Capture of Electroweak Multiplet Dark Matter in Neutron Stars

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Based on MF, K. Hamaguchi, N. Natsumi, J. Zheng, [arXiv:2204.02238]

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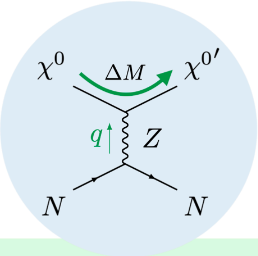
Today's Talk

We studied search strategy for **Electroweak Multiplet Dark Matter** (DM) in **Effective Field Theory (EFT) approach**

(1) DM Direct Detection DM-Nucleon Cross Section

(2) Neutron Star Obs. Mass Splitting btw Multiplet

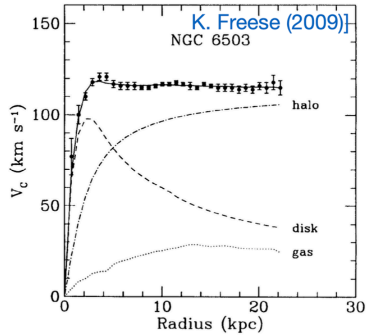
(Surface temperature obs.) trigger inelastic processes

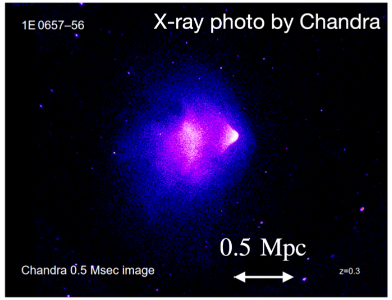


Key: **DM & Higgs Effective Operators** (suppressed by cut-off scale: Λ)

Complementarity btw DM Direct Detection & Neutron Star Obs. is revealed in the EFT framework

Dark Matter (DM)





Evidence

- Rotation curves of galaxies ($\sim$ kpc) [V. Rubin et al. (1980)]
- Bullet cluster ($\sim$ Mpc) [Markevich et al. (2002)] [Clowe et al. (2006)]
- Gravitational lensing [Oguri et al. (2018)]

➡ **Invisible(="Dark") unknown massive source**

※ Discovered independently in various scales

General Feature of DM

- Qualitative Features:
  - Electrically neutral
  - Stable / Long-lived
  - Non-relativistic component (≃Massive)

➡ **Necessary component for structure formation**
No candidate in the Standard Model (SM)

Various possibilities for DM candidates

- Quantitative Features:
  - Ratio of DM energy density : $\Omega h^2 = 0.120 \pm 0.001$ [N. Aghanim et al. [Planck] (2020)]
  - Local DM density : $\rho_{\odot}^{\mathrm{DM}} \simeq 0.3\ \mathrm{GeV/cm^3}$ Astro obs.: [M. Weber, W. De Boer (2010)] [P. R. Kafle et al. (2014)]
  - Local velocity : $\bar{v}_{\mathrm{DM}} \simeq 230\ \mathrm{km/s}$

Electroweak Multiplet DM

DM w/ Electroweak interaction

- Definition: DM has **Electroweak Charge** → Often appears in Phys. beyond the SM (eg. Supersymmetry, Extra-dim.)
  ※ DM stability should be realized by other symme.

- Feature 1: **TeV scale DM** explains correct DM energy density as thermal relic in expanding universe

$$\langle \sigma_{\rm ann} v \rangle \sim 3 \times 10^{-26}\ {\rm cm}^3/{\rm s} \simeq \alpha_2^2/m_{\rm DM}^2 \quad \Rightarrow \quad m_{\rm DM} \simeq \mathcal{O}(1)\ {\rm TeV}$$

α_2: SU(2)$_L$ fine structure const.

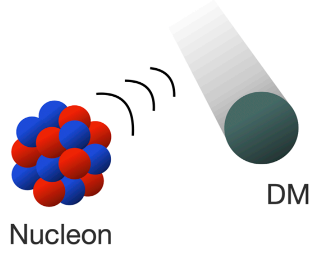
- Feature 2: **Small mass splitting** btw Electroweak multiplet

$$\Rightarrow \quad \Delta M_{\rm EW} \simeq \alpha_2 m_W \simeq \mathcal{O}(100)\ {\rm MeV}$$

(Radiative correction, assuming $m_{\rm DM} \gg m_W$)

Direction of DM Search

- DM production → Collider experiment
- DM annihilation → γ-ray/neutrino/Cosmic-ray obs.
- DM scattering → **Direct Detection exp.** : Searching for **Nucleon** recoil by **DM** scattering



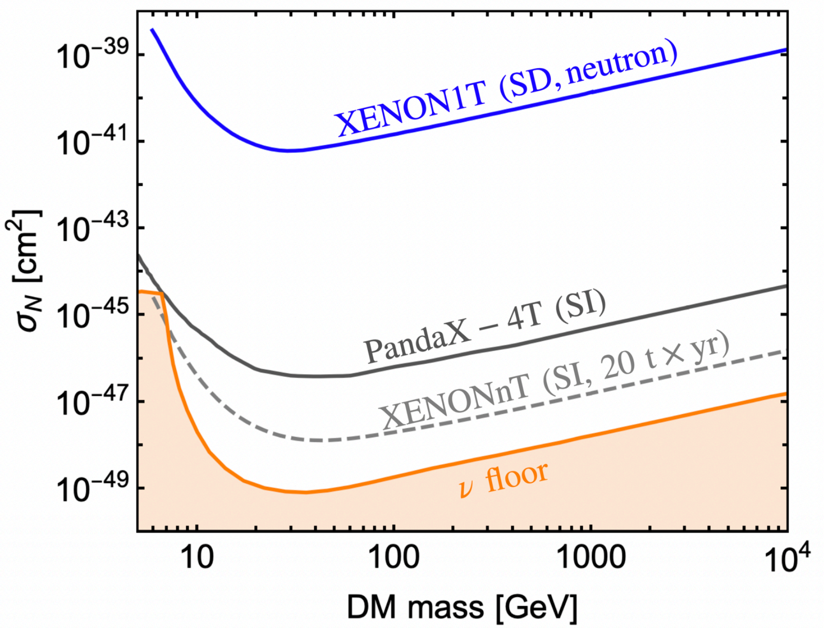
Direct Detection

DM-Nucleon Scattering Cross Section

- Spin-Independent (SI) int. is searched for very small cross section

  Current null signal → Severe bound on $\mathcal{O}(100)$ GeV region

  cf. $\sigma_{\rm SI}^{(N),\,\rm upper} \simeq 10^{-45}\ {\rm cm}^2$ for $\mathcal{O}(1)$ TeV DM mass



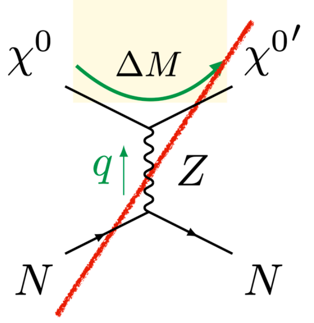
Accessibility

in context of Electroweak Multiplet DM...

- ▲ Sensitivity decreases for heavy DM: $m_{\rm DM} \gtrsim 100$ GeV → Next-generation exp. will be a good probe for TeV region
- ▲ "**Neutrino floor**" background = Impossible to probe DM → Some DM candidates sink below ν floor
- ▲ Weaker bound on Spin-Dependent (SD) effect → SI int. is relevant probe
- ▲ **Inelastic scatt. is suppressed** above $\Delta M \gtrsim \mathcal{O}(100)$ keV → $\Delta M_{\rm EW} \simeq \mathcal{O}(100)$ MeV

  cf. typical recoil energy in Direct Detection: $E_{\rm R} \simeq \mathcal{O}(100)$ keV

  EW loop dominates $\sigma^{(N)}$ (@renormalizable level)



Question: What is a complimentary search to probe **Electroweak Multiplet DM**?

DM Search in Neutron Star

- DM capture in NS: [C. Kovaris (2008)]…
- Inelastic DM: [N. F. Bell, G. Busoni, S. Robles (2018)]
- vs ν floor: [M. Baryakhtar et al. (2017)]
- SD interaction: [N. Raj, P. Tanedo, H-B. Yu (2018)]

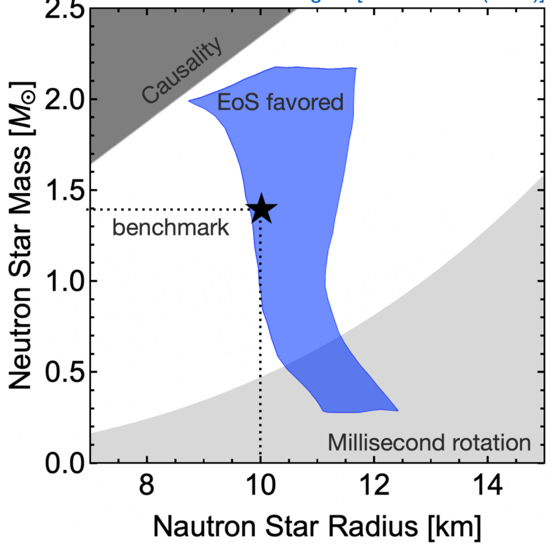
New direction: **Neutron Star may be a good probe of DM-Nucleon scattering effects**

General Feature of Neutron Star

- Star mainly composed of **neutrons** (Neutron degeneracy pressure vs Grav. pressure)
- Typical radius: $R \simeq 10$ km
- Typical mass: $M \simeq 1.4\ M_\odot$

} Determined by Eq. of State (EoS) for Neutron Star
(※ Uncertainty from model of nuclear force under high pressure)

EoS favored region [F. Ozel et al. (2016)]



