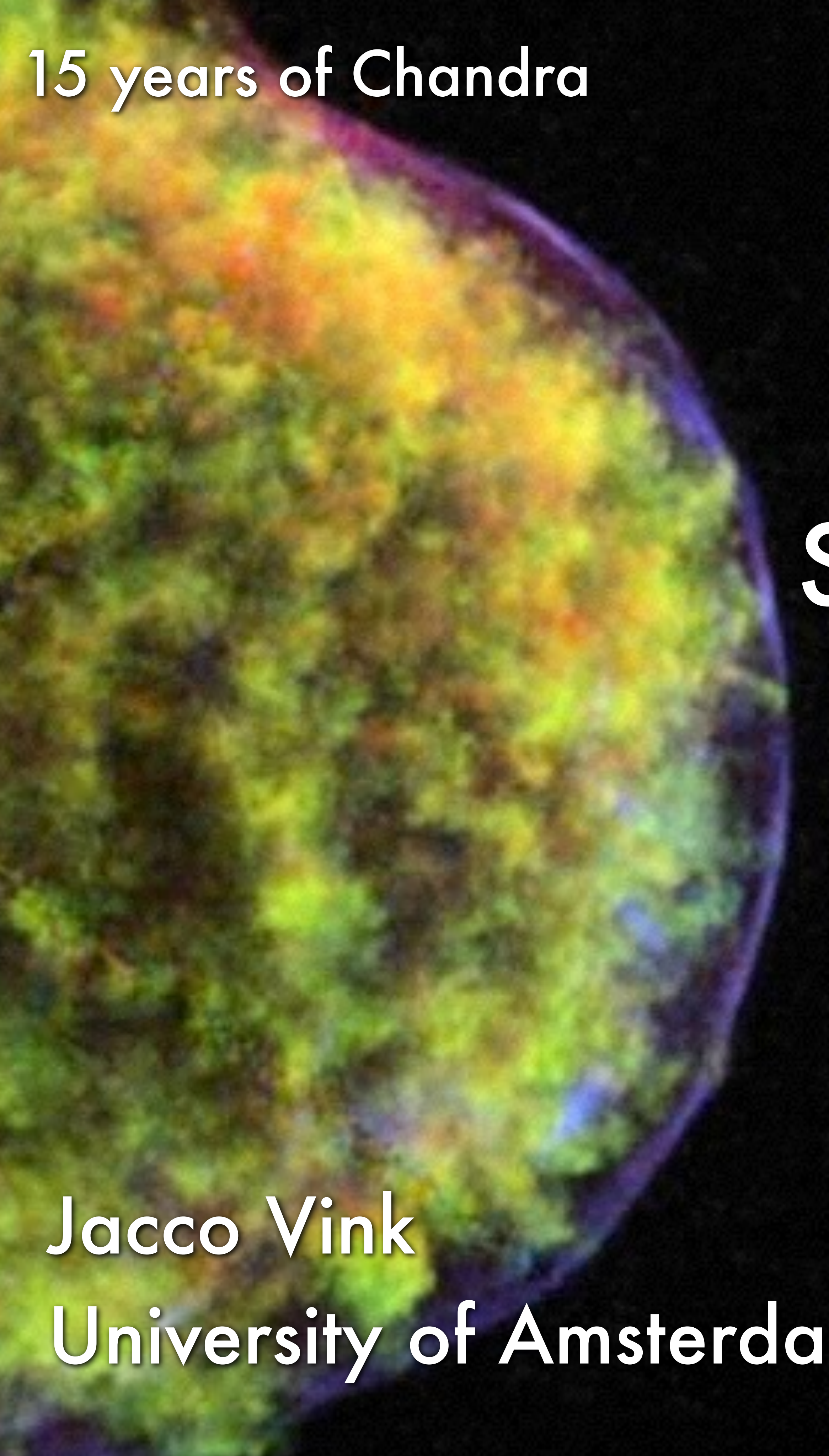
15 years of Chandra

GRAPPA

GRavitation AstroParticle Physics Amsterdam

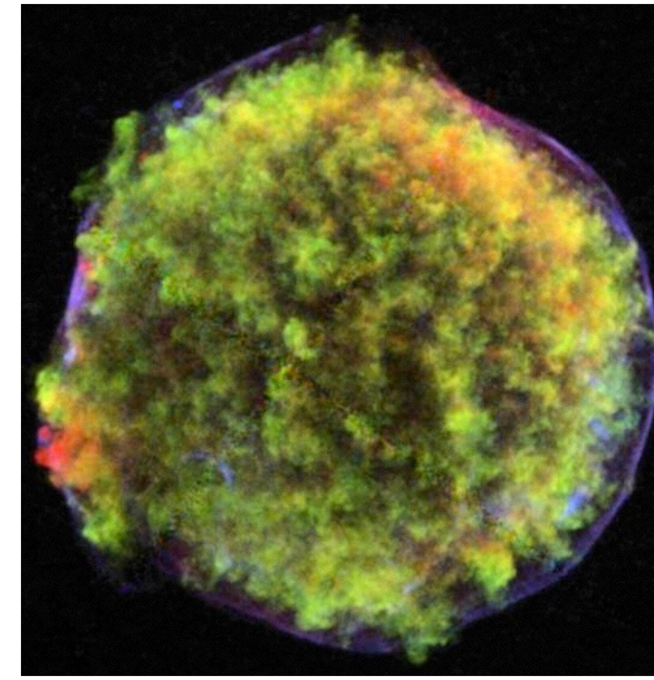


# X-ray views of Supernova Remnants and Cosmic Rays

Jacco Vink

University of Amsterdam

# Why study supernova remnants?



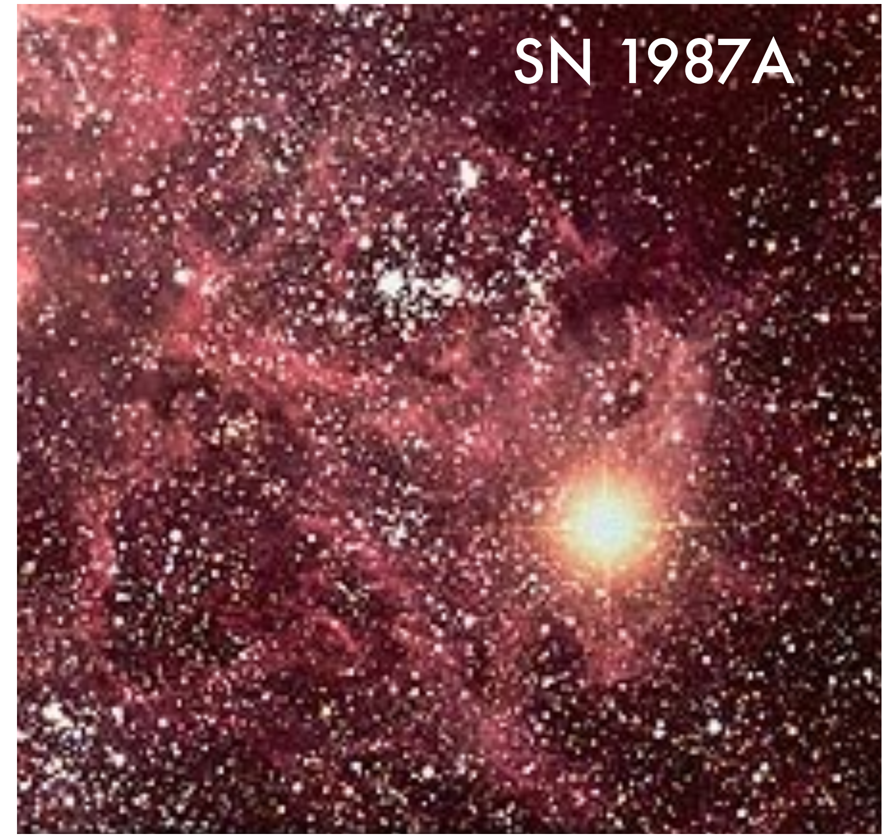
- A better understanding of the (local) supernova population

- Study the supernova properties
  - Composition → type, explosion mechanisms
  - Ejecta distribution/dynamics → explosion mechanisms
  - Circumstellar medium interactions → progenitor properties

- Study physics of supernova remnants
  - SNRs probably dominant source of *cosmic rays* → *acceleration properties*
  - Non-equilibrium plasma's → electron/ion temperatures, non-equilibrium ionization

See Vink, 2012, A&A Rev. for a review

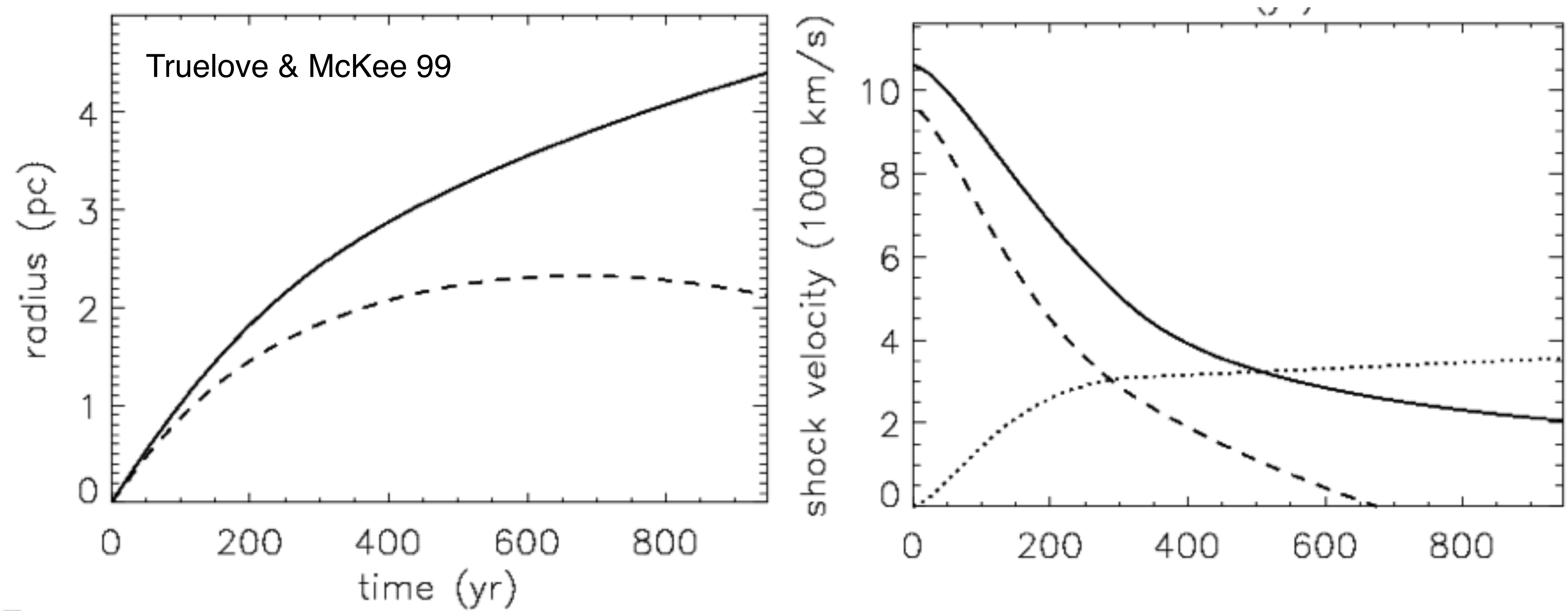
# Supernova classification




- Core collapse supernovae (Type II, Ib/c,..)
  - Progenitor: Massive star (>8$M_{sun}$)
  - Energy source: gravitational collapse (>$10^{53}$erg)
  - Kinetic energy: ~$10^{51}$ erg
  - Ejecta mass > 4 $M_{sun}$
  - Neutron star (or BH)

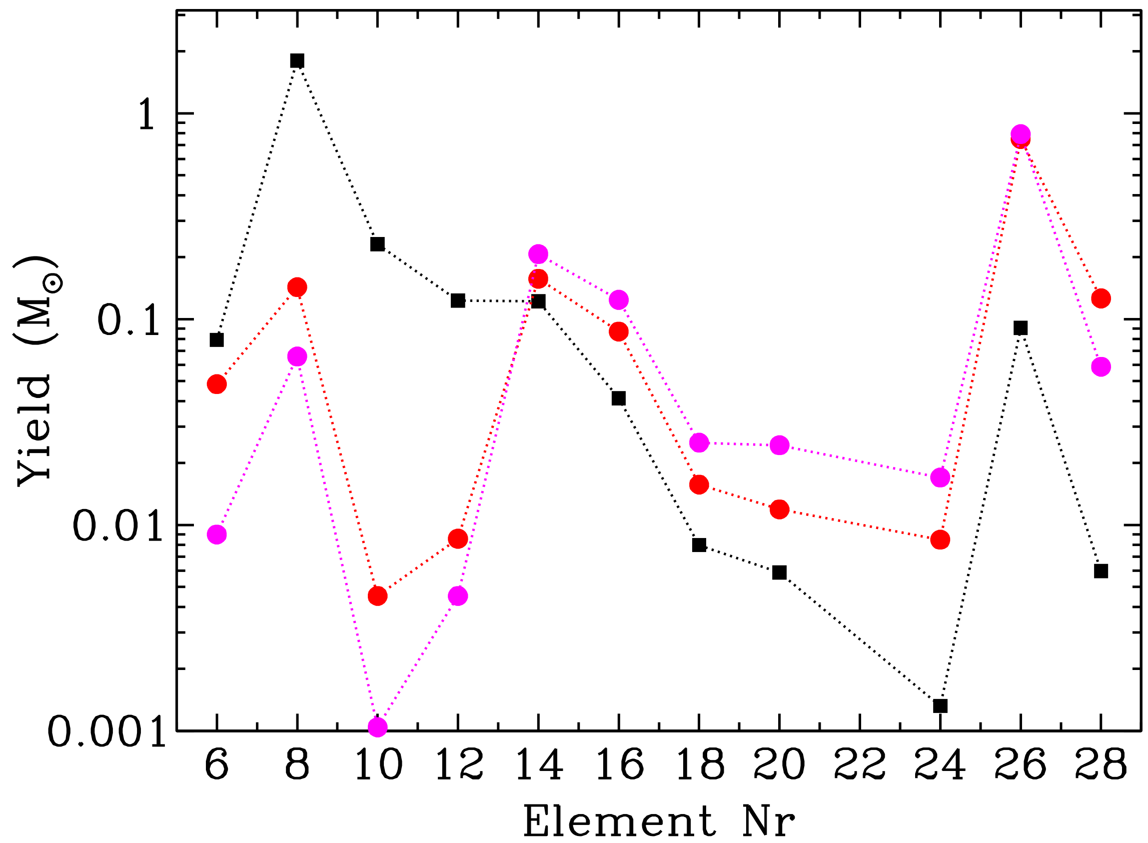
- Thermonuclear supernovae (Type Ia)
  - Progenitor: accreting CO white dwarf, or merging white dwarfs
  - Energy source: nuclear fusion (C/O → Fe-group)
  - Kinetic energy: 1.2x$10^{51}$erg
  - Ejecta mass ~1.4 $M_{sun}$
  - Total disruption of star

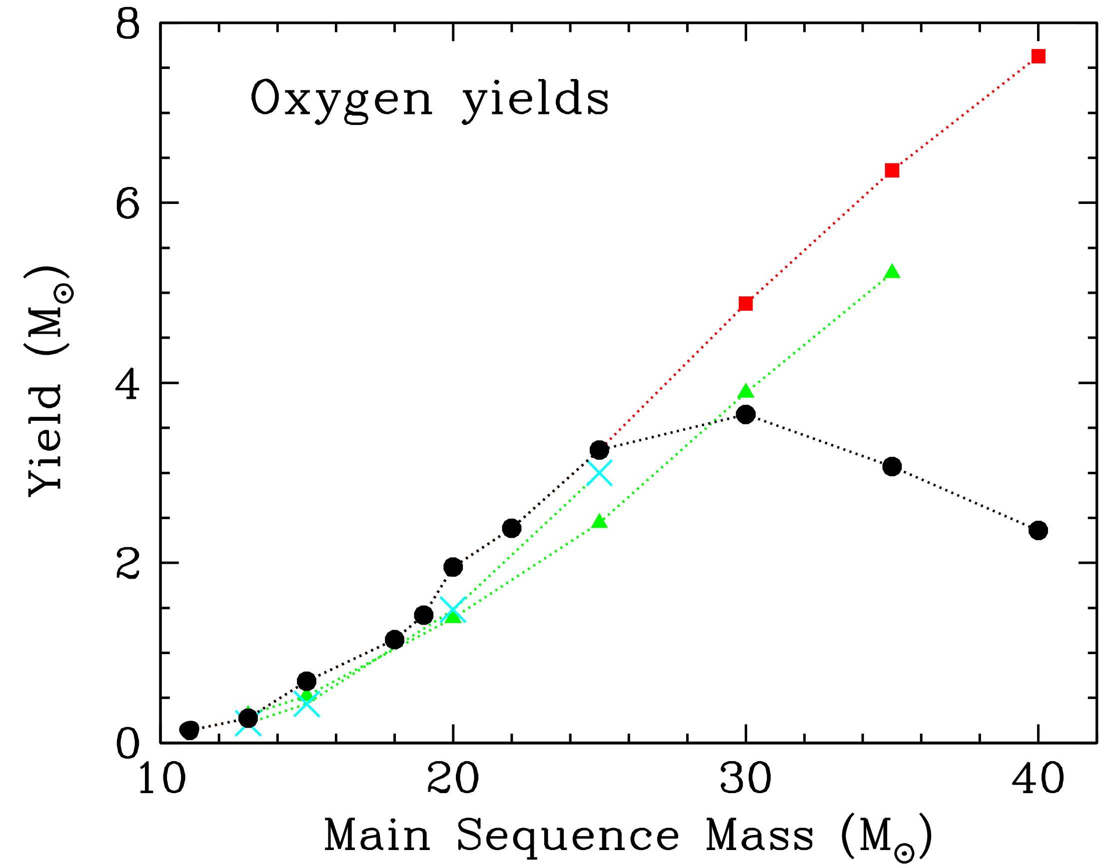
# Dynamics of supernova remnants




- Characterise by *expansion parameter* m: $R \propto t^m$, $m=(R/V_s)/t$
- Forward shock:
  - Ploughs ISM/CSM
  - Evolves from m≈0.8 to m≈ 0.4 (Sedov) to 0.25 (snow-plough phase)
    Deviations: non-uniform ISM
- Reverse shock:
  - Shock-heats the ejecta
  - Initial shock velocity slow ($|V_{rs}-V_{ej}|$), later $|V_{rs}-V_{ej}|>V_{fs}$

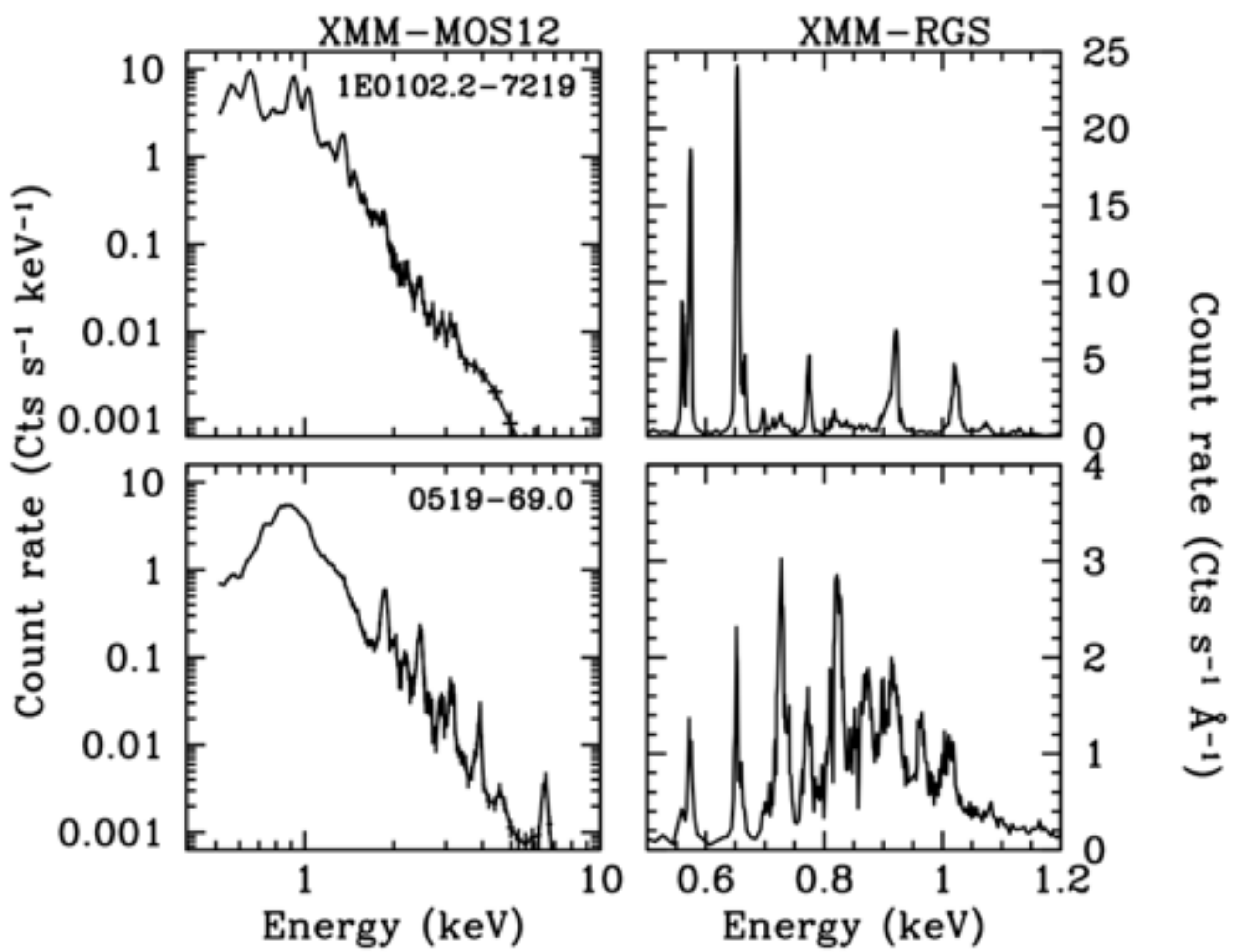
# The nucleosynthesis yields of supernova

