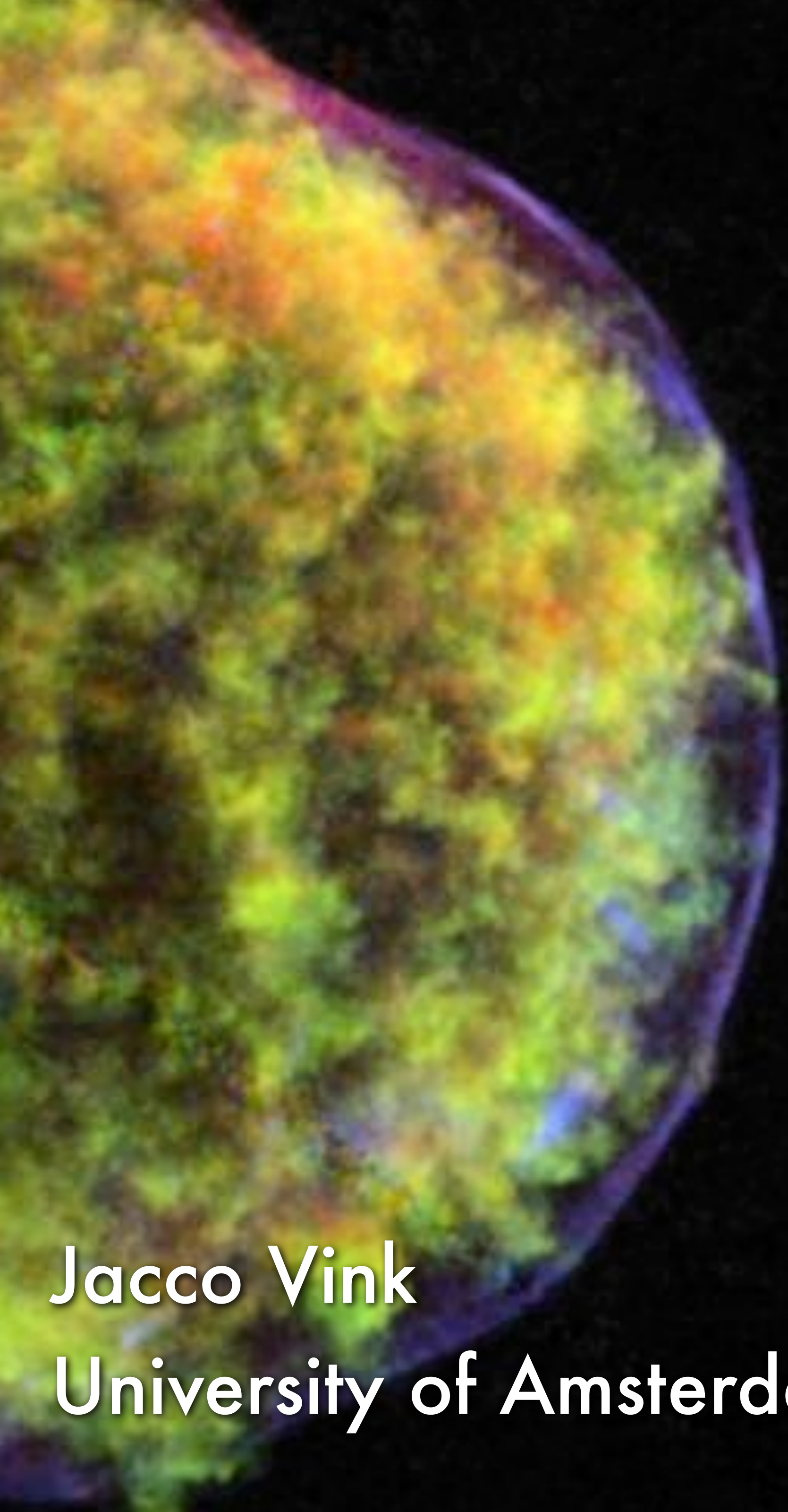
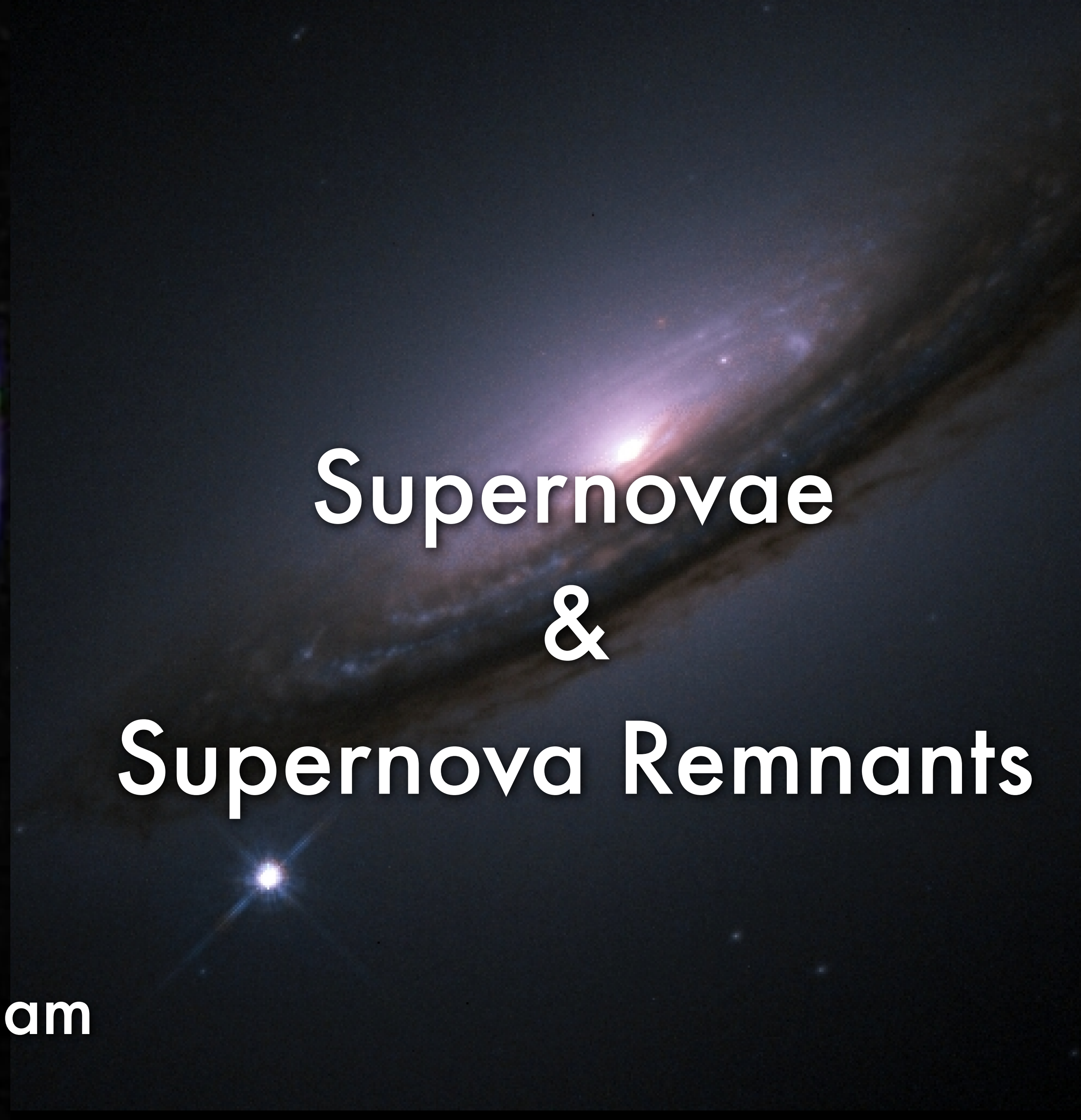




GRAPPA

GRavitation AstroParticle Physics Amsterdam

Supernovae & Supernova Remnants

Jacco Vink
University of Amsterdam

I
Supernovae


1572
apparuit
Cassiopea

Dawn of the scientific revolution

Tycho Brahe (1546-1601)

SN 1572

Johannes Kepler (1571-1630)

SN 1604

Historical supernovae

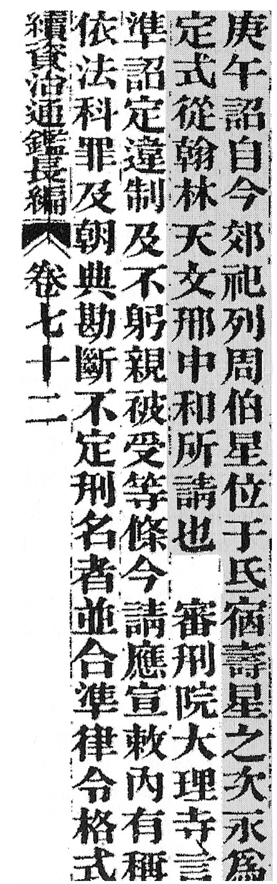
- SN 185: oldest source on a supernova (Chinese record)
- SN 1006: brightest historical supernova ($m_V \approx -9$ mag) recorded in China, the Arab world and Switserland
- SN 1054: recorded in Asia
- SN 1185: Chinese record
- SN 1572: China, Europe a.o Tycho Brahe
- SN 1604: China, Europe a.o Johannes Kepler

- After that

    No supernova spotted in the Milky Way

    Observational surveys of supernovae:

    expected 2-3 supernovae per century in the Milky Way


庚午詔自今郊祀列周伯星位于氐宿壽星之次永爲
定式從翰林天文邢中和所請也 審刑院大理寺言
準詔定違制及不躬親被受等條今請應宣敕內有稱
依法科罪及朝典勘斷不定刑名者並合準律令格式
續資治通鑑長編卷七十二

From Novae to Supernovae

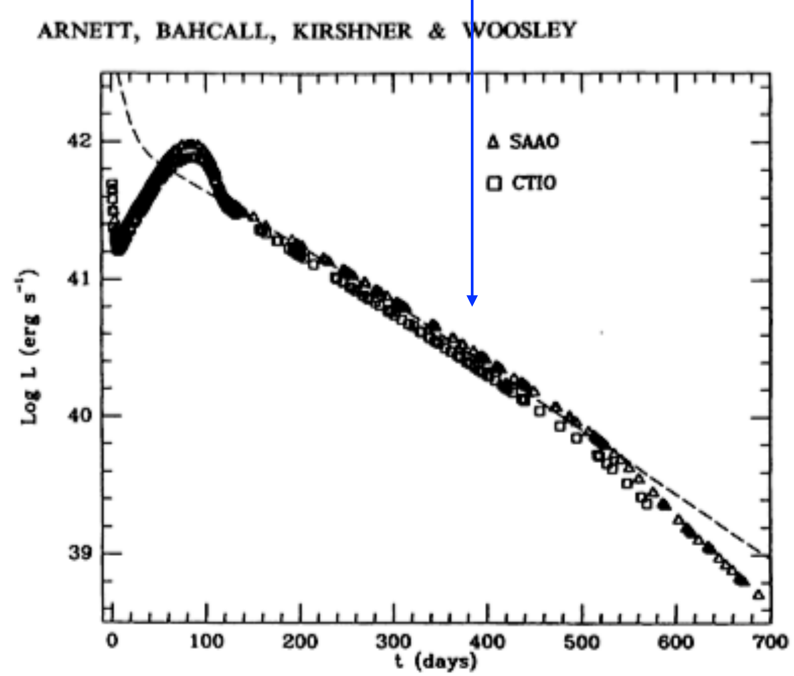
Walther Baade

Frits Zwicky

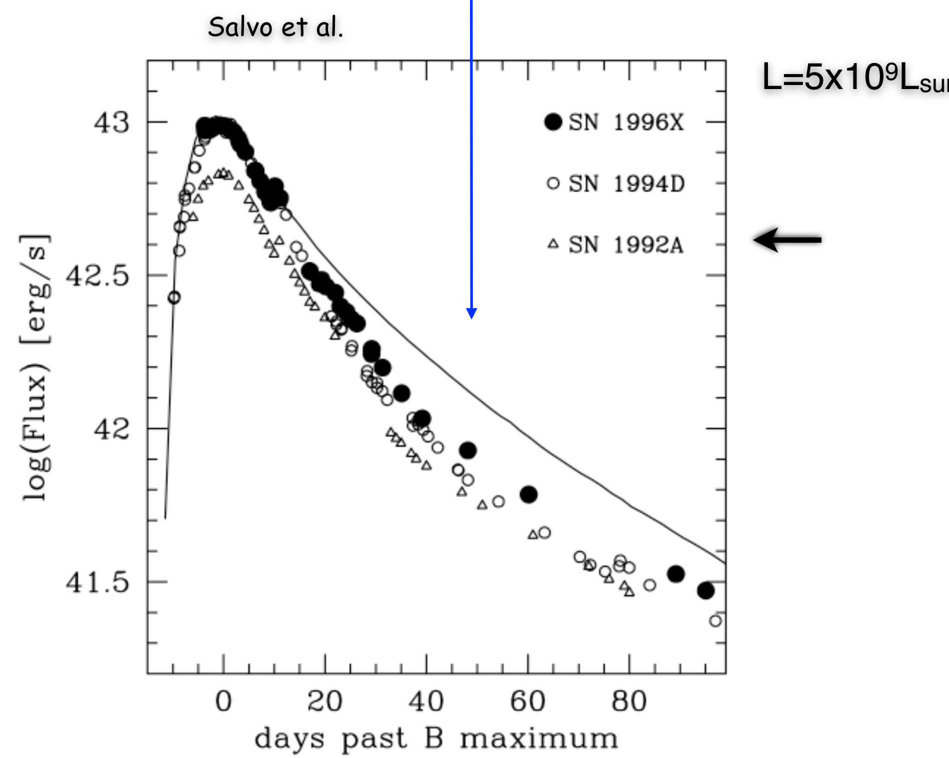
In addition, the new problem of developing a more detailed picture of the happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very 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.

Time scale and luminosity of supernovae: light curves

Tail due to heating by radioactivity
(in particular $^{56}Ni(8.8d) \rightarrow {}^{56}Co\ (111d) \rightarrow {}^{56}Fe$)



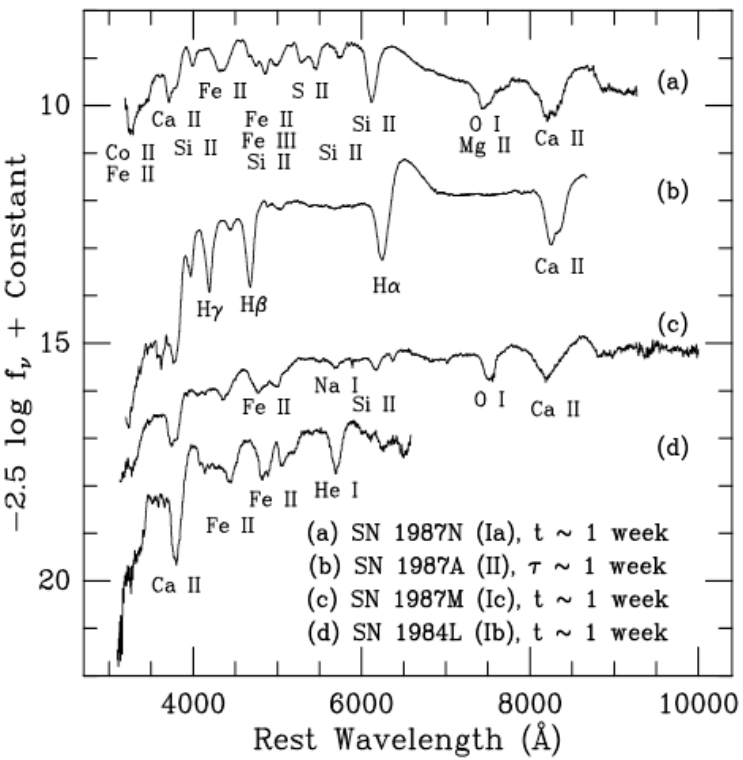
SN1987A
(a "low-luminosity" SN)



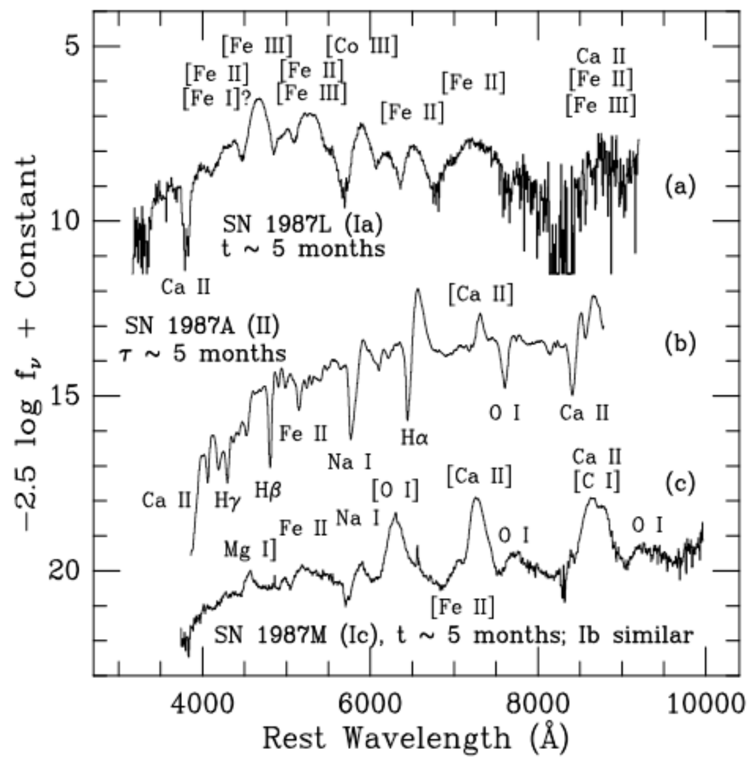
SN1992A, SN1994D,SN1996X

- Supernovae can have absolute visual magnitudes of V=-17 tot -19
- The brightness of galaxy nuclei or small galaxies as a whole!

Spectroscopy of supernovae



After 1 Week

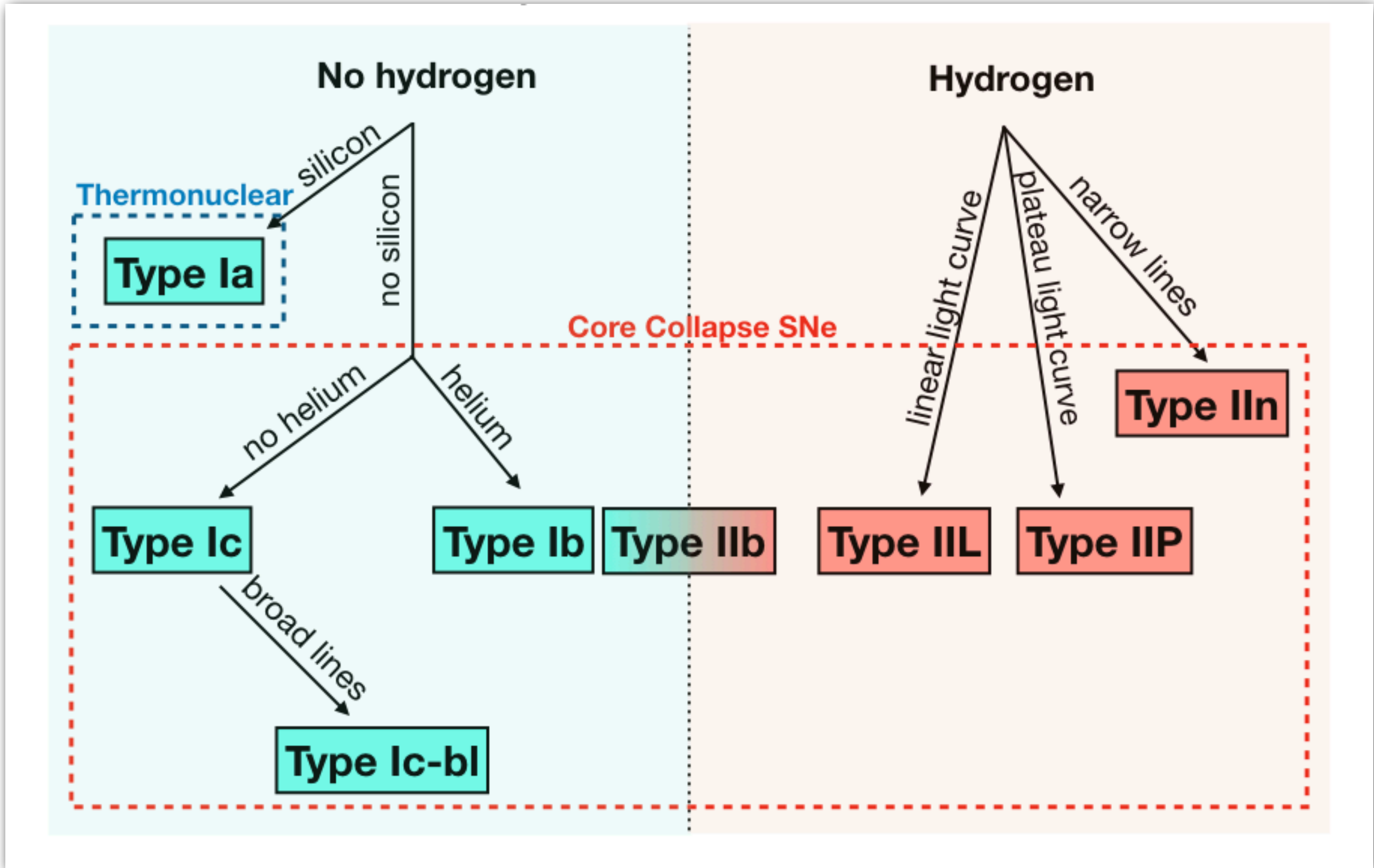


After 5 months

Rudolph Minkowski (1885-1976)

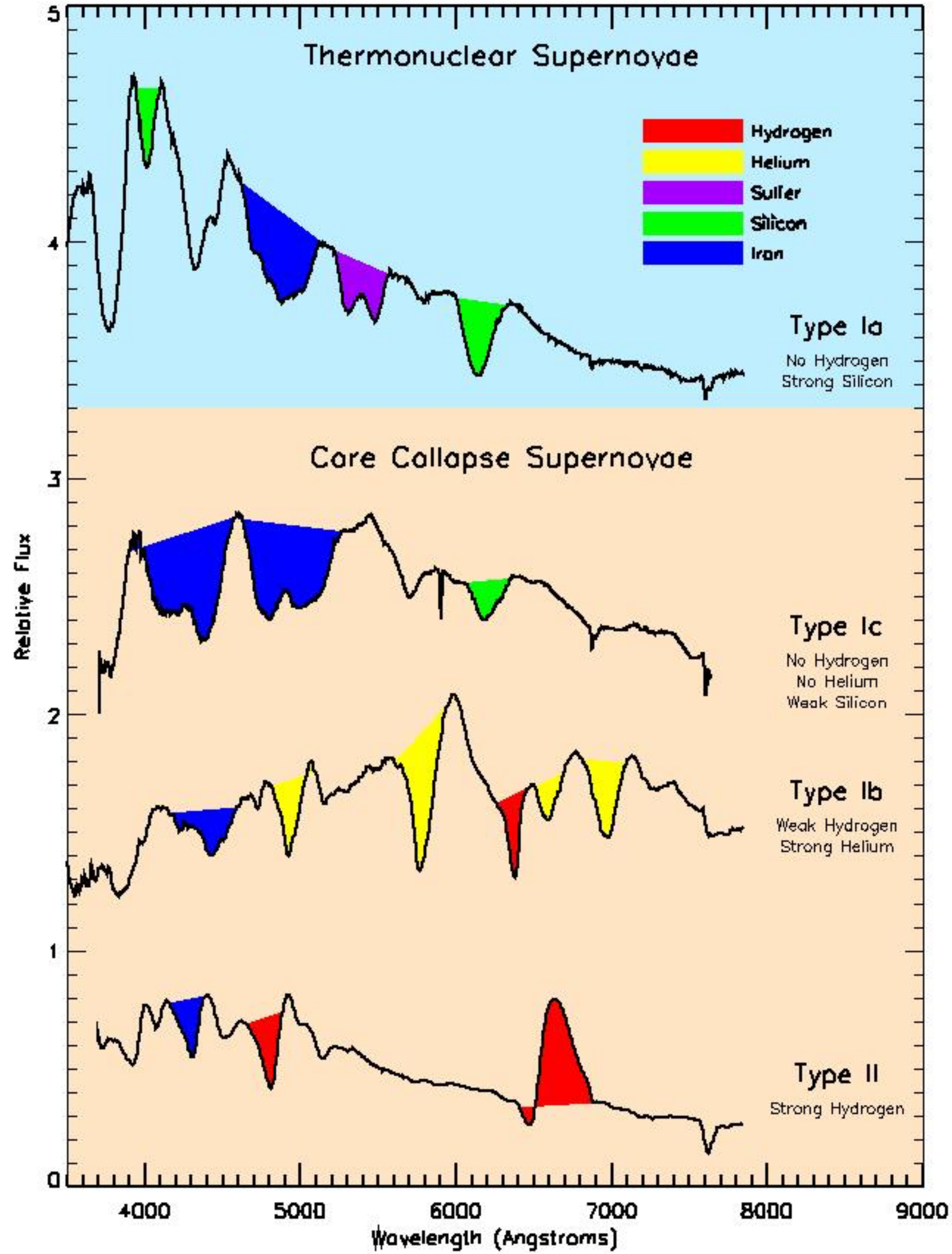
- Around 1941: two basic types of supernovae (Rudolph Minkowski):
  1. Type I: no hydrogen lines in spectrum
  2. Type II: hydrogen absorption lines clearly detected (H-alpha, Balmer lines)
- Later: more and more subclassifications
- Type I & II used till ~1985
- Late time spectra: emission lines = optically thin spectrum → “nebular phase”

Modern supernova classification



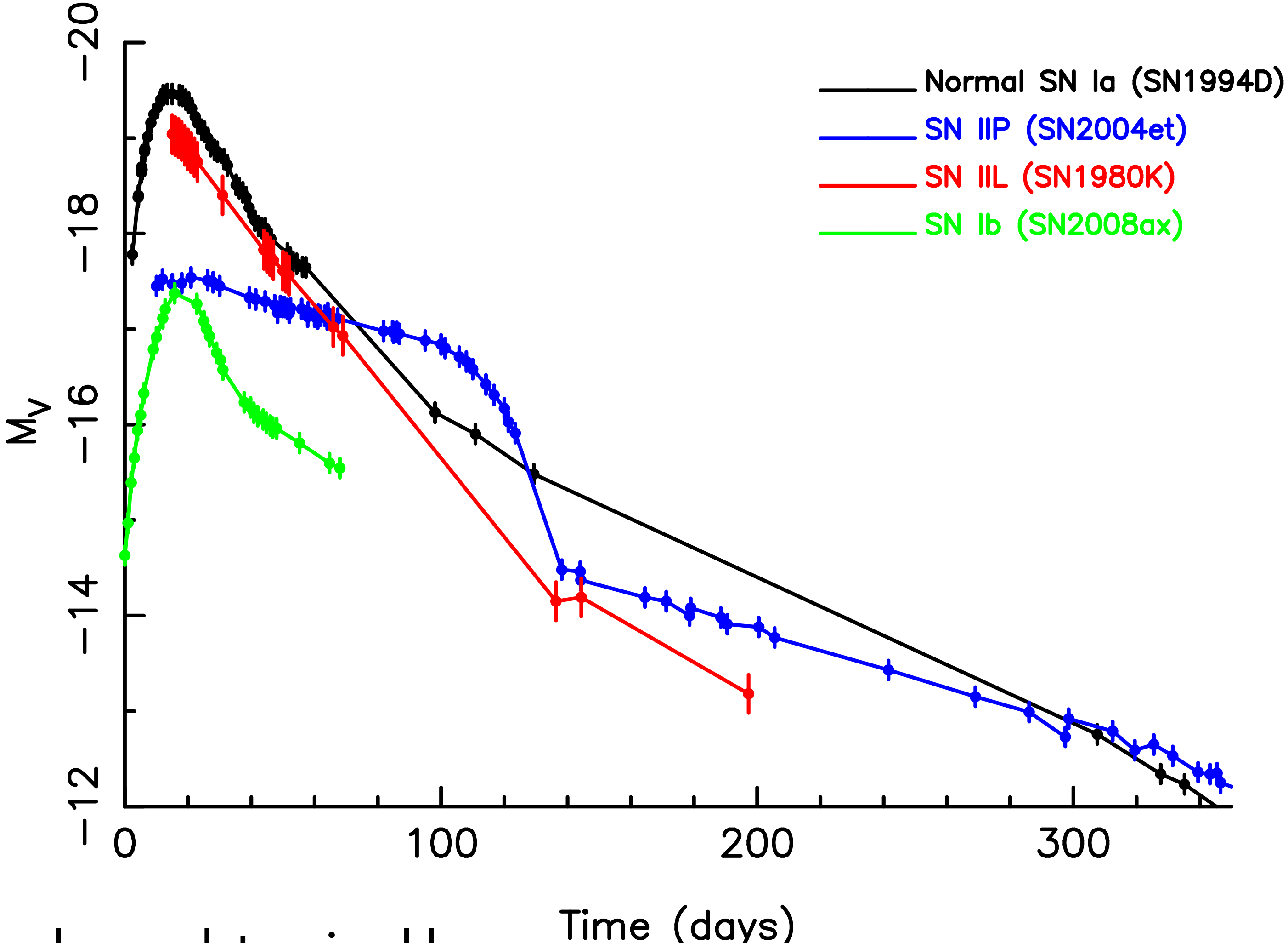
- We now know that there are two very fundamentally different types of SN explosions:
  - Core collapse supernovae: explosion of massive star/nucleus forms a neutron star (or black hole?)
  - Thermonucleair supernovae (or Type Ia): exploding carbon-oxygen white dwarfs
- Type II, IIb, Ib, Ic: core collapse SNe but hydrogen (& He for Ic) enveloped removed

SN spectra



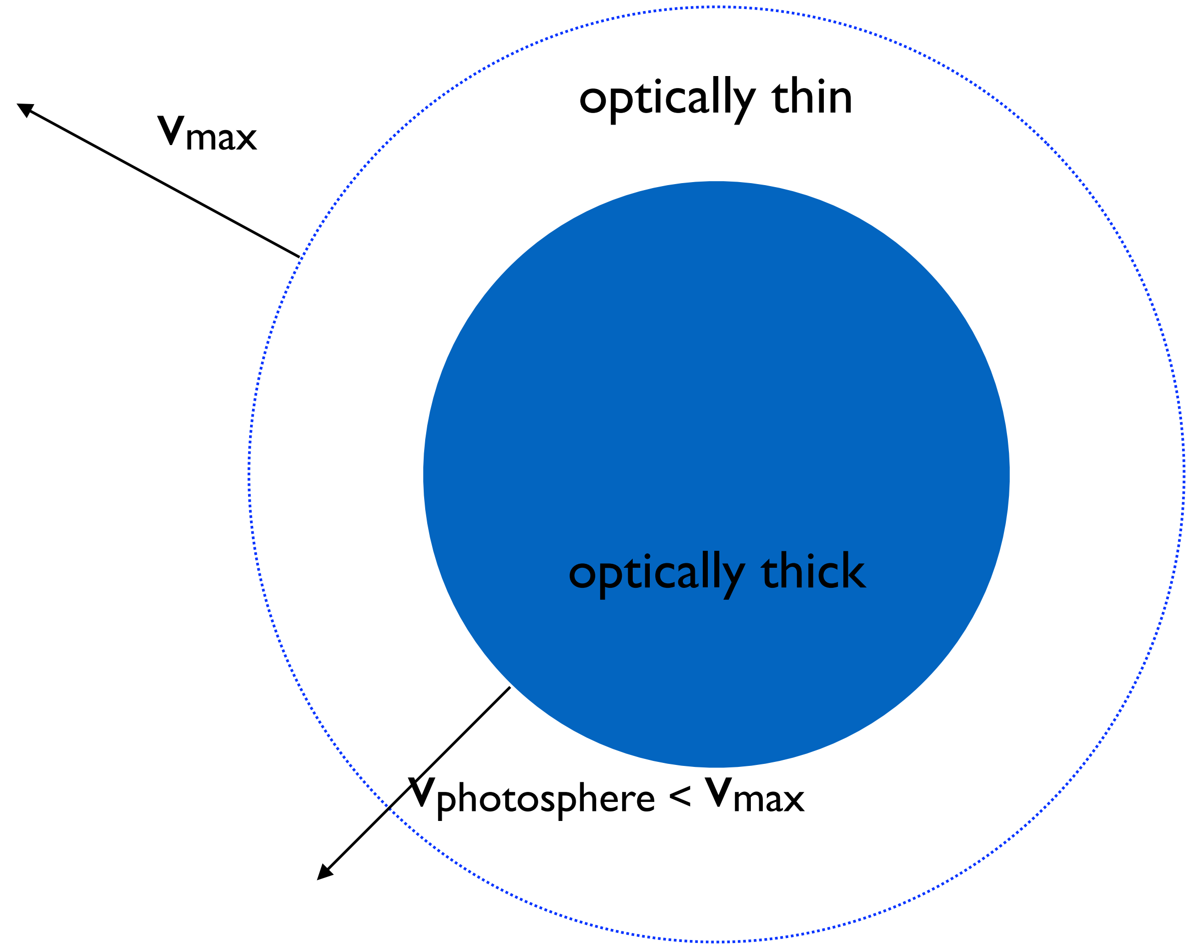
Thermonuclear Supernovae
Hydrogen
Helium
Sulfer
Silicon
Iron
Type Ia
No Hydrogen
Strong Silicon
Core Collapse Supernovae
Type Ic
No Hydrogen
No Helium
Weak Silicon
Type Ib
Weak Hydrogen
Strong Helium
Type II
Strong Hydrogen
Relative Flux
Wavelength (Angstroms)
0
1
2
3
4
5
4000
5000
6000
7000
8000
9000

Light curve shapes of different SN types



- Light curve shapes determined by:
  - Explosion energy
  - Amount of radioactive material (^{56}Ni) -> peak brightness and tail
    - Type Ia: 0.5-1 M_{sun} of ^{56}Ni!
  - Explosion mass: more massive -> radiation leaks out slower, broader peak
  - Plateau (IIP): more extended stellar envelopes

Photosphere



- As the hot supernova material expands and cools adiabatically
  - gas becomes optically thin (transparant)
  - velocity of SN appears to go down (outer layer: ~20,000, inner: ~5000 km/s)
  - in reality we are just looking more and more to the inside of the supernova
  - By observing for a long time we scan all supernova layers
- Layer for which optical thickness τ=1 ($I=I_0 \exp(-\tau)$) is called the *photosphere*
- Once completely optically thin: nebular spectrum (emission lines, instead of abs. lines)
- Expansion implies: adiabatic cooling
- Heating: radio-activity

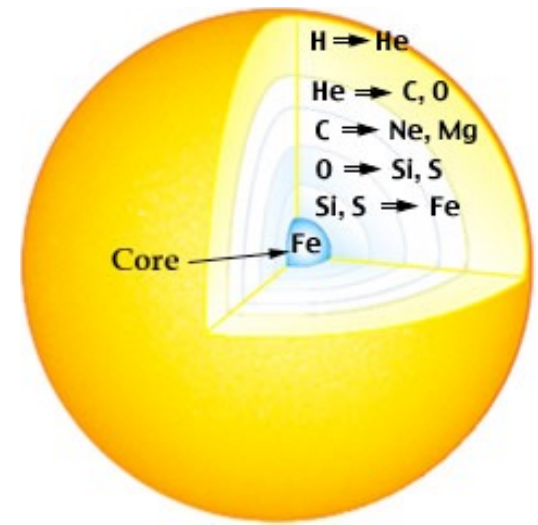
In which galaxies do SNe occur?

Spiral galaxies:
- All types of supernovae
- Stellar populations:
  - young (blue) & old (red)

- Milky Way: ± 2-3 supernovae per century

Elliptical galaxies:
- Only Type I(a)
- Stellar population: old

Progenitors of core collapse SNe (II, Ibc)



Helium burning (T = 0.2 x10^9 K)

$3 \times {}^4He \rightarrow {}^{12}C + \gamma$ ("triple α reaction")

${}^{12}C + {}^4He \rightarrow {}^{16}O + \gamma$

Carbon burning (T = 2 x10^9 K)

${}^{12}C + {}^{12}C \rightarrow {}^{20}Ne + {}^4He$

Neon burning (T = 2 x10^9 K)

${}^{20}Ne + \rightarrow {}^{16}O + {}^4He$

Oxygen burning (T = 3.6 x10^9 K)

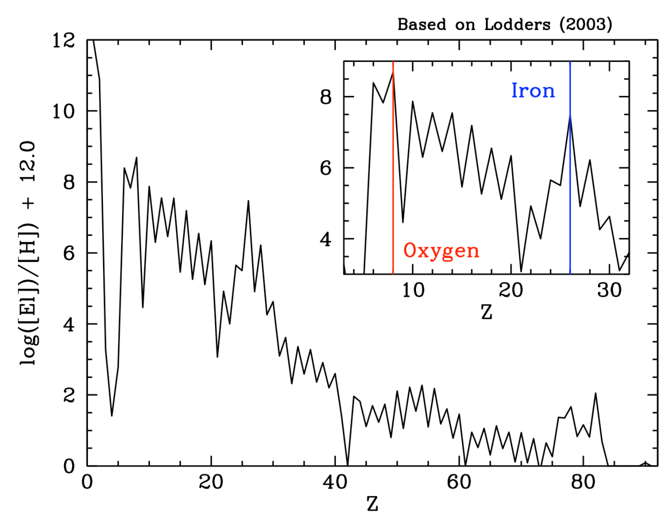
${}^{16}O + {}^{16}O \rightarrow {}^{28}Si + {}^4He$

Silicon burning (T = 5 x10^9 K)

${}^{28}Si + {}^4He \rightarrow {}^{32}S$

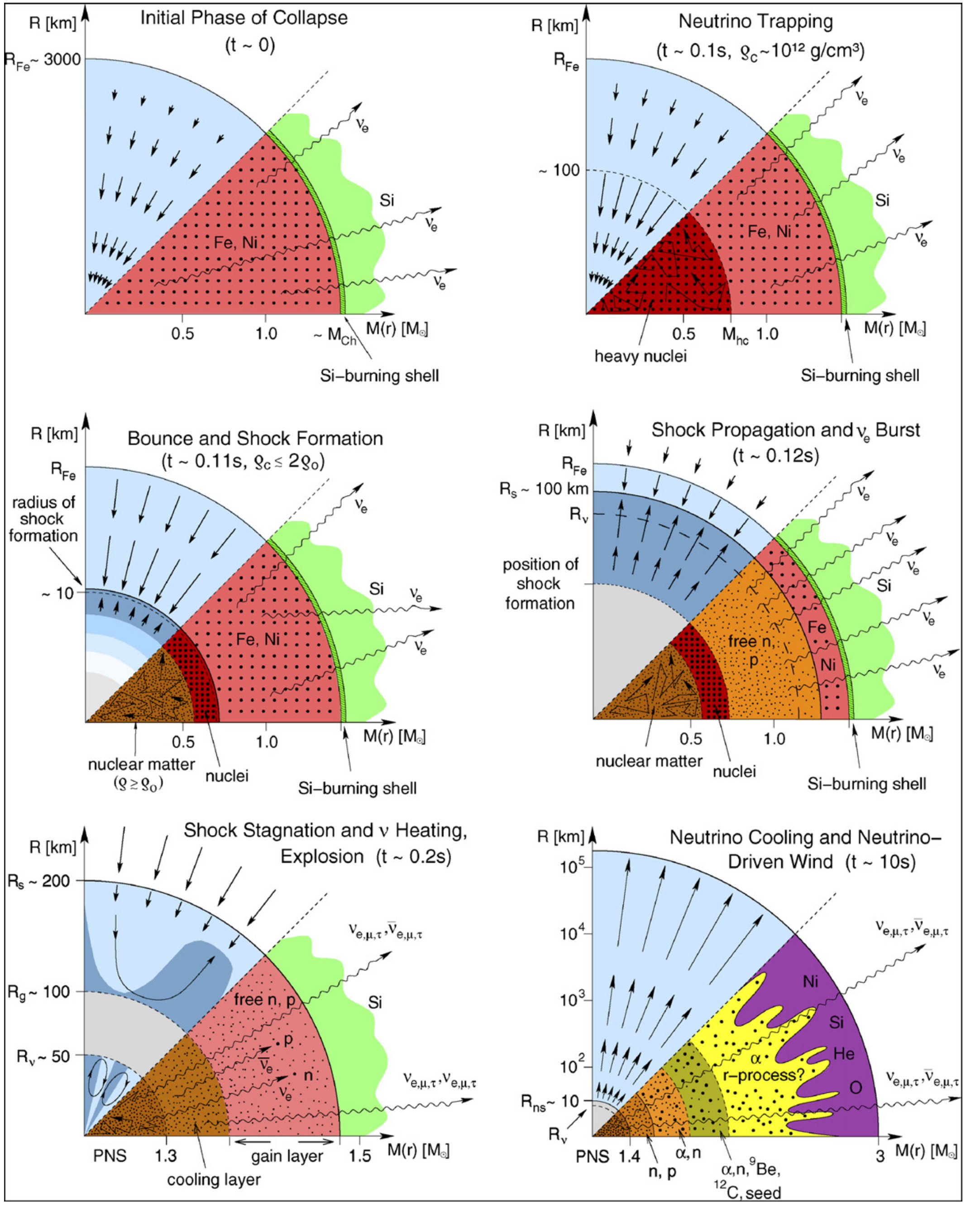
${}^{32}S + {}^4He \rightarrow {}^{32}Ar$,etc.

Important product ${}^{56}Ni$ ($\rightarrow$ ${}^{56}Fe$)



From implosion to explosion

H.-Th. Janka et al. / Physics Reports 442 (2007) 38–74



- The “stiffening” of the core into a proto-neutron star leads to shock formation
- Early idea: shock induces explosion
- Computer simulations:
    - shock stalls
    - neutrino absorptions may revive shock
    - But: computer simulations have difficulties showing a full explosion
- Uncertainties:
    - Neutrino physics
    - Role of rotation and magnetic fields

Standing Accretion Shock Instability

- Infall of material on proto-NS gives rise to accretion instabilities
- Could help explosions
- May help explain pulsar kicks
- Acronym: SASI

46 H.-Th. Janka et al. / Physics Reports 442 (2007) 38–74

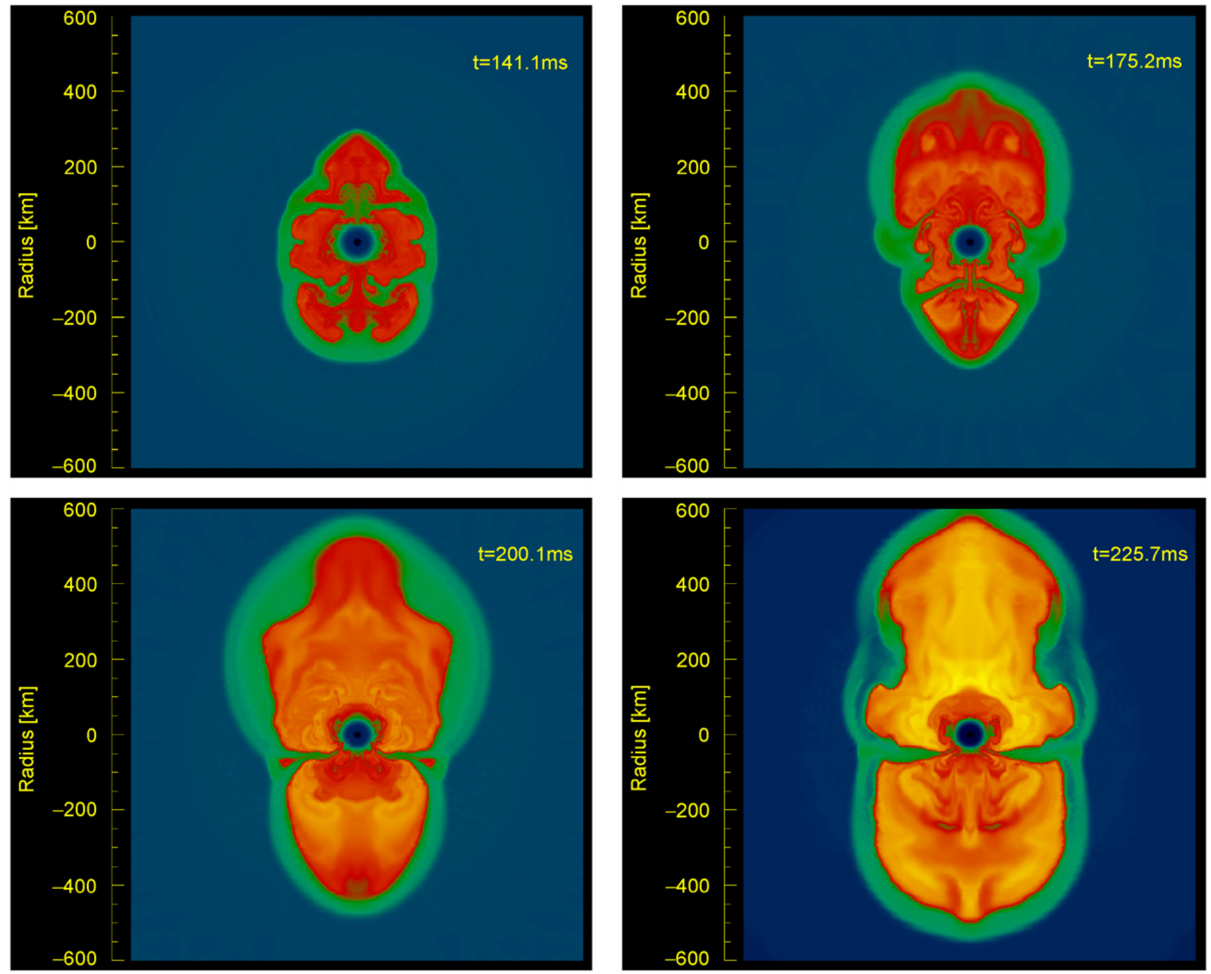
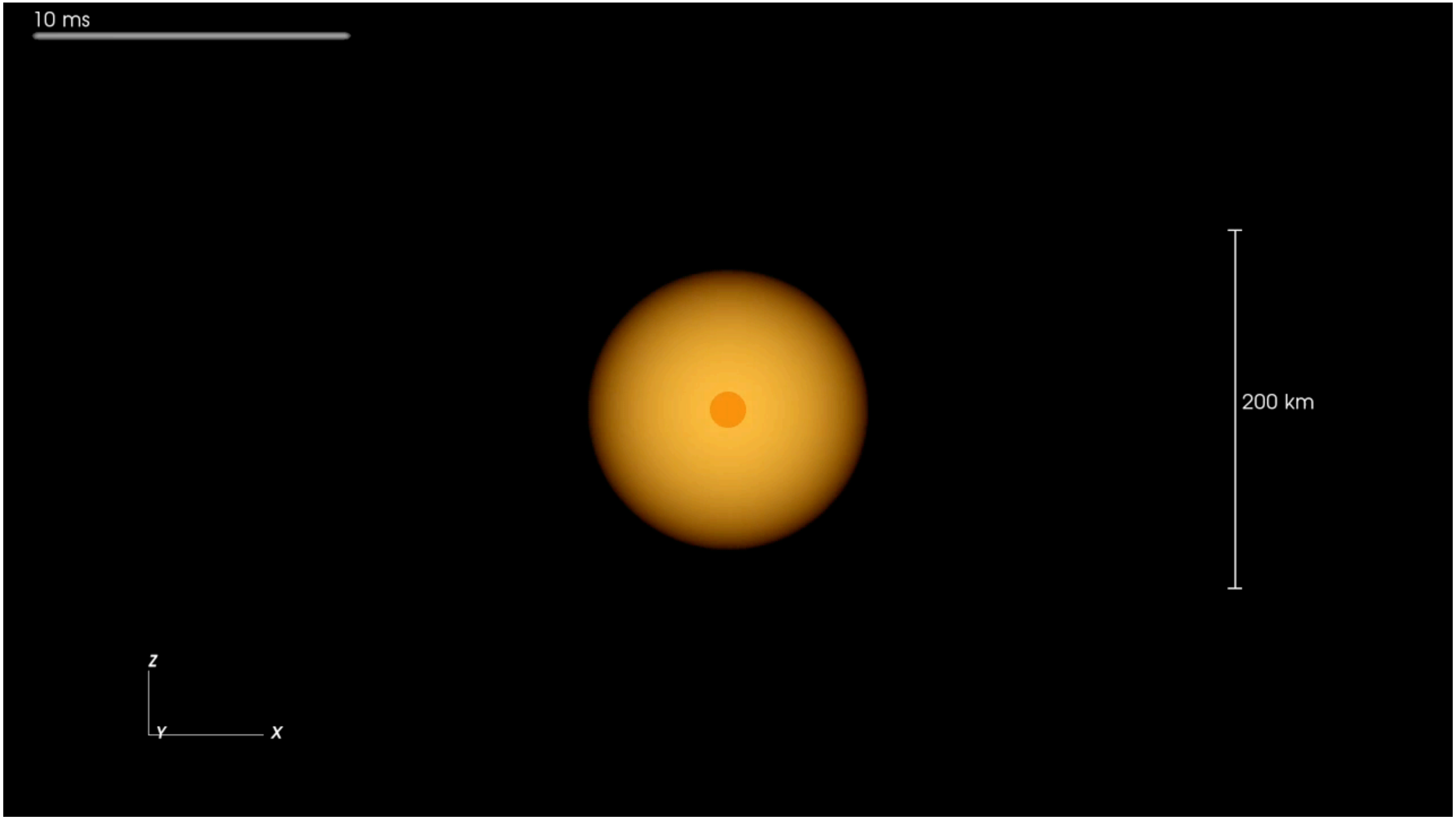


Fig. 4. Four stages (at postbounce times of 141.1, 175.2, 200.1, and 225.7 ms) during the evolution of a (non-rotating), exploding two-dimensional $11.2M_{\odot}$ model [12], visualized in terms of the entropy. The scale is in km and the entropies per nucleon vary from about $5\,k_B$ (deep blue), to 10 (green), 15 (red and orange), up to more than $25\,k_B$ (bright yellow). The dense neutron star is visible as low-entropy ($\lesssim 5\,k_B$ per nucleon) circle at the center. The computation was performed in spherical coordinates, assuming axial symmetry, and employing the "ray-by-ray plus" variable Eddington factor technique of Refs. [41,11] for treating ν transport in multi-dimensional supernova simulations. Equatorial symmetry is broken on large scales soon after bounce, and low-mode hydrodynamic instabilities (convective overturn in combination with the SASI) begin to dominate the flow between the neutron star and the strongly deformed supernova shock. The model develops a—probably rather weak—explosion, the energy of which was not determined before the simulation had to be stopped because of CPU time limitations.

