Circumstellar Medium of Supernovae as New Probes for Feebly-interacting Particles

Yu Cheng

University of Chicago / KAIST

2026 Phenomenology Symposium

Based on: *Circumstellar Medium of Supernovae as New Probes for Feebly-interacting Particles [arXiv: 2603.09615]*
by Y.C, Chui-Fan Kong ,Yen-Hsun Lin, Meng-Ru Wu , and Seokhoon Yun

Outline

1. Introduction:

- Brief overview of core-collapse supernovae (CCSNe)
- SN constraint on new physics (SN 1987A γ)

2. Overview on Circumstellar Medium (CSM) of SN

- Cold gas Envelope of the Progenitor star.

3. New physics/constraint from CSM

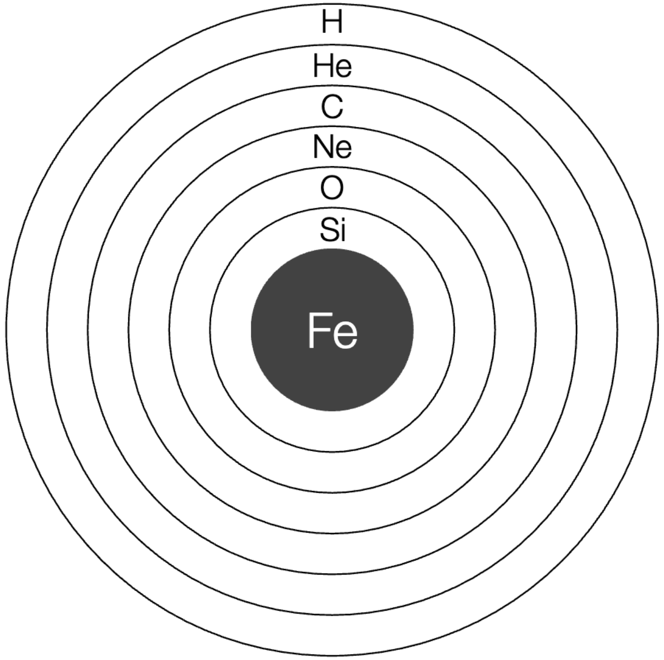
- Most stringent constraints on FIPs in the MeV mass range.

Yu Cheng [chengyu059@uchicago.edu]

Core-collapse supernovae (CCSNe)

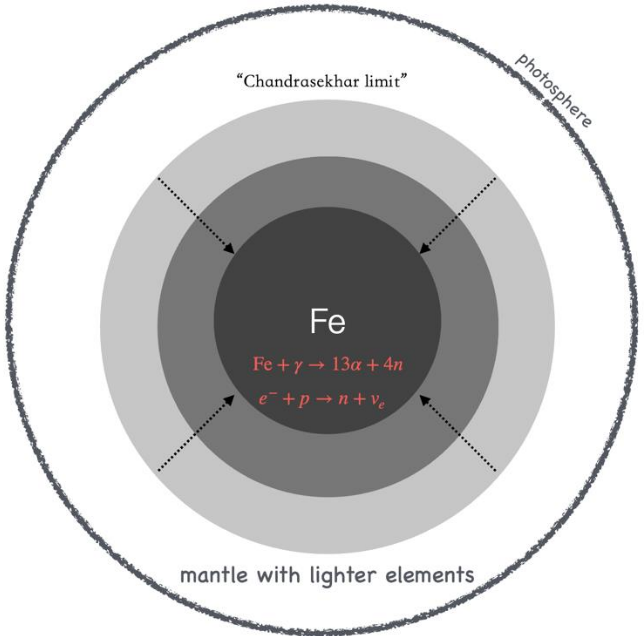
Red supergiant: $M_\star = (8 \sim 30)\, M_\odot$

$t < 0$



Onion-like layers of a massive, evolved star just before core collapse.

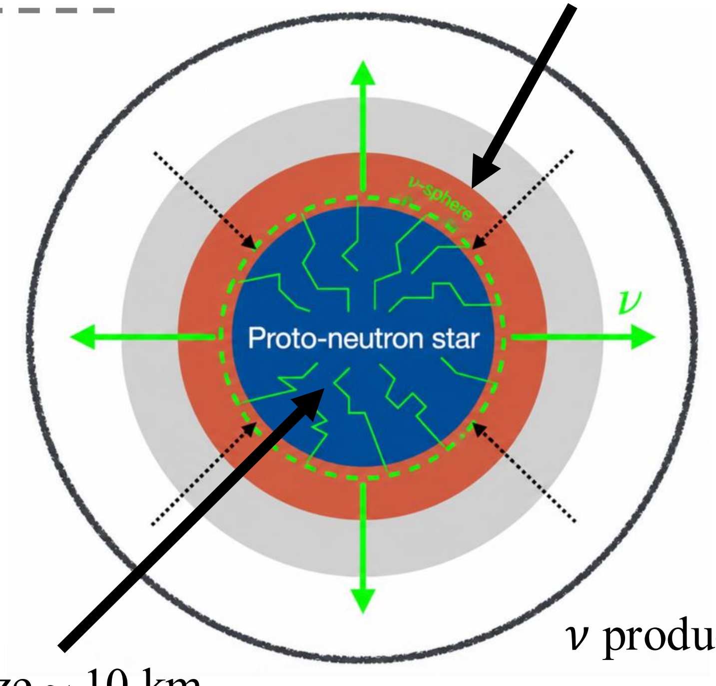
$t = 0$ Onset of Iron Core-Collapse



$\rho \to \rho_{sat} \sim 10^{14}\ g/\mathrm{cm}^3$

$t \approx 1\mathrm{sec}$

Bounce shock wave



ν produced

Core size ~ 10 km

Temperature ~ 40 MeV

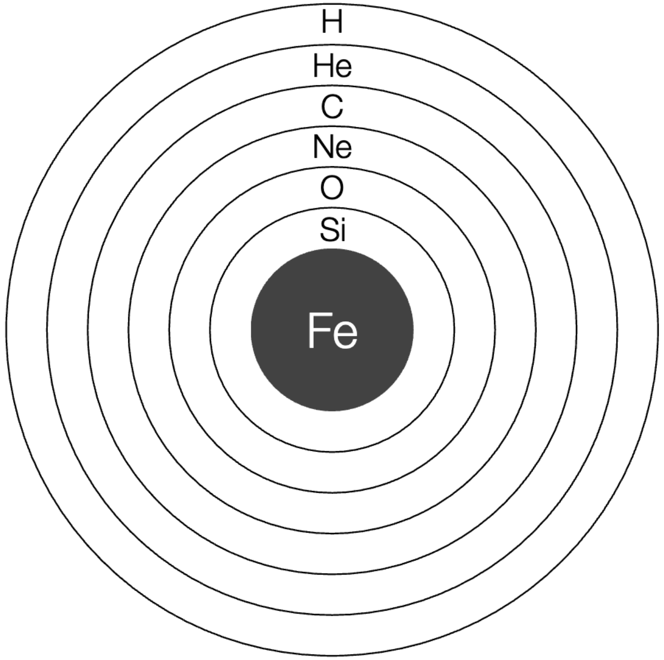
$L_\nu \sim 10^{52} \mathrm{erg\,s^{-1}}$

Core-collapse supernovae (CCSNe)

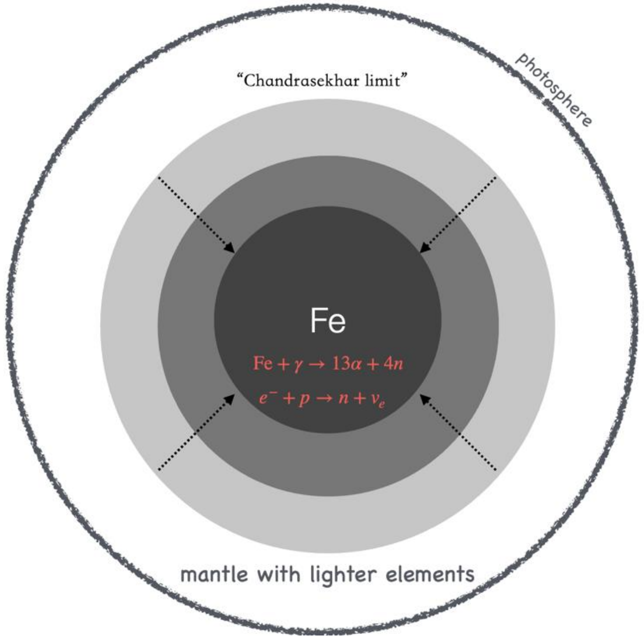
Red supergiant: $M_\star = (8 \sim 30)\ M_\odot$

