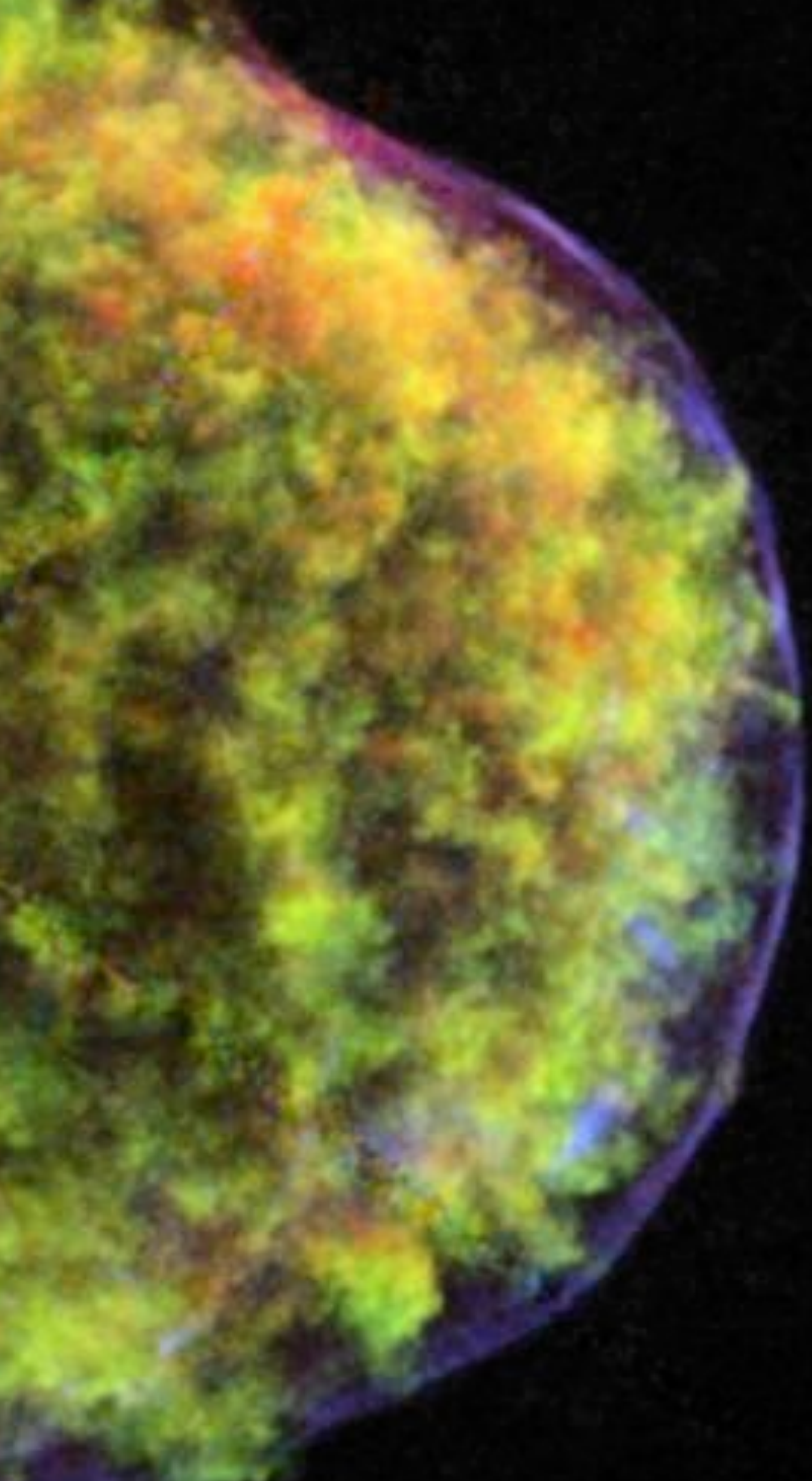


Supernovae and their <u>remnants</u>

Why study supernovae?

- Supernovae are of prime importance for the chemical evolution of the Universe
- Most important sources of energy for the interstellar medium. Part in the form of cosmic rays, which have an energy density of 1—2 eV cm^{-3}, thus containing one third of the energy density of ISM.
- standard candles for determining cosmological distances
- 2—3 per century in a spiral galaxy like ours

Why study supernova remnants?

- Supernova remnants contain information about:
  - the supernova explosion that caused them
  - the circumstellar medium surrounding the progenitor
- Supernovae studied at large distances: SNRs in local neighbourhood!
- Supernova remnants: clues about ISM enrichment by supernovae
- Supernova remnant likely account for cosmic rays in the Galaxy up to $3\text{x}10^{15}$ eV, requiring 10% acceleration efficiency
- Supernova remnant physics is rich: non-equilibrium ionisation and temperatures, shocks, highly magnetized plasmas, particle acceleration

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 Switzerland
- SN 1054: recorded in Asia
- SN 1185: observed by the Chinese
- SN 1572: China, Europe - Tycho Brahe
- SN 1604: China, Europe - Johannes Kepler

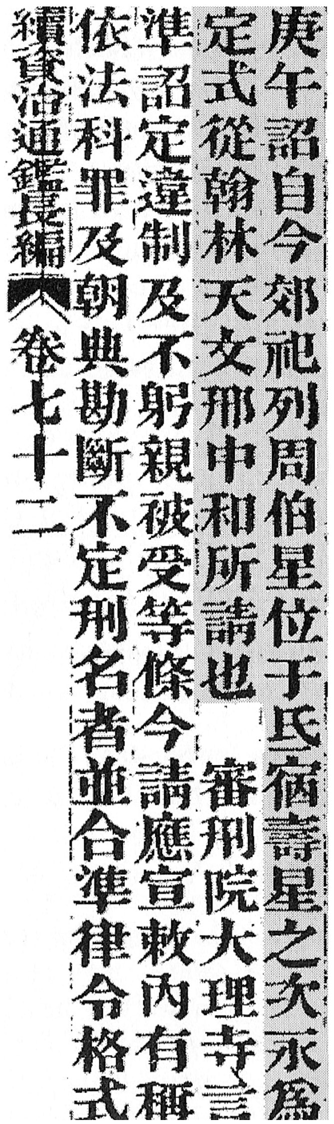
- After that

  No supernova spotted in the Milky Way

  Observational surveys of supernovae:

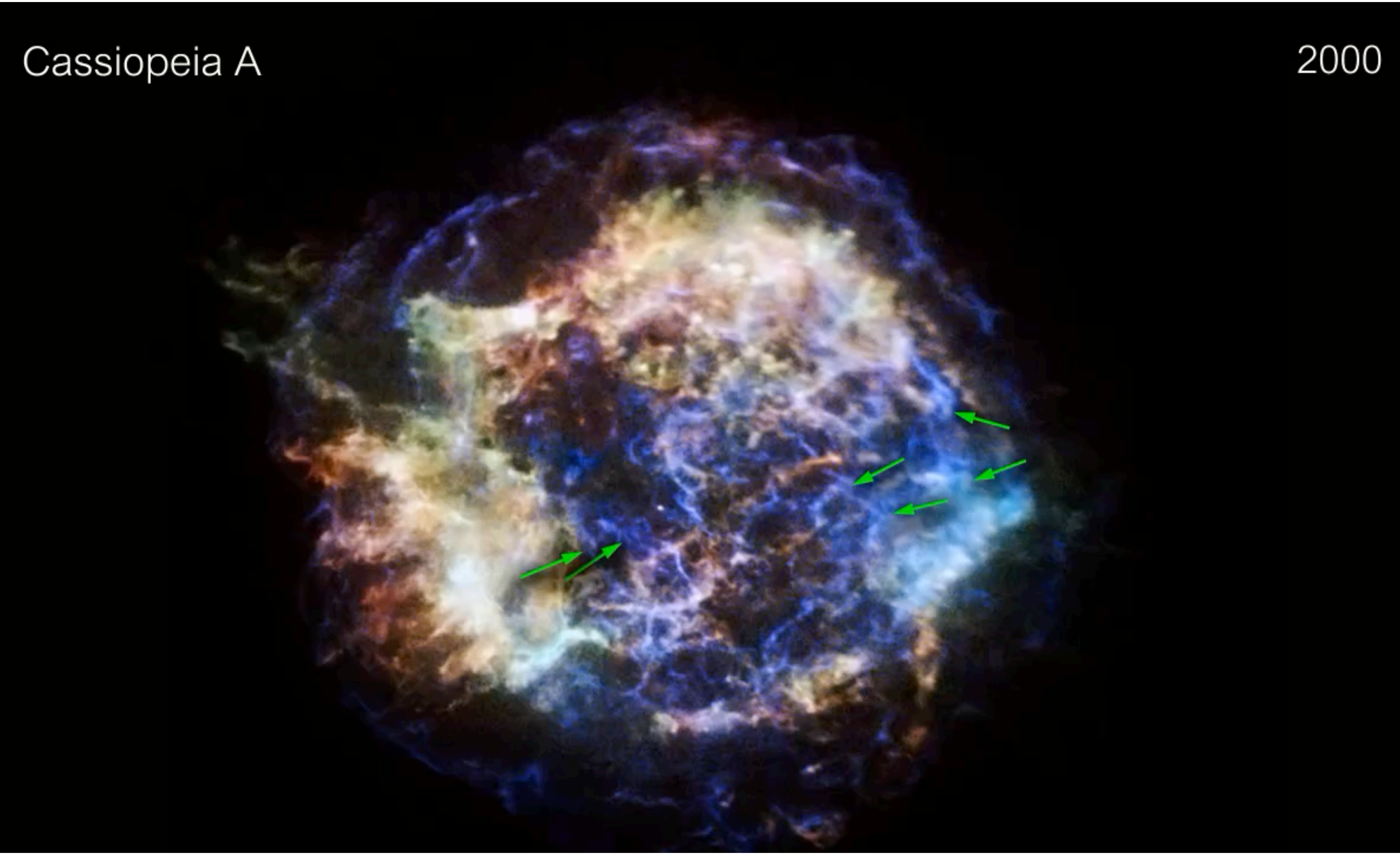
  expected 2-3 supernovae per century in the Milky Way

  One supernova exploding every second in the Universe!

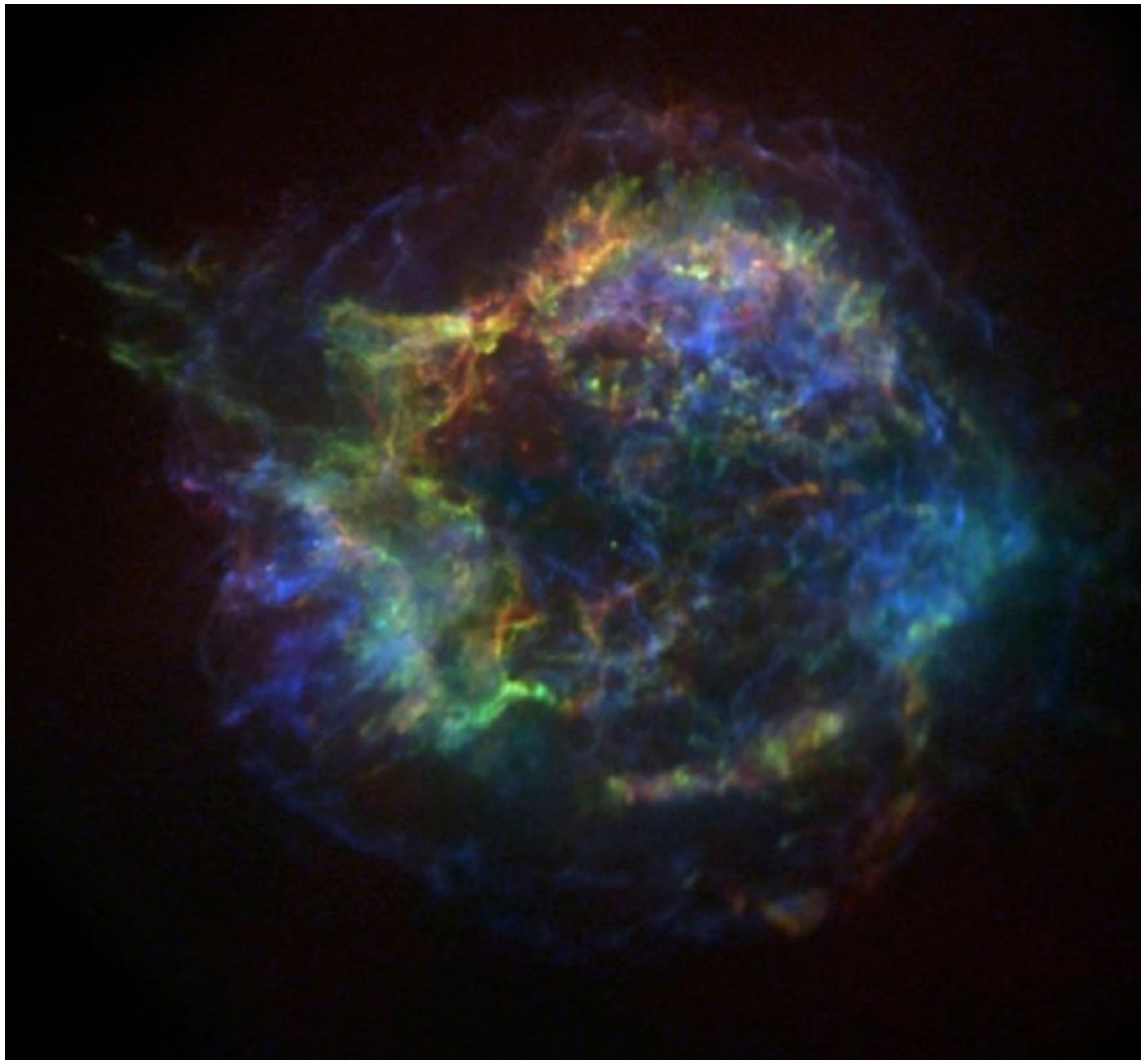


庚午詔自今郊祀列周伯星位于氐宿壽星之次永爲定式從翰林天文邢中和所請也　審刑院大理寺言準詔定違制及不躬親被受等條今請應宣敕內有稱依法科罪及朝典勘斷不定刑名者並合準律令格式

續資治通鑑長編　卷七十二


Cassiopeia A
2000

Youngest Galactic SNRs



- G1.9+0.3 (Green+ ‘08)
- Age: ~100 yr (Carlton+ ’11)

- Cassiopeia A
- Age: ~330 yr

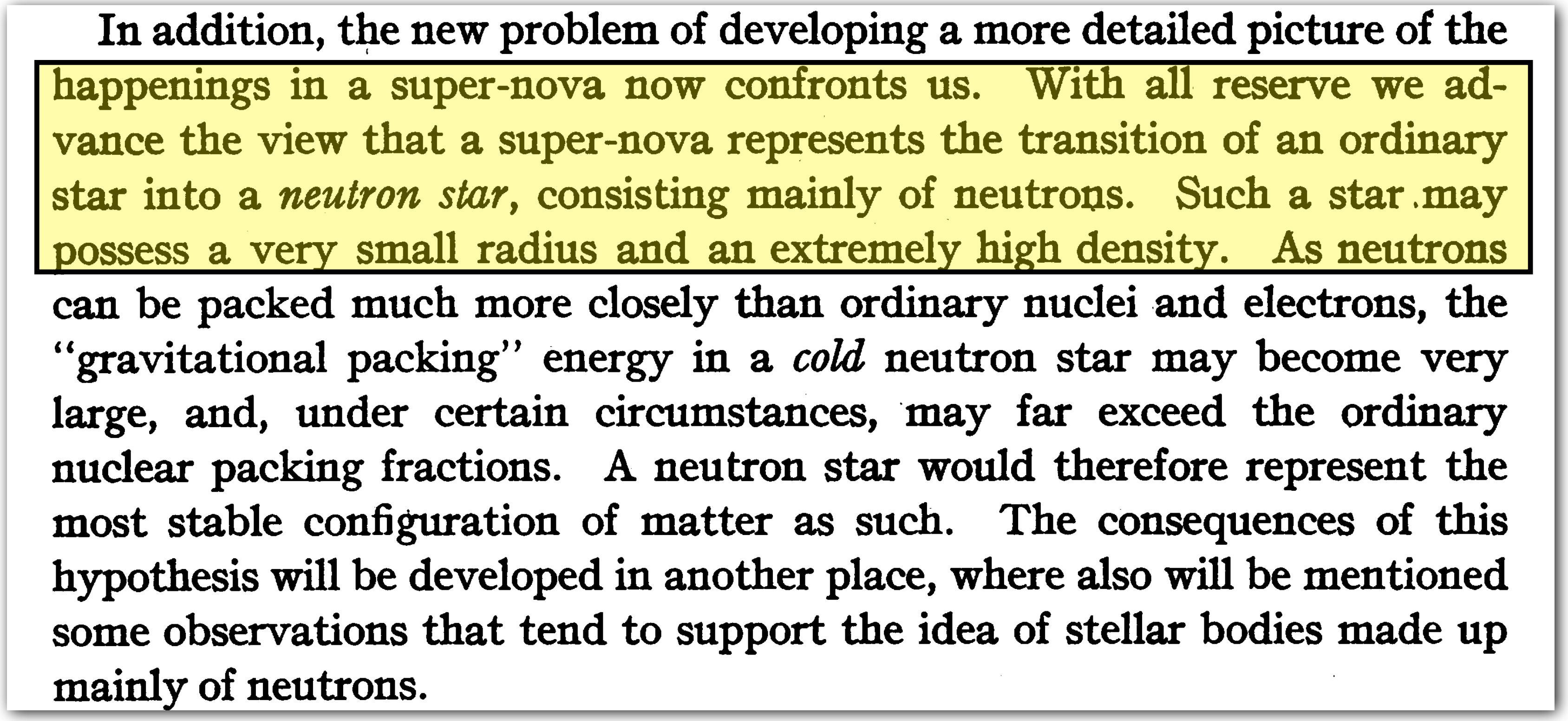
Supernovae

SN 1987A: February 23, 1987

From Novae to Supernovae

Walther Baade

Frits Zwicky



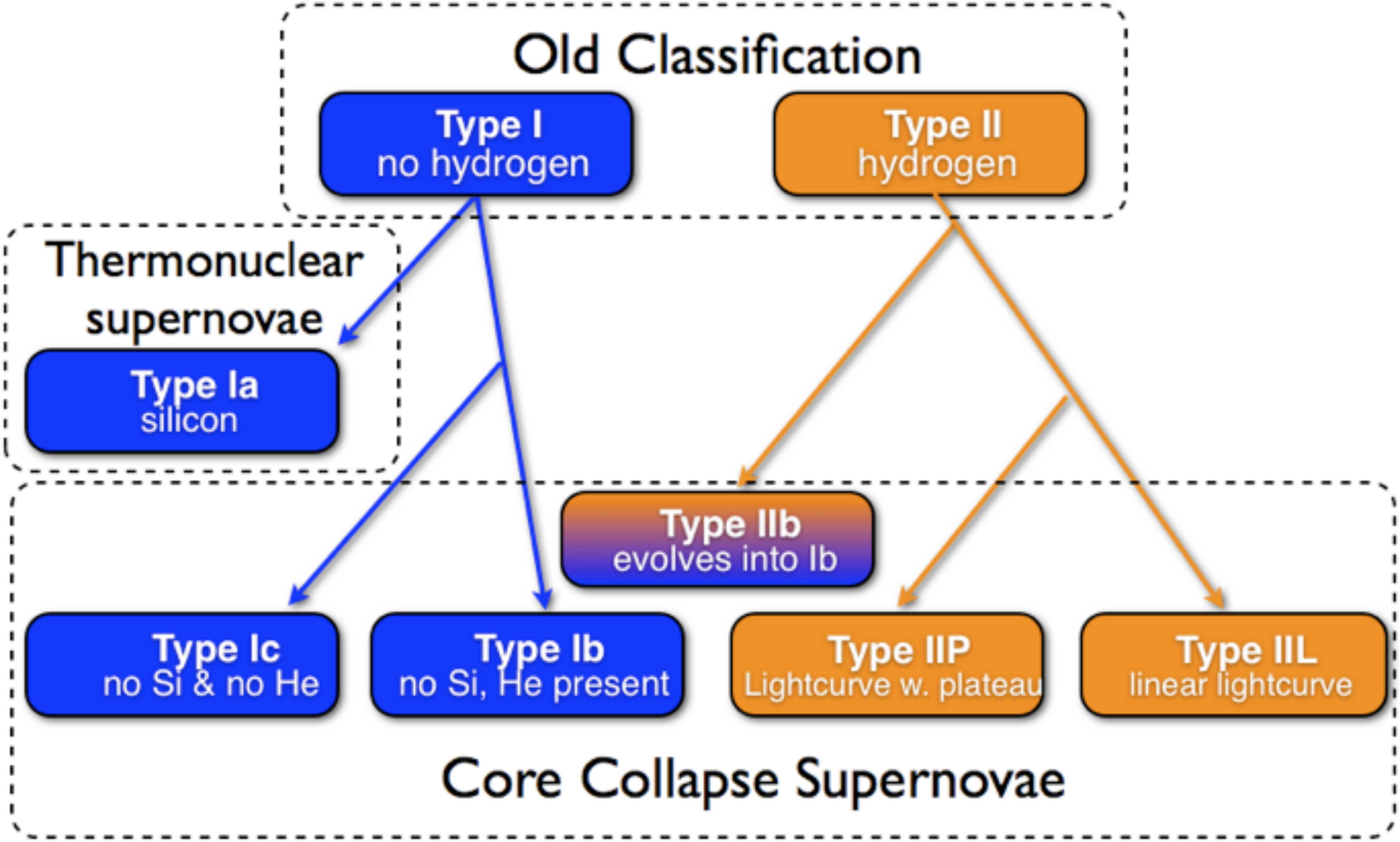
In addition, the new problem of developing a more detailed picture of the happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very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

Supernova types

- Late 1930ies early 1940ies (Minkowski 1941): two recognized classes
- Type I: *no hydrogen* in spectra, also occur in *elliptical* galaxies, linear light curve
- Type II: with *hydrogen* in spectra, only in spiral galaxies
- Since 1980ies: different types I: Type Ia, Ib, Ic

  Type Ia: also in ellipticals -> exploding C/O white dwarfs

Supernova classification



Old Classification

Type I
no hydrogen

Type II
hydrogen

Thermonuclear supernovae

Type Ia
silicon

Type IIb
evolves into Ib

Type Ic
no Si & no He

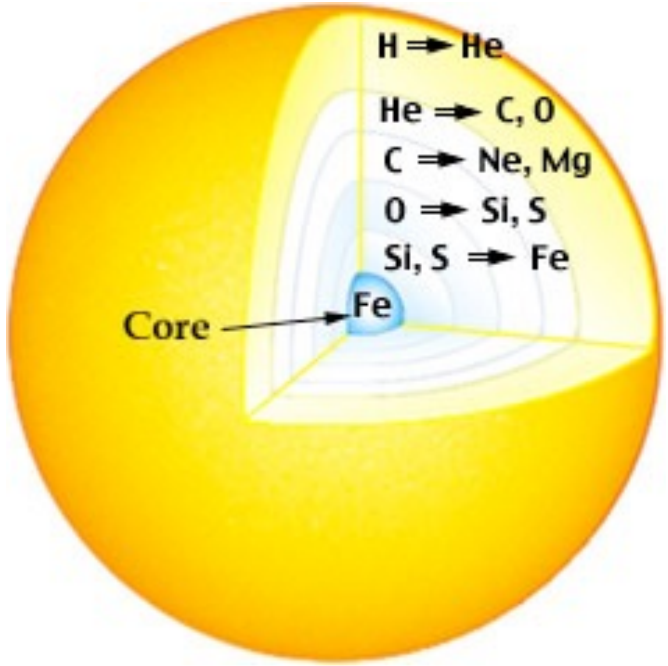
Type Ib
no Si, He present

Type IIP
Lightcurve w. plateau

Type IIL
linear lightcurve

Core Collapse Supernovae

Progenitors of core collapse SNe (II, Ibc)



Helium burning (T = 0.2 x10^9 K)

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

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

Carbon burning (T = 2 x10^9 K)

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

Neon burning (T = 2 x10^9 K)

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

Oxygen burning (T = 3.6 x10^9 K)

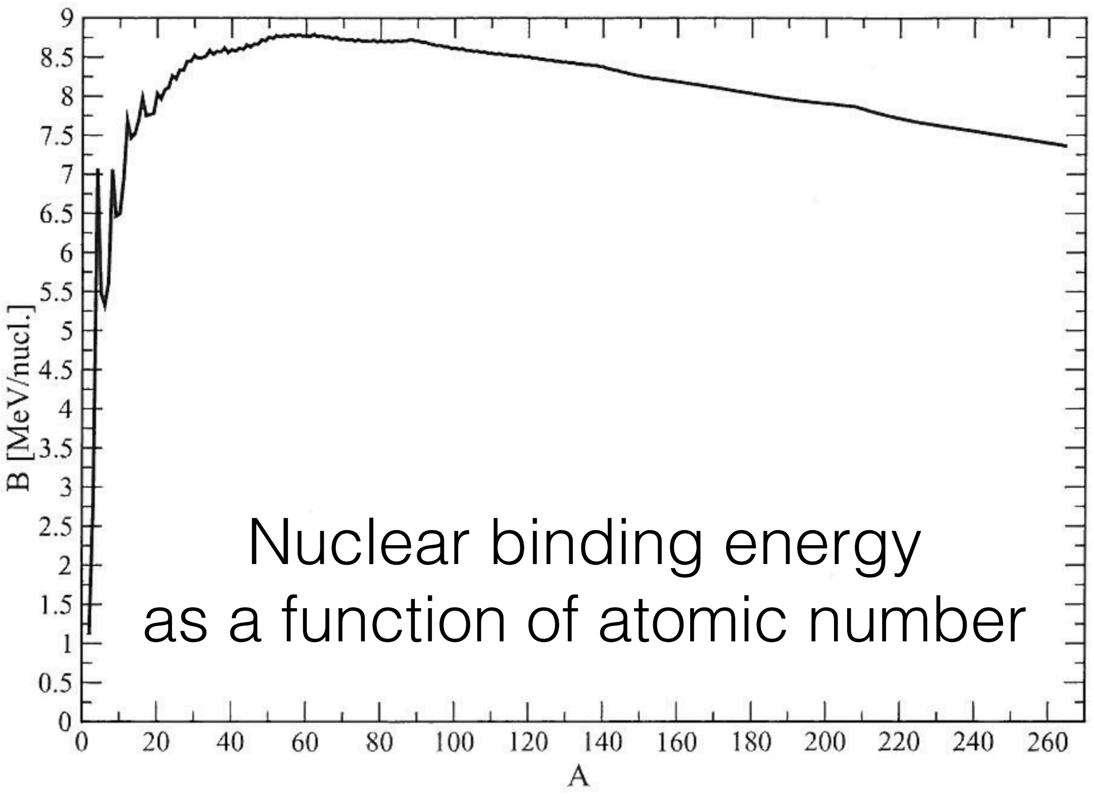
${}^{16}\mathrm{O} + {}^{16}\mathrm{O} \rightarrow {}^{28}\mathrm{Si} + {}^{4}\mathrm{He}$ (takes ~2 weeks)

Silicon burning (T = 5 x10^9 K)

${}^{28}\mathrm{Si} + {}^{4}\mathrm{He} \rightarrow {}^{32}\mathrm{S}$ (takes ~1 day!)

