



Forbidden Dark Matter Combusted around Supermassive Black Holes

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Yu Cheng, SFG, Xiao-Gang He, Jie Sheng [2211.xxxxx]



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李政道研究所
Tsung-Dao Lee Institute

- **Cosmic Ray Boosted DM & Diurnal Modulation**

SFG, Jianglai Liu, Qiang Yuan, Ning Zhou [Phys.Rev.Lett. 126 (2021) 9, 091804]

PandaX-II + **SFG**, Qiang Yuan [Phys.Rev.Lett. 128 (2022) 17, 171801]

- **Fermionic Absorption DM**

SFG, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [JHEP 05 (2022) 191]

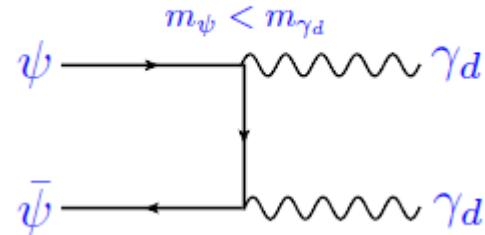
PandaX + **SFG**, Xiao-Gang He, Xiao-Dong Ma, Jie Sheng [Phys.Rev.Lett. 129 (2022) 16, 161804]

- **Forbidden DM**

Yu Cheng, **SFG**, Xiao-Gang He, Jie Sheng [2211.xxxxx]

Forbidden DM

1) forbidden annihilations:

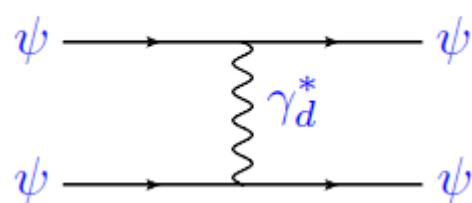


$$\langle \sigma_{\gamma_d \gamma_d} v \rangle \sim \alpha_d^2 / m_{\gamma_d}^2$$



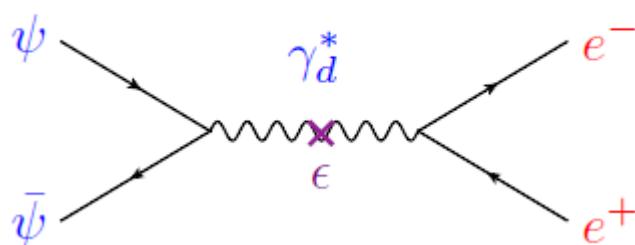
$$\langle \sigma_{\chi \bar{\chi}} v \rangle = \frac{(n_{\gamma_d}^{eq})^2}{(n_\psi^{eq})^2} \langle \sigma_{\gamma_d \gamma_d} v \rangle \approx 8\pi f_\Delta \frac{\alpha_d^2}{m_\psi^2} e^{-2\Delta x}$$

2) self-interactions:

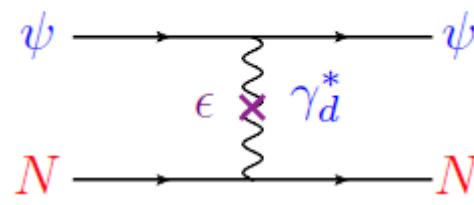


- Naturally includes large self-interactions.
- An exponentially larger cross section than the forbidden annihilation rate.

3) indirect detection:



4) direct detection:



- Signal suppressed by

D'Agnolo & Ruderman, Phys.Rev.Lett. 115 (2015) 6, 061301 [1505.07107]

How to test Forbidden DM?

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PHYSICAL REVIEW D

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Three exceptions in the calculation of relic abundances

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(Received 15 November 1990)

The calculation of relic abundances of elementary particles by following their annihilation and freeze-out in the early Universe has become an important and standard tool in discussing particle dark-matter candidates. We find three situations, all occurring in the literature, in which the standard methods of calculating relic abundances fail. The first situation occurs when another particle lies near in mass to the relic particle and shares a quantum number with it. An example is a light squark with neutralino dark matter. The additional particle must be included in the reaction network, since its annihilation can control the relic abundance. The second situation occurs when the relic particle lies near a mass threshold. Previously, annihilation into particles heavier than the relic particle was considered kinematically forbidden, but we show that if the mass difference is $\sim 5-15\%$, these “forbidden” channels can dominate the cross section and determine the relic abundance. The third situation occurs when the annihilation takes place near a pole in the cross section. Proper treatment of the thermal averaging and the annihilation after freeze-out shows that the dip in relic abundance caused by a pole is not nearly as sharp or deep as previously thought.

