Improved white dwarves constraints on inelastic dark matter and Left-Right Symmetric Models

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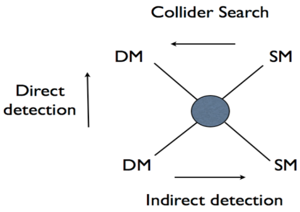
WIMP dark matter searches

- Cold Dark Matter (CDM): provides ∼25% of the energy density of the Universe; evidences are only through gravitational effects

- Weakly Interacting Massive Particles (WIMPs): one of the most popular candidates for CDM; mass in GeV – TeV scale

- WIMP searches:
  1. Direct detection
  2. Indirect detection
  3. Collider searches



- Direct detection: searches based on the scattering of local WIMPs against nuclear targets in terrestrial detectors

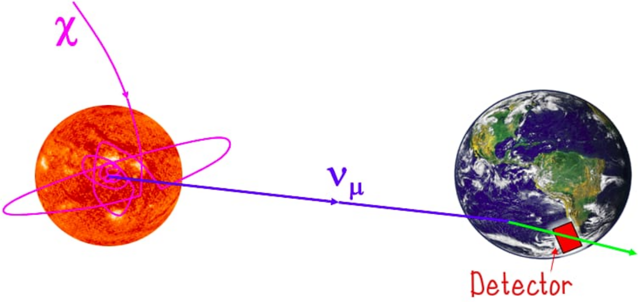
- Indirect detection:
  • searches for γ's/ν's/anti-particles produced in WIMP pair-annihilations (e.g., in Galactic Center, local dwarf galaxies)

WIMP capture

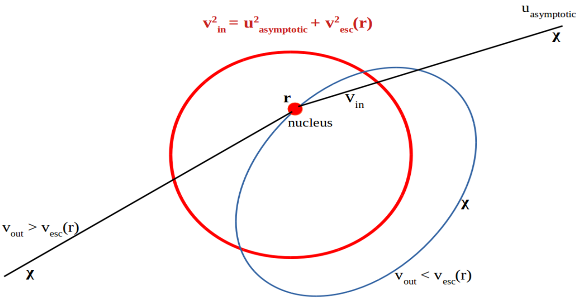
- Celestial bodies can accumulate WIMPs in their interior due to their gravitational potential

  Example: capture of WIMPs in the Sun

- Inside the celestial bodies (e.g. Sun) captured WIMPs can annihilate into SM particles
  $\chi\chi \to b\bar{b}, \tau^+\tau^-, W^+W^-, \ldots \Rightarrow \nu(\bar{\nu})$ [signal for neutrino telescopes]



WIMP capture mechanism

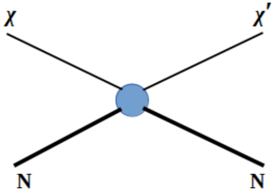


- Inside a celestial body the incoming WIMP is accelerated by the gravitational potential and acquires a large velocity
  $v_{\rm in} = \sqrt{u^2_{\rm asymptotic} + v^2_{\rm esc}(r)}$; $v_{\rm esc}(r) \equiv$ **local escape velocity**
- The WIMP can scatter off a nucleus inside the celestial body (via the same interaction probed by Direct Detections)
- If its outgoing speed ($v_{\rm out}$) after the scattering is below $v_{\rm esc}(r)$, the WIMP gets trapped into a gravitationally bound orbit
- The WIMP continues to scatter inside the celestial body and ultimately settles down in the core

Inelastic Dark Matter (IDM)

- WIMP DM (χ) scatters off a nucleus (N) by making a transition to a slightly heavier state (χ'): $\chi + \mathrm{N} \to \chi' + \mathrm{N}$
- χ and χ' are very close in mass: $m_{\chi'} - m_{\chi} \equiv \delta > 0$
- Elastic scattering $[\chi + \mathrm{N} \to \chi + \mathrm{N}]$ is absent

