White Dwarves as Dark Matter detectors

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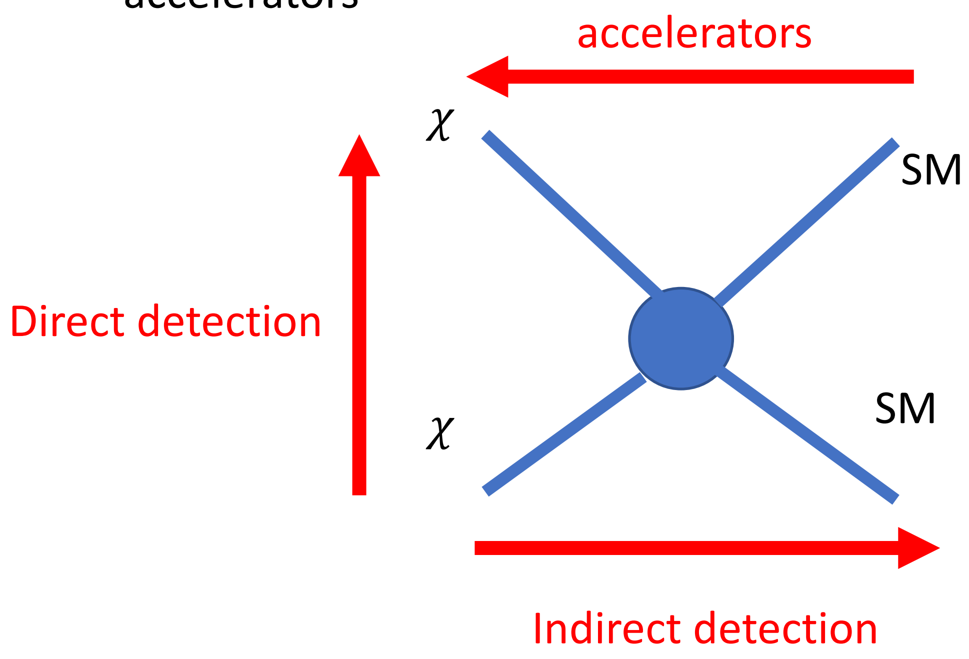
Based on: “Improved White Dwarves Constraints on Inelastic Dark Matter and Left–Right Symmetric Models”, A. Biswas, A. Kar, H. Kim, S. Scopel and L. Velasco-Sevilla, arXiv:2206.06667

WIMP searches:

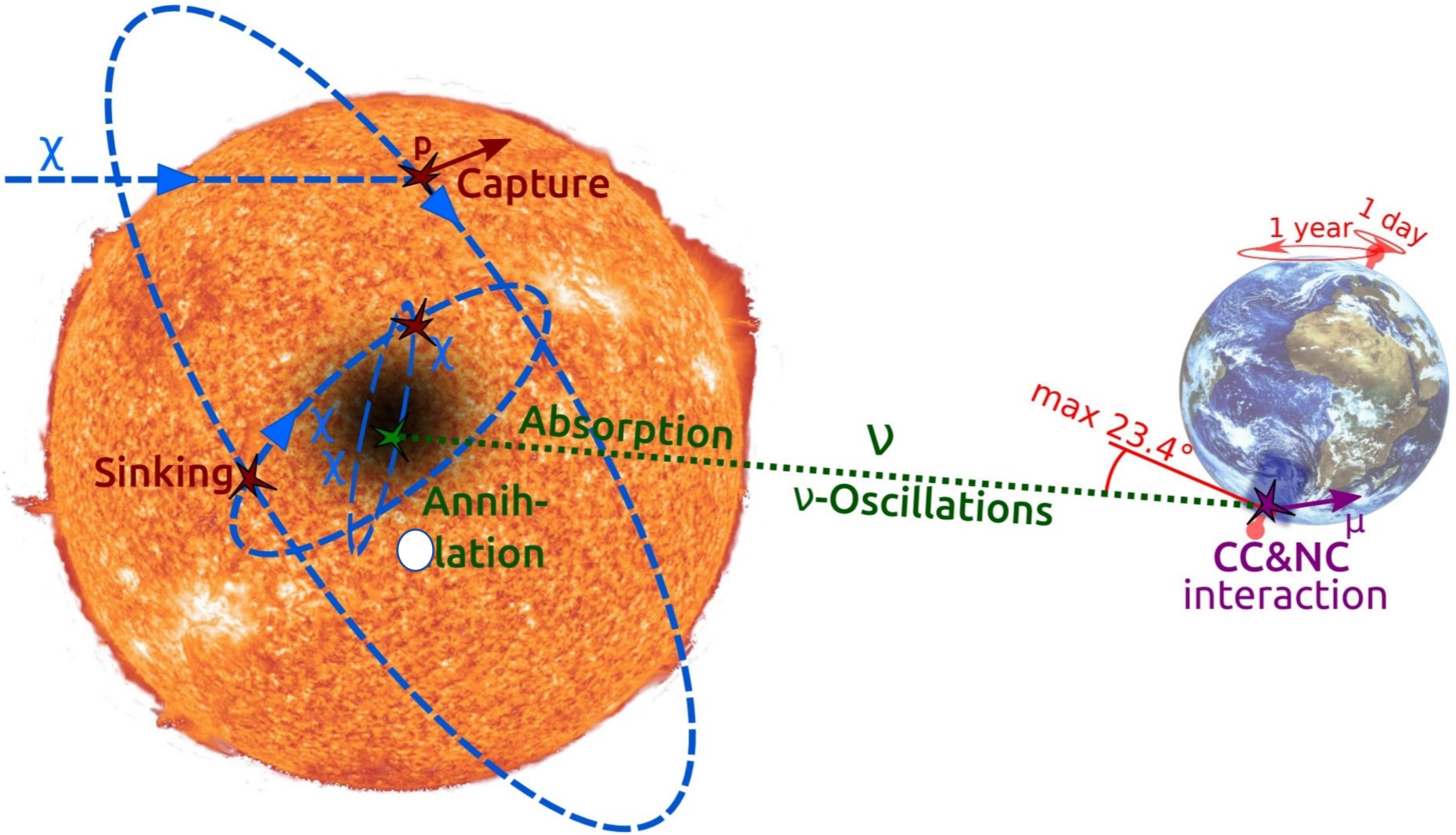
- Direct detection
- Indirect detection
- accelerators



Indirect detection:

- WIMP annihilation to photons/neutrinos/antiprotons/positrons in tha halo of our Galaxy
- Enhanced wherever the DM density is large (e.g. Galactic Center)
- Celestial bodies can accumulate WiMPs in their interior through their gravitational potential

