Probing Extreme Physics with Pulsar Wind Nebulae

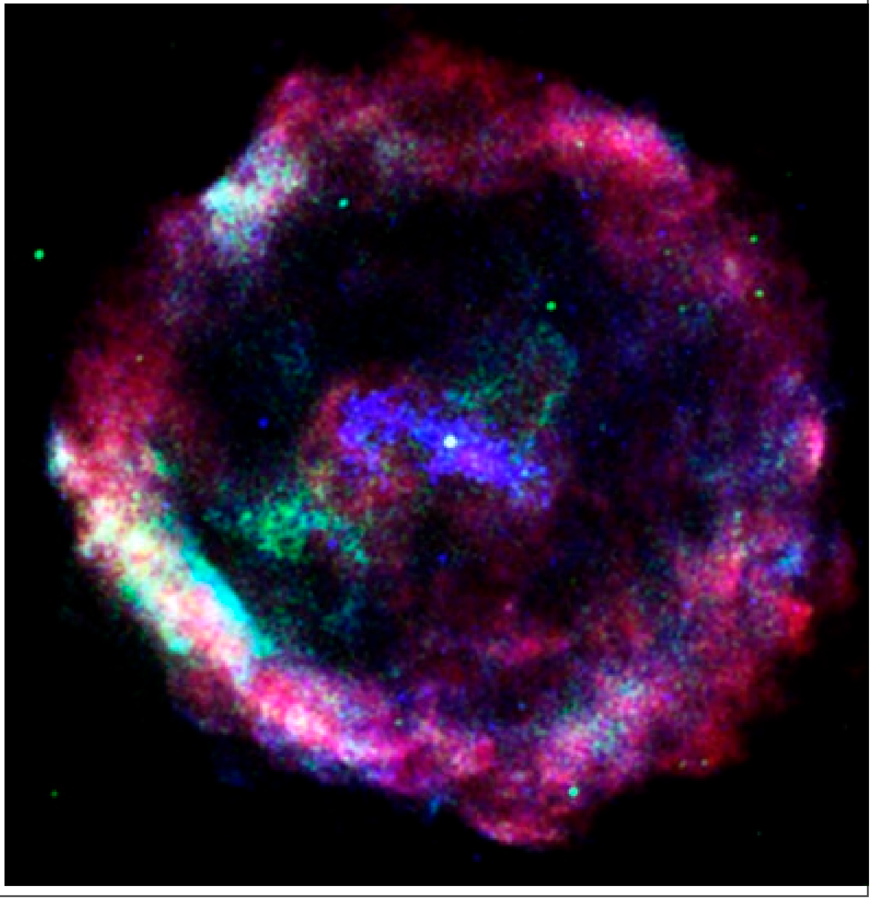
Joseph Gelfand (NYUAD)

جامعة نيويورك أبوظبي
NYU | ABU DHABI

S. M. Straal, S. Hattori (NYUAD), P. Slane, D. Castro (CfA), T. Temim (STScI), M. Roberts (NYUAD / Eureka), S. Safi-Harb (U. Manitoba), M.-H. Grondin, M. Lemoine-Goumard, T. Reposeur (CENBG)

What determines the properties of a PWN inside a SNR?

- Pulsar (Rotational) Energy
  - Total Energy (Initial Spin Period P_0)
  - Injection Rate (Spin-down Timescale τ_{sd}, braking Index p)
- Pulsar Wind
  - Magnetization η_B
  - Particle Number, Spectrum
- Surrounding SNR
  - SN properties (Ejecta Mass M_{ej}, Kinetic Energy E_{sn})
  - ISM (Density n_{ism})

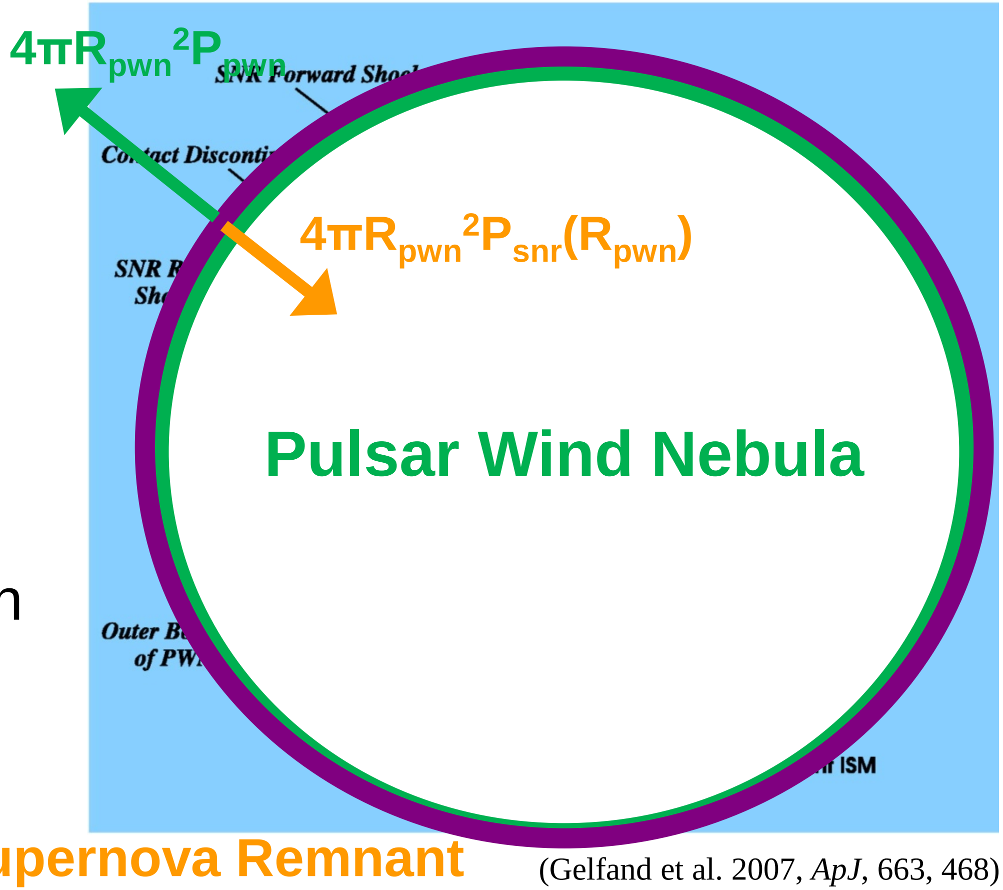


(Credit: X-ray: NASA/CXC/Eureka Scientific/M.Roberts et al.; Radio: NRAO/AUI/NSF)

Evolutionary Model for a Pulsar Wind Nebula Inside a Supernova Remnant

- Basics = Reynolds & Chevalier (1984)
- One-zone model
  - Uniform ISM, PWN
- Dynamical evolution determined by motion of swept-up material
  - Difference in pressure between PWN and SNR results in net force
- PWN's emission dominated by synchrotron radiation and Inverse Compton scattering of electrons off background photons

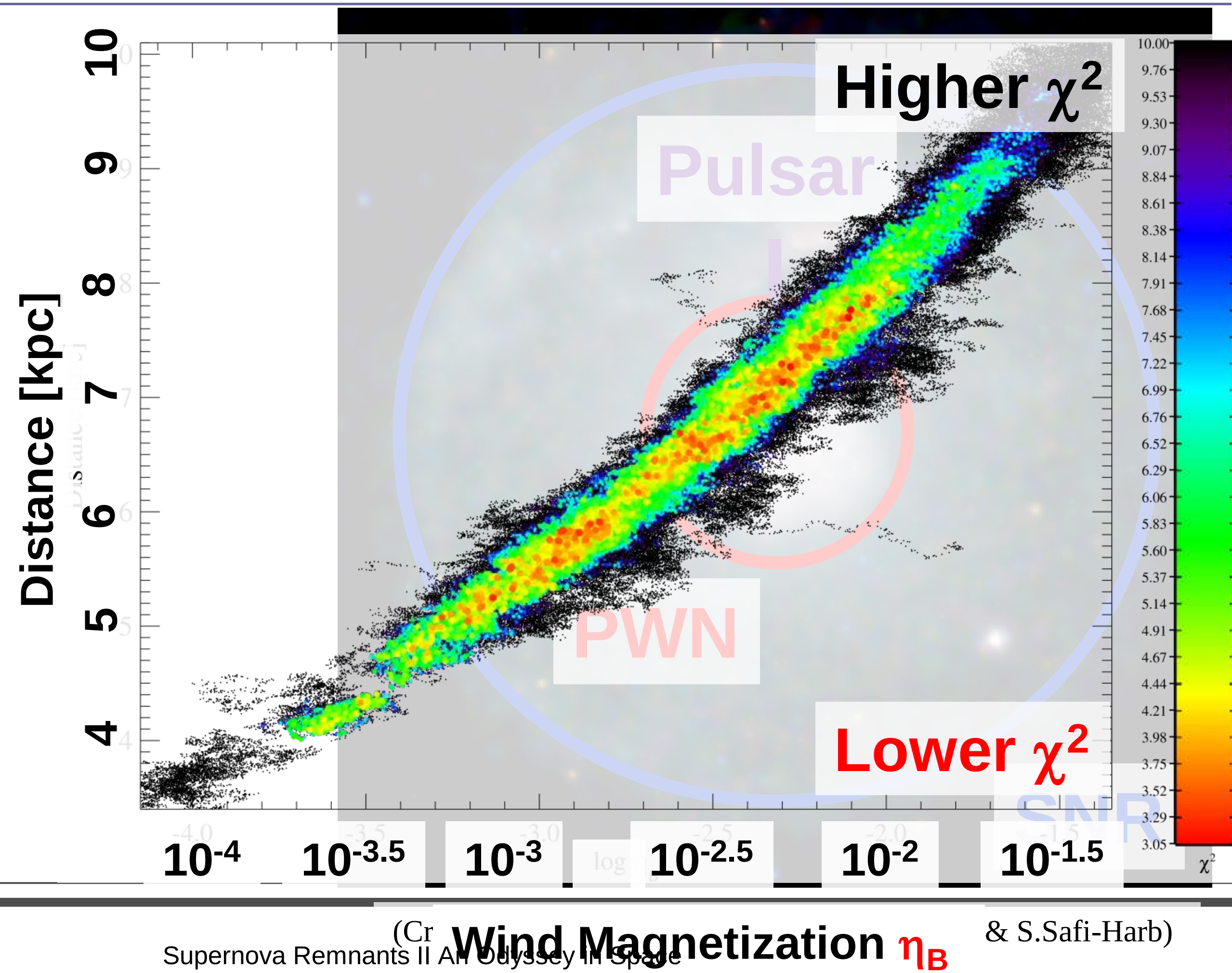
(Gelfand et al. 2009, *ApJ*, 703, 2051)



(Gelfand et al. 2007, *ApJ*, 663, 468)

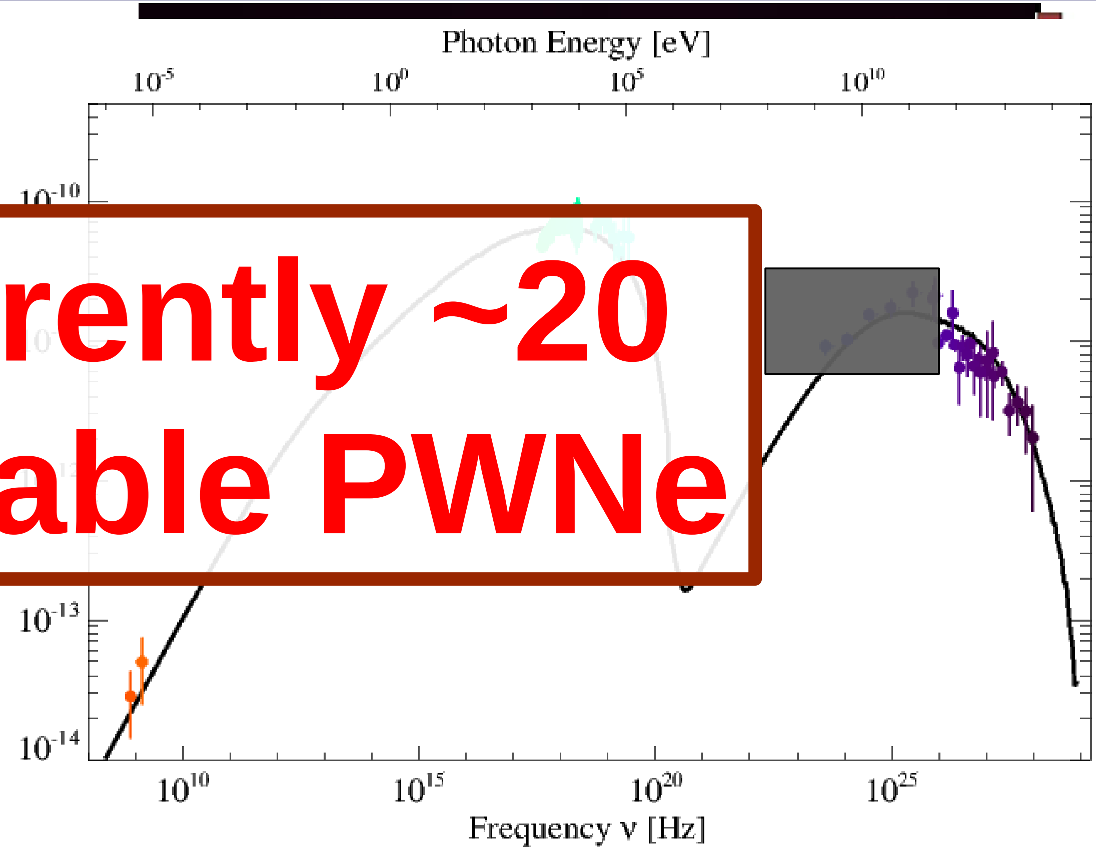
(Basic) Procedure

- Measure **volume-integrated** properties of the PWN (SNR, pulsar)
- Identify parameter **combinations** that reproduce observables
  - Significant degeneracies between parameters
- Interpret results



(Initial) Sample

- **G11.2-0.3**
  - χ^2=3.2/4 d.o.f
- **G21.5-0.9**
  - χ^2=34/11 d.o.f
- **G54.1+0.3**
  - χ^2=4.1/0 d.o.f
- **HESS J1640-465**
  - χ^2=25/15 d.o.f
- **Kes 75**
  - χ^2=1.17/0 d.o.f
- **MSH 15-52**
  - χ^2=384/129 d.o.f



