SRM UNIVERSITY AP
Andhra Pradesh

From Big Bang to Now: A Theory-Experiment Dialogue

Implications of Sgr A^* on γ-ray searches of Bino Dark Matter

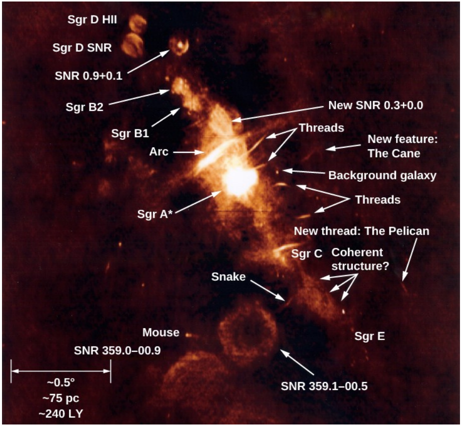
Rahul Puri
(rahul.puri@iopb.res.in)

IOP, Bhubaneswar & HBNI, Mumbai

08 November, 2024

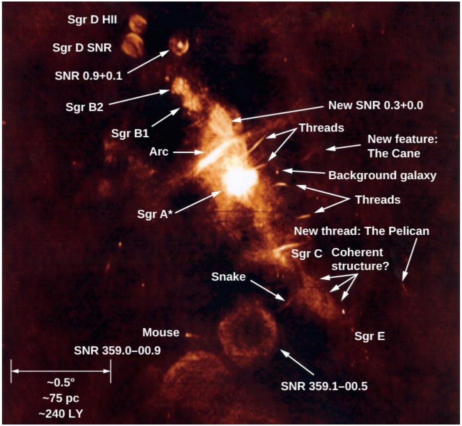
Introduction

Supermassive Black Hole at the Milky Way's galactic center, Sgr A*



Introduction

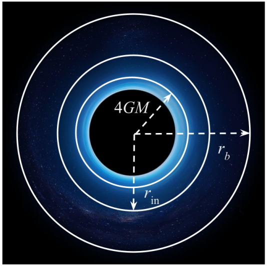
Supermassive Black Hole at the Milky Way's galactic center, Sgr A*



- SMBHs can create high **DM density spike** in their gravitational influence region.
- This spike **enhances DM annihilation rate**, boosting detectable signals like gamma rays.
- **Faint DM candidates** can be probed in regions around SMBHs.
- Observation data of our Milky Way's SMBH, **Sgr A*, might be hiding DM signals**.

Next: DM density around SMBH.

DM Density Spike around an SMBH [astro-ph/0101481]



- **Outside the Gravitational Influence Region of SMBH**

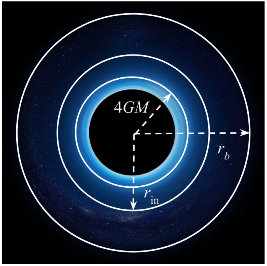
$$r > r_b$$

The DM density follows the general halo profile. The NFW profile can be approximated by simple power law.

$$\rho(r) =$$

$$\rho_{\text{NFW}}(r) \approx \rho_b \cdot \left(\frac{r_b}{r}\right)^{\gamma_c}$$

DM Density Spike around an SMBH [astro-ph/0101481]



- Outside the Gravitational Influence Region of SMBH
- **The Spike Region**

$$r_{\text{in}} < r \leq r_b$$

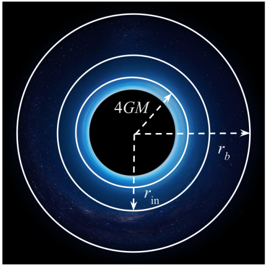
The profile starts to increase steeply with a power law with power index γ_{sp}.

$$\rho(r) =$$

$$\rho_{\text{NFW}}(r) \approx \rho_b \cdot \left(\frac{r_b}{r}\right)^{\gamma_c}$$

$$\rho_{\text{sp}}(r) \equiv \rho_b \cdot \left(\frac{r_b}{r}\right)^{\gamma_{\text{sp}}}$$