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

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

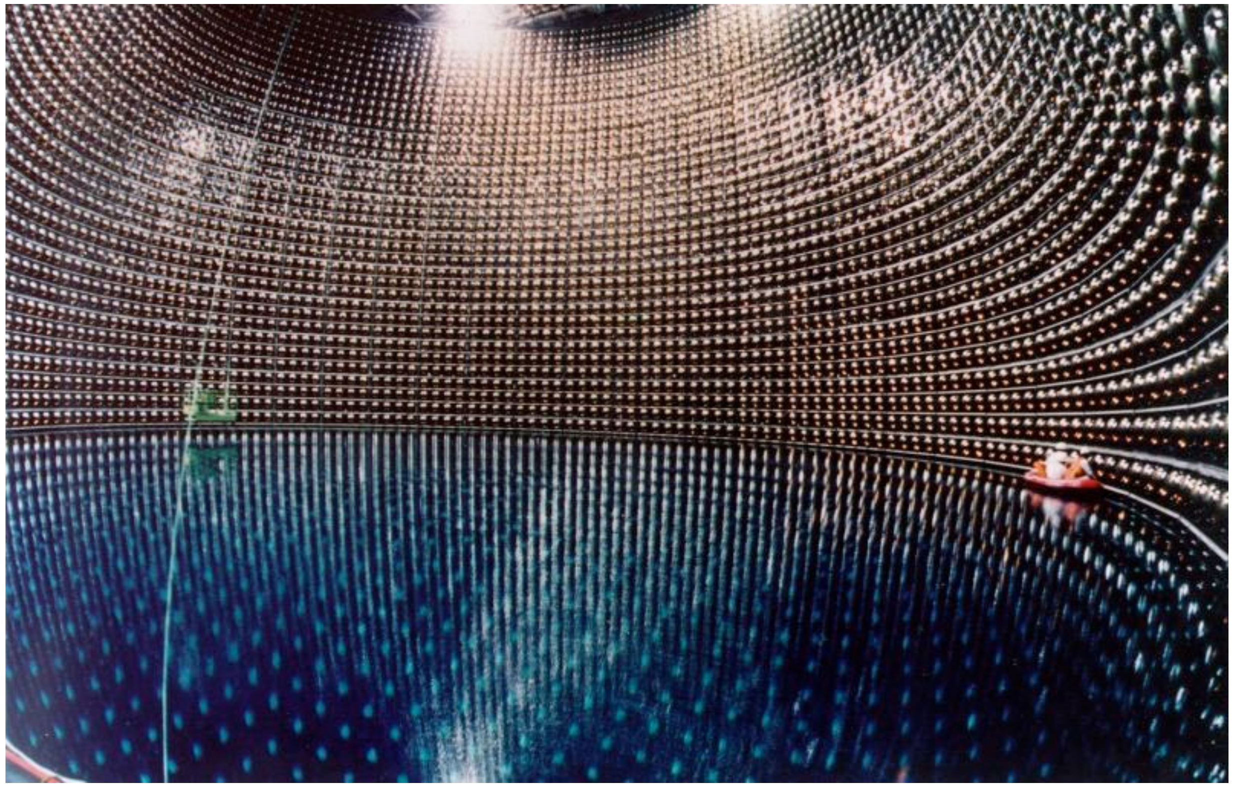


Nuclear binding energy
as a function of atomic number

Neutrino detection

$$n + e^{+} \rightarrow p + \nu_e$$

$$p + e^{-} \rightarrow n + \bar{\nu}_e$$



Kamiokande detector

Kamiokande detected
12 neutrinos on Februari 23 1987
Confirmation of neutron star formation theory!

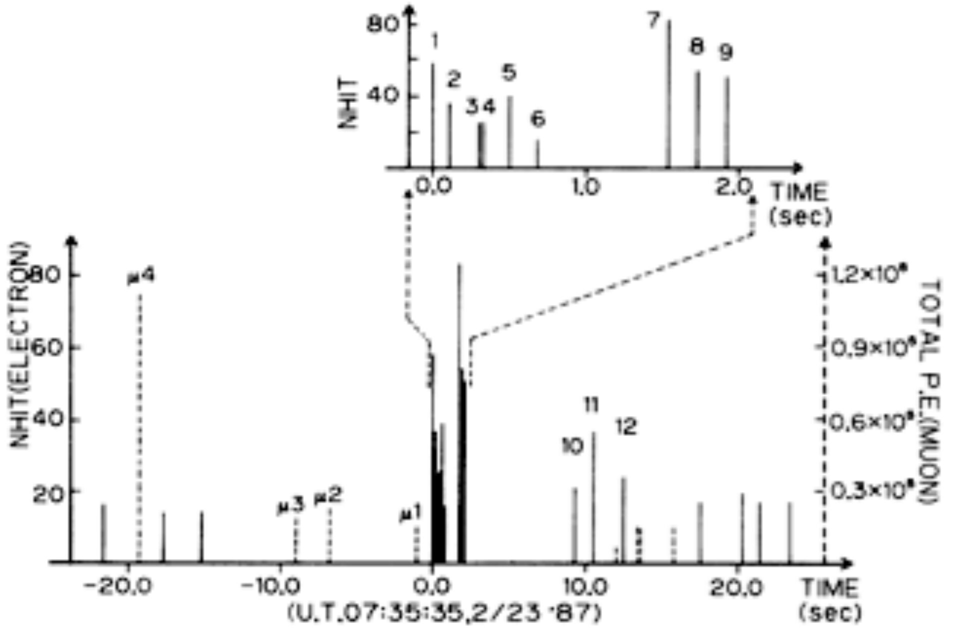
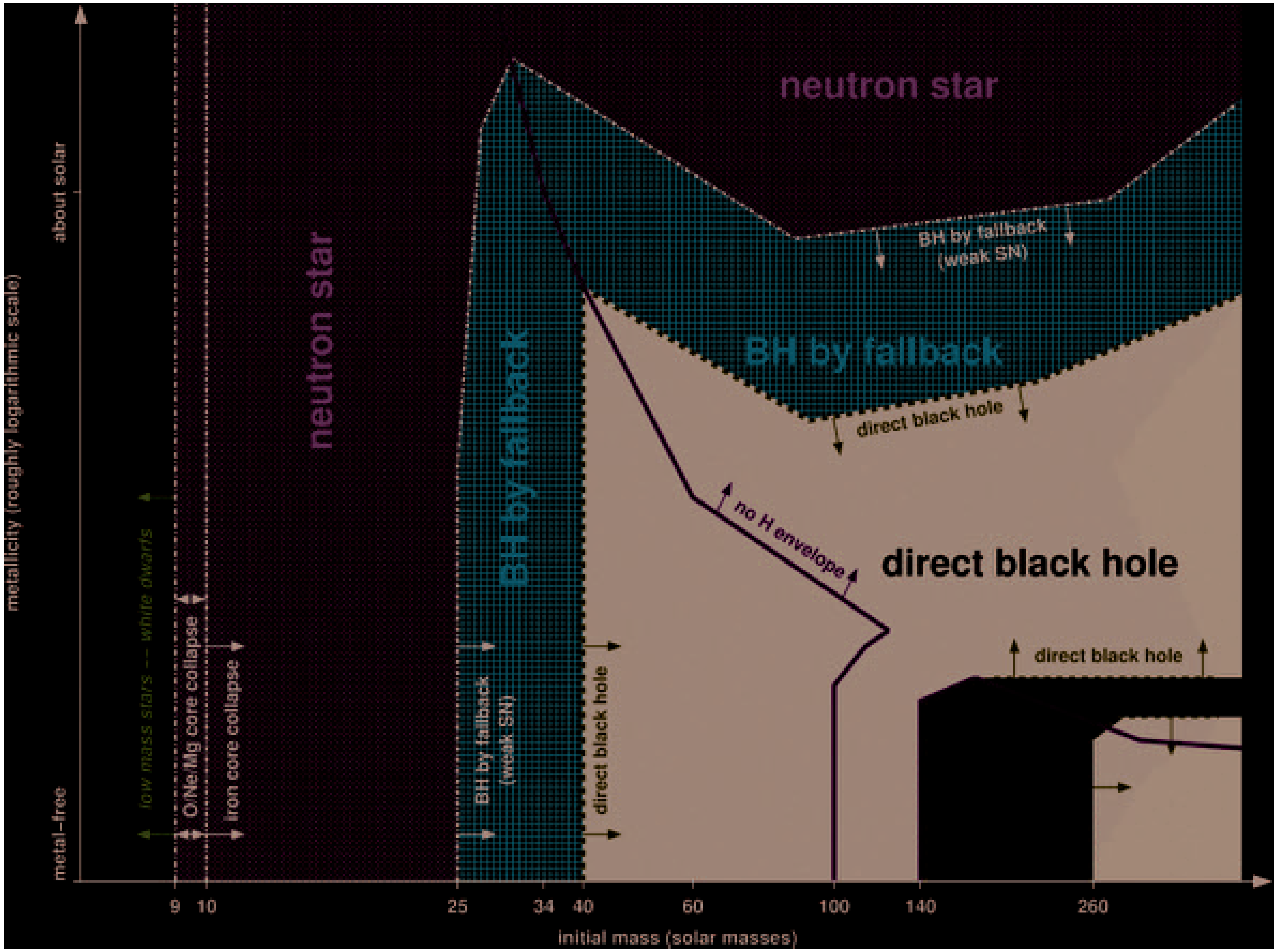


FIG. 2. The time sequence of events in a 45-sec interval centered on 07:35:35 UT, 23 February 1987. The vertical height of each ine represents the relative energy of the event. Solid lines represent low-energy electron events in units of the number of hit PMT's, N_{hit} (left-hand scale). Dashed lines represent muon events in units of the number of photoelectrons (right-hand scale). Events 1–μ4 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.

Neutron stars versus black holes

Heger+ 2003

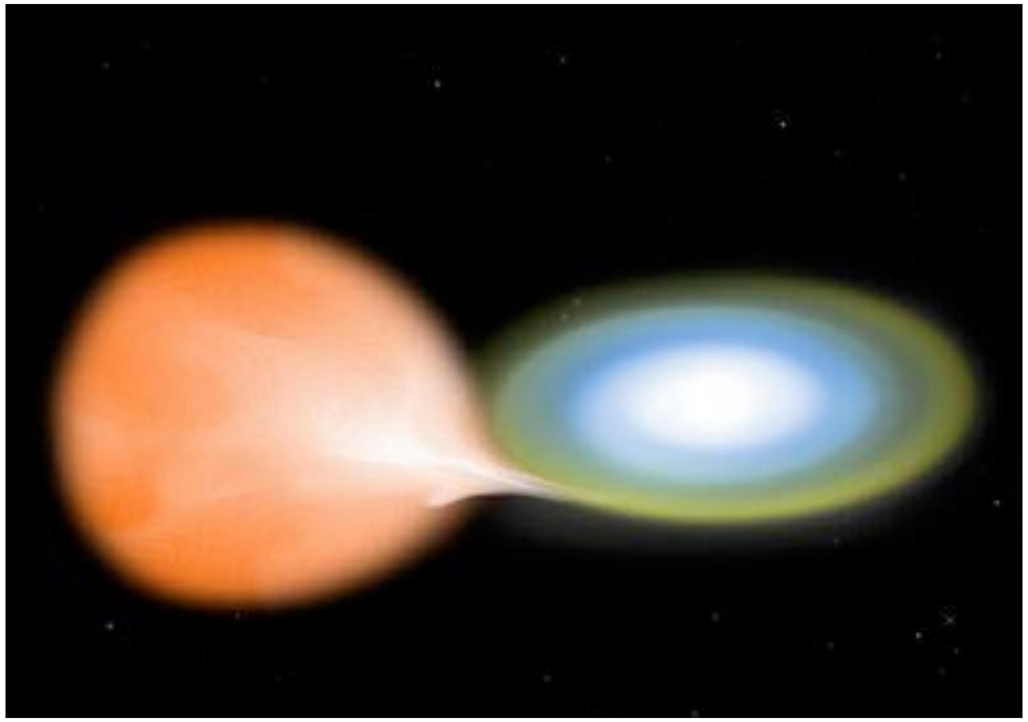


Simplistic view:

< 25 M_{sun} → produce neutron star

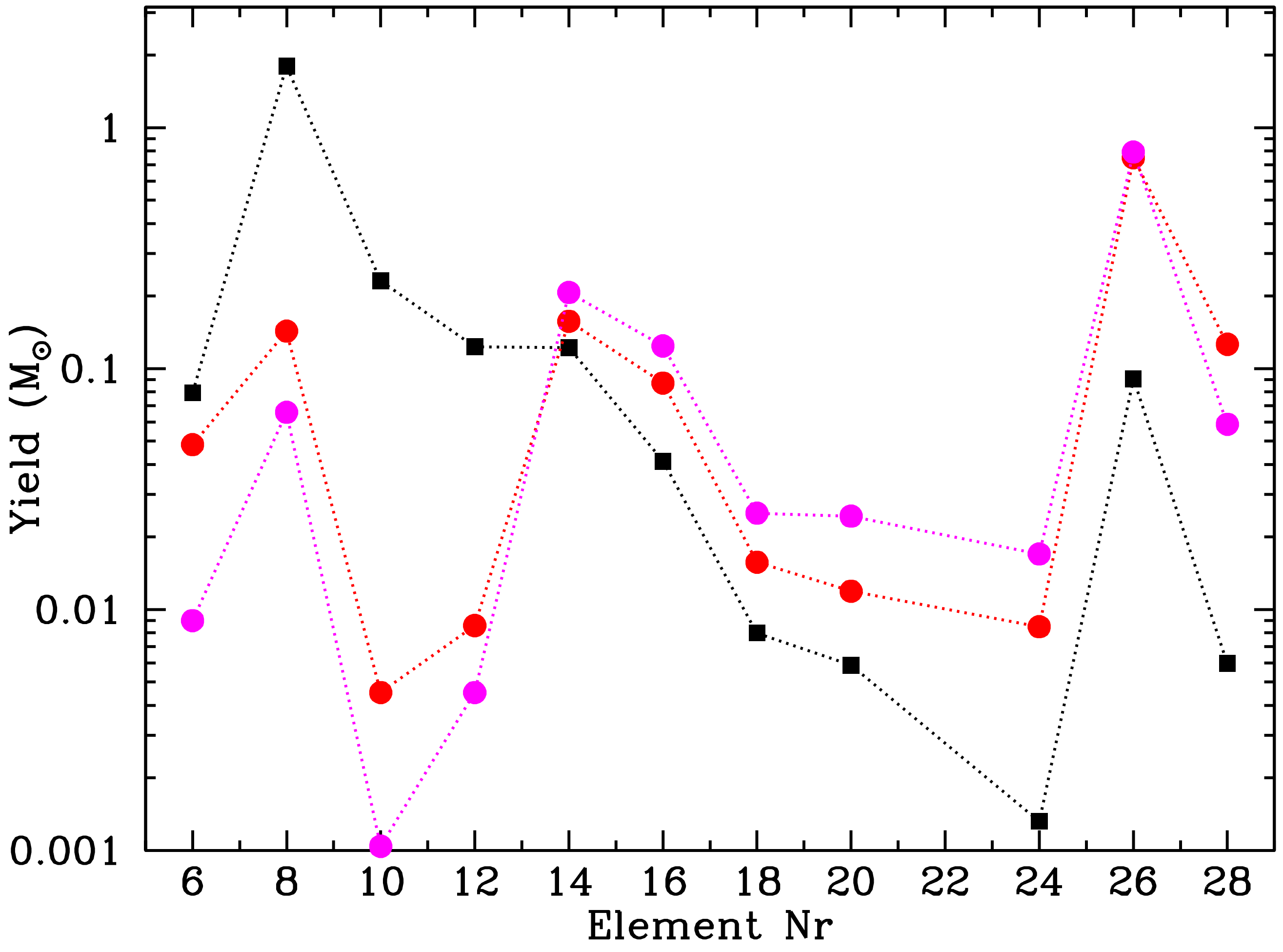
>25 M_{sun} → produce black hole

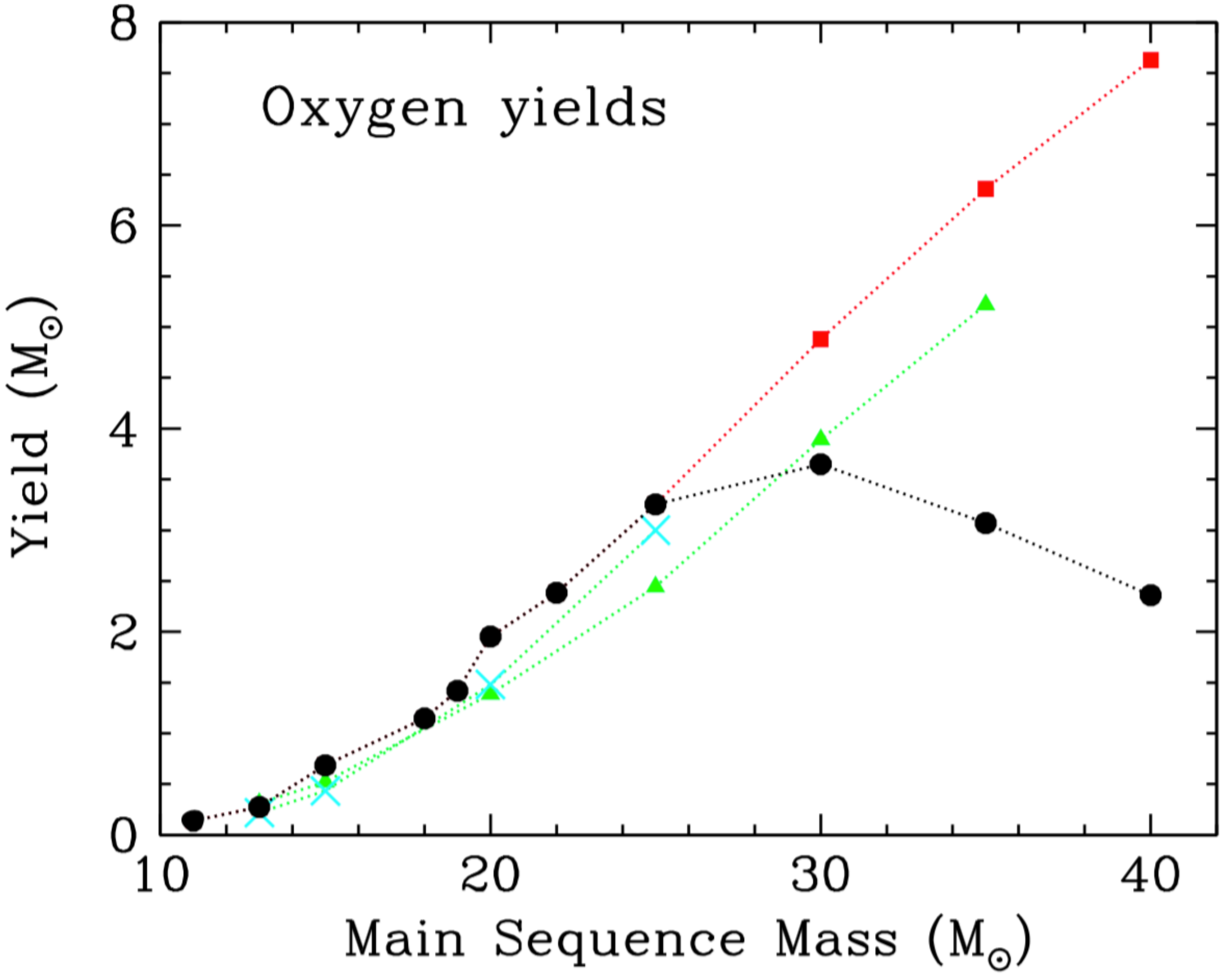
Thermonuclear explosions (Type Ia)



- C/O white dwarf close to 1.4 M_{sun}
- Mass accretion: density/pressure increases
- Explosive fusion of C/O
- Different explosion models (deflagration, delayed detonation…)
- Problems *single degenerate scenario*:
  - -only small range for stable accretion
  - -no donor stars found in Type Ia SNRs (Schaefer+ ’12, Kerzendorf ’14)
  - -no population of accreting WDs in elliptical found (Gilfanov+Bogdan, ’10)
- Popular alternative: *double degenerate scenario* (merging white dwarfs)
  - allows for super-Chandrasekhar supernovae

Type Ia vs Core Collapse SNRs

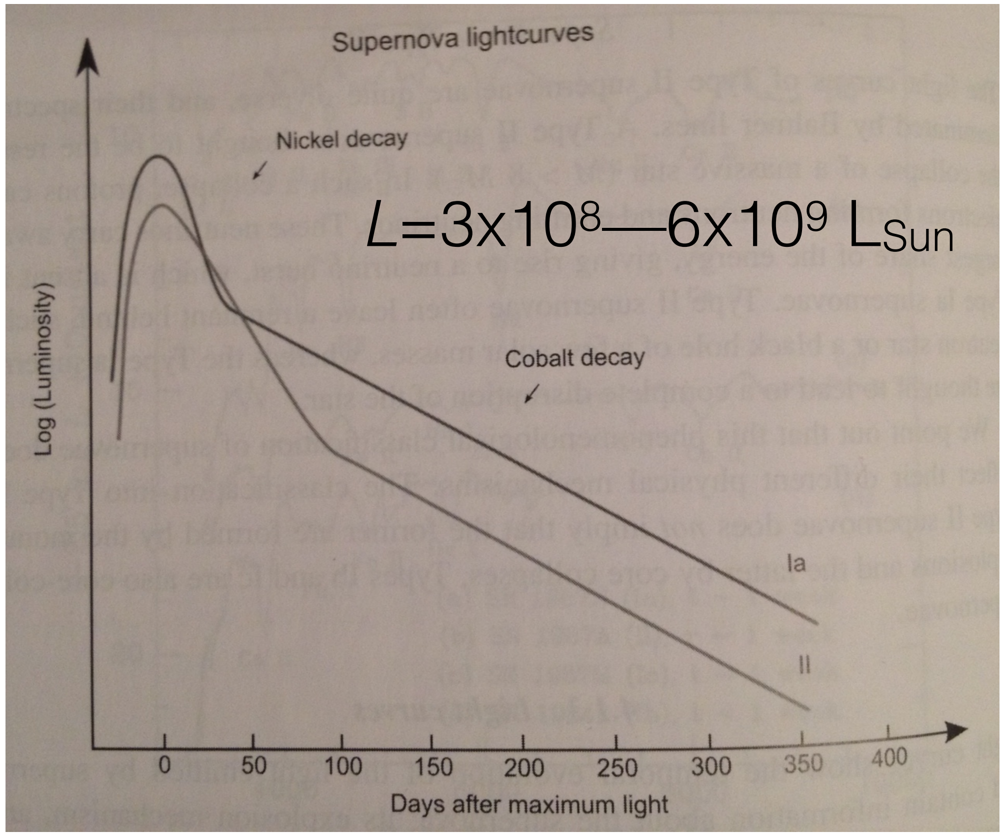




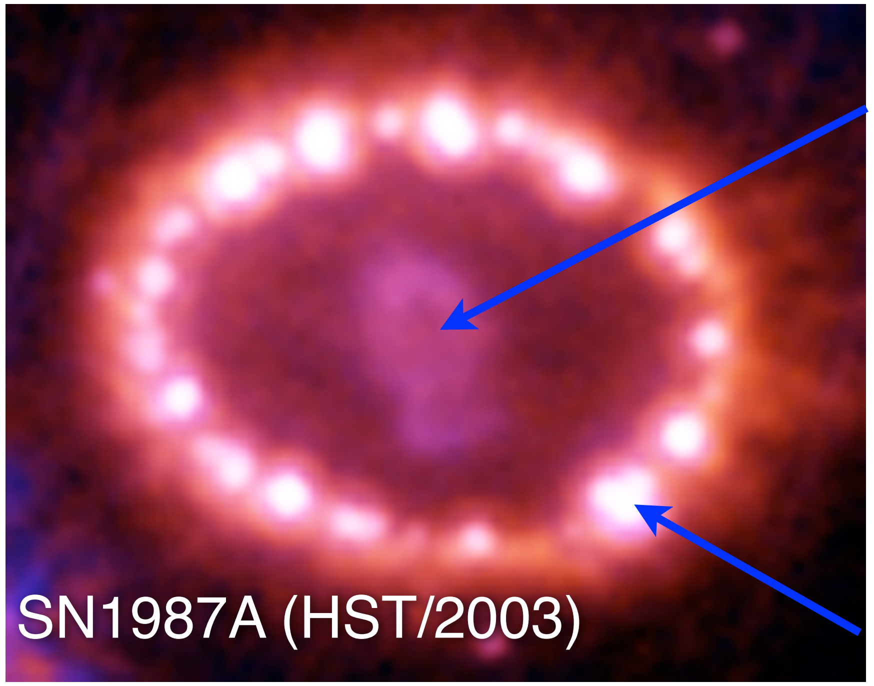
- Core collapse (black): rich in alpha elements (O, Ne, Mg,..)
- Type Ia: Fe-group (coloured, different models)

- above $30M_{Sun}$ models predict different O yields
- above $30M_{Sun}$ stellar cores may collapse into black holes and the amount of fallback is uncertain

From supernova to supernova remnant



$L = 3\times10^8 — 6\times10^9\ L_{Sun}$



SN1987A (HST/2003)

freely expanding ejecta heated by ^{44}Ti

shock-heated CSM ring

- $^{56}Ni + e^- \longrightarrow {}^{56}Co^* + \nu_e$ (τ=6.1 days)
- $^{56}Co + e^- \longrightarrow {}^{56}Fe + \nu_e$ (τ=77.1 days)
- SN expands -> ejecta cools (dust forms!!)
- Ejecta may still be warmed by late time radio-active heating (^{44}Ti)
- 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

Summary

- Supernovae come in two basic types
  1. thermonuclear supernovae
     - exploding C/O white dwarfs
     - ejecta mass ~ 1.4 Msun
     - energy comes from nuclear fusion (C/O->^{56}Ni)
     - produce lots of Fe (~0.6 Msun, product of ^{56}Ni)
     - no stellar remnant remains
  2. core collapse SNe
     - imploding stellar cores (Fe-grp elements)
     - stellar core becomes a neutron star
     - energy source: gravitational energy
     - most energy is neutrinos!
     - nucleosynthesis yield: stellar fusion + explosive fusion
     - yield dominated by oxygen

