Constraints on Pseudo-Nambu-Goldstone dark matter from direct detection experiment and neutron star reheating temperature

Yu-Pan Zeng 曾育盼

School of Physics, Sun Yat-Sen University

October 27, 2021

Overview

Introduction

PNGDM model

Direct Detection

Neutron Star

Results and Conclusion

Motivation

- WIMP–Direct-Detection tension
- Pseudo-Nambu-Goldstone dark matter (PNGDM) model with cancellation mechanism
- cancellation mechanism: zero direct detection in zero momentum transfer limit
- momentum transfer:
  $q = \sqrt{-t} = \sqrt{2m_f E_R} \sim 35\ \text{MeV}\ (E_R \sim 5\ \text{keV})$
- $\text{NS} \xrightarrow{capture} \text{DM} \xrightarrow{reheat} \text{NS} \xrightarrow{constraint} \text{DM-neutron interaction}$
- no energy threshold
- NS acceleration

Motivation

- WIMP–Direct-Detection tension
- Pseudo-Nambu-Goldstone dark matter (PNGDM) model with cancellation mechanism
- cancellation mechanism: zero direct detection in zero momentum transfer limit
- momentum transfer:
  $q = \sqrt{-t} = \sqrt{2m_f E_R} \sim 35$ MeV $(E_R \sim 5$ keV$)$
- NS $\xrightarrow{capture}$ DM $\xrightarrow{reheat}$ NS $\xrightarrow{constraint}$ DM-neutron interaction
- no energy threshold
- NS acceleration

Motivation

- WIMP–Direct-Detection tension
- Pseudo-Nambu-Goldstone dark matter (PNGDM) model with cancellation mechanism
- cancellation mechanism: zero direct detection in zero momentum transfer limit
- momentum transfer: $q = \sqrt{-t} = \sqrt{2m_f E_R} \sim 35$ MeV ($E_R \sim 5$ keV)
- NS $\xrightarrow{capture}$ DM $\xrightarrow{reheat}$ NS $\xrightarrow{constraint}$ DM-neutron interaction
- no energy threshold
- NS acceleration

Motivation

- WIMP–Direct-Detection tension
- Pseudo-Nambu-Goldstone dark matter (PNGDM) model with cancellation mechanism
- cancellation mechanism: zero direct detection in zero momentum transfer limit
- momentum transfer:
  $q = \sqrt{-t} = \sqrt{2m_f E_R} \sim 35$ MeV $(E_R \sim 5$ keV$)$
- NS $\xrightarrow{capture}$ DM $\xrightarrow{reheat}$ NS $\xrightarrow{constraint}$ DM-neutron interaction
- no energy threshold
- NS acceleration

Motivation

- WIMP–Direct-Detection tension
- Pseudo-Nambu-Goldstone dark matter (PNGDM) model with cancellation mechanism
- cancellation mechanism: zero direct detection in zero momentum transfer limit
- momentum transfer:
  $q = \sqrt{-t} = \sqrt{2m_f E_R} \sim 35$ MeV $(E_R \sim 5$ keV$)$
- NS $\overset{capture}{\longrightarrow}$ DM $\overset{reheat}{\longrightarrow}$ NS $\overset{constraint}{\longrightarrow}$ DM-neutron interaction
- no energy threshold
- NS acceleration

Motivation

- WIMP–Direct-Detection tension
- Pseudo-Nambu-Goldstone dark matter (PNGDM) model with cancellation mechanism
- cancellation mechanism: zero direct detection in zero momentum transfer limit
- momentum transfer:
  $q = \sqrt{-t} = \sqrt{2m_f E_R} \sim 35$ MeV $(E_R \sim 5$ keV$)$
- NS $\stackrel{capture}{\longrightarrow}$ DM $\stackrel{reheat}{\longrightarrow}$ NS $\stackrel{constraint}{\longrightarrow}$ DM-neutron interaction
- no energy threshold
- NS acceleration

