CSM for BSM

Chui-Fan Kong
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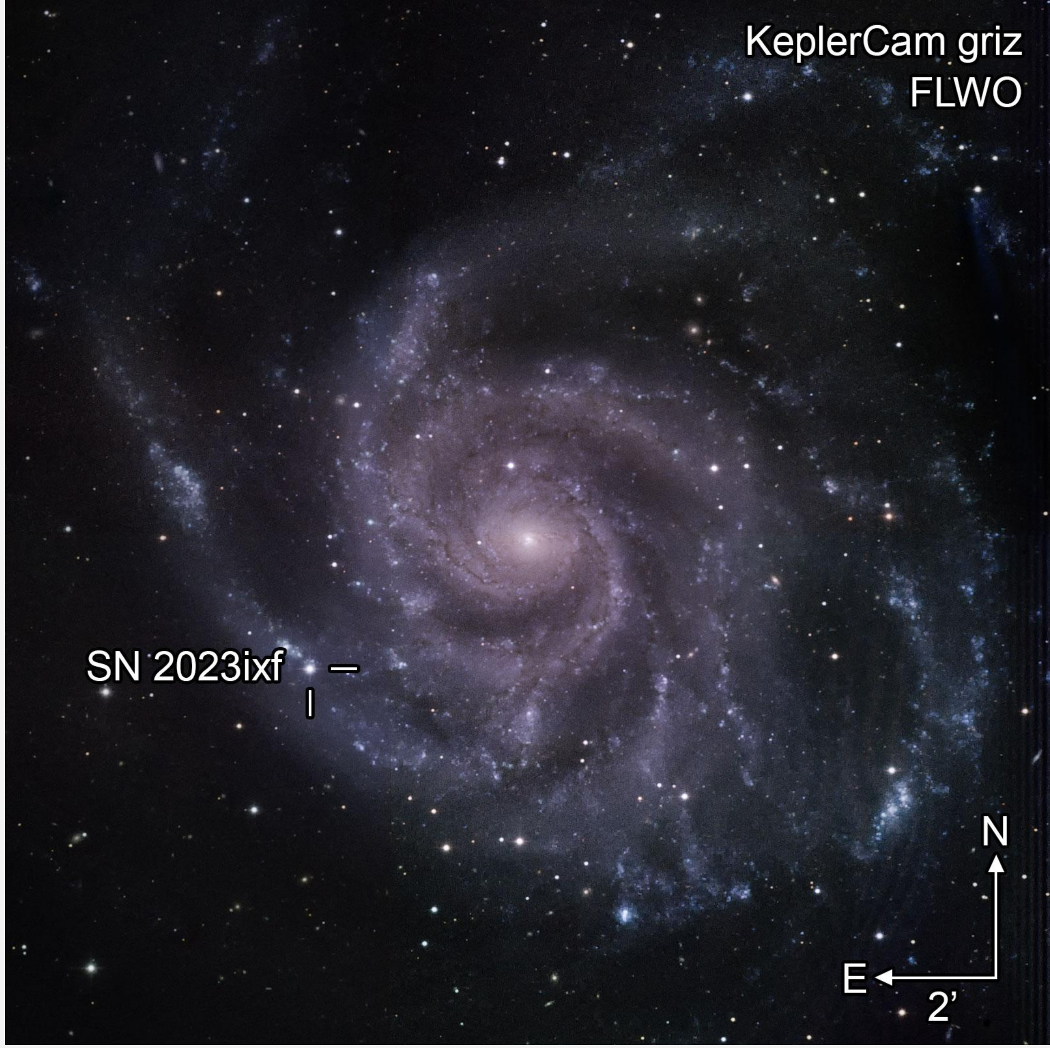
IBS-CTPU-PTC



Based on arXiv:2603.09615 [hep-ph]

In collaboration with:
Yu Cheng (KAIST & U. Chicago), Yen-Hsun Lin (Academia Sinica),
Meng-Ru Wu (Academia Sinica), Seokhoon Yun (KNU & IBS)

Institute for Basic Science

Light Dark World 2026 @ Carleton University

July 28, 2026

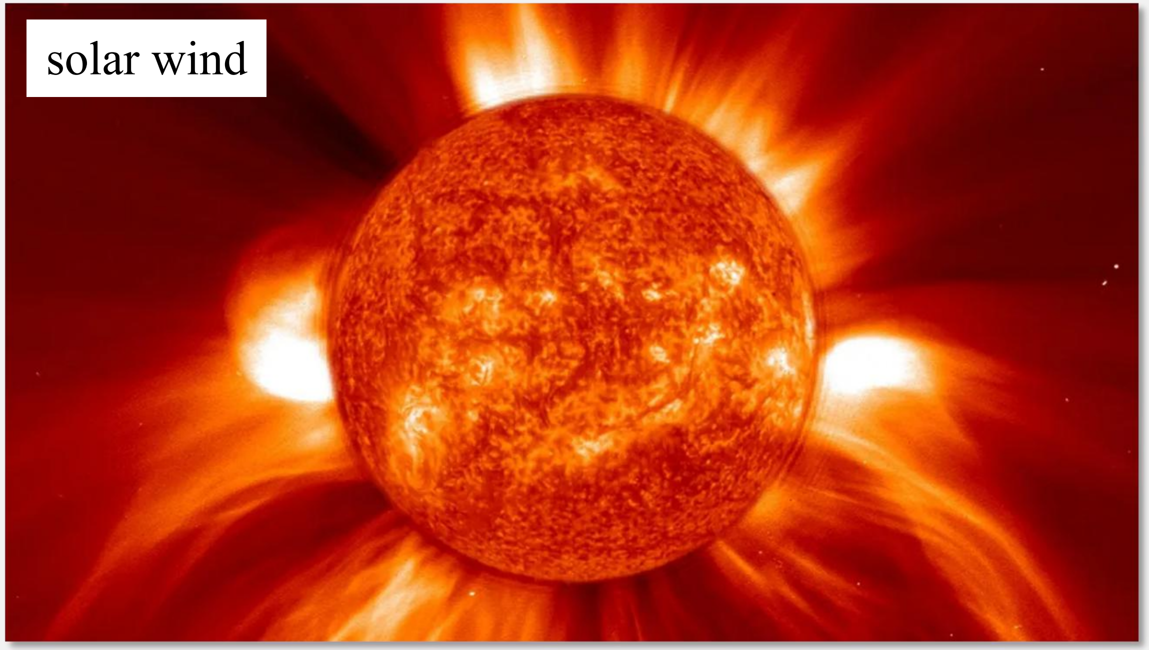
Contents

- *What* is circumstellar medium (CSM)
- *Why* we consider CSM
- *How* CSM constrains on feebly-interacting particles (FIPs)

What is CSM

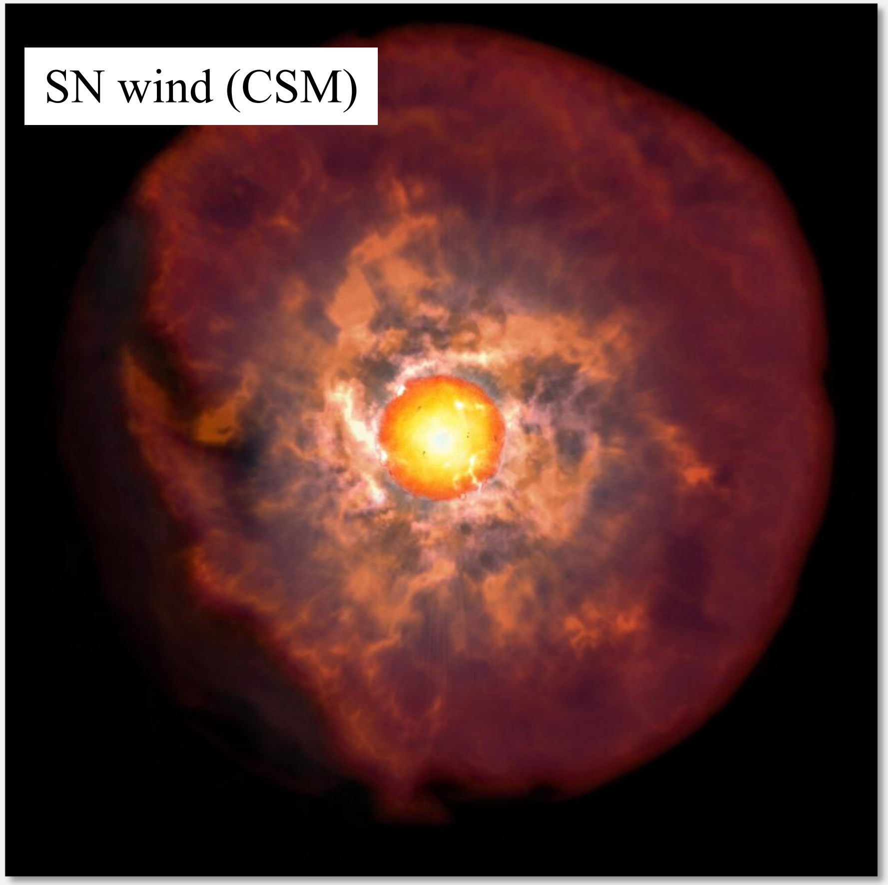
Production of CSM

Mass loss via the wind



credit: NASA

$$v \sim \mathcal{O}(100)\,\mathrm{km/s}$$

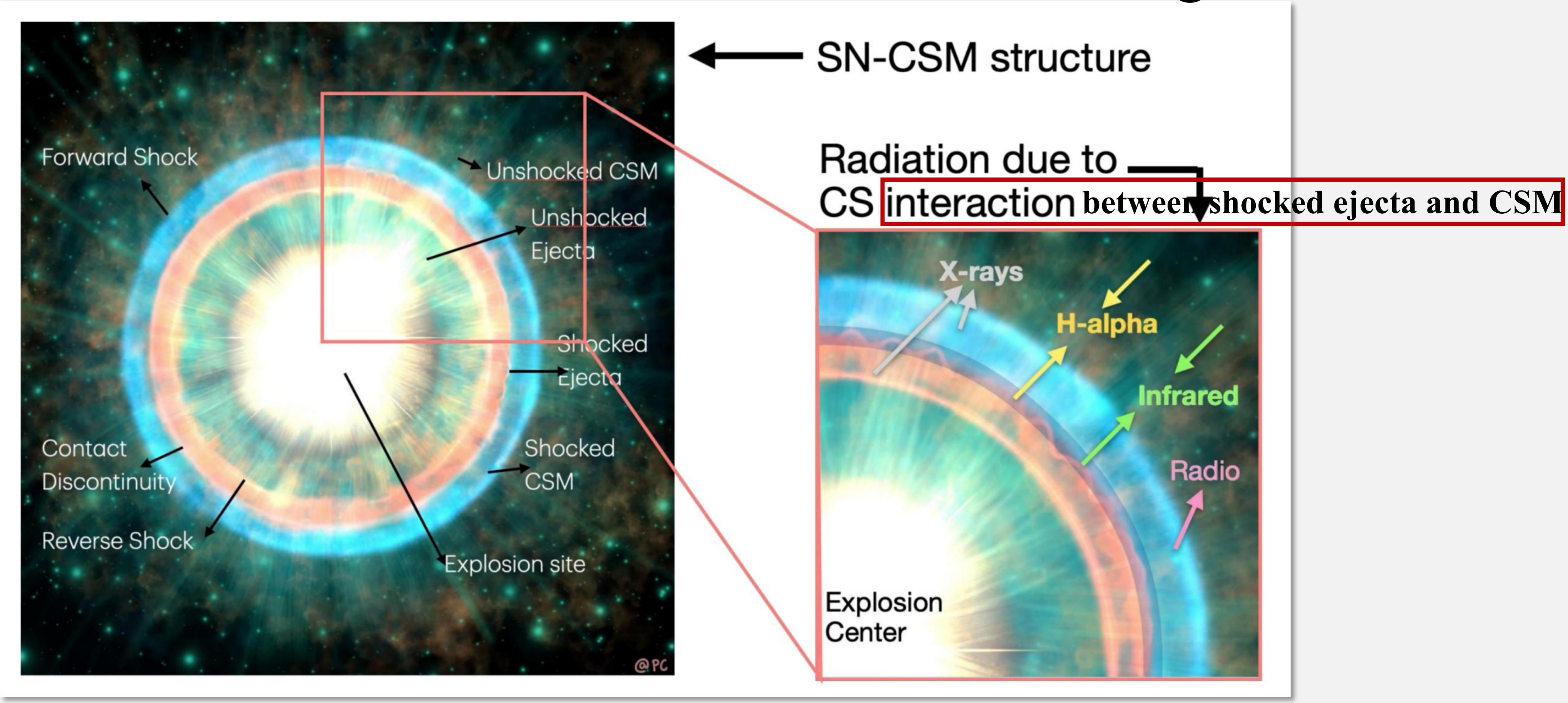


credit: NAOJ

$$v \sim \mathcal{O}(10)\,\mathrm{km/s}\ \text{for RSG}$$

Observational Evidence

How do we know there is CSM surrounding SN?

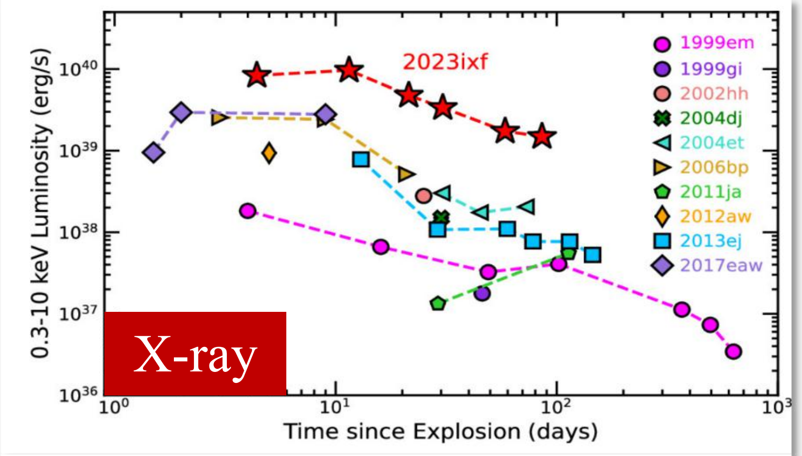


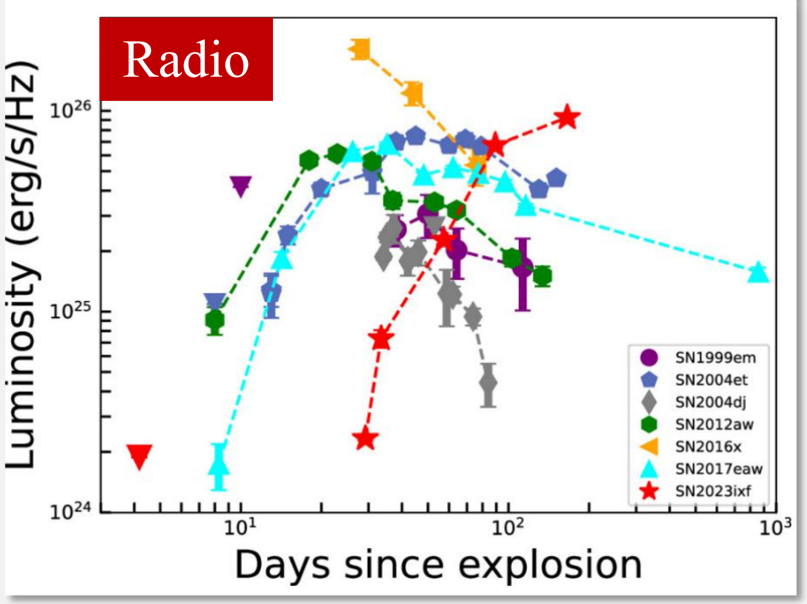
P. Chandra, arXiv:2510.20913

Observational Evidence

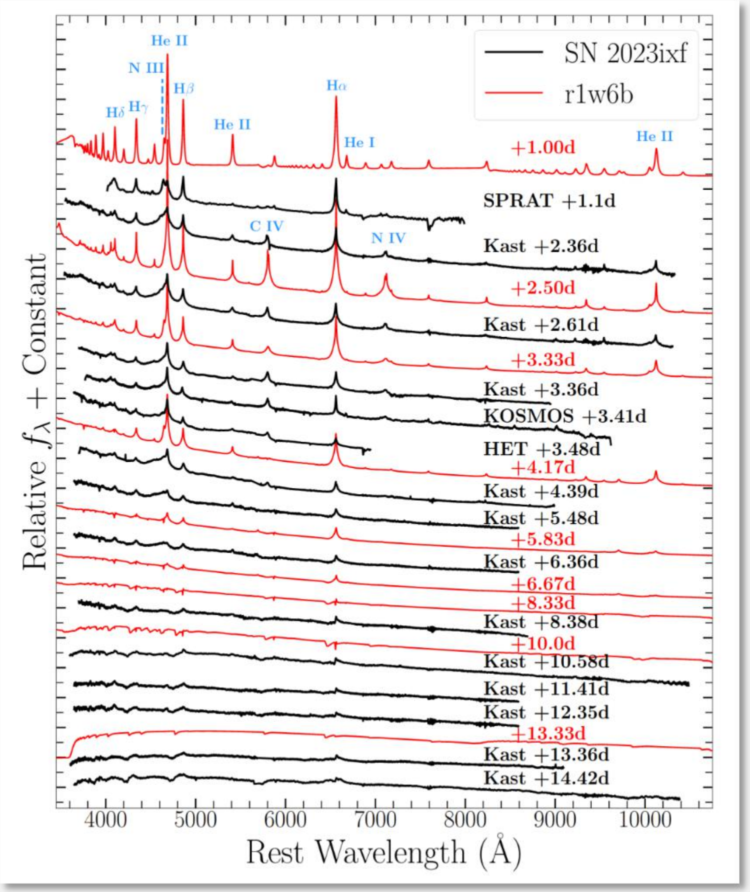
Institute for Basic Science

Plenty of measurements!

