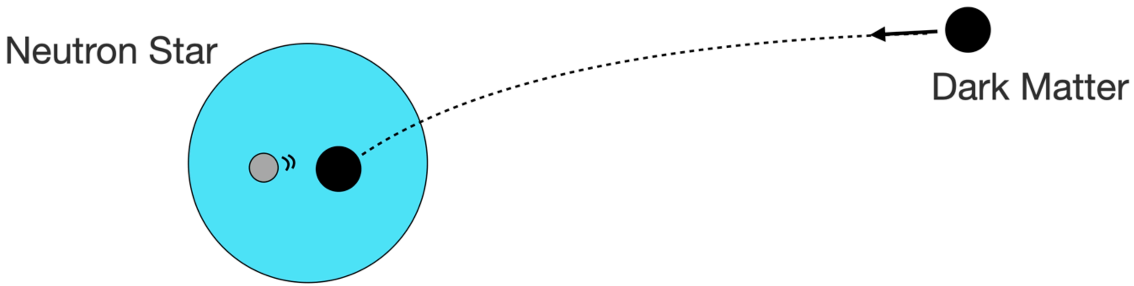
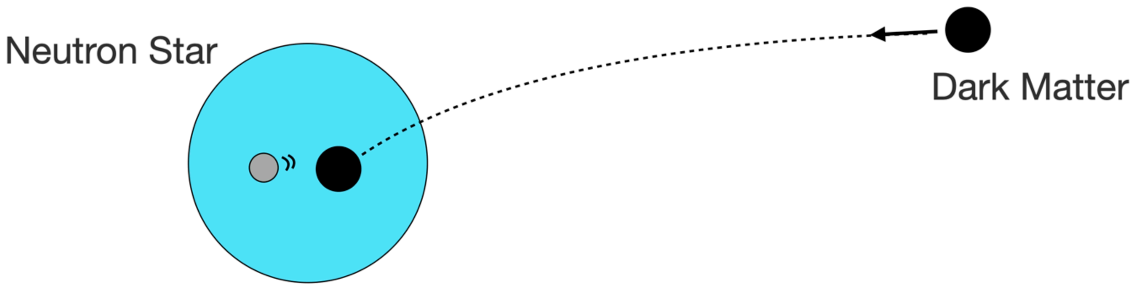
Capture of Dark Matter in Neutron Stars



Motoko Fujiwara (U. Tokyo)

Talk Slide @UGAP 2022 (Kashiwa/Online) June 13, 2022

Today's Talk



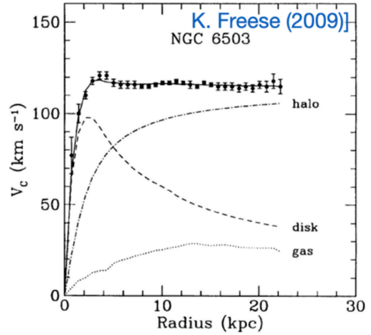
Neutron Star may be a good probe of Dark matter-Nucleon scattering effects!

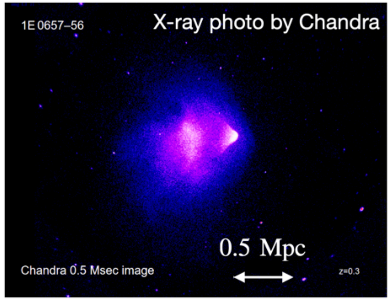
- High density of nucleus → **Wide window for DM mass & cross section**
- Strong gravitational potential → **Inelastic scattering** may be switched on

We have complementarity btw DM Direct Detection & Neutron Star Observation

eg. **Inelastic scattering** in **Electroweak Multiplet DM**

Dark Matter





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

= Dark Matter (DM)

General Feature

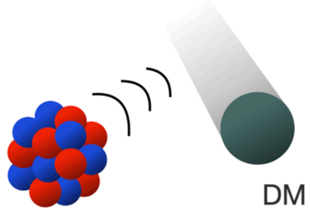
- Electrically neutral
- Stable / Long-lived
- Non-relativistic component (≃Massive)

→ Necessary component for structure formation
No candidate in the Standard Model (SM)
Various candidates are suggested

Weakly Interacting Massive Particle

- DM couples to the SM particles → DM energy density is explained as thermal relic abundance
- Probed by various experiments

eg. DM scattering → **Direct Detection exp.** : Searching for **Nucleon** recoil by **DM** scattering
cf. Talk by Dr. S. Kazama



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)]

