Signatures of synchrotron radiation from the annihilation of Dark Matter at the Galactic Centre

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- Dark Matter indirect detection by via synchrotron radiation.
- Dark Matter can be trapped by massive astrophysical objects such as Galactic Centre.
- When accumulated in considerable numbers the Dark Matter can undergo the process of self annihilation producing SM fermion-anti fermion pairs.
- If e^+e^- pairs are produced as annihilation product they, under the influence of the magnetic field at the GC region will produce synchrotron radiation.
- Such radiation may be detected as indirect signature of Dark Matter as radio signals at the upcoming radio telescopes such as SKA.

Dark Matter Candidate
(The Model)

- SM is extended by two new extra fields:- a fermion and a pseudoscalar.
- Both are singlets under the SM gauge group.
- The Lagrangian for such a case is given as

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{DM}} + \mathcal{L}_{\phi} + \mathcal{L}_{\mathrm{int}},$$

where,

$$\mathcal{L}_{\mathrm{DM}} = \bar{\chi}\left(i\gamma^{\mu}\partial_{\mu} - m\right)\chi.$$

$$\mathcal{L}_{\phi} = \frac{1}{2}\left(\partial_{\mu}\phi\right)^2 - \frac{1}{2}m_0^2\phi^2 - \frac{\lambda}{24}\phi^4.$$

$$\mathcal{L}_{\mathrm{int}} = -\frac{g_1}{\Lambda}\left(H^{\dagger}H\right)\bar{\chi}\chi - ig\phi\bar{\chi}\gamma^5\chi - \lambda_1\phi^2 H^{\dagger}H - V_H$$

$$V_H = \mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2$$

- The scalar potential can thus be written as

$$V = \mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H\right)^2 + \frac{1}{2} m_0^2 \phi^2 + \frac{\lambda}{24}\phi^4 + \lambda_1 H^\dagger H \phi^2,$$

- After spontaneous symmetry breaking we have

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_H + \tilde{H} \end{pmatrix}, \phi = v_\phi + S,$$

$$V = \frac{\mu_H^2}{2}\left(v_H + \tilde{H}\right)^2 + \frac{\lambda_H}{4}\left(v_H + \tilde{H}\right)^4 + \frac{m_0^2}{2}\left(v_\phi + S\right)^2 + \frac{\lambda}{24}\left(v_\phi + S\right)^4 + \frac{\lambda_1}{2}\left(v_H + \tilde{H}\right)^2 \left(v_\phi + S\right)^2 .$$

- From the minimization condition

$$\frac{\partial V}{\partial \tilde{H}}\Big|_{\tilde{H}=S=0} = \frac{\partial V}{\partial S}\Big|_{\tilde{H}=S=0} = 0$$

$$m_0^2 = -\frac{\lambda}{6}v_\phi^2 - \lambda_1 v_H^2$$

$$\mu_H^2 = -\lambda_H v_H^2 - \lambda_1 v_\phi^2$$

- H and S mixes and the mass matrix is

$$\mathcal{M} = \begin{pmatrix} m_{\tilde{H}}^2 & m_{\tilde{H},S}^2 \\ m_{\tilde{H},S}^2 & m_S^2 \end{pmatrix} = \begin{pmatrix} \frac{\partial^2 V}{\partial \tilde{H}^2} & \frac{\partial^2 V}{\partial S \partial \tilde{H}} \\ \frac{\partial^2 V}{\partial S \partial \tilde{H}} & \frac{\partial^2 V}{\partial S^2} \end{pmatrix} = \begin{pmatrix} 2\lambda_H v_H^2 & 2\lambda_1 v_\phi v_H \\ 2\lambda_1 v_\phi v_H & \frac{1}{3}\lambda v_\phi^2 \end{pmatrix}$$

- In the diagonal basis

$$\begin{pmatrix} h \\ \rho \end{pmatrix} = U \begin{pmatrix} \tilde{H} \\ S \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \tilde{H} \\ S \end{pmatrix}$$

