SuperNova Remnants (SNR)

Outline:

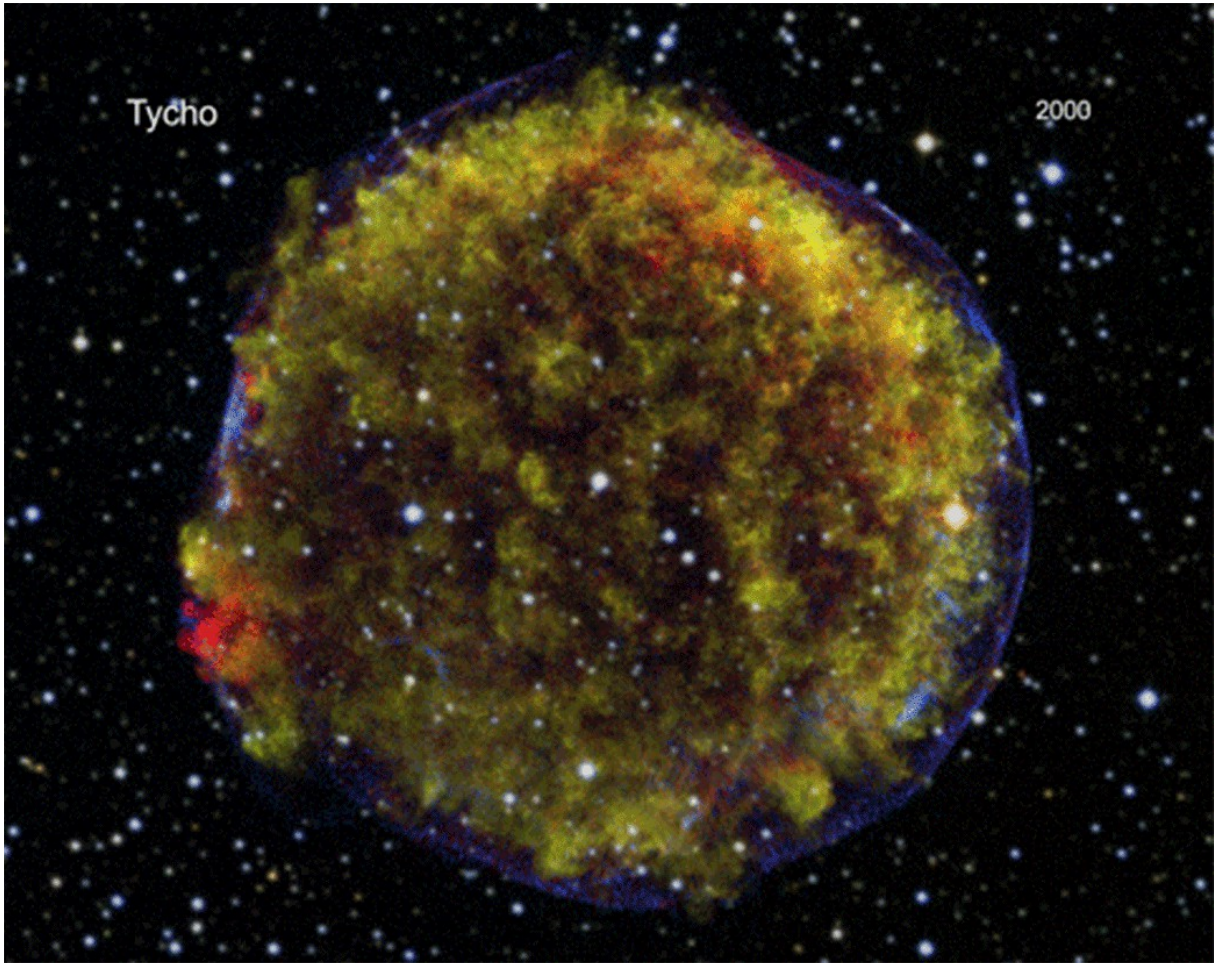
SN classification
(based on optical)

Which ones are radio detected

Models & caveats

Physical properties

Add SN in ext. Galaxies (eg Arp220)



Further reading: *Dubner & Giacani "Radio emission from supernova remnants" 2015, A&ARev, vol. 23*

- Weiler et al. 2002, ARAA, 40, 387 – 438
  Radio Emission from Supernovae and Gamma-Ray Bursters

- Smartt 2009, ARAA, 47, 63-106
  Progenitors of Core-Collapse Supernovae

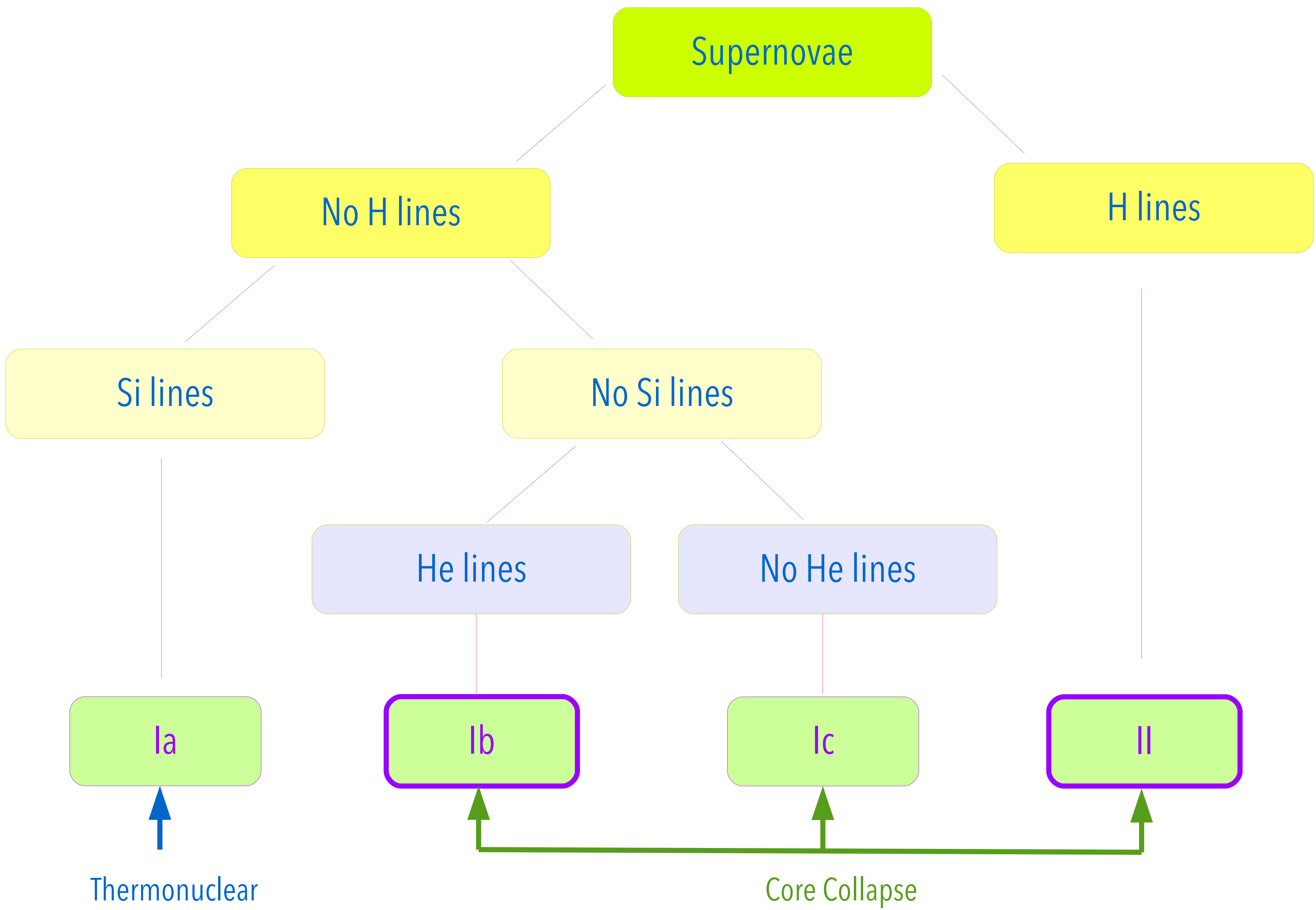
- McCray & Fransson, 2016, ARAA, 54, 19-52
  The Remnant of Supernova 1987A

- Holoien + 2017, https://arxiv.org/pdf/1704.02320.pdf
  The ASAS-SN Bright Supernova Catalog -- III. 2016

- Matsuura+, 2017,https://arxiv.org/pdf/1704.02324.pdf
  ALMA spectral survey of Supernova 1987A – molecular inventory, chemistry, dynamics and explosive nucleosynthesis

- Chap 15, Fanti & Fanti

Supernova Classification (based on optical spectrum)



SuperNova Remnants (SNR)

Supernovae: Type I (in all galaxy types)

Ia: (https://www.youtube.com/watch?v=DhkWx8-efq0)

- old stars, WD exceeds the Chandrasekar's limit, No H lines,
- ~ same profile of the light curve: maximum (M_{max} ~ – 18.5 ^{m}) it lasts for ~ a week,
- then decrease of 3^m in ~75 days, then exponential decay
- strong SiII absorption, v_{exp} ~ 10^4 km s^{-1}
- No radio emission (at 0.1 mJy level)

Wrong!

Ib, Ic: (in spirals and irregulars only)

- younger stars, ~1.5^m fainter, redder and often assiocated to HII regions
- no SiII lines, but He lines (**Ib**, if no He lines → **Ic**),
- Massive stars that lost their envelope (stellar wind? Mass transfer to a companion?), possibly WR stars
- (strong) radio emission when young
- fast decay of radio emission

SuperNova Remnants (SNR)

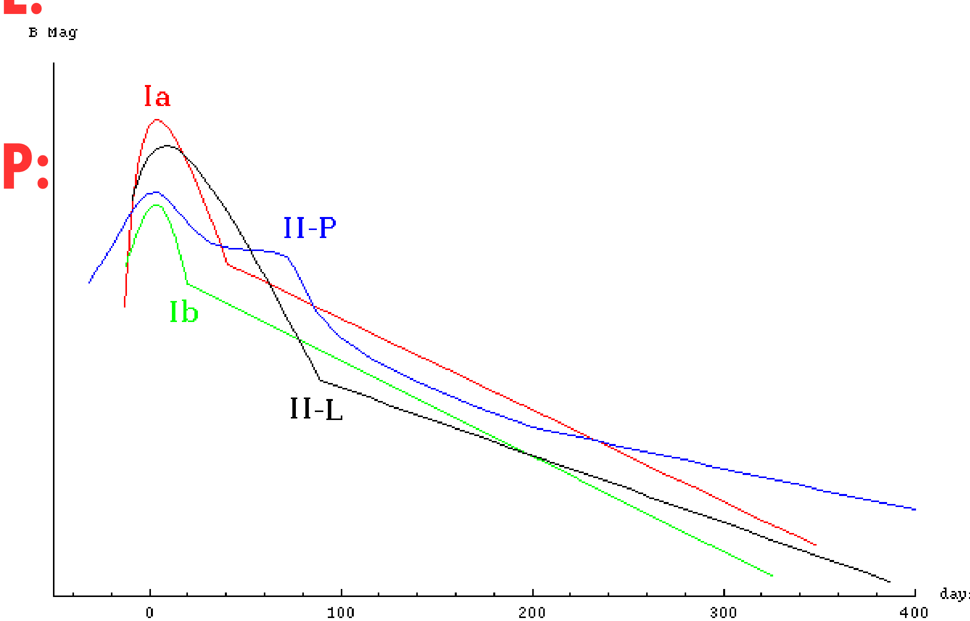
Supernovae: Type II (in spirals & irregulars only)

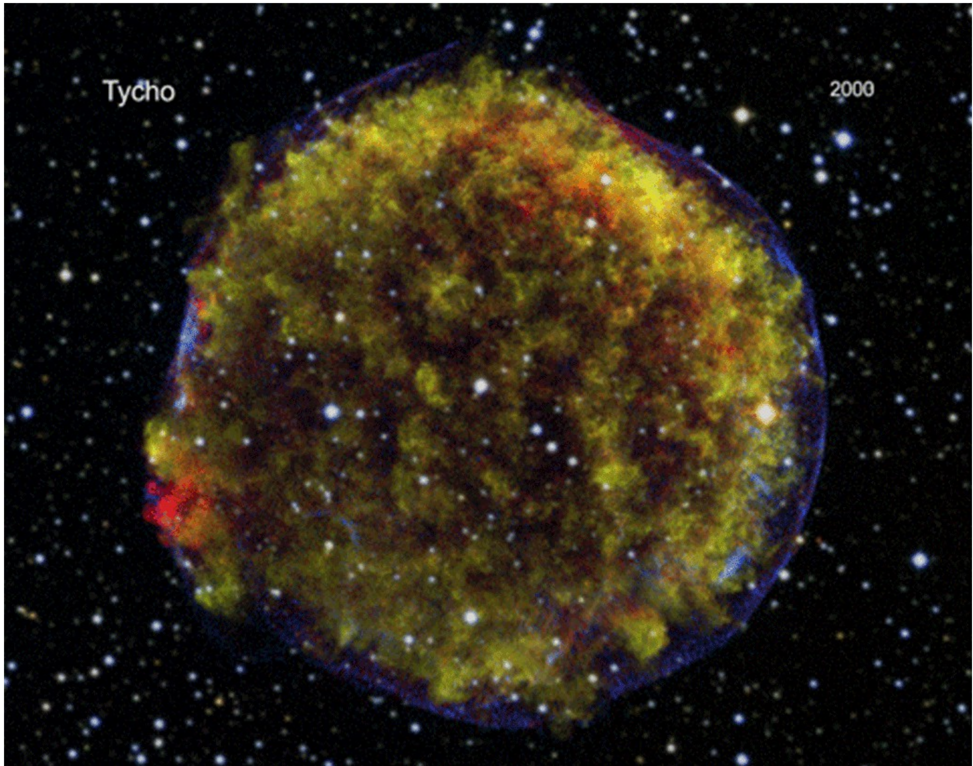
Inhomogeneous class (all but type I!)

- Strong Hα emission,
- $M_{max} \sim -16.5^m$, with a lot of dispersion, from red giants,
- $v_{exp} \sim$ a few 10^3 km s^{-1}, with some dispersion
- produce (weak) radio emission, relatively slow decay

II-L:

II-P:





SuperNova Remnants

Comparison SN: type I .vs. type II (Ib, Ic)

Type I		Type II
$\leq 1\ M_{sun}$	Ejected mass	$\geq 1\ M_{sun}$
$\geq 10^4$ km s^{-1}	V_{exp}	$\leq 10^4$ km s^{-1}
$\approx 10^{50} - 10^{51}$ erg	Kinetic energy	$\approx 10^{50} - 10^{51}$ erg

- Ia no radio emission (??), Ib/c steep radio spectrum $\alpha \geq 1$
- II radio emission with a wide range of luminosities, fainter than I, flatter spectrum $\alpha \leq 1$
- $\Rightarrow$ Only ~20% of supernovae have a radio counterpart
- ~1/4 of them are type Ib/Ic, ~3/4 are type II

WRONG!

SuperNova Remnants

Radio emission is generally a non-thermal power law as from synchrotron emission

i.e. B field & relativistic particles, the latter requiring some acceleration mechanism

At the very beginning, radio emission is optically thick then becomes thin at progressively lower frequencies, and the light curve (decline) is similar to optical

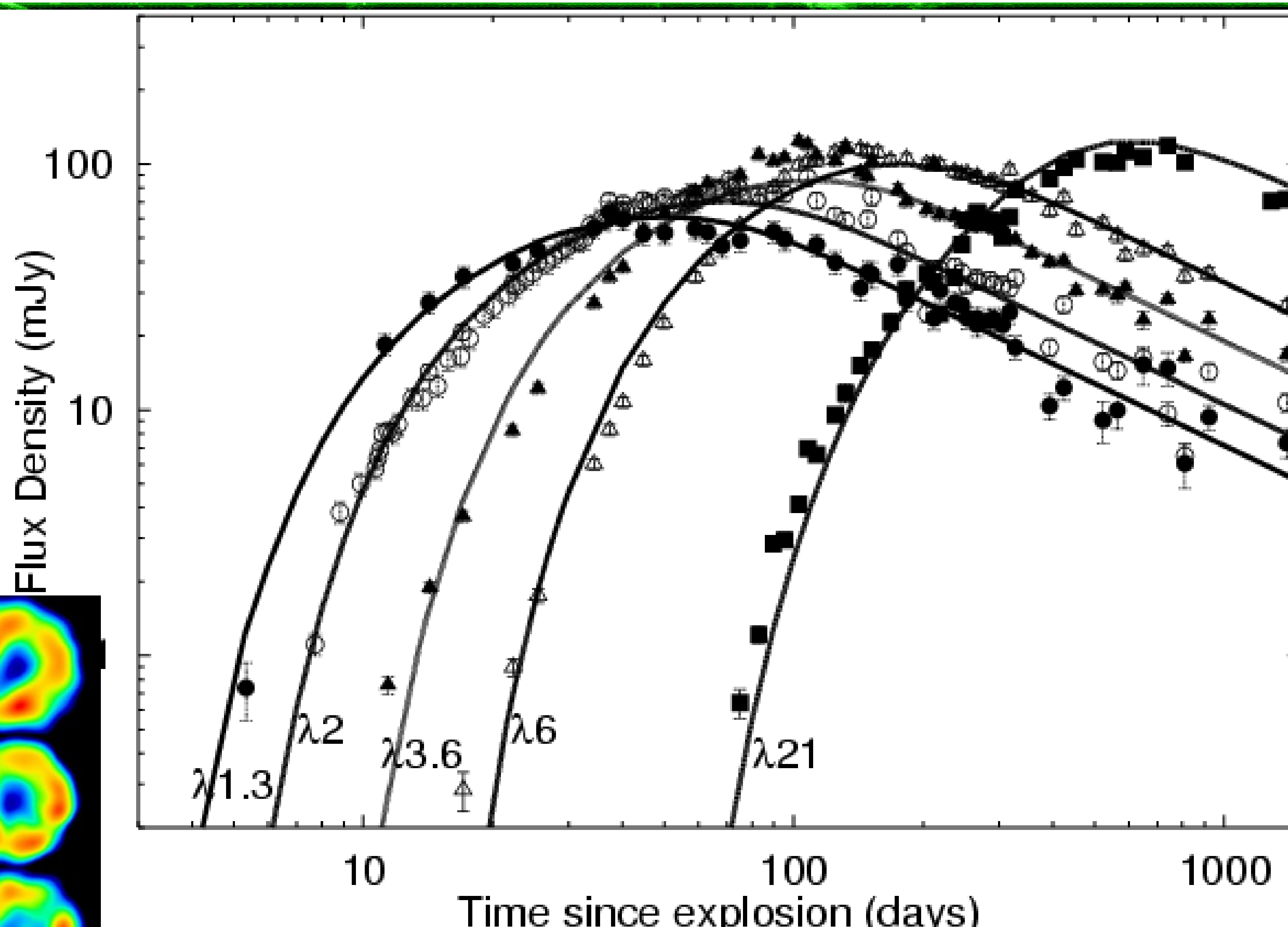
Radio emission may be produced by

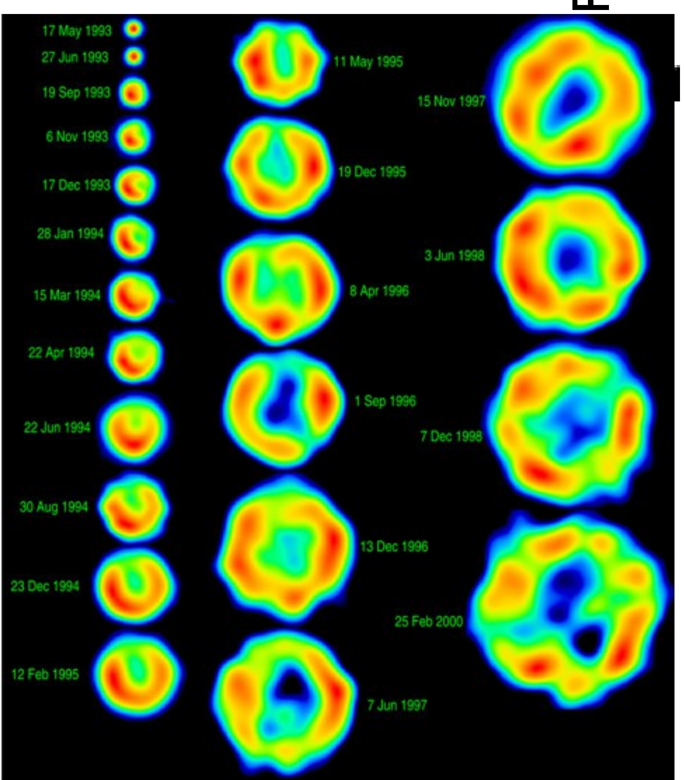
a. Rotating B field associated to a NS, accelerating electrons to relativistic regime

b. The outer layers/shells expands supersonically in a circum-stellar medium filled by stellar wind of the pre-SN accelerating particles

