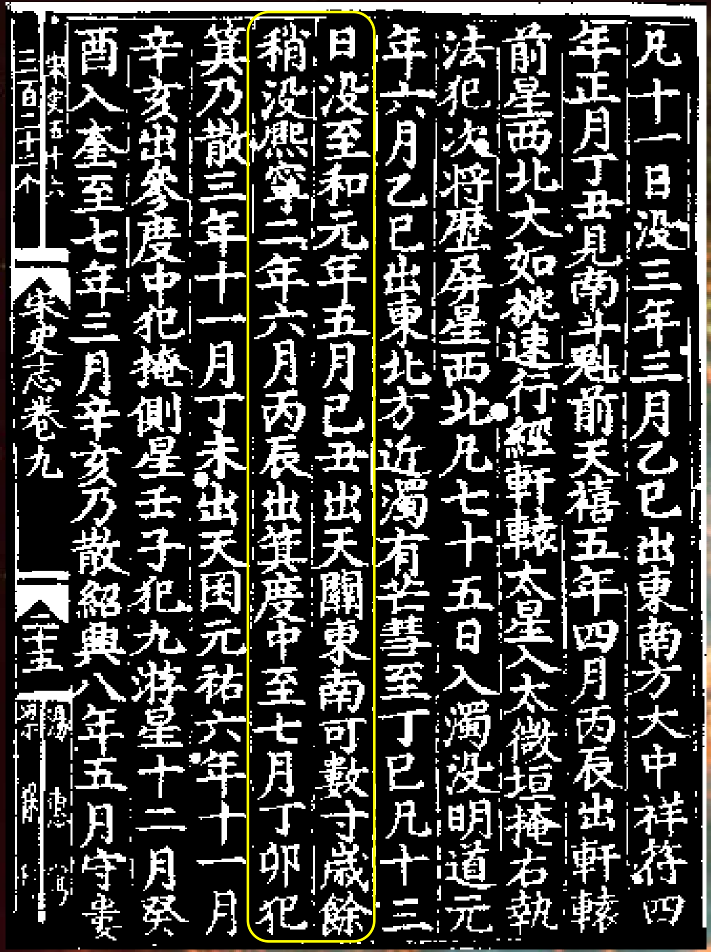
超新星遗迹及相关物理

南京大学 陈阳

“客星”：历史超新星


凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁
宋史志卷九

1054年中国北宋天文学家发现金牛座“客星”（超新星）

《宋史．天文志》：

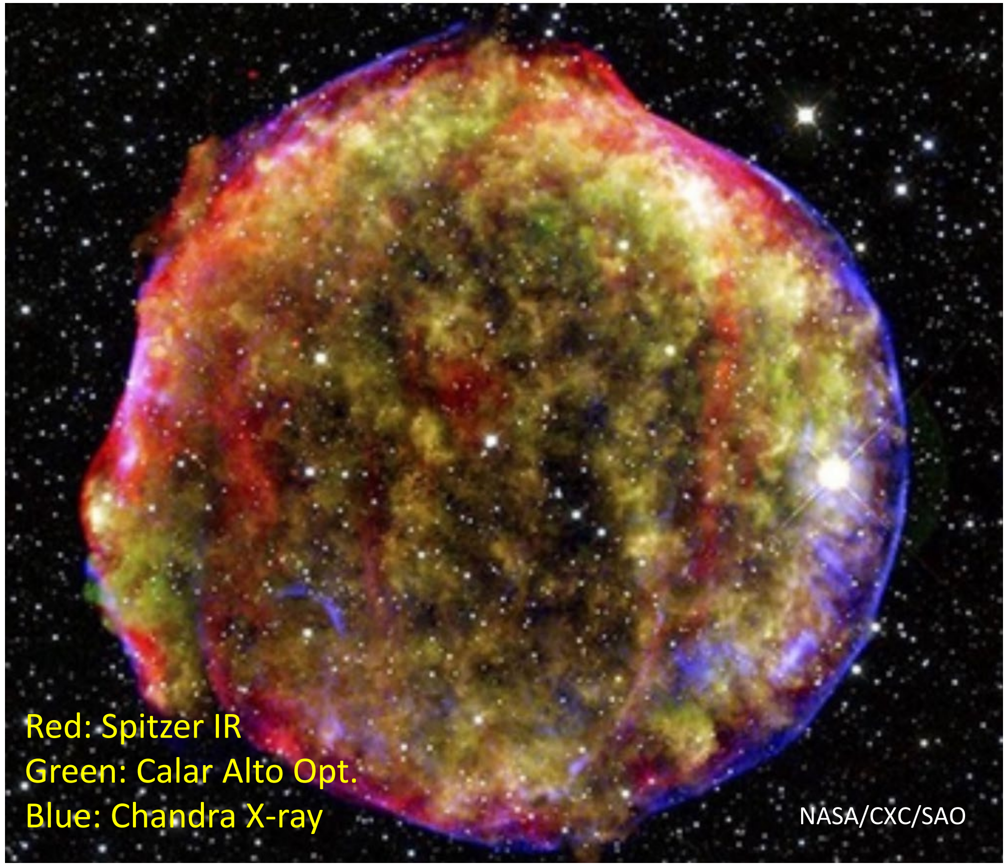
（宋）至和元年五月己丑（1054年7月4日），（客星）出天关东南可数寸，岁余稍没。

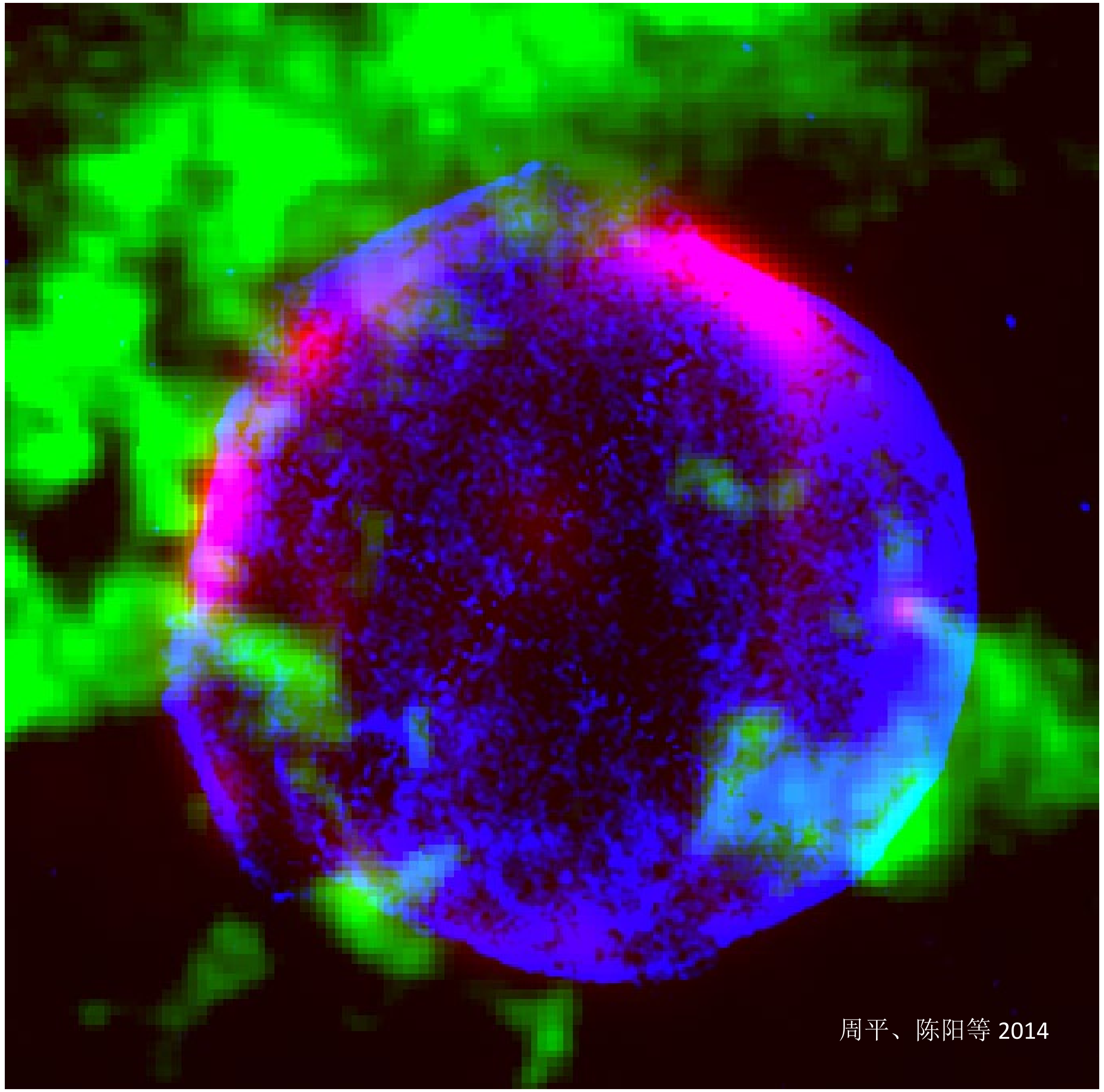
《宋会要》：

嘉祐元年（1056年）三月，司天監言：客星没，客去之兆也。初，至和元年（1054年）五月，**晨出東方，守天關，晝見如太白，芒角四出，色赤白，凡見二十三日。**

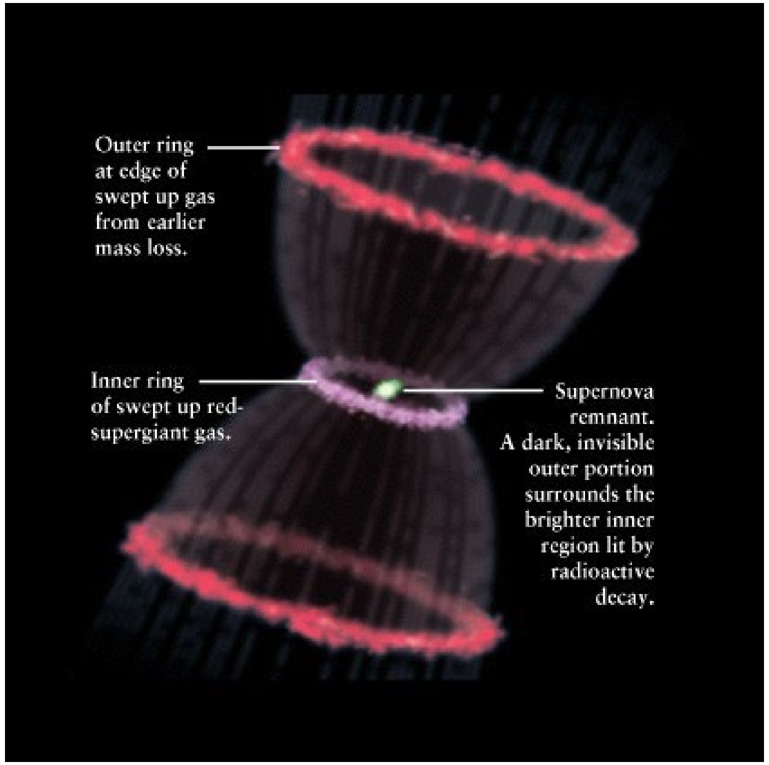
第谷（Tycho），AD1572（11月）

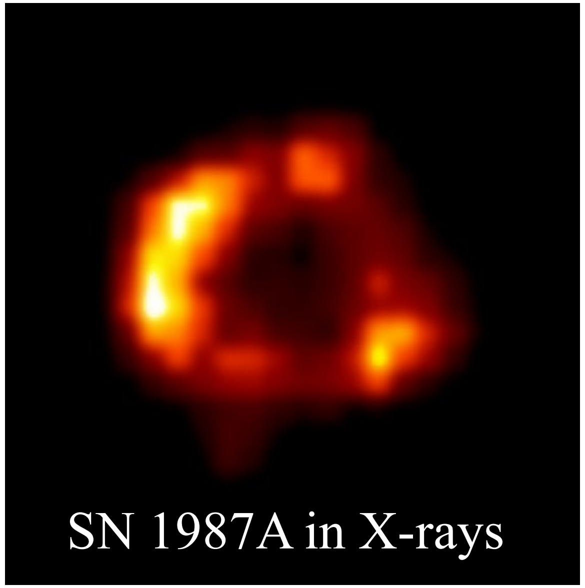
452周年





http://heasarc.gsfc.nasa.gov/docs/objects/heapow/archive/nebulae/sn1987a_acis.html

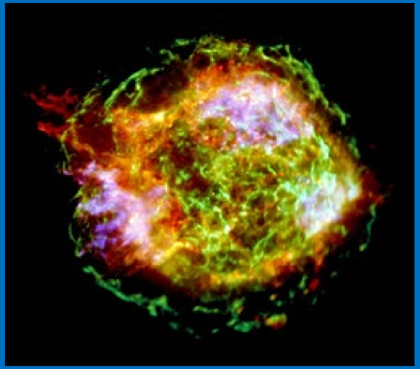




超新星爆炸

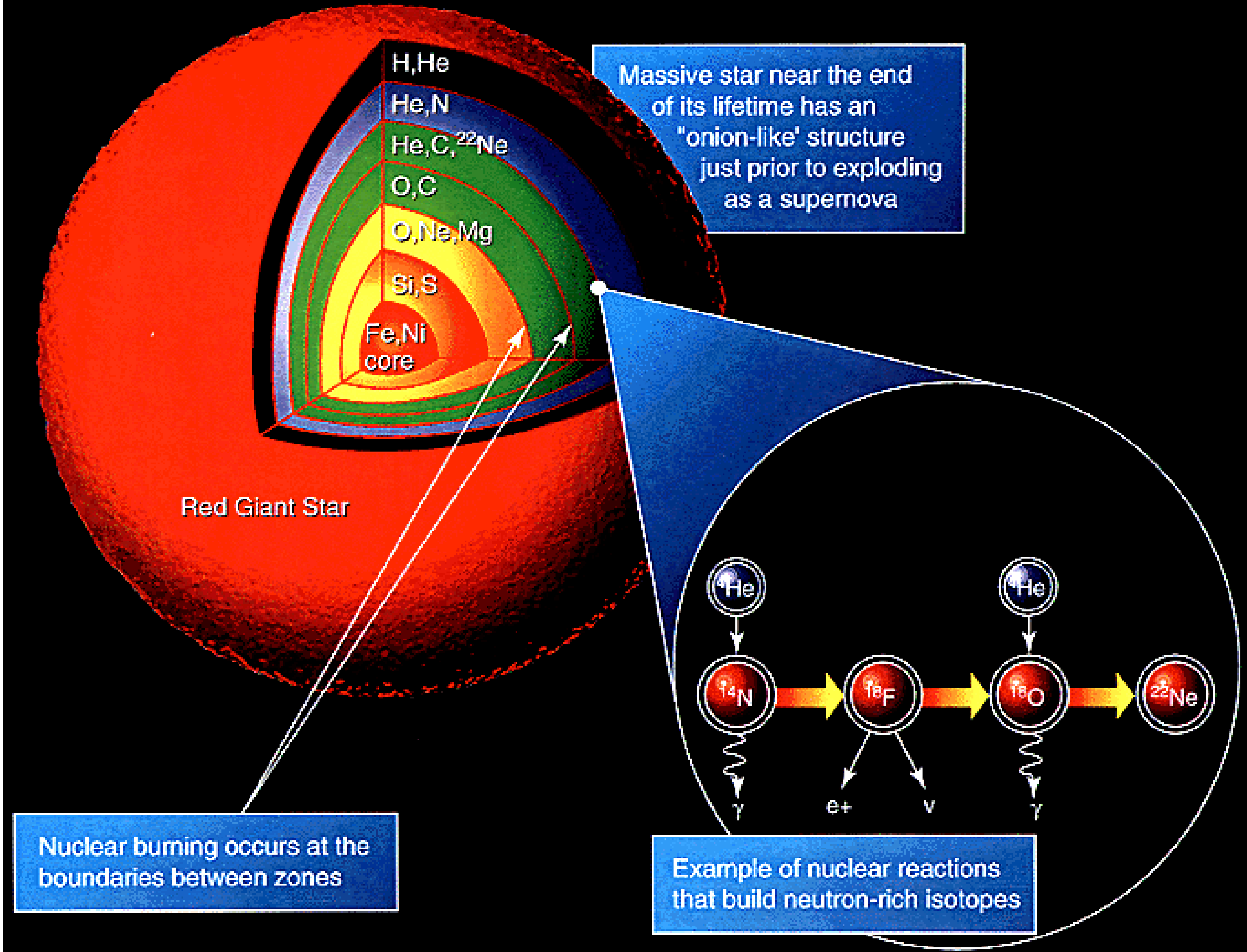
- 天体系统间物质、能量输运重要途径，深刻影响星系的生态和演化
- 宇宙学标准烛光（Ia）
- 也是重元素、河内宇宙线的重要发源地

恒星



星际

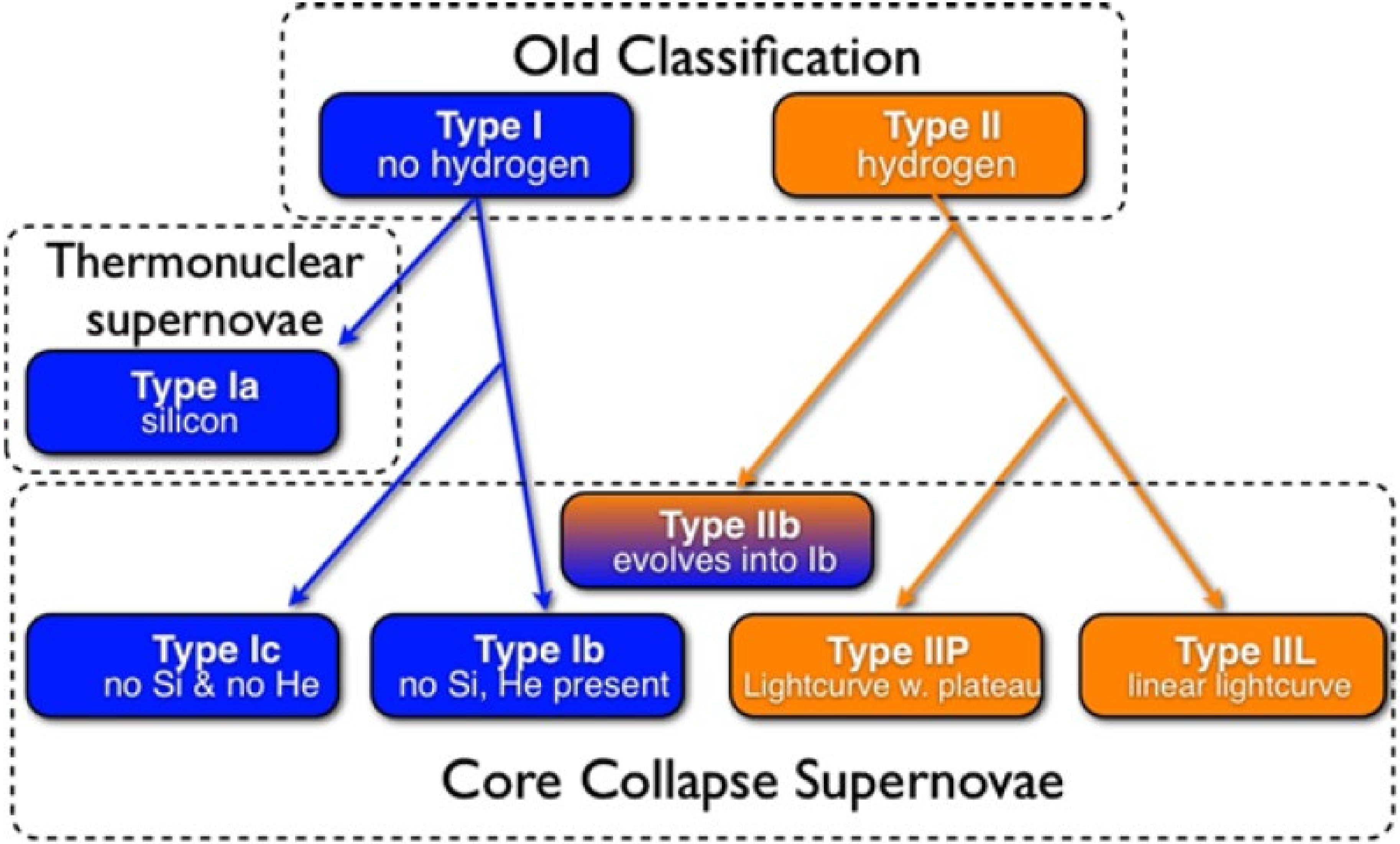
星系际


H,He
He,N
He,C,22Ne
O,C
O,Ne,Mg
Si,S
Fe,Ni core
Red Giant Star
Massive star near the end of its lifetime has an "onion-like' structure just prior to exploding as a supernova
4He
14N
18F
18O
22Ne
γ
e+
v
Nuclear burning occurs at the boundaries between zones
Example of nuclear reactions that build neutron-rich isotopes

"不要问我从哪里来"！

——三毛

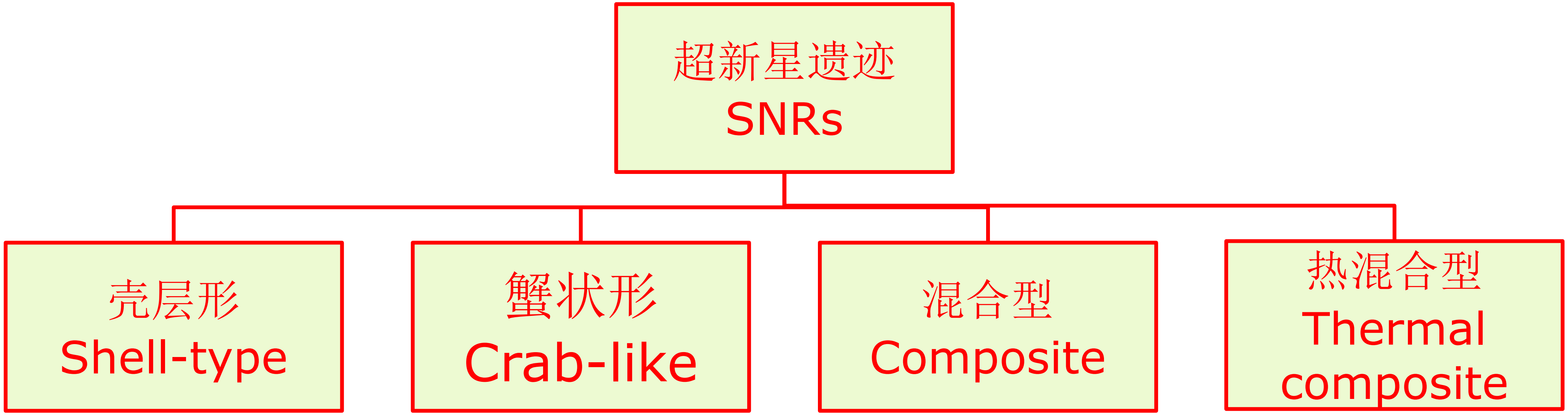
Classification of SNe



Classification of SNRs

Galactic: ~300

Magellanic: ~80

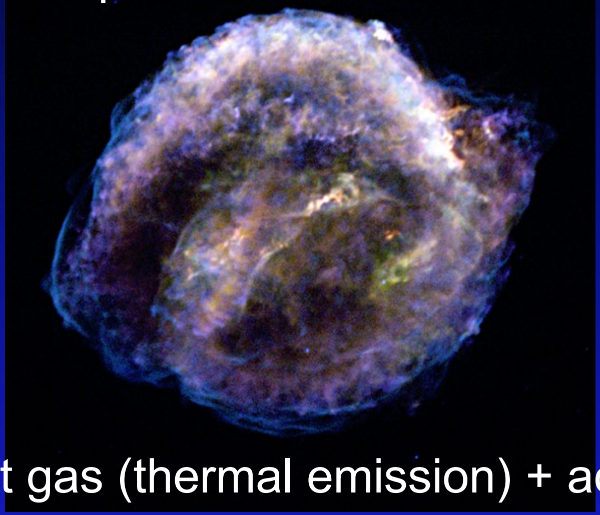


or: Mixed-morphplogy

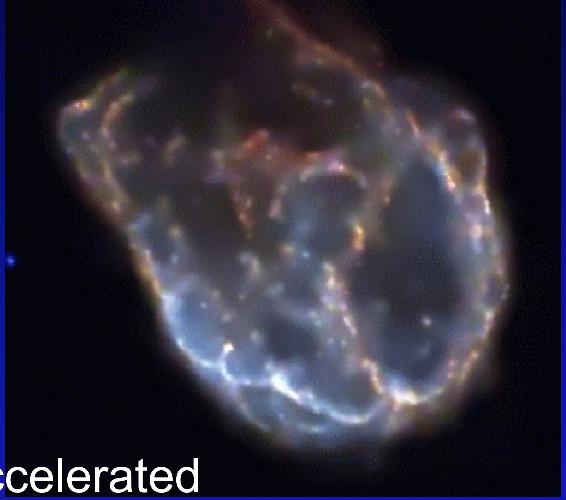
Shell-type SNRs

SN1006

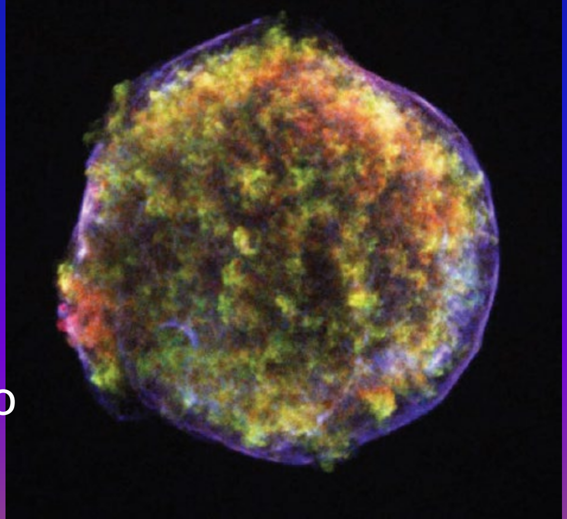
Kepler



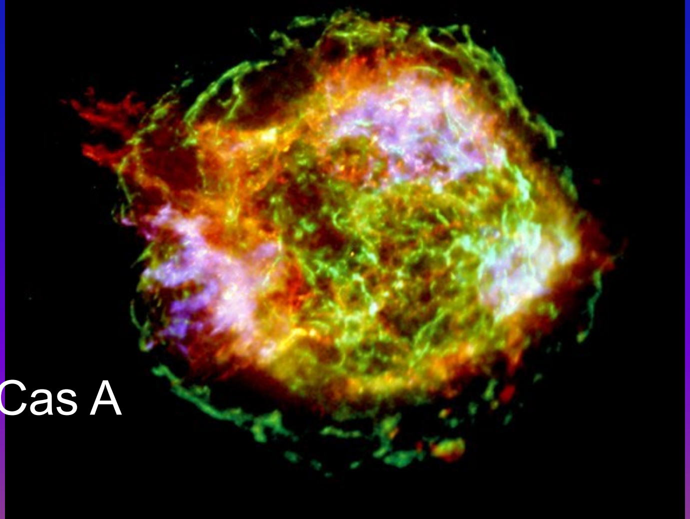
N132D （萧潇 & 陈阳 2007）



Swept-up heated hot gas (thermal emission) + accelerated relativistic particles (non-thermal emission)

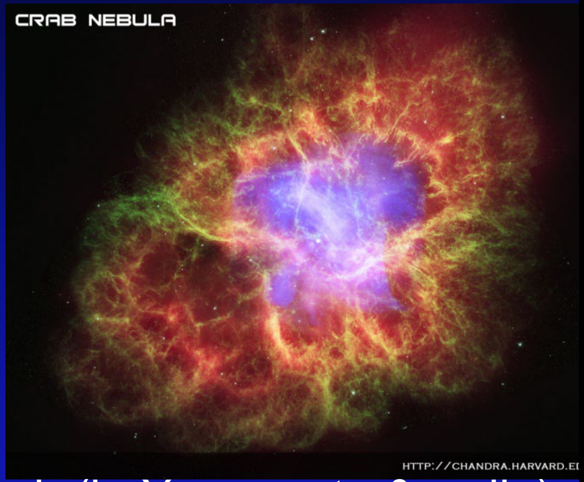


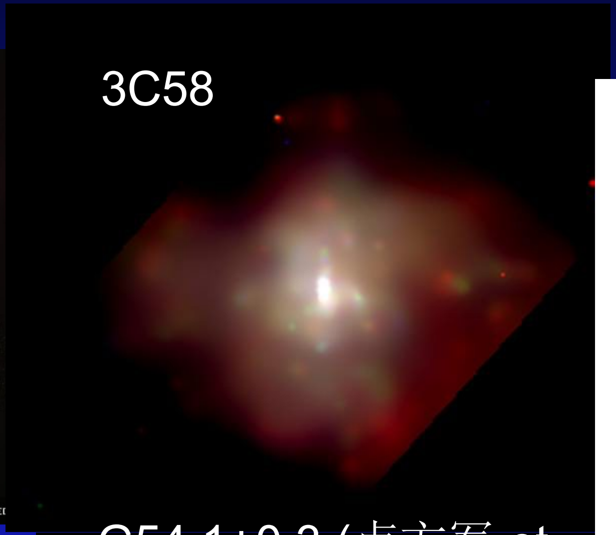
Tycho



Cas A

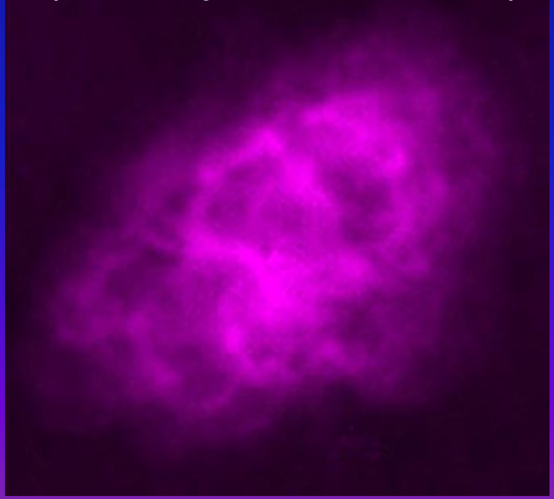
Crab-like SNRs

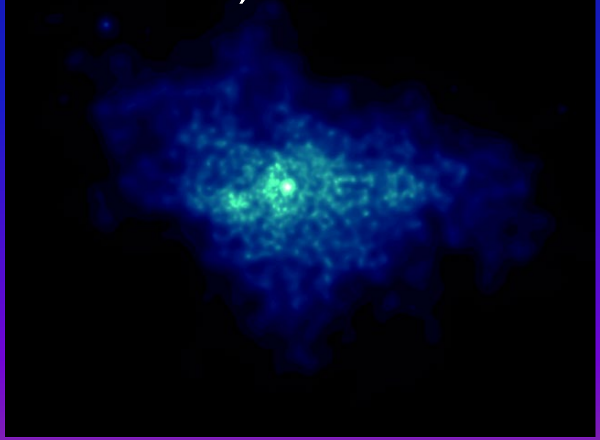


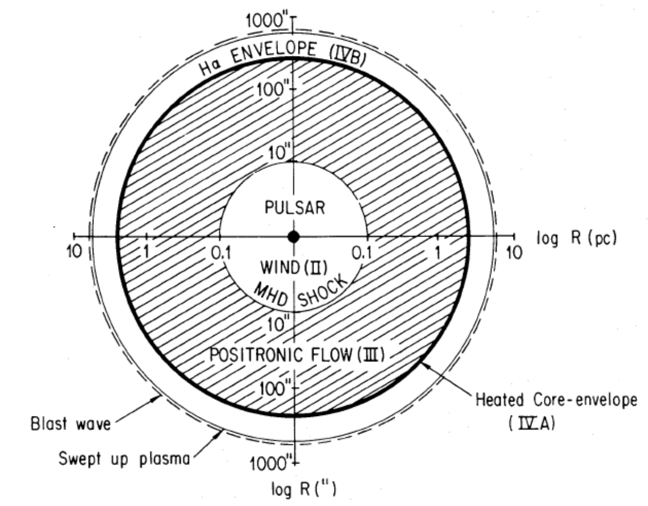


Crab (in X-ray, opt., & radio)

G54.1+0.3 (卢方军 et al. 2002)