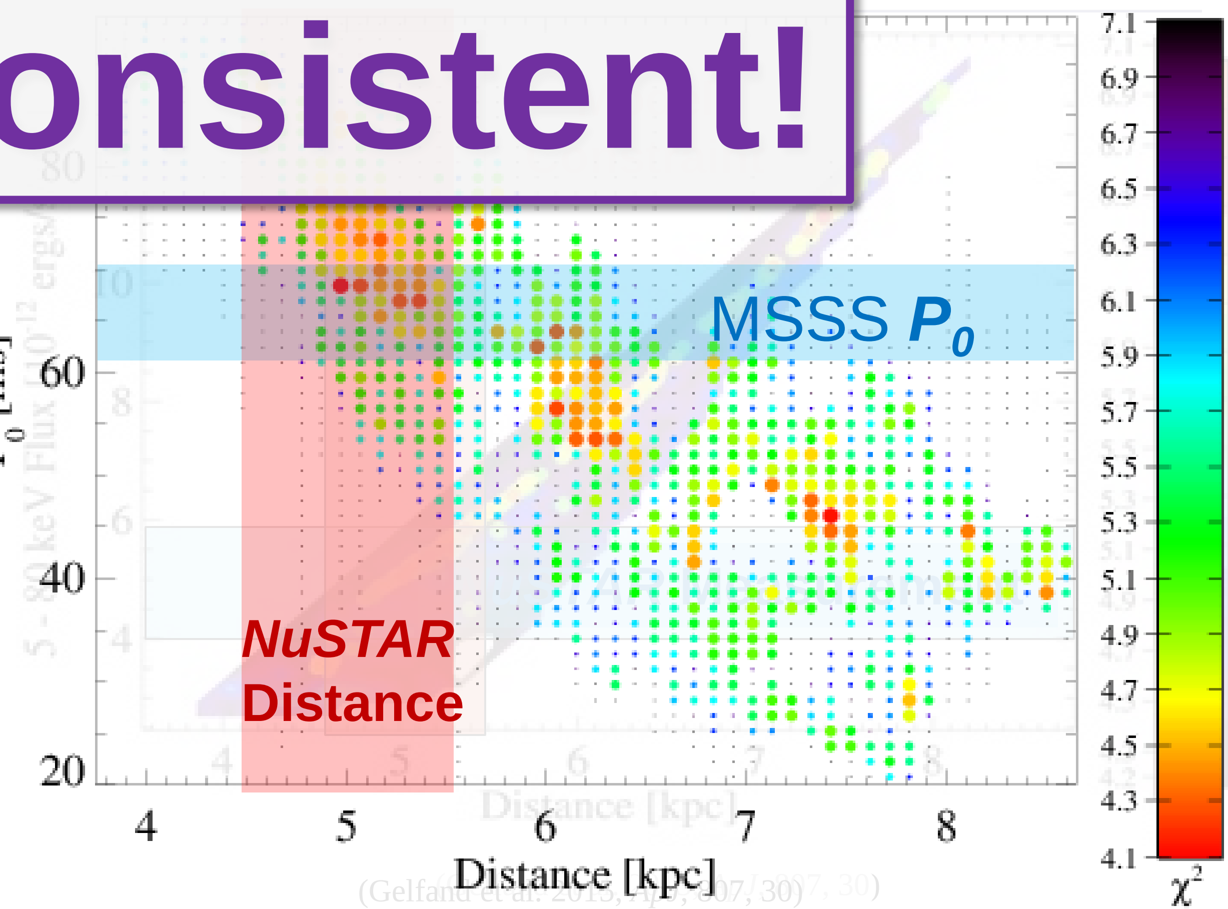
Currently ~20 suitable PWNe

(HESS Collaboration et al. (Reposeur et al., in prep.)

G54.1+0.3: Model predictions

Consistent!

- Expected 60 / 150 MHz flux densities
  - Sensitive to P_0
  - MSSS detection: S_{150}=0.3± 0.1 Jy
- Predict 5 – 80 keV flux
  - Consistent with *NuSTAR* observation
  - Implies d ~ 4.5 – 5.5 kpc
- Distance – P_0 degeneracy



Supernova Explosion Properties

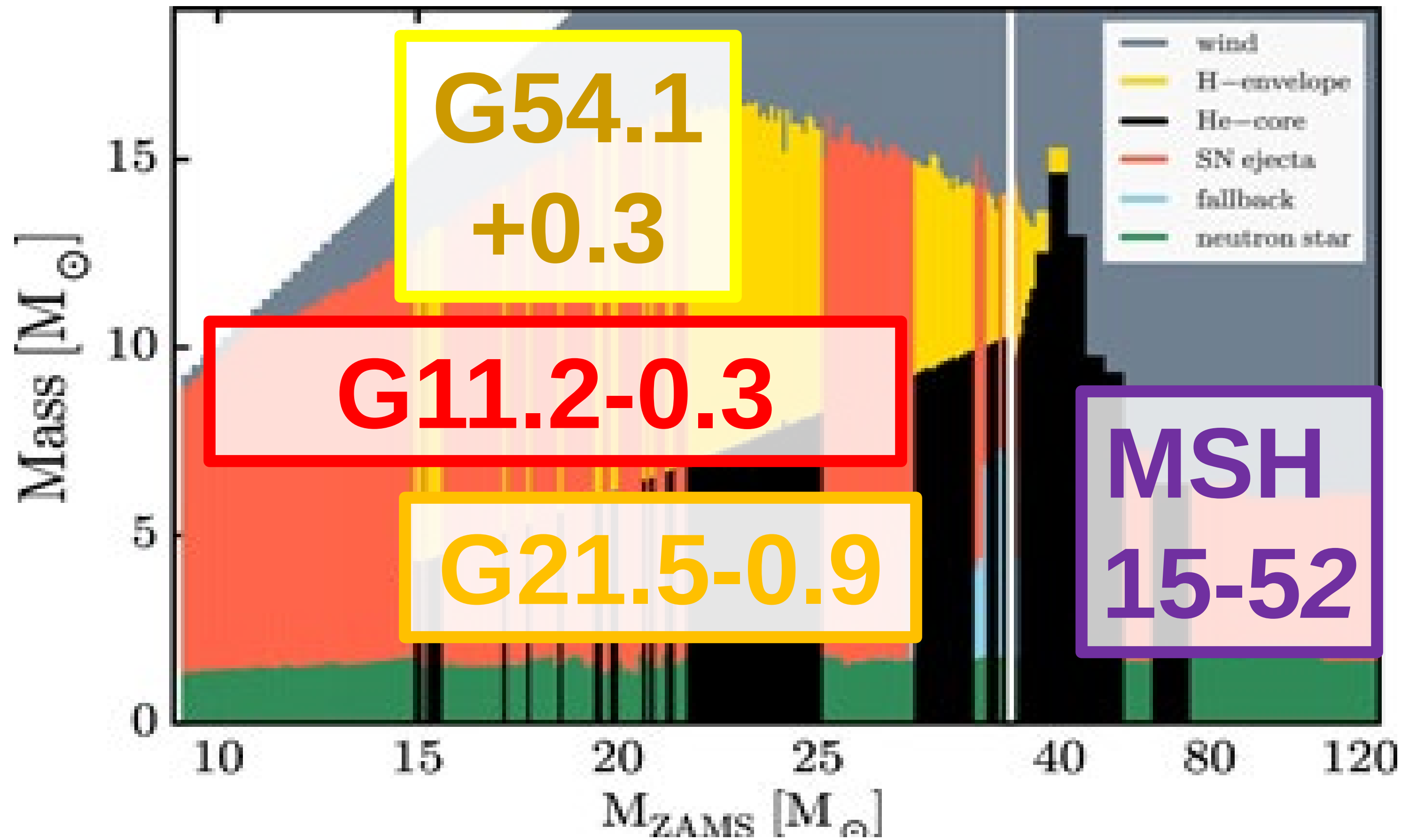
Low Energy / High Mass SN:
Consistent with simulations (?)
Minimal fallback either NS→BH

Name	E_{sn} [10^{51} ergs]	M_{ej} [$M_\odot$]	n_{ism} [cm^{-3}]
G11.2-0.3	0.05 – 0.2	6.5 – 16	1.5 – 5
G21.5-0.9	~0.1	~10	0.2
G54.1+0.3	0.08 – 0.3	6 – 40	$(0.03 – 6)\times10^{-3}$
HESS J1640-465	~0.2	~0.5	~0.03
Kes 75	~0.1	~0.4	~0.25
MSH 15-52	~2	~5.5	~1

Very low ejecta mass: "Wolf-Rayet" or Binary progenitor?

Low n_{ism}: Stellar wind bubble(s)?

(Single Star) Progenitor Masses



(Sukhbold et al. 2016, ApJ, 821, 38)

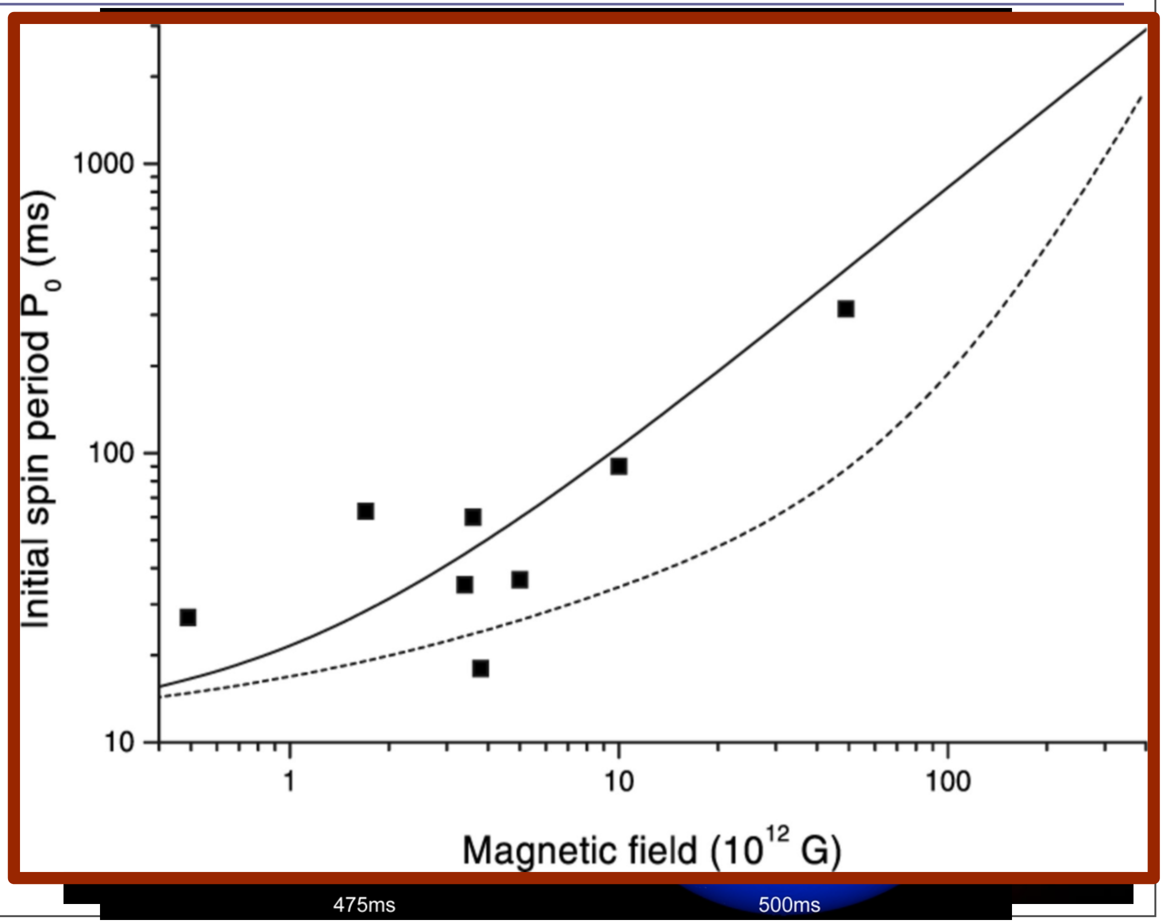
Neutron Star – Progenitor Connection?

Pulsar magnetic field depends on progenitor / supernova?

B_{sd} [G]	Supernova	Progenitor
1.7×10^{12}	Low E_{sn}, High M_{ej}	~8 – 30 $M_{\odot}$
3.6×10^{12}	Low E_{sn}, High M_{ej}	~15 – 30 $M_{\odot}$
1.0×10^{13}	Low E_{sn}, High M_{ej}	~15 – 20 $M_{\odot}$
1.4×10^{13}	Low M_{ej}	Wolf-Rayet / Binary ?
1.5×10^{13}		> 60 $M_{\odot}$
4.9×10^{13}	Low M_{ej}	Wolf-Rayet / Binary ?

Origin of Pulsar Spin

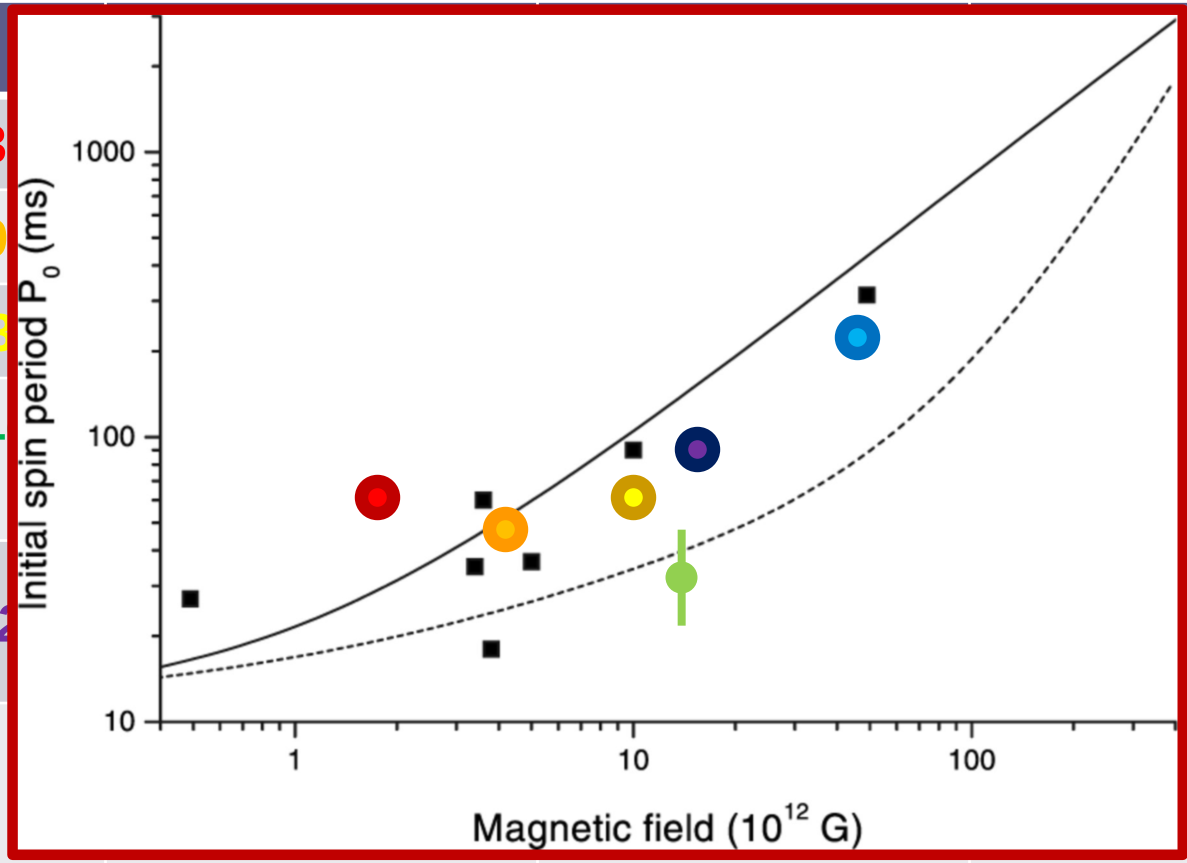
- Conservation of progenitor core's angular momentum?
- Fall-back accretion onto proto-neutron star?
  - P_0 related to B_{sd}?