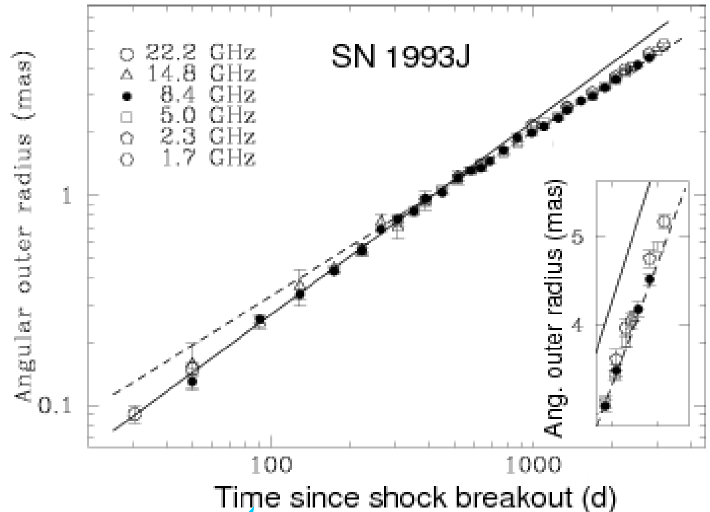
Perez – Torres +, 2001
SN 1993J in M81

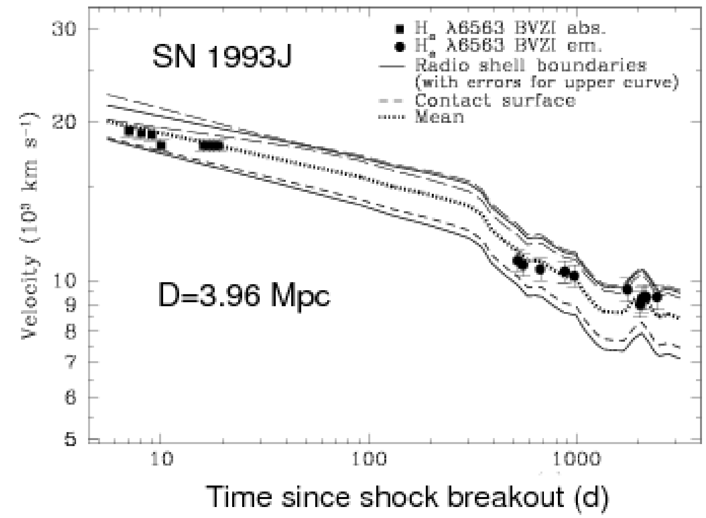
Radio light curves:
Lower frequencies
peak at later times





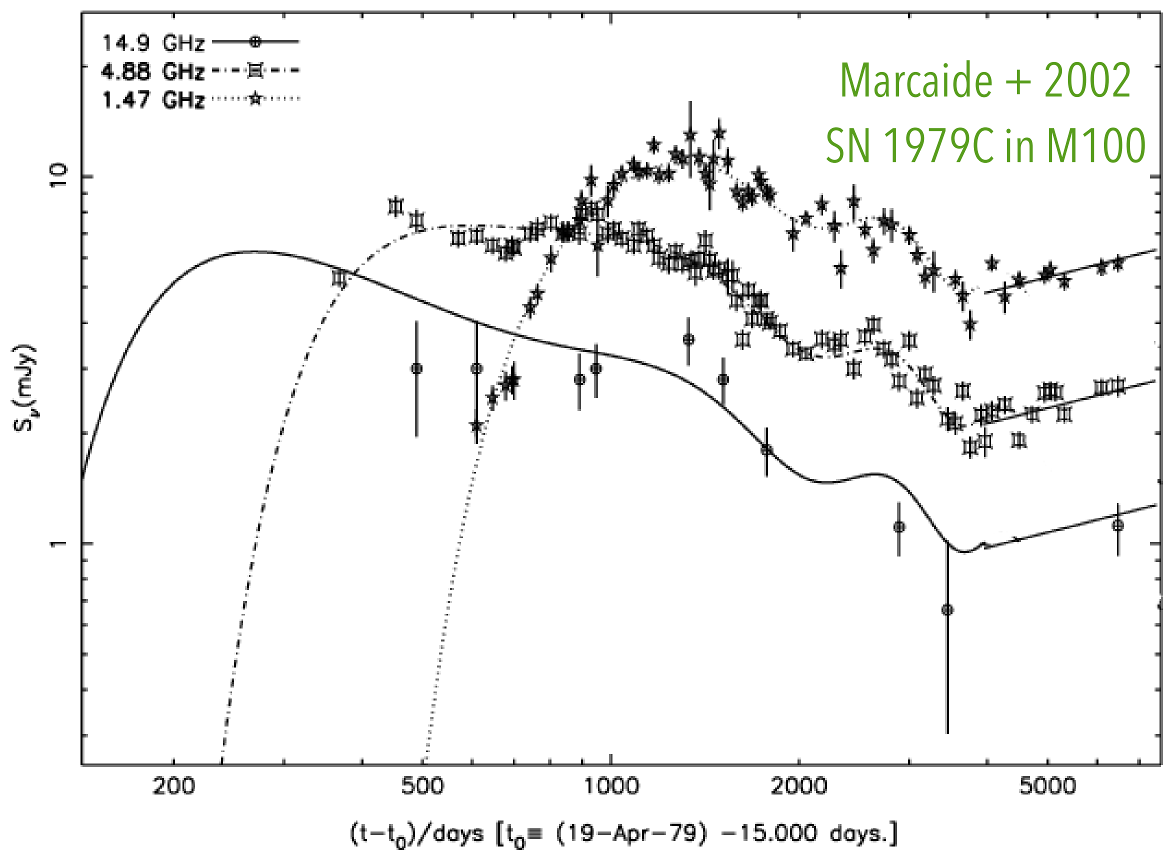
Radio light curves:





High frequencies have faster evolution

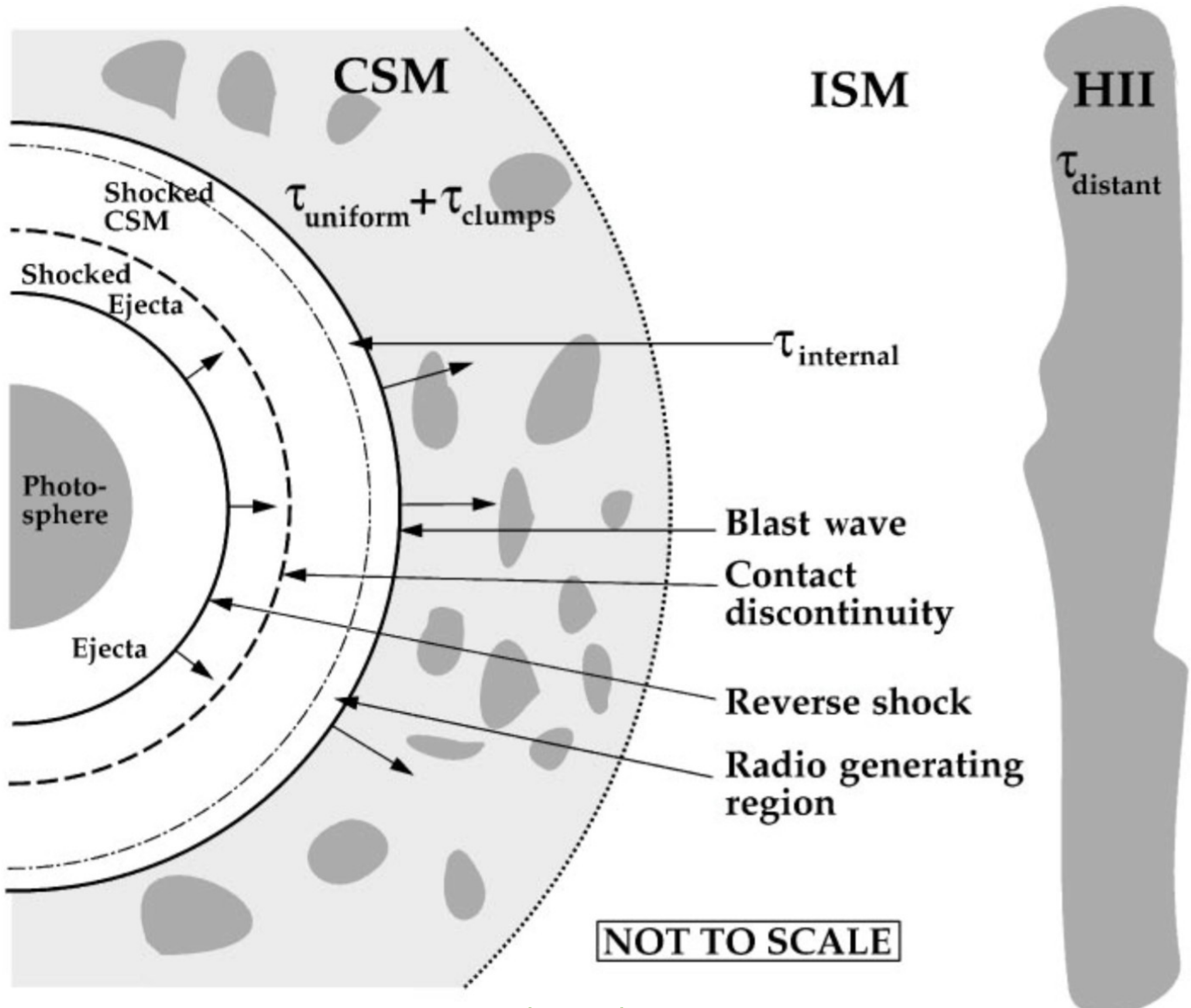
Measured deceleration!



A blast wave is expanding in an inhomogeneous CSM

Variations in the CSM density & temperature are responsible for irregular evolution of the light curve

The light curve may be used to to study the history of the stellar wind



Weiler et al. 2002

Timeline and dynamical evolution:
Four main phases corresponding to different physics and light curve

1. Free expansion

2. Adiabatic expansion

3. Radiative/isothermal expansion

4. Fading and death

N.B. There are transition phases in
which there is not a dominant process

1. Free (abiabatic) expansion (pre-Sedov phase)

- The ejected mass largely exceeds that of the CSM swept by the shock (blast) wave (v_{exp} » c_s).

$$v_{exp} = \text{constant}$$

$$T_{ejecta} V^{\Gamma-1} = \text{constant} \quad \rightarrow \quad T_{ejecta} \propto R^{-3(\Gamma-1)}$$

$T_{shocked}$ remains constantly high as long as v_{exp} is constant

The ejected material cools quite rapidly with time (i.e. R)

The entrained material is heated at about the same temperature

This fast stage lasts for 10 – 100 yr

The SNR has a size < 1 pc

2. Adiabatic expansion (Sedov phase, energy conservation)

$$M_{ejecta} \sim M_{entrained} \simeq \frac{4}{3}\pi[R(t)]^3\rho_{CSM} \quad \text{where} \quad \rho_{CSM}=n_{CSM}m_H$$

$$\text{If } n_{CSM} = 1\,cm^{-3} \quad M_{ejecta} = 1\,M\odot \quad v_{exp} = 10000 \; km\,s^{-1}$$

Such phase start after about 200 yr after the SN explosion, when the remnant has a size of about 2 pc.

A thin spherical shell (most of the mass concentrated behind the shock) is expanding.

The initial kinetic energy of the ejecta U_o is being transferred to the entrained mass as both kinetic (U_k) and thermal (U_{th}) energy, about evenly distributed.

The total energy, as well as the kinetic and thermal energies, are preserved.

In particular:

$$U_k = \frac{1}{2}U_o = \frac{1}{2}M_{entrained}v^2_{exp}(t) \simeq \frac{1}{2}\left(\frac{4}{3}\pi[R(t)]^3\right)\rho_{CSM}v^2_{exp}(t)$$

$$U_k = \frac{1}{2} U_o = \frac{1}{2} M_{entrained} v_{\exp}^2(t) \simeq \frac{1}{2}\left(\frac{4}{3}\pi[R(t)]^3\right) n_{CSM} m_H \left[\frac{dR(t)}{dt}\right]^2$$

If we integrate, assuming a negligible initial radius of the shell R_o, it is possible to obtain

$$R(t) = \left(\frac{75}{8\pi}\right)^{1/5} \left(\frac{U_o}{2 n_{CSM} m_H}\right)^{1/5} t^{2/5} \approx 6\times10^4 \left(\frac{U_o}{n_{CSM}}\right)^{1/5} t^{2/5}$$

$$v_{\exp}(t) = \dot{R}(t) \approx 6\times10^4 \left(\frac{U_o}{n_{CSM}}\right)^{1/5} \frac{2}{5} t^{-3/5} = \frac{2}{5}\frac{R(t)}{t}$$

- v_{exp} decreases with time (entrained material slows down the expansion)
- If n_{CSM}, t, and v_{exp} are known $\Rightarrow$ U_o can be derived
- t and v_{exp} are easy to measure, then the (U_o / n_{CSM}) ratio can be obtained

Hugoniot – Rankine conditions (M>>1) provide:

$$\rho_{shocked} = 4\rho_{CSM} \qquad p_{shocked} = \frac{3}{4}\rho_{CSM} v_{\exp}^2 \qquad T_{shocked} = \frac{3\, m_H v_{\exp}^2}{16\, k}$$

$$T = 6.4\times 10^{11}\left(\frac{U_o}{10^{51}}\right)^{2/5} n_{CSM}^{-2/5}\left(\frac{t}{yr}\right)^{-6/5} \quad {}^oK$$

$$P = 3.5\times 10^{-4}\, n_{CSM}^{3/5}\left(\frac{U_o}{10^{51}}\right)^{2/5}\left(\frac{t}{yr}\right)^{-6/5} \quad dyne\, cm^{-2}$$

Typical temperatures ~ 5 x 10 ^{8} ^{o}K, emission via bremsstrahlung (X-Rays) in a very **thin** outer shell.

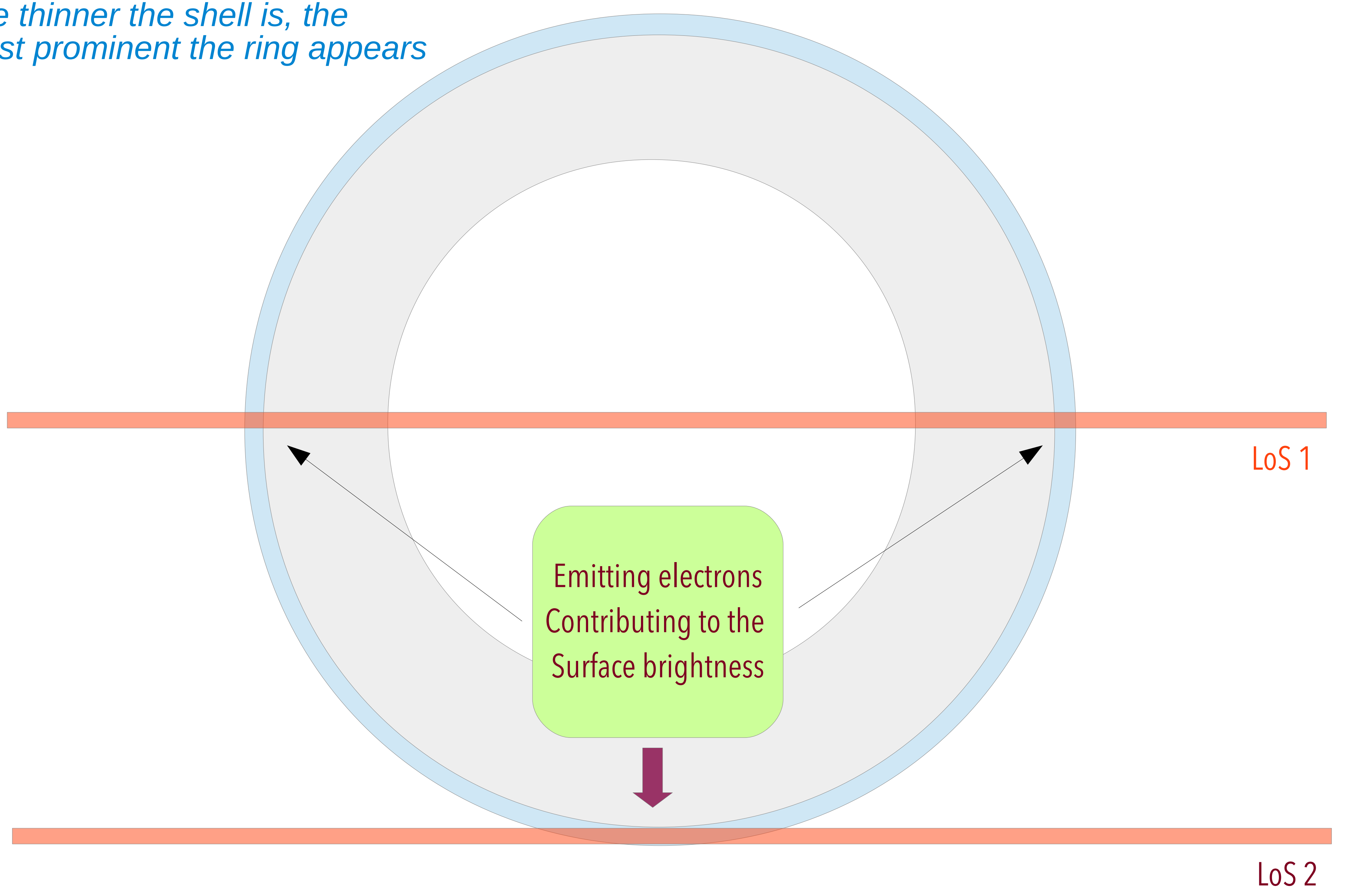
$$-\left(\frac{dU_o}{dt}\right)_{br} \simeq V_{SNR} J_{br}(T) \approx [R(t)]^3 n_e^2 T^{1/2} \approx 4\times 10^{-12} U_o^{4/5} t^{3/5} \quad erg\, s^{-1}$$