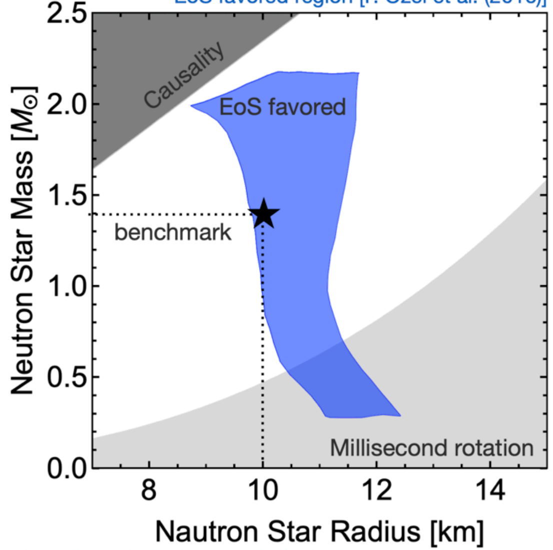
Today's Topic: **Neutron Star may be a good probe of DM-Nucleon scattering effects!**

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

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

2. Strong gravitational potential

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

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

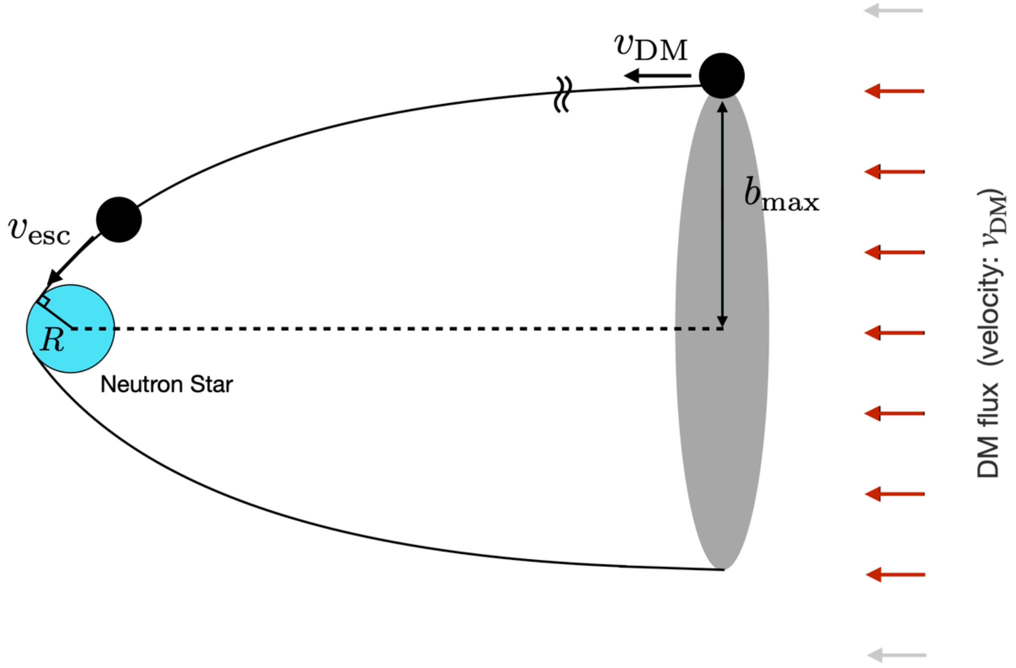
- DM flux through into old Neutron Stars
  - Initial DM is non-relativistic: $v_{\rm DM} \simeq 10^{-3}c$
  - Velocity reaches to comparable to speed of light: $v_{\rm esc} \simeq \sqrt{\dfrac{2GM_{\rm NS}}{R_{\rm NS}}}$
- Incoming DM grazes Neutron Star
  ⇔ (Perihelion) = (Neutron Star radius)

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

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

area, velocity, # density

$$\frac{dN}{dt} = \sqrt{\frac{6}{\pi}} \cdot \pi b_{\rm max}^2 \cdot v_{\rm DM} \cdot \frac{\rho_{\rm DM}}{m_{DM}}$$



DM Capture in Neutron Star (2/3)

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

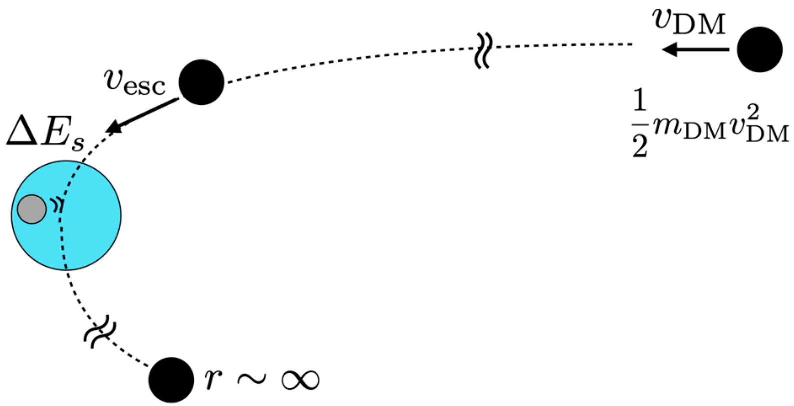
$v_{DM} \simeq 230$ km/s, $v_{esc} = \sqrt{\frac{2GM_{NS}}{R_{NS}}}$

