TeVPA 2023

DARKNESS IN WHITE
White dwarf cooling through dark sector physics

Effect of a dark photon on plasmon decay

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Based on: Phys. Rev. D 108, 043014

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HIDDeN

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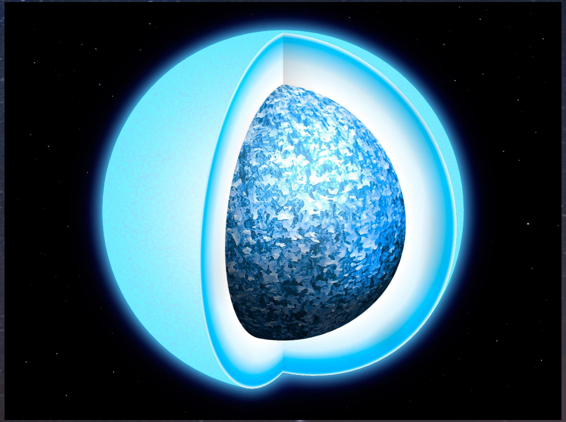
1. White dwarfs as Cosmic Laboratories

Dense star ($\sim 10^6 kg/m^3$)



Degenerate pressure from e-

Known EoS: TOV eqs. + Salpeter

Mass $< 1.33 M_{\odot}$

1. White dwarfs as Cosmic Laboratories

Cooling

$$dT_*/dt = -L_{\gamma/\nu}/(4\pi R_* \sigma_{SB} T_*)$$

Hot WDs: neutrino emission through plasmon decay

Cold WDs: photon surface emission

1. White dwarfs as Cosmic Laboratories

Salpeter EoS

$$E = E_0 + E_C + E_{TF} + E_{Ex} + E_{Cor}$$

- E_0 : energy from electron-degenerated ideal gas.
- E_C : total electrostatic energy per electron using the Wigner-Seitz approximation.
- E_{TF} : Thomas-Fermi energy, deviations from uniformity of charge distribution
- E_{Ex} : Exchange energy, effect of antisymmetrized wave functions for Coulomb potential, i.e., the exchange interaction spin-spin.
- E_{Cor} : correlation energy, it measures the effect of the EM field on the distribution of the electrons.

Salpeter, Astrophysical Journal, vol. 134, p.669

1. White dwarfs as Cosmic Laboratories

Tolman-Oppenheimer-Volkoff (TOV) equations

Einstein field equations for a perfect fluid in the metric of the interior of a star
Tolman, R. C. 1939, Phys. Rev., 55, 364 / Oppenheimer, J. R., & Volkoff, G. M. 1939, Phys. Rev., 55, 374

$$\frac{dp(r)}{dr} = -\frac{G}{c^2}\frac{\varepsilon(r)+p(r)}{r(r-\frac{2G}{c^2}m(r))}\left[m(r)+\frac{4\pi}{c^2}p(r)r^3\right]$$

$$\frac{dm(r)}{dr} = \frac{4\pi}{c^2}\varepsilon(r)r^2$$

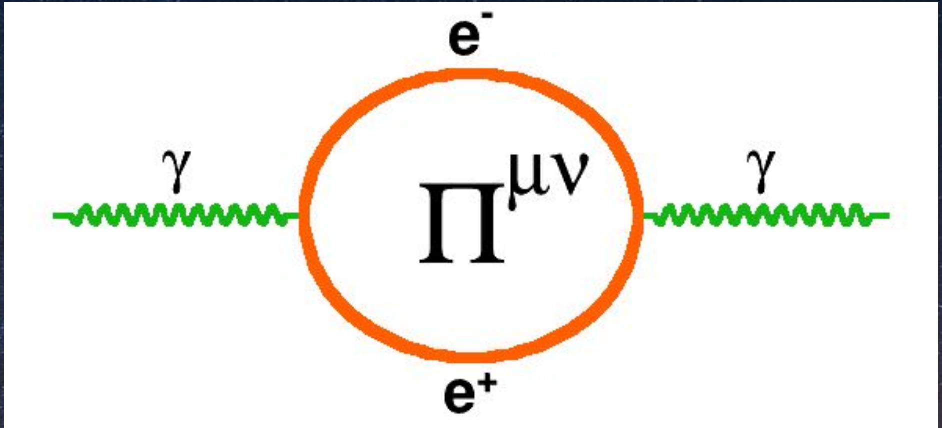
Arun Mathew and Malay K. Nandy 2017 Res. Astron. Astrophys. 17 061