Motivation

- WIMP–Direct-Detection tension
- Pseudo-Nambu-Goldstone dark matter (PNGDM) model with cancellation mechanism
- cancellation mechanism: zero direct detection in zero momentum transfer limit
- momentum transfer:
  $q = \sqrt{-t} = \sqrt{2m_f E_R} \sim 35\ \text{MeV}\ (E_R \sim 5\ \text{keV})$
- $\text{NS} \xrightarrow{capture} \text{DM} \xrightarrow{reheat} \text{NS} \xrightarrow{constraint} \text{DM-neutron interaction}$
- no energy threshold
- NS acceleration

PNGDM AND NS WORKS

- scalar portal PNGDM: SM/2HDM+complex scalar with U(1), SO(N) and SU(N) symmetry+soft breaking term[1]
- vector portal cancellation model: SM/$U(1)_{B-L}$ +$U(1)_X$[2]
- NS has been applied to constraint WIMPs, SIMPs, Pure Higgsinos, EFT, Inelastic Dark matter...[3]
- this method can be applied to more models
- DM velocity in PNGDM model is connected to momentum transfer and thus cross section

[1] **Gross2017**; **Alanne:2018zjm**; **Karamitros:2019ewv**; **Jiang:2019soj**.

[2] **Cai:2021evx**.

[3] **Baryakhtar:2017dbj**; Raj, Tanedo, and Yu, "Neutron stars at the dark matter direct detection frontier"; Bell, Busoni, and Robles, "Heating up neutron stars with inelastic dark matter".

PNGDM and NS works

- scalar portal PNGDM: SM/2HDM+complex scalar with U(1), SO(N) and SU(N) symmetry+soft breaking term[1]
- vector portal cancellation model: SM/$U(1)_{B-L}$ +$U(1)_X$[2]
- NS has been applied to constraint WIMPs, SIMPs, Pure Higgsinos, EFT, Inelastic Dark matter…[3]
- this method can be applied to more models
- DM velocity in PNGDM model is connected to momentum transfer and thus cross section

[1] **Gross2017**; **Alanne:2018zjm**; **Karamitros:2019ewv**; **Jiang:2019soj**.

[2] **Cai:2021evx**.

[3] **Baryakhtar:2017dbj**; Raj, Tanedo, and Yu, "Neutron stars at the dark matter direct detection frontier"; Bell, Busoni, and Robles, "Heating up neutron stars with inelastic dark matter".

PNGDM AND NS WORKS

- scalar portal PNGDM: SM/2HDM+complex scalar with U(1), SO(N) and SU(N) symmetry+soft breaking term[1]
- vector portal cancellation model: SM/$U(1)_{B-L}$ +$U(1)_X$[2]
- NS has been applied to constraint WIMPs, SIMPs, Pure Higgsinos, EFT, Inelastic Dark matter. . . [3]
- this method can be applied to more models
- DM velocity in PNGDM model is connected to momentum transfer and thus cross section

[1] **Gross2017**; **Alanne:2018zjm**; **Karamitros:2019ewv**; **Jiang:2019soj**.

[2] **Cai:2021evx**.

[3] **Baryakhtar:2017dbj**; Raj, Tanedo, and Yu, "Neutron stars at the dark matter direct detection frontier"; Bell, Busoni, and Robles, "Heating up neutron stars with inelastic dark matter".

PNGDM AND NS WORKS

- scalar portal PNGDM: SM/2HDM+complex scalar with U(1), SO(N) and SU(N) symmetry+soft breaking term[1]
- vector portal cancellation model: SM/$U(1)_{B-L}$ +$U(1)_X$[2]
- NS has been applied to constraint WIMPs, SIMPs, Pure Higgsinos, EFT, Inelastic Dark matter. . . [3]
- this method can be applied to more models
- DM velocity in PNGDM model is connected to momentum transfer and thus cross section

[1]**Gross2017**; **Alanne:2018zjm**; **Karamitros:2019ewv**; **Jiang:2019soj**.