II

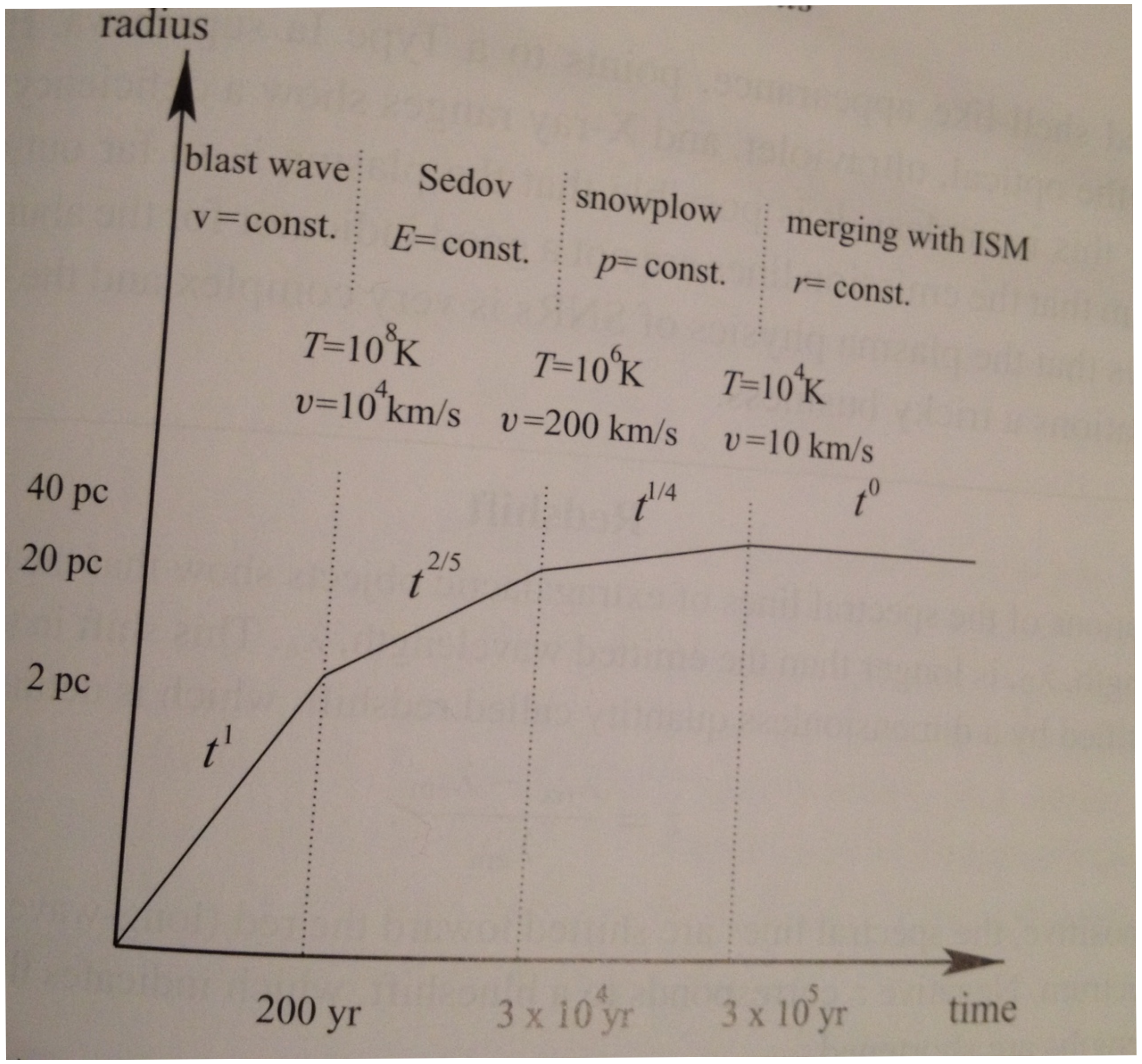
Supernova Remnants: Structure & Evolution

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
   - $M_{ej} \ll M_{swept}$
   - 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

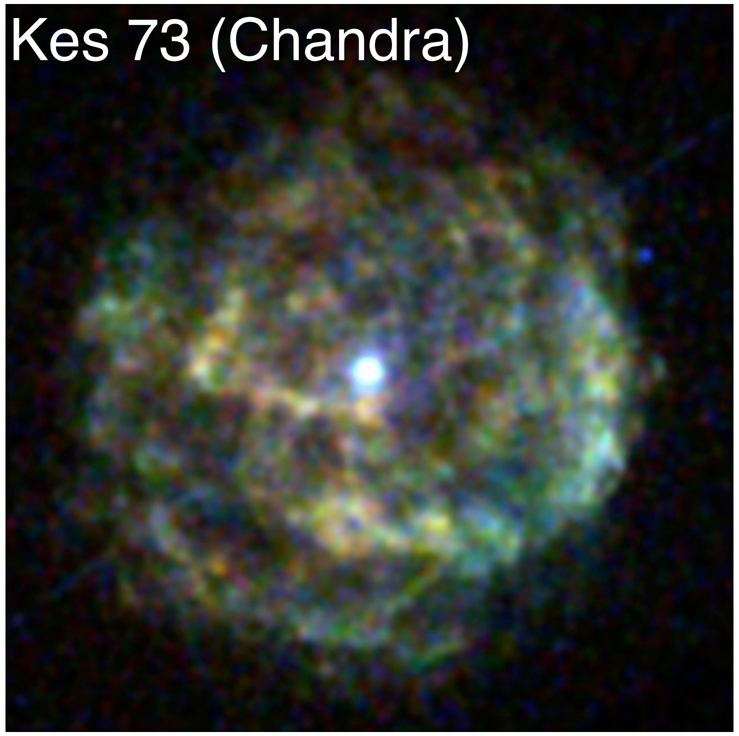
- Different parts of SNR may be in different phases!!



Ejecta dominated phase

- $E_{SN} \sim 1/2\ M_{ej}\ v_{ej}^2\ \sim 10^{51}$ erg
- Fast moving ejecta $v_{ej} \sim 10^4$ km/s $(E_{SN}/M_{Sol})^{1/3}(\rho_{ISM}/10^{-24}\ \mathrm{g\ cm^{-3}})^{-1/3}$
- shock-heating and sweeping up of the circumstellar medium
- heats the outer (cold) ejecta layers by *reverse shock*
- inner ejecta are cold

Adiabatic (non-radiative) Phase

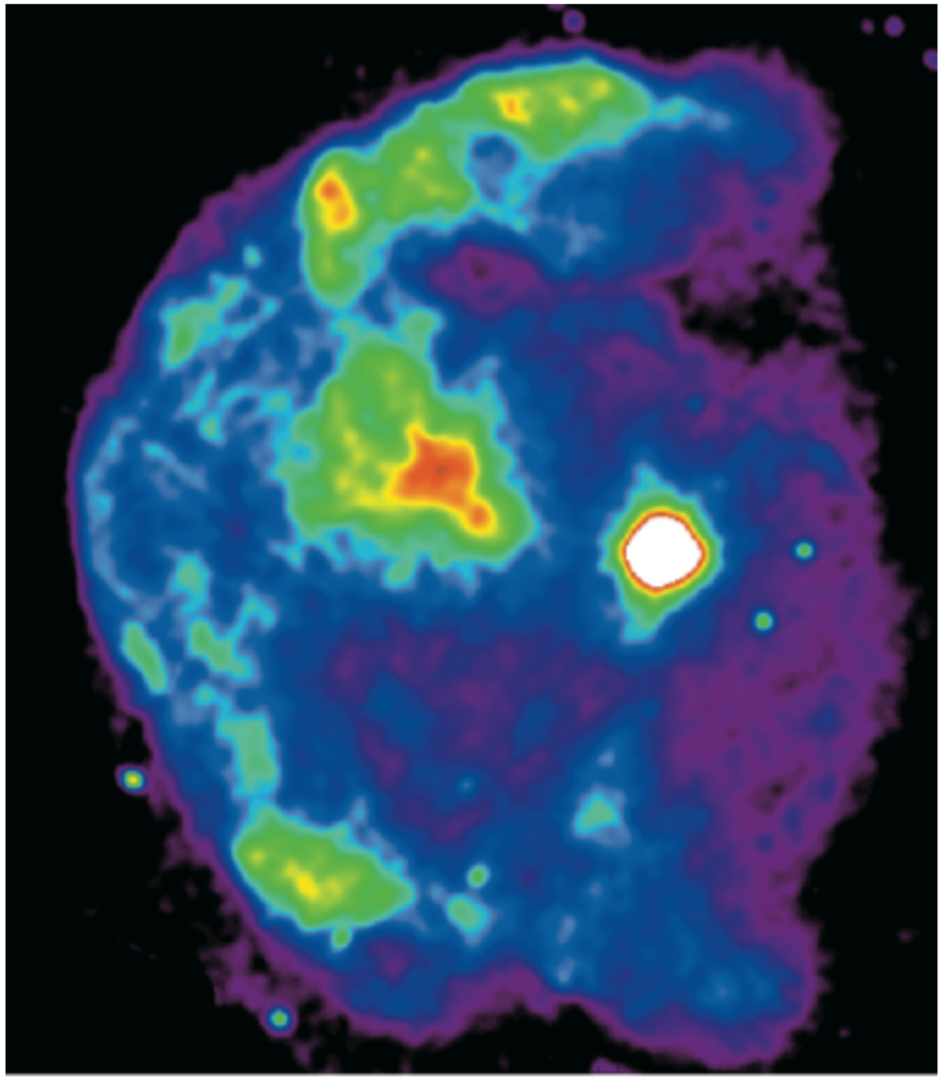


- Once $M_{\mathrm{swept}} > M_{\mathrm{ejecta}}$, but $V_s > 300$ km/s a SNR is said to be in the adiabatic phase
- (Almost) all energy is contained in the shock-heated plasma
- Evolution is usually described by so-called Sedov self-similar solution:

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

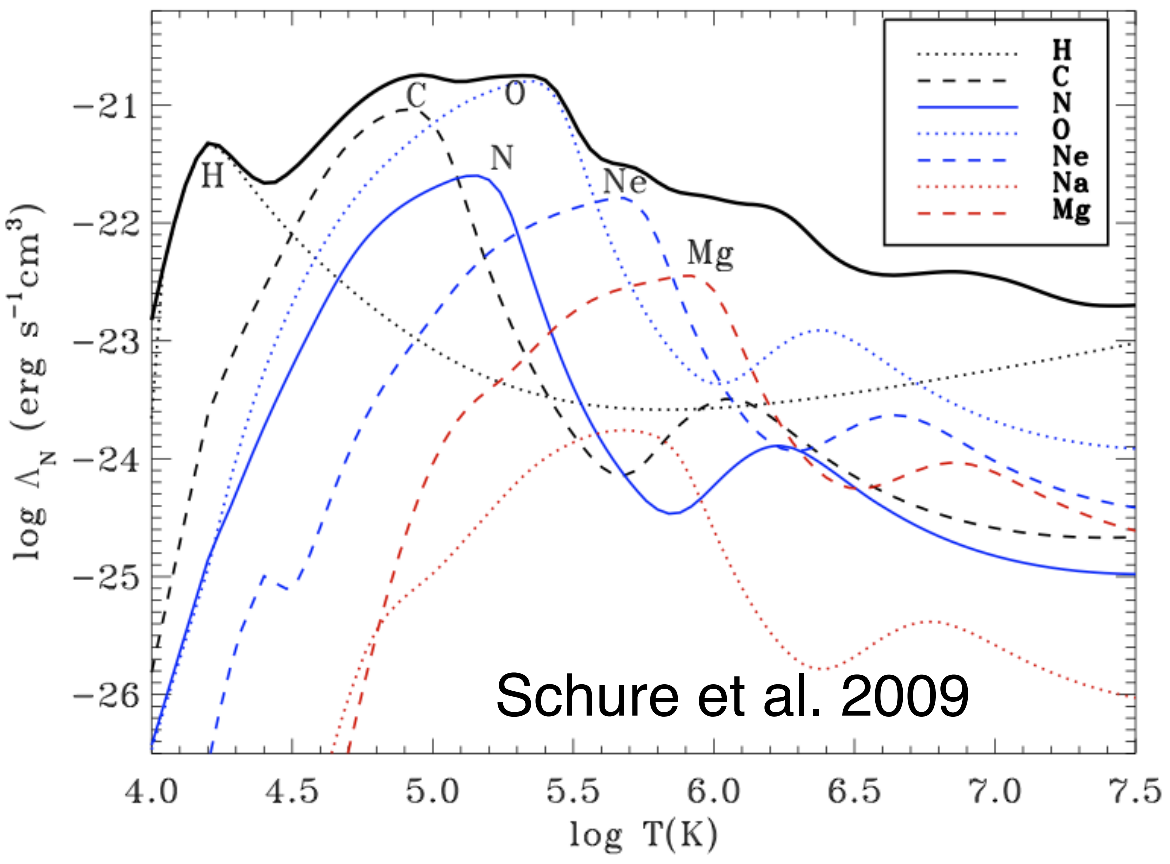
- material further out decelerates first, material further in starts to run into outer shells heating it up

Complications



- The environments of SNRs can be complex
- Some of that due to progenitor:
  - wind bubbles from various stellar phases
  - complex surroundings: molecular clouds, stellar winds from other stars, etc.
- Possible presence of pulsar wind nebula

"Mature SNRs": snow-plough phase

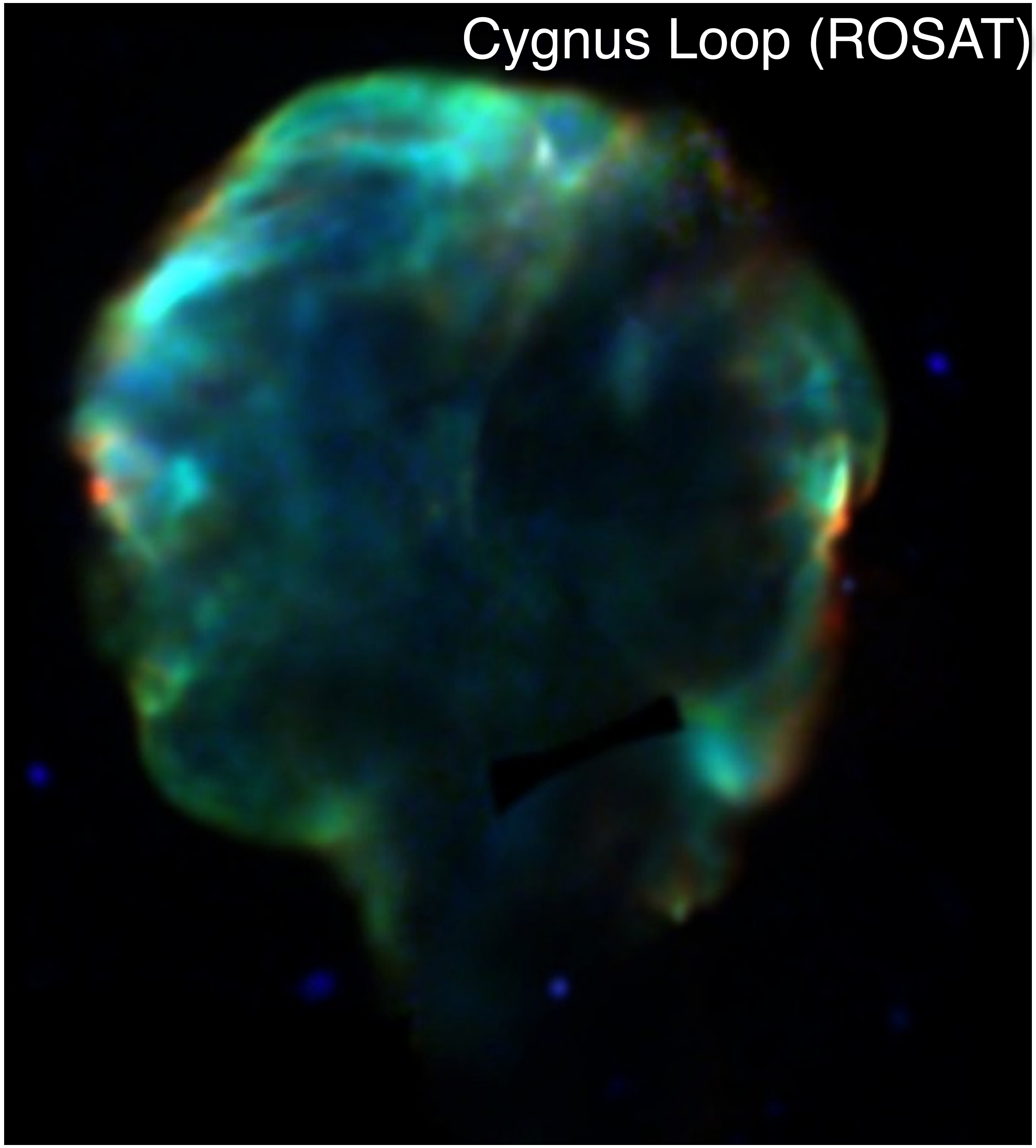


Schure et al. 2009

IC443

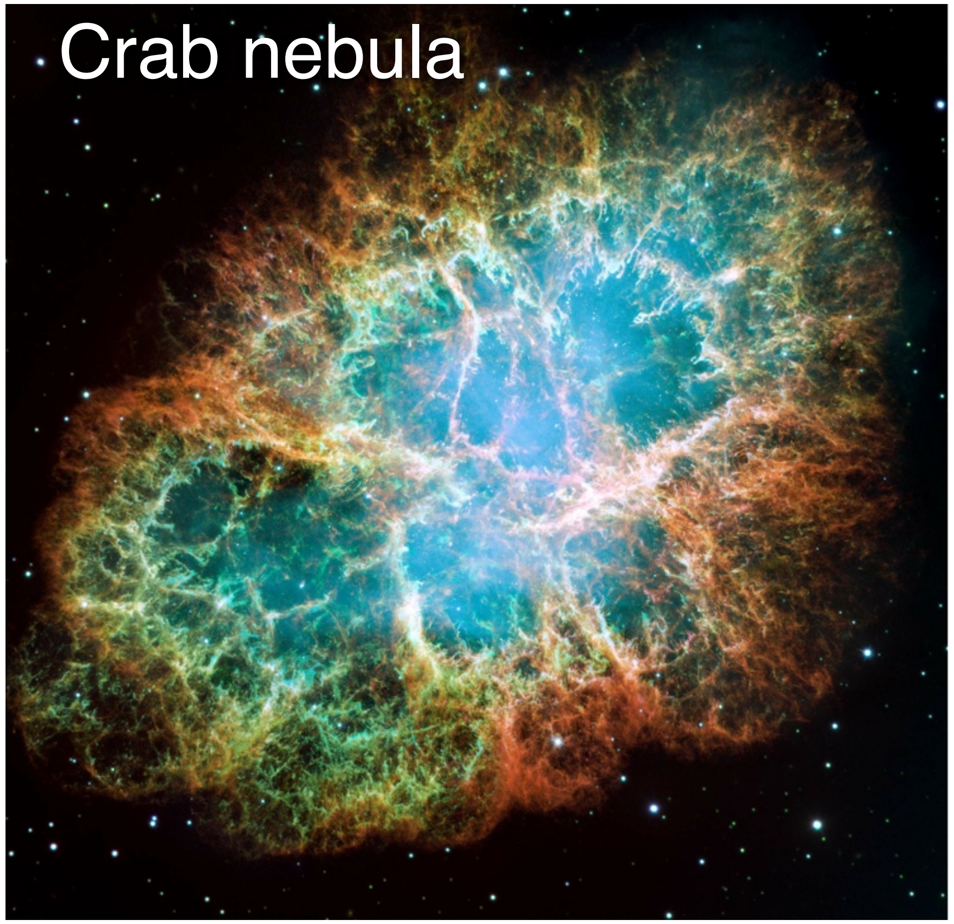
- For $T<5\times10^5$ K: cooling becomes very strong (oxygen line emission)
- Cooled gas: bright optical emission from [OIII], [NII],...
- This corresponds with $V_s<200$ km/s
- SNR *no longer adiabatic*: $R \sim t^{0.25}$ (momentum conservation)

SNR Types: shell-type



Cygnus Loop (ROSAT)

SNR Types: Plerion

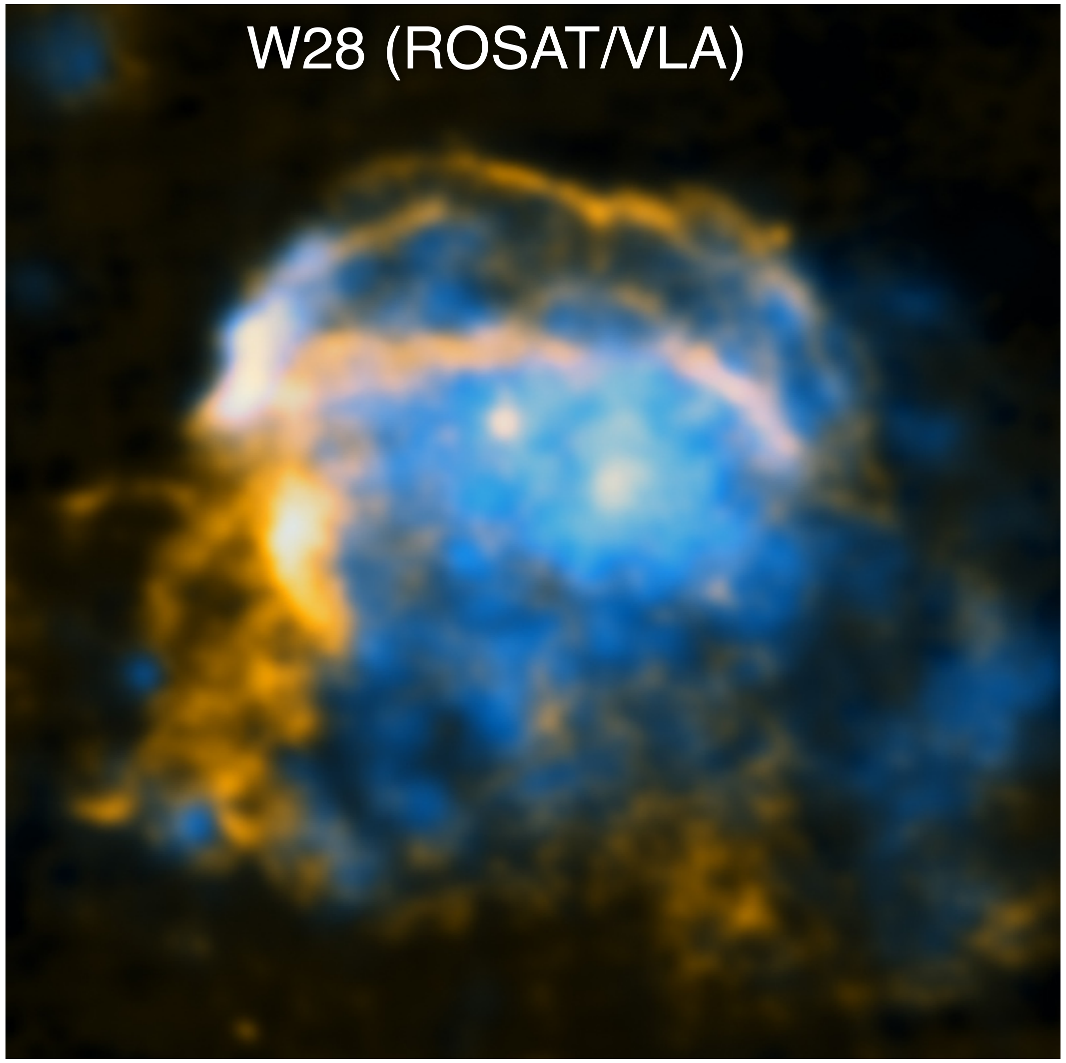


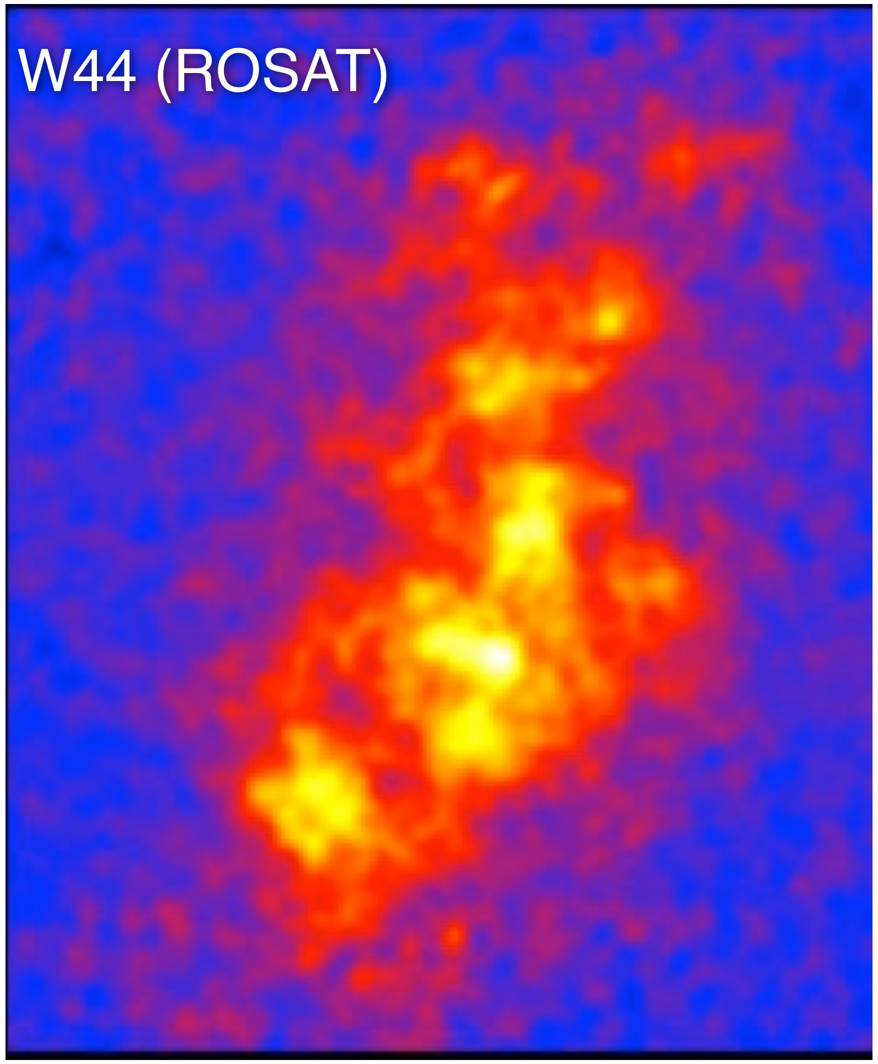
- Plerions are dominated by synchrotron emission from pulsar wind nebula
- They can still be considered SNRs as they have some ejecta components (in Crab nebula only seen in the optical)

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!

