X-ray emission from Type IIP Supernovae: A Tale of Two Shocks

Based on SN 2004dj: 2012 ApJ 761, 100, Chakraborti et al.
SN 2011ja: 2013 ApJ 774, 30, Chakraborti et al.
SN 2013ej: In preparation, Chakraborti et al.

Sayan Chakraborti

Junior Fellow, Society of Fellows and ITC Fellow, Harvard University

Open Questions:

- What is the origin of X-rays detected by the Chandra from young type IIP supernovae?
- How fast was the progenitor losing mass via winds in the final phase before explosion?
- How efficiently does the supernova accelerate cosmic ray electrons in its forward shock?
- What is the extent of turbulent magnetic field amplification in the post-shock material?
- Are synchrotron and inverse Compton losses important in explaining the radio light-curves?

Observations of SN 2004dj

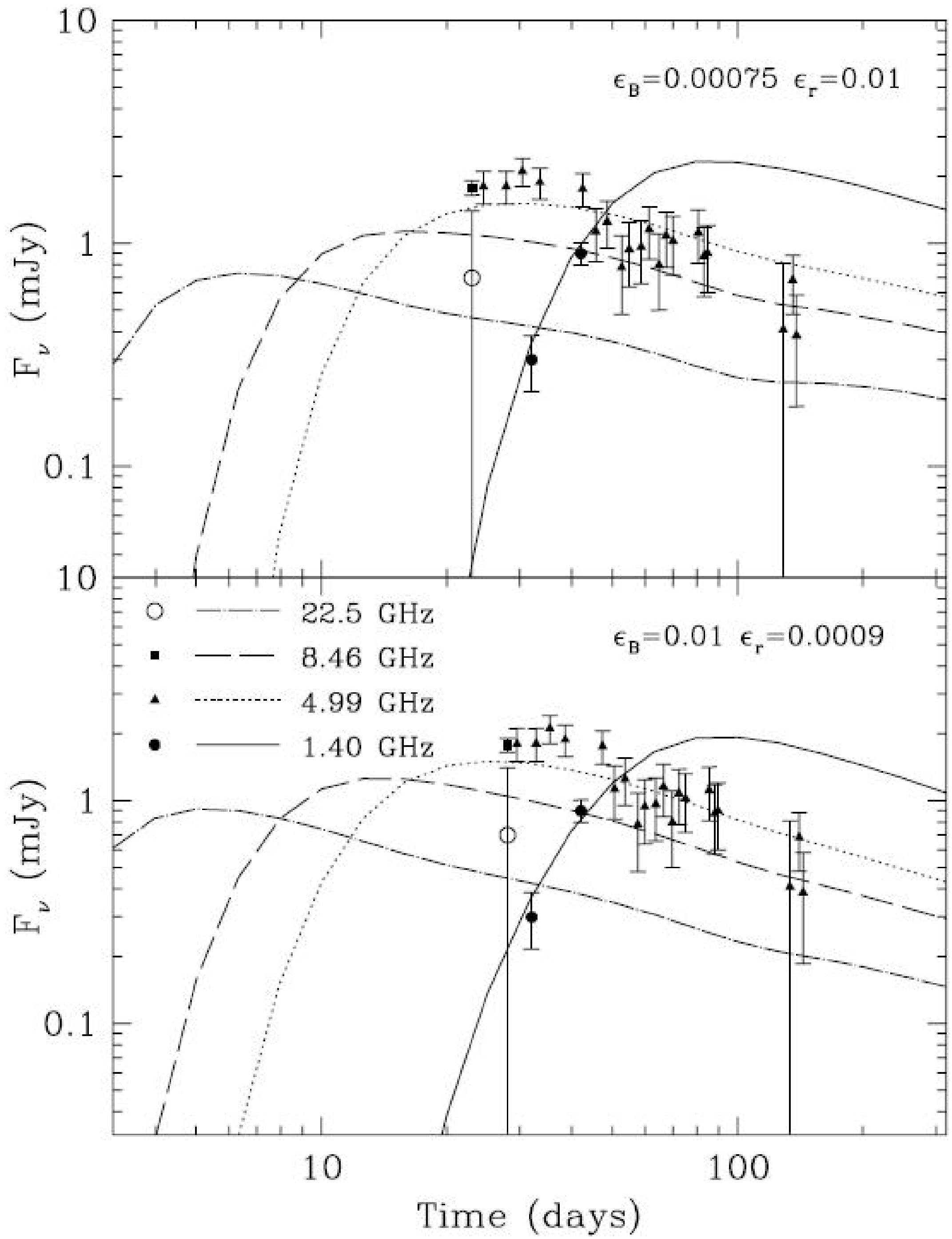
- Chandra X-Ray Observatory

OBSERVATION SUMMARY OF SN 2004DJ WITH CHANDRA

Date (2004)	Exposure (ks)	Count Rate (10^{-3} sec^{-1})	Flux (0.5-8 keV) (ergs cm^{-2} s^{-1})
Aug 09	40.9	12.80 ± 0.56	8.81×10^{-14}
Aug 23	46.5	10.03 ± 0.47	6.98×10^{-14}
Oct 03	44.5	5.60 ± 0.36	3.30×10^{-14}
Dec 22	49.8	3.05 ± 0.25	2.02×10^{-14}

