THE UNIVERSITY OF MELBOURNE

Gamma-ray Properties of Mixed Morphology Supernova Remnants

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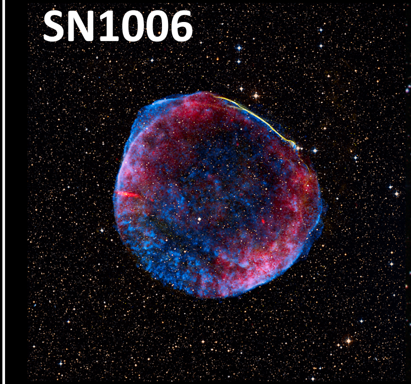
Supernova Remnants (SNRs)

Shell type:

- Bright radio/X-ray shell.
- Due to synchrotron radiation where particles have been accelerated at the shock front.

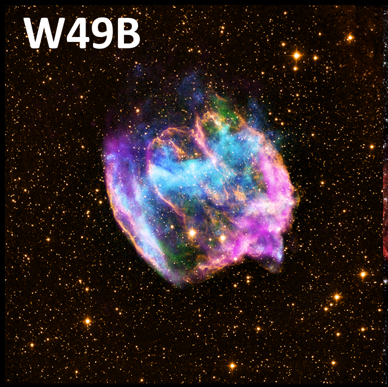


Composite:

- Bright radio/X-ray shell - synchrotron radiation.
- Bright centre due to pulsar wind nebula (PWN) emitting non-thermal synchrotron radiation.

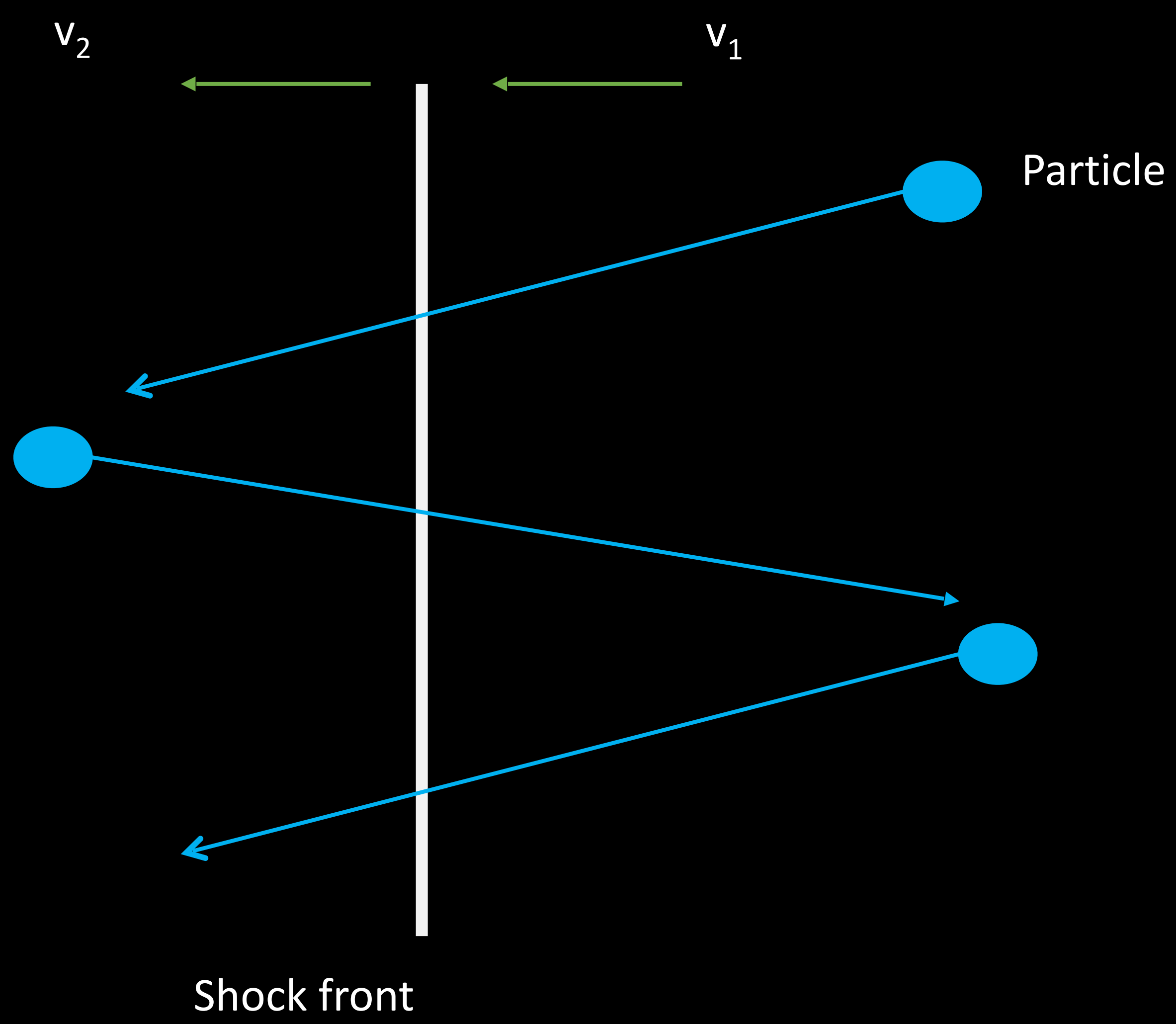
Mixed Morphology (MM):

- Bright shell – synchrotron radiation.
- Bright centre due to thermal X-rays from swept up ISM.
- Most found to be interacting with molecular clouds.



Images from NASA/CXC/SAO

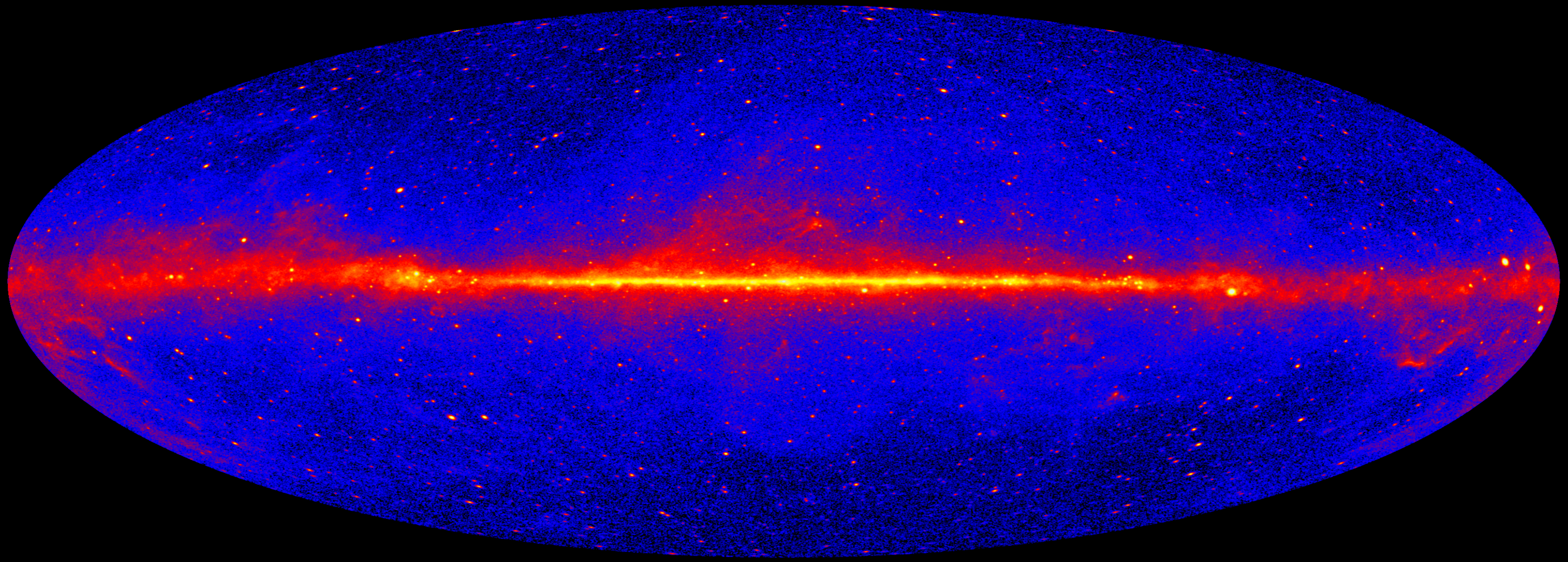
Diffusive Shock acceleration



Gamma-ray emission from MM SNRs

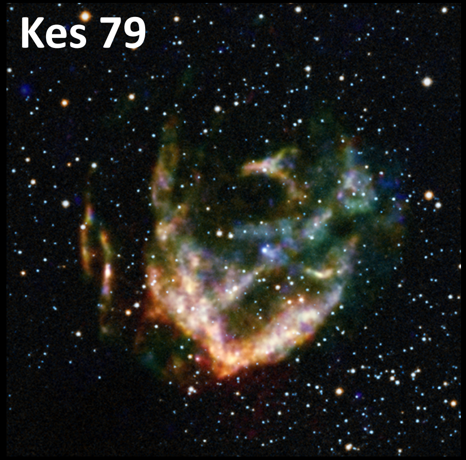
- Many are strong emitters of GeV gamma rays which is unexpected as most are middle aged.
- In an attempt to understand this many individual studies have been conducted but a consistent analysis of the population has not yet been undertaken.

Aim: Analyse 13.5 years of FERMI-LAT data for the population of MM SNRs in the Milky Way, to better understand the gamma ray and particle acceleration properties of this class.



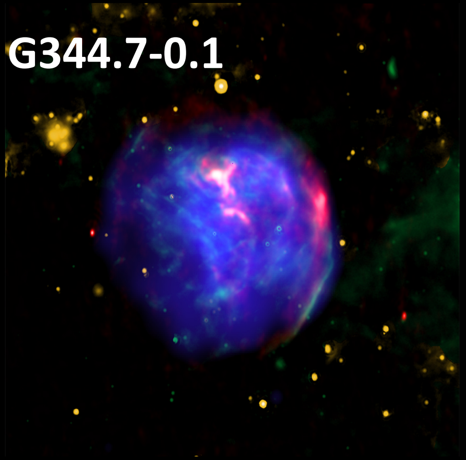
This view shows the entire sky at energies greater than 1 GeV based on 12 years of data from Fermi's Large Area Telescope. Credit: NASA/DOE/Fermi LAT Collaboration

Population



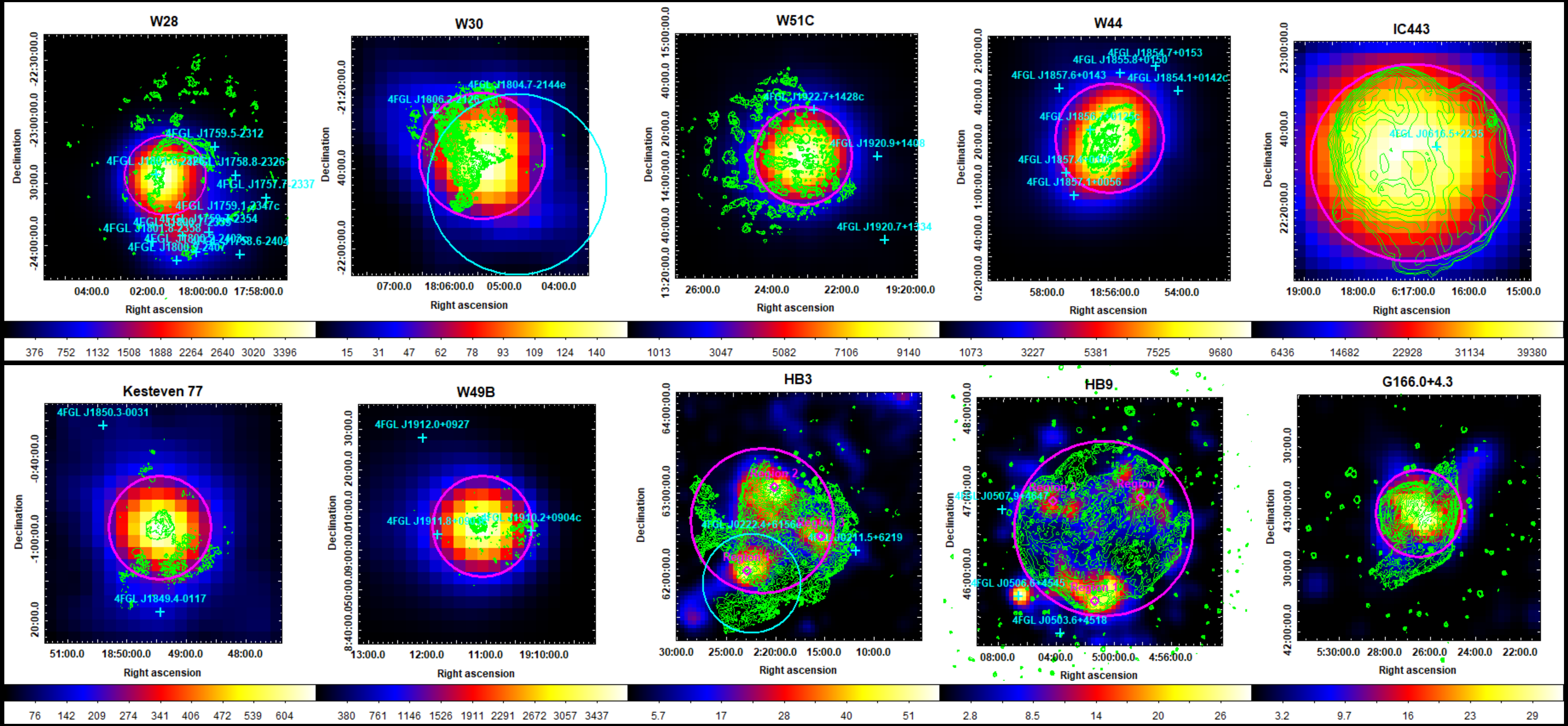
Remnant	Other names
G0.0+0.0	Sgr A East
G6.4-0.1	W28
G8.7-0.1	W30
G21.8-0.6	Kes 69
G31.9+0.0	Kes 77, 3C391
G33.6+0.1	Kes 79, 4C00.7,HC13
G34.7-0.4	W44, 3C392
G38.7-1.3	
G41.1-0.3	3C397
G43.3-0.2	W49B, 3C398
G49.2-0.7	W51C
G53.6-2.2	3C400.2, NRAO 611
G65.3+5.7	
G82.2+5.3	W63
G85.4+0.7	
G85.9-0.6	
G89.0+4.7	HB21
G93.3+6.9	DA 530, 4C(T)55.38.1
G93.7-0.2	CTB 104A, DA 551

Remnant	Other names
G116.9+0.2	CTB 1
G132.7+1.3	HB3
G156.2+5.7	
G160.9+2.6	HB9
G166.0+4.3	VRO 42.05.01
G189.1+3.0	IC 443, HB21
G272.2-3.2	
G290.1-0.8	MSH 11-61A
G298.6-0.0	
G304.6+0.1	Kes 17
G311.5-0.3	
G327.4+0.4	Kes 27
G337.8-0.1	Kes 41
G344.7-0.1	
G346.6-0.2	
G348.5+0.1	CTB 37A
G352.7-0.1	
G355.6-0.0	
G357.7-0.1	The Tornado, MSH 17-39
G359.1-0.5	