2. Plasmon decay

γ *self-energy*

Alters poles in propagators

Modifies dispersion relations



Changes field strength

Appears in relevant diagrams

E. Braaten and D. Segel, Phys. Rev. D 48, 1478 (1993)

$$=4e^2\int \frac{d^3K}{(2\pi)^3}\frac{f_e(E_K)+f_{\bar{e}}(E_K)}{2E_K} \times \frac{Q\cdot K(K^\mu Q^\nu + K^\nu Q^\mu) - Q^2 K^\mu K^\nu - (Q\cdot K)^2 g^{\mu\nu}}{(Q\cdot K)^2 - Q^4/4}$$

Needs to be taken out!

2. Plasmon decay

Dispersion relations

In Coulomb gauge ($\nabla \cdot A=0$) and momentum ($\omega,\mathbf{k}$):

$D^{00} = (\mathbf{k}^2-\Pi_l)^{-1} \longrightarrow (\omega_l/\mathbf{k})^2 * Z_l / (\omega^2-\omega_l^2)$ as $\omega\rightarrow\omega_l$

$D^{ij} = (\omega^2-\mathbf{k}^2-\Pi_t)^{-1}(\delta_{ij}-\hat{k}^i\hat{k}^j) \longrightarrow Z_t / (\omega^2-\omega_t^2)\,(\delta_{ij}-\hat{k}^i\hat{k}^j)$ as $\omega\rightarrow\omega_t$

THEN:

$$\omega_t(k)^2 = k^2 + \Pi_t(\omega_t(k),k)$$

$$k^2 = \Pi_l(\omega_l(k),k)$$

E. Braaten and D. Segel, Phys. Rev. D 48, 1478 (1993)

2. Plasmon decay

Dispersion relations

Coupling strength of plasmon:

$Z_t(k) = [1 - \partial\Pi_t/\partial\omega^2(\omega_t(k),k)]^{-1}$

$Z_l(k) = [- \partial\Pi_l/\partial\omega^2(\omega_l(k),k)]^{-1} * k^2 / \omega_l(k)^2$

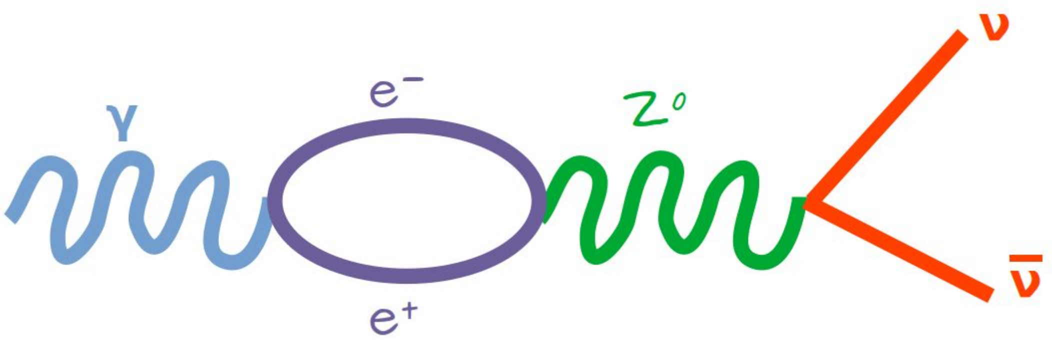
Polarization vectors:

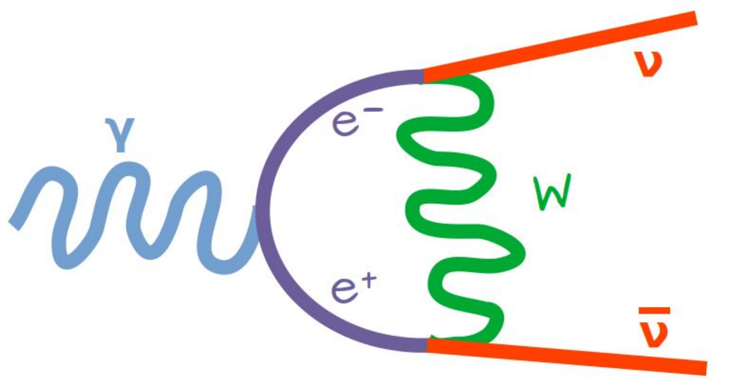
$\varepsilon^\mu(\mathbf{k},\lambda=0) = \omega_l(k) / k \sqrt{Z_l}(k)\ (1,0)^\mu$
$\varepsilon^\mu(\mathbf{k},\lambda=\pm1) = \sqrt{Z_t}(k)\ (0,\varepsilon_\pm(k))^\mu$

E. Braaten and D. Segel, Phys. Rev. D 48, 1478 (1993)

2. Plasmon decay

Decay into νs





$$\Gamma_l(q) = C_V^2 \frac{G_F^2}{48\pi^2\alpha} Z_l(q) \left(\omega_l(q)^2 - q^2\right)^2 \omega_l(q)$$

$$\Gamma_t(q) = \frac{G_F^2}{48\pi^2\alpha} Z_t(q) \frac{\omega_t(q)^2 - q^2}{\omega_t(q)} \times \left(C_V^2 \left(\omega_t(q)^2 - q^2\right)^2 + C_A^2 \Pi_A(\omega_t(q), q)^2 \right)$$

vector coefficients

axial coefficients

2. Plasmon decay

Emissivities

Energy per volume per time in form of neutrinos $\equiv \int \Gamma_\lambda \cdot \omega_\lambda \cdot n_B(\omega_\lambda)$

$$\mathcal{Q}_T = \left(\sum_\nu C_V^2\right) \frac{G_F^2}{48\pi^4 \alpha} \int_0^\infty dq\, q^2 Z_t(q) \left(\omega_t(q)^2 - q^2\right)^3 n_B(\omega_t(q))$$

$$\mathcal{Q}_A = \left(\sum_\nu C_A^2\right) \frac{G_F^2}{48\pi^4 \alpha} \int_0^\infty dq\, q^2 Z_t(q) \left(\omega_t(q)^2 - q^2\right) \times \Pi_A(\omega_t(q), q)^2 n_B(\omega_t(q))$$

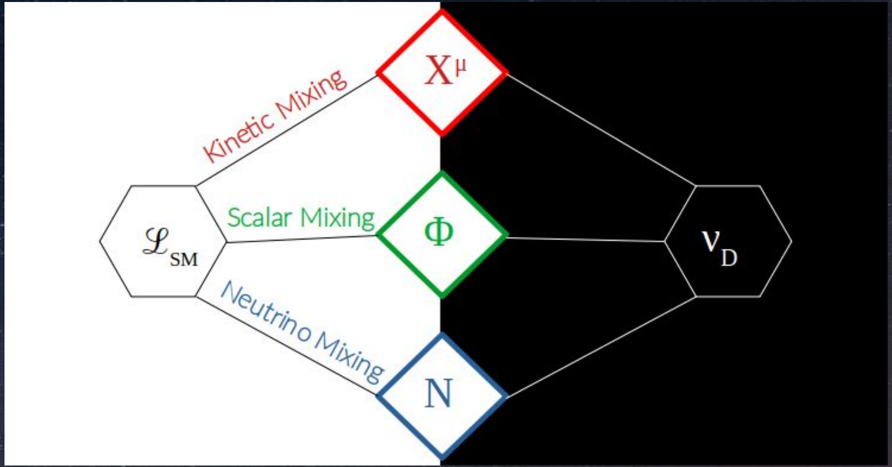
$$\mathcal{Q}_L = \left(\sum_\nu C_V^2\right) \frac{G_F^2}{96\pi^4 \alpha} \int_0^\infty dq\, q^2 Z_l(q) \left(\omega_l(q)^2 - q^2\right)^2 \times \omega_l(q)^2 n_B(\omega_l(q))$$