Key: **Very Compact Object of Nucleon → Several Advantages for DM Search**

1. High density of nucleon (mainly neutron)

Averaged density: $\bar{\rho}_{\rm NS} \sim \frac{3M_{\rm NS}}{4\pi R_{\rm NS}^3} = 6.7\times 10^{14}\ {\rm g/cm^3} \times \left(\frac{M_{\rm NS}}{1.4\ M_\odot}\right)\left(\frac{R_{\rm NS}}{10\ {\rm km}}\right)^{-3}$ ➡ **Efficient target for DM-Nucleon scatt.**

(cf. Nuclear saturation point: $\rho_0 \simeq 2\times 10^{14}\ {\rm g/cm^3}$)

2. Strong gravitational potential

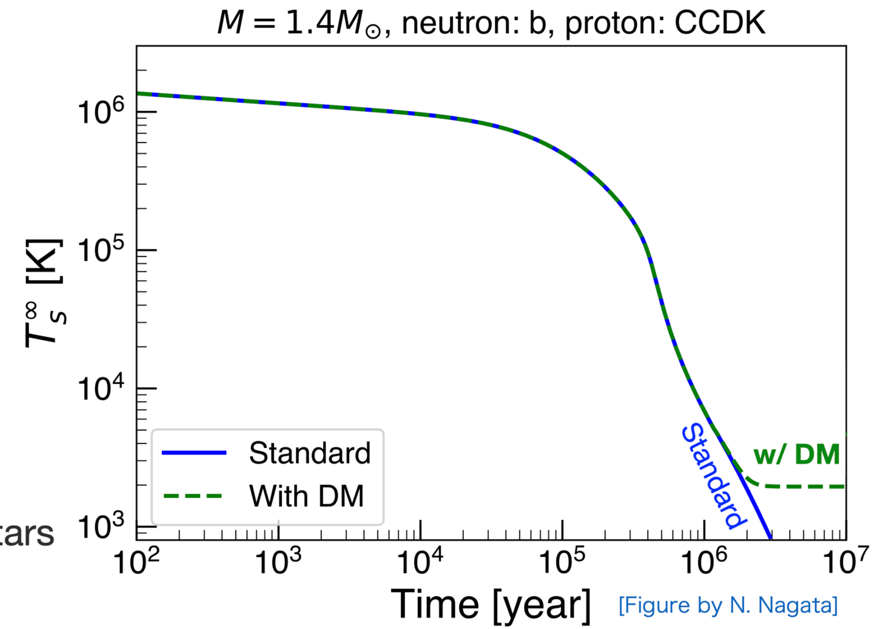
Escape velocity: $v_{\rm esc} \simeq \sqrt{\frac{2GM_{\rm NS}}{R_{\rm NS}}} = 0.65c\ \times \left(\frac{M_{\rm NS}}{1.4\ M_\odot}\right)^{\frac{1}{2}}\left(\frac{R_{\rm NS}}{10\ {\rm km}}\right)^{-\frac{1}{2}}$ ➡ **Accelerated DM has relativistic velocity**

$\Delta M \simeq \mathcal{O}(100)$ MeV **may be accessible**

Neutron Star Surface Temperature

Neutron Star Cooling

- Standard cooling scenario for old neutron stars is established
  → Prediction on Neutron Star surface temperature: T_s
- T_s for old Neutron Star (eg. $t_{\rm NS} \gtrsim 10^7$ yr) is predicted to have very low (due to photon radiation)



[Figure by N. Nagata]

Neutron Star **Heating by DM**

- If DM has sufficient int. w/ nucleon, it is captured by Neutron Stars
  → Energy injection occurs → Increase T_s
- If Neutron Star w/ low T_s is observed in future infrared telescopes, we may obtain constraint on DM-nucleon int.
  eg. James Webb Space Telescope (JWST) [J. P. Gardner et al. [JWST] (2006)]

Question: **Can we probe new aspects of DM theory through Neutron Star Observation?**

Our work: **We study Search Strategy for Electroweak Multiplet DM in** { **(1) Direct Detection** / **(2) Neutron Star obs.** }

Contents

DM Capture in Neutron Star

DM Capture in Neutron Star (1/3)

detailed analysis: [C. Kouvaris (2008)]
intuitive discussion: [M. Baryakhtar et al. (2017)]

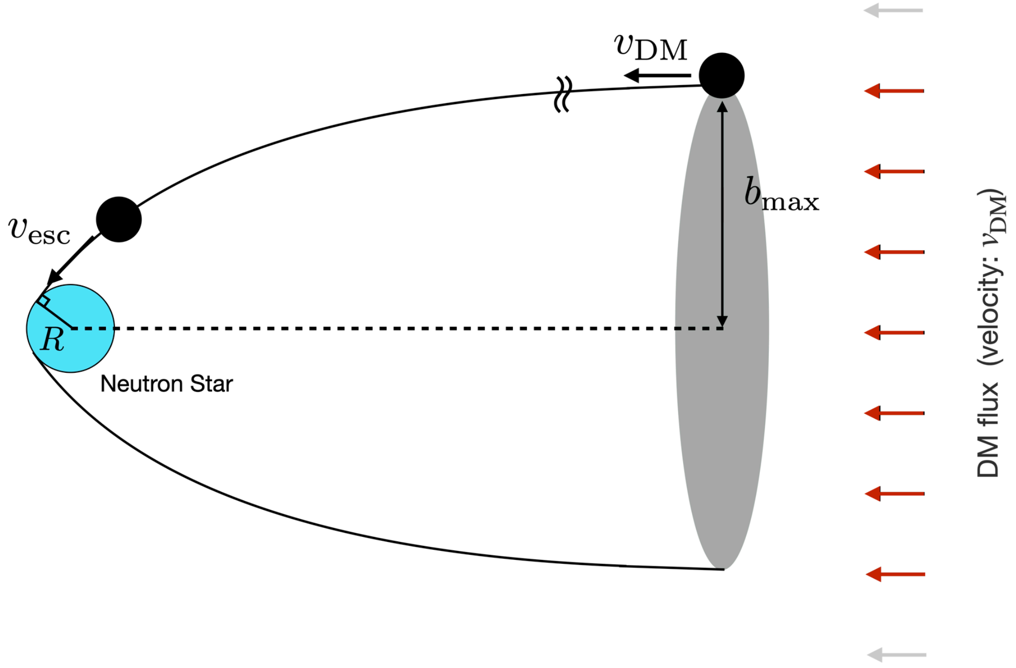
DM number rate into Neutron star

- DM flux through into Old Neutron Stars
  - Initial DM is non-relativistic: $v_{\rm DM} \simeq 10^{-3}c$
  - Velocity reaches to comparable to speed of light: $v_{\rm esc} \simeq \sqrt{\frac{2GM_{\rm NS}}{R_{\rm NS}}}$
- Incoming DM grazes Neutron Star
  ⇔ (Perihelion) = (Neutron Star radius)

$$b_{\rm max} = R_{\rm NS} \cdot \frac{v_{\rm esc}}{v_{\rm DM}} \cdot \left(1 - \frac{2GM_{\rm NS}}{R_{\rm NS}}\right)^{-\frac{1}{2}} \simeq 10^4 \text{ km}$$

- DM flux interacts w/ Neutron Star
  = DM flux **entering into circle area w/ radius** $b_{\rm max}$

$$\frac{dN}{dt} = \sqrt{\frac{6}{\pi}} \cdot \underbrace{\pi b_{\rm max}^2}_{\text{area}} \cdot \underbrace{v_{\rm DM}}_{\text{velocity}} \cdot \underbrace{\frac{\rho_{\rm DM}}{m_{DM}}}_{\text{\# density}}$$



DM Capture in Neutron Star (2/3)

intuitive discussion: [M. Baryakhtar et al. (2017)]

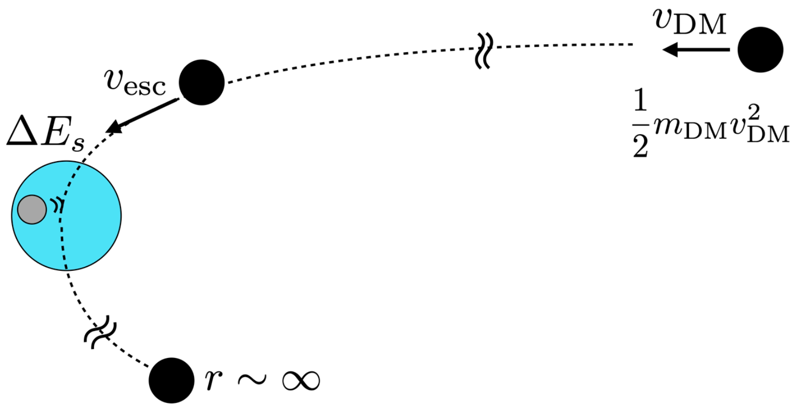
$v_{\rm DM} \simeq 230$ km/s, $v_{\rm esc} = \sqrt{\frac{2GM_{\rm NS}}{R_{\rm NS}}}$

$\gamma_{\rm esc} = \sqrt{1 - v_{\rm esc}^2}$

Energy deposit

- DM is accelerated by the gravitational potential of NS
  → Before scattering, (DM velocity) $\simeq v_{\rm esc}$

$$\overline{\Delta E_s} = \frac{m_n m_{\rm DM}^2 \gamma_{\rm esc}^2 v_{\rm esc}}{m_n^2 + m_{\rm DM}^2 + 2m_n m_{\rm DM}\gamma_{\rm esc}} \simeq 1 \text{ GeV} \quad (m_{\rm DM} \gg m_n)$$