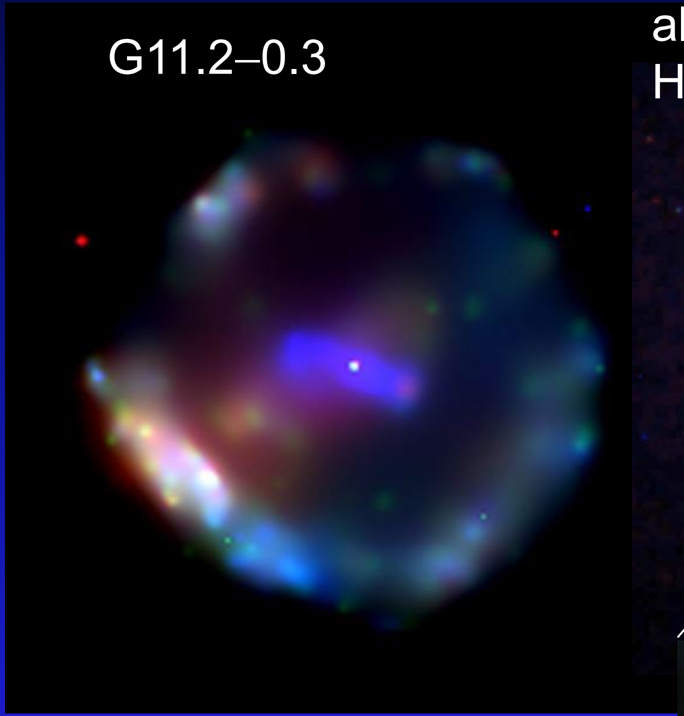




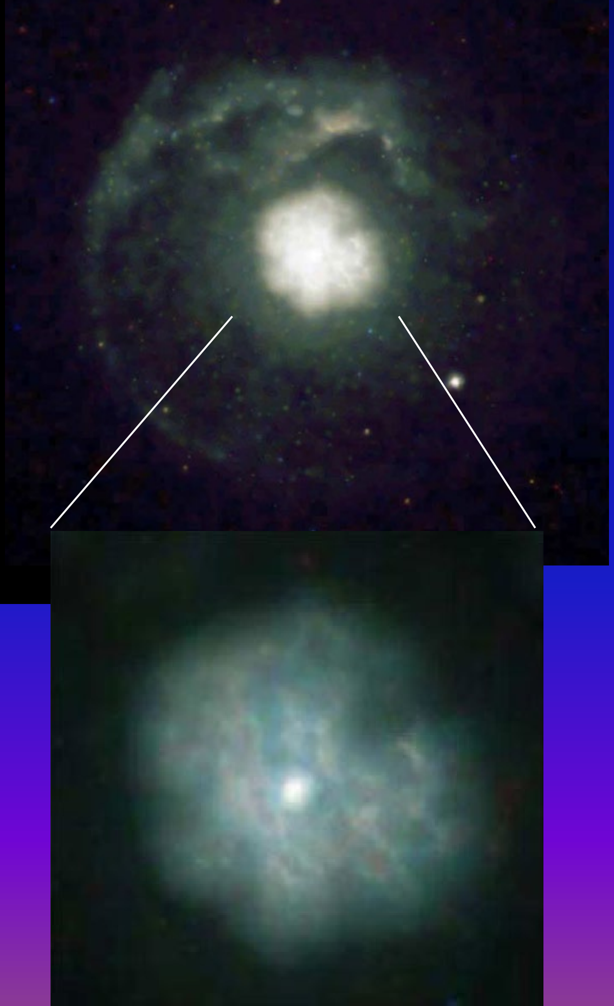


Pulsars, left by the core-collapse SN explosion, power the relativistic winds – pulsar wind nebulae (PWNe)

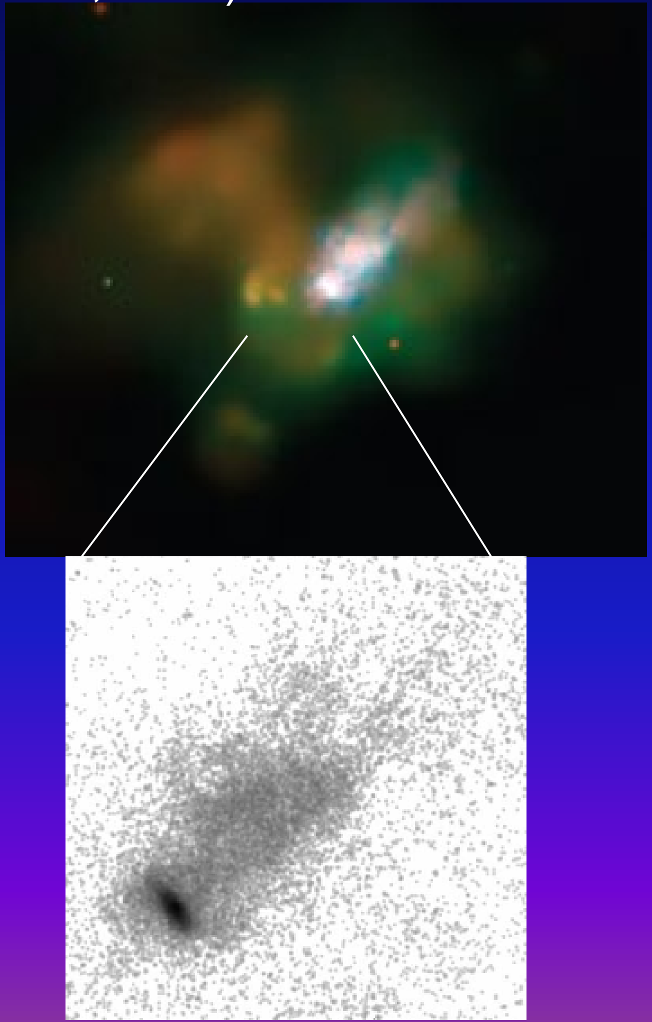
Composite SNRs

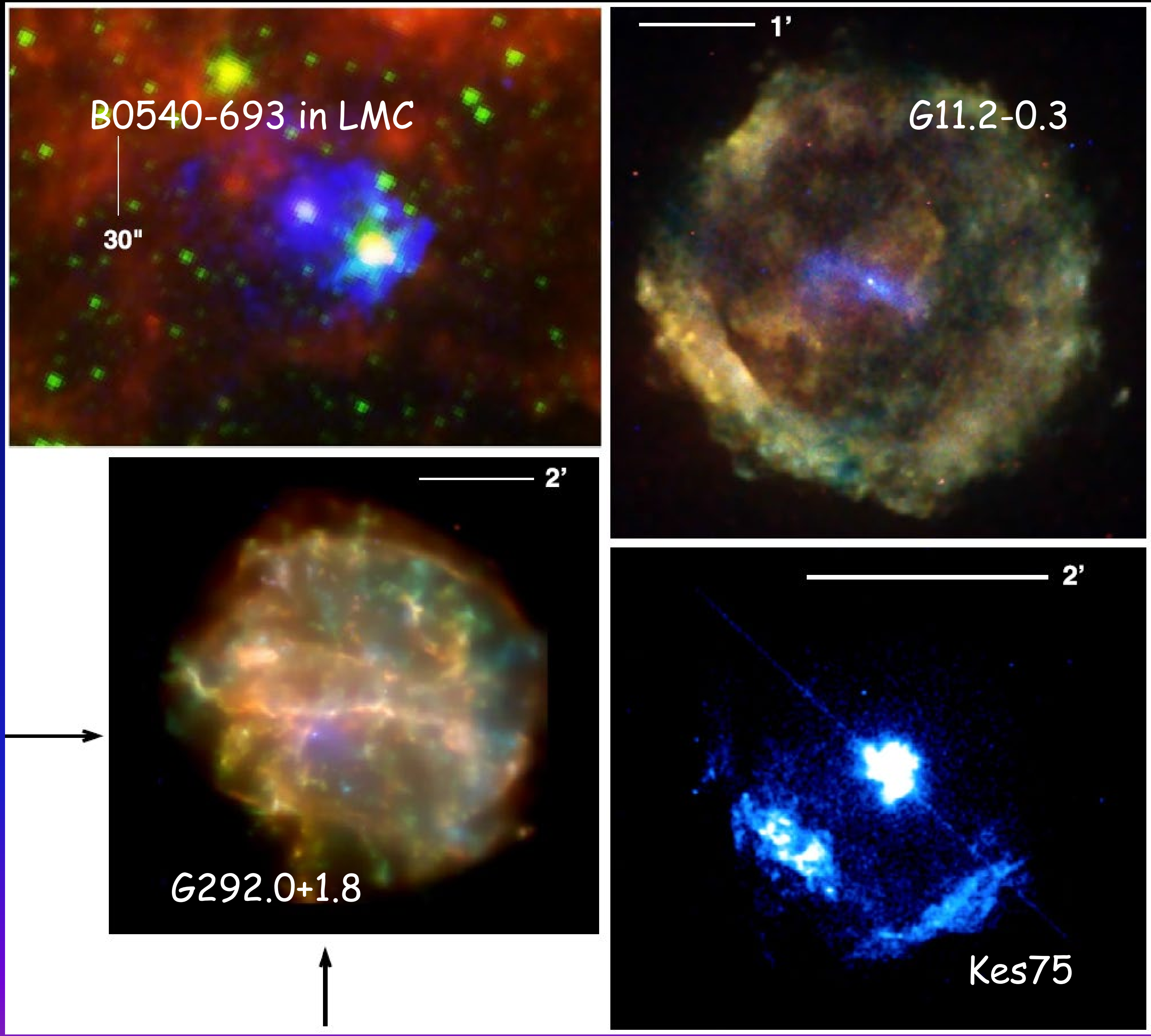


G21.5–0.9 (Slane & 陈阳 et al., 2001; Metheson & Safi-Harb 2005)



N157B (陈阳, 王青德, et al., 2006)





Reynolds 2017, SSR

Thermal Composite (Mixed morphology)

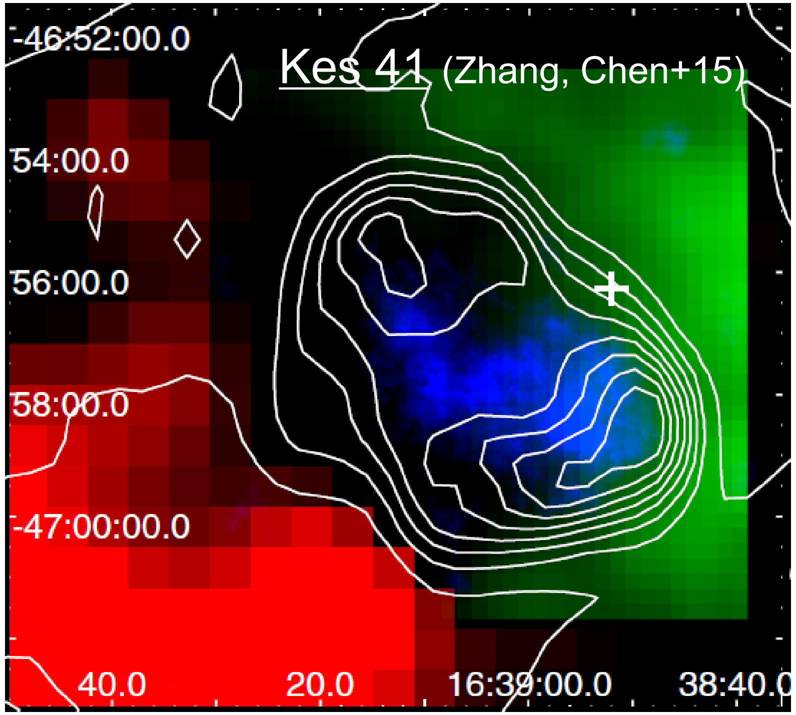
- Radio shell (blastwave)
- Associated with MCs (but not all)

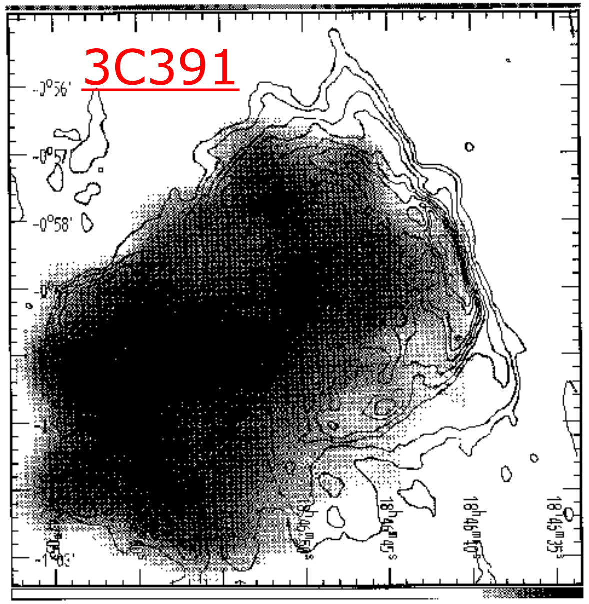
  often with OH Masers

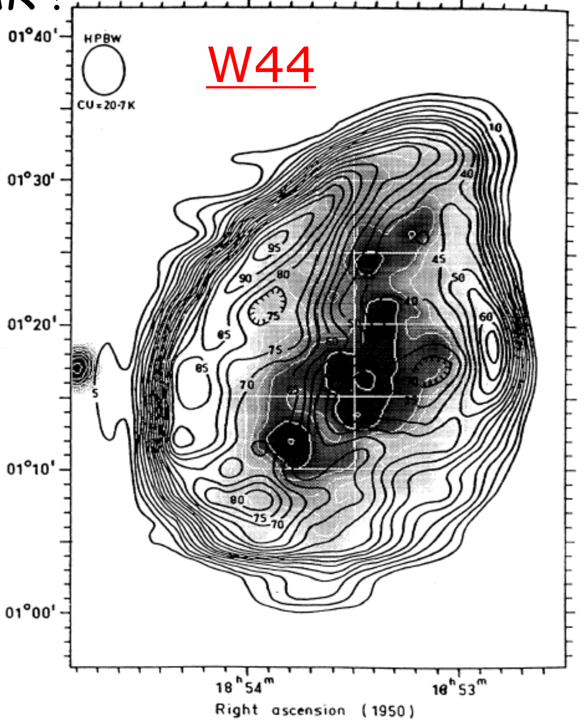
  (signpost of shock interaction with MCs)

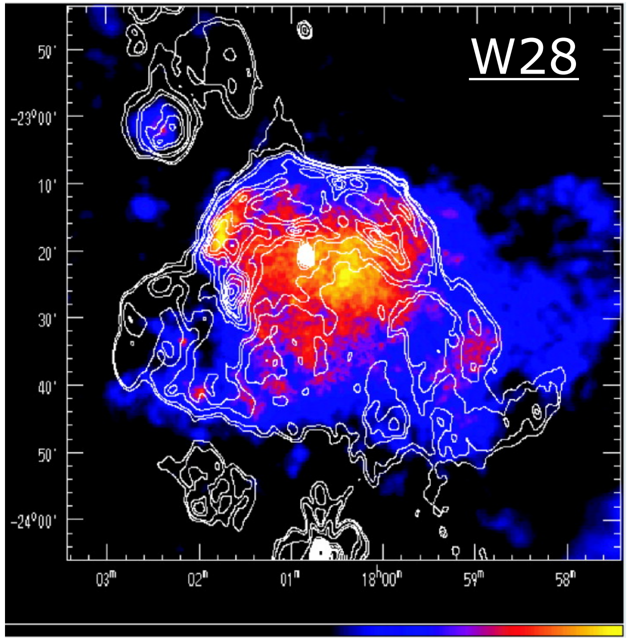
- Interior thermal X-rays, some with $T_z > T_e$

  intriguing, nature *UNCLEAR* !









Thermal composite SNRs in ~ GeV (*Fermi*)

Liu, B., Chen, Y. et al. 2015, ApJ, 809, 102

Parameters of the γ-ray Emission of the Galactic Thermal Composite SNRs Obtained from *Fermi*-LAT Observation

Source	Distance (kpc)	Γ	$L_{1-100\ \mathrm{GeV}}$ (10^{35} erg s^{-1})	MC Interaction[a]	References
G6.4–0.1 (W28)	2.0	2.74 ± 0.06[b]	1.0	Y	(1), (2)
G31.9+0.0 (3C 391)	7.2	2.50 ± 0.04[b]	4.0	Y	(3), (4)
G34.7–0.4 (W44)	2.8	3.02 ± 0.10[b]	2.7	Y	(5), (6)
G43.3–0.2 (W49B)	8	2.29 ± 0.02[c]	8.0	Y	(7), (8)
G49.2–0.7 (W51C)	6	2.5 ± 0.1[b]	4.4	Y	(9), (10)
G89.0+4.7 (HB 21)	1.7	2.33 ± 0.03[c]	0.13	Y	(11), (12)
G189.1+3.0 (IC 443)	1.5	2.61 ± 0.04[b]	1.0	Y	(5), (13)
G304.6+0.1 (Kes 17)	9.7	2.0 ± 0.[illegible][c]	12	Y	(14), (15)
G327.4+0.4 (Kes 27)	4.3	2.5 ± 0.1[c]	0.24	⋯	(16), (17)
G337.8–0.1 (Kes 41)	12	2.38 ± 0.03[c]	7.7	Y	(18)
G348.5+0.1 (CTB 37A)	11.3	2.19 ± 0.07[c]	7.8	Y	(19), (20), (21)
G357.7–0.1 (MSH 17-39)	12	2.5 ± 0.3[c]	5.8	Y	(22), (23)
G359.1–0.5	7.6	2.60 ± 0.05[c]	4.0	Y	(24), (25)
G0.0+0.0 (Sgr A East) (?)[d]	8.0	2.32 ± 0.03[c]	8.7	Y	(26), (23)
G132.7+1.3 (HB 3) (?)[d]	2.2	2.30 ± 0.11[c]	0.04	Y?	(27), (23)
G156.2+5.7 (?)[d]	3	2.35 ± 0.09[c]	0.26	⋯	(28), (23)
G290.1–0.8 (MSH 11-61A) (?)[d]	7	~2.28[c]	1.5	?	(22), (23)
G160.9+2.6 (HB 9) (?)[e]	1.0	2.30 ± 0.05[c]	0.013	?	(29)
G166.0+4.3 (?)[e]	4.5	2.27 ± 0.1[c]	0.11	?	(30), (31)

Hadronic!

1. $\Gamma > 2.0$ (vs. 1.4-1.8 for leptonic)
2. *L* (1-100GeV) >~ 10^{35} erg/s (vs. ~10^{34} erg/s for leptonic)
3. Detailed modellings favor hadroic interaction

超新星（遗迹）爆震波的演化

Type Ia SNe: 14%
Core-collapse (> $8M_\odot$) : 86%

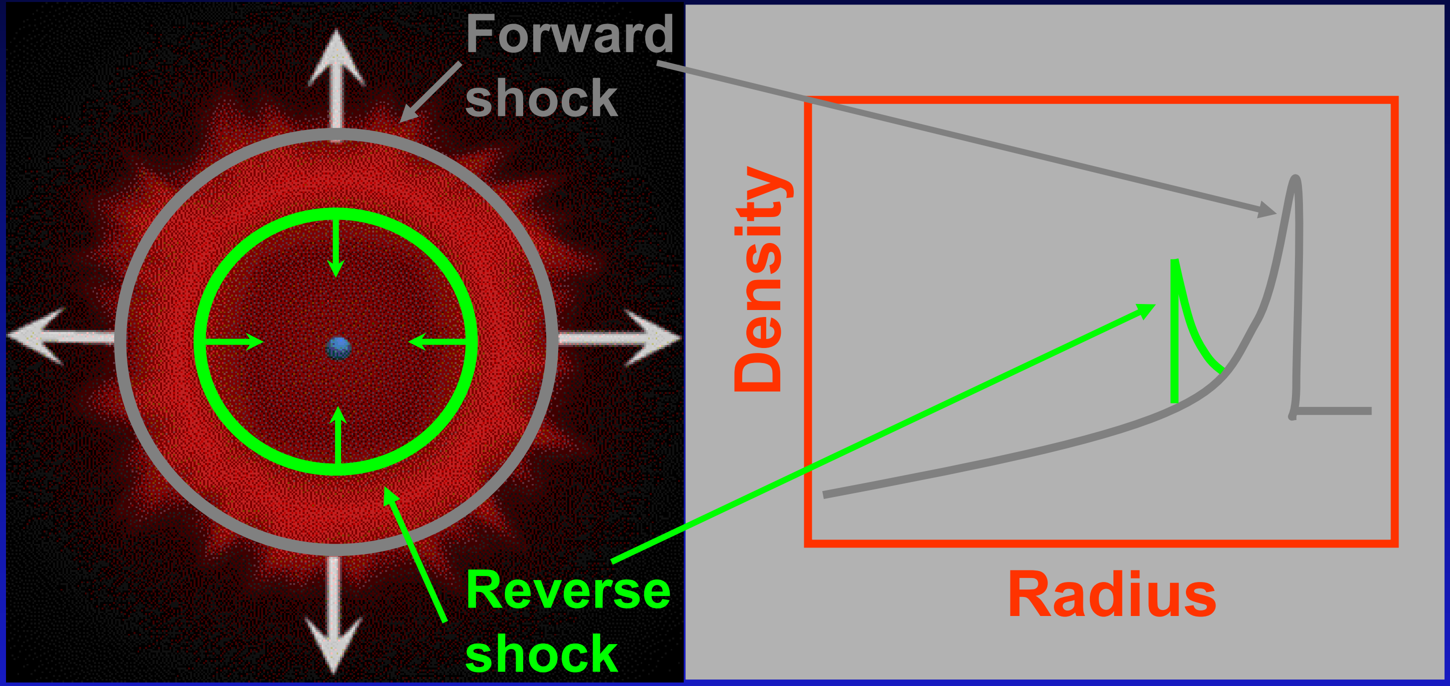
Isotropic explosion and further evolution

Homogeneous ambient medium

Three phases:

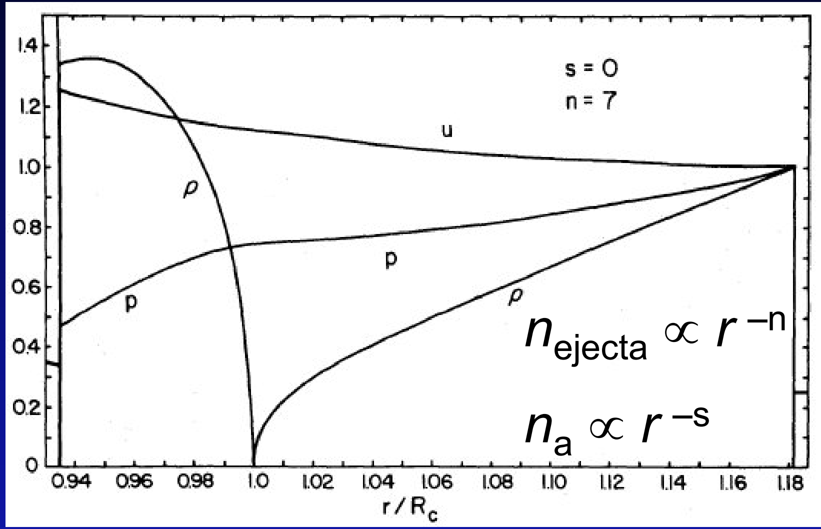
- Free expansion
- Adiabatic expansion
- Radiative expansion

超新星（遗迹）爆震波：自由膨胀相
Forward and reverse shocks

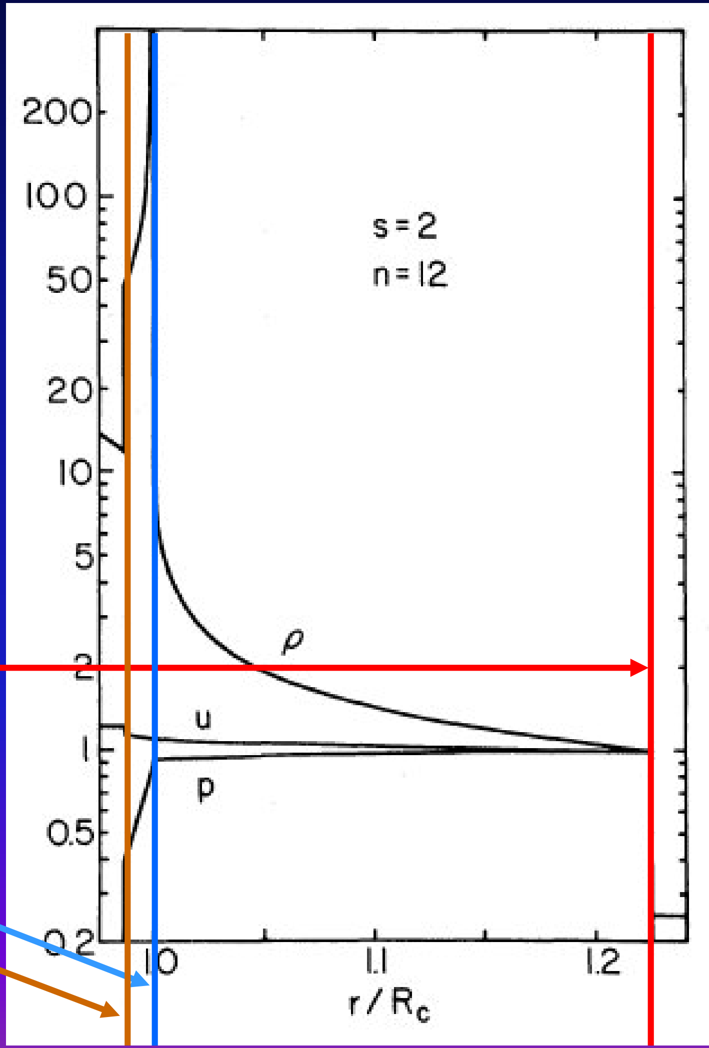


- Forward Shock: into the CSM/ISM (fast)
- Reverse Shock: into the Ejecta (slow)

自由相：Self-similar models



(Chevalier 1982)



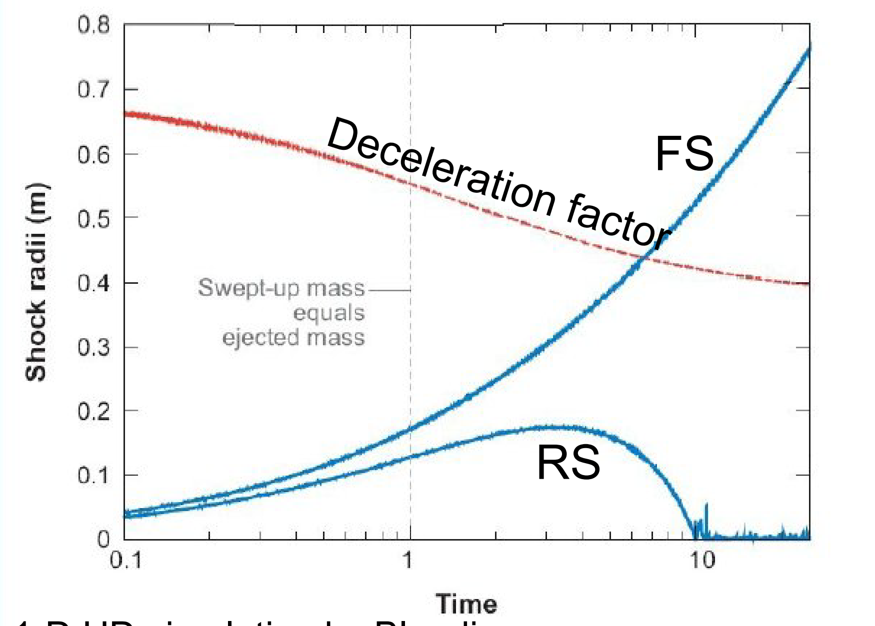
- Radial profiles
  - Ambient medium
  - Forward shock
  - Contact discontinuity
  - Reverse shock
  - Expanding ejecta

End of the free-exp. phase

Swept-up mass ~ Ejecta mass

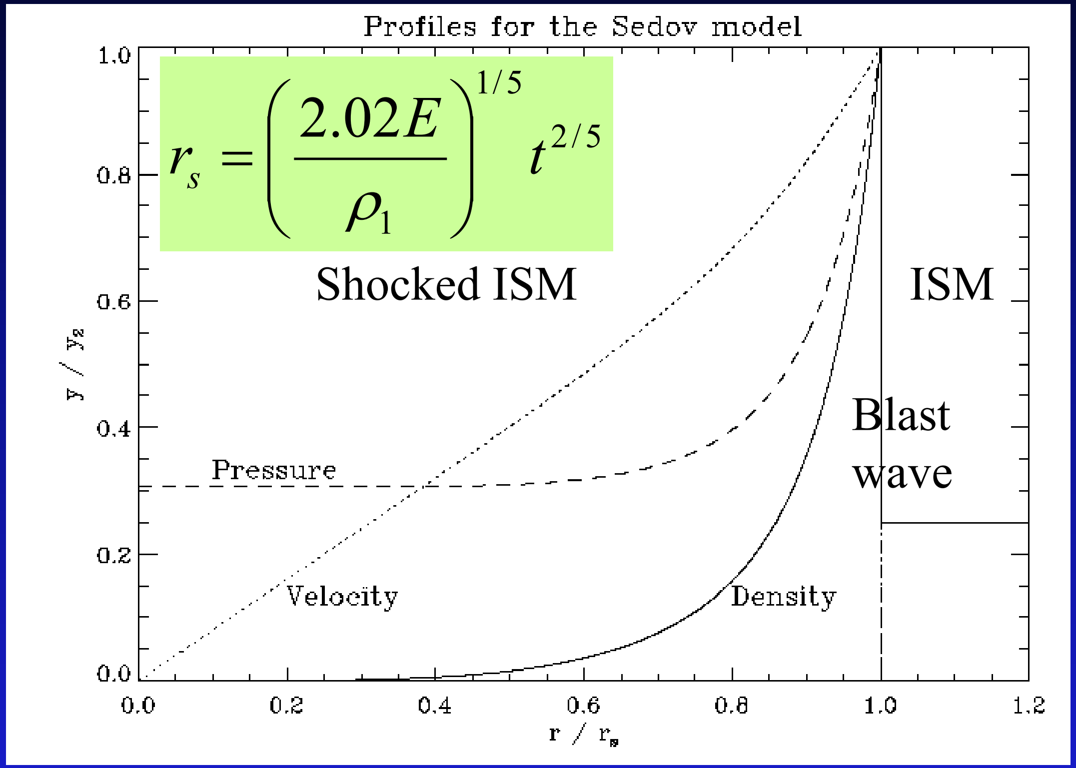
- Reverse shock has reached the core region of the ejecta (constant density)/the center
- ~2/3 E_k has been thermalized

See Truelove & McKee (1999) for a semi-analytic treatment of this phase



1-D HD simulation by Blondin

绝热相：The Sedov profiles



- Most of the mass is confined in a "thin" shell
- Kinetic energy is also confined in that shell
- Most of the internal energy in the "cavity"

Radiative phase

Shock wave gets so slow that
postshock gas is at a temperature

$$T_S < 6\times10^5\ \mathrm{K}$$

and the shock wave is radiative.

$$R_S = (147\times\epsilon\, E_{SNR} R_T{}^2/4\pi\rho_0)^{1/7}\, t^{2/7}$$

$\epsilon = 0.24$, R_T: radius at phase transition

(Blinnikov et al. 1982)

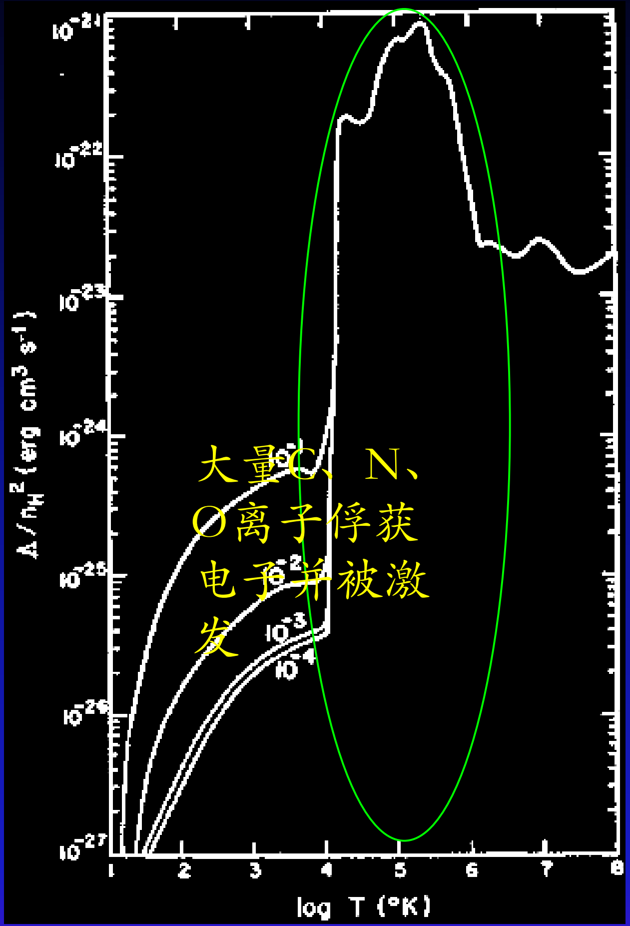
Radiative shocks

早先受到震激的(shocked)物质已冷却

$$N_{\rm rad} \cong 10^{17.5} V_{s7}^{\ 4}\ {\rm cm}^{-2}\ (60 < V_s < 150\ {\rm km\ s^{-1}})$$

$$t_{\rm cool} = N_{\rm rad} / n_0 V_s \approx 10^3 V_{s7}^{\ 3} / n_0\ {\rm yr}$$

$$F = \frac{1}{4} n_0 \mu\, m_{\rm H}\, V_s^{\ 3} = 5.8 \times 10^{-4} n_0 V_{s7}^{\ 3}\ {\rm ergs\ cm^{-2}\ s^{-1}}$$



- 辐射性前导 (Radiative precursor):
  UV光子电离 （V_s > 110 km/s可完全电离H、He）
  分子气体： 光致离解 （H_2→H+H）进而电离

- 跃变条件：

$T_1 = T_2$ （等温，相当于 γ=1）

$$\frac{\rho_2}{\rho_1} = \frac{4}{\frac{2}{M^2} + \frac{1}{M_A^{\ 2}} + \left[\left(\frac{2}{M^2} + \frac{1}{M_A^{\ 2}} \right)^2 + \frac{8}{M_A^{\ 2}} \right]^{1/2}}$$

√ $\to \sqrt{2} M_A \quad (1 << M_A << M^2)$

√ $\to M^2 \quad (1 \le M^2 << M_A)$

Two great ideas in a single short paper

COSMIC RAYS FROM SUPER-NOVAE

By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

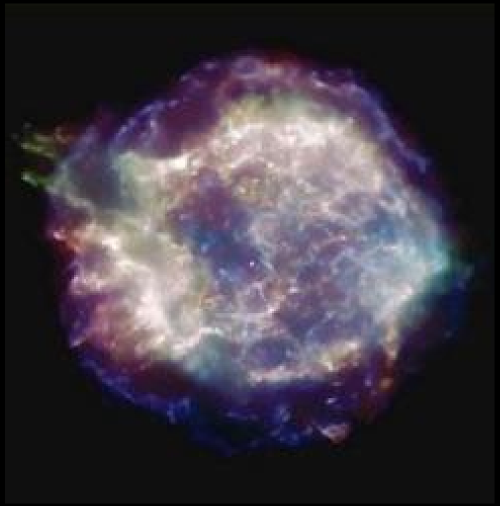
happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the "gravitational packing" energy in a *cold* neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such. The consequences of this hypothesis will be developed in another place, where also will be mentioned some observations that tend to support the idea of stellar bodies made up mainly of neutrons.