Image Credit: X-ray: *NASA/CXC/SAO/J.Hughes et al,* Optical: *NASA/ESA/Hubble Heritage Team (STScI/AURA)*

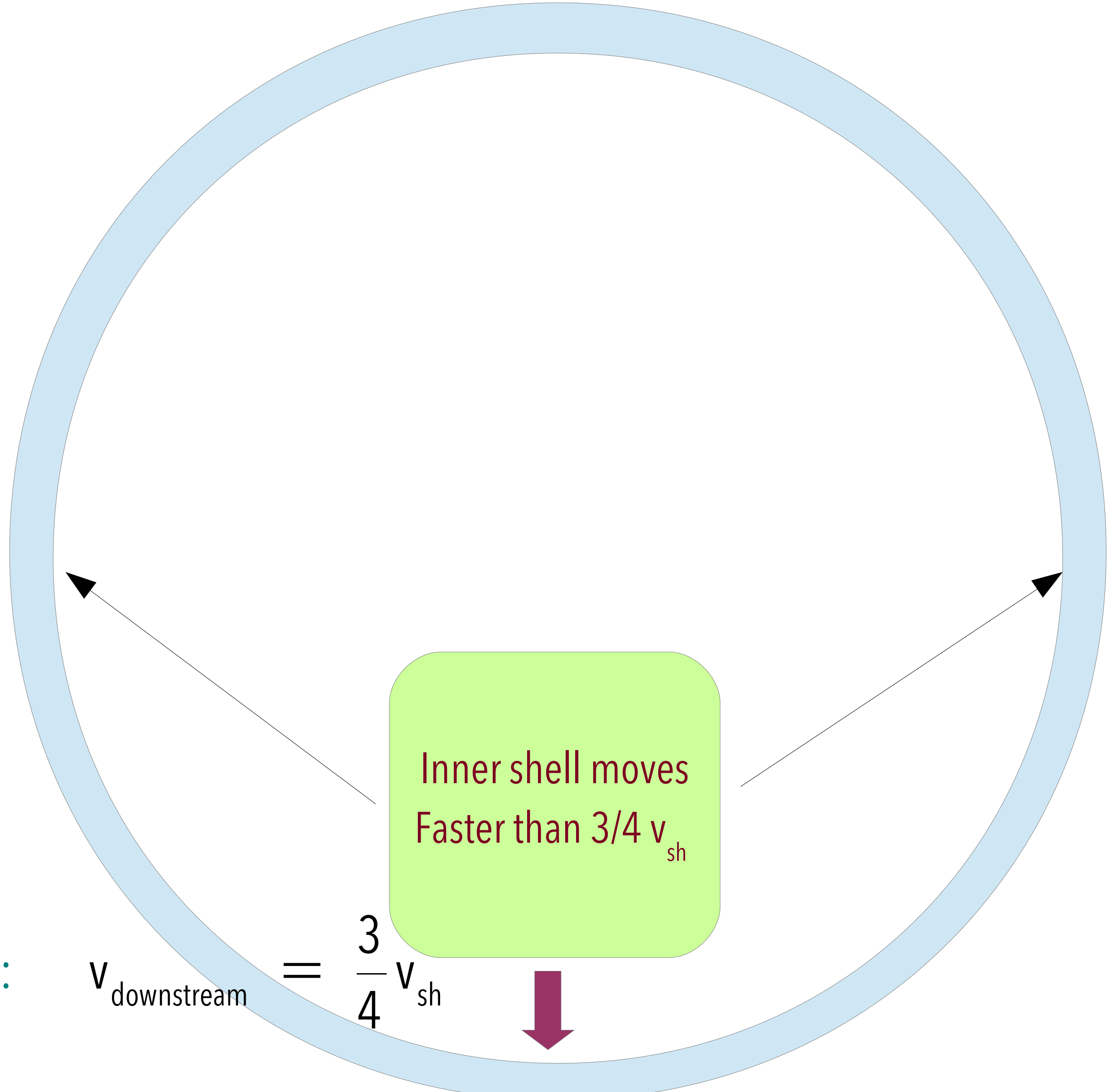
SNR 0509-67.5 (age ~400 yr) in the LMC, red= HST, green = Chandra

Supernova Remnants: why shells and why not disks (but it does not always work!)

The thinner the shell is, the most prominent the ring appears



Supernova Remnants: how thick/thin is the shell?



Hugoniot – Rankine: $$v_{downstream} = \frac{3}{4} v_{sh}$$

if v_{sh} is decreasing the inner part of the envelope is moving at $v_{downstream} > \frac{3}{4} v_{sh}$

being v_{sh} that one currently measured

Time dependent (bolometric) bremsstrahlung losses are:

$$-\left(\frac{dU_o}{dt}\right)_{br} \simeq V_{SNR} J_{br}(T) \approx [R(t)]^3 n_e^2 T^{1/2} \approx 4\times10^{-12} U_o^{4/5} t^{3/5} \qquad erg\, s^{-1}$$

at a given time the total energy radiated via bremsstrahlung is

$$W_{br} \simeq -\int_o^t \left(\frac{dU}{dt}\right) dt = 2.5\times10^{-12} U_o^{4/5} t^{8/5} \qquad erg$$

the fraction of the initial energy lost via bremsstrahlung radiation is

$$\frac{W_{br}}{U_o} \simeq 2.5\times10^{-12} U_o^{-1/5} t^{8/5} n_{CSM}^{6/5}$$

In general, the radiated energy via bremsstrahlung is a small fraction (~1%) of the initial energy over several in 10^4 yr, and then the process can be considered adiabatic

The kinetic energy of the SNR is half of the initial energy:

$$K = \frac{1}{2}\left(\frac{4}{3}\pi\rho_{CSM}R^3\right)v_{\exp}^2 = \frac{2}{3}\pi\rho_{CSM}R^3\dot{R}^2 \simeq \frac{1}{2}U_o$$

if energy is conserved, then $\frac{dK}{dt} = 0$ and after some maths it comes out that the shell expansion is driven by thermal pressure

→ HOWEVER, beyond bremsstrahlung, also recombination of "heavy" elements (C, N, O) takes place

$$-\left(\frac{dU}{dt}\right)_{CNO} = 8\times10^{-17}\frac{n_{CSM}}{T}R^3(t) = 3\times10^{-4}n_{CSM}^{9/5}U_o^{1/5}t^{12/5}$$ in the adiabatic phase

They grow much faster than bremsstrahlung losses and will become dominant ending the adiabatic phase

Integrating $$-\left(\frac{dU}{dt}\right)_{CNO} = 8\times10^{-17}\frac{n_{CSM}}{T}R^3(t) = 3\times10^{-4}n_{CSM}^{9/5}U_o^{1/5}t^{12/5}$$

And solving for t we get

$$t^* \approx 13\cdot U_o^{4/17}n_{CSM}^{-9/17}$$

which correspond to a radius

$$R(t^*) \simeq 1.7\cdot10^5 U_o^{5/17}n_{CSM}^{-7/17}$$

and the expansion velocity is

$$v_{\exp}(t^*) \approx 5\cdot10^3 U^{1/17}n_{CSM}^{2/17}$$

In case $U_o = 10^{50}$ erg, $n_{CSM} = 1\ cm^{-3}$ we get

$$t^* \approx 2.5\cdot10^5\ yr$$

$$R(t^*) \simeq 30\ \ pc$$

$$v_{\exp}(t^*) \approx 50\ \ km\,s^{-1}$$

The temperature of the expanding shell has decreased to a few in 10^4 °K and its pressure cannot support the expansion anymore

- End of adiabatic phase

3. Radiative phase: i.e. end of the adiabatic phase: very efficient radiative losses

$\Rightarrow$ energy cannot be considered constant any more.

The SNR enters the isothermal phase:

- the energy transferred to CSM (implying an increase of its internal energy) is nearly immediately radiated (leaving T unchanged!)
- Compression is not limited to 4 (H-R conditions) anymore and can reach 100s

Now momentum conservation holds:

$$[R(t)]^3 n_{CSM} m_H v_{exp} = [R(t)]^3 n_{CSM} m_H \left(\frac{dR(t)}{dt}\right) = [R(t^*)]^3 n_{CSM} m_H \left(\frac{dR(t^*)}{dt}\right) = const$$

Integrating we get:

$$R(t) \approx (t + const)^{1/4} \qquad v_{exp}(t) \approx (t + const)^{-3/4}$$

And the kinetic energy decreases as the the expansion progressively slows down

$$K(t) \approx \frac{1}{2} m v_{exp} \cdot v_{exp} \approx \frac{1}{2} U_o \left(\frac{v_{exp}(t)}{v_{exp}(t^*)}\right) \approx (t + const)^{-3/2}$$

At the end of the adiabatic phase the internal (thermal) pressure of the expanding gas becomes comparable or even smaller than the relativistic particles.

In that case, the expansion of the shell is powered by relativistic particles whose pressure is represented as cosmic rays pressure (inclusive of protons!)

$$\frac{d(mv)}{dt} = \frac{4}{3}\pi n_{CSM} m_H [R(t)]^2 \ddot{R}^2 + 4\pi n_{CSM} m_H R^2 \dot{R}^2 = 4\pi [R(t)]^2 \left(\frac{1}{3} \times \frac{U_{CR}}{4/3\pi R(t)^3} \right)$$

Assuming that CR (relativistic particles) expands adiabatically, with no subsequent (interaction) re-acceleration or particle injection we can integrate and get

$$[\dot{R}(t)]^2 = \frac{3}{4\pi} \frac{U_{CRo} R_o}{n_{CSM} m_H} \frac{1}{R(t)^4} + \frac{const}{R(t)^6} \approx \frac{3}{4\pi} \frac{U_{CRo}}{n_{CSM} m_H} \frac{1}{R(t)^3} + \frac{const}{R(t)^6} v$$

and, integrating again

$$R(t) \approx (t + const)^{1/3}$$

4. Fading phase:

- The radius of the remnant grows slower and slower $R(t) \propto t^s$, where $s < 1/4$, the expansion speed is <~ 20 km/s and T ~10000 K, size > 30 pc

- The shell merge and fades into the ISM mixing with it (1 Myr after the explosion) and cannot be distinguished anymore from the CSM/ISM

Supernova Remnants: (Radio) facts (1)

Nowadays ~ 300 galactic SNR are known http://www.mrao.cam.ac.uk/surveys/snrs/

$\Rightarrow$ Power law spectra

Crab nebula has $B \sim 500 \ \mu G$ and the synchrotron radiative lifetimes are

$\sim 10^5$ yr @ 500 MHz $\sim 10^2$ yr @ 600 nm ~ 2.4 yr @ 4 KeV

$\Rightarrow$ continuous generation of relativistic particles

Magnetic fields ~10s – 100s μG deacaying with time (expansion)

Evolution of a remnant in adiabatic expansion

Magnetic flux conservation $B(R) \simeq R^{-2}$

The SNR flux density should go as $S(\nu) \simeq R^{-2\gamma} \approx t^{-4\gamma/5}$

Implying a flux density decrease $\frac{dS(\nu)}{dt} = -\frac{4\gamma}{5t} \cdot S(\nu)$

HOWEVER, in young remnants, the flux density increases with time in the first ~100 yr

$\Rightarrow$ interaction with the circumstellar medium

Relativistic particles:

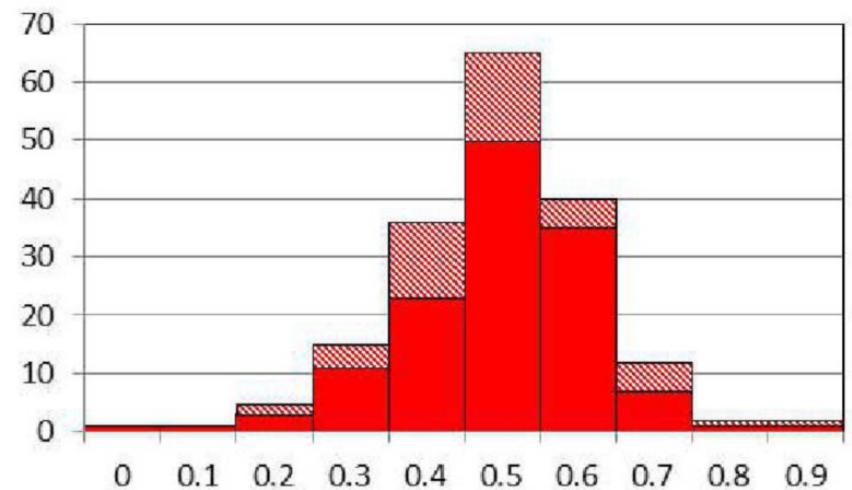
$\Rightarrow$ OK, if a pulsar @ the center

At later stages, shock waves can accelerate particles from entrained gas (DSA)

synchrotron spectral index from the compression ratio r : $\alpha = \dfrac{3}{2(r-1)}$

$\Rightarrow$ $\alpha = 0.5$ for strong shocks

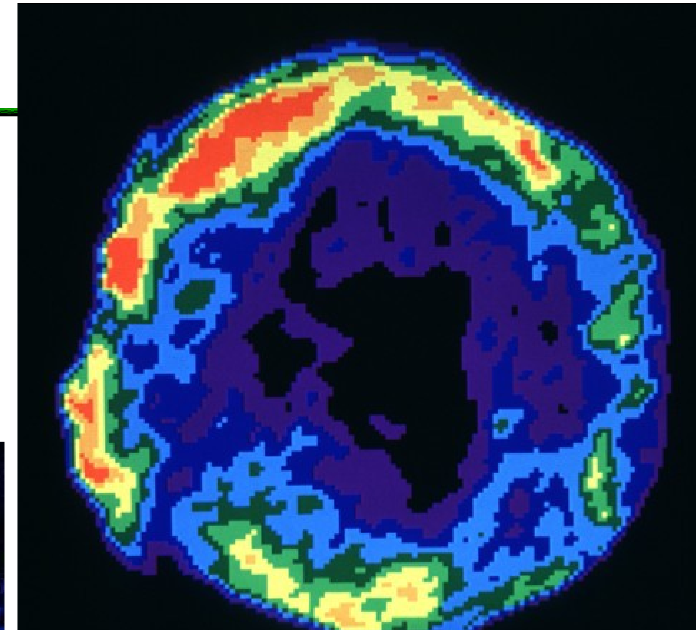
The field (mainly) responsible for acceleration and em is that of the CSM/ISM compressed by the explosion with some (non fully understood) extra-amplification



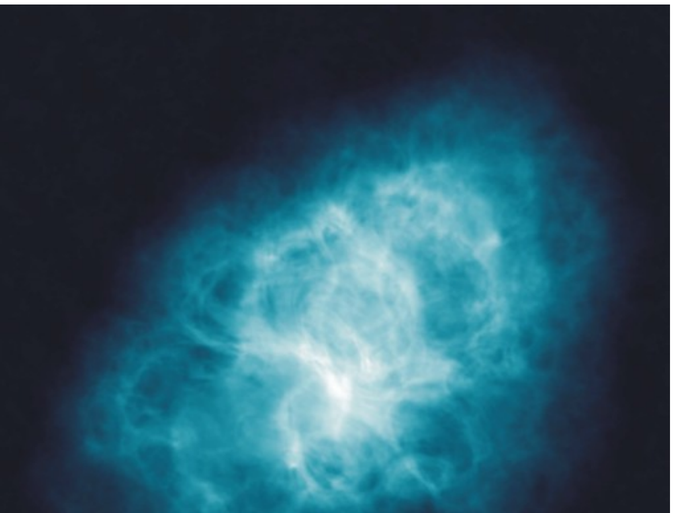
Histogram of radio spectral index distribution

Supernova Remnants: Radio Morphologies

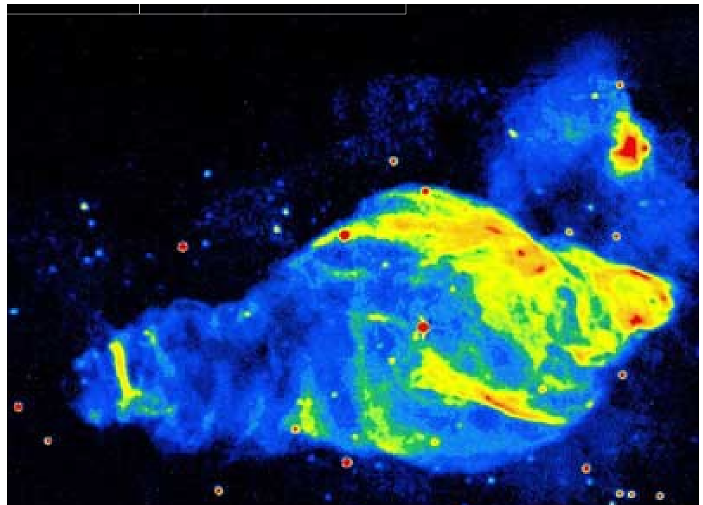
	Angular Size	Distance	Linear size
Cas A	3'x3'	3.4 kpc	...
Tycho	6'x6'	2.3 kpc	...
W50	2° x 1°	5.5 kpc	...