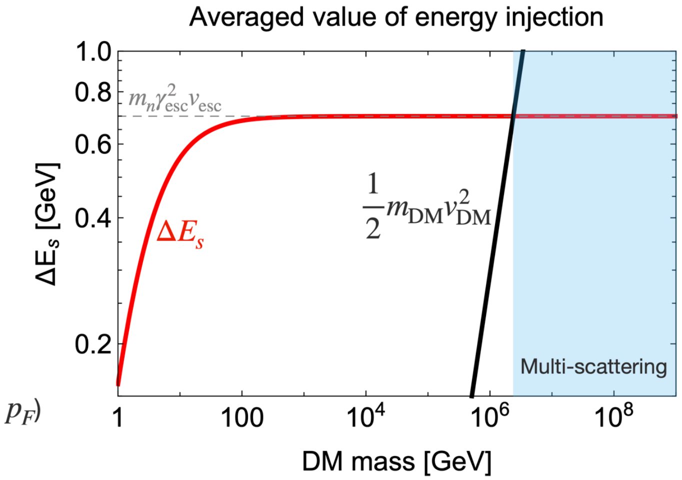
Condition for gravitational trap

- DM can escape Neutron Star gravitational trap
  ⇔ DM has $v > 0$ after scattering @$r \simeq \infty$

- Condition for DM capture after **one scattering**: $\Delta E_s \gtrsim \frac{1}{2}m_{\rm DM}v_{\rm DM}^2$

  ⇔ Only one scattering is necessary for DM capture
  if $1 \text{ GeV} \lesssim m_{\rm DM} \lesssim 1 \text{ PeV}$

※ For $m_{\rm DM} < 1$ GeV, Pauli blocking effects suppress scattering (typical momentum transfer: $\sqrt{2m_n\Delta E_s} < p_F$)



DM Capture in Neutron Star (3/3)

intuitive discussion: [M. Baryakhtar et al. (2017)]

Thermal balance equation

$$\dot{T} = \frac{1}{C}\left(L_{\rm heat} - L_\gamma - L_\nu\right)$$

C: Total heat capacity of star

L_X: Luminosity of each cooling/heat source

- Cooling mechanism
  - Neutrino emission
  - **Thermal photon emission** (dominant for $t_{\rm NS} > 10^5\ {\rm yr}$)
- Heating mechanism
  - Internal heating mechanisms (eg. Roto-chemical heating, Vortex Creep, etc)
  - **DM accretion**: Captured DM annihilates and releases its energy into stars

※ DM annihilation into neutrino also contributes to Neutron Star heating

$$L_{\rm heat}|_{\rm DM} \simeq m_{\rm DM} \times \frac{dN}{dt}$$

Surface Temperature

- $L^\infty_{\rm heat}$ (heating luminosity) = L^∞_γ (photon luminosity) for the late time

  → Surface temperature arise to reach $T_s = \mathcal{O}(1000)\ {\rm K}$ if DM accretion is dominant
- Infrared future telescope (eg. JWST) may probe this heating effects

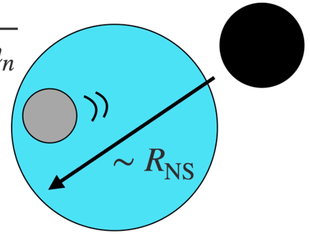
[J. P. Gardner et al. [JWST] (2006)]

Condition for DM Capture

$v_{\rm DM} \simeq 230\ {\rm km/s}$

$v_{\rm esc} = \sqrt{\dfrac{2GM_{\rm NS}}{R_{\rm NS}}}$

$\rho_n \sim \dfrac{M_{\rm NS}}{\pi R_{\rm NS}^3 m_n}$



Threshold Cross Section

- Minimum cross section for DM capture

  = cross section for DM to scatter **ONCE** in Neutron Star within one crossing

$$\sigma_{\rm th} \equiv \frac{\pi R_{\rm NS}^2 m_n}{M_{\rm NS}} \simeq 2.5 \times 10^{-45}\ {\rm cm}^2 \times \left(\frac{R_{\rm NS}}{11.43\ {\rm km}}\right)^2 \left(\frac{M_{\rm NS}}{1.4\ M_\odot}\right)^{-1}$$

detailed analysis

$\sigma_{\rm th}^{(n)} = 1.7 \times 10^{-45}\ {\rm cm}^2$ [N.F. Bell, et al.(2020)]

$\sigma_{\rm th}^{(n)} = 1.4 \times 10^{-44}\ {\rm cm}^2$ [F. Anzuini, et al. (2021)]

momentum trans. & effective nucleon mass are considered

Threshold Mass Difference for Inelastic Process

- Comparably large mass difference may be accessible (cf. $\Delta E_s \simeq 1\ {\rm GeV}$)
- Maximal mass difference that may appear in Neutron Star can be derived [N. F. Bell, G. Busoni, S. Robles (2018)]

$$\Delta M \simeq m_n \left(1 - \frac{2GM_{\rm NS}}{R_{\rm NS}}\right)^{-\frac{1}{2}} \simeq 330\ {\rm MeV}$$

Question: **Advantages of Neutron Star obs. against Direct Detection?**

(→ next page)

Direct Detection vs Neutron Star Obs.

		Direct detection		NS observation
Elastic	SI	$\sigma_{\rm SI}^{(N),{\rm upper}} \simeq 10^{-45}\ {\rm cm}^2$	$\simeq$	$\sigma_{\rm th}^{(N)} \simeq 10^{-45}\ {\rm cm}^2$
	SD	$\sigma_{\rm SD}^{(N),{\rm upper}} \simeq 10^{-40}\ {\rm cm}^2$	$\gg$	
Inelastic	SI	$\Delta M_0, \Delta M_\pm \lesssim \mathcal{O}(100)\ {\rm keV}$		$\Delta M_0, \Delta M_\pm \lesssim \mathcal{O}(100)\ {\rm MeV}$
	SD			

※ $N = n, p$

← Triggered by **Cross section**

← Triggered by **Mass splitting**

- (Threshold cross section in Neutron Star) $\simeq$ (Current bound in Direct Detection) for TeV scale DM
- Neutron Star obs. is even sensitive for SD couplings
- Accessible mass splitting $\simeq \mathcal{O}(100)\ {\rm MeV}$ → Inelastic scattering may be switched on

Next: **Derive Cross section & Mass splitting in EFT for Electroweak Multiplet DM**

Electroweak Multiplet DM:
EFT Approach

EFT of Electroweak Multiplet DM

Fermion DM w/ Electroweak Charge

- We focused on **Fermion $SU(2)_L$ n-plet** (→ No renormalizable coupling w/ the SM Higgs)
- Hypercharge: Y is fixed by requiring $\Delta M_{\rm EW} > 0$ (to make neutral comp. lighter)
  $Y = 0$ → Automatically satisfied
  $Y \neq 0$ → $n = 2Y + 1$
- Heavier particles that couple to DM and SM particles → Λ suppressed Operators in EFT (Λ: cut-off scale)

Key: DM-Higgs Effective Operator

- σ_N is affected through **tree-level (Λ suppressed) processes**
- ΔM obtain new contribution from **$SU(2)_L$ breaking operators**

(1) $Y = 0$ multiplet

(2) $Y \neq 0$ multiplet

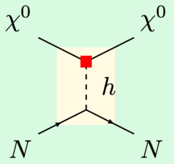
(1) Search strategy for $Y = 0$

$Y = 0$: Setup

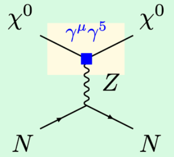
- We introduce one Weyl fermion ($SU(2)_L$ n-plet, $Y = 0$) (for minimality) $\to \chi^0$ (neutral, DM), $\chi^{\pm}$ (charged)
- Discussion **@renormalizable level**:
  - DM-nucleon elastic scattering → induced by electroweak loop
  - DM-nucleon inelastic scattering → induced @tree-level
  - Electroweak corrections: $\Delta M_{\pm}\Big|_{\mathrm{EW}} \simeq 166\ \mathrm{MeV}$ (assuming $m_{\mathrm{DM}} \gg m_W$)

Possible contribution from Effective Operators

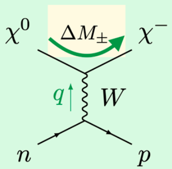
- **DM-Higgs coupling** → SI DM-nucleon cross section



- **DM-Z coupling, etc** → SD DM-nucleon cross section



- $\Delta M_{\pm}$ → Inelastic scatt.



→ Search Strategy in Direct detection & Neutron Star Obs.?

