The Heavy Dark Photon: Cosmological and Astrophysical Bounds revised

Jaeyoung Park(Seoul National University)

with Andrea Caputo(CERN), Francesco D'Eramo(University of Padova) and Seokhoon Yun(IBS,CTPU-PTC)

Work in progress

Dark Photon

-One of the simple extension of Standard Model

$$\Delta \mathcal{L} = -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{\varepsilon}{2} F_{\mu\nu} F'^{\mu\nu} + \frac{m^2_{\gamma'}}{2} A'_\mu A'^\mu \Rightarrow \varepsilon e A'_\mu J^\mu_{\text{EM}}$$

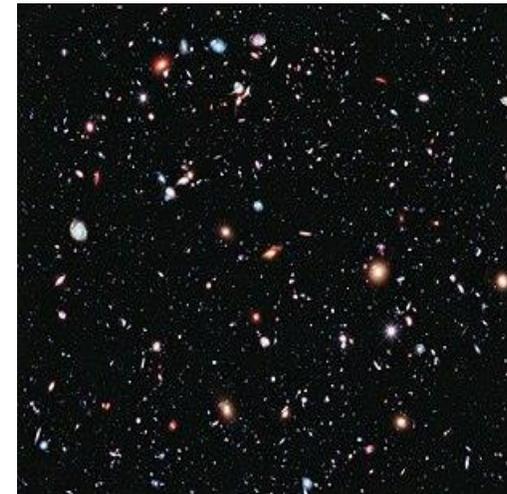|			
$A_\mu{}'$	Dark photon field	$F'_{\mu\nu}$	Dark photon field strength
$m_{\gamma'}$	Dark photon mass	ε	Kinetic mixing parameter

MeV Dark Photon

Supernovae as dark photon factory

- Internal temperature $T \sim$ MeV
- Dark photon modifies supernova observables
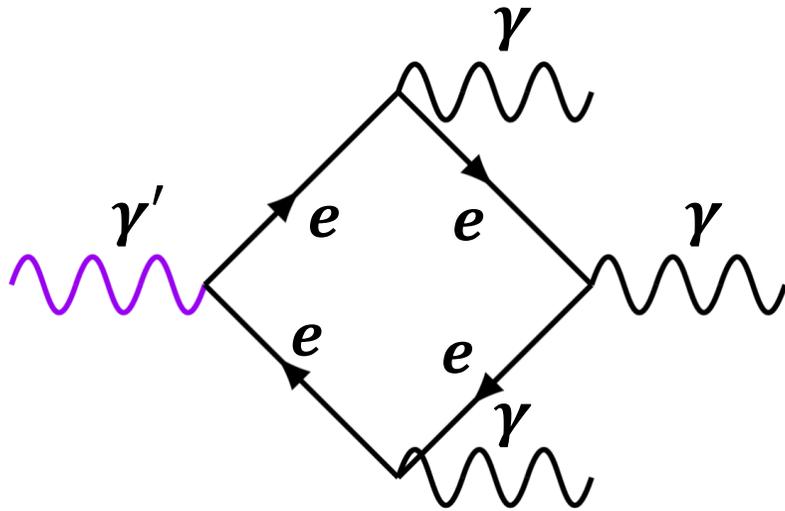

Dark photon in the early universe

- Reheating temperature $\geq O(1)$ MeV
- Thermal production until $T_{universe} \sim m_{\gamma'}$
- Influence on cosmological phenomena

Pictures from Wikipedia

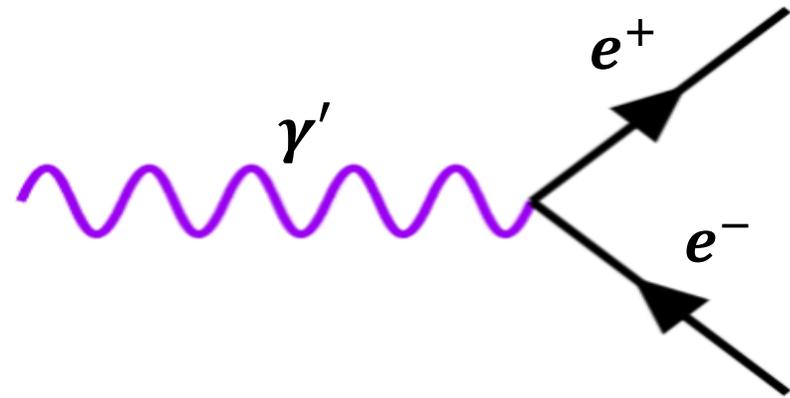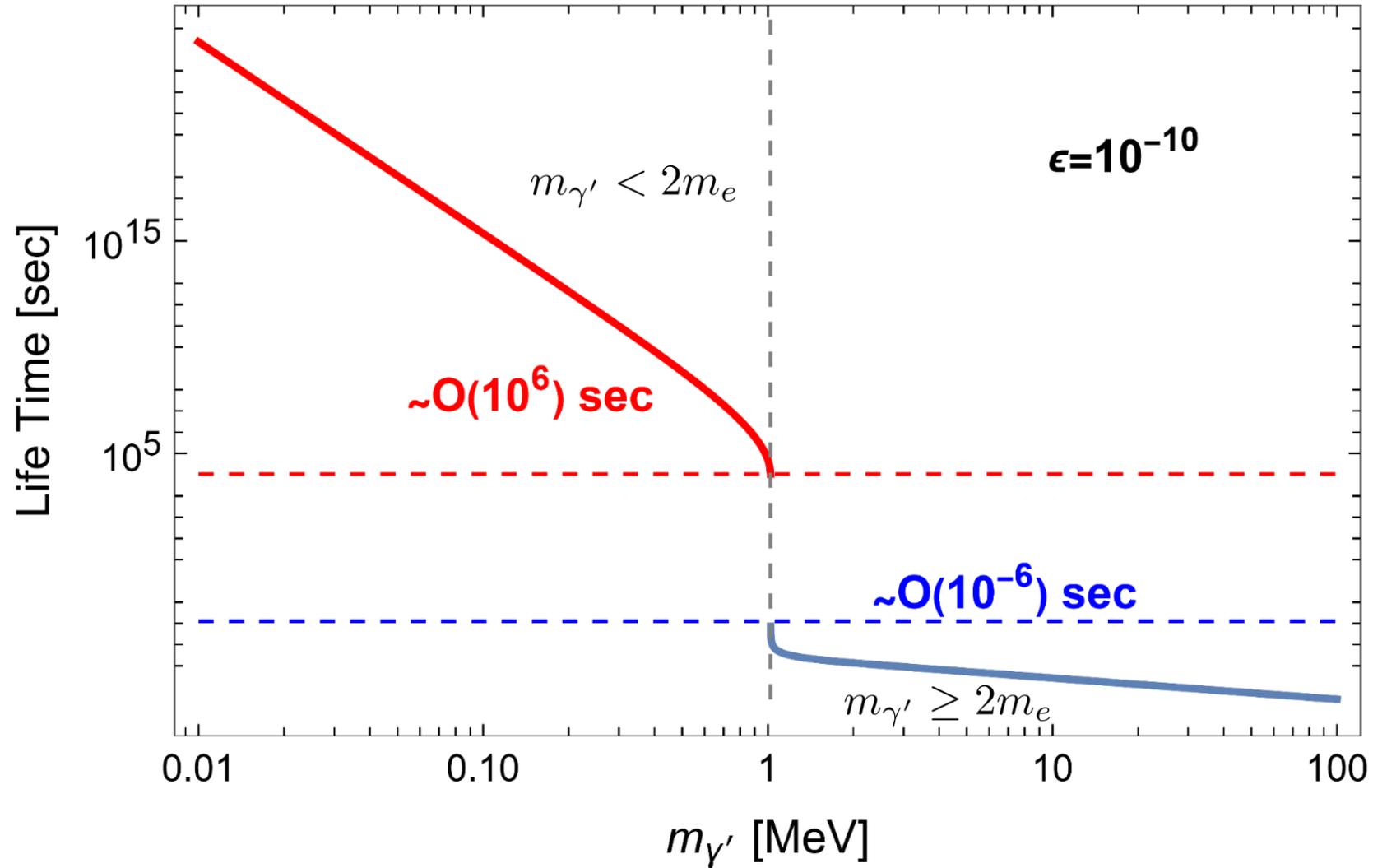# Lifetime of MeV Dark Photon

$m_{\gamma'} < 2m_e$

$$\gamma$$

$$\gamma'$$

$$e \quad e$$

$$\gamma$$

$$e \quad e$$

$$\gamma$$

$$\Gamma \propto \varepsilon^2 \frac{m_{\gamma'}^8}{(2m_e)^8} m_{\gamma'}$$

$m_{\gamma'} \geq 2m_e$

$$\gamma'$$

$$e^+$$

$$e^-$$

$$\Gamma \propto \varepsilon^2 m_{\gamma'}$$

Lifetime of MeV Dark Photon

Plasma effect on Dark Photon

-Plasma effect changes refractive properties of each photon polarization $\pi_{T,L}$ which can be expressed with plasma frequency ω_{pl}

-These changes modify coupling between dark photon and EM current

$$\varepsilon e \frac{m_{\gamma'}^2}{m_{\gamma'}^2 - \pi_{T,L}} A'_\mu J^\mu_{EM}$$

-When $m'_\gamma \approx \text{Re}\, \pi_{T,L}$: effective photon mass, resonant enhancement

