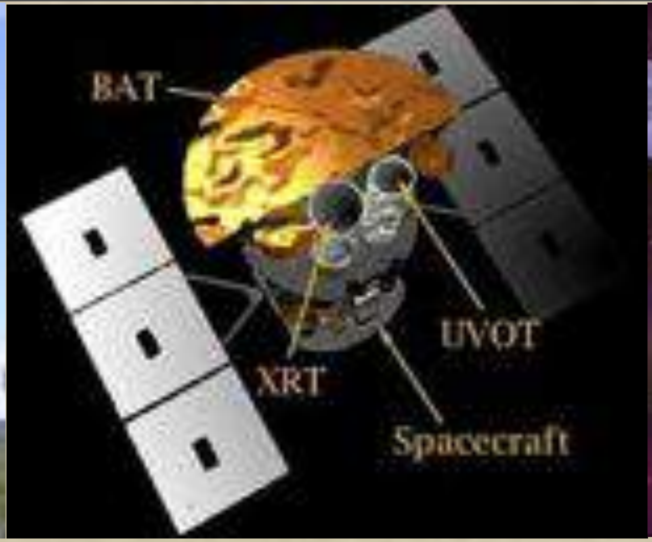
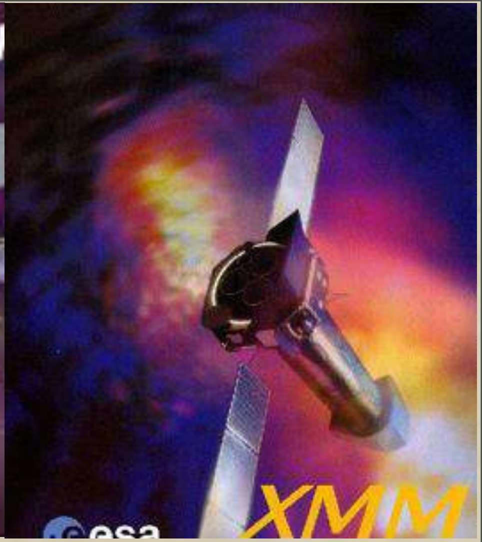
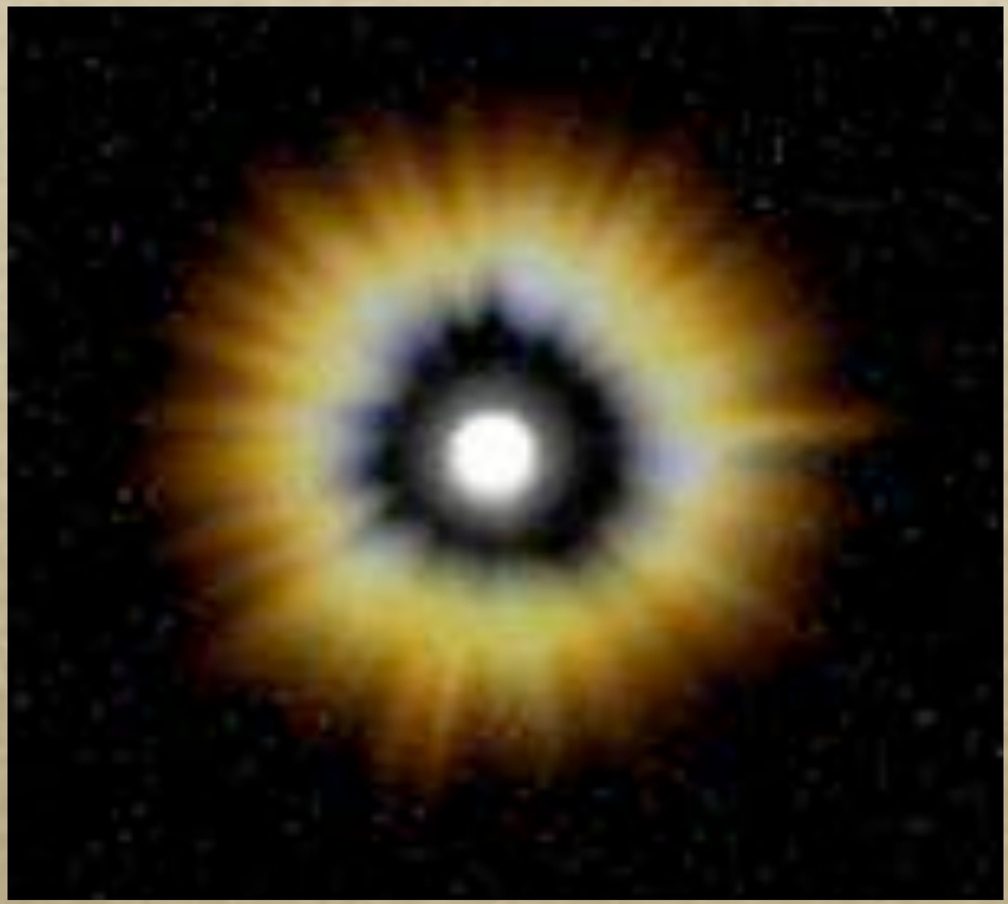




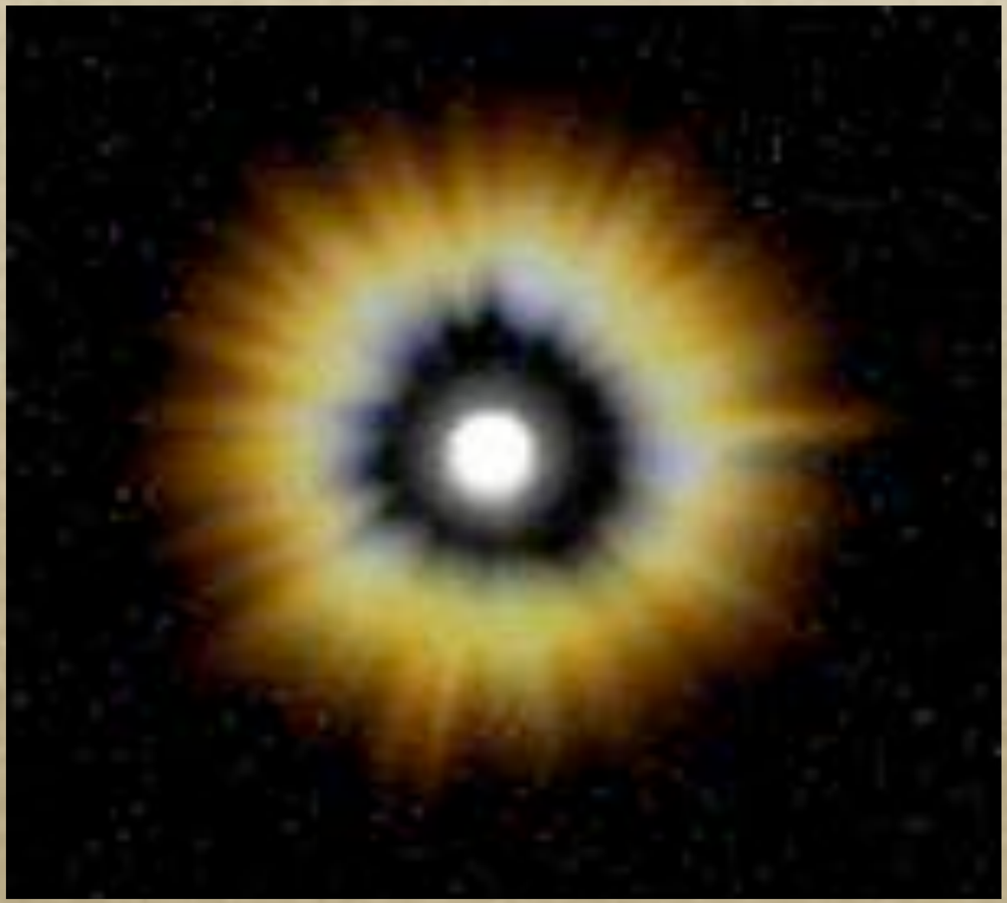
Supernovae: Shocked after the violent death of stars

Poonam Chandra
National Centre for Radio Astrophysics
Tata Institute of Fundamental Research

Evolution of massive stars



Evolution of massive stars



Evolution of massive stars

Supernovae from massive stars

- *Sequence of cataclysmic events*
  - *Exhaustion of fuel*
  - *Collapse under own gravity*
  - *Shock waves due to rebound*
  - *Ejection of star material (shock break out)*
  - ^{56}*Ni decay powering optical light curve.*
  - *Circumstellar interaction (powering radio and X-ray light curves)*

What is supernova explosion Physics?

- *We know that Gravity is the ultimate source of energy.*
- *Relative roles of neutrinos, fluid instabilities, rotation and magnetic field not clear.*
- *3D, general relativistic, magneto hydrodynamic simulations of rapidly rotating strongly magnetized core collapse (Mosta, Richers, Ott et al. 2014).*
- *3D dynamics of magneto-rotational core collapse if fundamentally different than 2D.*
- *Role of asymmetry crucial for explosion.*

Progenitors in archival images

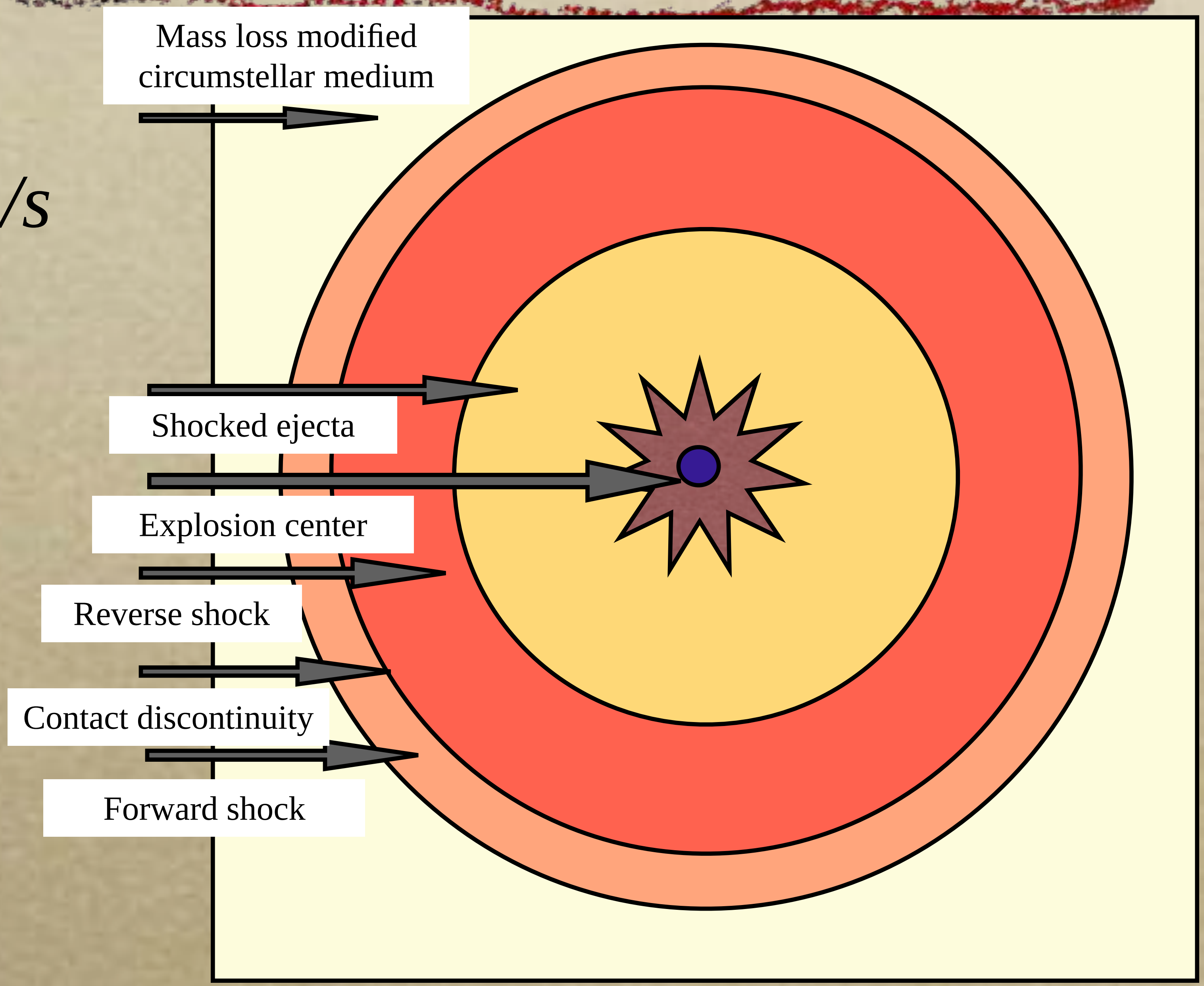
- *Possible for only nearby SNe (<30 Mpc).*
- *Many nearby SNe missing due to extinction.*
- *SN 1987A (blue supergiant), SN 1993J (binary), SN 2003gd (RSG progenitor of Type IIP supernova), SN 2005cs, 2004dj etc.*

Supernovae

- *Sequence of cataclysmic events*
  - *Exhaustion of fuel*
  - *Collapse under own gravity*
  - *Shock waves due to rebound*
  - *Ejection of star material*
  - *^{56}Ni decay powering optical light curve.*
  - *Circumstellar interaction*

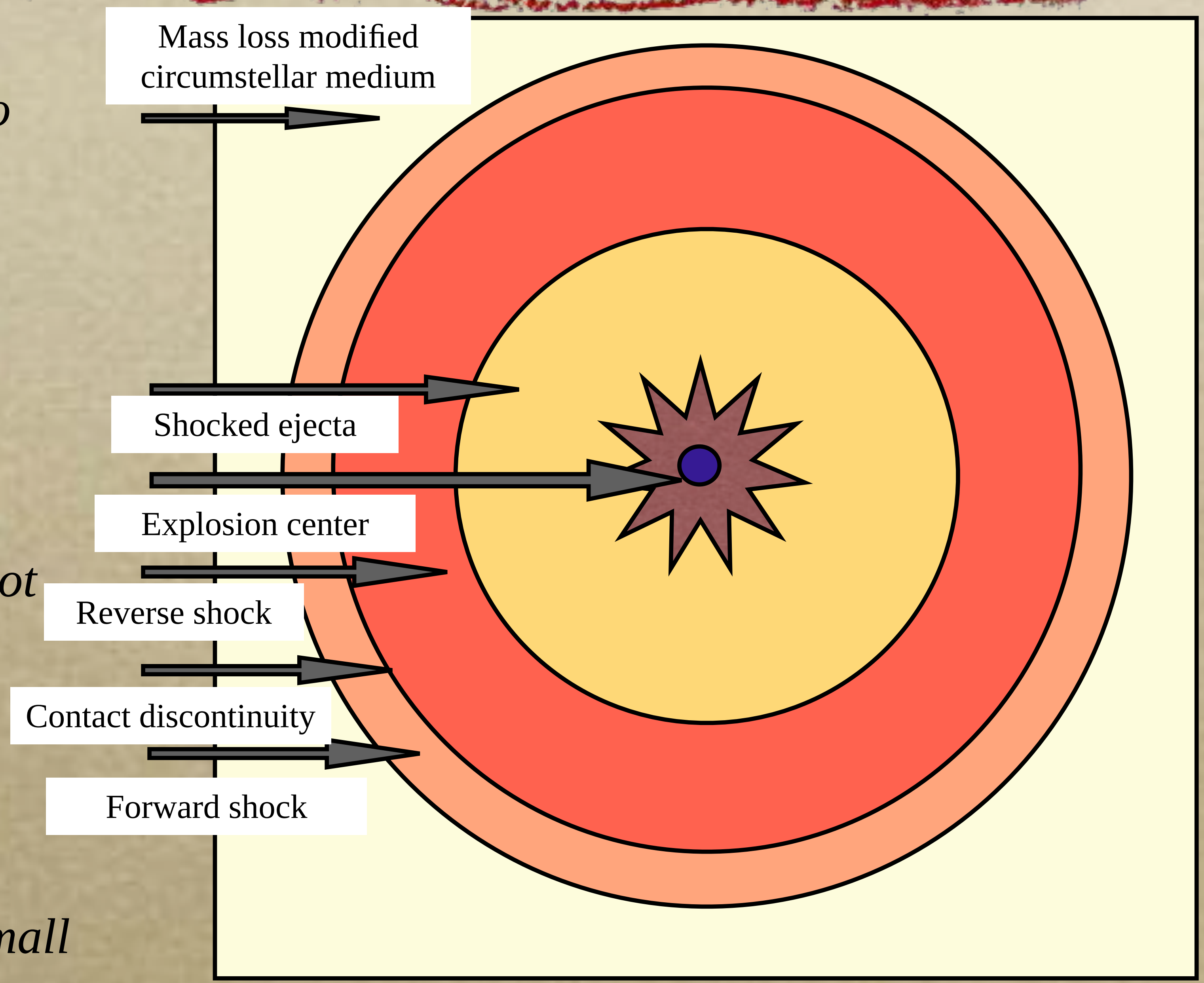
Time machine: Circumstellar interaction

- *Wind velocity ~10 km/s*
- *Ejecta speed 10,000 km/s*
- *Observations 1 year after explosion trace progenitor properties 1000 year before explosion*