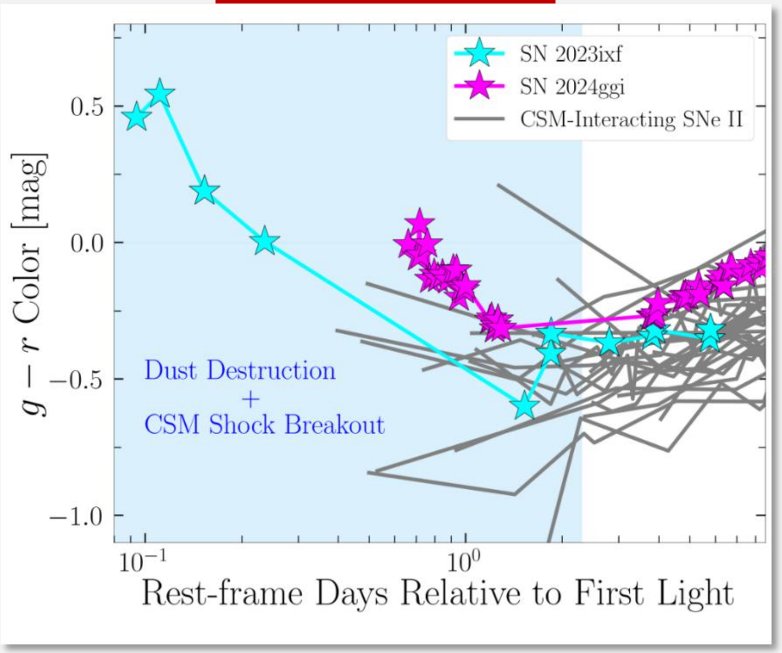




Spectroscopy



Photometric

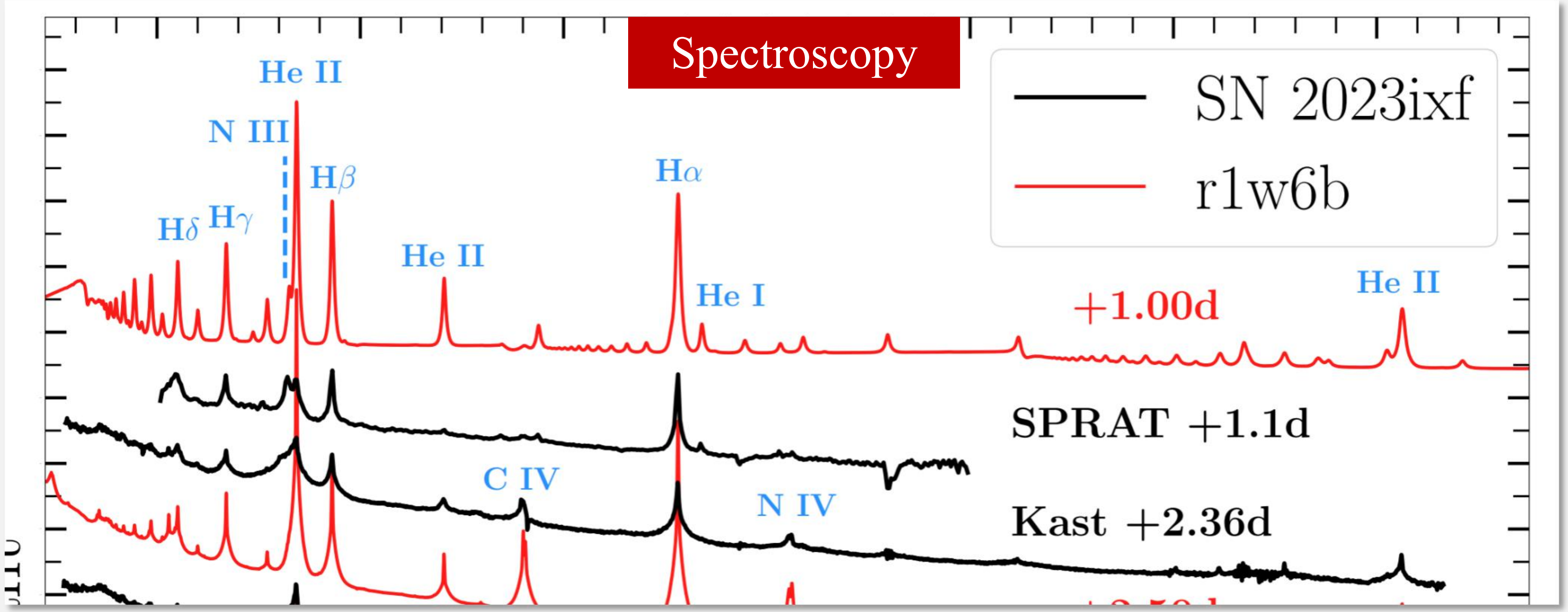


W.V. Jacobson-Galán, arXiv:2507.08078

Component of CSM

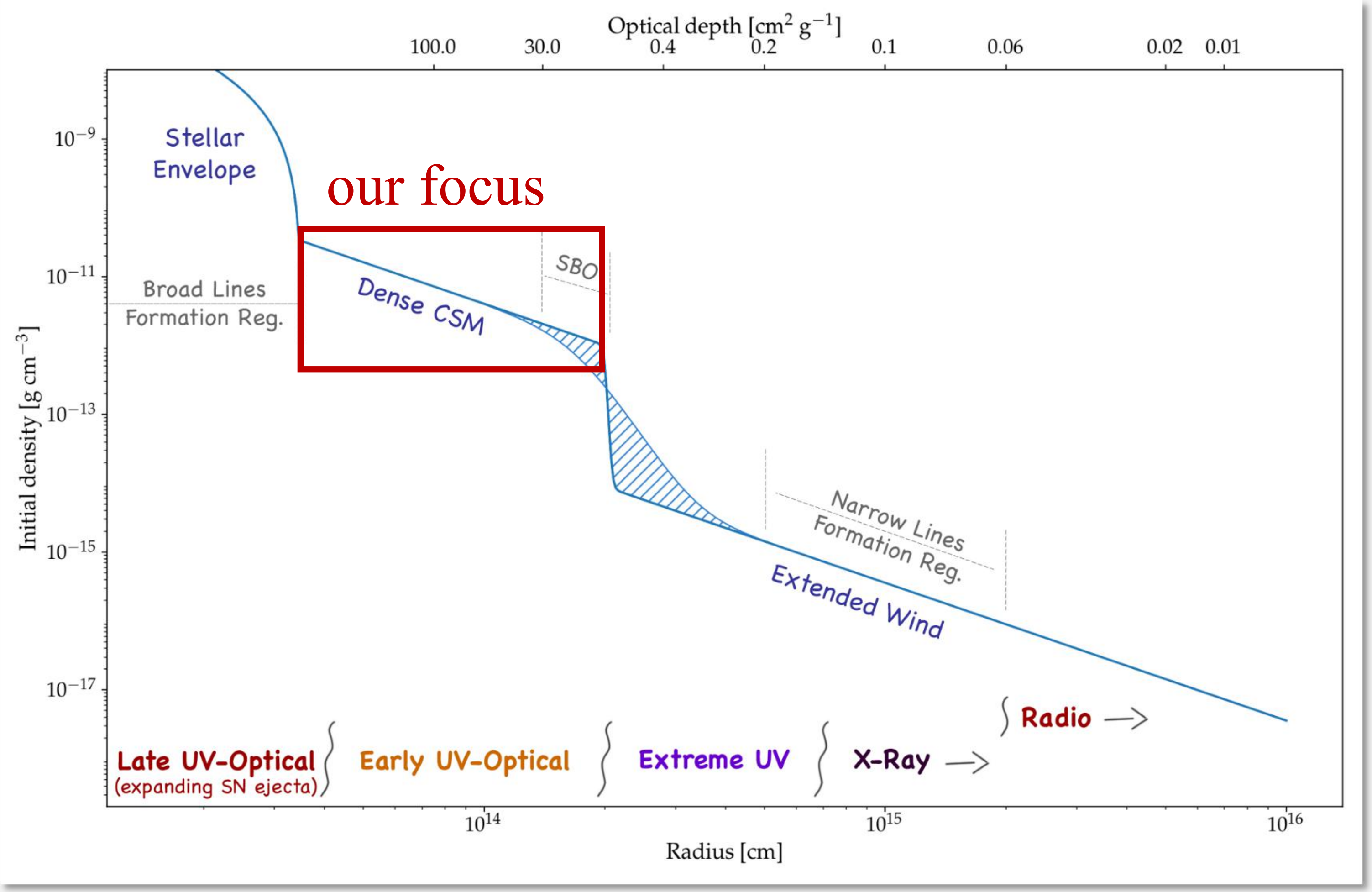
What makes of CSM

- Hydrogen
- Helium
- Carbon
- Nitrogen
- + Heavier elements



W.V. Jacobson-Galán, arXiv:2507.08078

CSM Density Profile



E.A. Zimmerman et al.
Nature 627 (2024) 759

Why we consider CSM

Traditional Method

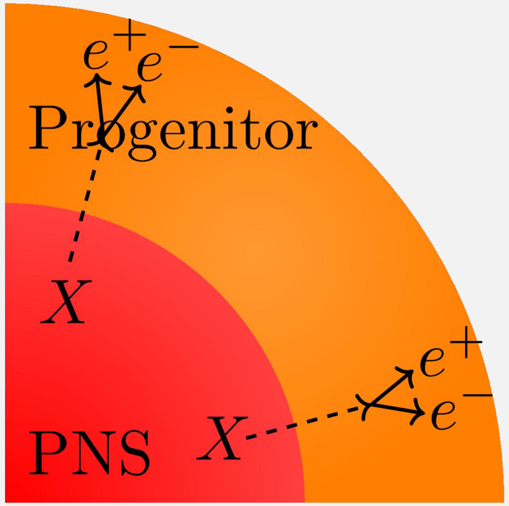
After FIPs (X) produced inside a proto-neutron star (PNS)

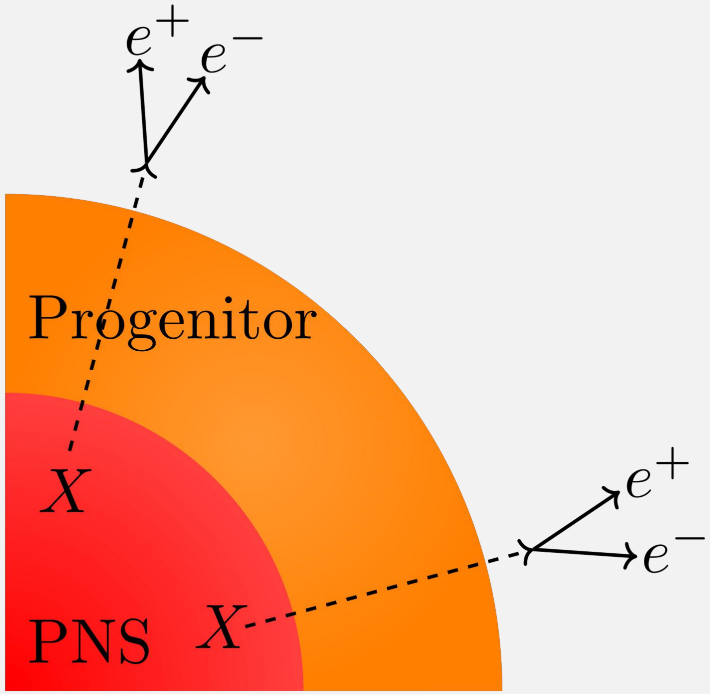
Decay inside → Energy trapped

Constraint from low-energy SN

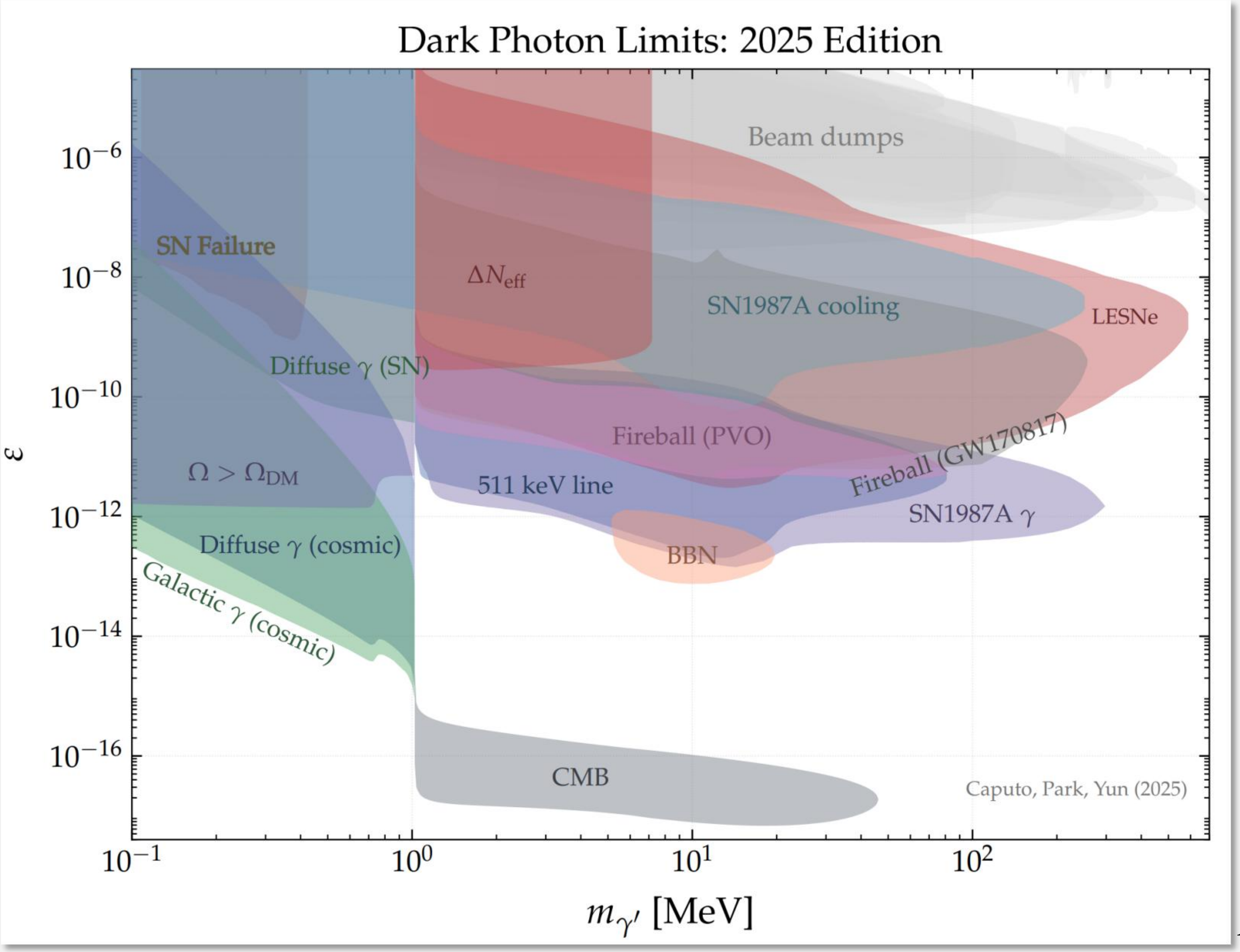
Decay outside → Energy escaped

Constraint from cooling, fireball, galactic positron (511 keV), prompt gamma ray





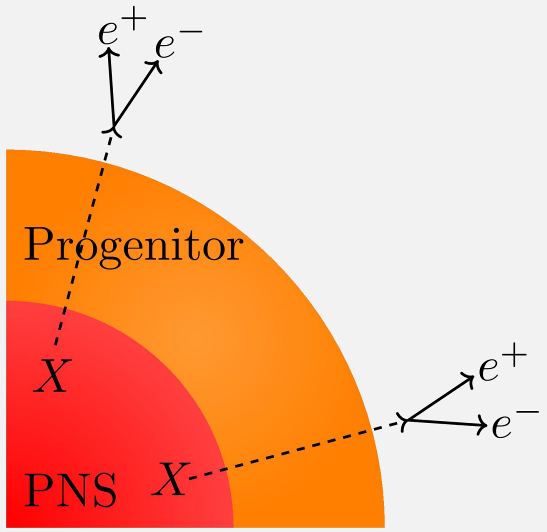
Exsisting Constraints w/o CSM



A. Caputo, J. Park, S. Yun
arXiv:2511.15785

CSM as A New Playground

However, CSM exists!