TOV Eqs + Salpeter

$$L_\nu = 4\pi \int_0^{R_\star} \mathcal{Q}(r) r^2 dr$$

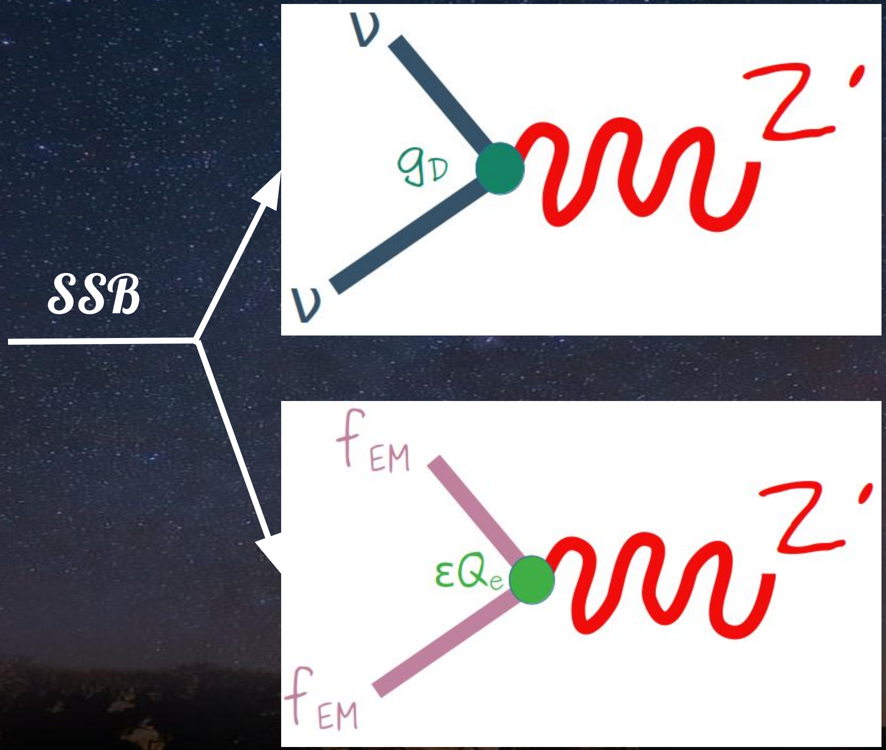
3. The Three Portal Model

Three Portal Model: Abdullahi, A. et al., Physics Letters B, 820, 136531 -> MB LEE, $(g\text{-}2)_\mu$



$$\mathscr{L} = \mathscr{L}_{\rm SM} + \overline{\nu}_D i \not{D}^x \nu_D$$
$$+ (D^x_\mu \Phi)^\dagger (D^{x\mu} \Phi) - V(\Phi, H)$$
$$- \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\epsilon}{2c_W} B_{\mu\nu} X^{\mu\nu}$$
$$+ \overline{N} i \not{\partial} N - [y^\alpha_\nu (\overline{L}_\alpha \cdot \widetilde{H}) N^c + \frac{\mu'}{2} \overline{N} N^c + y_N \overline{N} \nu^c_D \Phi + \mathrm{h.c.}]$$

3. The Three Portal Model



Dark Photon: Z'

