PPP16, NTHU   June 15-18, 2026

Circumstellar medium of SNe as new probes for feebly-interacting particles

Yen-Hsun Lin

Institute of Physics, Academia Sinica

based on 2603.09615

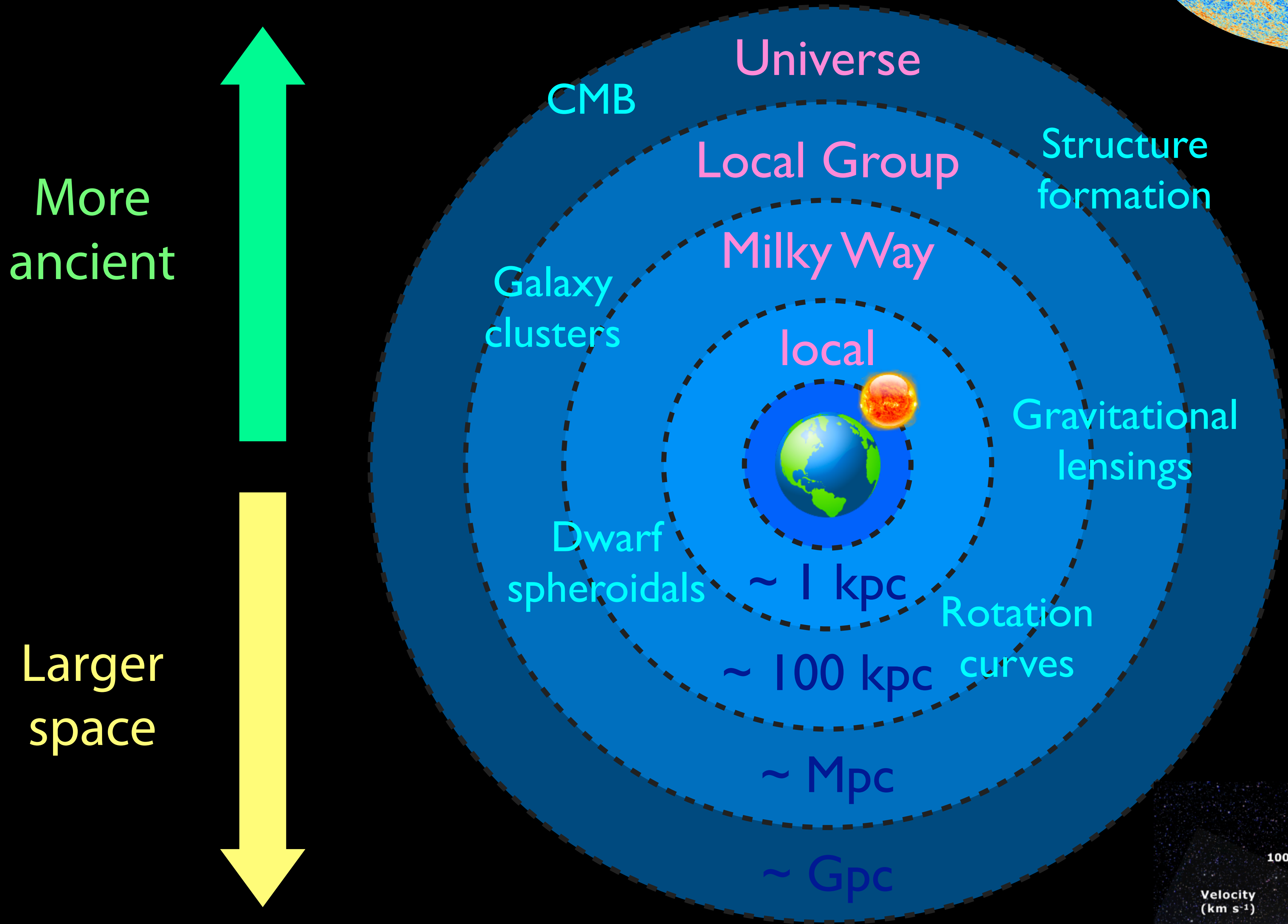
in collaboration with

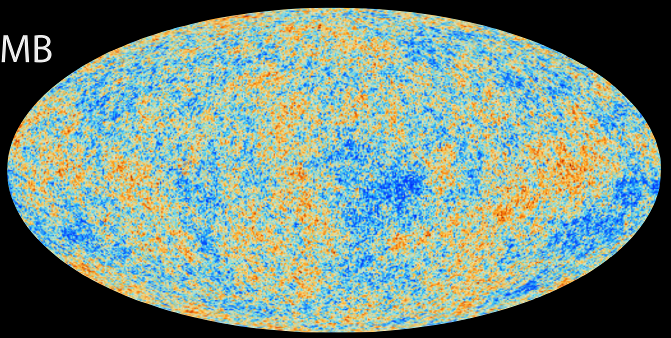
Yu Cheng (KAIST), Chui-Fan Kong (IBS), Meng-Ru Wu (AS) & Seokhoon Yun (KNU)

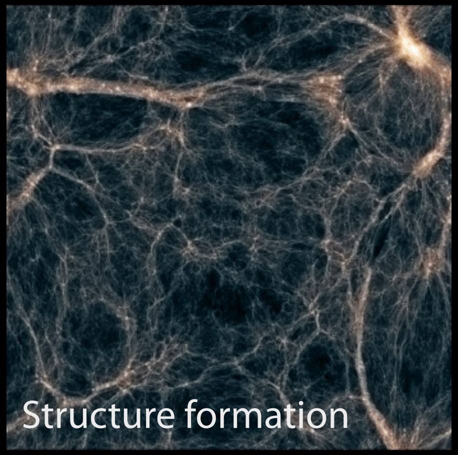
Outline

- Introduction
- Current status of probing FIPs in supernova (SN)
- How to probe FIPs with cicumstellar medium
- Summary

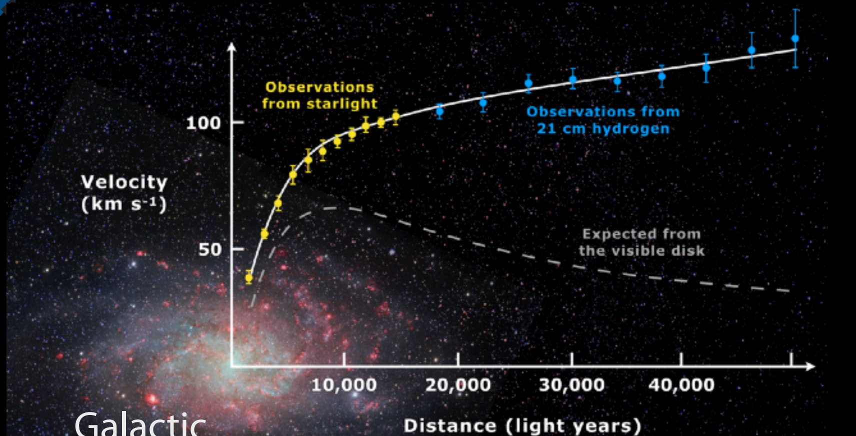
Dark matter is ***ubiquitous*!**




CMB


Structure formation


Gravitational lensing



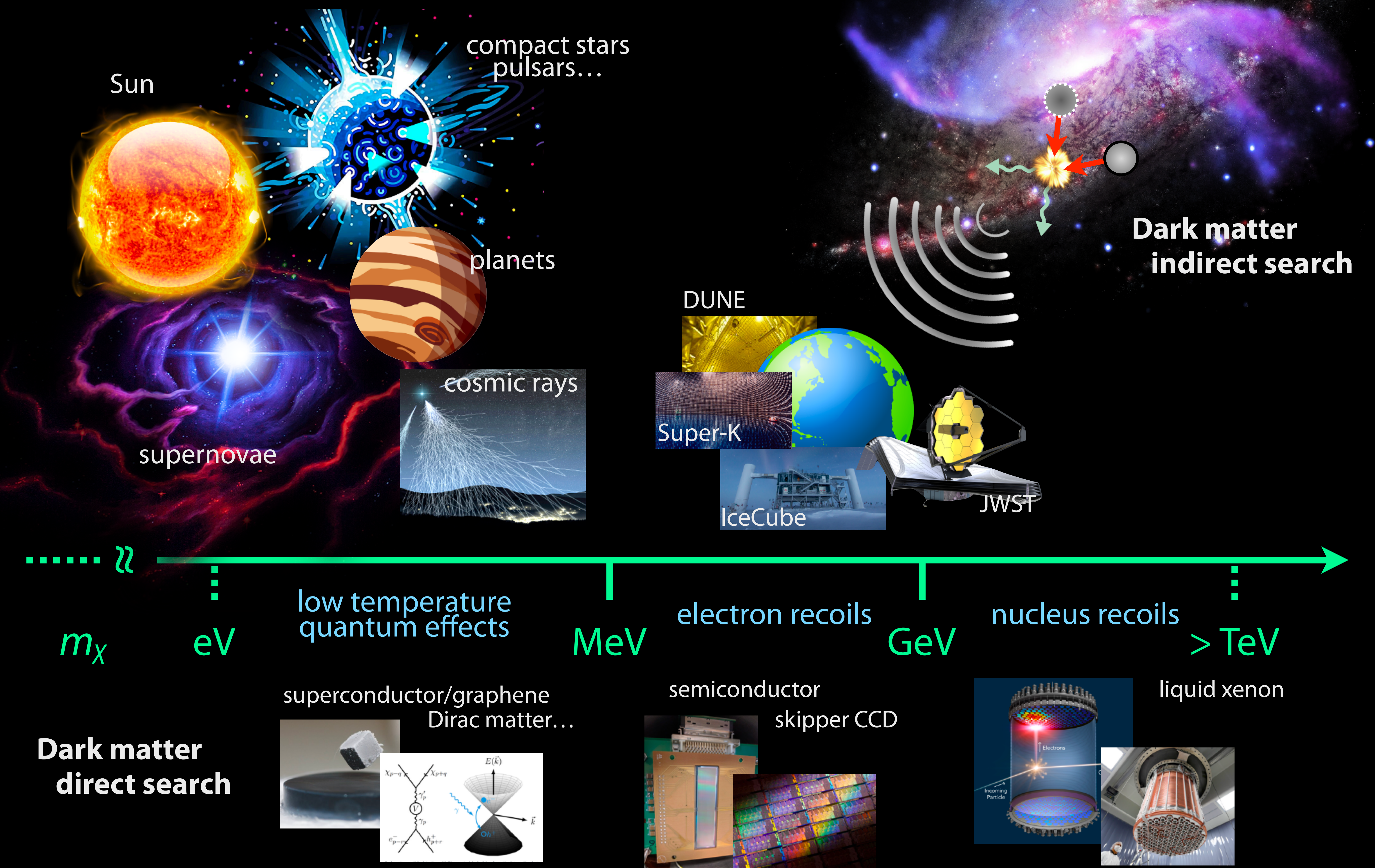
Galactic rotation curve

1 pc (parsec) ~ 3.3 light years ~ 3×10^{18} cm

not-to-scale

Lin, TASI Lecture, 1904.07915
Leane, 2006.00513

To probe mass & cross section

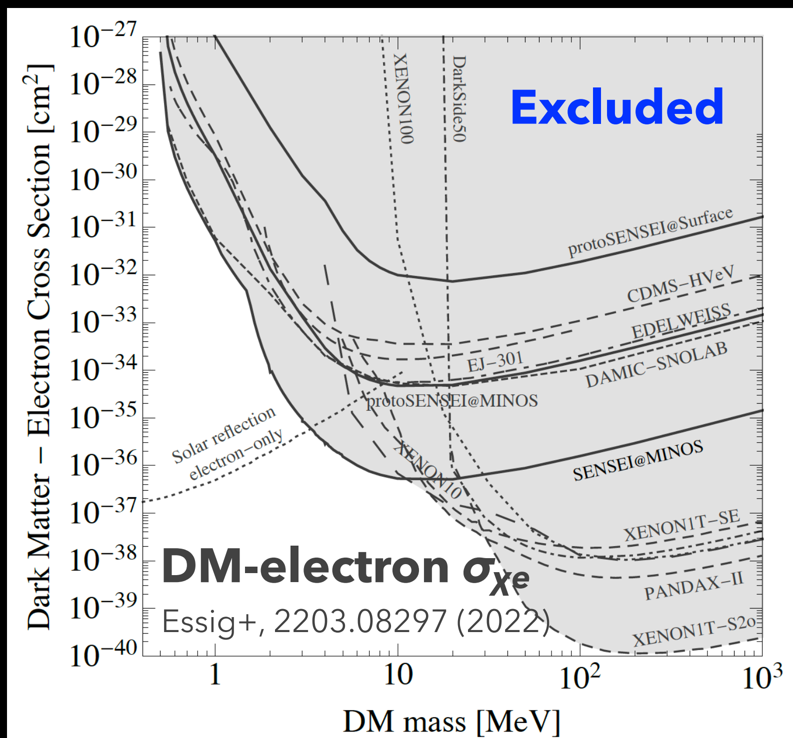


not-to-scale

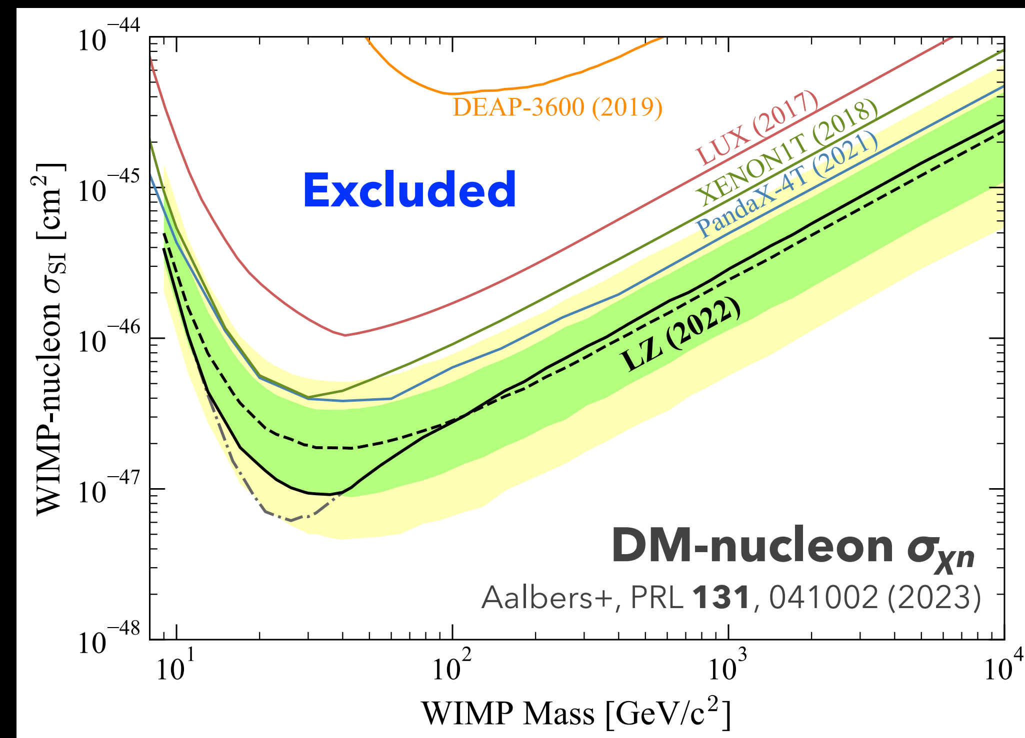
Lin, TASI Lecture, 1904.07915
Leane, 2006.00513
Bozorgnia+, Can. J. Phys. **103**, 671 (2025)

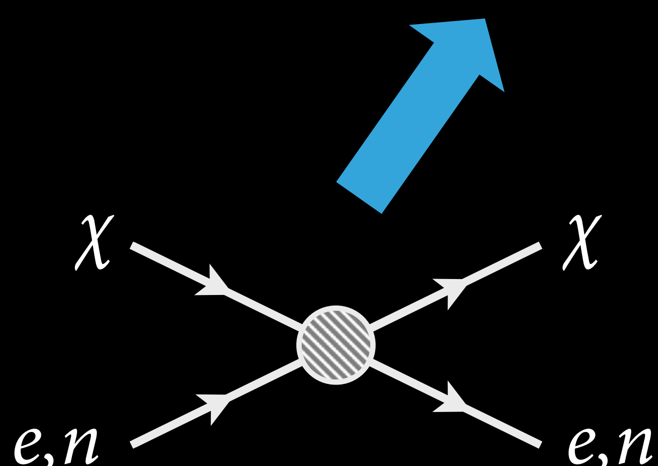
How small the cross section is?