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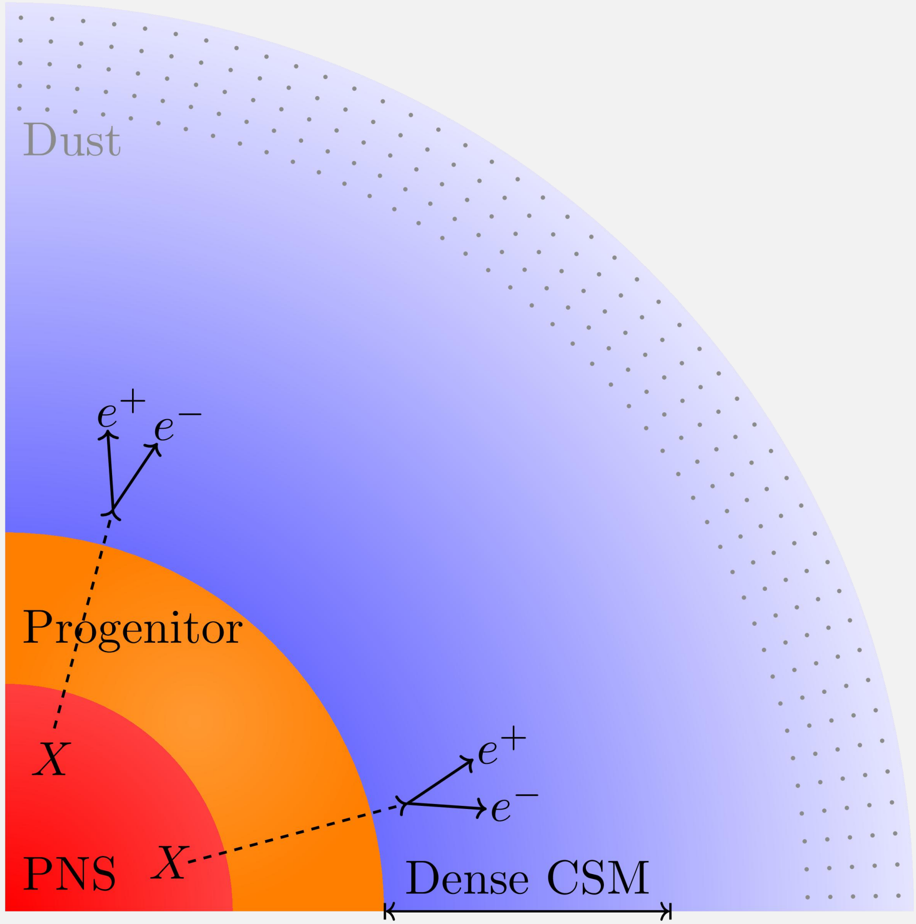

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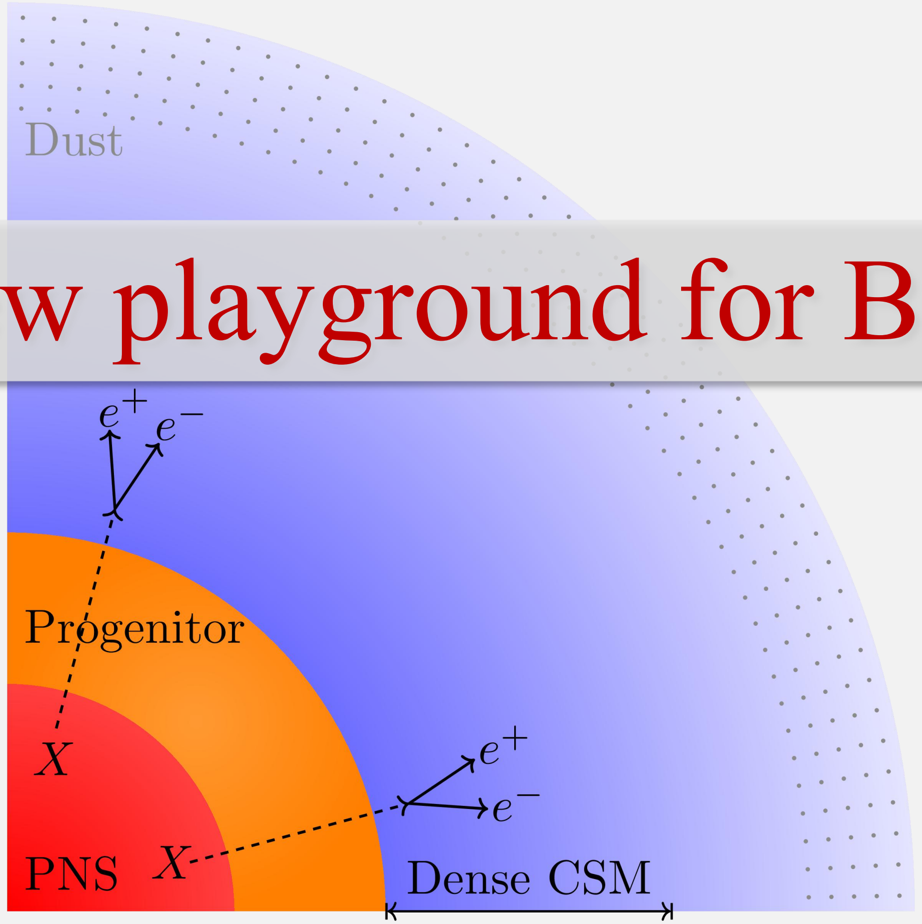
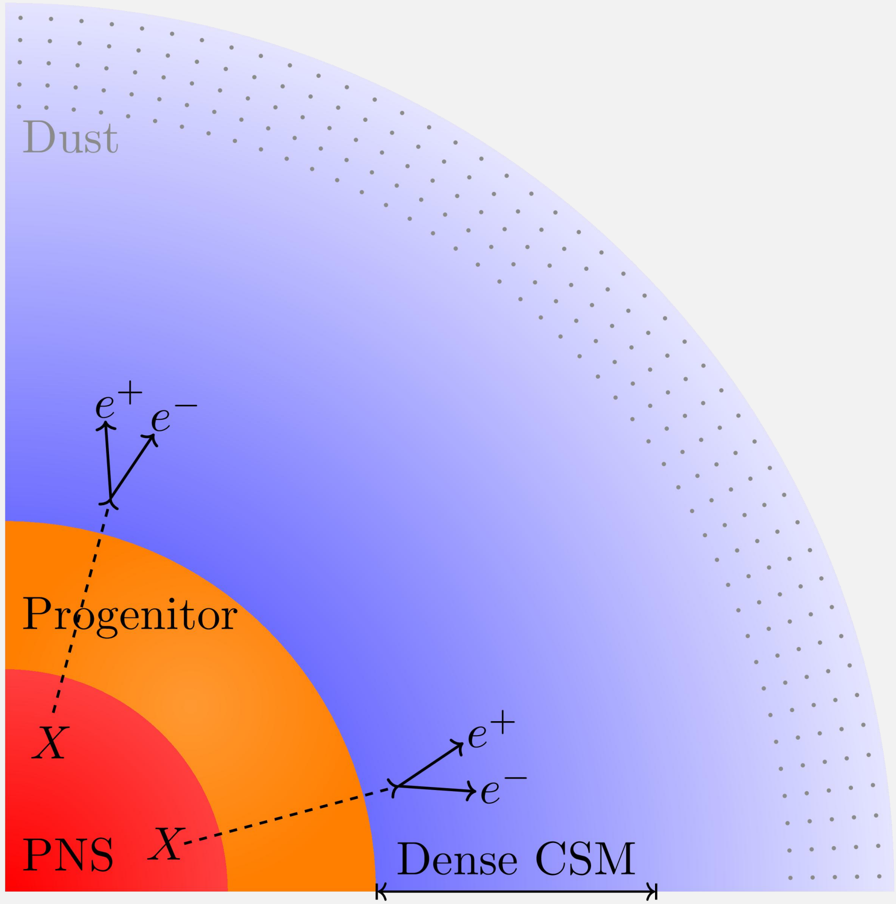


A new playground for BSM!

How CSM constrains on FIPs

Photosphere Induced by FIP Decay



*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
arXiv:2603.09615

FIPs decay into electron/positron inside CSM

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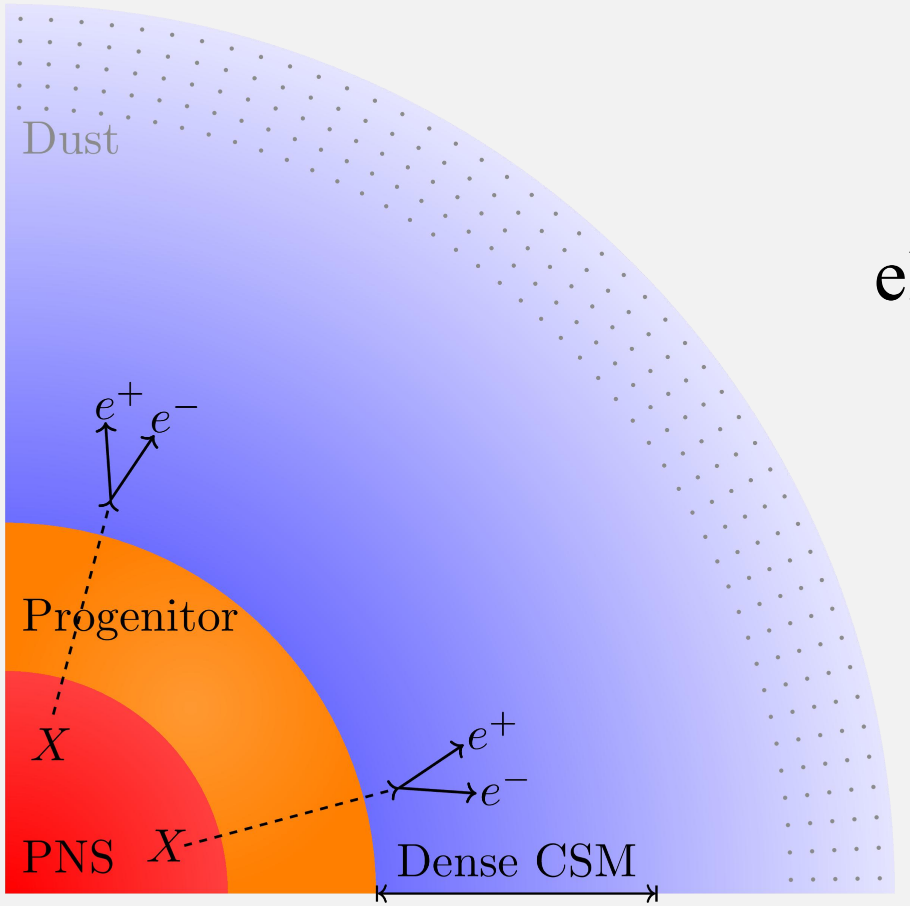

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FIPs decay into electron/positron inside CSM

↓

electron/positron energy deposition inside CSM

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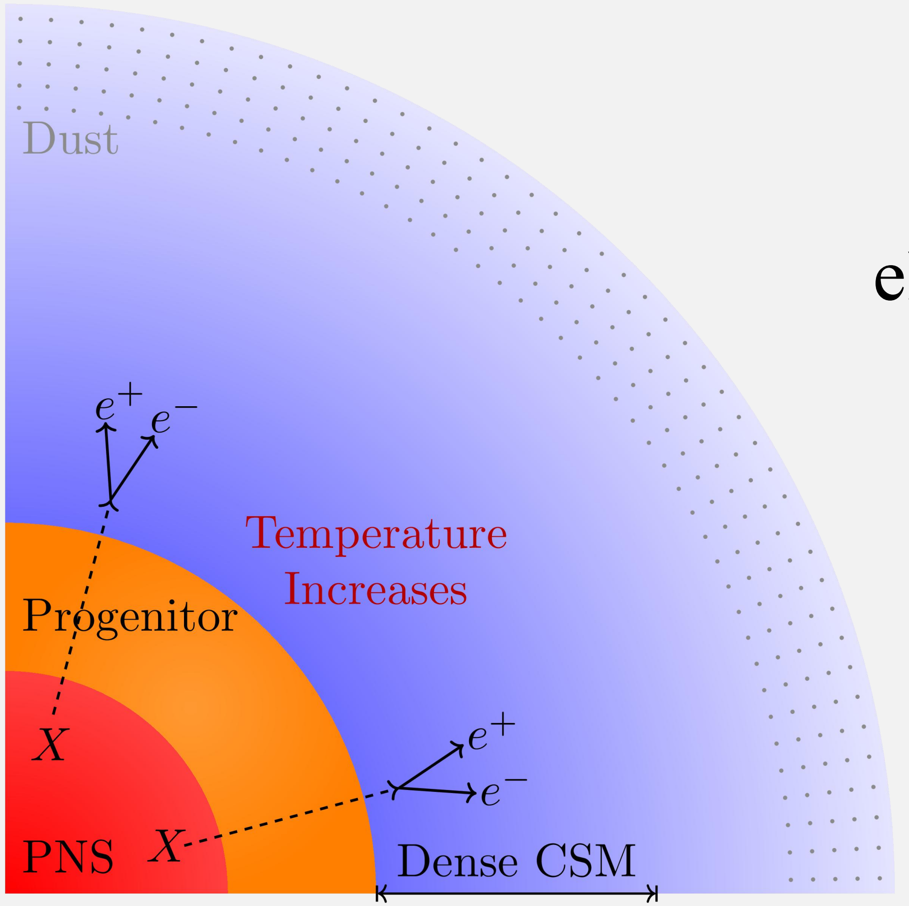

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FIPs decay into electron/positron inside CSM