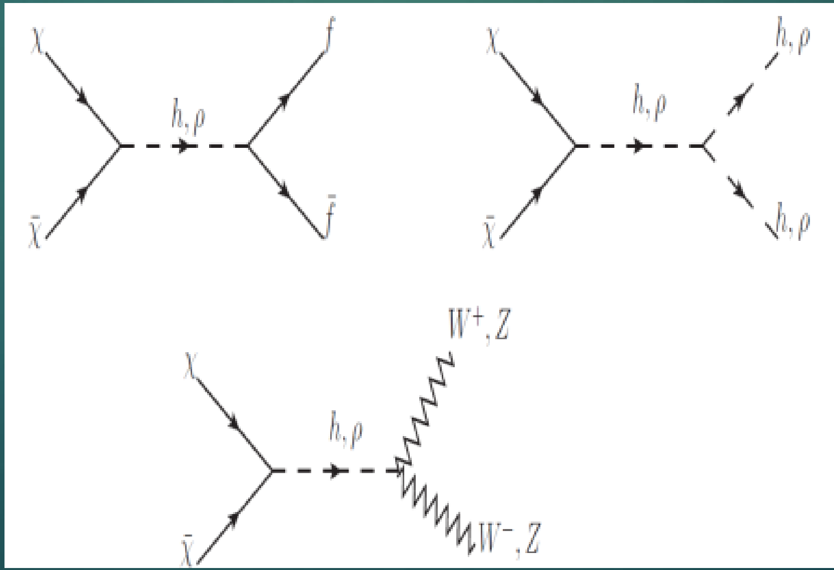
$$h = S\ \sin\theta + \tilde{H}\ \cos\theta,\ \rho = S\ \cos\theta - \tilde{H}\ \sin\theta$$

Constraining the parameter space

- The theoretical constraints
  - Vacuum Stabilty $\lambda > 0,\ \lambda_H > 0,\ \lambda\lambda_H > 6\lambda_1^2.$
  - Perturbativity $\lambda, \lambda_1, \lambda_H < 4\pi.$
- Experimental Constraints
  - PLANCK constraint on Relic Density $0.1172 \le \Omega_{\rm DM}{\rm h}^2 \le 0.1226,$
  - Collider Constraints
  - Direct Detection Bounds

Relic Density

- The Boltzmann equation is given as $$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle \left[n_\chi^2 - \left(n_\chi^{eq}\right)^2 \right]$$
- This equation after suitable transformation gives
$$\frac{1}{Y_0} = \frac{1}{Y_F} + \left(\frac{45G}{\pi}\right)^{-\frac{1}{2}} \int_{T_0}^{T_F} g_*^{1/2} \langle \sigma \mathrm{v} \rangle dT$$
- Finally the relic density is $$\Omega_{\mathrm{DM}} \mathrm{h}^2 = 2.755 \times 10^8 \left(\frac{m_\chi}{\mathrm{GeV}}\right) Y_0$$



Collider Constraints

- The signal strength of SM like Higgs boson h is

$$R_1 = \frac{\sigma(pp \to h)}{\sigma^{\rm SM}(pp \to h)} \frac{\mathrm{Br}(h \to xx)}{\mathrm{Br}^{\rm SM}(h \to xx)}$$

$$\mathrm{Br}^{\rm SM}(h \to xx) = \frac{\Gamma^{\rm SM}(h \to xx)}{\Gamma^{\rm SM}}, \ \mathrm{Br}(h \to xx) = \frac{\Gamma(h \to xx)}{\Gamma}.$$

$$\frac{\sigma(pp \to h)}{\sigma^{\rm SM}(pp \to h)} = \cos^2\theta \qquad R_1 = \cos^4\theta \frac{\Gamma^{\rm SM}}{\Gamma}$$

$$\Gamma = \cos^2\theta\, \Gamma^{\rm SM} + \Gamma^{\rm inv}.$$

$$\Gamma(h \to \chi\bar{\chi}) = \frac{g^2}{8\pi} \sin^2\theta \left({m_h}^2 - 4{m_\chi}^2\right)^{1/2} + \frac{\Lambda'^2 \cos^2\theta {v_H}^2}{8\pi {m_h}^2}\left({m_h}^2 - 4{m_\chi}^2\right)^{3/2}$$