Emission from circumstellar interaction

- *Emission comes mainly in radio and X-ray emission.*
- *Radio emission in non-thermal synchrotron by relativistic electrons in the presence of enhanced magnetic fields.*
- *X-ray emission thermal (from hot shocks) as well as non-thermal (inverse-Compton and synchrotron)*
- *In supernovae, emission from circumstellar interaction is a small part of total supernova power*



Mass loss: can give clues of the progenitor

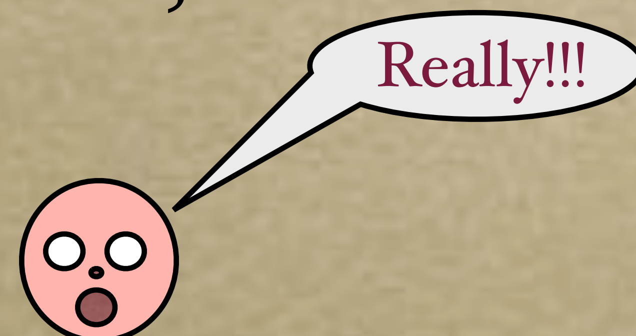
- *In form of steady winds ~10 km/s (Red supergiants- RSG)*
- *Episodic Outbursts (Luminous blue variable)*
- *Very high mass loss rate (massive progenitors)*
- *Mass loss rate (RSG)~10^{-5} M_{sun}/yr.*
- *LBV mass loss rate~10^{-2}-0.1 M_{sun}/yr*

Supernovae in dense environments

- *Type IIn Supernovae*
- *Explosions that had strong mass loss before the event*
- *Peak Optical luminosity powered by circumstellar interaction instead of ^{56}Ni decay as in other core collapse supernovae*

Mystery of Type IIn Supernovae

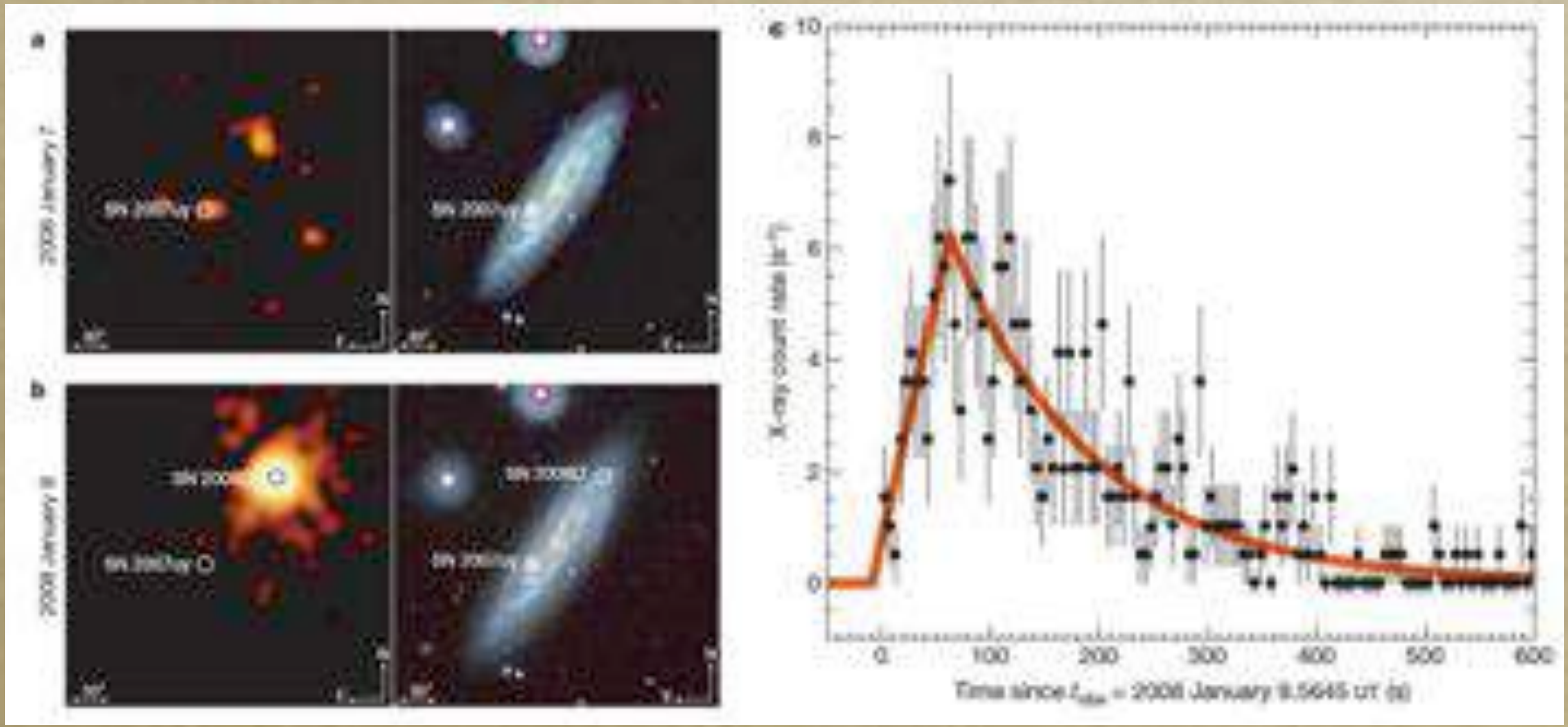
- *Extreme diversity*
- *Unknown progenitor nature*
- *SN 2005gl, SN 2009ip: H-rich >50M_{sun} (Luminous Blue Variable (LBV) progenitor!)*
- *SN imposter like SN 1961V!*
- *SN 2006gy: Ultraluminous, Pair-instability supernovae*
- *Even the Quark Novae*



Shock breakout in Type IIn Supernovae

- *Circumstellar interaction with surrounding medium stars once SN shock reaches stellar surface*
- *Shock Break Out in less dense environments*
    - *When shock reaches stellar surface, break out (τ~c/v)*
    - *Should be seen around a day after explosion*
    - *Last only for 30 Minutes*

SN 2008D: Serendipitous discovery of Shock breakout, Soderberg, ...Chandra et al. 2008

- 

Shock breakout in Type IIn Supernovae

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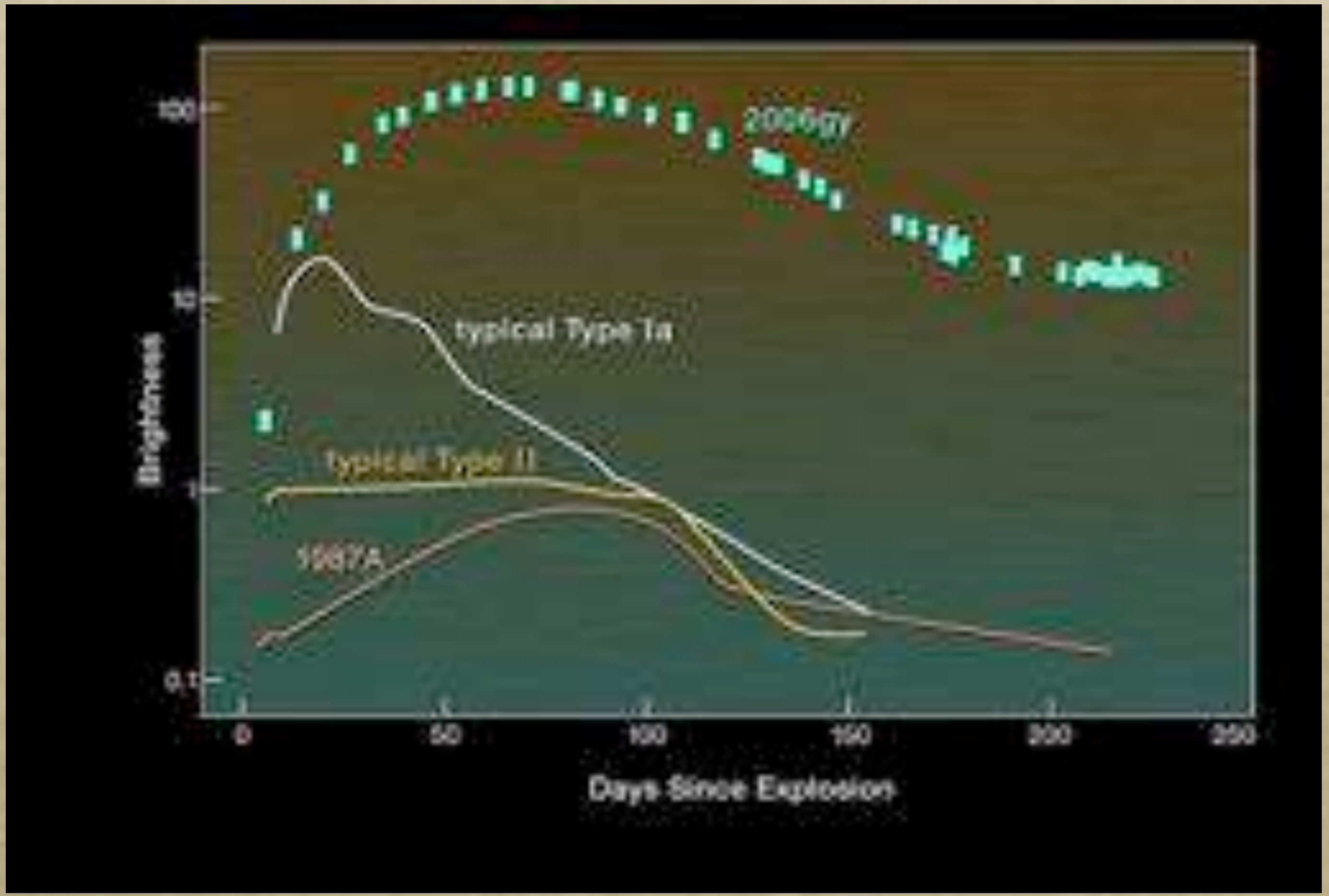
- *Shock Break Out in less dense environments*
  - *When shock reaches stellar surface, break out ($\tau \sim c/v$)*
  - *Should be seen around a day after explosion*
  - *Last only for 30 Minutes*
- *Shock break out in supernovae with dense environment*
  - *Medium becomes optically thick*
  - *Mass loss region optical depth $\tau > c/v$*
  - *Shock breakout happens in the mass loss wind $\tau \sim c/v$*
  - *Significant explosion energy radiated*
  - *Break out lasts for a much longer period*
  - *Rise in luminosity for 10s of days, e.g. SN 2006gy (Chevalier & Irwin 2011)*

SN 2006gy - Type IIn

- *In NGC 1260 (72 Mpc away)*
- *100 times brighter than normal supernovae, Mv<-19 for more than 250 days.*
- *Explosion from 150 Msun star!!*
- *A rare glimpse of how first stars died!*
- *SN 2005ap even brighter than SN 2006gy!!*



SN 2006gy: Progenitor scenarios

- *Pair instability supernova (Woosley et al. 2007)*
- *Type Ia SN exploding during a common envelope phase of a binary (Ofek et al. 2007).*
- *Quark nova:* supernova explosion of a massive star followed days later by the quark nova detonation of a neutron star, 20-40 Msun progenitor. *(Ouyed et al. 2012)*
- *IIn SN- interaction with a dense CSM, >15Msun ejecta, Moriya et al. 2012)*
- *1E49 ergs precursor event 8 years before the explosion. Now optical luminosity powered by the interaction, LBV progenitor (Smith et al. 2010)*

SN 2009ip - Type IIn

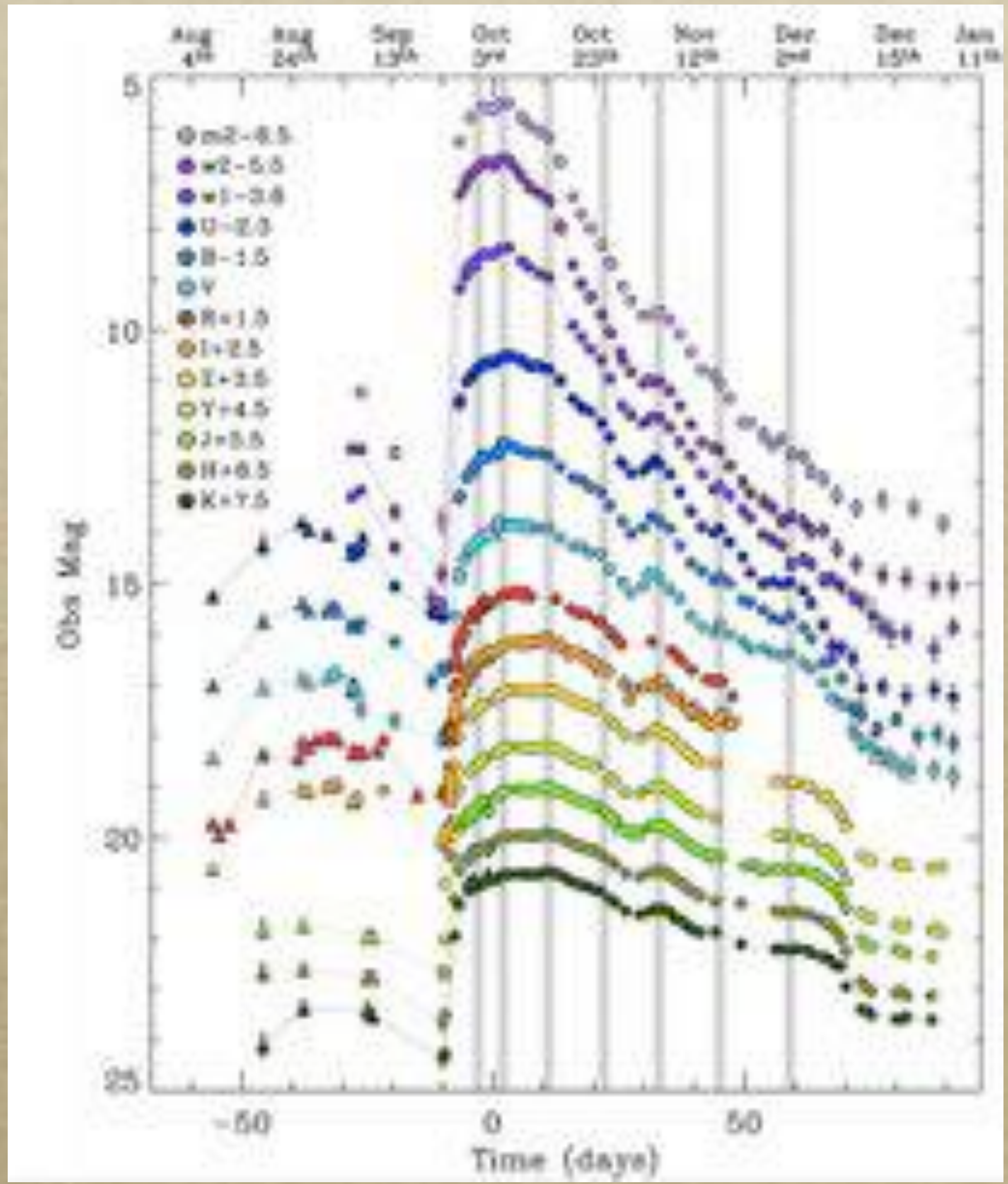
Margutti, Millisavljevic ..... Chandra et al. 2013

- *Discovered in 2009 in NGC 7259*
- *First confused with SN, later with LBV*
- *Multiple explosions in rapid succession in 2009.*
- *Some eruptions in 2010 and 2011*