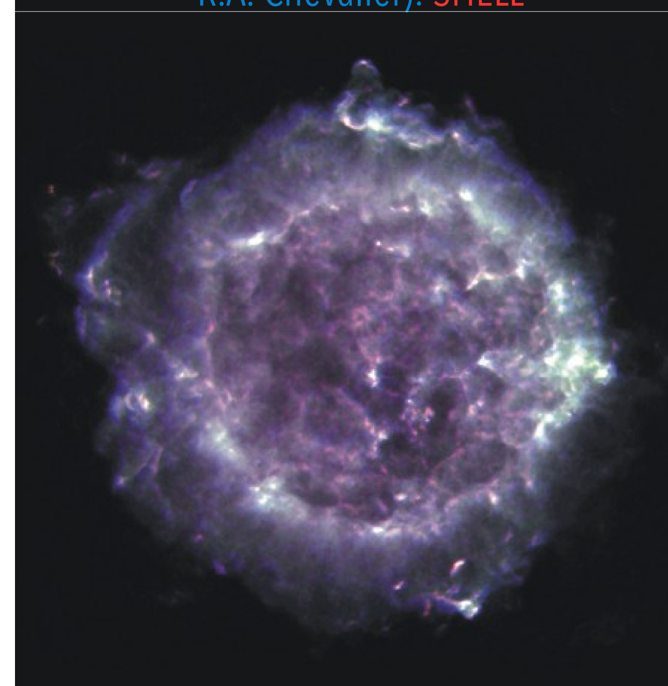
Tycho: VLA image at 1.4 GHz (Reynolds, R.A. Chevalier): SHELL



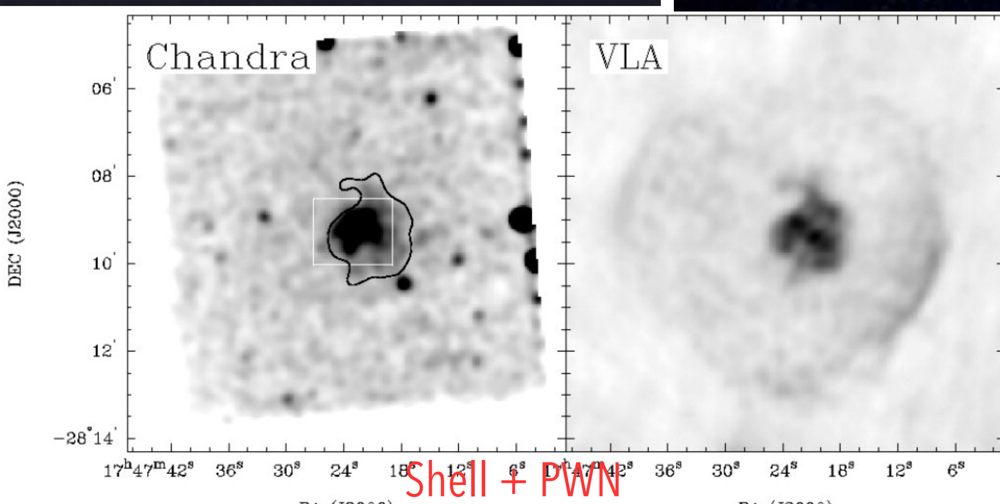
Crab Nebula:VLA image at 5 GHz. PWN
Image courtesy of NRAO/AUI and M. Bietenholz



W50: VLA image at 1.4 GHz (Dubner +)
COMPOSITE

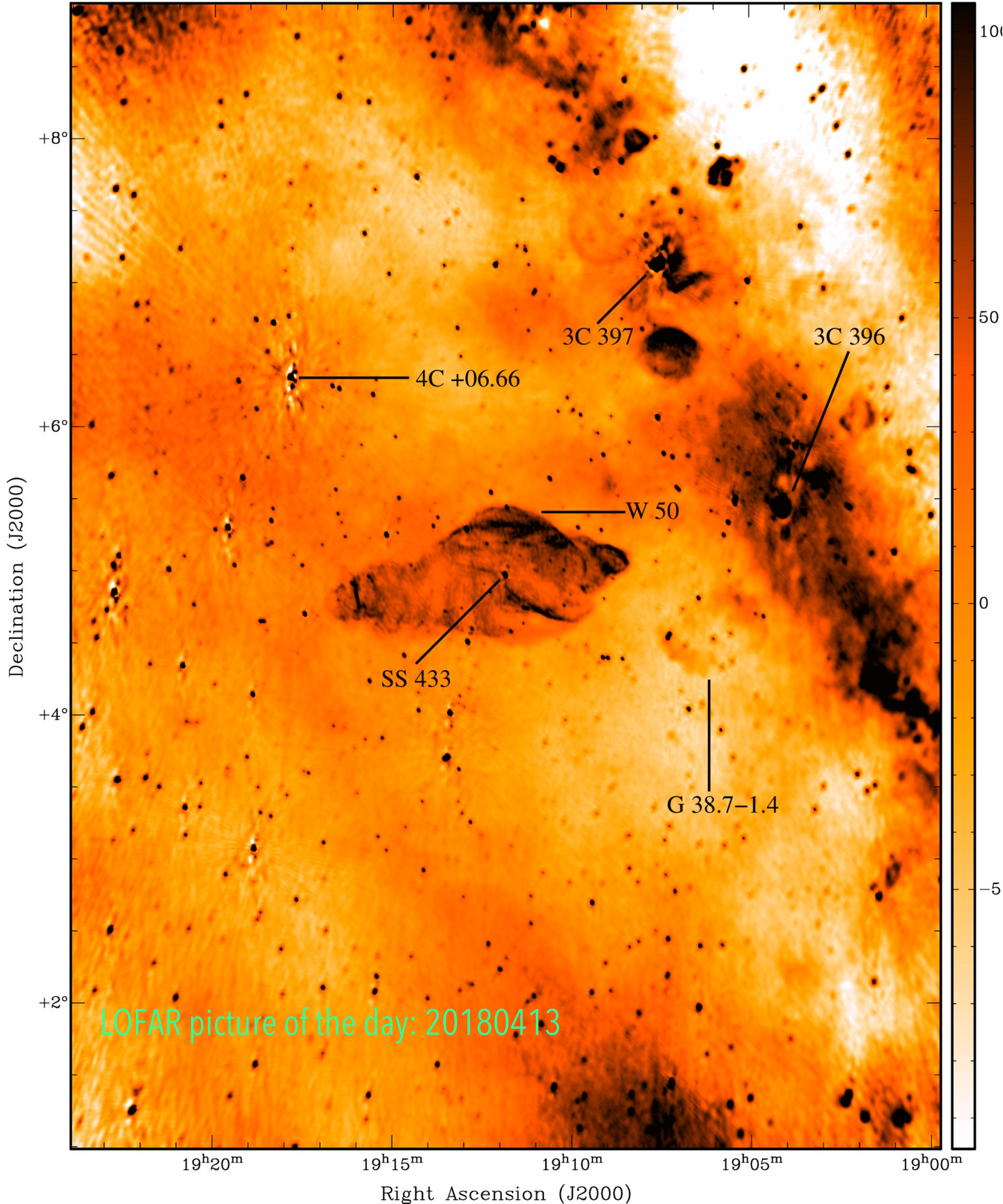


Cas A: VLA image from 3 different frequencies: 1.4, 5.0 and 8.4 GHz. (NRAO image gallery, Rudnick +). SHELL



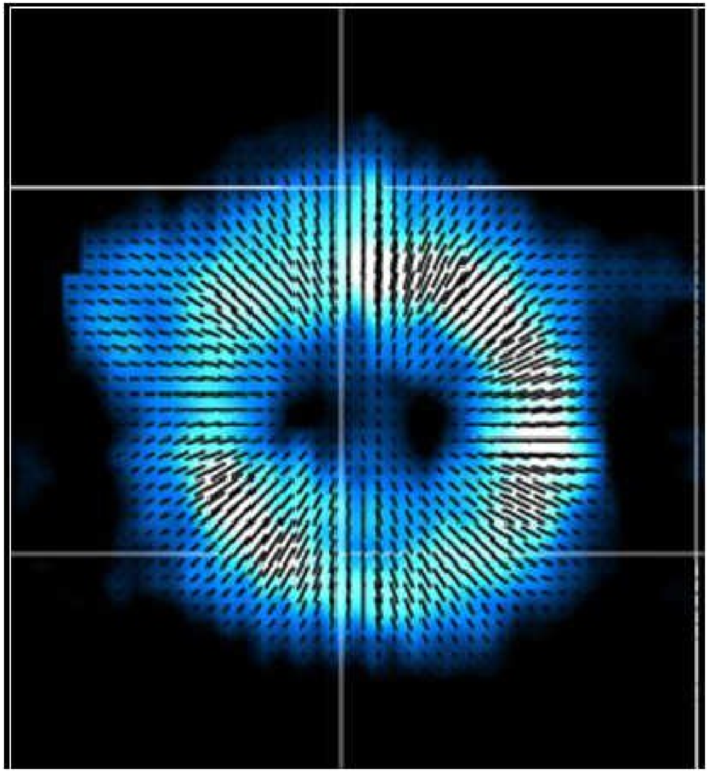
Shell + PWN

Supernova Remnants

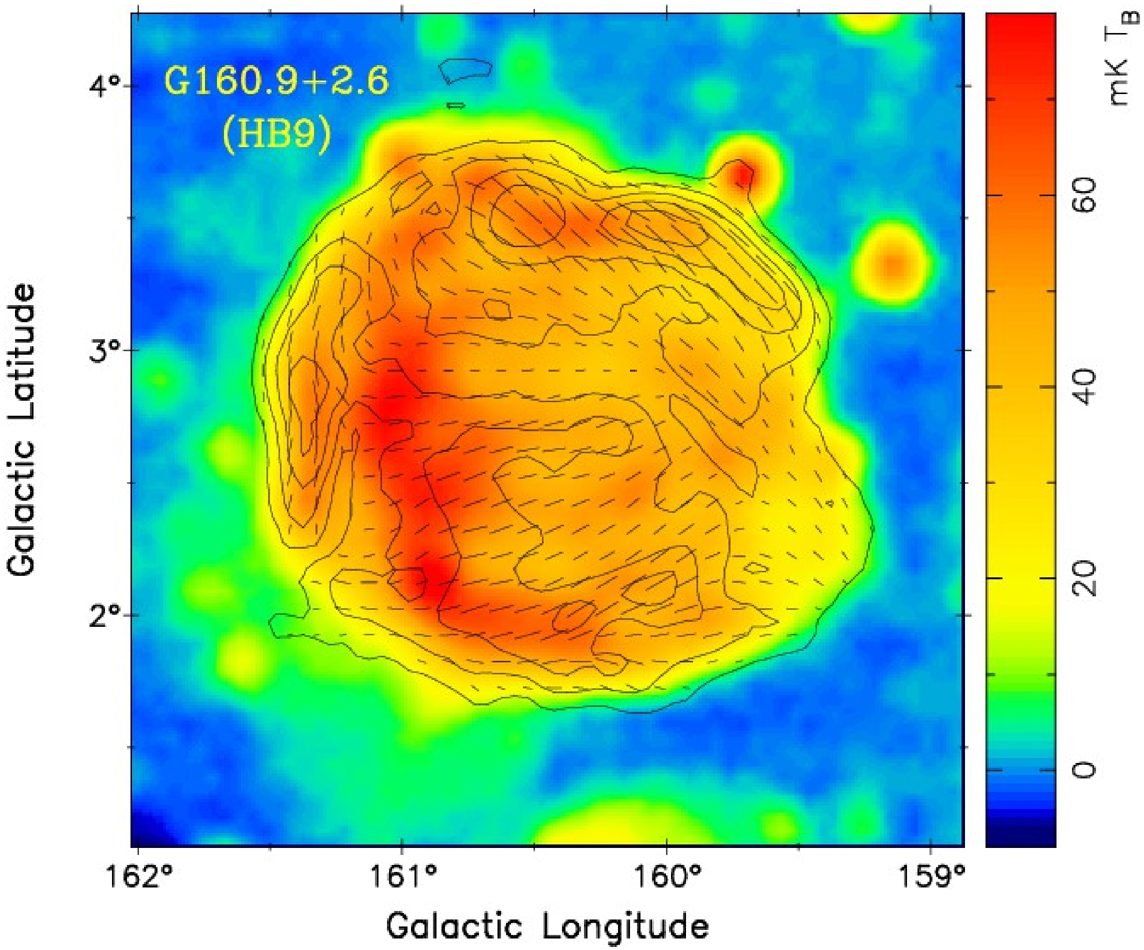


Radio polarization:

From Blast wave to Shock wave



Cas A at 32 GHz (Dubner & Giacani 2015)



Old SNR, vectors are B field projection (Han + 2013, IAU Symp.)

Radio polarization (2)

- In young SNR the field is radial, likely stretched by the rapidly expanding material (blast wave)
- In old SNR H is tangential (as in MHD shock waves)
- In "plerions" the field is disordered
- B ~ 10^{-4} – 10^{-5} G (both from equipartition and RM observations) depending on the size (age)

The $\Sigma - D$ relation:

$$\Sigma = AD^{-\beta}$$

In an adiabatically expanding radio source (filling factor $\Phi = 1$, no reacceleration, frozen H field), the luminosity is

$$L \sim D^{-2\delta} = D^{-2(2\alpha+1)}$$

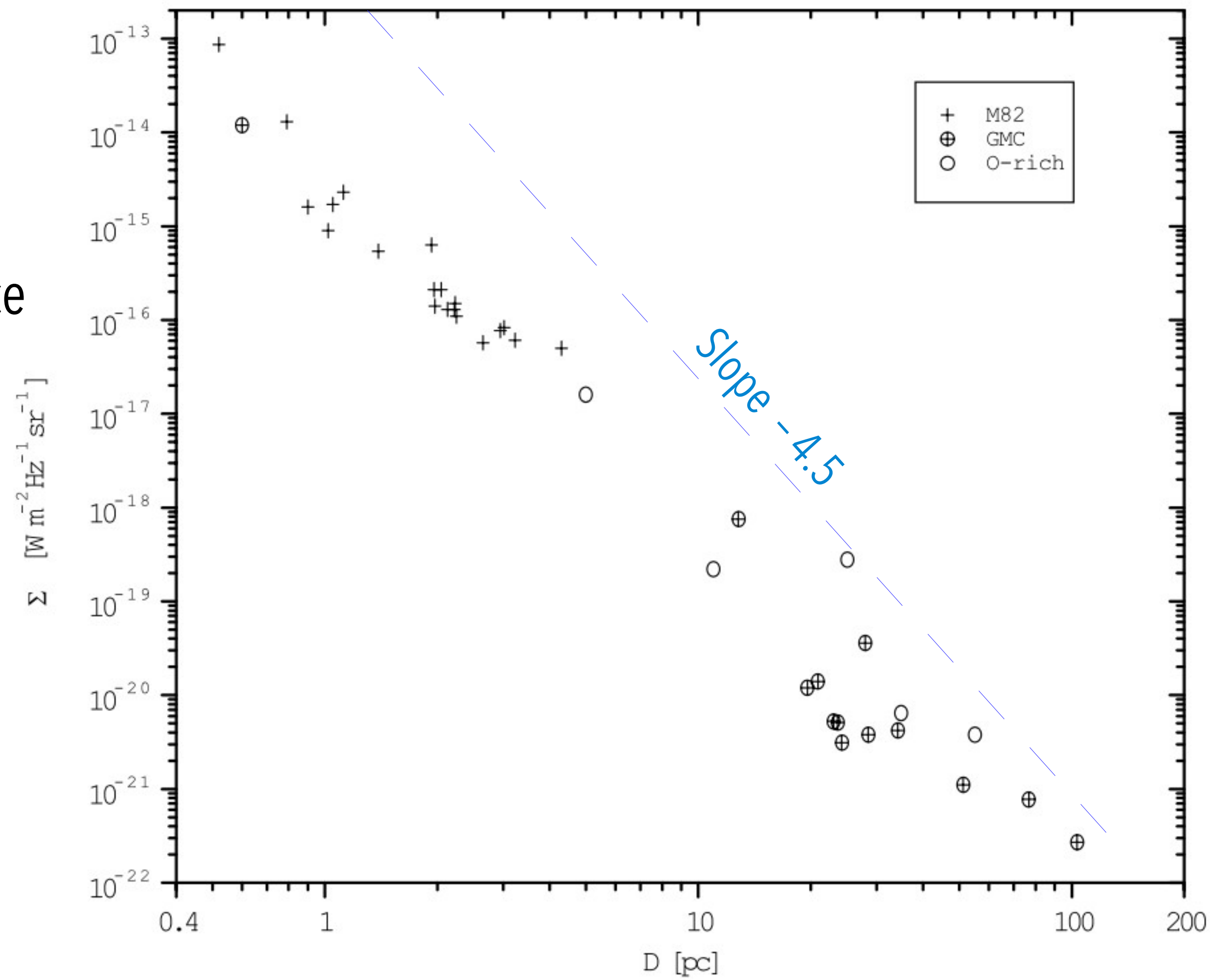
and the surface brightness is

$$\Sigma \sim L / D^2 \sim D^{-2\delta-2} \sim D^{-4(\alpha+1)}$$

In case the SNR is a *thin shell*

$$L \sim D^{-(3\delta-1)/2} \sim D^{-3\alpha-1}$$

$$\Sigma \sim D^{-(3\delta-1)/2-2} \sim D^{-3(\alpha+1)}$$



$\Sigma - D$ plot for M82 (crosses), GMC (encircled crosses) and O-rich SNRs (circles). Arbutina & Urosevic (2005)

In dense environments like those in figure, the slope is ~ -3.5

We might expect slight displacements depending on the SNR luminosity

- The L – D relation:

$$L = AD^{-\eta}$$

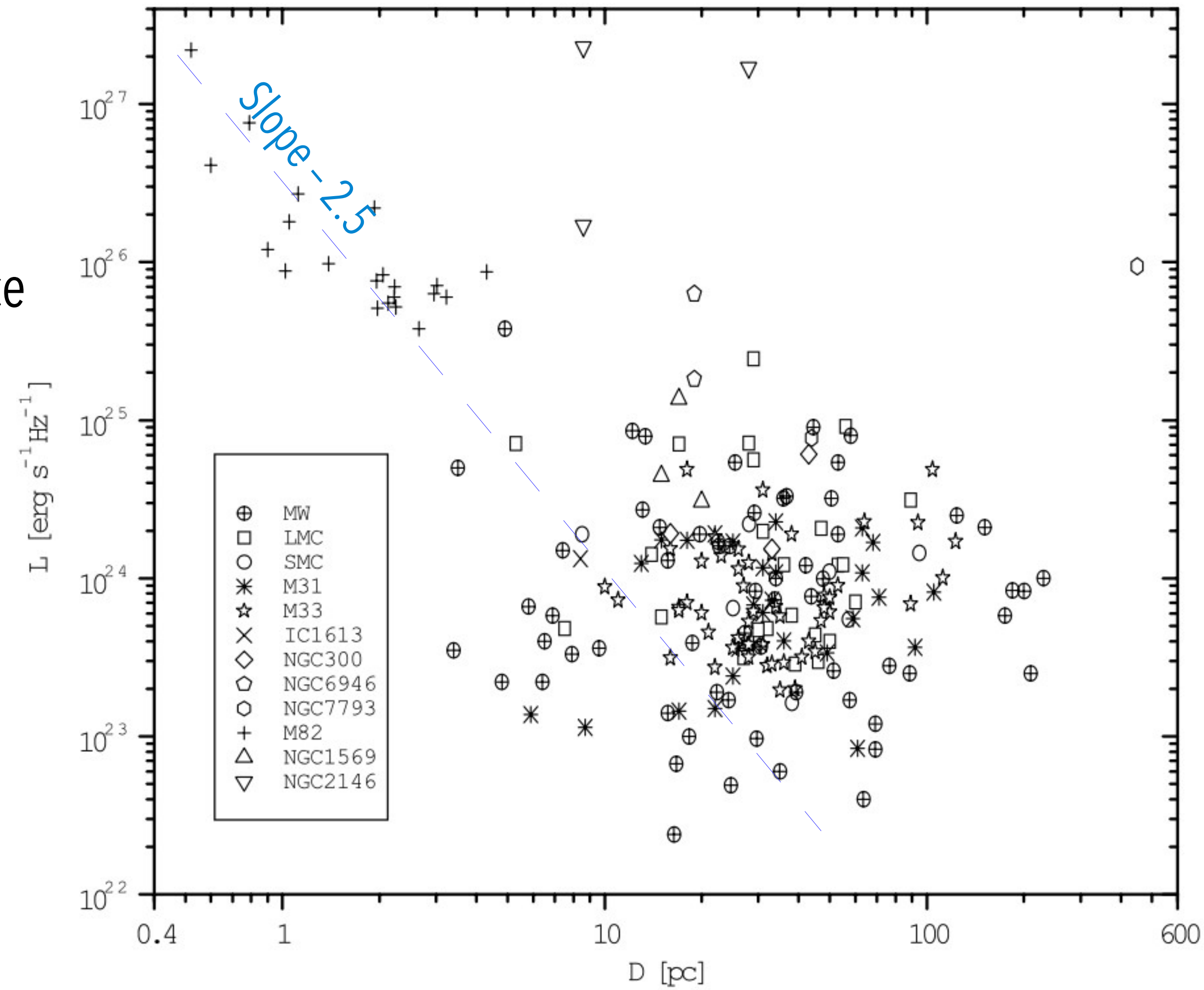
In an adiabatically expanding radio source

$$L \sim D^{-2\delta} = D^{-2(2\alpha+1)}$$

In case the SNR is a *thin shell*

$$L \sim D^{-(3\delta-1)/2} \sim D^{-3\alpha-1}$$

Perhaps there is a correlation for SNR in dense environments



There is no obvious correlation between luminosity and linear diameter, except for the M82 SNRs. Arbutina + (2004)

- Progenitor classification
- ~Certain only for recent events (optical spectroscopy, earlier observations of the progenitor)
- Old SNR cannot be classified for sure (light echoes, scattering of the explosion, e.g. Kraus + 2008)

Table 3. Estimates of the ambient density for individual remnants. Diameters and surface brightnesses, as well as the assumed SN type and SNR evolutionary phase, are given for comparison.

