Investigating the Symmetry and Progenitors of Supernova Remnants

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In collaboration with:
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Conclusions

➡ The wealth of data available on supernova remnants offers an exciting basis for comparison between sources

➡ SNRs can be "typed" based on their symmetry

➡ Jet-driven SNe (those with collimated outflows) occur at rates that we may expect to find a handful in MW and nearby galaxies

➡ Identified two possible jet-driven SNRs, W49B and SMC 0104-72.3, based on six observational characteristics

➡ SNRs with magnetars have the same symmetry as those without magnetars

➡ NuSTAR hard X-ray imaging revealing important insights about explosion asymmetries, progenitors, and particle acceleration

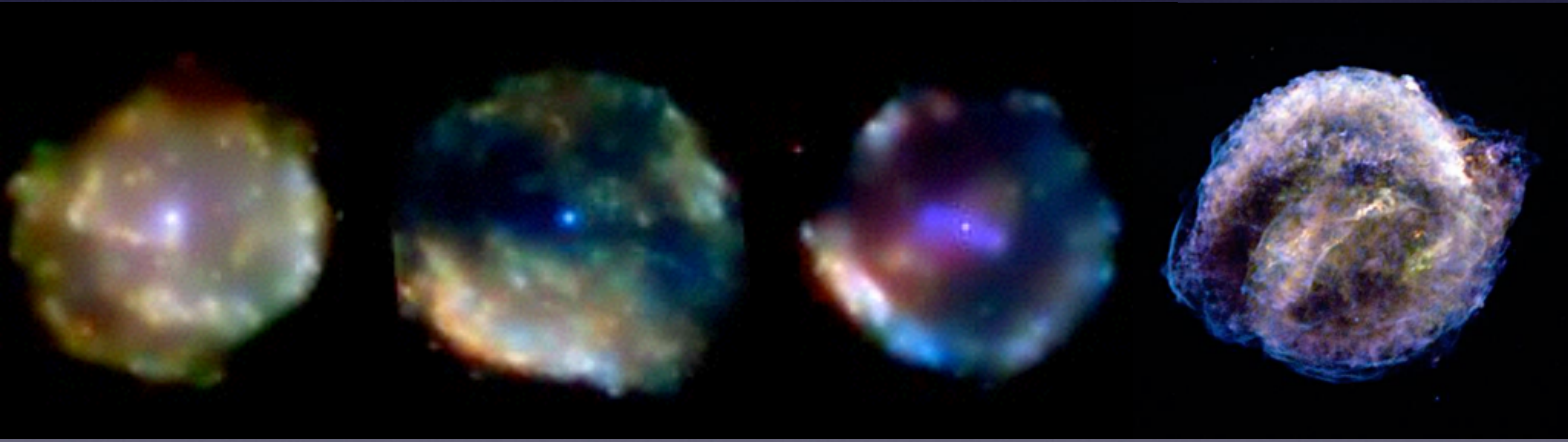
By the Numbers

- ➡ ~375 known supernova remnants in the Milky Way, Large and Small Magellanic Cloud
- ➡ 164 MW, LMC, and SMC SNRs imaged with X-ray telescopes
- ➡ ~20 of 164 are classified as Type Ia SNRs based on metal abundances
- ➡ 70 have detected central compact objects; 41 have pulsar wind nebulae
- ➡ 70 are interacting with molecular clouds

Use SNRs to test SN models, especially with statistical studies between populations to discern trends

Typing Supernova Remnants

I. Presence of a neutron star
II. Light echoes (light reflected by nearby dust retains spectral info)
III. Chemical abundances (e.g., O/Fe)
IV. Environment (ISM/CSM density & structure, star formation)
V. Morphological (a)symmetry



Measuring Symmetry in SNRs

My typing method: symmetry

Calculate multipole moments of the X-ray image (Buote & Tsai 1995, 1996; Jeltema et al. 2005)

Derived the same as in the expansion of 2D gravitational potential within a radius R (Binney & Tremaine, Section 2.4):

$$\Psi(R,\phi) = -2Ga_0 \ln\left(\frac{1}{R}\right) - 2G\sum_{m=1}^{\infty} \frac{1}{mR^m}\left(a_m \cos m\phi + b_m \sin m\phi\right)$$

$$a_m(R) = \int_{R' \le R} \Sigma(\vec{x}')\,(R')^m \cos m\phi' \, d^2x'$$

$$b_m(R) = \int_{R' \le R} \Sigma(\vec{x}')\,(R')^m \sin m\phi' \, d^2x'$$

x\`=(R\`,φ) and Σ is the mass surface density (X-ray surface brightness in our calculation)

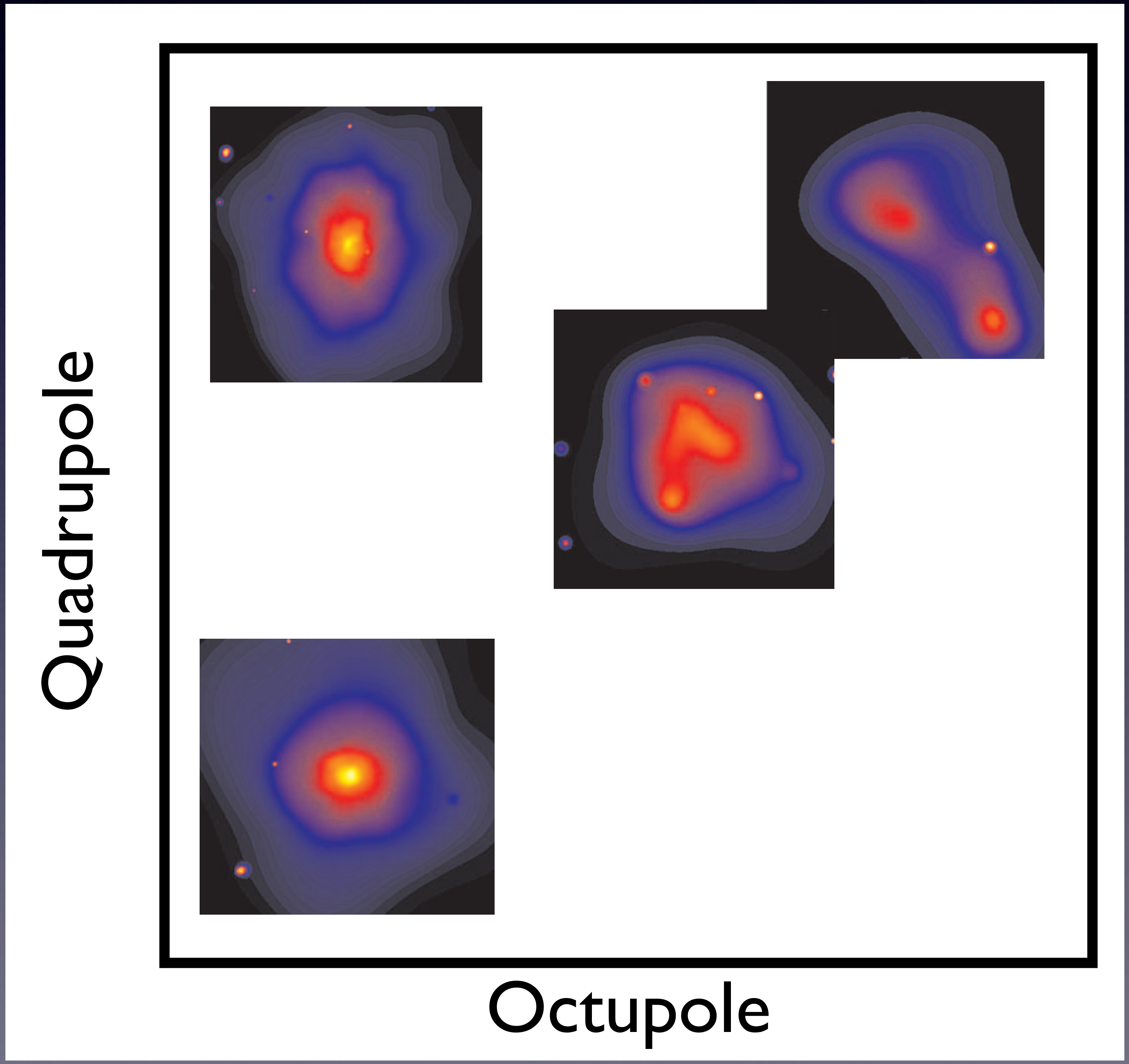
Lopez et al. 2009a/b

Measuring Symmetry

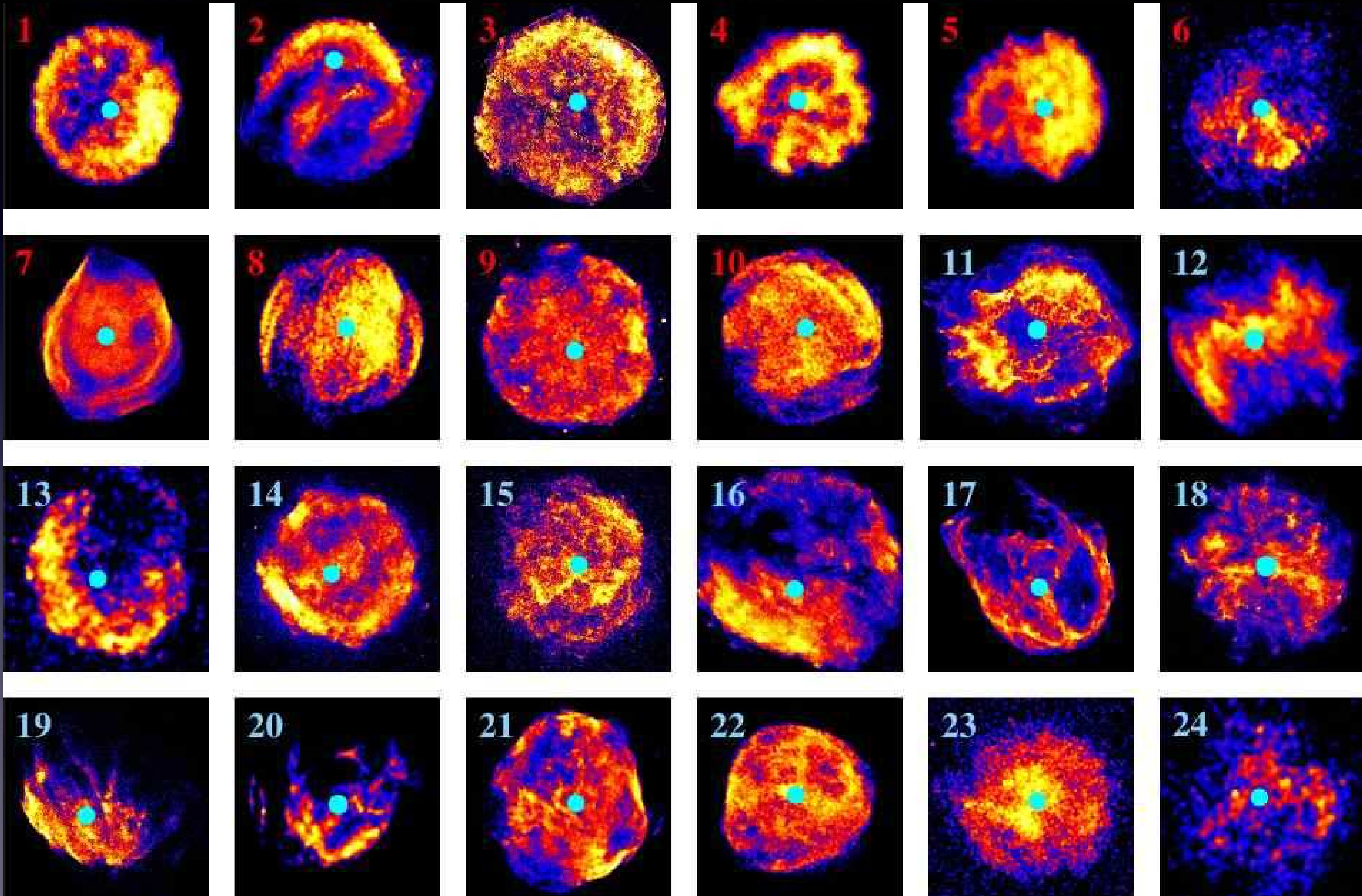
Calculate multipole moments of the X-ray image (Buote & Tsai 1995, 1996; Jeltema et al. 2005)

➡ Quadrupole:
measure of ellipticity
Large for elliptical source, small for circular source

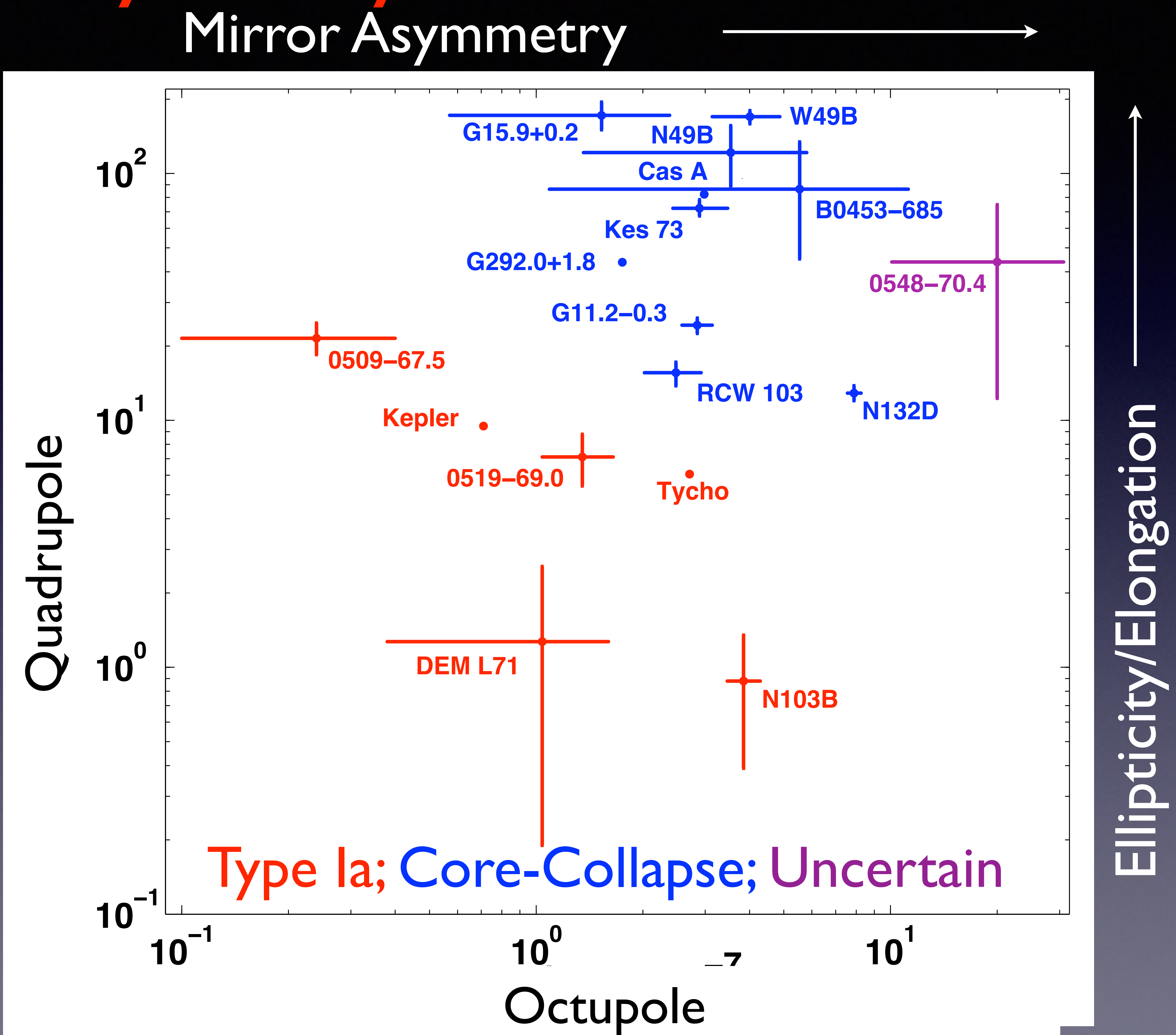
➡ Octupole:
measure of mirror asymmetry
Large for sources with one brighter side; small for homogeneous sources



