New Constraint from Supernova Explosions on Light Particles beyond the Standard Model

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Outline

Introduction

- Core-collapse supernova
- Existing supernova constraints
- New constraint from explosion energy

Example: dark photon

- Production/Absorption
- Plasma effect
- Results

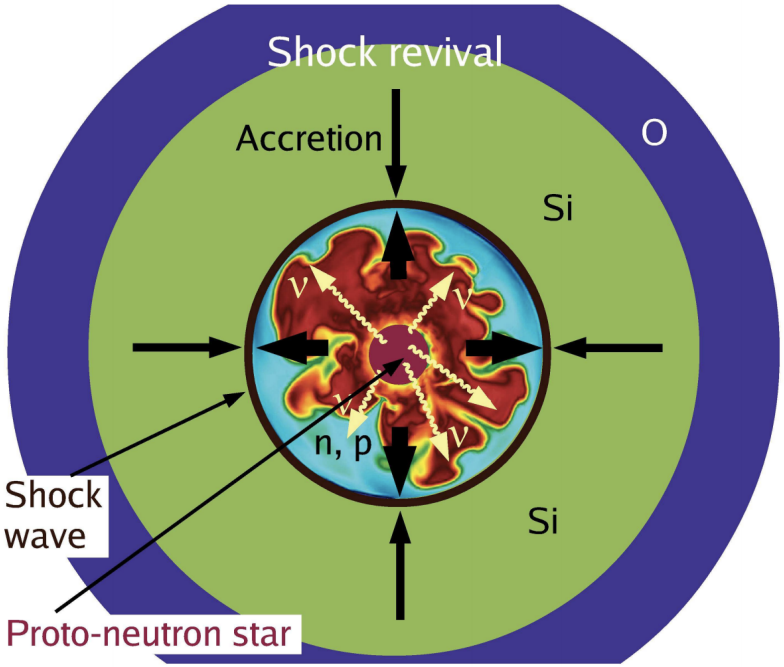
Discussions

- Implication on shock wave revival

Core-Collapse Supernova

Evolution of a Core-Collapse Supernova (CCSN)

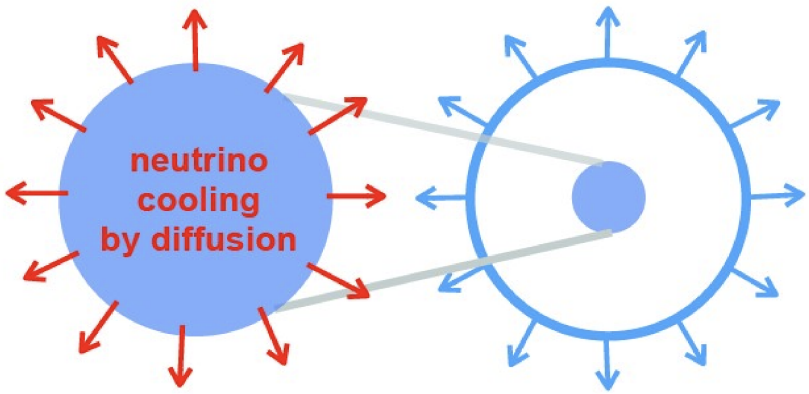
1. Iron core of massive star ($\gtrsim 10 M_\odot$) collapses
2. Core bounce causes shock wave
3. Proto-neutron star (PNS) forms in the center, emitting neutrinos
4. Stalled shock wave revives (possibly by neutrino), causing explosion



[H.-T. Janka+, 1211.1378]

Proto-Neutron Star (PNS)

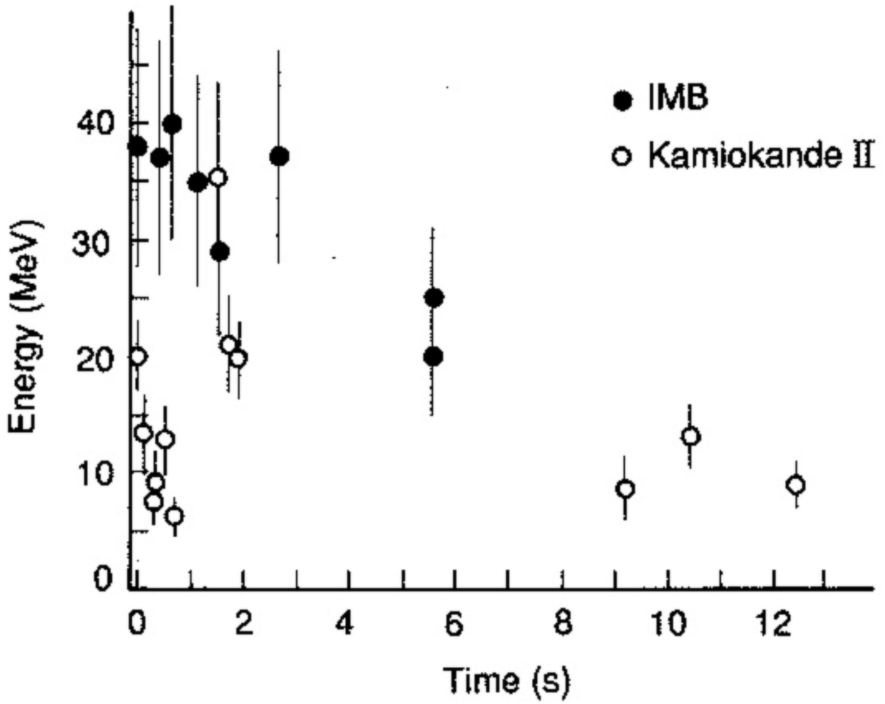
$M_{\rm PNS}\,(M_\odot)$	$R_{\rm PNS}\,({\rm km})$
1.4	$15 \sim 50$
$\rho\,({\rm g/cm^3})$	$T\,({\rm MeV})$
3×10^{14}	30