↓

electron/positron energy deposition inside CSM

↓

CSM temparature increases

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

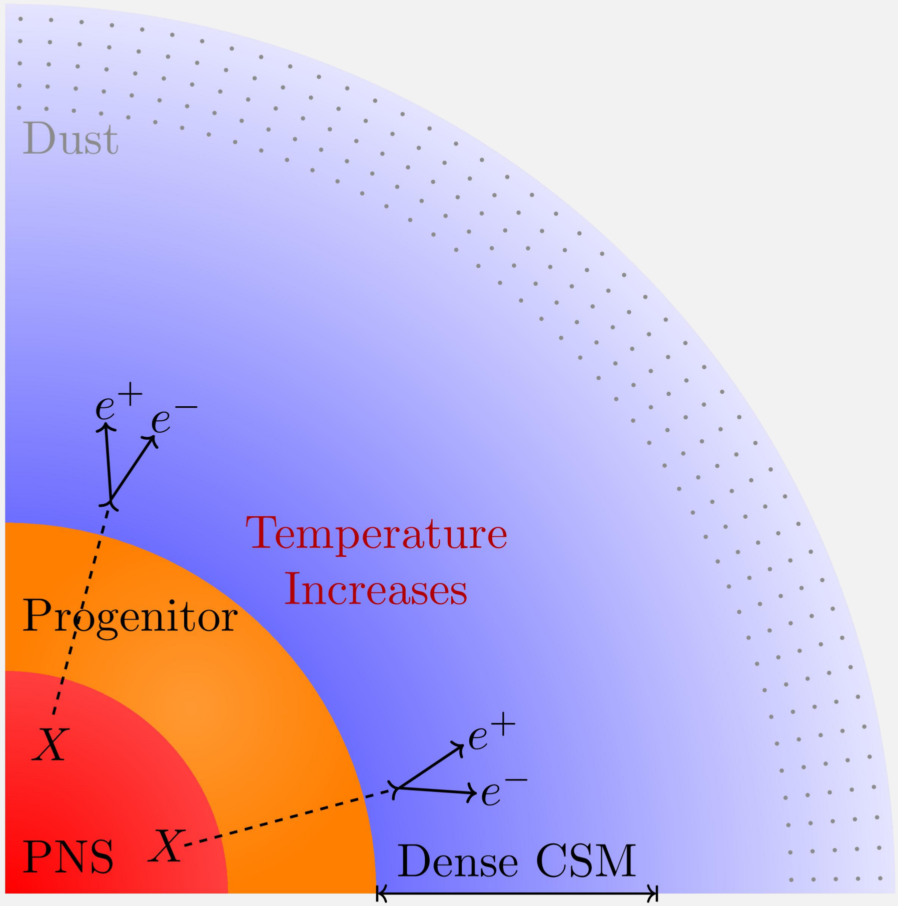
energy deposition efficiency

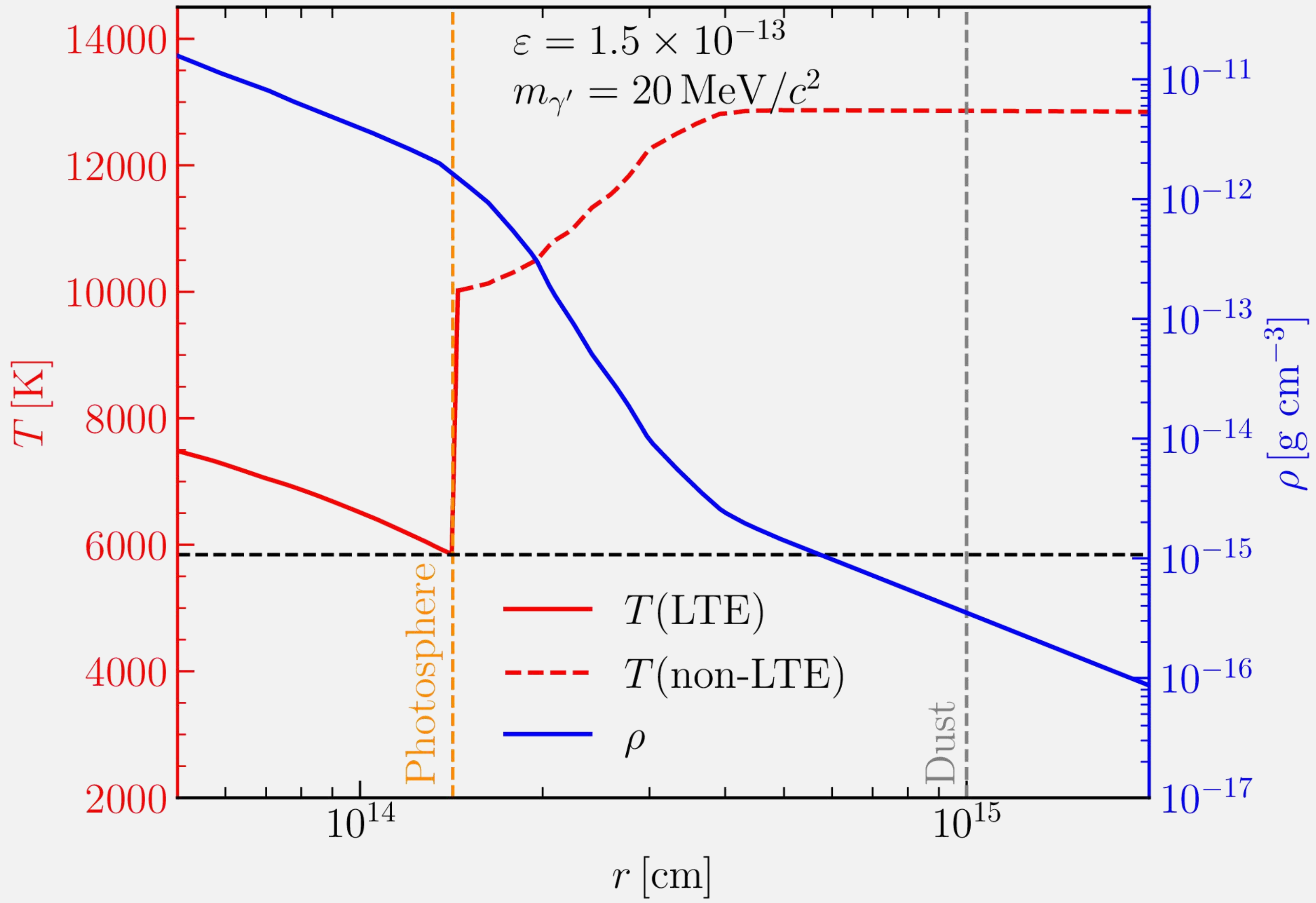
$u_{\rm gas} = (3/2)(n + n_e)k_B T$ internal energy density of ideal gas

ionization energy density

radiation energy density

Photosphere Induced by FIP Decay





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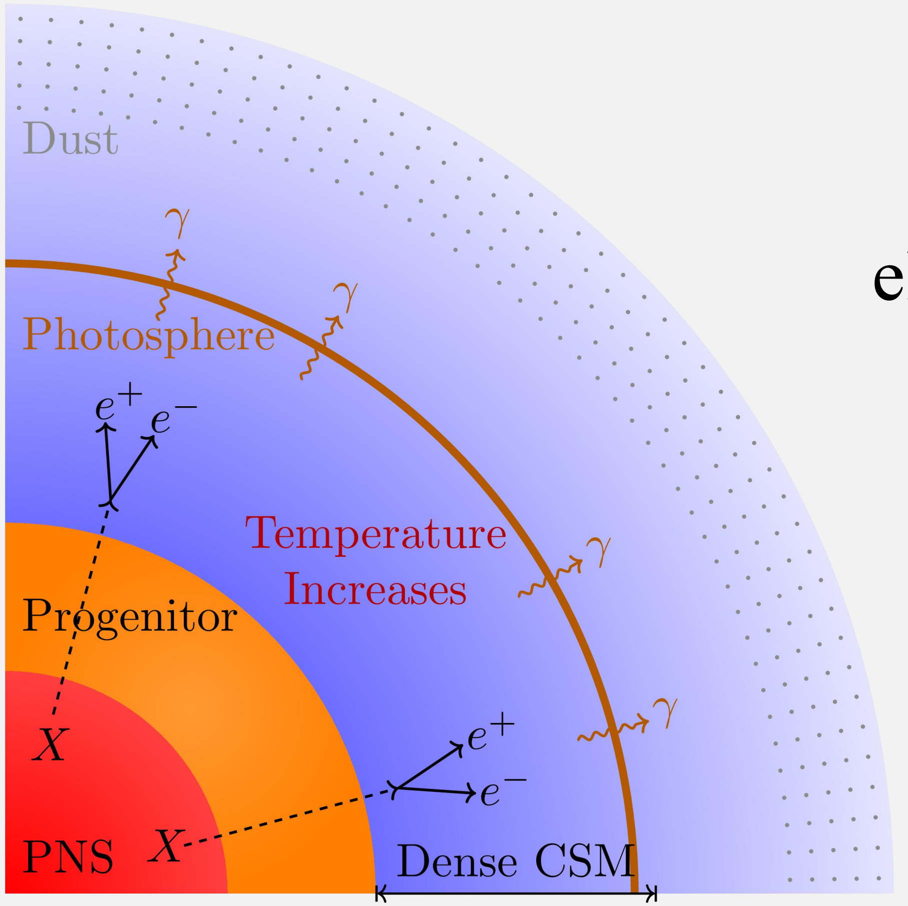

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FIPs decay into electron/positron inside CSM

↓

electron/positron energy deposition inside CSM

↓

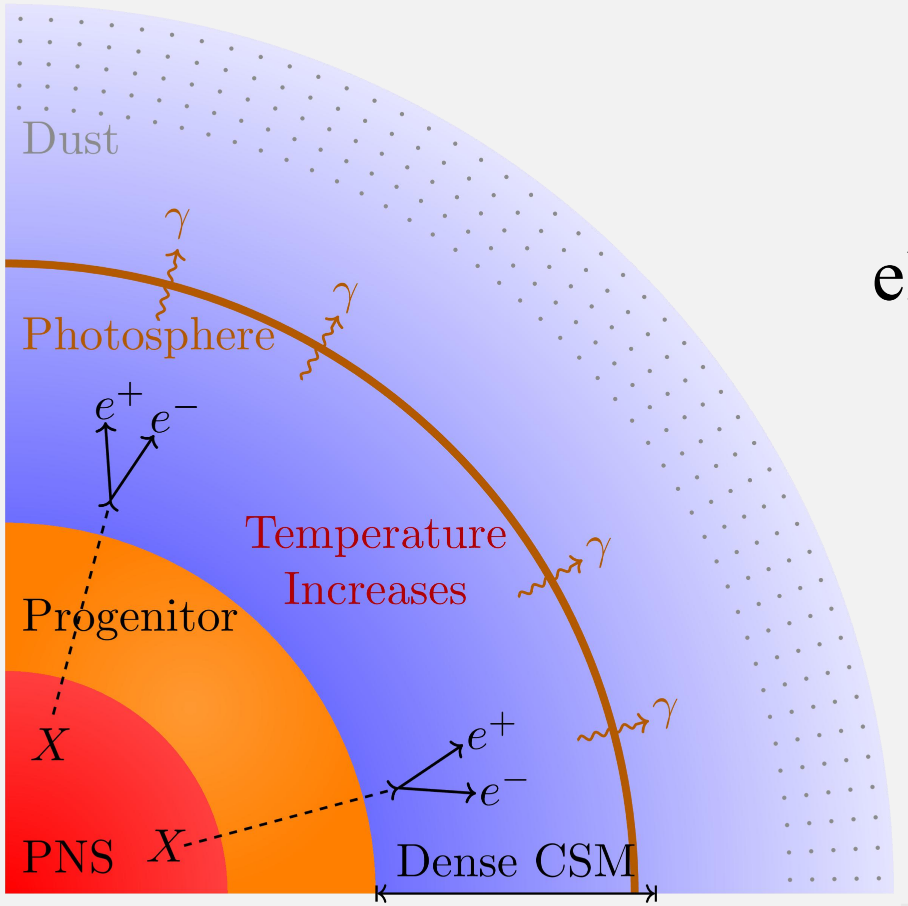
CSM temparature increases

↓

extra blackbody (BB) emission

$$L_{\rm BB} \simeq 4\pi r_{\rm ph}^2 \sigma_{\rm SB} T_{\rm ph}^4$$

Photosphere Induced by FIP Decay



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extra blackbody (BB) emission

$$L_{\rm BB} \simeq 4\pi r_{\rm ph}^2 \sigma_{\rm SB} T_{\rm ph}^4$$

constrained by observations!

SN 2023ixf as A Case Study

Institute for Basic Science

Inside the nearby galaxy Messier 101, with a distance ~ 6.85 Mpc

The closest supernova of the last decade!

nature

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Article | Published: 27 March 2024

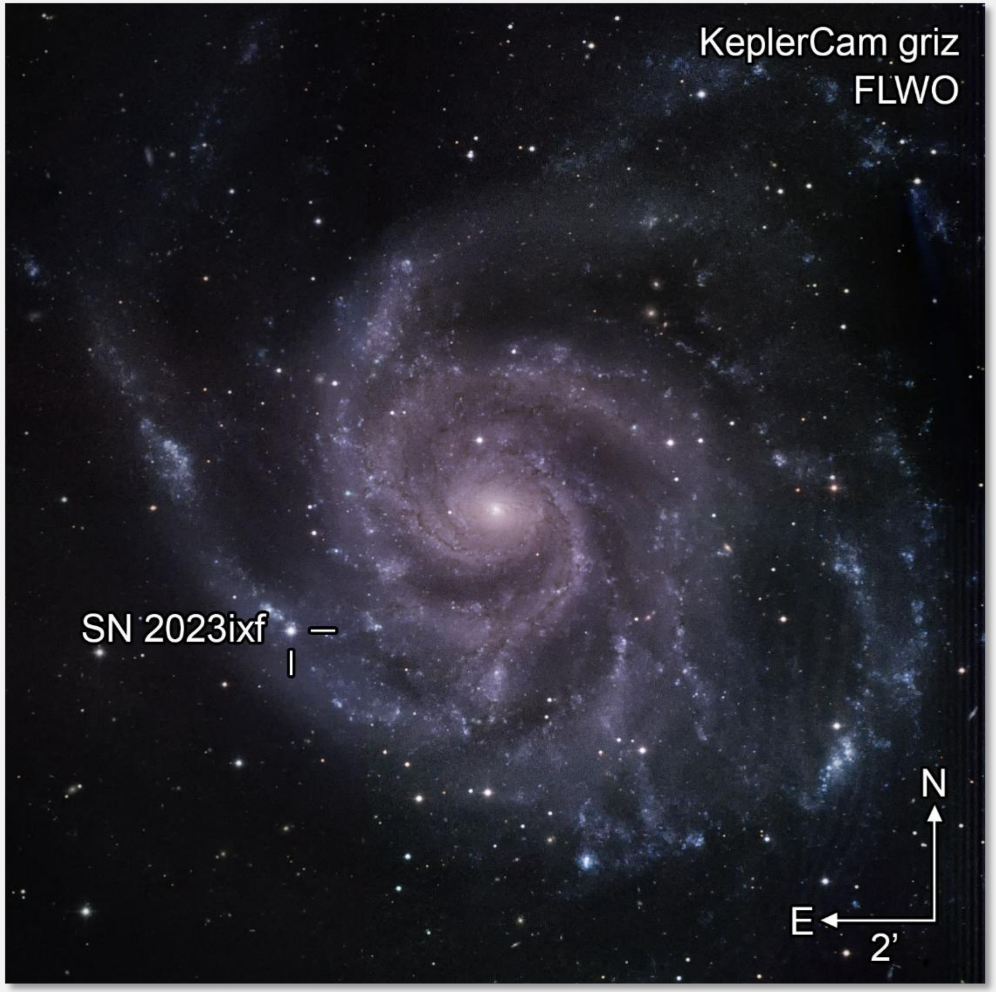
The complex circumstellar environment of supernova 2023ixf

E. A. Zimmerman, I. Irani, P. Chen, A. Gal-Yam, S. Schulze, D. A. Perley, J. Sollerman, A. V. Filippenko, T. Shenar, O. Yaron, S. Shahaf, R. J. Bruch, E. O. Ofek, A. De Cia, T. G. Brink, Y. Yang, S. S. Vasylyev, S. Ben Ami, M. Aubert, A. Badash, J. S. Bloom, P. J. Brown, K. De, G. Dimitriadis, ... K. Zhang + Show authors

Nature **627**, 759–762 (2024) | Cite this article

4259 Accesses | **121** Citations | **205** Altmetric | Metrics

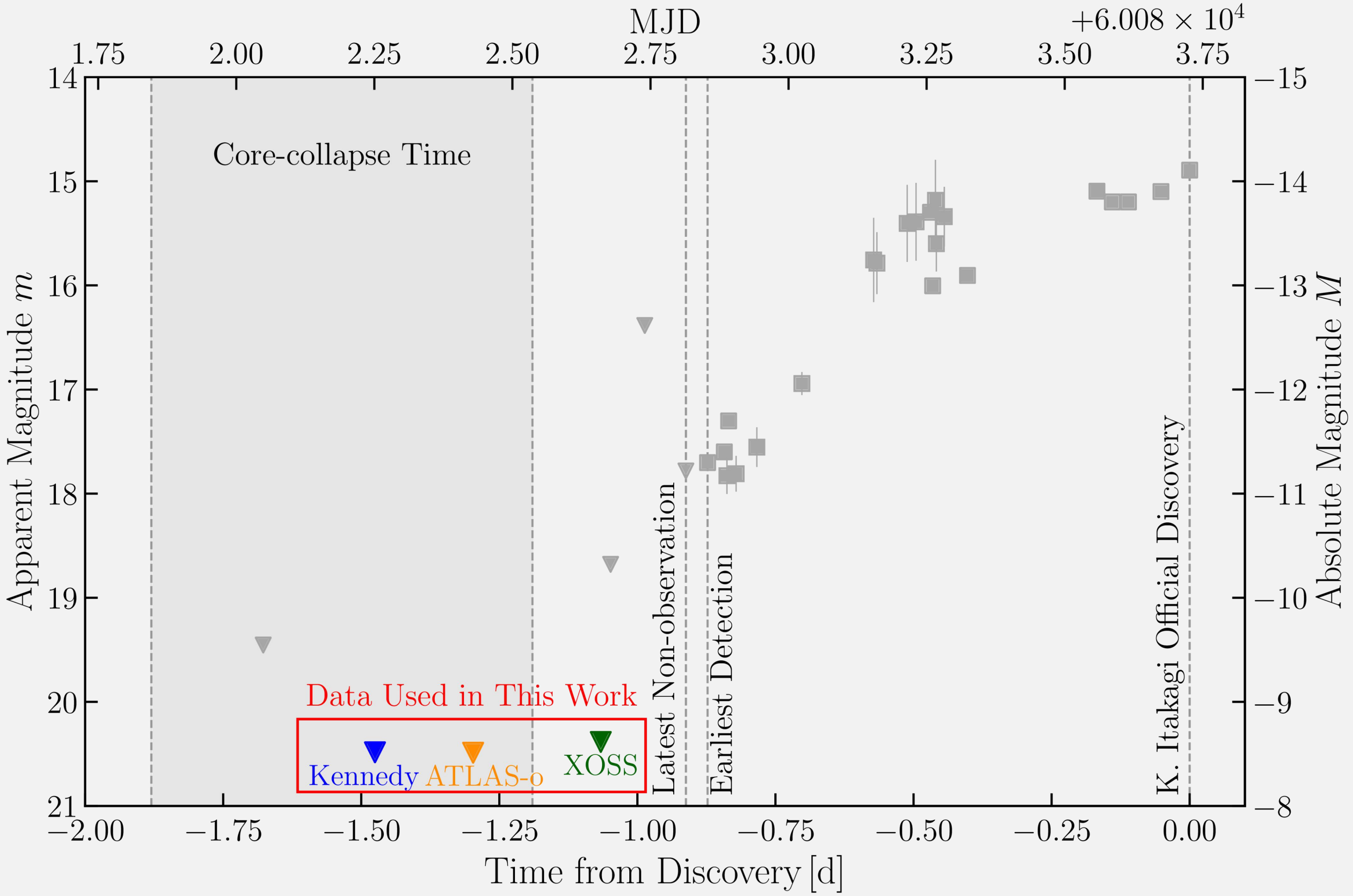
E.A. Zimmerman et al. Nature 627 (2024) 759



credit: S. Gomez/STScI

SN 2023ixf as A Case Study

Early-time observations of SN 2023ixf



optical band (400 nm -- 900 nm)