Observations of SN 2004dj

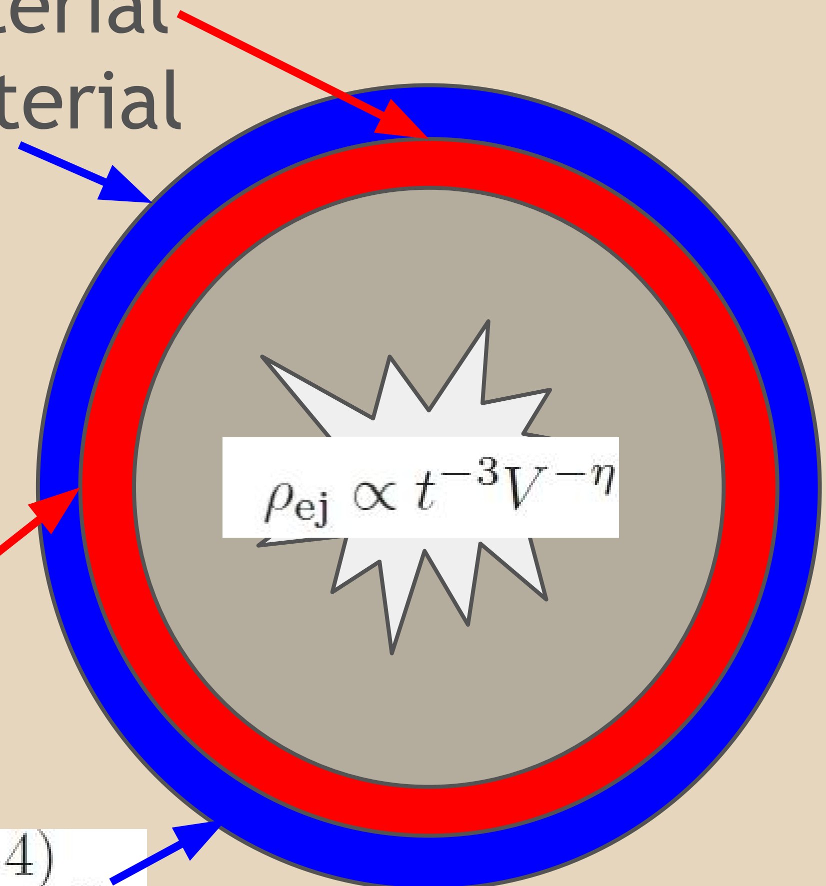
- Radio Observations



A Tale of Two Shocks

- Reverse Shocked Material
- Forward Shocked Material

$$\rho_{\rm w} = \frac{A}{r^2} = \frac{\dot{M}}{4\pi r^2 v_{\rm w}}$$

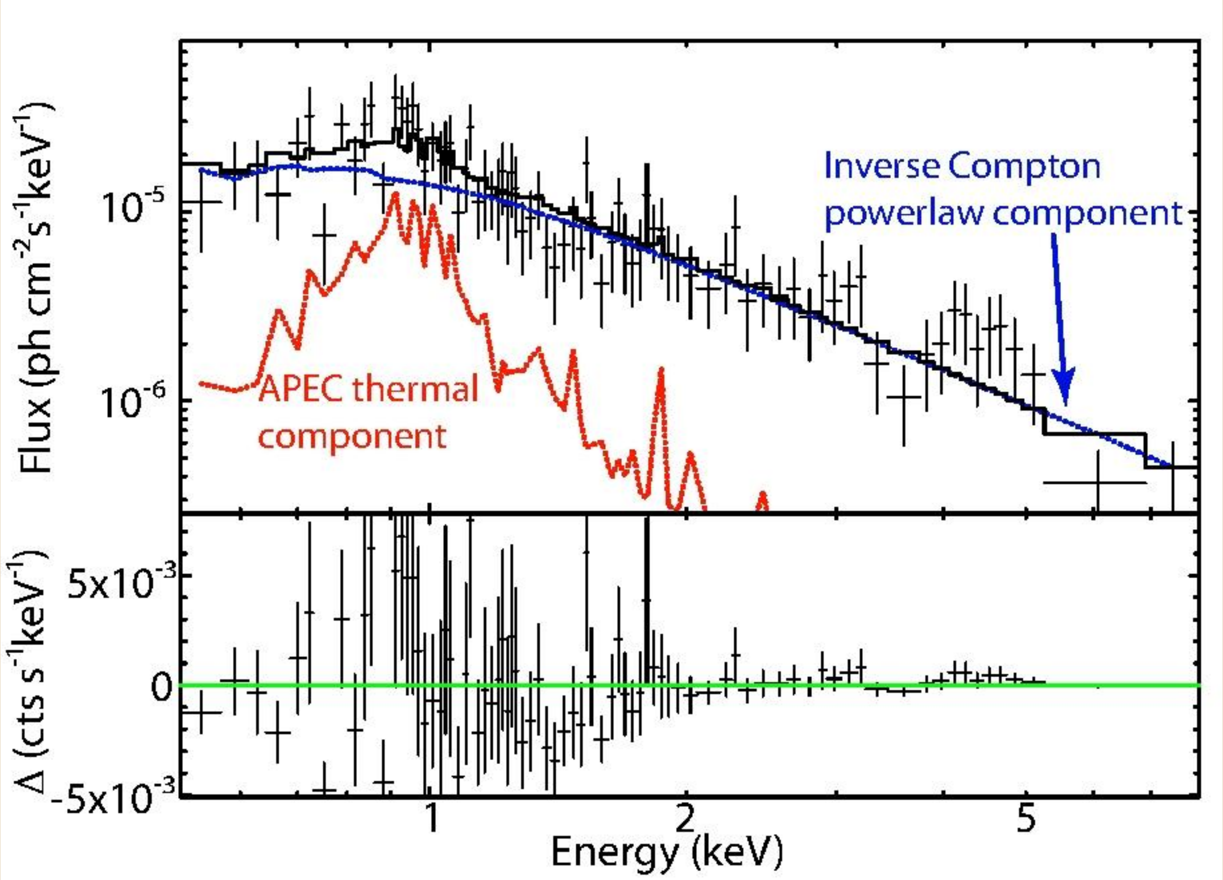


$$\rho_{\rm ej} \propto t^{-3} V^{-\eta}$$

$$\rho_0 = \frac{(\eta-3)(\eta-4)}{(3-s)(4-s)}\rho_{\rm cs}$$

A Tale of Two Shocks

- X-ray Spectral Fitting
- Model = wabs(powerlaw+apec)