SN1987A neutrinos:

$$E_{\rm grav} \sim \frac{GM_{\rm PNS}}{R_{\rm PNS}} \sim 10^{53}{\rm erg}$$

$\Rightarrow$ carried away by neutrinos within $\sim 10{\rm s}$



[K. Hirata+ 1987, R. M. Bionta+ 1987]

Existing Constraints on bSM Particles

From SN1987A observation:

- Cooling constraint [G. G. Raffelt 1990]

$$L_X \lesssim L_\nu \simeq 3 \times 10^{52}\,\mathrm{erg/s}$$

  $\Rightarrow$ Otherwise neutrino burst duration would have been shorter
- Prompt γ-ray non-observation [W. DeRocco+, 1901.08596]

New Constraint from Explosion Energy

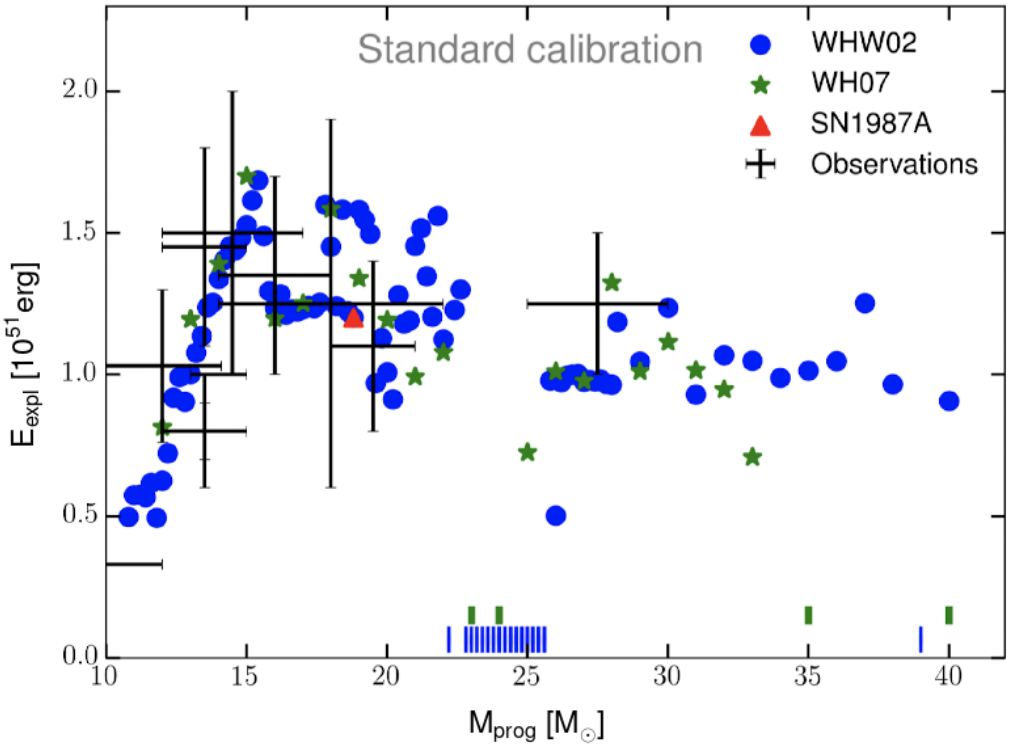
From CCSNe explosion energy:

$$E_d - E_b \lesssim E_{\rm expl}$$

- E_d: Energy deposited into stellar envelope
- E_b: Gravitational binding energy of stellar envelope
- $E_{\rm expl} \lesssim 2 \times 10^{51}$ erg

