Multi-wavelength Modeling of the Pulsar Wind Nebula in Kes 75

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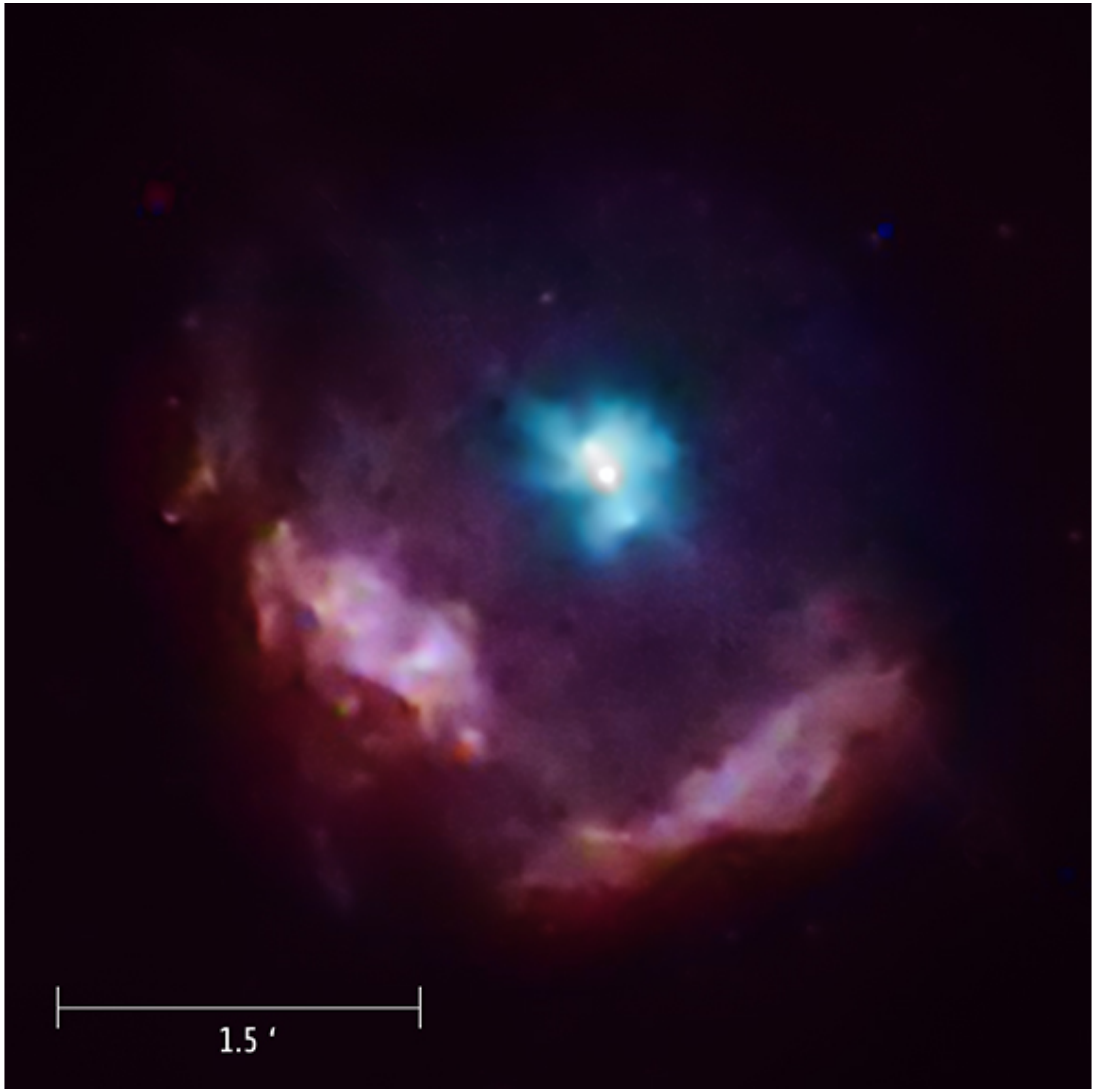
Outline

- Why is Kes 75 interesting?
- PWN Modelling
- Modelling Results and Key Findings
  - Progenitor Star
  - Implications of including Fermi-LAT data
- Summary and Conclusions