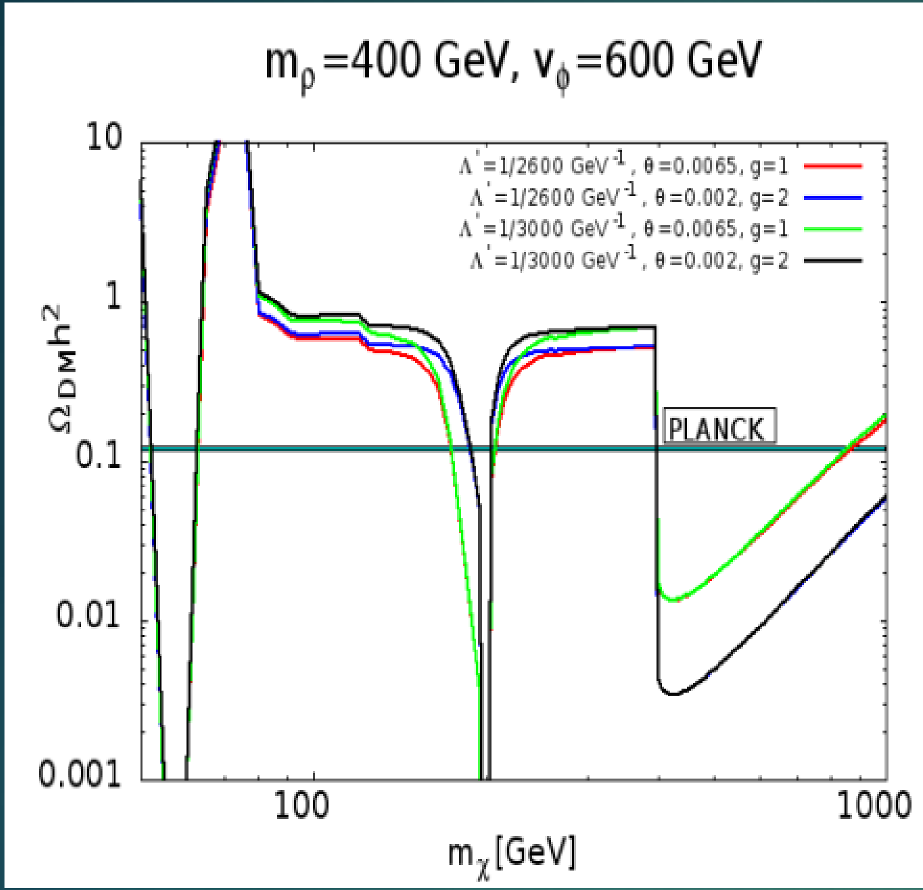
Direct Detection

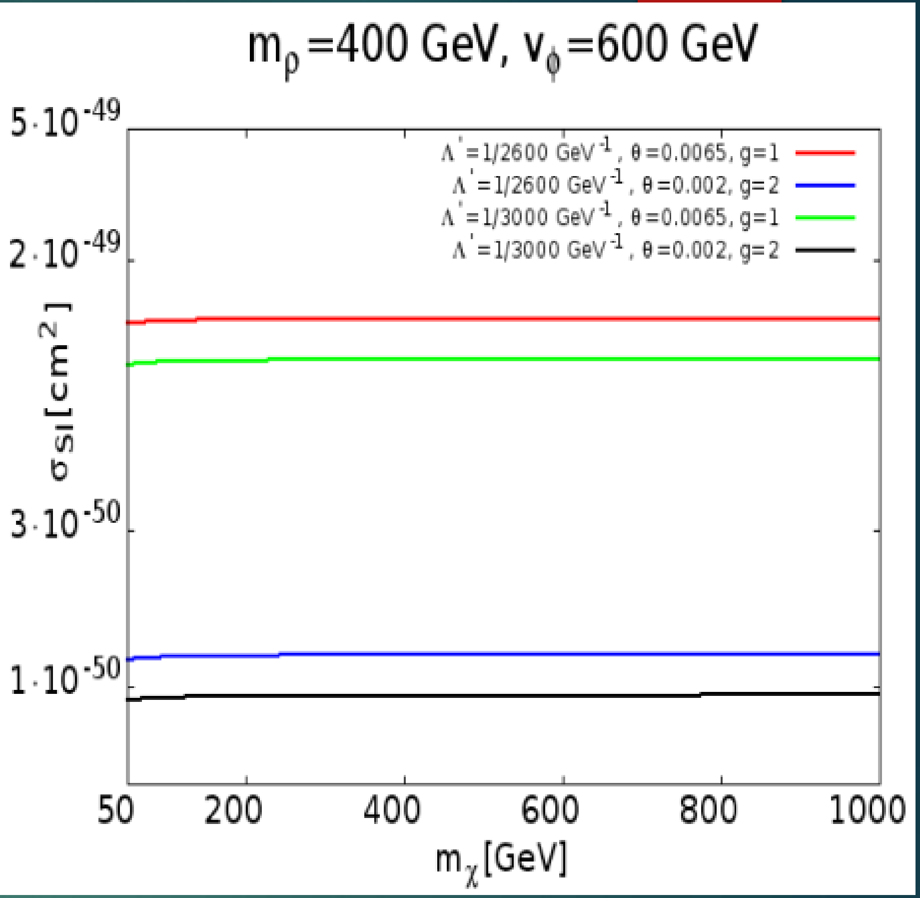
- Scattering of Dark Matter of a detector nucleus. At the quark level

$$\mathcal{L}_{\text{eff}} = \alpha_q \bar{\chi}\gamma^5\chi\bar{q}q + \alpha'_q\bar{\chi}\chi\bar{q}q$$

$$\sigma_{\text{SI}} \backsimeq \frac{v_H^2 \Lambda'^2}{4\pi} m_r^2 \sin^2\theta\cos^2\theta\left(\frac{1}{m_h^2} - \frac{1}{m_\rho^2}\right)^2 \lambda_p^2$$

$$\lambda_p = \frac{m_p}{v_H}\left[\sum_q f_q + \frac{2}{9}\left(1 - \sum_q f_q\right)\right] \simeq 1.3 \times 10^{-3}$$





BP	m_χ in GeV	v_ϕ in GeV	Λ' in GeV^{-1}	g	m_ρ in GeV	θ	$\Omega_{\rm DM}h^2$	$\sigma_{\rm SI}$ cm^2
1	101.5	600	$\frac{1}{2600}$	1	200	0.0065	0.1187	5.9258×10^{-50}
2	430	600	$\frac{1}{2600}$	1	200	0.0065	0.1183	6.0151×10^{-50}
3	565	600	$\frac{1}{2600}$	2	600	0.002	0.1195	1.4050×10^{-50}
4	307	600	$\frac{1}{2600}$	2	600	0.002	0.1187	1.4008×10^{-50}