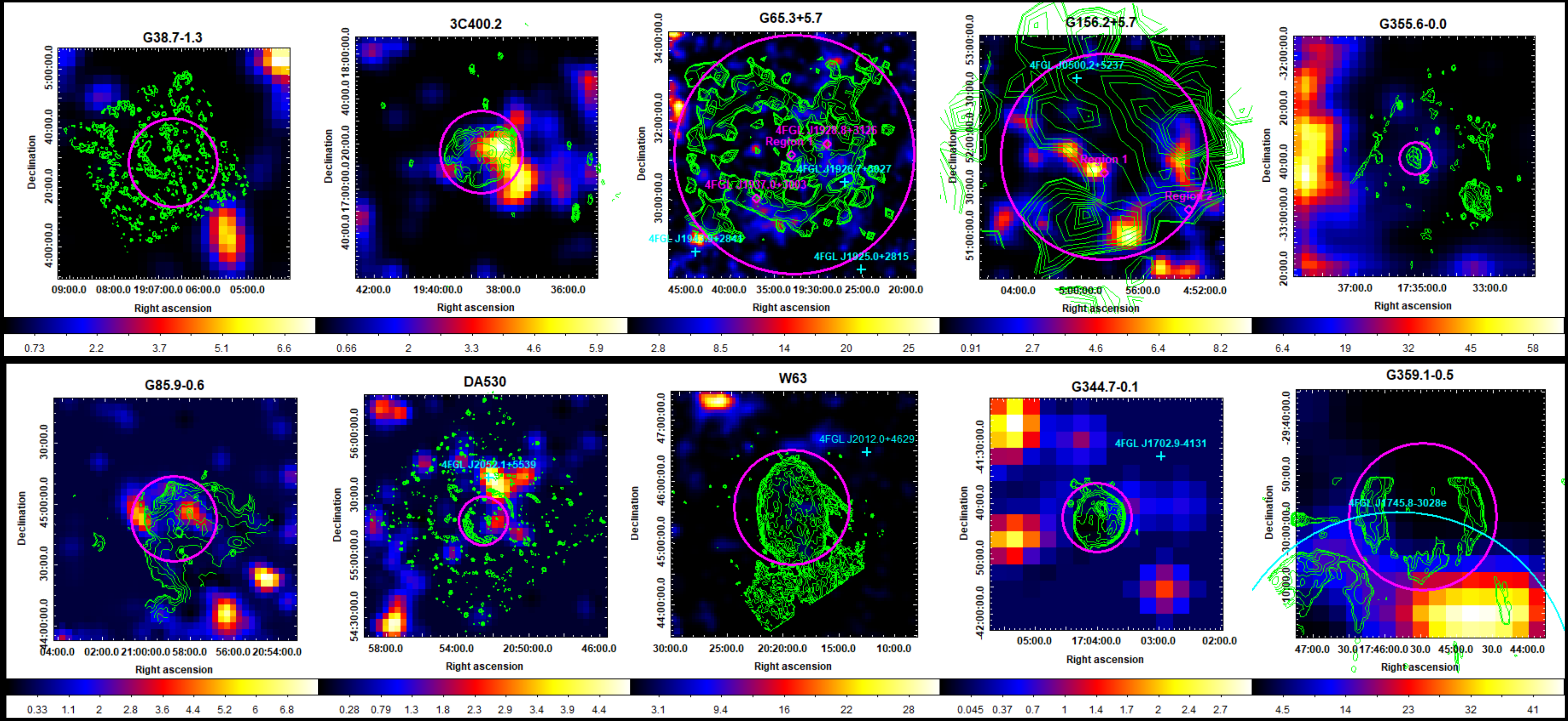


Images from NASA/CXC/SAO

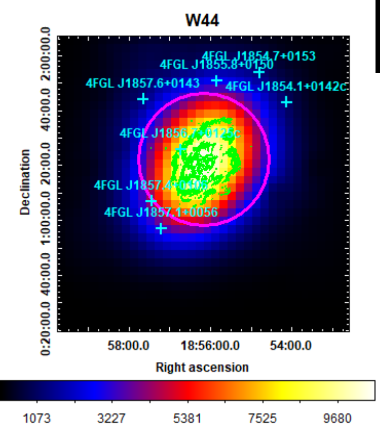
Detection significance maps – Detected Sources

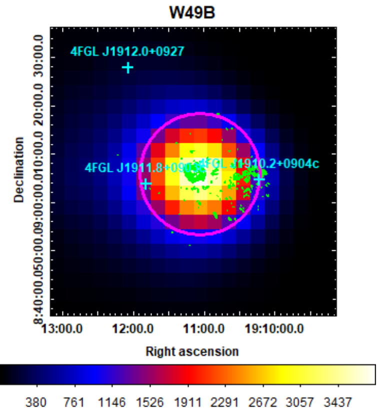


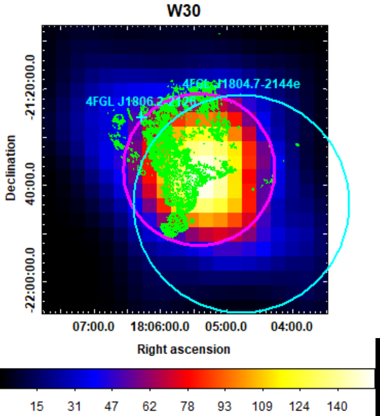
Detection significance maps – Non-detected Sources

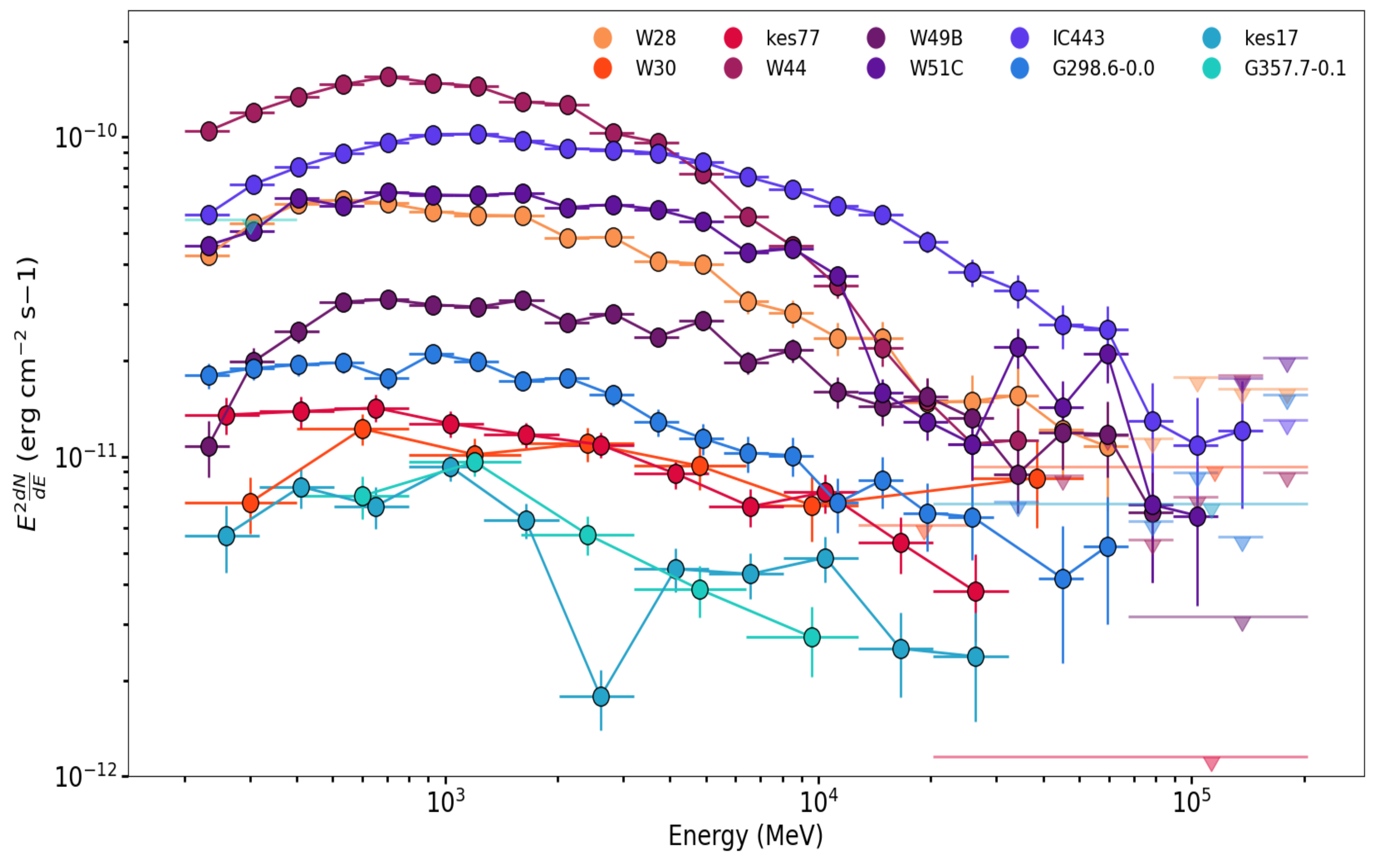


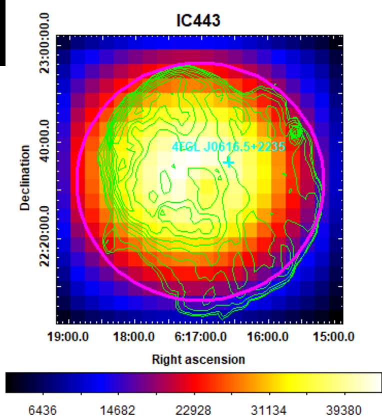
Spectral Energy Distribution (SED)

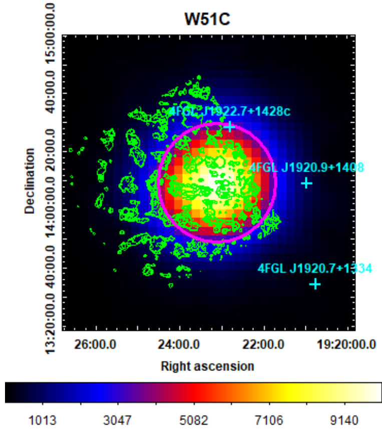


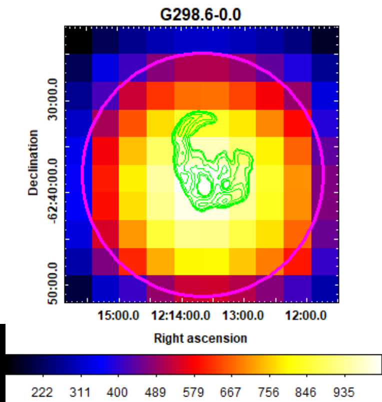












Fitting SEDs

Power law:

$$\frac{dN}{dE} = N_0 E^{-\Gamma}$$

Power law with Exponential Cut off:

$$\frac{dN}{dE} = N_0 E^{-\Gamma} e^{-\left(\frac{E}{E_c}\right)^{-\beta}}$$

Broken Power law:

$$\frac{dN}{dE} = N_0 E^{-\Gamma} \left(\left(1 + \left(\frac{E}{E_b} \right) \right)^{\Gamma - \Gamma_2} \right)^{-1}$$

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Γ = Photon index

Broken Power law:

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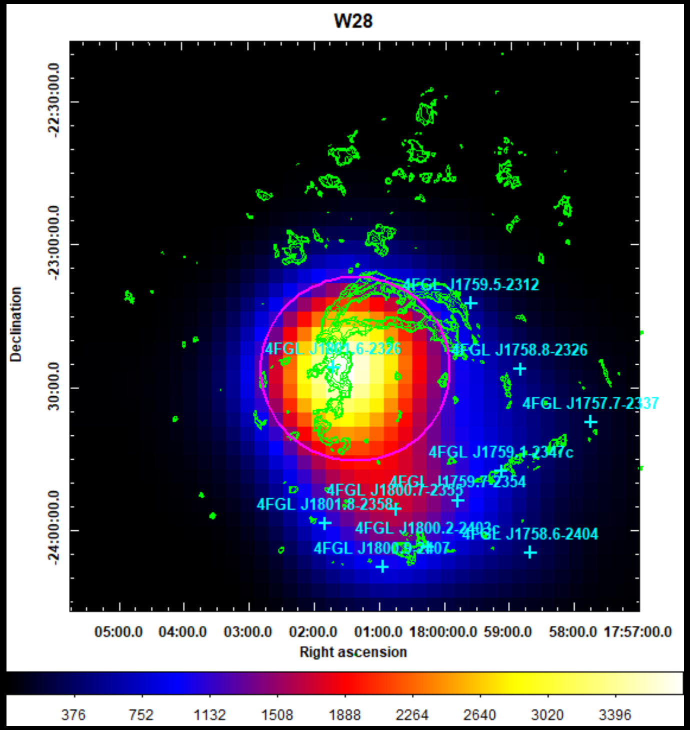
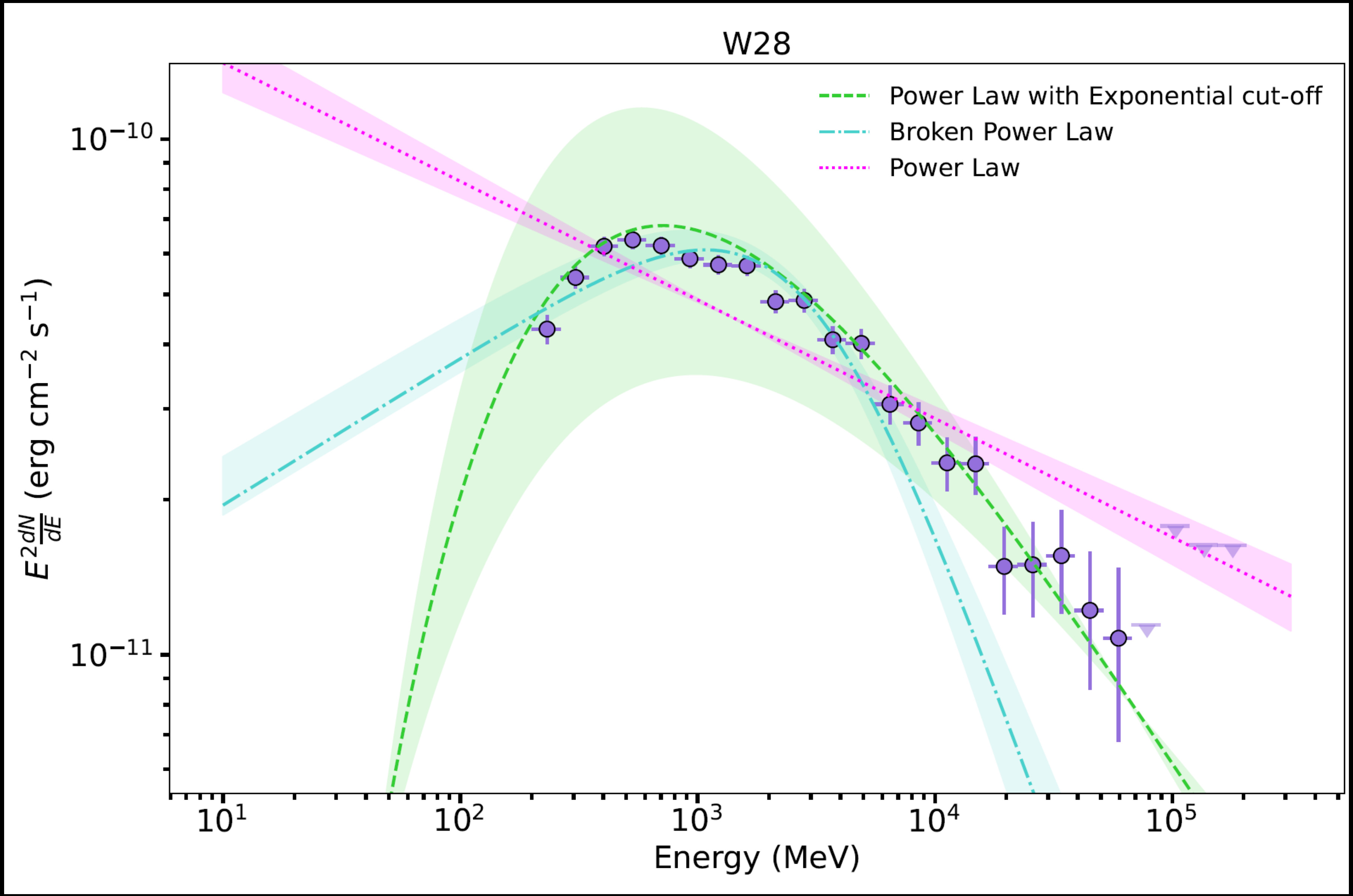
Fitting SEDs – W28





Best Fit:

Power Law with Exponential Cut off

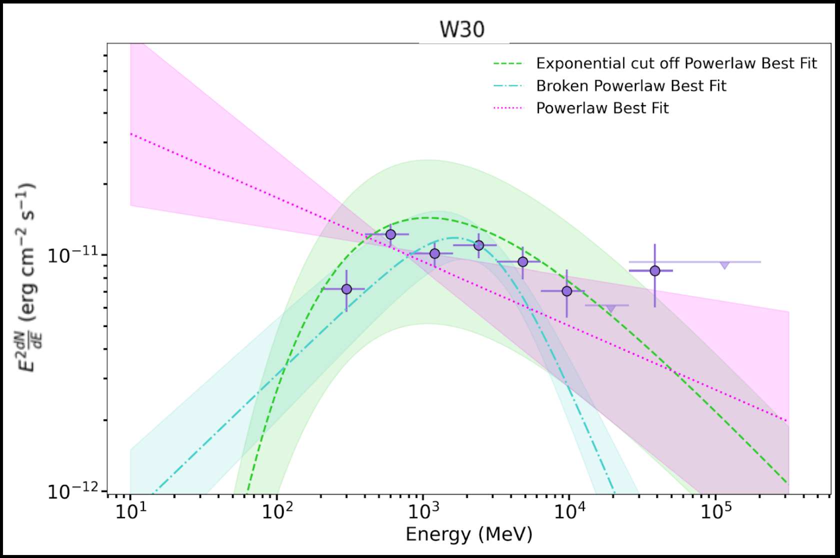
$N_0 = 2^{+0.5}_{-0.4} \times 10^{-10}\ MeV$

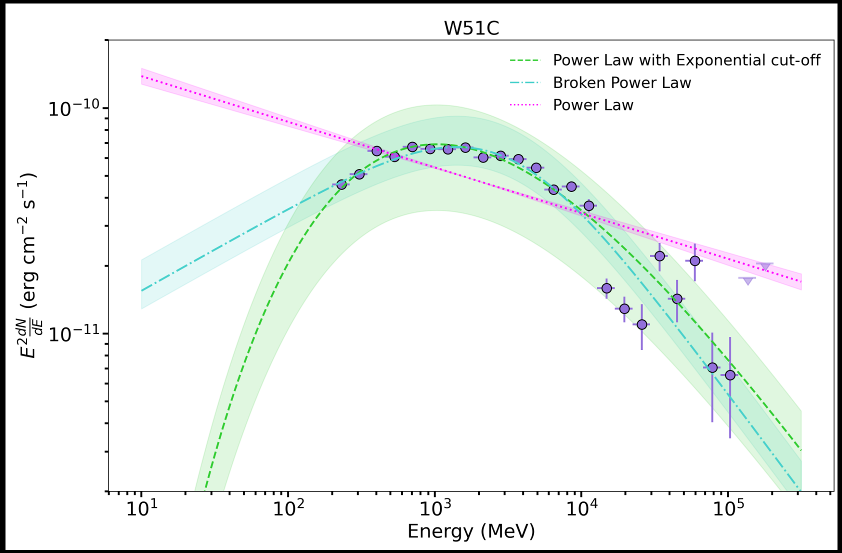
$\Gamma = 2.7 \pm 0.1$

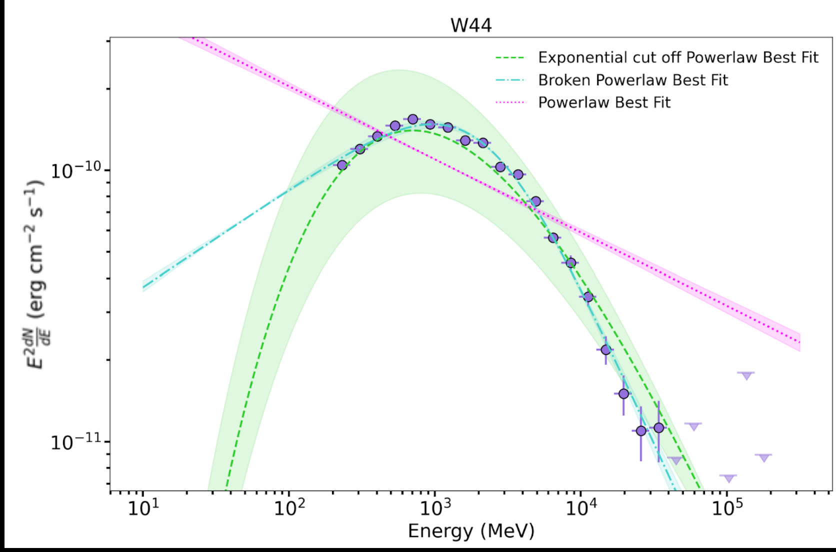
$E_C = 1.1^{+0.9}_{-0.3}$ GeV

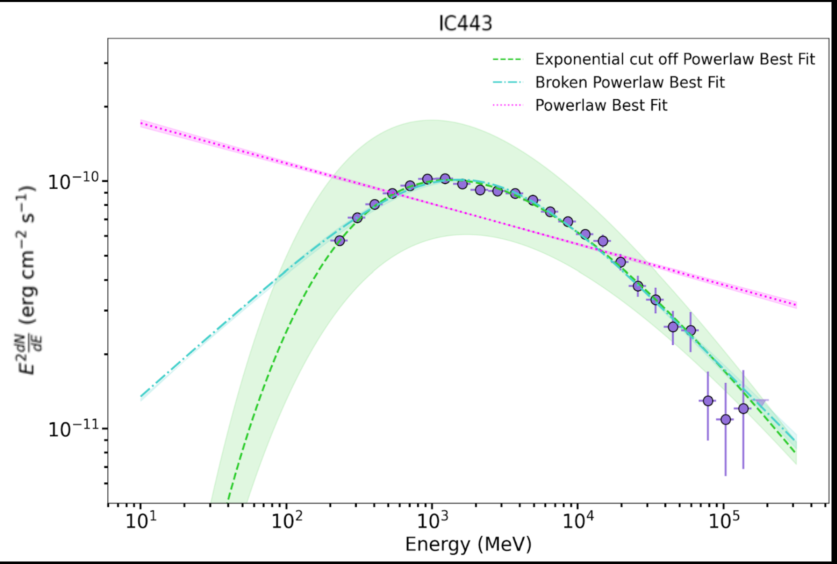
$\beta = 0.6 \pm 0.1$

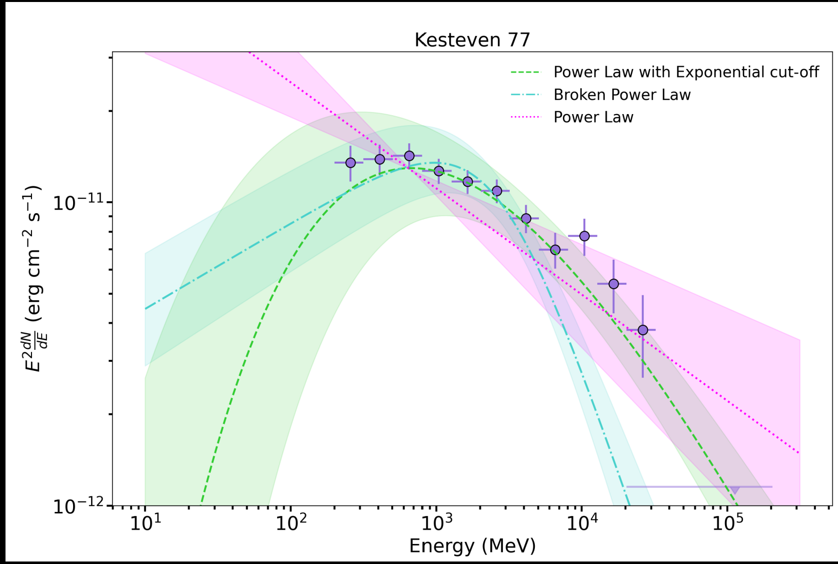
Fitting SEDs

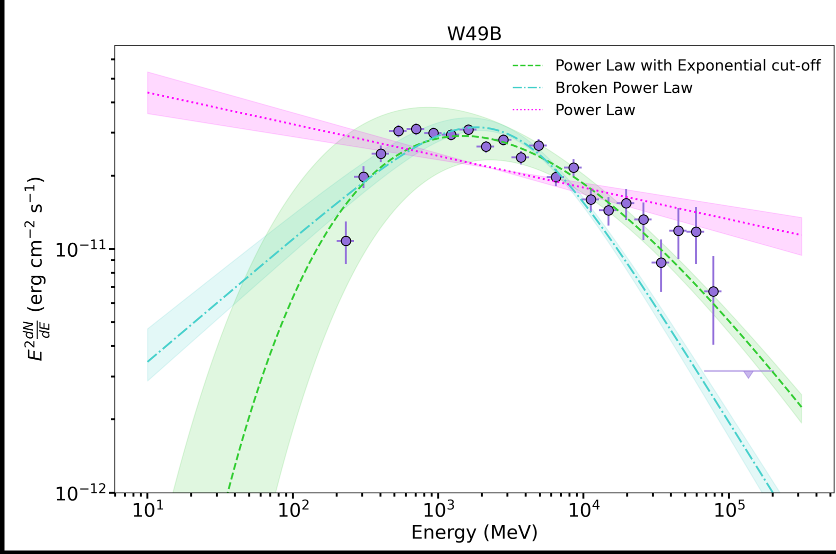




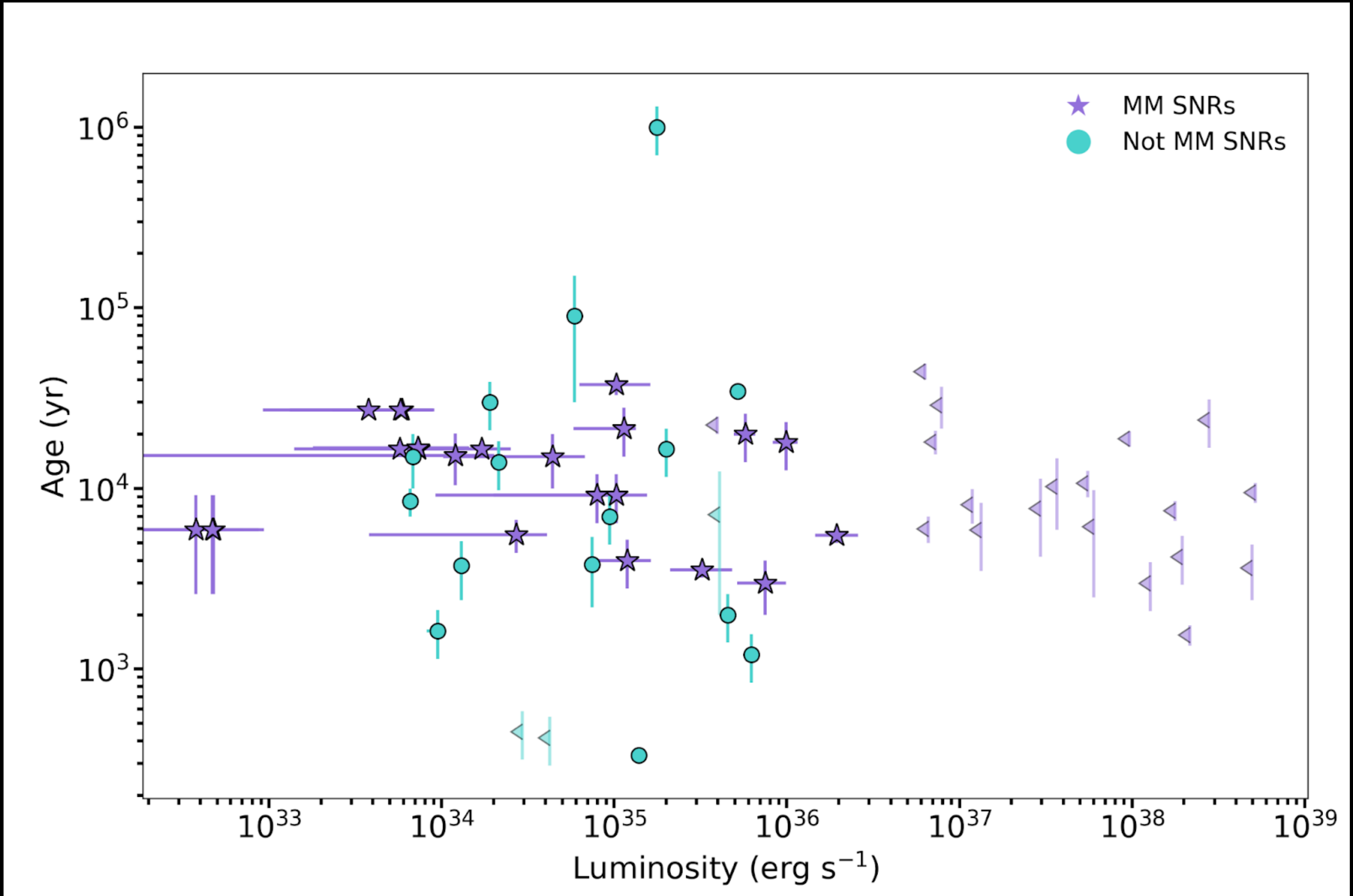






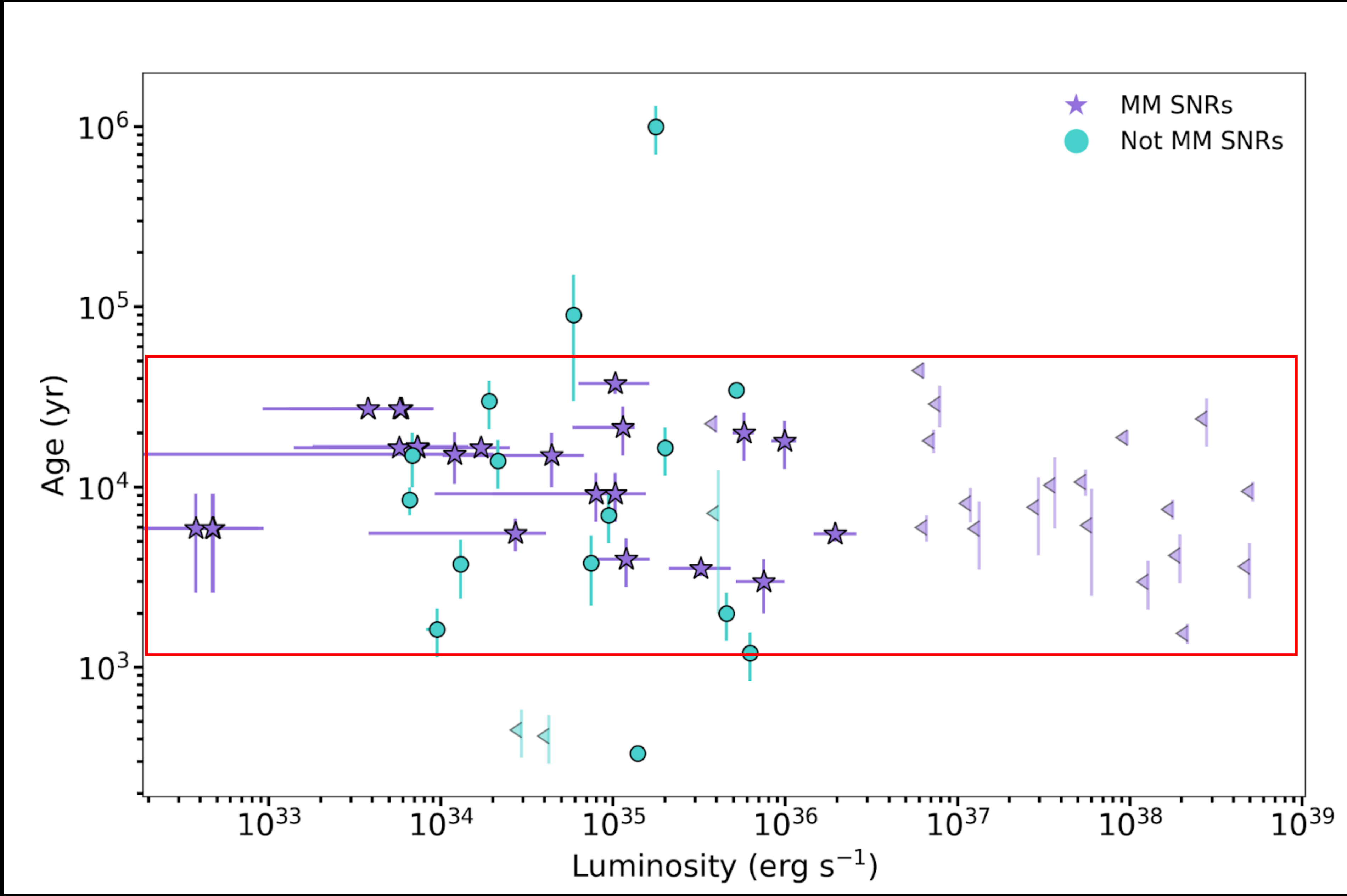


Results - Age



MM SNRs
Not MM SNRs
Age (yr)
10^6
10^5
10^4
10^3
10^{33}
10^{34}
10^{35}
10^{36}
10^{37}
10^{38}
10^{39}
Luminosity (erg s^{-1})