$M_{\rm prog}$ $(M_\odot)$	E_b (erg)
18	1.5×10^{51}
10.8	2.0×10^{50}

$E_{\rm expl} \approx$ K.E. of ejecta

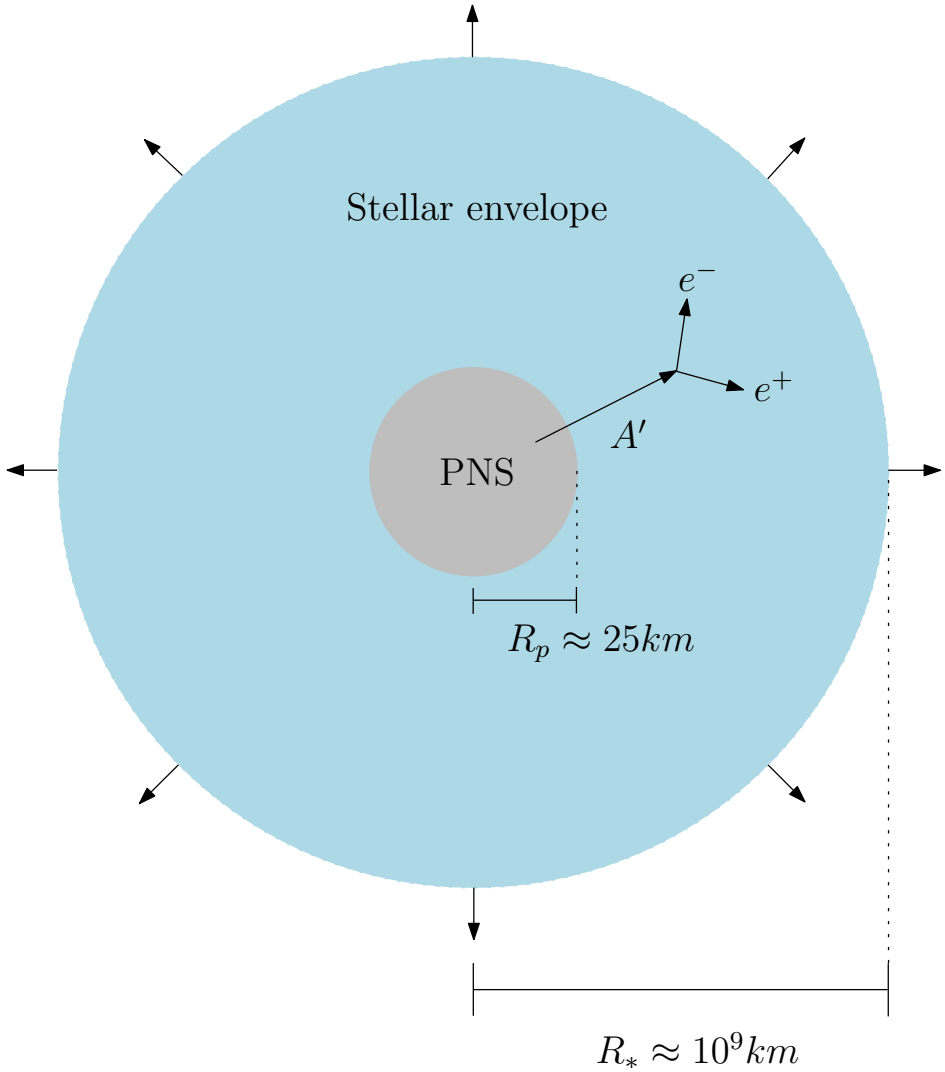


[K. Ebinger+, 1804.03182]

New Constraint from Explosion Energy

$$E_d \equiv K \cdot [L_X(R_p) - L_X(R_*)] \cdot \Delta t$$
$$\leq E_{\rm expl} + E_b \lesssim 3 \times 10^{51}\,{\rm erg}$$

- Cooling time scale: $\Delta t \simeq 10\,{\rm s}$
- K: efficiency of energy transfer (e.g. $K \simeq 1$ for dark photon)
- $\mathcal{O}(10^{-2})$ of critical cooling luminosity
- dark photon, axion/ALP, sterile ν, etc



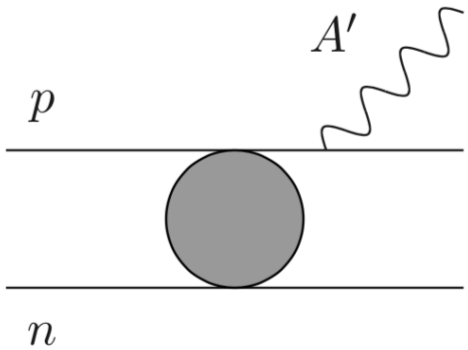
[AS+, 1903.07923]

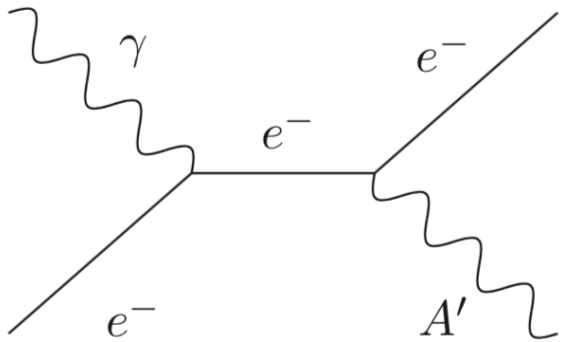
Example: Dark Photon

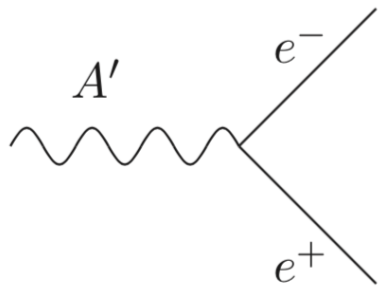
$$\mathcal{L}_{\text{Dark}} = -\frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu} - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu$$

[L. B. Okun 1982, B. Holdom 1986...]

- Nucleon Bremsstrahlung $np \rightleftharpoons npA'$
- Semi-Compton scattering $\gamma e^- \rightleftharpoons e^- A'$
- EM decay $A' \to e^+ e^-$
- Plasma effect [H. An+, 1302.3884, E. Hardy+, 1611.05852]

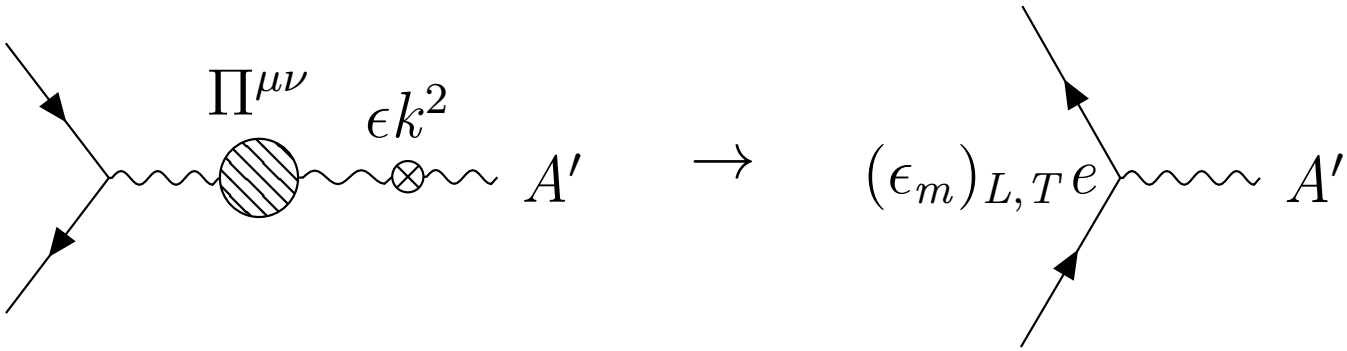






[J. H. Chang+, 1611.03864]

