What do Pulsar Wind Nebulae tell us about Supernovae?

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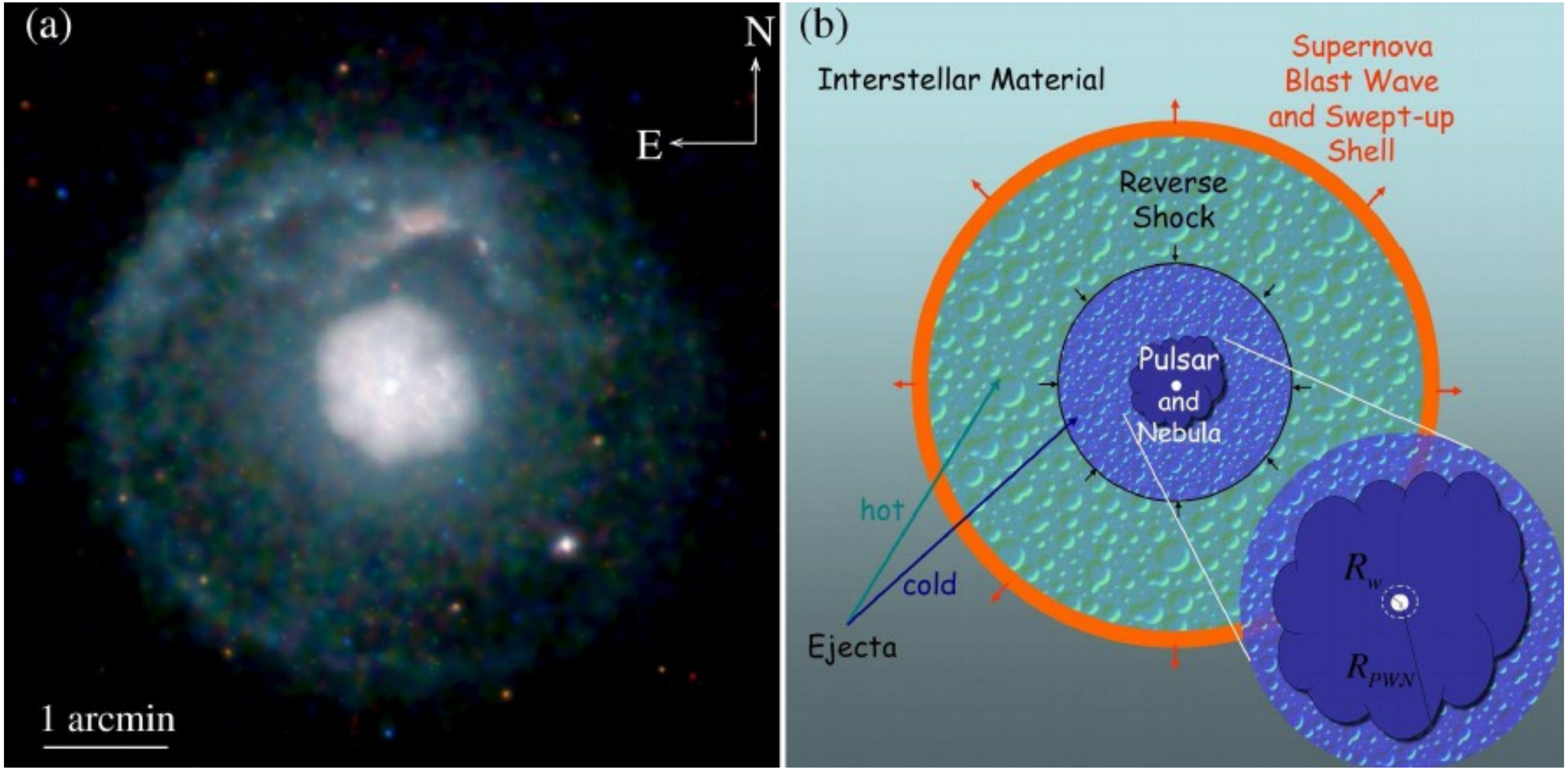
What are Pulsar Wind Nebulae?

- Majority of CC-SNe create a neutron star (NS)
- Rotational energy of these energetic NSs power a highly relativistic $e^{\pm}$ wind
- Interaction of pulsar 'wind' and environment form the pulsar wind nebula (PWN)
- PWN properties depend on NS birth properties and SN explosion characteristics