Contents

1. Introduction

2. Astrophysical Dark Photons
   -Supernova as dark photon factory
   -Dark photon effect on supernova observables
   :SN Cooling, Low energy explosion, Prompt Gamma ray, Positron injection, Fireball formation, Diffuse Gamma-ray
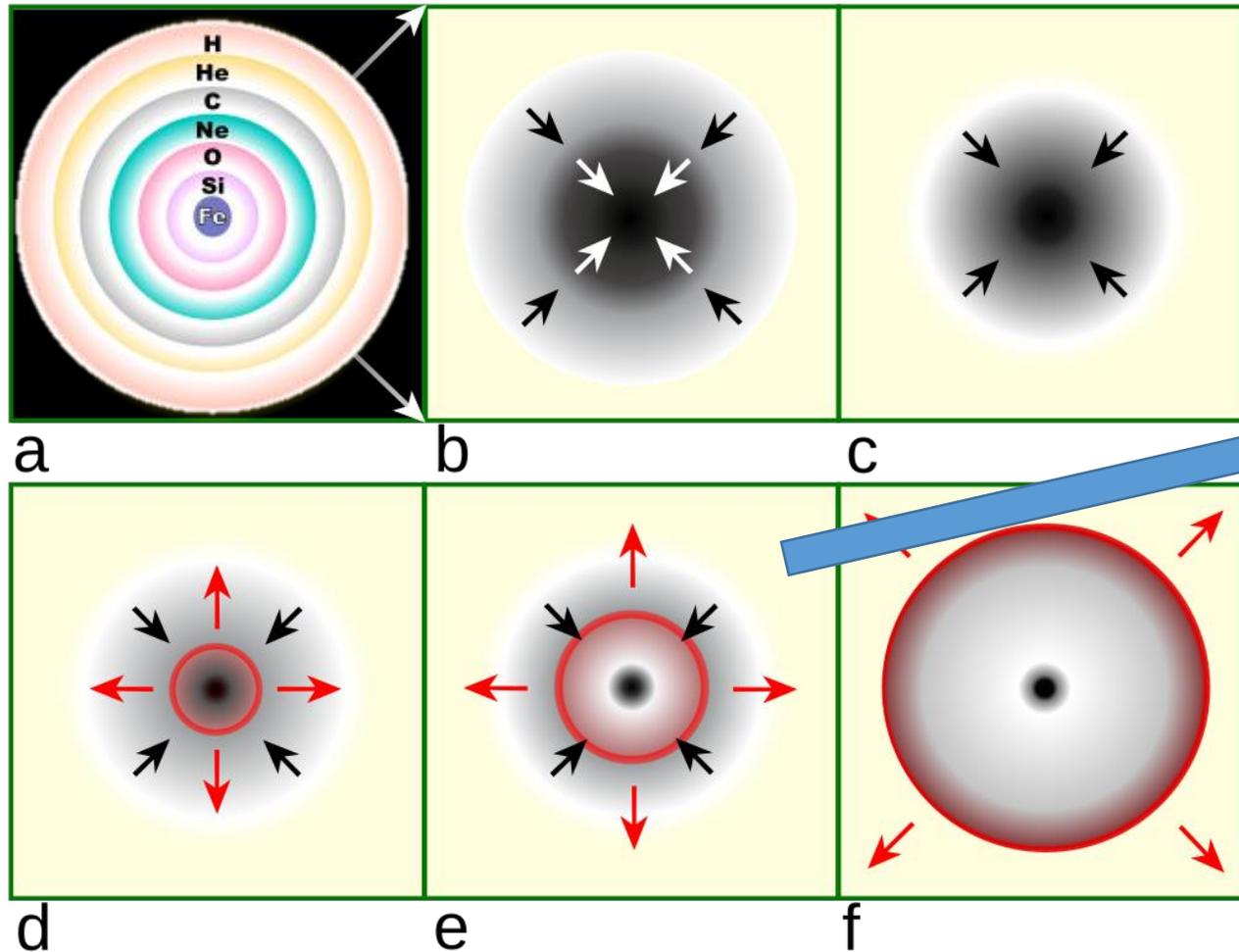
3. Cosmological Dark Photons
   -Dark photon freeze-in abundance
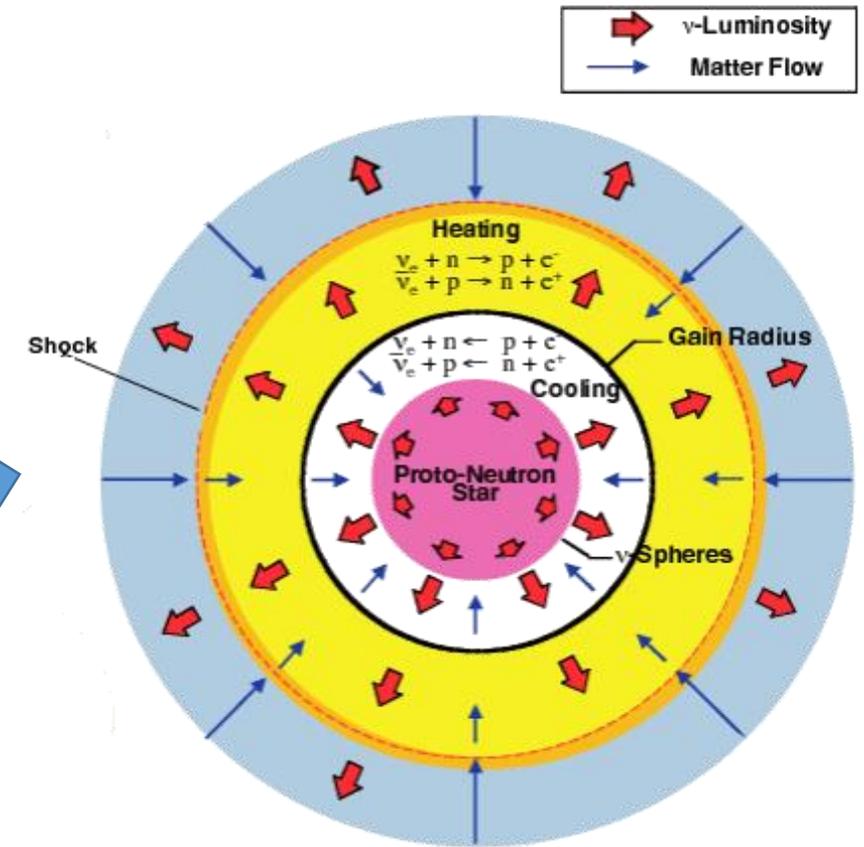   -Astrophysical & Cosmological consequences
   :Extra-/Galactic X-ray & CMB/BBN/ΔN_{eff}

Astrophysical Dark Photons

Core- Collapse SN

Wikipedia, Type II Supernova with modification

Tharrington, Arnold & Messer, Bronson & Hoffman, Forrest. (2006). Overview of NLCF FY 2006 Allocations. CUG Proceedings. 1.

Dark photon in SN

$-T_{PNS} \sim 30$ MeV

-Energetic dark photons from PNS

 decay into SM particles/are absorbed

 in PNS or in mantle(outside of PNS)

 or outside of progenitor star
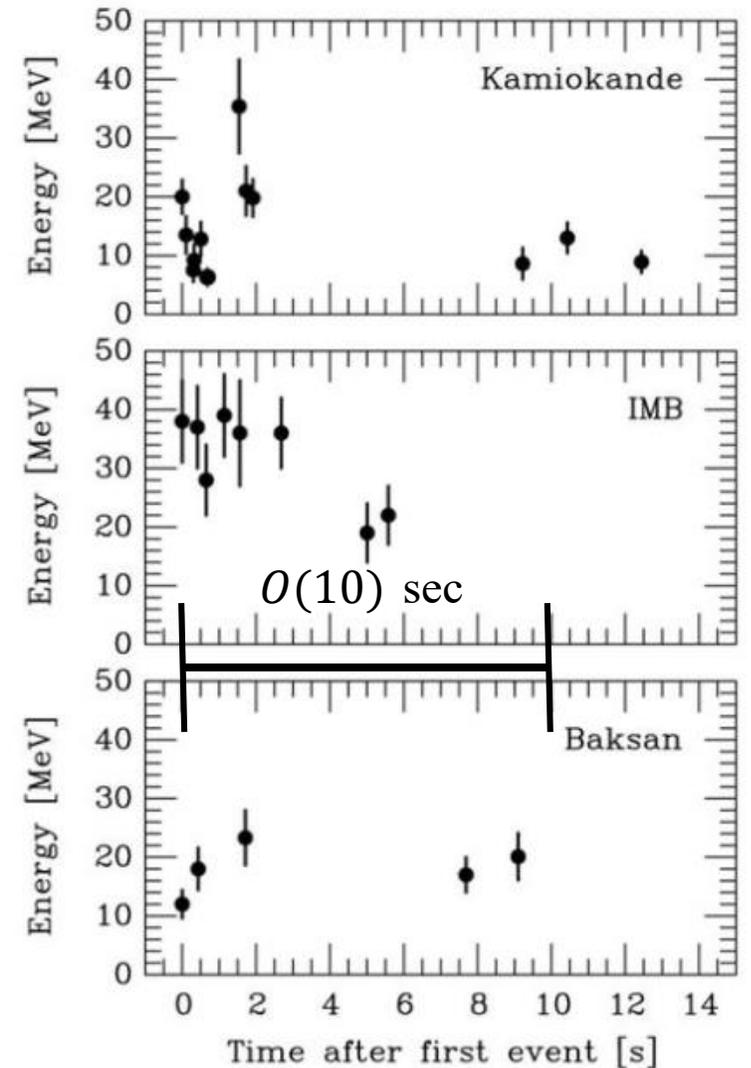
-Dark photon can modify supernova

 observables

SN 1987a Cooling

Additional cooling indicates

shorter time scale of SN neutrino signal:

Raffelt's criterion

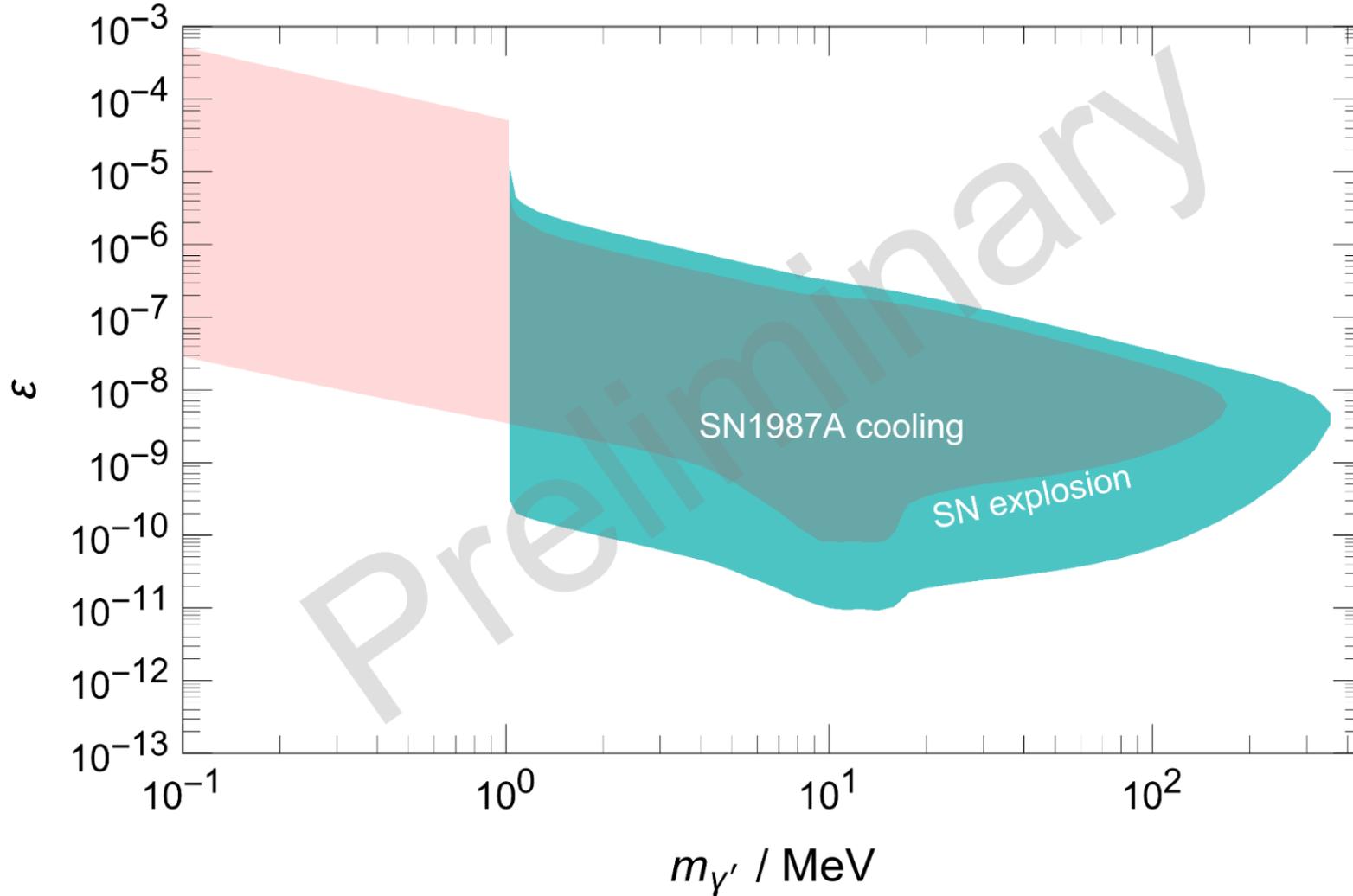$$L_{DP} \leq L_\nu \text{ at 1 sec}$$

SN 1987a Cooling

Low energy SN explosion

-Dark photon might dump its energy in the mantle

-Absorption process is not effective in mantle due
to low density of charged particle

-Low energy SN explosion limits maximal energy
from dark photon decay as $0.1\text{B} = 10^{50}$ erg

-Dark photon should decay
 before SN event end: Decay to e^+e^- pair

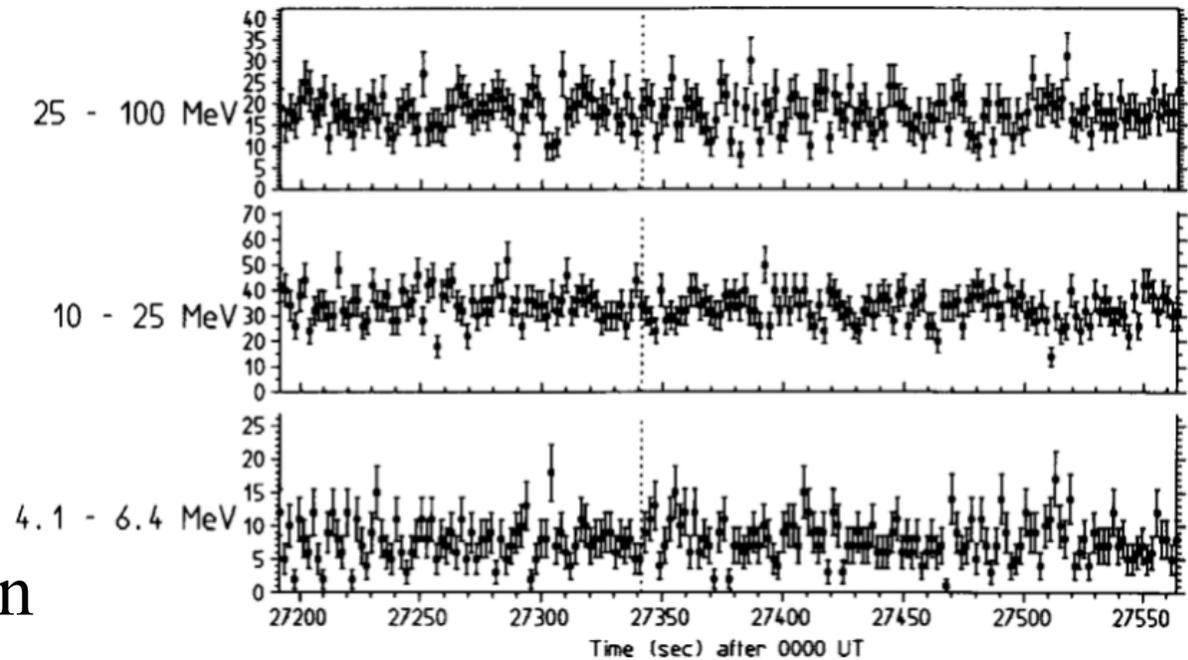$$E_{\text{decay}} \leq 10^{50}\text{erg}$$

Low energy SN explosion

SN 1987a Prompt gamma ray

-Dark photon might decay outside,
which might generate photon(s)
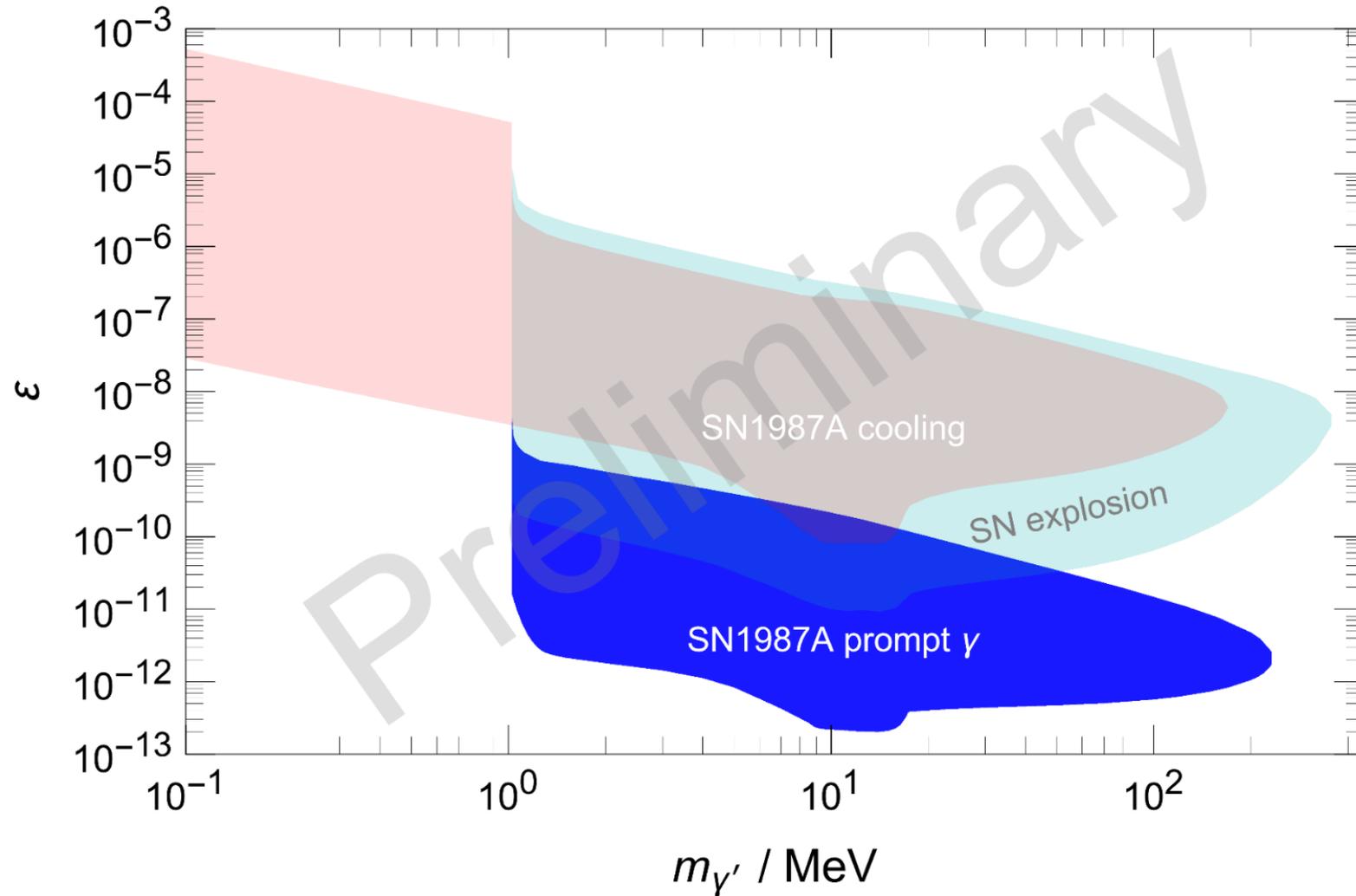
-During SN 1987a event,

