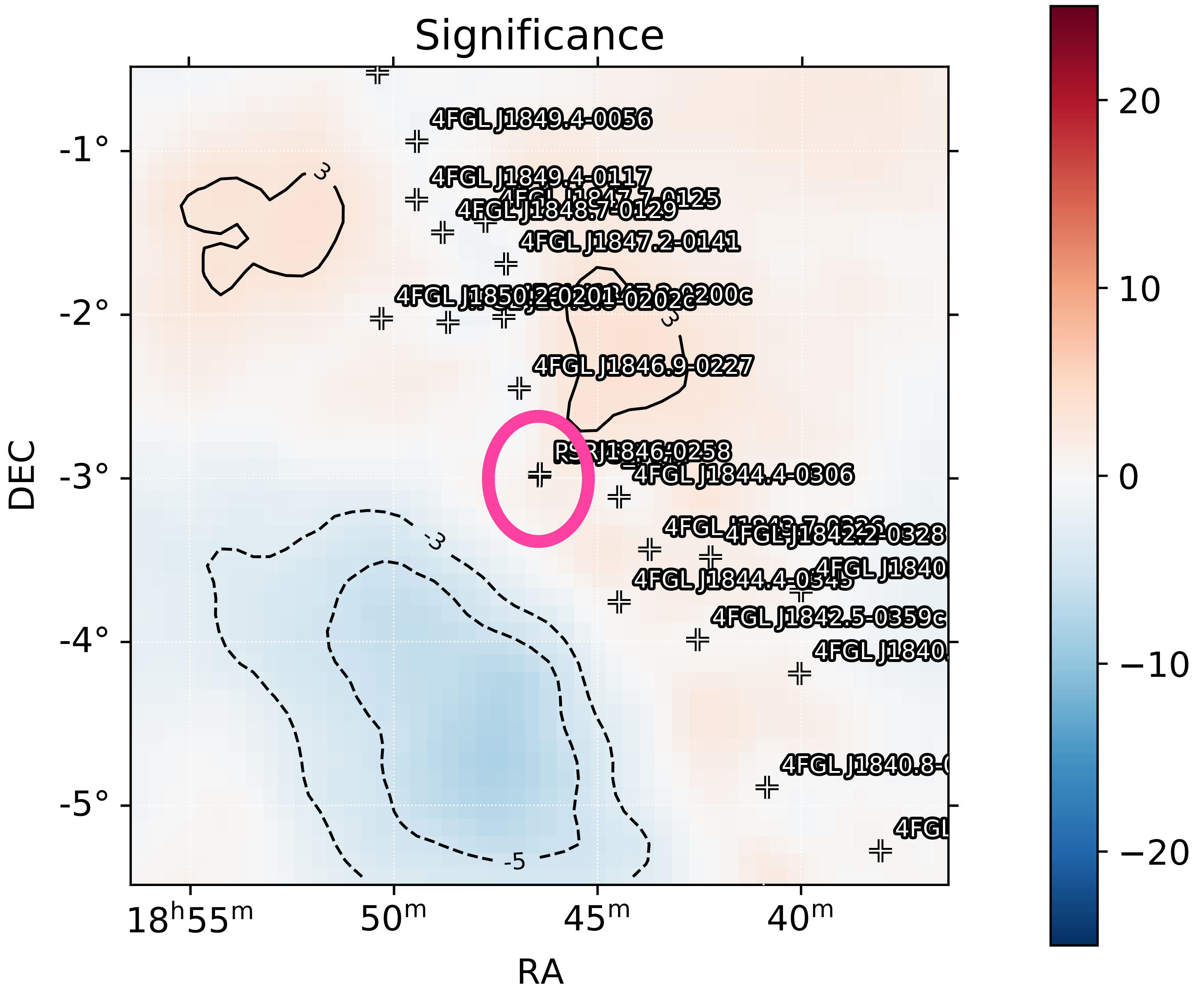
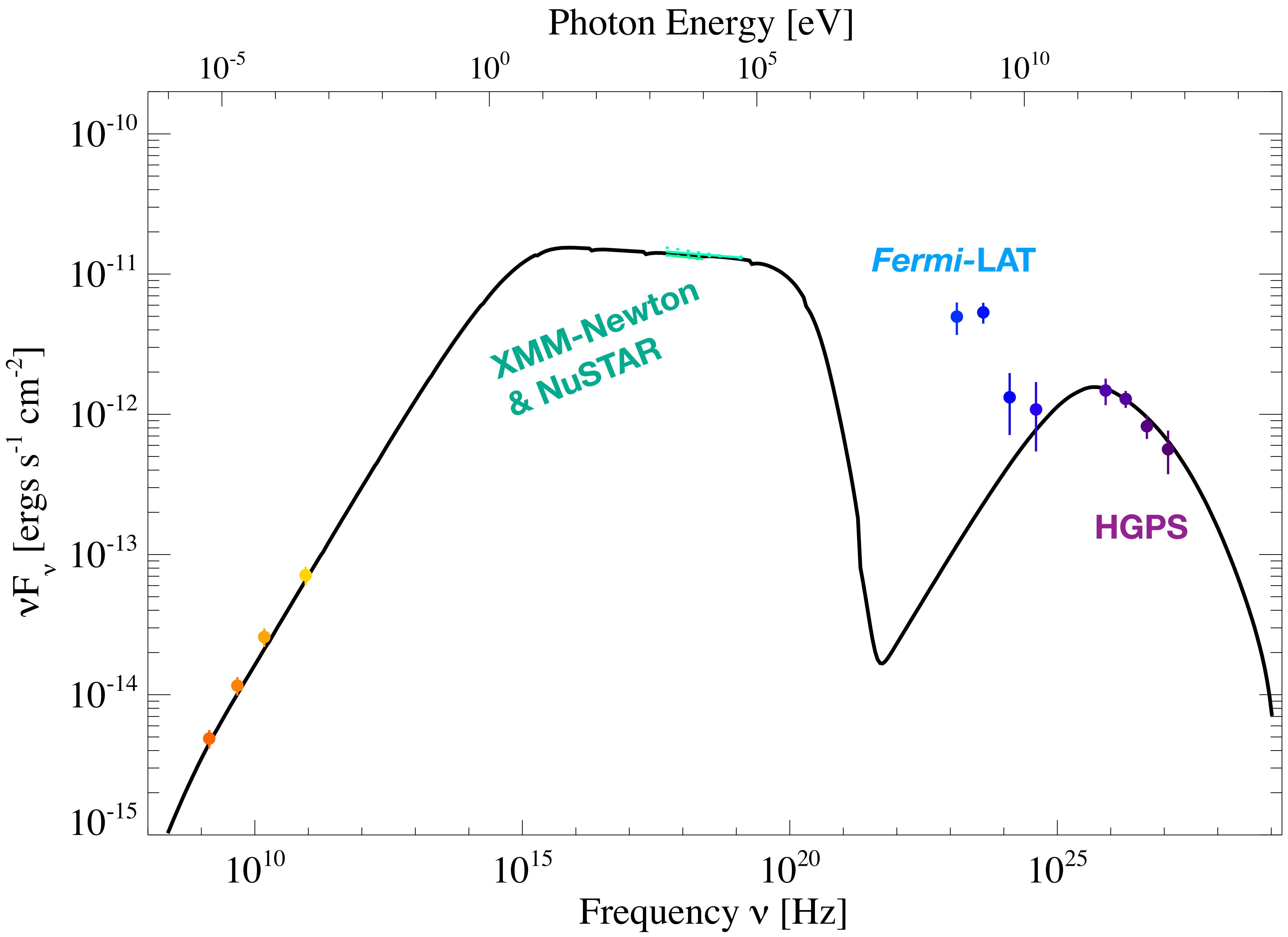