Coannihilation

Forbidden DM

Breit-Wigner

How to test Forbidden DM?

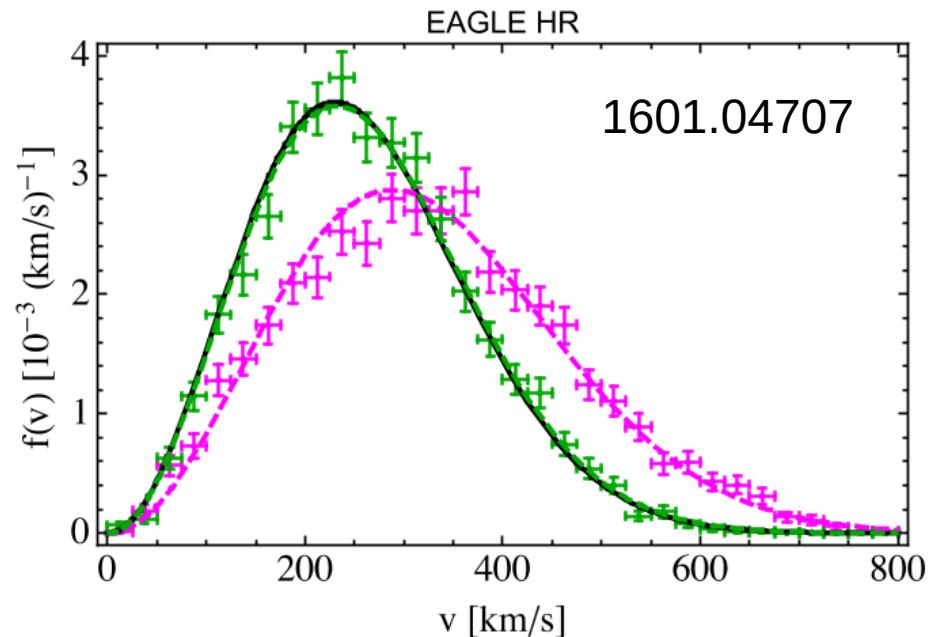
- Boltzmann Distribution

$$\Delta_{F\chi} \equiv \frac{m_F - m_\chi}{m_\chi} \sim 1\%$$



$$v_d \sim 10\%$$

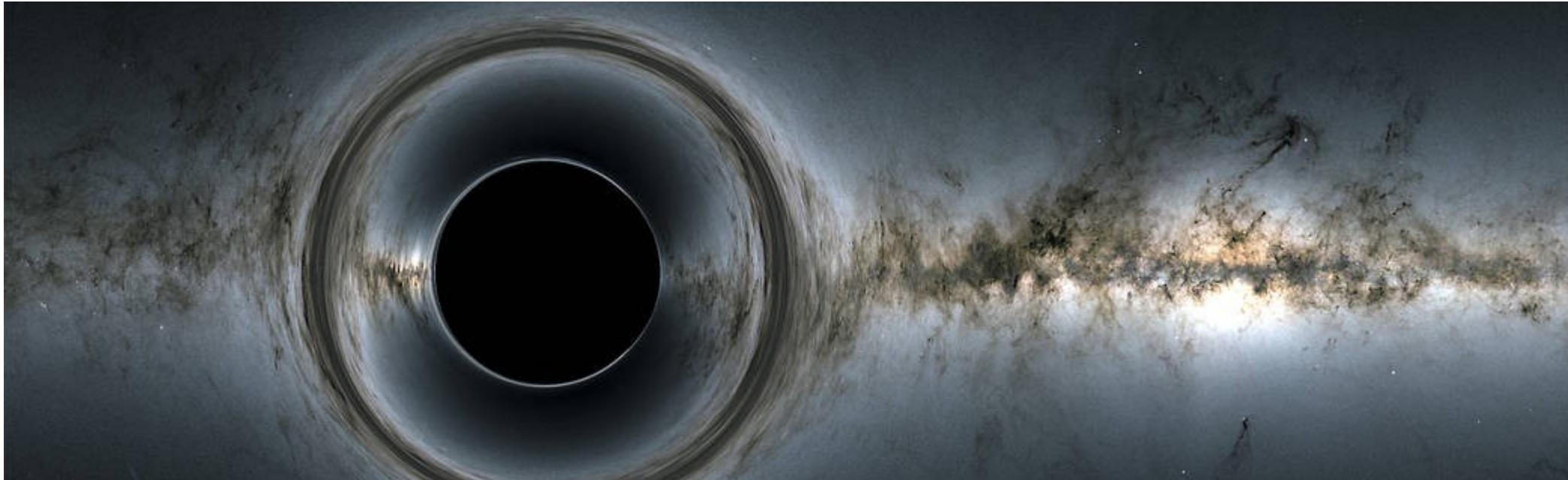
$$f_0(v) = \frac{\rho_\chi}{m_\chi} \frac{4}{\sqrt{\pi}} \frac{v^2}{(\sqrt{2/3}v_d)^3} e^{-\frac{v^2}{(\sqrt{2/3}v_d)^2}}$$