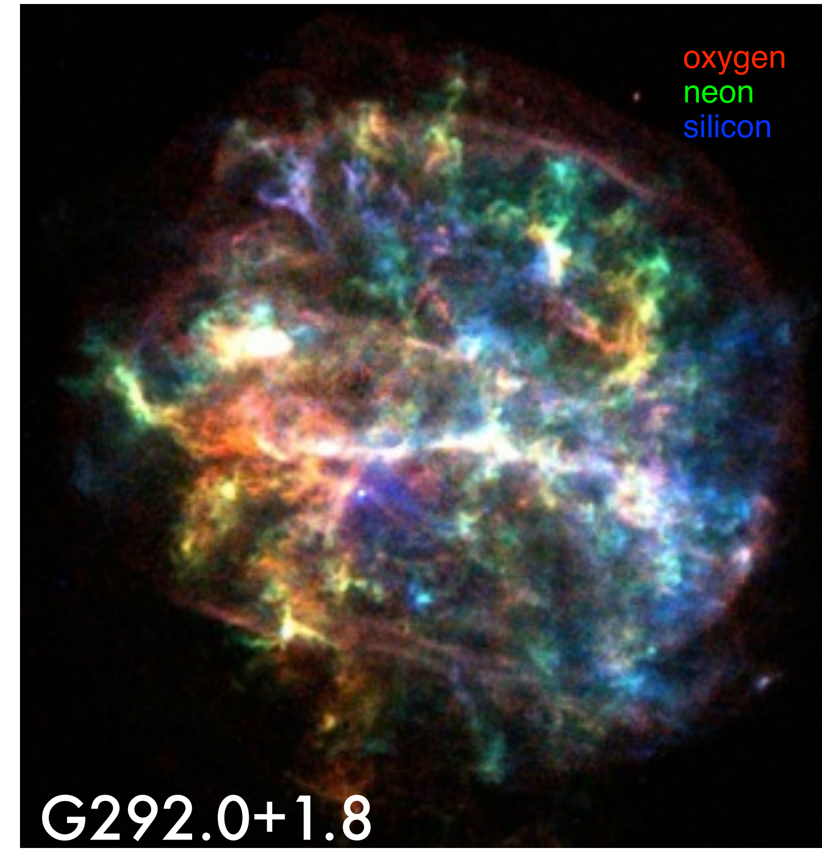


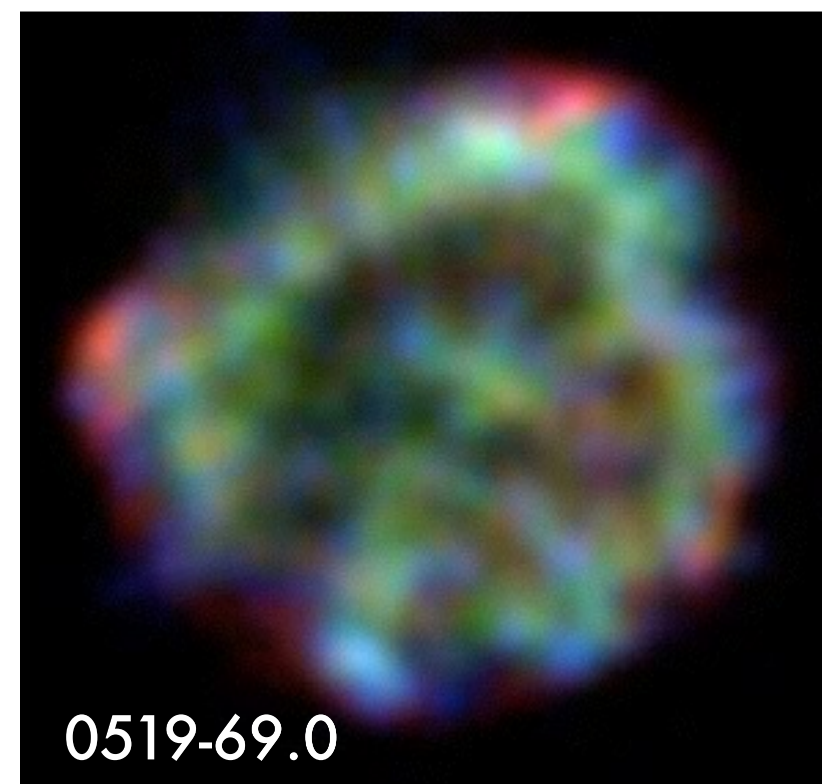




- Core collapse SNe:
  - oxygen-, neon-, magnesium-rich
  - oxygen mass proportional to main sequence mass
  - inner regions some iron (0.01-0.1 $M_{sun}$)
- Thermonuclear explosions:
  - intermediate mass elements (Si, S, Ar) and *iron-group*
  - Fe-mass: 0.5-1.2 $M_{sun}$
  - iron from decay of radio-active nickel-56

# Typing supernova remnants spectroscopically



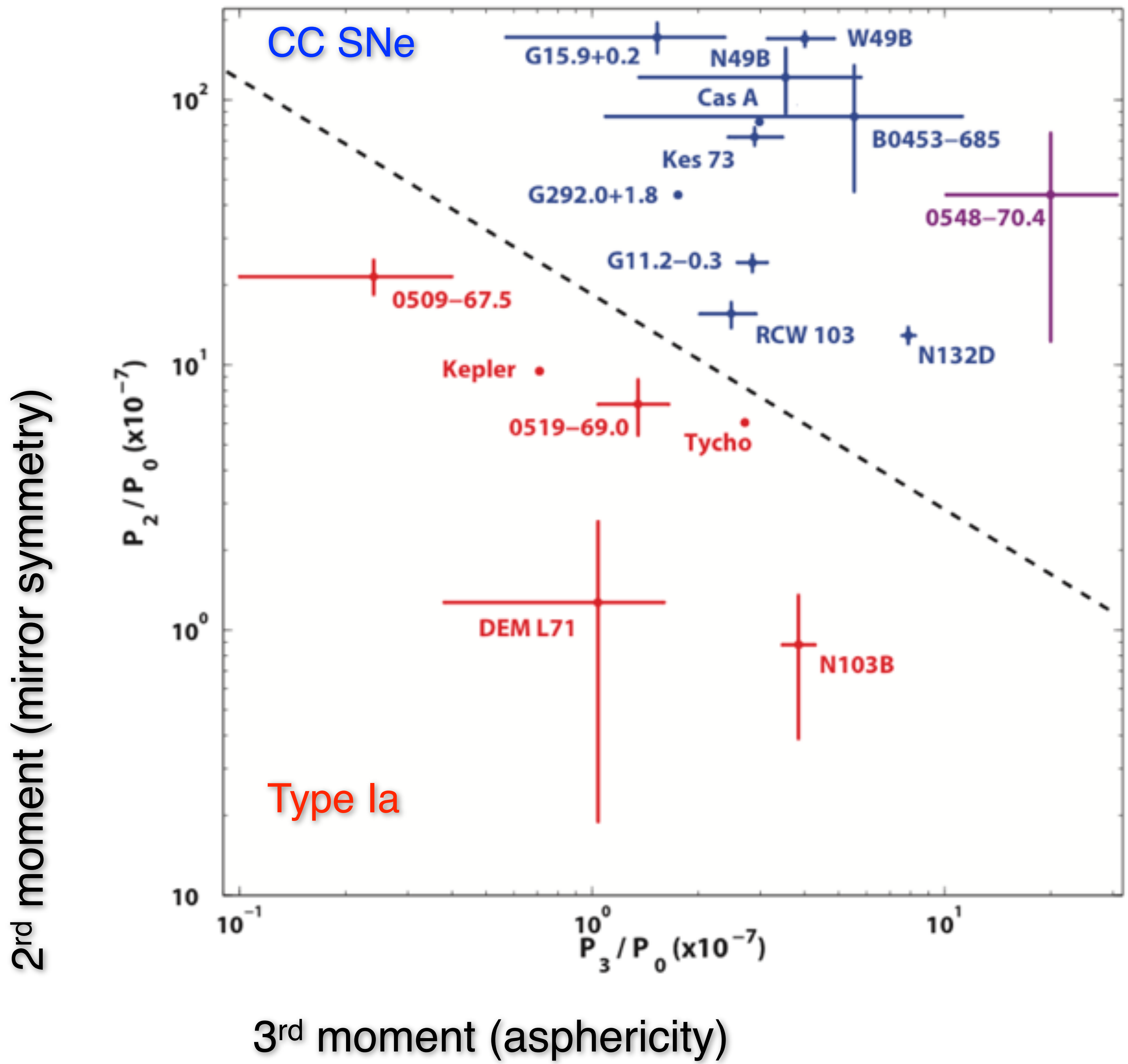




- Core collapse SNRs are rich in O, Ne, Mg
- Core collapse SNR appear irregular

- Type Ia SNRs are *iron-rich*
- Type Ia SNRs appear more regular/structured

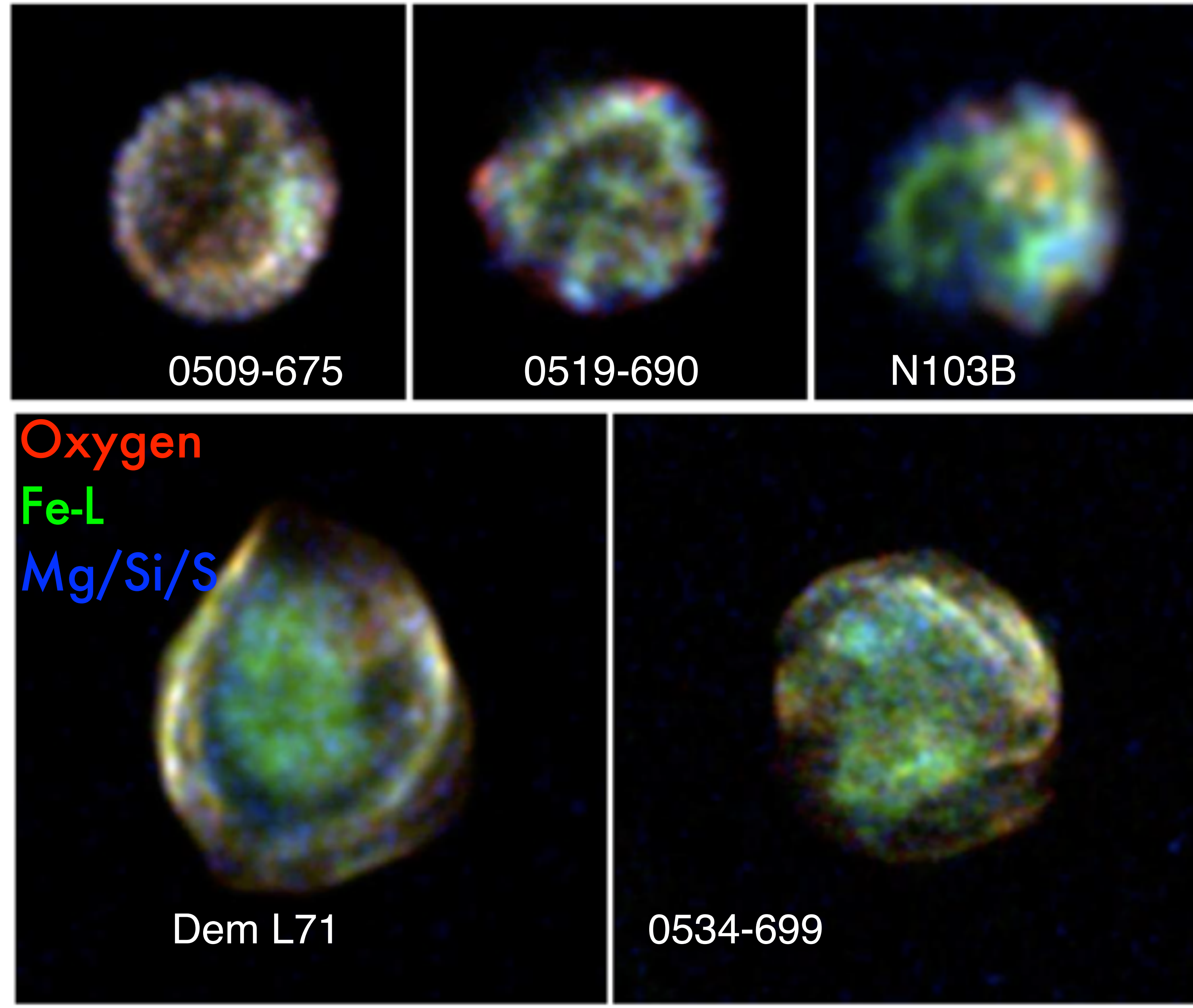
e.g. Hughes '95, Flanagan+ '04, Park+ '02;04, Kosenko+ '10

# Morphological differences core collapse vs SNe Ia



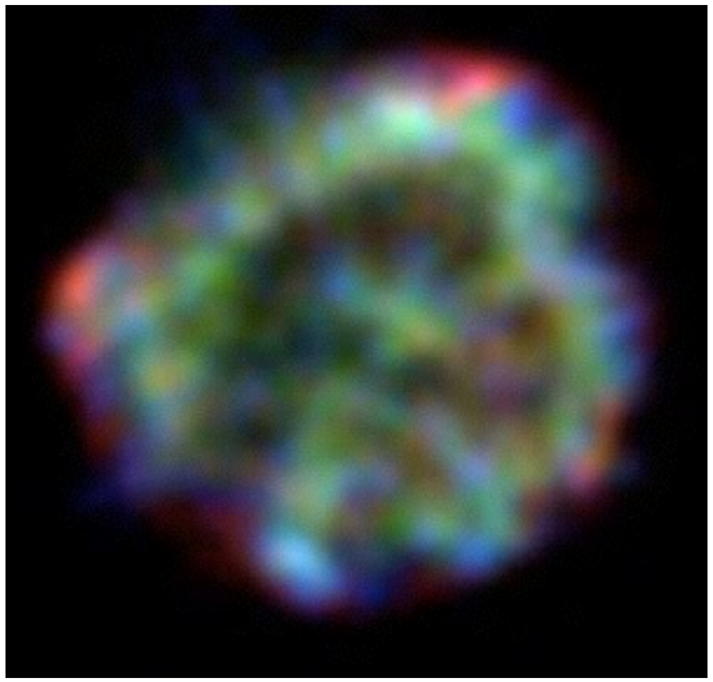

Lopez et al. 2009/11

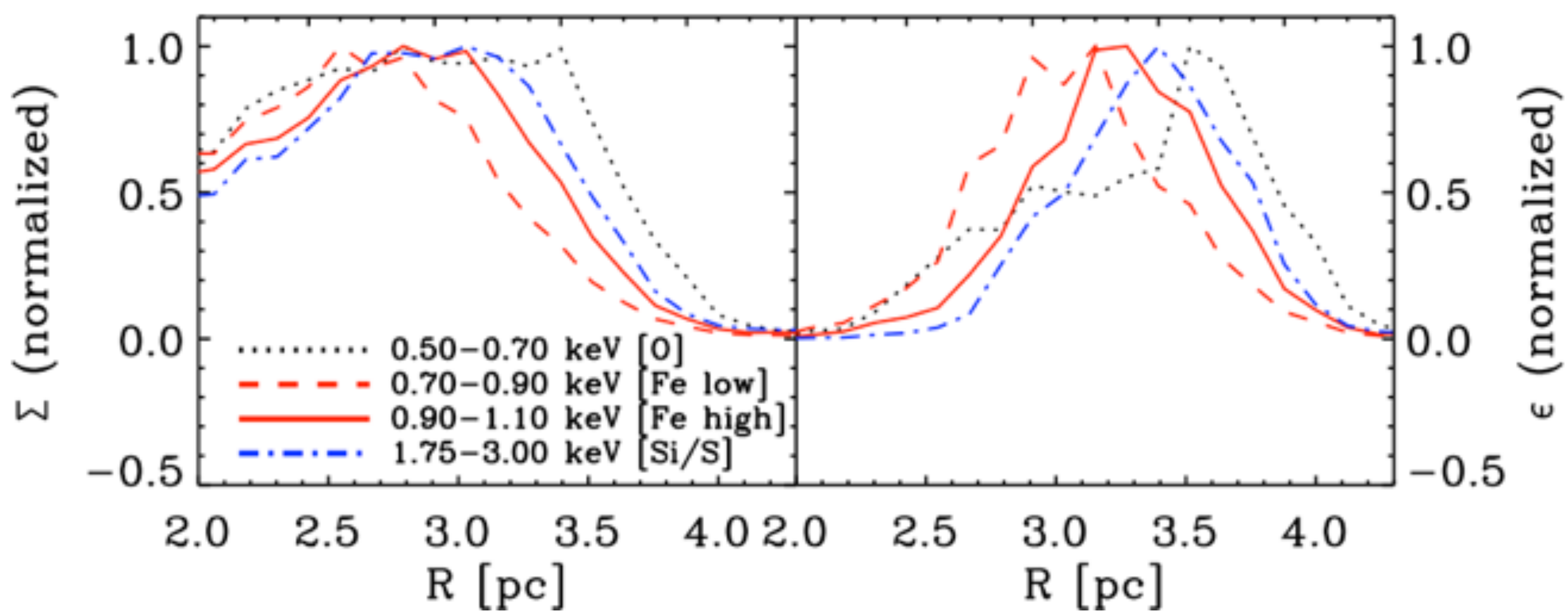
# Type Ia SNRs in the LMC



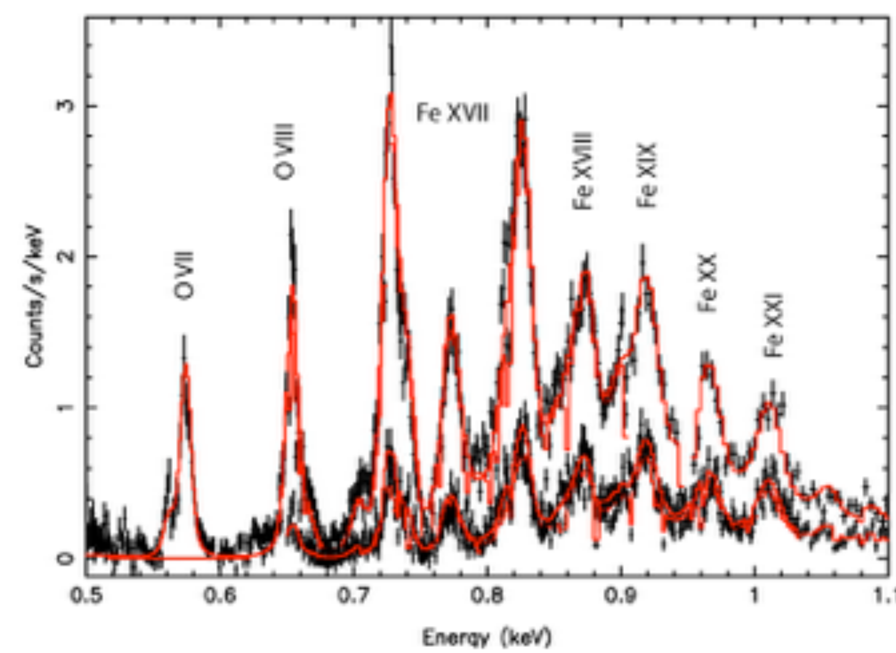

- Age sequence of some Type Ia SNRs LMC
  - Iron in center
  - With age more Fe gets shocked by reverse shock ($0.7 M_{sun}$)
  - SN Ia origin confirmed for 0509: Light echo spectra (Rest+ 08)

