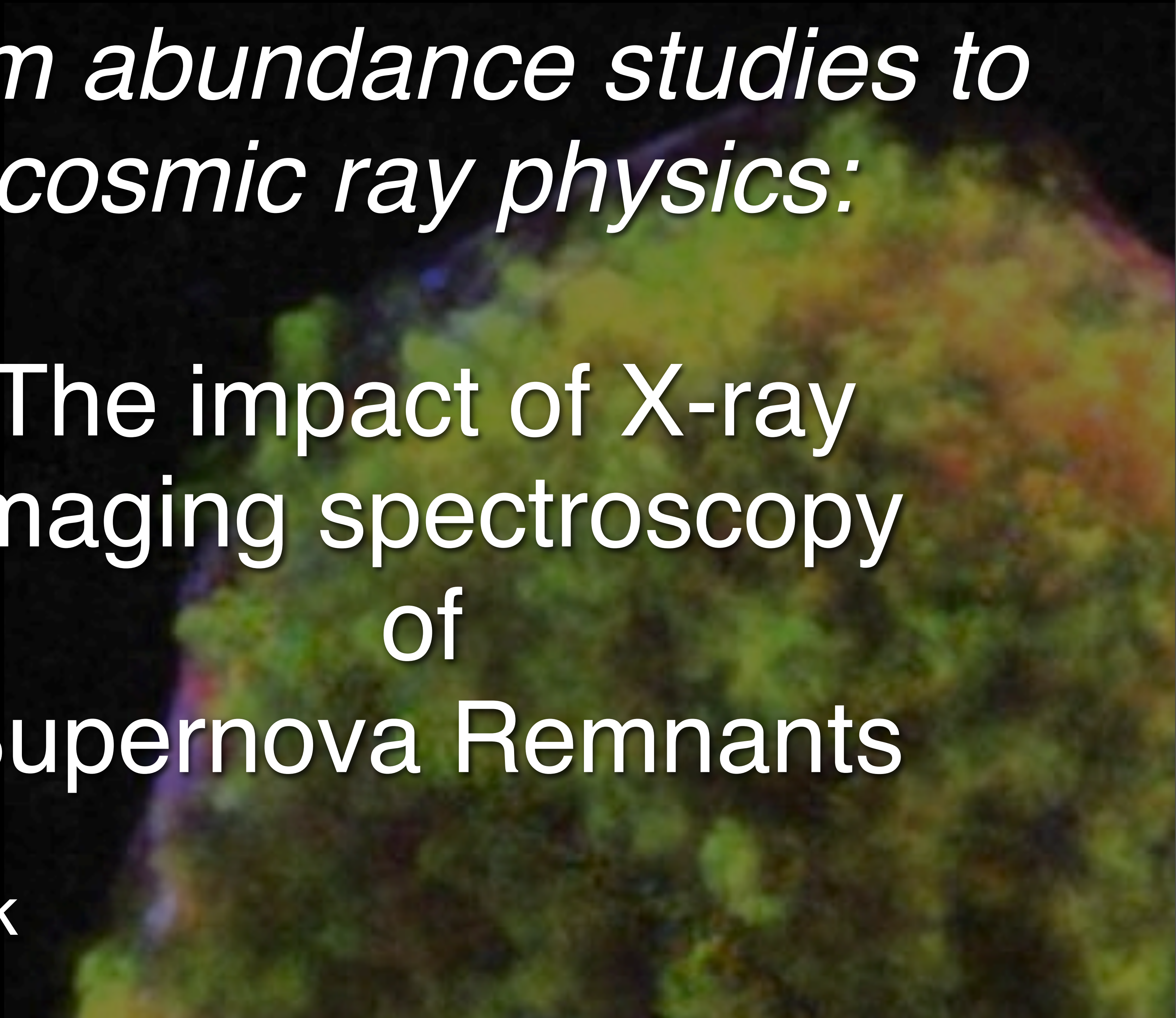
From abundance studies to cosmic ray physics:

The impact of X-ray imaging spectroscopy of Supernova Remnants



Jacco Vink

SNRs introduction

- SNRs are hot shells created by a SN explosion ($E \sim 10^{51}$ erg)
- The shells consist of a mixture of SN ejecta and shocked CSM
- Initial velocities are >~10000 km/s
- Young SNRs (~500 yr) have ~2000-5000 km/s
- SN ejecta shocked by reverse shock
- In “mature SNRs” reverse shock has reached center

- As long as Vs> 100 km/s: X-ray emission from hot plasma
- For V_s< 200 km/s ($kT<10^6$ K): rapid cooling -> energy loss important

- X-ray emission from hot plasma:
    - low density: non-equilibrium ionization -> plasma underionized!
    - Suzaku: some old SNRs may be overionized
- Additional X-ray emission: synchrotron radiation

This talk, concentrate on
1 X-ray emission from SN ejecta
2 X-ray synchrotron radiation

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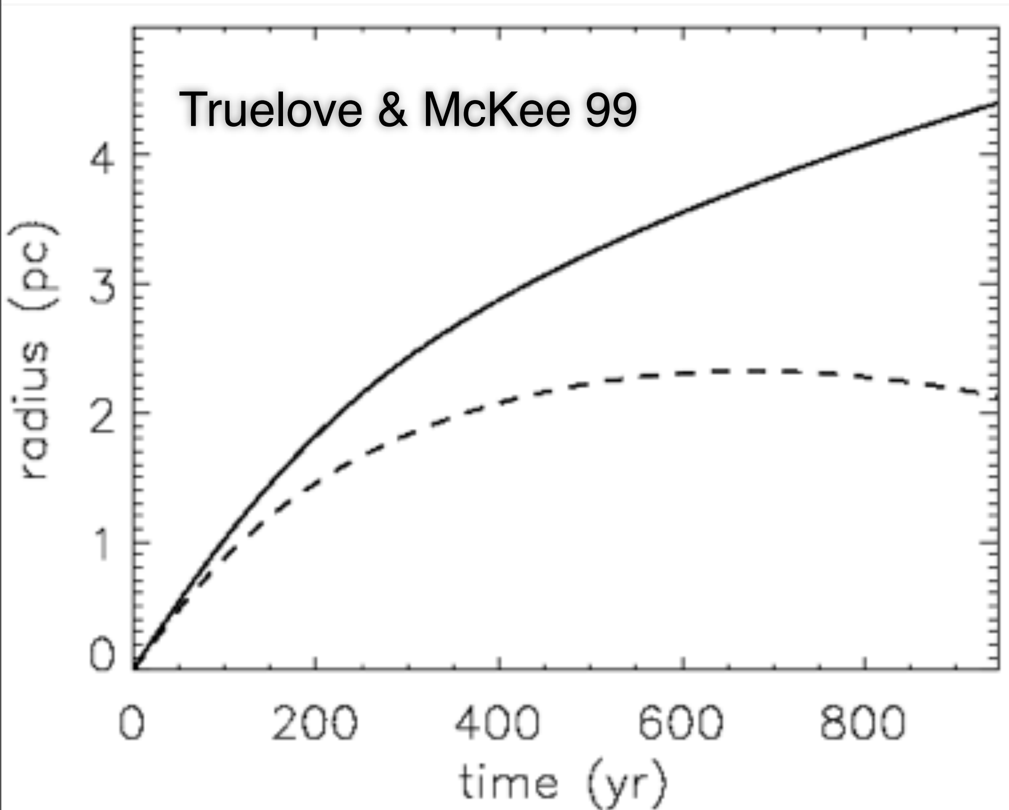
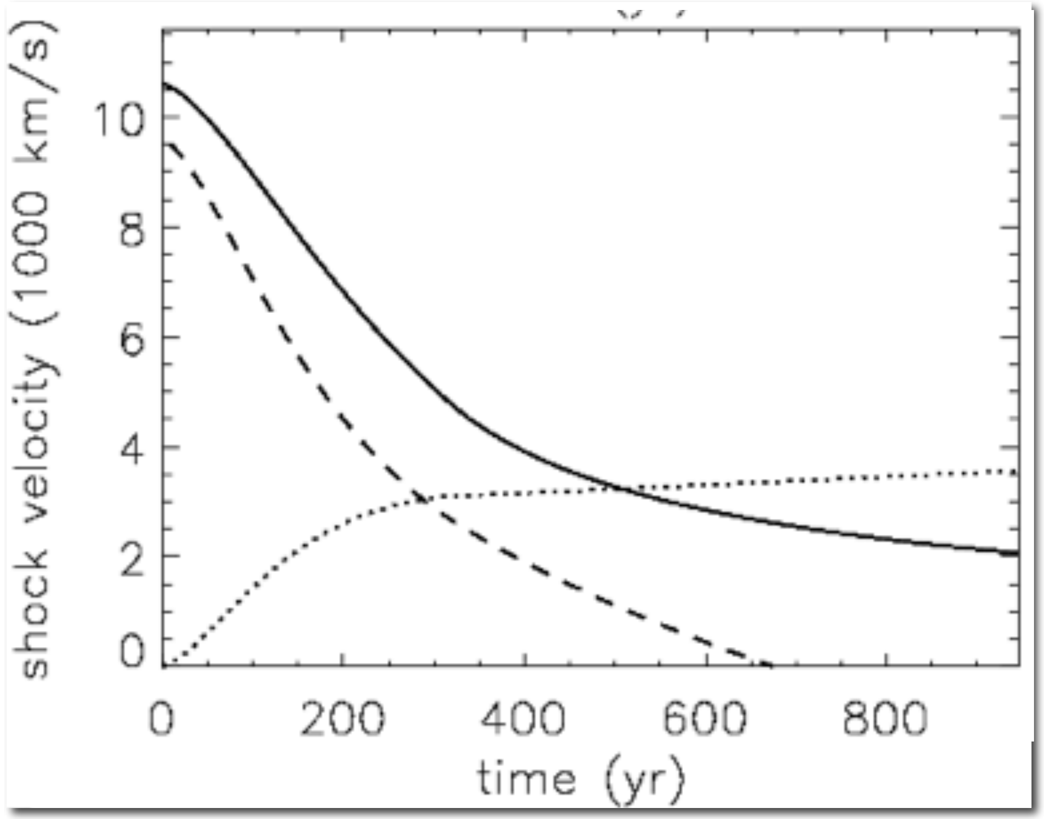
The X-ray Universe, Berlin 28-6-2011