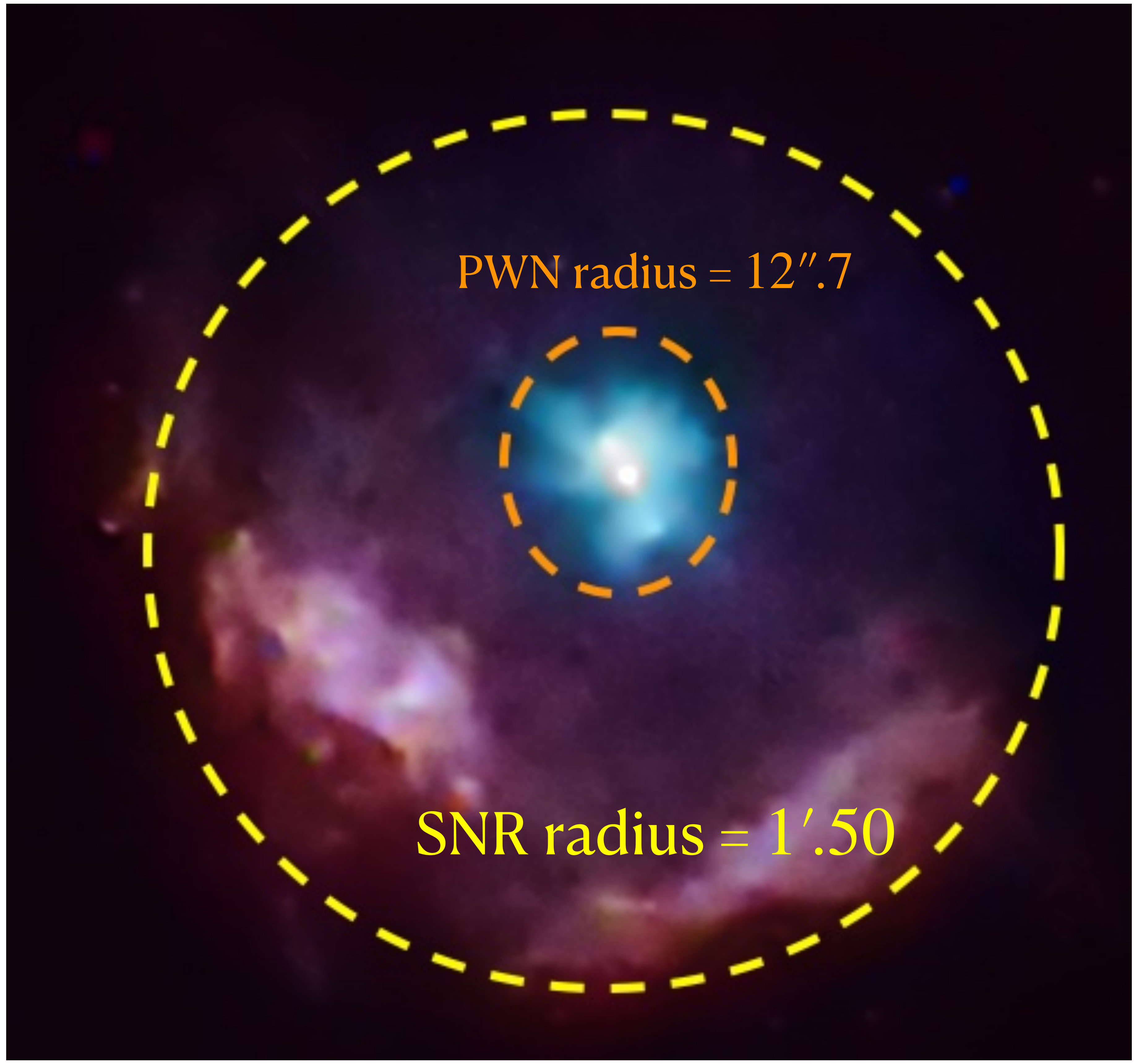


Chandra X-ray image of Kes 75. Credits: NASA/CXC/GSFC

Why is Kes 75 interesting?

- Powered by an X-ray RPP (PSR J1846-0258) which is :
    - Strong magnetic field ($B_{sd} \sim 5 \times 10^{13}$ G)
    - Energetic (High $\dot{E} \sim 8.1 \times 10^{36}$ ergs s^{-1})
    - Young (very low $\tau_c \sim$ 700 years)

What type of SN & Star should be the parent of such a NS ?



Credits: NASA/CXC/GSFC

- 2006 Magnetar-like Outburst accompanied with:
    - X-ray flux increase
    - Braking index change from $p = 2.65 \pm 0.01$ to $p = 2.16 \pm 0.13$

→ **Is this NS different from other RPPs or just an extreme example of one?**

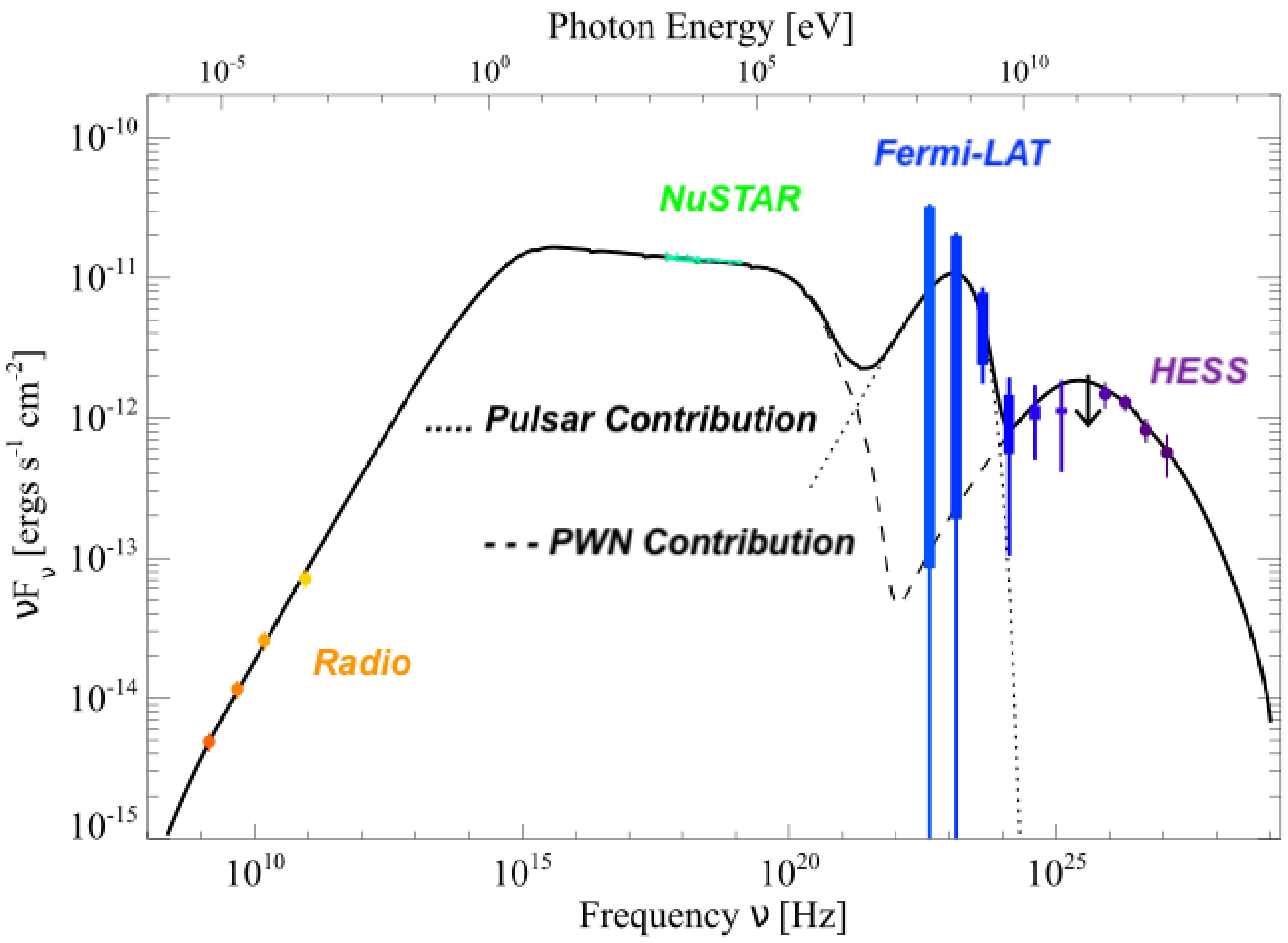
- Showed another outburst activity in 2021