Synchrotron Radiation Calculation

- Solve the standard time dependent diffusion equation

$$K(E)\nabla^2 n_e(E,\mathbf{r}) + \frac{\partial}{\partial E}\left[b(E,\mathbf{r})n_e(E,\mathbf{r})\right] + Q(E,\mathbf{r}) = 0$$

$$b(E,\mathbf{r}) = b_{\mathrm{synch}}(E,\mathbf{r}) + b_{\mathrm{IC}}(E,\mathbf{r}) + b_{\mathrm{brem}}(E,\mathbf{r})$$

$$b_{\mathrm{synch}}(E,\mathbf{r}) = \left.\frac{dE}{dt}\right|_{\mathrm{synch}} = \frac{4}{3}\sigma_T c U_{\mathrm{mag}}(\mathbf{r})\,\gamma^2\beta^2 = 3.4\times10^{-17}\mathrm{GeVs^{-1}}\left(\frac{\mathrm{E}}{\mathrm{GeV}}\right)^2\left(\frac{\mathrm{B}}{3\mu\mathrm{G}}\right)^2$$

$$b_{\mathrm{IC}}(E,\mathbf{r}) = \left.\frac{dE}{dt}\right|_{\mathrm{IC}} = \frac{2}{9}\frac{e^4 U_{\mathrm{rad}}(\mathbf{r})E^2}{\pi\epsilon_0^2 m_e^2 c^7} = 10^{-16}\mathrm{GeVs^{-1}}\left(\frac{\mathrm{E}}{\mathrm{GeV}}\right)^2\left(\frac{\mathrm{U_{rad}}(\mathbf{r})}{\mathrm{eVcm^{-3}}}\right)$$

$$b_{\rm brem}(E,\mathbf{r}) = \frac{dE}{dt}\Big|_{\rm brem} = 3\times 10^{-15}{\rm GeVs^{-1}}\left(\frac{\rm E}{\rm GeV}\right)\left(\frac{\rm n_H}{3\ {\rm cm^{-3}}}\right)$$

$$Q(E,\mathbf{r}) = \frac{1}{2}\left(\frac{\rho_\chi(\mathbf{r})}{m_\chi}\right)^2 \sum_f \langle\sigma v\rangle_f \frac{dN^f_{e^\pm}}{dE}$$

$$n_e(E,\mathbf{r}) = \frac{\int_E^{m_\chi} dE' Q(E',\mathbf{r})}{b(E,\mathbf{r})}$$