 No excess on photon with 1~100
MeV energy

-If DP decay can generate such photon
with certain parameters, it should be
ruled out

L. Oberauer. et.al 1993

SN 1987a Prompt gamma ray
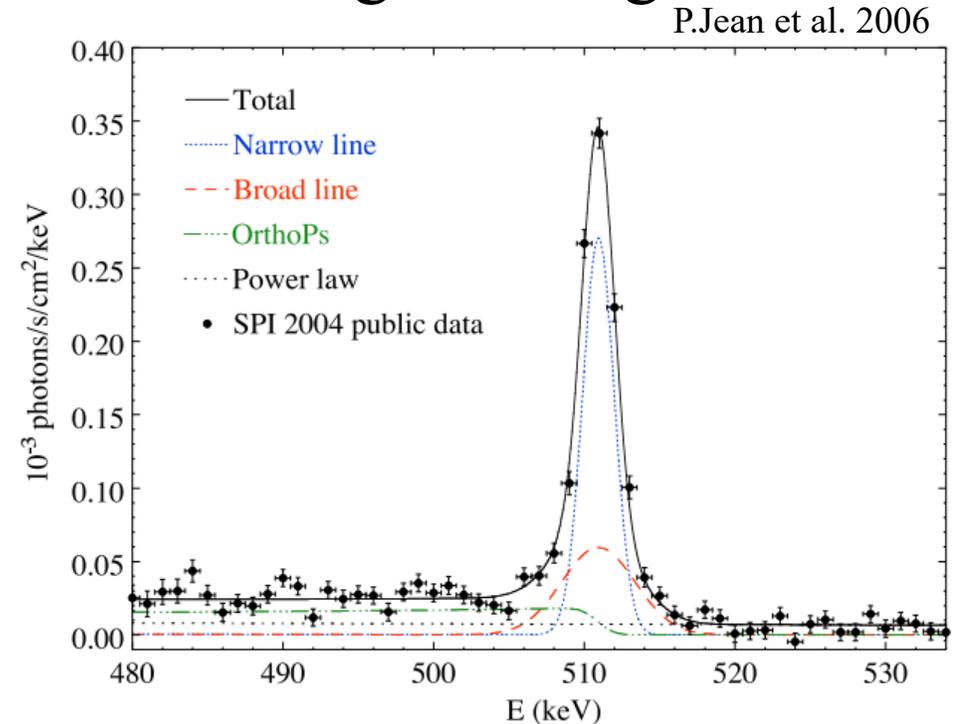
Positron injection

-Along with prompt gamma ray,

dark photon decay at outside of progenitor star can generate galactic
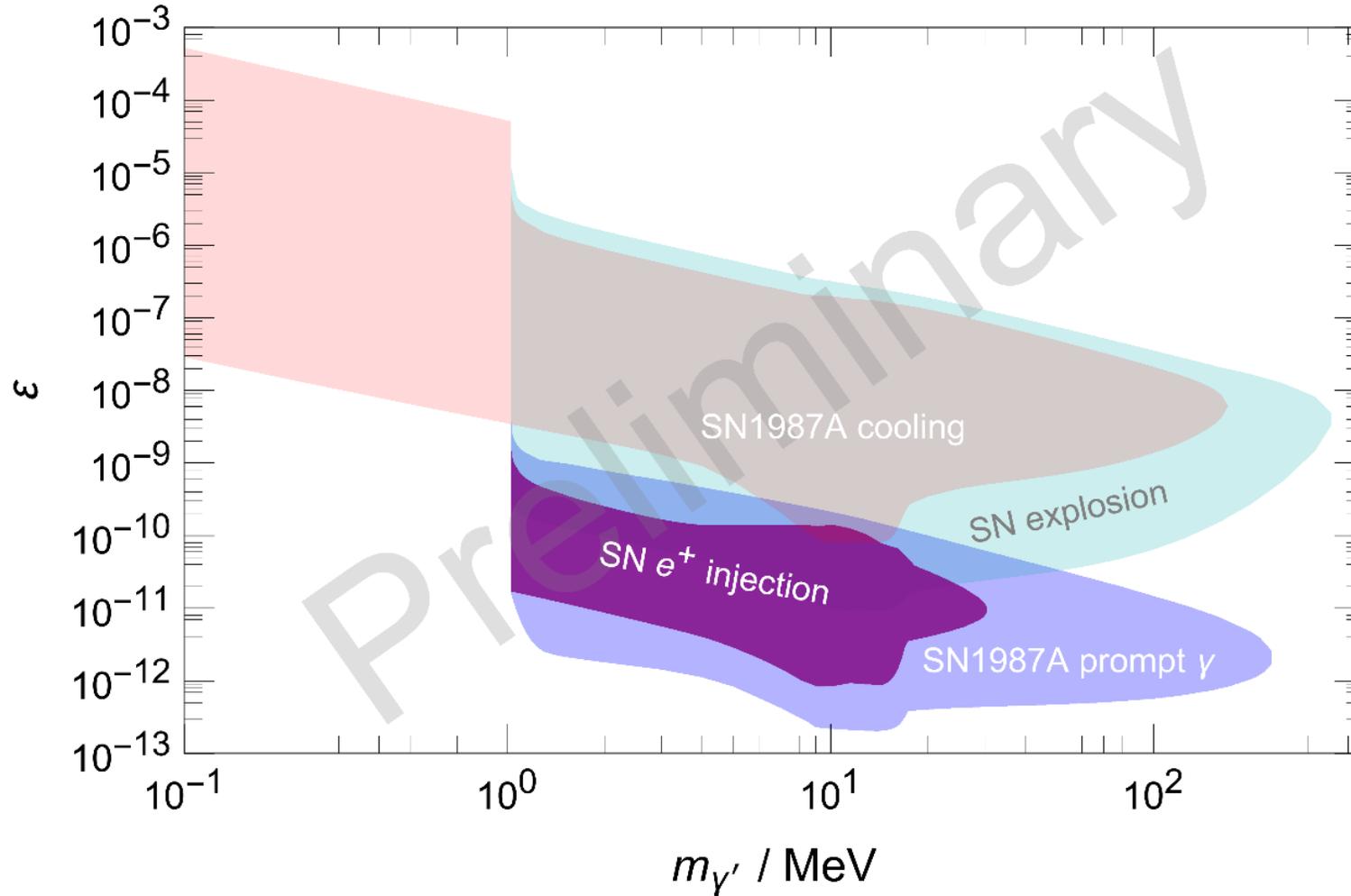
positron injection

-From INTEGRAL/SPI 511 keV line,

 Maximum positron injection rate:

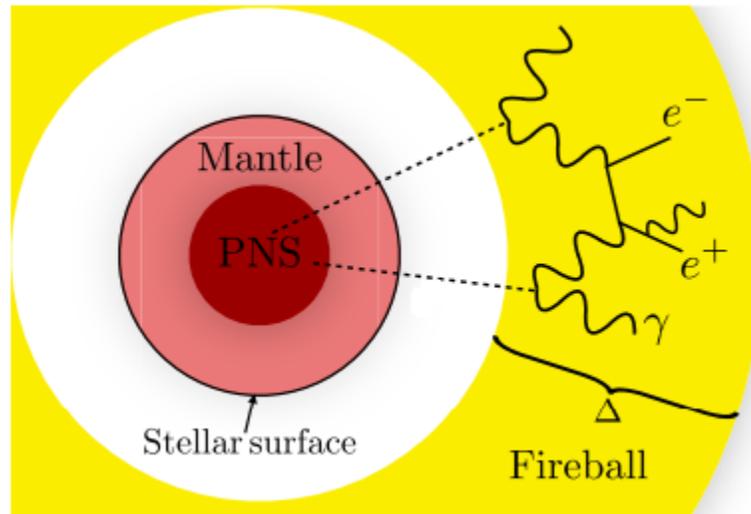$$P_{e^+} \leq O(10^{43}) \ \text{sec}^{-1}$$
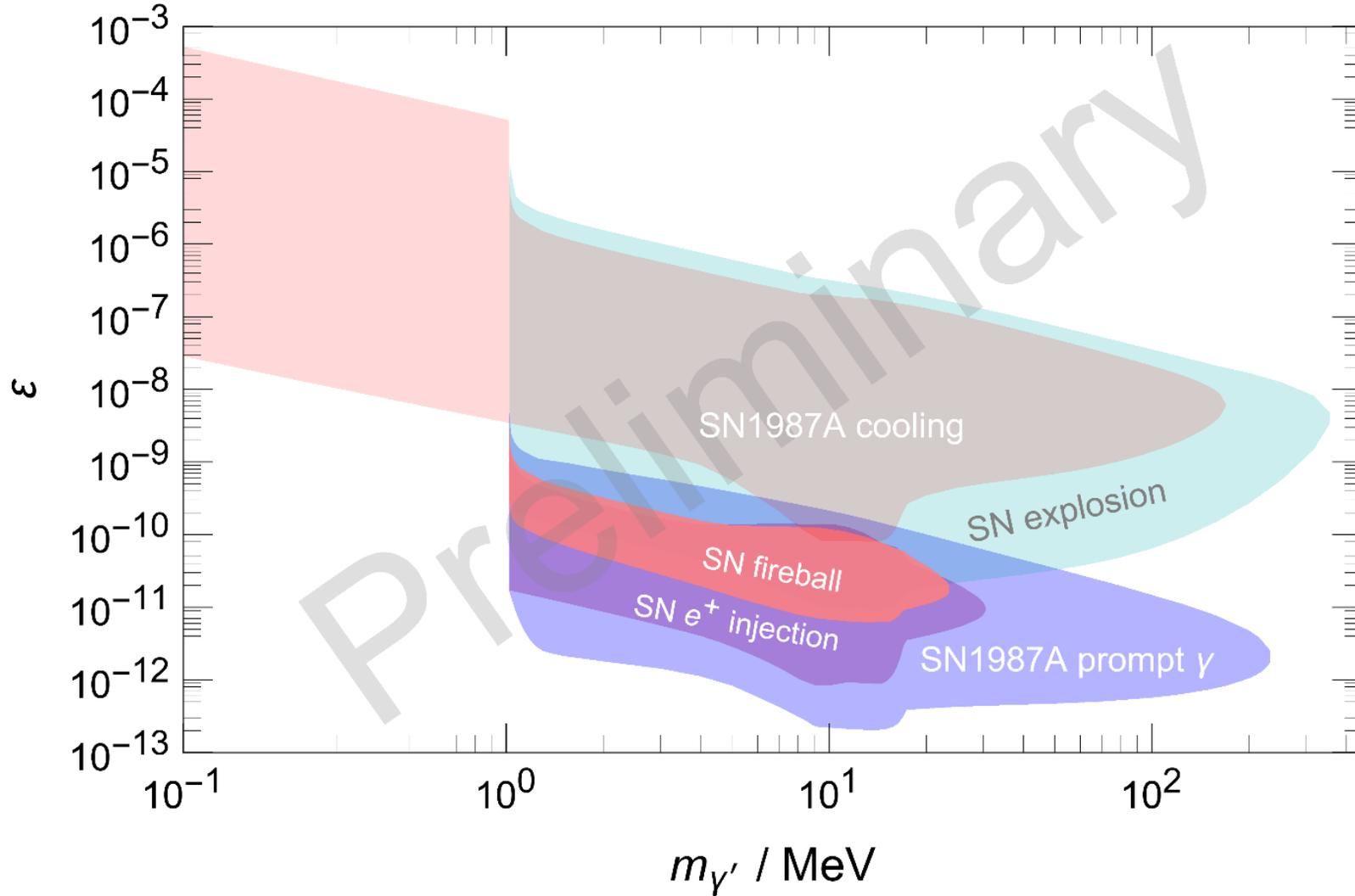
P.Jean et al. 2006