$$M \geq -8.6$$

$$\frac{L}{L'_\odot} = 10^{0.4(M'_\odot - M)}$$

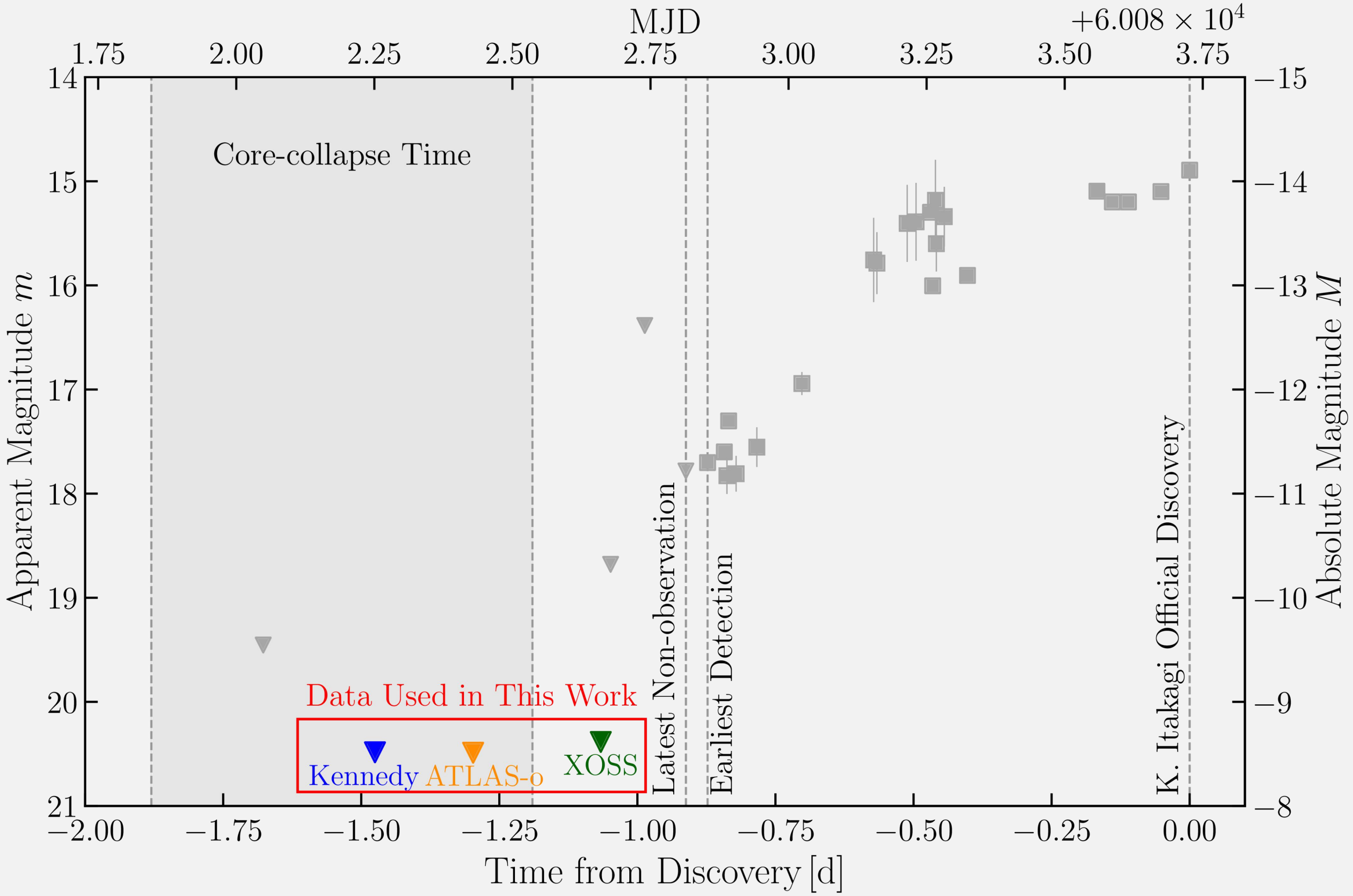
$L'_\odot$: solar luminosity in $400 - 900\,\mathrm{nm}$

$M'_\odot$: solar absolute magnitude in $400 - 900\,\mathrm{nm}$

*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
arXiv:2603.09615

SN 2023ixf as A Case Study

Early-time observations of SN 2023ixf



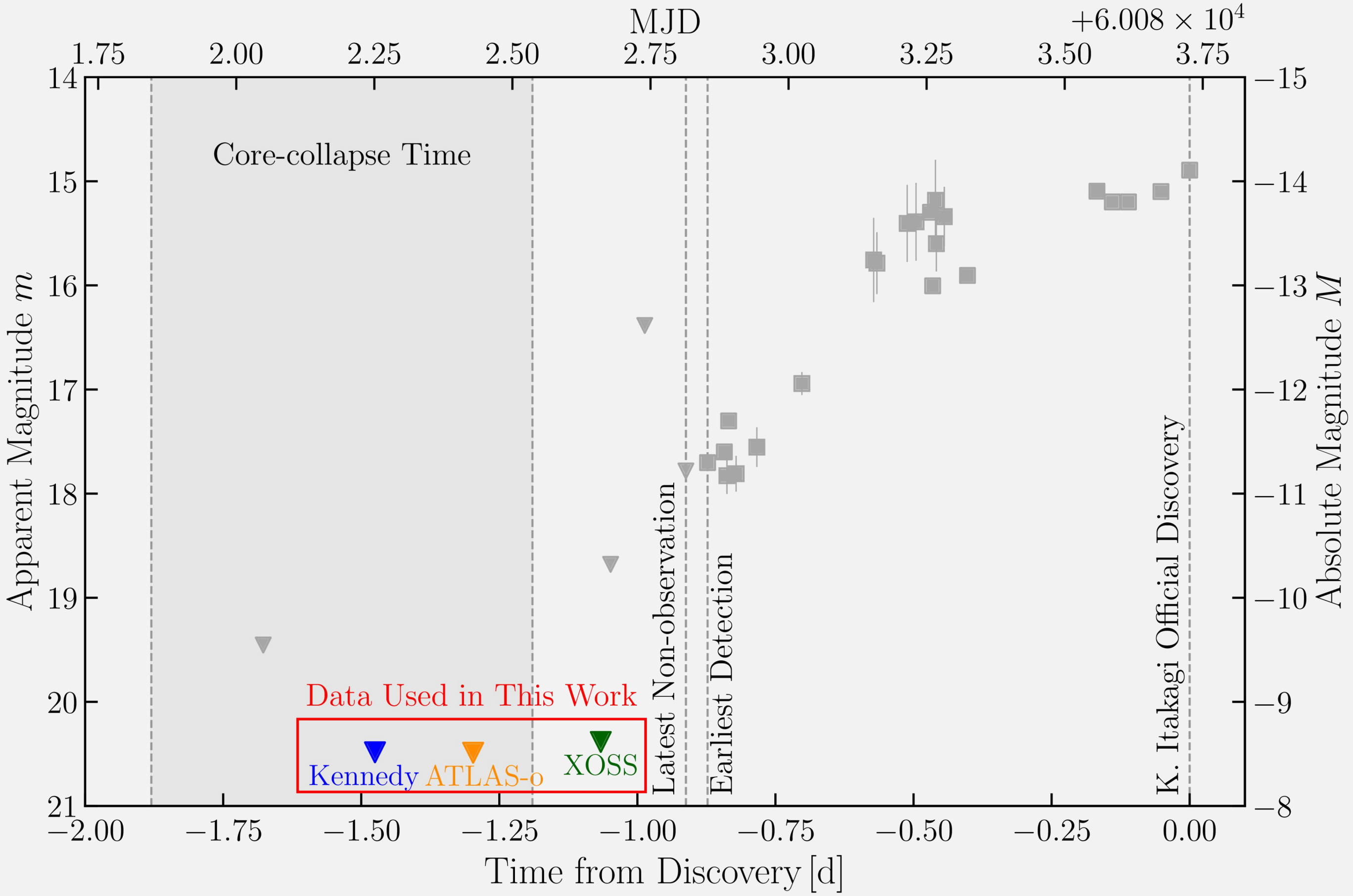
optical band (400 nm -- 900 nm)

$$M \geq -8.6$$

$$L \leq 8.16 \times 10^{38}\,\mathrm{erg\,s^{-1}}$$

*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
arXiv:2603.09615

Early-time observations of SN 2023ixf



optical band (400 nm -- 900 nm)

$$M \geq -8.6$$

$$\downarrow$$

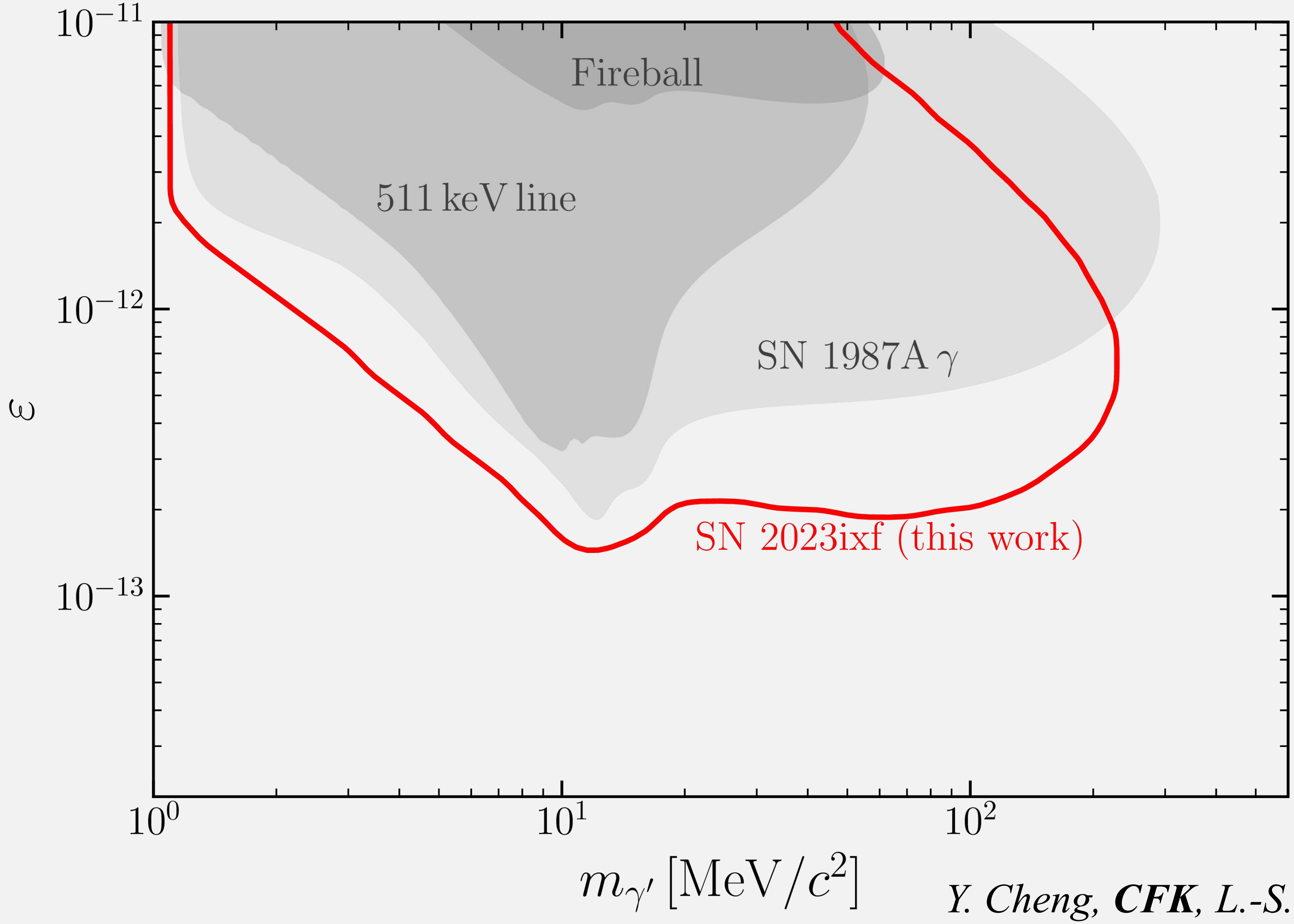
$$L \leq 8.16 \times 10^{38}\,\mathrm{erg\,s^{-1}}$$

our **conservative** criteria:

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

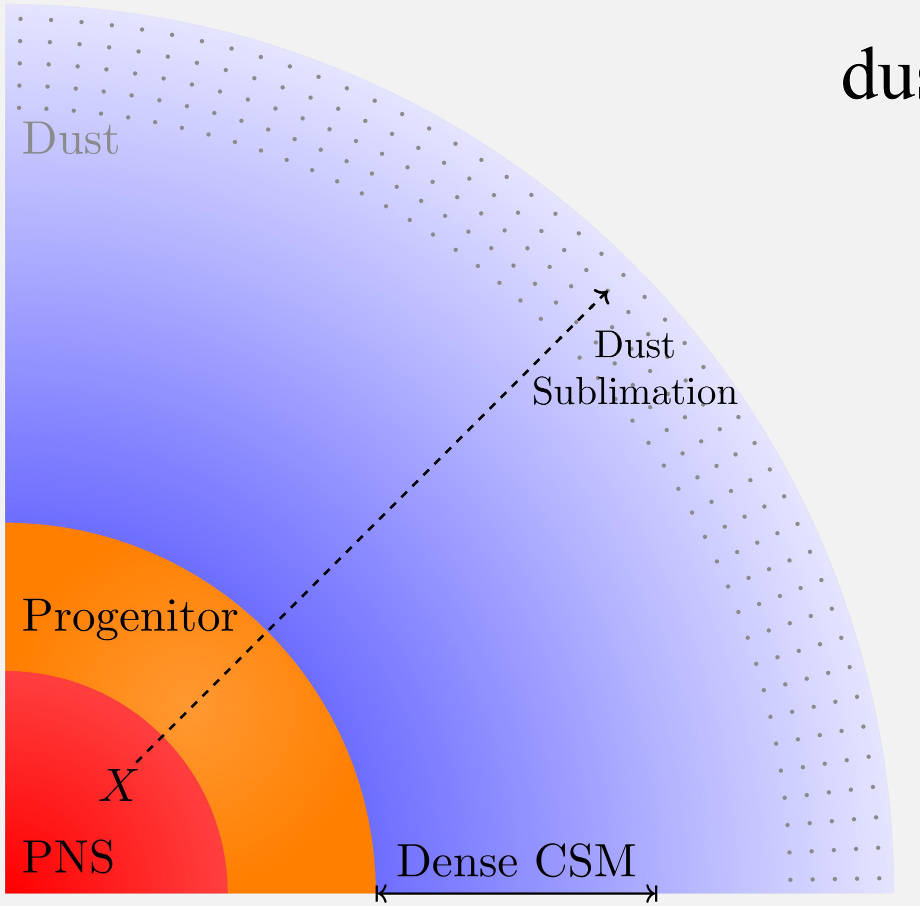
*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
arXiv:2603.09615

Constraint on DP (i)



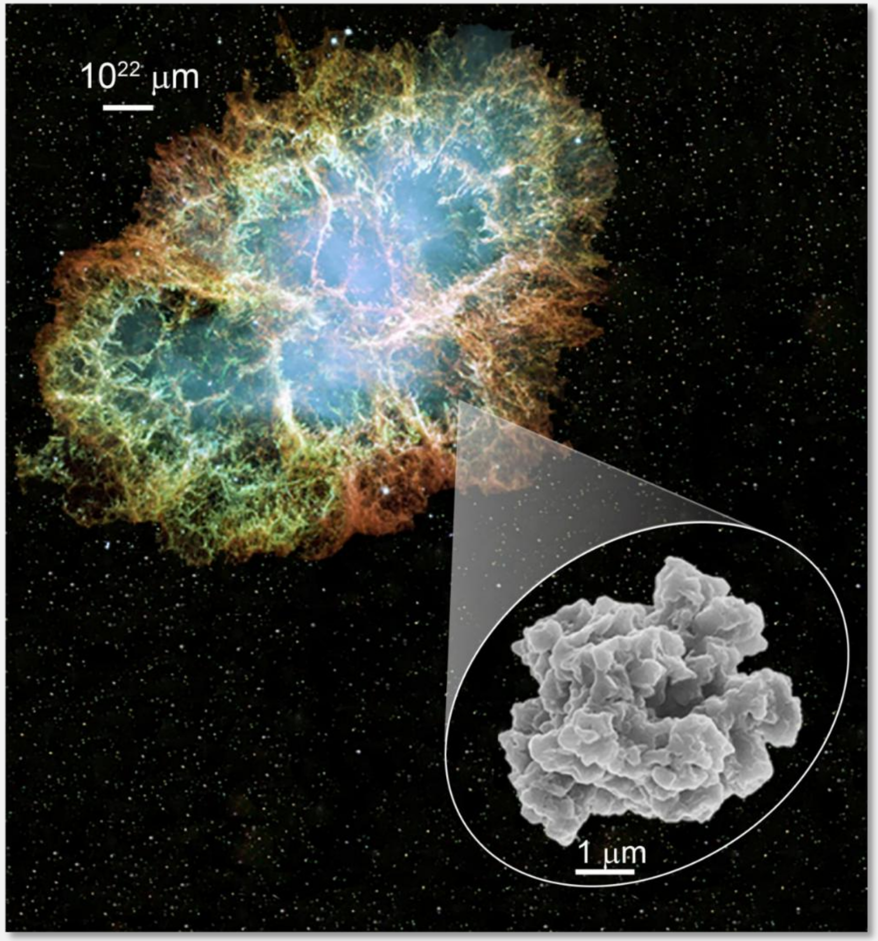
*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
arXiv:2603.09615

