Interaction of stellar explosions with moderately optically thick circumstellar media (At2018cow and SN2023ixf)

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Kyoto, Feb. 9, 2026

Energy sources of radiation from stellar explosions

- Radioactive decay of unstable nuclei
- Diffusion of shock-deposited energy (shock breakout + cooling emission)

Diffusion-dominated shock breakout

- Interaction with the circumstellar medium

X-ray vs. optical

- Central engine

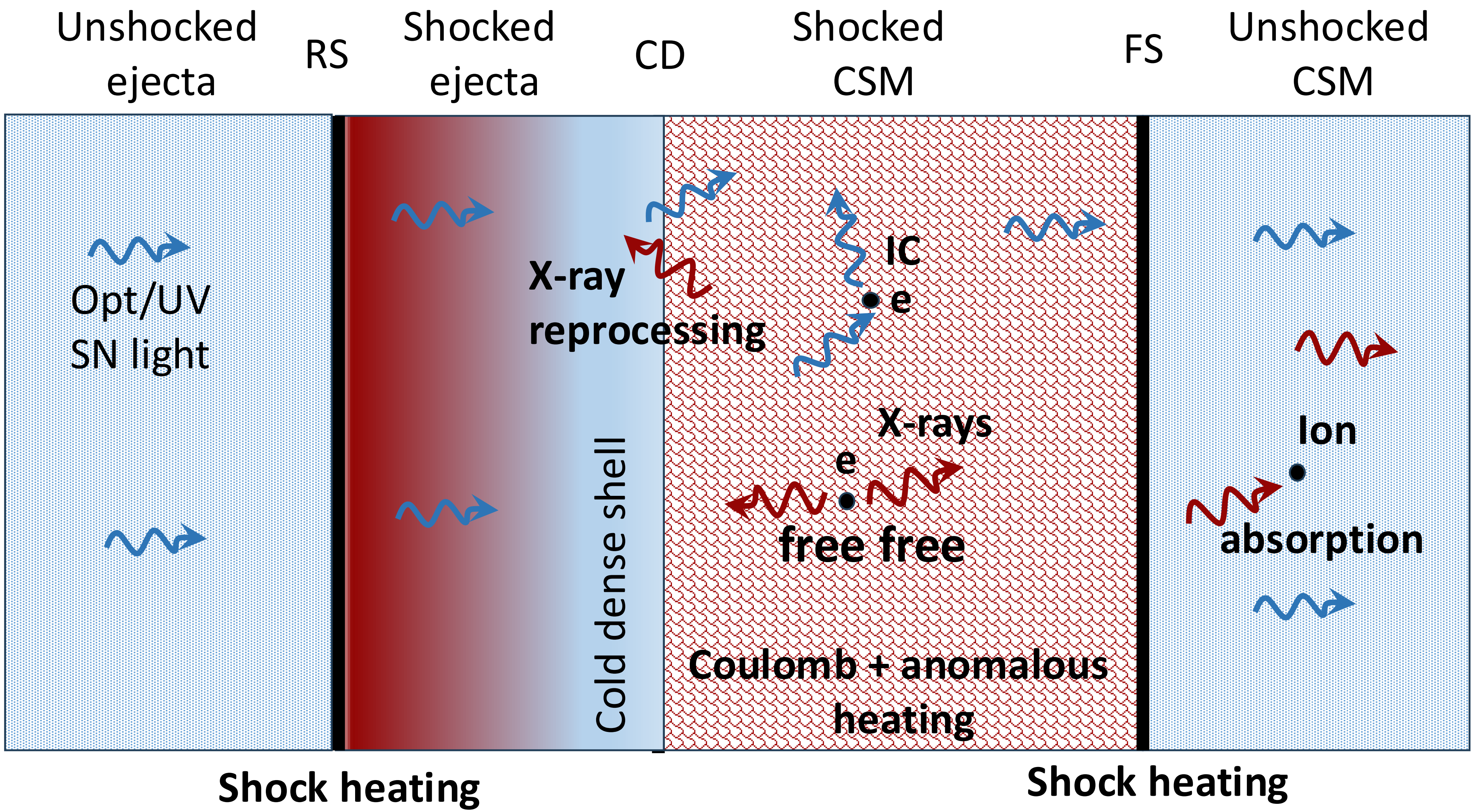
Goals:

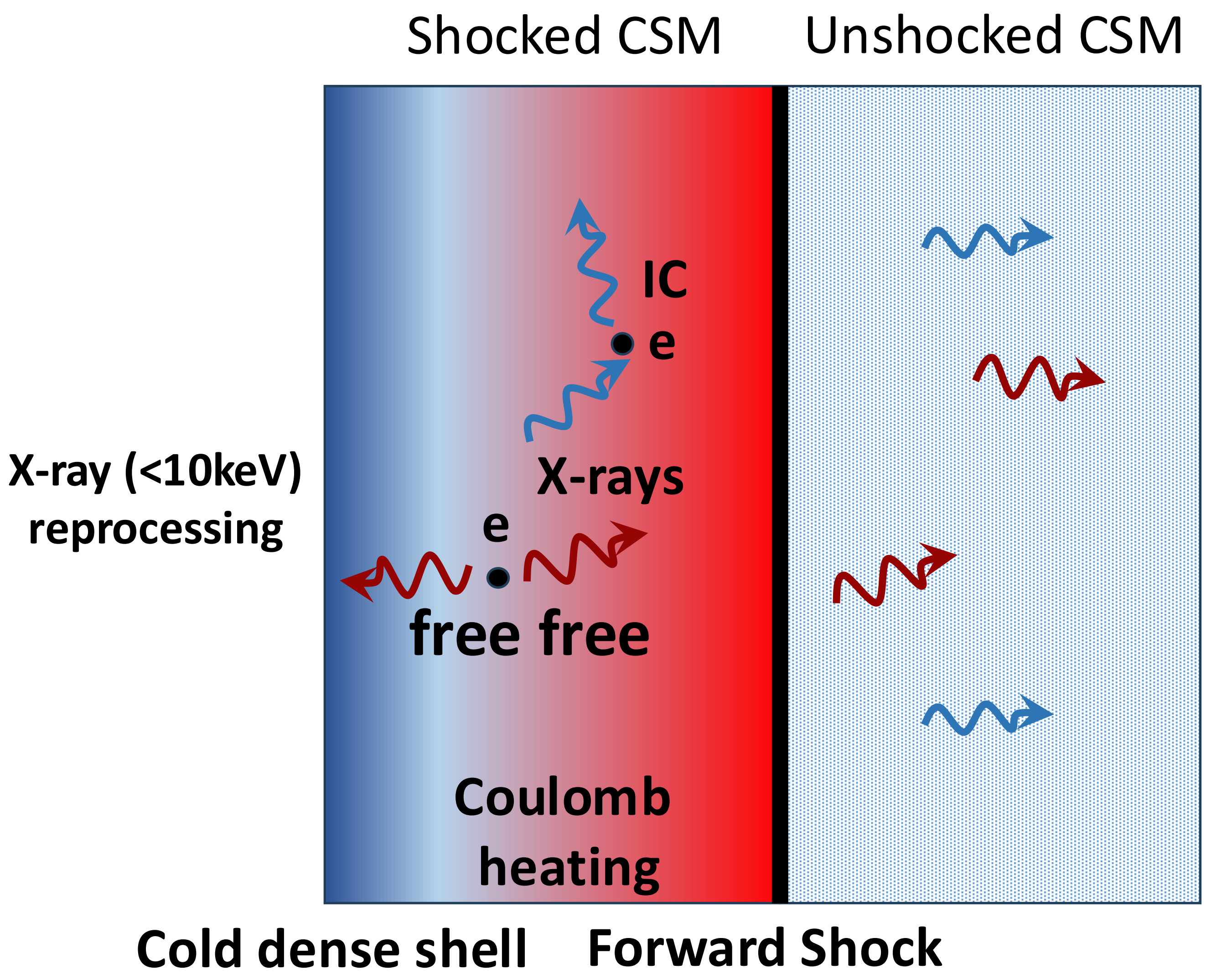
- Extracting the physical properties from observations
- Mapping the circum-explosion density (e.g., progenitor mass-loss history)

Outline

- Optical and X-rays from a shock in a moderate optical depth medium
  AT2018cow
- Breakout through an extended medium
  SN2023ixf early optical/UV
- X-ray transmission through a moderately Thomson-thick medium

Interaction powered emission


Unshocked ejecta
RS
Shocked ejecta
CD
Shocked CSM
FS
Unshocked CSM
Opt/UV SN light
X-ray reprocessing
Cold dense shell
IC
e
X-rays
e
free free
Coulomb + anomalous heating
Ion
absorption
Shock heating
Shock heating



Important parameters shaping the emission

t_{IC} – IC cooling time

t_{ff} – free-free cooling time

t_{ie} – Coulomb heating time

t_{dyn} – Dynamical time

Thomson thick or thin ($\tau_T > 1$ or $\tau_T < 1$)

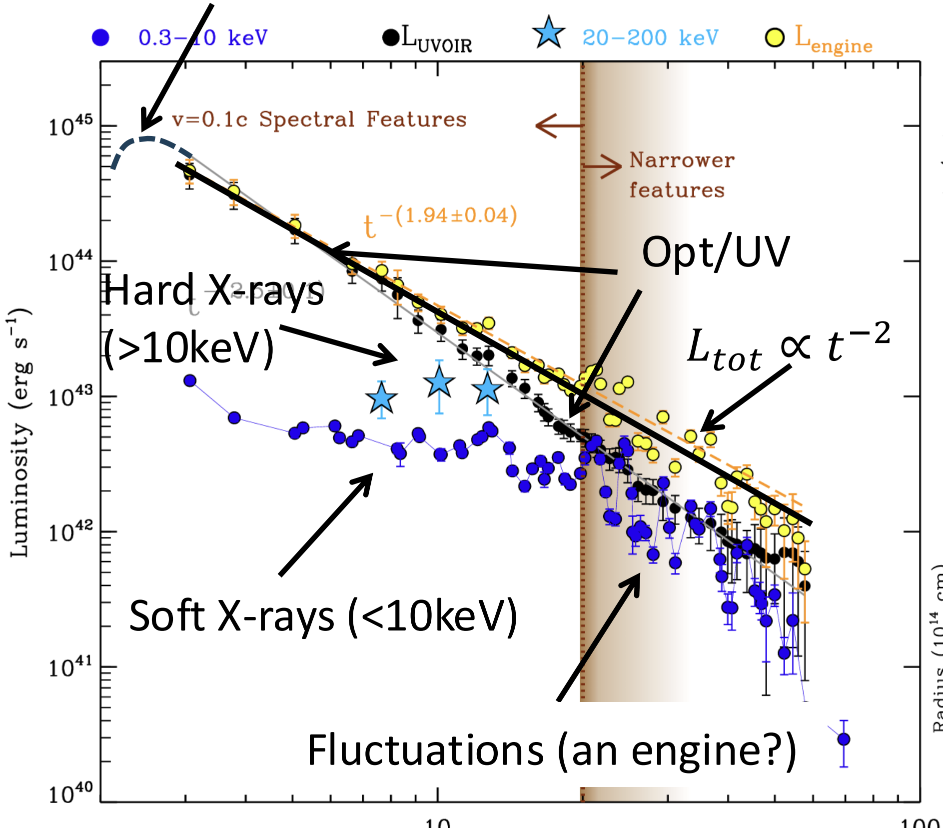
The phase space is divided into many regions with different behaviors