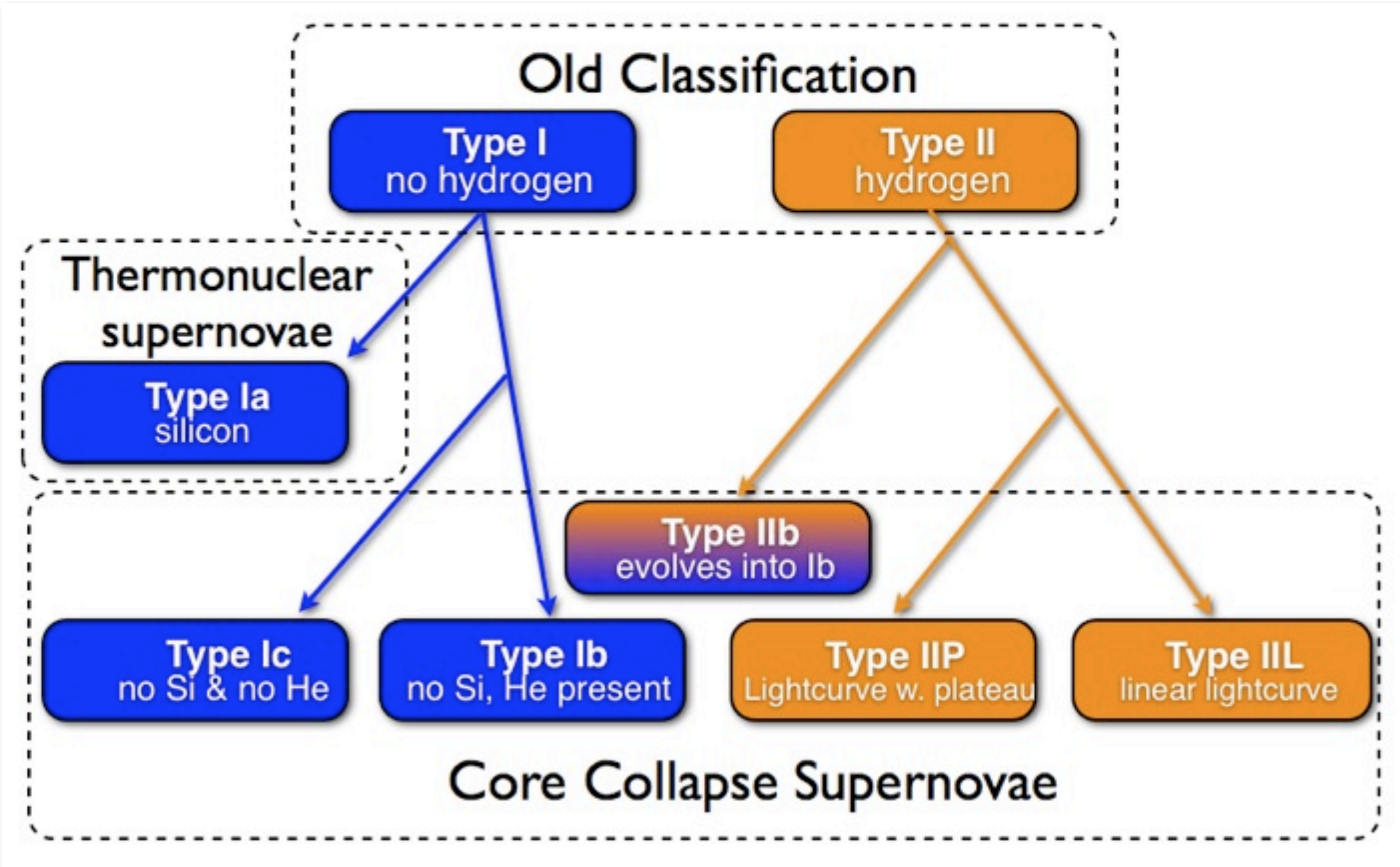
SNR structure & evolution





Studying Supernovae with Supernova Remnants

Supernova Types



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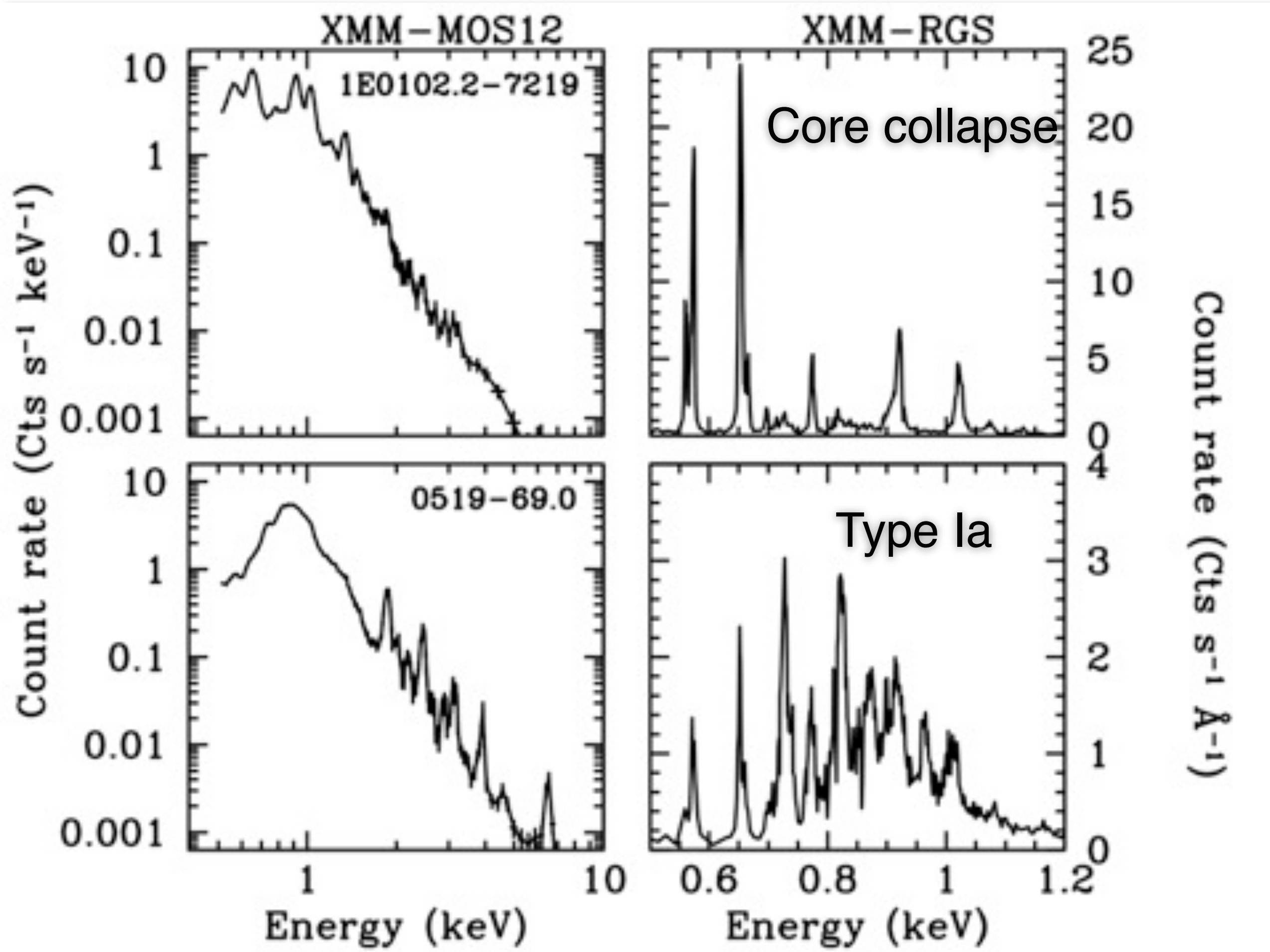
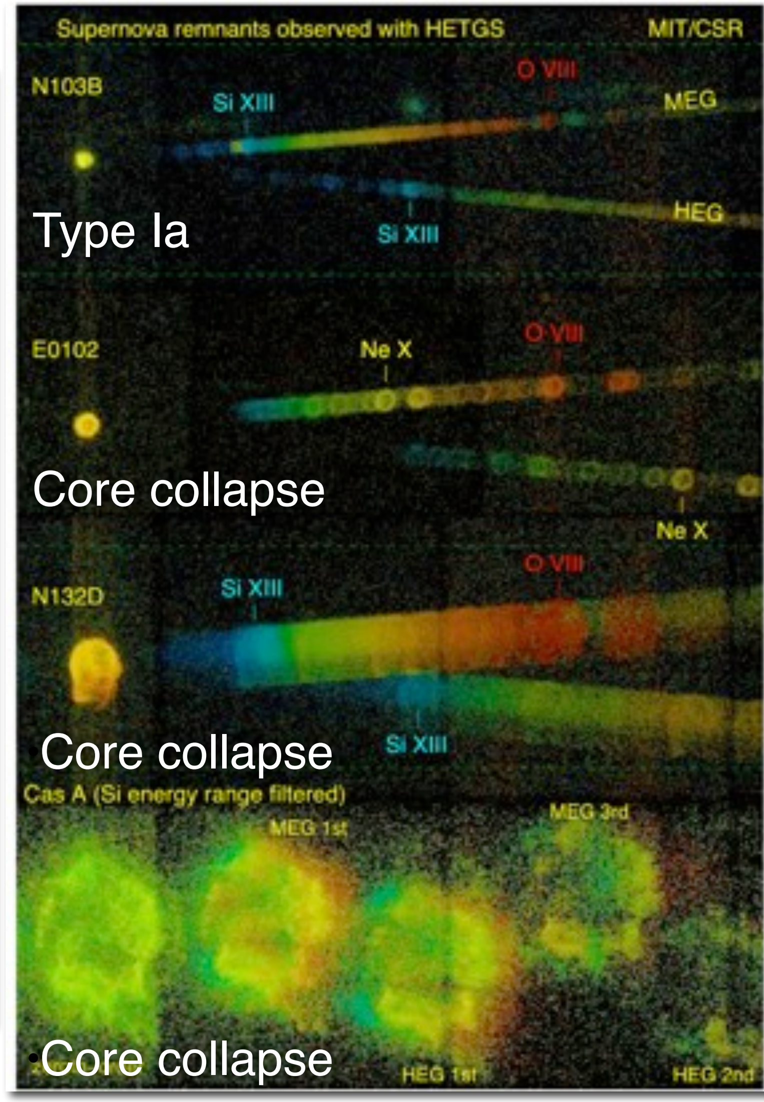
CCDs vs Grating Spectroscopy

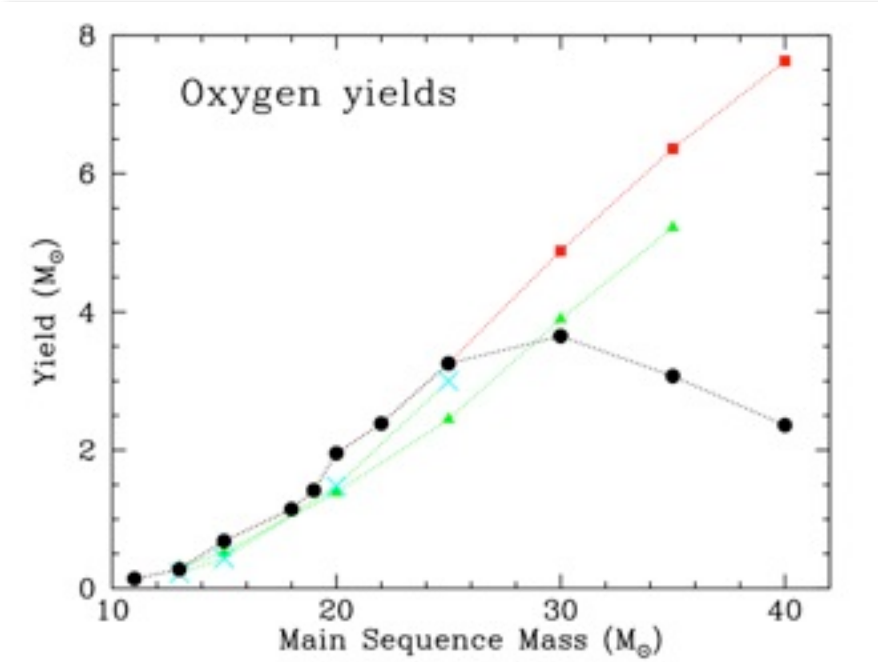


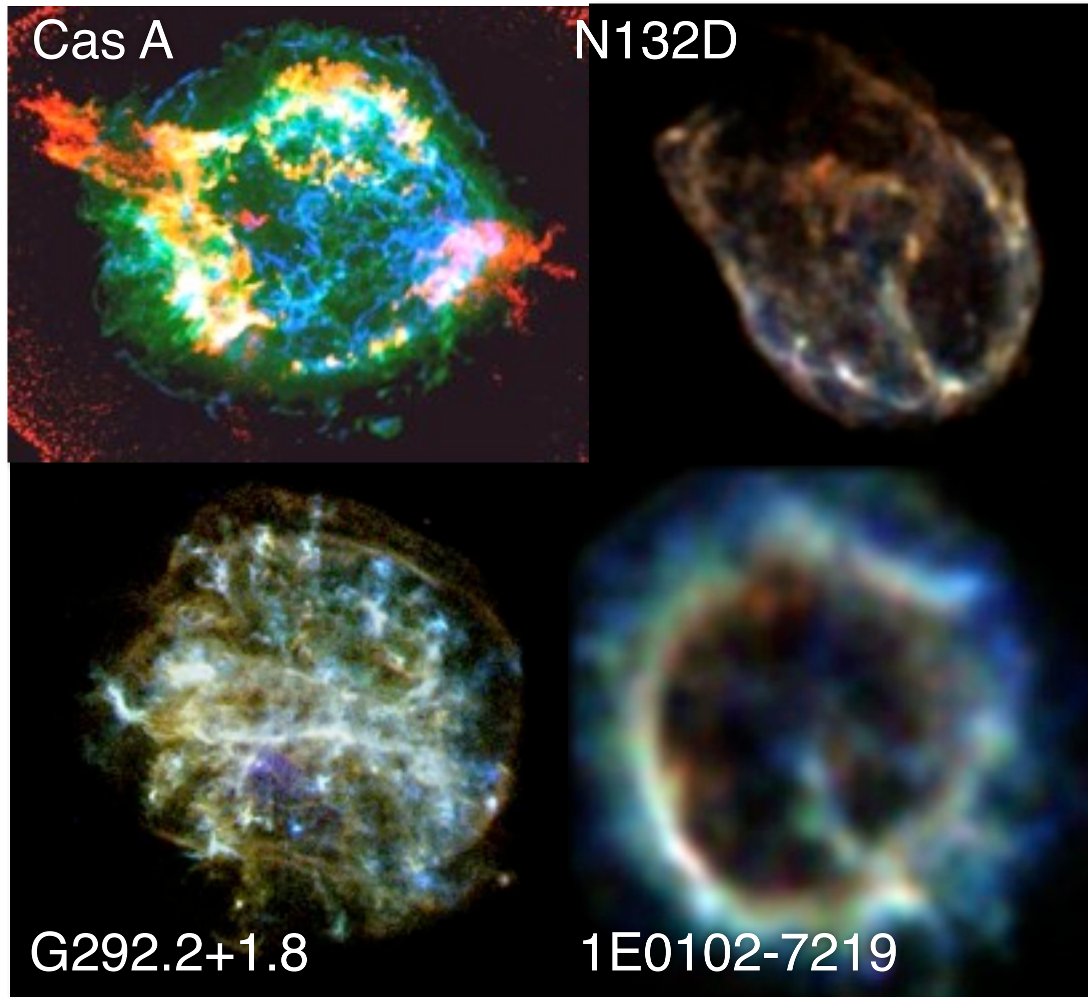


e.g. Hughes '95, Flanagan+ '04, Kosenko+ '10

Chandra MEG/HEG (Dewey)