Credit: Joseph Brimacombe

SN 2009ip

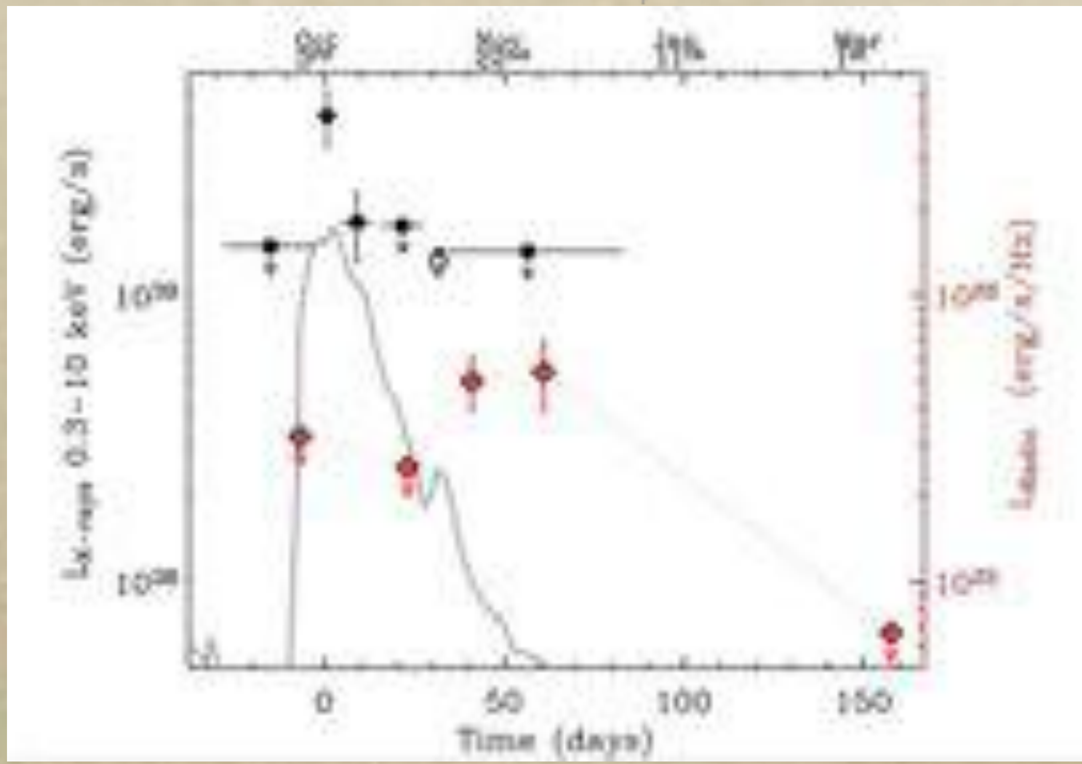
- *Rebrightened on 24th July, 2012.*
- *Dimmed 40 days later.*
- *Major rebrightening 23rd Sep, 2012, M_v < -18 (final supernova explosion?)*
- *Ejecta velocity in 2009 ~2000-7000 km/s*
- *Ejecta speed in Sept, 2013 13,000 km/s*

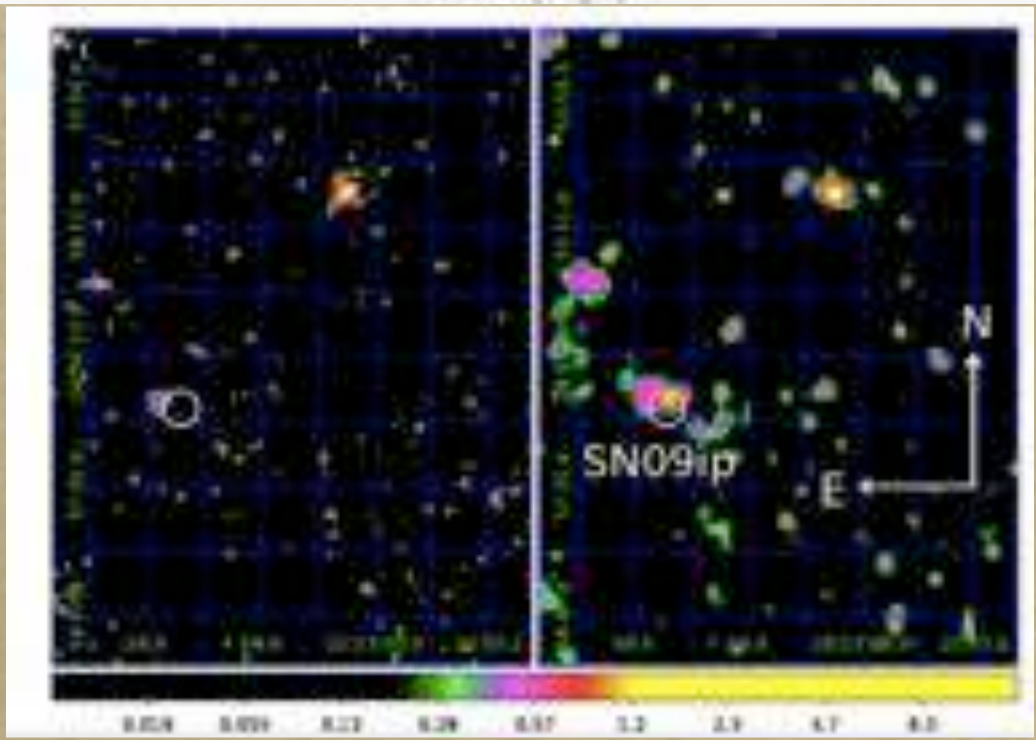


Margutti ..... Chandra et al. 2013

Radio and X-ray observations

Margutti ..... Chandra et al. 2013



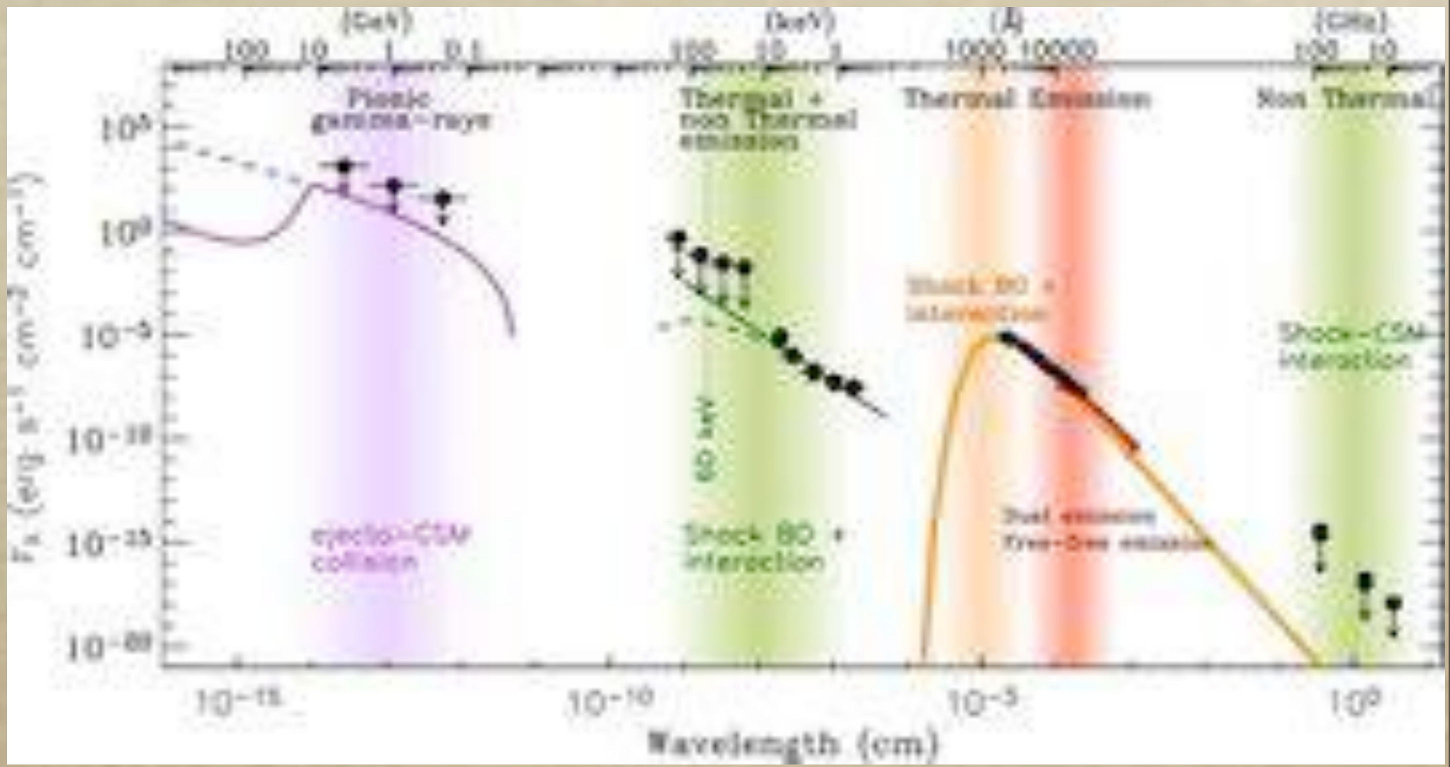


- *Radio/mm CARMA and VLA-no detection for first 50 days since Sept burst*
- *Radio light curve consistent with SN*
- *X-ray obs with Swift (PI: Soderberg) and XMM-Newton (PI : Chandra). No X-rays in July 2012 outburst, but detection in Sept 2012 outburst*

SN 2009ip

Margutti, Millisavljevic ..... Chandra et al. 2013

- *Peak bolometric luminosity 1.7E43 erg/s.*
- *Very similar to SN 2010mc.*
- *Radiated energy July outburst 1.5E48 and Sept outburst 3.2E49 ergs.*
- *Energy smaller than usual supernovae.*



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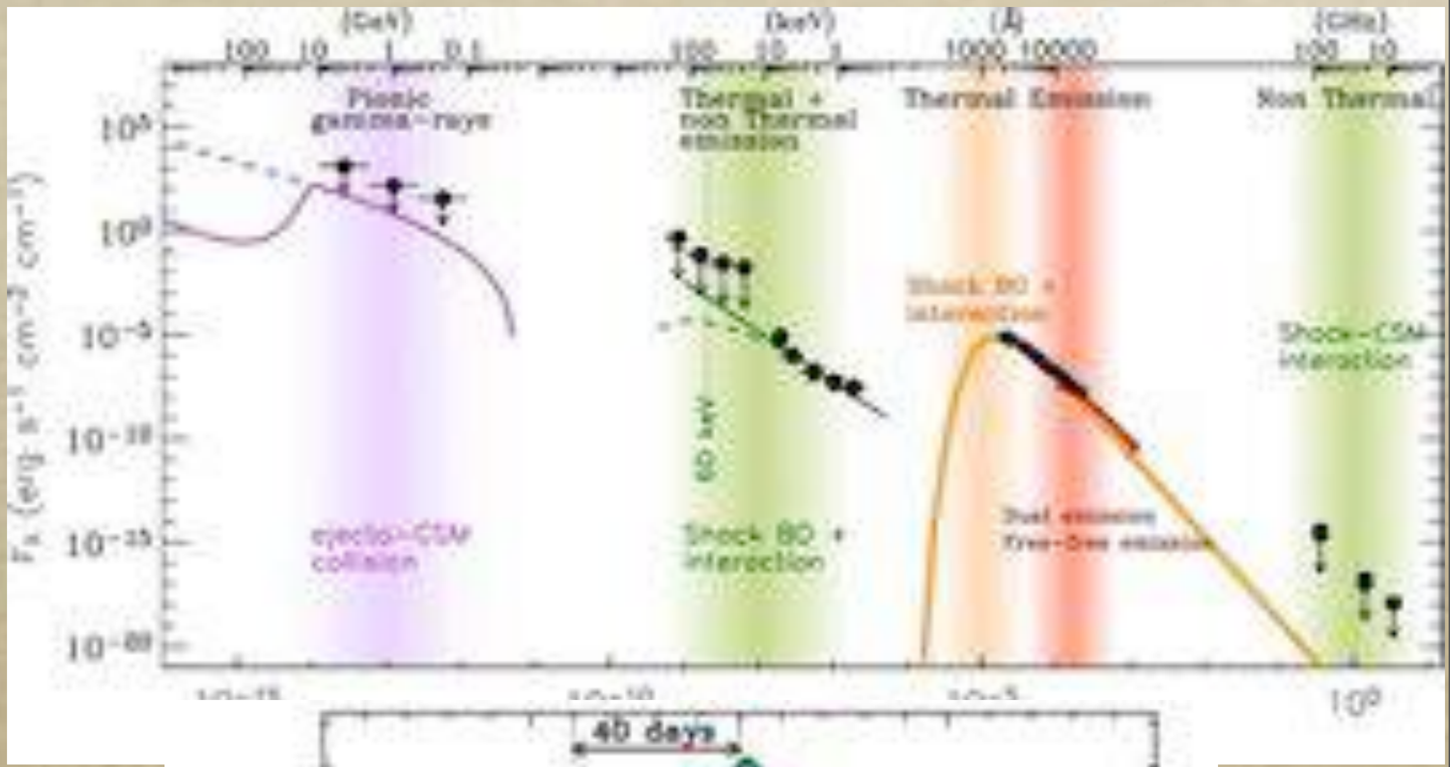
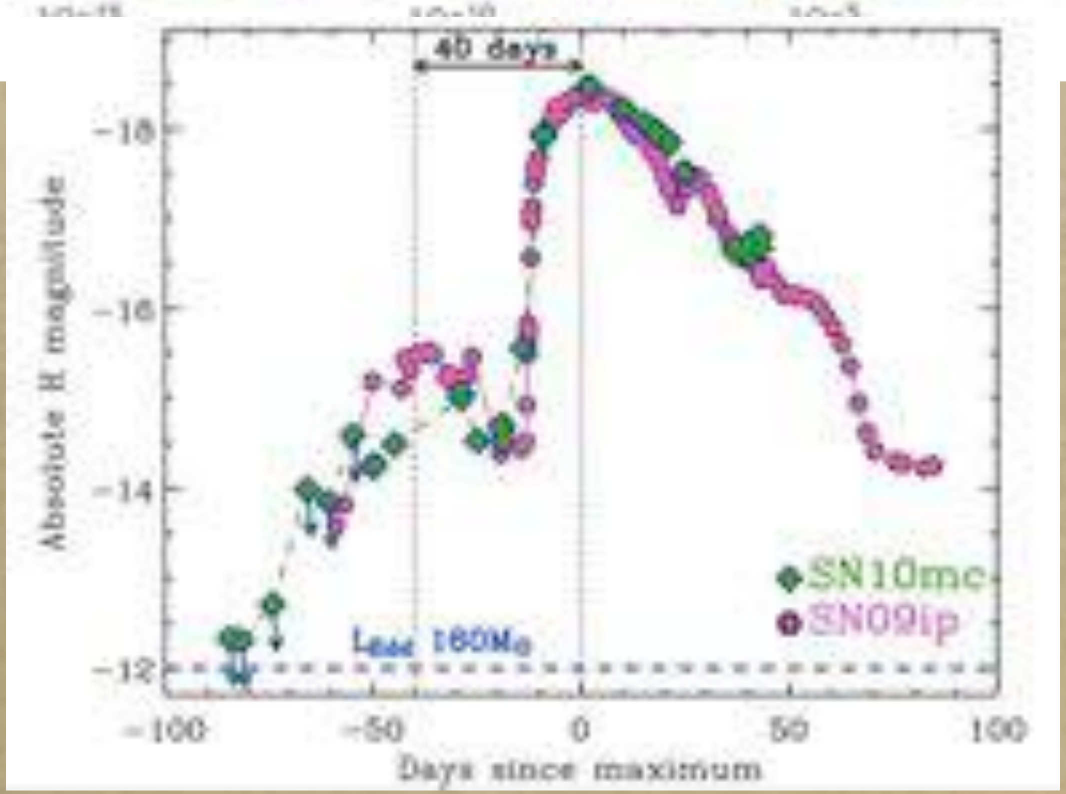




Final fate of the star

- *Was this much energy sufficient to unbind the star (Terminal explosion)?*
- *Or only lower energy explosion from the outer stellar envelope (non-terminal explosion)?*
- *Non-terminal explosion for Type IIn SNe 1994W (Dessart et al. 2009) and 2011ht (Humphreys et al. 2012)!*