D. Conclusions.—From the data available on super-novae we conclude

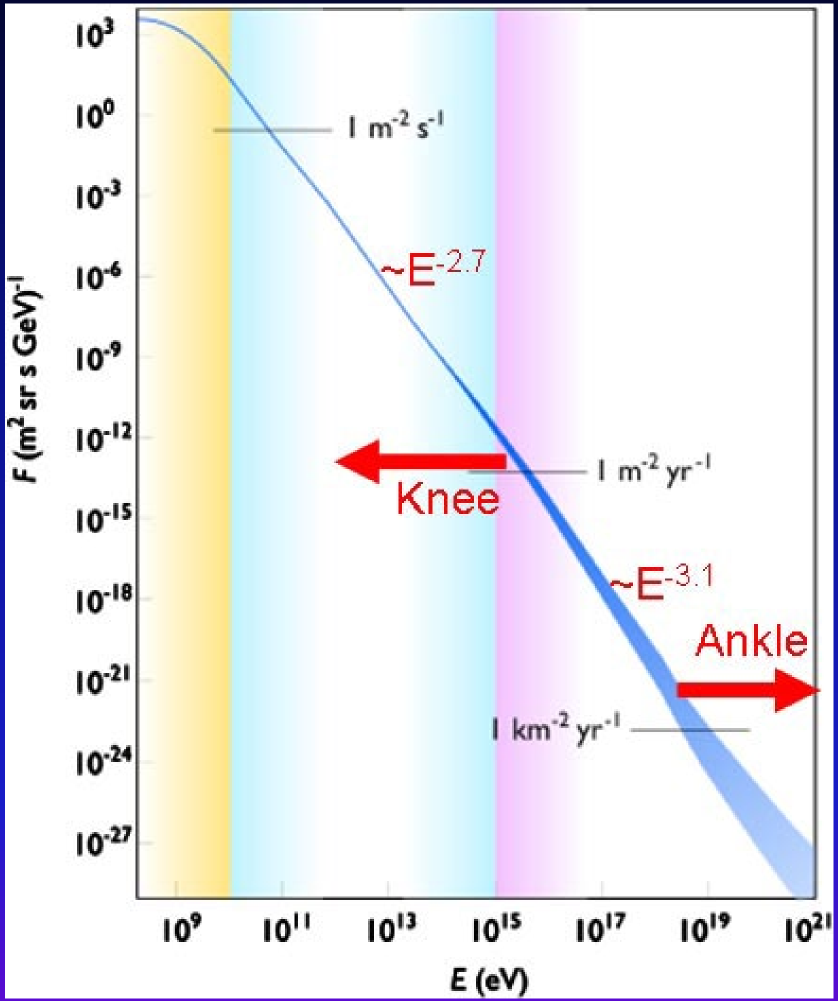
(1) Mass may be *annihilated* in bulk. By this we mean that an assembly of atoms whose total mass is M may lose in the form of electromagnetic radiation and kinetic energy an amount of energy E_T which probably cannot be accounted for by the liberation of known nuclear packing fractions. Several interpretations of this result are possible and will be published in another place.

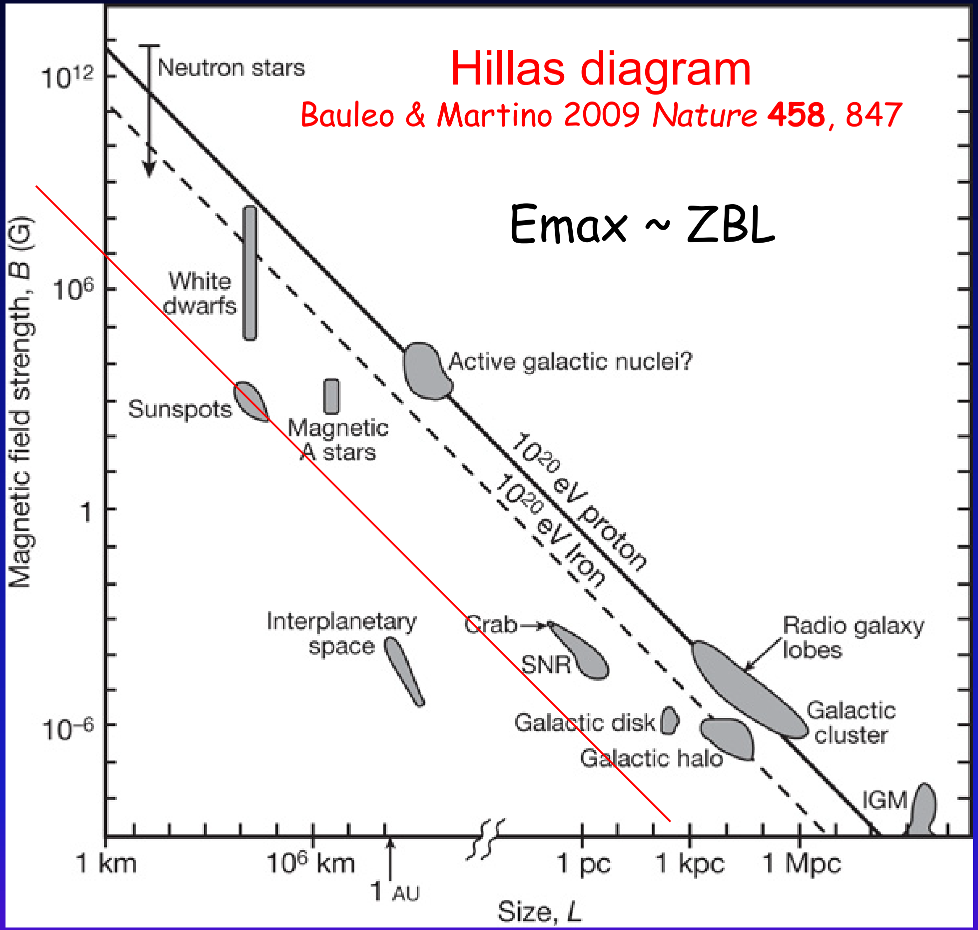
(2) The hypothesis that *super-novae emit cosmic rays* leads to a very satisfactory agreement with some of the major observations on cosmic rays.

Baade & Zwicky (1934) :
SN → NS & CRs



宇宙线能谱

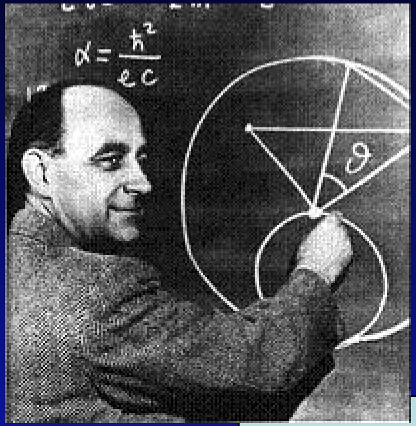




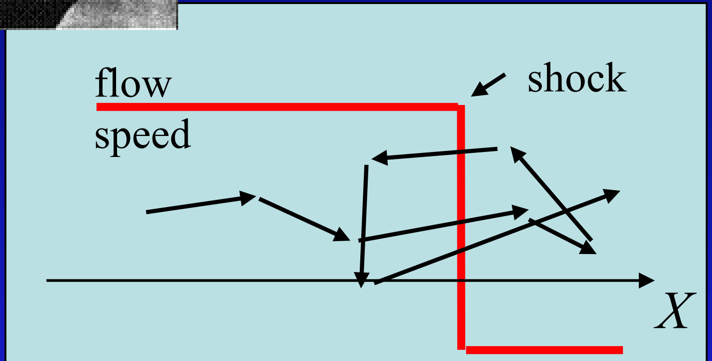
- “踝”以上：河外起源
- “膝”以下：河内起源（河内密度高于大小麦哲伦云）

SNR shock wave enables Diffusive shock acceleration (DSA)

Fermi acceleration:
basic mechanism!



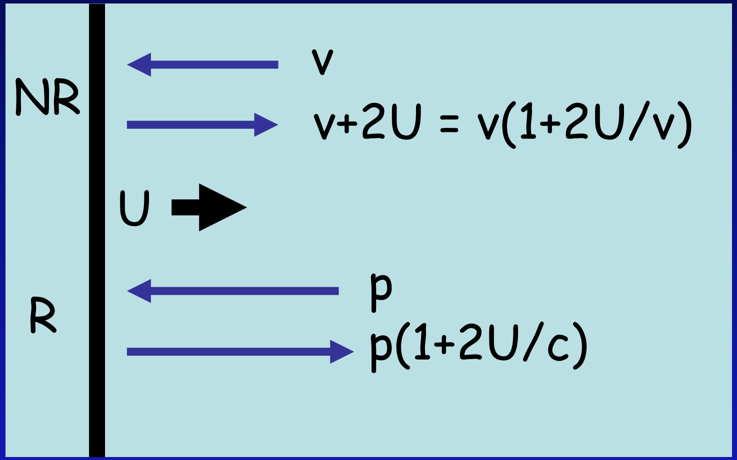
- Fermi acceleration
  - Converging flows
  - Particle diffusion
    (How possible, in a collisionless plasma?)
- Scattering on MHD waves



(in the shock reference frame)

A test particle approach (Bell 1978)

- Collision against a (N.R.) moving wall:



$$\langle \delta p \rangle = \frac{2}{3} \frac{p}{v} (u_1 - u_2)$$

(averaged over directions)

- Finally, the distribution

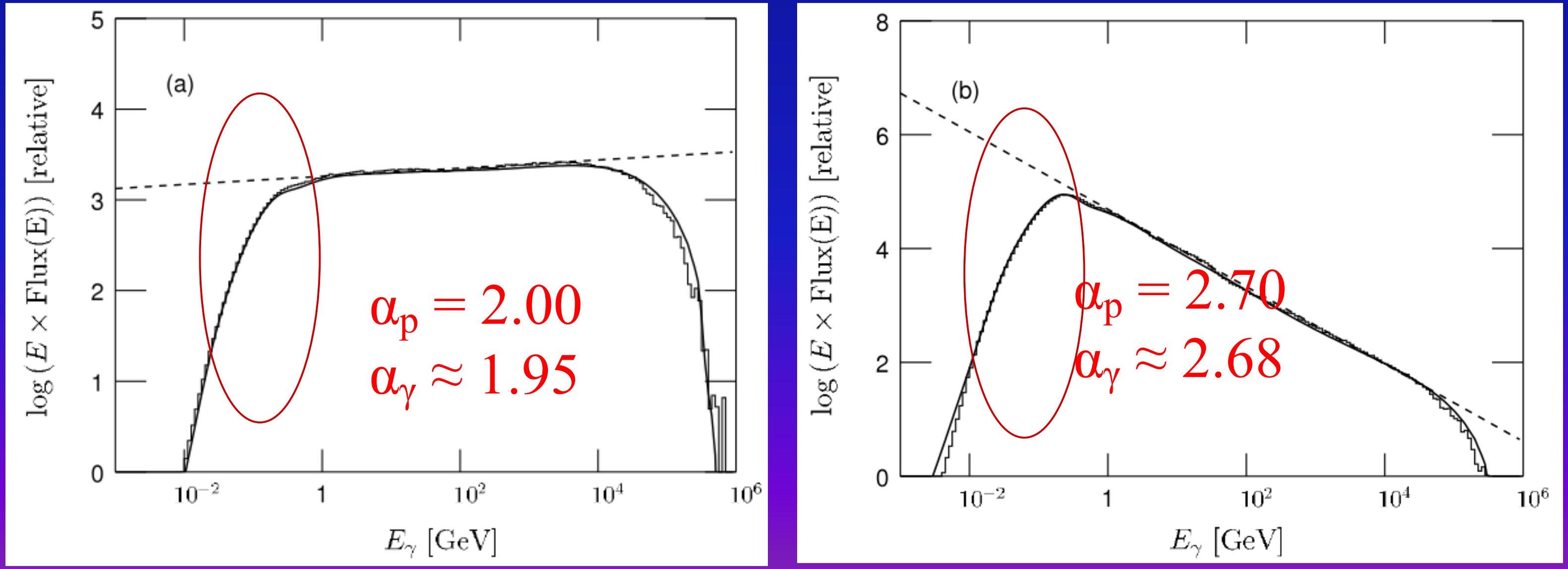
$$f(p) = \frac{\partial P}{\partial p} \propto p^{-(u_1+2u_2)/(u_1-u_2)} = p^{-(r+2)/(r-1)} = p^{-\sigma}$$

For r=4, σ=2. Spectral index 0.5 (as in radio!)

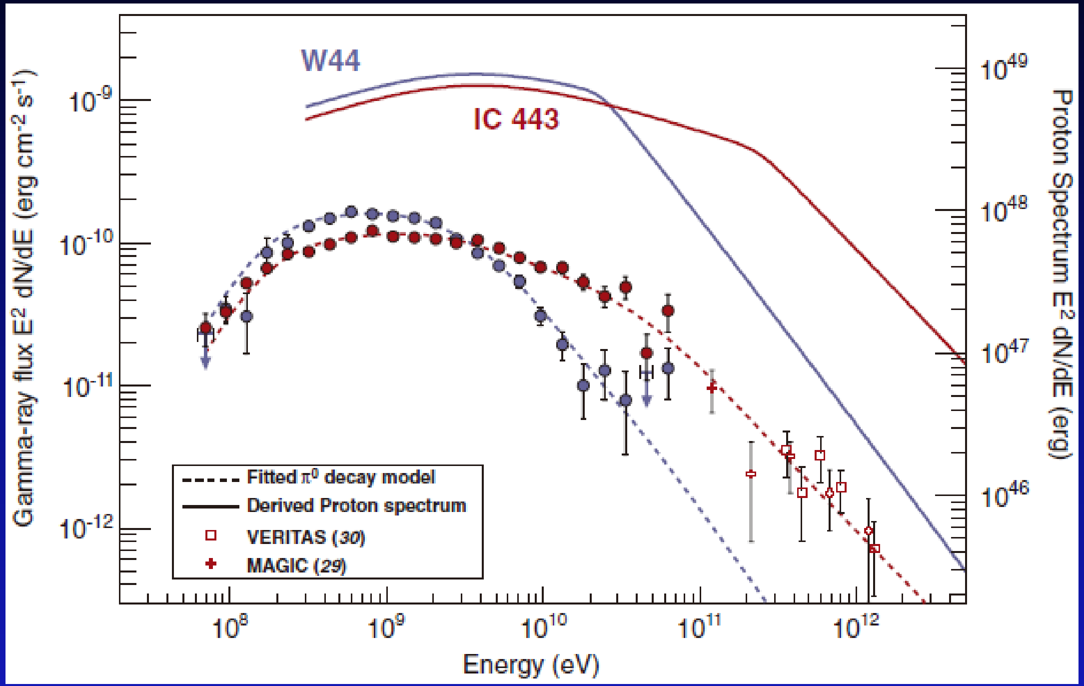
"pion - decay bump"

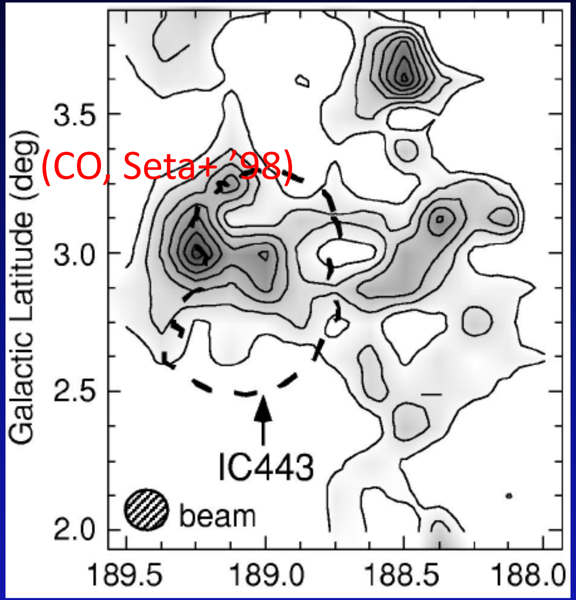
	Rest mass (MeV/c^2)	Mean lifetime (s)	decays to
$\pi^{+/-}$	139.5702 ± 0.0004	$2.6033 \pm 0.0005 \times 10^{-8}$	$\mu^{+/-} + \nu_\mu$
π^0	134.9766 ± 0.0006	$8.4 \pm 0.6 \times 10^{-17}$	$\gamma + \gamma$

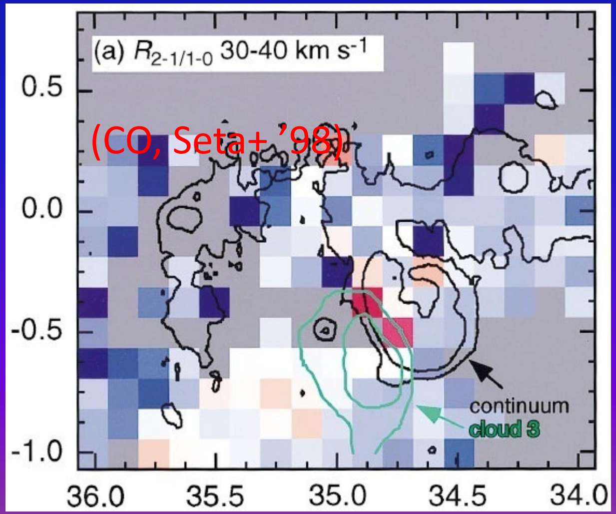
each with 67.5 MeV in the rest frame of π^0

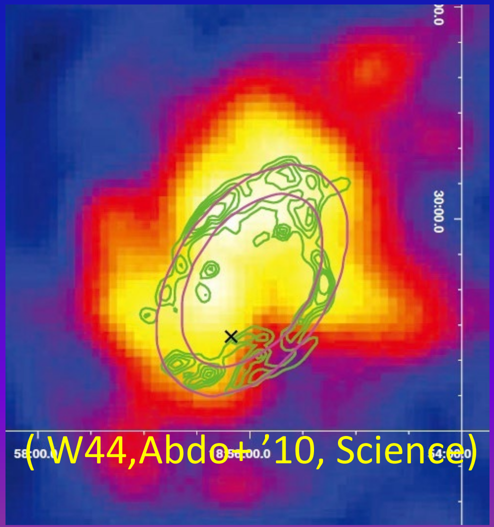


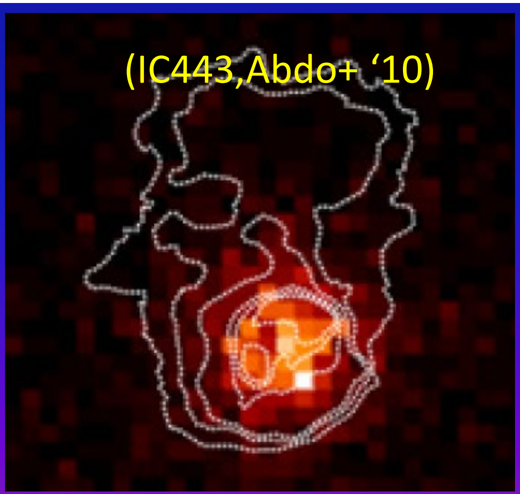
Fermi-LAT (Ackermann, M. et al. 2013, Science): W44 & IC443
AGILE (Giuliani, A. et al. 2011, ApJ, 742, L30): W44







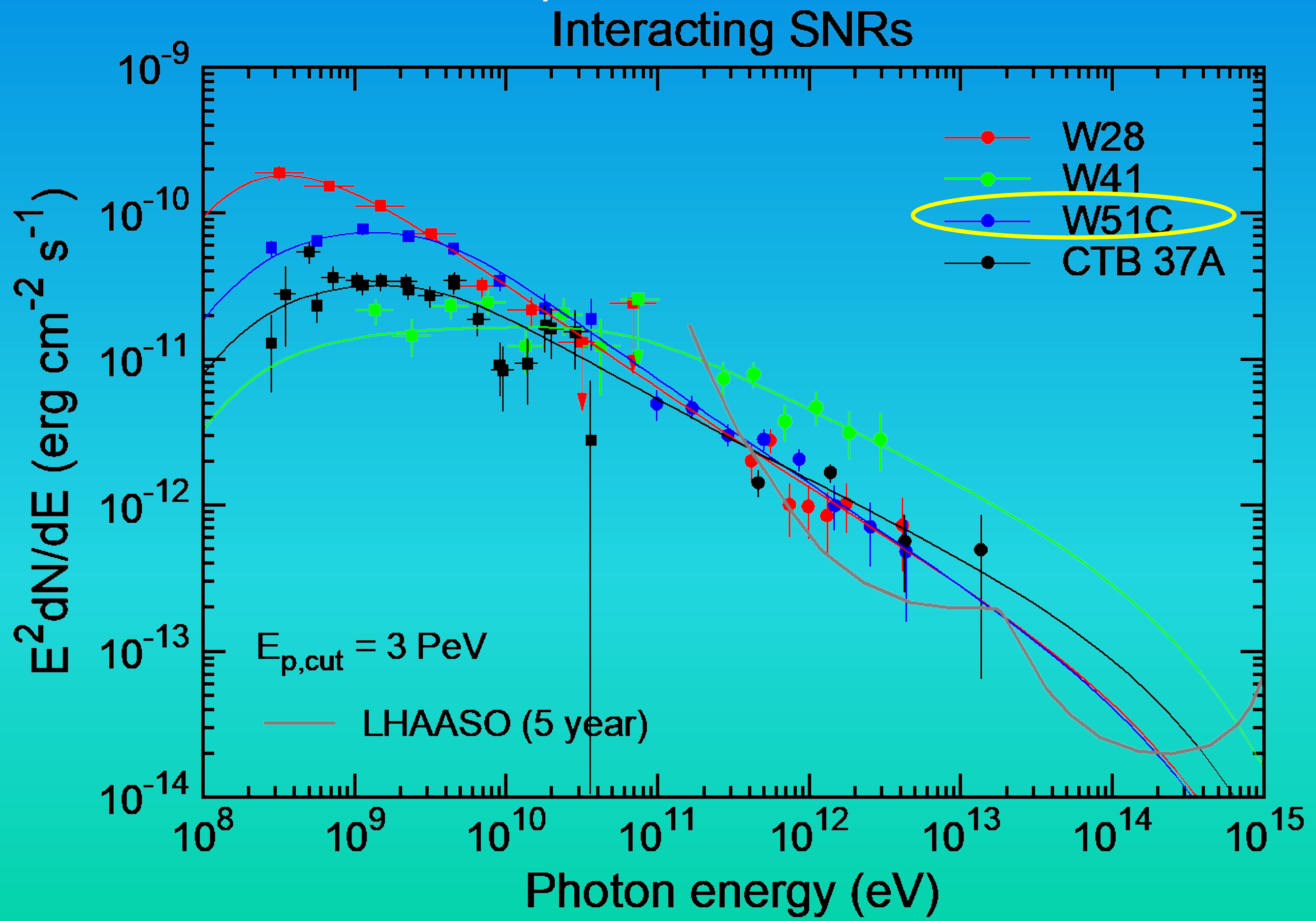




PeVatrons?: High energy spectral cutoff?

- Any energy cutoff at >10 TeV for known TeV shell-like SNRs? Any higher? Sign of E_{max}? Are SNRs “PeVatrons”?!

- “Accumulative diffusion model” predicts for 4 SNRs in LHAASO White Paper:



E_{max} of protons by DSA

- Canonical DSA (e.g. Bell78):

$$E_{max} = 0.03\,\eta_{acc} \left(\frac{B}{1\mu\mathrm{G}}\right) \left(\frac{V_s}{10^4\mathrm{km/s}}\right)^2 \left(\frac{t}{10^3\mathrm{yr}}\right)\ \mathrm{PeV} \qquad (\eta_{\mathrm{acc}} \sim 10)$$

interstellar B ~ 3μG, V_s ~ 5000 km/s, t ~ 400 yr (historic SNR)

$\Rightarrow E_{max}$ ~ $0.01\,\eta_{acc}$ PeV !? (But also see G106.3 below)

- Non-resonant hybrid instability (Bell+13):

$$E_{max} = 0.23 n_e^{1/2} \left(\frac{\eta}{0.03}\right) \left(\frac{V_s}{10^4\mathrm{km/s}}\right)^2 \left(\frac{R_s}{\mathrm{pc}}\right)\ \mathrm{PeV}$$

able to arrive at order of PeV, as a **hadronic PeVatron**

Around turning to Sedov

$R_s \propto t \quad \rightarrow \quad R_s \propto t^{2/5}$

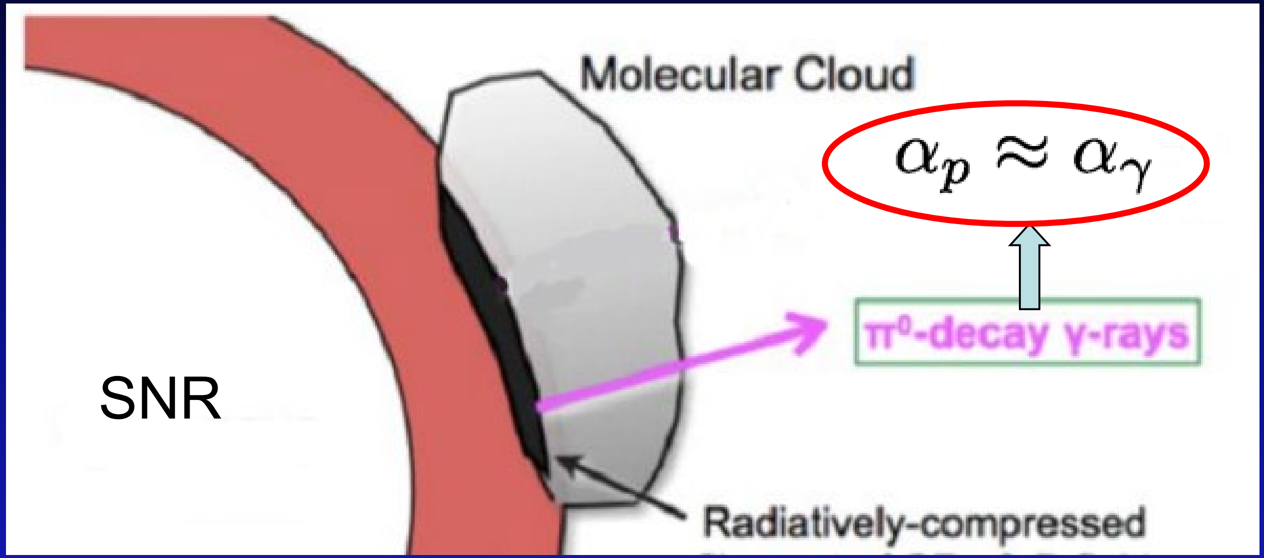
- Canonical DSA: $E_{max} \propto t \quad \rightarrow \quad E_{max} \propto t^{-1/5}$
- Non-resonant hybrid: $E_{max} \propto t \quad \rightarrow \quad E_{max} \propto t^{-4/5}$