(http://knoxblogs.com/atomi (Watts & Andersson 2002, *MNRAS*, 333, 943) 59)

Pulsar Initial Spin Periods

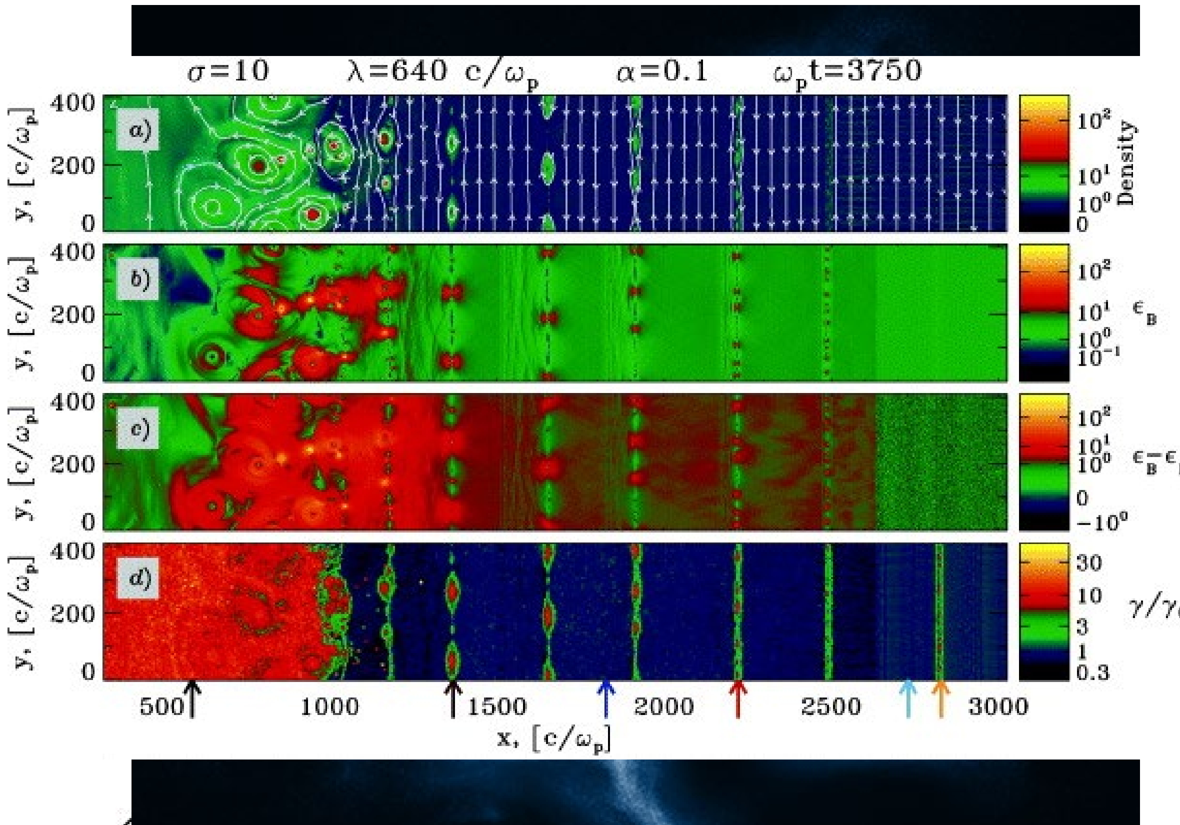
Name		ms]
G11.2-0.3		1.4
G21.5-0.9		50
G54.1+0.3		65
HESS J164 465		- 35
MSH 15-52		- 80
Kes 75		00



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

Particle Acceleration in a Pulsar Wind

- Unshocked wind:
  - Primarily e±
  - Equatorial
  - Magnetically striped
  - Magnetically dominated
- Confinement creates “termination shock”
- Compression of striped wind
  - Magnetic reconnection?

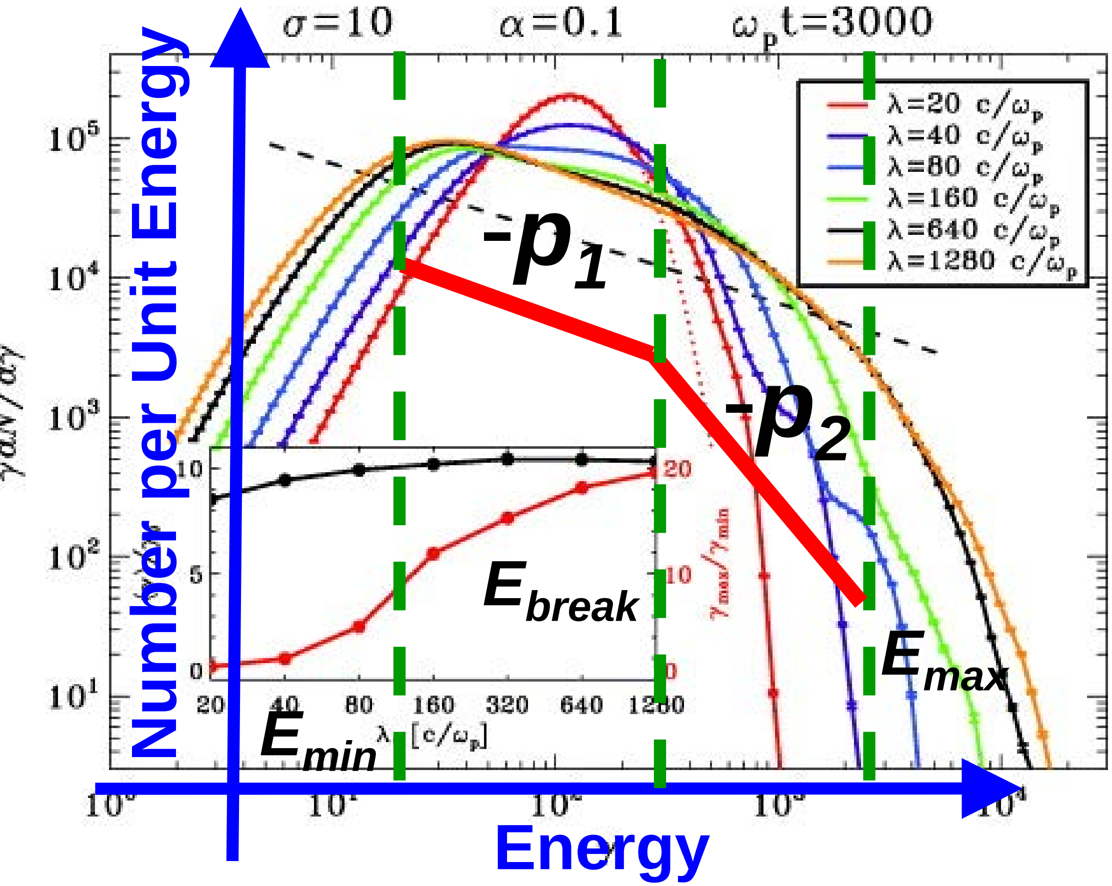


(Sironi & Spitkovsky, 2012, doi:10.1088/1749-4699/5/1/014014)

(Credit: X-ray: NASA/CXC/SAO)

Accelerated Particle Spectrum

- Depends on width of magnetic stripes
  - Thin → Mostly Maxwellian
  - Thick → Broken powerlaw
- Modeling favors broken power-law
  - Magnetic reconnection
    p₁ ~ 1.5
  - Fermi acceleration
    p₂ ~ 2.5



(Sironi & Spitkovsky, 2012, doi:10.1088/1749-4699/5/1/014014)

Pulsar Wind Particle Spectrum

Name	η_B	p_1	p_2	$\lambda / r_L \sigma$
G11.2-0.3	0.002 – 0.015	0.55 – 1.5	2.68 – 2.87	4.5×10^{-5}
G21.5-0.9	~0.003	~2.85	~2.5	
G54.1+0.3	$(0.4–2)\times10^{-3}$	1.4 – 2.1	2.00 – 2.78	$10^{-5} – 10^{-4}$
HESS J1640-465	~0.02	~0.3	~2.6	
Kes 75	~0.04	~1.7	~2.66	
MSH 15-52	~0.05	~1.8	~2.2	

Only source with $p_1 > p_2$

Narrow, NOT wide stripes

Wide range of η_B <<1

Maximum Particle Energy

Name	PSR	$\dot{E}_{psr}$	Φ_{psr}	E_{max}
G11.2-0.3	J1811-1925	6.4×10^{36}	4.4 PV	1 – 30 PeV
G21.5-0.9	J1833-1034	3.4×10^{37}	10 PV	~0.25 PeV
G54.1+0.3	J1930+1852	1.2×10^{37}	6.0 PV	>1 PeV
HESS J1640-465	J1640-4631	4.4×10^{36}	3.6 PV	~1.5 PeV
Kes 75	J1846-0258	8.1×10^{36}	4.9 PV	~1 PeV
MSH 15-52	B1509-58	1.7×10^{37}	7.1 PV	~0.4 PeV

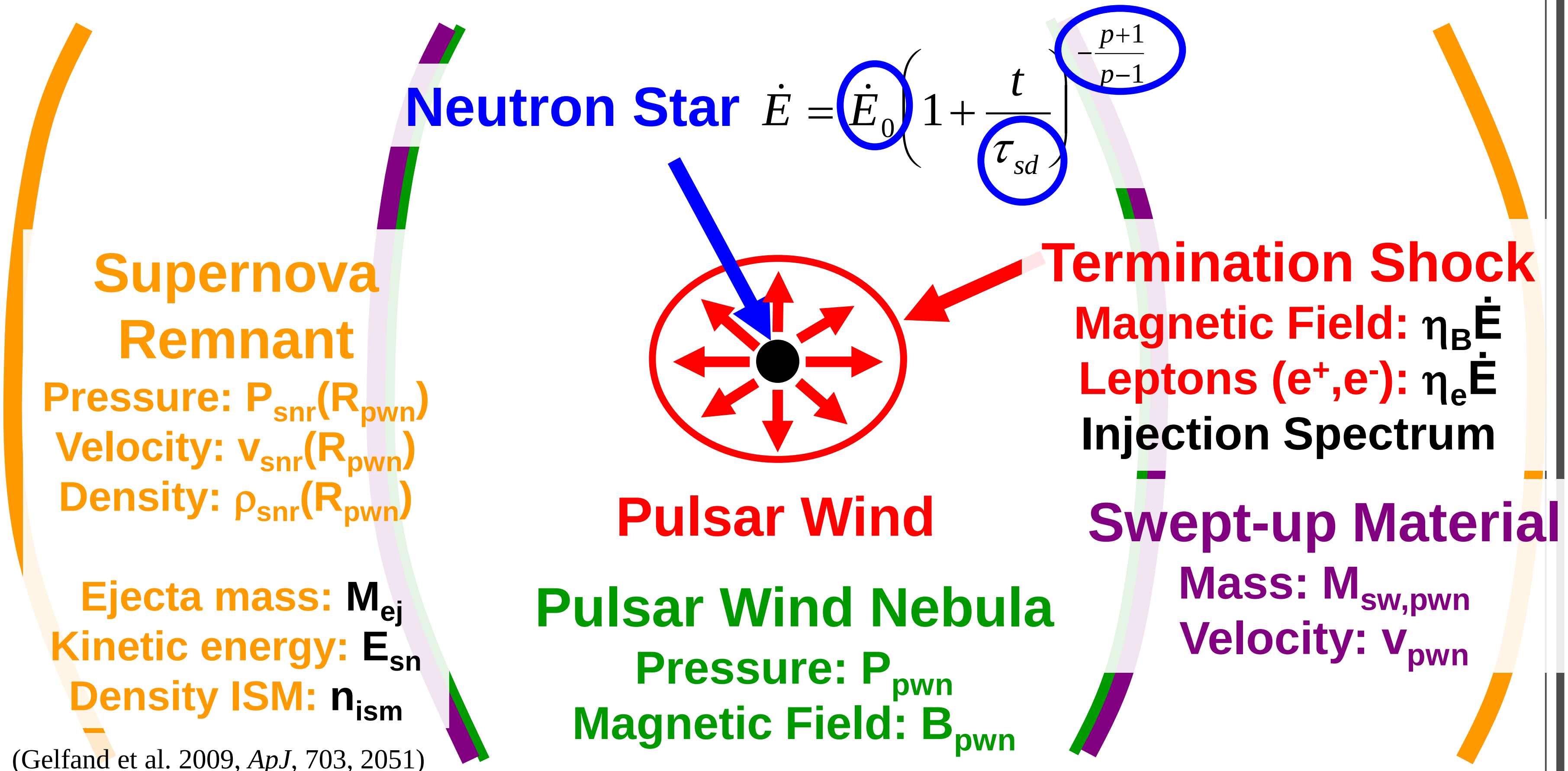
- In general $E_{max} < e\Phi_{psr}$
  - G11.2-0.3 likely exception

Summary

Thank you !