New particle X (axion, dark photon)
$m_X \approx \mathcal{O}(1-100)\mathrm{MeV}$

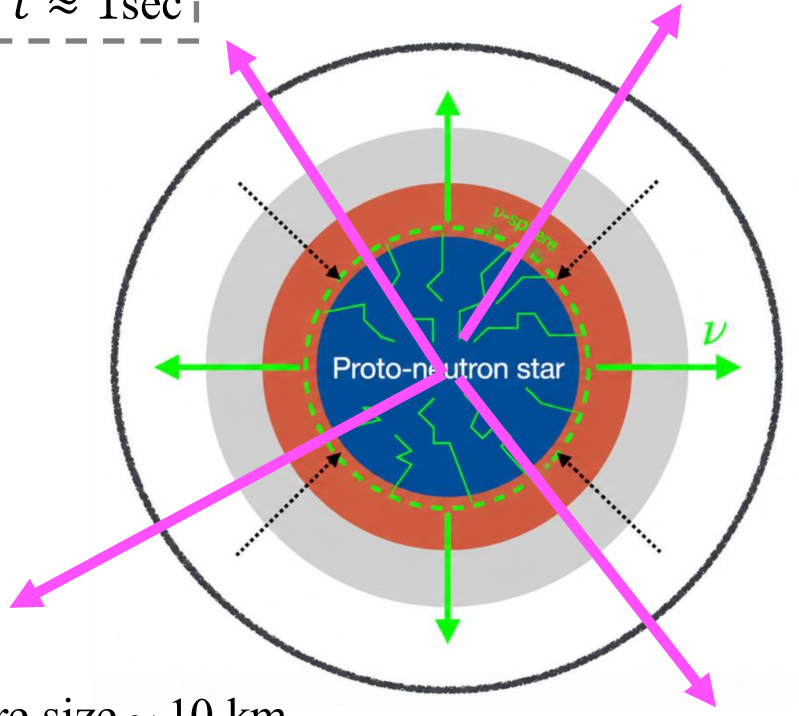
$t < 0$



$t = 0$ Onset of Iron Core-Collapse



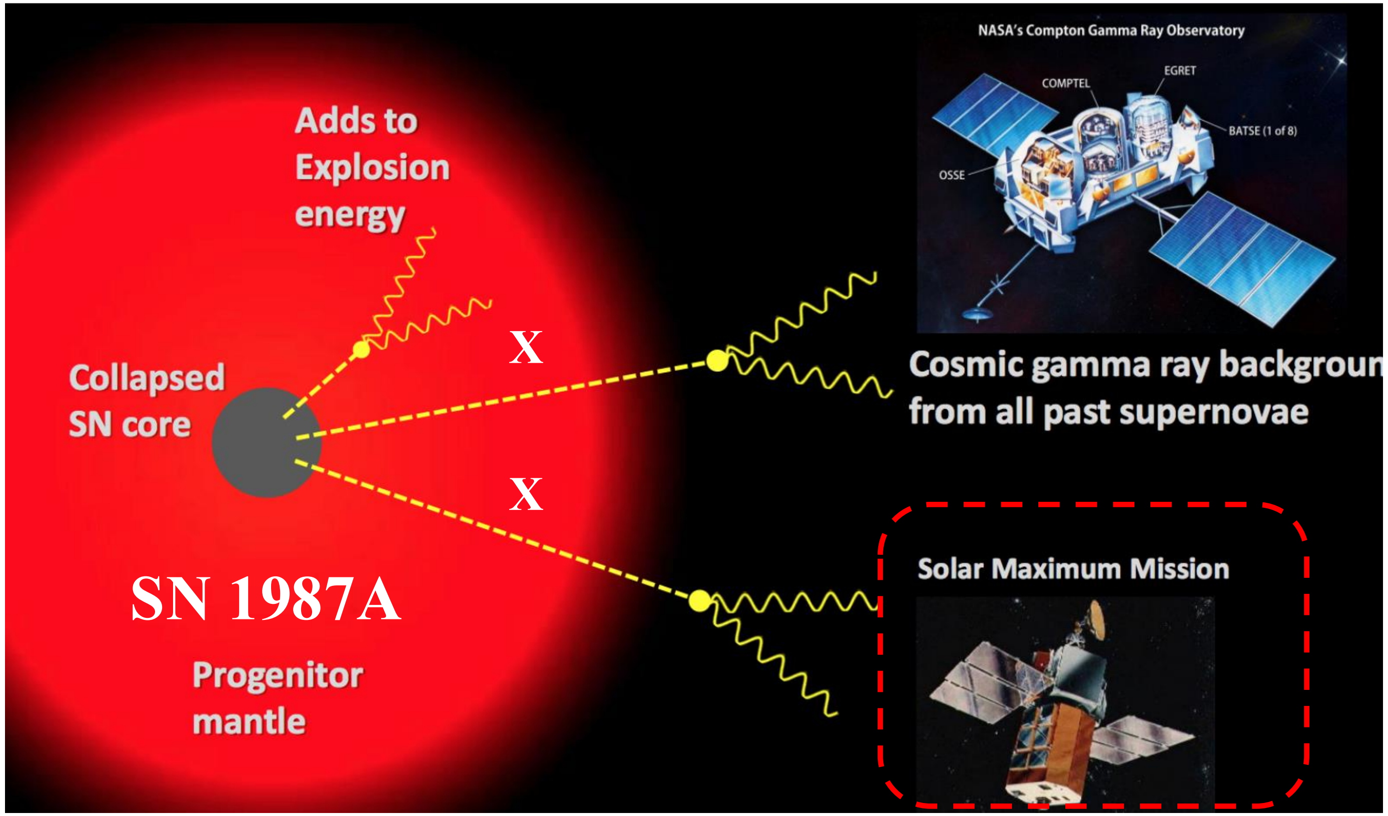
$t \approx 1\mathrm{sec}$



Core size ~ 10 km
Temperature ~ 40 MeV

Onion-like layers of a massive, evolved star just before core collapse.

SNe bound on *Feebly-interacting Particles* (FIPs)



The neutrino signal arrives first and lasts for about 10 seconds.

Consider X to be dark photon

$$\mathcal{L} = \varepsilon e A'_\mu \bar{\psi} \gamma^\mu \psi$$

ψ is the SM fermions.

For heavy DP, $m_{A'} > 2m_e \sim 1\text{MeV}$

$$A' \to e^+ e^- \longrightarrow n\gamma$$

Excess on γ − ray observations

For DP mass $m_{A'} < 2m_e$,

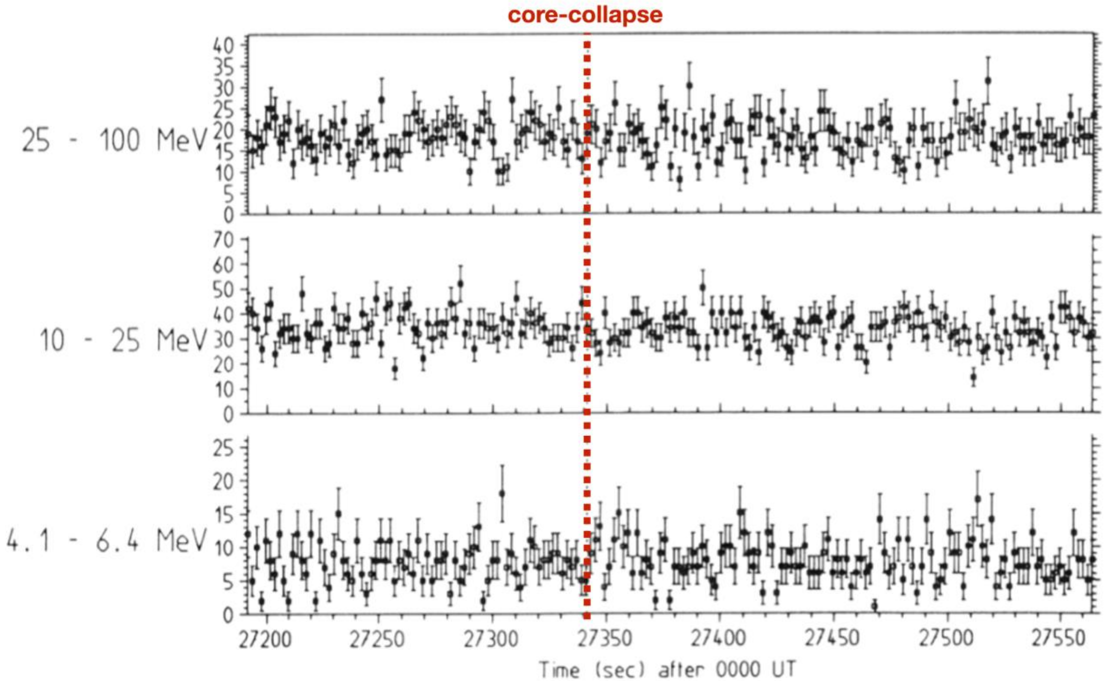
$A' \to 3\gamma$ long lived

Additional contribution to γ − ray background

Yu Cheng [chengyu059@uchicago.edu]

Non-detection limit

Even rates measured in the Gamma Ray Spectrometer of the Solar Maximum Mission



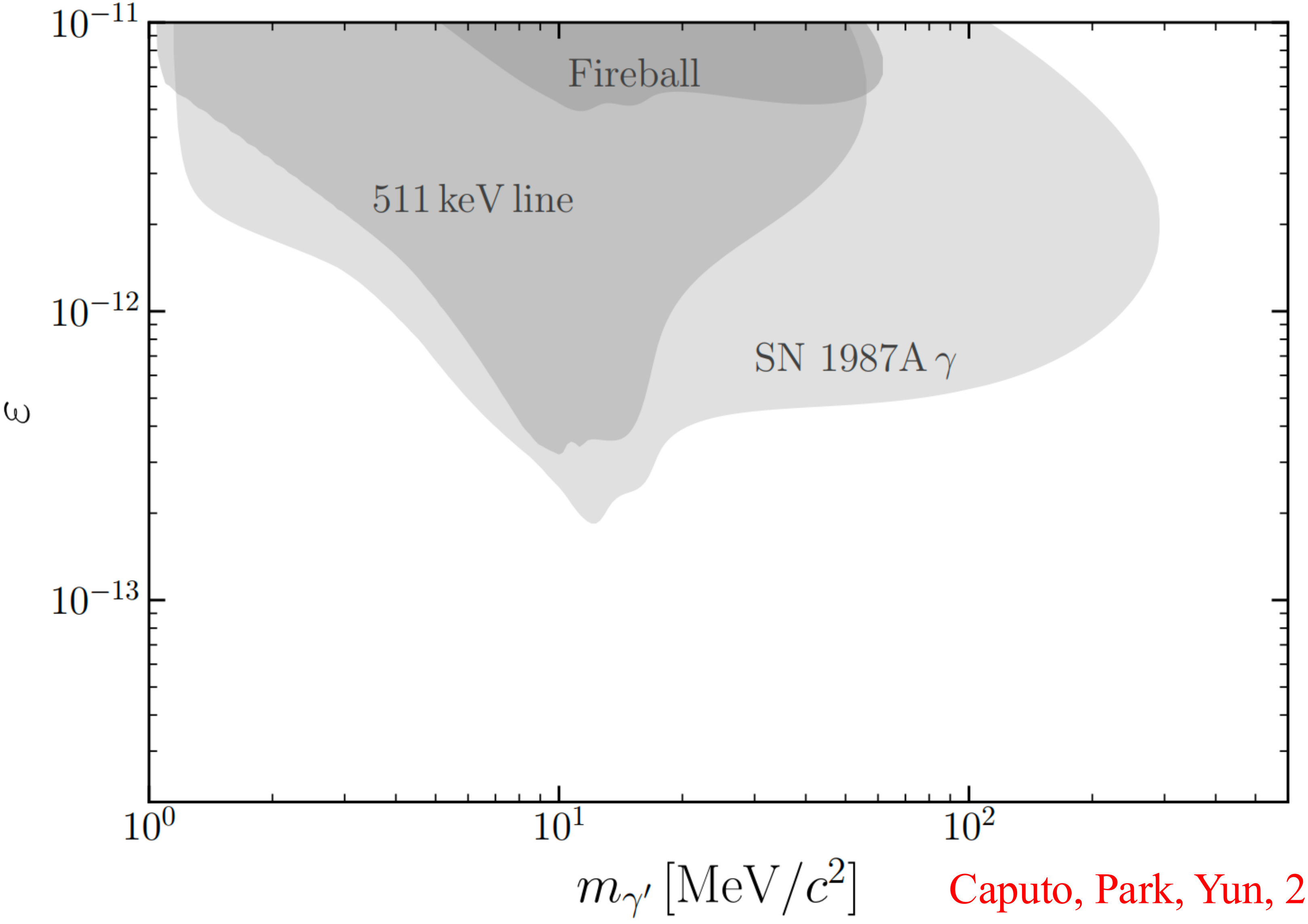
$\Delta t \sim 200\,\mathrm{sec}$

leading to upper bounds on the γ-ray fluence

$$\begin{aligned} \mathcal{F}_\gamma &< 6.11\,\mathrm{cm}^{-2} && [4.1\text{-}6.4\,\mathrm{MeV}]\,, \\ \mathcal{F}_\gamma &< 1.48\,\mathrm{cm}^{-2} && [10\text{-}25\,\mathrm{MeV}]\,, \\ \mathcal{F}_\gamma &< 1.84\,\mathrm{cm}^{-2} && [25\text{-}100\,\mathrm{MeV}]\,. \end{aligned}$$

No excess was detected in any energy range in Solar Maximum Mission observations.

SN 1987A γ Constraint



Caputo, Park, Yun, 2025

Stringent constraint for a long time

Limit
$\epsilon \sim (10^{-12} - 10^{-13})$

For
$m_{A'}$
$\sim (1 - 300)$ MeV

Our work:

Look into more details about SN Circumstellar Medium (CSM)

More stringent constraint!