Symmetry Sample

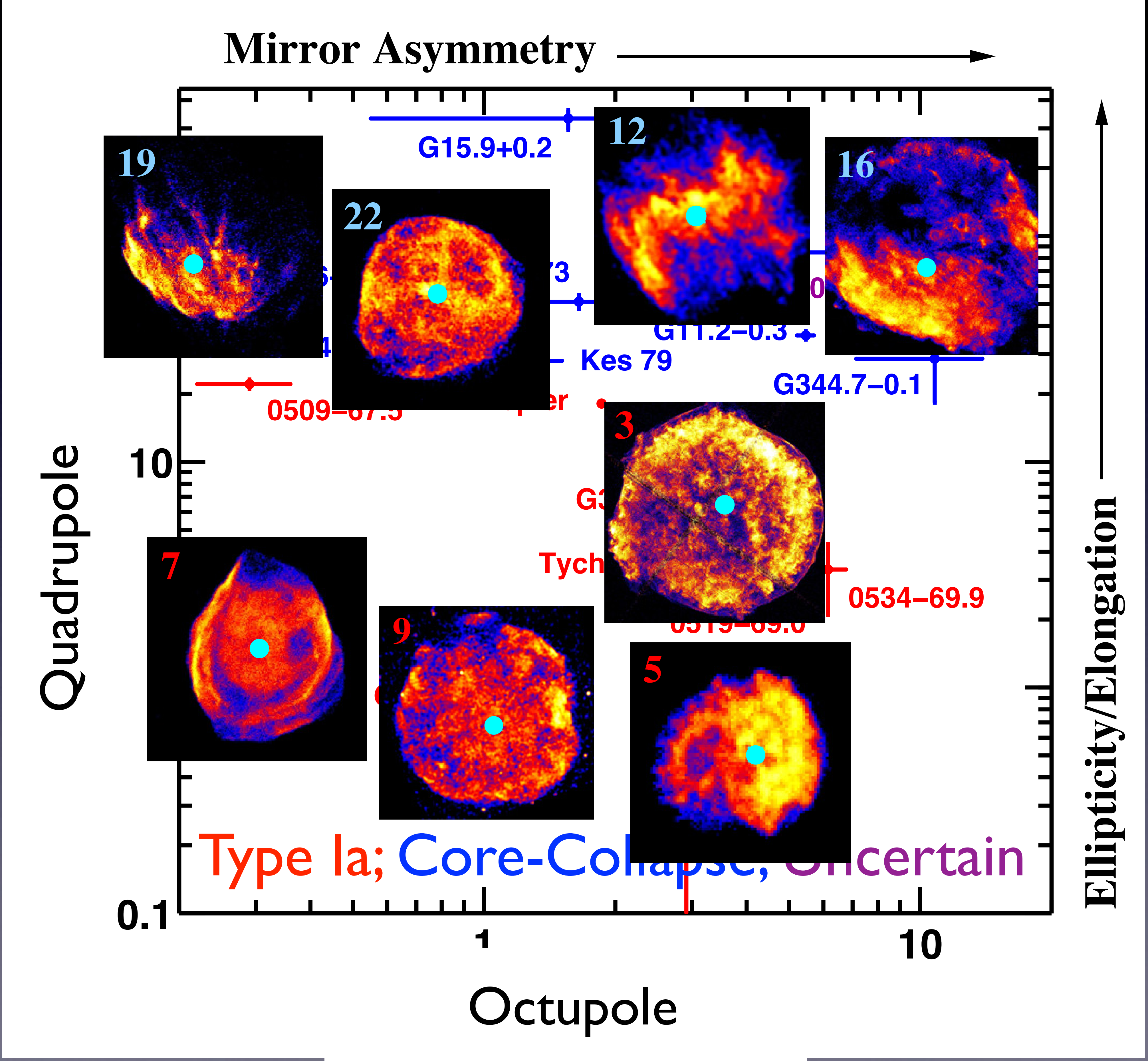


Symmetry of Silicon Line Emission



Lopez et al. 2009b

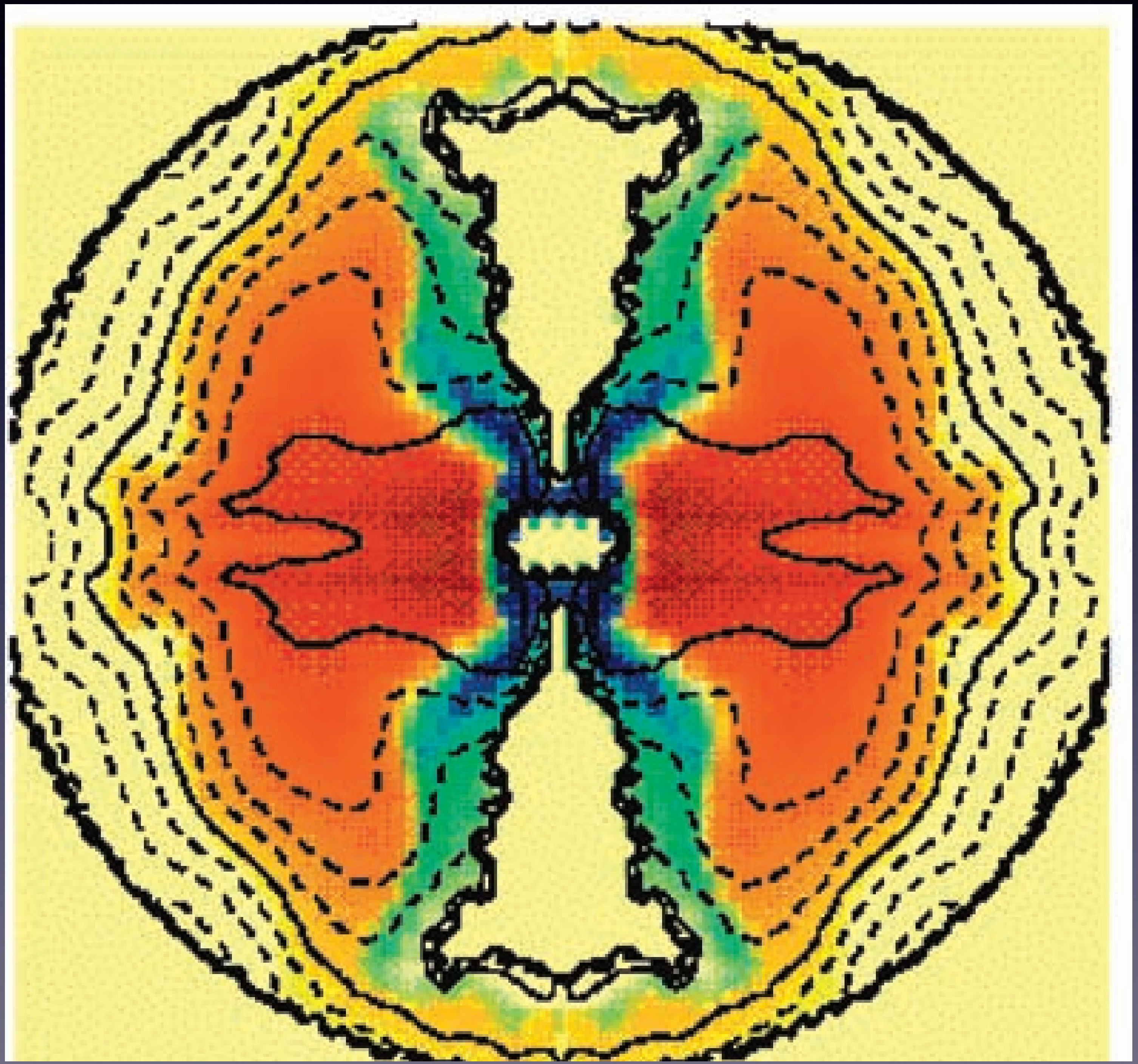
Symmetry of Thermal Emission



Lopez et al. 2011

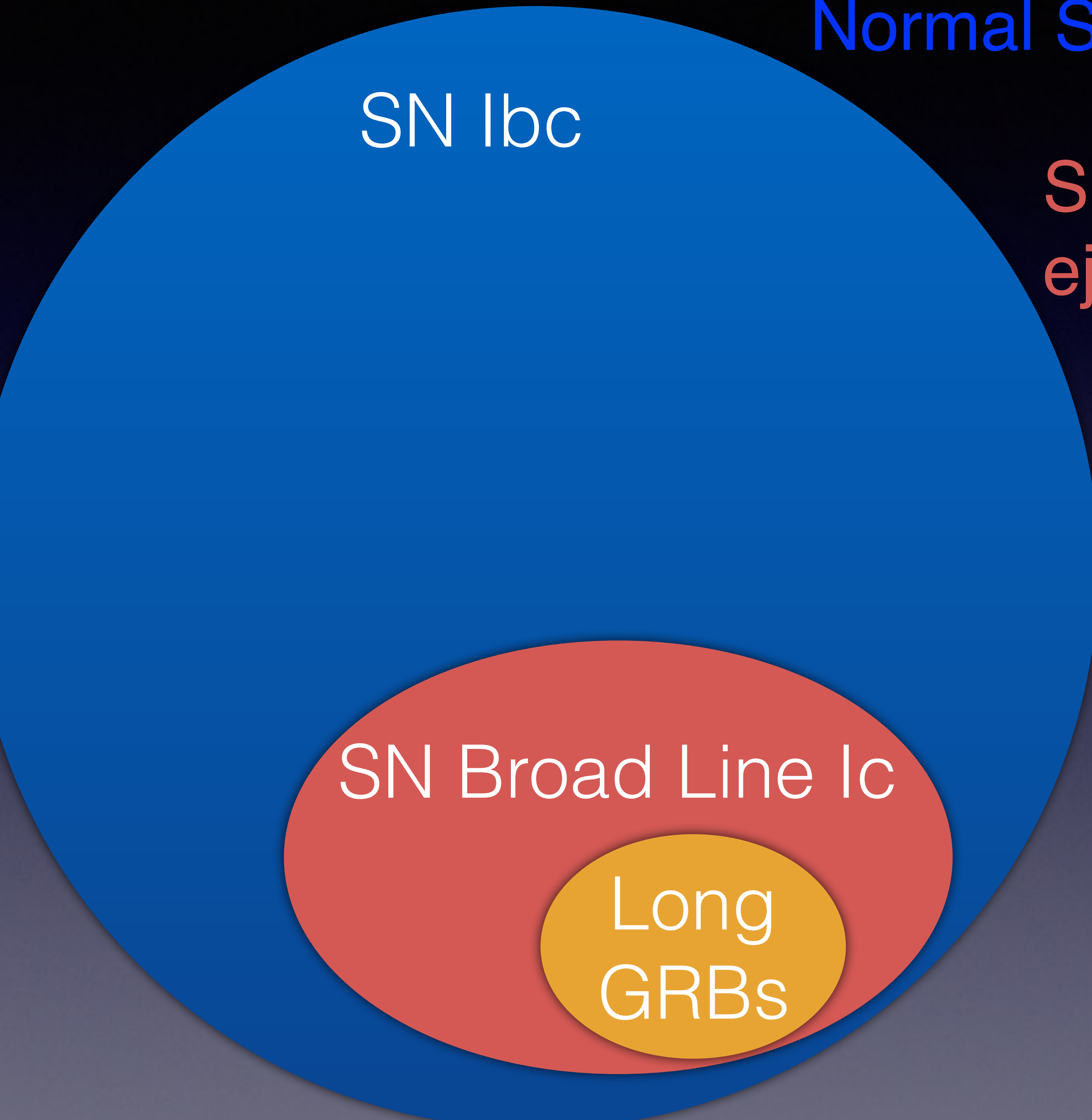
Jet-Driven SNe

Study of SNe and long GRBs has revealed a continuum of "engine-driven" SNe which depend on rotation and metallicity



Nickel; Oxygen Mazzali et al. 2006

GRB-SN connection



Normal SNe Ibc are non-relativistic

SN BL-Ic: mildly relativistic ejecta, 10^{52} erg kinetic energy

SN BL-Ic associated with long GRBs are relativistic

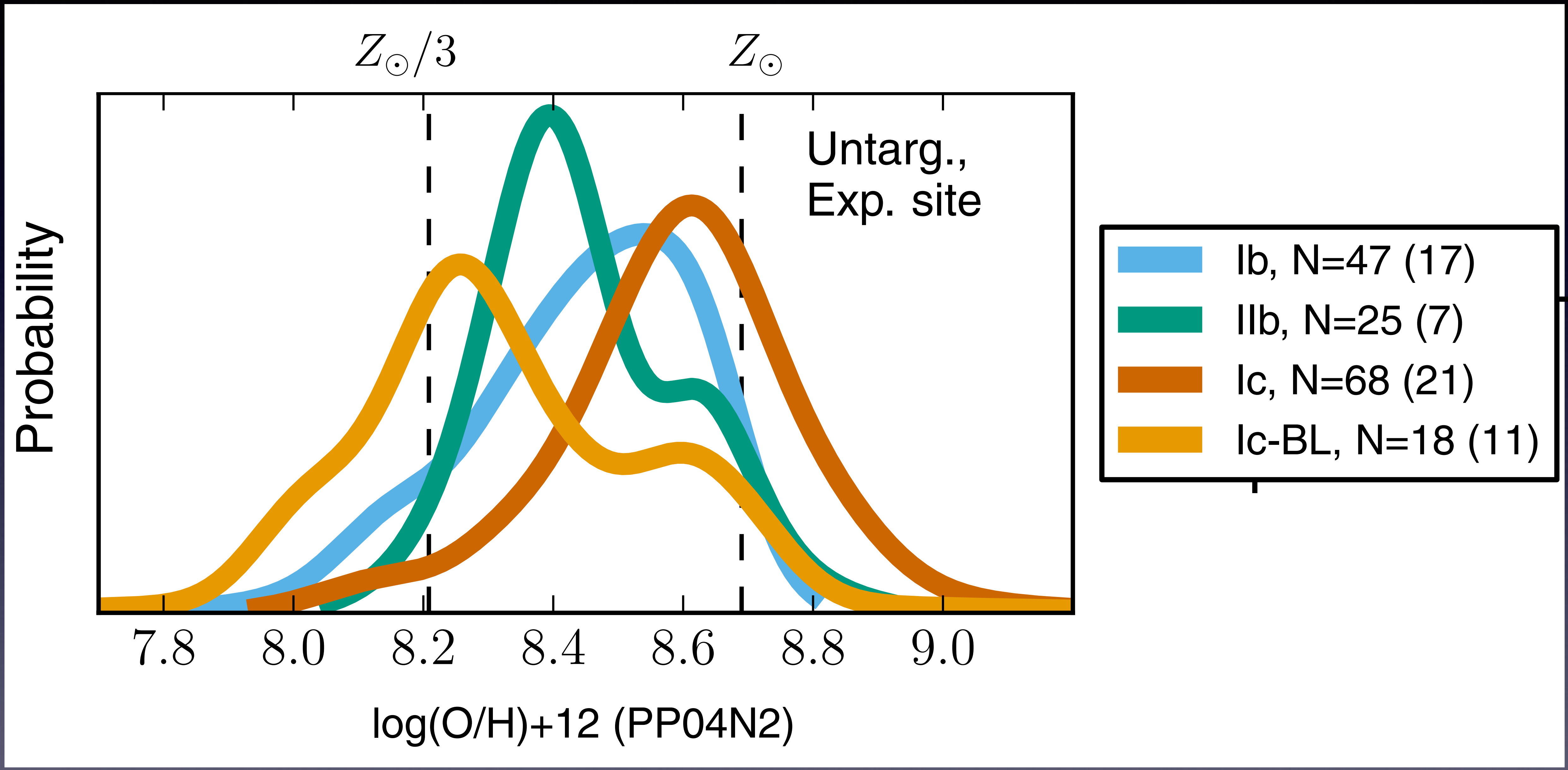
Discovery of BL-Ic which are relativistic yet sub-energetic (SN 2009bb, 2012ap)

Sub-energetic long GRBs

Soderberg et al. 2010; Chakraborti et al. 2014, Margutti et al. 2014, Milisavljevic et al. 2014

GRB-SN connection

Metallicity: Normal Ibc > BL-Ic > Long GRBs



Sanders et al. 2012

Long GRBs occur at even lower metallicity than SNe BL-Ic w/o GRBs (e.g., Modjaz et al. 2008; Graham & Fruchter et al. 2013)

Central Engines

No jet breakout

Yes jet breakout

"Normal" SNe

Relativistic, sub-E non-GRB SNe

Relativistic, sub-E GRB SNe

"Normal" GRBs

Rotation rate of stellar core

Metallicity

$Z > Z_{sun}$

$Z < 0.5\ Z_{sun}$

A Nearby Jet-Driven SNR?

One SN / 40 years	~300 known SNRs
↓	↓
Two CC / 100 years	~200 CC SNRs
↓	↓
One Type 1b/c / 200 years	~50 Type 1 b/c SNRs
↓	↓
A few % are bipolar or HNe: 1 / 10000 yrs	~1 SNR was bipolar / HNe

Jet-Driven SNRs

Two jet-driven SNRs

Lopez et al. 2013a

In Milky Way: $Z \sim Z_{sun}$

Lopez et al. 2014

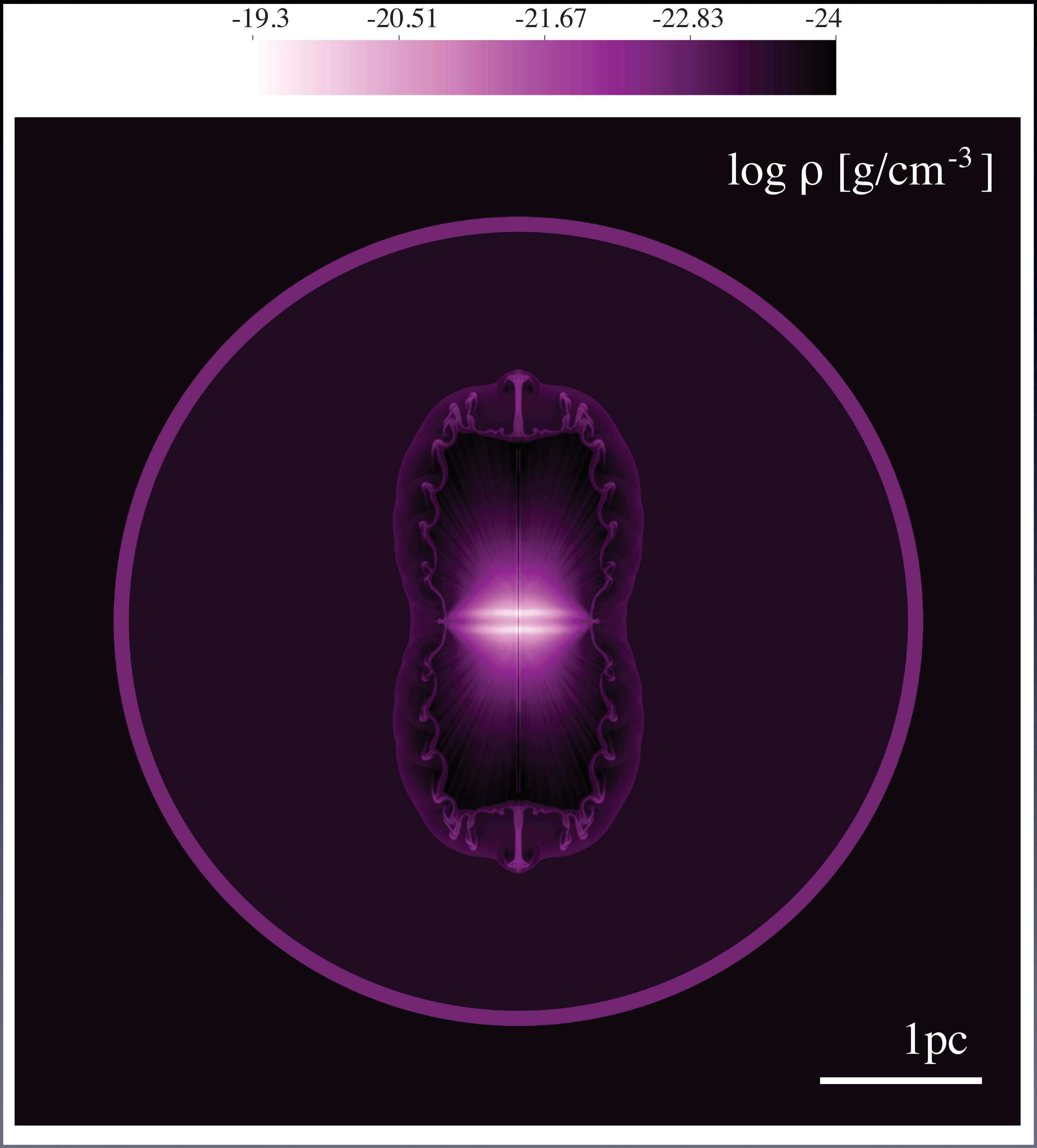
In SMC: $Z \sim 0.2\ Z_{sun}$

How Do We Recognize Jet-Driven SNRs?

