Supernova 1987A
Constraints on Low-Mass Hidden Sectors

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SUPERNOVA 1987A
Supernova 1987A

- Closest supernova since Kepler
- The only supernova which neutrinos from supernova explosion were detected
- The neutrino observations were consistent with the theoretical prediction
Supernova Constraints

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

\[ m \lesssim T_c \approx 30 \text{ MeV} \]

- Used for axions, sterile neutrinos, and dark photons
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 : ~13 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] \( L_v \)

Coupling Strength

Produced

Efficiently Trapped

Allowed

Excluded

Allowed
DARK PHOTON MODEL
\[ SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)' \]

- In low energies, \( \mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'_{\mu\nu} \)

- Called the vector portal
Dark Photon in Supernova

- Photon gets plasma mass and has longitudinal polarization
- Photon propagator changes
- Since Dark photon is mixed with photon, these effects must be considered
\( \Pi = \Pi_{\text{vac}} + \Pi_{\text{mat}} \)

- \( \Pi_{\text{vac}} \) is the vacuum part
- \( \Pi_{\text{mat}} \) describes thermal plasma effects
- \( \Pi_{\text{mat}} \gg \Pi_{\text{vac}} \)
In vacuum,

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

\[ \mathcal{L} \supset \epsilon e J_{EM}^{\mu} A'_{\mu} \]
• In supernova,

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

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

- $\epsilon_m \equiv \left| \frac{q^2}{q^2 - \Pi} \right| \epsilon$

- $\Pi \approx \omega_p^2 \rightarrow \epsilon_m \approx \left| \frac{q^2}{q^2 - \omega_p^2} \right| \epsilon$

- $\omega_p \sim 15 MeV$ is the plasma frequency

- $\epsilon_m \ll \epsilon, \quad q^2 \ll \omega_p^2$

- $\epsilon_m \gg \epsilon, \quad q^2 \approx \omega_p^2$

- $\epsilon_m \approx \epsilon, \quad q^2 \gg \omega_p^2$
Novelties in this Work

• Included the thermal effects to the supernova environment for the first time

• Varying temperature and density profiles

• Considered various dark photon models
Dark Photon Models

- Pure dark photon
- Dark sector fermion
- Millicharged dark matter (Work in progress)
PURE DARK PHOTON
All other hidden sector particle masses are much heavier than $T_c$

Consider $A'$ only

Dark photons are on-shell, $q^2 = m'^2$
• Dominant production process

• Trapping Process
Previous Works

- Bjorken et al, 2009
- Dent et al, 2012
- Rrapaj and Reddy, 2015
Comparison with Previous Work

- Bjorken, et al., 2009
- Dent, et al., 2012
- Kazanas, et al., 2014 (L)
- Kazanas, et al., 2014 (d)
- Rapaj & Reddy, 2015
Lower bounds are lifted for $m' \ll \omega_p$
\[ \epsilon_m \approx \frac{m'^2}{|m'^2 - \omega_p^2|} \epsilon \ll \epsilon \]
There is a dip at $m' \sim \omega_p$
\[ m' \left[ \text{MeV} \right] \quad \epsilon_m \approx \left| \frac{m'^2}{m'^2 - \omega_p^2} \right| \epsilon \gg \epsilon \]
Comparison with Previous Work

$$\epsilon \sim \frac{m'^2}{m'^2 - \omega_p^2} \epsilon \sim \epsilon$$
DARK SECTOR
FERMIONS
• Fermion charged under $U(1)'$: $\chi$

• Consider $A' + \chi$

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

• Dark photon can decay into a $\chi$ pair

• Dark photons can be off-shell, $q^2 \neq m'^2$
  ➢ Lower bound becomes stronger

• Cannot be absorbed without $\bar{\chi}$
  ➢ Upper bound changes significantly
• Dominant production process

• Trapping Process
\[ \alpha_D = \alpha, \ m_\chi = m'/3 \]
On-shell production: Two cases have same lower bounds.
\[ A' \text{ Only} \]
\[ A' + \chi \]

\[ \epsilon \]

Off-shell production dominates

\[ \alpha_D = \alpha, \ m_\chi = m'/3 \]
Upper bounds are significantly different

\[ \alpha_D = \alpha, \ m_\chi = m'/3 \]
$\bar{\sigma}_e$ [cm$^2$] vs $m_\chi$ [MeV]

- Elastic Scalar
- Asymmetric Fermion
- ELDER (SIMP $\uparrow$)
- Si, 1e$^-$, 1 kg$\cdot$yr
- SN1987A
  (Lower bound: $\alpha_D=0.5$)

$F_{DM}=1$
$m_A = 3 m_\chi$

XENON10
XENON100
Beam dump Collider WIMP–DD Searches

Preliminary
Conclusion

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

- For the dark photon models, thermal effects have a crucial role

- We calculated constraints for the pure dark photon and for the dark sector fermions, and constraints for the millicharged DM are in progress
THANK YOU
BACK UP
Temperature and Density Profiles

\[ T \text{ [MeV]} \]

\[ \rho \text{ [MeV]} \]

- **fiducial**
- **Swesty 15M\(_\odot\)**
- **Swesty 25M\(_\odot\)**
- **Fischer 11M\(_\odot\)**
- **Fischer 18M\(_\odot\)**
\[ L_{A'} = \int dV \int \frac{d^3 \vec{k}}{(2\pi)^3} \Gamma_{\text{prod}} e^{-\tau} \]

\[ \tau = \int_{r}^{r_f} \Gamma_{\text{abs}} dr' \]
\[ \omega_p^2 = \frac{4\pi\alpha n_e}{E_F} \]

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

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