First second in life of NS/SN



- https://www.youtube.com/watch?v=8BLiCZISwLY

Neutrino emission

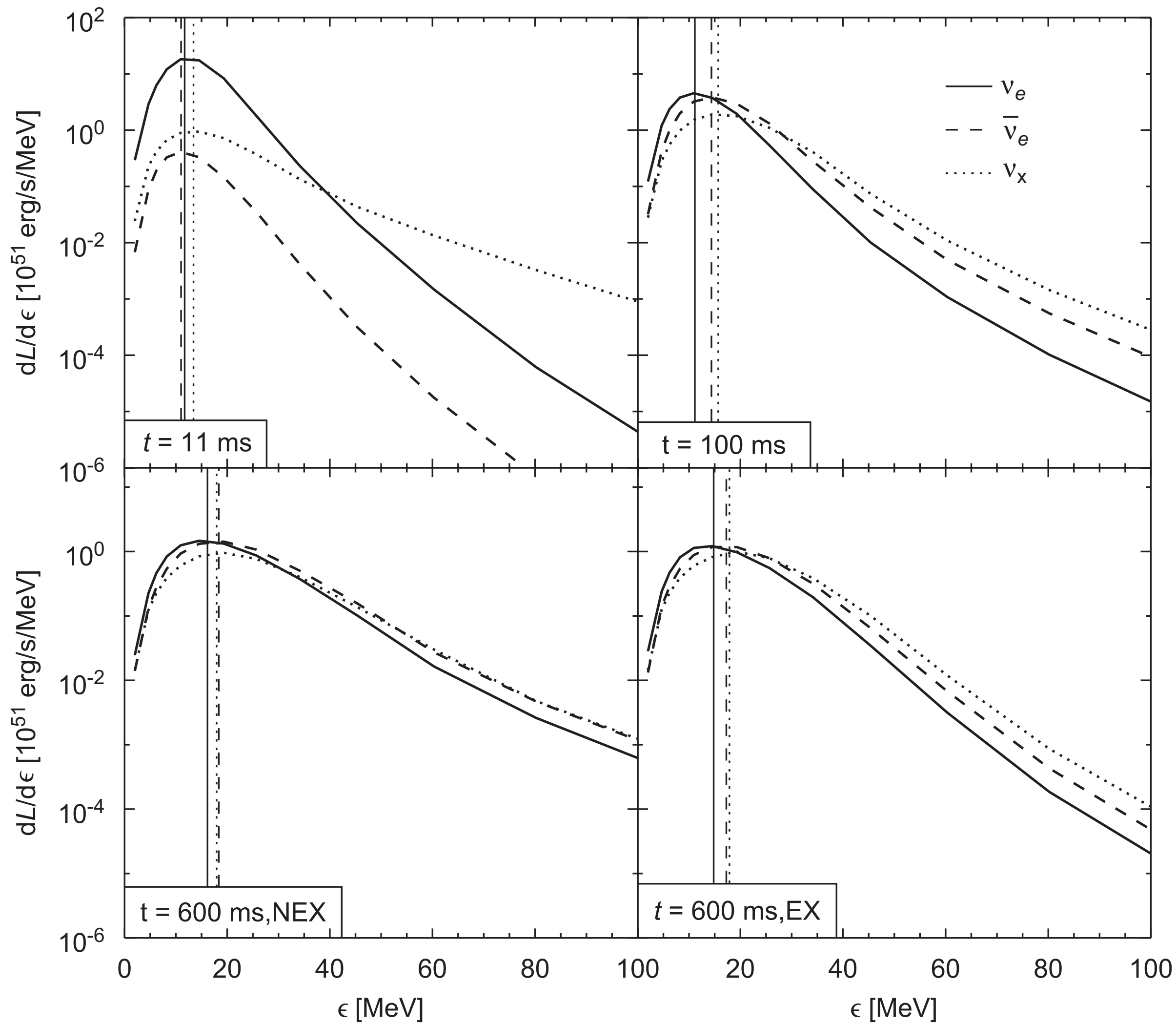
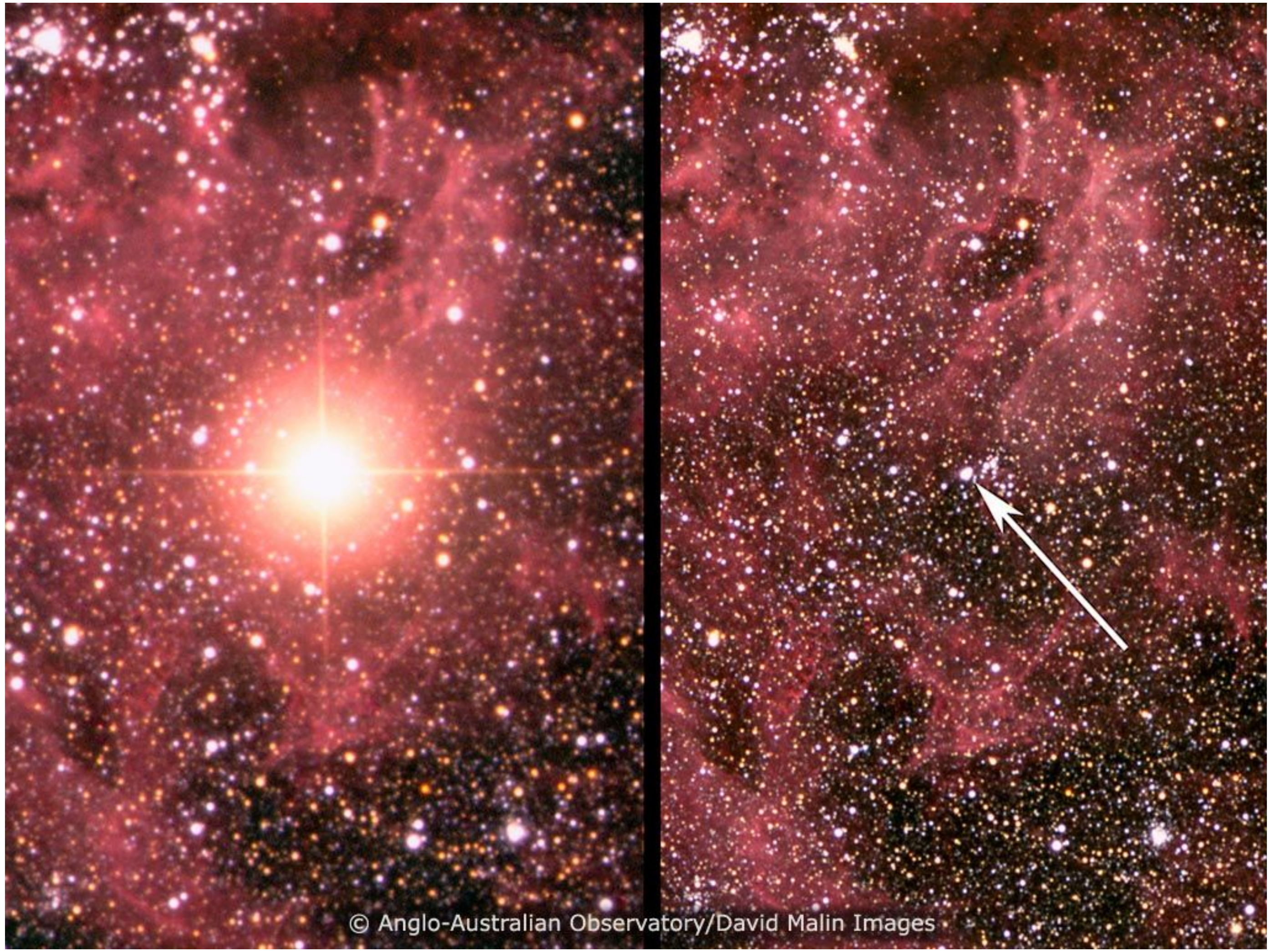


Fig. 2. Luminosity spectra for ν_e, $\bar{\nu}_e$, and heavy-lepton neutrinos ν_x for a spherically symmetric 20 $M_\odot$ model. The spectra are given for an obser at rest at 400 km for three different postbounce times: shortly after the peak of the ν_e shock breakout burst 11 ms after bounce, when the shock is n its maximum radius (around 100 ms p.b.), and at 600 ms after bounce. The lower left panel gives the spectra for a non-exploding model, the lov right panel for a corresponding simulation in which an explosion was artificially initiated at 230 ms after core bounce, thus stopping the accreti onto the nascent neutron star. The vertical lines mark the locations of the mean neutrino energies, which are defined as the ratio of energy flux number flux, $\langle\epsilon\rangle = L_e/L_n$. Note the similarity of $\langle\epsilon_{\bar{\nu}_e}\rangle$ and $\langle\epsilon_{\nu_x}\rangle$ at $t = 600$ ms (ν_x stands for muon and tau neutrinos and antineutrinos).

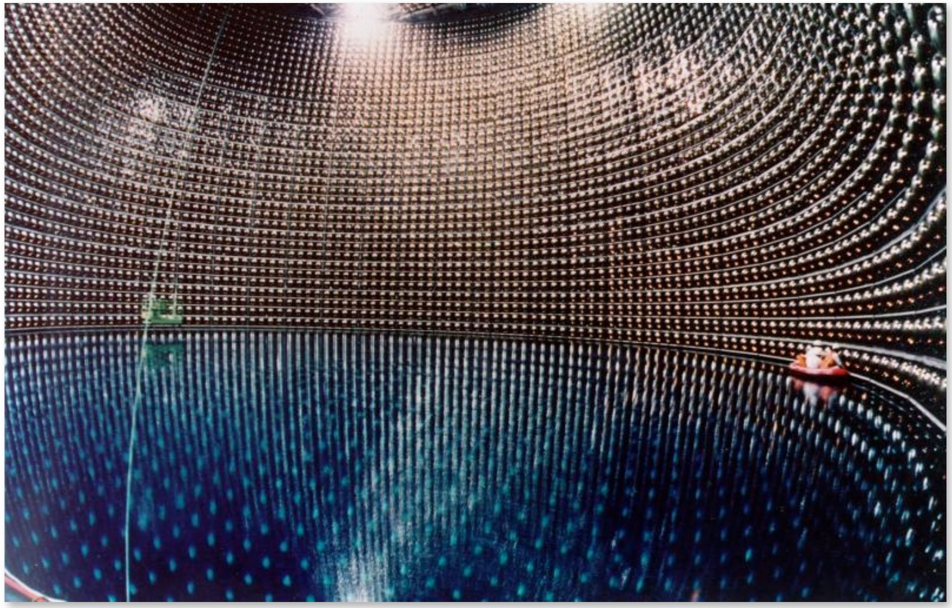
SN1987A



- Discovered on 23 February 1987 in the Large Magellanic Cloud (50kpc)
- Balmer lines: Type II supernova
- Progenitor(=star before supernova) was known: a blue supergiant
- Evolution a-typical for Type II SN.
- Also peak luminosity lower than average Type II (smaller sized star)

Neutrino detection 2 hr before SN1987A

Kamiokande detected
12 neutrinos on 23 feb '87
Confirmation of neutron star formation theory!!



Kamiokande

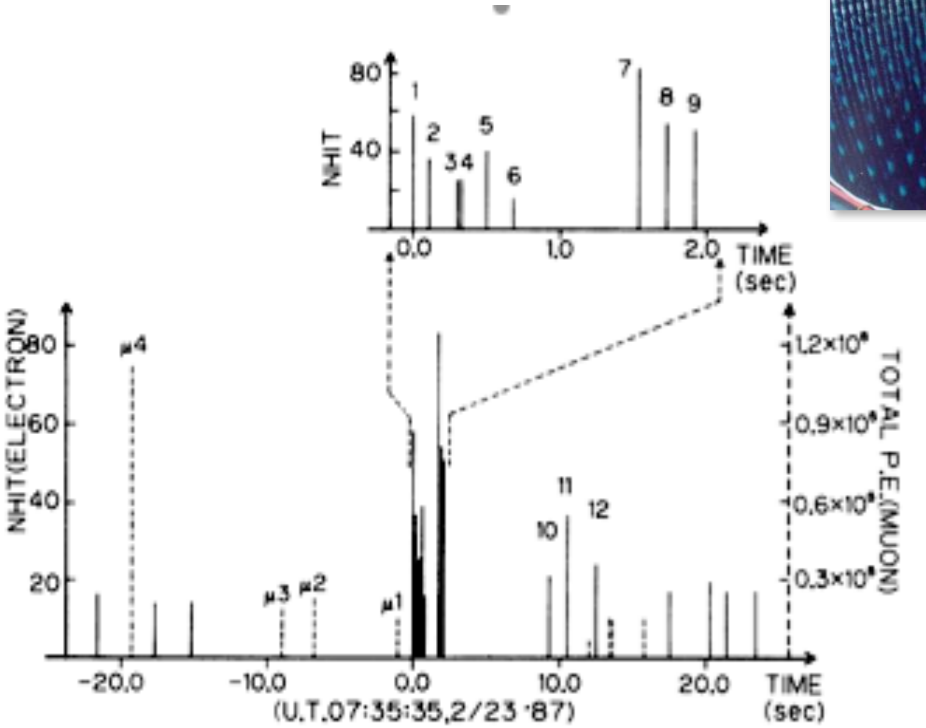
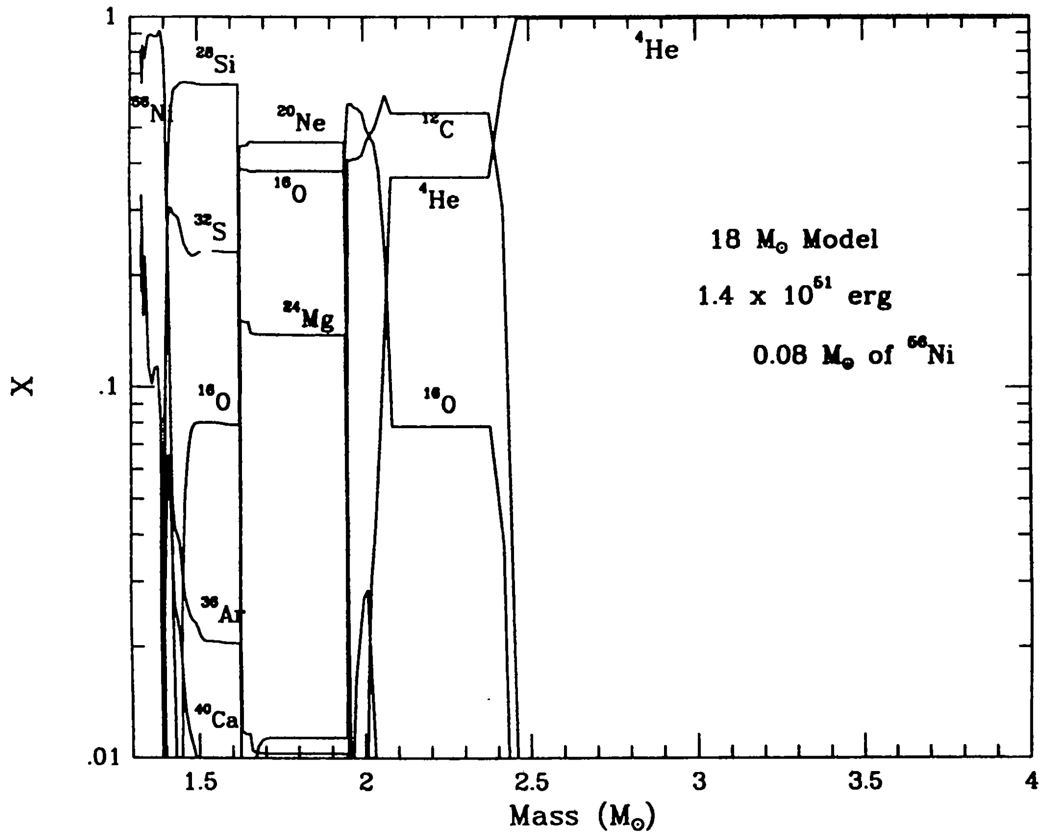
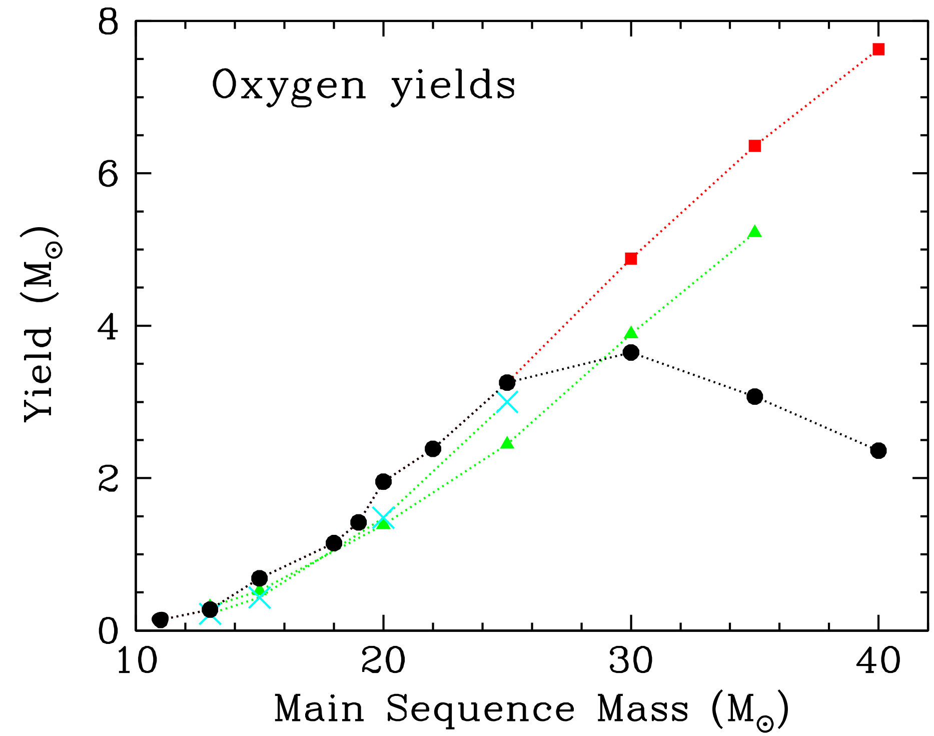


FIG. 2. The time sequence of events in a 45-sec interval centered on 07:35:35 UT, 23 February 1987. The vertical height of each line represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMT's, N_{hit} (left-hand scale). Dashed lines represent muon events in units of the number of photoelectrons (right-hand scale). Events $\mu1$–$\mu4$ are muon events which precede the electron burst at time zero. The upper right figure is the 0–2-sec time interval on an expanded scale.

Composition of a core collapse supernova

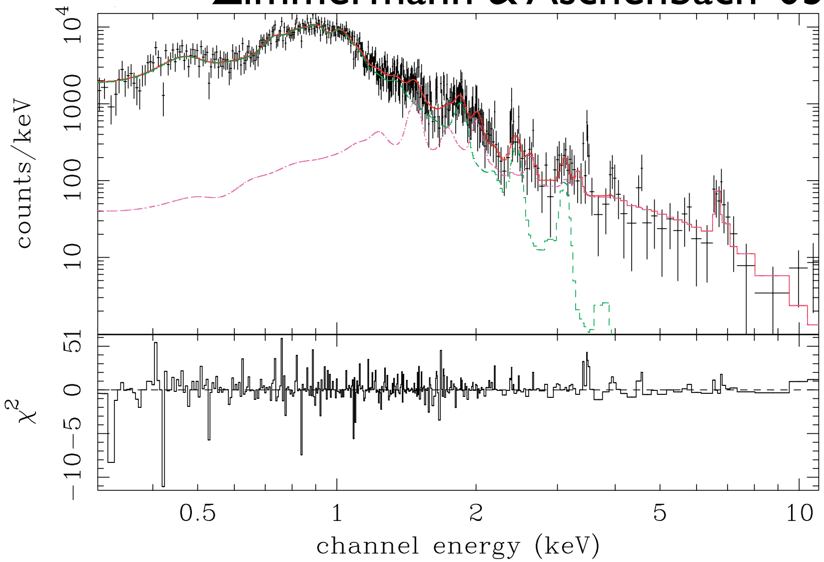


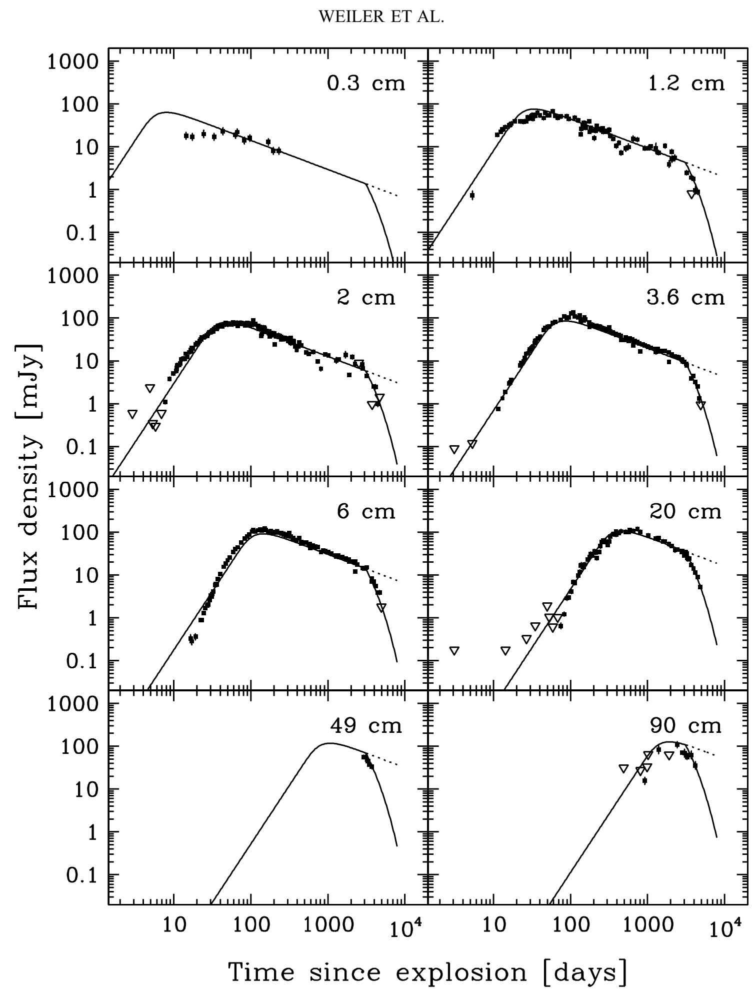


- SN material layered according to late shell burning stages
- During explosion: additional nucleosynthese near core
- Iron (and nickel) in supernova not from core, but formed during explosion
- Core collapse SNe: oxygen rich
- Oxygen scales with mass on main sequence
- $M>25M_{sun}$: uncertainty due possible BH formation

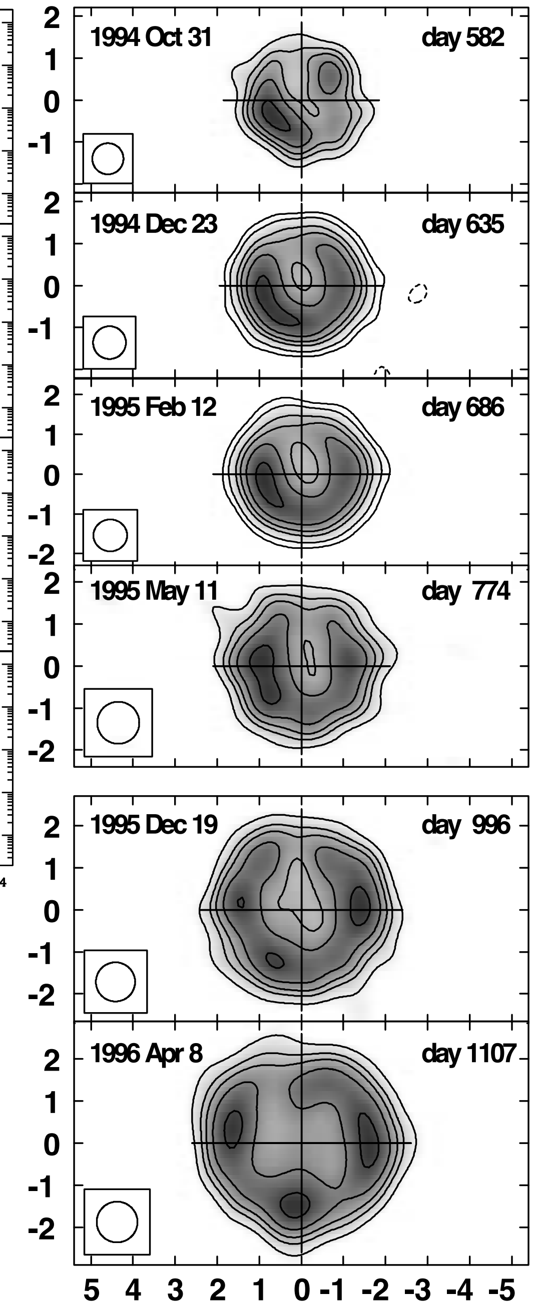
Radio supernovae

Zimmermann & Aschenbach '03



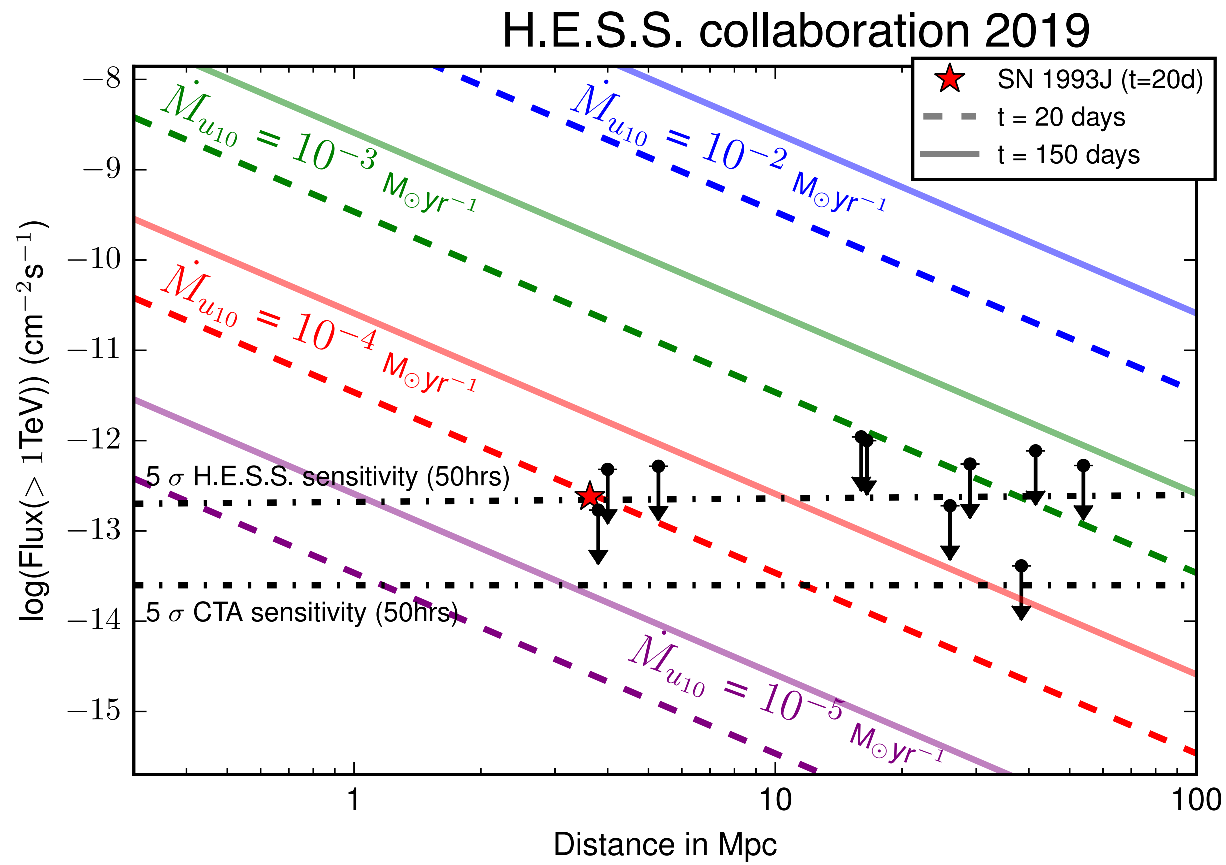


Bietenholz+ 03



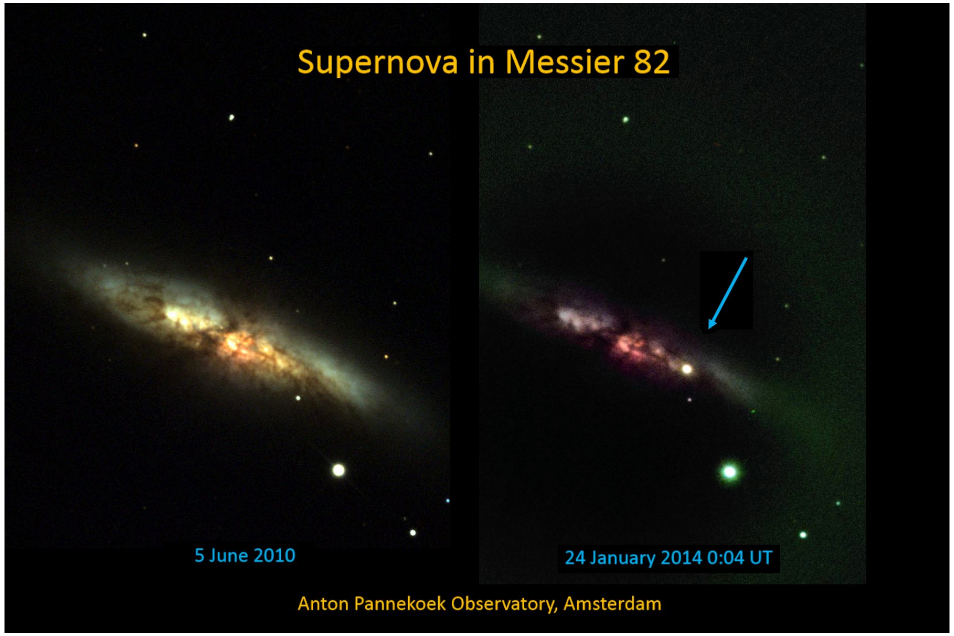
- Some CC SNe show early radio emission:
  - SNe shock interaction with dense CSM
    - -> heavy mass loss progenitor
  - Synchrotron self absorption important
  - Often IIb SNe
  - Shell can monitored using VLBI
  - Radio supernova=very young SNR

No gamma-ray emission from radio SNe yet



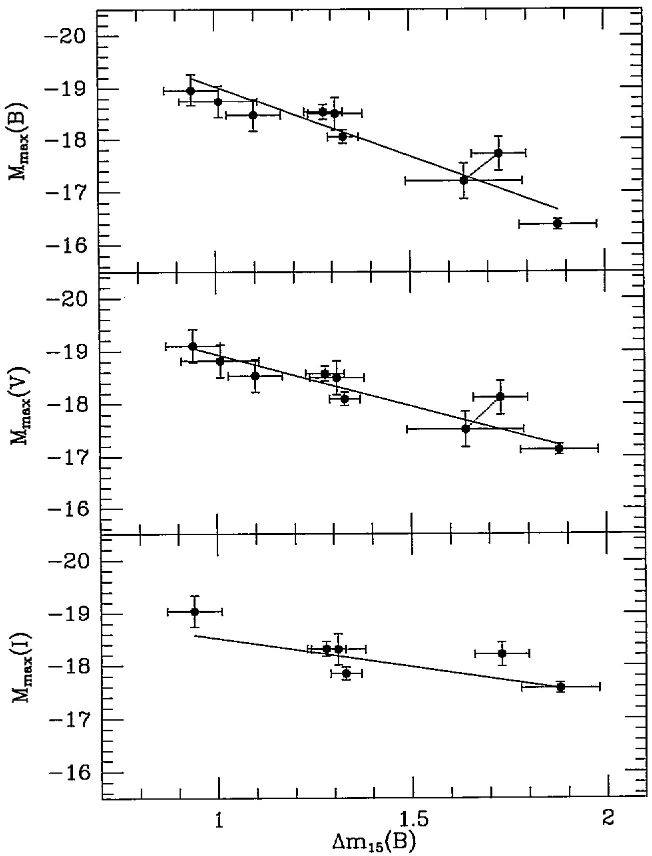
- Highest energy (Galactic) cosmic rays may originate from SN/CSM interaction
- Could solve PeVatron problem
- Need to observe SNe few months after explosion
- So far: upper limits -> constraint on the CSM density: $\rho_{\mathrm{CSM}} = \dfrac{\dot{M}}{4\pi r^2 v_{\mathrm{w}}}$

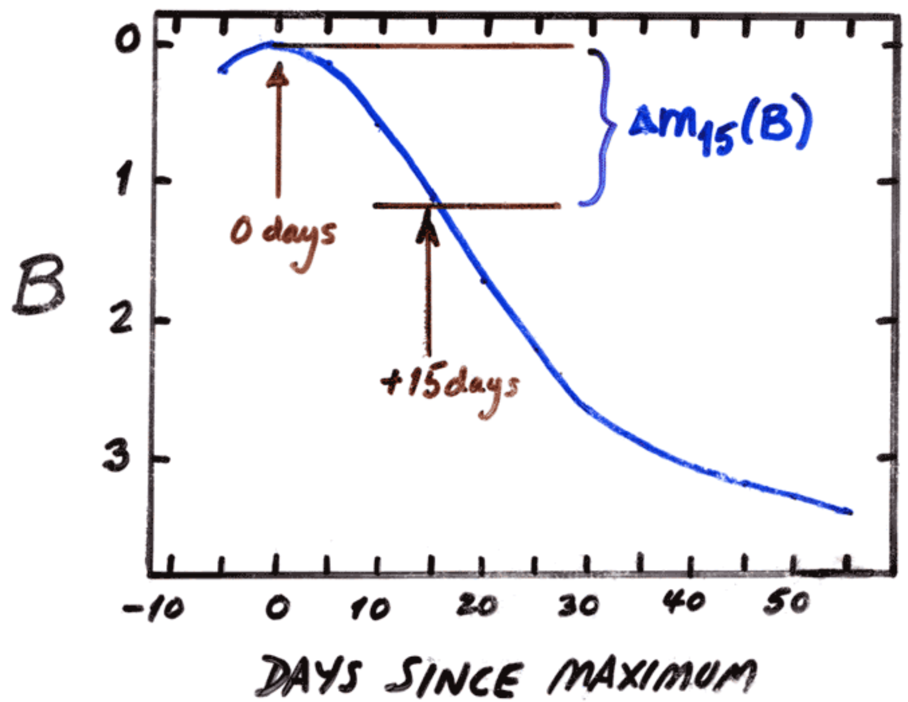
Thermonucleair supernovae



- C/O white dwarfs explosion needs to be triggered
- Density in nucleus high enough (e.g. accretion) → nucleus shrinks → nucleair reactions → runaway reactions (explosion)
- Around $M \sim 1.38\, M_{sun}$: density in nucleus high enough → explosion
  - nucleair reactions cause rise in temperature
  - nucleus does not expand, because pressure degenerate (not thermal) → runaway
  - most important burning product: C,O → ^{56}Ni
  - important decay chains:
    - ^{56}Ni →^{56}Co (8.8 d) (electron capture)
    - ^{56}Co→ ^{56}Fe (111 d) (electron capture and beta-decay, 19%)
  - Nett yield $\sim 0.7 M_{zon}$ of Fe!
- Supernova ejecta: expanding gas, rich in iron/nickel, silicon and other fresh nucleosynthesis products

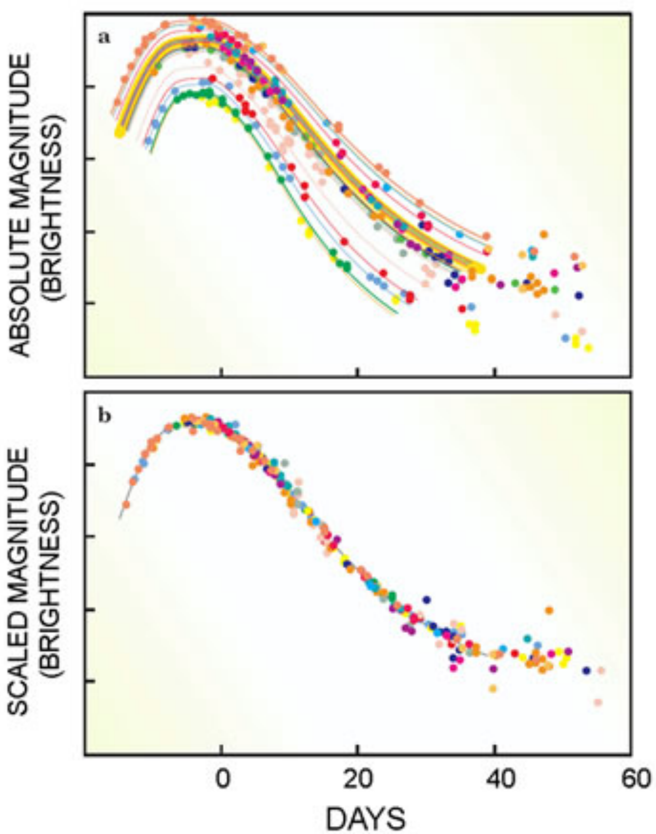
Type Ia supernovae and cosmology: the Phillips relation



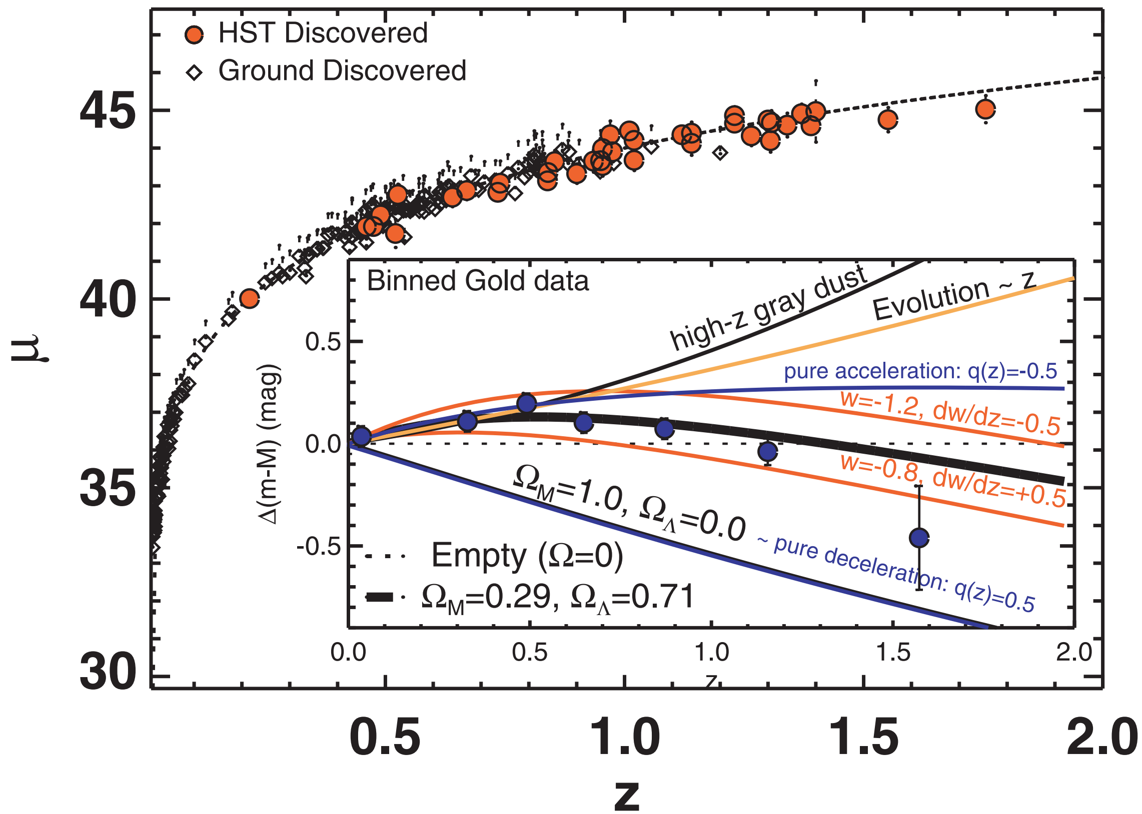


- Type Ia peak magnitude has less variation than Type II SNe
- But variation is even more reduced after application of Phillips-relation(1995):
- The peak brightness appears to be linearly correlated with how fast the brightness decreases (15 day difference in magnitude from peak)

Type Ia supernovae and cosmology: the Phillips relation

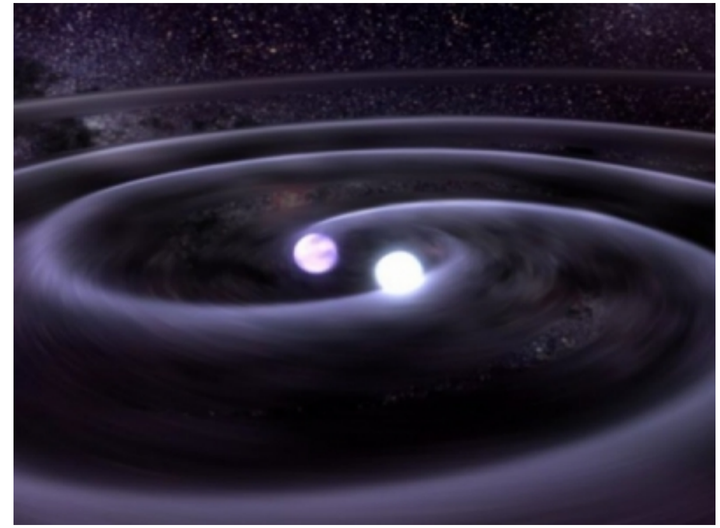


Riess et al 2007



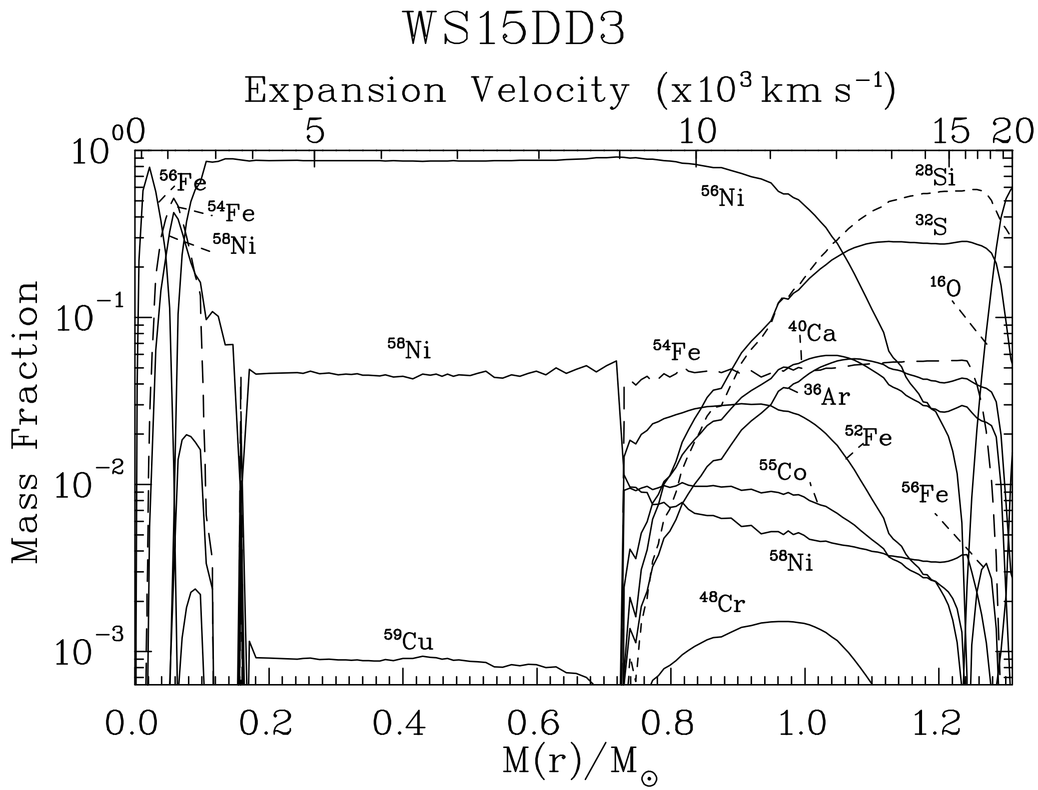
- Phillip's discovery made it possible to use Type Ia SNe as "standard candles" te gebruiken
- This resulted in the discovery that the Universe accelerates
- Nobel-price 2011 for Perlmutter, Riess, Schmidt

What kind of white dwarf binaries make SNe Ia?

