Prospects of constraining WIMP dark matter using celestial bodies

Arpan Kar

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Dark matter : WIMPs

- Dark Matter (DM) exists and provides ∼25% of the energy density of the Universe

- Microscopic natures of DM are still unknown

- Weakly Interacting Massive Particles (WIMPs) : one of the most popular candidates for DM
  - no electric charge, no colors, stable
  - mass at the weak scale (GeV – TeV)
  - weak interactions ($\sigma v \sim 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$) keep WIMPs in thermal equilibrium in the early Universe and provide correct relic abundance through thermal decoupling

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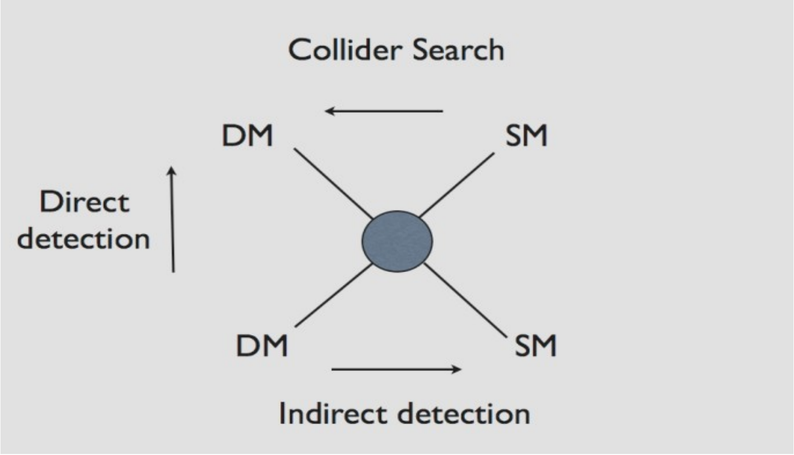
- WIMP searches :
  - Direct detection
  - Collider searches
  - Indirect detection



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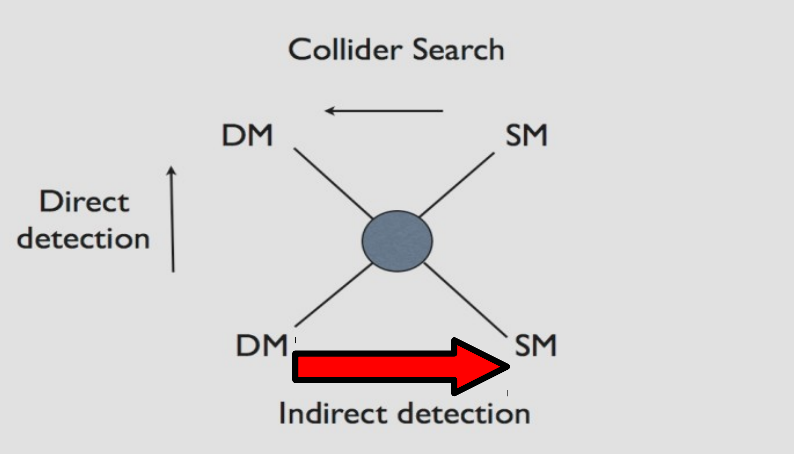
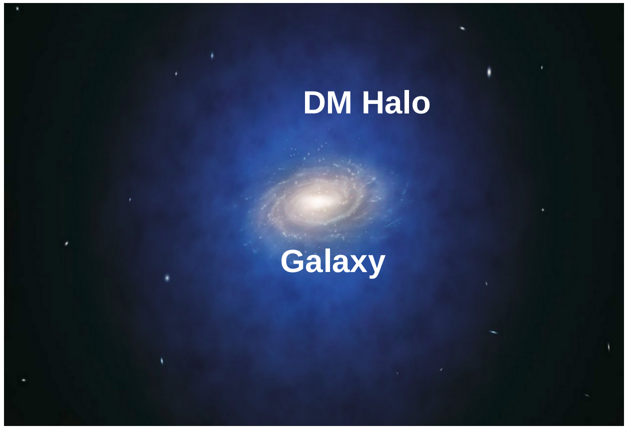
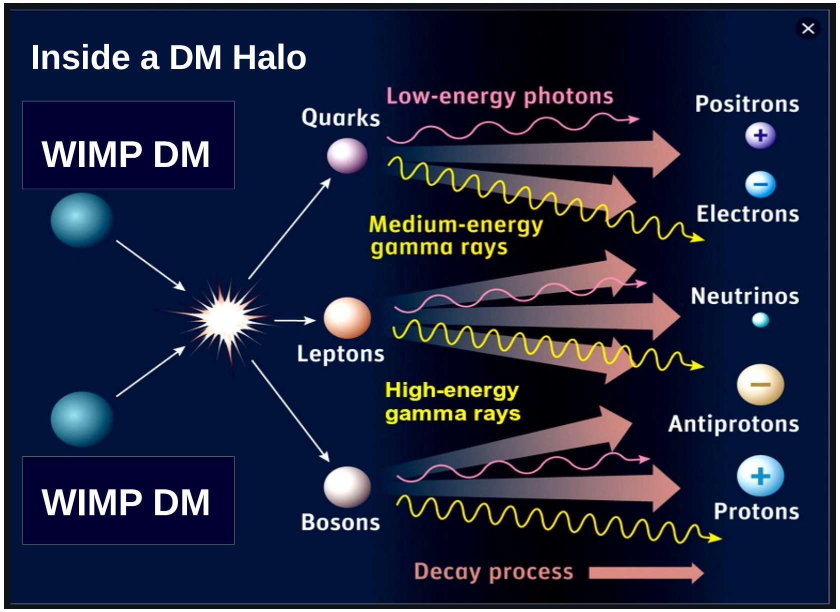