Conclusions

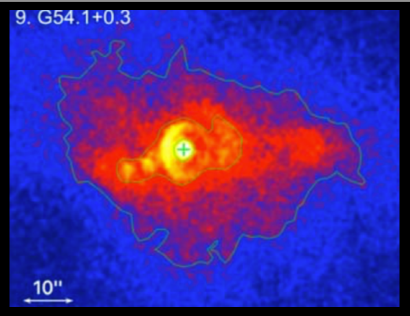
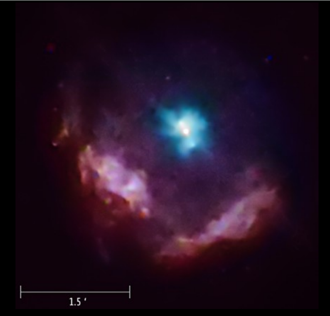
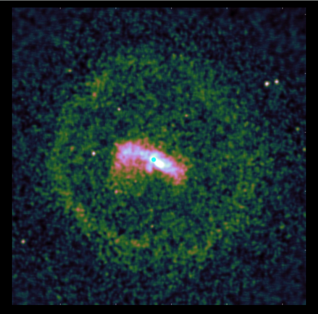
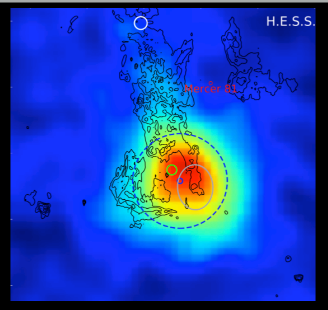
- From modelling the evolution of PWN inside a SNR we appear to successfully:
  - Reproduce observed properties of sample of systems
  - Obtain properties of the NS, SN explosion, progenitor, and its local environment
  - Obtain dominant particle acceleration processes
- From our sample we obtain:
  - High ejecta mass, low explosion energy generally preferred
  - No fast spinning pulsars at birth
  - No correlation between P and B -> Initial magnetic field consistent with accretion model
- *Fermi*-LAT is crucial to:
  - Understand the IC part of the PWN spectrum
  - Probe surrounding electron field
  - Probe high energy particle spectrum

Questions or suggestions?
Please reach out at:

@SStraal
straal@nyu.edu

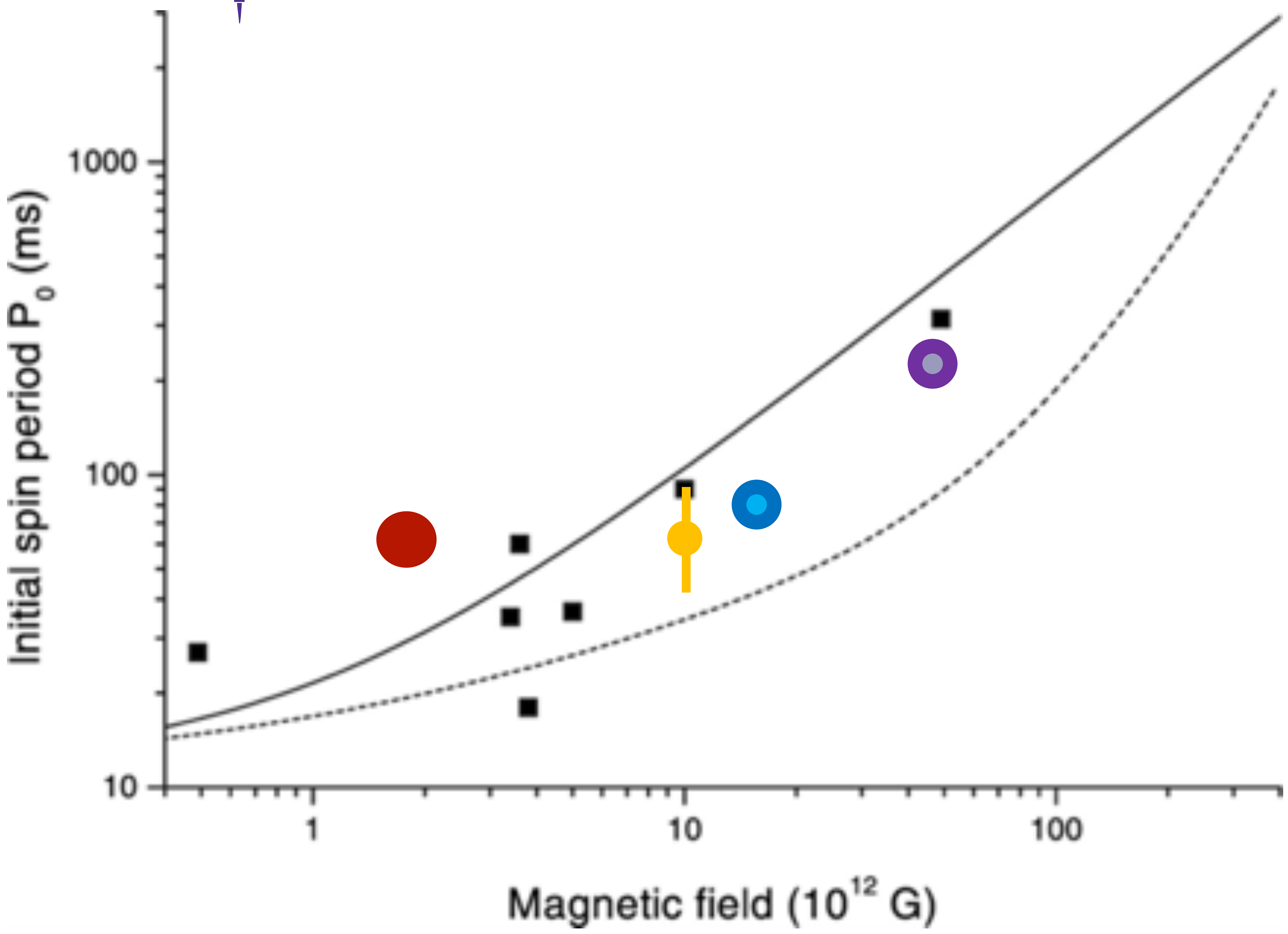
Extra

Neutron star birth parameters

Source		Progenitor mass ($M_\odot$)	B_{SD} (G)	P_0 (ms)	$\dot{E}_0$ (ergs s^{-1})
G54.1+0.3 Gelfand+2015		~15 - 20	1 $\times10^{13}$	~65	(0.06 - 2.5) $\times10^{39}$
G21.5-0.9 Hattori, **Straal,** 2020		~15	3.6 $\times10^{12}$	~50	8.3 $\times10^{37}$
Kes 75 Gotthelf et al, 2021 **Straal** et al, in prep		Stripped star	4.9 $\times10^{13}$	~200	2.1 $\times10^{37}$
G11.2-0.3		~15 - 20	1.7 $\times10^{12}$	~61.4	7.8 $\times10^{36}$
HESS J1640-465		~10 - 15	1.8 $\times10^{13}$	~10	1.5 $\times10^{42}$
MSH 15-52		> 60	1.5 $\times10^{13}$	70 - 80	~10^{38}

Neutron star (initial) parameters

- No obvious correlation between surface magnetic field B0 and initial spin period P0
- Possibly consistent with accretion model
- Inconsistent with α- Ω dynamo for magnetars



(Watts & Andersson 2002, *MNRAS*, 333, 943)