Plasma Effect



SM photon polarization tensor:

$$\Pi^{\mu\nu} = \Pi_L\, \varepsilon^{L\mu}\varepsilon^{L\nu} + \Pi_T \sum_{i=1,2} \varepsilon_i^{T\mu}\varepsilon_i^{T\nu}$$

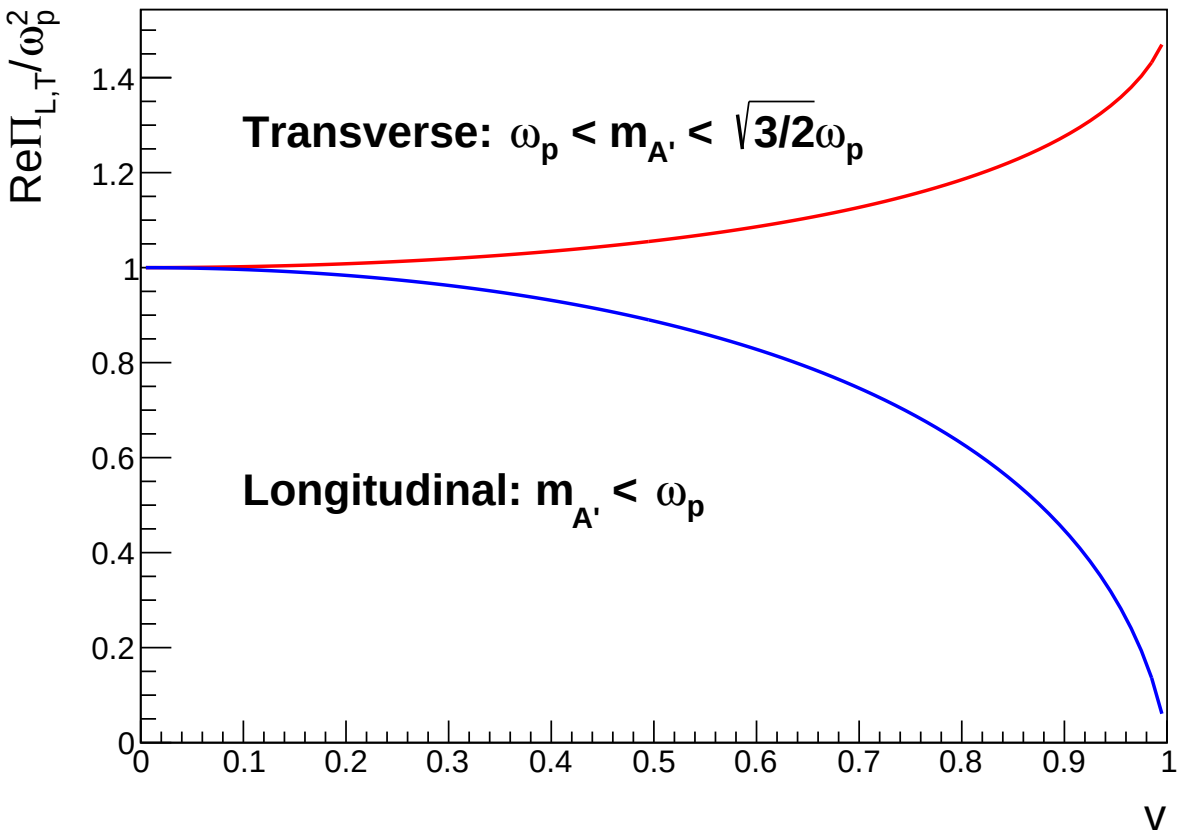
In-medium effective mixing:

$$\epsilon^2 \to (\epsilon_m)^2_{L,T} = \frac{\epsilon^2}{\left(1 - \mathrm{Re}\,\Pi_{L,T}/m^2_{A'}\right)^2 + \left(\mathrm{Im}\,\Pi_{L,T}/m^2_{A'}\right)^2}$$

Resonant enhancement: $\mathrm{Re}\,\Pi_{L,T} = m^2_{A'}$

Plasma Effect

Relativistic & degenerate electron medium [Braaten+, 9302213]



$$\omega_p^2 = 4\pi\alpha n_e / E_F$$

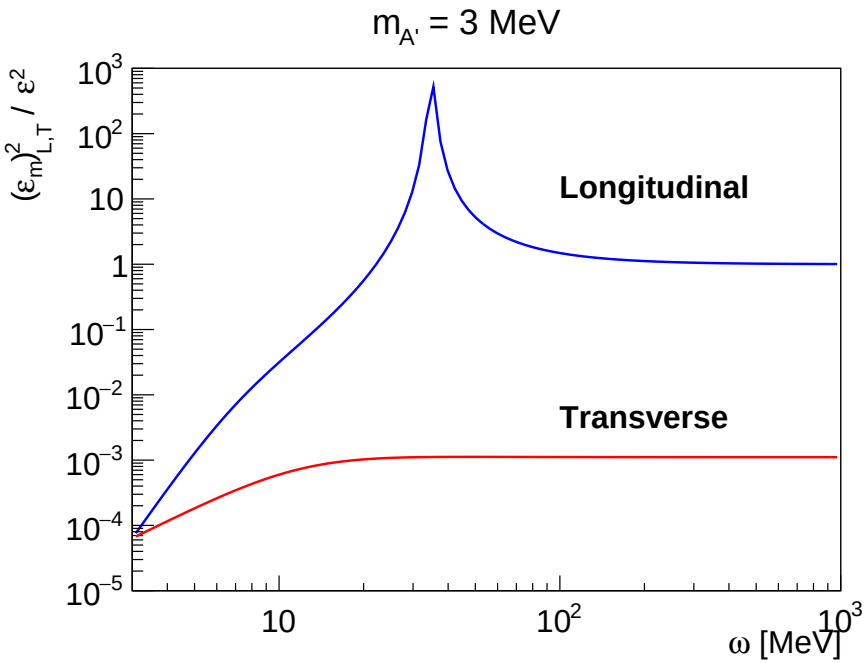
(Plasma frequency)