- Juttner Distribution

$$f_J(\mathbf{p}) = \frac{1}{4\pi T m_\chi^2 K_2(x)} e^{-\frac{\sqrt{|\mathbf{p}|^2 + m_\chi^2}}{T}} \quad x \equiv m_\chi/T$$

Velocity Scaling @ Black Holes



$$v^2 \sim \frac{GM}{r} \quad \rightarrow \quad v(r) \sim \frac{1}{\sqrt{r}}$$

$$\rho \propto r^?$$

Core: Isothermal Gas

➤ NFW Profile

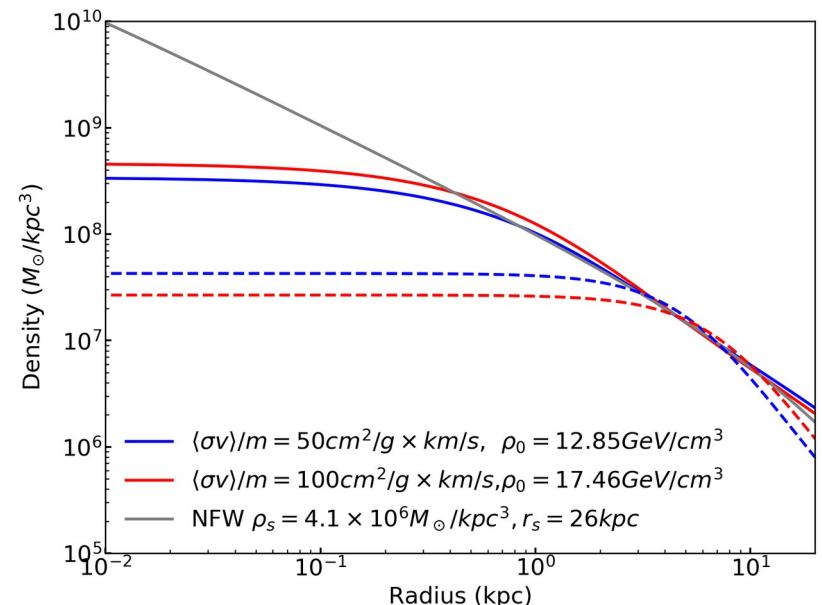
$$\rho(r) = \begin{cases} \rho_{\text{iso}}(r), & r < r_1 \\ \rho_{\text{NFW}}(r), & r > r_1 \end{cases}$$

$$\rho_{\text{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

➤ Jeans equation

$$\frac{d}{dr} \left(r^2 \frac{d \ln \rho}{dr} \right) = - \frac{4\pi G r^2 (\rho + \rho_b)}{\sigma_0^2}$$

1. Isothermal gas: constant velocity dispersion σ_0
2. Mass contained inside core the same
3. Continuity



Kaplinghat, Keeley, Linden & H. B. Yu, Phys. Rev. Lett. 113, 021302 (2014) [arXiv:1311.6524]