SN 2009ip: Single explosion or double explosion

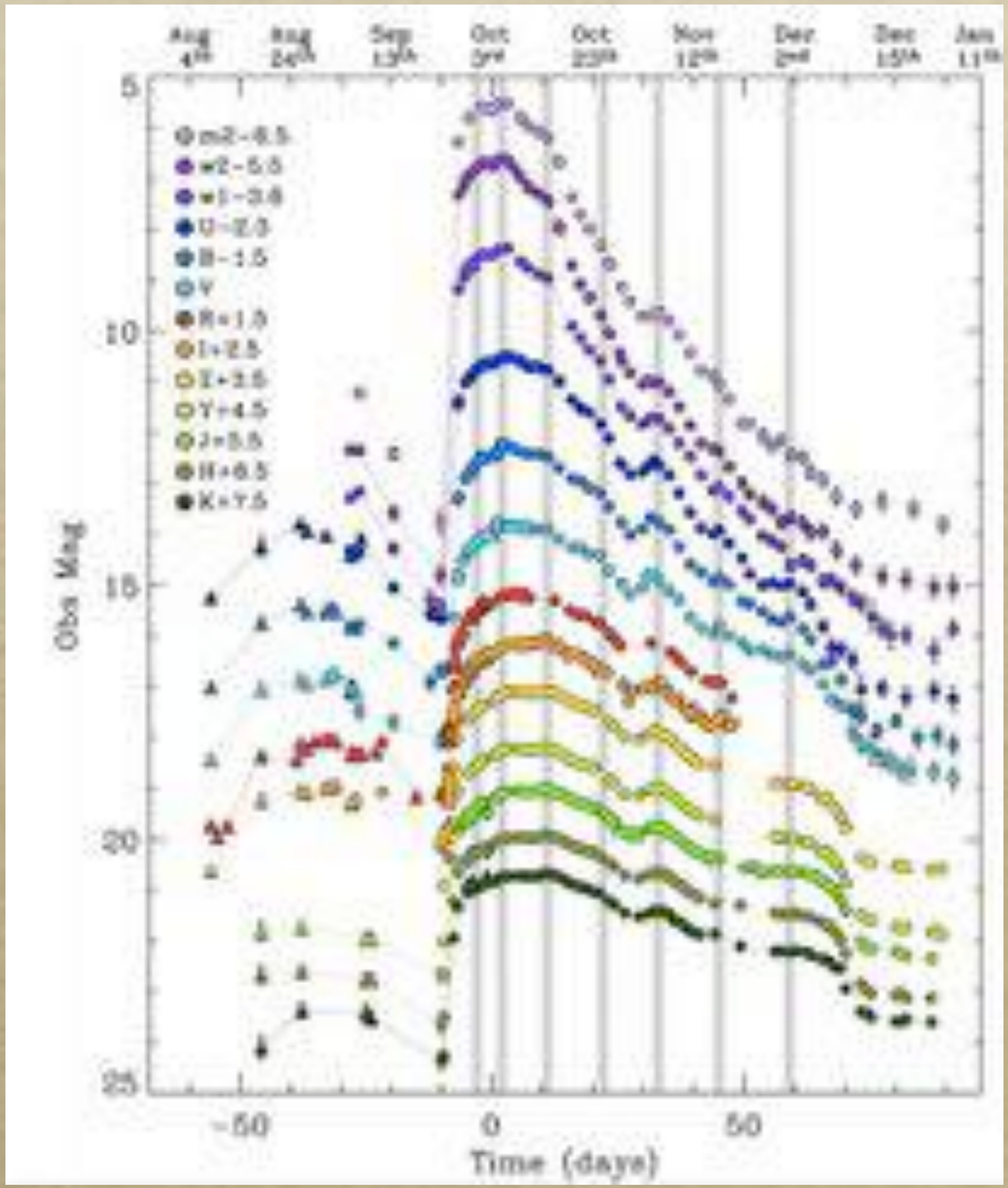
Margutti, Millisavljevic ..... Chandra et al. 2013

- *First bump SN explosion, second CSM interaction peak (Mauerhan et al. 2013). LBV progenitor.*

- *Precursor bump, second UV peak powered by shock breakout from material ejected by previous bump. Radio observations consistent (Margutti et al. 2013).*

- *SN or imposter: more outbursts to come?*

- *Only time will tell!*



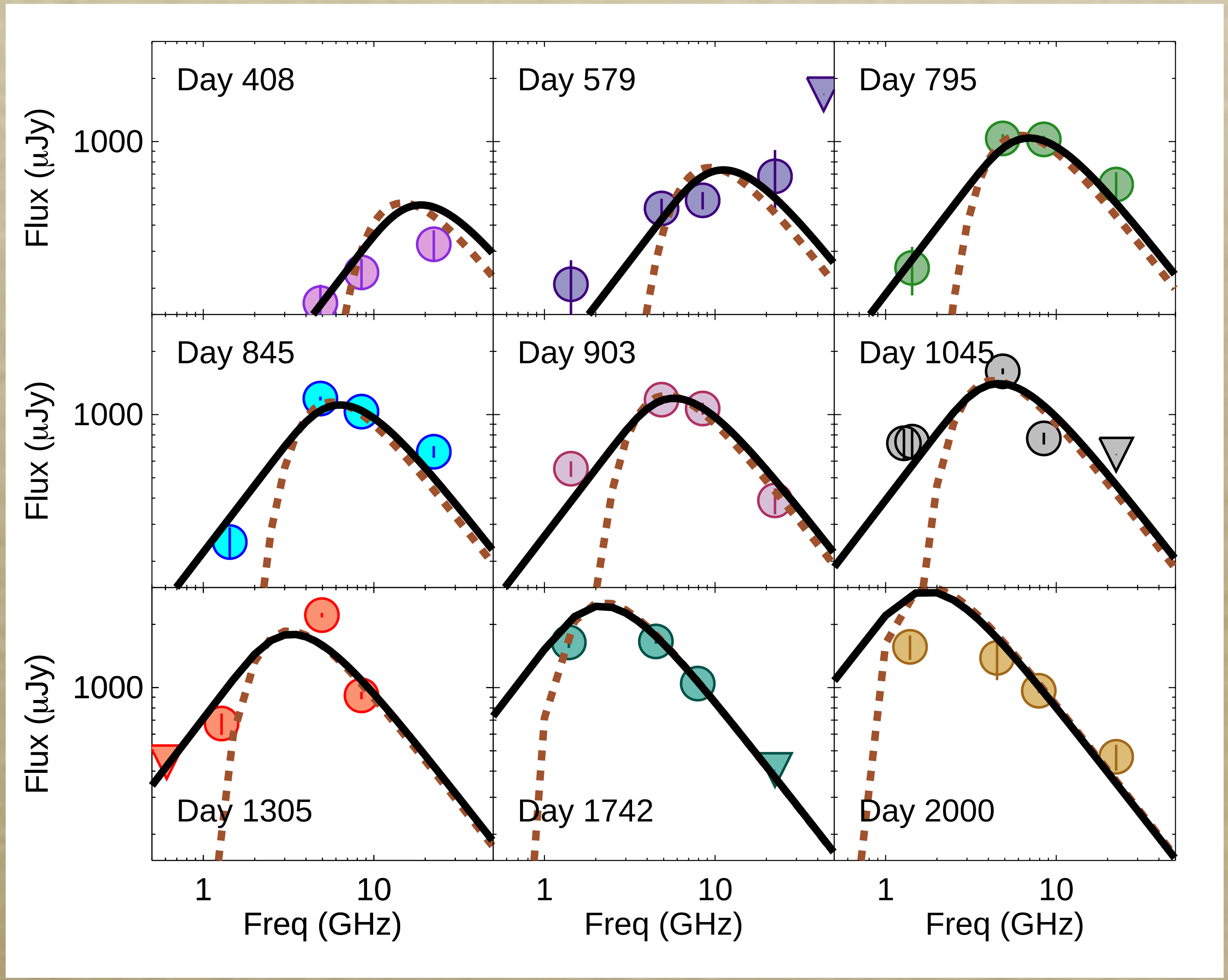
Type IIN- SN 2006jd

- *SN 2006jd (in UGC 4179) at discovery was classified as Type IIb supernova (SN 1993J Type).*
- *After a year and a half, reclassified as Type IIn supernova.*
- *Not too bright at discovery, but quite bright in radio and X-ray bands!*

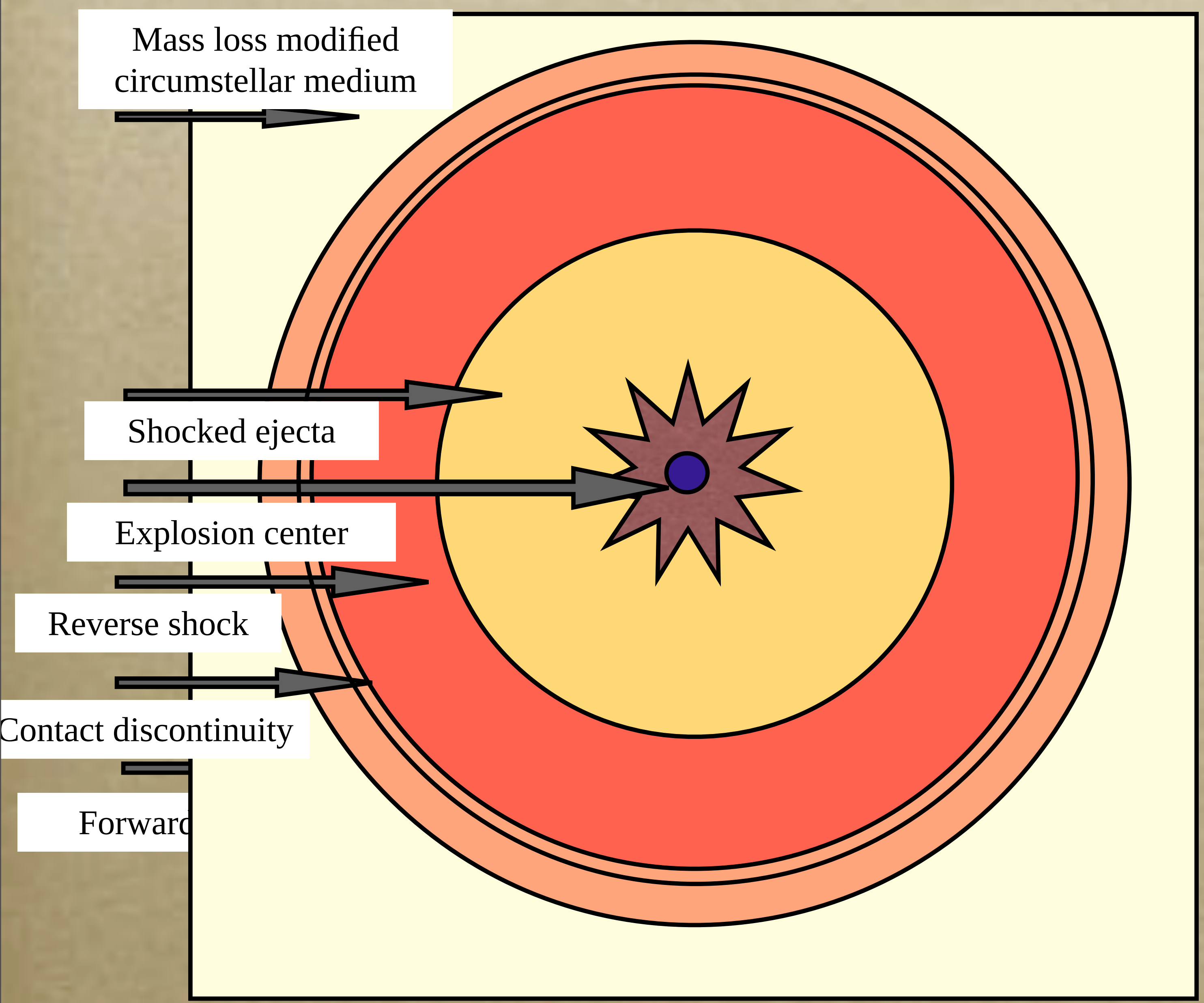
SN 2006jd- Progenitor environments

- *Radio emission heavily absorbed from the region of emission itself (internal free-free absorption).*
- *Mixing of cold (10^4-10^5K) gas in the Radio emitting forward shock itself.*
- *Only ~10-8 $T_4^{2.5} M_{sun}$ required to do required radio absorption.*
- *Radiative cooling of the dense gas in the shocked region.*

Chandra et al. 2012



Circumstellar interaction: mixing of cool gas



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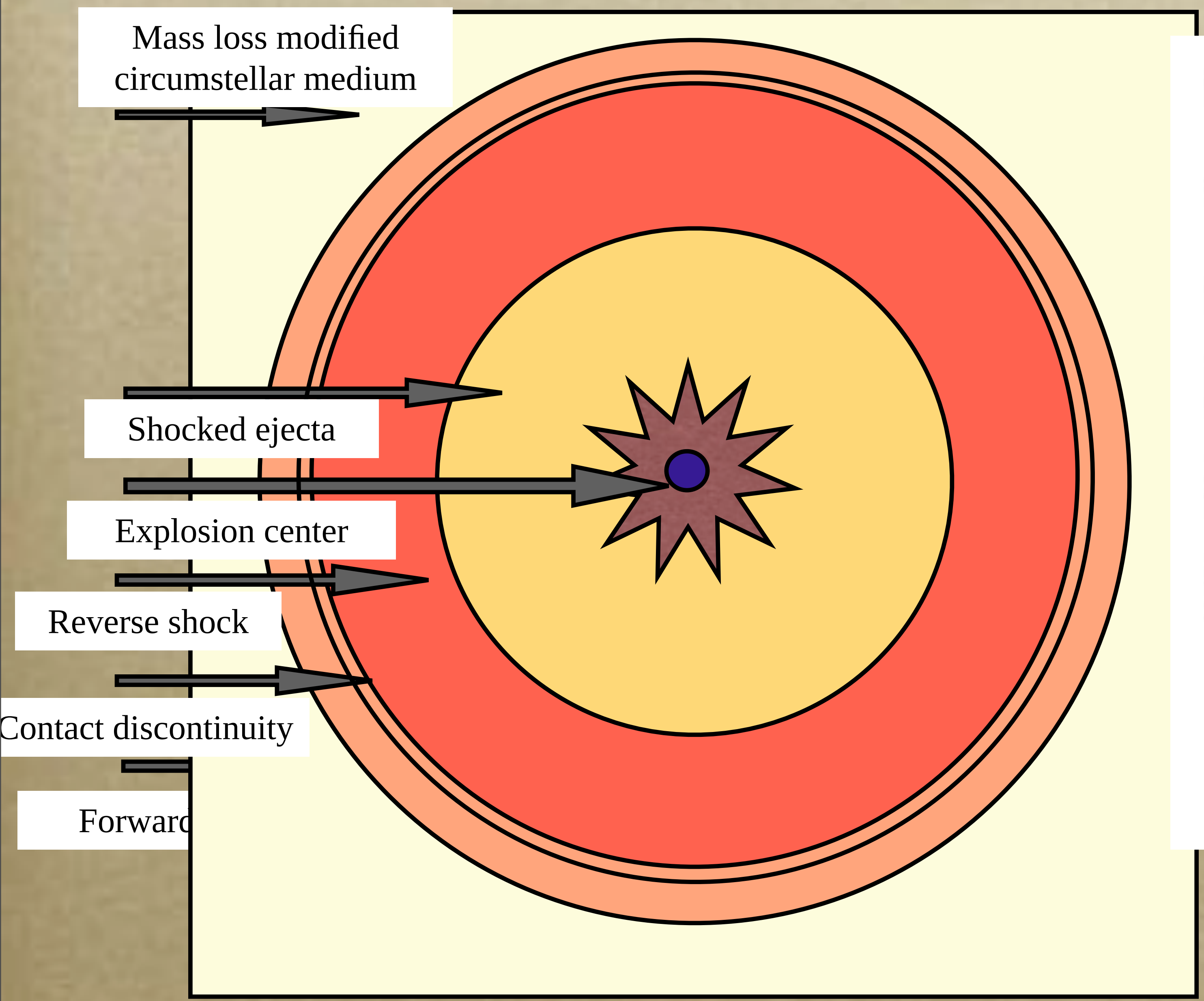
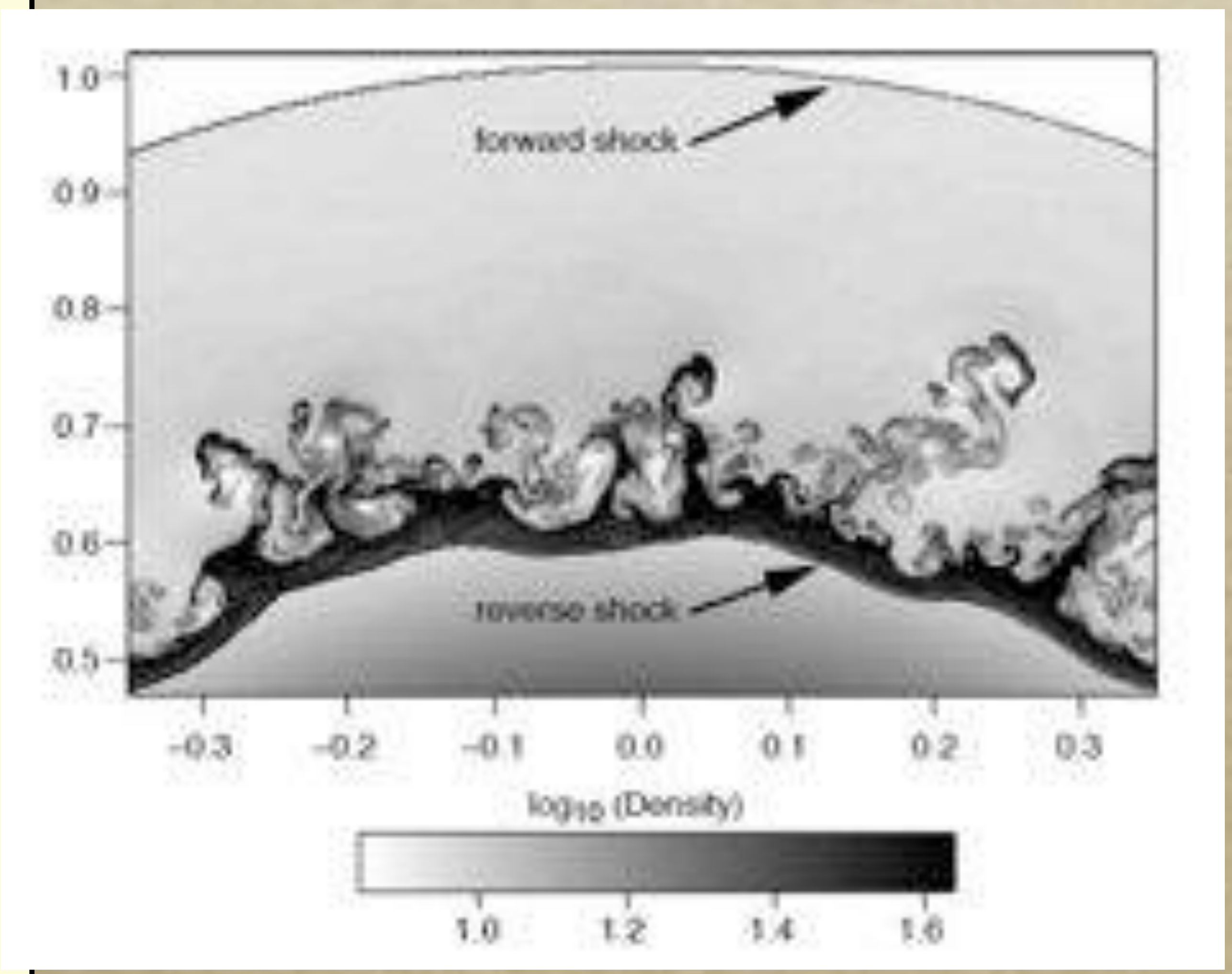