Indirect detection of WIMP DM

- DM is concentrated in the form of halos surrounding different galaxies (including our Galaxy)
  [Evidence: galactic rotation curves]



- Pair-annihilations of WIMP DM particles in such a halo can produce Standard Model particles which cascade further and produce flux of
  γ , e^+ / e^- , $p / \bar{p}$, $\nu 's / \bar{\nu} 's$, etc.



- Produced γ , e^+ , $\bar{p}$, $\nu 's / \bar{\nu} 's$ are searched using different experiments:

  γ- rays ⇨ Fermi-LAT, H.E.S.S., etc.

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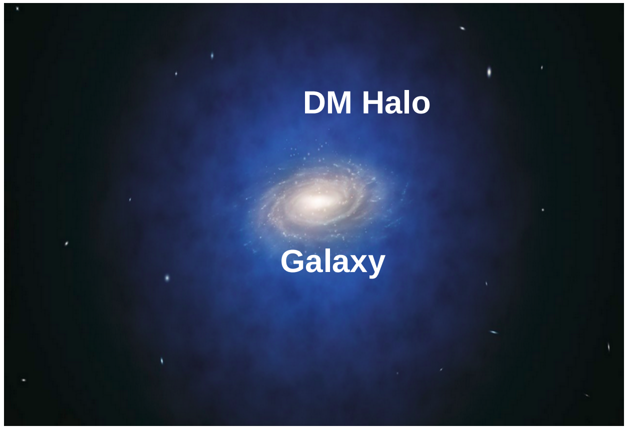

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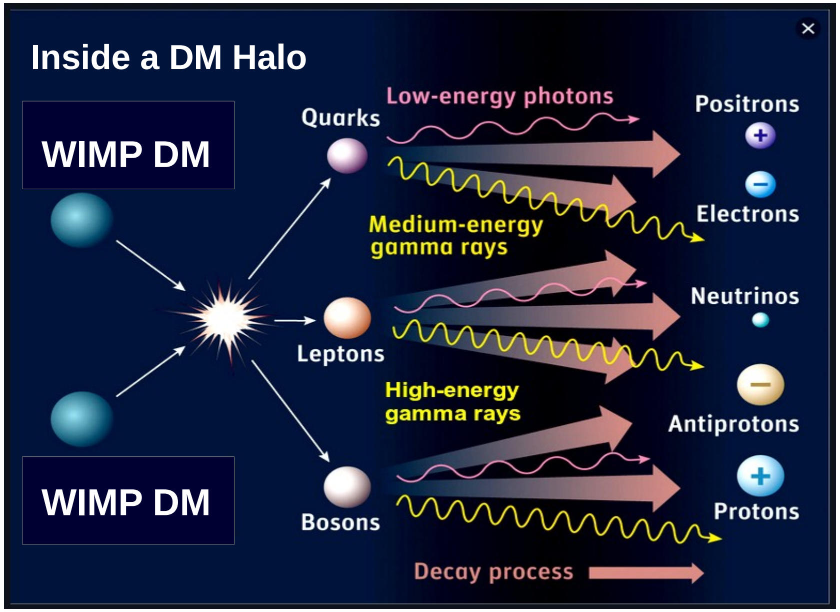

