CSM for BSM

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IBS-CTPU-PTC

Based on: 2603.09615 (PRL accepted) + 2609.xxxxx

In collaboration with:

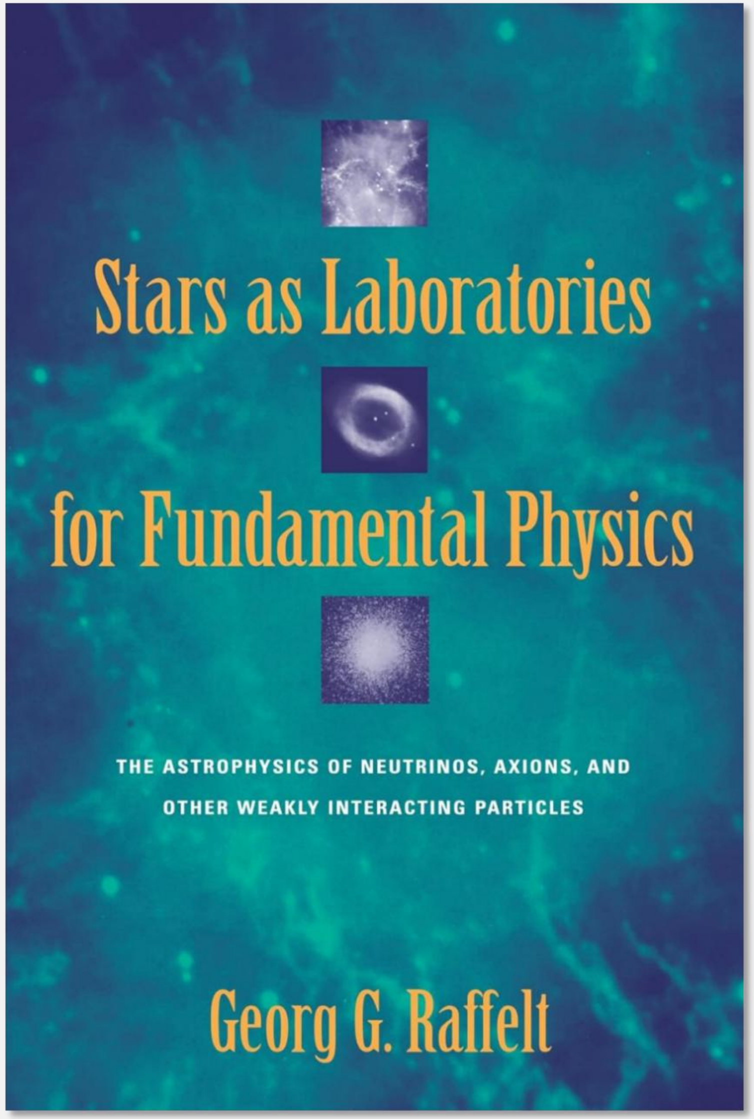
Yu Cheng (KAIST & U. Chicago), Yen-Hsun Lin (Academia Sinica), Meng-Ru Wu (Academia Sinica), Seokhoon Yun (KNU & IBS)

Institute for Basic Science

SSU 2026 @ Busan

August 24, 2026

Stars as Laboratories



Preface

400 years ago

Ever since Newton proposed that the moon on its orbit follows the same laws of motion as an apple falling from a tree, the heavens have been a favorite laboratory to test the fundamental laws of physics, notably classical mechanics and Newton's and Einstein's theories of gravity. This tradition carries on—the 1993 physics Nobel prize was awarded to R. A. Hulse and J. H. Taylor for their 1974 discovery of the binary pulsar PSR 1913+16 whose measured orbital decay they later used to identify gravitational wave emission. However, the scope of physical laws necessary to understand the phenomena observed in the super-lunar sphere has expanded far beyond these traditional fields. Today, astrophysics has become a vast playing ground for applications of the laws of *microscopic* physics, in particular the properties of elementary particles and their interactions. Now

credit: G. Raffelt

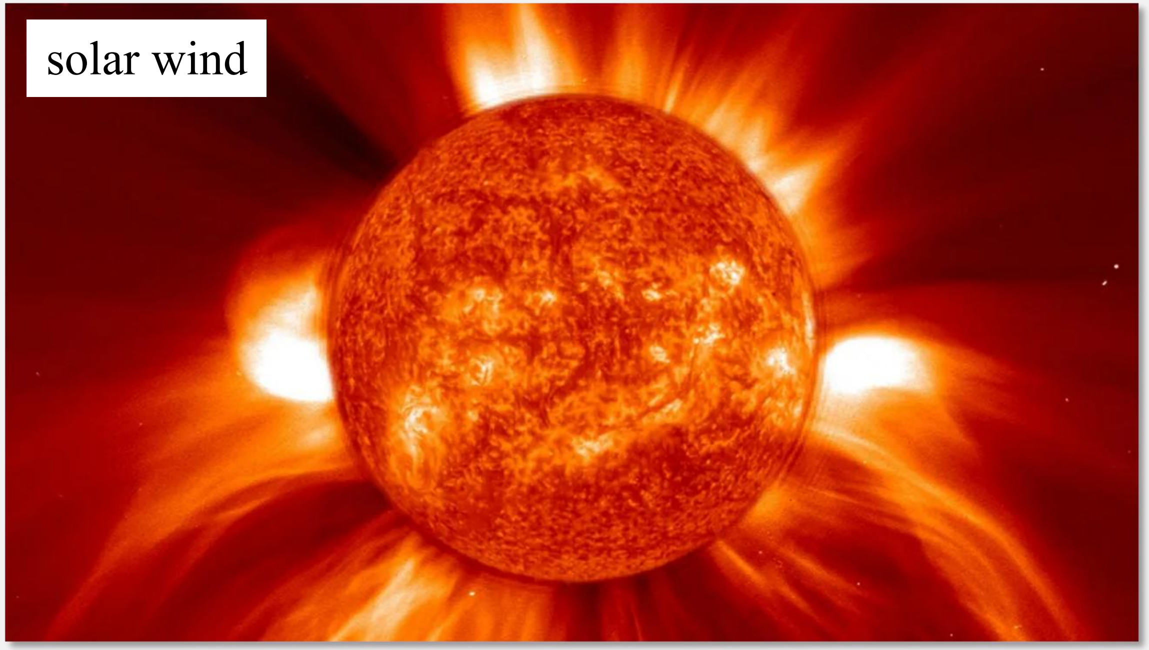
Outline

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

What is CSM

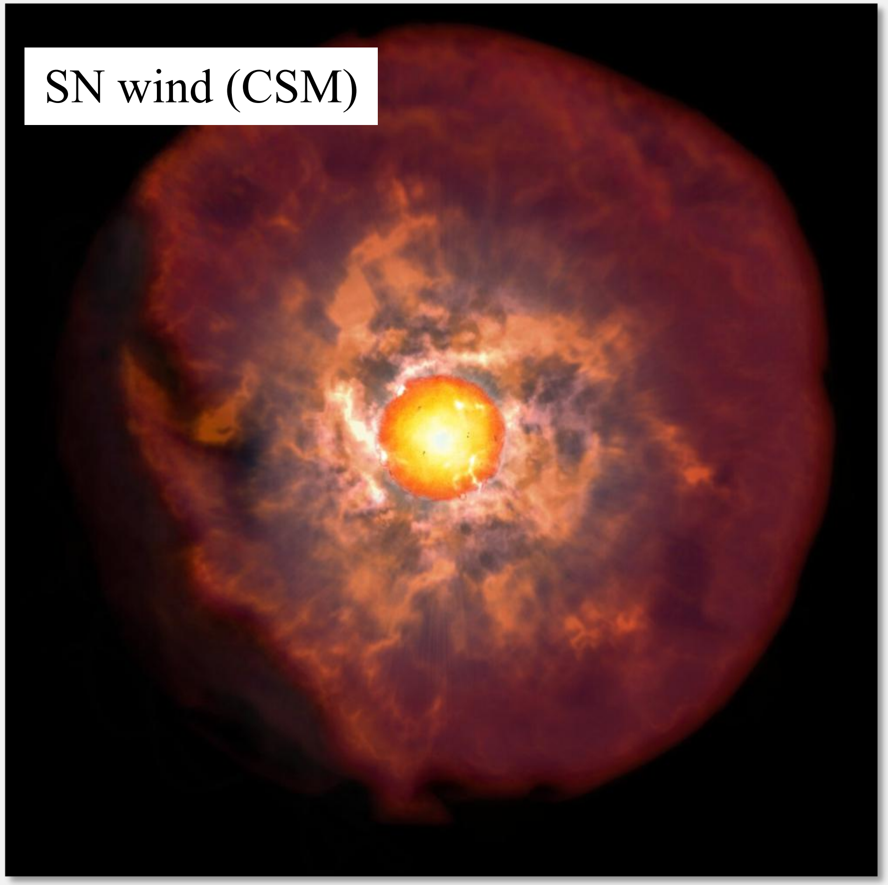
Production of CSM

Mass loss via the wind



credit: NASA

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

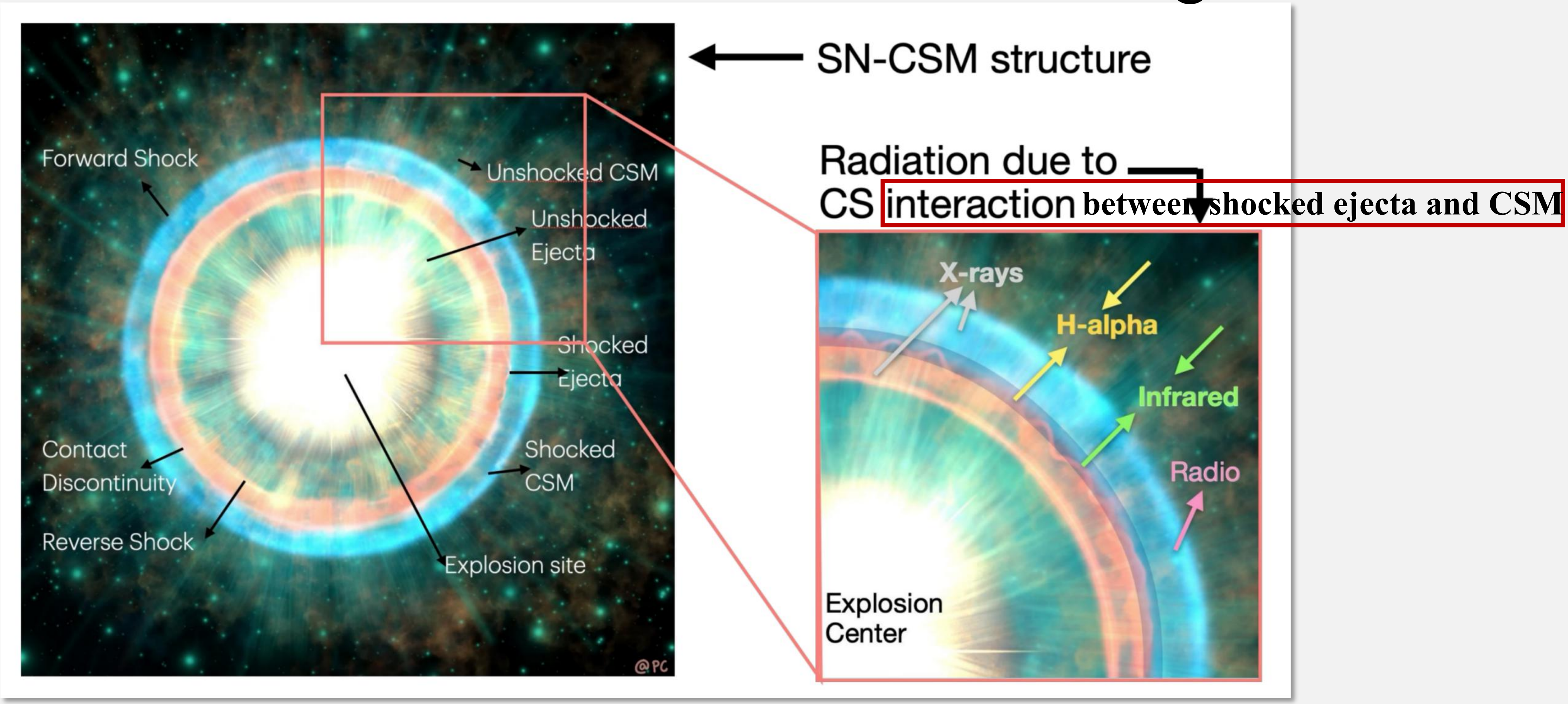


credit: NAOJ

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

Observational Evidence

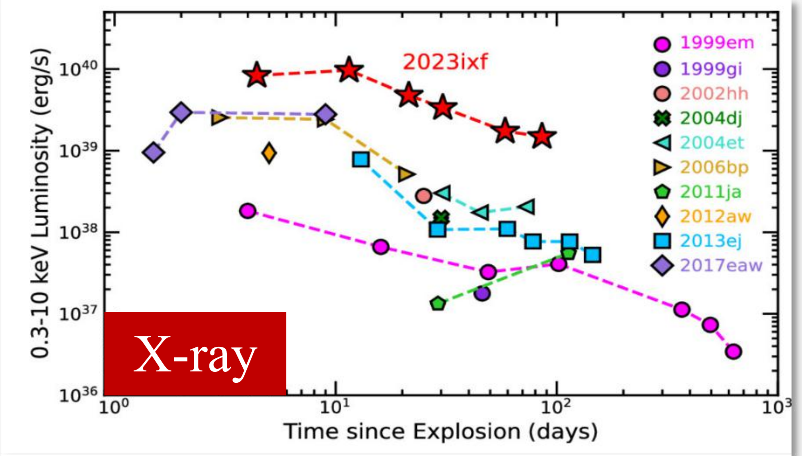
How do we know there is CSM surrounding SN?

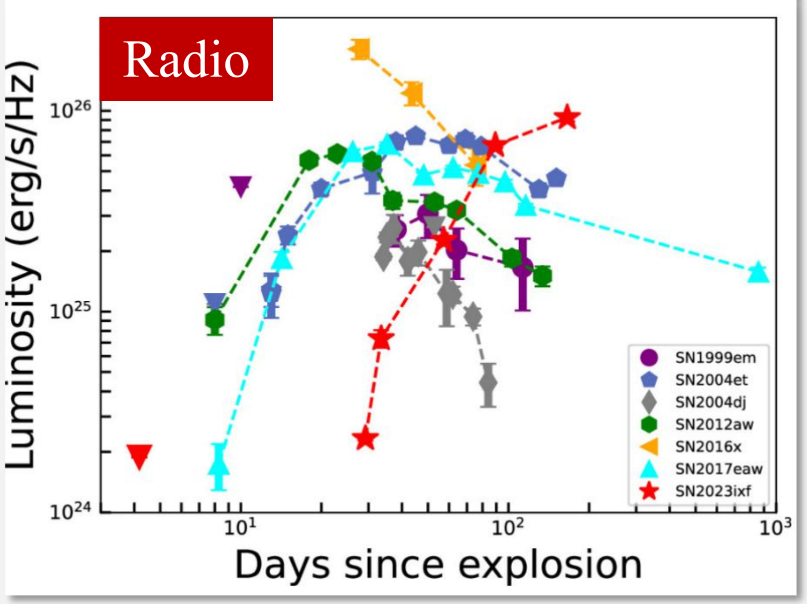


P. Chandra, arXiv:2510.20913

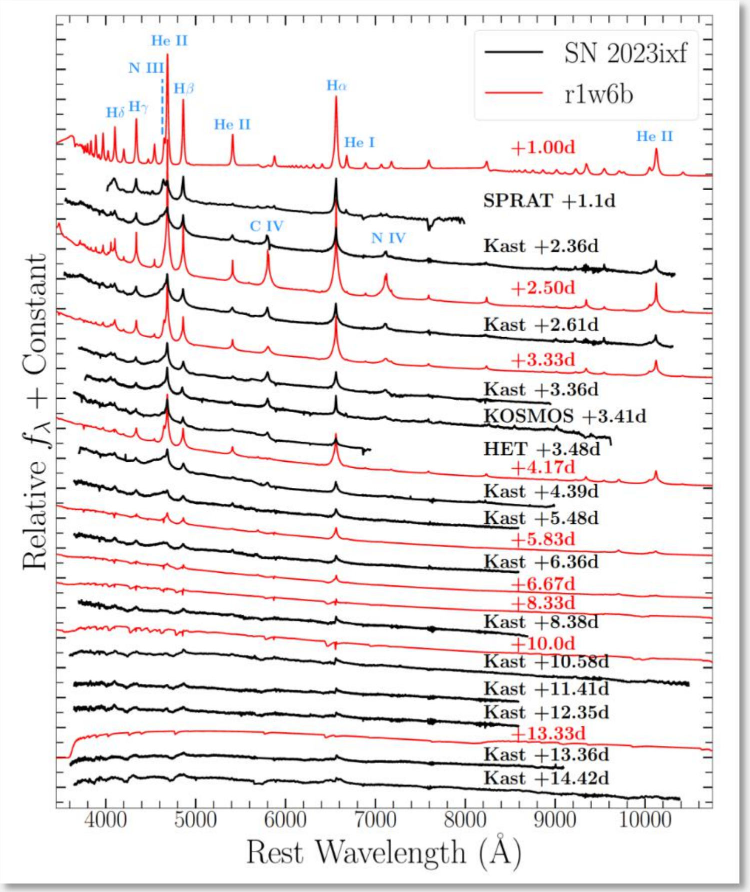
Observational Evidence

Plenty of measurements!