Kaplinghat, Tulin & H. B. Yu, Phys. Rev. Lett. 116, no.4, 041302 (2016) [arXiv:1508.03339]

Spike: Conductive Fluid

➤ Inner region more influenced by BH potential

$$\rho(r) = \begin{cases} \rho_{\text{NFW}}(r), & r > r_1, \\ \rho_{\text{iso}}(r), & r_0 < r < r_1 \\ \rho_{\text{spike}}(r), & r < r_0. \end{cases}$$

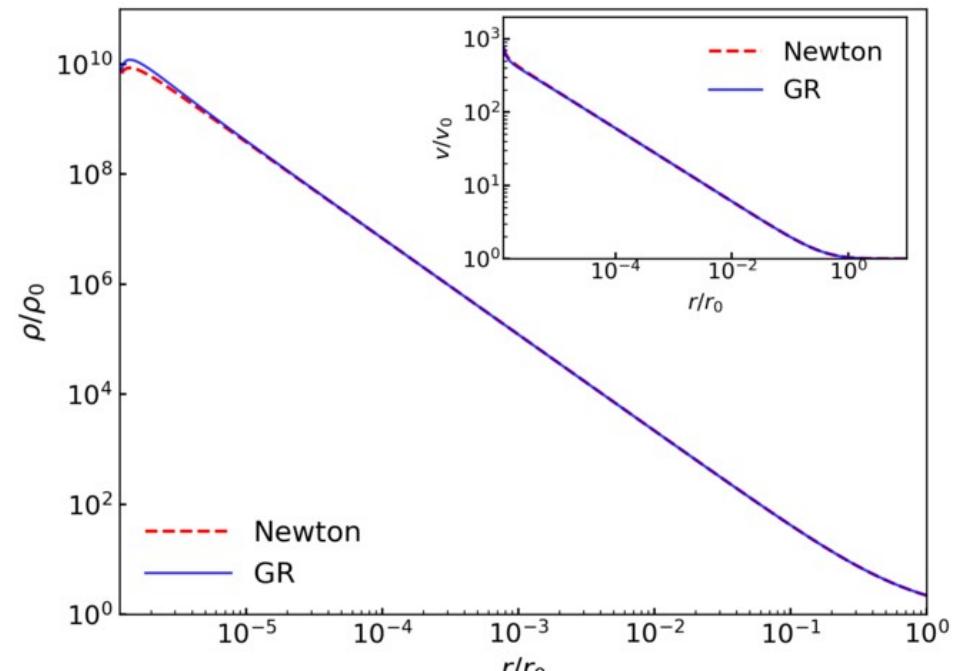
$$r_0 \equiv GM/v_0^2$$

➤ Conductive fluid

$$\frac{dv}{dr} = \frac{D}{v^{2-a}\rho^2 r^4}$$