Overview on CSM

- Circumstellar Medium (CSM)

SN Progenitor may be wildly unstable long before explosion

Mass Loss from Progenitor ➡ CSM

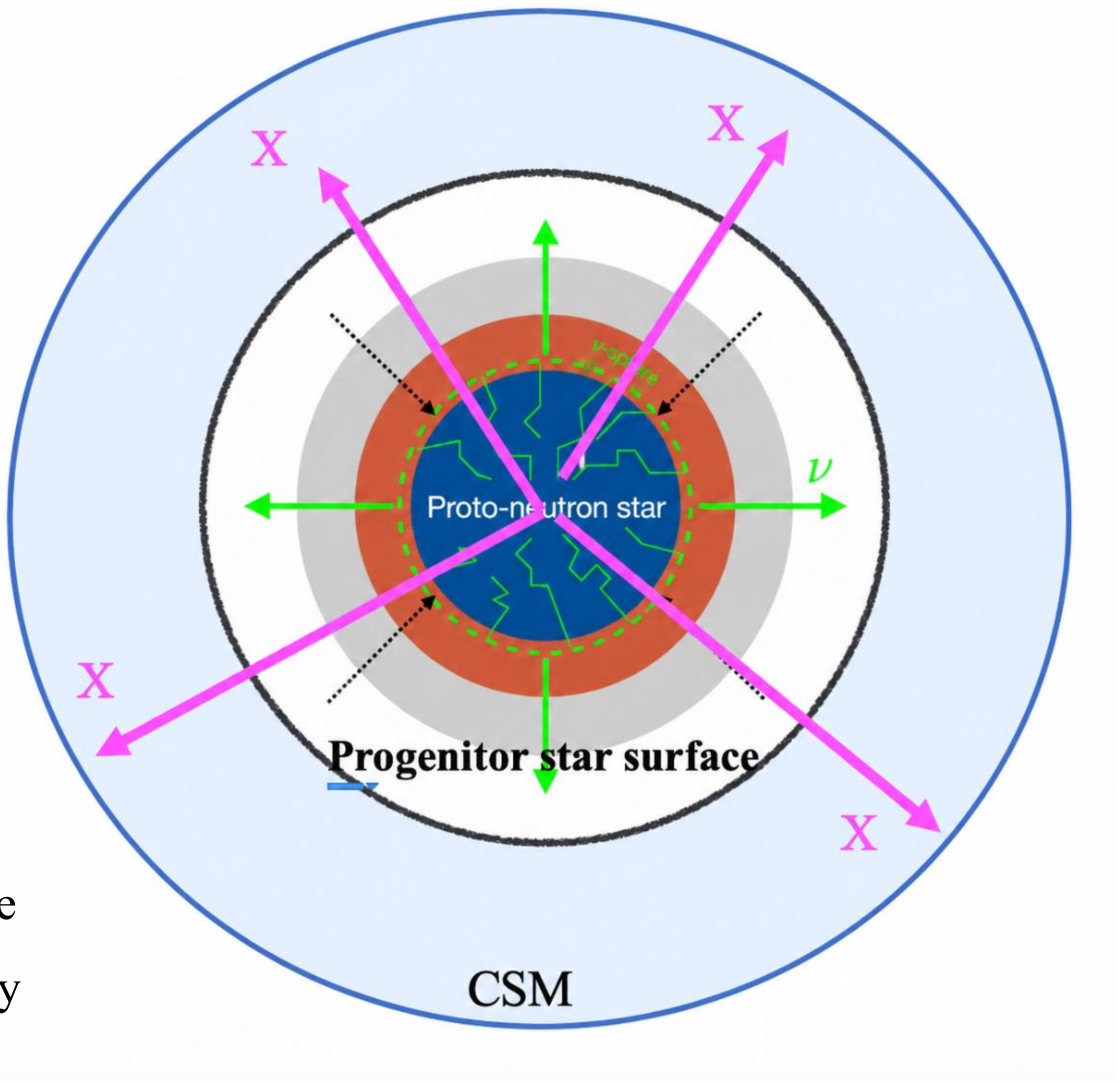
- Simplest density profile:
  Conservation of mass and isotropic

$$\rho(r) = \dot{M}/(4\pi r^2 v_w),$$

$\dot{M}$:Mass loss rate

v_w: Wind velocity

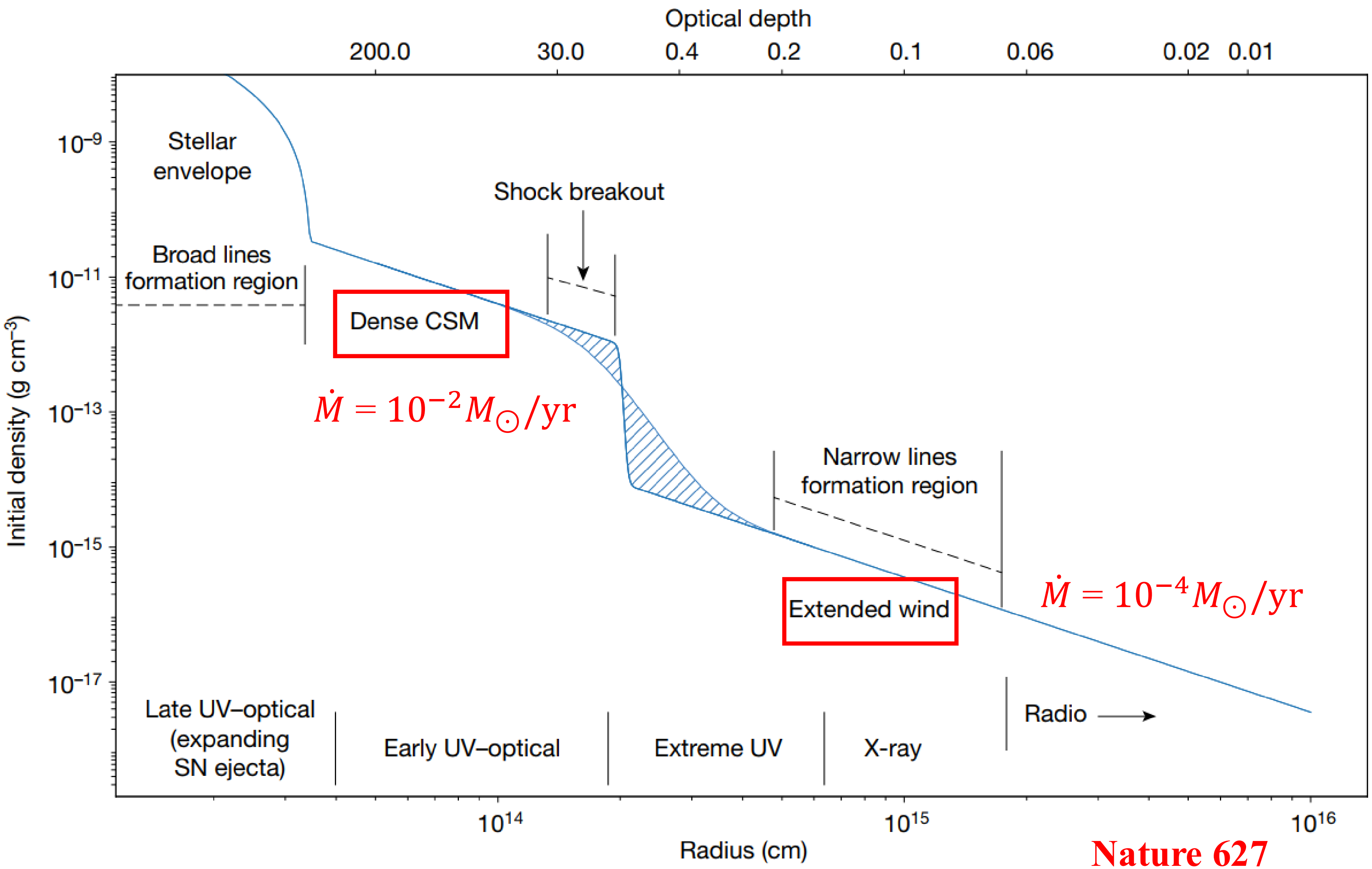
- CSM temperature is usual low, $T \ll 3000\text{K}$
  Red supergiant can not heat up CSM



Envelope of the Progenitor star

CSM for SN 2023ixf (Type II-P)

Progenitor Star : red supergiants



$\dot{M} = 10^{-2} M_\odot/\mathrm{yr}$

$\dot{M} = 10^{-4} M_\odot/\mathrm{yr}$

$$\rho(r) = \dot{M}/(4\pi r^2 v_w)$$

v_w = 30-50 km/s

Typical radius of red supergiant

$R_\star \sim 10^{13} cm$

Typical radius of dense CSM

$R_{\mathrm{CSM}} \sim (10^{14})\mathrm{cm}$

Nature 627 (Zimmerman 2024)

CSM as a probe of *Feebly-interacting Particles* (FIPs)

First few seconds, T~ 40 MeV

1. FIPs produce in PNS
2. FIPs free stream out from star surface

$$v_{\mathrm{FIPs}} \sim c \gg v_s \approx (8 \sim 10) \times 10^3 \mathrm{km/s}$$

FIPs arrive earlier than shock wave.

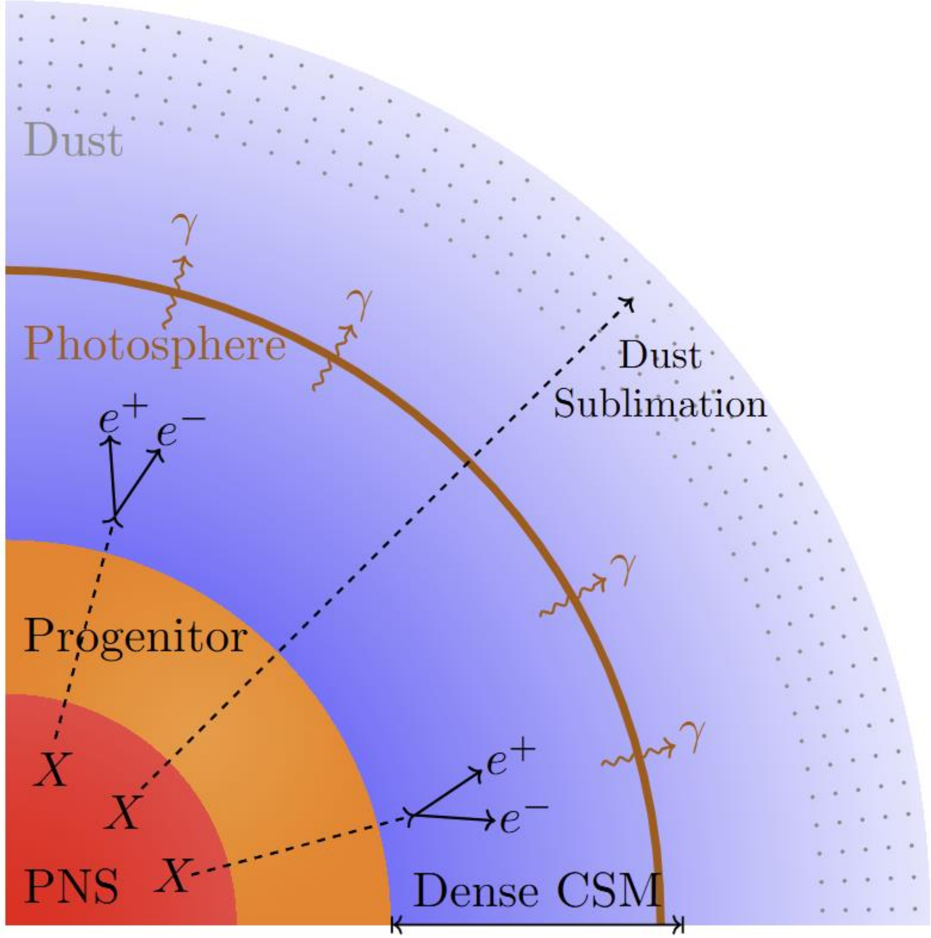
3. Decay inside CSM for some parameter space

$$\Gamma_{A' \to e^+ e^-} = \frac{1}{3} \alpha \epsilon^2 m_{A'} \sqrt{1 - \frac{4 m_e^2}{m_{A'}^2}} \left(1 + \frac{2 m_e^2}{m_{A'}^2}\right).$$

$$L_d = \frac{k}{m_{A'}} \Gamma_{A'}^{-1}$$

$m_{A'} = 100\mathrm{MeV}, |k| = 100\mathrm{MeV}, \epsilon = 10^{-12}$

$L_d \sim 10^{14}$ cm Typical CSM radius



4. Decay product stop inside CSM, Energy deposits inside CSM.
5. Lighten the CSM before shock arrive.

Yu Cheng [chengyu059@uchicago.edu]

Lighten the CSM by FIPs

Dense CSM region is Optical thick.