m_χ: 1 – 10^3 MeV

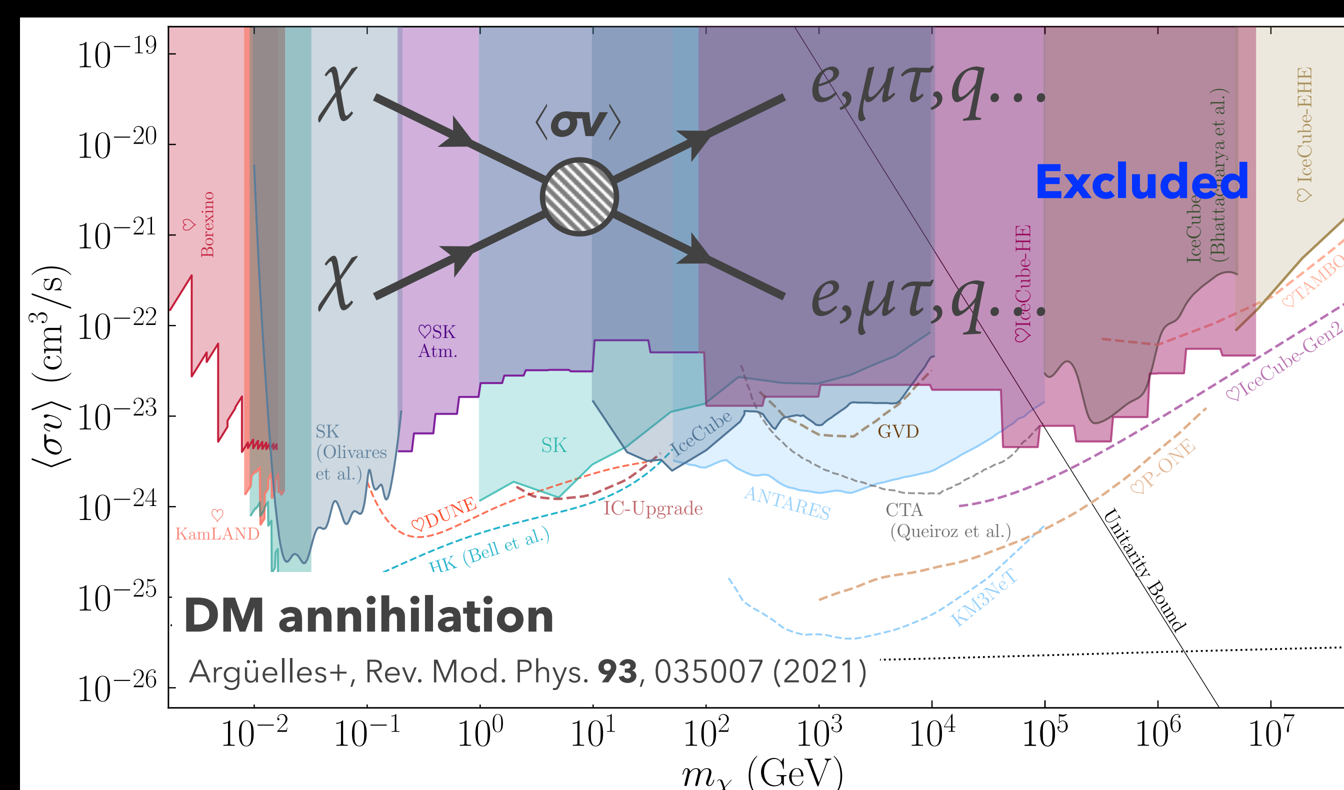


m_χ > GeV

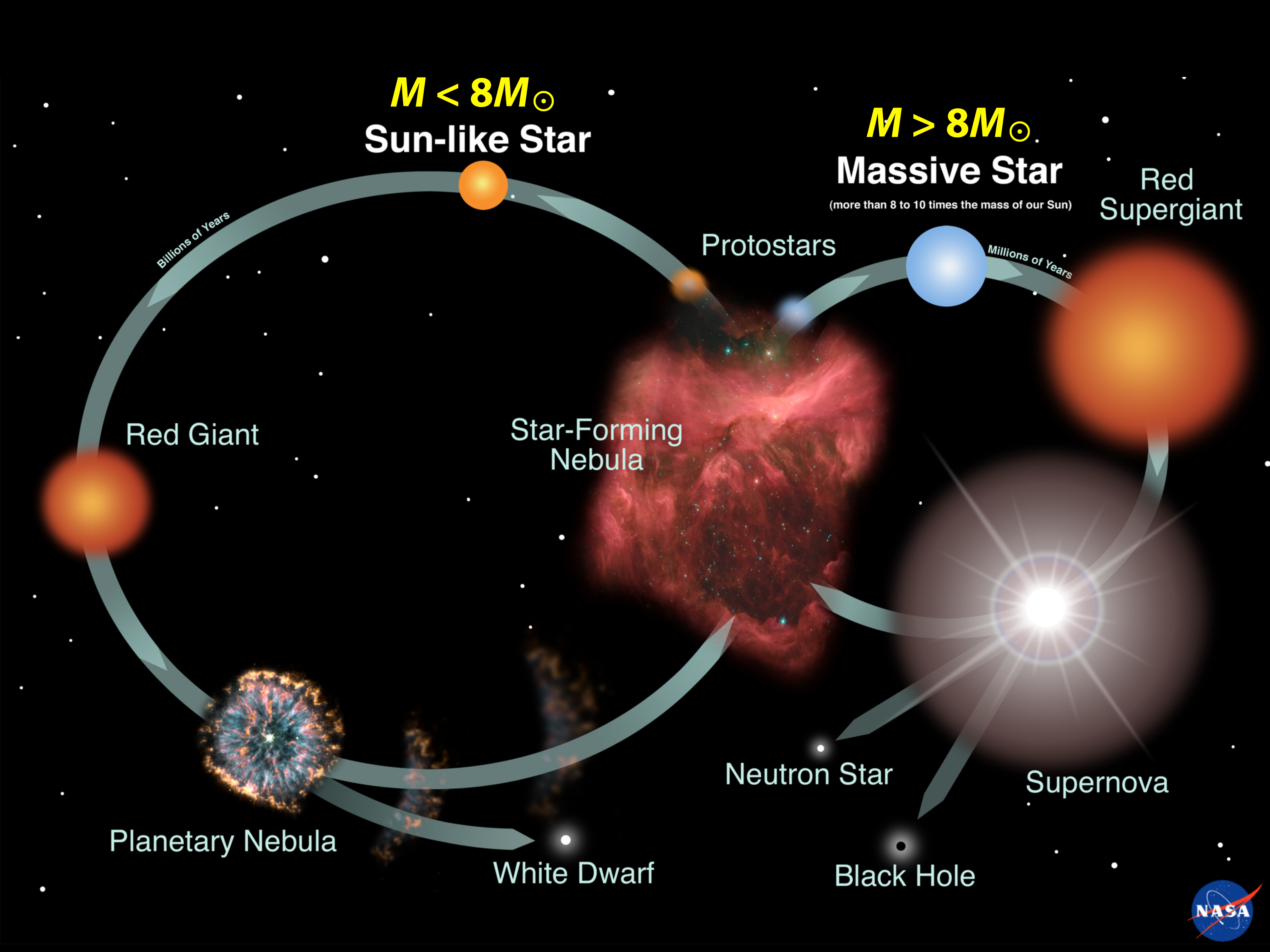




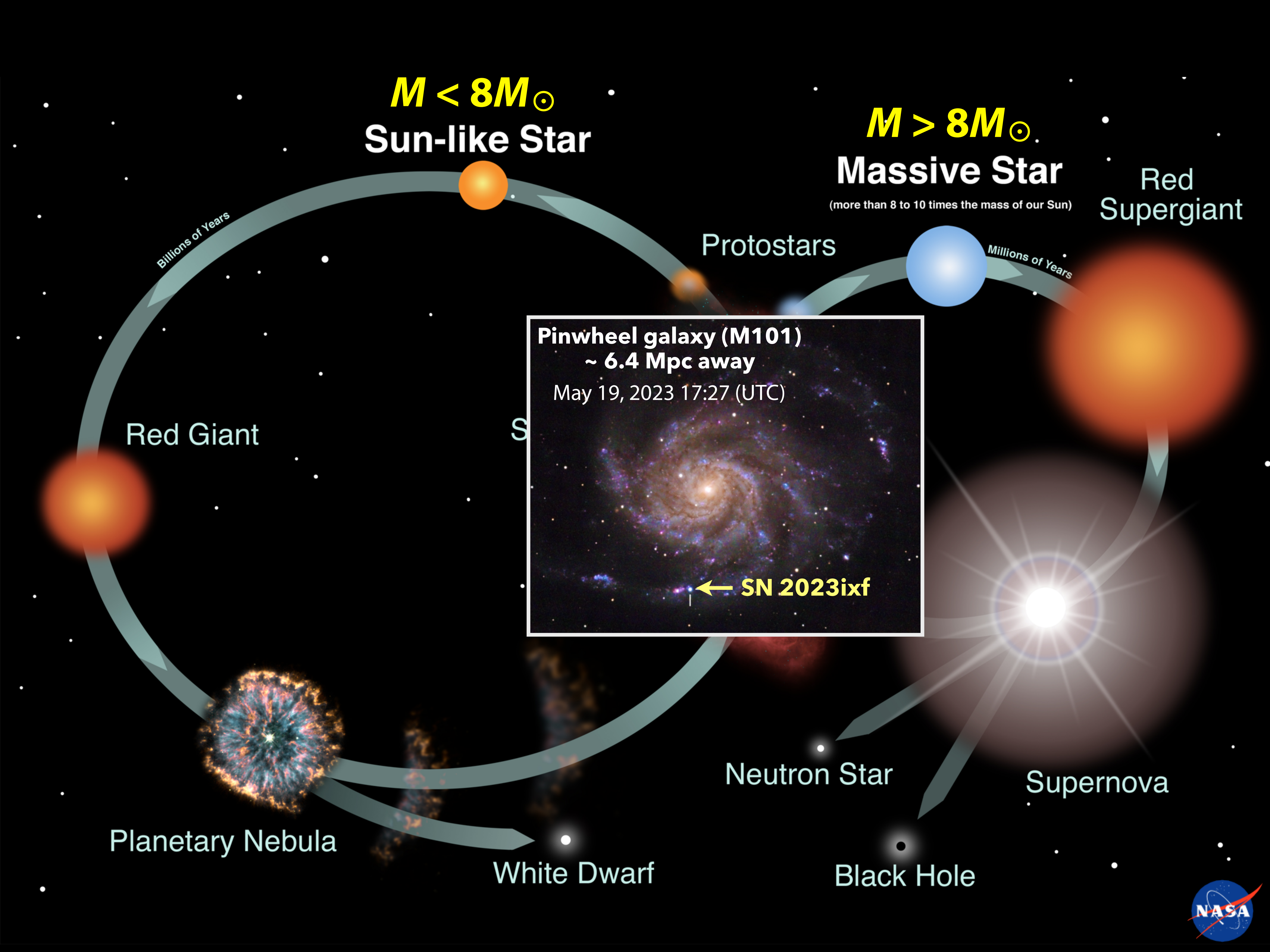
Direct detection



Supernova as the particle laboratories



$M < 8M_\odot$
Sun-like Star
$M > 8M_\odot$
Massive Star
(more than 8 to 10 times the mass of our Sun)
Red Supergiant
Billions of Years
Protostars
Millions of Years
Red Giant
Star-Forming Nebula
Neutron Star
Supernova
Planetary Nebula
White Dwarf
Black Hole
NASA



$M < 8M_\odot$
Sun-like Star
$M > 8M_\odot$
Massive Star
(more than 8 to 10 times the mass of our Sun)
Red Supergiant
Protostars
Billions of Years
Millions of Years
Red Giant
Pinwheel galaxy (M101)
~ 6.4 Mpc away
May 19, 2023 17:27 (UTC)
SN 2023ixf
Planetary Nebula
White Dwarf
Neutron Star
Supernova
Black Hole
NASA

What we already know about SN and its BSM detection

- During the supernova explosion, most energy is carried away by neutrinos within ~ 10 s

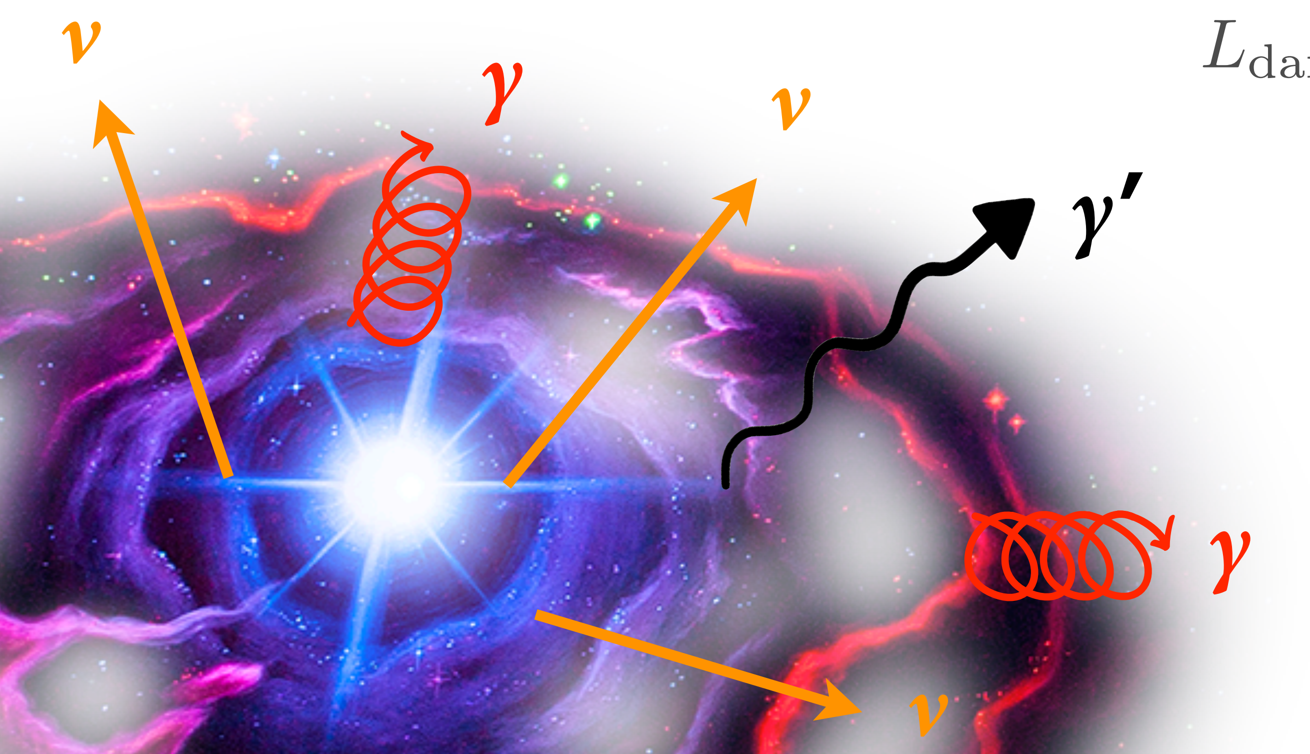
$$E_\nu \sim 10^{53} \text{ erg} \quad \text{where} \quad L_\nu \sim 10^{52} \text{ erg/s}$$

- ~ 10^{58} neutrinos are emitted with mean energy ~ 10 - 20 MeV
- Others are taken by kinetic energy and radiation

$$E_{\text{kin}} \sim 10^{51} \text{ erg} \quad \text{and} \quad E_{\text{rad}} \sim 10^{49} \text{ erg}$$

- Beyond Standard Model particles (dark photon, axion…etc) can be produced in the PNS and shares L_ν
- This gives the famous **Raffelt criterion** (SN cooling bound)

$$L_{\text{dark}} \lesssim L_\nu$$



Janka, Ann. Rev. Nucl. Part. Sci. **75**, 425 (2025)
Raffelt+, 2509.16306 (2025)

What we already know about SN and its capability in BSM detection

- We take dark photon (DP γ') as an illustrative model

Galison+, Phys. Lett **136B**, 279 (1984)
Holdom Phys. Lett. **166B**, 196 (1986)
Pospelov+, Phys. Lett. B **662**, 53 (2008)
…

$$\mathcal{L}_{\rm DP} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{m_{\gamma'}}{2}A'_\mu A'^\mu + eA_\mu J^\mu_{\rm EM}\,.$$

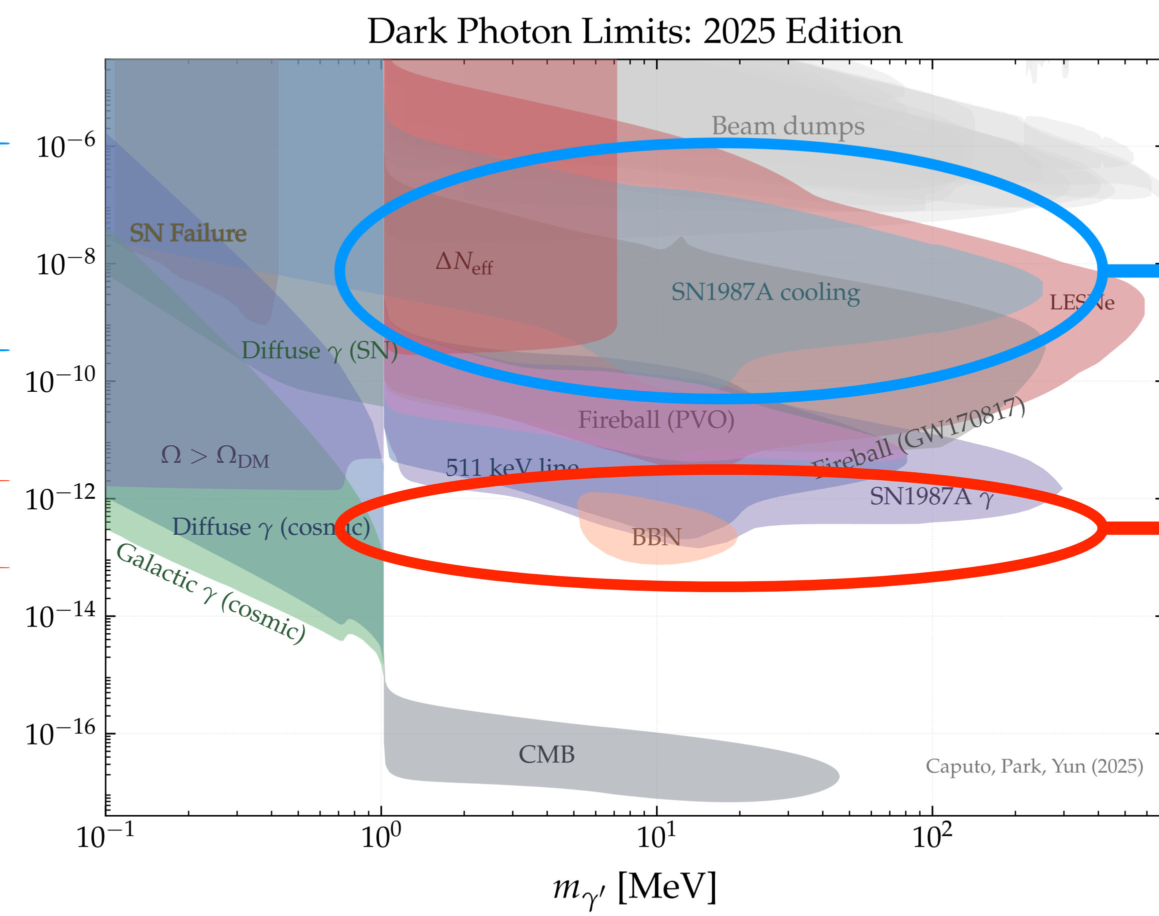
where $F^{(\prime)}_{\mu\nu} = \partial_\mu A^{(\prime)}_\nu - \partial_\nu A^{(\prime)}_\mu$ and $m_{\gamma'}$ the DP mass with a DP-SM coupling $\varepsilon e A'_\mu J^\mu_{\rm EM}$

- Current constraints on DP ($m_{\gamma'}$,ε):

See Review by Caputo+
Phys. Rev. D **113**, 075001 (2026)

$\sim 10^{-9}$–10^{-6}

$\sim 10^{-13}$–10^{-11}



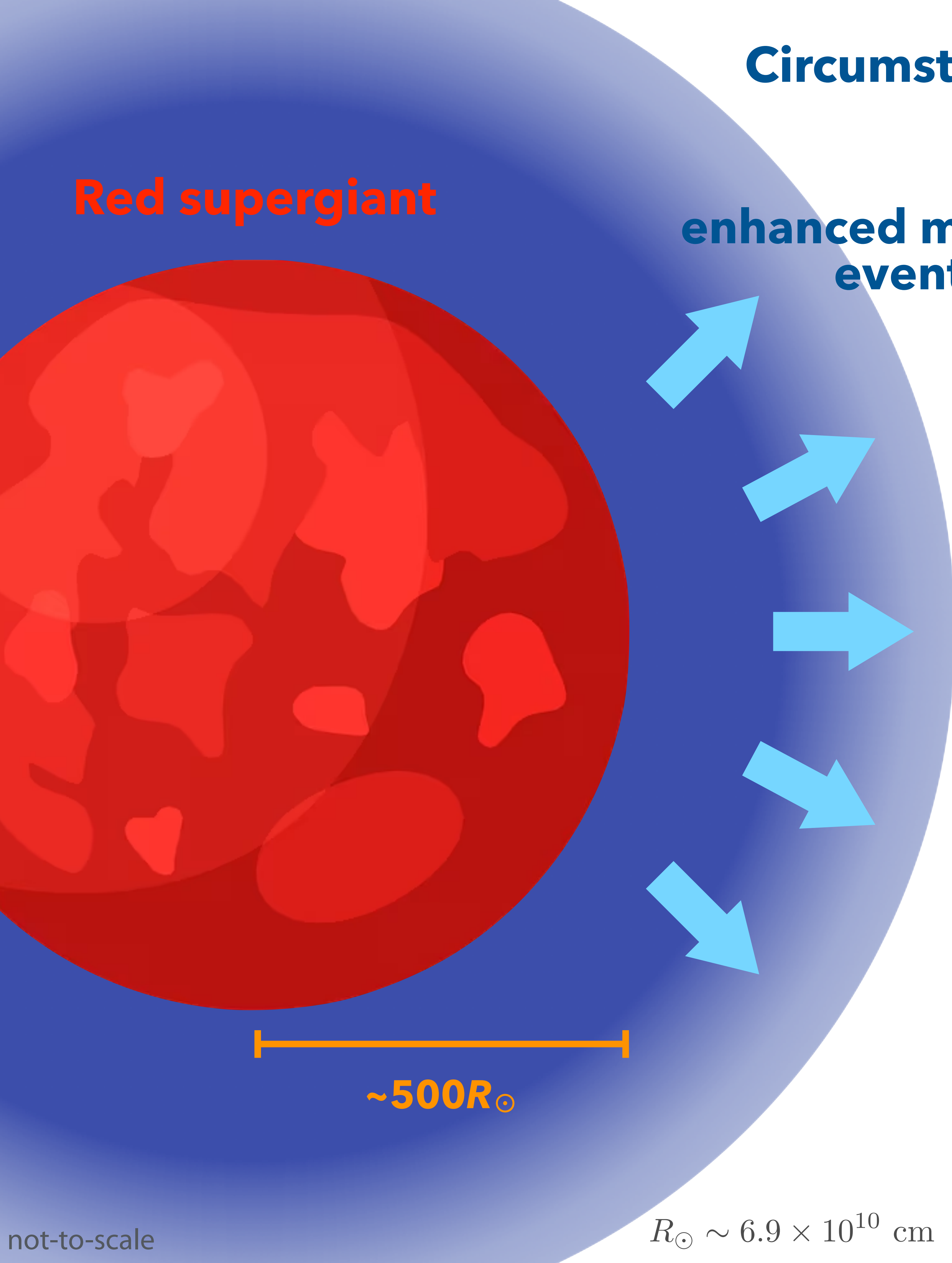
cooling bound
$L_{\rm dark} \lesssim L_\nu$

our new bound
2603.09615
(SN 2023ixf)