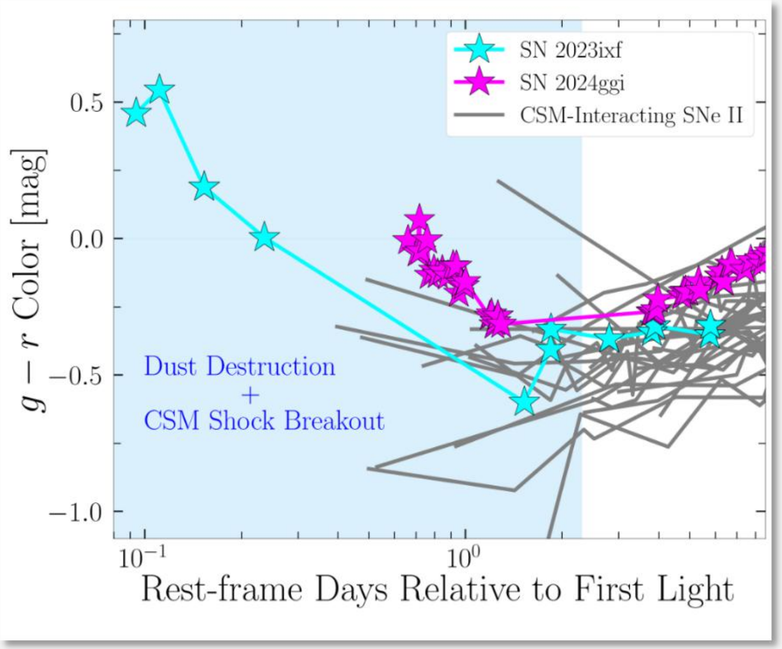




Spectroscopy



Photometric

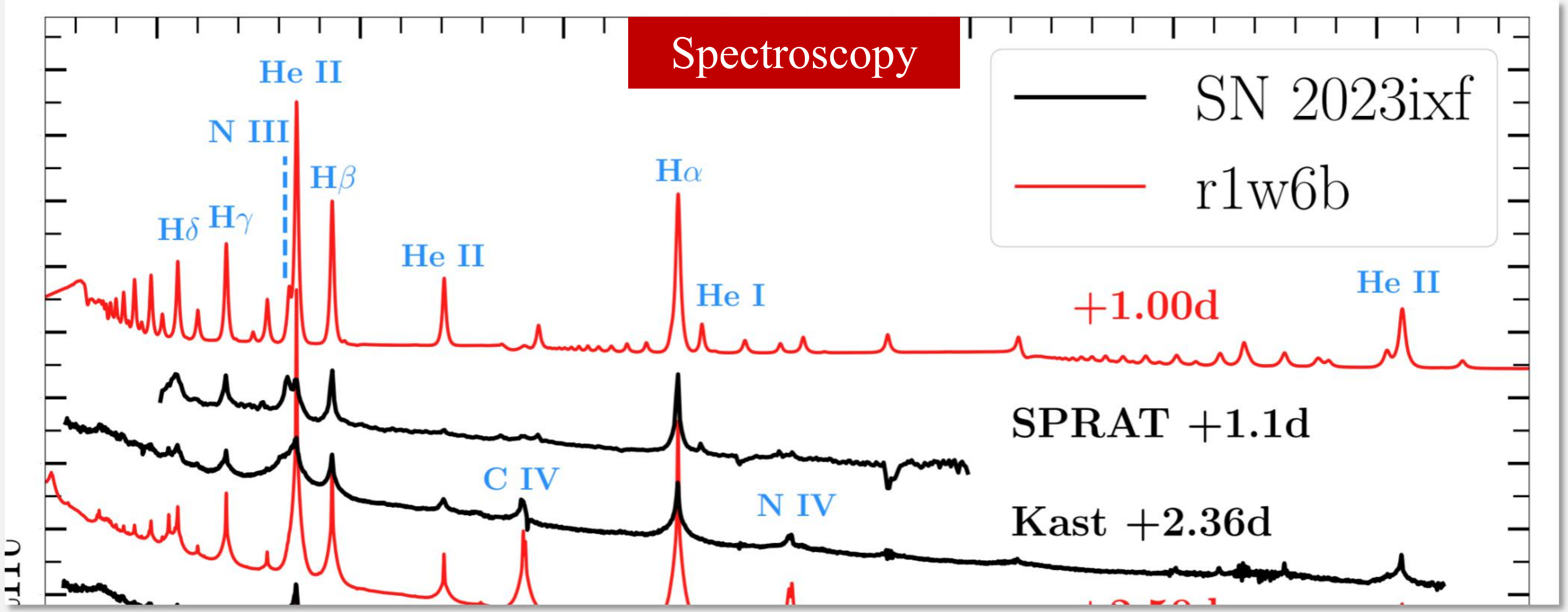


W.V. Jacobson-Galán, arXiv:2507.08078

Component of CSM

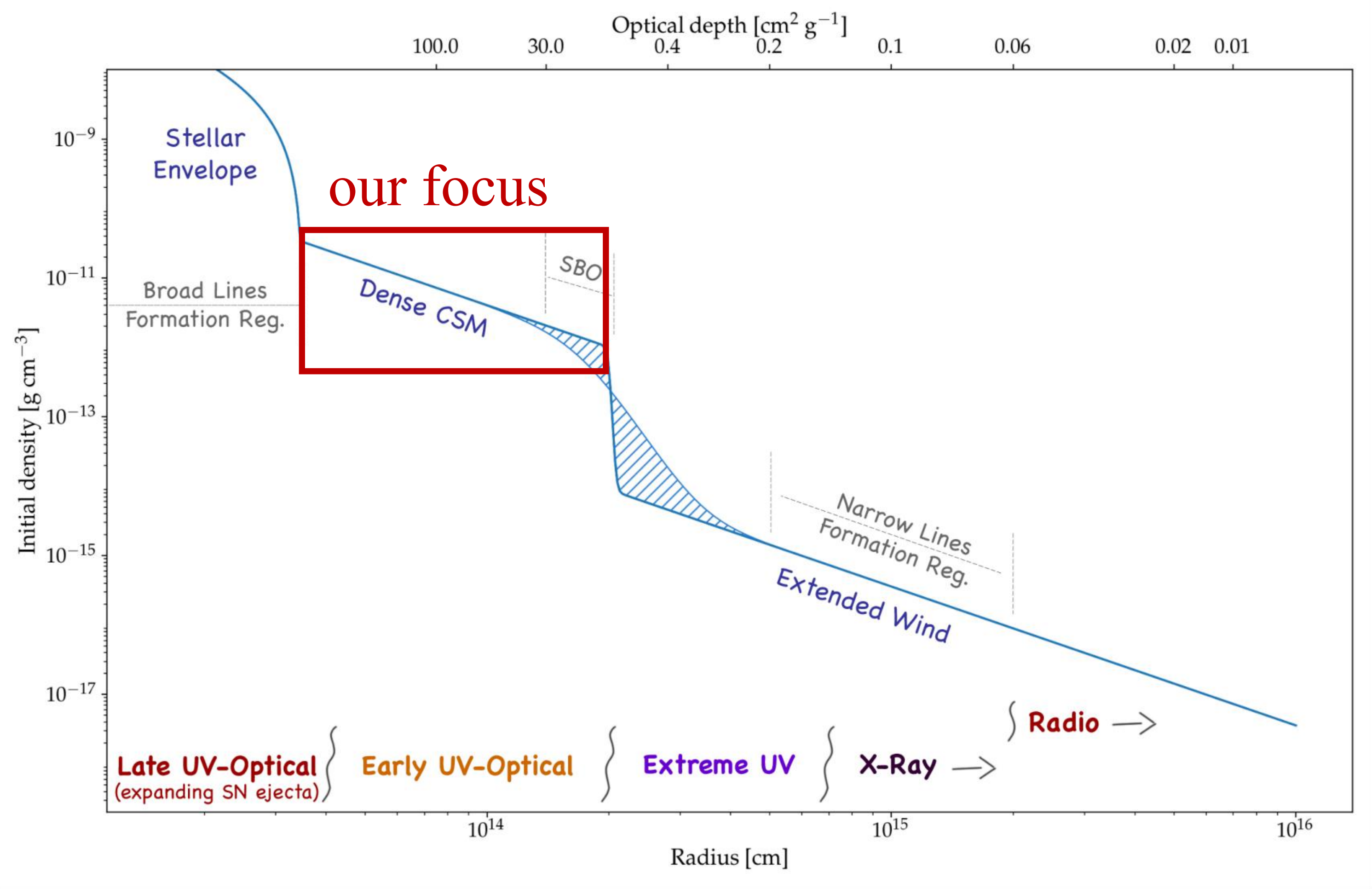
What makes of CSM

- 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

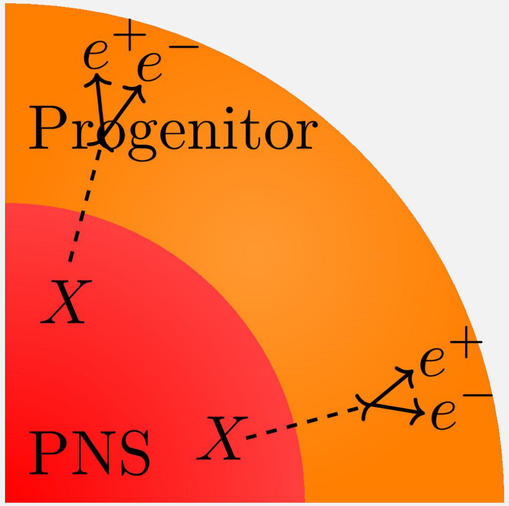
After FIPs (X) produced inside a proto-neutron star (PNS)

see also Edoardo's talk

Traditional Method

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

Decay inside mantle → Energy trapped



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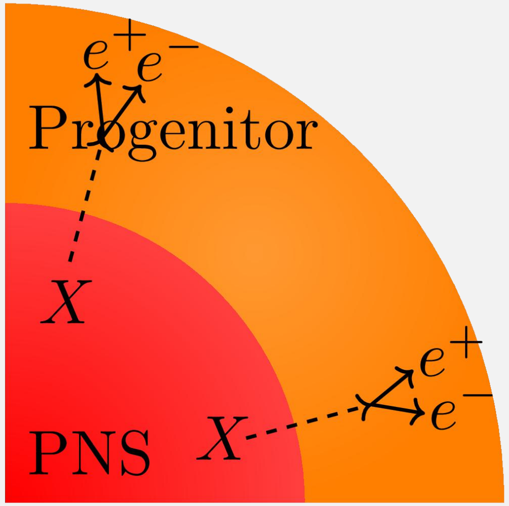
After FIPs (X) produced inside a proto-neutron star (PNS)

Decay inside mantle → Energy trapped

Constraint from low-energy SN



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Traditional Method

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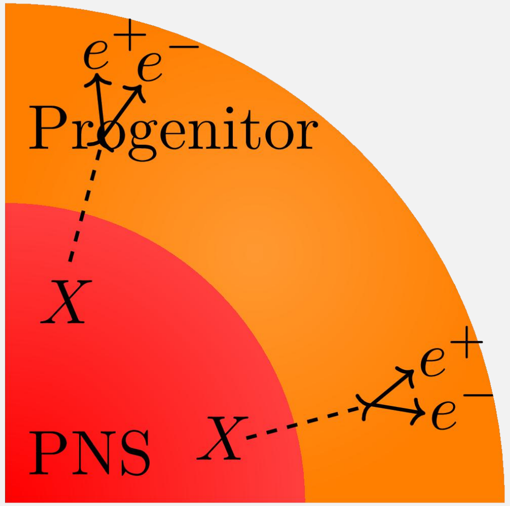
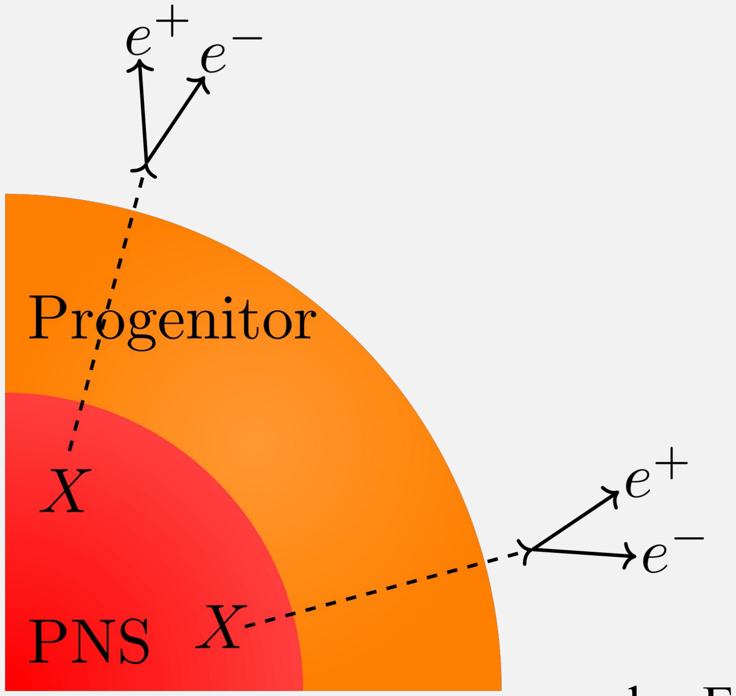
Decay inside mantle → Energy trapped

Decay outside mantle → Energy escaped

Constraint from low-energy SN





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Traditional Method

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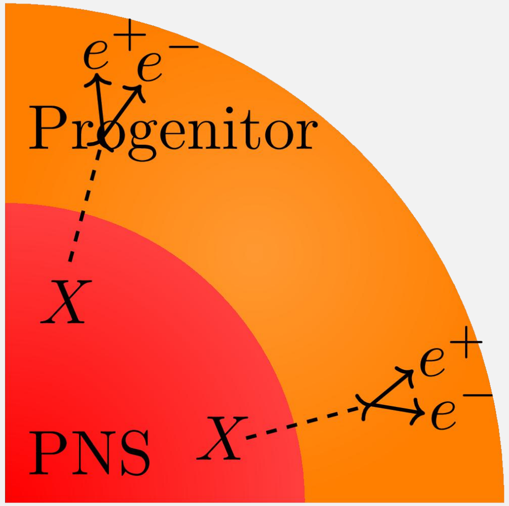
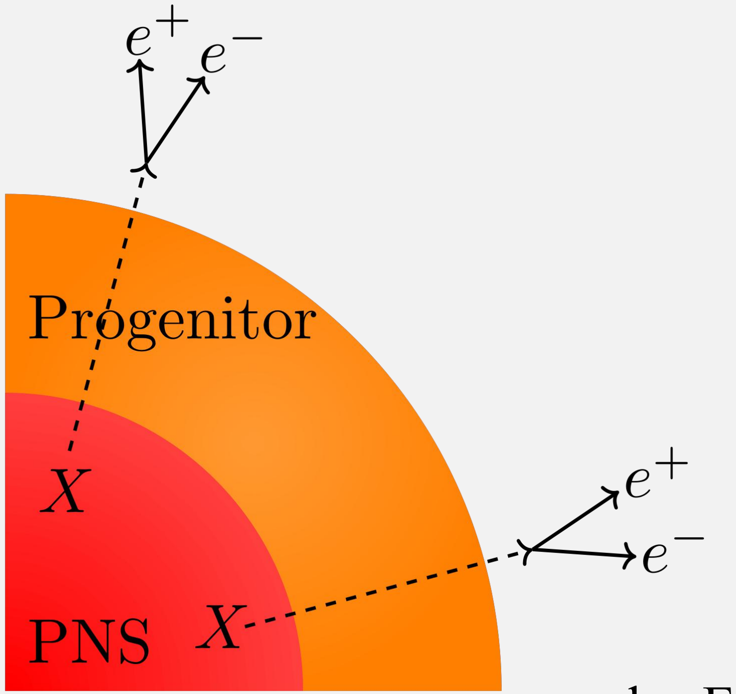


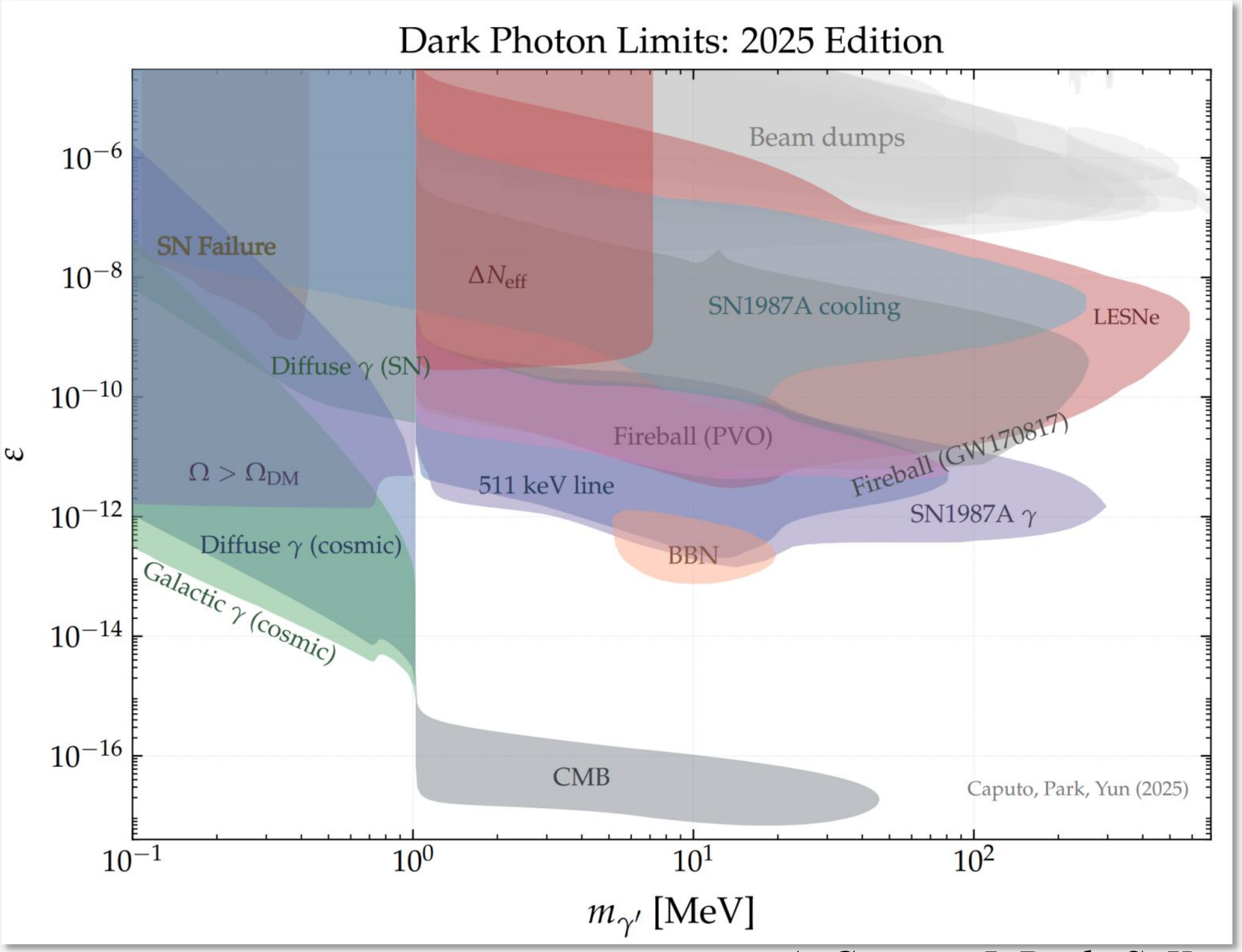
Decay outside mantle → Energy escaped

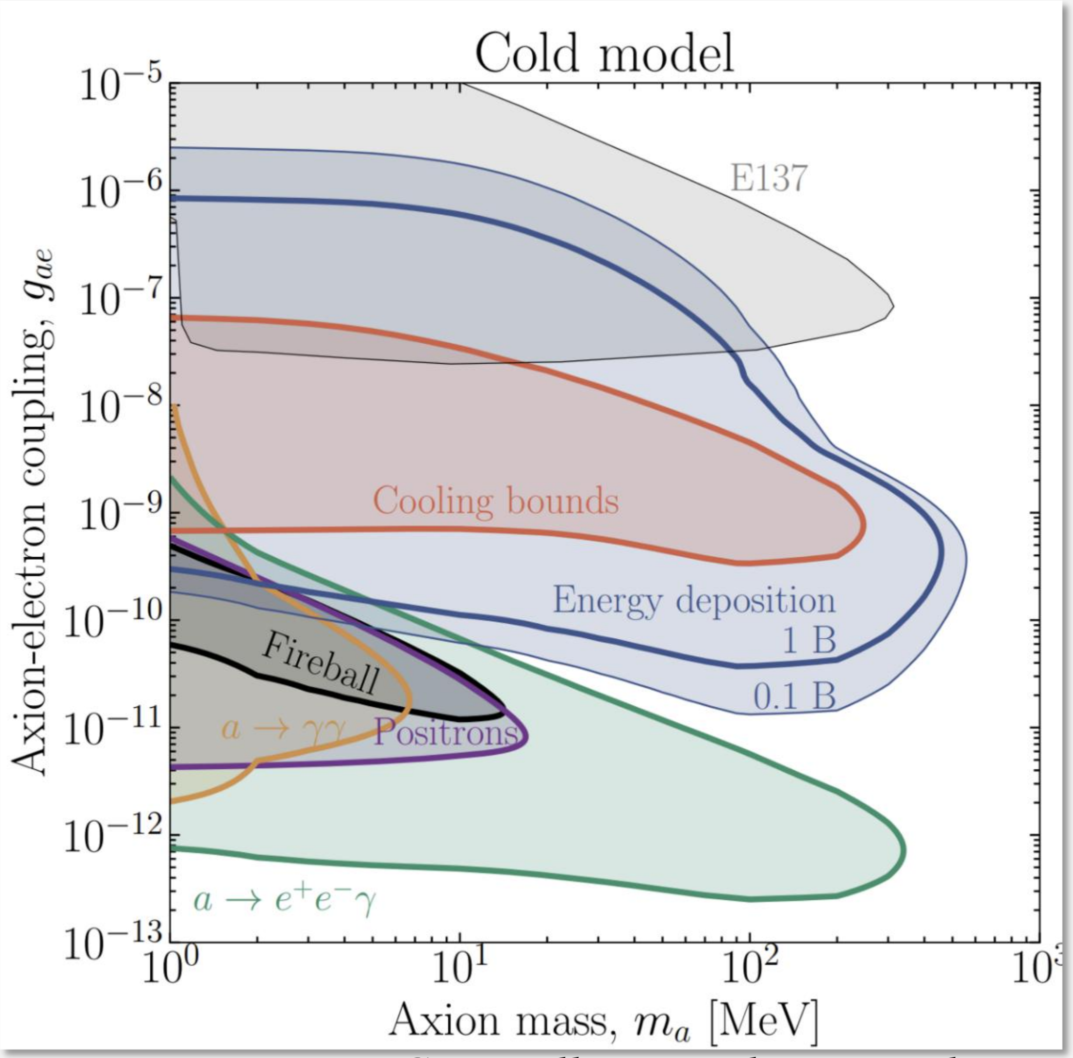
Constraint from cooling, fireball, galactic positron (511 keV), prompt gamma ray



see also Edoardo's talk

Exsisting Constraints w/o CSM



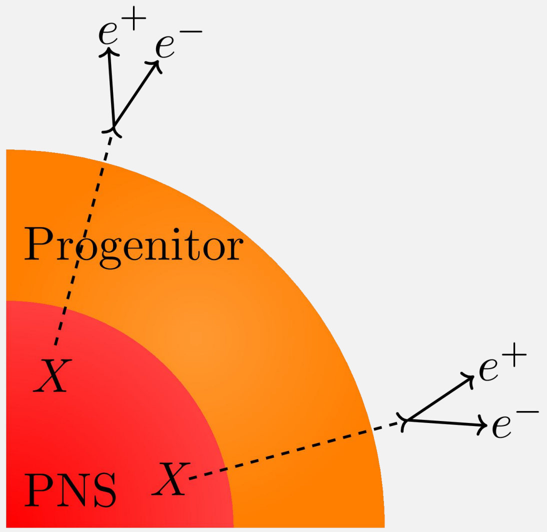


A. Caputo, J. Park, S. Yun
arXiv:2511.15785

D. F. G. Fiorillo, T. Pitik, E. Vitagliano
arXiv:2503.15630

CSM as A New Playground

However, CSM exists!



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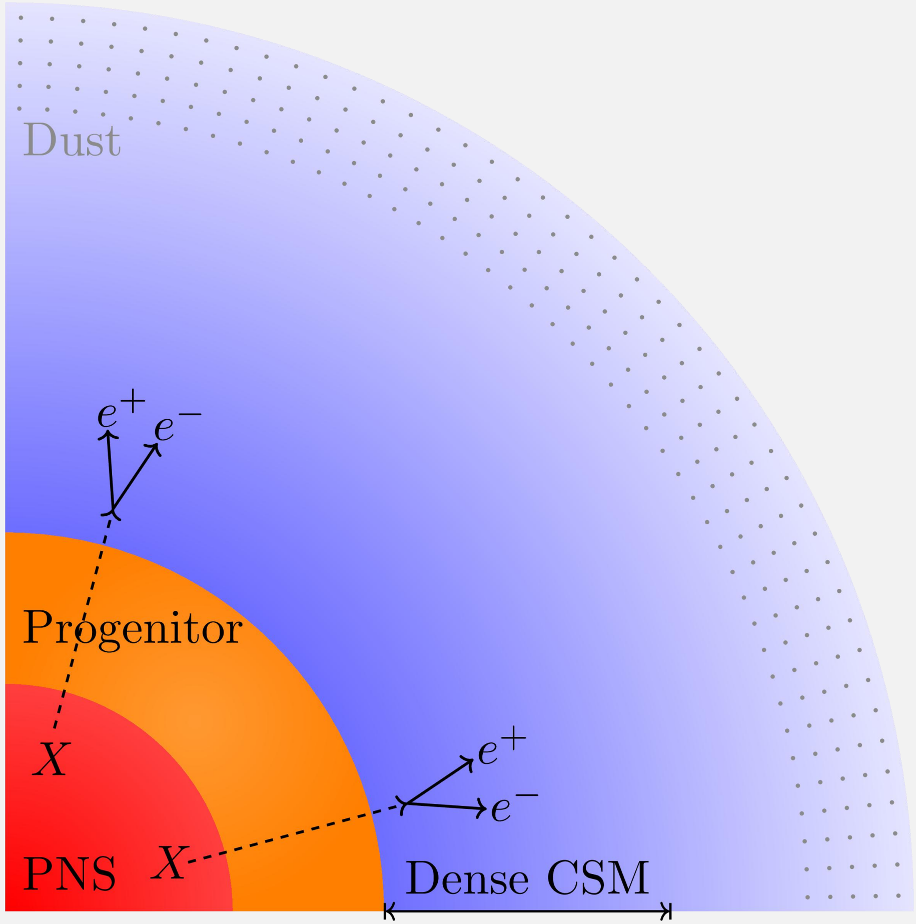