Dust Sublimation



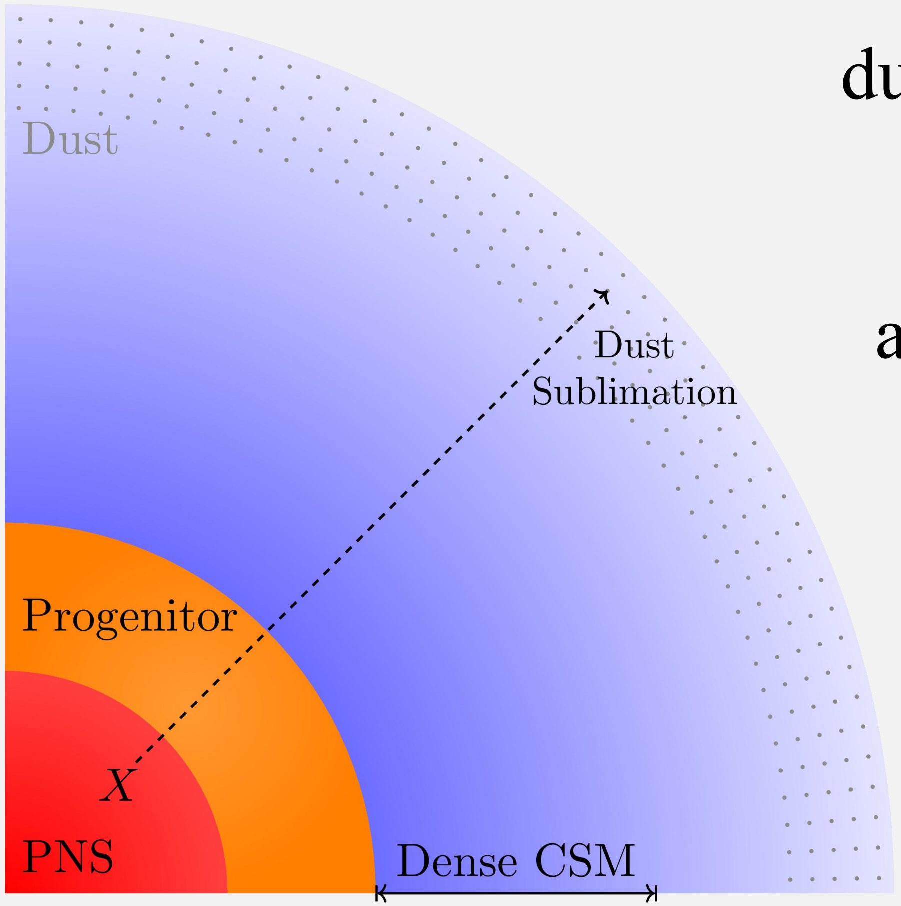
*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
arXiv:2603.09615

dust grains (molecules) exist in outer layer of CSM



credit: L. Nittler

Dust Sublimation



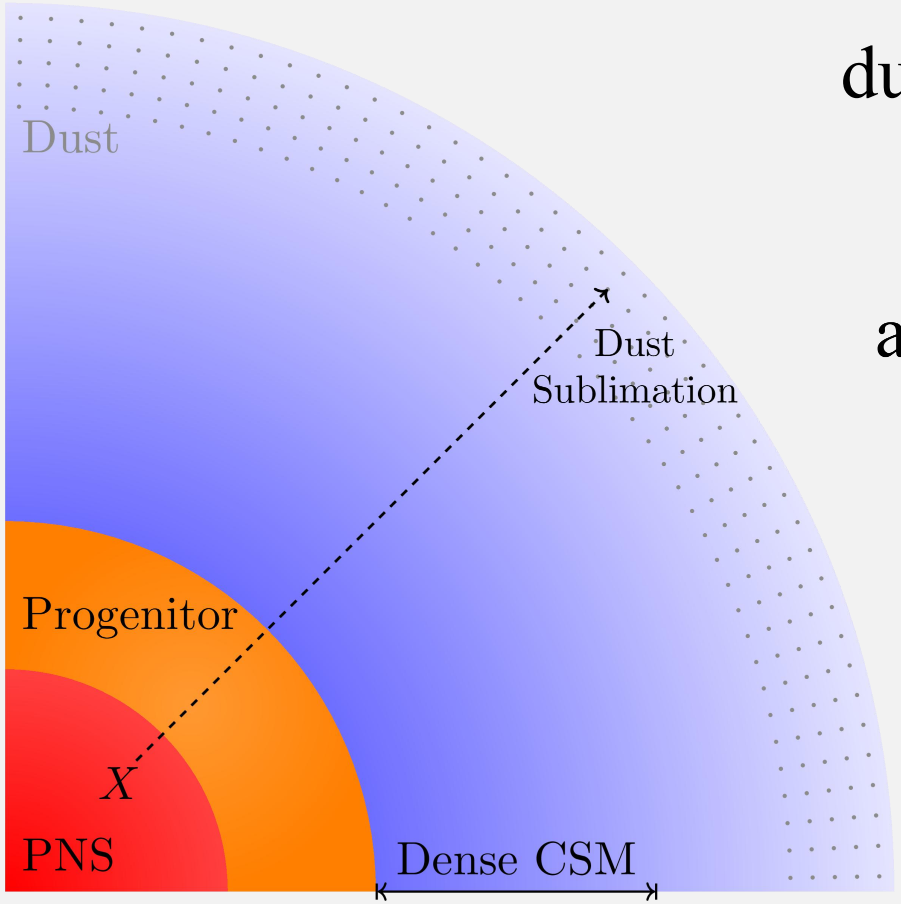
*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
arXiv:2603.09615

dust grains (molecules) exist in outer layer of CSM

↓

absorb optical photons and reprocess into infrared

Dust Sublimation



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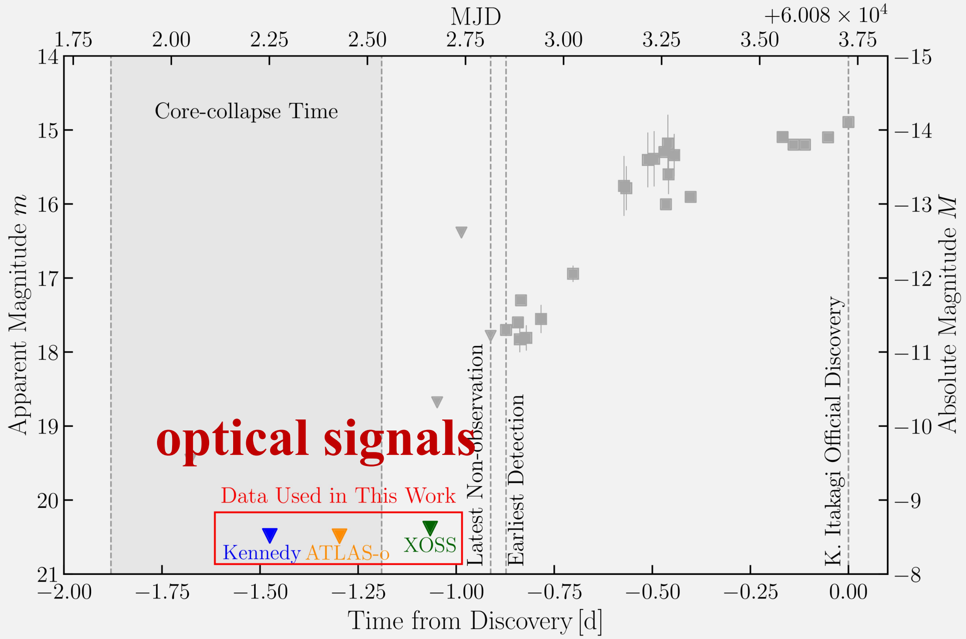
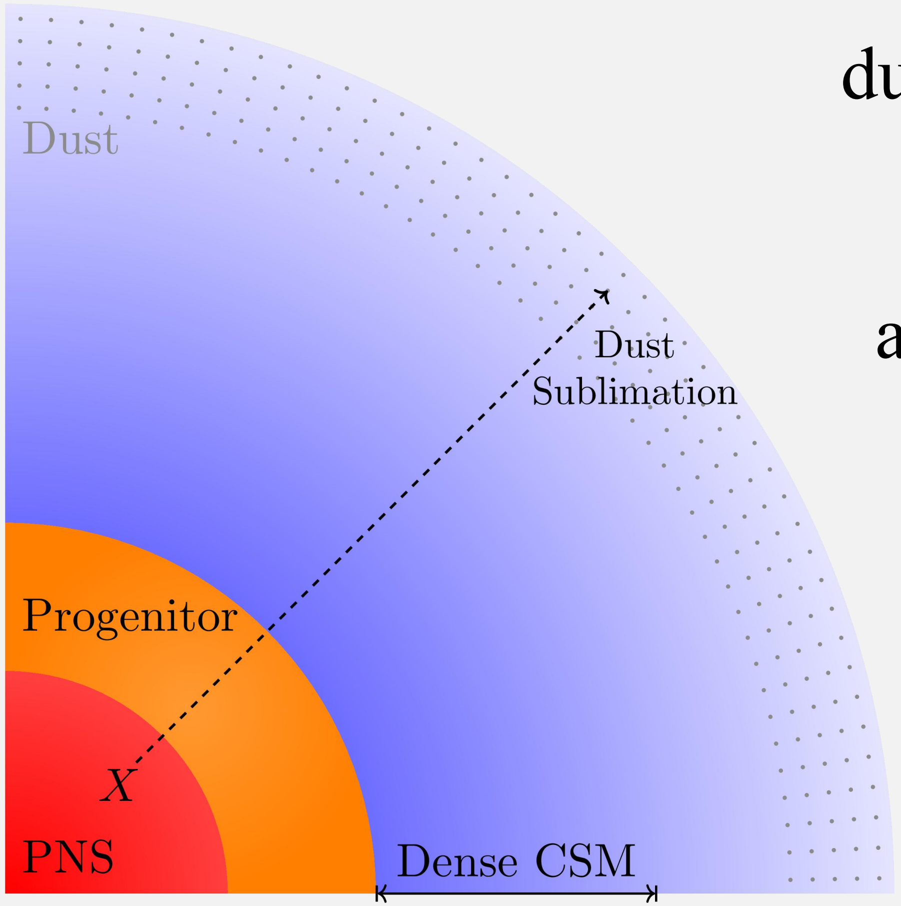


Dust Sublimation



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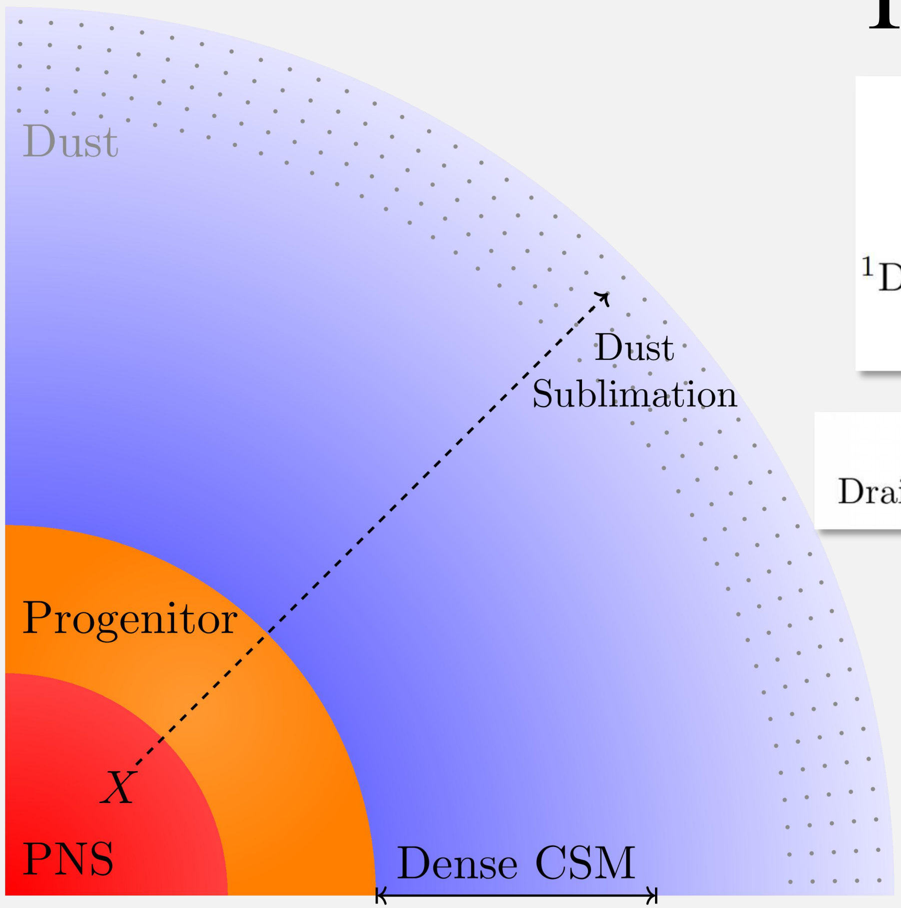
↓

an additional dust-destruction requirement

Dust Sublimation



*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
arXiv:2603.09615

How to destruct dust? Still heating!

Dust sublimation by GRBs and its implications

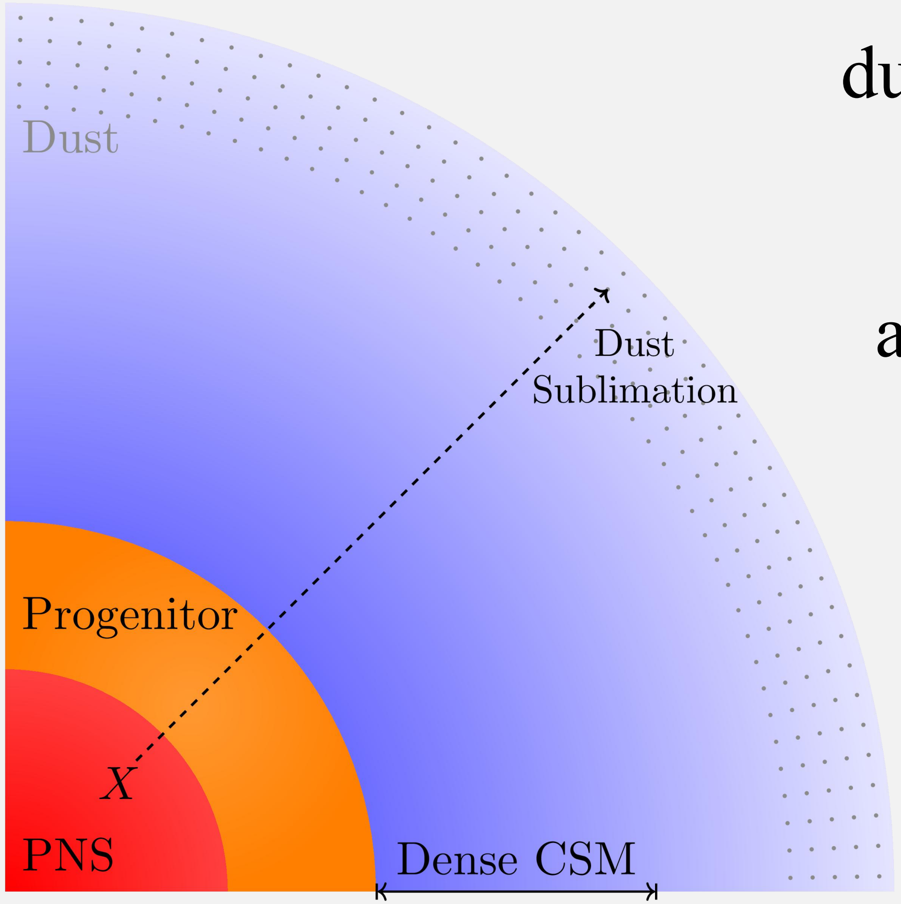
E. Waxman[1] and B. T. Draine[2]
[1]Department of Condensed-Matter Physics, Weizmann Institute, Rehovot 76100, Israel
[2]Princeton University Observatory, Peyton Hall, Princeton, NJ 08544

The infrared emissivity is quite different for graphite and silicate materials (Draine & Lee 1984; Draine 1999a). For the temperature range of interest for dust sublimation, $2000\,\mathrm{K} \lesssim T \lesssim 3000\,\mathrm{K}$,

same scale as Van der Waals force

E. Waxman, B. Draine
arXiv:astro-ph/9909020

Dust Sublimation



*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
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dust grains (molecules) exist in outer layer of CSM