- Simple model for evolution of PWN inside a SNR:
  - reproduces observed properties of numerous systems,
  - accurately predicted values of new observations.
- Application to a (small) sample of PWN:
  - Low energy – High mass explosions produce pulsars
  - Neutron star magnetic field strength (possibly) correlated with progenitor / supernova
  - Initial spin periods (fairly) consistent with fallback model
  - Particle spectrum (normally) consistent with magnetic reconnection + Fermi acceleration
  - Maximum energy (generally) consistent with pulsar voltage

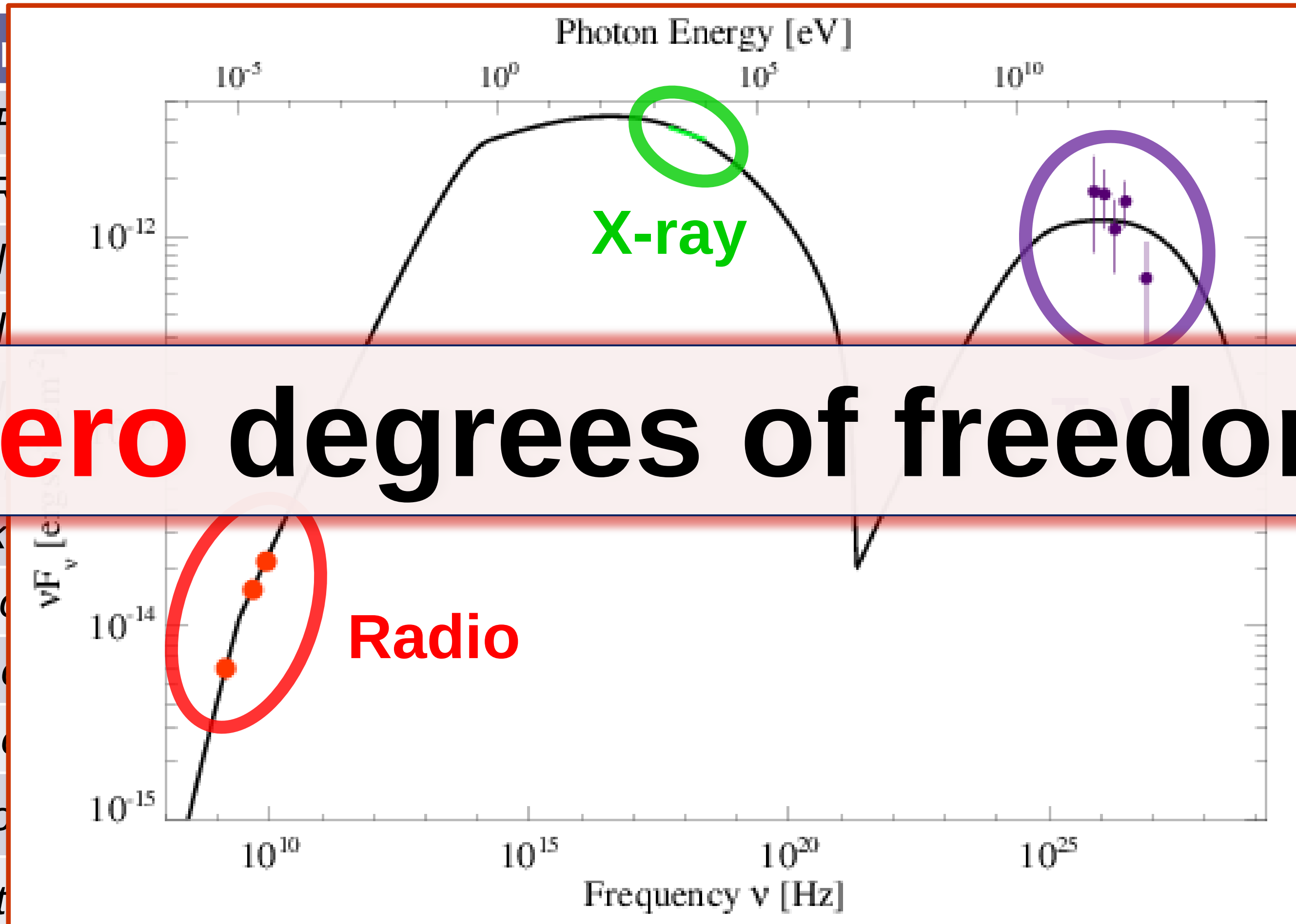
Schematic of a PWN inside a SNR



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

G54.1+0.3: MCMC Best Fit

Qua…	…d
PWN R…	…n
SNR R…	…n
1.4 GHz Fl…	
4.7 GHz Fl…	
8.5 GHz Fl…	
0.5 – 10 keV…	
2 – 10 k…	…/cm²/s
311 GeV Pho…	…TeV/cm²/s
492 GeV Pho…	…eV/cm²/s
780 GeV Pho…	…TeV/cm²/s
1.2 TeV Pho…	…eV/cm²/s
3 TeV Phot…	…eV/cm²/s

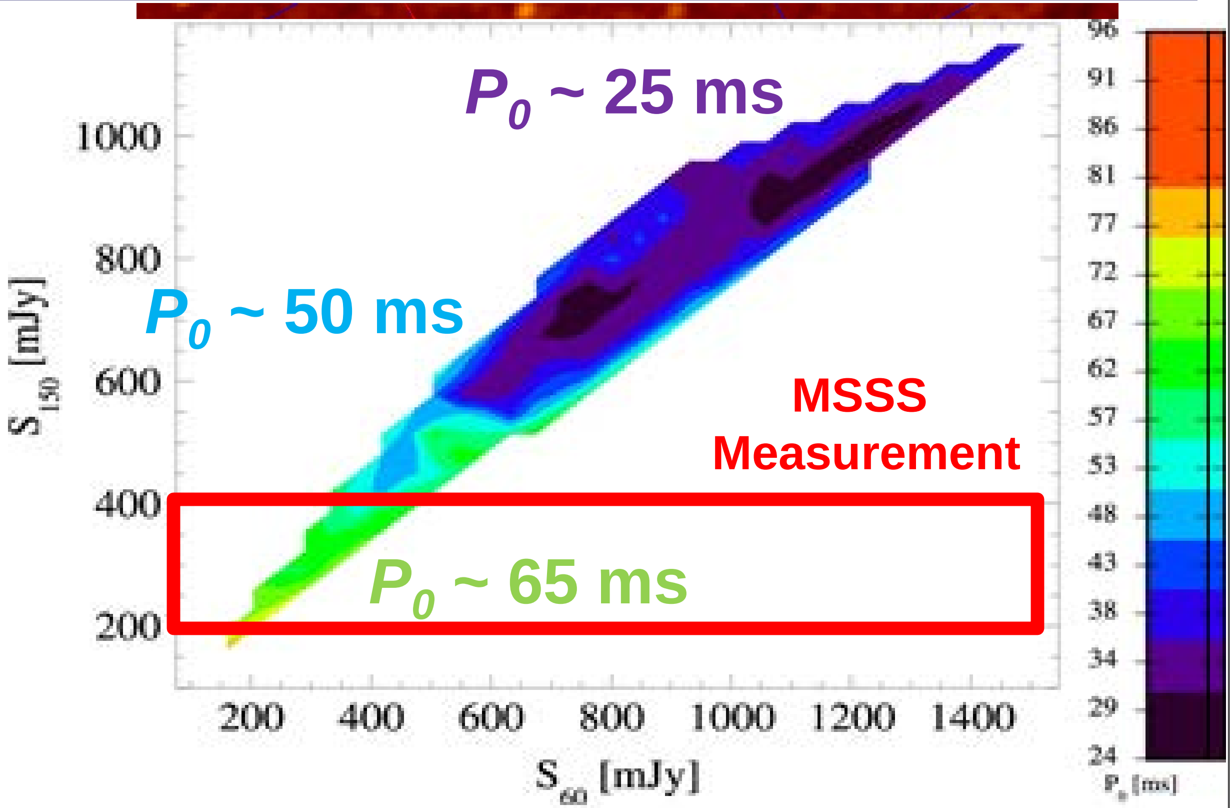


Zero degrees of freedom

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

Test: Low Frequency Flux Density

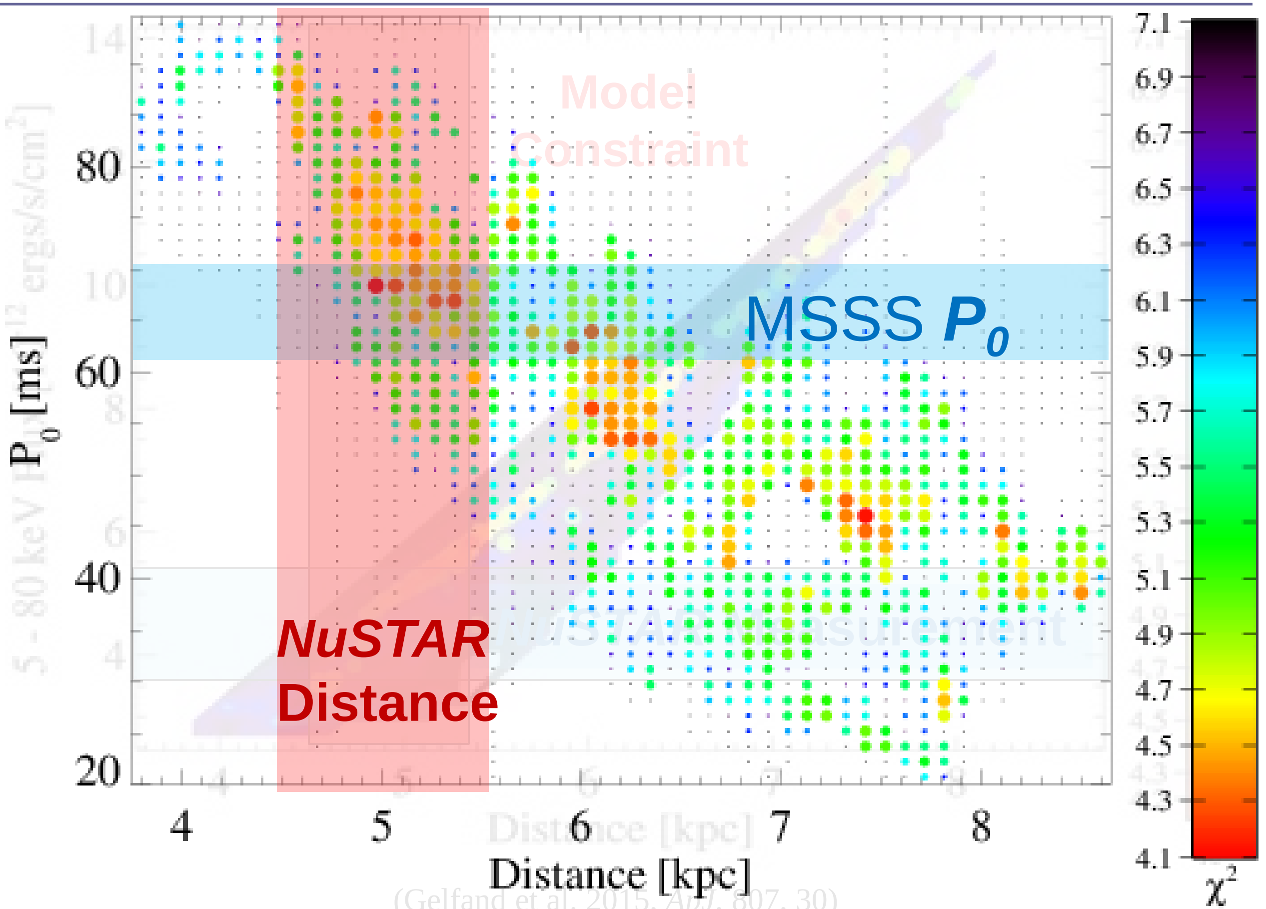
- MSSS detection: S_{150}=0.3± 0.1 Jy
  - Model predicts S_{60}=0.2 - 0.45 Jy
- Test using awarded LOFAR observation
- Important for measuring Initial Spin Period P_0



(Gelfand et al. 2015, *ApJ*, 807, 30)

Cross-check: Hard X-ray Flux

- Predict 5 – 80 keV flux
  - Consistent with *NuSTAR* observation
  - Implies d~4.5 – 5.5 kpc
- Consistent with $\boldsymbol{P_0}$!



(Gelfand et al. 2015, ApJ, 807, 30)

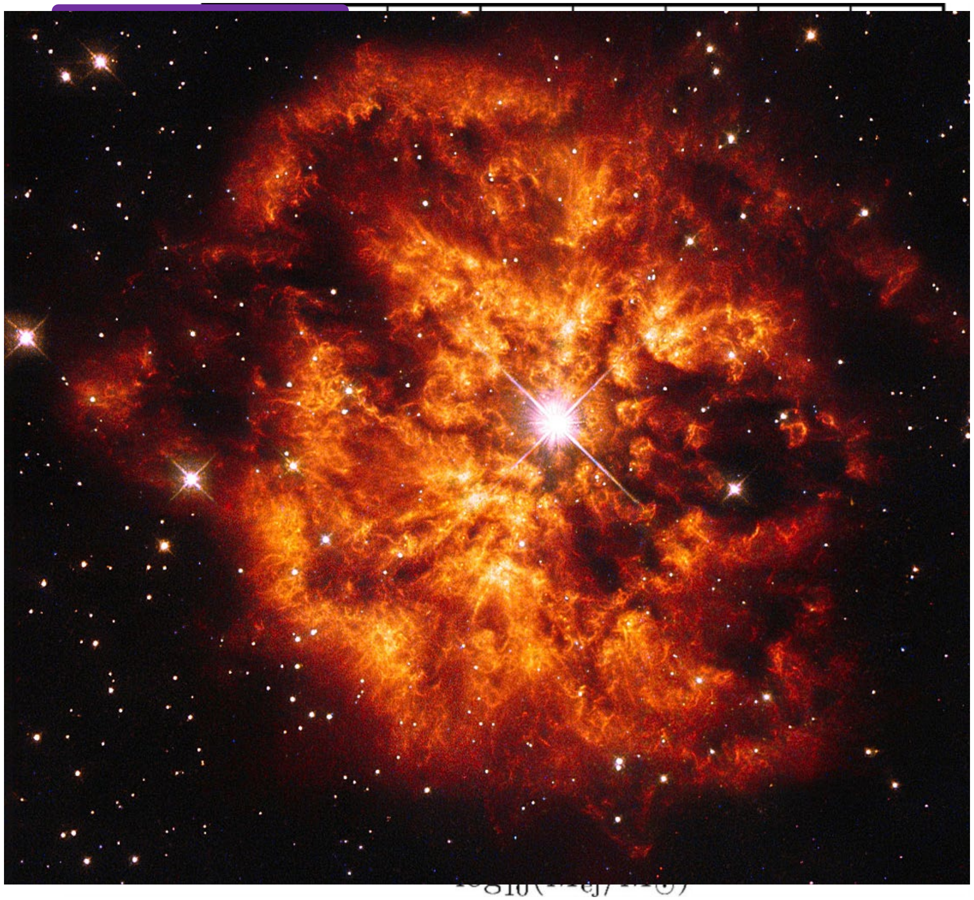
Supernova Explosion Properties

Name	E_{sn} [10^{51} ergs]	M_{ej} [$M_{\odot}$]	n_{ism} [cm^{-3}]
G11.2-0.3	0.05 – 0.2	6.5 – 16	1.5 – 5
G21.5-0.9	~0.1	~10	~0.2
G54.1+0.3	0.08 – 0.3	6 – 40	$(0.03 – 6)\times10^{-3}$
HESS J1640-465	~0.2	~0.5	~0.03
Kes 75	~0.1	~0.4	~0.25
MSH 15-52	~2	~5.5	~1

- ISM densities n_{ism} typically ~0.1 – 1 cm^{-3}
  - No molecular cloud environments
  - G54.1+0.3, HESS J1640-465 have lower densities → stellar wind bubbles?