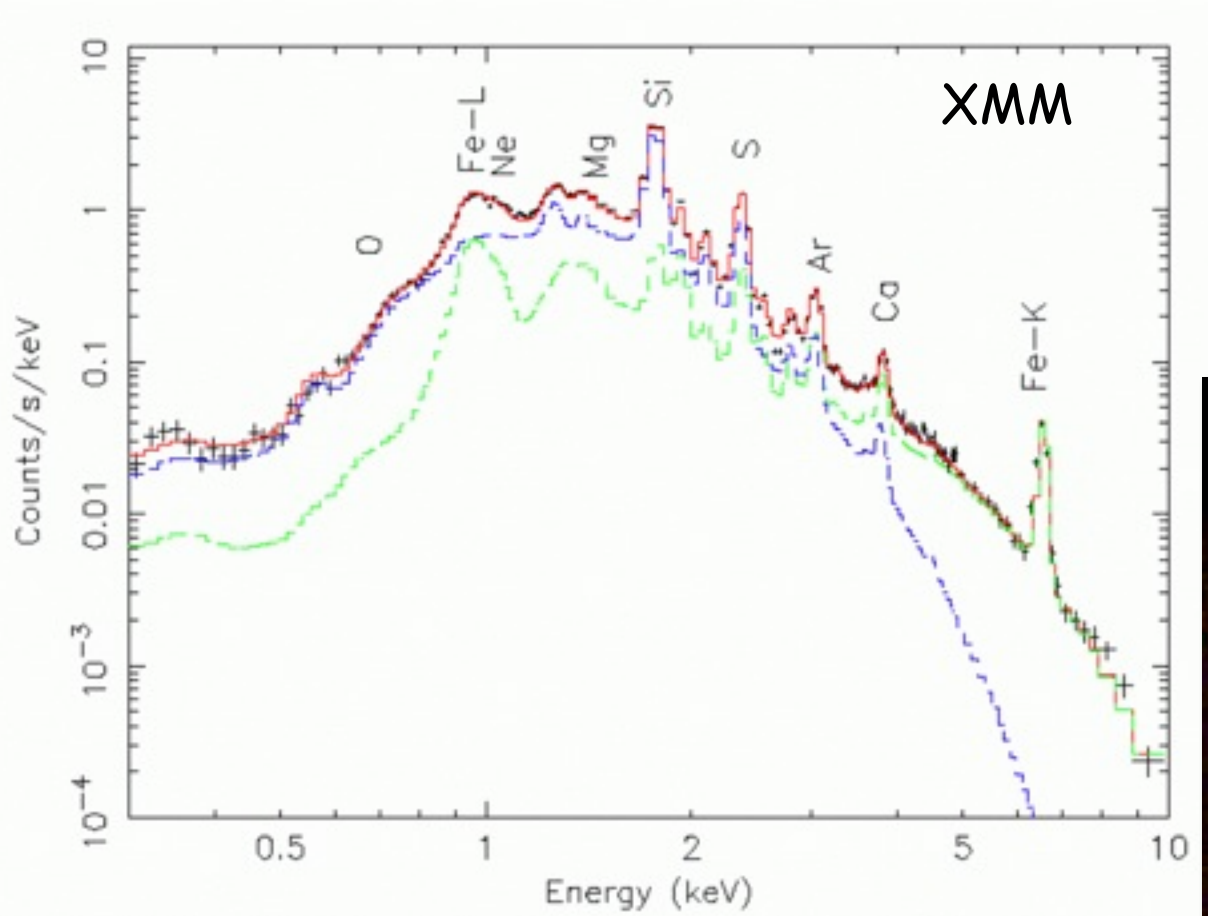
Oxygen-rich SNRs





- M_{Ox} correlates with MS mass
- Several O-rich SNRs known
- For several, but not all, evidence for neutron stars (the other: BHs?)

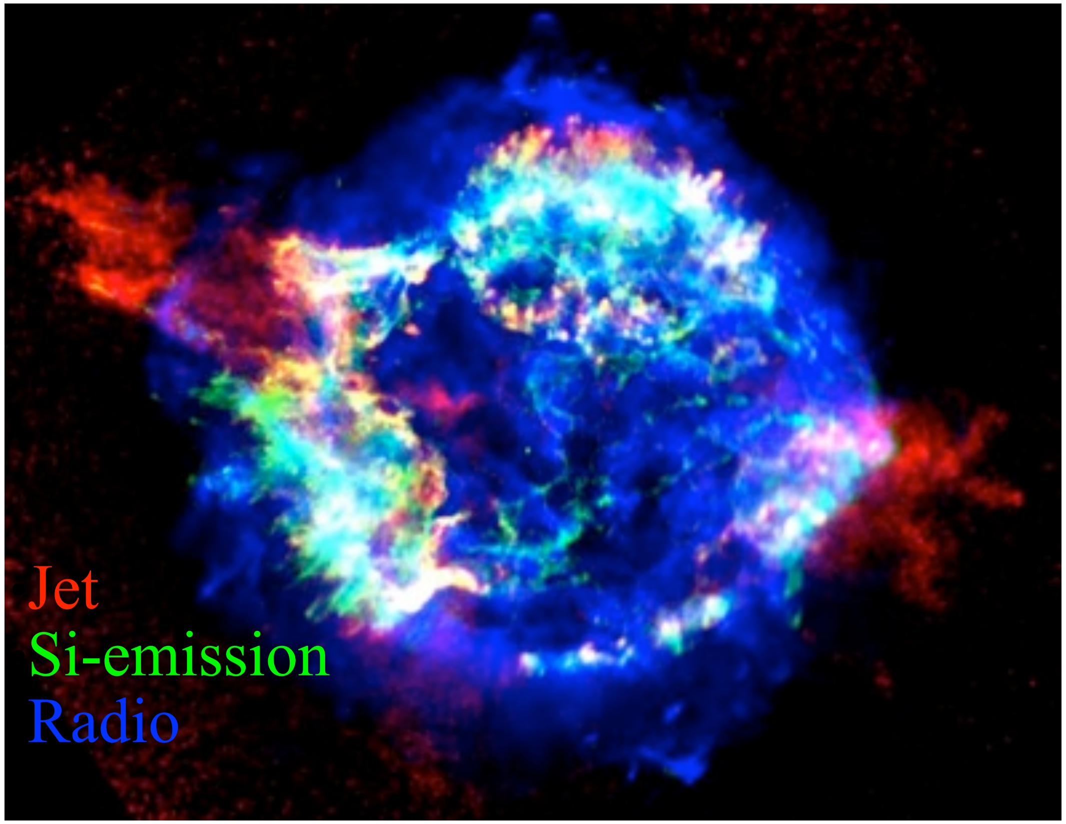
Cassiopeia A



- Lots of Si/S-rich material
- Poor in Ne/Mg
  (contrary to models!!)

- From light echo: SN Type IIb
  (Krause+ 08)

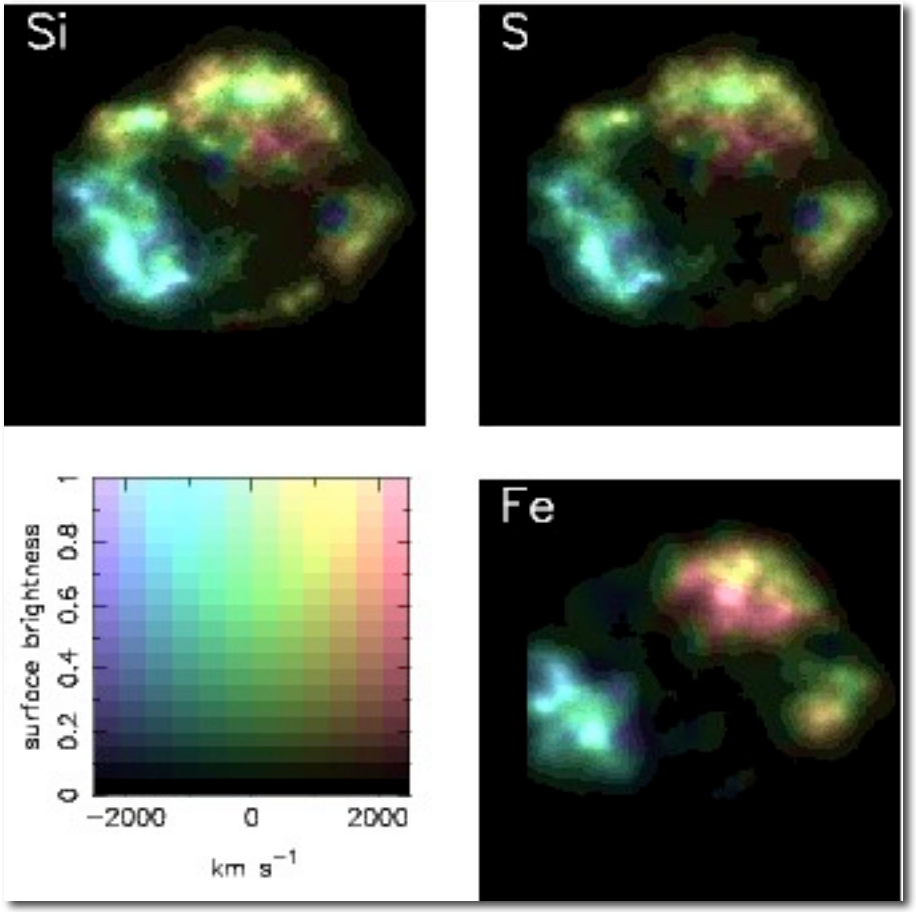
(A)symmetries I: Jet/Counter-jet

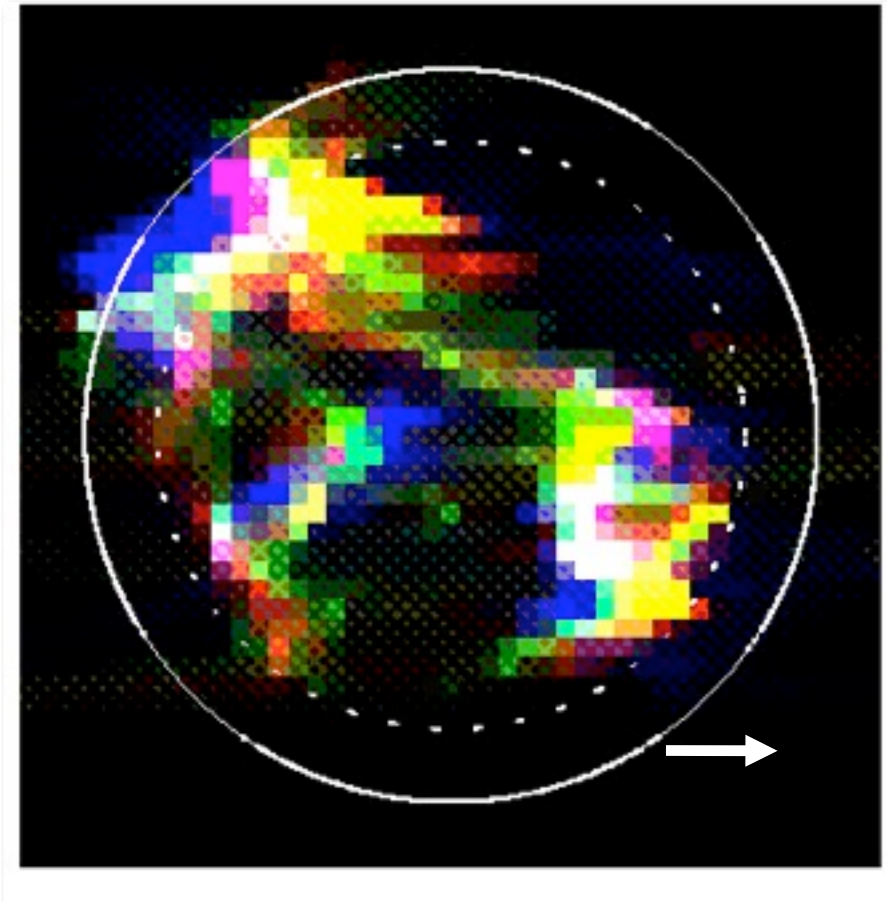


- In X-rays, brought out using Si/Mg ratio: Si-rich
- Optical: sulphur (not oxygen) fast moving knots
- If originating in core, why Si/S & not Fe rich? (Si bipolar/Fe irregular)
- Not a GRB jet: energy ~$10^{48\text{-}49}$ erg (Schure et al. '07)

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

(A)symmetries II





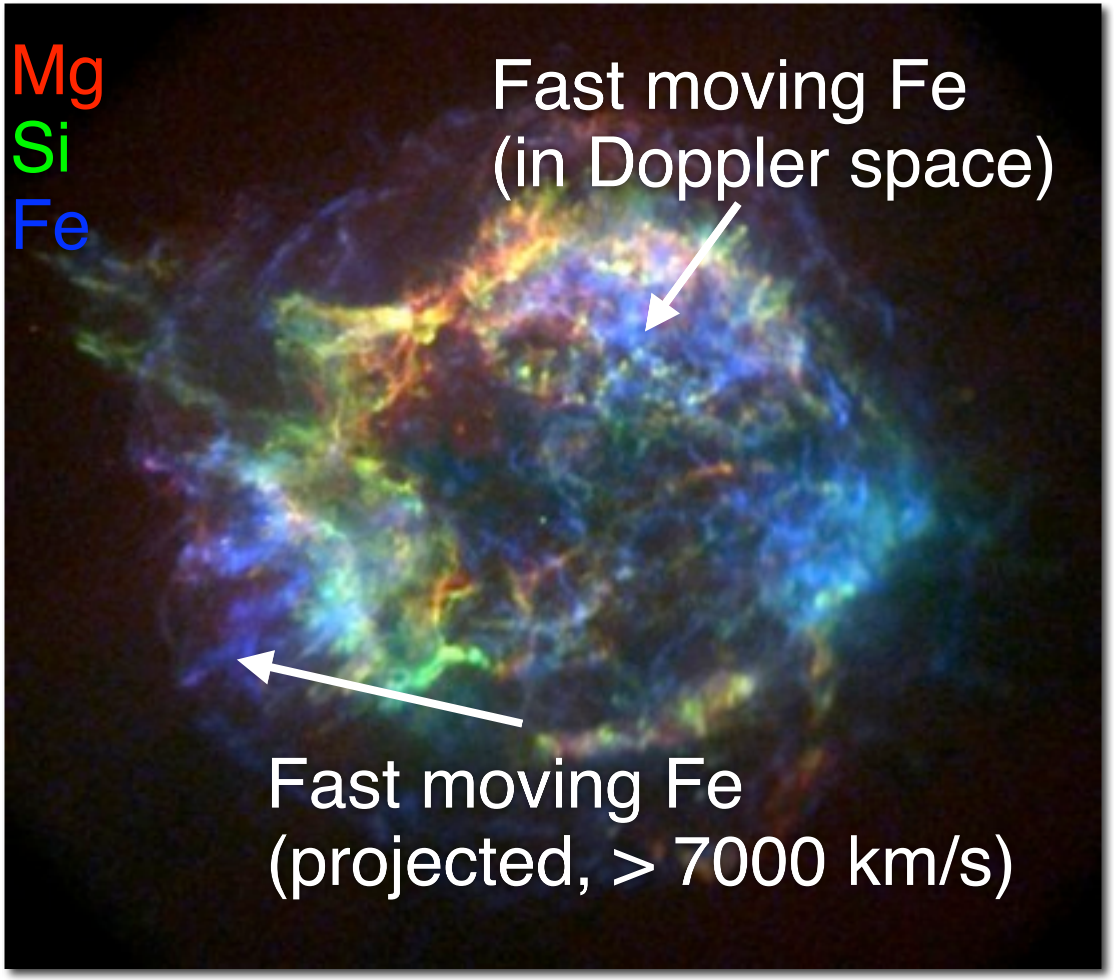
XMM-Newton based Doppler map + deprojection