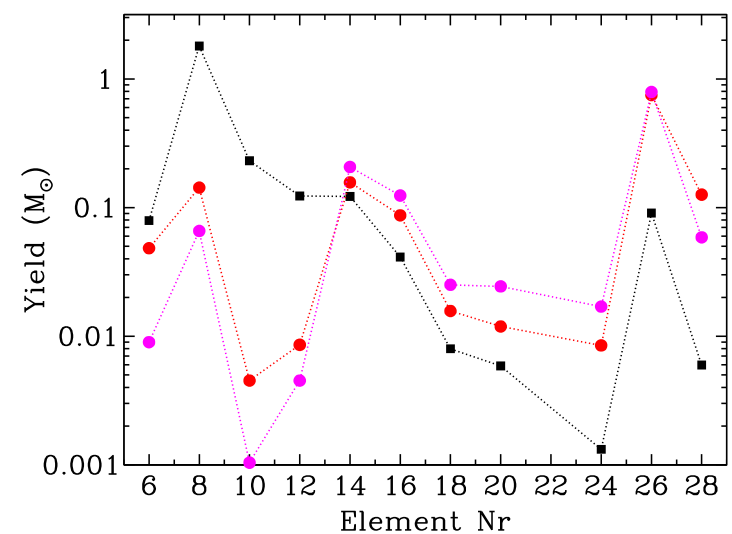


- There is a controversy about the types of systems that make Type Ia supernovae
- Two basic scenarios:
  - “single degenerate channel”: CO white dwarf accretes from “normal” star
  - “double degenerate channel”: merging of two CO white dwarfs
- Problems:
  - single degenerate:
    - no proof for surviving donor stars inside Type Ia supernova remnants
    - no proof for interaction of SN shock with the donor star and/or its wind
  - double degenerate:
    - few good models to check whether this gives Type Ia explosions
    - long time scales (>1 Gyr) for two WDs to merge due to gravitational radiation
    - fits not well with evidence for “short channel” (100 Myr) of Type Ia after star burst

Differences in composition



Type Ia explosion-model by Iwamoto '99

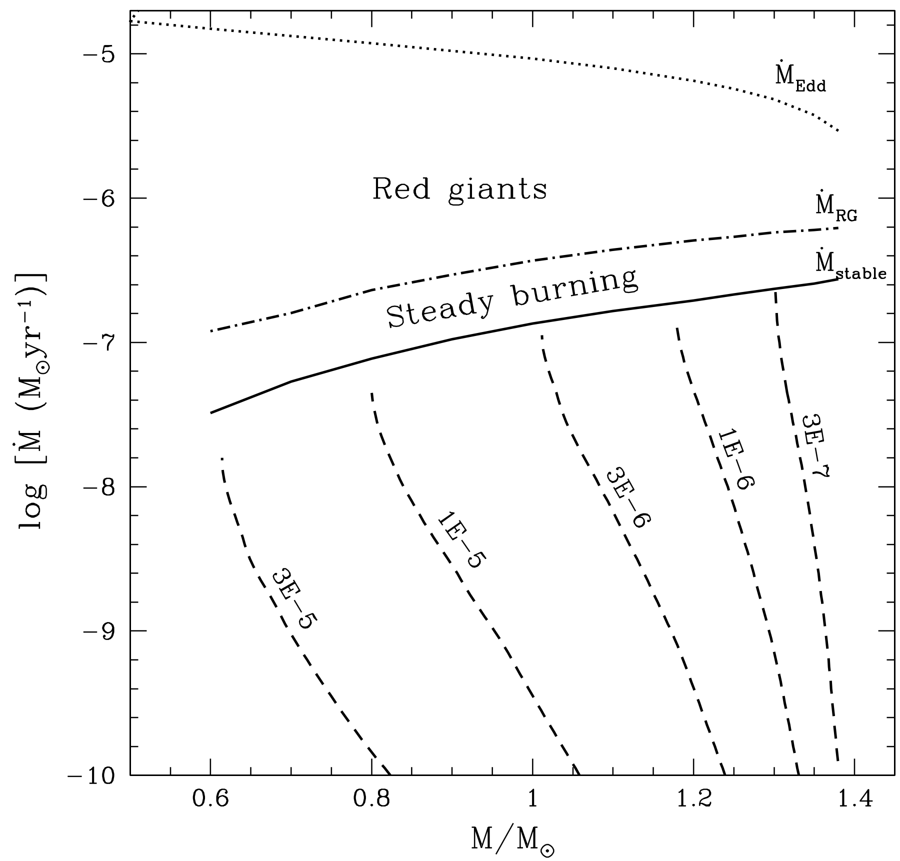


- Color: 2 different Type Ia models
- Black: mean yield of core collapse SNe

- Single WD explosion: multiple explosion models
  - Detonation (discarded now)
  - Deflagration
  - Delayed detonation

Accretion problem:

Nomoto 2007



- Nomoto (o.a. 2007): Stable accretion onto white dwarf only possible in narrow accretion rate ($dM/dt \approx 10^{-7}\ M_{sun}/yr$)
- Lower accretione: H/He layer builts up before explosion: probably more ejection than accretion (denkt men)
- Higher accretion rate: an extended envelope develops or collapse to neutron star
- Problem: only a small fraction of WD will accrete just in the right regime (fine-tuning problem). Hence not enough systems can make SN Ia

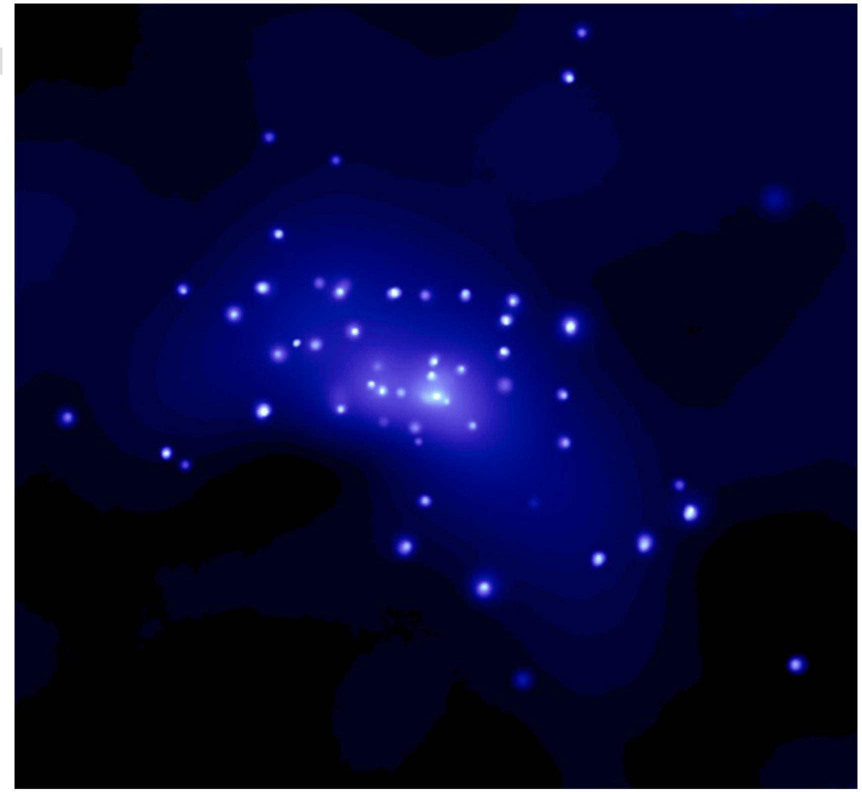
Proof against single degenerate channel I

nature Vol 463|18 February 2010|doi:10.1038/nature08685

LETTERS

An upper limit on the contribution of accreting white dwarfs to the type Ia supernova rate

Marat Gilfanov[1,2] & Ákos Bogdán[1]



- In elliptical galaxies only Type Ia
- Accretion of progenitors: there should be a soft X-ray glow from accretions that will become Type Ia
- Not enought soft X-ray emission to explain the frequency of SNe Ia

Proof against single degenerate channel I

NATURE | LETTER

日本語要約

An absence of ex-companion stars in the type Ia supernova remnant SNR 0509−67.5

Bradley E. Schaefer & Ashley Pagnotta

Affiliations | Contributions | Corresponding author

Nature **481**, 164–166 (12 January 2012) | doi:10.1038/nature10692
Received 29 June 2011 | Accepted 31 October 2011 | Published online 11 January 2012

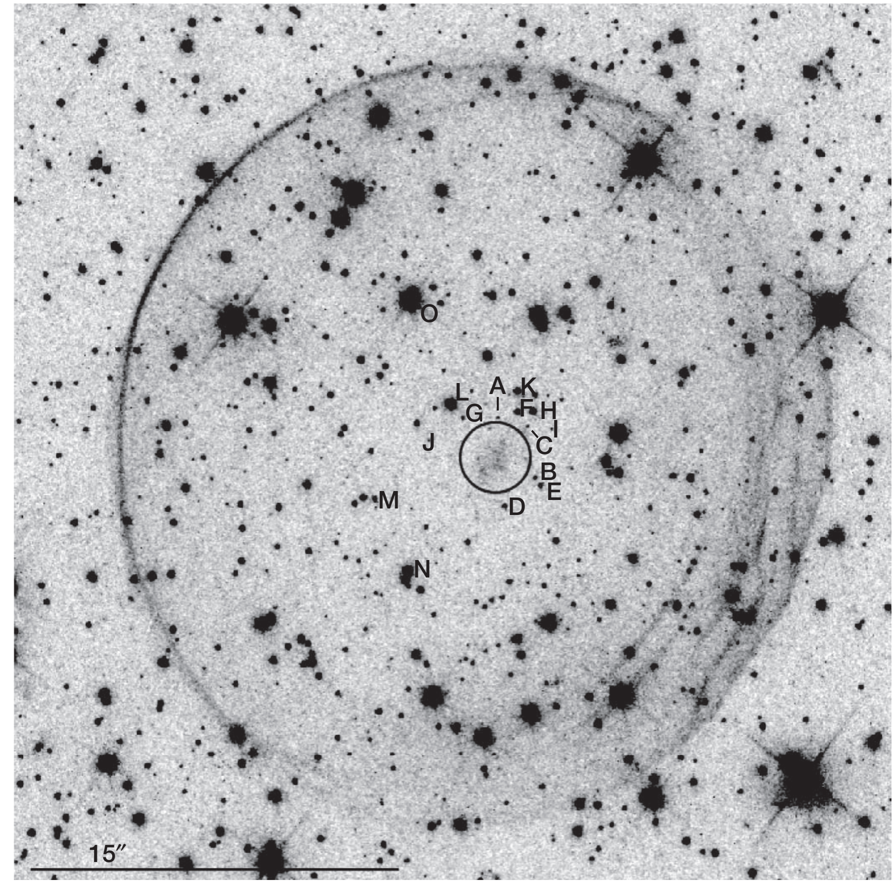
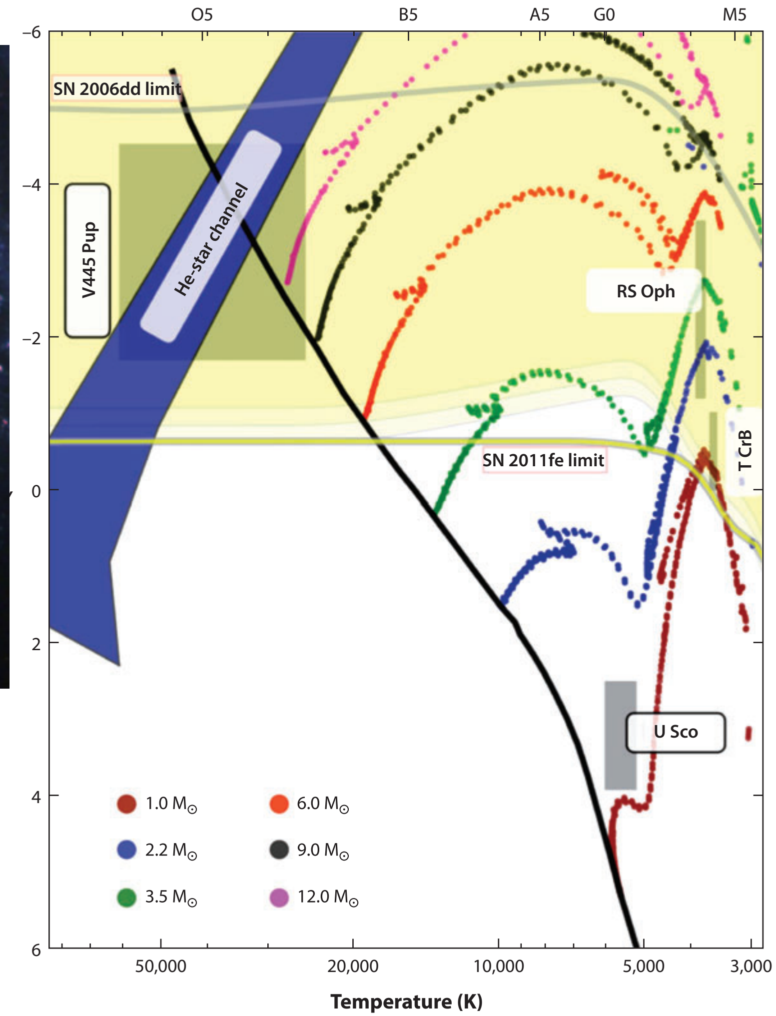


Figure 1 | SNR 0509−67.5 and the extreme 99.73% error circle. This is a

- In supernova remnant SNR0509-67.5: no surviving donor star
- Circle indicates search radius

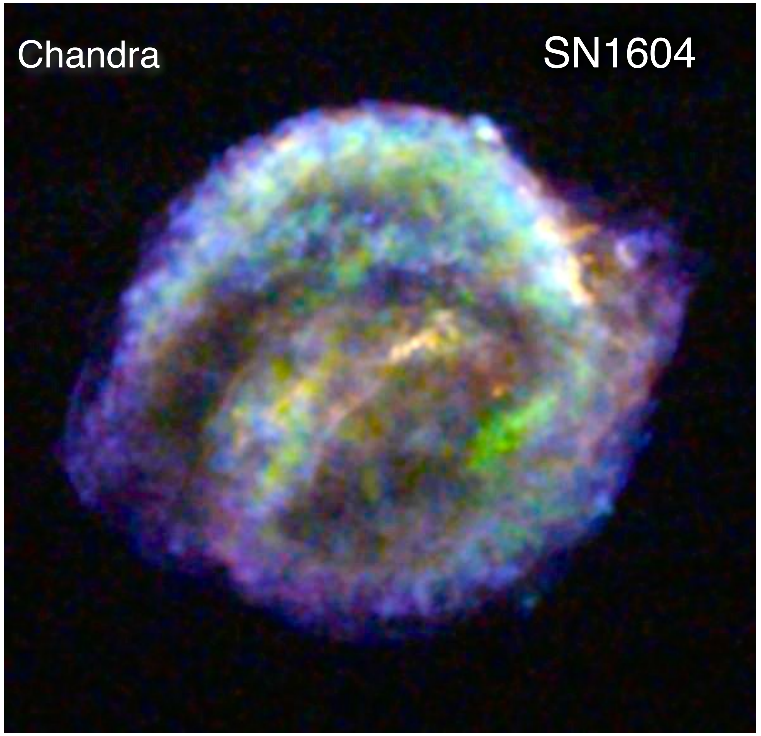
Lack of progenitor detection in SN2011fe

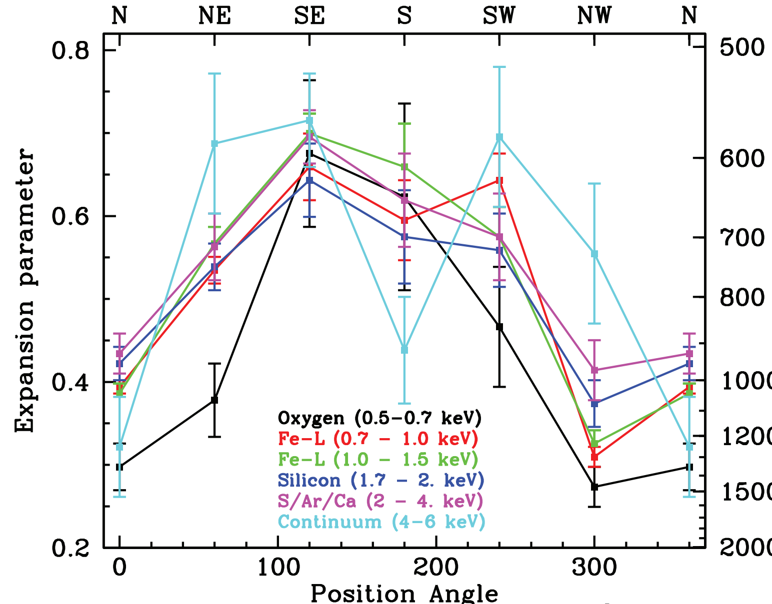
M101



- Red giant progenitor companions ($M>3.5\ M_{sun}$) excluded

Proof in favor of single degenerate channel I

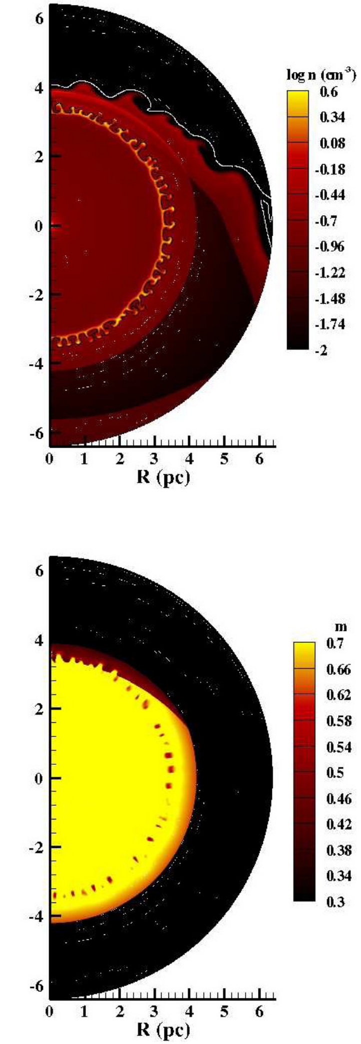




Vink 2008

Fig. 6.— Expansion parameter of Kepler's SNR as a function of azimuthal angle. The angle is measured from the north in a counterclockwise direction. The different colors indicate expansions measured in different energy bands, using the same color coding as in Fig. 3. The data points have been cyclic, so the data points at 360° repeat those at 0°. The vertical axis on the right indicates the corresponding expansion time.

Chiotellis Schure Vink 2012

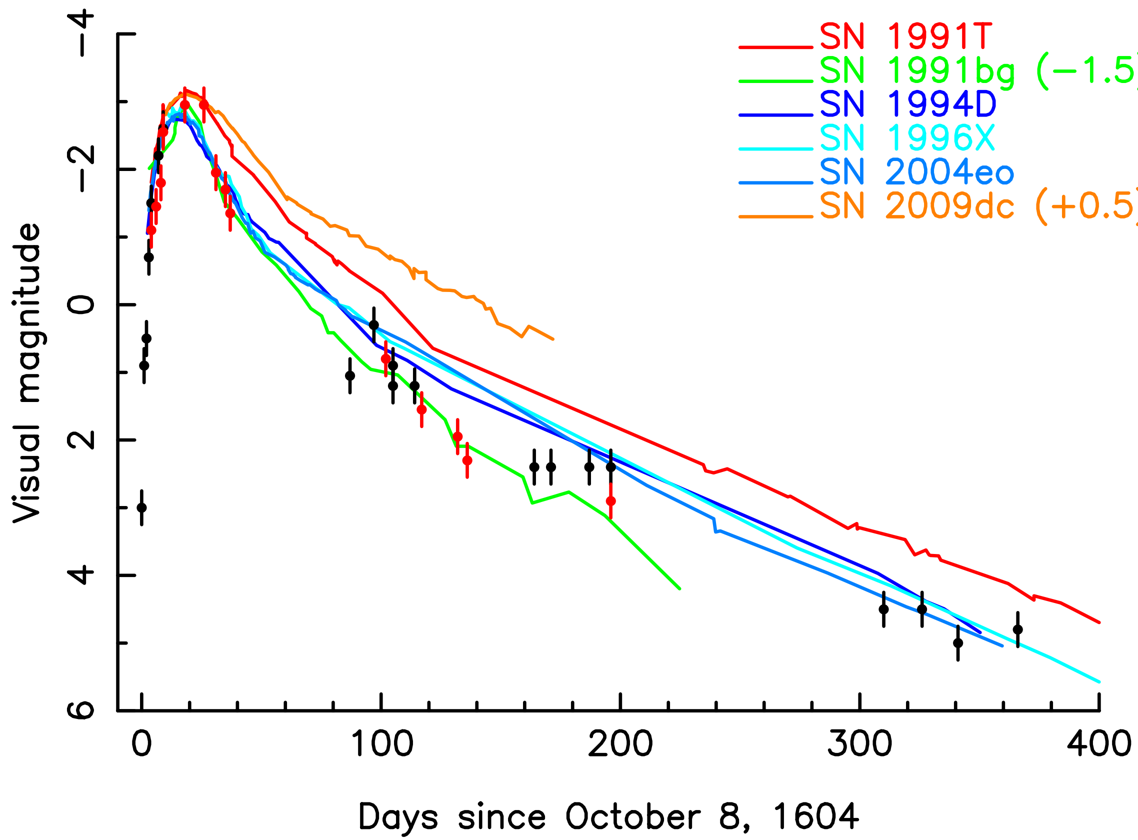


- Kepler's supernova remnant (SN1604):
  - High above Galactic plane (>500 pc)
  - Movement of progenitor out of Milky Way >250 km/s
  - Shock decelerated in the North: pre-supernova stellar material (Vink 2008)
  - At this distance from Milky Way no other origin of material than progenitor (Chiotellis, Schure, Vink, 2012)
  - White dwarfs don't have a stellar wind: a star must have been present

The historical light curve of SN 1604

Estimates of Brightness and Color of Nova Ophiuchi of 1604

Date (Gregorian)	Brightness of Nova	Color	Observer
1604 Oct. 8	Not seen		Several
Oct. 9	As bright as Mars	Like Mars	Anonymous physician (Cosenza)*
	As bright as Jupiter	Like half of ripe orange	Altobelli (Verona)†
Oct. 10	Somewhat brighter than on Oct. 9		Anonymous physician*
	Very similar in brightness to Mars	Like Mars	Capra-Marius (Padua)‡
Oct. 11	Still brighter than on Oct. 10		Anonymous physician*
	Twice as bright as Jupiter		Heck (Rome)§
Oct. 12	Almost as bright as Jupiter		Roeslin (Hagenau)‖
Oct. 15	As bright as Jupiter or somewhat more	Like Jupiter	Anonymous physician*
	Much brighter than Jupiter; no further increase after this day		Altobelli†
	As bright as Jupiter or a little more; no further increase afterward		Capra-Marius‡
	A little brighter than Jupiter	Like Jupiter; white, not red	Fabricius (Osteel)¶
	As bright as or brighter than Jupiter		Brenzoni (Verona)**
	Brighter than Jupiter and equal to Venus		Maestlin (Tübingen)††
Oct. 17	Much brighter than Jupiter (almost twice as bright)		Kepler (Prague)‡‡
1605 Jan. 3	Brighter than α Sco, much fainter than α Boo		Kepler‡‡
Jan. 13	Brighter than α Boo and Saturn		Kepler‡‡
Jan. 14	About as bright as Mars (in Oct., 1604)		Fabricius¶
~Jan. 21	About as bright as α Sco, a little brighter than Saturn		Maestlin††
End of Jan.	As bright as α Vir		Heydon (London)§§
March 20	Not much brighter than ζ and η Oph		Kepler‡‡
March 27	Not much brighter than ζ and η Oph		Brengger (Kaufbeuren)‖‖
~March 28	Not much brighter than η Oph		Cristini¶¶
April 12	As bright as η Oph		Fabricius¶
April 21	As bright as η Oph		Kepler‡‡
Aug. 12–14	As bright as ξ Oph		Kepler‡‡
Aug. 29	About as bright as ξ Oph		Kepler‡‡
Sept. 13	Fainter than ξ Oph		Kepler‡‡
Oct. 8	Difficult to see; fainter or equal ξ Oph		Kepler‡‡

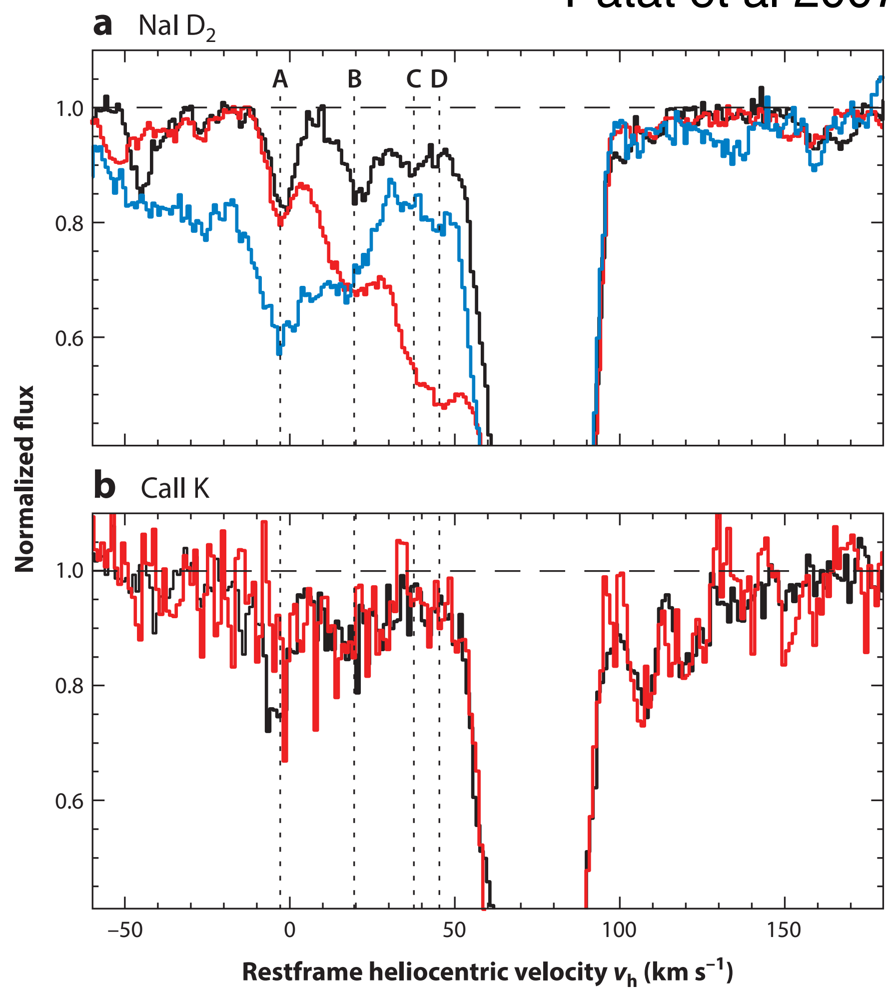


European obs: Walther Baade 1944

Korean: Stephenson & Green 2002

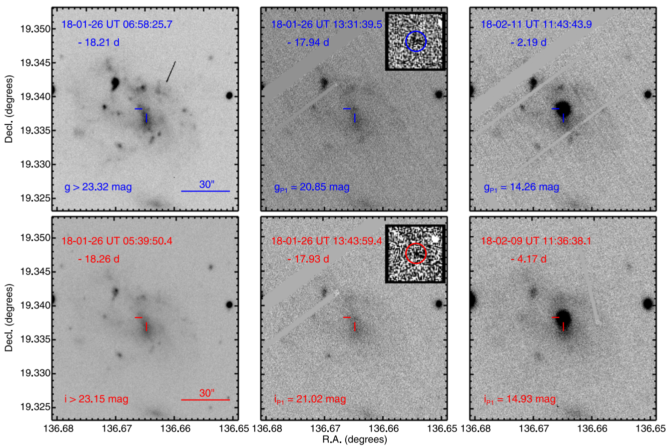
Proof in favor of single degenerate channel II
Blueshifted Na D lines

Patat et al 2007

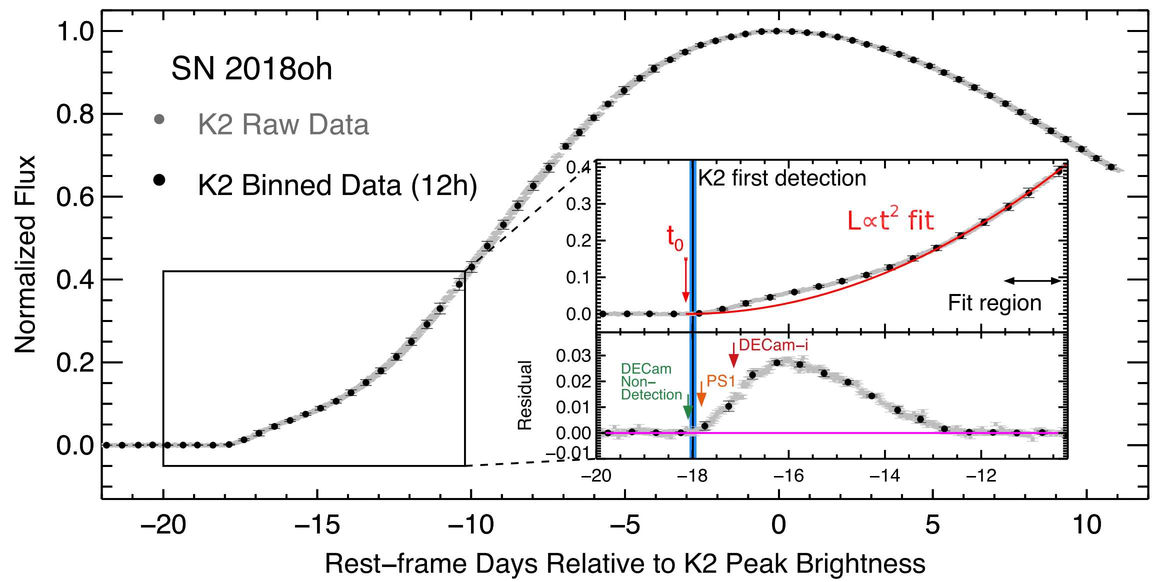


- Lack of radio/X-ray from circumstellar interaction -> DD scenario
- But some SNe Ia: Na D blueshifted absortpion -> expanding shell
  - Could be novae shell!

Proof in favor of single degenerate channel III
Early bump in light curve



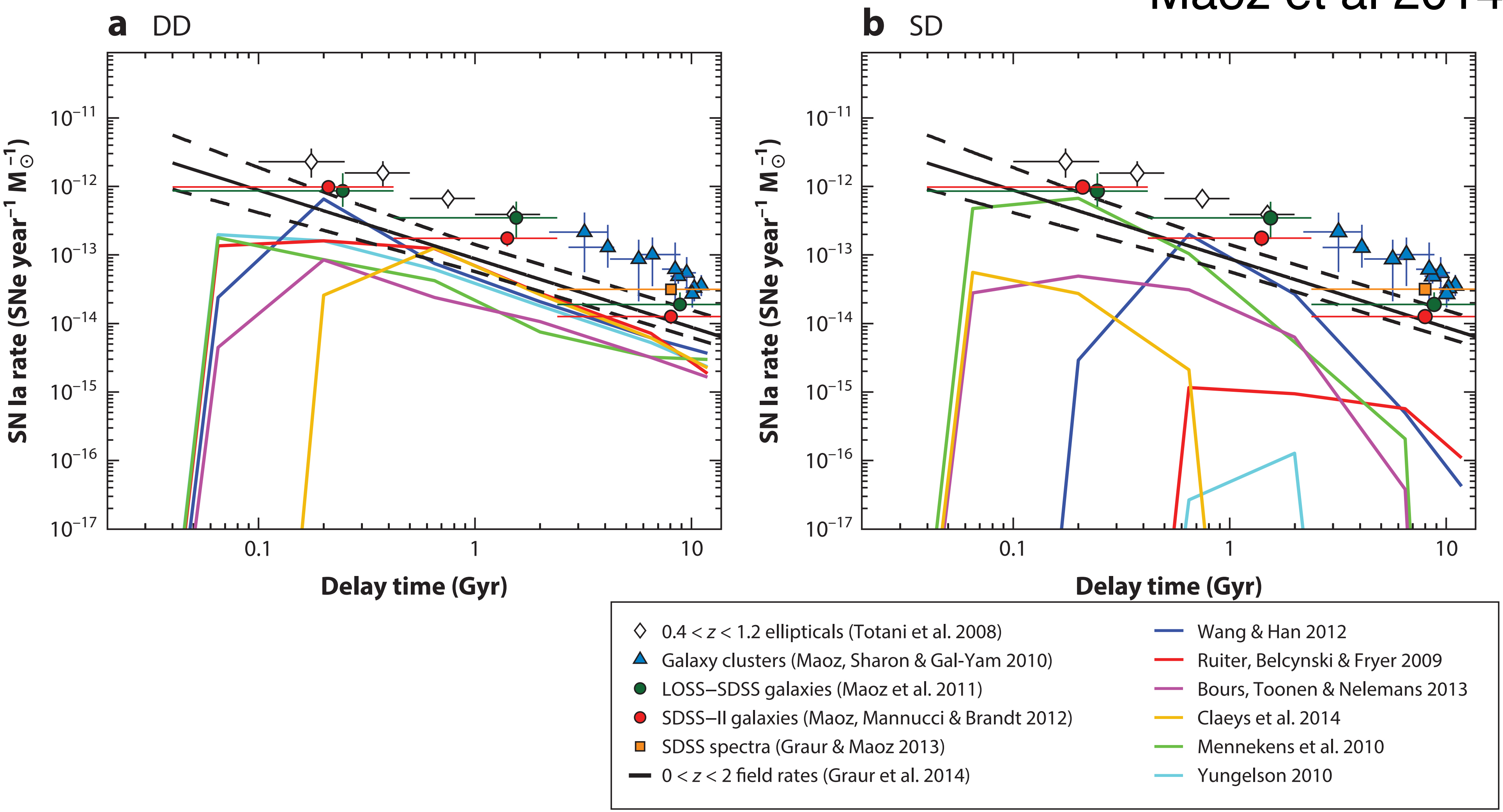
Dimitriadis+ 2019



- SN2018oh: detected by Kepler satellite
- Very early light curve!
- Shows early bump -> shock wave heating companion star?
    - Predicted by Kasen 2009

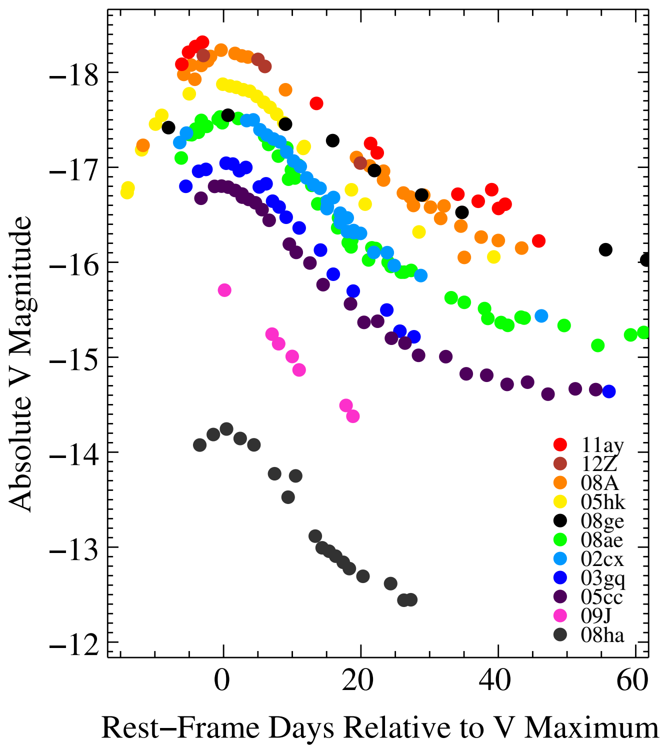
Type Ia delay time distribution

Maoz et al 2014

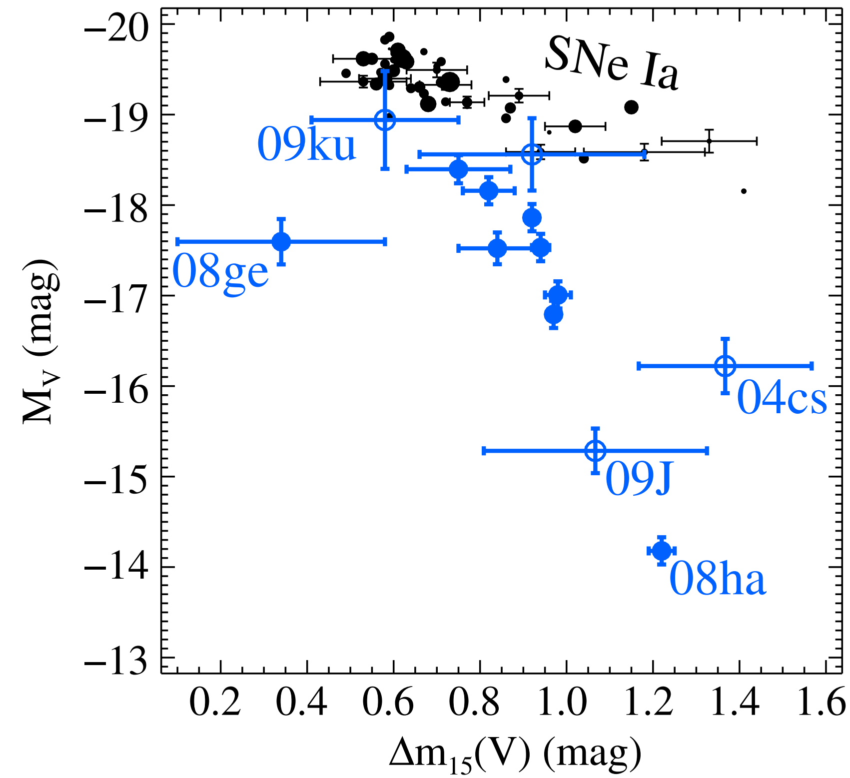


- DD scenarios have more difficulty explaining “early” SNe Ia
- SD cannot explain late time explosions
- Reality: a mix?

Type Iax: a SN Ia subclass



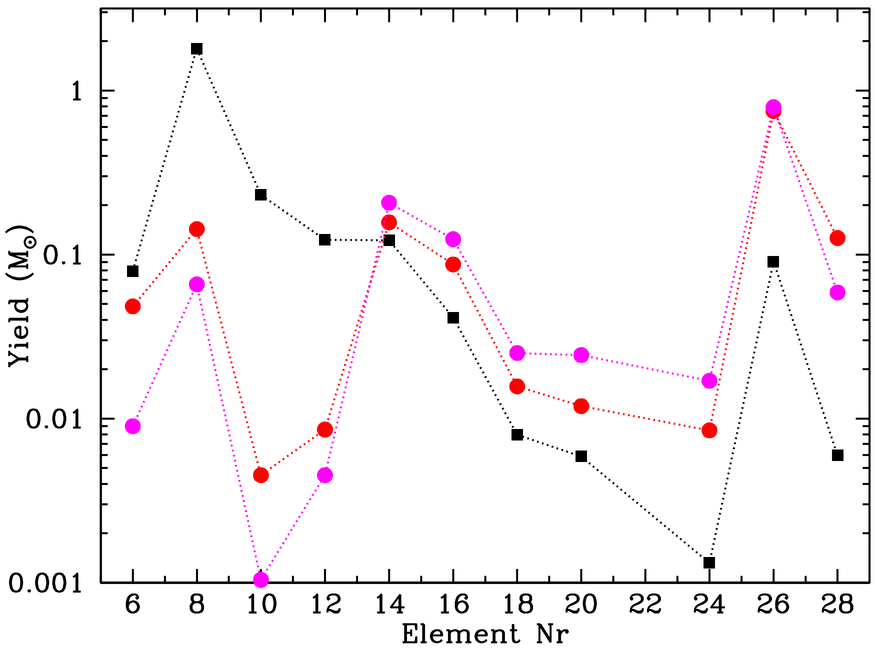
Foley et al . '13



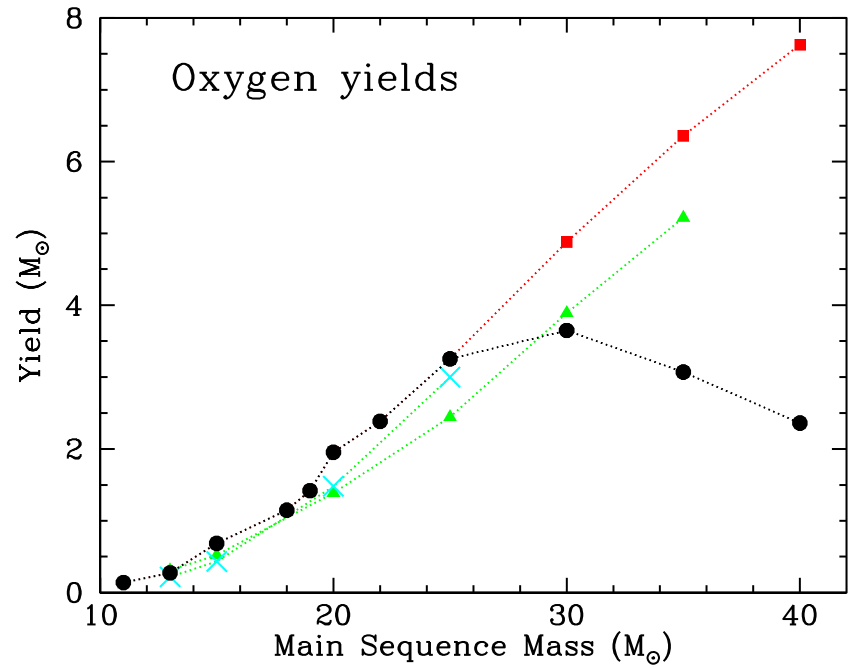
- SN Iax are less bright
- Comprises about 30% of SNe Ia
- Less mass ejected: may leave behind a white dwarf
- Progenitor detected optically: suggest a CO WD + He star companion (Foley + '14)

- NB with push for time domain astronomy: more subdivision/ classes of explsoive events will be identified (c.f. kilonovae)

Nucleosynthesis in supernovae

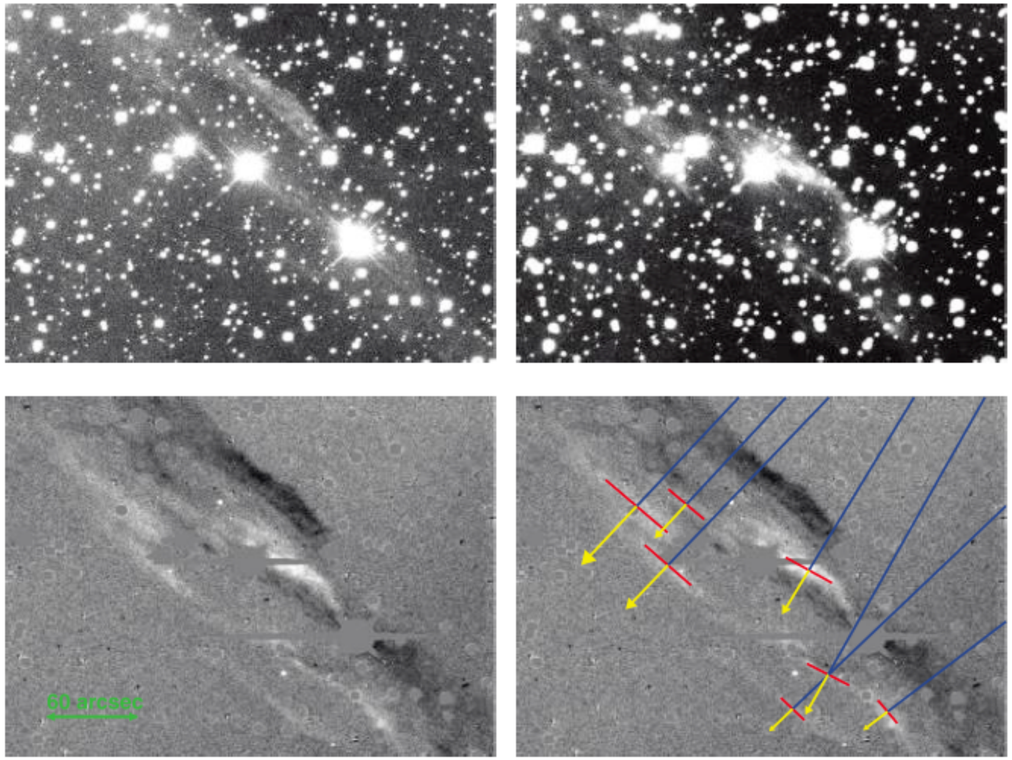


CC SNe

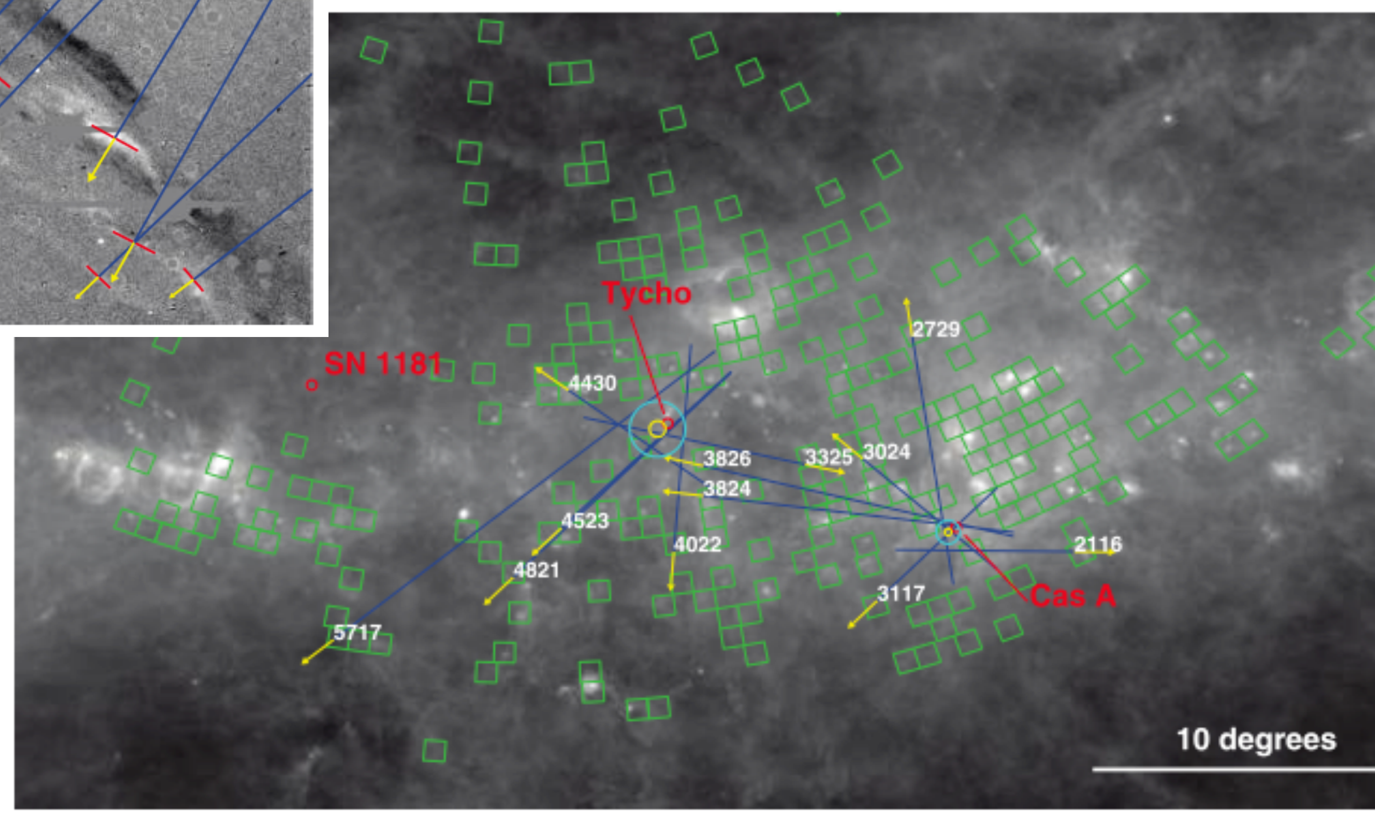


- Core collapse SNe: peak in O, Ne, Mg (<0.1 Msun of Fe)
  - partially stellar nucleosynthesis/partially explosive
  - depends strongly on mass (see oxygen)
- Thermonuclear (SN Ia) SNe: peak in Fe-group elements
- Both: intermediate elements (Si, S, Ar, Ca)

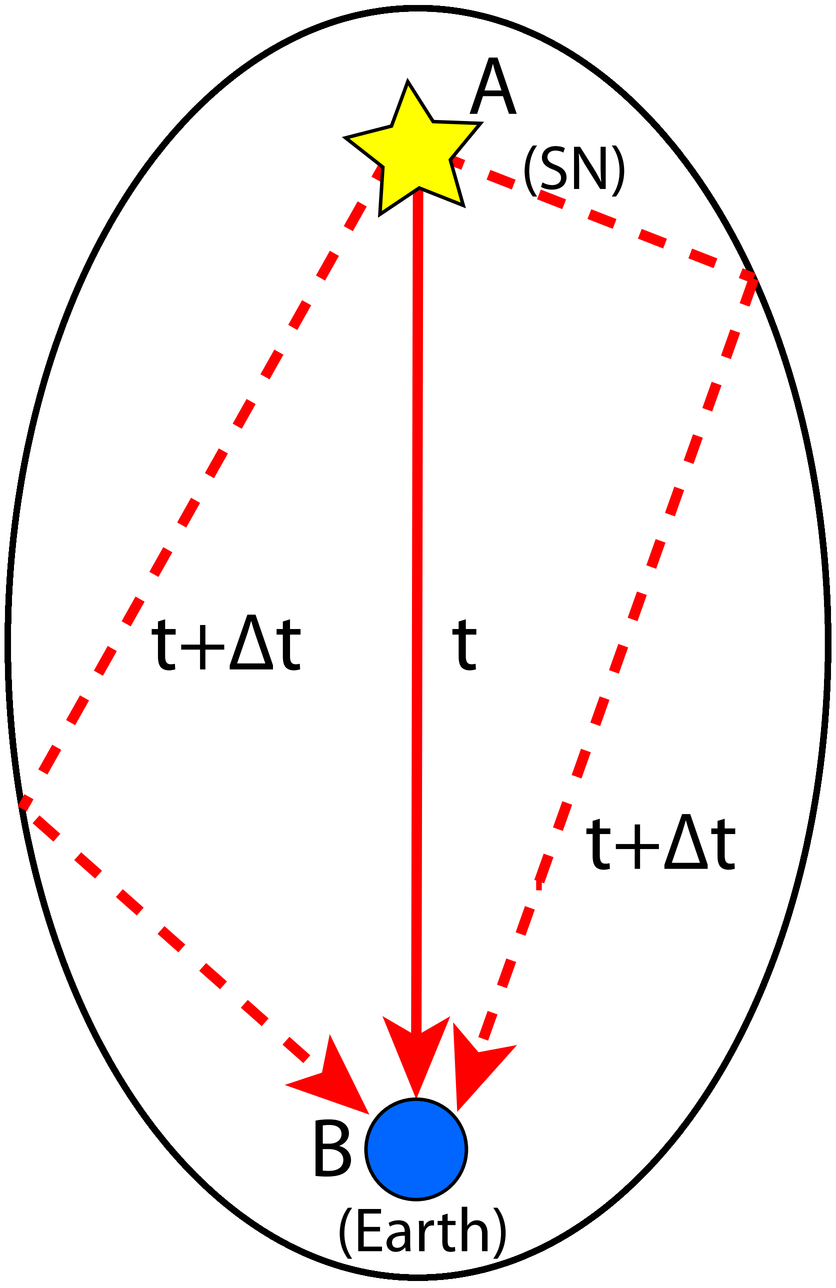
A direct SN/SNR link: light echoes



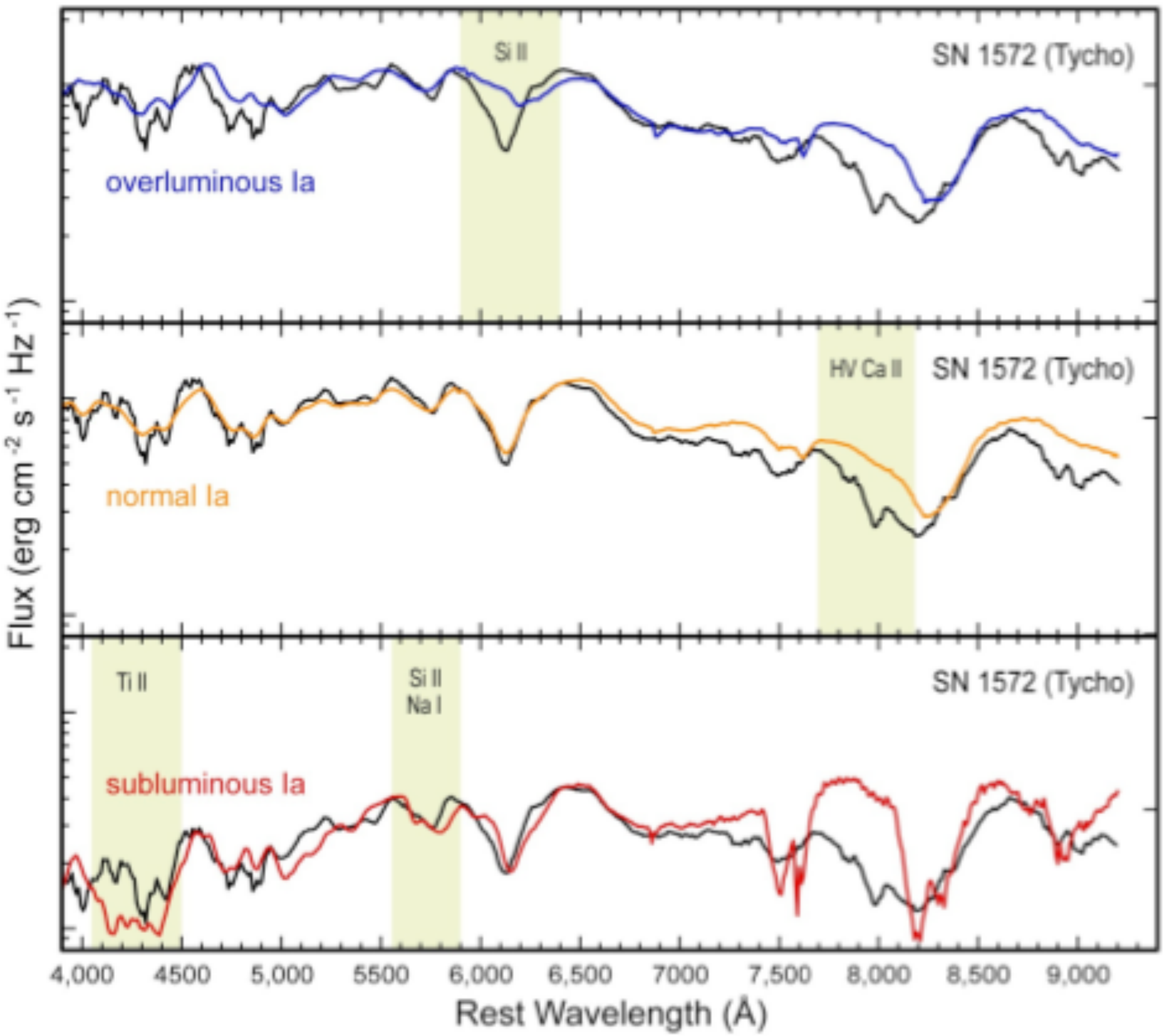
Armin Rest:
light echoes of
Cas A & SN1572