1. Bipolar / jet structure
2. Jets enhanced in heavy metals
3. A nearby molecular cloud
4. Dense circumstellar material and cavity
5. Black holes or magnetars
6. Nucleosynthesis differs from spherical CC SNe
7. Kinematics

How Do We Recognize Jet-Driven SNRs?

1. Bipolar / jet structure

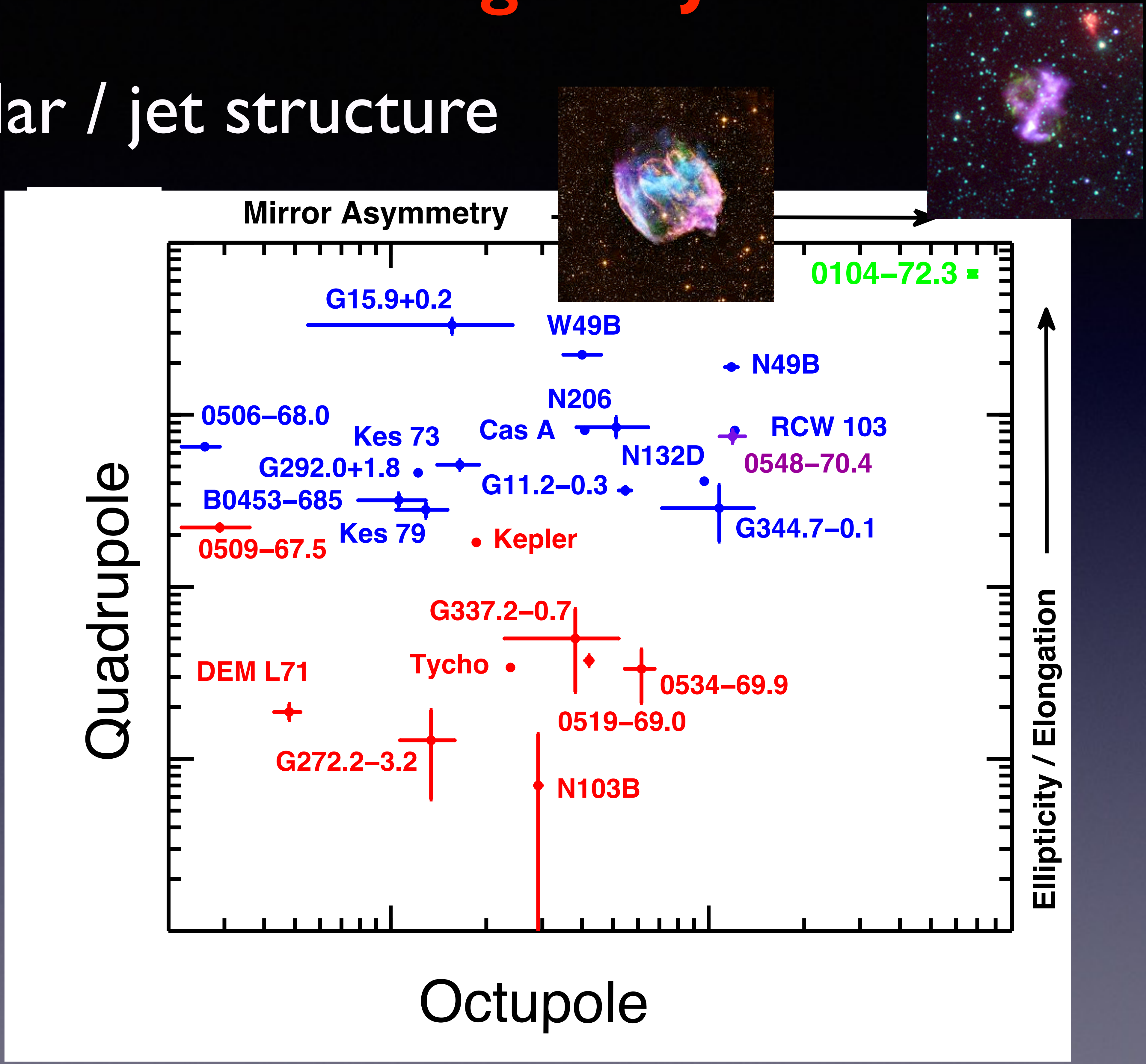


Gonzalez-Casanova et al. 2013

Maintain bipolar structure for thousands of years

How Do We Recognize Jet-Driven SNRs?

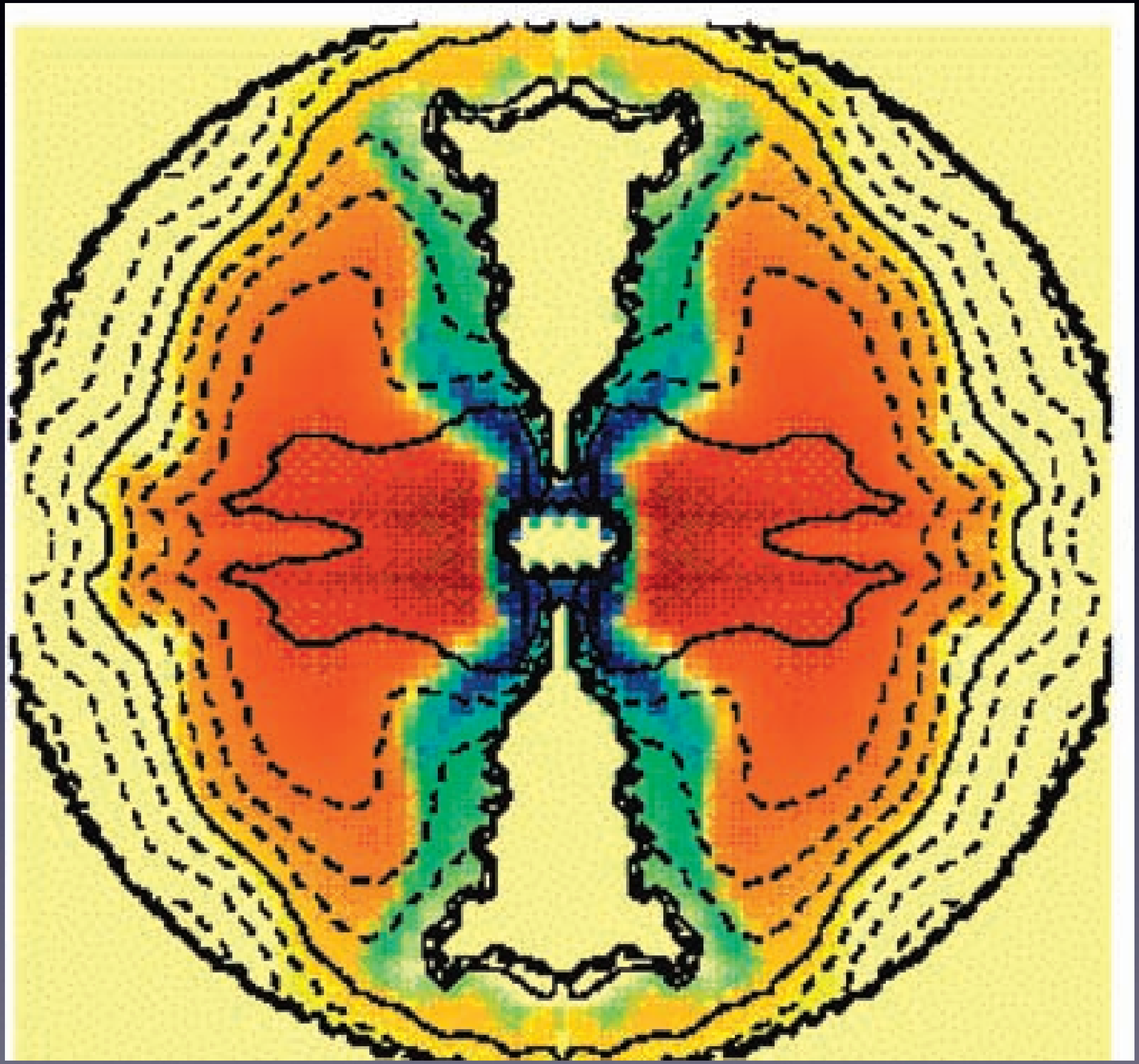
1. Bipolar / jet structure



Lopez et al. 2014

How Do We Recognize Jet-Driven SNRs?

2. Jet should be enhanced in heavy metals



Nickel; Oxygen Mazzali et al. 2006

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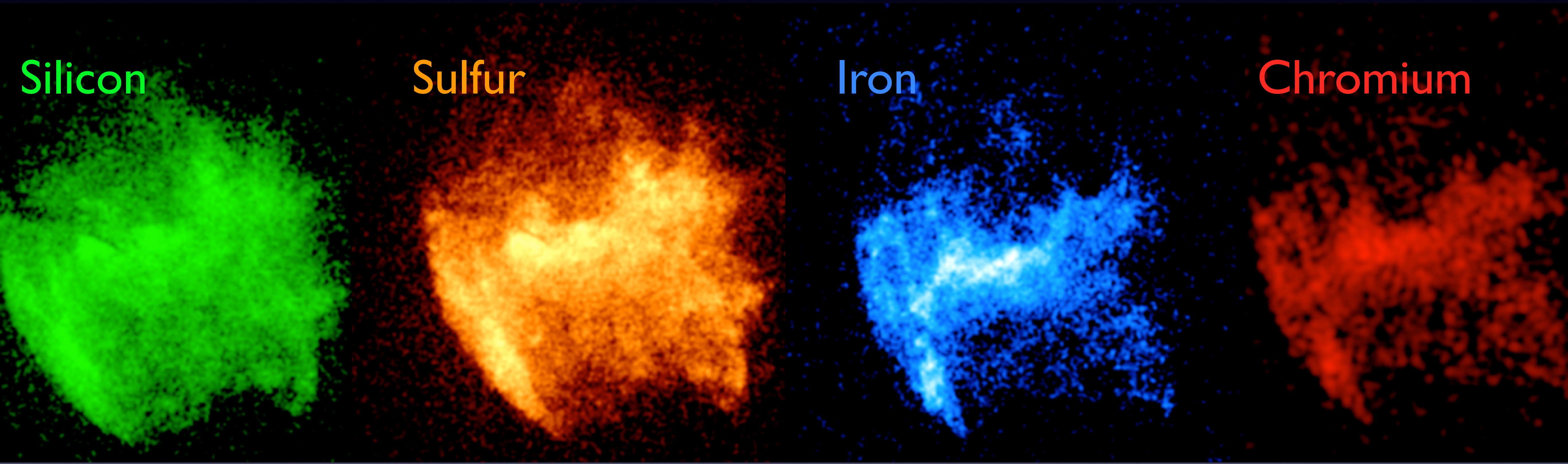
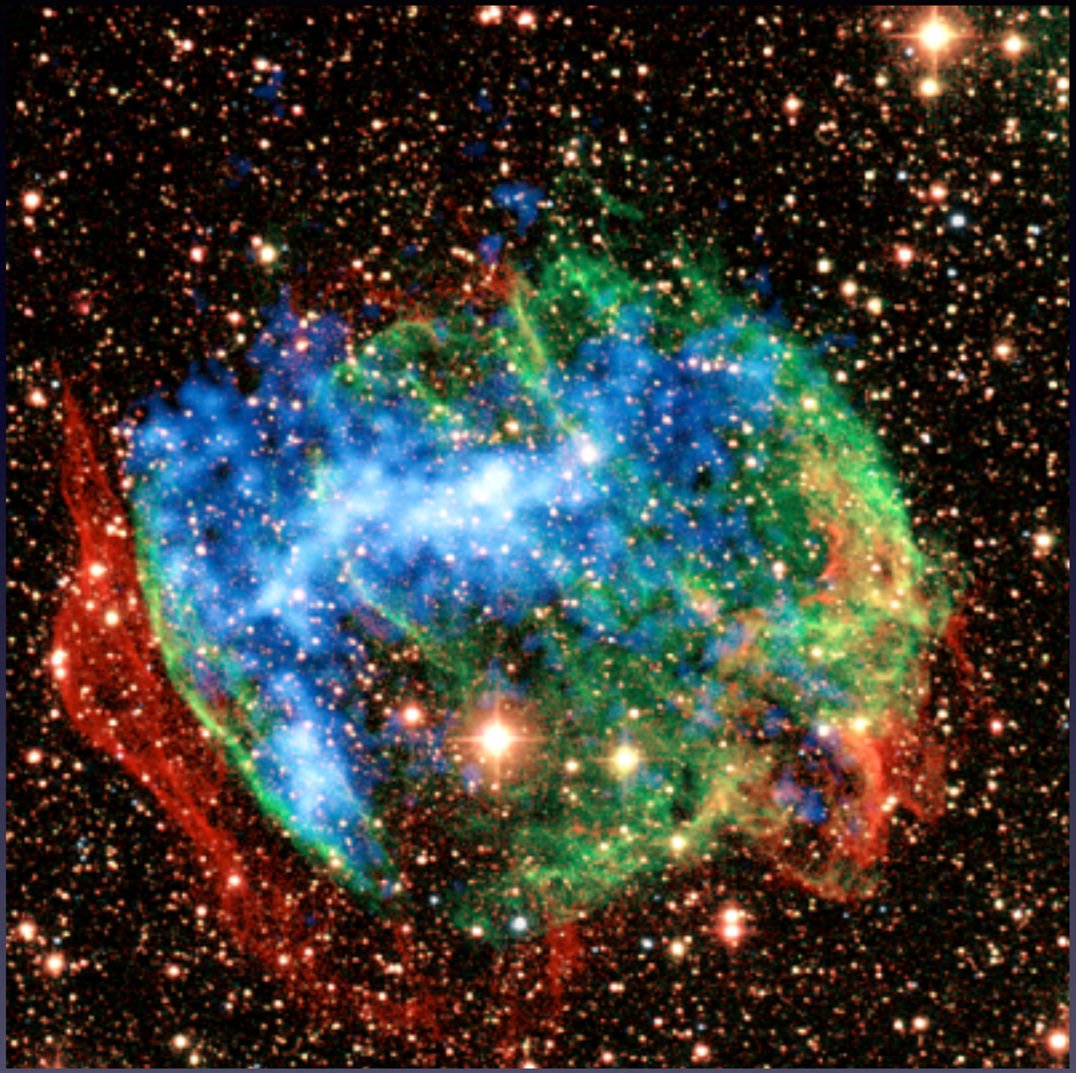


Lopez et al. 2013a

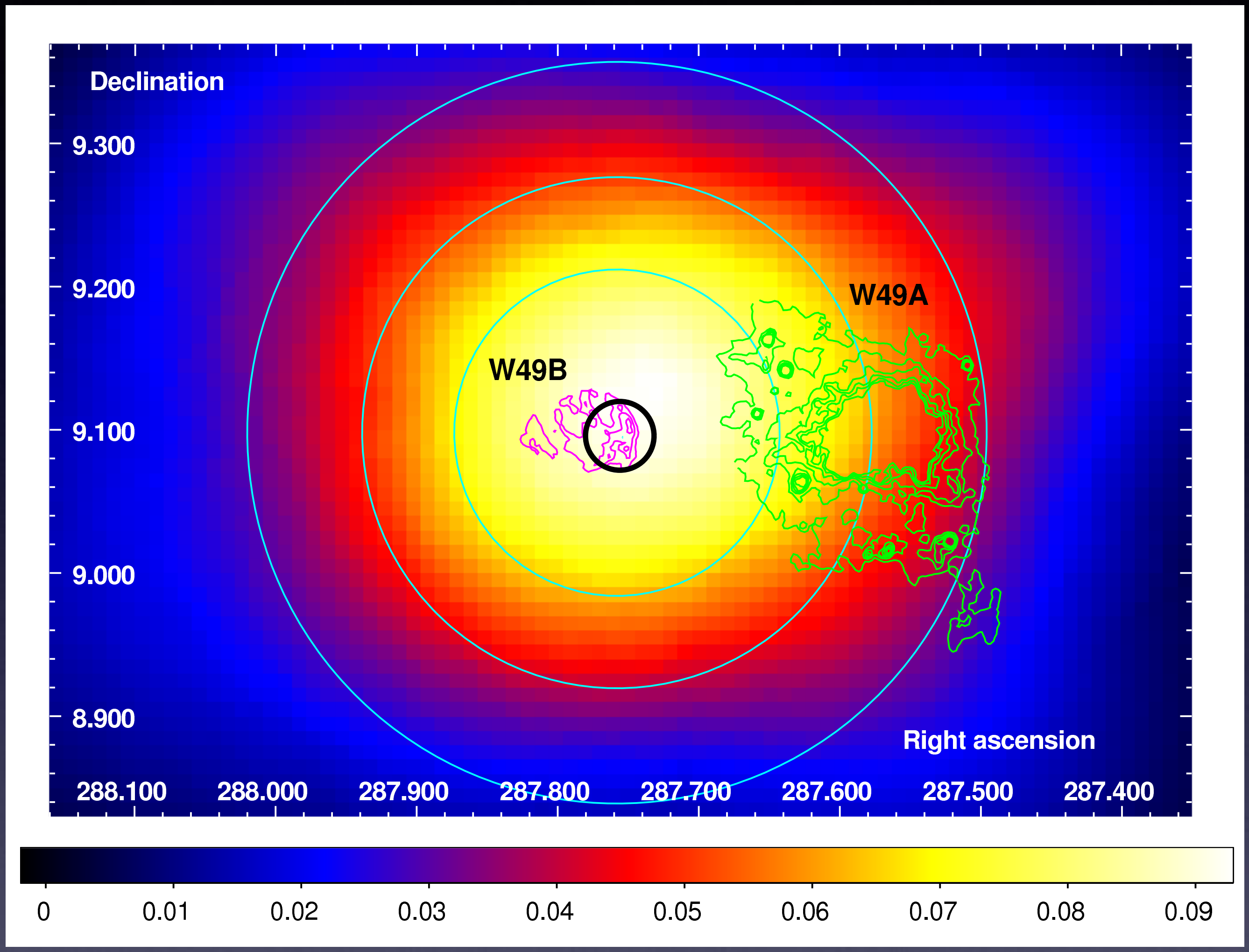
How Do We Recognize Jet-Driven SNRs?

3. Near a molecular cloud / recent star formation



X-rays; 1.64 um [Fe II];
2.12 um (shocked H_2)

Keohane et al. 2007



Fermi-LAT gamma rays
(2-6 GeV): Abdo et al.2010

How Do We Recognize Jet-Driven SNRs?