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

Energy deposit

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

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



Condition for gravitational trap

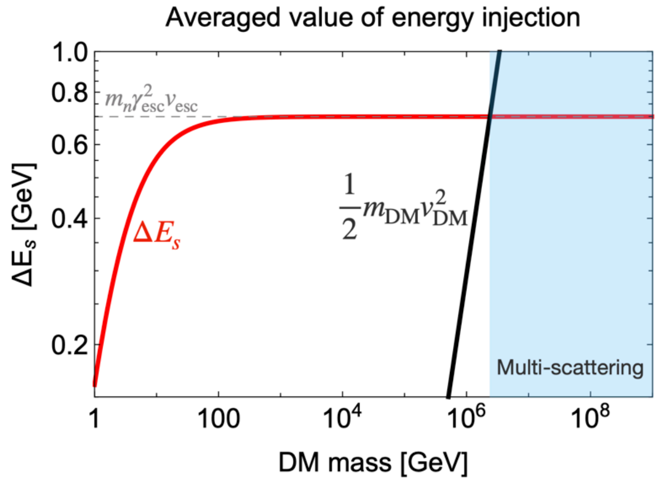
- DM can escape Neutron Star gravitational trap
  ⇔ DM has $v > 0$ after scattering @$r \simeq \infty$

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

  DM mass range that only one scattering is necessary for DM capture

$$1 \text{ GeV} \lesssim m_{DM} \lesssim 1 \text{ PeV}$$

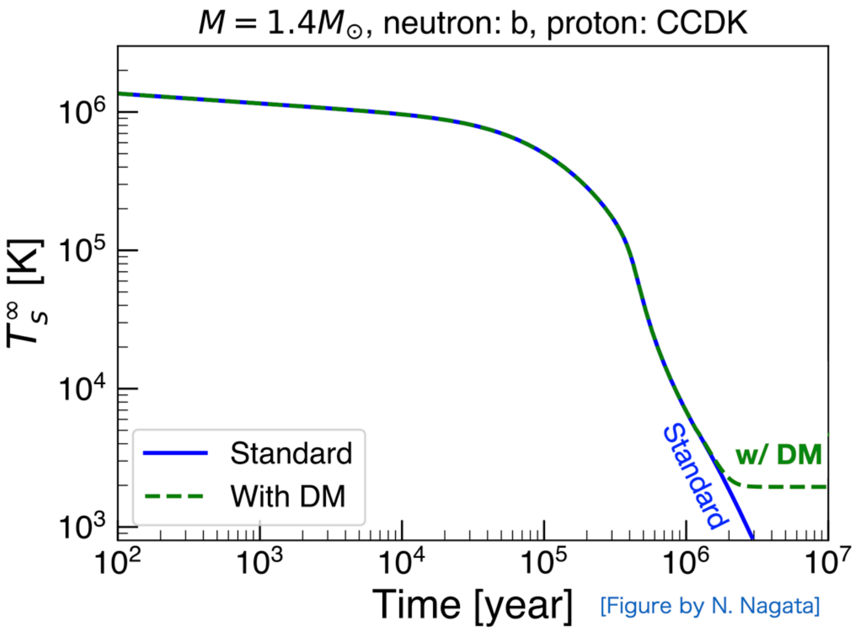
※ For $m_{DM} < 1$ GeV, Pauli blocking effects suppress scattering (typical momentum transfer: $\sqrt{2m_n\Delta E_s} < p_F$)



DM Capture in Neutron Star (3/3)

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 interaction w/ nucleon, it is captured by Neutron Stars
  → Kinetic/mass energy injection occurs
  → Observed T_s is increased
- Deviation from standard prediction may be detected by future infrared telescopes
  eg. James Webb Space Telescope (JWST) [J. P. Gardner et al. [JWST] (2006)]

Direct Detection vs Neutron Star Obs.

Condition for DM Capture

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

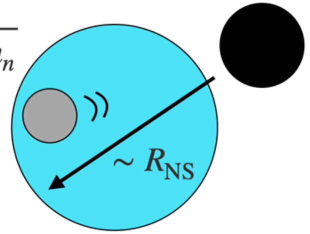
$v_{\rm esc} = \sqrt{\dfrac{2GM_{\rm NS}}{R_{\rm NS}}}$

(1) Threshold Cross Section

- Minimum cross section for DM capture in Neutron Stars

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

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



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

detailed analysis

$$\begin{cases} \sigma_{\rm th}^{(n)} = 1.7 \times 10^{-45}\ \mathrm{cm}^2 & \text{[N. F. Bell, et al.(2020)]} \\ \sigma_{\rm th}^{(n)} = 1.4 \times 10^{-44}\ \mathrm{cm}^2 & \text{[F. Anzuini, et al. (2021)]} \end{cases}$$

momentum trans. & effective nucleon mass are considered

(2) Threshold Mass Difference for Inelastic Process

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

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

Direct Detection vs Neutron Star Obs.