[2]**Cai:2021evx**.

[3]**Baryakhtar:2017dbj**; Raj, Tanedo, and Yu, "Neutron stars at the dark matter direct detection frontier"; Bell, Busoni, and Robles, "Heating up neutron stars with inelastic dark matter".

PNGDM AND NS WORKS

- scalar portal PNGDM: SM/2HDM+complex scalar with U(1), SO(N) and SU(N) symmetry+soft breaking term[1]
- vector portal cancellation model: SM/U(1)$_{B-L}$ +U(1)$_X$[2]
- NS has been applied to constraint WIMPs, SIMPs, Pure Higgsinos, EFT, Inelastic Dark matter…[3]
- this method can be applied to more models
- DM velocity in PNGDM model is connected to momentum transfer and thus cross section

[1] **Gross2017**; **Alanne:2018zjm**; **Karamitros:2019ewv**; **Jiang:2019soj**.

[2] **Cai:2021evx**.

[3] **Baryakhtar:2017dbj**; Raj, Tanedo, and Yu, "Neutron stars at the dark matter direct detection frontier"; Bell, Busoni, and Robles, "Heating up neutron stars with inelastic dark matter".

Overview

Introduction

PNGDM model

Direct Detection

Neutron Star

Results and Conclusion

Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \partial^\mu S^\dagger \partial_\mu S + \mu_S^2 |S|^2 - \lambda_S |S|^4 - 2\lambda_{SH} |H|^2 |S|^2 + \frac{{\mu'_S}^2}{4} S^2 + \text{h.c.}$$

$$V = -\mu^2 |H|^2 - \mu_S^2 |S|^2 + \lambda |H|^4 + \lambda_S |S|^4 + 2\lambda_{SH} |H|^2 |S|^2 - \frac{{\mu'_S}^2}{4} S^2 + \text{h.c.}$$

$$H = (0, \frac{v_h + h}{\sqrt{2}})^T, \; S = \frac{v_s + s + i\chi}{\sqrt{2}}$$

MASS SPECTRUM

$$
\begin{aligned}
& \frac{1}{2}\begin{pmatrix} h & s \end{pmatrix} OO^T \begin{pmatrix} 2\lambda v_h^2 & 2\lambda_{SH} v_h v_s \\ 2\lambda_{SH} v_h v_s & 2\lambda_S v_s^2 \end{pmatrix} OO^T \begin{pmatrix} h \\ s \end{pmatrix} \\
= \quad & \frac{1}{2}\begin{pmatrix} h_1 & h_2 \end{pmatrix} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \; \frac{1}{2}{\mu'_S}^2 \chi^2.
\end{aligned}
$$

$$
O = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \; \tan 2\theta = \frac{2\lambda_{HS} v_h v_s}{\lambda_S v_s^2 - \lambda v_h^2}.
$$

$$
m_{1,2}^2 = \lambda v_h^2 + \lambda_S v_s^2 \pm \sqrt{(\lambda v_h^2 + \lambda_S v_s^2) - 4\lambda v_h^2 \lambda_S v_s^2 + 4\lambda_{SH}^2 v_h^2 v_s^2}.
$$

AMPLITUDE

$$\frac{m_f}{v_h} h\bar{f}f = \frac{m_f}{v_h}(h_1 O_{11} + h_2 O_{12})\bar{f}f,$$

$$\begin{pmatrix} h & s \end{pmatrix} \begin{pmatrix} \lambda_{HS} v_h \\ \lambda_S v_s \end{pmatrix} \chi^2 = \frac{1}{2v_s} \begin{pmatrix} h_1 & h_2 \end{pmatrix} \begin{pmatrix} O_{21} m_1^2 \\ O_{22} m_2^2 \end{pmatrix} \chi^2.$$

$$\begin{aligned} i\mathcal{M} &= \frac{m_f}{v_h v_s}\left(\frac{O_{11}O_{21}m_1^2}{t - m_1^2} + \frac{O_{12}O_{22}m_2^2}{t - m_2^2}\right)\bar{u}(p_3)u(p_1) \\ &= \frac{m_f}{v_h v_s} \frac{tO_{12}O_{22}(m_2^2 - m_1^2)}{(t - m_1^2)(t - m_2^2)}\bar{u}(p_3)u(p_1) \end{aligned}$$