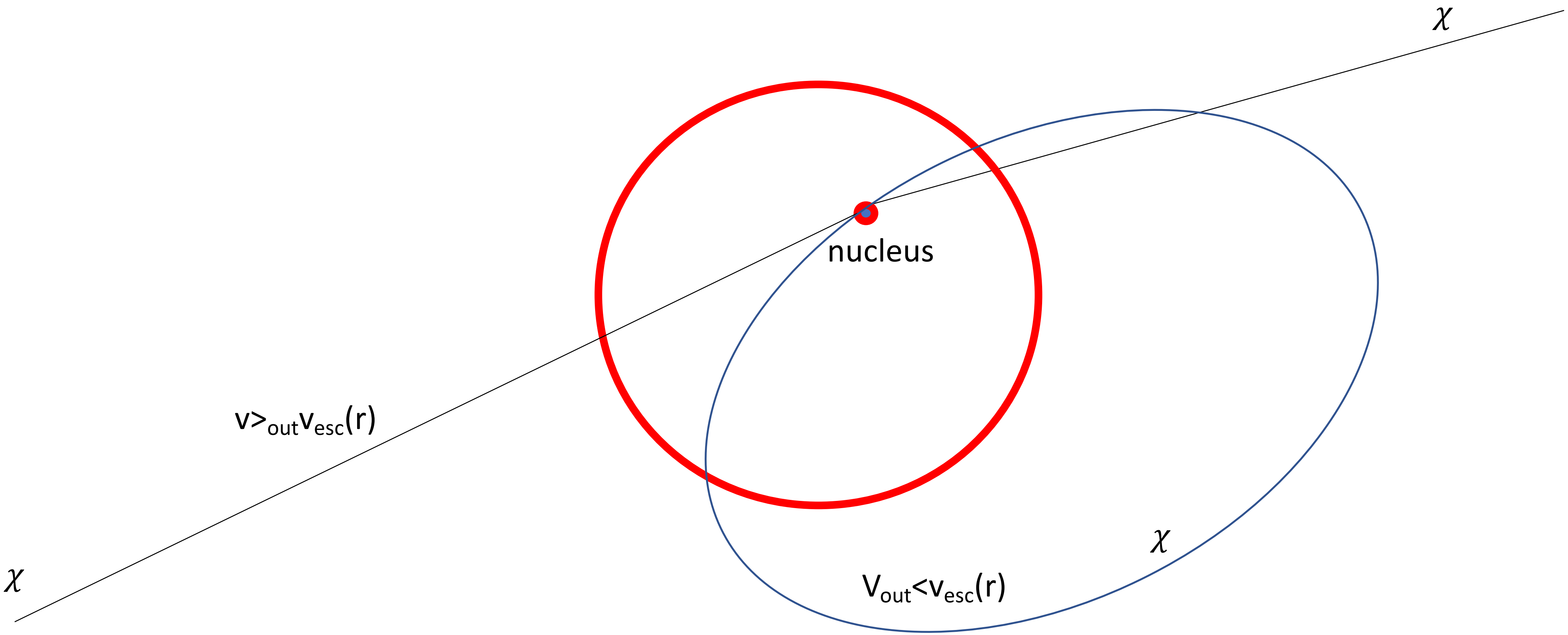
Example: WIMP capture in the Sun



Only neutrinos can escape -> up-going muons detected on Earth by Cherenkov detectors (Super-K, IceCube)

Capture mechanism:

- WIMP scatters off nucleus at distance r inside celestial body (same interaction probed by Direct Detection)
- If its outgoing speed v_{out} is below the escape velocity $v_{esc}(r)$ gets locked into gravitationally bound orbit
- Keeps scattering again and again until it settles down in the stellar core

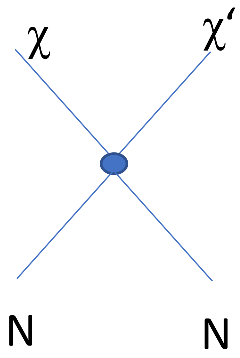


Inelastic Dark Matter

D. Tucker-Smith and N.Weiner, Phys.Rev.D 64, 043502 (2001), hep-ph/0101138

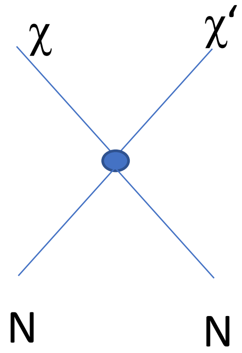
Two mass eigenstates χ and χ' very close in mass: $m_\chi - m_{\chi'} \equiv \delta$ with $\chi + N \rightarrow \chi + N$ forbidden

"Endothermic "scattering ($\delta>0$)



Kinetic energy needed to "overcome" step → rate no longer exponentially decaying with energy, maximum at finite energy E_*

"Exothermic" scattering ($\delta<0$)



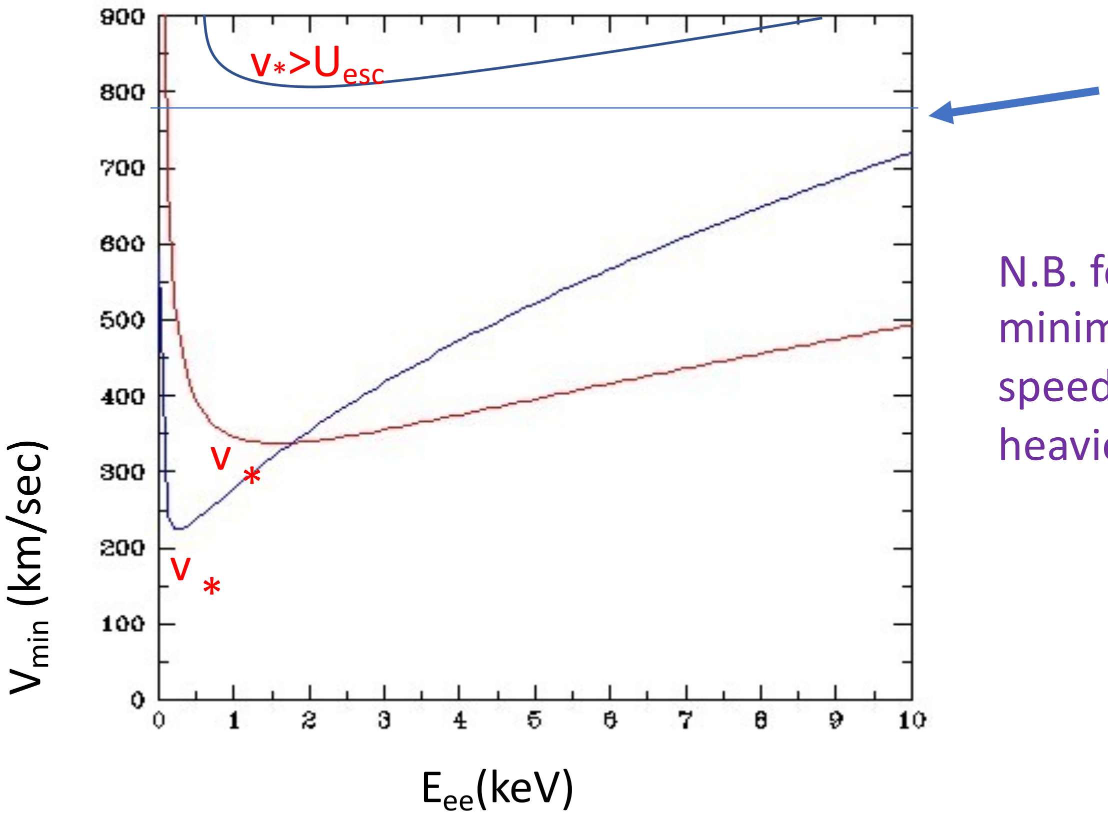
χ is metastable, δ energy deposited independently on initial kinetic energy (even for WIMPs at rest)

N.B. At this stage let's consider IDM at the phenomenological level, later on will consider specific example

V_{min}=minimal incoming WIMP speed required to impart recoil energy E_R to the nucleus

$$v_{min} = \frac{1}{\sqrt{2m_N E_R}}\left(\frac{m_N E_R}{\mu} + \delta\right) = a\sqrt{E_r} + \frac{b}{\sqrt{E_R}}$$

For inelastic DM WIMPs need at least the speed min(v_{min})=v_* to produce upscattering to heavy state



U_{esc}=escape velocity of WIMPs in the galaxy (boosted to nucleus rest frame)

N.B. for δ>0 WIMPs need a minimal absolute incoming speed v_* to upscatter to the heavier state