c. NASA/CXC/SAO

Evolution of a PWN inside a SNR



Gaensler & Slane 2006

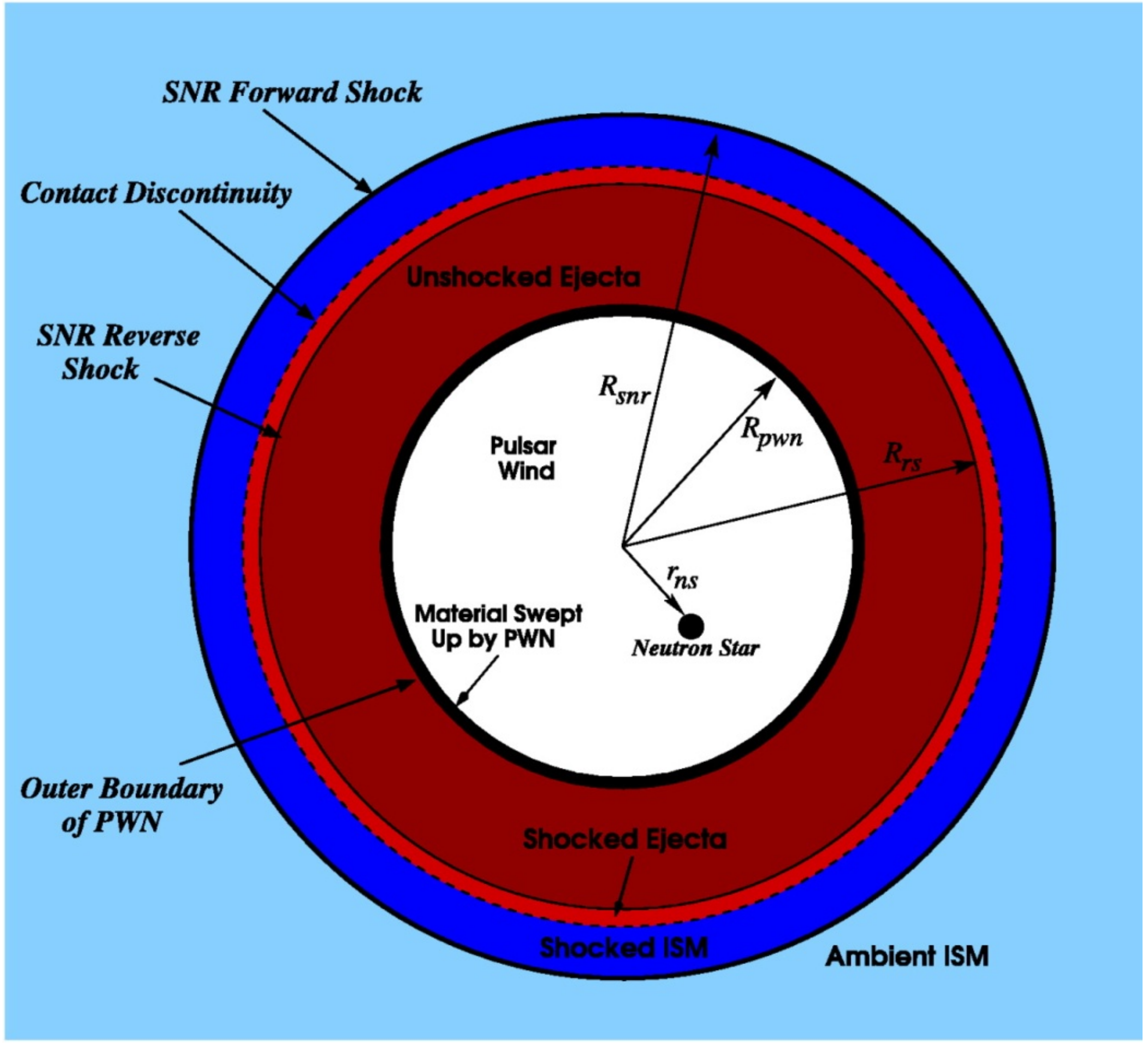
Open questions that PWNe can help with:

- What are the properties of core-collapse supernovae? (e.g. kinetic energy, ejecta mass)
- Which progenitor star produces which type of SN?
- How are neutron stars (NS) formed in SN explosions and what are their properties?
  - Depend on fall-back accretion onto PNS, cooling of PNS, GW emission…
- How are particles accelerated up to PeV energies in the PWN?

Modelling a PWN inside a SNR

- One-zone model that describes dynamic and radiative evolution (Gelfand+2009)
- Dynamic evolution depends on:
  - Initial kinetic energy
  - Mass of SN ejecta
  - Surrounding medium
  - Pulsar energy input (history)

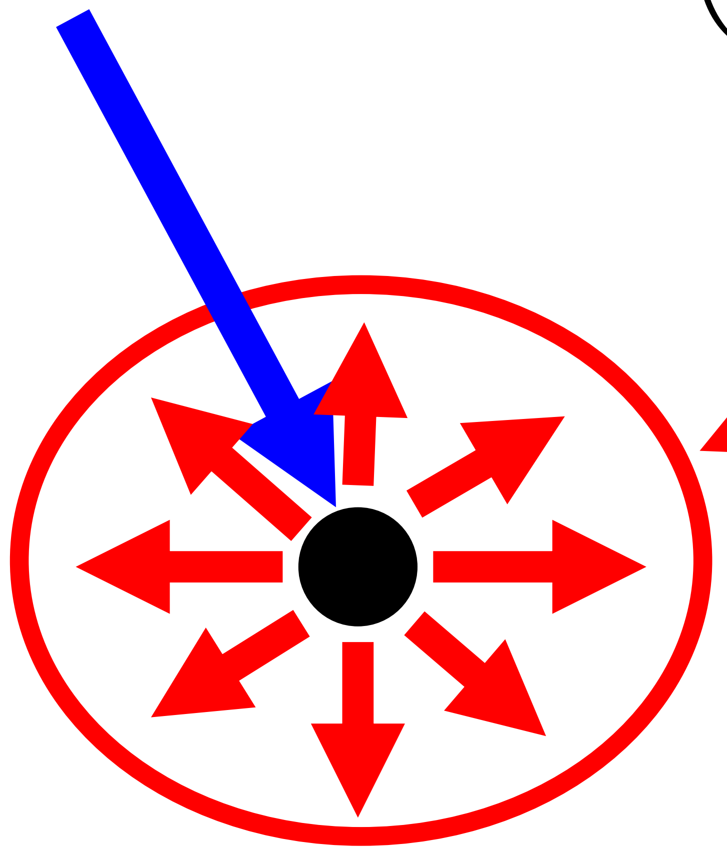
$$\dot{E}_0 = \dot{E}\left(1 + \frac{t_{age}}{\tau_{sd}}\right)^{\frac{p+1}{p-1}}$$



Gelfand+ 2007 (ApJ, 663, 468)

Evolution of a PWN inside a SNR

Neutron Star $\dot{E} = \dot{E}_0 \left(1+\frac{t}{\tau_{sd}}\right)^{-\frac{p+1}{p-1}}$



Supernova Remnant

Pressure: $P_{snr}(R_{pwn})$

Velocity: $v_{snr}(R_{pwn})$

Density: $\rho_{snr}(R_{pwn})$

Ejecta mass: M_{ej}

Kinetic energy: E_{sn}

Density ISM: n_{ism}

(Gelfand et al. 2009, *ApJ*, 703, 2051)