PWN Modelling:

- One zone evolutionary model of a PWN inside an SNR based on Gelfand et al. 2009
- Uses MCMC algorithm, along with current (measured) $\dot{E}$, τ_c and p, to reproduce the observed dynamical (Distance to, and angular size of SNR, angular size and expansion rate of the PWN) & spectral (radio through γ-ray) properties of the source

Fermi-LAT Analysis (Straal+ 2023):

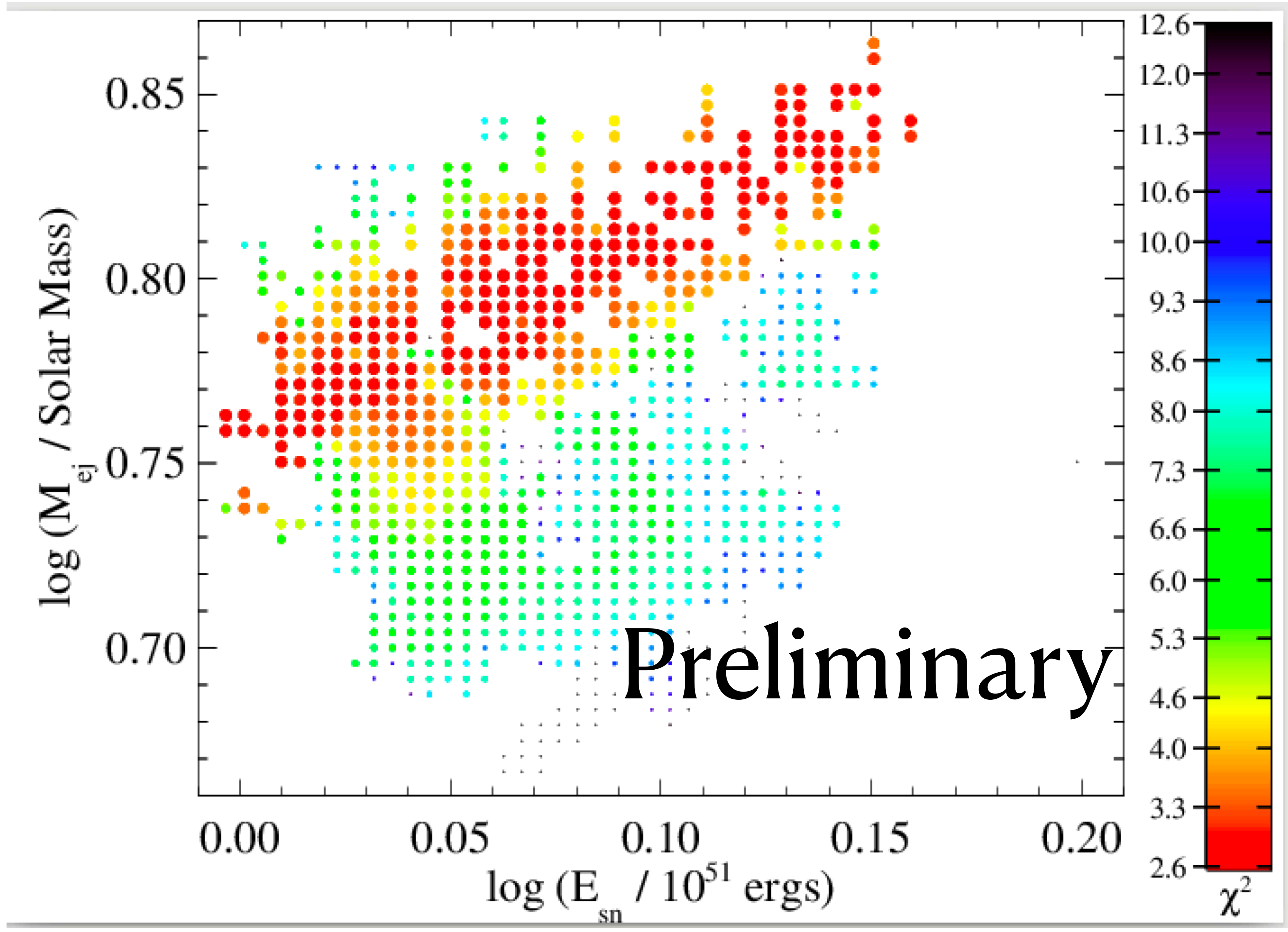
- Detected γ-ray emission from the pulsar and PWN
- Fermi-LAT spectrum is modeled as a combination of PWN emission + Power law with Exponential Cut-off from the pulsar magnetosphere



Broadband SED of PWN Kes 75. The best model fit that reproduces the spectral and dynamical properties of the system is the black solid line.

Modelling Results & Key Findings:

What type of SN & Star should be the parent of such a NS?