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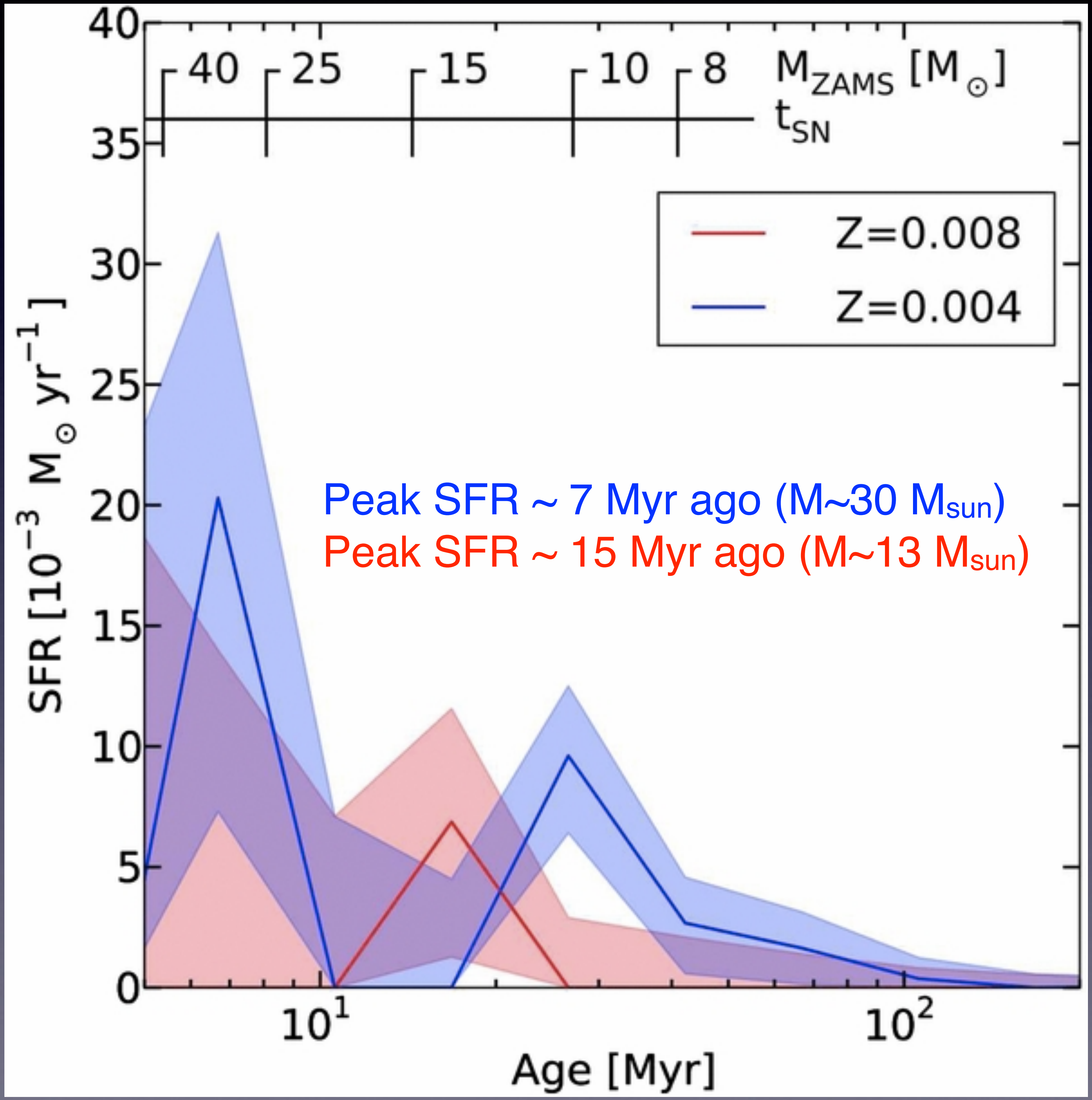
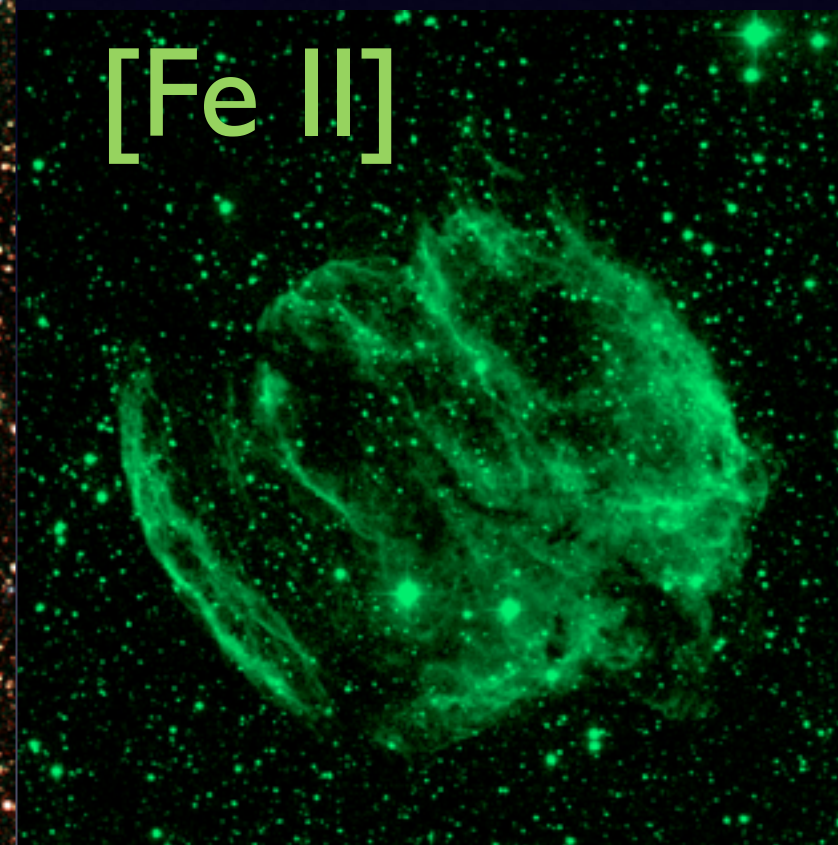
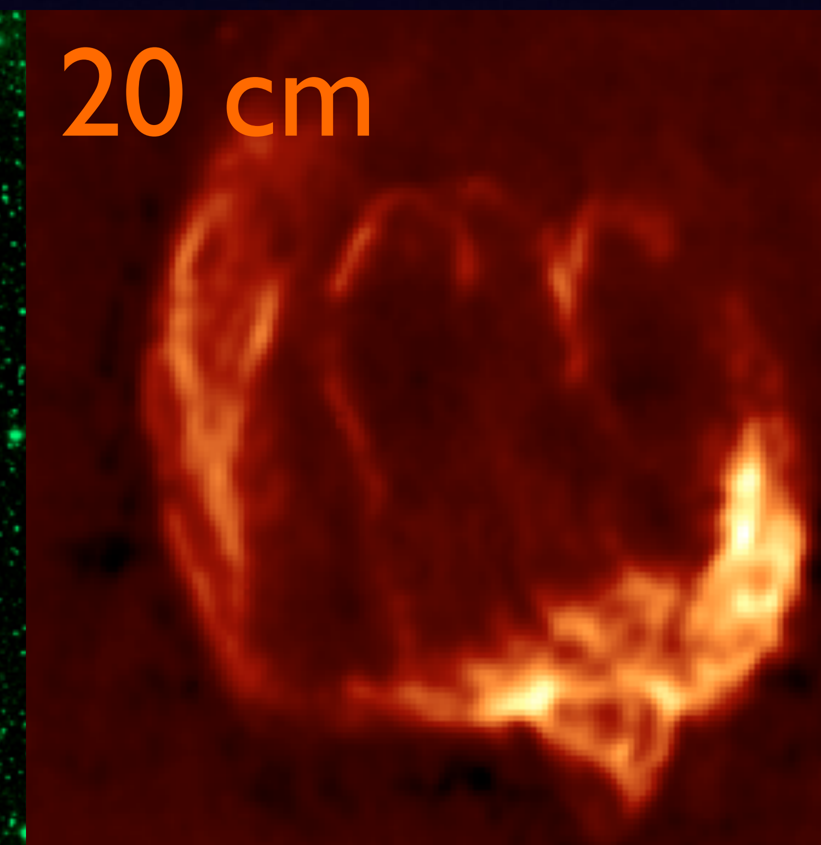


Lopez et al. 2014

How Do We Recognize Jet-Driven SNRs?

4. Dense circumstellar material and cavity





X-rays; 1.64 um [Fe II];
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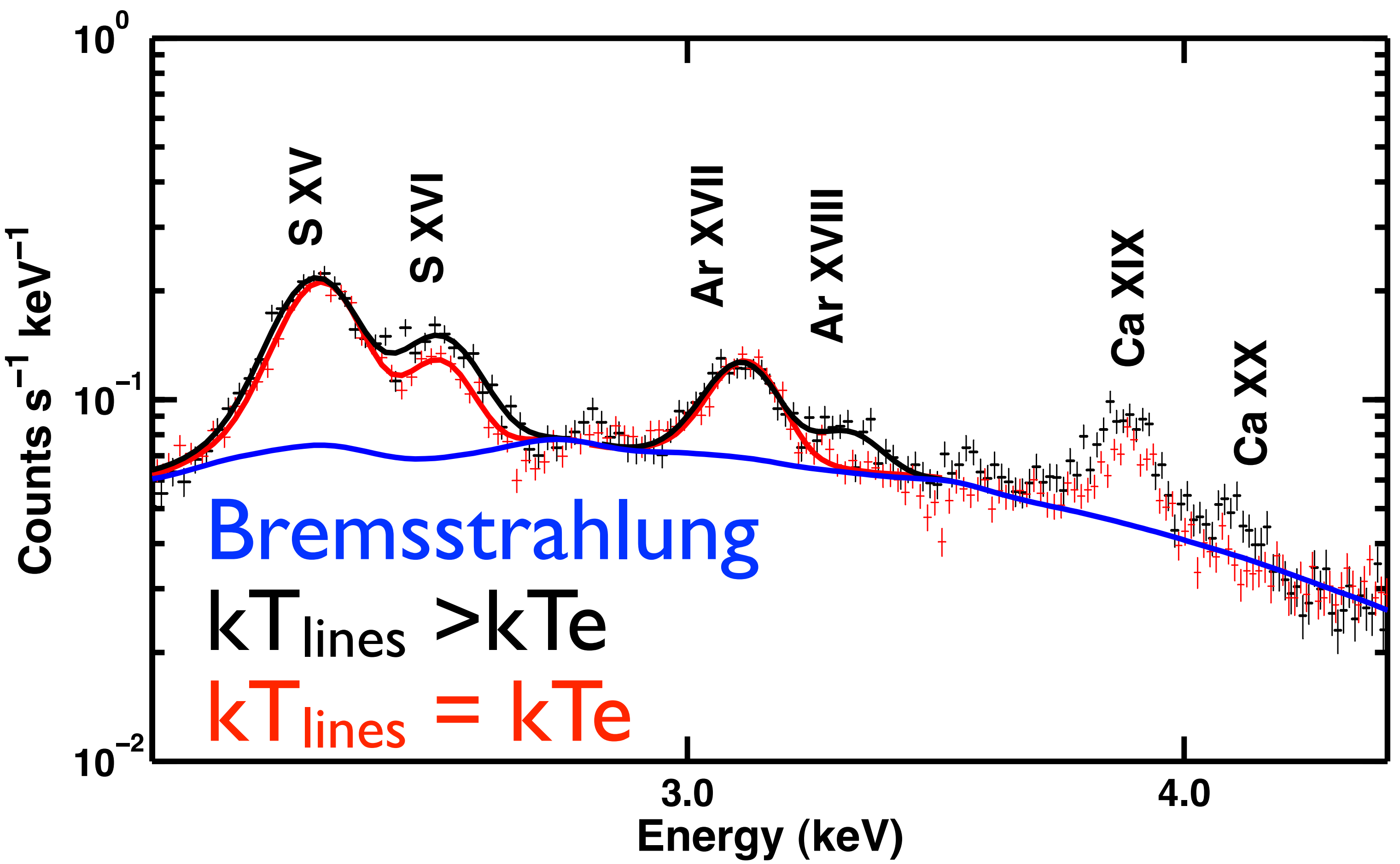
Keohane et al. 2007

How Do We Recognize Jet-Driven SNRs?

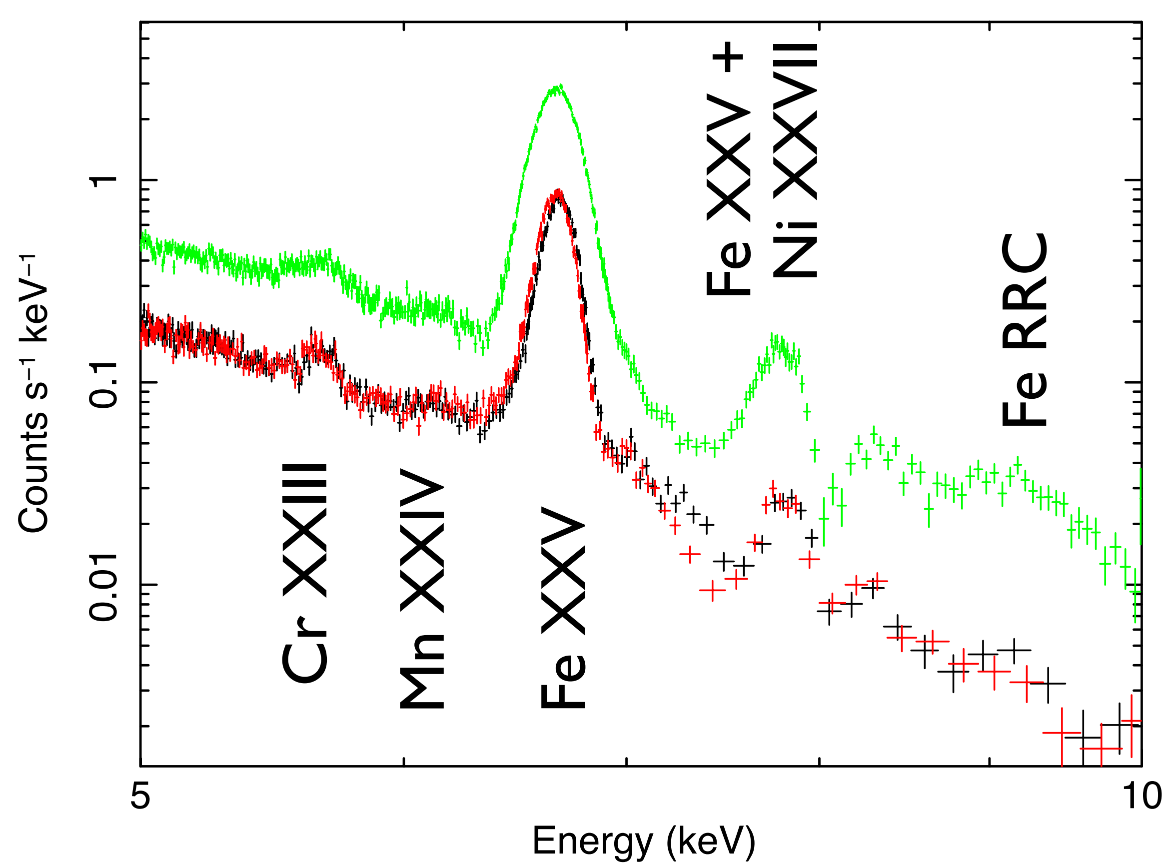
4. Dense circumstellar material and cavity

Overionization: Rapid cooling of ejecta following expansion from dense CSM to rarefied ISM