$Y = 0$: Operator Analysis

T^a: SU(2)$_L$ generators

$\tau^a = \sigma^a/2$

$(T^1)_{mn} = \frac{1}{2}\left[\sqrt{(j-n)(j+n+1)}\delta_{m,n+1} + \sqrt{(j+n)(j-n+1)}\delta_{m,n-1}\right]$

$(T^2)_{mn} = \frac{1}{2i}\left[\sqrt{(j-n)(j+n+1)}\delta_{m,n+1} - \sqrt{(j+n)(j-n+1)}\delta_{m,n-1}\right]$

$(T^3)_{mn} = n\ \delta_{mn}$

Ingredients: $\chi_m \sim (n,0),\ H \sim (2,1/2)$

$\mathscr{L} \overset{?}{\supset} \#\ \chi^\dagger \chi\ H^\dagger H$

$$\mathscr{L}_{\rm dim5} = \frac{\#}{\Lambda} \chi\, \mathbf{1}\, \chi\ H^\dagger \mathbf{1} H + \frac{\#}{\Lambda} \chi\ T_a\, \chi\ \ H^\dagger \tau_a H + \text{h.c.}$$

(cf. Fierz identity for SU(2)$_L$ indices)

$$\rightarrow \sum_{m,n} (-1)^m \chi_{-m} (T_a)_{mn} \chi_n = 0$$

$\because (-1)^m (T^a)_{-m,n}$: Anti-symme. for $m \leftrightarrow n$

- **DM-Higgs coupling arises** → Relevant for $\sigma_N^{(SI)}$ for low Λ
- Overall mass shift for neutral-charged components → No contribution to $\Delta M_\pm$

$$\mathscr{L}_{\rm dim6} = \frac{\#}{\Lambda^2} \chi^\dagger \bar{\sigma}^\mu \chi\ \ H^\dagger i\overleftrightarrow{D}_\mu H$$

- **DM-Z coupling arises** → Relevant for $\sigma_N^{(SD)}$ for low Λ

※ We also have quark operators: $\mathscr{L} \supset \frac{c_q}{\Lambda^2} \chi^\dagger \bar{\sigma} \chi_m\ q^\dagger \bar{\sigma}^\mu q$

→ The same discussion for $c_q \neq 0$

$$\mathscr{L}_{\rm dim7} = \frac{\#}{\Lambda^3} \chi\ T^a T^b \chi\ \ (H^\dagger \tau^a H)\ (H^\dagger \tau^b H)$$

- **Mass splitting is induced from dim. 7**

$\chi \cdot \chi$ should be combined w/ **Non-trivial SU(2)$_L$ representation**

Symme. term under exchange of SU(2)$_L$ indices: $j = 2,4,6,\cdots$ $\Big\} \rightarrow \chi^\dagger T^a T^b \chi$

$Y = 0$: Search Strategy

- DM-nucleon interaction

SI: $\mathscr{L} \supset -\dfrac{c_5}{2\Lambda} \sum_{m=-j}^{j} (-1)^m \chi_{-m}\chi_m \, H^\dagger H + h.c.$

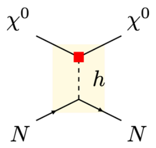
SD: $\mathscr{L} \supset \dfrac{c_6}{\Lambda^2} \sum_{m=-j}^{j} \chi_m^\dagger \bar{\sigma}^\mu \chi_m \, H^\dagger i \overleftrightarrow{D}_\mu H$

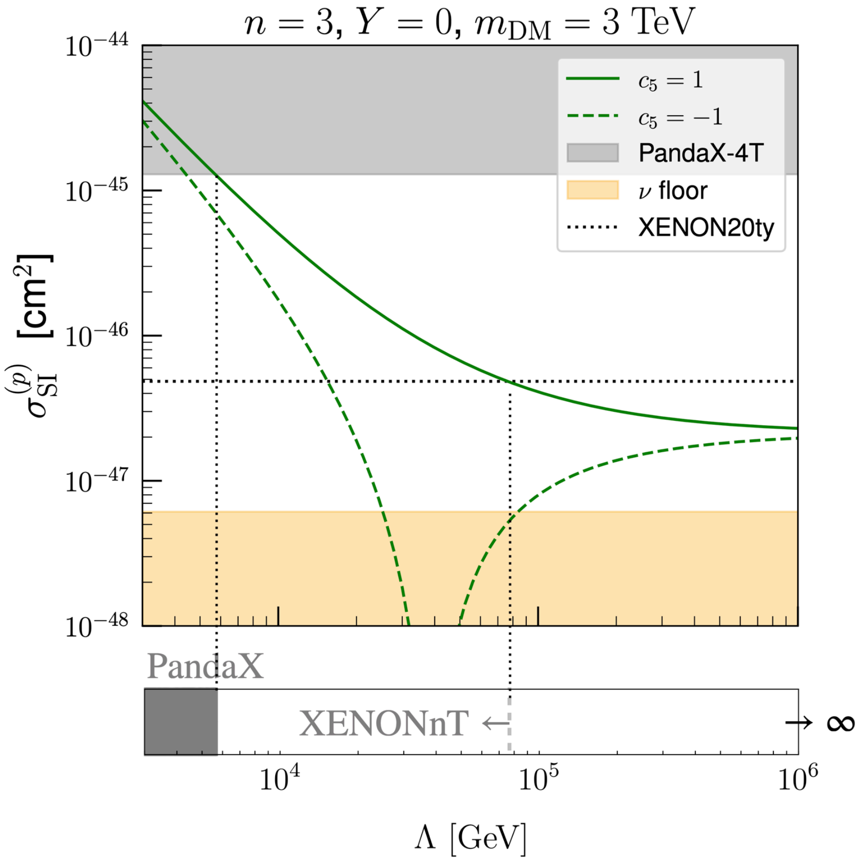
→ Contribute to $\sigma_{\rm SI}^{(N)}$ & $\sigma_{\rm SD}^{(N)}$, respectively (Relevant for low Λ)

→ Converged value = EW loop corrections (above ν-floor)

Direct Detection

Neutron Star





(1) [N.F. Bell, G. Busoni, S. Robles, and M. Virgato (2020)]
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$Y = 0$: Search Strategy

- DM-nucleon interaction

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Direct Detection
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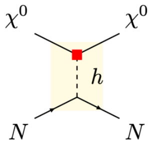

SD: $\mathscr{L} \supset \frac{c_6}{\Lambda^2} \sum_{m=-j}^{j} \chi_m^\dagger \bar{\sigma}^\mu \chi_m \, H^\dagger i \overleftrightarrow{D}_\mu H$

Direct Detection
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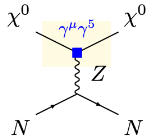
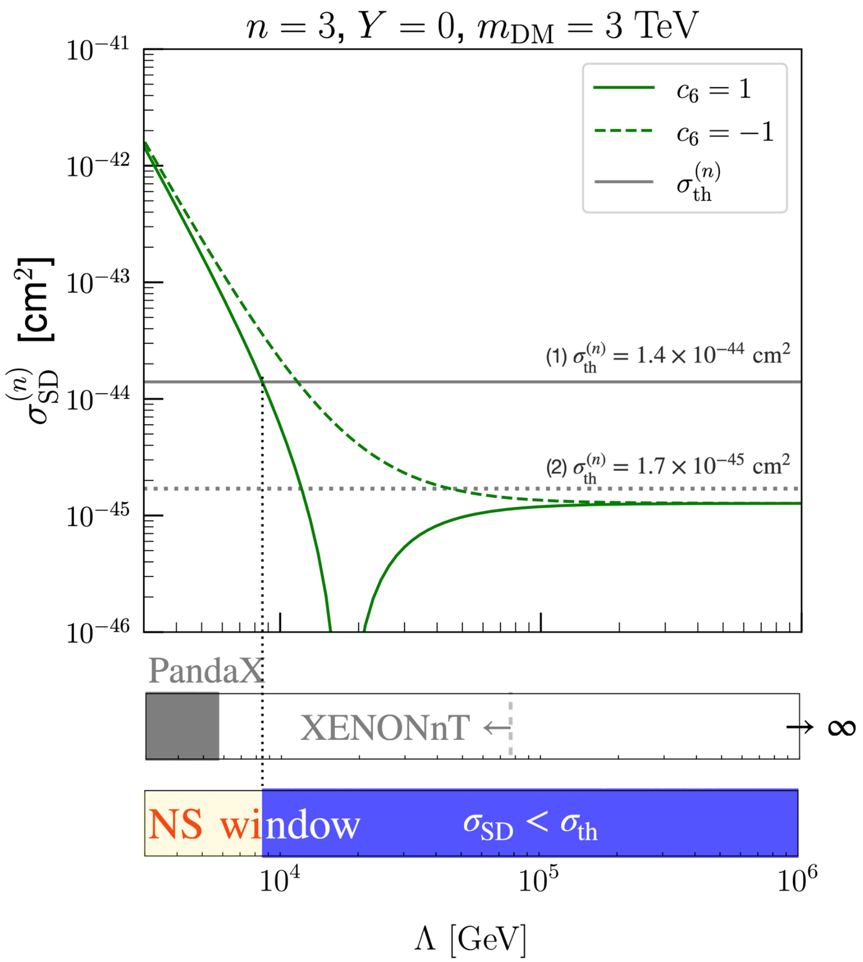


→ Contribute to $\sigma_{\rm SI}^{(N)}$ & $\sigma_{\rm SD}^{(N)}$, respectively (Relevant for low Λ)

→ Converged value = EW loop corrections (above ν-floor)



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$Y = 0$: Search Strategy

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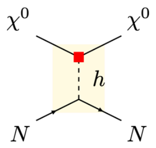
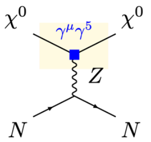
Direct Detection
Neutron Star



SD: $\mathscr{L} \supset \frac{c_6}{\Lambda^2} \sum_{m=-j}^{j} \chi_m^\dagger \bar{\sigma}^\mu \chi_m \, H^\dagger i\overleftrightarrow{D}_\mu H$

Direct Detection
Neutron Star

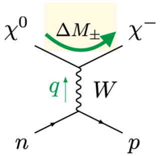


→ Contribute to $\sigma_{\rm SI}^{(N)}$ & $\sigma_{\rm SD}^{(N)}$, respectively (Relevant for low Λ)

→ Converged value = EW loop corrections (above ν-floor)