Results - Age



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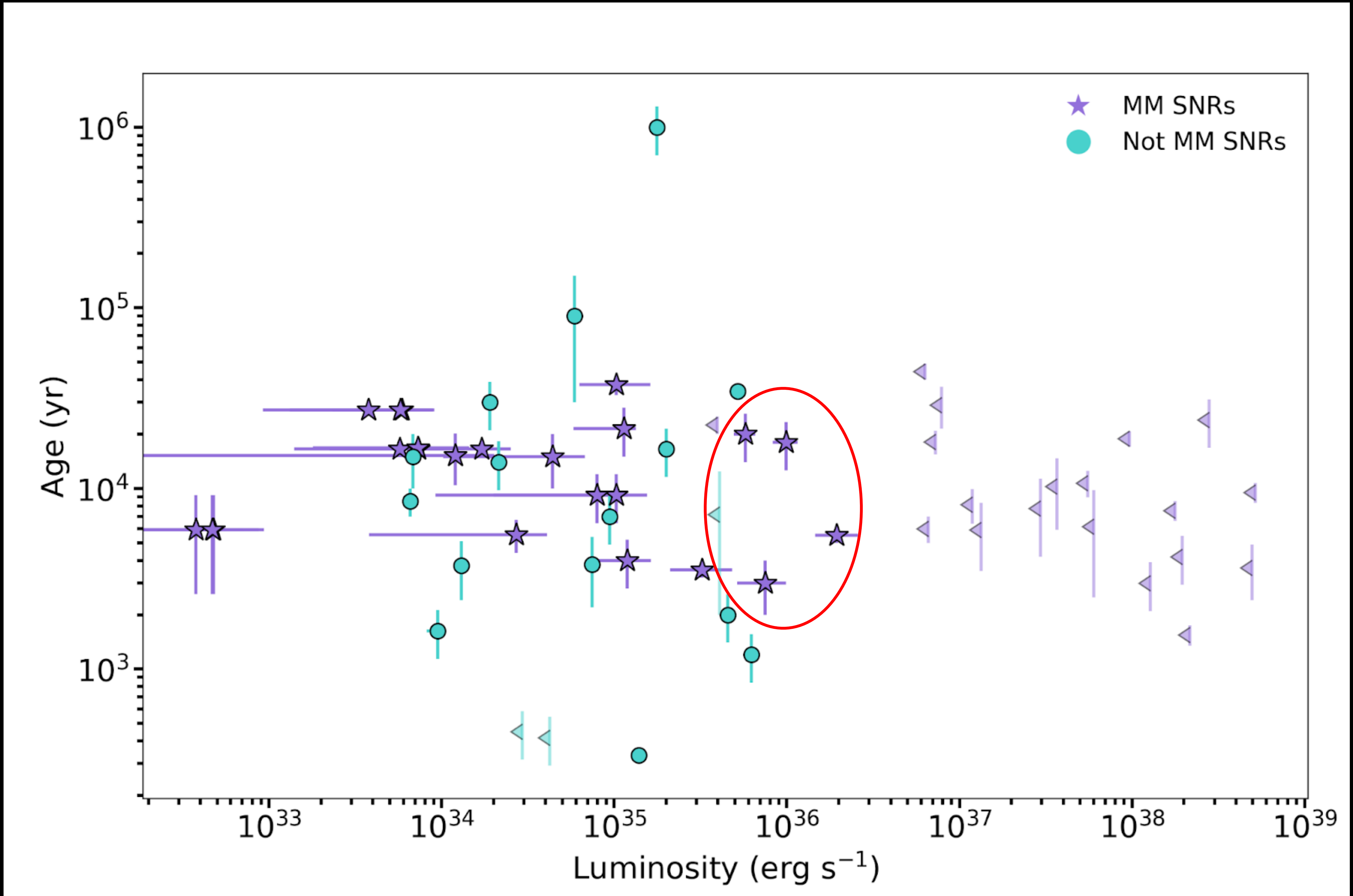
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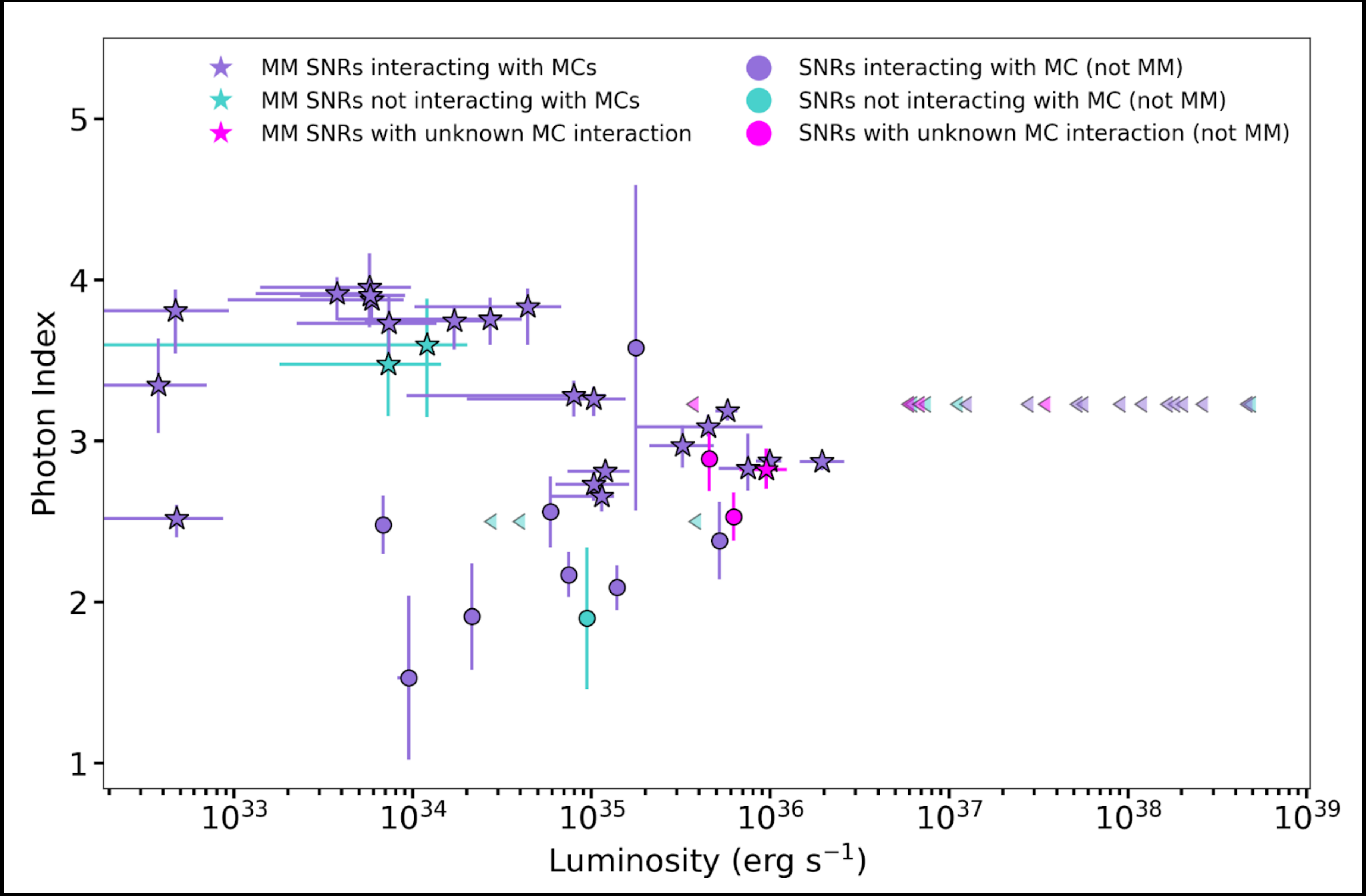
Luminosity (erg s^{-1})

Results - Molecular cloud interaction



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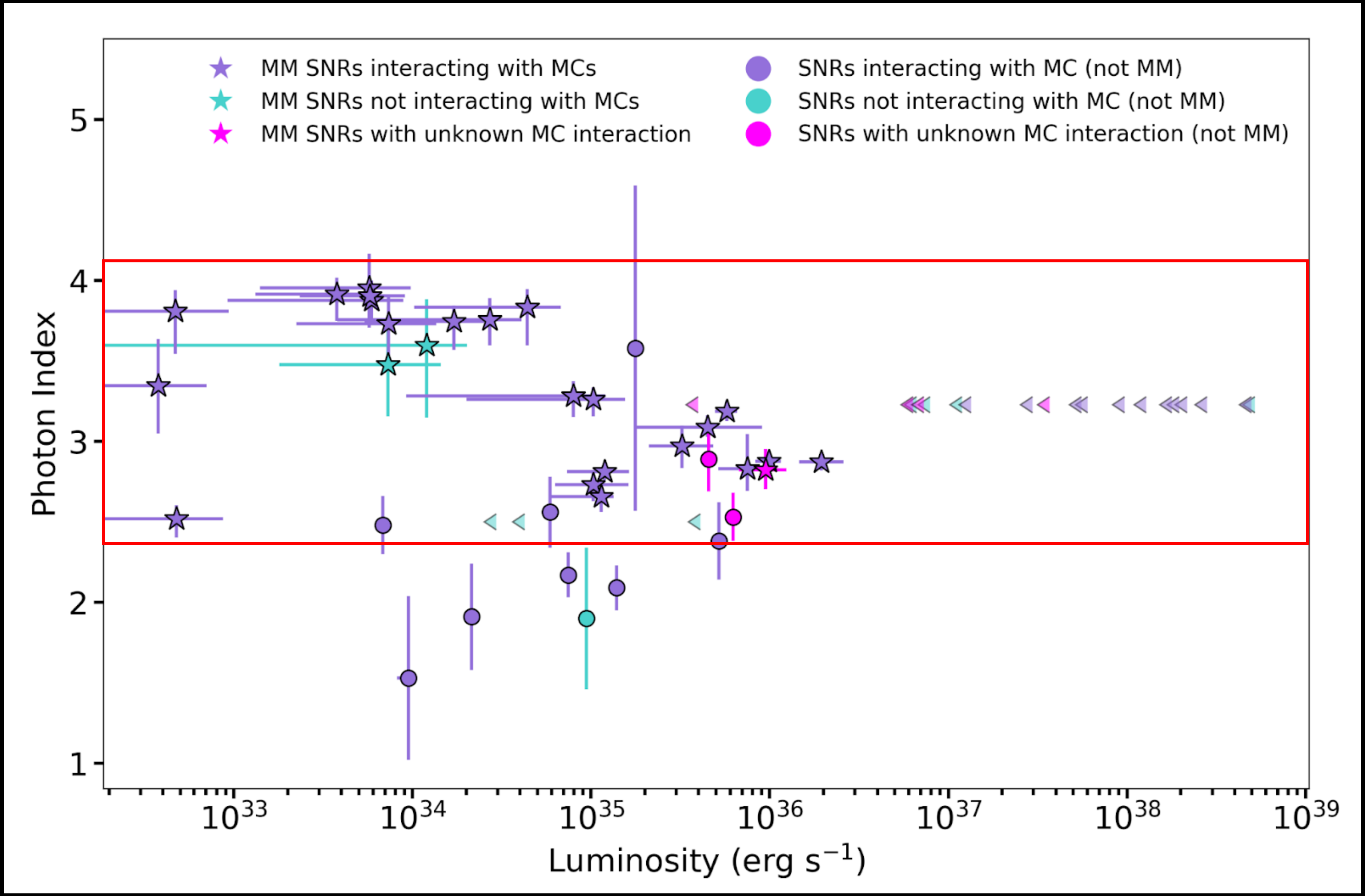
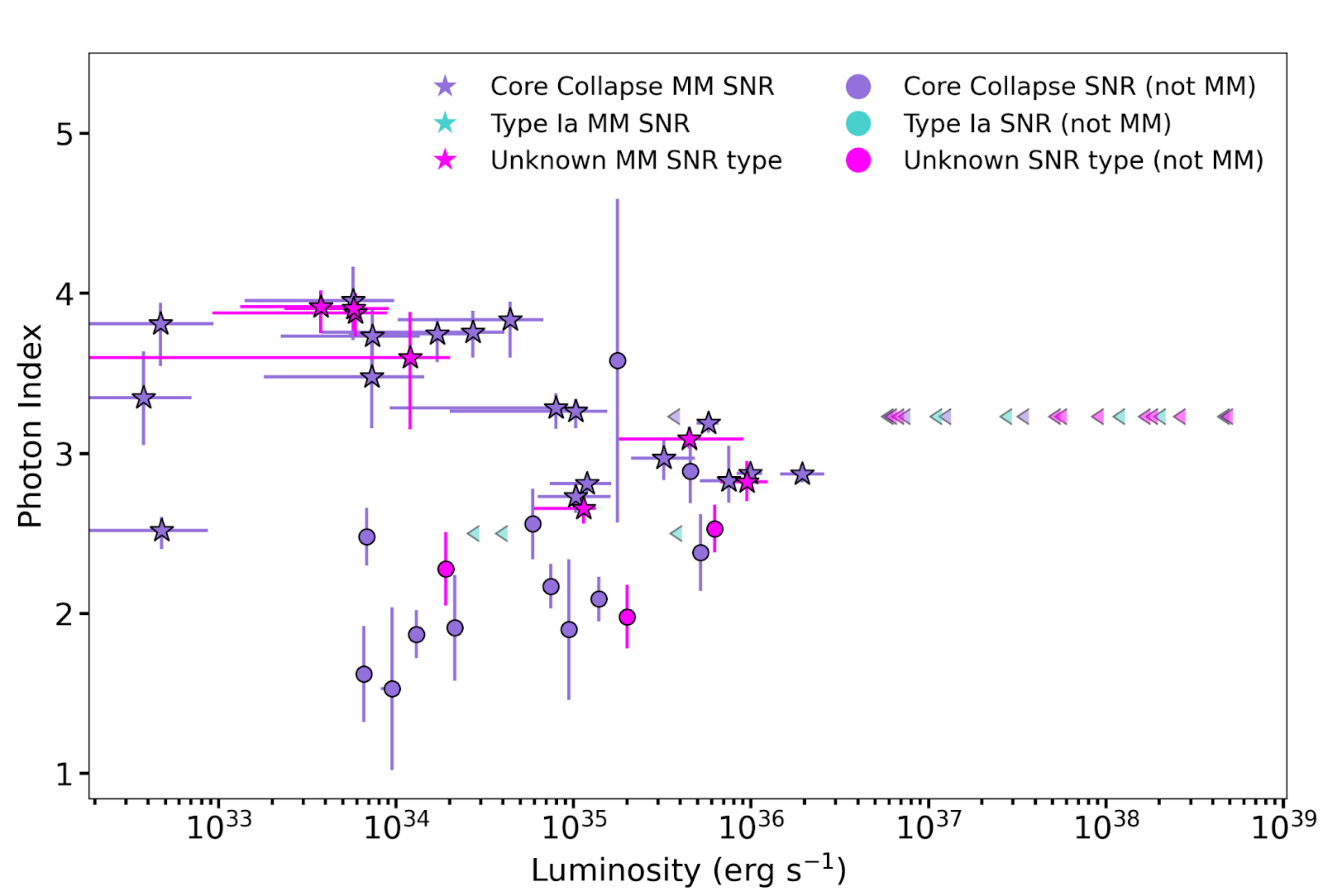