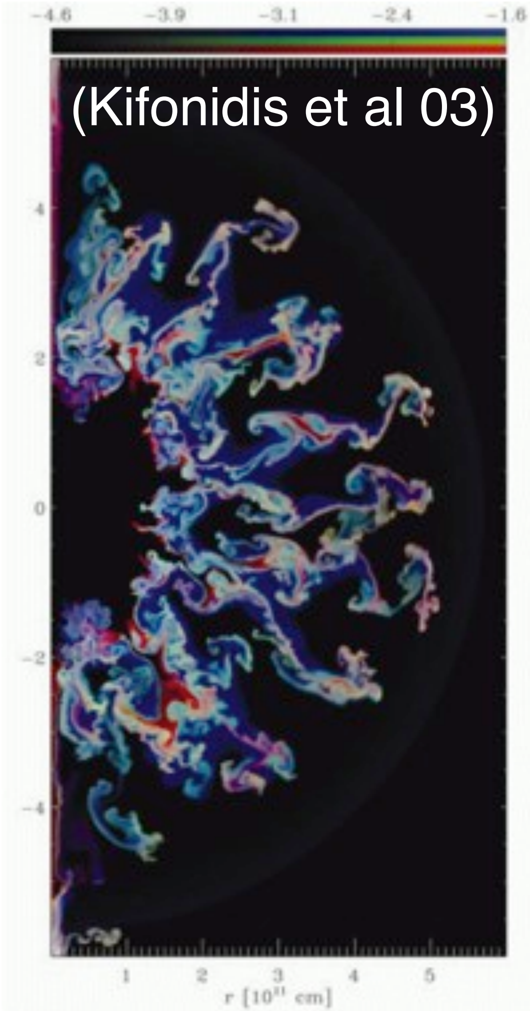
Cas A shows donut like shape

Willingale+ ‘02

See also recent multiwavelength study by Delaney et al. 2010

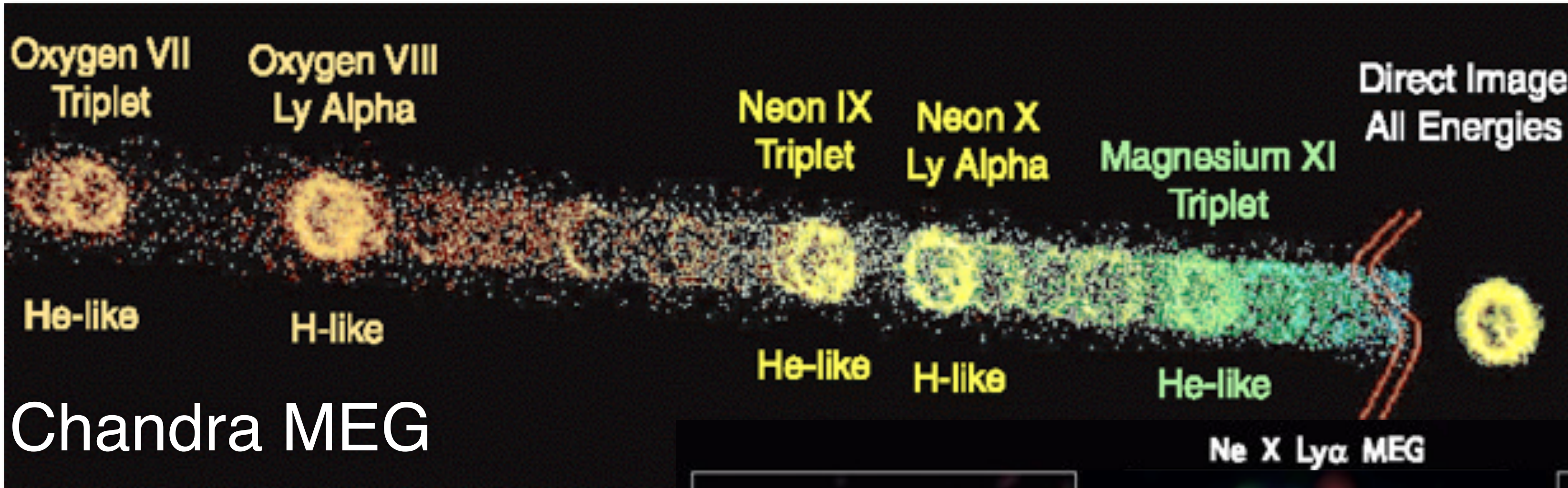
Evidence for fast Fe knots



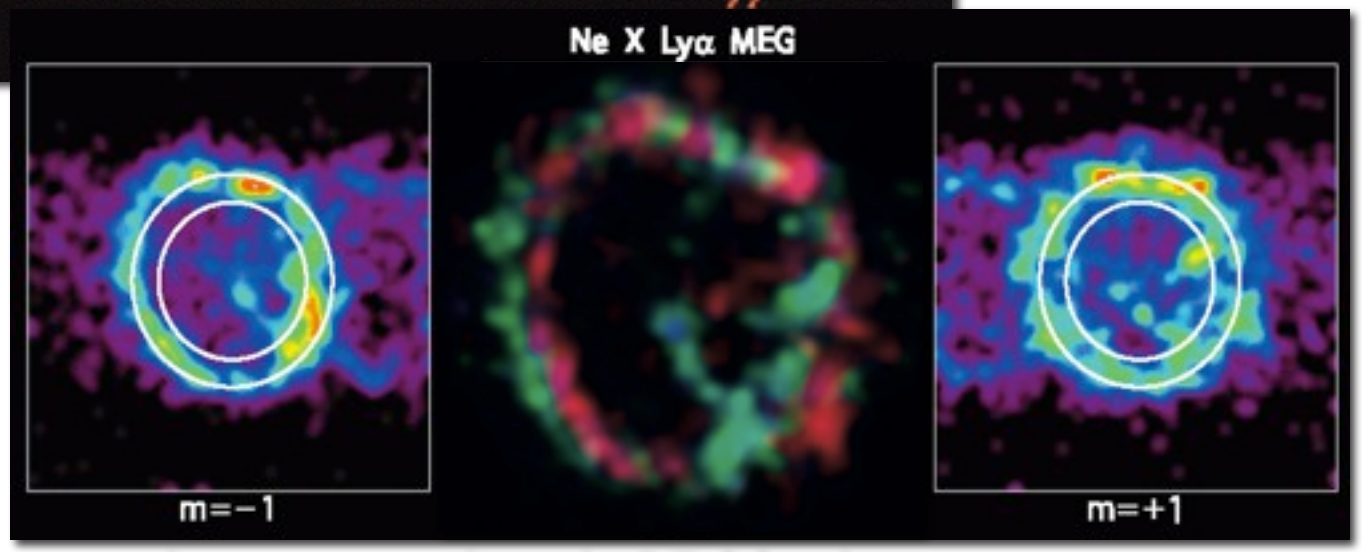


- Fast moving "pure" Fe plasma (Hughes+ '00,Laming&Hwang '03)
- Seen (to a lesser extent) in simulations (in Type Ib/c)

Spectroscopy of 1E0101.2-7219



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
- Expanding donut rather than sphere?

G292.0+1.8

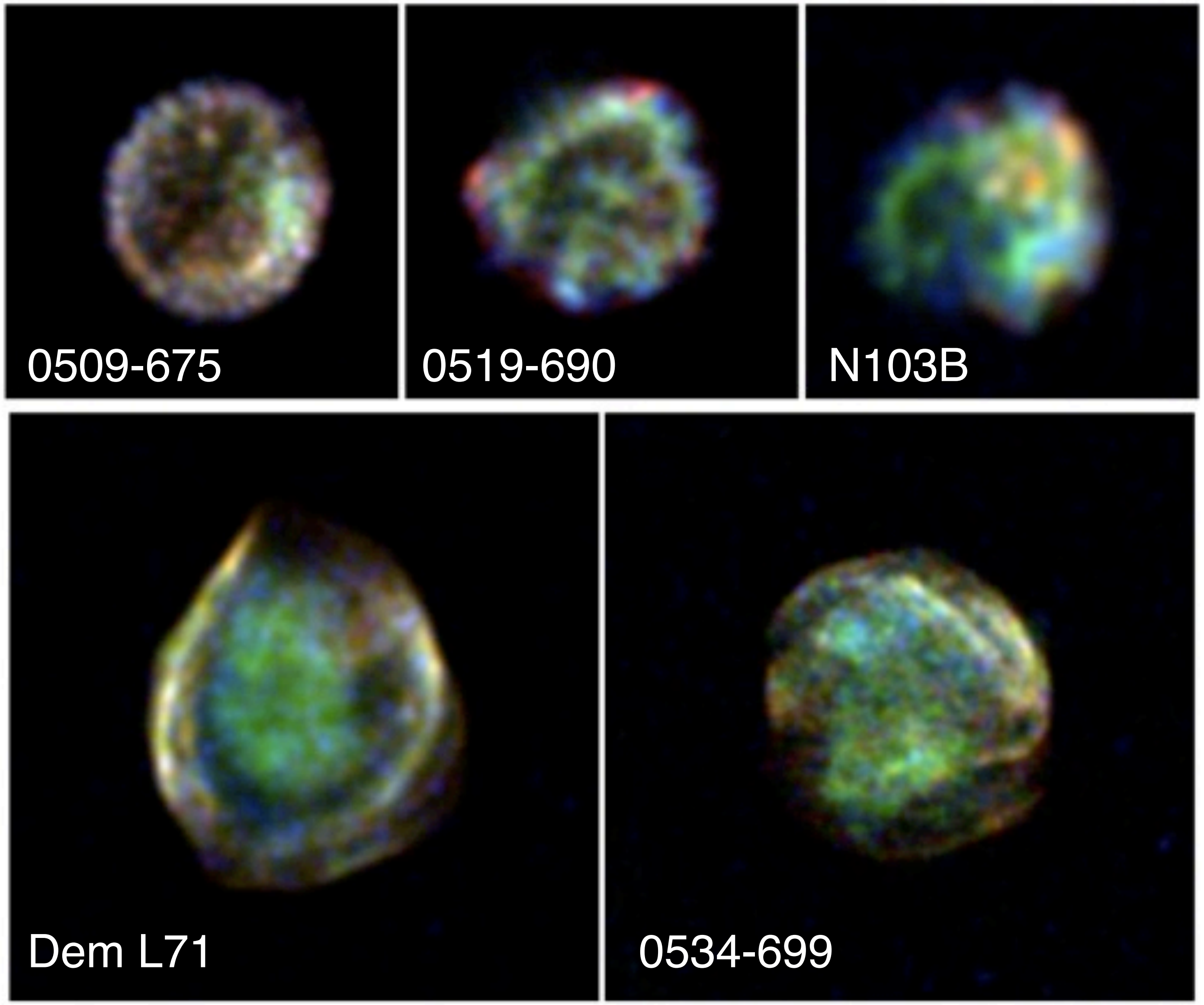
Park+ 07

- Asymmetric distribution of elements
- More Si/S/Ar in western part
- Lots of Ne/Mg (c.f. Cas A)
- Bar origin CSM(?)
- contains 135 ms pulsar
- pulsar wind nebula

- Interest: which stars make neutron stars, which ones BHs?
- Progenitor mass: 30 M_{sun}

(Gonzalez+ 03)