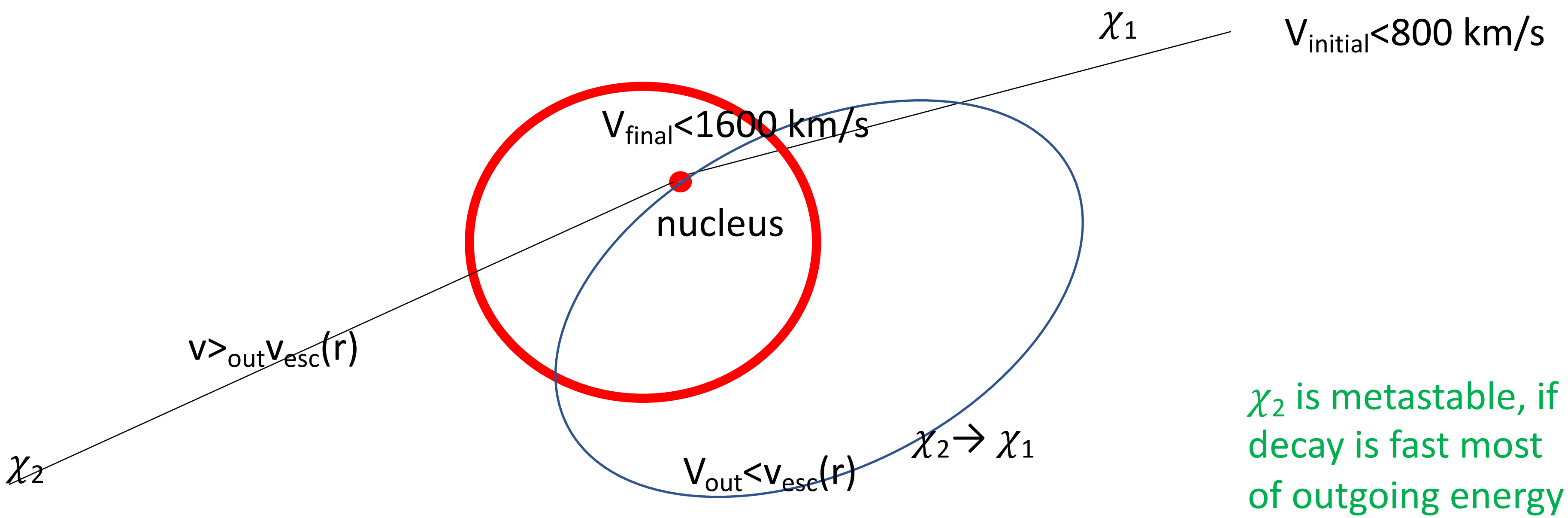
$$v^*_{min} = \sqrt{\frac{2\delta}{\mu_{\chi N}}}$$

($\mu_{\chi N}$ = WIMP-nucleus reduced mass)

→ vanishing rate if $v_* > v_{esc}$ (escape velocity)

For direct detection in underground detectors this implies that **$\delta \gtrsim$200 keV is not observable**

However inside the celestial body the WIMP is accelerated by the gravitational potential before scattering



χ_2 is metastable, if decay is fast most of outgoing energy carried by lighter states

Gravitional acceleration extends sensitivity to larger values of mass splitting δ compared to direct detection

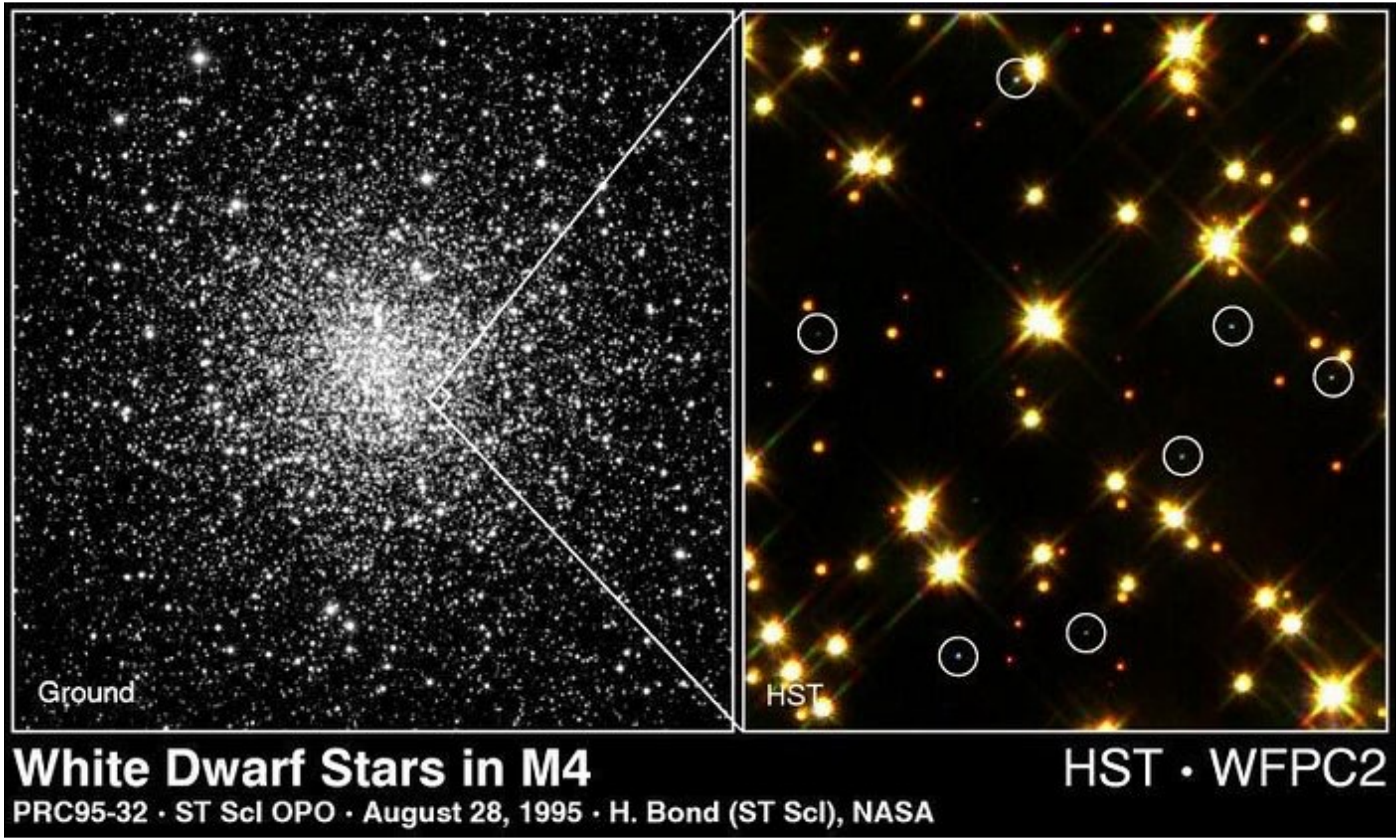
For the Sun: $\delta \lesssim 600$ keV

The largest the density of the celestial body, the higher the acceleration, the higher the observable mass splitting values δ!

- White Darves(WD): $v_{final} \simeq$ a few 10^4 km/s $\rightarrow \delta \lesssim$ a few tens of MeV
- Neutron stars(NS): $v_{final} \simeq$ a few 10^5 km/s $\rightarrow \delta \lesssim$ a few hudreds of MeV

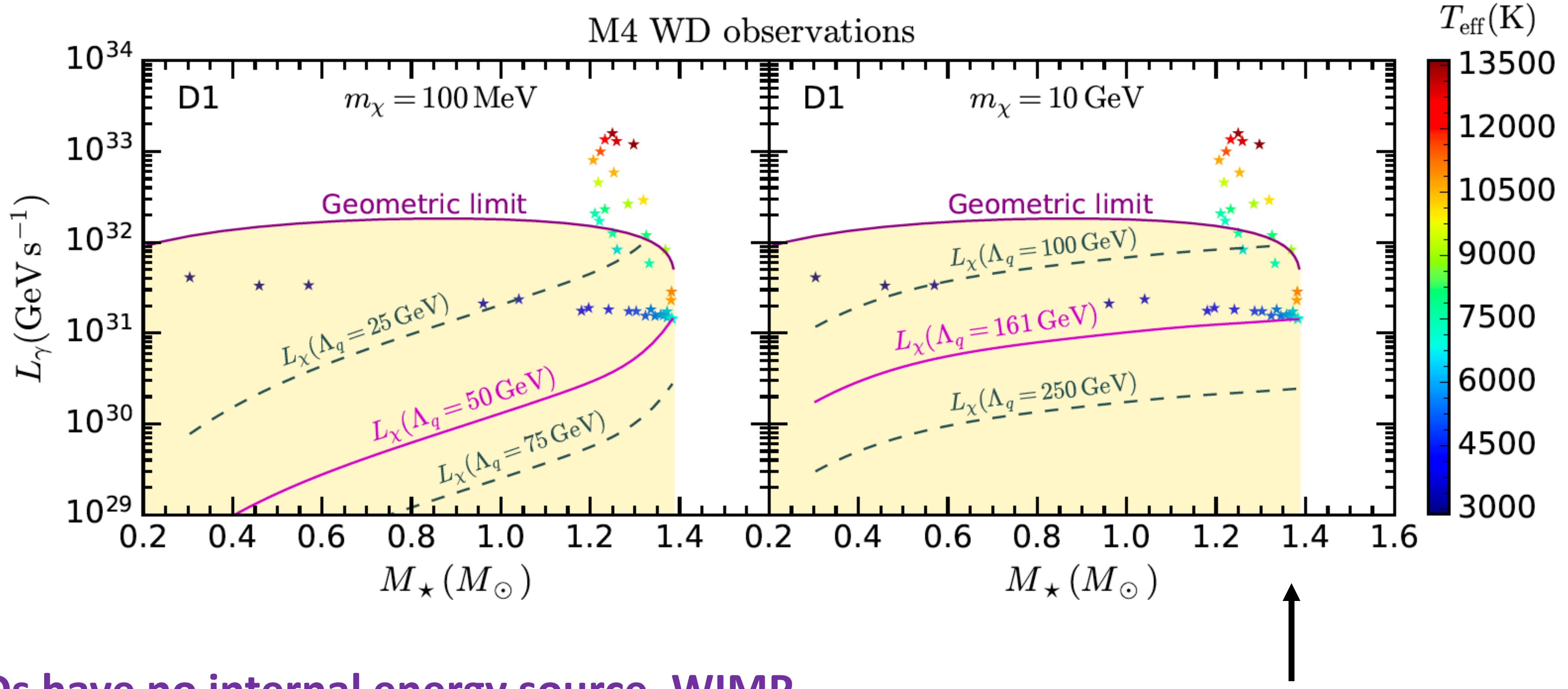
N.B. $M_{WD} \lesssim 1.4\ M_\odot$ but $r_{WD} < 2\%\ r_\odot$
$\rightarrow$ the central density of a White Dwarf can be 10^8 larger than in the Sun