- Mass splitting

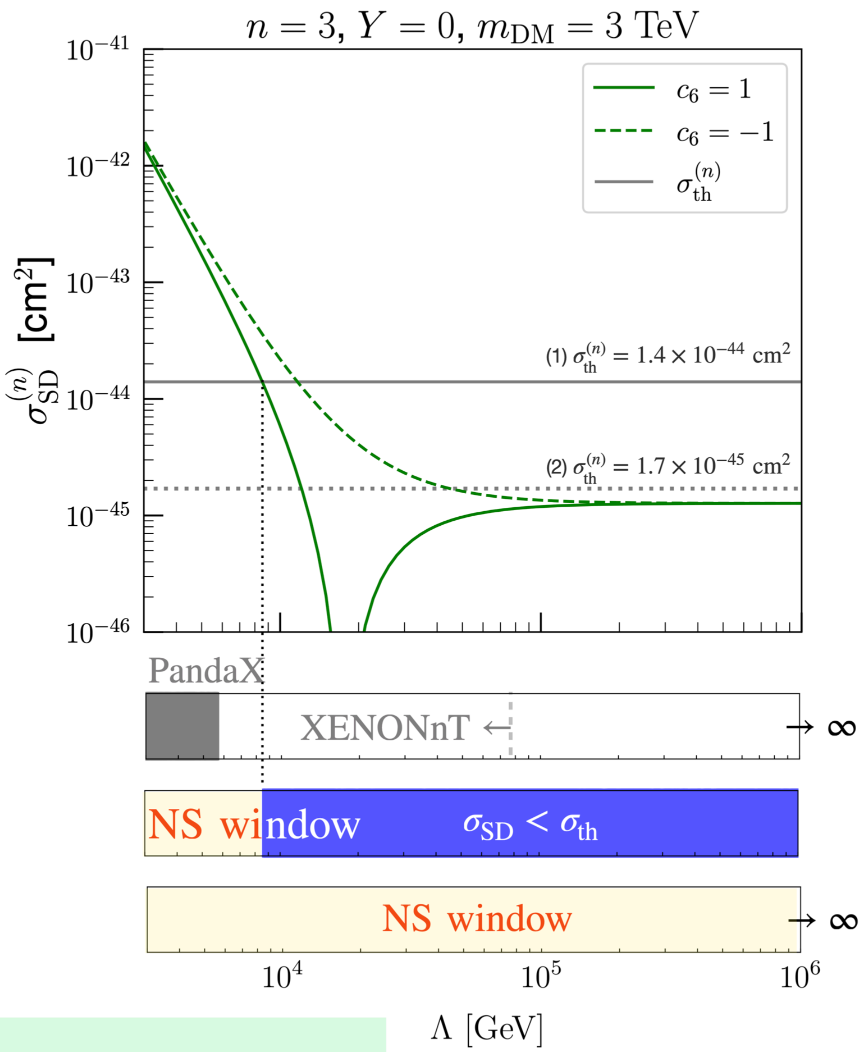
$$\mathscr{L} \supset -\frac{c_7}{2\Lambda^3} \sum_{m,n} (-1)^m \chi_{-m}(T_a T_b)_{mn}\chi_m \, (H^\dagger \tau_a H)(H^\dagger \tau_b H) + h.c.$$



$$\Delta M_\pm \Big|_\Lambda \simeq \frac{c_7}{16}\frac{v^4}{\Lambda^3} \simeq c_7 \left(\frac{\Lambda}{10\ \text{TeV}}\right)^{-3} \times 0.23\ \text{MeV}$$

→ EW radiative corrections dominate the mass splitting: $\Delta M_\pm \simeq 166$ MeV

→ **Inelastic scattering always occur in Neutron Star!**



$Y = 0$: Both Direct Detection & Neutron Star Obs. have wide Windows

※ The same argument for other n-plet w/ $Y = 0$

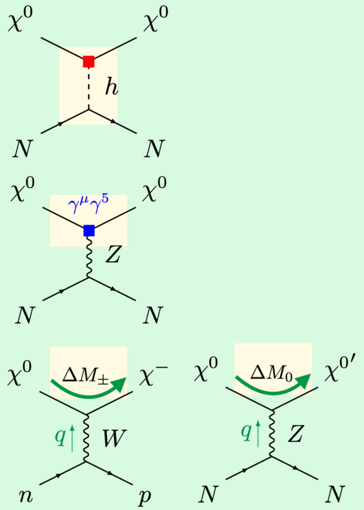
(2) Search strategy for $Y \neq 0$

$Y \neq 0$: Setup

- We introduce **two SU(2)$_L$ n-plet w/ $\pm Y$** $(Y > 0)$ to compensate gauge anomaly: $\{\chi_m, \eta_{m'}\}$
- Two neutral components $\{\chi^0, \chi^{0\prime}\}$ → Lightest component: χ^0 is DM candidate
- **Inelastic scattering via Z exchange** is constrained by Direct Detection → We focus on $\Delta M_0 \gtrsim \mathcal{O}(100)$ keV
- Effective operator to induce ΔM_0 is <u>required</u> → **EFT approach is mandatory**

Possible contribution from Effective Operators

- **DM-Higgs couplings** → SI DM-nucleon int.
- **DM-Z couplings, etc** → SD DM-nucleon int.
- $\Delta M_\pm$ & ΔM_0 → Inelastic scatt.



→ Search Strategy in Direct detection & Neutron Star Obs.?

$Y \neq 0$: Operator Analysis

T^a: SU(2)$_L$ generators

$\tau^a = \sigma^a/2$

$$(T^1)_{mn} = \frac{1}{2}\left[\sqrt{(j-n)(j+n+1)}\delta_{m,n+1} + \sqrt{(j+n)(j-n+1)}\delta_{m,n-1}\right]$$

$$(T^2)_{mn} = \frac{1}{2i}\left[\sqrt{(j-n)(j+n+1)}\delta_{m,n+1} - \sqrt{(j+n)(j-n+1)}\delta_{m,n-1}\right]$$

$$(T^3)_{mn} = n\ \delta_{mn}$$

Ingredients: $\chi_m \sim (n, Y),\ \eta_m \sim (n, -Y),\ H \sim (2, 1/2)$

$\mathscr{L} \overset{?}{\supset} \#\ \psi^\dagger\ \psi'\ H^\dagger\ H$ $\quad(\psi, \psi' = \chi, \eta)$

$$\mathscr{L}_{\text{dim5}} = \frac{\#}{\Lambda}\ \eta\ \mathbf{1}\ \chi\ \ H^\dagger \mathbf{1}\ H\ + \frac{\#}{\Lambda}\ \eta\ T_a\ \chi\ \ H^\dagger \tau_a\ H\ + \text{h.c.}$$

(cf. Fierz identity for SU(2)$_L$ indices)

non-vanishing

- **DM-Higgs coupling arises** → Relevant for $\sigma_N^{(SI)}$ for low Λ
- **Relevant contribution to $\Delta M_\pm$ for low Λ**

$$\mathscr{L}_{\text{dim6}} = \frac{\#}{\Lambda^2}\ \chi^\dagger \bar{\sigma}^\mu \chi\ \ H^\dagger i\overleftrightarrow{D}_\mu H + \frac{\#}{\Lambda^2}\ \eta^\dagger \bar{\sigma}^\mu \eta\ \ H^\dagger i\overleftrightarrow{D}_\mu H$$

- **DM-Z coupling arises** → Relevant for $\sigma_N^{(SD)}$ for low Λ

※ We also have other operators:

$$\mathscr{L} \supset \frac{c_q}{\Lambda^2}\chi^\dagger \bar{\sigma}\chi_m\ q^\dagger \bar{\sigma}^\mu q\ + \frac{c_6'}{\Lambda^2}\chi^\dagger \bar{\sigma}^\mu T^a \bar{\sigma}\chi\ H^\dagger \tau^a i\overleftrightarrow{D}_\mu H + \cdots$$

→ The same discussion for these operators

$$\mathscr{L}_{\text{spl}} = \frac{\#}{\Lambda^{(4Y-1)}}\ \chi\,\chi\,(H^*)^{4Y} + \frac{\#}{\Lambda^{(4Y-1)}}\ \eta\,\eta\,(H)^{4Y} + \text{h.c.}$$

- **Contribute to both $\Delta M_\pm$ & ΔM_0**
- **Dimension of Mass splitting operators depends on Y**
  - U(1) symme. ($\chi \mapsto e^{i\theta}\chi, \eta \mapsto e^{-i\theta}\eta$) should be broken to decompose Dirac fermion
  - $\chi\chi$ (Hypercharge = $2Y$) should be composed w/ $(H^*)^{4Y}$ (cf. $Y = 1/2$ for H)

→ More relevant for small Y

Let's find Neutron Star Windows!

$Y \neq 0$: Mass Splitting

- Relevant operators for mass correction

$$\mathscr{L} \supset -\frac{c_5}{\Lambda}\sum_{m=-j}^{j}\eta_{-m}\chi_m\,(H^\dagger H) \quad (\to \text{Overall shift only})$$

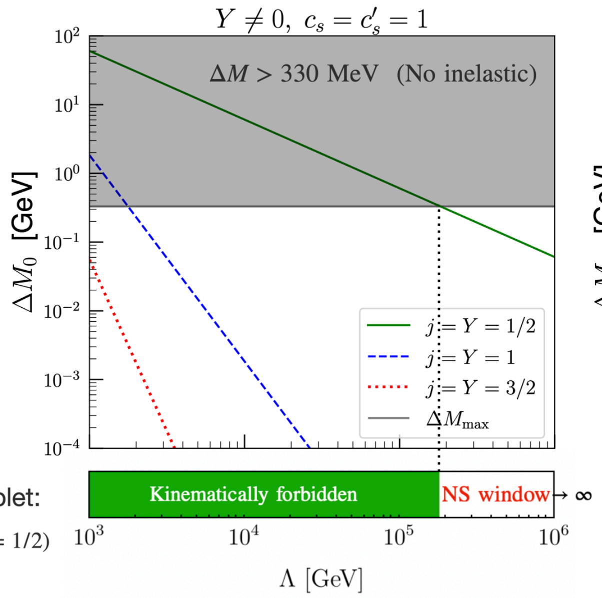
$$-\frac{c_5'}{\Lambda}\sum_{m=-j}^{j}(-1)^m\eta_{-m}(T_a)_{mn}\chi_m\,(H^\dagger\tau_a H)$$

$$-\frac{c_s}{2\Lambda^{(4Y-1)}}\sum_{M,m,n}(\text{CG coeff.})[(H)^{4Y}_{-M}]^*\chi_m\chi_{m'} - \frac{c_s'}{2\Lambda^{(4Y-1)}}\sum_{M,m,n}(-1)^{2Y+M}(\text{CG coeff.})[(H)^{4Y}_{-M}]^*\eta_m\eta_{m'} + h.c.$$

