Indirect search for decaying dark matter: a generic approach

Arpan Kar

Center for Quantum Spacetime (CQUeST), Sogang University

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Decaying dark matter

- We know that, nearly 25% of the universe's total energy density is attributed to dark matter (DM).
- Standard Model (SM) of particle physics does not provide a suitable DM candidate.

  $\Rightarrow$ Beyond Standard Model (BSM) theories.
- DM is not necessarily absolutely stable; but it can decay.
- In order to explain the observed DM density, it must be present till today.

  $\Rightarrow$ DM lifetime (τ) should be much larger than the age of the Universe $\sim 10^{17}\,\mathrm{s}$.

Indirect signals of decaying DM

- Longevity of DM particle ⇒ Very small DM-SM couplings.
- One promising way to look for decaying DM: Indirect search observations.
- Several production mechanisms exist.

  → Give rise to decaying DM particles over a wide range of masses.
- Usually considered DM decay channels (decay modes): a pair of SM particles ($\chi \to \mathrm{SM}_1\overline{\mathrm{SM}_2}$).
- Most of the existing and future indirect searches are sensitive to the signals of decaying DM particles in the GeV - TeV mass range.

Indirect signals of decaying DM

- We consider a decaying scalar DM in the mass range 10 GeV - 10 TeV.
- Its all possible two-body SM decay channels ($\mathrm{SM_1}\overline{\mathrm{SM_2}}$): $\{e^+e^-,\ \mu^+\mu^-,\ \tau^+\tau^-,\ b\bar{b},\ t\bar{t},\ q\bar{q},\ W^+W^-,\ ZZ,\ \gamma\gamma,\ gg,\ hh,\ Z\gamma,\ Zh,\ \nu\bar{\nu}\}$
- Primary DM decay products → γ, $e^-(e^+)$, $p(\bar{p})$ and $\nu(\bar{\nu})$.
- For this DM mass range, most sensitive indirect search observations:
  1. γ-rays: Fermi-LAT isotropic gamma-ray background (IGRB)
  2. $e^-(e^+)$, $p(\bar{p})$: AMS-02 cosmic-ray
  3. $\nu(\bar{\nu})$: Super-Kamiokande neutrino

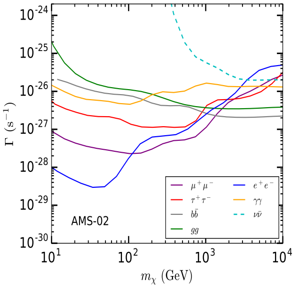
Usual approach

- A decaying DM scenario is specified by:
  - DM mass m_χ.
  - Total decay width Γ ($\equiv \tau^{-1}$).
  - Branching ratio (BR) of each decay channel.
- Data of indirect search observations constrain the DM parameter space.
- DM contributions are calculated and compared against the observed astrophysical data, taking the standard processes into account.

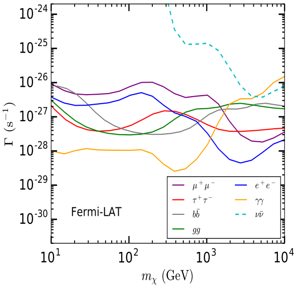
  → Maximum contribution from DM decay is constrained.

  ⇒ Upper limit on Γ.
- In the usual approach, a single decay channel is assumed at a time with 100% BR.

AMS-02 & Fermi-LAT constraints



AMS-02 positron constraints (95% C.L.).



Fermi-LAT IGRB constraints (95% C.L.).

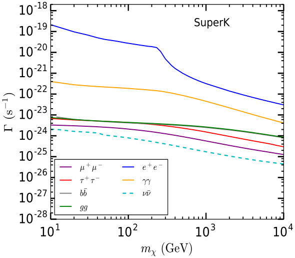
- For $\nu\bar{\nu}$ channel, $e^{\pm}$ and γ are produced via electroweak radiation.
  $\Rightarrow$ Fluxes are suppressed if $\nu\bar{\nu}$ pairs are of low energy.
  $\Rightarrow$ There exists no constraints for $m_\chi \lesssim$ a few hundreds of GeV.

Super-Kamiokande constraints

- The $\nu\bar{\nu}$ channel is not constrained by AMS-02 and Fermi-LAT for $m_\chi \lesssim$ a few hundreds of GeV.

  $\rightarrow$ One should include the neutrino flux observation experiments, such as the Super-Kamiokande.