$$\frac{d\rho}{dr} = -\frac{\rho}{v^2 r^2} - \frac{2D}{v^{3-a}\rho r^4}$$

$$\rho = 0, \quad r = r_{in} \equiv 4GM$$



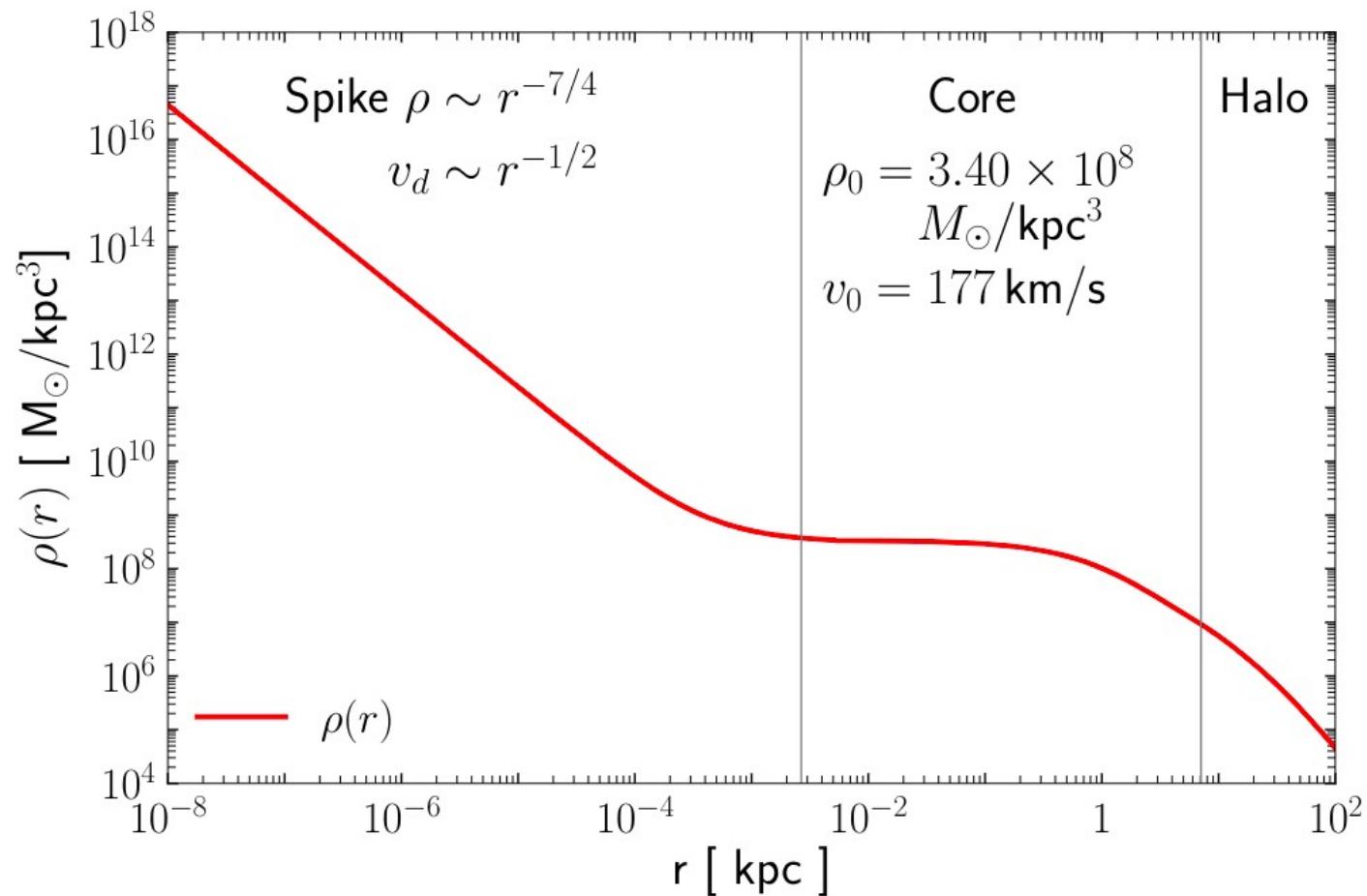
$$v_d \propto r^{-1/2} \quad \rho \propto r^{-(3+a)/4}$$

$$\sigma = \sigma_0 (v_d/v_0)^a$$

Shapiro & Paschalidis, Phys. Rev. D 89, no.2, 023506 (2014) [arXiv:1402.0005]

DM Profiles

$$\rho(r) = \begin{cases} \rho_{\text{NFW}}(r), & r > r_1, \\ \rho_{\text{iso}}(r), & r_0 < r < r_1 \\ \rho_{\text{spike}}(r), & r < r_0. \end{cases}$$