Janka, Ann. Rev. Nucl. Part. Sci. **75**, 425 (2025)
Raffelt+, 2509.16306 (2025)

Circumstellar medium (CSM)

~1500$R_\odot$

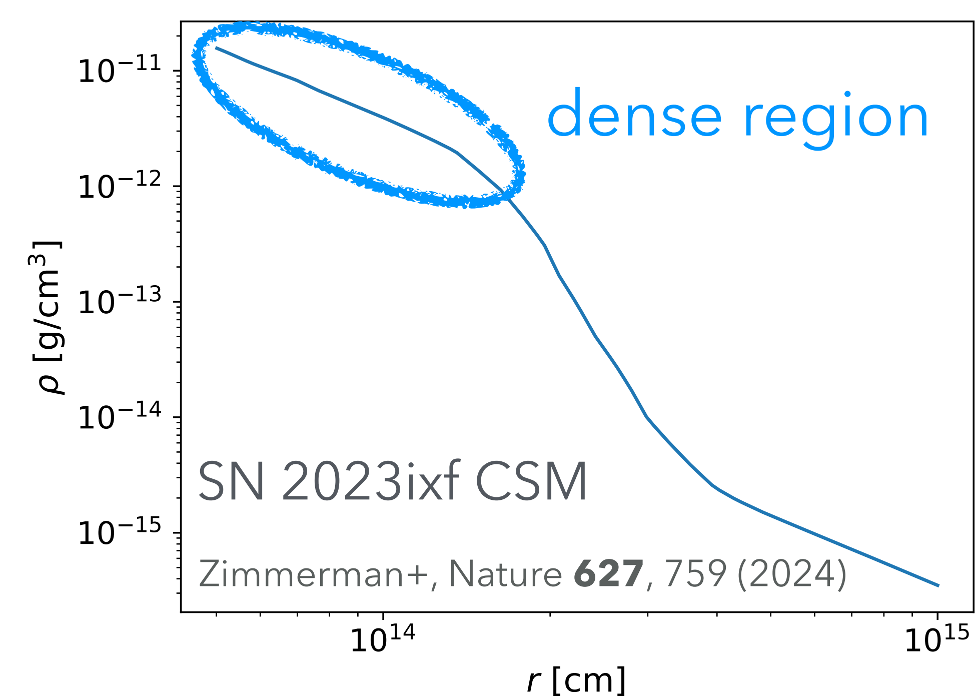


$$\rho_{\rm CSM}(r) \sim \frac{\dot{M}}{4\pi r^2 v_w}$$

$\dot{M}$: mass-loss rate, $M_\odot$/yr

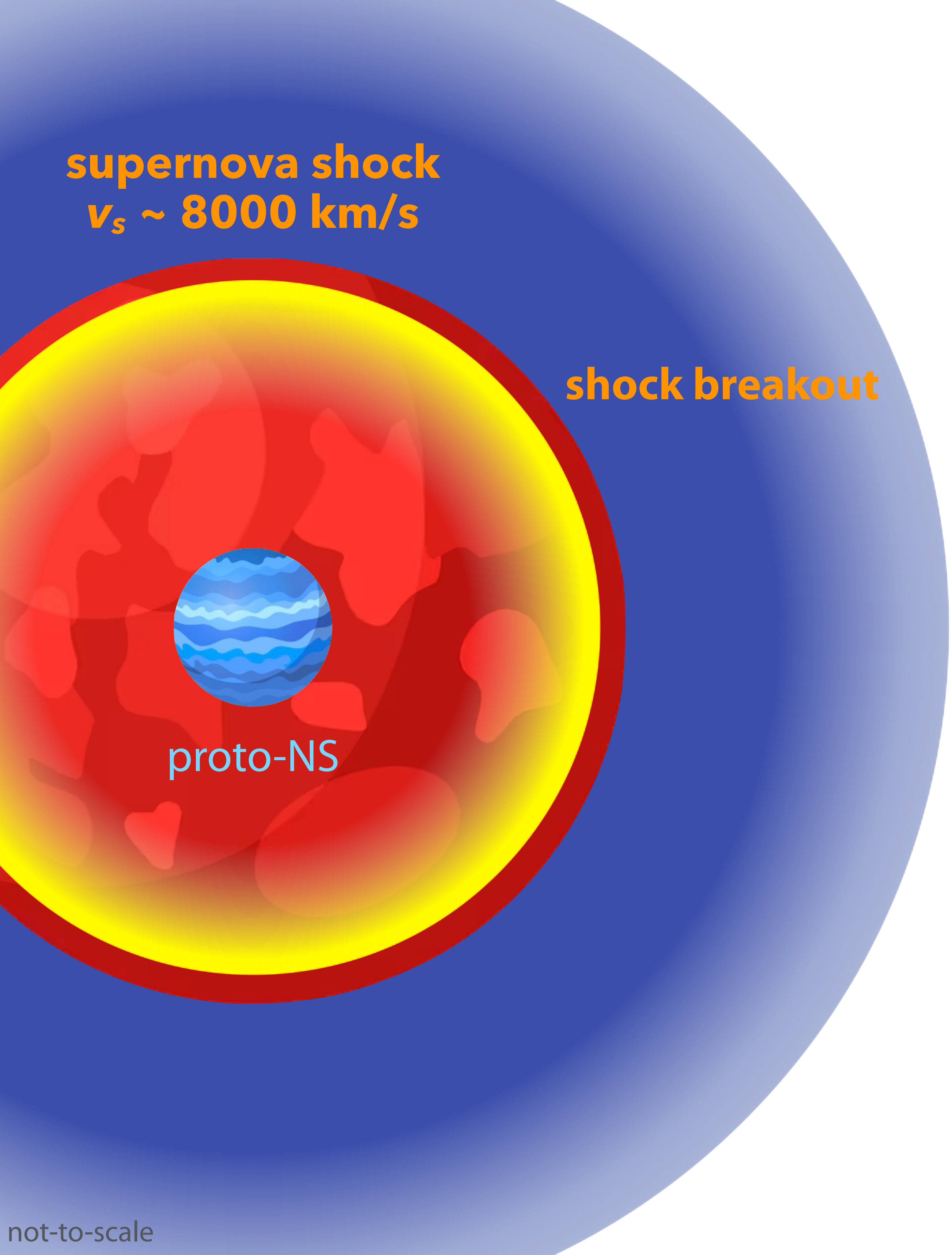
v_w : wind velocity, ~ 30 km/s

- $>$ 30% RSGs are expected to have dense CSM Forster+, Nature Astron. **2**, 808 (2018) Burch+, ApJ. **912**, 46 (2023)
- $10^{-4} \lesssim \dot{M} \lesssim 10^{-2}$ dense CSM

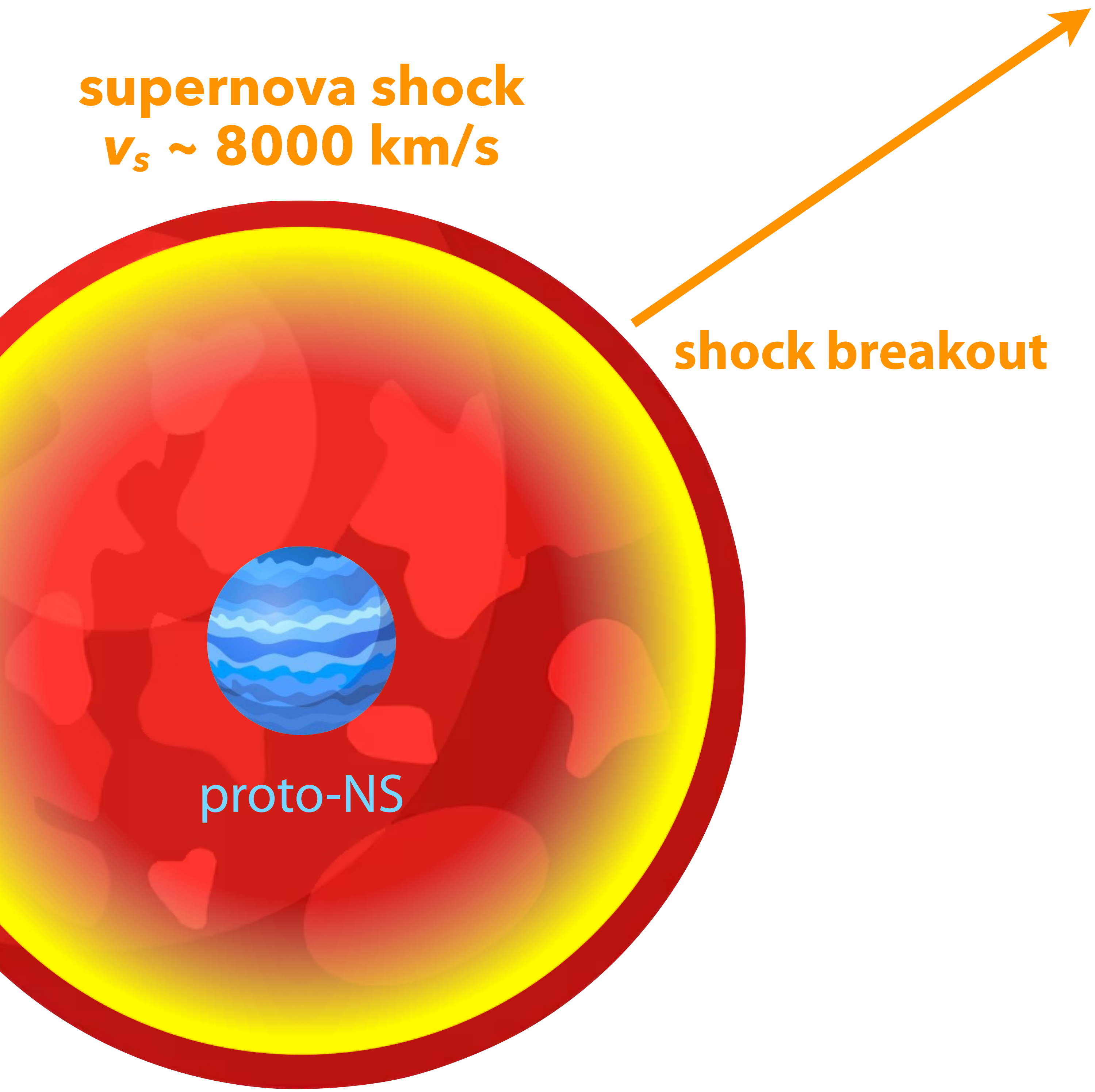


$R_\odot \sim 6.9 \times 10^{10}$ cm

Smith, Ann. Rev. Astron. Astrophys. **52**, 487 (2014)
TNS `https://www.wis-tns.org/`



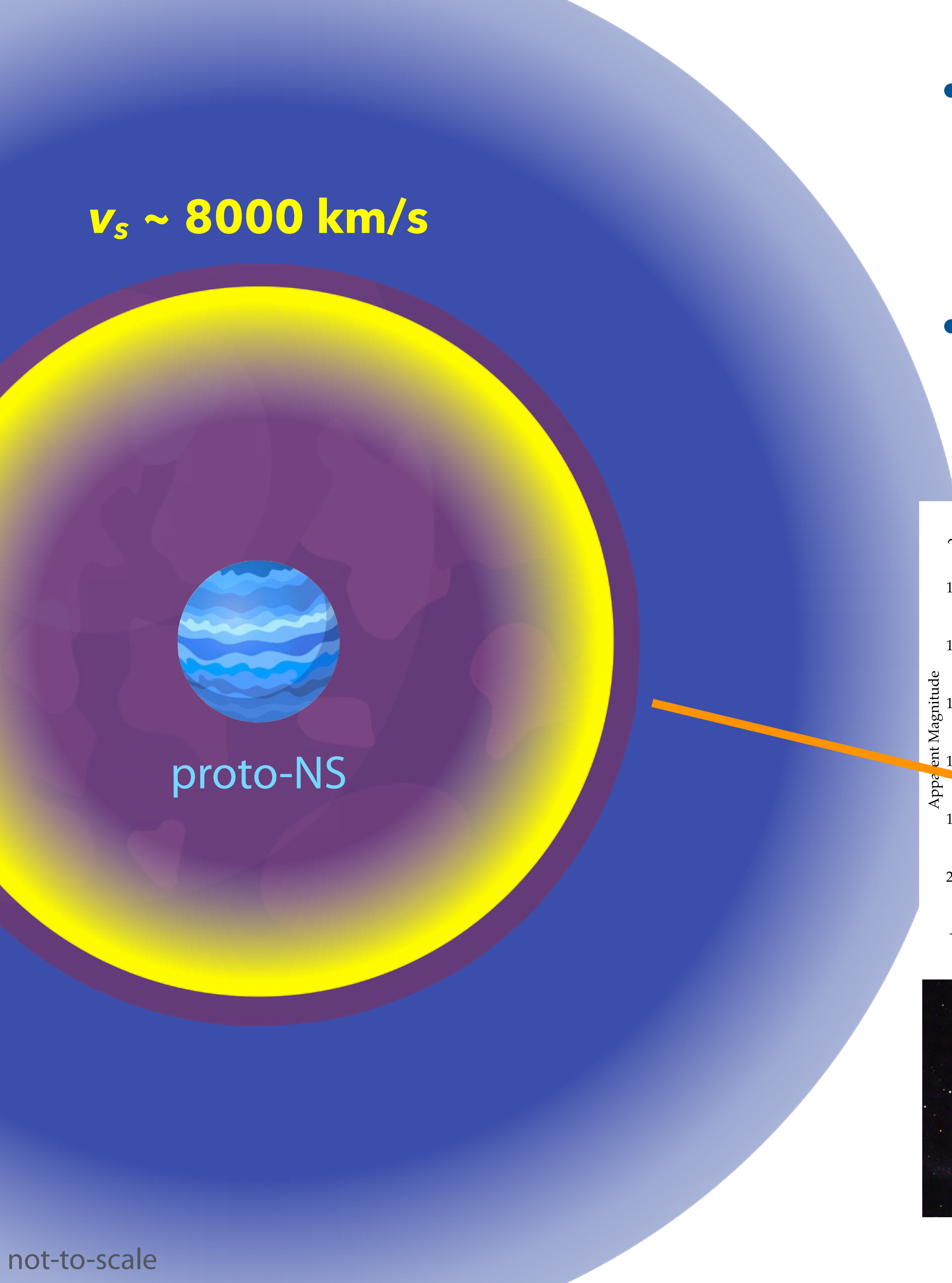
Smith, Ann. Rev. Astron. Astrophys. **52**, 487 (2014)
TNS `https://www.wis-tns.org/`



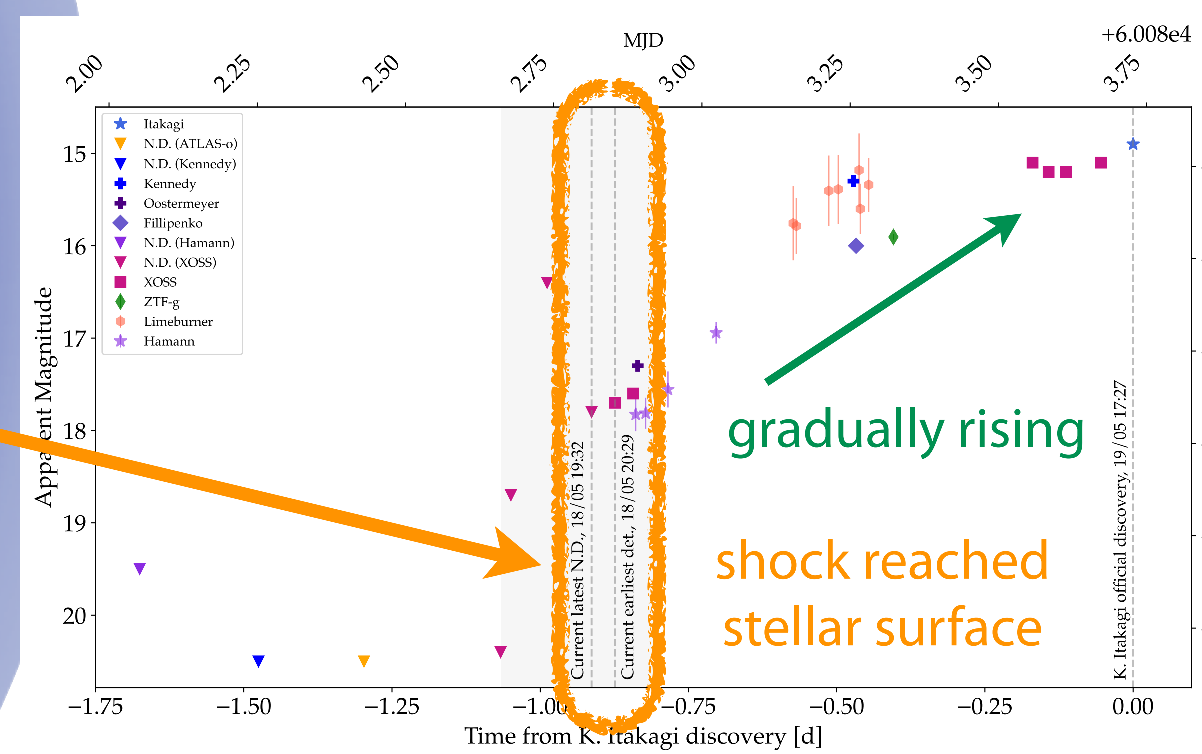
- Without CSM, we will see a sharp rising of luminosity when shock breaks out the stellar surface (~24 hrs after core-collapse)

not-to-scale

Smith, Ann. Rev. Astron. Astrophys. **52**, 487 (2014)
TNS `https://www.wis-tns.org/`