A shocked aspherical Cow

Taya Govreen-Segal

with C. Irwin, K. Hotokezaka, E. Quataert

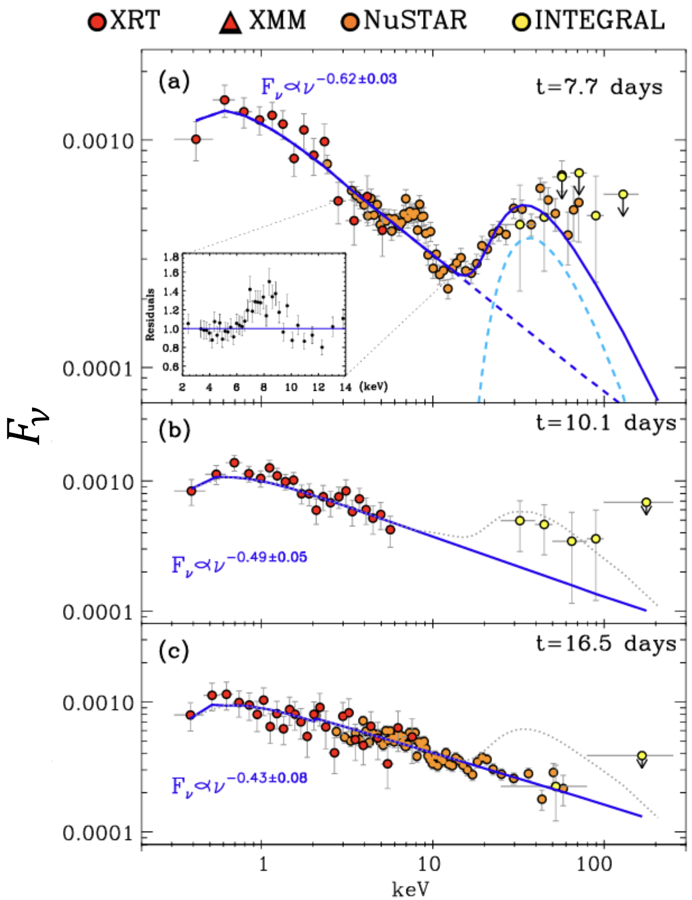
AT2018cow



Margutti et al. 19

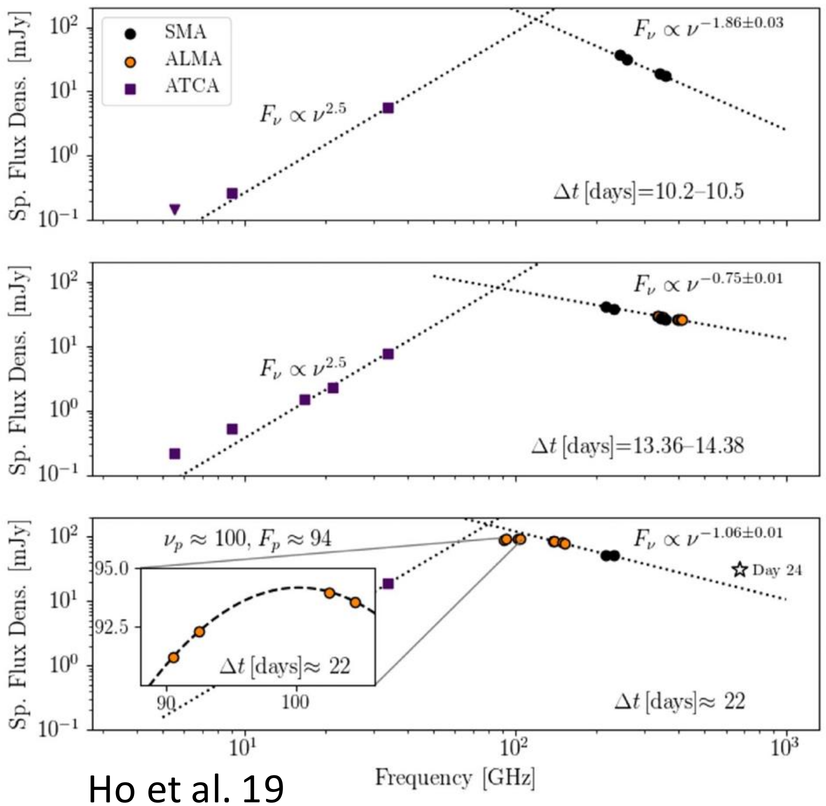
$$E_{opt} \sim 10^{50} erg$$

$$\frac{L_x}{L_{opt}} = 0.02 \rightarrow 1$$



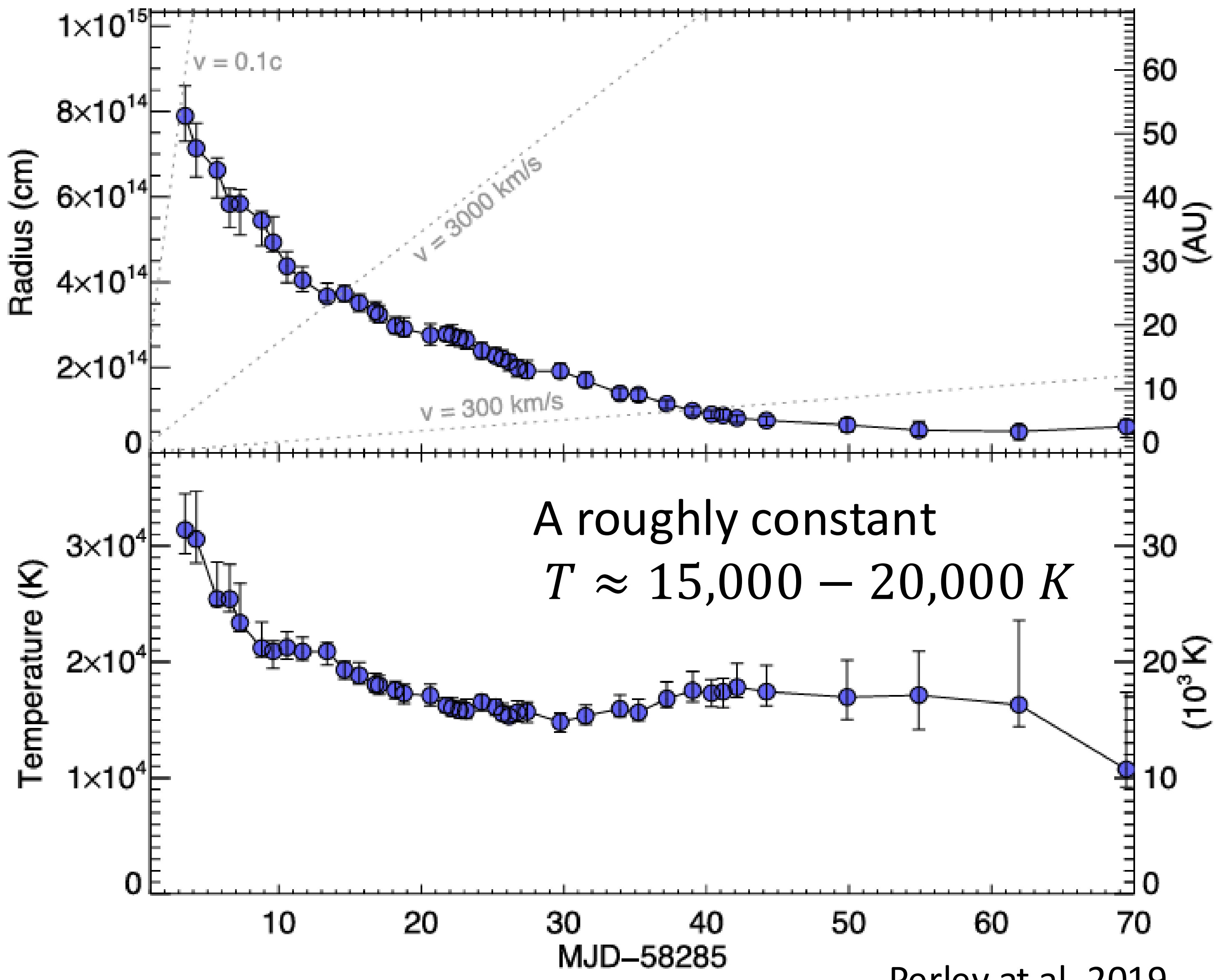
$$\frac{L_{x,hard}}{L_{x,soft}} = 4 \rightarrow 1$$

Radio



Ho et al. 19

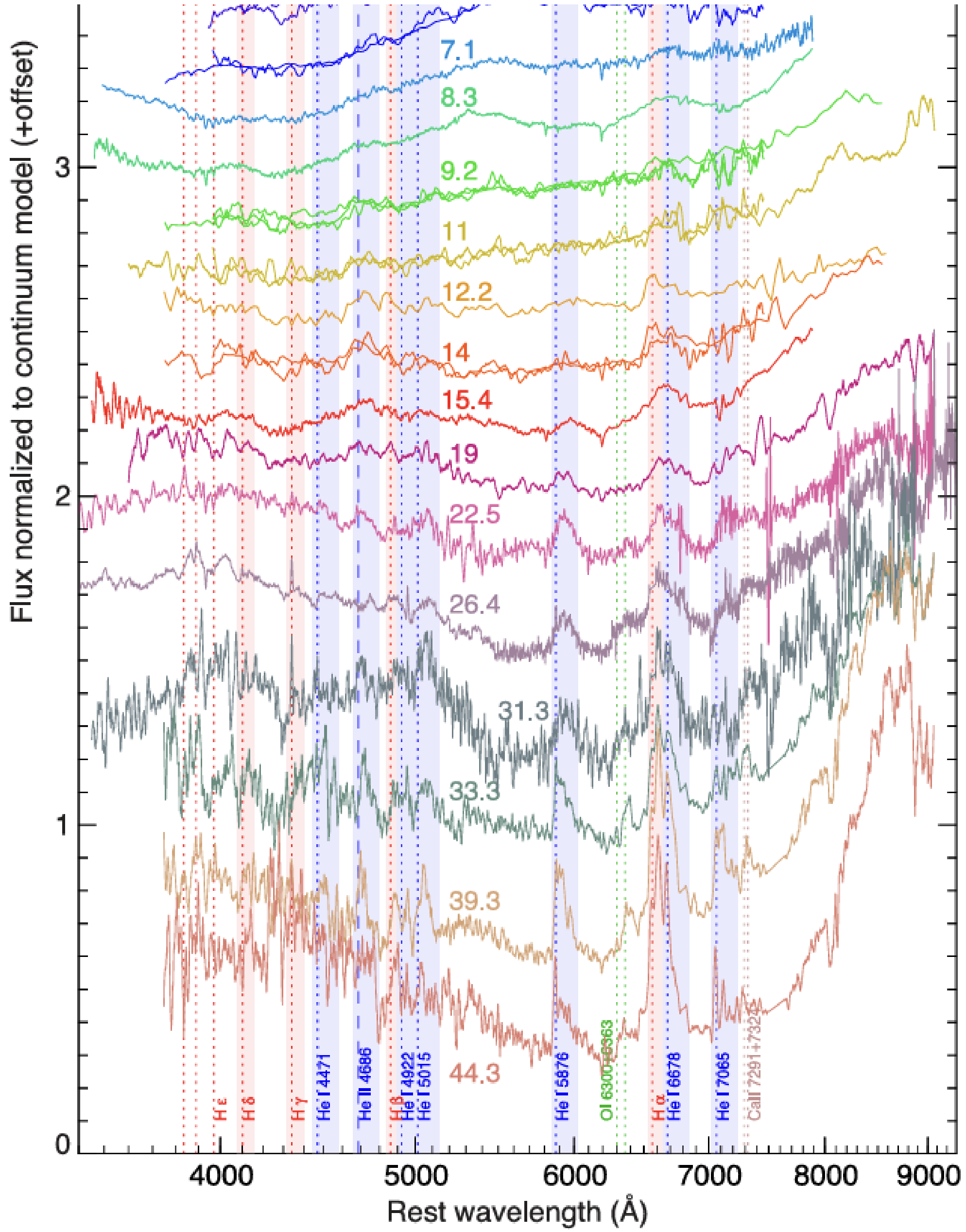
$$v_{sh} \sim 0.1c$$



Perley at al. 2019

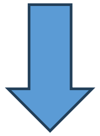
Decreasing Blackbody radius

A receding photosphere?



Perley at al. 2019

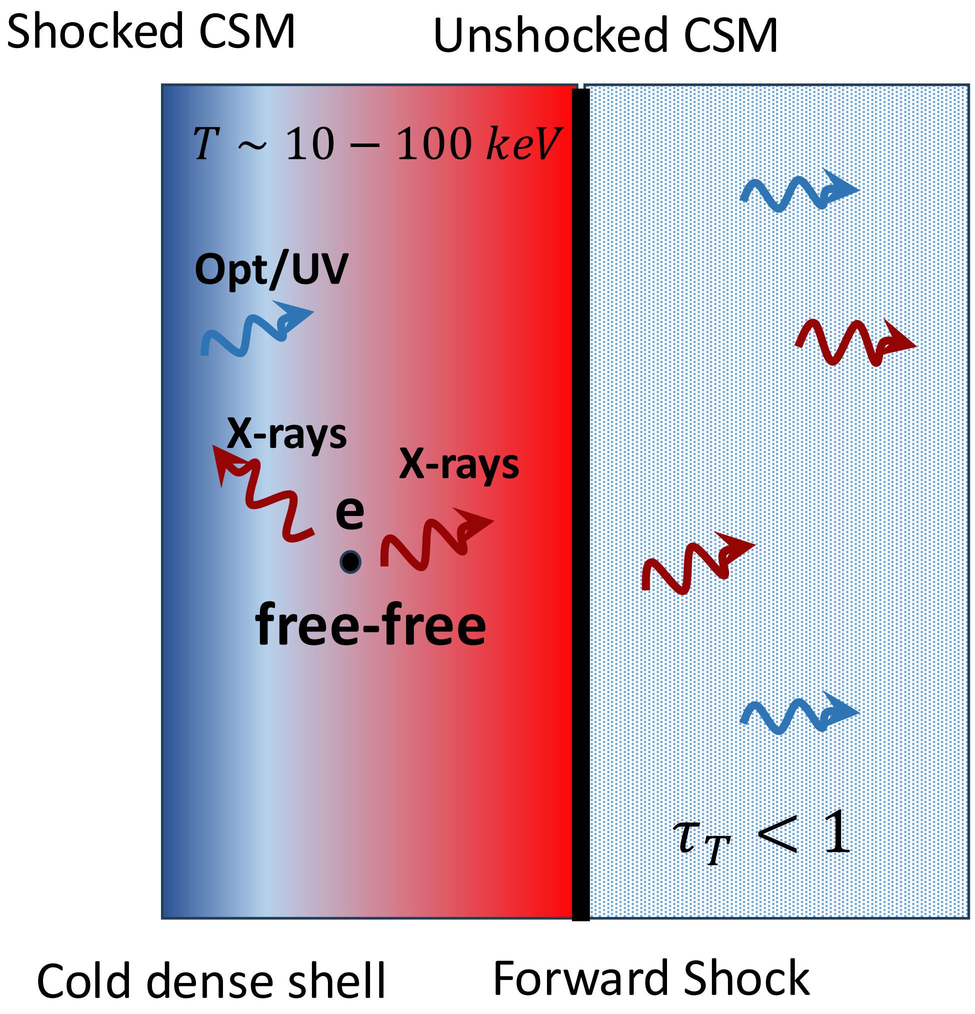
No narrow lines



No interaction power?

Fast cooling, free-free dominated shock in an optically thin medium

$t_{ie} < t_{ff} < t_{IC}, t_{dyn}$ and $\tau_T < 1$

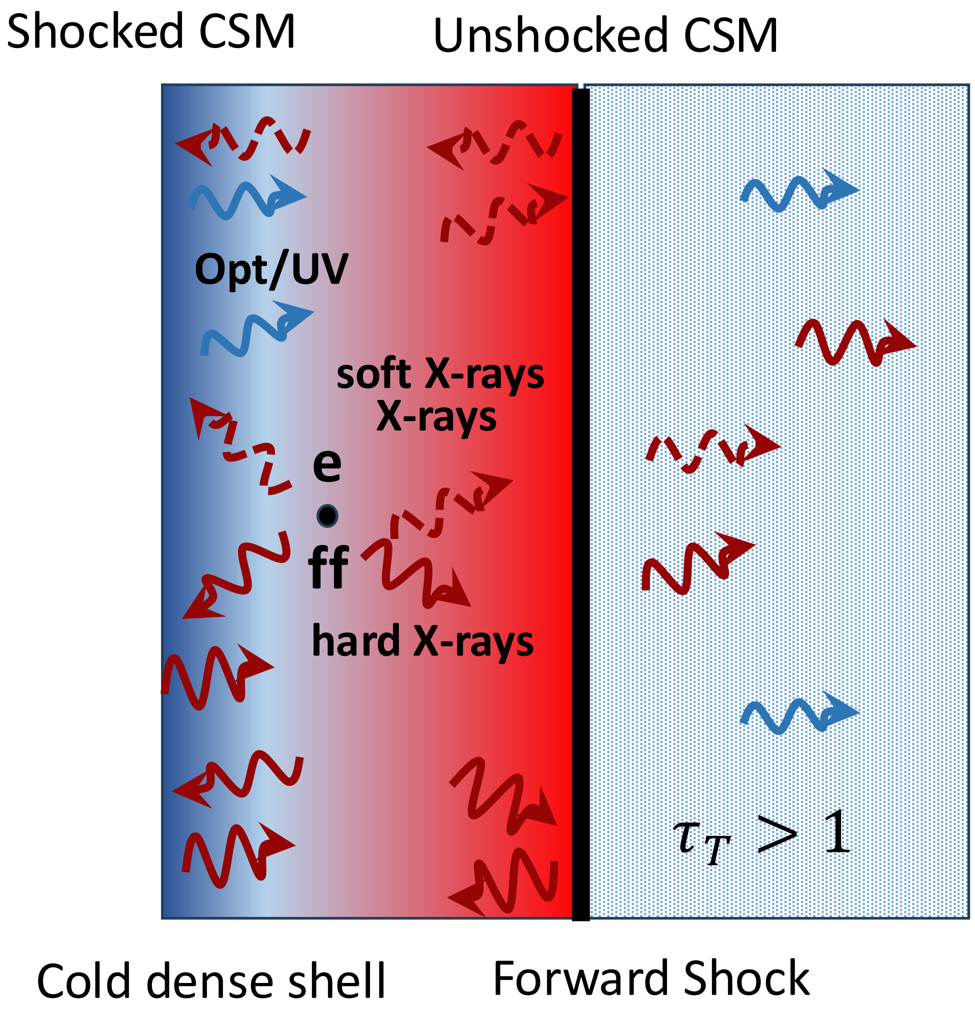


$$L_x \approx L_{opt}$$

$$L_{x,hard} \sim L_{x,soft}$$

Fast cooling, free-free dominated shock in an optically thick medium

$t_{ie} < t_{ff} < t_{IC}, t_{dyn}$ and $\tau_T > 1$



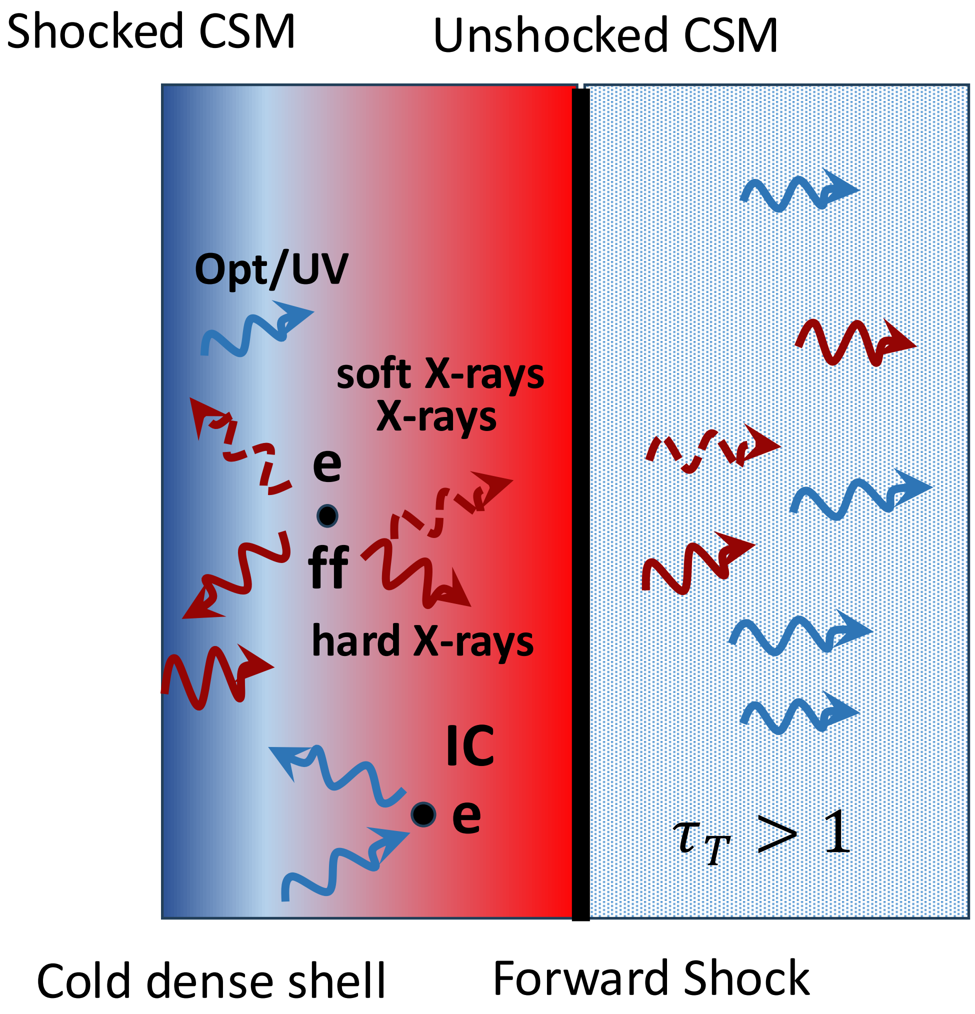
$$L_{x,soft} \approx \frac{1}{\tau} L_{opt}$$