Termination Shock

Magnetic Field: $\eta_B \dot{E}$

Leptons (e^+,e^-): $\eta_e \dot{E}$

Injection Spectrum

Pulsar Wind

Pulsar Wind Nebula

Pressure: P_{pwn}

Magnetic Field: B_{pwn}

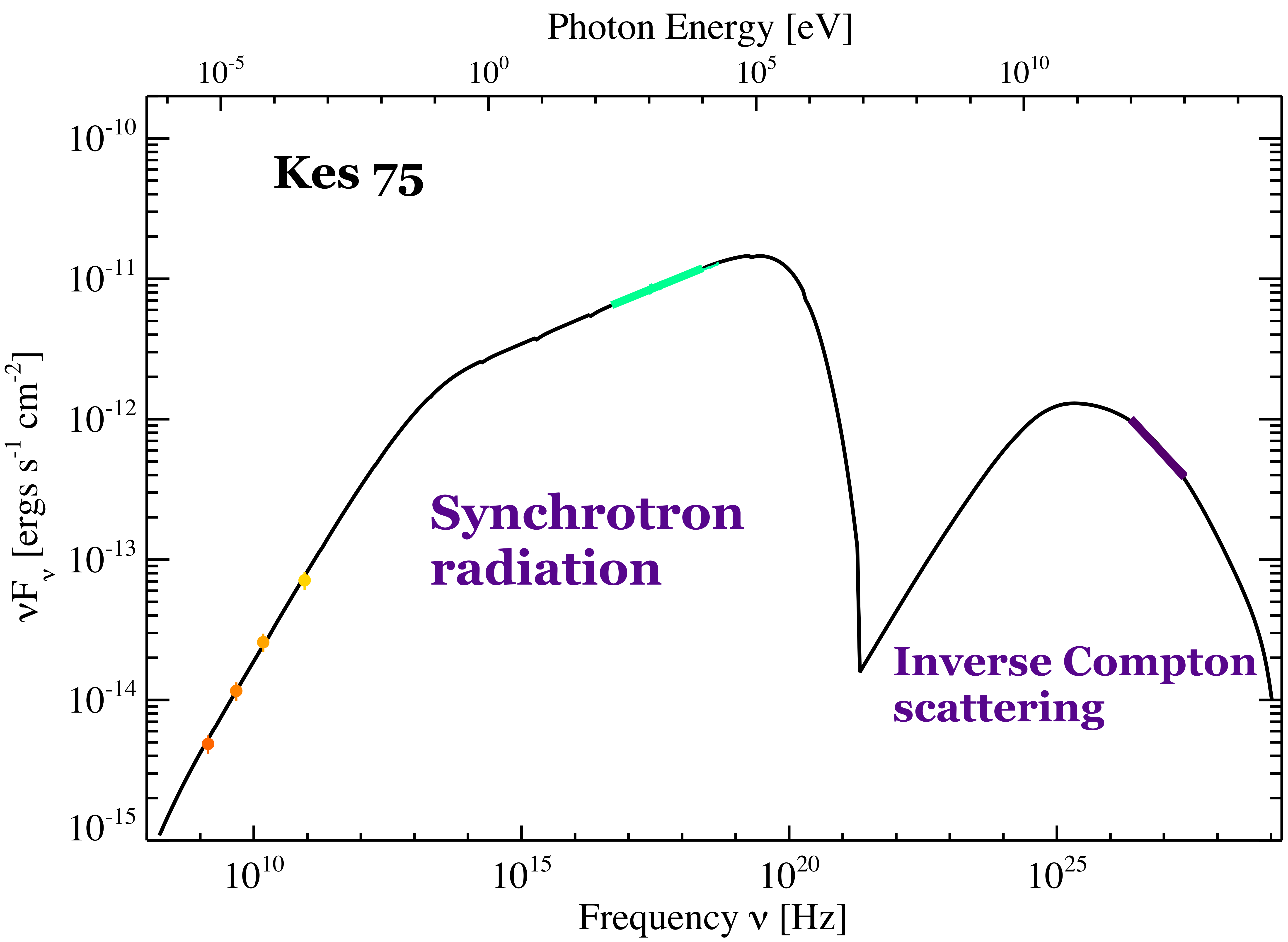
Swept-up Material

Mass: $M_{sw,pwn}$

Velocity: v_{pwn}

Modelling a PWN inside a SNR

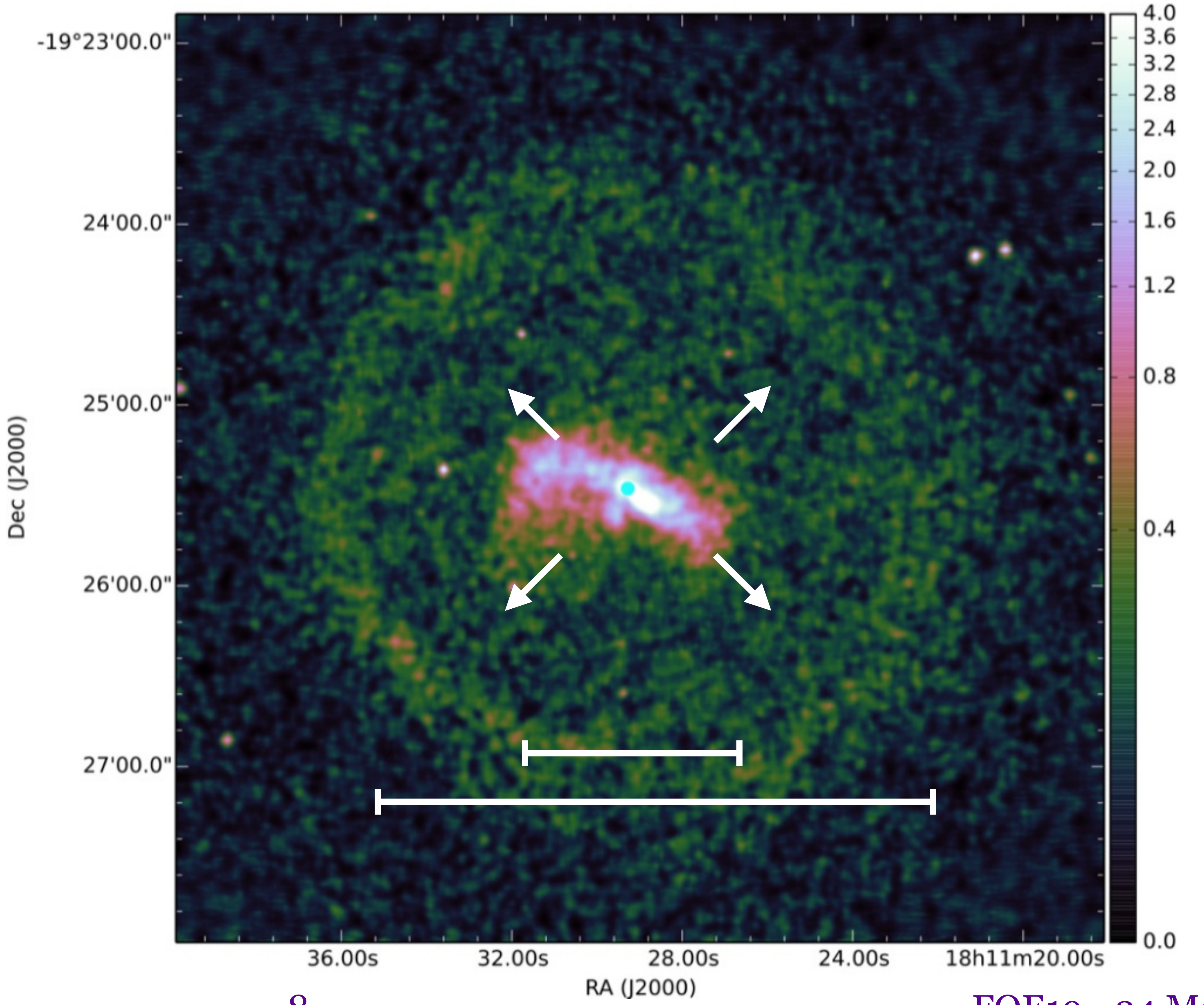
- One-zone model that describes dynamic and radiative evolution (Gelfand+2009)
- Radiative properties dominated by synchrotron and Inverse Compton emission.
- Evolution **also** depends on:
  - Pulsar wind magnetisation
  - Particle energy spectrum
  - Background photon field