Photon scatter multiple times and will form local thermal equilibrium (LTE).

$$\frac{dQ}{dr}\frac{\bar{\eta}}{4\pi r^2} = u_{\rm gas} + I_{\rm ion} + u_{\rm rad},$$

$\bar{\eta}$: energy deposition efficiency

$u_{\rm gas}$: internal energy density of ideal gas,

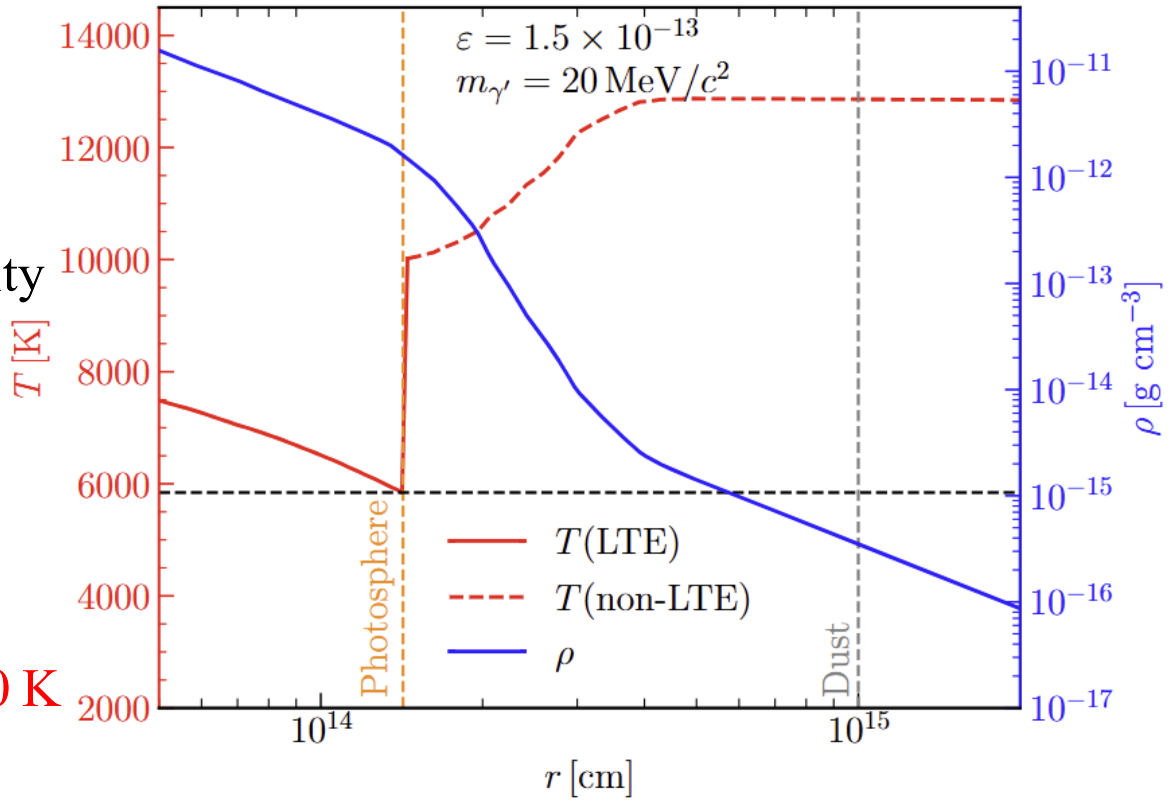
$$u_{\rm gas} = (3/2)(n+n_e)k_B T$$ n number density

$u_{\rm rad}$: internal energy density of radiation, $4\sigma_{\rm SB}T^4/c$

$\sigma_{\rm SB}$ Stefan-Boltzmann constant

$I_{\rm ion}$: ionization energy density

- Typical temperature of sphere of red supergiant, T~ 3000 K



Non-detections of excessive early luminosity

- CSM Temperature ➡ Emit photons at photosphere

Blackbody radiation: $L_{\mathrm{BB}} \simeq 4\pi r_{\mathrm{ph}}^2 \sigma_{\mathrm{SB}} T_{\mathrm{ph}}^4$

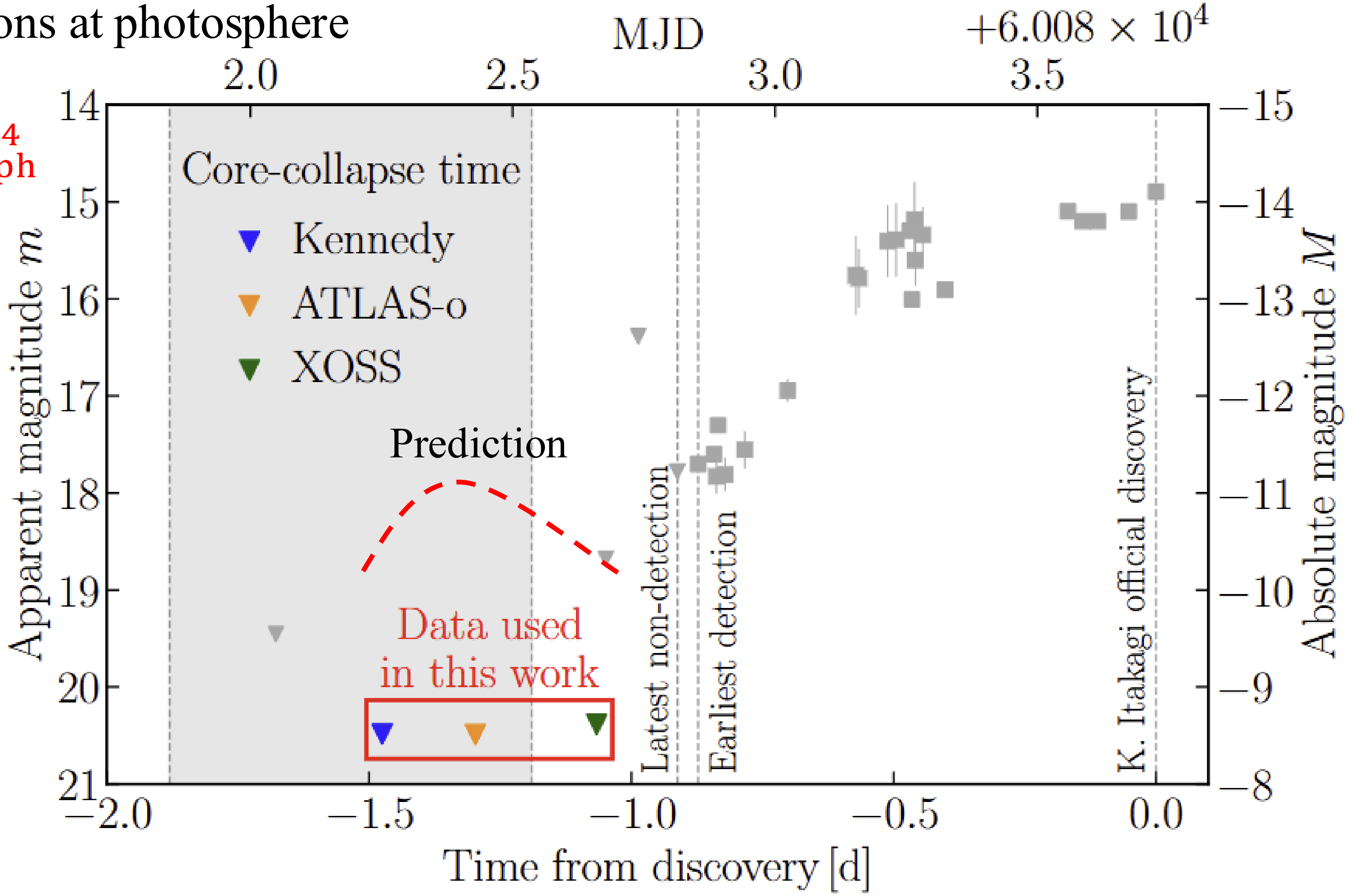
- Data: $L \lesssim 8.16 \times 10^{38} \mathrm{erg\,s}^{-1}$.

  luminosity within 400-900 nm

- Conversative constraint:

$$\iota(T_{\mathrm{ph}}) L_{\mathrm{BB}}(\varepsilon, m_{\gamma'}) \leq 10L = 8 \times 10^{39} \mathrm{erg\,s}^{-1}$$

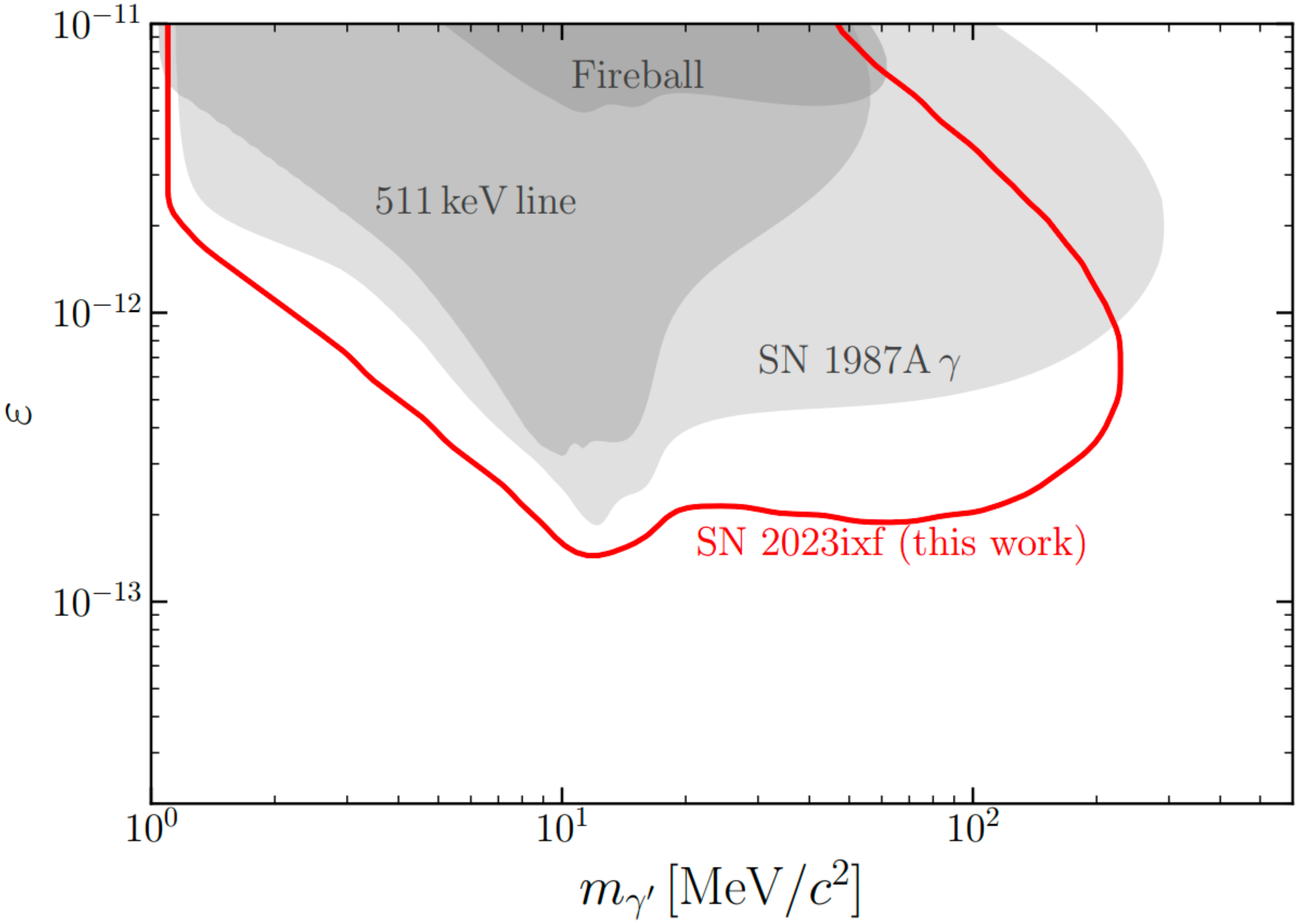
$\iota(T_{\mathrm{ph}})$ is the normalization factor



No excessive optical emission

Yu Cheng [chengyu059@uchicago.edu]

CSM Constraint on FIPs



SN model: SHFo-s18.8

- Most stringent constraint
  Especially at high $m_{A'}$

Other constraint: fireball, 511 keV line

If the SN used to derive the constraint has CSM, the constraint should be carefully reexamined

Summary & Take home messages

- Core-collapse supernovae are powerful probe for feebly-interacting particles.

