Circumstellar Medium of Supernovae as New Probes for BSM

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arXiv:2603.09615

@ "New perspectives on flavor and symmetries in particle physics"

Outline

01 Introduction

- Brief overview of core-collapse supernovae (CCSNe)
- Implications of BSM w/o **circumstellar medium (CSM)**

02 BSM w/ CSM

- Visible decay in CSM ➡ Heating prior to shock breakout
- Inner CSM: increasing opacity & T ☞ L_{BB} ⇧
- Outer CSM: dust resublimation

03 Application to Dark Photons

- In-medium production in PNS
- $\gamma' \to e^- e^+$ in CSM

04 Results

- None-detection of excessive precursor BB luminosity of SN 2023ixf
- [Future galatic SNe] spectral transition (IR → Optical/UV) before SBO

CCSNe & BSM w/o CSM

- Gravitational collapse of iron core & proto-neutron star formation

✓ Diffusive νenergy transport & ν-driven SN explosion

➡ **Cooling argument of novel particles in PNS & gain region**

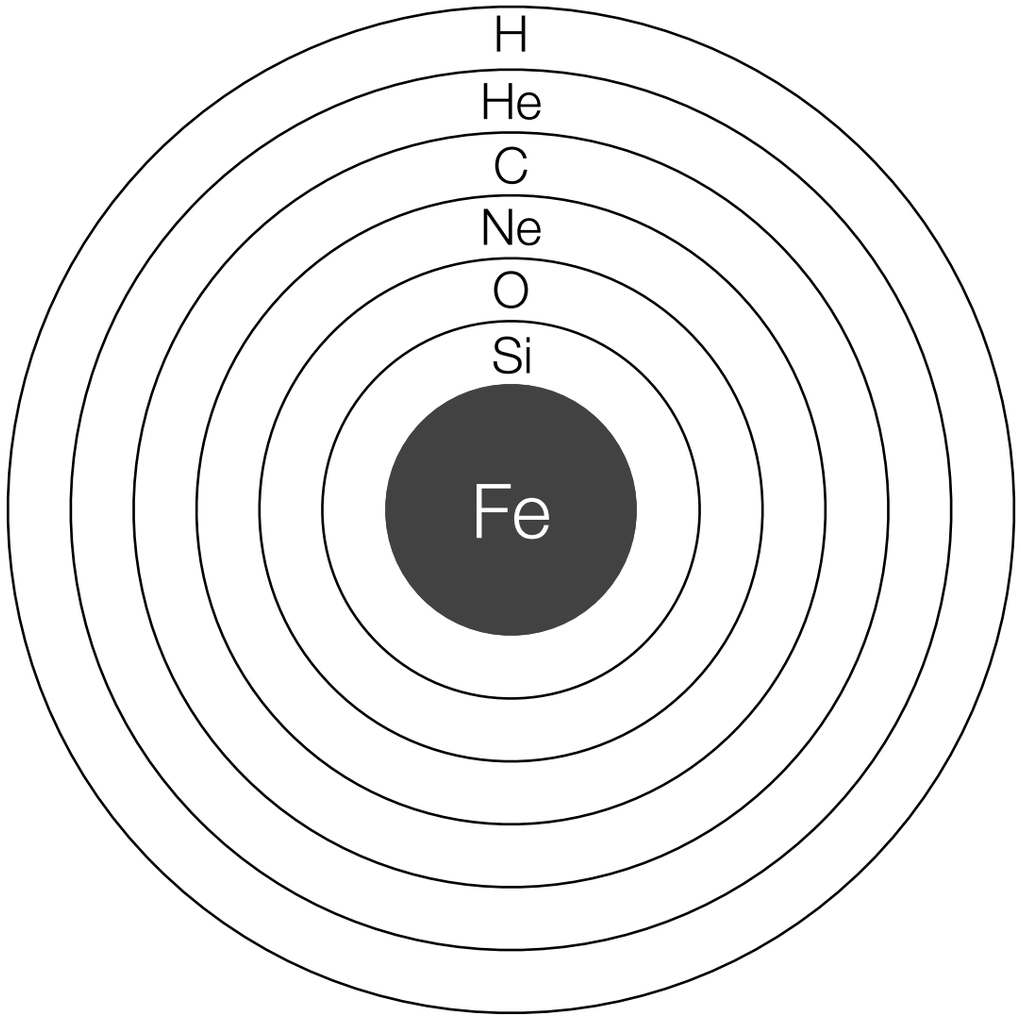
✓ Energy transport to outer regions, leading to visible signals

- **mantle: supernova explosion energy**
- **outside the progenitor: fireball formation, galactic 511keV, prompt γ-ray**

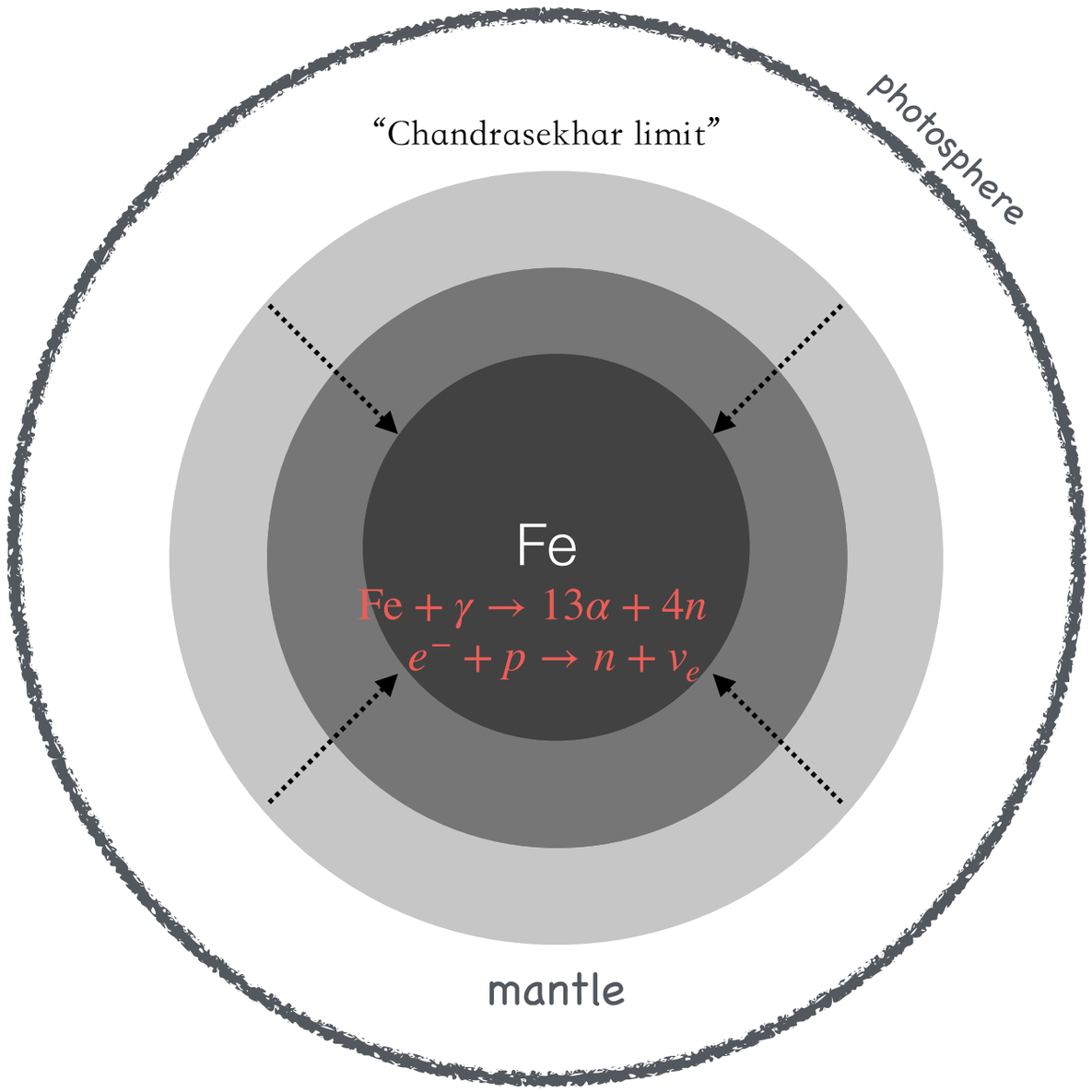
★ **conventionally, in assumption of vacuum outside progenitor**

Core-Collapse Supernova

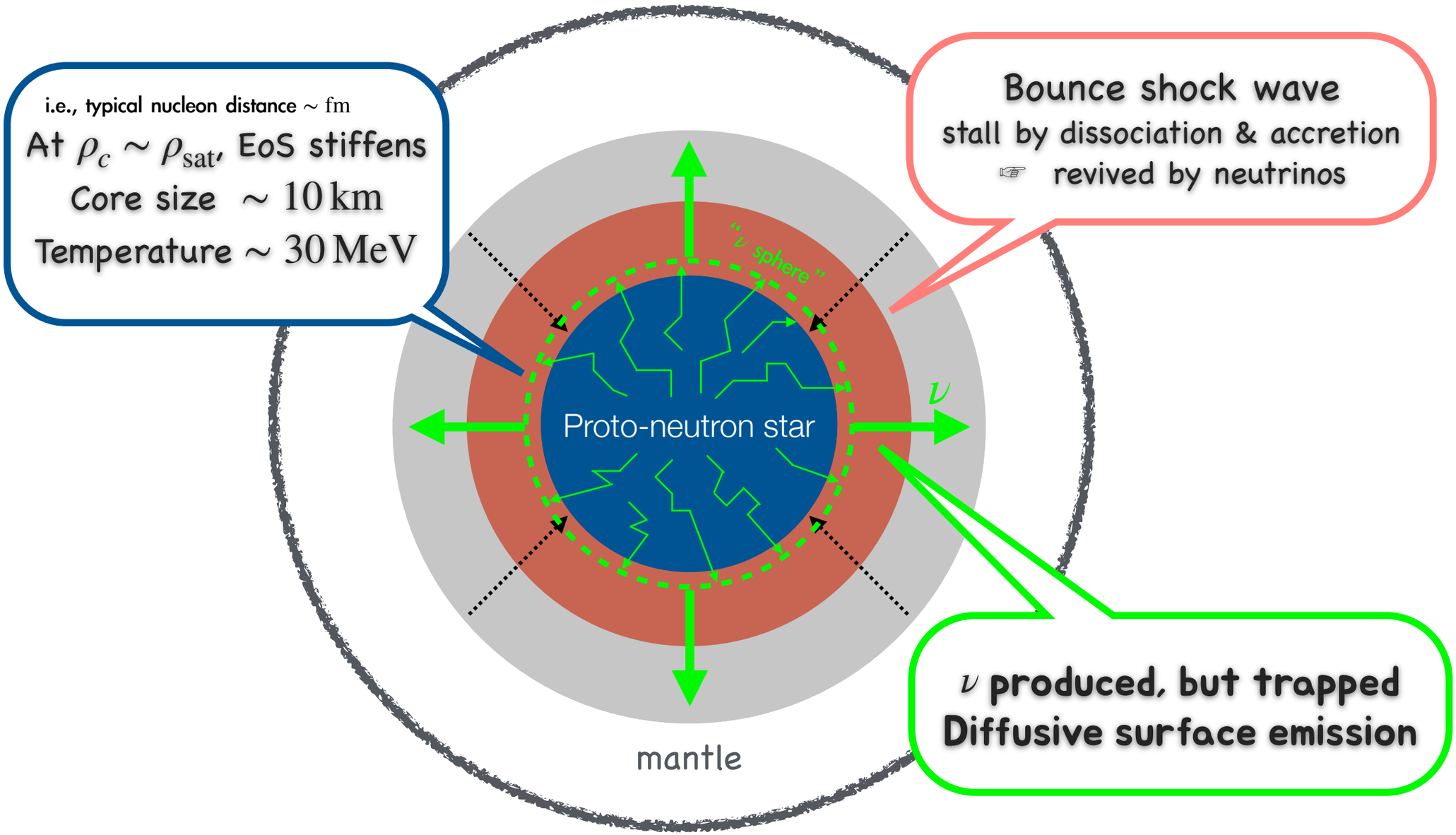
progenitor like super red-giants



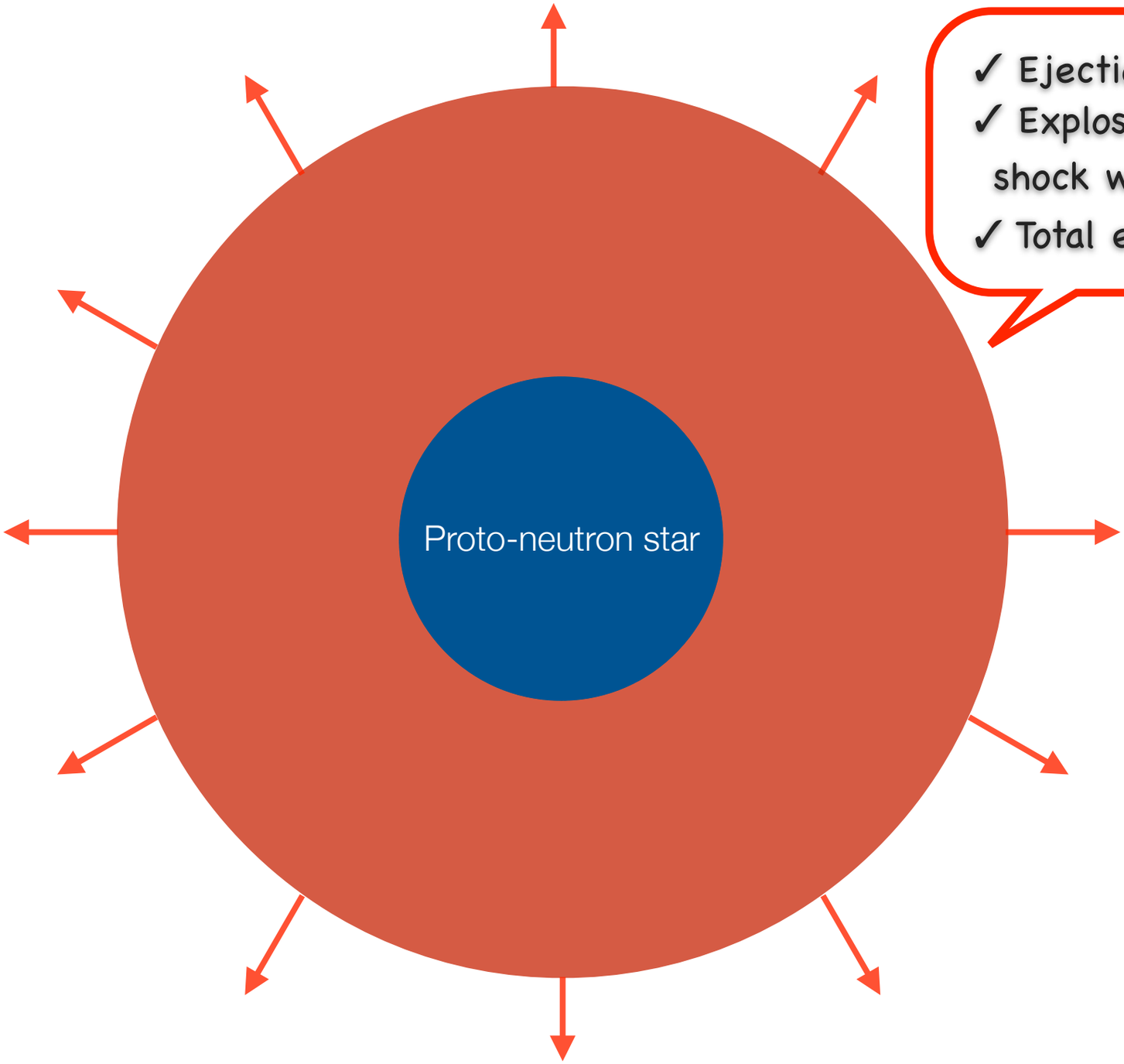
Core-Collapse Supernova



Core-Collapse Supernova



Core-Collapse Supernova



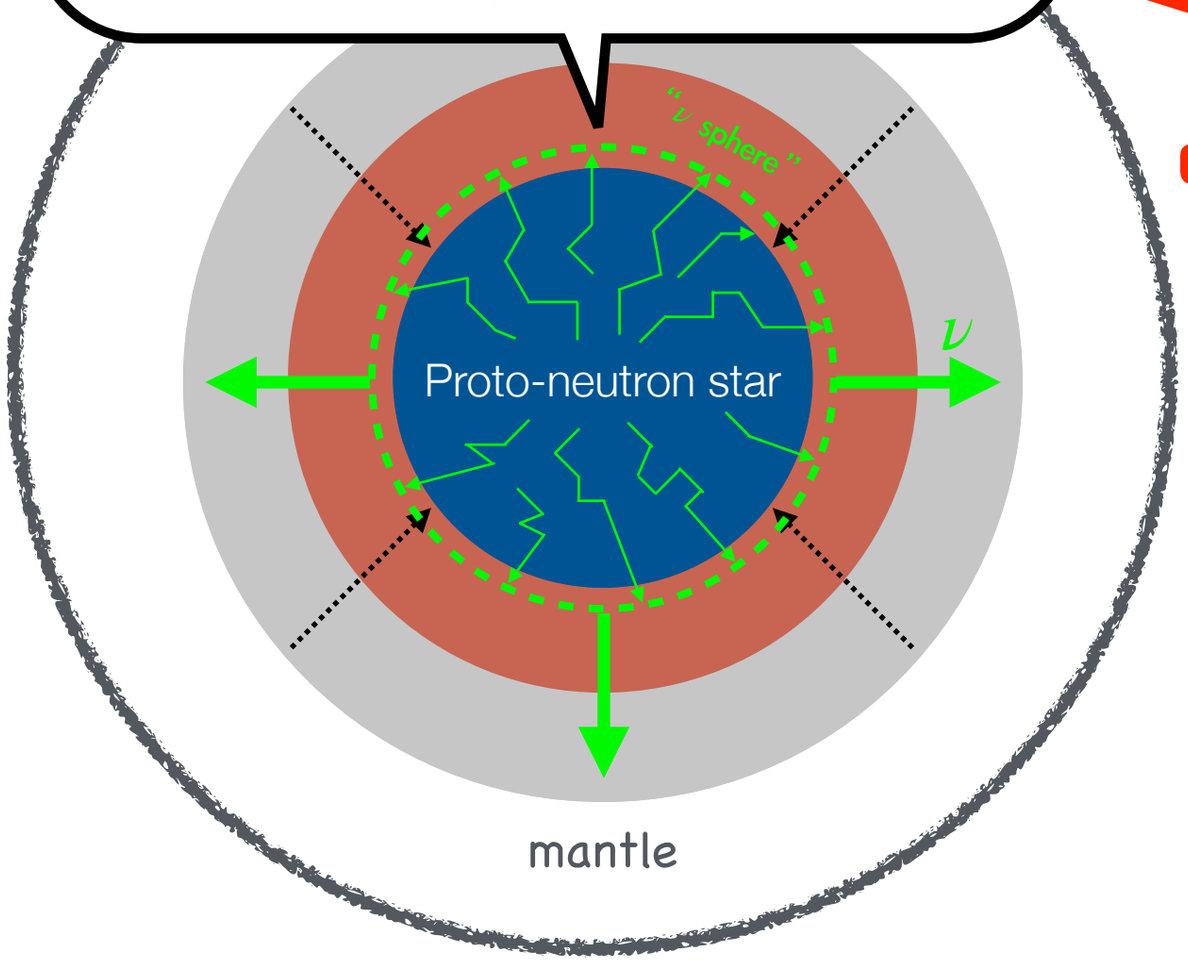
✓ Ejection of outer layer
✓ Explosion energy by
shock wave + ν transport
✓ Total energy $\sim 10^{51}$ erg