Gamma Fluxes

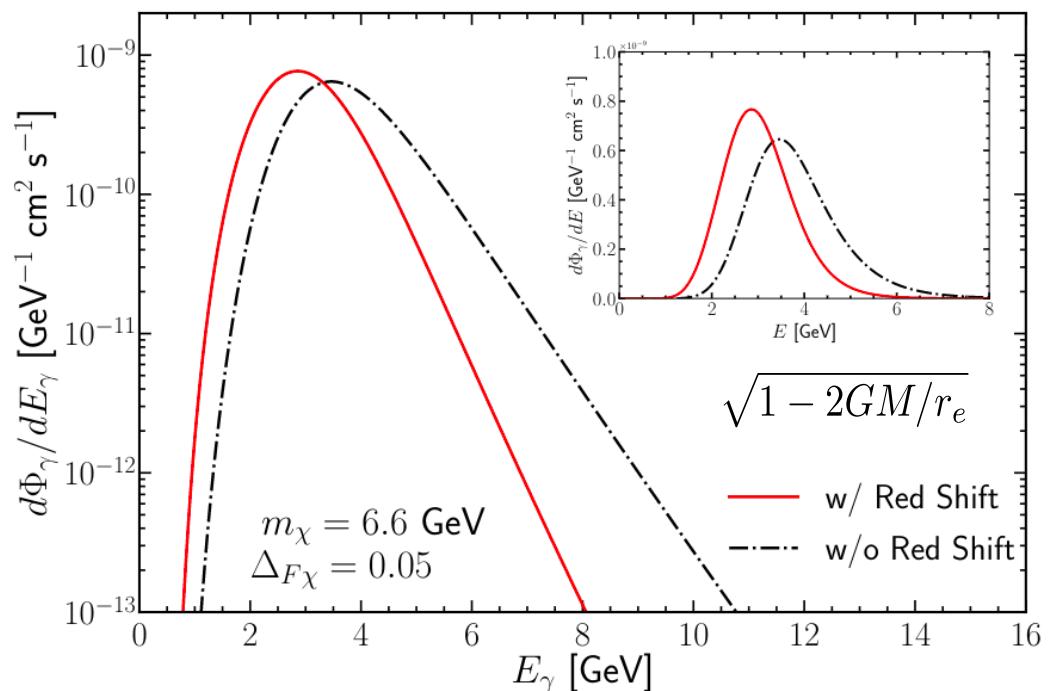
$$\mathcal{L}_{\text{DM}} = g_\chi \bar{\chi} \gamma^\mu \chi \phi_\mu + g_F \bar{\chi} \gamma^\mu F \phi_\mu$$

➤ Forbidden channel

$$\chi \bar{\chi} \rightarrow F \bar{F} \quad m_\chi \lesssim m_F$$

$$\frac{d\sigma}{d\Omega} \approx \sqrt{\frac{s - 4m_F^2}{s - 4m_\chi^2}} \frac{4m_F^2 + 4m_\chi^2 + s}{64\pi^2(s - m_\phi^2)^2}$$