Supernova Explosion Properties

- **3 (out of 6)** have low E_{sn}, high M_{ej}
  - Consistent with latest simulations
- **MSH 15-52** has low ejecta mass for E_{sn}
- $M_{ej} < 1M_{☼}$ for **HESS J1640-465** and **Kes 75**
  - Wolf-Rayet star?
  - Binary progenitor?

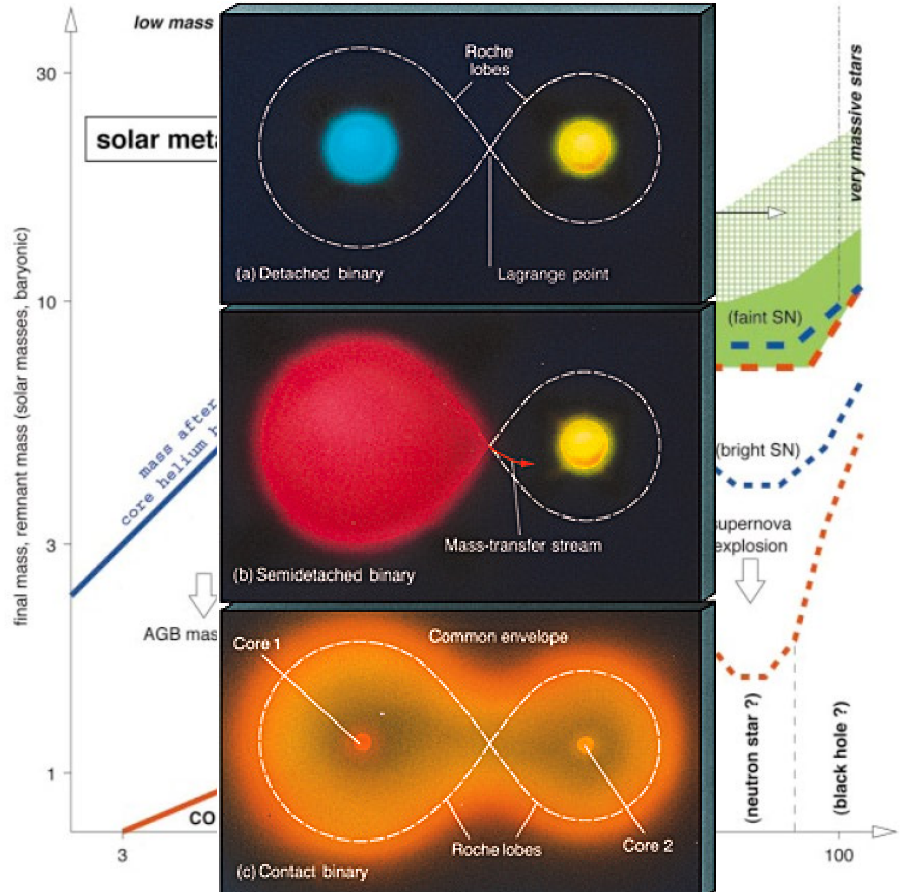


[Credit: ESA/Hubble & NASA
Acknowledgement: Judy Schmidt (geckzilla.com)]

(Müller et al. 2016, *MNRAS*, 460, 742)

Supernova Progenitors

- Ejecta mass M_{ej} connected to progenitor star
- Single star → Stellar Evolution
  - M_{ej} depends on initial mass, metallicity
- Binary system → Binary Evolution
  - Likely low ejecta mass due to mass transfer

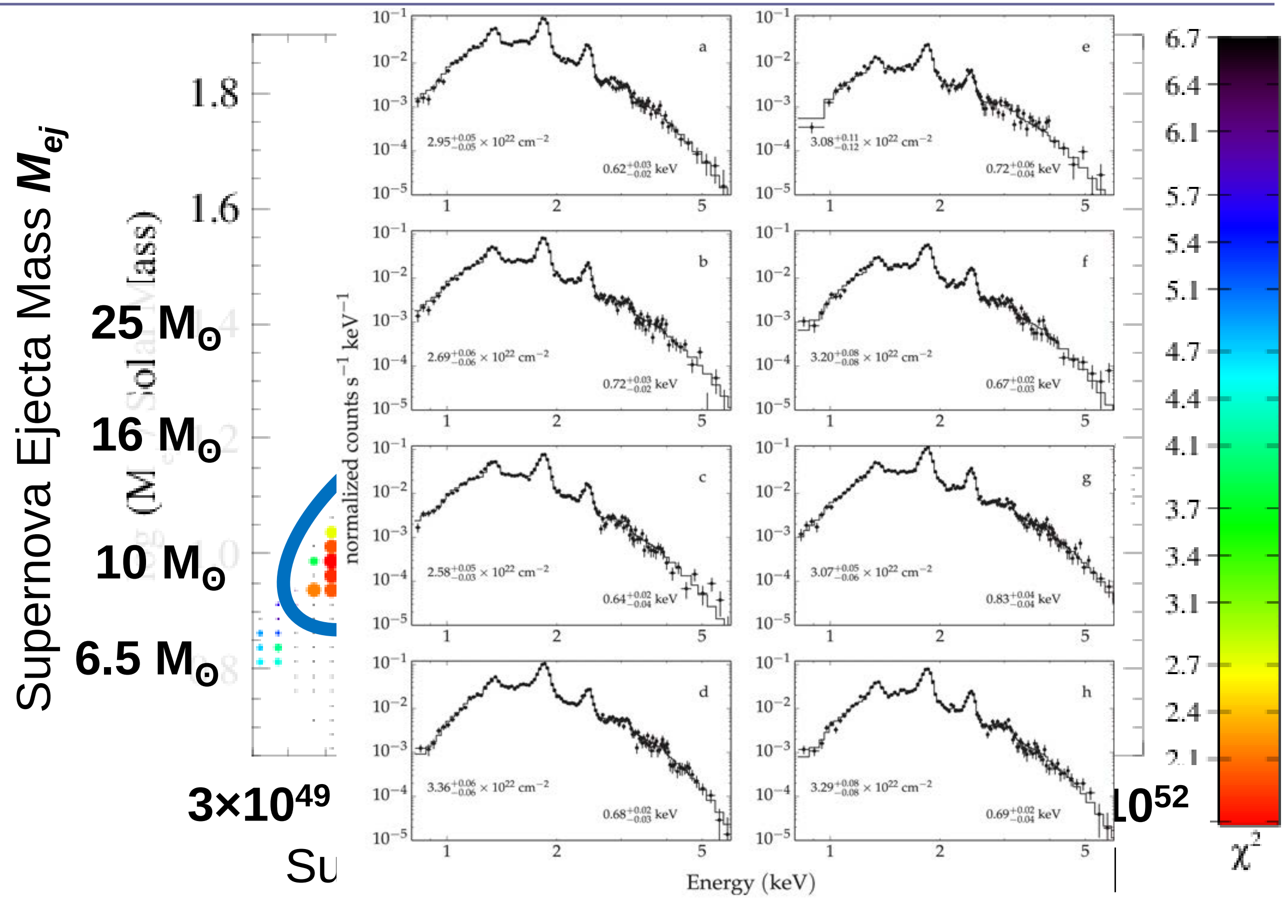


(Woosley et al. 2002, *RvMP*, 74, 1015)

http://www2.astro.psu.edu/users/rbc/a1/lec16n.html

SNR G11.2-0.3: Supernova Explosion

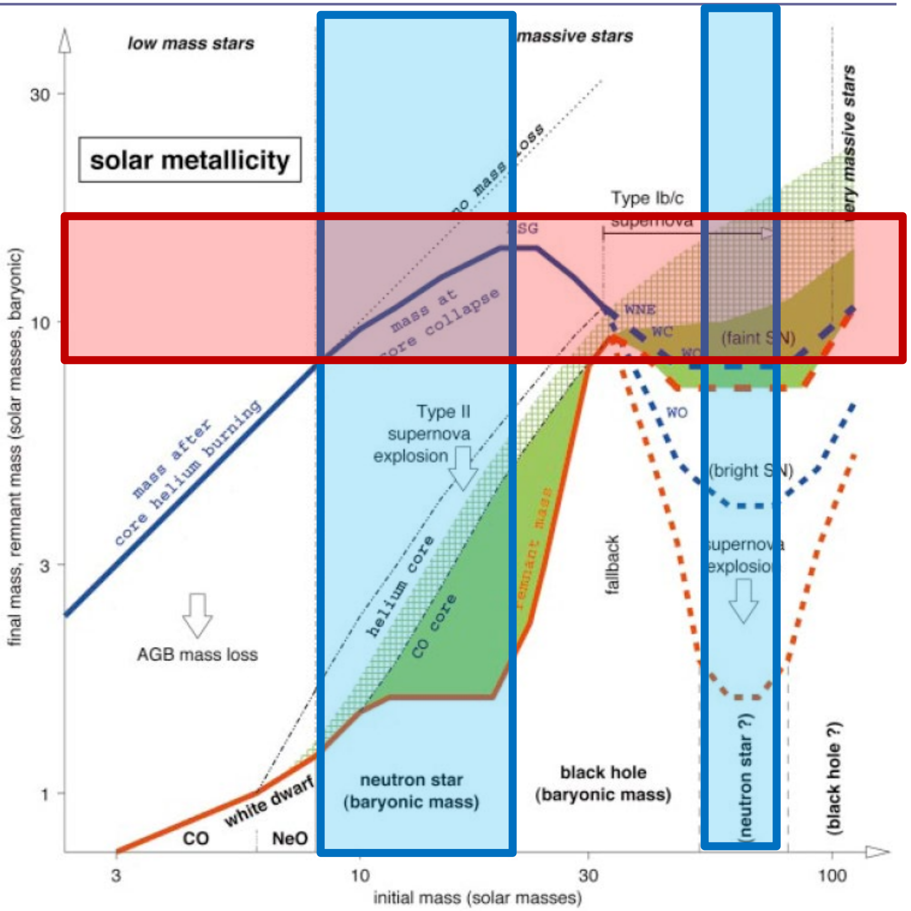
- Supernova properties
  - M_{ej} ~ 8 – 16$M_\odot$
  - E_{sn} ~ (0.3-3)×10^{50} erg
- Consistent with E_{sn} ~ 2×10^{50} erg estimated from thermal X-ray spectrum of SNR shell.



(Borkowski et al. 2016, *ApJ*, 819, 160)

SNR G11.2-0.3: Progenitor Star

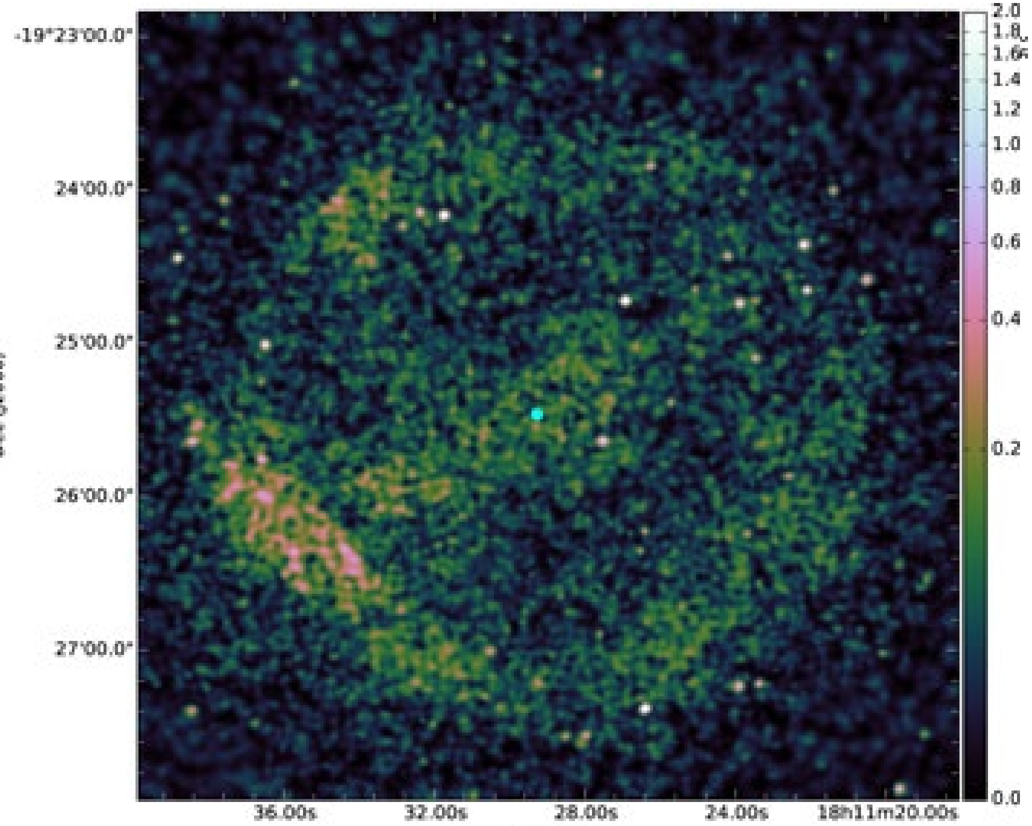
- Progenitor properties:
  - Produced a neutron star
  - M_{ej} ~ 8 – 16M$_\odot$
- ~8 – 20 M$_\odot$ star which exploded as a RSG (Type II supernova explosion)



(Woosley et al. 2002, *RvMP*, 74, 1015)