Messier 4 (M4): the closest globular cluster to the Earth (2.2kpc≃4.5e8 AU)



B. M. S. Hansen et al., Astrophys. J. Suppl. 155 (2004) 551, [astro-ph/0401443]; L. R. Bedin et al., APJ 697 (June, 2009) 965–979, [0903.2839].

Several high-mass, low luminosity WD's observed by Hubble in M4



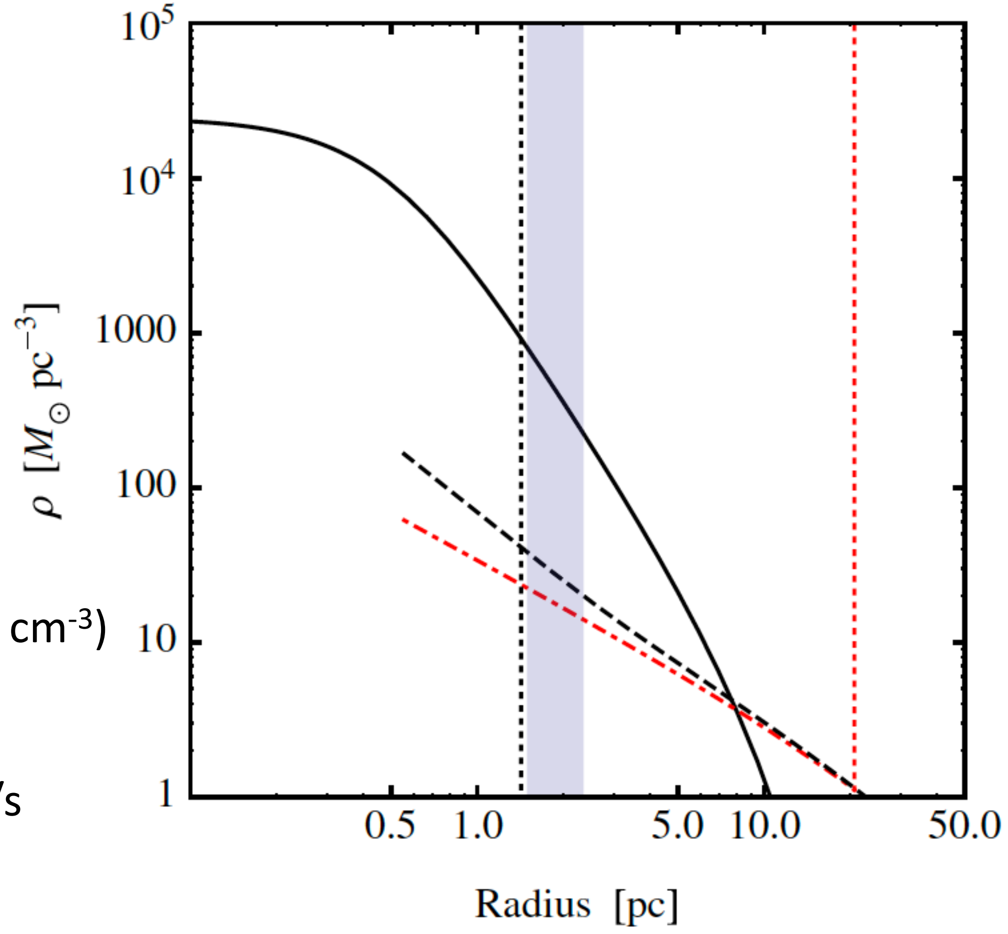
Chandrasekhar limit, $M_{WD} \lesssim 1.4\ M_\odot$

WDs have no internal energy source, WIMP annihilations can drive their luminosity above the observed value

Caveat: the density profile of Dark Matter in M4 cannot be reconstructed from observation, for the Dark Matter abundance need to rely of models of Galaxy formation

McCullough, Fairbairn, PHYSICAL REVIEW D 81, 083520 (2010)

Less than 1% for DM of original subhalo "eaten up" by the Milky Way survives due to tidal stripping in the final globular cluster



$\rho_{DM} \simeq 800$ GeV cm^{-3}
(in neighborhood of the Sun $\rho_{DM} \simeq 0.4$ GeV cm^{-3})

$v_{rms} \simeq 8$ km/s
(in neighborhood of the Sun $v_{rms} \simeq 300$ km/s

Optically-thin limit: scattering length much larger than WD size. After a single scattering with $v_{out}<v_{esc}(r)$ WIMP becomes gravitationally bound

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

$$w(r) = \sqrt{u^2 + v_{esc}(r)^2}$$

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

density of nucleus N

WIMP-nucleus differential cross section

Conditions for capture:

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

$E>E_{cap}$

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

w=WIMP speed at scattering

u=asymptotic WIMP speed at large distance

f(u)=WIMP velocity distribution

When the cross section is large capture saturates geometrical limit (all the WIMPS swept by celestial body are captured)

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

Evolution of DM number density inside WD:

$$\frac{dN_\chi}{dt} = C_* - AN_\chi^2 \rightarrow 0$$

(equiliibrium between capture and annihilations reached after $\tau_{eq} \simeq 10^{-6}$ years for $<\sigma v>=<\sigma v>_{thermal}$)

with:

$$\Gamma_{\rm ann} = \frac{1}{2} A N_\chi^2.$$

Then:

$$\Gamma_{\rm ann} = C_*/2$$

($t >> \tau_{eq}$)