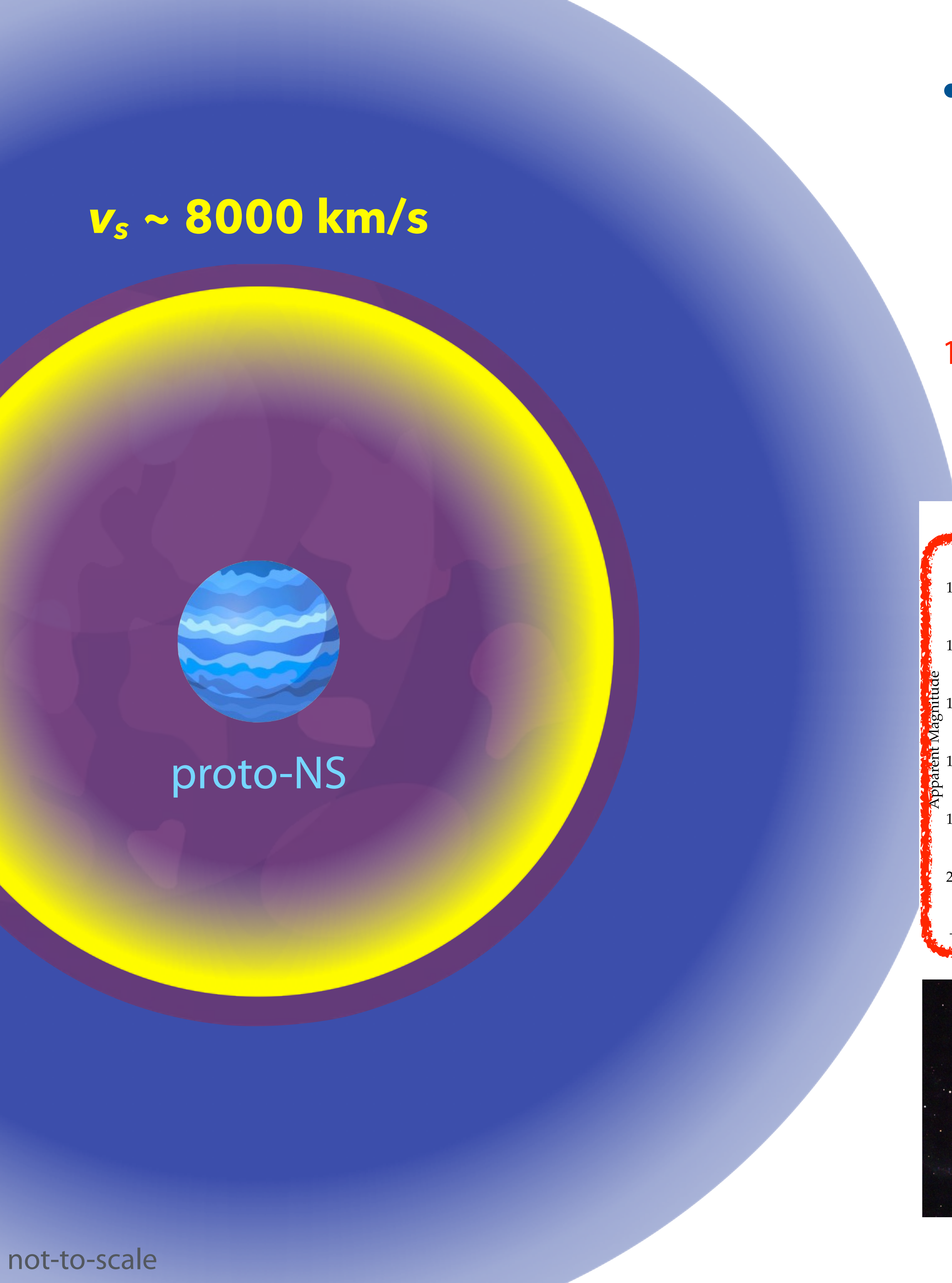


- Without CSM, we will see a sharp rising of luminosity when shock breaks out the stellar surface (~24 hrs after core-collapse)
- With dense CSM, the luminosity rises gradually and reaches a plateau for days to weeks Zimmerman+, Nature **627**, 759 (2024)



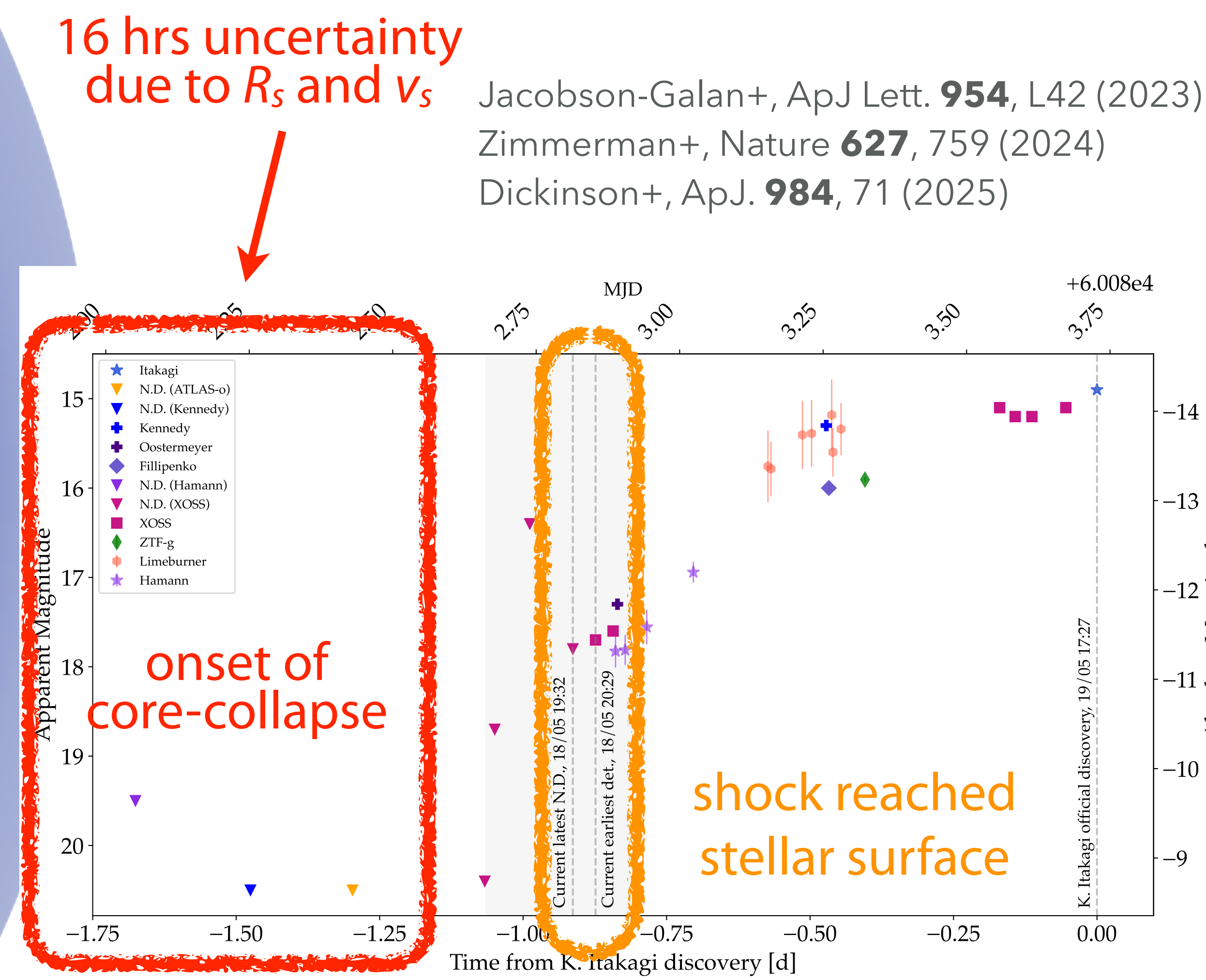
continues for days to weeks

Smith, Ann. Rev. Astron. Astrophys. **52**, 487 (2014)
TNS `https://www.wis-tns.org/`

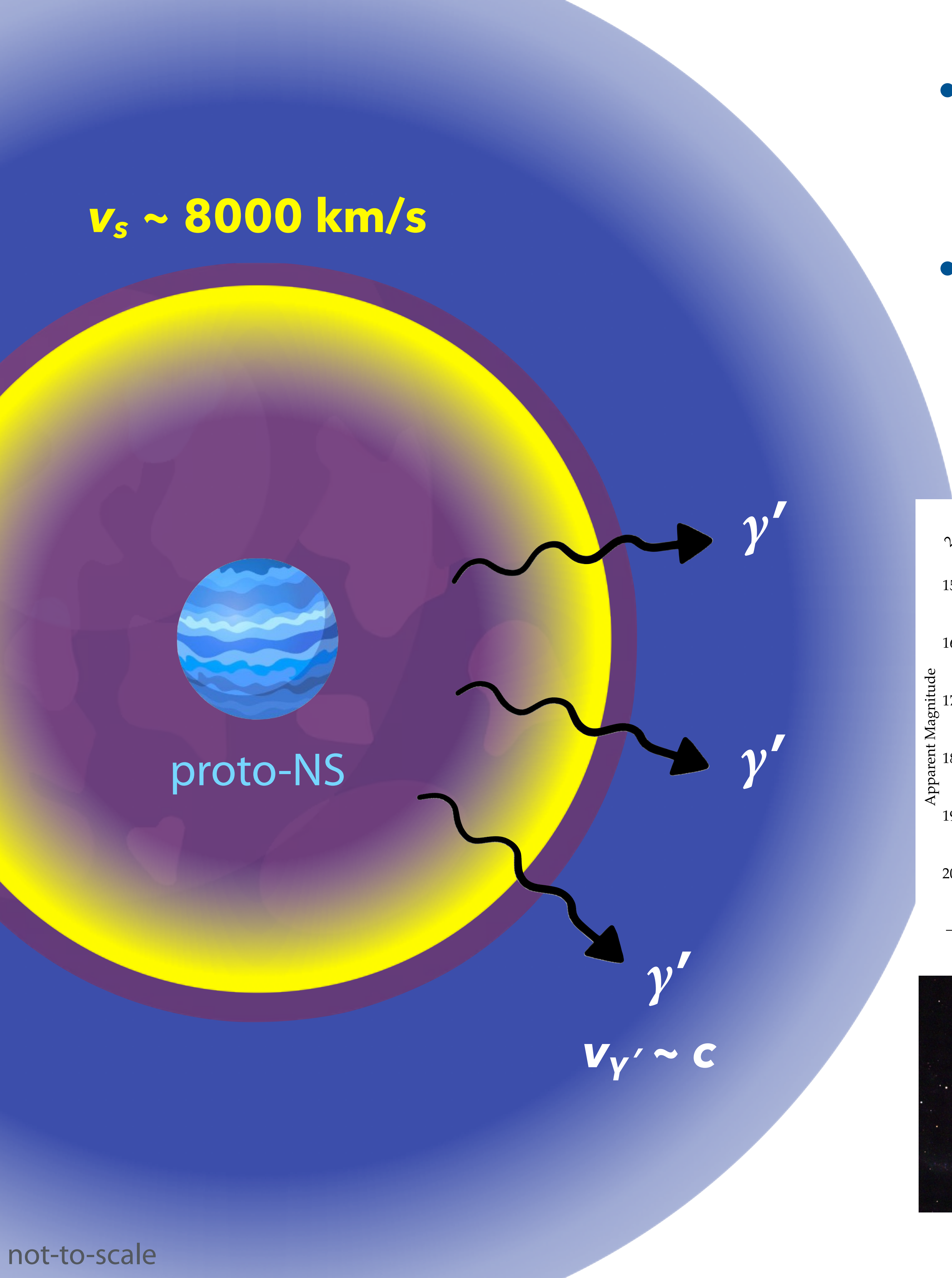


- Knowing the shock breakout time, the reconstruction of the onset of core-collapse is possible

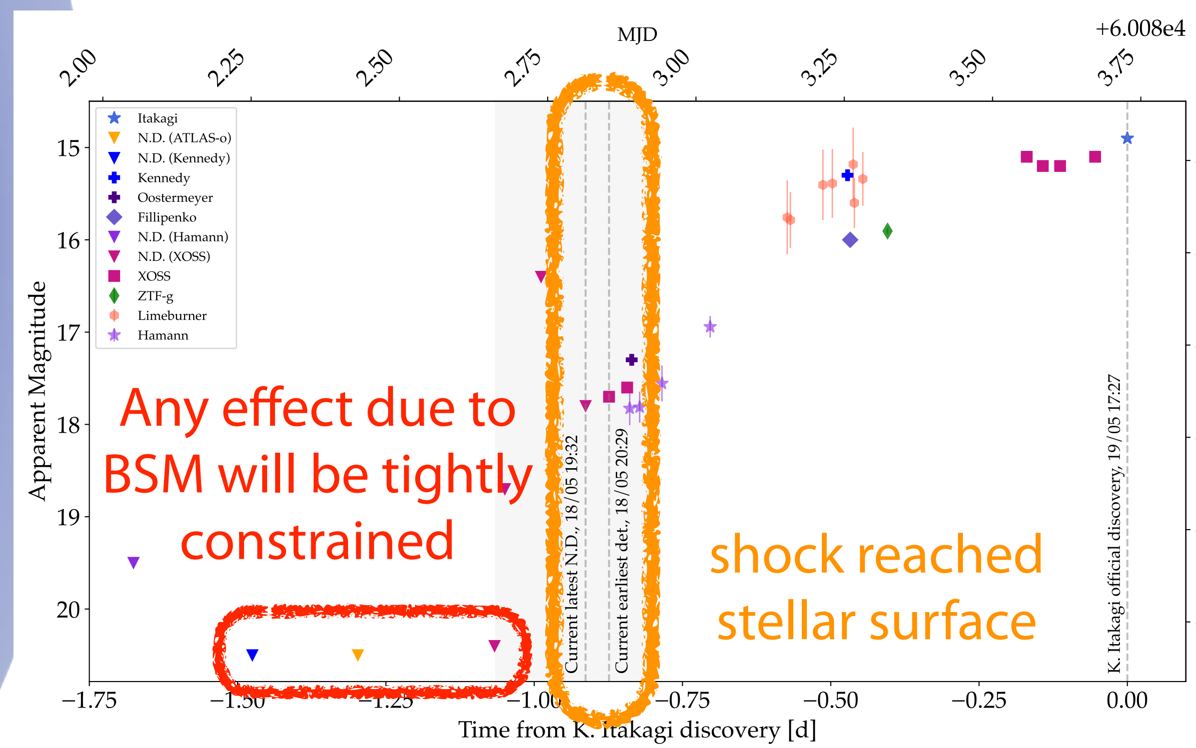
Jacobson-Galan+, ApJ Lett. **954**, L42 (2023)
Zimmerman+, Nature **627**, 759 (2024)
Dickinson+, ApJ. **984**, 71 (2025)

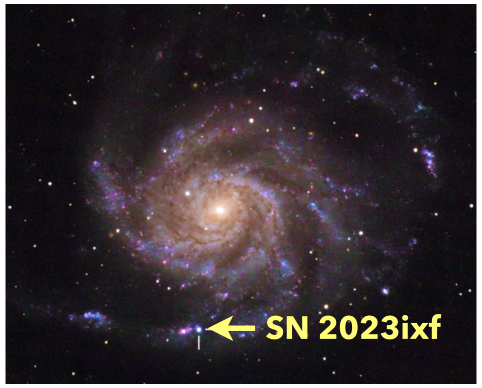


Smith, Ann. Rev. Astron. Astrophys. **52**, 487 (2014)
TNS `https://www.wis-tns.org/`



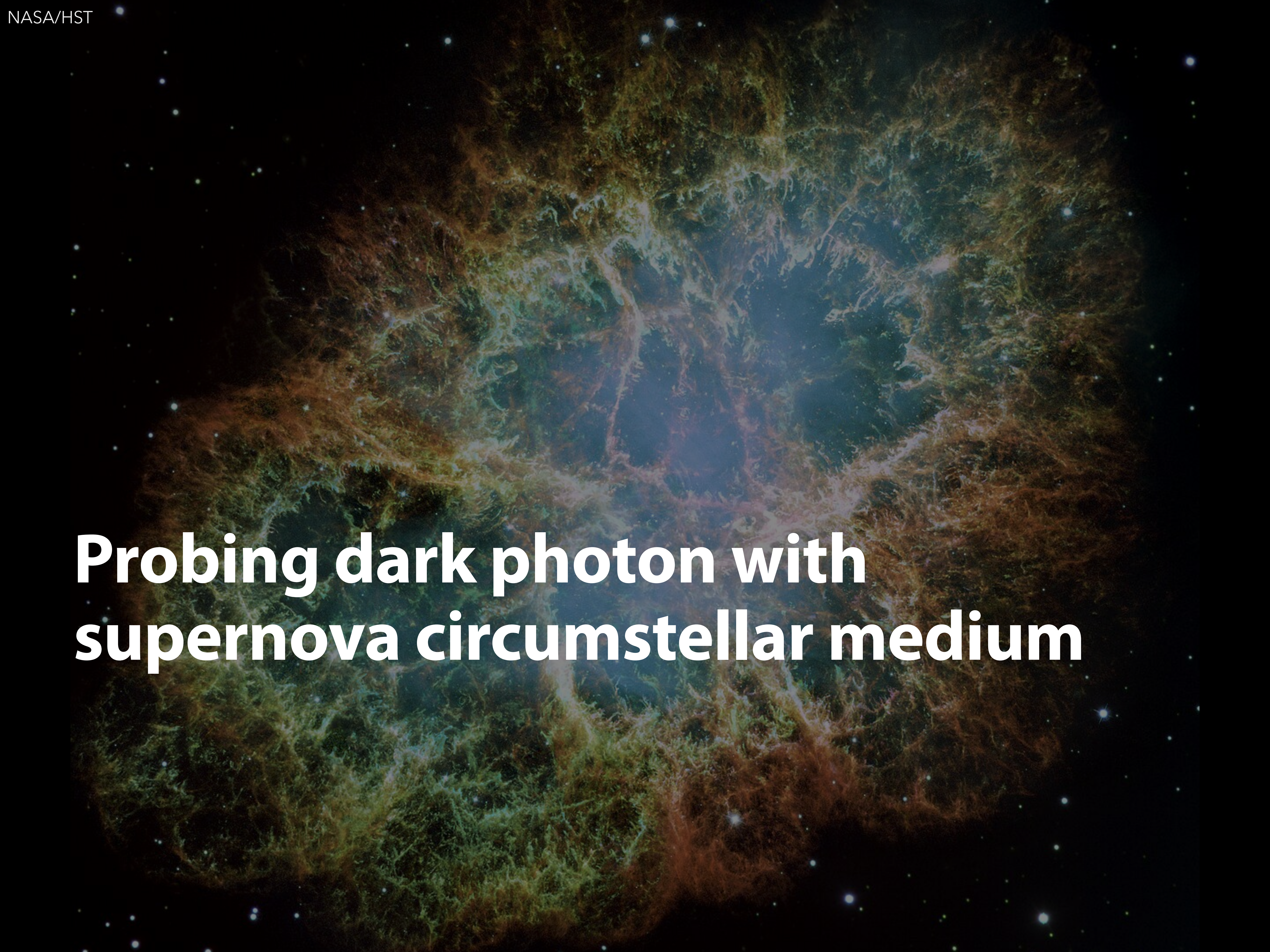
- Knowing the shock breakout time, the reconstruction of the onset of core-collapse is possible
- Any abnormal luminosity due to BSM before shock breakout will be tightly constrained (as $v_{\gamma'} \sim c$)