  [Smith *et al.* (PRD 64, 043502 (2001))]



- Kinetic energy of the incoming DM particle χ should be large enough to overcome the mass splitting δ

$$\frac{1}{2}\,\mu_{\chi\mathrm{N}}\,v_{\mathrm{in}}^2 > \delta\,, \qquad [\mu_{\chi\mathrm{N}} \equiv \mathrm{reduced\,mass} = \frac{m_\chi m_\mathrm{N}}{m_\chi + m_\mathrm{N}}]$$

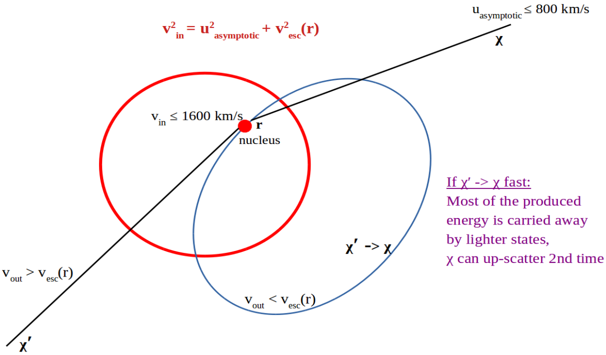
$$\Rightarrow v_{\mathrm{in}} > \sqrt{\frac{2\delta}{\mu_{\chi\mathrm{N}}}}$$

Inelastic Dark Matter (IDM)

- Direct detection:
  $v_{\rm in} \lesssim 800$ km/s (Galactic escape velocity w.r.t the Earth frame)

  $$\Rightarrow \quad \boldsymbol{\delta \lesssim 200\ \text{keV}} \qquad \text{(for Xe based detectors)}$$

- WIMP capture in the Sun:
  The incoming WIMP is accelerated by the strong gravitational potential of the Sun before scattering; $\boldsymbol{v_{\rm in} \lesssim 1600\ \text{km/s}}$



$$\Rightarrow \quad \boldsymbol{\delta \lesssim 600\ \text{keV}} \qquad \text{(for capture in the Sun)}$$

IDM capture in compact stars

- Compact stars have much larger steller densities compared to that of the Sun; [e.g., White Darves (WDs), Neutron stars (NSs)]

  $\Rightarrow$ DM particles are gravitationally accelerated to very high speeds

  $\Rightarrow$ IDM capture is possible for higher mass splitting δ

- Interior density of the heaviest WDs ($M_* \sim 1.4\, M_\odot$) can be 10^8 times larger than in the Sun

  $\Rightarrow$ the incoming WIMP speed can reach up to a few 10^4 km/s

  $\Rightarrow$ **$\delta \lesssim$ a few tens of MeV**

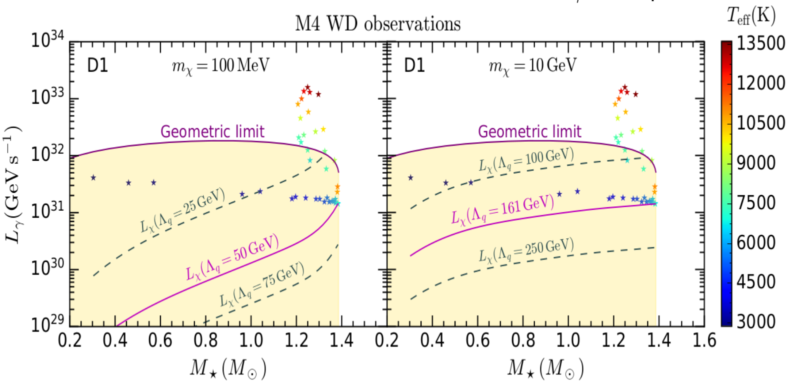
- For NSs, the incoming WIMP speed can reach up to a few 10^5 km/s

  $\Rightarrow$ **$\delta \lesssim$ a few hundreds of MeV**

WDs in M4 globular cluster

Hubble Space Telescope (HST) has observed many faint and cold WDs in the core of Messier 4 (M4), the closest globular cluster to the Earth (∼2 kpc)