SNR	D (pc)	$\log \Sigma_{1\,\mathrm{GHz}}$ $(\mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}})$	n_H $(\mathrm{cm^{-3}})$	Type	Phase
Kepler	4	−18.5	$0.4 - 0.7^{a,b}$	Ia	pre-Sedov
Tycho	5	−18.9	$0.3 - 0.5^{a,c,d}$	Ia	pre-Sedov
0509–67.5	7	−19.4	$0.05^{e,f}$	Ia	pre-Sedov
0519–69.0	8	−19.2	$\sim 0.1^{e}$	Ia	pre-Sedov
DEM L71	19	−21.1	$0.4 - 0.8^{e,g,h}$	Ia	Sedov
SN 1006	19	−20.5	$0.06^{a}, 0.3^{i}$	Ia	Sedov
0548–70.4	25	−20.3	$\sim 0.1^{e}$	Ia	Sedov
Cas A	5	−16.8	3^{a}	~~Ib~~ IIb	pre-Sedov
IKT 22	11	−18.7	2^{j}	Ib	Sedov
N132 D	25	−18.6	3^{e}	Ib	Sedov?
IKT 23	55	−20.4	$0.2^{j,k}$	Ib	Sedov?

Arbutina & Urosevic (2005)

Kraus + (2008)

SN1987A (23 Feb 1987, in the LMC)

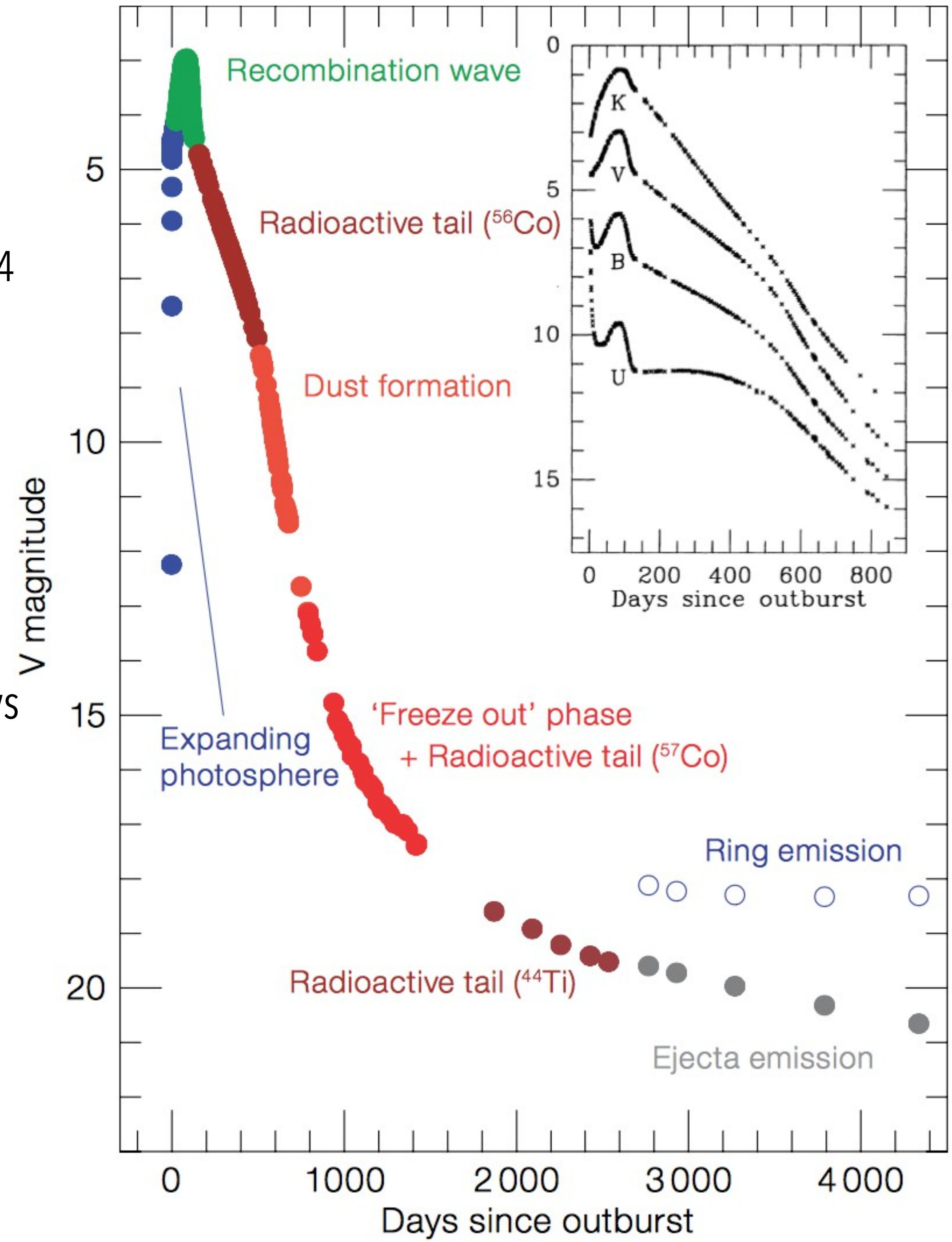
(see Giovanna Zanardo, PhD thesis)

- Type II, from a B3 (~ 20 Mo) star, optical peak M_V ~ - 14

- Preceeded by ~ 20 neutrino events
  (2 hr prior of the optical flash)

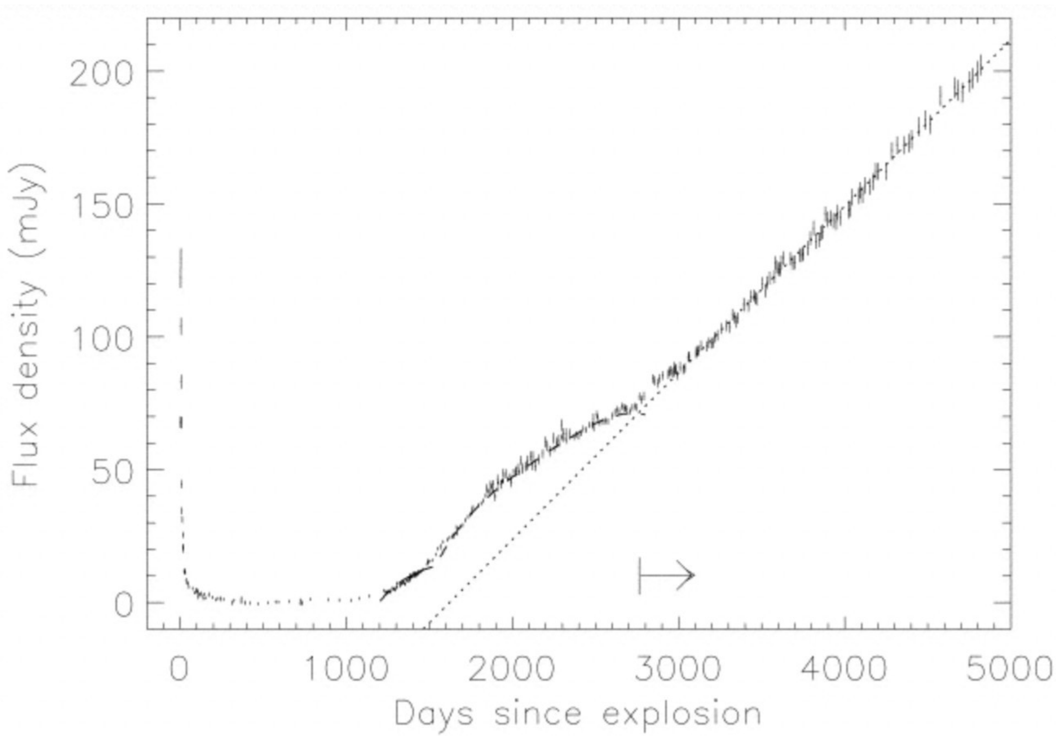
- Optical light curve consistent with radioactive decays

$^{56}Ni \xrightarrow{\beta+ (6.1d)} {}^{56}Co \xrightarrow{\gamma+(77.1d)} {}^{56}Fe$??

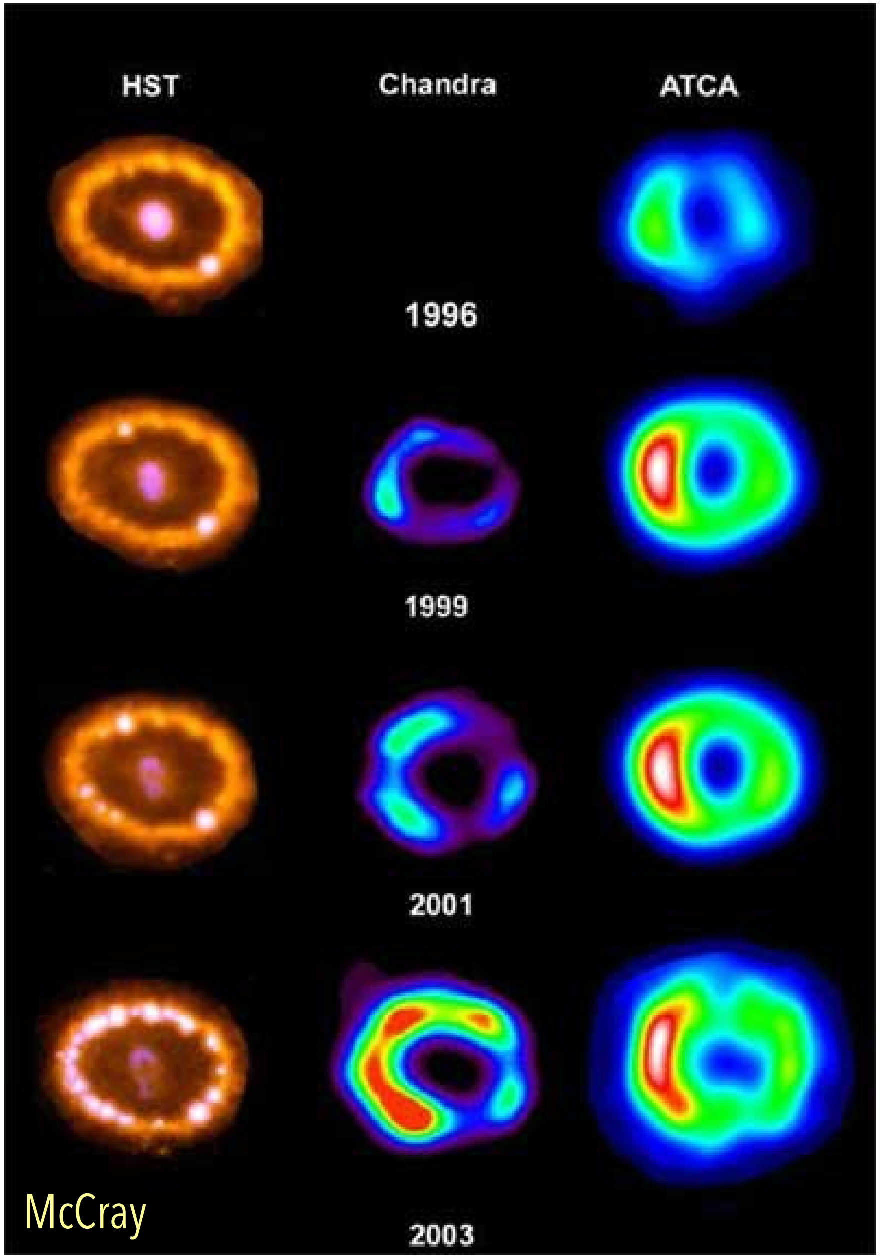


SN1987A

....across the electromagnetic spectrum
(in 1996 Chandra was launched yet)



Radio light curve: flux densities for SN 1987A at 843 MHz between
Feb 87 and May 2000. Error bars are the quoted about 3% uncertainties.
Ball et al. 2001, ApJ, 549, 599



Radio emission: example SN1987A

Prompt phase of radio emission
began almost immediately after the explosion, peaked about four days later, then decayed and became undetectable after just a few weeks.

Second phase of radio emission from SN1987A, started in June 1990, some 3 and a half years after the explosion, and continues to brighten steadily.

- due to electrons accelerated at the supernova shock via the mechanism called `diffusive shock acceleration'.

modification of the shock by other particles (mainly protons) which are also accelerated. The accelerated protons contribute significantly to the pressure in front of the shock

⟹ Variations are related to inhomogeneities in the stratified CSM deposited by the stellar wind

Supernova Remnants

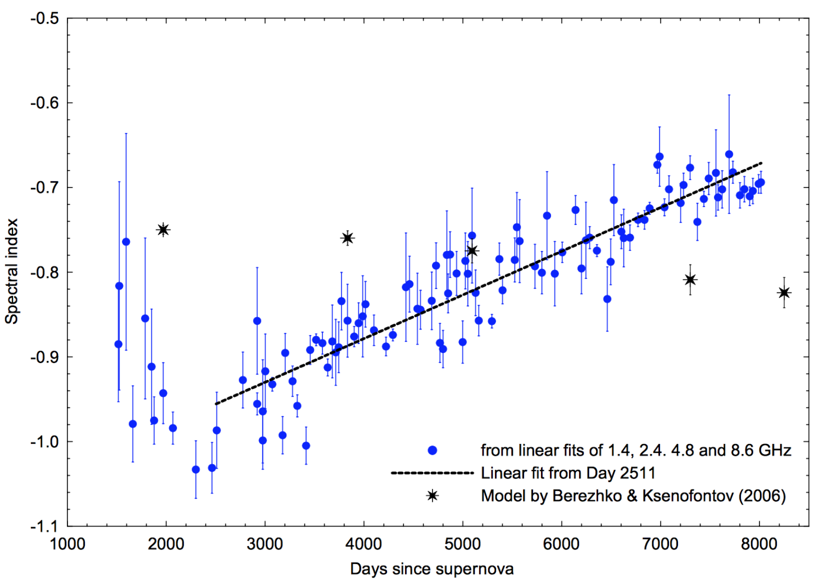
SN1987A:

The radio spectral index is flattening with time: 0.9 → 0.7

$$\alpha = \frac{3}{2(\sigma - 1)}$$

$$\sigma = \frac{\rho'}{\rho_0}$$

acceleration (flat) is more efficient than particle losses (steep)