Smith, Ann. Rev. Astron. Astrophys. **52**, 487 (2014)
TNS `https://www.wis-tns.org/`

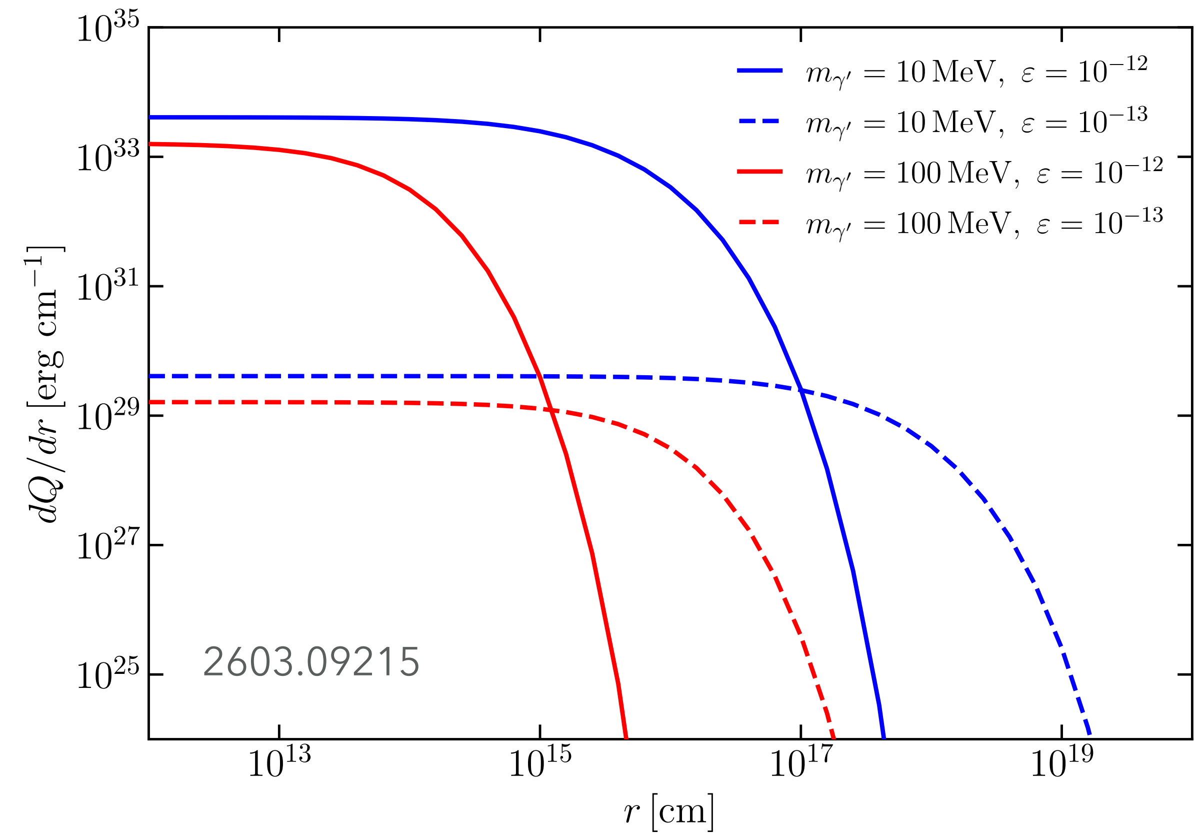
NASA/HST



Probing dark photon with supernova circumstellar medium

- When γ' is produced at PNS, it will free-stream to CSM and decay in to $e^\pm$
- Kinetic energy dQ carried by decayed $e^\pm$ at different shell radius r

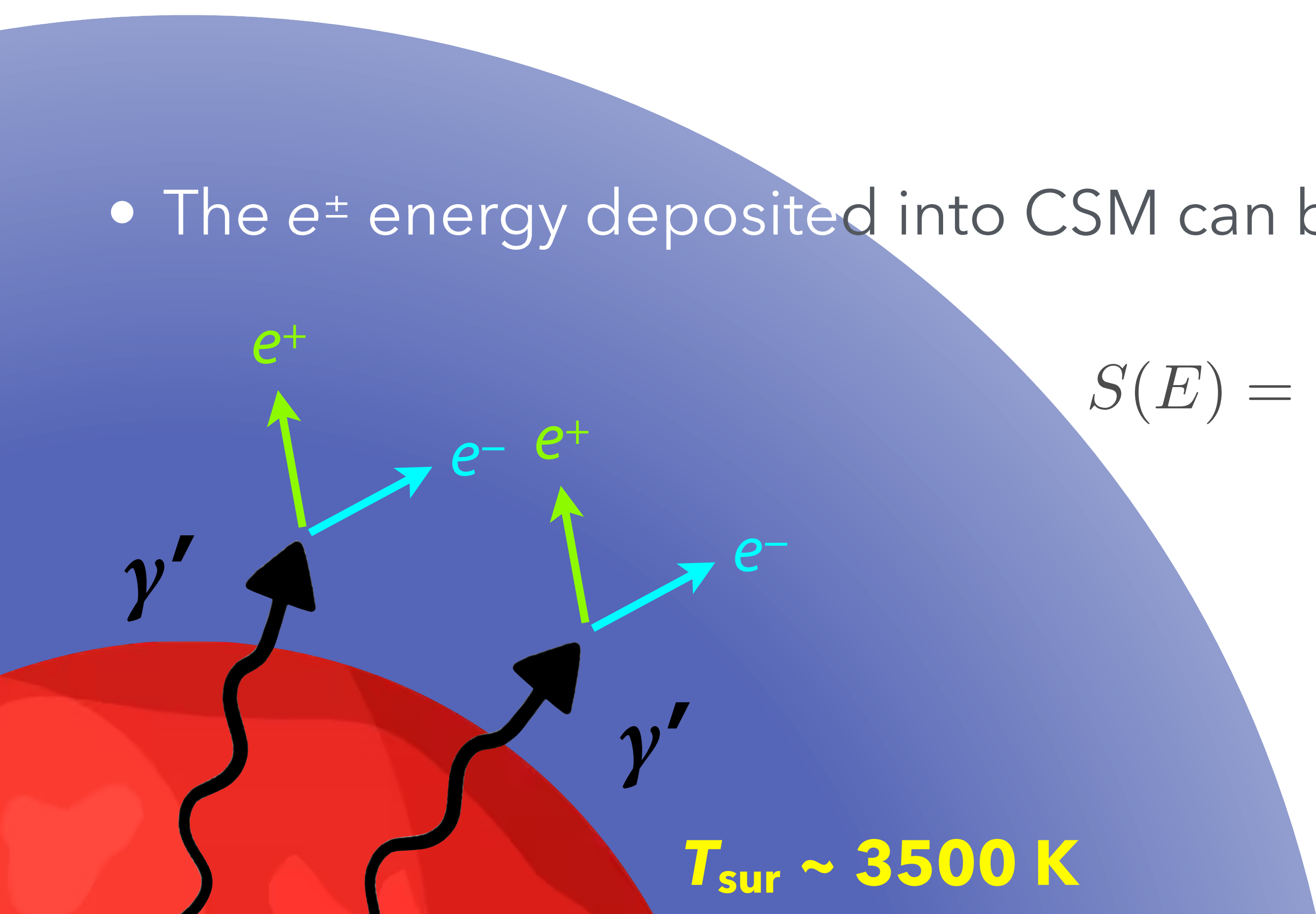
$$\frac{dQ}{dr} = \int \overbrace{dk \frac{1}{L_d} \frac{dN_{\gamma'}}{dk} e^{-r/L_d}}^{\text{number of } e^\pm \text{ produced per } dr} \underbrace{\sum_i \int dE_i E_i \frac{dN_i}{dE_i}}_{\text{integrated } e^\pm \text{ energy spectrum}} =$$



- The $e^\pm$ energy deposited into CSM can be calculated by stopping power

$$S(E) = -\frac{1}{\rho}\frac{dE}{dx}$$

National Institute of Standards and Technology (NIST)
https://physics.nist.gov

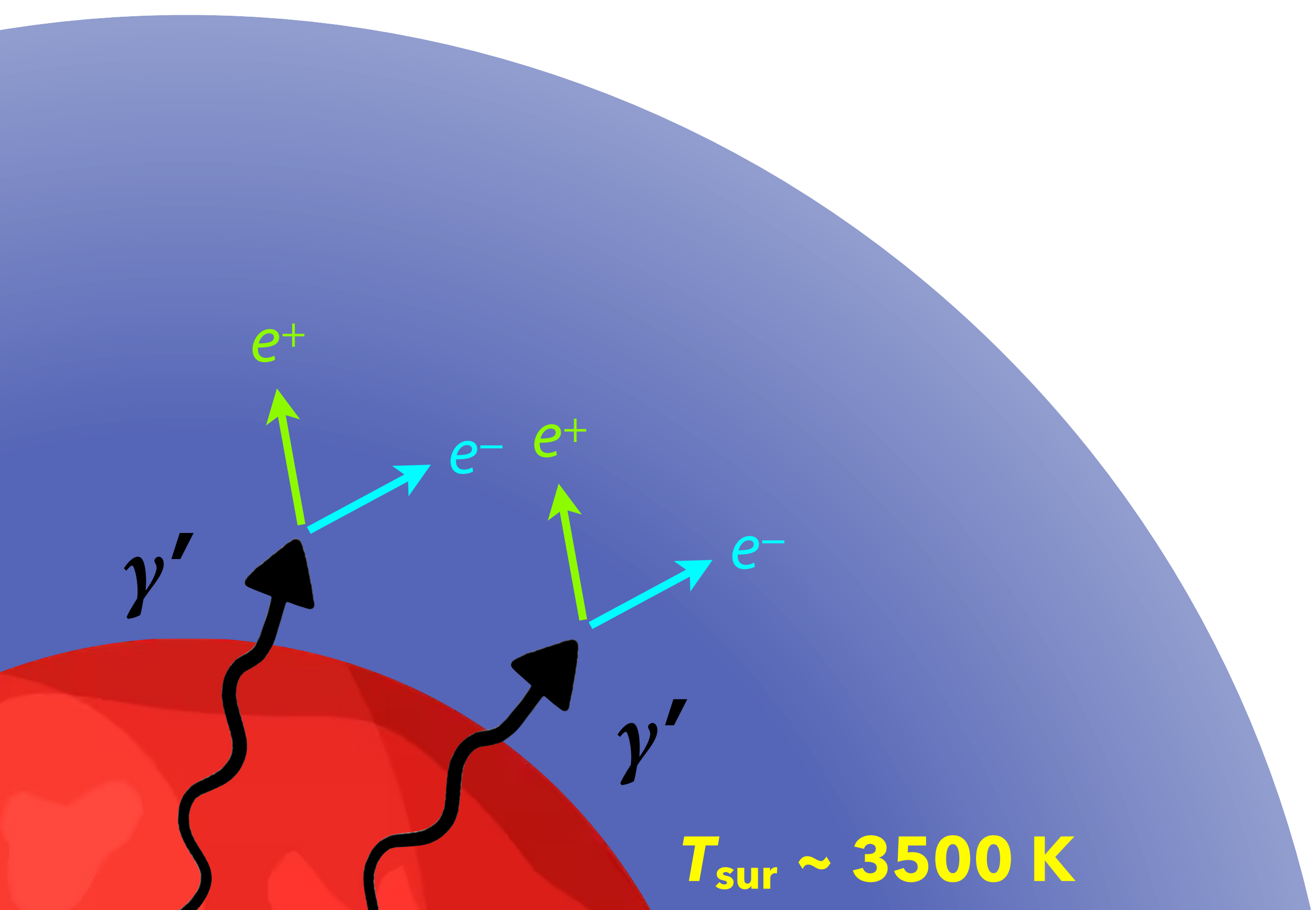


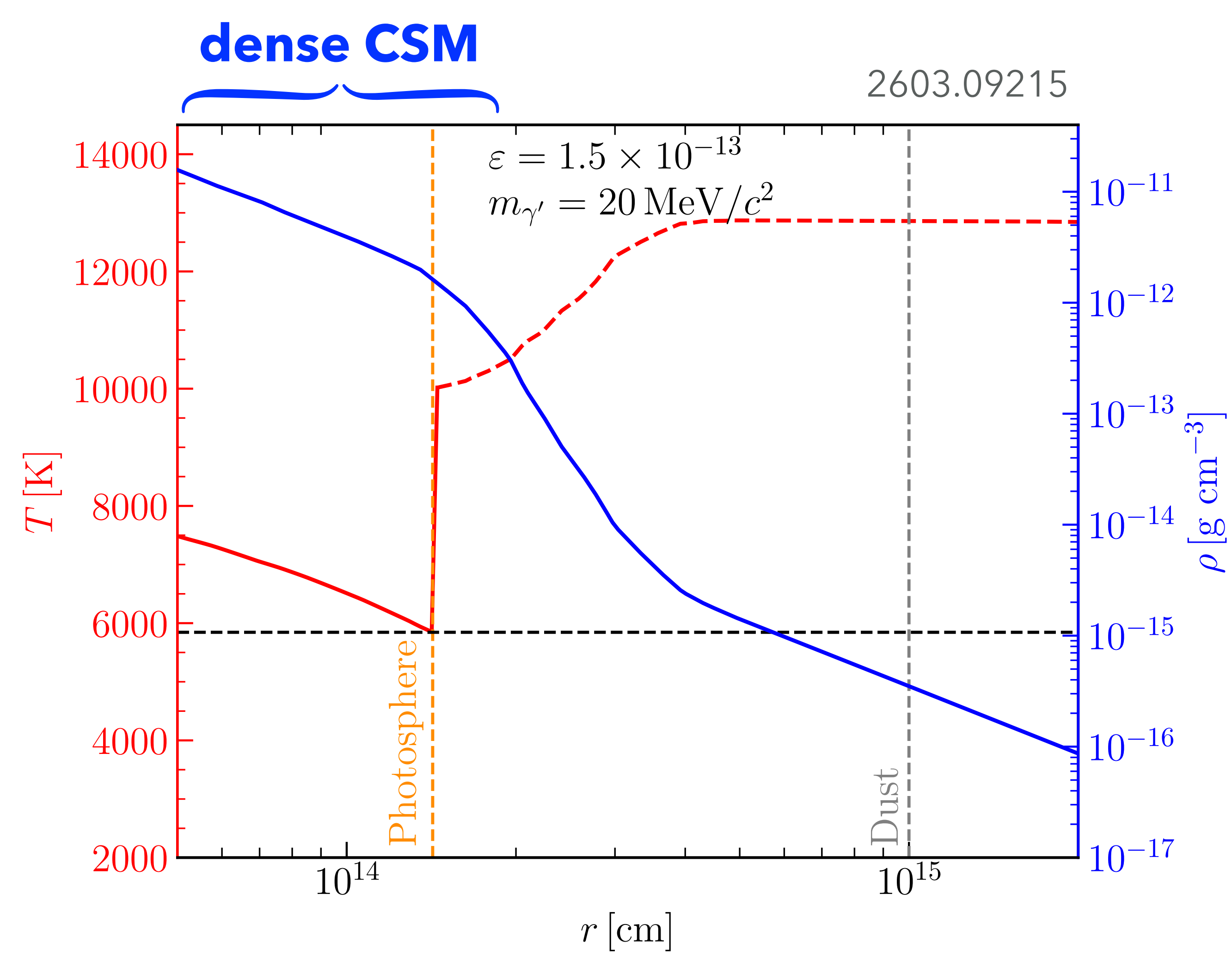
- Energy deposition per shell of $e^{\pm}$ raises the CSM temperature

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

where $\bar{\eta}$ is the energy deposition efficiency

- When temperature is heated beyond 5000 K, opacity κ increases rapidly
- γ'-photosphere $r_{\rm ph}$ corresponds to optical depth τ ~ 2/3





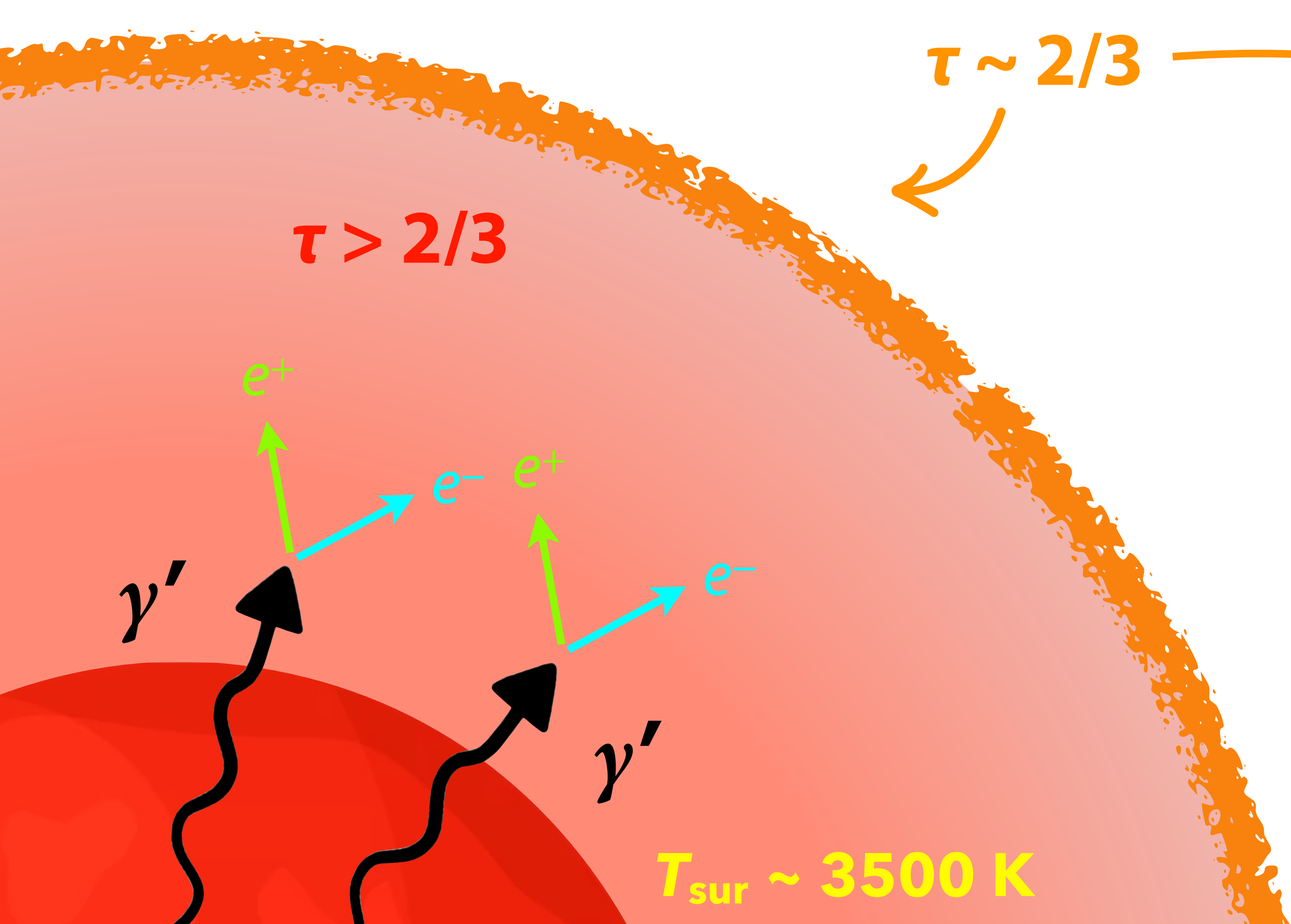
- Energy deposition per shell of e± raises the CSM temperature