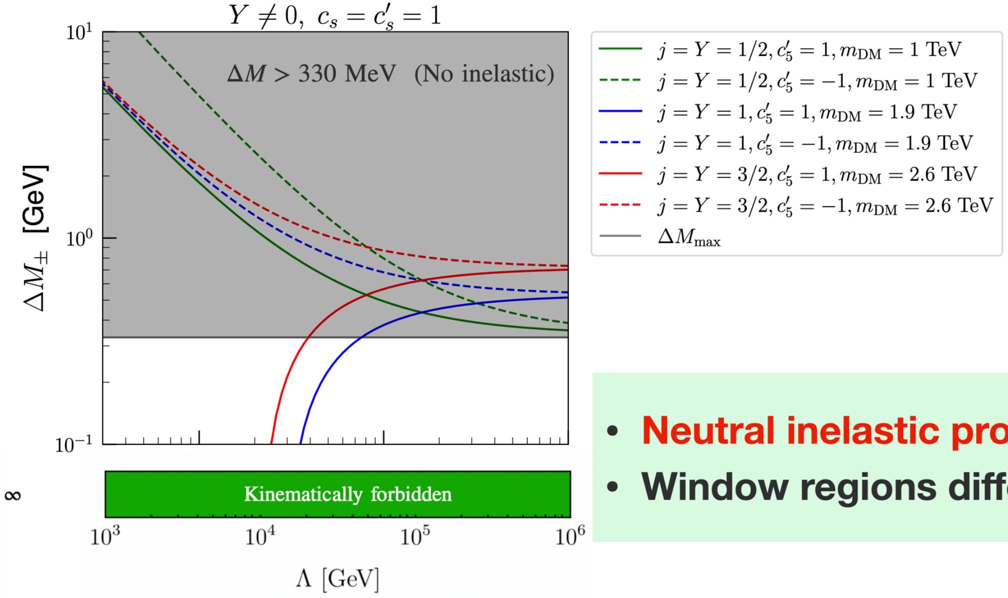
※ (CG coeff.) = Clebsch-Gordan coefficient

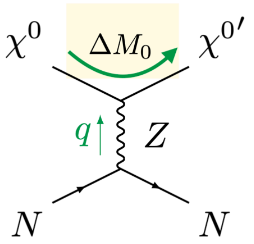
	$n=2$	$n=3$	$n=4$
	$Y=1/2$	$Y=1$	$Y=3/2$
c_s, c_s'-term	dim. 5	dim. 7	dim. 9

→ Contribution to ΔM_0 & $\Delta M_\pm$



eg. Doublet: ($n = 2,\ Y = 1/2$)

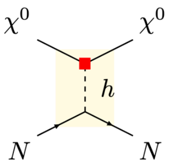




- **Neutral inelastic process is important**
- **Window regions differ by each Multiplet**

$Y \neq 0$: Search Strategy

Direct Detection



- SI DM-nucleon coupling is induced from

  (1) $\{c_5, c_5', c_s, c_s'\}$ interaction via Higgs exchange (from dim. 5)

  (2) EW loops contribution (depending on Y)

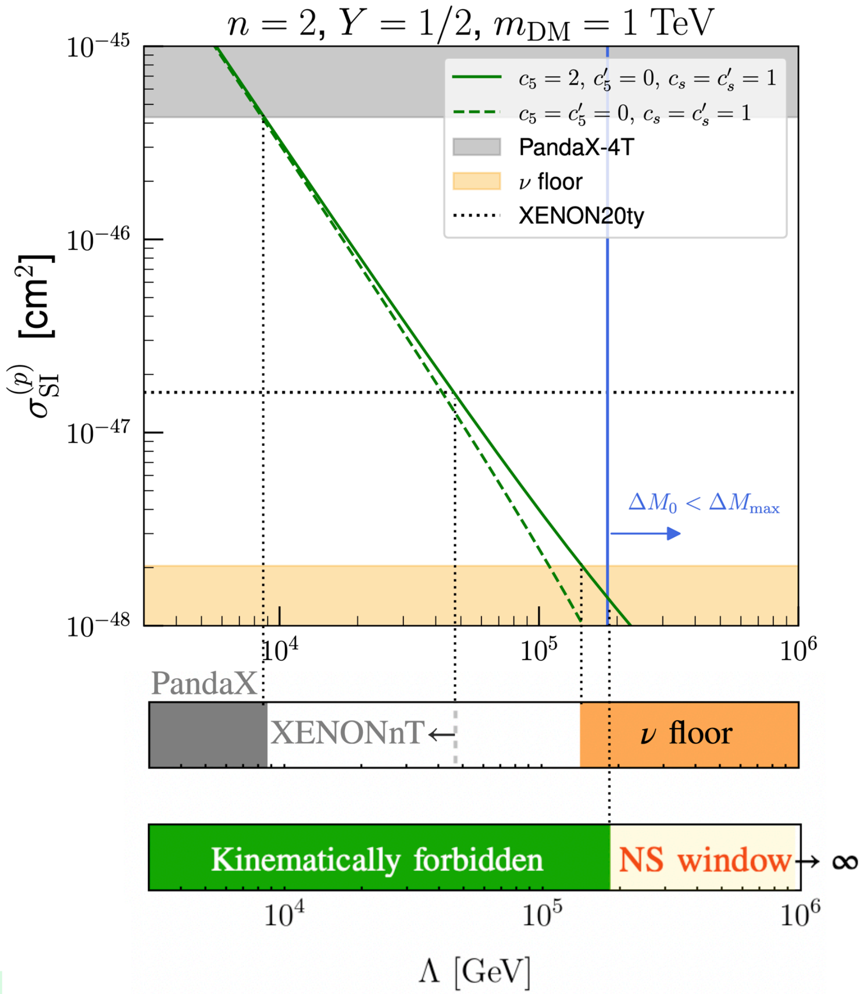
$$f_N^{(\mathrm{EW})} = 4Y\, f_N^W + Y^2\, f_N^Z \quad \begin{bmatrix} f_p^W \simeq 2.8 \times 10^{-11}\ \mathrm{GeV}^{-2}\,, & f_n^W \simeq 2.7 \times 10^{-11}\ \mathrm{GeV}^{-2}\,. \\ f_p^Z \simeq -1.9 \times 10^{-10}\ \mathrm{GeV}^{-2}\,, & f_n^Z \simeq -1.8 \times 10^{-10}\ \mathrm{GeV}^{-2}\,. \end{bmatrix}$$

(assuming $n = 2Y + 1$)

Strategy for Doublet DM $(n = 2,\ Y = 1/2)$

- For large cut-off region: $\Lambda \gtrsim 10^5$ GeV
  - DM-Nucleon cross section is smaller than ν-background
  - **Inelastic scattering process is switched on in Neutron Star**

Direct detection & Neutron Star observation will be a complimentary probe for EW Multiplet DM