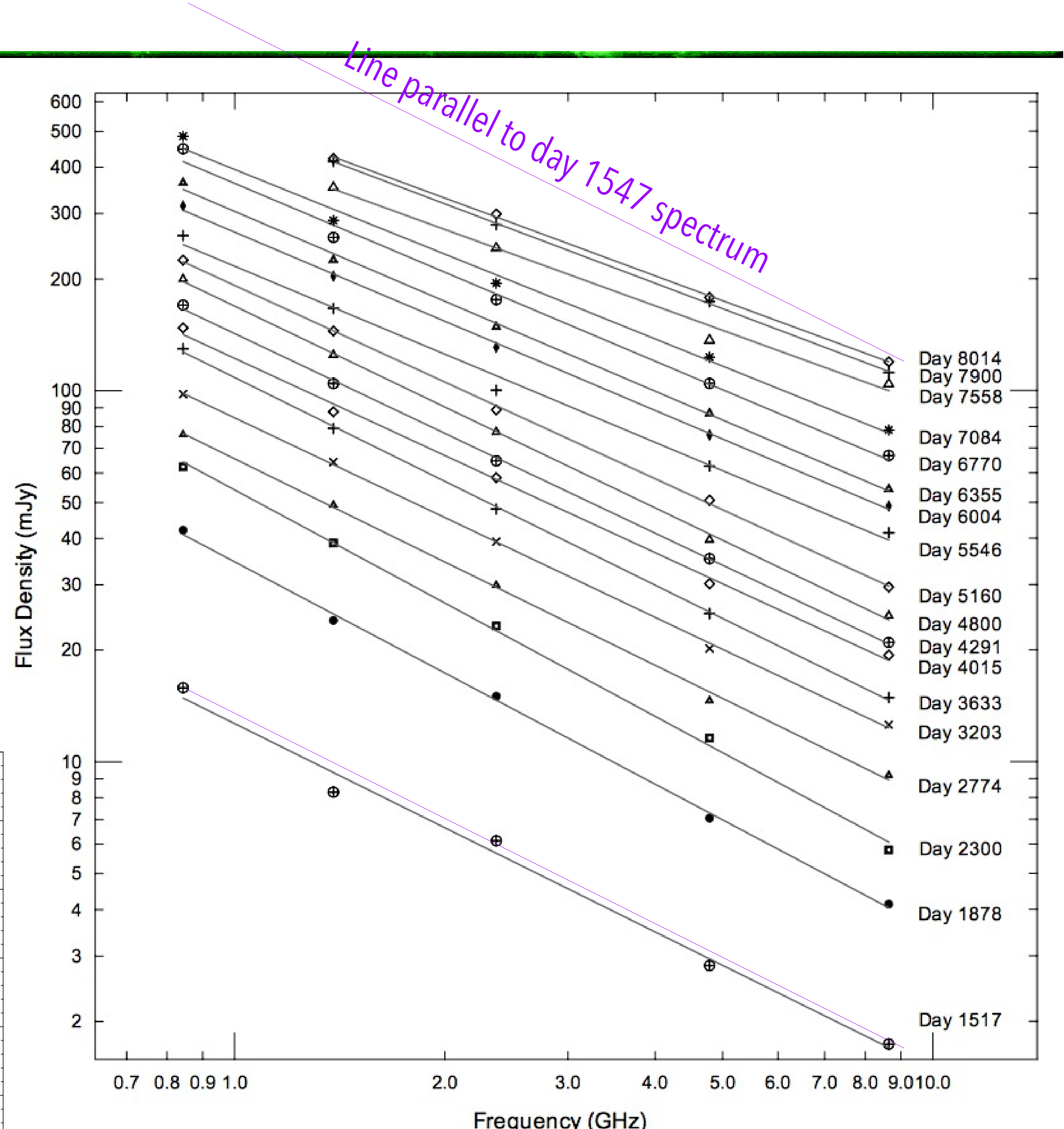
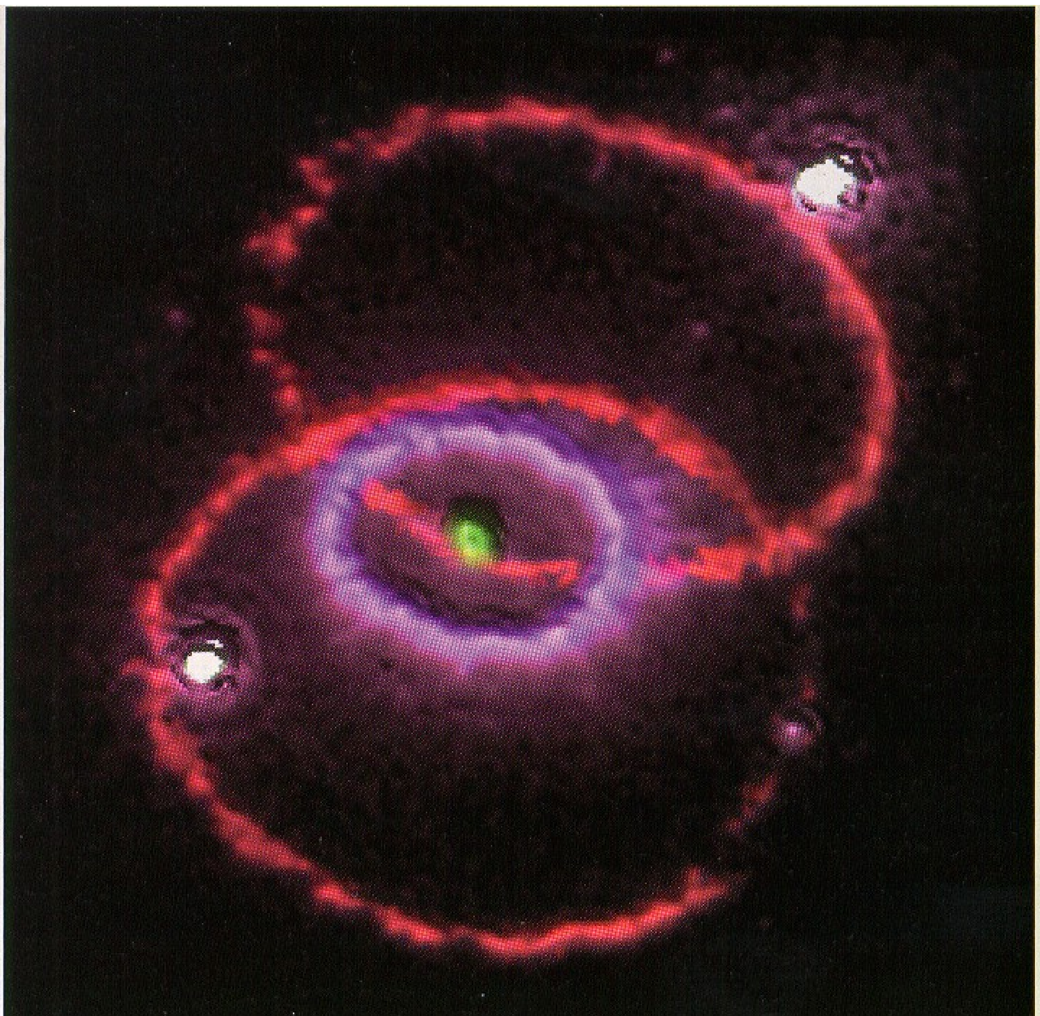
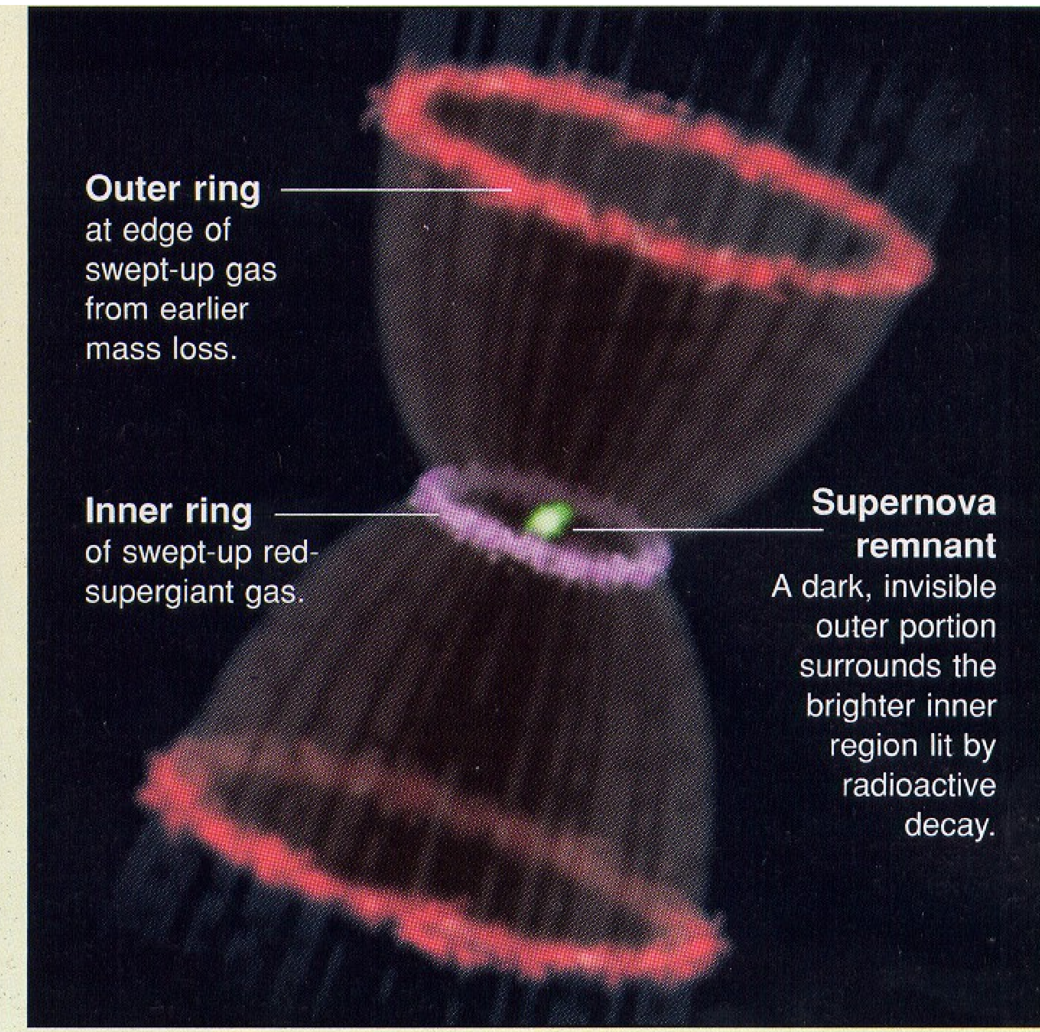


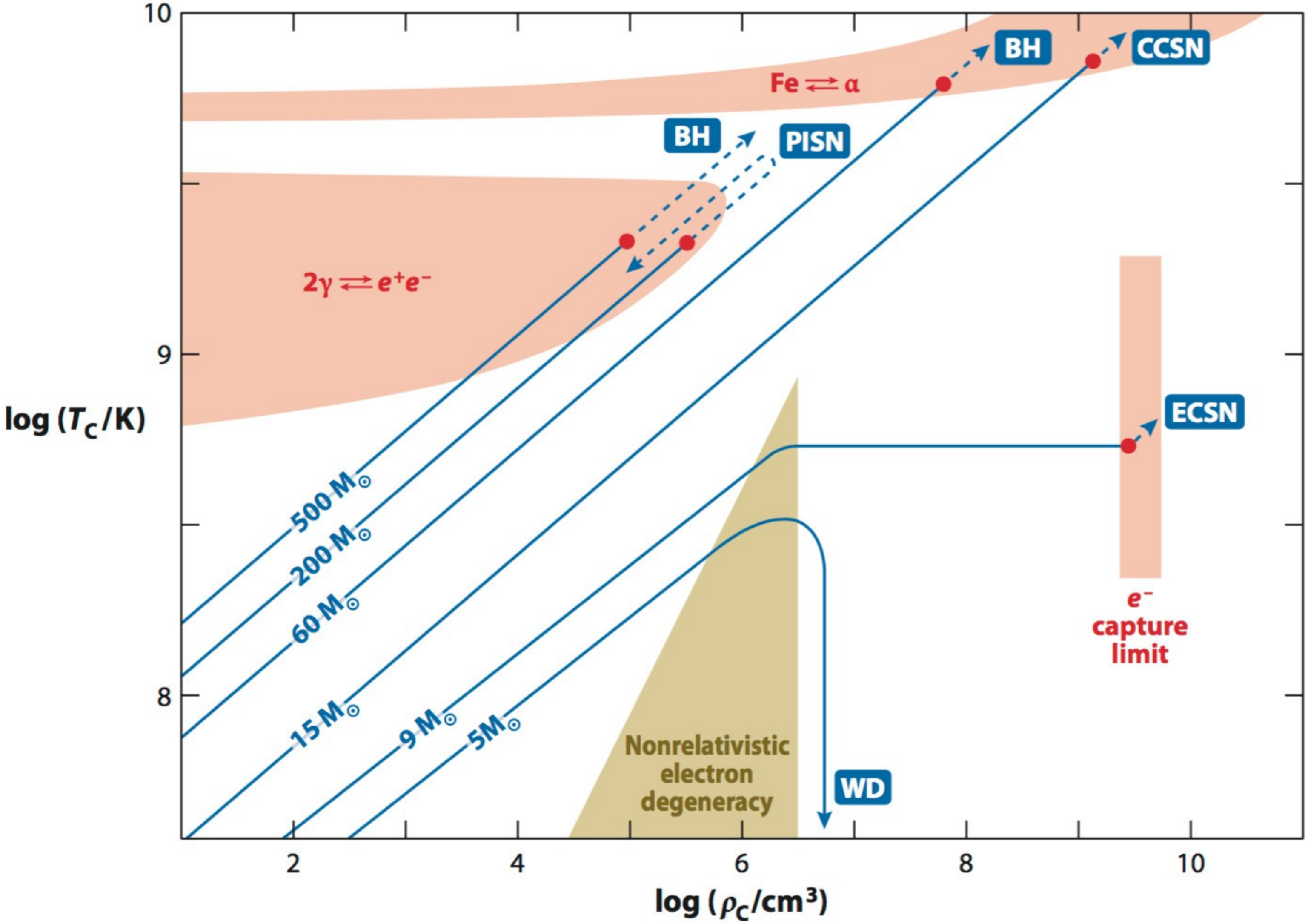
Figure 2.6: Radio spectra from Year 4 to Year 22 since the supernova explosion at, approximately, yearly spaced epochs.

SN1987A, just a picture gallery

....across the electromagnetic spectrum
(in 1996 Chandra was launched yet)



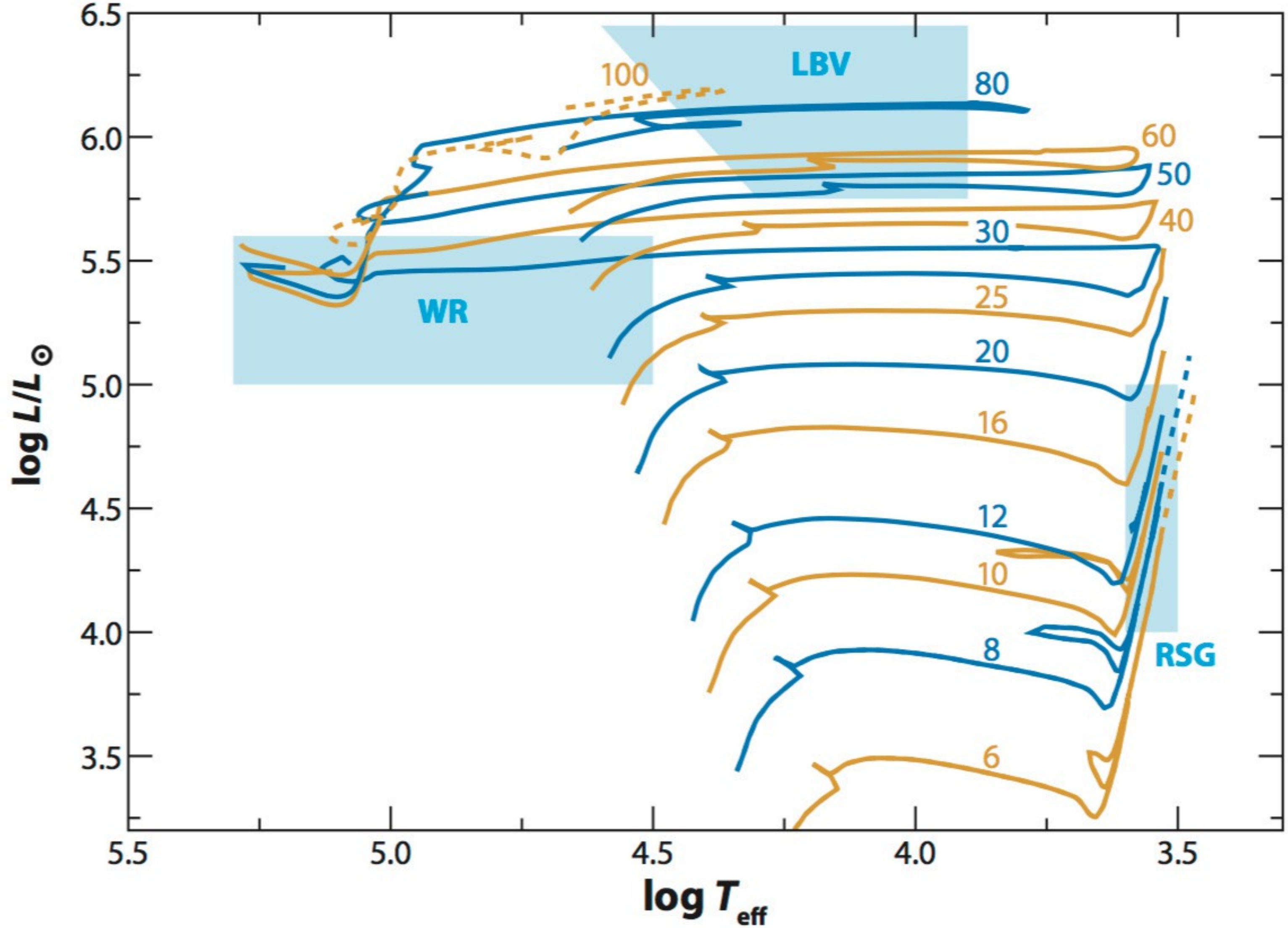




Schematic evol. tracks of the centers of single stars of various masses in the T-density plane (blue lines). Solid lines indicate hydrostatic evolution, big red dots indicate the start of the collapse of the core, and dashed lines imply hydrodynamic evolution, i.e., collapse or explosion. In the three light red areas, the stellar core is prone to collapse, whereas the brown area represents nonrelativistic electron degeneracy. Labels on the evolutionary tracks indicate the initial mass and the final fate. At high metallicity, mass loss may prevent the most massive stars from entering the region ofe ± production, whereas at very low metallicity, rotational mixing may lead stars above 60 Mử into the pair-unstable regime. Rapid rotation could also lead to the formation of long-duration gamma-ray bursts for those stars that produce black holes (BH) or neutron stars.

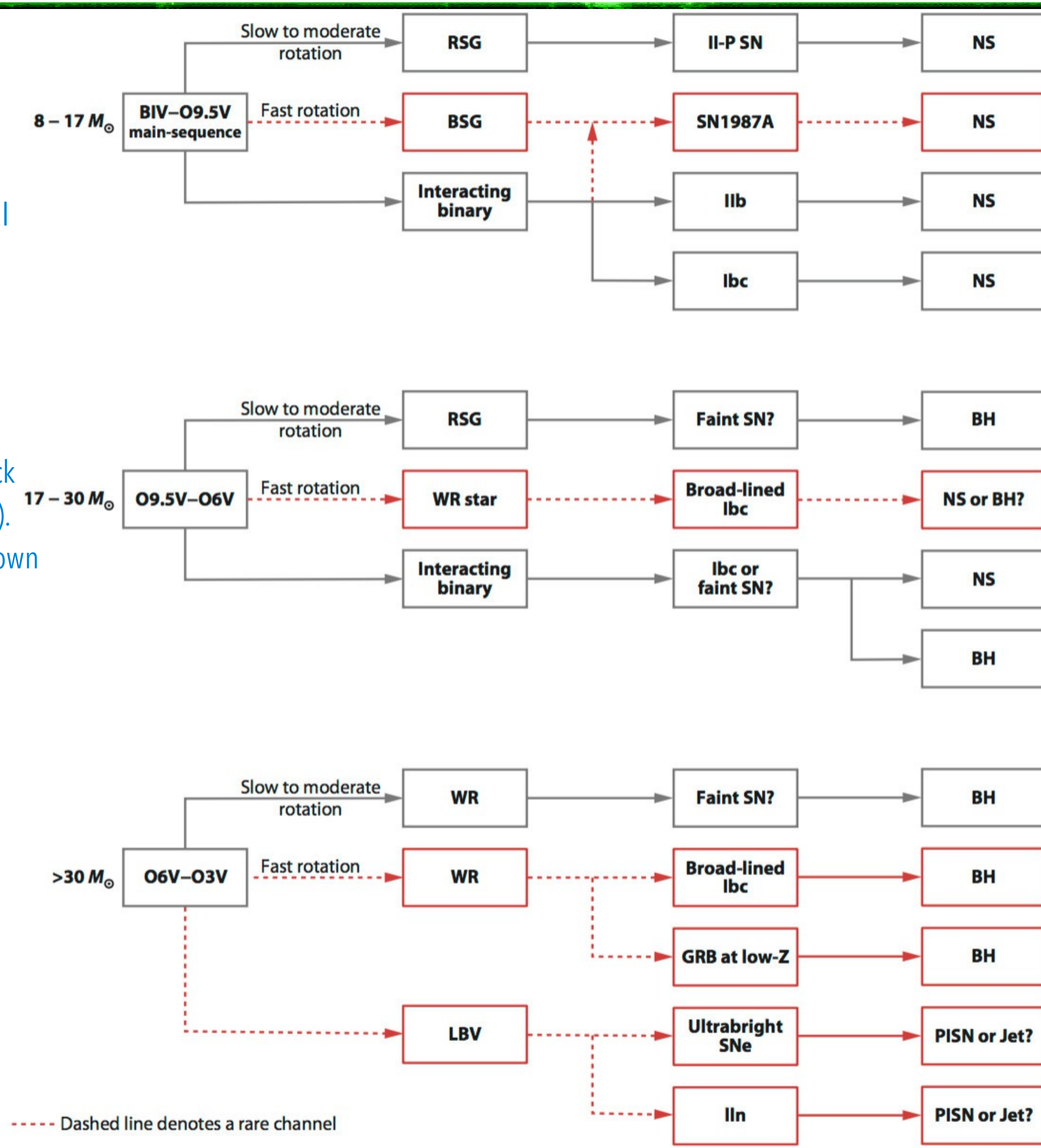
Abbreviations: CCSN, iron core-collapse supernova; ECSN, electron-capture supernova; PISN, pair-instability supernova

Supernova Remnants



H-R diagram of the STARS evolutionary tracks (Eldridge & Tout 2004). The location of the classical luminous blue variables (LBV) is from Smith, Vink & de Koter (2004). SN2005gl had a luminosity of at least log L/Lử □ 6, which puts it in the LBV region indicated or at even higher luminosities if it was hotter and, hence, had a significant bolometric correction. The region where we should see Wolf-Rayet (WR) progenitors is shown, and the only progenitor detected close to this region is that of SN2008ax. The red supergiants (RSG) where progenitors have been detected is shown again for reference.