$m_1 \to m_h,\ m_2 \sim O(10)$ MeV

GENERAL VIEW

$$\begin{pmatrix} h_1 & h_2 & \dots & s \end{pmatrix} OO^T \begin{pmatrix} \dots & a \\ \dots & b \\ \dots & \dots \\ \dots & x \end{pmatrix} OO^T \begin{pmatrix} h_1 \\ h_2 \\ \dots \\ s \end{pmatrix}$$

$$= \begin{pmatrix} hm_1 & hm_2 & \dots \end{pmatrix} diag\{m_1^2, m_2^2, \dots\} \begin{pmatrix} hm_1 \\ hm_2 \\ \dots \end{pmatrix}$$

$$\begin{pmatrix} h_1 & h_2 & \dots & s \end{pmatrix} OO^T \begin{pmatrix} a/v_s \\ b/v_s \\ \dots \\ x/v_s \end{pmatrix} k\chi^2 = \begin{pmatrix} hm_1 & hm_2 & \dots \end{pmatrix} \begin{pmatrix} m_1^2 O_{n1} \\ m_2^2 O_{n2} \\ \dots \end{pmatrix} \frac{k}{v_s}\chi^2$$

$$\lambda_i h_i \bar{f} f = \lambda_i O_{ij} hm_j \bar{f} f \to \mathcal{M} \propto \frac{\lambda_i k}{v_s} \frac{O_{ij} m_j^2 O_{nj}}{t - m_j^2} \xrightarrow{t \to 0} \frac{\lambda_i k}{v_s} O_{ij} O_{nj} = 0$$

Overview

DM-quark to DM-nucleon

$$\frac{d\sigma_f}{dE_r} = \frac{1}{E_r^{max}} \frac{1}{16\pi s} \frac{2m_f^2}{v_h^2 v_s^2} \frac{t^2(m_2^2 - m_1^2)^2 \sin^2\theta \cos^2\theta}{(t - m_1^2)^2 (t - m_2^2)^2} (2m_f^2 - \frac{t}{2}),$$

$$f_{l\in\{p,n\}} = m_l \left(\sum_{q=u,d,s} f_q^l \frac{\lambda_{\chi q}}{m_q} + \frac{2}{27} f_G^l \sum_{q=c,b,t} \frac{\lambda_{\chi q}}{m_q} \right)$$

$$f_u^p = 0.026,\ f_d^p = 0.038,\ f_s^p = f_s^n = 0.044,$$
$$f_u^n = 0.018,\ f_d^n = 0.056,\ f_G^l = 1 - \sum_{q=u,d,s} f_q^l$$

$$f_q^l(t) = \frac{f_q^l}{(1 - t/Q_0^2)^2},\ f_G^l(t) = \frac{f_G^l}{(1 - t/Q_0^2)^2}$$

DM-nucleon to DM-Nucleus

$$\lambda_{\chi N} = Zf_p + (A-Z)f_n,$$

$$\frac{d\sigma_N}{dE_R} = \left.\frac{d\sigma_N}{dE_R}\right|_{\rm PLN} F^2(E_R),$$

$$\left.\frac{d\sigma_N}{dE_R}\right|_{\rm PLN} = \frac{1}{E_R^{max}}\frac{1}{16\pi s}\frac{2}{v_h^2 v_s^2}\frac{t^2(m_2^2-m_1^2)^2\sin^2\theta\cos^2\theta}{(t-m_1^2)^2(t-m_2^2)^2}(2m_N^2-\frac{t}{2})$$
$$\times\left(Zm_p\left(\sum_{q=u,d,s} f_q^p + \frac{2}{9}f_G^p\right) + (A-Z)m_n\left(\sum_{q=u,d,s} f_q^n + \frac{2}{9}f_G^n\right)\right)^2,$$

