Dark Matter search using astrophysical observations: present status and future prospects

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July 27, 2023

Introduction

- Cold Dark Matter (CDM):

  provides ∼25% of the energy density of the Universe

- Evidences only through gravitational effects:

  galactic rotation curves, CMB anisotropy, structure formation, bullet clusters, etc.

- $\Omega h^2 \simeq 0.12$

- The Standard Model (SM) of particle physics cannot explain CDM

- Candidates of CDM:
  - Thermal WIMPs (GeV-TeV)
  - Sub-GeV DM
  - PBHs
  - Ultralight bosonic DM
  - ....

- A variety of detection methods is needed to search for various DM candidates

Searches for particle DM signal

- Collider searches:

  search for the missing-E_T signal caused by the produced DM particles at the LHC

- Direct detection searches:

  search for the recoil signal produced by the interactions of local DM particles with the targets inside terrestrial detectors

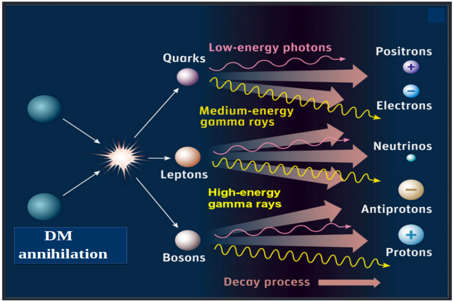
- Indirect detection:

  search for the products of the annihilation/decay of DM particles in DM-dense astrophysical systems

  $\Rightarrow$ An alternative search strategy for DM

Indirect detection

- DM is concentrated in the form of halos surrounding galaxies
- Annihilation/decay of DM particles in a galactic halo (e.g., MW Galaxy, dwarf galaxies) can produce SM particles, which can lead to further cascades and produce γ, $e^{\pm}$, $p^{\pm}$, ν's, etc.



- Searches in various experiments:
  1. γ-rays: Fermi-LAT, HESS, etc.
  2. e^{+}, $\bar{p}$: AMS-02 (cosmic-ray), etc.
  3. $\nu(\bar{\nu})$: Super-K, IceCube, etc.
  4. Planck (obsv. of CMB)

Secondary particle flux from DM annihilation in an astrophysical system

- Source function:

$$\chi\chi \to \underbrace{\mathrm{SM}_1\,\bar{\mathrm{SM}}_2}_{f} \qquad Q_i^{annihilation}(E,r) = \langle\sigma v\rangle \left\{\frac{\rho_\chi^2(r)}{2m_\chi^2}\right\} \left\{\sum_f \frac{dN_f^i}{dE} B_f\right\}$$

$\langle\sigma v\rangle$: annihilation cross-section of DM particle χ

$\frac{\rho_\chi^2(r)}{2m_\chi^2}$: number density of DM pairs

Annihilation channel f: $\tau^+\tau^-$, $\mu^+\mu^-$, e^+e^-, $t\bar{t}$, $b\bar{b}$, $q\bar{q}$, W^+W^-, ZZ, $\gamma\gamma$, gg, hh, $Z\gamma$, Zh, $\nu\bar{\nu}$

B_f: branching fraction for channel f

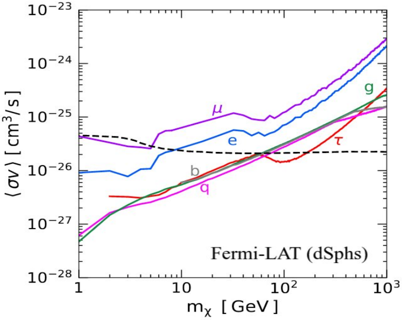
$\frac{dN_f^i}{dE}$: spectrum of secondary particle i produced per annihilation

$[i \Rightarrow \gamma,\ e^+(e^-),\ \nu(\bar{\nu}),$ etc.$]$

Indirect searches for WIMP DM

γ-ray searches

- WIMP annihilations in a galactic halo produce γ-rays
- Fermi-LAT γ-ray observation of dwarf spheroidal (dSph) galaxies
  $\rightarrow$ constrains GeV-TeV scale WIMPs

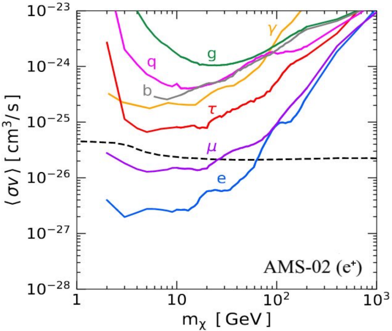


[Fermi-LAT, 2016]
[Leane, *et al.*, PRD 98, 023016]

Cosmic-ray e^+ searches

- WIMP annihilations in the Milky Way (MW) produce $e^\pm$
- $e^\pm$ undergo diffusion and energy losses and ultimately reach the Earth
- AMS-02 measures cosmic-ray e^+ flux

  → put upper limit on $\langle \sigma v \rangle$ of GeV-TeV scale WIMPs

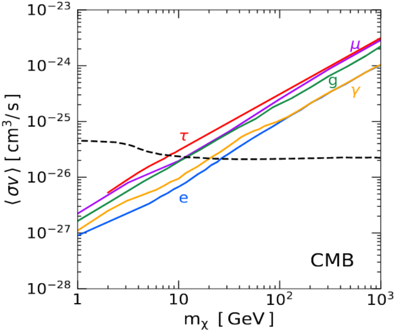


[AMS-02 (e^+), 2019]

[Leane, *et al.*, PRD 98, 023016]

CMB observation

- γ and $e^{\pm}$ from WIMP annihilations at high redshift
  → modify the ionization history through energy injection
  → perturb CMB anisotropies
- Planck measurement of CMB anisotropies
  → upper limits on $\langle \sigma v \rangle$



[Planck, 2015]

[Leane, *et al.*, PRD 98, 023016]

Going beyond the standard approach

- Thermal WIMP DM: $\langle\sigma v\rangle_{\rm relic} \simeq 3\times10^{-26}\,{\rm cm}^3\,{\rm s}^{-1}$ gives $\Omega_\chi h^2 = 0.12$ $[\Omega_\chi h^2 \propto 1/\langle\sigma\, v\rangle]$

  → A WIMP of mass m_χ is allowed if the corresponding upper limit on total $\langle\sigma v\rangle > \langle\sigma v\rangle_{\rm relic}$

- In a generic DM model, WIMP χ may annihilate into multiple channels simultaneously with different branching fractions (B_f)

  → flux distributions are determined by B_fs

  → limits obtained for individual channels are not applicable

- Constraints obtained from different observations vary largely

  → For a given channel, $\langle\sigma v\rangle$ allowed by one observation may be ruled out by others

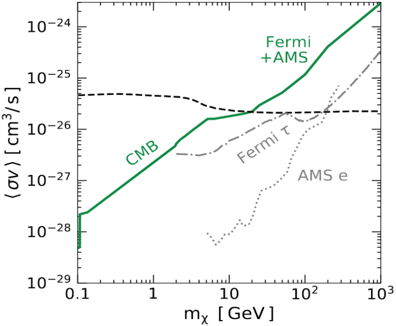
- **A B_f independent upper limit on total $\langle\sigma v\rangle$, allowed by all observations, is needed**