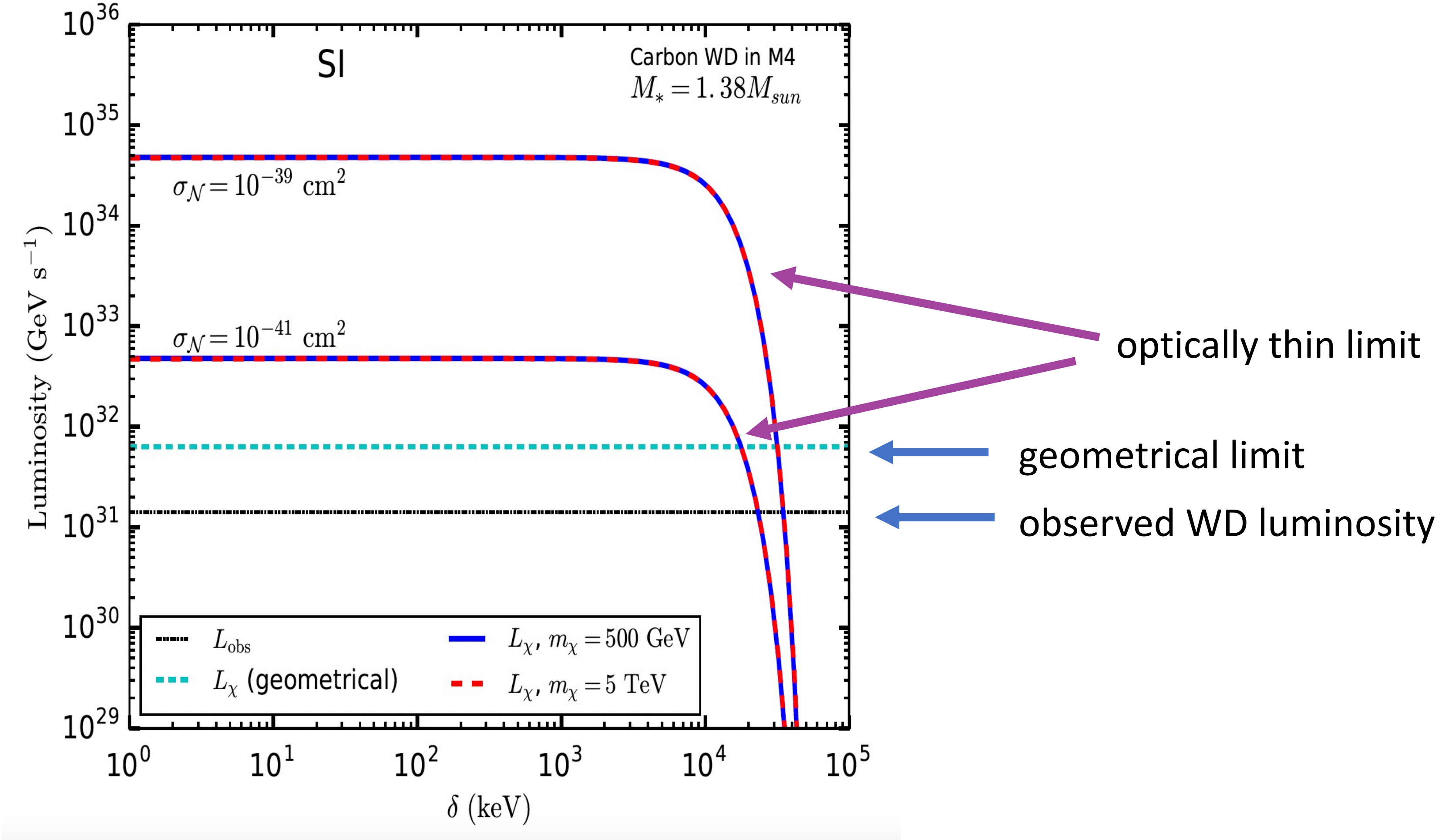
All the energy injected in the WD from WIMP annihilation ends up into and increase of its total luminosity:

$$L_\chi = 2 m_\chi \Gamma_{\rm ann}$$

Bolometric signal (including final-state neutrinos if the WIMP mass is large enough)

Heavy WD's made of carbon (^{12}C) and oxygen (^{16}O) → assume 100% carbon to get conservative bound in the case of a Spin-Independent coupling (cross section scales as atomic number squared)

N.B. when m_χ >> nuclear target mass the capture rate falls as 1/ m_χ → luminosity independent on m_χ



A. Biswas, A. Kar, H. Kim, SS, L. Velasco-Sevilla, arXiv:2206.06667

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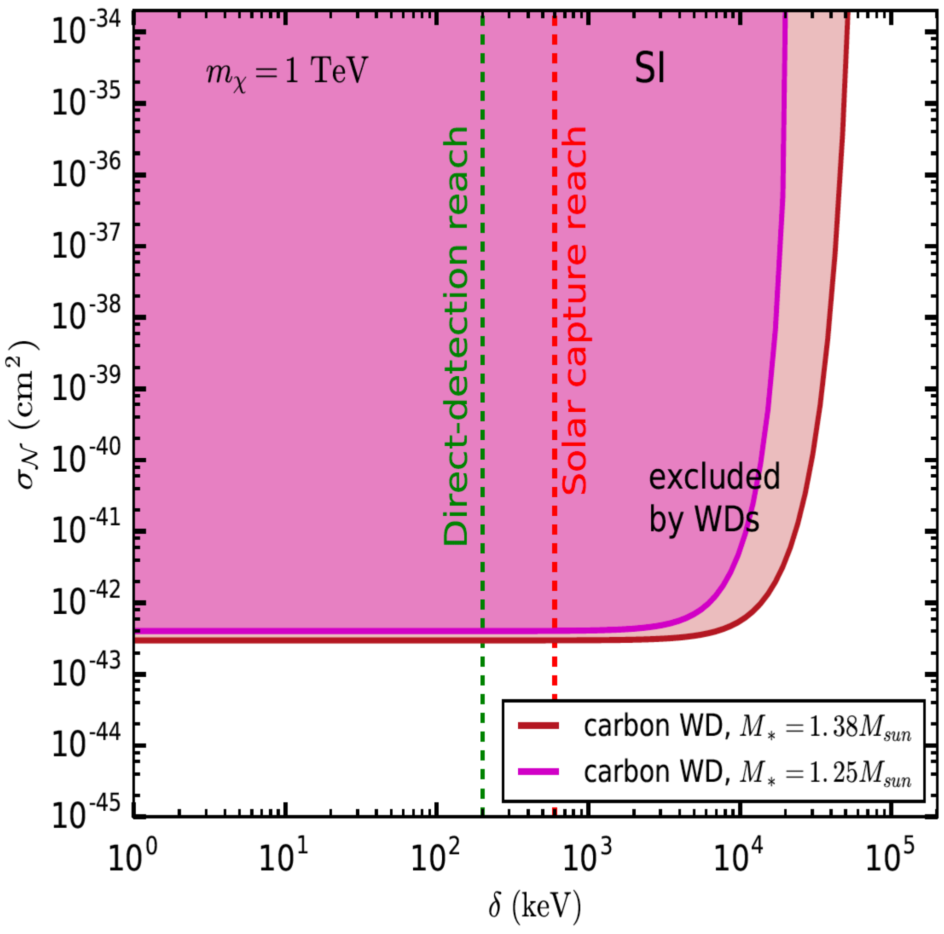
Excluded parameter space in δ-σ_N plane (Spin-Indipendent coupling)

σ_N=WIMP-nucleon cross section



Direct detection reach

Capture in the Sun reach

An explicit realization of inelastic Dark Matter: bi-doublet fermionic Dark Matter in Left-Right symmetric models (LRSM)

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

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

Higgs bi-doublet Φ (EW symmetry breaking) →

Higgs bi-triplet T_R ($SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_Y$ symmetry breaking) →

Fermion bi-doublet DM →

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 ➡ Z_R and W_R masses generated

EW symmetry broken by bi-doublet $\mathbf{\Phi}$ with vevs v_1 and v_2 ➡ Z_L and W_L masses generated (standard gauge bosons)

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

g_L,g_R couplings of $SU(2)_L$ and $SU(2)_R$

Four mixings: ϑ_R (W_R^3-B), ϑ_W (W^3_L-B_Y), ϕ (Z_R-Z_L), ξ($W_R^\pm$-$W_L^\pm$)

(B_μ=gauge boson of $U(1)_{B-L}$)

$$\theta_W = \tan^{-1}\left(\frac{g_Y}{g_L}\right), \ \theta_R = \sin^{-1}\left(\frac{g_L}{g_R}\tan\theta_W\right), \ \phi \simeq \frac{1}{2}\tan^{-1}\left(-2\cos\theta_W\cos\theta_R\frac{g_R}{g_L}\frac{M_{Z_L}^2}{M_{Z_R}^2}\right)$$

$$M_{Z_L}^2 \simeq M_{Z_1}^2 = \frac{g_L^2}{4\cos^2\theta_W}v^2 = M_Z^2, \ \ M_{Z_R}^2 \simeq M_{Z_2}^2 = \frac{g_R^2}{\cos^2\theta_R}v_R^2 + \frac{g_R^2}{4}\cos^2\theta_R v^2.$$

$$\xi \simeq \frac{1}{2}\tan^{-1}\left(-4\frac{g_R}{g_L}\frac{M_{W_L}^2}{M_{W_R}^2}\frac{v_1 v_2}{v^2}\right)$$

$$M_{W_L}^2 \simeq M_{W_1}^2 = \frac{g_L^2}{4}v^2 = M_W^2, \qquad M_{W_R}^2 \simeq M_{W_2}^2 = \frac{1}{4}g_R^2\left(v^2 + 2v_R^2\right)$$