HST data for the observed WDs in M4 shown in the $L_\gamma - M_*$ plane



[McCullough *et al.* (PRD 81, 083520 (2010)) ; Bell *et al.* (JCAP10(2021)083)]

- WIMP annihilations can drive the WD luminosity above the observed value

  ⇒ It is possible to constrain the WIMP parameter space
  (Colder and heavier WDs are more useful)

DM density in M4

Prediction for the DM abundance in M4 relies on the Galaxy formation models

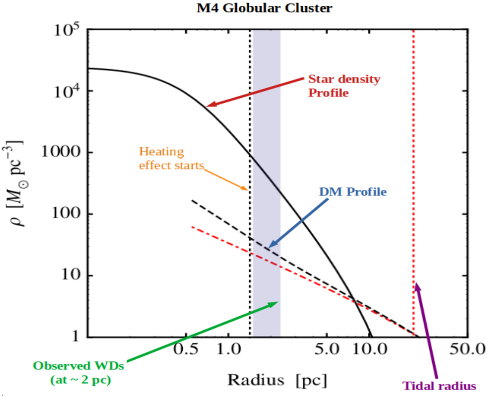
$\rho_{\rm DM} \simeq$ **800 GeVcm^{-3}**
@ radius ~ 2 pc
(well within $r_{\rm tidal}$)

$[\rho_{\rm DM\odot} \simeq 0.3\ {\rm GeVcm^{-3}}]$

$v_{\rm rms} \lesssim 8\ {\rm km/s}$

$[v_{\rm rms\odot} \simeq 300\ {\rm km/s}]$

$v_* \sim v_{\rm rms}$



[McCullough *et al.* (PRD 81, 083520 (2010))]

The total estimated DM content that survives the tidal stripping is less than 1% of the original halo

→ conservative estimate
→ consistent with the observed lack of DM in globular clusters

Capture rate of IDM in WDs & the annihilation luminosity

- Optically-thin limit for capture: When the scattering cross-section is relatively small (i.e., scattering length larger than WD size)

$$C_{\rm opt-thin} = \frac{\rho_\chi}{m_\chi} \int_0^{R_*} dr\, 4\pi r^2 \int_0^\infty du\, \frac{f(u)}{u}\, w\, \Omega(w,r)\, \Theta\left(\frac{1}{2}\mu_{\chi \rm N} w^2 - \delta\right)$$

$$\Omega(w,r) = \eta_{\rm N}(r)\, w\, \Theta(E_{\max} - E_{\rm cap}) \int_{\max[E_{\min}, E_{\rm cap}]}^{E_{\max}} dE\, \frac{d\sigma[\chi + {\rm N} \to \chi' + {\rm N}]}{dE}$$

Nuclear density in WD
(WD equation of state)

differential cross-section

$w = \sqrt{u^2 + v_{\rm esc}^2(r)}$ (incoming WIMP speed before scattering $= v_{\rm in}$)
u = asymptotic WIMP speed at large distance
$f(u)$ = WIMP speed distribution in M4 $\rightarrow$ Maxwell Boltzmann distribution

Condition for IDM scattering:

$\frac{1}{2}\mu_{\chi \rm N} w^2 > \delta$

Condition for capture:

$E > E_{\rm cap} = \frac{1}{2} m_\chi u^2 - \delta$

(corresponds to $v_{\rm out} < v_{\rm esc}(r)$)

Capture rate of IDM in WDs & the annihilation luminosity

- Geometrical limit for capture: When the cross-section is large, capture saturates to the geometrical limit (i.e., all the WIMPs crossing the star are captured)

$$C_{\rm geom} = \pi R_*^2 \left(\frac{\rho_\chi}{m_\chi}\right) \int_0^\infty du \, \frac{f(u)}{u} \, w^2(R_*)$$