Limit on total $\langle\sigma v\rangle$

- Fermi-LAT, AMS-02 and Planck data are used and B_f of each channel is arbitrarily varied (ensuring $\sum_f B_f = 1$)

  → maximum allowed total $\langle\sigma v\rangle$ is obtained

  → WIMPs of $m_\chi \lesssim 20\,\mathrm{GeV}$ are excluded



[Leane, *et al.*, PRD 98, 023016]

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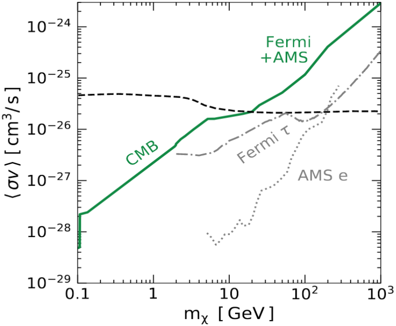


[Leane, *et al.*, PRD 98, 023016]

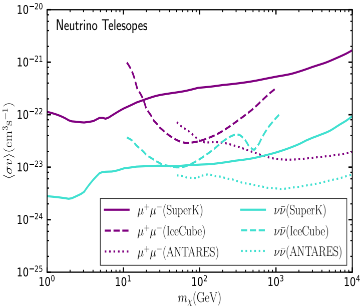
- **WIMP annihilation into $\nu\bar{\nu}$ is not considered**

Neutrino observation constraints

- Super-Kamiokande, IceCube, ANTARES neutrino observations of the inner Galactic halo

  [dominant background: atmospheric neutrinos]

  → constrain $\chi\chi \to \nu\bar{\nu}$ for $m_\chi \sim \mathcal{O}(\mathrm{GeV} - \mathrm{TeV})$



[Super-K, 2016]
[IceCube, 2017]
[ANTARES, 2016]

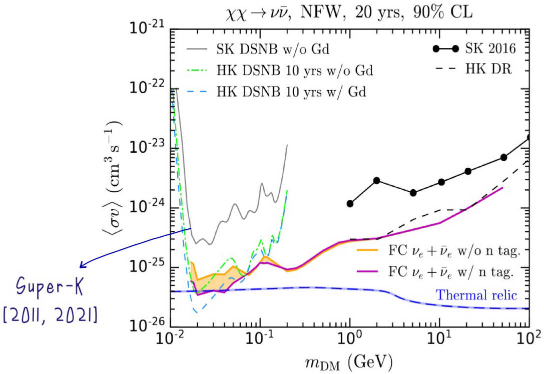
[K. Dutta, A. Ghosh, AK, B. Mukhopadhyaya, arxiv:2212.09795]

Constraints from Super-K low energy ν search

- Low energy ($10 \sim 100\,\mathrm{MeV}$) neutrino observation of Super-Kamiokande is used to search for diffuse supernovae neutrino background (DSNB)

  [dominant background: atmospheric neutrinos]

  → this observation can also be used to constrain $\chi\chi \to \nu\bar{\nu}$ for $m_\chi \sim$ a few tens of MeV



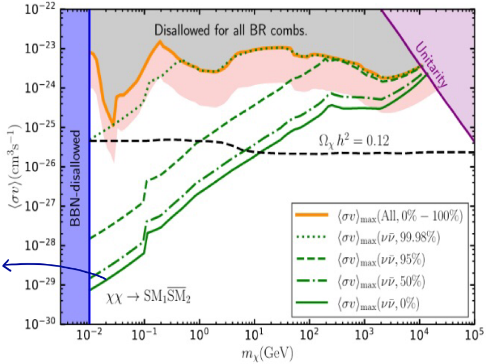
[Bell, *et al.*, JCAP09(2020)019]

$\langle \sigma v \rangle$ of thermal WIMP: most general limit

- Arbitrary B_f's are attributed to all channels including $\nu\bar{\nu}$, (ensuring $\sum_f B_f = 1$) and data of neutrino observations are included

  → upper limit on total $\langle \sigma v \rangle$ substantially relaxes

  → **all m_χ values in the range 10 MeV - 100 TeV are allowed**



$\nu\bar{\nu}$ channel
not considered

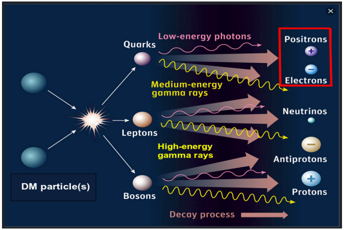
[Constraint on standard thermal WIMP annihilating into SM particle pairs]

[K. Dutta, A. Ghosh, AK, B. Mukhopadhyaya, arxiv:2212.09795]

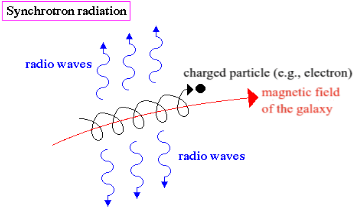
Indirect search for DM using radio waves (Prospects in upcoming radio telescopes)

Radio synchrotron signal from DM

$e^{\pm}$ production from DM inside a galactic halo



propagation of $e^{\pm}$ through the galaxy



Radio telescopes on Earth

$e^{\pm}$ source function & propagation

- $e^{\pm}$ source function:

$$\chi\chi \rightarrow \underbrace{\mathrm{SM}_1\,\bar{\mathrm{SM}}_2}_{f} \qquad\qquad Q_e^{annihilation}(E,r) = \langle\sigma v\rangle \left\{\frac{\rho_\chi^2(r)}{2m_\chi^2}\right\}\left\{\sum_f \frac{dN_f^e}{dE} B_f\right\}$$

- Propagation of $e^{\pm}$:

$$D(E)\nabla^2\left(\frac{dn_e}{dE}\right) + \frac{\partial}{\partial E}\left(b(E)\frac{dn_e}{dE}\right) + Q_e(E,r) = 0$$

$D(E)$: Diffusion term

$D(E) = D_0\ (E/GeV)^{\gamma}$; $D_0 \equiv$ diffusion coefficient

$b(E)$: Energy loss term

[Inverse Compton, synchrotron, Coulomb interactions, Bremsstrahlung]

$b_{synch}(E) \propto B^2\ (E/GeV)^2$; $B \equiv$ ambient magnetic field

Synchrotron emission & predicted signal

- Synchrotron emissivity:

$$j_{synch}(r,\nu) = 2\int_{m_e}^{m_\chi} dE \;\; \frac{dn_e}{dE}(E,r)\;\underbrace{P_{synch}(E,B,\nu)}_{\text{synchrotron power}}$$

$B \equiv$ ambient magnetic field
$\nu \equiv$ frequency of the emitted radio flux

- Signal at observation:

$$S_\nu(\nu) = \frac{1}{4\pi}\int_\Omega d\Omega \int_{l.o.s.} dl \; j_{sync}(l,\nu)$$

Targets for DM induced radio signals search

- Local dwarf spheroidal (dSph) galaxies are promising candidates mainly due to:
  - High mass to light ratio
$\Rightarrow$ high dark matter content
  - Close proximity ($\lesssim$ 100 kpc)
  - Astrophysical processes (e.g., star formation) are well suppressed
$\Rightarrow$ low background

Radio telescopes

Australia Telescope Compact Array (ATCA)
MeerKAT
Australian SKA Pathfinder (ASKAP)
Low-Frequency Array (LOFAR)
Green Bank Telescope (GBT)
Giant Metrewave Radio Telescope (GMRT)
Murchison Widefield Array (MWA)
.....