# Typical SN Ia: 0519-69



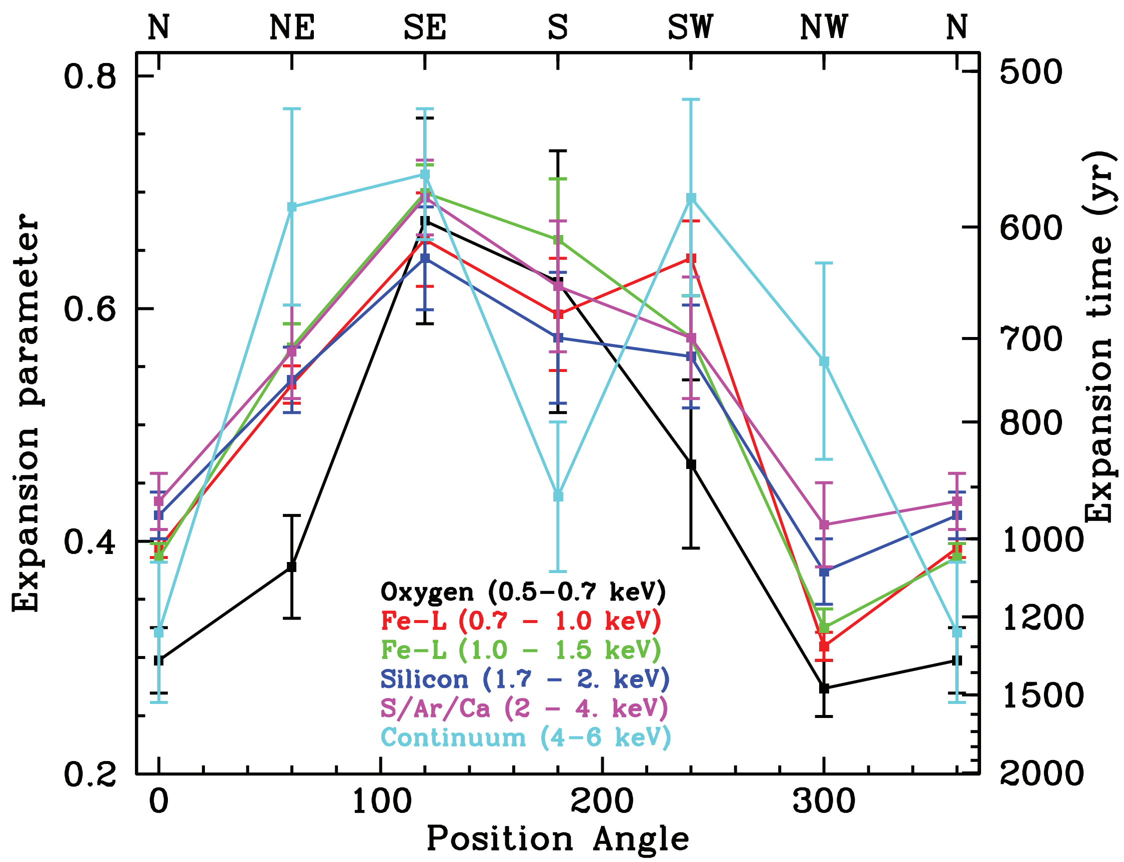



- LMC analogue of Tycho's SNR
- Strong stratification
- 30% O /55% Fe
- XMM-RGS: $\sigma_V$=1900 km/s
- Age: 440+/-200 yr

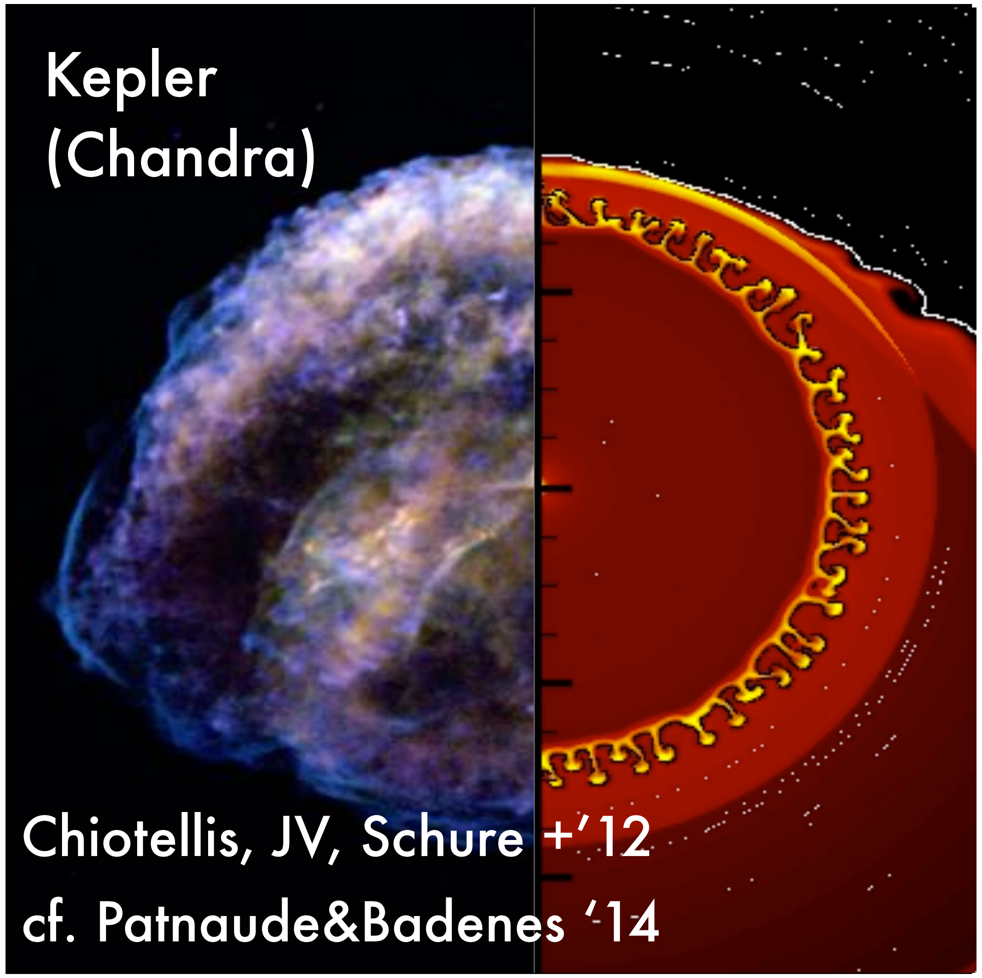



Kosenko, Helder, JV 2010

# Kepler's SNR a puzzling SN Ia

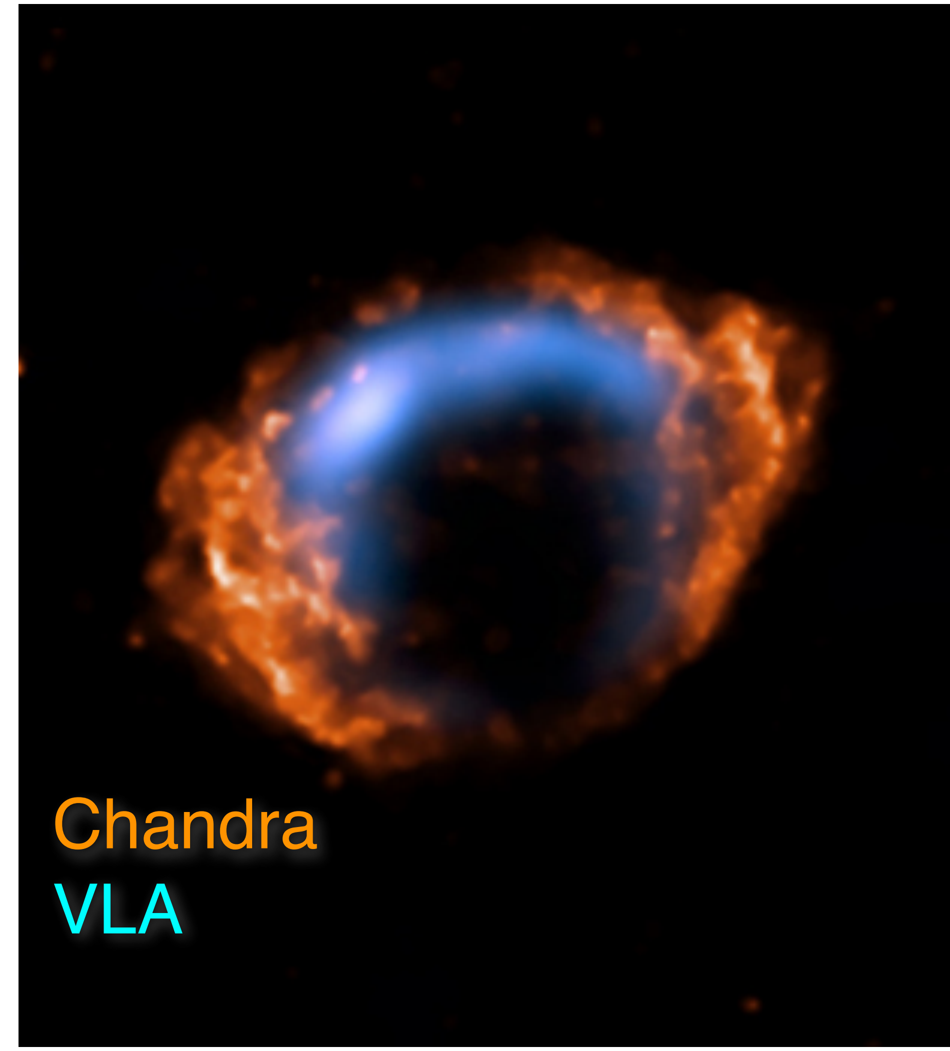



Vink '08, Katsuda+ '08



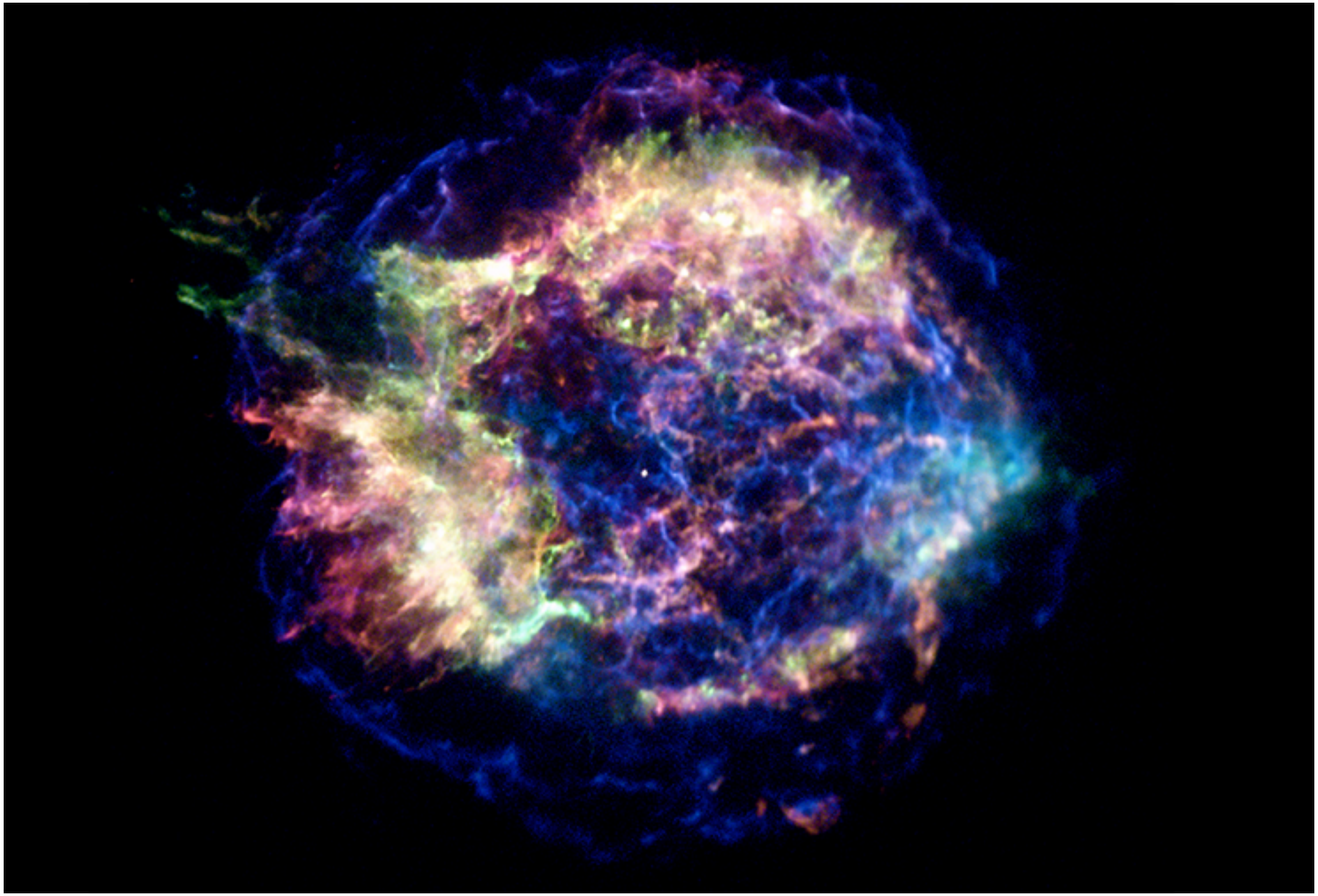

- X-ray spectrum Fe-L/Fe-K dominated/no neutron star → Type Ia SNR (Reynolds+ 07)
- High above Gal. plane (>400 pc), distance probable > 6 kpc
- Chandra expansion (Vink 08,Katsuda+ 08): m<0.4 in North
  - ⇒Shock runs into high density CSM
- Best explanation: progenitor system had high density wind!
- Implications for Type Ia scenarios:
  - Single degenerate (?)
  - How to eject a binary system with v>200 km/s from MW (triple system?)

# G1.9+0.3 the youngest Galactic SNR. Is it a Type Ia?



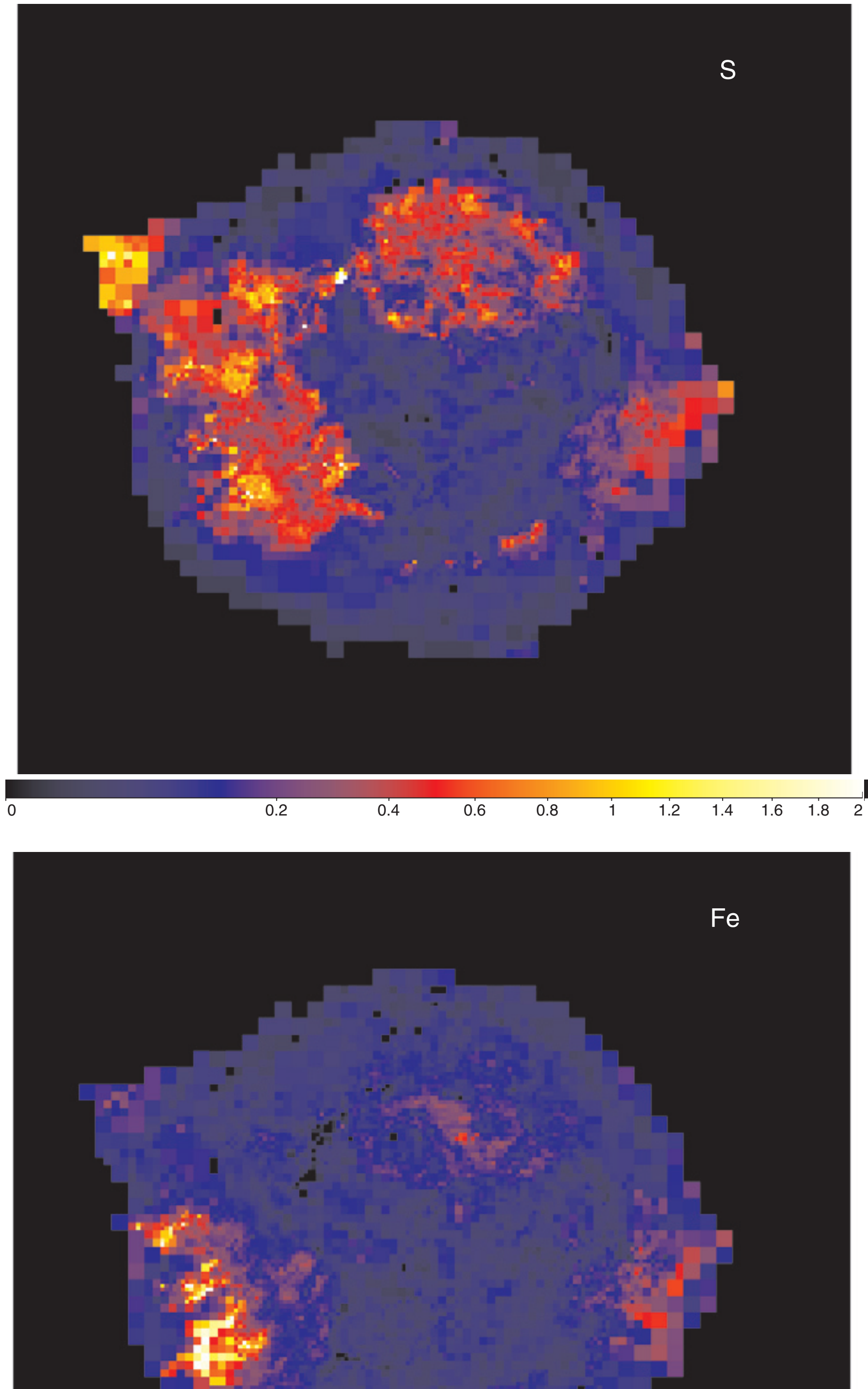

- In 2008 confirmed as SNR
  (Green+ 08, Reynolds+ '09)
- X-ray synchrotron dominated
- Broad emission lines (28,000km/s FWHM)
  (Borkowski+ '10)
- Evidence for radio-active $^{44}$Ti
  (Borkowski+ '10)
- Expansion age: 156±11 yr; real age ~100 yr
  (Carlton+ 11, Borkowski+ '14)

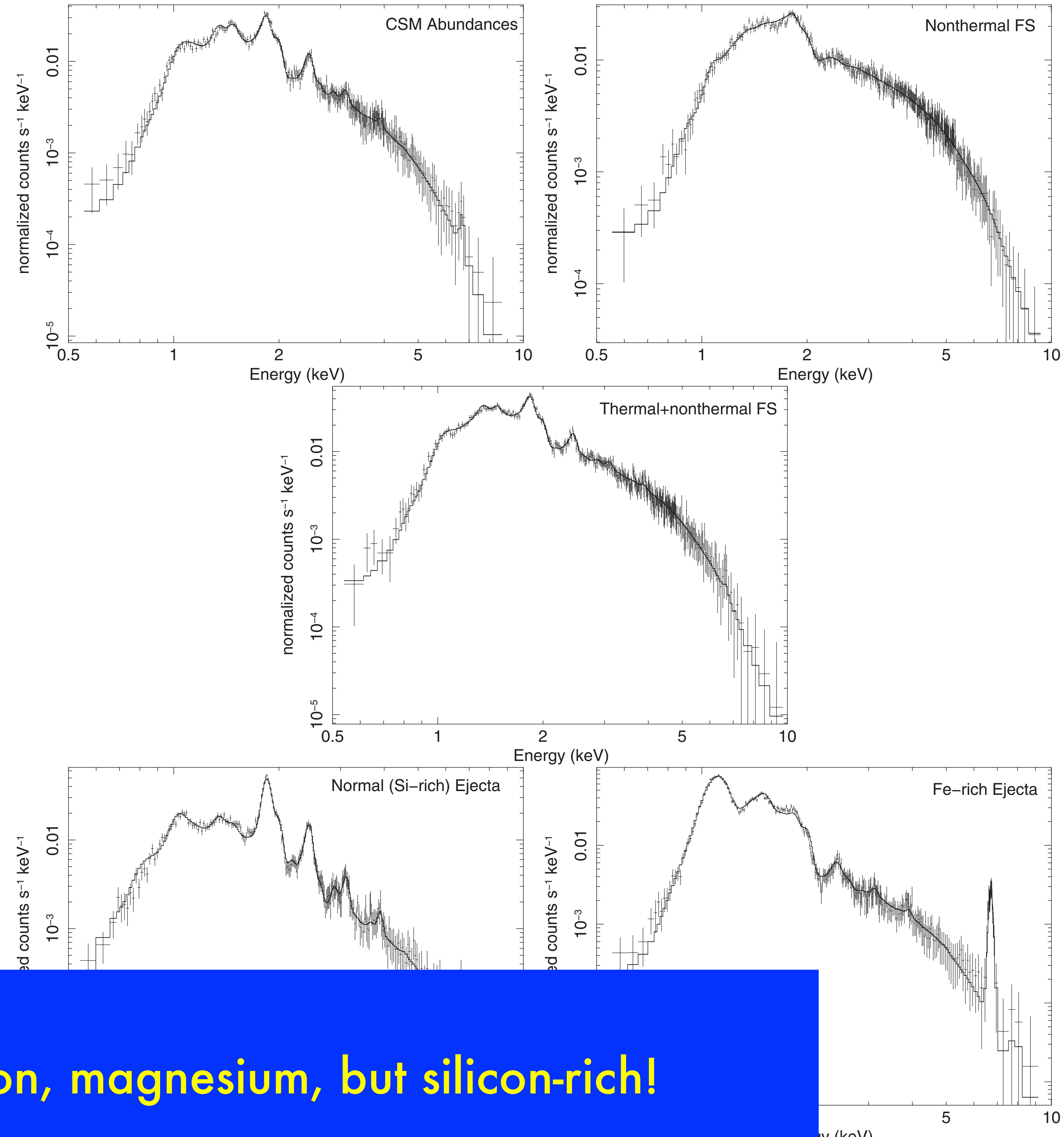
# Core collapse par excellence: Cassiopeia A



- First light image of Cas A: central compact object (Tananbaum '99)
- Chandra VLP (Hwang+ 04)

# Cas A: X-ray spectral variety



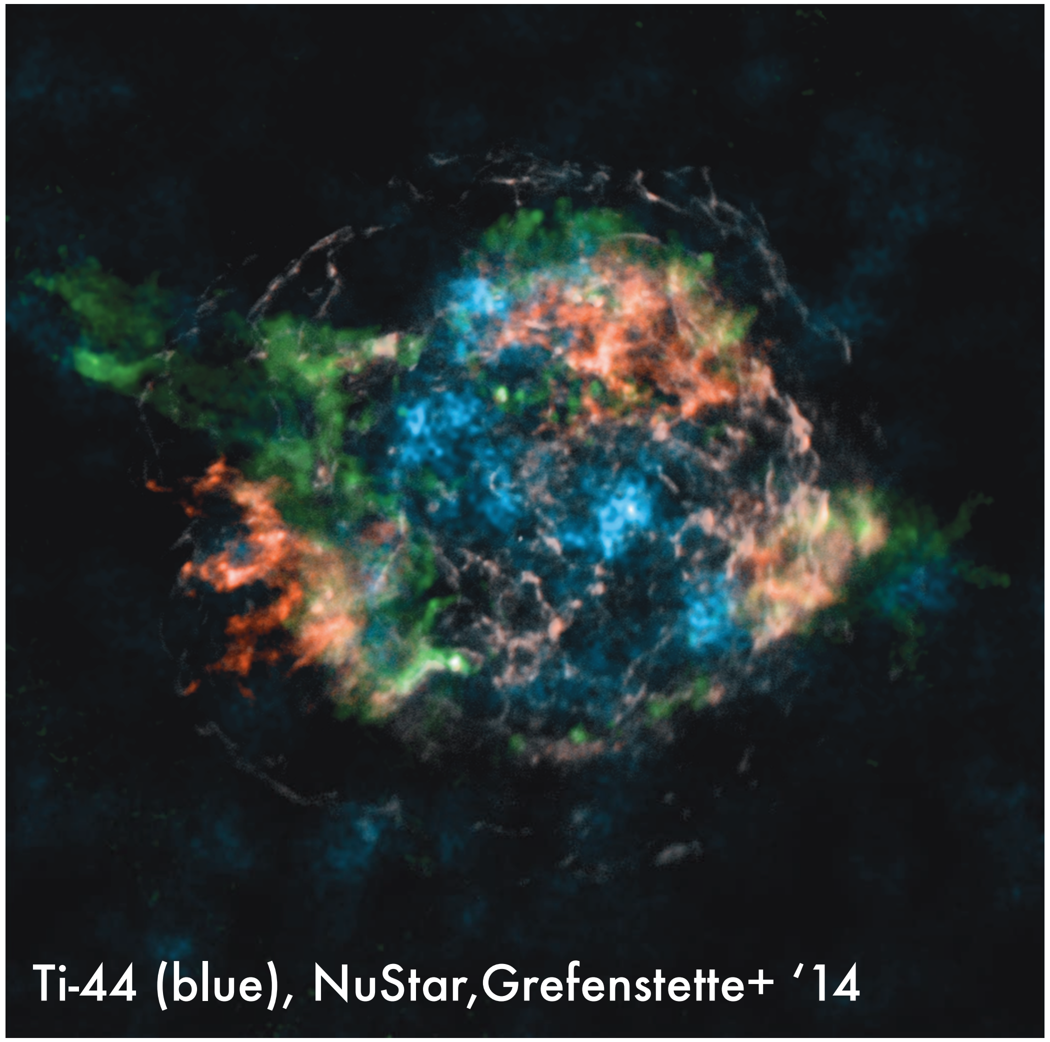

Peculiar:

Oxygen-rich, but lack of neon, magnesium, but silicon-rich!