$v_R >> v_1, v_2 >> v_L \simeq 0$

$$v = \sqrt{v_1^2 + v_2^2} = 246$$

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

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

SU(2)$_L$ x SU(2)$_R$ invariant lagrangian:

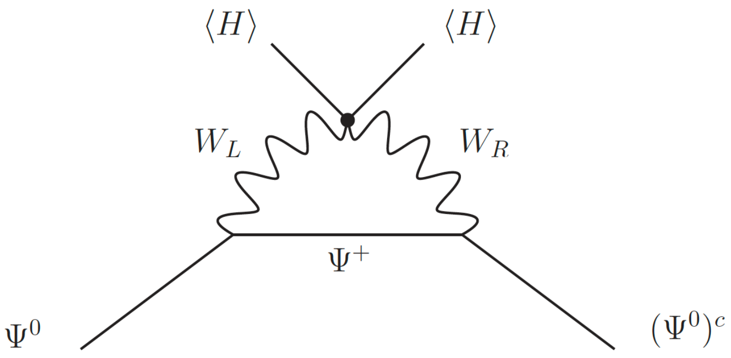
$$\mathcal{L}_{\rm BD} = \frac{1}{2}\mathrm{Tr}\left[\overline{\Psi} i \not{D} \Psi\right] - \frac{1}{2} M_\Psi \mathrm{Tr}\left[\overline{\Psi}\Psi\right]$$

Covariant derivative:

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

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

- Radiative corrections split the masses of $\psi^{\pm}$ and ψ^0 ($\Delta M \lesssim 200$ MeV)
- Moreover, when ϕ acquires vevs the mixing between $W_L^{\pm}$ and $W_R^{\pm}$ induces a transition between ψ^0 and $(\psi^0)^c$ that generates a tiny off-diagonal Majorana mass term δM



- The Dirac fermion ψ^0 splits into two Majorana states χ_1 and χ_2:

$$\chi_{1,2} = \frac{1}{\sqrt{2}}\left(\psi^0 \mp (\psi^0)^c\right)$$

$$M_{\chi_{1,2}} = M_\Psi \mp \delta M$$

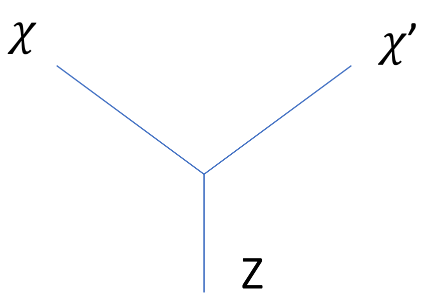
Mass splitting: $$\delta = 2\,\delta M = \frac{g_L^2}{16\pi^2}\frac{g_R}{g_L}\sin(2\xi) M_\Psi \left[f(r_{W_1}) - f(r_{W_2})\right]$$

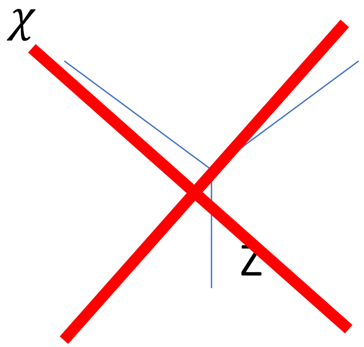
(in the following $\sin(2\xi)$=1 to get conservative bounds)

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

($\chi_1 \to \chi$, $\chi_2 \to \chi'$)

Non-vanishing hyper-charge → χ-nucleon scattering driven by Z exchange





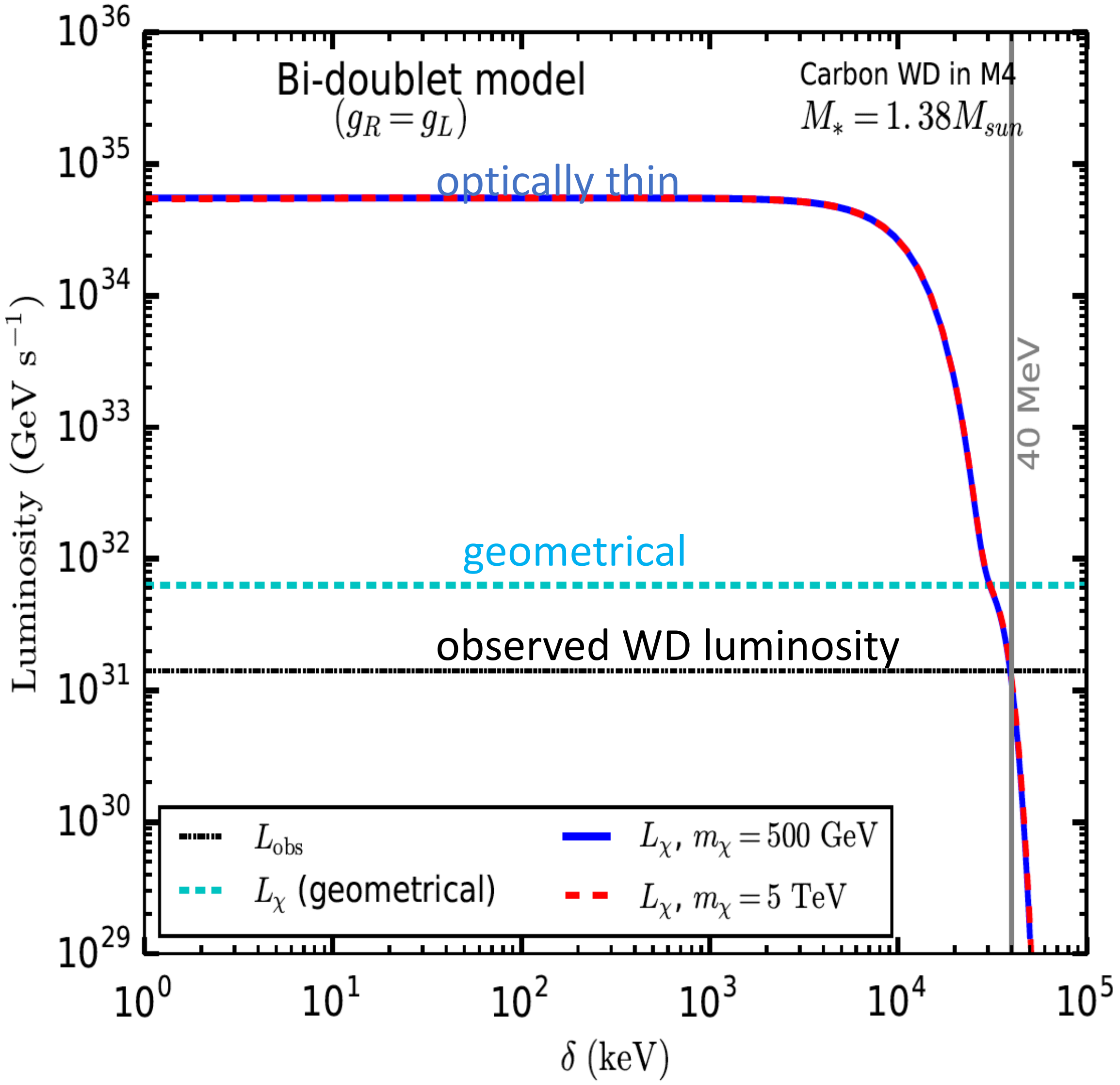
(inelastic scattering, diagonal coupling vanishes)

$$\mathcal{L}_{\chi\chi' Z} = g_\chi \overline{\chi} \not{Z} \chi'$$

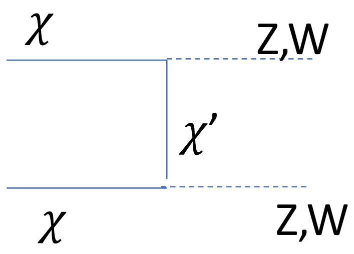
Explicit IDM realization

$$g_\chi = \frac{1}{2}\left(g_L \cos\theta_W \cos\phi + g_R \sin\theta_W \sin\theta_R \cos\phi + g_R \cos\theta_R \sin\phi\right)$$