Upcoming:
Square Kilometre Array (SKA)

Square Kilometre Array (SKA)

- Upcoming radio telescope
- Large effective area

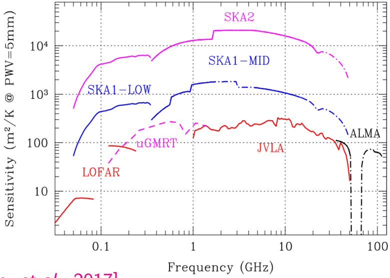
  $\Rightarrow$ High sensitivity
  (low rms noise level)

$$N_{\rm rms} = \frac{\sqrt{2}\, K_B\, T_{\rm sys}/A_{\rm eff}}{\sqrt{\Delta\nu\; t_{\rm obs}}}$$

$\Delta\nu \equiv$ Band-width

$t_{\rm obs} \equiv$ observation time

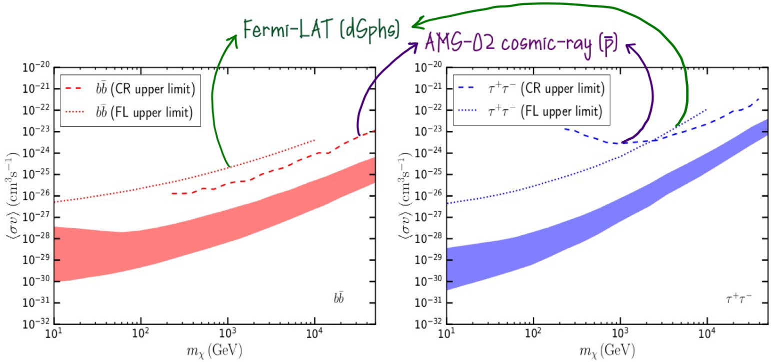
- frequency range:
  50 MHz – 50 GHz



[Braun, *et al.*, 2017]

- The wide frequency range and relatively high sensitivity make SKA useful in exploring DM in a wide mass range

SKA detectability



SKA detectability threshold for a 100 hours of observation towards Draco dSph

Diffusion coefficient $D_0 = 3 \times 10^{28} \mathrm{cm}^2\mathrm{s}^{-1}$
magnetic field $B = 0.1 - 1\ \mu G$

[AK, S. Mitra, B. Mukhopadhyaya, T.R. Choudhury, PRD 101, 023015 (2020)]

Decaying DM at the SKA

- DM can be an unstable particle
- Its lifetime τ_χ $(= 1/\Gamma)$ must be much larger than the age of the Universe ($t_U \sim 10^{17}\,\mathrm{s}$), but it can still decay into SM particle pairs

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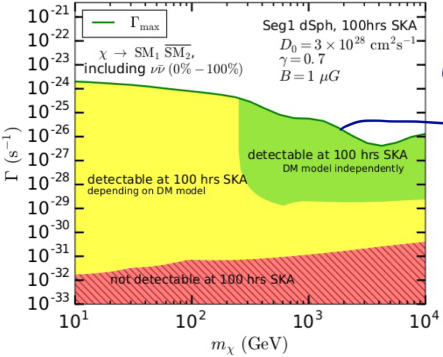


Existing upper limit (Fermi-LAT + AMS-02 + CMB + neutrino telescopes)

SKA (100 h) observation of the local dSph Seg I

[considering all possible 2-body SM decay channels (including $\chi \to \nu\bar{\nu}$)]

[K. Dutta, A. Ghosh, AK, B. Mukhopadhyaya, JCAP 09 (2022) 005]

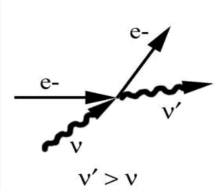
Sub-GeV DM at the SKA

Radio signals from MeV DM

- MeV scale BSM particles are often proposed as viable candidates for DM
- Annihilation/decay of MeV DM particles inside a galaxy can produce mildly relativistic $e^{\pm}$
- Synchrotron emission from MeV $e^{\pm}$ are too weak (in frequency) to be detected in radio telescopes

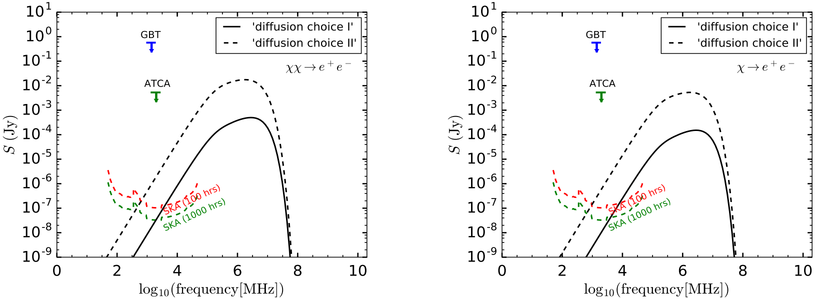
Radio signals from MeV DM

- MeV scale BSM particles are often proposed as viable candidates for DM
- Annihilation/decay of MeV DM particles inside a galaxy can produce mildly relativistic $e^{\pm}$
- Synchrotron emission from MeV $e^{\pm}$ are too weak (in frequency) to be detected in radio telescopes
- Inverse Compton (IC) scattering of $e^{\pm}$ on CMB photons inside a galactic system produces relatively high frequency photon flux



- For MeV $e^{\pm}$, such photon flux fall (at least partially) inside the usual frequency range of radio telescopes like the SKA

IC flux from MeV DM: radio signal at the SKA



$\chi\chi \to e^+e^-$
$(m_\chi = 2$ MeV$)$

$\chi \to e^+e^-$
$(m_\chi = 4$ MeV$)$

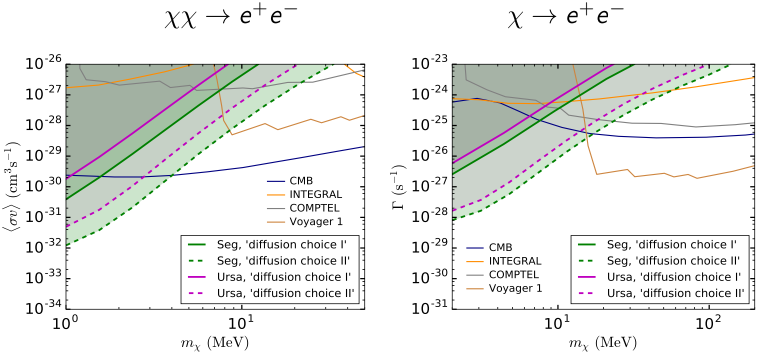
IC flux from Seg I dSph

- Independent of the ambient magnetic field B

[B. Dutta, AK, L. E. Strigari, JCAP 03 (2021) 011]

SKA detectability

$\chi\chi \to e^+e^-$ $\chi \to e^+e^-$



SKA threshold limits for detecting (in 100 h observation) DM induced IC flux from dSphs

- Independent of the ambient magnetic field B

[B. Dutta, AK, L. E. Strigari, JCAP 03 (2021) 011]