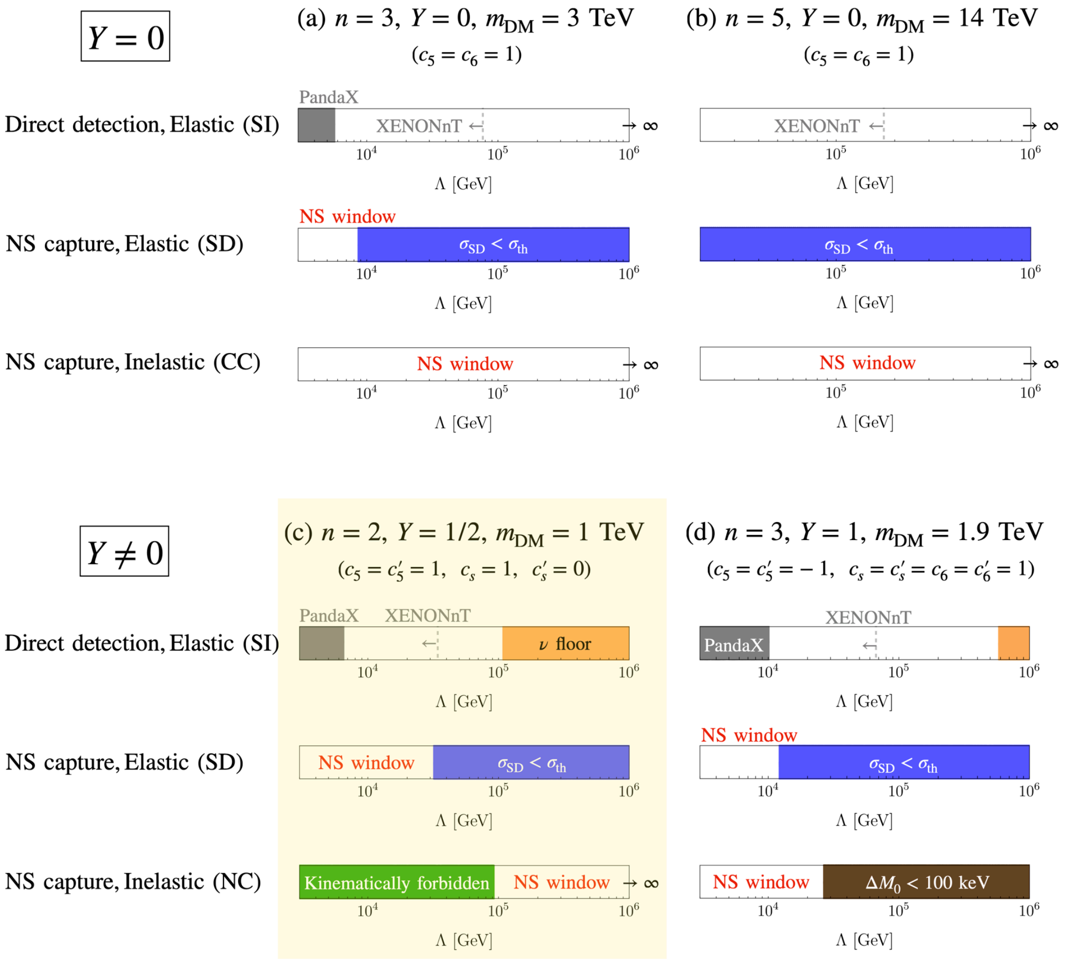


Results

- 4 benchmark multiplet models:
  - $Y = 0$: (a) $n = 3, \quad Y = 0$
    (b) $n = 5, \quad Y = 0$
  - $Y \neq 0$: (c) $n = 2, \quad Y = 1/2$
    (d) $n = 3, \quad Y = 1$
- DM capture via SD scattering is also investigated for $Y \neq 0$
  - Contribution from dim. 6 operators
  - DM-Z coupling induced if $c_s \neq c_s'$ (miss-alignment from maximal mixing)
  - EW loop correction

  → Enlarge Neutron Star window
- Search strategy for each model
  - $Y = 0$: Direct detection & Neutron Star obs. are both promising
  - $Y \neq 0$: Neutron Star windows depend on hypercharge

  → **Complementarity is found for Doublet DM using EFT**



Search strategy for each Electroweak Multiplet DM is revealed using the EFT framework

Summary

DM Capture in Neutron Star

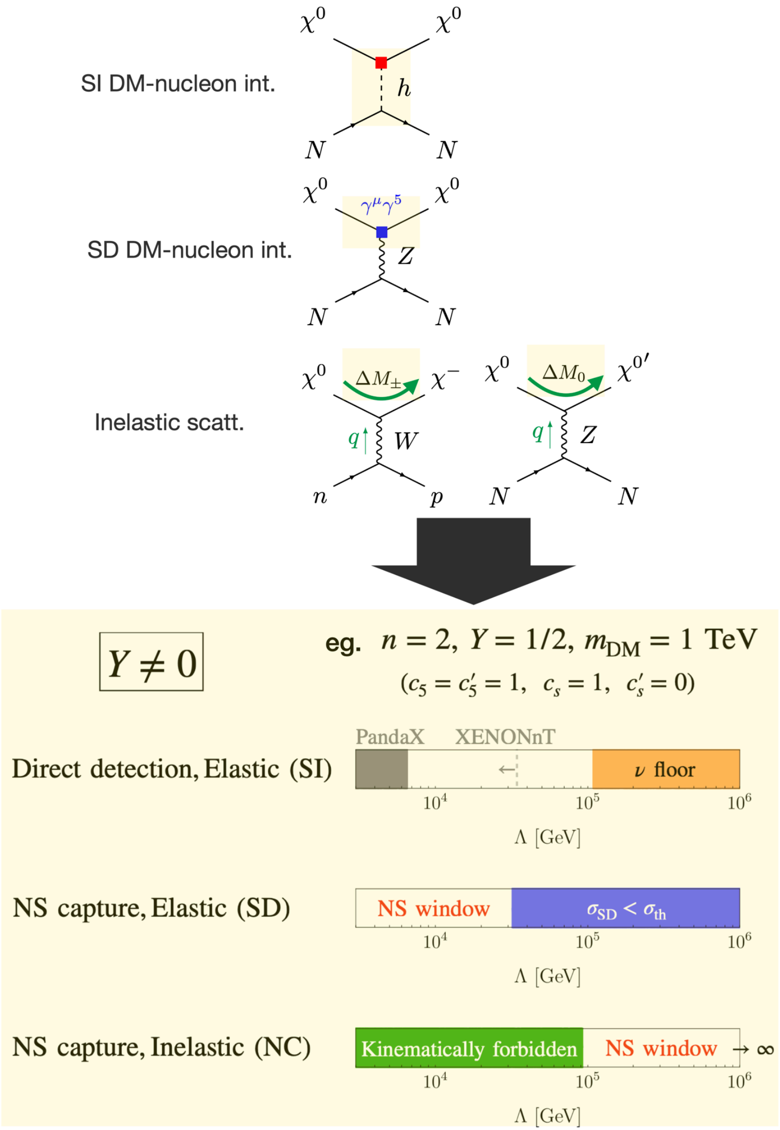
- DM capture heats up Neutron Stars to be probed in future IR telescope
- Strong gravitational force → We may probe new aspects of DM theory
  - Threshold cross section: $\sigma_N \simeq 10^{-45}\ \mathrm{cm}^2$
  - Threshold mass splitting: $\Delta M \lesssim \mathcal{O}(100)\ \mathrm{MeV}$

EFT Approach

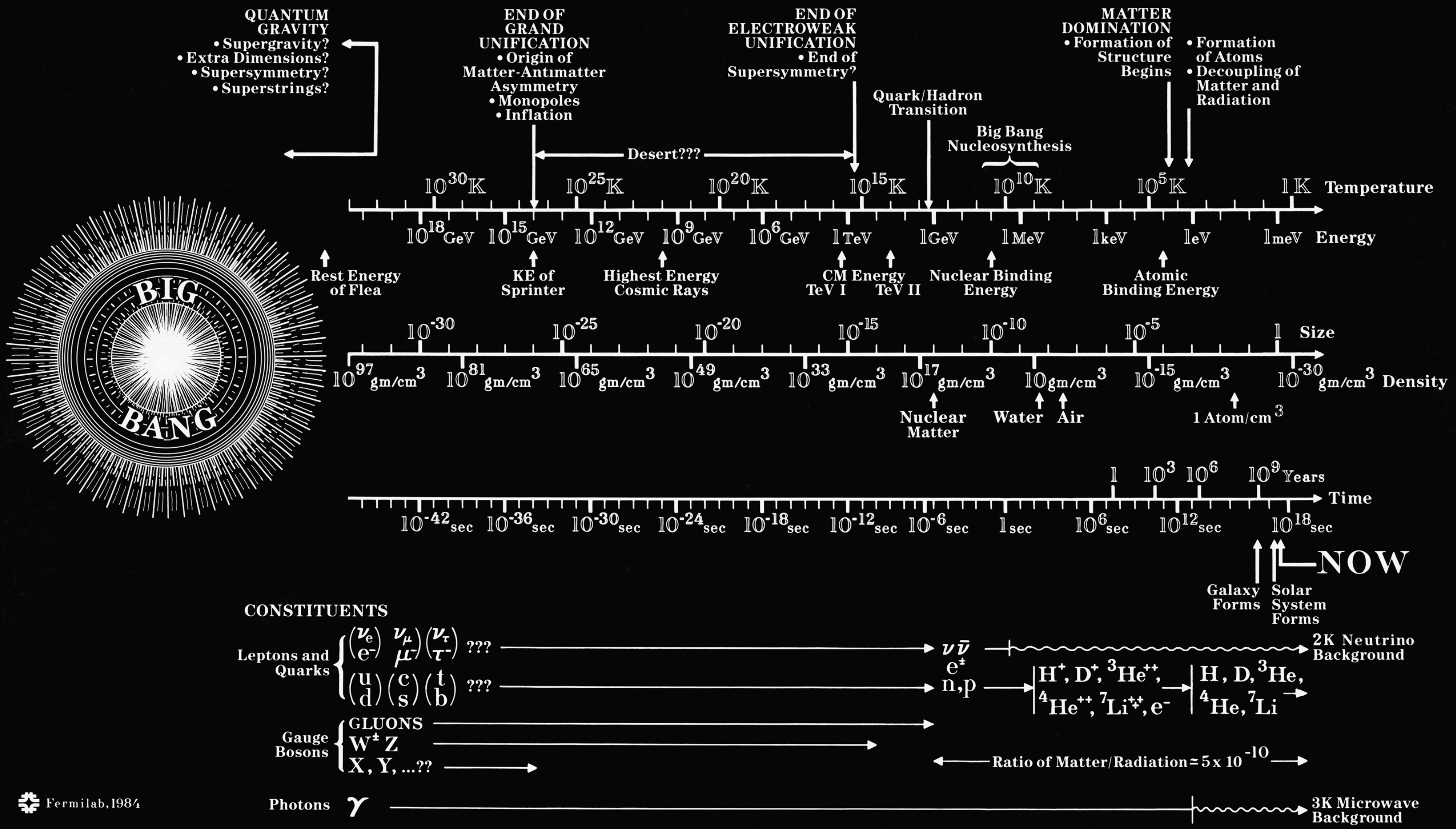
- **DM-Higgs effective operators** are key to reveal search strategy
  - σ_N is induced from low dim. operator → Direct detection is good probe
  - ΔM is suppressed for large Λ → Inelastic scattering may occur in Neutron Star

Search Strategy

- $Y = 0$: Direct detection & Neutron Star obs. are both promising
- $Y \neq 0$: Neutron Star windows depend on operator dimension (cf. Complimentarity in Doublet case)