Neutrino-Cooling of Proto-Neutron Star

ν emission @ ν-sphere

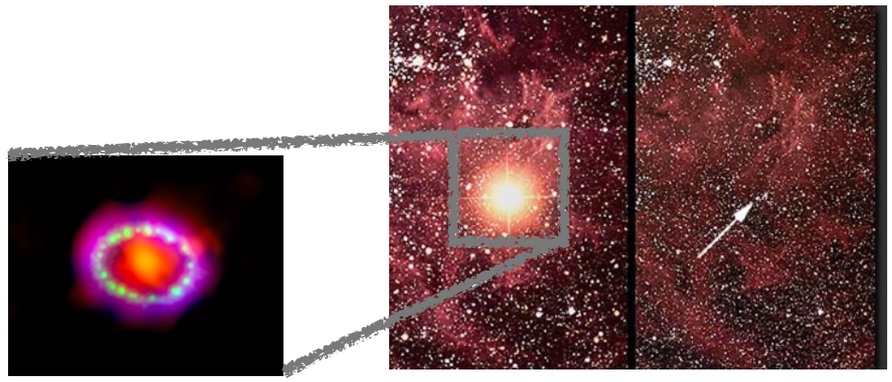
$$E_{\rm tot} \sim \frac{GM}{R_c} \sim 10^{53}\,{\rm erg} \;\&\; \mathbf{t_{diff}} \sim \frac{\mathbf{R_c^2}}{\lambda} \sim \mathbf{10}\,{\rm sec}$$

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

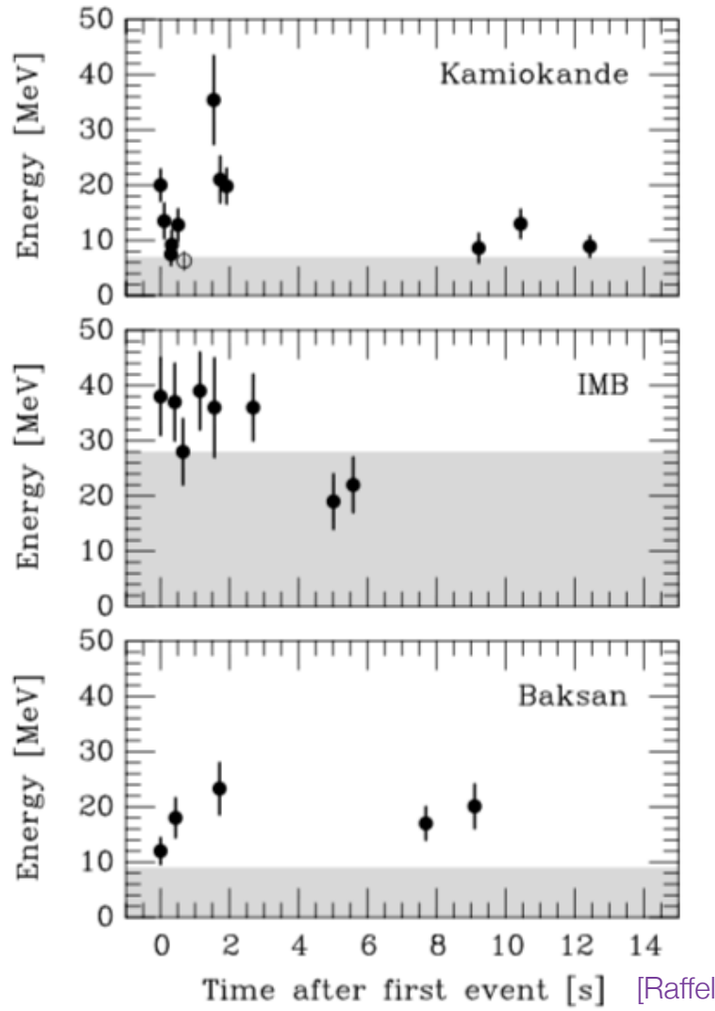


consistent!

[Chandra]

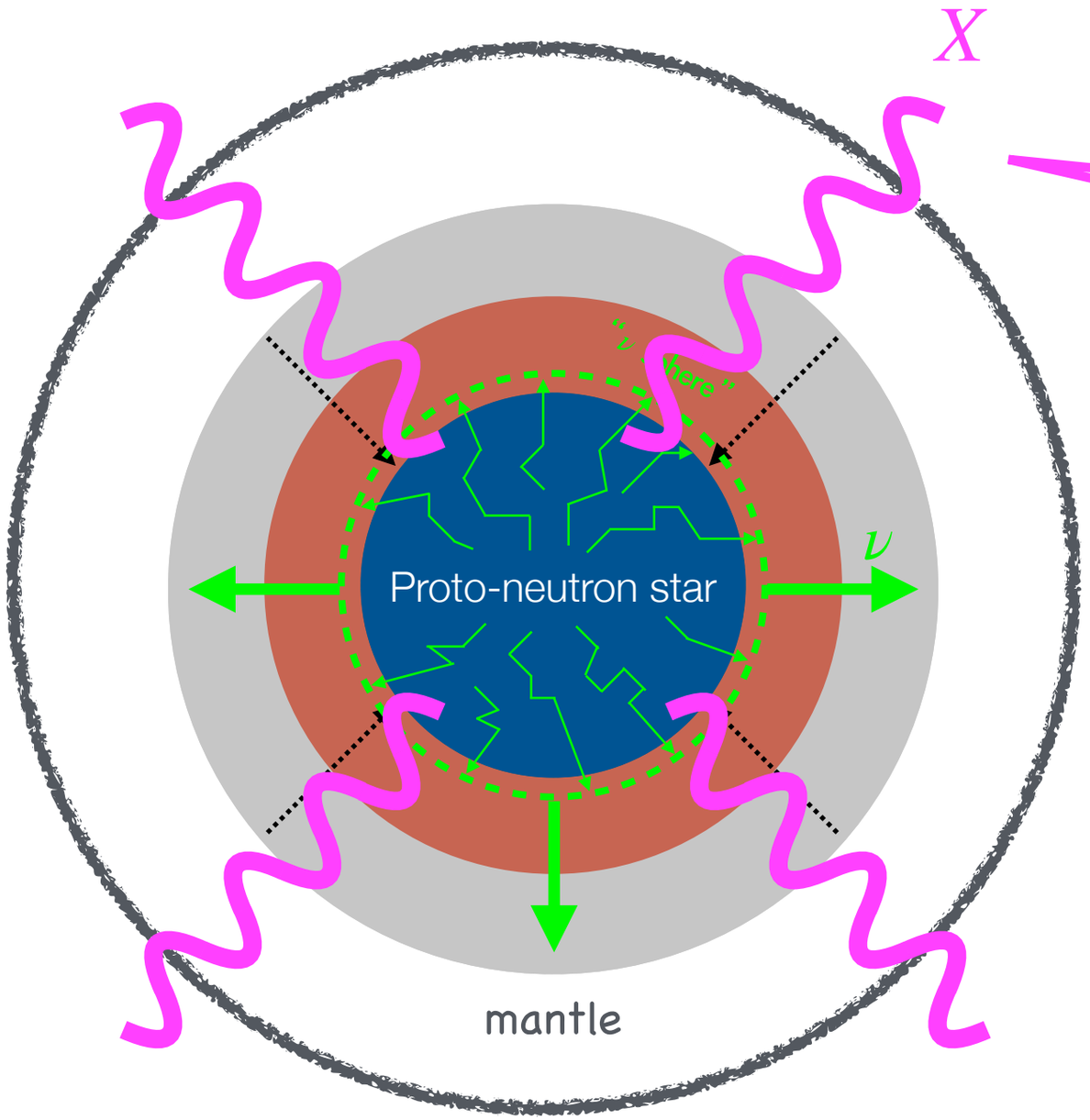


◉ neutrino flux of SN1987A



[Raffelt, 95]

Cooling Argument on SNe



- X emission as extra cooling
- free stream $\Rightarrow$ volume emit
- **Not to reduce ν-signal duration**

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

"Raffelt crietrion"

✓ L_X VS L_ν @ 1sec

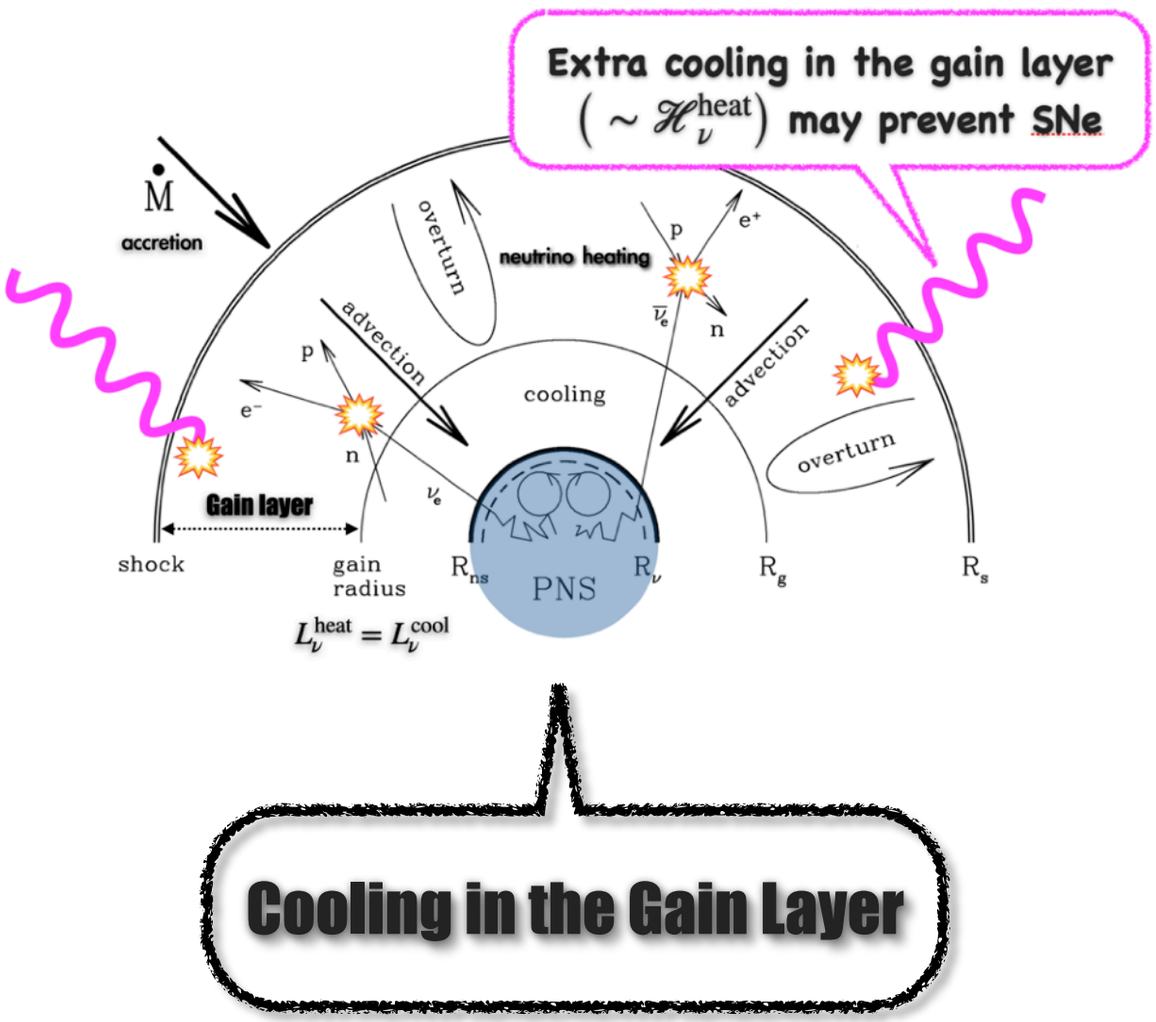
✓ No impact on earlier stage?

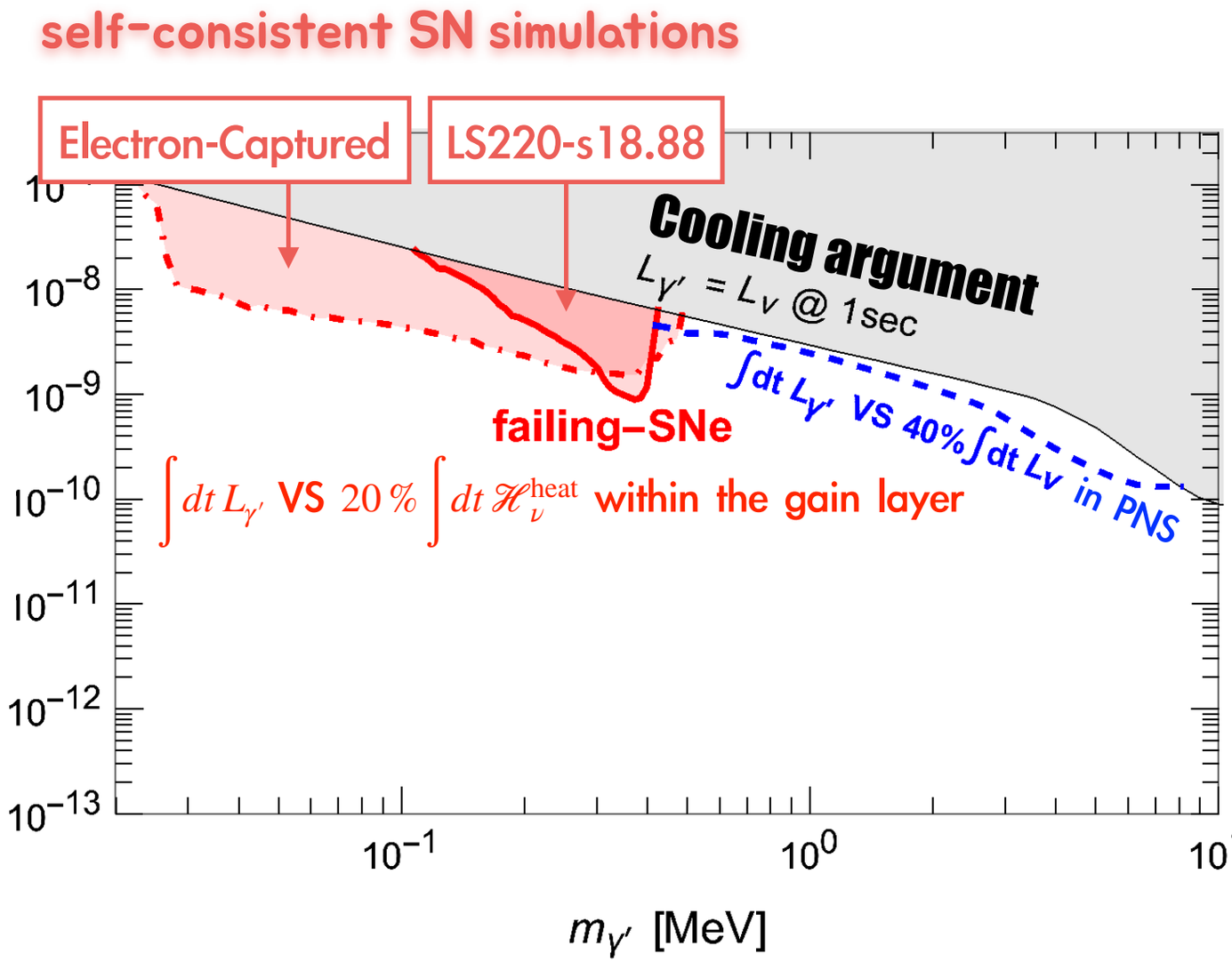
✓ Other Self-consistency?

- in particular, **explosion**?