Dark Matter probes using compact stars

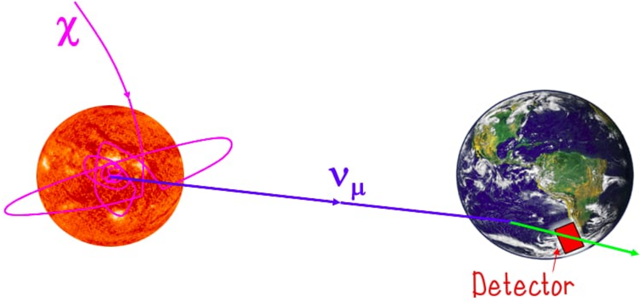
WIMP capture in celestial bodies

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

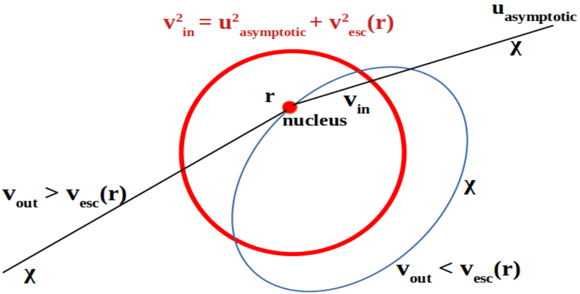
  Example: gravitational capture of WIMPs in the Sun

- Inside the celestial bodies (e.g. Sun) captured WIMPs can annihilate into SM particles

  $\chi\chi \to b\bar{b}, \tau^+\tau^-, W^+W^-, ... \Rightarrow \nu(\bar{\nu})$ [signal for neutrino telescopes]



WIMP capture mechanism

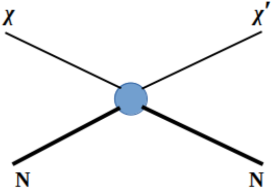


- Inside the celestial body the incoming WIMPs is accelerated by the gravitational potential $v_{\text{in}} = \sqrt{u^2_{\text{asymptotic}} + v^2_{\text{esc}}(r)}$
- The WIMP can scatter off a nucleus inside the celestial body **(via the same interactions probed by Direct Detections)**
- If its outgoing speed (v_{out}) after the scattering is below $v_{\text{esc}}(r)$, 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'): $\chi + \mathrm{N} \rightarrow \chi' + \mathrm{N}$
- χ and χ' are close in mass: $m_{\chi'} - m_{\chi} \equiv \delta > 0$
- Elastic scattering $[\chi + \mathrm{N} \rightarrow \chi + \mathrm{N}]$ is absent

[D. Smith and N. Weiner (PRD 64, 043502 (2001))]



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

$$\frac{1}{2}\,\mu_{\chi\mathrm{N}}\;v_{\mathrm{in}}^{2}\;>\;\delta \qquad \Rightarrow v_{\mathrm{in}} > \sqrt{\frac{2\delta}{\mu_{\chi\mathrm{N}}}}$$

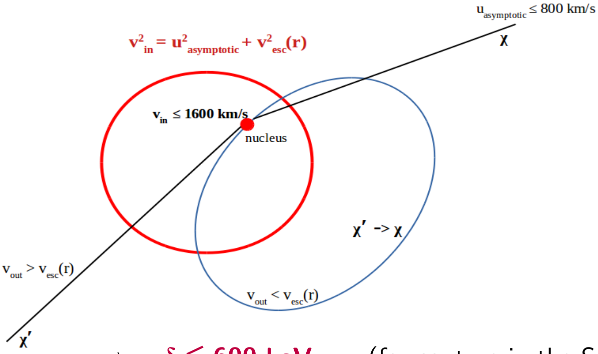
$[\mu_{\chi\mathrm{N}} \equiv \mathrm{reduced\,mass} = \frac{m_\chi m_\mathrm{N}}{m_\chi + m_\mathrm{N}}]$

Inelastic Dark Matter (IDM)

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

  $\Rightarrow$ **$\delta \lesssim 200$ keV** (for Xe based detectors)

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



$\Rightarrow$ **$\delta \lesssim 600$ keV** (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 heavier 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**

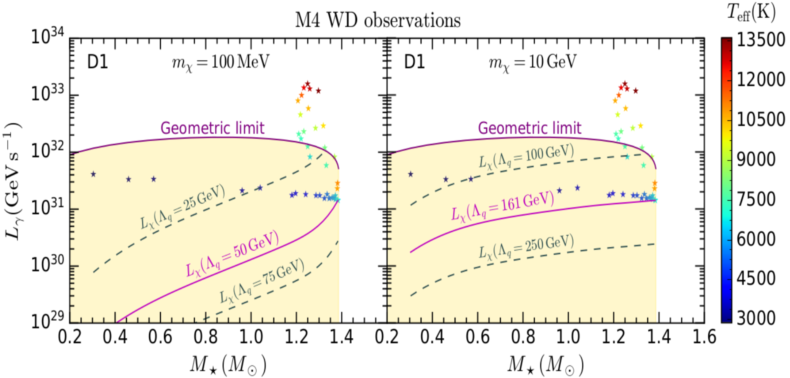
- For NSs, the incoming WIMP speed can reach up to a few 10^5 km/s

  $\Rightarrow$ **$\delta \lesssim$ 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)]

Annihilations of captured WIMPs can increase WD luminosities above the observed values

⇒ It is possible to constrain the WIMP parameter space

DM density in M4

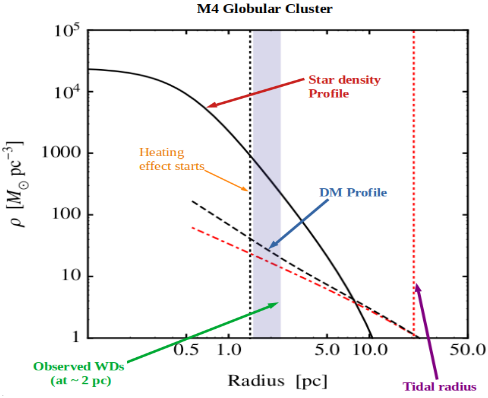
Prediction for DM abundance in M4 relies on Galaxy formation models

$\rho_{\rm DM} \simeq 800\ {\rm GeVcm}^{-3}$

@ radius $\sim$ 2 pc

(well within $r_{\rm tidal}$)

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



[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

→ consistent with the observed lack of DM in globular clusters

Capture rate of IDM in WDs

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

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

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

Nuclear density in WD
(WD equation of state)

differential cross-section

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

Condition for IDM scattering:

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

Condition for capture:

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

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

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 WD star are captured)

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

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

- Inside WDs the captured WIMPs annihilate and produce SM particles

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

- 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, if m_χ is large)

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

Capture rate of IDM in WDs & the annihilation luminosity

Heavy WDs are mostly made of ${}^{12}_{6}\mathrm{C}$ or ${}^{16}_{8}\mathrm{O}$

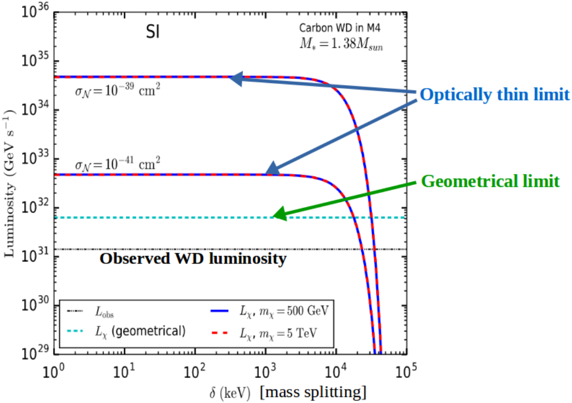
$\Rightarrow$ WIMP capture in WDs is driven by Spin-Independent (SI) interaction