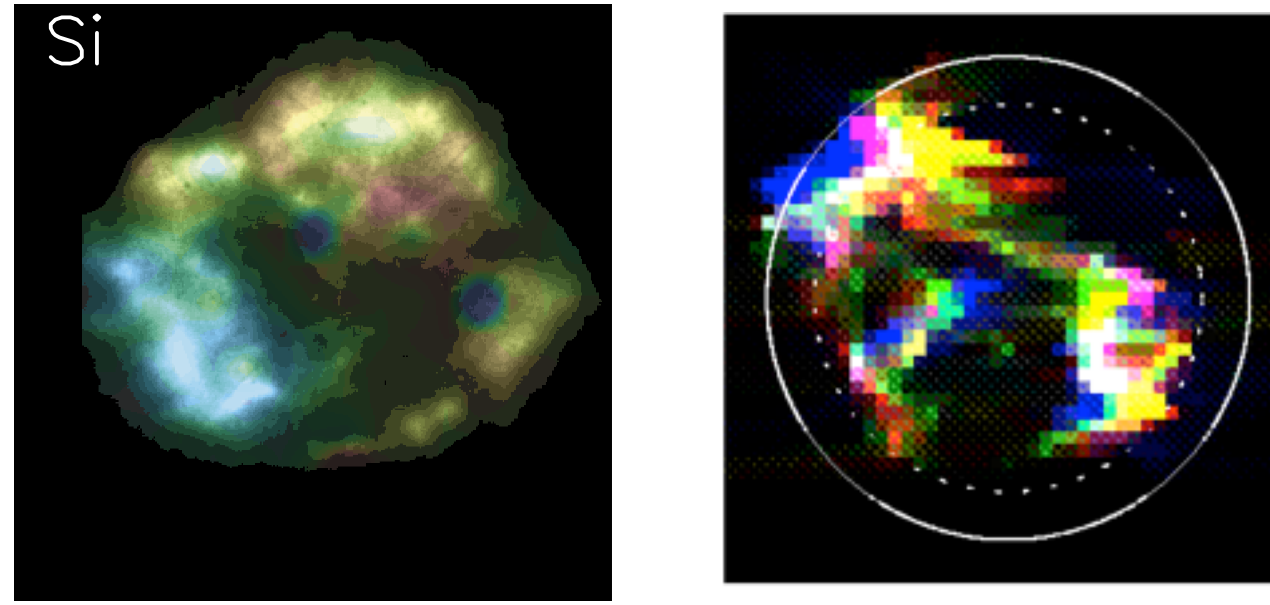
(Fesen 90,Vink+ 96)

Hwang+ 04, Hwang & Laming 2012

# Aspherical expansion



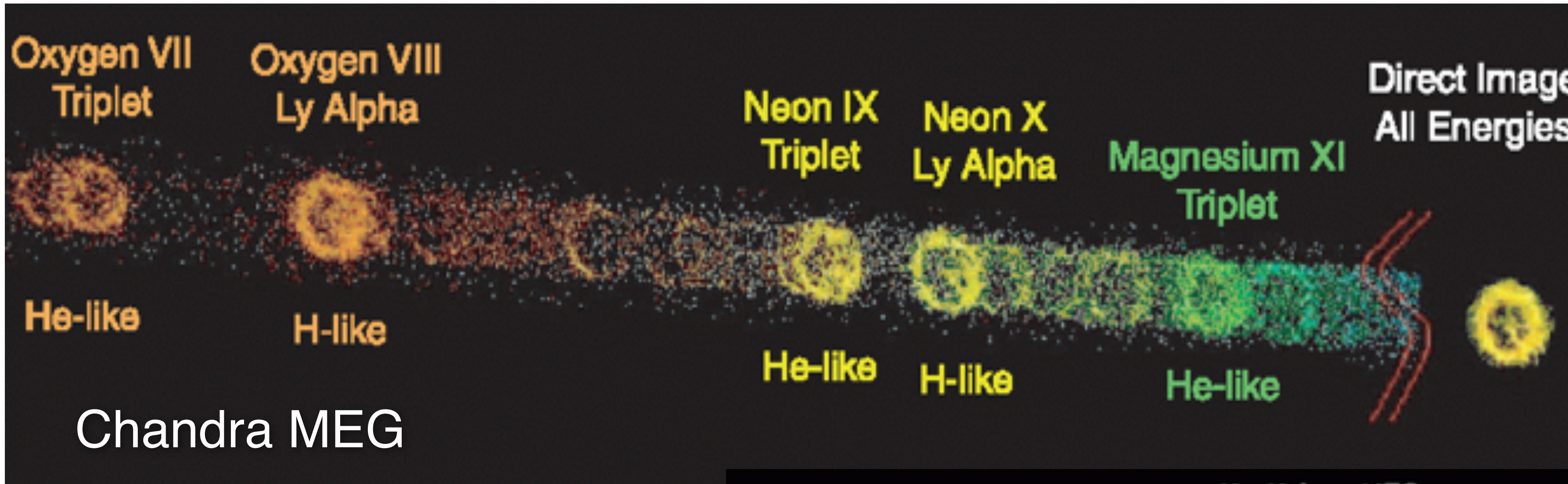
Ti-44 (blue), NuStar,Grefenstette+ '14



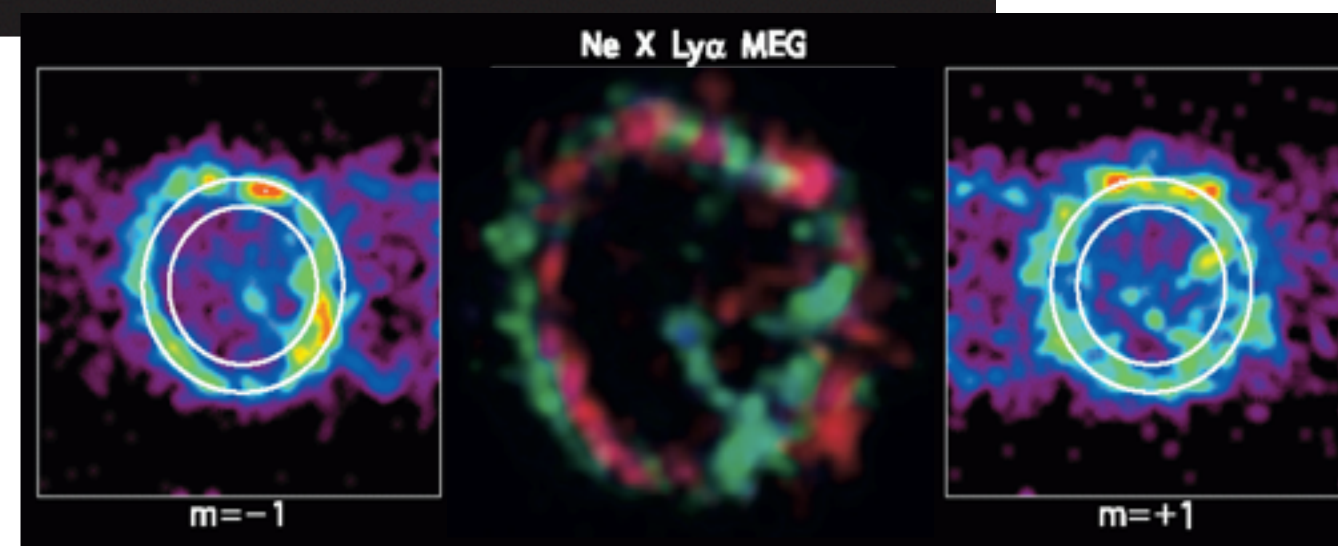

XMM Doppler map (Willingale+ 02)
and "side view"

- Jet: in X-rays brought out using Si/Mg ratio: Si-rich! (Hwang+ 04)
- If originating in core, why Si/S & not Fe rich? (Si bipolar/Fe irregular)
- Not a GRB jet: energy $10^{48}$-$10^{49}$ erg (Schure et al. '07)
- $^{44}$Ti: asymmetric explosion, reveals unshocked material
  (Iyudin+ 94, Vink+'01,Renaud+ '06, Grefenstette+ 14)
- Core collapse simulations: need stripped star!! (Kifonidis+ 04, Janka+)

# High resolution X-ray spectroscopy (Chandra gratings) of 1E0102.2-7219

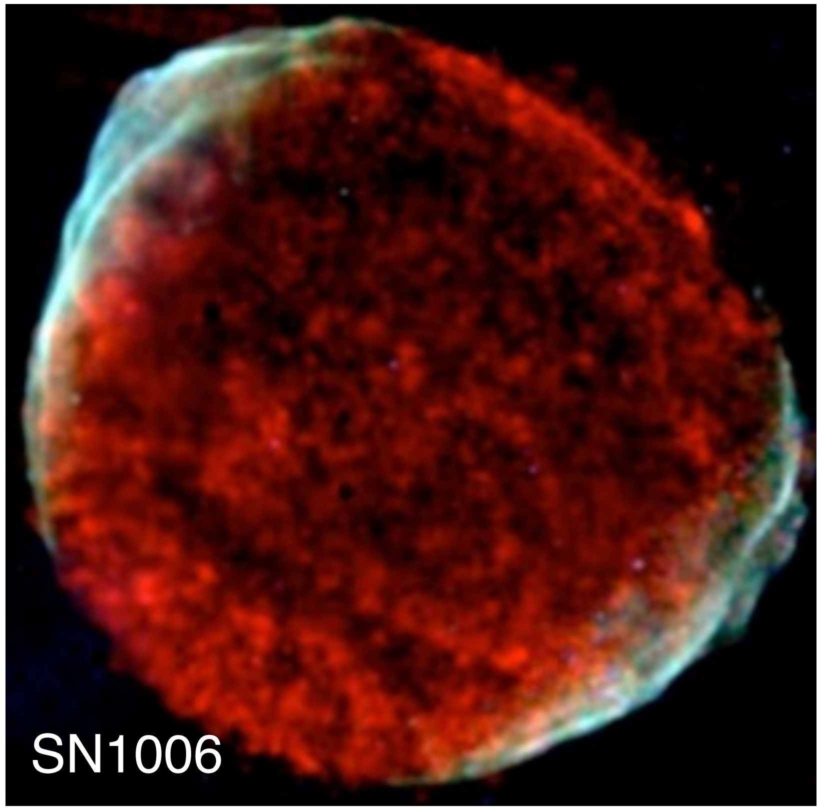


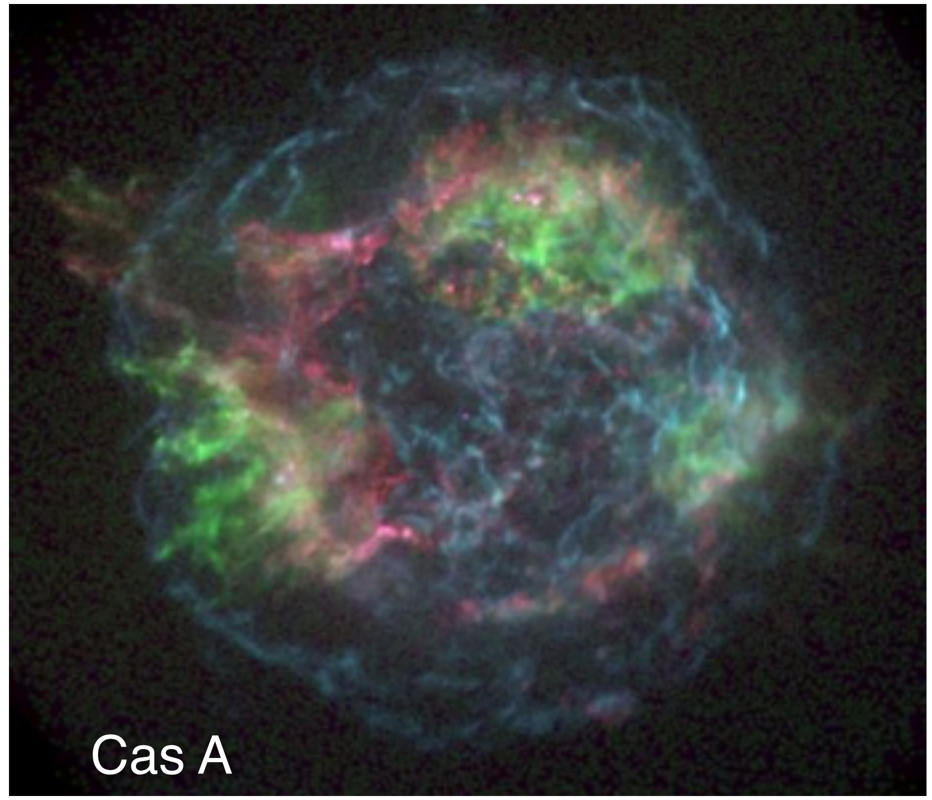

Flanagan et al. '04

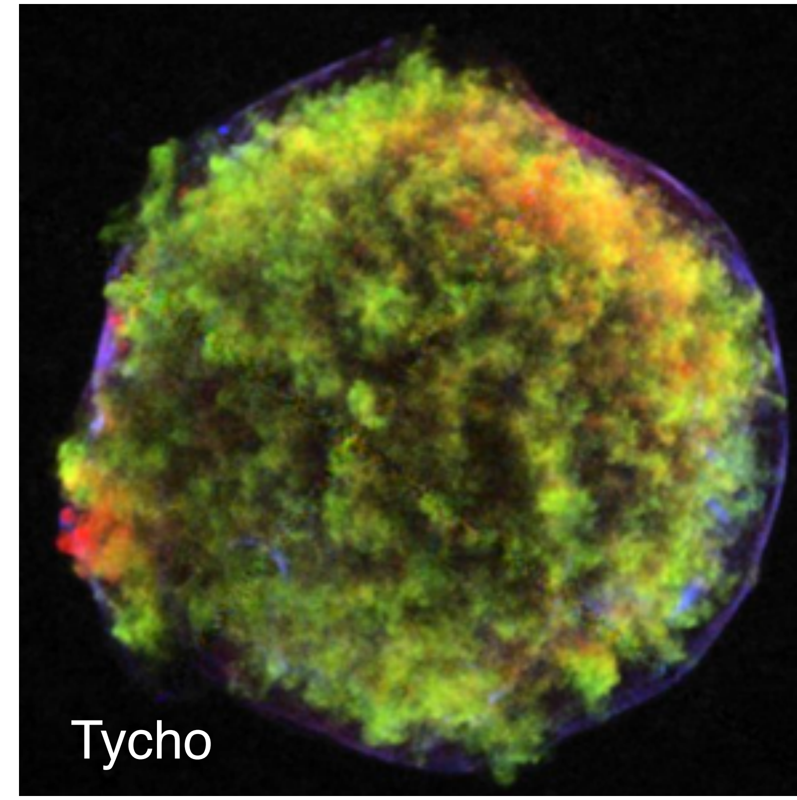



- SMC remnant
- Oxygen rich (6 $M_{sun}$): i.e. massive progenitor (~35 $M_{sun}$)
- Difference +/- orders (wavelengths are mirrored, images not)
  → aspherical doppler shifts (Flanagan+ 04)
- Expanding donut rather than sphere? (c.f. Cas A)

# Particle acceleration: Narrow X-ray synchrotron filaments




- X-ray synchrotron from SNR shocks first established for SN1006 (Koyama+ 95)
- Chandra: all young (<1500-2000 yr) SNR appear X-ray synchrotron emitters
- For Cas A, Tycho, Kepler: filaments are very thin (<2″)
  (Gotthelf+ '01, Hwang+ 02,Vink&Laming '03, Reynolds+ 07)

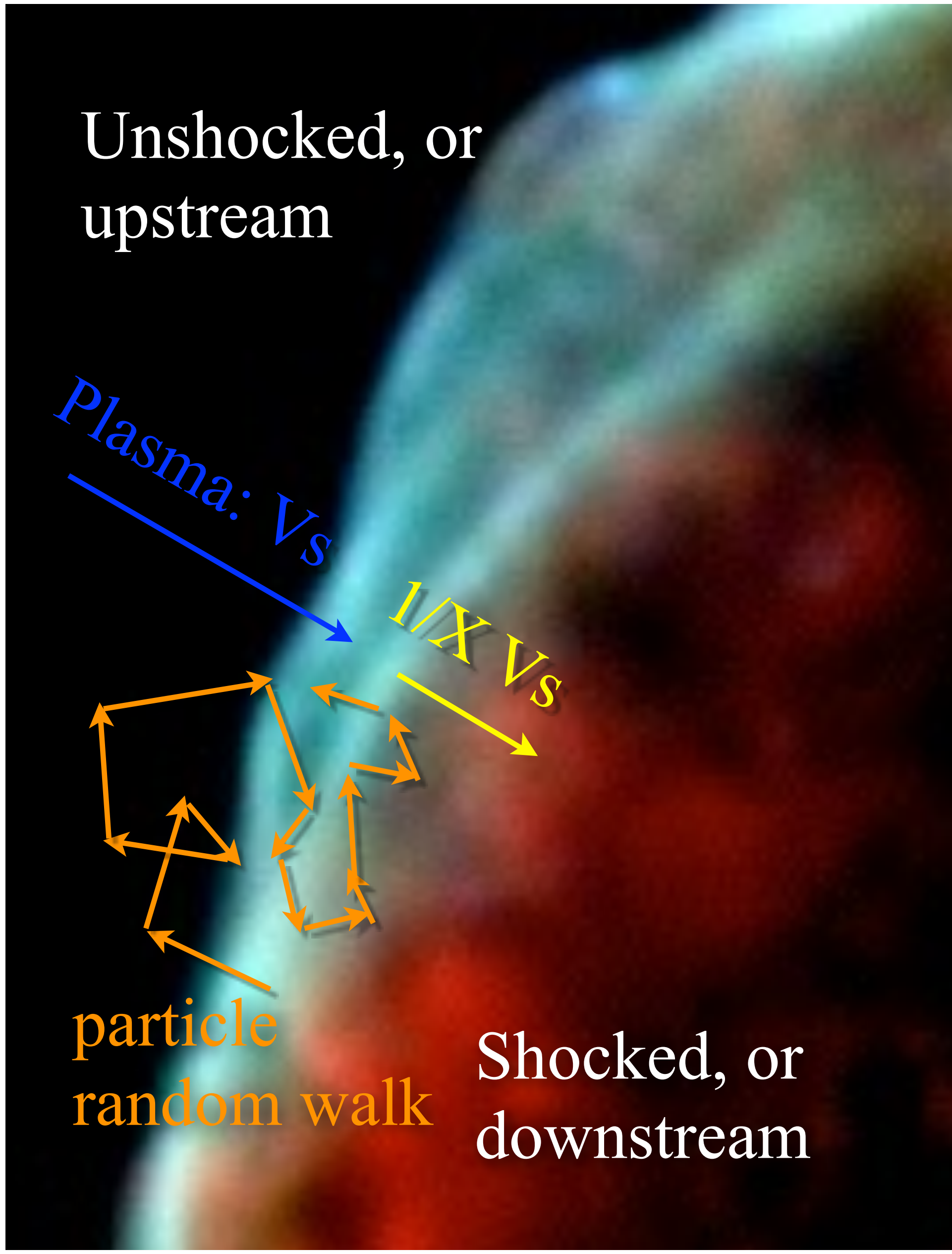
# Diffusive Shock Acceleration

- Particles scatter elastically
  → B-field turbulence
- Each shock crossing the particle increases its momentum with a fixed fraction ($\Delta p = \beta p$)
- Net movement downstream (particles taken away from shock)
- Resulting spectrum (e.g. Bell 1978):

