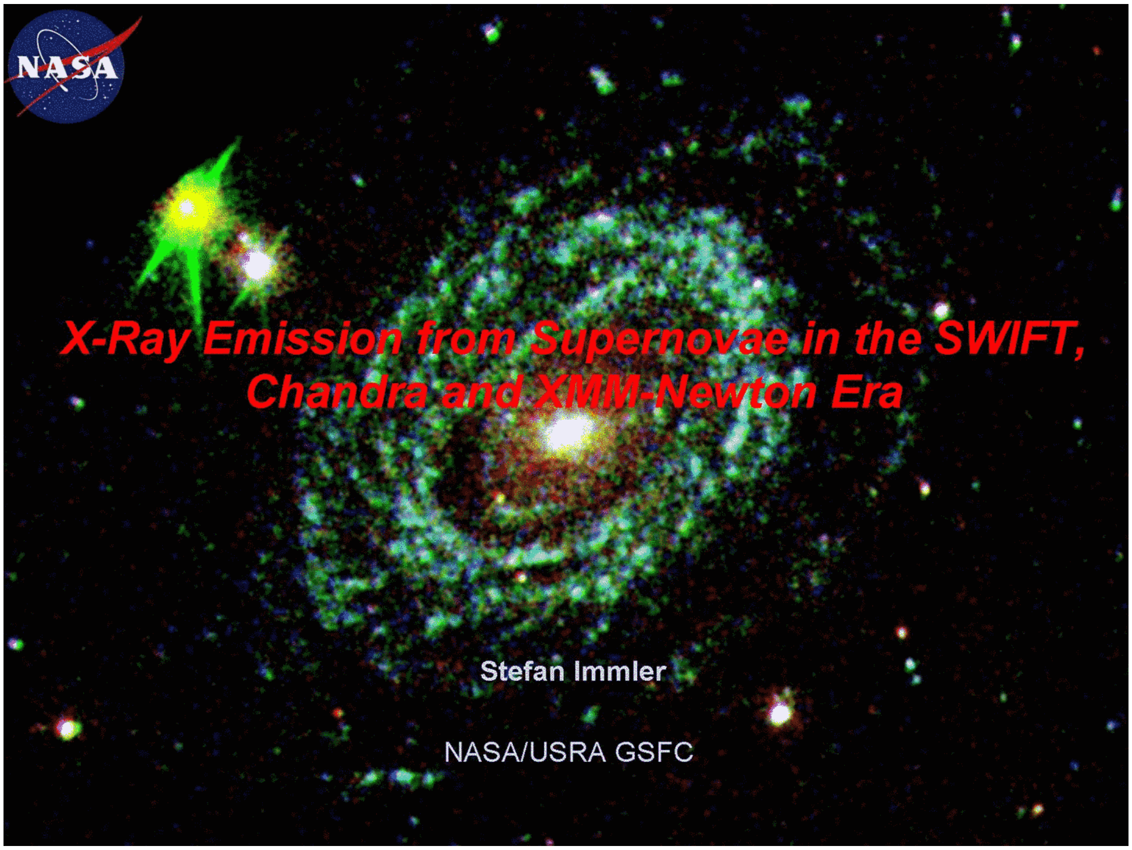
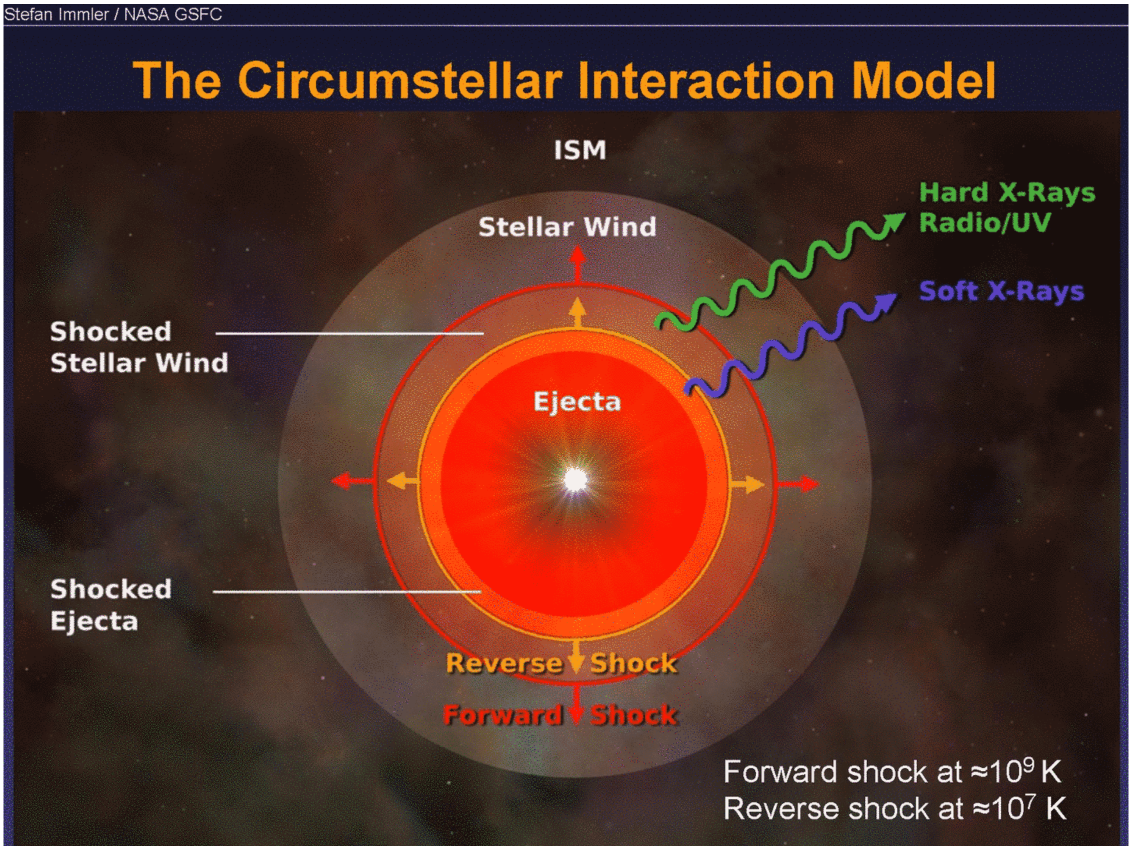


Stefan Immler / NASA GSFC

X-Ray Supernovae

- 24 SNe have been detected in X-rays over the past 25 years In the near aftermath (days to months) after their explosions
- X-ray luminosities range from 10^{34} ergs/s (SN 1987A) to some 10^{41} ergs/s (e.g., SNe 1988Z, 1995N, 2002hi)
- Approx. half of all detections are from *Chandra*
- *XMM-Newton* only resulted in one new detection (SN 2002ap) but is very successful in follow-up observations to monitor the long-term X-ray evolution of SNe (see this talk)
- Due to its rapid response and multi-wavelength coverage, *Swift* is playing an increasingly important role in probing CSM interaction with UV and X-ray observations of young SNe

Golden Age of SN research



Stefan Immler / NASA GSFC

The Circumstellar Interaction Model

- Stellar wind scenario: CSM is deposited by the SN progenitor. Continuum equation requires mass loss rate of:

$$\dot{M} = 4\pi \, r^2 \, \rho_{wind}(r) \times v_{wind}(r) \qquad \text{(I)}$$

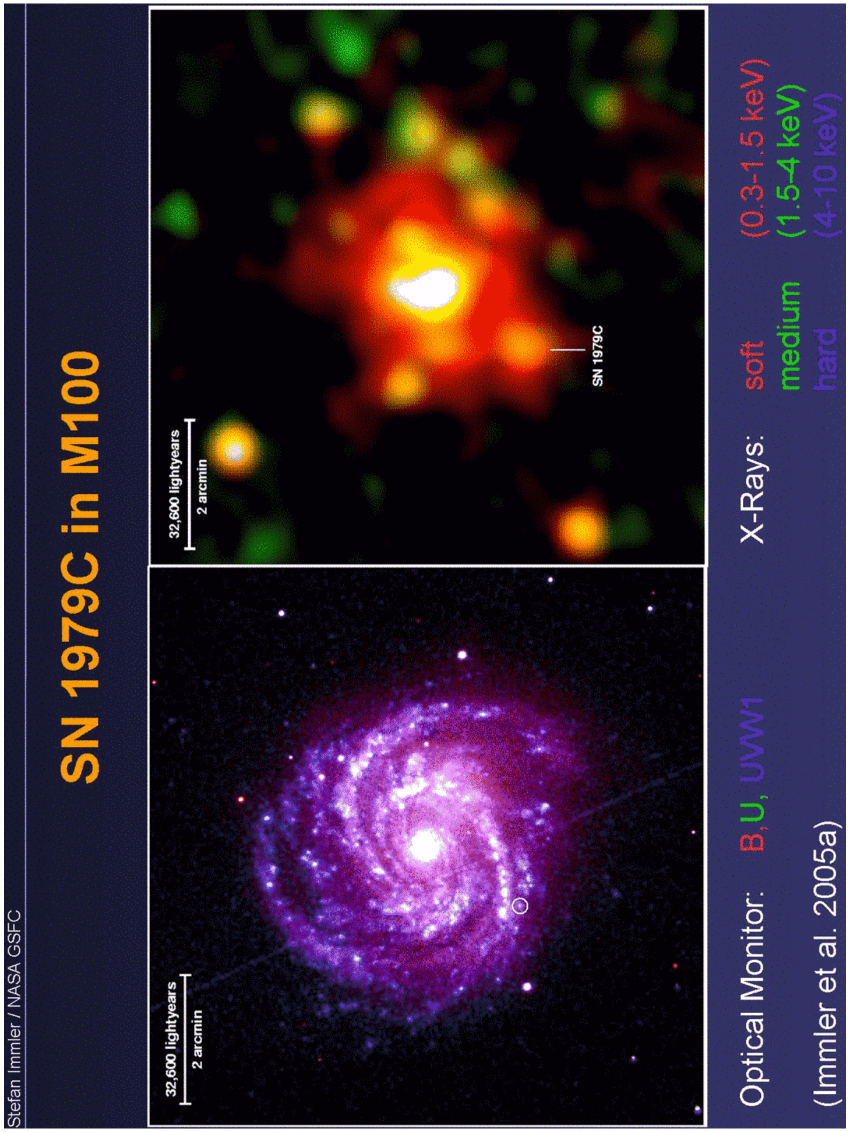
- Thermal X-ray luminosity of the shock-heated plasma:

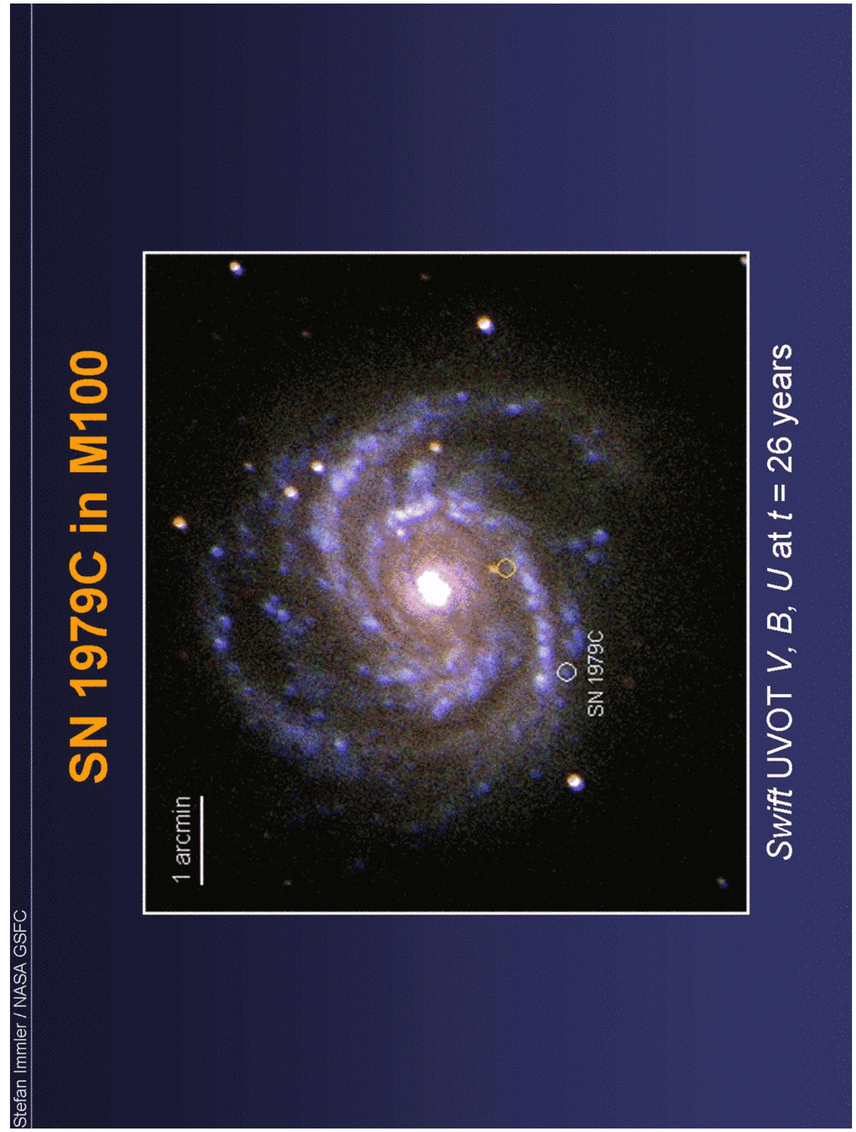
$$L_x = \Lambda(T, Z, \Delta E) \, n^2 \, dV \qquad \text{(II)}$$

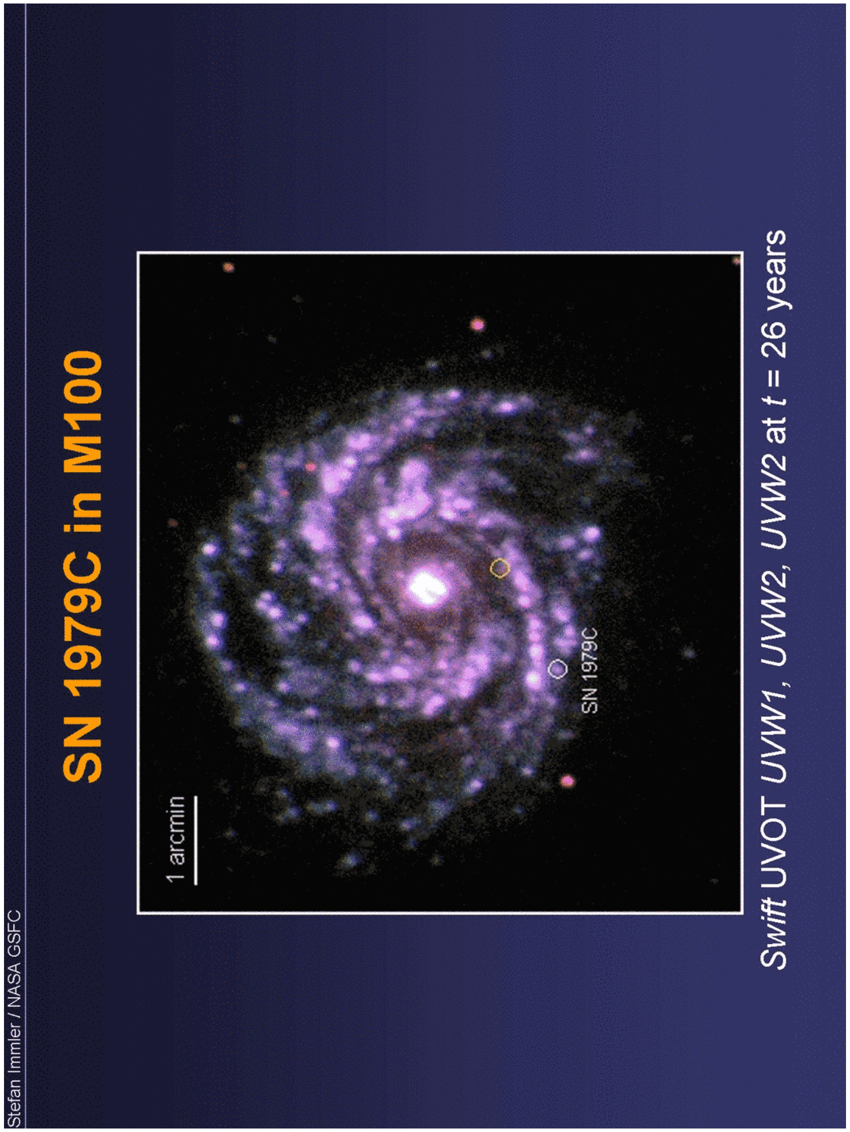
where $n = \rho_{csm}/m_{H+He}$ is the number density of the CSM. Equ. (I) in (II):