$$L_\nu(\mathbf{r}) = \int dE \mathcal{P}(\nu,E) n_e(E,\mathbf{r})$$

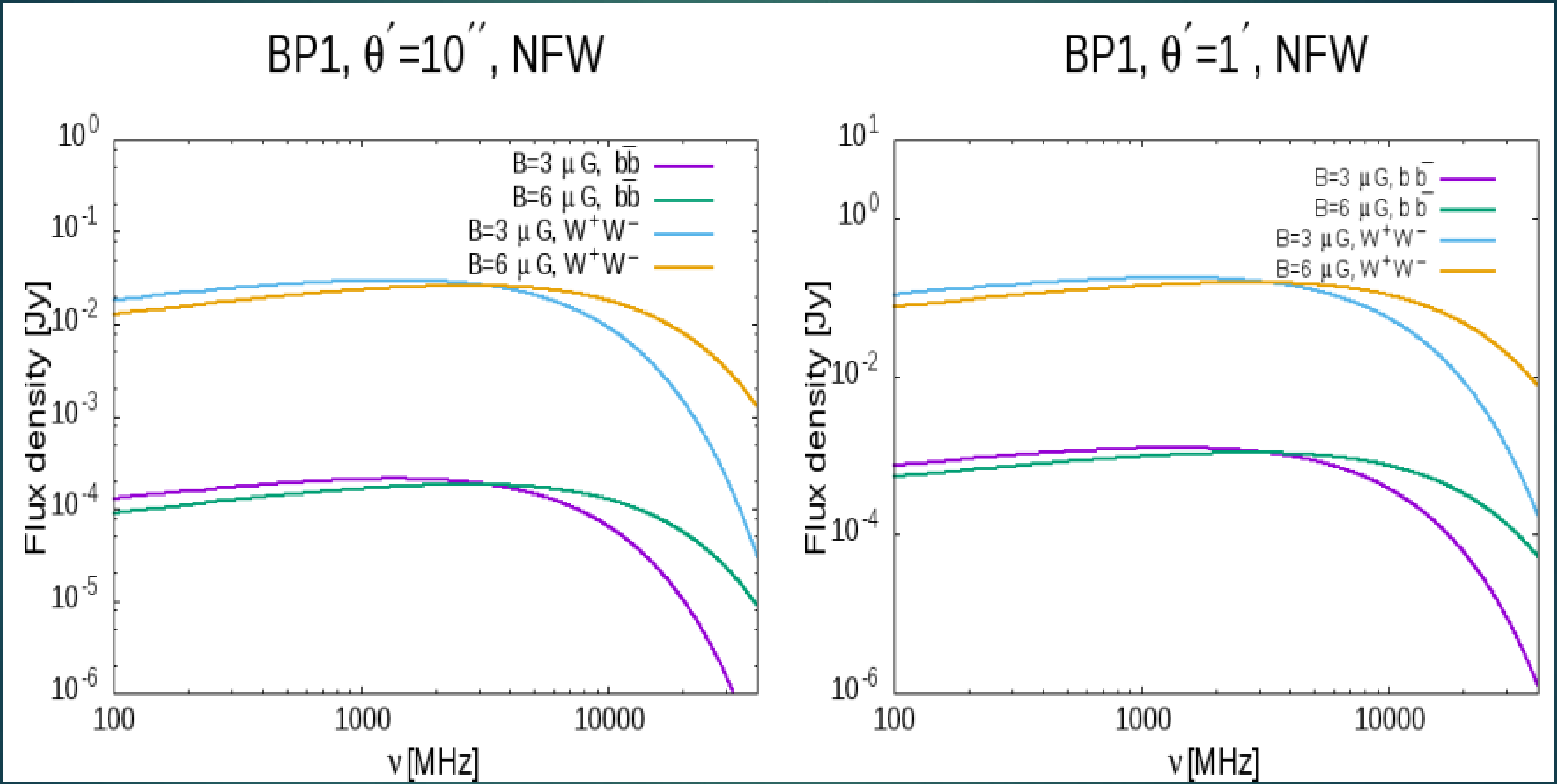
- Synchrotron Radiation flux density is given by