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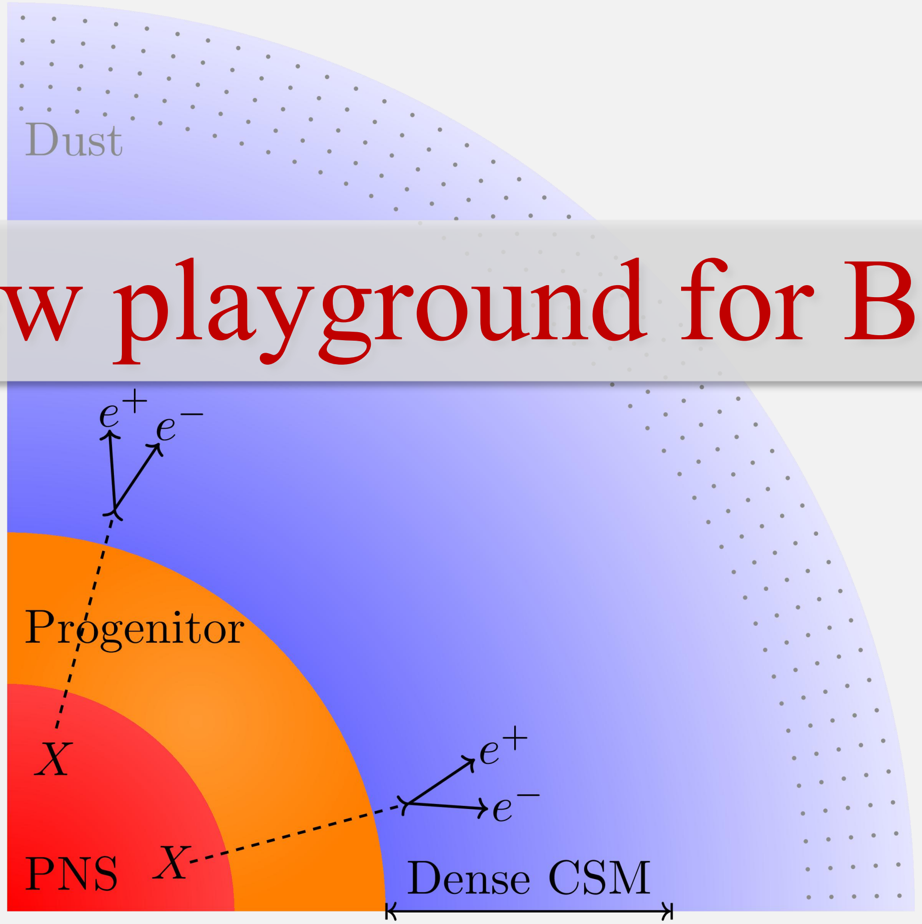
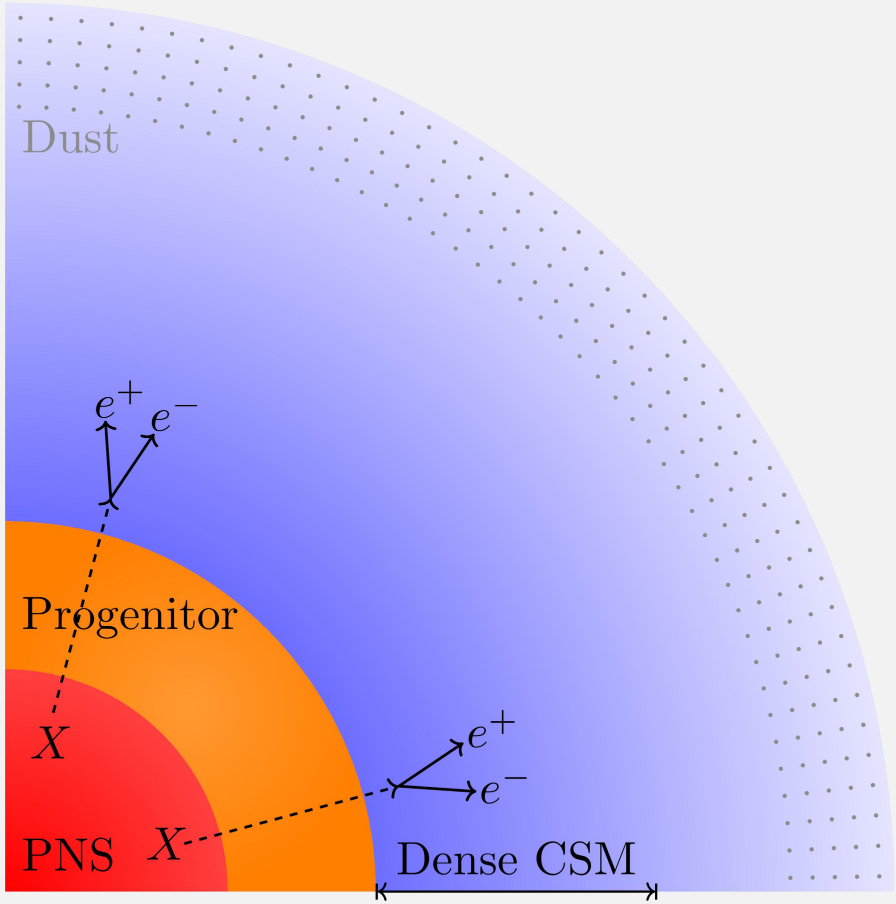


A new playground for BSM!

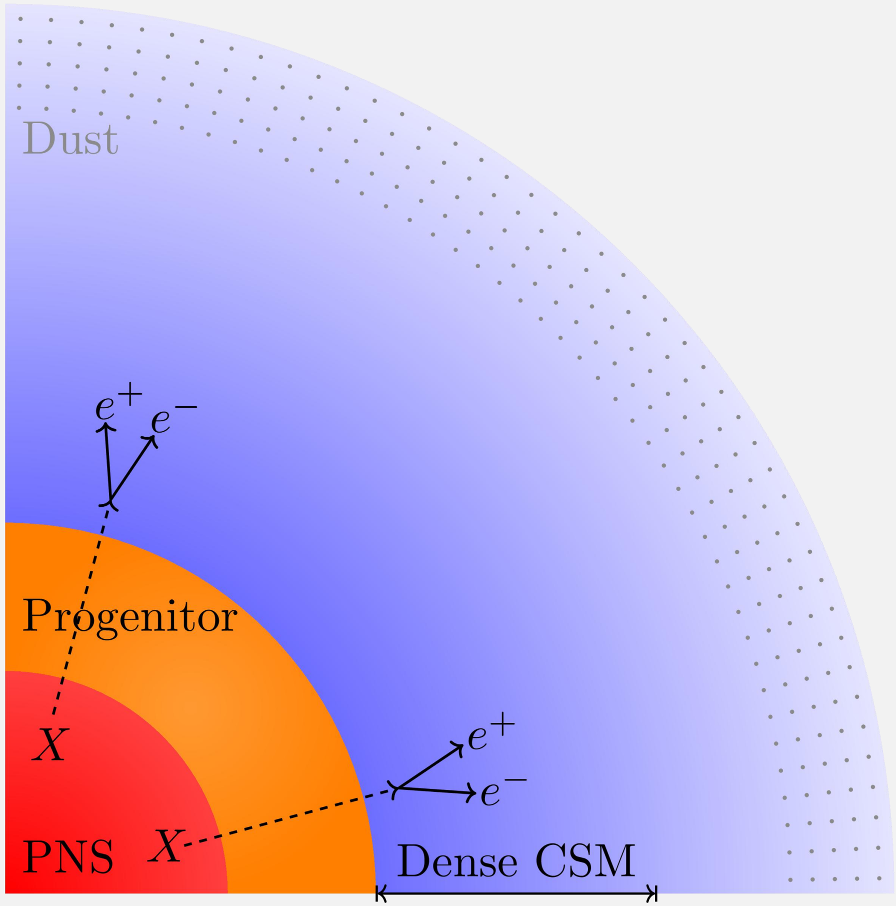
How CSM constrains on FIPs

Photosphere Induced by FIP Decay



FIPs decay into electron/positron inside CSM

Photosphere Induced by FIP Decay



FIPs decay into electron/positron inside CSM

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

DP momentum

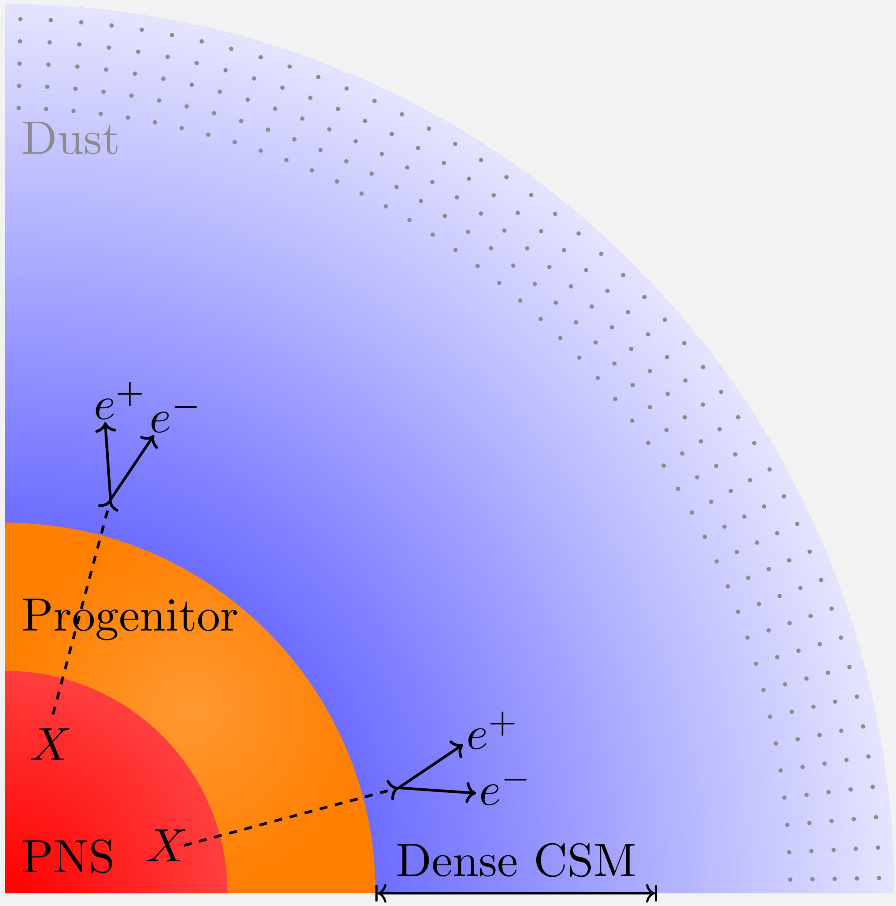
DP decay length

DP momentum distribution

electron/positron energy

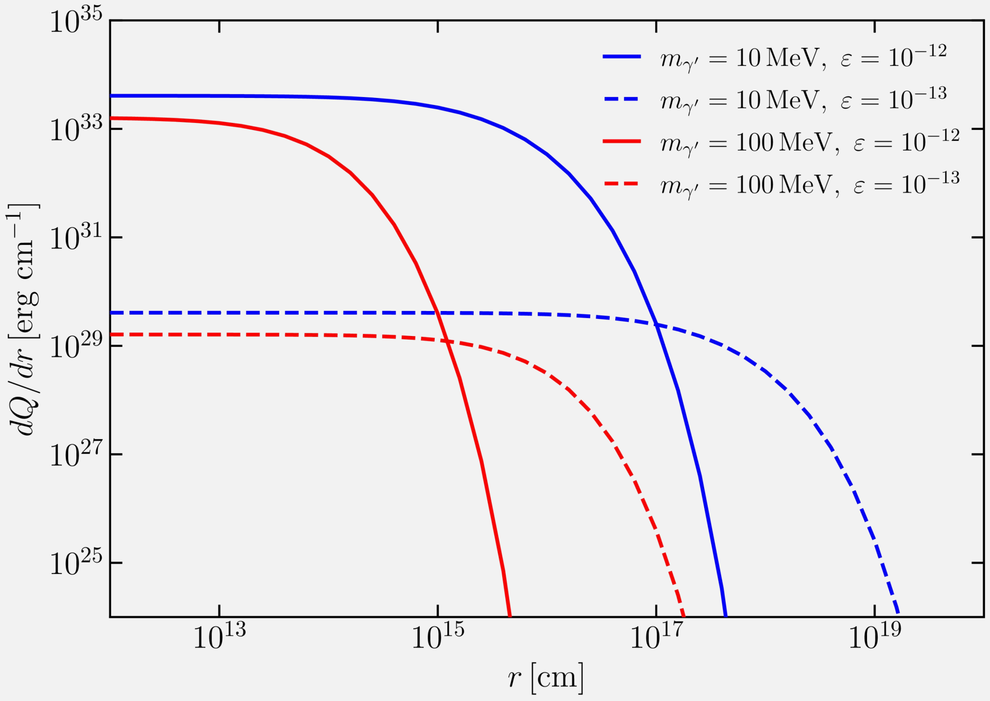
electron/positron energy distribution

Photosphere Induced by FIP Decay



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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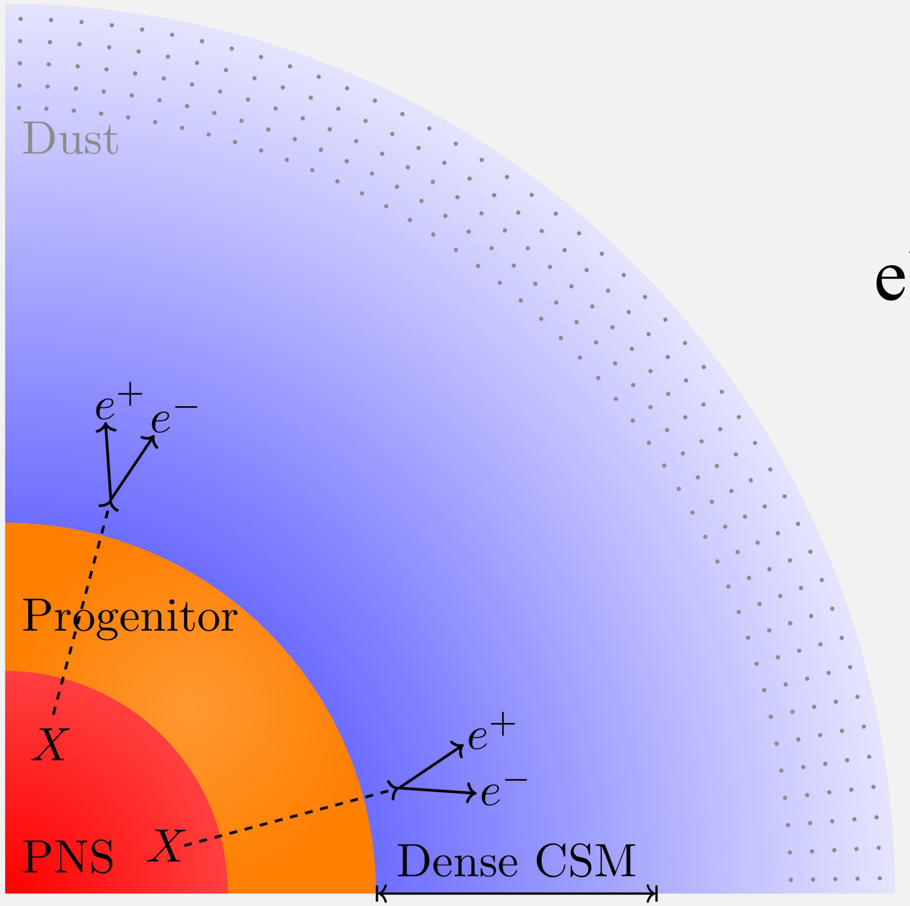
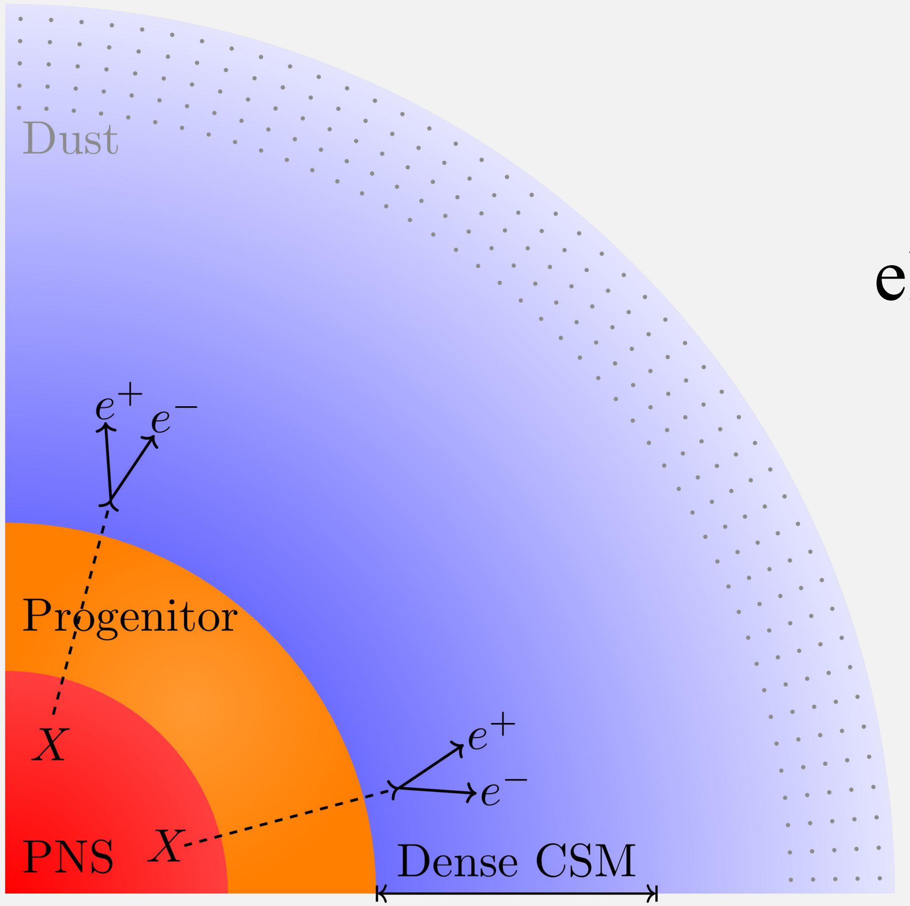


FIPs decay into electron/positron inside CSM

↓

electron/positron energy deposition inside CSM

Photosphere Induced by FIP Decay



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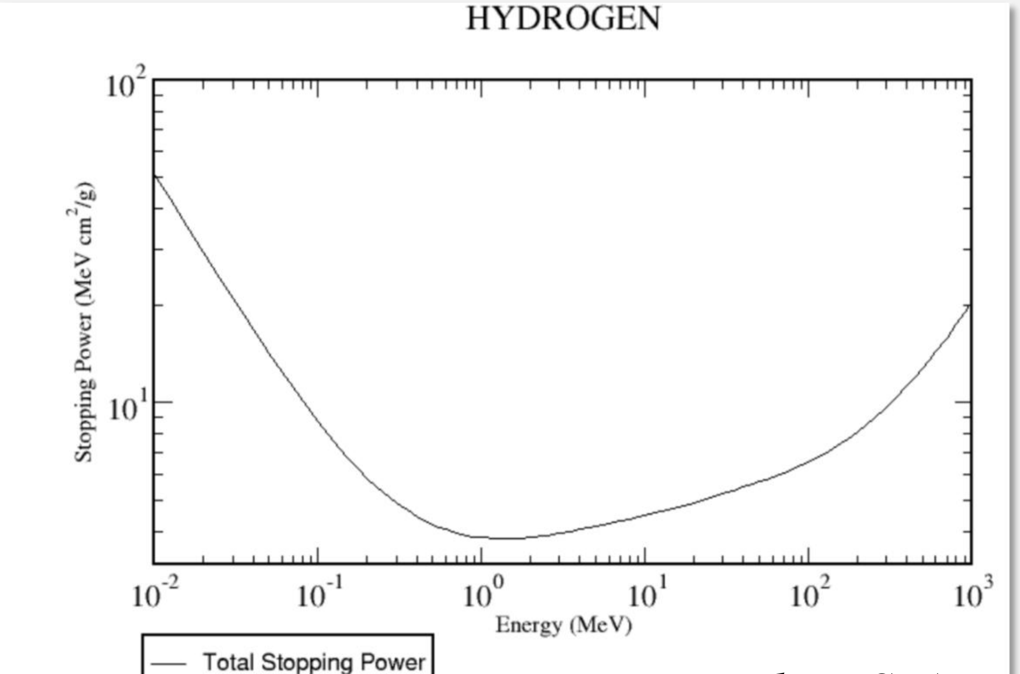
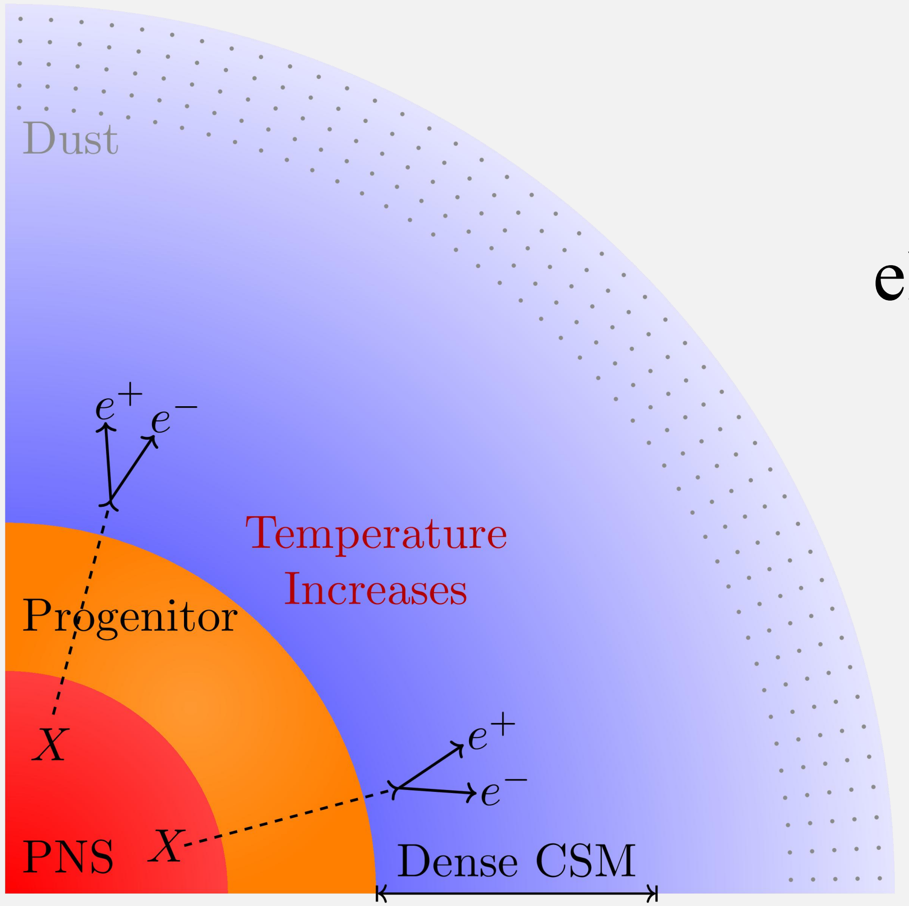


credit: ESTAR

Photosphere Induced by FIP Decay



FIPs decay into electron/positron inside CSM

↓

electron/positron energy deposition inside CSM

↓

CSM temparature increases

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

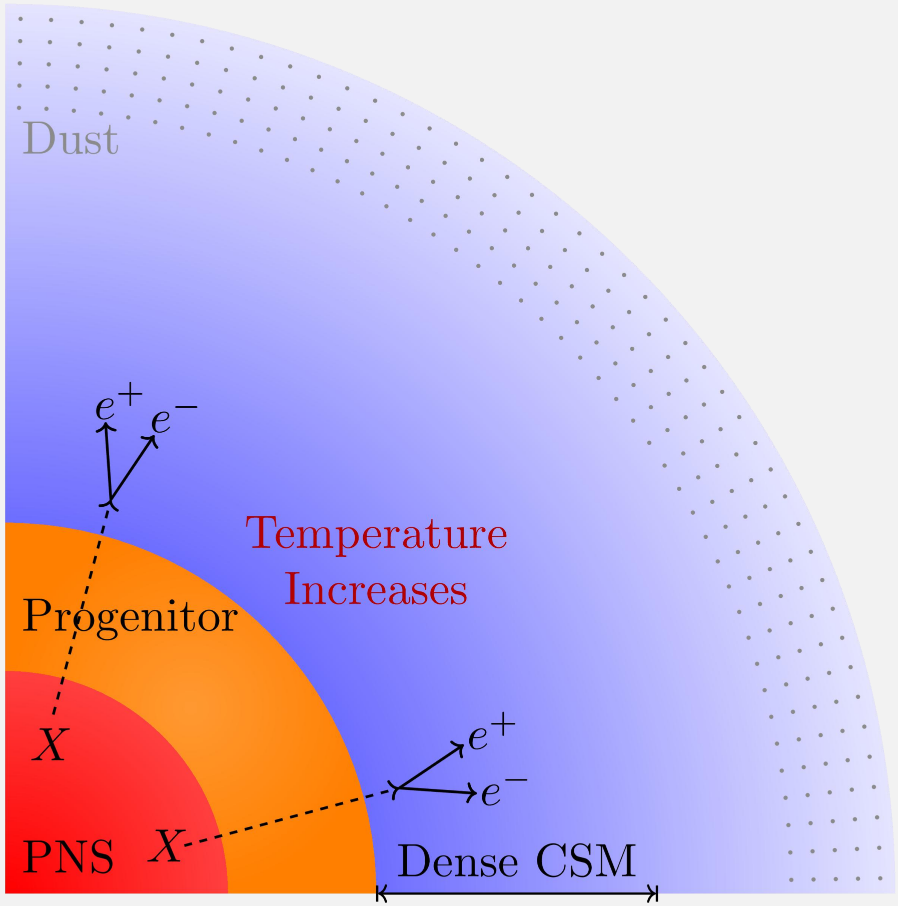
$\bar{\eta}$: energy deposition efficiency