Type Ia supernova remnants



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

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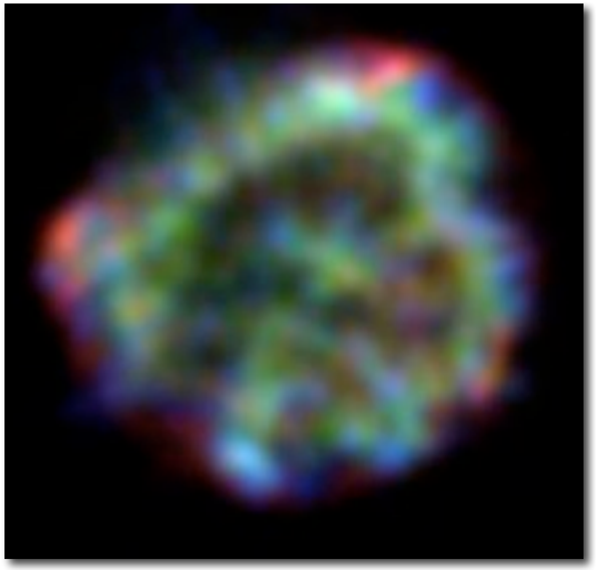
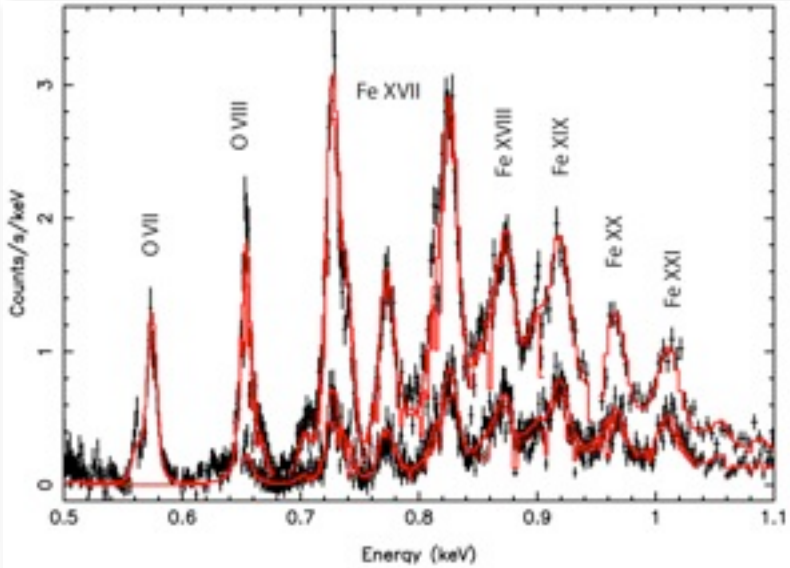
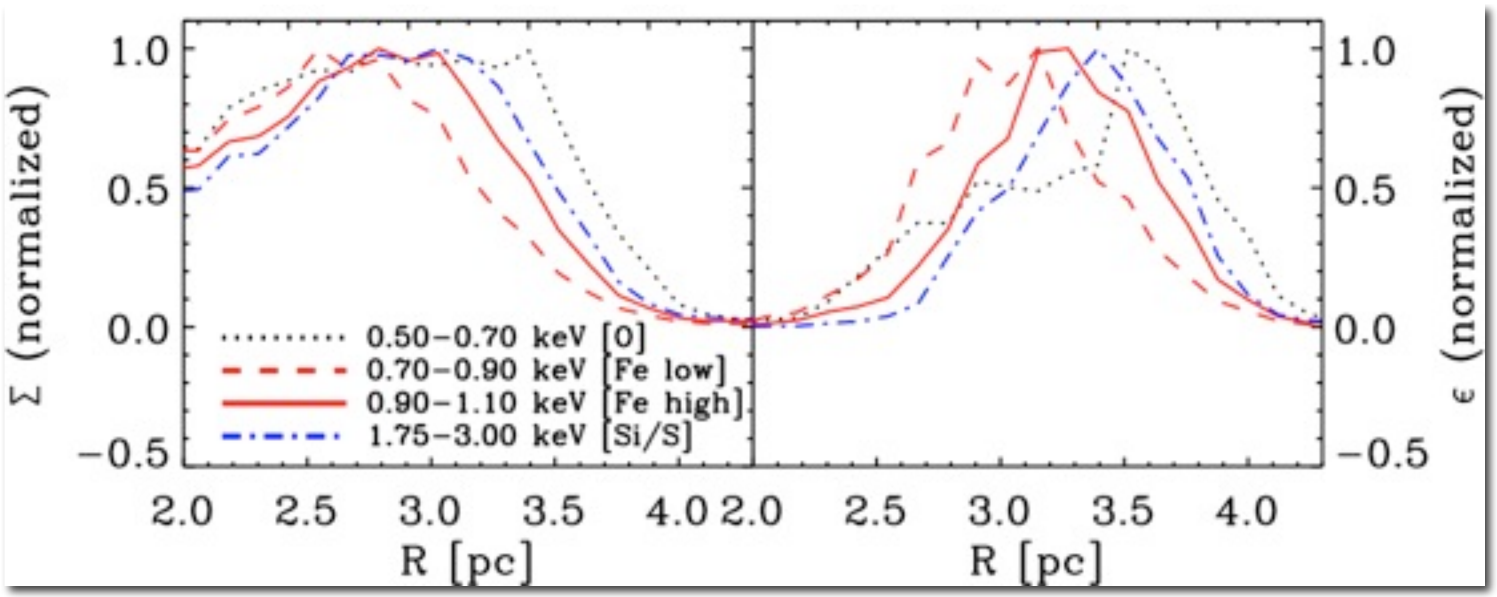
Example: 0519-69.0



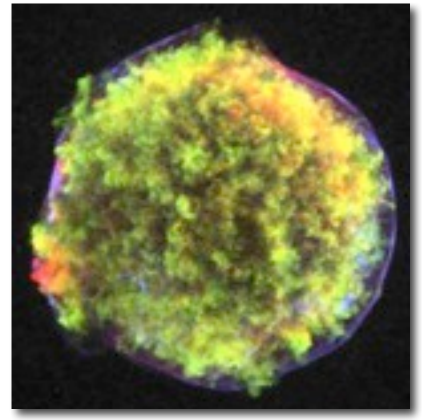


- Strong stratification
- 30% O /55% Fe
- RGS: σ_V=1900 km/s
- Age: 440+/-200 yr

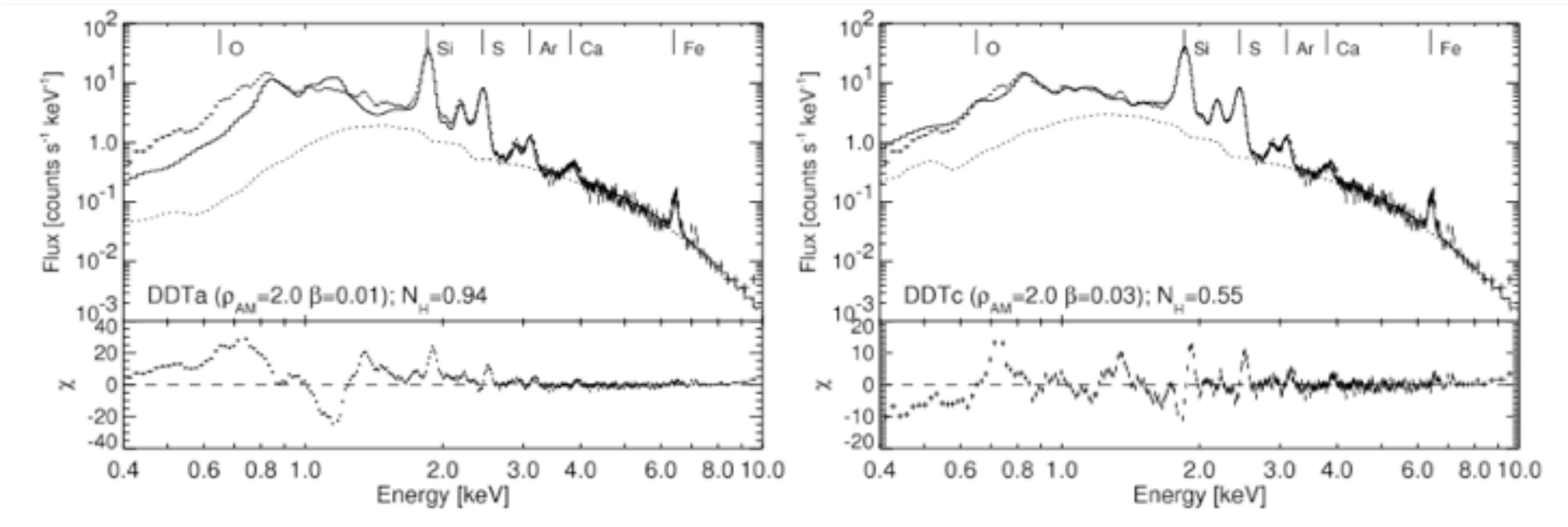


Kosenko, et al. 2010

Full Hydro/X-ray modeling Type Ia

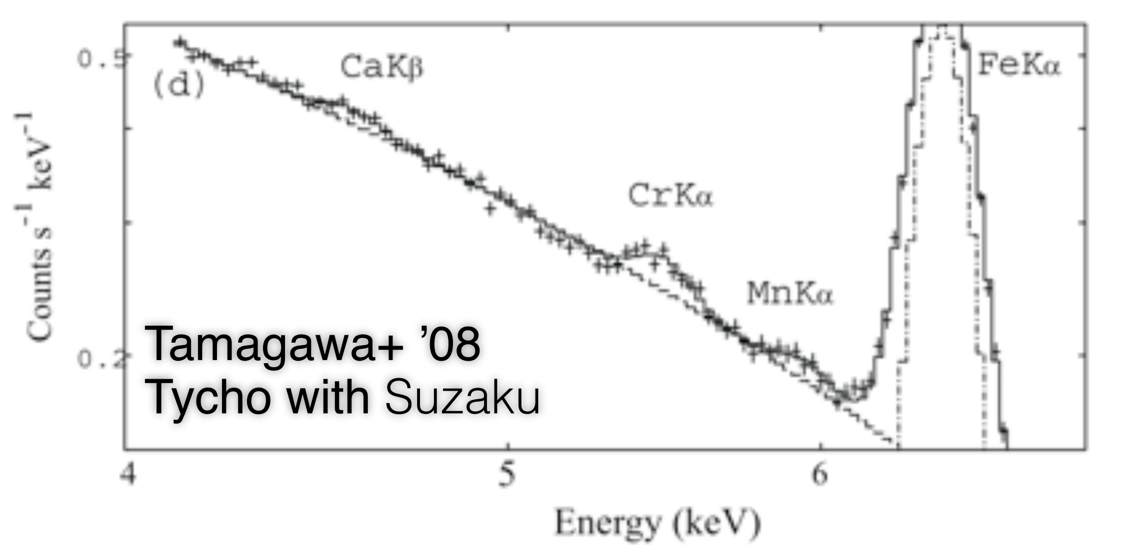


- Type Ias well suited for full modeling
  →they are much better stratified
- 2 groups: Badenes, Bravo+ & Blinnikov, Kosenko+
- Uncertainty about non-thermal distributions
- Results mainly for Tycho's SNR and 0509-690
(both have optical light echo spectra: Type Ia!)

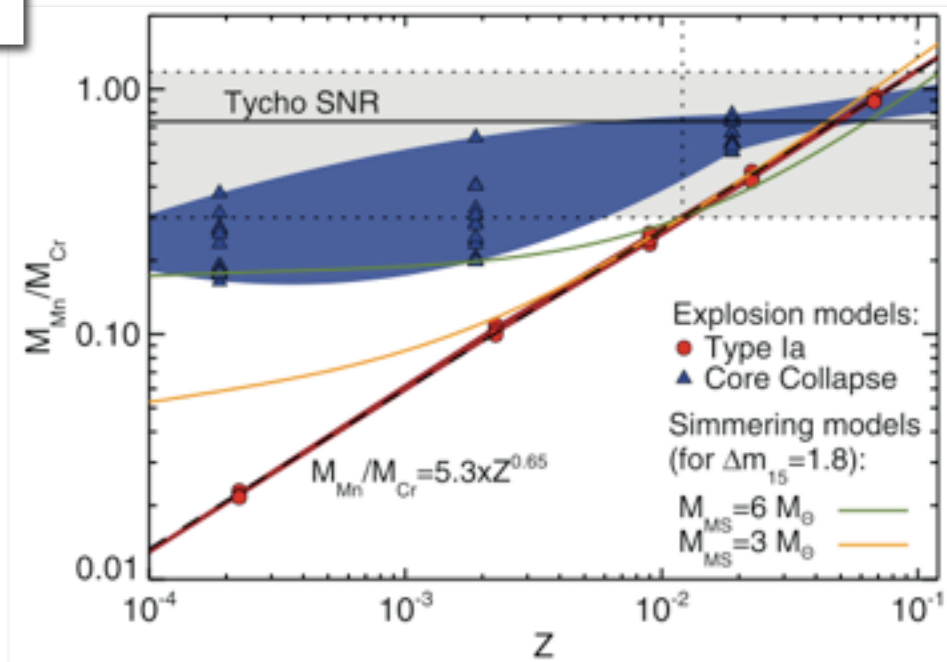


Tycho XMM (Badenes+ '06)

New territory: Manganese and Chromium



- Several SNRs show evidence for Mn and Cr line emission
- Mn/Cr ratio can constrain the progenitor metallicity (Badenes+ 08)
- May be important diagnostic tool with Athena