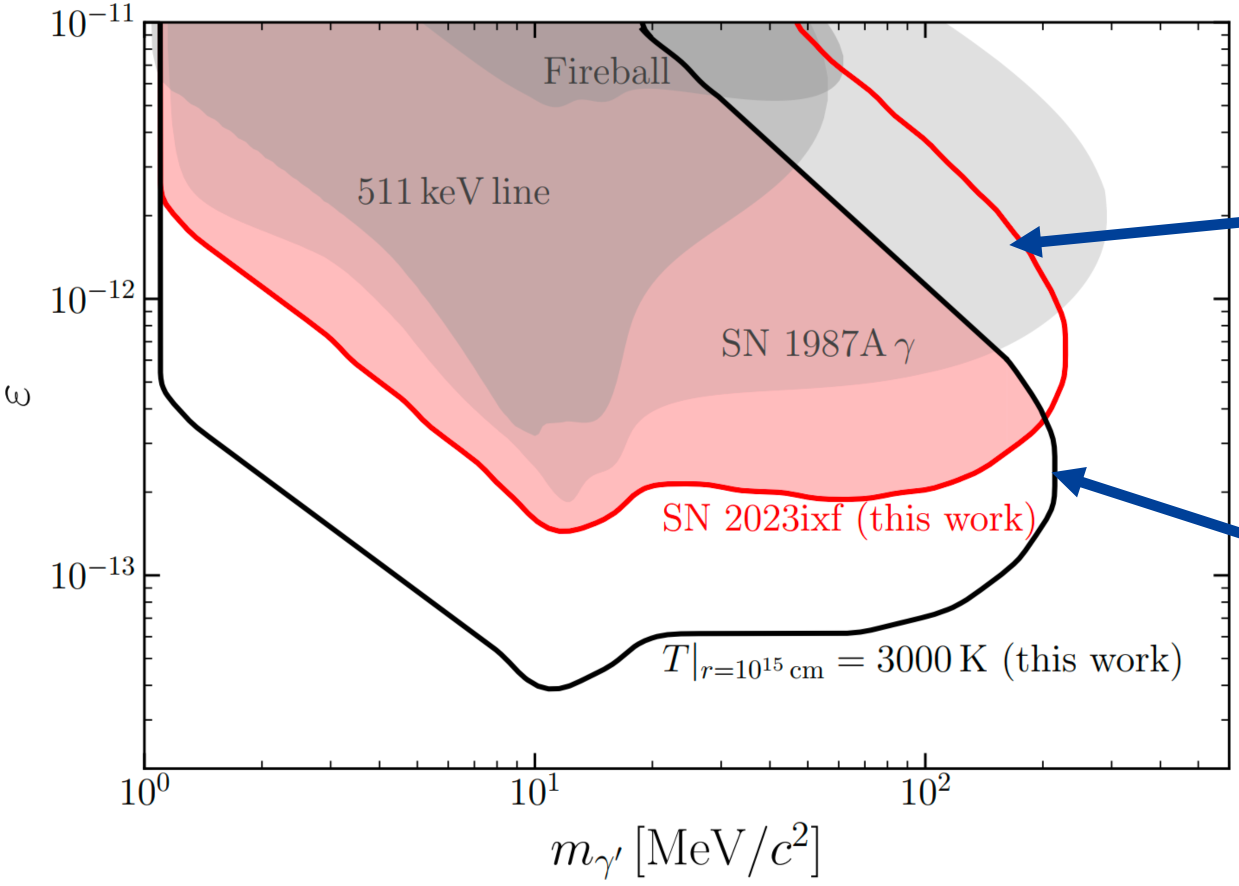
- For a substantial fraction of SNe, the existence of CSM must be taken into account when deriving constraints.

- Non-detection limit from SN 2023ixf observations
  Most stringent constraint

- Easily extended to other exotic particles, such as axions and right-handed neutrinos.

Dust (molecules, silicates, carbon-rich grains)

A lot of dust at $r \sim 10^{15}$cm → BB emission can be reprocessed into the infrared,



DP decay inside region so dust may affect our constraint

Heating from FIPs decay can eliminate the dust.

Energy deposition in CSM

- Consider FIPs to be dark photon (DP), for $m_{\gamma'} > 2\,m_e$, $\gamma' \to e^+ e^-$

  Decay length for DP with momentum k: $L_d = \frac{k}{m_{\gamma'}} \Gamma_{\gamma'}^{-1}$

- Inside Dense CSM, $\delta r_{\text{stop}} / \Delta r << 1$

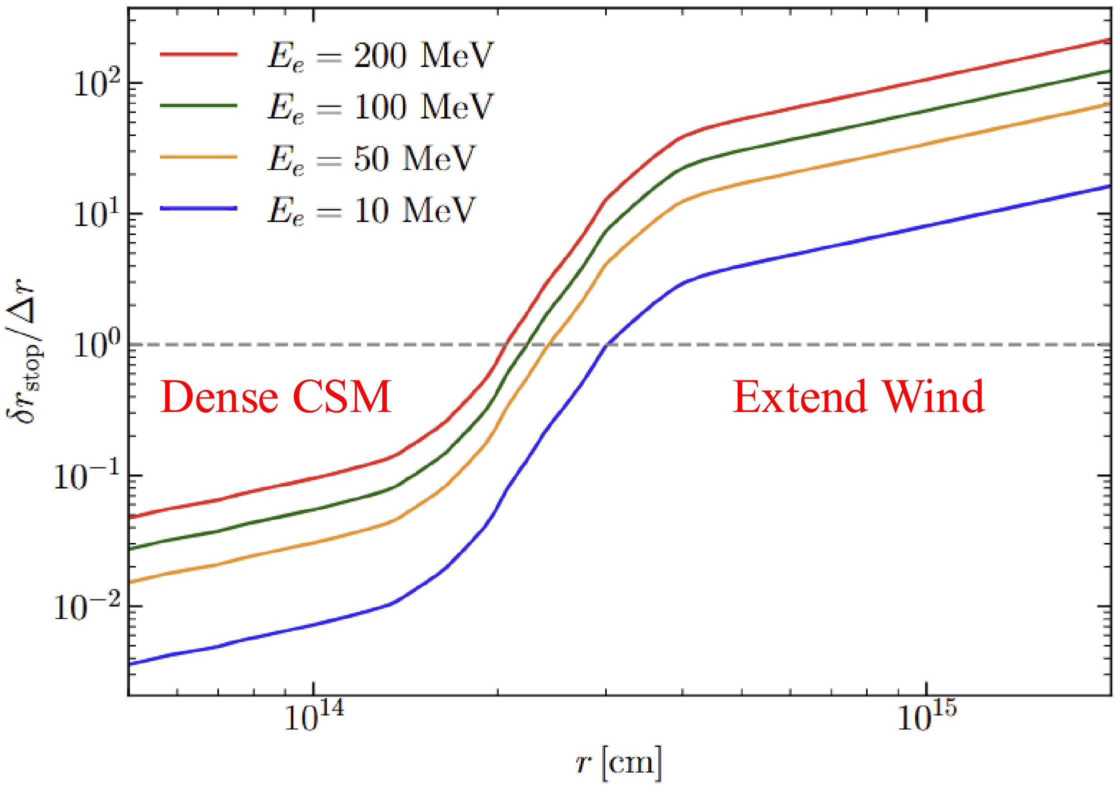
  Almost all electron stops inside the dense CSM

  Energy deposits locally with deposition rate $\bar{\eta} \approx 1$

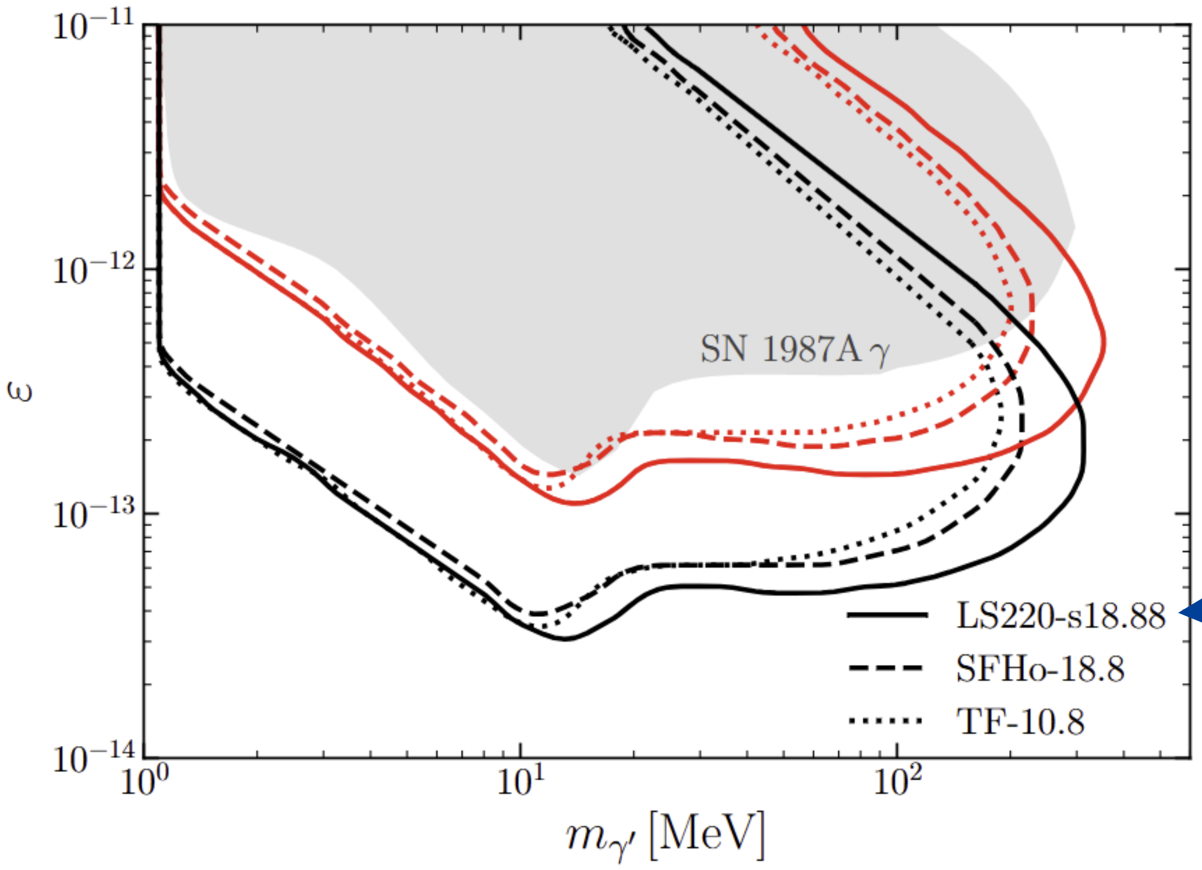
- Extend Wind, $\bar{\eta} < 1$

- Energy injection per unit radius

$$\frac{dQ}{dr} = \int dk \frac{1}{L_d} \frac{d\mathcal{N}_{\gamma'}}{dk} e^{-r/L_d} \sum_i \int dE_i E_i \frac{dN_i}{dE_i},$$



Different SN models



Progenitor mass

FIG. S2. The derived CSM-based constraints using different SN models: LS220-s18.88 (solid line), SFHo-18.8 (dashed line) and TF-10.8 (dotted line).