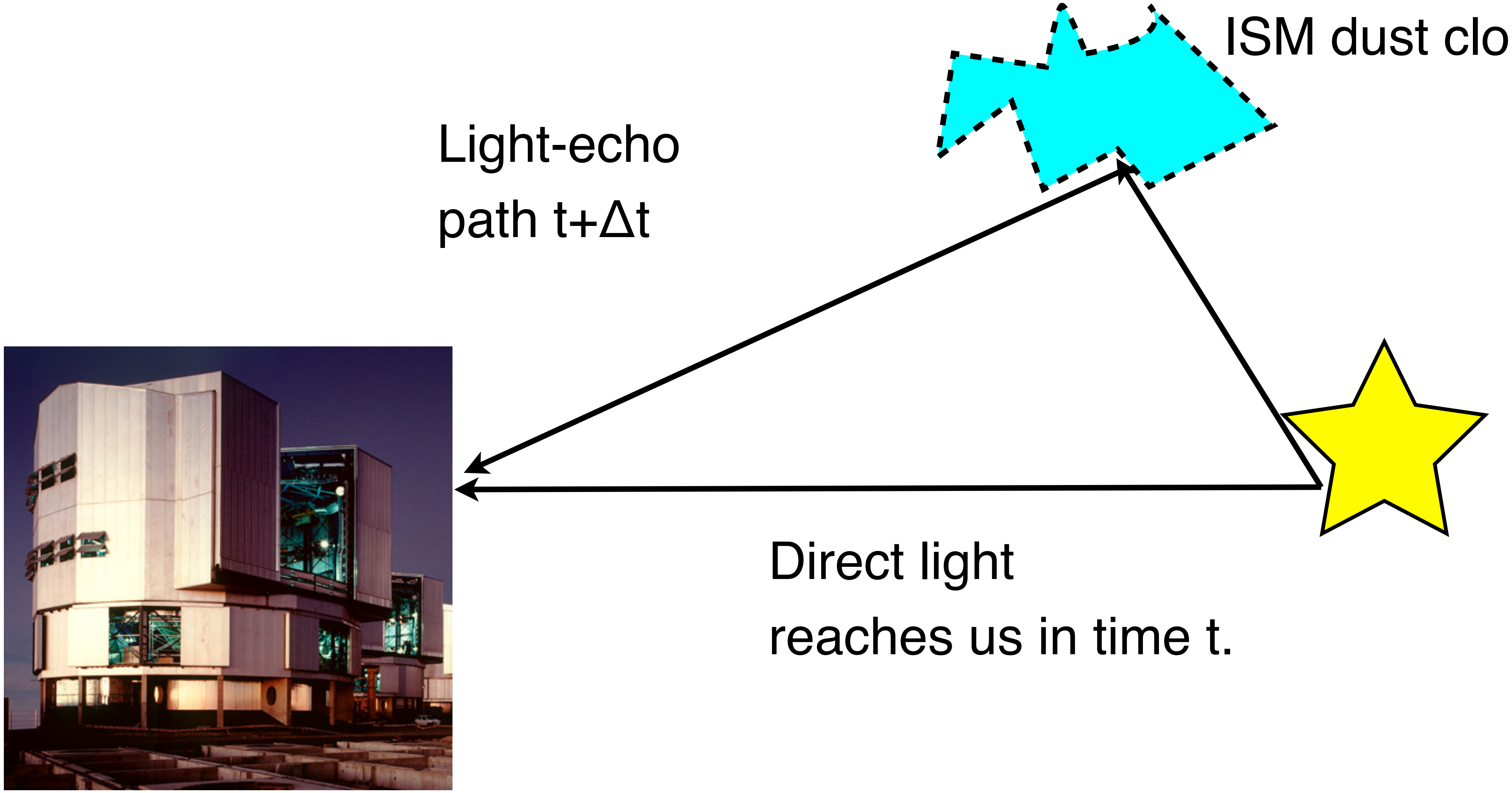
Mixed-morphology/Thermal composite SNRs





- 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!!

Confirmation of SNR typing: light echoes

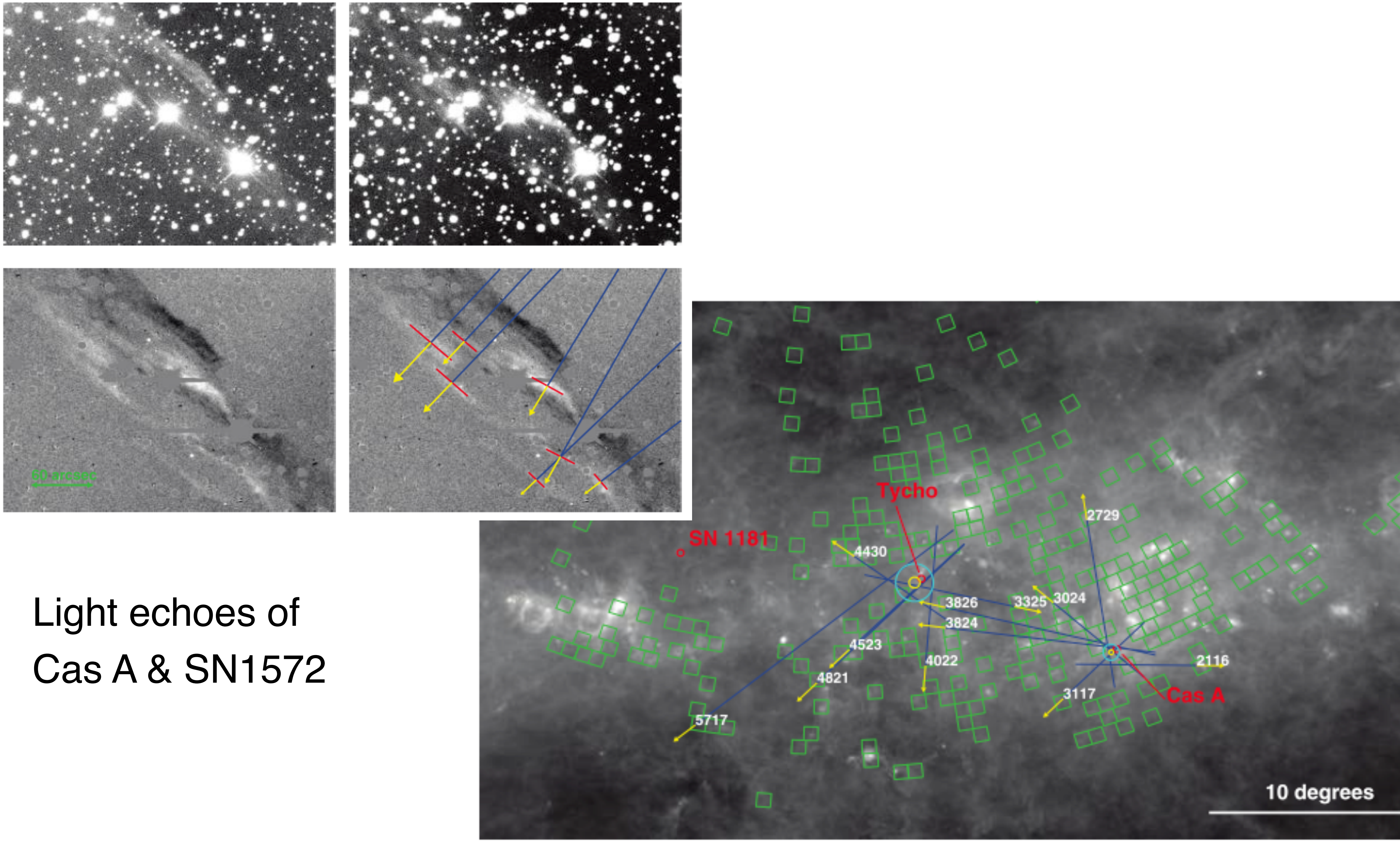


ISM dust cloud

Light-echo
path t+Δt

Direct light
reaches us in time t.

Confirmation of SNR typing: light echoes

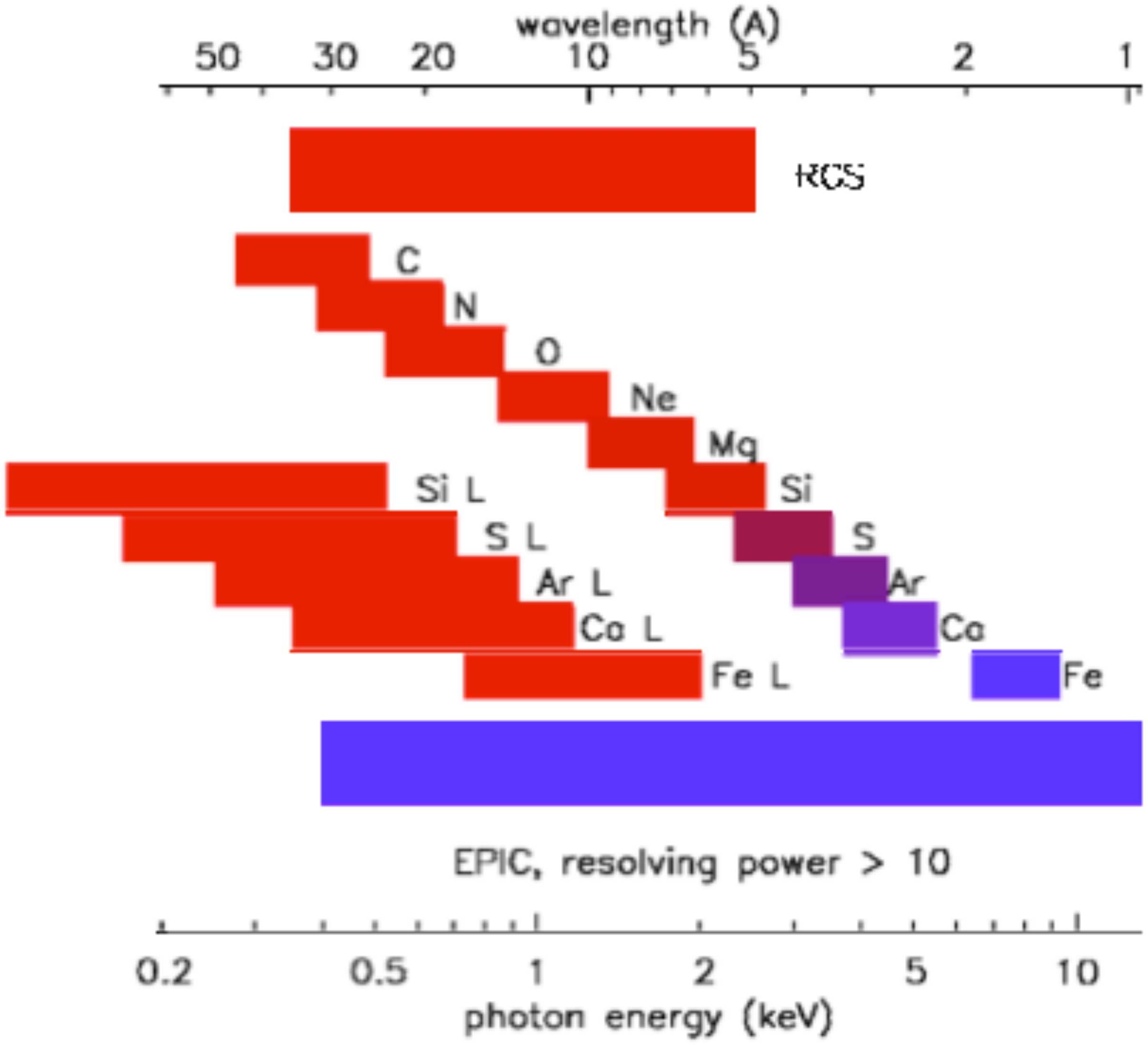


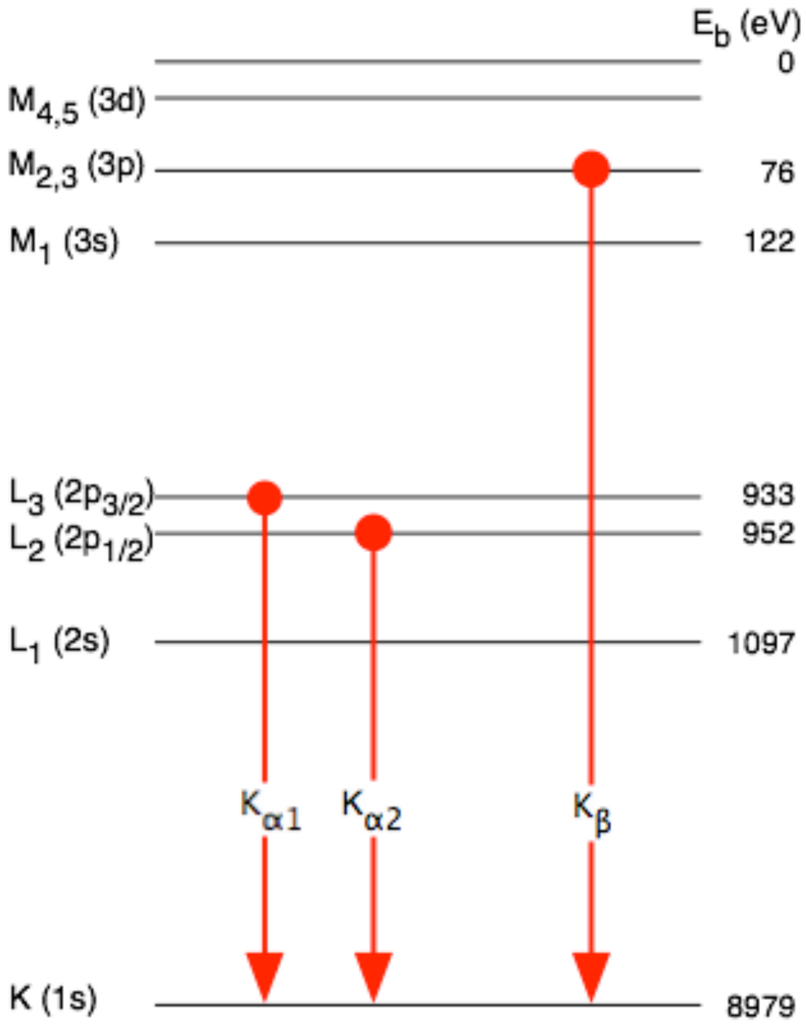
Light echoes of
Cas A & SN1572

III

Emission from core collapse SNRs

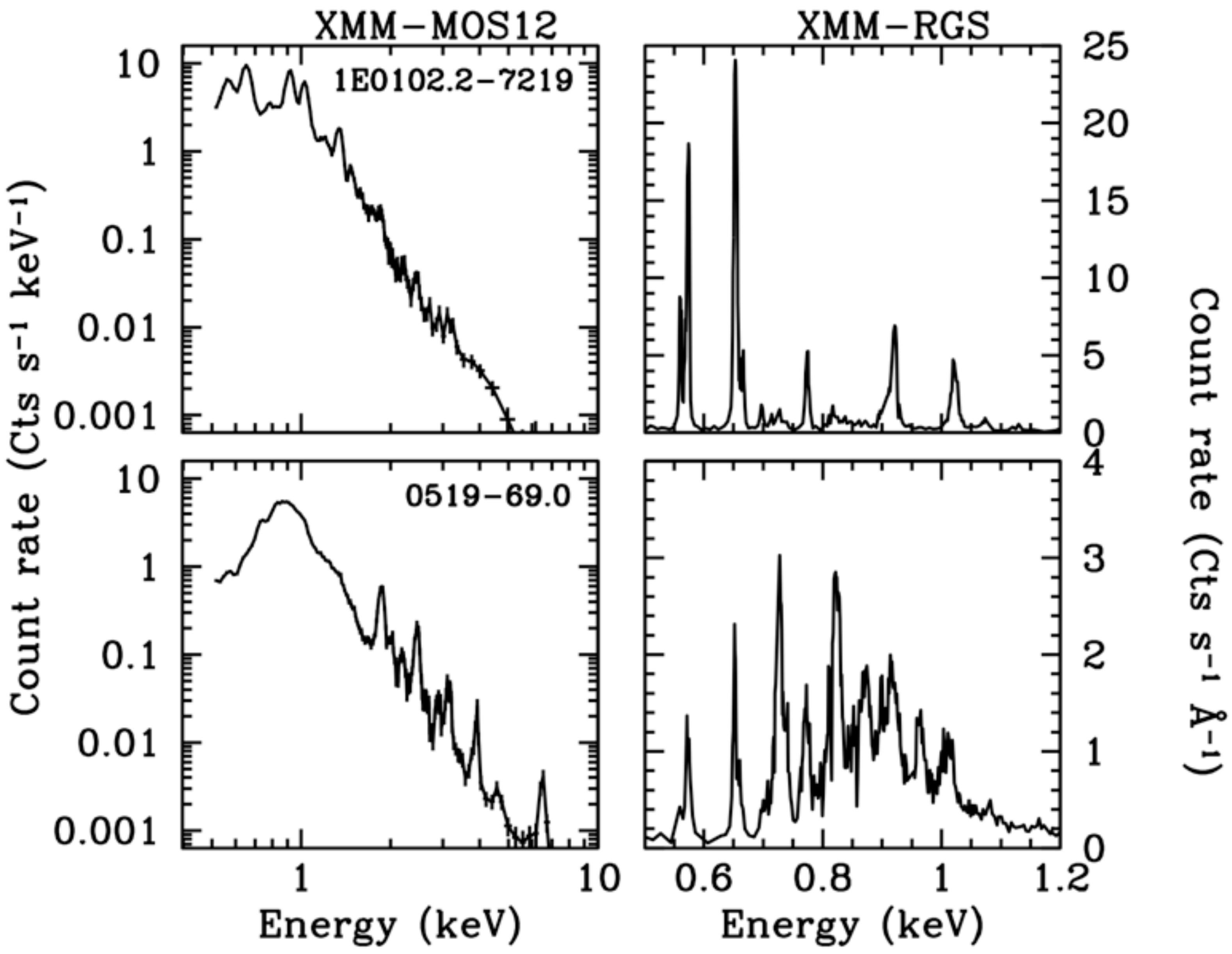
Which elements, where?

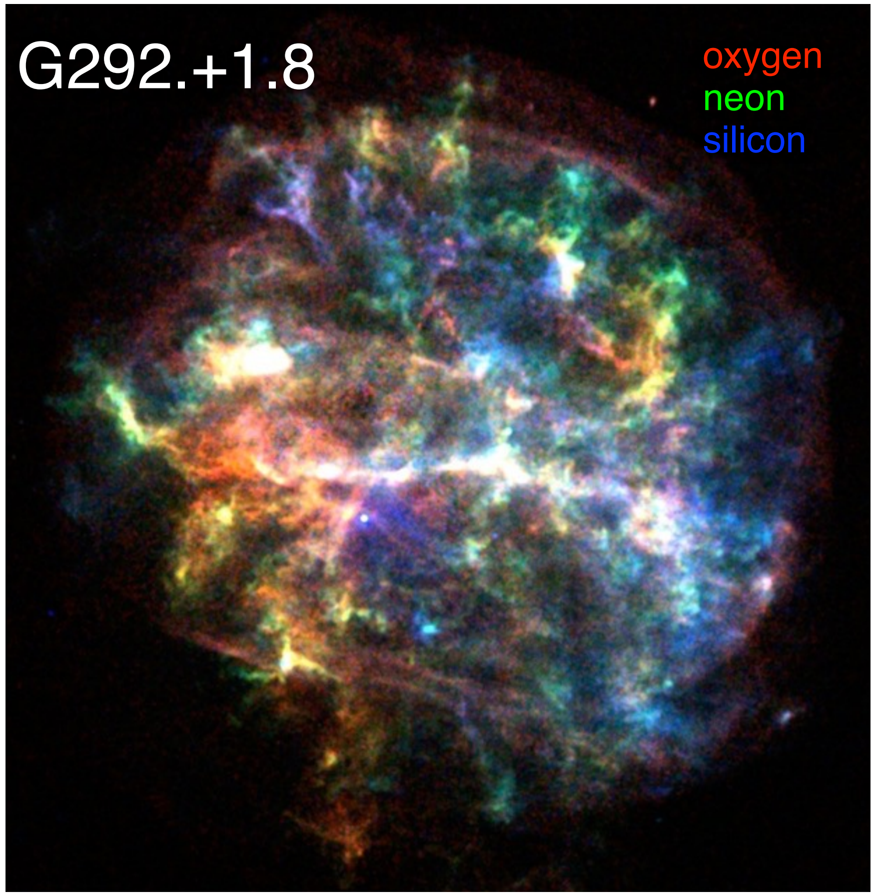


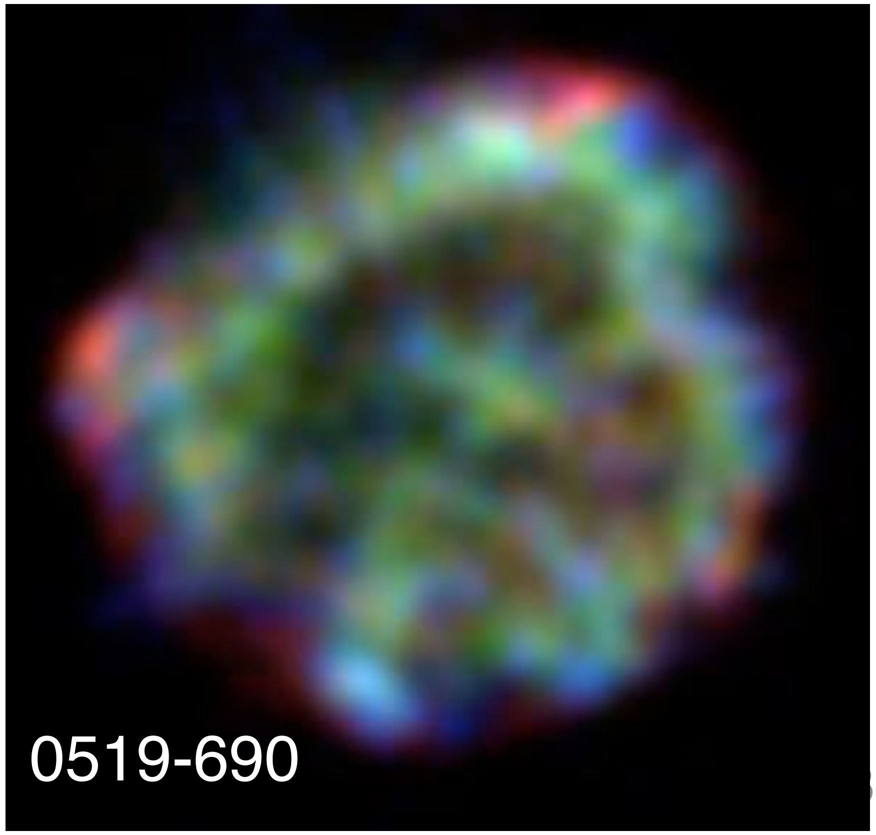


X-ray lines between neutral fluorescent n=2-1, and H-like n=1-∞ (think of the Bohr model!)