Light echoes



Spectrum of SN1572



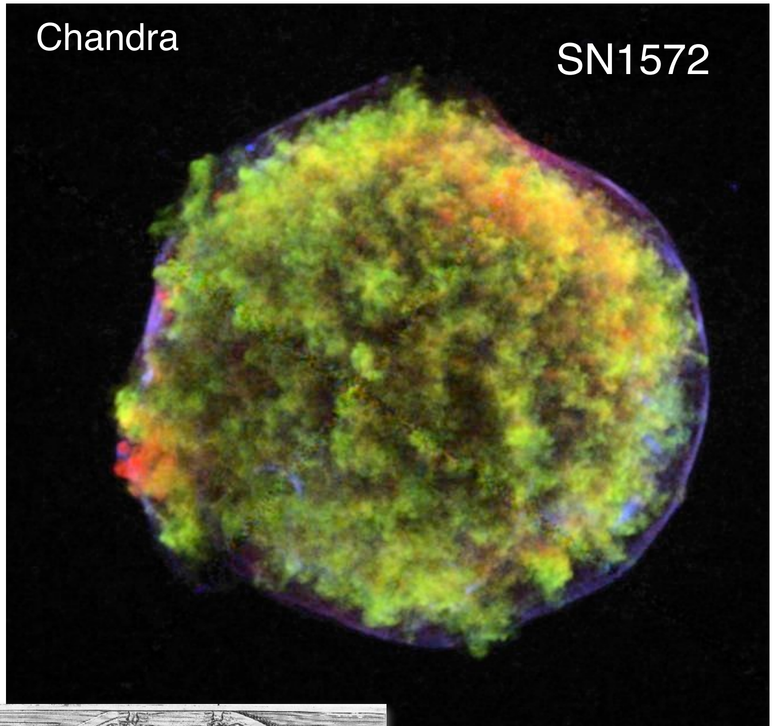
Krause e.a.:
Nature 2008

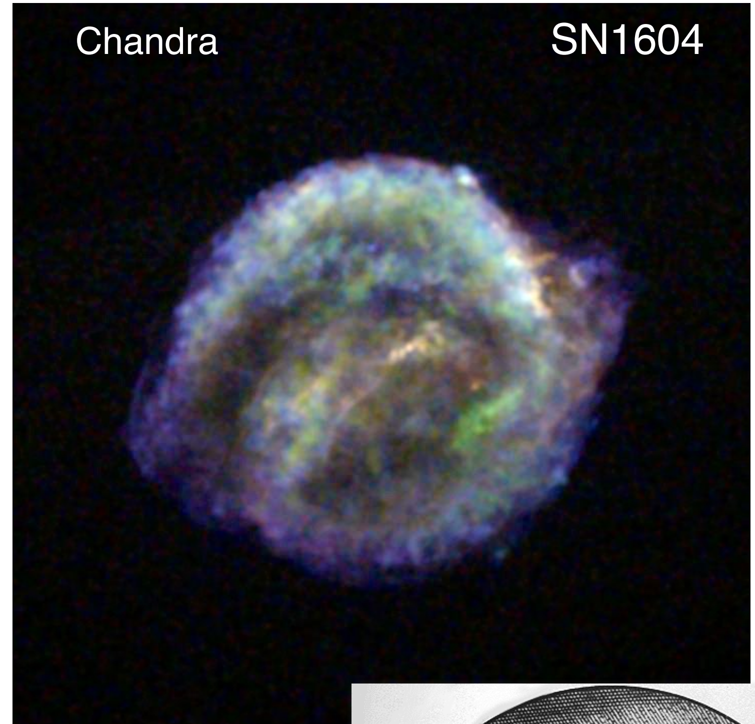
Supernovae: summary

- Supernovae come in two distinct classes
  - Core collapse supernova -> massive stars ($M>8\ M_{sun}$)
    - Type IIL, IIP, IIb, Ib, Ic, IIn,..
  - Thermonuclear supernovae -> involving white dwarf
    - Type Ia (with some subclassification, 91T-like, Iax,Ca-rich…)
- Explosion origin very distinct
  - CC: gravitational -> mostly in neutrinos ($>10^{53}$erg)
  - Thermonuclear: nuclear fusion -> C and O into Fe-group + IME
- Explosions not fully understood:
  - CC: how to revive the shock in star (neutrino physics/jets)?
  - Thermonuclear: single or double degenerate?

II
Supernova remnants
i. Population, evolution, classification

SN1572 & SN1604 in 2019

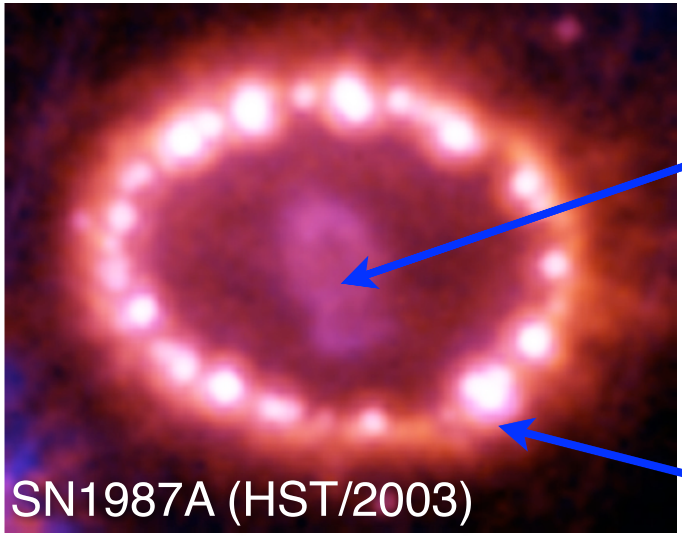




Tycho Brahe

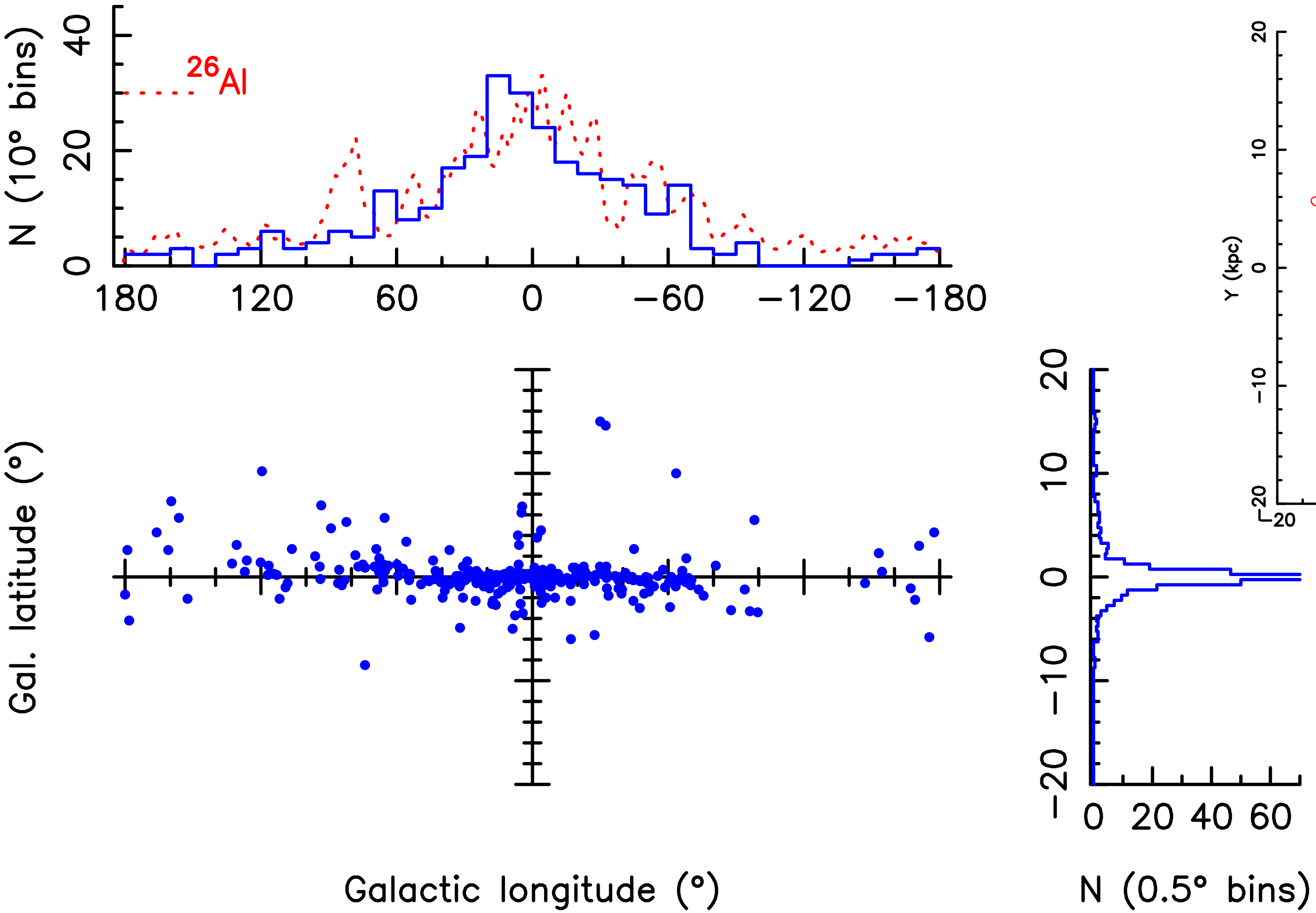
Johannes Kepler

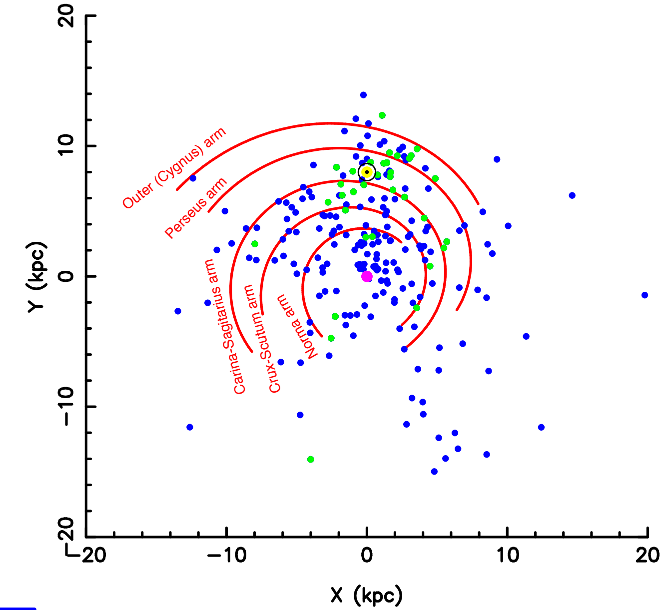
From supernova to supernova remnant



- SN expands -> ejecta cools
  - Fast: within a year dust may form (e.g. SN1987A), requiring T<1500 K
- Ejecta may still be warmed by late time radio-active heating
- Depending on the circumstellar density
  - outer shock wave heats up a shell that may give rise to X-ray emission
  - shock wave may accelerate particles -> relativistic electrons -> radio emission
  - few SNe show this (so-called radio supernovae, with dense CSM)

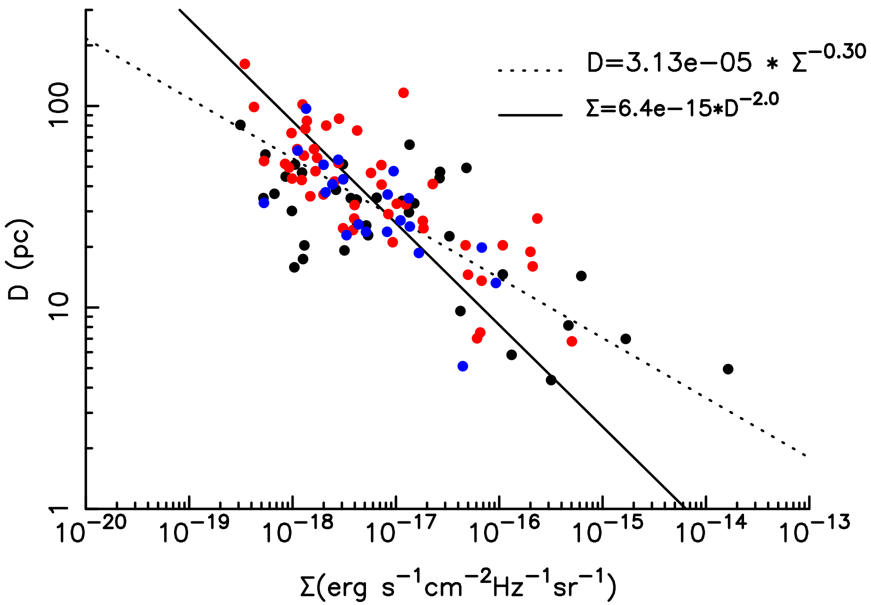
SNR population: Galactic distribution

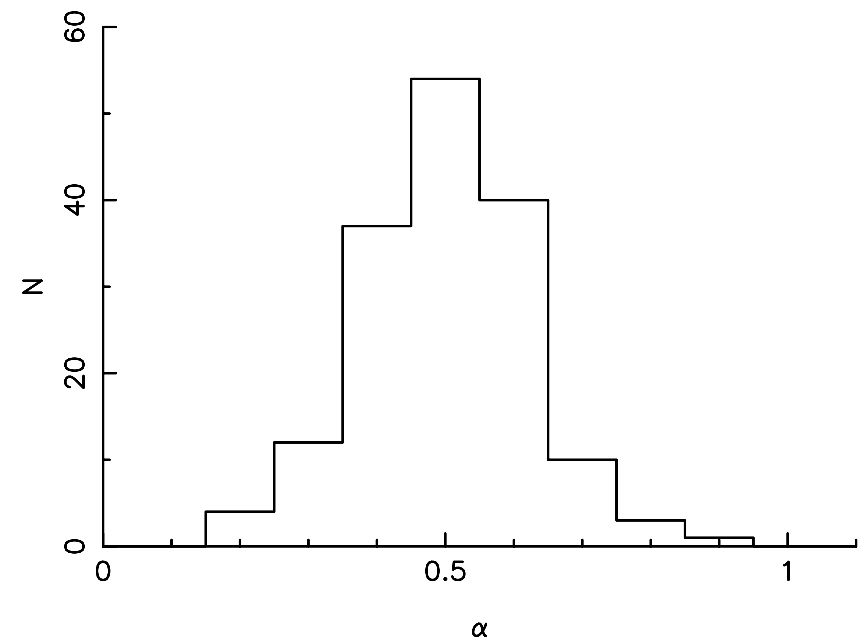




- About 300 Galactic SNRs known
- For t_{max}=50,000 yr, rate of 2-3/century: 1000-1500 expected
- Sample far from complete, but t_{max} unknow/varies

Radio properties: Sigma-D relation, α





radio spectal index

$$\Sigma_\nu \equiv \frac{S_\nu}{\Omega} \approx \frac{L_\nu(\nu)/(4\pi d^2)}{\frac{1}{4}\pi D^2/d^2} = \frac{L_\nu}{\pi^2 D^2}.$$

$$N(E) \propto E^{-q} \rightarrow F_\nu \propto \nu^{-(q-1)/2} \propto \nu^{-\alpha}$$

- Spectral index α~0.5 (consistent with DSA, q=2)
- Young SNRs are brighter/higher surface brightness

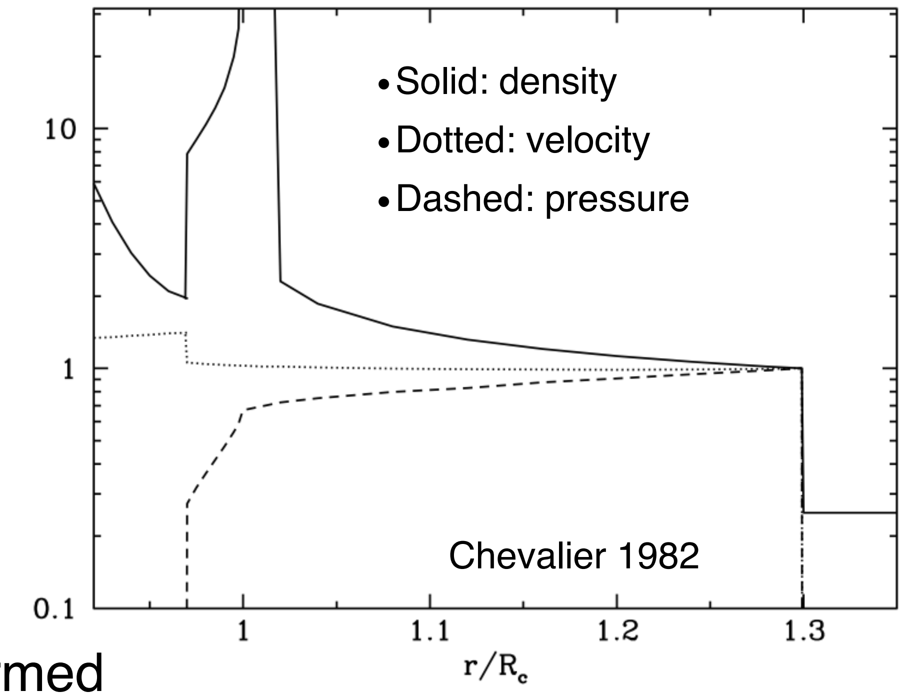
SNR evolutionary phases (simplified)

Four phases are recognised

1. Ejecta dominated phase (a.k.a. free expansion phase)
    - First 10-few 100 yr
    - V_s>3000 km/s
    - $M_{ej} > M_{swept}$
2. Adiabatic or Sedov-Taylor phase
    - Few 100 yr to few 5000 yr
    - 200 km/s < V_s <3000 km/s
    - $M_{ej} << M_{swept}$
    - Radiative losses unimportant
3. Snow plough phase
    - 5000-50000 yr
    - 20 km/s < V_s <200 km/s
    - Radiative losses, momentum conserved
4. Disappearance phase
    - V_s comparable to turbulent motions ISM

- Different parts of SNR may be in different phases!!

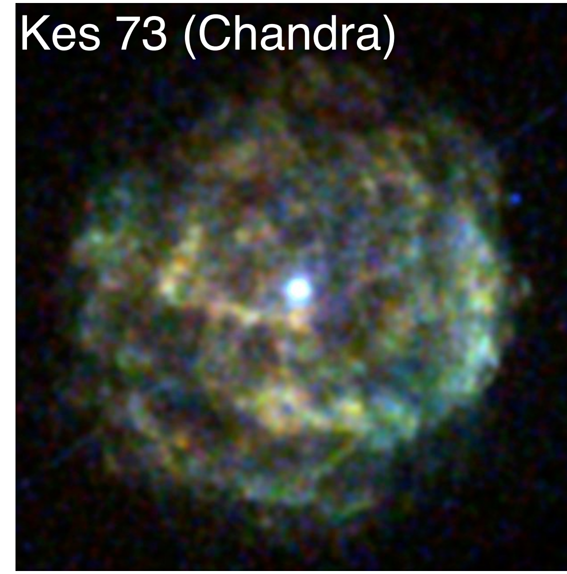
Ejecta dominated phase



- Fast moving ejecta -> a shock wave has formed
- shock-heating and sweeping up of the circumstellar medium
- heats the outer (cold) ejecta layers by *reverse shock*
- inner ejecta are cold
- power law profiles: n~7-12, s=0 (ISM), s=2 (stellar winds)
- m=1: free expansion
- from early age m< 1 !

$$\rho_{\rm ej}(v) \propto v^{\rm n},\ \rho_{\rm csm} \propto r^{-s} \rightarrow R_{\rm s}(t) \propto t^{\rm m}, m = \frac{n-3}{n-s}$$

Adiabatic Phase

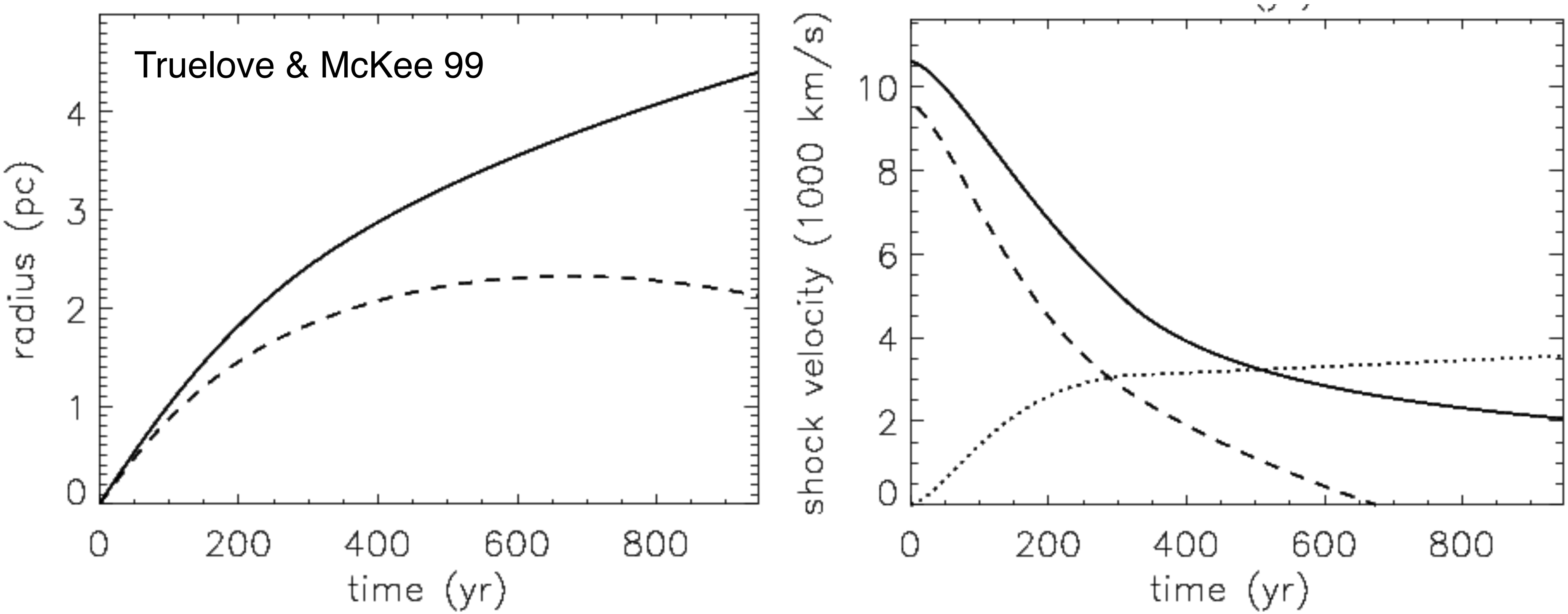


- Once $M_{swept} > M_{ejecta}$, but V_s> 300 a SNR is said to be in the adiabatic phase
- (Almost) all energy is contained in the shock-heated plasma (instead of freely expanding ejecta)
- Evolution is usually described by so-called Sedov self-similar solution:

$$R_{\rm s} = \left(\xi \frac{Et^2}{\rho_0}\right)^{1/5} \qquad V_{\rm s} = \frac{dR_{\rm s}}{dt} = \frac{2}{5}\left(\xi \frac{E}{\rho_0}\right)^{1/5} t^{-3/5} = \frac{2}{5}\frac{R_{\rm s}}{t}.$$

- Note: m=2/5, s=0
- For s=2, Sedov solution gives m=2/3

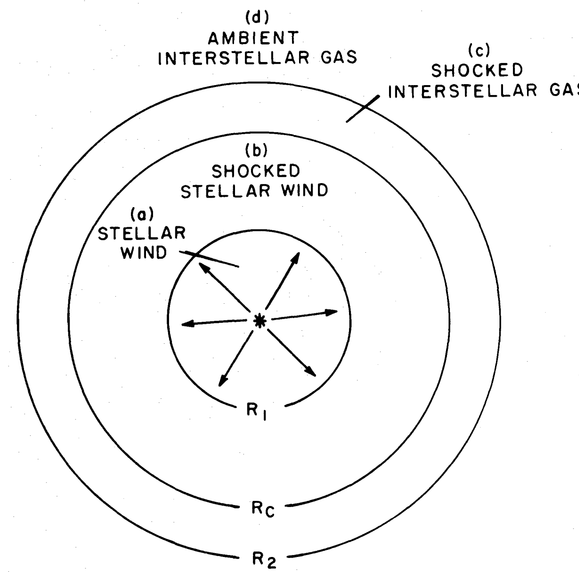
Truelove & McKee model



- Reverse shocks move first outward than inward, eventually heating all ejecta
- Asymptotically approaches Sedov solution
- Reverse shock physical speed: $V_s = dR_{rev}/dt - R/t$
- Truelove & McKee model uses characteristic scales:

$$R_{ch} \equiv M_{\rm ej}^{1/3}\rho_0^{-1/3},\ t_{ch} \equiv E^{-1/2}M_{\rm ej}^{5/6}\rho_0^{-1/3},\ M_{ch} \equiv M_{\rm ej}$$

Supernova remnants and wind bubbles

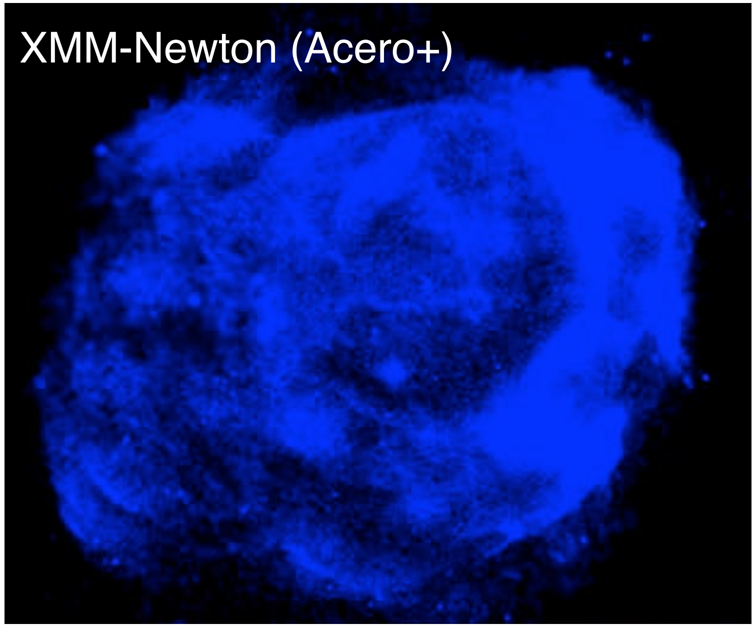


- Standard wind bubble theory:
  - Weaver, McCray, Castor, Shapiro, Moore 1977
  - Bubble size depends on wind power L, density and age

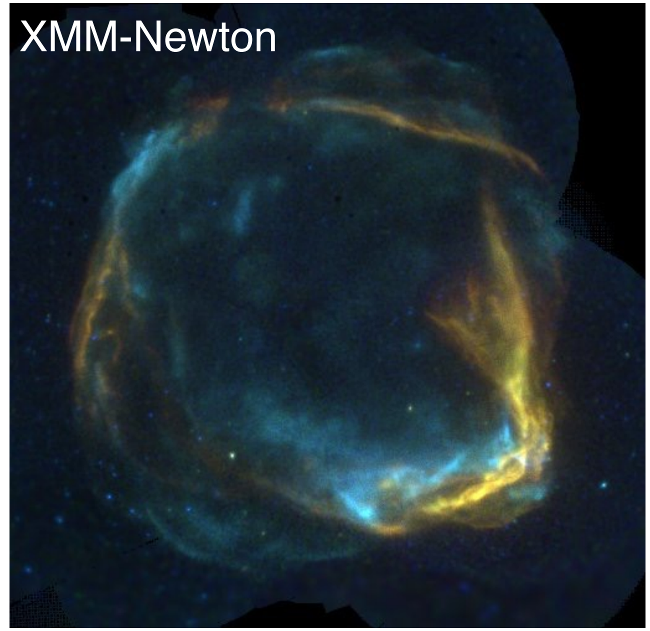
$$R_2 = \left(\frac{250}{308\pi}\right)^{1/5} L_w^{1/5} \rho_0^{-1/5} t^{3/5} ,$$

  - Bubble size can be very large: >100 pc!

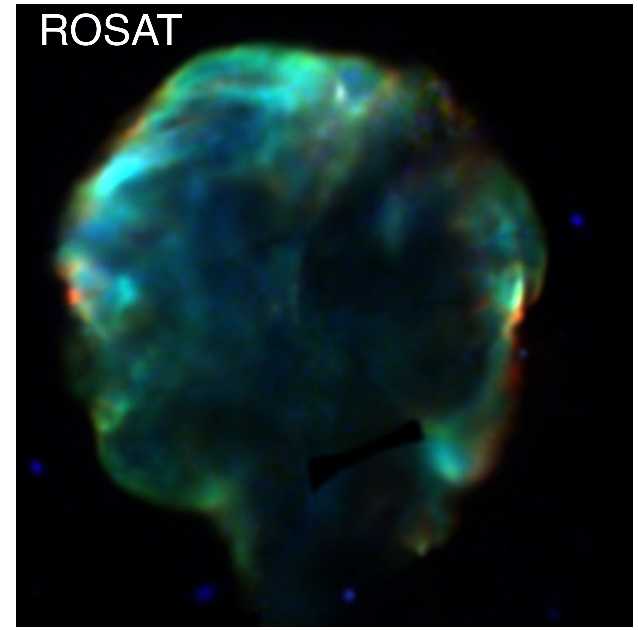
Three SNRs evolving in wind bubbles



RX J1713



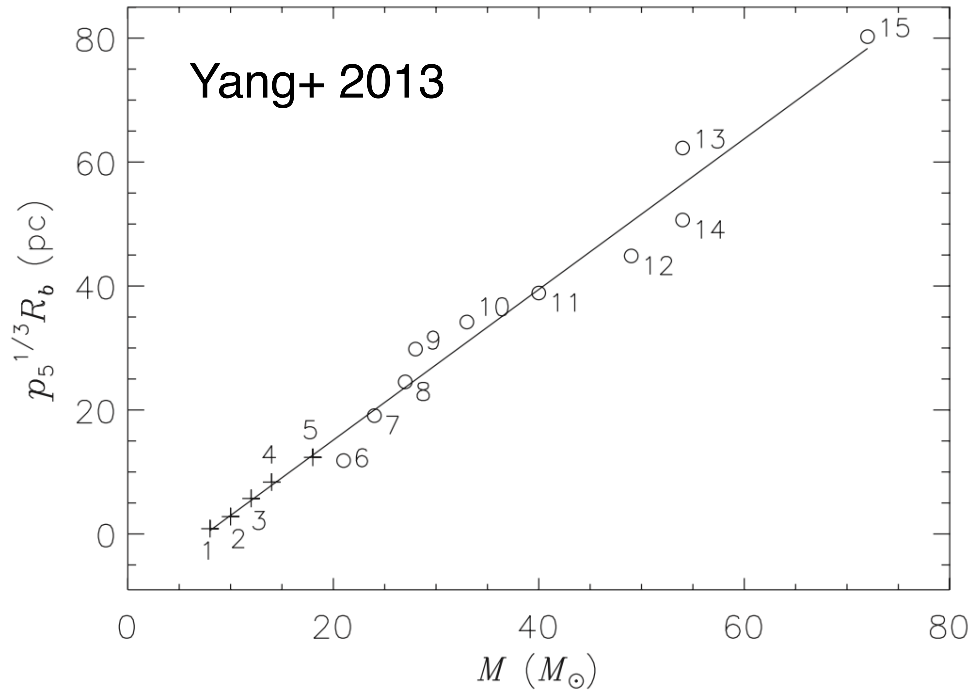
RCW 86



Cygnus Loop

- A number of SNRs seem to have evolved inside wind cavity
- Their radii seems to be 10-15 pc
- Much smaller than Weaver+ 77
- Are we missing SNRs in larger cavities due to low densities?

Chevalier model

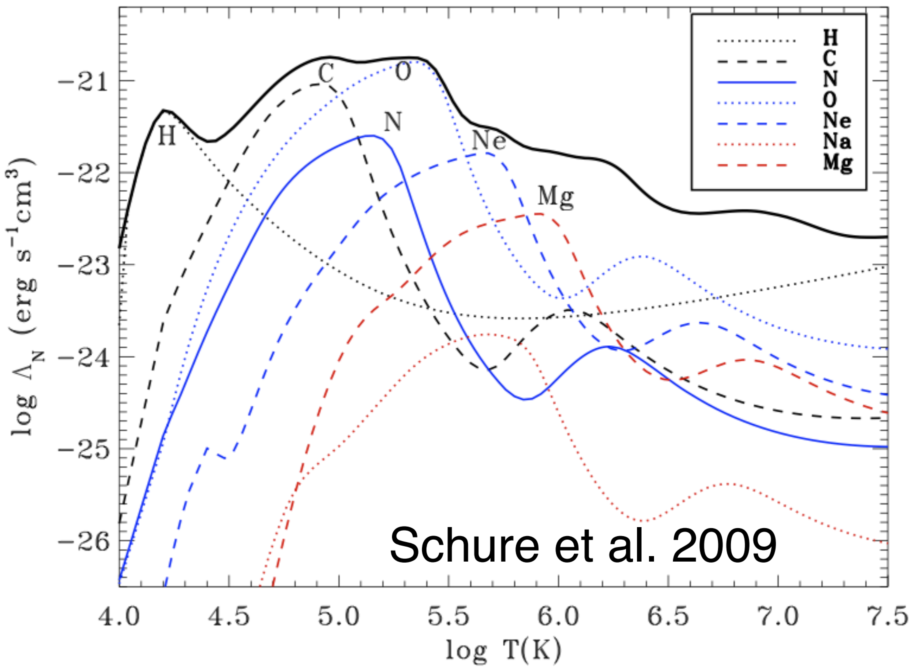


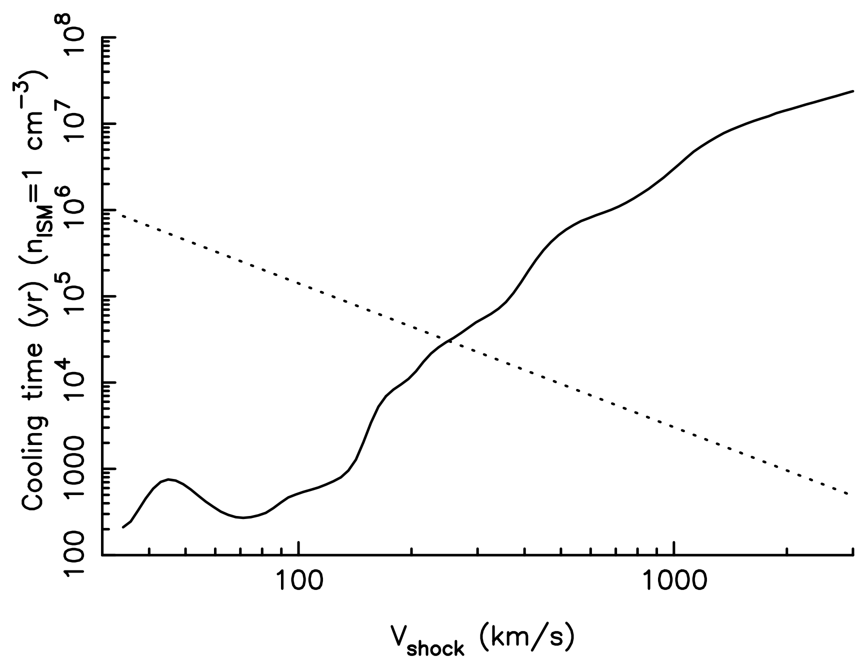
- Chevalier 1999:
  - Winds evolve in high pressure ISM (dense molecular clouds)
  - Expansion stops when $P_{bubble}=P_{ism}$:

$$\frac{1}{2}\,\dot{M}v_w^2\,\tau_{\rm ms} = \left(\frac{4}{3}\,\pi R_b^3\right)\frac{3}{2}\,p_0$$

- $P_{ism}=10^5$ K cm^{-3}
- Small correction needed: work done on environment
- Radii agree better with observations than Weaver+ 77
- Most cavities between 5-15 pc as observed

“Mature SNRs”: snow-plough phase





- For $T<10^6$ K: cooling becomes very strong (oxygen line emission)
- Cooled gas: bright optical emission from [OIII], [NII],...
- This corresponds with V_s<200 km/s
- SNR *no longer adiabatic*: $R \sim t^{0.25}$ (momentum conservation)

$$t = t_{\rm rad} + \frac{R_{\rm rad}}{4V_{\rm rad}}\left[\left(\frac{R}{R_{\rm rad}}\right)^4 - 1\right], \quad t_{\rm rad} \approx 44,600\left(\frac{E_{51}}{n_{\rm H}}\right)^{1/3} {\rm yr}, \quad R_{\rm rad} \approx 23\left(\frac{E_{51}}{n_{\rm H}}\right)^{1/3} {\rm pc}$$

Radiative shocks

Cygnus Loop/Veil nebula: HST

Raymond 79

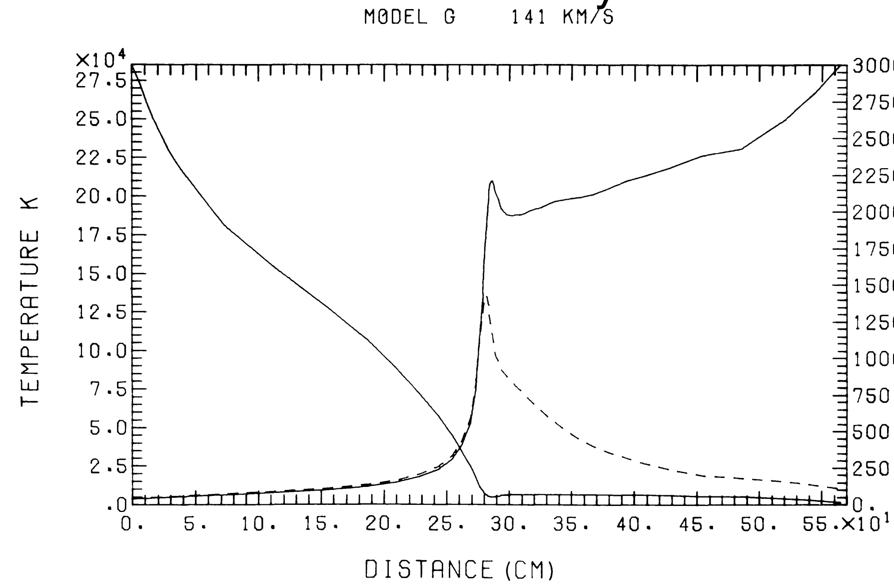
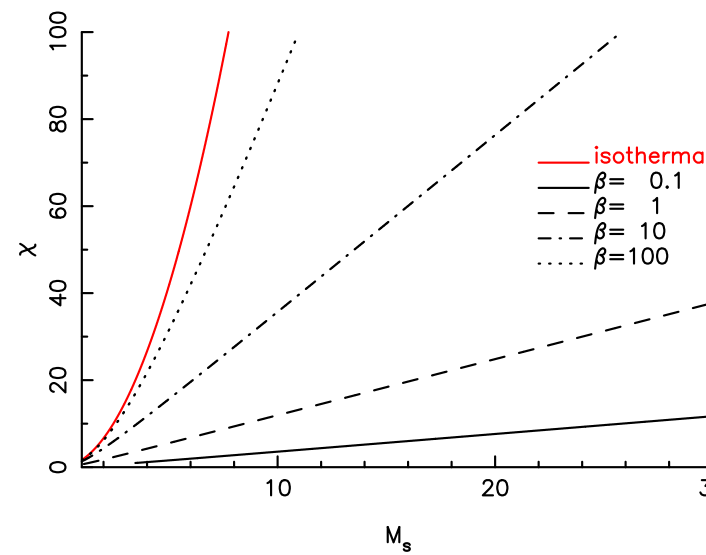
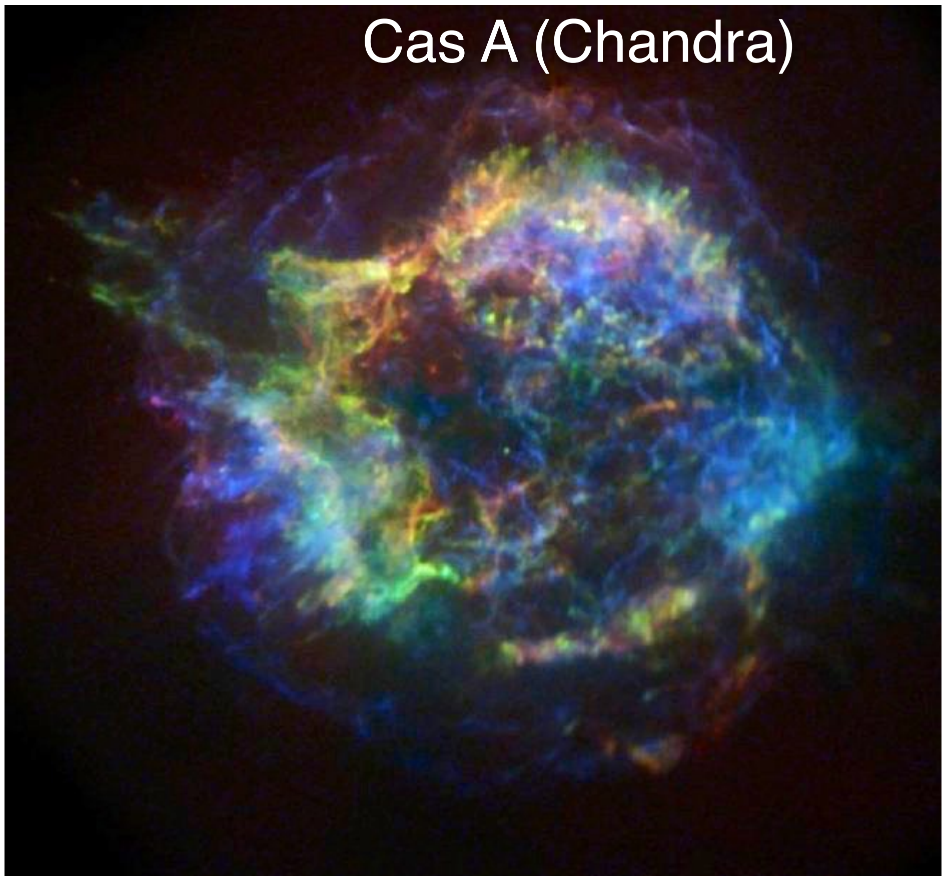
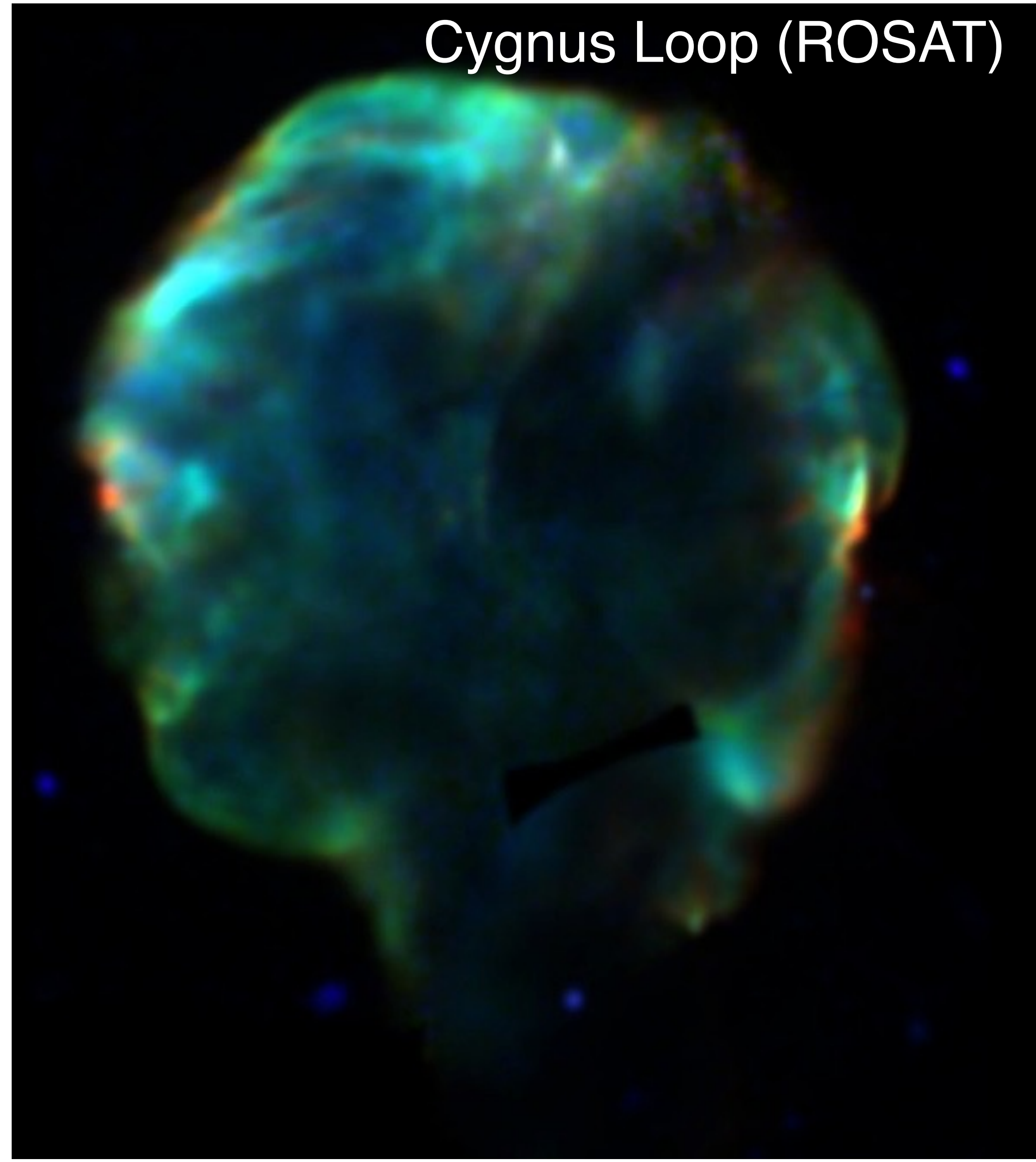