- Most stringent constraints are obtained for $\nu\bar{\nu}$ channel.



Super-Kamiokande constraints (95% C.L.).

Necessity for a generic approach

- Given a particular DM decay channel, the constraints obtained from different observations are quite different.

  → Therefore, for a specific channel, a value of Γ allowed by one observation may be ruled out by other observations.

- Similarly, given any particular observation, the upper-limits on Γ are obtained for different DM decay channels also largely vary.

- In a generic model of decaying DM: χ may decay to multiple channels with arbitrary BRs.

- **One needs a methodology to obtain a BR independent upper-limit on Γ which is allowed by all observations.**

Generic approach

For a given m_χ, scan over all possible BR combinations

↓

For each BR combination obtain the **strongest** upper limit on Γ among different observations

↓

Find the **weakest** limit among the allowed Γ values obtained for different BR combinations: $\Gamma_{\max}$

- $\Gamma > \Gamma_{\max}$: No BR combination is allowed by all observations.
- $\Gamma < \Gamma_{\max}$: At least one BR combination is always allowed by all observations.

Maximum allowed total decay width $\Gamma_{\max}$

- Top panel: $\text{BR}(\chi \to \nu\bar{\nu}) = 0\%$

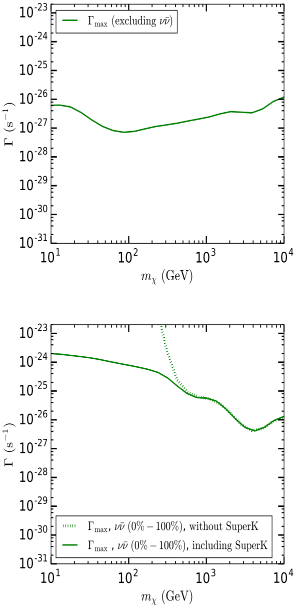
  → Constraints are weaker than 100% BR scenarios.

- Bottom panel:
  $\text{BR}(\chi \to \nu\bar{\nu}) = 0\% - 100\%$

  → $\Gamma_{\max}$ is large for $m_\chi \lesssim$ a few hundreds of GeV.

  - When Super-Kamiokande data is included

  → constraint on $\Gamma_{\max}$ strengthens for lower values of m_χ.



Detection prospects in upcoming radio observations

- DM decays inside DM dominated astrophysical objects generate energetic $e^{\pm}$ pairs.

  → Radiate energy via cycloidal motion in the galactic magnetic field.

  → Give rise to radio synchrotron fluxes which can be observed in radio telescopes.

  → New avenue for DM indirect search observations.

- Local dwarf spheroidal (dSph) galaxies are most suitable targets because of their

  - Proximity to the Milky Way galaxy.
  - High DM content.
  - Low star formation rates.

- We have considered the ultrafaint dSph Seg 1 as the target.

Square Kilometre Array (SKA)

- Upcoming radio telescope to be built in Australia and South Africa.

  - Larger effective area

$\Rightarrow$ Lower rms noise level.

  - Wide frequency range (50 MHz - 50 GHz).

  - Highly sensitive to GeV - TeV scale decaying DM signals.

- **We investigate the detectability prospect of the DM signal at the SKA in a BR independent manner, assuming a 100 hours of observation of Seg 1 dSph.**

Methodology to determine the SKA detectability

For a given m_χ and Γ, scan over all possible BR combinations

$\downarrow$

Obtain the **maximum radio flux** $S_\nu^{\max}$ in each frequency bin

$\downarrow$

Obtain the **minimum radio flux** $S_\nu^{\min}$ in each frequency bin

- $S_\nu^{\max}$ and $S_\nu^{\min}$ determine the detectability of any given parameter point (m_χ, Γ).