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

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

$C_* \sim 1/m_\chi$

L_χ independent of m_χ



Optically thin limit

Geometrical limit

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

Capture rate of IDM in WDs & the annihilation luminosity

Heavy WDs are mostly made of ${}^{12}_{6}\mathrm{C}$ or ${}^{16}_{8}\mathrm{O}$

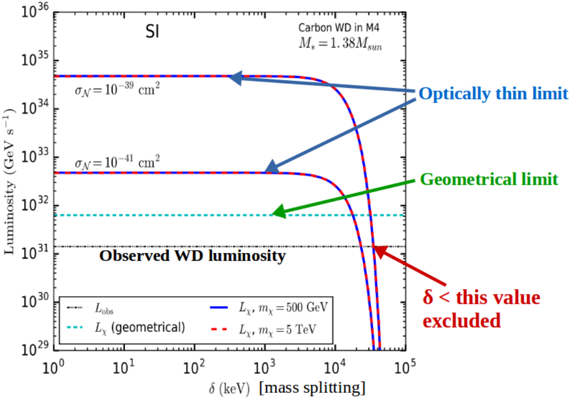
$\Rightarrow$ WIMP capture in WDs is driven by Spin-Independent (SI) interaction

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

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

$C_* \sim 1/m_\chi$

L_χ independent of m_χ



Optically thin limit

Geometrical limit

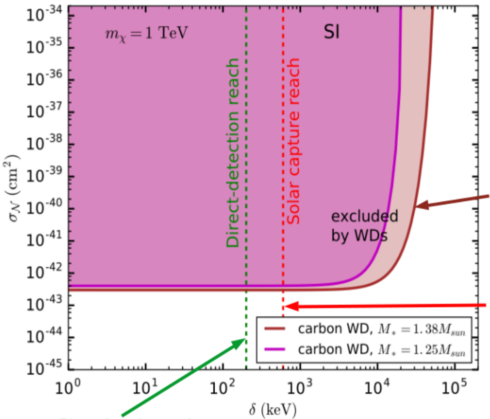
δ < this value excluded

[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

Independent of m_χ, when $m_\chi >> m_{nucleus}$



WD reach

($M_* = 1.38\ M_\odot$)

Solar capture reach

Direct detection reach

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

A realization of IDM in Left-Right symmetric models (LRSM)

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

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

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

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

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

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 is 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 is 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)

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

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:

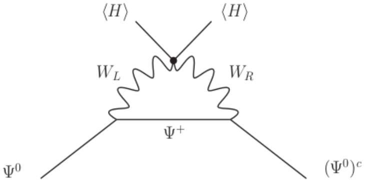
$$\mathcal{L}_{\rm BD} = \frac{1}{2} \mathrm{Tr}\left[\overline{\Psi} i \not{D} \Psi\right] - \frac{1}{2} M_\Psi \mathrm{Tr}\left[\overline{\Psi}\Psi\right]$$

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

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

Mass splitting in Bi-doublet fermionic DM

When Φ acquires vevs, $W_L^{\pm}$ and $W_R^{\pm}$ mixing 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

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

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

$$\begin{pmatrix} W_L^+ \\ W_R^+ \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} W_1^+ \\ W_2^+ \end{pmatrix}$$

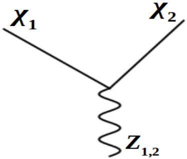
$$\tan 2\xi \simeq -4\,\frac{g_R}{g_L}\frac{M_{W_L}^2}{M_{W_R}^2}\frac{v_1 v_2}{v^2}$$

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

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

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)]

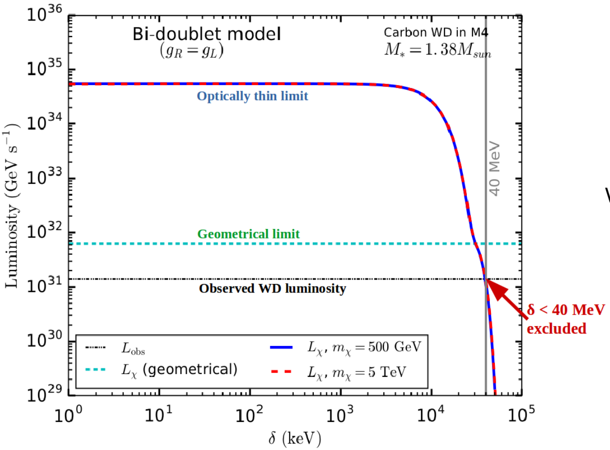
Large scattering cross-section

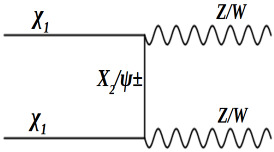
⇒ parameter space gets excluded

unless scattering is kinematically forbidden by large mass splitting δ

[N.B. $\delta = \delta(g_R, M_\Psi, M_{W_2})$]

WD luminosity induced by Bi-doublet IDM



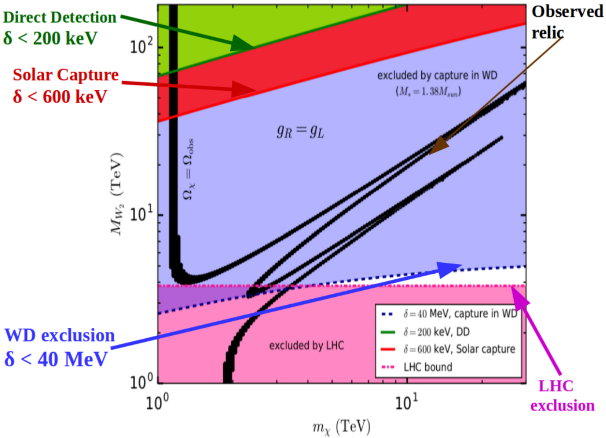


WIMP annihilation in WD

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

Exclusion on LRSM parameter space

$g_R = g_L$



Direct Detection
$\delta < 200$ keV

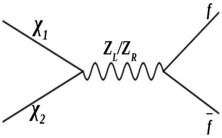
Solar Capture
$\delta < 600$ keV

WD exclusion
$\delta < 40$ MeV

Observed relic

LHC exclusion

at Early Universe:



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

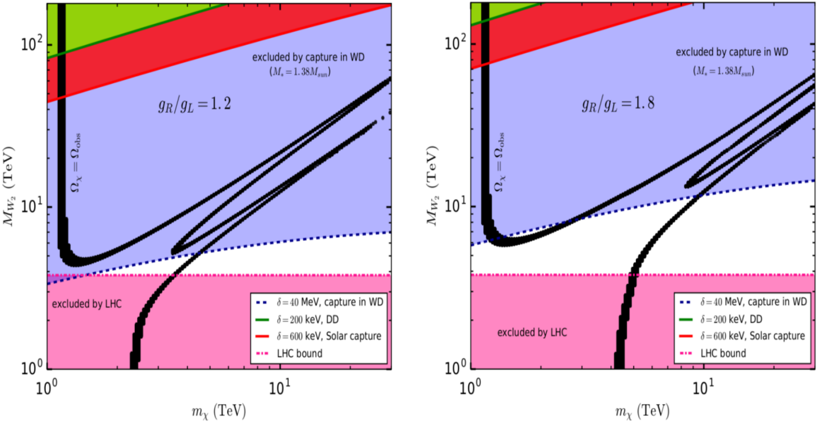
[A. Biswas, AK, H. Kim, S. Scopel, L. V. Sevilla, PRD 106, 083012 (2022)]