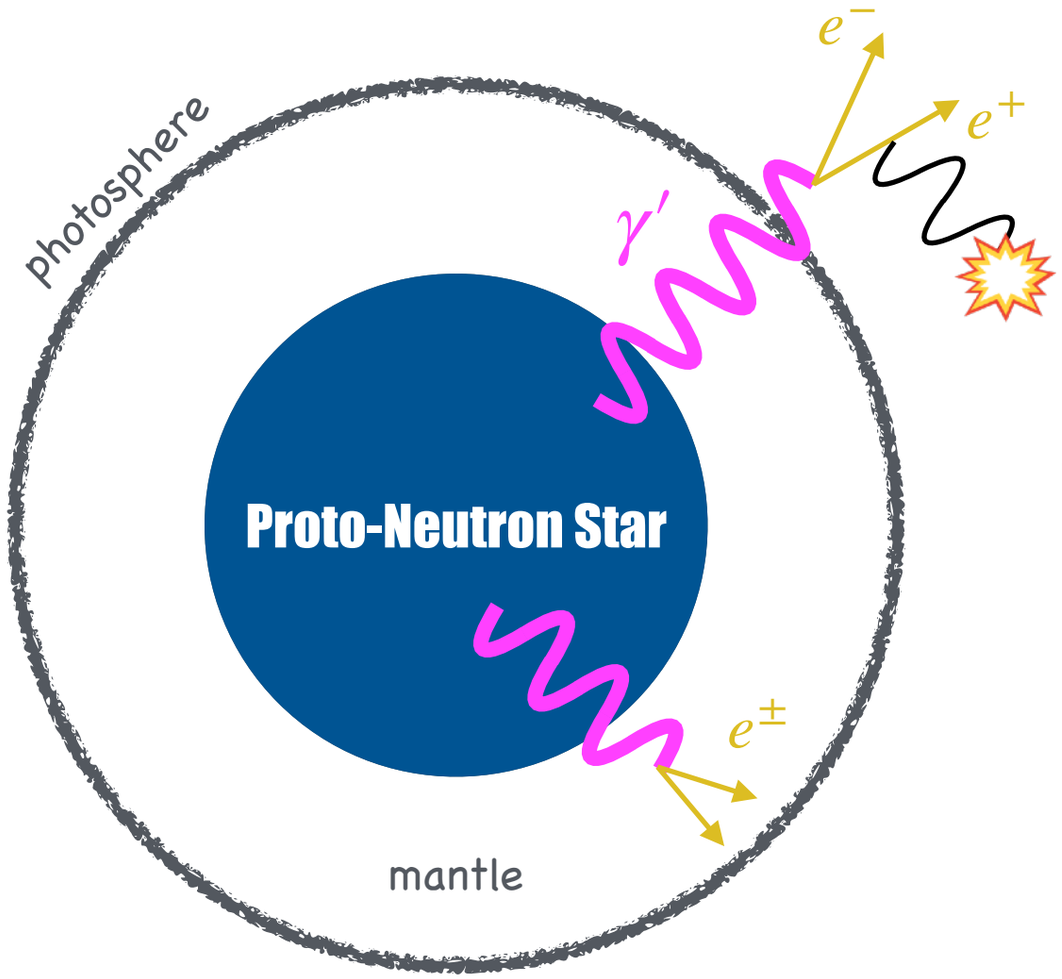
Impact on SN explosion mechanism

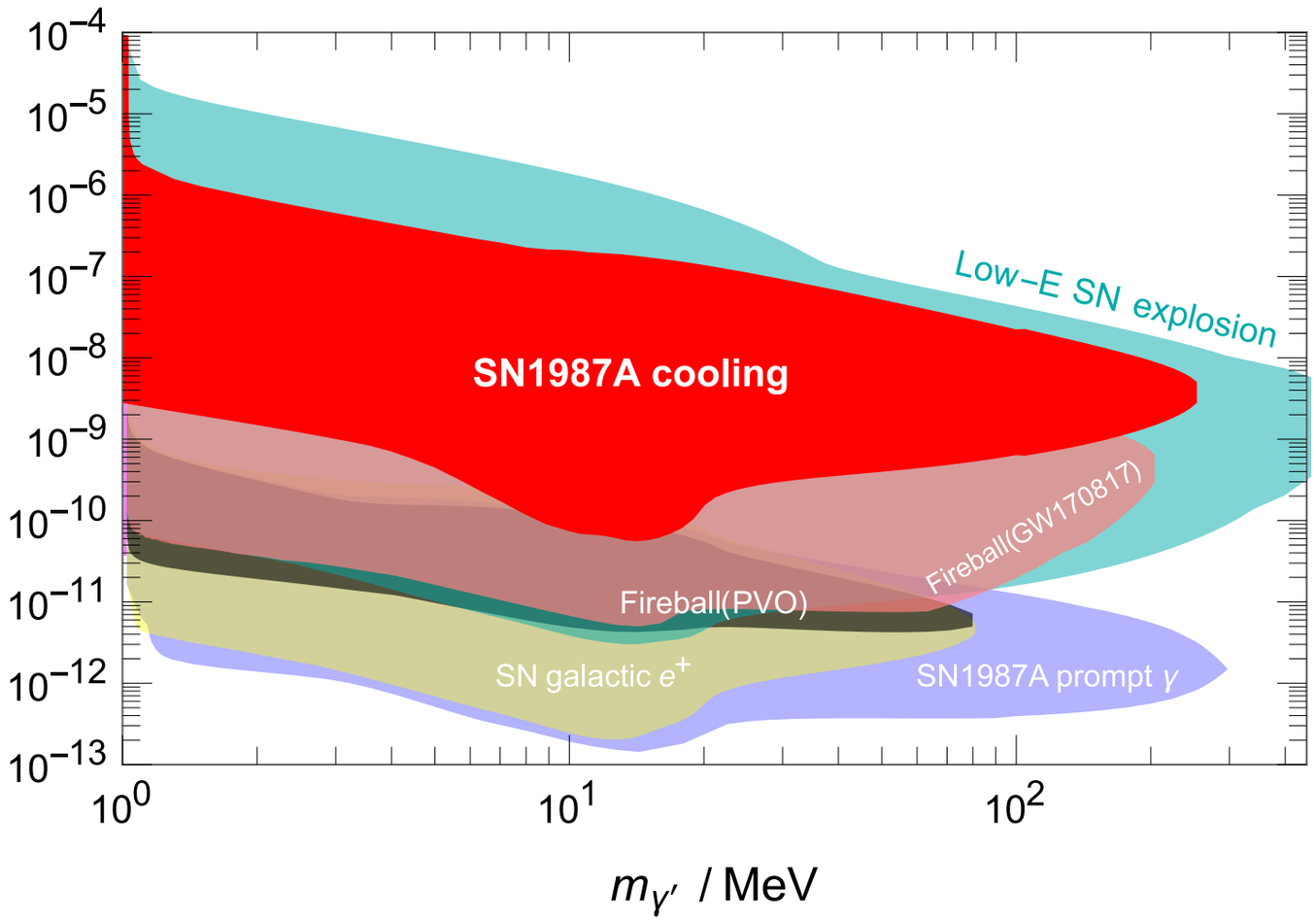
[A. Caputo, T. Janka, G. Raffelt, **SY**, 25]





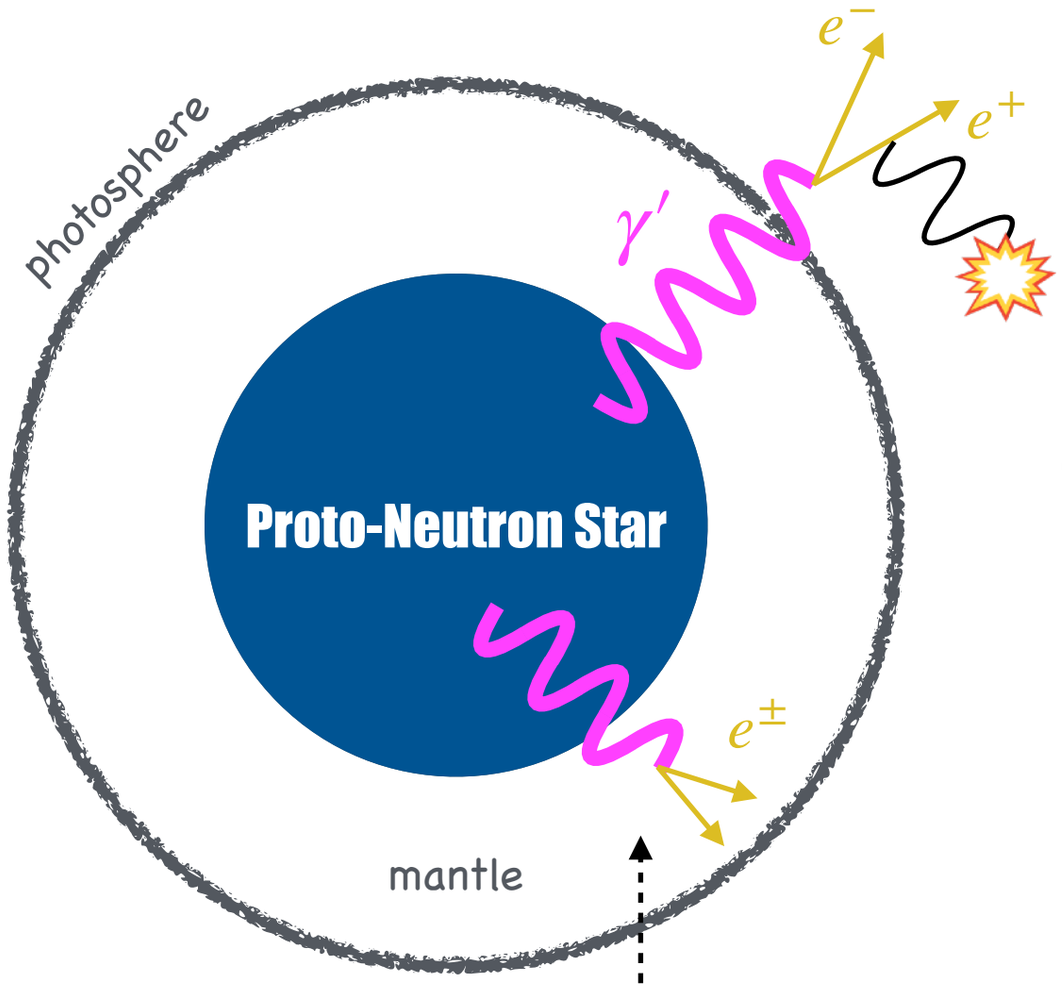
Other SN Constraints w/o CSM

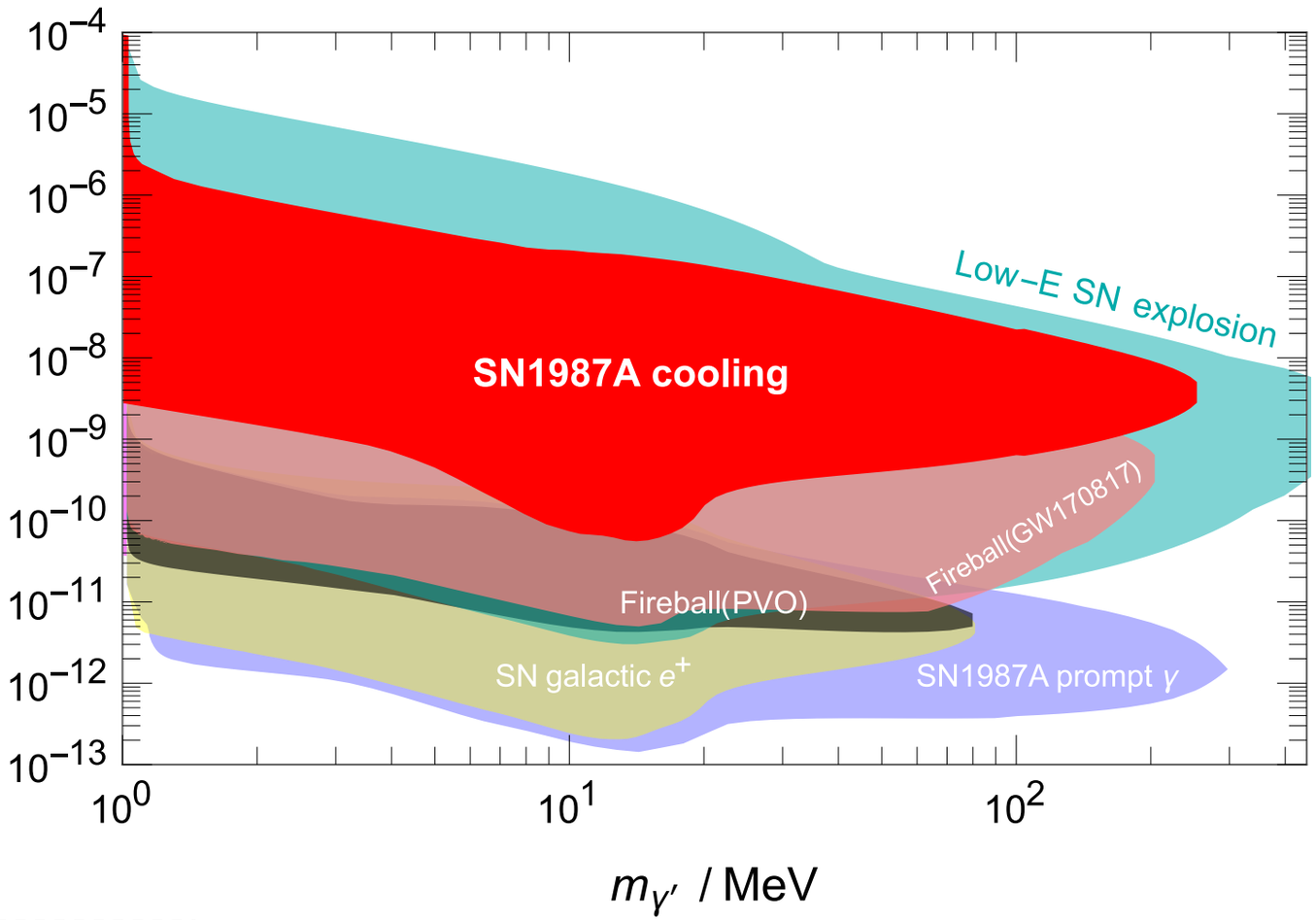




[A. Caputo, J. Park, **SY**, 26]

Other SN Constraints w/o CSM





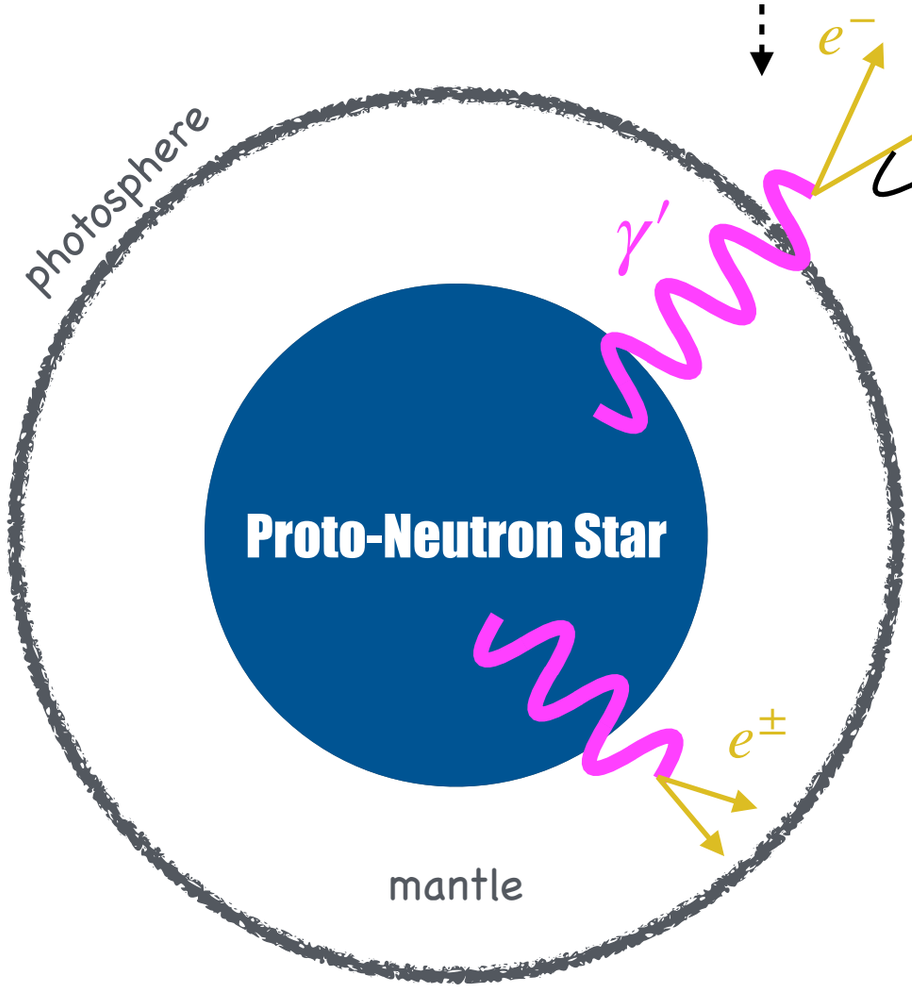
- Energy deposition into the mantle
  - ✓ Contributing to SN explosion energy

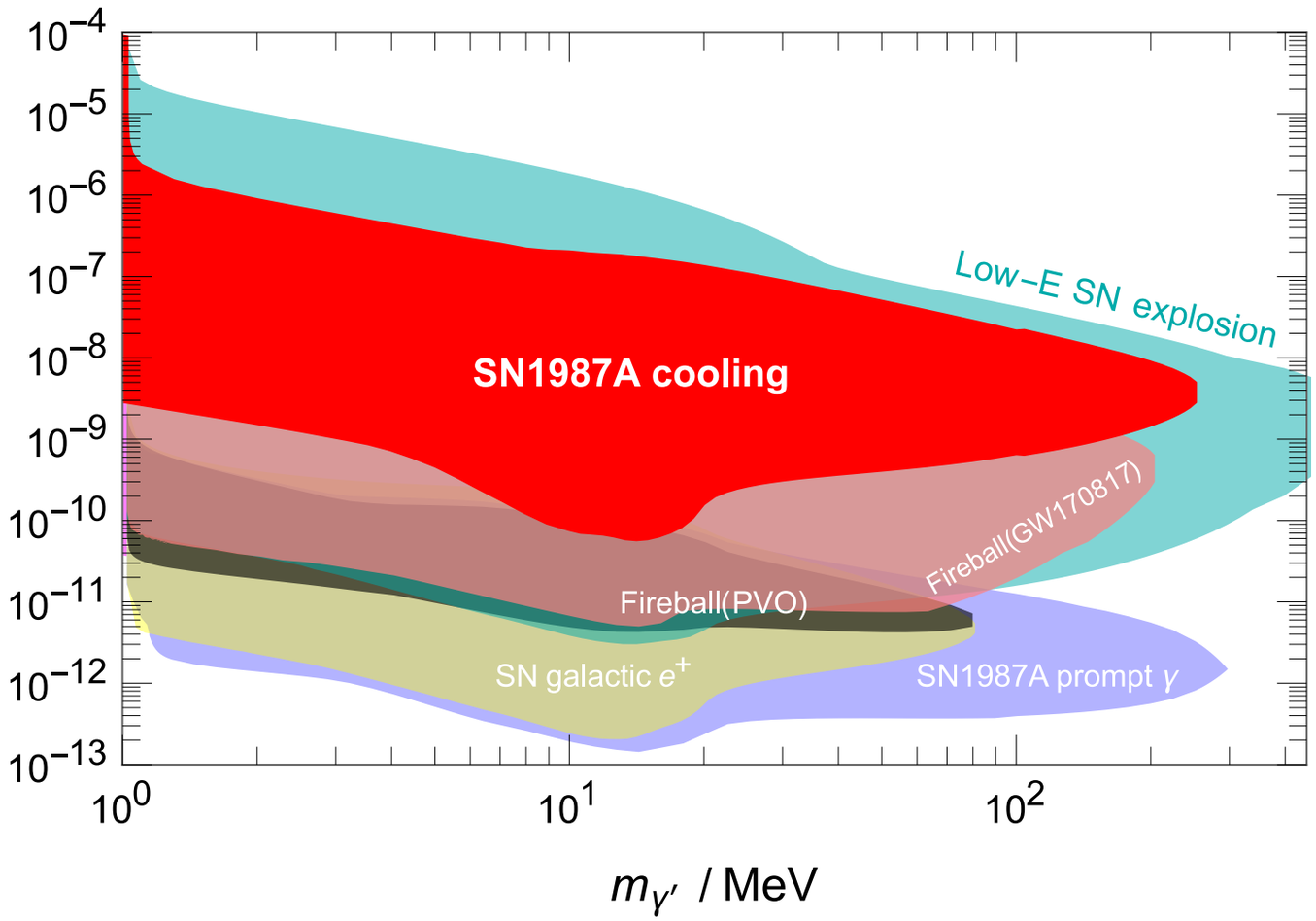
[A. Caputo, J. Park, **SY**, 26]