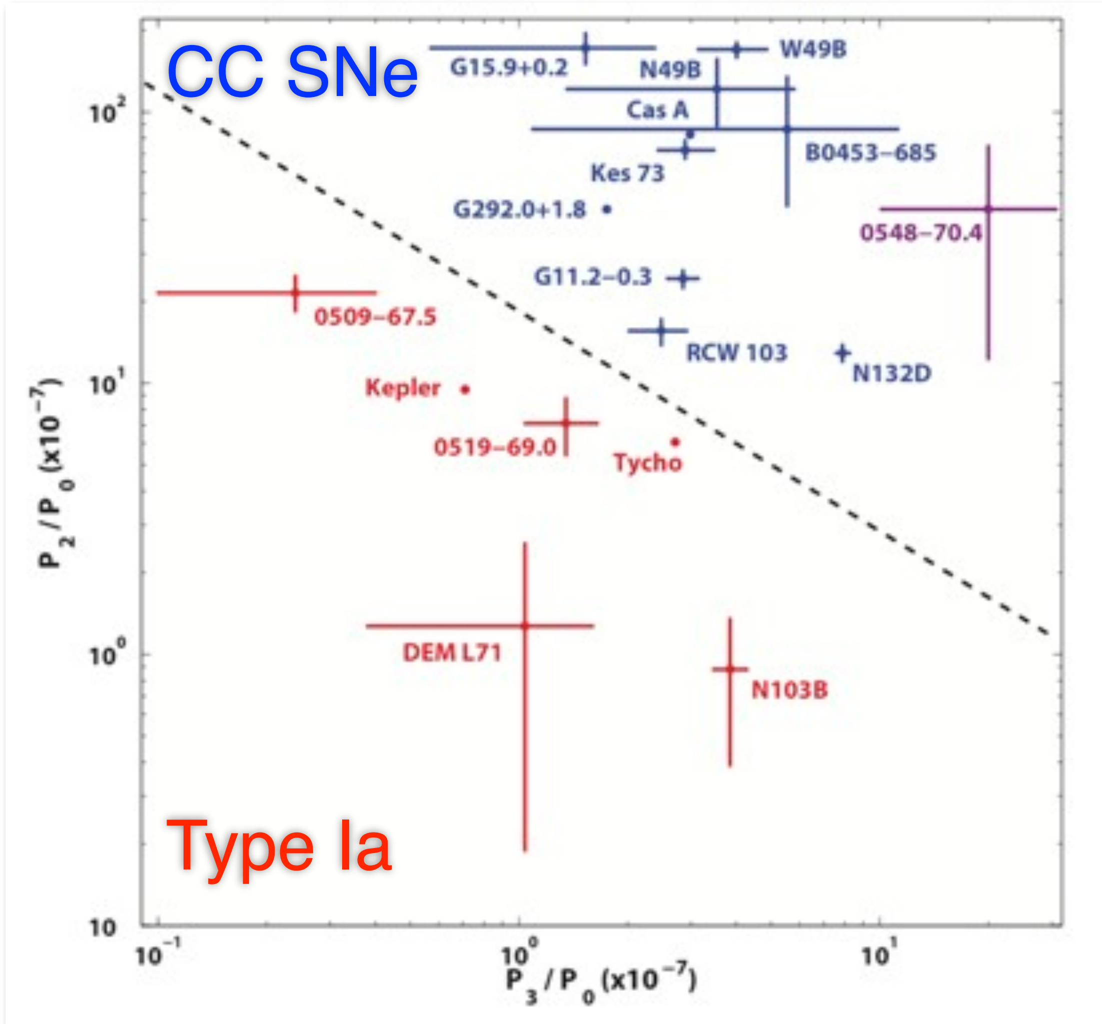


Badenes+ '08

Type Ia vs Core Collapse SNe

•Apart from obvious differences in composition:

- Type Ia are more regular stratified
- Have a more regular morphology



2rd moment (mirror symmetry)

3rd moment (asphericity)

Lopez et al. 2009/11

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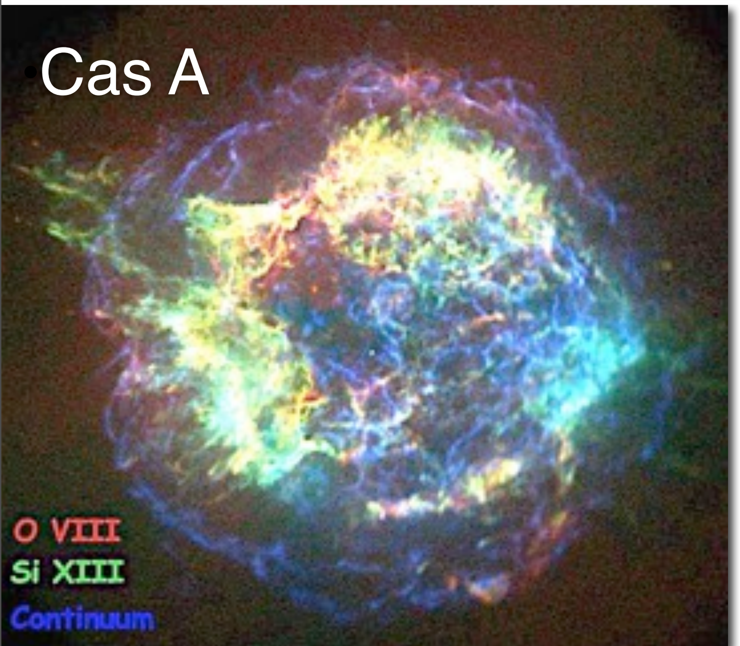
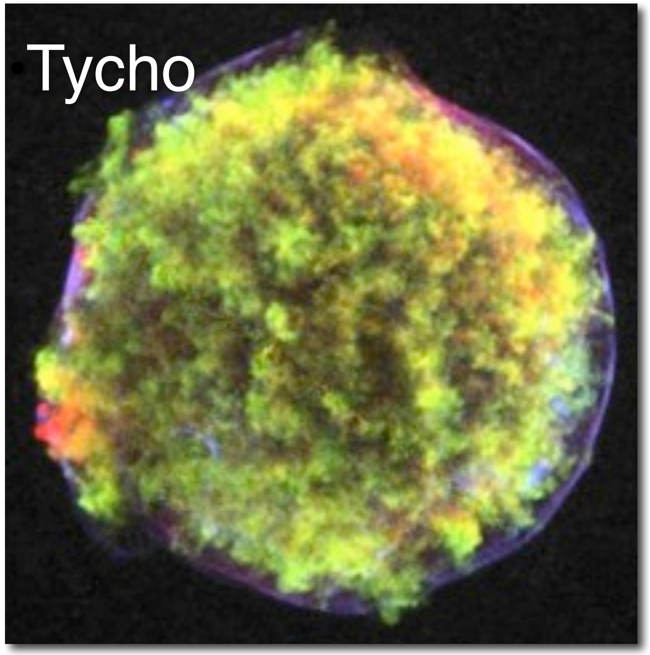
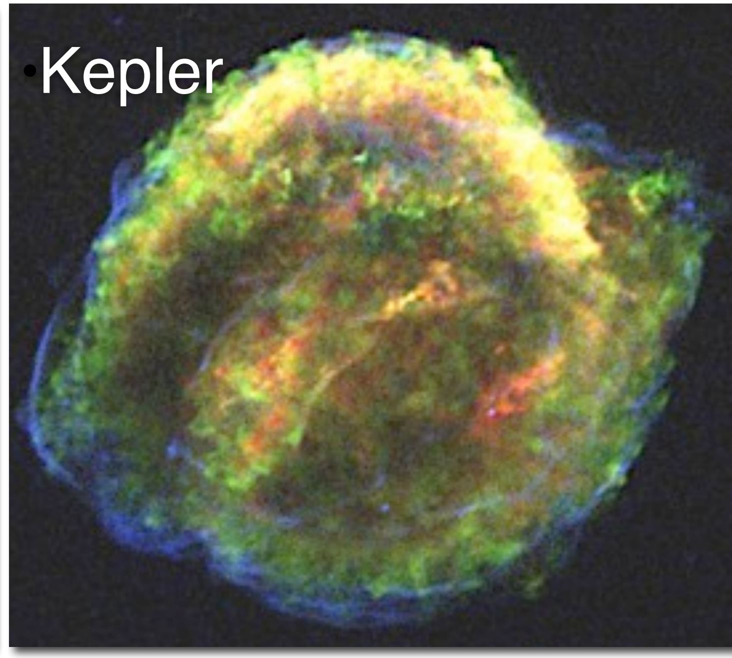
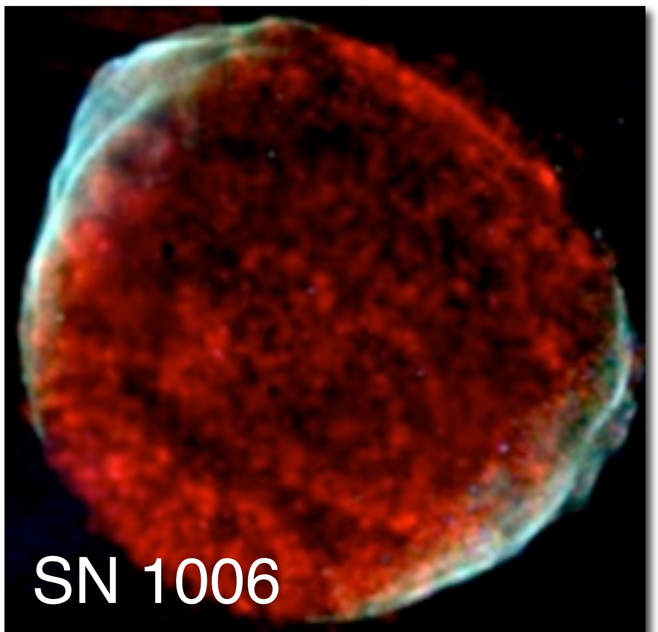
Studying
Shock Heating
&
Particle Acceleration
in
Supernova Remnants

X-ray synchrotron emission









- All historical shell SNRs emit X-ray synchrotron emission
  (1st detected SN1006: Koyama et al. '95)
- Implies $E_{max,electron}$ ~ 10-100 TeV
- Requires fast shocks
- Emission regions often narrow (few ") (Cas A/Tycho/Kepler)

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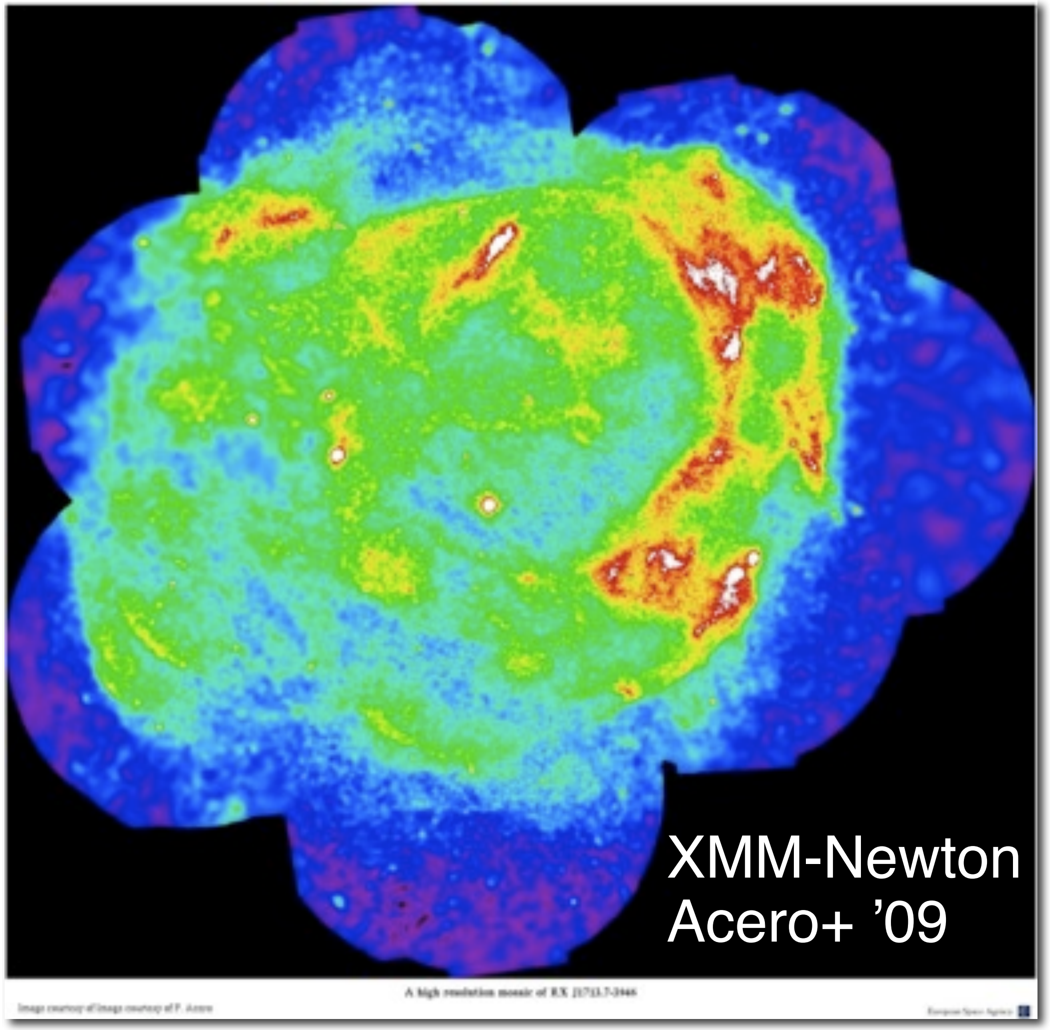
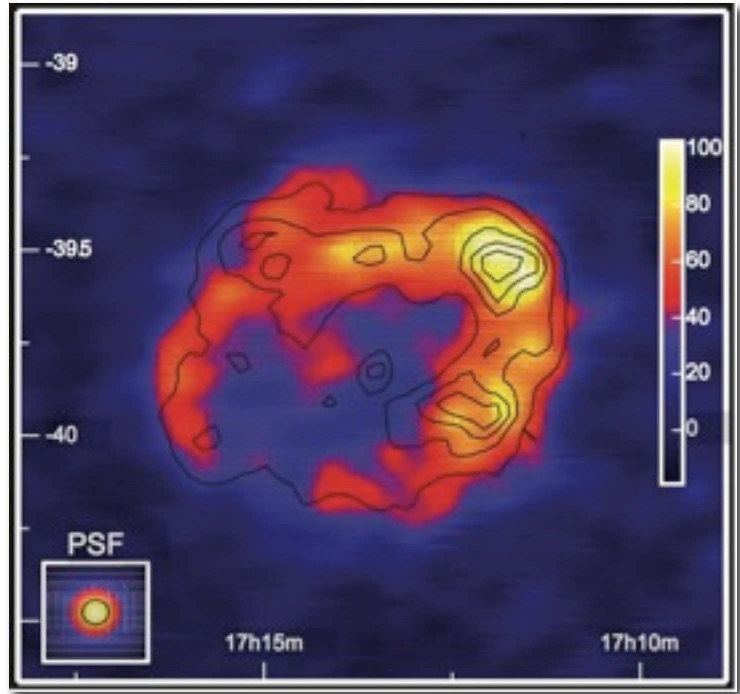
RX J1713: only X-ray synchrotron