- Explore the parameter space & degeneracy between E_{SN} & M_{ej} to constrain the progenitor star properties
  - M_{ej} ~ (5.5 - 7.0) $M_{\odot}$ → $M_{@Explosion}$ ~ (7.0 - 8.5) $M_{\odot}$

Low Mass Progenitor ($\sim$ 8.0 - 10.0) $M_{\odot}$ that didn't have a lot of mass before exploding

High Mass Progenitor ($\gtrsim$ 30.0 $M_{\odot}$) that lost a lot of material before blowing up

- Recent SN simulations (Sukhold et al 2016) suggest:
  - Low mass progenitor case: E_{SN} ~ 10^{50} ergs
  - High mass progenitor case: E_{SN} ~ 10^{51} ergs

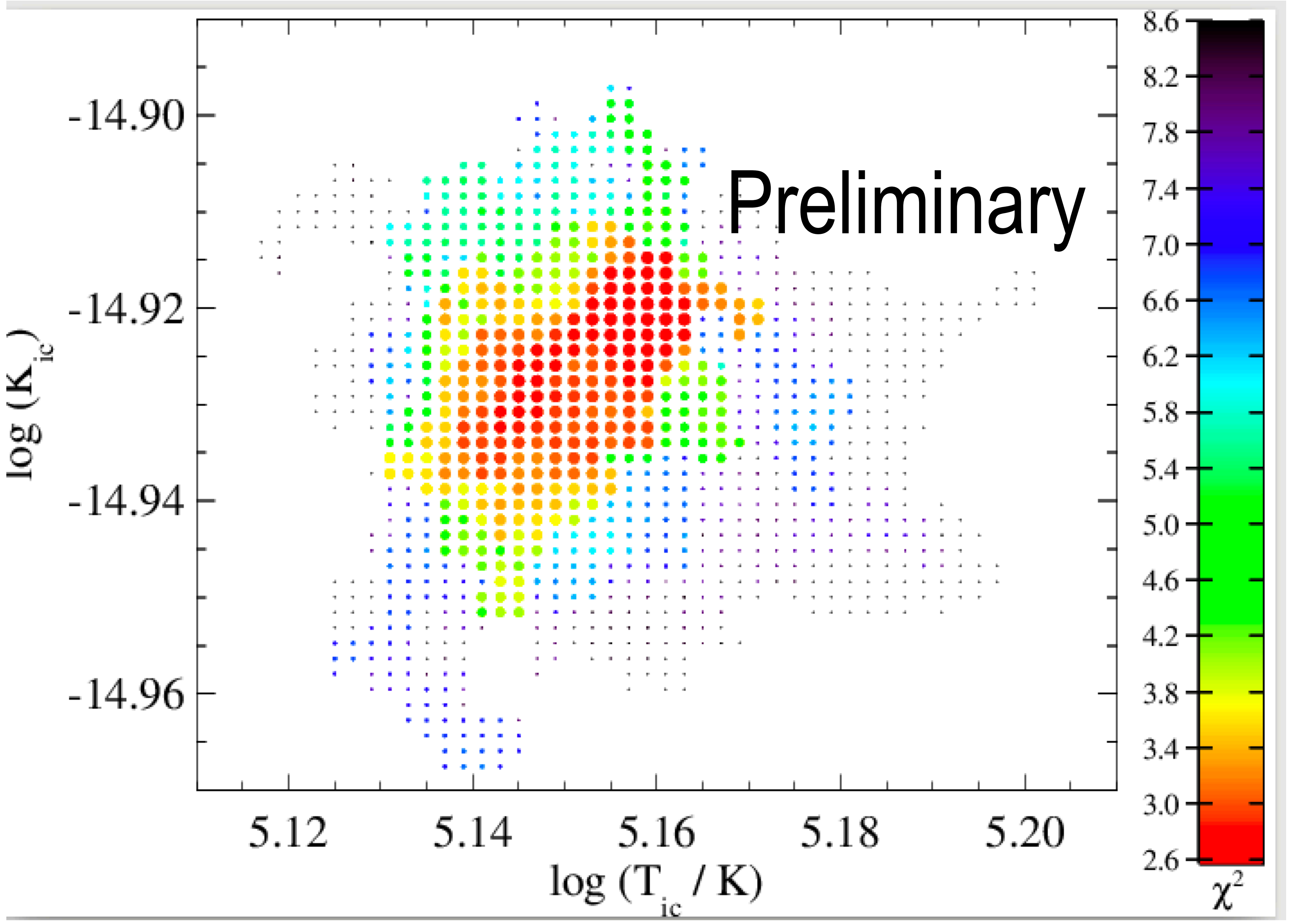
Since we get E_{SN} ~ $(1 - 1.4) \times 10^{51}$ ergs, our results favor **the high mass progenitor scenario**

Modelling Results & Key Findings:

Implications of Incorporating Fermi-LAT Data

- Hot & intense 2^{nd} photon field is required to fit the Fermi-LAT data
  - $T_{ic,2}$ ~ 1.5×10^5 k
  - $u_{ic,2}$ ~ 3.4 keV cm^{-3}

→ **Orders of magnitudes larger than local interstellar radiation**



What is the possible source of that field?

- Since our results favor a massive progenitor, other massive stars are likely to exist nearby
- The stellar properties of the 2^{nd} photon field translate to that of a Wolf-Rayet Star
- If present, the WR star was then likely the binary companion of the progenitor of PWN Kes 75

Search for the WR candidate

- To identify the WR candidate, we analyzed the source population within 1′ of Kes 75 using their Near Infrared Magnitude values obtained from UKIDSS Galactic Plane Survey

- We identified the WR candidate by:
  1. Their unusual IR colors
  2. Lack of counterparts in less sensitive surveys (due to high extinction towards kes 75)