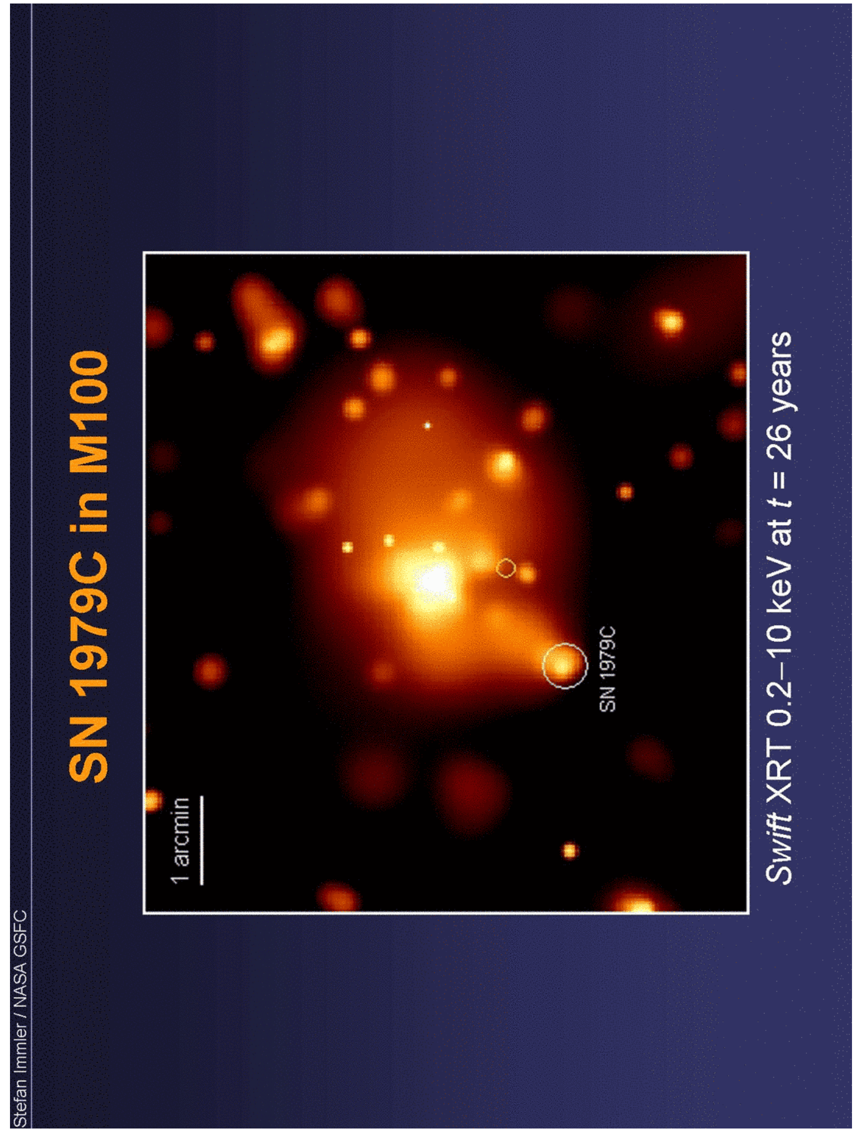
- **CSM Interaction Luminosity:**

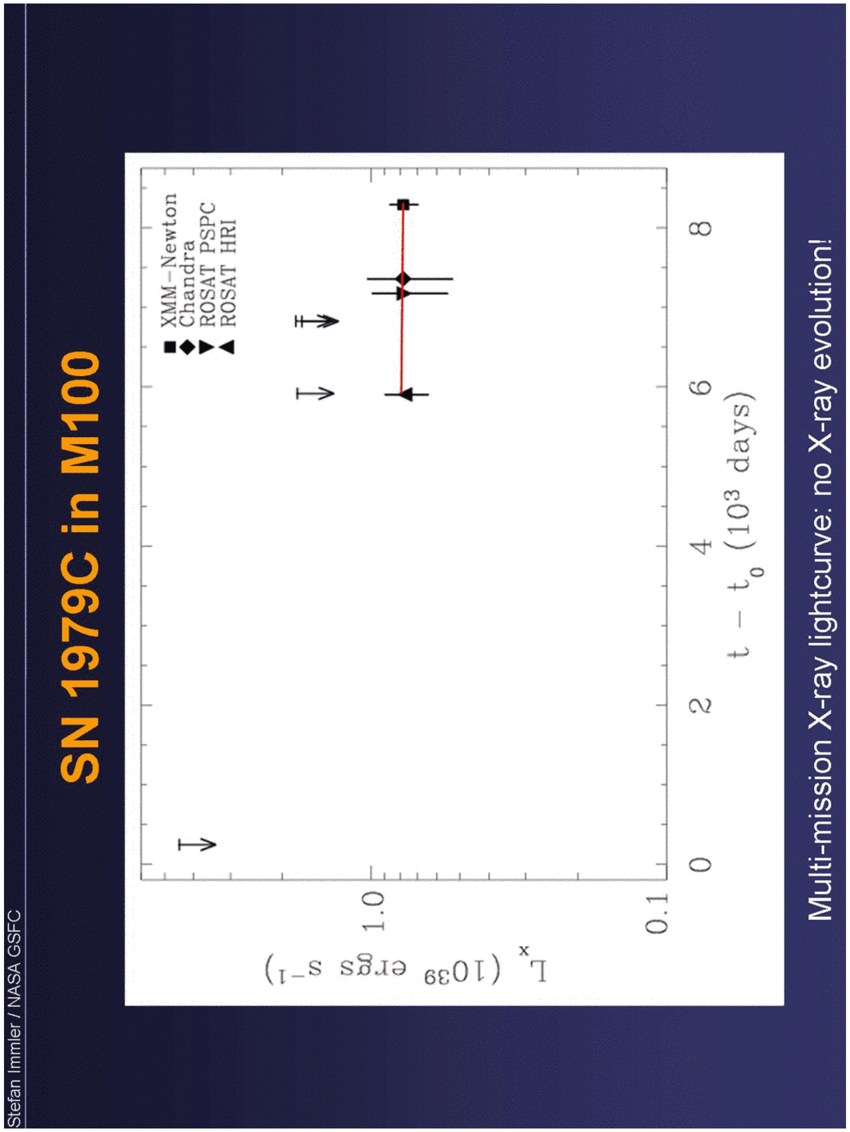
$$L_x = 4/(\pi m^2_{H+He}) \, \Lambda(T) \times (\dot{M}/v_{wind})^2 \times (v_{shock} \, t)^{-1}$$

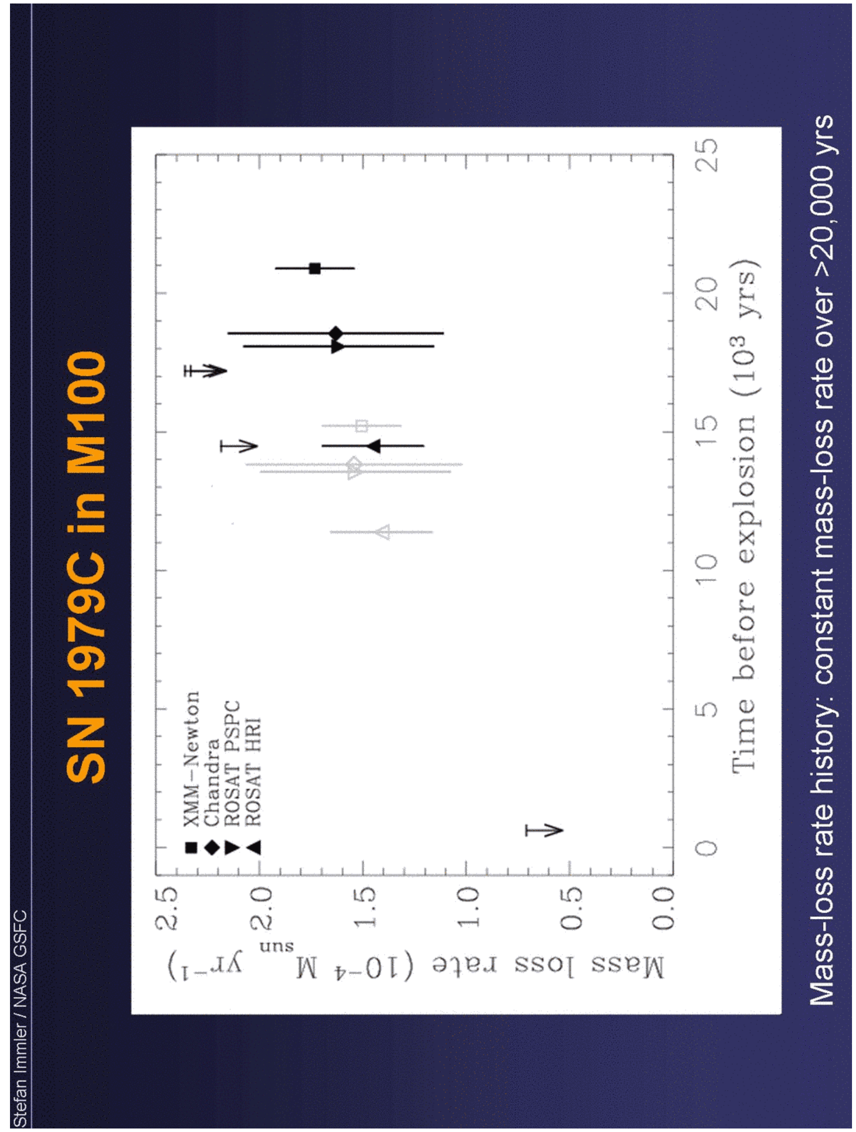

SN 1979C in M100
32,600 lightyears
2 arcmin
32,600 lightyears
2 arcmin
SN 1979C
Optical Monitor: B,U, UVW1
X-Rays: soft (0.3-1.5 keV)
medium (1.5-4 keV)
hard (4-10 keV)
(Immler et al. 2005a)
Stefan Immler / NASA GSFC

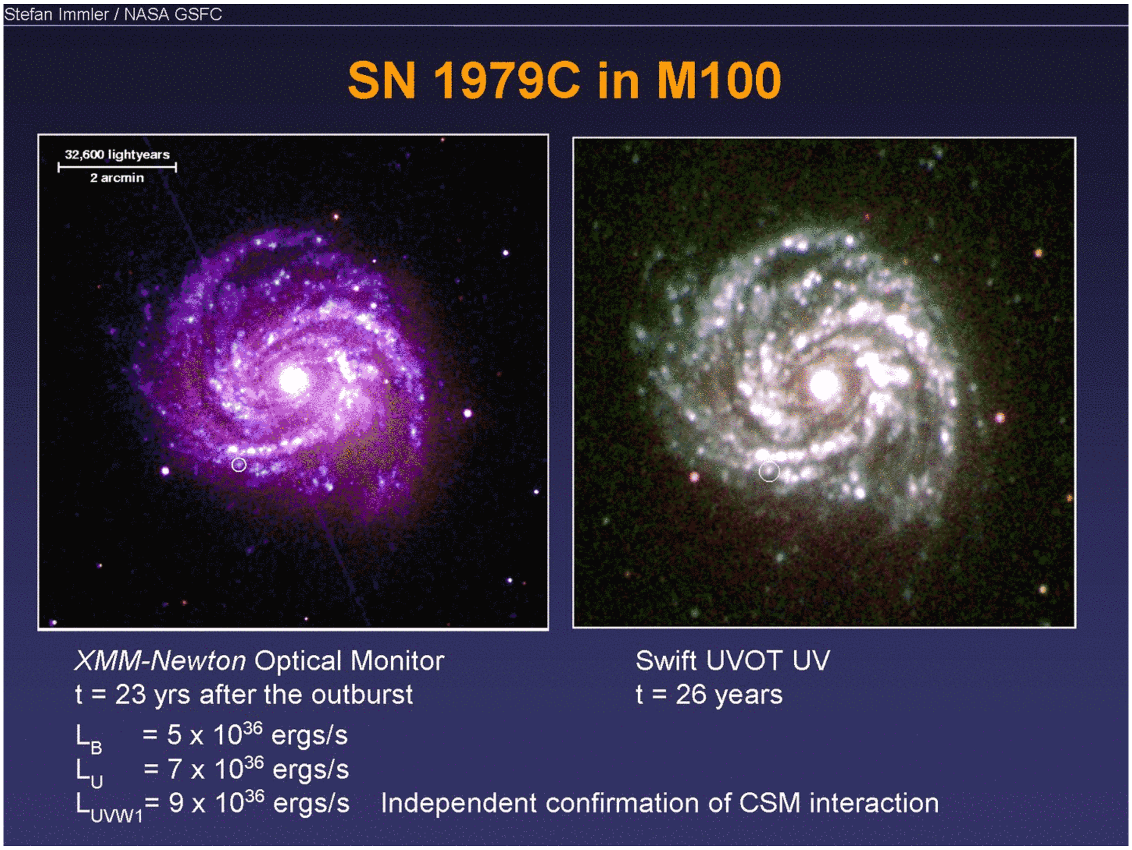

SN 1979C in M100
1 arcmin
SN 1979C
Swift UVOT *V*, *B*, *U* at *t* = 26 years
Stefan Immler / NASA GSFC