- **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})



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

Summary

- Astrophysical observations can provide useful ways to reveal the nature of DM interactions
- Existing data put strong constraints on thermal WIMPs for annihilation into specific channels
- However, a general analysis using all existing data still allows standard thermal WIMPs over the entire mass range 10 MeV - 100 TeV
- Indirect searches of DM through radio observations can play important role in DM phenomenology
- The upcoming radio telescope SKA can probe the DM parameter space for a wide range of DM mass
- With just about 100 hours of observation the SKA can probe the DM parameter space beyond the reach of existing experiments
- The SKA is sensitive to the MeV DM signals for the parameter space that is allowed by existing data

Summary

- Observation of compact stars can be useful for constraining DM
- We use the luminosities of low–temperature heavy WDs observed by HST in the core of M4 globular cluster to improve the existing constraints on Inelastic Dark Matter (IDM)
- WD data can exclude the inelastic mass splitting $\delta \lesssim$ 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 more compact objects like neutron stars, IDM scattering can be active up to $\delta \simeq$ a few hundreds of MeV

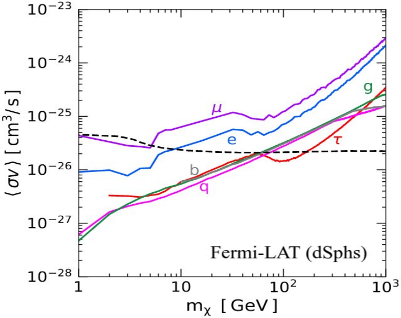
  ⇒ future observations of neutron stars (e.g., by James Webb Space Telescope) with temperatures $\lesssim$ a few thousand Kelvin would rule out the full parameter space of LRSM bi-doublet DM

Thank You

Backup slides

γ-ray searches

- WIMP annihilations in a galactic halo produce γ-rays
- Fermi-LAT γ-ray observation of dwarf spheroidal (dSph) galaxies
  $\rightarrow$ constrains GeV-TeV scale WIMPs

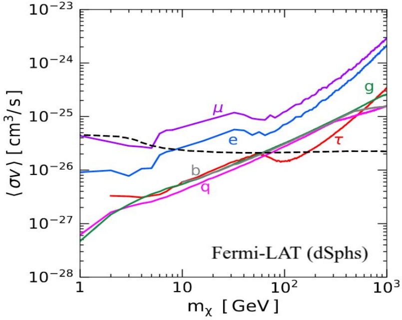


[Fermi-LAT, 2016]

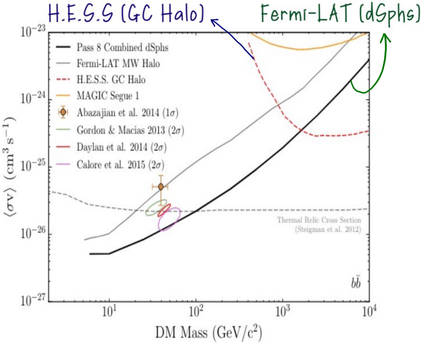
[Leane, *et al.*, PRD 98, 023016]

γ-ray searches

- WIMP annihilations in a galactic halo produce γ-rays
- Fermi-LAT γ-ray observation of dwarf spheroidal (dSph) galaxies
  → constrains GeV-TeV scale WIMPs
- H.E.S.S γ-ray observation of inner Galactic halo
  → give stronger constraints for multi-TeV WIMPs



[Fermi-LAT, 2016]
[Leane, *et al.*, PRD 98, 023016]



[H.E.S.S, 2015, 2021]
[Ackermann, *et al.*, PRL 115, 231301]

γ-ray lmits

- Fermi-LAT:

→ Integrated photon energy flux in the energy bin $[E_{\rm min}, E_{\rm max}]$ for the i-th dSph,

$$\Phi_{E\,i} = \frac{\langle \sigma v \rangle\, J_i}{8\pi\, m_\chi^2} \int_{E_{\rm min}}^{E_{\rm max}} \sum_f B_f \frac{dN_f}{dE_\gamma}\, E_\gamma\, dE_\gamma,$$

→ Modified joint likelihood:

$$\tilde{\mathcal{L}}_{\rm joint}(\mu) \;=\; \prod_i \mathcal{L}_i(\mu|\mathcal{D}_i) \times \frac{1}{\ln(10)\, J_i \sqrt{2\pi}\sigma_i} e^{-\left(\log_{10}(J_i) - \log_{10}(J_i^{\rm pred})\right)^2/2\sigma_i^2},$$

→ Extremized to obtain 95% C.L. upper limit on $\langle \sigma v \rangle$

γ-ray lmits

- H.E.S.S:
  → Signal events from i-th ON(OFF) region:

$$\begin{aligned} N^S_{i,\mathrm{ON(OFF)}} &= \frac{\langle \sigma v \rangle \, J_{i,\mathrm{ON(OFF)}}}{8\pi \, m_\chi^2} \, T_{\mathrm{obs}} \\ &\times \int_{E_{\mathrm{th}}}^{m_\chi} \int_0^\infty dE'_\gamma dE_\gamma \sum_f B_f \frac{dN_f}{dE_\gamma}(E_\gamma) \, A_{\mathrm{eff}}(E_\gamma) \, R(E_\gamma, E'_\gamma), \end{aligned}$$

  → Constructed likelihood function:

$$\mathcal{L} = \prod_i \frac{(N^S_{i,\mathrm{ON}} + N^B_i)^{N_{\mathrm{ON},i}}}{N_{\mathrm{ON},i}!} e^{-(N^S_{i,\mathrm{ON}} + N^B_i)} \times \frac{(N^S_{i,\mathrm{OFF}} + N^B_i)^{N_{\mathrm{OFF},i}}}{N_{\mathrm{OFF},i}!} e^{-(N^S_{i,\mathrm{OFF}} + N^B_i)},$$

  → Extremized to obtain 95% C.L. upper limit on $\langle \sigma v \rangle$

$e^{\pm}$ propagation through MW

- $e^{\pm}$ propagate through MW following the diffusion-loss eq:

$$\begin{aligned}\frac{\partial N_i}{\partial t} &= \vec{\nabla}.(D\vec{\nabla})N_i + \frac{\partial}{\partial p}(b(p,\vec{r}))N_i + Q_i(p,\vec{r}) \\ &\quad + \sum_{j>i} \beta n_{gas}(\vec{r})\sigma_{ji}N_j - \beta n_{gas}(\vec{r})\sigma_i^{\mathrm{in}}(E_k)N_i,\end{aligned}$$