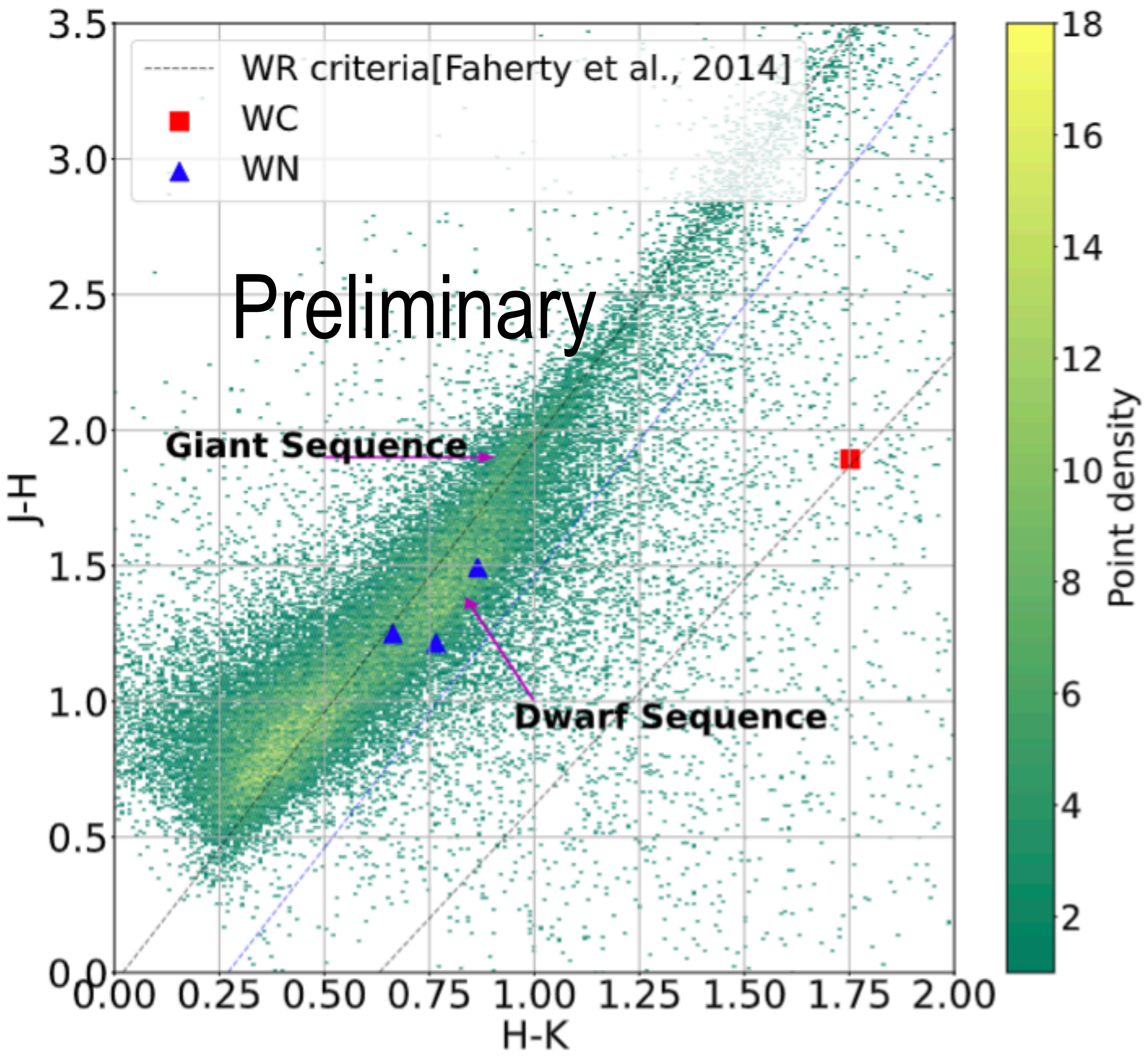


Figure 6. The Placement of Final WR candidates on Color-Magnitude Diagram and two-color diagrams presented in Lucas et al., 2008

Results:

- Found one candidate (WC star) with ~ 90% confidence since searches in other random locations yield 10%

Summary & Conclusions

- Analysis of Fermi-LAT data detected γ-ray emission from the pulsar and PWN in the Kes 75 region
- Incorporating the Fermi-LAT data in modeling the broadband SED necessitates the presence of a hot & intense photon field, suggesting the presence of a WR star
- Search for the WR star yields one WC candidate with 90% confidence
- Exploring the $E_{SN} - M_{ej}$ parameter space favors $E_{SN} \sim (1 - 1.4) \times 10^{51}$ & M_{ej} ~ (5.5 - 7.2) $M_{\odot}$, suggesting kes 75 had a massive progenitor

Thank You

Straal et al. 2023

Back up Slides

PWN Modelling

Model Parameters/Input:

- SN properties: E_{SN}, M_{ej} & n_{ism}
- Pulsar Wind Properties: E_{min}, E_{max} & fraction of energy deposited in magnetic/particle energy
- Pulsar properties: τ_{sd}, t_{age}, P_0, $\dot{E}_0$, magnetospheric γ-ray emission

4.1.2. Comparison to 2PC

To determine whether the magnetospheric γ-ray emission of J1846−0258 is comparable to that of RPPs not associated with magnetar-like activities, we compare the pulsar properties obtained from our modeling to that of other young, energetic RPPs as compiled in the second Fermi pulsar catalog (2PC; Abdo et al. 2013).[10] The properties we obtain for the pulsar and compare to the pulsars in Abdo et al. (2013) are given in Table 2. In Abdo et al. (2013), Figures 7–10 describe pulsar properties from the detected sample to which we can compare our obtained properties. The magnetic field at the light cylinder is taken from the ATNF catalog ($B_{\rm LC} = 1.31 \times 10^4$ G; Manchester et al. 2005), and the gamma-ray luminosity in the 0.1–100 GeV range derived in this work is given in Table 2.

The gamma-ray efficiency η_γ of 0.97% is typical for gamma-ray pulsars with similar spin-down energy. Its gamma-ray luminosity ($L_\gamma \approx 7.86 \times 10^{34}$ erg s^{-1}) seems to be on the lower end and more in line with $L_\gamma \propto \dot{E}^{\frac{1}{2}}$ than a linear relation, consistent with the findings in 2PC on gamma-ray pulsars. The obtained photon index of $\Gamma = 1.29$ seems to be harder than most other pulsars of similar spin-down energy, but within the range of values observed in this sample. The cutoff energy of the spectrum of $\sim$1 GeV compared to its magnetic field at the light cylinder is observed to be similar to other pulsars in the $B_{\rm LC} \sim 10^4$ G region.

The obtained pulsar properties agree well with what is obtained for the larger sample of gamma-ray-emitting pulsars, supporting the assumption that this additional component originates in the pulsar's magnetosphere, and suggesting that the underlying physical emission mechanism is similar to that observed from RPPs.