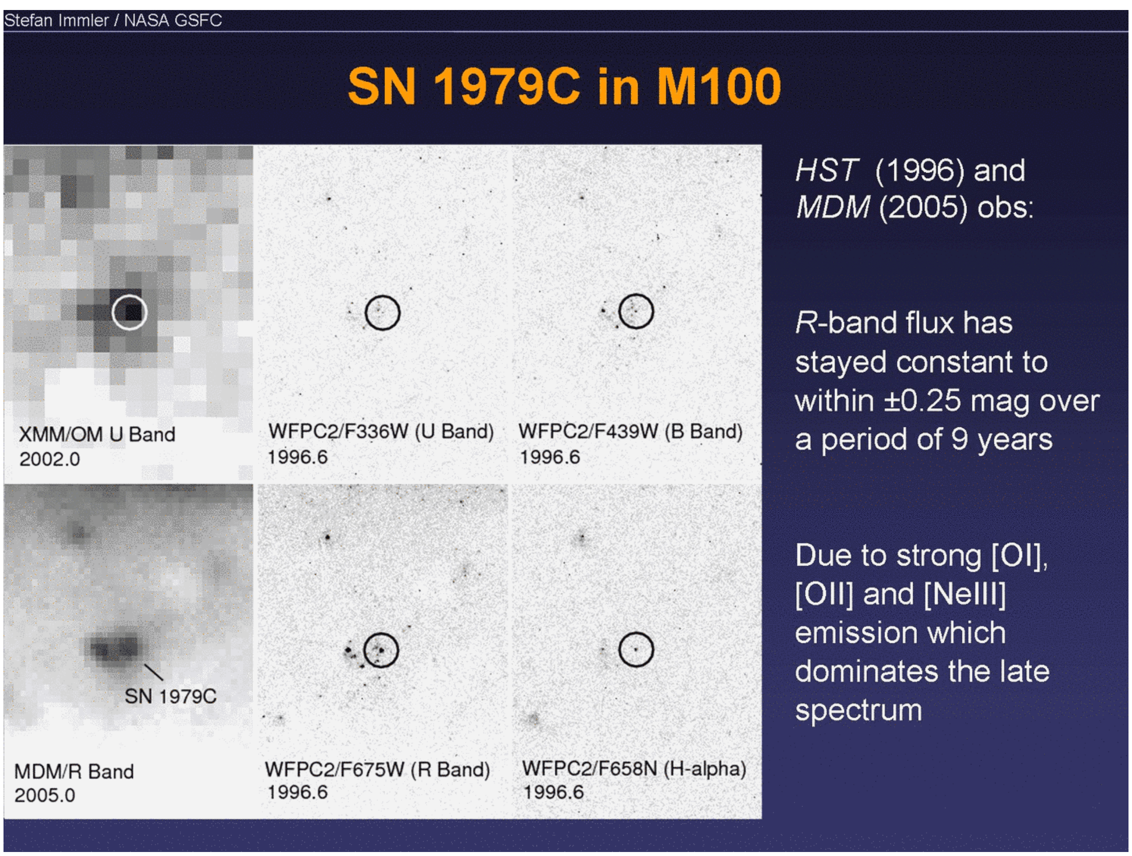

SN 1979C in M100
1 arcmin
SN 1979C
Swift UVOT *UVW1*, *UVW2*, *UVW2* at *t* = 26 years
Stefan Immler / NASA GSFC


SN 1979C in M100
1 arcmin
SN 1979C
Swift XRT 0.2–10 keV at *t* = 26 years
Stefan Immler / NASA GSFC


SN 1979C in M100
Stefan Immler / NASA GSFC
XMM−Newton
Chandra
ROSAT PSPC
ROSAT HRI
L$_x$ (10^{39} ergs s^{-1})
0.1
1.0
0
2
4
6
8
t − t$_0$ (10^3 days)
Multi-mission X-ray lightcurve: no X-ray evolution!

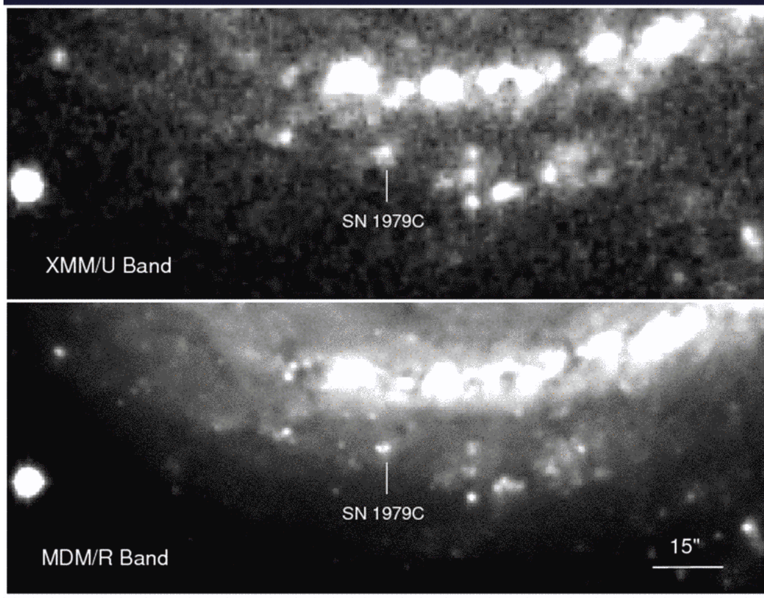

SN 1979C in M100
Stefan Immler / NASA GSFC
XMM−Newton
Chandra
ROSAT PSPC
ROSAT HRI
Mass loss rate (10^{-4} M$_{sun}$ yr^{-1})
0.0
0.5
1.0
1.5
2.0
2.5
0
5
10
15
20
25
Time before explosion (10^3 yrs)
Mass-loss rate history: constant mass-loss rate over >20,000 yrs


Stefan Immler / NASA GSFC
SN 1979C in M100
32,600 lightyears
2 arcmin
XMM-Newton Optical Monitor
t = 23 yrs after the outburst
L_B = 5 x 10^{36} ergs/s
L_U = 7 x 10^{36} ergs/s
L_{UVW1} = 9 x 10^{36} ergs/s
Swift UVOT UV
t = 26 years
Independent confirmation of CSM interaction


Stefan Immler / NASA GSFC
SN 1979C in M100
XMM/OM U Band
2002.0
WFPC2/F336W (U Band)
1996.6
WFPC2/F439W (B Band)
1996.6
SN 1979C
MDM/R Band
2005.0
WFPC2/F675W (R Band)
1996.6
WFPC2/F658N (H-alpha)
1996.6
HST (1996) and MDM (2005) obs:
R-band flux has stayed constant to within ±0.25 mag over a period of 9 years
Due to strong [OI], [OII] and [NeIII] emission which dominates the late spectrum

Stefan Immler / NASA GSFC

SN 1979C in M100



SN 1979C still bright in the optical/UV, 23 years after the outburst.

The late U- and UV-band emission (10^{36} ergs/s) is indicative of strong CSM interaction.

This is confirmed by MDM *R*-band data.

Stefan Immler / NASA GSFC

SN 1979C in M100

- High X-ray luminosity, $L_x = 8 \times 10^{38}$ ergs/s (0.3–2 keV) 26 years after its outburst
- No X-ray evolution over the observed period (16–26 yrs)
- High and constant mass-loss rate of $1.5 \times 10^{-4}\ M_\odot\ yr^{-1}$ over >20,000 yrs in the history of the progenitor
- Best-fit two-component X-ray spectral model with

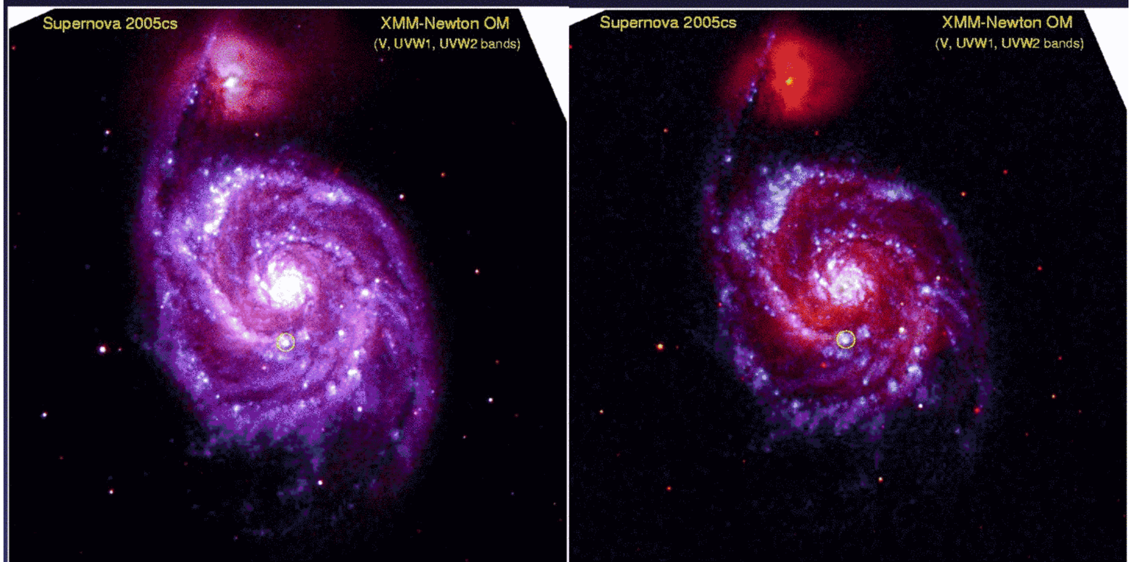
  kT_{low} = 0.8 keV   64% of the flux (0.3–2 keV band)
  kT_{high} = 4.1 keV   36% of the flux (0.3–2 keV band)

  characteristic of the reverse (soft) and forward shock (hard)
- High B, U, UV (XMM-Newton OM, Swift UVOT) and R-band (MDM) fluxes indicating substantial CSM interaction

Immler et al. 2005a

Stefan Immler / NASA GSFC

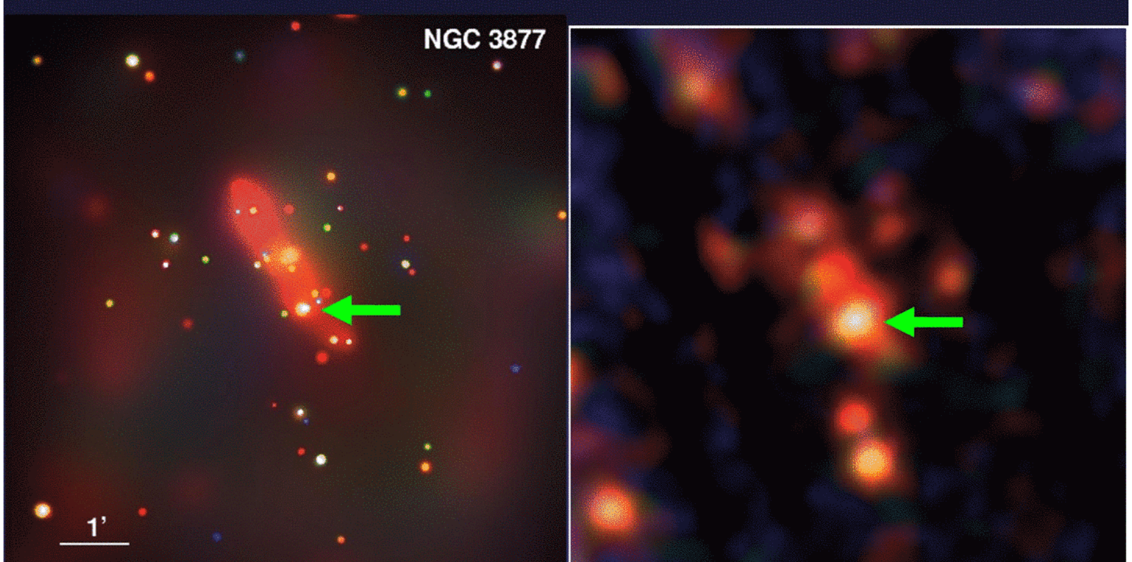
SN 2005cs in M51



- $L_x < 5 \times 10^{37}$ ergs s^{-1} at t = 3 days, $\dot{M} < 10^{-6}$ $M_\odot$ yr^{-1}
- XMM-Newton OM optical/UV magnitudes: 14.5 (V), 14.4 (B), 13.2 (U), 12.9 (UVW1), 12.9 (UVW2)