$$L_{x,hard} \sim L_{opt}$$

$$L_{x,soft} \approx \frac{1}{\tau} L_{x,hard}$$

Fast cooling, **IC** dominated shock in an optically thick medium

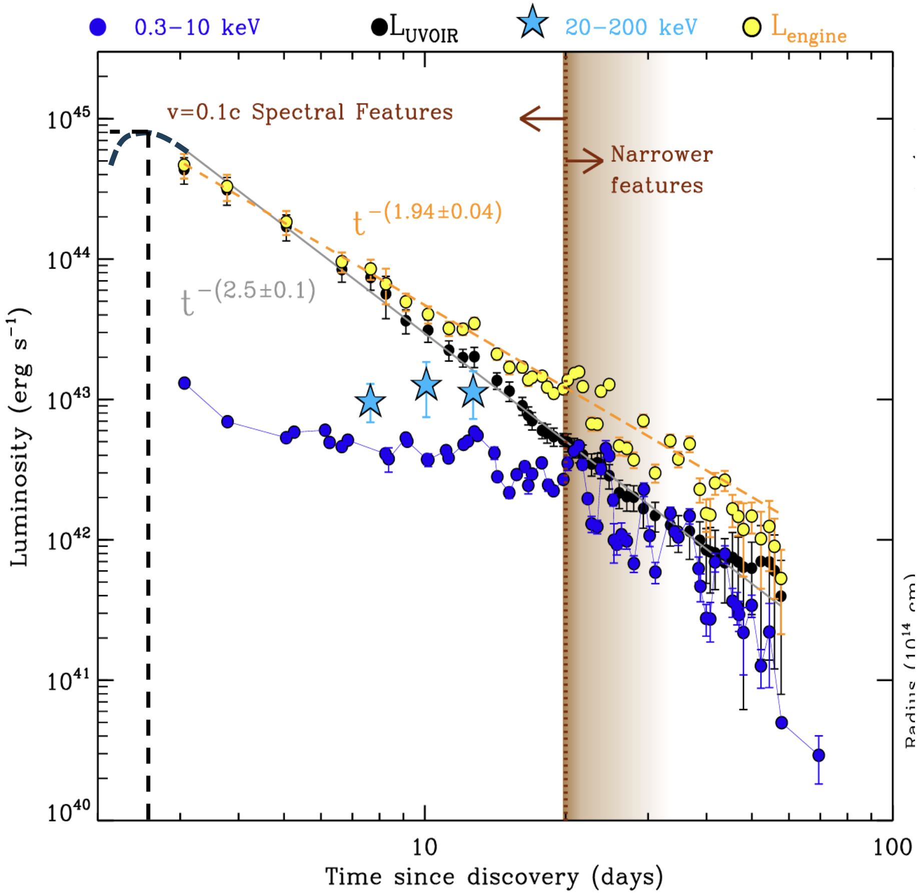
$t_{ie} < t_{ff} < t_{IC}, t_{dyn}$ and $\tau_T > 1$



$$L_{x,soft} \approx \frac{t_{IC}}{t_{ff}} \frac{1}{\tau} L_{opt}$$

$$L_{x,hard} \sim \frac{t_{IC}}{t_{ff}} L_{opt}$$

$$L_{x,soft} \approx \frac{1}{\tau} L_{x,hard}$$



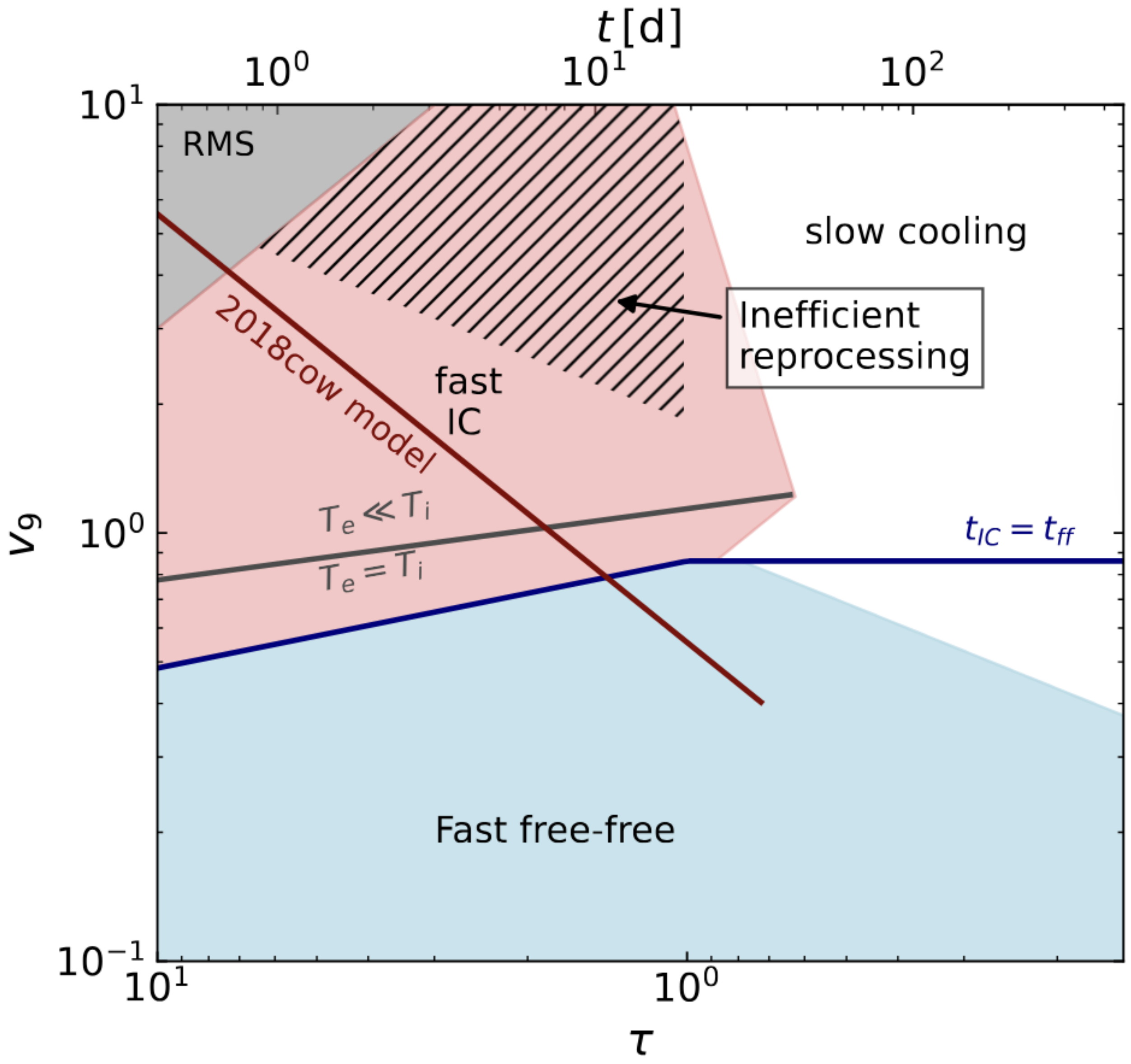
Observables

1. L_{bo}
2. L_{tot} power law
3. t_{bo} (1-3 days)
4. v_{bo} (0.1-0.2 c)
5. L_{opt}/L_x (function)
6. $L_{x,soft}/L_{x,hard}$ (function)
7. X-ray spectum
8. Fluctuations

Model free parameters

1,2,3. $v = v_{bo}\left(\frac{t}{t_{bo}}\right)^{-k}$

4. $\rho \propto r^{-s}$



$$v = v_{bo}\left(\frac{t}{t_{bo}}\right)^{-k}$$

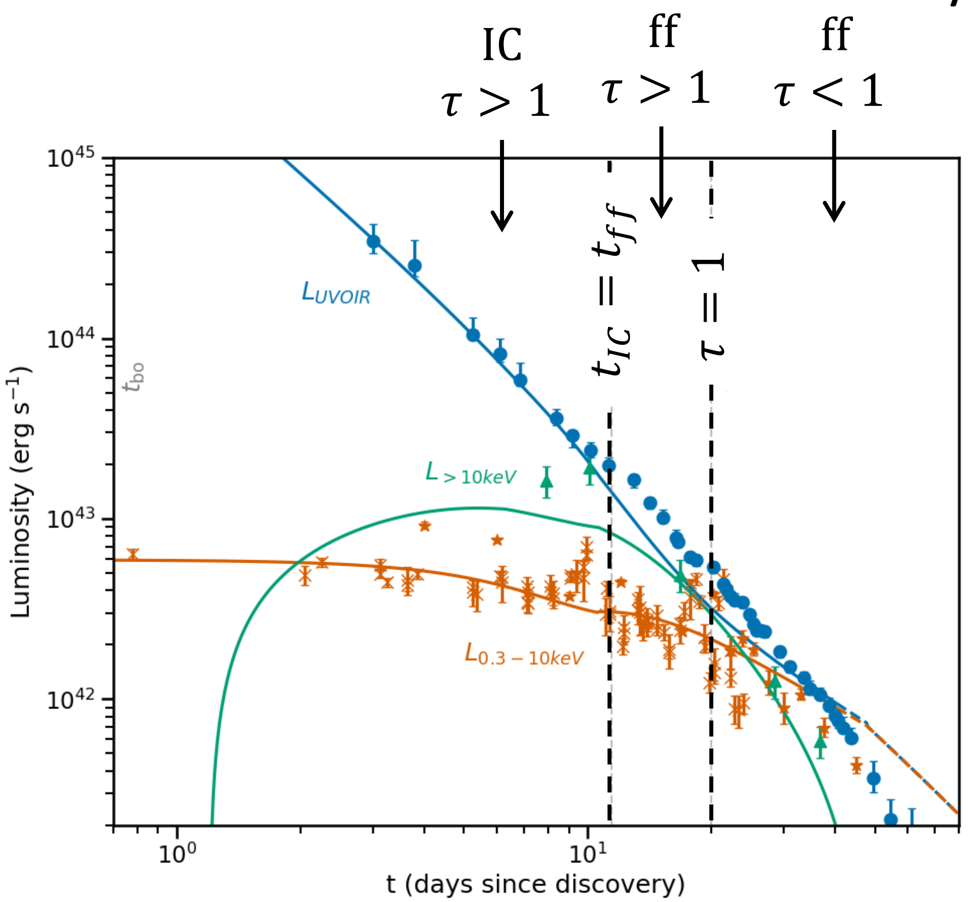
$$\rho \propto r^{-s}$$

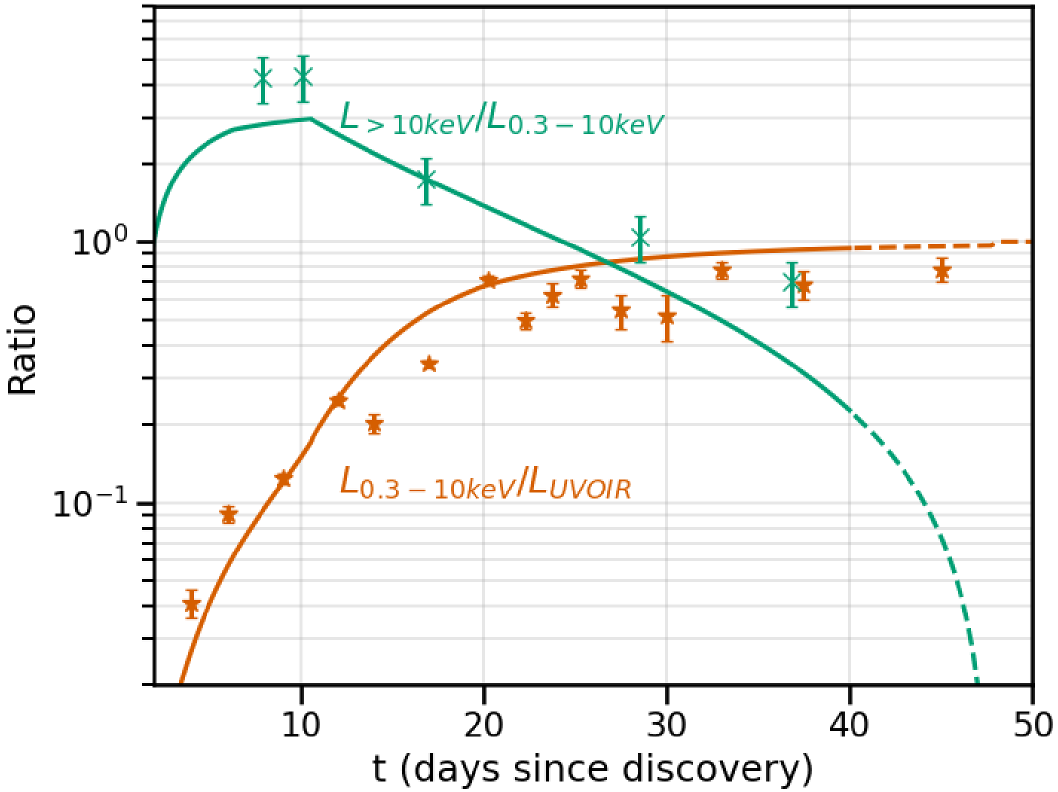
$$s \approx 2.5 \;\&\; k \approx 0.6$$

An aspherical CSM

s=2.5 ; k=0.6

An aspherical medium





$E_{ej} \sim 10^{50} erg\ ; v_{ej} > 0.1c\ ; M_{ej} < 0.005 M_{\odot}$

$\mathrm{M_{CSM}} \sim 0.01 M_{\odot}$ @ r=1 $\times 10^{15}\ cm\ ; \rho \propto r^{-2.5}$

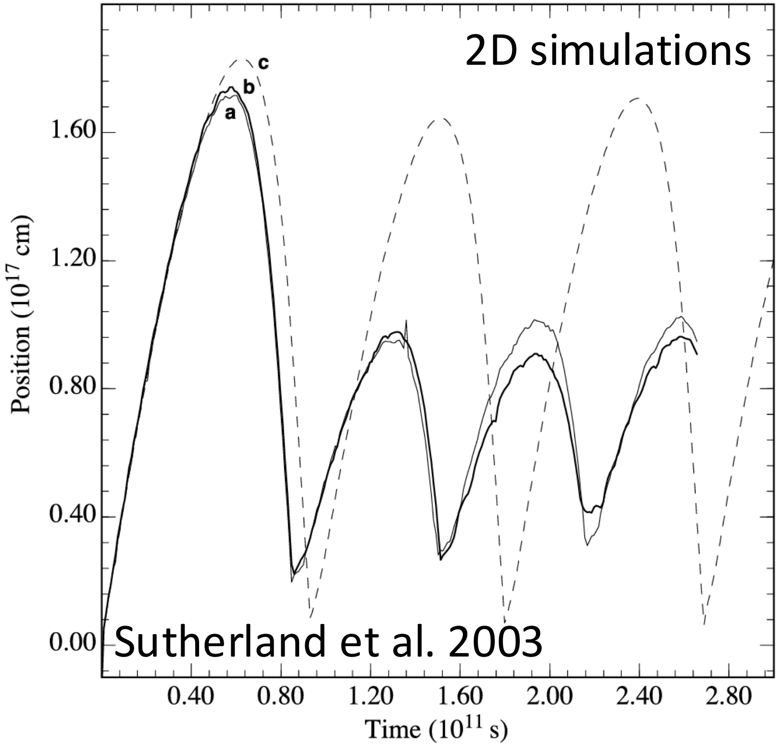
Acretion Induced Collapse?

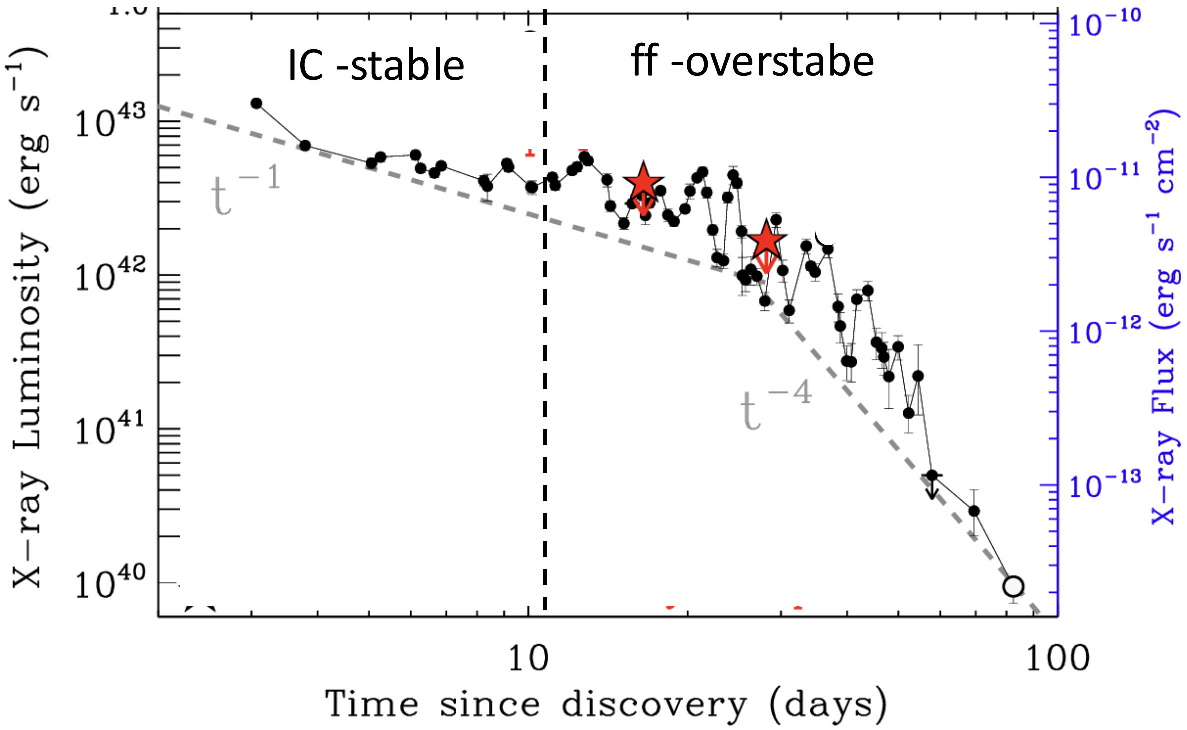
Ultra-stripped SN?