WR Stars

- WR stars are massive ($>$ 25 solar masses) and hot (T ~ 20,000 - 210,000 K)
- They are highly luminous due to their high temperature
- Divided into 3 sub-classes:
  - **WC:** Carbon dominant, no nitrogen
  - **WN:** Nitrogen dominant, no carbon
  - **WO:** $C/O < 1$
- It's estimated that 50% occur in binary systems where the companion is another WR star or a compact object such as NS/BH

Conversion of Photon Field

2. CALCULATION OF STELLAR PROPERTIES FROM IC PHOTON FIELD

2.1. *Conversion of Photon Field properties*

In this work, we repeated the calculations from Straal et al., 2023 using an updated modeling of the PWN (Abdelmaguid et al., in prep.) to enhance precision and constrain uncertainties, also accounting for the off center and farther back located possibility of the WR star inside the PWN. To convert the photon field values we get from modeling into properties associated with a specific source of photons, we start calculating the energy density of the IC photons as

$$u = KaT^4 \tag{1}$$

, where K is the normalization and T the temperature of the field assuming the photon field as originating from a single object whose emission could be characterized by a Black Body. The total photon energy contributed by the source within the PWN was determined as

$$E = \frac{4}{3}\pi(R_{PWN})^3 \cdot u \tag{2}$$

, considered as a sphere with the radius $R_{PWN} = \theta \cdot d_{PWN}$. The energy injection rate (L) was then computed as

$$L = \frac{E}{t} \tag{3}$$

, where t is the time a photon emitted by the source stays within the PWN and

$$t = \frac{R_{PWN}}{c} \tag{4}$$

, assuming the source of interest is positioned at the center of the PWN. This assumption reflects the faintest possible magnitude of the source, and we calculated the source radius as

$$R = \sqrt{\frac{L}{4\pi\sigma T^4}} \tag{5}$$

Search for the WR candidate

To identify the WR candidate, we analyzed the source population within $1'$ of Kes 75 using their Near Infrared Magnitude values obtained from UKIDSS Galactic Plane Survey

Filtering Criteria

1. Distinguishing WR candidates from Background population based on Near-Infrared (NIR) color
2. Selecting candidates with the Correct apparent Magnitudes
3. Testing if chosen candidates are located at the distance of Kes 75 by confirming the lack of counterparts in less sensitive surveys (N_H is high towards Kes 75)
4. Distinguishing between WR stars and red giants

Results:

1. One final candidate (WC star) and 3 WN stars match the criteria (They are located within the PWN radius)
2. The WN sources lie on the contaminated Dwarf sequence identified, so we don't consider them as possible candidates

False Probability Test

1. We searched for a WR candidate at 170 random locations within 1° from kes 75
2. Results: ~ 90% of the time, the search returns fewer candidates than the number obtained from the kes 75 region

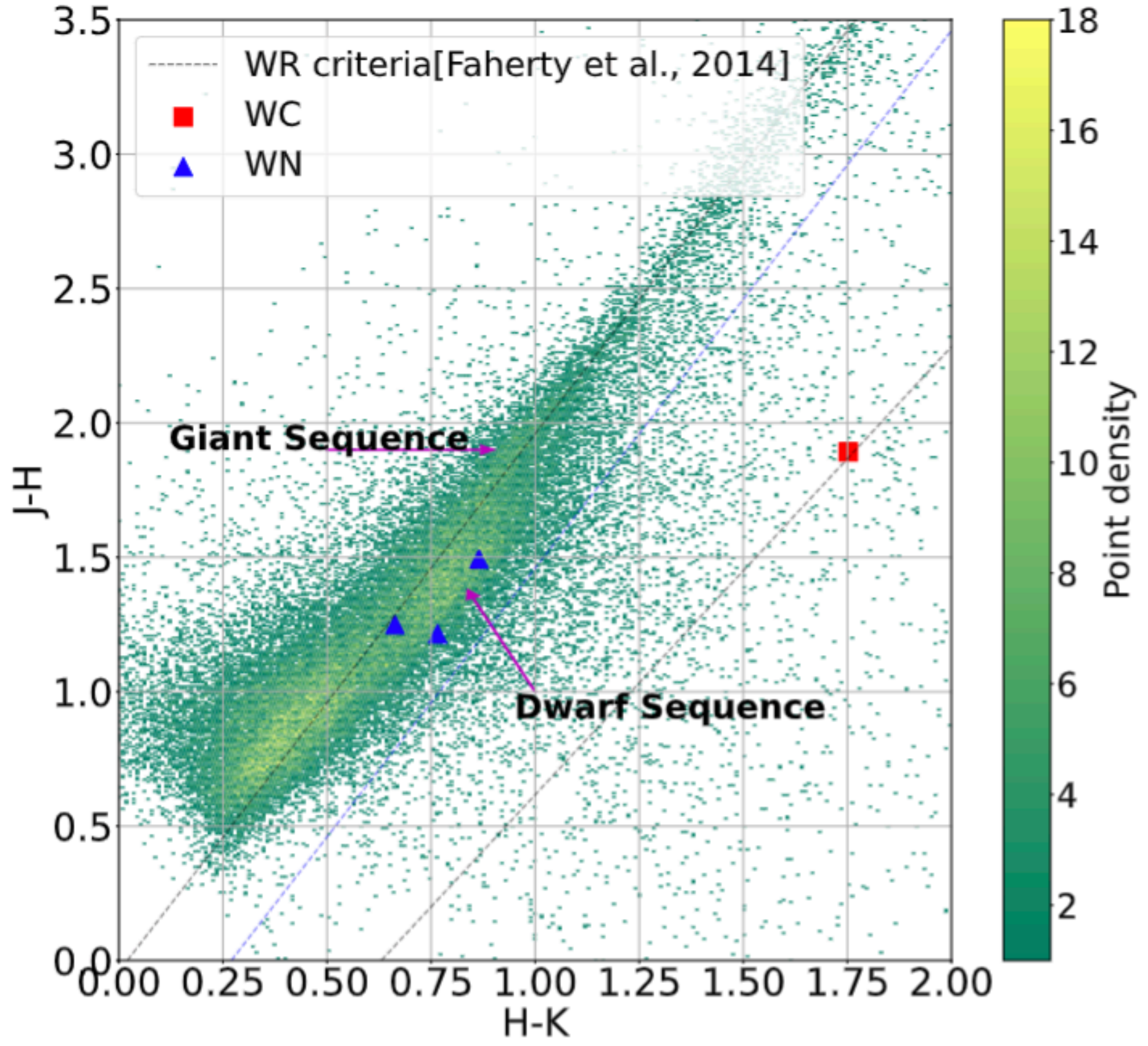


Figure 6. The Placement of Final WR candidates on Color-Magnitude Diagram and two-color diagrams presented in Lucas et al., 2008