- $C_* = \min[C_{\rm opt-thin}, C_{\rm geom}]$

- Capture and annihilation processes equilibrate (since $\tau_{\rm equilibrium} \ll t_{\rm WD}$)
$\Rightarrow \Gamma_{\rm ann} = C_*/2$

- For a large m_χ, almost all the energy injected by WIMP annihilations is absorbed in the WD star and increases its luminosity
(true even for ν's in the final products of annihilations)

$$\boldsymbol{L_\chi \simeq 2 m_\chi \Gamma_{\rm ann} = m_\chi C_*}$$

Heavy WDs are made of mostly Carbon ($^{12}_{6}\mathrm{C}$), Oxygen ($^{16}_{8}\mathrm{O}$) and Neon ($^{20}_{10}\mathrm{Ne}$)
$\Rightarrow$ WIMP capture in WDs is driven mainly by Spin-Independent (SI) interaction

$\sigma^{\mathrm{SI}} \propto (\mathrm{atomic\,number})^2$

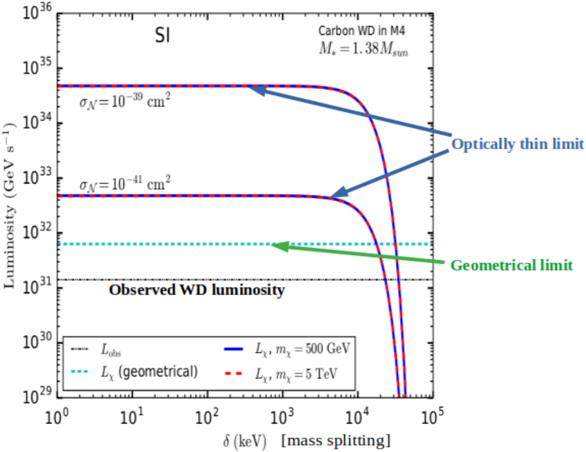
We assume 100% Carbon to get conservative bound

$\sigma_{\mathcal{N}}$: WIMP-nucleon SI cross-section

For $m_\chi \gg m_{\mathrm{nucleus}}$

$C_* \sim 1/m_\chi$

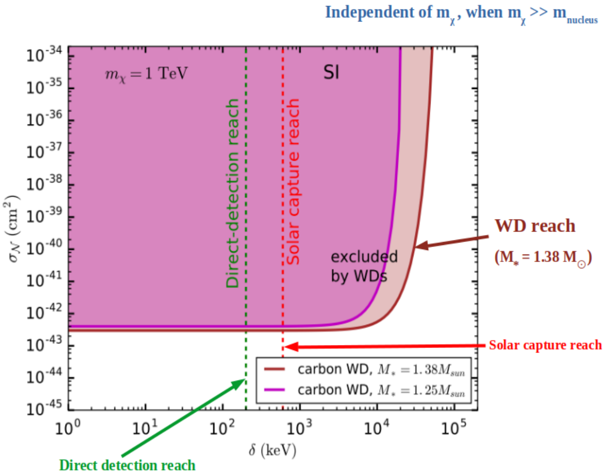
L_χ independent of m_χ



[A. Biswas, AK, H. Kim, S. Scopel, L. V. Sevilla, PRD 106, 083012 (2022)]

WD exclusion for IDM

Excluded parameter space in $\delta - \sigma_{\mathcal{N}}$ plane (SI interaction) for IDM



[A. Biswas, AK, H. Kim, S. Scopel, L. V. Sevilla, PRD 106, 083012 (2022)]

A specific realization of IDM: Bi-doublet fermionic DM in Left-Right symmetric models (LRSM)