$$F^2(E_R) = \frac{e^{-u}}{A^2}\left(A + \sum_{n=1}^{5} c_n u^n\right)^2, \text{ with } u = \frac{m_N E_R}{m_{n0}(45A^{-\frac{1}{3}} - 25A^{-\frac{2}{3}})\text{ MeV}},$$

where m_{n0} is the unit necleon mass, and
$c_1 = -132.841,\ c_2 = 38.4859,\ c_3 = -4.08455,\ c_4 = 0.153298,\ c_5 = -0.0013897.$

EVENT RATE

$$\frac{dR}{dE_R} = N_T \int \frac{\rho_\chi v}{m_\chi} \frac{d\sigma_N}{dE_R} f(\vec{v}, \vec{v}_e) d^3 v,$$

$$f(\vec{v}, \vec{v}_e) = \frac{1}{N_0} e^{-\frac{(\vec{v}+\vec{v}_e)^2}{v_0^2}} = \frac{1}{N_0} e^{-\frac{(v^2+v_e^2+2vv_e\cos\theta)^2}{v_0^2}},$$

$$N_0 = \pi^{\frac{3}{2}} v_0^3 \left(\mathrm{erf}\left(\frac{v_{esc}}{v_0}\right) - \frac{2v_{esc}}{\pi^{\frac{1}{2}} v_0} e^{-\frac{v_{esc}^2}{v_0^2}} \right)$$

$$\int d^3 v = 2\pi \begin{cases} \int_{v_{min}}^{v_{esc}-v_e} v^2 dv \int_{-1}^{1} d\cos\theta \\ + \int_{v_{esc}-v_e}^{v_{esc}+v_e} v^2 dv \int_{-1}^{c_*} d\cos\theta, & v_{min} < v_{esc} - v_e \\ \int_{v_{min}}^{v_{esc}+v_e} v^2 dv \int_{-1}^{c_*} d\cos\theta, & v_{esc} - v_e < v_{min} < v_{esc} + v_e \end{cases}$$

where $c_* = \cos\theta_* = \frac{v_{esc}^2 - v^2 - v_e^2}{2vv_e}$

POINT LIKE NUCLEUS LIMIT AND ZERO MOMENTUM LIMIT

$$\frac{d\sigma}{dE_R} = \left.\frac{d\sigma}{dE_R}\right|_{\mathrm{PLN}} F^2(E_R),$$

$$\frac{d\sigma}{dE_R} = \frac{m_N \sigma_0}{2\mu_N^2 v_\chi^2} F^2(E_R),$$

$$\sigma_0 = \int_0^{\frac{2\mu_N^2 v_\chi^2}{m_N}} \left.\frac{d\sigma}{dE_R}\right|_{E_R=0} dE_R$$

$$\frac{d\sigma}{dE_R} = \left.\frac{d\sigma}{dE_R}\right|_{E_R=0} F^2(E_R)$$

Overview

NEUTRON STAR

$$M = 1.5M_{\odot},\ R = 10\text{km}\ \sigma_t = \pi R^2 m_n / M \approx 1.76 * 10^{-45}\text{cm}^2$$

$$r_c = \min(\sigma/\sigma_t, 1),\ \text{for } 1\text{ GeV} \leq m_\chi \leq 10^6\text{ GeV}$$

$$b = R\frac{v_{es}}{v_\chi}(1 - 2GM/R)^{-\frac{1}{2}},\ \dot{n} = \pi b^2 \frac{\rho_\chi}{m_\chi} v_\chi$$

$$E_t = m_\chi\left(\frac{1}{\sqrt{1-\omega^2}} - 1\right),\ \omega = \sqrt{v_\chi^2 + v_{es}^2}$$