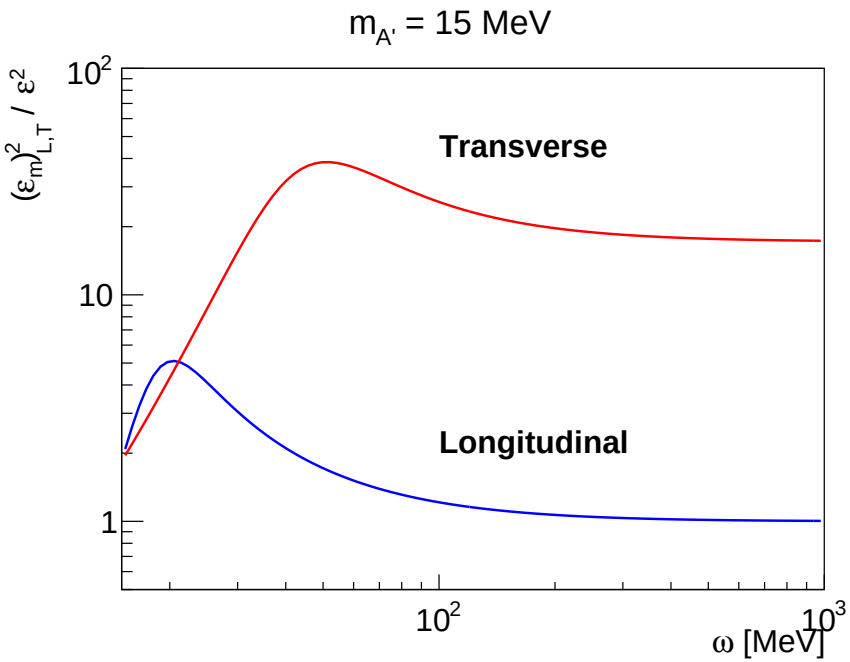
$$v = \sqrt{1 - \frac{m_{A'}^2}{\omega^2}}$$

$$\mathrm{Im}\,\Pi_{L,T} = -\omega\left(\Gamma^{\mathrm{abs}}_{L,T} - \Gamma^{\mathrm{prod}}_{L,T}\right) = -\omega(1 - e^{-\omega/T})\Gamma^{\mathrm{abs}}_{L,T}$$

Plasma Effect

Resonant enhancement of effective mixing ϵ_m





At the PNS center:

$\rho\,(\mathrm{g/cm^3})$	$T\,(\mathrm{MeV})$	$\mu_e\,(\mathrm{MeV})$	Y_e	$\omega_p\,(\mathrm{MeV})$
3.6×10^{14}	17	240	0.3	13.6

Dark Photon Production in PNS

Luminosity (through some surface of radius $R > R_p$):

$$L_{A'}(R) = \sum_{L,T} \int_{r=0}^{R_p} \int_{\omega=m_{A'}}^{\infty} 4\pi r^2 \, \frac{\omega^3 v}{2\pi^2} \, \Gamma^{\rm prod}_{L,T}(\omega, r) \, e^{-\tau_{L,T}(\omega,r,R)} \, d\omega \, dr$$