Other SN Constraints w/o CSM

- Energy transport outside the progenitor

✓ fireball, galactic e^+ (511keV), prompt γ-ray





[A. Caputo, J. Park, **SY**, 26]

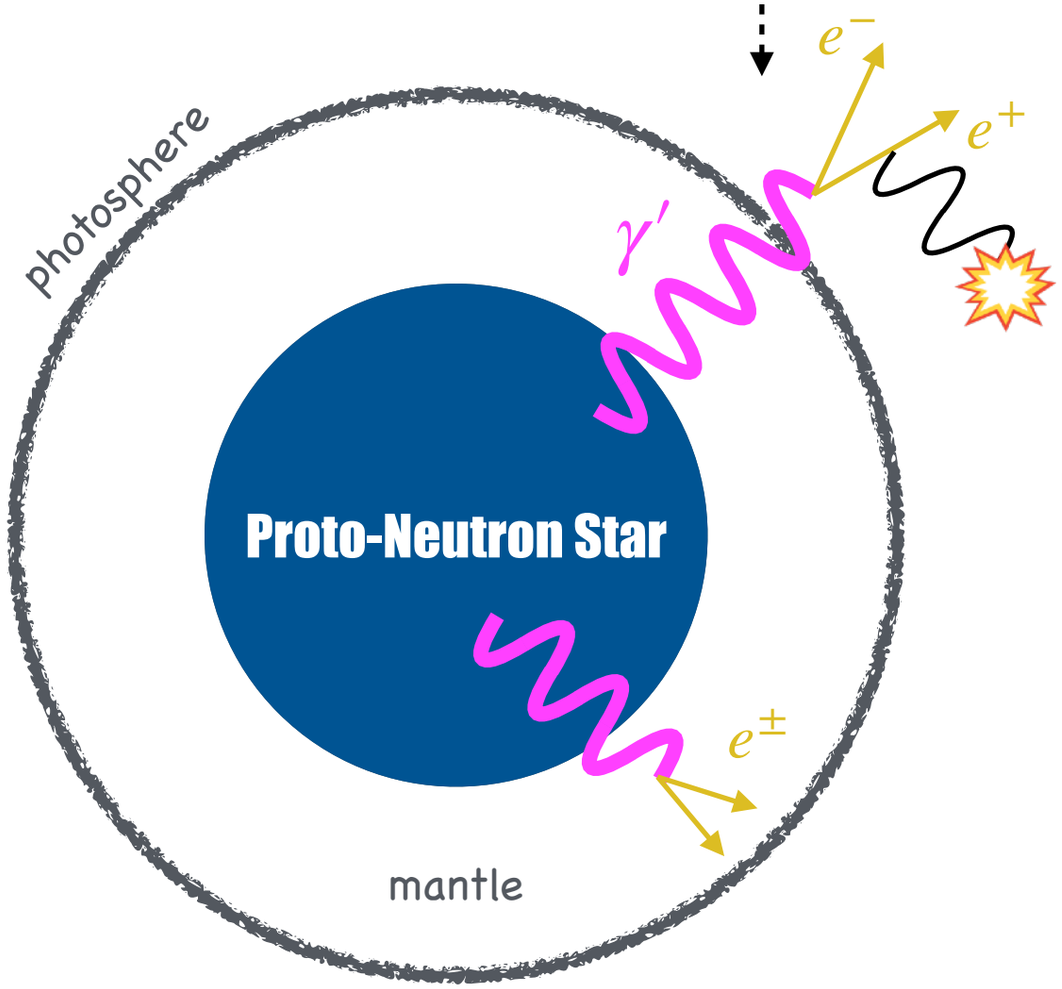
Other SN Constraints w/o CSM

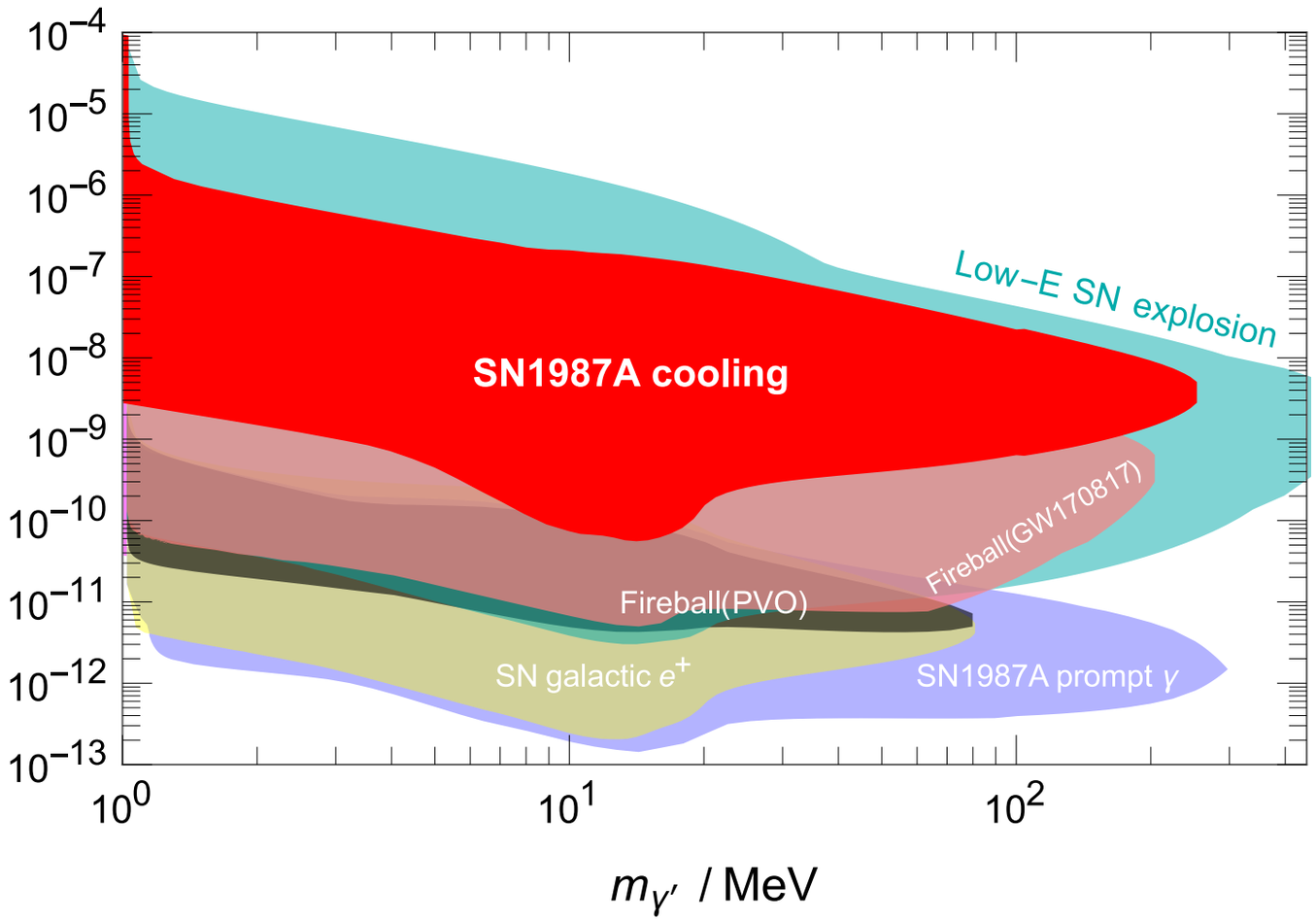
- Energy transport outside the progenitor

✓ fireball, galactic e^+ (511keV), prompt γ-ray

- conventionally - vacuum

? medium due to mass-loss

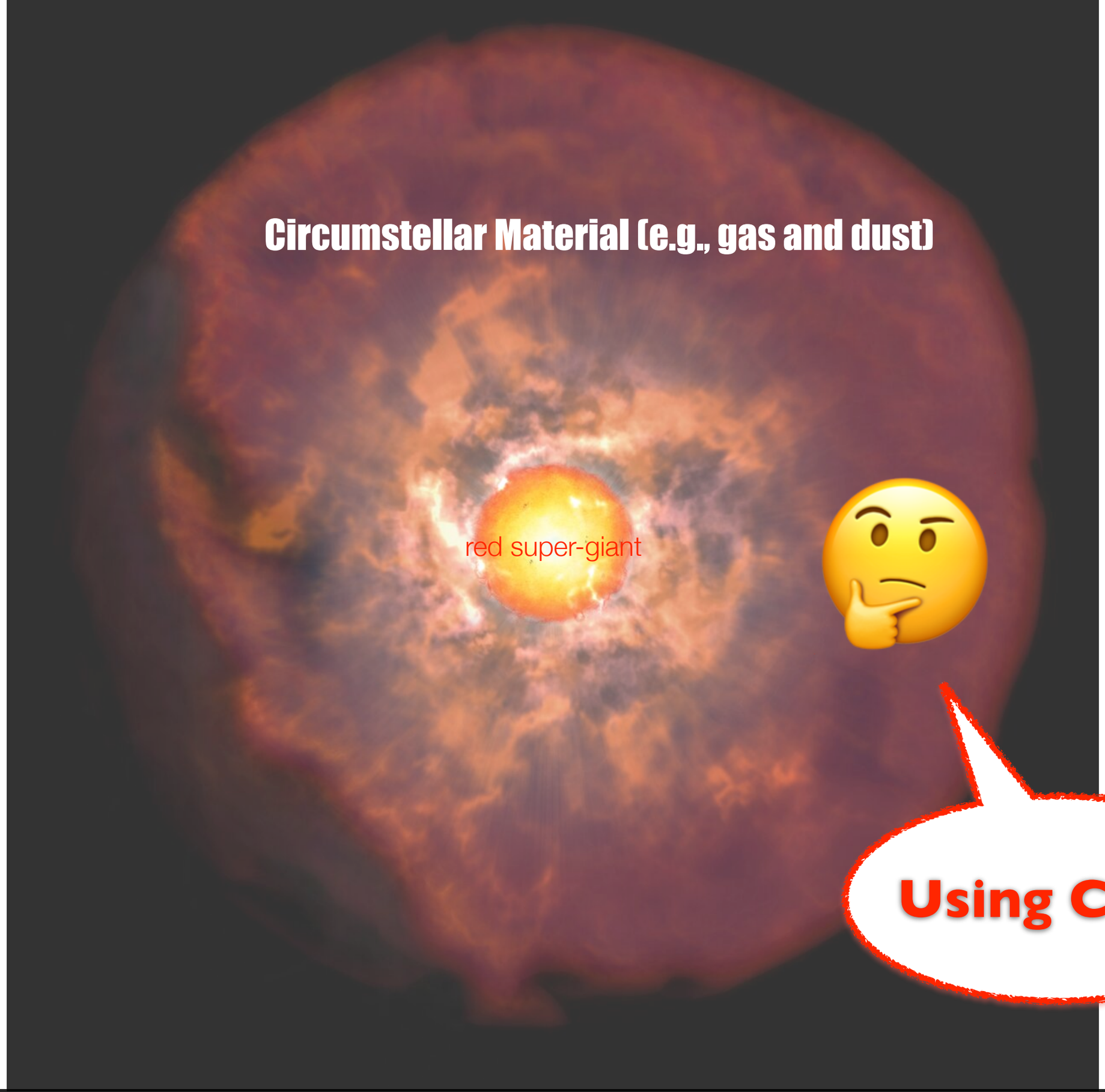




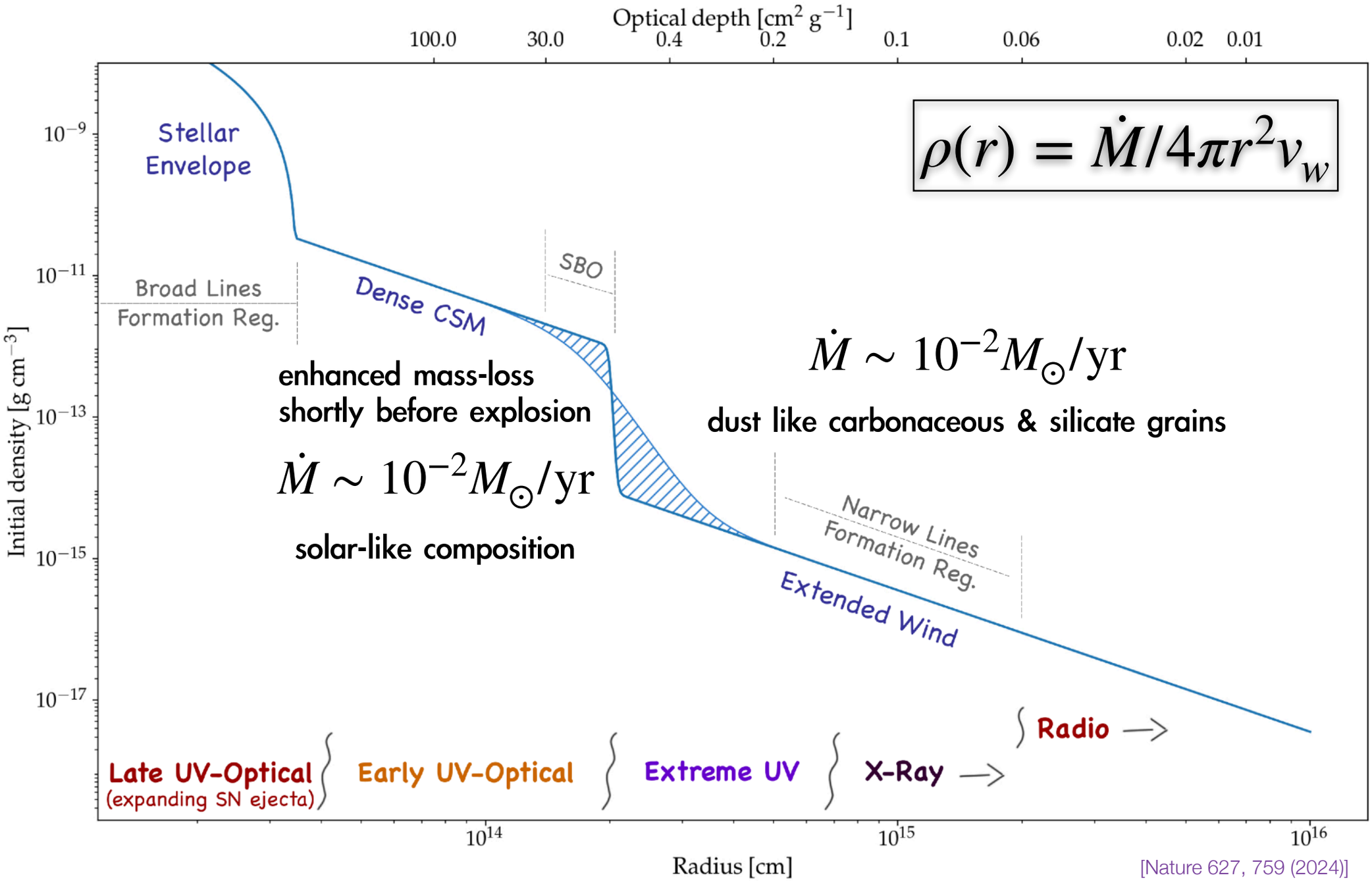
[A. Caputo, J. Park, **SY**, 26]

BSM w/ CSM

- Circumstellar medium due to mass-loss
  - ✓ Inner (dense) CSM before explosion
  - ✓ Outer (diluted) CSM like standard wind
- Energy deposition in CSM
  - ✓ Opacity & T ⬆ ☞ $L_{\rm BB}$ ⬆ - inner CSM
  - ✓ Dust sublimation - outer CSM