Positron injection

Fireball formation

-Fireball(optically thick plasma) formation might occur around SN

-Fireball changes the estimated photon spectrum and positron injection rate

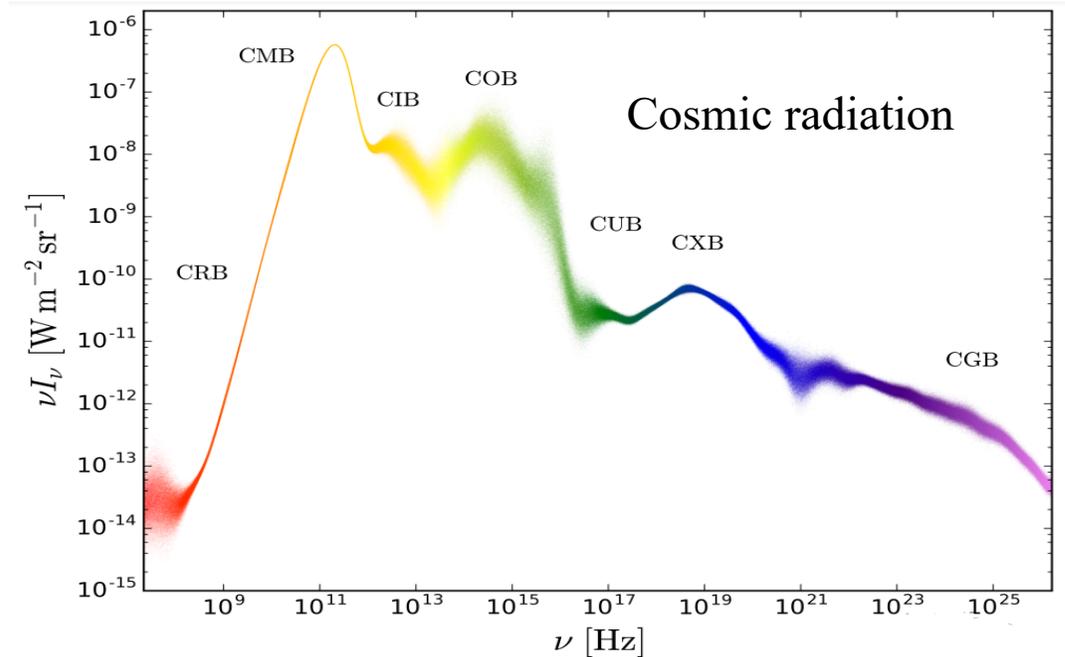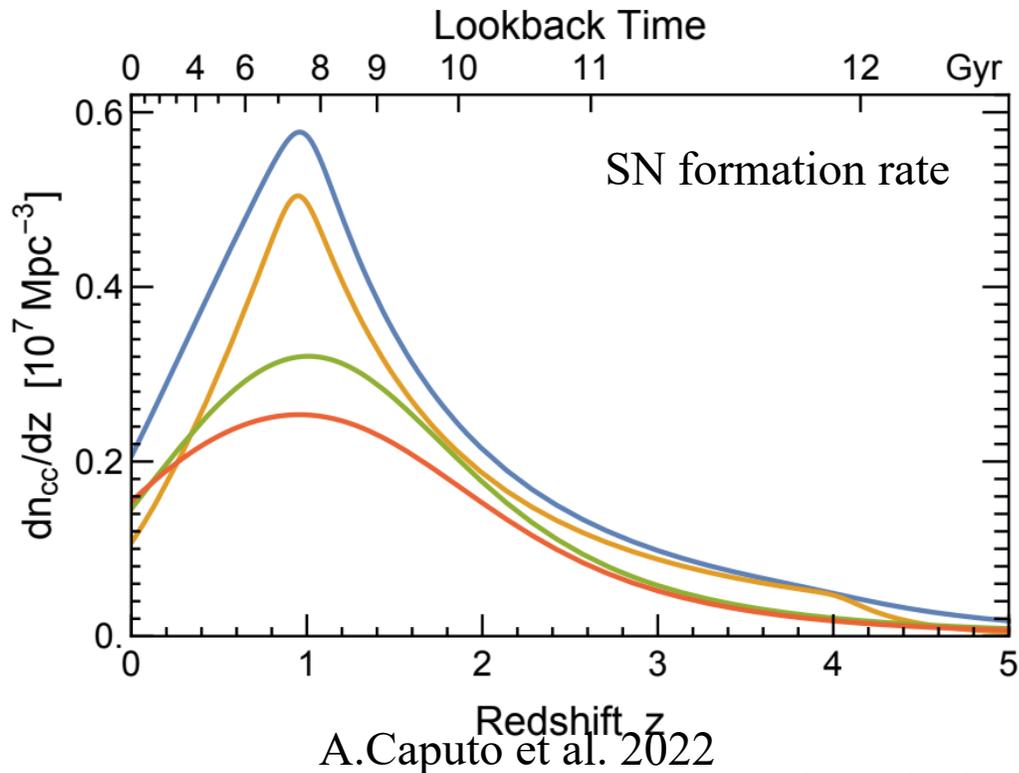-Pierre Venus Orbiter(PVO) indicated SN1987a event excludes the fireball formation