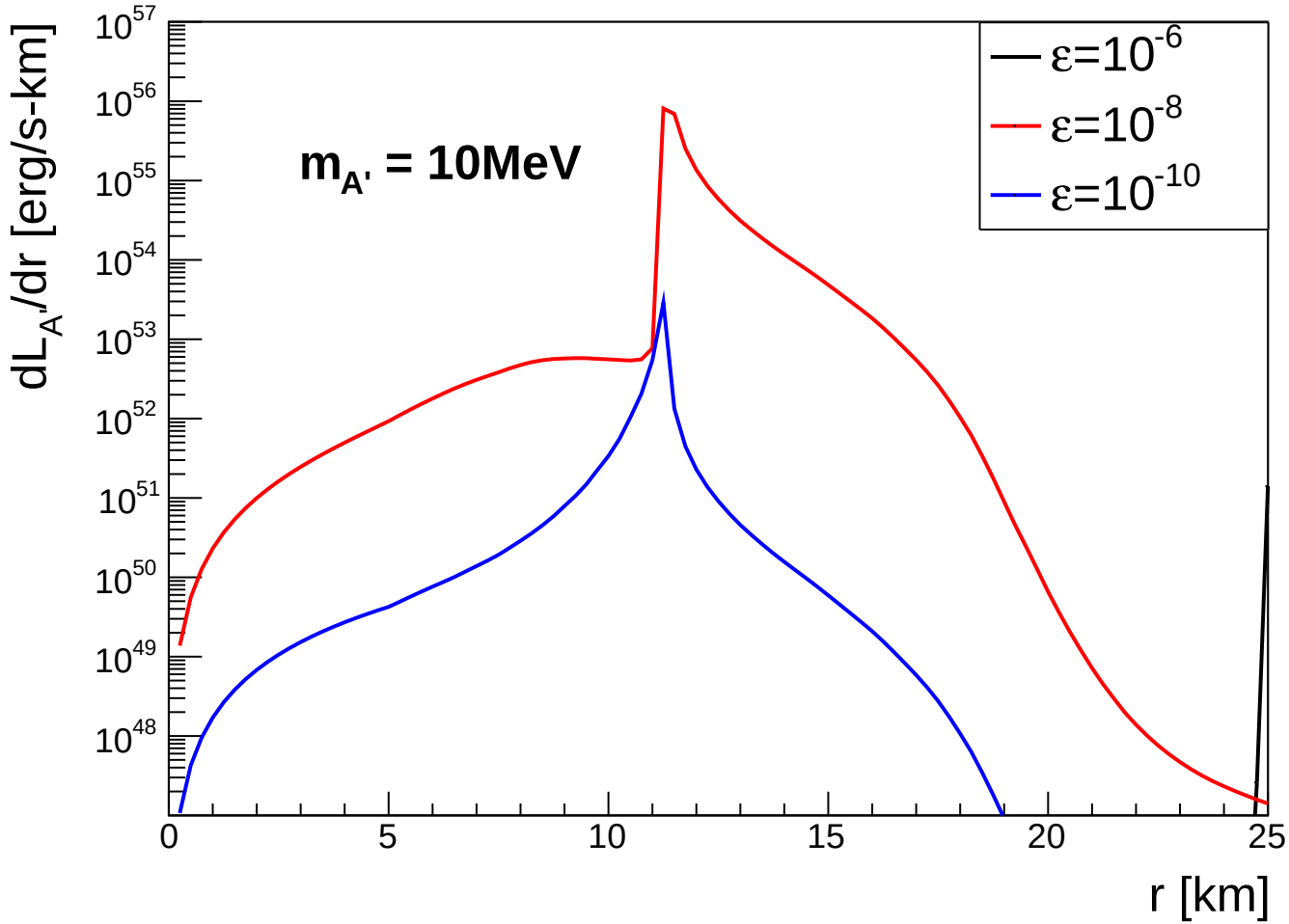
$$\Gamma^{\rm prod}_{L,T} = \Gamma^{\rm Brem}_{L,T} + \Gamma^{\rm sC}_{L,T} \propto (\epsilon_m)^2_{L,T} \text{ (L-mode suppressed by } \tfrac{m^2_{A'}}{\omega^2}\text{)}$$

Optical depth:

$$\tau_{L,T}(\omega, r, R) = \int_r^R \frac{d\tilde{r}}{v} \left[\Gamma^{\rm abs}_{L,T}(\omega, \tilde{r}) + \Gamma^{\rm decay}_{L,T}(\omega, \tilde{r}) \right] \propto (\epsilon_m)^2_{L,T}$$