Linking SNRs with SN classes



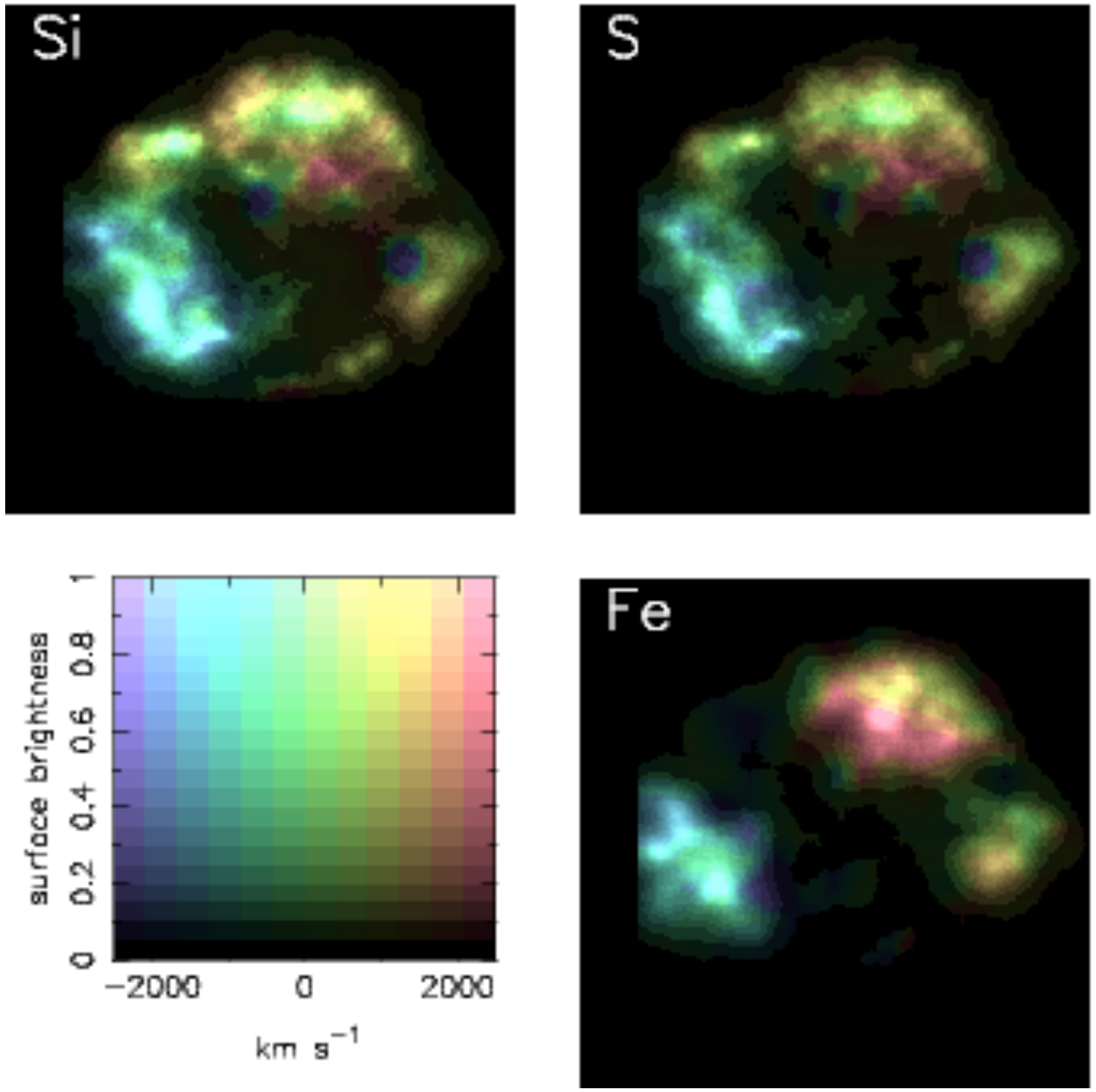


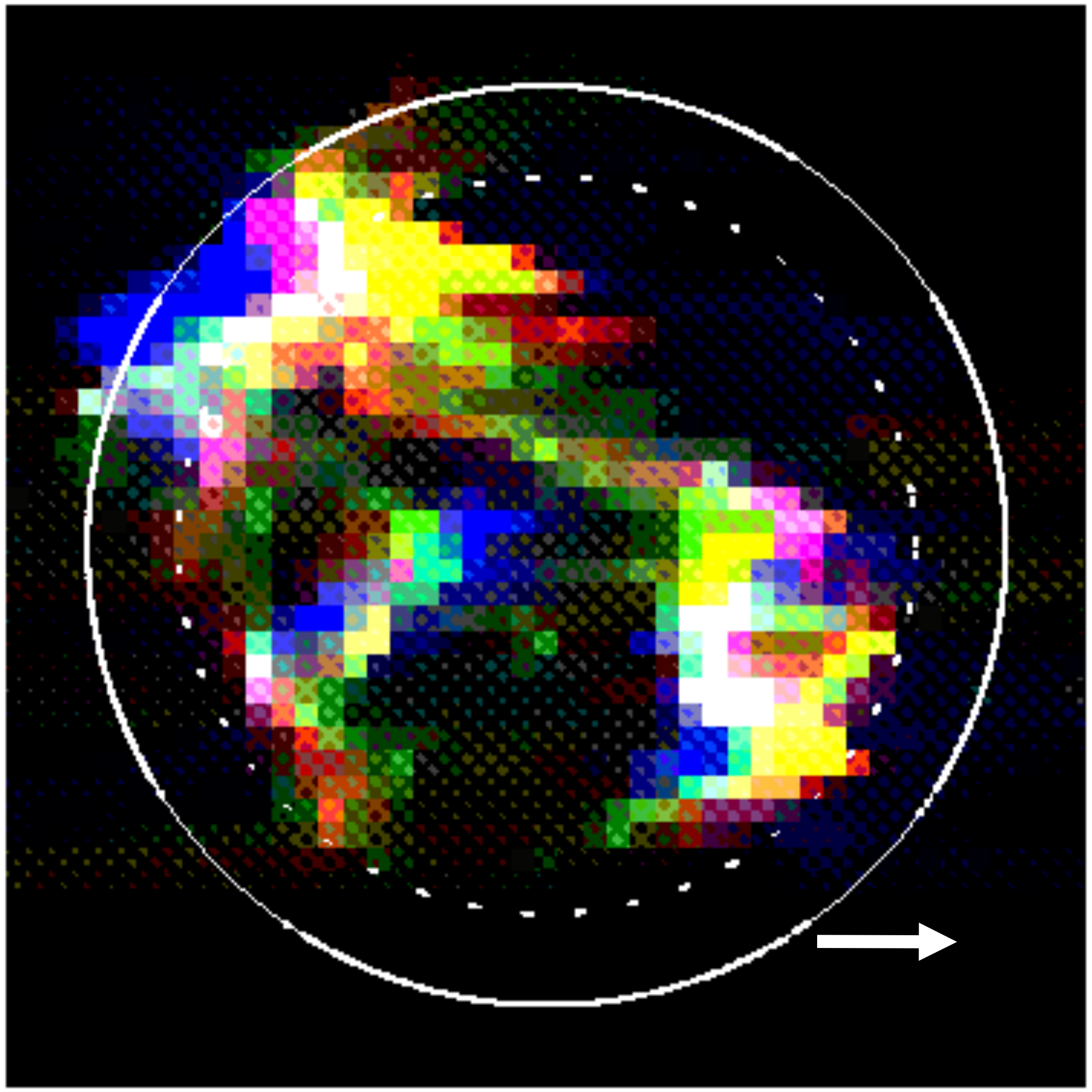


- Core collapse SNRs are rich in O, Ne, Mg
- Type Ia SNRs are iron-rich

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

Cassiopeia A: (A)symmetries I





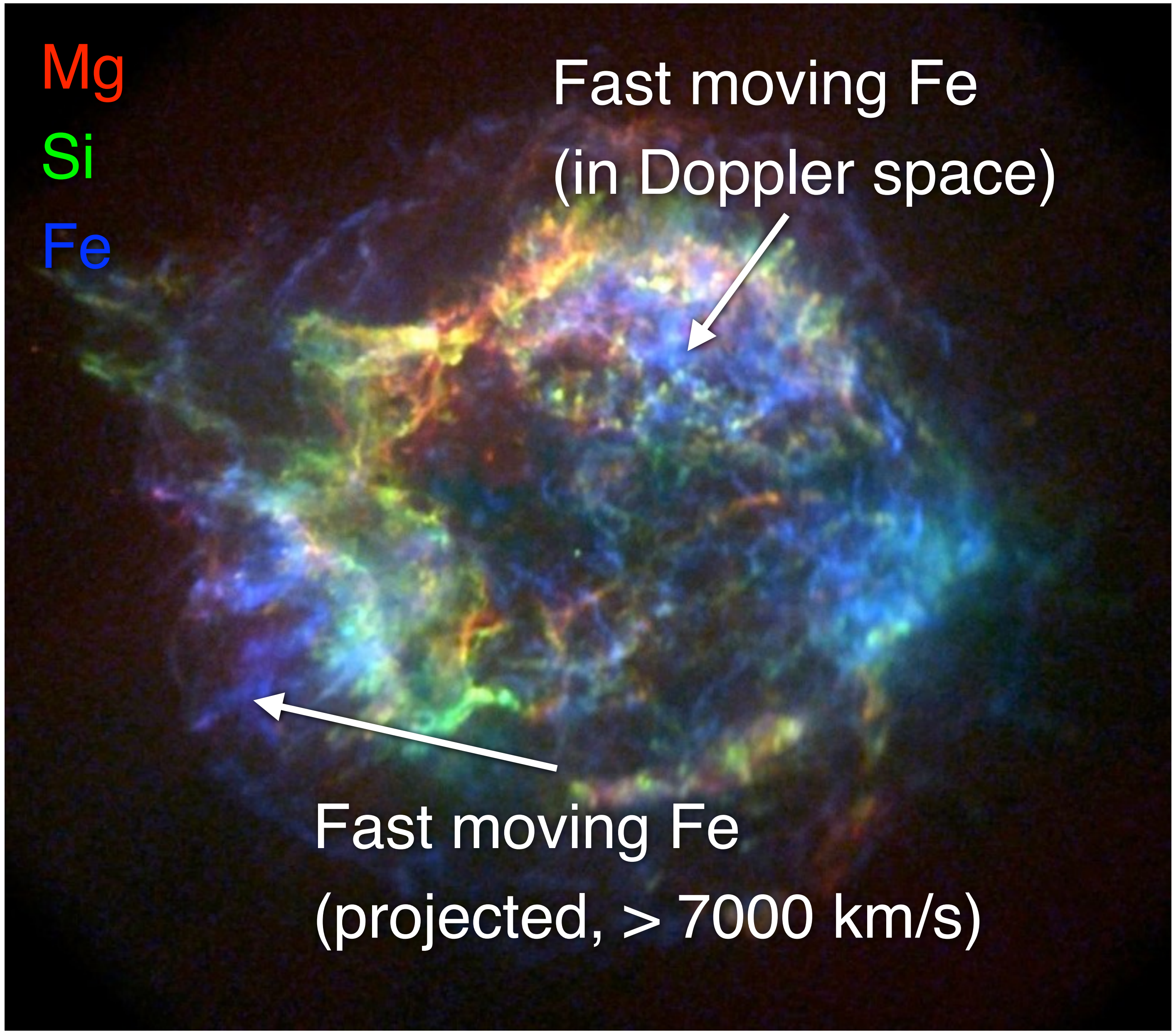
XMM-Newton based Doppler map + deprojection

Cas A shows donut like shape

Willingale+ ’02

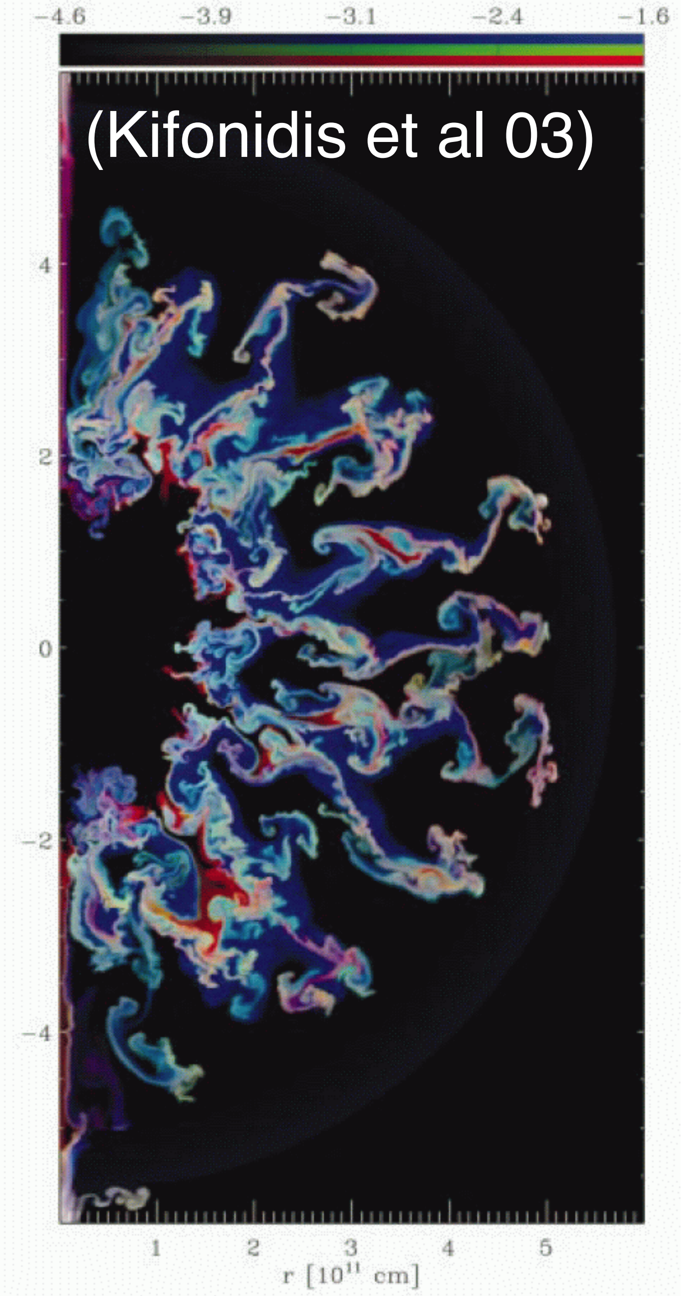
see also Delaney et al ‘10

Evidence for fast Fe knots

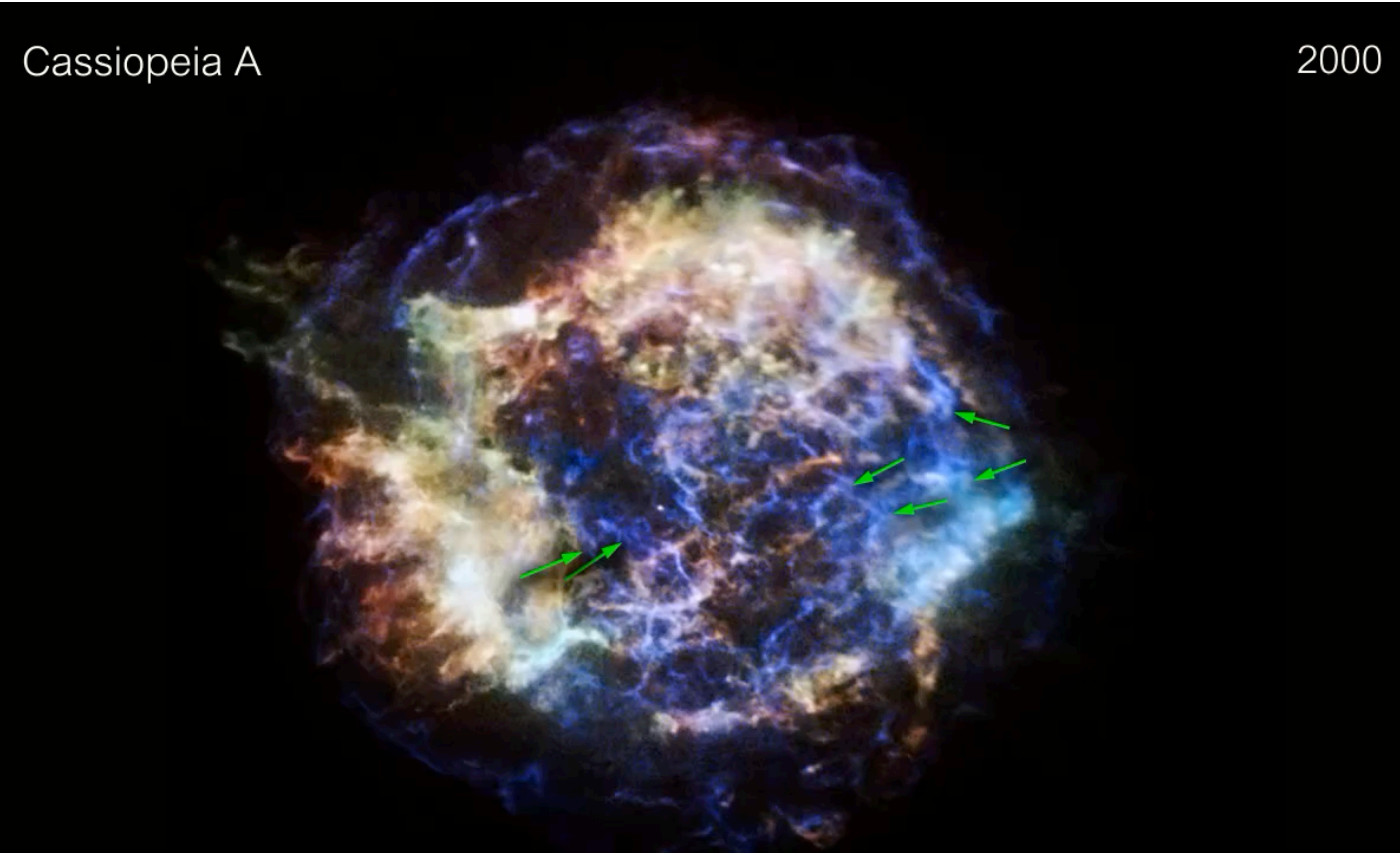


Fast moving Fe
(in Doppler space)

Fast moving Fe
(projected, > 7000 km/s)


(Kifonidis et al 03)

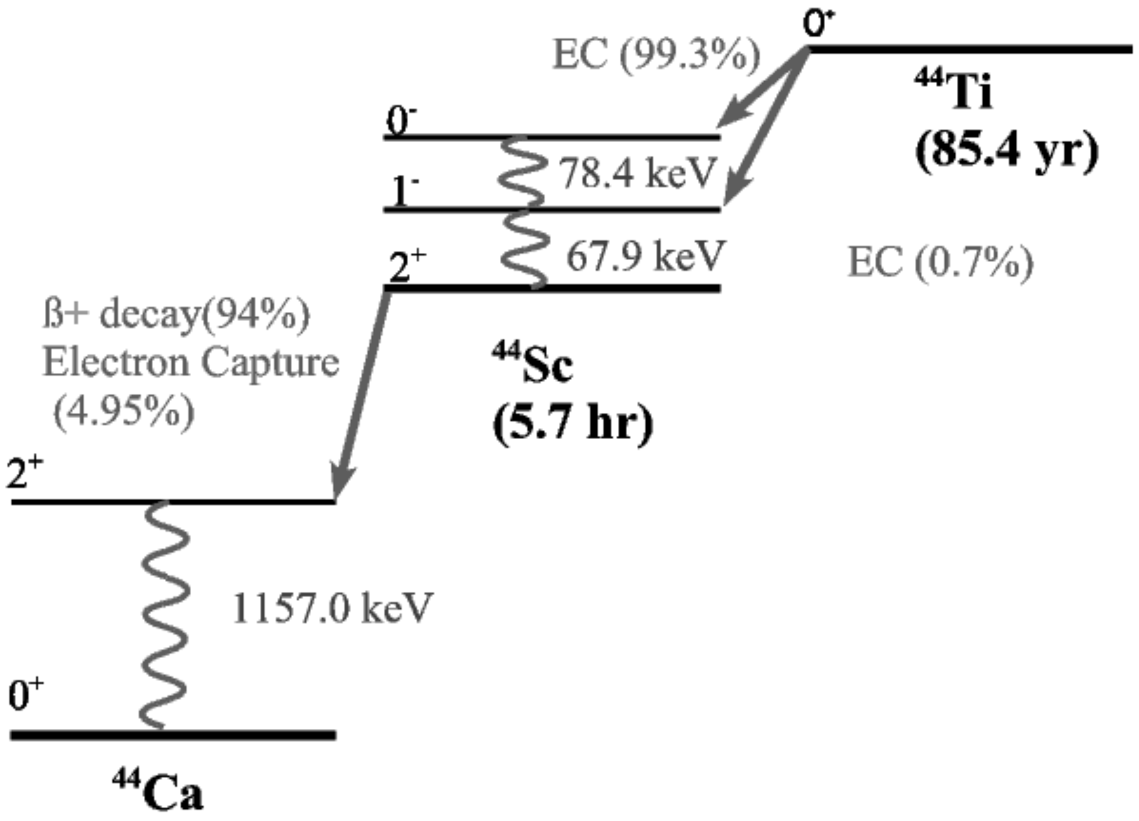
- Fast moving “pure” Fe plasma (Hughes+ ’00,Laming&Hwang ‘03)
- Seen (to a lesser extent) in simulations (in Type Ib/c)

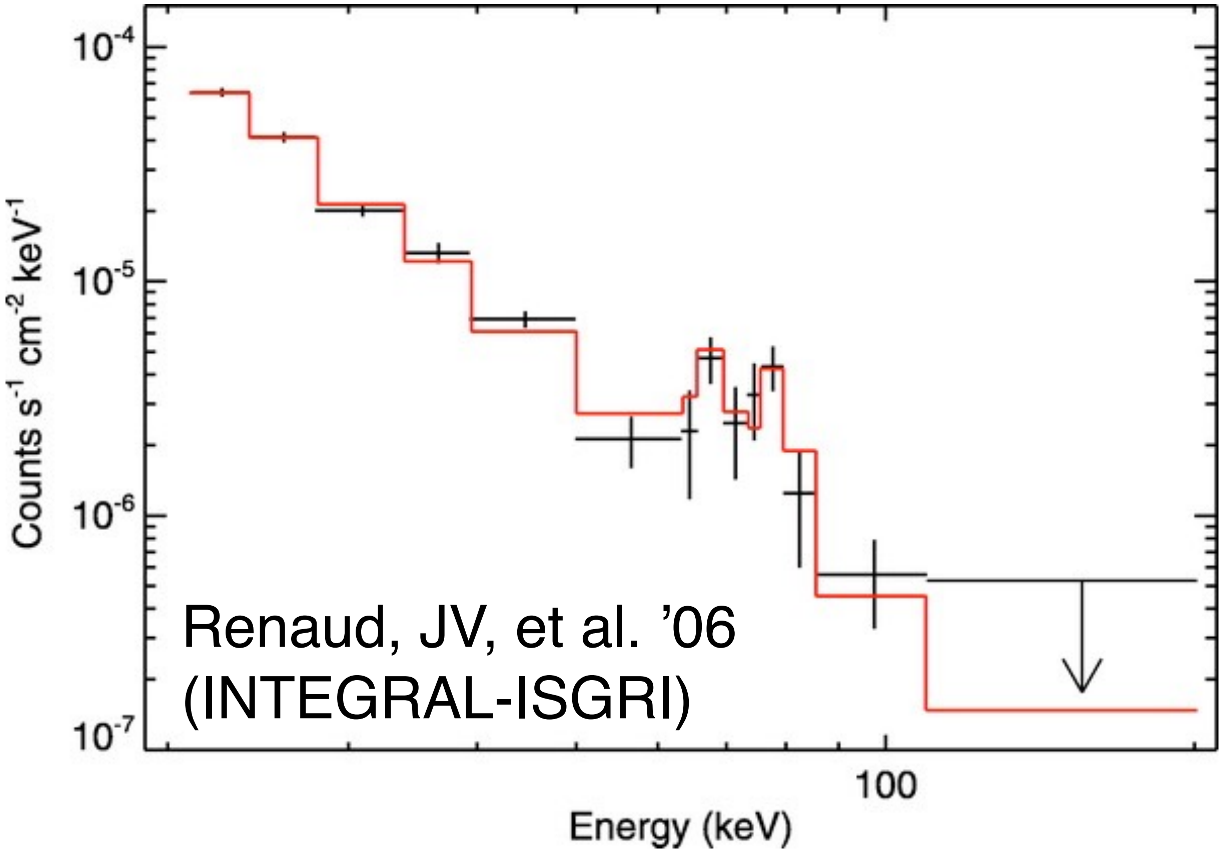


Cassiopeia A

2000

^{44}Ti decay



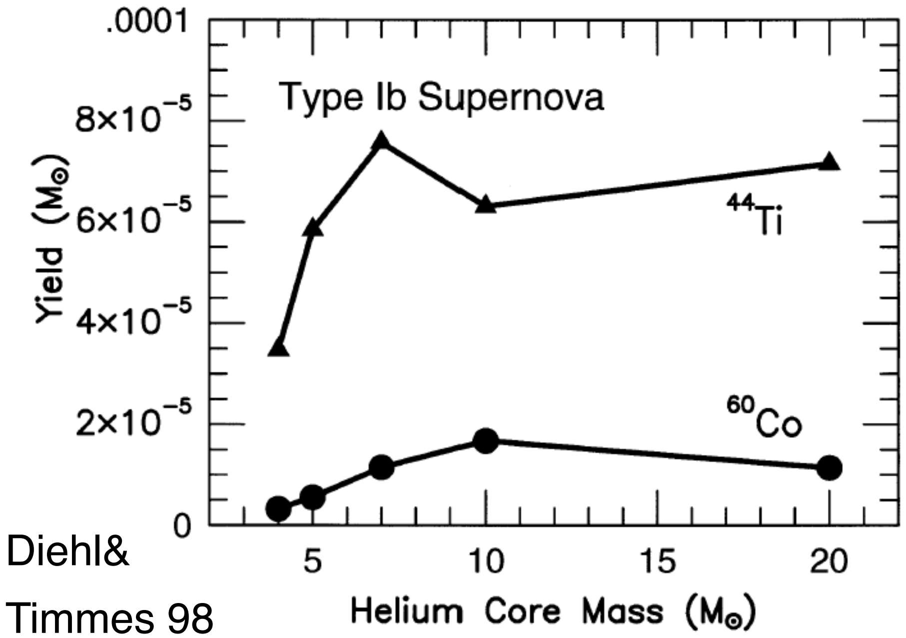


Renaud, JV, et al. ’06
(INTEGRAL-ISGRI)

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

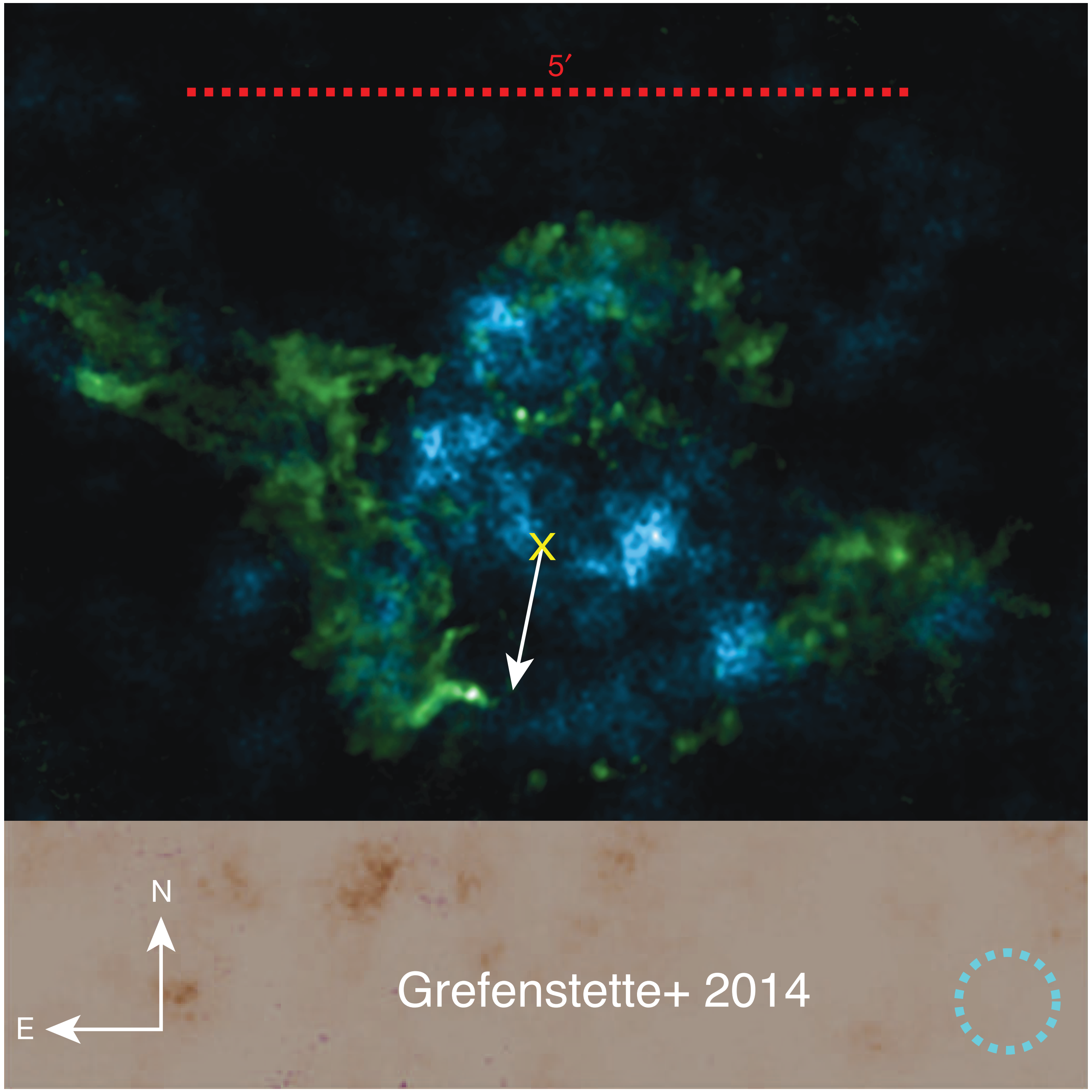
  (Iyudin+ 94, Vink+ ’01, Renaud+ 06, Grefenstette+ 14, Siegert+ ’15)