E_{max} is reached at the beginning of the Sedov phase

- Diffusion length: $R_{diff} = 2(D\ t)^{1/2} \propto t^{1/2}$

Paricles with E_{max} can escape from the Sedov shock

MCs near SNRs: a probe for accelerated CR protons



I. In situ interaction

A. New CRs are produced in the SNRs

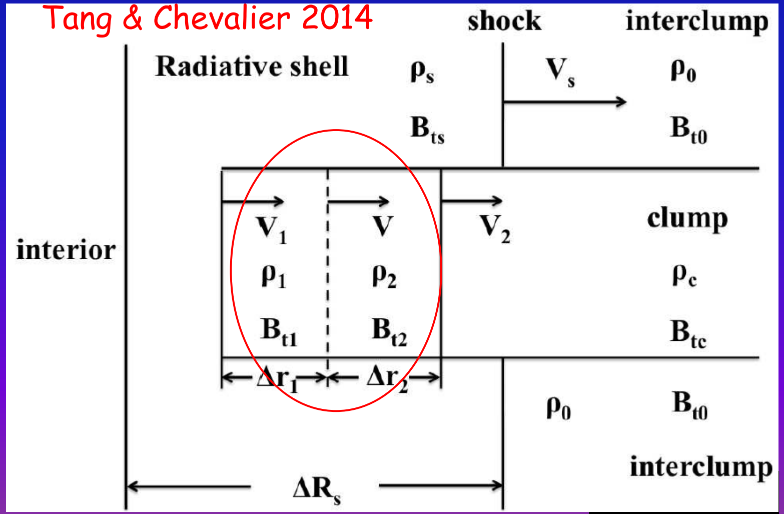
Inoue et al. 2010; Fang & Zhang 2010

Malkov et al. 2011

B. pre-exsiting CRs (compressed/reaccelerated) with 'crushed' MCs

Blandford & Cowie 1982 ; Uchiyama et al. 2010

Tang & Chevalier 2014; …



MCs near SNRs: a probe for accelerated CR protons

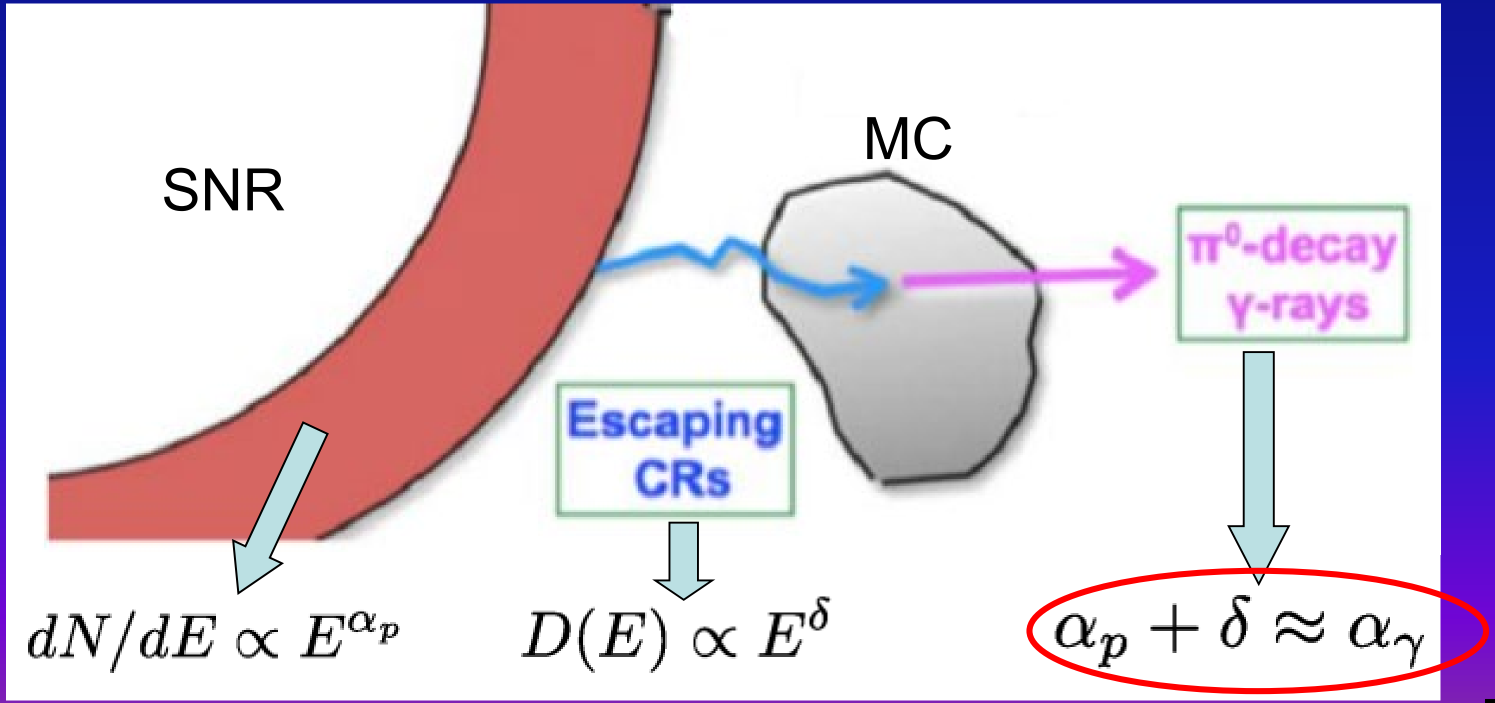
II. Illumination by escaped protons

Aharonian & Atoyan 1996

Gabici et al. 2009

Li, H. & Chen, Y. 2010, 2012

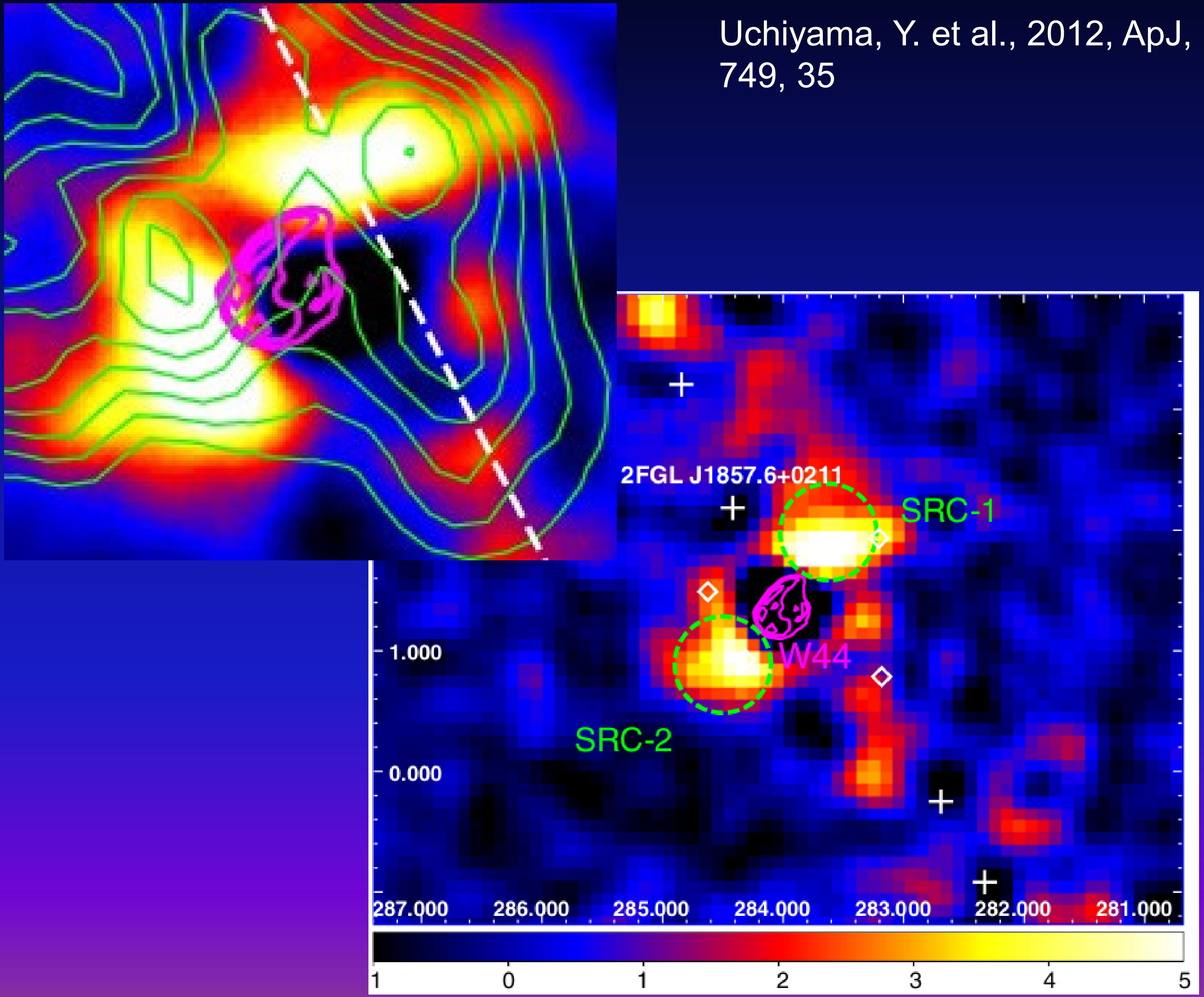
Ohira et al. 2011, 2012

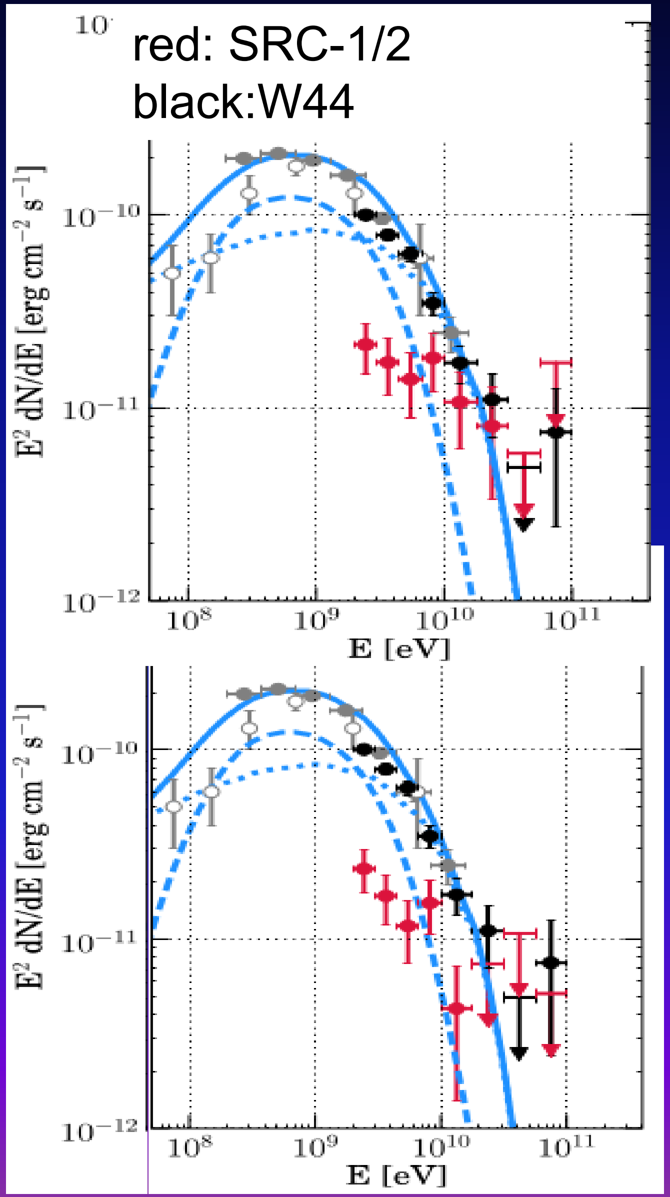


[redacted]

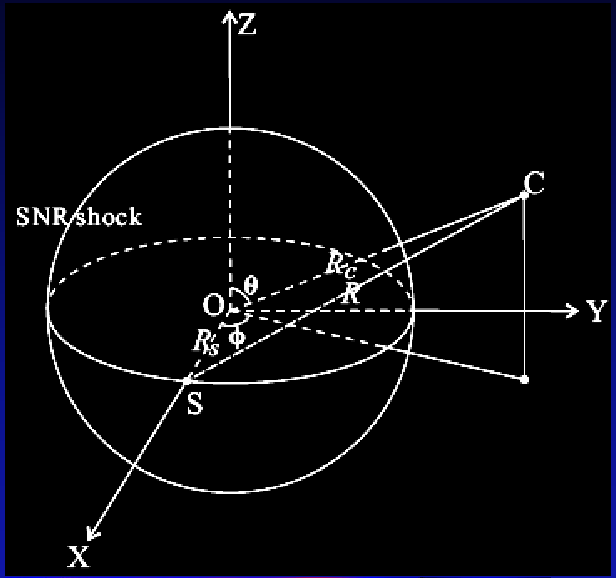
Obervational evidence of escaping protons

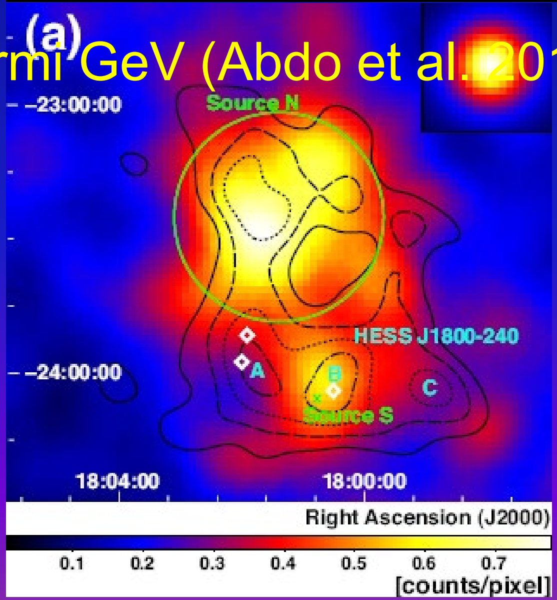
Uchiyama, Y. et al., 2012, ApJ, 749, 35



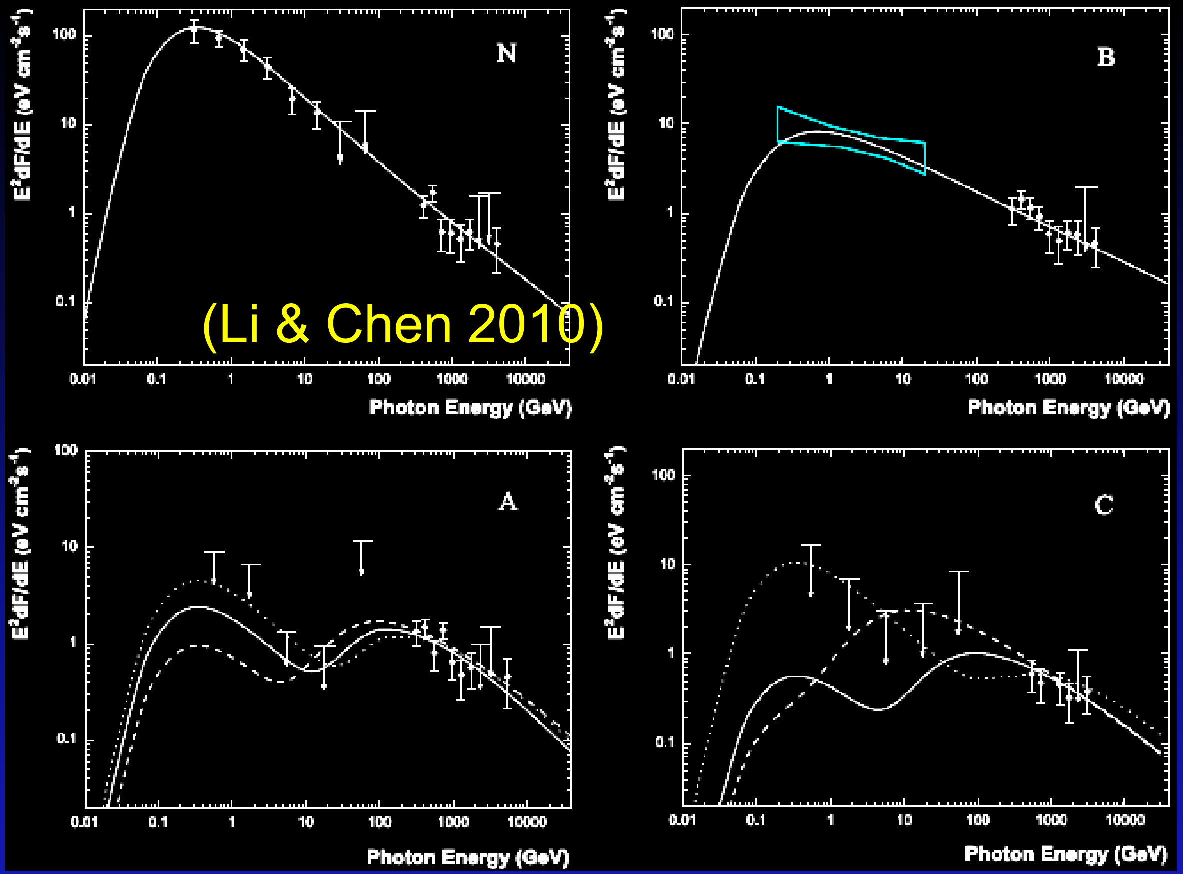


W28

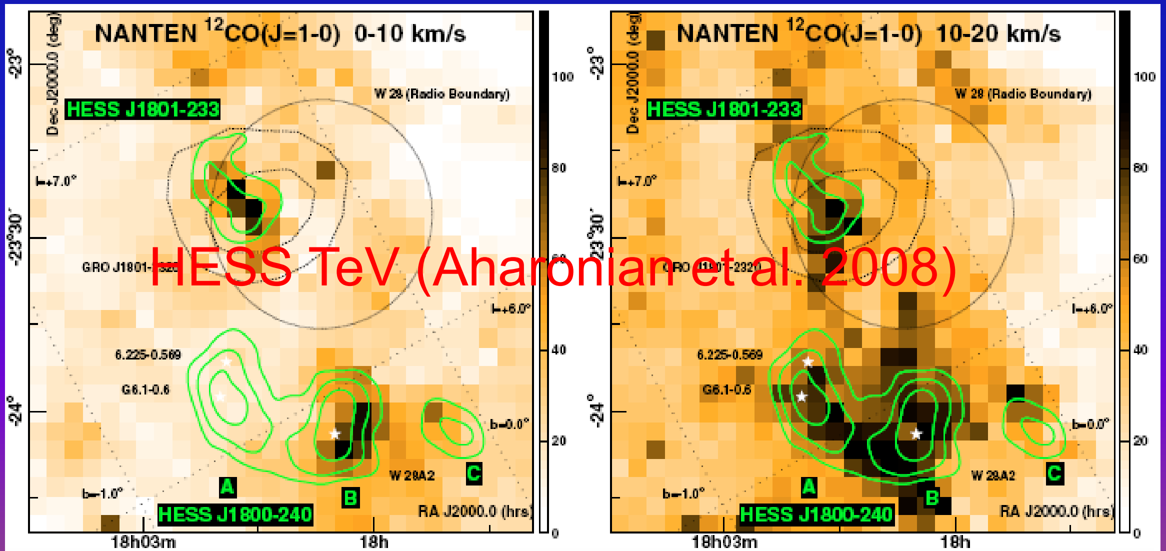




Fermi GeV (Abdo et al. 2010)



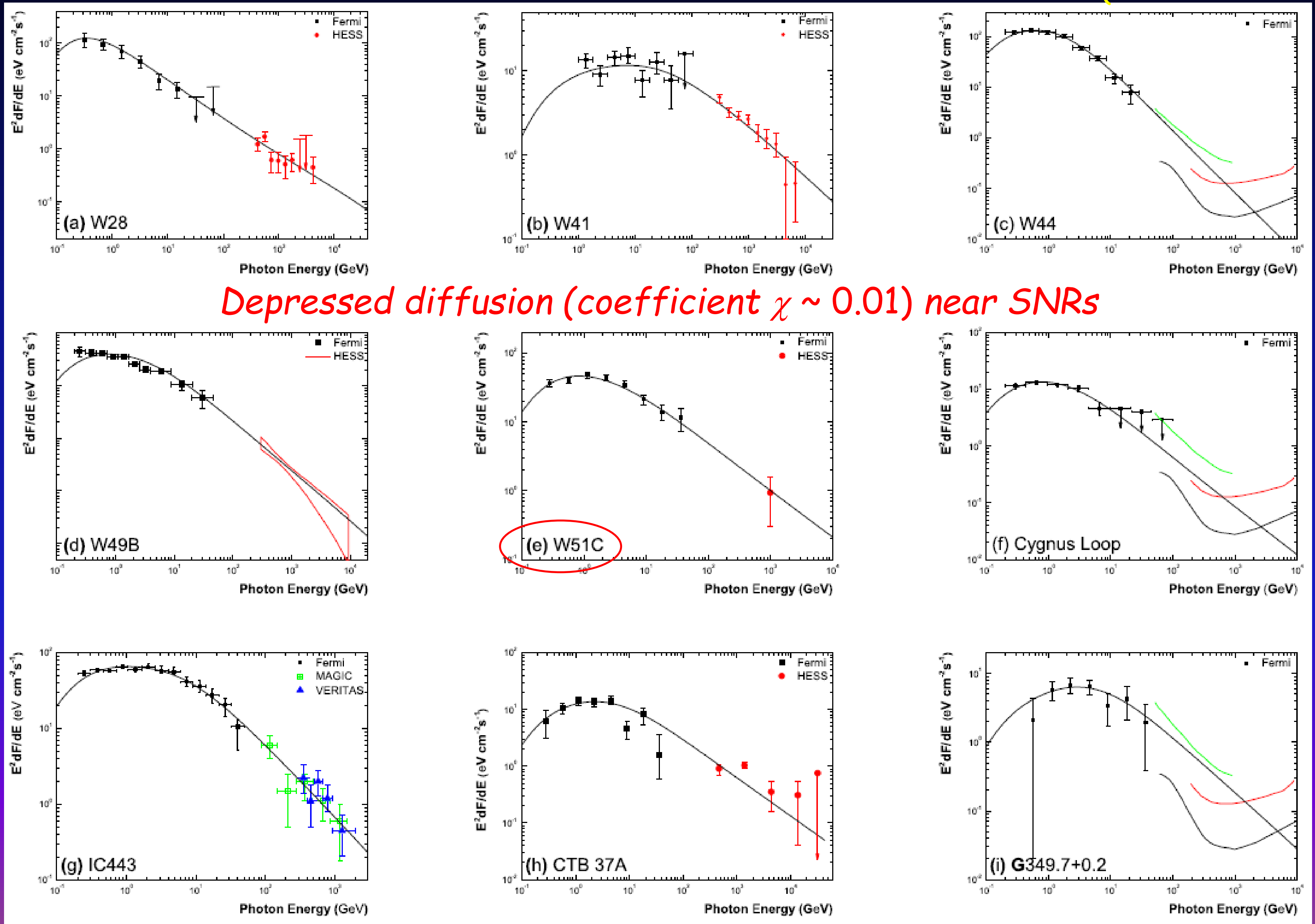
(Li & Chen 2010)



HESS TeV (Aharonian et al. 2008)

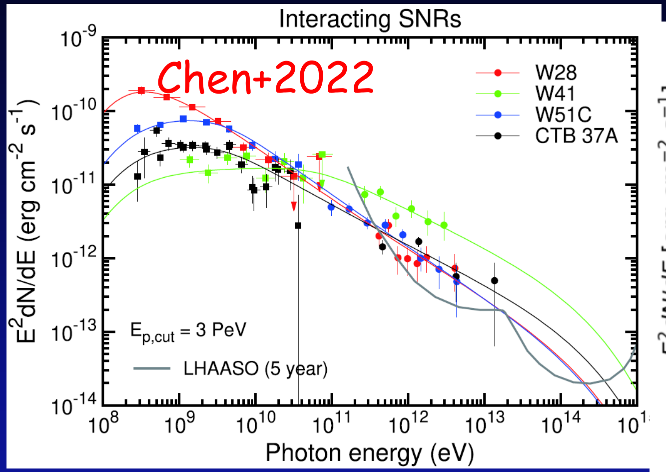
9 SNRs interacting with MCs

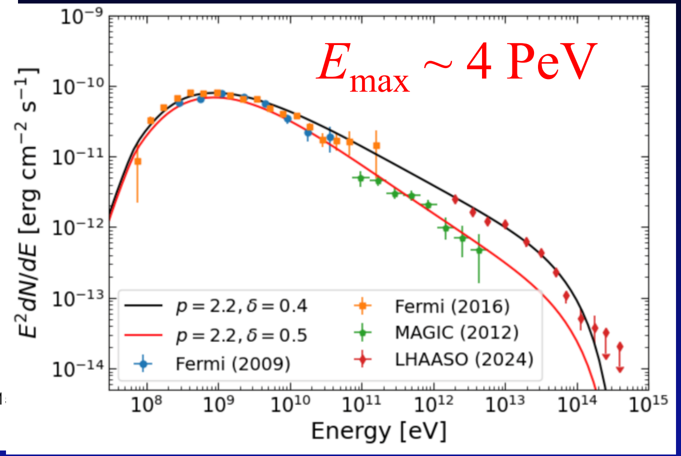
(Li & Chen 2012)

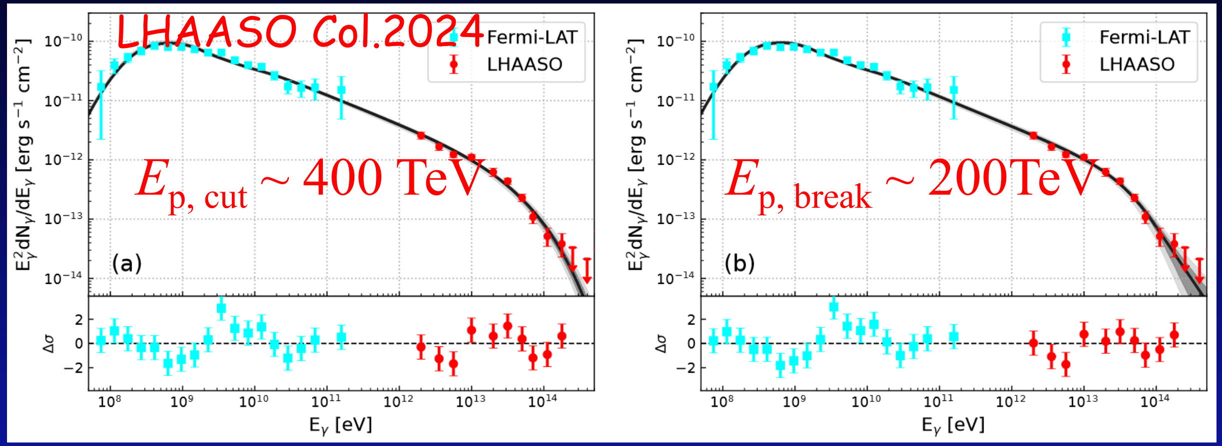


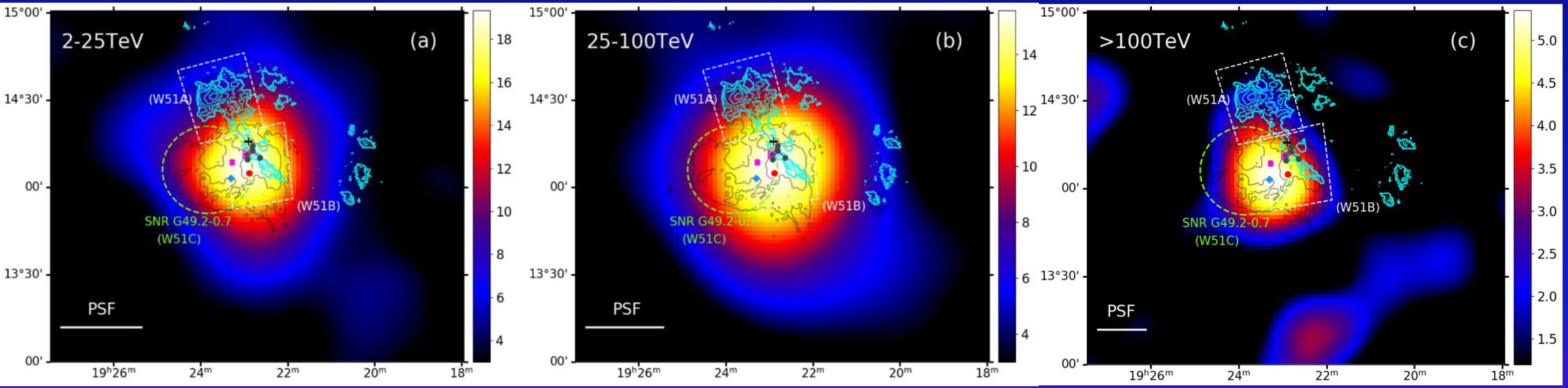
Depressed diffusion (coefficient χ ~ 0.01) near SNRs

Hadronic PeVatron SNRs? W50C





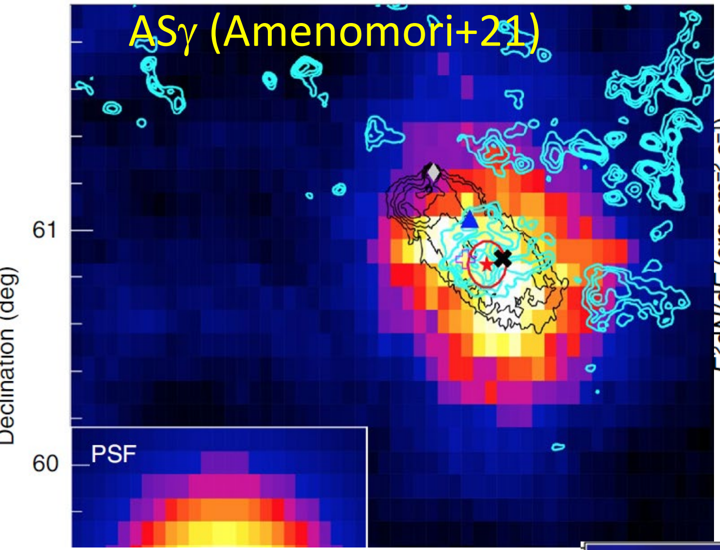


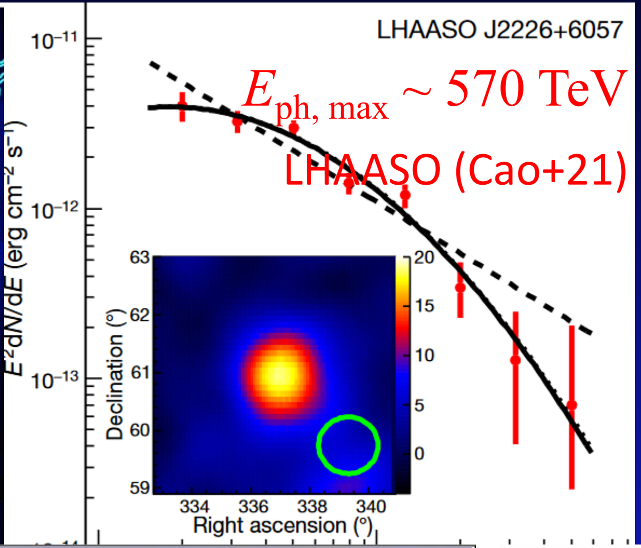


Difficulties:

1. Why 1-D diffusion?
2. Can not exclude contribution from star formation regions inside W51B

Hadronic PeVatron SNRs? G106.3+2.7

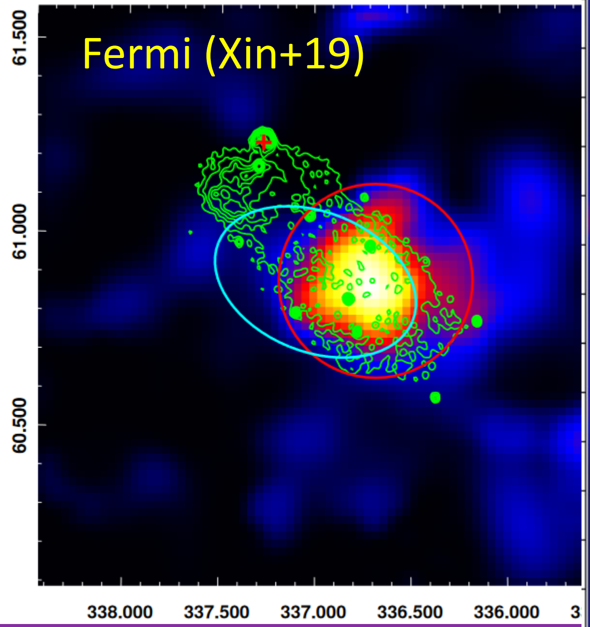


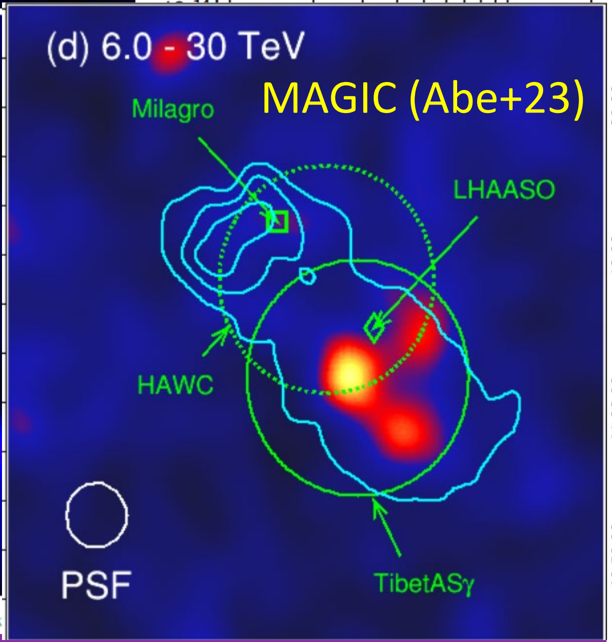


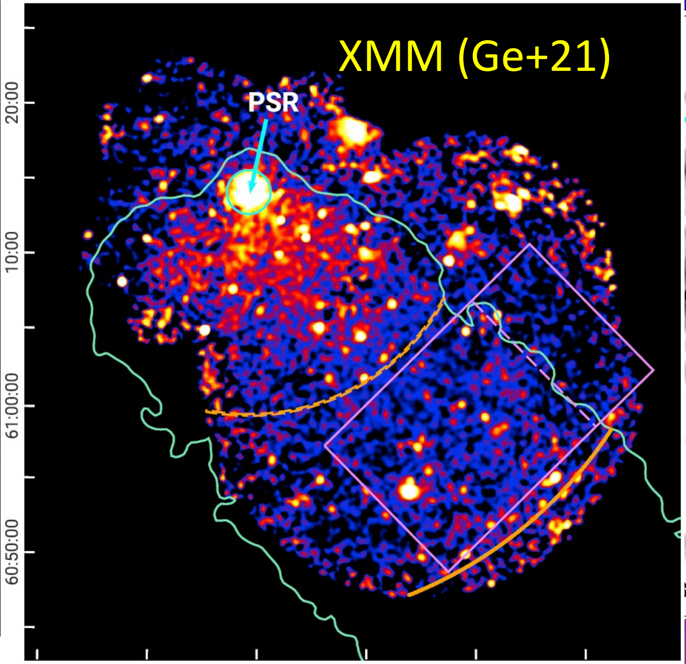
$$E_{max} \approx 3 \left(\frac{B}{10\mu G}\right)\left(\frac{\epsilon_{max}}{7keV}\right)\left(\frac{t}{10^4 yr}\right) \text{ PeV}$$