FIG. 3a

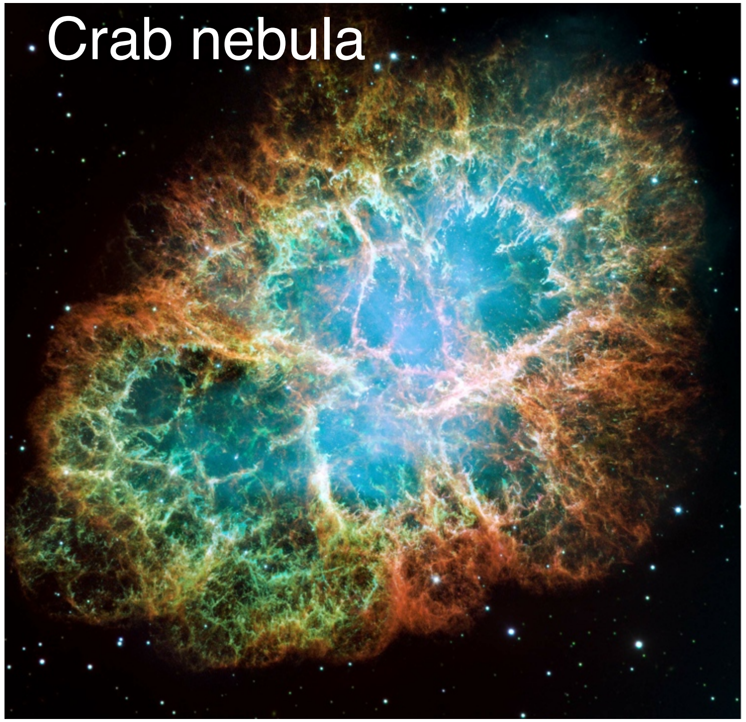


SNR Types: shell-type





SNR Types: Plerion

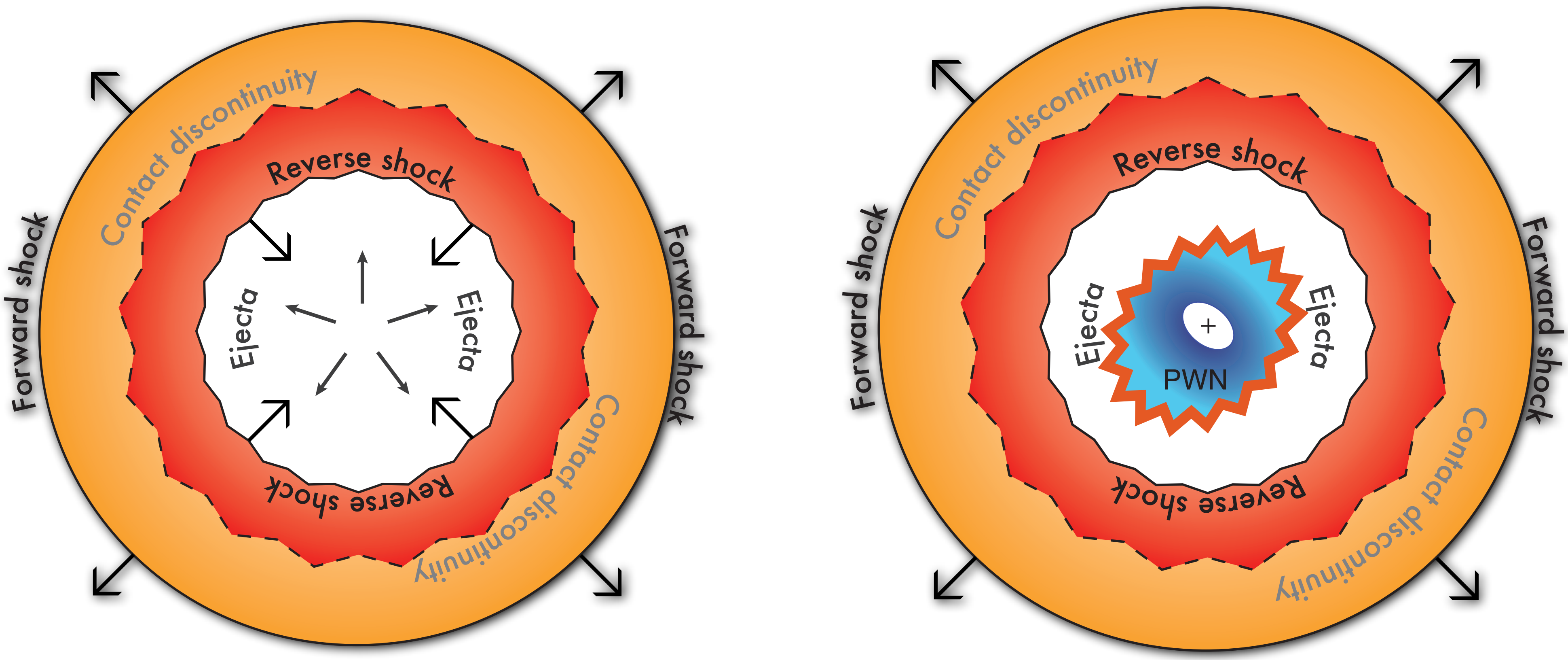


- Plerions are dominated by synchrotron emission from pulsar wind nebula
- They can still be considered SNRs as they have some ejecta components (in Crab nebula only seen in the optical)

SNR Types: Composite SNRs

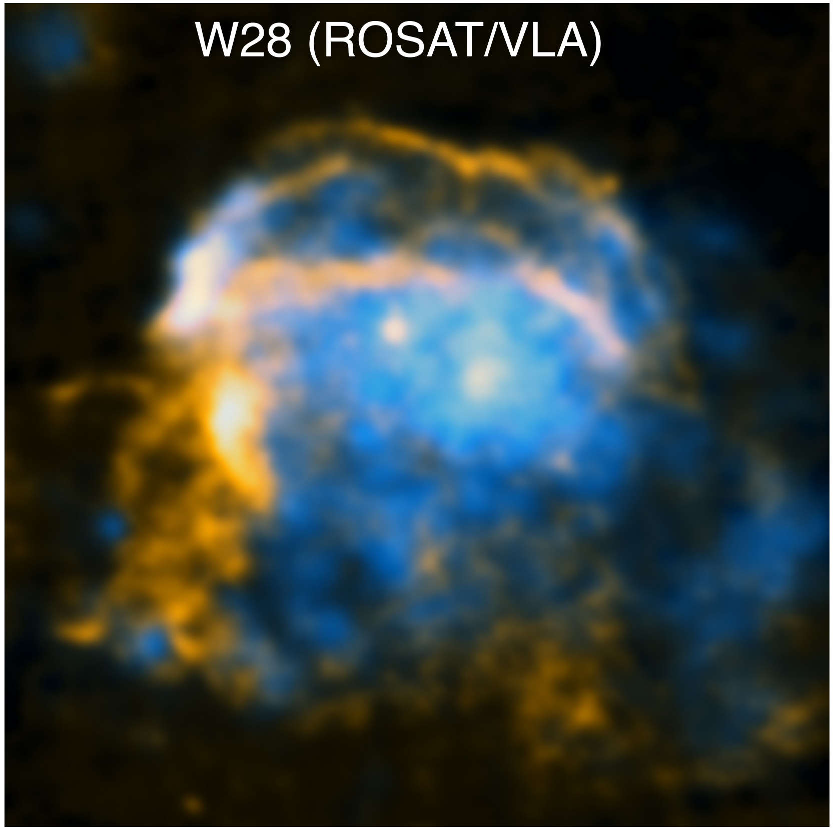
- Composite are a combination of a shell-type SNR and a pulsar wind nebula
- Not all core collapse SNRs are plerions/composites:
  neutron stars not always powerful pulsars!

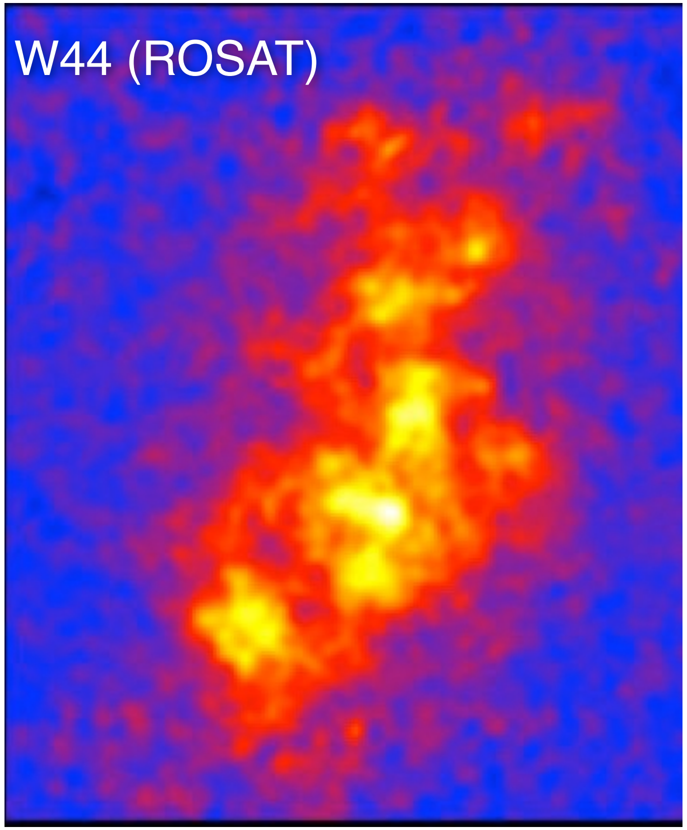
Cartoons of SNR structures



- Pulsar wind nebulae change structure of SNRs
  - May push against unshocked ejecta (Crab nebula?)
  - Or may halt reverse shock

Mixed-morphology/Thermal composite SNRs





- Mixed-morphology SNRs are shell-like in radio, and centrally bright in X-rays
- X-ray emission is thermal
- Evidence for enhanced abundances
- Are older SNRs
- Idea: shell too cool for X-rays, but center hot enough for X-rays (Cox+ ’99)
- Many of the gamma-ray emitting mature SNRs are MM!!

II
Supernova remnants
ii. Heating and ionisation

Thermal X-ray emission

- Most of the shock heated plasma consists of thermal population
- The X-ray emission mostly determined by:
  - *electron* distribution (=electron temperature)
  - abundances and charge states of the atoms
- Emission processes (not necessarily thermal!)
  - *bremsstrahlung* (continuum) -> quasi power-law with exponential

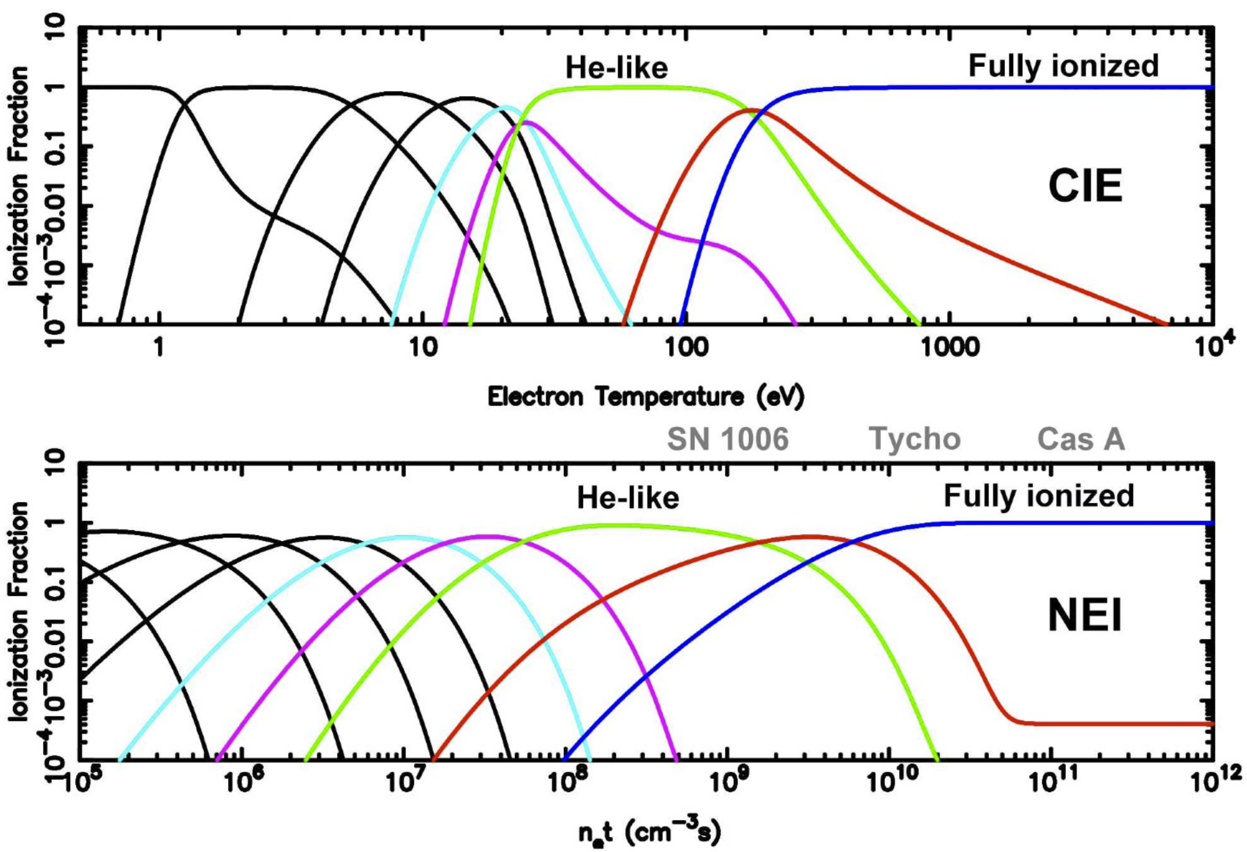
$$n(\nu) \propto n_{\mathrm{e}} \Sigma_i n_i Z_i^2 g_{\mathrm{ff}}(\nu) T_{\mathrm{e}}^{-1/2}\ \nu^{-1} \exp\left(-\frac{h\nu}{kT_{\mathrm{e}}}\right)$$

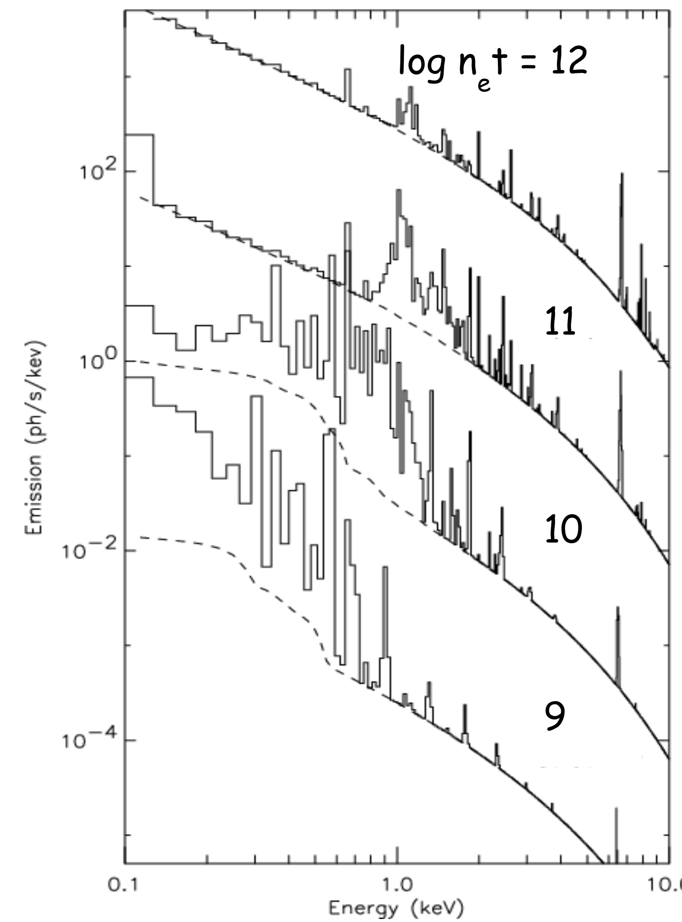
  - *free bound emission* (continuum)
  - *two-photon emission* (continuum, 2photons from forbidden line transition)
  - *line emission* (direct excitation, thru recombination): L-shell, K-shell

Thermal X-ray radiation important for inferring
- *Electron* temperatures
- Densities (measure $n_e n_H V$)
- Abundances (mostly from alpha and Fe-group elements)

Non-equilibrium ionization (NEI)

Vink 2012



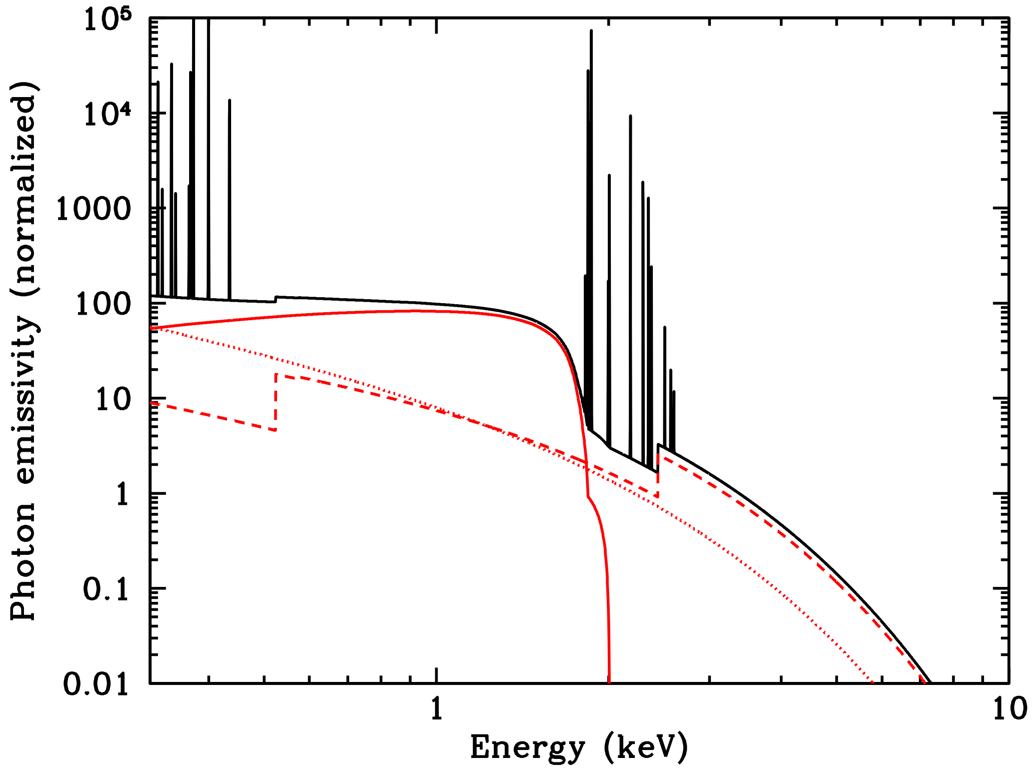


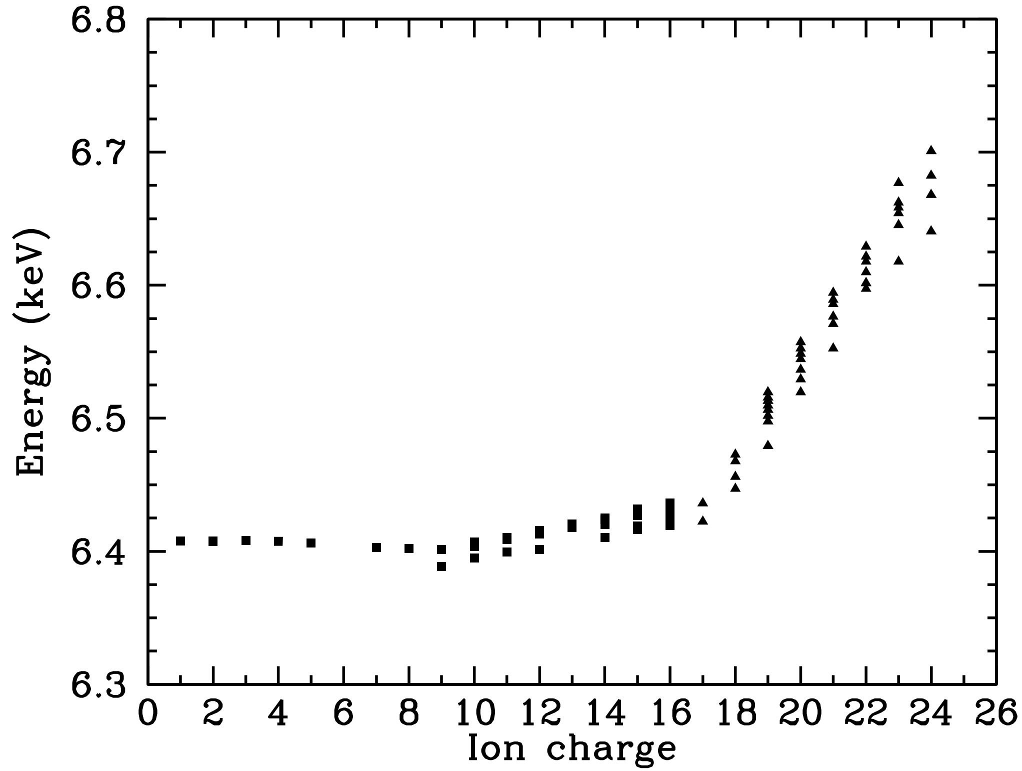
- Densities in SNR plasmas low (n_e=0.01-100 cm^{-3})
- Plasmas recently shocked (~100-~10000 yr) ⇒ still in process of ionisation
- Ionisation history:

$$\frac{1}{n_{\rm e}}\frac{dF_i}{dt} = \alpha_{i-1}(T)F_{i-1} - \left[\alpha_i(T) + R_{i-1}(T)\right]F_i + R_i(T)F_{i+1}$$

- Relevant parameter: $n_e t$ (ionisation age)

Thermal X-ray emission

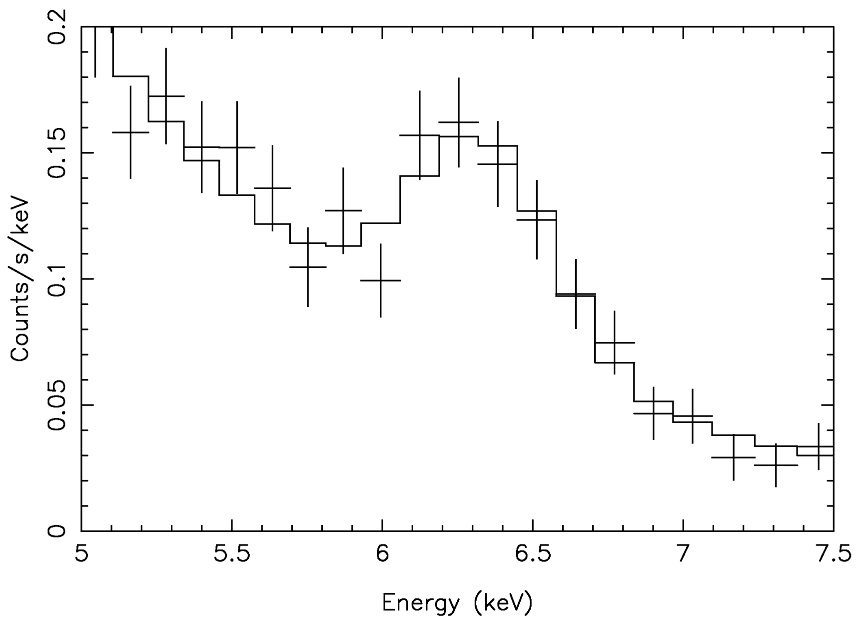


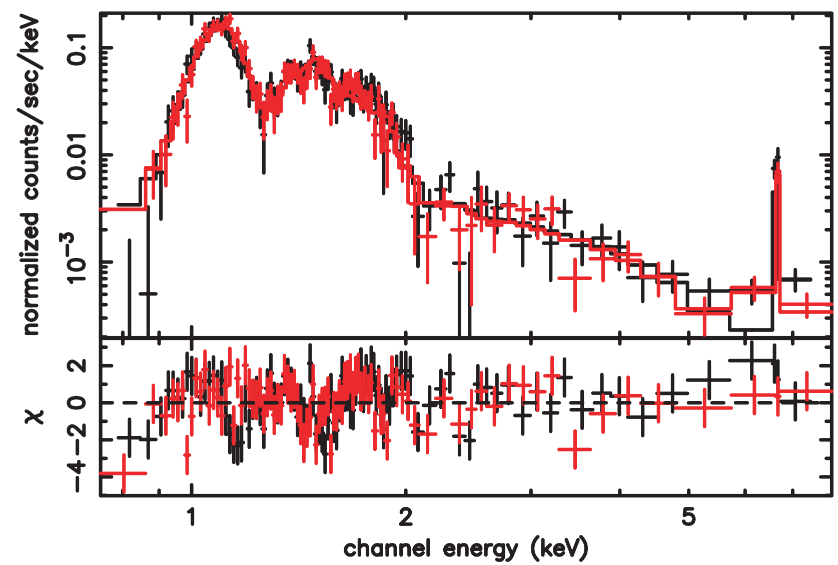


- Model emission of pure Si-plasma
- kT_e=1 keV,$n_e t$=5x^{10}10cm-3s

- Line energies of Fe-atoms with different charge states
- Most common in hot plasmas: He-like Fe (=Fe XXV): 6.7 keV
- Cold Fe 6.4 keV

Fe-K line diagnostics

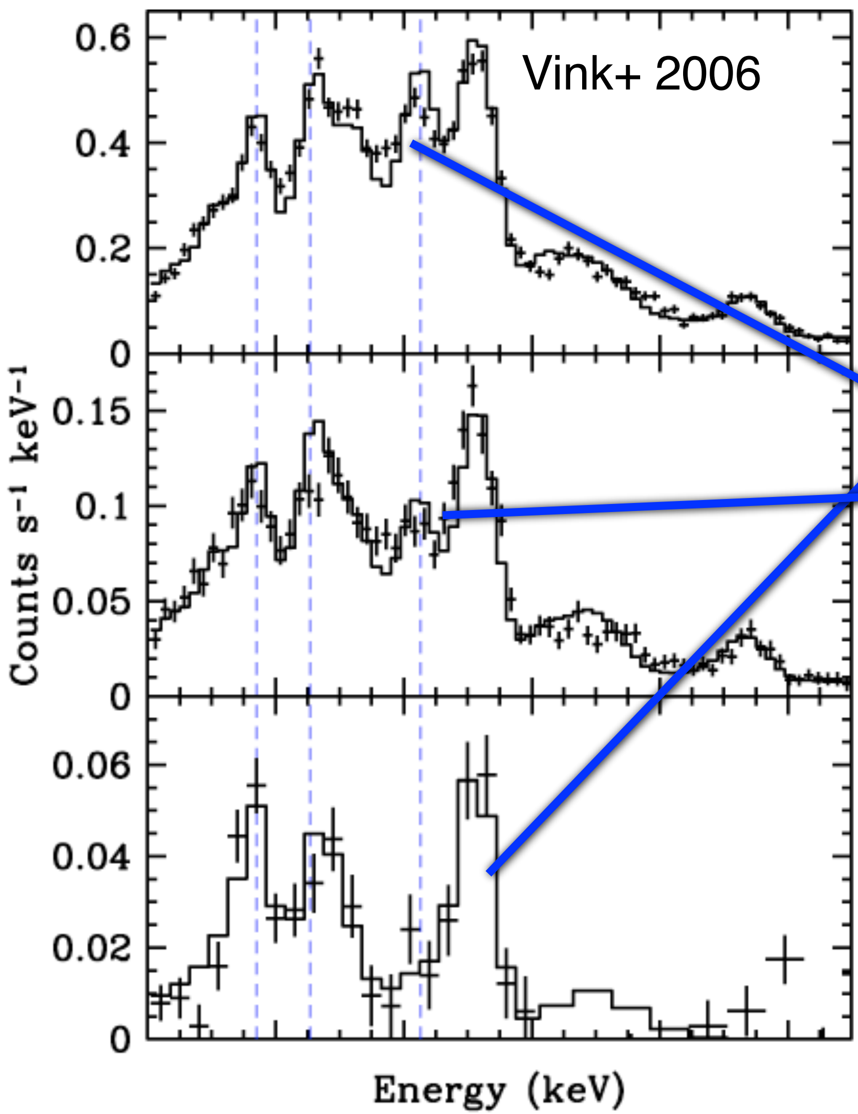


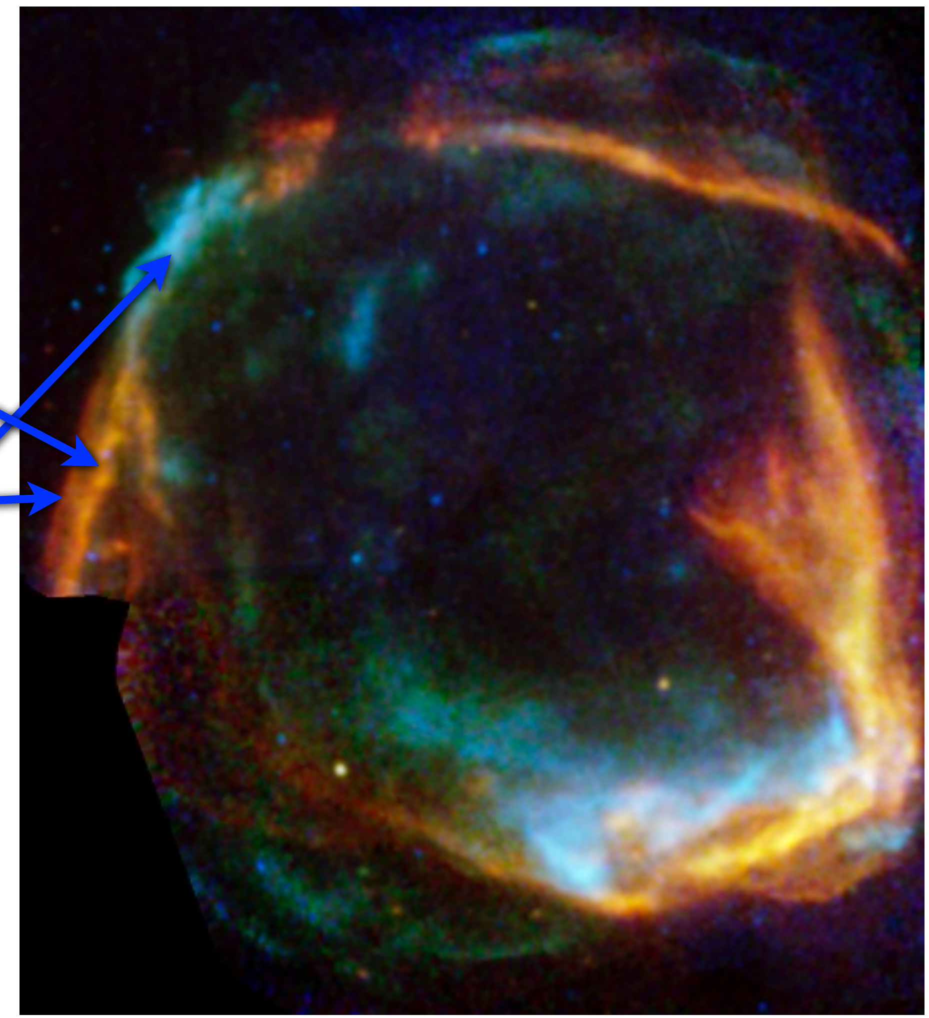


Fe-K in RCW 86: 6.4 keV
(Vink+ 97)

Fe-K in Cas A: 6.7 keV
(Hwang & Laming 03)

Absence of Fe-L in NE of RCW 86





- Fe-L: ionization state Fe XVII or higher
- In RCW 86 (SN185) eastern part: faint thermal emission in association with X-ray synchrotron -> low $n_e t$

Supernova remnant shock physics

- Atmospheric shocks: heating in shock due to particle-particle collisions
- In astrophysical plasmas: density (n) is very low
- Mean free path= nσv can be very long for particles

- Estimate of cross sections, two particle m_1 and m_2, charge Z_1,Z_2
- Impact parameter = b
- Relevant b: kinetic energy=potential energy

$$\frac{1}{2}\frac{m_1 m_2}{m_1+m_2}v^2 = \frac{Z_1 Z_2 e^2}{b}$$

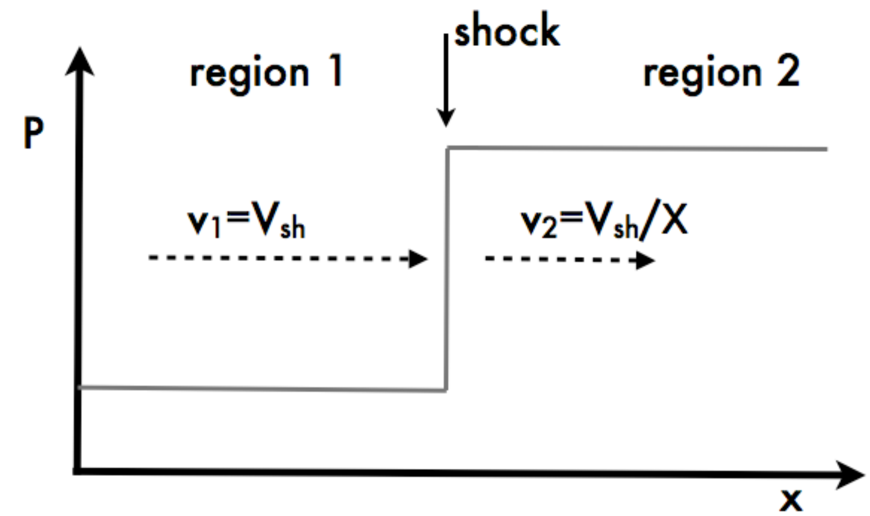
$$\sigma_{\rm Coulomb} \approx 4\pi \frac{Z_1^2 Z_2^2 e^4}{v^4}\left(\frac{m_1+m_2}{m_1 m_2}\right)^2$$

- For v≈1000 km/s, n=1cm^{-3} one finds for proton-proton

$$\lambda_{\rm p} \approx 10^{20} n_{\rm p}^{-1}\ {\rm cm}$$

- This is larger than the size of most supernova remnants!!
- Hence: shocks must be *collisionless:*
  - Heating due to *electric/magnetic fields & waves*!!

Rankine-Hugionot relations



- Rankine-Hugoniot relations:
  - mass-, momentum- & enthalpy-flux conservation
  - do not depend on collisionlessness of shock!

$$\rho_1 v_1 = \rho_2 v_2$$

$$P_1 + \rho_1 v_1 = P_2 + \rho_2 v_2 \quad \rightarrow \chi \equiv \frac{\rho_2}{\rho_1} = \frac{v_1}{v_2}$$

$$(P_1 + u_1 + \frac{1}{2}\rho_1 v_1^2) v_1 = (P_2 + u_2 + \frac{1}{2}\rho_2 v_2^2) v_2$$

- Solutions for strong shocks:

$$\chi = \frac{(\gamma_{\rm g} + 1) M_1^2}{(\gamma_{\rm g} - 1) M_1^2 + 2} \qquad \rightarrow 4 \text{ for } \; M_1^2 \equiv \frac{1}{\gamma_{\rm g}} \frac{\rho_1 v_1^2}{P_1} \rightarrow \infty$$

But what about electrons vs ions?

- Rankine-Hugoniot equations: observe conservations laws
- There is some freedom regarding the internal division of momentum, energy between electrons, protons, ions
- Collisional shocks: collision exchange makes that

  $kT = kT_p = kT_e = kT$

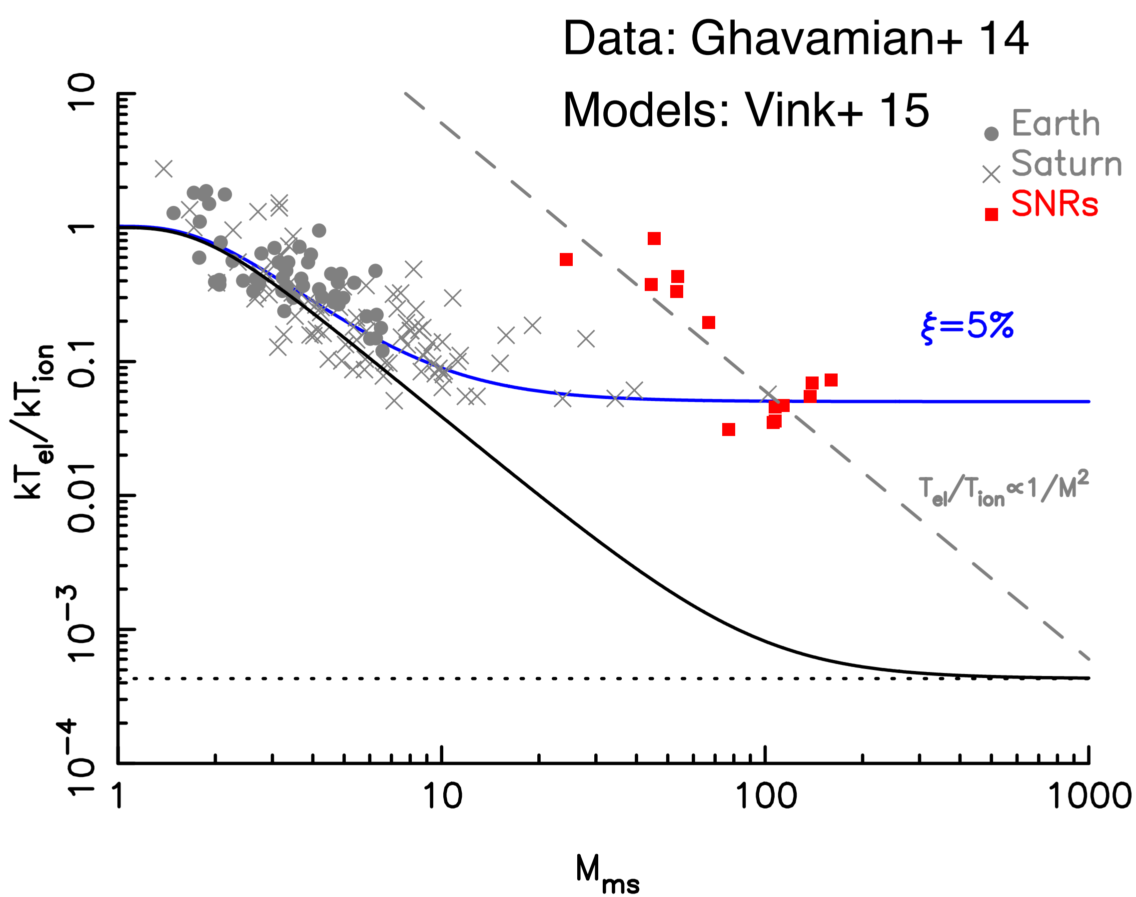
- What about collisionless shocks?
  - Electrons and ions heated without interparticle exchange
  - Most extreme cases:
    - Full equilibration
    - Full non-equilibration

      (kT $\propto$ mass)

$$kT = \frac{2(\gamma - 1)}{(\gamma + 1)^2}\mu m_{\rm p} V_{\rm s}^2 = \frac{3}{16}\mu m_{\rm p} V_{\rm s}^2$$

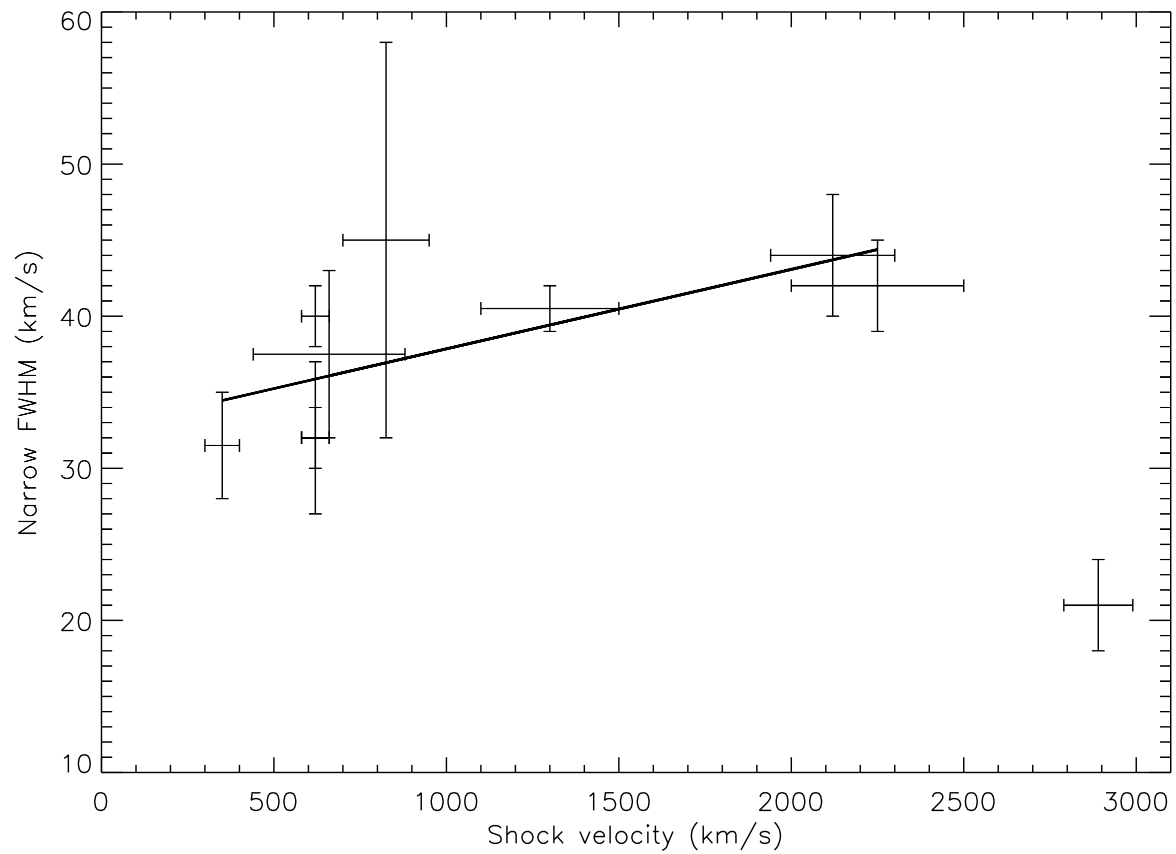
$$kT_i = \frac{3}{16} m_{\rm i} V_{\rm s}^2$$

Comparison to observations



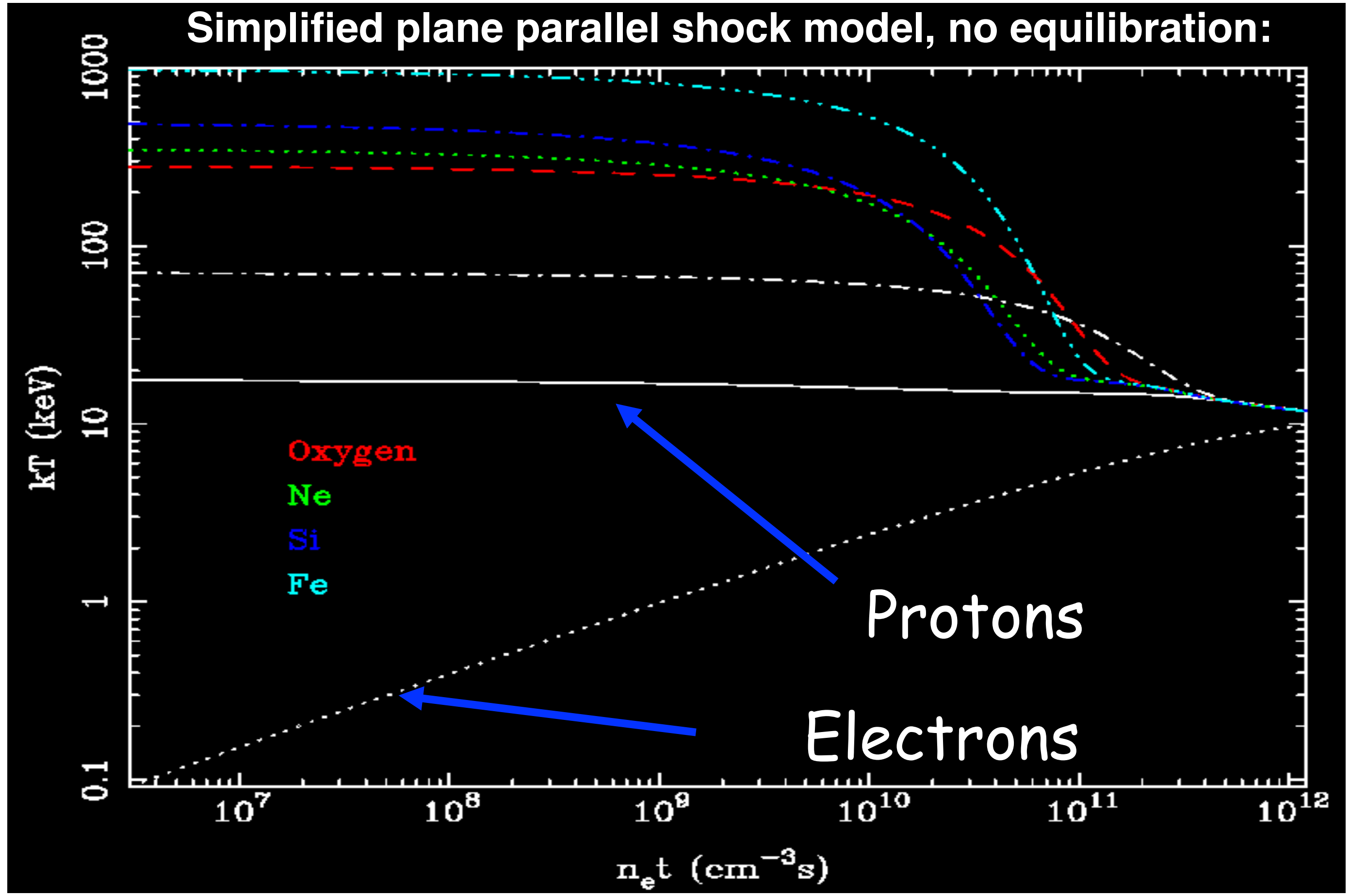
- Relation works for M<10
- For M>10: 5% energy between electrons and ions needed
- SNRs: seems to have shifted
  - Probably: upstream medium is hotter than assumed
  - Mach number overestimated!