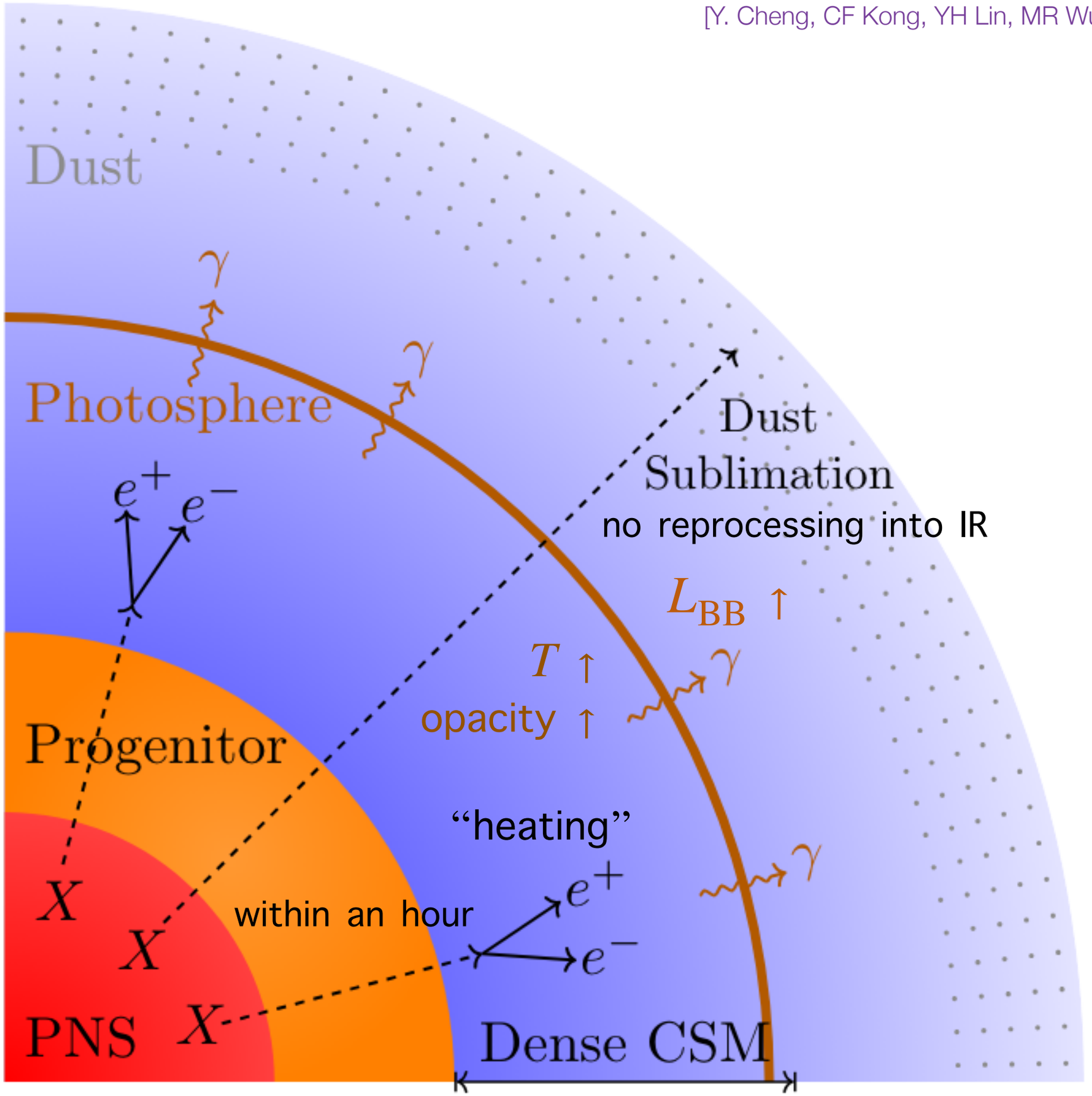

Circumstellar Material (e.g., gas and dust)
red super-giant
Using CSM?

CSM Density Profile



[Nature 627, 759 (2024)]

[Y. Cheng, CF Kong, YH Lin, MR Wu, **SY**, 26]



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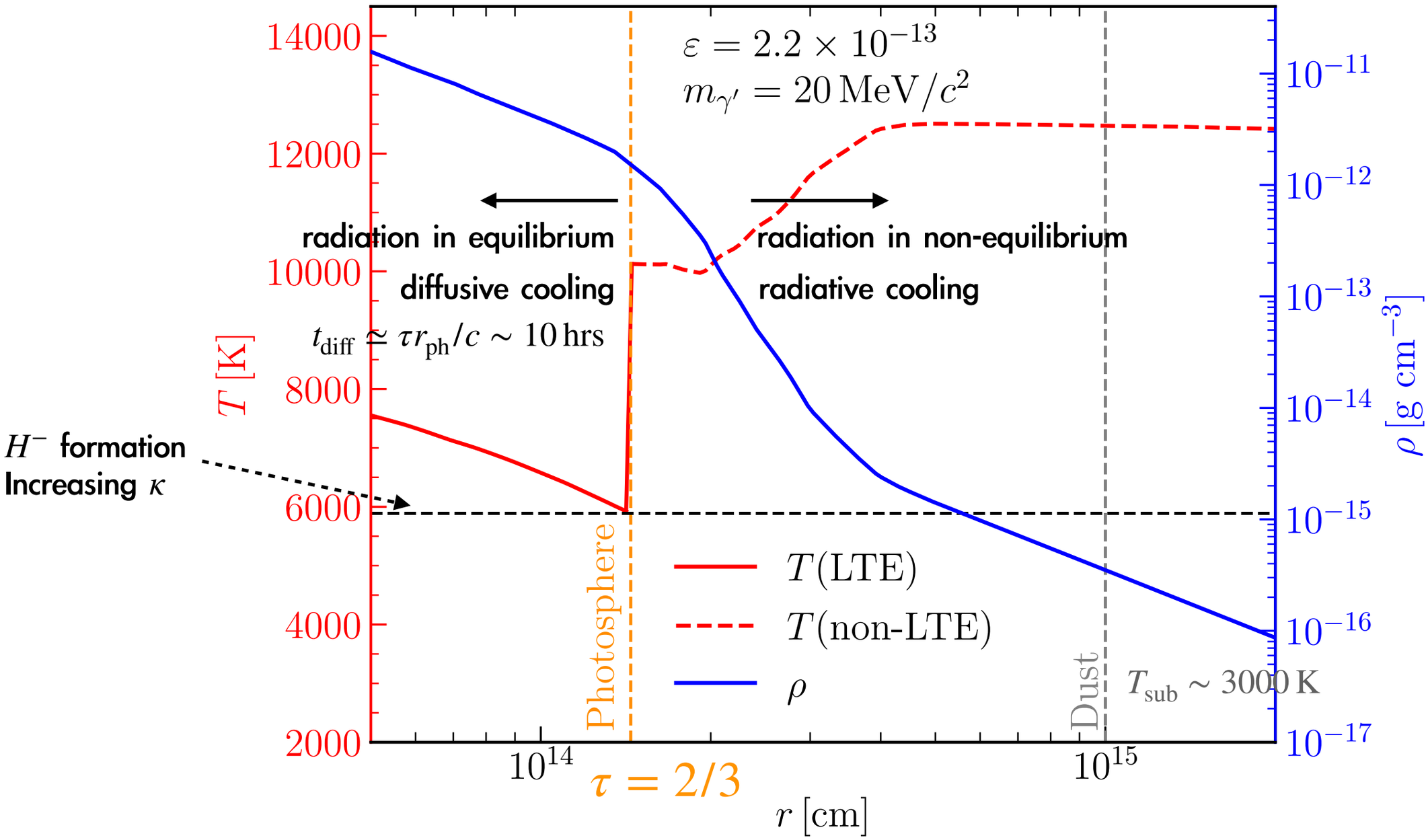
BSM-induced CSM heating



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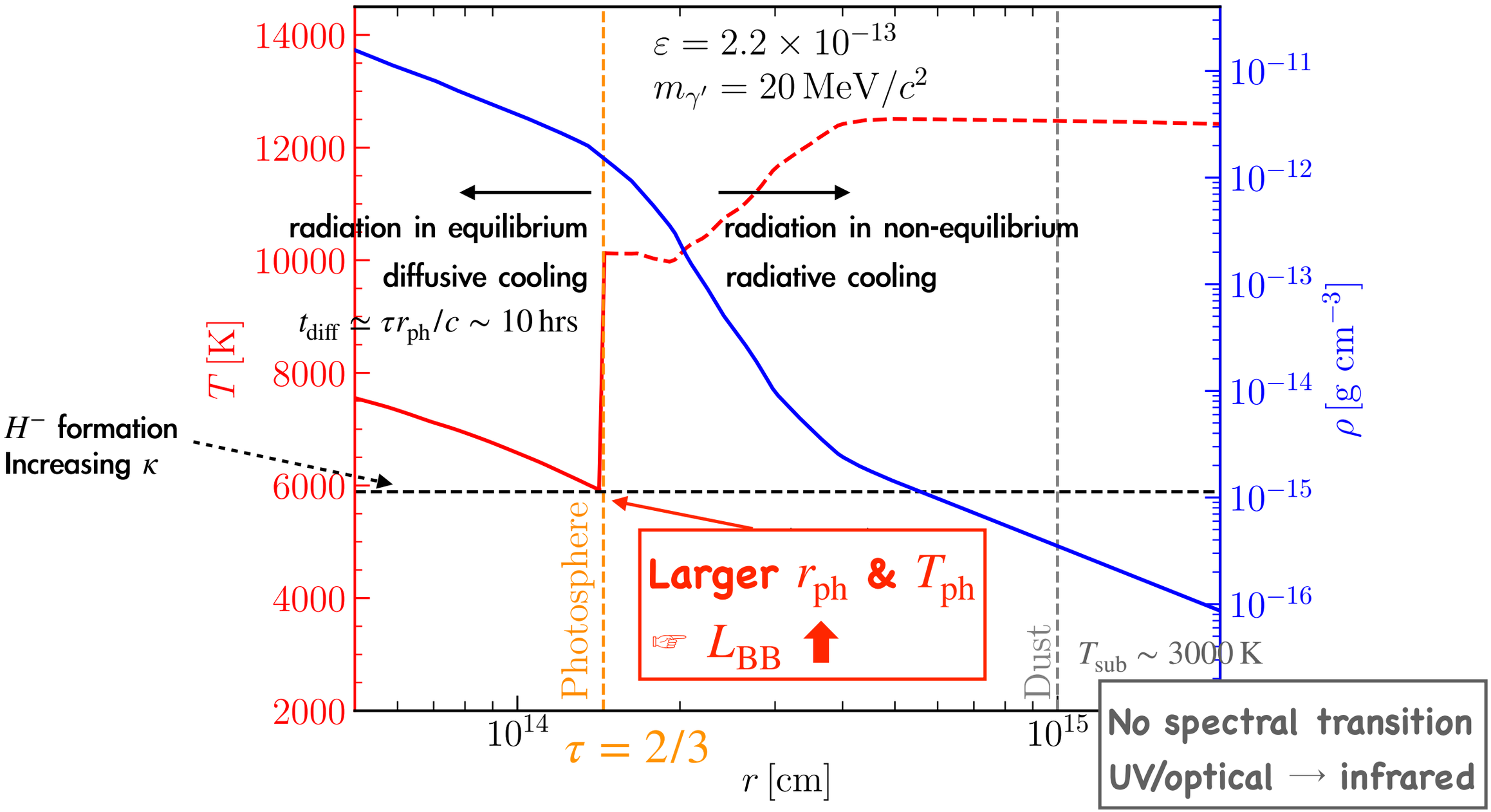

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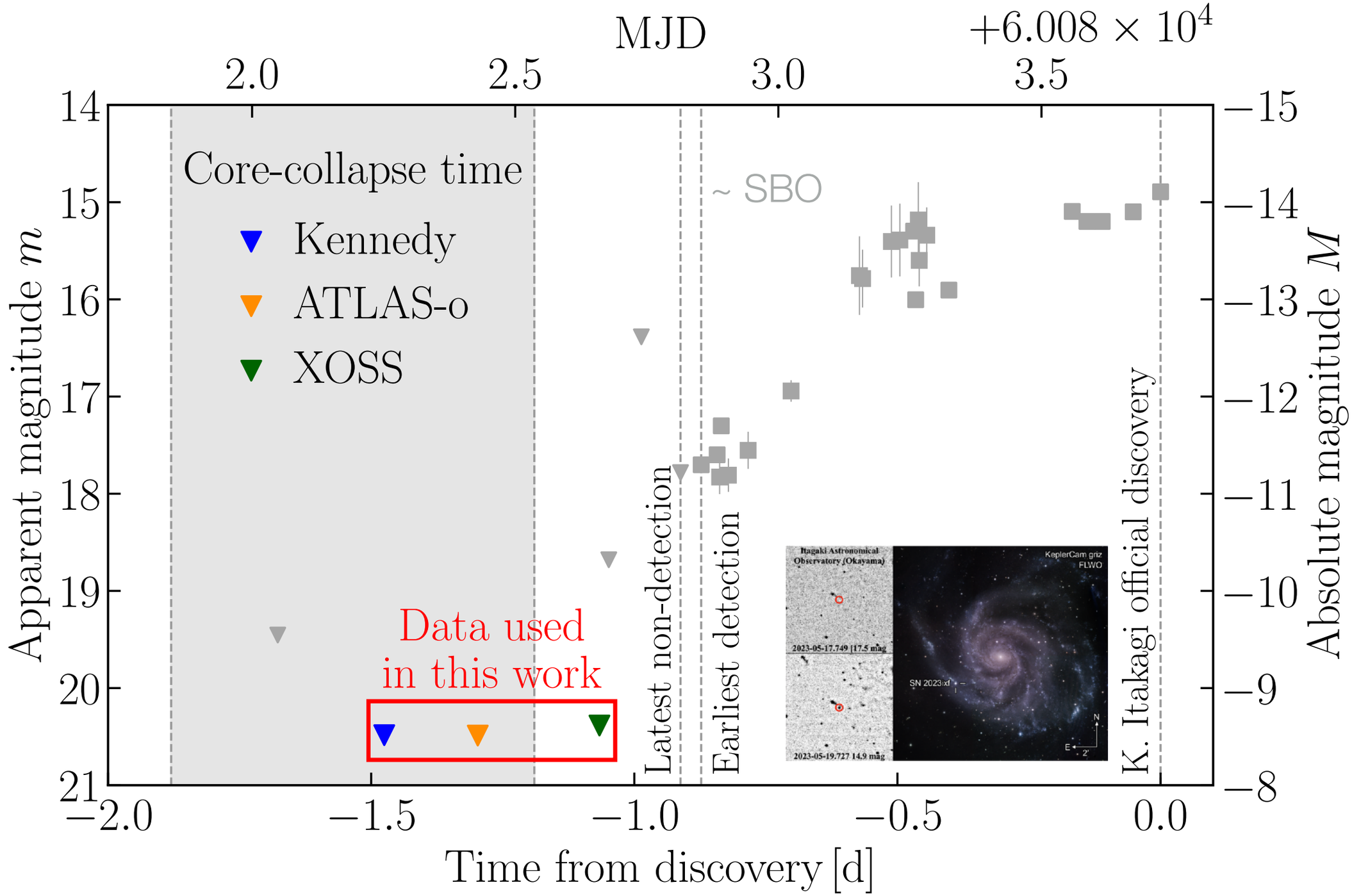
Early Time Data for SN 2023ixf



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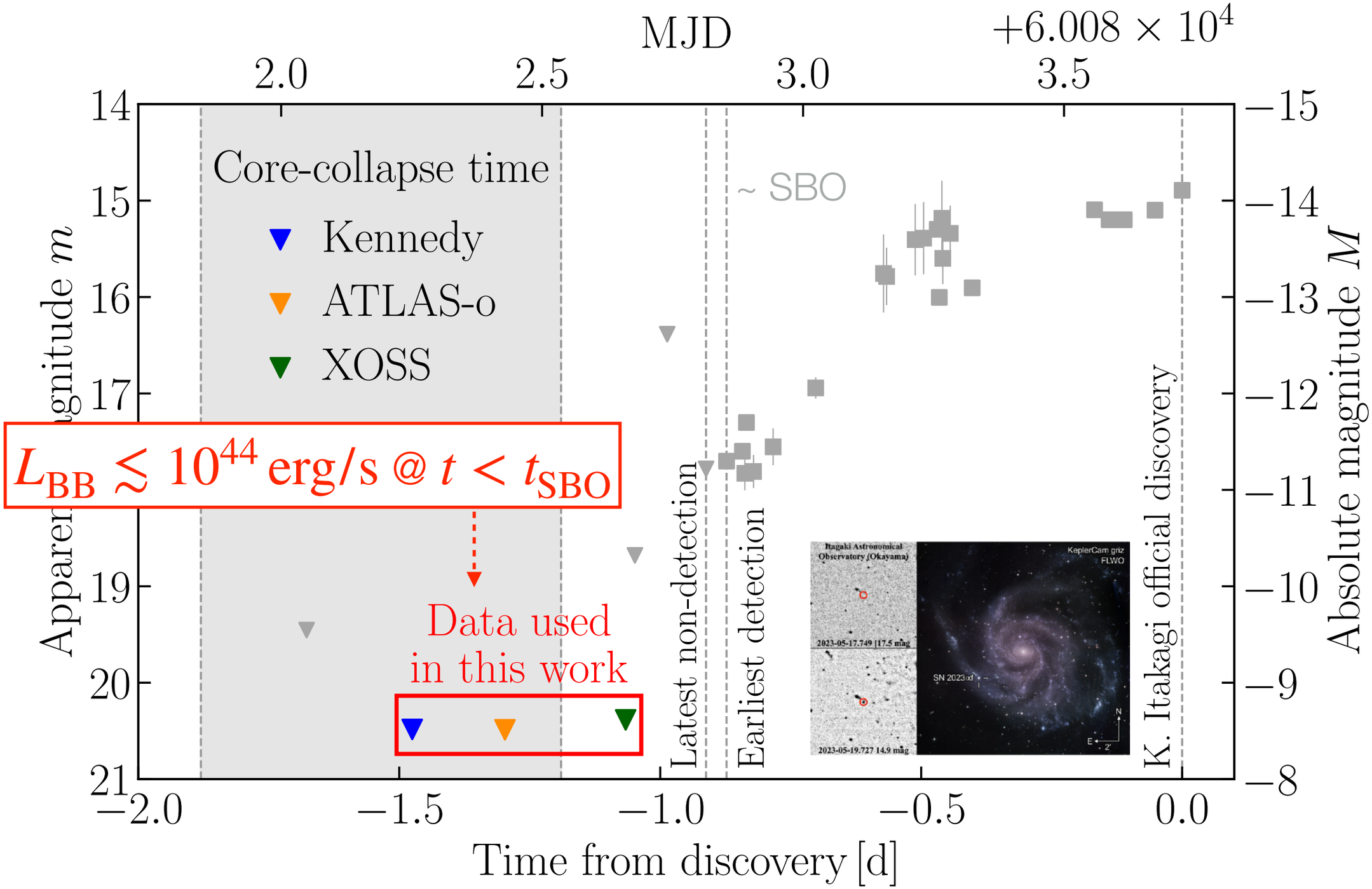