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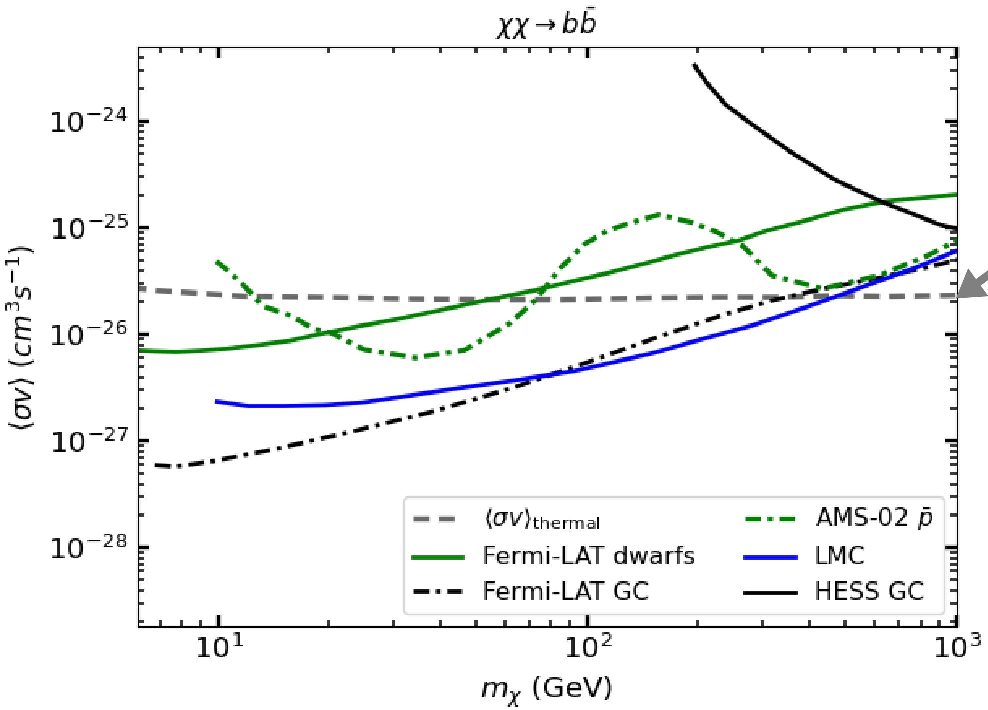
- **Constrain $<\sigma v>$ (WIMP pair-annihilation cross-section times velocity) and DM mass m_χ**

Present upper bounds on <σ v> from Indirect Detection searches



$<\sigma\, v>_{thermal}$ ⇨ gives correct relic density

(*s*-wave annihilation)

$\Omega_\chi h^2 = 0.12$ (observed)

$\Omega_\chi h^2 \propto 1/\langle\sigma\, v\rangle$

Fermi-LAT γ-ray search from nearby dwarf galaxies [Albert *et al*., ApJ 834 110 (2017)]

Fermi-LAT γ-ray search from the Galactic Center (GC) [Abazajian *et al*., PRD 102, 043012 (2020)]

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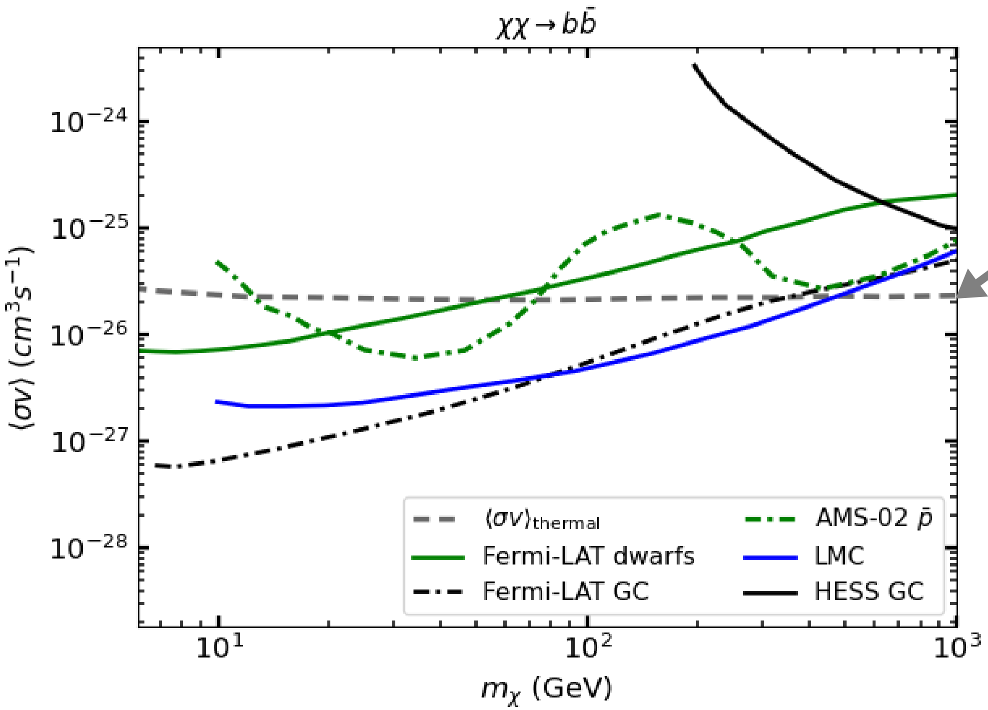