Large coupling, excluded unless scattering is kinematically forbidden by mass splitting δ



WIMP annihilation inside WD:



Large coupling, excluded unless scattering is kinematically forbidden by mass splitting δ

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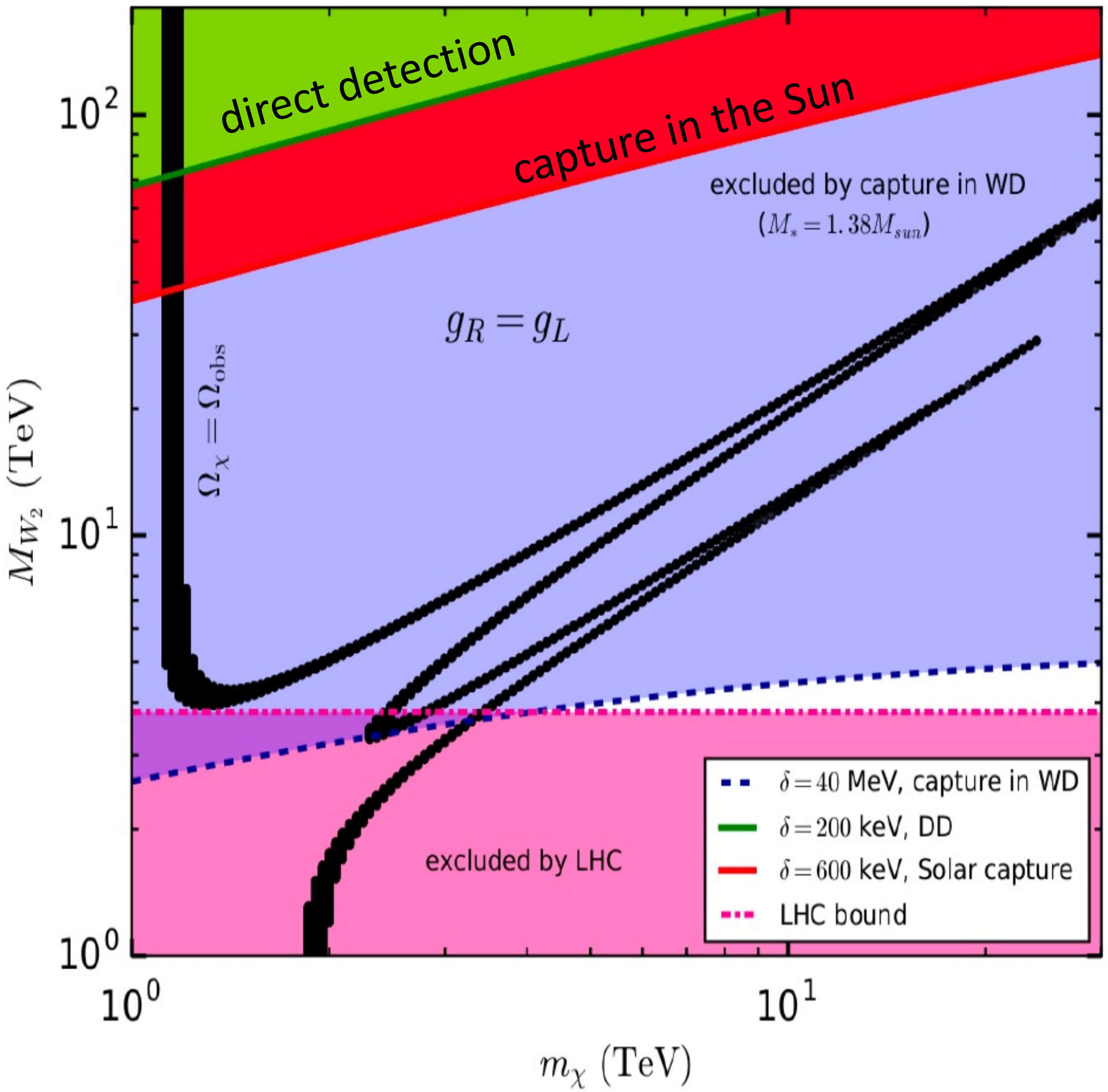
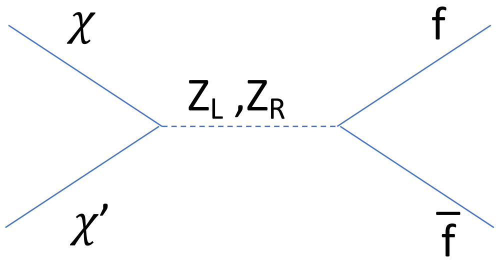
Parameter space of LRSM for $g_L=g_R$



Early Universe:



(coannihilations, δ<<T_{dec})

WD bound wipes out all cosmologically viable parameter space if $g_L=g_R$

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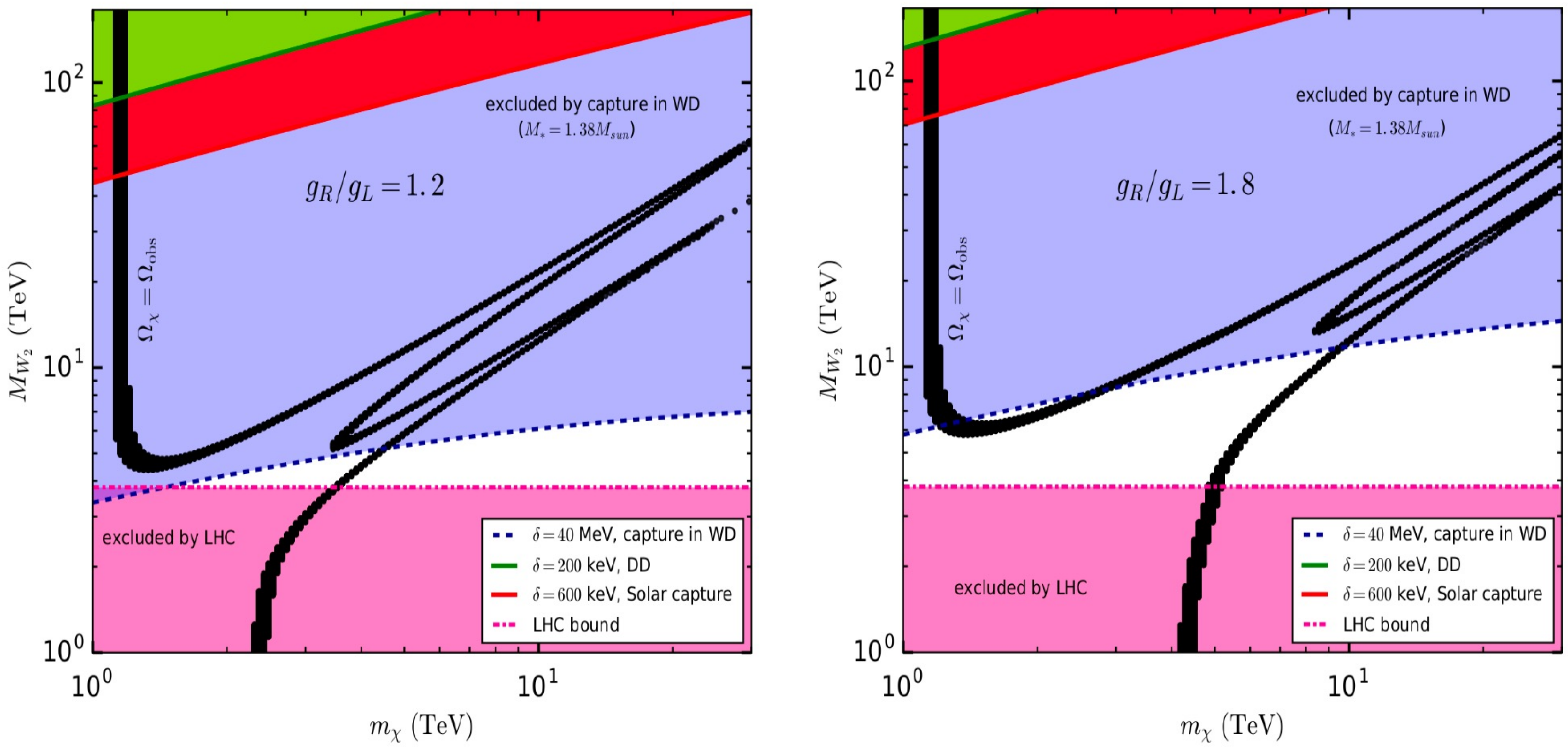
To recover cosmologically viable parameter space need to increase δ at fixed m_χ and M_{W2} → $g_R > g_L$