DM Density Spike around an SMBH [astro-ph/0101481]



- Outside the Gravitational Influence Region of SMBH
- The Spike Region
- **The Annihilation Plateau**

$$4GM < r \leq r_{\text{in}}$$

The spike ceases to rise further due to large annihilation rates.

$$\rho(r) =$$

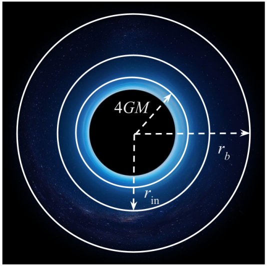
$$\rho_{\text{NFW}}(r) \approx \rho_b \cdot \left(\frac{r_b}{r}\right)^{\gamma_c}$$

$$\rho_{\text{sp}}(r) \equiv \rho_b \cdot \left(\frac{r_b}{r}\right)^{\gamma_{\text{sp}}}$$

$$\rho_{\text{in}}(r) \equiv \rho_{\text{ann}} \cdot \left(\frac{r_{\text{in}}}{r}\right)^{\gamma_{\text{in}}}$$

$$\rho_{\text{ann}} \equiv \frac{m_{\tilde{\chi}_1^0}}{\langle \sigma v \rangle \tau}$$

DM Density Spike around an SMBH [astro-ph/0101481]



- Outside the Gravitational Influence Region of SMBH
- The Spike Region
- The Annihilation Plateau
- **Inside Marginally Bound Orbits**

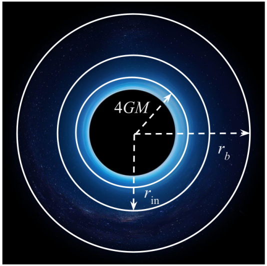
$$r \leq 4GM$$

DM is effectively captured by the SMBH resulting in no DM in the region.

$$\rho(r) =$$

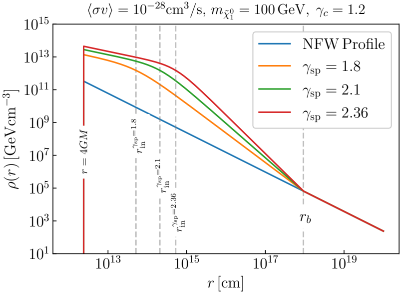
$\rho_{\rm NFW}(r) \approx \rho_b \cdot \left(\frac{r_b}{r}\right)^{\gamma_c}$	$\rho_{\rm sp}(r) \equiv \rho_b \cdot \left(\frac{r_b}{r}\right)^{\gamma_{\rm sp}}$	$\rho_{\rm in}(r) \equiv \rho_{\rm ann} \cdot \left(\frac{r_{\rm in}}{r}\right)^{\gamma_{\rm in}}$ $\rho_{\rm ann} \equiv \frac{m_{\tilde{\chi}_1^0}}{\langle\sigma v\rangle\tau}$	0

DM Density Spike around an SMBH [astro-ph/0101481]



- Outside the Gravitational Influence Region of SMBH
- The Spike Region
- The Annihilation Plateau
- Inside Marginally Bound Orbits

$$\rho(r) = \begin{cases} 0 & (r < 4GM), \\ \dfrac{\rho_{\rm sp}(r)\rho_{\rm in}(r)}{\rho_{\rm sp}(r) + \rho_{\rm in}(r)} & (4GM \leq r \leq r_b), \\ \rho_b \left(\dfrac{r_b}{r}\right)^{\gamma_c} & (r_b < r \leq r_\odot), \end{cases}$$



Next: DM Indirect Detection.

DM Indirect Detection

Master formula for photon flux:

$$\underbrace{\frac{d\Phi}{dE_\gamma}}_{\substack{\text{Differential}\\ \text{photon flux}\\ \text{at earth}}} = \frac{\overbrace{\langle \sigma_{\rm ann} v \rangle}^{\substack{\text{Annihilation}\\ \text{cross-section}}}}{8\pi m_\chi^2} \frac{dN}{dE_\gamma} \underbrace{\int_{\Delta\Omega} d\Omega \int_{\rm LOS} \boldsymbol{\rho_\chi^2(r)} ds}_{J-\text{factor}}$$

Next: The MSSM.