Stefan Immler / NASA GSFC

SN 1998S in NGC 3877



Chandra ACIS:

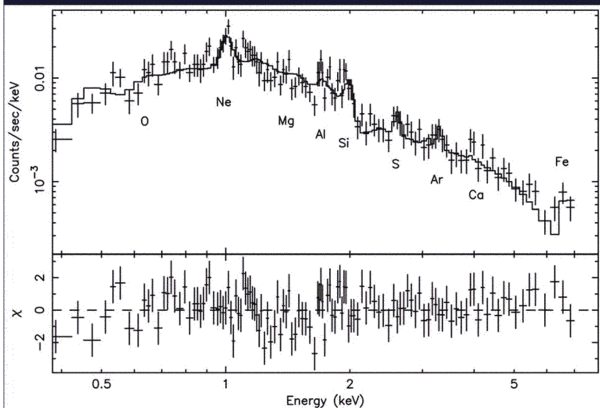
L_x = 2.2 x 10^{39} ergs/s (0.4–2 keV)
2.4 yrs after the outburst

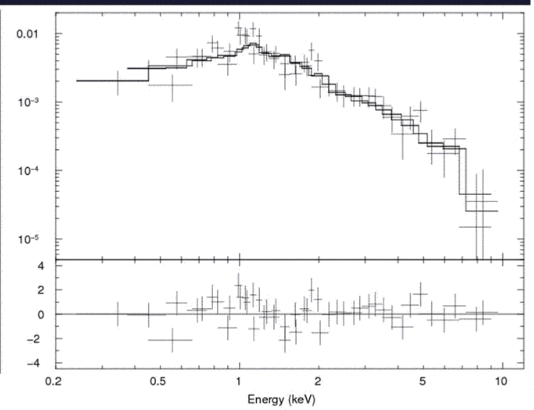
XMM-Newton MOS:

L_x = 1.5 x 10^{39} ergs/s (0.4–2 keV)
3.1 yrs after the outburst

Stefan Immler / NASA GSFC

SN 1998S in NGC3877





Chandra:

Possible softening of the emission:
day 678: 10 keV
day 1048: 8 keV

(Pooley et al. 2002)

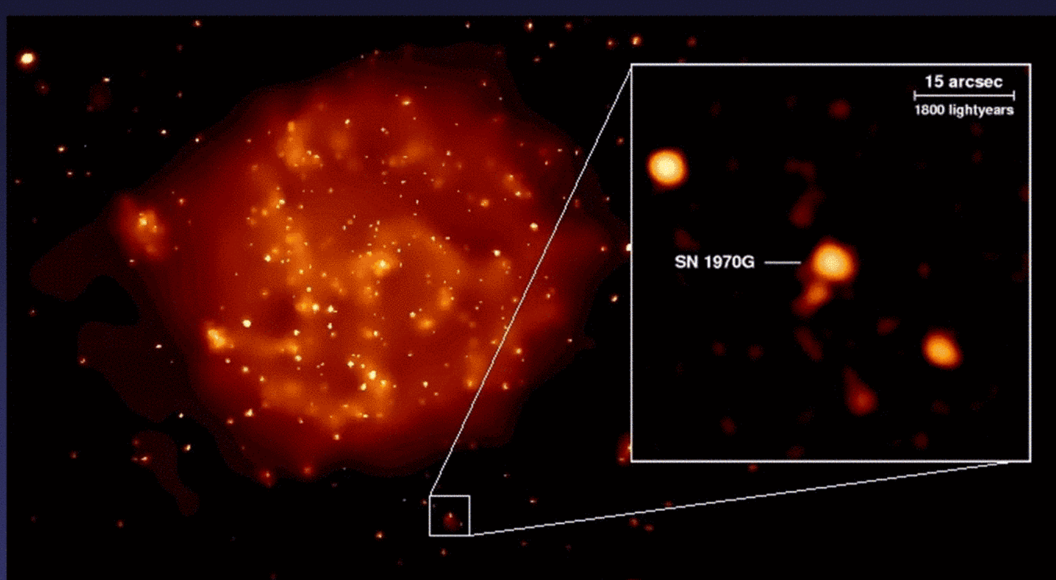
XMM-Newton:

day 1,140: 5.6 keV (χ^2=0.92)
or two-component model with
kT_{low} = 0.8 keV,
kT_{high} = 8 keV (χ^2=1.02)

(Immler et al. 2005b)

Stefan Immler / NASA GSFC

SN 1970G in M101

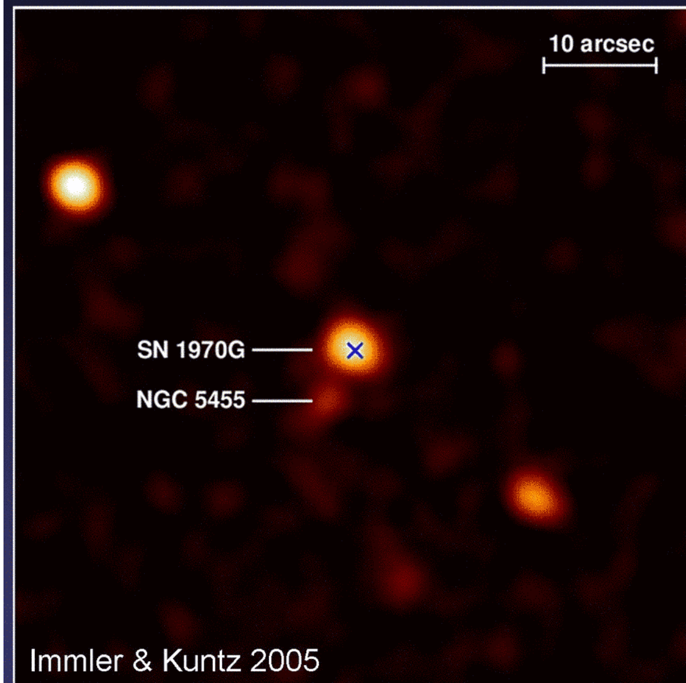


Chandra 1 Ms survey of M101
Detection of a point-like X-ray source at the position of SN 1970G 35 years after its explosion

Immler & Kuntz 2005

Stefan Immler / NASA GSFC

SN 1970G in M101



Chandra 1 Ms survey of M101 (Kuntz et al. 2005)

Detection of a point-like X-ray source at the position of SN 1970G

$L_x = 1 \times 10^{37}$ ergs/s

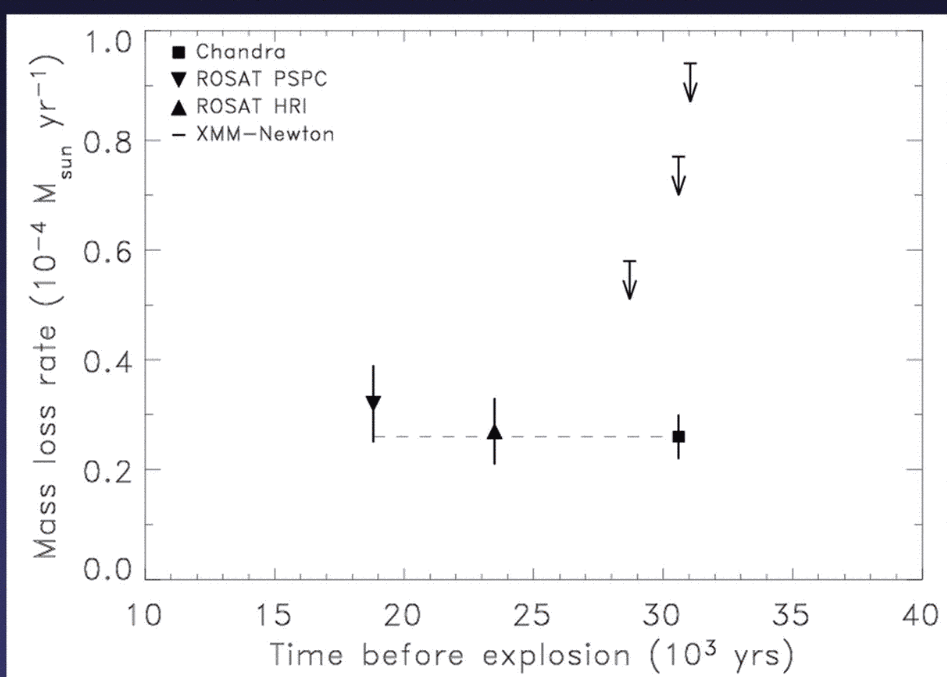
At an age of 35 years, SN 1970G is the oldest known X-ray SN to date

Recovered in previous ROSAT HRI and PSPC obs

X-ray rate of decline of $L_x \propto t^{-s}$ with index $s = 2.7$

Stefan Immler / NASA GSFC

SN 1970G in M101



Mass-loss rate history: no evolution over >30,000 yrs

Stefan Immler / NASA GSFC

SNe observed with *Swift*

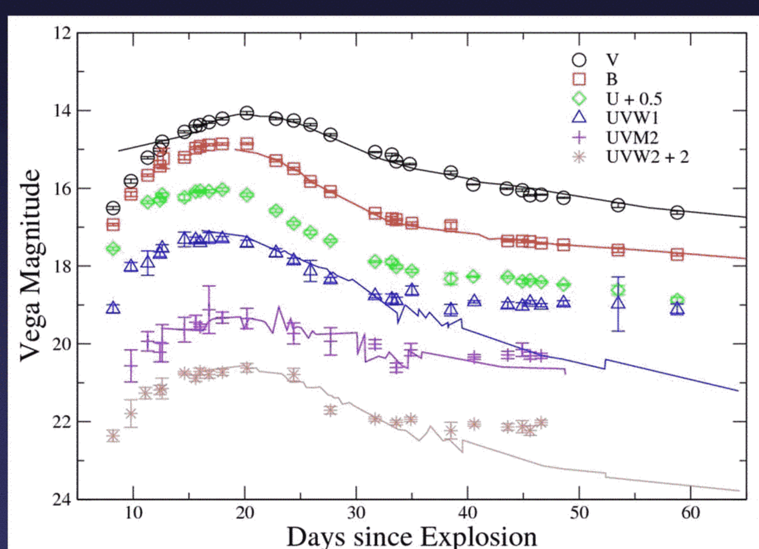
Fast response, paired with broad-band wavelength coverage, makes *Swift* the perfect "SN hunter"