Evidence for hot gas near SNR shocks



- Narrow Hα line emission SNRs: reflects kT unchecked gas
- Sollerman+ 2003: FWHM much broader than thought
  - Preheating of gas required
  - Preheating may be due to radiative or cosmic-ray precursor

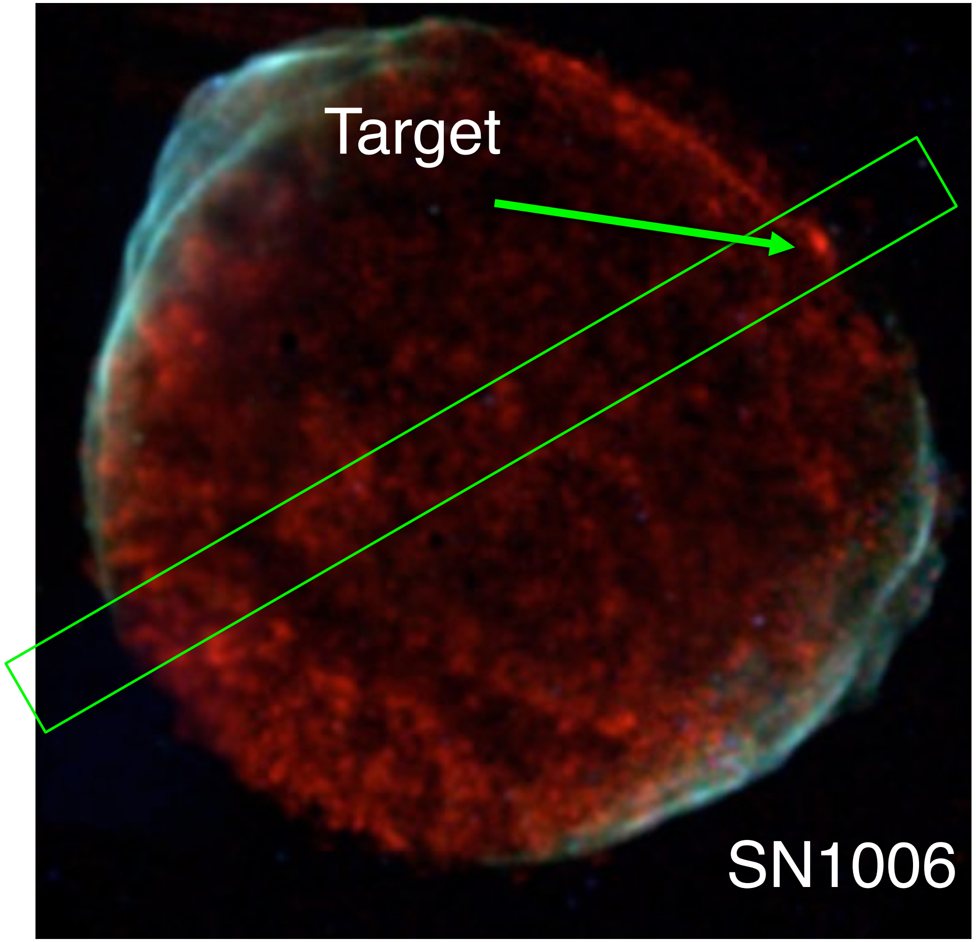
Temperature non-equilibration

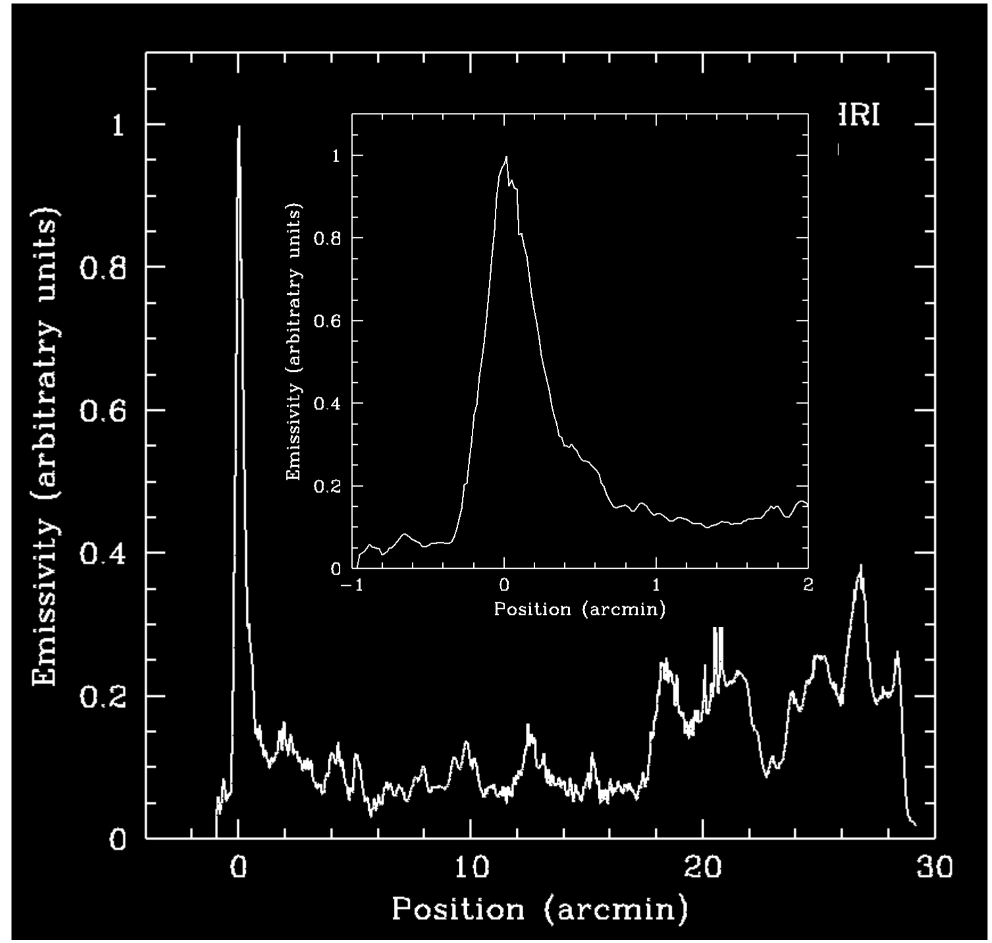


For young SNRs electron temperatures low (~3 keV expected ~20 keV)

- *Electron* and proton temperatures different at shock: $kT \sim \langle m \rangle V^2$ or $kT_i \sim m_i V^2$?
- Coulomb equilibration slow $n_e t \sim 10^{12}$ cm^{-3}s
- Non-linear cosmic-ray acceleration takes away shock energy
- Measuring ion temperatures ⇒ thermal Doppler broadening

Extreme NEI: SN1006



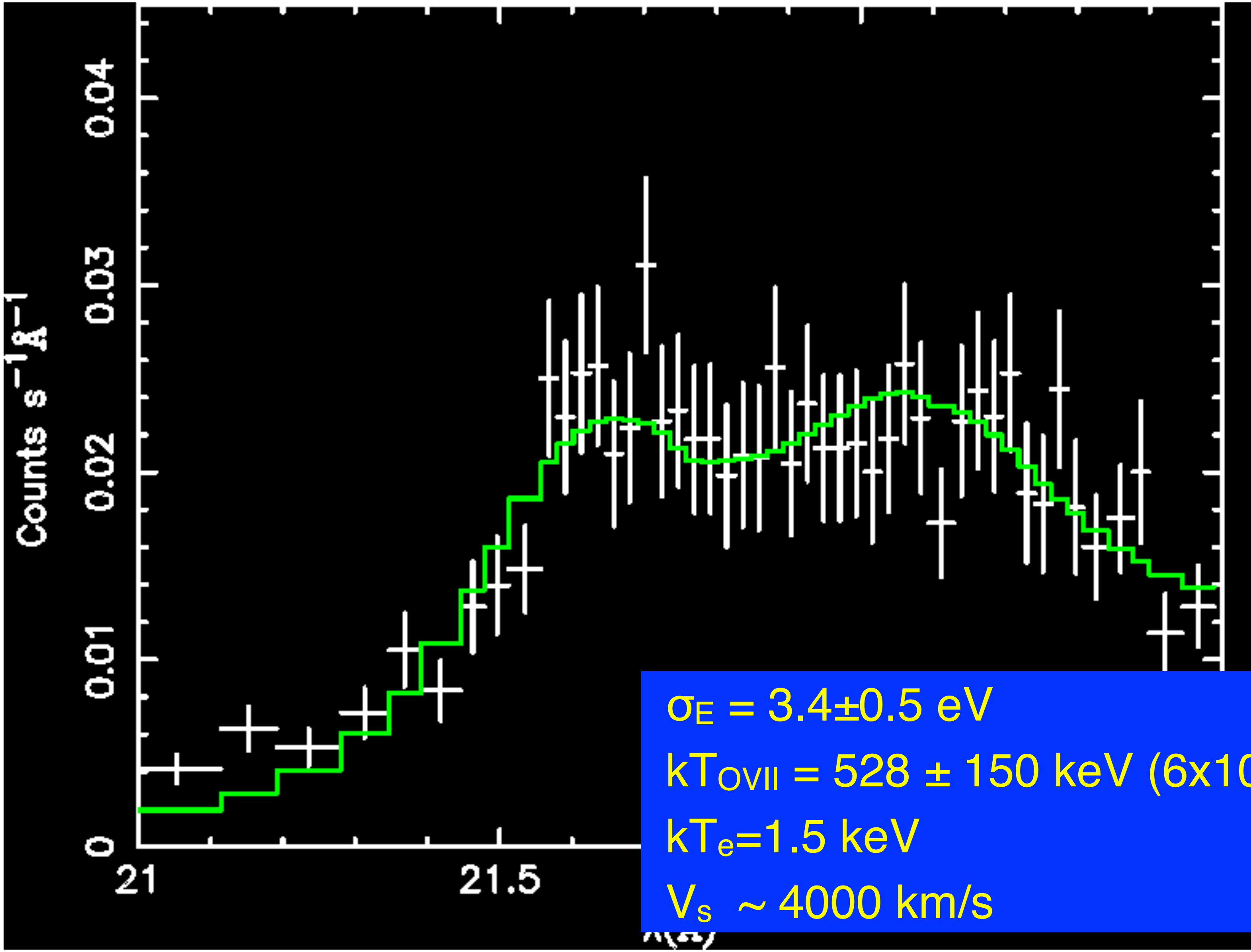


- Knot size ~ 1 arcmin   (0.4 arcmin FWHM)
- Target for XMM-Newton Reflective Grating Spectrometer
- Spectral resolution for bright lines , e.g OVII (~22Å): ~ 1/170

  Vink+ 2003, Vink ’05, Broersen+ 2013

The OVII Thermal Broadening

Vink+ ’05, Broersen+ ‘15



σ_E = 3.4±0.5 eV

kT_{OVII} = 528 ± 150 keV (6×10^9 K)

kT_e=1.5 keV

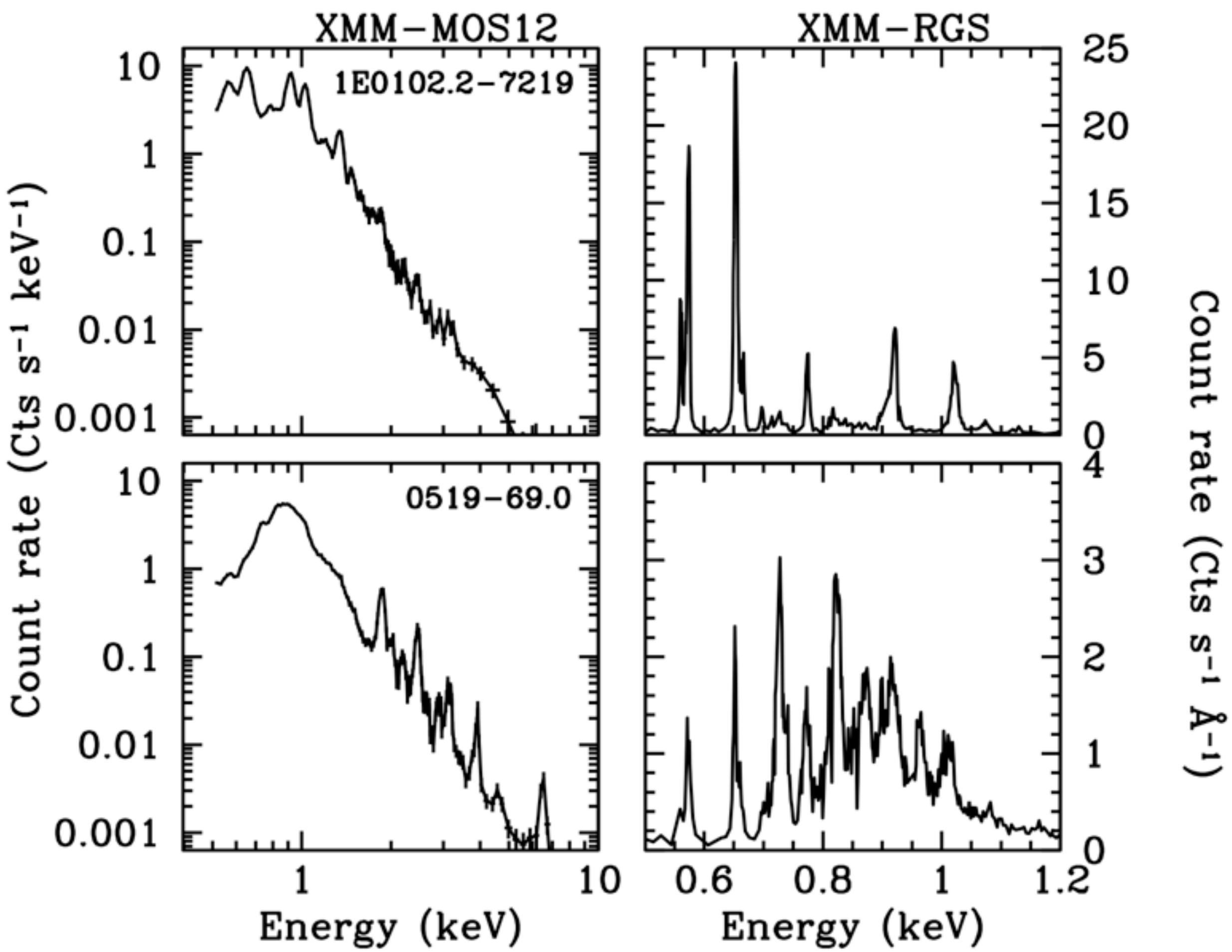
V_s ~ 4000 km/s

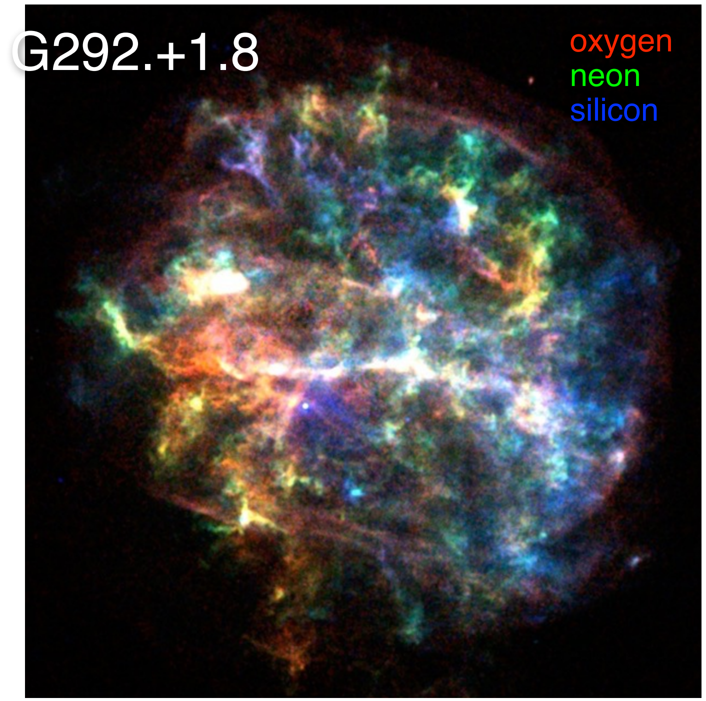
II

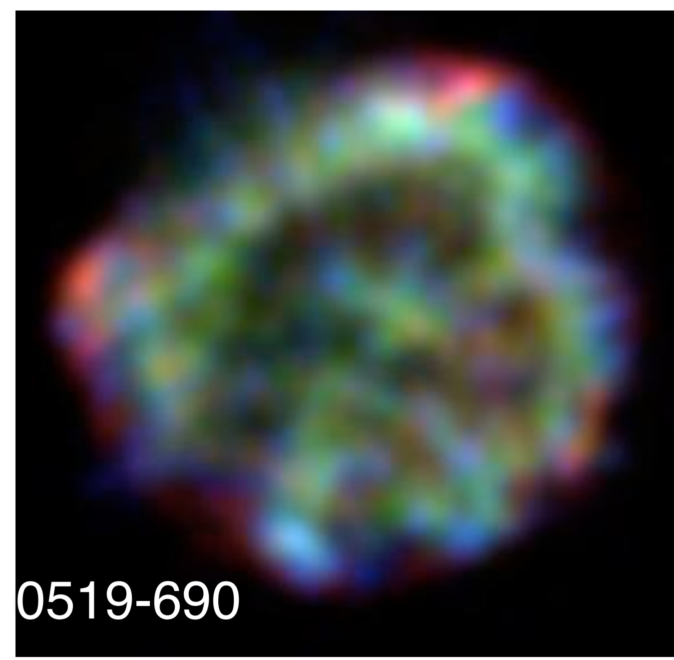
Supernova remnants

iii. Clues toward explosion properties

Linking SNRs with SN classes





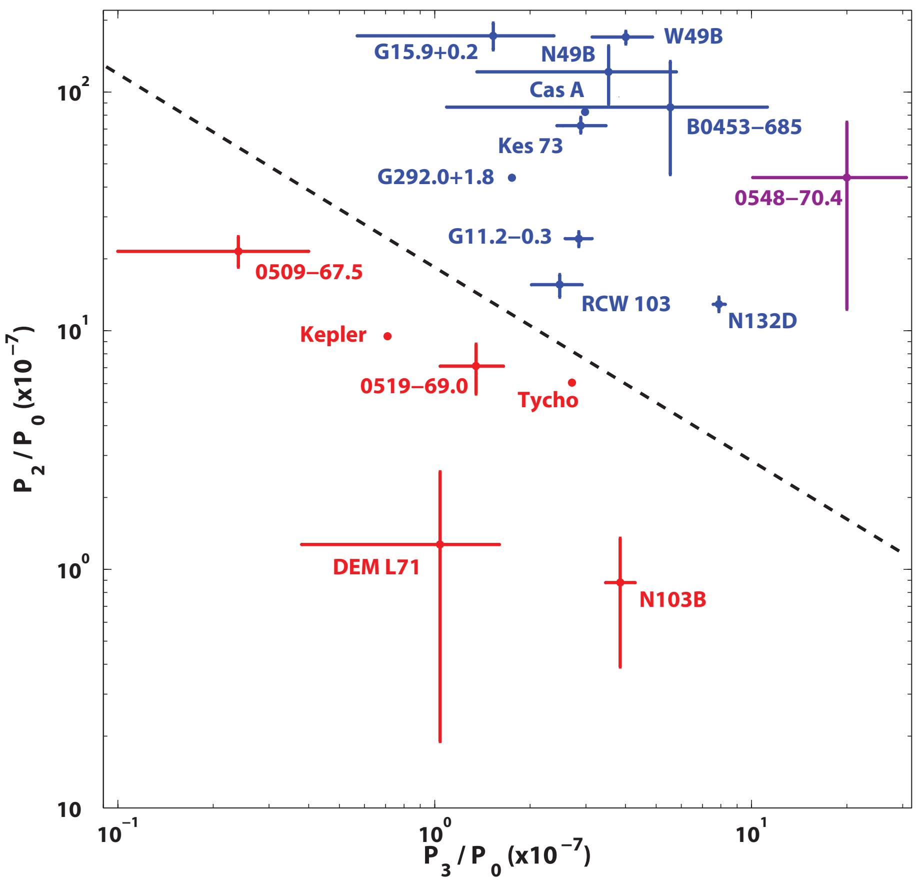


- Core collapse SNRs are rich in O, Ne, Mg
- Type Ia SNRs are iron-rich (Fe-L bump @ ~1 keV)

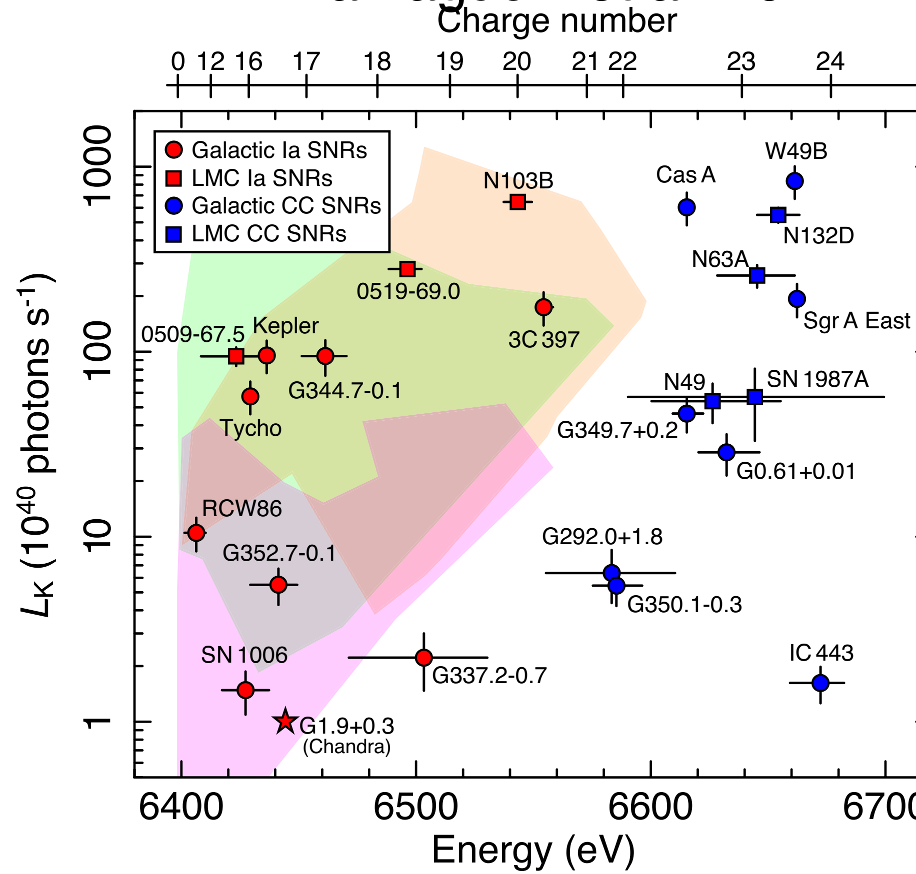
e.g. Hughes ’95, Flanagan+ ‘04, Kosenko+ ‘10

Difference between CC and SN Ia SNRs

Lopez et al. 2009

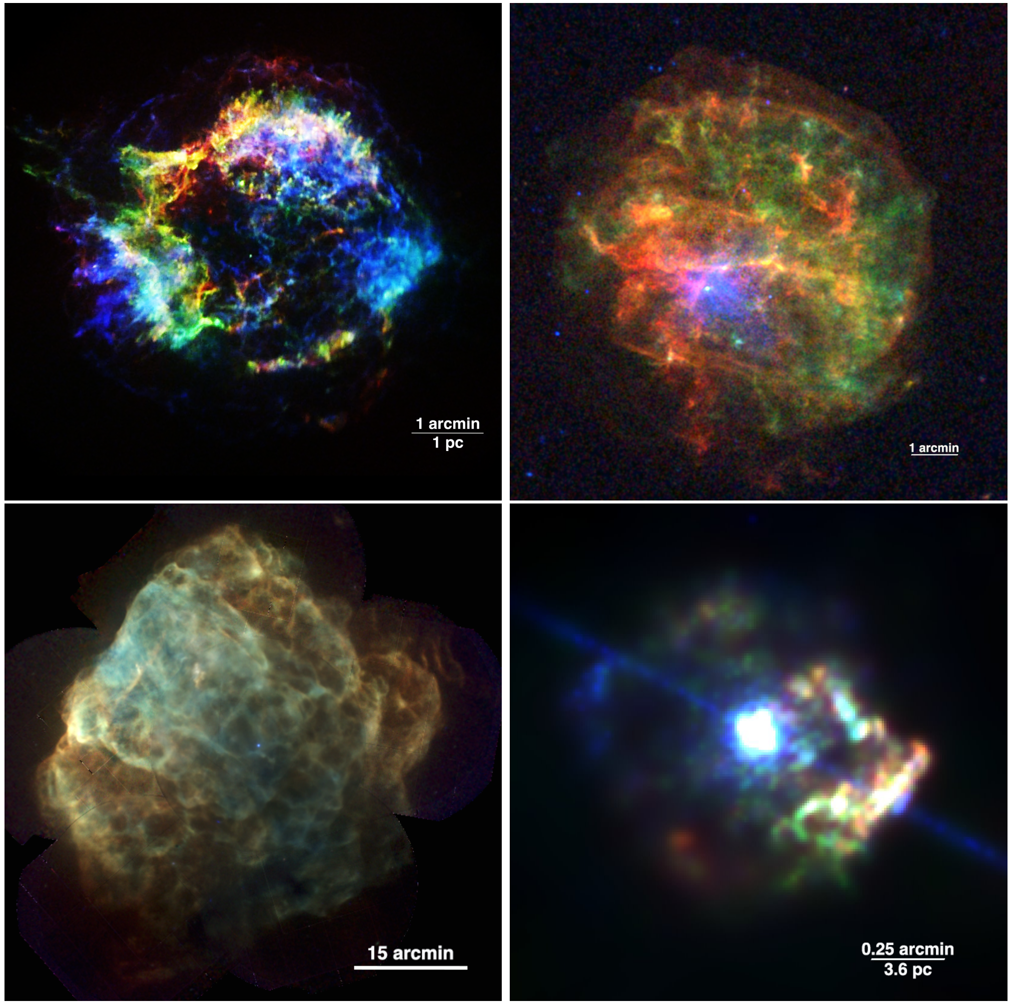


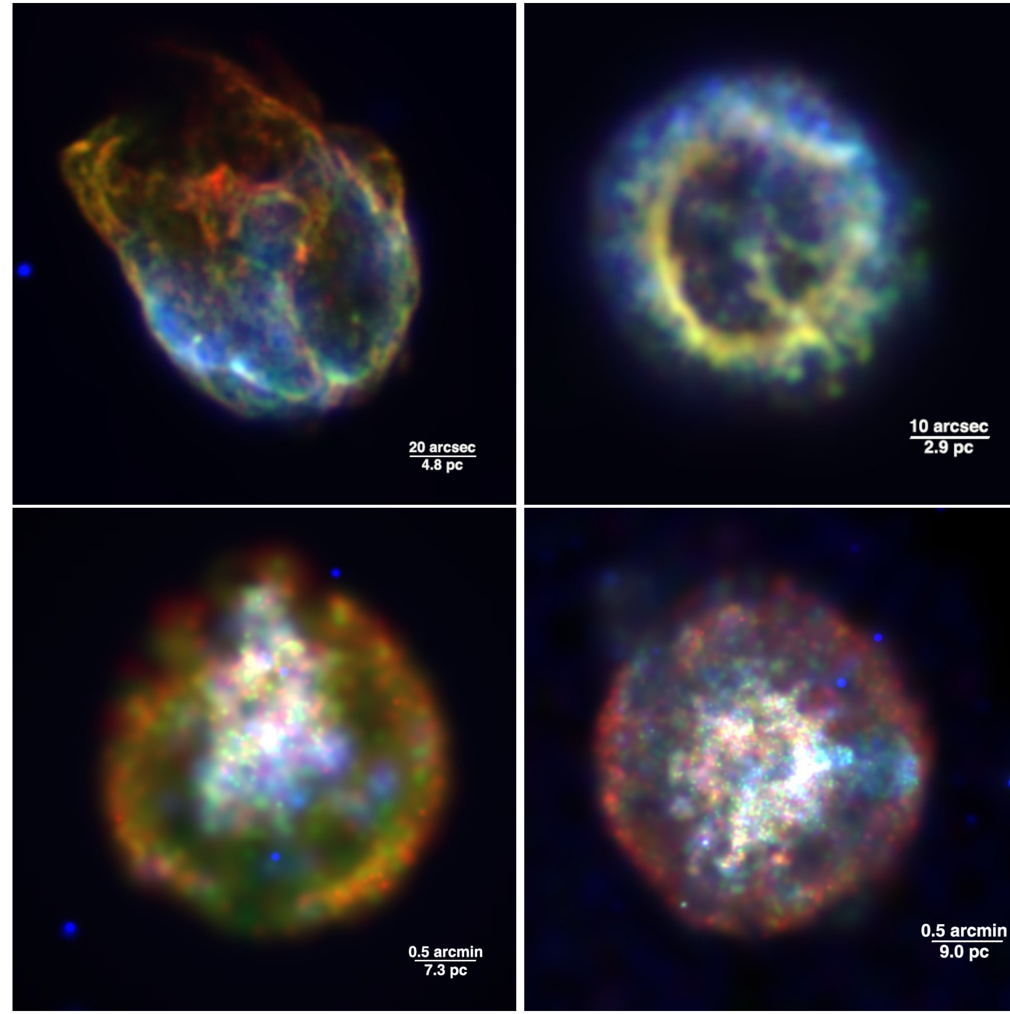
Yamaguchi et al. 2014



- SN Ia:
  - tend to be more roundish
  - Fe K lower energy (6.5 keV) -> low ionisation -> lower CSM densities?
  - Halpha shock only SN Ia remnants
- Are exceptions and caveats: W49B may be SN Ia (Zhou&Vink '18)

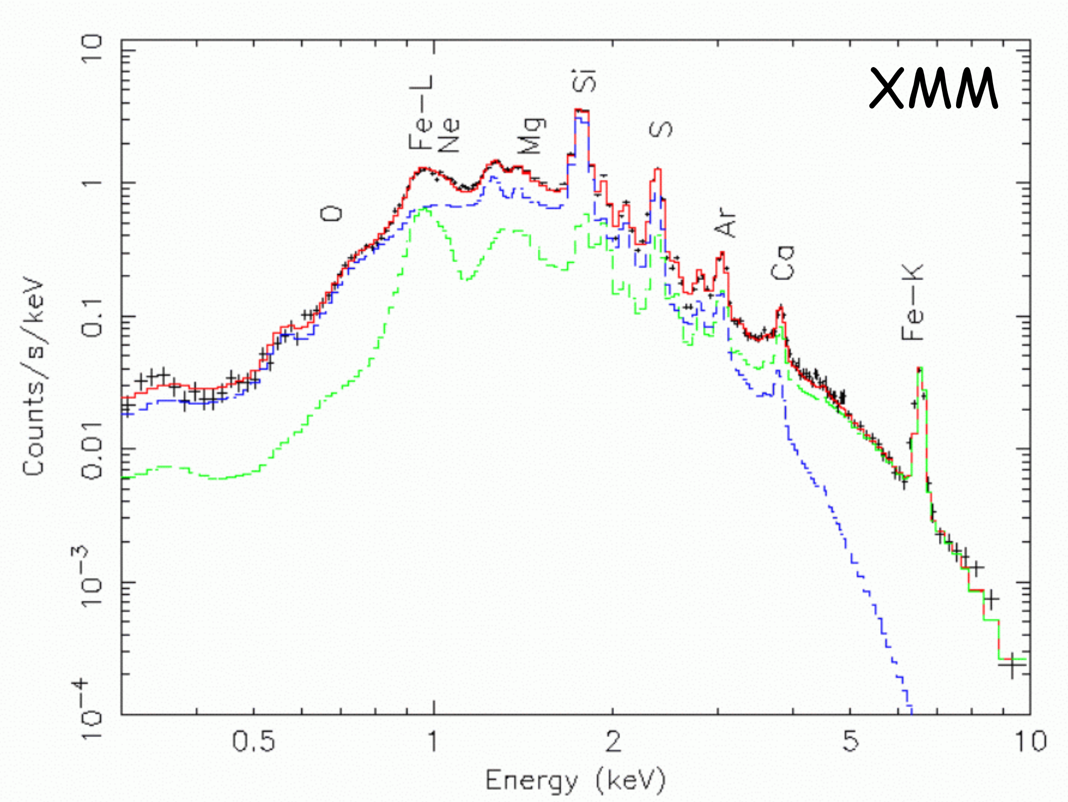
Oxygen-rich supernova remnants

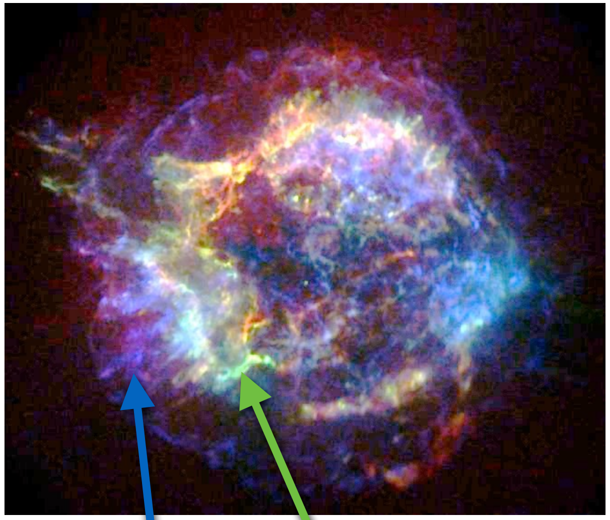


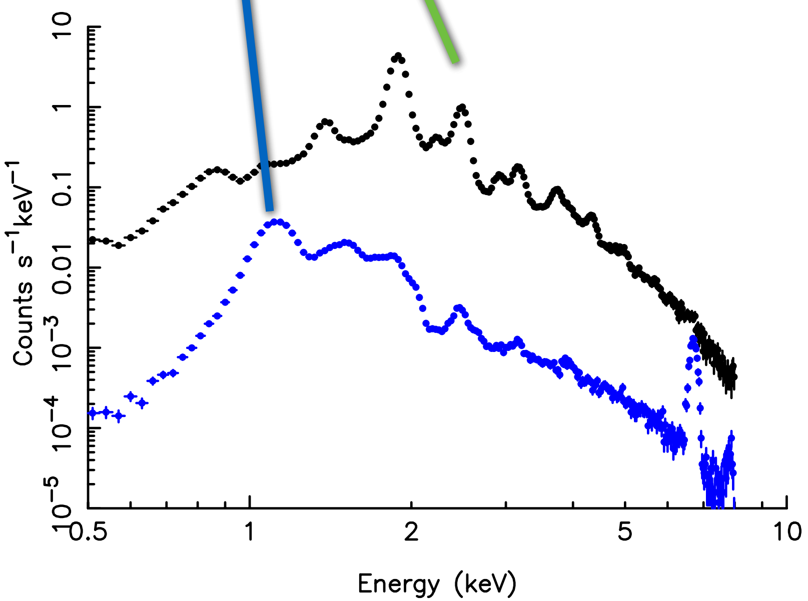


- Oxygen-rich SNRs: most likely more massive progenitors ($M>18\ M_{sun}$)
- Irregular shapes
  - except SMC SNRs!
- Some with, some without pulsar wind nebulae

Cassiopeia A

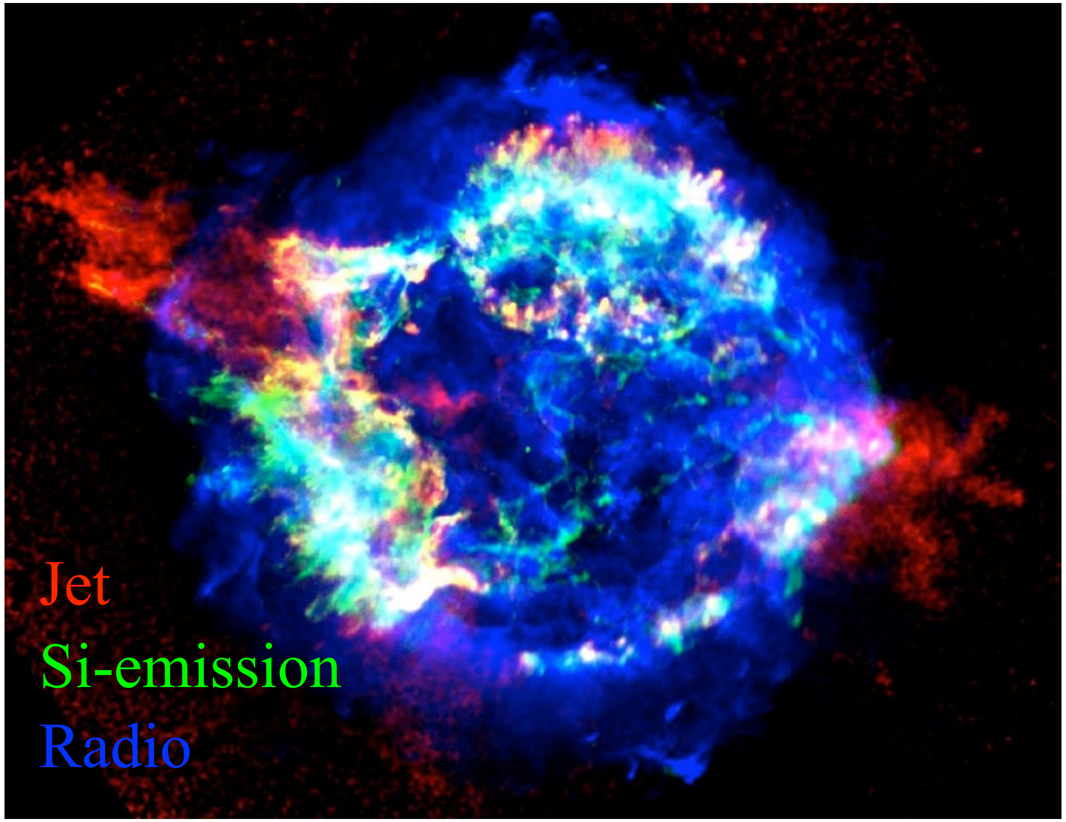




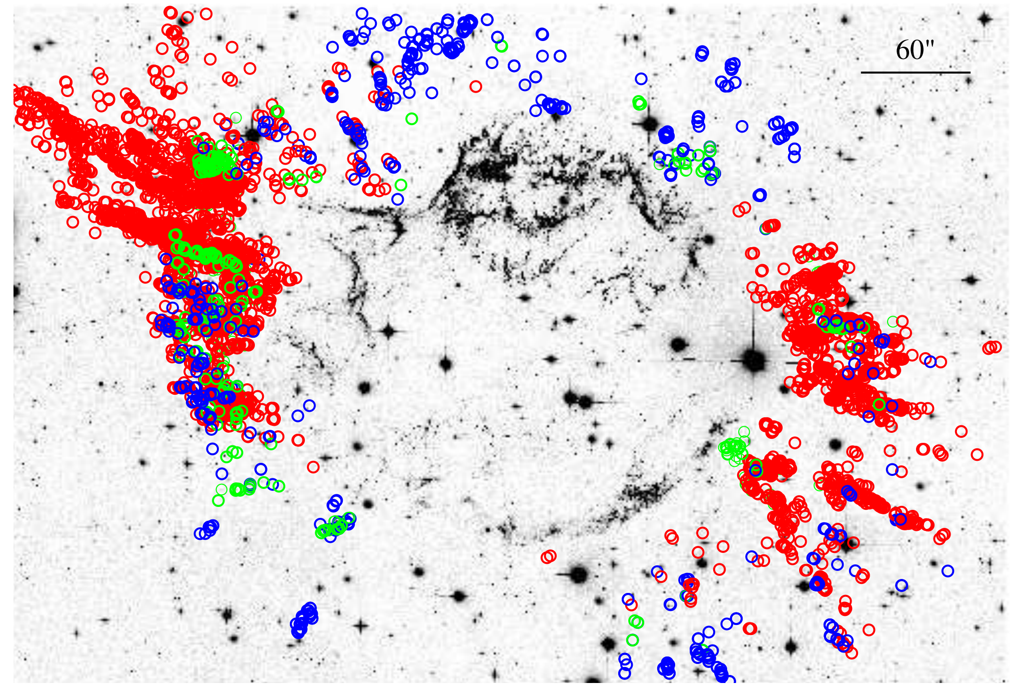


- Lots of Si/S-rich material
- Poor in Ne/Mg (contrary to models!!)
- In some places: iron overtaken Si!
  (Hughes+ '00)

(A)symmetries I: Jet/Counter-jet



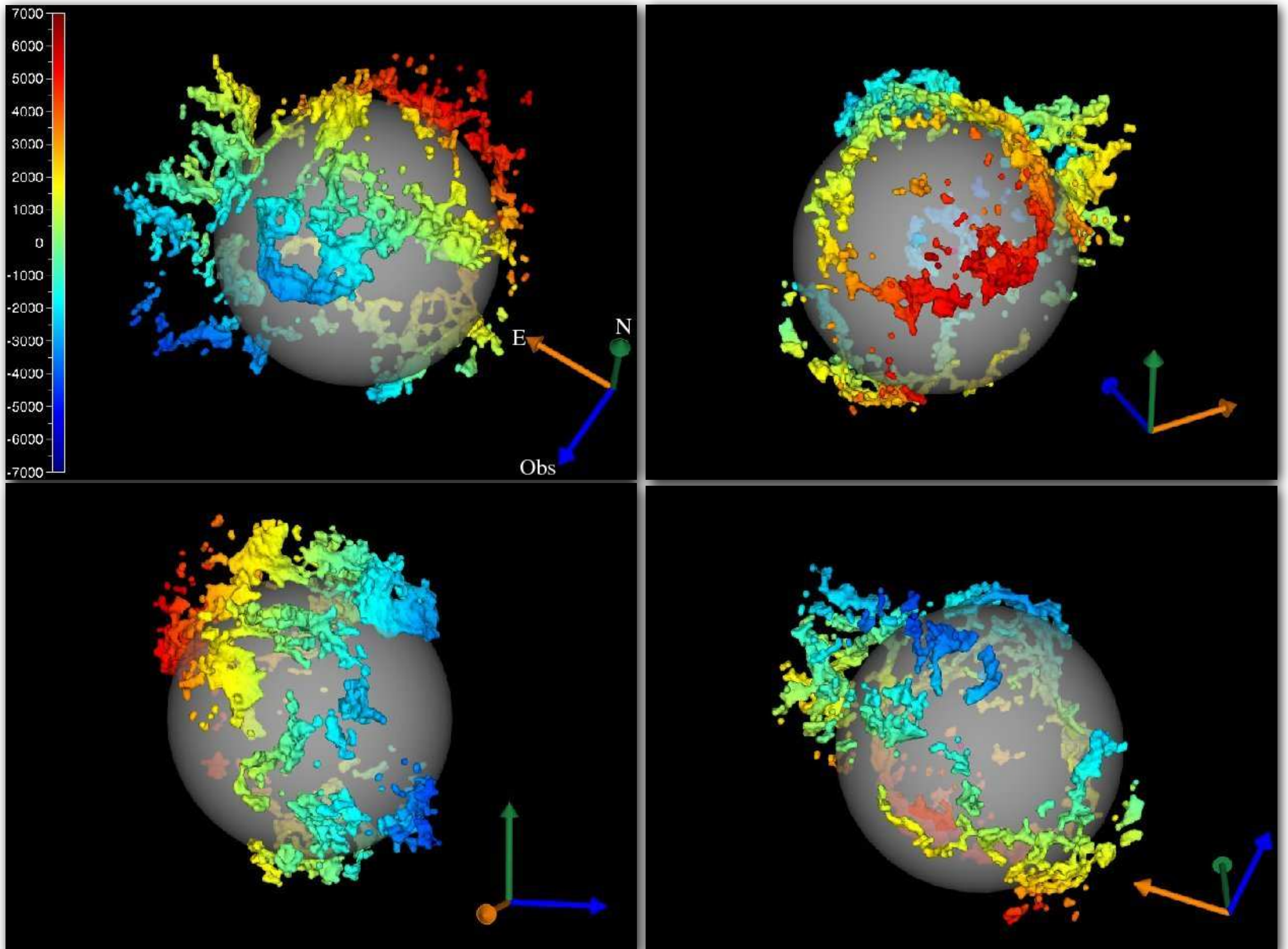
Optical: sulfer (red) vs oxygen (blue)



- In X-rays, brought out using Si/Mg ratio: Si-rich
- Optical: sulphur (not oxygen) fast moving knots
- If originating in core, why Si/S & not Fe rich? (Si bipolar/Fe irregular)
- Not a GRB jet: energy ~$10^{48\text{-}49}$ erg (Schure et al. '07)

Fesen et al. '01, Vink '04, Hwang+ 04, Hines+ '04, Laming et al.'06, Schure+ '07

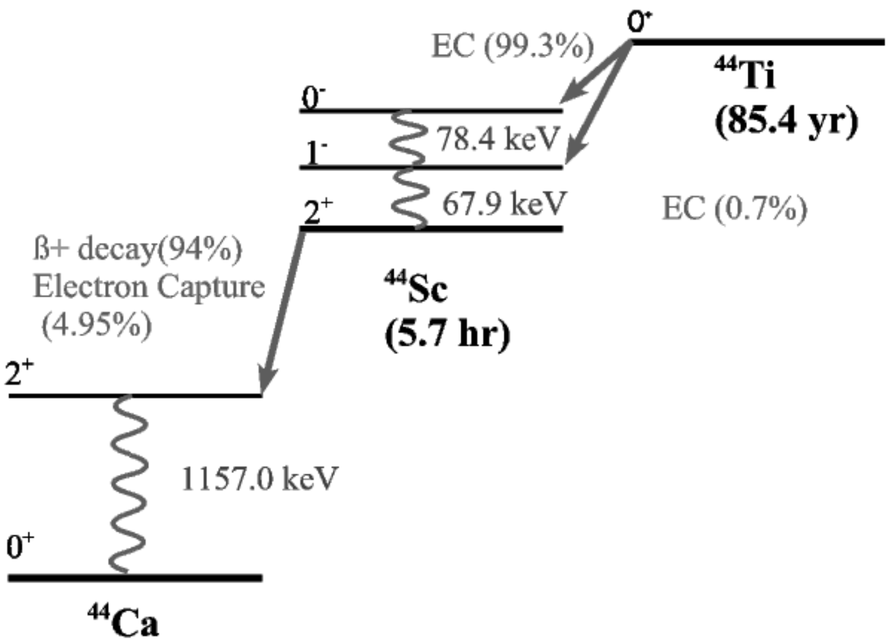
Optical knots: ring-like structures

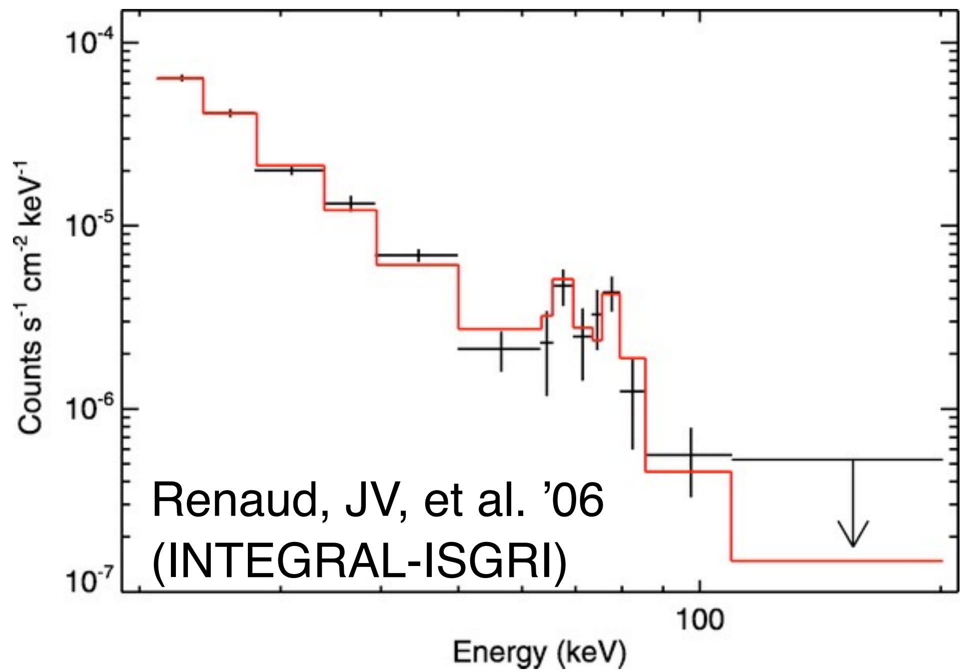


Milsisavljevic & Fesen '13

- Many dense ejecta knots: emit in optical ([S II], [O III])
- [S II] knots concentrated along jet/counter jet axis
- Ring-like morphologies: Ni/Fe plumes pushed aside O/Si layers?