Supernova Remnant G11.2-0.3

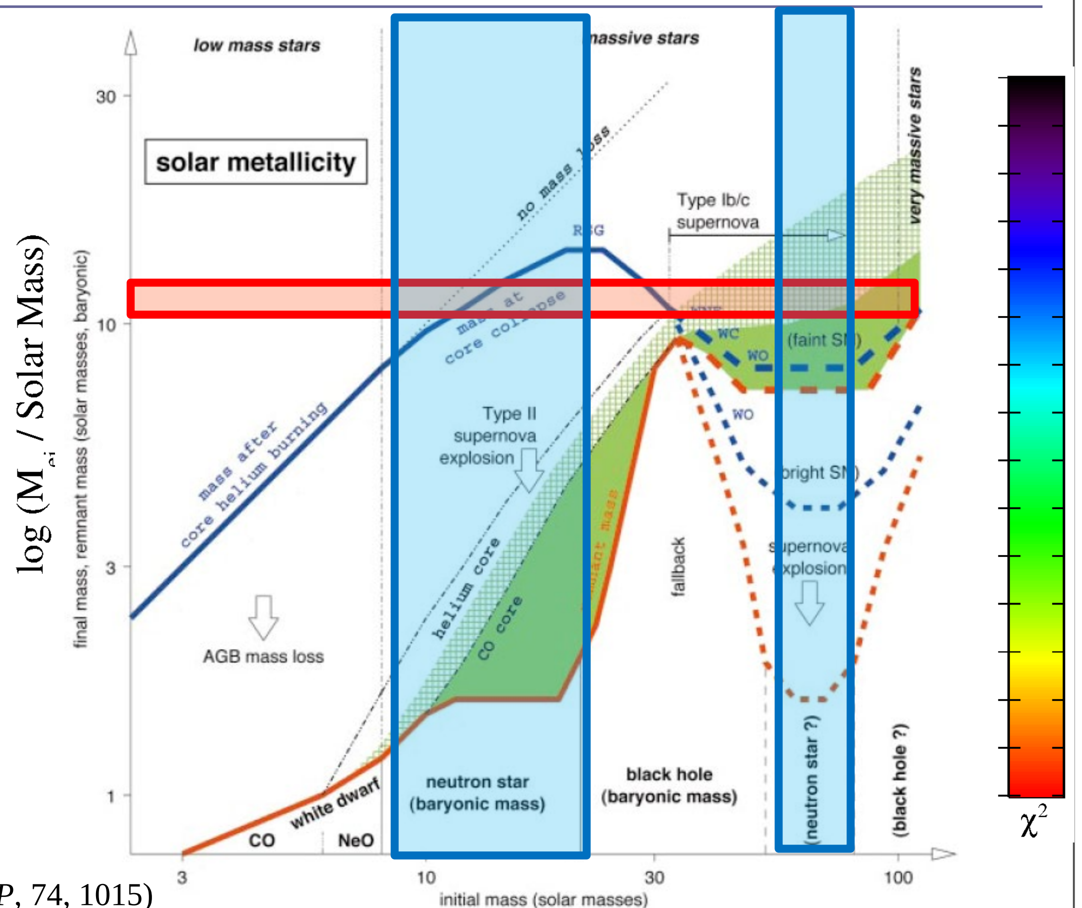
- Hard X-ray "rim"
  - Consistent with predicted location of SN reverse shock
- Energetic background photon field
  - T_{ic} ~ (1.5-6.5)×10^6 K
  - u_{ic} ~ 74 keV/cm^3 – 1 MeV/cm^3
  - Consistent with SNR thermal X-ray emission



(Borkowski et al. 2016 ApJ 819 160)

G21.5-0.9: Progenitor Supernova Explosion and Star

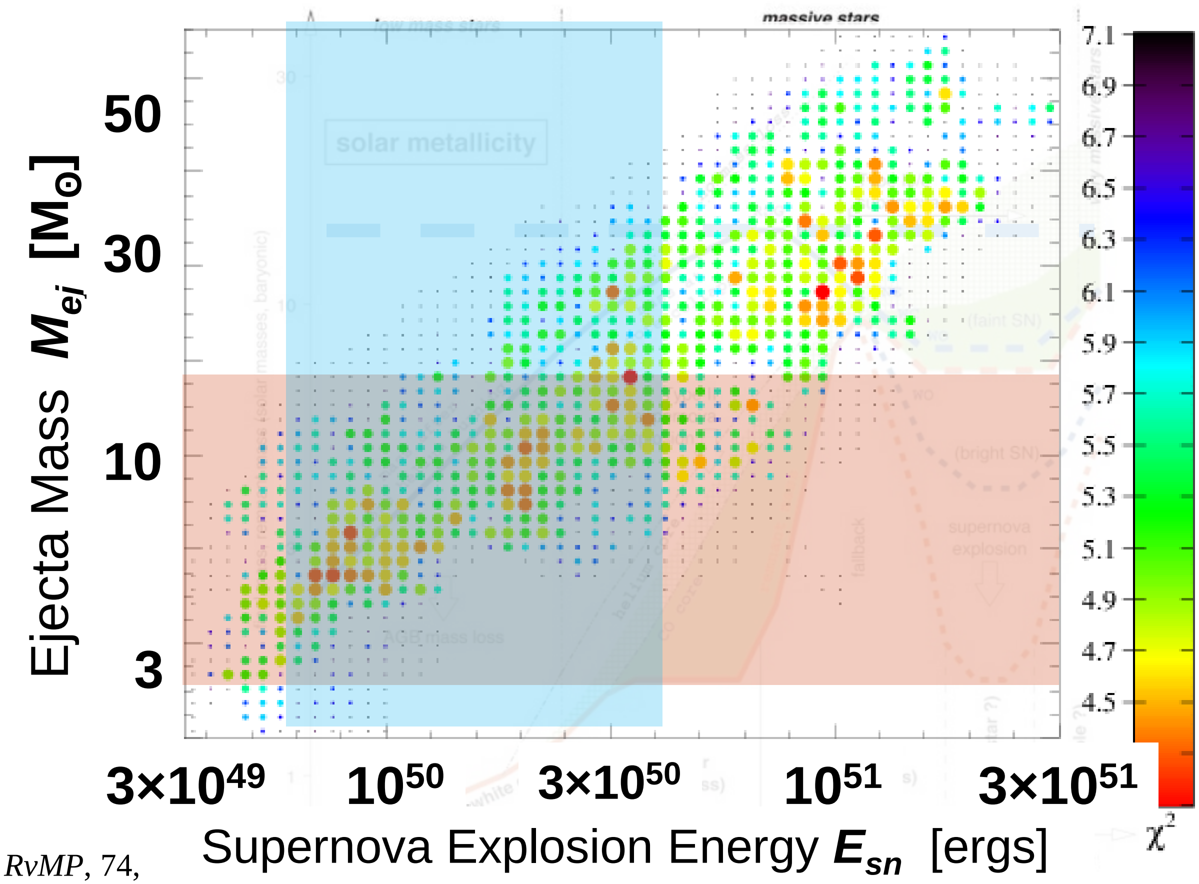
- Preliminary results
  - $E_{sn} \sim 10^{50}$ ergs
  - $M_{ej} \sim 10\ M_☉$
- Stellar evolution models suggest ~15 $M_☉$ progenitor
  - Ongoing exploration of parameter space



(Woosley et al. 2002, *RvMP*, 74, 1015)

G54.1+0.3: Supernova Explosion

- Broad range of allowed E_{sn} and M_{ej}
  - Realistically $M_{ej} \leq 20$ M$_\odot$
  - $E_{sn} \leq 3\times10^{50}$ erg



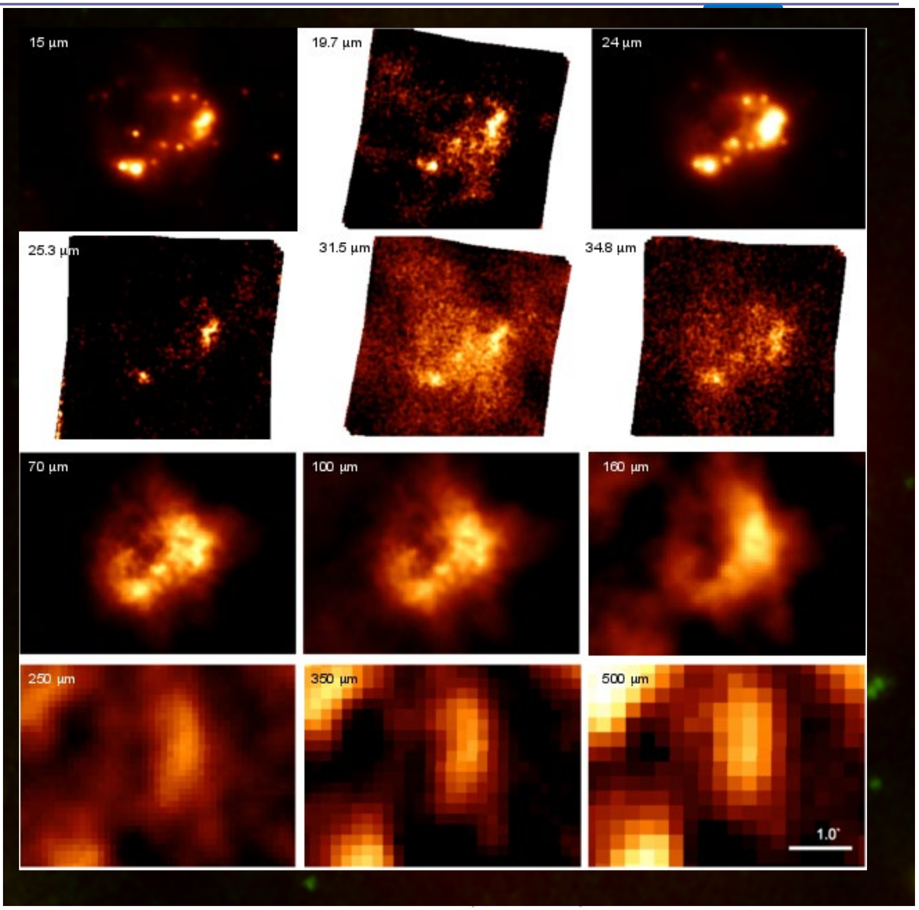
(Woosley et al. 2002, *RvMP*, 74,

(Gelfand et al. 2015, *ApJ*, 807, 30)

G54.1+0.3: Progenitor Star

- $>10^{50}$ erg SN requires $\boldsymbol{M_{ej}} > 10\ M_\odot$
  - ~15 – 20 $M_\odot$ progenitor
- Massive progenitor has a short lifetime
  - Supernova likely near birth site / massive star cluster
  - Supported by O/B stars embedded in associated IR shell
- Analysis of IR emission suggests ~16 – 27 $M_\odot$ progenitor

(Woosley et al. 2002, *RvMP*, 74, 1015)

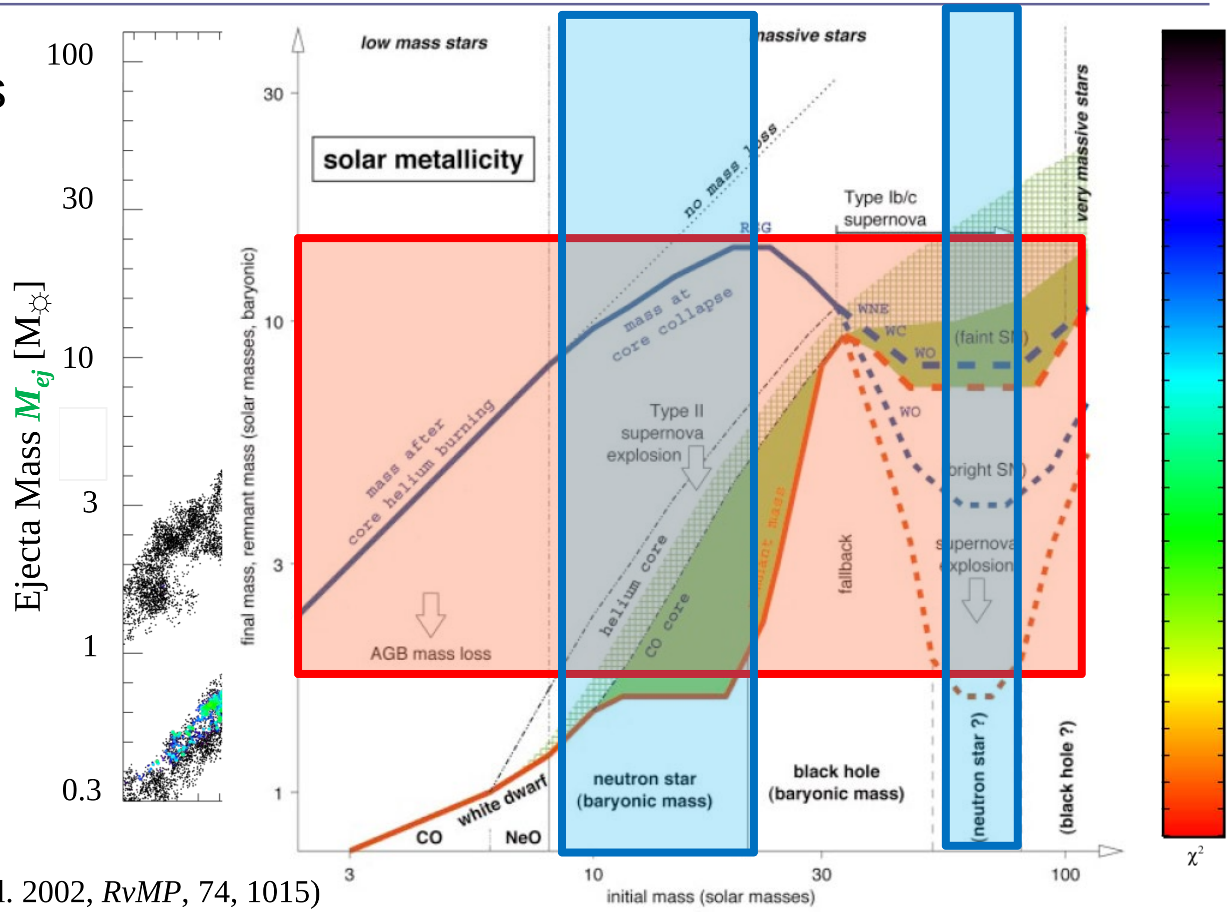


(X-ray: NASA/CXC/SAO/T.Temim et al.; IR: NASA/JPL-Caltech)

(Temim et al. 2017, *ApJ*, 836, 129)

Kes 75: Progenitor Supernova Explosion and Star

- Wide range of allowed parameters
  - $E_{sn} = 10^{50} - 10^{52}$ ergs
  - $M_{ej} = 2 - 20\ M_\odot$
- Stellar evolution models predict $M_{ej} \approx 4 - 20\ M_\odot$
  - Most massive (Wolf-Rayet) stars have low M_{ej}
- Wolf-Rayet scenario allowed
  - Prefers slightly sub-energetic supernova



(Woosley et al. 2002, *RvMP*, 74, 1015)

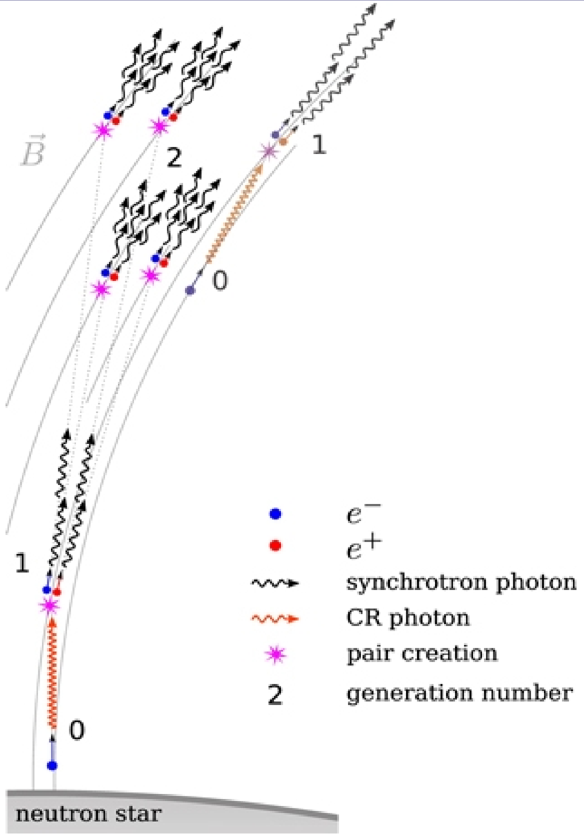
(Gelfand et al. 2014, *AN*, 335, 318)