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

※ $N = n, p$
DM mass $\simeq 1\ {\rm TeV}$

- (Threshold cross section in Neutron Star) $\simeq$ (Current bound in Direct Detection (SI)) 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

We expect different advantages for Direct Detection & Neutron Star observation

Capture of

Electroweak Multiplet DM

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

Electroweak Multiplet DM

DM w/ Electroweak interaction

- Definition: DM has **Electroweak Charge** → Often appears in Phys. beyond the SM (eg. Supersymmetry, Extra-dim.)

  ※ Electroweak Symmetry: $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$, DM stability should be realized by other symmetry

- Feature 1: Correct DM energy density is explained as thermal relic in expanding universe for **TeV scale DM**

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

α_2: SU(2)$_L$ fine structure const.

- Feature 2: **Small mass splitting** btw Electroweak multiplet ➡ $\Delta M_{\rm EW} \simeq \alpha_2 m_W \simeq \mathcal{O}(100)\ \mathrm{MeV}$

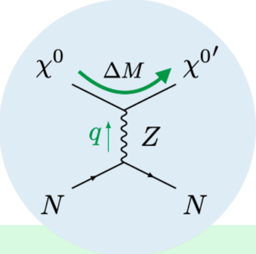
(Radiative correction, assuming $m_{\rm DM} \gg m_W$)

Search Strategy

(1) DM Direct Detection
(2) Neutron Star Obs.

} **DM-Nucleon Cross Section** & **Mass Splitting btw Multiplet**

Trigger



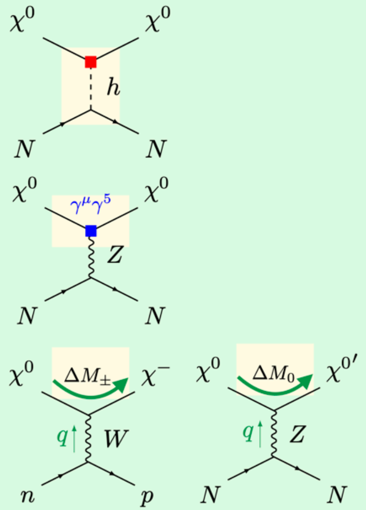
Inelastic Scattering process may be switched on in Neutron Star

$Y \neq 0$ Multiplet Model

- 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 required → **Effective Field Theory 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.



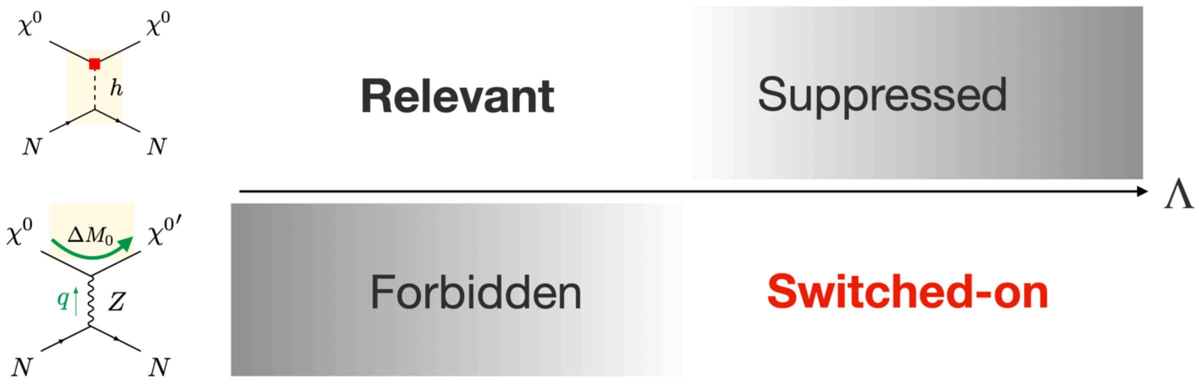
→ Search Strategy in Direct detection & Neutron Star Obs.?