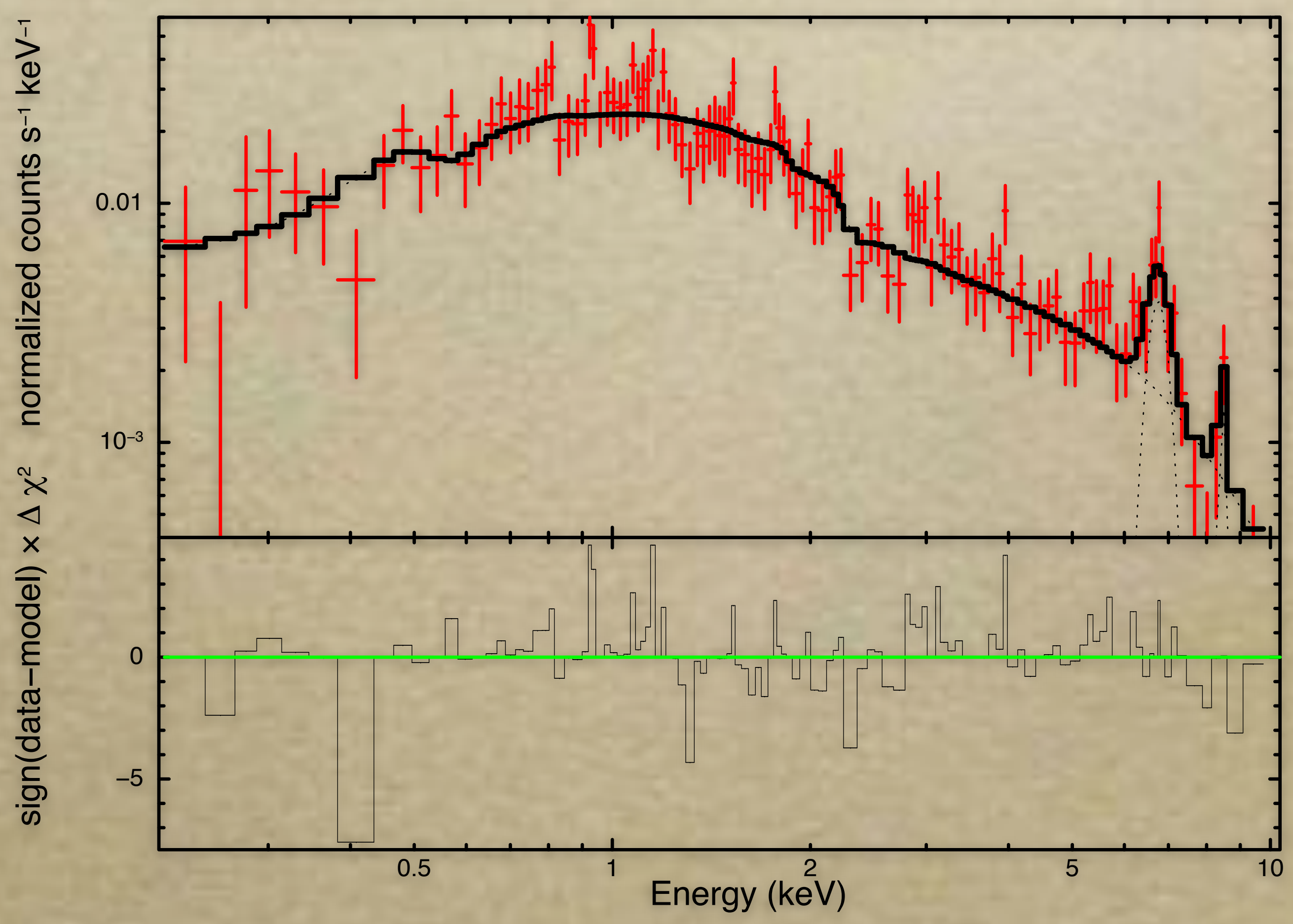
Chevalier et al. 1994



Evidence of cool gas in X-ray data

Chandra et al. 2012

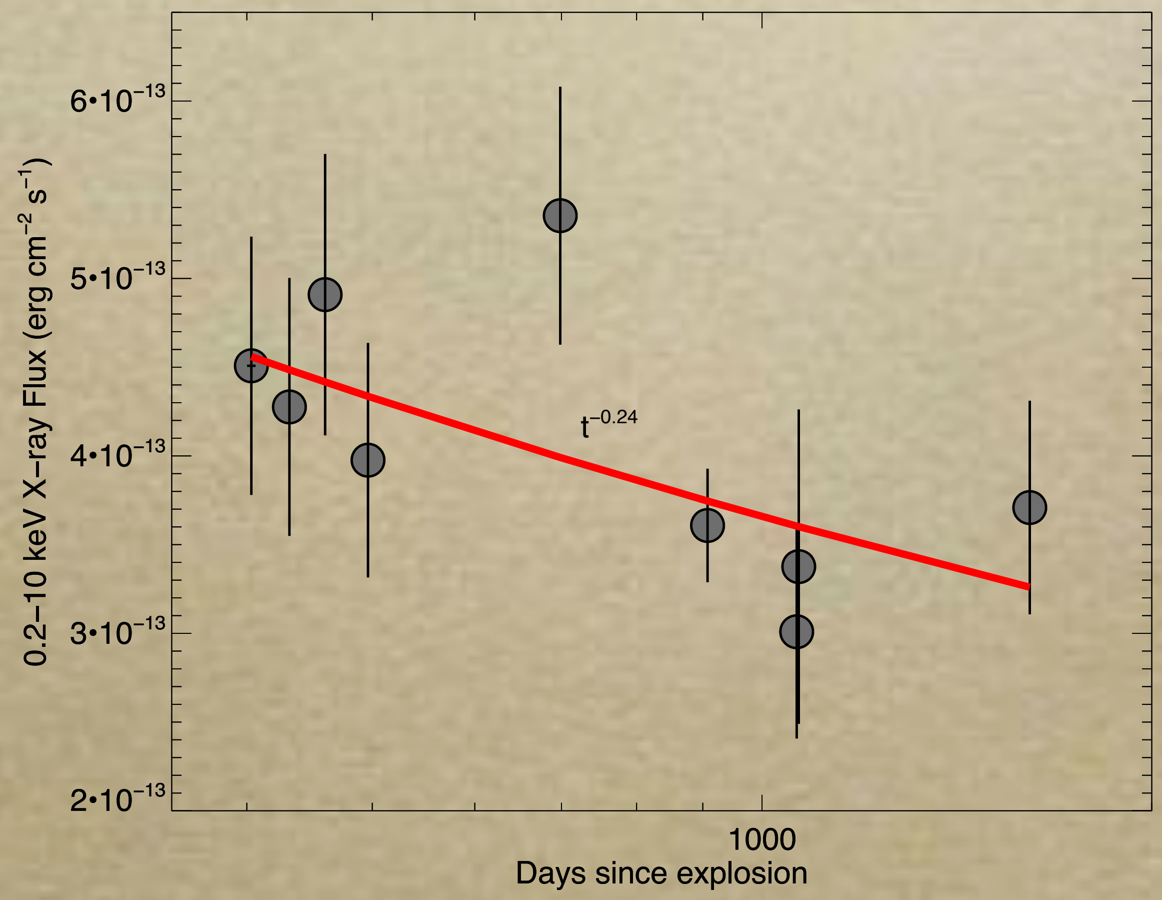
- *Presence of Fe Kα line (6.9 keV)*
- *Column width 1.4 keV, much higher than expected ~0.1-0.2 keV.*
- *Mixing of cool gas which would give 6.4 keV line.*



SN 2006jd

- *Analysis of bright radio and bright X-ray emission*
- *Living in a dense $3x10^{-6}$ cm^{-3} CSM.*
- *CSM density profile is not following typical $\rho \sim R^{-2}$ behaviour*

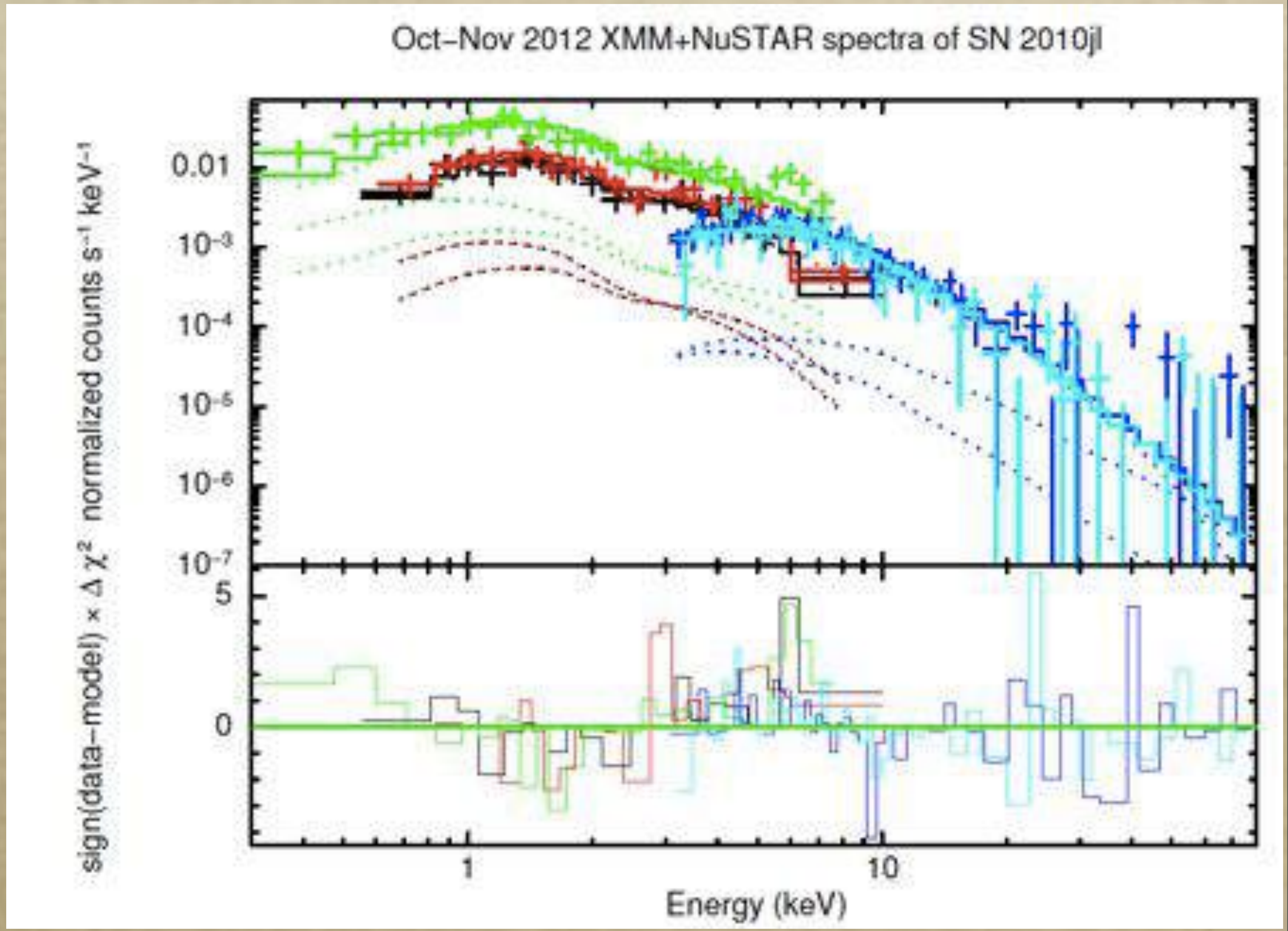
Chandra et al. 2012



SN 2010jl

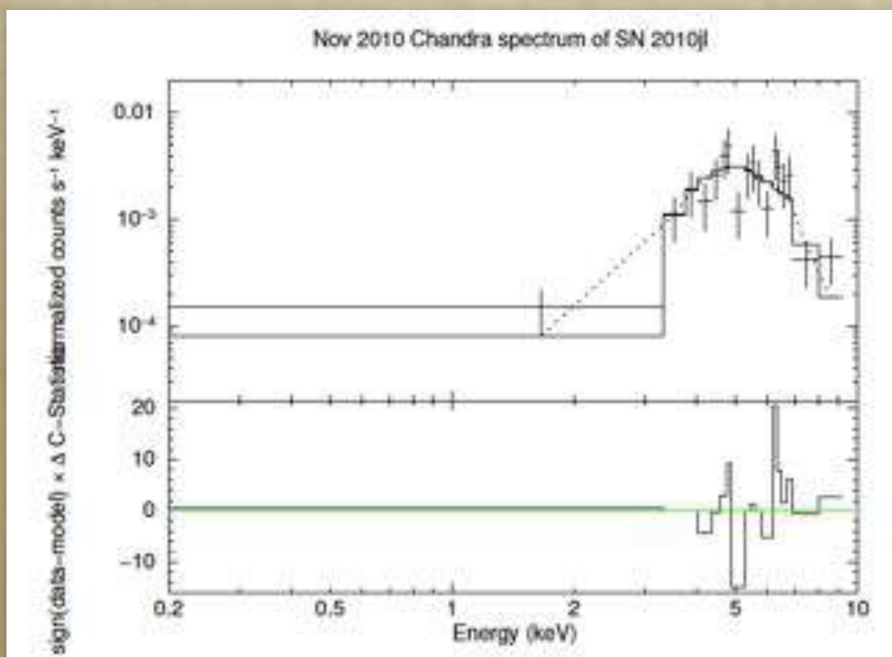
- *Observed with peak magnitude 12.9 (d=50 Mpc).*
- *Several radio and X-ray observations.*
- *Brightest Type IIn X-ray supernova so far.*
- *Radio emission started after day 500.*
- *Observed with Chandra, Swift-XRT, NuSTAR, XMM-Newton spectra*
- *NuSTAR+XMM spectra: Very hot forward shock*
- *All X-ray coming from forward shock*
- *Extremely high Column density, 3000 times Galactic at first month*