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- **Enhanced annihilation signals are expected from the DM dense regions (e.g., Center of Galaxies)**

DM distribution at the Center of Galaxies : DM density spikes !

- Observational evidence indicates that almost every large galaxy has a **Supermassive Black Hole (SMBH)** at its center
  - The Milky Way galaxy has a SMBH at its center, corresponding to the radio source $\mathrm{Sgr\ A^*}$ with mass $M_{BH} \sim 3\times10^{6}\ M_{\odot}$

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- **Halo DM near the galactic center can be accreted and redistributed by the central massive Black Hole into a dense "Spike"** (due to *Adiabatic Compression*)

[Gondolo & Silk, PRL 83, 1719 (1999)]

$\rho_\chi \sim r^{-\gamma_{sp}}$ near the galactic center (GC)
(within inner ~ 0.1 pc of the Milky Way center)

γ_{sp} depends on the initial halo profile

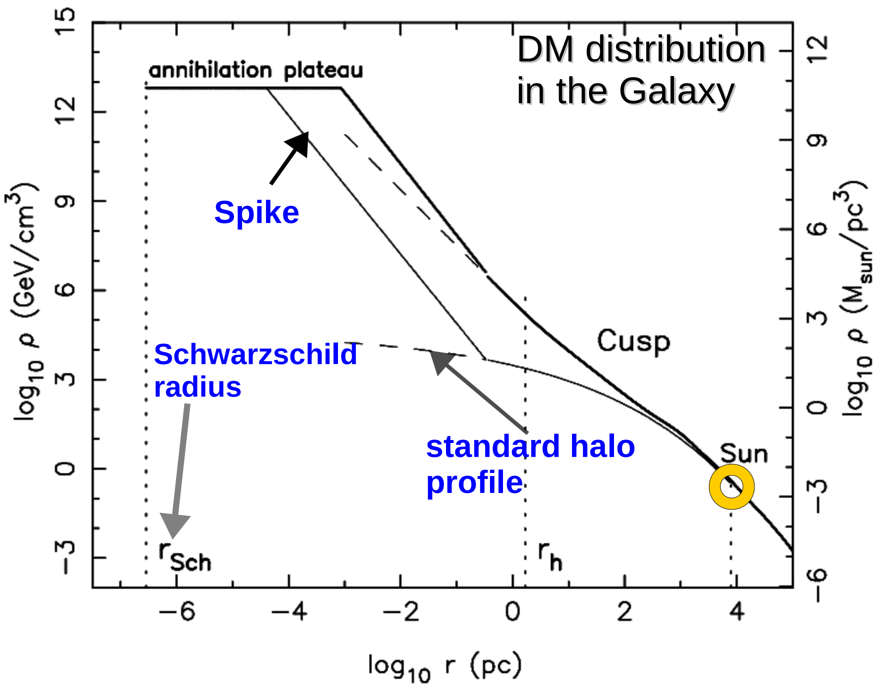

Fig. from [Bertone & Merritt, Mod. PLA 20 (2005) 1021]