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

X=shock compression ratio

- X=4 → $dN/dE = C\ E^{-2}$




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

# Loss-limited X-ray synchrotron emission

- 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 (diffusion coeff. D, compression X):

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

Bohm diffusion (smallest D/fastest acceleration): η=1

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

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

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

e.g. Aharonian&Atoyan '99, Zirakashvili&Aharonian 07

# Implications X-ray synchrotron emission

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

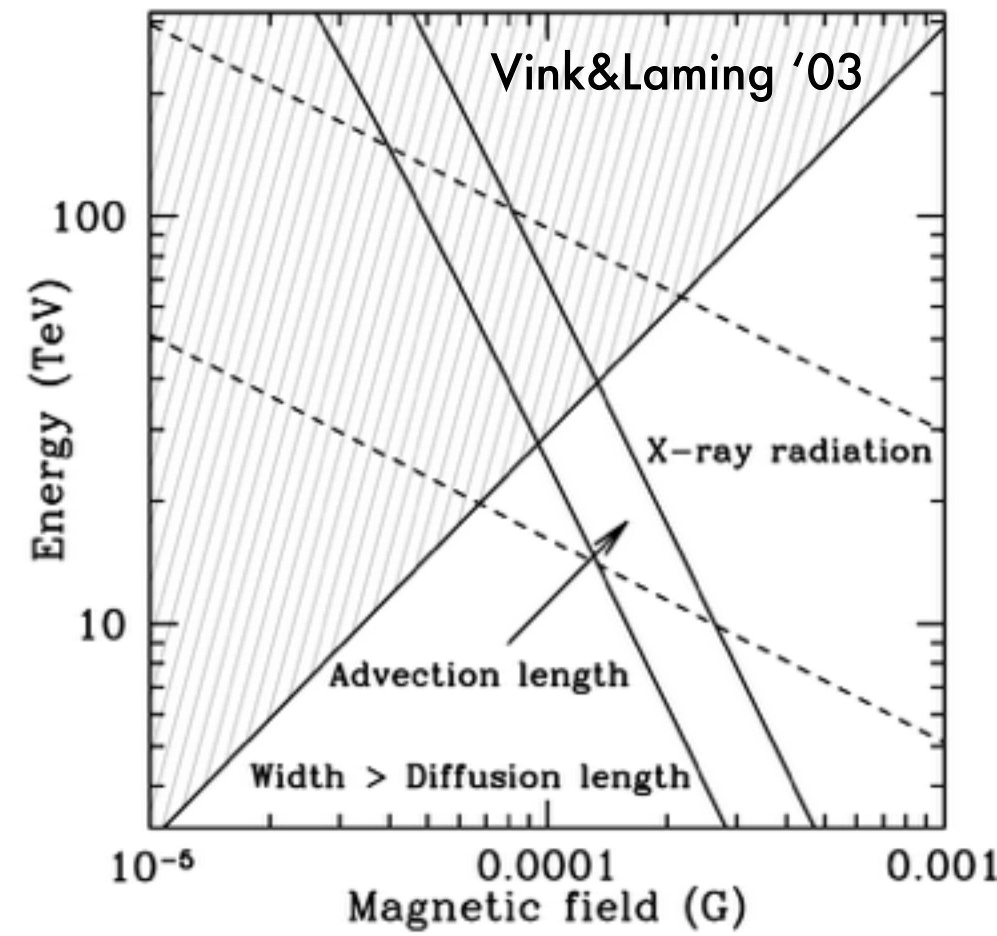
$$1 < \eta < 20$$

- The higher the B-field -> faster acceleration, but for electrons: Emax 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 (loss times 10-100 yr)
- that acceleration is still ongoing
- that particles can be accelerated at least up to $10^{14}$ eV

# Narrowness X-ray synchrotron filaments: high B-fields




- Width rims≈diffusion length ≈ ΔV x $\tau_{loss}$:

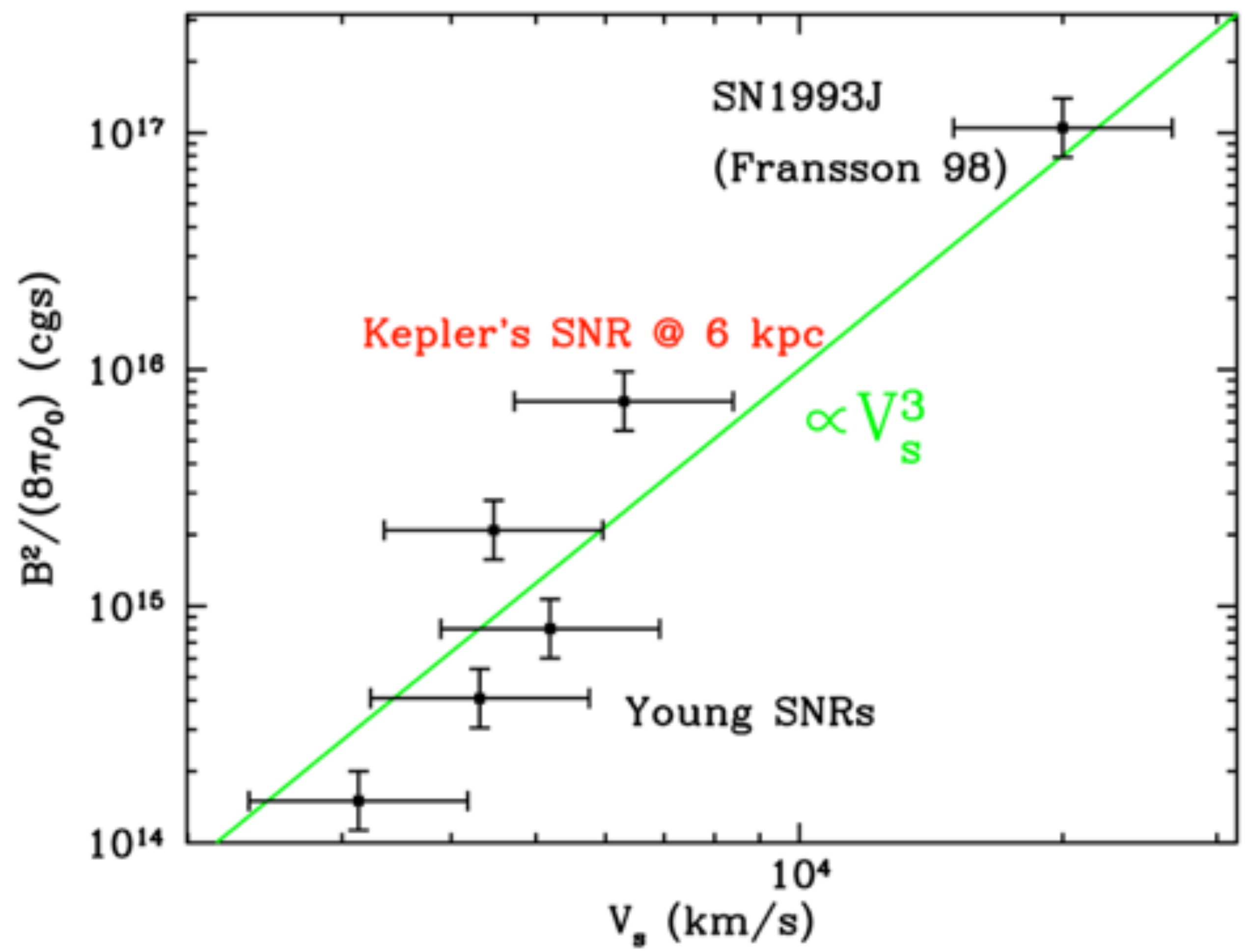
$$B_2 \approx 26 \left( \frac{l_{\rm adv}}{1.0 \times 10^{18} {\rm cm}} \right)^{-2/3} \eta^{1/3} \left( \chi_4 - \frac{1}{4} \right)^{-1/3} \ \mu{\rm G}$$

- Narrow rims → high B-field
- Cas A/Tycho/Kepler: 100-500 μG
  (e.g. Vink&Laming '03, Völk et al. 03, Bamba+ '04, Warren+ '05, Parizot+ '06, Helder+ '12)
- 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

# Magnetic energy density proportional to mass density and $V_s^3$

- Proportionality consistent with theories of magnetic field amplification (Bell 04)

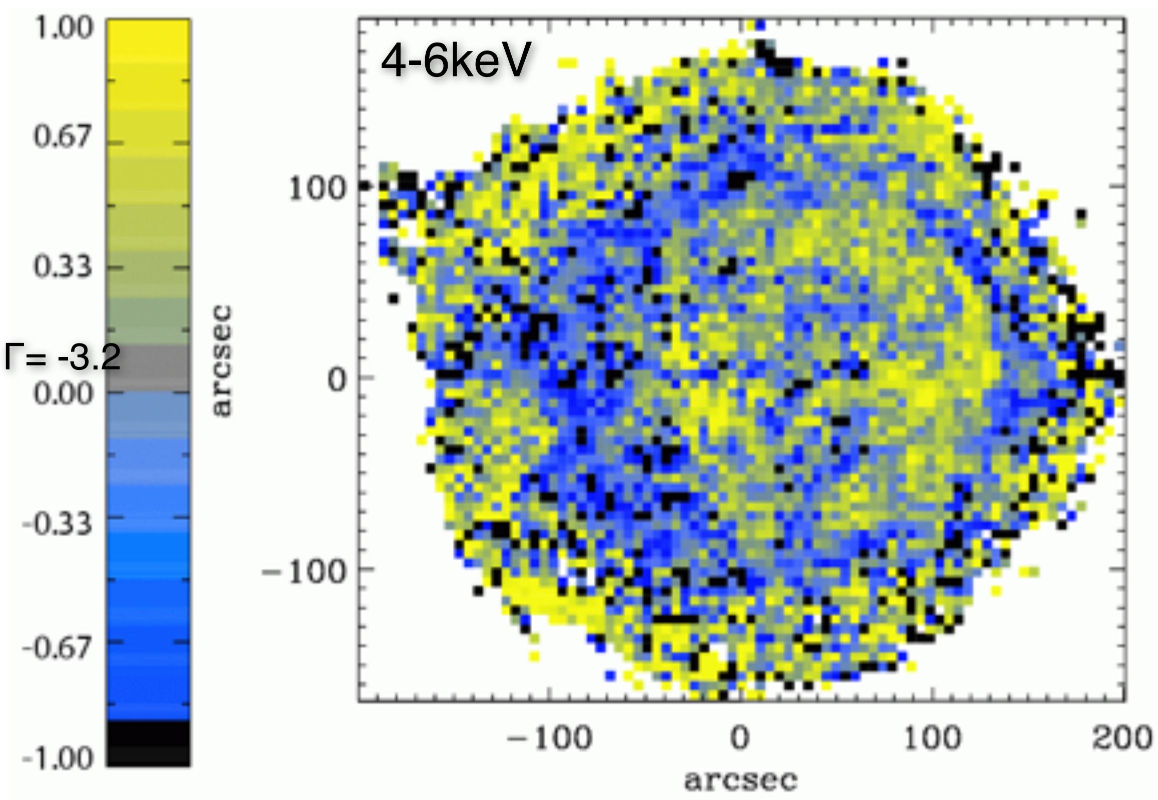


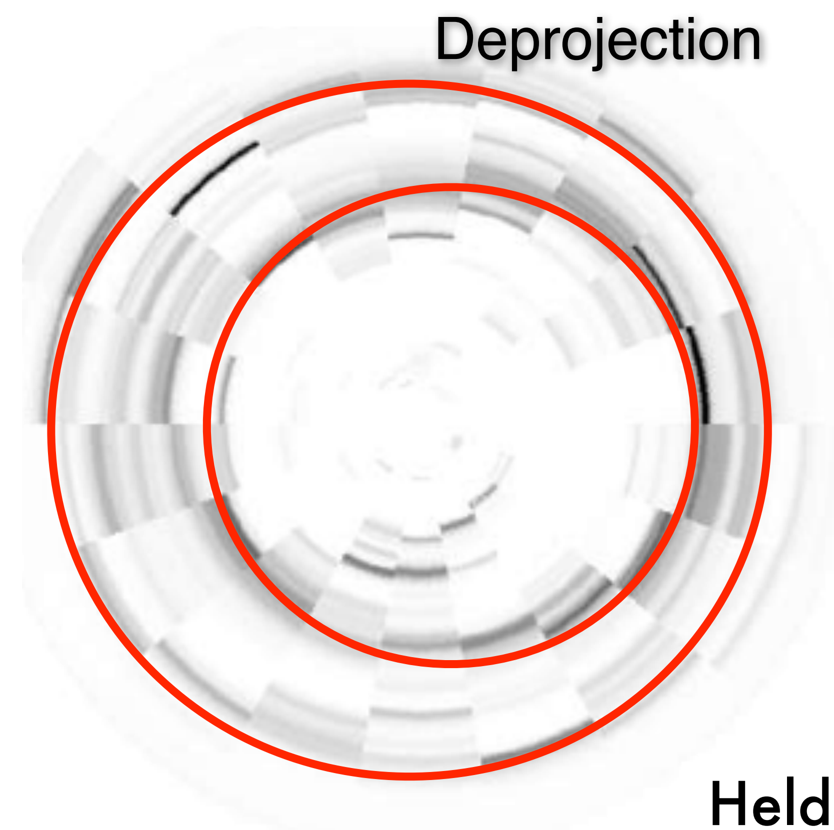

a.o. Helder+ '12

**Table 2** Observed widths of synchrotron filaments and downstream inferred magnetic field strength

| SNR | Age (yr) | Dist (kpc) | Radius (pc) | $R_w$ ($''$) | $l_{adv}$ ($10^{17}$ cm) | $B_2$ (μG) | $E_{el}$ (TeV) | $\tau_{syn}$ (yr) |
|---|---|---|---|---|---|---|---|---|
| G1.9+0.3 (SW) | 110 | 8.5 | 1.8 | 3.1 | 2.8 | 67 | 33 | 86 |
| Cas A (NE) | 334 | 3.4 | 2.5 | 1.1 | 0.4 | 246 | 17 | 12 |
| Kepler (SE) | 401 | 6.0 | 3.7 | 1.8 | 1.1 | 122 | 24 | 35 |
| Tycho (W) | 433 | 3.0 | 3.7 | 1.6 | 0.5 | 207 | 19 | 16 |
| SN1006 (E) | 999 | 2.2 | 9.1 | 9.1 | 2.1 | 81 | 30 | 64 |
| RX J1713.7-3946 (SW) | 1612 | 1.0 | 7.8 | 63.5 | 6.7 | 37 | 44 | 206 |
| RCW 86 (NE) | 1820 | 2.5 | 16.0 | 28.6 | 7.6 | 35 | 46 | 232 |
| RX J0852.0-4622 (N) | 2203 | 1.0 | 16.3 | 28.4 | 3.0 | 64 | 34 | 92 |

# Acceleration @ Cas A reverse shock




Helder&Vink '08

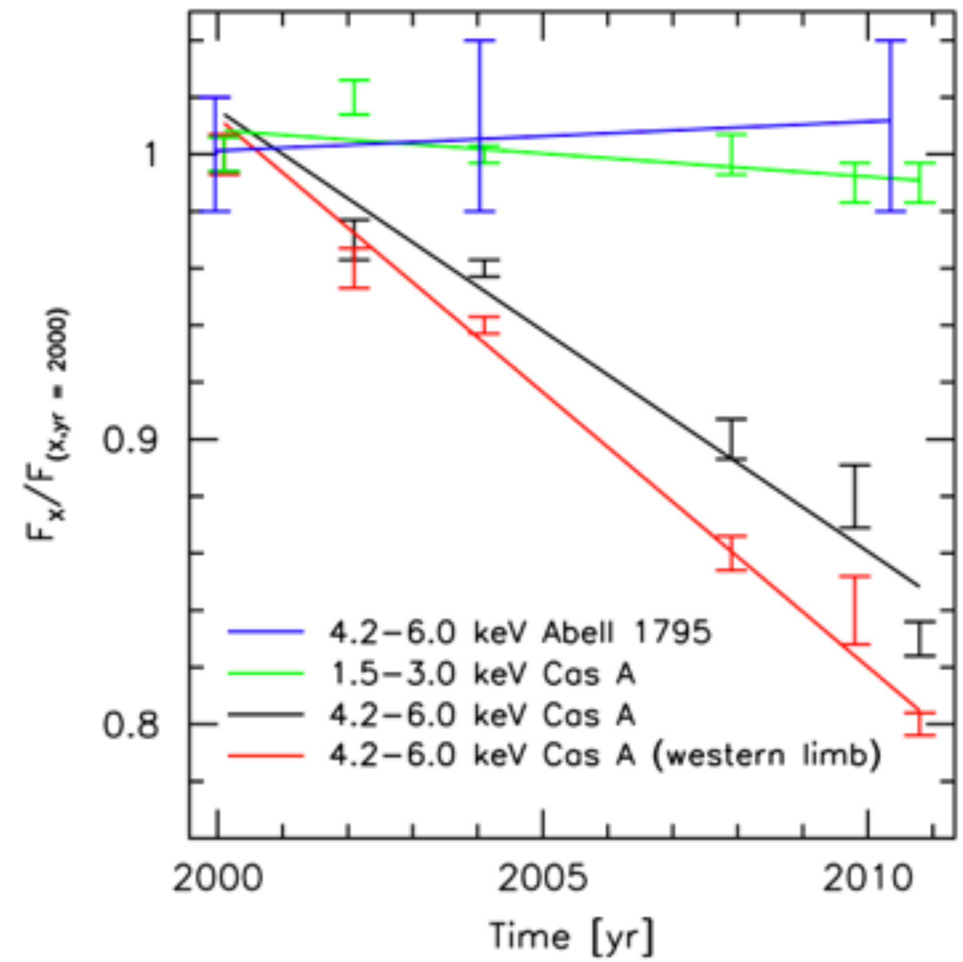
- Spectral index: 2 regions of hard emission: X-ray synchrotron emission
- Deprojection: Most X-ray synchrotron from reverse shock!
- Prominence of West: No expansion ⇒ ejecta shocked with V>6000 km/s
- Reverse shock: metal-rich → more electrons → bright radio

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

# The rapid decline of X-ray synchrotron radiation from Cas A

Patnaude, JV, Laming, Fesen ‘11

- X-ray synchrotron flux (4-6 keV) declines strongly:
  - Whole SNR: $-(1.5 \pm 0.17)\%\ \mathrm{yr}^{-1}$
  - Western part: $-(1.9 \pm 0.10)\%\ \mathrm{yr}^{-1}$
  - Accompanied by steepening of spectral index Γ




- Decline more than in radio: not adiabatic cooling
- Likely cause: shock deceleration → changing cut-off energy

$$\frac{1}{F(\nu)}\frac{dF(\nu)}{dt} = -2\frac{d\Gamma}{dt} \qquad \frac{d\nu_c}{dt} = -4\sqrt{\frac{\nu_c}{\nu}}\nu_c\frac{d\Gamma}{dt}$$

- Decline high, may imply small η, hence very fast acceleration!
- Questions: spectral shape: why near power law?