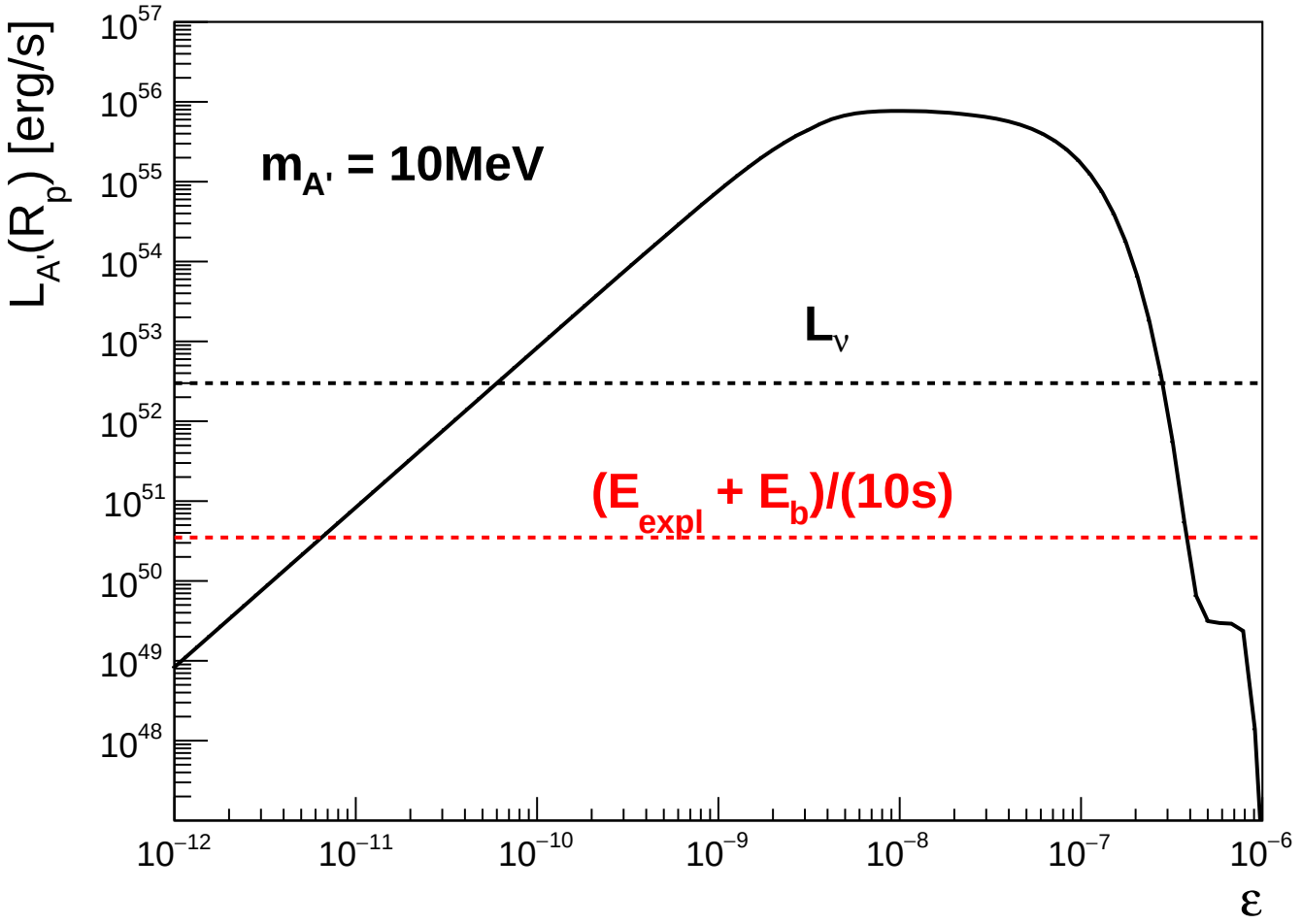
Dark Photon Production in PNS

Dark photon trapped when ϵ is sufficiently large



Dark Photon Production in PNS

Stronger constraint from the new criterion



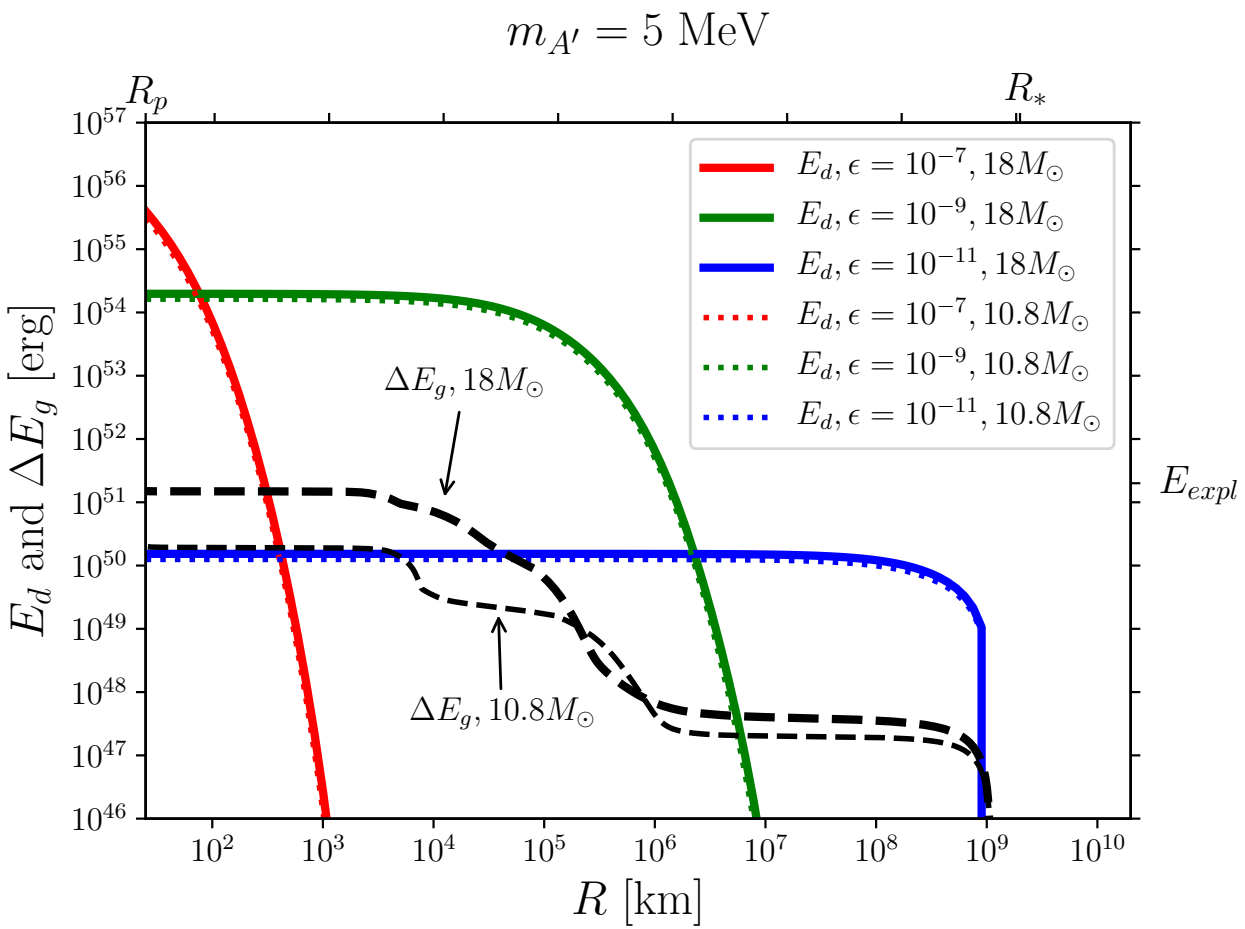
Deposited and Gravitational Binding Energy