^{44}Ti decay

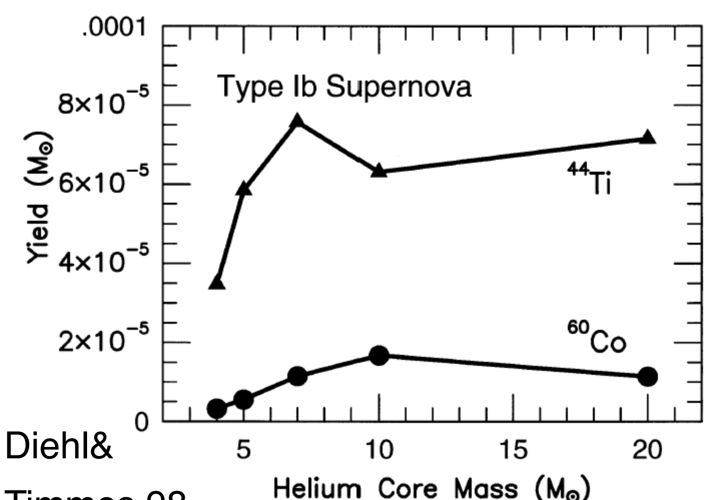




- ^{44}Ti exclusive explosive nucleosynthesis
- Decay time ~86 yr
- Yield: sensitive to mass-cut, expansion, and asymmetries!
- Detected in Cas A

  (Iyudin+ 94, Vink+ '01, Renaud+ 06, Grefenstette+ 14, Siegert+ '15)

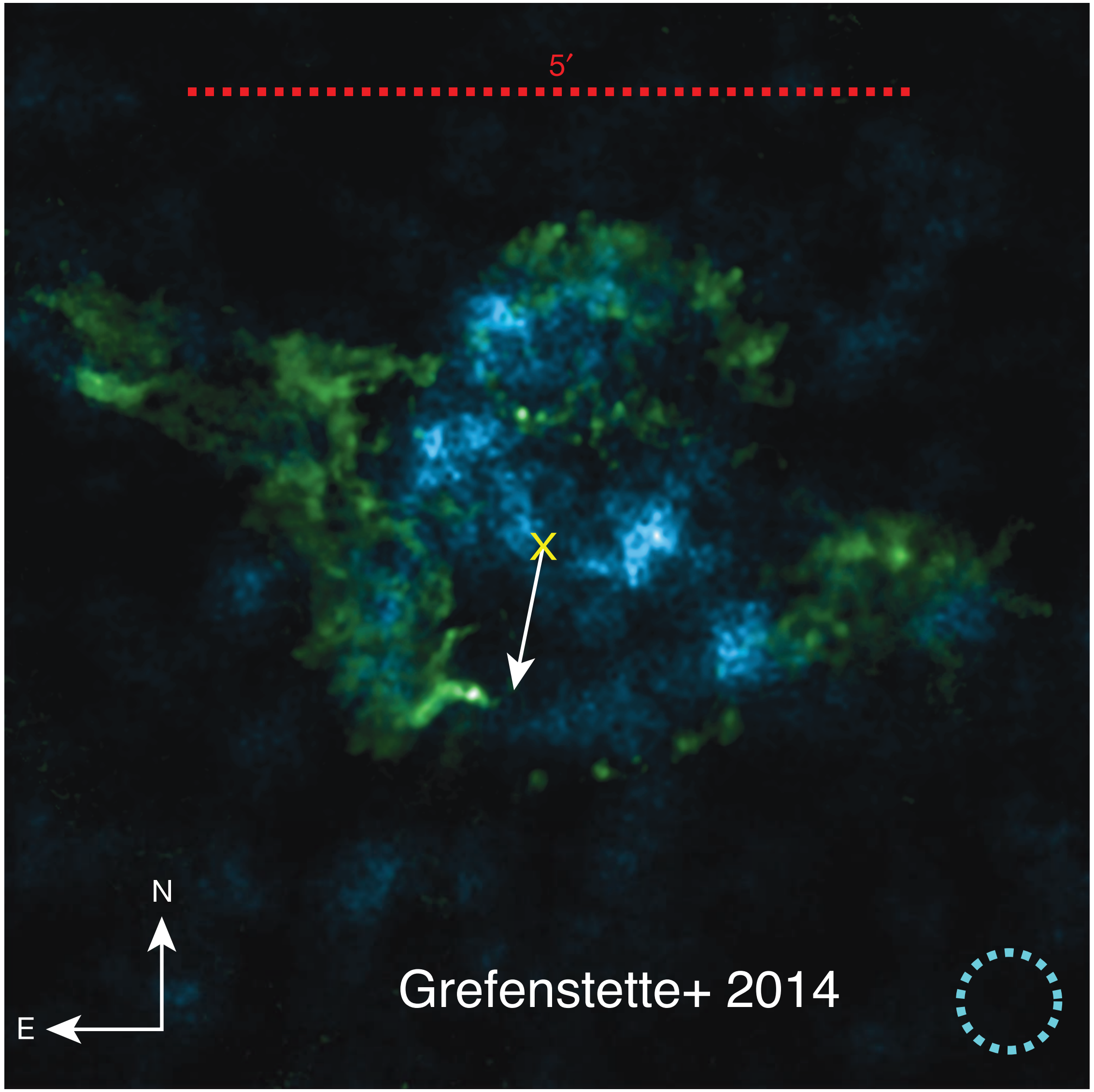
- Yield: (1.1-1.6)x10^{-4} M_{sun}



Diehl&

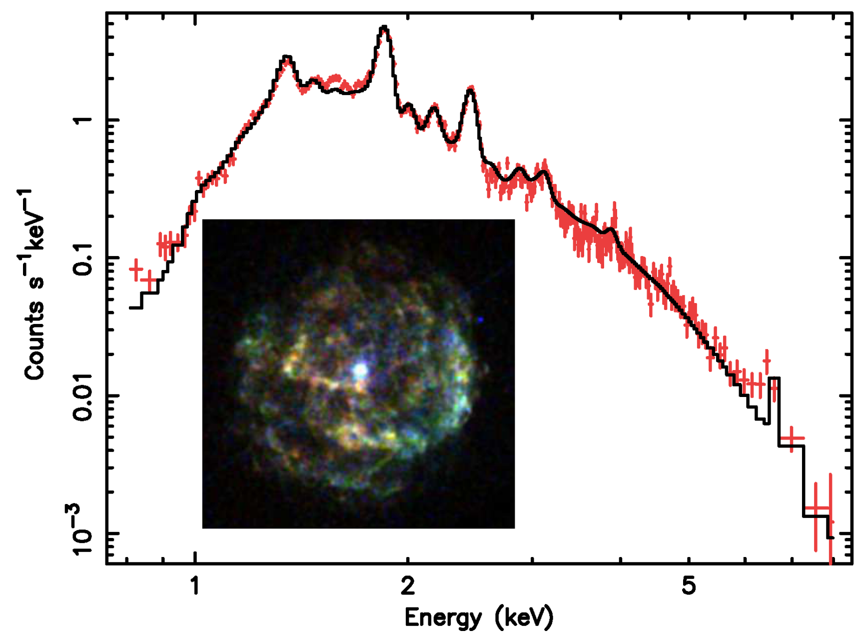
Timmes 98

^{44}Ti map NuStar



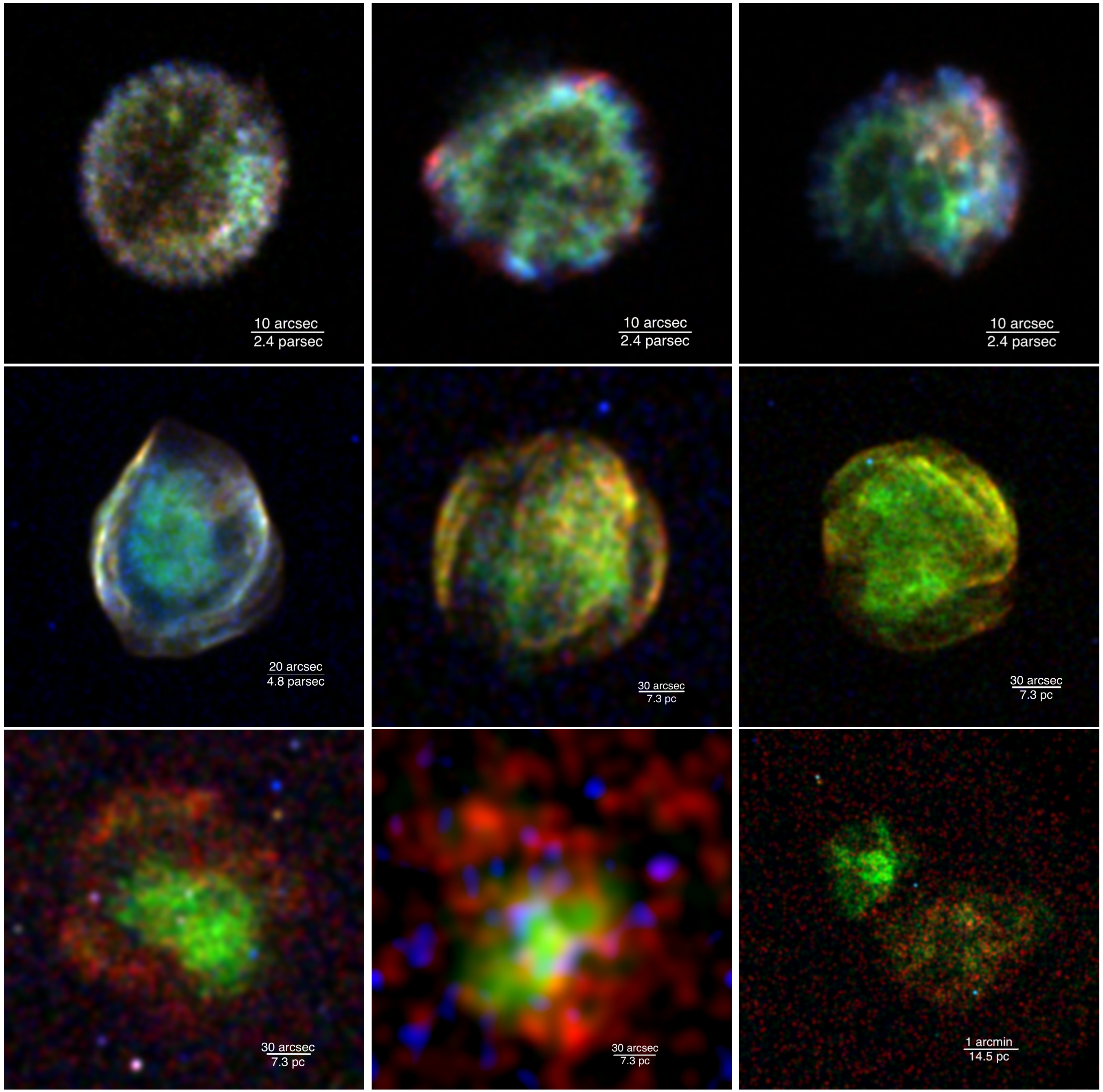
- ^{44}Ti in blue
- Si/Mg ratio green
- Most ^{44}Ti in unshocked interior
- Lines redshifted by 1000 km/s

Relation neutron stars and SNRs



- Simplistic view:
  - M<25 Msun -> make pulsar
  - M>25 Msun -> make BH
- What about other properties: spin and magnetic fields
- Trends among SNRs? Not really
  - Some O-rich have normal pulsar (G292.0+1.8)
  - Some O-rich have low field pulsar (Puppis A)
- Popular magnetar formation theory: dynamo in fastests spinning proto-NS
  - Expect then energetic supernovae ($E_{spin}= 10^{52}$ $(P/ms)^{-2}$)
  - However: SNRs with magnetars have normal to low explosion energies (Vink&Kuiper 2006)

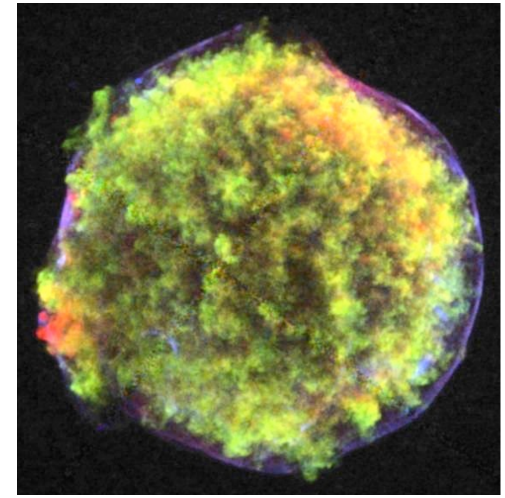
Chandra images LMC SN Ia remnants

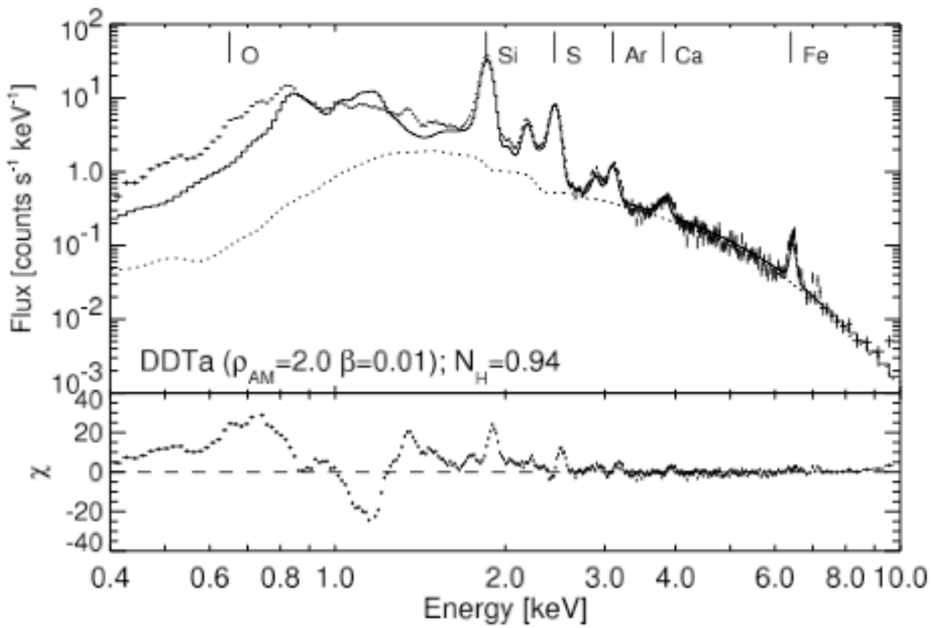


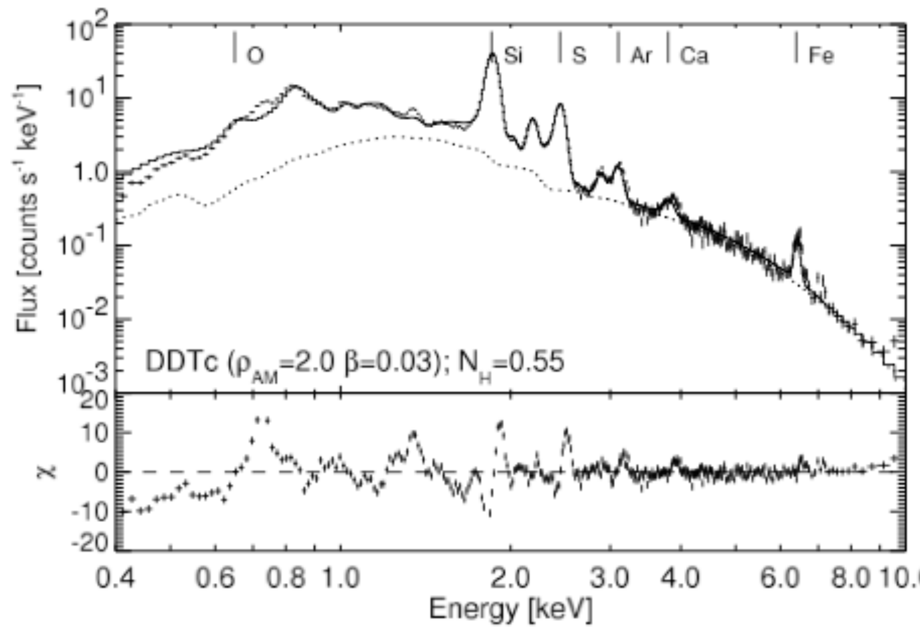
Full Hydro/X-ray modeling Type Ia

- Type Ias well suited for full modeling
  →they are much better stratified
- 2 groups: Badenes, Bravo+ & Blinnikov, Kosenko+
- Uncertainty about non-thermal distributions
- Results mainly for Tycho's SNR and 0509-690

(both have optical light echo spectra: Type Ia!)



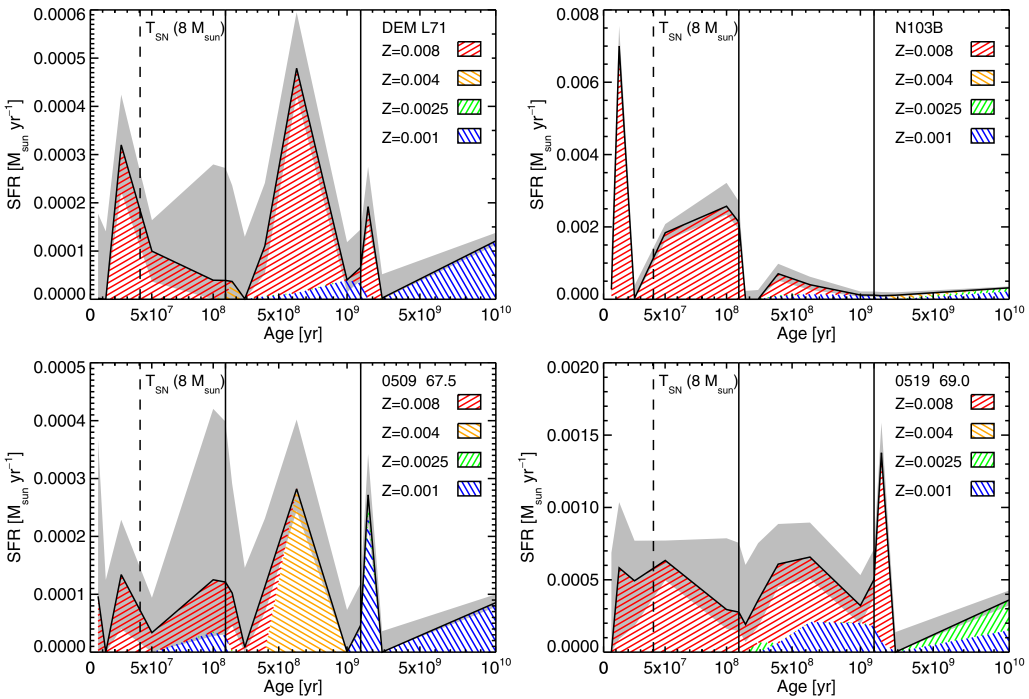




Tycho XMM (Badenes+ '06)

Distributions of Type Ia and CC SNRs

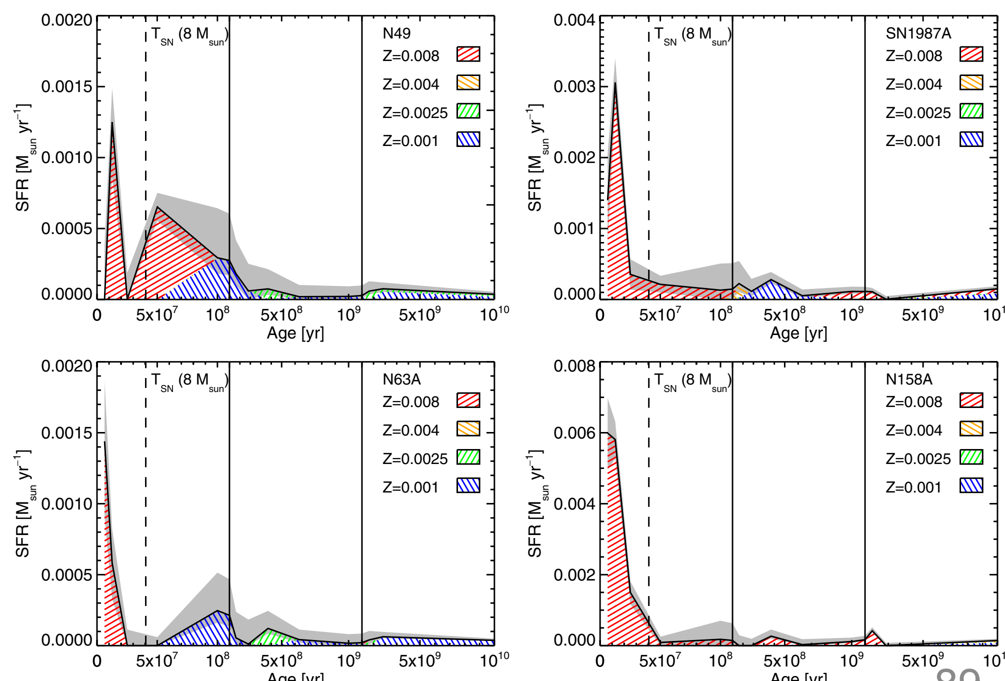
LMC Type Ia SNRs



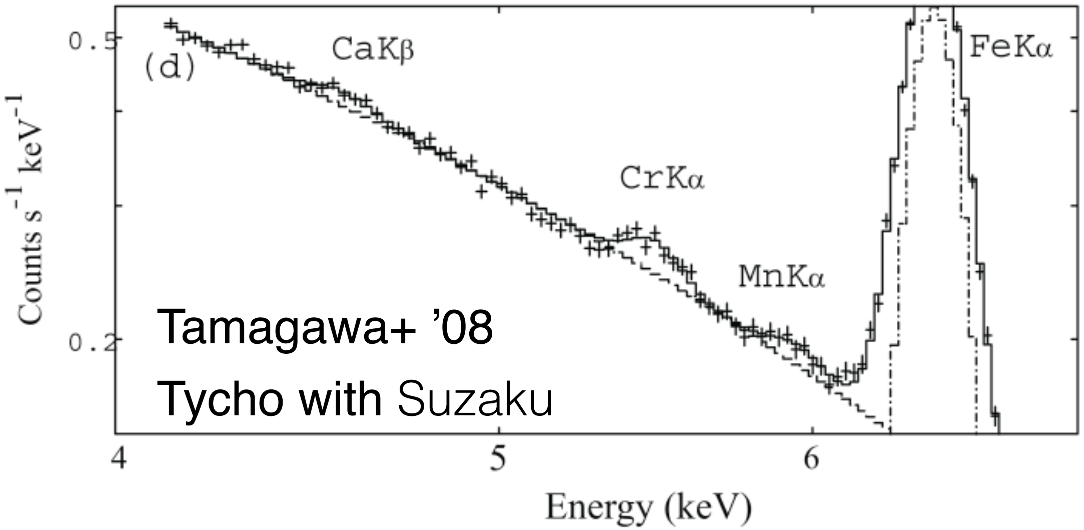
Study by Badenes, Harris, Zaritsky, Prieto, 2009

- Core collapse SNRs in regions with recent star formation
- Type Ia SNRs, more diverse

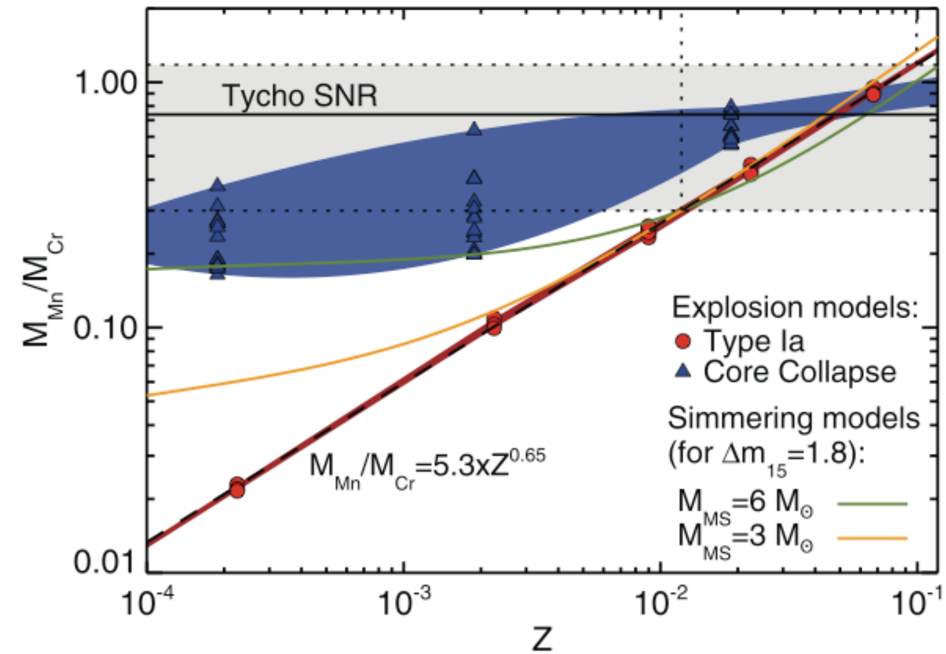
LMC core collapse SNRs



New territory: Manganese and Chromium



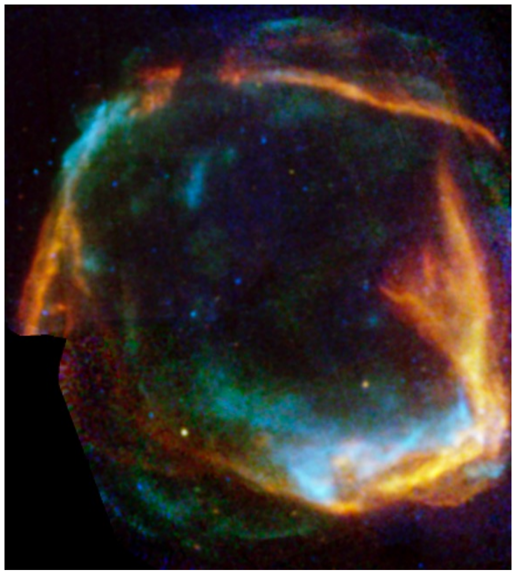
Badenes+ '08



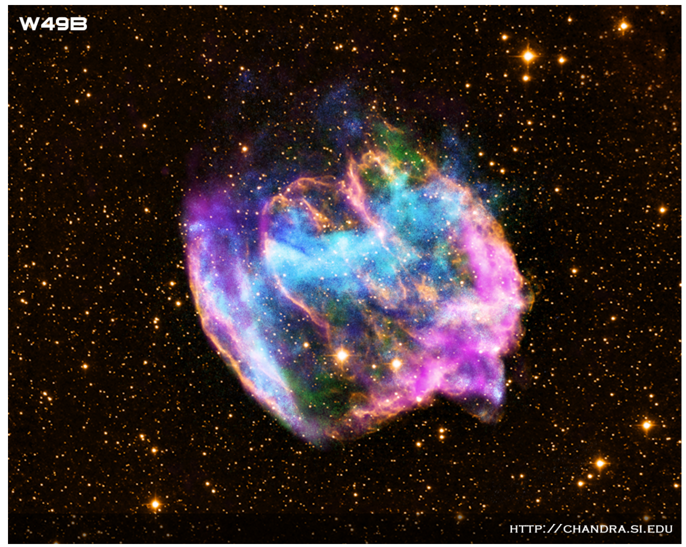
- Several SNRs show evidence for Mn and Cr line emission
- Mn/Cr ratio and Mn abundance inform us about:
  - progenitor metalicity (Z higher, more neutrons more Mn)
  - simmering: nuclear reactions in WD core prior to explosion -> more neutrons
  - made during explosion if density high -> need WDs close to Chandrasekhar mass
- Conclusion:
  - for 3C397 and W49B we need near Chandrasekhar mass
  - best explained by single degenerate scenario

Mass loss around SNe Ia: SD scenario?

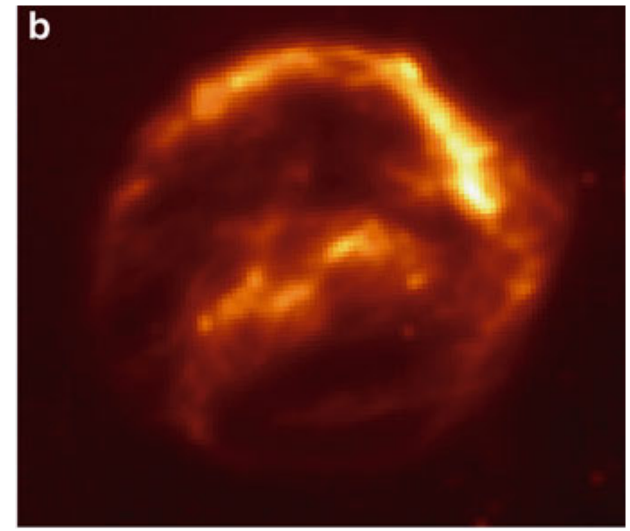
RCW 86: large cavity
(e.g. Badenes 08/Broersen+ 14)



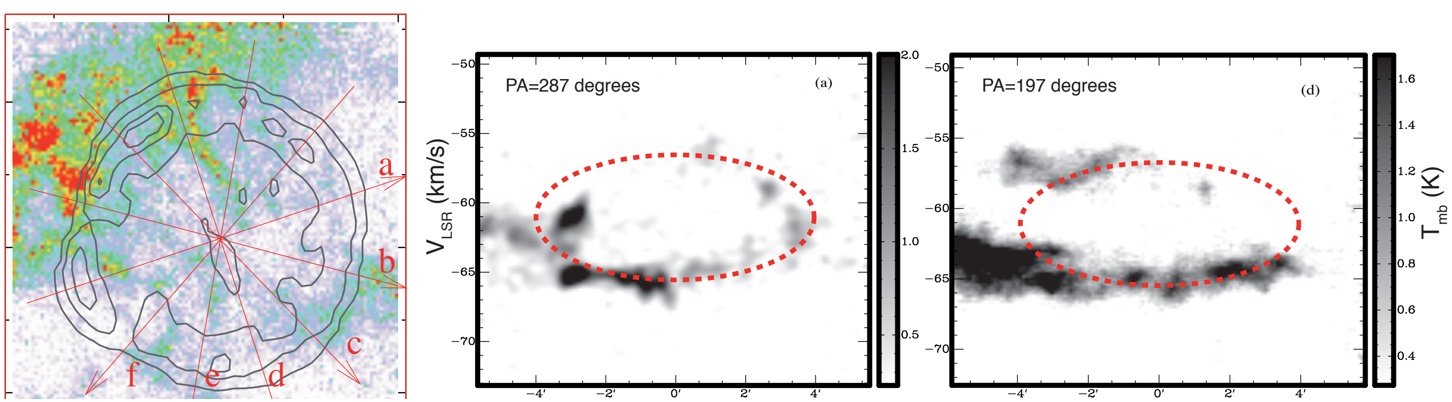
W49B (e.g. Zhou & Vink 18):
small cavity
dense CSM



Kepler (e.g. Vink '08/ Blair+ '07):
nitrogen-rich shell/Si-rich dust
500 pc above Gal. plane

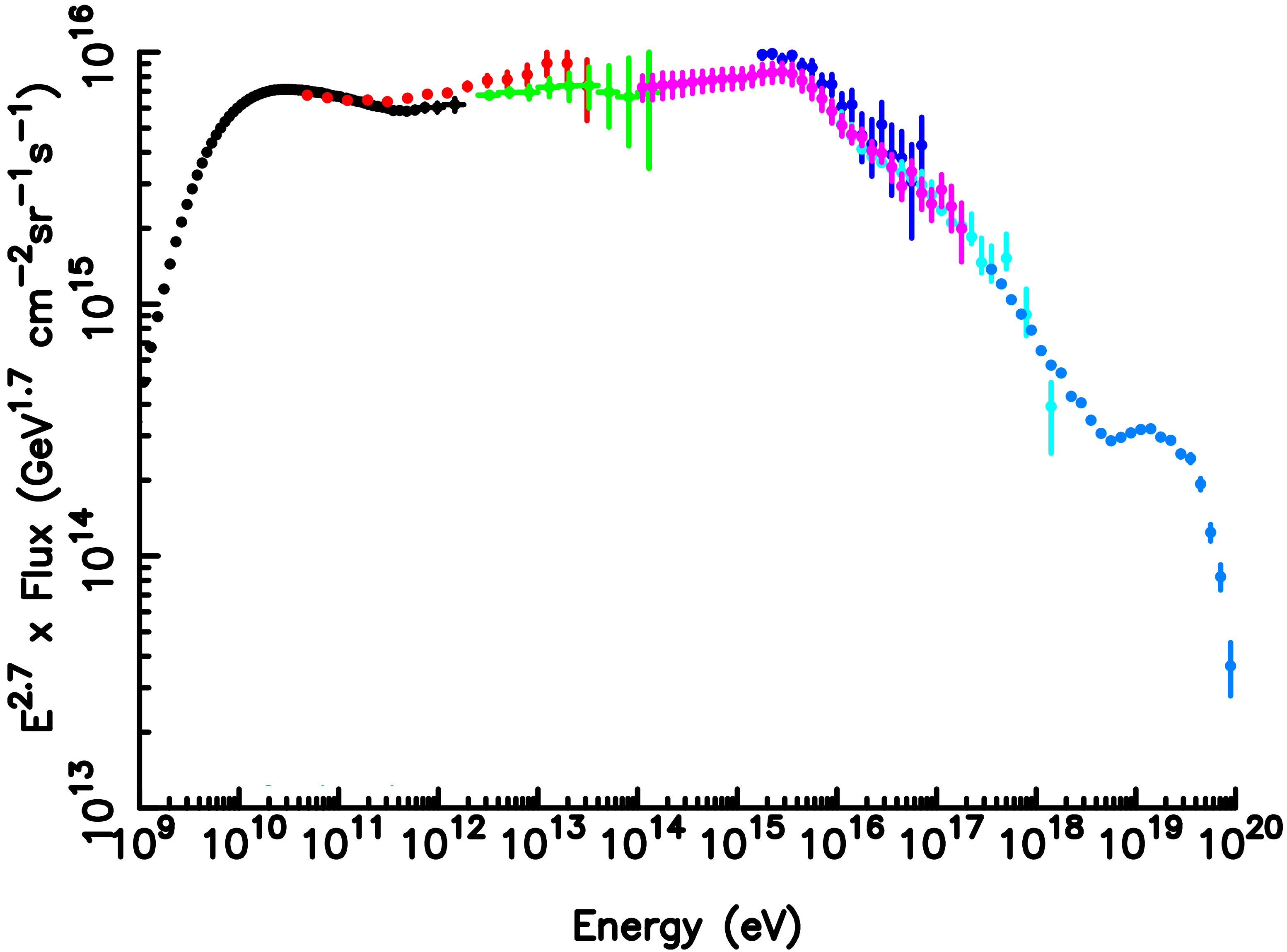


Tycho's SNR (Zhou+ '16): molecular expanding sphere



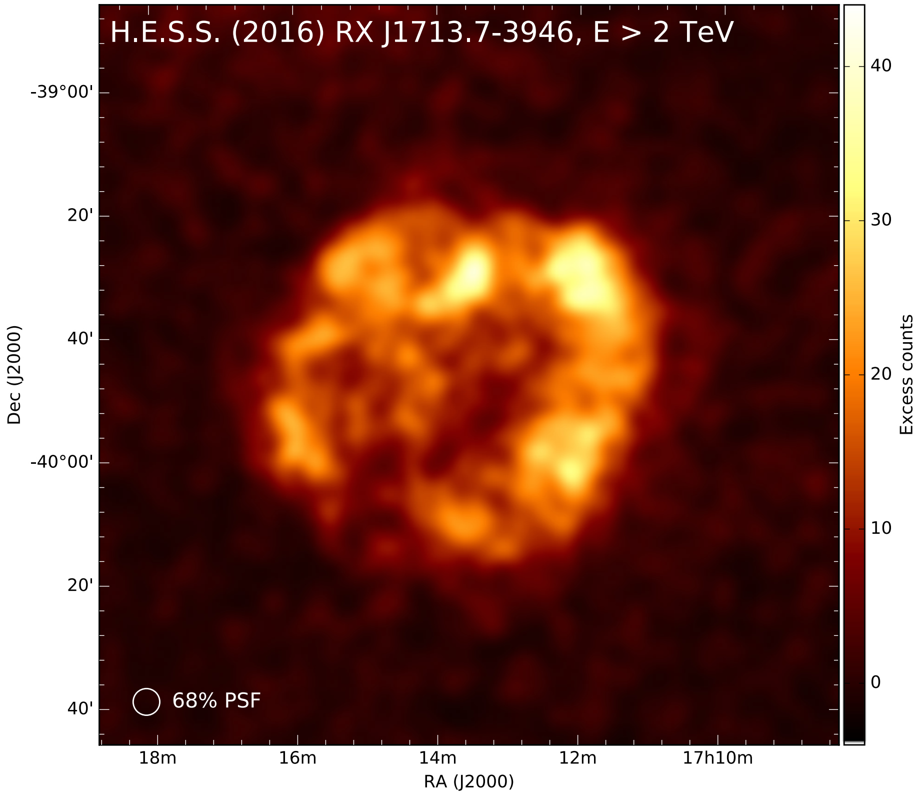
II
Supernova remnants
iv. Particle acceleration

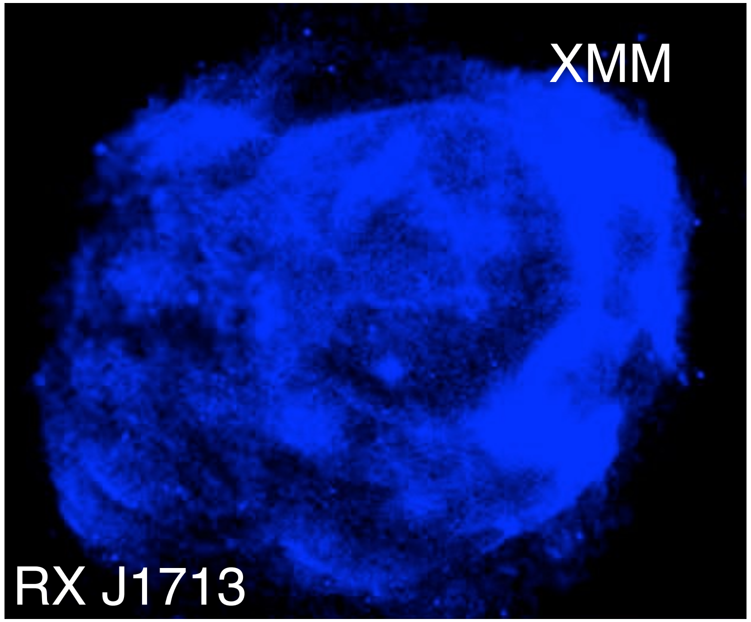
Cosmic rays



$E^{2.7}$ x Flux (GeV$^{1.7}$ cm^{-2}sr^{-1}s^{-1})
10^{16}
10^{15}
10^{14}
10^{13}
10^{9} 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
Energy (eV)

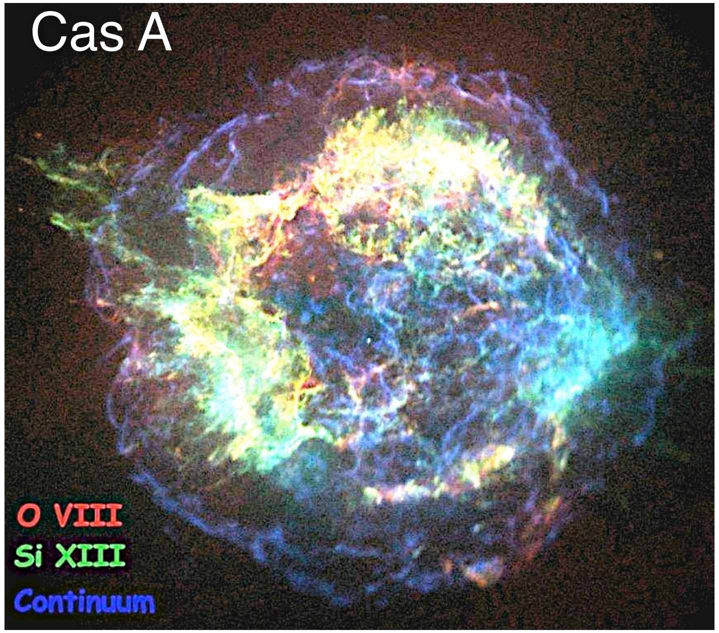
Gamma-ray and X-ray evidence

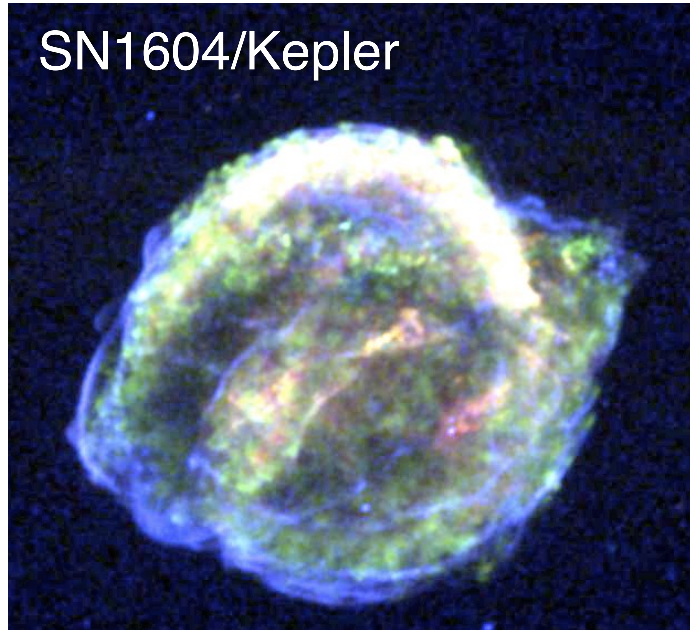


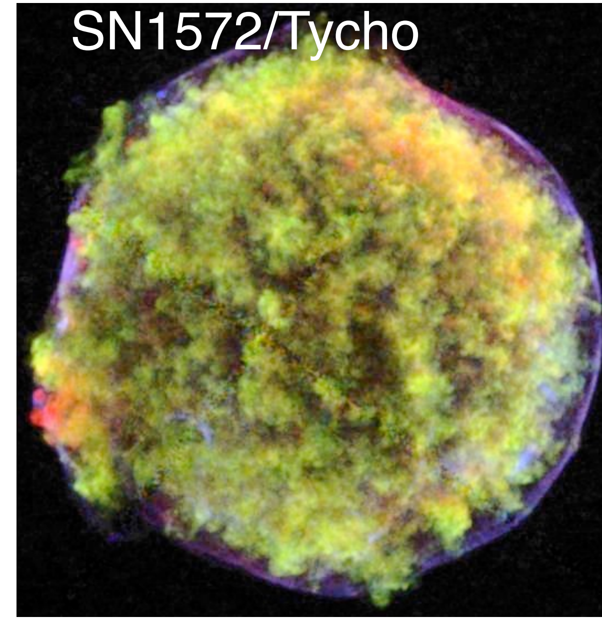


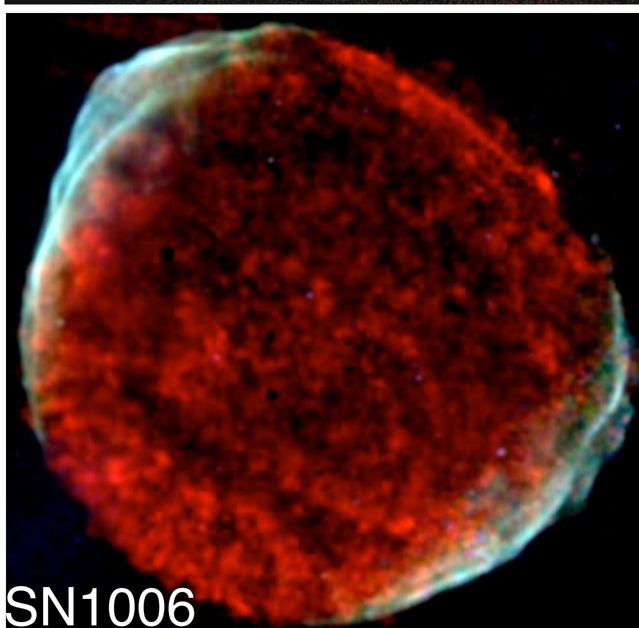
- Last two decades: growing evidence for fast acceleration
  - Detection of X-ray synchrotron emission
  - Gamma-ray detection > 1 TeV
- RX J1713:
  - Brightest TeV gamma-ray SNR
  - X-ray: totally dominated by synchrotron emission (Acero, Katsuda+ ’17)

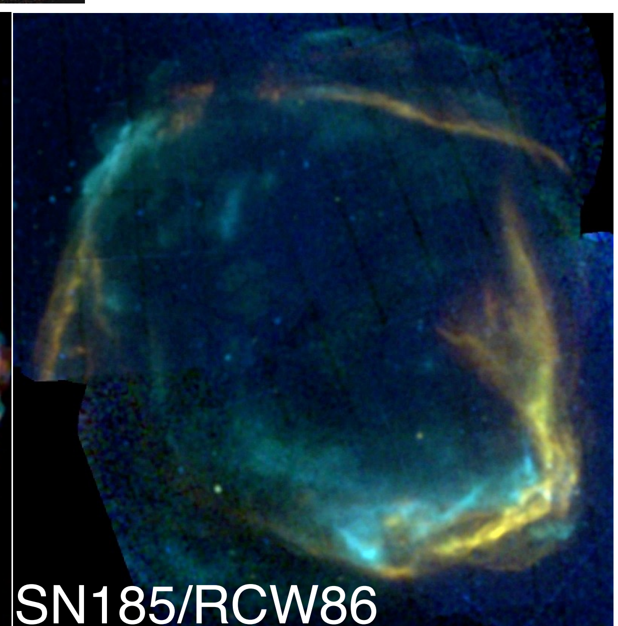
X-ray synchrotron from young SNRs

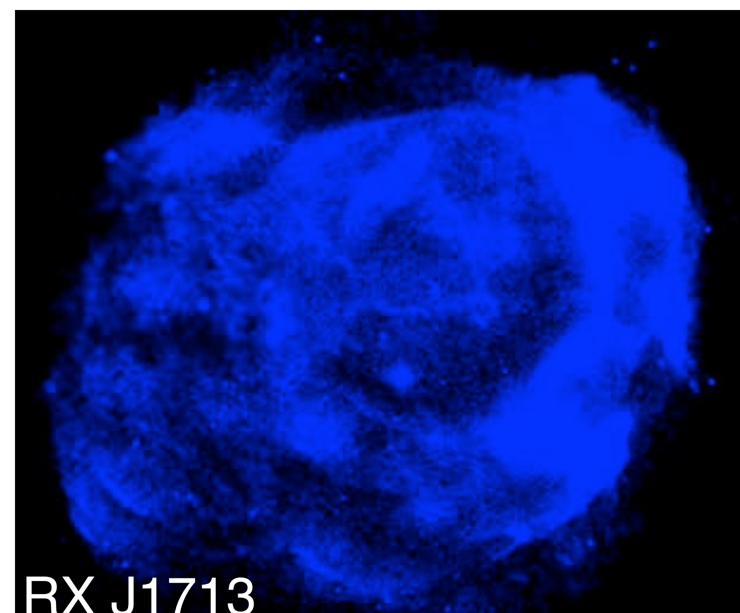












Loss-limited synchrotron cut-off

- Synchrotron loss-time

$$\tau_{\rm syn} = \frac{E}{dE/dt} = 12.5 \left(\frac{E}{100\ {\rm TeV}}\right)^{-1} \left(\frac{B_{\rm eff}}{100\mu{\rm G}}\right)^{-2}\ {\rm yr}.$$

- Diffusive acceleration time (depends on diffusion coeff. D, compression X)

$$\tau_{\rm acc} \approx 1.83 \frac{D_2}{V_{\rm s}^2} \frac{3\chi^2}{\chi - 1} = 124\eta B_{-4}^{-1} \left(\frac{V_{\rm s}}{5000\ {\rm km\,s^{-1}}}\right)^{-2} \left(\frac{E}{100\,{\rm TeV}}\right) \frac{\chi_4^2}{\chi_4 - \frac{1}{4}}\ {\rm yr},$$

- Equating gives expected cut-off for loss-limited case

$$\boxed{h\nu_{\rm cut-off} = 1.4\eta^{-1} \left(\frac{\chi_4 - \frac{1}{4}}{\chi_4^2}\right) \left(\frac{V_s}{5000\ {\rm km\,s^{-1}}}\right)^2\ {\rm keV}}$$

- NB in loss limited case, frequency cut-off independent of B!!