Thermal instability of radiative shocks

Langer, Chanmugam, Shaviv 1981 ; Chevalier & Imamura 1982 ; Gaffet 1983 ; …

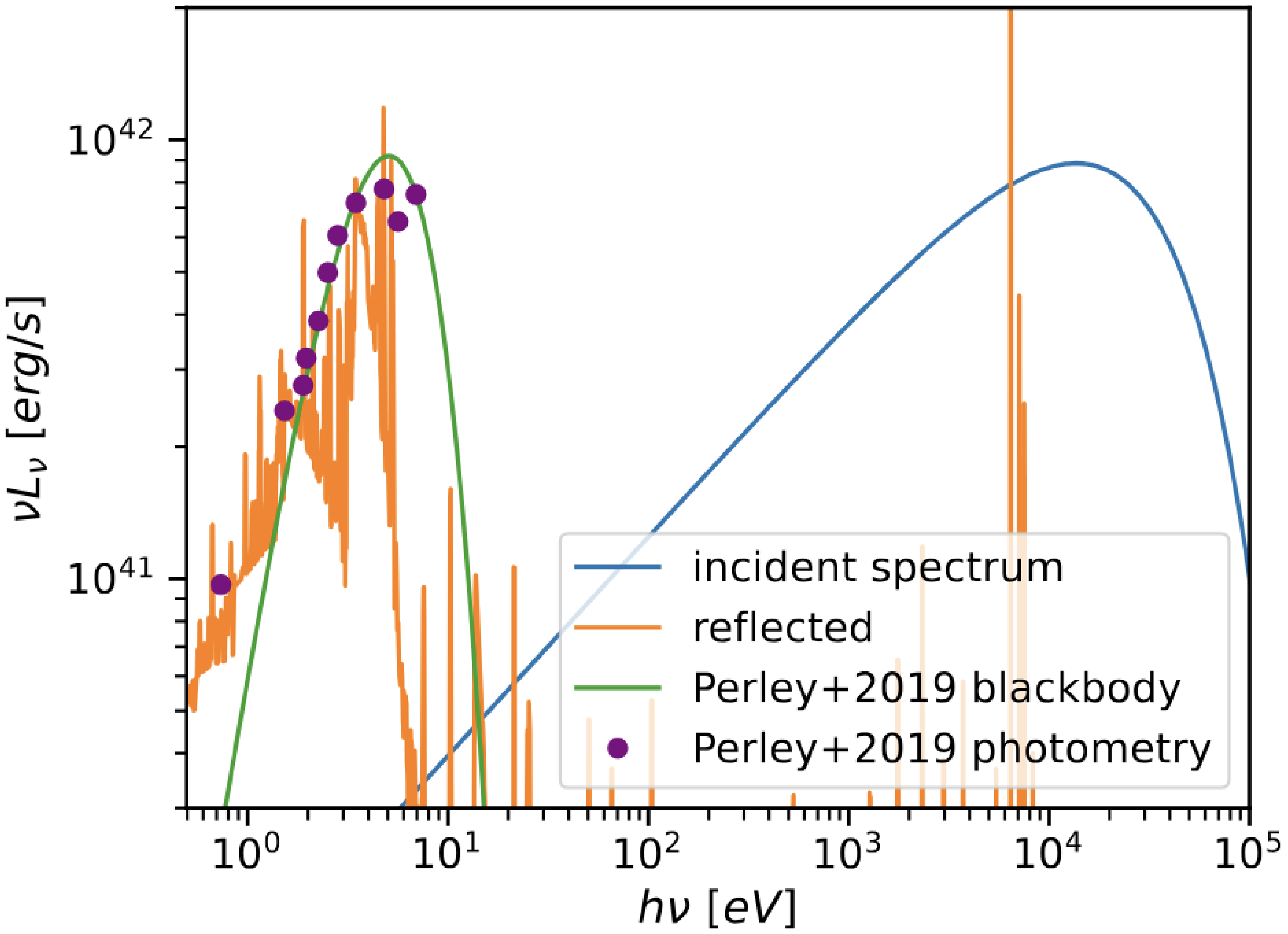
$t_{osc} \sim t_{cooling}$





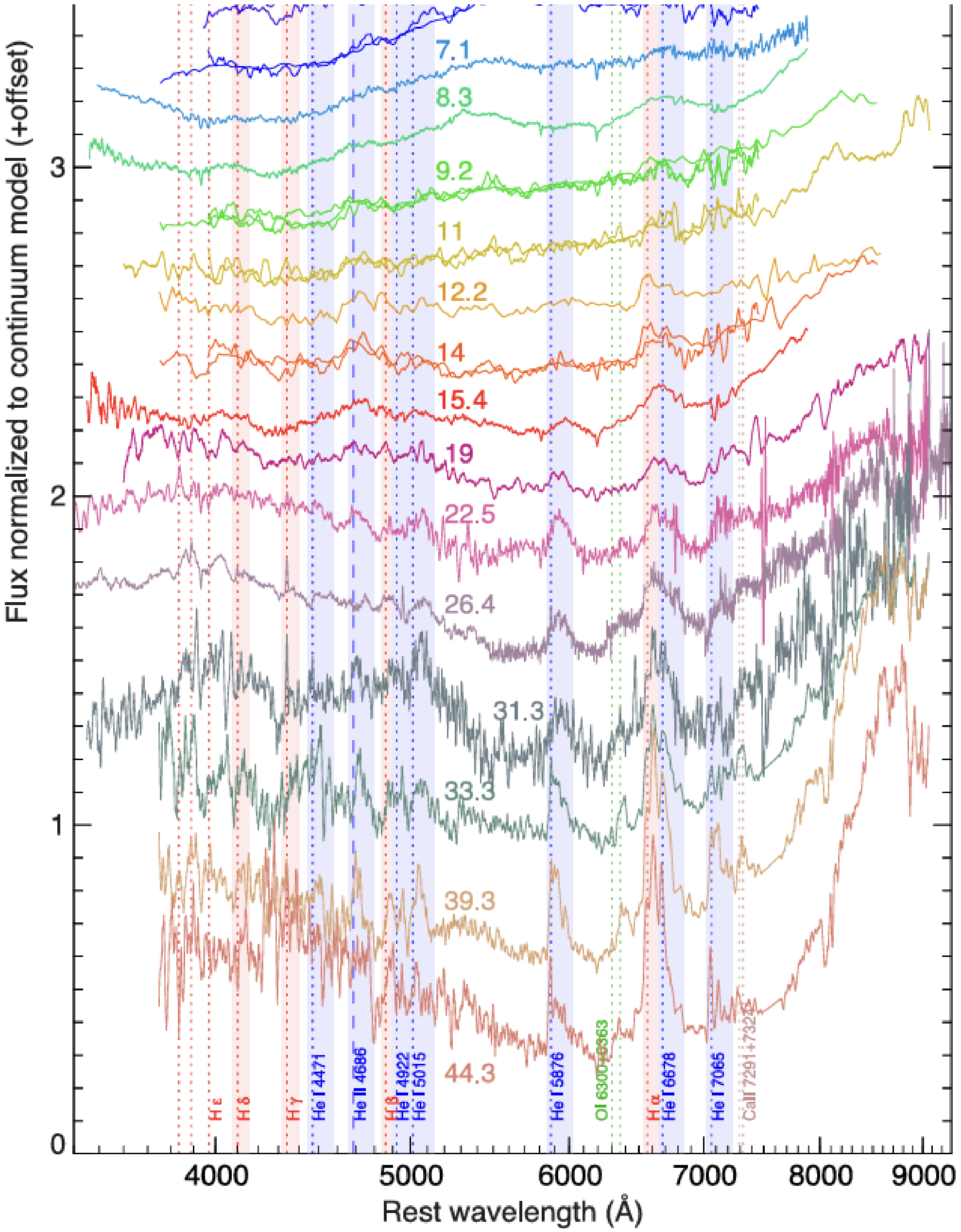
Fast cooling shocks are overstable if the cooling dependence on the temperature is strong enough

A reflected spectrum



The cooling function serves as a thermostat ➔ Roughly constant $T \approx 15{,}000 - 20{,}000\ K$

Droping luminosity and costant T ➔ A decreasing BB radius

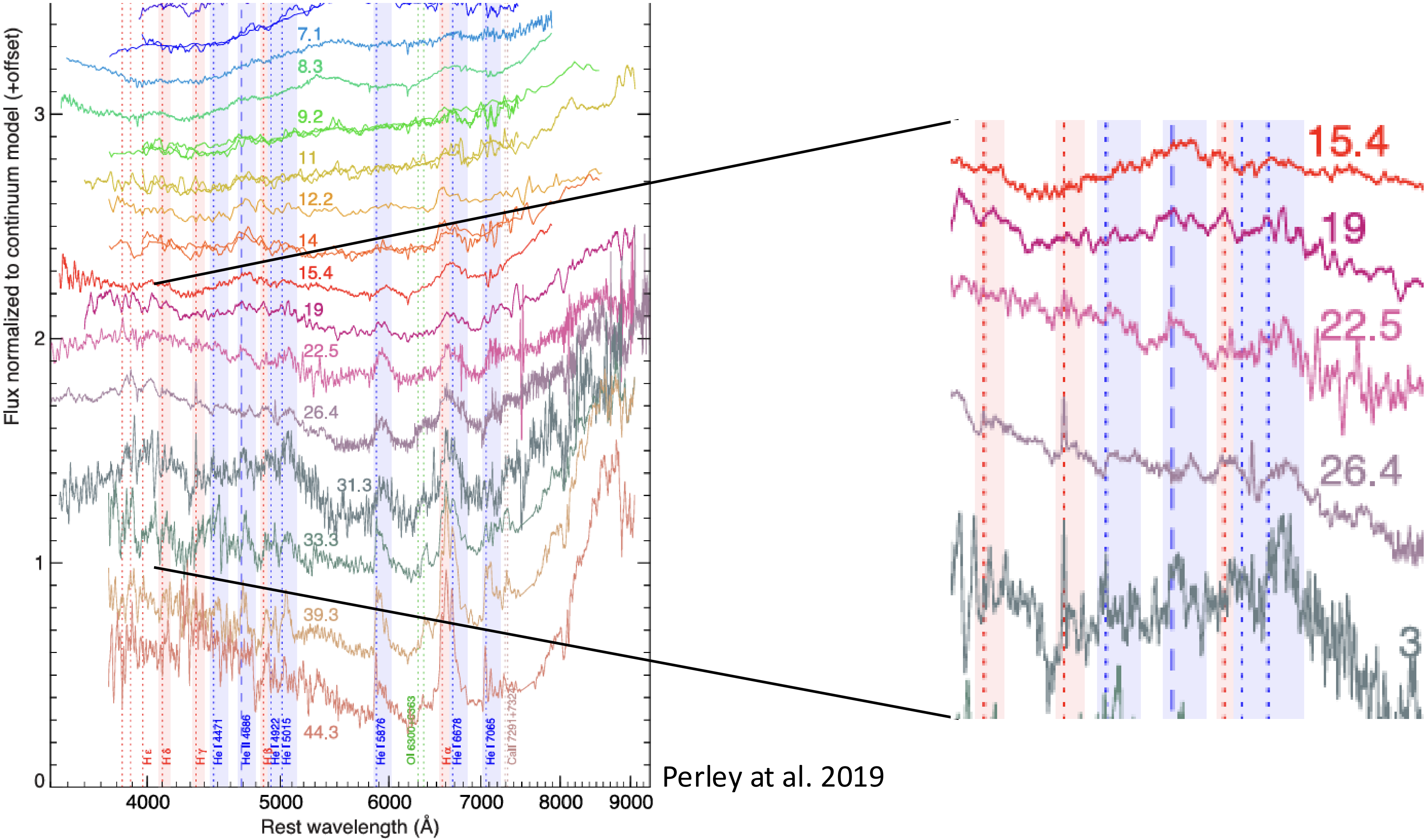


Perley at al. 2019

Early time – High L_x : CSM $T \sim 10$keV

No narrow lines

Late time – Low L_x : CSM T drops



Perley at al. 2019

Summary I

- The cow observations are well explained by an interaction model

$$E_{ej} \sim 10^{50} erg \,;\, v_{ej} \sim 0.1c \,;\, M_{ej} \sim 0.005 M_{\odot}$$

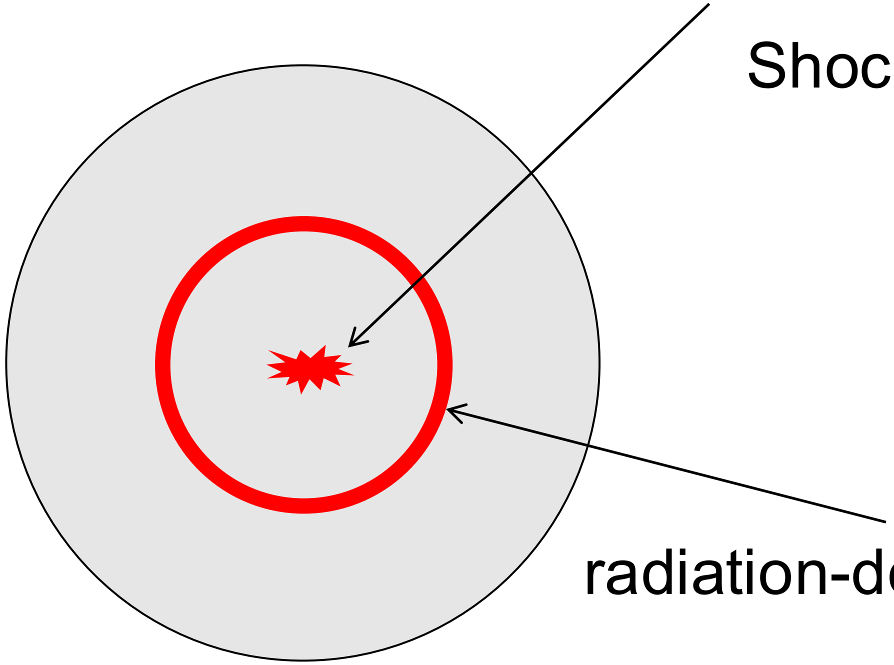
$$\mathrm{M_{CSM}} \sim 0.01 M_{\odot} \text{ @ r=1 } \times 10^{15}\, cm \,;\, \rho \propto r^{-2.5}$$

- The ratios of the hard/soft X-ray/optical fluxes provide a strong probe of the interaction's physical properties
- Interaction may have various signatures:
  - Not all interaction powered transients show narrow lines
  - A constant temperature of ~20,000 K + non-blackbody spectrum may be a signature of interaction powered reflected spectrum.
- A low significance detection of QPEs: if correct, cannot be explained by our model
- Next step: check if interaction can explain other LFBOTS