1. SN 2004dk Ib
2. SN 2005am Ia lightcurve
3. SN 2005az Ib
4. SN 2005bc Ia
5. SN 2005bf Ib/c
6. SN 2005cf Ia lightcurve
7. SN 2005cs II lightcurve
8. SN 2005da Ic
9. SN 2005df Ia lightcurve
10. SN 2005ek Ic
11. SN 2005gj Ia
12. SN 2005hk Ia lightcurve
13. SN 2005ke Ia lightcurve
14. SN 2005mz Ia
15. SN 2006E Ia
16. SN 2006T II

9 SNe Ia (thermonuclear explosion of a WD)
7 SNe Ib/c, II (core-collapse of a massive star)
6 of these have good coverage lightcurves

Stefan Immler / NASA GSFC

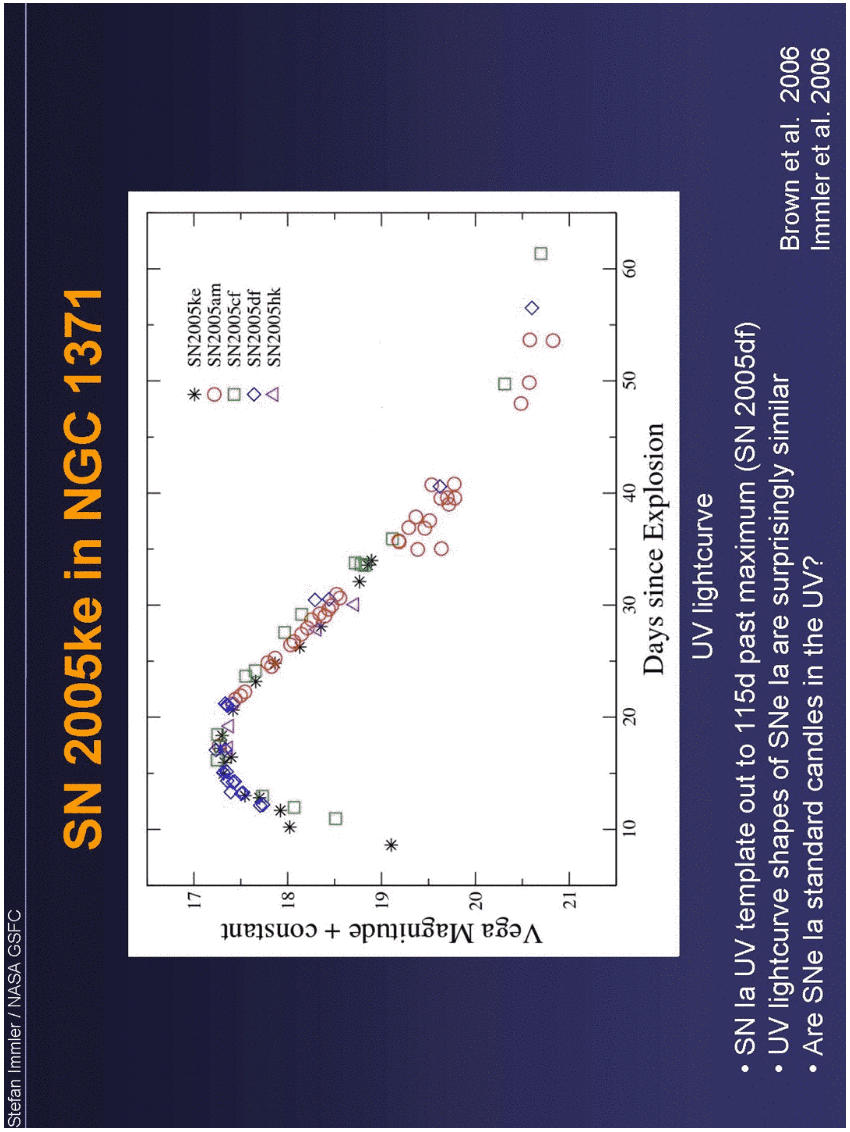
SN 2005ke in NGC 1371

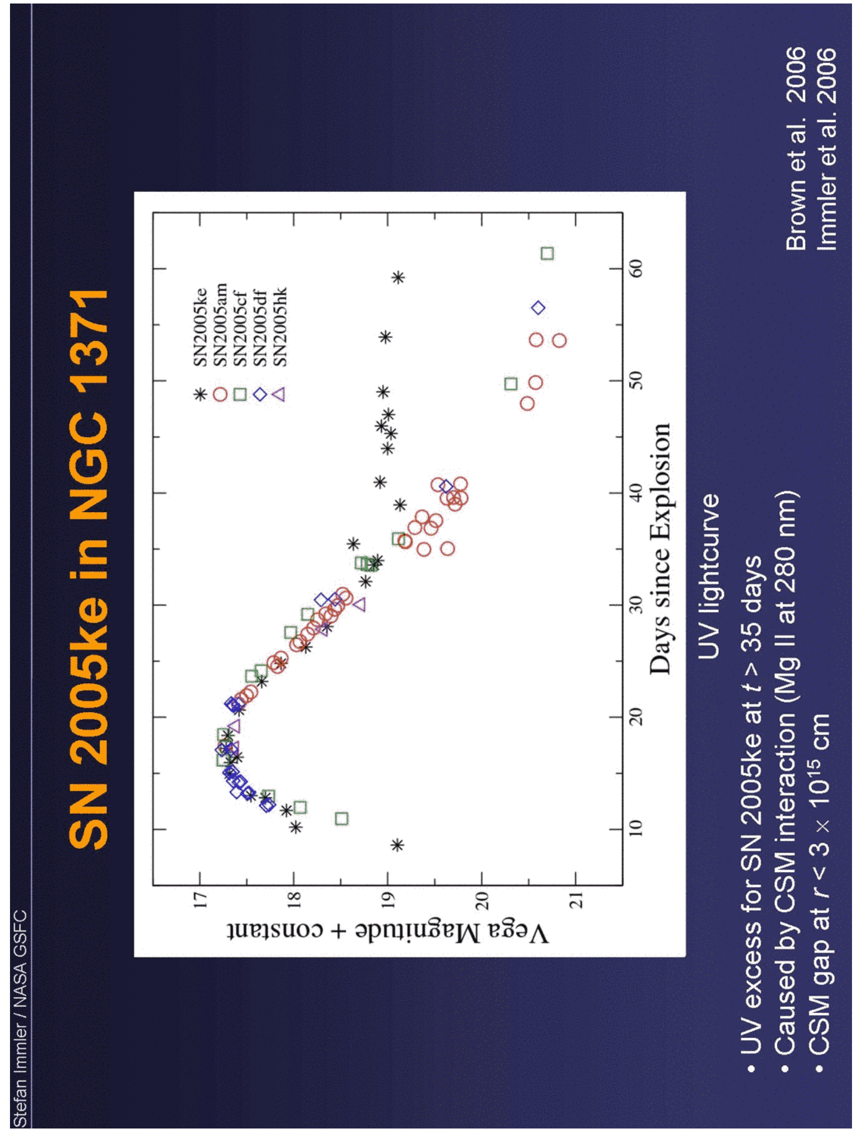


opt/UV lightcurve

- Excess UV emission at t > 35 days after the explosion
- No excess in the optical
- Independent evidence of CSM interaction

Immler et al. 2006


SN 2005ke in NGC 1371
SN2005ke
SN2005am
SN2005cf
SN2005df
SN2005hk
Vega Magnitude + constant
Days since Explosion
UV lightcurve
• SN Ia UV template out to 115d past maximum (SN 2005df)
• UV lightcurve shapes of SNe Ia are surprisingly similar
• Are SNe Ia standard candles in the UV?
Brown et al. 2006
Immler et al. 2006
Stefan Immler / NASA GSFC


SN 2005ke in NGC 1371
SN2005ke
SN2005am
SN2005cf
SN2005df
SN2005hk
Vega Magnitude + constant
Days since Explosion
UV lightcurve
• UV excess for SN 2005ke at $t > 35$ days
• Caused by CSM interaction (Mg II at 280 nm)
• CSM gap at $r < 3 \times 10^{15}$ cm
Brown et al. 2006
Immler et al. 2006
Stefan Immler / NASA GSFC

Stefan Immler / NASA GSFC

SN 2005ke in NGC 1371

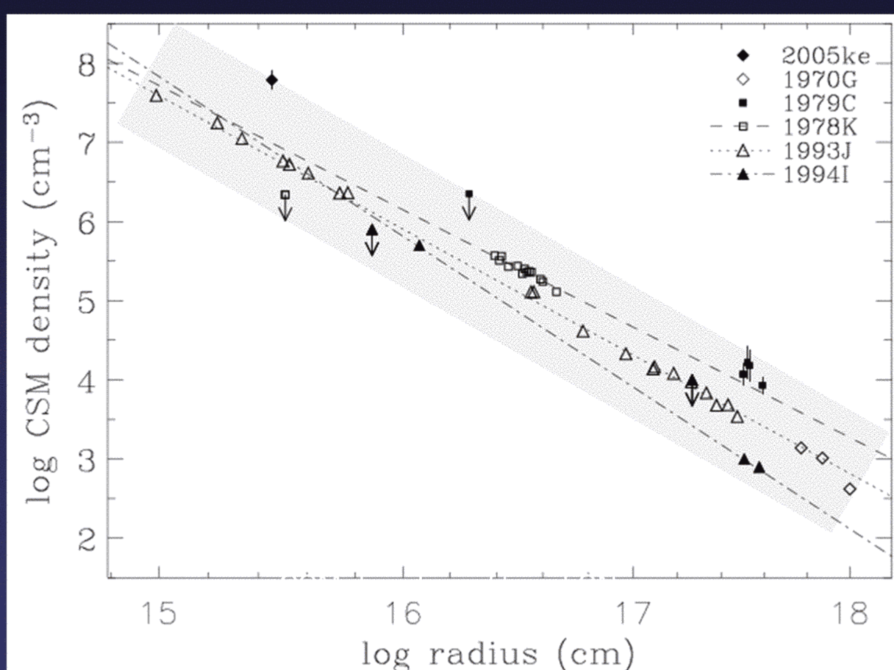
- First detection of CSM interaction for a SN Ia in the UV
- Direct obs. evidence for a companion star in a SN Ia system
- Companion's mass-loss rate and CSM matter density can be measured for the first time:

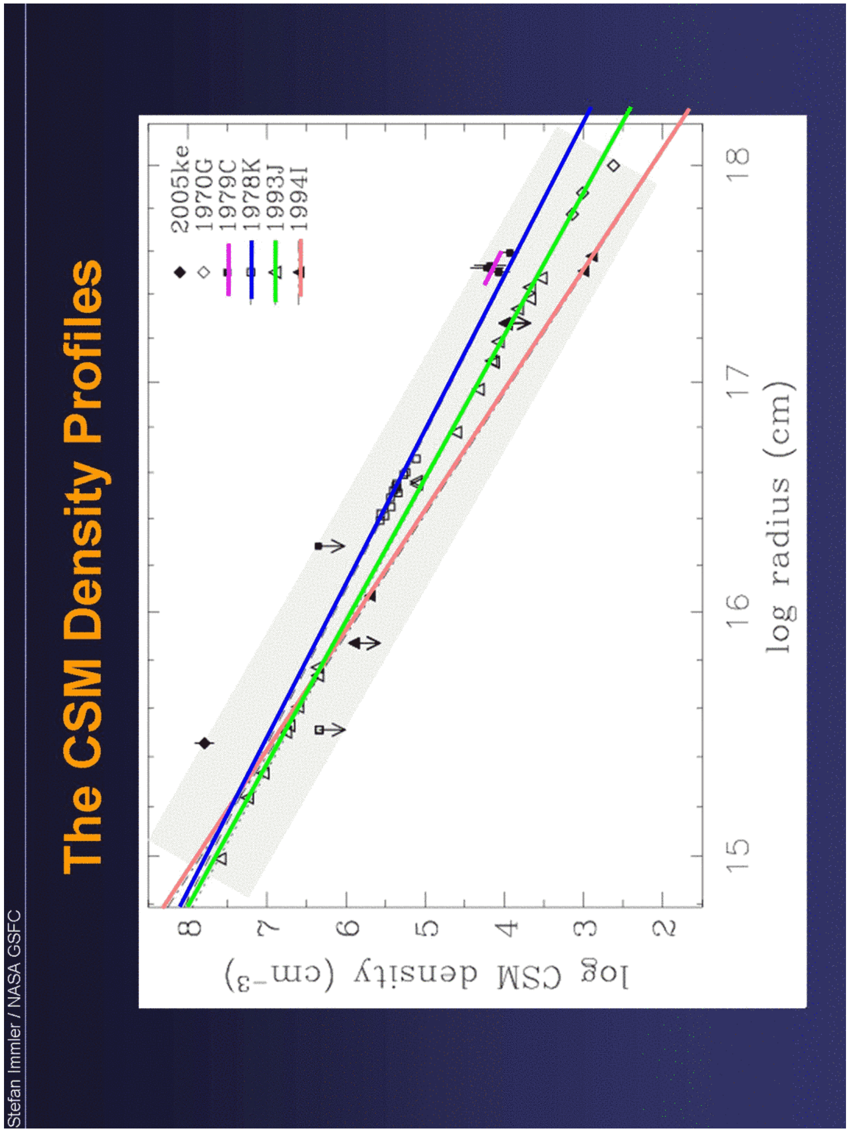
  $M = 8 \times 10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$
  $\rho_{CSM} = 8 \times 10^{7}\ \mathrm{cm}^{-3}$ at a distance of $r = 3 \times 10^{15}$ cm

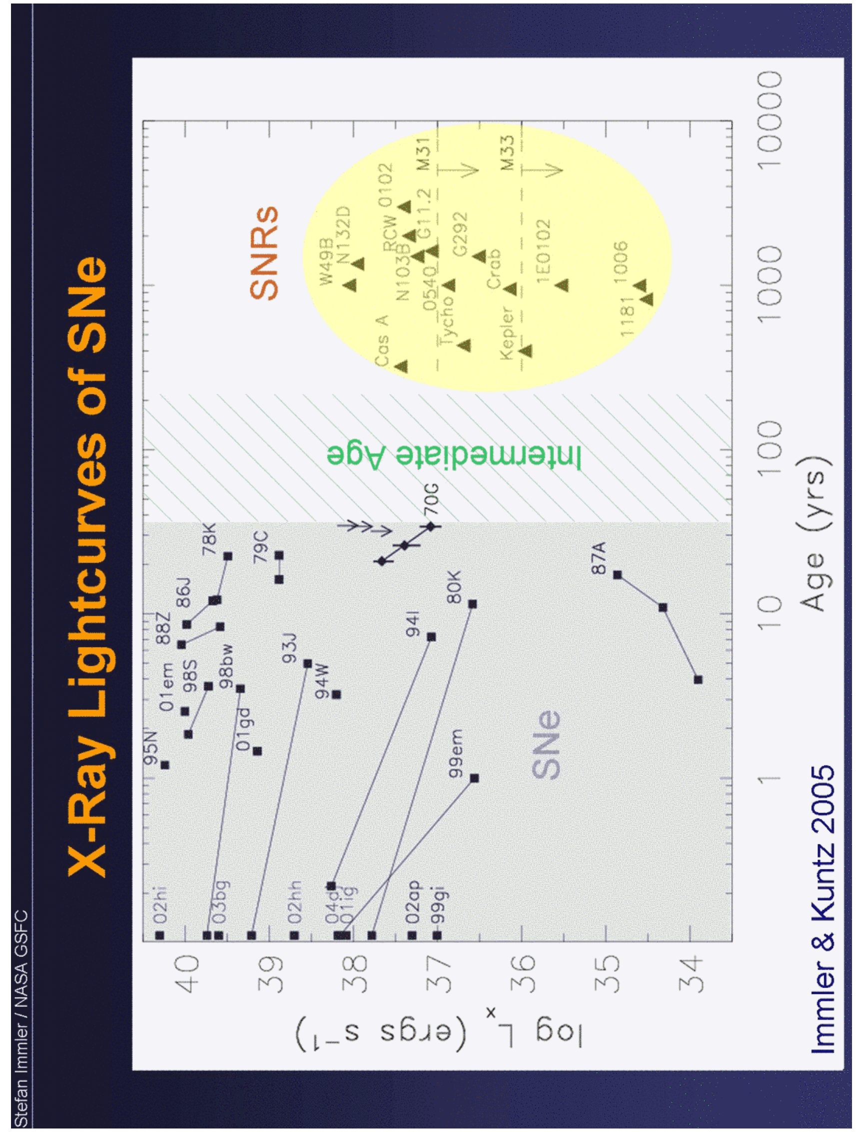
- Similar shape of all SN Ia UV lightcurves gives hope that they can be used as standard candles in the UV