$$\dot{E} = \pi b^2 \frac{\rho_\chi}{m_\chi} E_t v_\chi$$

TEMPERATURE

$$T = \left(\frac{\int f(\vec{v}_\chi, \vec{v}_N)\pi b^2 \frac{\rho_\chi}{m_\chi} E_t v_\chi r_c}{4\pi\sigma_{SB}R^2}\right)^{\frac{1}{4}}(1-2GM/R)^{\frac{1}{2}}$$
$$= \left(\int f(\vec{v}_\chi, \vec{v}_N) r_c \frac{\rho_\chi E_t v_{es}^2}{4m_\chi \sigma_{SB} v_\chi}(1-2GM/R)\right)^{\frac{1}{4}}$$

[4] calculated the maximal temperature

$$T_{max} = \left(\frac{\rho_\chi E_t v_{es}^2}{4m_\chi \sigma_{SB}\bar{v}_\chi}(1-2GM/R)\right)^{\frac{1}{4}}$$

to be about 1750 K with $\bar{v}_\chi$ being the mean velocity of DM. Furthermore,[5] considered the distribution of $\frac{1}{v_\chi}$ and resulted in a T_{max} of 1700 K. Here we have also taken into account the velocity-dependent r_c and E_t.

[4]Baryakhtar et al., "Dark Kinetic Heating of Neutron Stars and an Infrared Window on WIMPs , SIMPs , and Pure Higgsinos".

[5]Bell, Busoni, and Robles, "Heating up neutron stars with inelastic dark matter".

Overview

PARAMETERS SETTING AND METHOD

	m_2	m_χ	λ_S	λ_{SH}
PNG1	variable	variable	0.1	0.01
PNG2	1 GeV	variable	0.1	variable

Table: Two scenarios of parameters used to constrain PNGDM model.

method to calculate DM relic abundance $\Omega_\chi h^2$
Lagrangian→`FeynRules 2`→`MadGraph` plugin `MadDM`

RESULTS

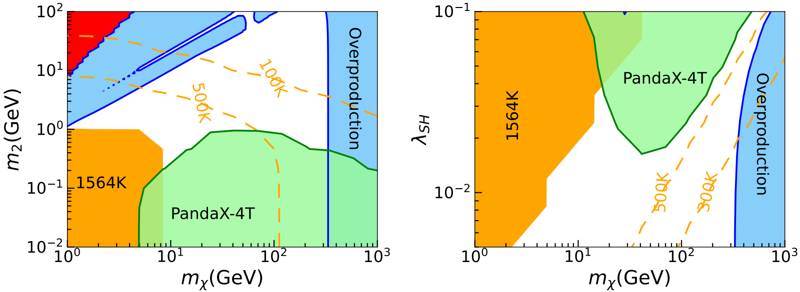


Figure: Constraints on the PNGDM model from the direct detection and NS temperature for two scenarios PNG1 and PNG2 are shown in the left and right panels, respectively. Green areas are excluded by the PandaX-4T experiment. Orange areas are parameters space corresponding to the maximal NS reheating temperature of 1564 K, while reheating temperatures of 100 K, 300 K and 500 K are labeled by dashed orange lines, respectively. Light blue areas are excluded by the Planck experiment, and the red area on the left panel is parameter space where freeze-out occurs too early, leading to a too big DM relic abundance. The observed DM relic abundance lies in the blue lines, except for the one between the red and light blue area on the left panel, which is caused by the default setting of the DM relic abundance in the red area as −1.

Conclusion

- we have introduced two new phenomenology constraints to the PNGDM model: direct detection and NS temperature constraints
- The current direct detection can exclude large parameters space of the PNGDM model, while the NS temperature observations have very good sensitivities.
- These two phenomenology constraints can be applied to different PNGDM models in the same paradigm.
- Besides, the direct detection of non-zero momentum transfer parameters space is worth exploring for other momentum-suppressing models.
- The effects of full integral of velocity distribution in NS constraint are expected to be significant in dealing with relativistic DM.