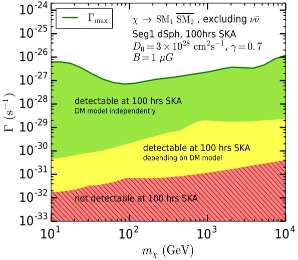
  → **detectable for all BR combs.** (both $S_\nu^{\max}$ and $S_\nu^{\min}$ are above the SKA threshold)

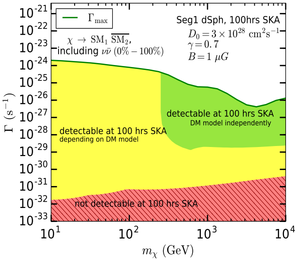
  → **detectable for specific BR combs.** (only $S_\nu^{\max}$ is above the SKA threshold)

  → **non-detectable for any BR combs.** (both $S_\nu^{\max}$ and $S_\nu^{\min}$ are below the SKA threshold)

SKA Projections

- $m_\chi - \Gamma$ plane can be classified based on the SKA detectability:
  $\rightarrow$ detectable for all BR combs.
  $\rightarrow$ detectable for specific BR combs.
  $\rightarrow$ non-detectable for any possible BR combs.
- Top panel: $\mathrm{BR}(\chi \rightarrow \nu\bar{\nu}) = 0\%$
  - Large portion of the DM parameter space can be probed.
- Bottom panel:
  $\mathrm{BR}(\chi \rightarrow \nu\bar{\nu}) = 0\% - 100\%$
  - BR independent probe is possible for $m_\chi \gtrsim 250\,\mathrm{GeV}$ (otherwise, $\nu\bar{\nu}$ pairs are low energetic).





Conclusion

- For a GeV - TeV scale DM decaying into two-body SM decay channels, robust BR independent upper limit on Γ ($\Gamma_{\rm max}$) has been derived, combining various astrophysical data.
- There exists no BR combination for which any value of Γ larger than $\Gamma_{\rm max}$ is allowed by all observations. At least one BR combination consistent with all observations always exist for all values of Γ smaller than $\Gamma_{\rm max}$.
- When $\nu\bar{\nu}$ channel is included, the BR independent upper limit on Γ weakens for DM mass less than a few hundreds of GeV. However, for heavier DM particles, the DM parameter space is still severely constrained.

Conclusion

- Future SKA observation will probe a larger region of the allowed DM parameter space, in a BR independent way.
- On including $\nu\bar{\nu}$ channel one finds that, BR independent probe of the decaying DM parameter space at the SKA is possible only when DM mass is larger than a few hundreds of GeV.

Backup slides

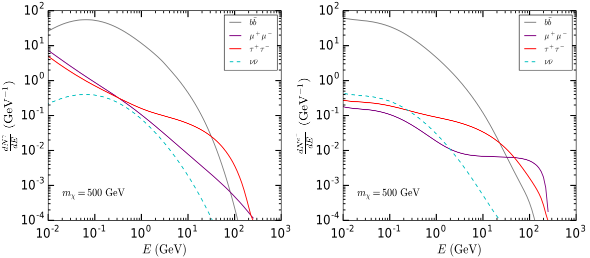
DM decay scenarios

- Many BSM scenarios make the DM absolutely stable by imposing global continuous symmetries
- Such symmetries may be broken due to some high-scale suppressed interactions

  $\Rightarrow$ Preferably by Planck-scale mediated interactions
  [ArXiV :1508.06635]

Fluxes from $\nu\bar{\nu}$ final state

- γ and $e^{\pm}$ spectra from the $\nu\bar{\nu}$ channel are produced via the radiation of electroweak gauge bosons.
- On-shell W and Z-bosons are not abundantly produced from low energy $\nu\bar{\nu}$ pairs.
- Fluxes are suppressed compared to the corresponding fluxes obtained from other decay channels.



γ and $e^{\pm}$ spectra for $\mu^+\mu^-, \tau^+\tau^-, b\bar{b}$ and $\nu\bar{\nu}$ assuming 100% BR for each channel.

Planck CMB constraints

- Planck data of CMB anisotropy measurement is also useful
- e^+e^- and γ produced from DM decays inject energy to perturb the CMB spectra.
- Any substantial perturbation to the CMB spectra is strongly constrained by the Planck CMB measurement and upper limit on Γ is derived
- 95% C.L. Upper limit on Γ obtained from Planck data of CMB measurement:

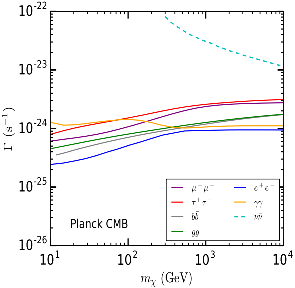
$$\Gamma \lesssim \left(\frac{\vec{N}.\vec{e}_1}{\vec{e}_1(30\,\mathrm{MeV}\ e^+e^-)} \right)^{-1} \left(2.6 \times 10^{25}\,\mathrm{s}\right)^{-1}.$$

$\vec{N}$: Contains the γ and $e^{\pm}$ spectra induced by DM decay.