The Minimal Supersymmetric Standard Model (MSSM)

- MSSM Lagrangian:

$$\begin{aligned}
\mathcal{L}_{\text{MSSM}} &= \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{Soft}} \\
\mathcal{L}_{\text{Soft}} &= -\frac{1}{2}\left(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B} + \text{c.c.}\right) \\
&\quad - \left(\tilde{\bar{u}}\mathbf{a_u}\tilde{Q}H_u - \tilde{\bar{d}}\mathbf{a_d}\tilde{Q}H_d - \tilde{\bar{e}}\mathbf{a_e}\tilde{L}H_d + \text{c.c.}\right) \\
&\quad - \tilde{Q}^\dagger\mathbf{m^2_Q}\tilde{Q} - \tilde{L}^\dagger\mathbf{m^2_L}\tilde{L} - \tilde{\bar{u}}\mathbf{m^2_{\bar{u}}}\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\mathbf{m^2_{\bar{d}}}\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\mathbf{m^2_{\bar{e}}}\tilde{\bar{e}}^\dagger \\
&\quad - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - B_\mu(H_uH_d + \text{h.c.}) \\
\mathcal{W}_{\text{MSSM}} &= \bar{u}y_uQH_u - \bar{d}y_dQH_d - \bar{e}y_eLH_d + \mu H_uH_d
\end{aligned}$$

- Neutral Electroweak Sector $\left[\tilde{B}, \tilde{W}, \tilde{H}_u, \tilde{H}_d\right]$

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu & 0 \end{pmatrix}$$

$$\tilde{\chi}^0_1 = N_{11}\tilde{B} + N_{12}\tilde{W}^0 + N_{13}\tilde{H}^0_u + N_{14}\tilde{H}^0_d$$

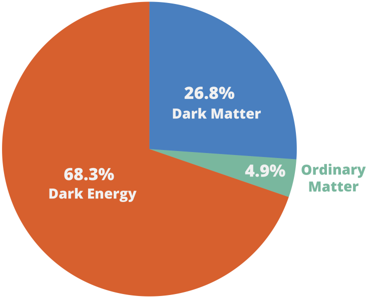
- Bino LSP Scenerio:

$$N_{11} \gg N_{1i} \quad \Rightarrow \quad \tilde{\chi}^0_1 \sim \tilde{B}$$

Why Bino?

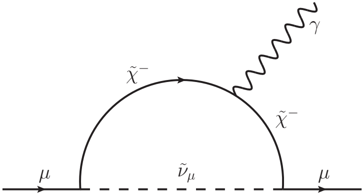
Why Bino?

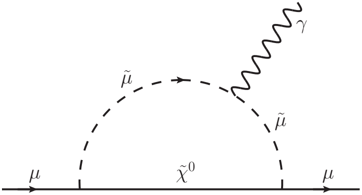
- **It can account for observed DM relic abundance.**



Why Bino?

- It can account for observed DM relic abundance.
- **It can explain $(g-2)_\mu$ discrepancy between SM and experiments.**



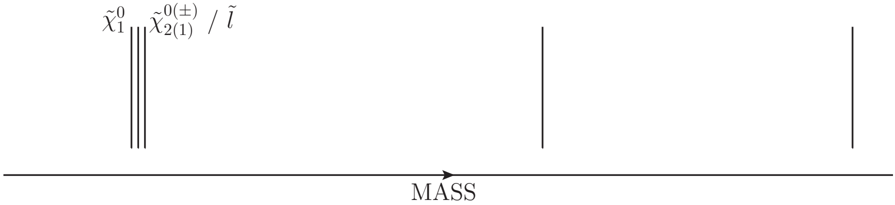


Why Bino?

- It can account for observed DM relic abundance.
- It can explain $(g-2)_\mu$ discrepancy between SM and experiments.