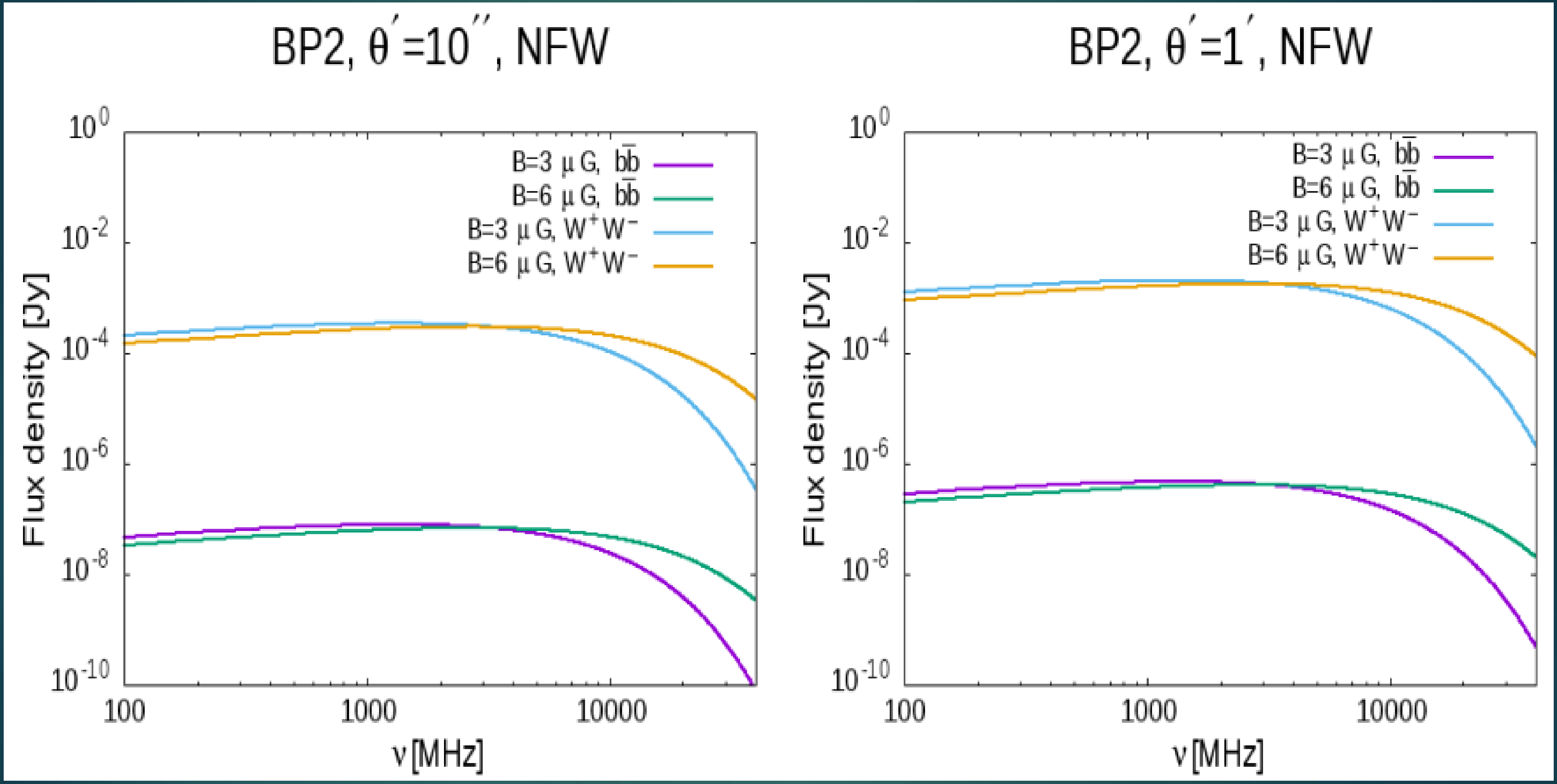
$$F_\nu = \frac{1}{4\pi}\int d\Omega \int_{\rm l.o.s} dl\, L_\nu(\mathbf{r})$$

The Detectors

- GMRT/uGMRT
  - Frequency Ranges 130-260 MHz, 250-500 MHz, 550-900 MHz, 1000-1450 MHz (Most Sensitive between 250-1000 MHz).
  - Flux density of the order of mJy (1 Jy=10^{-26} W/Hz/m^2/sr)
  - Opening Angle 10'-1"
- SKA
  - Frequency Range 70 MHz-10GHz
  - Flux Density Limit:-mJy to μJy
- Jodrell Bank
  - Opening Angle 4"
  - Frequency 408 MHz
  - Upper Bound on Radio Flux 15 mJy

Results


BP1, θ′=10′′, NFW
B=3 μ G, b$\bar{b}$
B=6 μ G, b$\bar{b}$
B=3 μ G, W$^+$W$^-$
B=6 μ G, W$^+$W$^-$
Flux density [Jy]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
100
1000
10000
ν [MHz]
BP1, θ′=1′, NFW
B=3 μ G, b $\bar{b}$
B=6 μ G, b $\bar{b}$
B=3 μ G, W$^+$W$^-$
B=6 μ G, W$^+$W$^-$
Flux density [Jy]
10^1
10^0
10^{-2}
10^{-4}
10^{-6}
100
1000
10000
ν [MHz]


BP2, θ′=10″, NFW
B=3 μ G, $b\bar{b}$
B=6 μ G, $b\bar{b}$
B=3 μ G, W^+W^-
B=6 μ G, W^+W^-
Flux density [Jy]
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
100
1000
10000
ν [MHz]
BP2, θ′=1′, NFW
B=3 μ G, $b\bar{b}$
B=6 μ G, $b\bar{b}$
B=3 μ G, W^+W^-
B=6 μ G, W^+W^-
Flux density [Jy]
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
100
1000
10000
ν [MHz]

B=3 μG, NFW density profile.