- Motivation: explain observed maximal parity violation in SM weak-sector
- In LRSM the SM gauge group is enlarged to contain $SU(2)_L$ and $SU(2)_R$
- $SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow SU(3) \times SU(2)_L \times U(1)_Y \rightarrow SU(3) \times U(1)_{em}$

$$Y = T_R^3 + \frac{1}{2}(B-L)$$

$$Q = T_L^3 + Y = T_L^3 + T_R^3 + \frac{1}{2}(B-L)$$

$$\frac{1}{g_Y^2} = \frac{1}{g_R^2} + \frac{1}{g_{B-L}^2}$$

$$\frac{1}{e^2} = \frac{1}{g_L^2} + \frac{1}{g_Y^2}$$

Minimal Left Right Symmetric Model		
Matter	Generations	$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C$
Fermions		
L_L	3	$(\mathbf{2}, \mathbf{1}, -1, \mathbf{1})$
L_R	3	$(\mathbf{1}, \mathbf{2}, -1, \mathbf{1})$
Q_L	3	$(\mathbf{2}, \mathbf{1}, +\frac{1}{3}, \mathbf{3})$
Q_R	3	$(\mathbf{1}, \mathbf{2}, +\frac{1}{3}, \mathbf{3})$
Scalars		
Φ	1	$(\mathbf{2}, \overline{\mathbf{2}}, 0, \mathbf{1})$
T_R	1	$(\mathbf{1}, \mathbf{3}, +2, \mathbf{1})$
T_L	1	$(\mathbf{3}, \mathbf{1}, +2, \mathbf{1})$
DM Candidates		
Fermion		
Ψ	1	$(\mathbf{2}, \mathbf{2}, 0, \mathbf{1})$

- Left-right symmetry broken at scale M_R by triplet T_R with vev v_R
  $\Rightarrow$ masses of Z_R and W_R are generated
- EW symmetry broken by bi-doublet Φ with vevs v_1 and v_2
  $\Rightarrow$ masses of Z_L and W_L are generated (SM gauge bosons)

$$v_R \gg v_1, v_2 \,;\; v_L \simeq 0 \qquad \sqrt{v_1^2 + v_2^2} = v \simeq 246 \text{ GeV}$$

Bi-doublet fermionic DM

LRSM is minimally extended by adding a self-conjugate fermionic bi-doublet Ψ

$$\Psi = \begin{bmatrix} \psi^0 & \psi^+ \\ \psi^- & -\left(\psi^0\right)^c \end{bmatrix} \qquad (\tilde{\Psi} \equiv -\sigma_2 \Psi^c \sigma_2 = \Psi)$$

$SU(2)_L \times SU(2)_R$ invariant Lagrangian for bi-doublet(BD) Ψ:

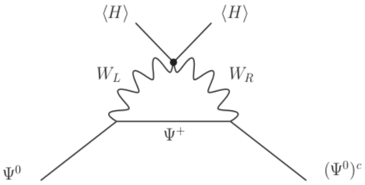
$$\mathcal{L}_{\rm BD} = \frac{1}{2}{\rm Tr}\left[\overline{\Psi} i \not{D} \Psi\right] - \frac{1}{2} M_\Psi {\rm Tr}\left[\overline{\Psi}\Psi\right]$$

covariant derivative: $D_\mu \Psi = \partial_\mu \Psi - i\frac{g_L}{2}\sigma_a W^a_{L\,\mu} \Psi + i\frac{g_R}{2}\Psi\,\sigma_a W^a_{R\,\mu}$

$$\begin{aligned} \mathcal{L}_{\rm BD} \quad \ni \quad & \frac{g_L}{2}\left(\overline{\psi^0}\not{W}^3_L\psi^0 - \overline{\psi^-}\not{W}^3_L\psi^- + \sqrt{2}\,\overline{\psi^0}\not{W}^+_L\psi^- + \sqrt{2}\,\overline{\psi^-}\not{W}^-_L\psi^0\right) \\ & -\frac{g_R}{2}\left(\overline{\psi^0}\not{W}^3_R\psi^0 + \overline{\psi^-}\not{W}^3_R\psi^- + \sqrt{2}\,\overline{\psi^0}\not{W}^-_R\psi^+ + \sqrt{2}\,\overline{\psi^+}\not{W}^+_R\psi^0\right) \end{aligned}$$