$10\ \text{MeV} < m_{Z'} < 10\ \text{GeV}$

3. The Three Portal Model

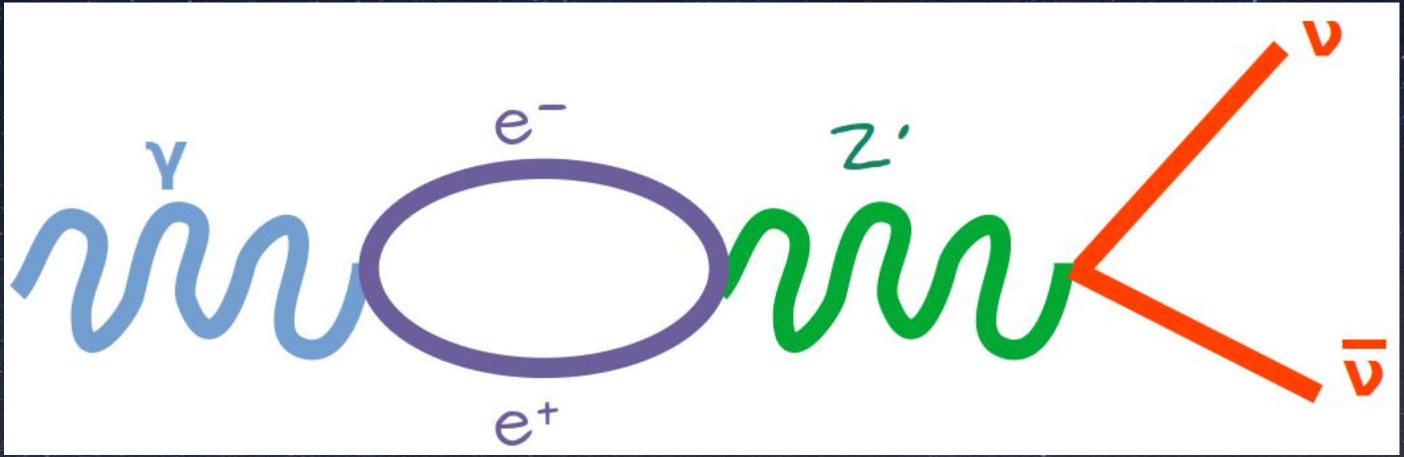
$$\begin{pmatrix} 0_{3\times 3} & m_{DR}^{\mathrm{T}} & m_{DL}^{\mathrm{T}} & 0 & 0 \\ m_{DR} & \mu'_R & \mu_D^{\mathrm{T}} & \Lambda_{RR}^{\mathrm{T}} & \Lambda_{RL}^{\mathrm{T}} \\ m_{DL} & \mu_D & \mu'_L & \Lambda_{LR}^{\mathrm{T}} & \Lambda_{LL}^{\mathrm{T}} \\ 0 & \Lambda_{RR} & \Lambda_{LR} & 0 & \mu_{DD}^{T} \\ 0 & \Lambda_{RL} & \Lambda_{LL} & \mu_{DD} & 0 \end{pmatrix} \text{ acting on: } \begin{pmatrix} \nu_\alpha \\ N_R^C \\ N_L \\ \nu_{DR}^C \\ \nu_{DL} \end{pmatrix}$$