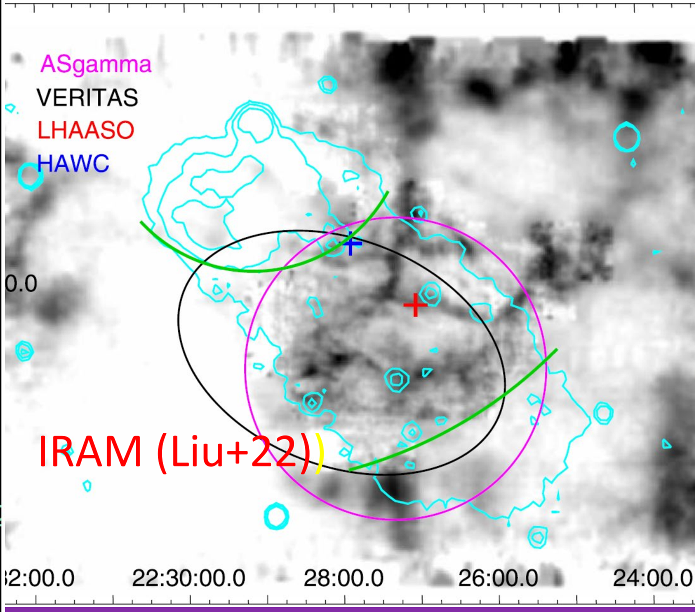
Difficulties:

1. Why GeV-TeV spectrum that hard (α<2)?
2. Associated MC (pp-target) not conclusive



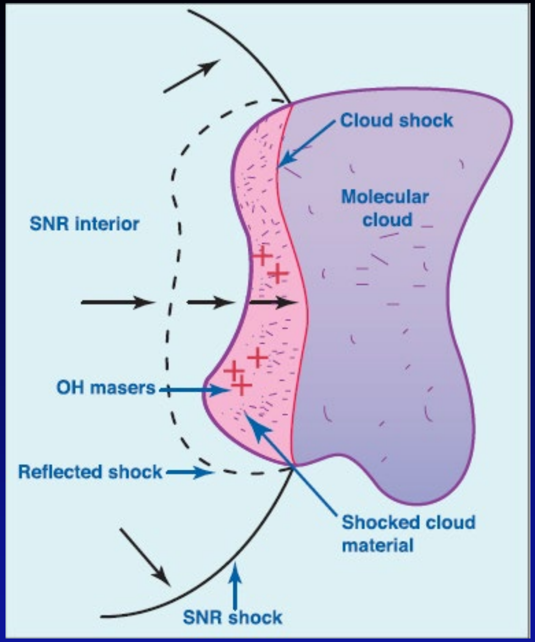


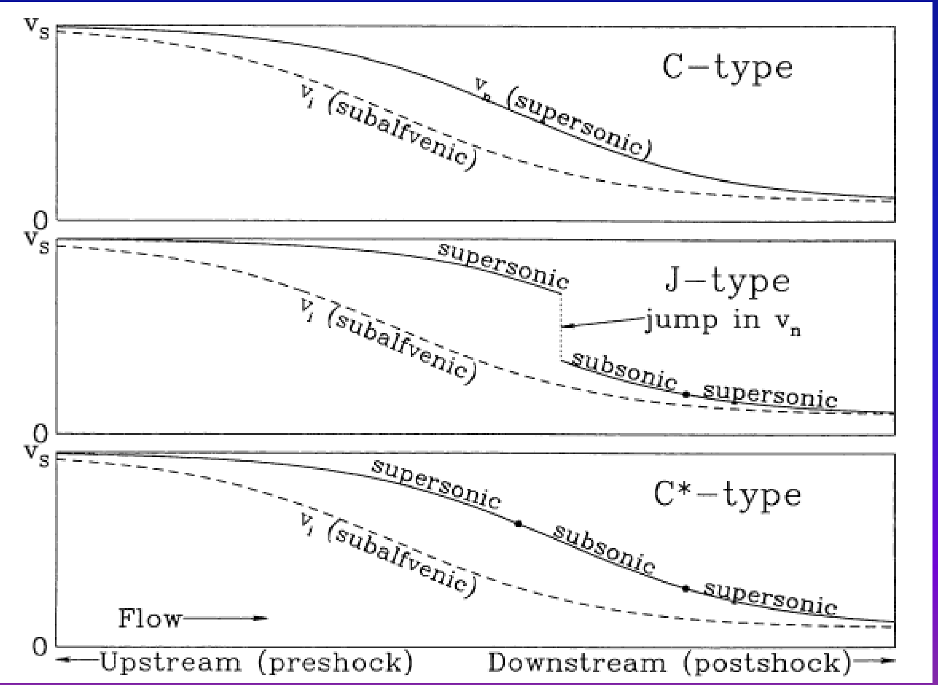




SNRs shock against MCs

- Compress, heat, and drive molecular gas
- Excite, ionize, and even dissociate molecules
- C-type shock propagates in MCs
- Influence chemical evolution & produce otherwise impossible molecular emission （e.g. 1720MHz OH maser, HCO^+, etc.）
- Shock-cloud p-p collision $\rightarrow \pi^0 \rightarrow 2\gamma$, expected to be TeV γ-ray source





SNR-MC associations & Observational Criterions
64 (Jiang, Chen+ 2010) + 6 (Jeong+ 2012)

Name	Other Name	Type[a]	Evidence[b]	Reference[c]	Group[d]	γ-ray detection[e] (Reference[f])
G0.0+0.0	Sgr A East	TC	OH maser, CS MA & LB, H_2	1, 2, 3, 4, 5	Y	HESS(67)
G1.05–0.1	Sgr D SNR	S	OH maser	2, 6	Y	
G1.4–0.1		S	OH maser	2, 6	Y	
G5.4–1.2	Milne 56	C?	OH maser	7	Y	
G5.7–0.0		?	OH maser	7	Y	HESS(68)
G6.4–0.1	W28	TC	OH maser, CO MA & LB, H_2 MA, NIR	2, 8, 9, 10	Y	EGRET(69), HESS(68)
G8.7–0.1	W30	TC	OH maser	7	Y	HESS(70)
G9.7–0.0		S	OH maser	7	Y	
G16.7+0.1		C	OH maser, CO MA	2, 11, 12	Y	
G18.8+0.3	Kes 67	S	CO MA & LB, CO ratio	13, 14	Y	
G21.8–0.6	Kes 69	TC	OH maser, CO MA & LB, HCO^+, H_2	2, 11, 15, 16	Y	
G29.7–0.3	Kes 75	C	CO MA & LB	17	Y	
G31.9+0.0	3C 391	TC	OH maser, molecular MA & LB, H_2, NIR	2, 18, 19, 20	Y	
G32.8–0.1	Kes 78	S	OH maser	21	Y	
G34.7–0.4	W44	TC	OH maser, molecular LB, H_2 MA, NIR, CO ratio	2, 8, 10, 22	Y	EGRET(69)
G39.2–0.3	3C 396	C	H_2 & NIR MA, CO MA & LB	16, 23, 24	Y	
G41.1–0.3	3C 397	TC	CO MA & LB	25	Y	
G49.2–0.7	W51	TC	OH maser, CO MA & LB, HCO^+ LB	2, 11, 26	Y	HESS(71), Milagro(72)
G54.4–0.3	HC40	S	CO MA & LB, IR MA	27, 28	Y	
G89.0+4.7	HB21	TC	CO MA & LB, CO ratio, H_2, NIR	29, 30, 31	Y	
G109.1–1.0	CTB 109	S	CO MA & LB	32	Y	
G189.1+3.0	IC 443	TC	OH maser, CO ratio, H_2, molecular MA & LB	2, 8, 22, 33, 34, 35	Y	EGRET(69), MAGIC(73) Milagro(72), VERITAS(74) AGILE(75)
G304.6+0.1	Kes 17	S	H_2, IR MA & colors	16, 28	Y	
G332.4–0.4	RCW 103	S	IR MA & colors, NIR, H_2 & HCO^+ MA	28, 36, 37	Y	
G337.0–0.1	CTB 33	S	OH maser	18	Y	
G337.8–0.1	Kes 41	S	OH maser	21	Y	
G346.6–0.2		S	OH maser, H_2, IR colors	21, 16, 28	Y	
G347.3–0.5		S?	CO MA & LB	38	Y	CANGAROO(76) HESS(77), Fermi(78)
G348.5–0.0		S?	OH maser, H_2, IR MA	2, 16, 28	Y	
G348.5+0.1	CTB 37A	S	OH maser, CO MA	2, 12, 18	Y	HESS(79)
G349.7+0.2		S	OH maser, CO MA & LB, CO ratio, H_2, IR MA	2, 18, 13, 16, 28	Y	
G357.7+0.3	Square Nebula	S	OH maser	2, 6	Y	
G357.7–0.1	MSH 17–39	TC	OH maser, CO & H_2 MA	2, 18, 39	Y	
G359.1–0.5		TC	OH maser, CO & H_2 MA	2, 40, 41, 42	Y	HESS(80)

34 confirmed

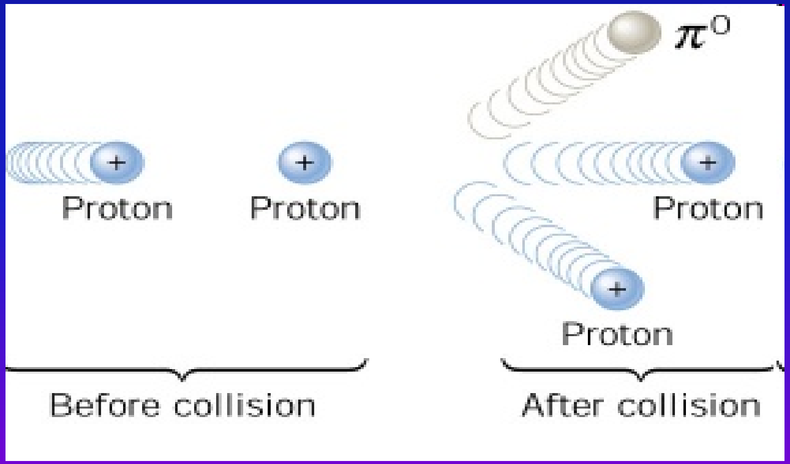
Criterions:

1. 1720MHz OH masers
2. Molecular line broadening (LB)
3. High line ratio, e.g. CO2-/CO1-0
4. NIR [FeII], vibrational /rotational H_2
5. Specific (Spitzer) IR colors
6. Morphology agreement (MA) of spatial features

MCs as probes of CRs

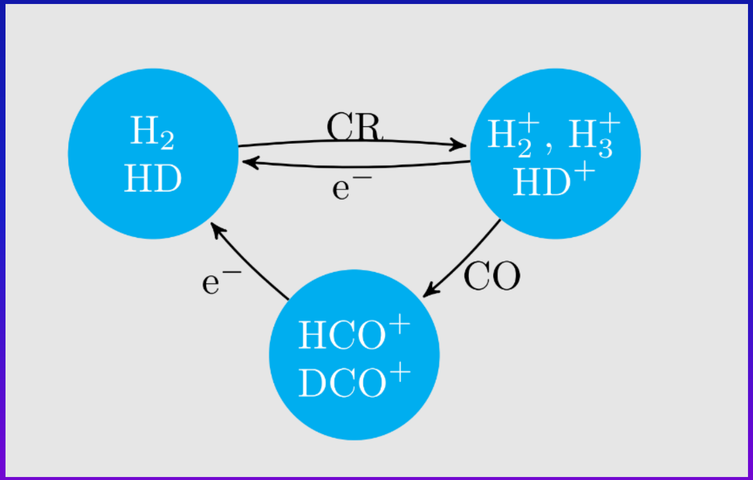
1. For E_p> 280 MeV:

p-p hadronic process

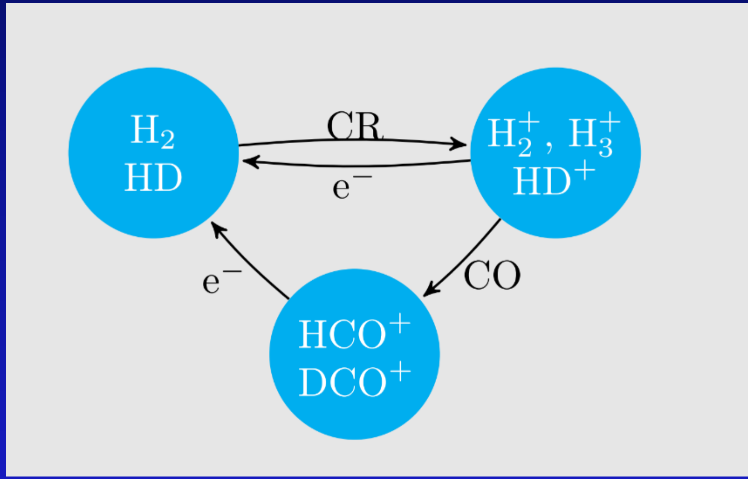


2. For E_p< 280 MeV:

Ionization by CRs



Chemical effect of CRs



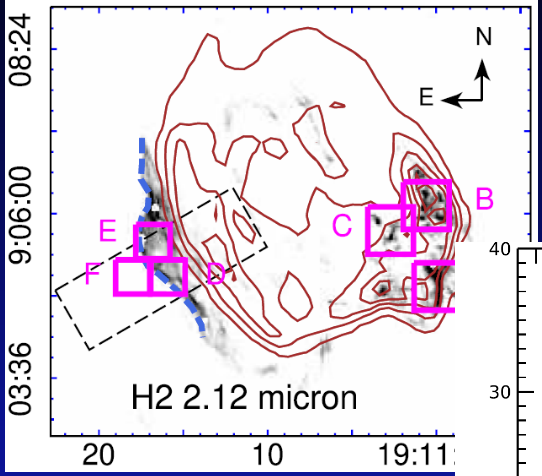
Main channels:

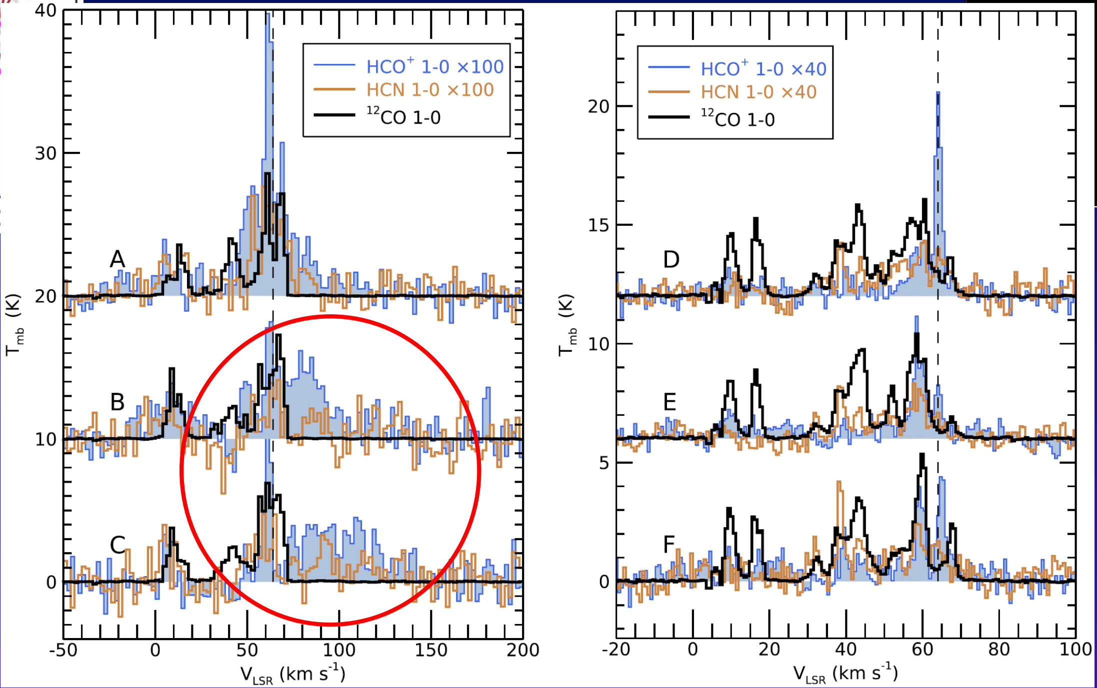
H_2 (by p) $\rightarrow H_2^+ + e^-$
$H_2^+ + H_2 \rightarrow H_3^+ + H$

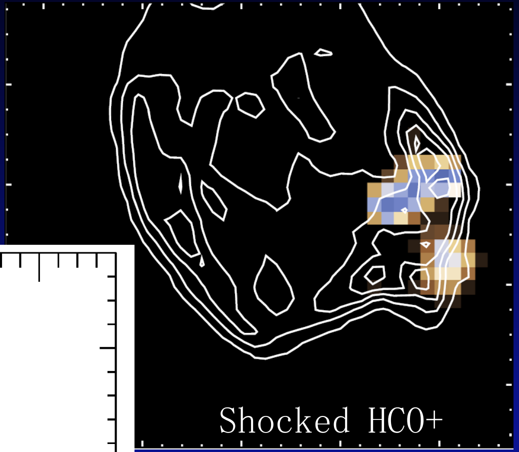
$CO + H_3^+ \rightarrow HCO^+ + H_2$
HCO (by p) $\rightarrow HCO^+ + e^-$

W49B: high HCO^+/CO, CR ionization?

(Zhou+ 22)







- Very broad HCO+ line width
- $I(HCO^+)/I(CO) \sim 1.1 \pm 0.4$ (B) & 0.70 ± 0.16(C),
- significantly larger than that in typical MCs ($<\sim 10^{-2}$)
- CR induced?

- Narrow HCO+ line, but
- $I(HCO^+)/I(CO) > 0.2$ (D) also very high
- X-ray dissociation

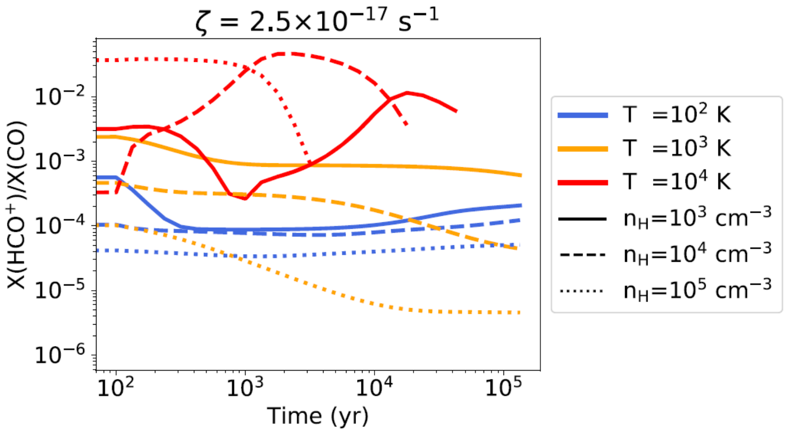
CR ionization in the shocked MC (W49B)

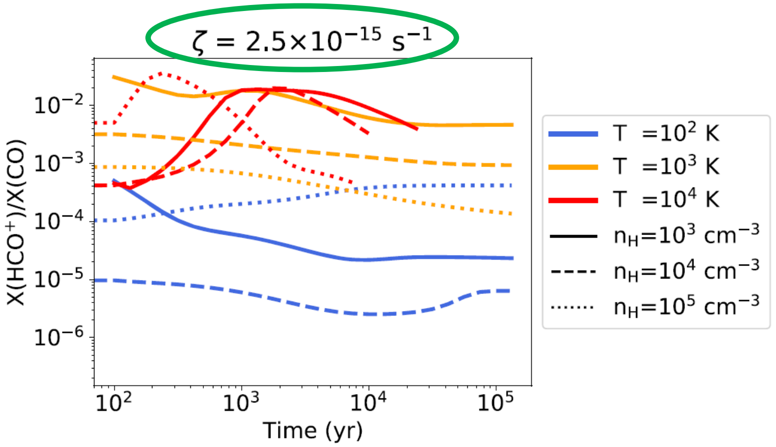
(Zhou+ 22)

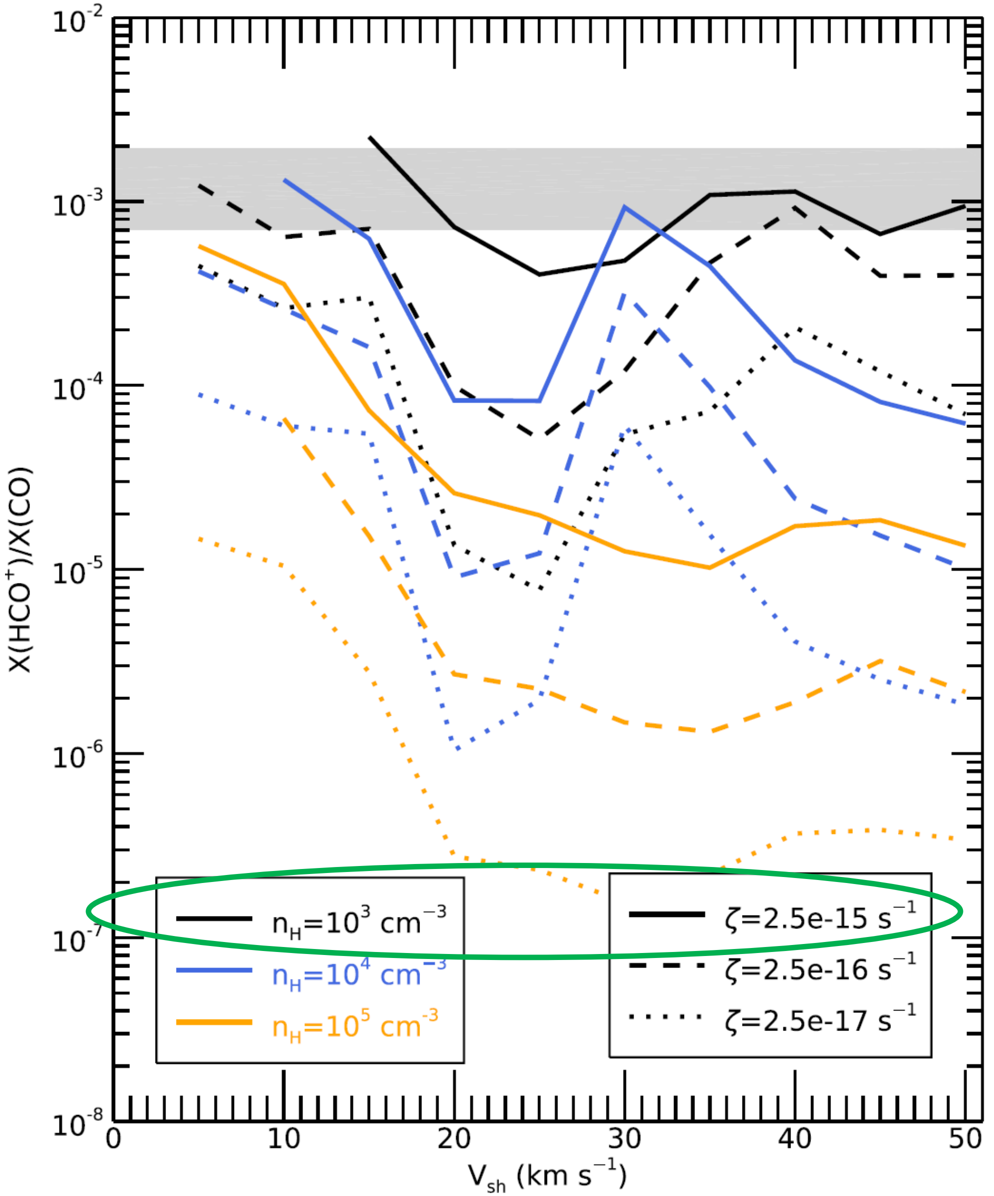
Main channels:

$HCO \rightarrow HCO^+ + e^-$

$CO + H3^+ \rightarrow HCO^+ + H_2$

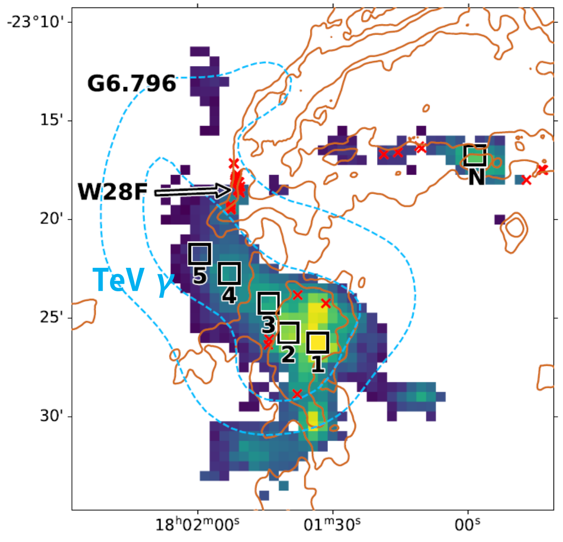




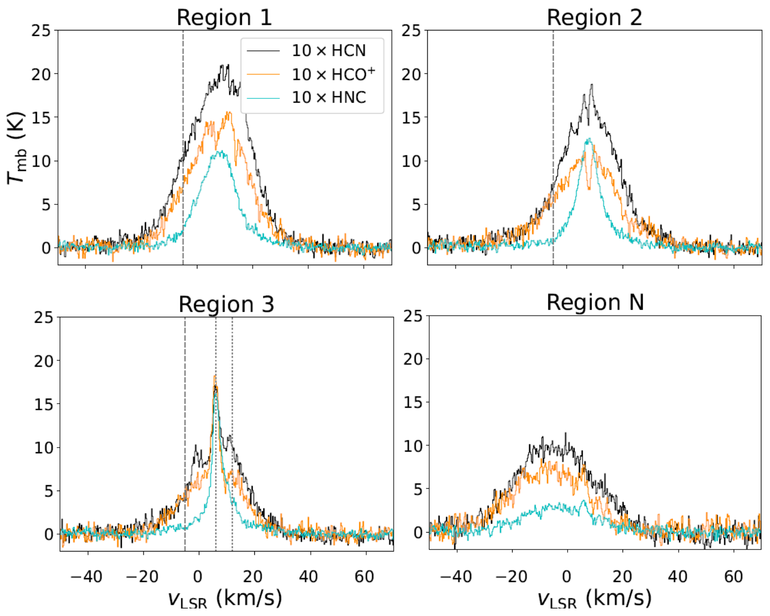


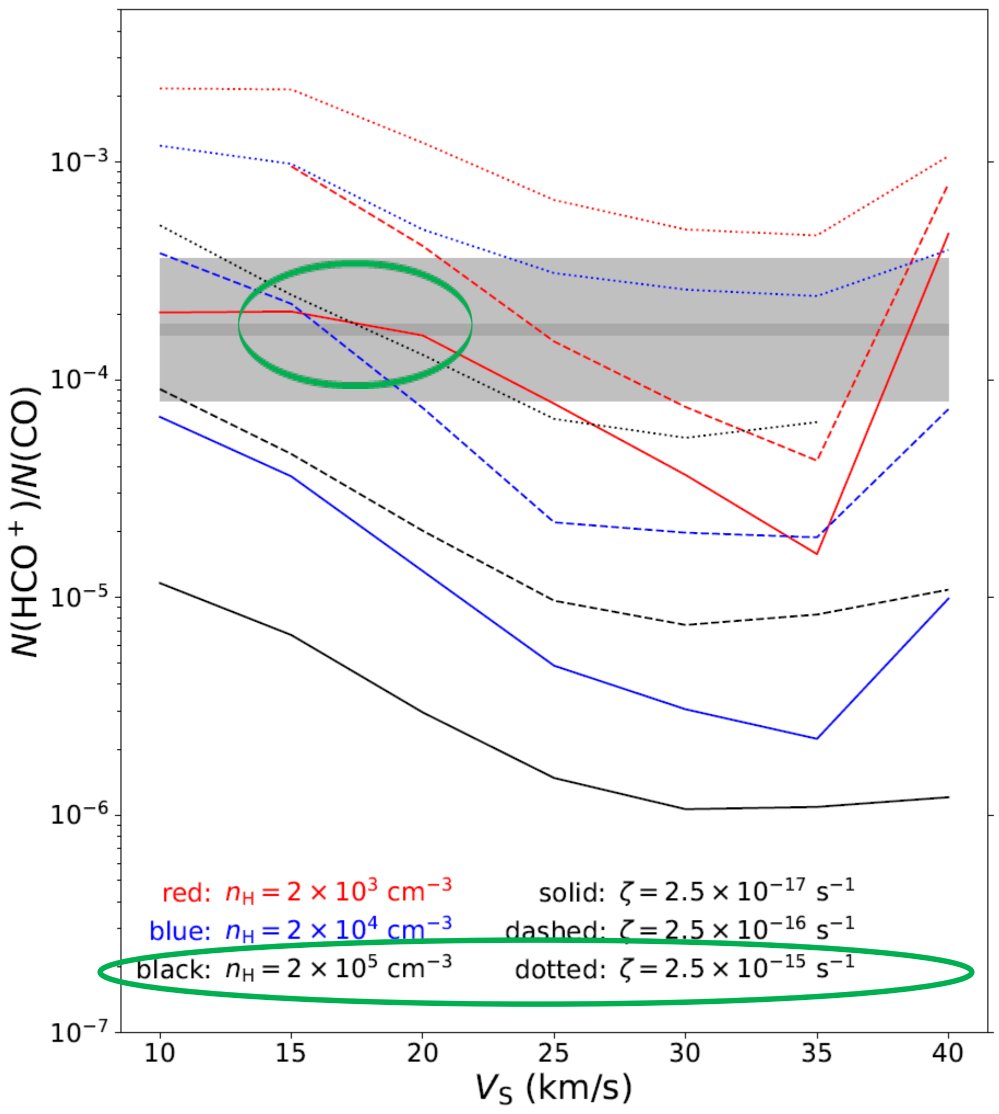
CR ionization in the shocked MC (W28)

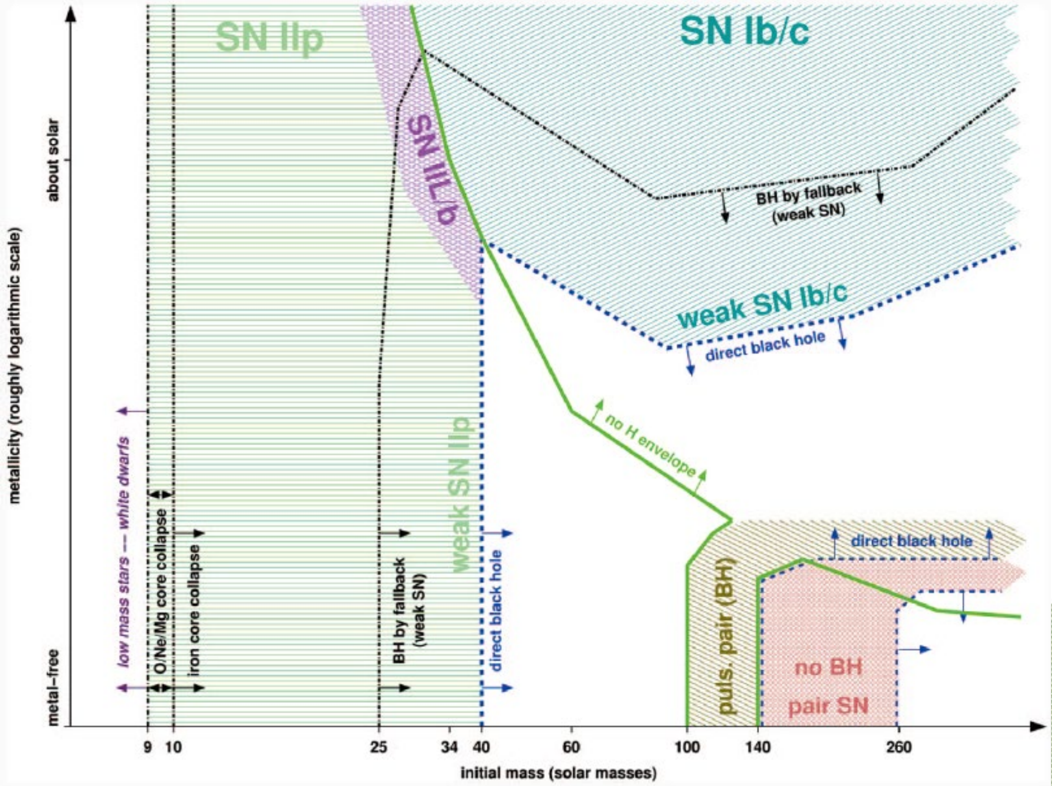
(Tu, Chen+ 24)