Mass splitting in Bi-doublet fermionic DM

When Φ acquires vevs, the mixing between $W_L^\pm$ and $W_R^\pm$ induces a $\psi^0 \to (\psi^0)^c$ transition that generates a tiny off-diagonal Majorana mass term δM



[Garcia-Cely *et al.* (JCAP03(2016)021)]

The Dirac fermion Ψ^0 splits into two Majorana states χ_1 and χ_2

$$\chi_{1,\,2} = \frac{1}{\sqrt{2}}\left(\psi^0 \mp (\psi^0)^c\right)$$
$$m_{\chi_{1,\,2}} = M_\Psi \mp \delta M$$
$$\delta = m_{\chi_2} - m_{\chi_1} = 2\delta M$$

$$\delta = \frac{g_L^2}{16\pi^2}\frac{g_R}{g_L}\sin(2\xi)M_\Psi\left[f(r_{W_1}) - f(r_{W_2})\right] = \delta(g_R, M_\Psi, M_{W_2})$$

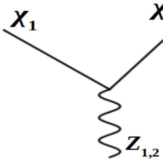
$$\begin{pmatrix} W_L^+ \\ W_R^+ \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix}\begin{pmatrix} W_1^+ \\ W_2^+ \end{pmatrix} \qquad \tan 2\xi \simeq -4\,\frac{g_R}{g_L}\frac{M_{W_L}^2}{M_{W_R}^2}\frac{v_1 v_2}{v^2}$$

Loop function: $f(r_V = M_V/M_\Psi) = 2\int_0^1 dx\,(1+x)\log\left[x^2 + (1-x)r_V^2\right]$

Bi-doublet DM interaction

$$\mathcal{L}_{\rm BD}^{NC} \in \frac{g_L}{2}\left(\overline{\psi^0}\not{W}_L^3\psi^0\right) - \frac{g_R}{2}\left(\overline{\psi^0}\not{W}_R^3\psi^0\right)$$
$$= \frac{1}{2}\overline{\chi_1}\left(g_L\not{W}_L^3 - g_R\not{W}_R^3\right)\chi_2$$

Only off-diagonal interaction term; no diagonal interaction term



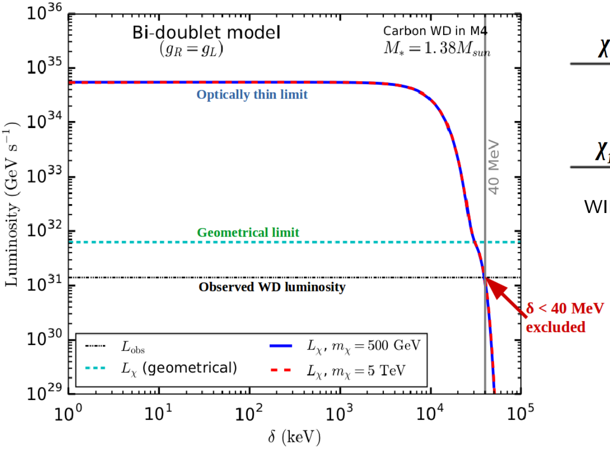
Inelastic scattering

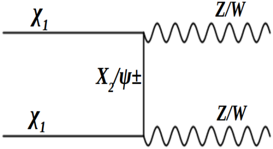
(An explicit IDM realization)

lighter state (χ_1) automatically stable

$\tau(\chi_2 \to \chi_1) \ll t_U$ [χ_1 dominant DM candidate (χ)]

Large scattering cross-section
$\Rightarrow$ parameter space gets excluded
unless scattering is kinematically forbidden by large mass splitting δ
[N.B. $\delta = \delta(g_R, M_\Psi, M_{W_2})$]