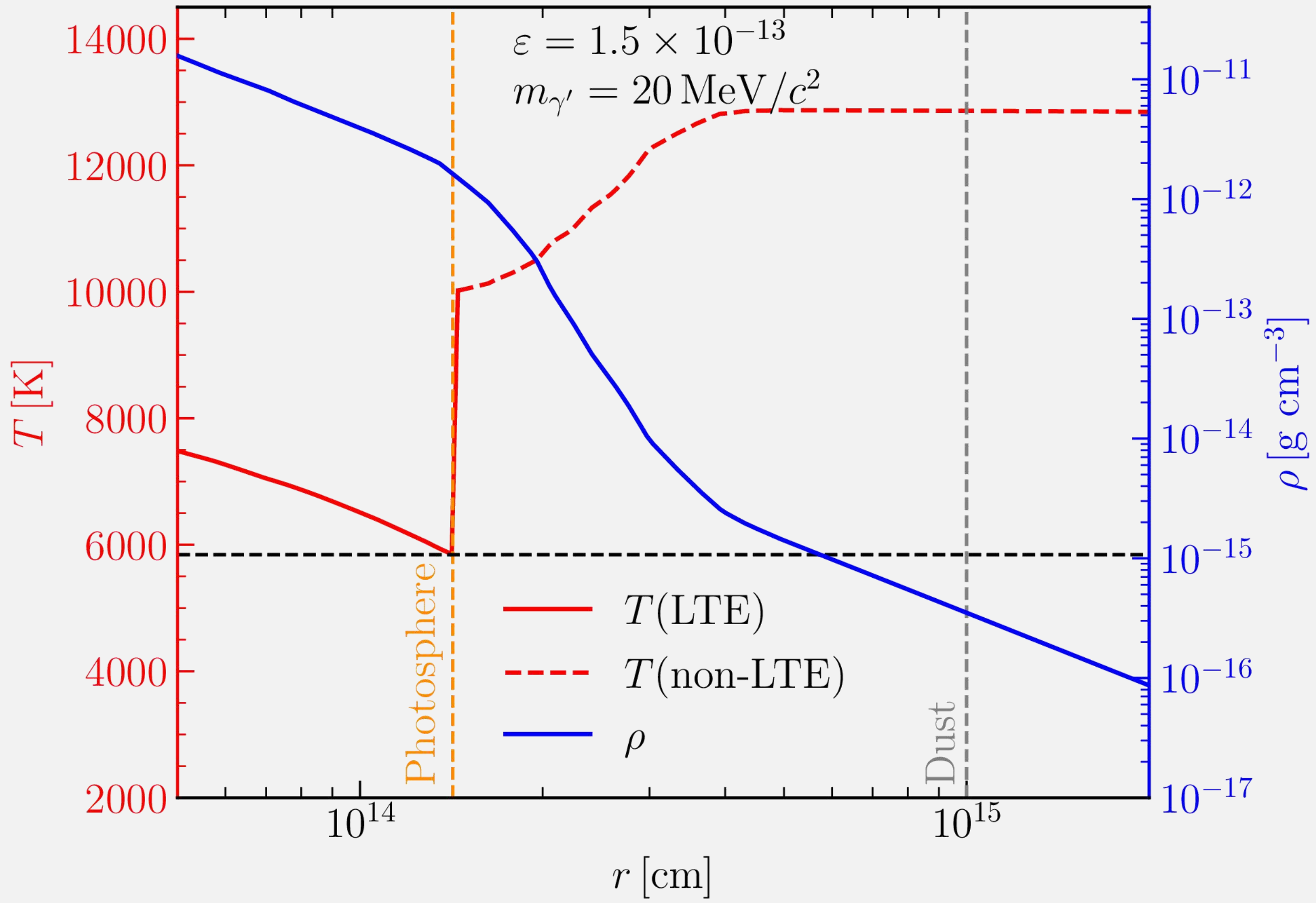
$u_{\rm gas} = (3/2)(n + n_e)k_B T$ internal energy density of ideal gas

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

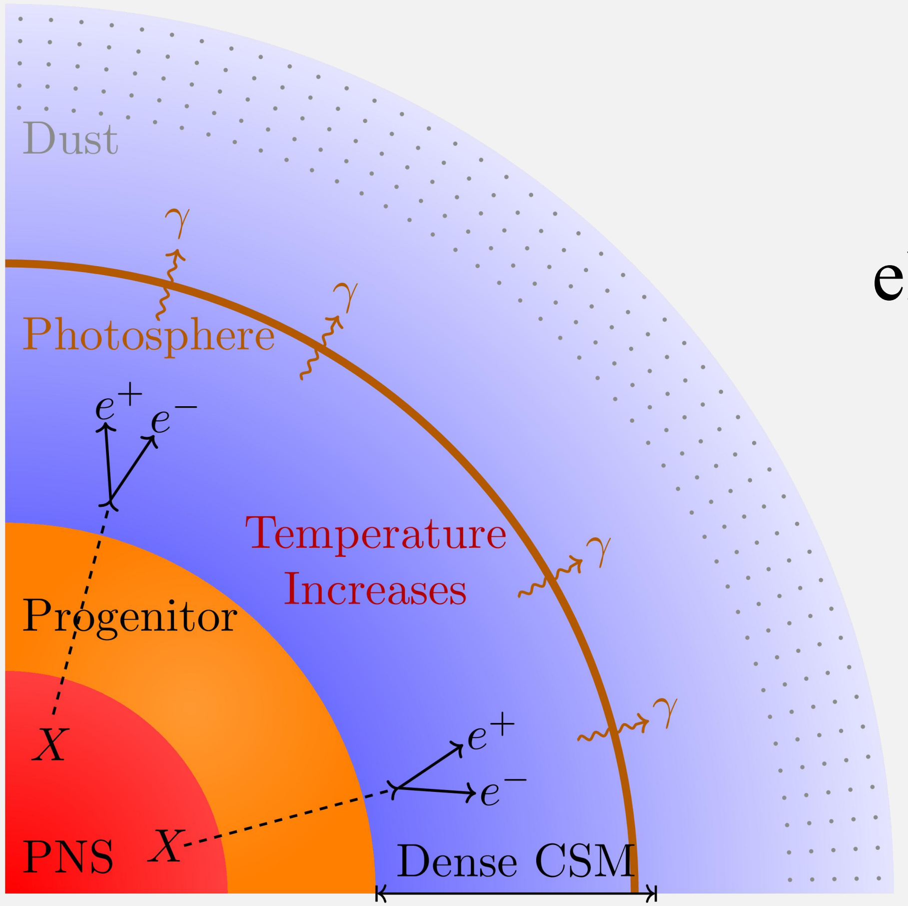
$u_{\rm rad}$: radiation energy density

Photosphere Induced by FIP Decay





Photosphere Induced by FIP Decay



FIPs decay into electron/positron inside CSM

↓

electron/positron energy deposition inside CSM

↓

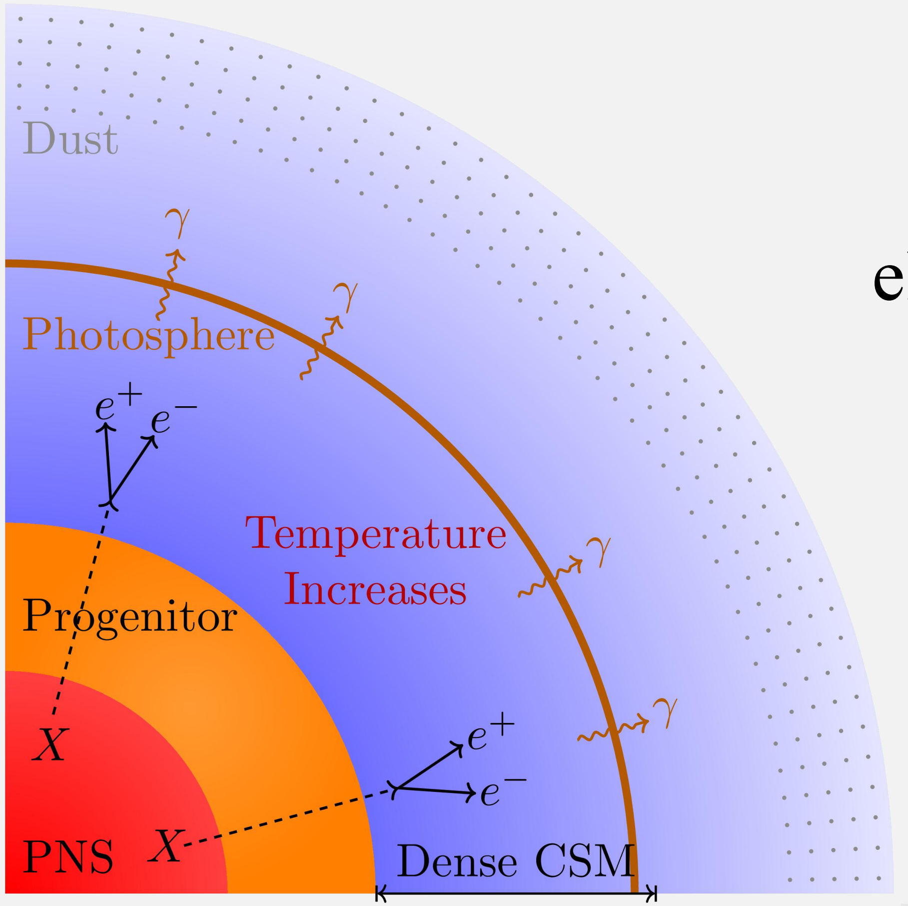
CSM temparature increases

↓

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



FIPs decay into electron/positron inside CSM

↓

electron/positron energy deposition inside CSM

↓

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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

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

Review

SN 2023ixf: The Closest Supernova of the Decade

Wynn Jacobson-Galán[1,2]

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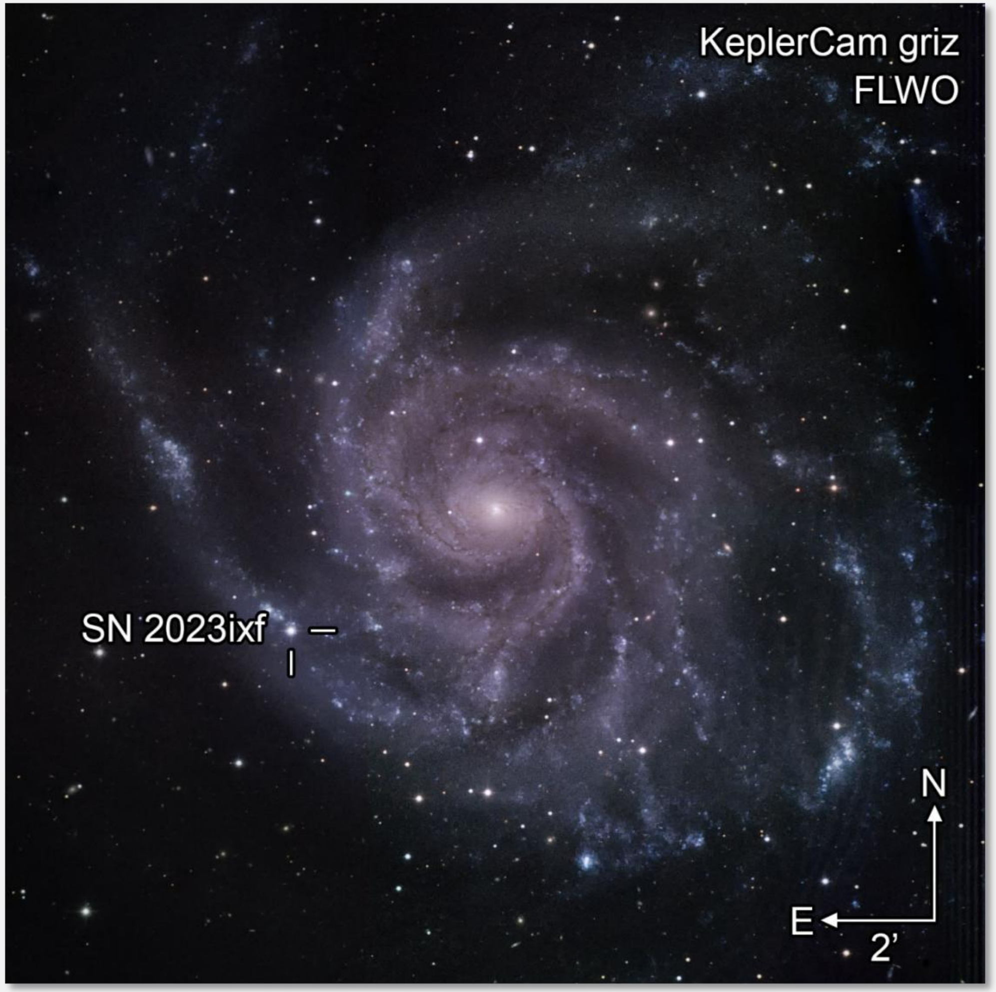
Article | Published: 27 March 2024

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

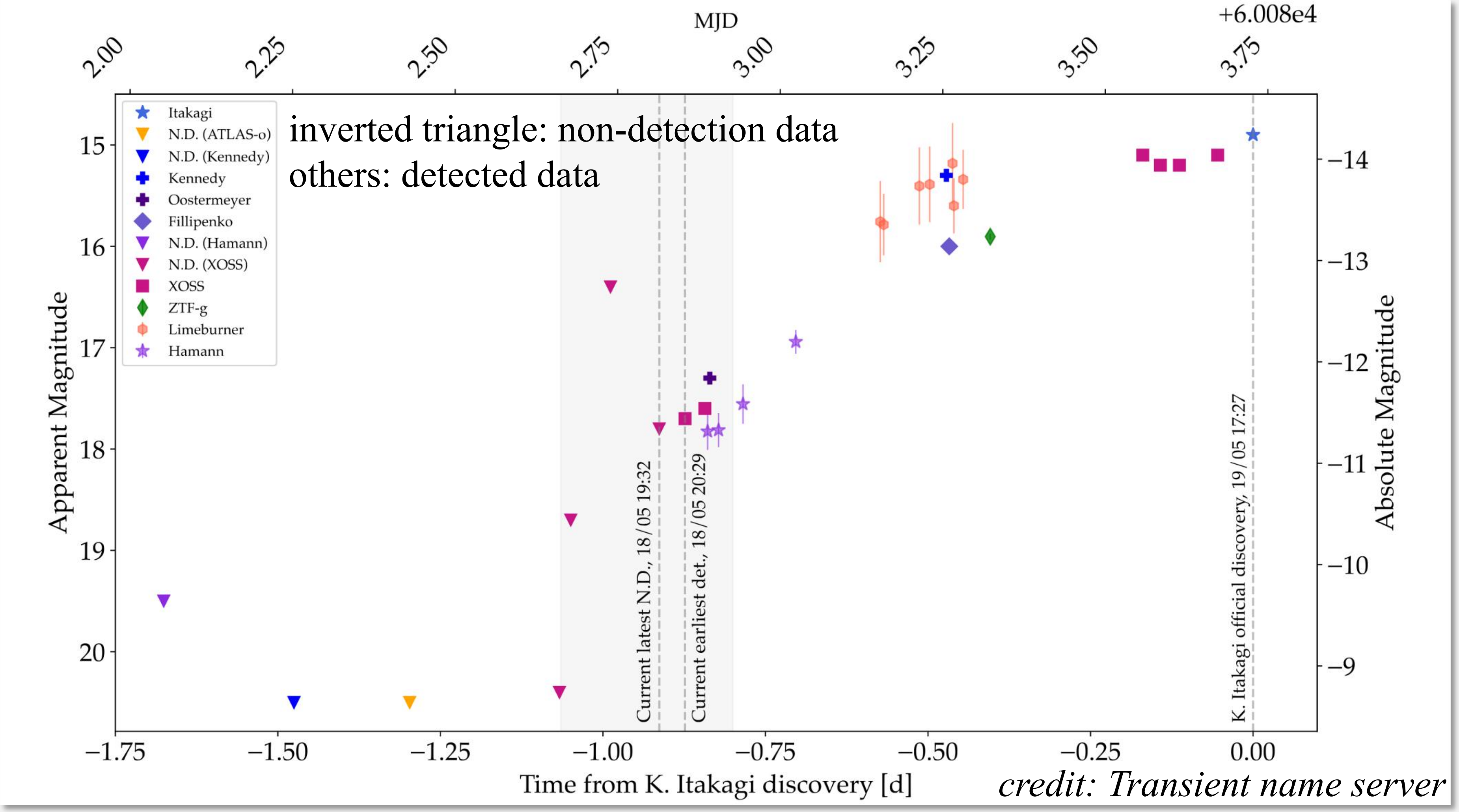
E.A. Zimmerman et al.
Nature 627 (2024) 759



credit: S. Gomez/STScI

SN 2023ixf as A Case Study

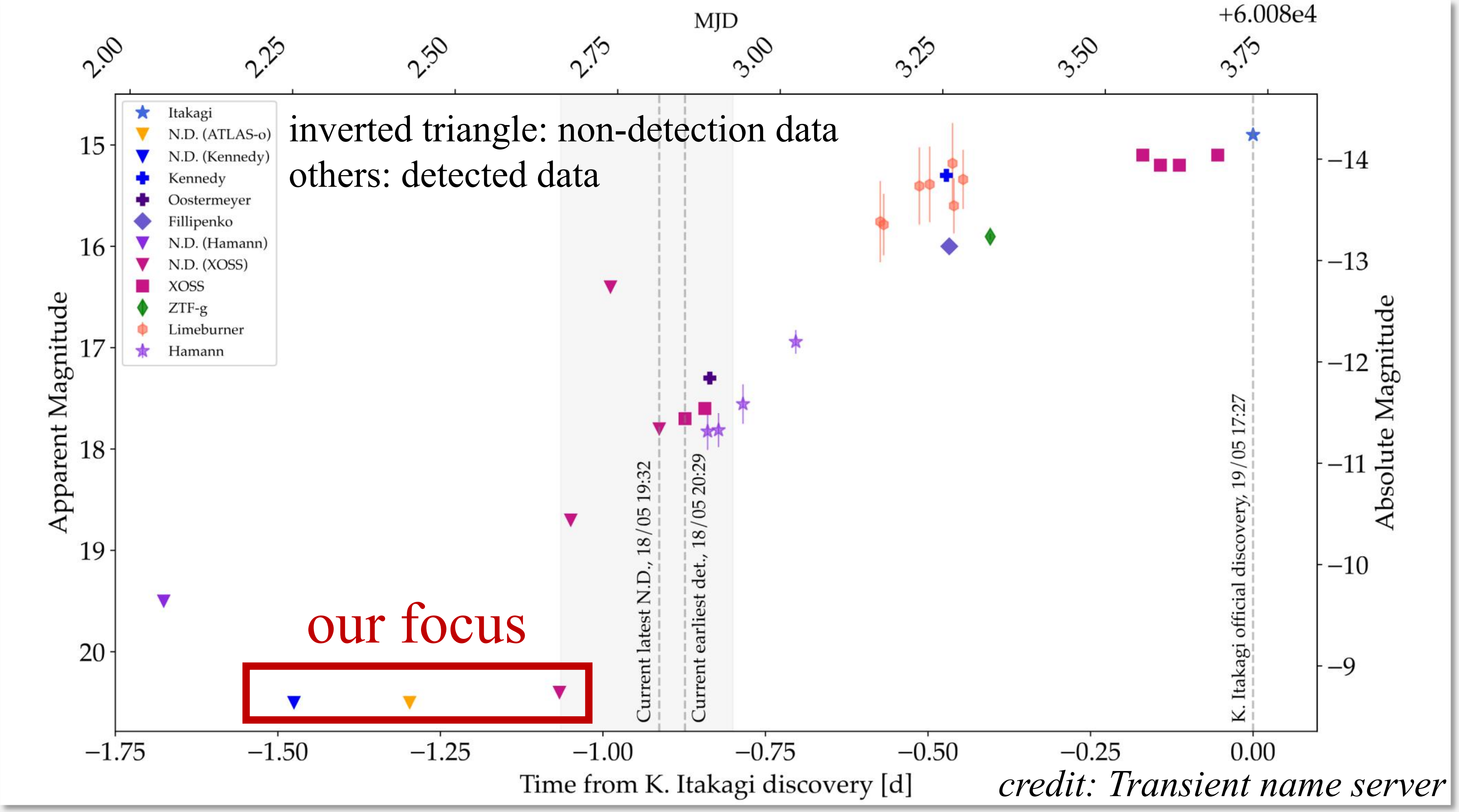
Early-time observations of SN 2023ixf



credit: Transient name server

SN 2023ixf as A Case Study

Early-time observations of SN 2023ixf



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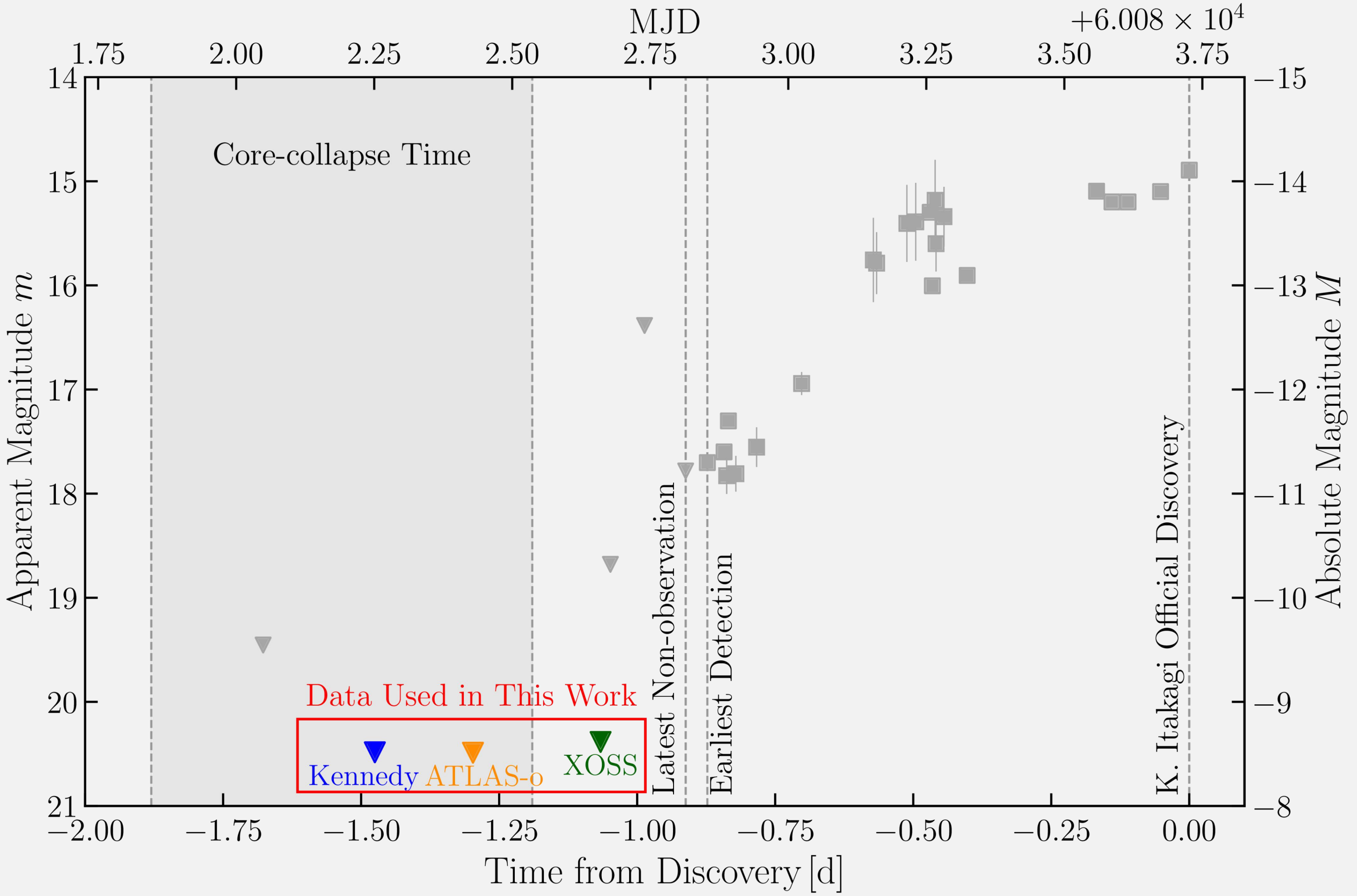