↓

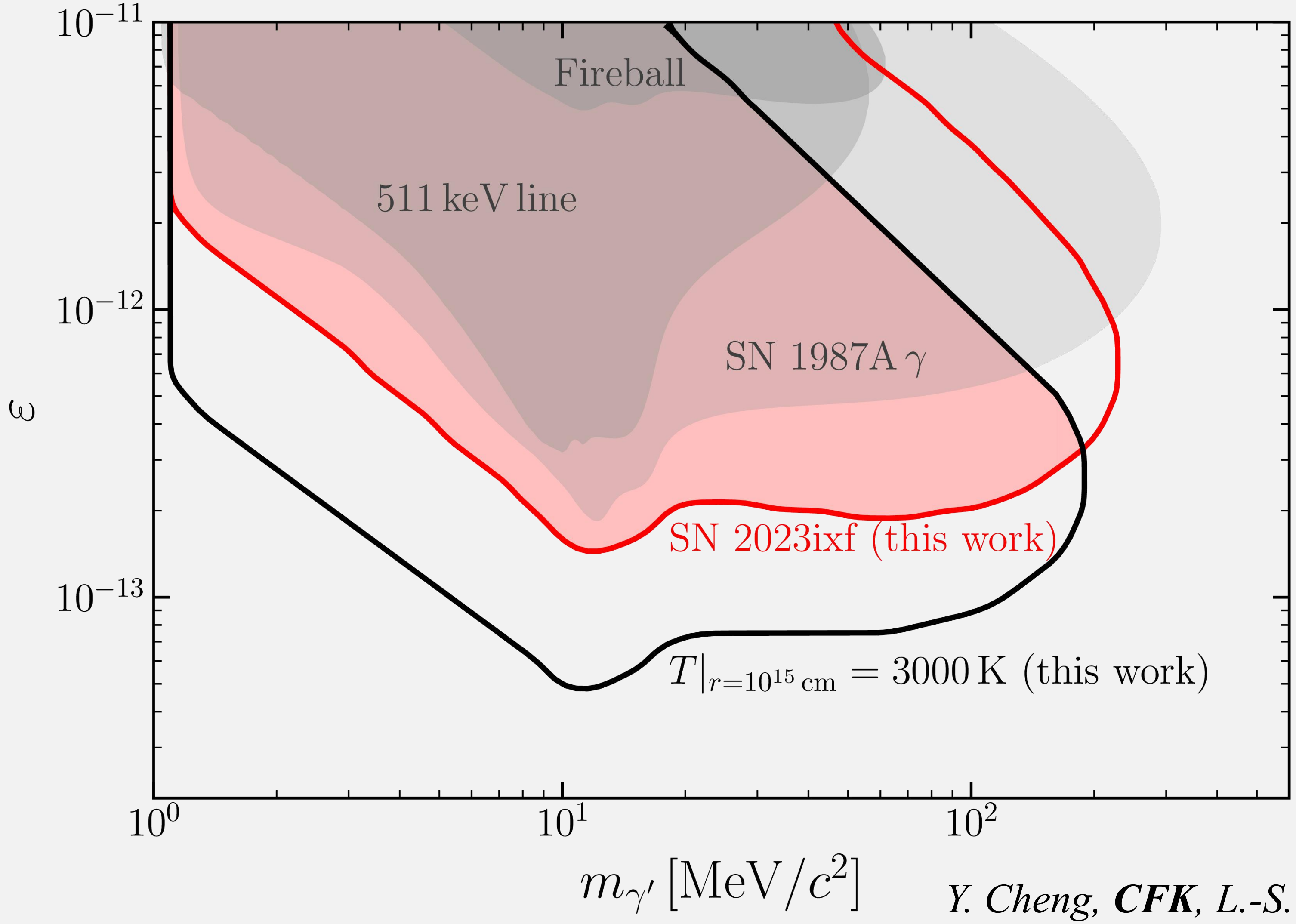
absorb optical photons and reprocess into infrared

↓

an additional dust-destruction requirement

$$T\big|_{r=10^{15}\,\mathrm{cm}} > 3000\,\mathrm{K}$$

Constraint on DP (ii)



Y. Cheng, ***CFK****, L.-S. Lin, M.-R. Wu, S. Yun*
arXiv:2603.09615

Summary

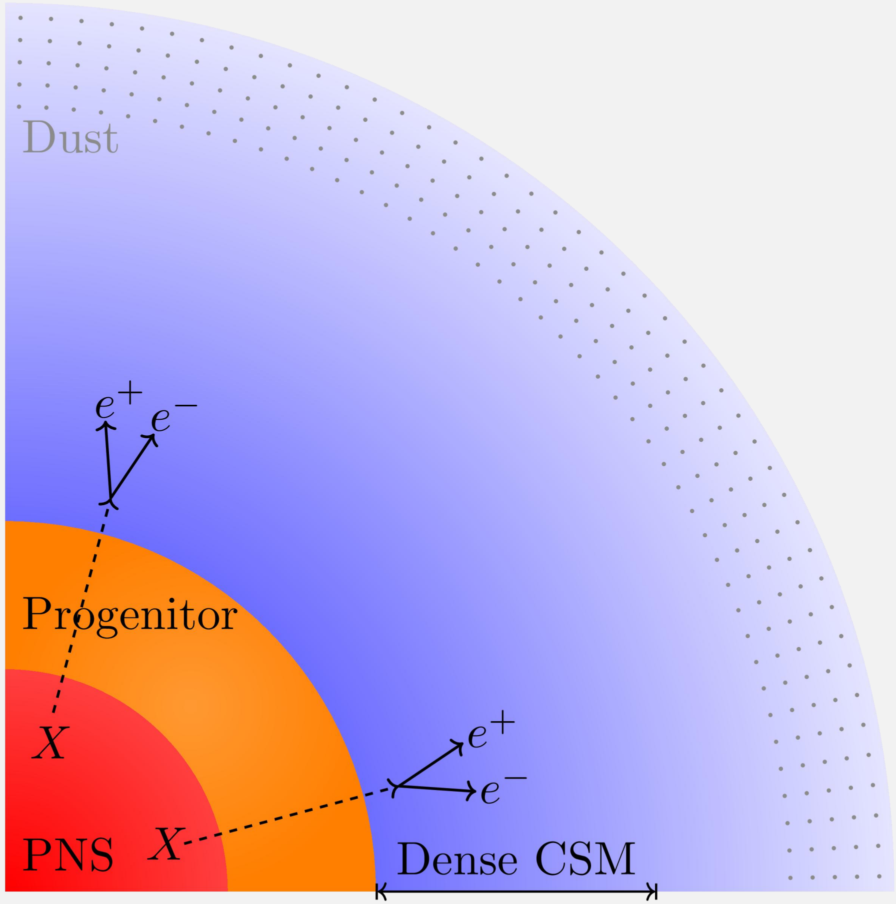
- Circumstellar medium (CSM) exists in the outsphere of SN
- Decay product of FIPs can depoisit energy into CSM
- CSM is heated up by extra energy depoisition and emits light via blackbody radiation
- Early-time observation of SN 2023ixf luminosity provides a strong constraint on such extra energy depoisition

Thank you for your attention!

Back up

Back up

Photosphere Induced by FIP Decay



*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
arXiv:2603.09615

FIPs decay into electron/positron inside CSM

$$\frac{dQ}{dr} = \underbrace{\int d\boxed{k}\,\boxed{\frac{1}{L_d}}\,\boxed{\frac{dN_{\gamma'}}{dk}}\,e^{-r/L_d}}_{\#\text{ of } e^\pm \text{ produced at } r}\ \underbrace{\sum_i \int dE_i\,\boxed{E_i}\,\boxed{\frac{dN_i}{dE_i}}}_{\text{integrated energy spectra}}$$

DP momentum

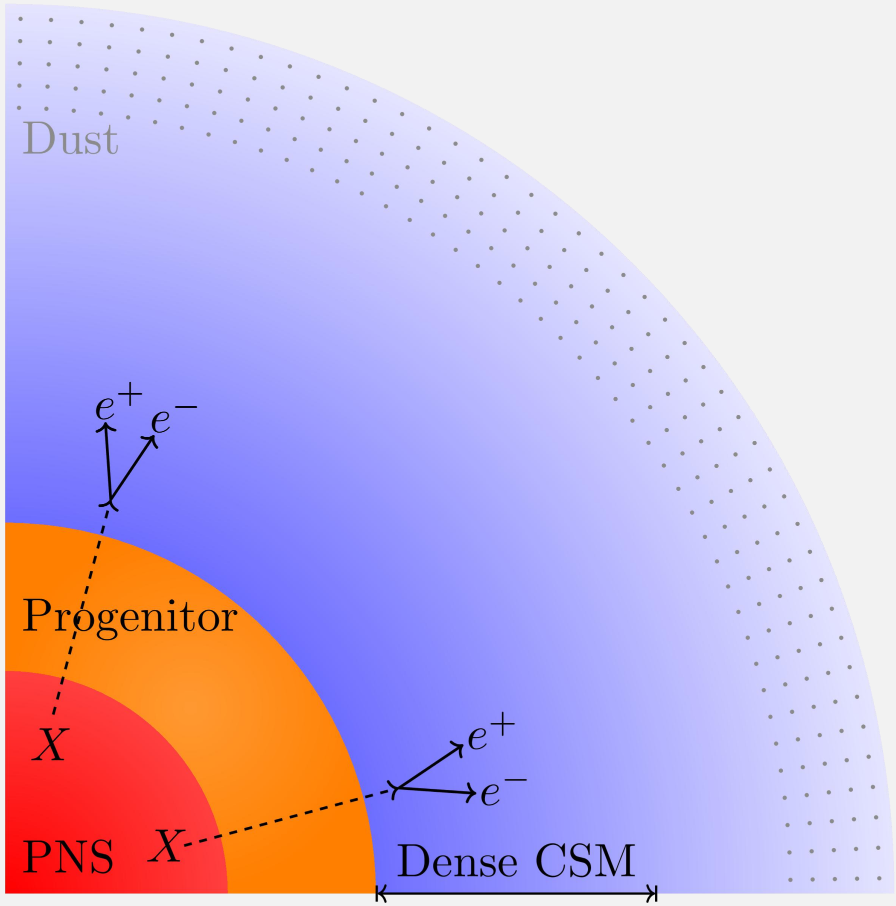
DP decay length

DP momentum distribution

electron/positron energy

electron/positron energy distribution

Photosphere Induced by FIP Decay



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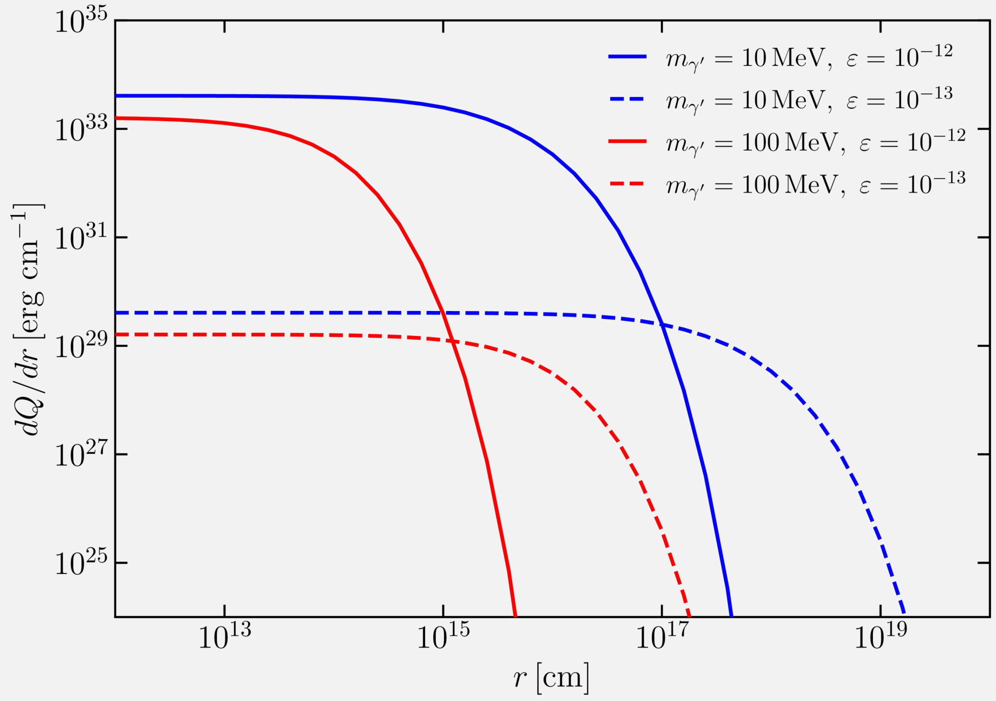
FIPs decay into electron/positron inside CSM

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



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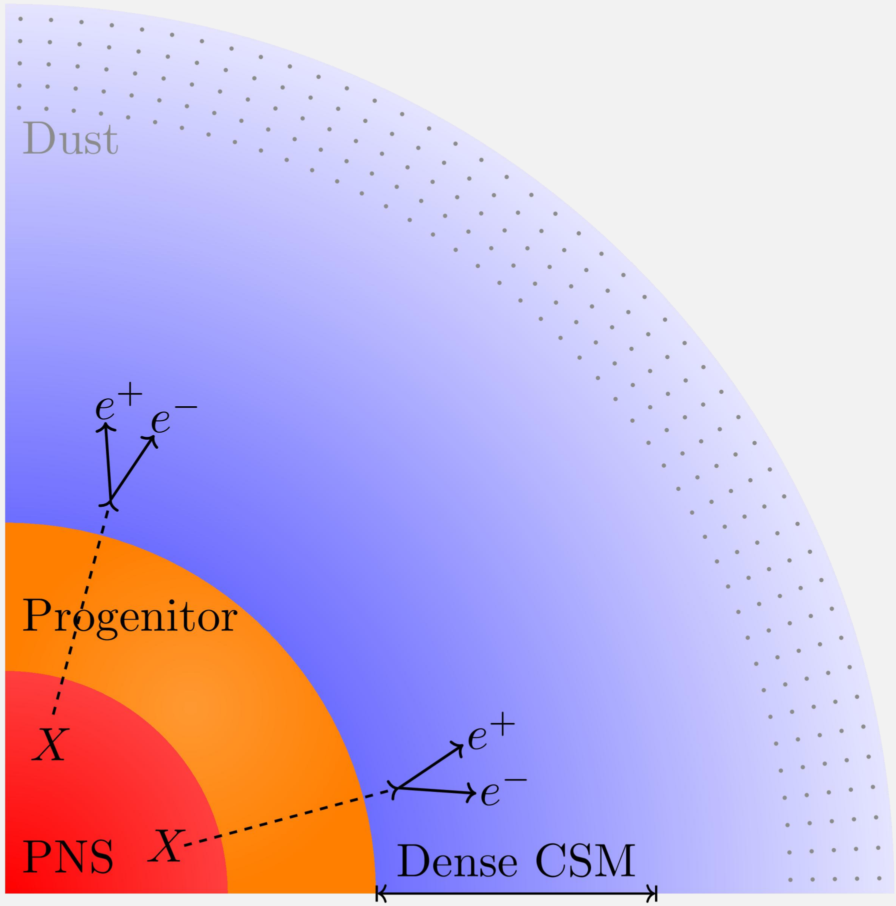