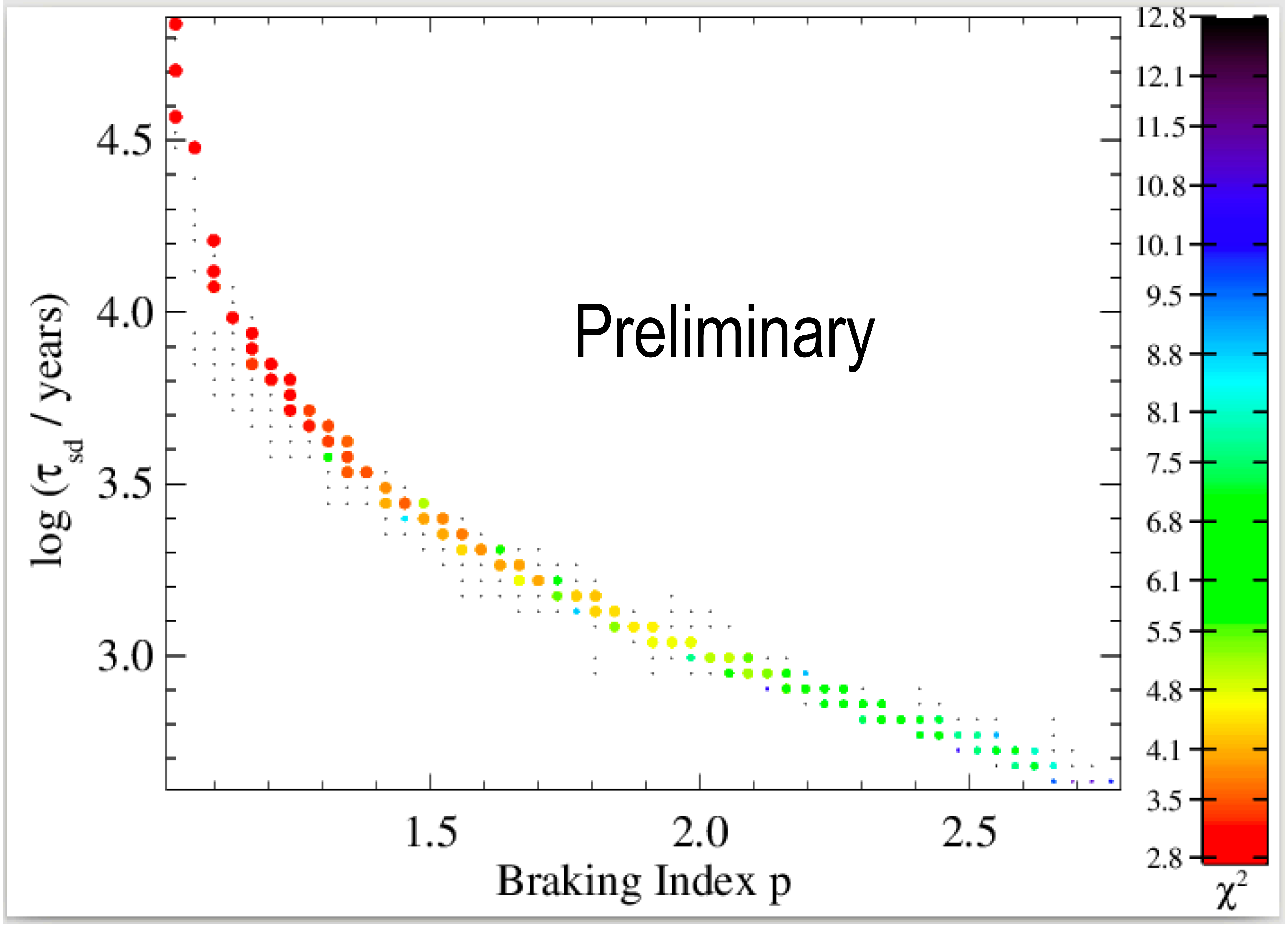
Modelling Results & Key Findings:

Braking Index & Spin-down Timescale Degeneracy

- Pre-outburst value: 2.65
- Post-outburst value: 2.11
- Current value of the braking index is uncertain
- Model favors low values of braking indices (p ~ 1 - 1.3)

$$t_{age} = \frac{2t_{ch}}{p-1} - \tau_{sd} \quad (1)$$

$$\dot{E}_0 = \dot{E}\left(1 + \frac{t_{\rm age}}{\tau_{\rm sd}}\right)^{+\frac{p+1}{p-1}} \quad (2)$$



Suggests the pre-2006 outburst was a transient state, but we need to measure the current p value

Full model parameters

Derived Properties of PWN Kes 75 from Modeling of This Source

Property	Derived in Gotthelf et al. (2021)	Derived in this work
Supernova explosion energy E_{sn}	0.126×10^{51} erg	0.11×10^{51} erg
Supernova ejecta mass M_{ej}	0.51 $M_{\odot}$	0.37 $M_{\odot}$
ISM density n_{ism}	0.56 cm^{-3}	0.63 cm^{-3}
Wind magnetization η_B	0.0724	0.115
Minimum energy of injected leptons E_{min}	2.0 GeV	1.9 GeV
Break energy of injected leptons E_{break}	2.042 TeV	1.92 TeV
Maximum energy of injected leptons E_{max}	1.00 PeV	1.11 PeV
Low-energy particle index p_1	1.73	1.17
High-energy particle index p_2	3.04	3.05
Temperature of external photon field 1 T_{ic}	32 K	32 K
Normalization of external photon field 1 K_{ic}	1.17×10^{-3}	2.88×10^{-3}
Temperature of external photon field 2 T_{ic}[a]	…	1.46×10^{5} K
Normalization of external photon field 2K_{ic}[a]	…	1.40×10^{-15}
Pulsar		
Pulsar spin-down timescale τ_{sd}	398 yr	432 yr
Pulsar initial spin-down luminosity $\dot{E}_0$	4.69×10^{37} erg s^{-1}	3.9×10^{37} erg s^{-1}
Pulsar initial spin period P_0	≈200 ms	≈268 ms
Pulsar photon index (γ-rays)[a]	…	1.29
Pulsar cutoff energy E_{cut}[a]	…	~1 GeV
Gamma-ray efficiency $\eta = L_{\gamma}/\dot{E}$[a]	…	0.97%
Gamma-ray luminosity L_{γ} (0.1–100 GeV)	…	7.86×10^{34} erg s^{-1}
χ^2/degrees of freedom	…	2.4/4