neutrino mass matrix

sterile states

dark states

4. Plasmon decay through a dark photon



$$U_D \equiv U_{Di}$$

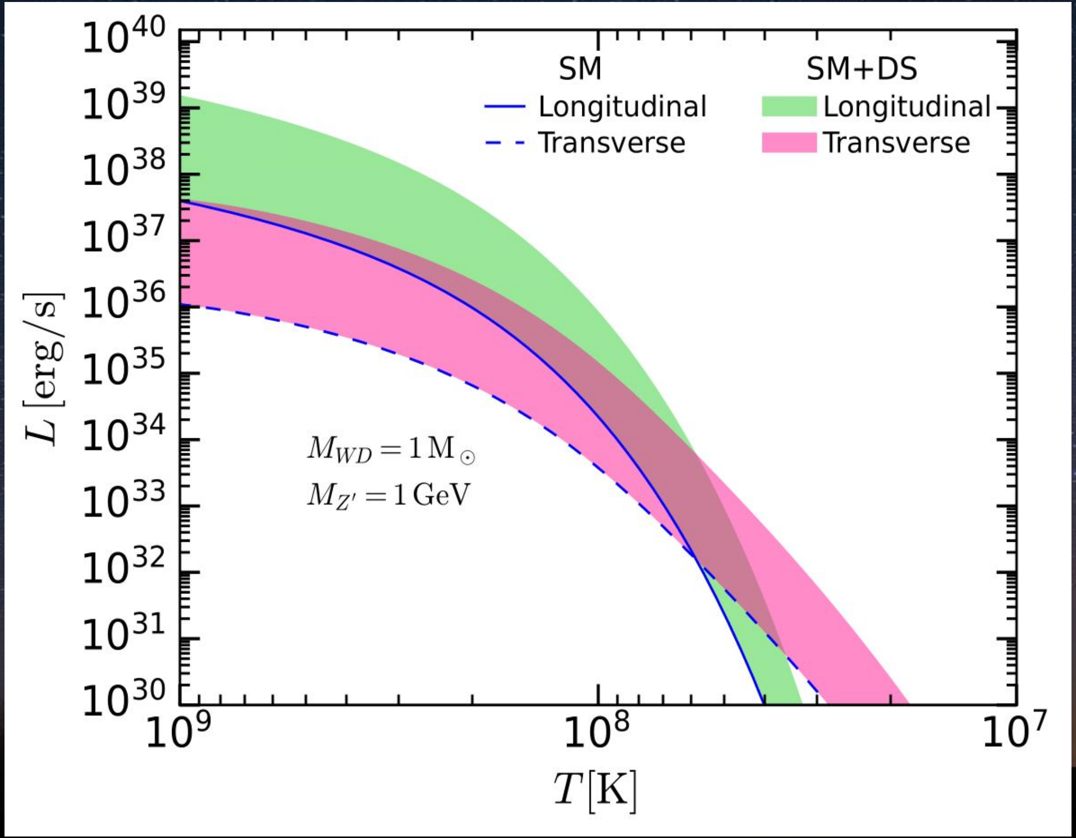
$$\sum c_V^2 \rightarrow \sum_{\alpha} \left(c_V^{\mathrm{SM}}\right)^2 + \frac{\sqrt{8\pi\alpha}}{G_F} \frac{\epsilon g_{\mathrm{D}} \left|U_{\mathrm{D}}\right|^2}{M_{Z'}^2 - Q^2} \Re\left[\sum_{\alpha, i, j} c_{V,\alpha}^{\mathrm{SM}} U_{\alpha i}^{*} U_{\alpha j}\right] + \frac{18\pi\alpha}{G_F^2} \frac{\epsilon^2 g_{\mathrm{D}}^2 \left|U_{\mathrm{D}}\right|^4}{(M_{Z'}^2 - Q^2)^2}$$