optical band (400 nm -- 900 nm)

$$M \geq -8.6$$

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

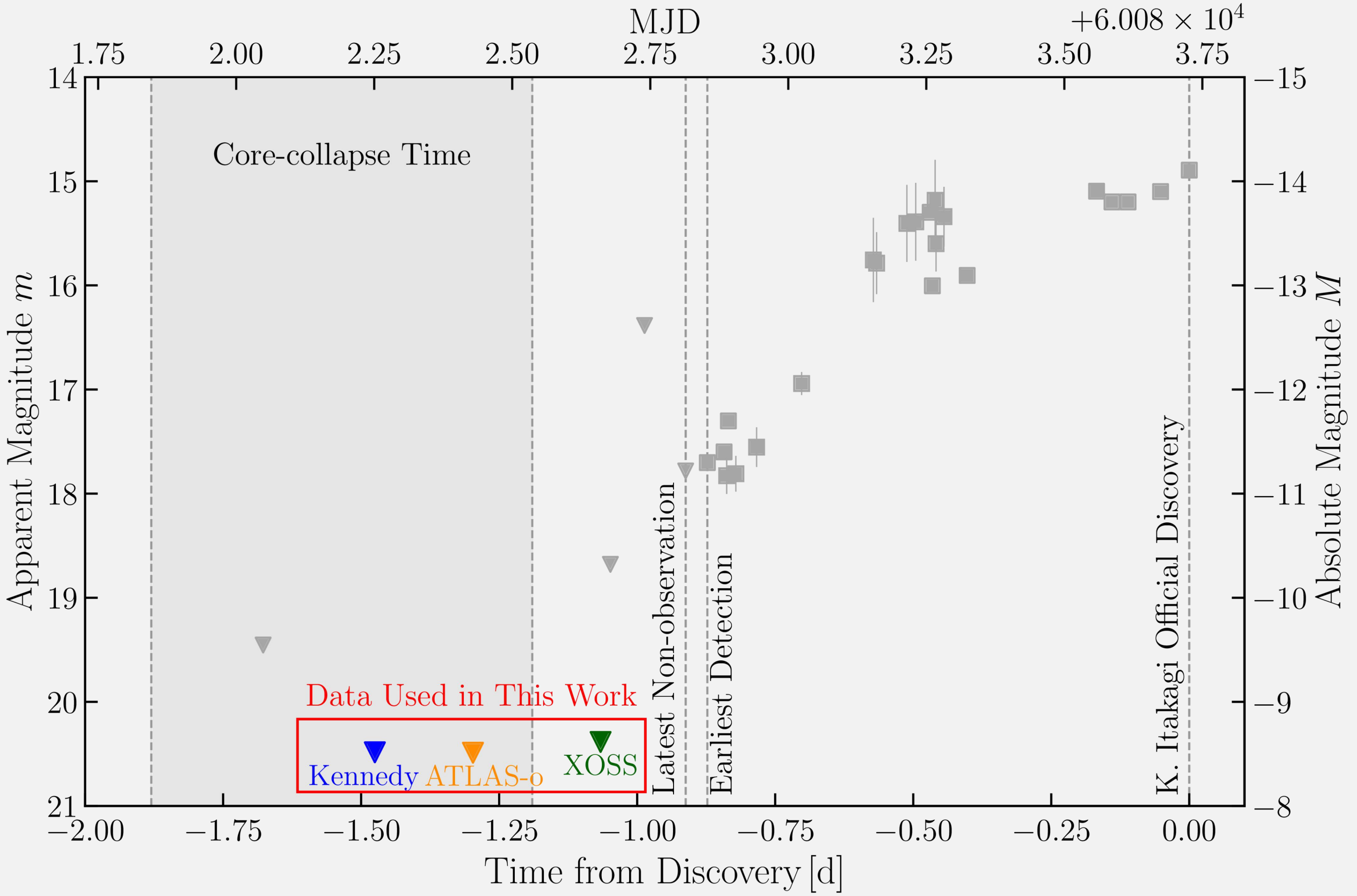
$L'_\odot$: solar luminosity in $400 - 900\,\mathrm{nm}$

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

*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
PRL 26

SN 2023ixf as A Case Study

Early-time observations of SN 2023ixf



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↓

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

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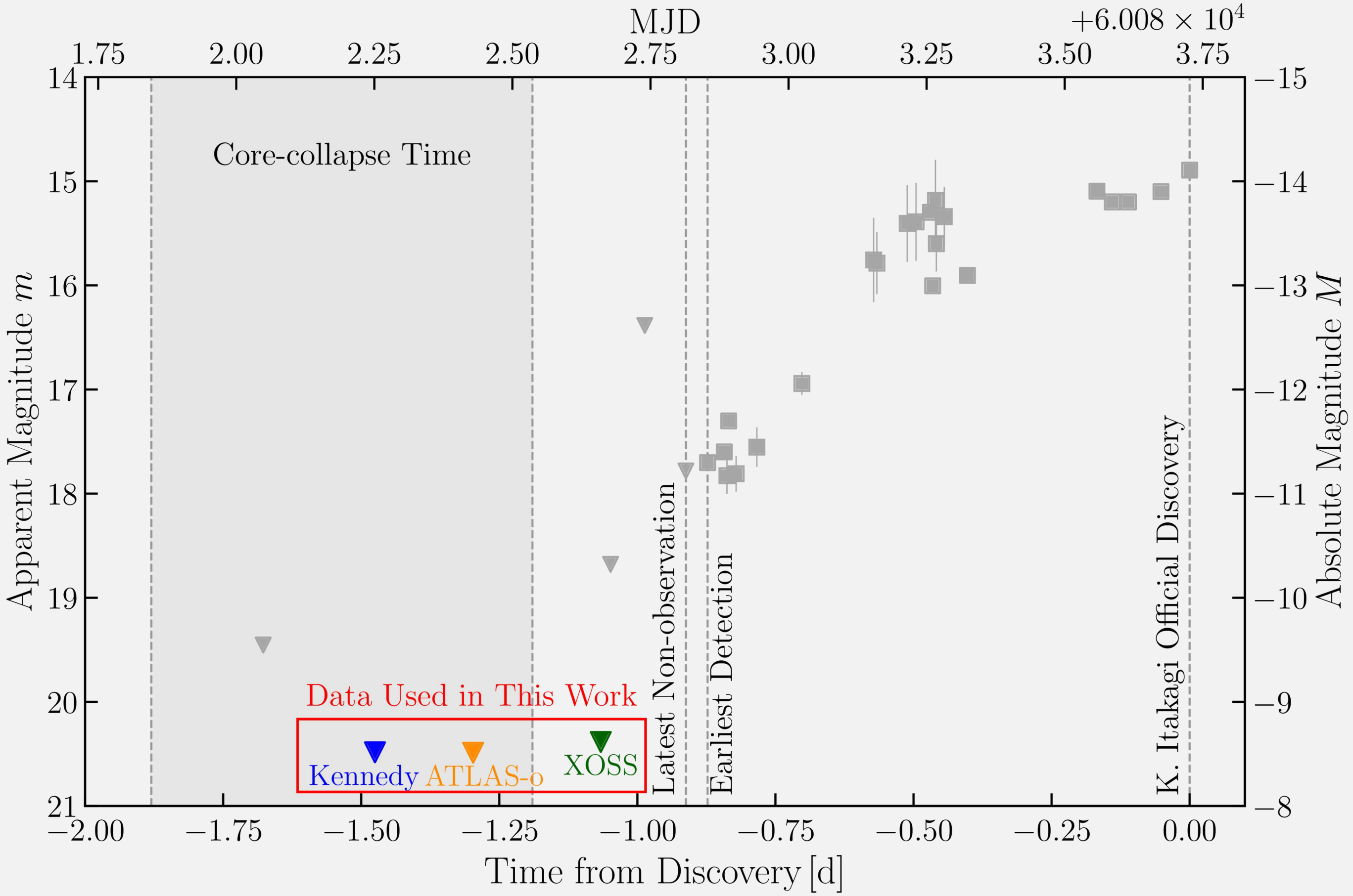

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↓

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

our **conservative** criteria:

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

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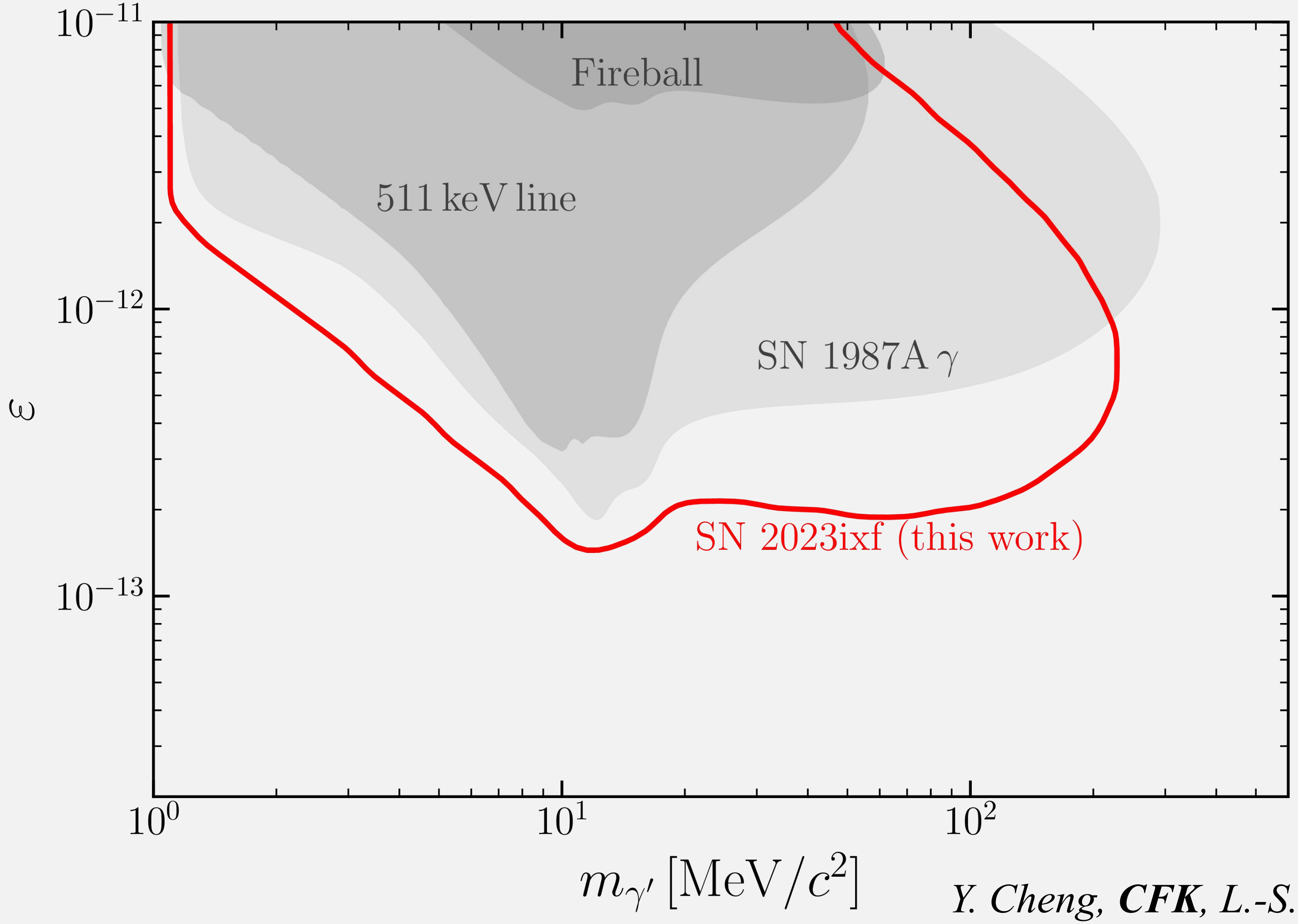
Constraint on DP (i)



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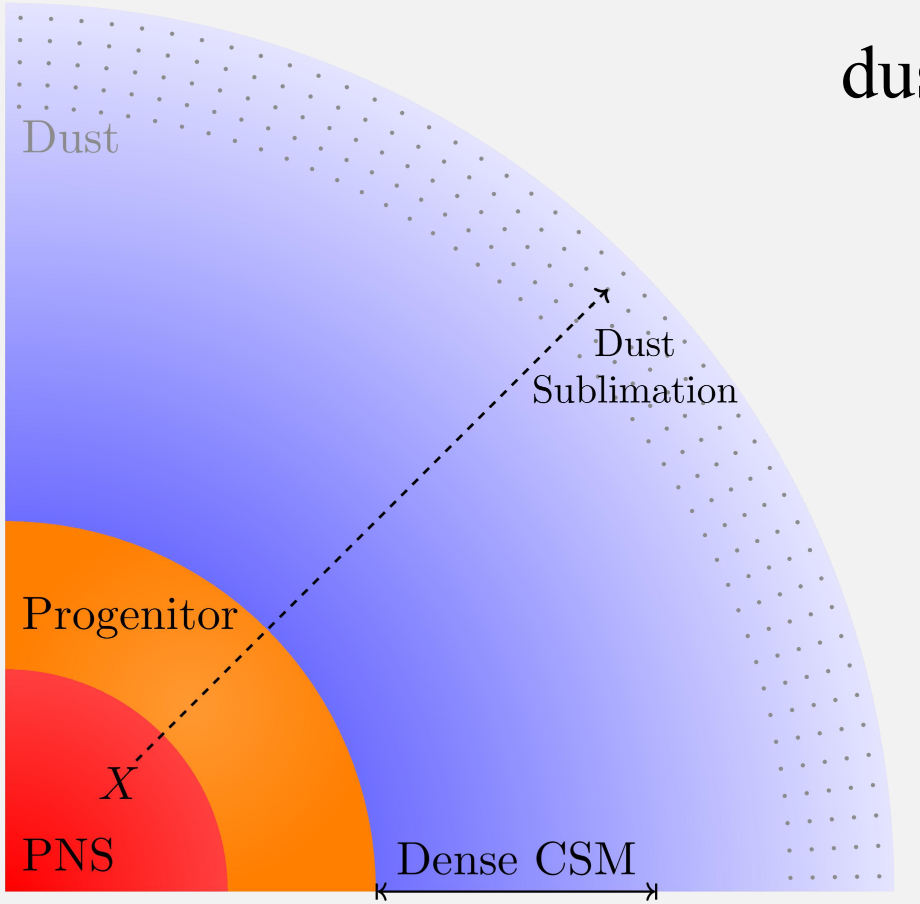
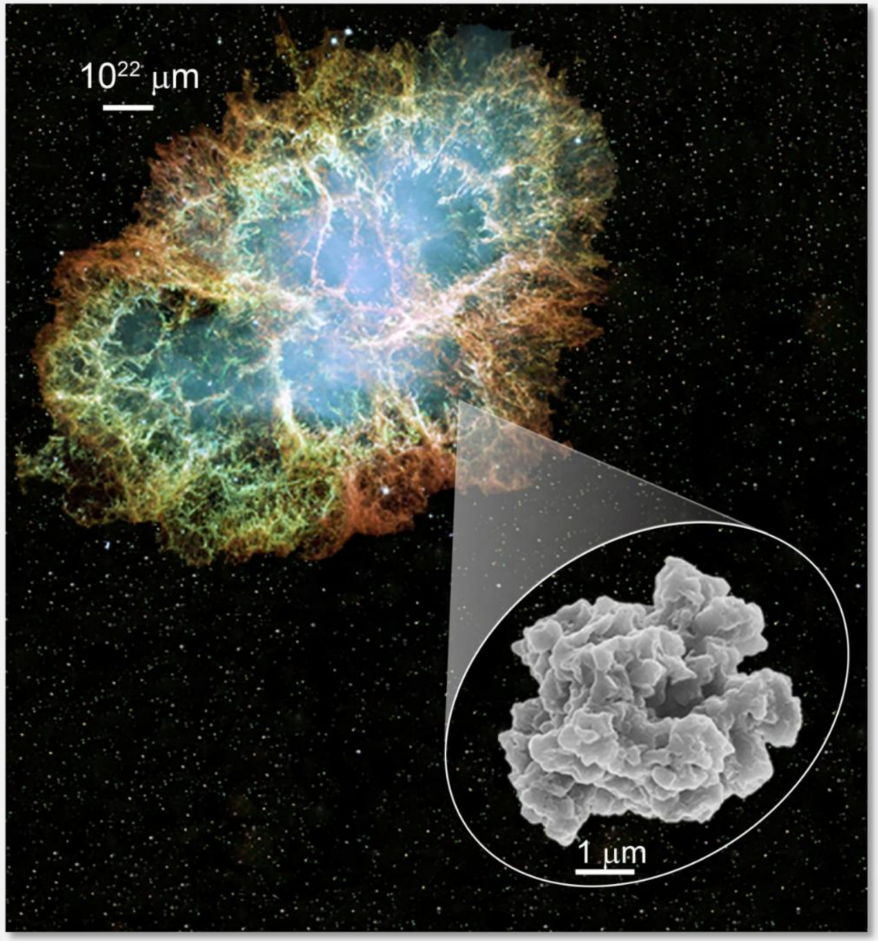
Dust Sublimation