Pulsar Birth Properties

Name	PSR	B_{sd} [G]	P_0 [ms]	t_{ch} [yr]	τ_{sd} [yr]	t_{age} [yr]
G11.2-0.3	J1811-1925	1.7×10^{12}	≈61.4	2.3×10^{4}	(2-3.5) $\times10^{4}$	2100-2700
G54.1+0.3	J1930+1852	1.0×10^{13}	≈65	2900	2000 – 4000 (***p*** = 1.94)	2200-2400 (***p*** = 1.94)
MSH 15-52	B1509-58	1.5×10^{13}	72 – 78	1600	~500	~1200
HESS J1640-465	J1640-4631	1.4×10^{13}	20 – 35	3350	≤30 (***p*** = 3.15)	~3100 (***p*** = 3.15)
Kes 75	J1846-0258	4.9×10^{13}	≈200	730	~400	~500
G21.5-0.9	J1833-1034	3.6×10^{12}	~50	4850	~2900	~1700

Particle Creation in Neutron Star Magnetospheres

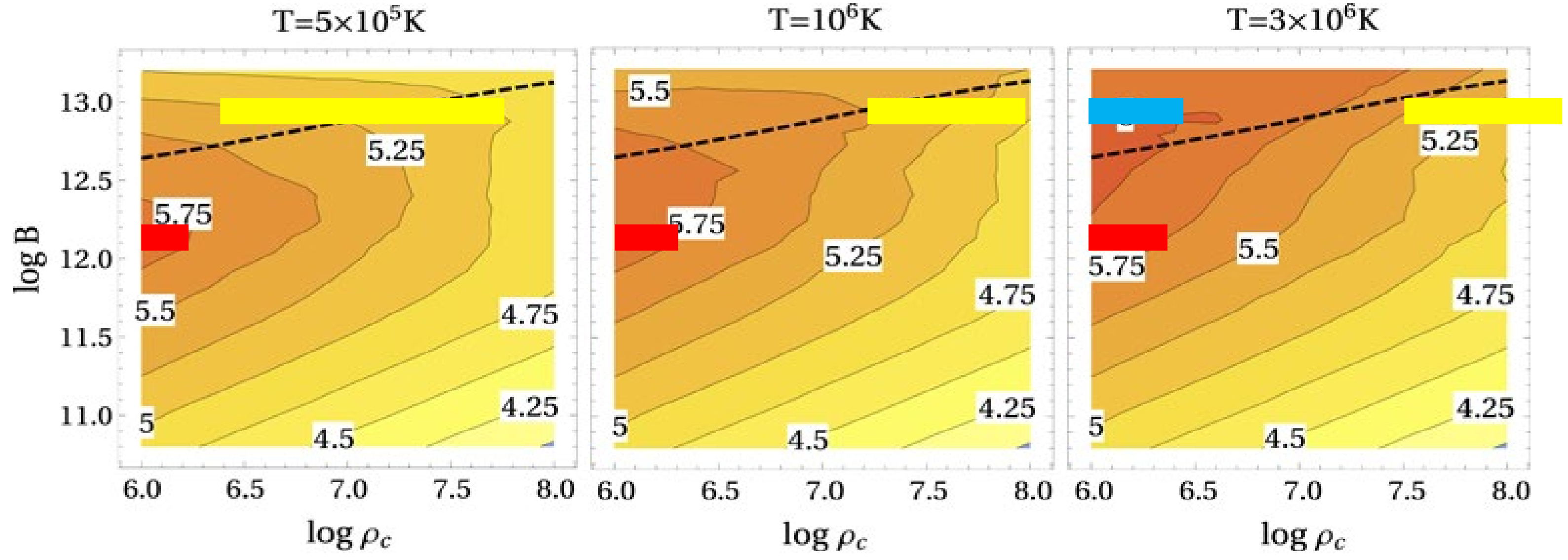
- Particle creation process depends on:
  - Magnetic field strength B_{ns}
  - Field Line radius of curvature at polar cap ρ_c
  - Surface temperature T
- PWN modeling provides "time-integrated multiplicity" κ_{int}
  - (Total number of particles) / (Integrated Goldreich-Julian current density)



(Timokhin & Harding 2015, *ApJ*, 810, 144)

Pulsar Multiplicities

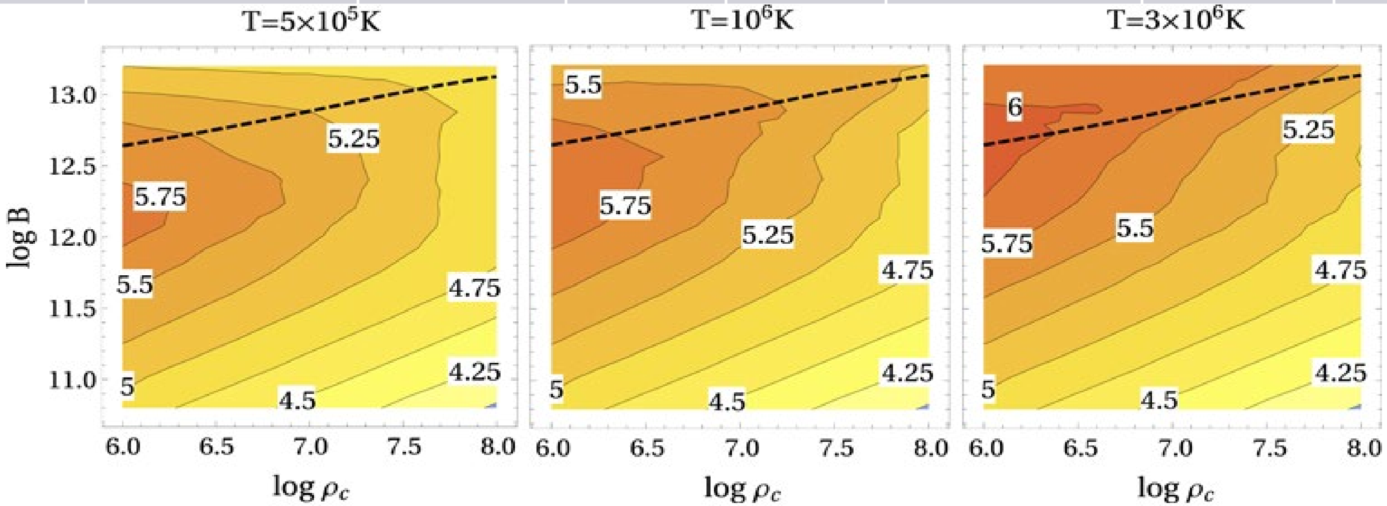
Name	PSR	B_{sd} [G]	κ_{int}	ρ_c	T
G11.2-0.3	J1811-1925	1.7×10^{12}	$\sim7\times10^{5}$	<30 km	
G54.1+0.3	J1930+1852	1.0×10^{13}	$(1\text{-}3)\times10^{5}$	>30 km	
Kes 75	J1846-0258	4.9×10^{13}	$>3\times10^{6}$	<30 km	3×10^{6}



(Timokhin & Harding, 2019, *ApJ*, 871, 12)

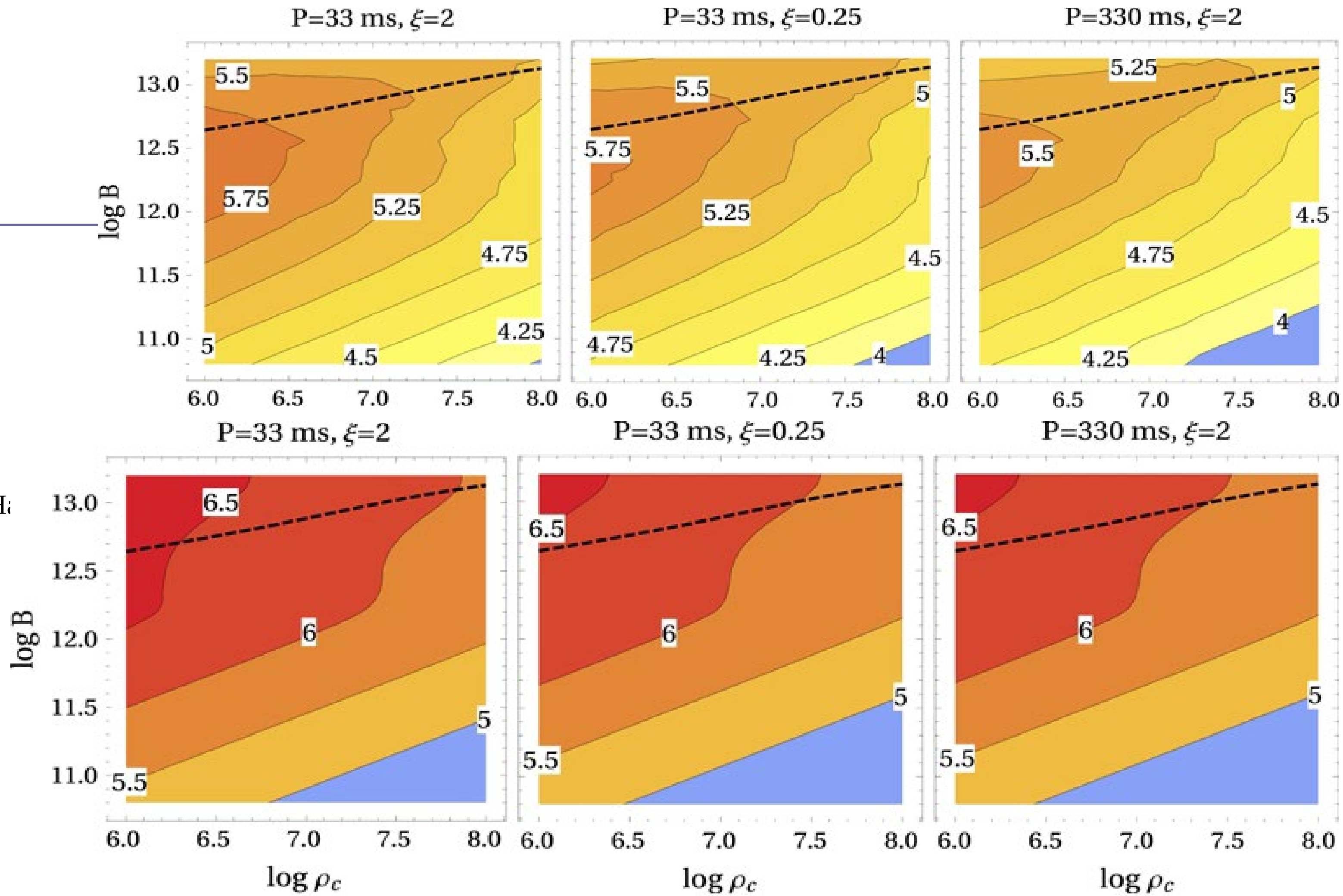
Particle Creation

Name	PSR	B_{sd} [G]	P [ms]	P_0 [ms]	κ_{int}	ρ_c	T
G11.2-0.3	J1811-1925	1.7×10^{12}	64.7	≈61.4	~7×10^5		
G54.1+0.3	J1930+1852	1.0×10^{13}	136.9	≈65	$(1\text{-}3)\times10^5$		
Kes 75	J1846-0258	4.9×10^{13}	326.6	≈200	$>3\times10^6$		



(Timokhin & Harding, 2019, *ApJ*, 871, 12)

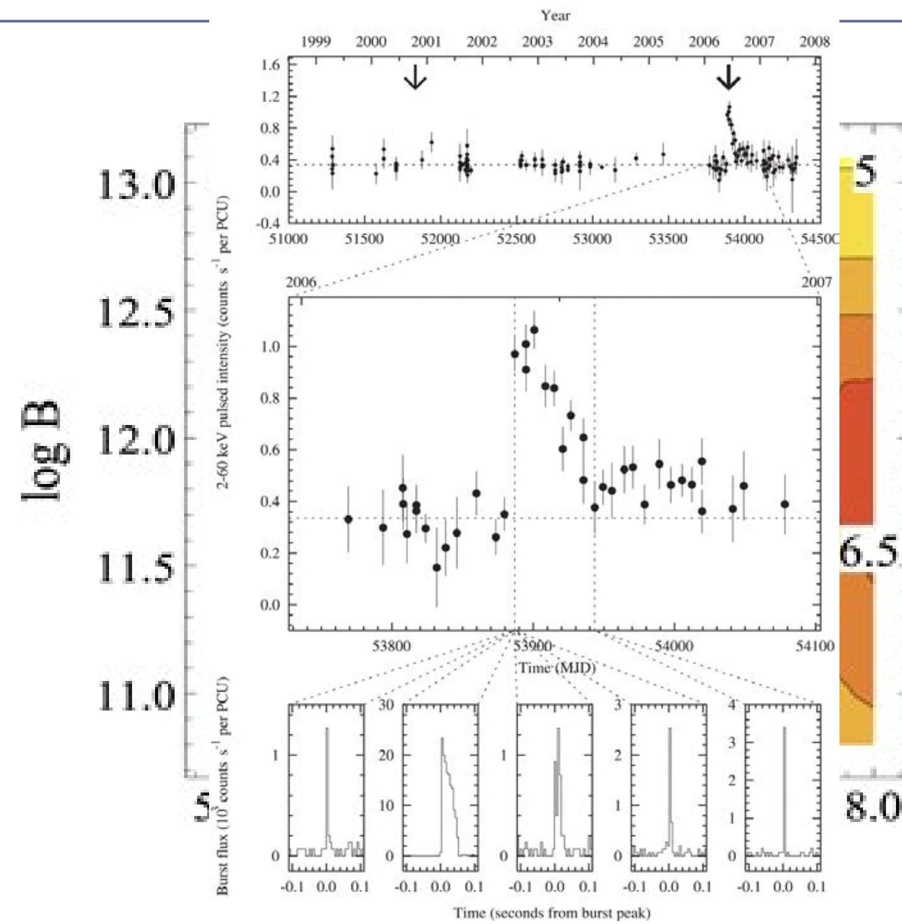
(Timokhin & Ha



(Timokhin & Harding 2019, *ApJ*, 871, 12)

Kes 75: Pulsar Multiplicities

- PWN Kes 75 / PSR J1845 – 025
  - $B_{ns} = 5\times10^{13}$ G
  - $\kappa_{int} > 3\times10^{6}$
- Too high for current models
  - Additional particle creation related to “magnetar” behavior?