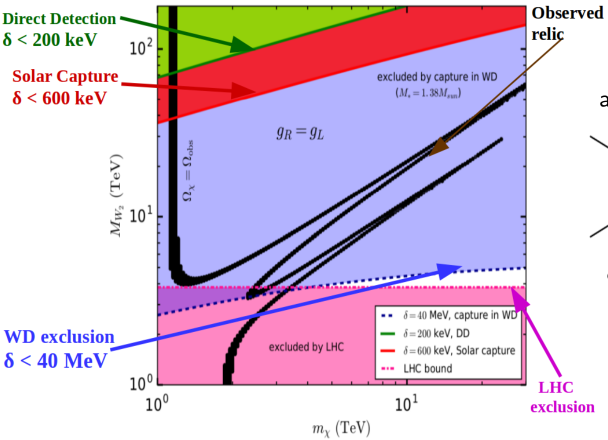


WIMP annihilation channel

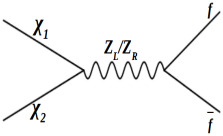
[A. Biswas, AK, H. Kim, S. Scopel, L. V. Sevilla, PRD 106, 083012 (2022)]

Exclusion on LRSM parameter space

$$g_R = g_L$$



at Early Universe:



co-annihilation
($\delta \ll T_{\rm dec}$)

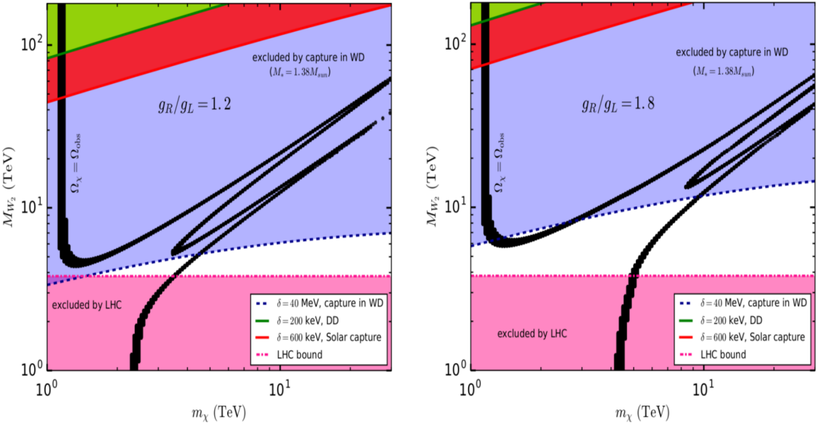
[A. Biswas, AK, H. Kim, S. Scopel, L. V. Sevilla, PRD 106, 083012 (2022)]

- **WD bounds exclude all cosmologically viable parameter space (for $g_R = g_L$)**

Exclusion on LRSM parameter space (for $g_R > g_L$)

To recover cosmologically viable parameter space one needs to increase δ (at fixed m_χ and M_{W_2})

$\Rightarrow$ increase g_R (i.e., $g_R > g_L$) , since $\delta \propto g_R$ (at fixed m_χ and M_{W_2})



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Conclusions

- Models of structure formation suggest that the inner region of the Messier 4 (M4) globular cluster should have a large DM density
- We use the luminosities of low–temperature heavy WDs observed by HST in the core of M4 to improve the existing constraints on Inelastic Dark Matter (IDM)
- **WD data can exclude $\delta \lesssim$ a few tens of MeV**
  (for Direct Detection $\delta \lesssim 200$ keV; for capture in the Sun $\delta \lesssim 600$ keV)
- We apply such constraint to a specific IDM scenario:
  LRSM + Bi-doublet fermion DM

  → **WD bounds significantly reduce the cosmologically viable parameter space of such scenario, and require $g_R > g_L$**
- In neutron stars, IDM scattering can be active up to $\delta \simeq$ a few hundreds of MeV

  ⇒ future observations of neutron stars (e.g., by James Webb Space Telescope) with temperatures $\lesssim$ a few thousand Kelvin would rule out the full parameter space of LRSM bi-doublet DM

Thank You