Lopez et al. 2013b

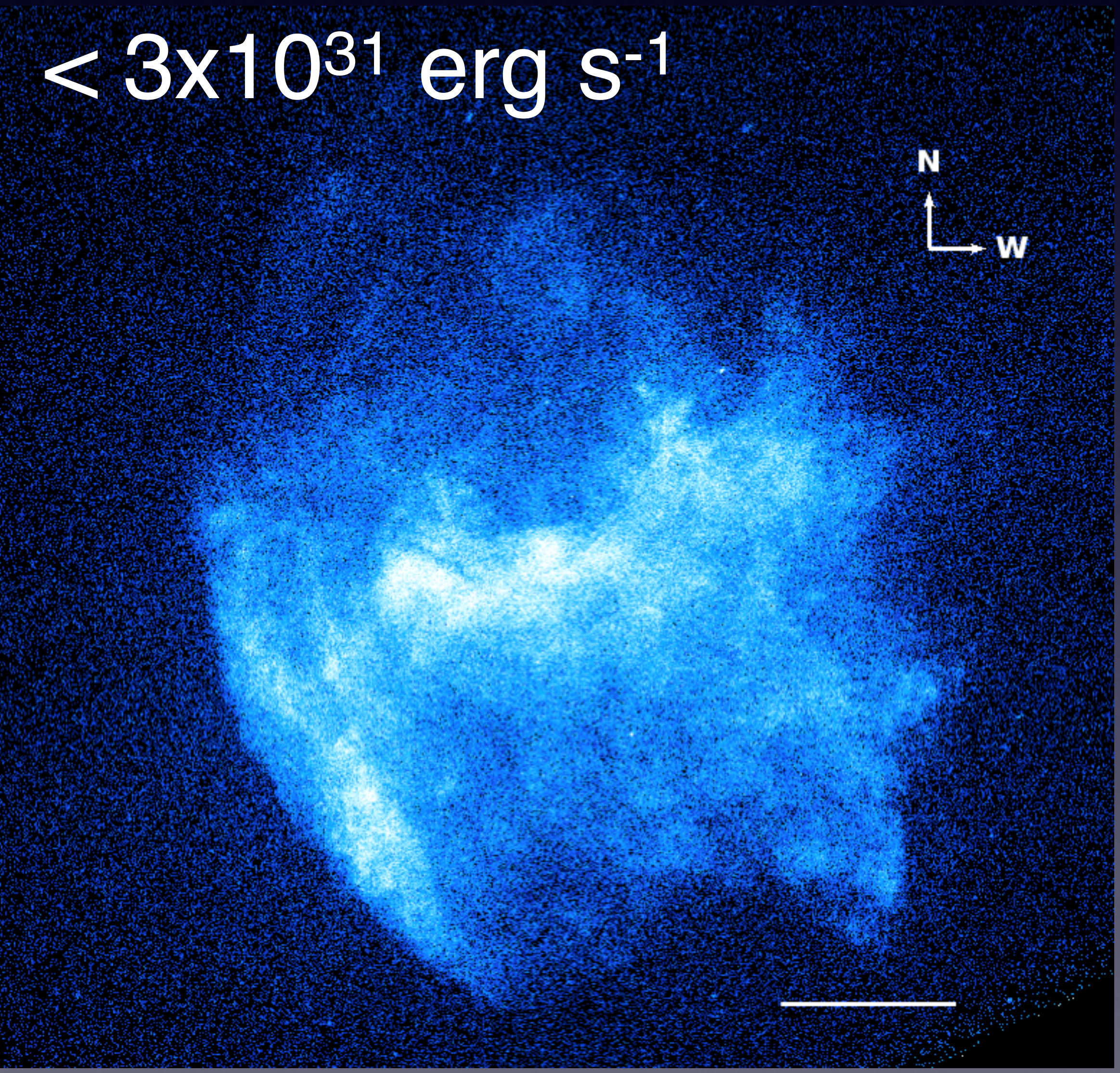


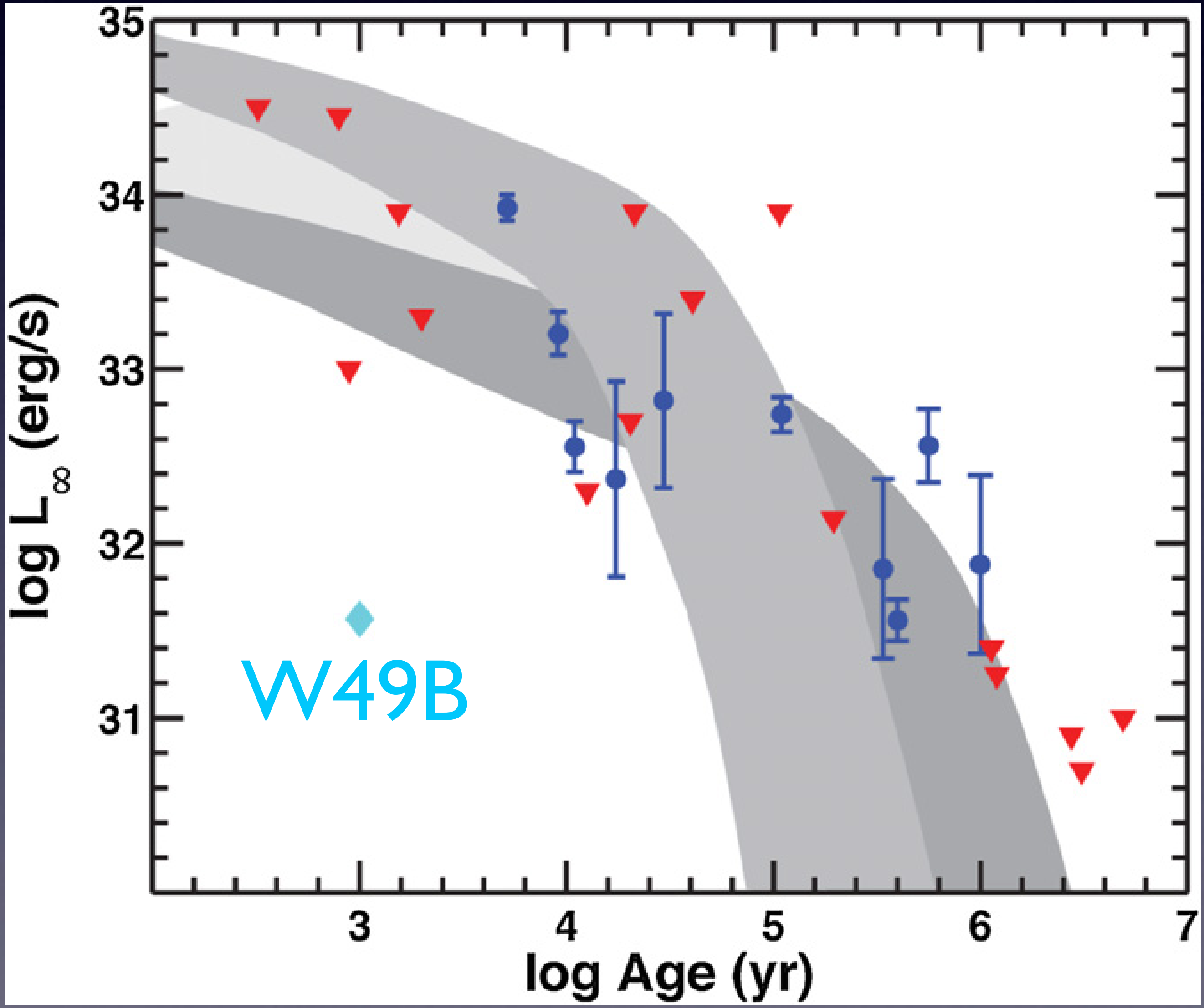
Lopez et al. 2016



How Do We Recognize Jet-Driven SNRs?

5. Black hole (or magnetar) central compact object





Lopez et al. 2013a

How Do We Recognize Jet-Driven SNRs?

6. Nucleosynthesis is different than spherical CC SN

➡ Nickel (iron) yields increase with asphericity, explosion energy and progenitor mass

➡ Candidates have similar nickel yields:

✳ 2003dh: ~0.25-0.45 M_{sun}
✳ 2003lw: ~0.45-0.65 M_{sun}
✳ 1998bw: ~0.20-0.70 M_{sun}

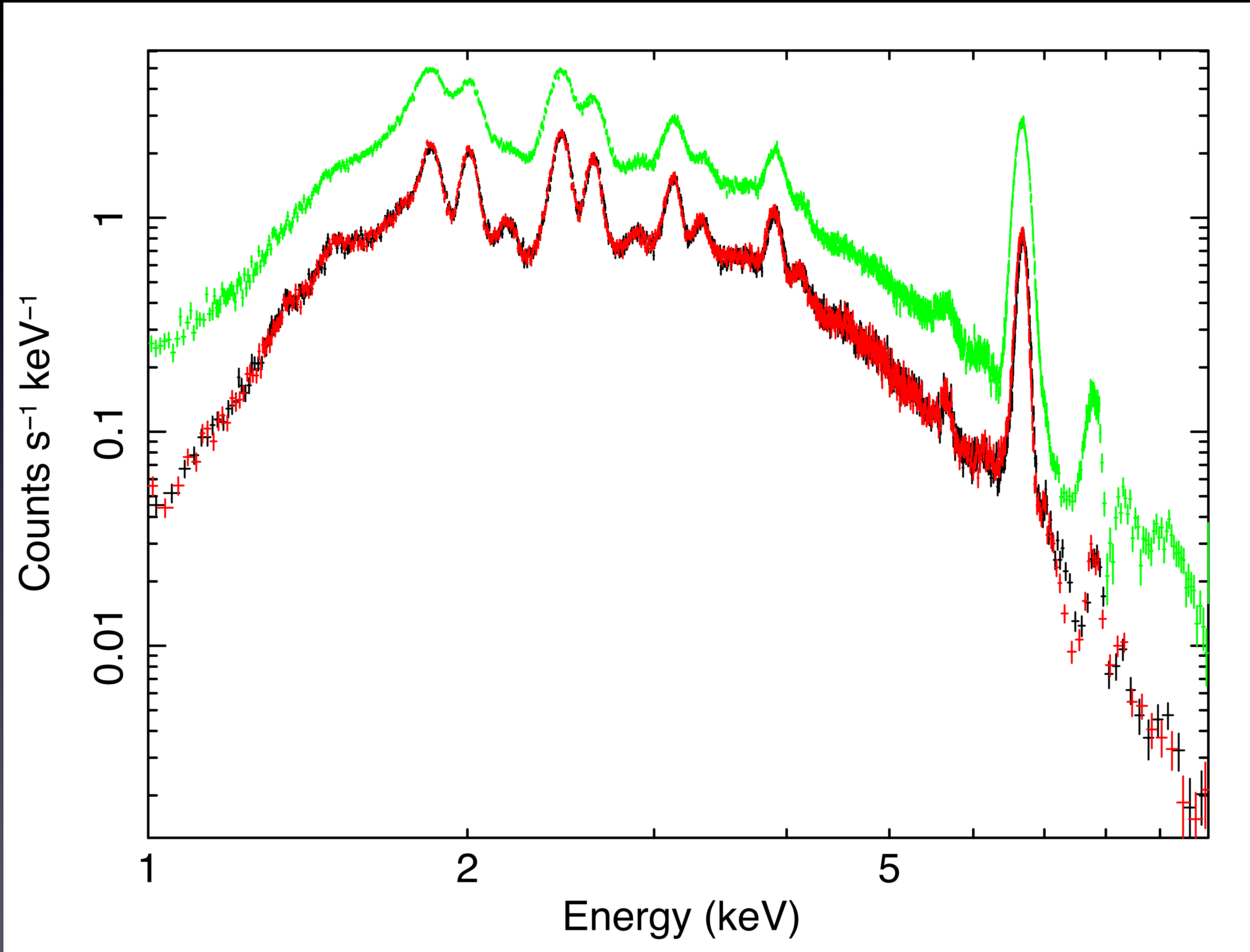
W49B: M_{Fe} ~ 0.80+/-0.60 M_{sun}

0104-72.3: Ne/Fe ~ 3-4

References: Woosley et al. 1999; Mazzali et al. 2003; Mazzali et al. 2006; Kaneko et al. 2007; Umeda & Nomoto 2008

How Do We Recognize Jet-Driven SNRs?

7. Kinematics: Fe faster than Si



Lopez et al. 2016

How Do We Recognize Jet-Driven SNRs?

1. Bipolar / jet structure
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7. Kinematics

W49B: Satisfies #1-6
0104-72.3: Satisfies #1-3, 6

Identification of local analogs among the nearby SNR population would help to understand these explosions

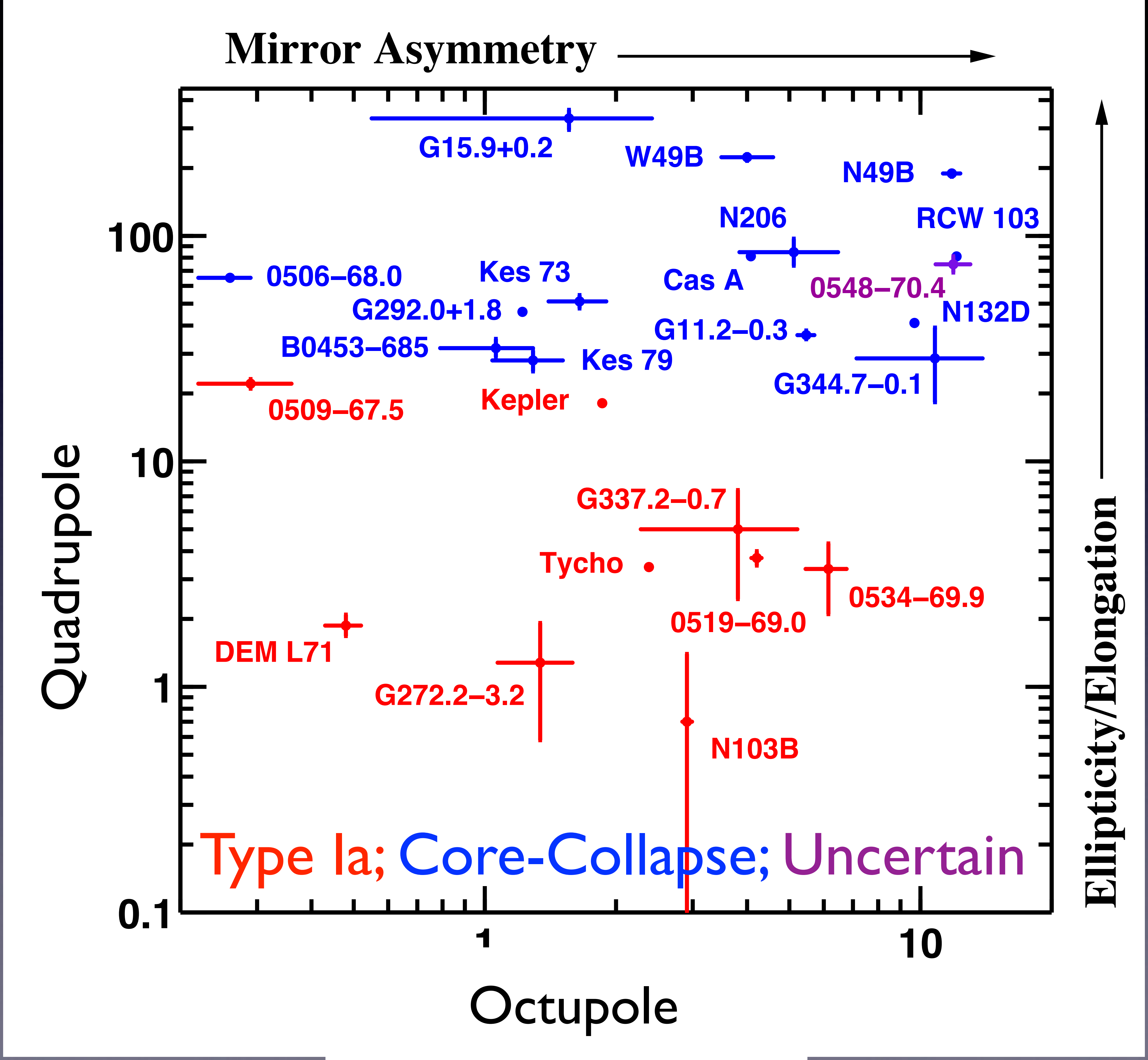
The Magnetar / Jet-Driven SN Connection

Table 7
Magnetar Associations and Distances

Name	Proposed Associations	SNR Age (kyr)	References	Distance (kpc)	Measured To	Reference	z (pc)	L_X[a]
CXOU J010043.1−721134	SMC	···	1	62.4(1.6)	SMC	28	···	65
4U 0142+61	···	···	···	3.6(4)	0142+61	29	−27(3)	105
SGR 0418+5729	···	···	···	∼2	Perseus Arm	30	∼180	0.00096
SGR 0501+4516	SNR HB 9[b]	4–7	2, 3	∼2	Perseus Arm	31	∼68	0.40
SGR 0526−66	LMC, SNR N49[b], SL 463	∼4.8	4–6	53.6(1.2)	LMC	32	···	189
1E 1048.1−5937	GSH 288.3−0.5−28[b]	···	7	9.0(1.7)	1048.1−5937	29	−82(15)	49
1E 1547.0−5408	SNR G327.24−0.13	···	8	4.5(5)	1547.0−5408	33	−10.3(1.1)	1.3
PSR J1622−4950	SNR G333.9+0.0	<6	9	∼9	J1622−4950	34	∼−16	0.44
SGR 1627−41	CTB 33, MC −71, SNR G337.0−0.1	···	10, 11	11.0(3)	G337.0−0.1	11	−21.4(6)	3.6
CXOU J164710.2−455216	Westerlund 1	···	12	3.9(7)	Westerlund 1	35	−29(5)	0.45
1RXS J170849.0−400910	···	···	···	3.8(5)	J170849.0−400910	29	2.4(3)	42
CXOU J171405.7−381031	SNR CTB 37B	$0.65^{+2.50}_{-0.30}$	13, 14	∼13.2	CTB 37B	36	∼86	56
SGR J1745−2900	Galactic Center	···	15	∼8.5	Galactic Center	37	∼−7.0	<0.11
SGR 1806−20	W31, MC 13A, Star cluster	···	16, 17	$8.7^{+1.8}_{-1.5}$	Star cluster	38	$-36.7^{+6.3}_{-7.6}$	163
XTE J1810−197	···	···	···	$3.5^{+0.5}_{-0.4}$	J1810−197	39	$-9.7^{+1.1}_{-1.4}$	0.043
Swift J1822.3−1606	M17	···	18	1.6(3)	M17	18	−28.5(5.3)	<0.0077
SGR 1833−0832	···	···	···	···	···	···	∼3.6	<2.4
Swift J1834.9−0846	SNR W41	∼100	19, 20	4.2(3)	W41	40	−25(2)	<0.0084
1E 1841−045	SNR Kes 73	0.5–1	21, 22	$8.5^{+1.3}_{-1.0}$	Kes 73	22	$-0.97^{+0.11}_{-0.15}$	184
SGR 1900+14	Star cluster	···	23	12.5(1.7)	Star cluster	41	167(23)	90
1E 2259+586	SNR CTB 109	14(2)	24, 25	3.2(2)	CTB 109	42	−55.6(3.5)	17
SGR 1801−23	···	···	···	···	···	···	∼12	···
SGR 1808−20	···	···	···	···	···	···	∼−45	···
AX J1818.8−1559	···	···	···	···	···	···	∼−44	20
AX 1845.0−0258	SNR G29.6+0.1	<8	26	∼8.5	Scutum Arm	43	∼16	2.9
SGR 2013+34	W58	···	27	∼8.8	W58	27	∼−16	···