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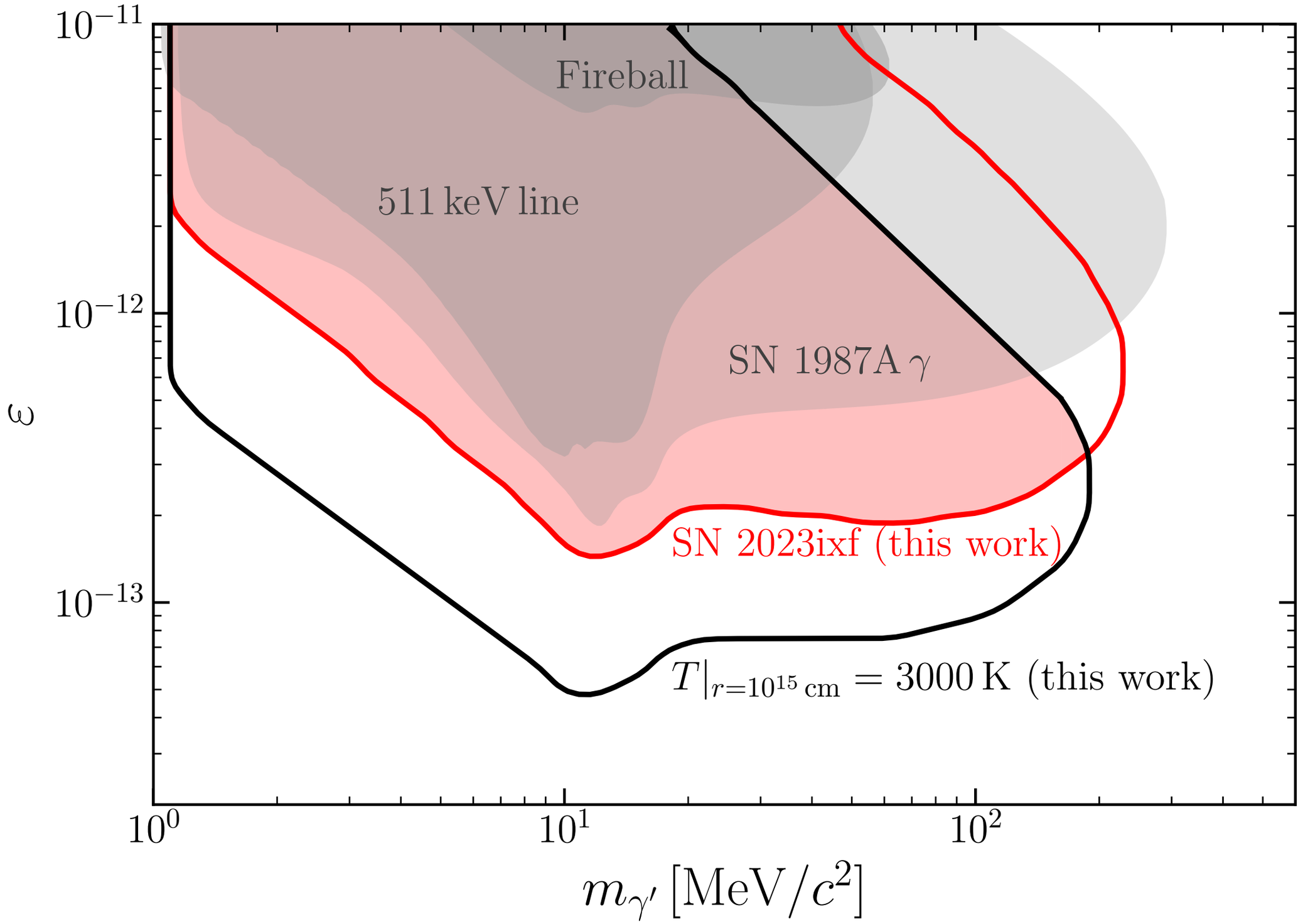

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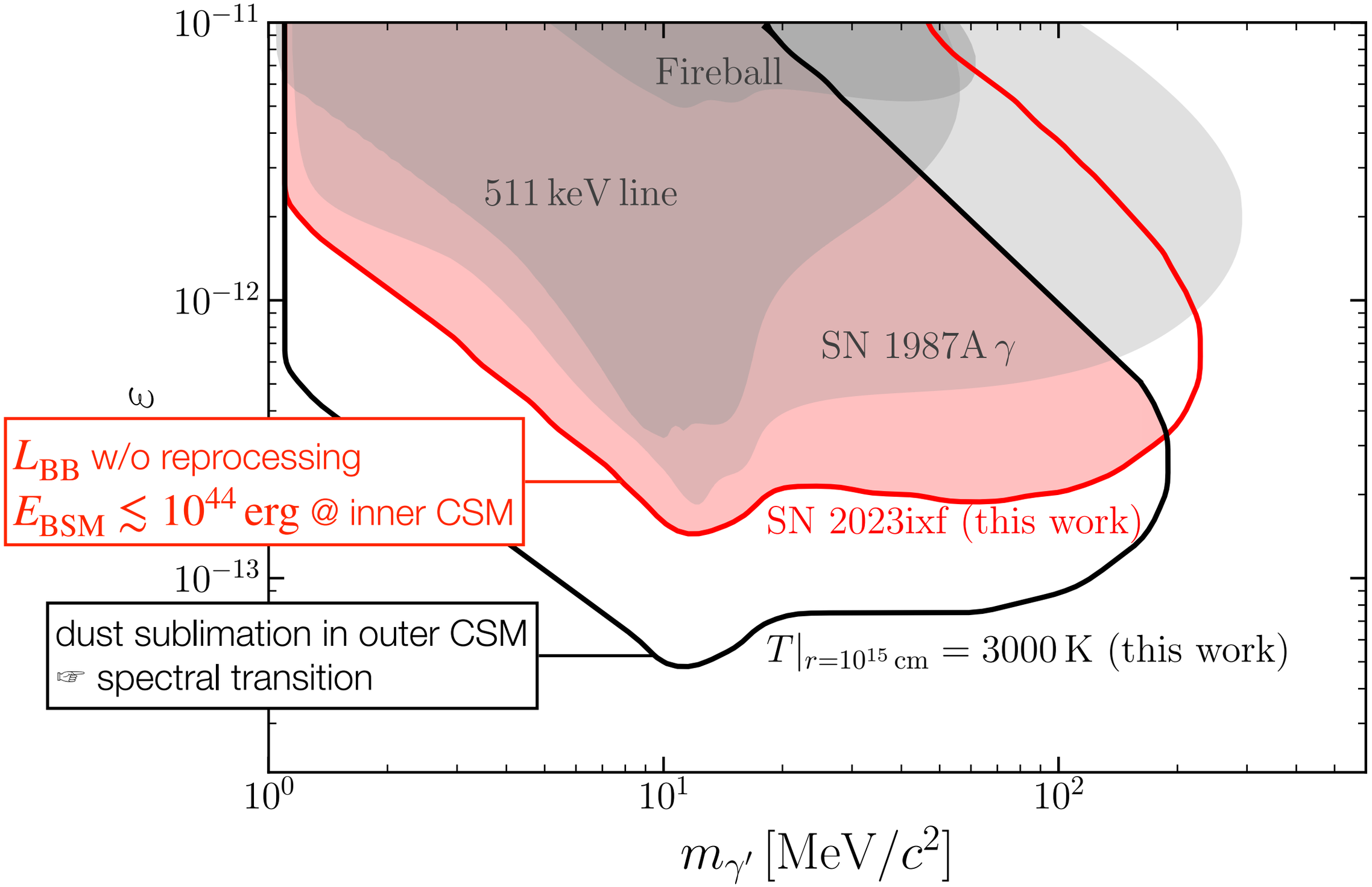

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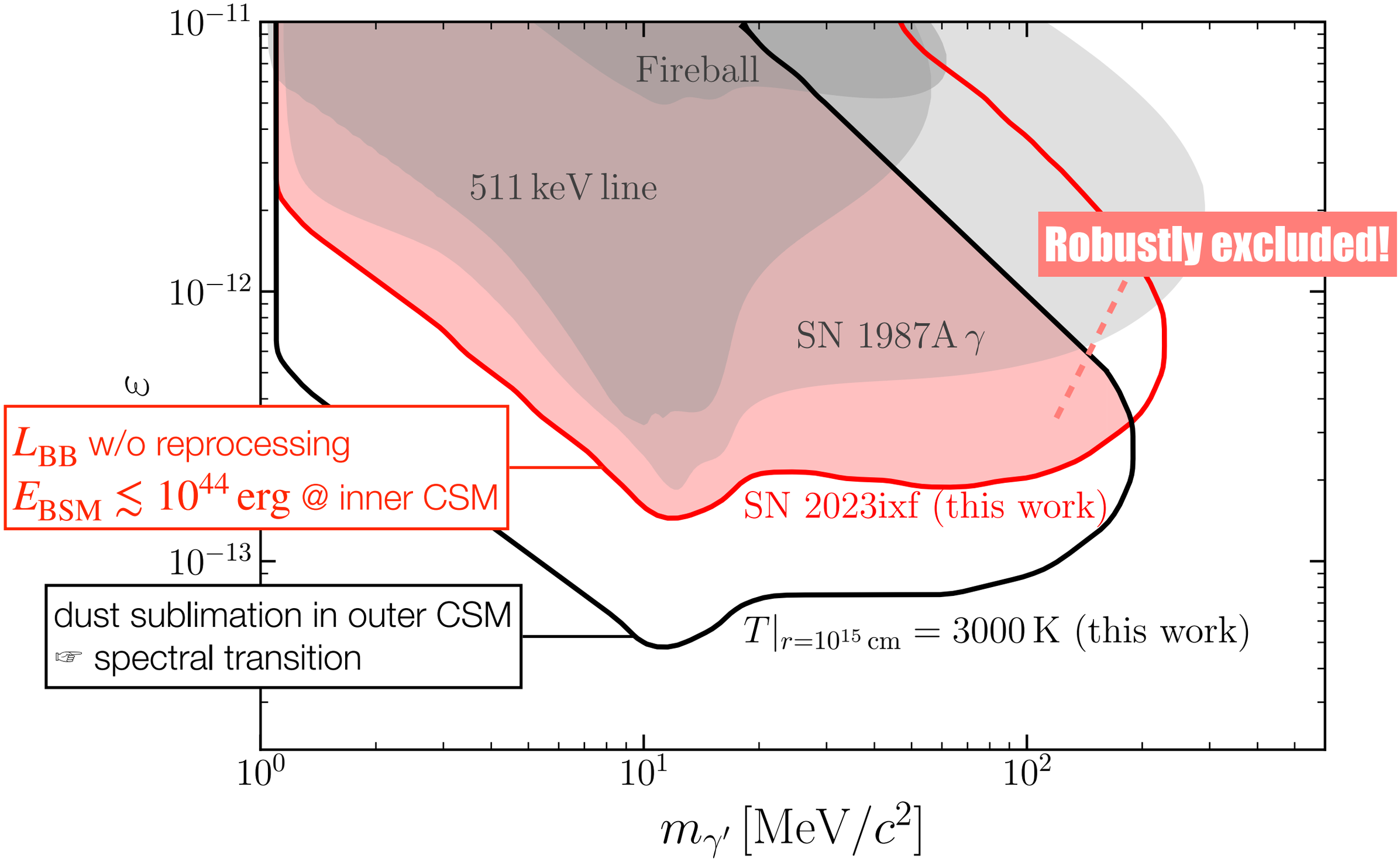

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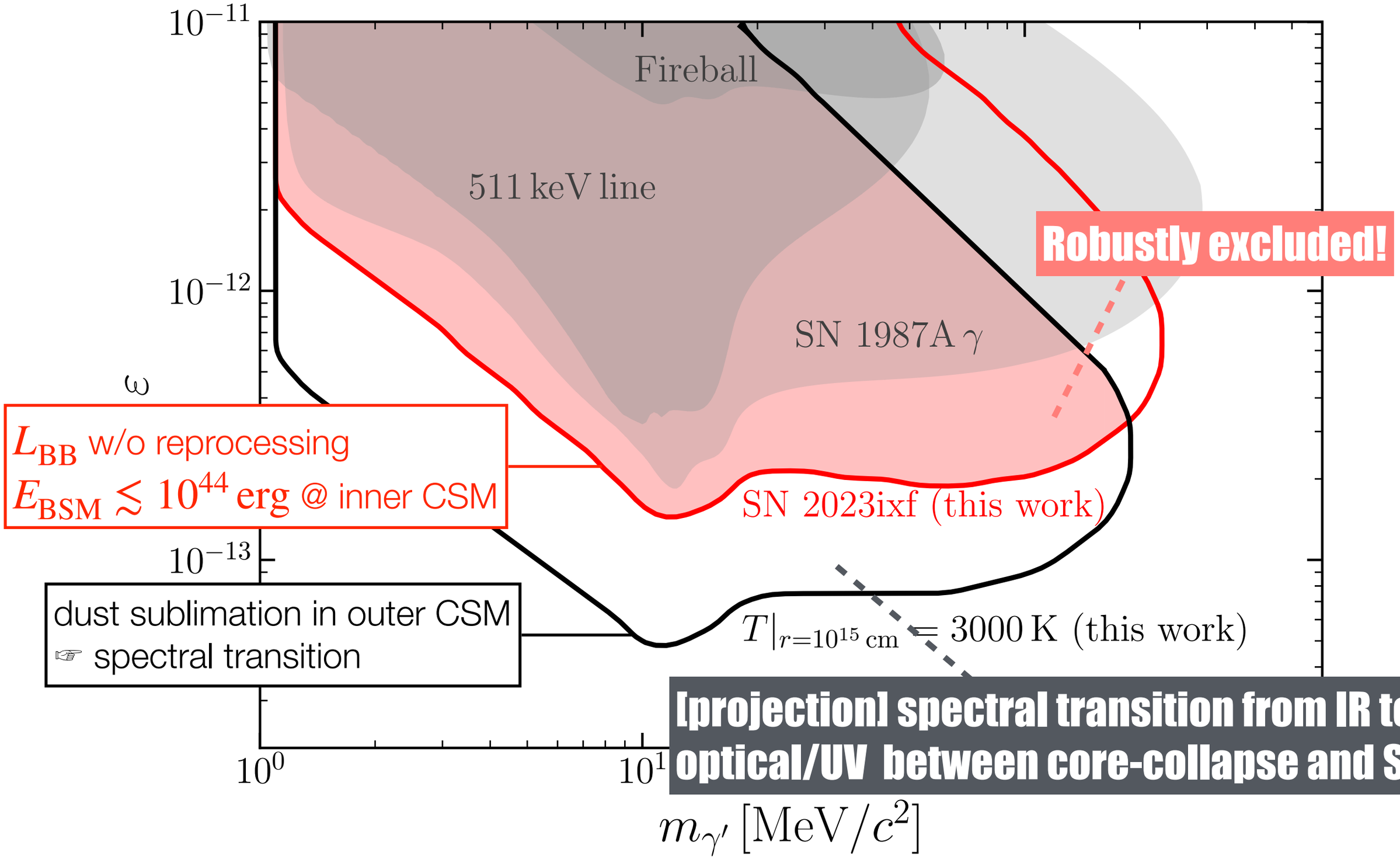
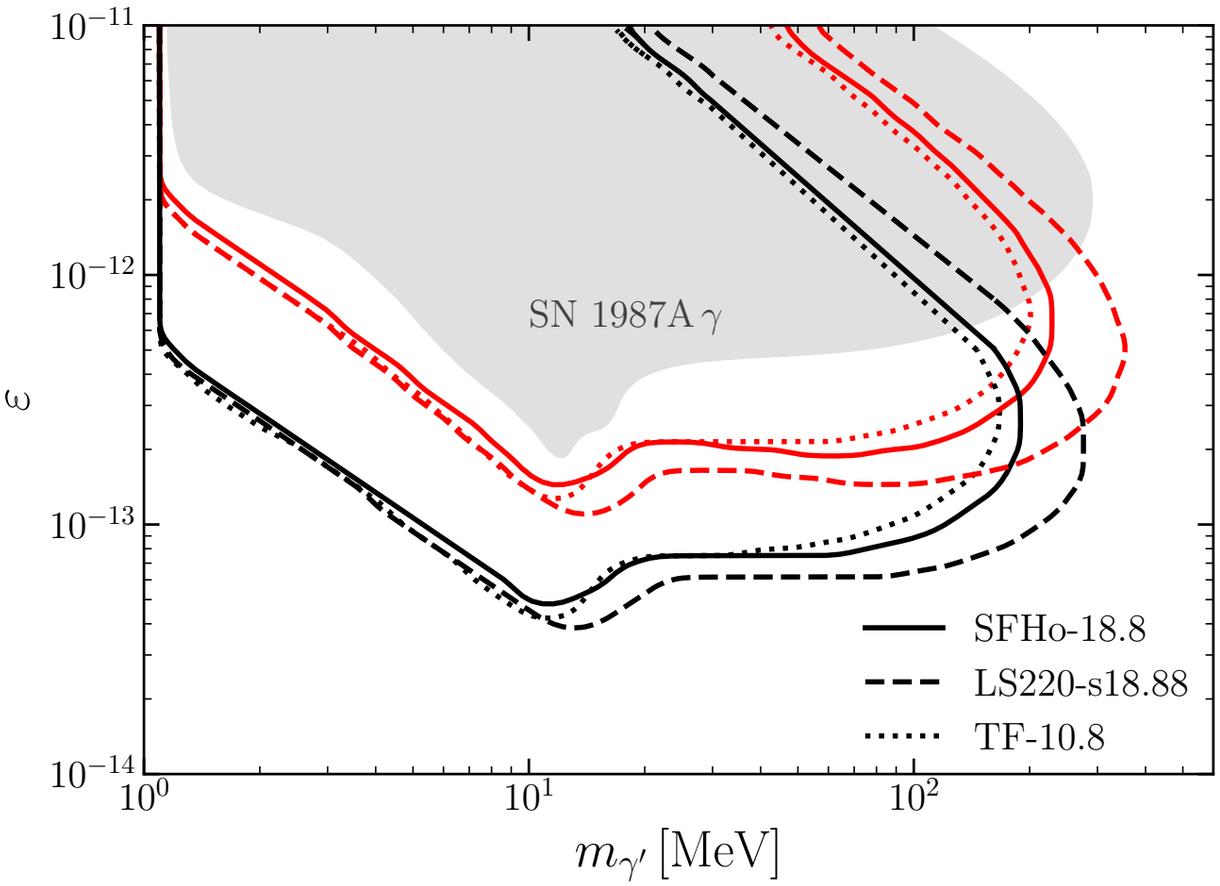