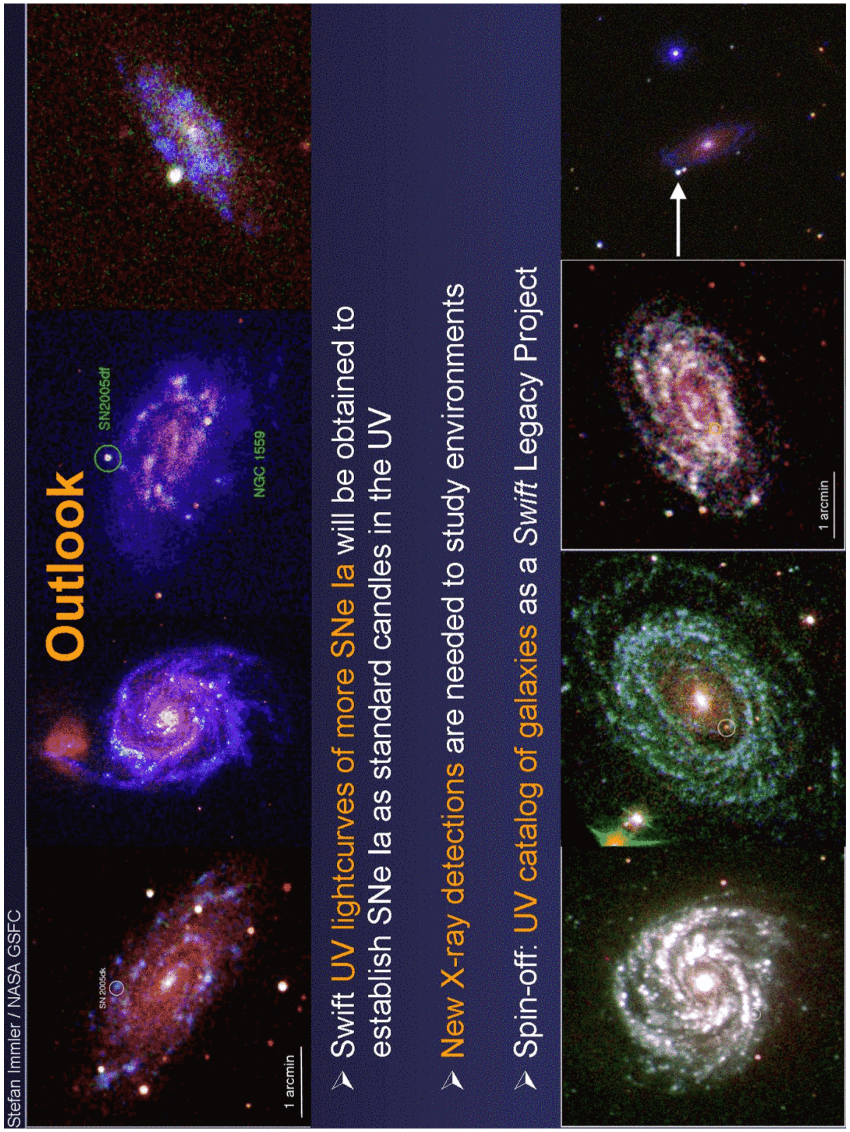
Stefan Immler / NASA GSFC

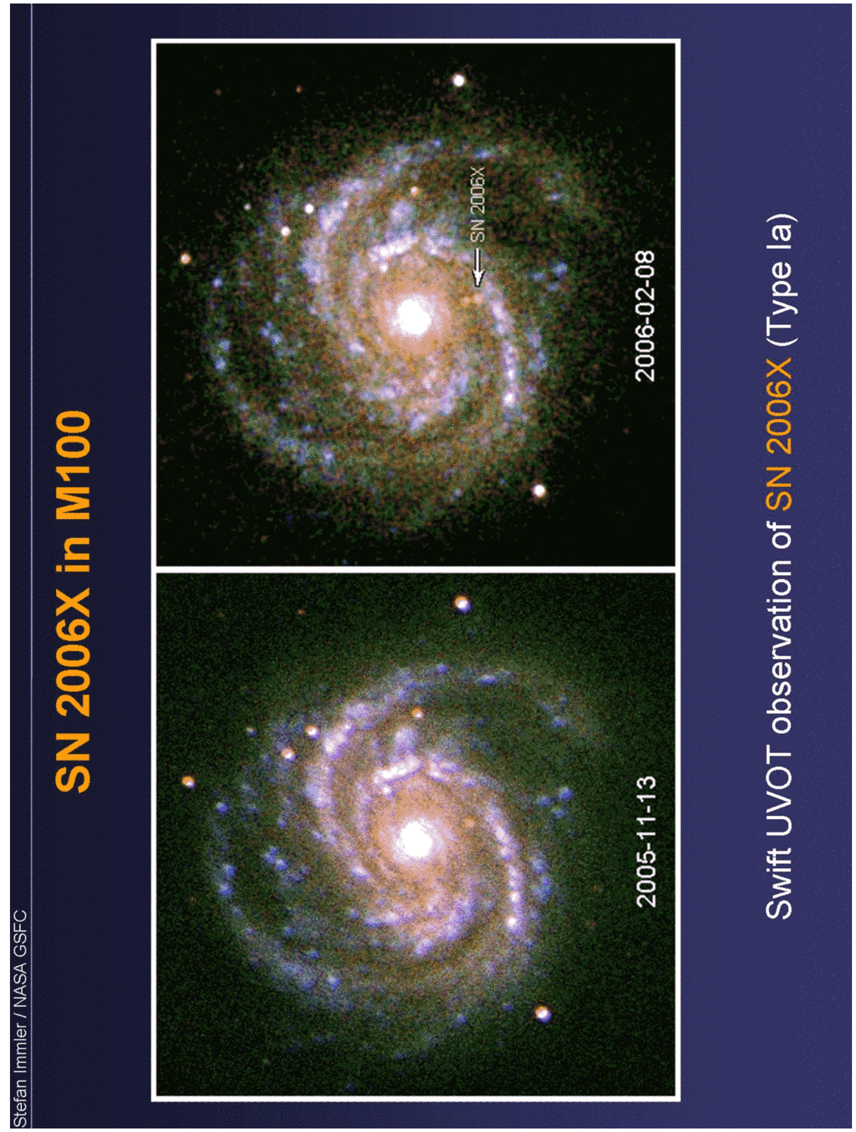
The CSM Density Profiles

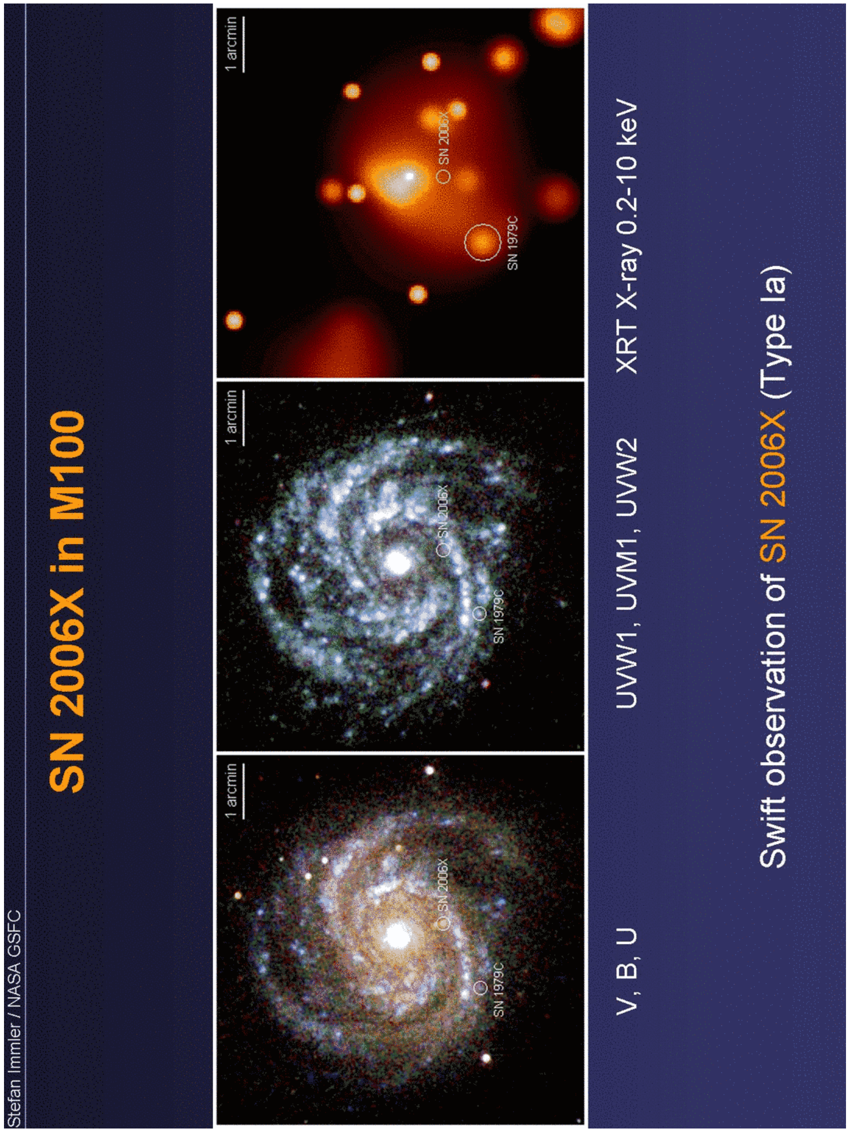


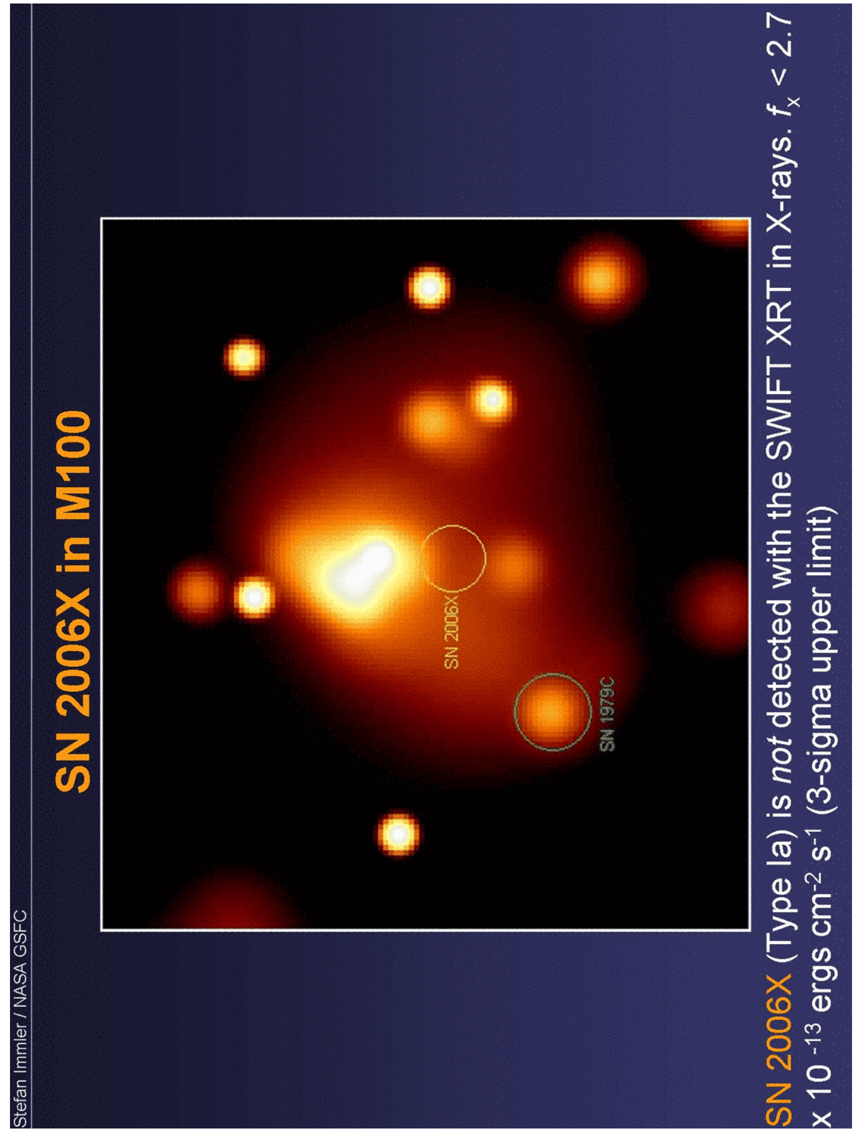

The CSM Density Profiles
Stefan Immler / NASA GSFC
2005ke
1970G
1979C
1978K
1993J
1994I
log CSM density (cm^-3)
log radius (cm)


X-Ray Lightcurves of SNe
Stefan Immler / NASA GSFC
SNRs
Intermediate Age
SNe
log L_x (ergs s^-1)
Age (yrs)
Cas A
Tycho
Kepler
Crab
1006
1181
W49B
N132D
RCW
0102
M31
M33
1E0102
G292
87A
70G
Immler & Kuntz 2005


Stefan Immler / NASA GSFC
Outlook
SN2005df
NGC 1559
1 arcmin
Swift UV lightcurves of more SNe Ia will be obtained to establish SNe Ia as standard candles in the UV
New X-ray detections are needed to study environments
Spin-off: UV catalog of galaxies as a Swift Legacy Project
1 arcmin


Stefan Immler / NASA GSFC
SN 2006X in M100
SN 2006X
2006-02-08
2005-11-13
Swift UVOT observation of SN 2006X (Type Ia)


Stefan Immler / NASA GSFC
SN 2006X in M100
1 arcmin
SN 2006X
SN 1979C
V, B, U
UVW1, UVM1, UVW2
XRT X-ray 0.2-10 keV
Swift observation of SN 2006X (Type Ia)


Stefan Immler / NASA GSFC
SN 2006X in M100
SN 2006X
SN 1979C
SN 2006X (Type Ia) is *not* detected with the SWIFT XRT in X-rays. $f_x < 2.7 \times 10^{-13}$ ergs cm^{-2} s^{-1} (3-sigma upper limit)