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



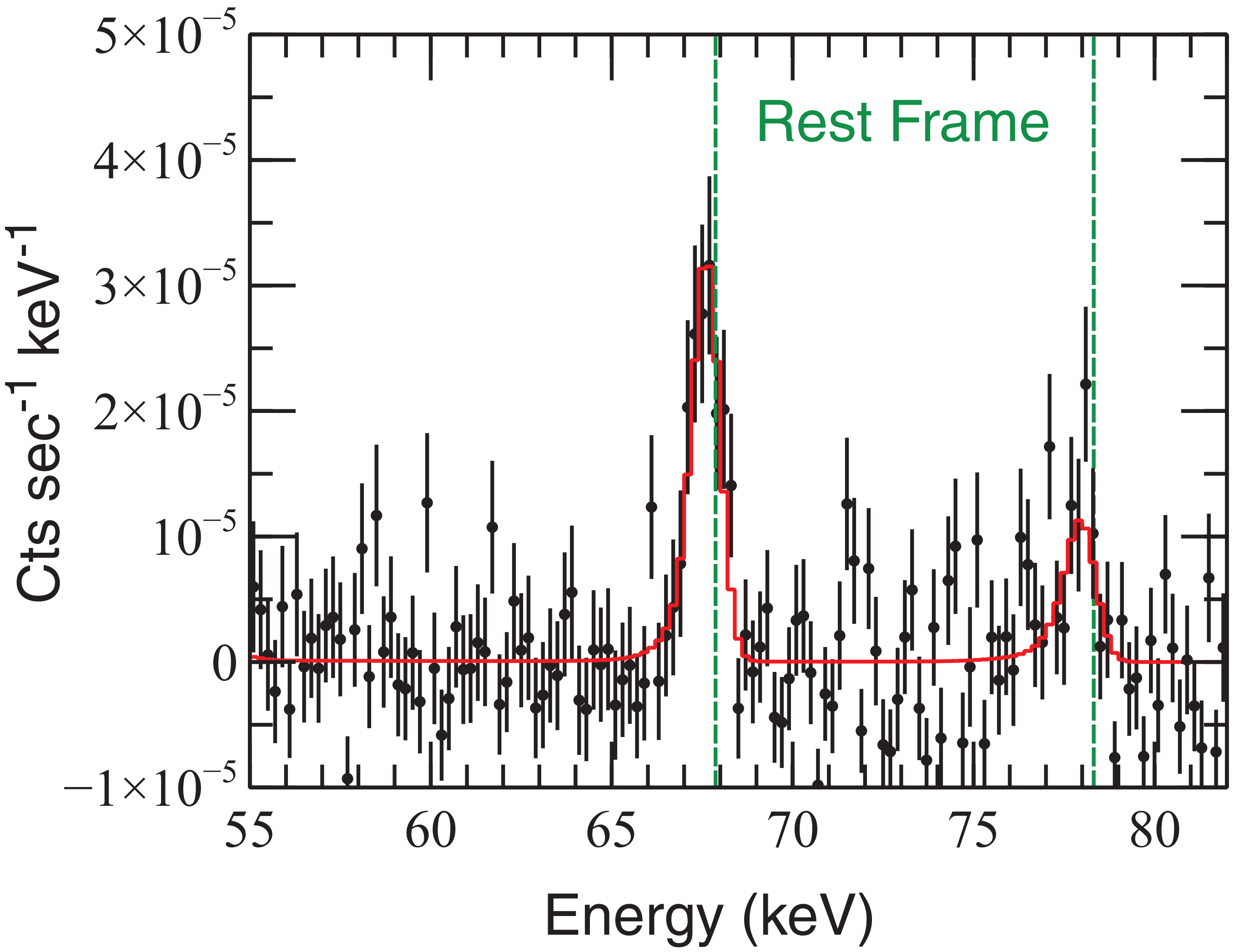
Diehl&
Timmes 98

^{44}Ti map NuStar



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

^{44}Ti in SN1987A

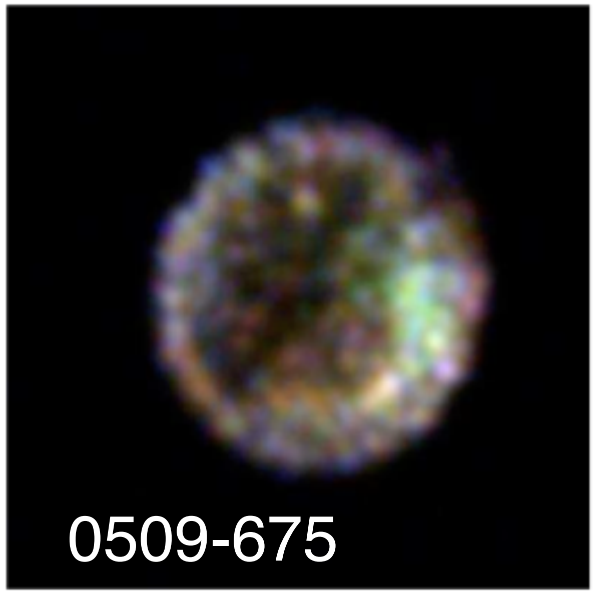


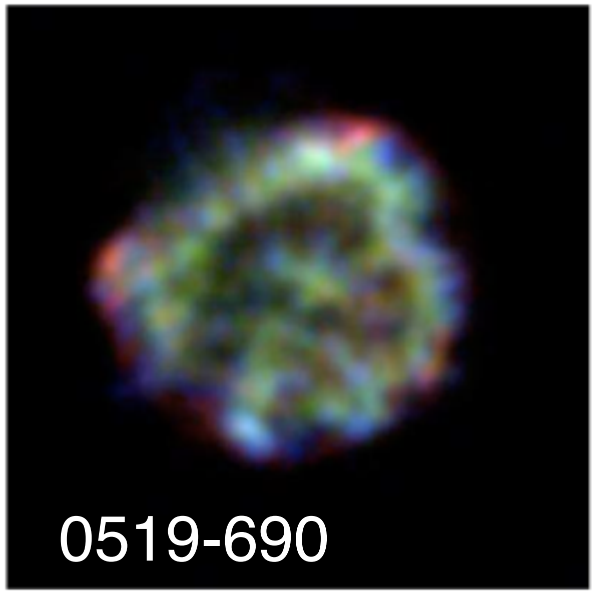
Boggs et al. 14

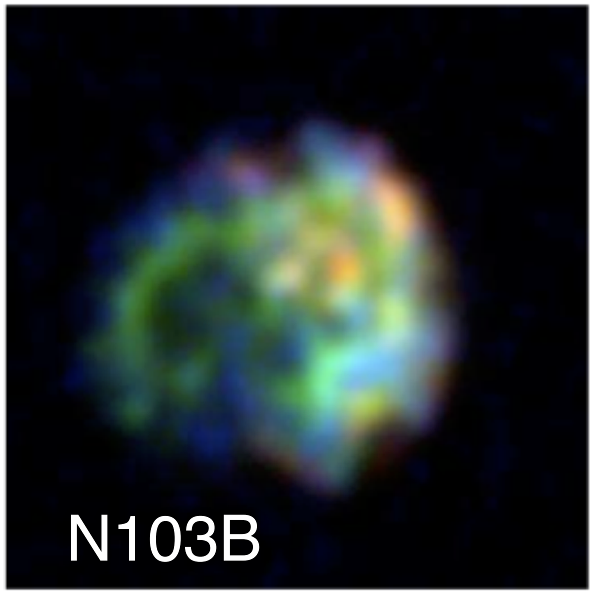
- Redshifted ^{44}Ti in SN1987A → asymmetric core
- ^{44}Ti yield: 1.5 x 10^{-4} Msun
- Very similar to Cas A

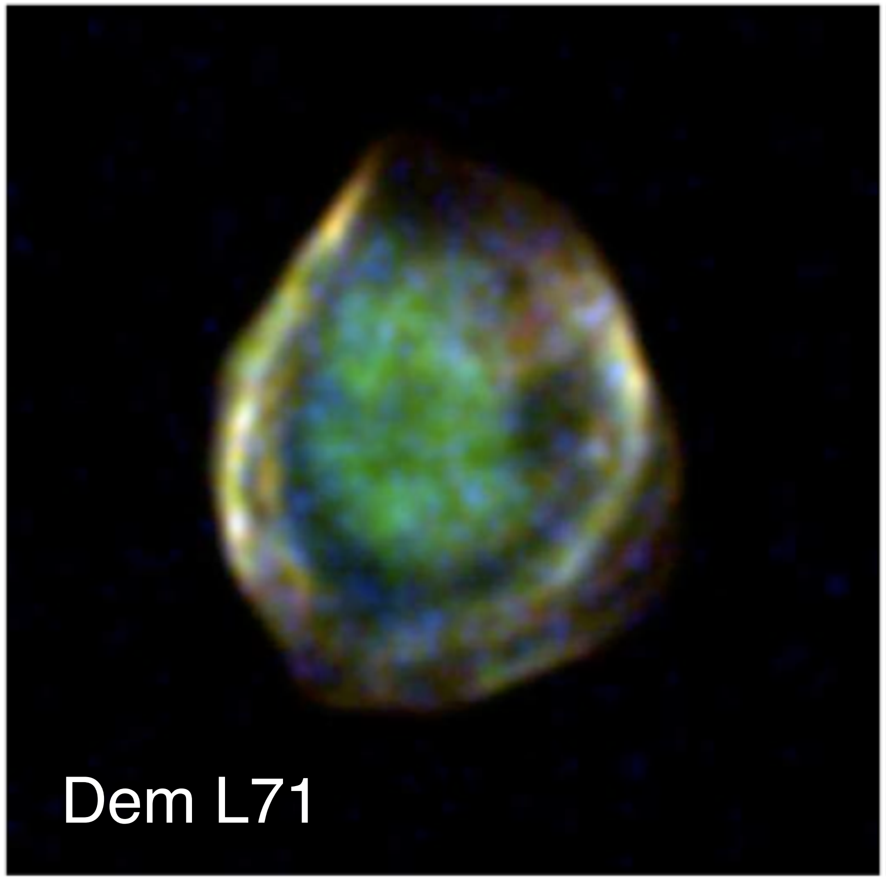
IV
Emission from Type Ia SNRs

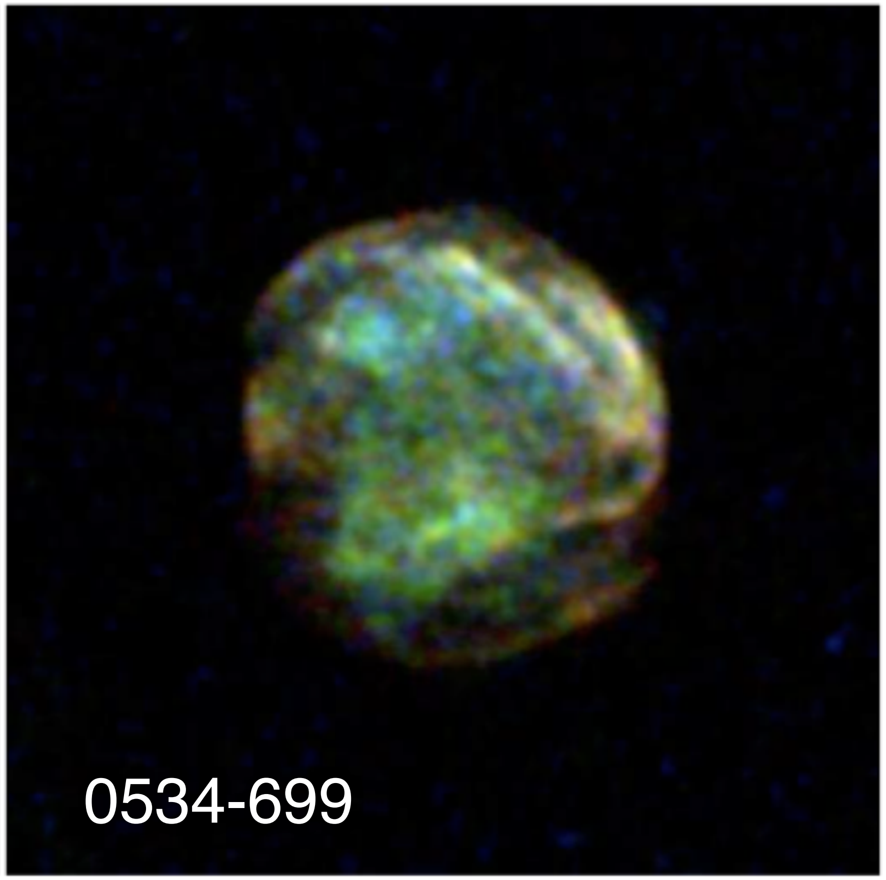
Type Ia supernova remnants


0509-675


0519-690


N103B


Dem L71


0534-699

Type Ia SNR in LMC

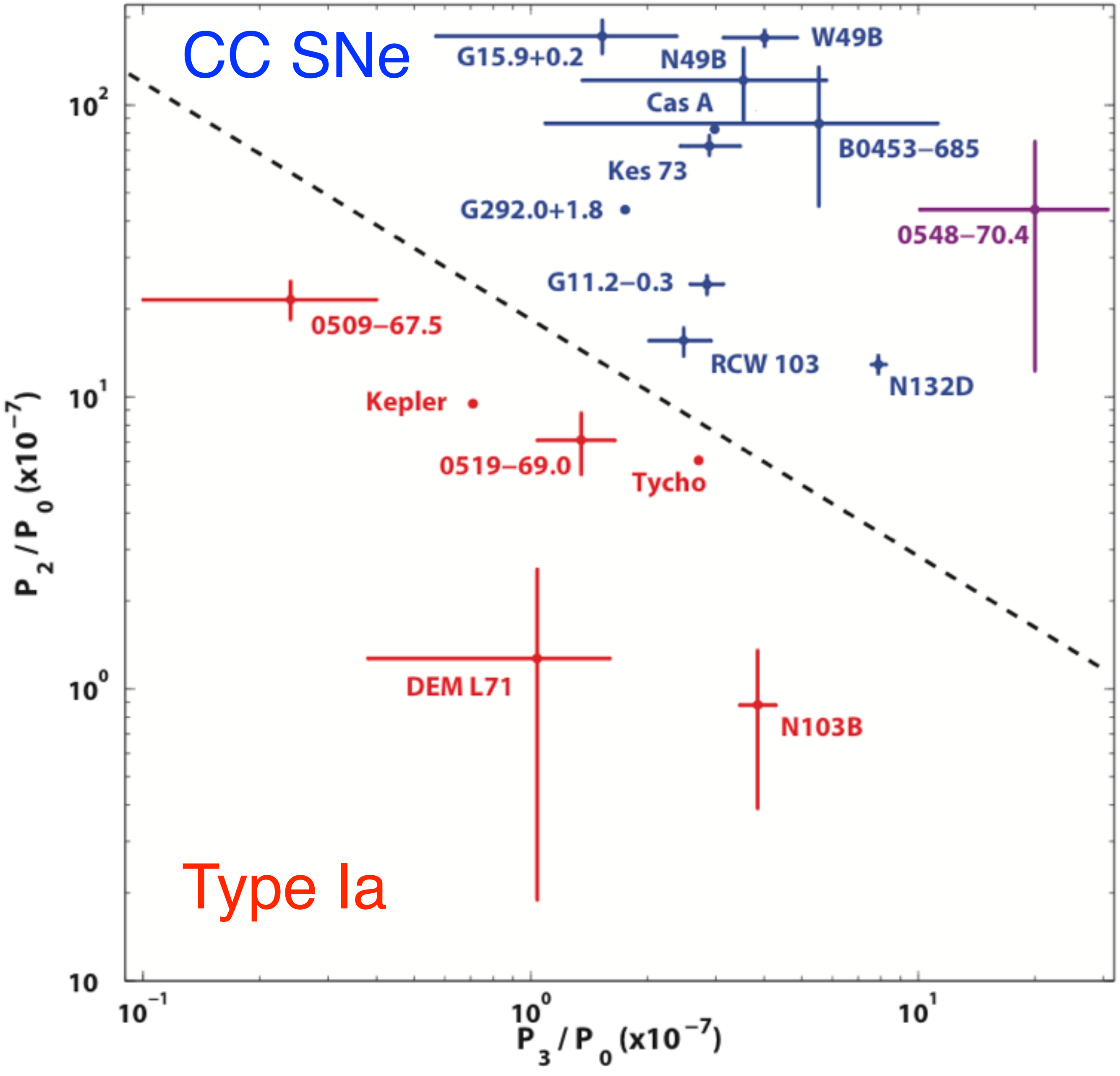
- Red: oxygen
- Green: Fe-L
- Blue: Mg/Si/S

- Iron in center
- With age more Fe gets shocked by reverse shock
- Light echo spectra exists for 0509

Type Ia vs Core Collapse SNe

- Apart from obvious differences in composition:
  - Type Ia are more regular stratified
  - Have a more regular morphology

2^{rd} moment (mirror symmetry)



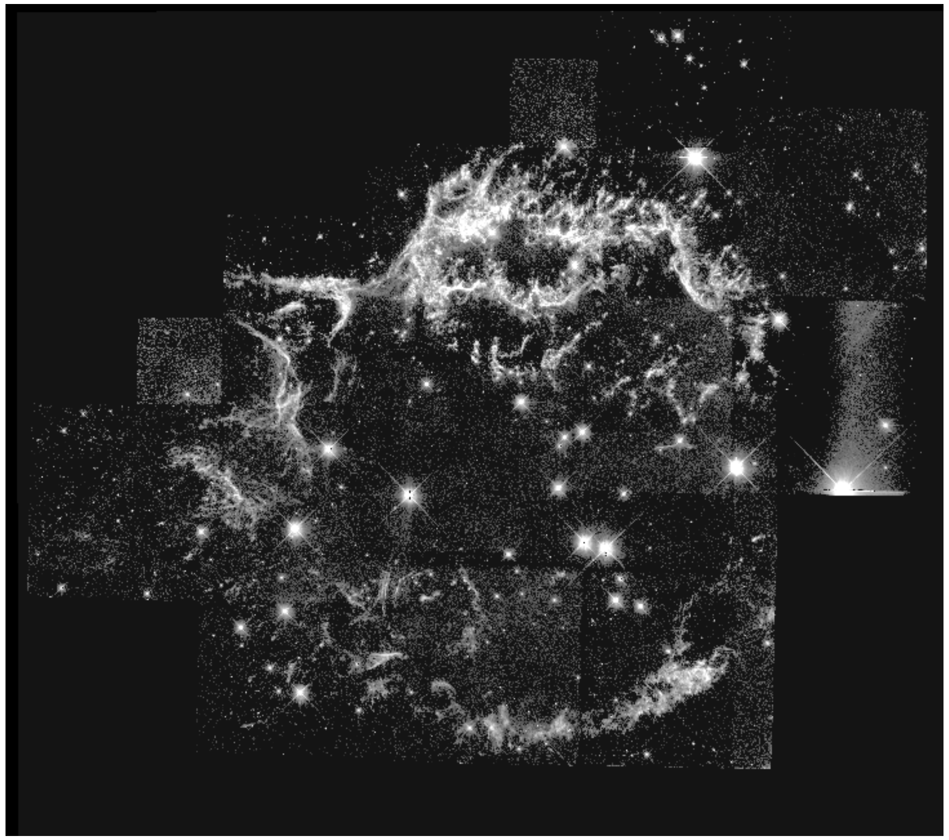
3^{rd} moment (asphericity)

Lopez et al. 2009/11

Non-X-ray emission

Type Ia: SNR0509-695

Hubble Hα + Chandra



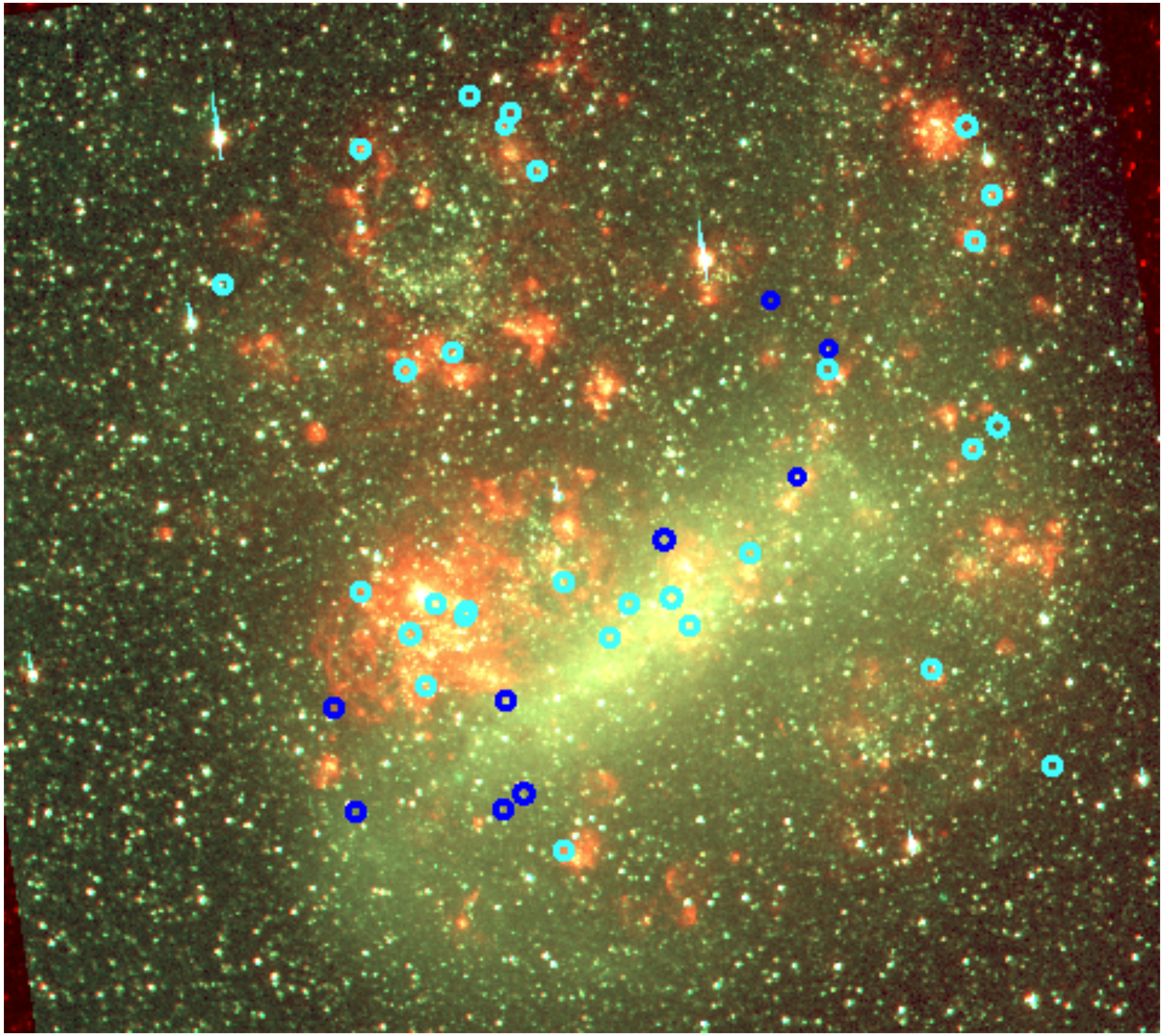
CC SNR: Cas A

Hubble Hα

- In general:
  - Type Ia have Hα associated with shock → partial neutral medium
  - CC have not → shock through fully ionised material
- Type Ia + partial neutral medium:

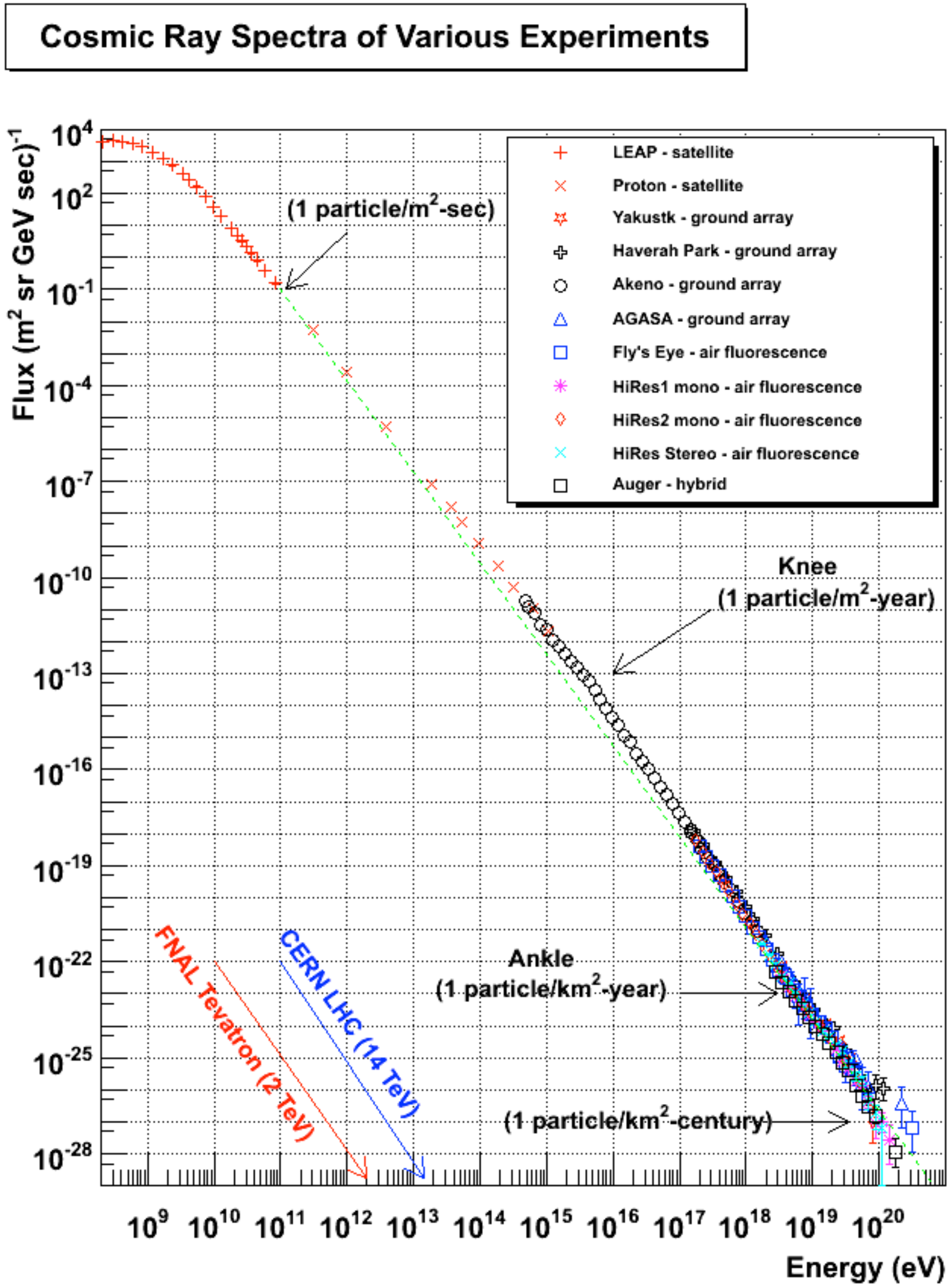
  ⇒*rules out supersoft sources as progenitor (progenitor not a source of strong UV emission)!!*

LMC SNR distribution



- Likely Type Ia SNRs: blue
- All other: cyan (may include Type Ia)
- Likely core collapse SNRs: associated with HII regions

Cosmic Rays



- Up to ~3x10^{18}eV of Galactic origin
- Galactic CRs: likely powered by supernovae (Baade & Zwicky), as they provide sufficient power
- The “Knee” (10^{15}eV): must be linked to a common property among Galactic accelerators
- Are particles mainly accelerated in supernova remnant phase?
- Alternatives:
  - -in SN phase, or <50 yr
  - -collective effects in superbubbles (Bykov, Parizot)

Why supernova (remnants) as sources?