# Summary/final remarks

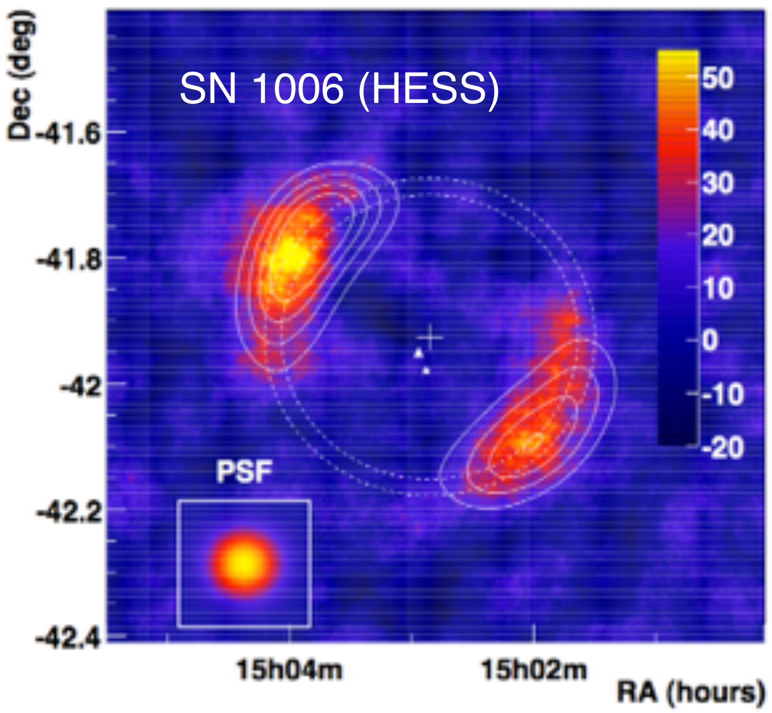
- Chandra had a big impact on understanding SNRs:
  - detailed imaging spectroscopy ejecta distribution out to LMC
  - expansion measurements (Cas A, Tycho, Kepler, RCW86, G1.9)
  - detecting narrow (<2”) X-ray synchrotron rims
  - identifying neutron stars

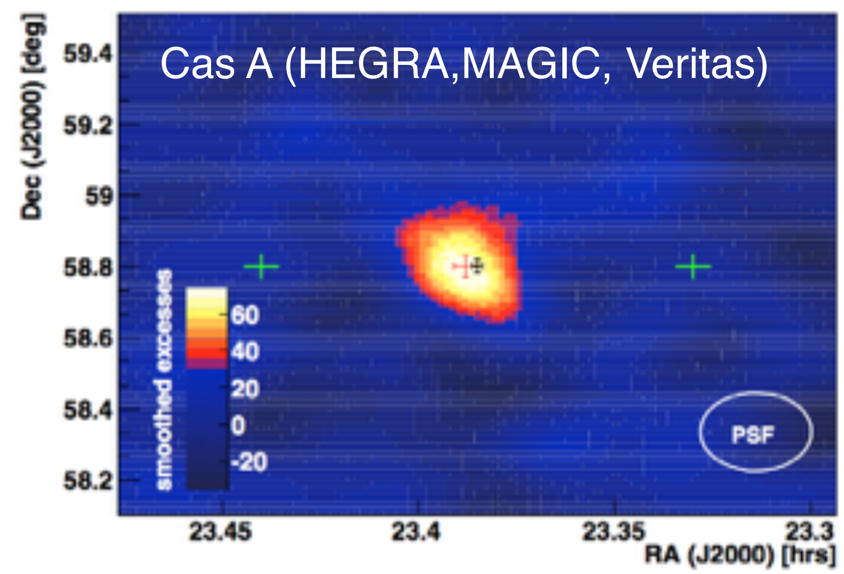
- Take home messages
  - Type Ia SNRs have regular shapes and iron distributed in interior
  - Core collapse SNRs are irregular, sometimes bipolar/donut shaped
  - In young SNRs:
    - -X-ray synchrotron radiation
    - - 10-100 TeV electrons
    - - Particle acceleration fast: close to Bohm limit
    - - Magnetic field amplified to >100 μG even at reverse shock
    - - High B-field: protons can be accelerated > 100 TeV ($3\times10^{15}$eV?)

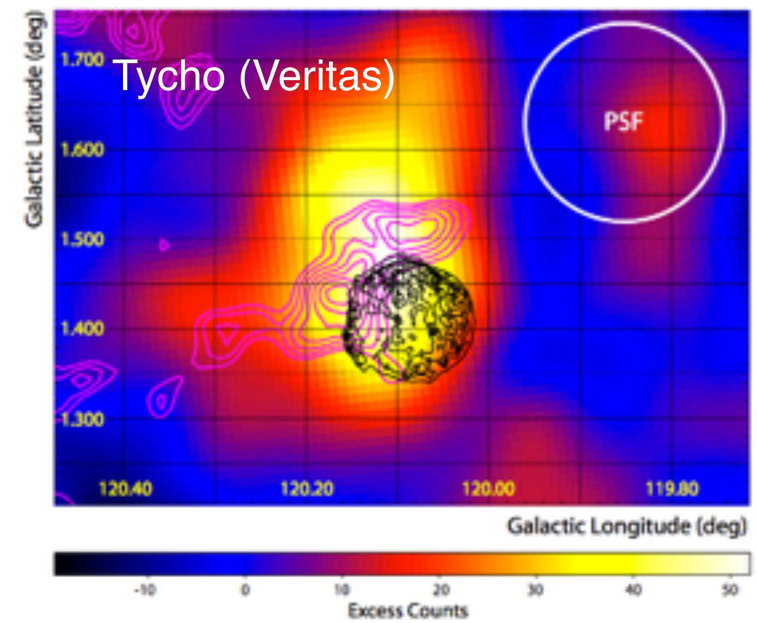
Not discussed here: Mature SNRs and overionization; SN1987A (it is still brightening!); Relation between SNRs and compact object (seems random!); Evidence for high compression ratios (cosmic ray related?); Mn, Cr lines

# Backup slides

# TeV (H.E.S.S., Veritas, MAGIC) counterparts

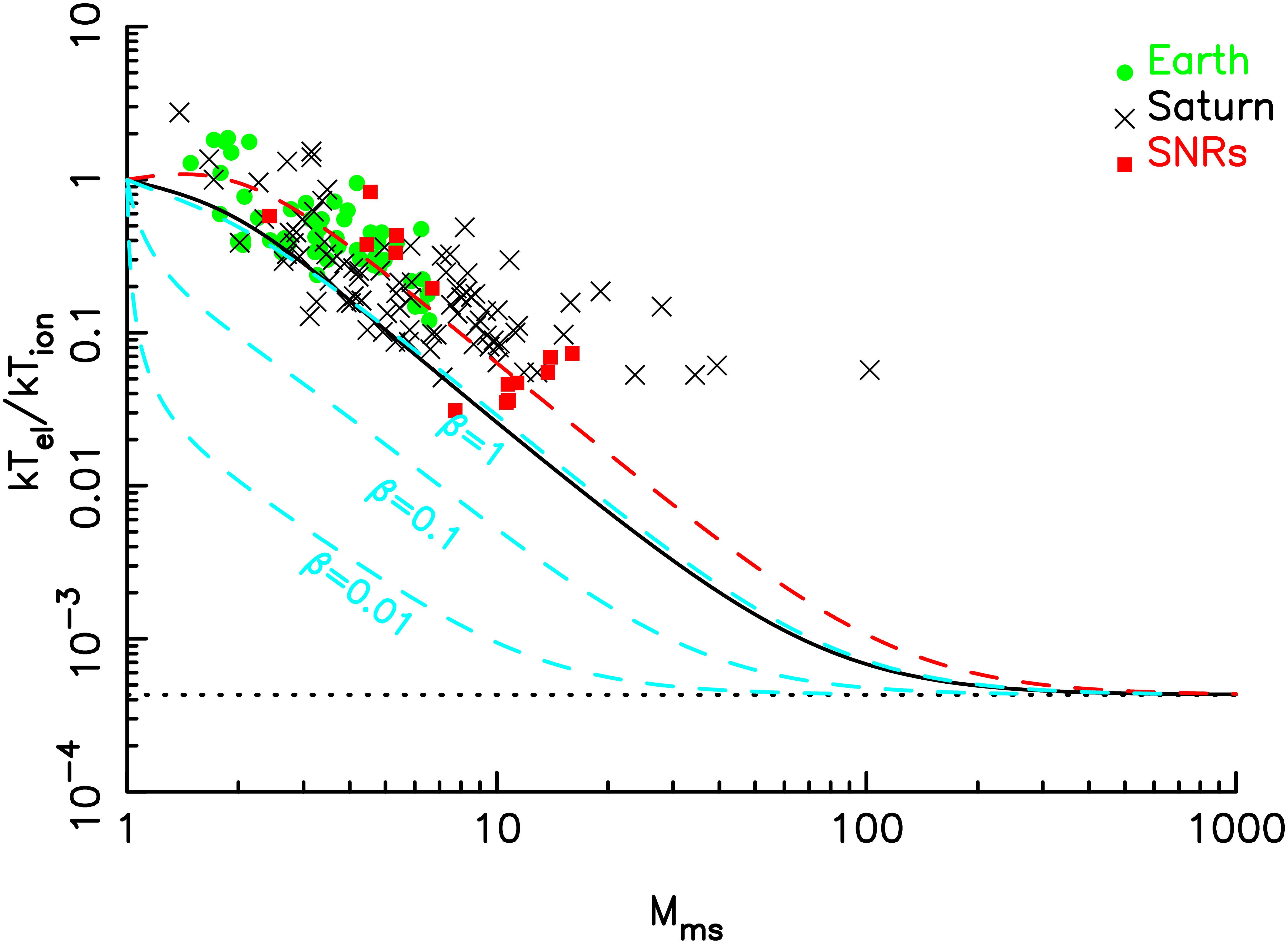



- Most X-ray synchrotron emitters als TeV gamma-ray sources
- May be common origin: inverse Compton scattering TeV electrons
- Other: ion-ion collisions → pion production + decay

# Temperature ratio



# Narrowness rims: advection+losses or diffusion?

- Two possible ways of reasoning:
  - rim widths associated with synchrotron loss time & advection:

$$l_{\rm adv} = \tau_{\rm syn}\Delta v = \tau_{\rm syn}\frac{V_s}{\chi}$$

  - rim widths correspond to diffusion length scale of >10 TeV electrons:

$$l_{\rm diff} = \frac{2D}{\Delta v} = \frac{2Ec\chi}{3eBV_s}$$

- Turns out the two are more or less equivalent!

$$\tau_{\rm acc} = \frac{2D}{\Delta v^2} = \frac{l_{\rm diff}}{\Delta v} \qquad \tau_{\rm syn} = \frac{l_{\rm adv}}{\Delta v}$$

- So near break frequency: $\tau_{\rm syn} \approx \tau_{\rm acc} \leftrightarrow l_{\rm adv} \approx l_{\rm diff}$
- So we can use either system provided we are near the break frequency
- In reality the width is combination from advection and diffusion

# The origin of Galactic cosmic rays

The energy source that powers Galactic cosmic rays are thought to be supernovae.

For this to be true minimally two conditions need to be satisfied:

1. 5-10% ($\simeq 10^{50}$ erg) of kinetic energy used for cosmic rays
   - Pertains mostly to low energy cosmic rays (GeV)!

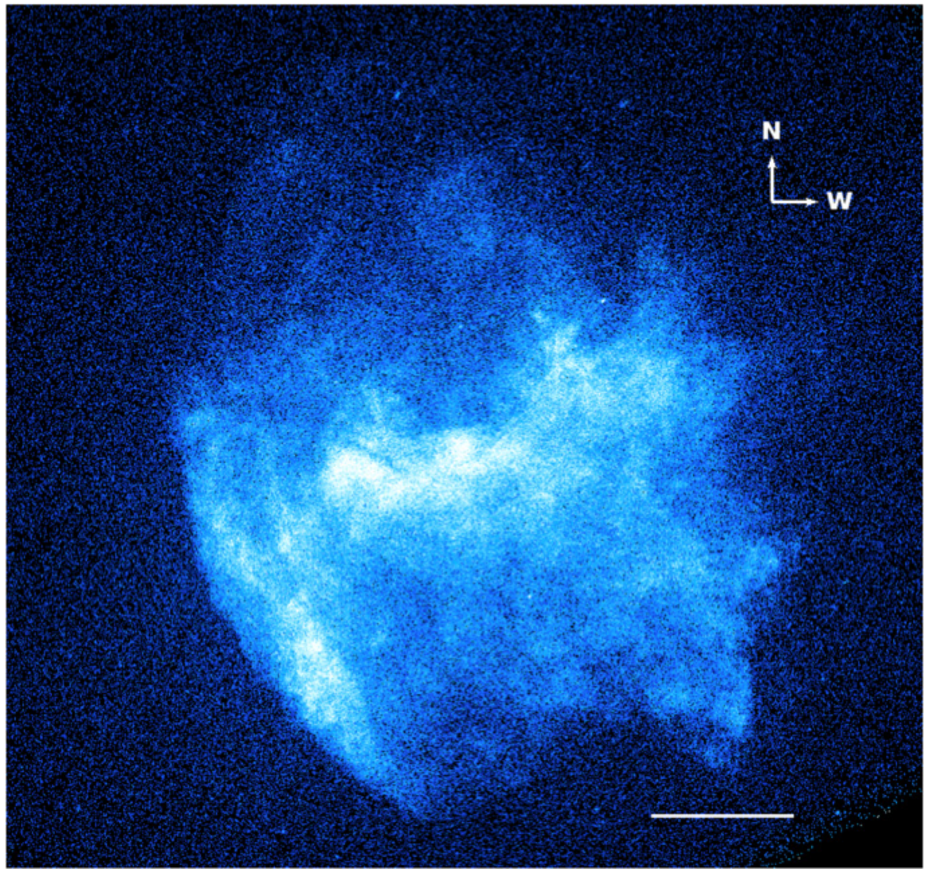
   ➜ *when does this happen, early, young, or Sedov SNR-stage?*

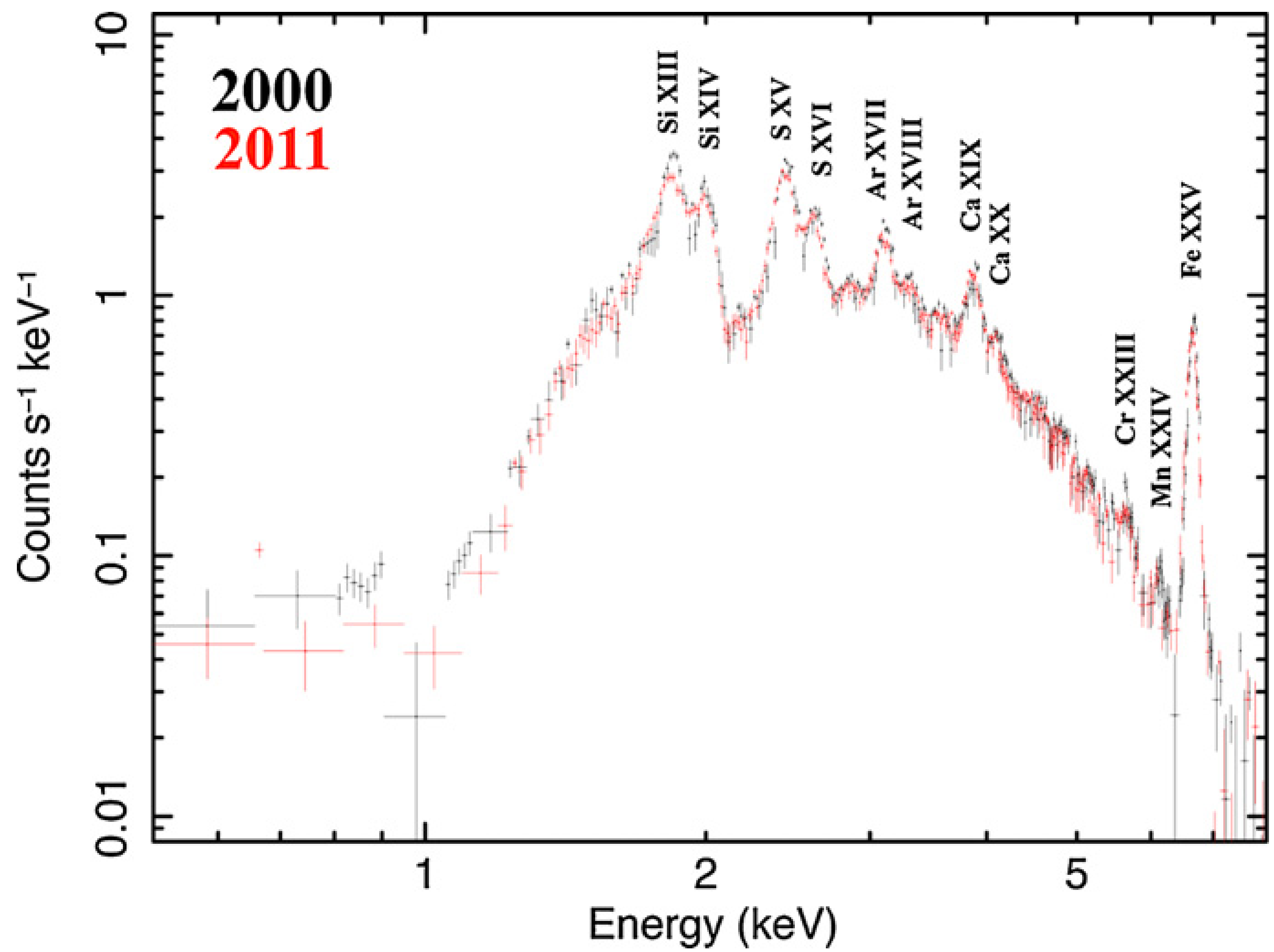
   ➜ *should collective effects be considered* ➜ super bubbles?

2. The sources  should be able to accelerate particles to $>3\times10^{15}$eV

   ➜ *where are the Galactic PeVatrons?*

# W49B: bipolar, iron-rich and dense

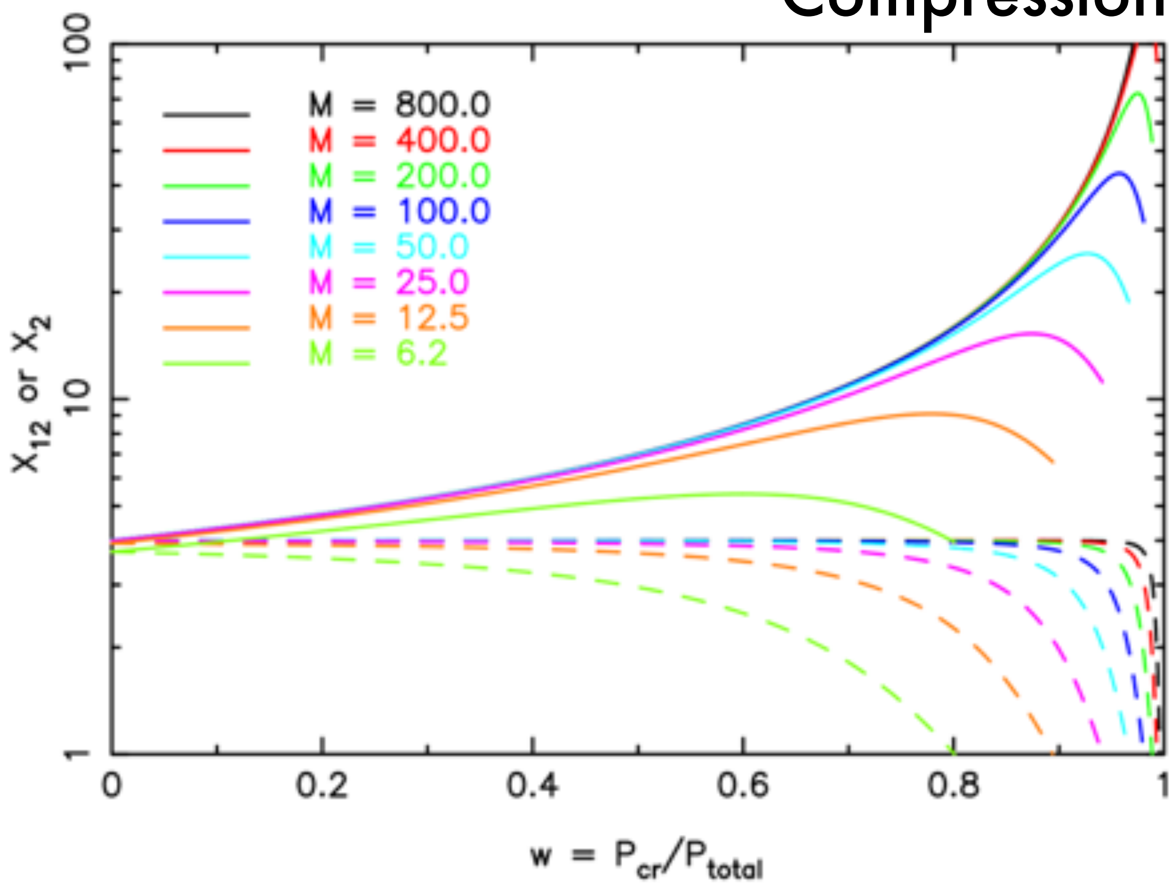


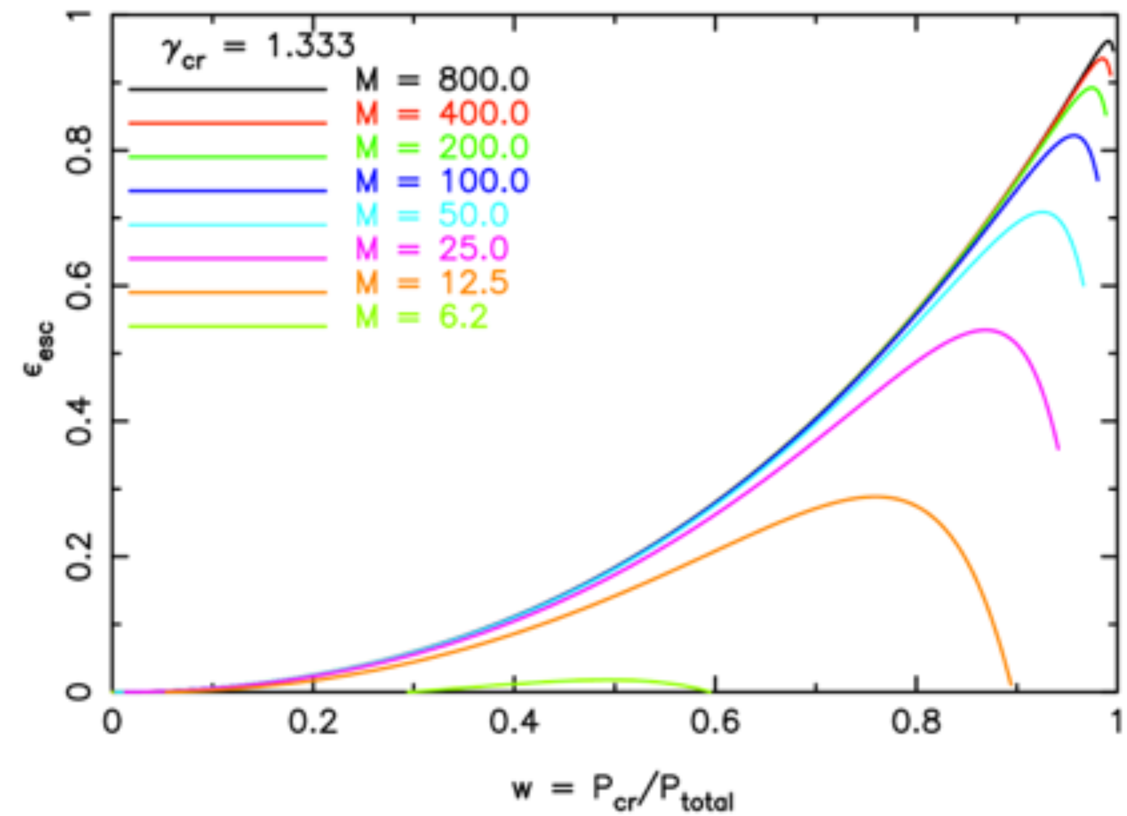

- Young SNR
- Unusual X-ray spectrum: RRCs, highly (over)ionized, and very Fe/Ni-rich
- No evidence for neutron star → *was a black hole formed?* (Lopez+ '13)
- Has been suggested (and contested) as a GRB remnant (Keohane+ '04,Miceli+ '06)