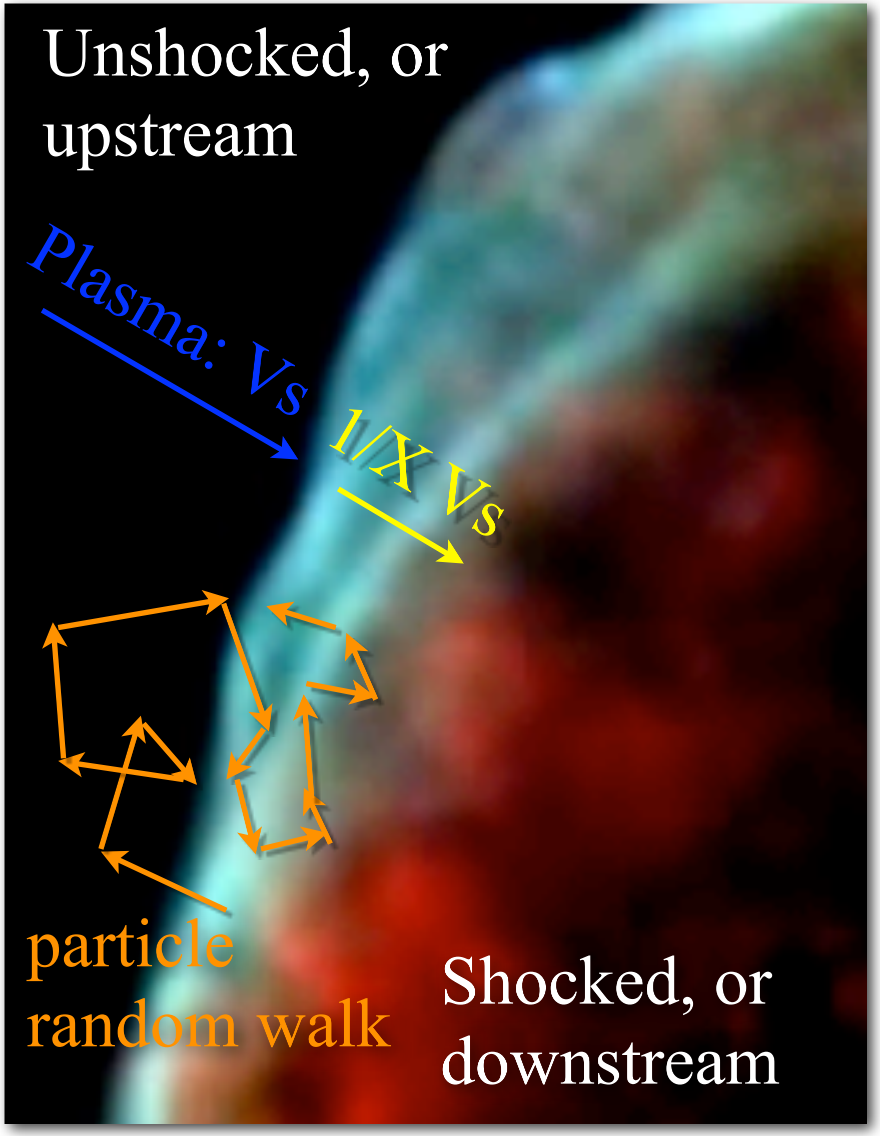




Brightest TeV SNR
(Aharonian ’04)

Pfefferman& Aschenbach ’96, Koyama+ 97, Slane+ ’99, Cassam-Chenai + ’04, Hiraga+ ’05, Acero+ ’09

Diffusive Shock Acceleration



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

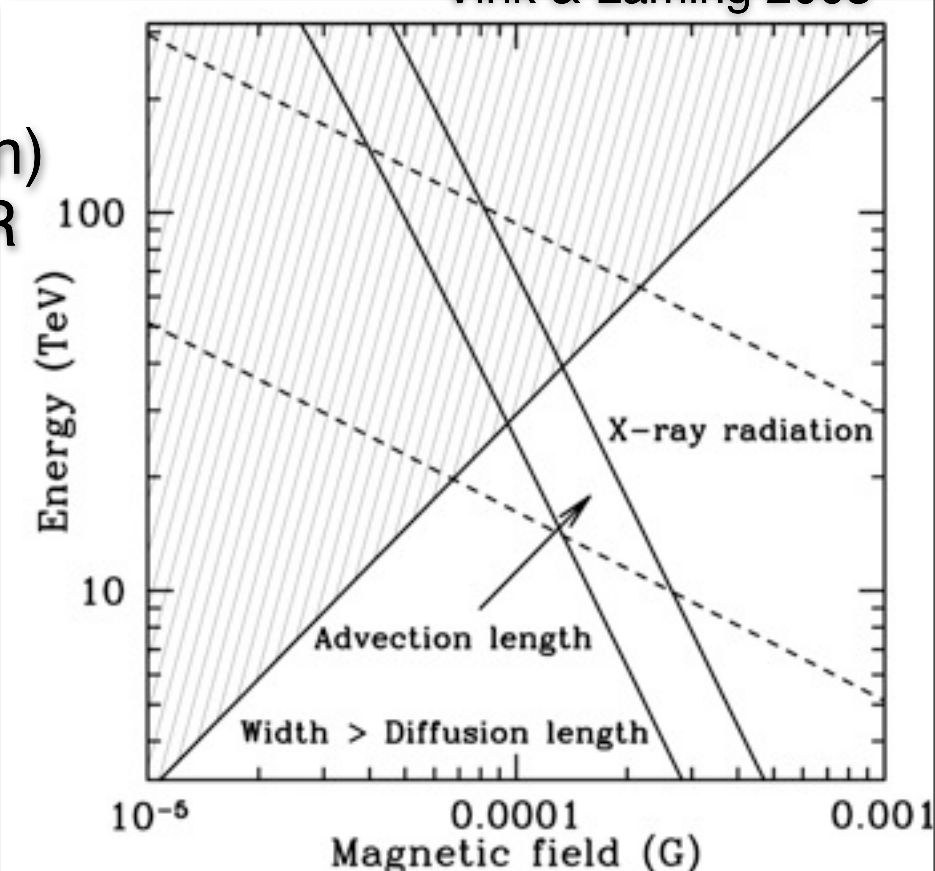
Axford et al. , Blanford & Ostriker, Krymsky, and Bell (all 1977-78)

Evidence for B-field amplification

- Rim width: interplay between advection of electrons + synchrotron losses + diffusion
- Narrower → higher B-field
- B ~ 25 $(L/10^{18}\ \mathrm{cm})^{-2/3}$ μG
- Tycho/Cas A/Kepler B ~ 100-500 μG

- Implies fast acceleration (Bohm diffusion)
- Suggests B-field amplification e.g.by CR streaming (Bell & Lucek ‘02, Bell ‘04)
- High B-field: efficient acceleration possible up to ~10^{15}eV