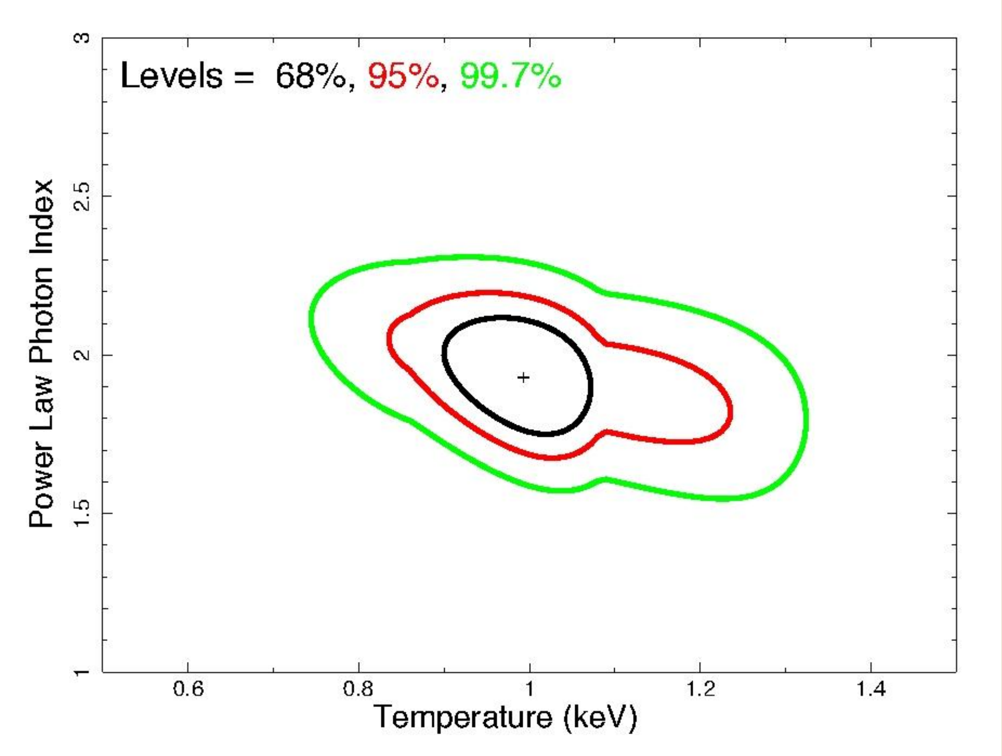


A Tale of Two Shocks

- Blastwave Velocity

$$T_0 = 2.27 \times 10^9 \mu \frac{(3-s)^2}{(\eta - s)^2} V_4^2 \;\; \mathrm{K}$$

$$V_s = 10^4 \sqrt{\frac{kT_0}{1.19 \text{ keV}}} \;\; \mathrm{kms}^{-1}$$



A Tale of Two Shocks

- Circumstellar Density

$$\rho_0 = \frac{36\dot{M}}{\pi r^2 v_{\rm w}}$$

$$\rho_0 M_0 = \frac{144}{\pi}\left(\frac{\dot{M}}{v_{\rm w}}\right)^2 \frac{1}{R_s}$$

$$M_0 = \frac{\eta - 4}{4 - s} M_{\rm cs} = \frac{4\dot{M} R_s}{v_{\rm w}}$$

A Tale of Two Shocks

- Circumstellar Density

$$\int n_e n_H dV = \frac{144}{\pi}\left(\frac{\dot{M}}{v_{\rm w}}\right)^2 \frac{1}{(1.17\mathrm{amu})(1.40\mathrm{amu})R_s}$$