$D = D_0 e^{|z|/z_t}\left(\frac{\rho}{\rho_0}\right)^{\delta}$: Diffusion term,

$b(p,\vec{r})$: Energy loss term,

$Q_\chi(p,r,z) = \frac{\rho_\chi^2(r)\langle\sigma v\rangle}{2m_\chi^2}\sum_f B_f \frac{dN_f}{dE_{e^{\pm}}}$: DM contribution,

- $\rho_\chi(r)$: NFW with $\rho_\odot = 0.25\,\mathrm{GeV cm^{-3}}$
- Diffusion-loss eq is solved using `DRAGON` to obtain e^+ flux at Earth
- The signal is combined with a polynomial background and fitted against the AMS-02 e^+ data to obtain the 95% C.L. upper limit on $\langle\sigma v\rangle$

CMB constraints

- CMB:

  → Planck 2015 data put constraints on thermal WIMPs:

$$\epsilon_{\rm eff}(m_\chi)\frac{\langle \sigma v\rangle}{m_\chi} \lesssim 4.1\times 10^{-28}\,{\rm cm^3\,s^{-1}\,GeV^{-1}}$$

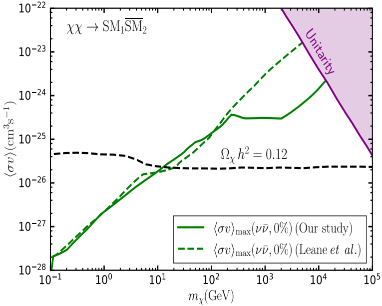
  → weighted efficiency factor:

$$\epsilon_{\rm eff}(m_\chi) \;=\; \frac{1}{2m_\chi}\int_0^{m_\chi}\sum_f\left(2\epsilon_{e^\pm}B_f\frac{dN_f}{dE_{e^\pm}}E_{e^\pm}dE_{e^\pm}+\epsilon_\gamma B_f\frac{dN_f}{dE_\gamma}E_\gamma dE_\gamma\right)$$

  → $\epsilon_{e^\pm}$ is energy injection efficiency for $e^\pm$ and ϵ_γ is that for photons

Importance of H.E.S.S

- H.E.S.S GC data strengthens the constraints for $m_\chi \gtrsim 200\,\mathrm{GeV}$



[K. Dutta, A. Ghosh, AK, B. Mukhopadhyaya, arxiv:2212.09795]

Neutrino telescope constraints

- Super-Kamiokande:

  A. Neutrino observation from galactic halo is used for GeV-TeV scale WIMPs

  → 35° ON region around GC and 35° OFF region opposite to GC

  → upper limit on ($N_{\rm ON}$ - $N_{\rm OFF}$) is used to obtain constraints

  B. Low energy ν observation data has been used to constrain 10 - 100 MeV WIMPs

  → signals obtained via inverse-β decay: $\bar{\nu}_e + p \rightarrow n + e^+$

  → Four different backgrounds:

  1. Atmospheric ν_μ induced $\mu^\pm$ decay at rest and give $e^\pm$
  2. Atmospheric ν_e induced $e^\pm$
  3. Atmospheric ν_e via NC give low-energy ν_e which give $e^\pm$
  4. Atmospheric ν_μ via NC give extra μ/π, which decay into $e^\pm$

  → All four backgrounds and the signal are fitted against the data to derive constraints

Neutrino telescope constraints

- IceCube and ANTARES:

  → Number of signal events in the i-th bin:

$$N_i^S = \frac{\langle \sigma v \rangle J_i}{8\pi\, m_\chi^2} T_{\rm obs} \int_0^{m_\chi} \sum_f B_f \left(\frac{dN_f}{dE_\nu} A_{\rm eff}(E_\nu)\, dE_\nu + \frac{dN_f}{dE_{\bar\nu}} A_{\rm eff}(E_{\bar\nu})\, dE_{\bar\nu} \right),$$

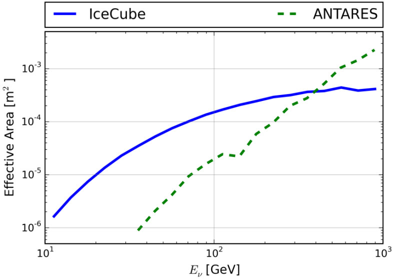
  → Likelihood function is constructed:

$$\mathcal{L}(\mu) = \prod_i \frac{(n_{\rm obs}^{\rm tot}(\mu\, f_s^i + (1-\mu)\, f_B^i))^{n_{{\rm obs},i}}}{n_{{\rm obs},i}!}\, e^{-n_{\rm obs}^{\rm tot}(\mu\, f_s^i + (1-\mu)\, f_B^i)}$$

where $f_s^i = N_i^S / \sum_i N_i^S$, $f_B^i = N_i^B / \sum_i N_i^B$.

→ $\mathcal{L}(\mu)$ is extremized to obtain $\mu_{95\%}$, which gives $\langle \sigma v \rangle_{95\%}$

[Albert, *et al.*, PRD 102, 082002]



Decaying DM

- DM can decay into SM particle pairs → fluxes of γ, $e^-(e^+)$, $\nu(\bar{\nu})$
- Source function for DM decay:

$$\chi \rightarrow \underbrace{\mathrm{SM}_1\,\mathrm{S\bar{M}}_2}_{f} \qquad Q_i^{decay}(E,r) = \Gamma \left\{ \frac{\rho_\chi(r)}{m_\chi} \right\} \left\{ \sum_f \frac{dN_f^i}{dE} B_f \right\}$$

$$Q_i^{annihilation}(E,r) = \langle \sigma v \rangle \left\{ \frac{\rho_\chi^2(r)}{2m_\chi^2} \right\} \left\{ \sum_f \frac{dN_f^i}{dE} B_f \right\}$$

Γ: decaywidth of DM particle χ

$\frac{\rho_\chi(r)}{m_\chi}$: number density of DM particles

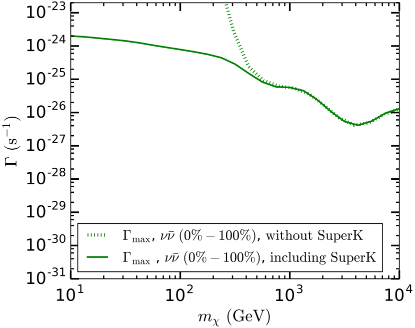
decay channel f: $b\bar{b}$, $\tau^+\tau^-$, W^+W^-, ...

B_f: branching fraction for channel f

$\frac{dN_f^i}{dE}$: spectrum of secondary particle i produced per decay

Decaying DM: present status

- Non-observations of DM decay induced fluxes of γ, $e^-(e^+)$, $\nu(\bar{\nu})$ in exisiting observations give constriants on DM parameter space



Fermi-LAT IGRB, AMS-02 e^+, Planck CMB and Super-Kamiokande atmospheric neutrino data have been used

[considering all possible 2-body SM decay channels (including $\chi \to \nu\bar{\nu}$)]

[K. Dutta, A. Ghosh, AK, B. Mukhopadhyaya, JCAP 09 (2022) 005]

DM density profiles

- Choices for the dSph DM density profile:

$$\rho_\chi^{NFW}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)^{\delta}\left(1+\frac{r}{r_s}\right)^{3-\delta}}, \quad \delta = 1$$

$$\rho_\chi^{Einasto}(r) = \rho_s \; exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right\}, \quad \alpha \simeq 0.3$$

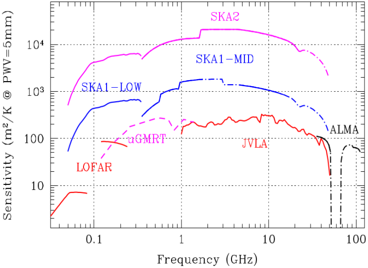
$$\rho_\chi^{Burkert}(r) = \frac{\rho_s}{\left(1+\frac{r}{r_s}\right)\left(1+\left(\frac{r}{r_s}\right)^{2}\right)}$$

Telescope RMS noise

$$N_{rms} \propto \frac{K_B T_{sys}}{\sqrt{\Delta t}\, A_{eff}}$$

A_{eff}: Effective area of the radio telescope
Δt: Observation time
T_{sys}: System Temperature

T_{sys} includes CMB, galactic, atmospheric, ground radiation, antenna receiver contributions etc.