$\vec{e}_1$: First principal component.

$\rightarrow$ Eigenvector corresponding to the largest eigenvalue of the marginalized Fisher matrix.

Planck CMB constraints



Planck CMB constraints (95% C.L.).

Fermi-LAT IGRB constraints

- Extra-galactic γ-ray flux:

$$\frac{d\Phi^{\mathrm{EG}}}{dE_\gamma} = \frac{\Gamma}{4\pi m_\chi} c\,\Omega_{\mathrm{DM}}\,\rho_c \sum_f B_f \int_0^\infty dz \frac{1}{H(z)} e^{-\tau(E_\gamma,z)} \left[\frac{dN_f^\gamma}{dE_\gamma}(E_\gamma(1+z)) + \frac{2}{E_\gamma(1+z)} \times \int_{m_e}^{m_\chi/2} dE_e \frac{P_{\mathrm{IC}}^{\mathrm{CMB}}(E_\gamma(1+z), E_e, z)}{b_{\mathrm{IC}}^{\mathrm{CMB}}(E_e)} \int_{E_e}^{m_\chi/2} d\tilde{E}_e \frac{dN_f^{e^+}}{d\tilde{E}_e}(\tilde{E}_e) \right].$$

- Background flux:

$$\frac{d\Phi^{\mathrm{BG}}}{dE_\gamma} = I_{100} \left(\frac{E_\gamma}{100\,\mathrm{MeV}} \right)^{-\beta} \exp\left(-\frac{E_\gamma}{E_c} \right).$$

AMS-02 positron constraints

- Diffusion-loss equation:

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

- DM source term:

$$Q_\chi(p,\vec{r}) = \frac{\Gamma}{m_\chi}\sum_f B_f\,\frac{dN_f^{e^+}}{dE}(E)\rho_d(\vec{r}).$$

$\rho_d(\vec{r})$: NFW profile, $r_\odot = 20\,\text{kpc}$ and $\rho_\odot = 0.25\,\mathrm{GeV\,cm^{-3}}$.

- Diffusion term: $D(\rho,|\vec{r}|,z) = D_0\,e^{|z|/z_t}\,\left(\frac{\rho}{\rho_0}\right)^\delta$
  $D_0 = 2.7\times 10^{28}\,\mathrm{cm^2 s^{-1}}$, $\delta = 0.6$ and $z_t = 4\,\mathrm{kpc}$.
- Local magnetic field $B_\odot = 8.9\,\mu\mathrm{G}$.

Super-Kamiokande constraints

- ON source region: A circular region centered around the galactic center (GC) with half-opening angle 80°.

  OFF source region: Another circular region of the same size but offset by 180° in Right Ascension with respect to the GC.
- Neutrino flux:

$$\frac{d\Phi_{\mathrm{ON,OFF}}}{dE_\nu} = \mathrm{J}_{\mathrm{ON,OFF}} \frac{\Gamma}{4\pi\, m_\chi} \sum_f B_f \frac{2}{3} \frac{dN_f^\nu}{dE_\nu}(E_\nu).$$

- Astrophysical J-factors:

$$J_{\mathrm{ON,OFF}} = \int_{\Delta\Omega_{\mathrm{ON,OFF}}} d\Omega \int_{l.o.s} ds\, \rho_d(\vec{r}).$$

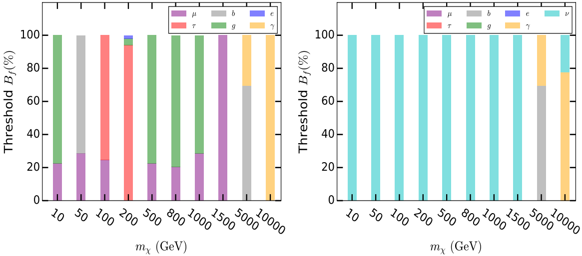
Threshold BR combinations

- Threshold BR: The BR combination for which $\Gamma_{\max}$ is obtained.