Isotropic in the C.O.M. frame



➤ Signal channel

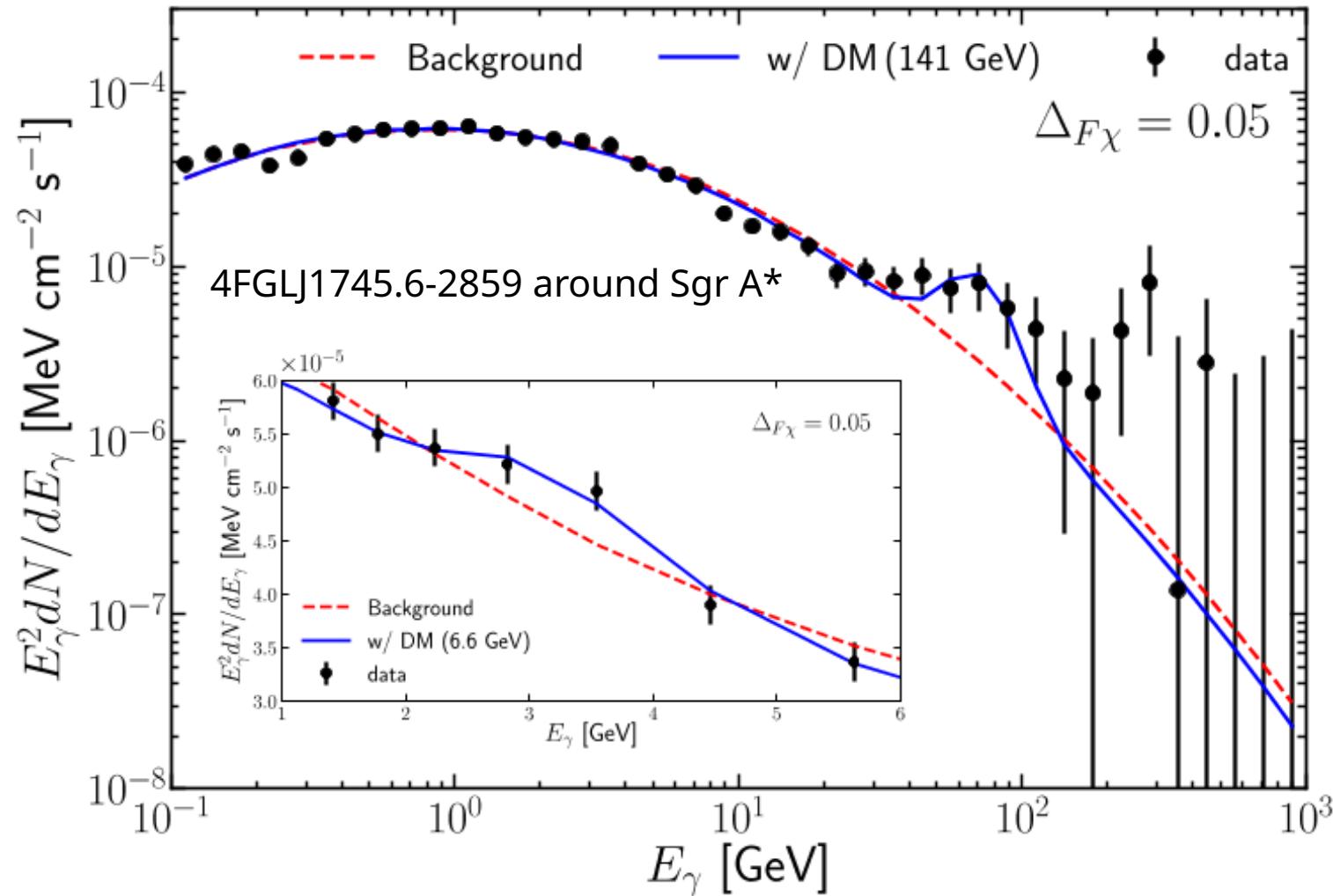
$$F \rightarrow \nu \gamma$$

Box-shaped spectrum in C.O.M.

$$\frac{dF_\gamma}{dE_\gamma}(r) = \int_0^1 dV_r dV_c \mathcal{P}_r(V_r, V_c) \sigma V_r \frac{dN_\gamma}{dE_\gamma}(V_r, V_c)$$