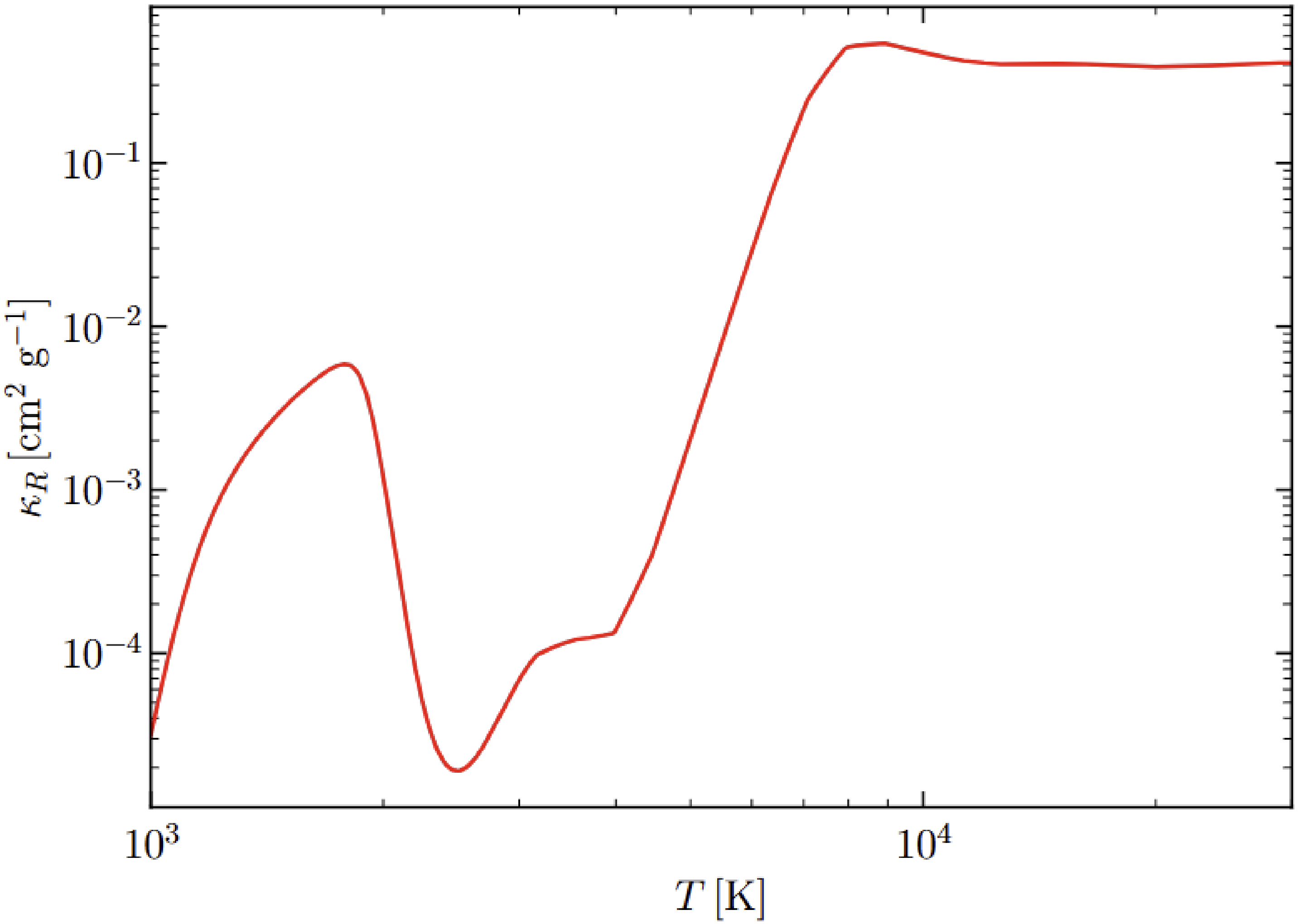
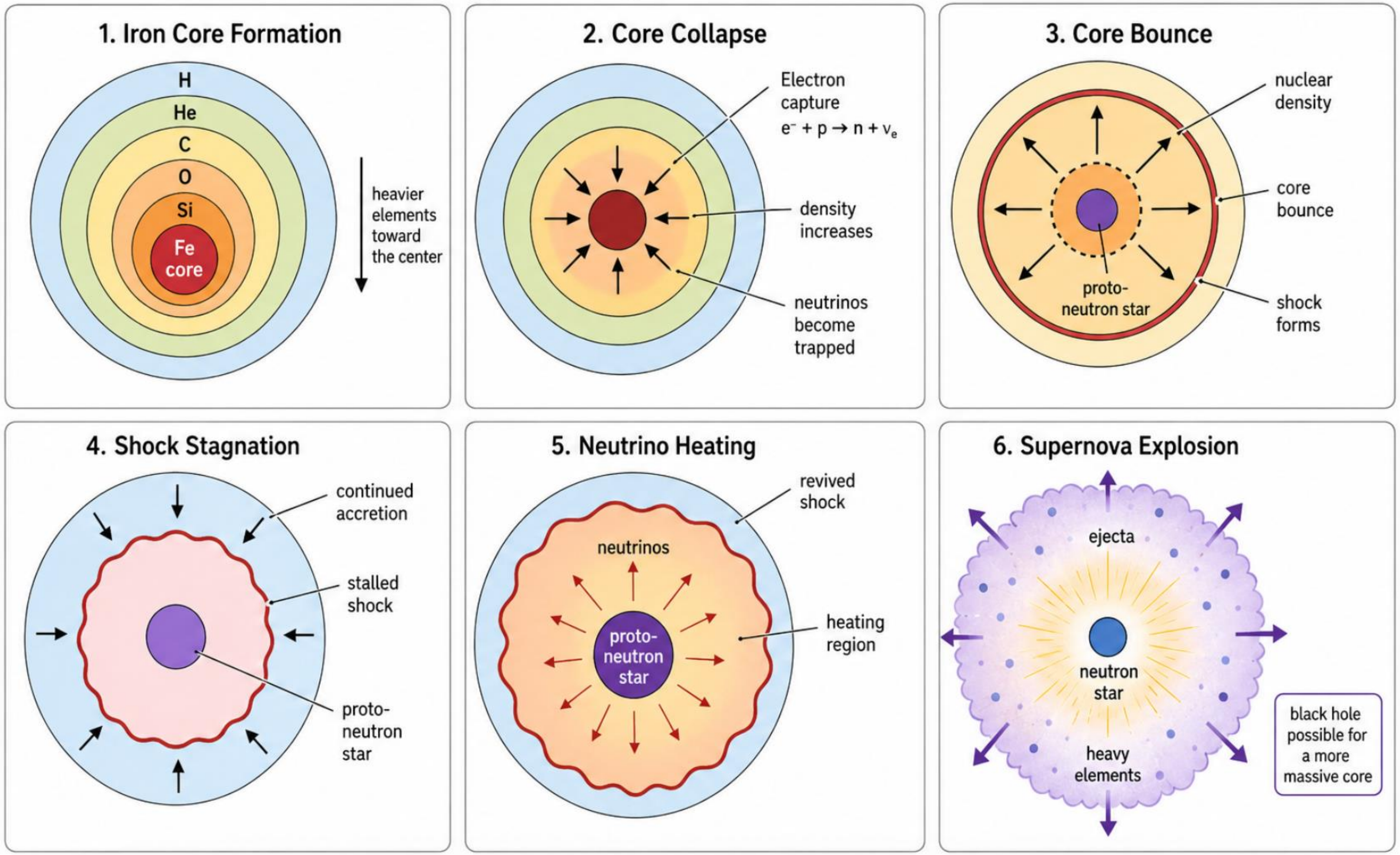


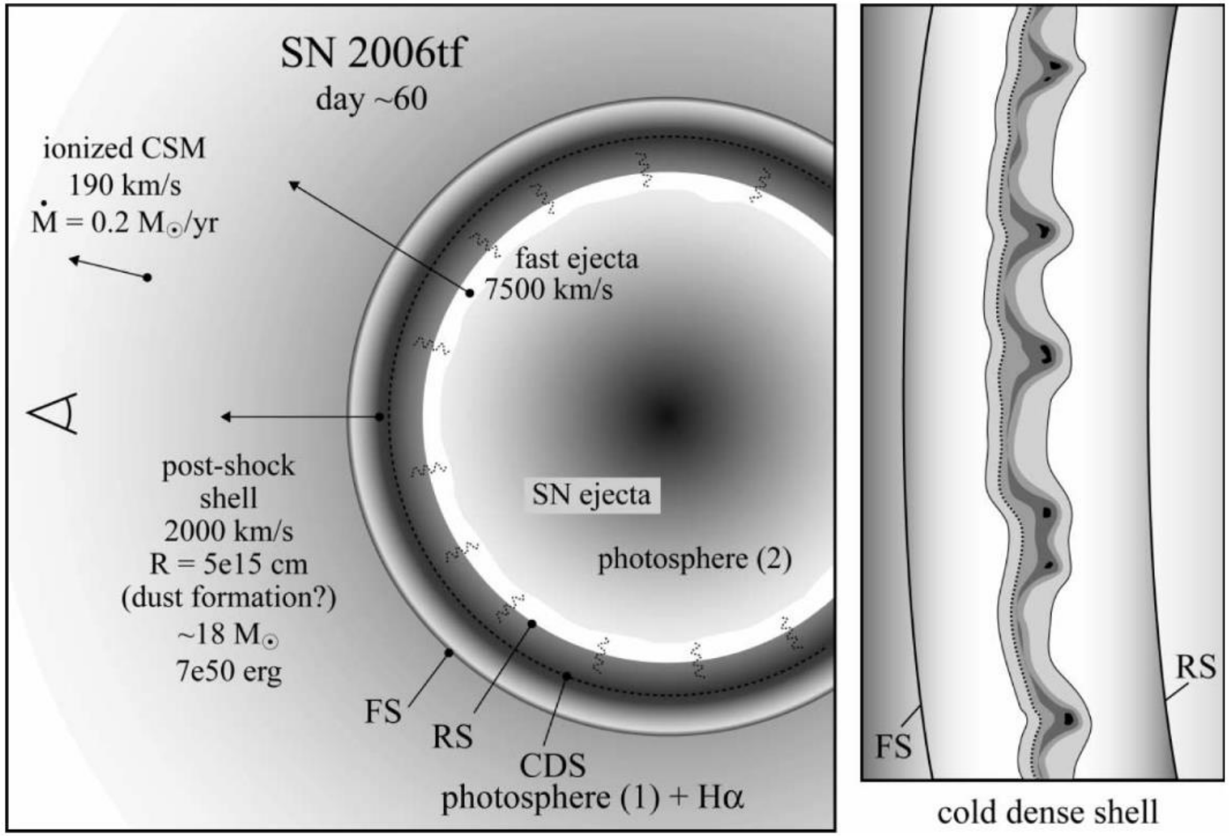
FIG. S4. The Rosseland mean opacity κ_R as a function of temperature, assuming $\rho \approx 2 \times 10^{-12}\,\mathrm{g\,cm^{-3}}$.