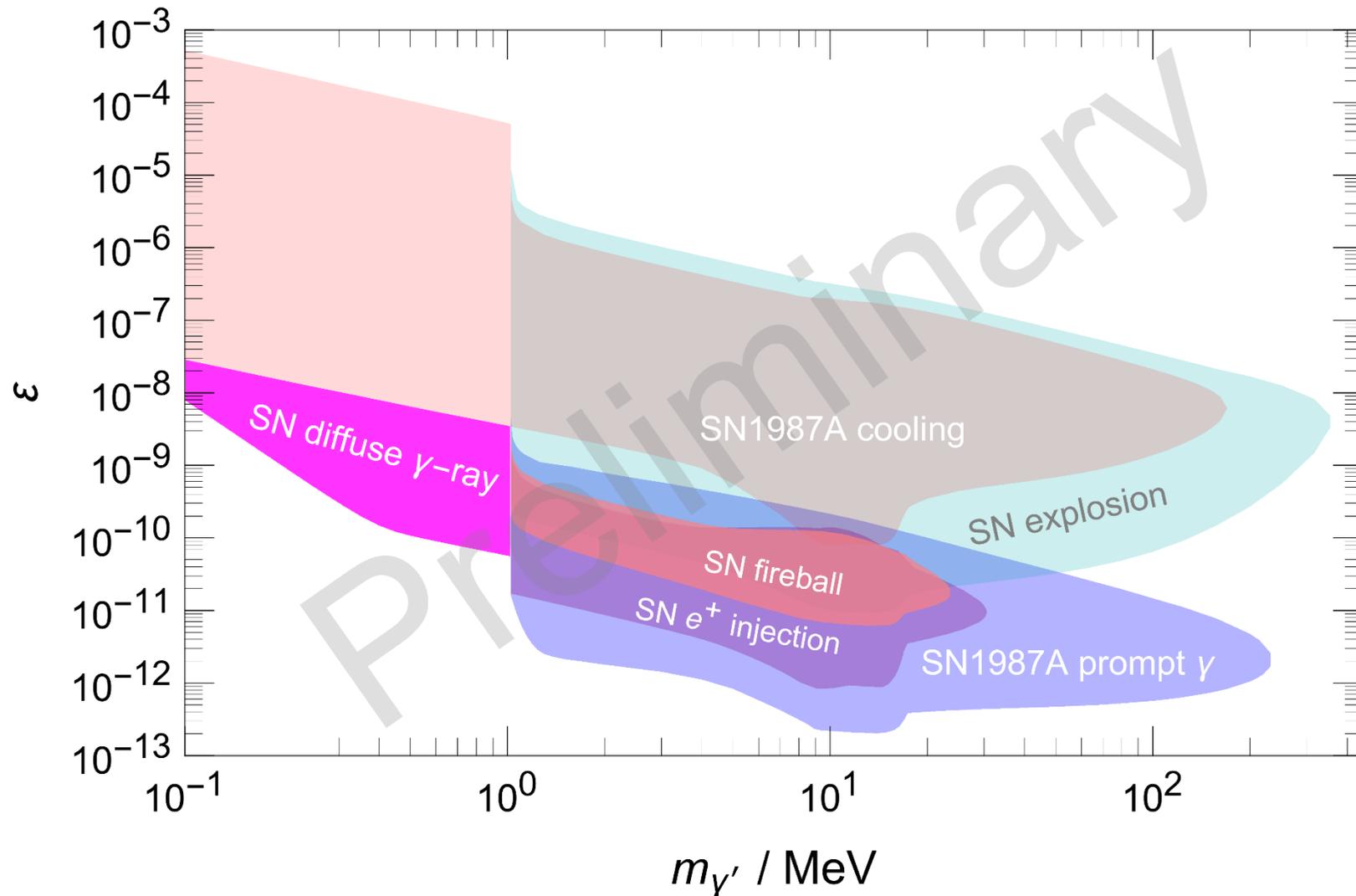M.Diamond et al., 2023

Fireball formation

Supernova diffuse Gamma-ray

-Using SN formation rate, cosmic dark photon density can be derived

-These dark photon would make cosmic radiation

A.Caputo et al. 2022
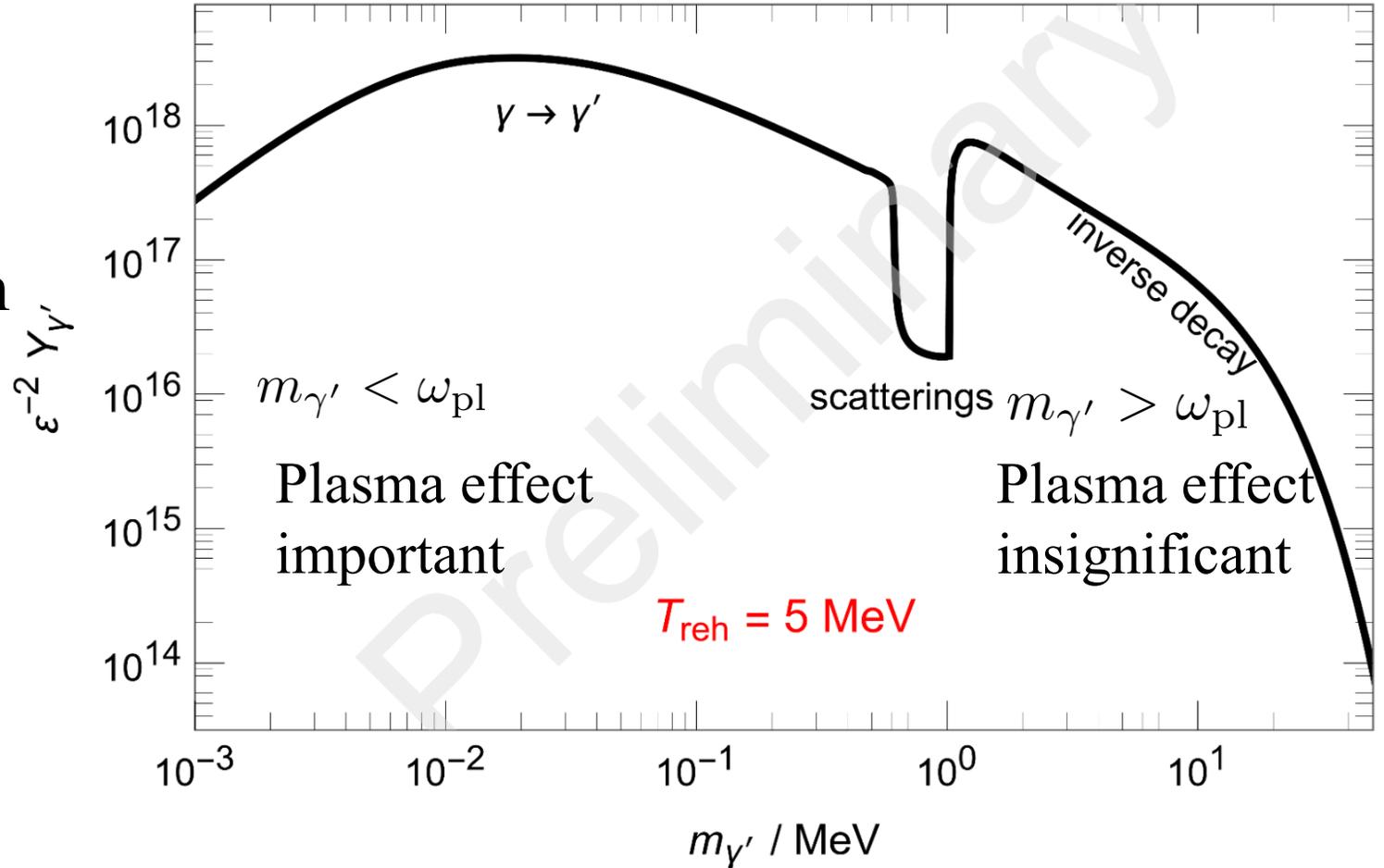
R.Hill et al. 2018

Supernova diffuse Gamma-ray

Cosmological Dark Photons

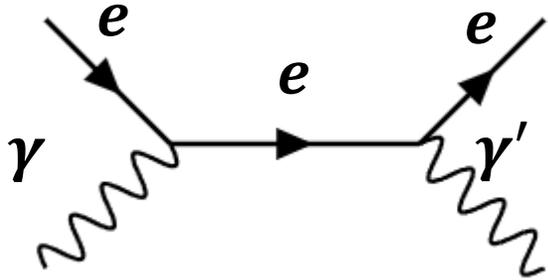# Dark photon abundance by freeze-in

-Freeze-in Scenario:
Small kinetic mixing
& IR dominant production

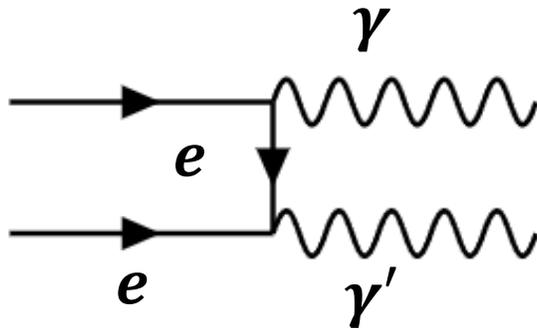-Thermal production
persists until $T \sim m_{\gamma'}$
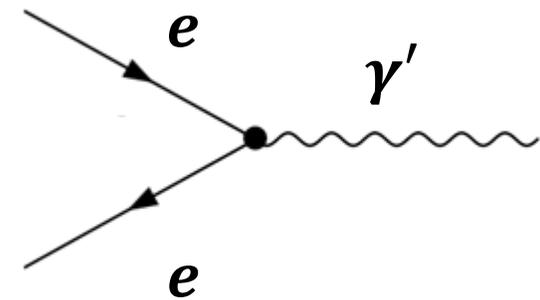
Scattering

Compton-like scattering
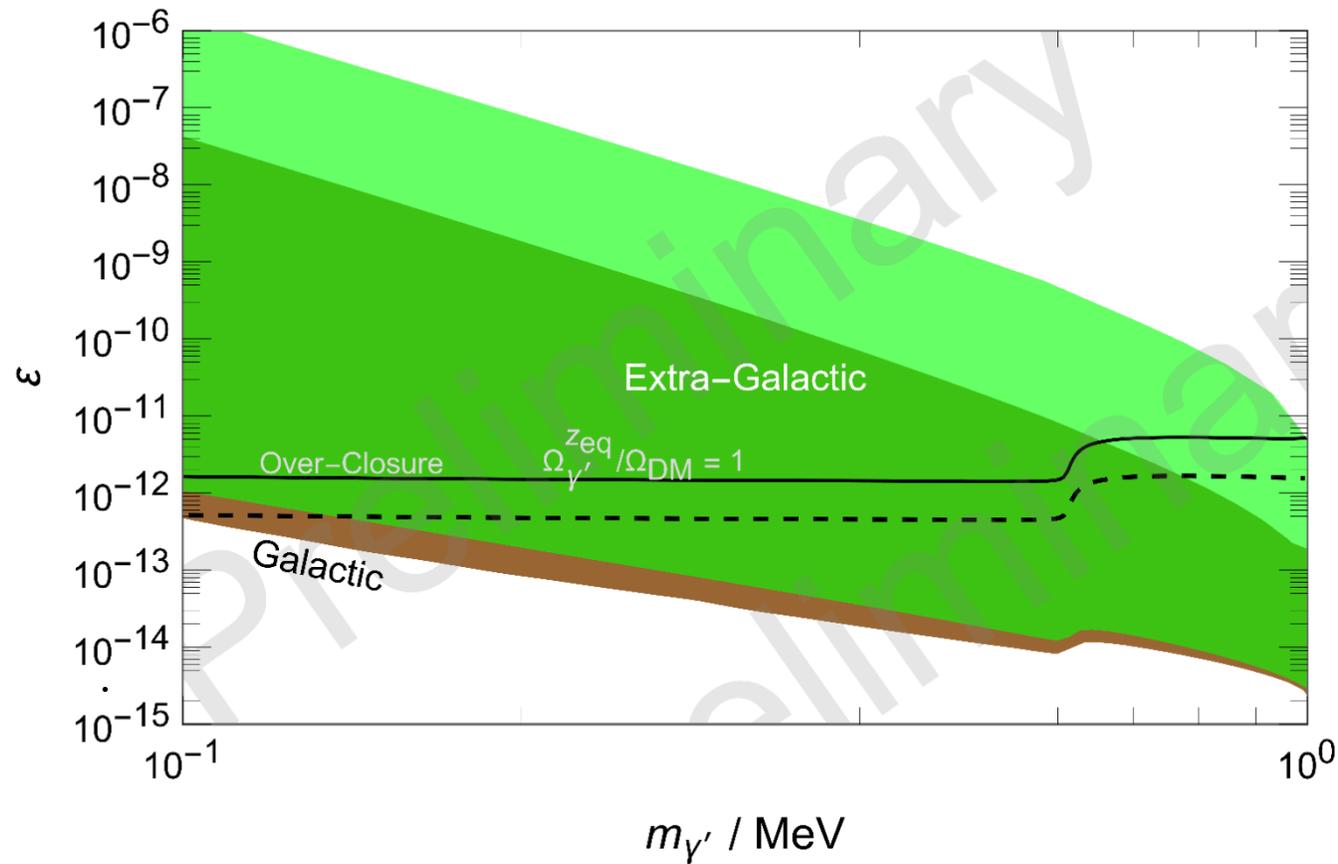
Pair-annihilation