Implications

- Synchrotron emissivity profile broad: gradual steepening beyond break
- Fact that young SNRs are synchrotron emitters: acceleration must proceed close to Bohm-diffusion limit!

$$1 < \eta < 20$$

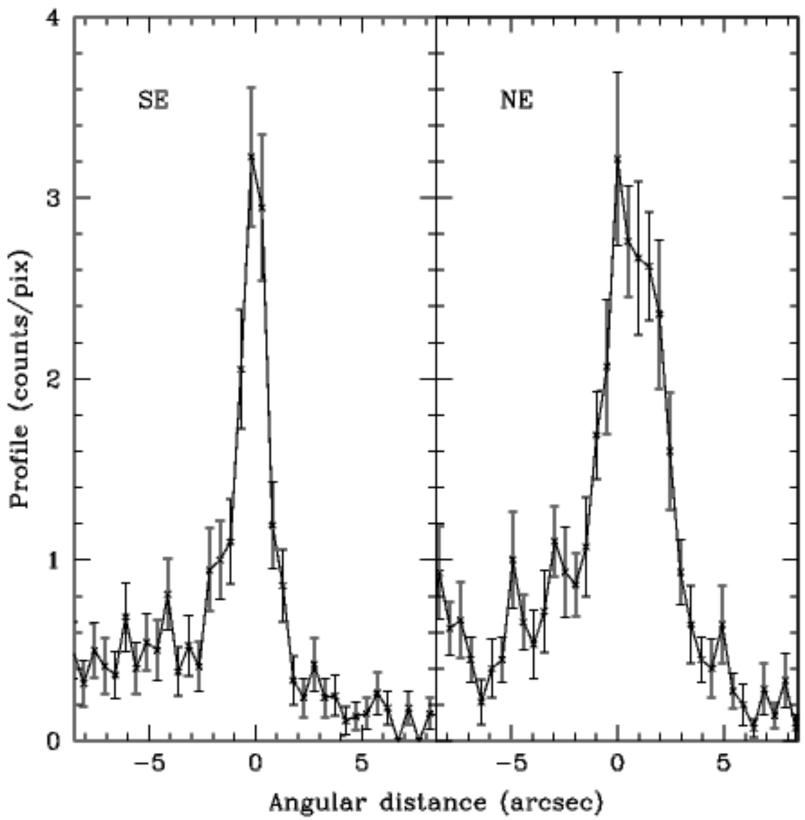
- The higher the B-field -> faster acceleration, but for electrons: E_{max} lower!
- For B=10-100 μG: presence of 10^{13}-10^{14} eV electrons
- Loss times are:

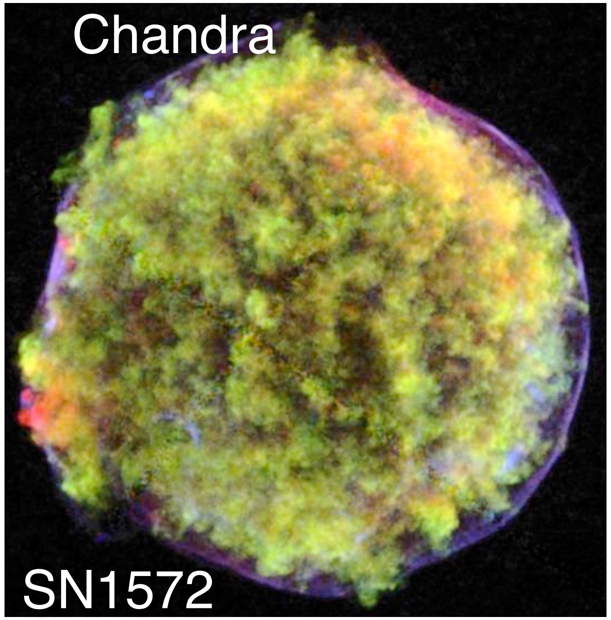
$$\tau_{\rm syn} = \frac{E}{dE/dt} = 12.5 \left(\frac{E}{100~{\rm TeV}}\right)^{-1} \left(\frac{B_{\rm eff}}{100\mu{\rm G}}\right)^{-2}~{\rm yr}.$$

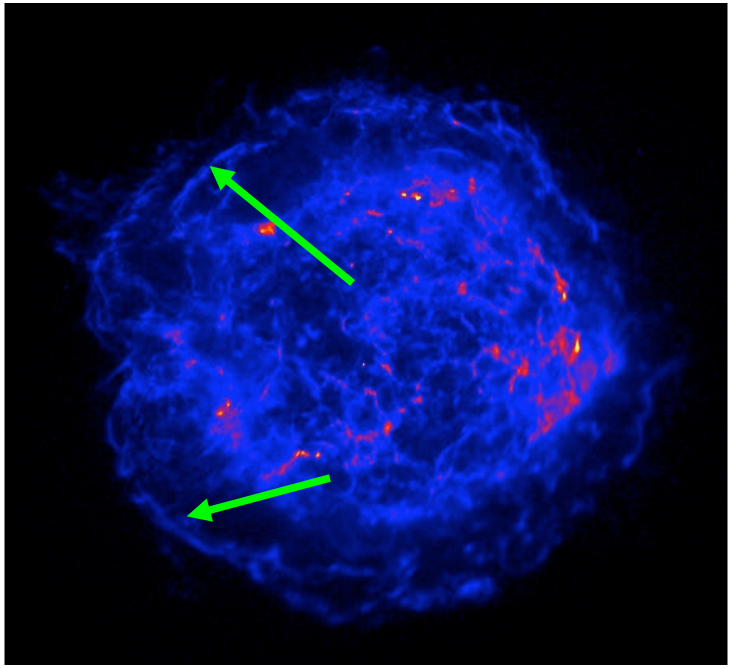
X-ray synchrotron emission tells us that
- electrons can be accelerated fast
- that acceleration is still ongoing (loss times ~10-100 yr)
- that particles can be accelerated at least up to 10^{14} eV

Narrow X-ray synchrotron filaments

- In many cases X-ray synchrotron filaments appear very narrow (1-4")
- Including deprojections implies $l \approx 10^{17}$cm







Vink & Laming 03

Explanation narrow synchrotron rims

- Two possible ways of reasoning:
  - length scale associated with synchrotron loss time & advections:

$$l_{\mathrm{adv}} = \Delta v \tau_{\mathrm{syn}} = \frac{V_{\mathrm{s}}}{\chi}\tau_{\mathrm{syn}} \rightarrow \tau_{\mathrm{syn}} = \frac{\chi l_{\mathrm{adv}}}{V_{\mathrm{s}}}$$

  - length scale corresponds to diffusion length scale of 10-100 TeV electrons:

$$l_{\mathrm{diff}} = \frac{D_2}{\Delta v} \approx \frac{\chi^2 D_1}{V_{\mathrm{s}}}$$

- Turns out the two are more or less equivalent

$$\tau_{\mathrm{acc}} \approx \frac{\kappa D_1}{V_{\mathrm{s}}^2} = \frac{\kappa l_{\mathrm{diff}}}{\chi^2 V_{\mathrm{s}}}$$

- So near break frequency:

$$\tau_{\mathrm{acc}} \approx \tau_{\mathrm{syn}} \leftrightarrow l_{\mathrm{diff}} \approx \frac{\chi^3}{\kappa} l_{\mathrm{adv}} \approx 0.25 l_{\mathrm{adv}}$$

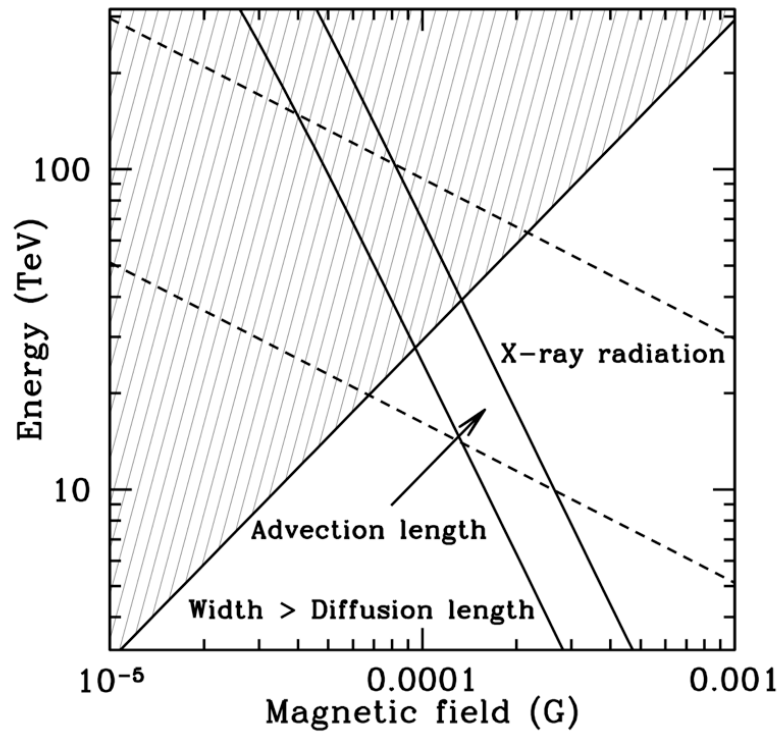
- So we can use either system provided we are near the break frequency
- In reality the width is combination from advection and diffusion

Explanation narrow synchrotron rims

- Combining diffusion and advection:

$$B_2 \approx 26 \left(\frac{l_{\rm adv}}{1.0 \times 10^{18} {\rm cm}} \right)^{-2/3} \eta^{1/3} \left(\chi_4 - \frac{1}{4} \right)^{-1/3} \ \mu{\rm G}$$

- Rim width can be used to measure B-field:
  $B \approx 110\ (L/10^{17}\mathrm{cm})^{-2/3}\ \mu\mathrm{G}$



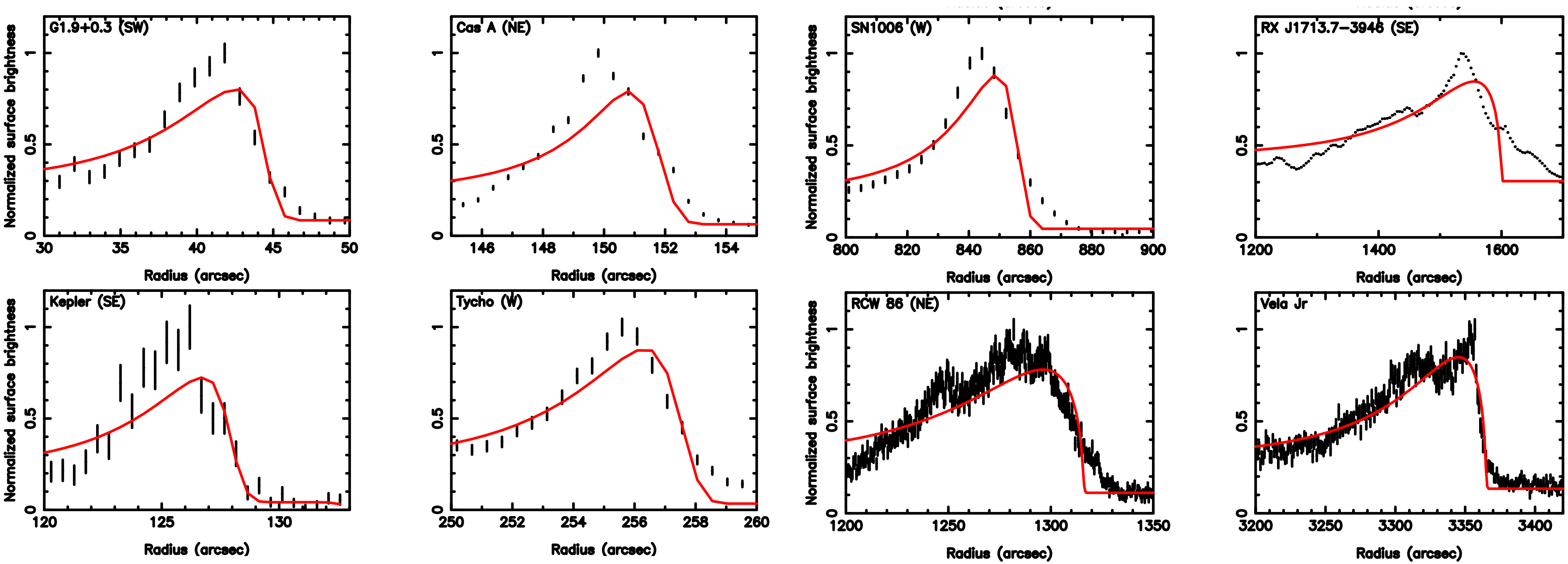
Vink&Laming '03

- Cas A/Tycho/Kepler: ~100-500 μG (e.g. Vink&Laming '03, Völk et al. 03, Bamba+ '04, Warren+ '05, Parizot+ '06)

- High B ⇒fast acceleration ⇒ protons beyond 10^{15}eV?

- High B-field likely induced by cosmic rays (e.g. Bell '04)
- High B-fields are a signature of efficient acceleration

X-ray synchrotron profiles



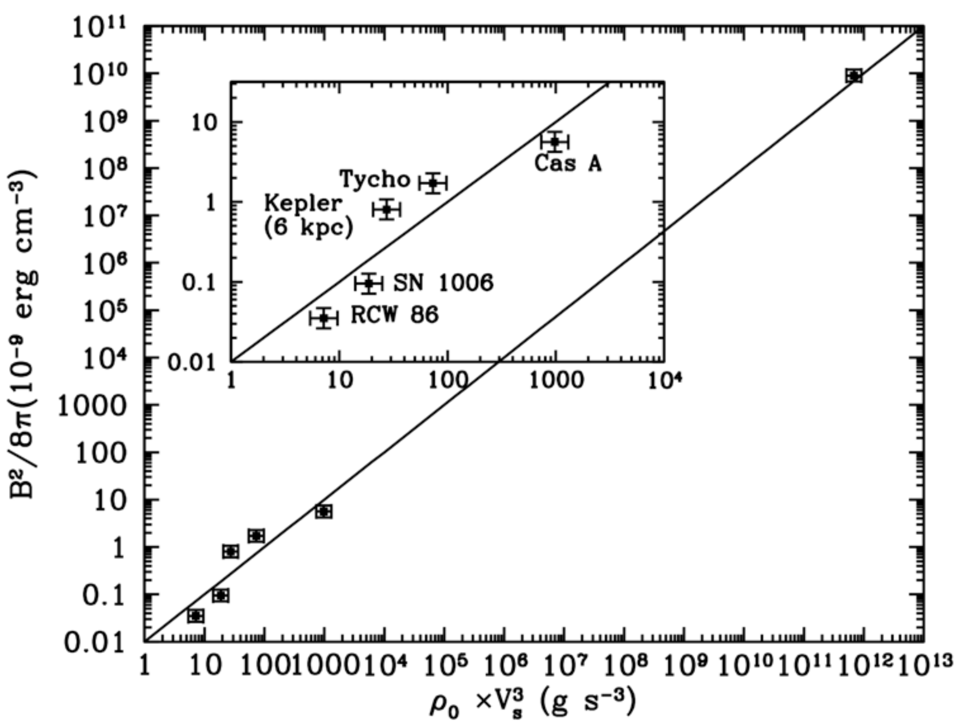
Helder, JV, et al. 2012

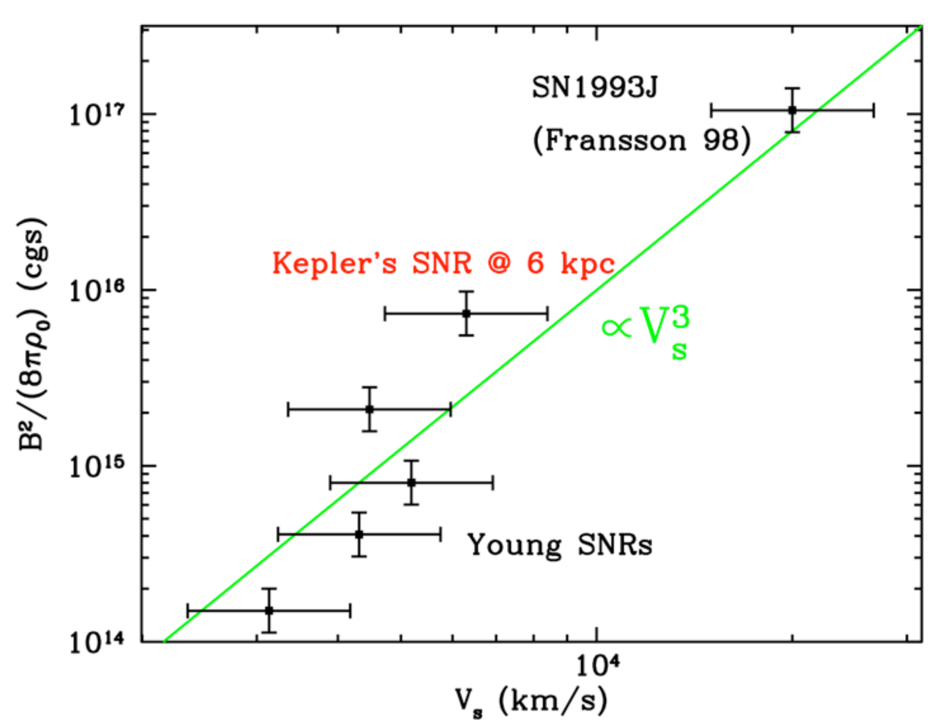
- Model: sudden increase at shock + exponential fall off (projected)
- Models do generally not fit very (exception Vela jr)

Magnetic Field Amplification

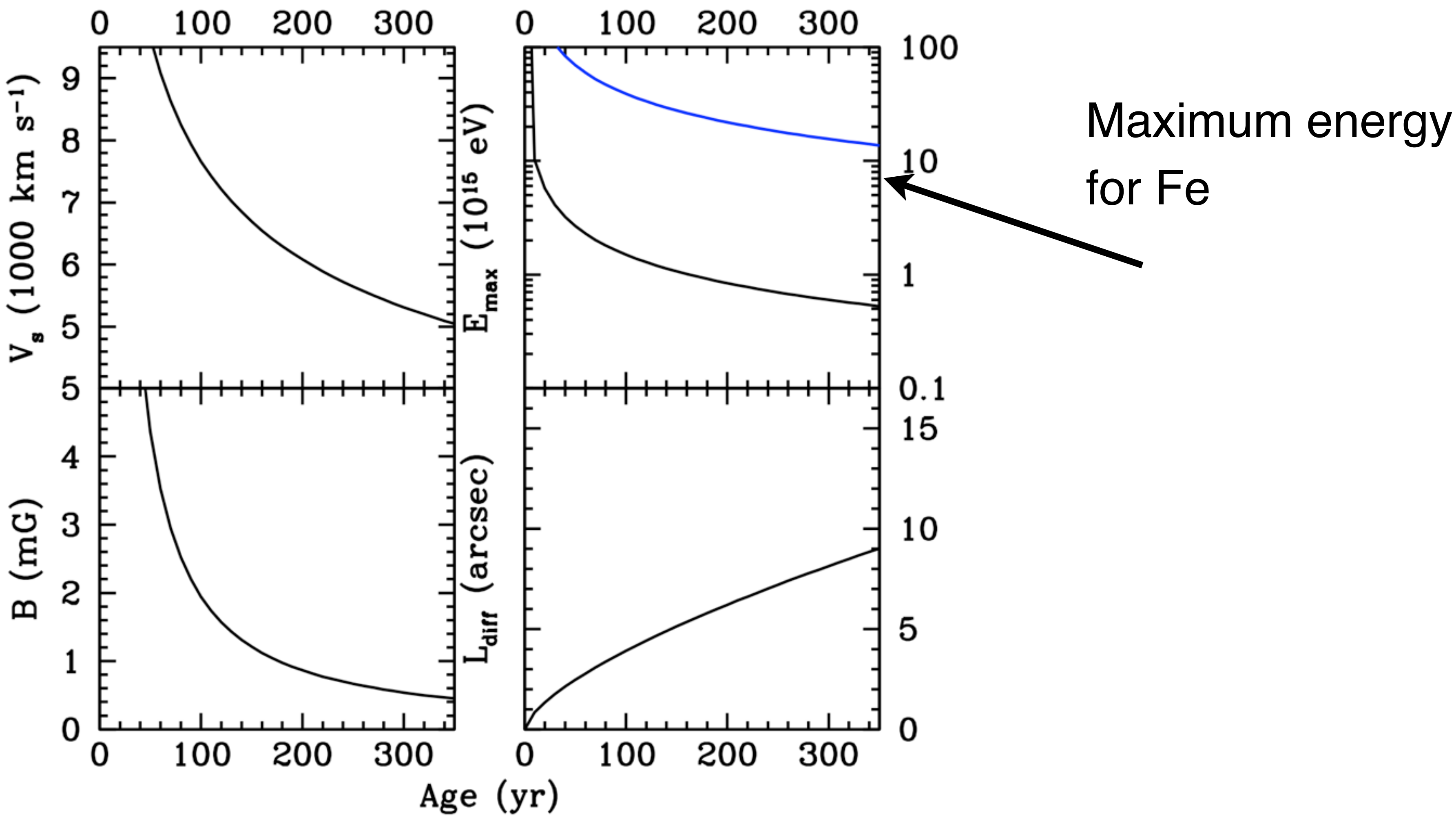
- There is a clear correlation between ρ, V and B, in rough agreement with theoretical predictions (e.g. Bell 2004)
- Relation may even extend to supernovae ($B^2 \propto \rho V_s^3$?)

  (Völk et al. ’05, Vink ‘08)





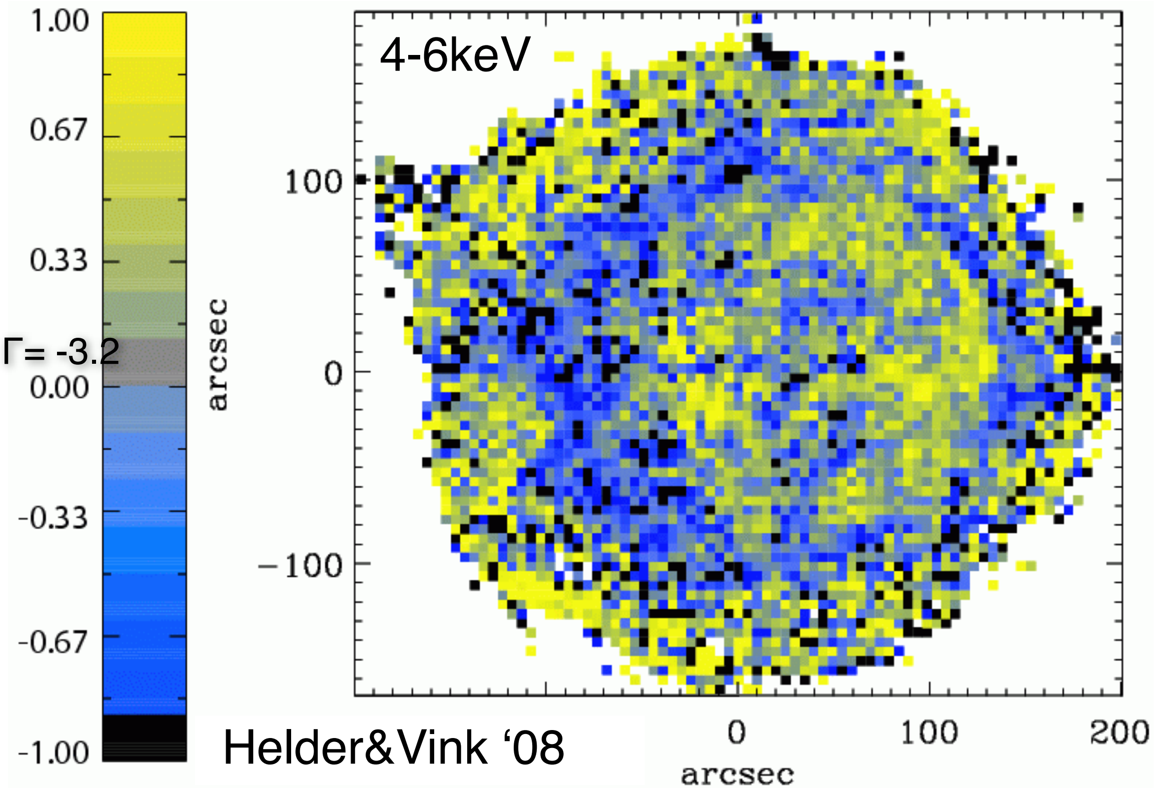
A possible history for Cas A



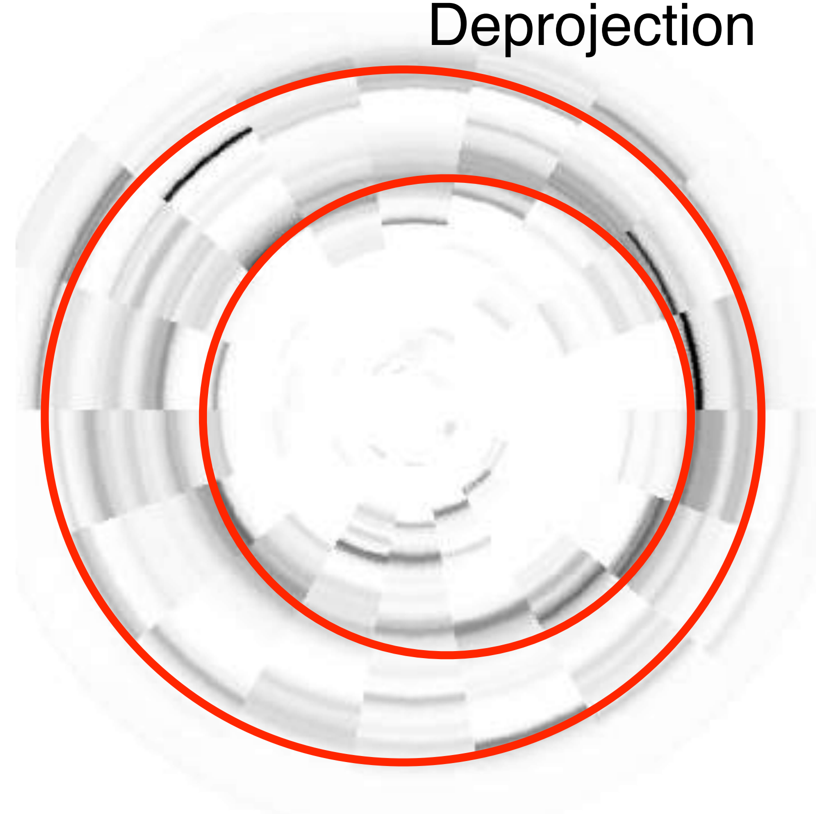
•Acceleration most efficient early on in supernovae in red supergiant winds (Type II/ Type IIb) (e.g. Cas A, SN1993J)

•Highest energy CRs may escape first (Ptuskin & Zirakashvili '05)

Acceleration @ Cas A reverse shock



Helder&Vink ‘08



•Spectral index: 2 regions of hard emission: X-ray synchrotron emission

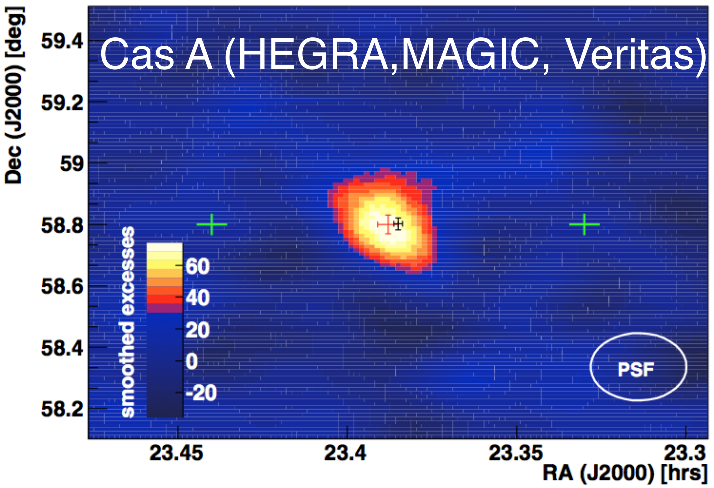
•Deprojection: Most X-ray synchrotron from *reverse* shock!

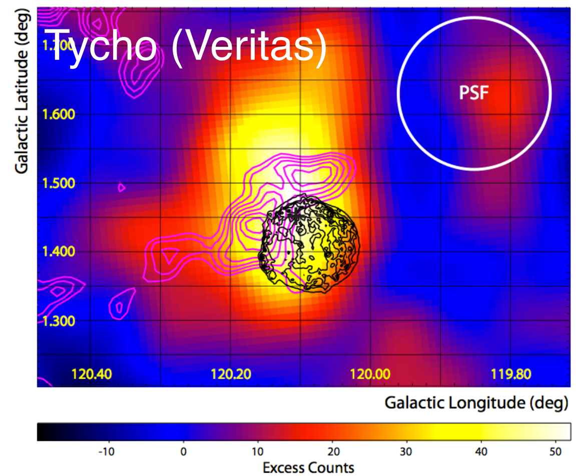
•Prominence of West: No expansion ⇒ ejecta shocked with V>6000 km/s

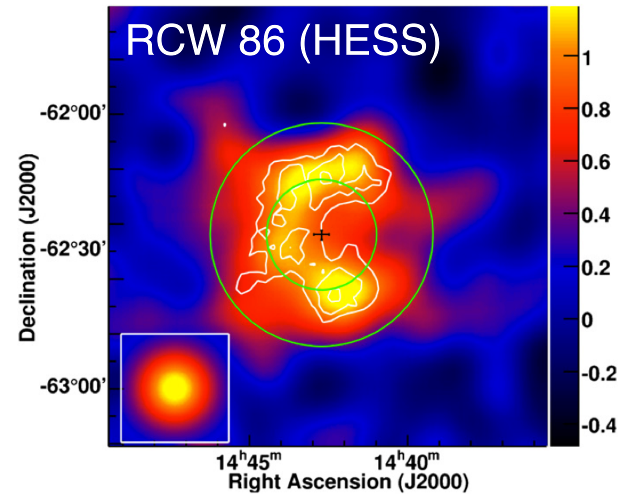
•Reverse shock: metal-rich -> more electrons -> bright radio

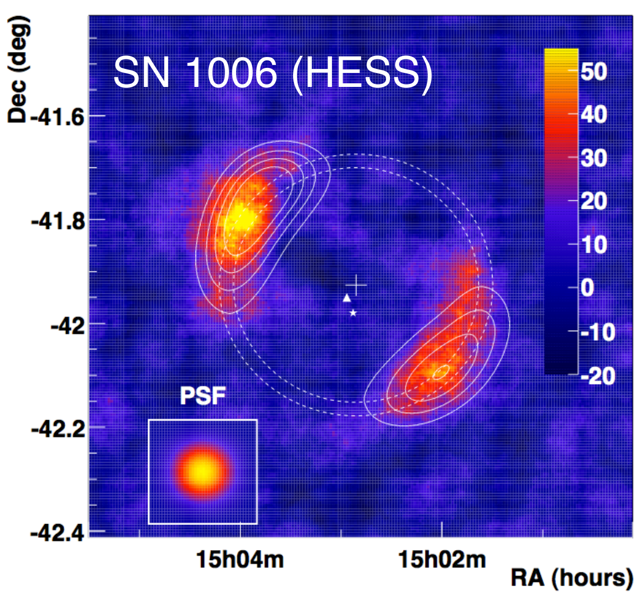
B-field amplification is not very sensitive to initial B-field!

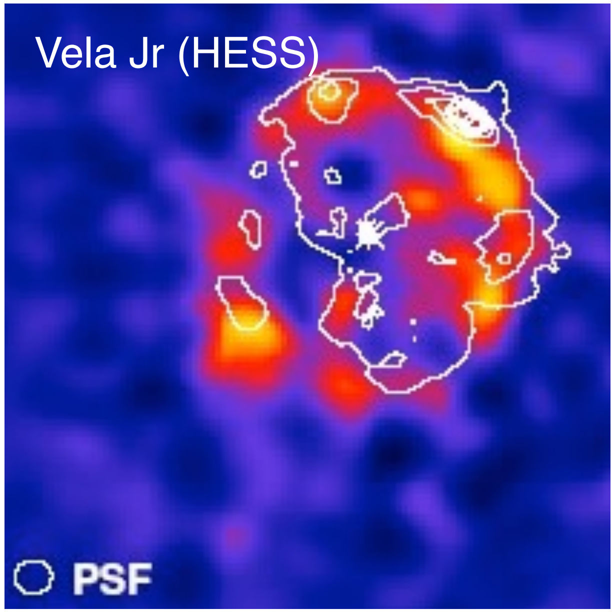
Young SNRs detect in TeV gamma-rays

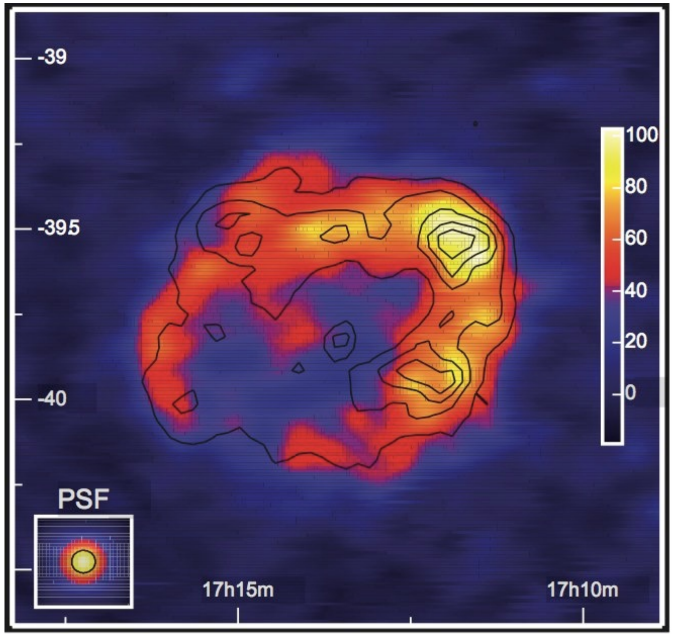






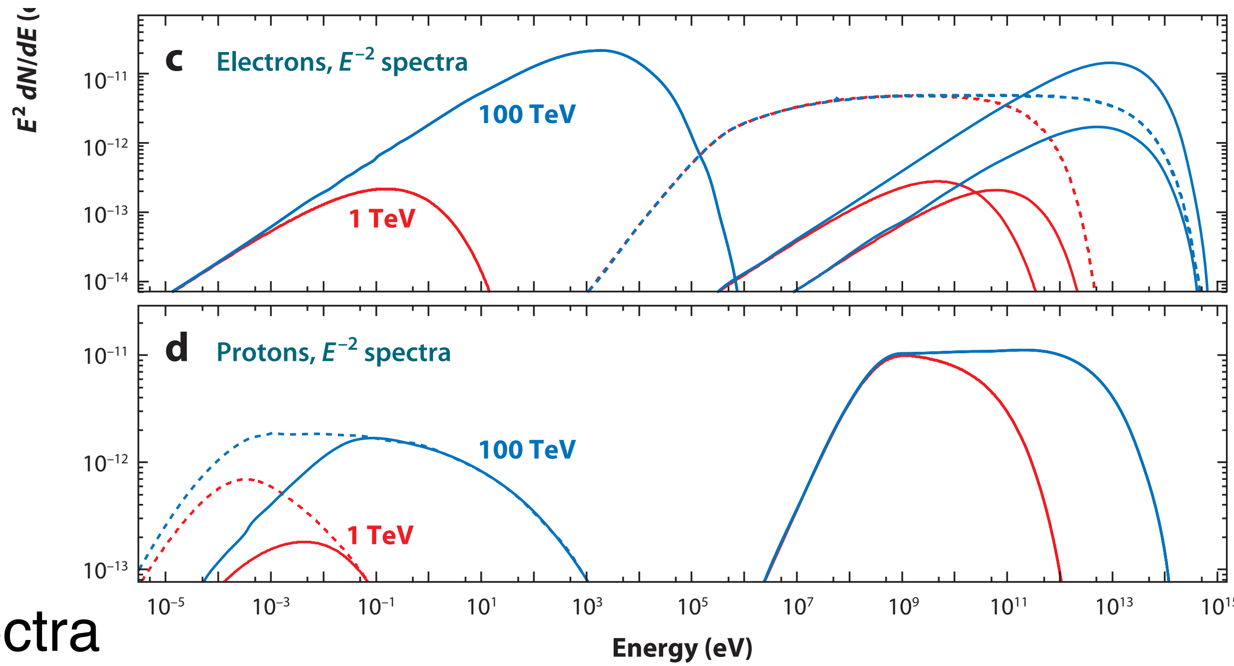






Emission: hadronic or leptonic?

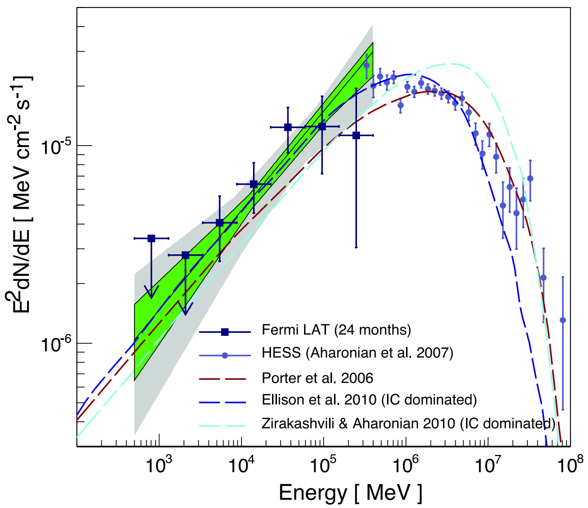
Hinton & Hofmann 2008

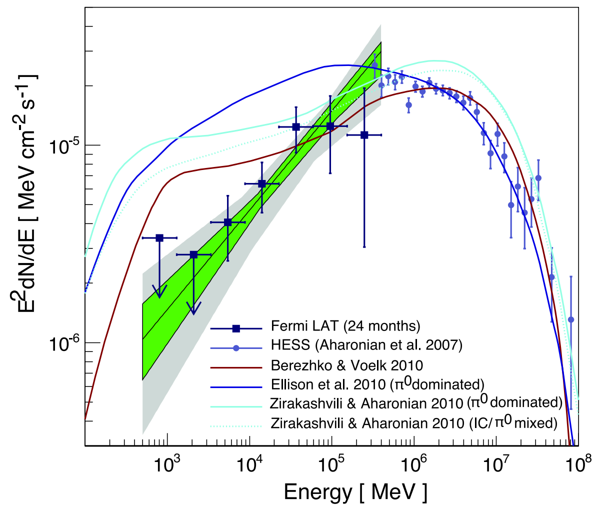


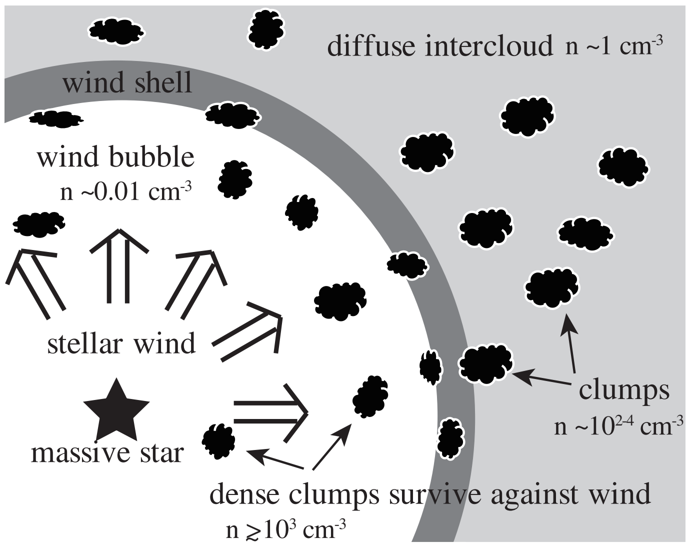
- Inverse Compton: harder spectra
- Pion decay: pion bump
- Relative emission ratio depends on density:
  - high density: target for protons -> large pion production
  - Electrons produce both
    - synchrotron radiation (scales with B2/8π)
    - inverse compton emission (scales with U_{rad})
    - can be used to constrain B

Emission RX J1713: hadronic or leptonic?

Abdo et al 2011



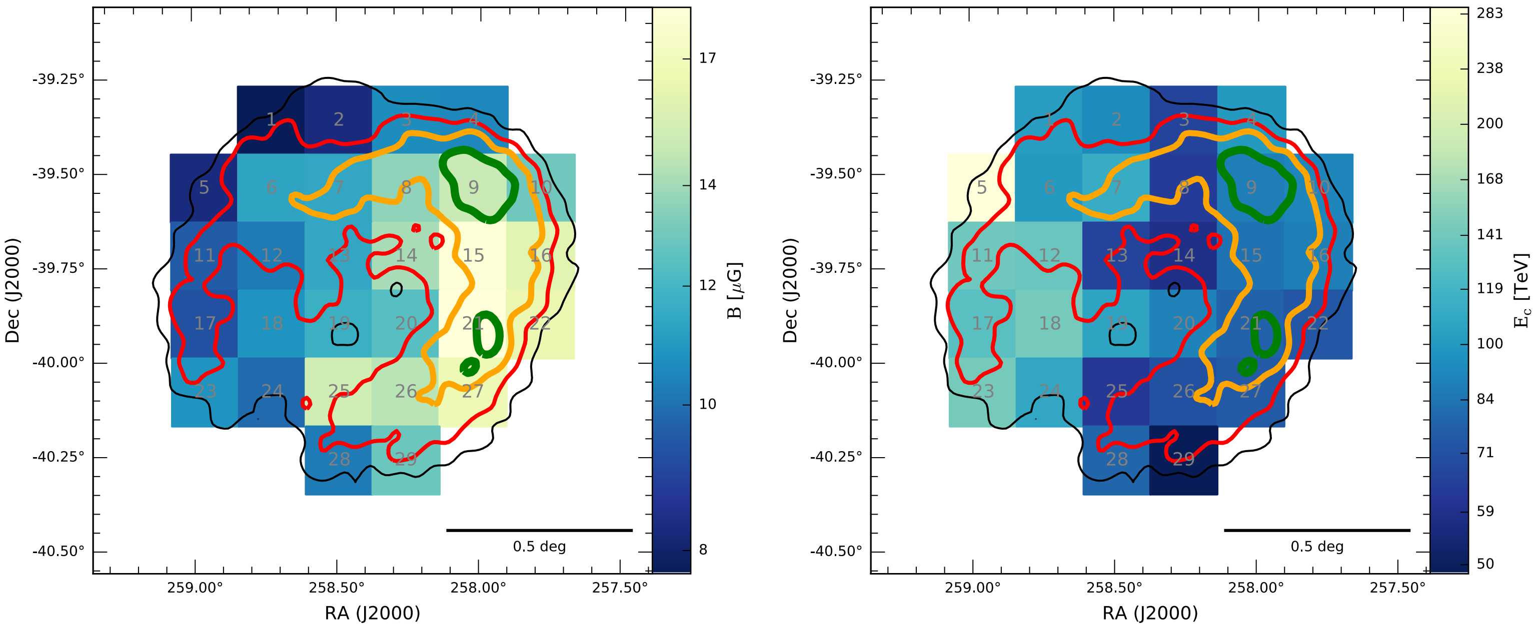




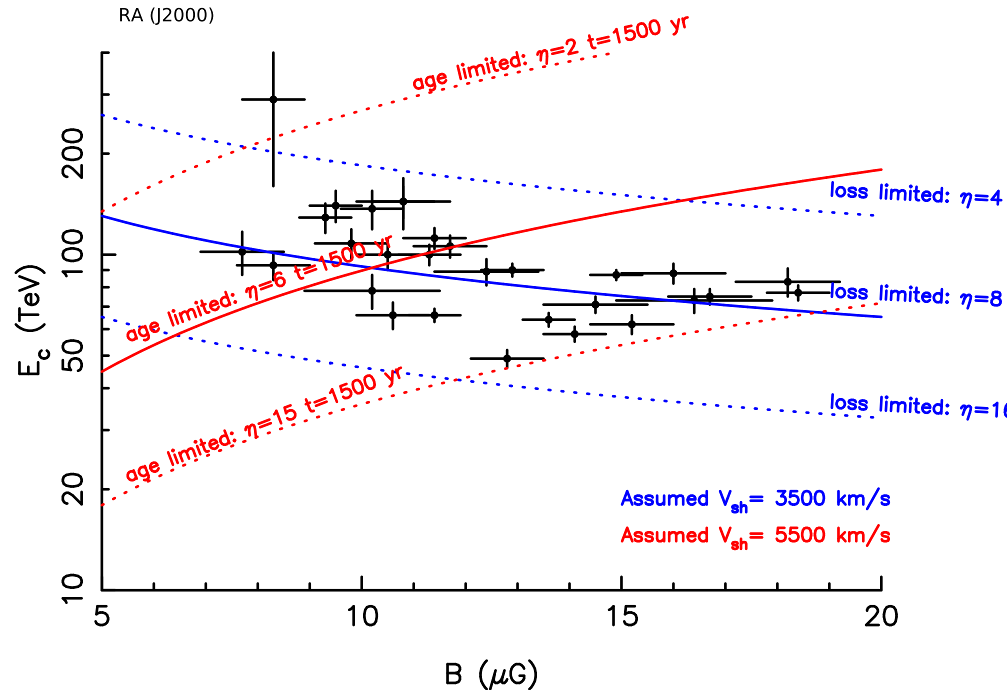
- Spectral hardness suggests inverse Compton emission
- Alternative: emission from clumps irradiated by hadronic cosmic rays (Inoue+ ’13, Gabici & Aharonian ’15)

Magnetic field map RX J1713

HESS collaboration 2018

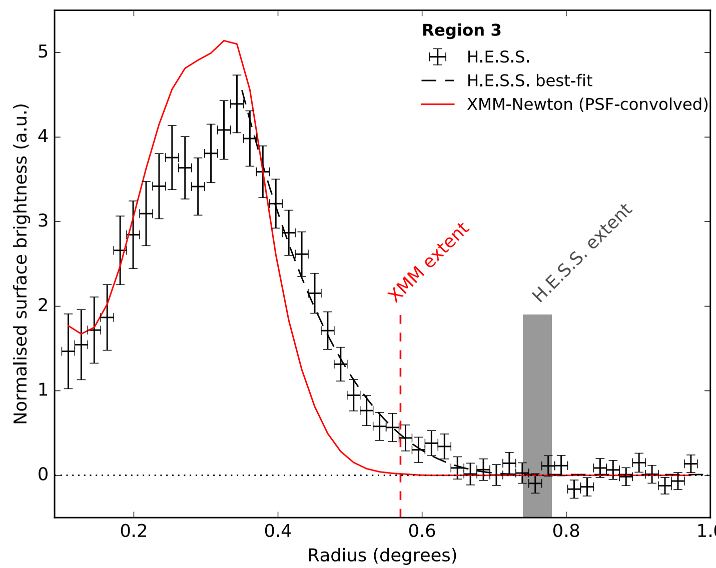


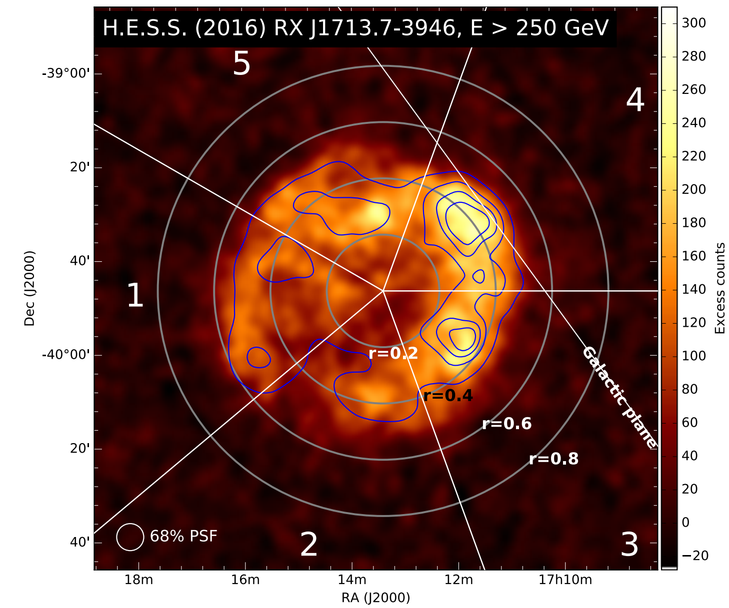
- Assumes leptonic emission
- Cut-off consistent with B-field and age



Escape of cosmic rays?

HESS collaboration 2018



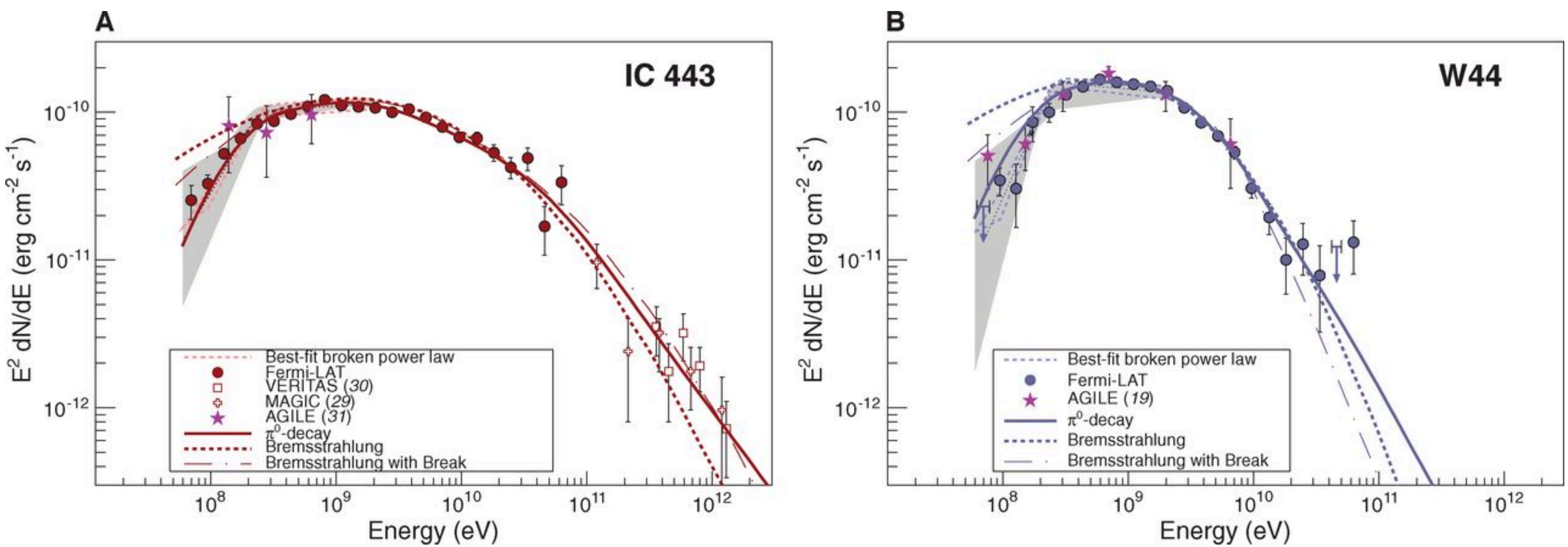


- Gamma-ray emission ahead of X-ray emission:
  - Population of particles ahead of shock
    - Escape: i.e. particles will not be over run by shock?
    - Cosmic-ray precursor? (i.e. particles still being accelerated)
- Either way: requires a low value of B/η
  - Slowing down of shock in region 3? Drop in B turbulence?

$$\frac{B}{\eta} \approx 0.36 \left(\frac{E}{10\,\mathrm{TeV}}\right)\left(\frac{u_{\rm shock}}{3000\,\mathrm{km\,s^{-1}}}\right)^{-1}\left(\frac{\Delta r}{\mathrm{pc}}\right)^{-1} \mu\mathrm{G}$$

Detection of the pion bump

Ackermann+ '13



- Clear detection by Fermi of "pion bump"
- SNRs IC 443 & W44: mature SNRs, interacting with molecular cloud

Future developments

- High resolution X-ray spectroscopy (XRISM & Athena)
  - XRISM: launch 2022; Athena: 2030+
  - XMM/Chandra gratings, not ideal for extended sources
  - Get: accurate line ratios and kinematic/thermal Doppler shifts/widths
- X-ray polarisation:
  - characterise magnetic field turbulence near shocks
- Cherenkov Telescope Array
  - 10x better sensitivity than H.E.S.S./Veritas/MAGIC: new SNRs/PWNe
  - broader energy range
  - evidence for PeVatrons?
  - Detecting supernovae

Supernova remnants: summary

- Supernova remnants interesting for three reasons
  - Interesting shock physics:
    - collisionless heating: electrons cooler than ions
    - ionisation: non-equilibrium ionisation
    - CR acceleration:
      - evidence for hadronic particles (pion bump)
      - evidence for fast acceleration, B-field amplification and turbulence
      - evidence for escape
  - Probe the supernova explosion products/geometry:
    - Abundance patterns: SN Ia -> Fe-group; CC: O, Ne, Mg
    - (a)symmetries: jets and rings in Cas A
    - link with neutron stars: no apparent pattern (yet)
  - Probe the circumstellar medium:
    - Clues to SNe Ia progenitors: evidence for shells around SNe Ia