# Results of simple Rankine-Hugoniot extensions

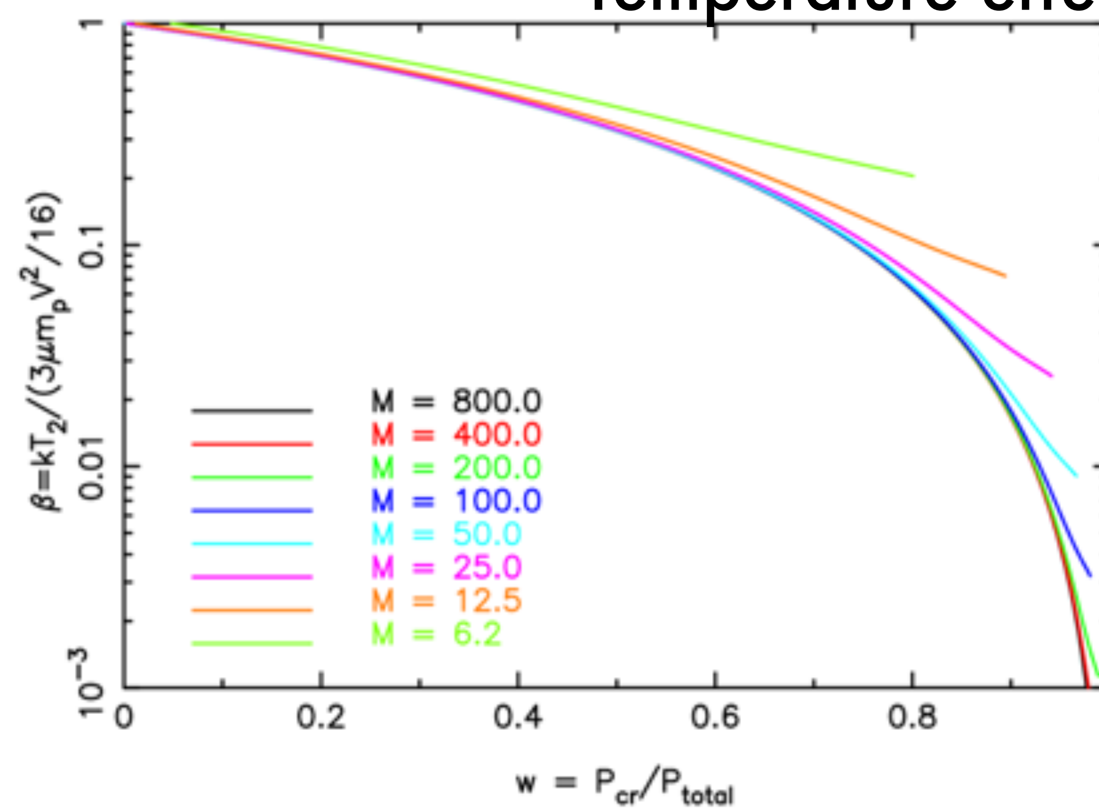
Compression




Escape




Temperature effects




Higher acc. efficiencies

$w = P_{cr}/P_{tot}$

Vink+ '10, Vink&Yamazaki '14

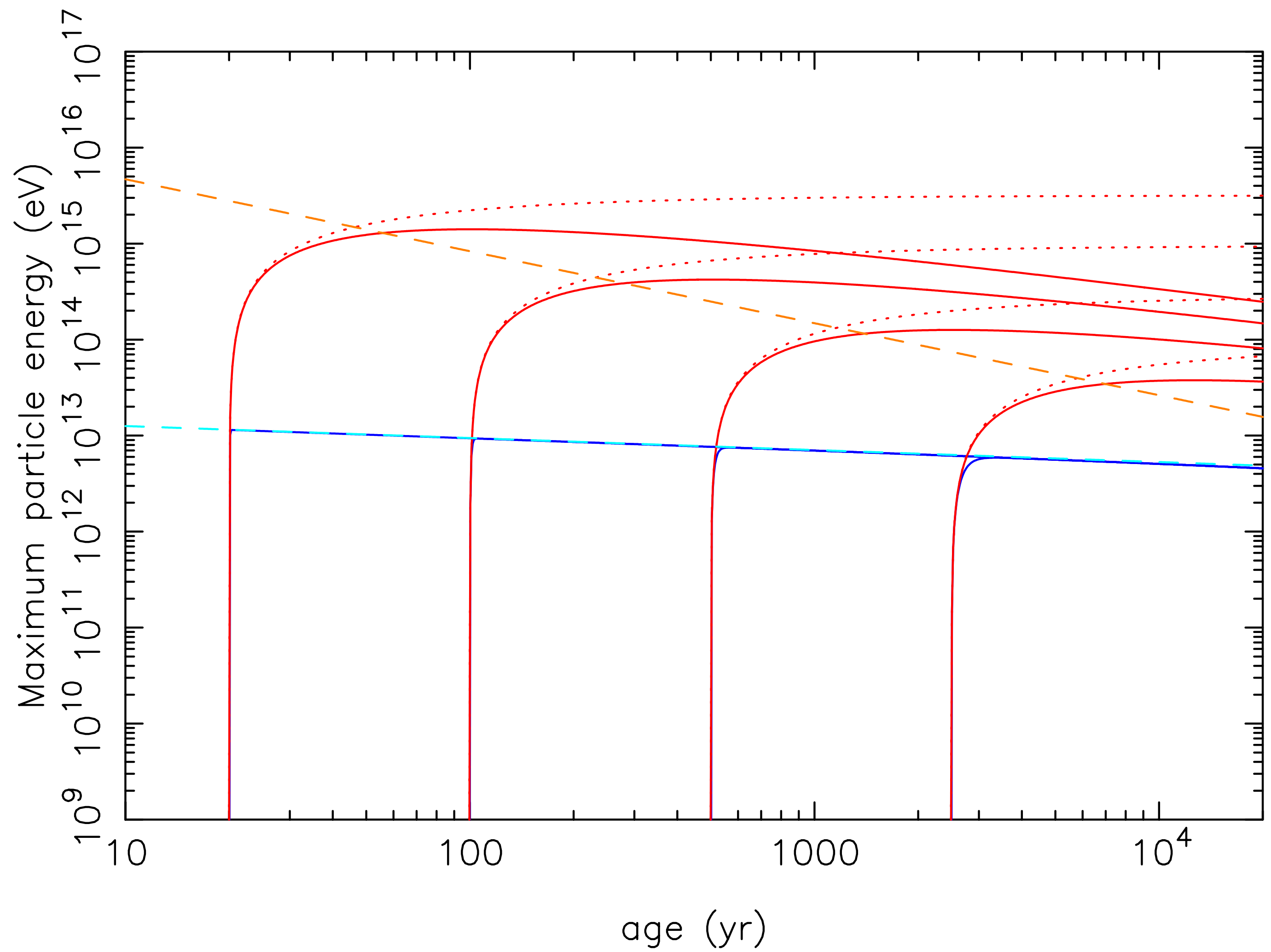
# The maximum CR energy with B-field amplification

max. particle energies

electrons, protons, loss-limited

loss-limited, $B^2 \alpha n V^3$,

B(300yr)=400μG

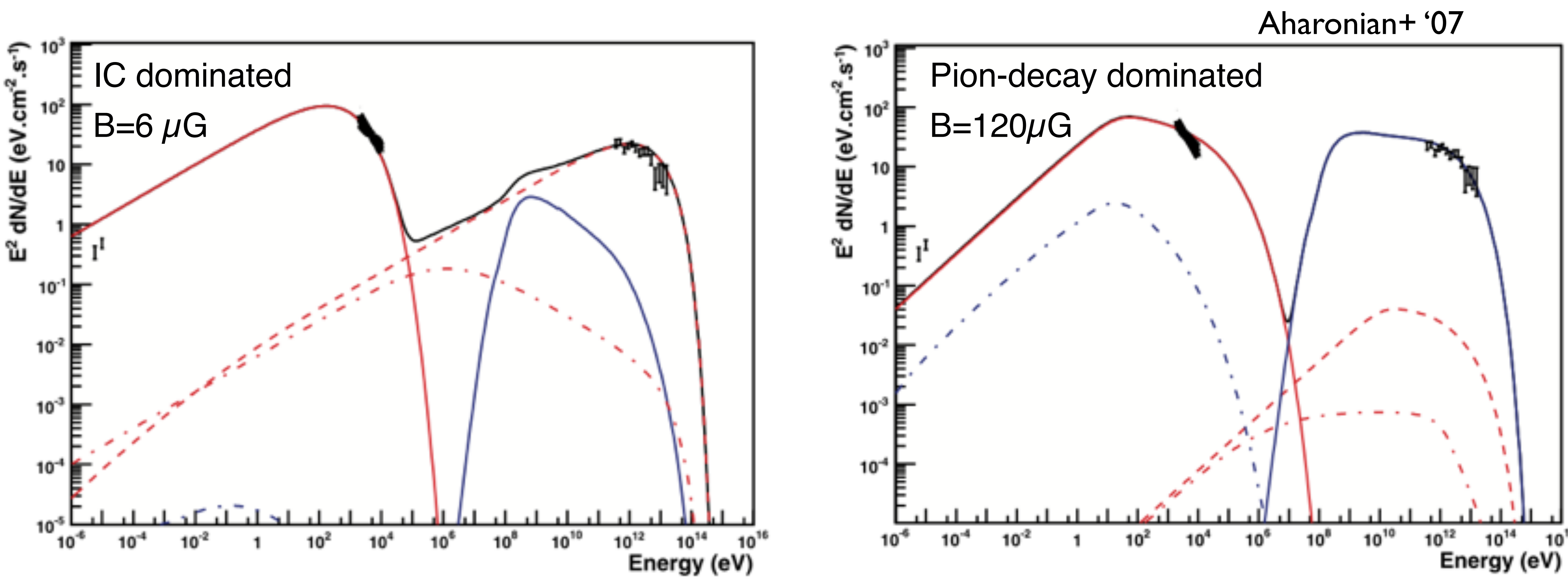



- CR induced B-field amplification SNRs
  - Acceleration up to $3x10^{15}$eV possible, but only very early on (20 yr)
  - *Only a sub-set of SNRs can achieve this: need high density wind (Cas A)*
  - Particles better escape when they reach maximum:

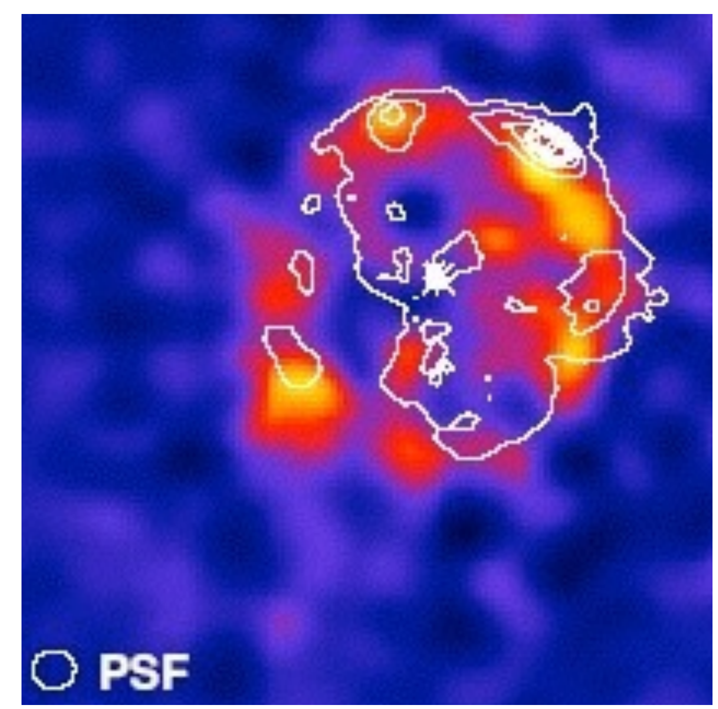
    -turns out adiabatic expansion important when $l_{diff} \approx 0.1\ R_{snr}$

    -escape prevents adiabatic cooling

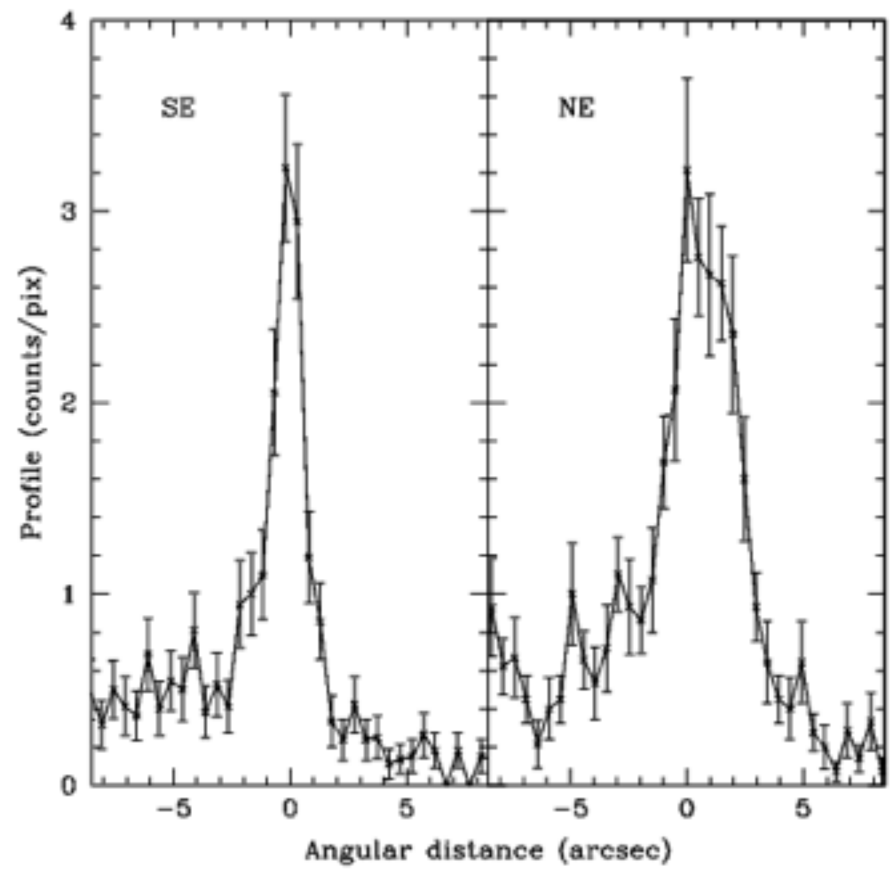
# TeV γ-rays: hadronic or leptonic emission?

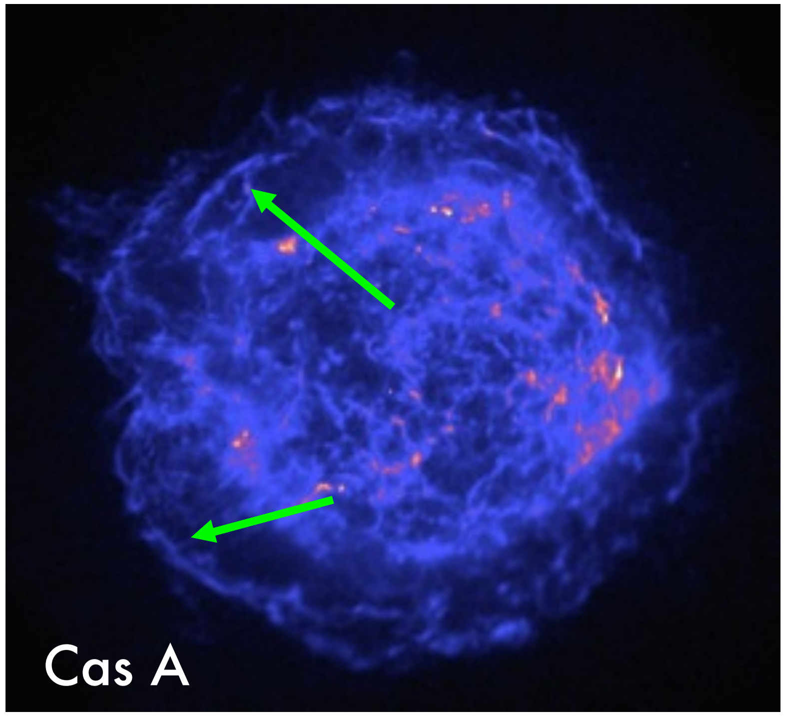


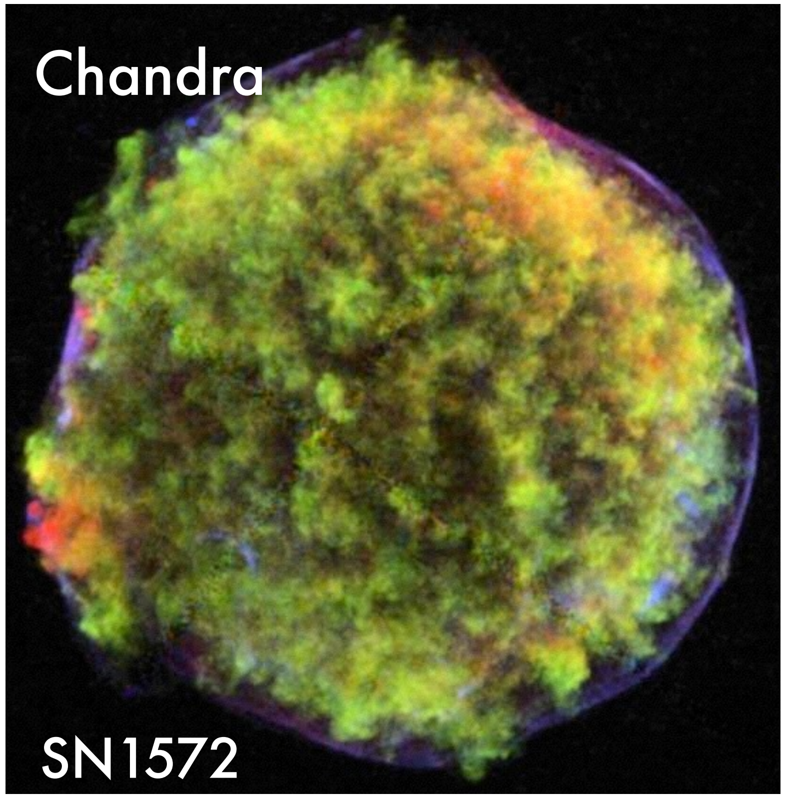

- Debates on the nature of most TeV SNRs
- Most heated: RXJ1713 and Vela Jr
- Heated debates on gamma-ray emission
  - pion decay: requires high densities/high B-fields
- Adding GeV data (Fermi/Agile):
  - Can solve the case
  - But depends on intrinsic CR spectrum