Core-Collapse Supernova (CCSNe) Process



SN interacting with CSM - Basic Physical Picture

- After SN, the Shock wave/ejecta will interact with CSM.
- When a SN explodes inside a dense CSM, four zones are delineatedin the simplest picture:



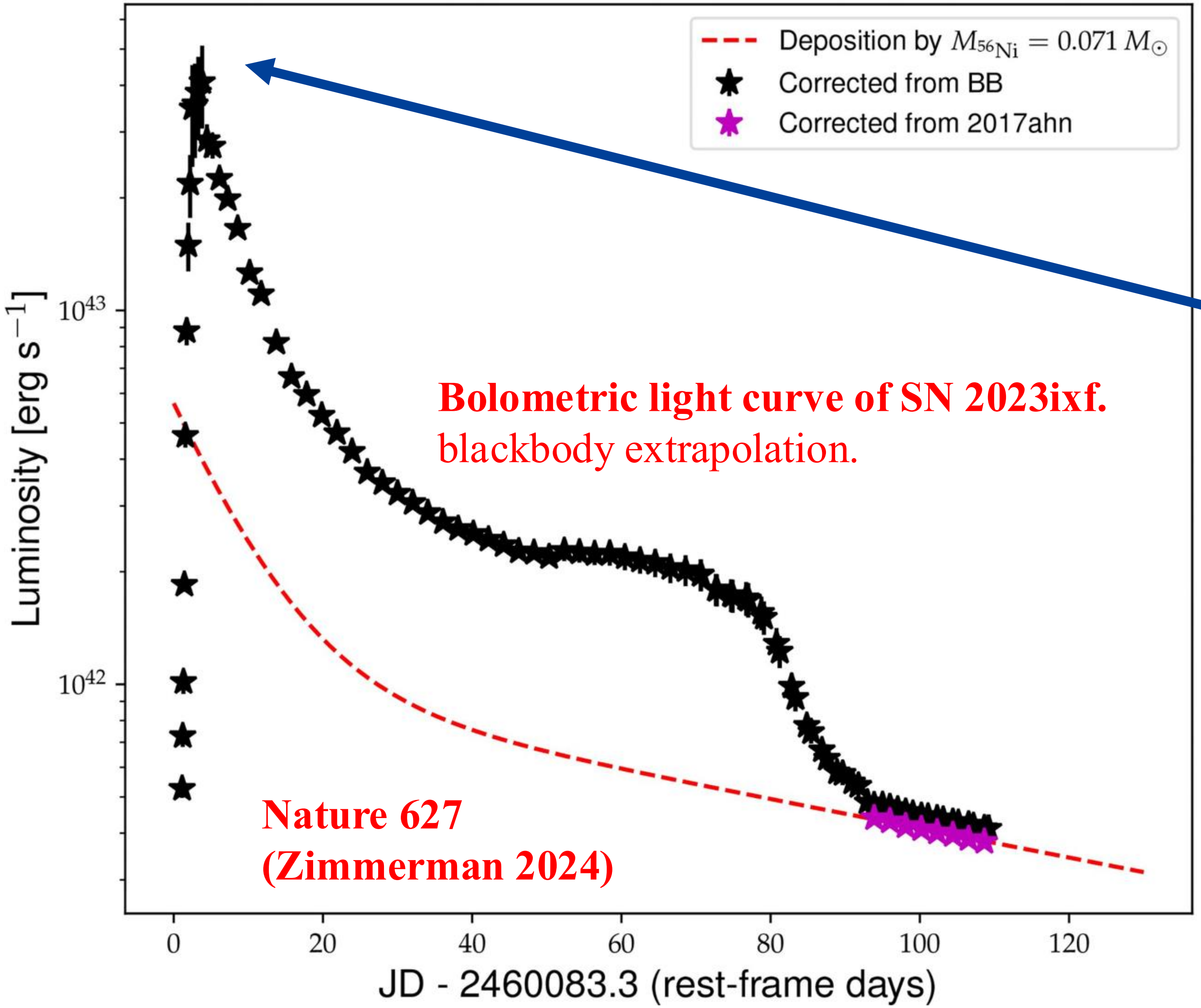
- The unshocked CSM outside the forward shock (FS)
- The swept-up CSM between FS and “cold dense shell” (CDS)
- The decelerated SN ejecta encountering the reverse shock (RS)
- The freely expanding SN ejecta inside RS

(Smith+ 2008)

Yu Cheng [chengyu059@uchicago.edu]

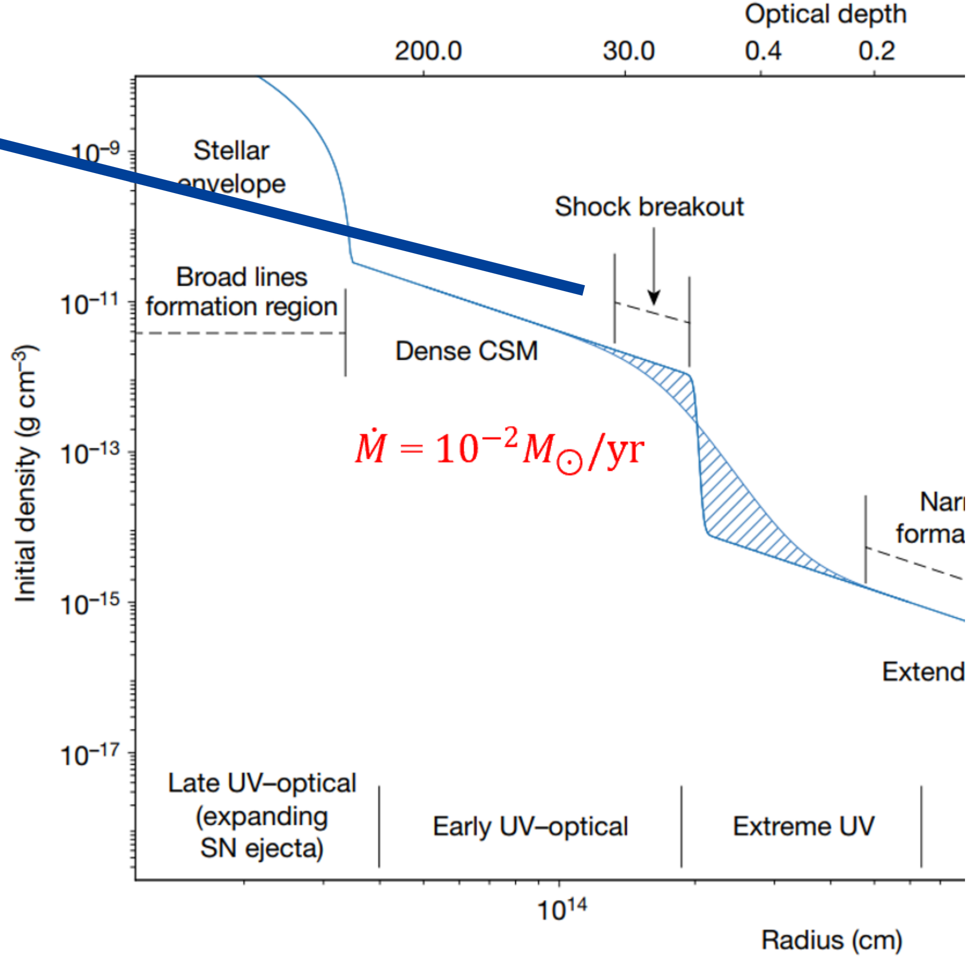
Observations (light curve)

- Dense CSM is optical thick at this stage
- Bright super-luminous transients After optical depth < 1.



Bolometric light curve of SN 2023ixf.
blackbody extrapolation.

Nature 627
(Zimmerman 2024)

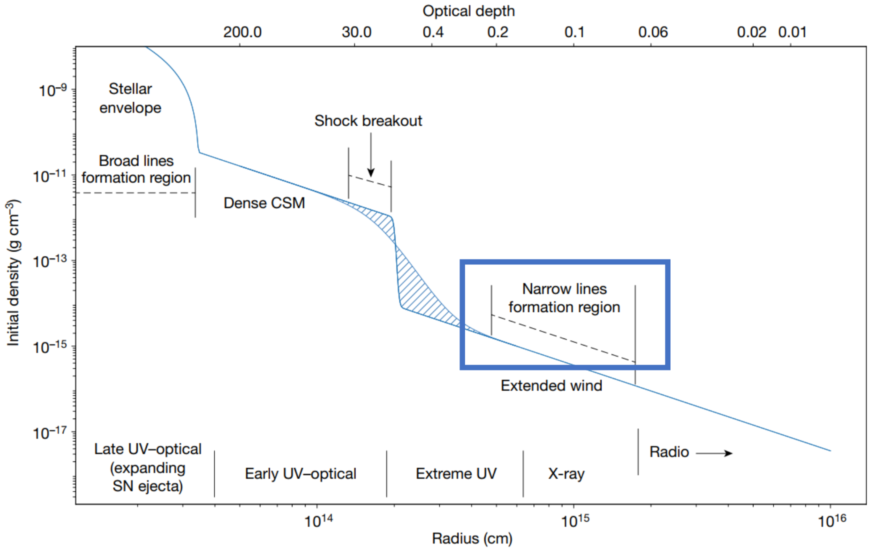


$\dot{M} = 10^{-2} M_\odot/\mathrm{yr}$

Observations (spectroscopy)

The Hα line consists of three contributions.

1. narrow line (< 1000 km/s) pre-shock CSM



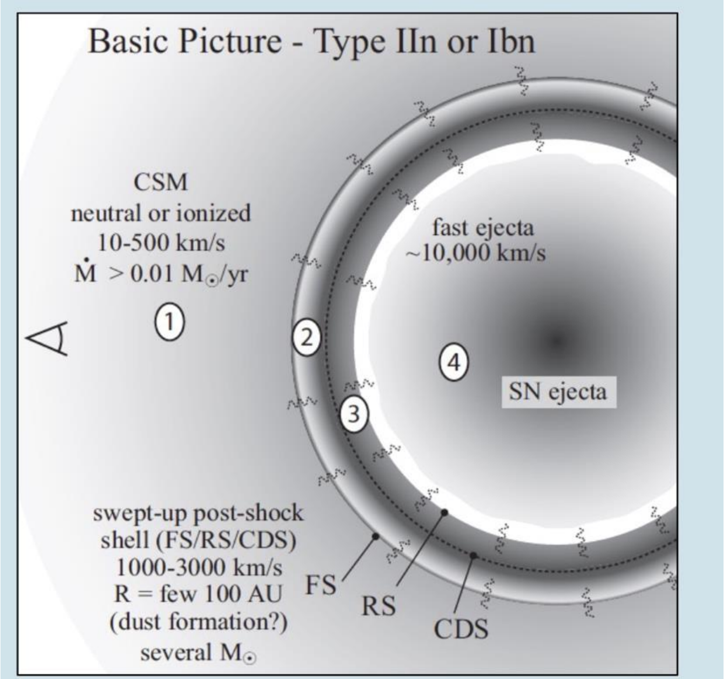
UV from shock-swept region generate narrow line.