Embedding the LRSM into a GUT need to enlarge the minimal model to obtain :

1. GUT unification
2. allowed proton decay rate
3. $v_R \lesssim$ a few TeV (+color multiplets)
4. $g_R > g_L$ (+D-parity breaking)

Additional Matter for conserving D parity		
Fermions		
F'_c	4	$(\mathbf{1},\, \mathbf{1},\, 0\ \mathbf{3})_L \oplus (\mathbf{1},\, \mathbf{1},\, 0,\, \mathbf{3})_R$
F_d	1	$(\mathbf{2},\, \mathbf{2},\, 0\ \mathbf{1})_L \oplus (\mathbf{2},\, \mathbf{2},\, 0,\, \mathbf{1})_R$

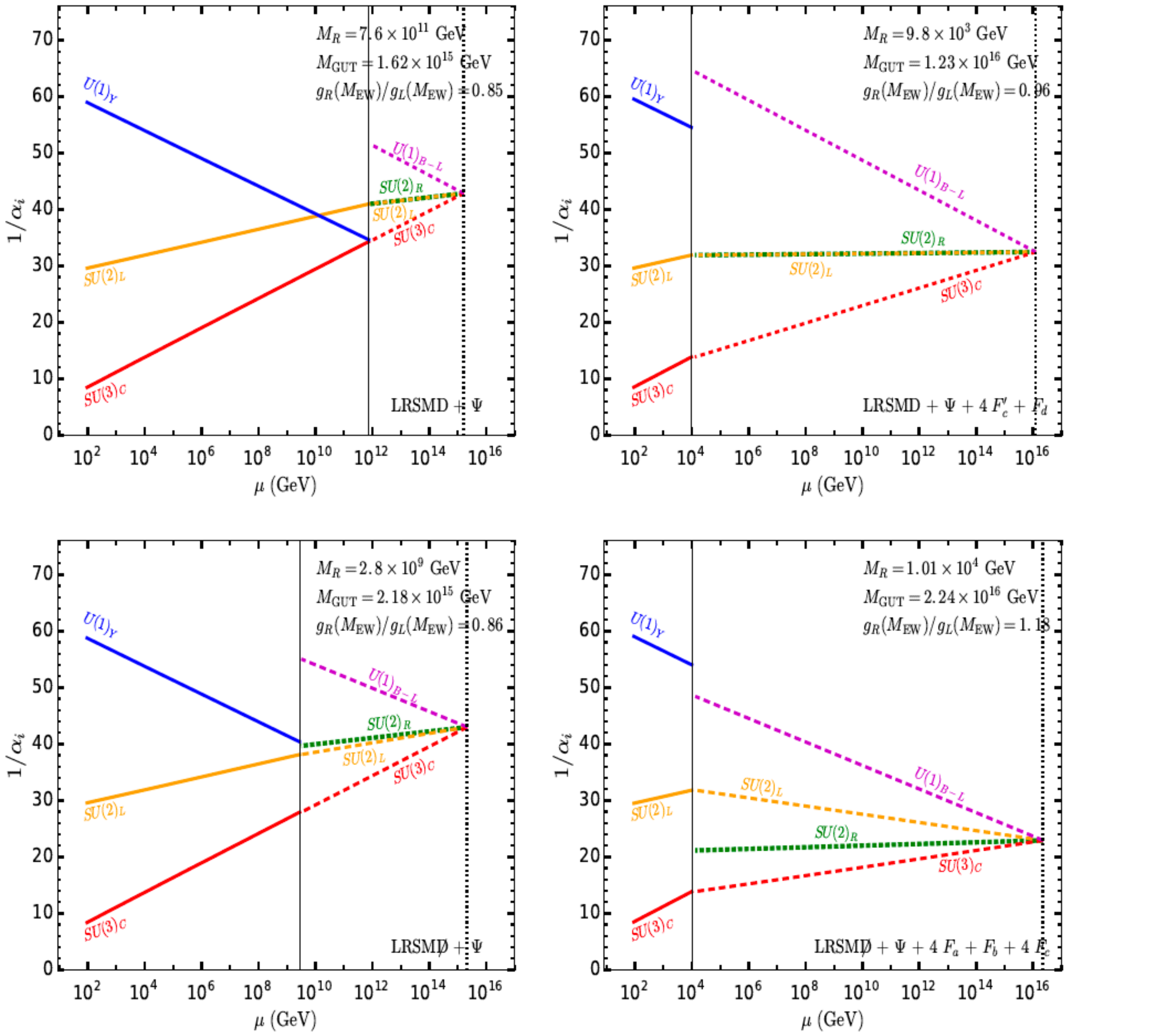
Additional Matter for $\not{D}$ parity		
Fermions		
F_a	4	$(\mathbf{2},\, \mathbf{1},\, 0\ \mathbf{3})$
F_b	1	$(\mathbf{1},\, \mathbf{2},\, 0,\, \mathbf{3})$
F_c	4	$(\mathbf{1},\, \mathbf{1},\, 0,\, \mathbf{3})$

D parity=LRSM invariance by the interchange of any multiplet of $SU(2)_L$ into the corresponding $SU(2)_R$ multiplet

Table 1. Proton decay lifetime $\tau(p \to \pi^0 e^+)$[yrs]. The 1 σ errors are extracted from a chi–square with the observables at the electroweak scale.

Model Predictions	
LRSMD	$(1.3 \pm 0.9) \times 10^{32}$
LRSMD + Ψ	$(2.9 \pm 1.9) \times 10^{32}$
LRSMD + Ψ + 4 F'_c + F_d	$(5.4 \pm 3.7) \times 10^{36}$
LRSM$\not{D}$	$(3.8 \pm 2.5) \times 10^{36}$
LRSM$\not{D}$ + Ψ	$(7.6 \pm 5.2) \times 10^{32}$
LRSM$\not{D}$ + Ψ + 4 F_a + F_b + 4 F_c	$(2.0 \pm 1.3) \times 10^{37}$

Experimental bounds/discovery	
Current Bound: 1.6×10^{34} at 95% C.L [88, 89]	Projected Discovery: 6.3×10^{34} [90]
Projected Bound: 7.8×10^{34} 90% C.L [90]	



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Conclusions

- Models of structure formation suggest that the inner part of globular clusters should have a DM density that largely exceeds that estimated in the solar neighborhood
- We used the observed luminosities of low–temperature large-mass WDs in the Messier 4 globular cluster to improve the existing constraints on Inelastic Dark Matter (IDM)
- WDs exclude $\delta \lesssim$ a few tens of MeV (for Direct Detection $\delta \lesssim$200 keV)
- Specific IDM scenario: LRSM
  - WD bounds significantly reduce the cosmologically viable parameter space and require $g_R > g_L$. For instance, for g_R/g_L = 1.8 we two viable DM mass ranges: 1.2 TeV $\lesssim m_\chi \lesssim$ 3 TeV and 5 TeV $\lesssim m_\chi \lesssim$ 10 TeV when the charged $SU(2)_R$ gauge boson mass M_{W2} is less than $\simeq$ 12 TeV.
- Embedding the LRSM in different GUT scenario yields $M_R \gtrsim 10^{10}$ GeV, with fast proton decay; minimal extension LRSMD+ψ slightly increases M_R and proton decay rate → need to add additional degrees of freedom at high energy to get $M_R \lesssim$a few TeV (including colored particles) and to break D-symmetry to get g_R>g_L
- a future observation of neutron stars with temperatures T $\lesssim$a few thousand Kelvin would rule out the full parameter space of LRSM bi–doublet DM