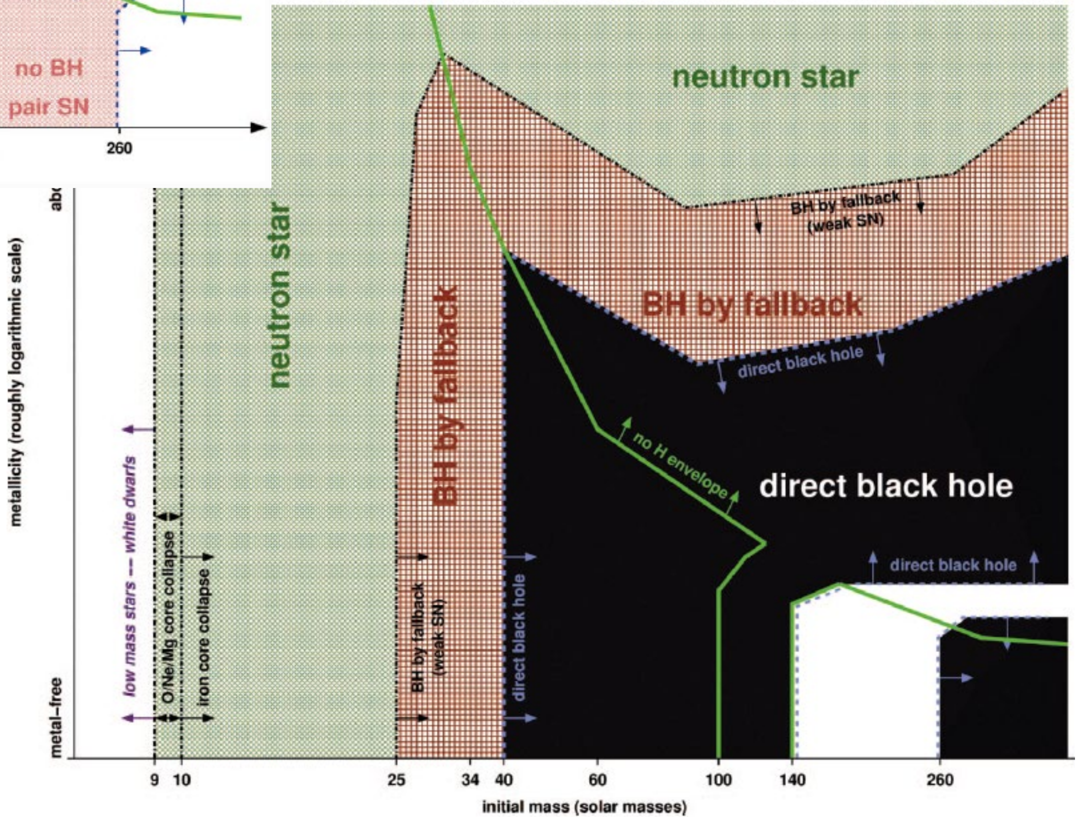
FWHM(HCO^+) >~ 20 km/s






SN IIp
SN Ib/c
SN IIL/b
BH by fallback
(weak SN)
weak SN Ib/c
direct black hole
no H envelope
weak SN IIp
low mass stars — white dwarfs
O/Ne/Mg core collapse
iron core collapse
BH by fallback
(weak SN)
direct black hole
puls. pair (BH)
direct black hole
no BH
pair SN
metallicity (roughly logarithmic scale)
about solar
metal-free
9
10
25
34
40
60
100
140
260
initial mass (solar masses)

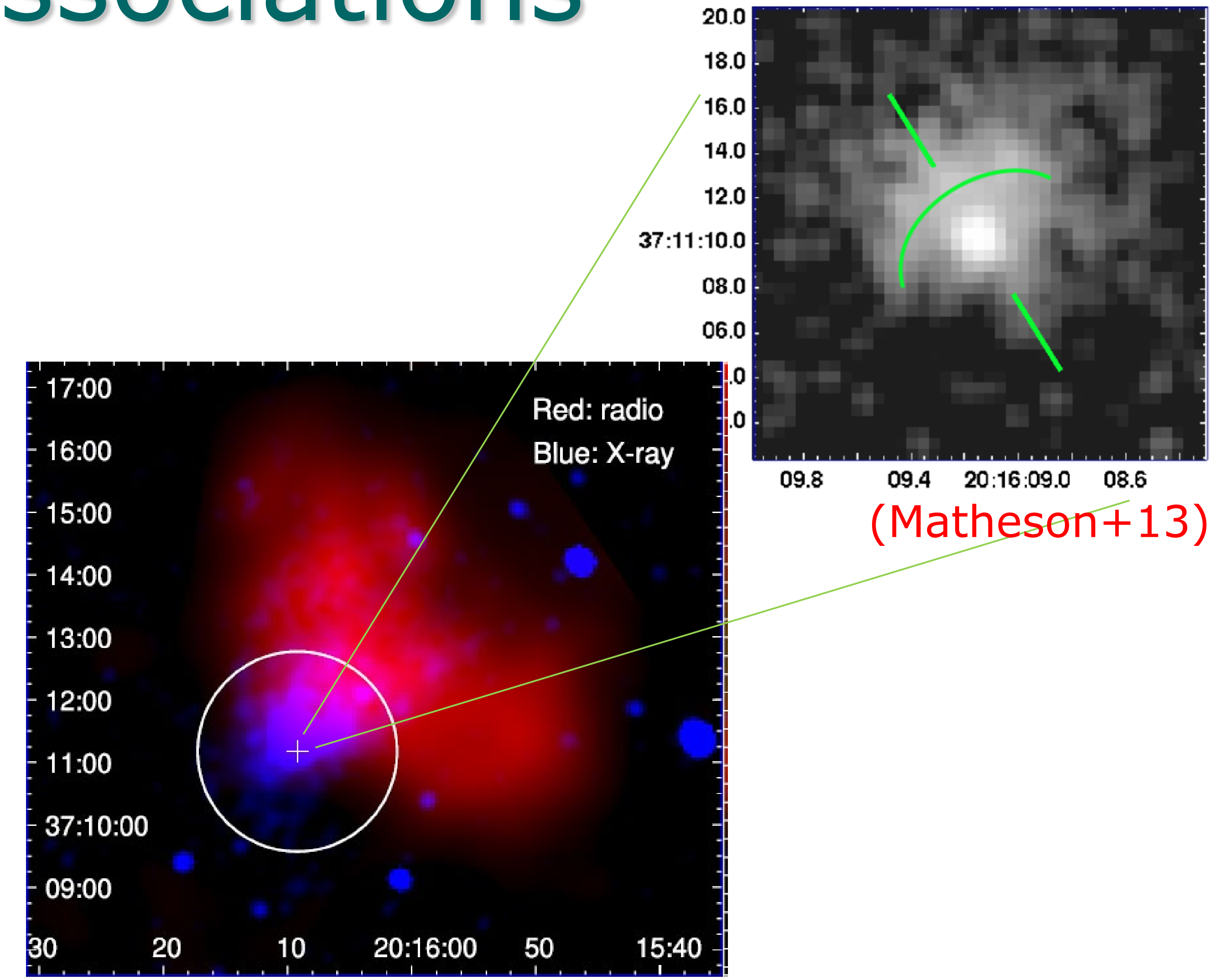
Heger+2003


neutron star
BH by fallback
(weak SN)
BH by fallback
direct black hole
neutron star
BH by fallback
no H envelope
direct black hole
direct black hole
low mass stars — white dwarfs
O/Ne/Mg core collapse
iron core collapse
BH by fallback
(weak SN)
direct black hole
metallicity (roughly logarithmic scale)
metal-free
9
10
25
34
40
60
100
140
260
initial mass (solar masses)

SNR-NS associations

(Credit: Fu, Lei)

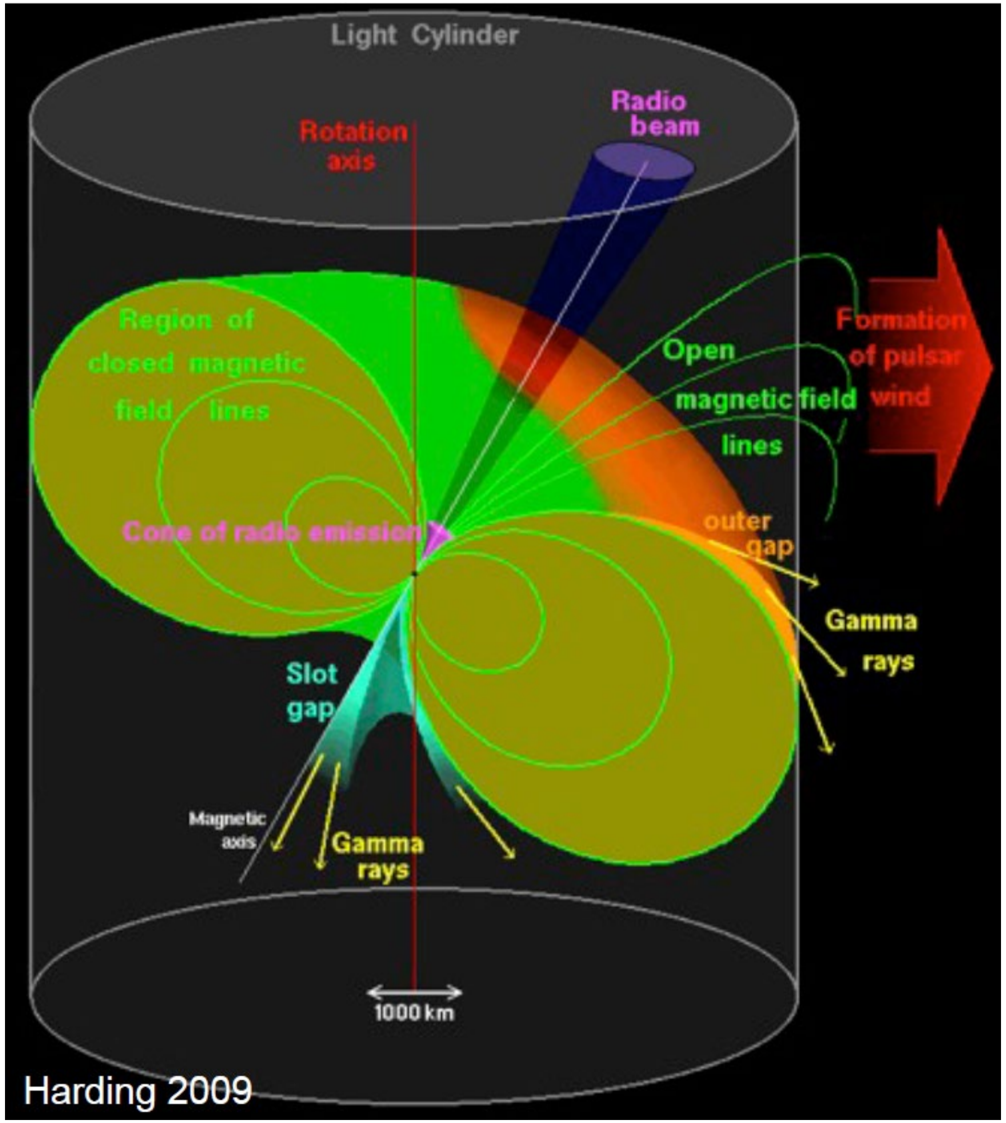
1	PSRJ	P	P_dot	ASSOC	Age	B_surf	SNR age(yr)
2	J0007+7303	0.315873192	3.60550E-13	GRS:1FGL_J0007.0+7303,XRS:RX_J	1.39e+04	1.08e+13	5k-15k
3	J0205+6449	0.065715928	1.93754256E-13	SNR:3C58,GRS:1FGL_0205.6+6449[	5.37e+03	3.61e+12	830-7k
4	J0525-6607	8.047	6.5E-11	XRS:SGR_0526-66,SNR:N49(?)[ekl+	1.96e+03	7.32e+14	5k-10k
5	J0534+2200	0.033084716	4.22765E-13	SNR:Crab_PWN[ccl+69],GRS:1FGL_	1.24e+03	3.78e+12	
6	J0537-6910	0.016122222	5.1784338E-14	EXGAL:LMC,SNR:N157B	4.93e+03	9.25e+11	<5k
7	J0538+2817	0.143158259	3.6694515E-15	SNR:S147[acj+96]	6.18e+05	7.33e+11	20k-100k
8	J0540-6919	0.050498818	4.78924621E-13	EXGAL:LMC,SNR:0540-693	1.67e+03	4.98e+12	760-1660
9	J0633+0632	0.297395191	7.9592E-14	GRS:1FGL_J0633.7+0632,XRS:Swift	5.92e+04	4.92e+12	*
10	J0659+1414	0.384891195	5.500309E-14	SNR:Monogem_Ring[tbb+03],GRS:1F	1.11e+05	4.66e+12	86k
11	J0821-4300	0.112799437	1.2E-15	SNR:PUPPIS_A,XRS:RX_J0822-4300	1.49e+06	3.72e+11	3.7k
12	J0835-4510	0.089328385	1.25008E-13	SNR:Vela,GRS:1FGL_J0835.3-4510[	1.13e+04	3.38e+12	11k-12.3k
13	J0855-4644	0.064686131	7.26269E-15	SNR:RX_J0852.0-4622(?)[rm05]	1.41e+05	6.94e+11	1.7k-4.3k
14	J1016-5857	0.107386458	8.08342E-14	SNR:G284.3-1.8(?)	2.1e+04	2.98e+12	10k
15	J1119-6127	0.407962984	4.0202200E-12	SNR:G292.2-0.5[cgk+01]	1.61e+03	4.1e+13	3k
16	J1124-5916	0.135476854	7.52566E-13	SNR:G292.0+1.8,GRS:1FGL_J1124.(	2.03e+04	1.02e+13	2.7k-3.7k
17	J1210-5226	0.424130749	6.6E-17	SNR:G296.5+10.0;XRS:1E_1207.4-52	1.02e+08	1.69e+11	10k
18	J1341-6220	0.193339746	2.53107E-13	SNR:G308.8-0.1[cks+92]	1.21e+04	7.08e+12	32.5k
19	J1437-5959	0.061696123	8.5870E-15	SNR:G315.9-0.0	1.14e+05	7.37e+11	22k
20	J1513-5908	0.150657551	1.53652913E-12	SNR:G320.4-1.2(MSH 15-52),GRS:1F	1.55e+03	1.54e+13	6k-20k
21	J1550-5418	2.06983302	2.318E-11	XRS:1E_1547.0-5408[gg07],SNR:G32	1.41e+03	2.22e+14	*
22	J1632-4818	0.813452834	6.50425E-13	SNR:G336.1-0.2(?)[mbc+02]	1.98e+04	2.33e+13	*
23	J1635-4735	2.594578	*	XRS:SGR_1627-41,SNR:G337.0-0.1(	*	*	*
24	J1646-4346	0.231603329	1.12753E-13	SNR:G341.2+0.9(?)[fgw94]	3.25e+04	5.17e+12	*
25	J1709-4429	0.102459246	9.298454E-14	SNR:G343.1-2.3(?)[mop93],GRS:HES	1.75e+04	3.12e+12	5k
26	J1726-3530	1.110132444	1.216751E-12	SNR:G352.2-0.1(?)[mbc+02]	1.45e+04	3.72e+13	*
27	J1747-2809	0.052152855	1.5557E-13	XRS:CXOU_J174722.8-280915,SNR:(	5.31e+03	2.88e+12	1k-7k
28	J1801-2451	0.124924207	1.279057E-13	SNR:G5.4-1.2[fk91],XRS:PWN[kggl0	1.55e+04	4.04e+12	14k
29	J1801-2304	0.41582709	1.1293023E-13	SNR:W28(?)[fkv93]	5.83e+04	6.93e+12	35k-150k(42
30	J1803-2137	0.13366692	1.34359375E-13	SNR:G8.7-0.1(?)[kw90],GRS:J1804-2	1.58e+04	4.29e+12	15k-39k
31	J1808-2024	7.55592	5.49E-10	SNR:G10.0-0.3(W31),SGR_1806-20	218	2.06e+15	3k-10k
32	J1809-2332	0.146788548	3.44207E-14	GRS:1FGL_J1809.8-2332,XRS:CXOU	6.76e+04	2.27e+12	10k-100k
33	J1811-1925	0.064667	4.40E-14	SNR:G11.2-0.3	2.33e+04	1.71e+12	1.6k(AD386?
34	J1813-1749	0.044699298	1.5E-13	SNR:12.8-0.0,GRS:HESS_J1813-178	4.6e+03	2.65e+12	285-2.5k
35	J1833-1034	0.061865672	2.02025e-13	SNR:G21.5-0.9[gmga05],SN:BC48[wl	4.85e+03	3.58e+12	200-1k
36	J1841-0456	11.7789433	4.470E-11	SNR:Kes73,XRS:1E_1841-045	4.18e+03	7.34e+14	500-2k
37	J1845-0256	6.97127	*	SNR:G29.6+0.1,AX_J1845.0-0300	########	*	1.4k-8k
38	J1846-0258	0.325684249	7.08330E-12	SNR:Kes75,XRS:PWN[hcg03]	728	4.86e+13	0.9k-4.3k
39	J1850-0006	2.191497968	4.32E-15	SNR:G32.45+0.1(?)	8.04e+06	3.11e+12	*
40	J1852+0040	0.104912611	8.68E-18	SNR:Kes79,XRS:CXOU_J185238.6+(	1.92e+08	3.05e+10	3k-7.8k
41	J1856+0113	0.26743961	2.083598E-13	SNR:W44,XRS:PWN[pks02]	2.03e+04	7.55e+12	7k,5k
42	J1907+0602	0.106632746	8.68208E-14	GRS:1FGL_J1907.9+0602,SNR:G40.	1.95e+04	3.08e+12	20k-40k
43	J1907+0919	5.1689178	7.783E-11	SNR:G42.8+0.6(?),SGR_1900+14	1.05e+03	6.42e+14	15.5k
44	J1930+1852	0.136855047	7.5057E-13	SNR:G54.1+0.3,XRS	2.89e+03	1.03e+13	2.5k-3.3k
45	J1952+3252	0.039531193	5.844803E-15	SNR:CTB80,GRS:1FGL_J1952.9+32	1.07e+05	4.86e+11	77k
46	J1957+2831	0.307682865	3.10989E-15	SNR:G65.1+0.6[tl06]	1.57e+06	9.9e+11	44k-140k
47	J2021+4026	0.265317661	5.4682E-14	GRS:1FGL_J2021.5+4026,SNR:G78.	7.69e+04	3.85e+12	4k-7k
48	J2022+3842	0.024287756	4.3192E-14	XRS:CXOU_J202221.68+384214.8,SI	8.91e+03	1.04e+12	5k
49	J2229+6114	0.051623574	7.827E-14	SNR:G106.6+2.9,GRS:1FGL_J2229.(	1.05e+04	2.03e+12	10k
50	J2301+5852	6.978948446	4.8430E-13	SNR:CTB109,XRS:1E_2259.1+586	2.28e+05	5.88e+13	6.7k-21k
51	J2337+6151	0.495369868	1.934498E-13	SNR:G114.3+0.3[frs93]	4.06e+04	9.91e+12	10k-100k

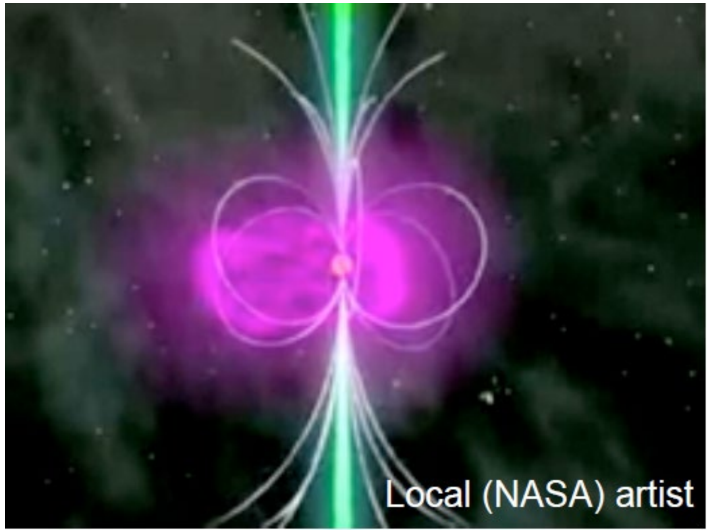


(Matheson+13)

Latest discovered association: the **51ms** pulsar in CTB87, discovered with FAST (Liu, Zhang, Chen+24)

Pulsars





Pulsars are neutron stars with active magnetospheres populated by ultra-relativistic particles emitting non-thermal radiation (synchrotron, curvature, inverse Compton).

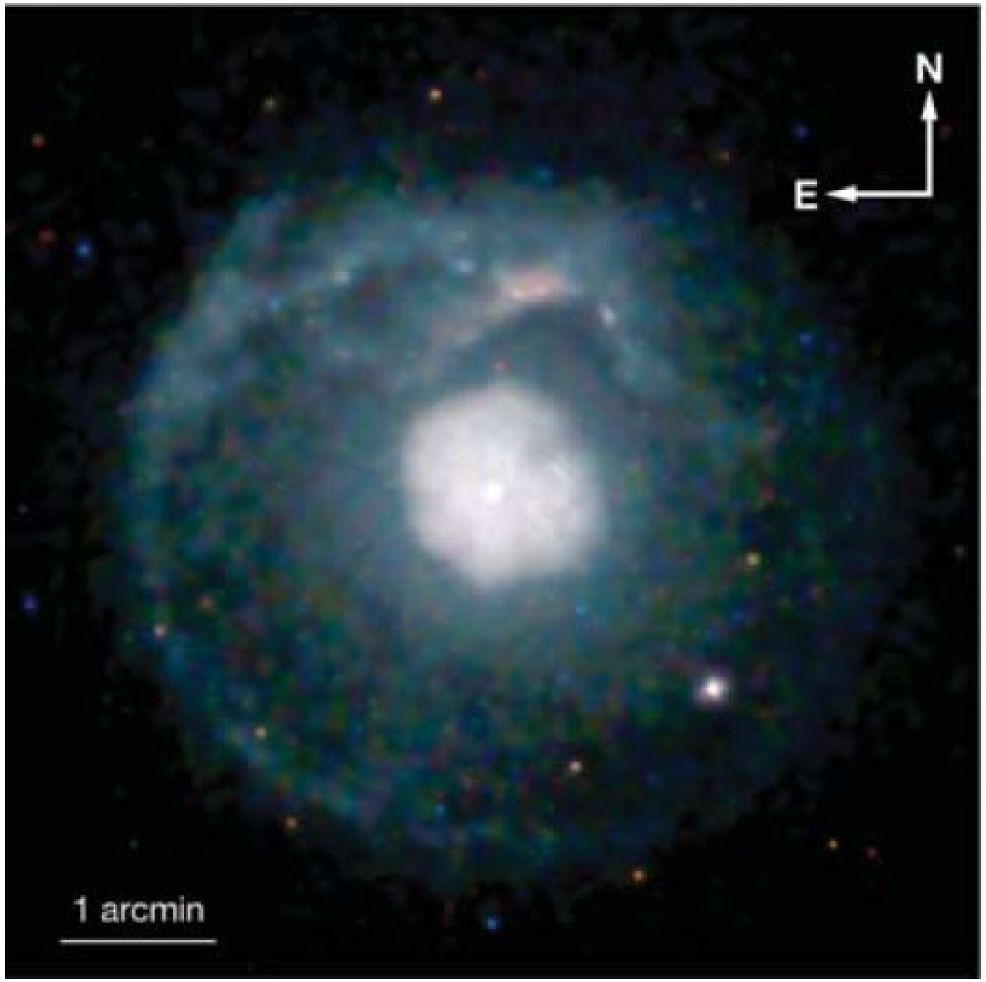
Power Source: NS rotation - $\dot{E}$

Emitted fraction of $\dot{E}$
<0.001% - radio
~0.01-10% - X-rays and gamma-rays
the rest is **pulsar wind !**

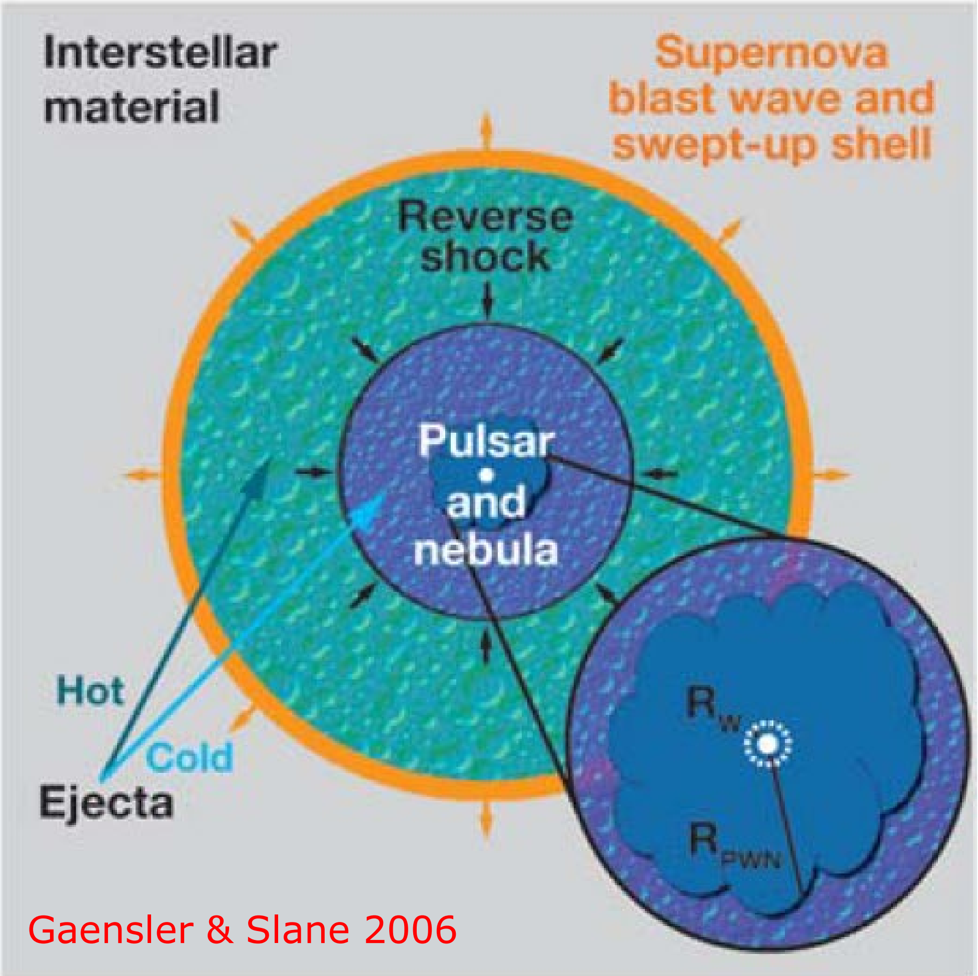
Pulsar wind nebula (PWN)

Magnetized particle wind: e+, e-

a

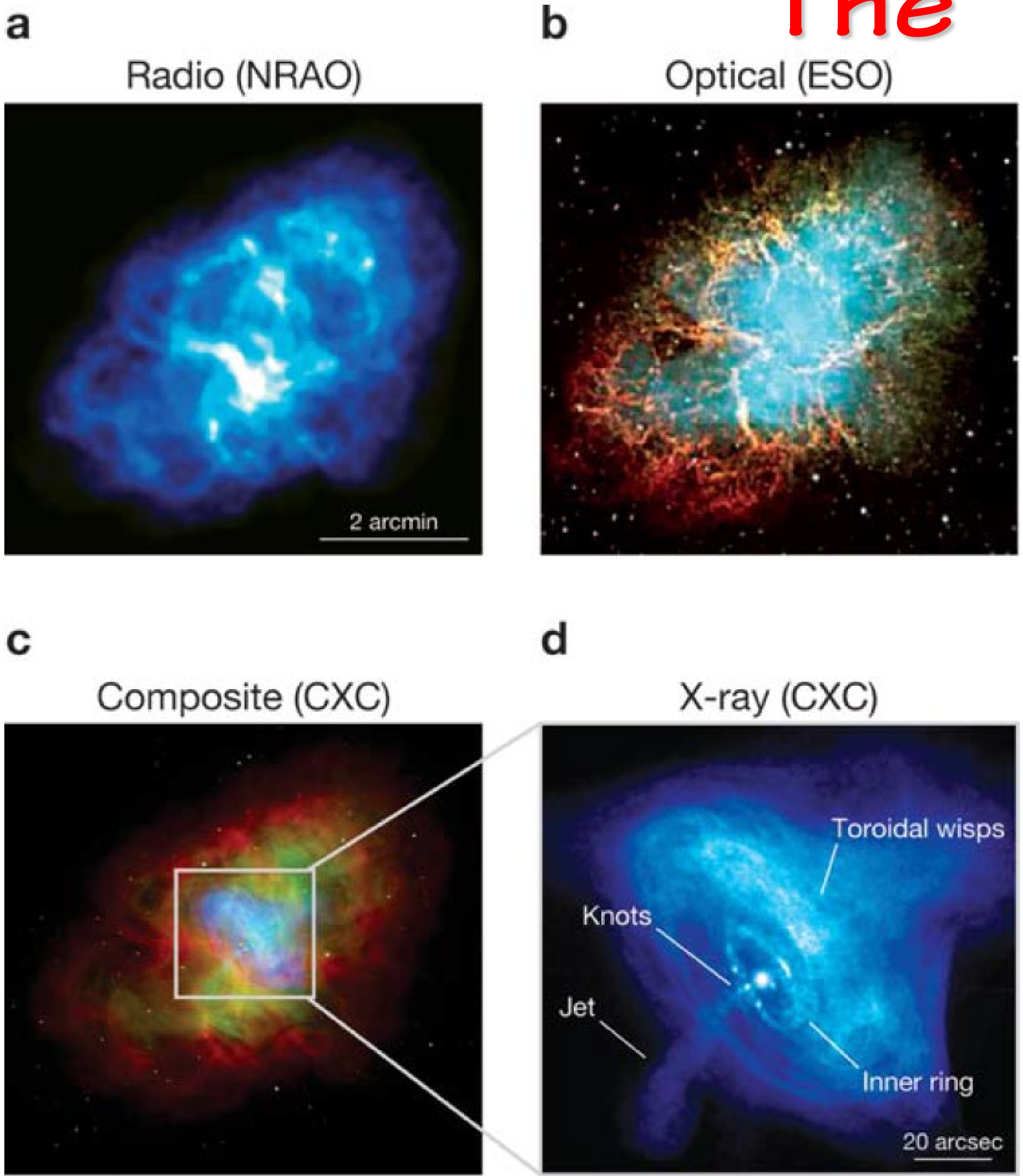


b



Termination shock: $R_W = [\dot{E}/(4\pi\omega c\ P_{PWN})]^{1/2}$

The "Crab"



Magnetization parameter:

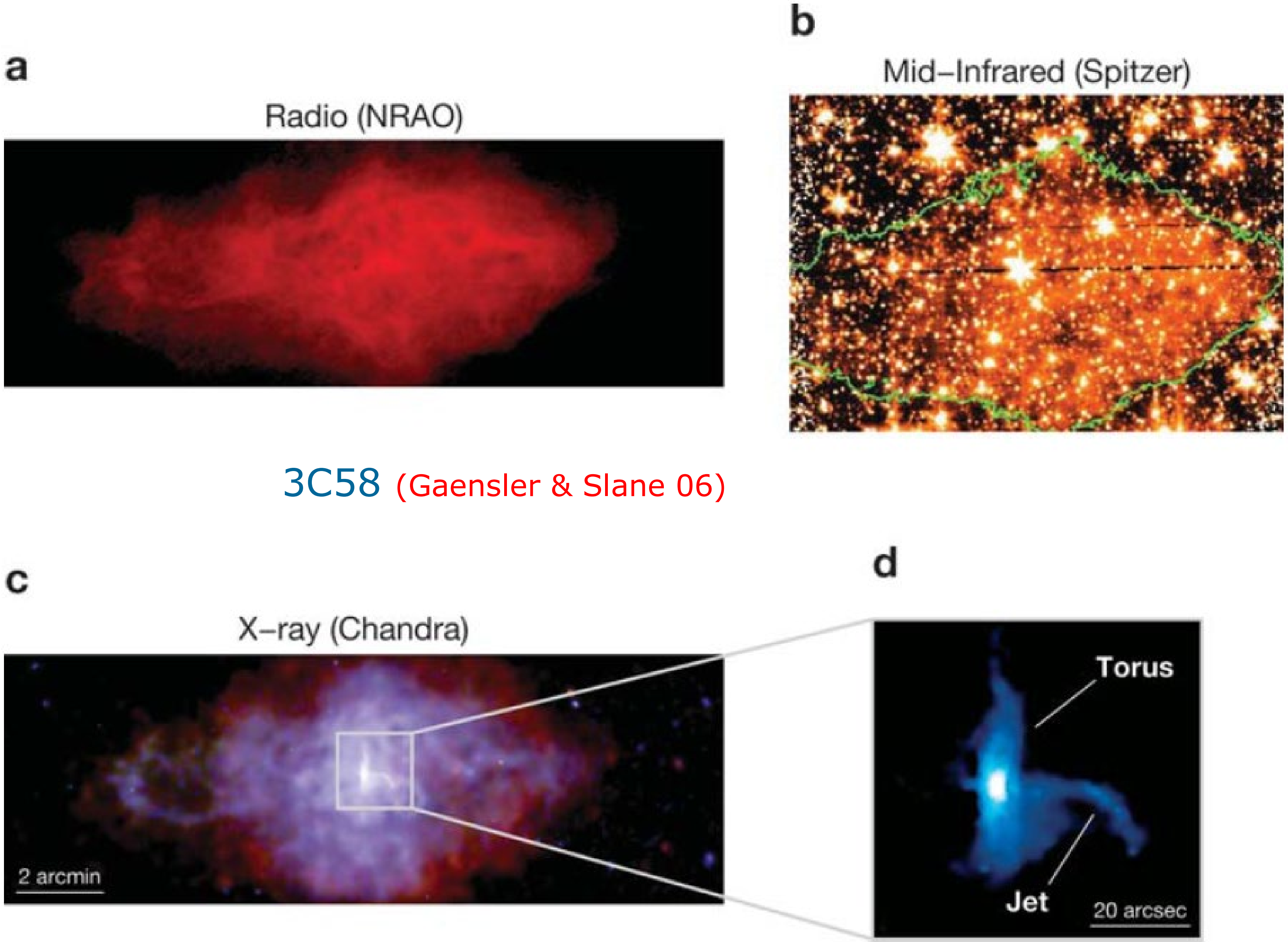
$$\sigma \equiv \frac{F_{E\times B}}{F_{\rm particle}} = \frac{B^2}{4\pi\rho\gamma c^2}$$

$\ll 1$

Particle dominated wind, with $\gamma \sim 10^6$

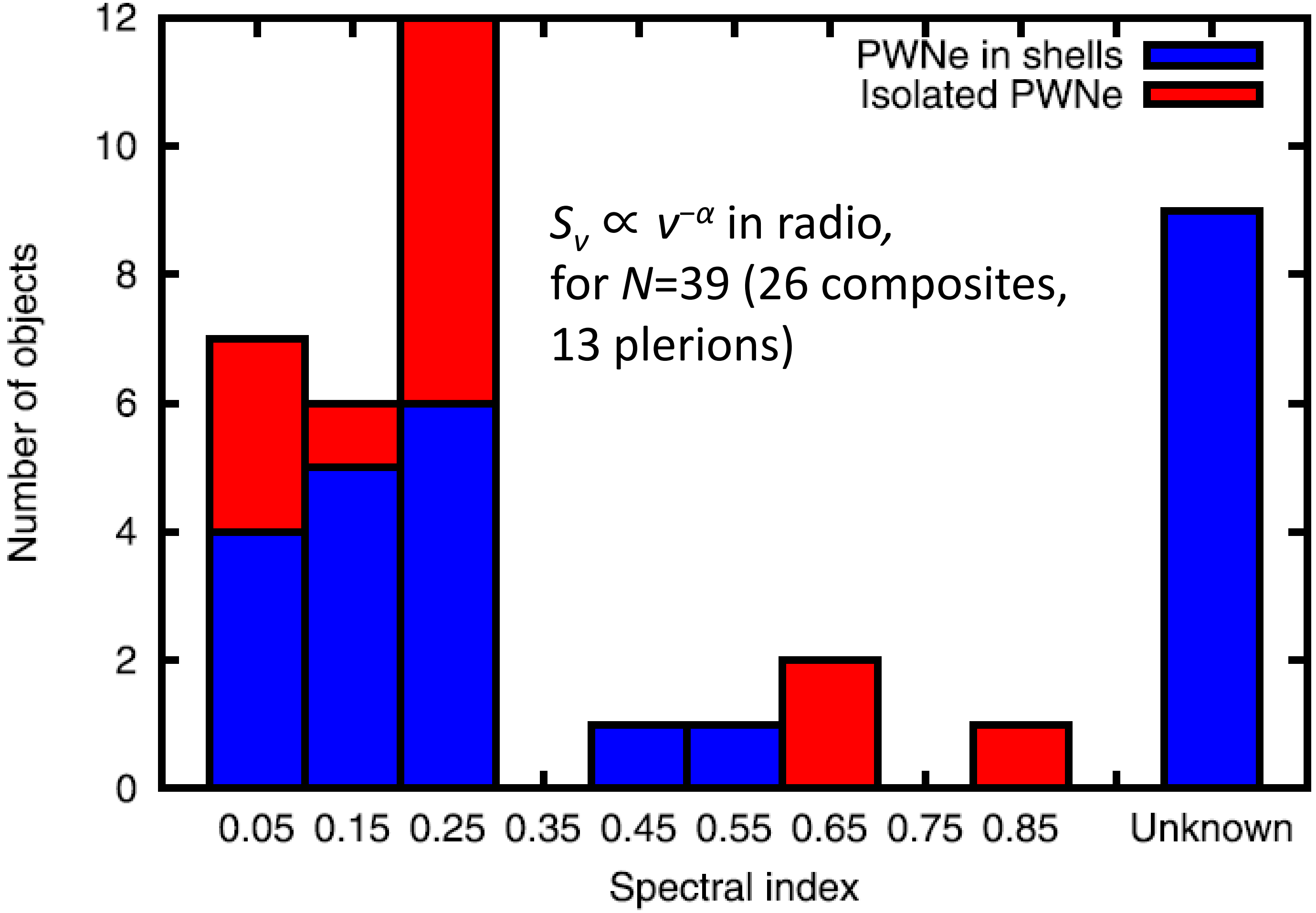
Kennel & Coroniti 1984

Torus+jets structure



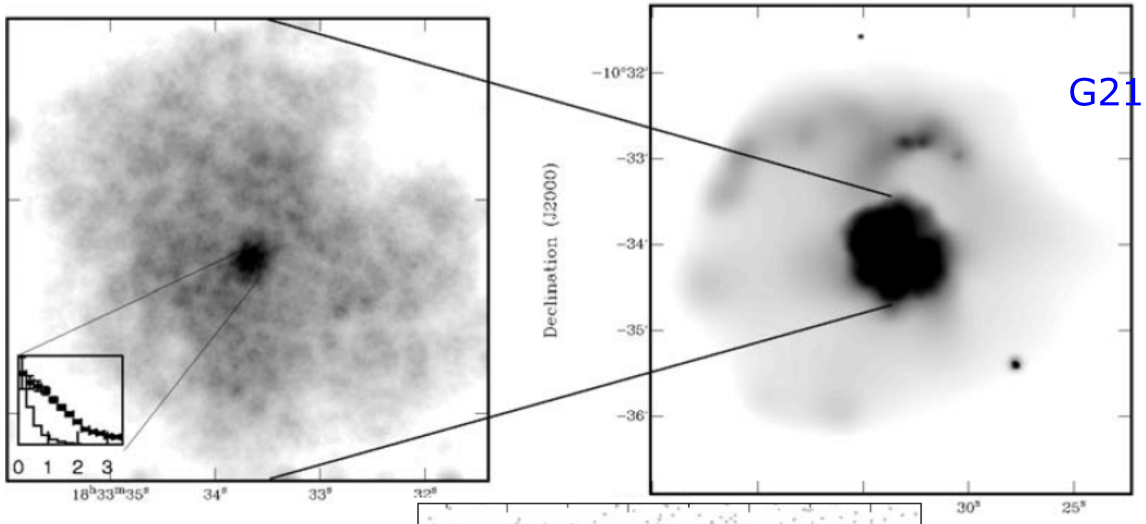
3C58 (Gaensler & Slane 06)

Spectral indices

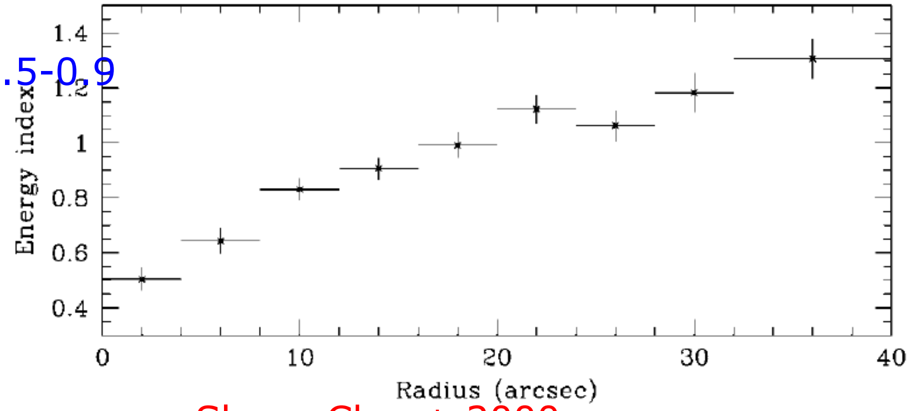


$S_\nu \propto \nu^{-\alpha}$ in radio,
for N=39 (26 composites, 13 plerions)

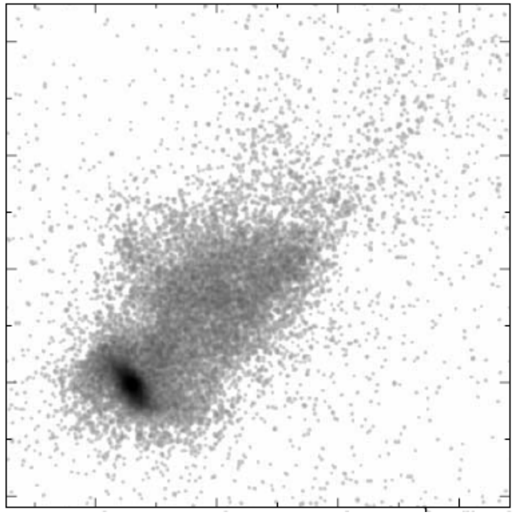
Synchrotron loss



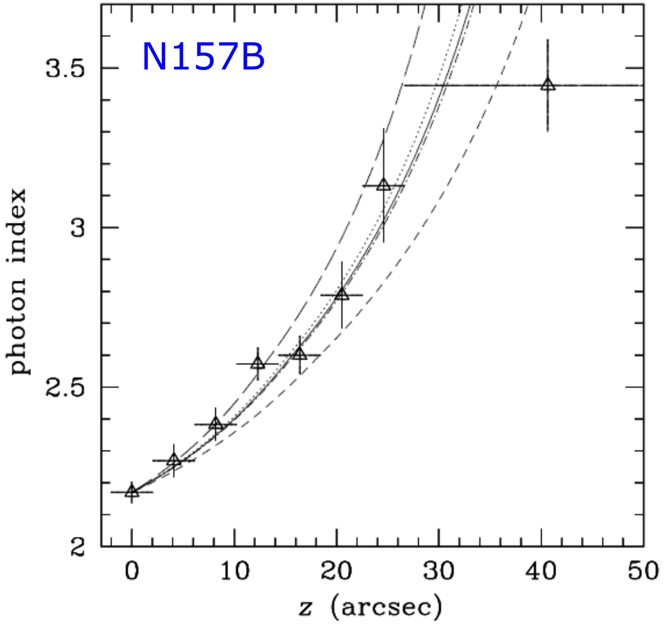
G21.5-0.9



Slane, Chen+ 2000



N157B



Chen+ 2006

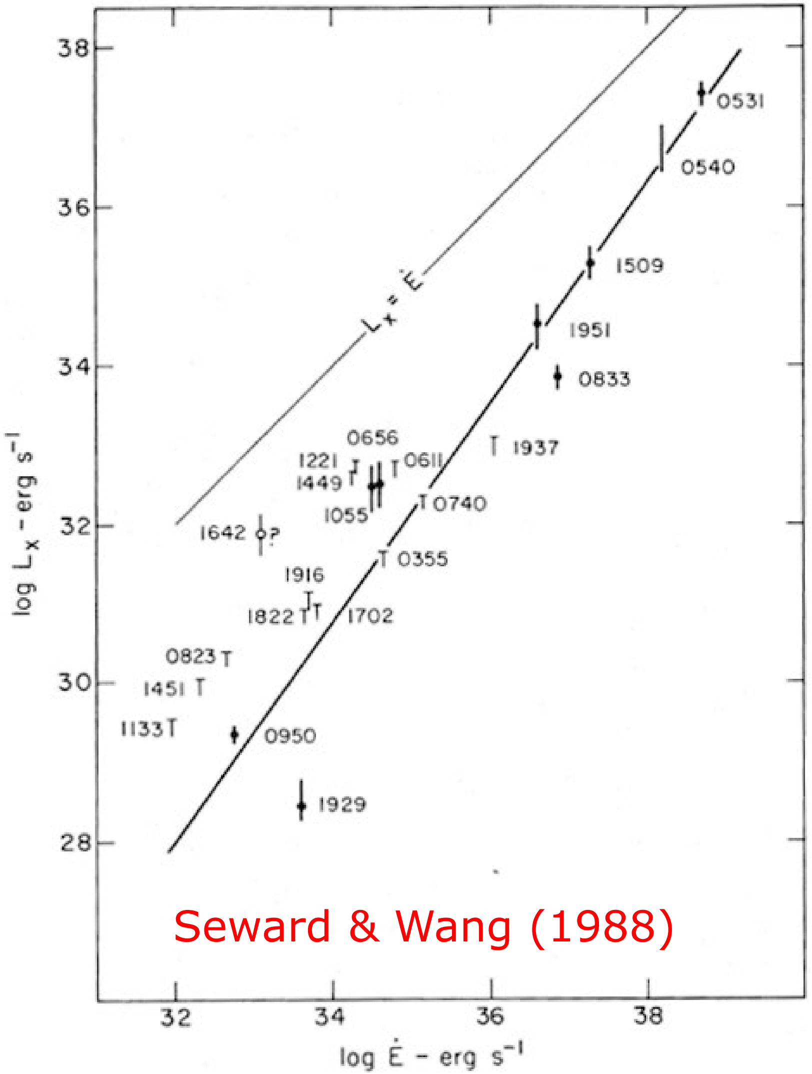
$dE/dt \propto E^2B^2$

$\Rightarrow$

$$\bar{\Gamma} = \frac{p+1}{2} + \frac{p-1}{2}\,\frac{\left(\sqrt{\varepsilon_m/\varepsilon_l}-1\right)^{p-2} - \left(\sqrt{\varepsilon_m/\min(\varepsilon_u,\varepsilon_m)}-1\right)^{p-2}}{\left(\sqrt{\varepsilon_m/\varepsilon_l}-1\right)^{p-1} - \left(\sqrt{\varepsilon_m/\min(\varepsilon_u,\varepsilon_m)}-1\right)^{p-1}}$$

Seward-Wang Relation

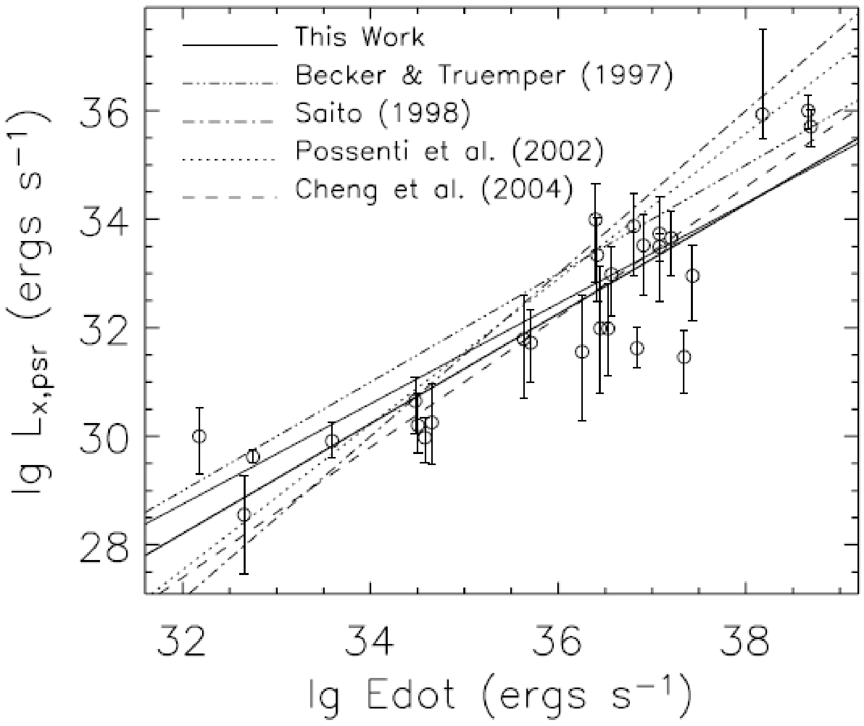
汪珍如教授 1937-2017

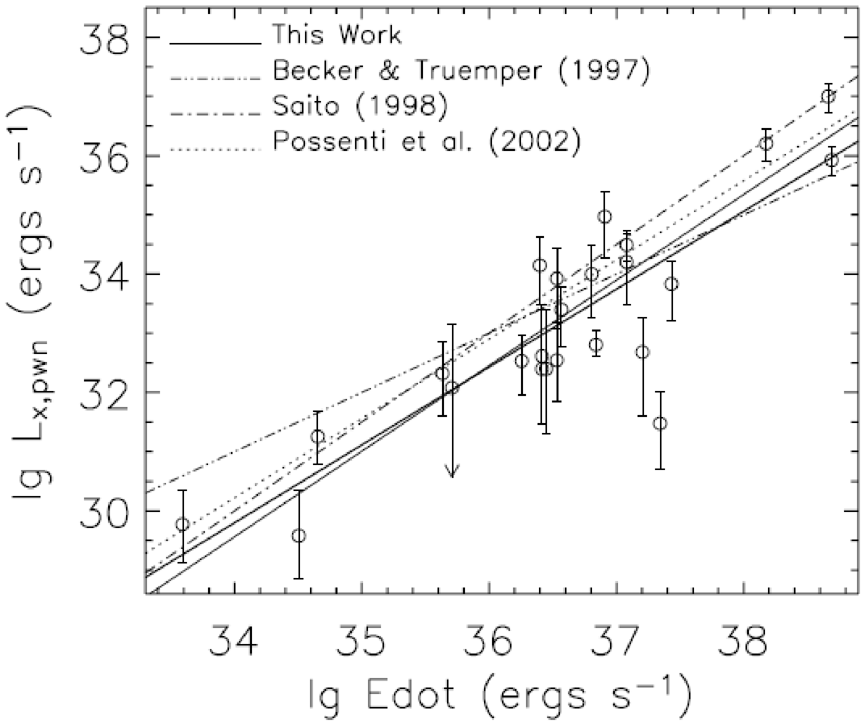


Seward & Wang (1988)

…… *she pioneered X-ray astronomy in China.*
- Richard McCray (1937-2021)

Relations between the X-ray luminosity and spin-down power (with a sample of 24 PWNe)





$$L^*_{\mathrm{X,\,psr}} = 10^{-4.2\pm3.7}\dot{E}^{1.0\pm0.1}$$

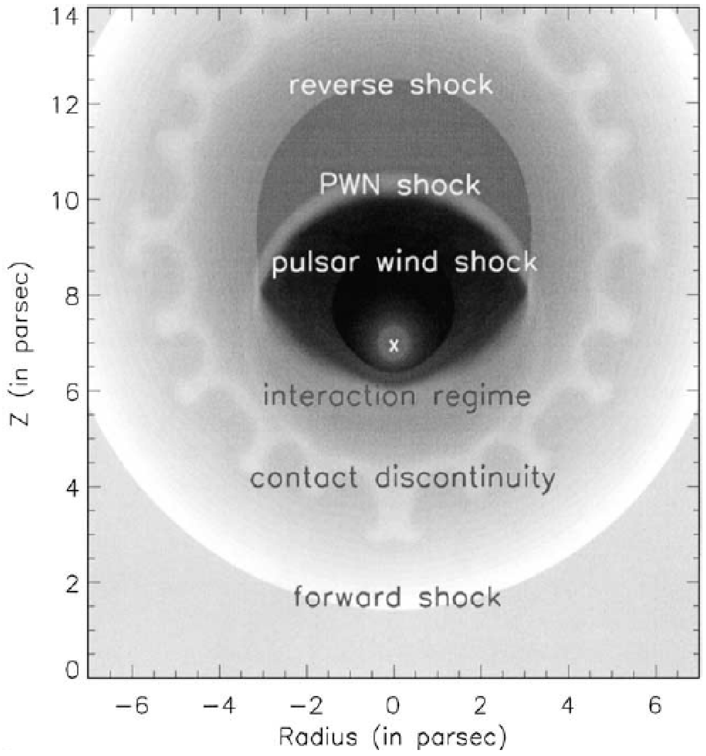
$$L^*_{\mathrm{X,\,pwn}} = 10^{-14.9\pm6.0}\dot{E}^{1.3\pm0.2}$$

The more energetic pulsars intend to release a bigger fraction of their spin-down power in their PWNe.

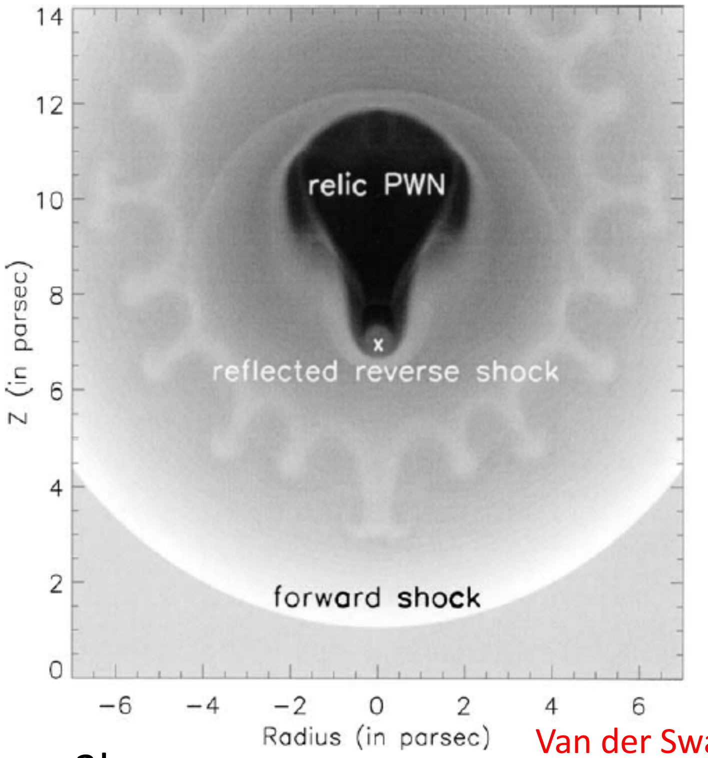
Li, Lu & Li 2008, ApJ 682, 1166

Evolution of PWNe

(1) 在脉冲星减速时标τ以内（$t < \tau$）,受到终止激波震击的超高压的脉冲星风等离子体在抛射物的核区内迅速向外扩张形成小泡，表面激波依$\propto t^{6/5}$超声速加速膨胀。
(2) 泡面受到从遗迹壳层传回的反向激波碰撞（发生的典型时标为几千年），在数千年内经历若干次压缩、反弹的轮回震荡，乃至压破。



2kyr



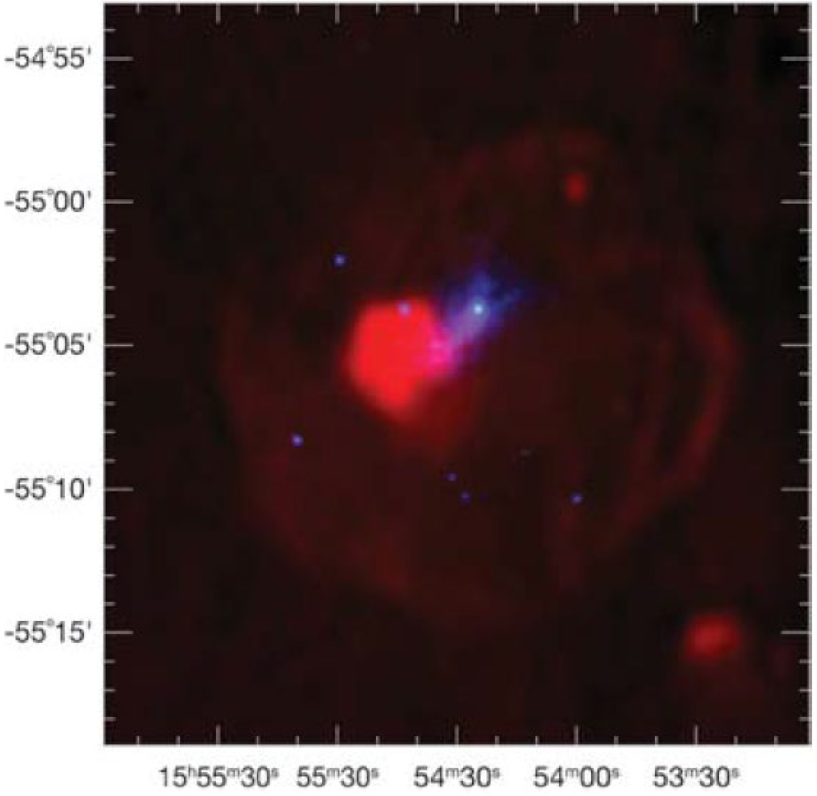
3kyr

Van der Swaluw 2004

Evolution of PWNe

(3) 脉冲星风云在处于Sedov相的遗迹内部高温气体中亚声速膨胀。若$t < \tau$，演化律为$\propto t^{11/15}$；若$t > \tau$，则按$\propto t^{0.3}$强烈减速。

(4) 由于脉冲星在超新星爆炸时获得“踢出”速度（典型值为每秒500公里上下），脉冲星穿出原先的风泡，生成新的、较小的星风云，新旧星风云各自主要呈现在X射线和射电波段。



G327.1-1.1

PSR escapes from radio *relic PWN* left behind

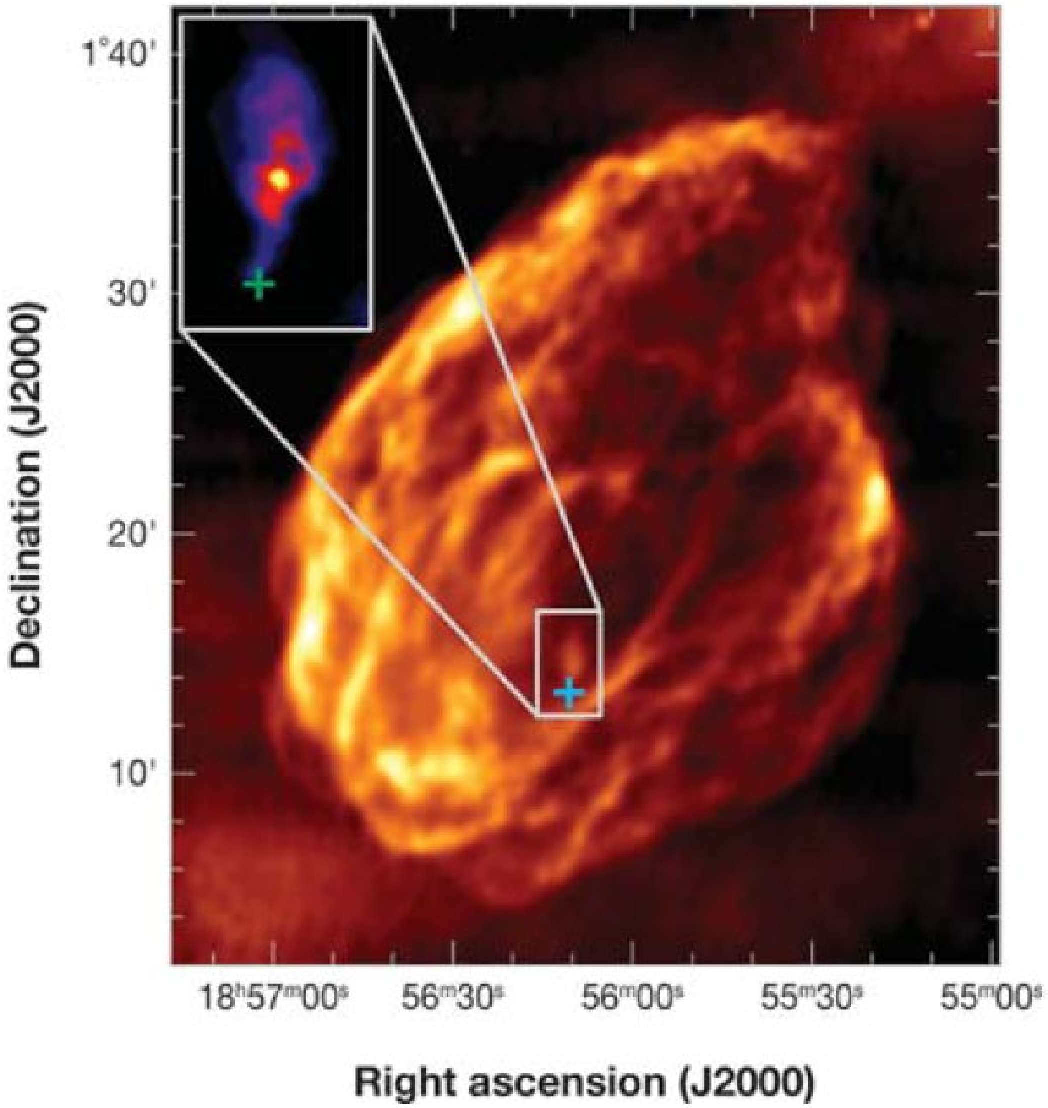
Gaensler & Slane 2006

Evolution of PWNe

(5) 随着遗迹内部气体的冷却，脉冲星的穿行成为超声速运动，星风云外表出现弓激波，呈彗星样的拖尾状，不再膨胀。

Transition to bow shock at 68% r_s

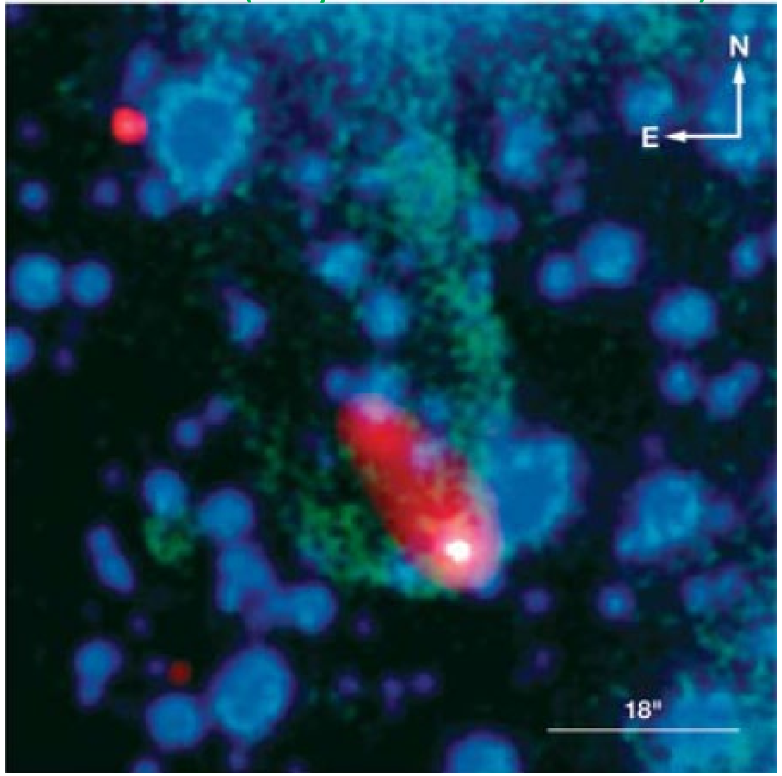
W44



Gaensler & Slane 2006

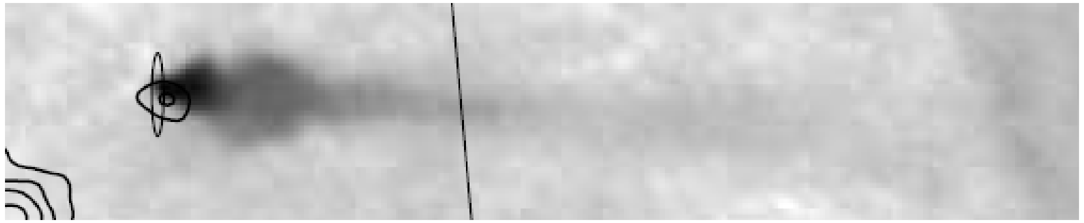
Evolution of PWNe

PSR B1957+20 (recycled `black widow')