SM contribution

Interference term

Dark contribution

5. Results



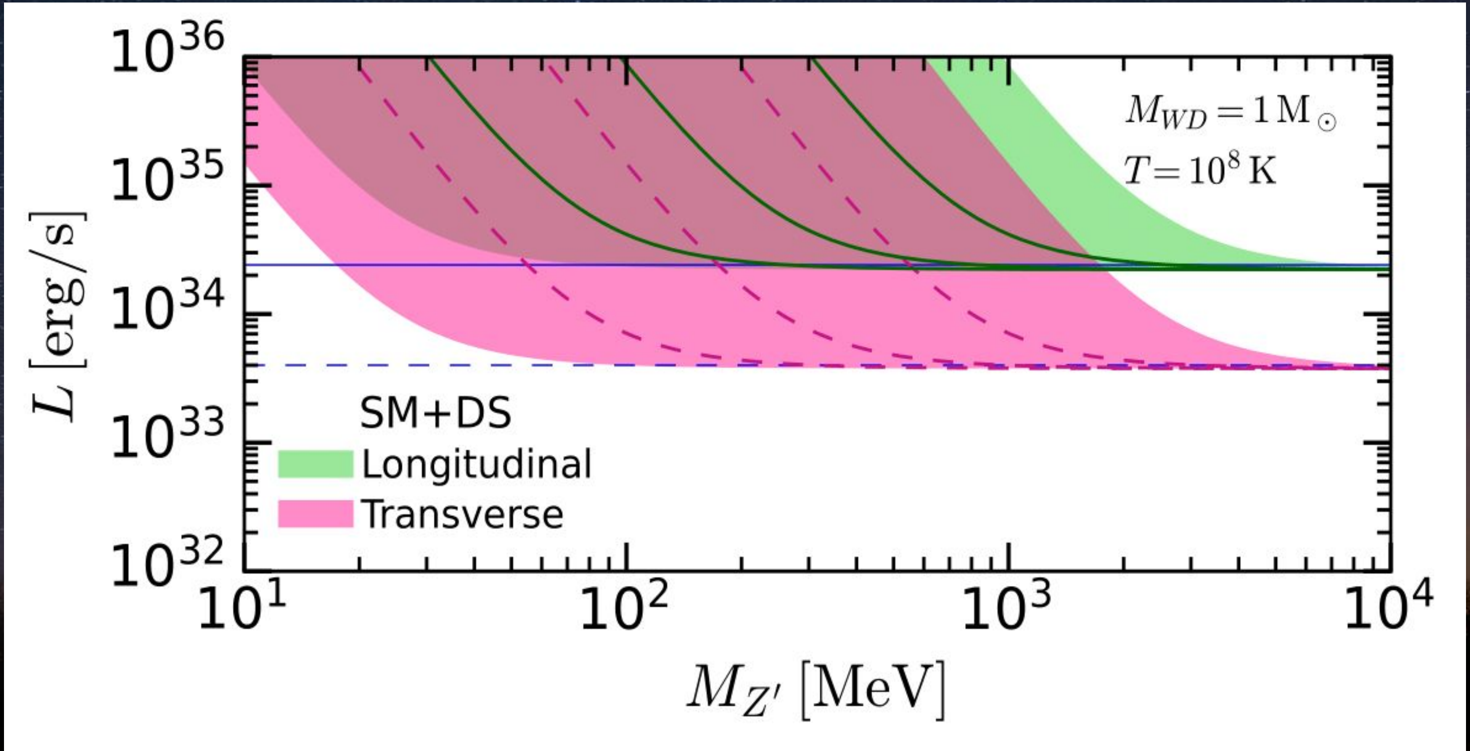
$M_{WD} = 1 M_\odot$
$10^{-8} < \varepsilon g_D |U_D|^2 < 10^{-4}$