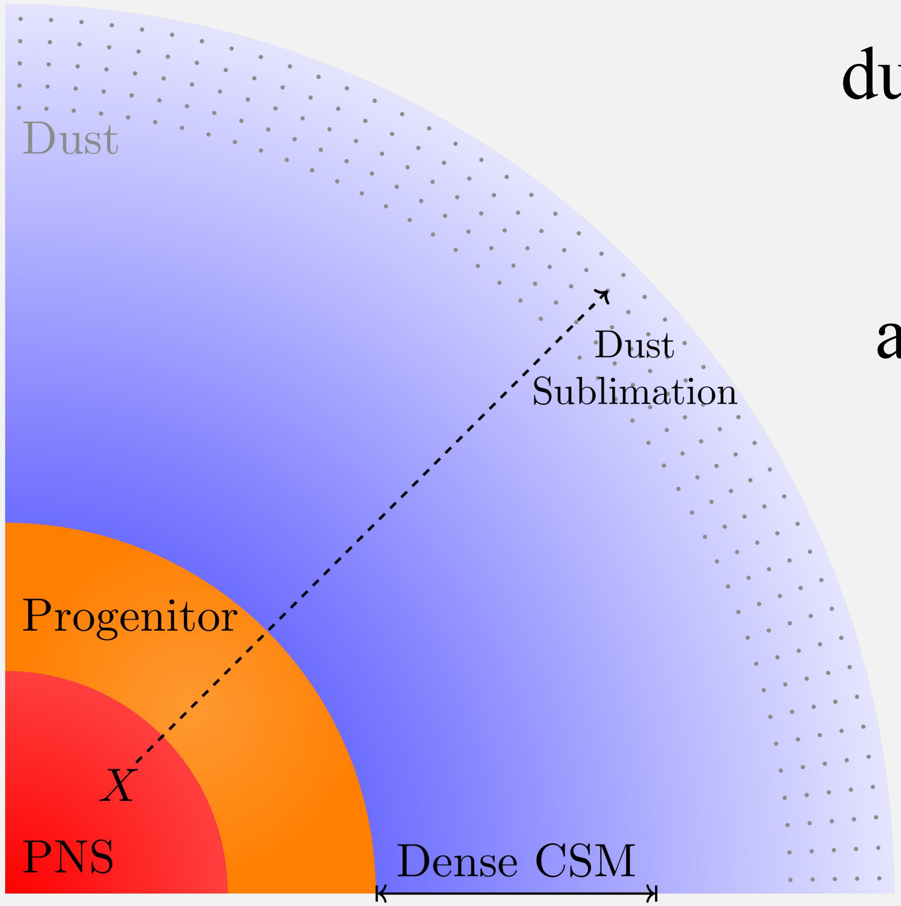


dust grains (molecules) exist in outer layer of CSM



credit: L. Nittler

Dust Sublimation

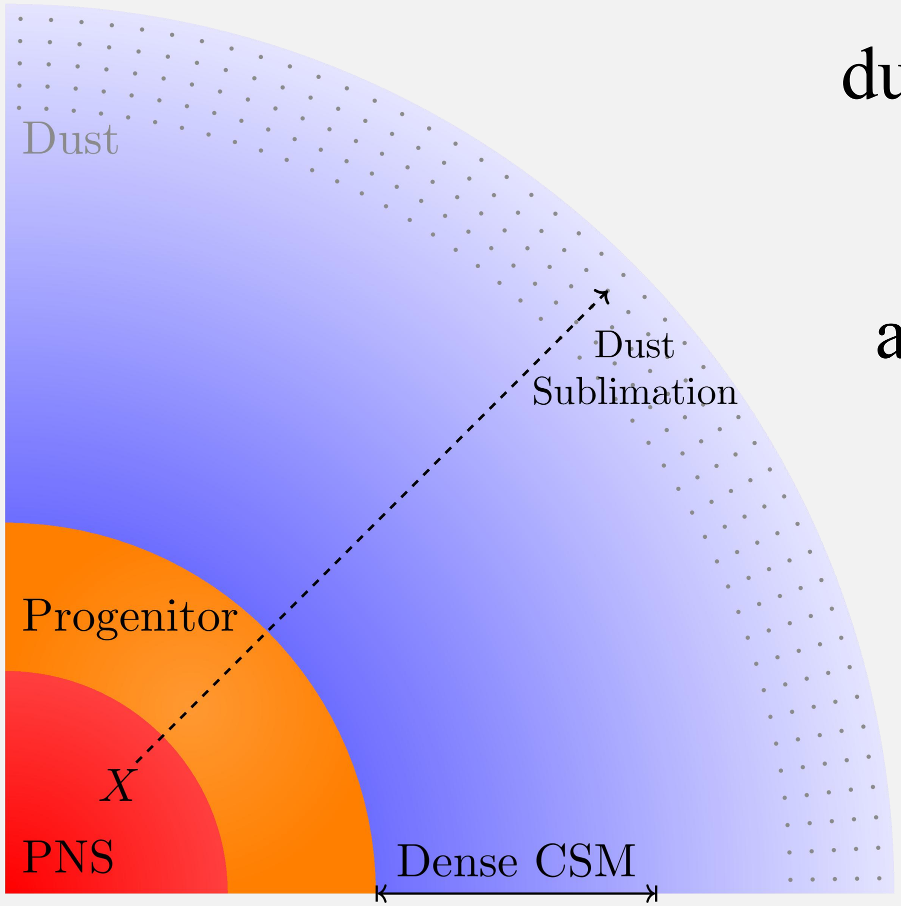


dust grains (molecules) exist in outer layer of CSM

↓

absorb optical photons and reprocess into infrared

Dust Sublimation



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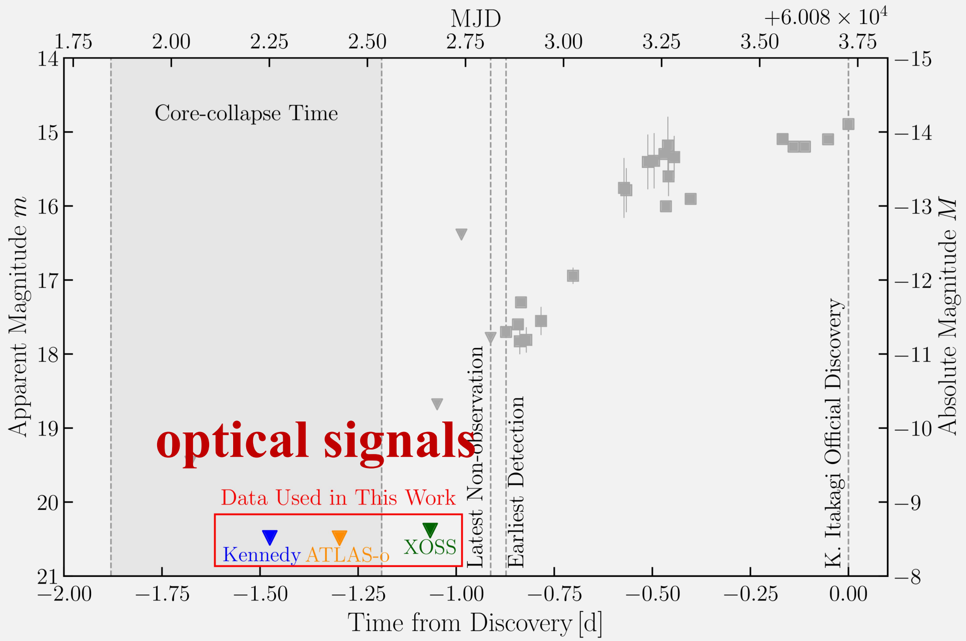
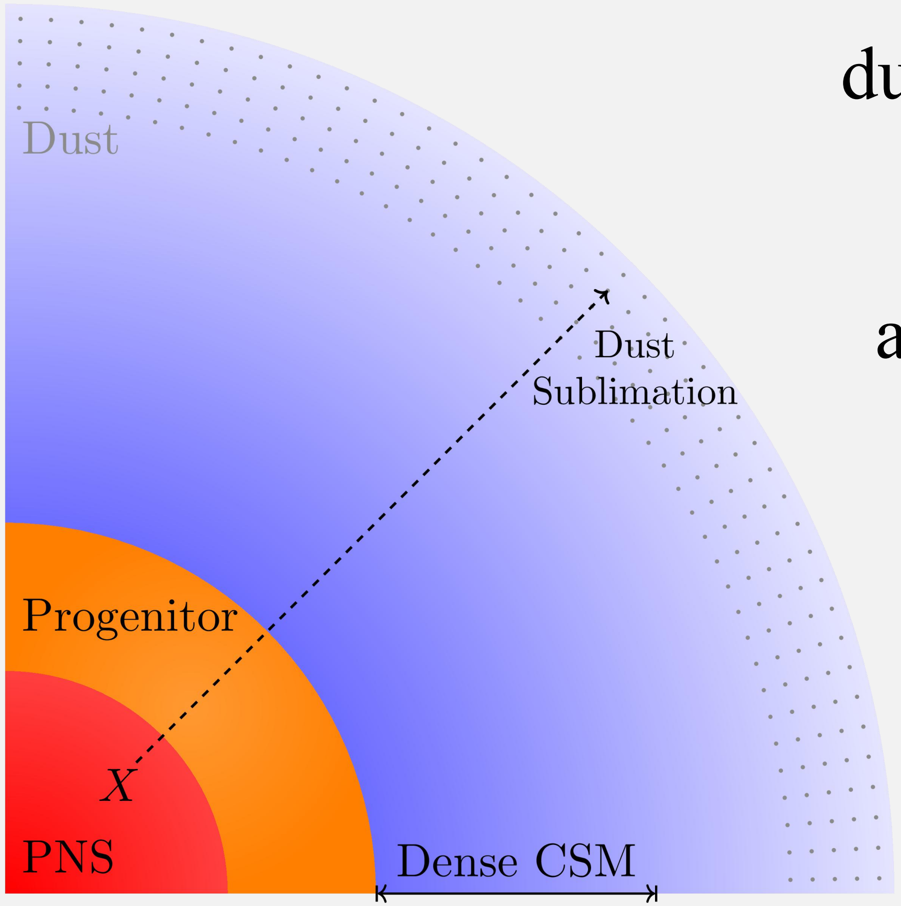


Dust Sublimation



dust grains (molecules) exist in outer layer of CSM

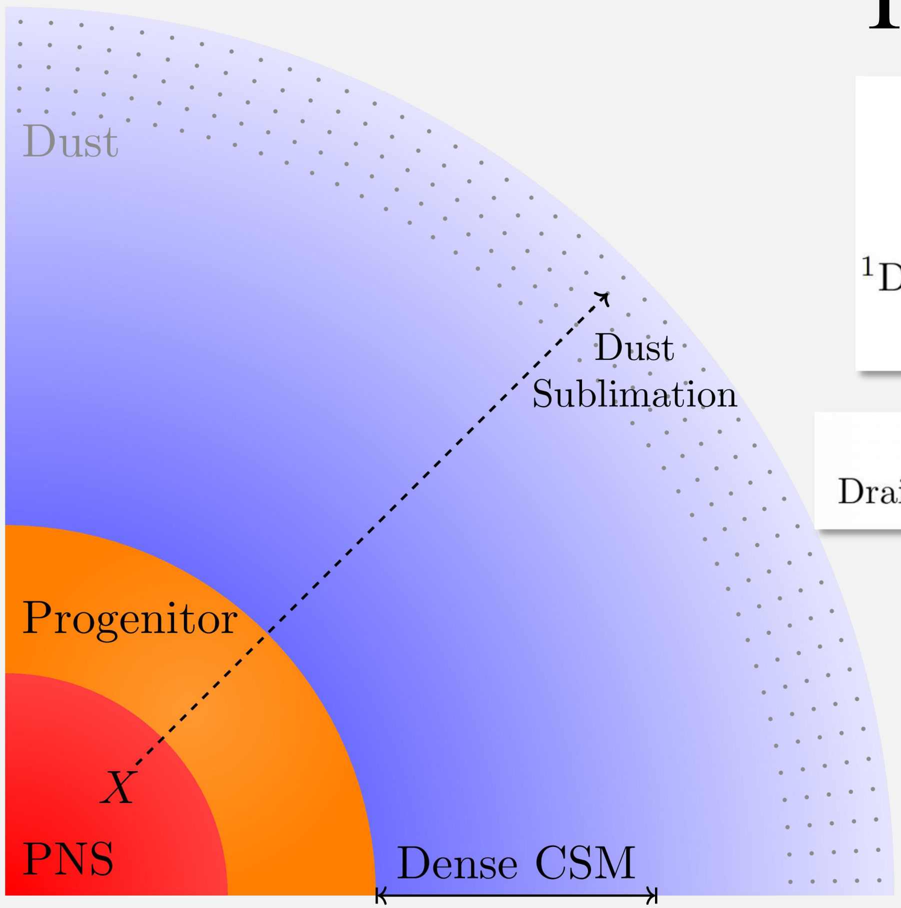
↓

absorb optical photons and reprocess into infrared

↓

an additional dust-destruction requirement

Dust Sublimation



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

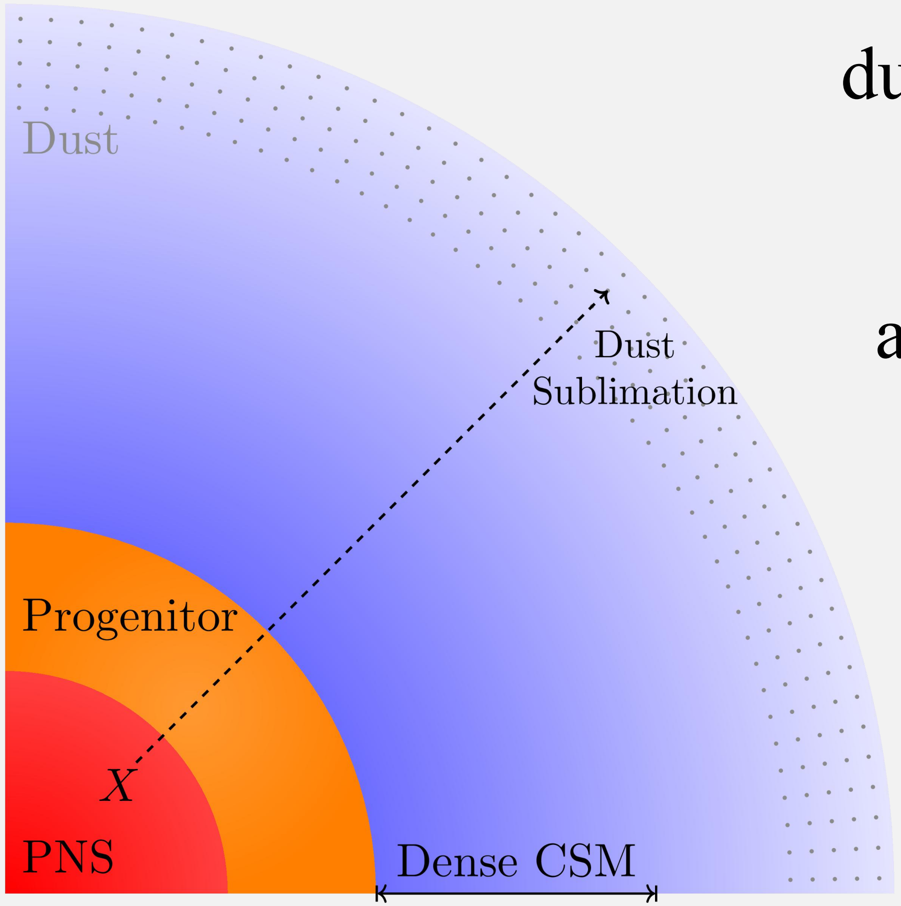
[2]Princeton University Observatory, Peyton Hall, Princeton, NJ 08544

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



dust grains (molecules) exist in outer layer of CSM

↓

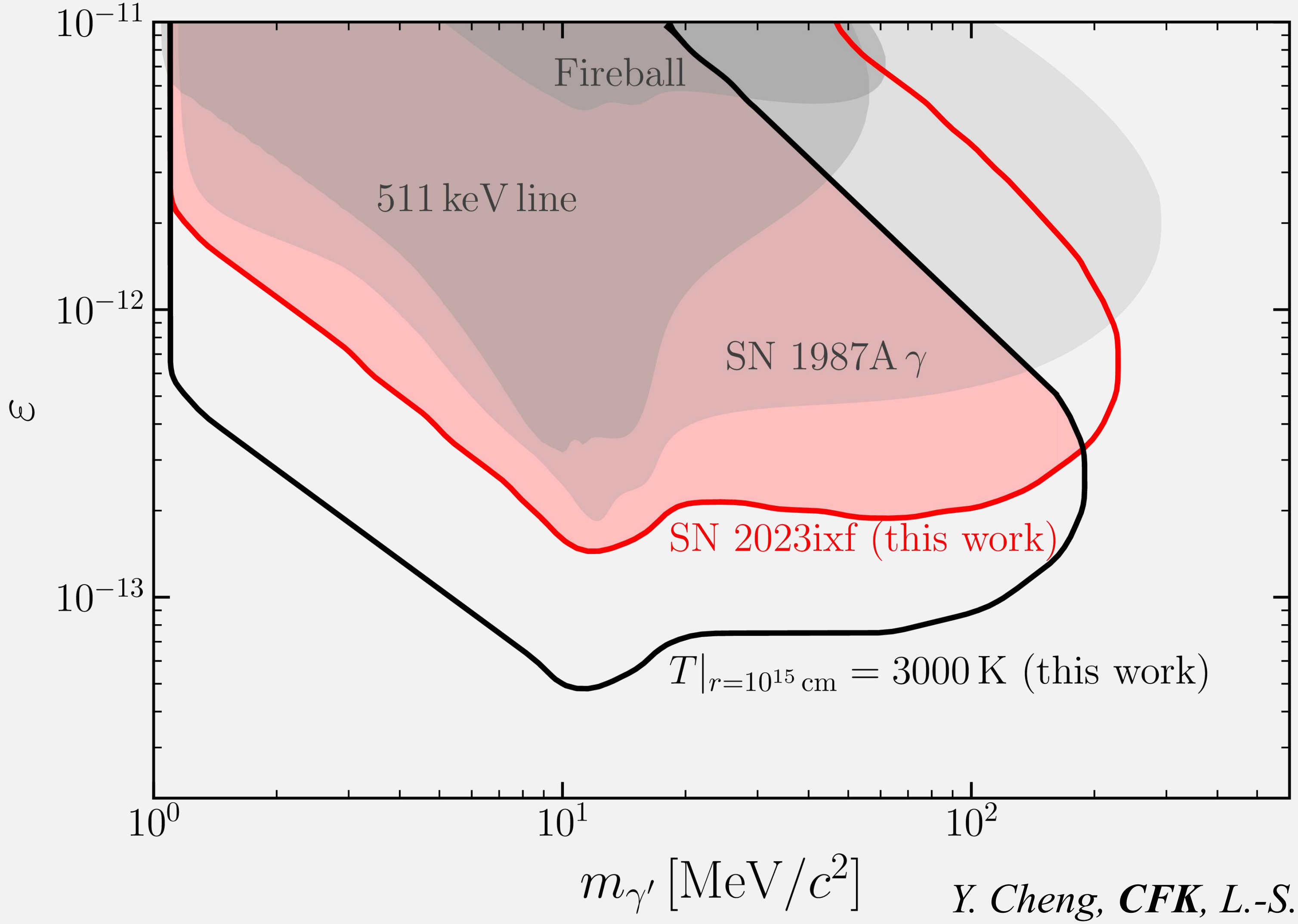
absorb optical photons and reprocess into infrared

↓

an additional dust-destruction requirement

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

Constraint on DP (ii)



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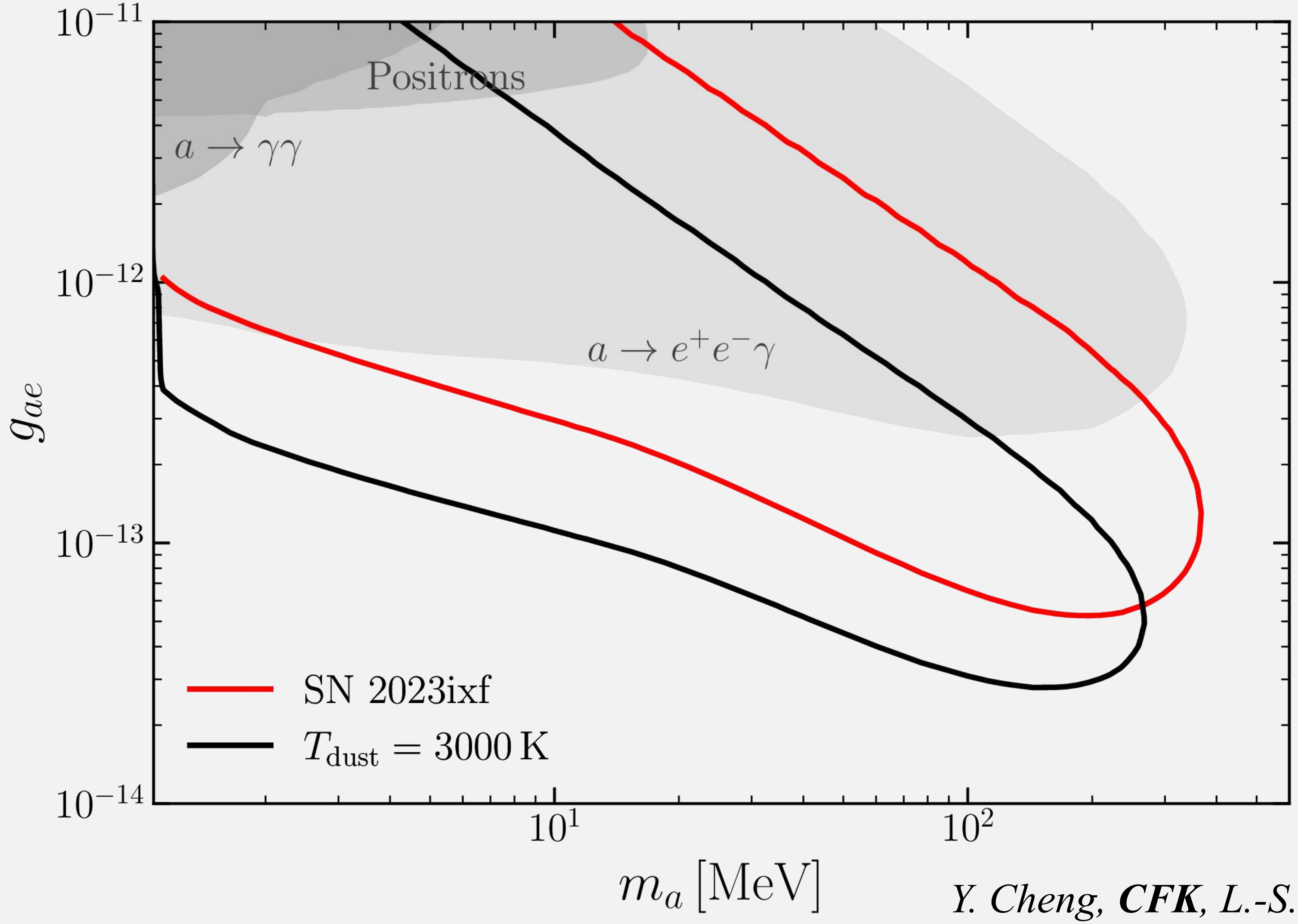
PRL 26