- In normal spiral galaxies as the Milky Way: SNe most energetic sources
  - Cosmic rays remain in Galaxy for $t_{cr}\sim10^7$ yr
  - Steady state/homogeneity requires $t_{recur} << 10^7$ yr
  - SNe rate is 2-3 per century
  - SN explosion energy $E_{kin}=10^{51}$ erg
- SNe fulfil cosmic-ray energy requirements
  - Energy density CRs $u_{cr}\sim1$ eV/cm^3
  - Volume Galaxy: $V_{gal}=\pi R_{disk}^2(2z) \sim 3\times10^{11}$ pc^3 $\sim10^{67}$ cm^3
  - Power needed: $L=u_{cr}V_{gal}/t_{cr}=5\times10^{40}$ erg/s
  - SN power: $L_{SN}=10^{51}/t_{SN}= 6\times10^{41}$ erg/s

SNe provide enough power for cosmic rays if efficiency is ~10%

SNRs should be able to accelerate protons beyond 10^{15}eV

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

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

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

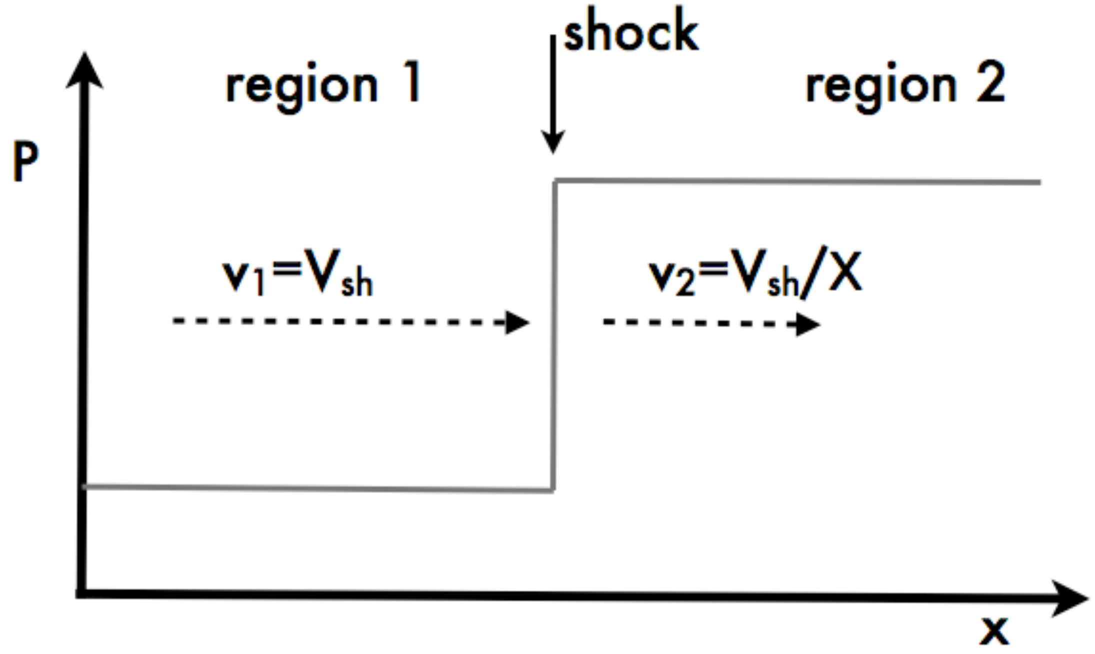
- For v≈1000 km/s, n=1cm^{-3} one finds for proton-proton

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

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

Supernova remnant shocks:

the Rankine-Hugionot relations



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

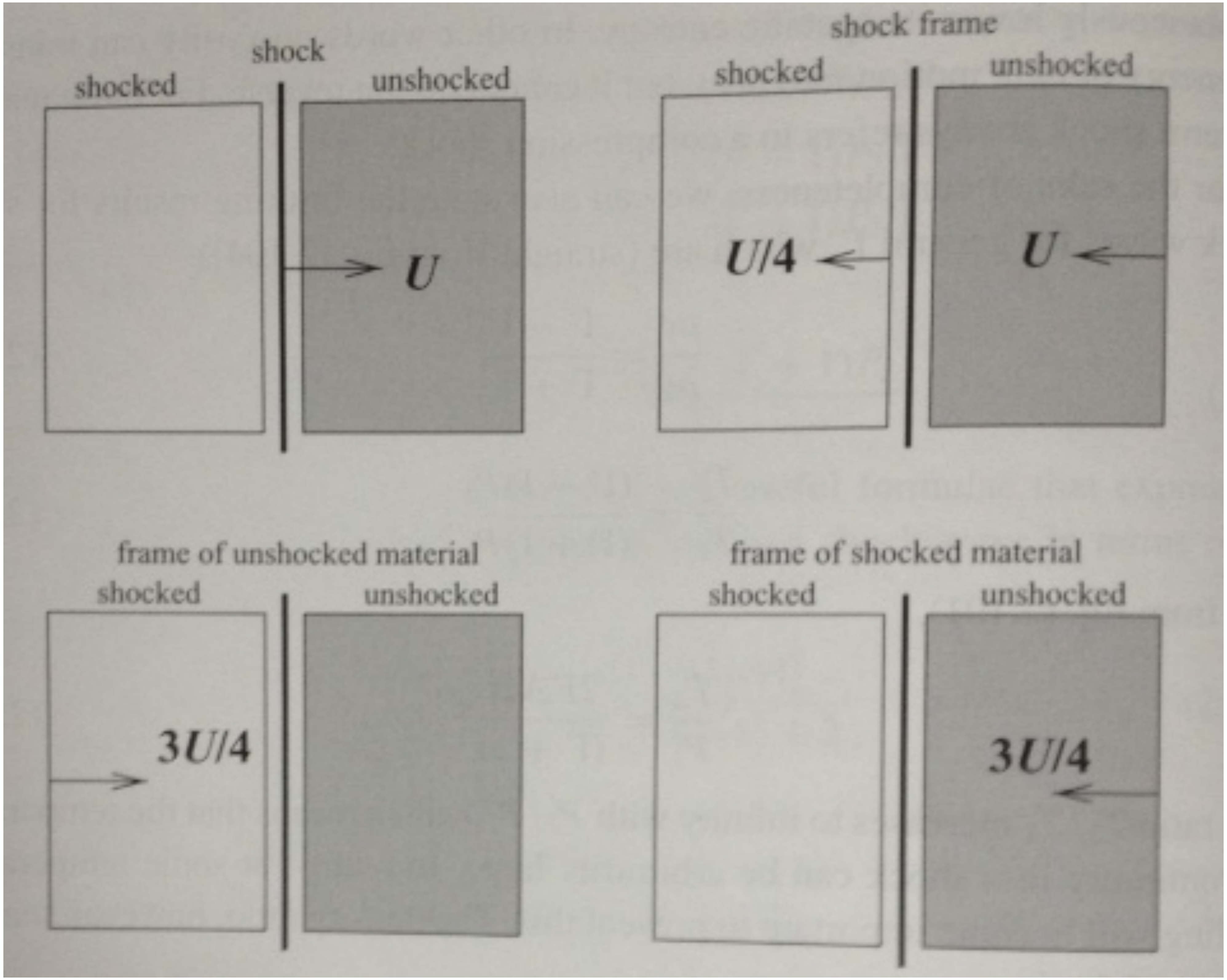
$$\rho_1 v_1 = \rho_2 v_2$$

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

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

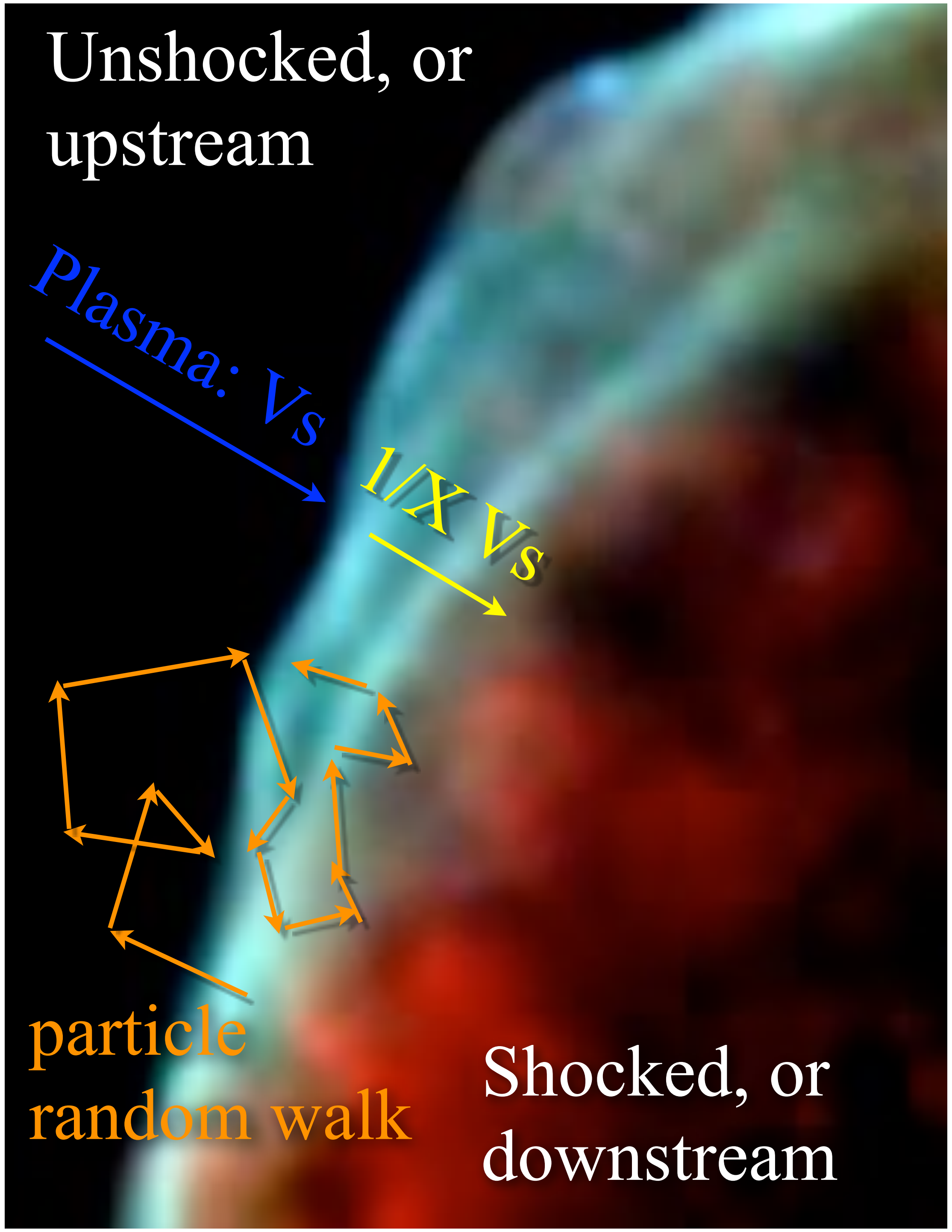
- Solutions for strong shocks:

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



shock
shocked
unshocked
U
shock frame
shocked
unshocked
U/4
U
frame of unshocked material
shocked
unshocked
3U/4
frame of shocked material
shocked
unshocked
3U/4

Diffusive shock acceleration theory



- Particles scatter elastically (B-field turbulence)
- Each shock crossing the particle increases its energy by a factor $\beta=1+v/c$
- After *j* crossings, a particle with energy E_0 will have an energy $E=E_0\beta^j$
- Resulting spectrum (e.g. Bell 1978):

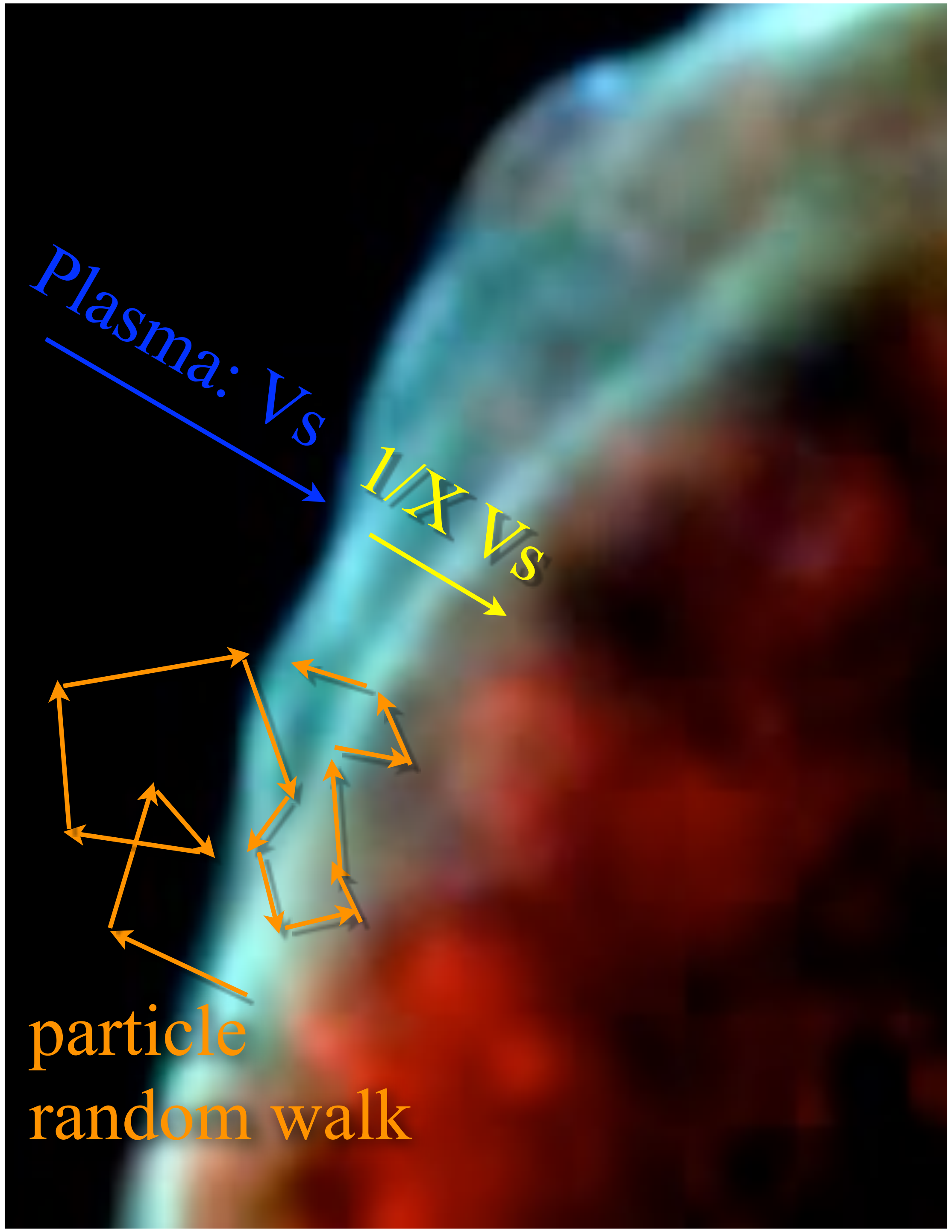
$$dN/dE = C\ E^{-(1+3/(X-1))}$$

X shock compression ratio,

$X=4 \rightarrow dN/dE = C\ E^{-2}$

Axford et al. , Blanford & Ostriker, Krymsky, and Bell (all 1977-78)

Diffusive shock acceleration theory



- Smaller mean free path, smaller D, faster acceleration
- Bohm diffusion:

$$\lambda_{\rm mfp} = r_{\rm gyro}$$
$$D = \eta \lambda_{\rm mfp} \frac{1}{3} c = \eta \frac{cE}{3eB}$$

Acceleration of a 100 keV proton to 10^{15} keV by a V_s=5000 km s^{-1} shock requires 1400 crossings

Protons and nuclei can be accelerated to higher energies than the lighter electrons, because the loose less energy to synchrotron radiation

(X-ray) synchrotron emission from SNRs

First evidence for particle acceleration

- Since the 1950-ies SNRs associated with bright radio synchrotron sources
- Synchrotron emission: relativistic electrons deflected in magnetic fields
- Characteristic frequency

$$\nu_{\rm ch} = 46 \frac{B_\perp}{10\ \mu{\rm G}} \left(\frac{E}{1\,{\rm GeV}}\right)^2 {\rm MHz}$$

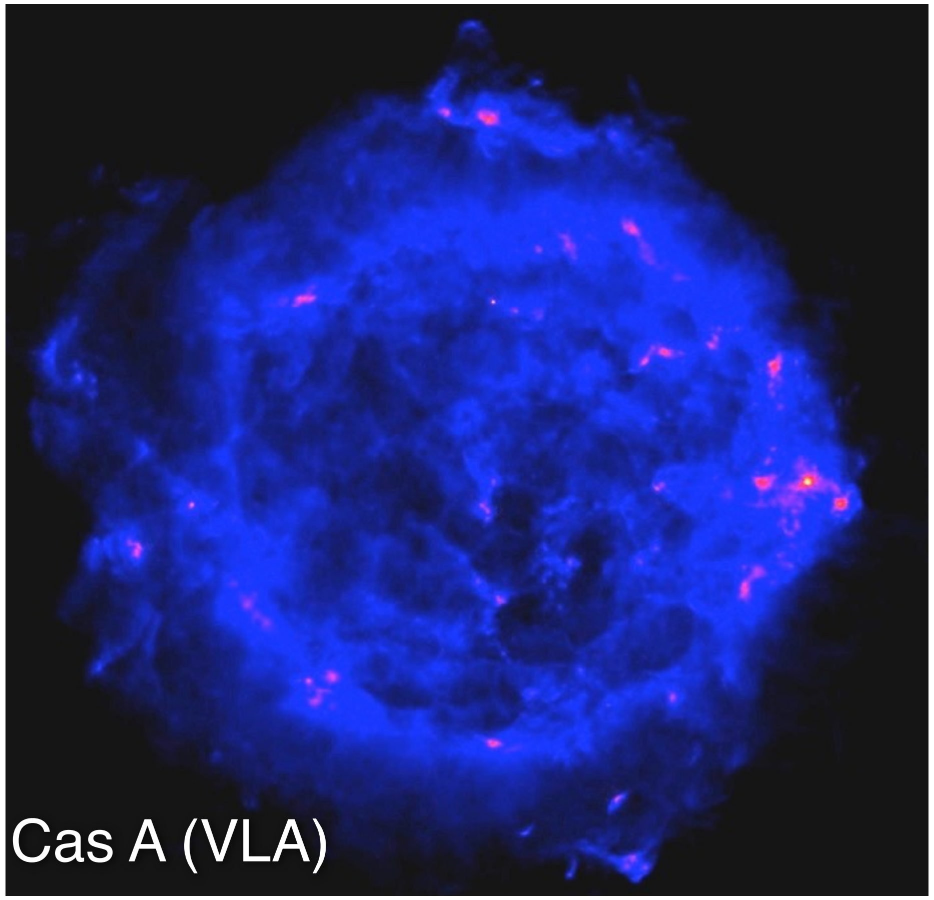
- Radio synchrotron ➔ electrons with GeV energies
- Brightness: number of rel. electrons + B-field
- For power law electron distribution

$$N_{\rm e} \propto KE^{-q},\ I_\nu \propto KB^{(q+1)/2}\nu^{-(q-1)/2}$$

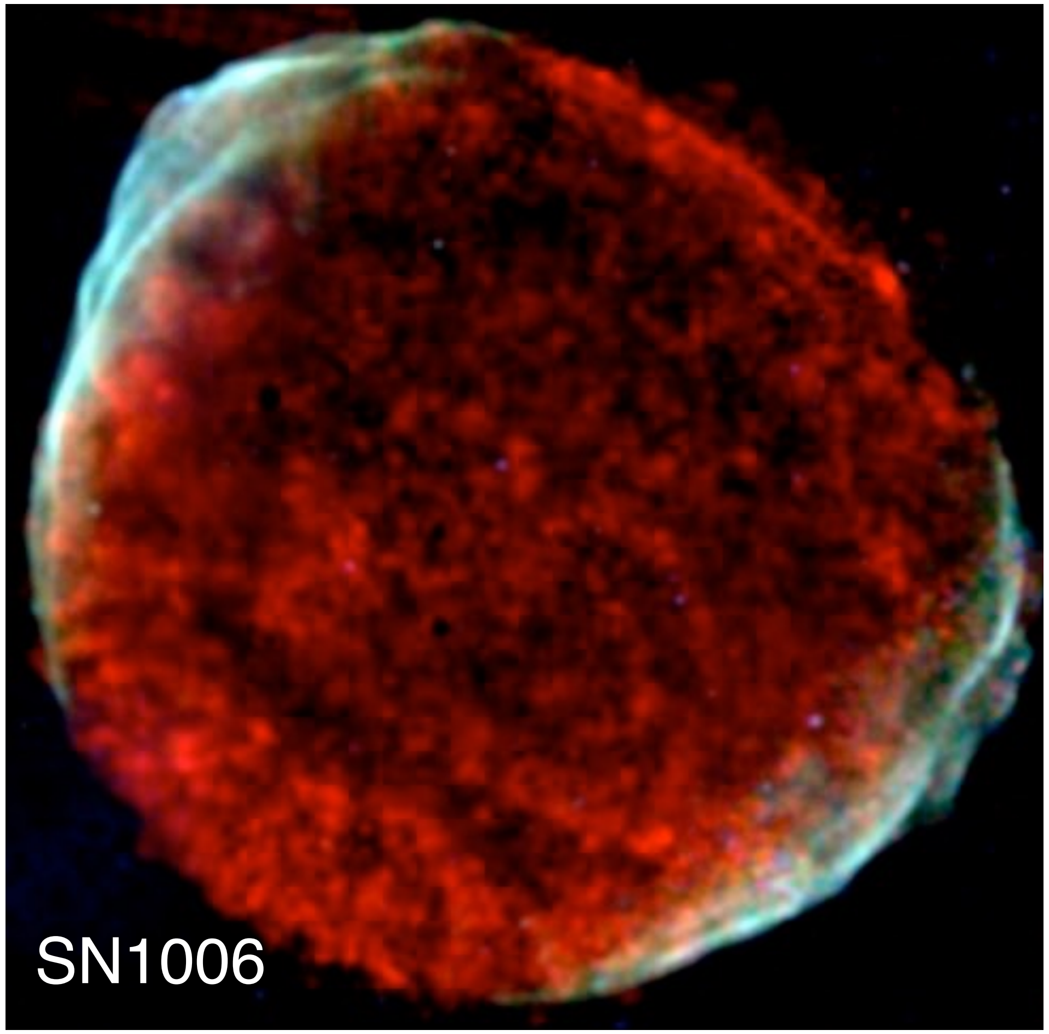
- Relation electron and radio spectral index:

$$\alpha = (q-1)/2$$

- Typical young SNRs in Radio: α=0.6 ➔ q= 2.2


Cas A (VLA)

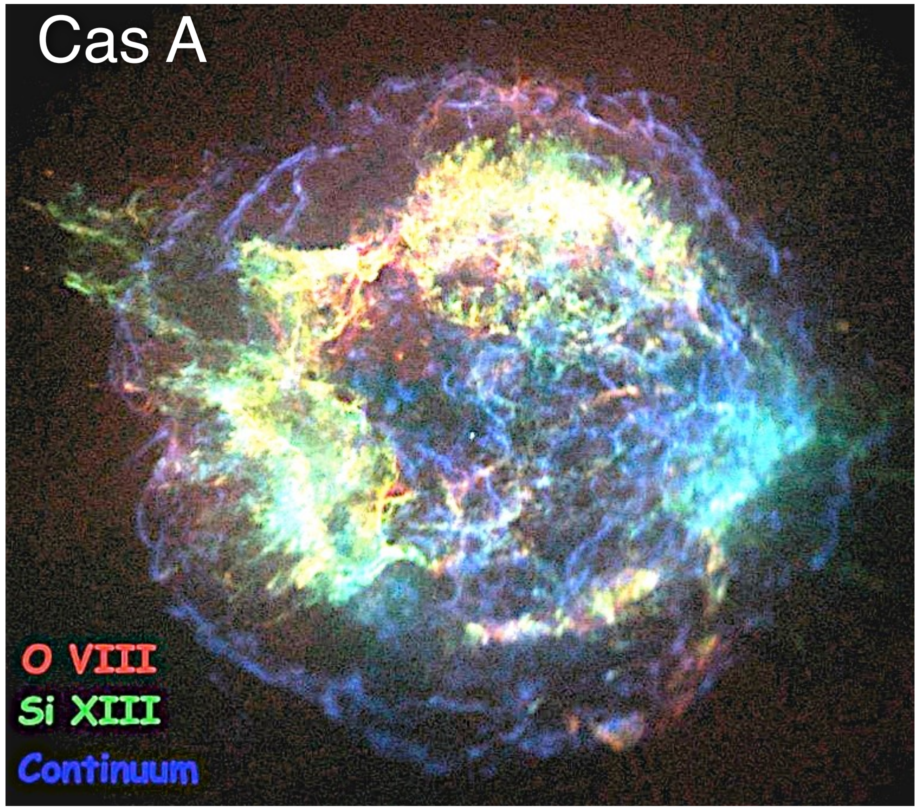
X-ray synchrotron emission

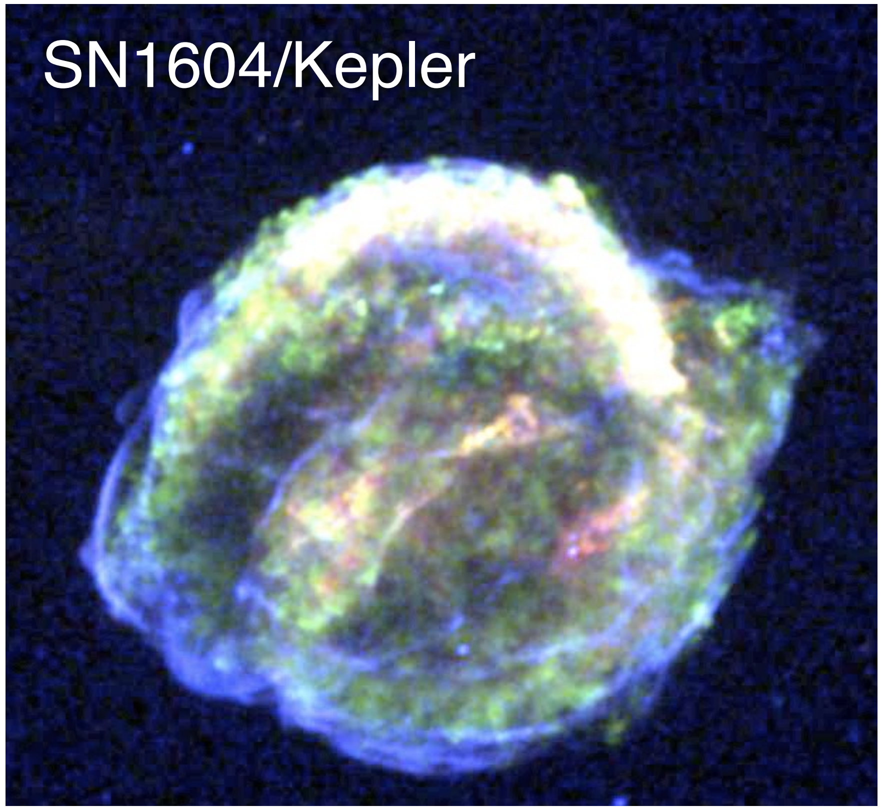


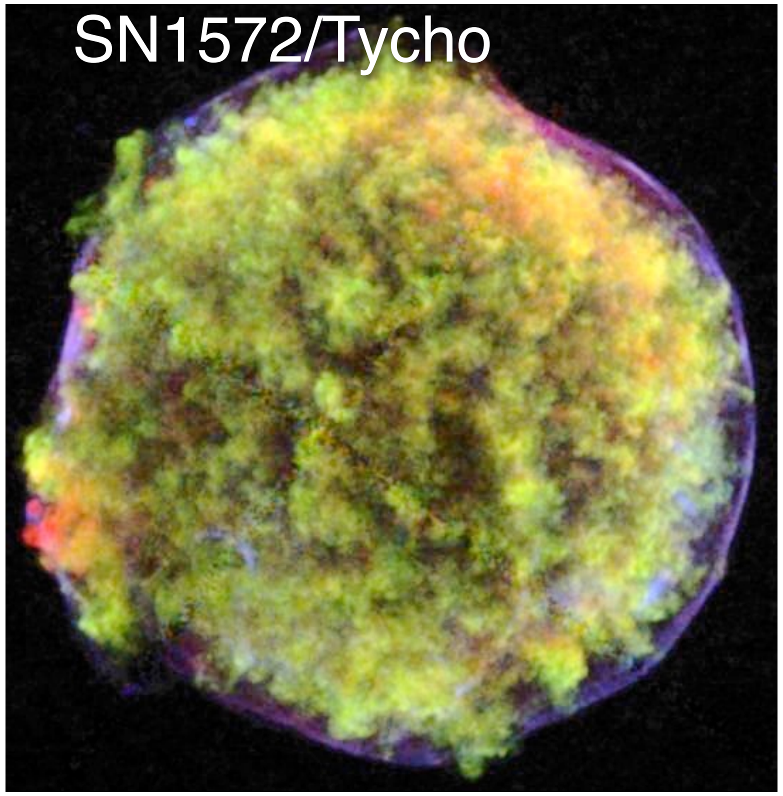
- In 1995 ASCA showed that the X-ray emission from SN 1006 was a combination of thermal X-ray and synchrotron radiation (Koyama et al. 1995)
- X-ray synchrotron emission implies presence of 10-100 TeV electrons!!