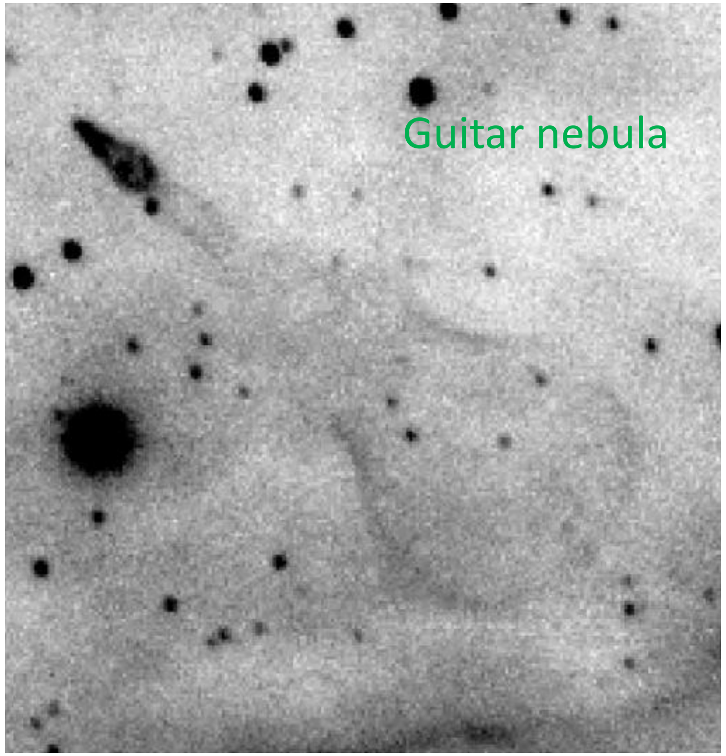


Gaensler & Slane 2006

Mouse Nebula



Gaensler+ 2004

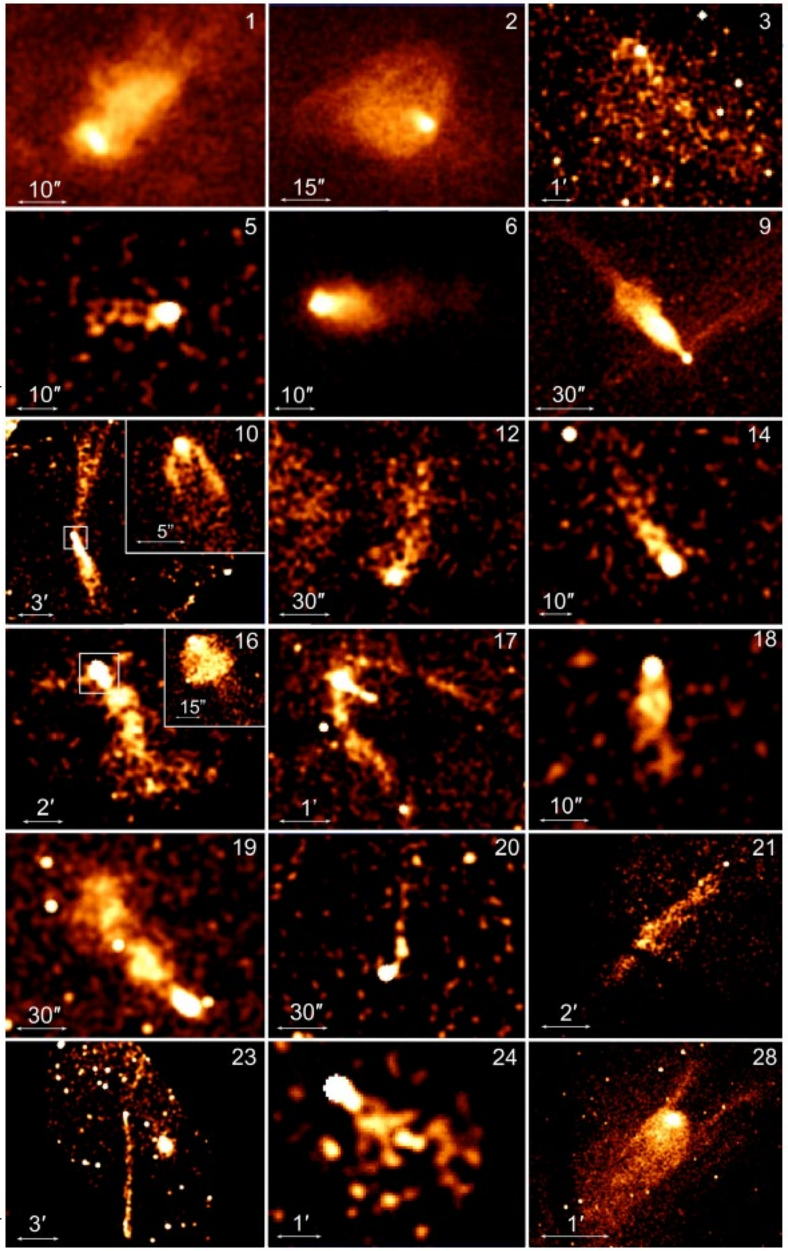


Chatterjee & Cordes 2002

(6) 脉冲星逃逸出遗迹壳层（发生的典型时标为若干万年），穿行于星际介质中，通常高度超声速；星风云受限于星际弓激波，呈彗星拖尾状。
(7) 最后阶段，脉冲星运行到低密度区域，不再超声速，能量输出微弱，裹在一个静态或缓慢膨胀的、为星际介质热压力束缚的相对论性气体腔中。

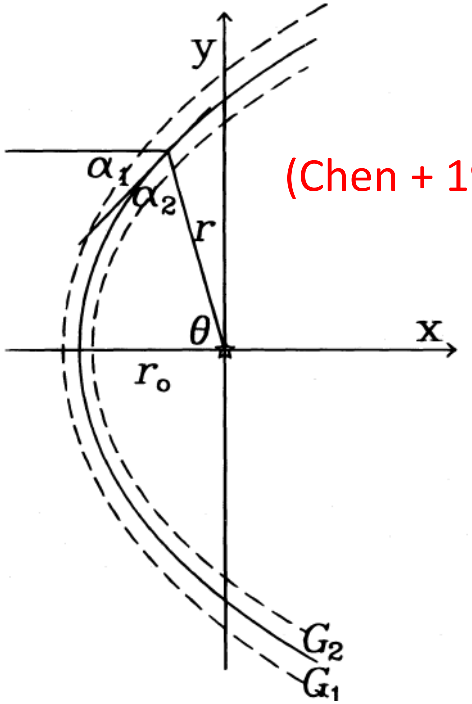
Supersonic PWN

#	Pulsar	Associated Object(s)	d kpc	$\log \dot{E}$ erg s^{-1}	$\log \tau$ yrs	B_{11} 10^{11} G	$v_\perp$ km s^{-1}
1	J0537–6910[a]	SNR N157B	49.7	38.68	3.69	9.25	...
2	B1951+32	SNR CTB 80	3	36.57	5.03	4.86	460
3	J1826–1256	HESS J1825–137	~ 3.9[b]	36.56	4.16	37	...
4	B1706-44	SNR G343.1–2.3	2.6	36.53	4.24	31.2	$\lesssim 100$
5	B1757–24	SNR G5.27–0.9, Duck PWN	3.8	36.41	4.19	40.4	198
6	J1747–2958	Mouse PWN	5	36.40	4.41	24.9	306 ± 43
7	J1135–6055	...	~ 2.8[b]	36.32	4.36	30.5	< 330
8	J1437–5959	SNR G315.9–0.0, Frying Pan PWN	8	36.15	5.06	7.37	~ 300
9	J1101–6101	Lighthouse Nebula, SNR G290.1–0.8	~ 7[b]	36.13	5.06	7.24	~ 2000
10	J1509–5850	...	4	35.71	5.19	9.14	200 – 600
11	B0906–49	...	1	35.69	5.05	12.9	~ 60
12	B1853+01[a]	SNR W44	3.3	35.63	4.31	75.5	400^{+114}_{-73}
13	B0740–28	...	2	35.28	5.2	16.9	275[c]
14	B1957+20	the Black Widow pulsar	1.73	35.20	9.18	0.002	~ 220
15	J0538+2817	SNR S147	1.39[p]	34.69	5.79	7.33	357^{+59}_{-43}
16	B0355+54	Mushroom PWN	1.04[p]	34.66	5.75	8.39	61^{+12}_{-9}
17	J0633+1746	Geminga PWN	0.25[p]	34.51	5.53	16.3	~ 200
18	J2030+4415	...	~ 1[b]	34.46	5.74	12.3	...
19	J1741–2054	...	0.3	33.97	5.59	26.8	155
20	J2124–3358	...	0.41	33.83	9.58	0.003	75[c]
21	J0357+3205	Morla PWN	0.5	33.77	5.73	24.3	~ 2000
22	J0437–4715	...	0.156[p]	33.74	9.2	0.006	104.7 ± 0.9
23	J2055+2539[a]	...	~ 0.6[b]	33.69	6.09	11.6	$\lesssim 2300$
24	B1929+10	...	0.36[p]	33.59	6.49	5.18	177^{+4}_{-5}
25	B2224+65	Guitar Nebula	1.88	33.07	6.05	26	1626
26	...	SNR IC443[a]	1.4	...	...	...	~ 250
27	...	SNR MSH 15–56, G326.3–1.8	4	...	...	...	100–400
28	...	G327.1–1.1, Snail PWN	7	...	...	...	~ 500

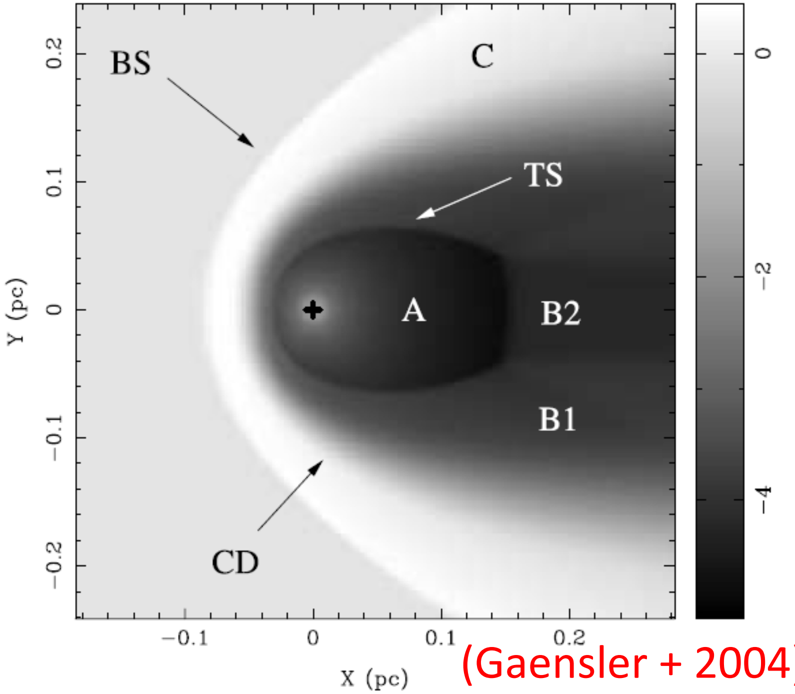


Kargaltsev+1708.00456

Bow shock



(Chen + 1996)



(Gaensler + 2004)

Balance of ram pressure/ momentum fluxes

$$j_0 \sin^2 \alpha_1 - j_w \sin^2 \alpha_2 = \frac{\sigma v_t^2}{R} ,$$

$$j_0 \sin \alpha_1 \cos \alpha_1 + j_w \sin \alpha_2 \cos \alpha_2 = \frac{1}{y} \frac{d}{ds} (\sigma v_t^2 y)$$

$$j_0 \equiv \rho_0 v_*^2 \text{ and } j_w \equiv \dot{M} v_w/(4\pi r^2)$$

$$\dot{E}/(4\pi r^2 c)$$

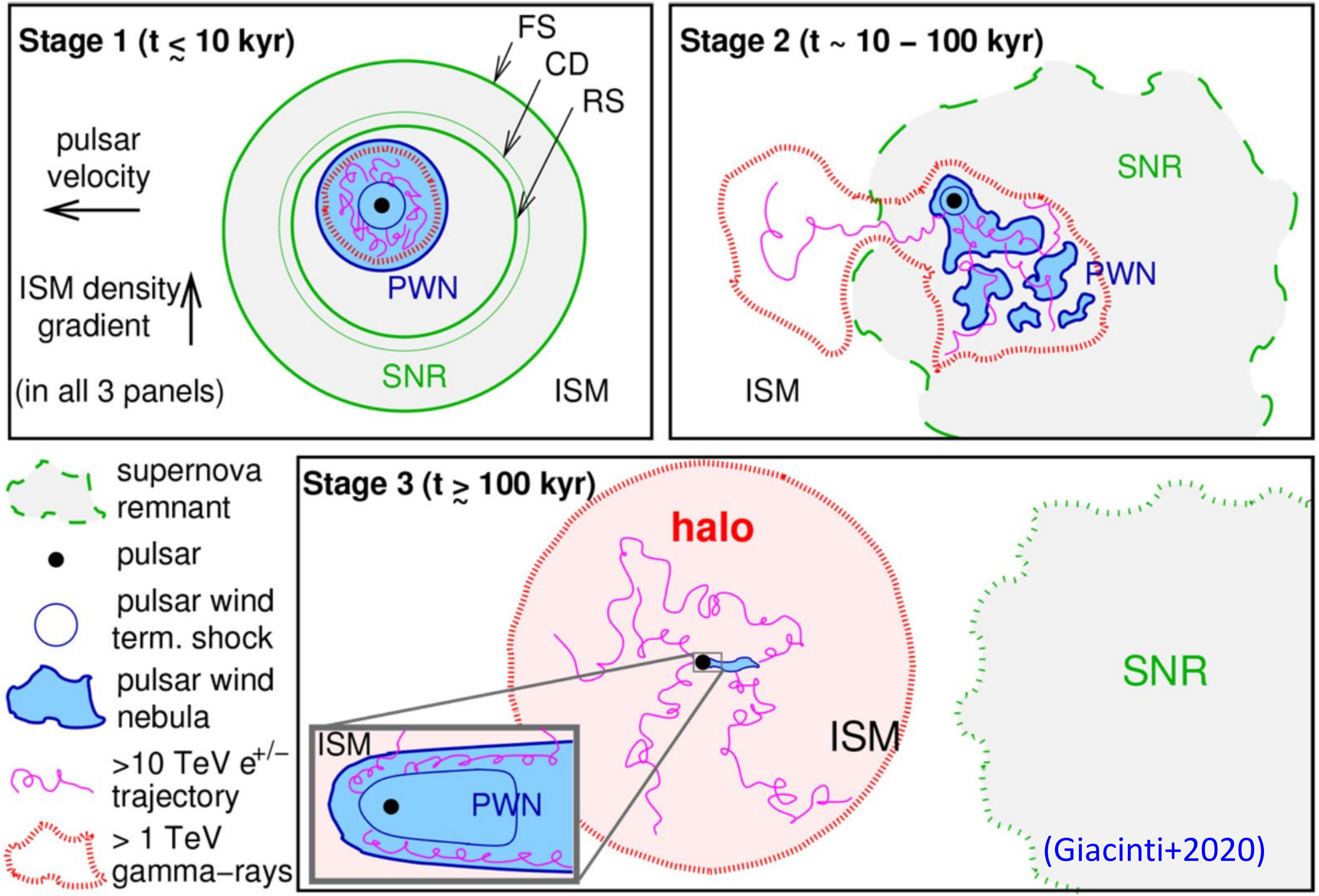
Cartesian (Chen+ 1996) :

$$\xi + 1 = \frac{3}{10} \eta^2 + \frac{3}{280} \eta^4$$

Polar (Wilkin 1996) :

$$R(\theta) = R_0 \csc \theta \sqrt{3(1 - \theta \cot \theta)}$$

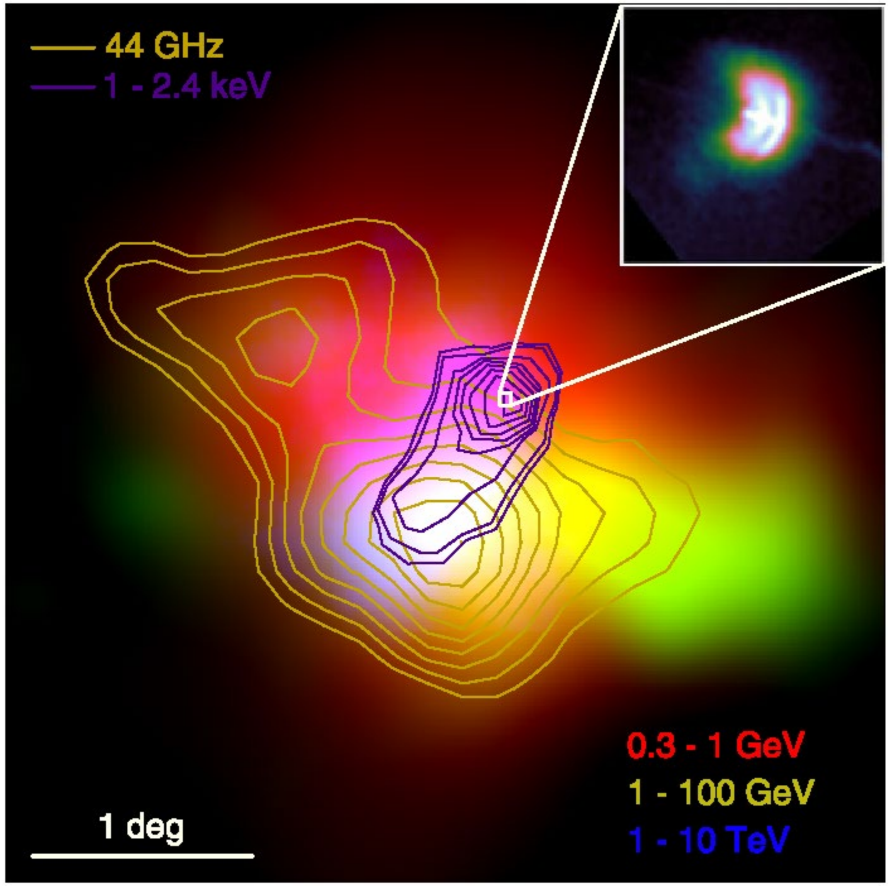
Pulsar (TeV) halos

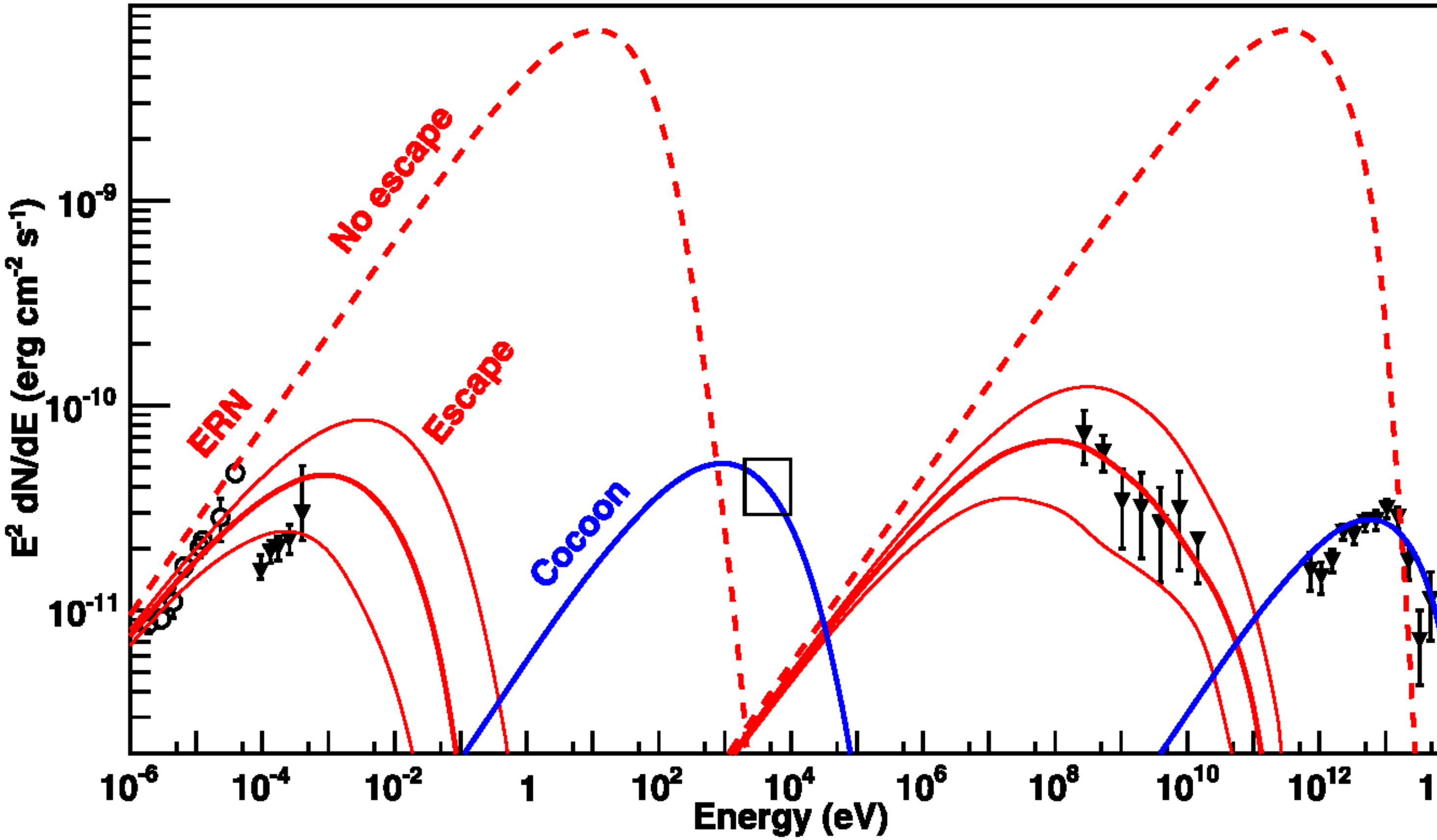


(Giacinti+2020)

Vela PWN, Pulsar halo

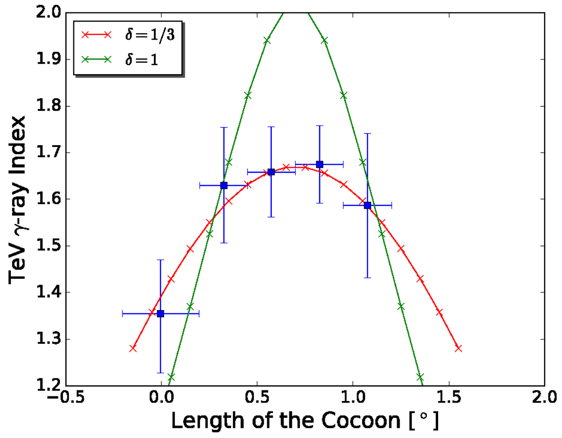
(Reynolds 2017)

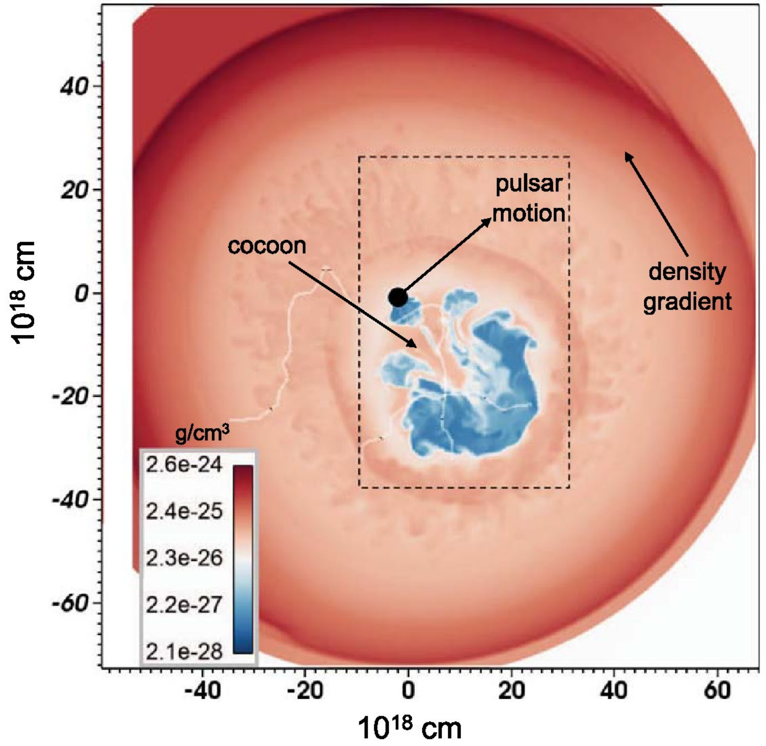


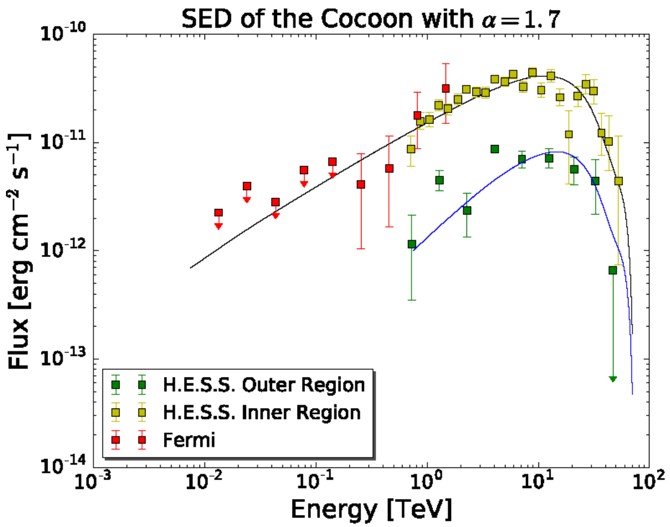


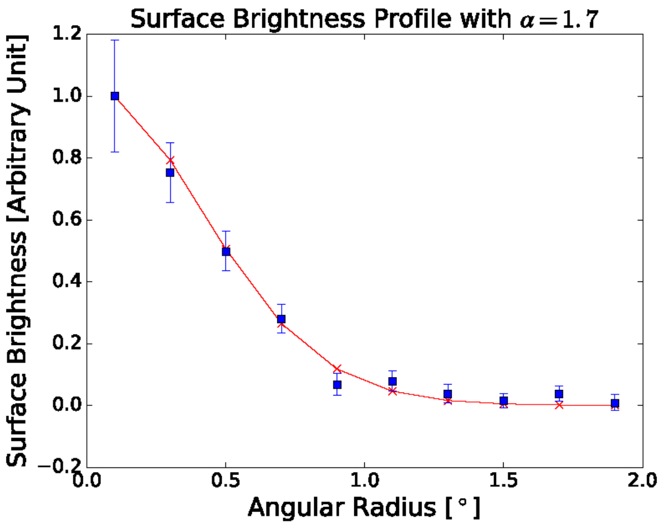
Vela pulsar halo

(Bao+ 2019)







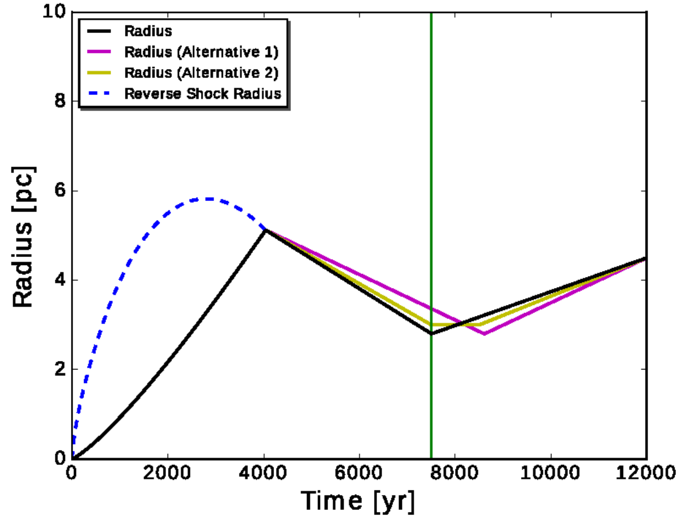


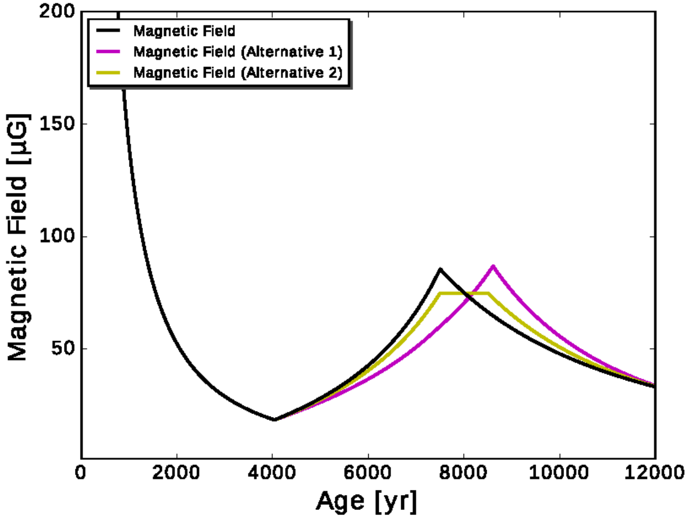
$D_0=1\times10^{26}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$ for 10TeV

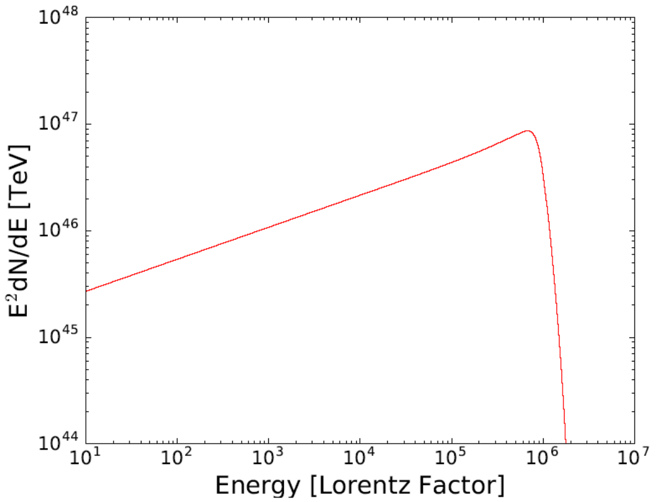
more than three orders of magnitude lower than that in the ISM

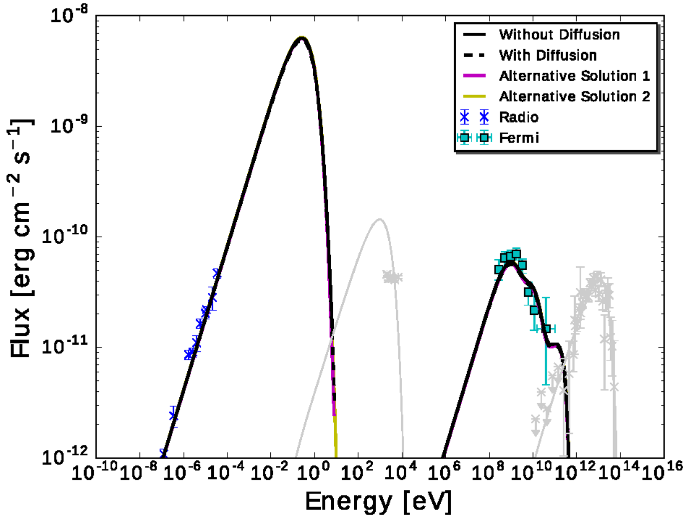
Extended radio nebula

(Bao & Chen 2019)









祝同学们暑假快乐！