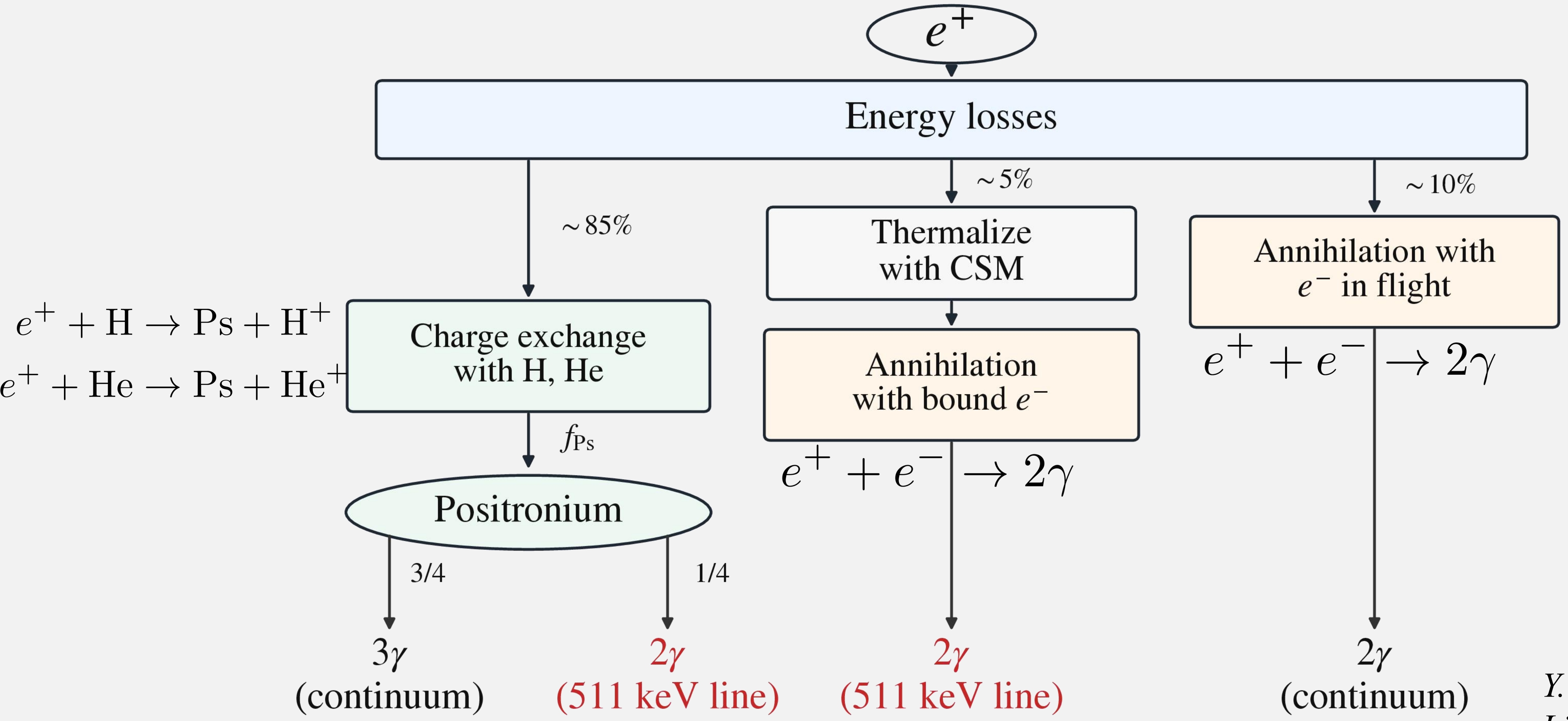
Constraint on Axion-Electron Coupling



*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun*
in preparation

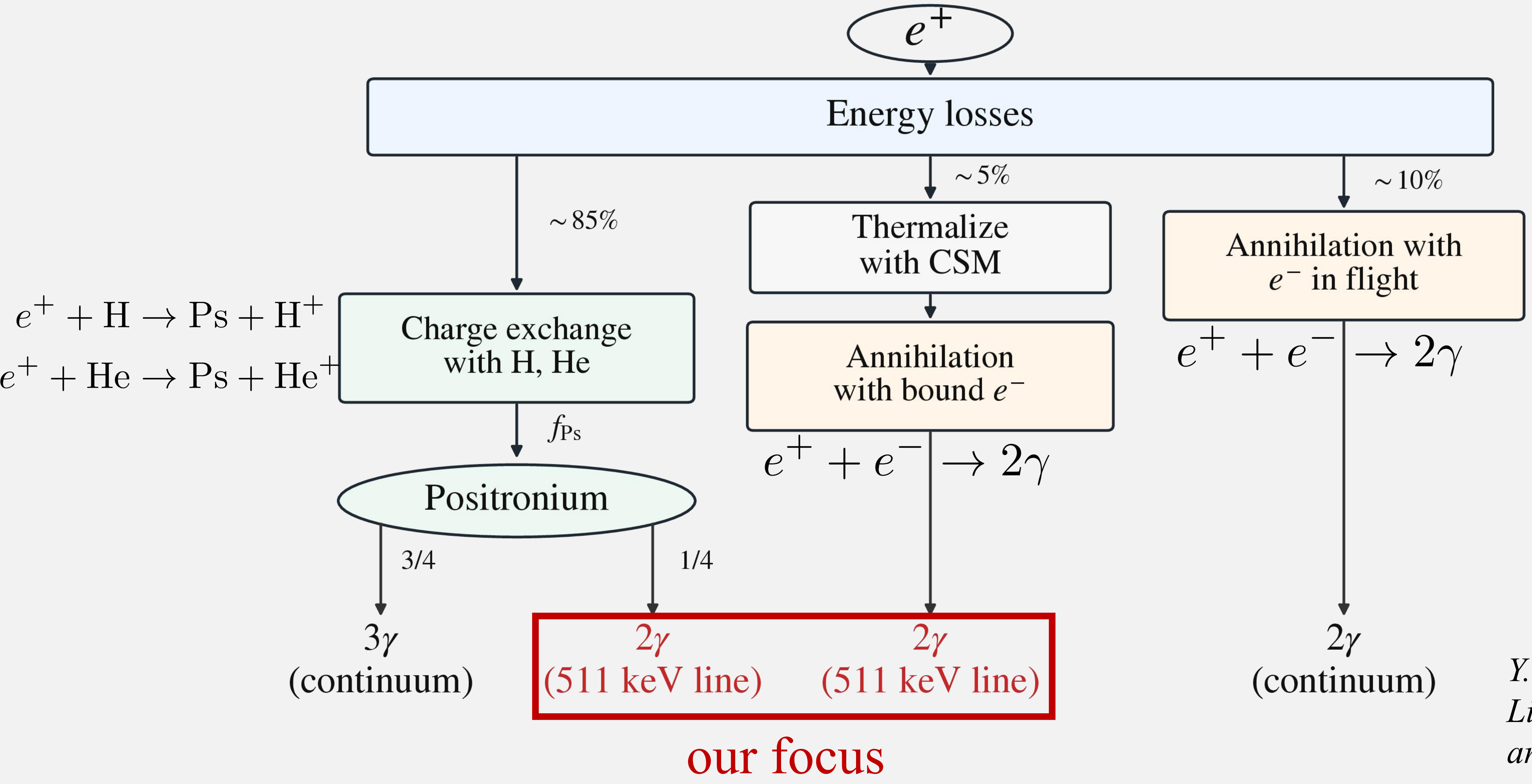
Besides extra BB radiation, what's more?

511 keV Photon Production



*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun arXiv:2609.xxxxx*

511 keV Photon Production



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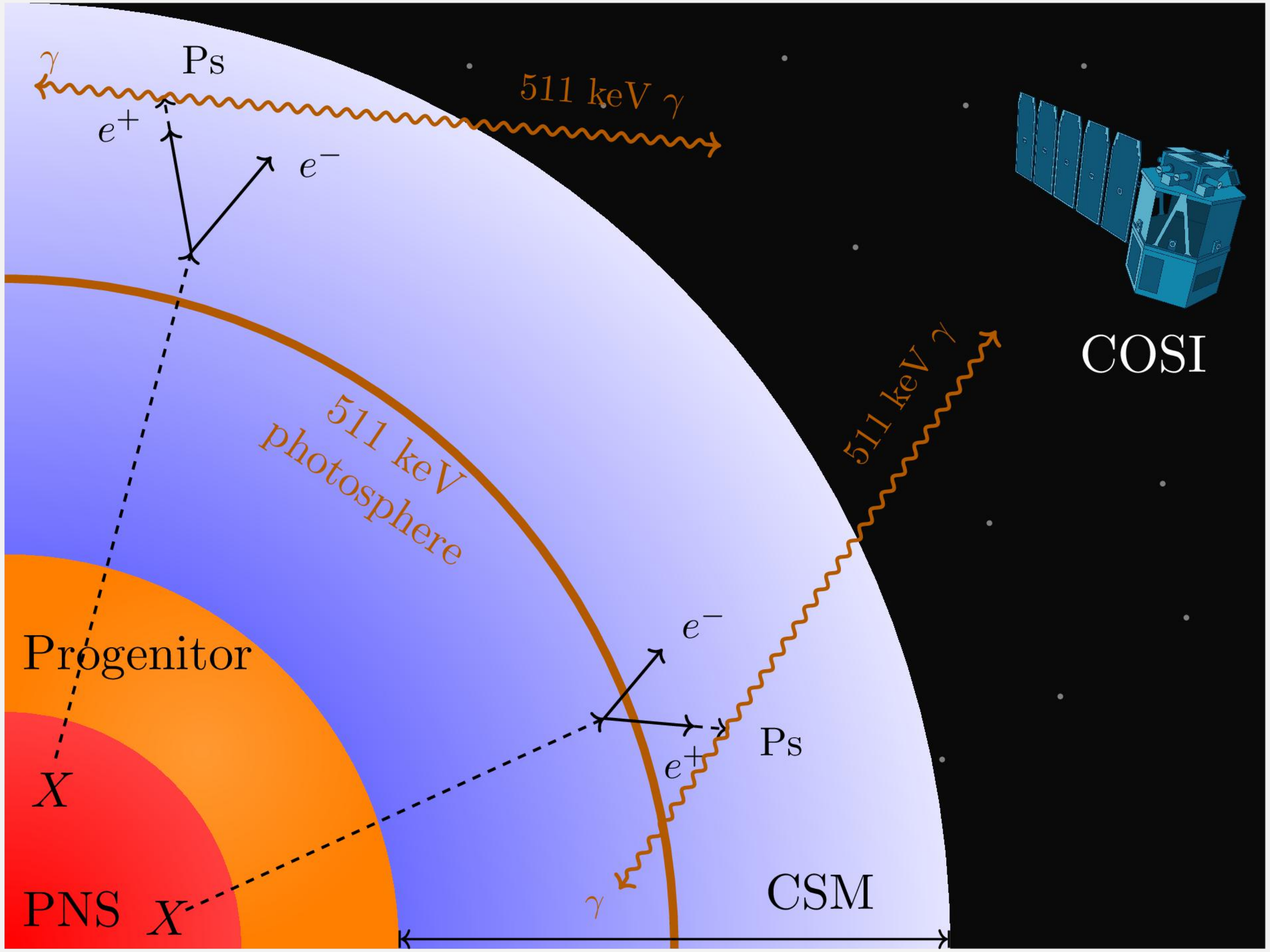
511 keV Photon Production



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511 keV Photon Production

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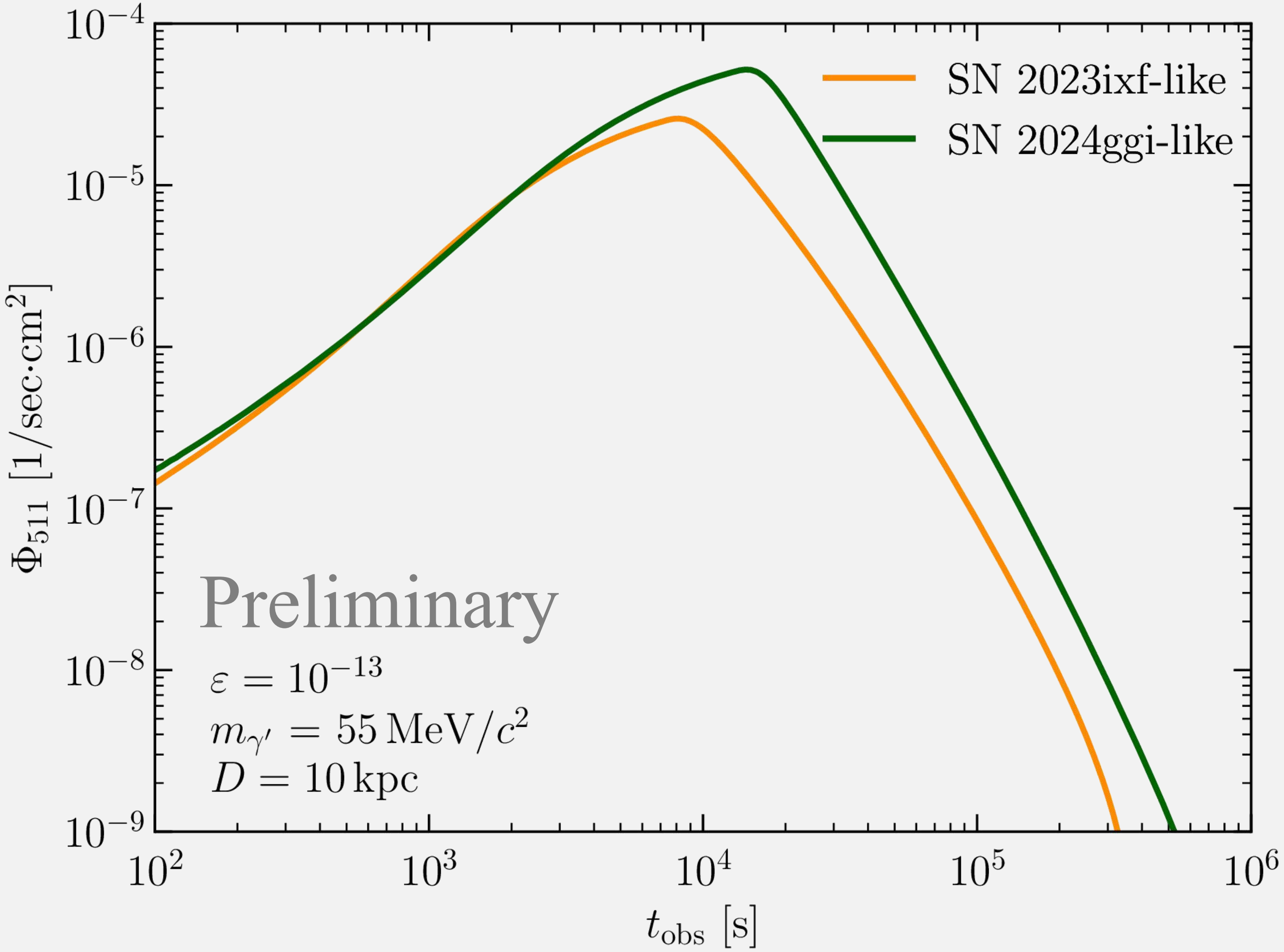

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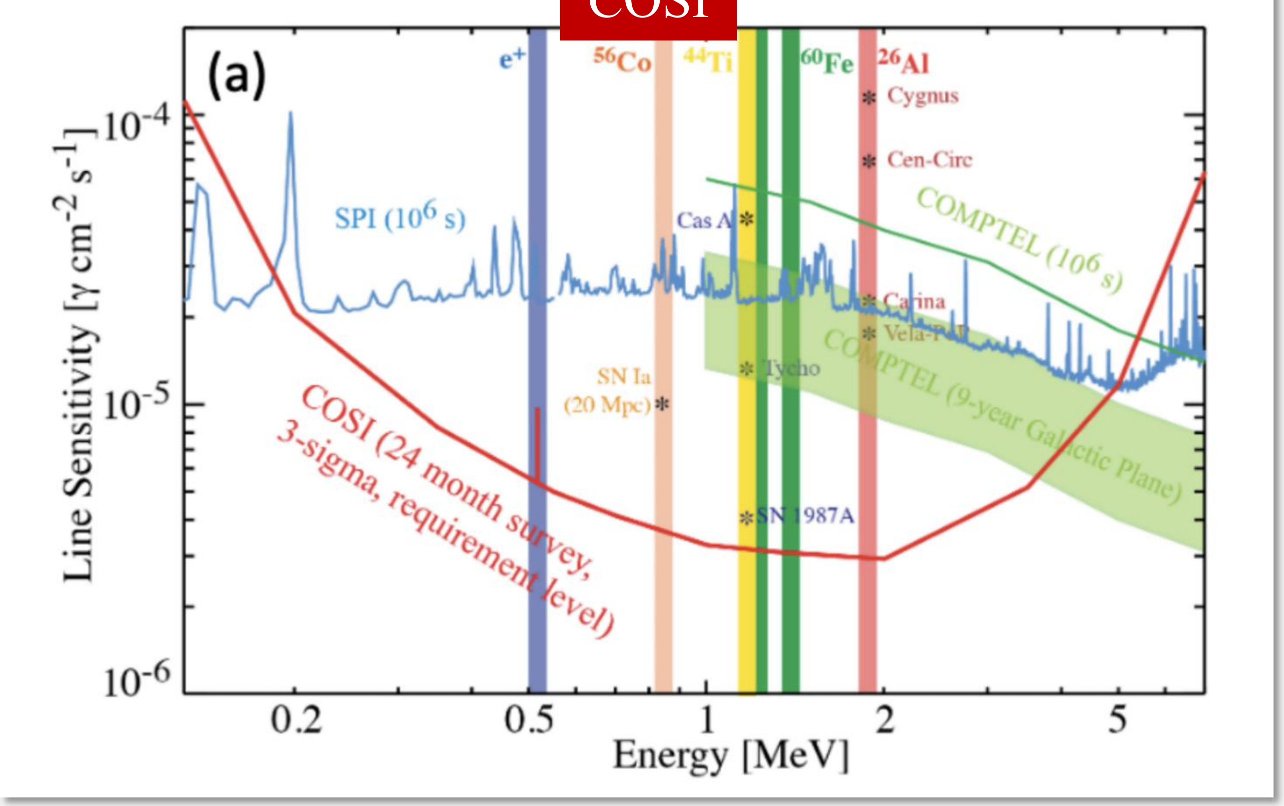
arXiv:2609.xxxxx

Experimental Sensitivities

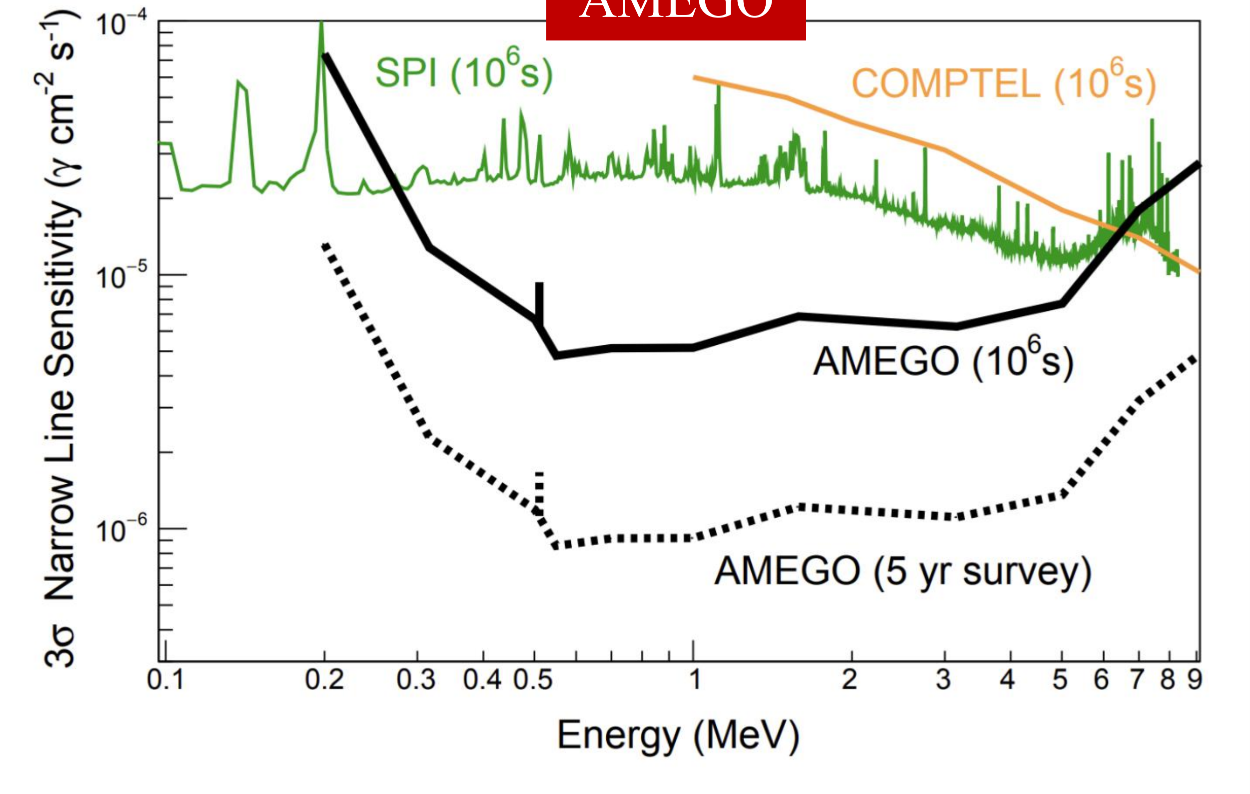
launch planned in 2027

COSI



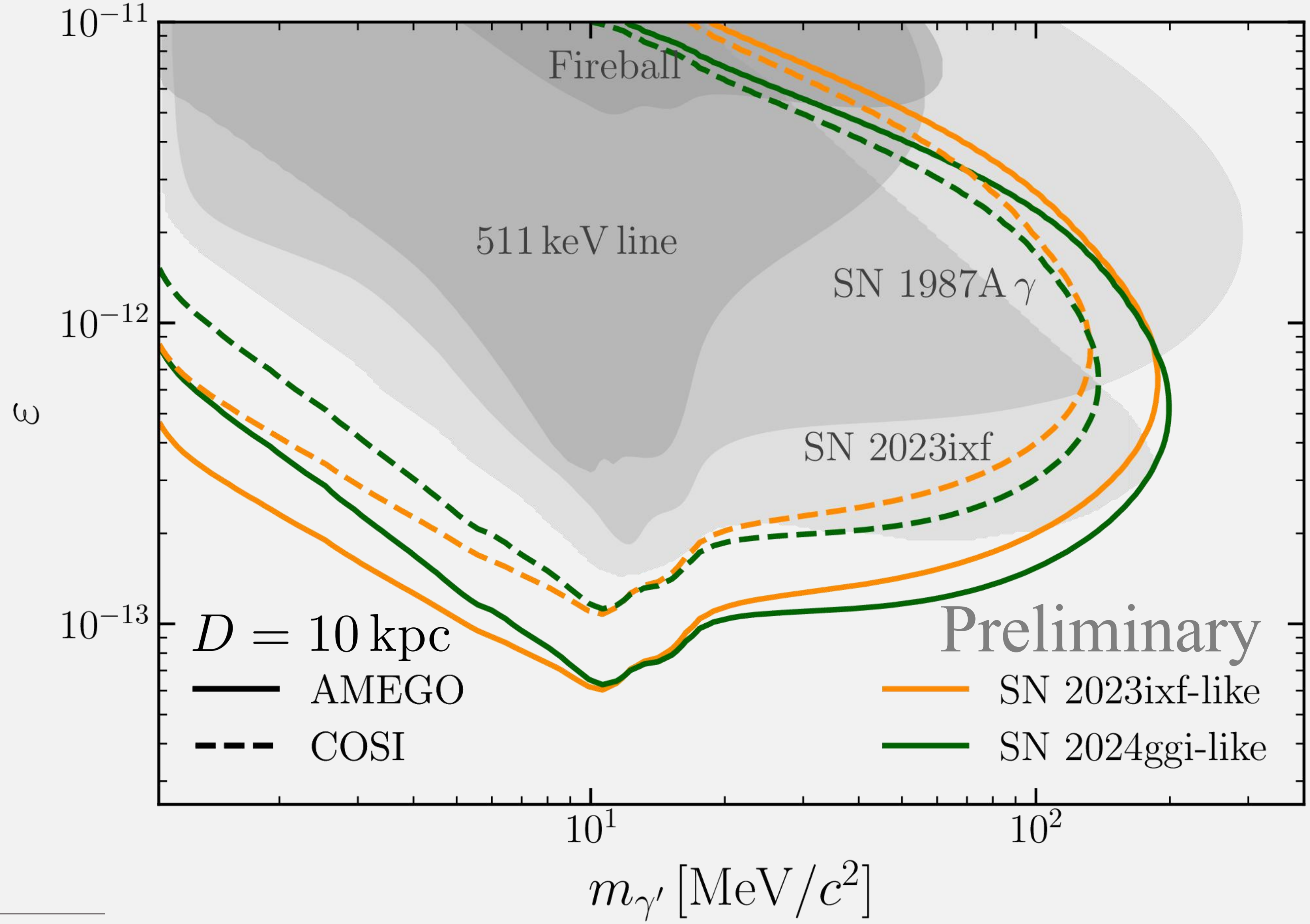
COSI Collaboration arXiv:2308.12362

AMEGO



AMEGO Collaboration arXiv:1907.07558

Projected Constraints from 511 keV Line



*Y. Cheng, **CFK**, L.-S. Lin, M.-R. Wu, S. Yun arXiv:2609.xxxxx*

Summary

- Circumstellar medium (CSM) exists in the outsphere of SN
- CSM can be 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
- 511 keV line search can also put a strong projected contraint

Summary

- Circumstellar medium (CSM) exists in the outsphere of SN
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Thank you for your attention!