Breakout through an extended medium - SN 2023ixf

With C. Irwin and K. Hotokezaka

Shock Breakout from a star

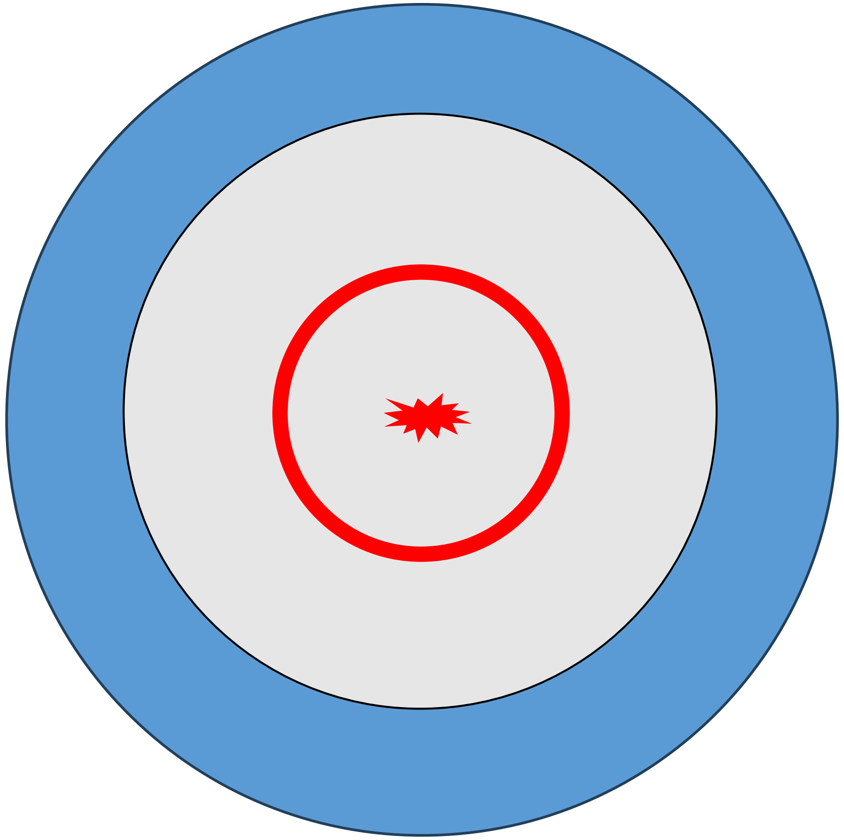


Shock width = optical depth to observer

Shock breakout

- Diffusion of the radiation deposited by the shock (*cooling emission*) starts immediately after the shock breakout

Shock Breakout from a circumstellar material (CSM)



Shock breakout at $\tau \approx c/v$

↓

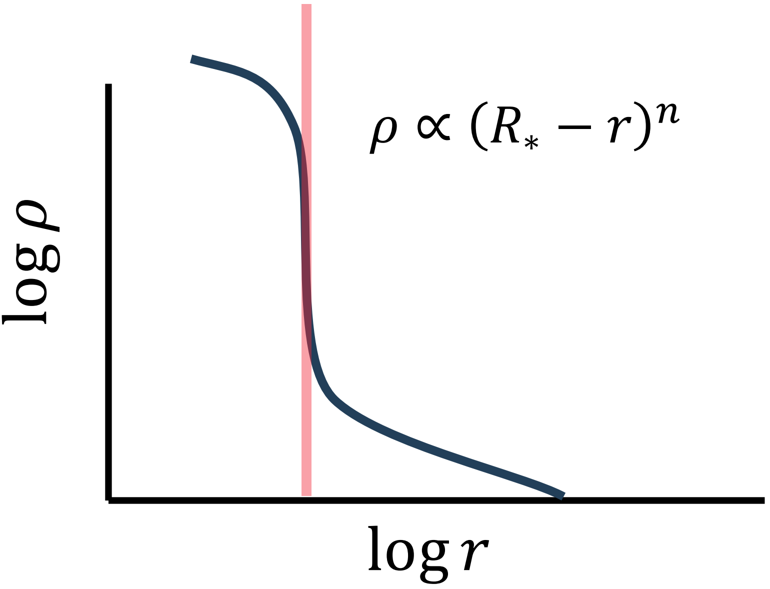
Transition to a collisionless shock in a Thomson-thick medium

↓

A collisionless shock in a Thomson-thin medium

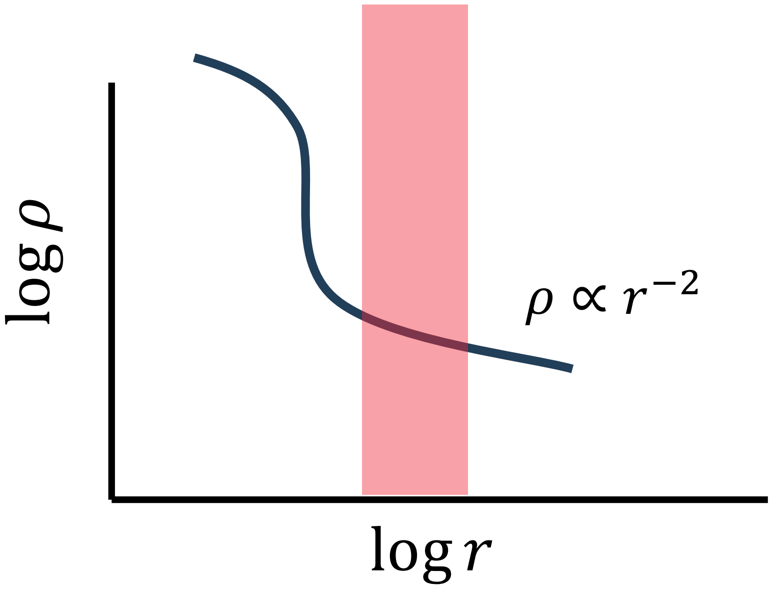
The width of the Shock Breakout layer

$\Delta \ll R_{bo}$



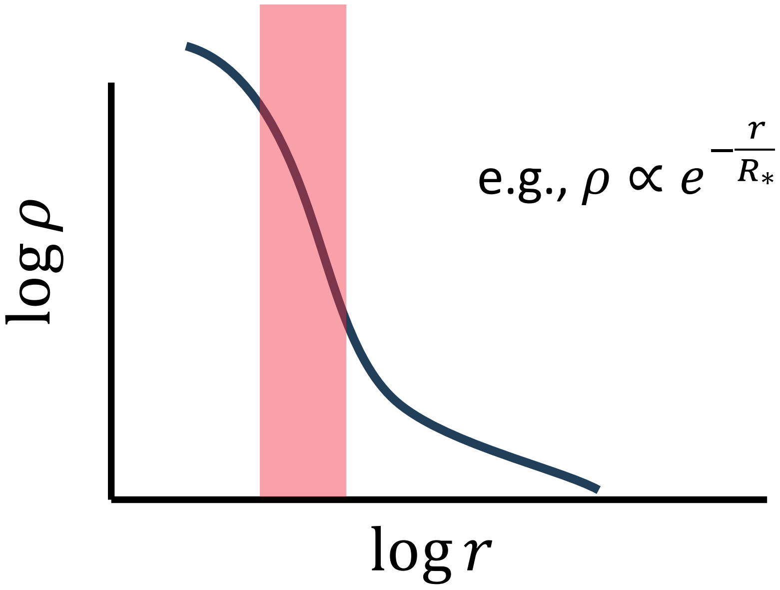
Breakout from a hydrostatic envelope

$\Delta \approx R_{bo}$



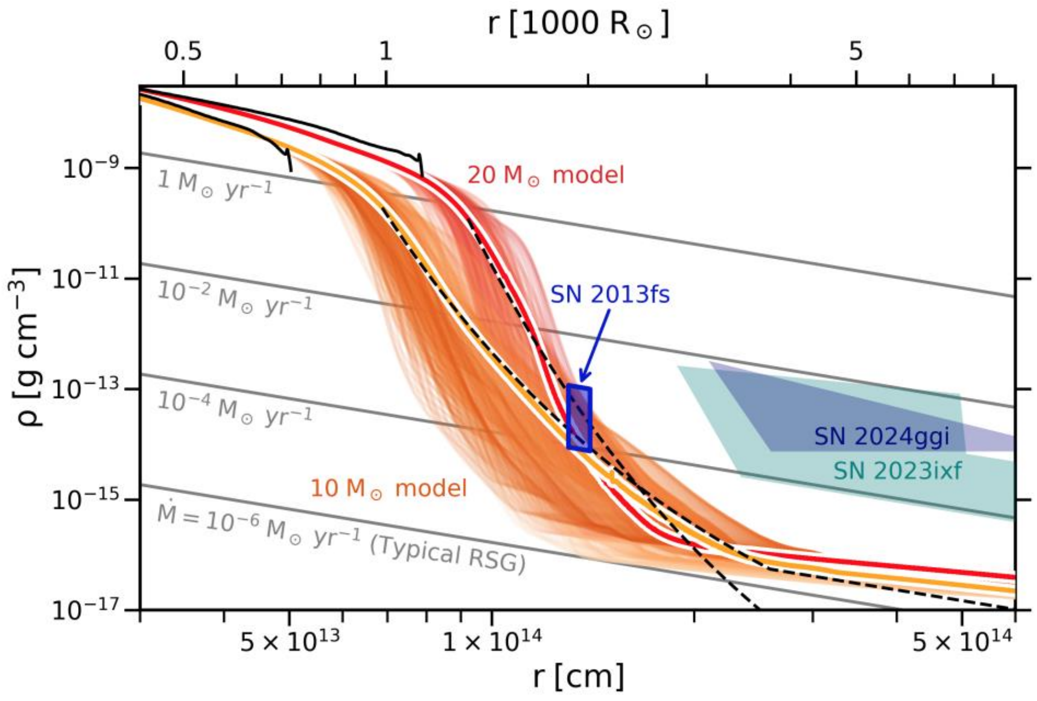
Breakout from a wind

$\Delta \approx R_{bo}$

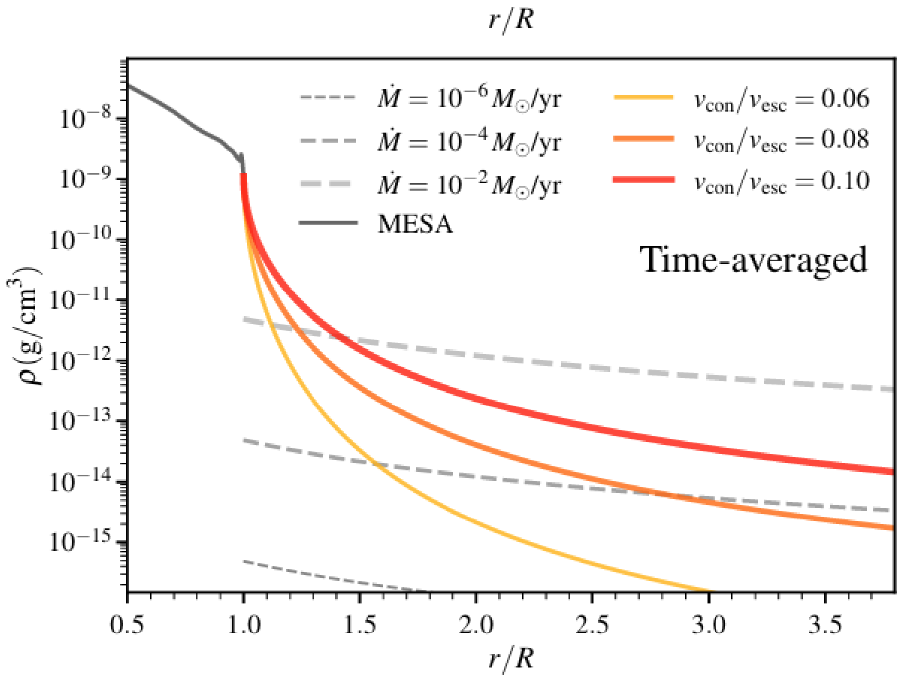


Breakout from an extended envelope

Δ The width of the layer overwhich the optical depth changes where $\tau \approx \frac{c}{v}$



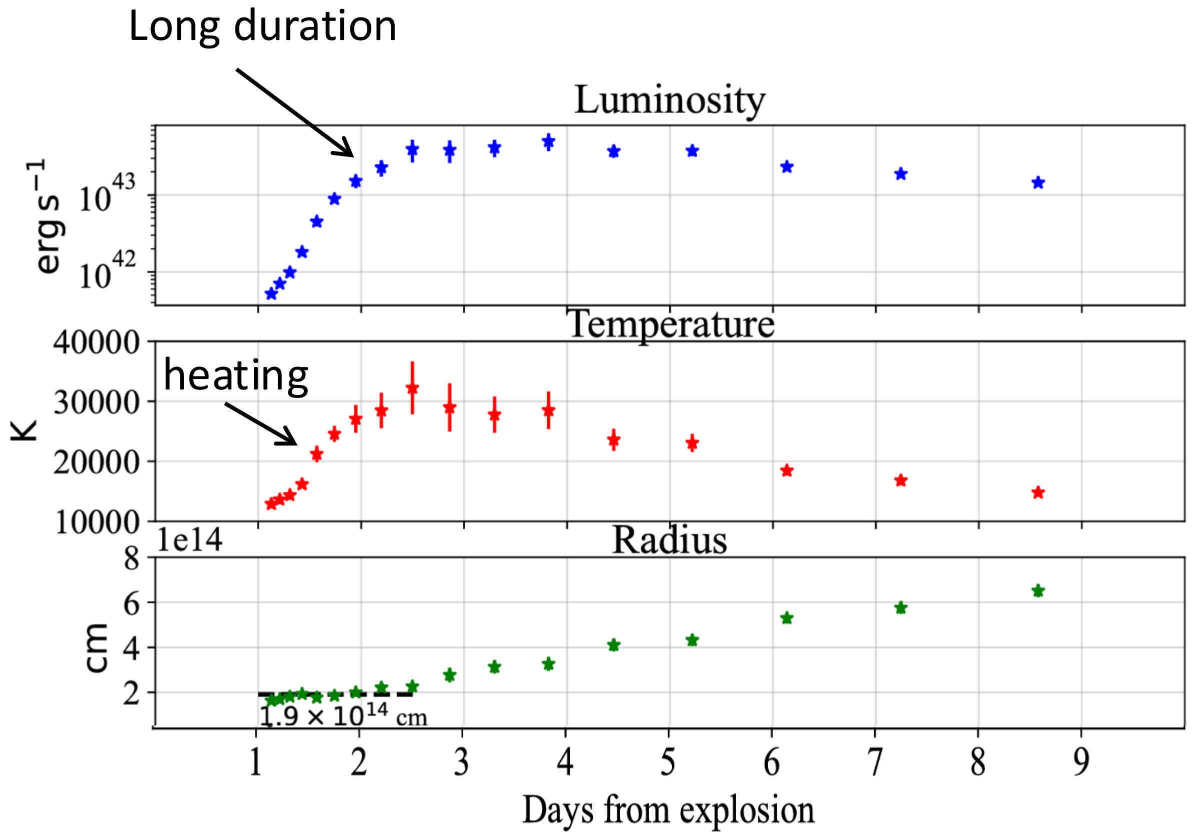
Ma et al. 2025

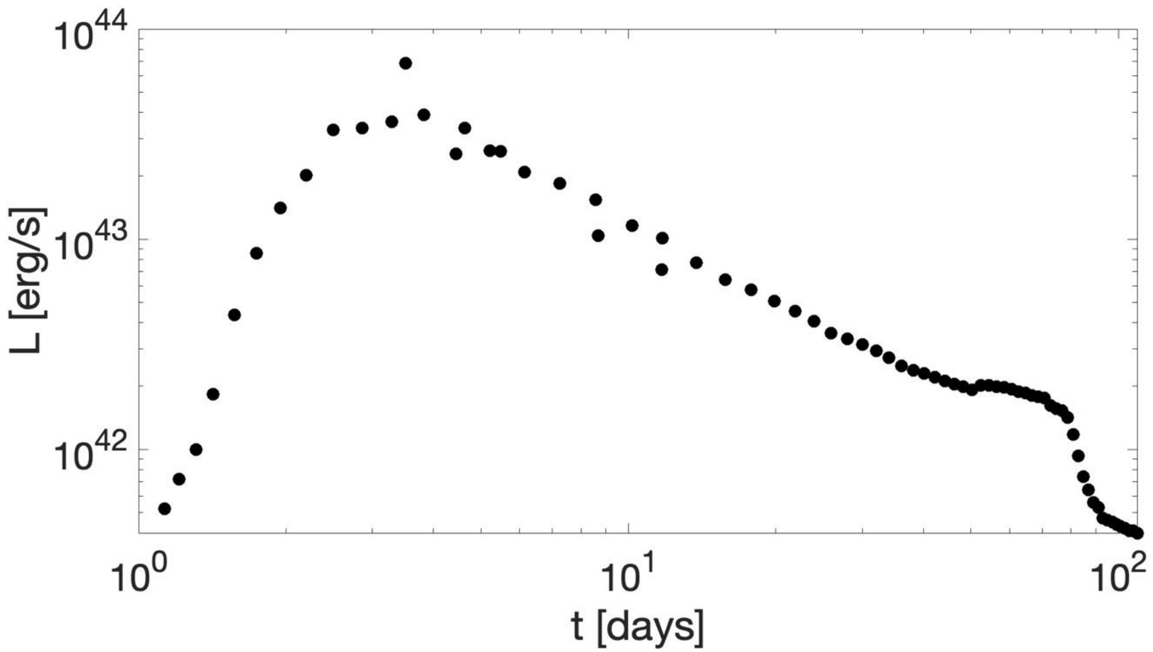


Fuller & Tsuna 2024

SN 2023ixf Optical/UV

(Rishabh Singh et al 23; Jacobson-Galán et al. 23; Gaici et al. 23; Zimermman et al., 24; and more)





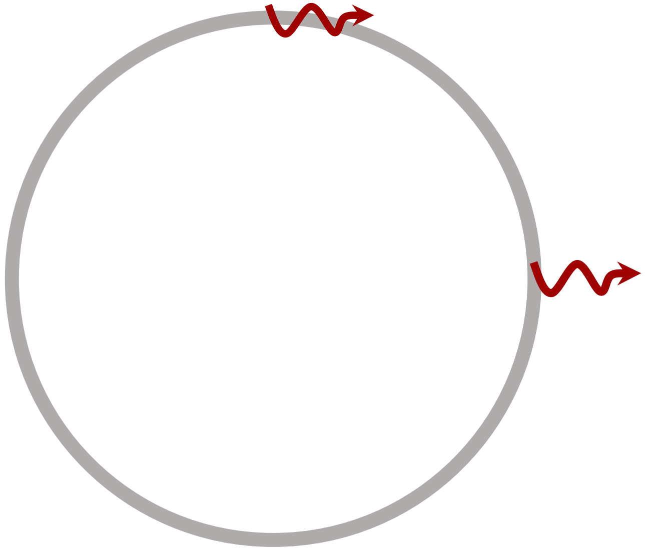
Zimermman et al., 24

What sets the breakout duration?