Backup


QUANTUM GRAVITY
• Supergravity?
• Extra Dimensions?
• Supersymmetry?
• Superstrings?
END OF GRAND UNIFICATION
• Origin of Matter-Antimatter Asymmetry
• Monopoles
• Inflation
END OF ELECTROWEAK UNIFICATION
• End of Supersymmetry?
Quark/Hadron Transition
Big Bang Nucleosynthesis
MATTER DOMINATION
• Formation of Structure Begins
• Formation of Atoms
• Decoupling of Matter and Radiation
Desert???
10^{30}K
10^{25}K
10^{20}K
10^{15}K
10^{10}K
10^{5}K
1 K
Temperature
10^{18}GeV
10^{15}GeV
10^{12}GeV
10^{9}GeV
10^{6}GeV
1 TeV
1 GeV
1 MeV
1 keV
1 eV
1 meV
Energy
Rest Energy of Flea
KE of Sprinter
Highest Energy Cosmic Rays
CM Energy TeV I
TeV II
Nuclear Binding Energy
Atomic Binding Energy
BIG BANG
10^{-30}
10^{-25}
10^{-20}
10^{-15}
10^{-10}
10^{-5}
1
Size
10^{97} gm/cm^3
10^{81} gm/cm^3
10^{65} gm/cm^3
10^{49} gm/cm^3
10^{33} gm/cm^3
10^{17} gm/cm^3
10 gm/cm^3
10^{-15} gm/cm^3
10^{-30} gm/cm^3
Density
Nuclear Matter
Water
Air
1 Atom/cm^3
1
10^{3}
10^{6}
10^{9} Years
Time
10^{-42}sec
10^{-36}sec
10^{-30}sec
10^{-24}sec
10^{-18}sec
10^{-12}sec
10^{-6}sec
1 sec
10^{6}sec
10^{12}sec
10^{18}sec
NOW
Galaxy Forms
Solar System Forms
CONSTITUENTS
Leptons and Quarks
$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}\begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}\begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}$???
$\begin{pmatrix}u\\ d\end{pmatrix}\begin{pmatrix}c\\ s\end{pmatrix}\begin{pmatrix}t\\ b\end{pmatrix}$???
$\nu\bar{\nu}$
$e^{\pm}$
n, p
H^+, D^+, $^3He^{++}$, $^4He^{++}$, $^7Li^{+++}$, e^-
H, D, ^{3}He, ^{4}He, ^{7}Li
2K Neutrino Background
Gauge Bosons
GLUONS
$W^{\pm}$ Z
X, Y, ...??
Ratio of Matter/Radiation ≈ 5 x 10^{-10}
Photons γ
3K Microwave Background
Fermilab, 1984

Is Neutron Star Obs. Promising?

Can we really detect such inflated signatures?

- Recently, study of JWST sensitivity on DM heating is released [S. Chatterjee et al. [arXiv:2205.05048]]
- Neutron Star w/ (1) $T_s \gtrsim 2400\ \mathrm{K}$ & (2) 10 pc distance may be detectable in JWST (through NIRCAM filter)

Can we discriminate DM heating effects against other Neutron Star internal heating mechanisms?

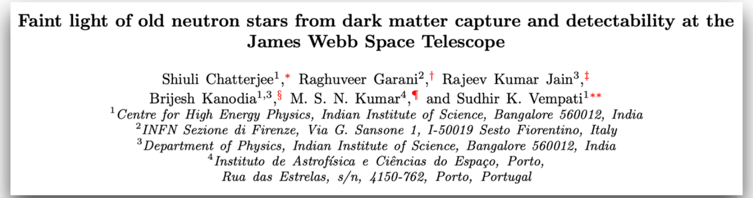
- eg. Rotochemical heating → Irrelevant if initial rotational period: P_0 is sufficiently large [K. Hamaguchi et al. (2019)]
- We need to study other internal heating mechanisms to conclude whether or not we can really detect DM heating
- If we observe Neutron Star w/ $T_s \lesssim 10^3\ \mathrm{K}$, **DM w/ nucleon int. can be widely constrained** for GeV-PeV range

Can we control uncertainty in Neutron Star (astro obs.) compared w/ Direct Detection (Underground exp.)?

- We do have uncertainty from
  - Astrophysics (eg. Internal unknown structure of compact star, initial condition)
  - Nuclear Physics (eg. Nuclear force model under high density)
- Still, we may overcome some disadvantages in Direct Detection by combining Neutron Star obs.

To establish this new direction, continuous efforts to form fundamental phys. is mandatory

JWST Sensitivity


Faint light of old neutron stars from dark matter capture and detectability at the James Webb Space Telescope

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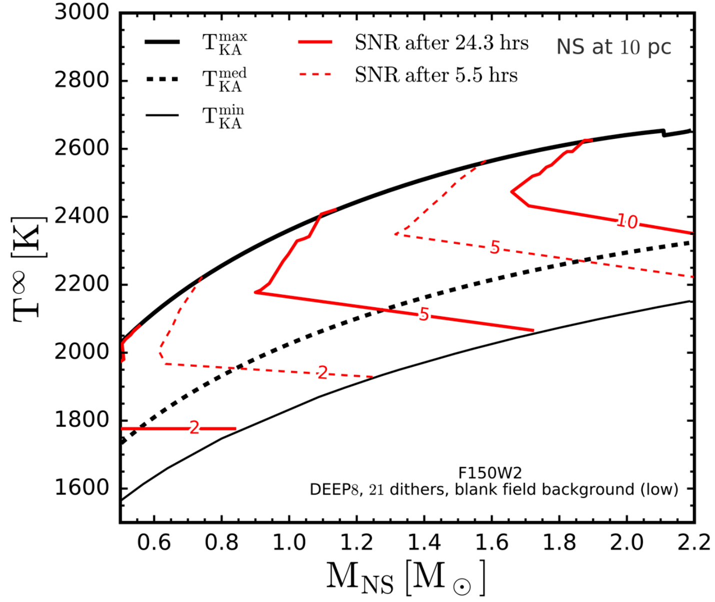
Targets

- Our targets: Isolated & old Neutron Stars near close to us
- Spatial distribution of stars are predicted by Monte-Carlo orbital simulations
  → 1-2 (100-200) old isolated Neutron Stars within 10 (50) pc are expected



DM capture rate

- Maximum surface temperature is derived by considering uncertainties:
  - EoS allowed region (on radius-mass plots)
  - Neutron Star-DM phase space distribution
  → $T_s \simeq 2600$ K (w/ 40 % validation)

JWST Sensitivity for DM heating

- Wave length of DM black body radiation : $\lambda \simeq 2\ \mu$m
- NIRCAM filter F150W2 provides the best sensitivity
  → Detection w/ Signal to Noise Ratio (SNR) $\gtrsim$ 10 within 24 hours of exposure time

※ After releasing the first scientific data on July 12, 2022, JWST will start scientific works

BU

DM Annihilation into **Neutrino**

Standard Scenario: Neutron Star Heating by DM Annihilation

(1) DM is captured by Neutron Star if DM-nucleon cross section exceeds threshold value

(2) DM annihilates into **the SM particles**, which is thermalized and release its energy ($\simeq$ DM mass) into Neutron Star

※ If DM annihilates into non-SM particles, final state particles may escape from stars (cf. "Secluded DM" scenario)

(3) Neutron Star Surface Temperature will be increased to reach JWST-sensitivity: $T_s \simeq \mathcal{O}(1000)\ \mathrm{K}$

Question: Can we apply this standard scenario to **DM annihilation channel into neutrino**?

Answer: **Yes**, neutrino lose its energy before escaping from Neutron Star

$$L_\nu \simeq \frac{1}{\bar{n}_n \sigma_{n\nu}} \sim \frac{1}{\bar{n}_n \times G_F^2 E_\nu^2} = 2.5\ \mathrm{m} \left(\frac{100\ \mathrm{MeV}}{E_\nu} \right)^2$$

Neutrino mean free path : L_ν

Neutron averaged density : $\bar{n}_n = 10^{37}\ \mathrm{cm}^{-3}$

Neutron-neutrino cross section : $\sigma_{n\nu} \propto G_F^2 E_\nu^2$

Initially, neutrino from DM pair annihilation has $E_\nu \simeq m_{\mathrm{DM}}$

→ Neutrino should lose its energy (to reach $E_\nu \ll 100\ \mathrm{MeV}$) to escape from star

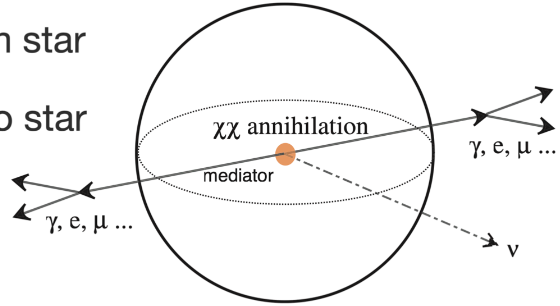
cf. Neutrino trapping in Supernova: ν ($E_\nu \gtrsim 10\ \mathrm{MeV}$) is trapped in core of Supernova core ($\rho \sim 10^{11}\ \mathrm{g/cm^3}$)

→ **Neutrino may inject almost all its energy into Neutron Star before escaping**

Indirect Detection @Compact Star

Escape from Star: “Secluded DM” [B. Batell, M. Posselov, A. Ritz, Y. Shang (2010)]

- Secluded DM: DM mainly annihilates into non-SM mediator first (which finally decay into the SM particles)
- If (mean free path of annihilation final state) > (star radius), mediator may escape from star
- Mediator decays outside of star, which may bring astro-signatures of DM capture into star
  This scenario is studied in the context of indirect detection



Indirect Detection @Neutron Star

- Target: **Neutron Star**
- Region: **Galactic Center & Globular Cluster**
- Channel: γ-ray (H.E.S.S. data is used)
- Result: DM-nucleon cross section is constrained
  (Constrained region scales as the product of DM & celestial body densities)

[R. K. Leane et al. (2021)]