Different view of cancellation mechanism: non-linear representation

$$S = \frac{v_s + s}{\sqrt{2}} e^{i\frac{\chi}{v_s}} ,$$

$$\begin{aligned} V_{soft} &= -\frac{\mu_S'^2}{4}(v_s + s)^2 \cos\left(\frac{2\chi}{v_s}\right) \\ &= -\frac{\mu_S'^2}{4} v_s^2 \left(1 + \frac{2s}{v_s} + \frac{s^2}{v_s^2}\right)\left(1 - \frac{2\chi^2}{v_s^2} + \ldots\right) , \end{aligned}$$

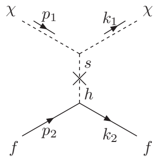
$$m_\chi^2 = \mu_S'^2 \, , \mathcal{L}^{(1)}_{s\chi^2} = -\frac{m_\chi^2}{v_s} s\chi^2 ,$$

$$\begin{aligned} \mathcal{L}_{kin} &= (\partial_\mu S)^* \partial^\mu S \\ &= \frac{1}{2}(\partial_\mu s)^2 + \frac{1}{2}(\partial_\mu \chi)^2 + \frac{s}{v_s}(\partial_\mu \chi)^2 + \frac{1}{2}\frac{s^2}{v_s^2}(\partial_\mu \chi)^2 . \end{aligned}$$

Different view of cancellation mechanism: non-linear representation

$$\mathcal{L}^{(2)}_{s\chi^2} = \frac{s}{v_s}(\partial_\mu \chi)^2 = \frac{1}{v_s}\left\{\partial_\mu\left[s\chi\partial^\mu\chi - \frac{1}{2}(\partial^\mu s)\chi^2\right] + \frac{1}{2}(\partial^2 s)\chi^2 - s\chi\partial^2\chi\right\} .$$

$$\mathcal{L}_{s\chi^2} = \frac{1}{2v_s}(\partial^2 s)\chi^2 - \frac{s}{v_s}\chi(\partial^2 + m_\chi^2)\chi .$$



$$i\mathcal{M} \sim \left(\frac{-it}{v_s}\right)\frac{i}{t-m_s^2}\left(-i2\lambda_{SH} v v_s\right)\frac{i}{t-m_h^2}\left(\frac{-im_f}{v}\right)\bar{u}_f(k_2)u_f(p_2) ,$$

Different view of cancellation mechanism:define new particle

$$-\mathcal{L} \supset \lambda_H v^2 h^2 + 2\lambda_{SH} v v_s h s + \lambda_S v_s^2 s^2 + \frac{1}{2} m_\chi^2 \chi^2 + \lambda_{SH} v h \chi^2 + \lambda_S v_s s \chi^2 \,,$$

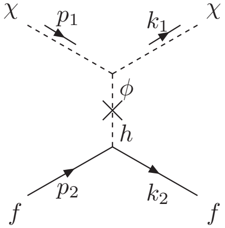
$$-\mathcal{L} \supset \left(\lambda_H - \frac{\lambda_{SH}^2}{\lambda_S}\right) v^2 h^2 + \frac{1}{\lambda_S}(\lambda_{SH} v h + \lambda_S v_s s)^2 + \frac{1}{2} m_\chi^2 \chi^2 + (\lambda_{SH} v h + \lambda_S v_s s)\chi^2$$

define new scalar $\phi \equiv (\lambda_{SH} v h + \lambda_S v_s s)/\lambda_S v_s$

$$\mathcal{L} \supset \frac{1}{2}\left[1 + \left(\frac{\lambda_{SH} v}{\lambda_S v_s}\right)^2\right] \partial_\mu h \partial^\mu h + \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - \frac{\lambda_{SH} v}{\lambda_S v_s}\partial_\mu h \partial^\mu \phi - \left(\lambda_H - \frac{\lambda_{SH}^2}{\lambda_S}\right) v^2 h^2 - \lambda_S v_s^2 \phi^2 - \frac{1}{2} m_\chi^2 \chi^2 - \lambda_S v_s \phi \chi^2,$$