Inverse decay

Extra-/Galactic Constraints

-From 3 photon decay, the estimated photon

spectrum should be smaller than the

observed one

-Galactic data from XNM-Newton,

INTEGRAL, NuSTAR

-Extra-Galactic data from R. Hill et al.,

2018

-Over the black solid line, dark photon
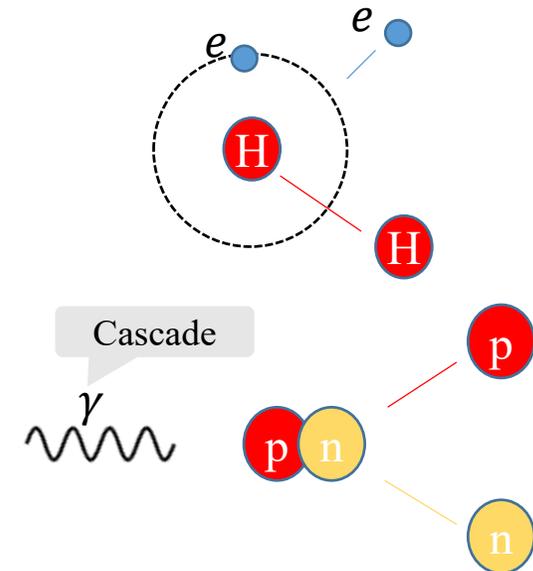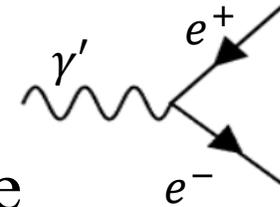
abundance cause over-closure problem

CMB/BBN/ΔN_{eff} Constraints

-Dark photon decay into e^+-e^- pair
might affect cosmological phenomena in the early universe
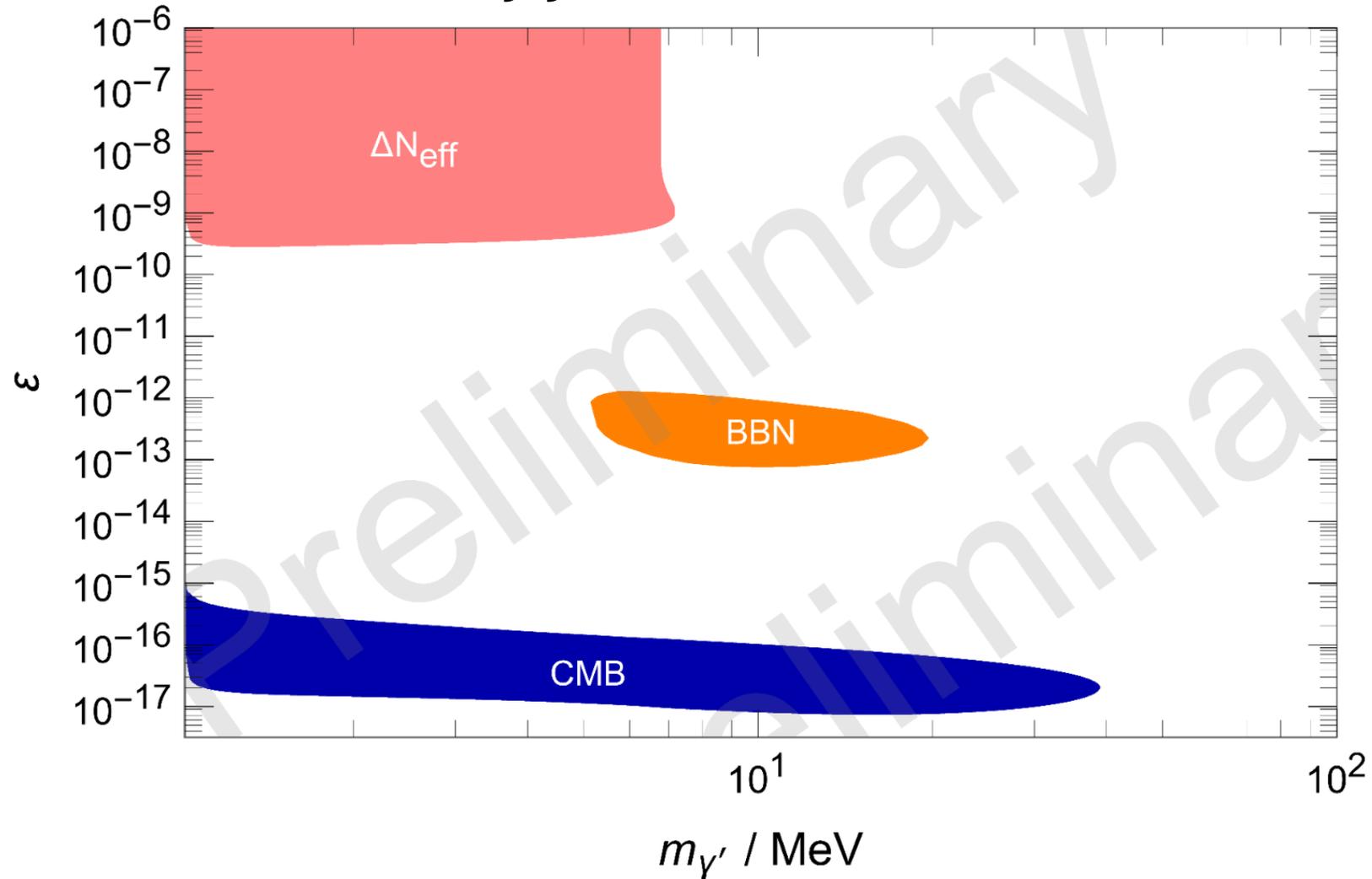
-The additional electron/positron enhance
ionization fraction, which affects CMB anisotropy

-The modified photon spectrum leads to additional
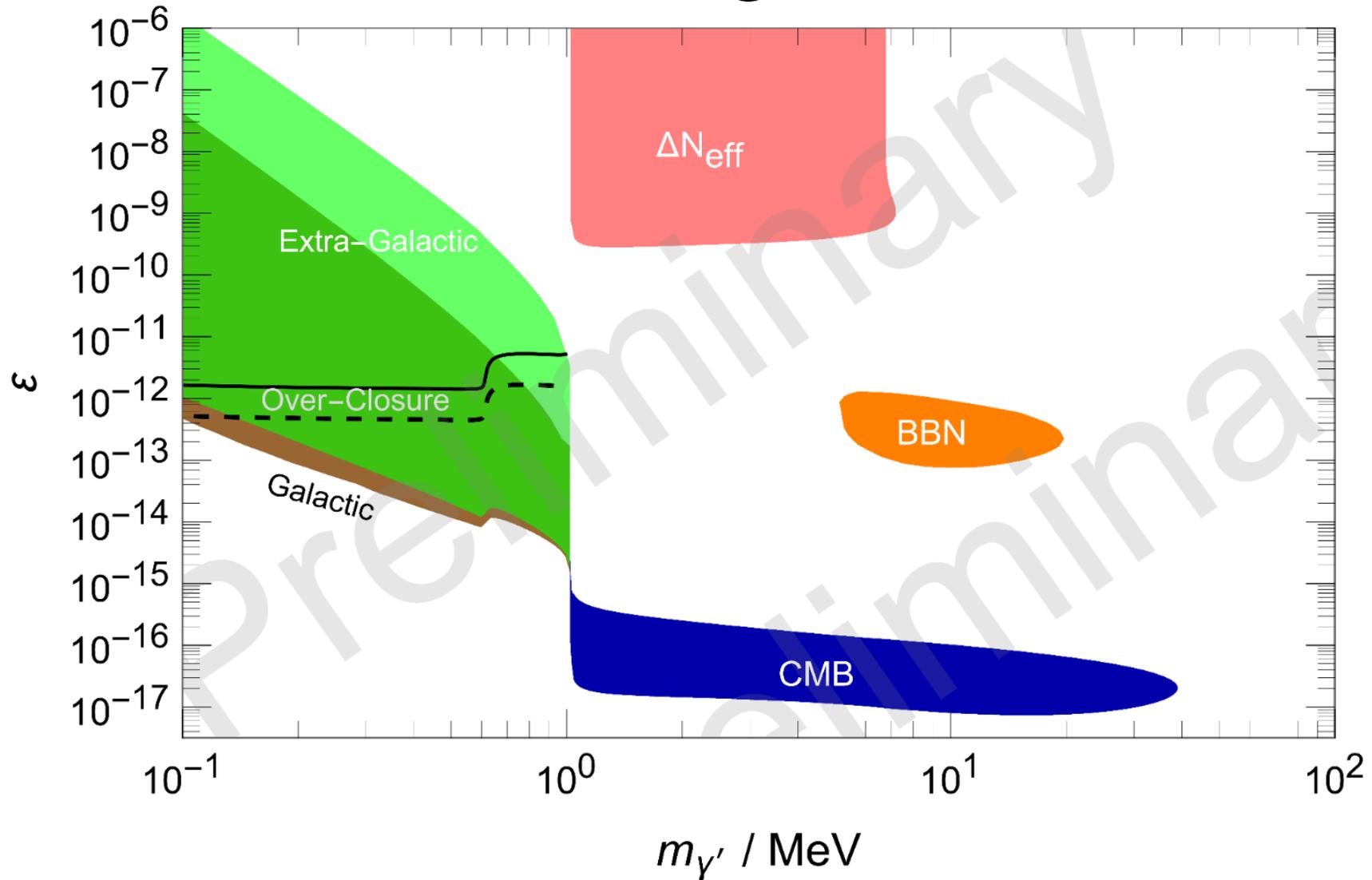photo-dissociation of light nuclei