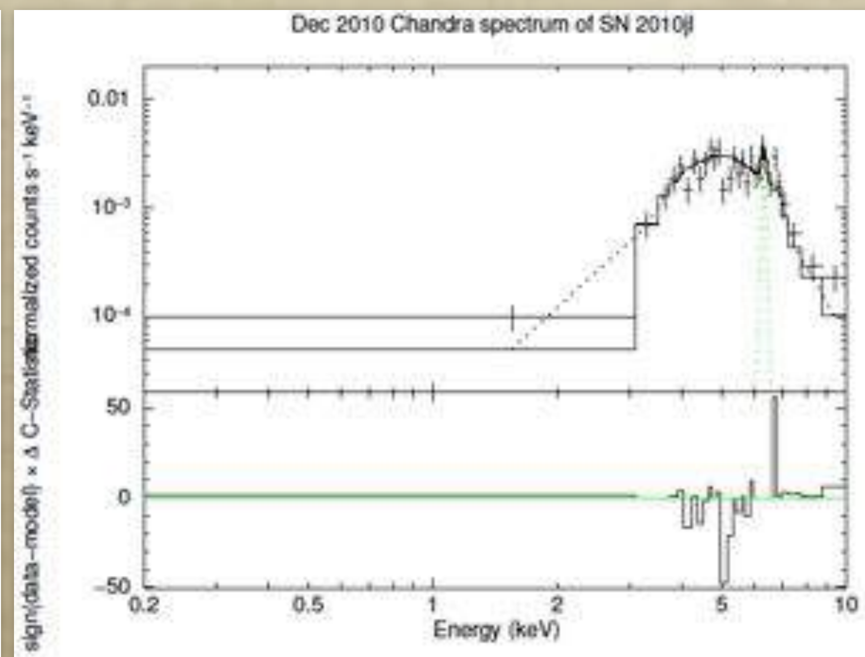
Chandra et al. 2012b, 2015

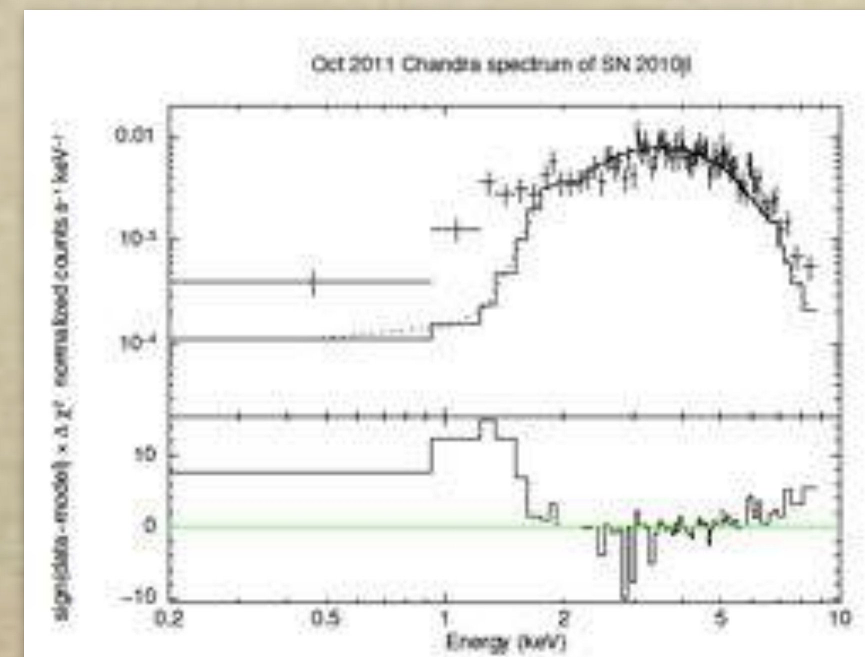


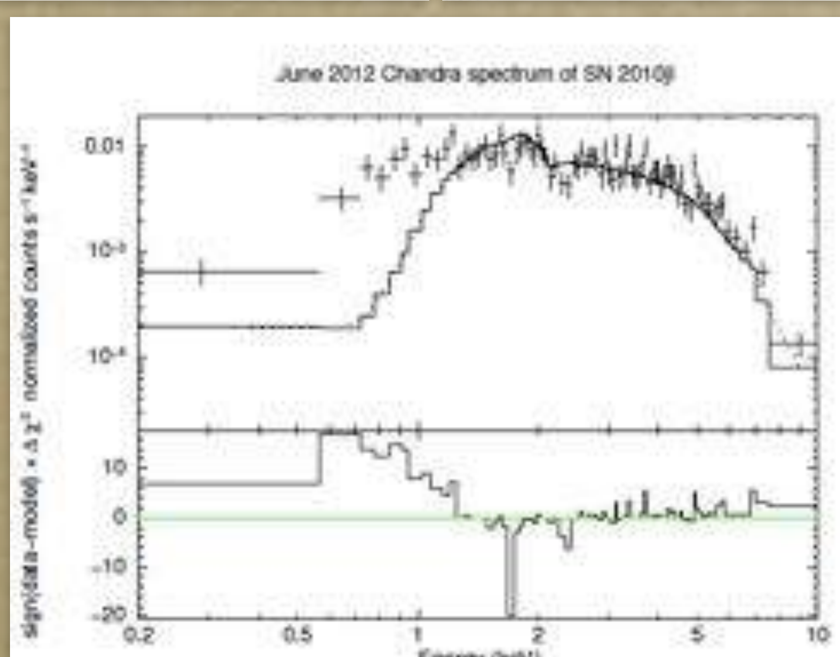
Evolution of Column density: from 1000 times Galactic to 10 times Galactic