What is the source of the red to blue evolution?

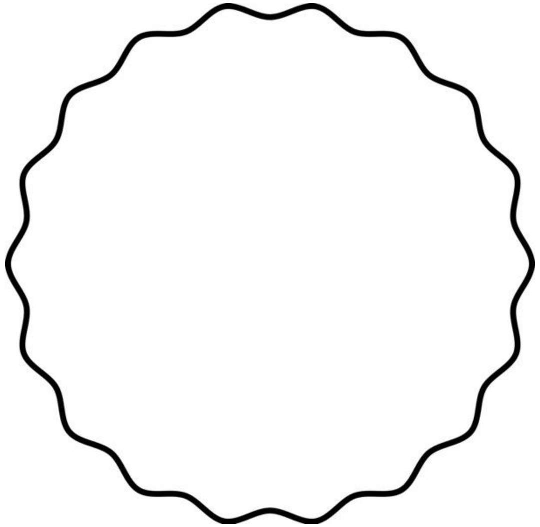
The breakout duration has three components

Light travel time



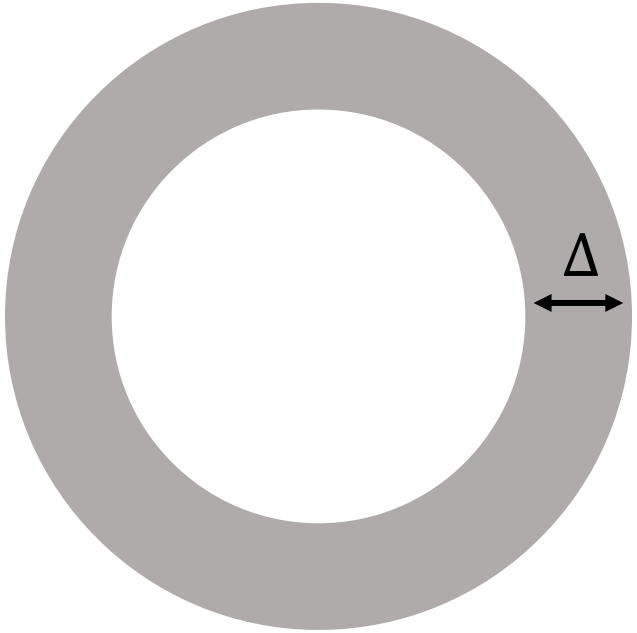
$$t_{lt} = R/c$$

Geometry



$$t_{geom} < R/v_{sh}$$

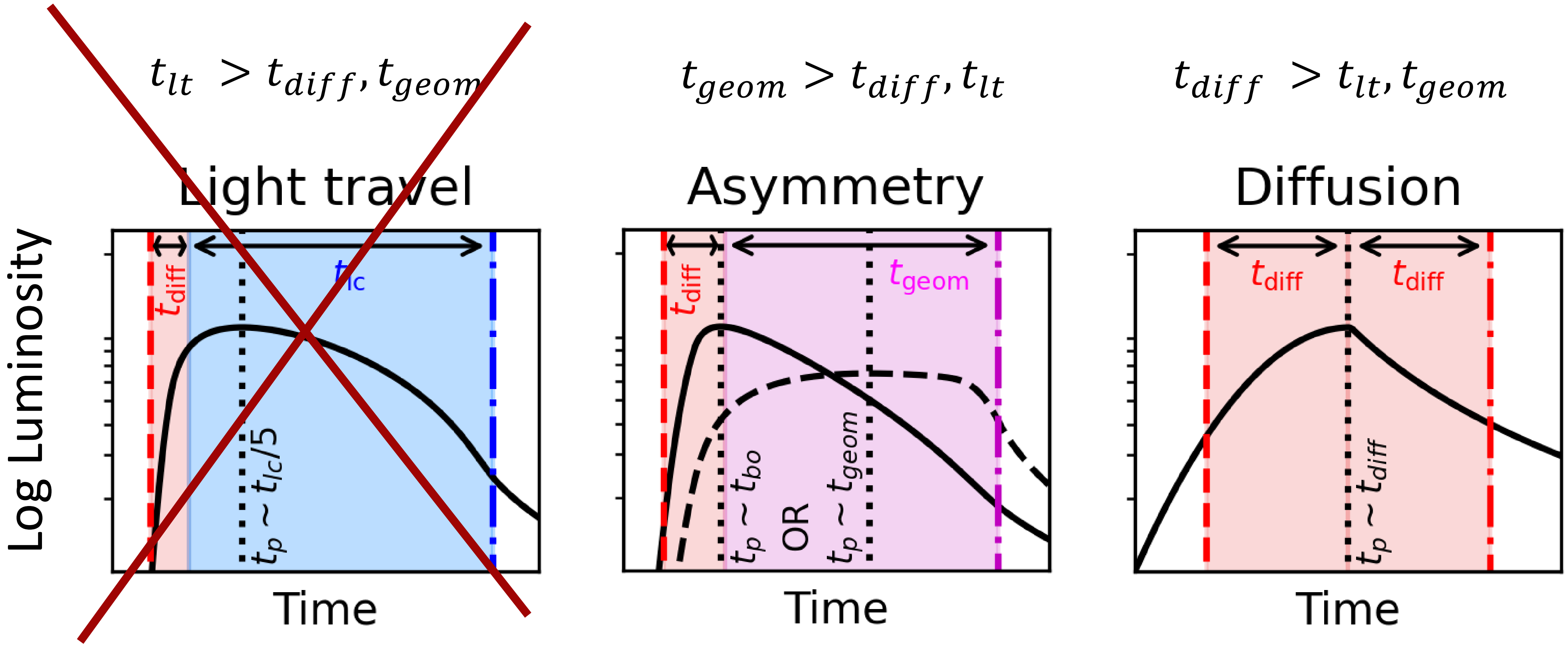
Diffusion time



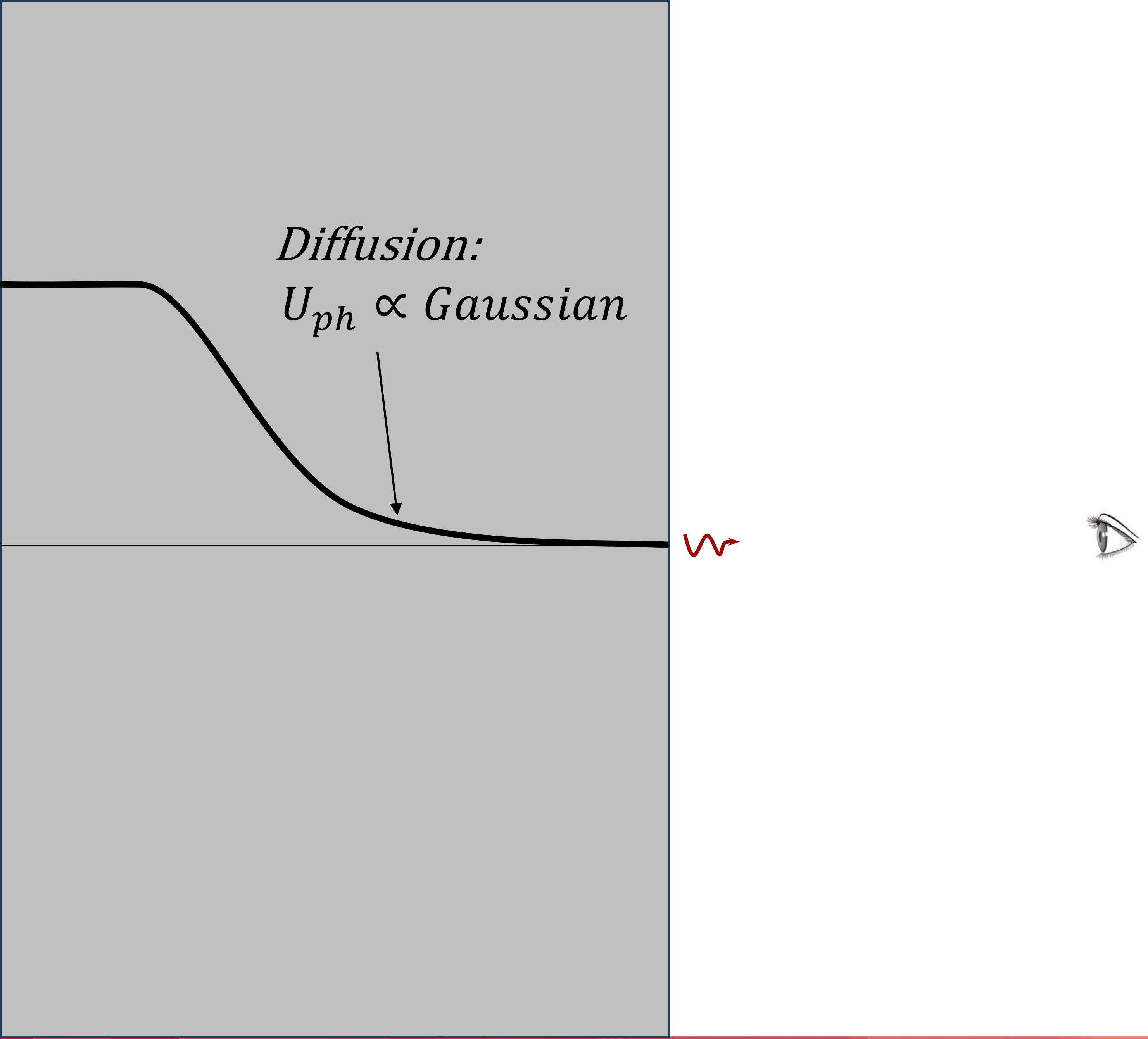
$$t_{diff} = \Delta/v_{sh}$$

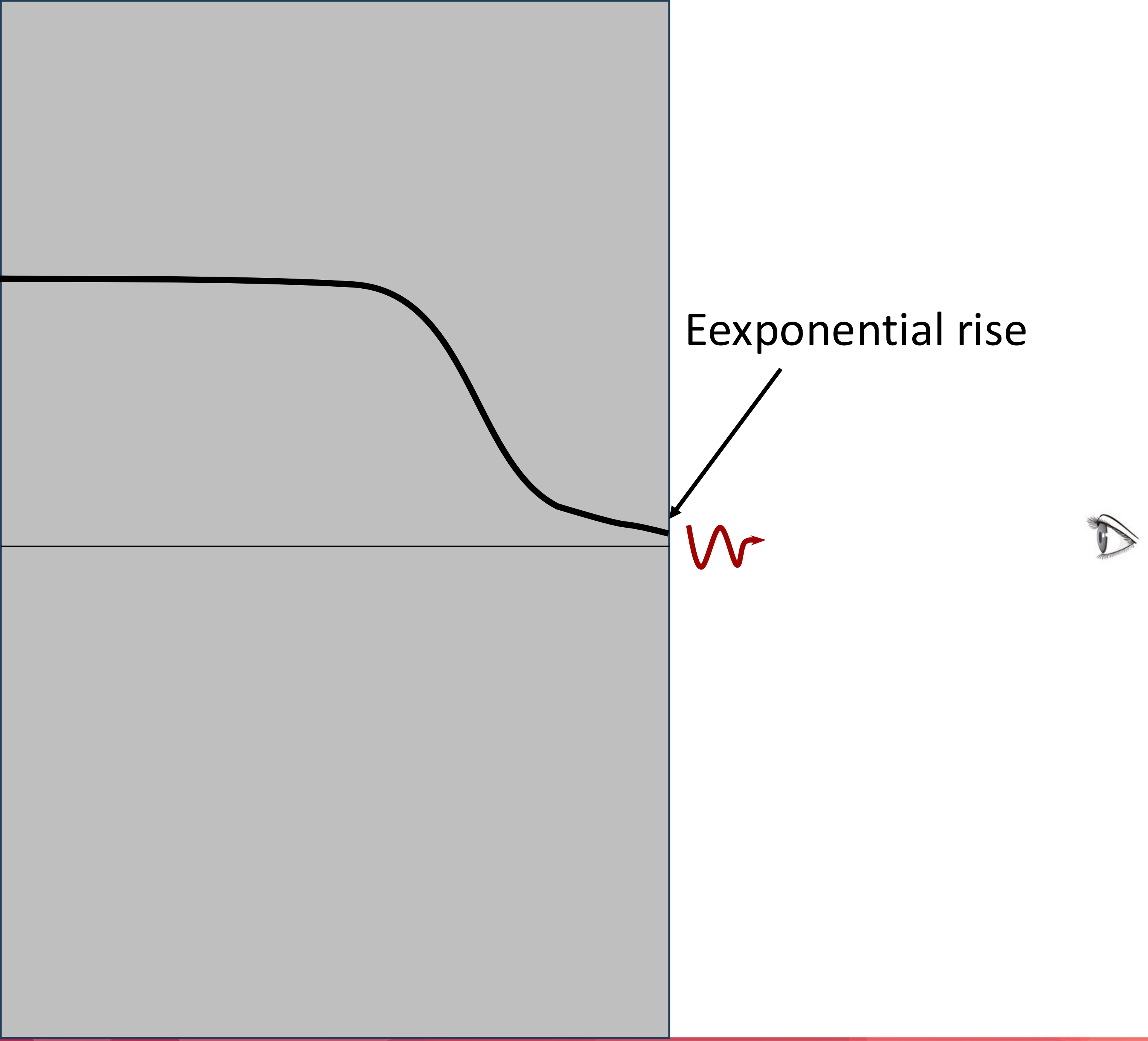
Δ – scale over which the opacity changes when $\tau \approx \frac{c}{v_{sh}}$

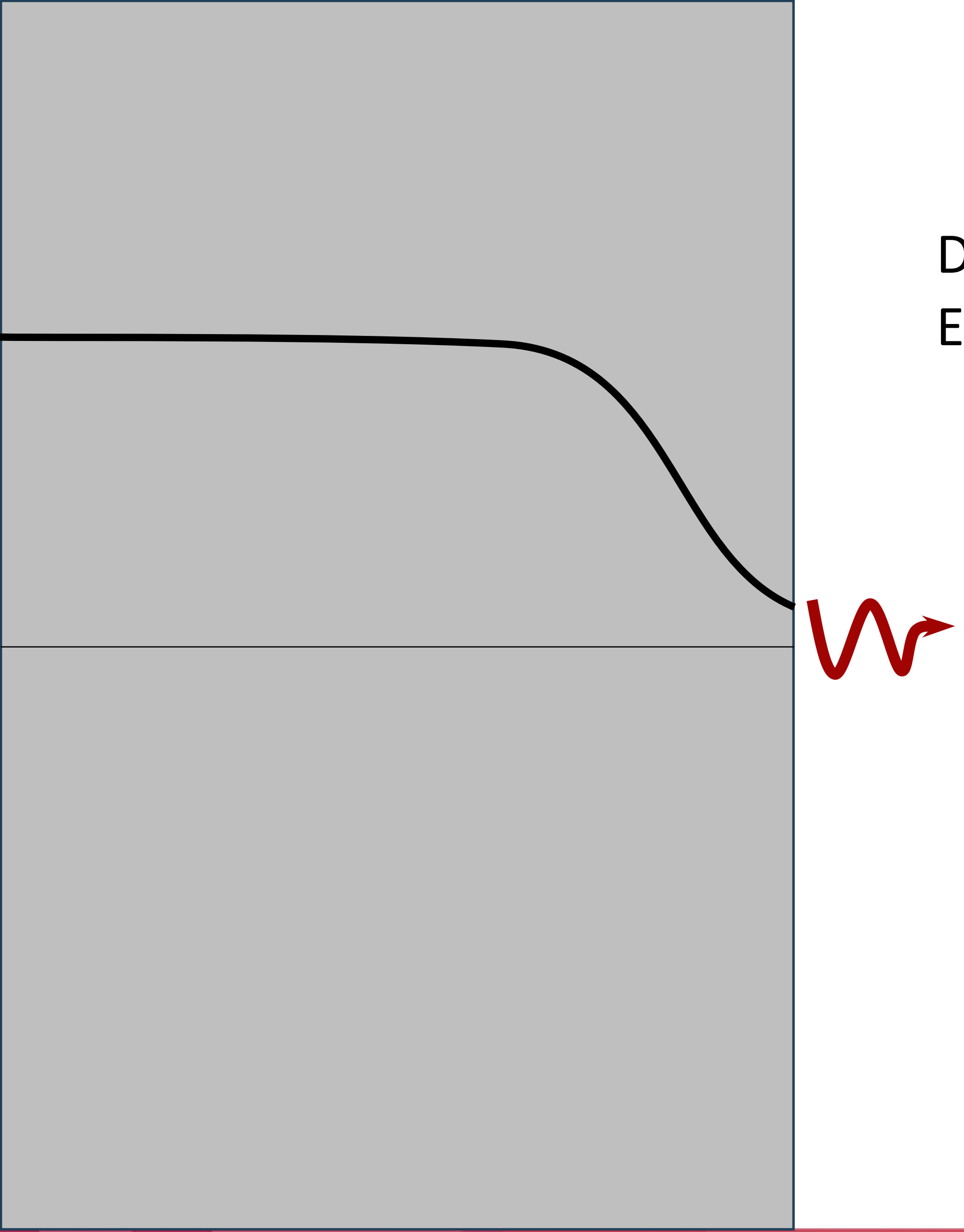
The breakout duration



Which process dominates the breakout in 2023ixf?