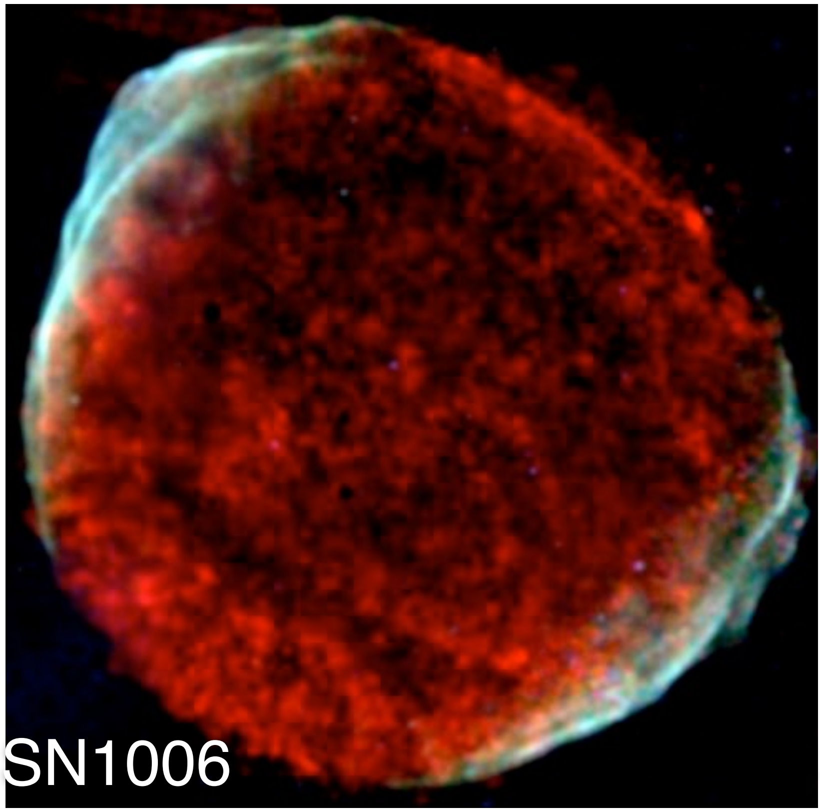
$$h\nu_{\rm ch} = 13.9\left(\frac{B_\perp}{100\,\mu{\rm G}}\right)\left(\frac{E}{100\,{\rm TeV}}\right)^2\ {\rm keV}$$

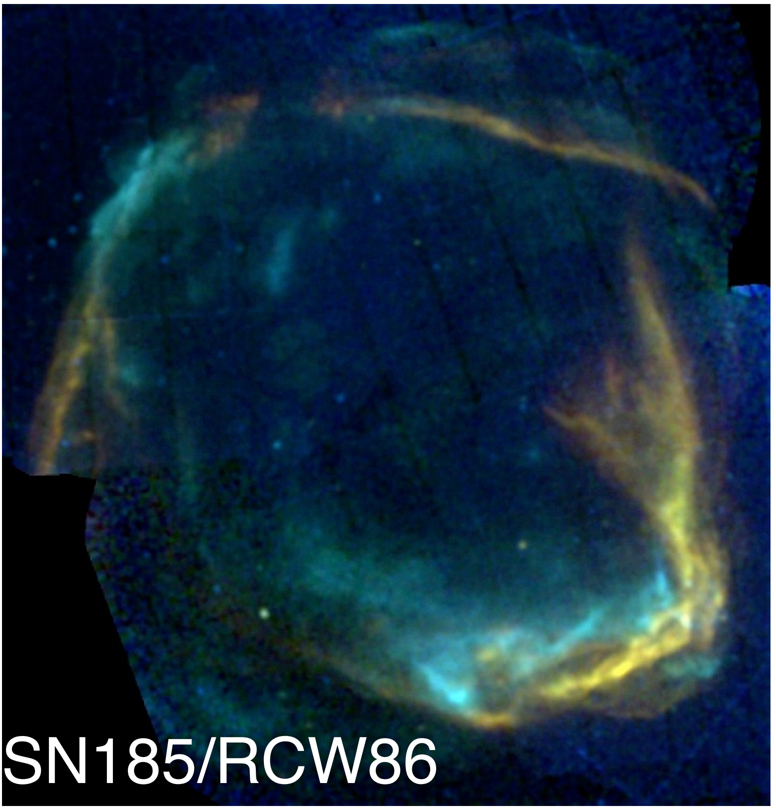
X-ray synchrotron from young SNRs

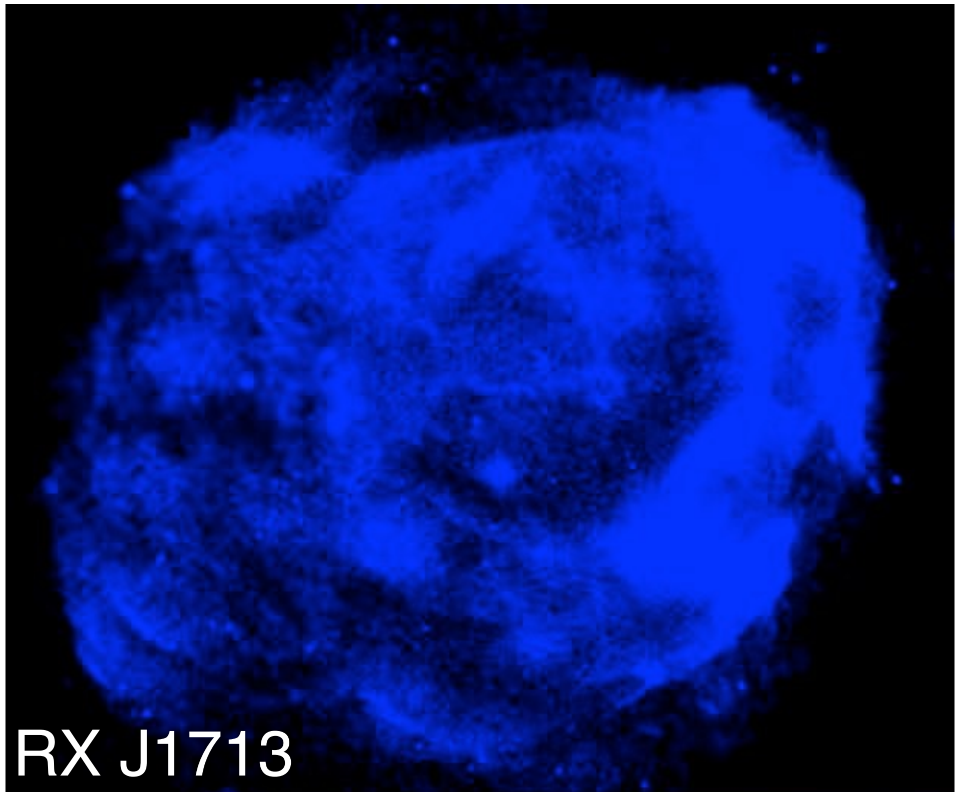

Cas A


SN1604/Kepler


SN1572/Tycho


SN1006


SN185/RCW86


RX J1713

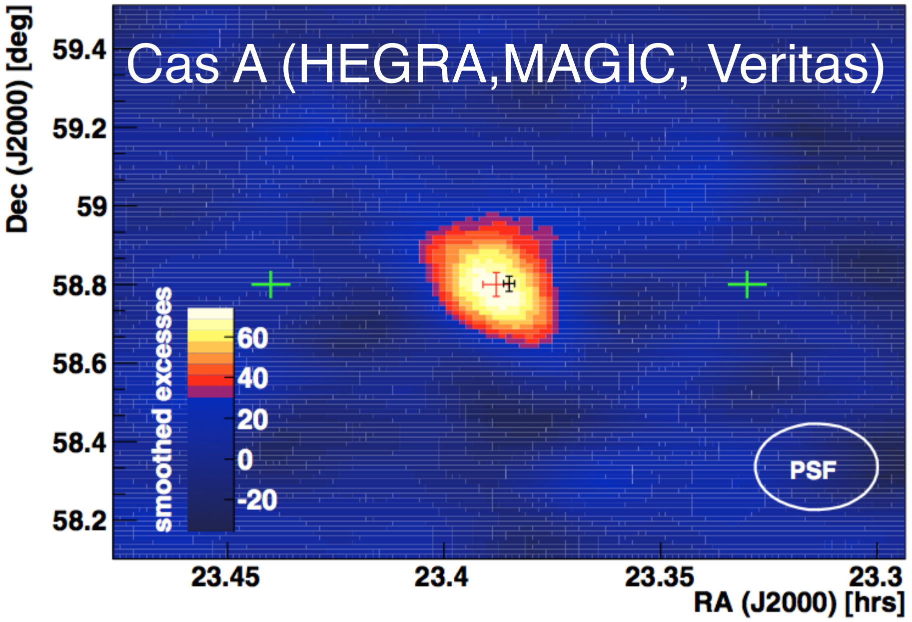
Implications

- For B=10-100 μG: presence of 10^{13}-10^{14} eV electrons
- Loss times are:

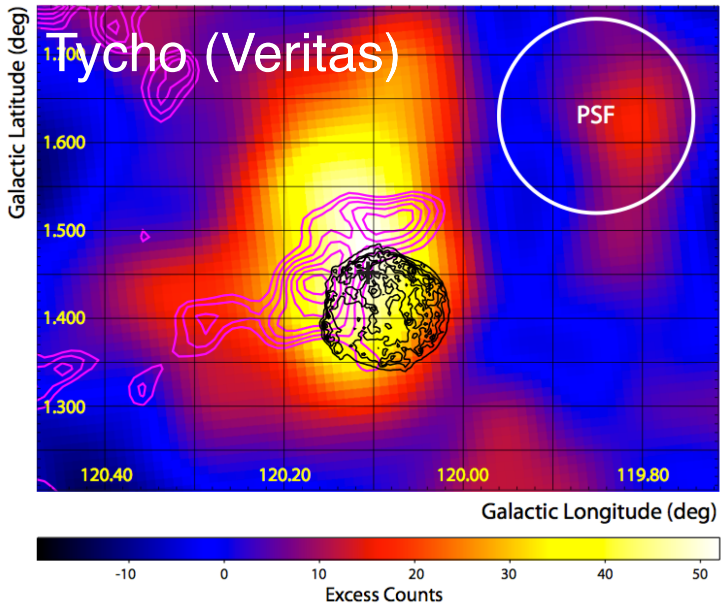
$$\tau_{\rm syn} = \frac{E}{dE/dt} = 12.5 \left(\frac{E}{100 \ {\rm TeV}}\right)^{-1} \left(\frac{B_{\rm eff}}{100\mu{\rm G}}\right)^{-2} \ {\rm yr}.$$

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

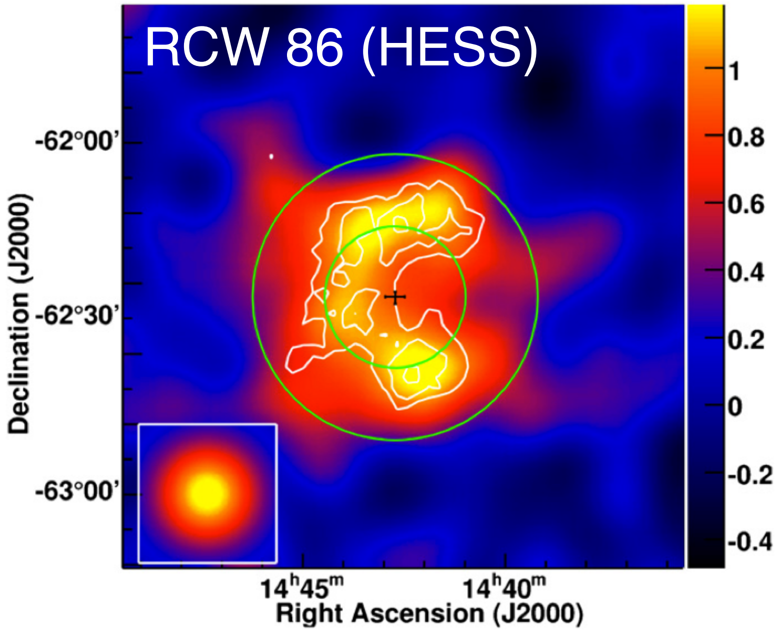
Young SNRs detect in TeV gamma-rays



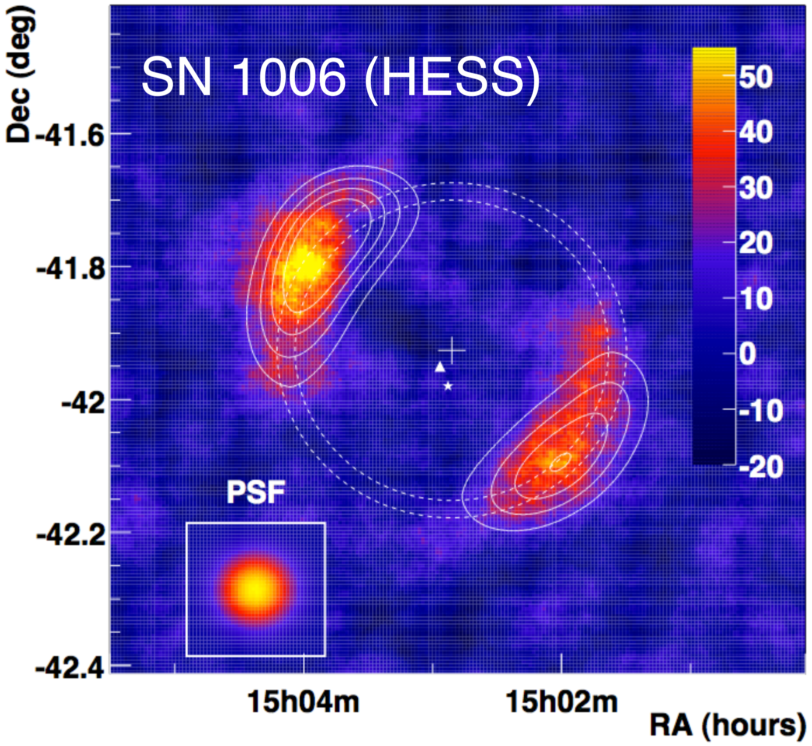
Cas A (HEGRA,MAGIC, Veritas)



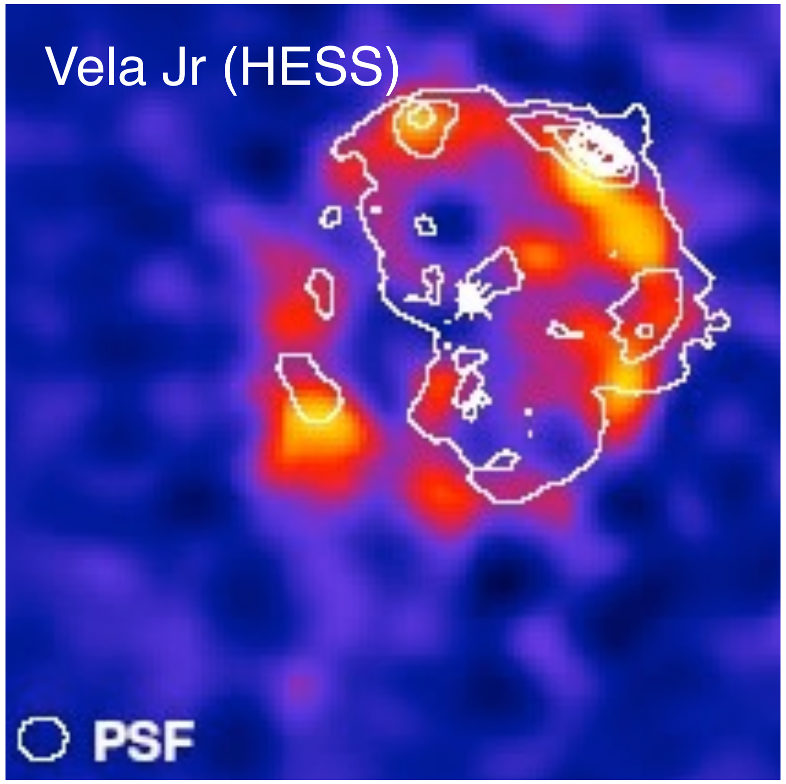
Tycho (Veritas)



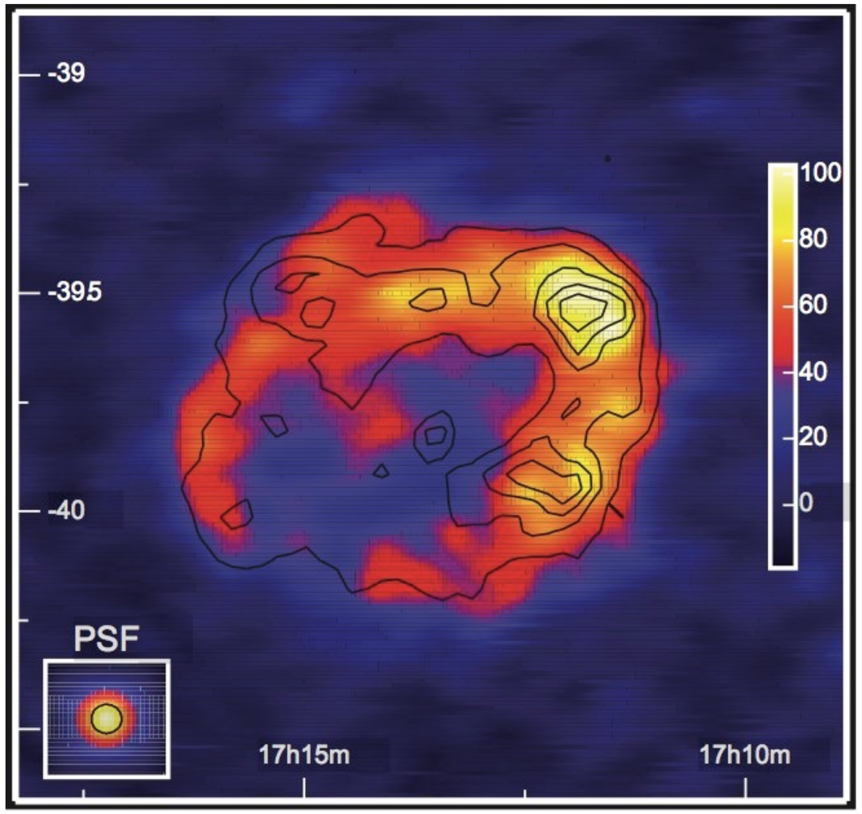
RCW 86 (HESS)



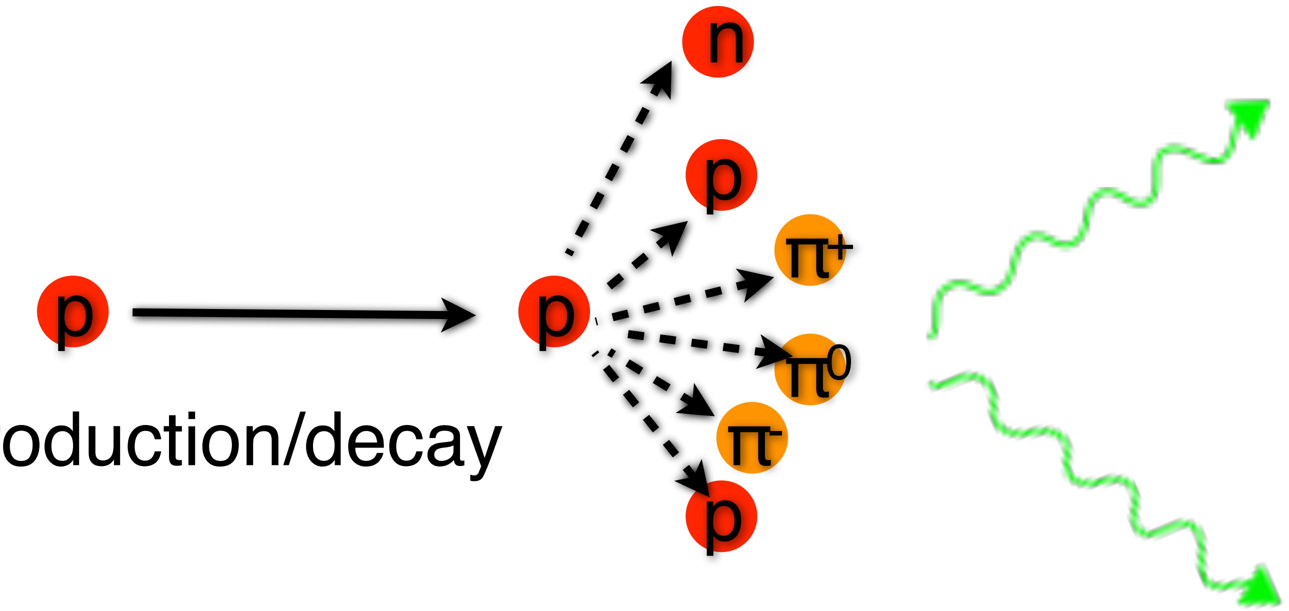
SN 1006 (HESS)



Vela Jr (HESS)



Gamma-ray emission processes



Neutral pion production/decay

$$\begin{aligned}
\pi^0 &\rightarrow && 2\gamma \\
\pi^+ &\rightarrow && \mu^+ + \nu_\mu \\
& && \mu^+ \rightarrow e^+ + \nu_\mathrm{e} + \bar{\nu}_\mu \\
\pi^- &\rightarrow && \mu^- + \bar{\nu}_\mu \\
& && \mu^- \rightarrow e^- + \bar{\nu}_\mathrm{e} + \nu_\mu
\end{aligned}$$

if pion decay, then 10^{49} erg in high energy protons (compared to 10^{51} erg in the kinetic energy of the expansion of the remnant or 10^{53} erg of binding energy released in the formation of a neutron star)

Summary

- Supernovae come in two very different types:
  - Core collapse SNe → leave neutron star, oxygen rich
  - Thermonuclear/Type Ia → exploding CO white dwarf
    - Model uncertain: single- or double degenerate?
      - single degenerate model has problems
- Supernova remnants phases:
  - 1. Ejecta dominated;
  - 2. Adiabatic phase;
  - 3. Momentum conservation phase;
  - 4. Disappearance phase
    - Simple model may not be sufficient: effect of stellar wind bubbles
- Shock heating process:
  - Shocks are collisionless
- Thermal X-ray emission from plasmas with $kT > \sim 10^6$ K (0.1 keV)

Summary (continued)

- Type Ia can be distinguished from core-collapse SNRs:
  - Type Ia: iron-rich; CC: oxygen-rich
  - Type Ia: Hα emission
  - Type Ia: layered structure; CC: chaotic
  - Type Ia: symmetric morphology
- For core collapse SNRs: evidence for asymmetric explosions
  - Jets in Cas A
  - Donut like shapes
- Cosmic ray spectrum near power law over 12 orders of magnitude in energy
  - most like origin in supernovae (other sources not energetic enough)
  - requires SNRs to accelerate up to $3\text{x}10^{15}$eV (proton)
  - requires that SNR put ~10% of kinetic energy (10^{50} erg) in cosmic rays
    - diffusive shock acceleration (1st order Fermi)
- Radio synchrotron: oldest evidence for particle (electron) acceleration in SNRs
- X-ray synchrotron: identified since 1995 (SN1006 by ASCA)
- X-ray synchrotron:
  - electron acceleration up to 10-100 TeV
  - location @ shock + fast loss times -> shocks are responsible for acceleration
- Cherenkov Telescopes → detection of TeV gamma-rays from SNRs