Results – Type Ia vs Core-collapse



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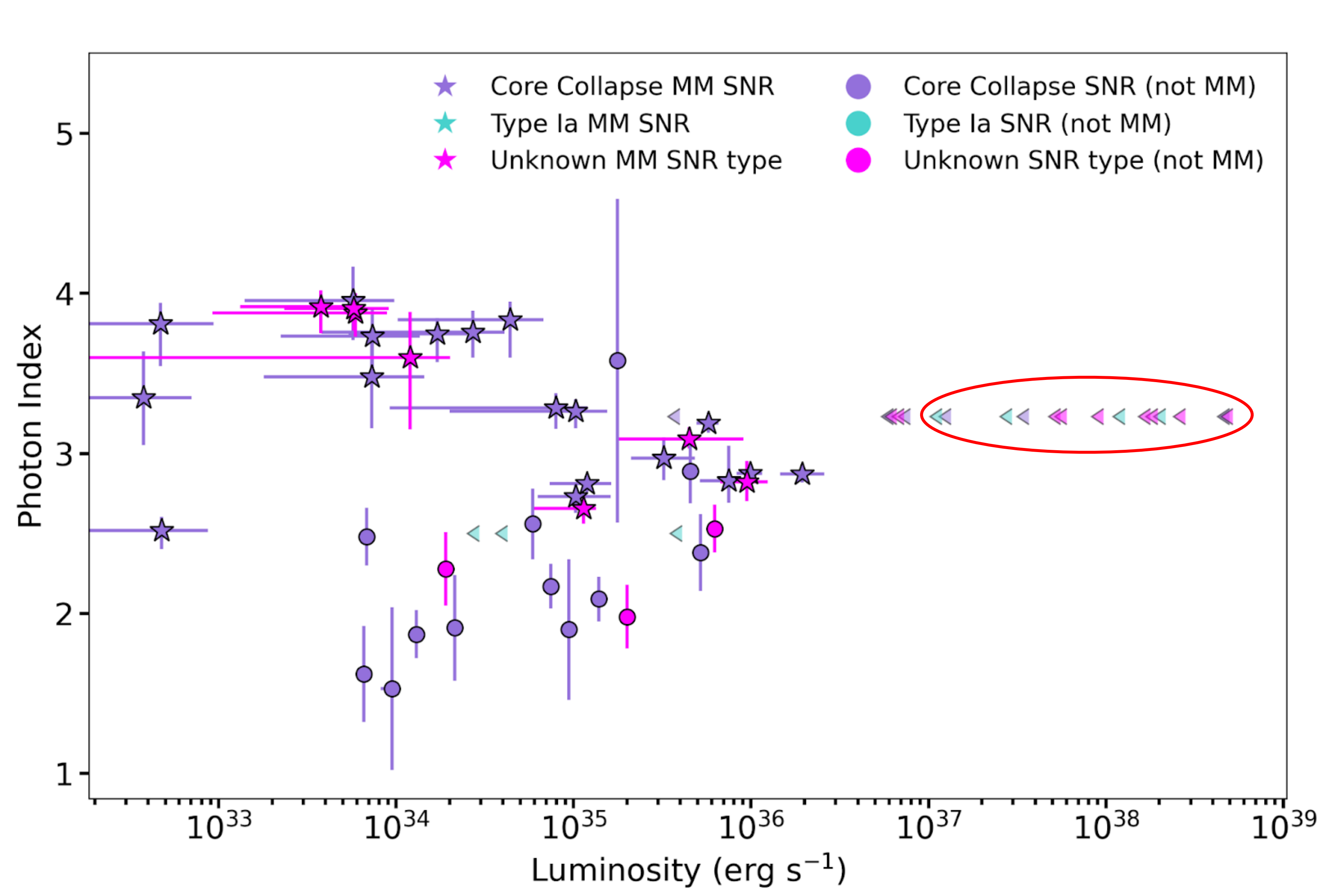
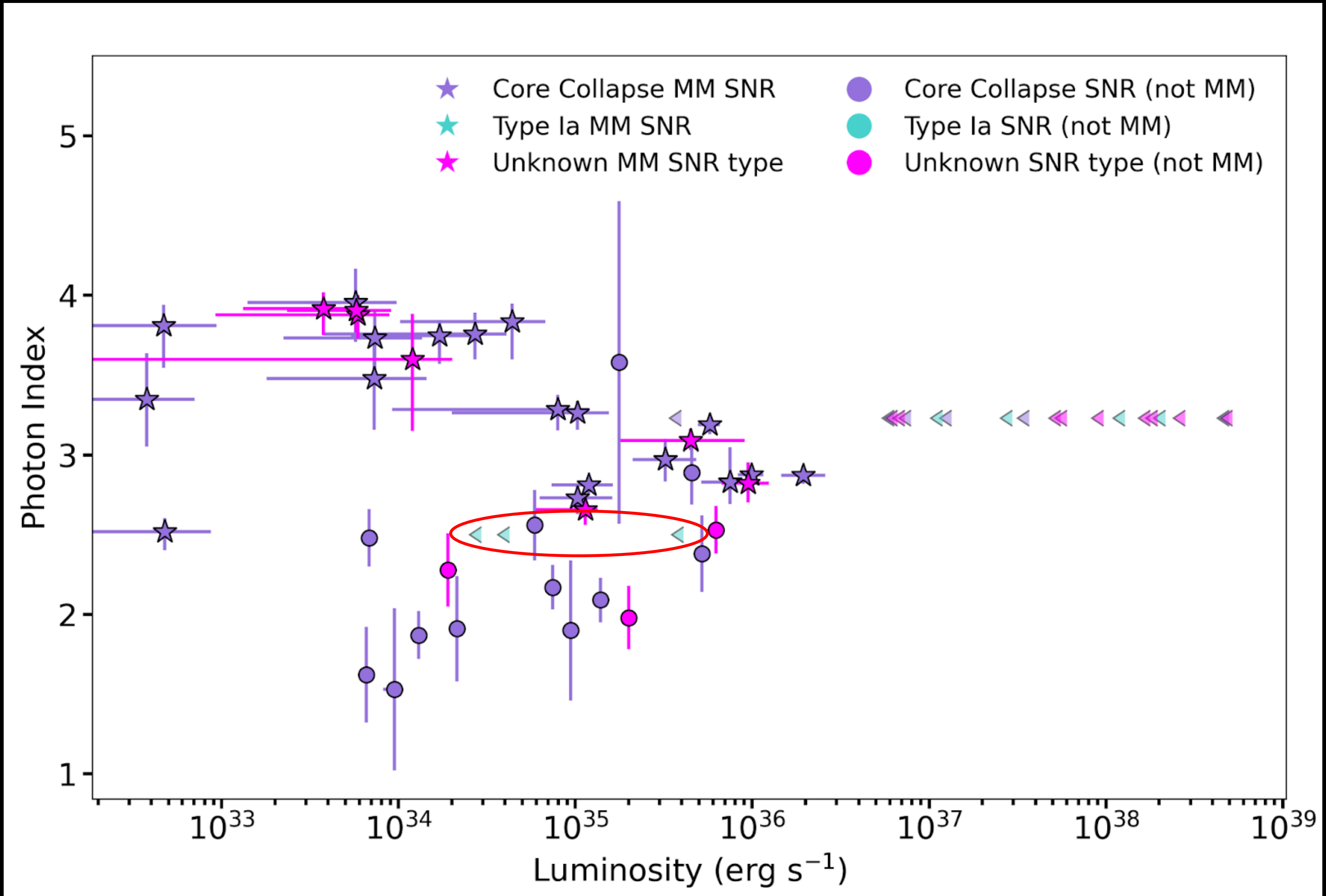
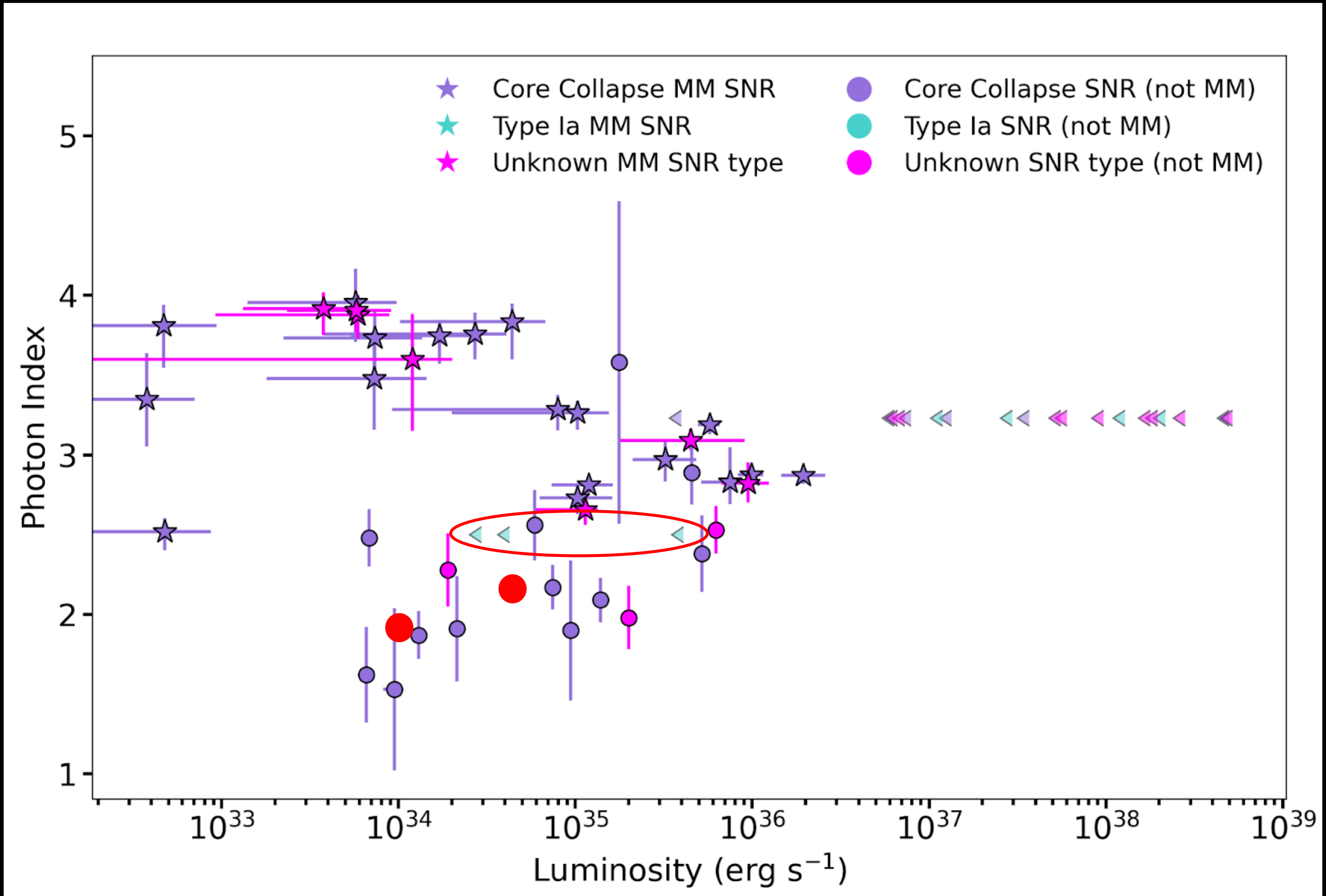


Results – Type Ia vs Core-collapse

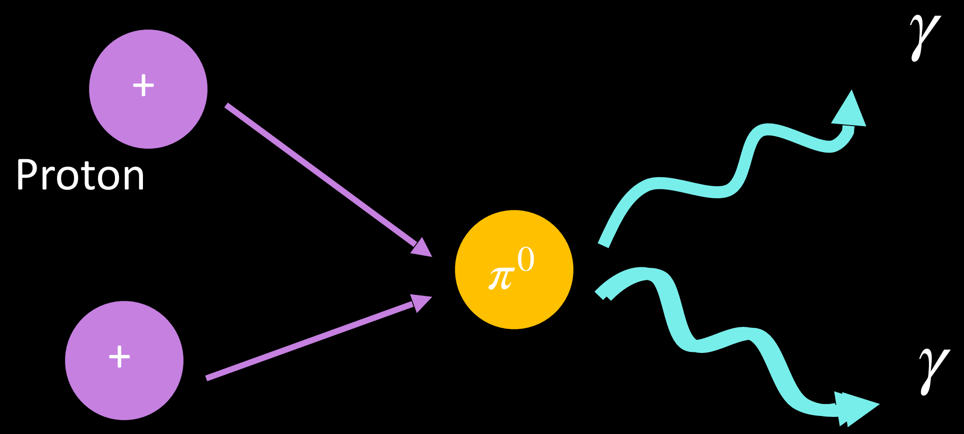


Results – Type Ia vs Core-collapse

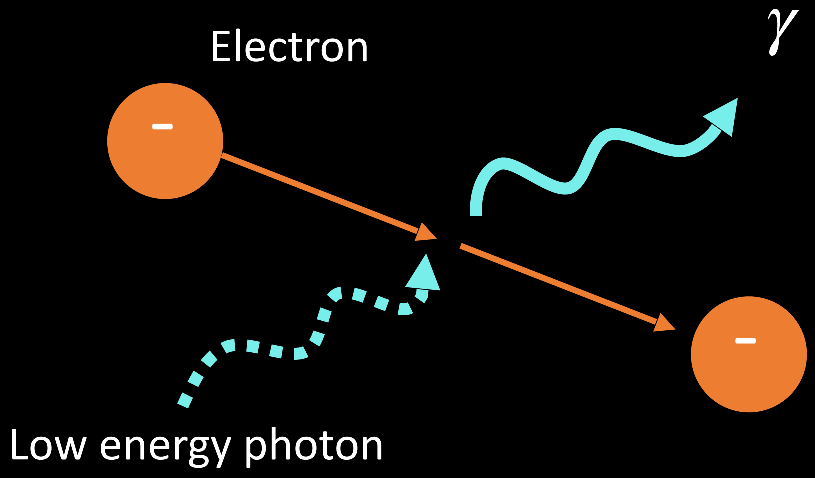


Gamma-ray emission processes

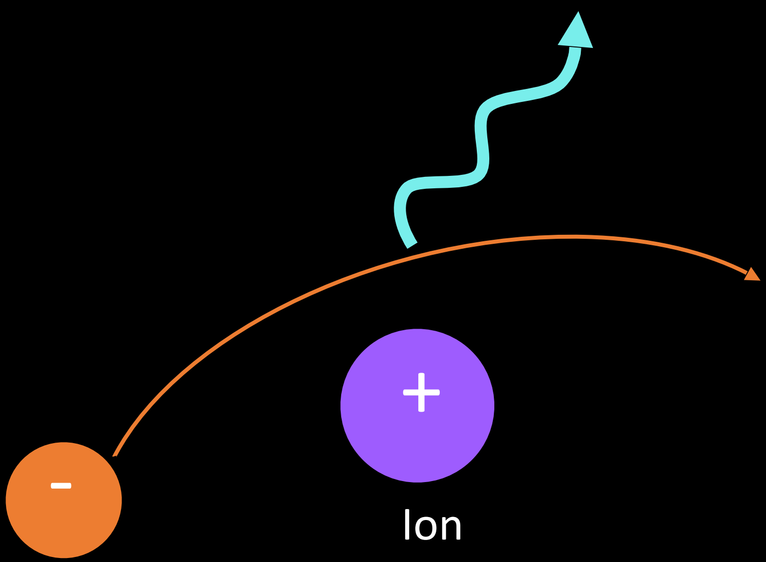
Neutral pion decay:



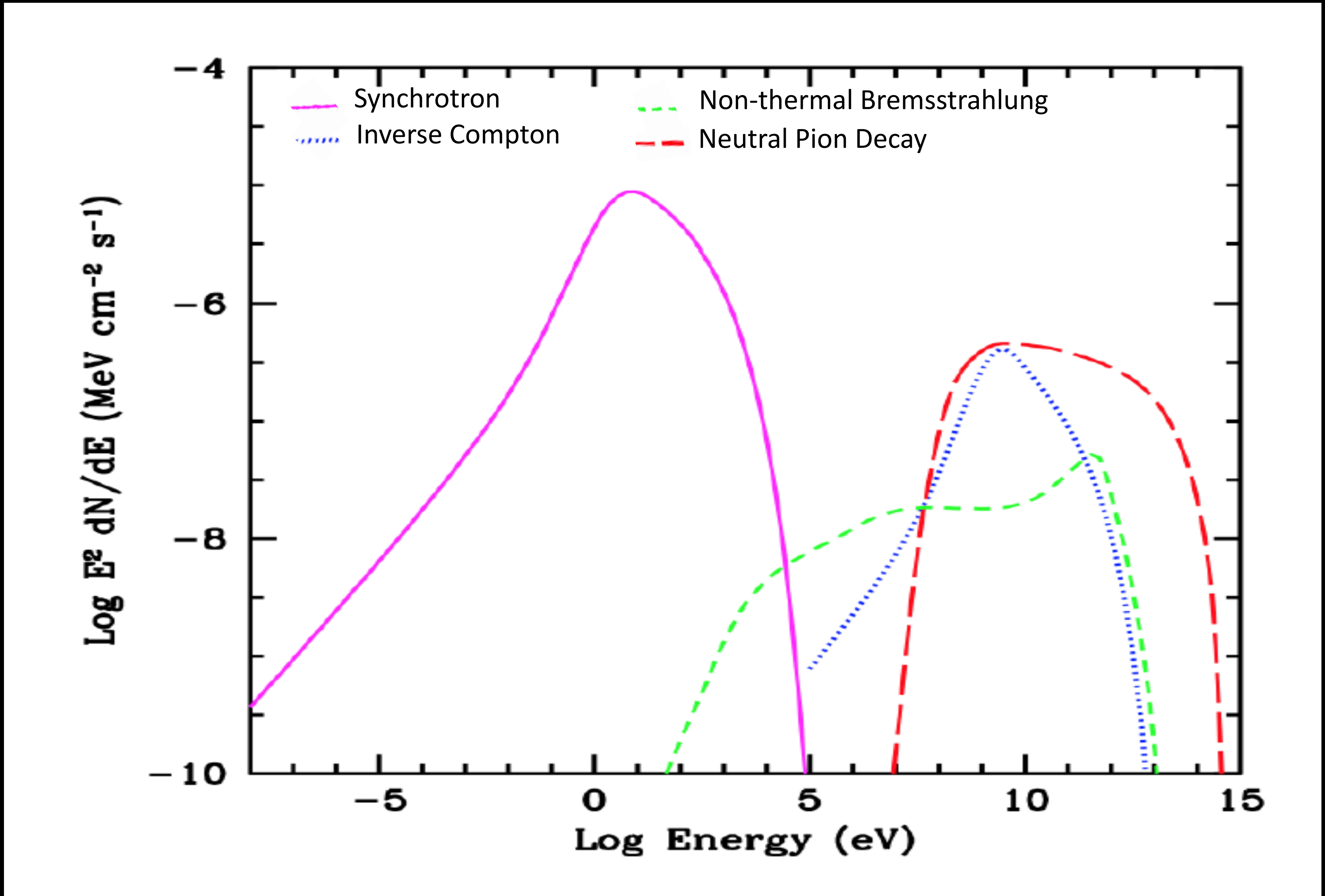
Inverse Compton Scattering:



Non-thermal Bremsstrahlung:

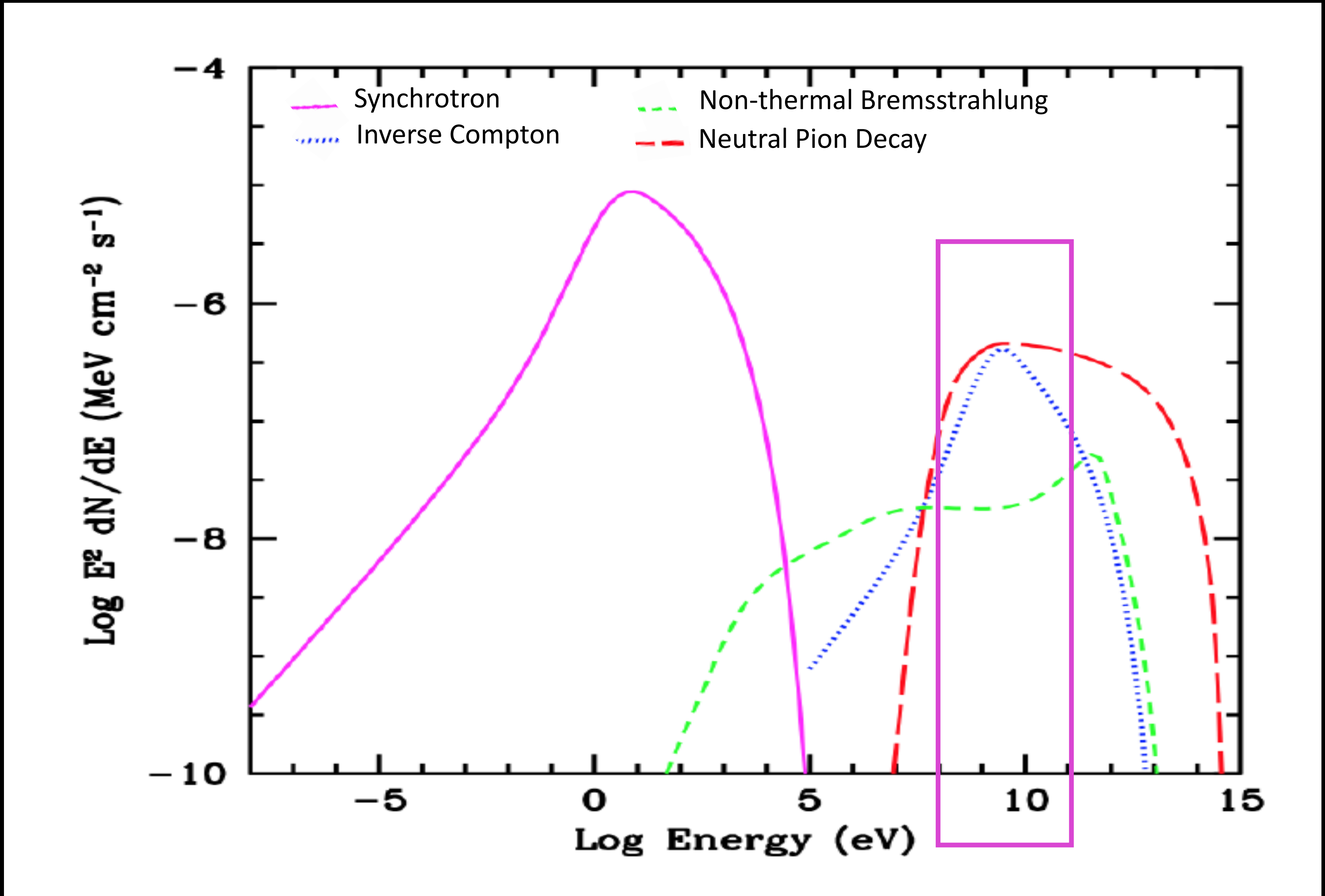


Gamma-ray emission from SNRs



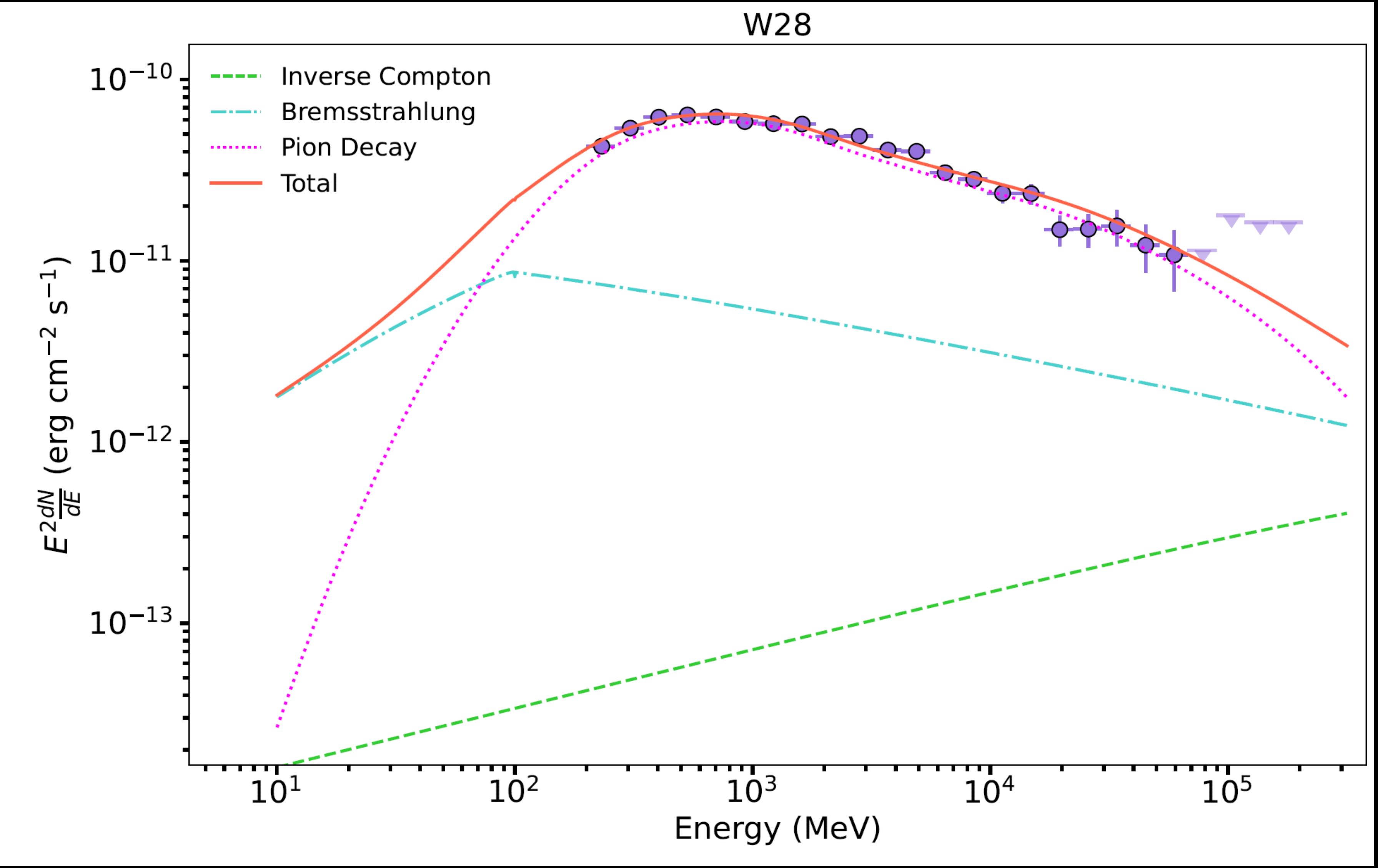
Simulated broadband spectrum from a supernova remnant undergoing efficient diffusive shock acceleration of electrons and protons (Slane et al 2015).

Gamma-ray emission from SNRs



Simulated broadband spectrum from a supernova remnant undergoing efficient diffusive shock acceleration of electrons and protons (Slane et al 2015).

Modelling the Origin of the Gamma-ray emission

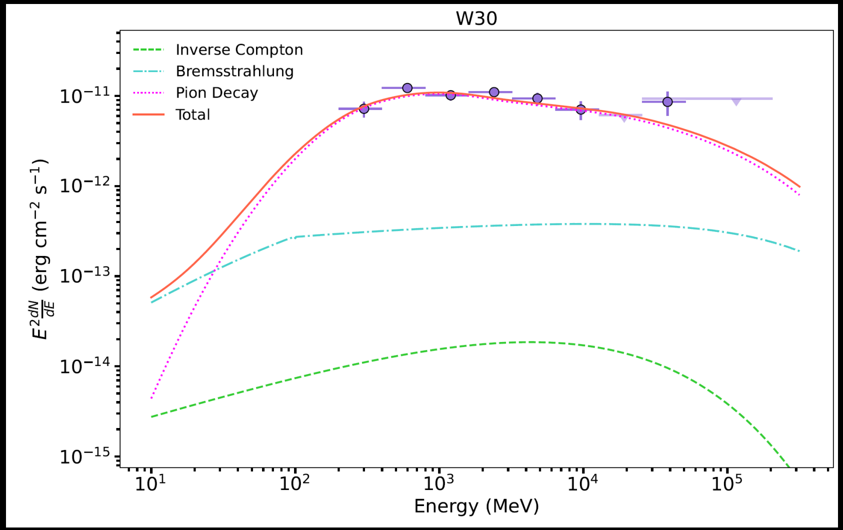


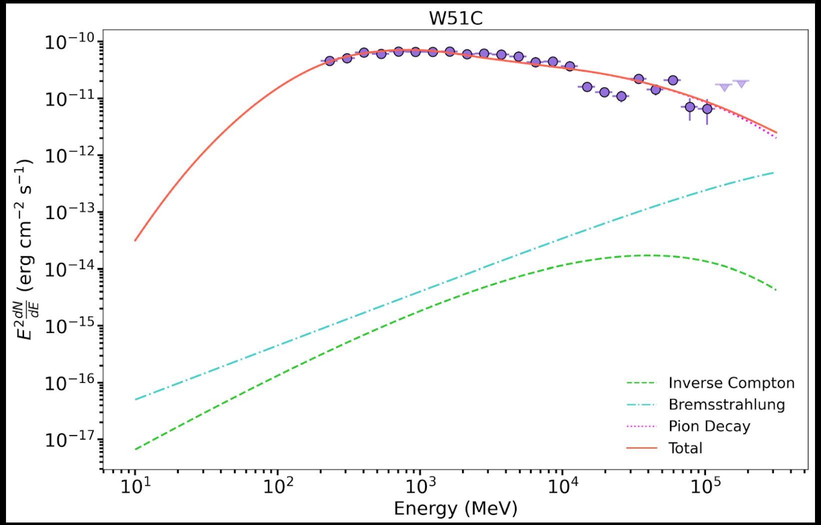
Density: 62 ± 6 cm^{-3}

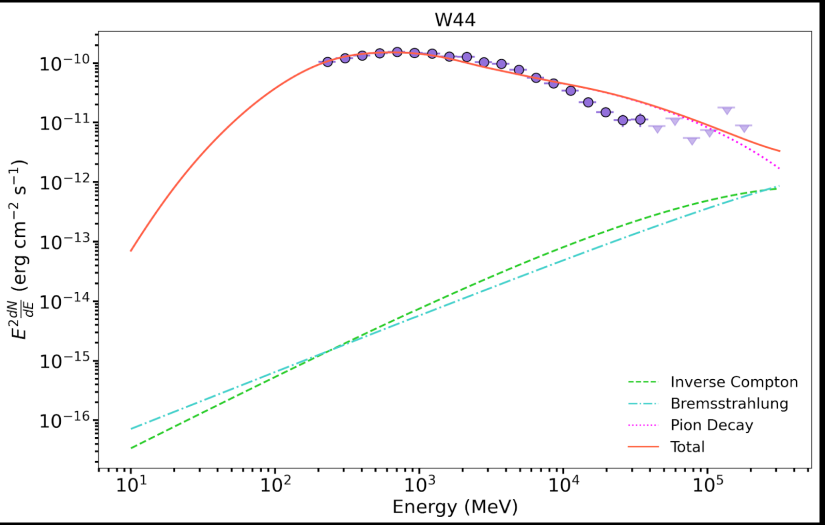
Proton energy: $1^{+0.3}_{-0.1} \times 10^{49}$ erg