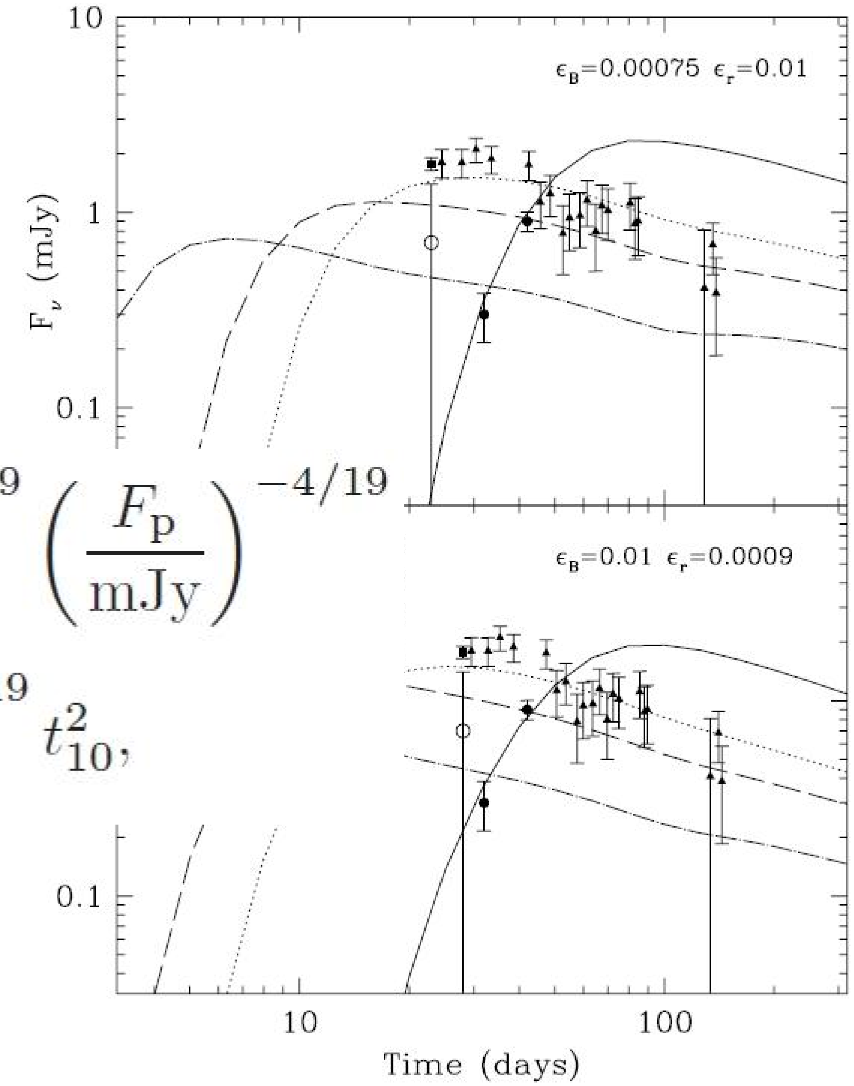
$$\frac{10^{-14}}{4\pi[D_A(1+z)]^2}\int n_e n_H dv = (7.5 \pm 2.7) \times 10^{-6}$$

$$\dot{M} = (3.2 \pm 1.1) \times 10^{-7}\left(\frac{v_{\rm w}}{10\ \mathrm{km/s}}\right)\ \mathrm{M_\odot\ yr^{-1}}$$

A Tale of Two Shocks

- Forward-Shocked material

$$S_\star = A_\star \epsilon_{B-1} \alpha^{8/19} = 1.0 \left(\frac{f}{0.5}\right)^{-8/19} \left(\frac{F_\mathrm{p}}{\mathrm{mJy}}\right)^{-4/19} \times \left(\frac{D}{\mathrm{Mpc}}\right)^{-8/19} \left(\frac{\nu}{5\ \mathrm{GHz}}\right)^{-4/19} t_{10}^2,$$