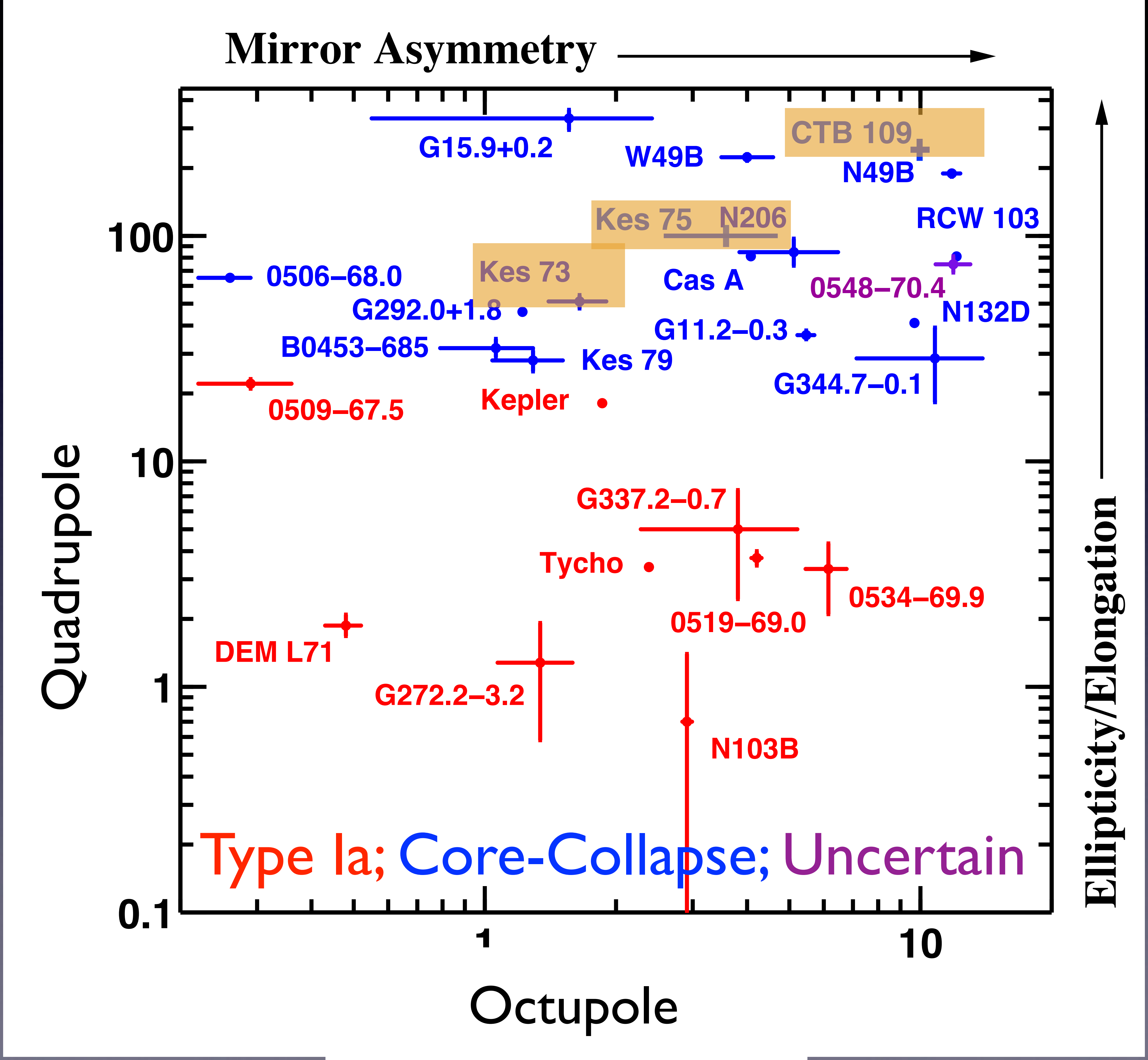
Olausen & Kaspi 2014

The Magnetar / Jet-Driven SN Connection



Lopez et al. 2011

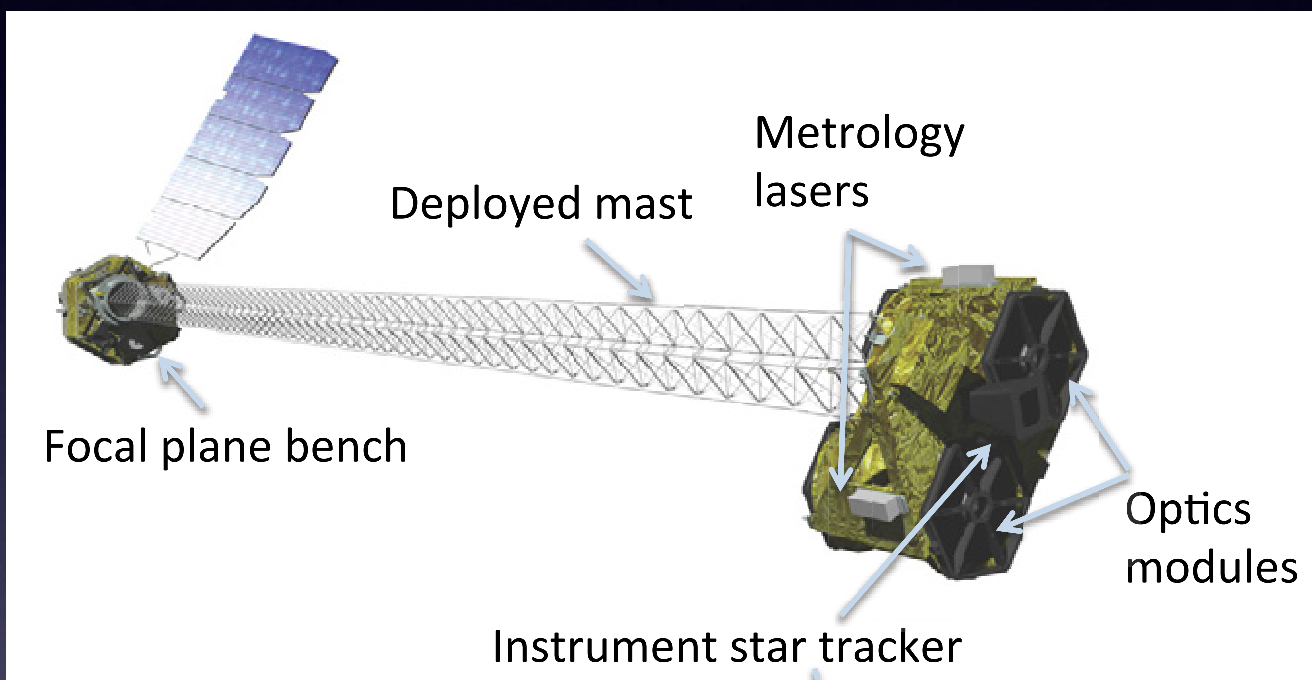
The Magnetar / Jet-Driven SN Connection

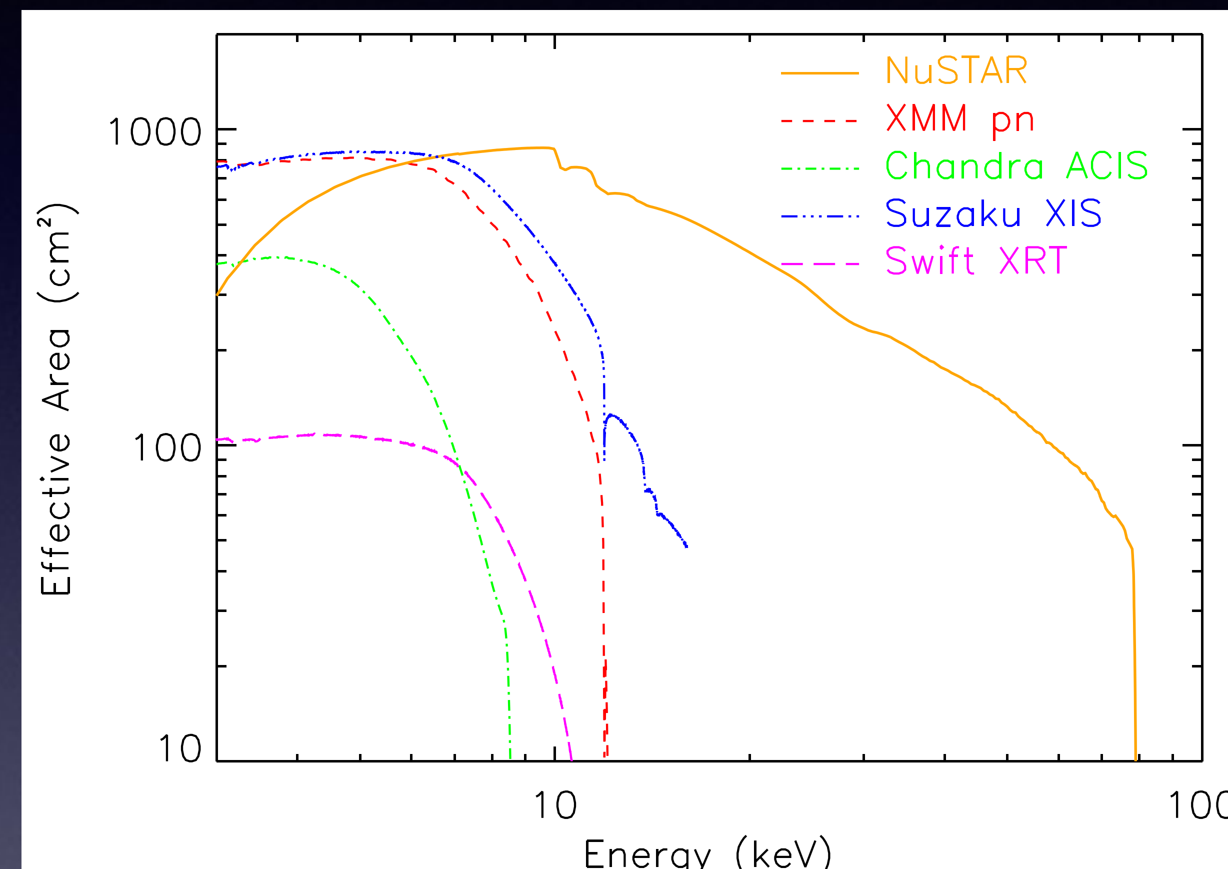


NuSTAR: Nuclear Spectroscope Array

Launched 13 June 2012

First focusing hard (3-79 keV) X-ray telescope in orbit





Harrison et al. 2013

Angular resolution: 18” PSF (FWHM)

Spectral resolution: 400 eV at 10 keV; 900 eV at 60 keV

Two identical 2x2 arrays with 12’ FOV

NuSTAR Study of SNRs

In its first two years, NuSTAR observed SNRs for ~6.3 Ms

SN 1987A: 2.1 Ms (Boggs et al. 2015)
Cassiopeia A: 2.4 Ms (Grefenstette et al. 2014, 2015)

G1.9+0.3: 350 ks (Zoglauer et al. 2014)
Tycho: 750 ks (Lopez et al. 2015)
Kepler: 250 ks (+250 ks soon)

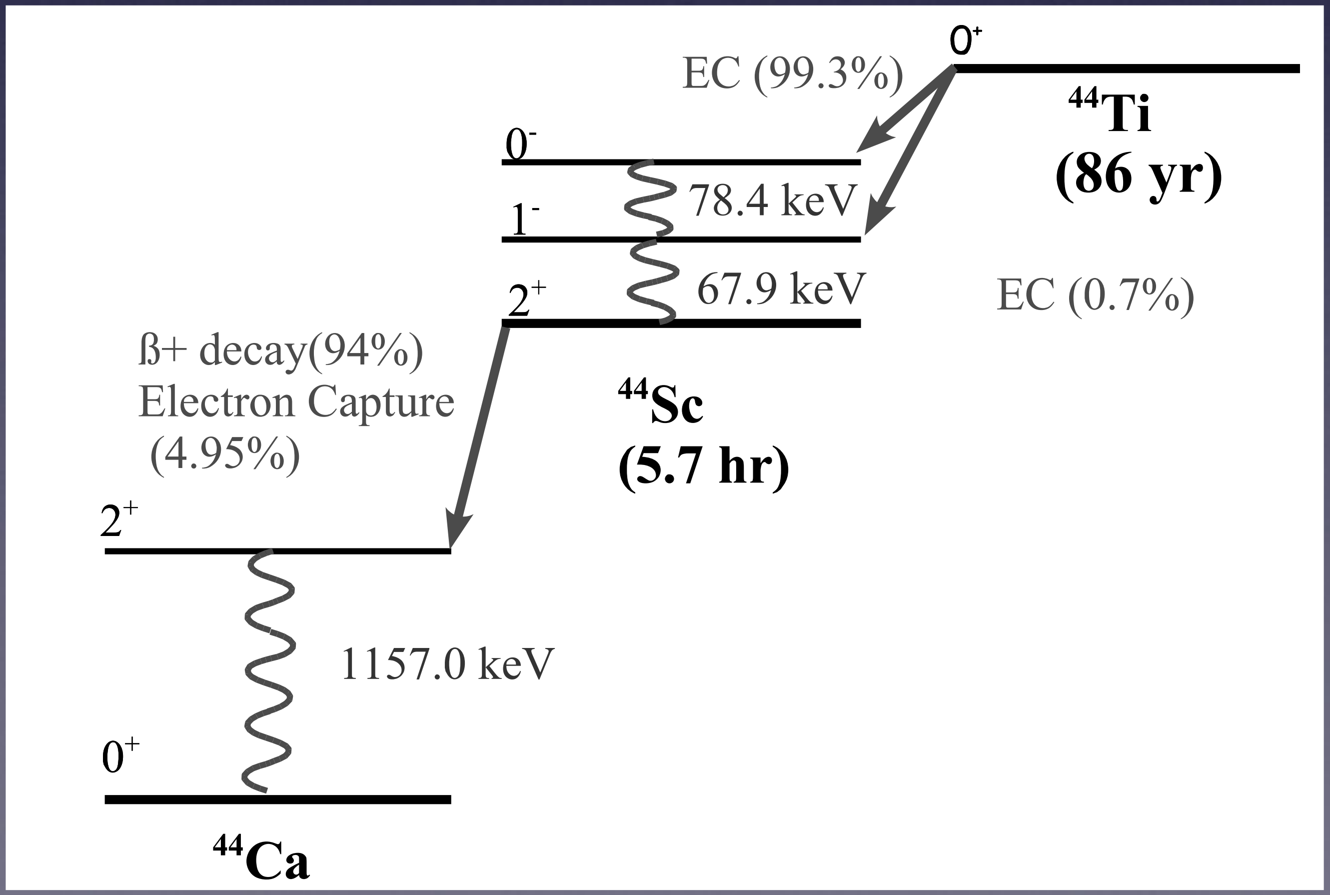
G21.5-0.9: 280 ks (Nynka et al. 2014)
MSH 15-52: 130 ks (An et al. 2014)
Crab: 60 ks (Madsen et al. 2015)

Symmetry of Metals

Ti-44 is an alpha-rich freeze-out product, sensitive to mass cut, explosion asymmetry, and ejecta velocities (Timmes et al. 1996; Woosley et al. 2012)

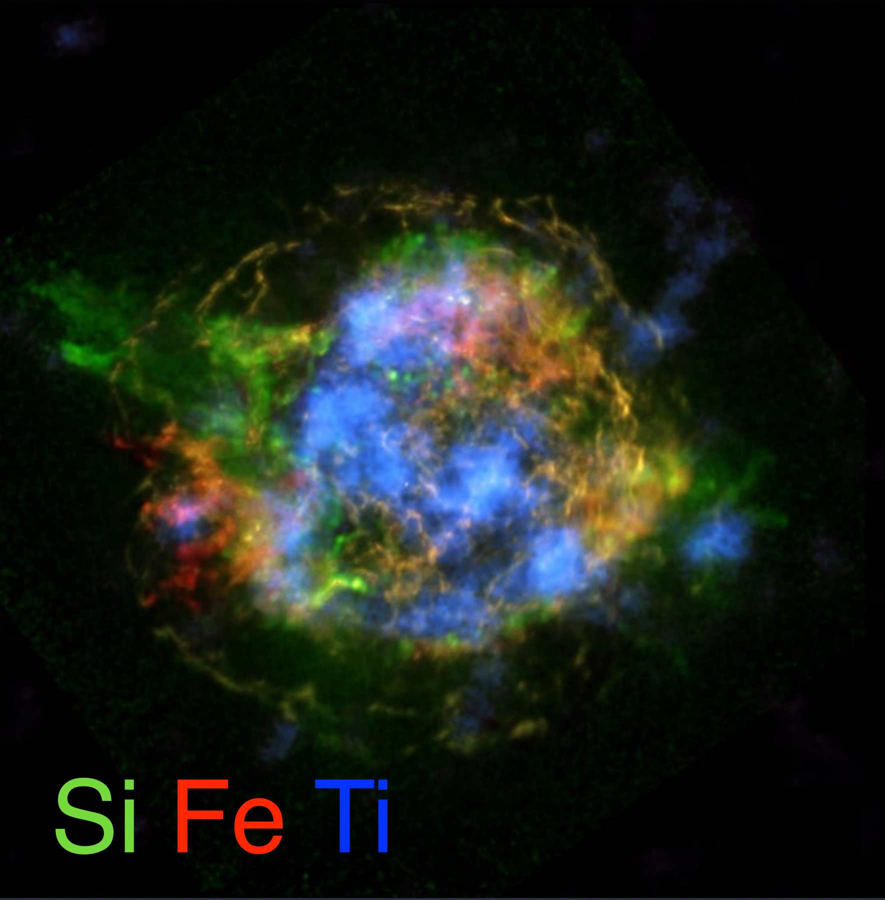
$t_{1/2}$ = 58.9 yrs, mean lifetime = 85 yrs (Ahmad et al. 2006)

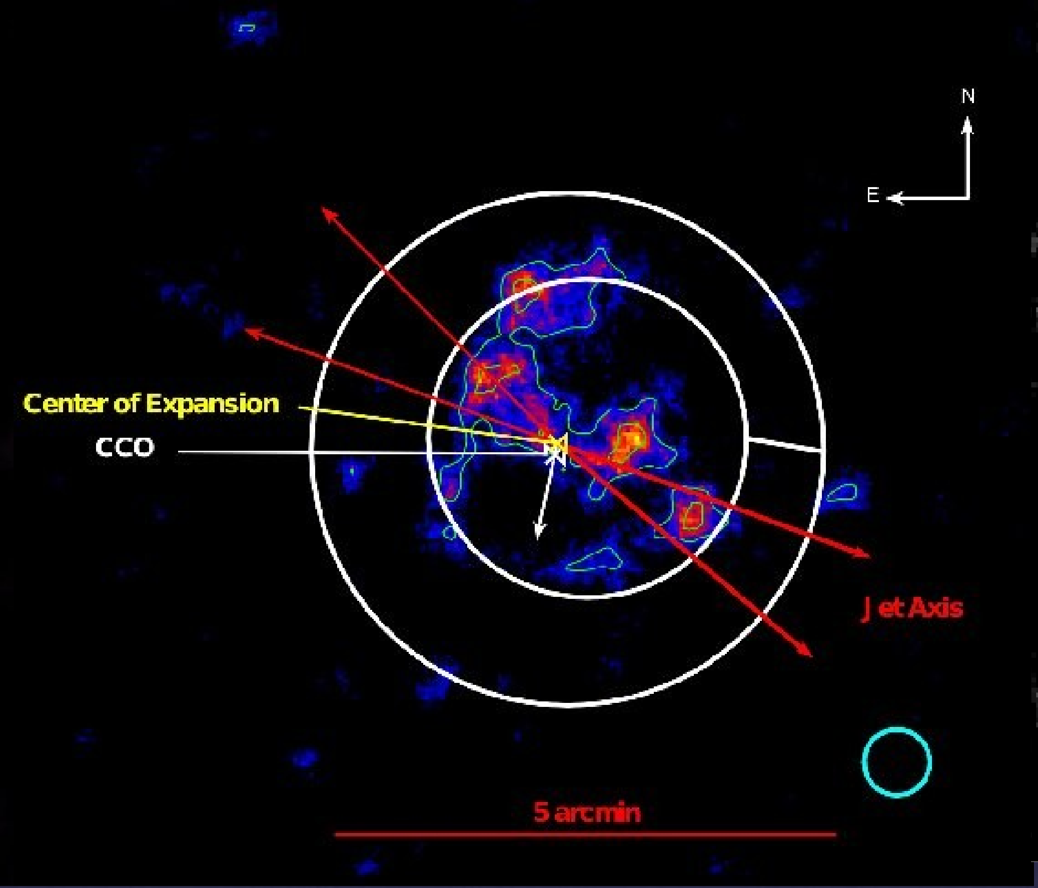
Observable lines at 68, 78, and 1157 keV