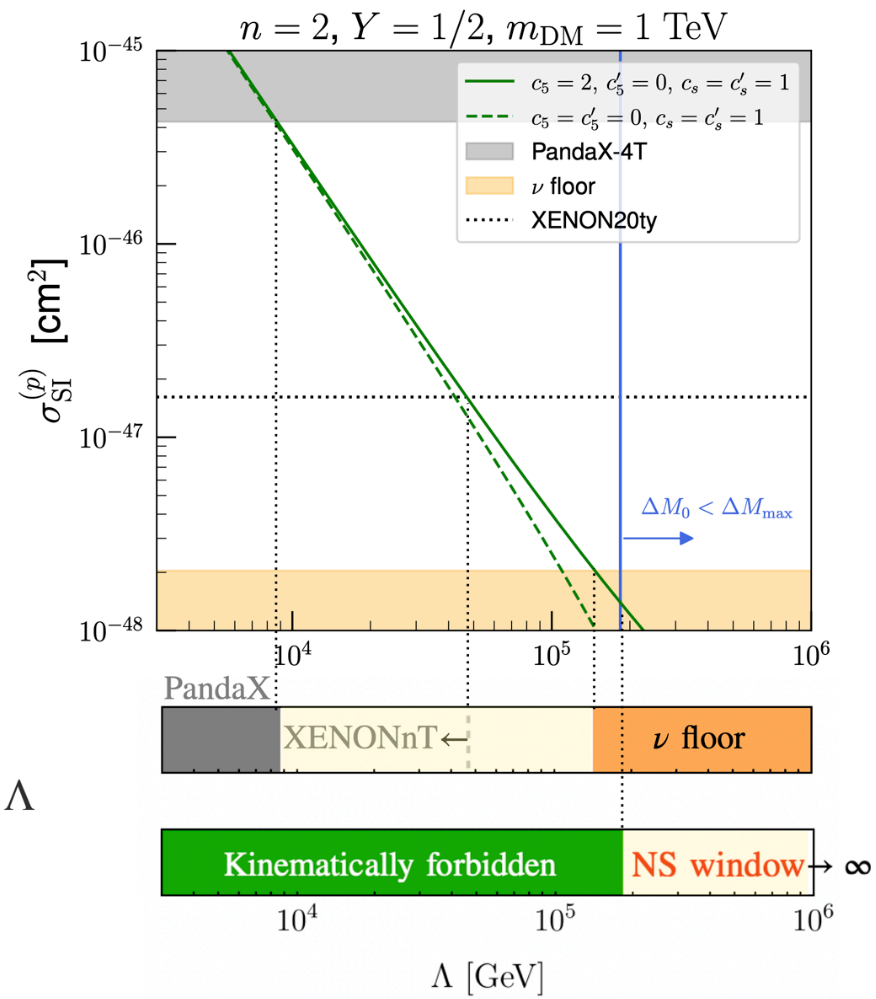
Search Strategy

eg. 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
  - Mass splitting gets smaller by Λ^{-1} suppression
    → **Inelastic scattering process is switched on in Neutron Star**

Expectation:



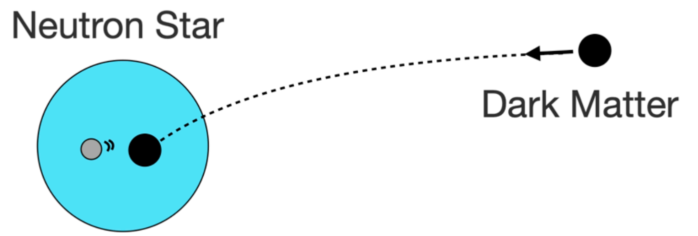


Direct detection & Neutron Star obs. will be a complimentary probe for EW Multiplet DM

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: $\Delta M \lesssim \mathcal{O}(100)\ \mathrm{MeV}$