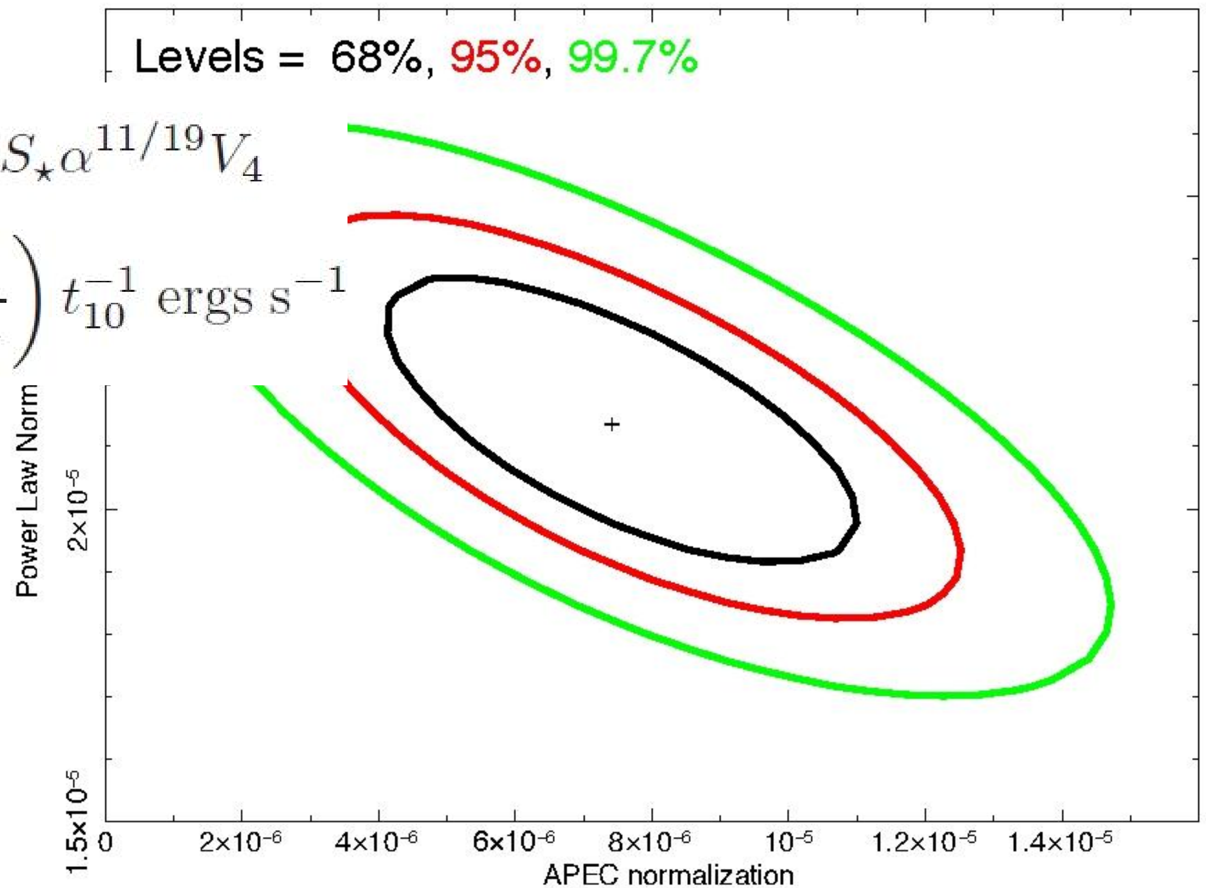


A Tale of Two Shocks

- Forward-Shocked material

$$E\frac{dL_{\rm IC}}{dE} \approx 8.8 \times 10^{36}\gamma_{\rm min}S_{\star}\alpha^{11/19}V_4 \times \left(\frac{L_{\rm bol}(t)}{10^{42}\ {\rm ergs\ s^{-1}}}\right)t_{10}^{-1}\ {\rm ergs\ s^{-1}}$$

$$\alpha \sim 23 \times \gamma_{\rm min}^{-19/11}$$



A Tale of Two Shocks

- Forward-Shocked material

X-Ray from Reverse Shock

Radio from Forward Shock

$$S_\star = A_\star \epsilon_{B-1} \alpha^{8/19} = 1.0 \left(\frac{f}{0.5}\right)^{-8/19} \left(\frac{F_{\rm p}}{\rm mJy}\right)^{-4/19} \times \left(\frac{D}{\rm Mpc}\right)^{-8/19} \left(\frac{\nu}{5\ \rm GHz}\right)^{-4/19} t_{10}^2,$$

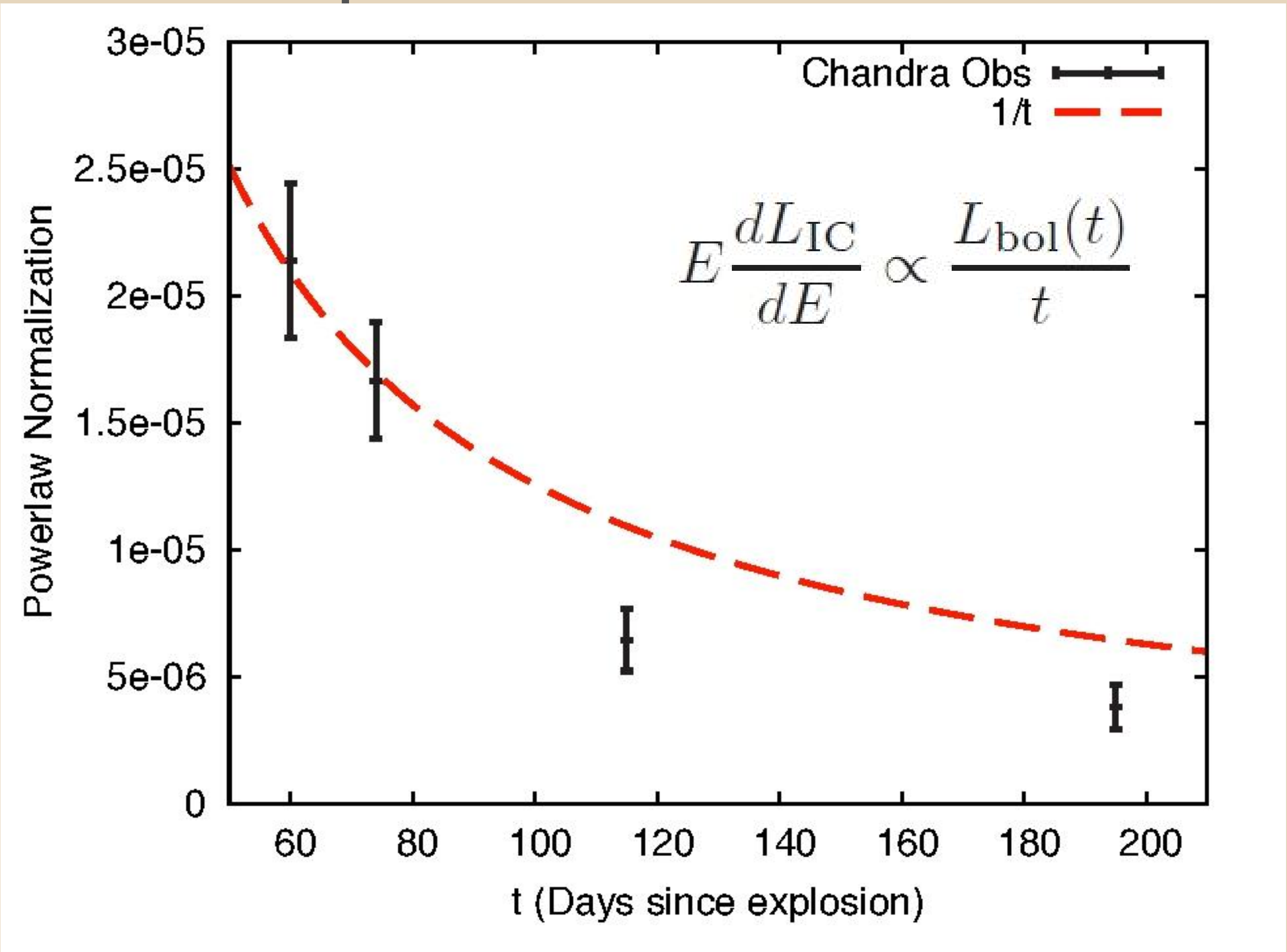
$$\alpha \sim 23 \times \gamma_{\rm min}^{-19/11}$$