Modelling a PWN inside a SNR

- Determine combination of model input parameters that best reproduce the observed dynamical and radiative properties

- From interpretation obtain:
  - SN progenitor star
  - Neutron star birth properties
  - Particle acceleration mechanism

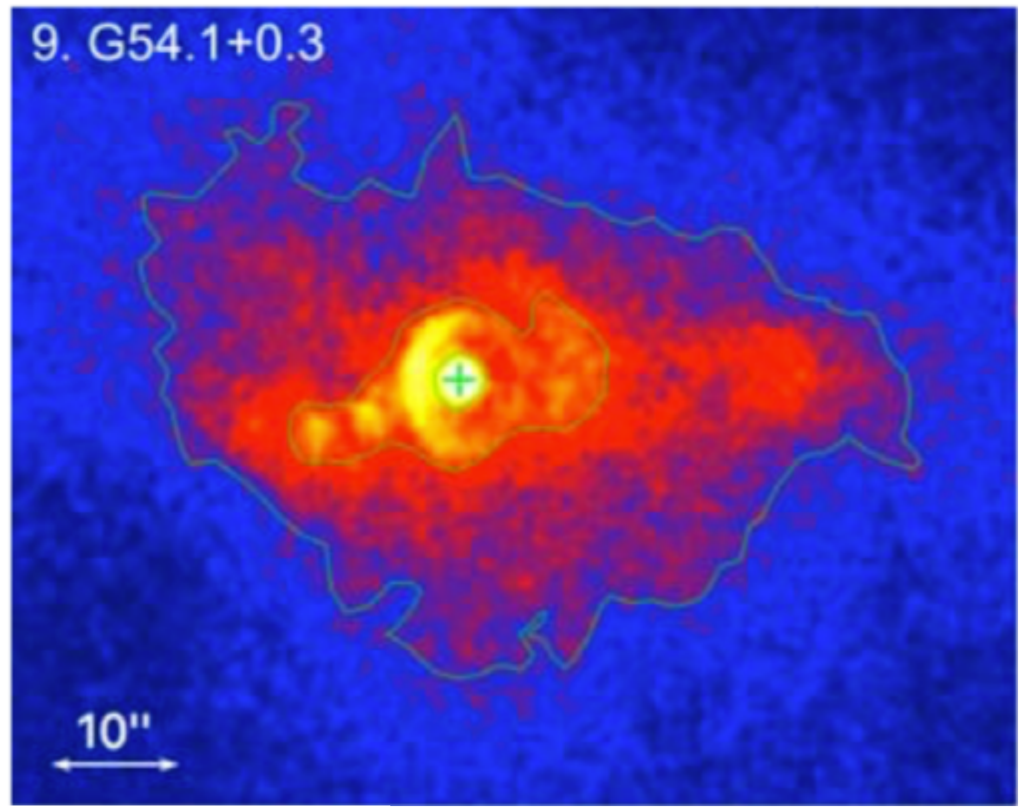


SNR/PWN G11.2-0.3

Borkowski+2016

Modelling of PWN G54.1+0.3 (Gelfand+2015)

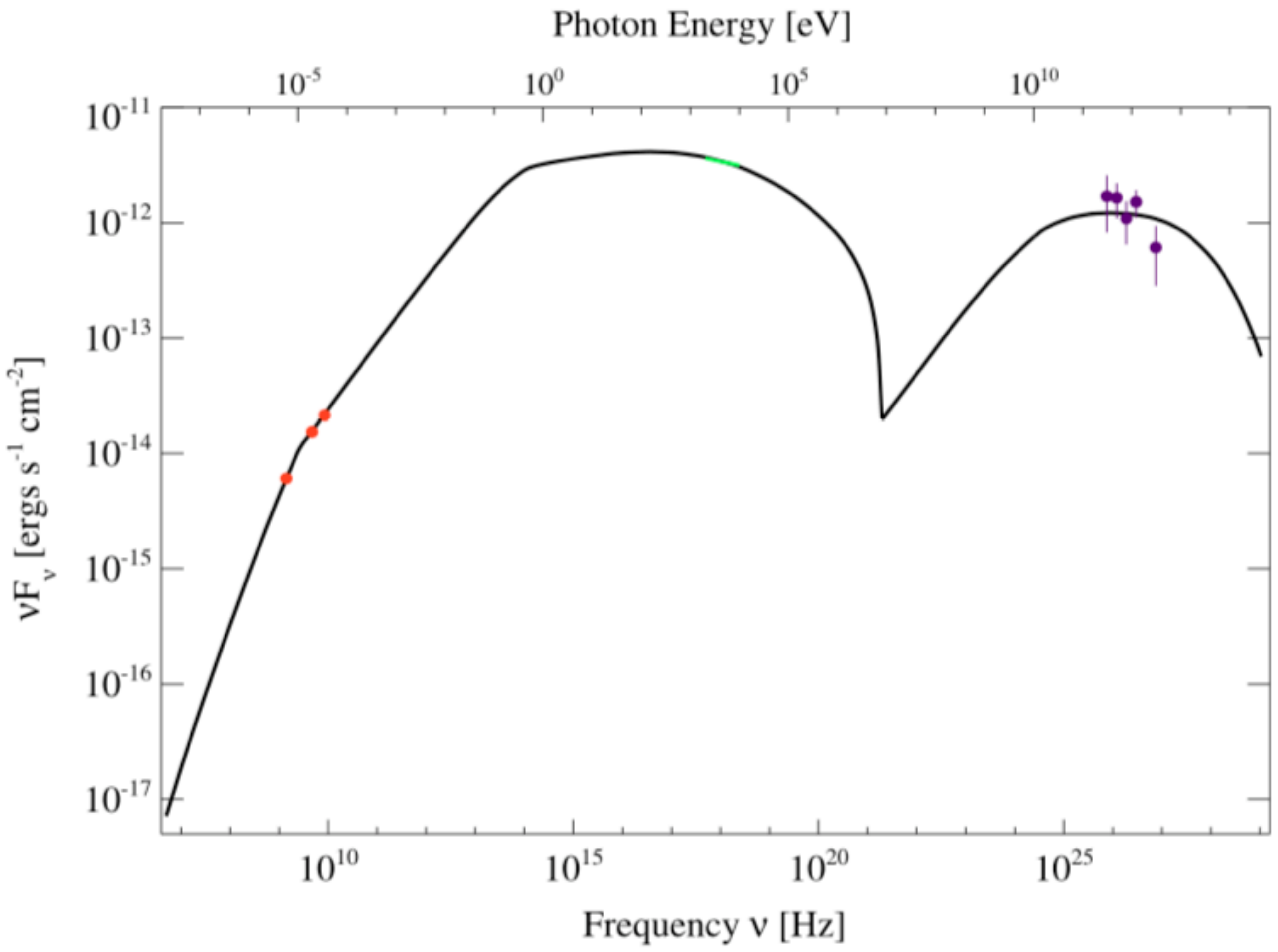
- ✦ Powered by PSR J1930+1852
  - ✦ Radio & γ-ray pulsar
  - ✦ t_{char} = 2900 years
  - ✦ $\dot{E}$ = 1.2E37 erg/s
- ✦ PWN detected in radio, X-ray, TeV energies
- ✦ SNR ~ 5.7 - 8'