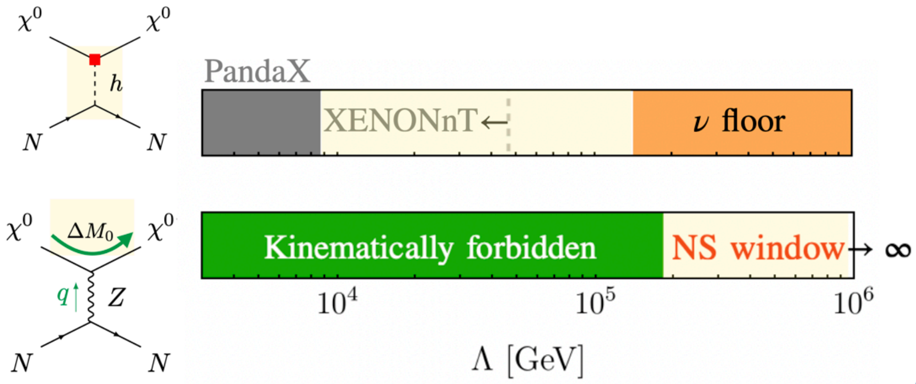


Effective Field Theory Approach

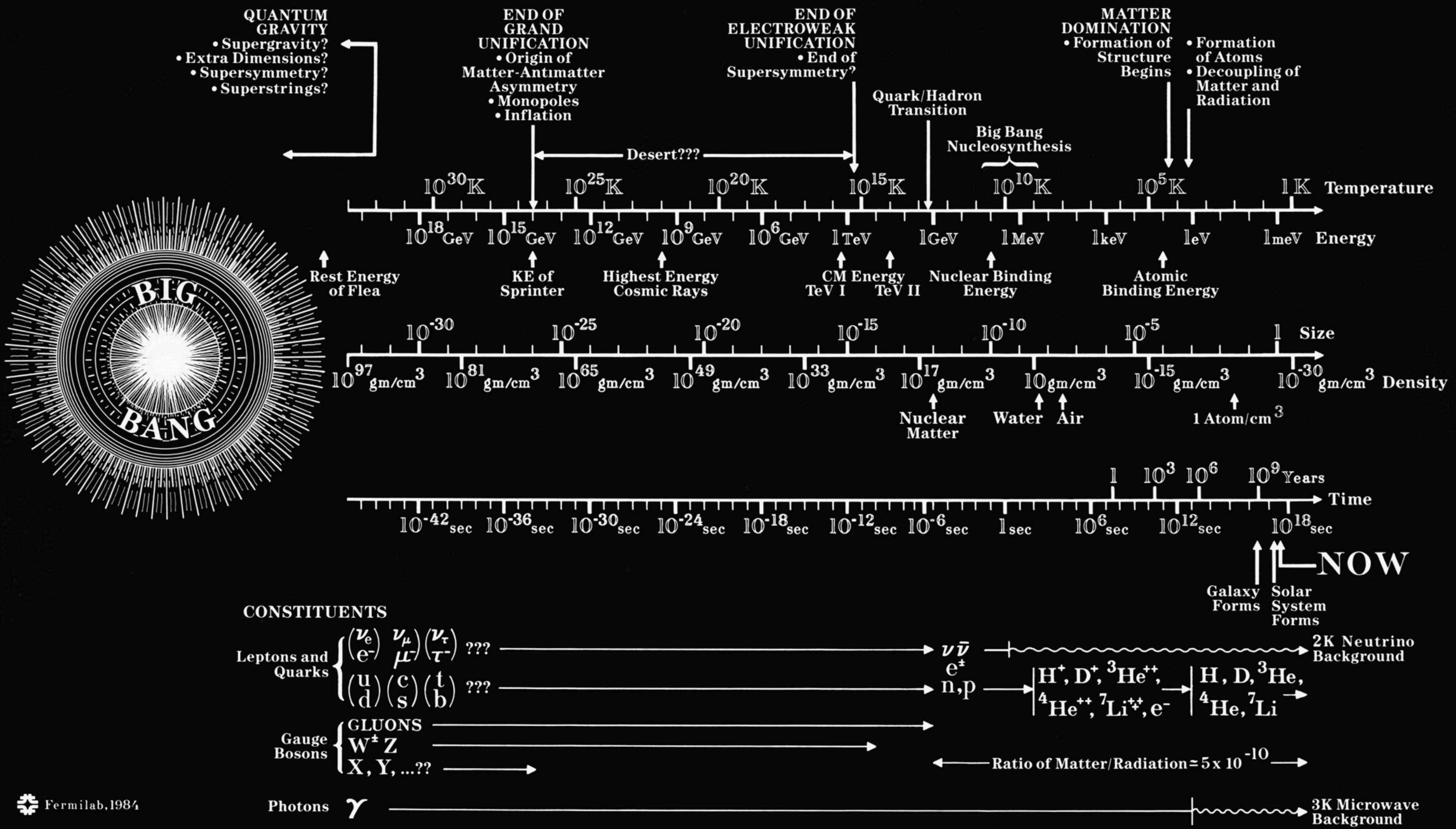
- **DM-Higgs Effective Operators** are key to reveal search strategy
  - σ_N is induced from low dim. operator → Probed in Direct Detection
  - ΔM is suppressed for large Λ→ Inelastic scatt. occur in Neutron Star

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
(νe e-) (νμ μ-) (ντ τ-) ???
(u d) (c s) (t b) ???
ν ν̄
e±
n,p
H+, D+, 3He++, 4He++, 7Li+++, e-
H, D, 3He, 4He, 7Li
2K Neutrino Background
Gauge Bosons
GLUONS
W± Z
X, Y, ...??
Ratio of Matter/Radiation ≈ 5 x 10^-10
Photons γ
3K Microwave Background
Fermilab, 1984

$Y \neq 0$: 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: $\chi_m \sim (n, Y),\ \eta_m \sim (n, -Y),\ H \sim (2, 1/2)$