  - Different for different m_χ.
- Left panel: BR($\chi \to \nu\bar{\nu}$) $= 0\%$

  - Threshold BR are mostly determined by $\mu^+\mu^-, \tau^+\tau^-, b\bar{b}, gg$.
- Right panel: BR($\chi \to \nu\bar{\nu}$) $= 0\% - 100\%$

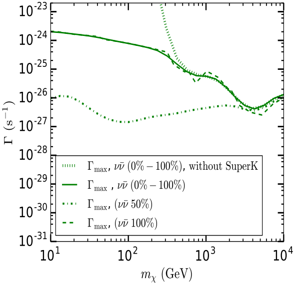
  -Threshold BR are mostly dominated by the $\nu\bar{\nu}$ channel for $m_\chi \lesssim \mathcal{O}(\mathrm{TeV})$.



- Not-unique, several BR combinations give similar $\Gamma_{\max}$.

Effects of the $\nu\bar{\nu}$ decay mode

- When BR for the $\nu\bar{\nu}$ channel is fixed at 50% upper limit on Γ strengthens for $m_\chi \lesssim$ a few hundreds of GeV.
- Super-Kamiokande data dictates the limit for lower m_χ if $\mathrm{BR}(\chi \to \nu\bar{\nu}) = 100\%$, while Planck, Fermi-LAT and AMS-02 decides the limit for $m_\chi \gtrsim$ a few hundreds of GeV.



DM decay induced radio signals

- Transport equation:

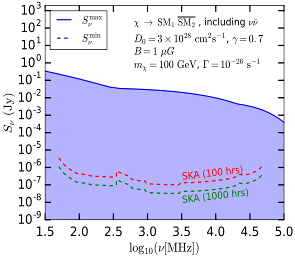
$$D(E)\nabla^2\left(\frac{dn_e}{dE}(E,\vec{r})\right)+\frac{\partial}{\partial E}\left(b(E)\frac{dn_e}{dE}(E,\vec{r})\right)+Q_\chi(E,\vec{r})=0.$$

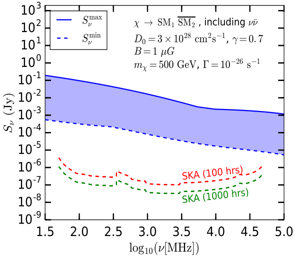
- Diffusion term: $D(E)=D_0\,(E/\mathrm{GeV})^\gamma$ where $D_0=3\times10^{28}\,\mathrm{cm}^2\mathrm{s}^{-1}$, $\gamma=0.7$.
- Energy loss term for synchrotron loss: $b_{\mathrm{Synch}}\propto\left(\frac{E}{\mathrm{GeV}}\right)^2\left(\frac{B}{\mu G}\right)^2$ with $B=1\,\mu\mathrm{G}$.
- DM source term: $Q_\chi(E,\vec{r})=\frac{\Gamma}{m_\chi}\sum_f B_f\,\frac{dN_f^{e^+}}{dE}(E)\rho_d(\vec{r})$ where $\rho_d(\vec{r})$ is Einasto profile.
- Radio flux:

$$S_\nu(\nu)=\frac{1}{4\pi}\int_{\Delta\Omega}d\Omega\int_{l.o.s}ds\left(2\int_{m_e}^{m_\chi/2}dE\,\frac{dn_e}{dE}(E,r(s,\Omega))P_{\mathrm{Synch}}(\nu,E,B)\right)$$

SKA detectability criteria

- Both $S_\nu^{\rm max}$ and $S_\nu^{\rm min}$ lie above the SKA sensitivity curve in at least one bin $\Rightarrow$ (m_χ, Γ) point is detectable for all possible BR combinations.
- Only $S_\nu^{\rm max}$ lies above the sensitivity curve in at least one bin, but $S_\nu^{\rm min}$ lies below the sensitivity curve in all bins $\Rightarrow$ Detectable for certain specific BR combinations.
- Both $S_\nu^{\rm max}$ and $S_\nu^{\rm min}$ lie below the sensitivity level $\Rightarrow$ Non-detectable.
- When $\nu\bar{\nu}$ channel is included, $m_\chi \lesssim$ *a few hundreds of GeV*, $S_\nu^{\rm min}$ is negligibly small for all values of Γ.





SKA Projections: effects of $\nu\bar{\nu}$

- Left panel: BR$(\chi \rightarrow \nu\bar{\nu}) = 50\%$

  - BR independently detectable even for $m_\chi \lesssim$ a few hundreds of GeV.

- Right panel: BR$(\chi \rightarrow \nu\bar{\nu}) = 100\%$

  - Radio fluxes from the $\nu\bar{\nu}$ channel are non-detectable for $m_\chi \lesssim$ a few hundreds of GeV.