# Narrowness of X-ray synchrotron filaments



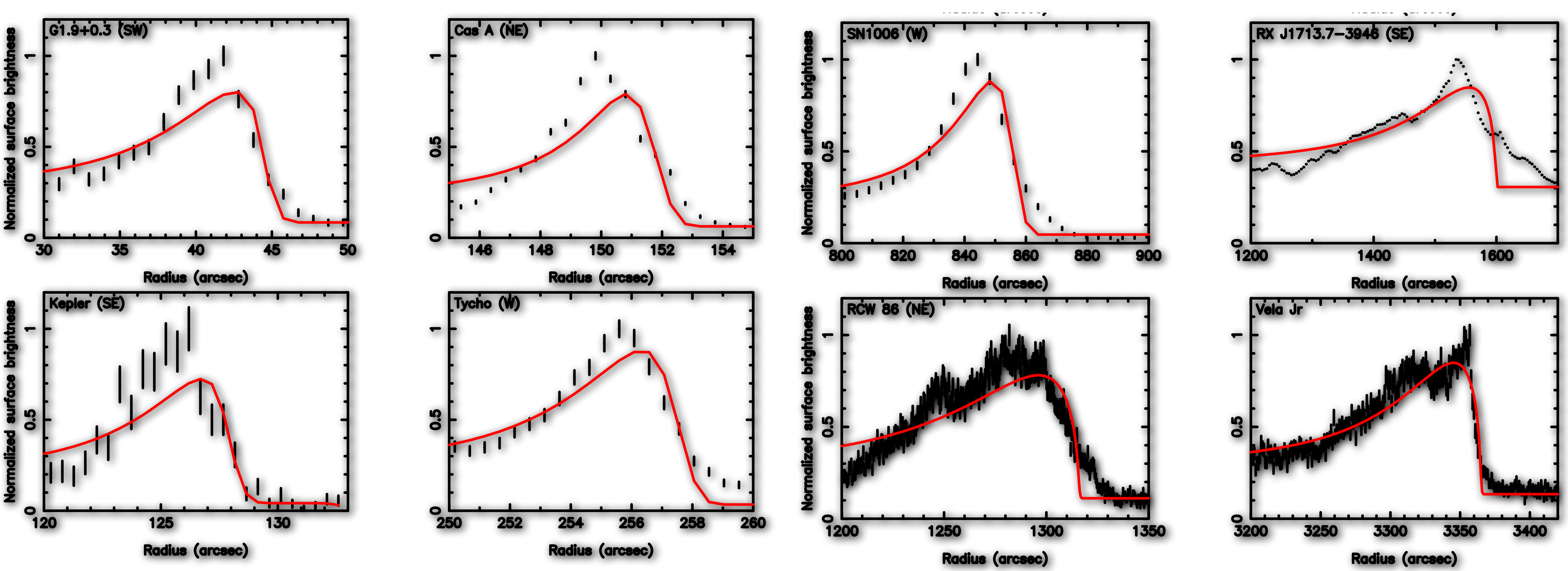




- In many cases X-ray synchrotron filaments appear very narrow (1-4″)
- Including deprojections implies $l \approx 10^{17}$cm

e.g. Vink&Laming ’03, Völk et al. 03, Bamba+ ’04, Ballet ’06,Warren+ ’05, Parizot+ ’06)

# X-ray synchrotron profiles

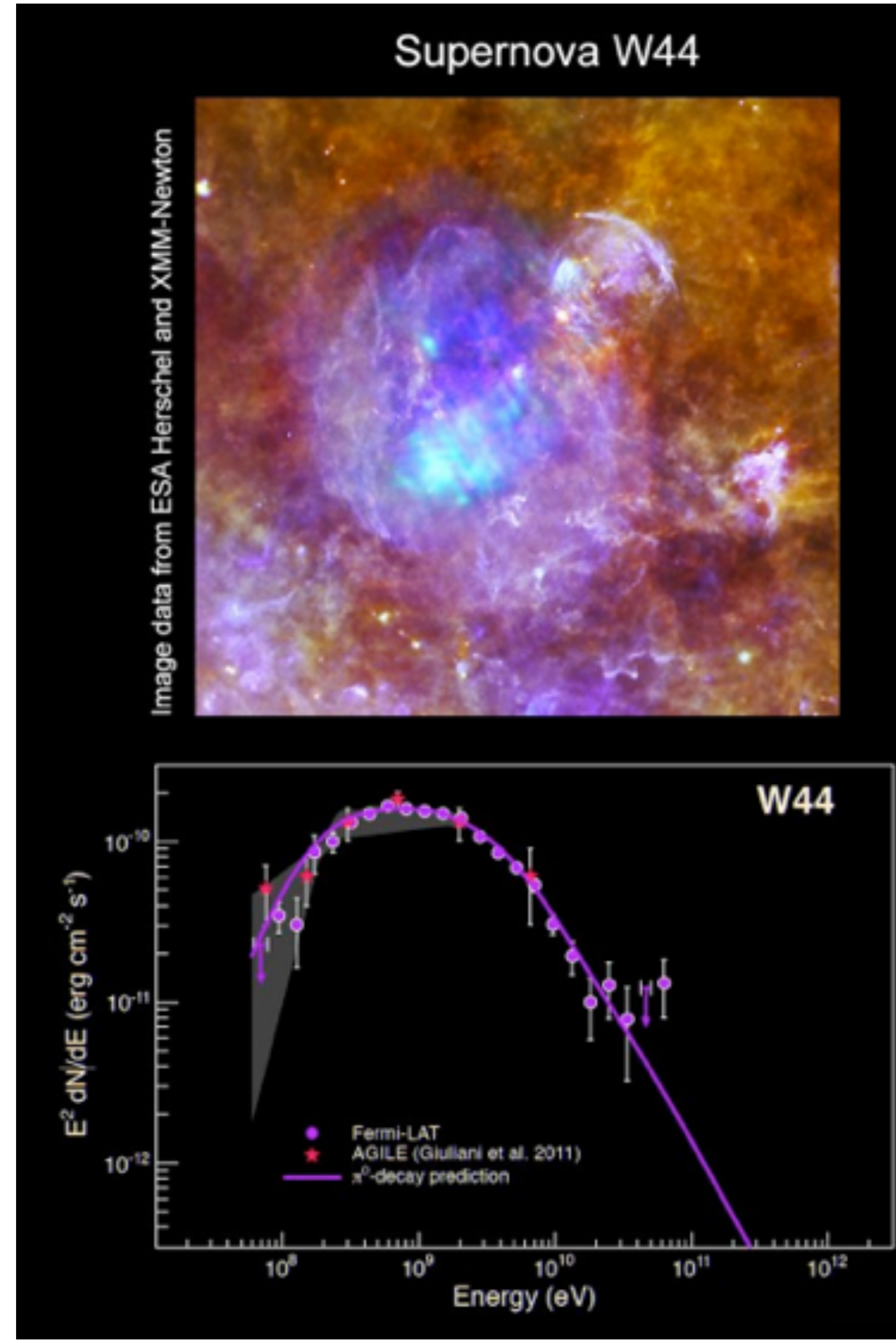



Helder, JV, et al. 2012

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

# Fermi does detect hadronic emission

Ackermann+ 2013

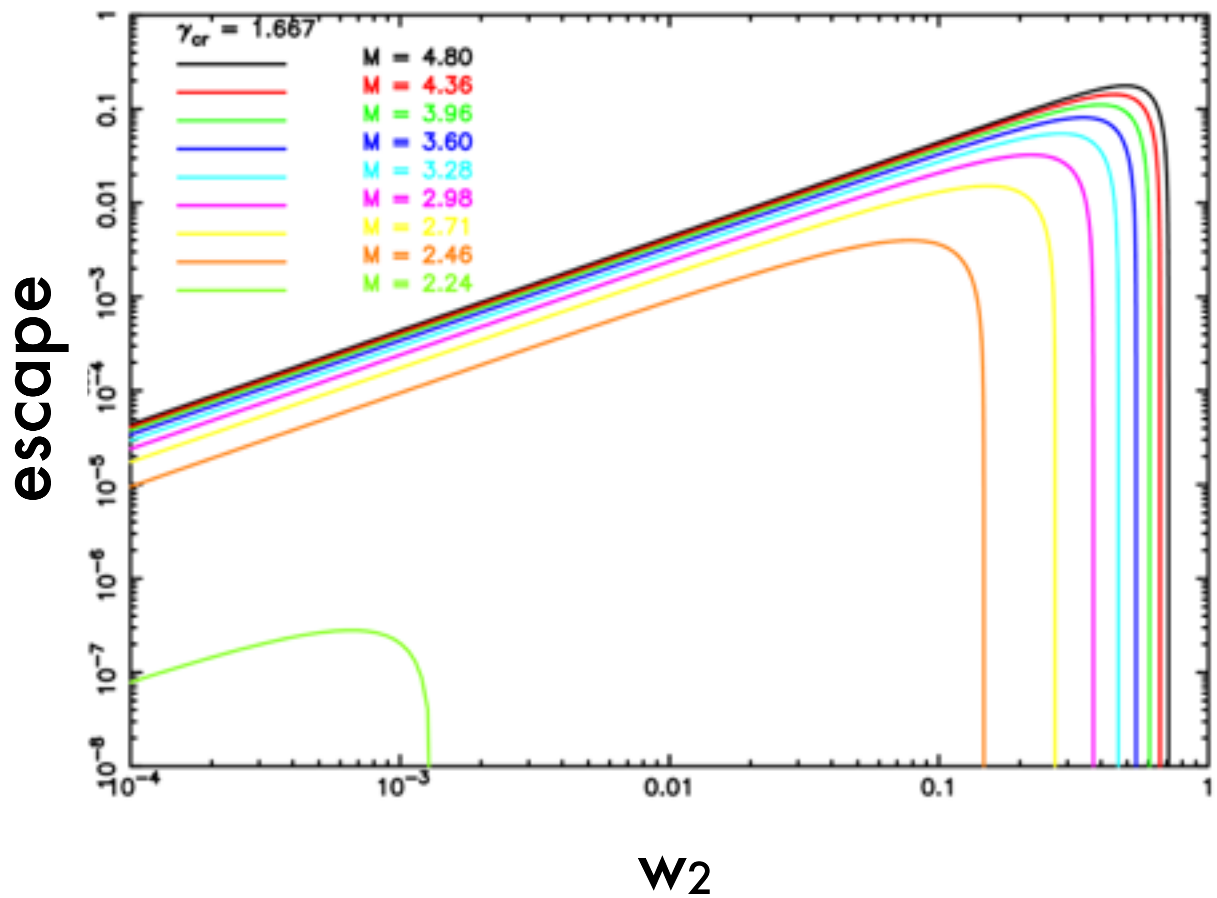



- Pion-production: expect turnover $\sim$200 MeV
- Detected in at least 2 SNRs W44 & IC443 (Agile/Fermi)
- *Proof that protons/ions accelerated!!*
- But:
  - In these sources 10 GeV cut-off!!
    - Where have the > TeV protons gone?
    - Escape seems to be important and happens before < 3000 yr

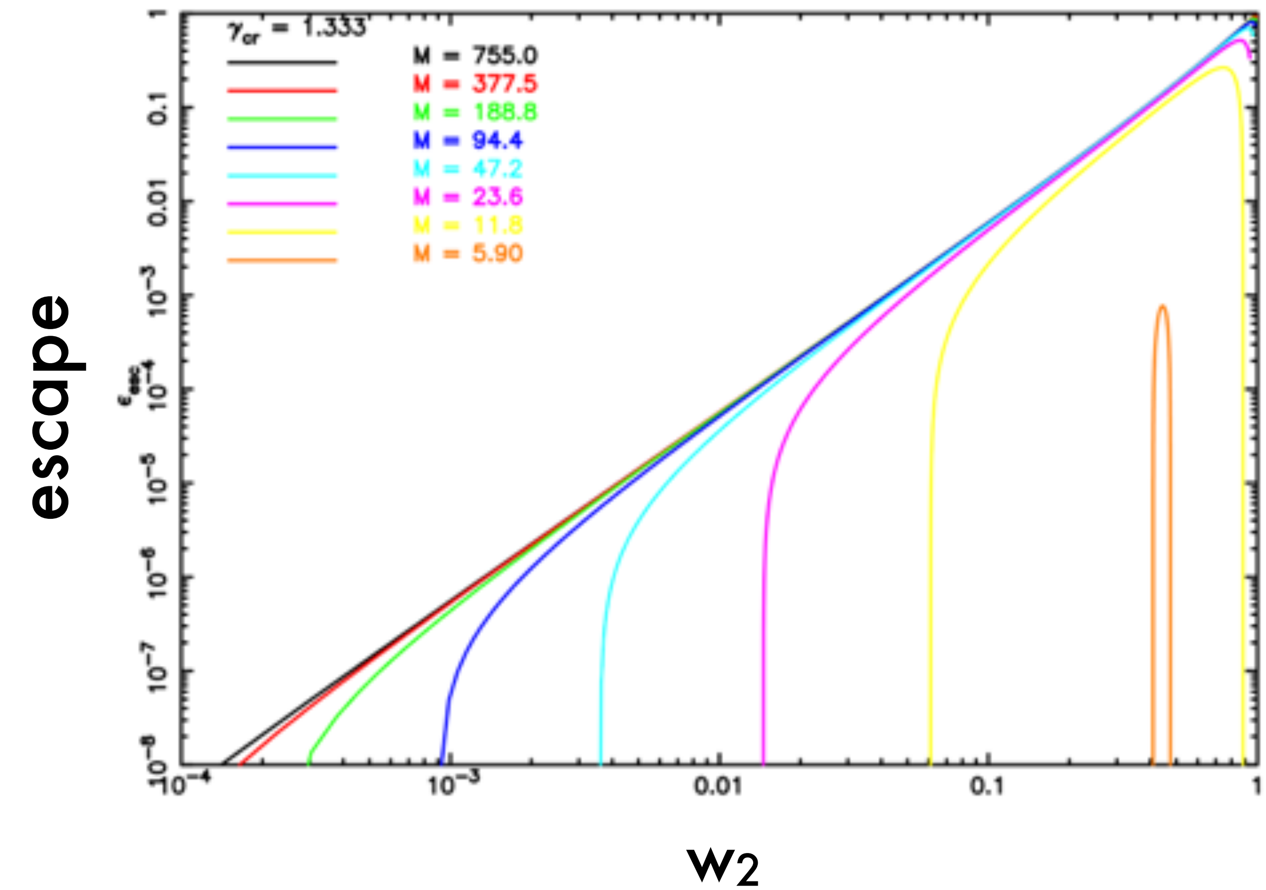
      Compare recent non-detection of Puppis A by H.E.S.S.!

# No non-linear acceleration & efficiency at low Mach numbers

Vink+ '10, Vink&Yamazaki '14



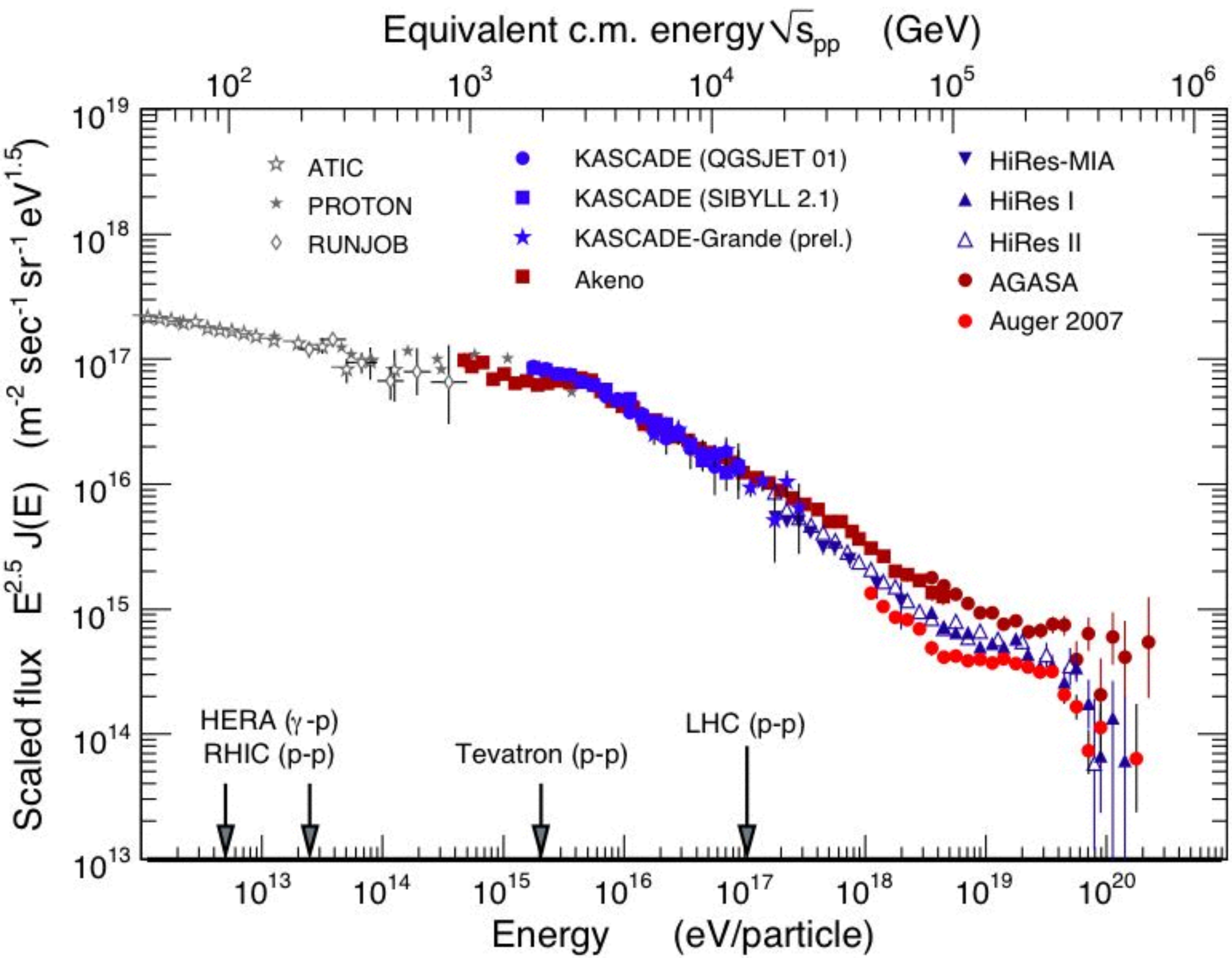

Non-relativistic particle population



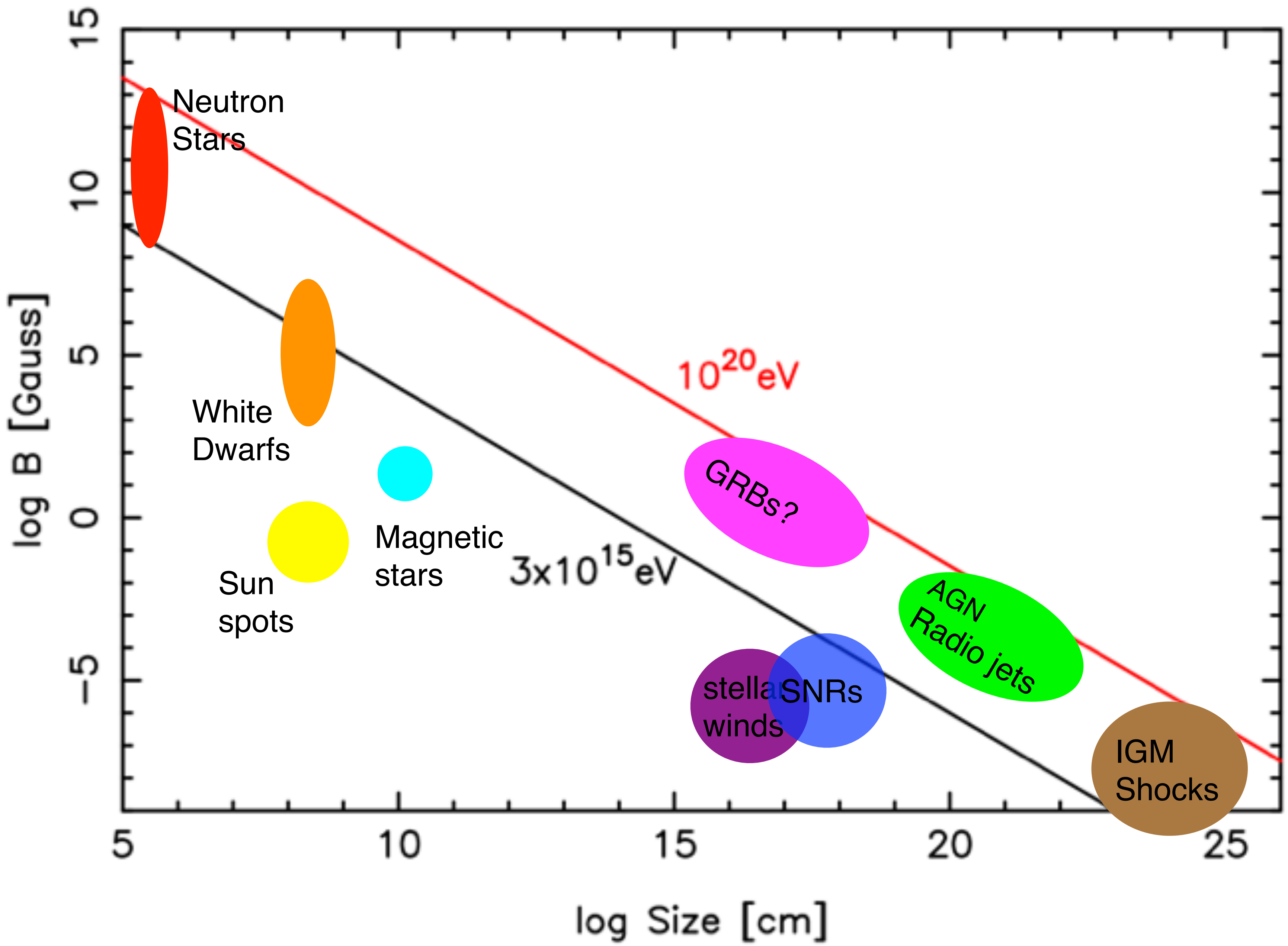

Relativistic particle population

- For non-relativistic cosmic rays: $M > \sqrt{5} \approx 2.236$
- For relativistic dominated particles ($\gamma_{cr}=4/3$): Mach nr $M > 5.88$
- Different behavior for $\gamma_{cr}=4/3$ and $\gamma_{cr}=5/3$

# The Cosmic Ray Spectrum



# Hillas plot




- Hillas' (1984) criterion: $B_{\mu G} L_{pc} > 2E_{15}/Z\beta$

(Diffusion lengthscale < size object)