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

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

(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**

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

- **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

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

- **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

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

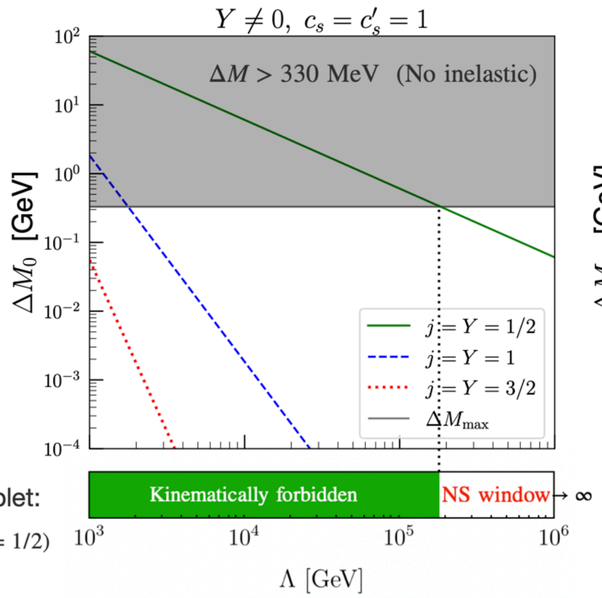
$$-\frac{c_5'}{\Lambda}\sum_{m=-j}^{j}(-1)^m\eta_{-m}(T_a)_{mn}\chi_m\,(H^\dagger\tau_a H)$$

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

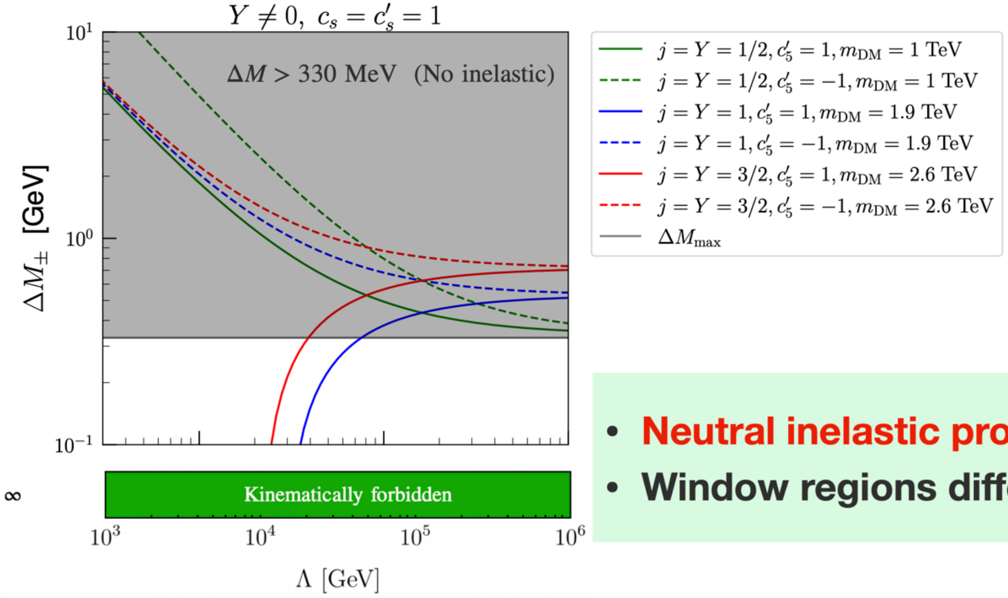
※ (CG coeff.) = Clebsch-Gordan coefficient

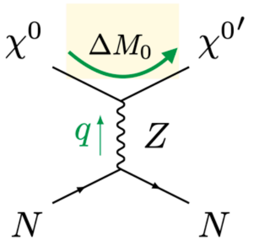
	$n=2$	$n=3$	$n=4$
	$Y=1/2$	$Y=1$	$Y=3/2$
c_s, c_s'-term	dim. 5	dim. 7	dim. 9