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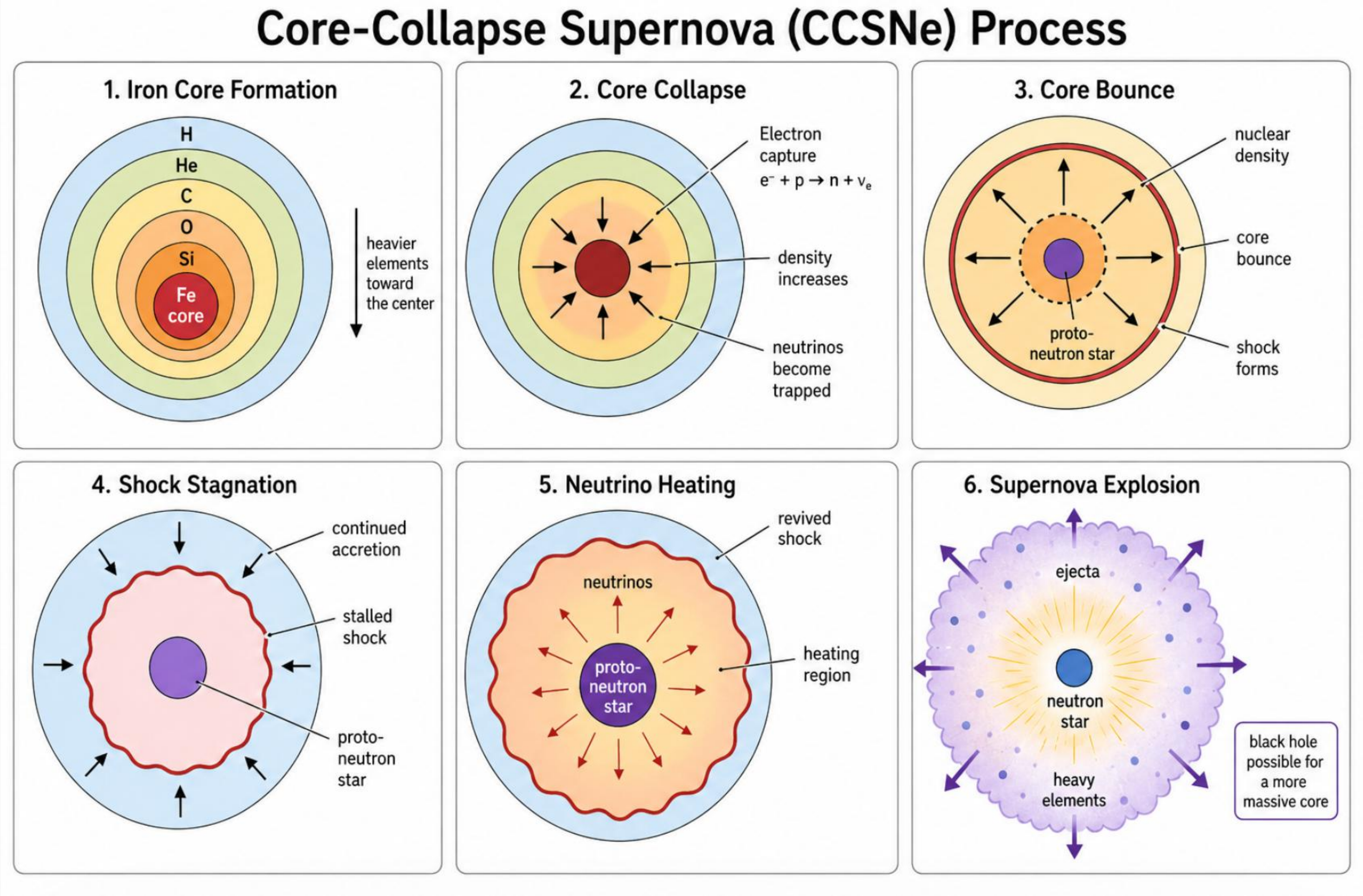
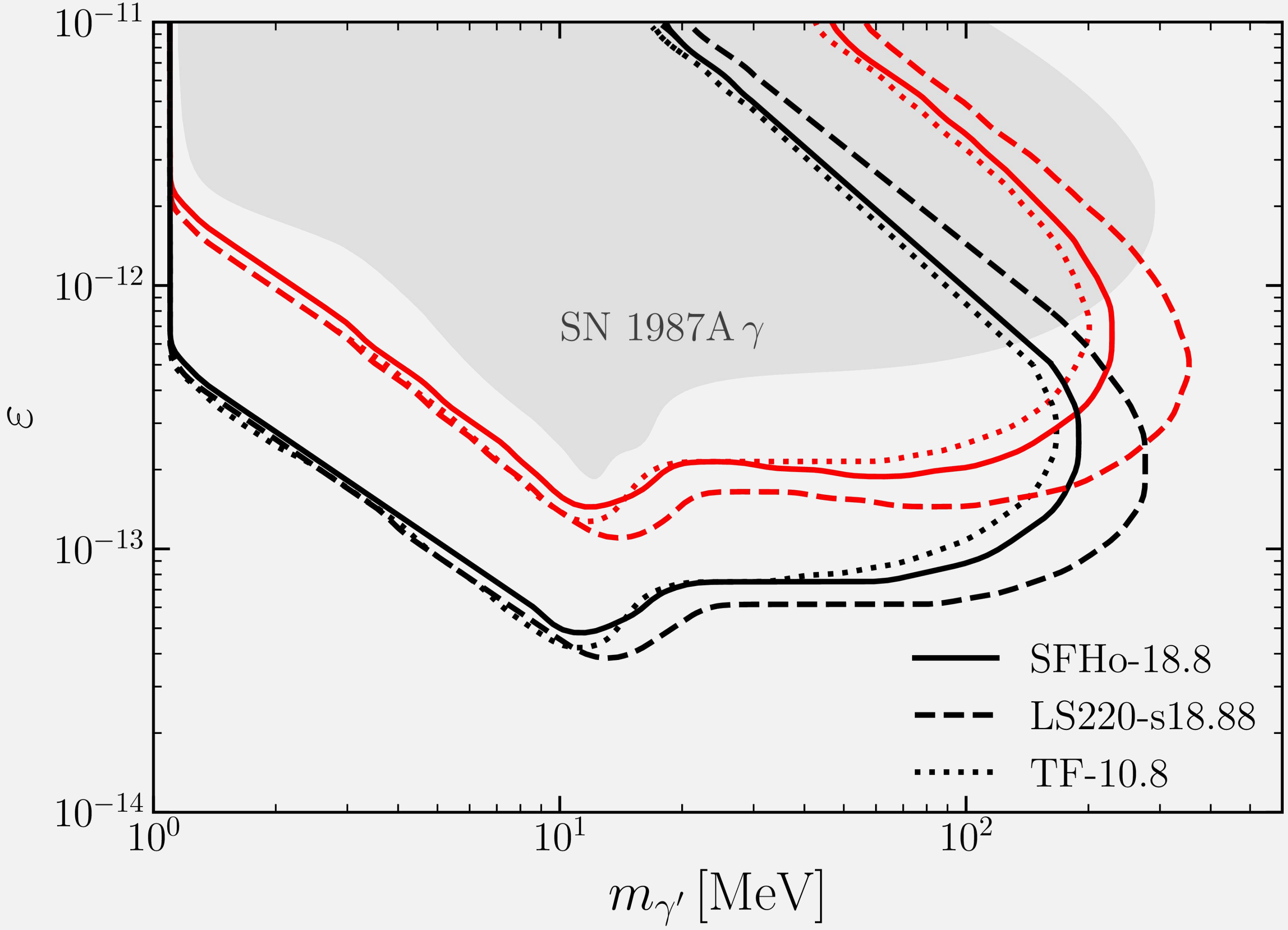
Back up

SN



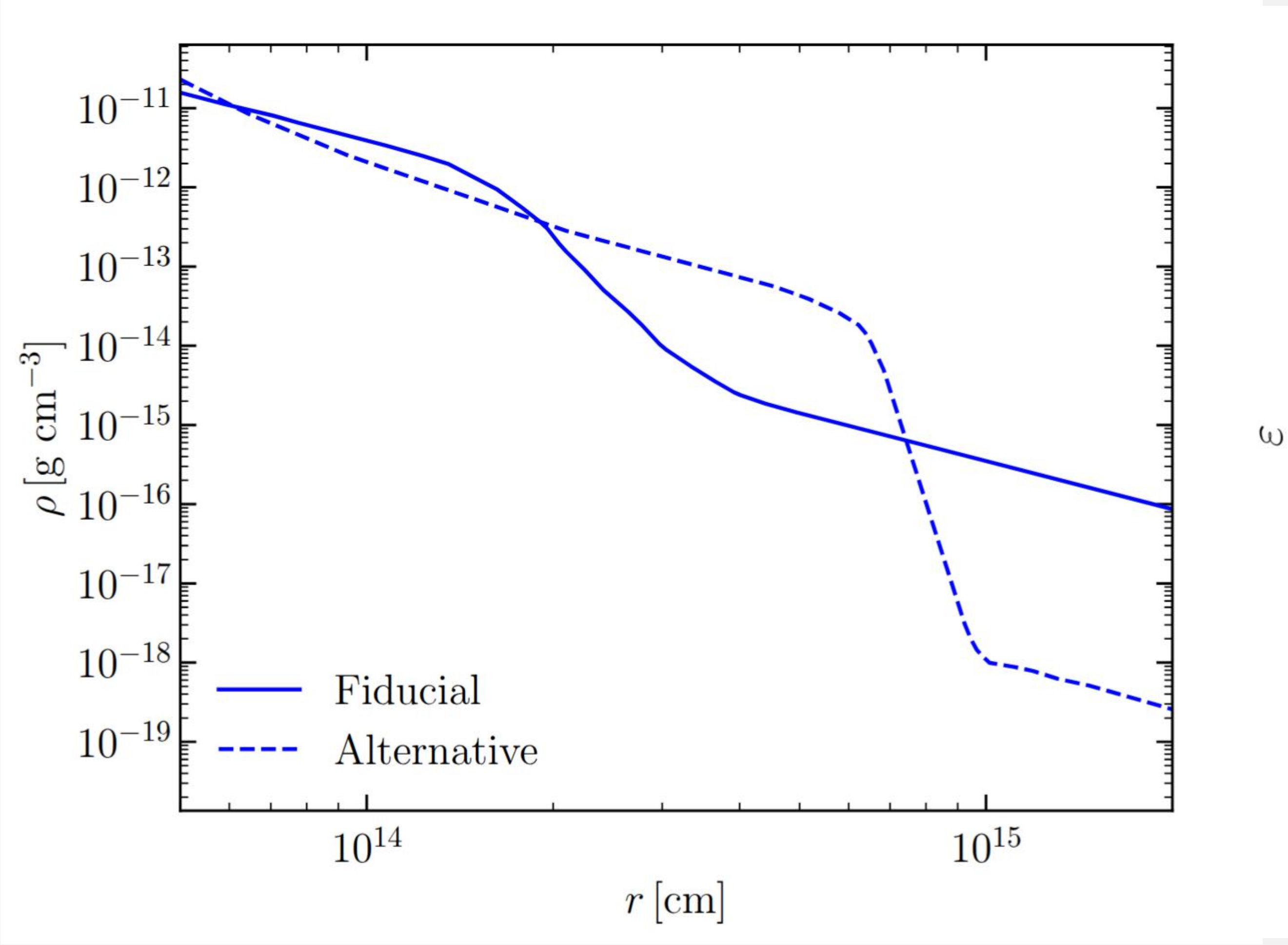
Core-Collapse Supernova (CCSNe) Process
1. Iron Core Formation
H
He
C
O
Si
Fe core
heavier elements toward the center
2. Core Collapse
Electron capture
e⁻ + p → n + νe
density increases
neutrinos become trapped
3. Core Bounce
nuclear density
core bounce
shock forms
proto-neutron star
4. Shock Stagnation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

Back up

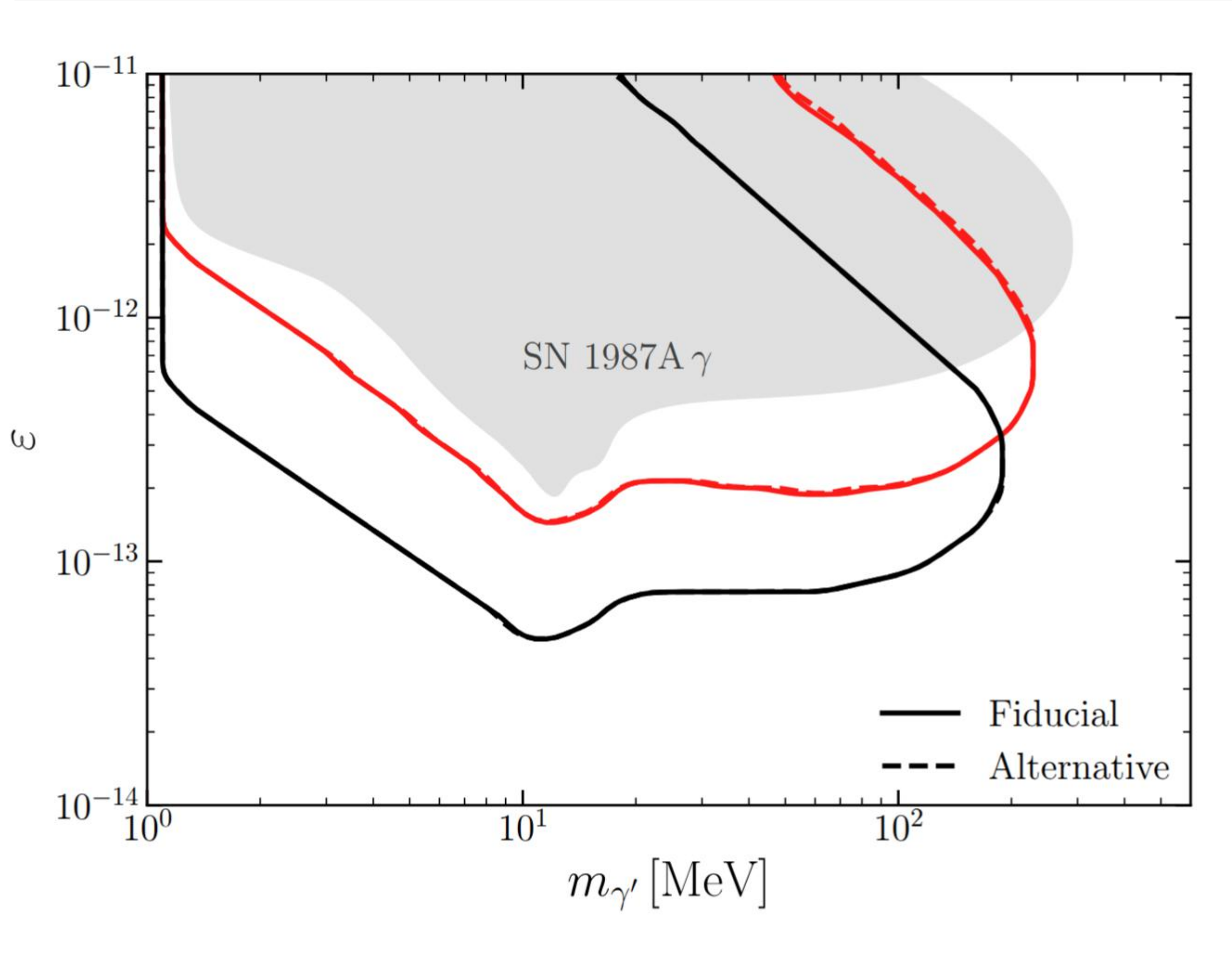


10^{-11}
10^{-12}
10^{-13}
10^{-14}
ε
SN 1987A γ
SFHo-18.8
LS220-s18.88
TF-10.8
10^{0}
10^{1}
10^{2}
$m_{\gamma'}$ [MeV]

Back up

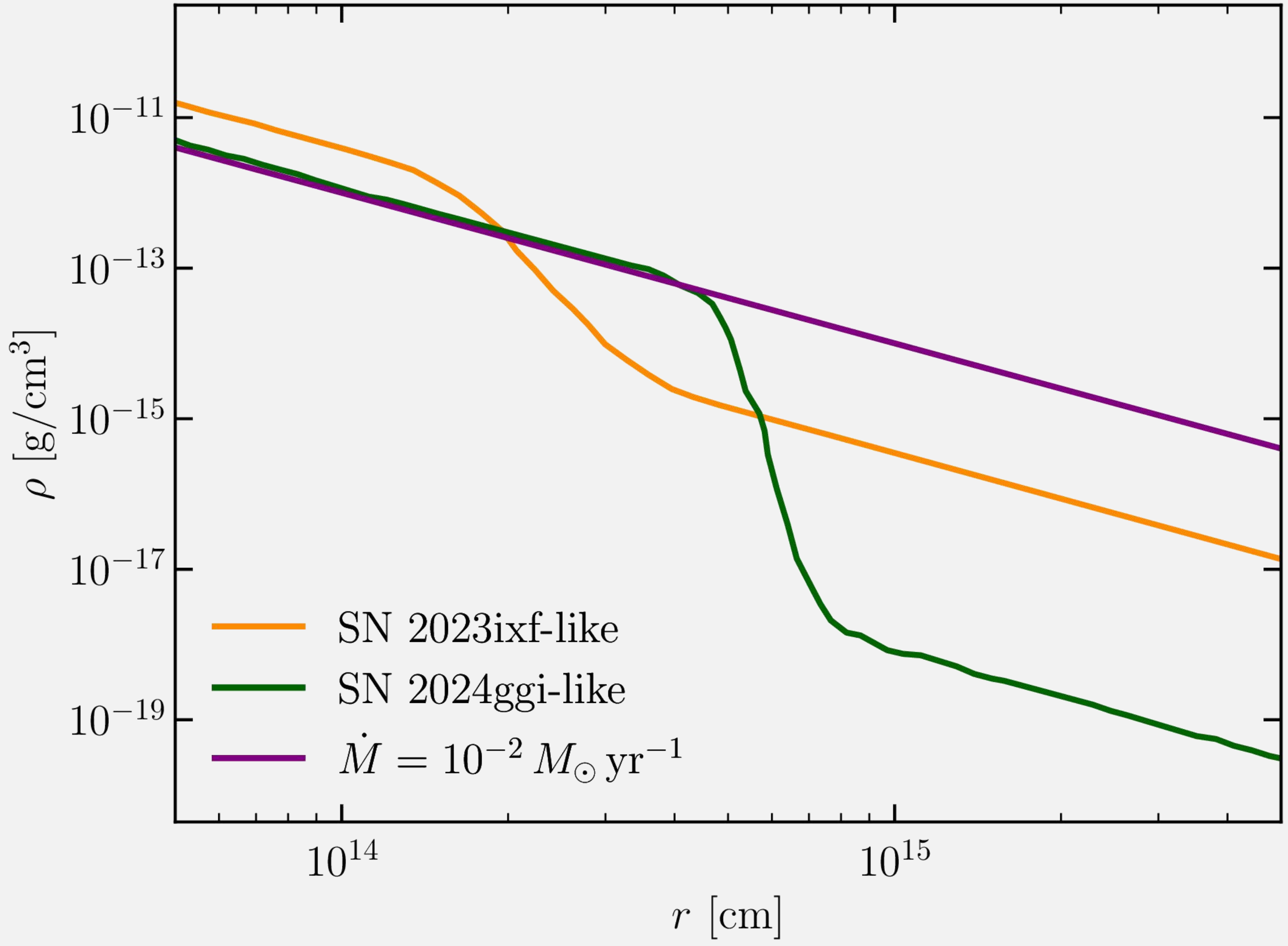


10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
$\rho\,[\mathrm{g\ cm^{-3}}]$
10^{14}
10^{15}
$r\,[\mathrm{cm}]$
Fiducial
Alternative



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

Back up



10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
ρ [g/cm^3]
10^{14}
10^{15}
r [cm]
SN 2023ixf-like
SN 2024ggi-like
$\dot{M} = 10^{-2}\, M_\odot\, \mathrm{yr}^{-1}$

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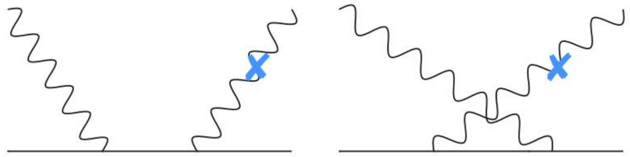
$$\mathcal{L}_{\rm DP} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{\gamma'}}{2}A'_\mu A'^\mu + eA_\mu J^\mu_{\rm EM}$$

Back up

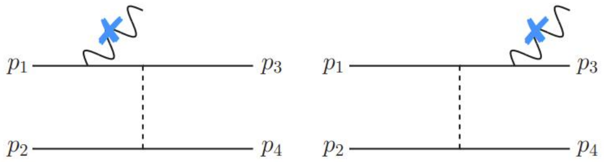
SN γ' production

- *Electrons* in highly degenerate and relativistic limit
  - $p_F \sim 0.1\text{-}1\,\text{fm}^{-1} \gg T \sim 1\text{-}10\,\text{MeV}$
  - Pauli blocking makes processes associated with electrons (e.g., $e + \gamma \to e + \gamma'$)



➡ $R > R_{\text{core}}$

- *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)



$+ \quad \cdots$ ➡ $R < R_{\text{core}}$

from Seokhoon Yun's slides

Back up

Explosion energy = Ejecta kinetic energy

Back up

Survival probability

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Table 1. Energy threshold of reactions induced by positrons.

Process	Threshold (eV)	
$e^+ + H \to Ps + H^+$	6.8	charge exchange
$e^+ + H \to e^+ + e^- + H^+$	13.6	ionization
$e^+ + H \to e^+ + H^*$	10.2	excitation
$e^+ + H \to e^+ + H^{**}$	12.1	excitation
$e^+ + He \to Ps + He^+$	17.8	charge exchange
$e^+ + He \to e^+ + e^- + He^+$	24.6	ionization
$e^+ + He \to e^+ + He^*$	21.2	excitation
$e^+ + H_2 \to Ps + H_2^+$	8.6	charge exchange
$e^+ + H_2 \to e^+ + e^- + H_2^+$	15.4	ionization
$e^+ + H_2 \to e^+ + H_2^*$	12.0	excitation

Back up

$$S(T_{\rm win}) = S_{\rm ref}\left(\frac{T_{\rm ref}}{T_{\rm win}}\right)^{1/2}$$