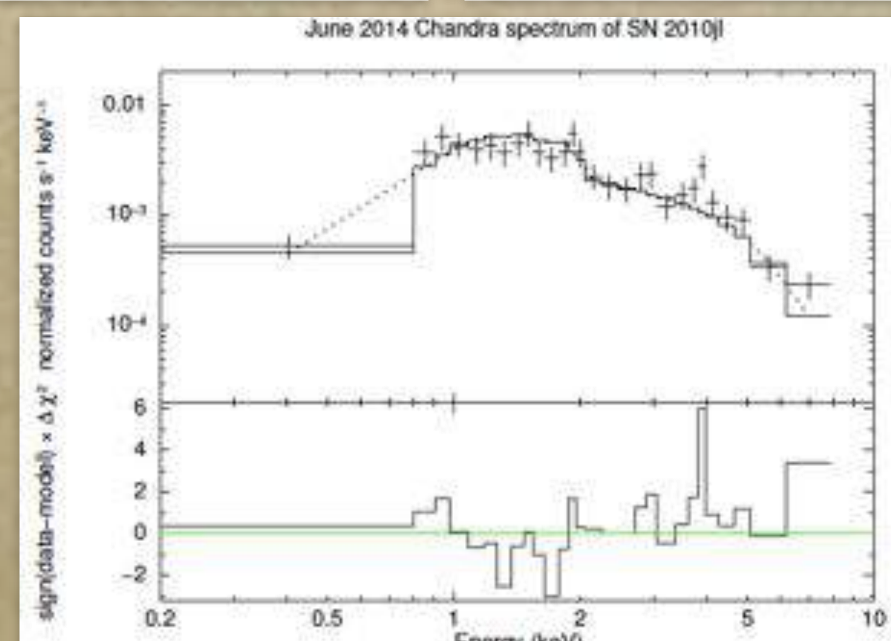
Chandra et al. 2012b, 2015





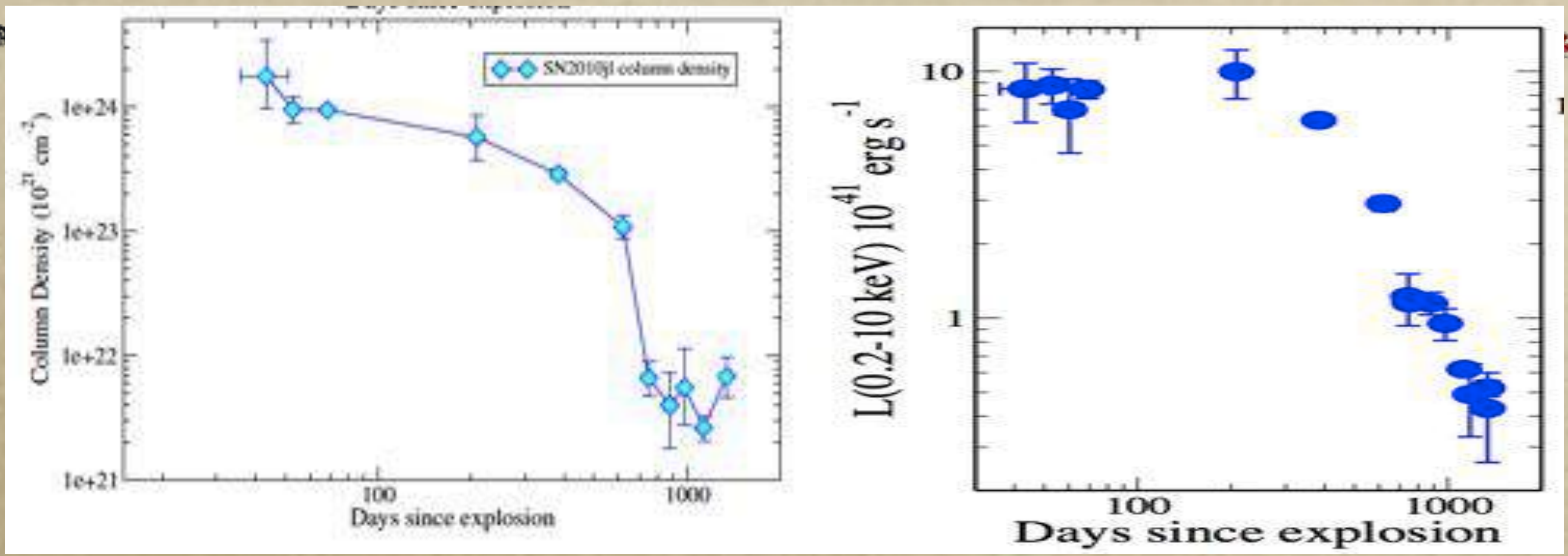






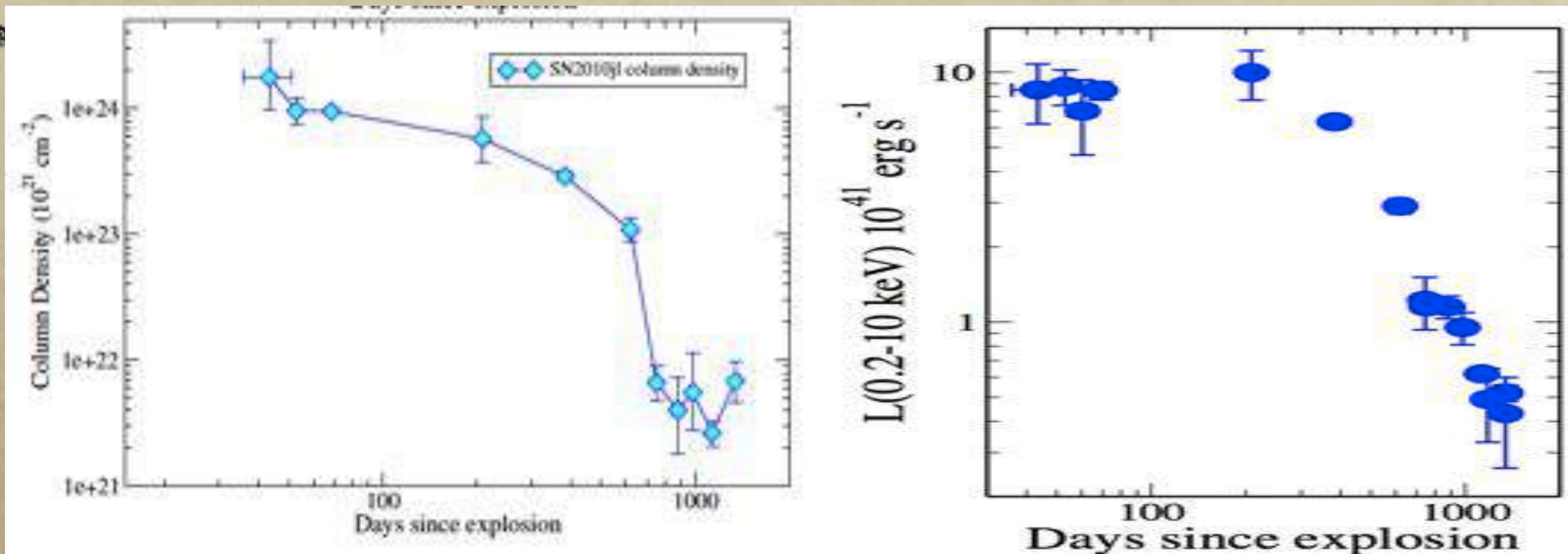
Evolution of column density

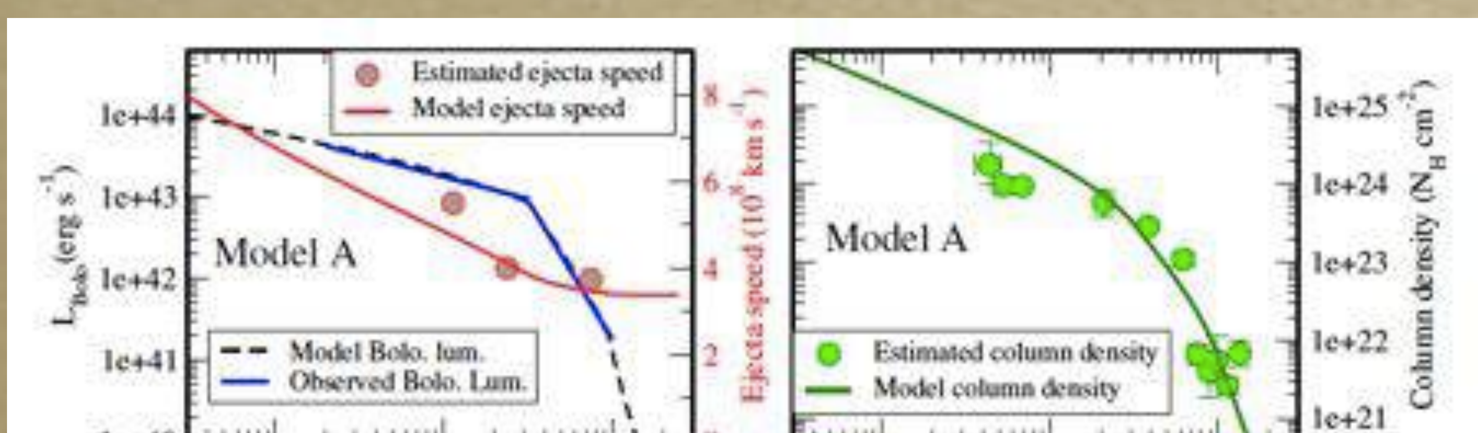
Chandra et al. 2012, 2015



Evolution of column density

Chandra et al. 2012, 2015

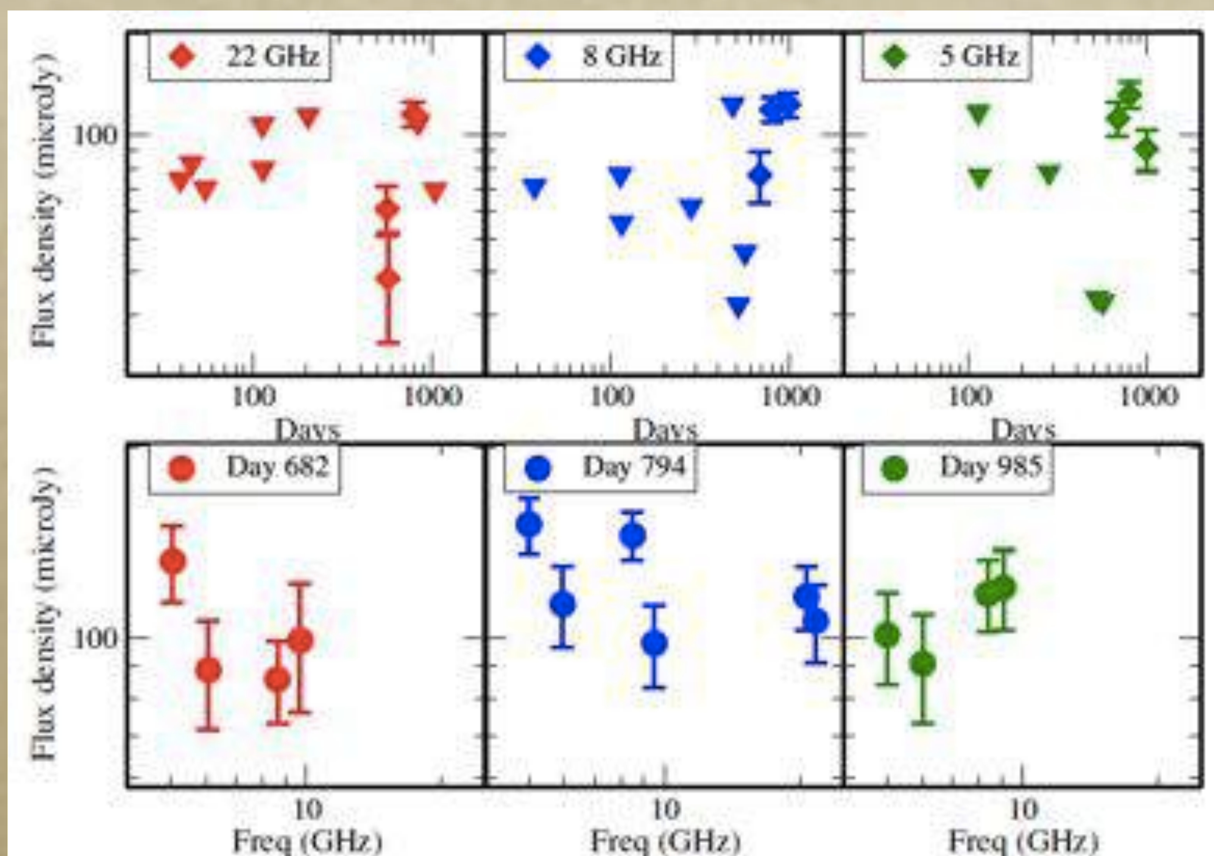


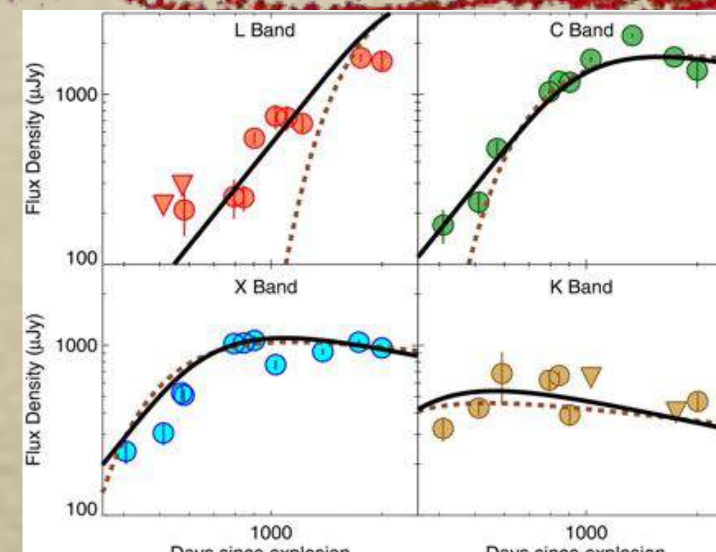


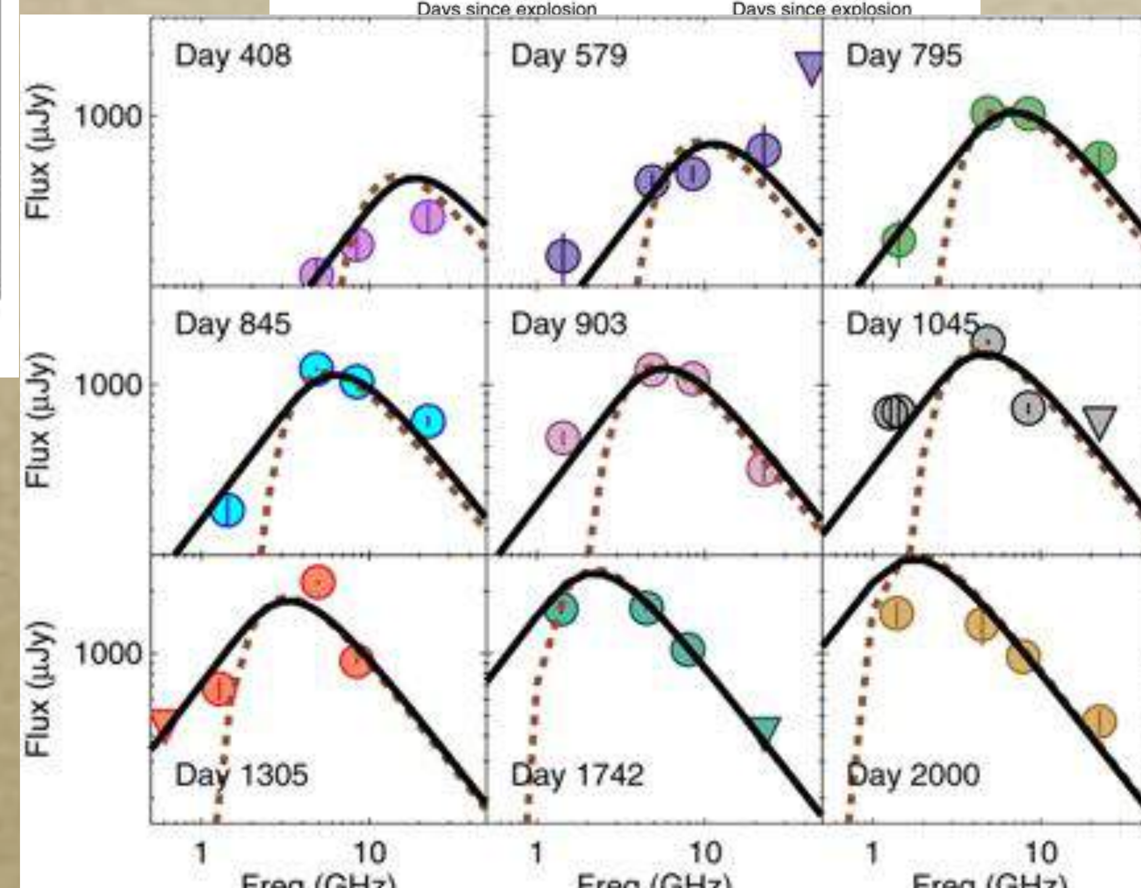
Cool shell radiative and absorbing all X-ray emission from reverse shock
Optical light curve is powered by the CSM interaction
Density goes as -1.6 and then drop at ~1.3x10^{16} cm.

Comparison of radio properties: SN 2006jd versus SN 2010jl

Chandra et al. 2012, 2015



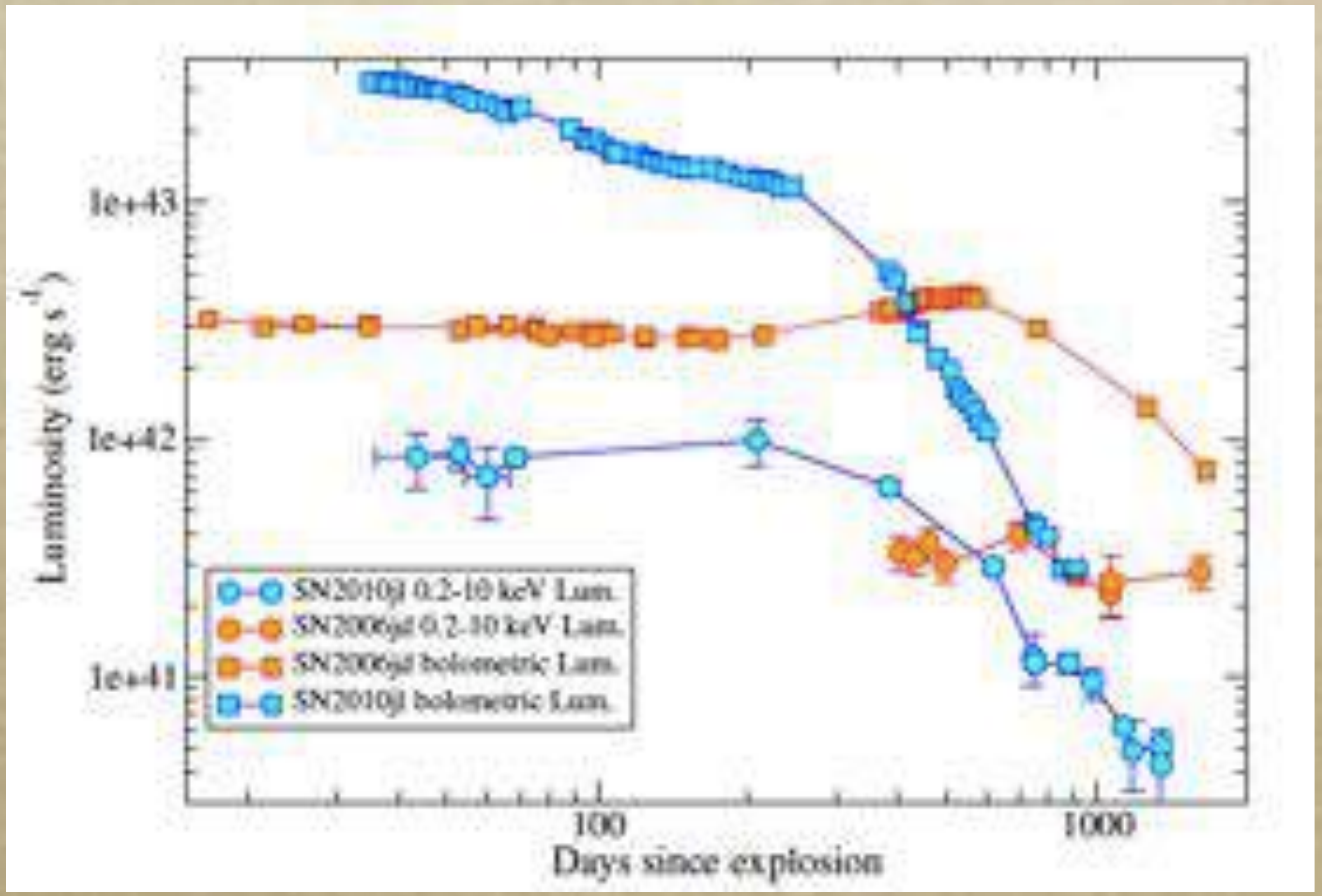




Comparison

- *Very flat evolution of SN 2006jd as compared to SN 2010jl.*
- *Indicative of slow and steady mass loss in SN 2006jd and fast quick ejection of mass loss in SN 2010jl*
- *Signifies difference in progenitors*
- *Consistent with LBV.*
- *Model gives mass lost 40 years before the explosion, 0.06-0.1M_{sun}/yr*

Chandra et al. 2012, 2015



SN 2006jd versus SN 2010jl

- *Very dense cool shell*
- *Very hot forward shock*
- *X-rays from reverse shock are absorbed in the cool shell, all emission from forward shock*
- *Very bright X-ray emission*
- *Signatures of asymmetry in the explosion*

Comparison SN 2006vs SN 2010jl

- **SN 2010jl**
- *Very bright, (m_v~12.9, d=50 Mpc)*
- *Column density 1000 times Galactic*
- *Evolving column density*
- *Radio free-free absorbed by the external medium*
- *Episodic mass loss, shortly before explosion (~40 years)*
- *Mass loss rate 0.1 M_{sun}/yr*
- *Density ~10^8 cm^{-3}*
- *Most likely LBV progenitor*

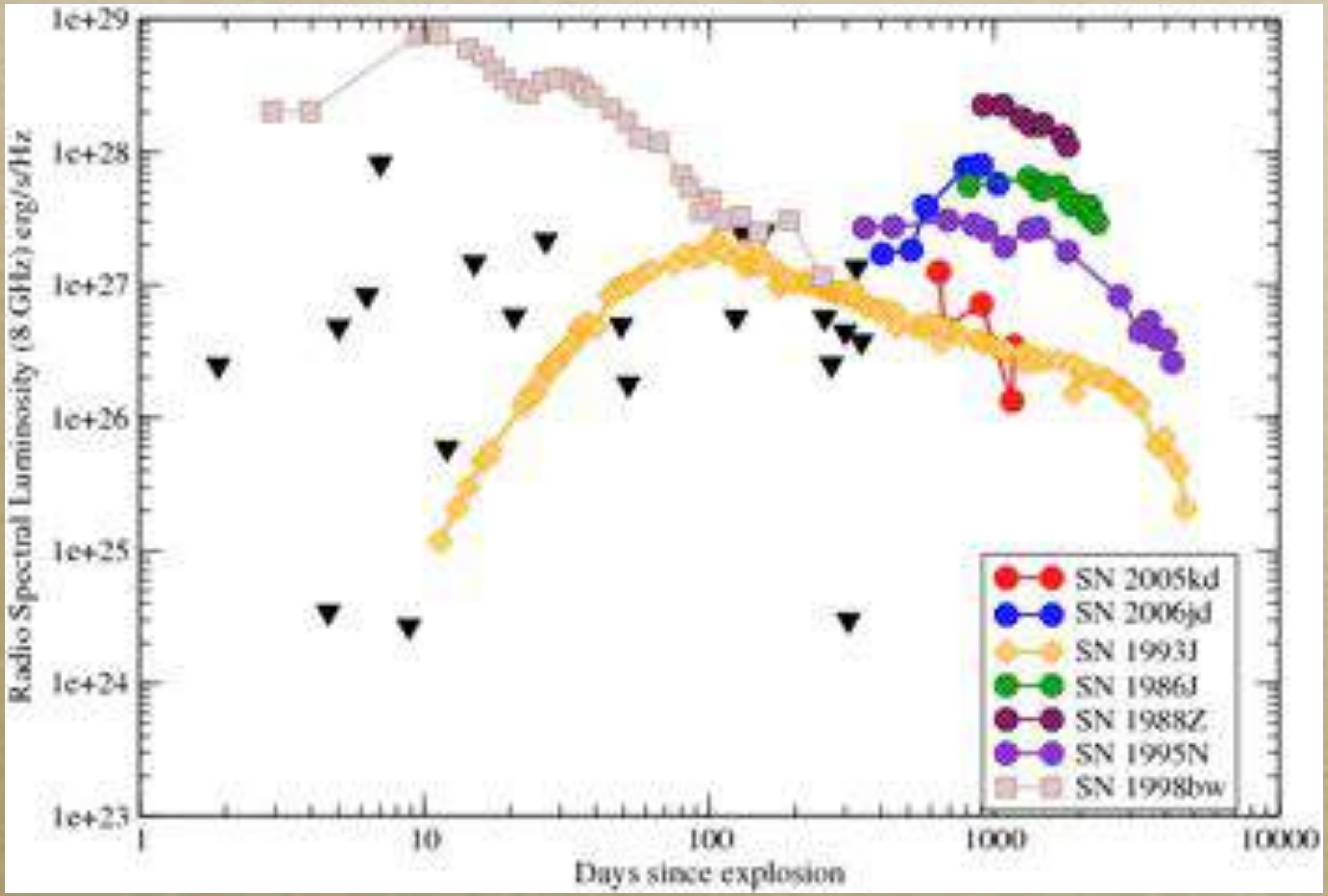
- **SN 2006jd**
- *Not too bright (m_v=17.2, d=79 Mpc)*
- *Column density only 2.5 times Galactic*
- *Constant column density*
- *Radio internally absorbed by the mixing of cool gas*
- *Steady mass loss, much longer duration of mass ejection*
- *Mass loss rate 5x10^{-3} M_{sun}/Yr*
- *Density 6x$10^6$$cm^{-3}$*
- *Non-LBV progenitor*

Predictions of SN 2010jl

- *If LBV, we may see another rebrightening in X-rays*
- *We don't have to wait for too long due to time machine effect, although it is less efficient for Type IIn supernovae!*