However, it's detection is challenging, as it:

- **Can evade LHC constraints (for compressed spectra).**

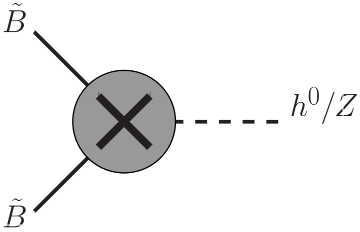


Why Bino?

- It can account for observed DM relic abundance.
- It can explain $(g-2)_\mu$ discrepancy between SM and experiments.

However, it's detection is challenging, as it:

- Can evade LHC constraints (for compressed spectra).
- **Can evade direct detection due to absent gauge/higgs couplings.**

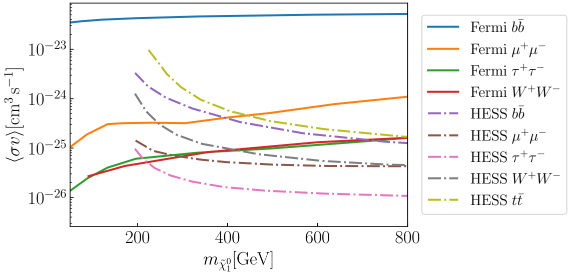


Why Bino?

- It can account for observed DM relic abundance.
- It can explain $(g-2)_\mu$ discrepancy between SM and experiments.

However, it's detection is challenging, as it:

- Can evade LHC constraints (for compressed spectra).
- Can evade direct detection due to absent gauge/higgs couplings.
- **Cannot be probed by conventional indirect searches due to small annihilation cross-section.**



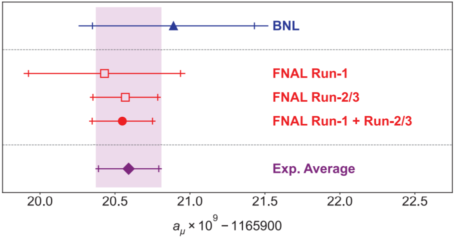
$$\langle\sigma v\rangle \lesssim \mathcal{O}(10^{-27})\,\mathrm{cm^3/s}$$

Next: Discrepency in $(g-2)_\mu$

The discrepency in $(g-2)_\mu$

$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

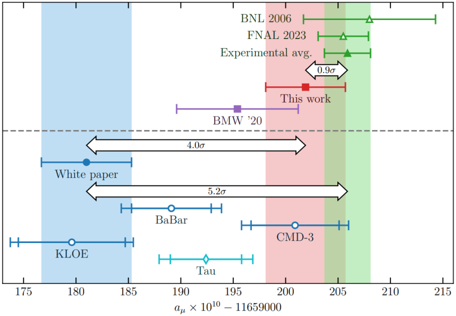
Experiments:



World Average PRL.131.161802:

$$a_\mu^{\text{exp}} = 116592059(22) \times 10^{-11}$$

Standard Model Predictions (arXiv:2407.10913):



The deficit in the SM value of $(g-2)_\mu$ from the observed value indicates BSM contribution.

$$a_\mu^{\text{BSM}} = a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$$

Next: The Benchmarks.

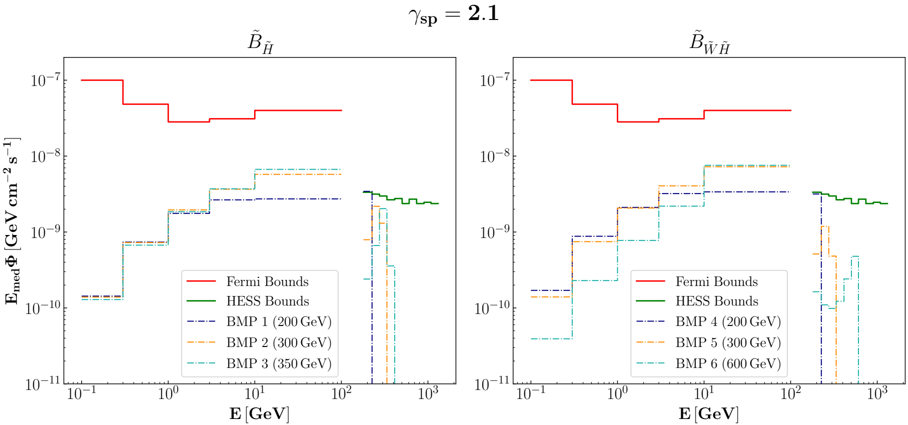
Benchmarks

Benchmarks:

	$\tilde{B}_{\tilde{H}}$			$\tilde{B}_{\tilde{W}\tilde{H}}$		
	BMP 1	BMP 2	BMP 3	BMP 4	BMP 5	BMP 6
M_1 [GeV]	200	300	350	200	300	600
M_2 [GeV]	1500	1500	1500	230	302	582
μ [GeV]	810	800	800	810	900	1200
$\tan\beta$	16	47	45	16	25	55
$m^{\rm in}_{\tilde{e}_L}, m^{\rm in}_{\tilde{e}_R}$ [GeV]	221	335	379	221	350	624
$m^{\rm in}_{\tilde{\mu}_L}, m^{\rm in}_{\tilde{\mu}_R}$ [GeV]	225	340	381	225	357	635
m_A [GeV]	3000	4000	4000	3000	4000	4200
$m_{\tilde{\chi}_1^0}$ [GeV]	199.4	300.3	350.5	199.4	300.4	603.5
$\Omega_{\rm DM}h^2$	0.119	0.122	0.121	0.121	0.119	0.118
$a_\mu^{\rm SUSY}$ $\times 10^9$	1.77	2.14	1.59	2.82	1.94	1.51

Benchmarks

Benchmark photon flux plots:

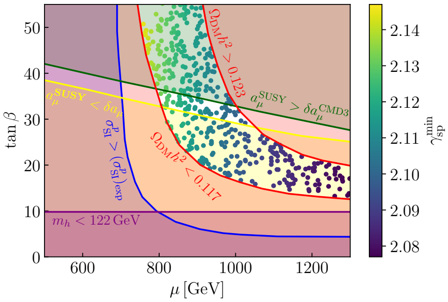


Next: The param. dependence.

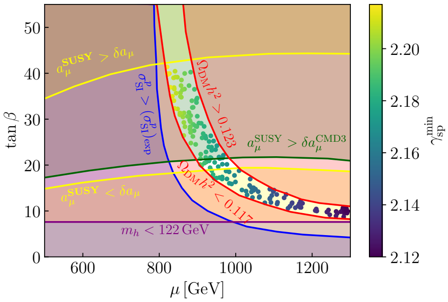
Parametric Dependence of BMPs.

μ and $\tan\beta$ dependence.

BMP-2 $\left(\tilde{B}_{\tilde{H}}\right)$



BMP-5 $\left(\tilde{B}_{\tilde{W}\tilde{H}}\right)$



Next: The Scans.

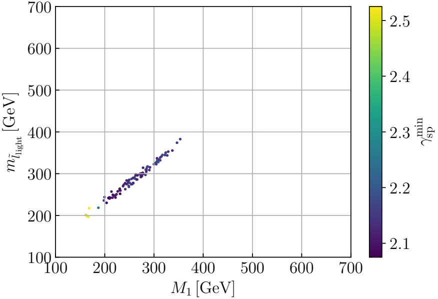
Random Scan of the Parameter Space

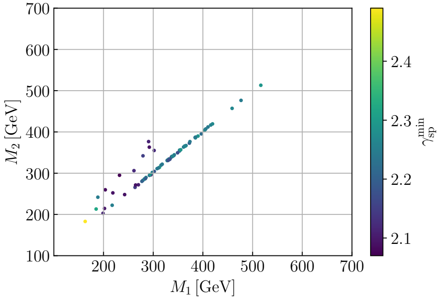
$\tilde{B}_{\tilde{H}}$

$$\begin{array}{rcccl} 100\,\text{GeV} & \leq & M_1 & \leq & 700\,\text{GeV}, \\ & & M_2 & = & 1.5\,\text{TeV} \\ 2.0\,\text{TeV} & \leq & M_A & \leq & 4.5\,\text{TeV}, \\ 500\,\text{GeV} & \leq & \mu & \leq & 1500\,\text{GeV}, \\ 100\,\text{GeV} & \leq & m_{\tilde{l}_{L,R}} & \leq & 1\,\text{TeV}, \\ 5 & \leq & \tan\beta & \leq & 55. \end{array}$$