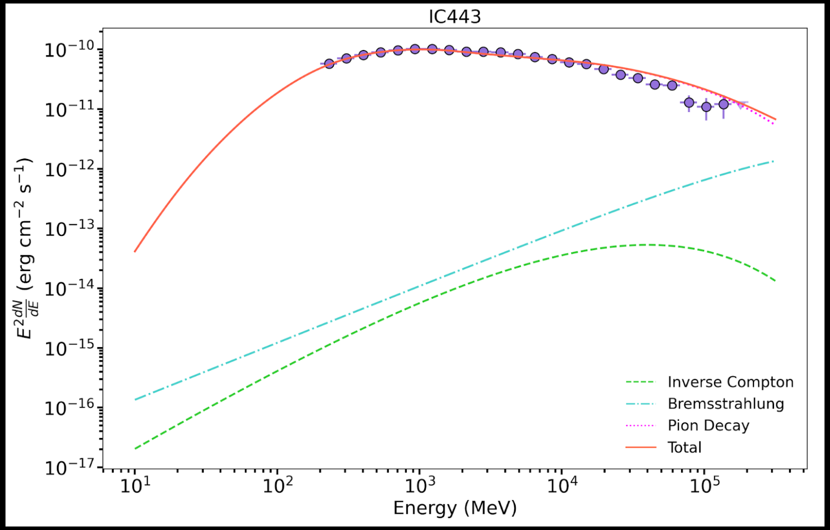
Electron energy: $3^{+3}_{-2} \times 10^{47}$ erg

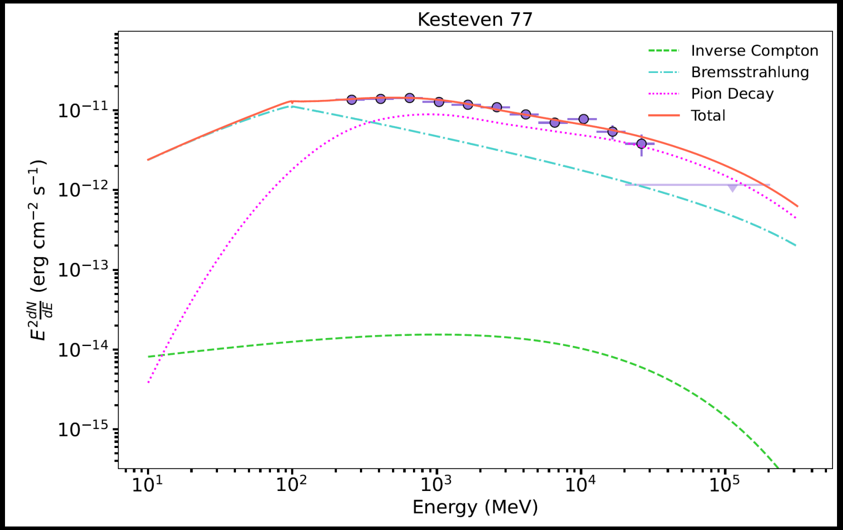
Origin of the Gamma-ray emission

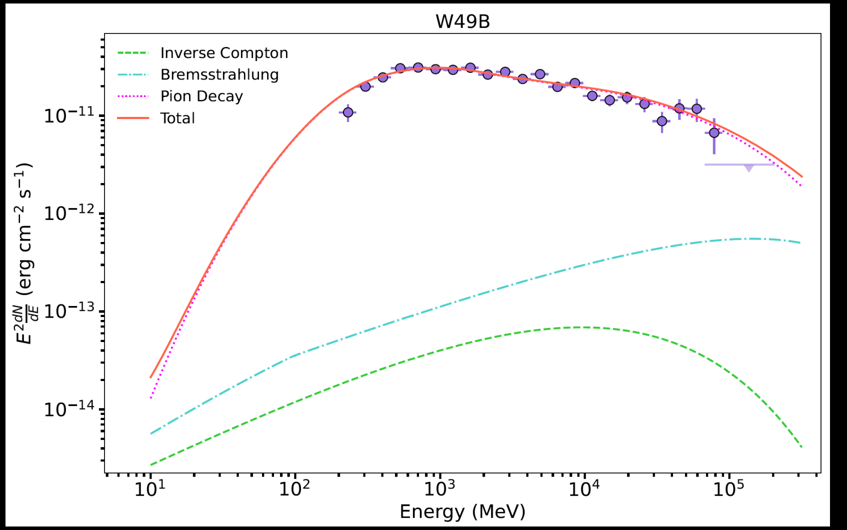












Density

Source	Amplitude $\times 10^{47}\,TeV^{-1}$	Γ_p	Γ_e	E_{cp} (TeV)	E_{ce} (TeV)	n_h (cm^{-3})	K_{ep} ($\times 10^{-3}$)	$\ln\mathcal{L}$
W28	$1.56^{+0.37}_{-0.37}$	$2.46^{+0.04}_{-0.04}$	$2.39^{+0.09}_{-0.19}$	$2.22^{+0.37}_{-0.28}$	$77.97^{+45.69}_{-30.29}$	$62.13^{+6.14}_{-6.07}$	$9.83^{+1.07}_{-1.28}$	-13.5
W44	$3.48^{+0.44}_{-0.45}$	$2.57^{+0.01}_{-0.01}$	$0.54^{+0.06}_{-0.04}$	$1.06^{+0.01}_{-0.01}$	$4.56^{+1.31}_{-1.33}$	$131.74^{+15.49}_{-12.69}$	$5.02^{+0.61}_{-0.6}$	-205.31
IC443	$0.71^{+0.08}_{-0.06}$	$2.22^{+0.01}_{-0.01}$	$0.12^{+0.02}_{-0.02}$	$0.99^{+0.0005}_{-0.0004}$	$0.97^{+0.003}_{-0.005}$	$519.26^{+31.70}_{-30.47}$	$10.92^{+1.05}_{-1.23}$	-46.99
W51C	$3.01^{+0.59}_{-0.54}$	$2.36^{+0.02}_{-0.01}$	$0.11^{+0.02}_{-0.03}$	$0.99^{+0.002}_{-0.002}$	$0.97^{+0.006}_{-0.007}$	$599.64^{+104.32}_{-96.79}$	$10.64^{+2.95}_{-2.43}$	-163.48
W49B	$97.3^{+29.3}_{-19.6}$	$2.27^{+0.03}_{-0.03}$	$1.91^{+0.27}_{-0.5}$	$1.47^{+0.15}_{-0.16}$	$0.98^{+0.009}_{-0.009}$	$50.59^{+11.72}_{-13.04}$	$10.42^{+1.94}_{-1.7}$	-21.78
G298.6-0.0	$23.7^{+10.50}_{-6.91}$	$2.44^{+0.04}_{-0.05}$	$2.05^{+0.35}_{-0.49}$	$1.44^{+0.24}_{-0.25}$	$0.98^{+0.010}_{-0.009}$	$50.94^{+14.16}_{-12.70}$	$10.44^{+3.03}_{-3.58}$	-7.11
Kesteven 77	$9.31^{+5.08}_{-3.46}$	$2.33^{+0.14}_{-0.17}$	$2.52^{+0.06}_{-0.12}$	$1.3^{+0.12}_{-0.16}$	$0.98^{+0.005}_{-0.005}$	$53.62^{+16.08}_{-10.65}$	$10.69^{+3.47}_{-3.00}$	-3.96
W30	$5.21^{+6.94}_{-2.51}$	$2.25^{+0.10}_{-0.15}$	$2.02^{+0.29}_{-0.62}$	$1.47^{+0.45}_{-0.35}$	$0.98^{+0.01}_{-0.01}$	$48.12^{+33.83}_{-24.57}$	$10.05^{+6.99}_{-5.40}$	-3.09
Kesteven 17	$19.8^{+19.20}_{-19.80}$	$2.39^{+0.13}_{-0.62}$	$2.06^{+0.52}_{-0.93}$	$1.45^{+0.22}_{-0.20}$	$0.98^{+0.009}_{-0.007}$	$48.12^{+22.12}_{-15.34}$	$9.91^{+5.17}_{-4.07}$	-3.84
G357.7-0.1	$6.85^{+10.50}_{-6.85}$	$2.5^{+0.24}_{-0.31}$	$2.02^{+0.61}_{-0.96}$	$1.42^{+0.24}_{-0.19}$	$0.97^{+0.01}_{-0.01}$	$50.03^{+20.84}_{-23.43}$	$9.95^{+4.61}_{-5.27}$	-4.38

- Density ranges between 48-600 cm^{-3}.
- X-ray densities range between 0.01-10 cm^{-3}.
- This discrepancy may be due to the presence of cold clumps of material that do not emit in thermal X-rays.

Particle Energy

Source	W_p $\times10^{49}$ ergs	W_{eBrem} $\times10^{47}$ ergs	W_{eIC} $\times10^{46}$ ergs	W_e $\times10^{47}$ ergs	W_{ep} $\times10^{49}$ ergs
W28	$1.16^{+0.16}_{-0.33}$	$1.8^{+2.68}_{-1.28}$	$7.63^{+7.64}_{-4.17}$	$2.56^{+3.44}_{-1.69}$	$1.18^{+0.19}_{-0.34}$
W44	$4.2^{+0.50}_{-0.54}$	$0.21^{+0.01}_{-0.008}$	$2.14^{+0.95}_{-0.81}$	$0.43^{+0.19}_{-0.16}$	$4.2^{+0.50}_{-0.54}$
IC443	$0.17^{+0.01}_{-0.01}$	$0.011^{+0.002}_{-0.002}$	$0.11^{+0.02}_{-0.02}$	$0.023^{+0.004}_{-0.005}$	$0.17^{+0.01}_{-0.01}$
W51C	$1.33^{+0.26}_{-0.18}$	$0.05^{+0.03}_{-0.01}$	$0.47^{+0.14}_{-0.14}$	$0.09^{+0.03}_{-0.03}$	$1.33^{+0.26}_{-0.18}$
W49B	$29.37^{+9.97}_{-5.53}$	$9.22^{+25.8}_{-6.40}$	$73.35^{+121.96}_{-45.98}$	$16.56^{+38.00}_{-11.00}$	$29.54^{+10.35}_{-5.64}$
G298.6-0.0	$15.7^{+5.16}_{-3.52}$	$4.55^{+32.16}_{-3.74}$	$30.58^{+108.25}_{-23.39}$	$7.61^{+32.99}_{-6.08}$	$15.78^{+5.59}_{-3.58}$
Kesteven 77	$3.48^{+1.47}_{-1.25}$	$34.25^{+32.05}_{-23.55}$	$99.59^{+84.24}_{-60.91}$	$44.21^{+40.47}_{-29.64}$	$3.92^{+1.88}_{-1.55}$
W30	$1.35^{+1.33}_{-0.56}$	$0.82^{+4.38}_{-0.73}$	$5.62^{+18.80}_{-4.80}$	$1.38^{+36.25}_{-1.21}$	$1.36^{+1.39}_{-0.58}$
Kesteven 17	$10.68^{+6.54}_{-10.68}$	$3.18^{+105.18}_{-3.18}$	$21.44^{+205.05}_{-21.44}$	$5.32^{+125.68}_{-5.32}$	$10.73^{+7.80}_{-10.73}$
G357.7-0.1	$7.57^{+6.66}_{-7.57}$	$0.49^{+30.87}_{-0.49}$	$3.86^{+74.51}_{-3.86}$	$0.87^{+38.32}_{-0.87}$	$7.58^{+7.04}_{-7.58}$

- Average total particle energy is 8×10^{49} erg.
- ~8% of a the 10^{51} erg released by a supernova goes into accelerating particles.

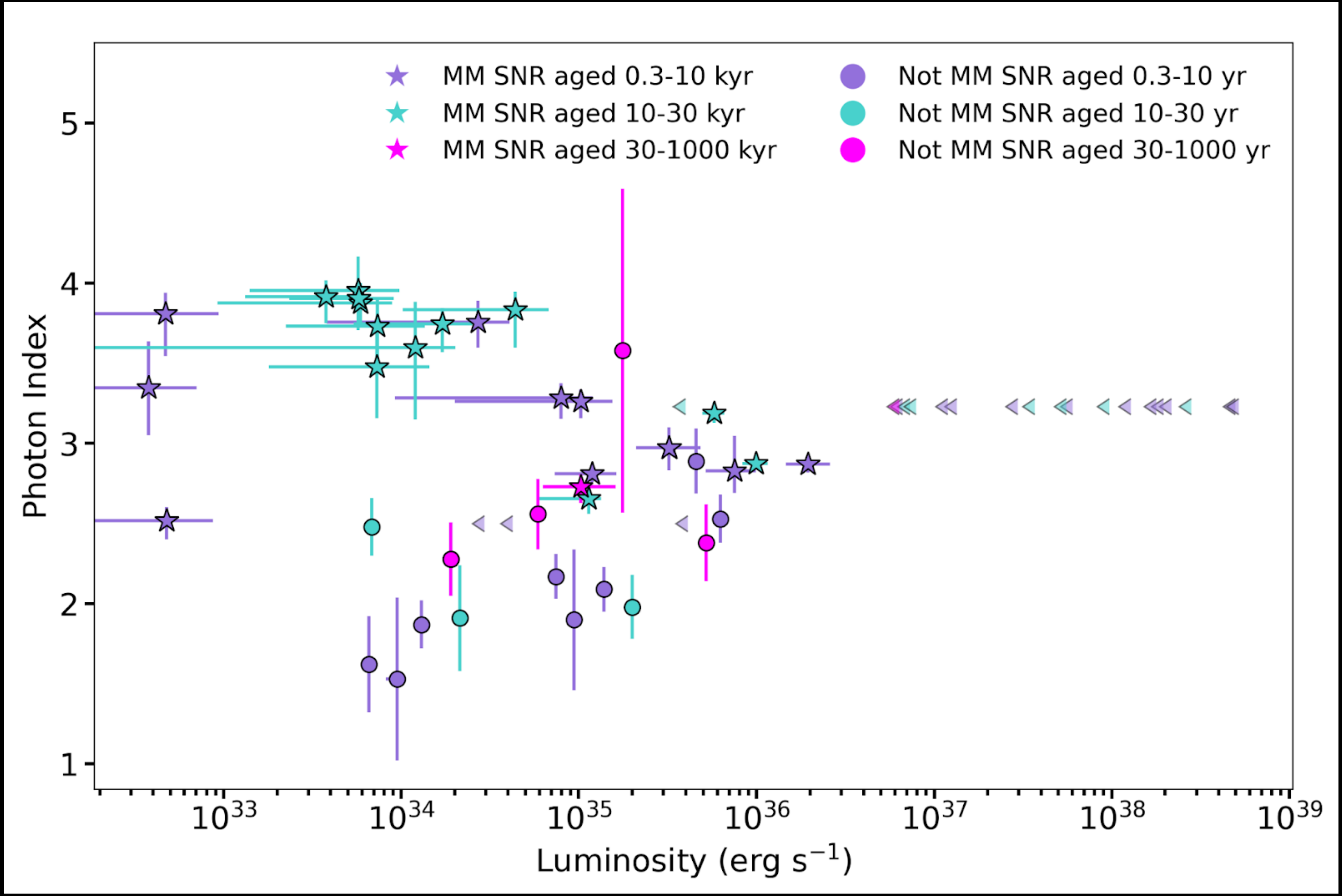
Summary

- MM SNRs are extremely bright GeV gamma-ray emitters.
- Their dense environment leads to significantly impact the gamma-ray emission from SNRs.
- Potentially only MM SNRs from core-collapse supernovae are detected in gamma-rays.
- MM SNRs have a narrow age range and their average detected age is much higher than non-MM SNRs.
- Neutral pion decay dominates the gamma-ray emission.
- ~8% of a supernova's explosion energy goes into particle acceleration.
- Gamma-ray densities are much higher than those derived using X-rays.