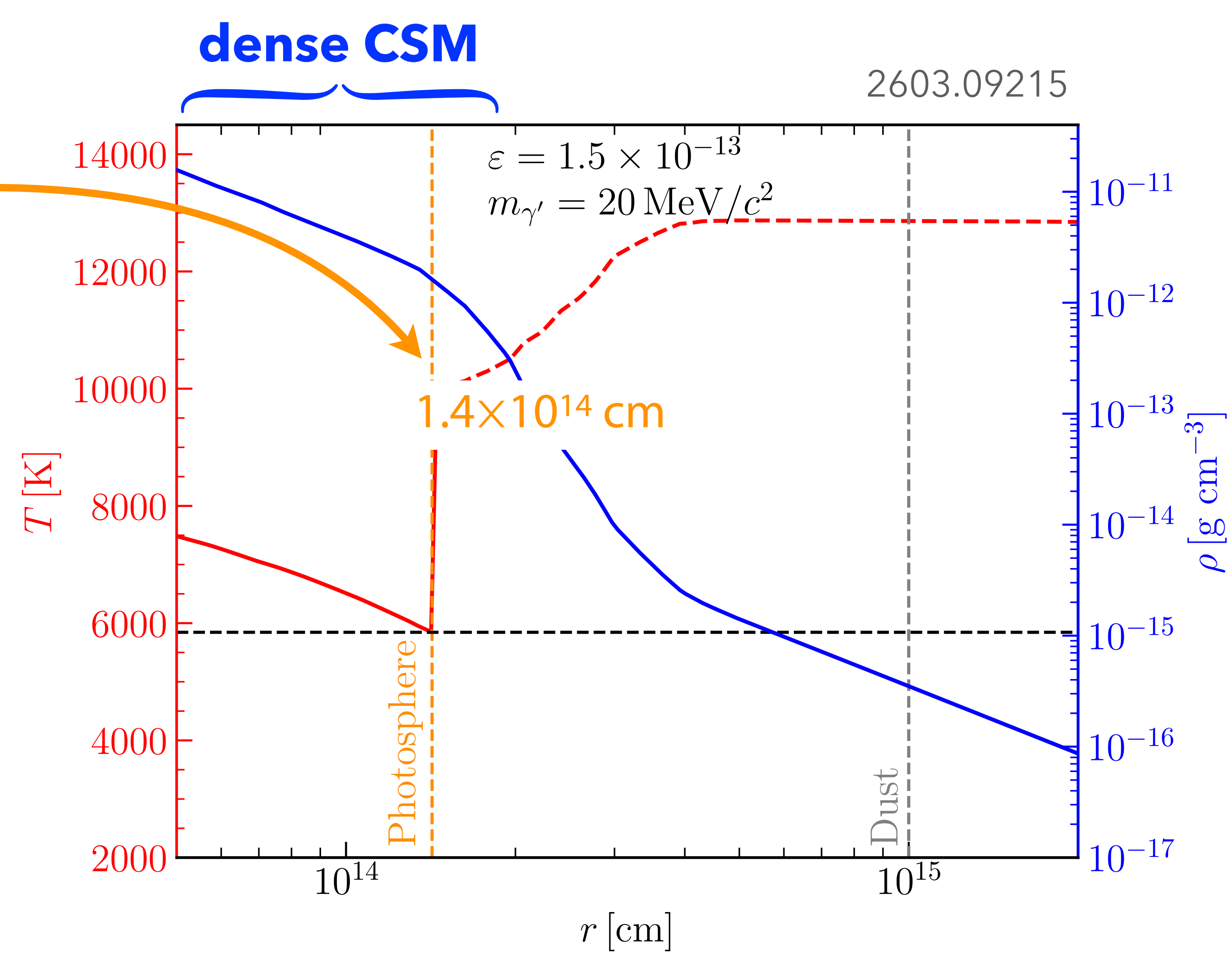
$$\frac{dQ}{dr}\frac{\bar{\eta}}{4\pi r^2} = u_{\rm gas} + I_{\rm ion} + u_{\rm rad}$$

where $\bar{\eta}$ is the energy deposition efficiency

- When temperature is heated beyond 5000 K, opacity κ increases rapidly

- γ′-photosphere $r_{\rm ph}$ corresponds to optical depth τ ~ 2/3





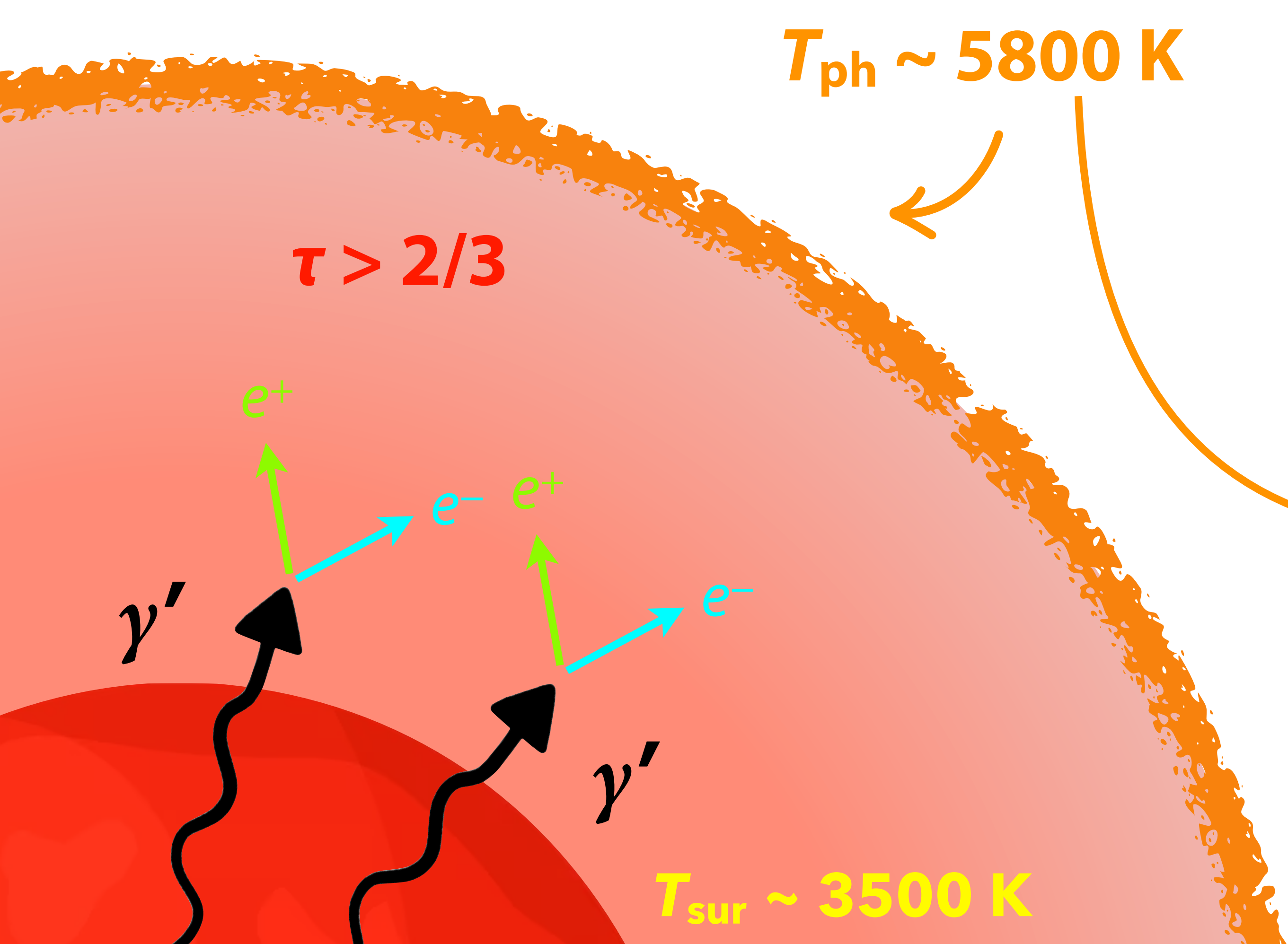
- The photosphere temperature $T_{\rm ph}$ ~ 5800 K with with blackbody radiation

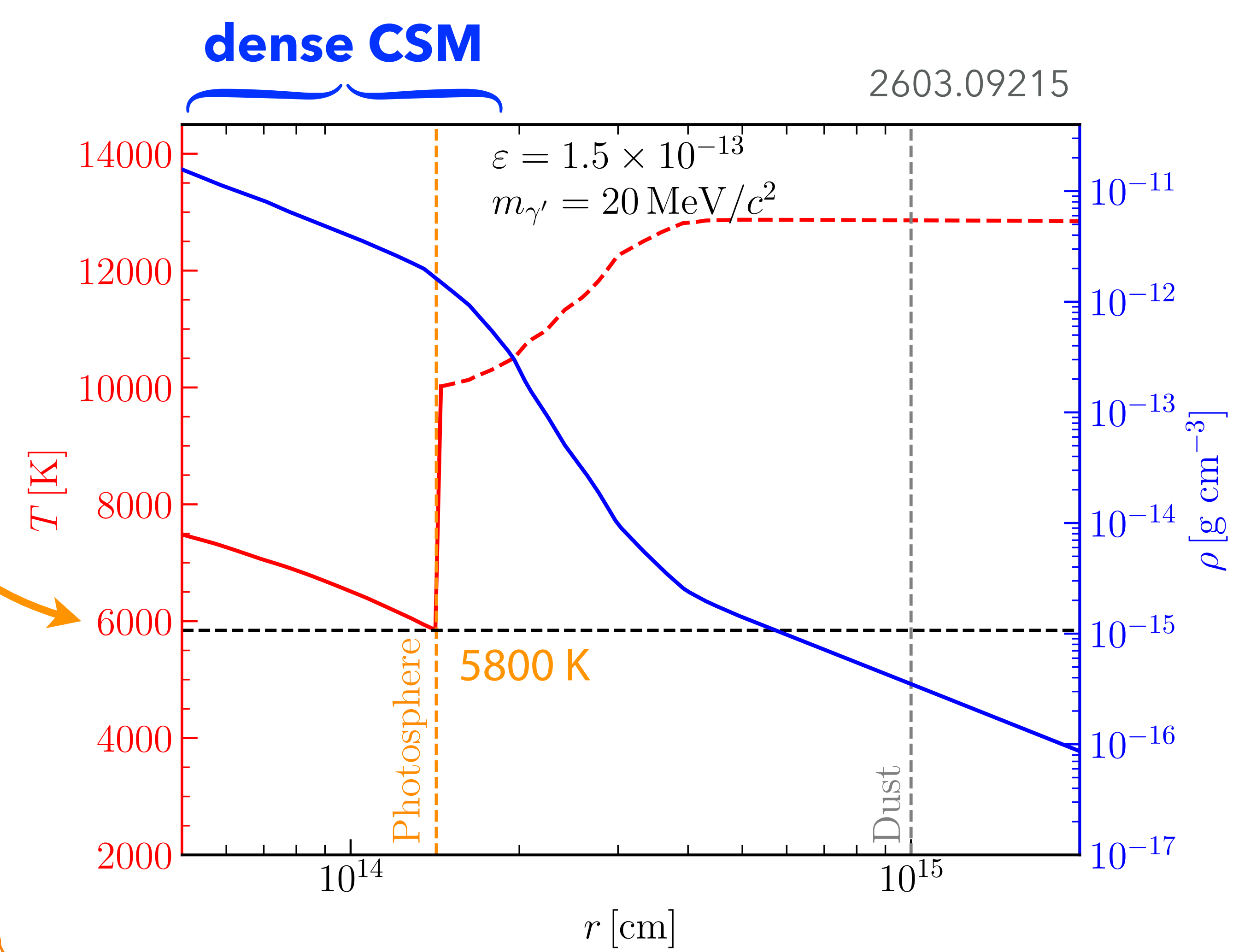
$$L_{\rm BB} = 4\pi r_{\rm ph}^2 \sigma_{\rm SB} T_{\rm ph}^4 \sim 8 \times 10^{39} \ {\rm erg/s}$$

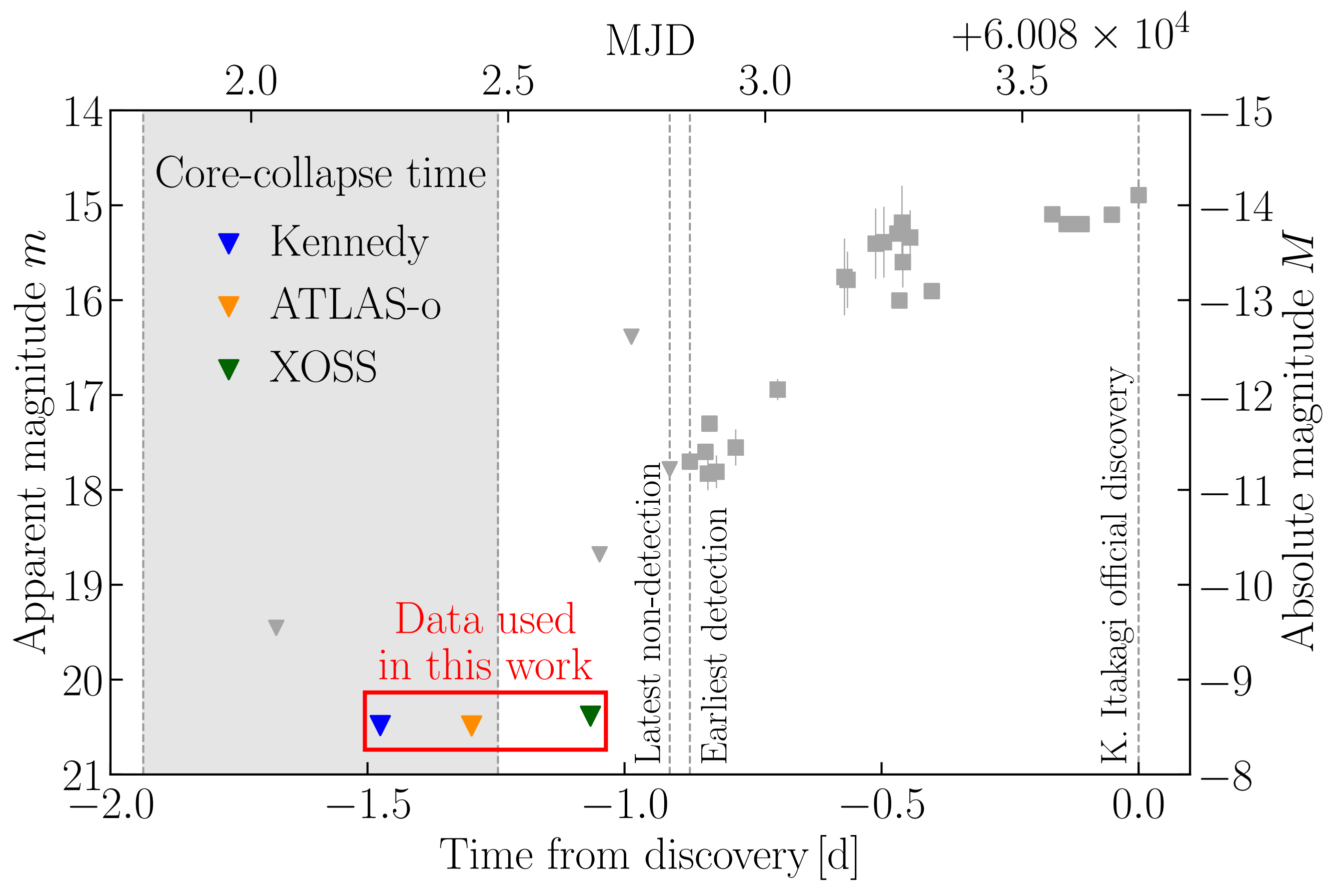
- The average optical depth $\bar{\tau} \sim 17.6$ and the photosphere will radiate light about

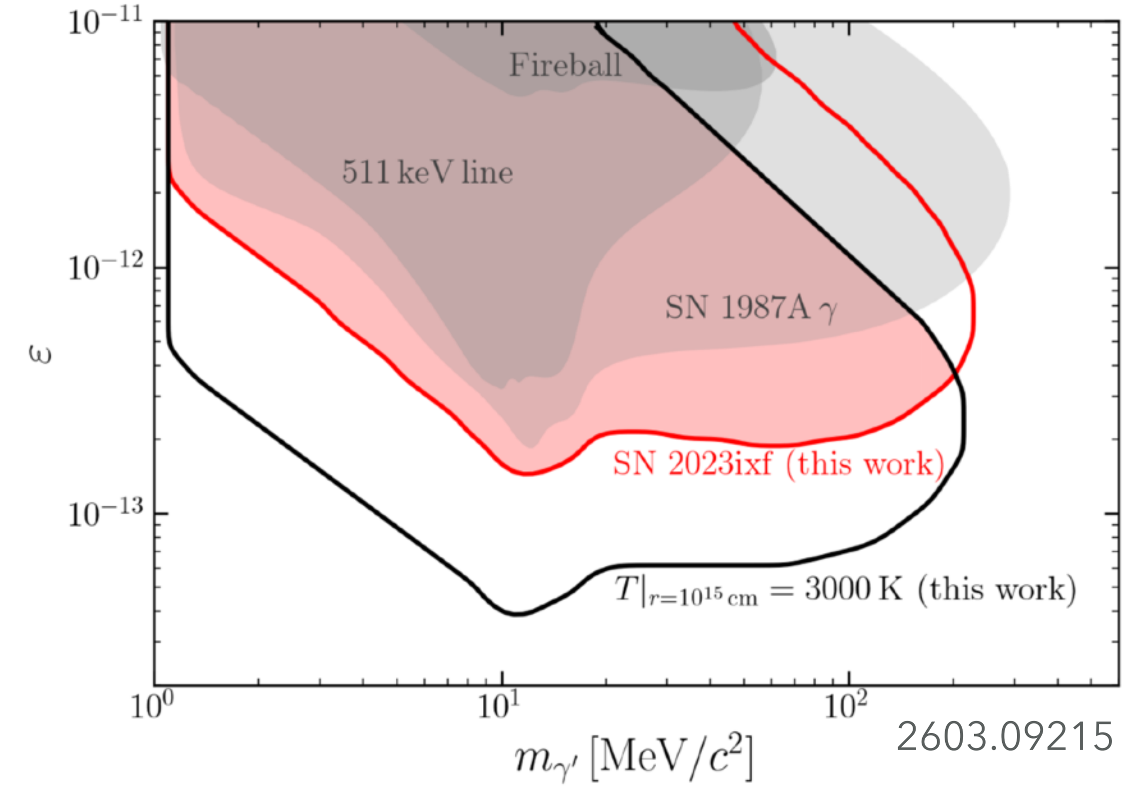
$$t_{\rm last} \sim \frac{\bar{\tau} r_{\rm ph}}{c} \sim 22.8 \ {\rm hrs}$$

- γ' arrives CSM 3 hrs after core-collapse and the induced-photosphere will radiate about 22.8 hrs → precursor signal to shock breakout