Kargaltsev+2017

Modelling results yield:

- ✦ $M_{ej} < 20\ M_{\odot}$, likely ~ $10\ M_{\odot}$
- ✦ E_{sn} = < 3E50 erg
- ✦ Progenitor: 15 - 20 $M_{\odot}$ star
- ✦ P_0 = 30 - 80 ms | P_{cur} = 136 ms



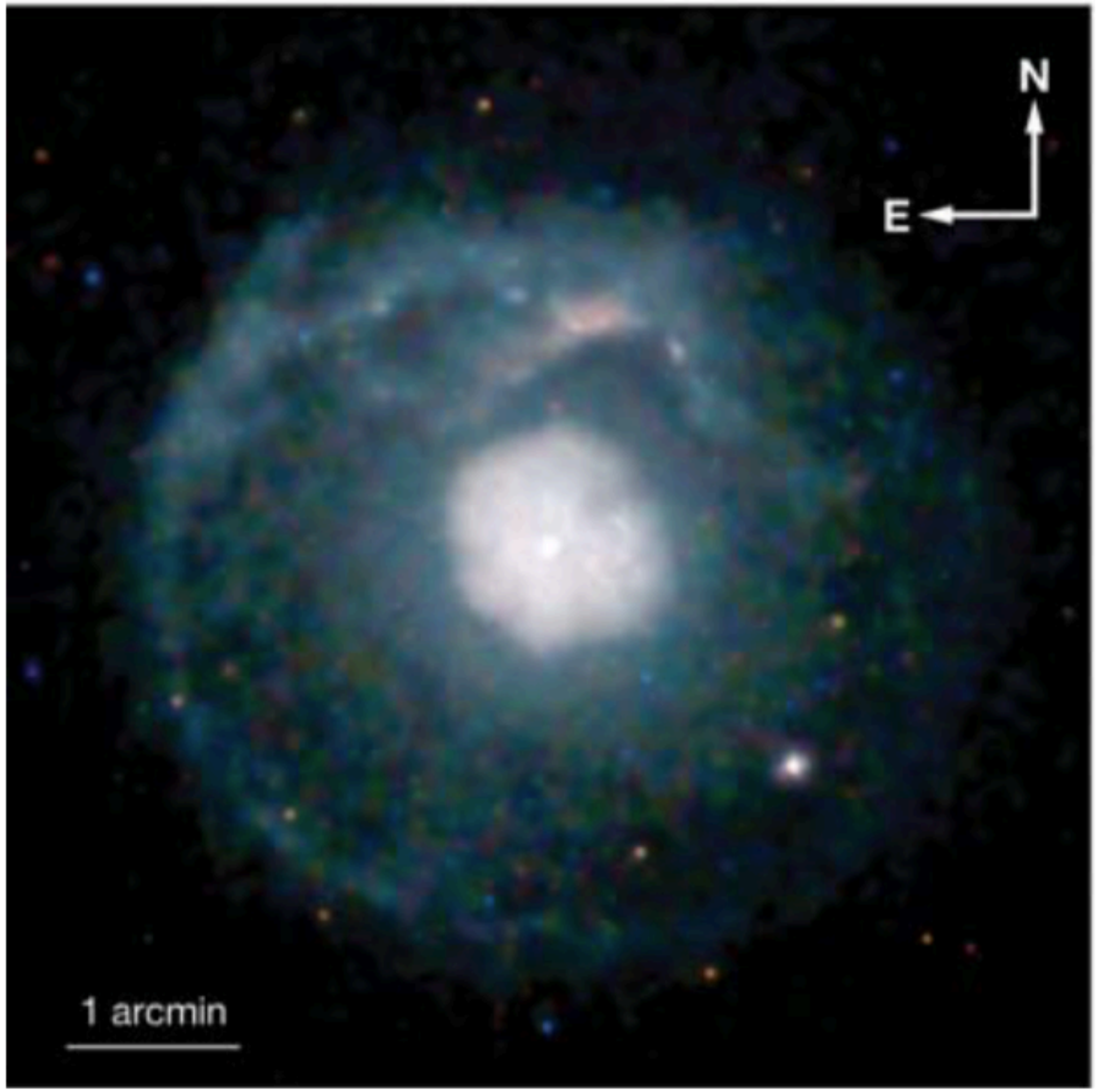
Gelfand+2015

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
- PWN ~ 40”
- SNR ~ 180”