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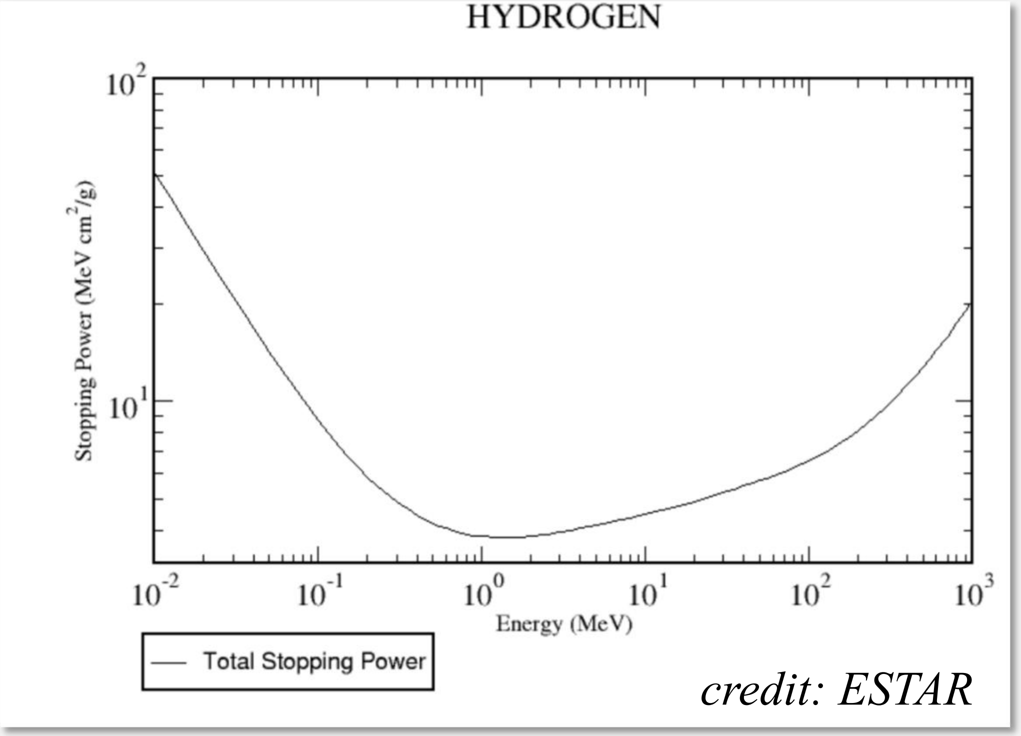
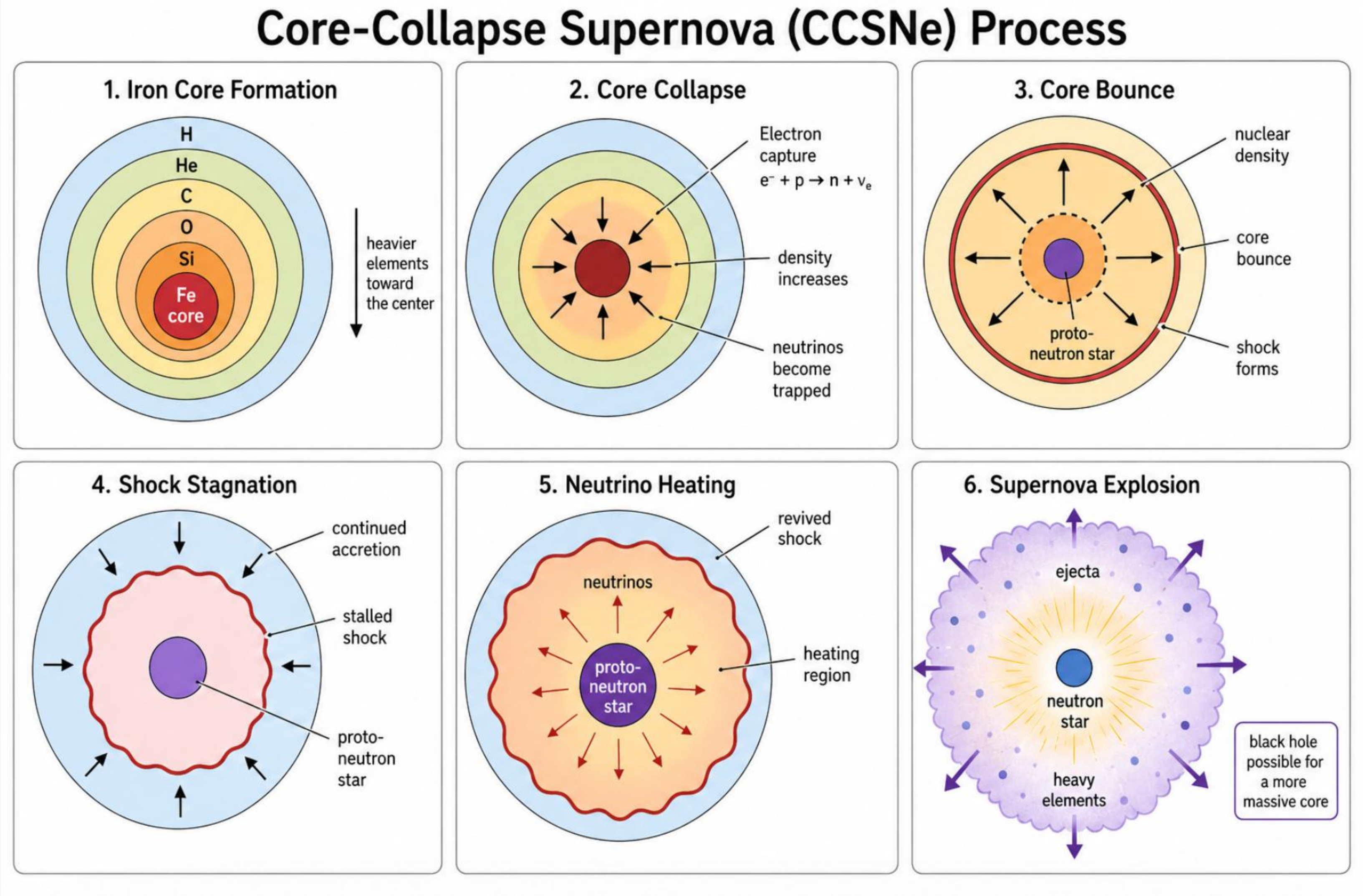
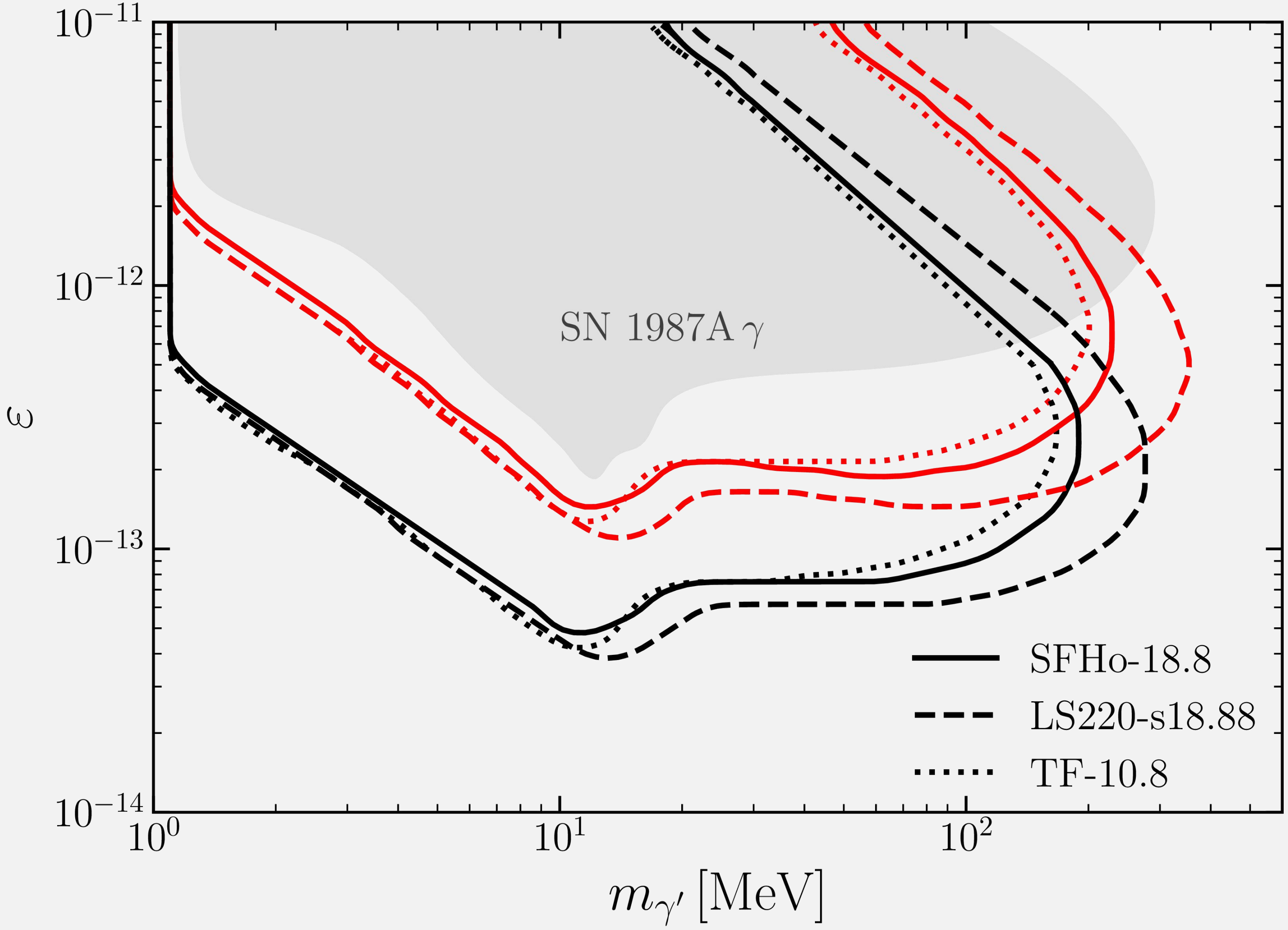


credit: ESTAR

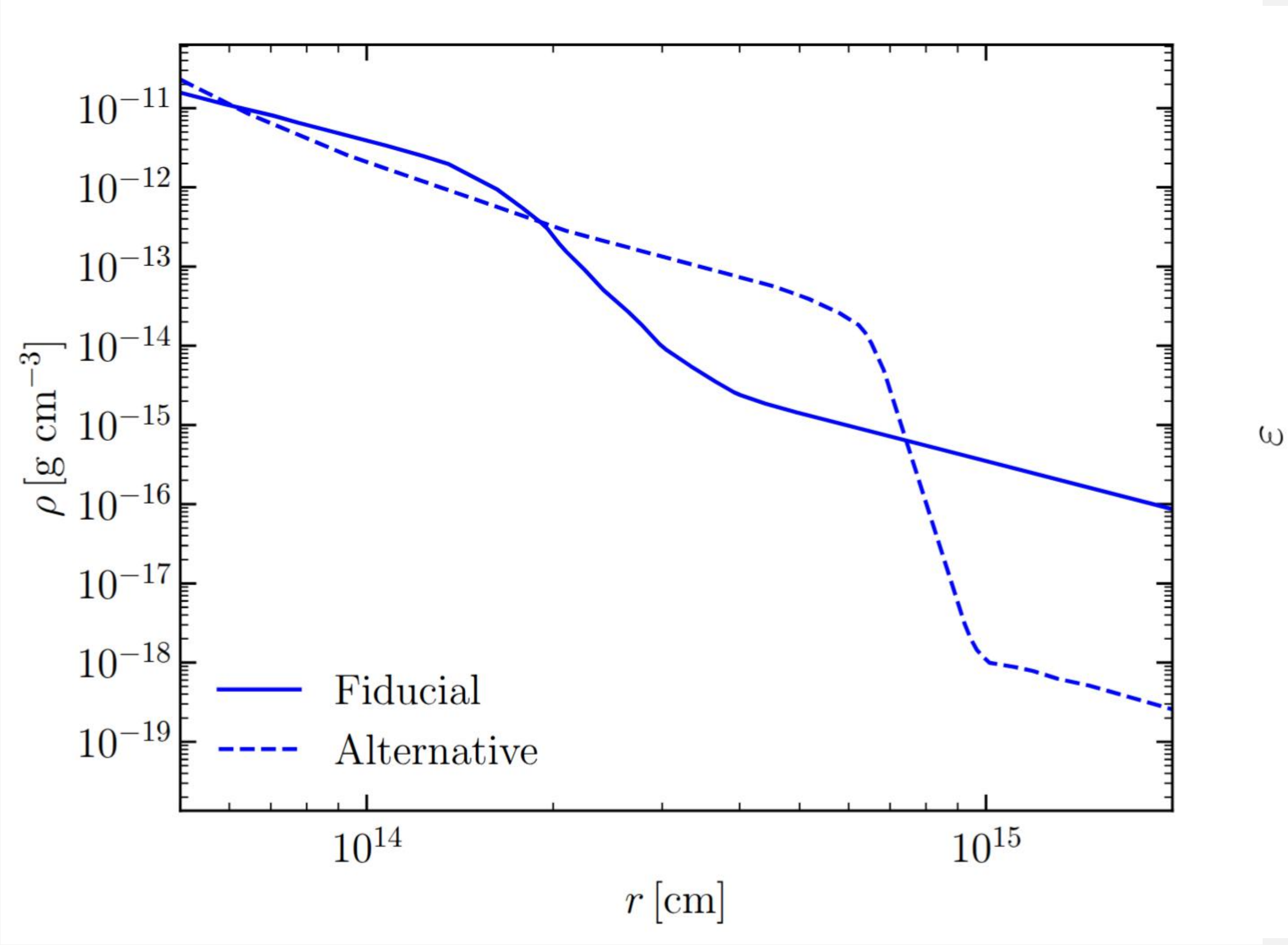
SN


Core-Collapse Supernova (CCSNe) Process
1. Iron Core Formation
H
He
C
O
Si
Fe core
heavier elements toward the center
2. Core Collapse
Electron capture
e⁻ + p → n + νₑ
density increases
neutrinos become trapped
3. Core Bounce
nuclear density
core bounce
shock forms
proto-neutron star
4. Shock Stagnation
continued accretion
stalled shock
proto-neutron star
5. Neutrino Heating
revived shock
neutrinos
proto-neutron star
heating region
6. Supernova Explosion
ejecta
neutron star
heavy elements
black hole possible for a more massive core

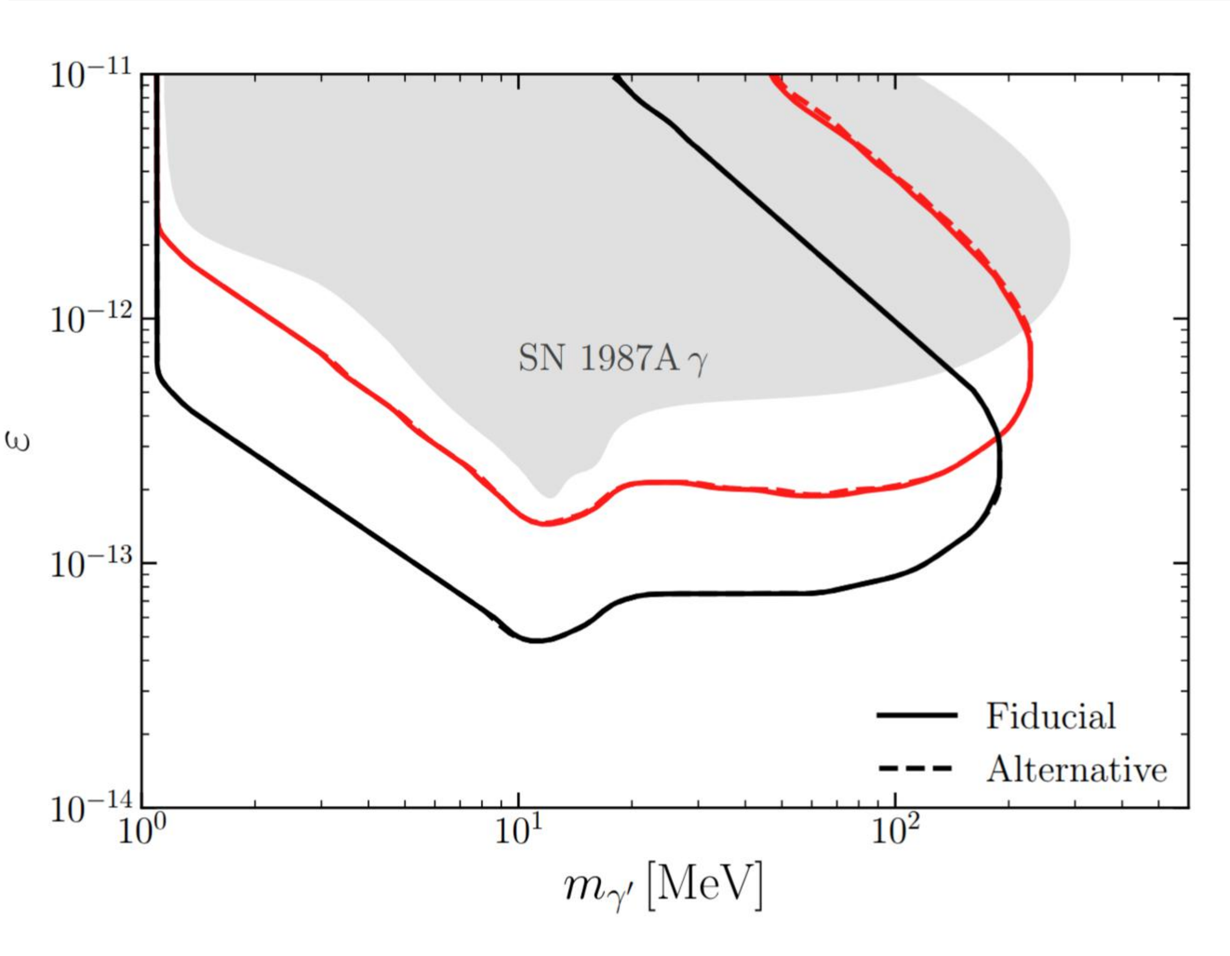
Back up


SN 1987A γ
SFHo-18.8
LS220-s18.88
TF-10.8
ε
$m_{\gamma'}$ [MeV]
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{0}
10^{1}
10^{2}

Back up



10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\rho\,[\mathrm{g\ cm^{-3}}]$
Fiducial
Alternative
10^{14}
10^{15}
r [cm]



10^{-11}
10^{-12}
10^{-13}
10^{-14}
ε
SN 1987A γ
Fiducial
Alternative
10^{0}
10^{1}
10^{2}
$m_{\gamma'}$ [MeV]

Back up

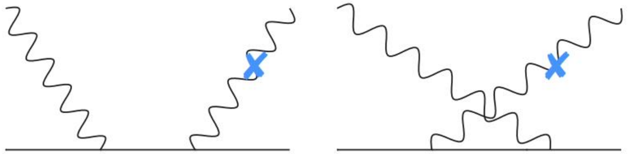
$$\mathcal{L}_{\rm DP} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{\gamma'}}{2}A'_\mu A'^\mu + eA_\mu J^\mu_{\rm EM}$$

Back up

SN γ' production

◉ *Electrons* in highly degenerate and relativistic limit

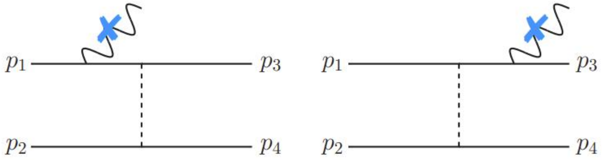
- $p_F \sim 0.1\text{-}1\,\mathrm{fm}^{-1} \gg T \sim 1\text{-}10\,\mathrm{MeV}$
- Pauli blocking makes processes associated with electrons (e.g., $e + \gamma \to e + \gamma'$)



➡ $R > R_{\mathrm{core}}$

◉ *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)



$+ \quad \cdots$

➡ $R < R_{\mathrm{core}}$

from Seokhoon Yun's slides

Back up

Explosion energy = Ejecta kinetic energy