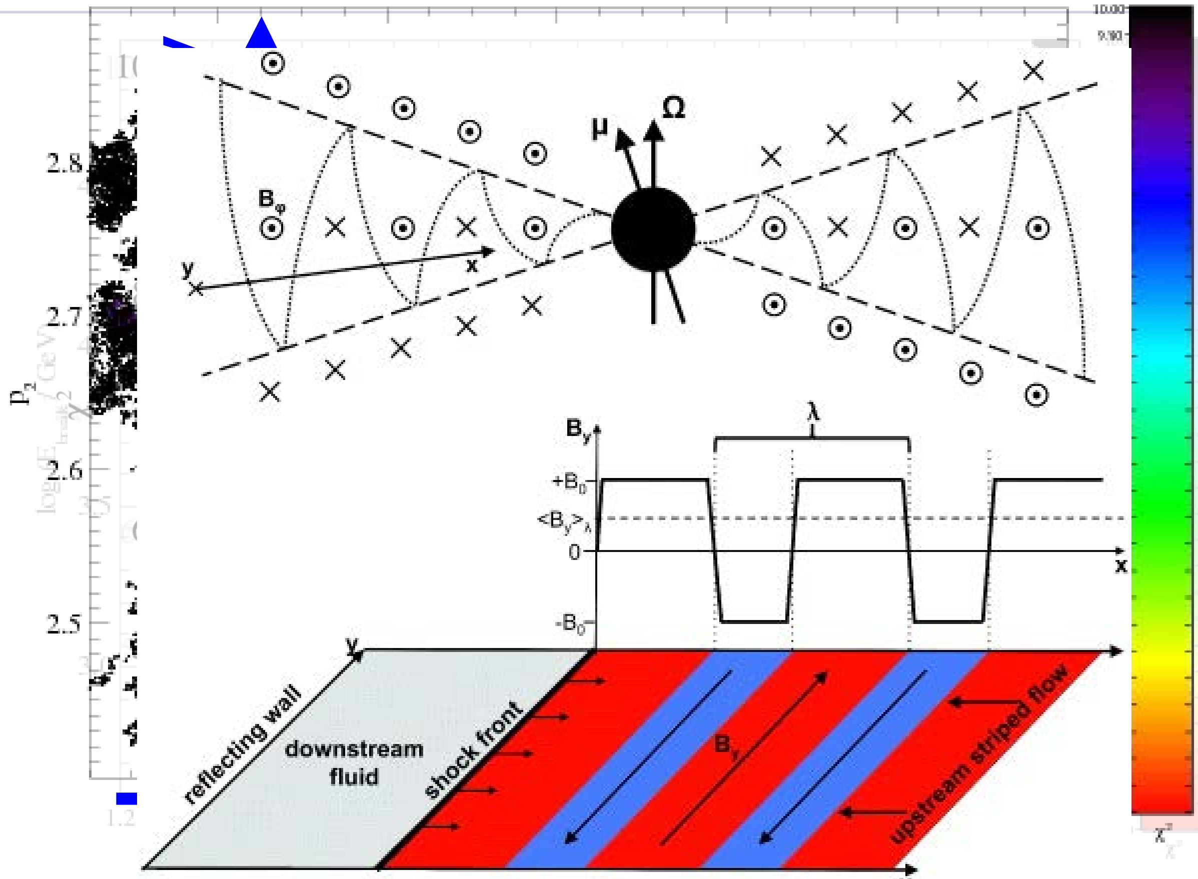
(Timokhin & Harding 2015, *ApJ*, 810, 144)

Pulsar Wind Particle Acceleration

Name	PSR	$\dot{E}_{psr}$	Φ_{psr}	E_{min}	E_{break}	E_{max}
G11.2-0.3	J1811-1925	6.4×10^{36}	4.4 PV	10 – 150 MeV	10 – 45 GeV	1 – 30 PeV
G54.1+0.3	J1930+1852	1.2×10^{37}	6.0 PV	0.3 – 15 GeV	~0.7 – 10 TeV	>1 PeV
MSH 15-52	B1509-58	1.7×10^{37}	7.1 PV	=511 keV	~0.2 TeV	~0.4 PeV
HESS J1640-465	J1640-4631	4.4×10^{36}	3.6 PV	~100 keV	~0.2 TeV	~1.5 PeV
Kes 75	J1846-0258	8.1×10^{36}	4.9 PV	~1 GeV	~0.4 TeV	~1 PeV
G21.5-0.9	J1833-1034	3.4×10^{37}	10 PV	~12.5 GeV	~1 TeV	~0.25 PeV

G54.1+0.3: (Post-shock) Pulsar Wind

- Particle-dominated
  - $\eta_B \sim 10^{-3}$
- Broken Power-Law Spectrum
  - $E_{min} \approx 11$ GeV
  - $E_{break} = 2 – 20$ TeV
  - $p_1 = 1.7 – 2.1$
  - $E_{max} > 1$ PeV
  - $p_2 = 2.6 – 2.8$



(Gelfand et al., *ApJ* submitted)

(Sironi & Spitkovsky, 2012, doi:10.1088/1749-4699/5/1/014014)

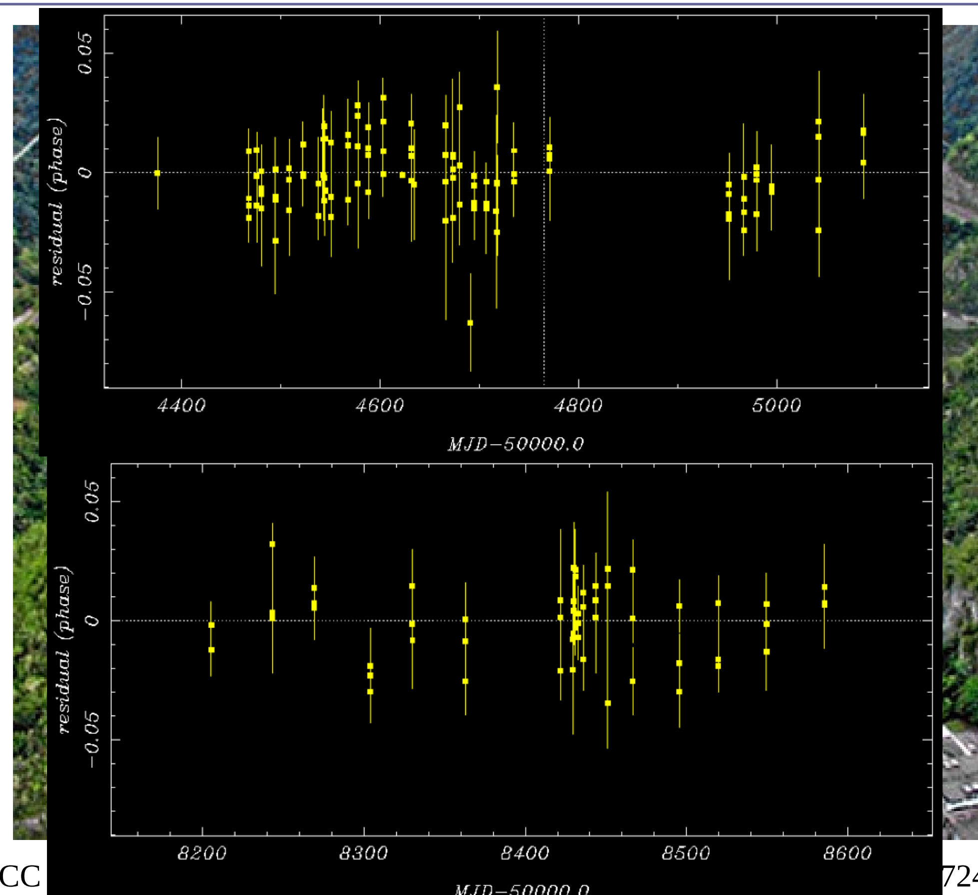
Summary

- Simple model for evolution of PWN inside a SNR:
  - reproduces observed properties of numerous systems,
  - accurately predicted values of new observations.
- Application to a (small) sample of PWN:
  - Low energy – High mass explosions produce pulsars
  - Neutron star magnetic field strength correlated with progenitor mass (?)
  - Initial spin periods (fairly) consistent with fallback model
  - Inferred multiplicities (barely) achieved by current theory
  - Particle spectrum (normally) consistent with magnetic reconnection + Fermi acceleration
  - Maximum energy (generally) consistent with pulsar voltage

Thank you !

Timing campaign(s) on PSR J1930+1852

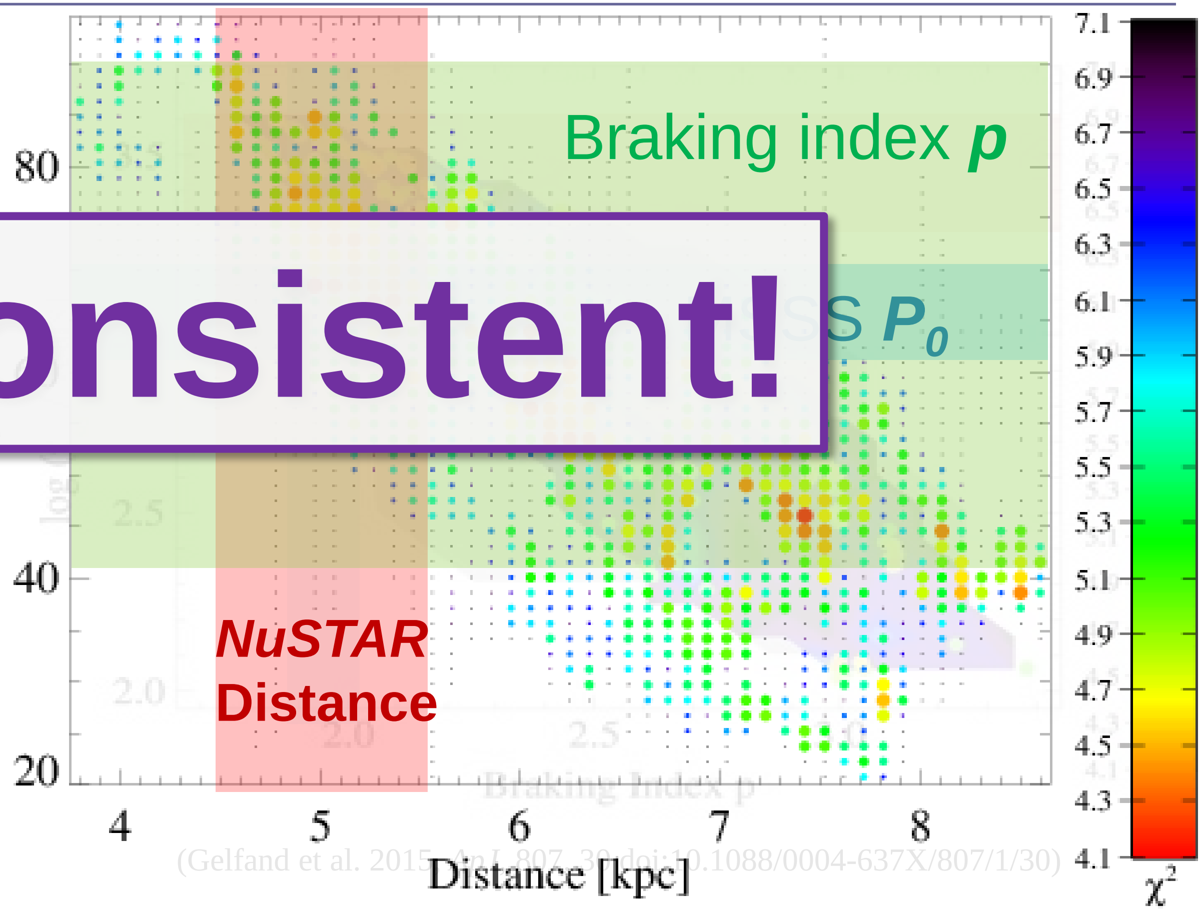
- Two timing campaigns
  - Arecibo: 2007 Oct. – 2009 Sept.
  - GBT: 2018 Mar. – present
- Success!
  - Braking index ***p***=1.9372 ± 0.0031



(By JidoBG - Own work, CC … 7240)

Properties of PSR J1930+1852 / PWN G54.1+0.3

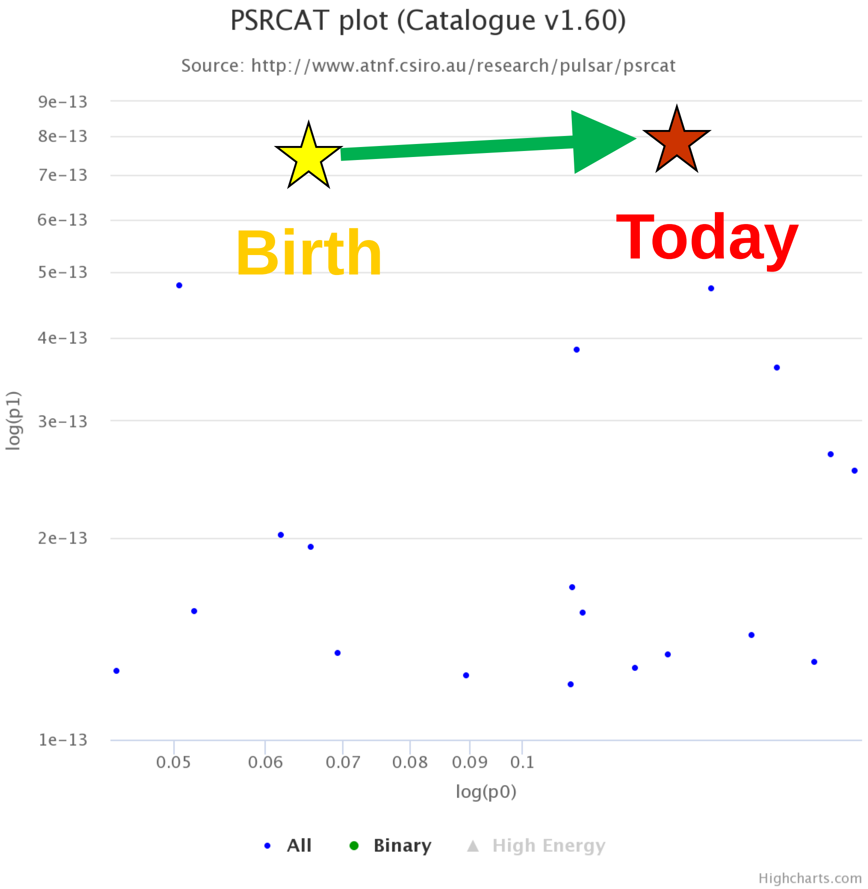
- Measured ***p*** + PWN fitting
  - τ_{sd} ~ 2000 – 4000 yr
- Implications:
  - Age ~ 2200 – 4200 yr
  - P_0 ~ 40 – 90 ms



Consistent!

Birth properties and Evolution of PSR J1930+1852 in G54.1+0.3

- “New” properties:
  - ***p*** = 1.9372
  - $\boldsymbol{P_0}$ ~ 65 ms
- Birth properties:
  - **Age** ≈ 3100 years
  - Initial $\boldsymbol{B_{sd}}$=7e12 G
  - Now $\boldsymbol{B_{sd}}$ = 1e13 G
- 50% increase in “magnetic field”



What's next? More data!

- New / Improved observatories
  - Better SEDs
  - More PWNe
  - Timing young pulsars