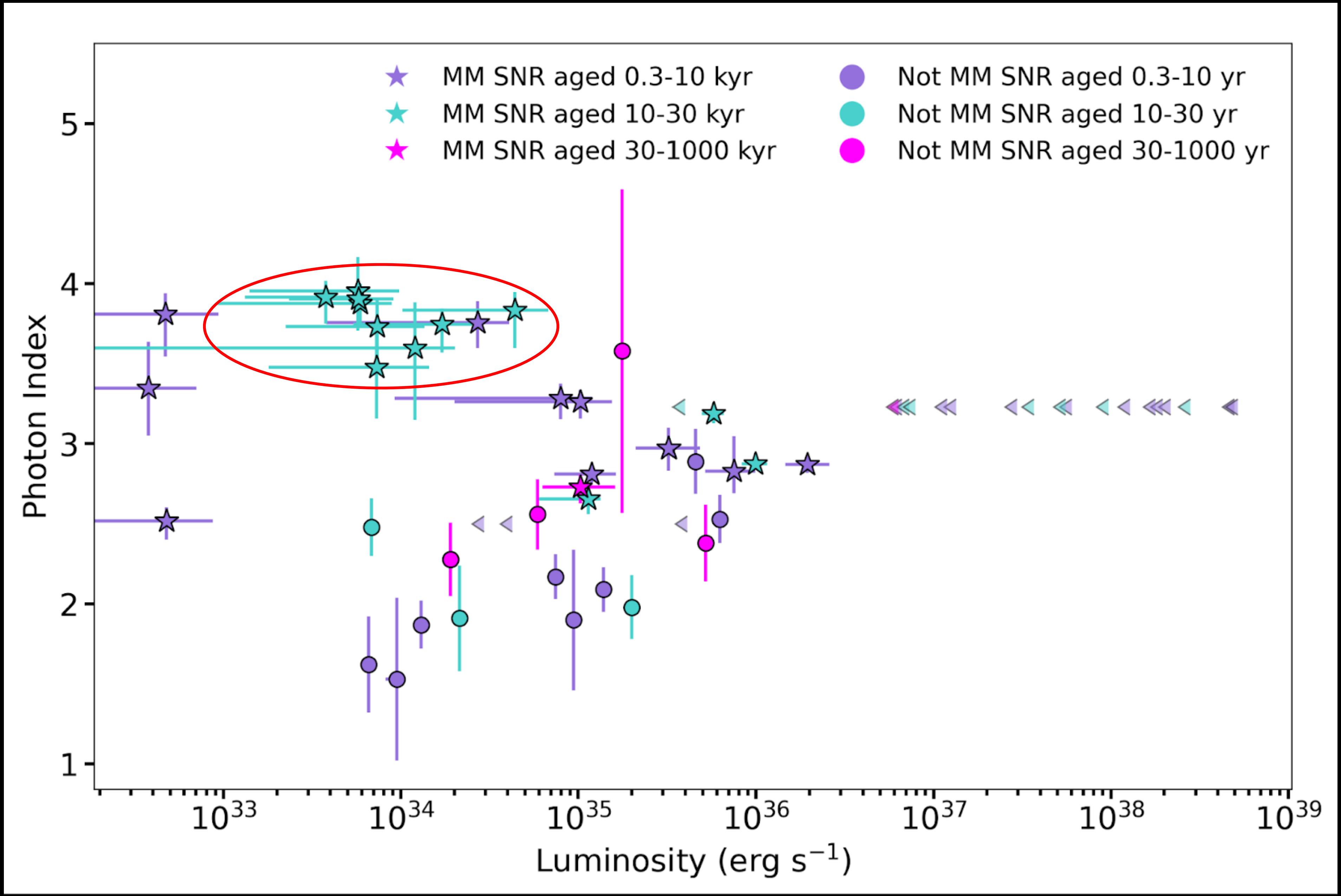
Future Work with CTA

- CTA will be able to provide a resolution of $\sim$ few arcmin over an energy range $\sim 10 - 10^5$ GeV
- Obtain higher resolution data of these MM SNRs compared to Fermi-LAT.
- By using data from both CTA and Fermi-LAT a broader energy range of gamma-ray emission can be analysed.

Results - Age


MM SNR aged 0.3-10 kyr
MM SNR aged 10-30 kyr
MM SNR aged 30-1000 kyr
Not MM SNR aged 0.3-10 yr
Not MM SNR aged 10-30 yr
Not MM SNR aged 30-1000 yr
Photon Index
5
4
3
2
1
10^{33}
10^{34}
10^{35}
10^{36}
10^{37}
10^{38}
10^{39}
Luminosity (erg s^{-1})

Results - Age



MM SNR aged 0.3-10 kyr
MM SNR aged 10-30 kyr
MM SNR aged 30-1000 kyr
Not MM SNR aged 0.3-10 yr
Not MM SNR aged 10-30 yr
Not MM SNR aged 30-1000 yr
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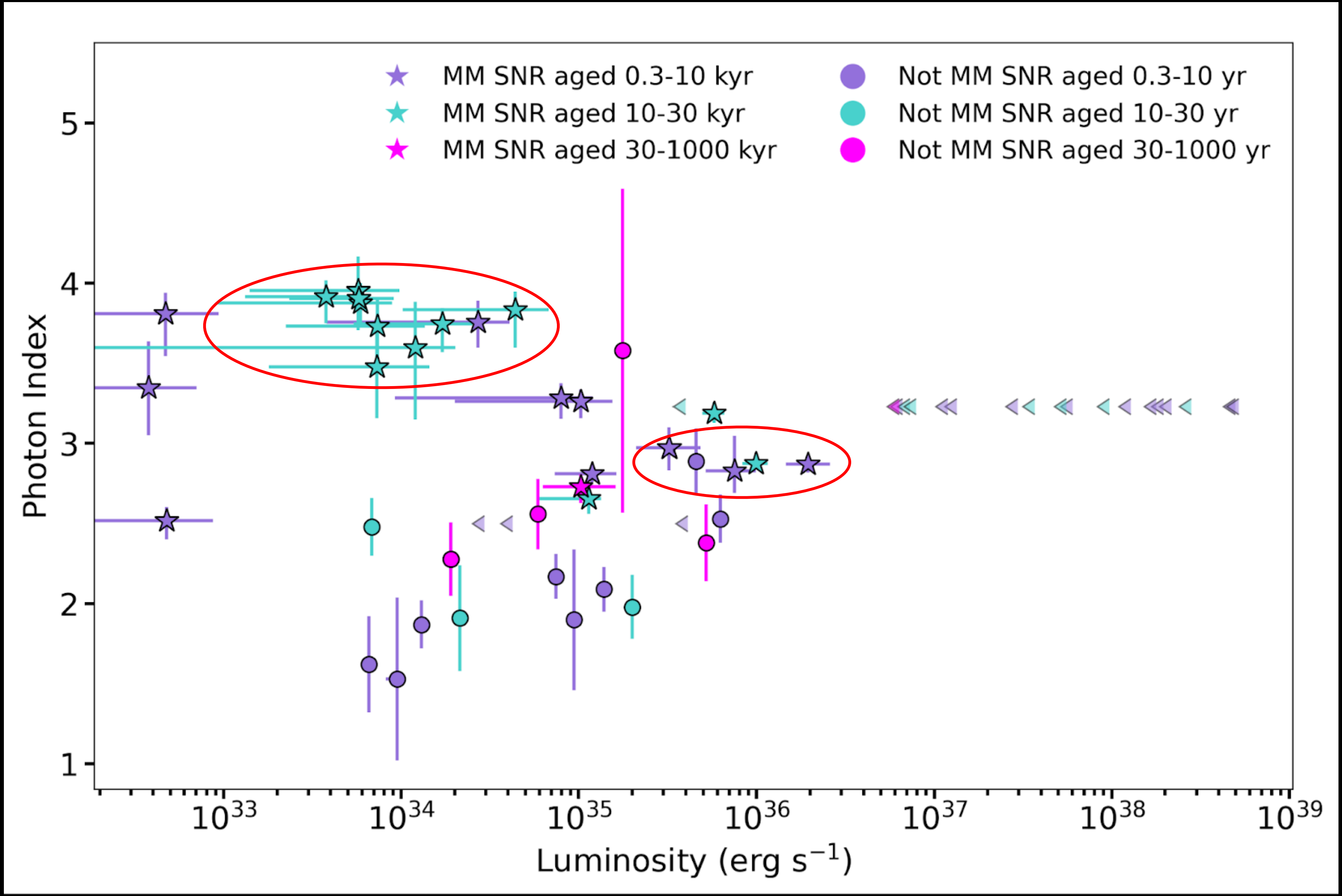
10^{37}
10^{38}
10^{39}
Luminosity (erg s^{-1})

Results - Age



MM SNR aged 0.3-10 kyr
MM SNR aged 10-30 kyr
MM SNR aged 30-1000 kyr
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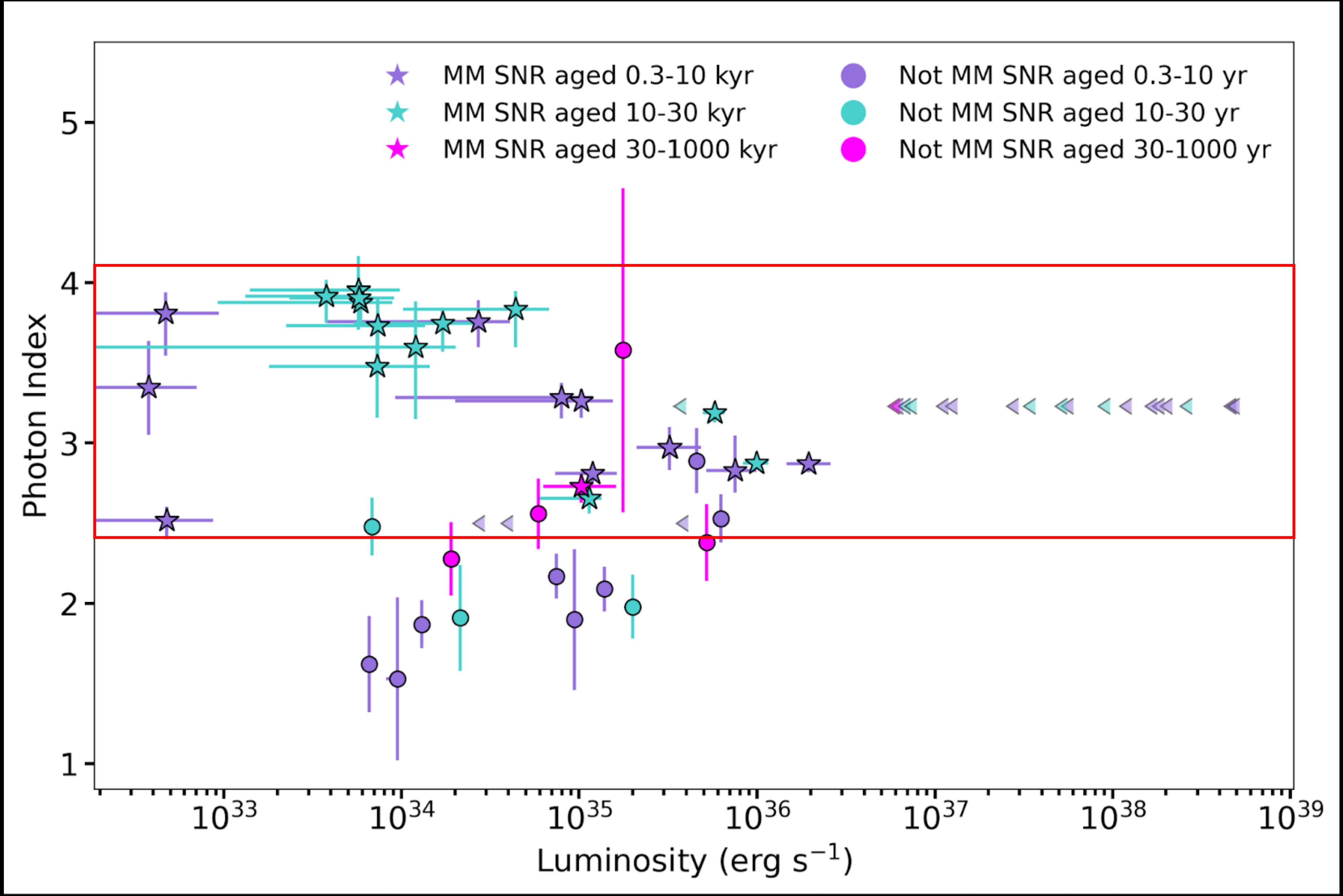
10^{36}
10^{37}
10^{38}
10^{39}

Results - Age



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MM SNR aged 10-30 kyr
MM SNR aged 30-1000 kyr
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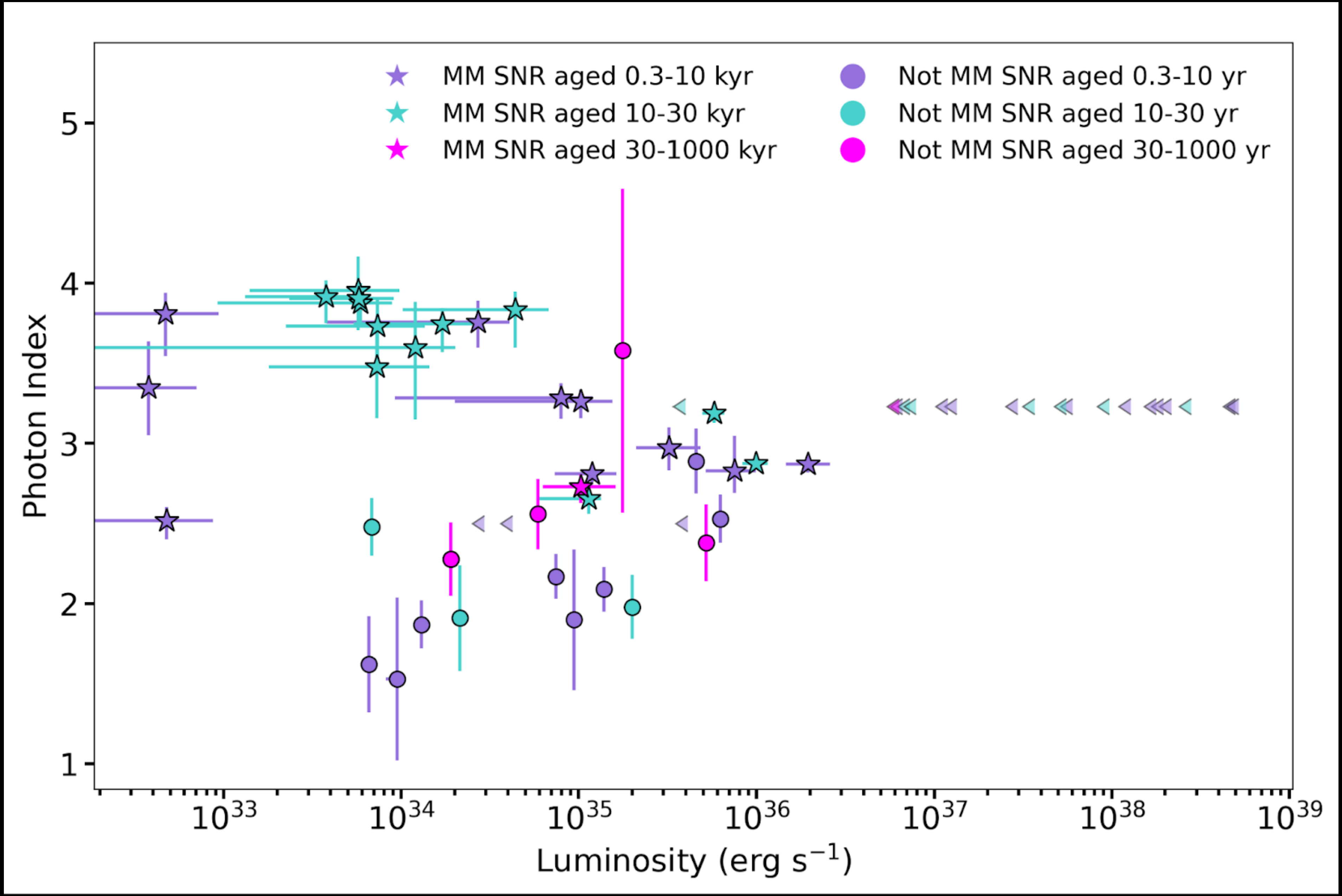
10^{38}
10^{39}
Luminosity (erg s^{-1})

Results - Age



MM SNR aged 0.3-10 kyr
MM SNR aged 10-30 kyr
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Luminosity (erg s^{-1})