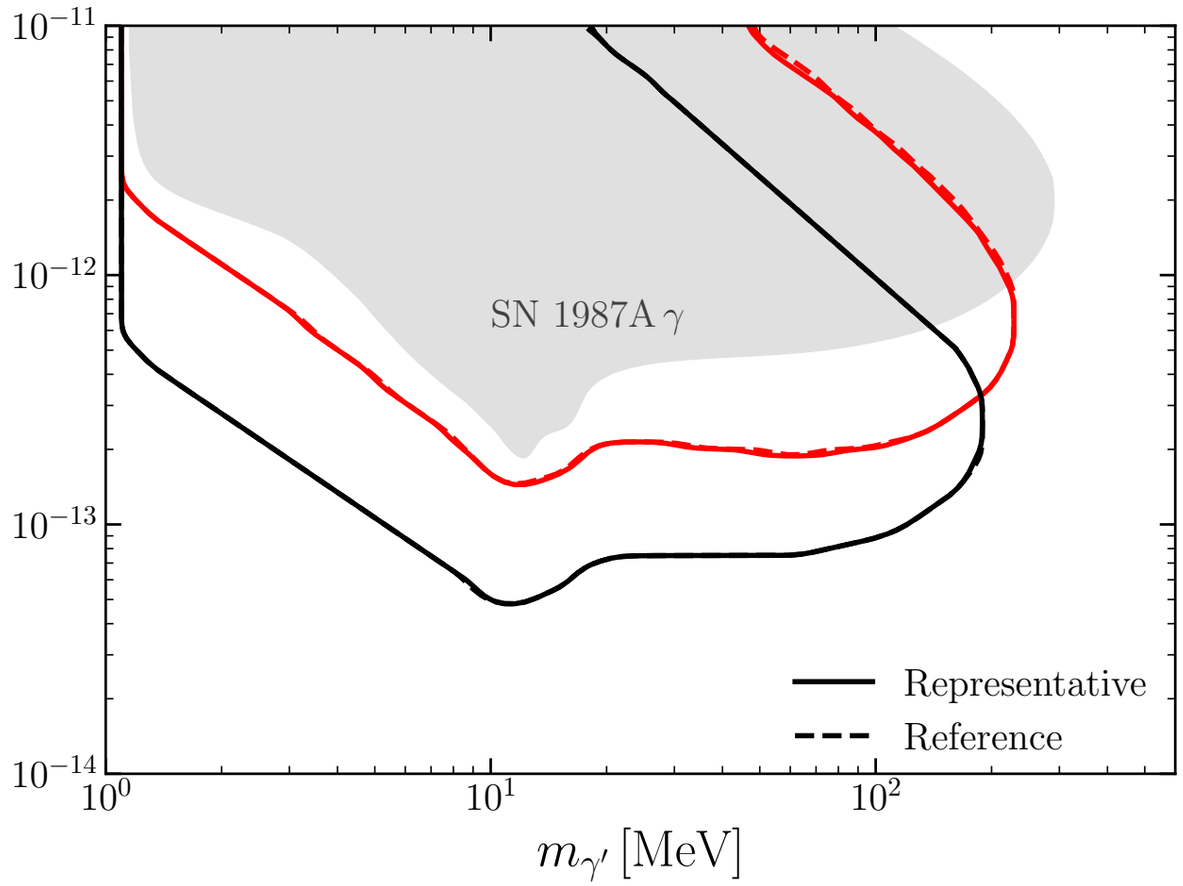
[Y. Cheng, CF Kong, YH Lin, MR Wu, **SY**, 26]

Model Dependence

◉ Core-collapse SN profiles



◉ CSM density profiles



Conclusion

- CSM can provide a probe of BSM
  - production in PNS + visible decay in CSM ☞ energy deposition in CSM prior to SBO
  - @ inner CSM - increasing κ & T ☞ increasing blackbody luminosity
  - @ outer CSM - dust sublimation ☞ suppressed spectral transition (UV/optical → IR)
- Observational constraints
  - none-excessive precursor BB luminosity (SN 2023ixf)
  - for future galactic SNe, rapid spectral transition from infrared-excess to optical/UV dominance between core-collapse and SBO
  - Examine the dark photon scenario as a reference, and find the stringent constraints in the parameter space, which is previously unexplored

Back up

Supernova Dark Photons

- Indirect electromagnetic interaction via kinetic mixing
- Thermal field theory framework
  - **Plasma (or in-medium) effect : refractive index & mixing effect**
  - **Possible resonance of $\gamma \leftrightarrow \gamma'$**

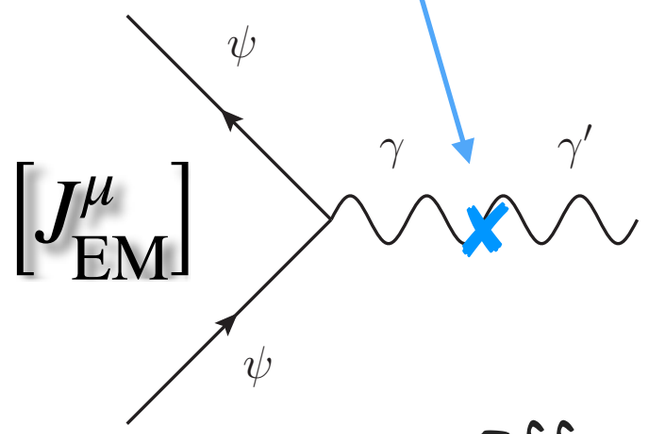
Kinetic Mixing with Photon

◉ Low-energy effective γ' couplings

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\varepsilon}{2}F_{\mu\nu}X^{\mu\nu} - \frac{1}{2}m_{\gamma'}^2 X_\mu X^\mu + eA_\mu J^\mu_{\mathrm{EM}} + e'A'_\mu J'^\mu$$

EM field strength — DP field strength — **kinetic mixing** [B. Holdom, 86] — γ' mass — EM current — γ' current
- hadron (ChPT)
- lepton

◉ Effective γ' couplings:



In the vacuum

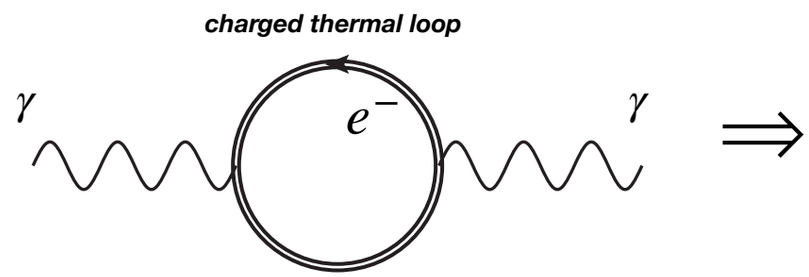
$\gamma\,(A^\mu)$ is massless

☞ $\varepsilon e\, J^\mu_{\mathrm{EM}} A'_\mu$

★ Effective couplings in a dense medium?

Effective coupling of γ' in medium

✓ Plasma effect on ***photon*** dispersion



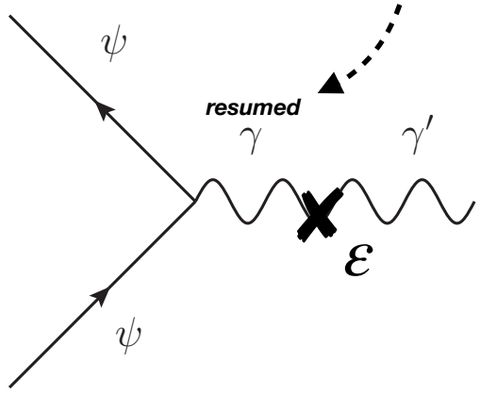
$$\Rightarrow$$

$$\mathscr{L}_{\Pi}^{\text{eff}} = -\frac{1}{2}\Pi^{\mu\nu}A_{\mu}A_{\nu}$$

"polarization tensor"

$$\text{Re}\left[\Pi^{\mu\nu}\right] = e^2\left\langle J^{\mu}_{\text{EM}}J^{\nu}_{\text{EM}}\right\rangle = \pi_{\text{T}}\sum \epsilon^{*\mu}_{\text{T}}\epsilon^{\mu}_{\text{T}} + \pi_{\text{L}}\epsilon^{*\mu}_{\text{L}}\epsilon^{\mu}_{\text{L}}$$

✓ Kinetic mixing (ε)



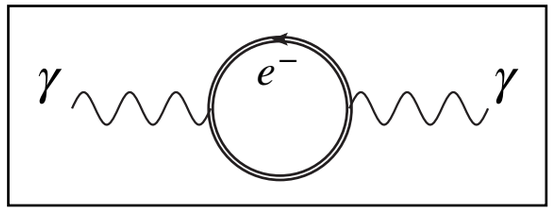
$$\Rightarrow$$

$$\mathscr{L}_{\varepsilon}^{\text{eff}} = \varepsilon e\frac{m^2_{\gamma'}}{m^2_{\gamma'} - \pi_{\text{T,L}}}J^{\mu}_{\text{EM}}A'_{\mu}$$

resumed photon propagator

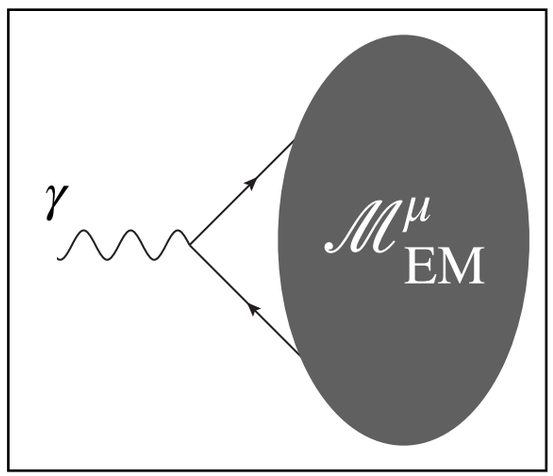
Polarization tensor $\pi_{\mathrm{T,L}}$

- Real part: photon refractive index (i.e., effective photon mass)
  - from coherent forward scatterings
  - parametrized by plasma frequency $\omega_{\mathrm{pl}} \propto \sqrt{n_e}$



$$\mathrm{Re}\left[\pi_{\mathrm{T}}\right] \sim \omega_{\mathrm{pl}}^2 \qquad\qquad \mathrm{Re}\left[\pi_{\mathrm{L}}\right] \sim \frac{m_{\gamma'}^2}{\omega^2}\omega_{\mathrm{pl}}^2$$

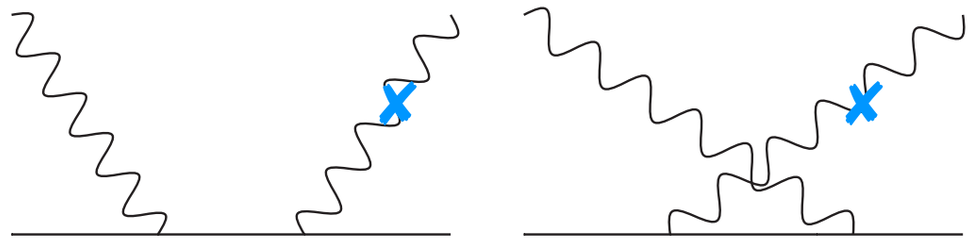
- Imaginary part: massive photon absorption width
  - w/ the corresponding dispersion ($\omega^2 - k^2 = m_{\gamma'}^2$)
  - detailed balance ☞ $\mathrm{Im}\,\pi_{\mathrm{T,L}} = -\,\omega\left(e^{\omega/T} - 1\right)\Gamma^{\mathrm{P}}_{\gamma_{\mathrm{T,L}}}$
  - $\mathrm{Im}\,\pi_{\mathrm{T,L}} \ll \mathrm{Re}\,\pi_{\mathrm{T,L}}$ leading to $\gamma \to \gamma'$ resonance



SN γ' production

◉ *Electrons* in highly degenerate and relativistic limit

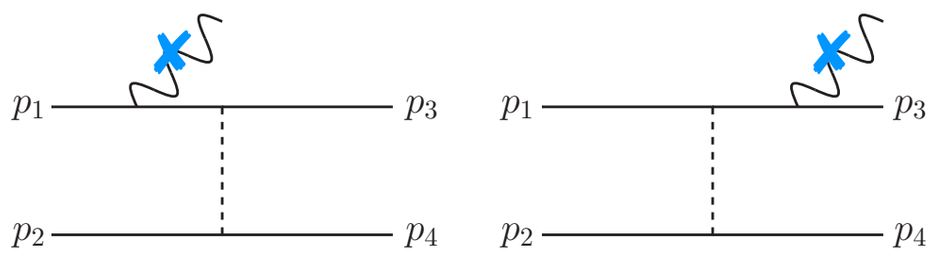
- $p_F \sim 0.1\text{-}1\,\mathrm{fm}^{-1} \gg T \sim 1\text{-}10\,\mathrm{MeV}$
- Pauli blocking makes processes associated with electrons (e.g., $e + \gamma \to e + \gamma'$)



➡ $R > R_{\mathrm{core}}$

◉ *Nucleons* in approximately non-degenerate and non-relativistic limit

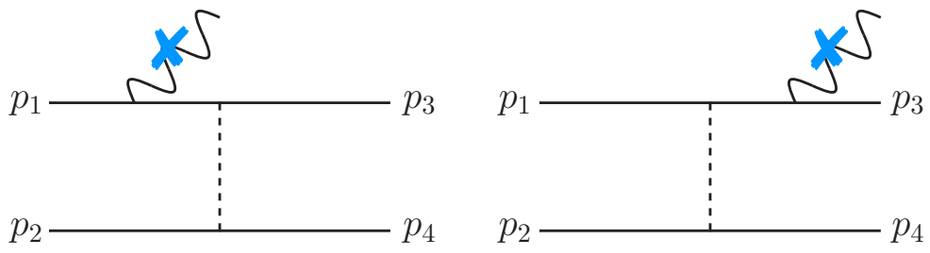
- ***N-N bremsstrahlung*** with mediators associated with strong interaction
- Neutron-proton scatterings: dipole radiation (i.e., different center of mass and charge)



$+ \quad \cdots$

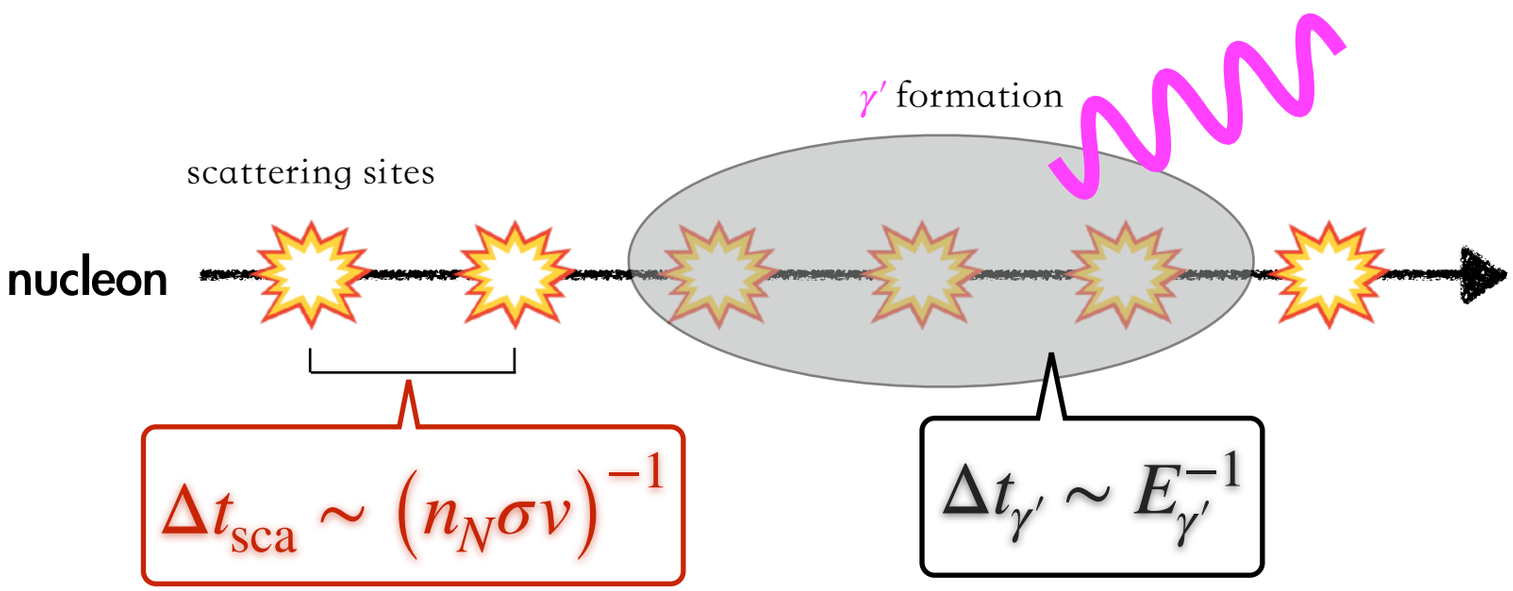
➡ $R < R_{\mathrm{core}}$

Bremsstrahlung in dense medium



+ ⋯

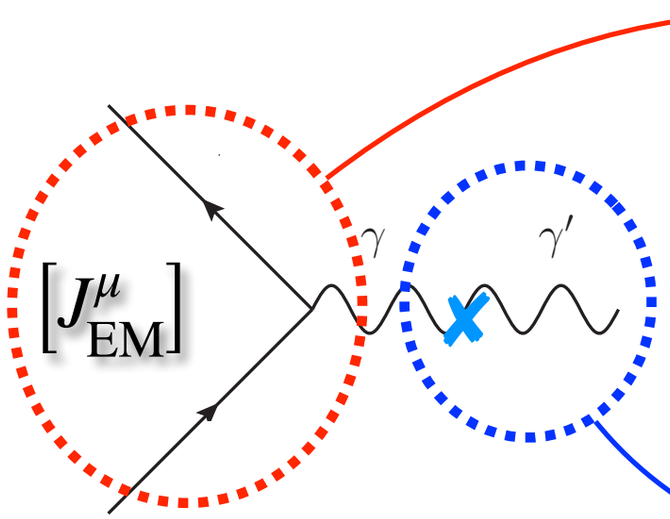
- Corrections to bremsstrahlung rate with respect to the vacuum
  - relativistic treatment, effective nucleon mass in medium, modified N-potential, ⋯
  - ***Multiple scattering effect (i.e., the Landau-Pomeranchuk-Migdal mechanism)***