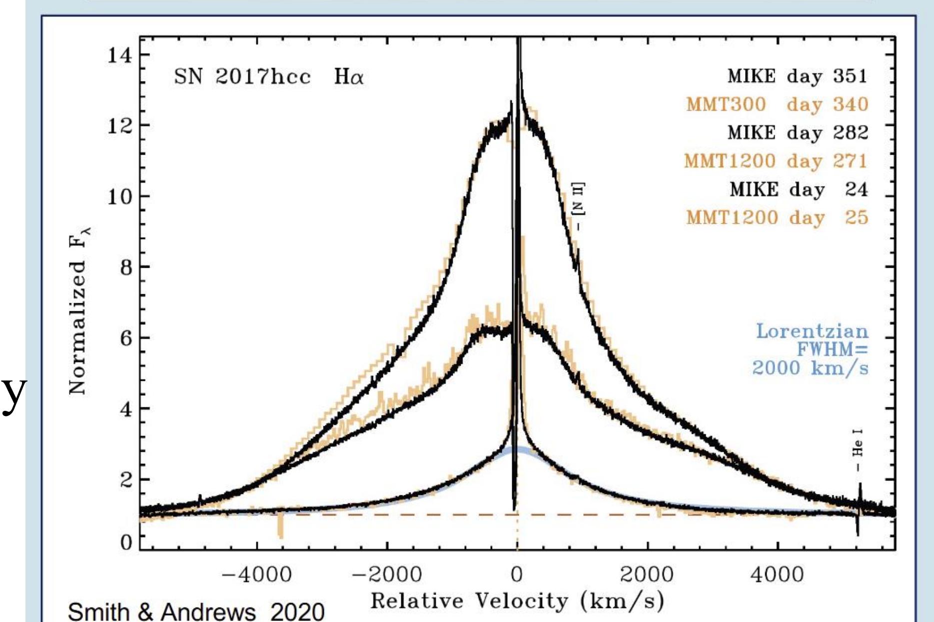
From Doppler effect

Obtain the unshocked CSM velocity v_w

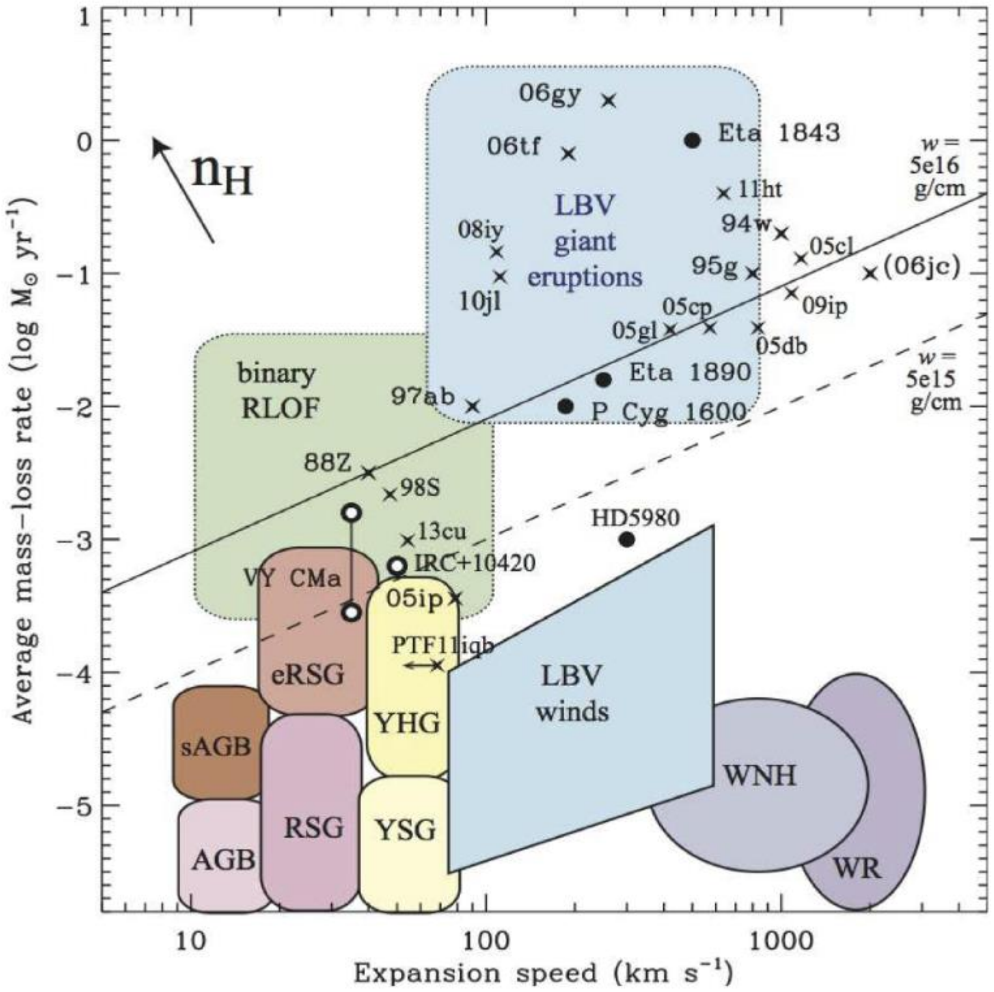
2. intermediate-width (1000-3000 km/s) fromshocked CSM (or e- scattering at early times).
3. Broad (~3,000-15,000 km/s) components atsome phases (especially late) from reverse shocked SN ejecta.

Photon scatter with high velocity electron for many times.



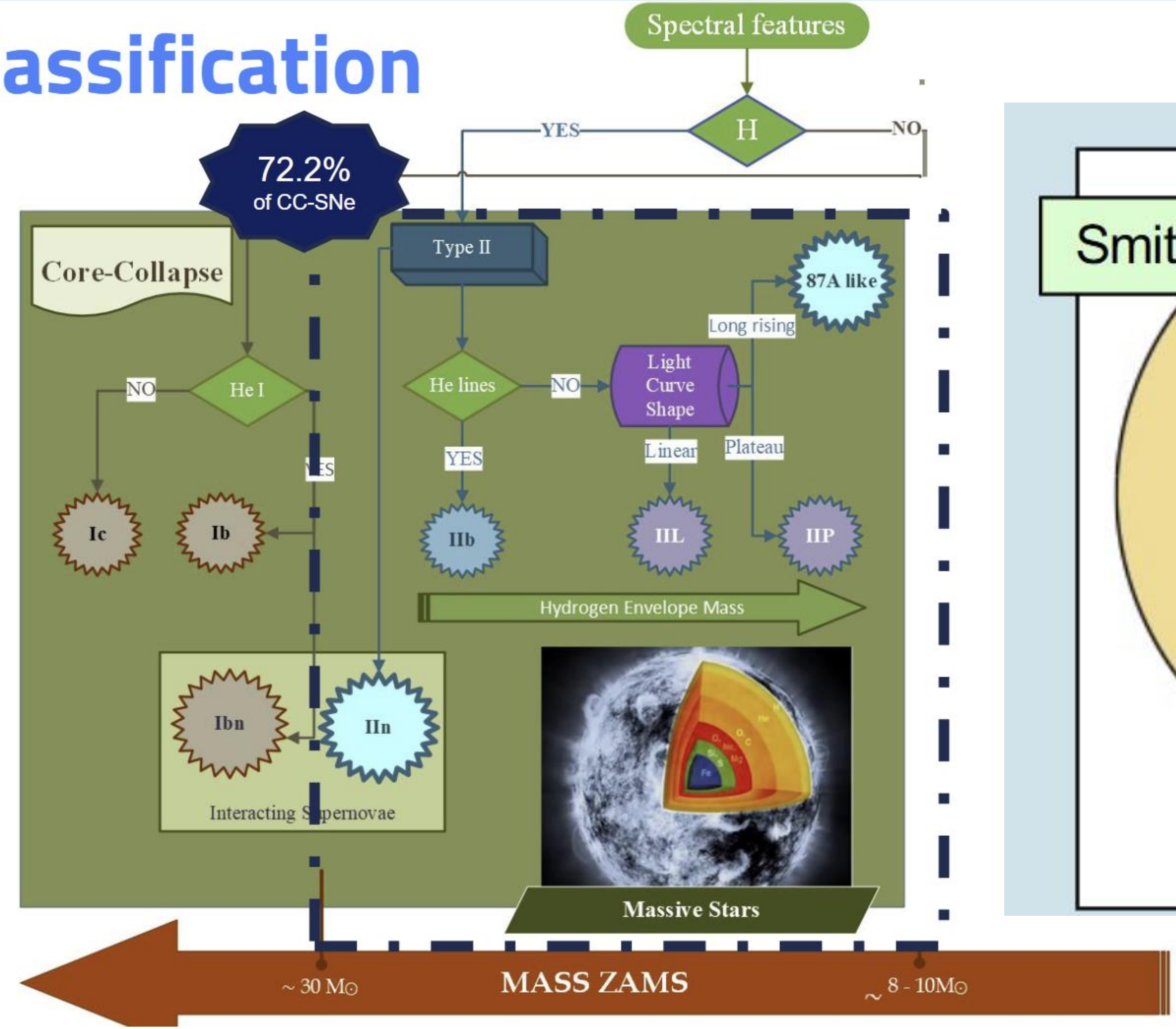


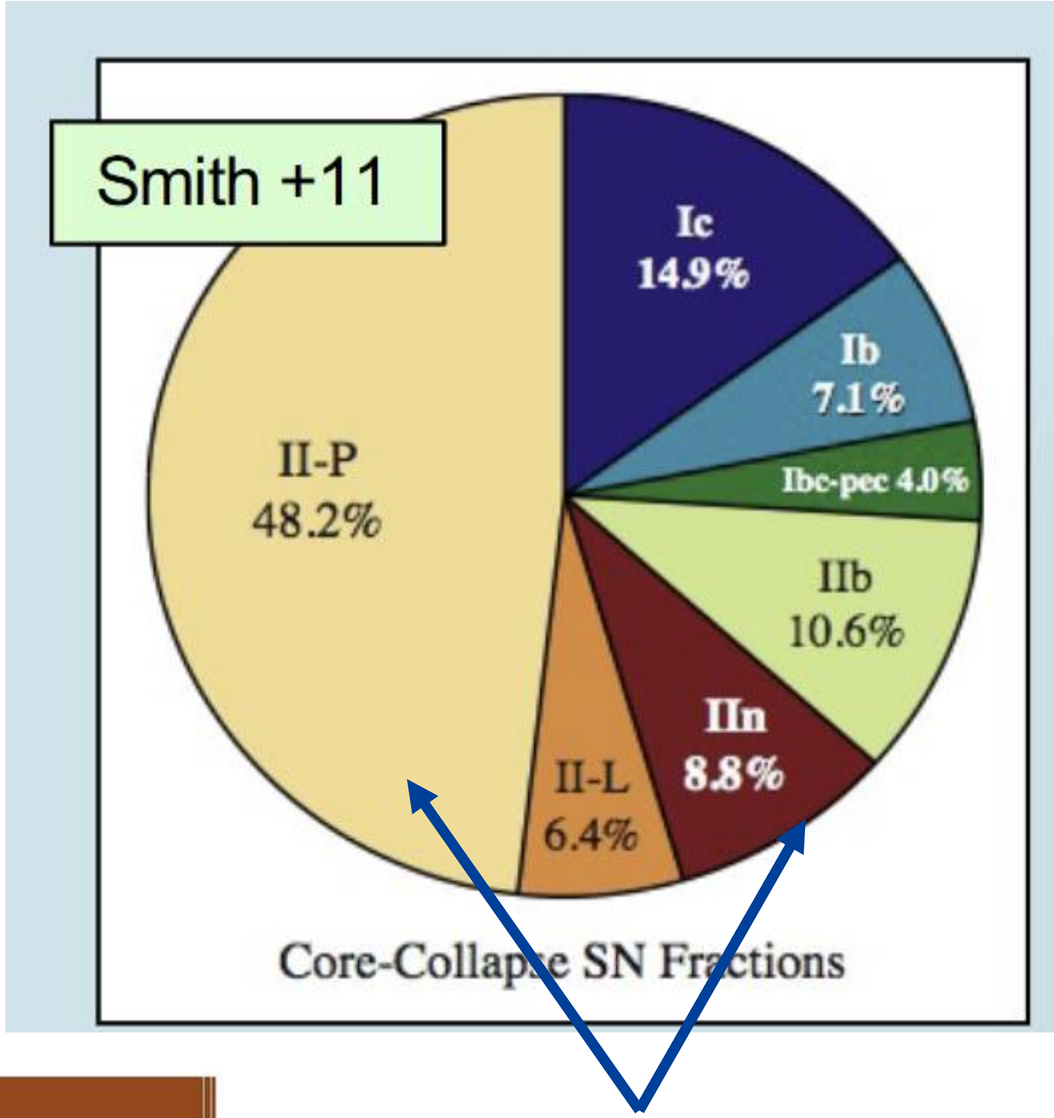
Smith & Andrews 2020



Mass-loss rate $\dot{M}$ as a function of wind velocity v_w, for interacting SNe to those of known types of stars (Smith 2014)

SN classification





Many of them have CSM
More than 50%