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



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

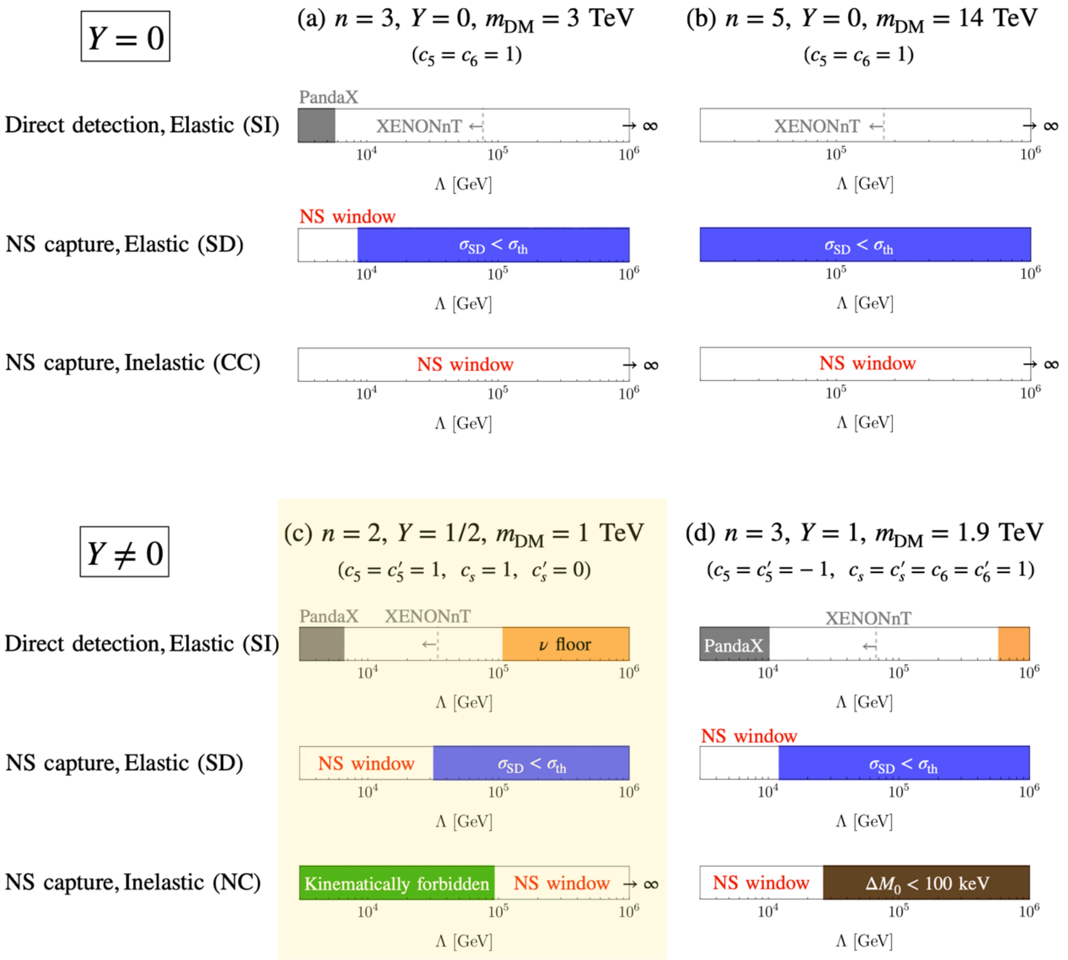




- **Neutral inelastic process is important**
- **Window regions differ by each Multiplet**

Results

- 4 benchmark multiplet models:
  - $Y = 0$: (a) $n = 3$, $Y = 0$
    (b) $n = 5$, $Y = 0$
  - $Y \neq 0$: (c) $n = 2$, $Y = 1/2$
    (d) $n = 3$, $Y = 1$
- 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

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 (≃ 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

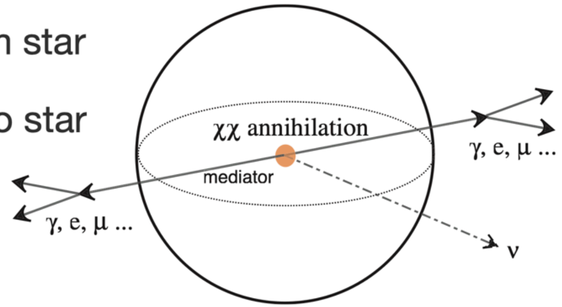
cf. Neutrino trapping in Supernova: ν ($E_\nu \lesssim 10\ \mathrm{MeV}$) is trapped in core of Supernova core ($\rho \sim 10^{11}\ \mathrm{g/cm^3}$)

→ **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)]

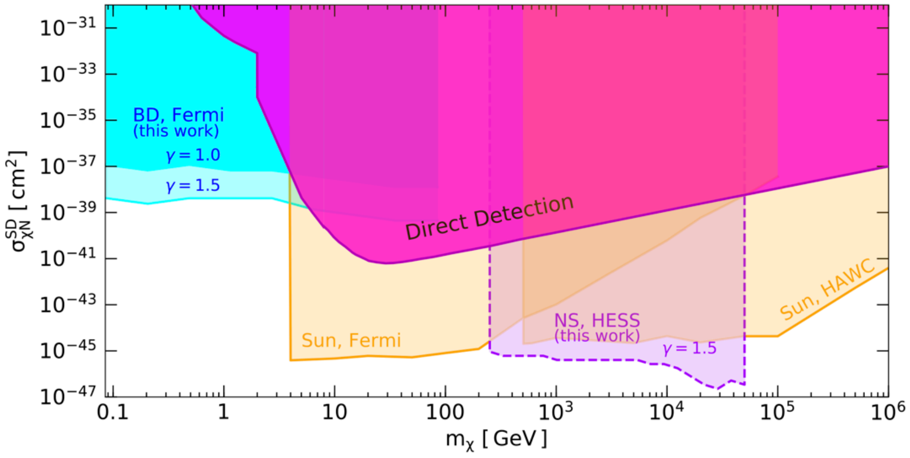
- Secluded DM: DM mainly annihilates into non-SM mediator first (which finally decay into the SM particles)
- If (mean free path of annihilation final state) > (star radius), mediator may escape from star
- Mediator decays outside of star, which may bring astro-signatures of DM capture into star
  This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



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