Supernova 1987A
Constraints on Low-Mass Dark Sectors

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Supernova 1987A

- Type II Supernova observed in 1987
- Closest supernova since Kepler (~50 kpc)
- The only supernova that neutrinos from supernova explosion were detected
- Can be used to constrain new particles
Supernova 1987A
99% of energy is carried by neutrinos
Kamiokande II, IMB, and Baksan detected the neutrinos at the same time

Hirata et al, 1988
- Cooling time: $\sim 10$ seconds
- Consistent with the SM prediction
If a new particle exists
Supernova 1987A

- Supernova cools faster
Raffelt Criterion

- Energy loss through new particles must be less than energy loss through neutrinos

- $L_{\text{new}} < L_{\nu}$
Luminosity [arb. units] vs. Coupling Strength

Produced

Efficiently Trapped

Allowed

Excluded

Allowed
Supernova Constraints

- Any type of light novel particles coupled to the SM can be constrained

- $m \lesssim T_c \approx 30 \text{ MeV}$

- Provides reasonable lower bounds for experiment searches
Supernova Constraints

- Pure dark photons
- Dark sector fermions
- Inelastic dark matter
- Millicharged particles
- QCD Axions
- Axion-like particles
Supernova Constraints

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PURE DARK PHOTON
- $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$

- Dark photon ($A'$) is the gauge boson of $U(1)'$

- In low energies, $\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu}$
• Dominant production process

• Trapping Process
Comparison with Previous Work

\begin{figure}
\centering
\includegraphics[width=\textwidth]{comparison_plot}
\caption{Comparison with previous work on the relationship between $\epsilon$ and $m'$.}
\end{figure}

- Bjorken, et al., 2009
- Dent, et al., 2012
- Rrapaj & Reddy, 2015
- Kazanas, et al., 2014 (L)
- Kazanas, et al., 2014 (d)
Novelties in this Work(s)

- Varying temperature and density profiles
- Novel treatment for the upper bounds
- Included the thermal effects to the supernova environment for the first time
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DARK SECTOR
FERMIONS
- A Dirac fermion charged under $U(1)'$: $\chi$

- $\chi$ is stable $\rightarrow$ Dark matter candidate

- $\chi$ provides a new cooling channel $\rightarrow$ Stronger lower bounds

- Trapping process is totally different $\rightarrow$ Upper bounds changes
- Dominant production process

- Trapping Process
Mass Hierarchy

- Depending on mass hierarchy, dark photon may decay to a $\chi \bar{\chi}$ pair.
- This changes phenomenology of $\chi$ production and absorption.
- Consider both heavy DM case and light DM case.
Light Dark Matter Case

\[ \varepsilon = \frac{\chi}{\alpha} \]

\[ m' = \frac{m'}{3}, \alpha_d = 0.5 \]
Light Dark Matter Case

\[ \sigma \equiv \sigma_e \quad \text{[cm}^2\text{]} \]

\[ \alpha_D \quad = \quad \text{0.005} \]

\[ \alpha_D \quad = \quad \text{0.5, } m_1 \quad = \quad 3 \, m_{\chi} \]

\[ \text{SN1987A} \]

\[ \text{Fiducial} \]

\[ \text{Fischer, 11.8} M_{\odot} \]

\[ \text{Fischer, 18} M_{\odot} \]

\[ \text{Nakazato, 13} M_{\odot} \]
OTHER MODELS
Heavy Dark Matter Case
Inelastic Dark Matter

$y = \epsilon^2 \alpha_D (m_1 / m')^4$

$\alpha_D = 0.1, m' = 3m_1, \Delta = 0.4m_1$
Millicharged Particles

![Graph depicting Millicharged Particles](image-url)
QCD Axions

\[ f_a \cdot C_{\text{KSVZ}} / C \quad [\text{GeV}] \]

\[ m_a \cdot C / C_{\text{KSVZ}} \quad [\text{eV}] \]

- PDG (2016)
- fiducial
- Fischer, 11.8\(M_\odot\)
- Fischer, 18\(M_\odot\)
- Nakazato, 13\(M_\odot\)
Axion-like Particles

Fiducial
Fischer, $11.8M_\odot$
Fischer, $18M_\odot$
Nakazato, $13M_\odot$
CONCLUSION
Conclusion

- Supernova1987A can give constraints on low-mass dark sector particles

- We calculated constraints for various models, which provides reasonable lower bound for experiment searches
THANK YOU
BACK UP
Dark photon couples to charged SM particles with charge $\epsilon e$:

$$\mathcal{M} \propto e \times \frac{1}{q^2} \times \epsilon q^2 = \epsilon e$$

$$\mathcal{L} \supset \epsilon e j_{EM}^{\mu} A_\mu'$$
Real Part of Polarization Tensor

\[ \omega^2 - k^2 = \text{Re}\Pi \]

- \(\text{Re}\Pi\) acts like a photon mass

- \(\text{Re}\Pi \approx \omega_p^2\)

\(\omega_p \approx 15\text{MeV}\) is the plasma frequency
Imaginary Part of Polarization Tensor

- From the optical theorem, but diagrams includes background particles

\[ \text{Im} \Pi = \omega (\Gamma_{\text{abs}} - \Gamma_{\text{prod}}) \]
In supernova,

\[ M \propto e \times \frac{1}{q^2 - \Pi} \times \epsilon q^2 = e \frac{q^2}{q^2 - \Pi} \epsilon \]

\[ L \supset \epsilon_m e J_{EM}^\mu A'_\mu, \quad \epsilon_m \equiv \left| \frac{q^2}{q^2 - \Pi} \right| \epsilon \]
Mixing angle in Supernova

- \( \epsilon_m \equiv \left| \frac{q^2}{q^2 - \Pi} \right| \epsilon \)
- \( \text{Re}\Pi \approx \omega_p^2, \quad q^2 = m'^2 \rightarrow \epsilon_m \approx \left| \frac{m'^2}{m'^2 - \omega_p^2} \right| \epsilon \)
- \( \omega_p \sim \text{15MeV} \) is the plasma frequency

- \( \epsilon_m \ll \epsilon, \quad m' \ll \omega_p \)
- \( \epsilon_m \gg \epsilon, \quad m' \approx \omega_p \)
- \( \epsilon_m \approx \epsilon, \quad m' \gg \omega_p \)
Comparison with Previous Work

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Particle Luminosity

\[ L = \int dV \int \frac{d^3 \vec{k}}{(2\pi)^3} \omega \Gamma_{\text{prod}} e^{-\tau} \]

\[ P = \int dV \int \frac{d^3 \vec{k}}{(2\pi)^3} \omega \Gamma_{\text{prod}} \]

\[ \tau = \int_{r}^{r_f} \Gamma_{\text{abs}} dr' \]
Particle Luminosity

\[ dL = e^{-\tau} dP \]

Odds of escaping
\[ \tau = \int \Gamma_{abs} dr \] is called the optical depth
$$\omega_p^2 = \frac{4\pi \alpha n_e}{E_F}$$

$$E_F^2 = m_e^2 + (3\pi n_e)^{2/3}$$

$$\bar{\sigma}_e = \frac{16\pi \mu \chi_e \varepsilon^2 \alpha \alpha_D}{(m'^2 + \alpha^2 m_e^2)^2}$$