Diffusion:
$U_{ph} \propto Gaussian$


Eexponential rise



Diffusion phase:
Exponential rise with e-fold time $t_{diff} = \Delta/v$

Color evolution for $t<t_{diff}$

All SN breakouts start with an exponential luminosity rise during the diffusion phase (Sapir & Waxman 2011; Shussman & Nakar 2016)

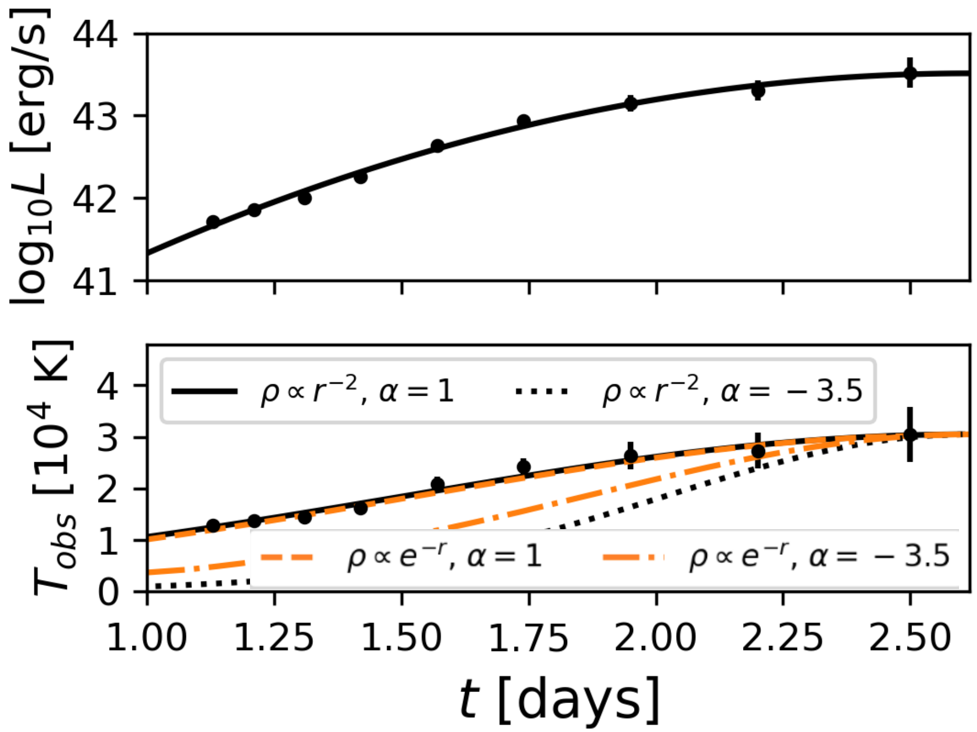
The photosphere radius is not changing much

⇓

A temperature rise (Zimmerman et al. 24)
A red-to-blue evolution during diffusion

(Almost) Only the diffusion phase shows a significant heating

SN 2023ixf

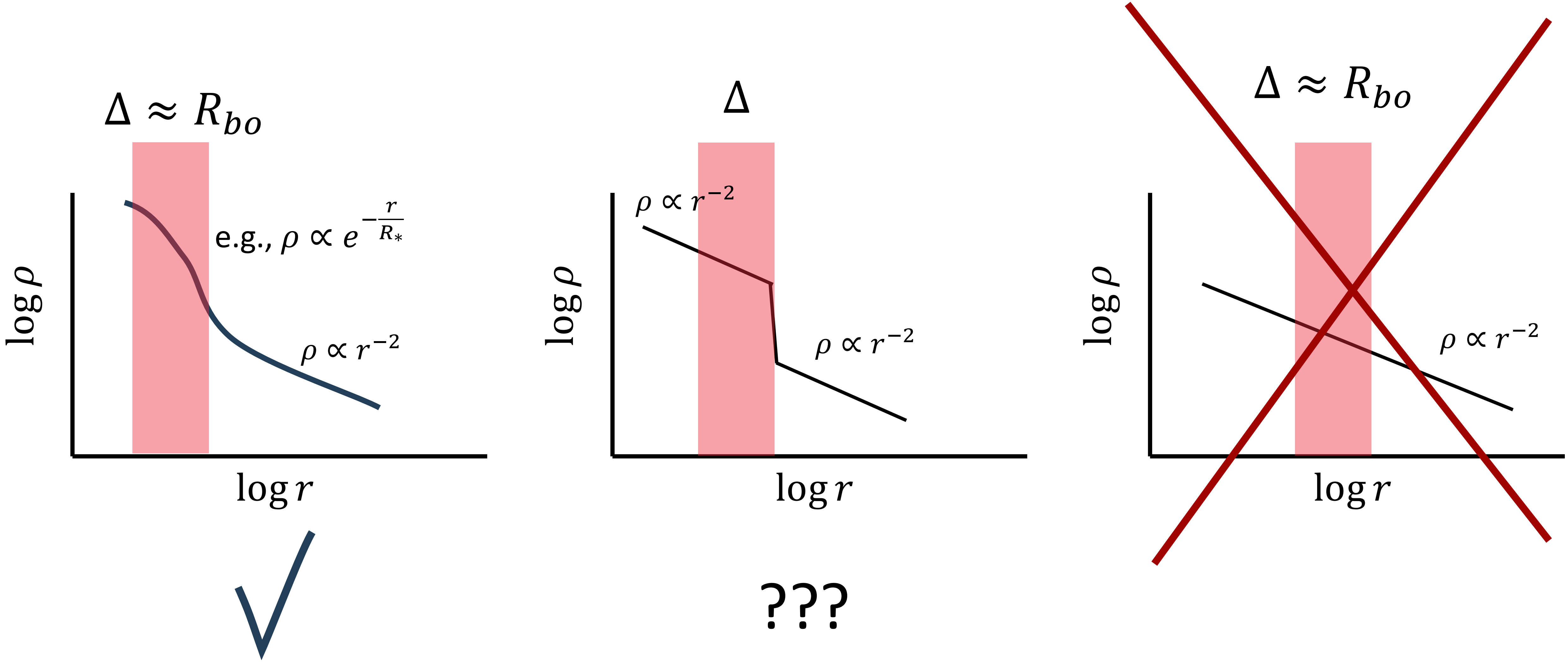


Exponential rise with e-folding time $\approx 1d$

Temprature rises

2023ixf was dominated by diffusion

$$\Delta \approx 5 \times 10^{13} cm \sim R_{bo}$$



UV/Opt Temprature + X-rays

Summary II

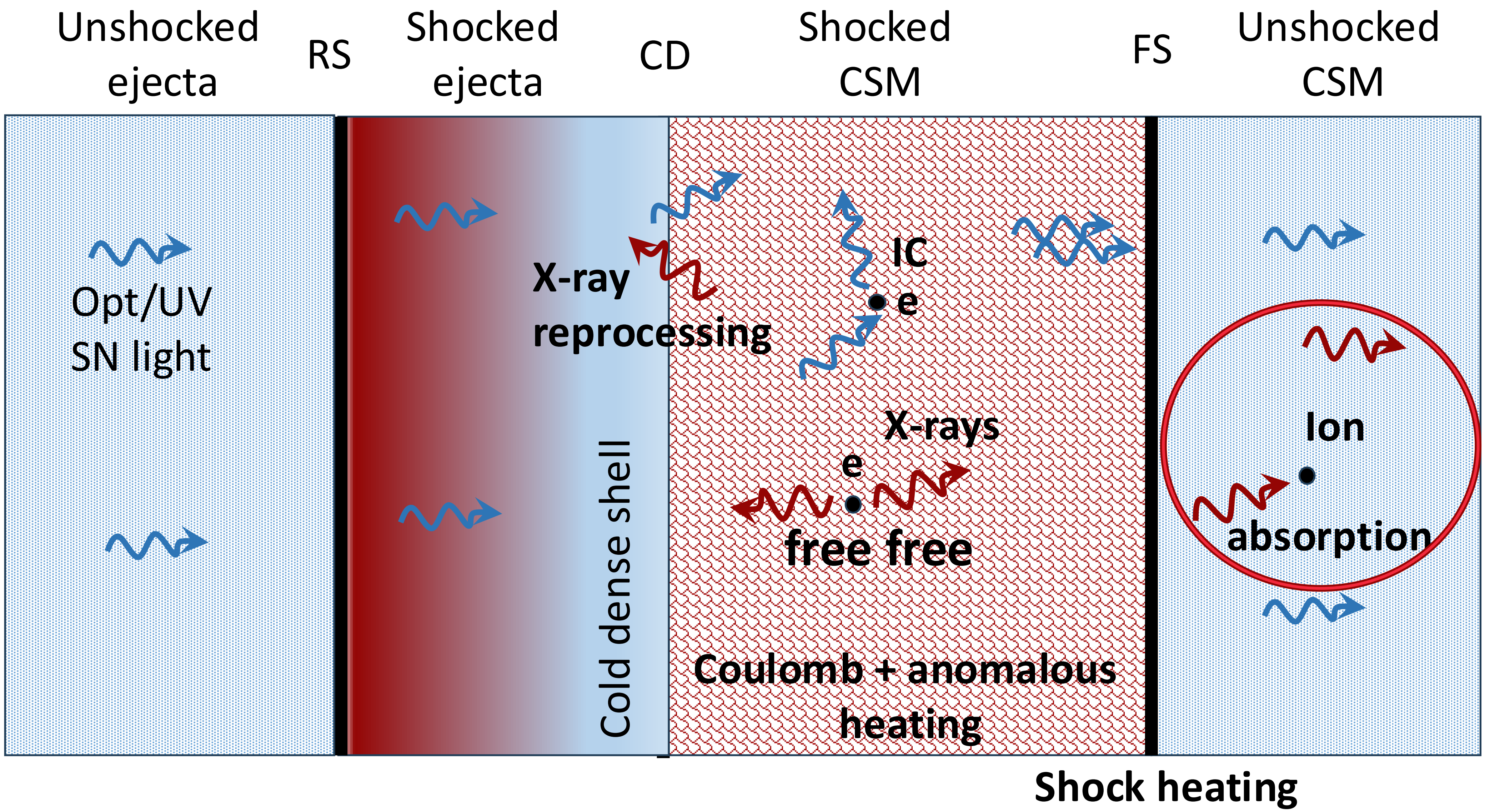
- A diffusion-dominated breakout:
  - Exponential rise
  - Red to blue evolution

- SN2023ixf
  - Diffusion-dominated breakout
  - Width of layer with $\tau \approx c/v$: $\Delta \approx 5 \times 10^{13} cm \sim R_{bo}$
  - Most likely: breakout from an extended envelope, not a wind

X-ray Transmission Through Gas with Moderate Thomson Optical Depth

Govreen-Segal, Nakar & Quataert 2026

Goal: A simple criterion to find when the gas can be modeled as fully neutral, when it can be modeled as fully ionized, and when a detailed modeling is needed


Unshocked ejecta
RS
Shocked ejecta
CD
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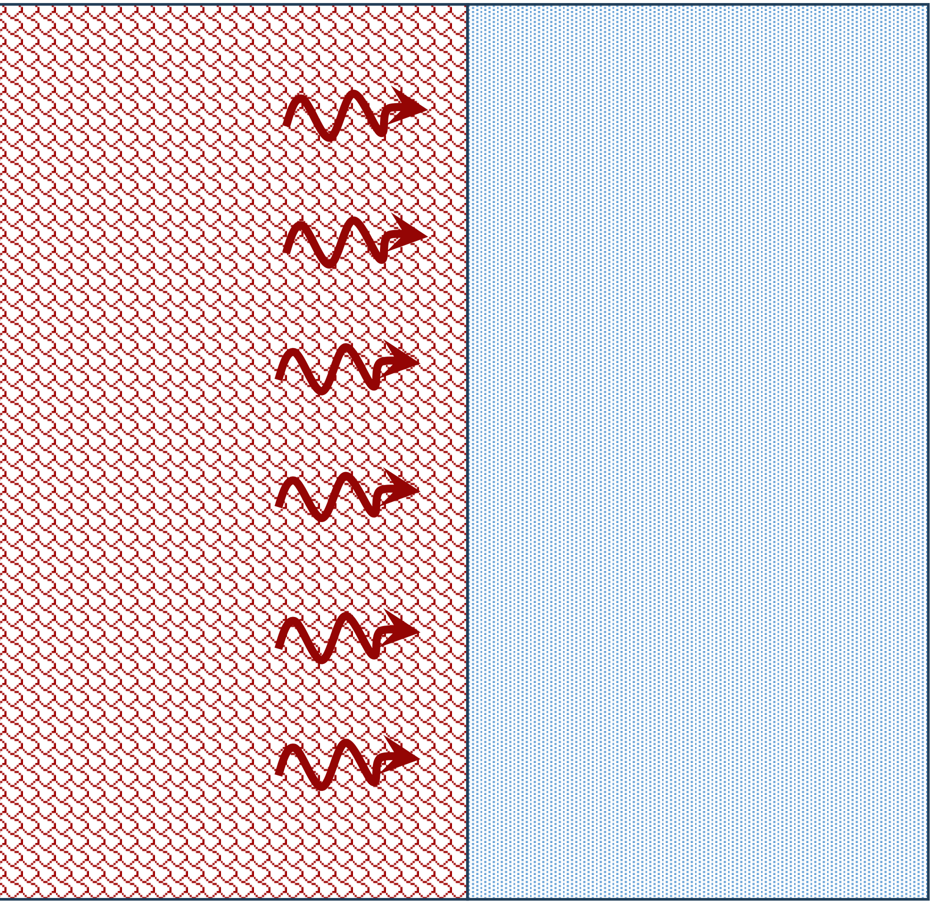
FS
Unshocked CSM
Opt/UV SN light
X-ray reprocessing
Cold dense shell
IC
e
X-rays
e
free free
Coulomb + anomalous heating
Ion
absorption
Shock heating