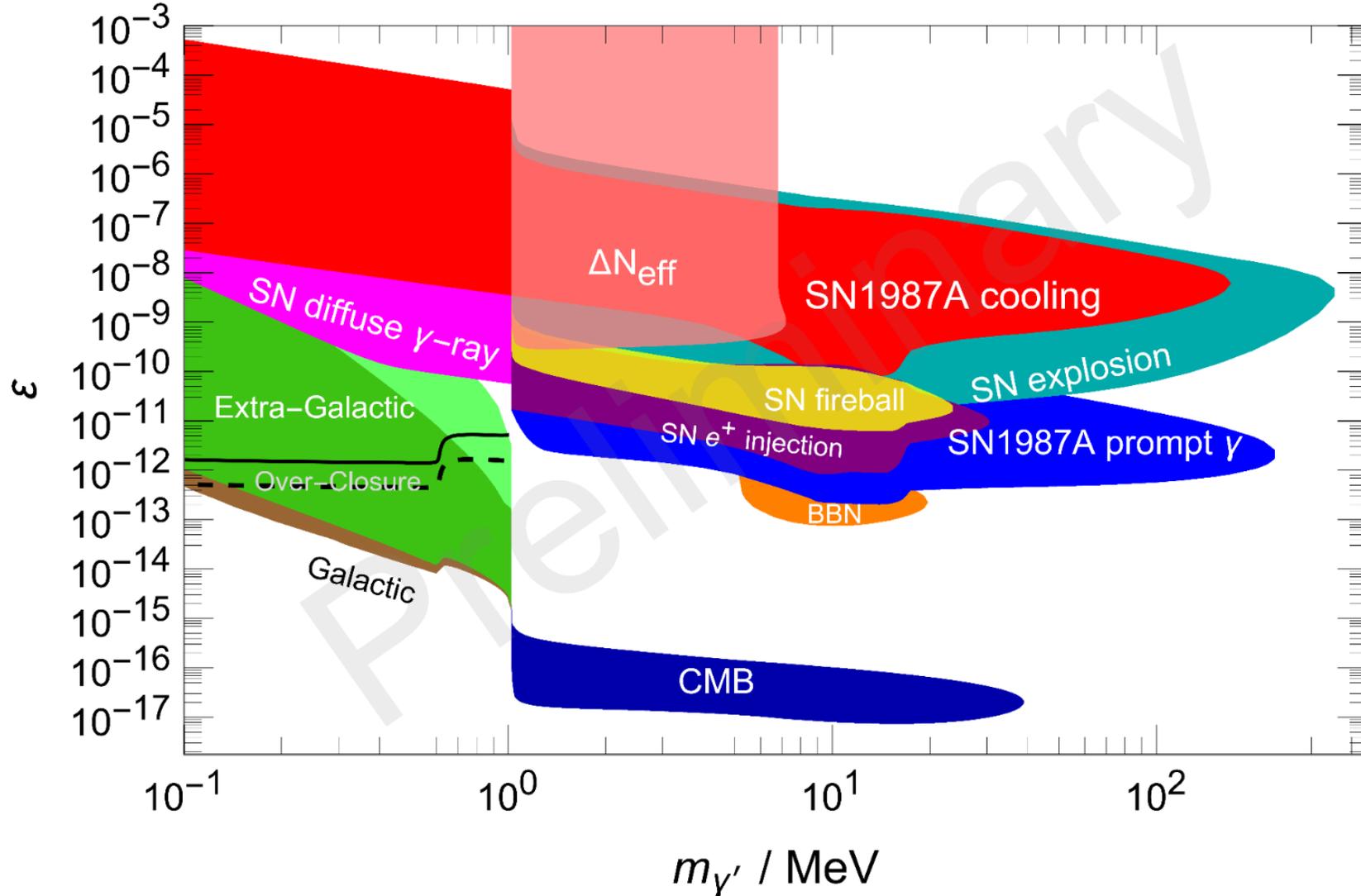-The additional photon energy injection
might give ΔN_{eff} constraint

CMB/BBN/ΔN_{eff} Constraints

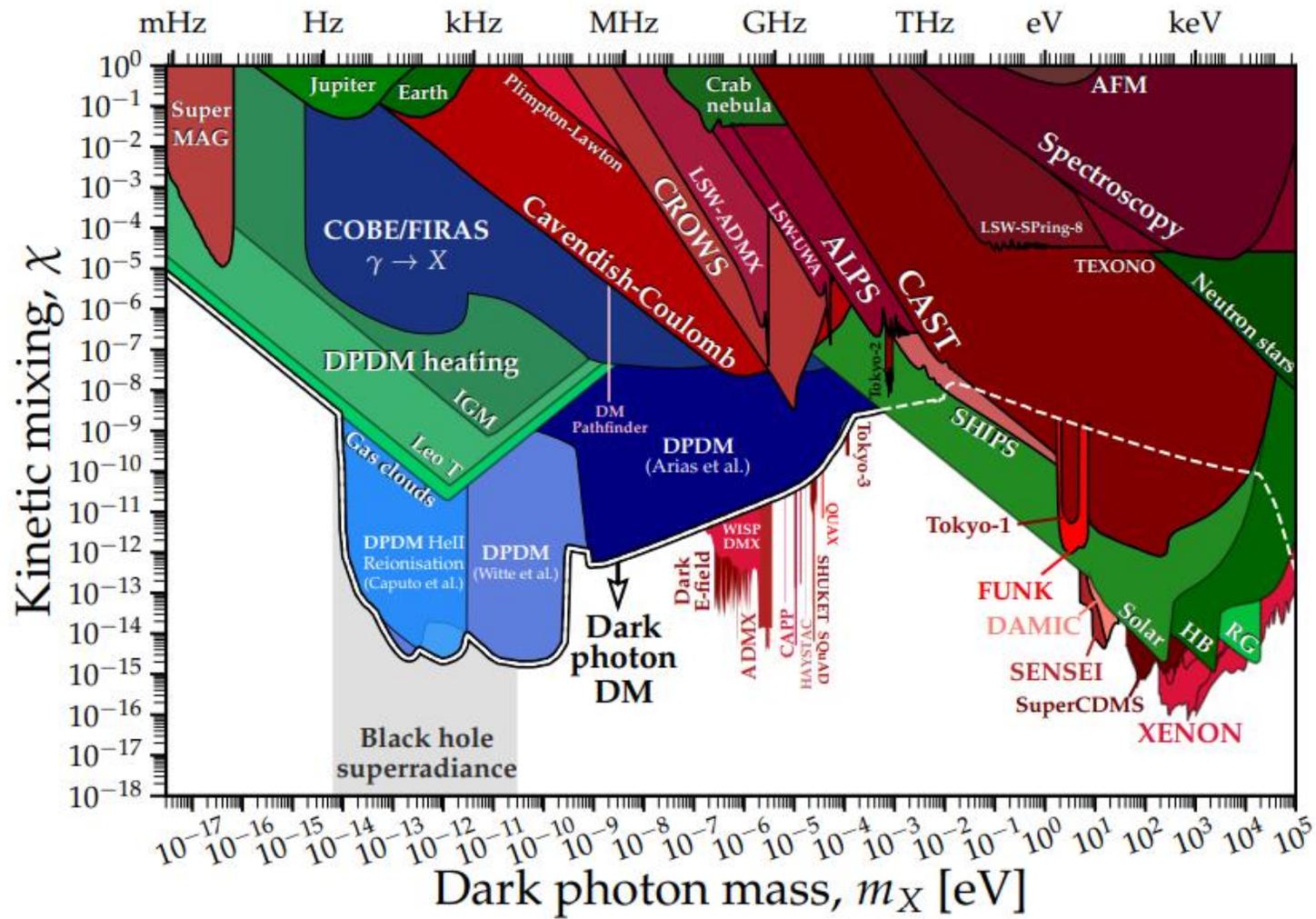# Constraints of Cosmological Dark Photon

Final Plot

Summary

-MeV Dark photon constraint is revisited

-Dark photons produced by SN modify supernova observables, by which we derived constraints: SN Cooling, Low energy explosion, Prompt Gamma ray, Positron injection, Fireball formation, Diffuse Gamma-ray

-Using dark photon freeze-in abundance, we derived constraints from Extra-/Galactic X-ray & CMB/BBN/ΔN_{eff}

Back up

A.Caputo et al.,2022

Plasma effect causes resonant conversion from photon to dark photon

$$\varepsilon e \frac{m_{\gamma'}^2}{m_{\gamma'}^2 - \pi_{T,L}} A'_\mu J^\mu_{EM}$$

$\mathrm{Re}\pi_{T,L}$: Photon effective mass

$\mathrm{Im}\pi_{T,L}$: Absorption rate

$$\mathrm{Re}\pi_T \approx \frac{3}{2}\omega_{pl}^2(T)$$

$$\mathrm{Re}\pi_L \approx \frac{\tilde{\omega}^2}{\omega^2}m_{\gamma'}^2$$