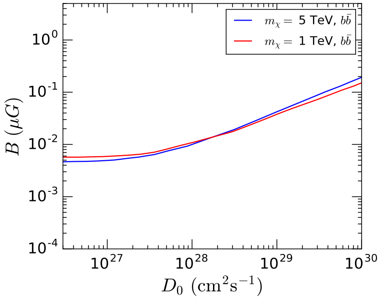
[Braun, *et al.*, 2017]

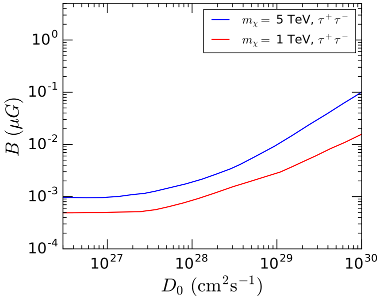
Choice of B and D_0 in local dSphs

- Various theoretical arguments predict $B \approx \mu G$ in nearby dSphs
- D_0 can be as low as $\approx 10^{26}\text{cm}^2\text{s}^{-1}$
  or can be as high as $\approx 10^{30} - 10^{31}\text{cm}^2\text{s}^{-1}$
- $D_0 \approx 10^{28}\text{cm}^2\text{s}^{-1}$ for the Milky Way

Detectability in the B, D_0 plane

Independent knowledge of m_χ and $\langle \sigma v \rangle$ can enable one to identify the viable regions of astrophysical parameters of a dSph





Limits in the $B - D_0$ plane to observe DM annihilation induced radio signals at SKA (100 hours) from Draco dSph

(m_χ and $\langle \sigma v \rangle$ are consistent with cosmic-ray antiproton observation)

[AK, S. Mitra, B. Mukhopadhyaya, T.R. Choudhury, PRD 101, 023015 (2020)]

Mechanism of producing IC signal

- Source function:

$$Q_e^{annihilation}(E,r) = \langle \sigma v \rangle \left\{ \frac{\rho_\chi^2(r)}{2m_\chi^2} \right\} \left\{ \frac{dN^e}{dE} \right\} \qquad [\chi\chi \to e^+e^-]$$

or,

$$Q_e^{decay}(E,r) = \Gamma \left\{ \frac{\rho_\chi(r)}{m_\chi} \right\} \left\{ \frac{dN^e}{dE} \right\} \qquad [\chi \to e^+e^-]$$

- Propagation:

$$D(E)\nabla^2 \left(\frac{dn}{dE} \right) + \frac{\partial}{\partial E} \left(b(E) \frac{dn}{dE} \right) + Q_e(E,r) = 0$$

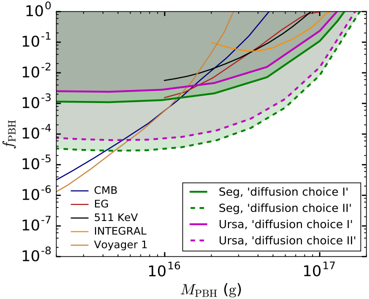
- IC flux:

$$S_\nu(\nu) = \frac{1}{4\pi} \int d\Omega \int_{\mathrm{los}} dl \left(2 \int dE \frac{dn}{dE} \, P_{\mathrm{IC}} \right)$$

Primordial black hole (PBH) DM at the SKA

Search for PBH DM using SKA

- PBHs can contribute to the observed DM abundance of the universe ($M_{\rm PBH} \gtrsim 10^{15}$ g)
- PBHs in the mass range 10^{15}–10^{17} g can produce MeV $e^{\pm}$ via Hawking radiation
- SKA probe of the corresponding IC flux can help to constrain the PBH fraction of the total DM density ($f_{\rm PBH} \equiv \Omega_{\rm PBH}/\Omega_{\rm DM}$)



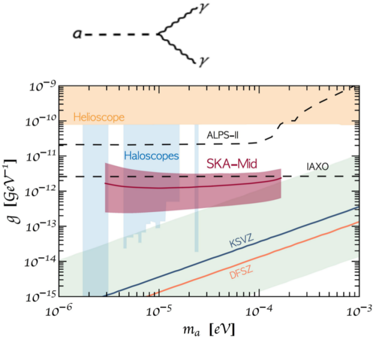
[B. Dutta, AK, L. E. Strigari, JCAP 03 (2021) 011]

SKA threshold limits in the $f_{\rm PBH} - M_{\rm PBH}$ plane
(for 100 h observation of local dSphs)

Ultralight bosonic DM at the SKA

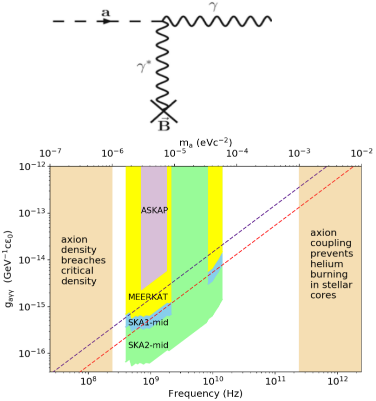
Search for Axion/ALP cold dark matter

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a$$



SKA observation of local dSphs

[Caputo, *et al.* (PRD 98, 083024 (2018))]



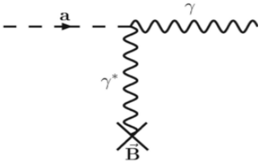
Radio observation of the Interstellar Medium

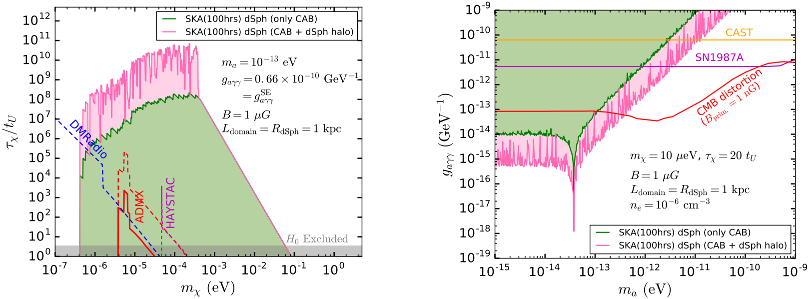
[Kelley, *et al.* (ApJL 845 L4 (2017))]

Search for relativistic axions

$\chi \longrightarrow a\ a$

(DM)





SKA (100 h) observation of Seg I dSph

[AK, T. Kumar, S. Roy, J. Zupan (2212.04647)]