$\tilde{B}_{\tilde{W}\tilde{H}}$

$$\begin{array}{rcccl} 100\,\text{GeV} & \leq & M_1 & \leq & 700\,\text{GeV}, \\ 100\,\text{GeV} & \leq & M_2 & \leq & 1\,\text{TeV}, \\ 2.0\,\text{TeV} & \leq & M_A & \leq & 4.5\,\text{TeV}, \\ 500\,\text{GeV} & \leq & \mu & \leq & 2.0\,\text{TeV}, \\ 100\,\text{GeV} & \leq & m_{\tilde{l}_{L,R}} & \leq & 1\,\text{TeV}. \\ 5 & \leq & \tan\beta & \leq & 55, \end{array}$$





Conclusion

- Supermassive black holes (SMBHs) may host a significant concentration of dark matter within their gravitational influence, though this remains an area of active research.
- Within the Minimal Supersymmetric Standard Model (MSSM), a Bino-like neutralino forming compressed spectra with sleptons, heavier neutralinos, and/or charginos presents a viable dark matter candidate.
- Such a scenerio also evades the experimental constraints in various regions of the parameter space successfully.
- This scenario could also provide a complementary explanation for the observed value of the muon's anomalous magnetic moment, $(g-2)_\mu$.
- If dark matter signals remain elusive in indirect detection efforts, the potential enhancement of dark matter density around SMBHs could serve as a probe to either constrain or validate the viability of such dark matter candidates.
- Conversely, if DM is detected first, the slope of the density spike, $\gamma_{\rm sp}$, could also be constrained based on the findings.

Outlook of the Paper (arXiv:2407.14603) accepted in JCAP.

Implications of Sgr A* on the γ-rays searches of Bino Dark Matter with $(g-2)_\mu$

Utpal Chattopadhyay,[1,*] Debottam Das,[2,3,†] Sujoy Poddar,[4,‡] Rahul Puri,[2,3,§] and Abhijit Kumar Saha[2,3,¶]

[1] *School of Physical Sciences, Indian Association for the Cultivation of Science, Jadavpur, Kolkata 700032, India*

[2] *Institute of Physics, Sachivalaya Marg, Bhubaneswar, 751005, India*

[3] *Homi Bhabha National Institute, Training School Complex, Anushakti Nagar, Mumbai 400094, India*

[4] *Department of Physics, Diamond Harbour Women's University, Diamond Harbour Road, Sarisha, South 24 Parganas, West Bengal — 743368, India*

Abstract: We analyse the impact of dark matter density spike around the Milky Way's supermassive black hole (SMBH), Sgr A*, in probing the Bino-dominated neutralino dark matter (DM) $\tilde{\chi}_1^0$ within the MSSM, which typically produces relatively faint signals in the conventional DM halos. In particular, we explore the indirect search prospects of sub-TeV Bino-Higgsino and Bino-Wino-Higgsino DM in the MSSM, consistent with the supersymmetric predictions required to explain the anomalous magnetic moment of the muon. Typical over-abundance of Bino DM is ameliorated with slepton and/or Wino coannihilations. The lightest neutralino, thus may be associated with a compressed supersymmetric particle spectrum, which, in general, is difficult to probe at conventional LHC searches. Similarly, for a rather tiny Higgsino mixing, $\tilde{\chi}_1^0$ does not offer much prospect to assess its predictions at dark matter direct detection searches. Accommodating the inclusive effects of density spike, here, we present the requisite boost factor to facilitate $\gamma-$ray searches of Bino-dominated DM in the MSSM, especially focusing on the Fermi-LAT and HESS observations.

Thank you!