2603.09215

- The three non-detection data points set an upper limit on the luminosity of SN 2023ixf before shock breakout

$$L_{\gamma'} \lesssim 10 L_{\rm obs} \approx 8 \times 10^{39}\ {\rm erg/s}$$

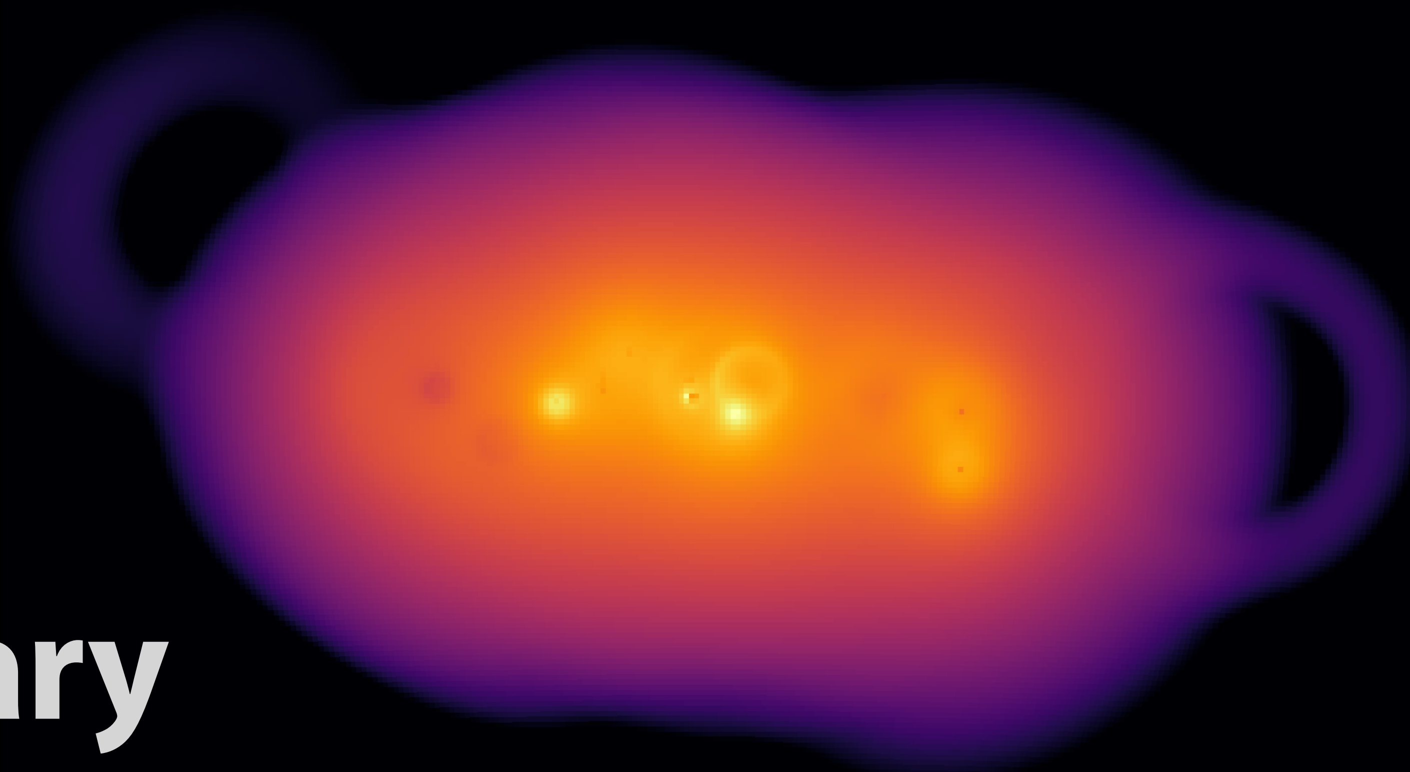
- The maximum energy can be carried by γ' to avoid exceeding $L_{\rm obs}$

$$Q_{\gamma'} \lesssim 2.5 \times 10^{44}\ {\rm erg}$$

- The constraint is shown by the pink-shaded region.

- Black solid line encloses the region where the signal will not be reprocessed by dust (due to sufficient γ' heat to sublimate the dust)

Summary

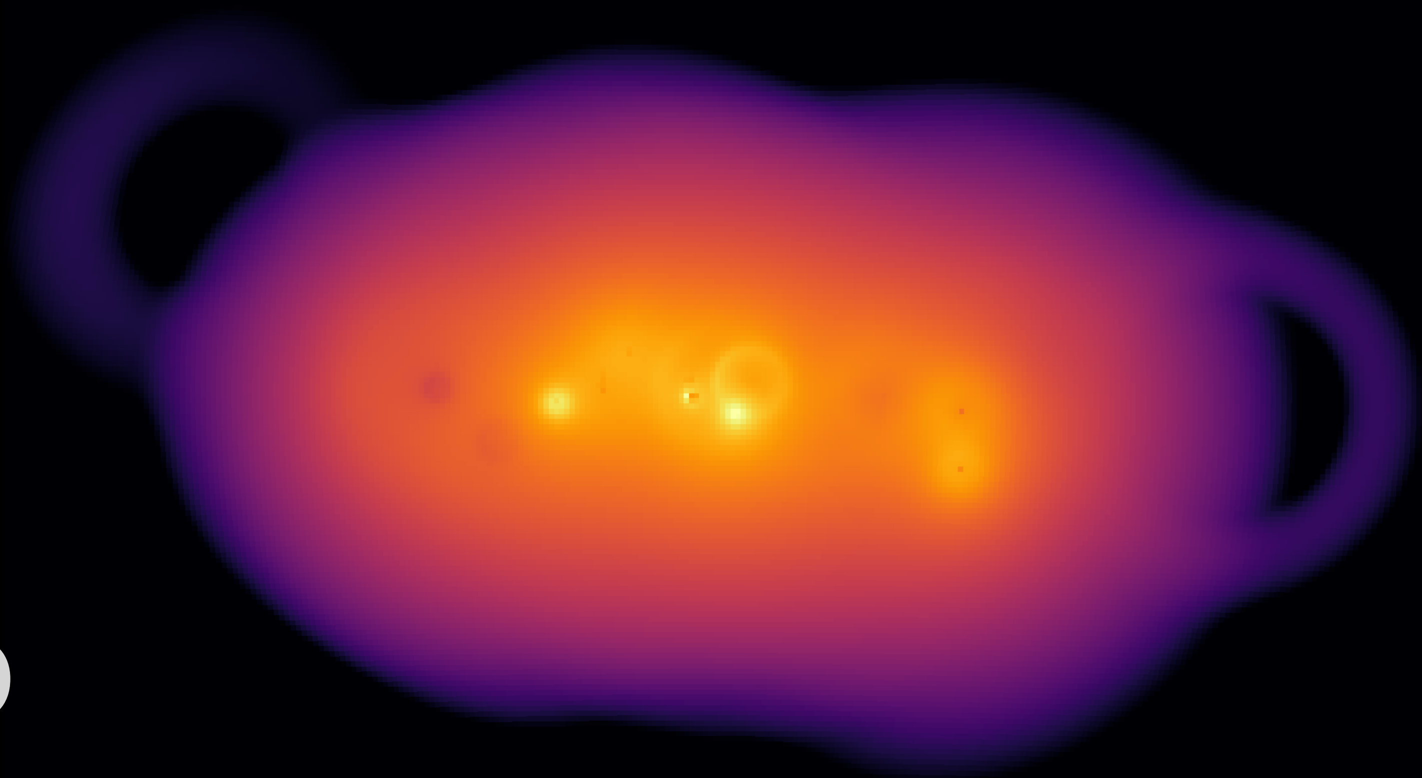


Summary

- We demonstrate that CSM can be a novel probe for precursor signature from FIP particles produced during SN explosion
- The first derived constraint from SN 2023ixf that outperforms other existing ones
- Maximum energy can be transferred to FIP is (new cooling bound)

$$Q_{\gamma'} \lesssim 2.5 \times 10^{44}\ \mathrm{erg}$$

- Next galactic SN will offer significantly better constraint due to the onset of core-collapse will be known better from SN neutrino
- Dust sublimation can be a potential treatment to probe lower ε than the CSM for the next galactic SN



Backup

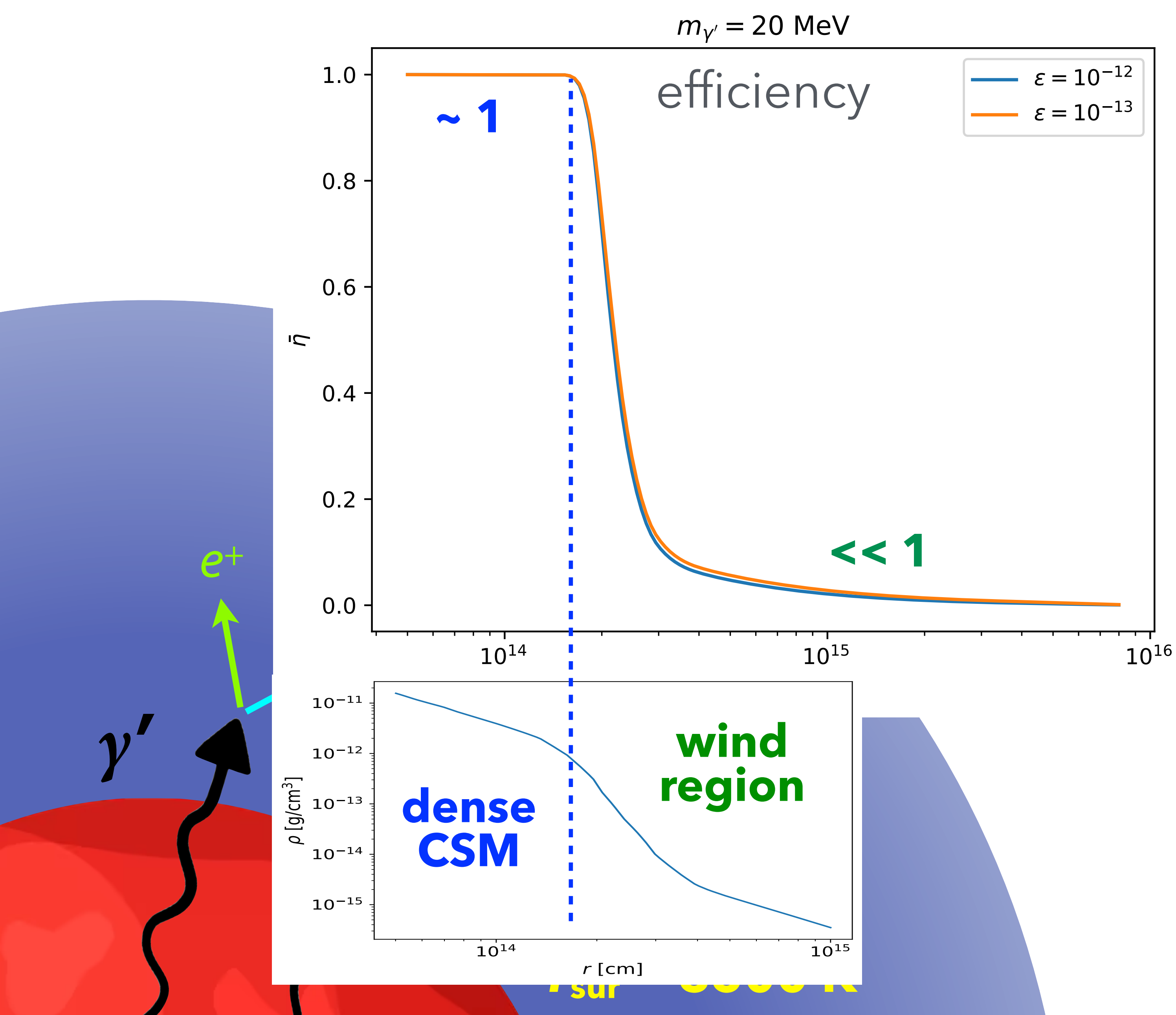
- When e± propagates, it loses its kinetic energy to the CSM via scattering

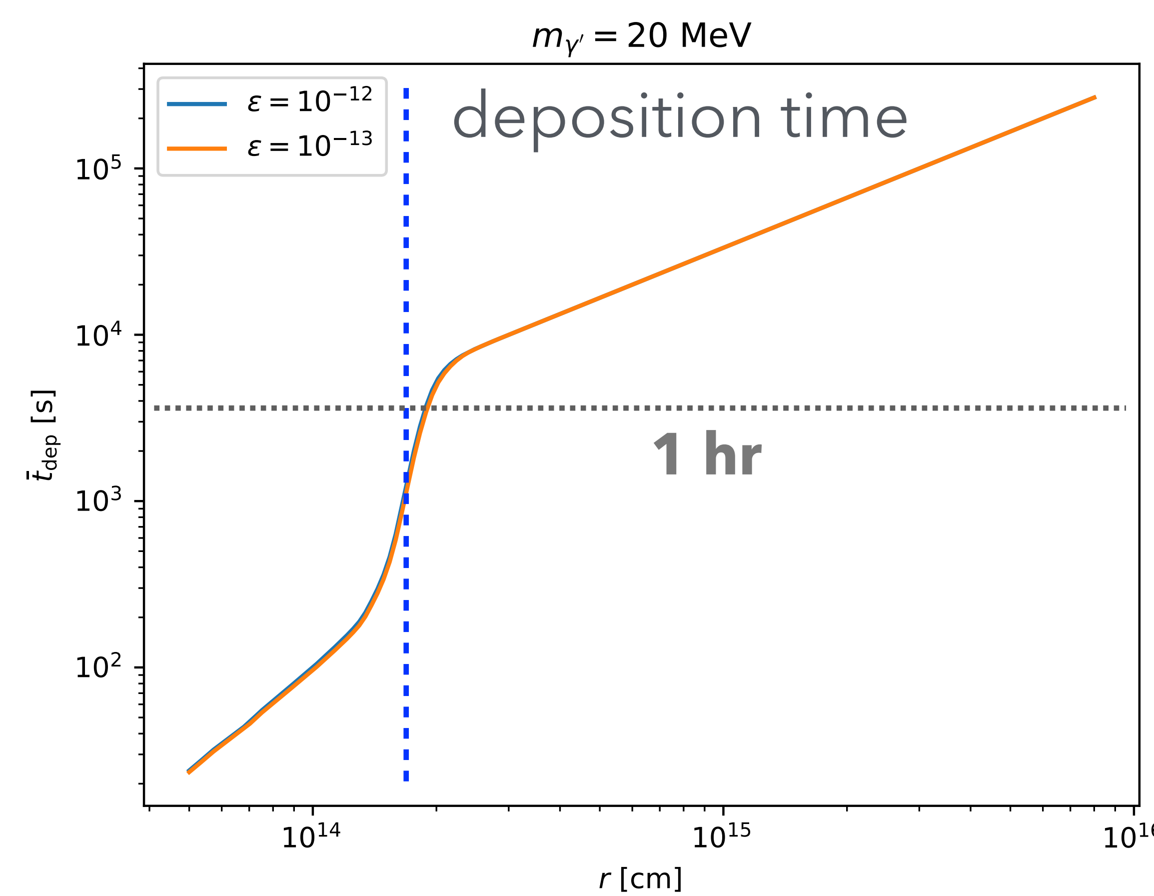
$$S(E) = -\frac{1}{\rho}\frac{dE}{dx}$$

National Institute of Standards and Technology (NIST)
https://physics.nist.gov

where $S(E)$ is the electron stopping power (MeV cm^2/g) at different energy and medium taken from the ESTAR table provided by NIST