Lorentzian shape ansatz

$$\Gamma_{\rm medium} \simeq \frac{E_{\gamma'}^2}{E_{\gamma'}^2 + (n_N \sigma v)^2/4} \Gamma_{\rm vacuum}$$

Resonant condition



$$\frac{d\Phi_{\gamma'}}{d\omega} \propto \frac{|\,\mathrm{Im}\,\pi_i\,|}{e^{\omega/T}-1} \frac{\varepsilon^2 m_{\gamma'}^4}{(m_{\gamma'}^2 - \mathrm{Re}\,\pi_i)^2 + |\,\mathrm{Im}\,\pi_i\,|^2}$$

✓ Enhancement of γ'coupling to EM @ $m_{\gamma'} = \mathrm{Re}\,\pi_i$

- for transverse, $m_{\gamma'} \simeq \omega_{\mathrm{pl}}$
- for longitudinal, $\omega \simeq \omega_{\mathrm{pl}}$ if $m_{\gamma'} < \omega_{\mathrm{pl}}$

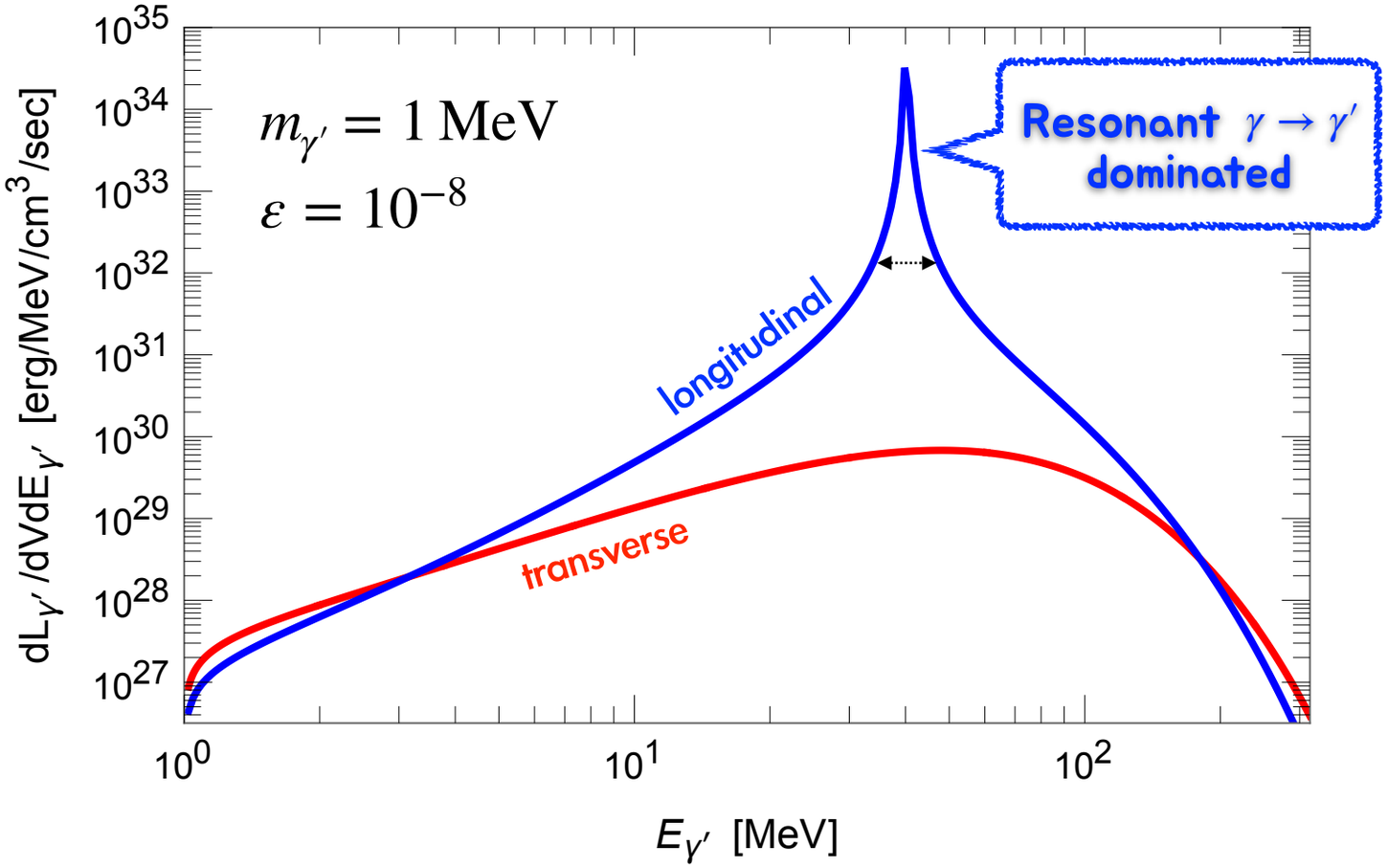
✓ $\mathrm{Re}\,\pi_i \gg \mathrm{Im}\,\pi_i \Rightarrow$ resonant $\gamma \leftrightarrow \gamma'$ conversion

$$\left.\frac{d\Phi_{\gamma'}}{d\omega}\right|_{\mathrm{res}} \simeq P_{\gamma\to\gamma'} \frac{d\Phi_{\gamma}}{d\omega}$$

$t_{\rm pb} \sim 1\,{\rm sec}$

SN γ' Volume Emissivity

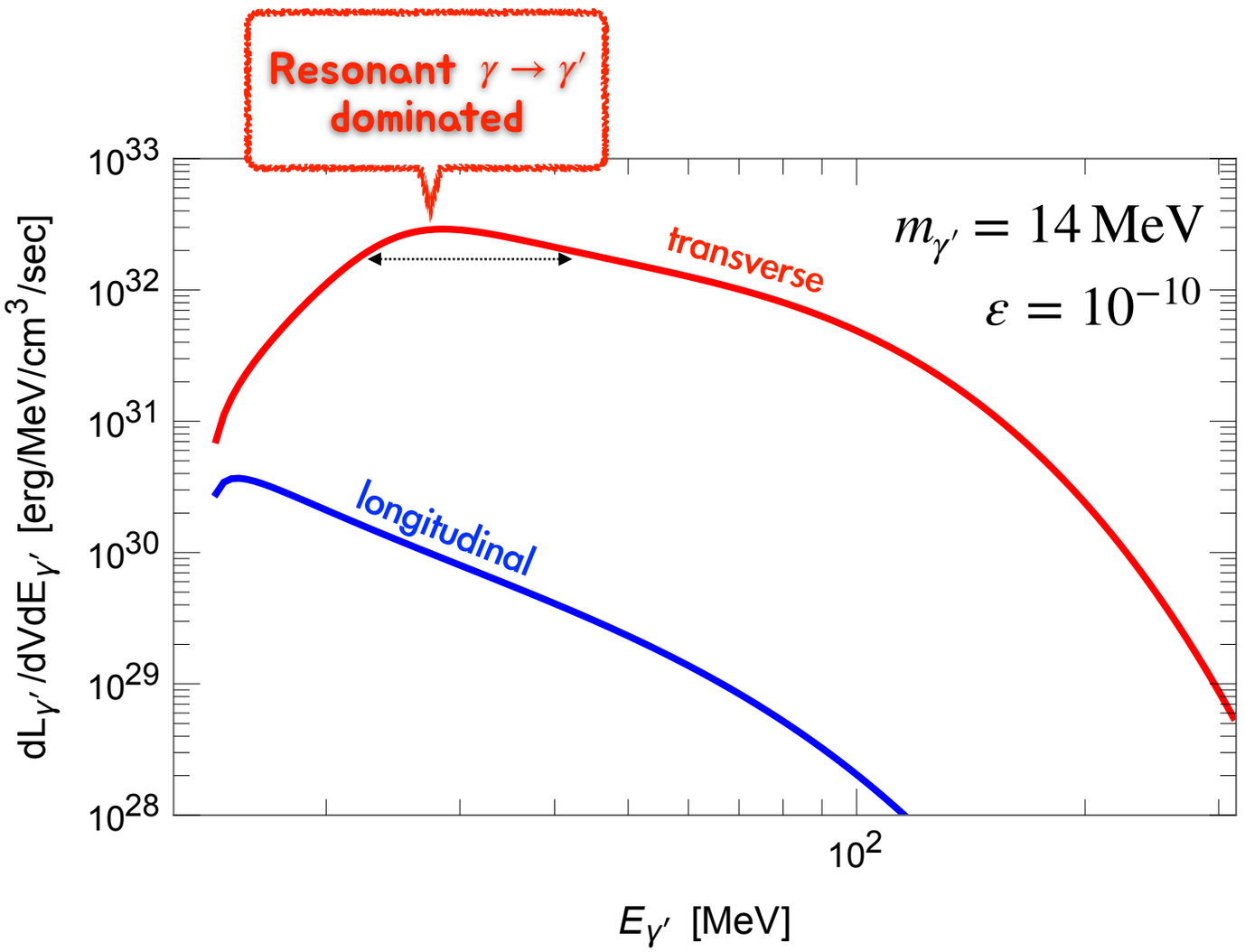
$$@\, R = 6\,{\rm km} \quad \Rightarrow \quad \omega_{\rm pl} \simeq 12.5\,{\rm MeV} \quad \& \quad T \simeq 30\,{\rm MeV}$$



$t_{\rm pb} \sim 1\,{\rm sec}$

SN γ' Volume Emissivity

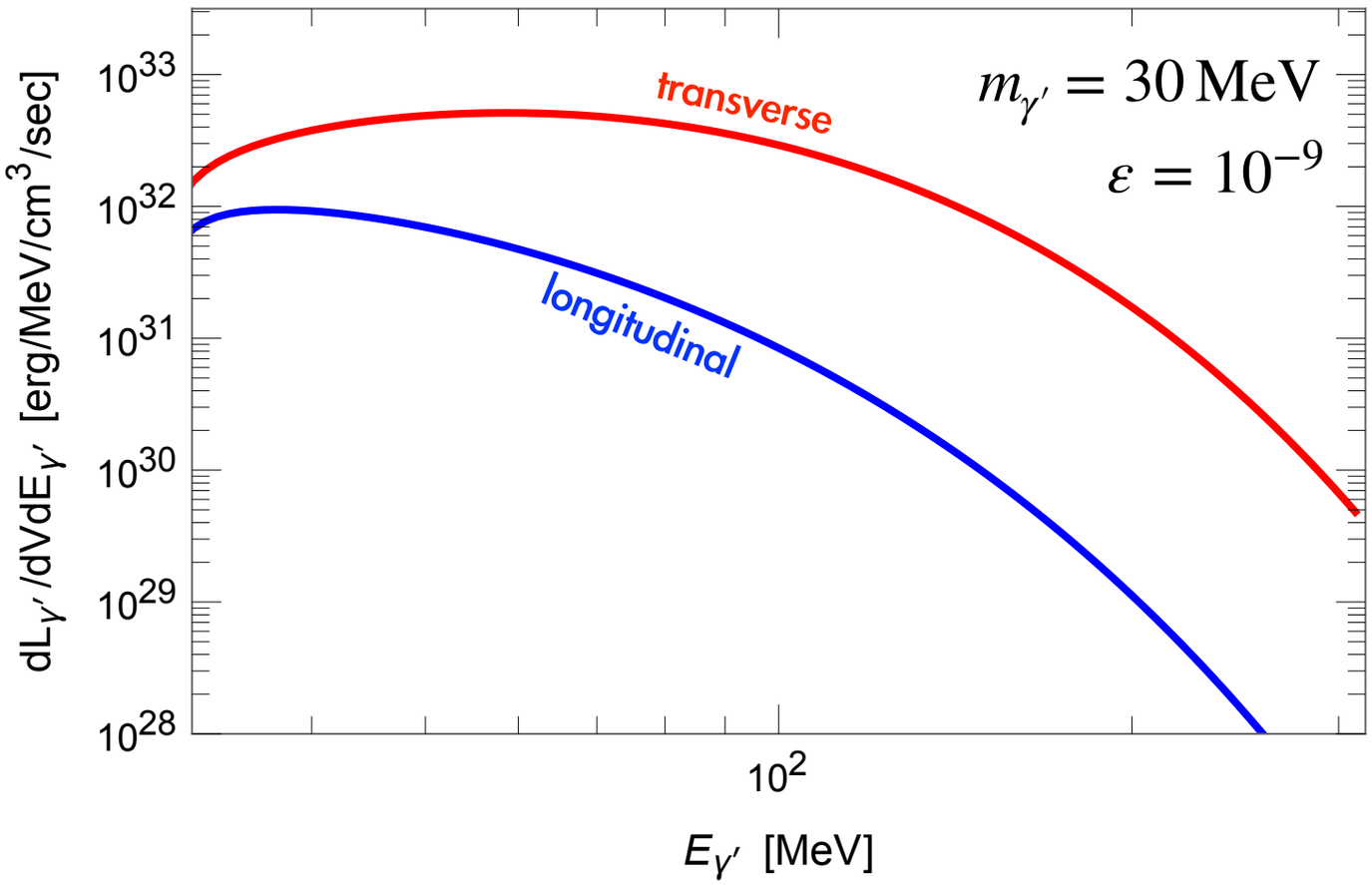
$$@\, R = 6\,{\rm km} \quad \Rightarrow \quad \omega_{\rm pl} \simeq 12.5\,{\rm MeV} \quad \& \quad T \simeq 30\,{\rm MeV}$$



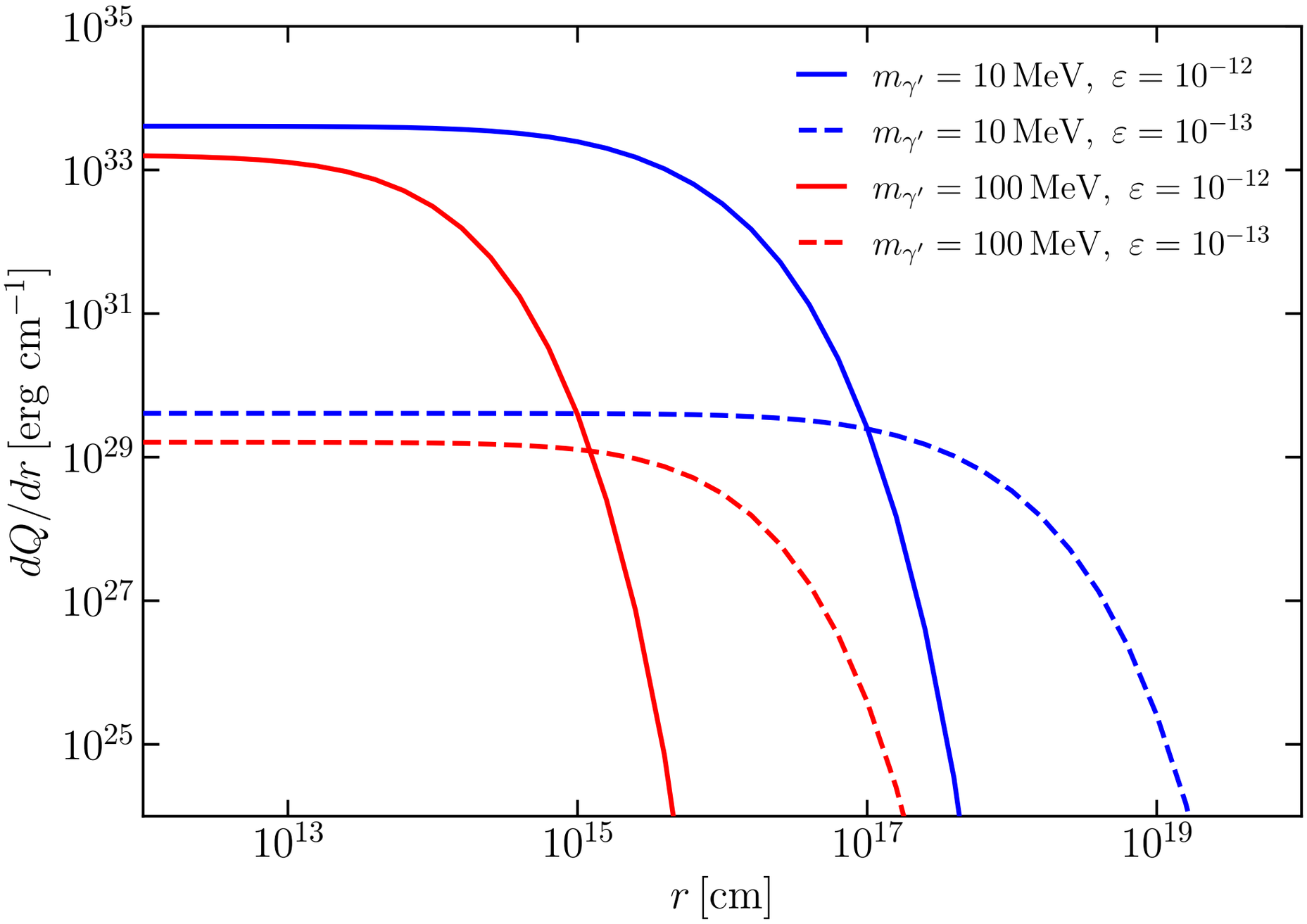
$t_{\rm pb} \sim 1\,{\rm sec}$

SN γ' Volume Emissivity

$$@\, R = 6\,{\rm km} \quad \Rightarrow \quad \omega_{\rm pl} \simeq 12.5\,{\rm MeV} \quad \& \quad T \simeq 30\,{\rm MeV}$$



SN γ' Energy Deposition Rate



CSM Profiles