$M_{Z'} = 1\,\mathrm{GeV}$

5. Results

$M_{WD} = 1 M_{\odot}$

$10^{-8} < \varepsilon g_D |U_D|^2 < 10^{-4}$



$T = 10^{8} K$

5. Results

$M_{WD} = 1 M_\odot$

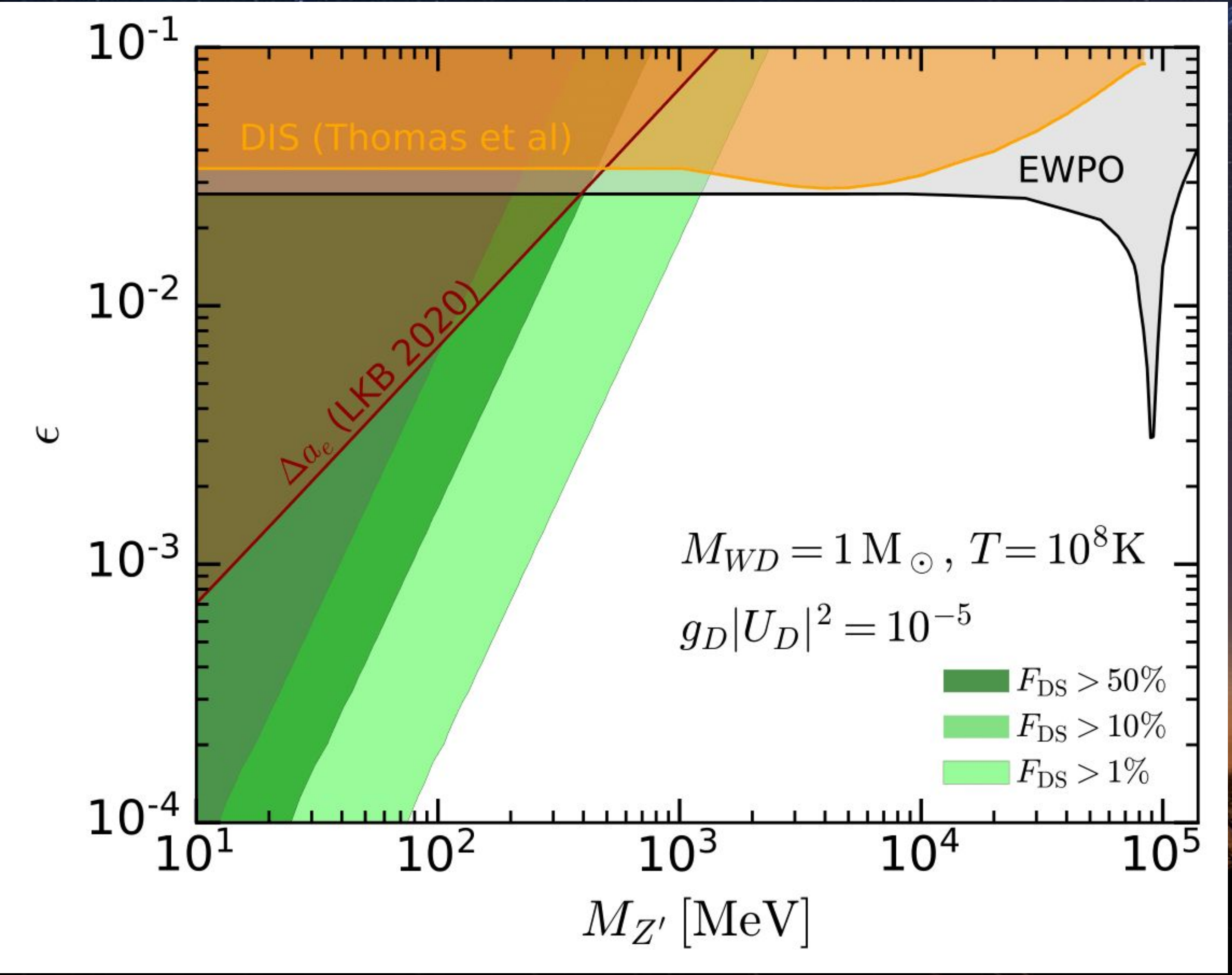
$g_D |U_D|^2 = 10^{-5}$

$T = 10^8 K$

$10 < M_{Z'} < 10^4$ MeV

$(M_{Z'} / M_Z)^2 << 1$

$F_{DS} \equiv (L_{DS+SM} - L_{SM}) / L_{SM}$



6. Conclusions

1. We computed the luminosity of a WD of 1 $M_\odot$ and considered the scenario of a dark photon contribution to its cooling (from 3 Portal).
2. Depending on the parameters, the luminosity from new physics can really exceed the SM one.
3. We looked for limits of 1%,10% and 50% of extra dark contribution.
4. Cooling of WDs is REALLY promising to searching for new physics: a very compact object whose EoS is approximately well understood.

Grazie a tutti!

Extra information

Plasma in WD

E. Braaten and D. Segel, Phys. Rev. D 48, 1478 (1993)

Plasma frequency
v ≡ p/E

$$\omega_p^2 = \frac{4\alpha}{\pi}\int_0^\infty dp\,\frac{p^2}{E}\left(1-\frac{1}{3}v^2\right)\left[n_F(E) + \bar{n}_F(E)\right]$$