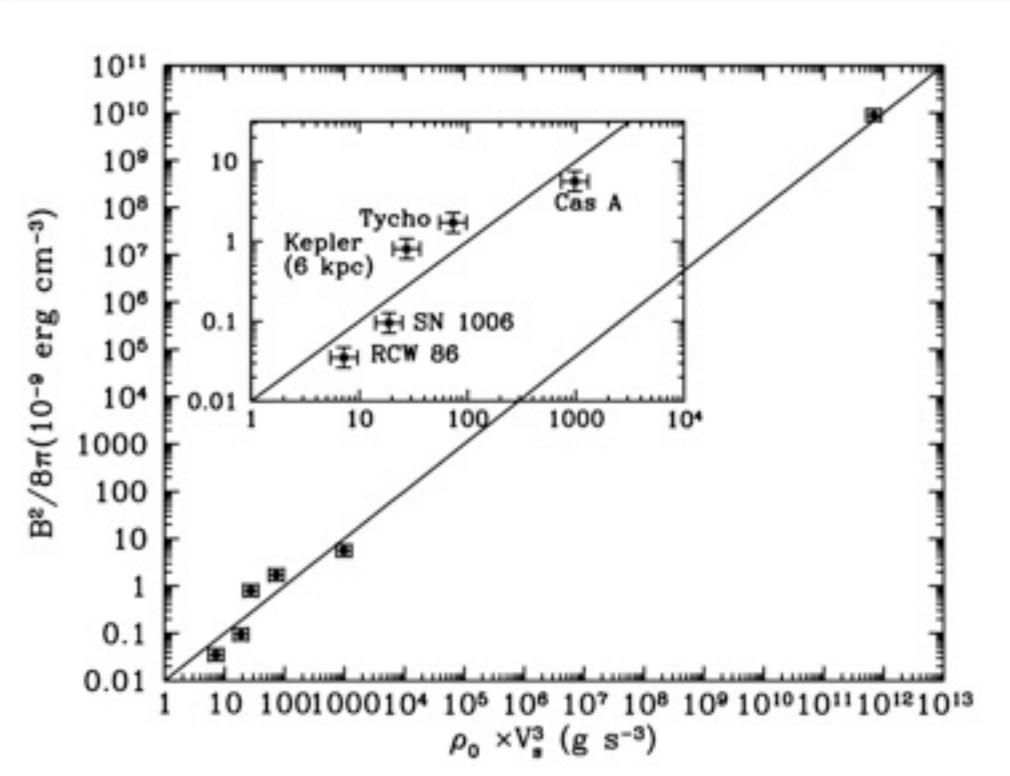
Vink & Laming 2003

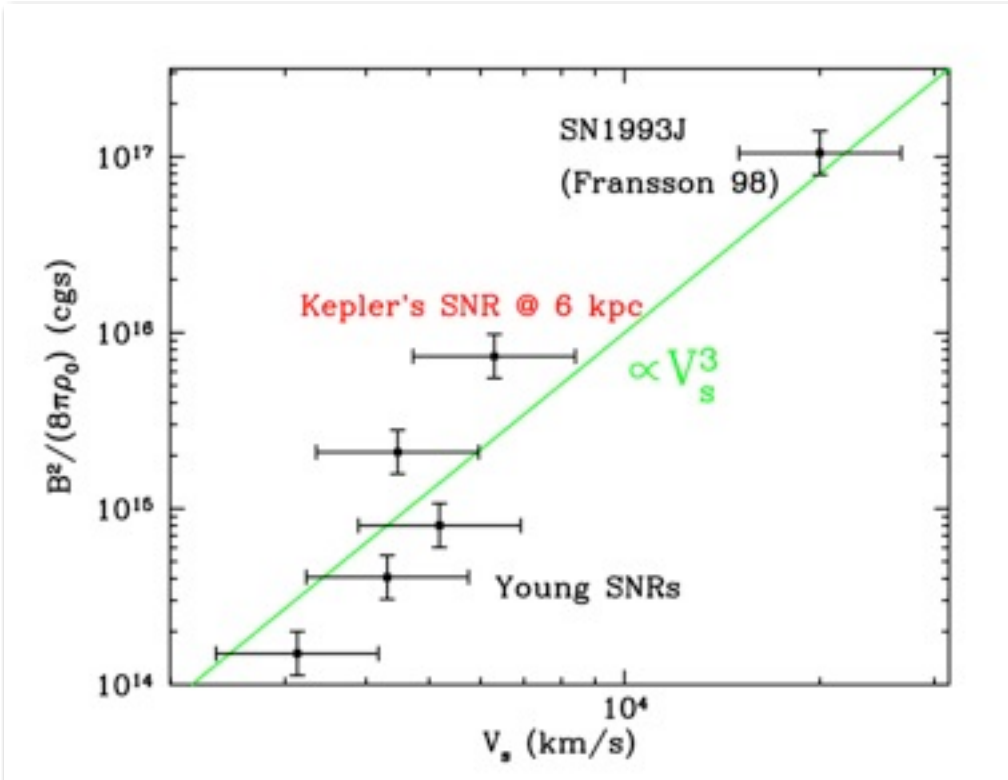


Vink&Laming ’03, Bamba+ ’03, Bamba+ ’04, Berezhko+ ’04,Völk+ ’05

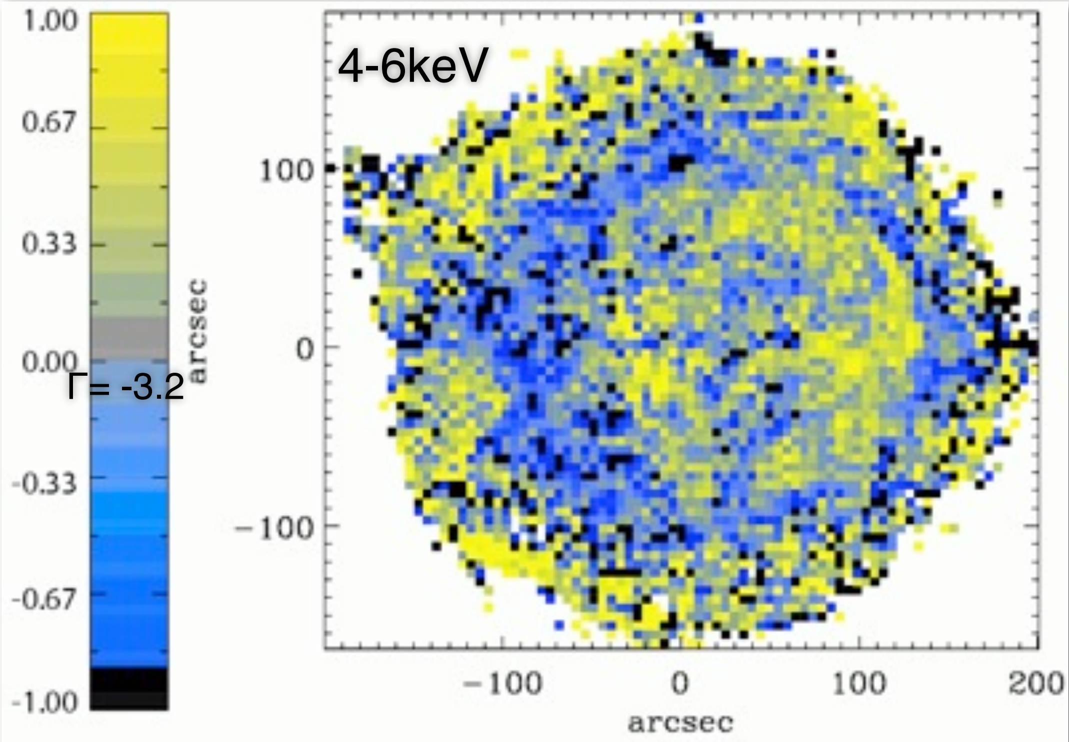
Magnetic Field Amplification

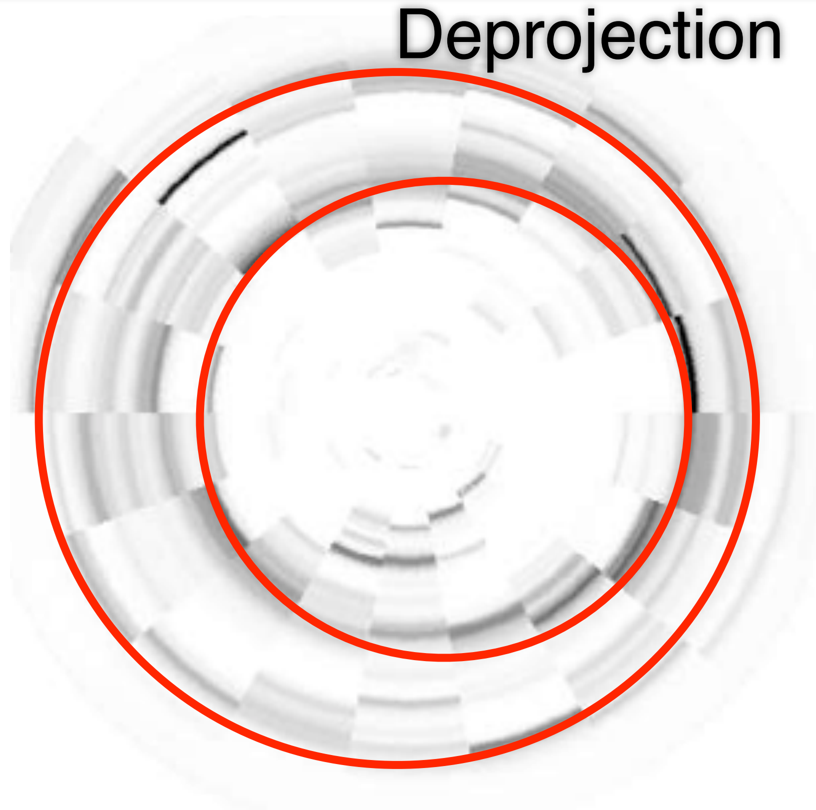
- There is a clear correlation between ρ, V and B, in rough agreement with theoretical predictions (e.g. Bell 2004)
- Relation may even extend to supernovae ($B^2 \propto \rho V_s^3$?) (Völk+ '05, Vink '08)





Acceleration @ Cas A reverse shock





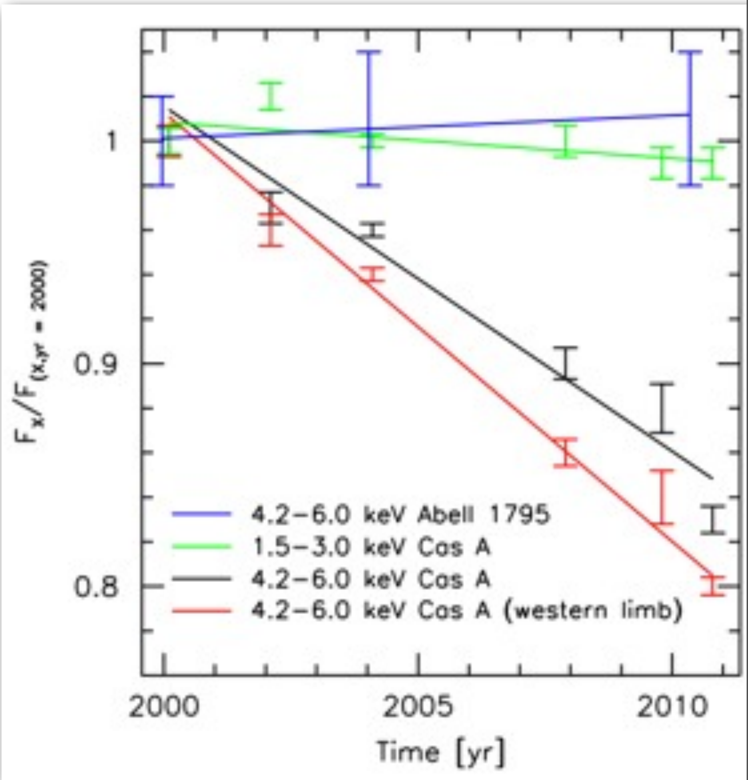
- Spectral index: 2 regions of hard emission: X-ray synchrotron emission
- Deprojection: Most X-ray synchrotron from **reverse shock**!
- Prominence of West: No expansion ⇒ ejecta shocked with V>6000km/s

Final amplified B-field insensitive to initial field!?

Helder&Vink '08
Uchiyama+ '08

Results on monitoring of Cas A with Chandra

- X-ray synchrotron flux (4-6 keV) declines strongly:
  Whole SNR: –(1.5 ± 0.17)% yr–1
  Western part: –(1.9 ± 0.10)% yr–1
  Accompanied by *steepening* of spectral index Γ
- Critical check:
  no decline in line rich band (1.5-3 keV)
  no 4-6 keV decline cluster A1795



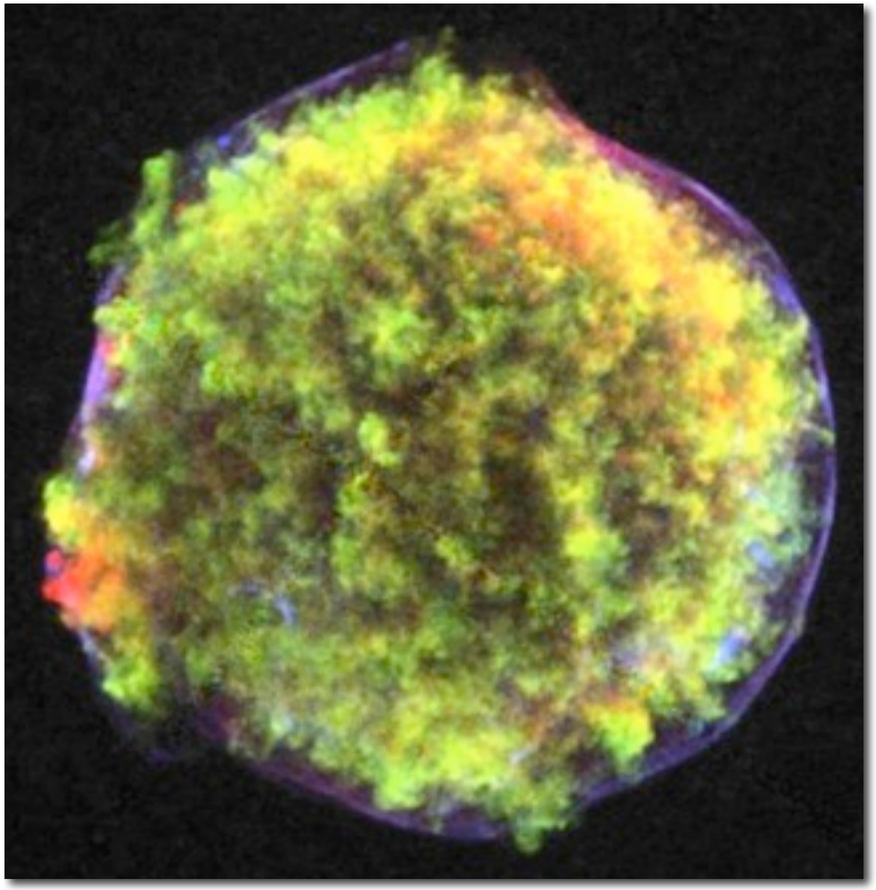
- Decline more than in radio: not adiabatic cooling
- Likely cause: shock deceleration

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

- Confirms basic interpretation of synchrotron model
- Decline somewhat high, may imply small η, hence very fast acceleration
- Questions: spectral shape? gittering?

Patnaude, JV, Laming, Fesen, 2011

Cosmic ray dominated shocks



Decourchelle et al. '01, Warren et al. '05
Cassam-Genai et al. '07

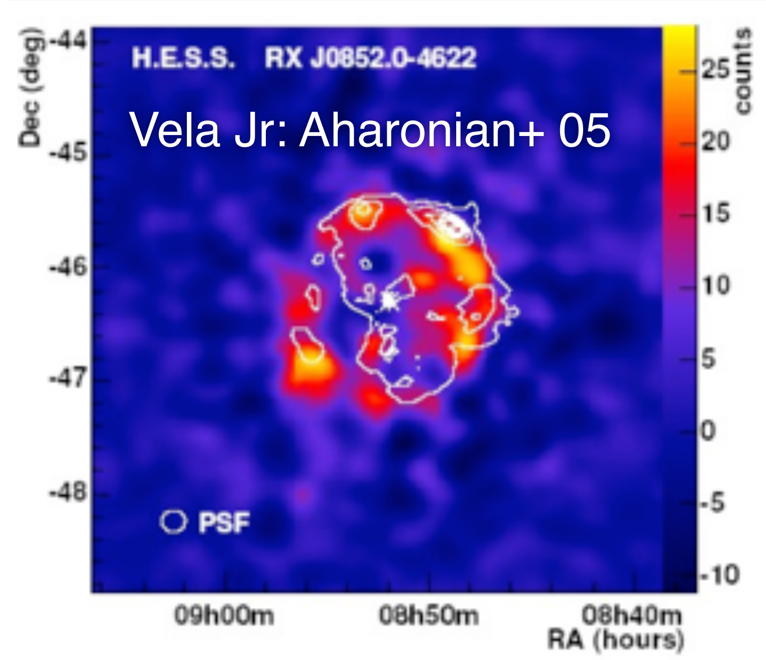
- In Tycho/Kepler: ejecta close to forward shock
- Suggests high compression ratio (>4)
- Expected for cosmic ray dominated shocks (E_{int} >50% CRs)

Cosmic-ray dominated shocks or not?

- Strong evidence for high cosmic-ray acceleration efficiency from X-rays/optical:
  - Relatively high magnetic fields
  - Evidence for high compression ratios
  - Lower than expected temperatures (rest energy in CRs?)

- Evidence from (GeV/TeV) gamma-ray astronomy weak:
  - Many GeV/TeV detections
  - No evidence for acceleration > 10^{15} eV
  - <10% $E_{explosion}$ in cosmic rays
    (Cas A , E_{CR}<4%)

- Debate goes on: stay tuned!



The Future

- ASCA/XMM/Chandra/Suzaku have shown the power of imaging spectroscopy with low spectral resolution
- Future: Calorimeters: high spectral resolution imaging
- Missions: Astro-H, Athena

- Importance for SNRs:
  - accurate Doppler mapping of SNRs (also for low velocities)
  - higher sensitivity for weak lines
    - abundances of Na, Al, Sc, Ti, V, Cr, Mn:
      - For Type Ia: preconditions of explosion
      - For Core Collapse: inner ejecta influenced by neutrinos?

  - Thermal Doppler broadening: total thermal content:
    - indirect evidence for Cosmic Rays
    - are electron and ion temperatures same or not?

Conclusions

- Chandra/XMM have shown that:
  - Core collapse SNRs are messy:
    - Kinematics are not spherical symmetric
    - Sometimes no symmetry at all
    - In Cas A: evidence for jets
  - Type Ia SNRs are well behaved:
    - Strong stratification of O, Si/S (IME), Fe-group (outside in)
    - Older SNRs: center dominated by Fe-L emission

- Young SNRs are actively accelerating particles
  - They emit X-ray synchrotron radiation (loss times short)
  - X-ray confined to shock: high magnetic fields
  - Magnetic field amplification (even @ reverse shock)
  - Cosmic rays influence the hydro/thermodynamics of shock
  - X-ray/ TeV connection: how efficient is acceleration?