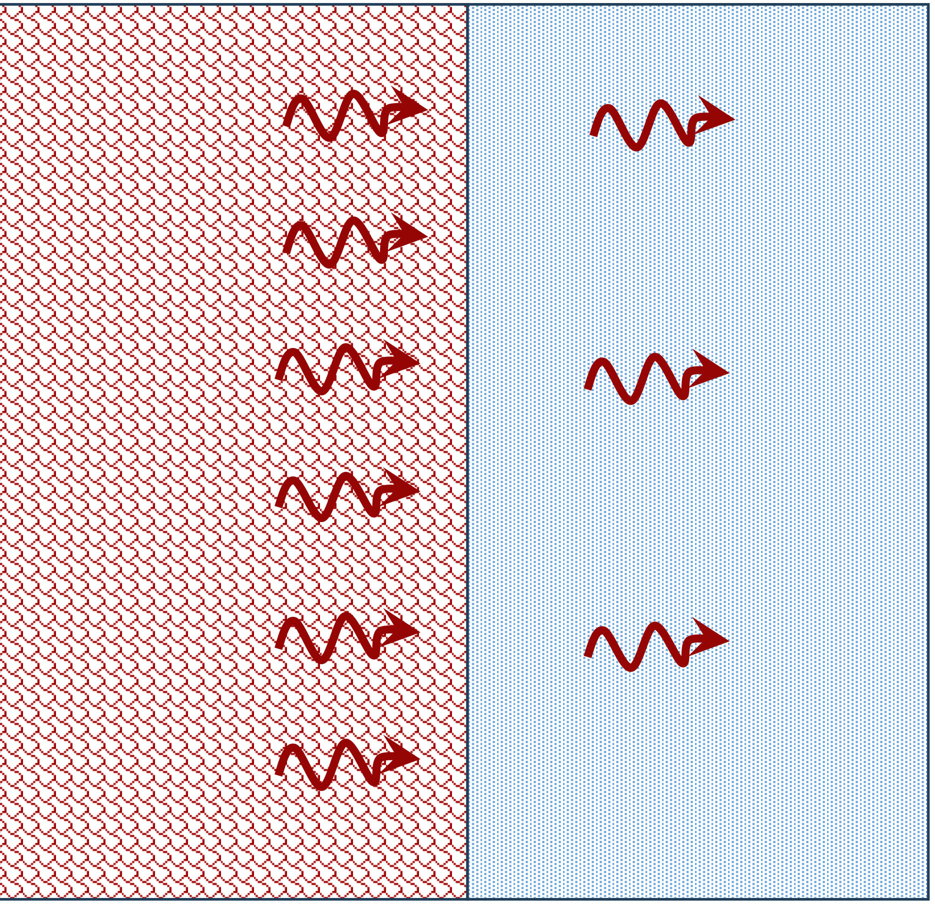
Ionization parameter: $\xi \approx \frac{\dot{N}(1keV)}{4\pi n_e r^2 c} \approx 0.2 \frac{\nu L_\nu(1keV)}{10^{40}\ erg\ s^{-1}} \left(\frac{\Sigma}{10^{24} cm^{-2}}\right)^{-1} \left(\frac{r}{10^{14}\ cm}\right)^{-1}$



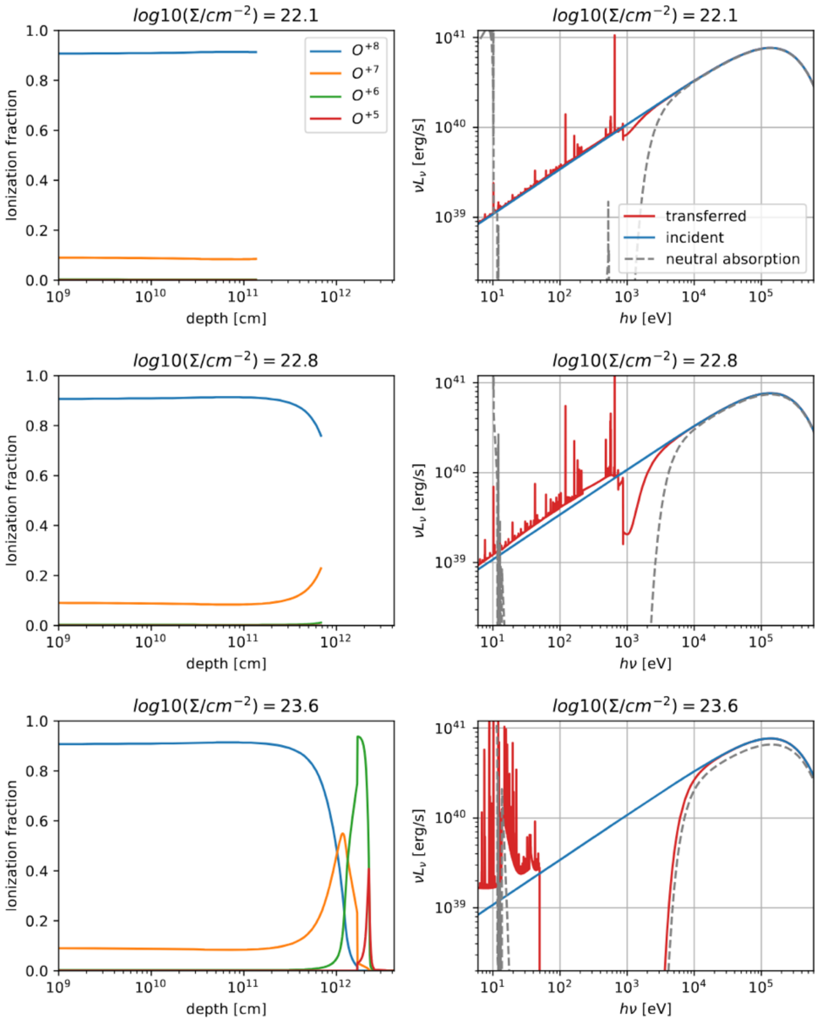
$\xi < \xi_c$ ➔ effectivly neutral

$\xi_c \approx 0.15$

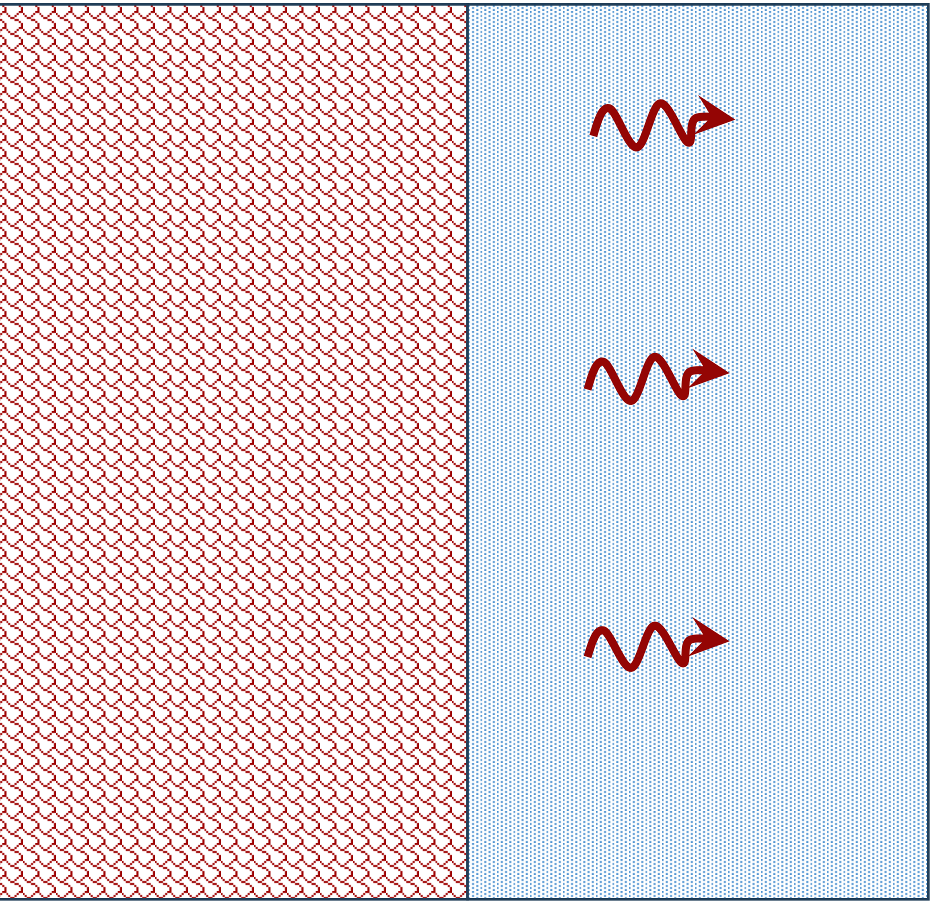
Ionization parameter: $\xi \approx \frac{\dot{N}(1keV)}{4\pi n_e r^2 c} \approx 0.2 \frac{\nu L_\nu(1keV)}{10^{40}\ erg\ s^{-1}} \left(\frac{\Sigma}{10^{24} cm^{-2}}\right)^{-1} \left(\frac{r}{10^{14}\ cm}\right)^{-1}$



$\xi > \xi_c$



Ionization parameter: $\xi \approx \frac{\dot{N}(1keV)}{4\pi n_e r^2 c} \approx 0.2\,\frac{\nu L_\nu(1keV)}{10^{40}\ erg\ s^{-1}}\left(\frac{\Sigma}{10^{24} cm^{-2}}\right)^{-1}\left(\frac{r}{10^{14}\ cm}\right)^{-1}$

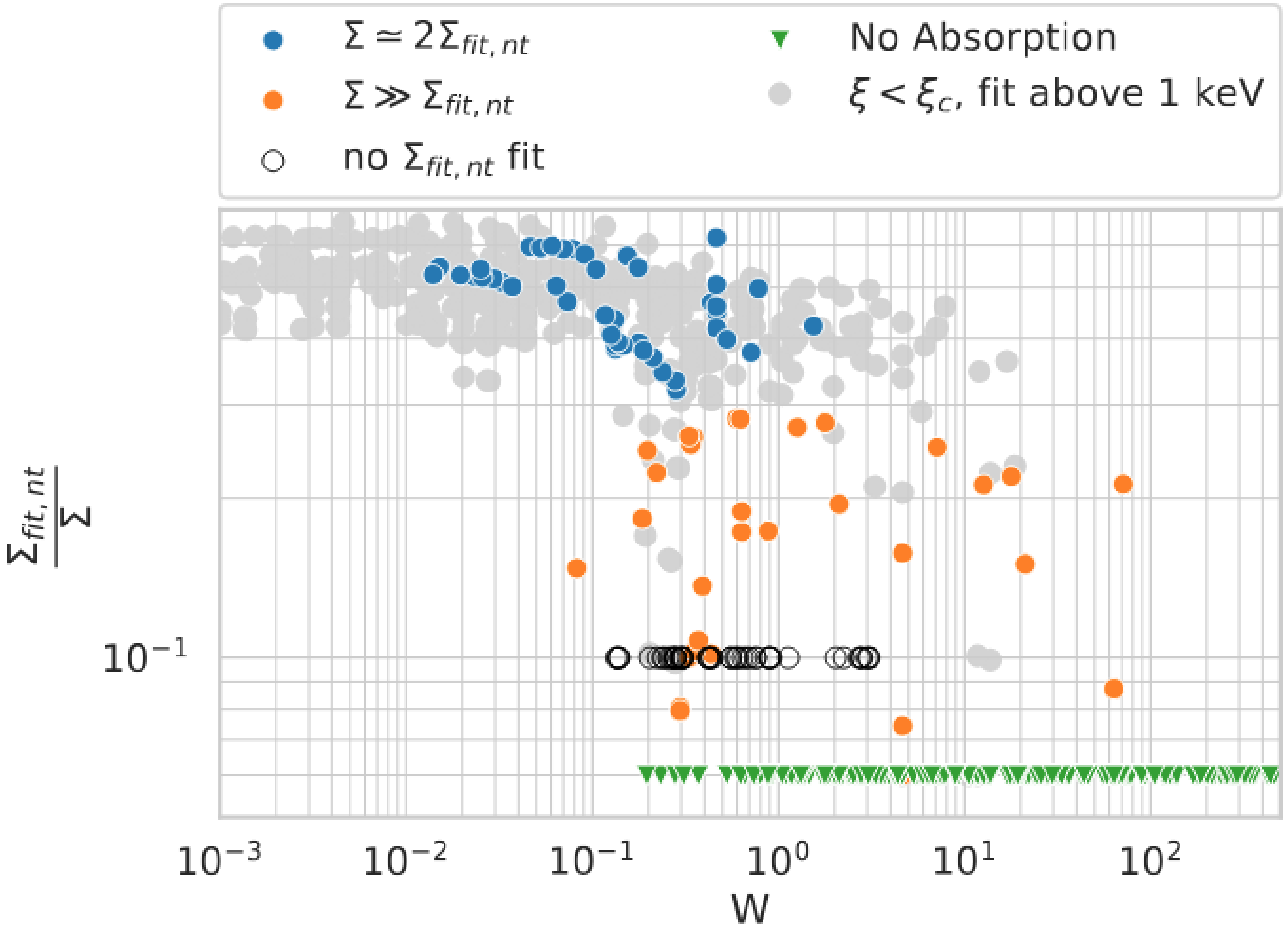


$$W \equiv \frac{\xi^{\beta}}{\Sigma\sigma_{eff}}\frac{z_\odot}{Z}$$

σ_{eff} & β calibrated numerically

W^{-1} – effective optical depth to X-rays

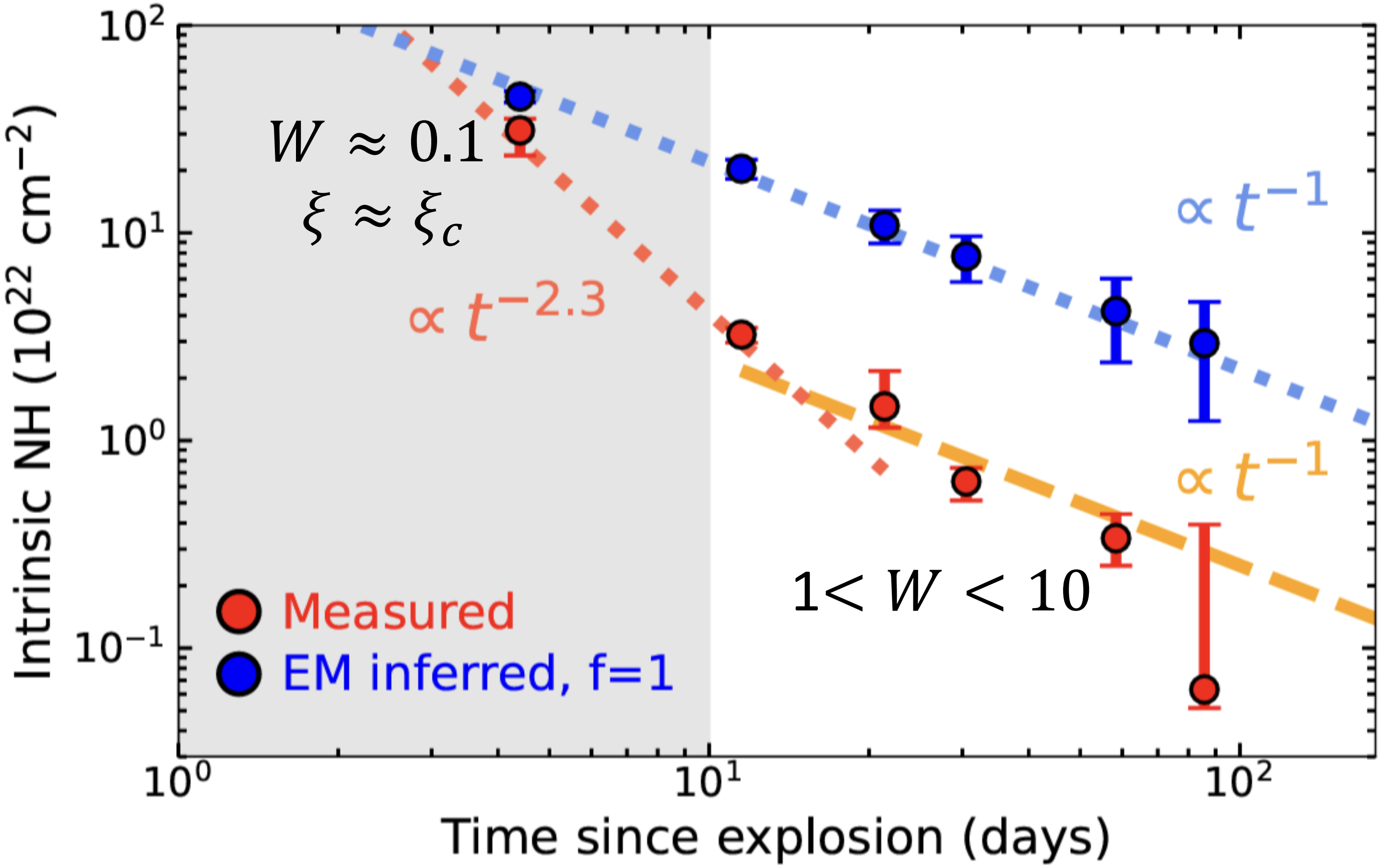
$$\xi > \xi_c \quad \rightarrow W \begin{cases} \gg 10 & fully\ ionized \\ 0.1 - 10 & detailed\ modeling \\ \ll 0.1 & effectively\ neutral \end{cases}$$



$$W \approx 1.7\xi \left(\frac{\Sigma}{10^{24}\mathrm{cm}^{-2}}\right)^{-1} \left(\frac{Z}{Z_\odot}\right)^{-1}$$

$$\approx 0.3 \frac{\nu L_\nu(1\ \mathrm{keV})}{10^{40}\ \mathrm{erg/s}} \left(\frac{r}{10^{14}}\right)^{-3} \left(\frac{n}{10^{10}}\right)^{-2} \left(\frac{Z}{Z_\odot}\right)^{-1},$$

SN 2023ixf X-rays



Nayana et al. 2024

A shocked aspherical Cow