Notes. The free parameters in the physical models used to reproduce the observed properties of PWN Kes 75 are listed in Table 1. The reported values are the combination that had the highest likelihood $\mathcal{L}$, which corresponds to the given χ^2.
[a] Parameters not modeled in Gotthelf et al. (2021).

Neutron Stars

- Neutron stars are formed in CCSe & can be manifested observationally as:
  - **RPPs:** Powered by loss of rotational energy (Vast majority)
  - **Magnetars:** Powered by decay of their ultra strong B_{field}
  - **CCOs:** Thermal emission from a low magnetic field source

Pulsar Wind Nebulae:

- The rotational energy of the NS power a highly relativistic $e^{\pm}$ wind
- Interaction of $e^{\pm}$ wind with the surrounding environment creates a PWN
- Emission Mechanism:
  - Relativistic particles + B_{field} ➡ Synchrotron Emission (Radio through X-rays)
  - Relativistic particles + lower energy photon fields ➡ ICS (γ-rays)

Multi-Wavelength Data Analysis & Modeling:

- γ-rays:
  - HESS: HESS Collaboration
  - **Fermi-LAT : Samayra Straal (Our Group)**
- X-rays:
  - **XMM-Newton and NuSTAR analysis by our collaborator Eric Gotthelf**
- Radio:
  - 3 radio points (1.4, 4.7 & 15 GHz) by Salter et al 1989
  - 1 radio point (89 GHz) by Bock & Gaensler 2011

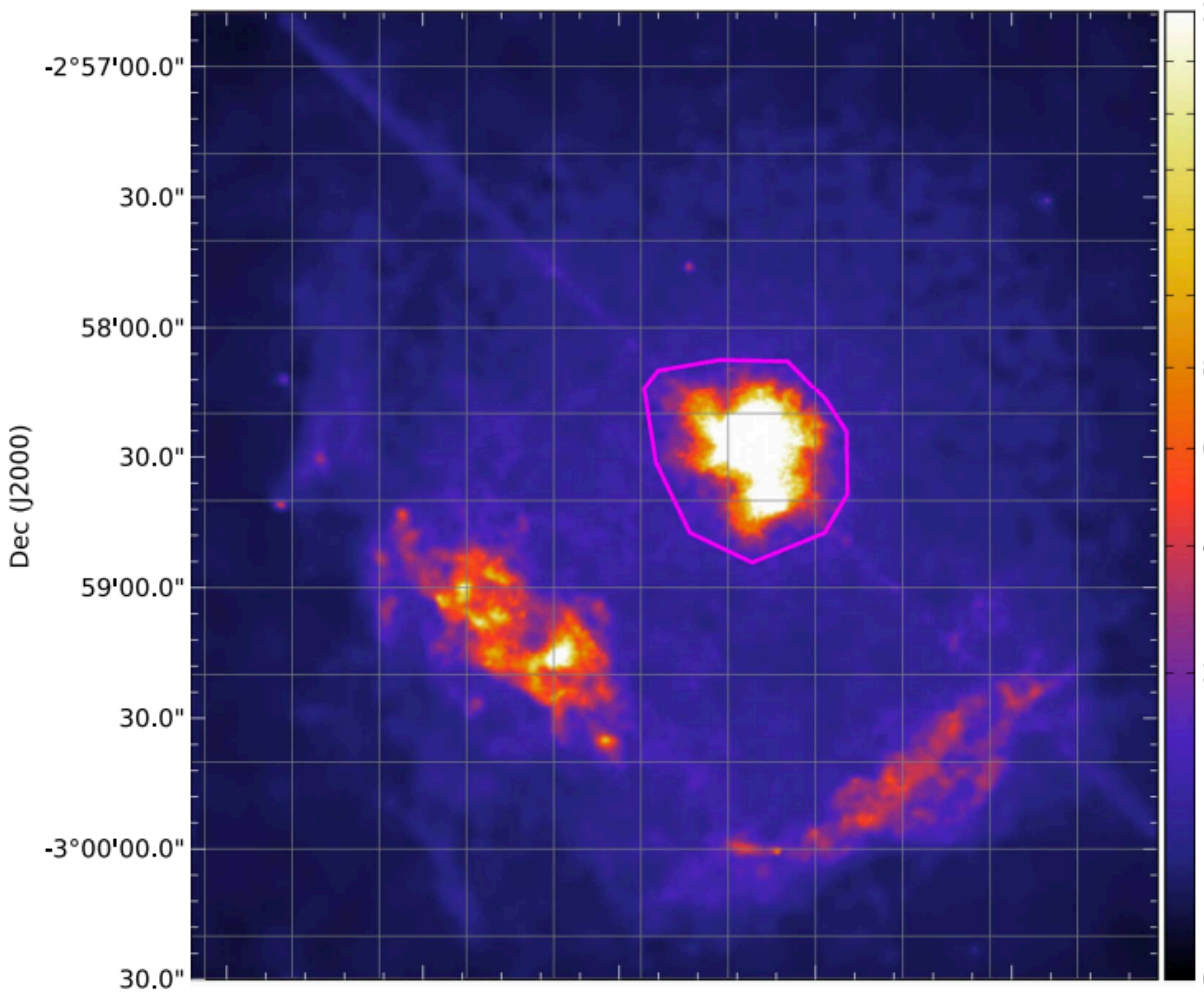


Figure 2: X-ray image of Kes 75 (circled) in the 0.7–8 keV energy range from 2006. Adopted from Reynolds et al. 201