DIFFERENT VIEW OF CANCELLATION MECHANISM:DEFINE NEW PARTICLE

$$i g_{h\phi} q^2 = -i \frac{\lambda_{SH} v}{\lambda_S v_s} q^2$$



$$D_\phi(q) = \frac{i}{q^2 - m_\phi^2}, \qquad D_h(q) = \frac{i}{\xi_h q^2 - m_h^2},$$

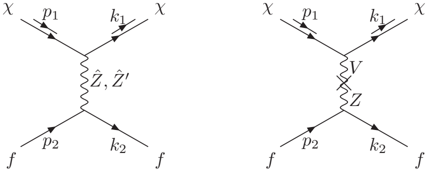
$$i\mathcal{M} = (2i\lambda_S v_s) \frac{i}{t - m_\phi^2} \left(-i \frac{\lambda_{SH} v}{\lambda_S v_s} t \right) \frac{i}{\xi_h t - m_h^2} \left(-i \frac{m_q}{v} \right) \bar{u}(k_2) u(p_2) + \ldots$$

VECTOR PORTAL CANCELLATION MECHANISM

$SU(2)_L \times U(1)_Y \times U(1)_X$ MODEL

$$
\begin{aligned}
D_\mu H &= \left[\partial_\mu - i\begin{pmatrix} eA_\mu + \frac{g c_{2W}}{2c_W} Z_\mu & \frac{g W^+_\mu}{\sqrt{2}} \\ \frac{g W^-_\mu}{\sqrt{2}} & \frac{g}{2c_W} Z_\mu \end{pmatrix}\right]\begin{pmatrix} H^+ \\ H^0 \end{pmatrix}, \\
D_\mu \Phi &= \left[\partial_\mu - i\begin{pmatrix} eA_\mu + \frac{g c_{2W}}{2c_W} Z_\mu + g_X X_\mu & \frac{g W^+_\mu}{\sqrt{2}} \\ \frac{g W^-_\mu}{\sqrt{2}} & \frac{g}{2c_W} Z_\mu + g_X X_\mu \end{pmatrix}\right]\begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}, \\
D_\mu \Psi &= \left[\partial_\mu - i\begin{pmatrix} eA_\mu + \frac{g c_{2W}}{2c_W} Z_\mu + g_X X_\mu & \frac{g W^+_\mu}{\sqrt{2}} \\ \frac{g W^-_\mu}{\sqrt{2}} & \frac{g}{2c_W} Z_\mu + g_X X_\mu \end{pmatrix}\right]\begin{pmatrix} \chi^+ \\ \chi \end{pmatrix},
\end{aligned}
$$

PROOF OF CANCELLATION MECHANISM



define new vector $V_\mu = (gZ_\mu/(2c_W) + g_X X_\mu)/g_X$

$$\begin{aligned}\mathcal{L} \supset\ & -\frac{1}{4}\left(1+\frac{g^2}{4c_W^2 g_X^2}\right)(\partial_\mu Z_\nu - \partial_\nu Z_\mu)^2 - \frac{1}{4}(\partial_\mu V_\nu - \partial_\nu V_\mu)^2 \\ & + \frac{g}{4c_W g_X}(\partial_\mu V_\nu - \partial_\nu V_\mu)(\partial^\mu Z^\nu - \partial^\nu Z^\mu) \\ & + \sum_f \bar{f}(g^V_{Z\bar{f}f}\gamma^\mu + g^A_{Z\bar{f}f}\gamma^\mu\gamma^5)fZ_\mu + g_X\overline{\chi}\gamma^\mu\chi V_\mu\ .\end{aligned}$$