BP	m_χ in GeV	ν in MHz	θ'	observational limit GMRT in Jy	observational limit SKA in Jy	calculated flux density $\chi\bar{\chi} \rightarrow b\bar{b}$ in Jy	calculated flux density $\chi\bar{\chi} \rightarrow W^+W^-$ in Jy
1	101.5	325	10″	0.04×10^{-3}	10^{-6}-10^{-3}	1.7275×10^{-4}	2.4706×10^{-2}
		610		0.02×10^{-3}		1.9549×10^{-4}	2.7958×10^{-2}
		1400		0.03×10^{-3}		2.1021×10^{-4}	3.0064×10^{-2}
		325	1′	0.04×10^{-3}		1.0359×10^{-3}	1.4815×10^{-1}
		610		0.02×10^{-3}		1.1723×10^{-3}	1.6765×10^{-1}
		1400		0.03×10^{-3}		1.2606×10^{-3}	1.8028×10^{-1}
2	430	325	10″	0.04×10^{-3}	10^{-6}-10^{-3}	6.5159×10^{-8}	2.8442×10^{-4}
		610		0.02×10^{-3}		7.3736×10^{-8}	3.2186×10^{-4}
		1400		0.03×10^{-3}		7.9291×10^{-8}	3.4611×10^{-4}
		325	1′	0.04×10^{-3}		3.9073×10^{-7}	1.7056×10^{-3}
		610		0.02×10^{-3}		4.4217×10^{-7}	1.9301×10^{-3}
		1400		0.03×10^{-3}		4.7548×10^{-7}	2.0755×10^{-3}
3	565	325	10″	0.04×10^{-3}	10^{-6}-10^{-3}	2.3737×10^{-8}	1.7479×10^{-4}
		610		0.02×10^{-3}		2.6862×10^{-8}	1.9780×10^{-4}
		14000		$.03\times10^{-3}$		2.8885×10^{-8}	2.1270×10^{-4}
		325	1′	0.04×10^{-3}		1.4234×10^{-7}	1.0482×10^{-3}
		610		0.02×10^{-3}		1.6108×10^{-7}	1.1861×10^{-3}
		1400		0.03×10^{-3}		1.7322×10^{-7}	1.2755×10^{-3}
4	307	325	10″	0.04×10^{-3}	10^{-6}-10^{-3}	8.3656×10^{-7}	1.7722×10^{-3}
		610		0.02×10^{-3}		9.4668×10^{-7}	2.0055×10^{-3}
		1400		0.03×10^{-3}		1.0180×10^{-6}	2.1566×10^{-3}
		325	1′	0.04×10^{-3}		5.0165×10^{-6}	1.0627×10^{-2}
		610		0.02×10^{-3}		5.6769×10^{-6}	1.2026×10^{-2}
		1400		0.03×10^{-3}		6.1045×10^{-6}	1.2932×10^{-2}

B=3 μG, NFW density profile.

BP	m_χ in GeV	ν in MHz	θ'	observational limit Jodrell Bank in Jy	calculated flux density $\chi\bar{\chi} \to b\bar{b}$ in Jy	calculated flux density $\chi\bar{\chi} \to W^+W^-$ in Jy
1	101.5	408	4″	50×10^{-3}	5.3718×10^{-5}	7.6826×10^{-3}
2	430				2.0262×10^{-8}	8.8450×10^{-4}
3	565				7.3814×10^{-9}	5.4353×10^{-5}
4	307				2.6014×10^{-7}	5.5109×10^{-4}

THANK YOU