A summary diagram of possible evolutionary scenarios and end states of massive stars. These channels combine both the observational and theoretical work discussed in this review, and the diagram is meant to illustrate the probable diversity in evolution and explosion. It is likely that metallicity, binarity, and rotation play important roles in determining the end states. The acronyms are neutron star (NS), black hole (BH), and pair-instability supernova (PISN). The probable rare channels of evolution are shown in red. The faint supernovae are proposed and have not yet been detected.
(Smartt, 2009)



Summary:

- SN are (relatively) rare events arising from two main progenitors: WD (SN Ia) and massive stars (Ib, Ic & type IIs)

- They deposit about 10^{51} erg into the CSM & ISM

- The radio emission is quite common (> 20 – 25%) and the radio luminosities spans a few (5) orders of magnitude, reaching a few in 10^{20} W Hz^{-1}

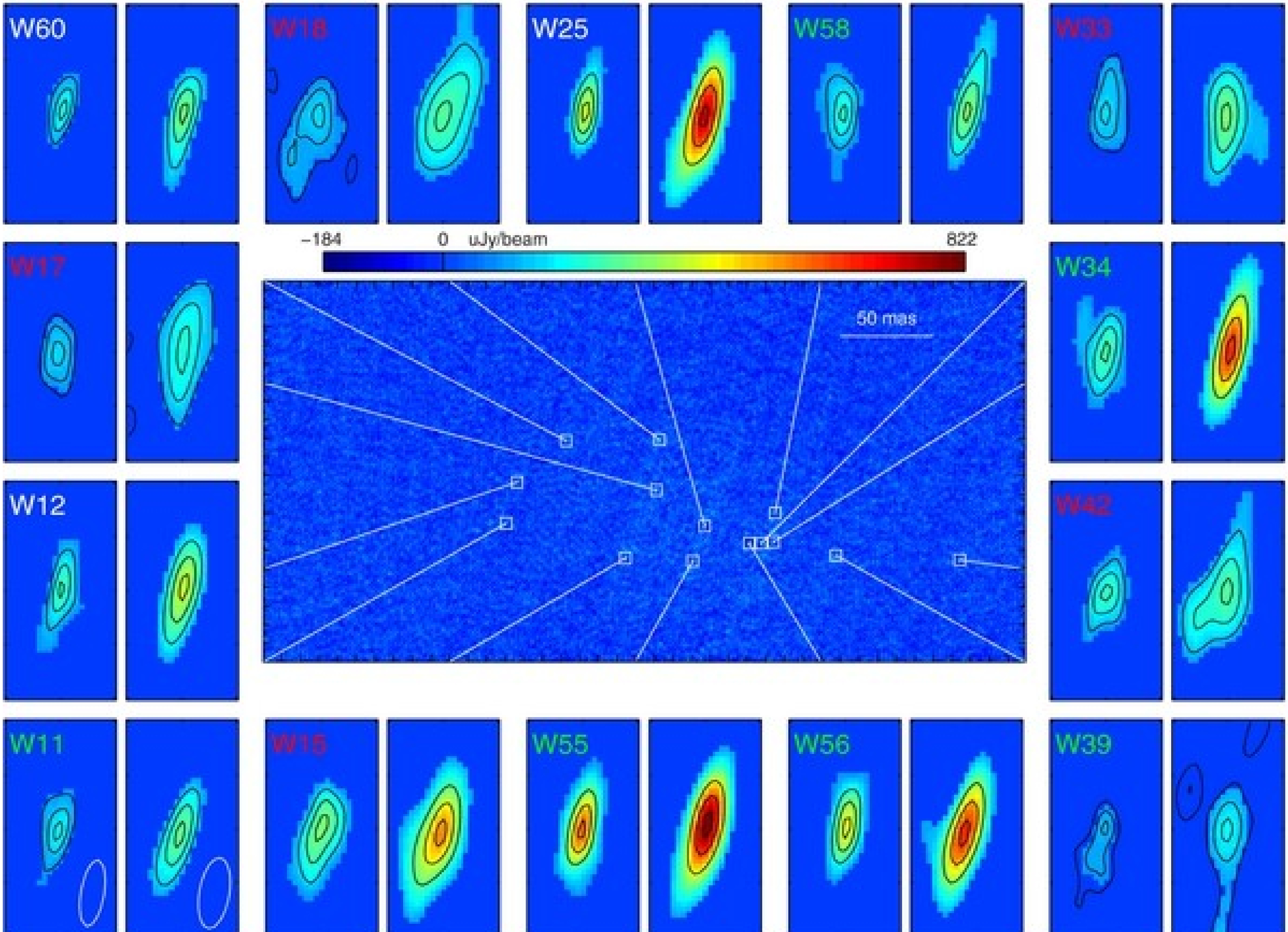
- A radio emitting galactic SNR can be visible for a few in 10^{5} yr, and reach a size of several 10s of pc

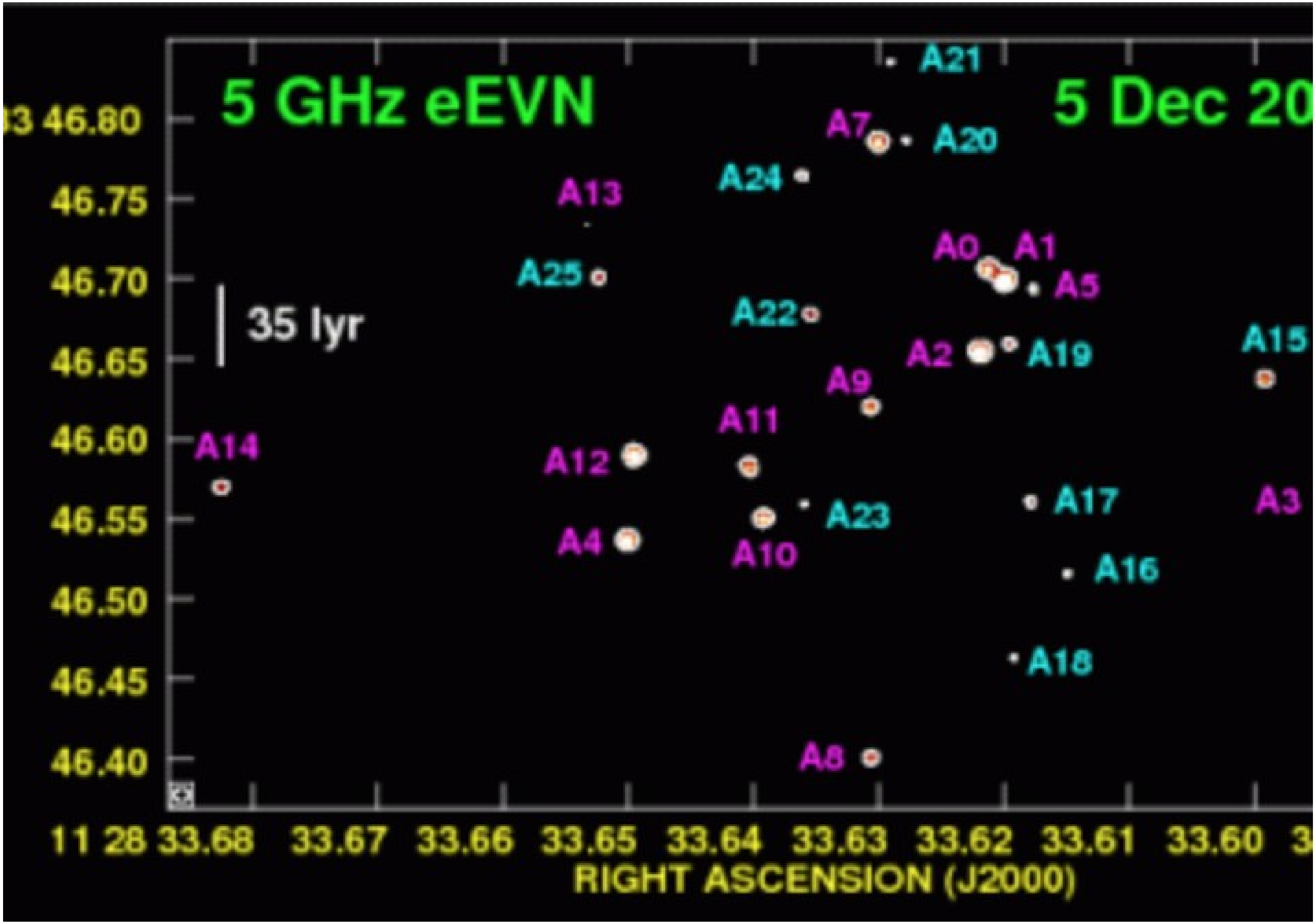
- SN provide CR supply, as well as metal enrichment of the ISM

- A model consisting of 4 main stages grossly describes the evolution of a (radio) SNR

Supernova Remnants in external galaxies

https://iopscience.iop.org/0004-637X/740/2/95 ARP 220: Images at 2 and 3.6 cm (Batejat + 2011)





5 GHz eEVN
5 Dec 20
35 lyr
A21
A7
A20
A24
A13
A0
A1
A25
A5
A22
A2
A19
A15
A9
A11
A14
A12
A17
A3
A23
A4
A10
A16
A18
A8
46.80
46.75
46.70
46.65
46.60
46.55
46.50
46.45
46.40
11 28 33.68
33.67
33.66
33.65
33.64
33.63
33.62
33.61
33.60
RIGHT ASCENSION (J2000)

Supernovae:

Measure the "instant" rate of large mass stars (they last for a very short cosmological time)

Inject energy in the GMC/IMC, possibly enhancing/quenching further star formation

Contribute to the CR generation (and radio diffuse emission)

Convert H into heavier elements (Enrichment)

Where "a lot" of cold gas is converted into stars (then supernovae!) there is a STARBURST galaxy

Enhanced mm, sub-mm and IR emission ⟷ with diffuse radio emission

1. Measure the (massive) star formation rate (individual objects in the nearby universe)
   1b. Can probe the IMF

2. Can probe the Local ISM to the SNR

3. Can probe the LoS (Faraday rotation)

4. Can be related to other indicators of star formation
   4a. Molecular gas amount
   4b. Dust amount
   4c. UV radiation (but affected by 4b)

See later on when discussing star forming galaxies (in a couple of weeks)

Here … "THE END" of supernovae, and now … pulsars

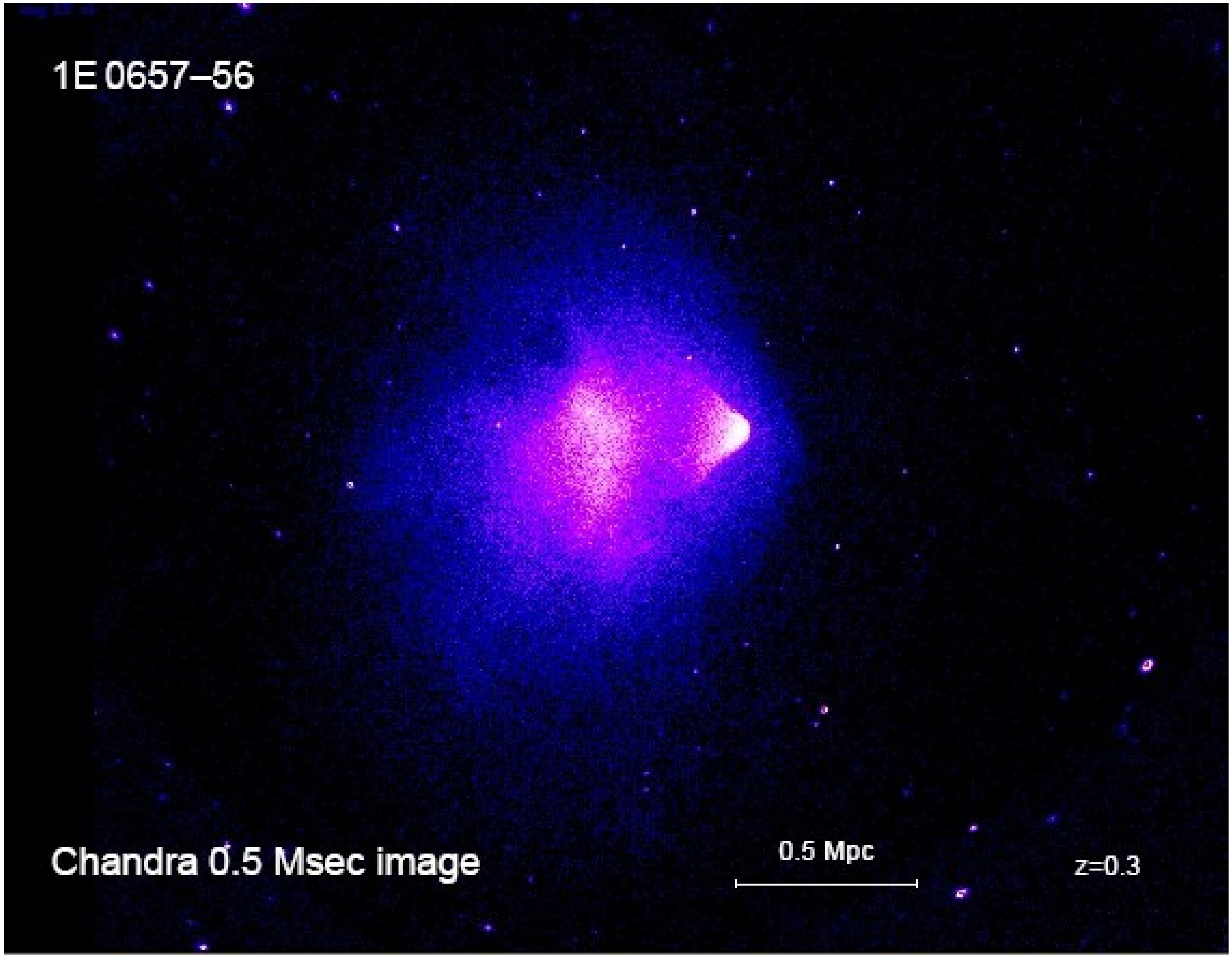
Shock waves are not reversible discontinuities in the properties of a fluid when a body (solid, another fluid, …) is propagating within that fluid faster than the sound speed..

In the ideal case:

- LTE is supposed to hold everywhere except in the shock front ($\partial/\partial x=0$)
- a stationary regime is considered ($\partial/\partial t=0$)

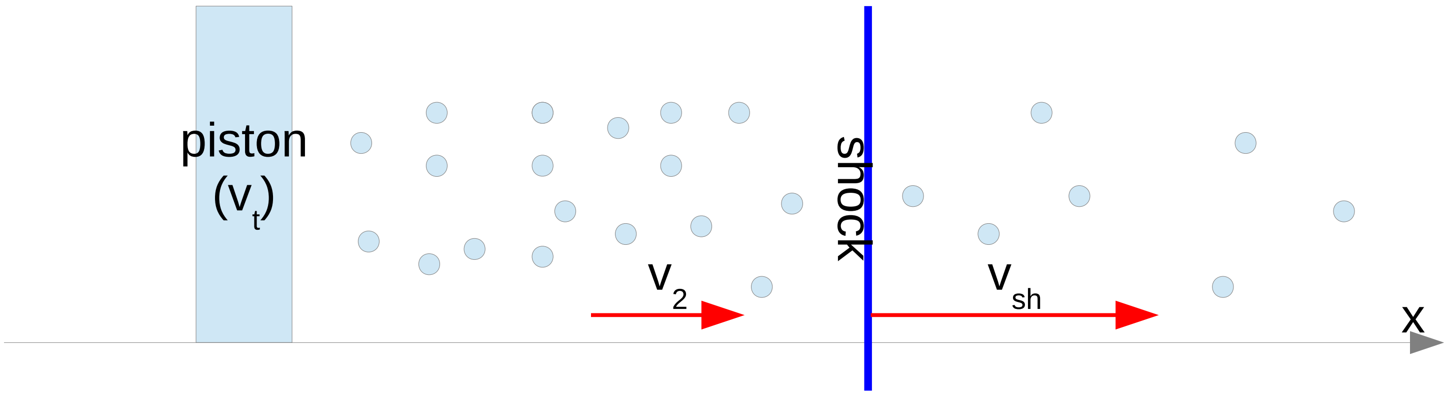
⇨ Search for relationships between perturbed (downstream) and unperturbed (upstream) parameters

Mach number: $\frac{V_{sh}}{c_s}$



downstream
(perturbed fluid)
$\rho_2, p_2, \varepsilon_2, T_2$

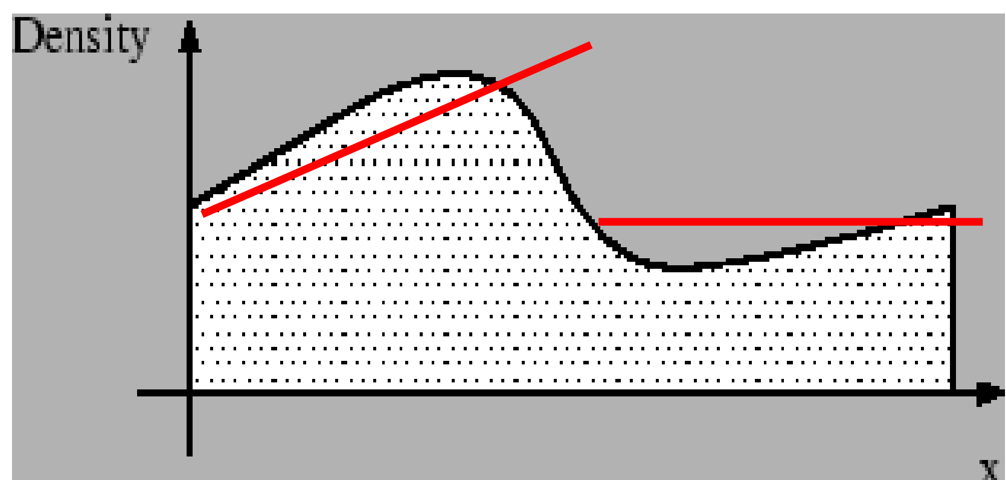
upstream
(unperturbed fluid v_1=0)
$\rho_1, p_1, \varepsilon_1, T_1$



a shock is formed when a perturbation is moving with a velocity larger than the sound speed pushing/compressing the fluid encountered during its motion

also adiabatic sound waves can grow to shock waves

[c_s is higher where ρ , T are higher, leaving the denser regions progressively move at higher velocities (c_s continuously grows!) until a jump is formed]



the shock compresses, heats and drags the shocked material

I t is possible to define a (comoving) surface where physical quantities abruptly change;

In that RF all the HD equation must hold
[simplest case, they have a stationary form $(\partial/\partial t=0)$, and happen along a given direction, i.e. x]

$$\frac{\partial \rho v_x}{\partial x} = 0$$

$$\frac{\partial}{\partial x}(\rho v_x^2+p) = 0; \quad \frac{\partial}{\partial x}(\rho v_x v_y) = 0; \quad \frac{\partial}{\partial x}(\rho v_x v_z) = 0$$

$$\frac{\partial}{\partial x}[\rho v_x(w+\frac{v^2}{2})] = 0$$

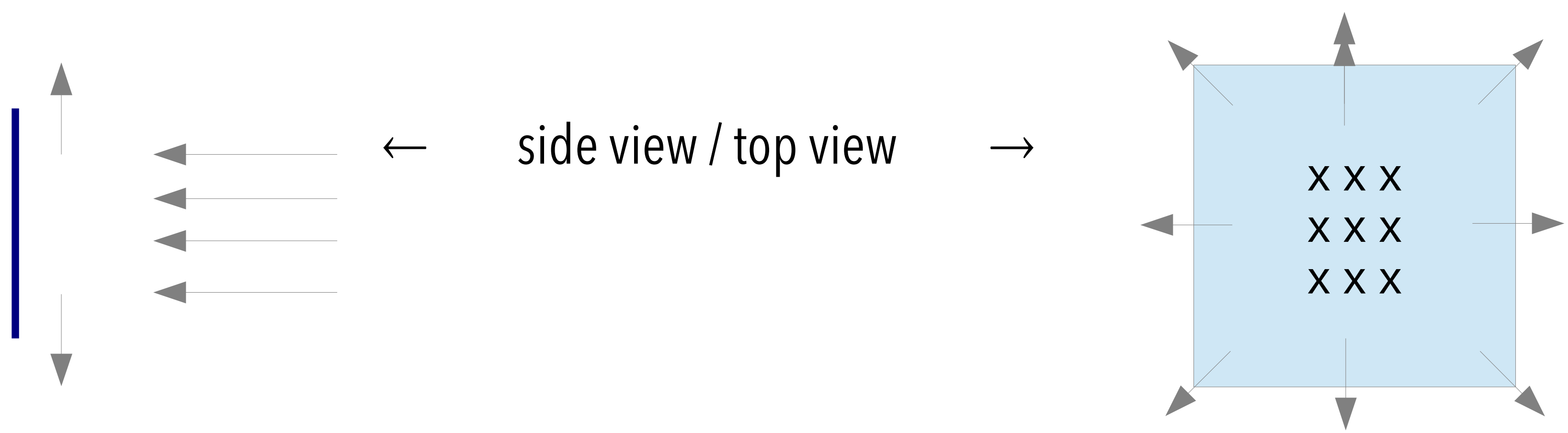
Case 1: Any mass can't cross the surface $\rho_1 v_{1x} = \rho_2 v_{2x} = 0$

Density can't be 0, consequently all velocities are 0;

from the second equation $\dfrac{\partial p}{\partial x} = 0$ and then only ρ, v_y, v_z can be discountinuou

(tangential discontinuity)

It is possible to show that such tangential discontinuities are unstable (grow). In this case the two fluids will be mixed by turbulence



Case 2: In general (= all the other cases) the mass flux across the surface

$\dfrac{\partial \rho v_x}{\partial x}$ is not 0 and v_{1x}, v_{2x} are not 0 anymore while v_y and v_z become continuous.