Modelling (initial) results:

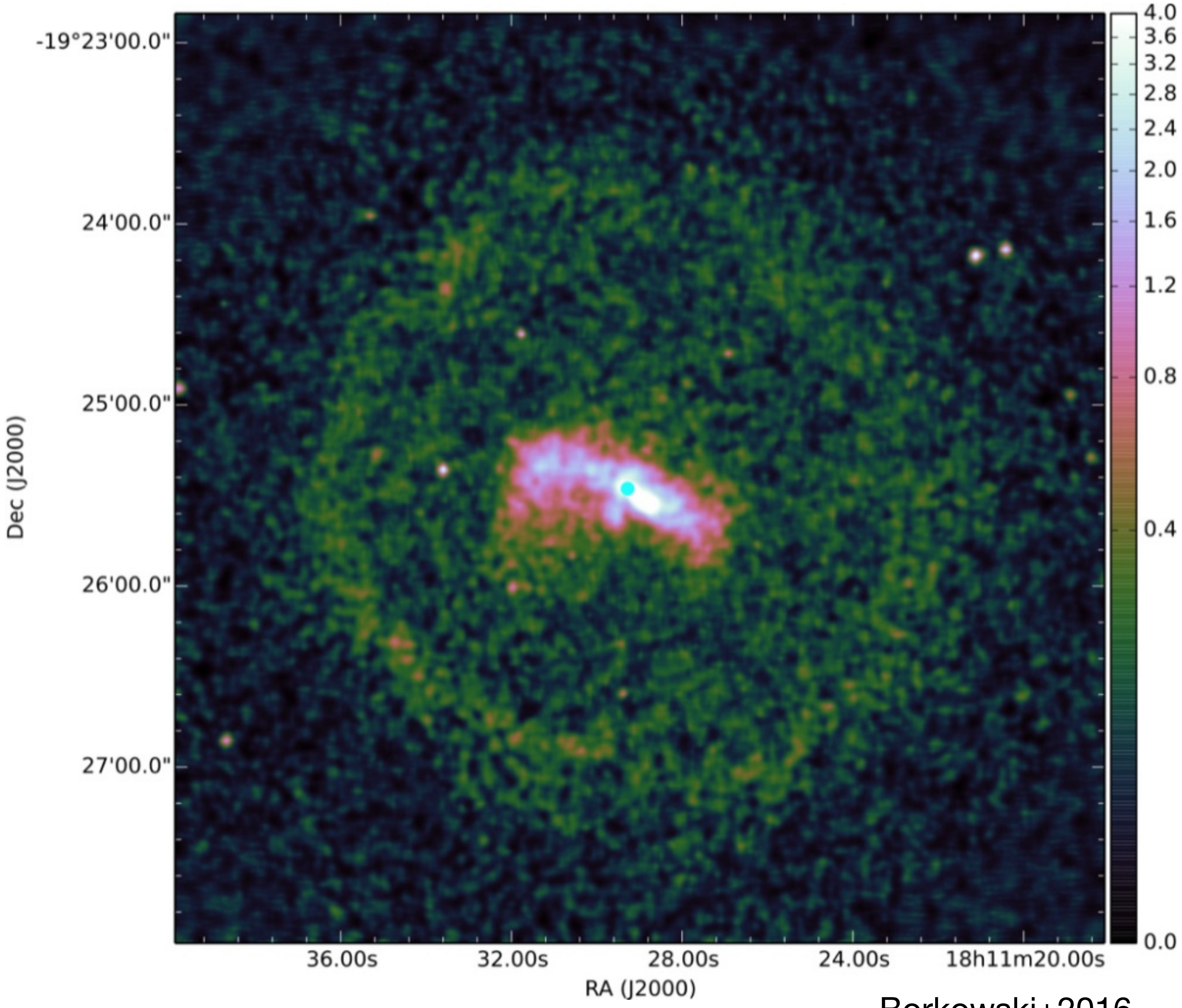
- M_{ej} ~ 10 M_{o}
- E_{sn} ~ < 1E50 erg
- Progenitor: ~ 15 M_{o}



Matheson & Safi-Harb 2005

PWN G11.2-0.3 (aka "the turtle")

- Powered by PSR J1811-1925
  - X-ray pulsar
  - t_{char} = 22500 year
  - age ~ 2000 year
  - $\dot{E}$ = 6.4E36 erg/s
- PWN detected in radio, X-ray, TeV energies
- PWN ~ 37"
- SNR ~ 2.1'



Borkowski+2016

Modelling (initial) results:

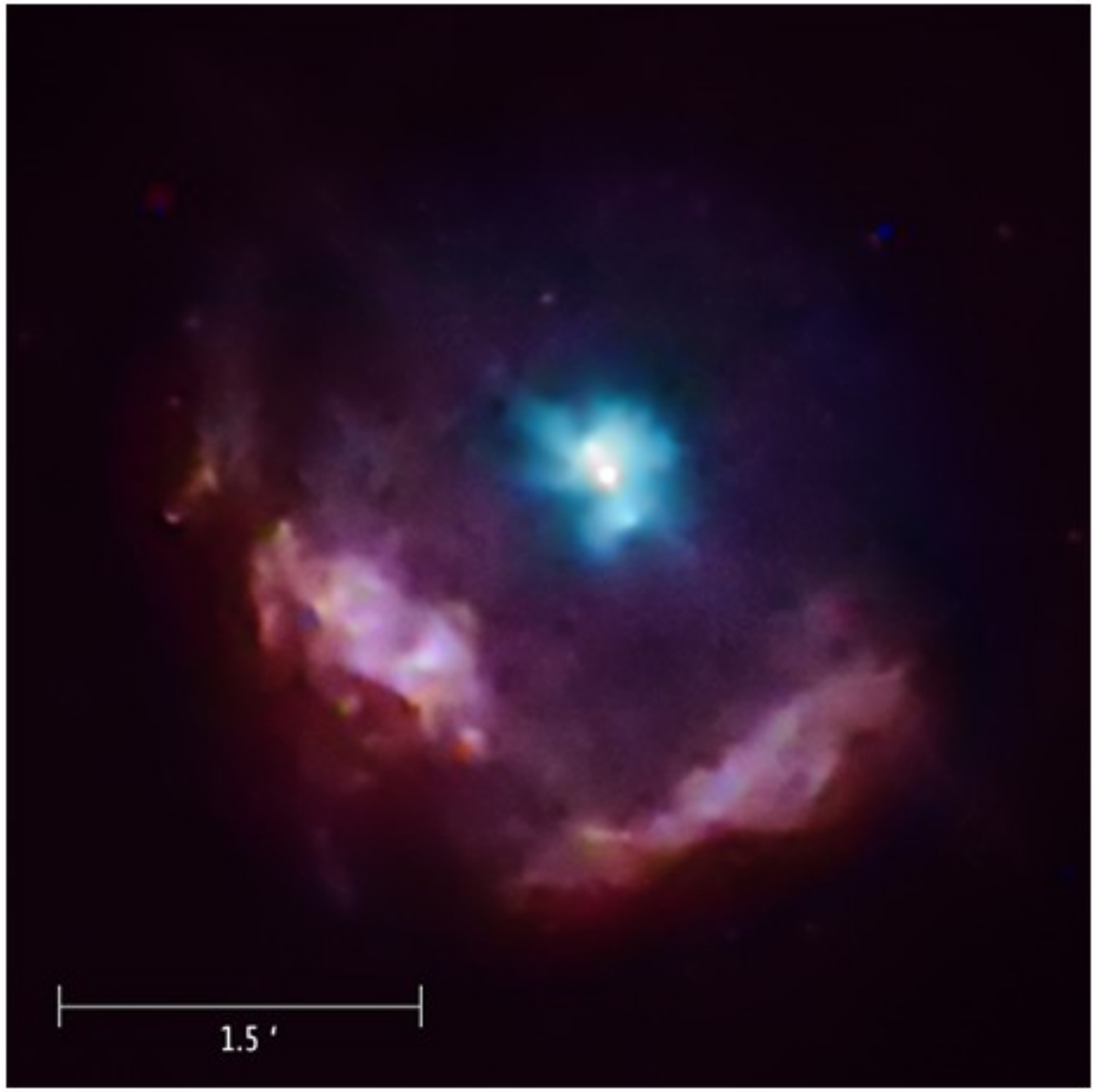
- M_{ej} ~ 8 - 16 M_{o}
- E_{sn} ~ 0.3 - 3E50 erg
- Progenitor: ~ 8-20 M_{o} exploded as a RSG

PWN Kes 75

- Powered by PSR J1846-0258
  - X-ray pulsar, showing magnetar behaviour
  - t_{char} = 728 years
  - $\dot{E}$ = 8.1E36 erg/s
- PWN detected in radio, X-ray, TeV energies
- PWN ~ 30”
- SNR ~ 1.5’

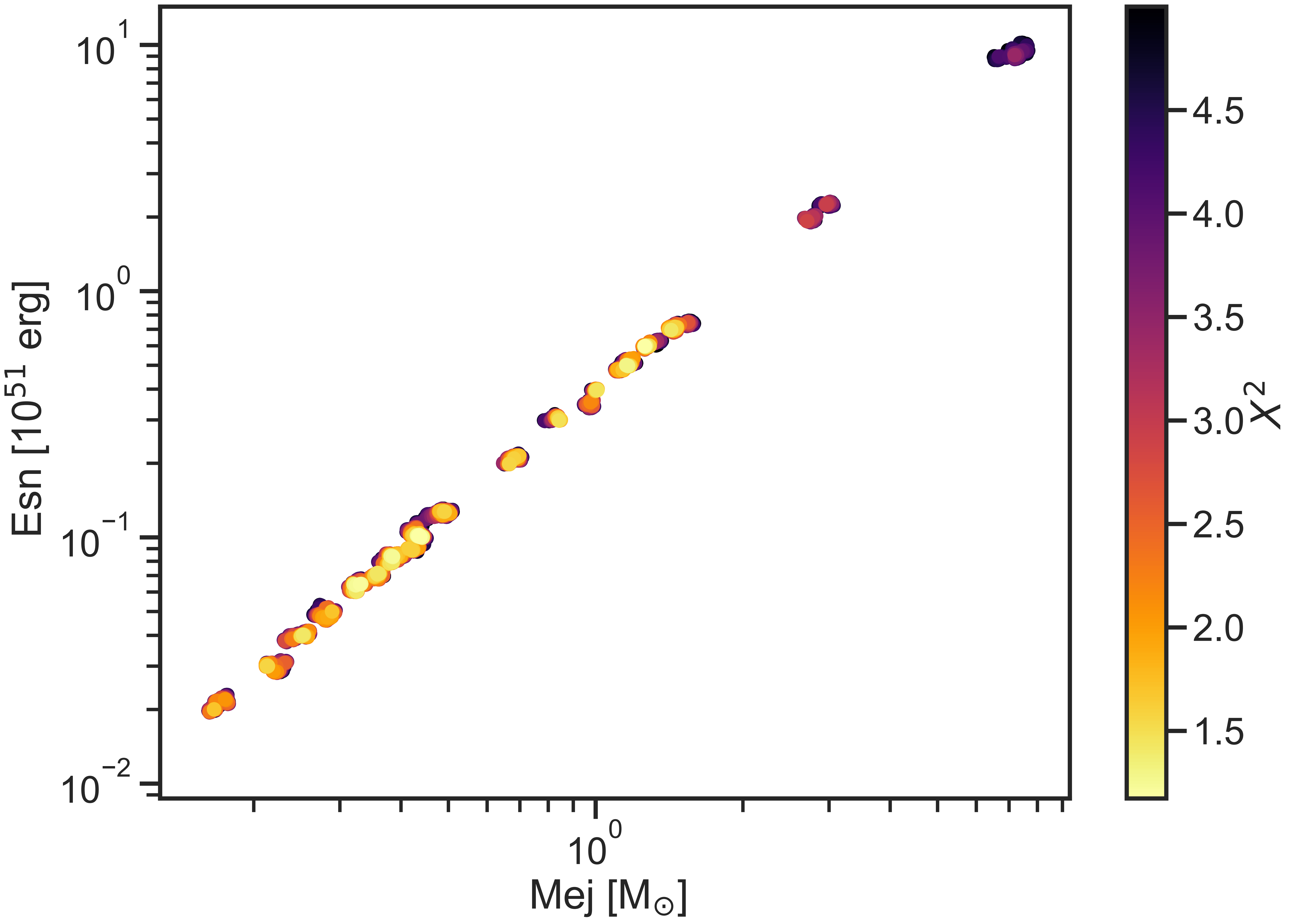
Modelling (initial) results:

- M_{ej} ~ 0.5 M_{o}
- E_{sn} ~ 1E50 erg
- Progenitor: Stripped or Wolf-Rayet star



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

Kes 75 - Ejecta Mass and Kinetic Energy degeneracy



Summary of the supernova parameters

Source	~ E_{sn} (ergs)	~ M_{ej} ($M_{\odot}$)	Progenitor mass ($M_{\odot}$)
G54.1+0.3	$< 3 \times 10^{50}$	10 - 15	~15 - 20
G21.5-0.9	$\sim 10^{50}$	~10	~15
Kes 75	$\sim 10^{50}$	~0.2 - 8	Stripped or WR
G11.2-0.3	$0.3 - 3 \times 10^{50}$	~8 - 16	~15 - 20

- Low explosion energies with high ejecta masses often favoured
- Theory seems to favour low ejecta mass/ low progenitor mass for these low explosion energies (e.g., Sukhbold+2016)
    - Hints for compactness of progenitor core?
- Does observational bias come into play for detection of these systems?

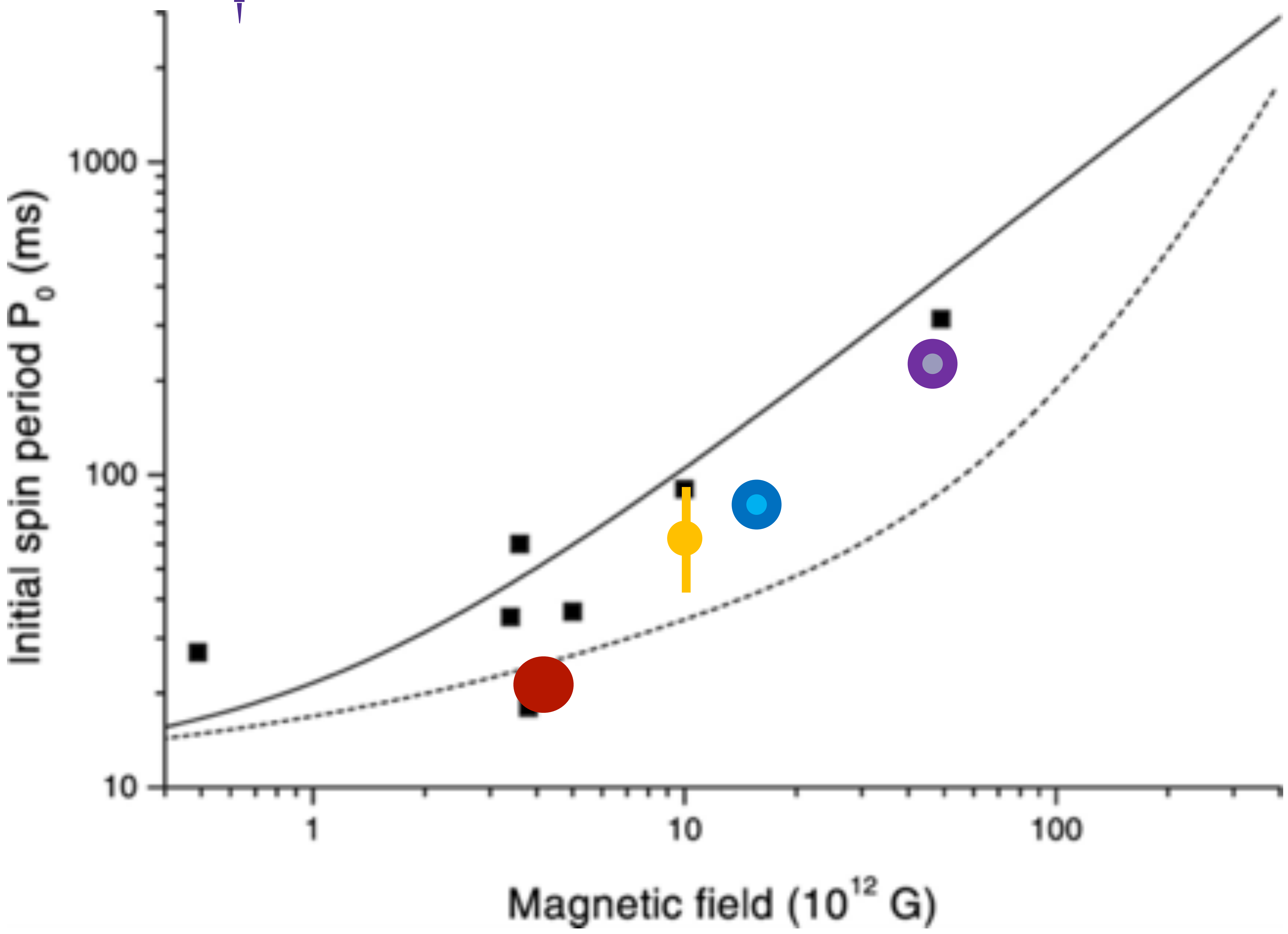
Summary of the neutron star (initial) parameters

Source	Pulsar	B_{ns}	Initial spin period P_0	Current spin period P
G54.1+0.3	J1930+1852	1E13 G	~40 - 80 ms	137 ms
G21.5-0.9	J1833-1034	3.6E12	~15	61.9 ms
Kes 75	J1846-0258	5E13 G	200 ms	327 ms
G11.2-0.3	J1811-1925	1.7E12 G	61.4 ms	64.7 ms

- No obvious correlation with B_{ns} and P_0

Neutron star (initial) parameters

- No obvious correlation between surface magnetic field B_0 and initial spin period P_0
- Possibly consistent with accretion model
- Inconsistent with α- Ω dynamo for magnetars



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

Summary:

- From modelling the evolution of PWN inside a SNR we appear to successfully:
  - Reproduce observed properties of a sample of systems
  - Consistent with independent analysis techniques
  - Can also predict new observables
    (i.e. for PWN G54.1+0.3 initial spin period can be confirmed from its low-frequency flux)

Pulsar wind nebulae inform us about:

- Neutron star formation during CCSNe
- Core-collapse SN properties
- Progenitor stars for CCSNe which form neutron stars
- Particle creation in NS magnetosphere
- Particle acceleration in a PWN