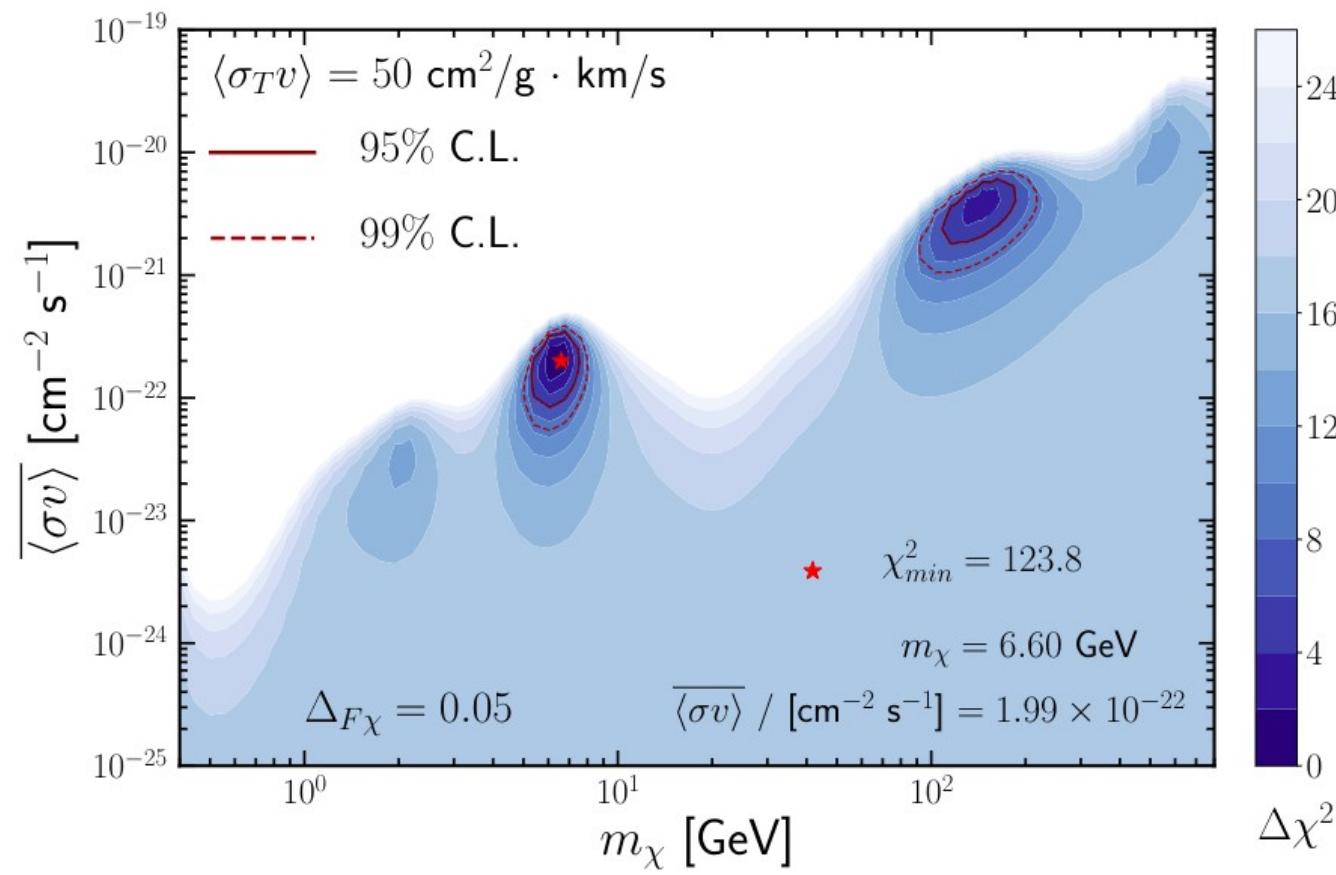
$$\mathcal{P}_r(V_r, V_c) \equiv \frac{x^2}{K_2^2(x)} \frac{\gamma_r^3(\gamma_r^2 - 1)V_c^2}{(1 - V_c^2)^2} e^{-x\sqrt{(2+2\gamma_r)/(1-V_c^2)}}$$

Fitting the Fermi-LAT data



Background Model:
$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0} \right)^{-\alpha-\beta \log(E/E_0)}$$

Sensitivity Plots



- Bkg-only hypothesis

$$\chi^2_{\text{BKG}} = 140.8$$

- 1st Peak @ 6.6GeV

$$\overline{\langle\sigma v\rangle} = 1.99 \times 10^{-22} \text{ cm}^3 \text{ s}^{-1}$$

- 2nd Peak @ 141GeV

$$\overline{\langle\sigma v\rangle} = 4.12 \times 10^{-21} \text{ cm}^3 \text{ s}^{-1}$$

Forbidden Dark Matter Combusted Around Supermassive Black Hole

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The forbidden dark matter cannot annihilate into heavier partner or SM particles by definition at the late stage of the cosmological evolution. We point out the possibility of reactivating the annihilation channel of forbidden dark matter around supermassive black holes. Being attracted towards black hole, the forbidden dark matter is significantly accelerated to overcome the annihilation threshold. The subsequent decay of the annihilation products to photon leaves localized signal around the black hole, which can serve as smoking gun of the forbidden dark matter.

[arXiv:2211.xxxxx]

- **Forbidden DM intrinsically cannot be indirectly probed!**
- **Direct detection may also be suppressed!**
- **How to uniquely test forbidden DM**
- **Point source around supermassive BH**



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Thank You

Weighted Thermally Averaged Xsec

$$\overline{\langle \sigma v \rangle} \equiv \frac{\int_{4GM}^{r_b} 4\pi r^2 \rho^2(r) \langle \sigma v(r) \rangle}{\int_{4GM}^{r_b} 4\pi r^2 \rho^2(r)}$$