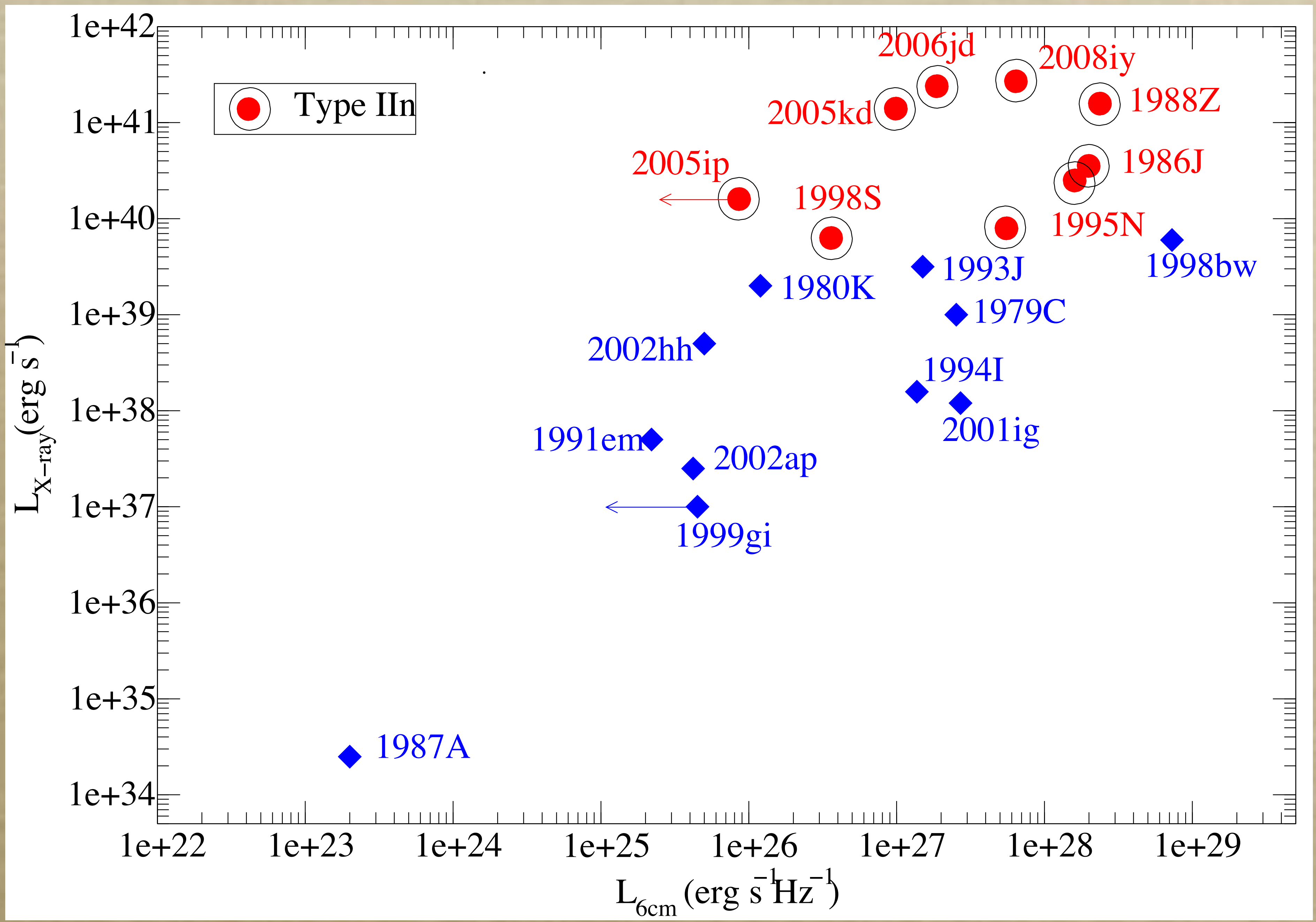
Radio emission in Type IIn

Chandra et al. 2015b



Trends in radio and X-ray emission

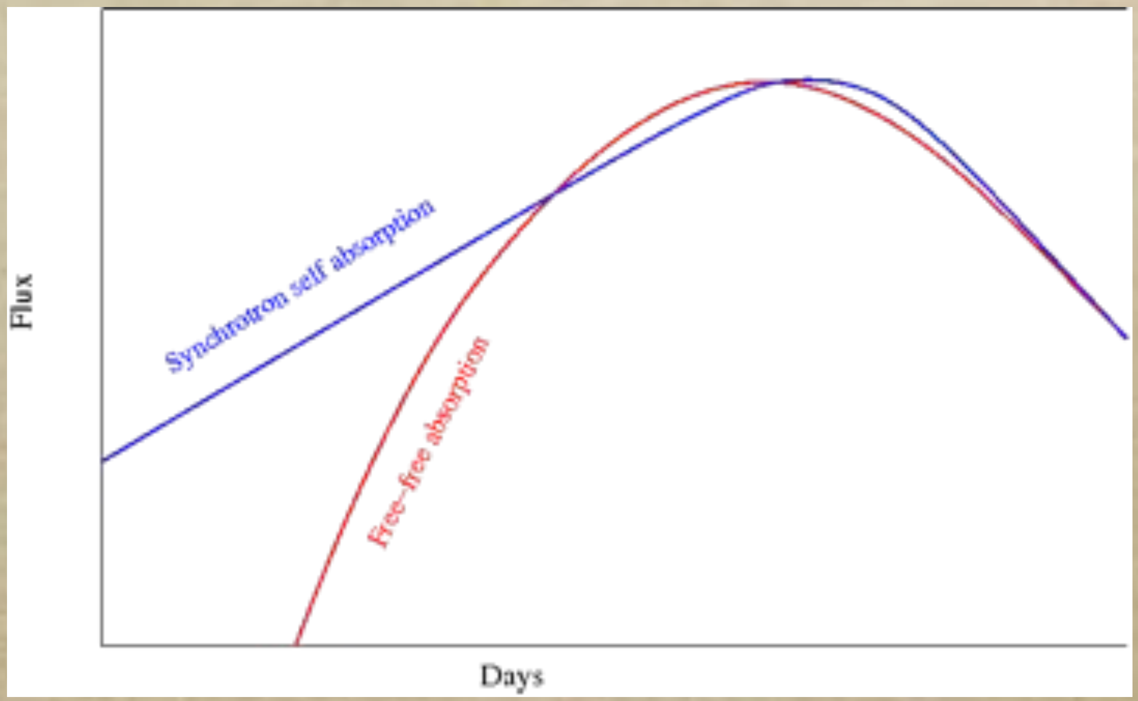
Chandra et al. 2015b



Causes of possible non-detection in radio bands

- *Some Type IIn supernovae are actually thermonuclear origin (These are called Type Ia-CSM!, Fox et al. 2013)*

- *Extremely high absorption due to dense shells.*



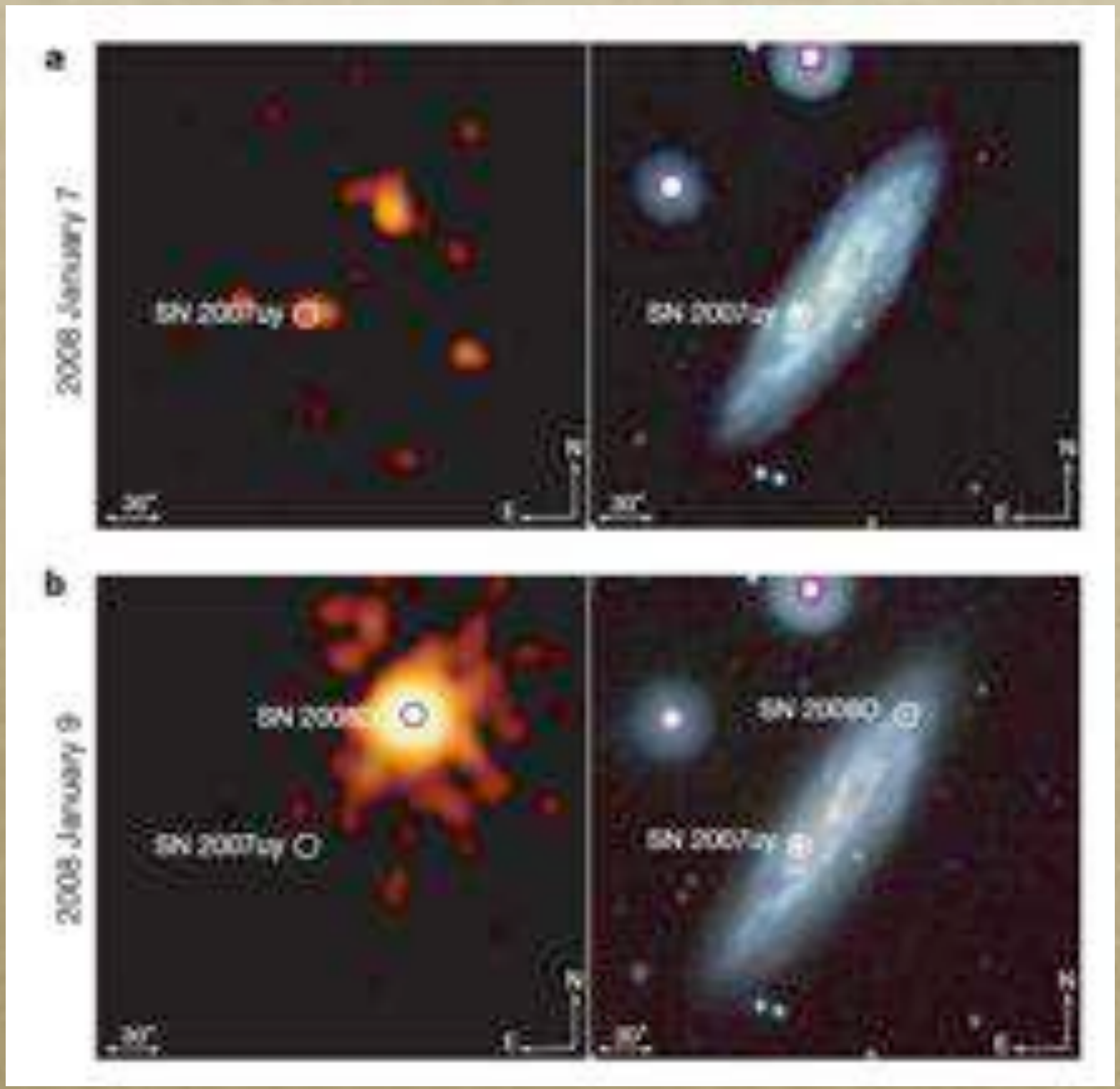
Conclusions

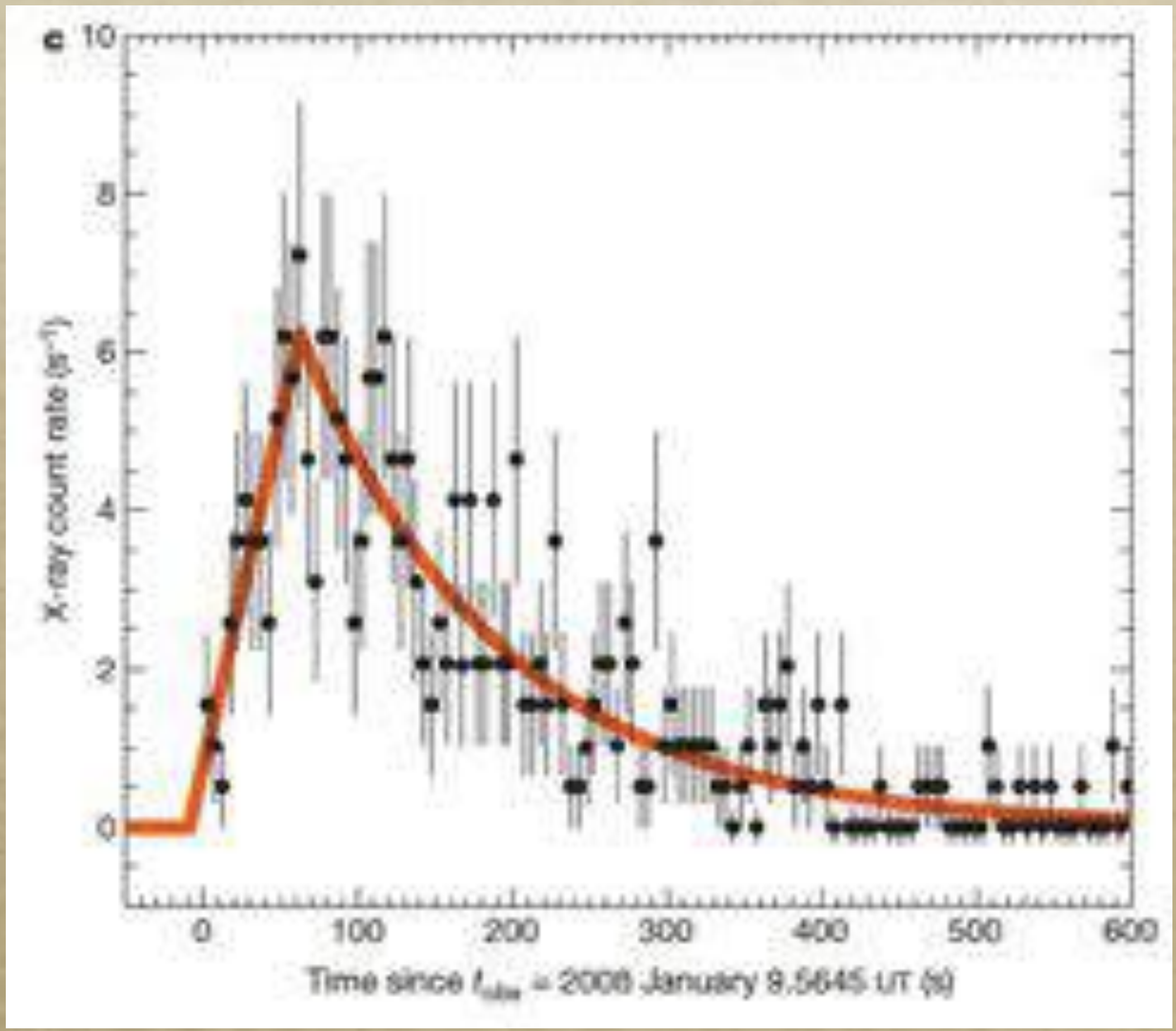
- *Every single supernova in dense environment seems to show a different progenitor history*
- *Very small sample. Progenitor nature very uncertain.*
- *We are far from understanding the stellar deaths in dense environments!*

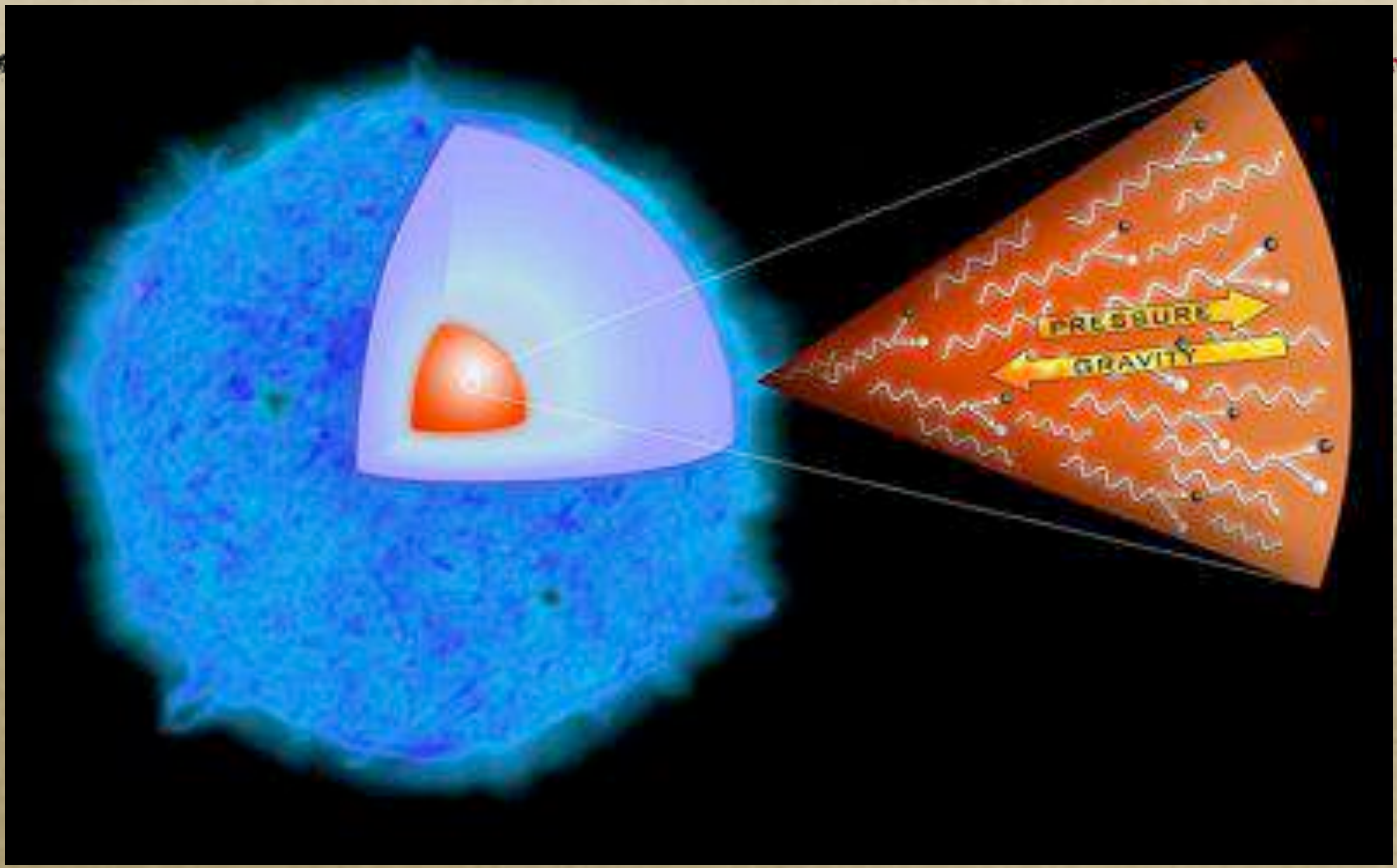
Thanks

SN 2008D: Serendipitous discovery of Shock breakout

Soderberg, Berger ..... Chandra et al. 2008



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GRAVITY