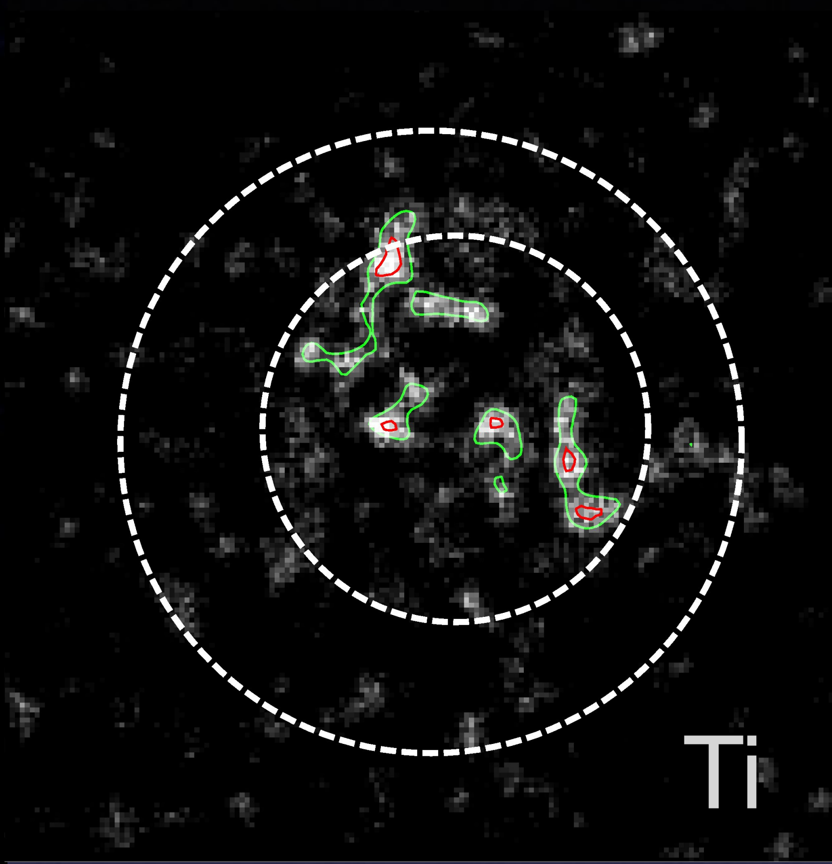


Vink 2012

Titanium in Core-Collapse SNRs







Grefenstette et al. 2014

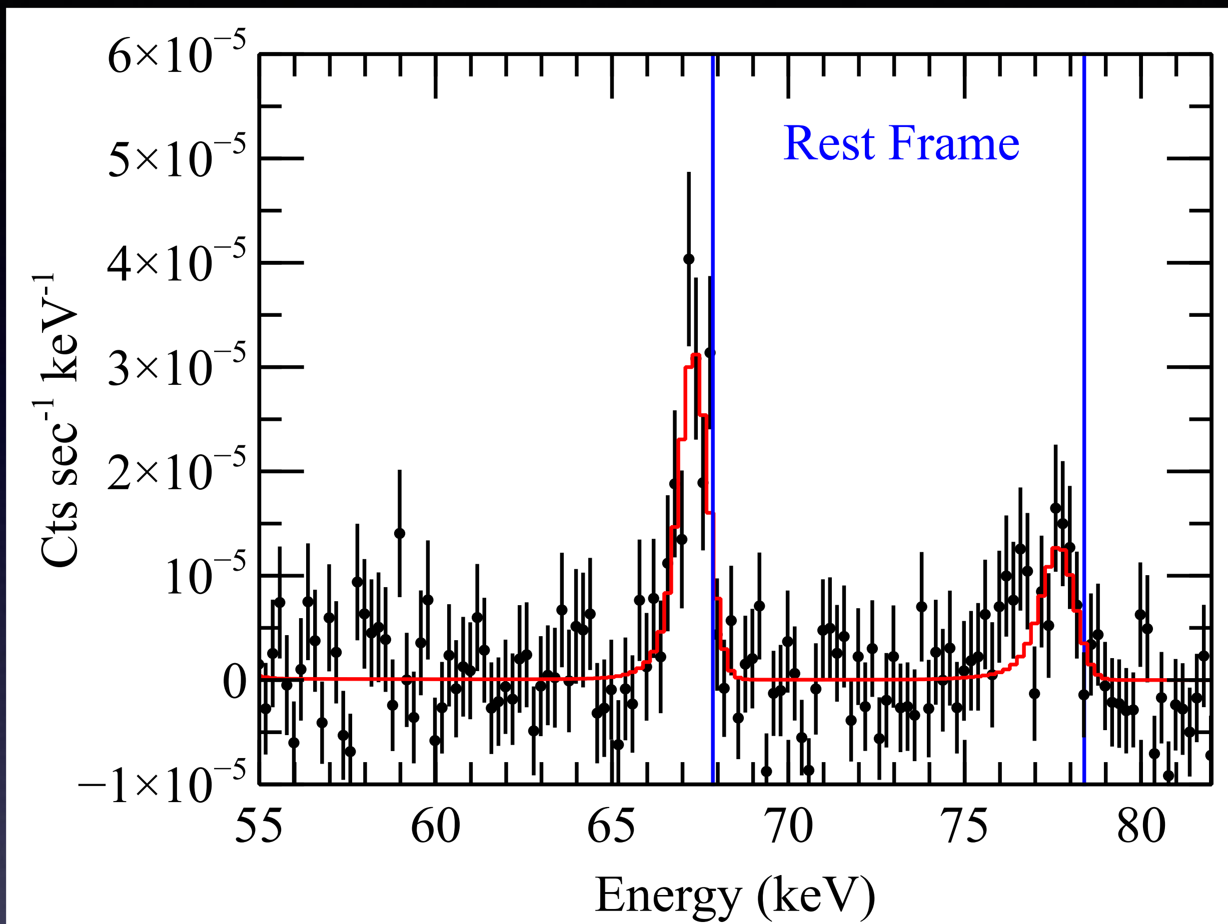
Titanium is located mostly inside of reverse shock