[AS+, 1903.07923]

$$E_d(R) = [L_{A'}(R) - L_{A'}(R_*)]\Delta t$$

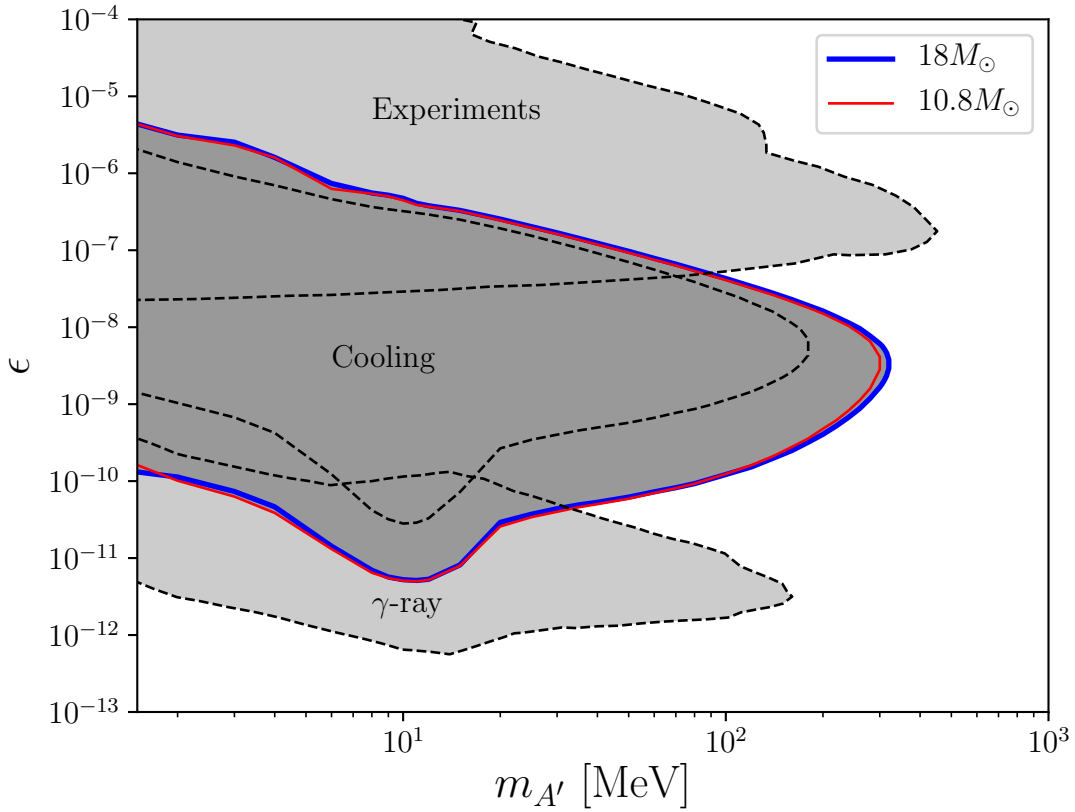
Criterion:

$$E_d(R_p) - E_b(R_p) \leq E_{\rm expl}$$



Excluded Region

- Improved lower boundary compared to cooling
- Gap closed between cooling and γ-ray

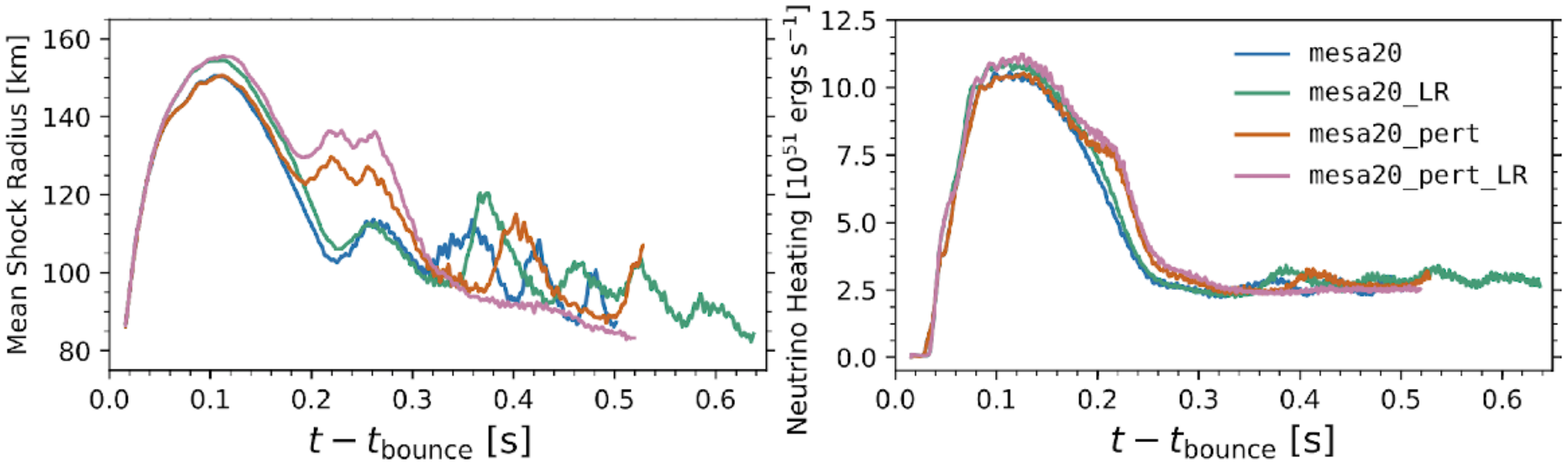


[AS+, 1903.07923]

Implication on Shock Wave Revival

New particles cannot revive shock wave

- Instantaneous heating rate $\gtrsim 10^{51}$ erg/s
- Would have caused overenergetic explosion



[E. O'Connor+, 1807.07579]

Summary

- New CCSN constraint from explosion energy stronger than existing cooling constraint
- Can be applied to dark photon, axion/ALP, sterile ν, etc
- Dark photon: improve lower boundary, close gap between cooling and γ-ray bounds
- New particles cannot revive shock wave

Thank You!