$$\epsilon_B \equiv 0.1 \times \epsilon_{B-1} \sim 0.082$$

$$\epsilon_e \equiv \alpha \times \epsilon_B \sim 0.39$$

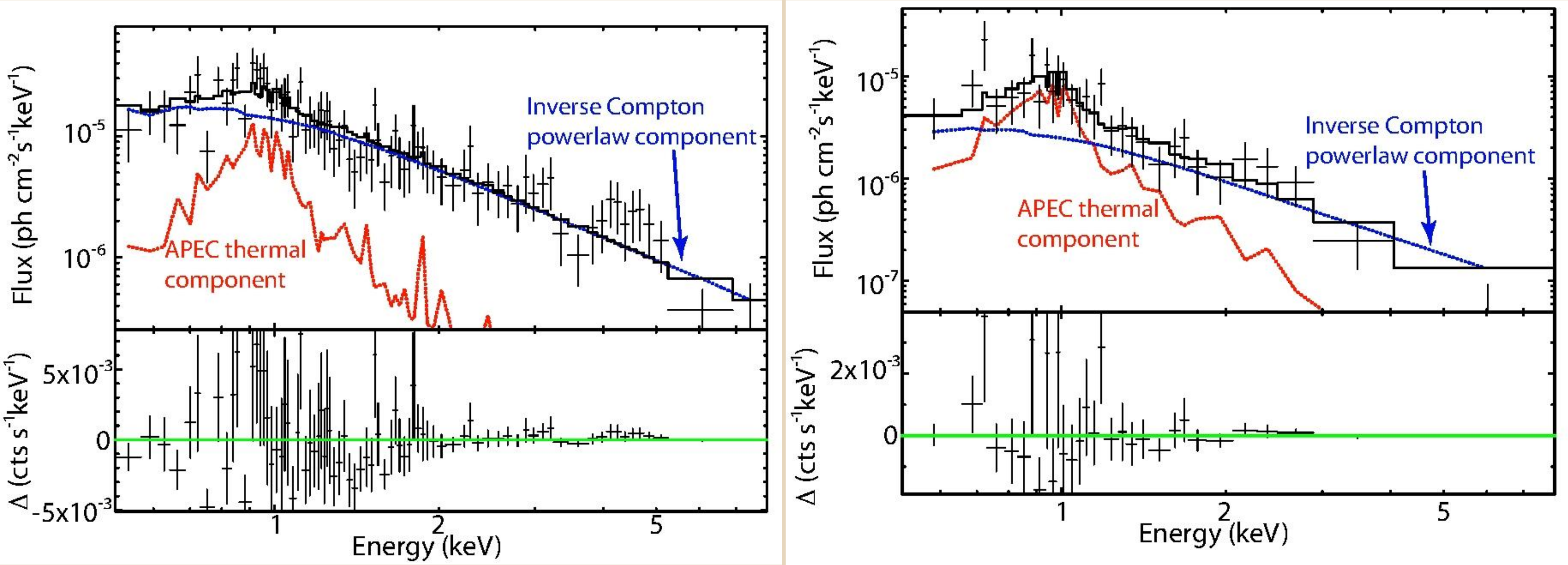
Time Evolution

- Inverse Compton



Spectral Evolution

High+Hard → Low+Soft



Conclusions:

- X-rays from both thermal and nonthermal processes
- Progenitors lose around a solar mass per mega-year
- Cosmic ray electron acceleration is very efficient
- Lesser but comparable energy put into magnetic fields
- Inverse Compton losses important for radio supernovae