Let's choose a RF on the shock front: unperturbed material falls with $v'_1 = -v_{sh}$

The shocked matter is dropped behind at $v'_2 = v_2 - v_{sh}$

An external observer measures $v_1 = 0,\ v_2$ and $v_{sh} > v_2$

Let's write the conservation laws for HD fluids on the discontinuity surface:

$$\rho_1 v'_1 = \rho_2 v'_2 \qquad \text{i.e.} \qquad \frac{\rho_1}{\rho_2} = \frac{v'_2}{v'_1}$$

$$\rho_1 v'^2_1 + p_1 = \rho_2 v'^2_2 + p_2 \qquad \text{i.e.} \qquad \rho_1 v'^2_1 - \rho_2 v'^2_2 = p_2 - p_1$$

$$\rho_1 v'_1 \left(\frac{v'^2_1}{2} + \underbrace{\varepsilon_1 + \frac{p_1}{\rho_1}}_{w_1} \right) = \rho_2 v'_2 \left(\frac{v'^2_2}{2} + \underbrace{\varepsilon_2 + \frac{p_2}{\rho_2}}_{w_2} \right)$$

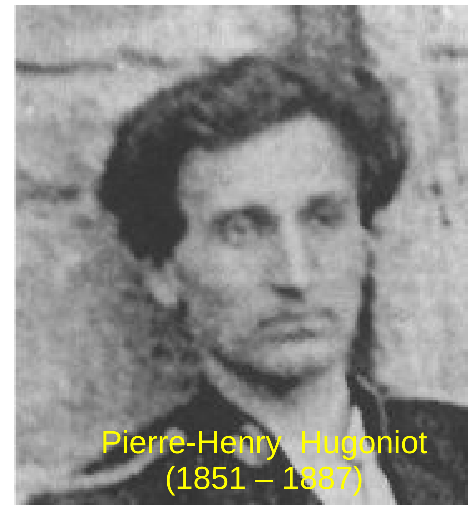
where ε and $w = \varepsilon + p/\rho$ are the energy and is the enthalpy per unit mass.

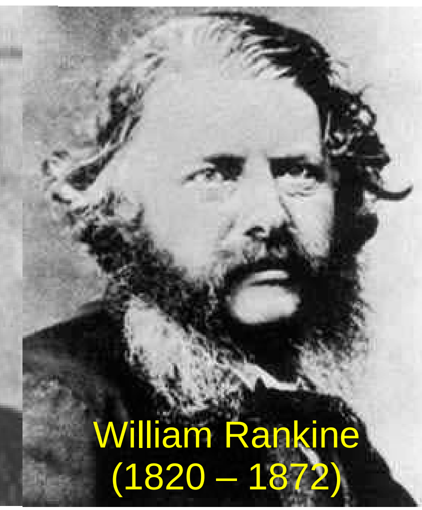
then p_2 and v'_2 can be obtained; finally after some algebra we get

$$\frac{\rho_2}{\rho_1} = \frac{(\Gamma + 1)M^2}{2 + (\Gamma - 1)M^2} = \frac{v'_1}{v'_2}$$

and then ρ_2 and v'_2 are

$$\frac{p_2}{p_1} = \frac{2\Gamma M^2 - (\Gamma - 1)}{(\Gamma + 1)}$$





known as Hugoniot-Rankine relationships in the shock RF.

From the first equation

$$\frac{v'_2}{v'_1} = \frac{2 + (\Gamma - 1)M^2}{(\Gamma + 1)M^2} \begin{cases} = \frac{1}{4} & \text{if monoatomic gas}, \quad M \to \infty \\ = 1 & \text{if } M \to 1 \end{cases}$$

in the observer's frame, with M ế 1: $v_2 = (v_{sh} - v'_2) = \frac{3}{4} v_{sh}$

Strong (adiabatic) shock waves : in case of M ế 1

$$\frac{v'_1}{v'_2} = \frac{\rho_2}{\rho_1} = \frac{(\Gamma + 1)M^2}{2 + (\Gamma - 1)M^2} \simeq \frac{(\Gamma + 1)}{(\Gamma - 1)}$$

$$\frac{p_2}{p_1} = \frac{2\Gamma M^2 - (\Gamma - 1)}{(\Gamma + 1)} \simeq \frac{2\Gamma}{(\Gamma + 1)} \cdot M^2$$

since $PV \; \alpha \; T$ then $\frac{P}{\rho} \; \alpha \; T$ and we can constrain the jump in temperature:

$$\frac{T_2}{T_1} = \frac{p_2}{p_1} \cdot \frac{\rho_1}{\rho_2} \simeq \frac{2\Gamma}{(\Gamma + 1)} \cdot M^2 \cdot \frac{\Gamma - 1}{\Gamma + 1} = \frac{2\Gamma(\Gamma - 1)}{(\Gamma + 1)^2} \cdot M^2$$

→ The temperature (and pressure) of the shocked material can grow without limitations.

From Bell (1978) the spectrum of the relativistic particles is: $N(E) = N_o E^{-\delta}$

where the index δ is given by:

$$\delta = \frac{2 v_{down} - v_{up}}{v_{up} - v_{down}}$$

v_{up} = upstream velocity

v_{down} = downstream velocity

In presence of (strong) shocks, the limiting case is when $v_{up} = 0$ and $v_{down} = \frac{3}{4} v_{sh}$

and applies when $M \gg 1$ namely, in case of strong shocks (the upstream velocity is nigligible)

$$\delta = \frac{2 v_{down} - v_{up}}{v_{up} - v_{down}} = \frac{2v_{down}}{-v_{down}} = -2 \quad \rightarrow \quad \alpha = -0.5$$

The shock converts kinetic to internal (thermal) energy

Also entropy is discontinuous on the shock surface $s_2 \neq s_1$ and then $s_2 > s_1$ while it is preserved upstream and downstream. The entropy increase generated by collisions among fluid particles

Thickness: is of the order of the mean free path λ; from the relation $\lambda n \sigma = 1$

$$\lambda = 1/n\sigma$$

where n=numeric density; σ=cross section of the process

Summary:
knowing the parameters of the unperturbed/perturbed medium (pedex 1/2) it is therefore possible to derive those of the shocked/unshocked material

For instance:
electronic radius 5.3 x 10^{-11} m, $n_{ISM} \sim 1\ cm^{-3}$, 1 pc =3.09 x 10^{16}m, UA = 1.5 10^{11} m

The shock converts kinetic to internal (thermal) energy

The case of SNR:

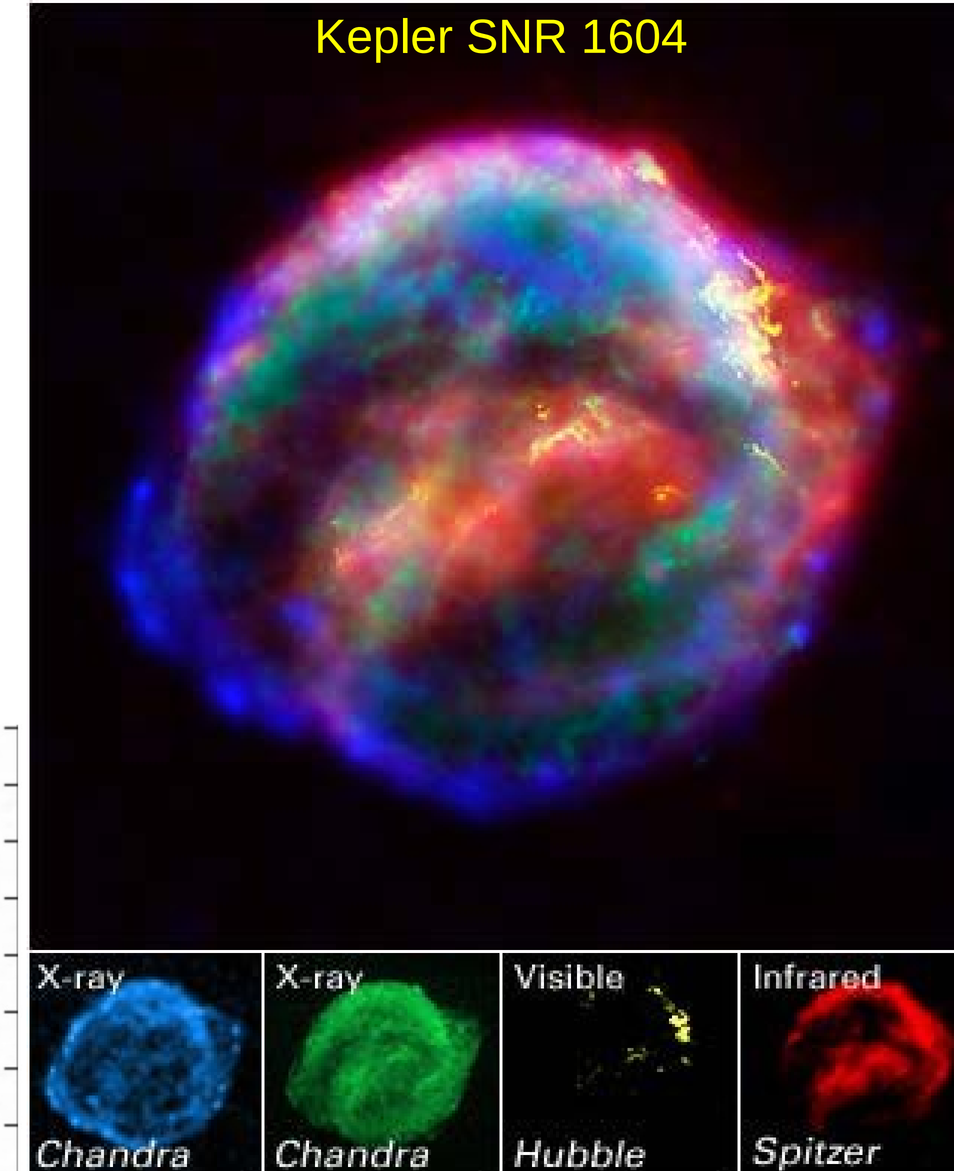
$n_1 \sim 1 - 10\ cm^{-3}$

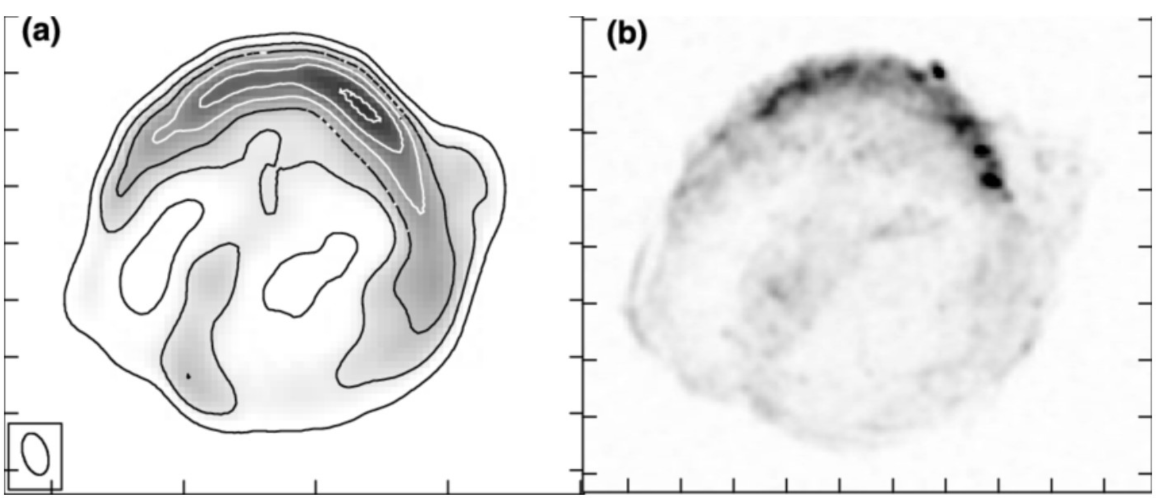
$T \sim 1000\ K$;

$\mu = m_H \sim 1.7 \times 10^{-27}\ kg$;

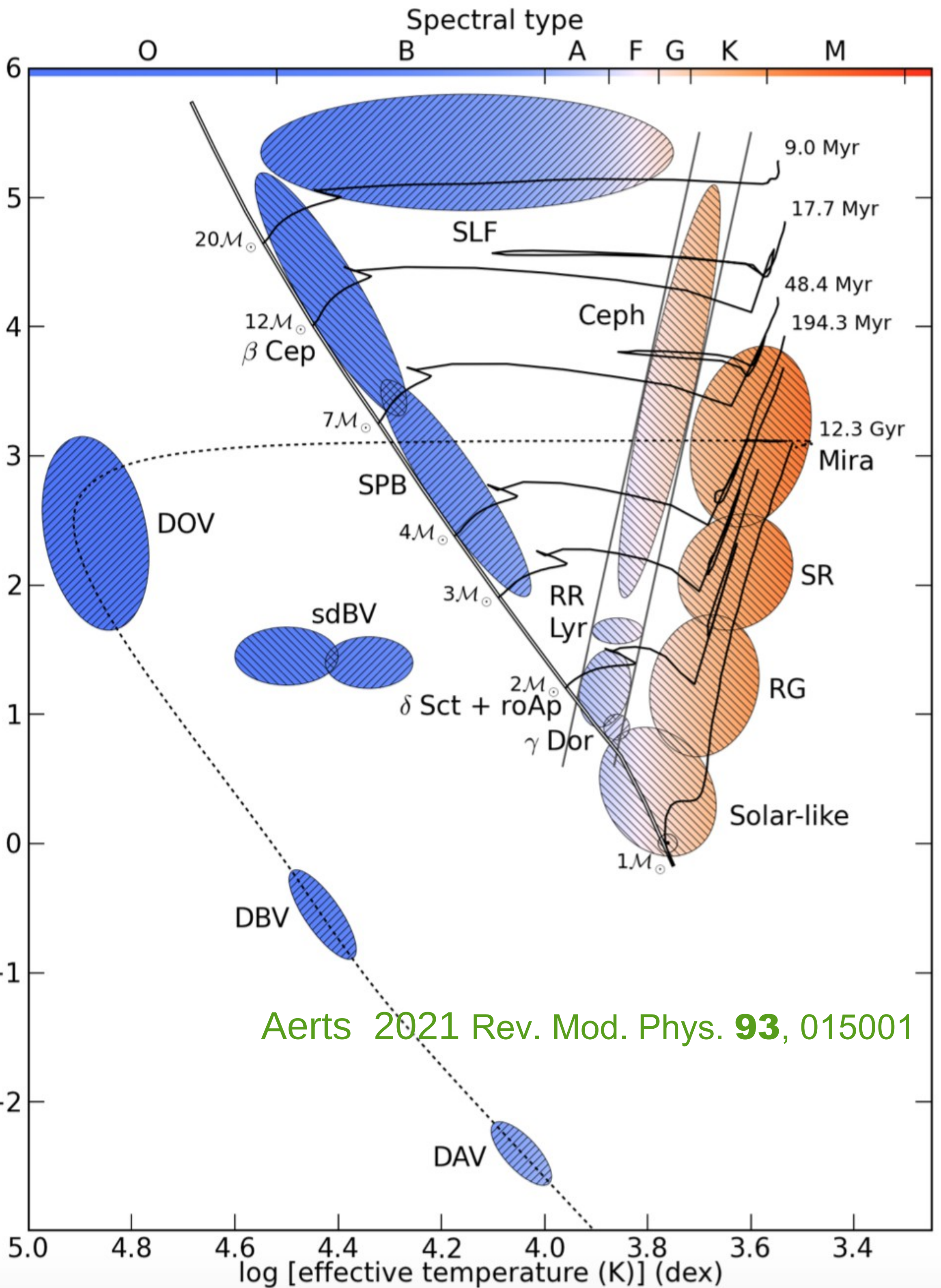
$c_s = (\Gamma kT/\mu)^{1/2}$ $\qquad v_{SN} \sim 10^4\ km/s$;

The star envelope expands at M » 1





—(a) Radio continuum image of Kepler's SNR obtained with the VLA at 1.4 GHz (Reynoso & Goss 1999). The beam, 22B7 ; 12B8, P:A: ¼ 17N1, is indicated in the bottom left corner. (b) X-rays image of Kepler's SNR obtained with Chandra in the range 2–10 keV.



ent classes of pulsating stars. The abbreviation of
, to which we refer for extensive discussions of all
cal periods and amplitudes of the oscillations. The
e of oscillation mode in each class: // for gravity
quency (SLF) variability in O-type stars and blue
ith previous versions of this plot. The solid black
, with birth masses and evolutionary timescales as
lines, while the double line represents the zero-age
isen-Dalsgaard (Aarhus University) and by Pieter
s based on the version in his PhD Thesis (Pápics,