- The energy deposition efficiency $\eta = \delta E_e / E_e$

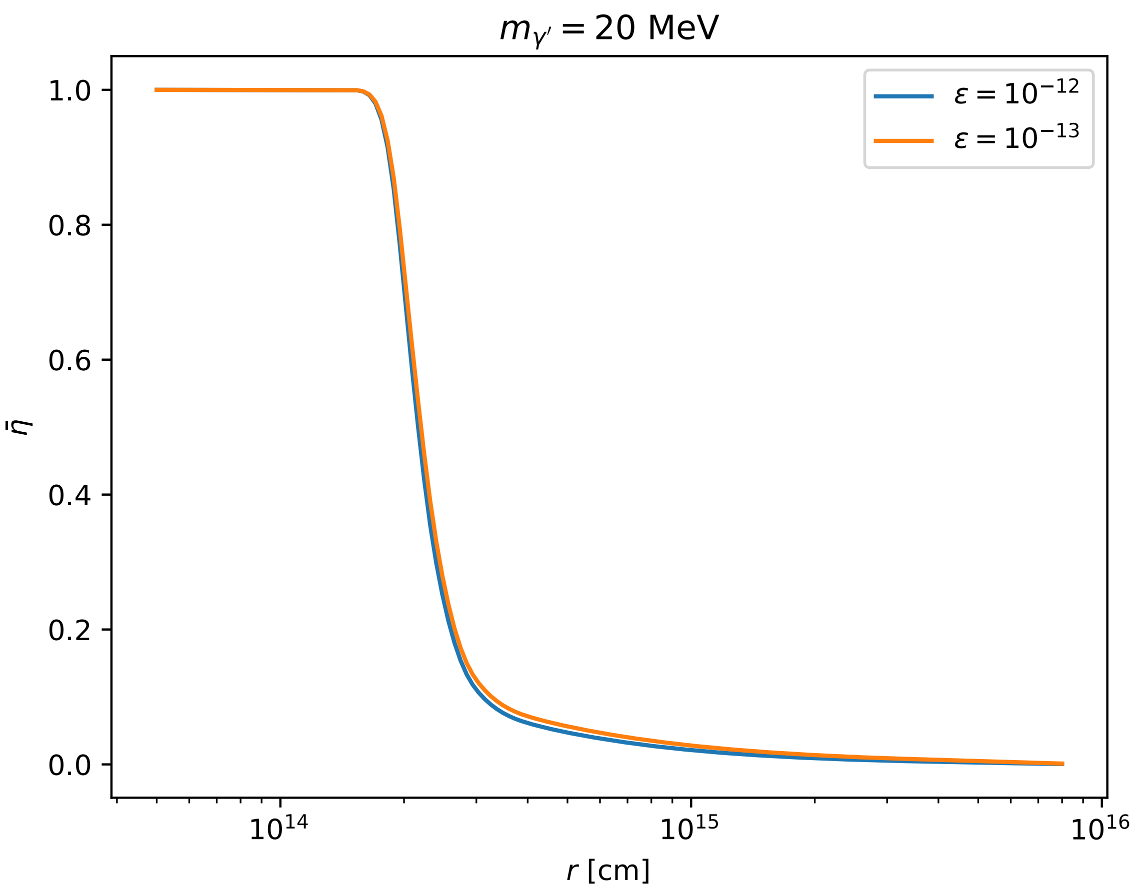


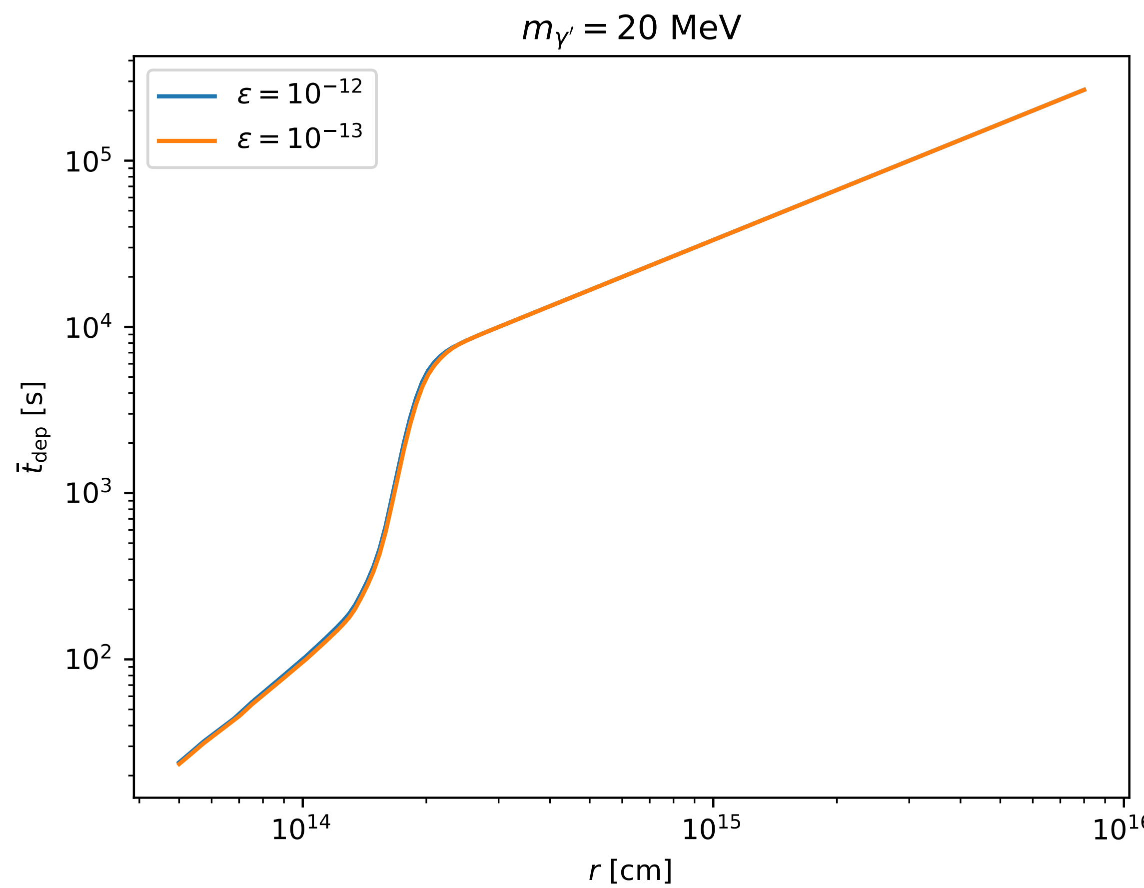


$$\bar{t}_{\rm dep} \gg \tau_{\rm dyn} \sim \mathcal{O}(1\text{–}10)\ \rm yrs$$

e± heating is considered as instantaneous average energy deposition efficiency

average energy deposition time





$$\eta = \frac{E_0 - E'}{E_0}$$

$$t_{\rm dep} = \frac{\delta r_{\rm stop}}{c}$$

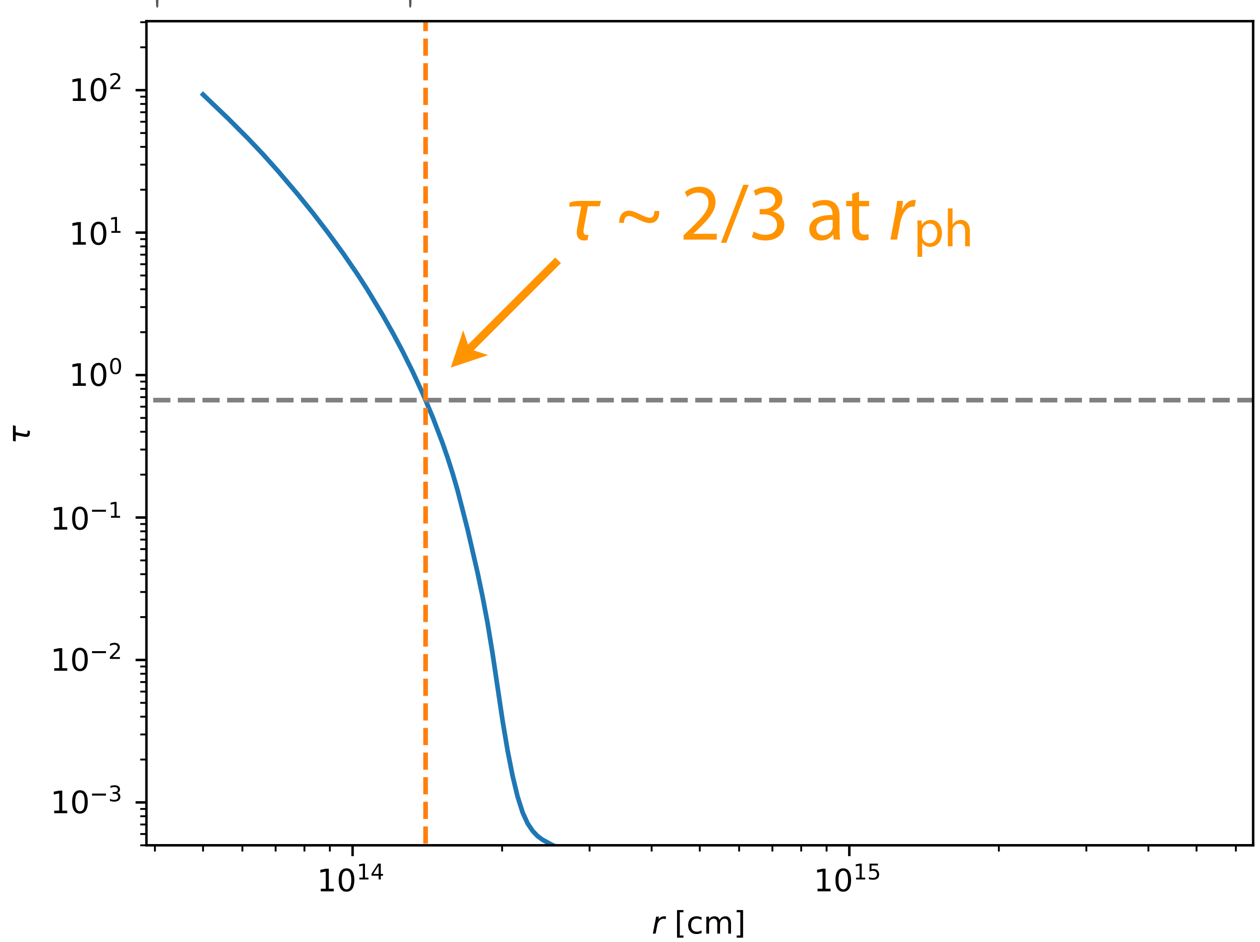
$$\bar{\eta}(r) = \frac{\int dE_e \frac{dQ(r)}{dr dE_e} \eta(E_e, r)}{\int dE_e \frac{dQ(r)}{dr dE_e}}$$

$$\bar{t}_{\rm dep}(r) = \frac{\int dE_e \frac{dQ(r)}{dr dE_e} t_{\rm dep}(E_e, r)}{\int dE_e \frac{dQ(r)}{dr dE_e}}$$

- The length to make $E' = 0$ is the stop-ping length $\delta r_{\rm stop}$
- Numerically, we take $\delta r_{\rm stop} = \min(\delta r_{\rm stop}, r)$

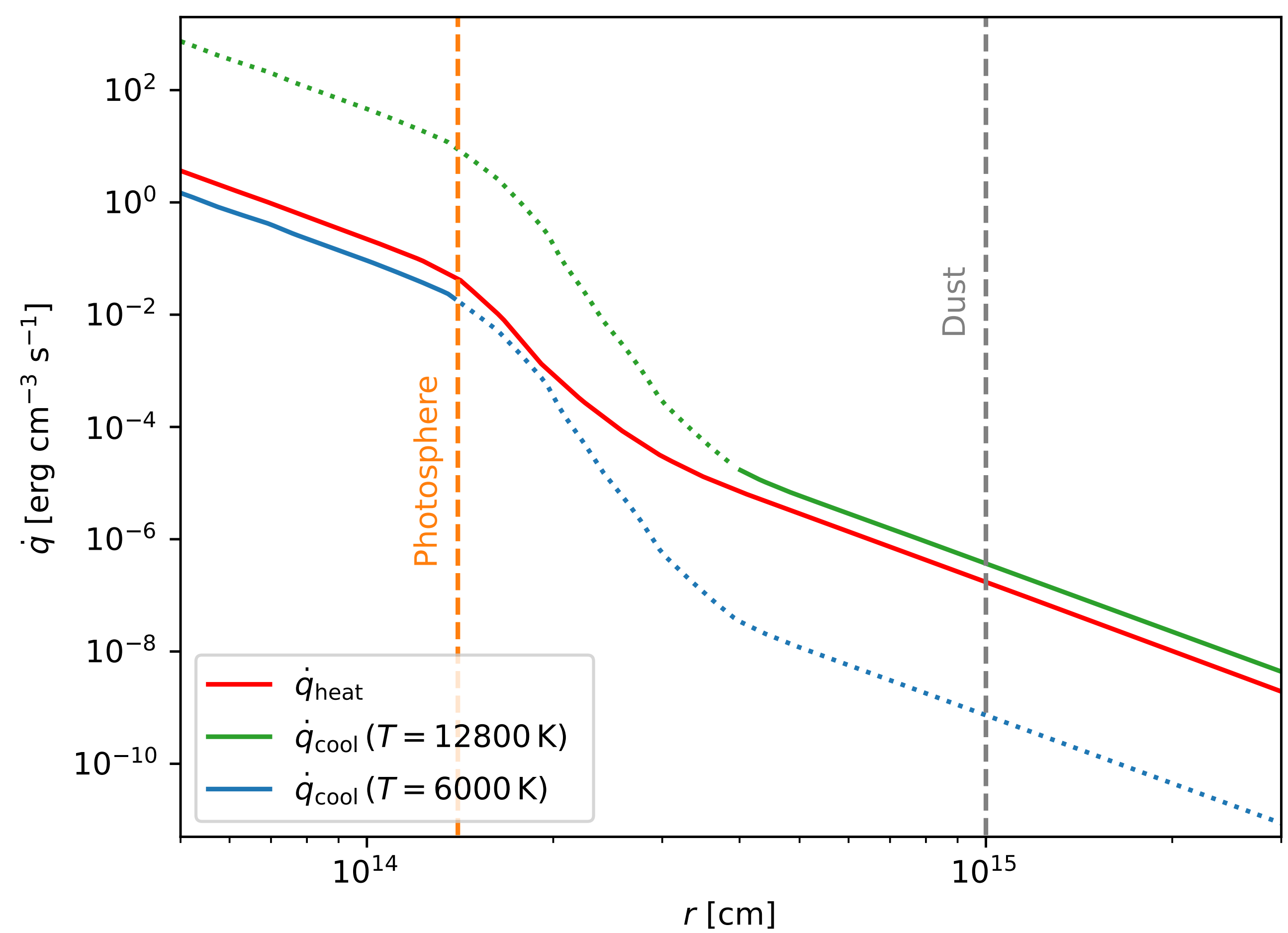
$$\int_r^{r+\delta r_{\rm stop}} \rho(x) dx = -\int_{E_0}^{0} \frac{dE}{S(E)}$$

$\bar{\tau} \approx 17.6$



optical depth

$\varepsilon = 10^{-12}$ and $m_{\gamma'} = 20$ MeV

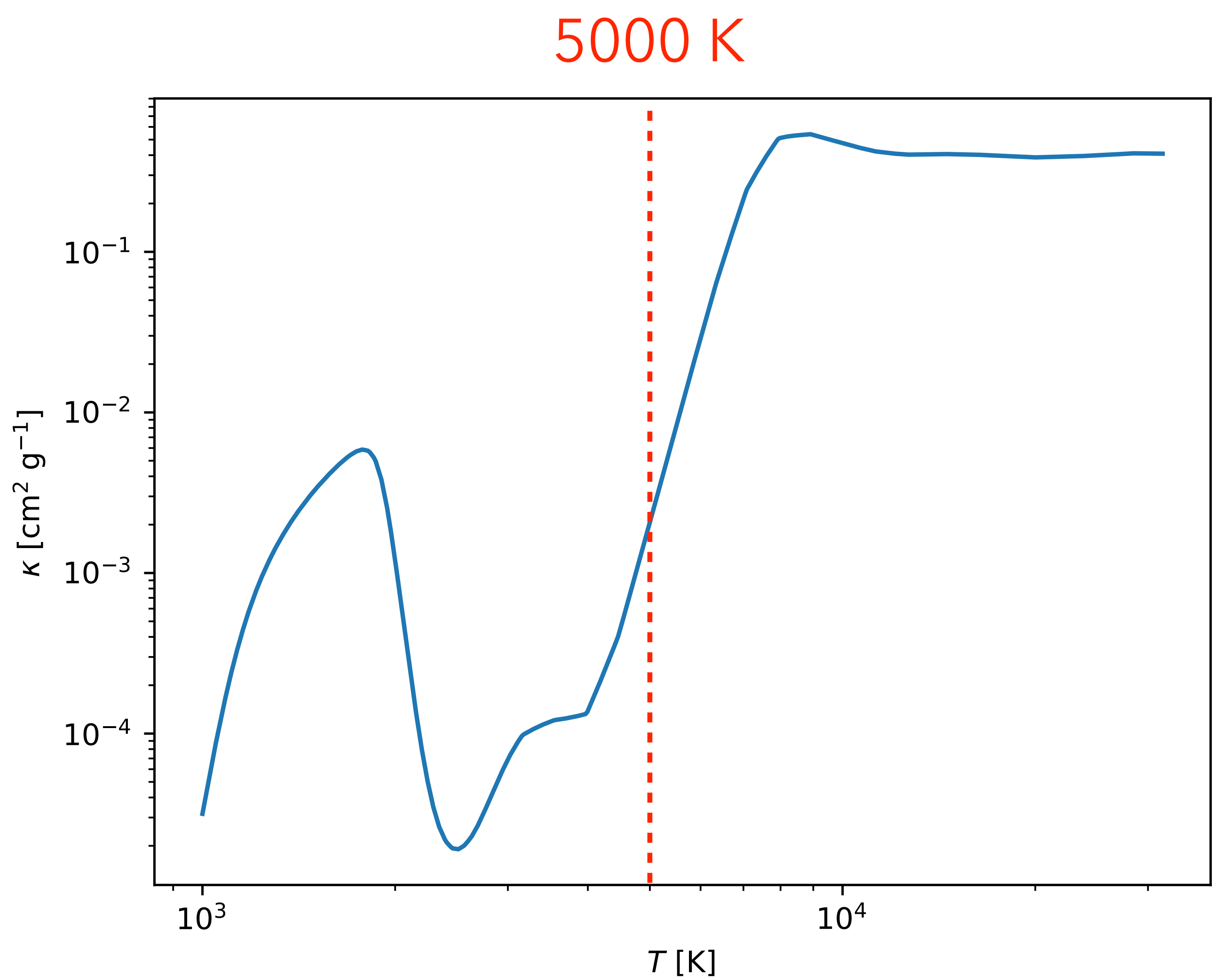


comparison of cooling rate & heating rate

$$q_{\rm cool}(T) = \Lambda(T) n_H^2$$

$\Lambda(T)$: radiative loss function (cm^3 erg/s)

Schure+, Astron. Astrophys. **508**, 751 (2009)

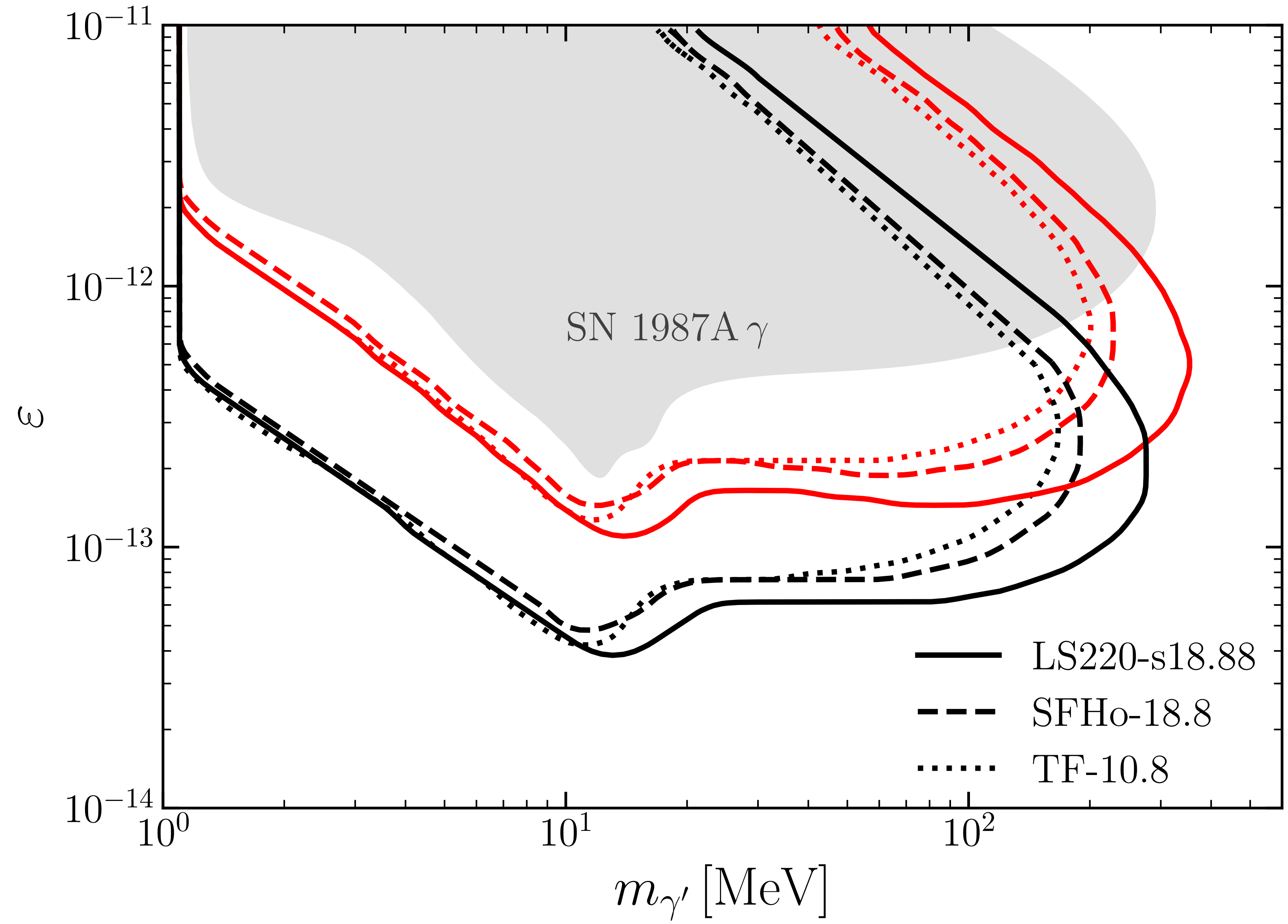


opacity

solar composition (H,He,metals) = (0.7,0.28,0.02)

Tables from { Ferguson when $T < 10^4$ K
OPAL otherwise

Iglesias+, ApJ. **464**, 943 (1996)
Ferguson+, ApJ. **623**, 585 (2005)



Constraints derived from different EoS