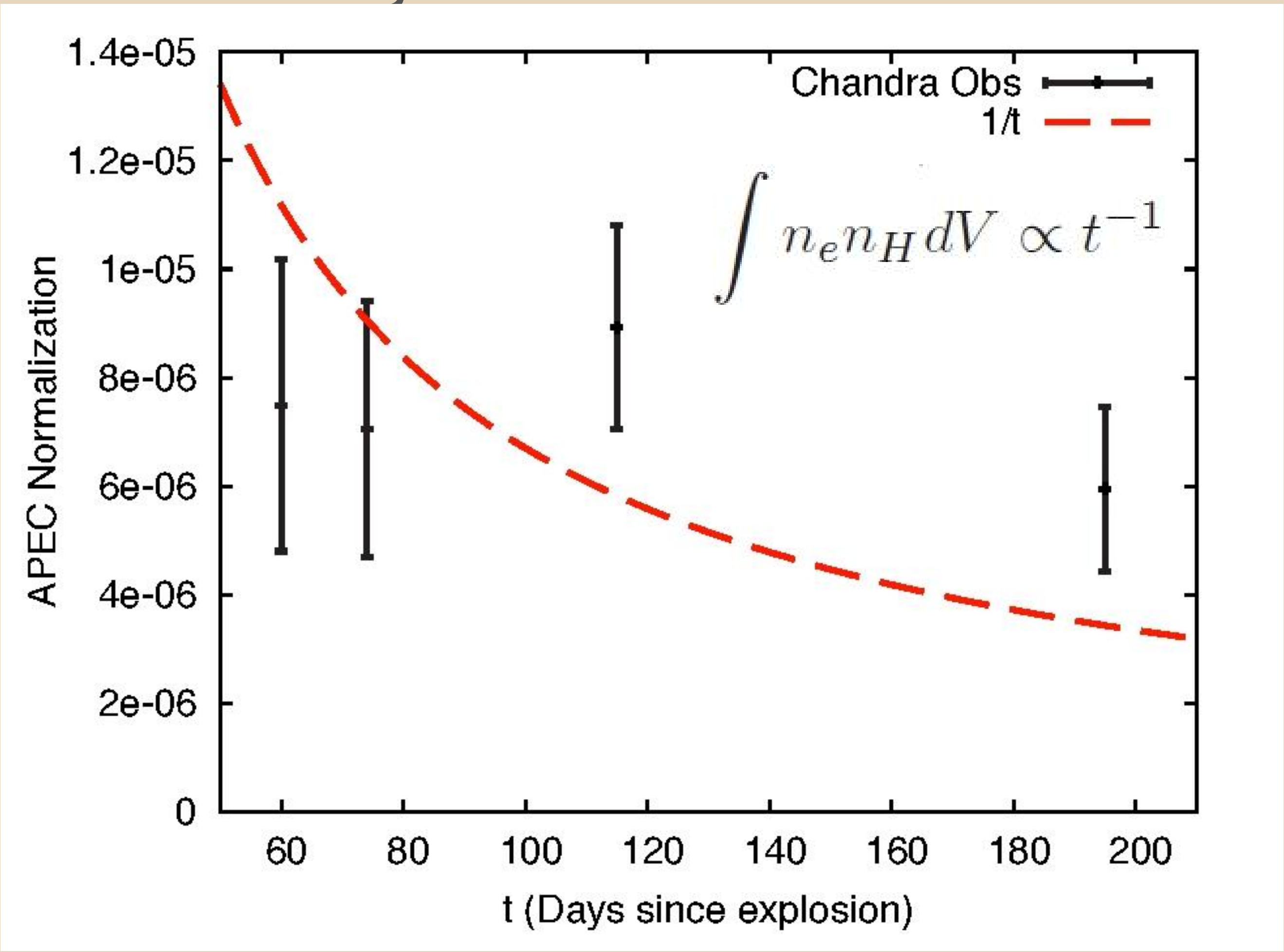
Thanks

Catch up with me at:

schakrborti@fas.harvard.edu

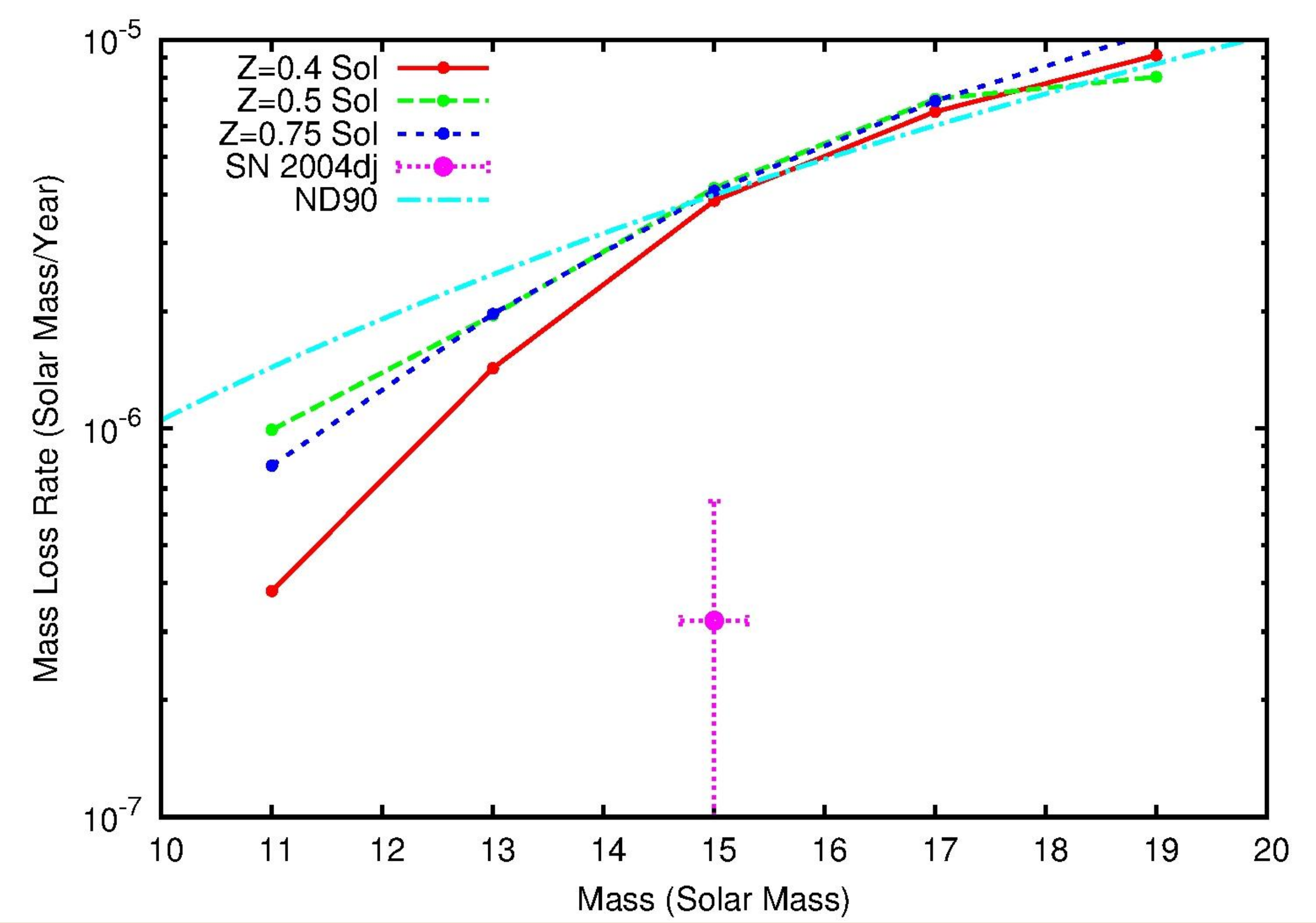
Time Evolution

- Thermal X-Rays



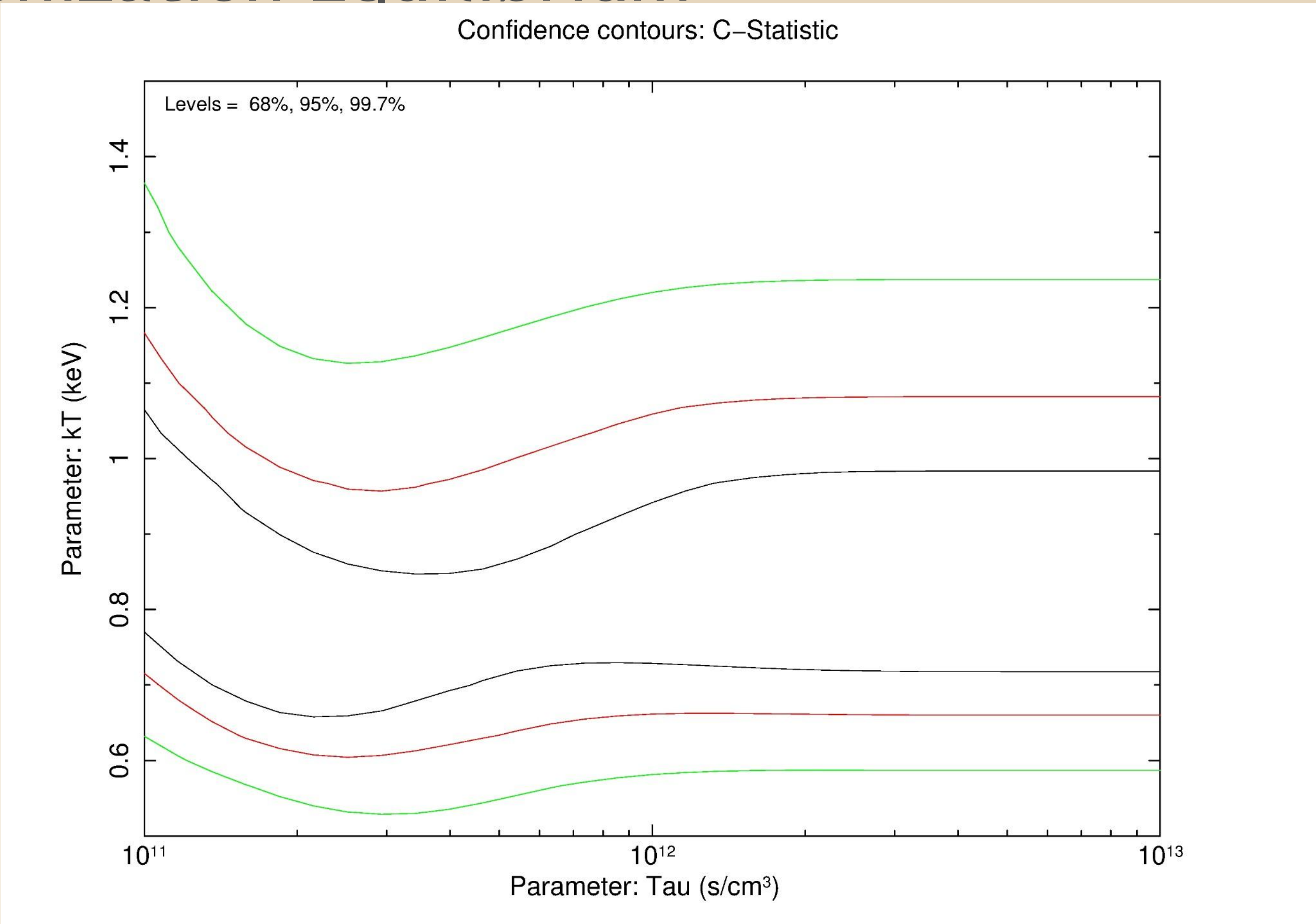
Implications

- Progenitors of type IIP Supernovae



Implications

- Ionization Equilibrium



Implications

- Particles and Magnetic Fields

$$\nu_{\rm Syn} = 240 \left(\frac{\epsilon_B}{0.1}\right)^{-3/2} \left(\frac{\dot{M}}{10^{-6}\ {\rm M_\odot\ yr^{-1}}}\right)^{-3/2} \times \left(\frac{v_{\rm w}}{10\ {\rm km\ s^{-1}}}\right)^{3/2} \left(\frac{t}{60\ {\rm days}}\right)\ {\rm GHz},$$

$$\nu_{\rm IC} = 8 \left(\frac{\epsilon_B}{0.1}\right)^{1/2} \left(\frac{\dot{M}}{10^{-6}\ {\rm M_\odot\ yr^{-1}}}\right)^{1/2} \times \left(\frac{v_{\rm w}}{10\ {\rm km\ s^{-1}}}\right)^{-1/2} \left(\frac{t}{60\ {\rm days}}\right) \times \left(\frac{V_s}{10^4\ {\rm km\ s^{-1}}}\right)^{4} \left(\frac{L_{\rm bol}(t)}{10^{42}\ {\rm ergs\ s^{-1}}}\right)\ {\rm GHz}.$$

A Tale of Two Shocks

Supernova bursts

Hot gas emits xray photons

Chandra catches them