Titanium is not spatially correlated with Fe

1. If Ti tracks ejecta, most ejecta must not be shocked yet
2. Lack of Ti/Fe correlation not predicted by models

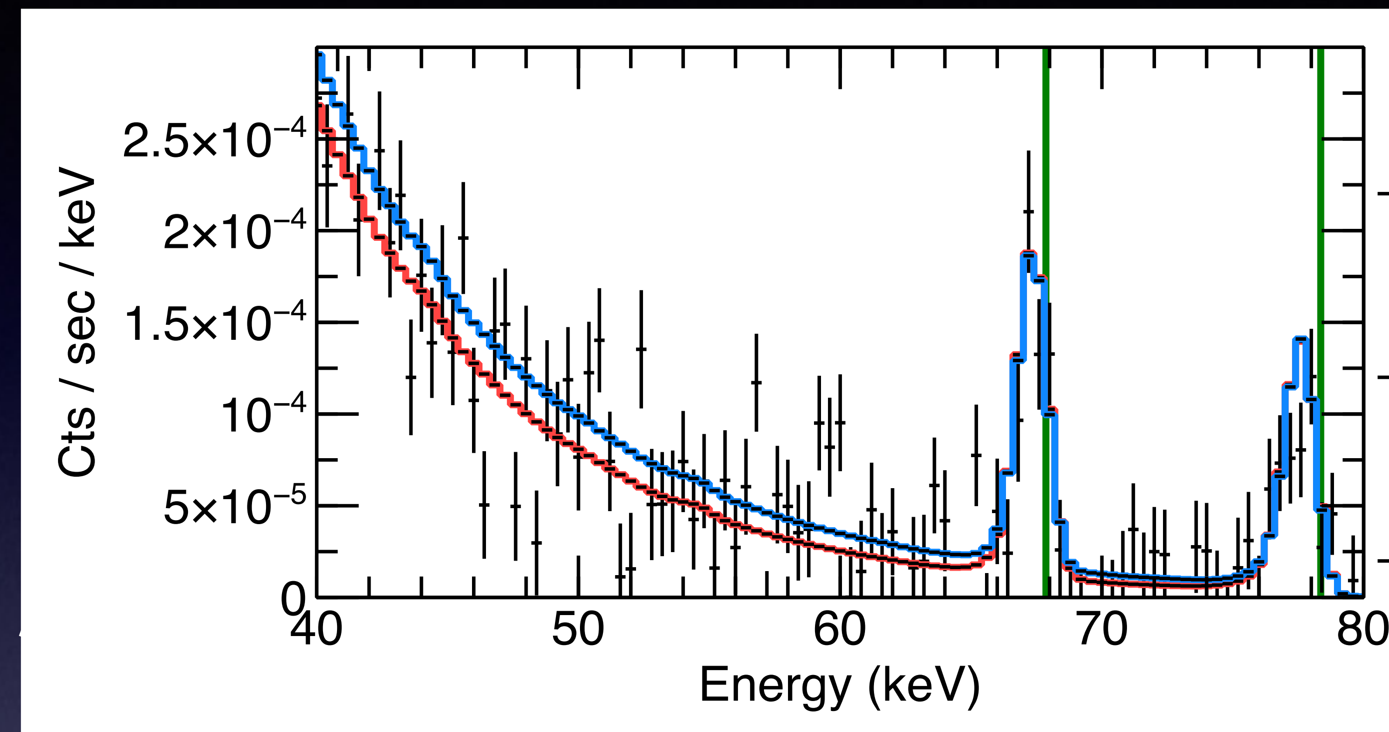
Symmetry of Metals

SN 1987A



Boggs et al. 2015

Cassiopeia A



Grefenstette et al. 2014

M_{44} = (1.6+-0.4)x10^{-4} M_{sun}

v = 700+-500 km s^{-1}

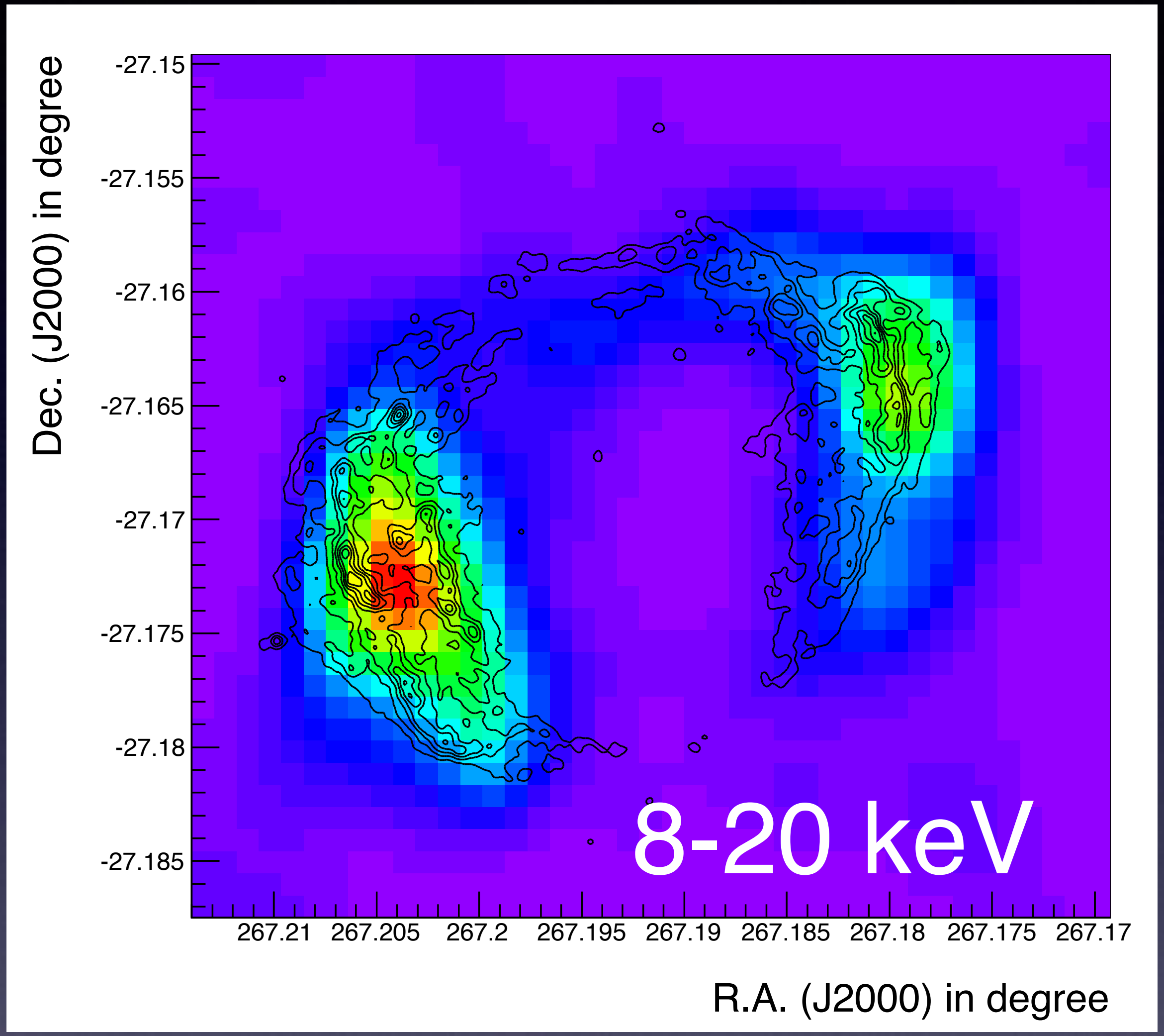
M_{44} = (1.3+-0.3)x10^{-4} M_{sun}

v = 1950+-950 km s^{-1}

M_{44} scales with asymmetry of explosions

Titanium in Type Ia SNRs

G1.9+0.3

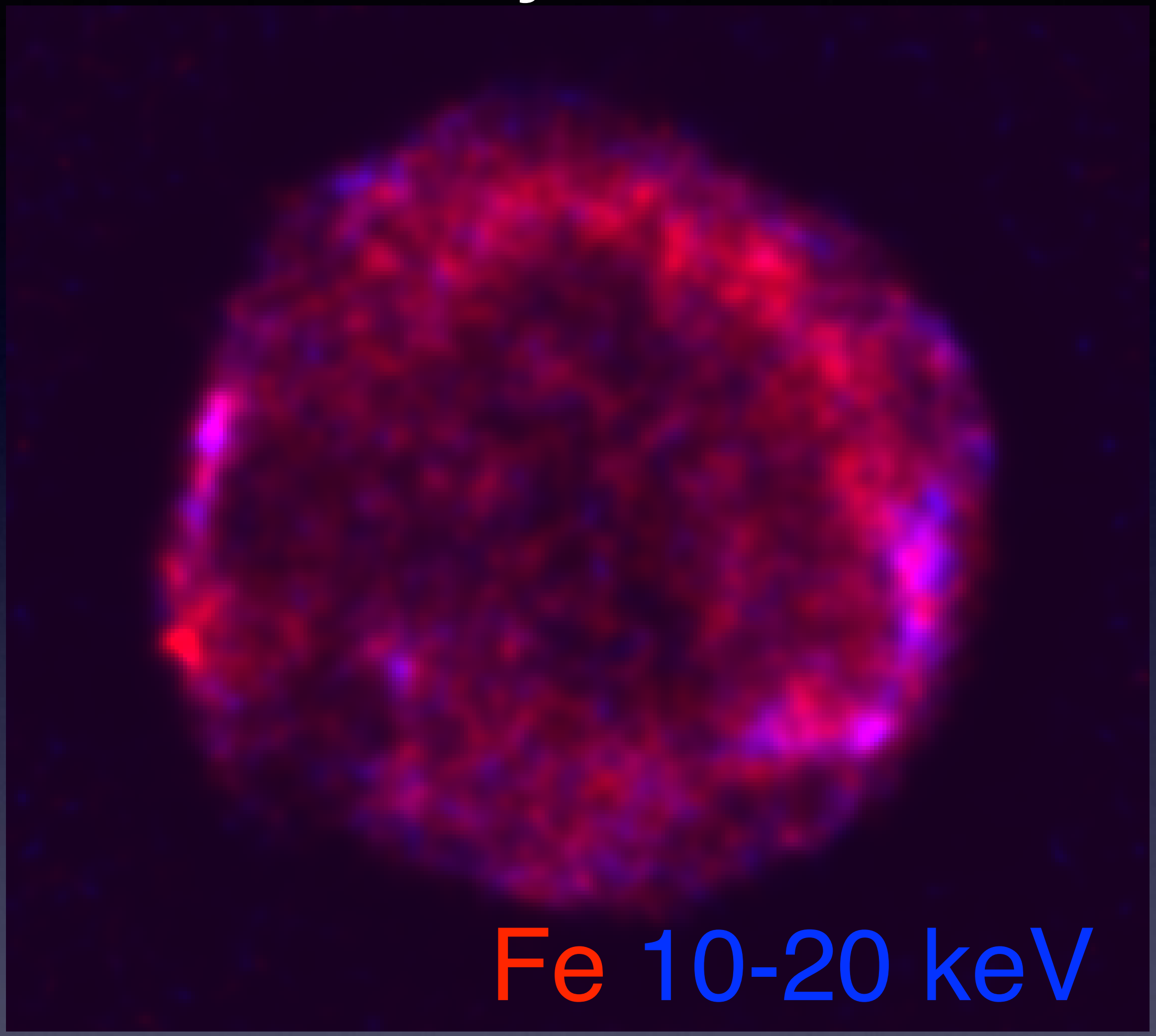


Zoglauer et al. 2014

$F < 1.5 \times 10^{-5}$ ph cm^{-2} s^{-1}

$M_{44} < 5 \times 10^{-5}\ M_{sun}$

Tycho



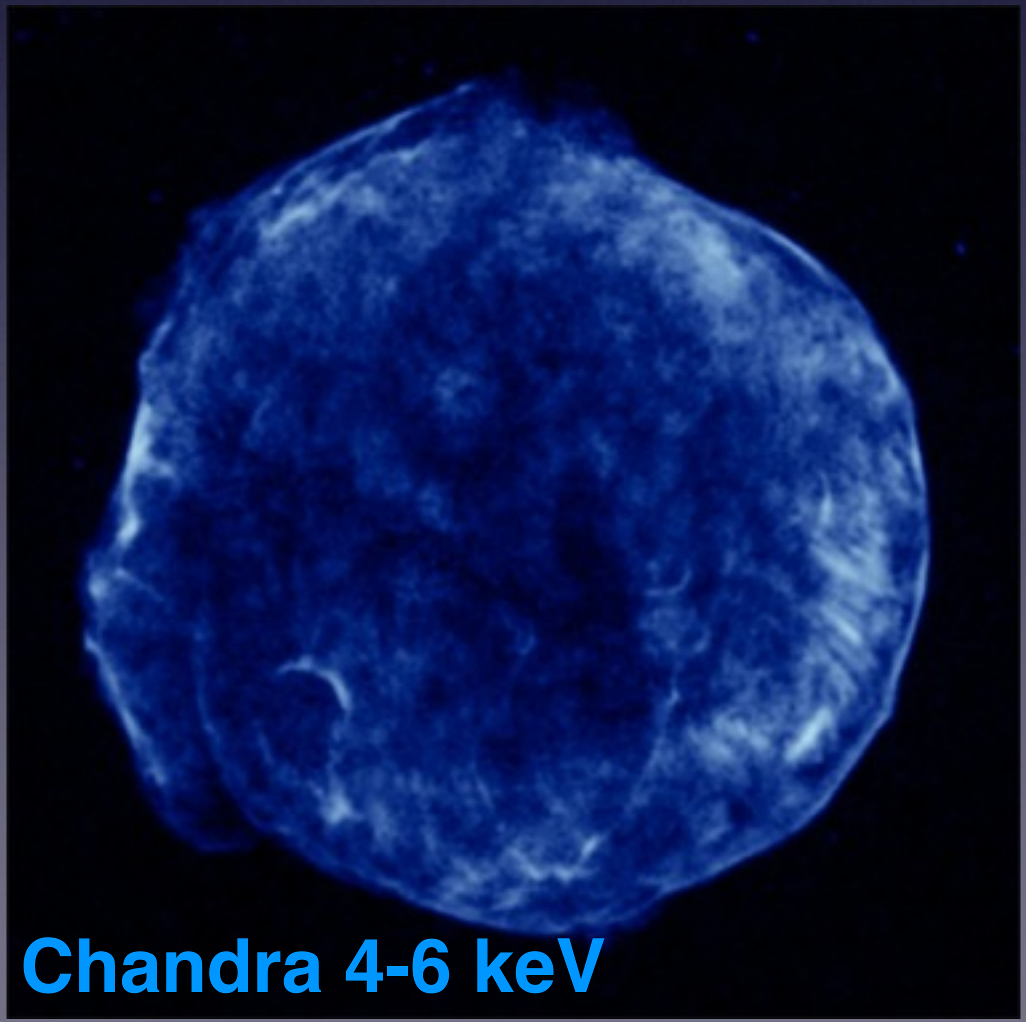
Lopez et al. 2015

$F < 2 \times 10^{-5}$ ph cm^{-2} s^{-1}

$M_{44} < 2 \times 10^{-4}\ M_{sun}$

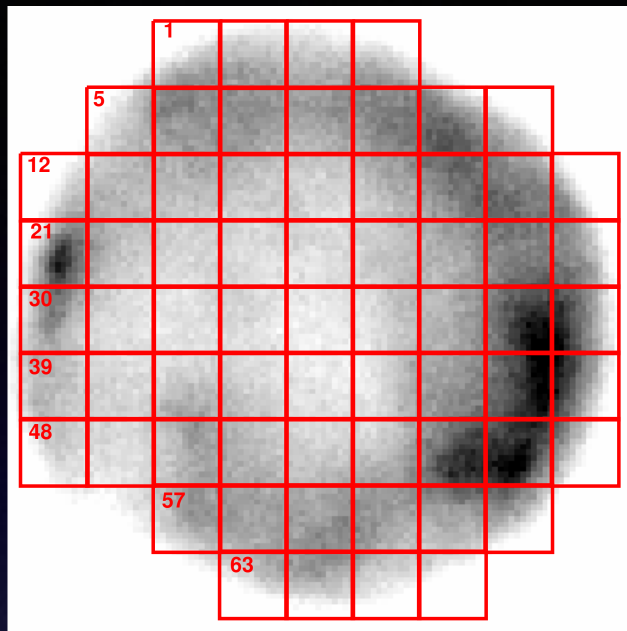
Using Hard X-rays to Probe Particle Acceleration
Tycho's SNR

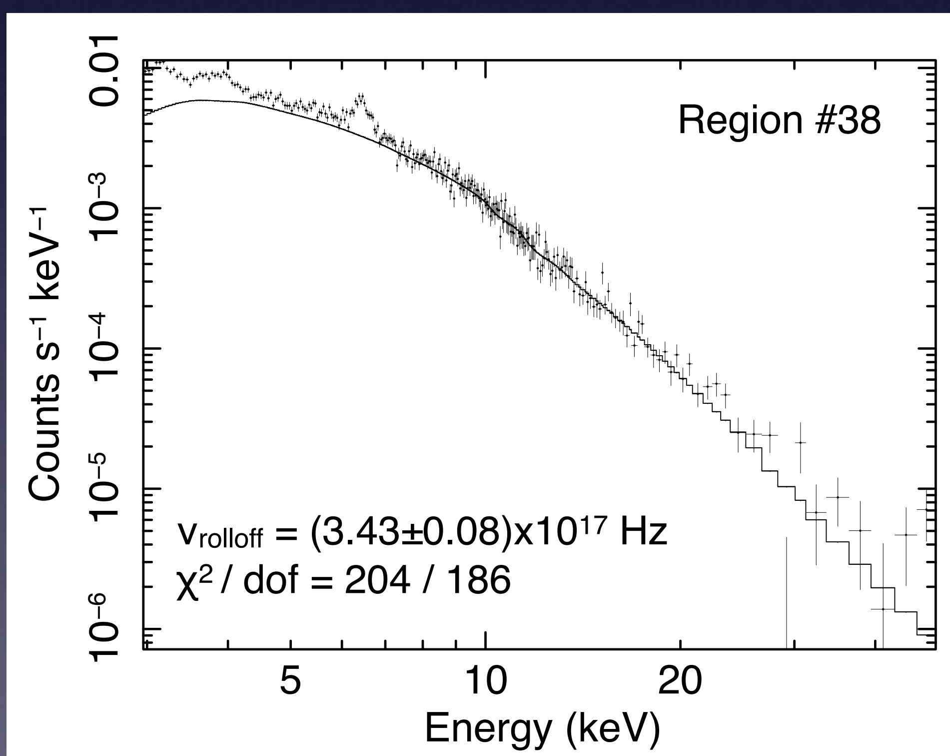
Lopez et al. 2015

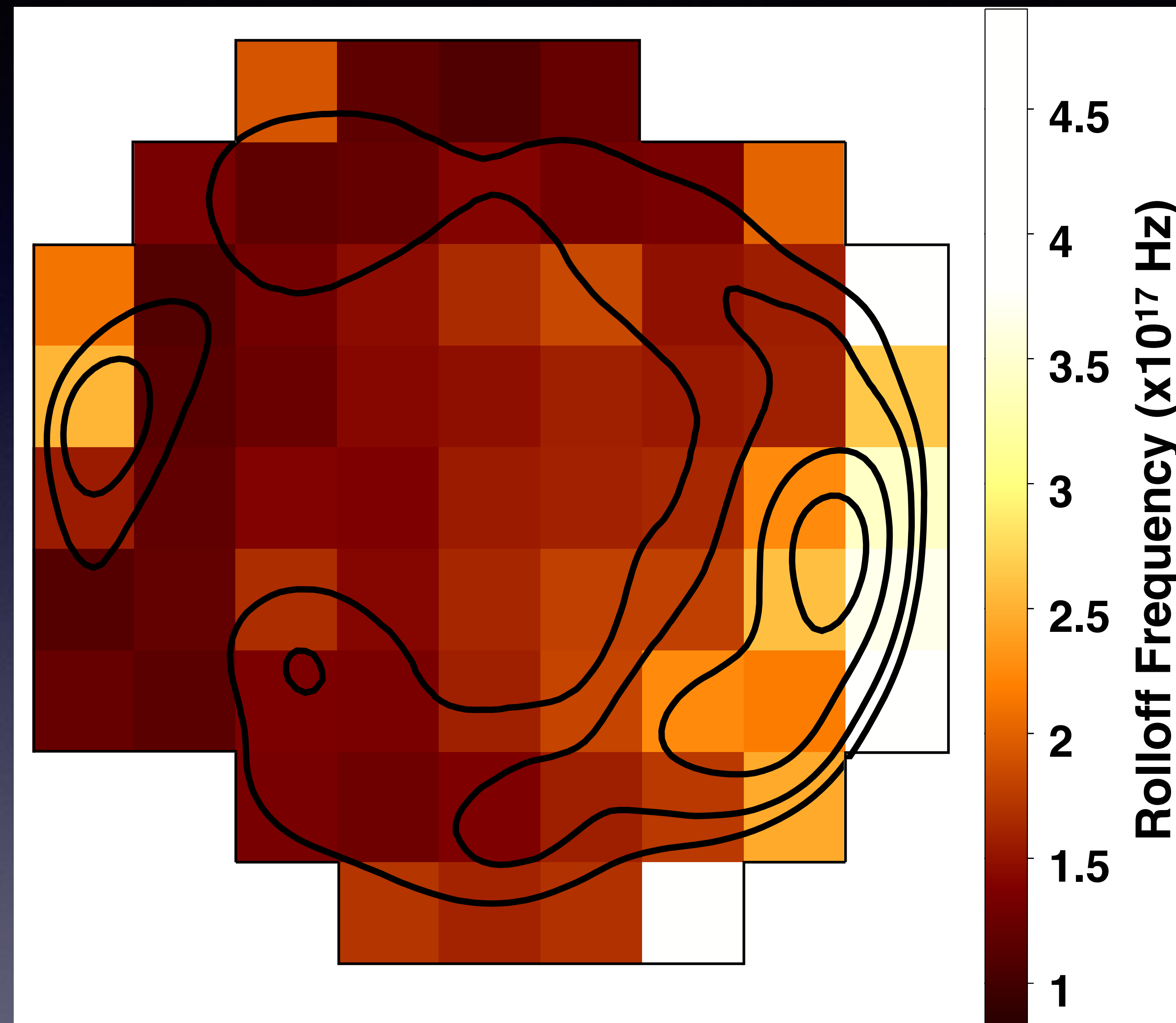


Eriksen et al. 2011

Using Hard X-rays to Probe Particle Acceleration
Tycho



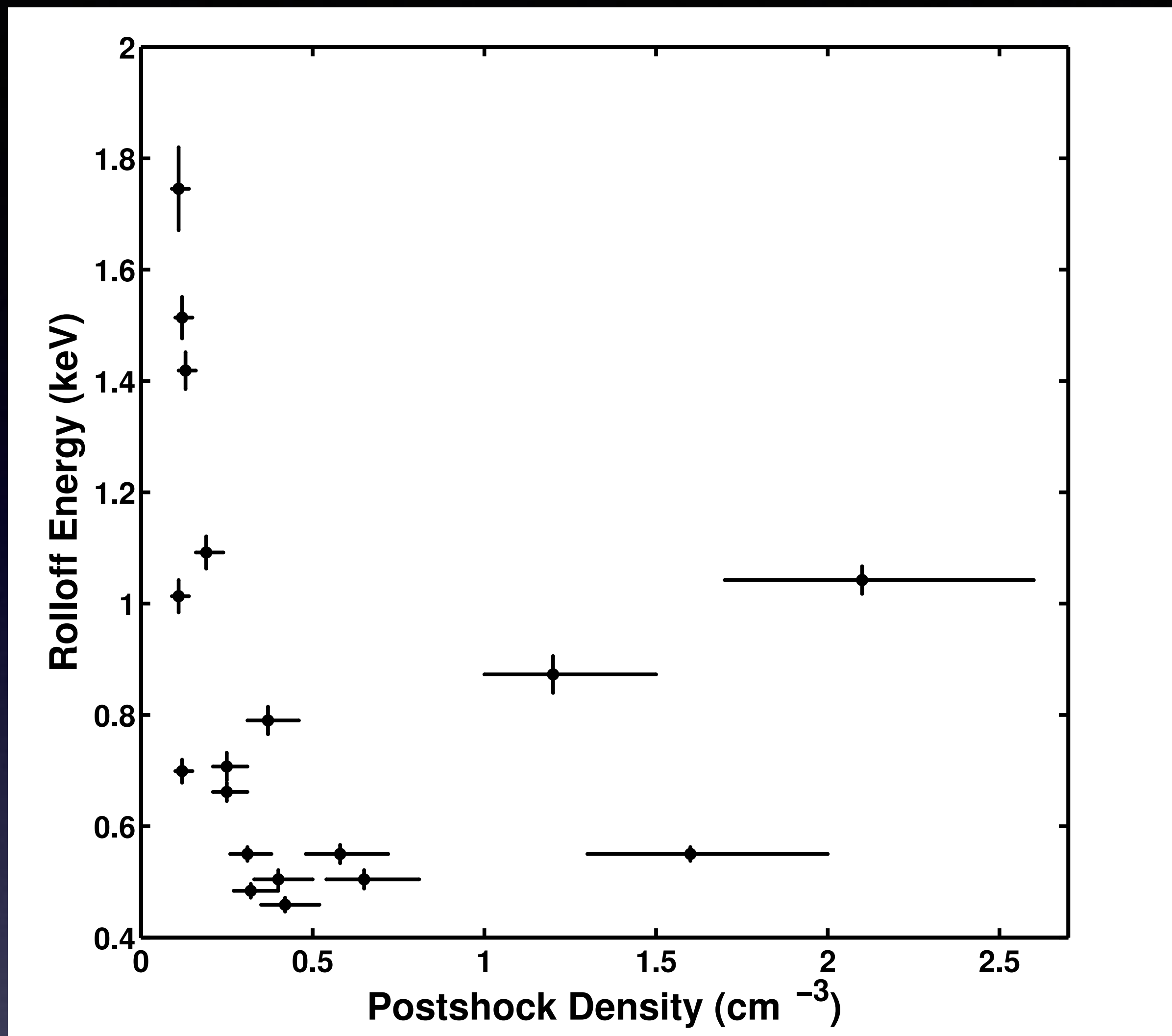


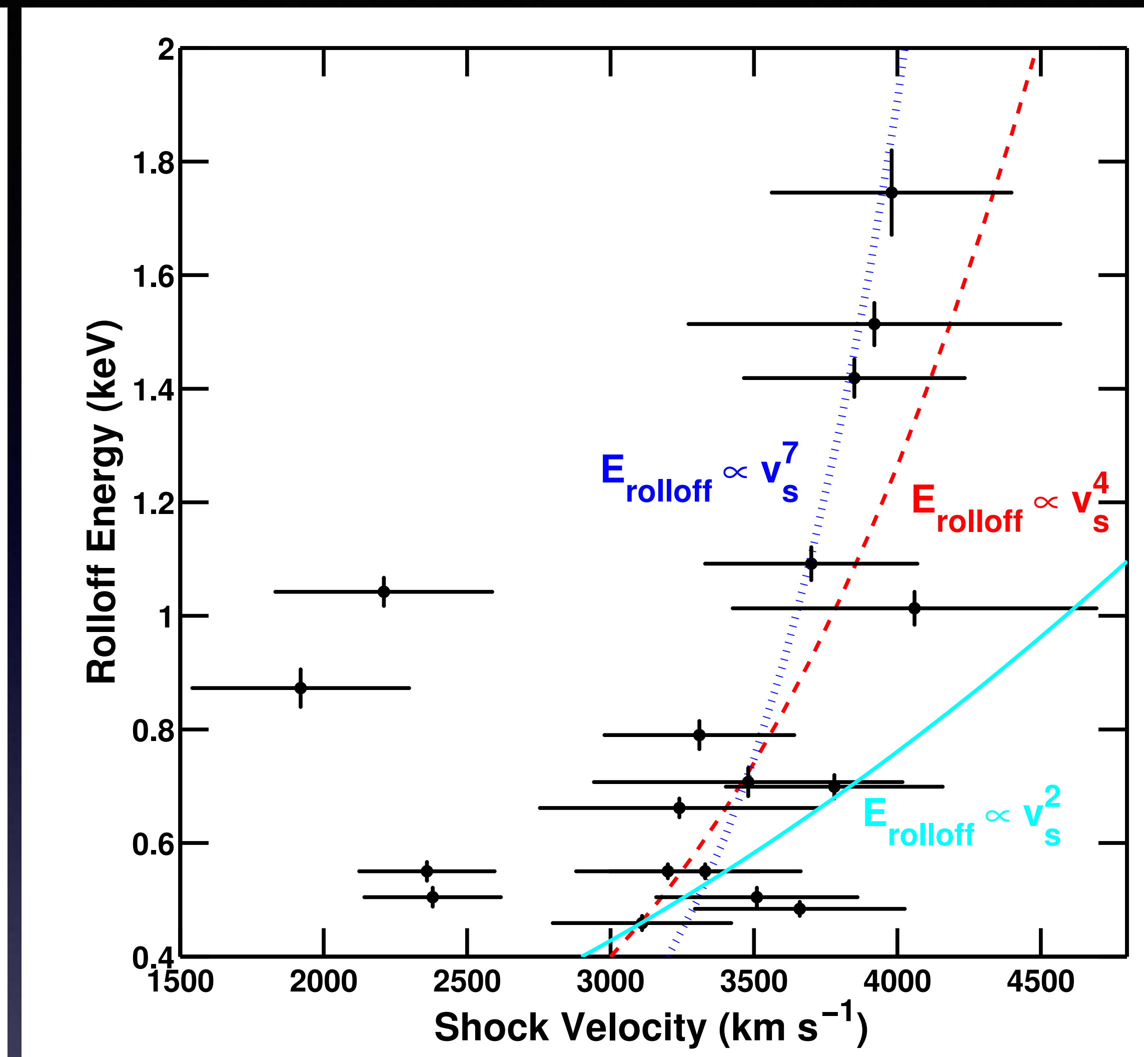


Lopez et al. 2015

$$E_{\rm max} = 120 \left(\frac{h\nu_{\rm rolloff}}{1\ \rm keV} \right)^{1/2} \left(\frac{B}{\mu \rm G} \right)^{-1/2} \quad \rm TeV$$

What Limits the e⁻ Acceleration?





Lopez et al. 2015

$$E_{\rm rolloff}(\rm age) \propto v_s^4 t^2 B^3 (\eta R_{\mathcal{J}})^{-2}$$

Age-limited case

$$E_{\rm rolloff}(\rm loss) \propto v_s^2 (\eta R_{\mathcal{J}})^{-1}$$

Loss-limited case

$$E_{\rm rolloff}(\rm esc) \propto B^3 \lambda_{\rm mfp}^2.$$

Escape-limited case

Conclusions

➡ The wealth of data available on supernova remnants offers an exciting basis for comparison between sources

➡ SNRs can be "typed" based on their symmetry

➡ Jet-driven SNe (those with collimated outflows) occur at rates that we may expect to find a handful in MW and nearby galaxies

➡ Identified two possible jet-driven SNRs, W49B and SMC 0104-72.3, based on six observational characteristics

➡ SNRs with magnetars have the same symmetry as those without magnetars

➡ NuSTAR hard X-ray imaging revealing important insights about explosion asymmetries, progenitors, and particle acceleration