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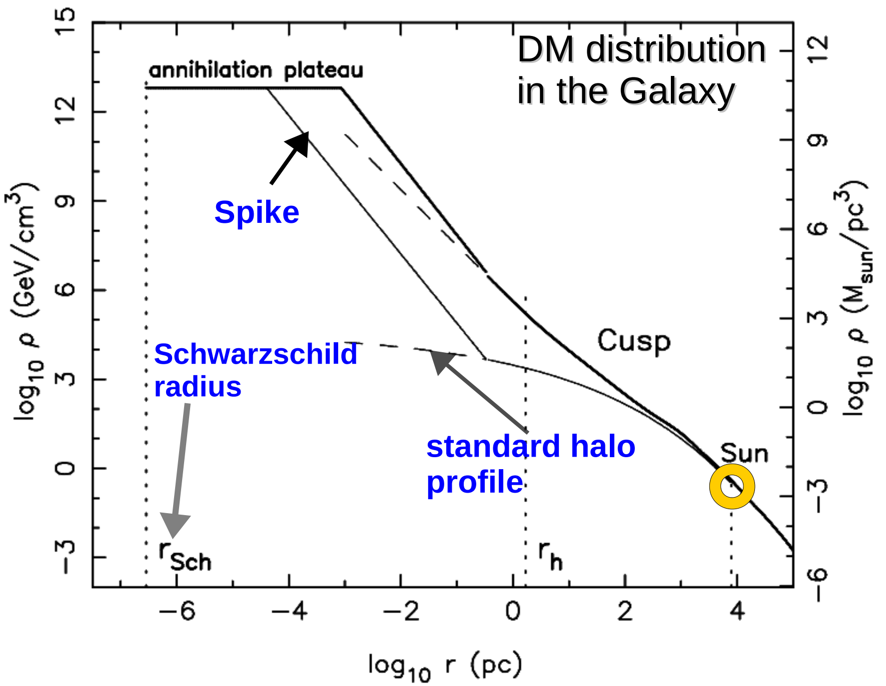
- WIMP annihilation signal $\propto n_\chi^2 \equiv \rho_\chi^2 / 2m_\chi^2$

WIMP annihilation signals are very sensitive to γ_{sp}

What is the value of γ_{sp} ?



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DM density spike model near Supermassive Black Holes (SMBHs)

$\rho_{\rm sp}(r) \sim r^{-\gamma_{\rm sp}}$ for $4\,r_{\rm Sch} < r < r_{\rm sp}$ Schwarzschild radius: $r_{\rm Sch} = 2GM_{\rm BH}/c^2$

- If the initial halo profile $\rho_{\rm halo}(r)$ is "Cuspy" :

$$\rho_{\rm halo}(r) = \rho_s \left(\frac{r}{r_s}\right)^{-\gamma} \quad \text{with} \quad 0 \le \gamma \le 2$$

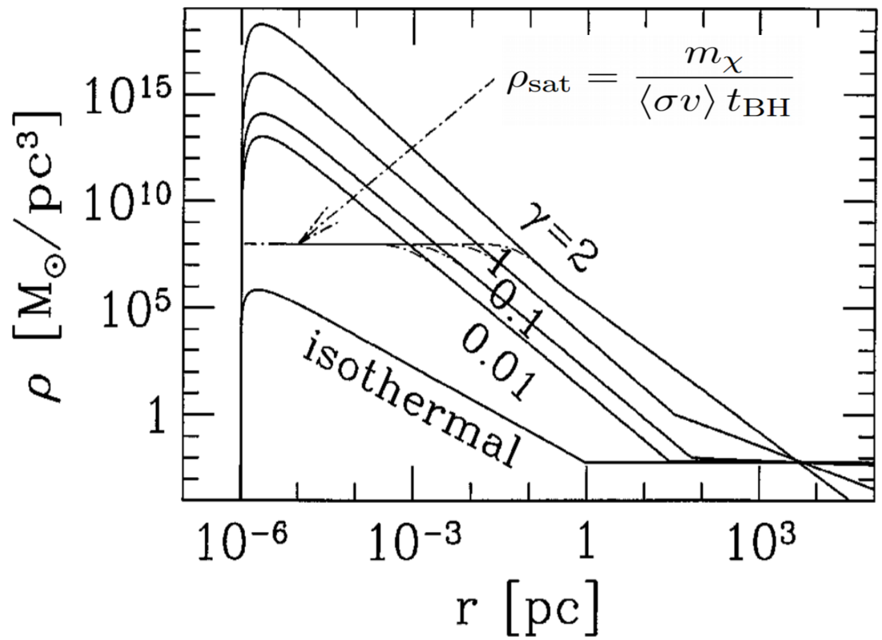
$$\gamma_{\rm sp} = \frac{9-2\gamma}{4-\gamma} \Rightarrow 2.25 < \gamma_{\rm sp} < 2.5$$

- If $\rho_{\rm halo}(r)$ is "Cored" / flat (e.g., Isothermal profile)

$\gamma_{\rm sp}$ = 1.5

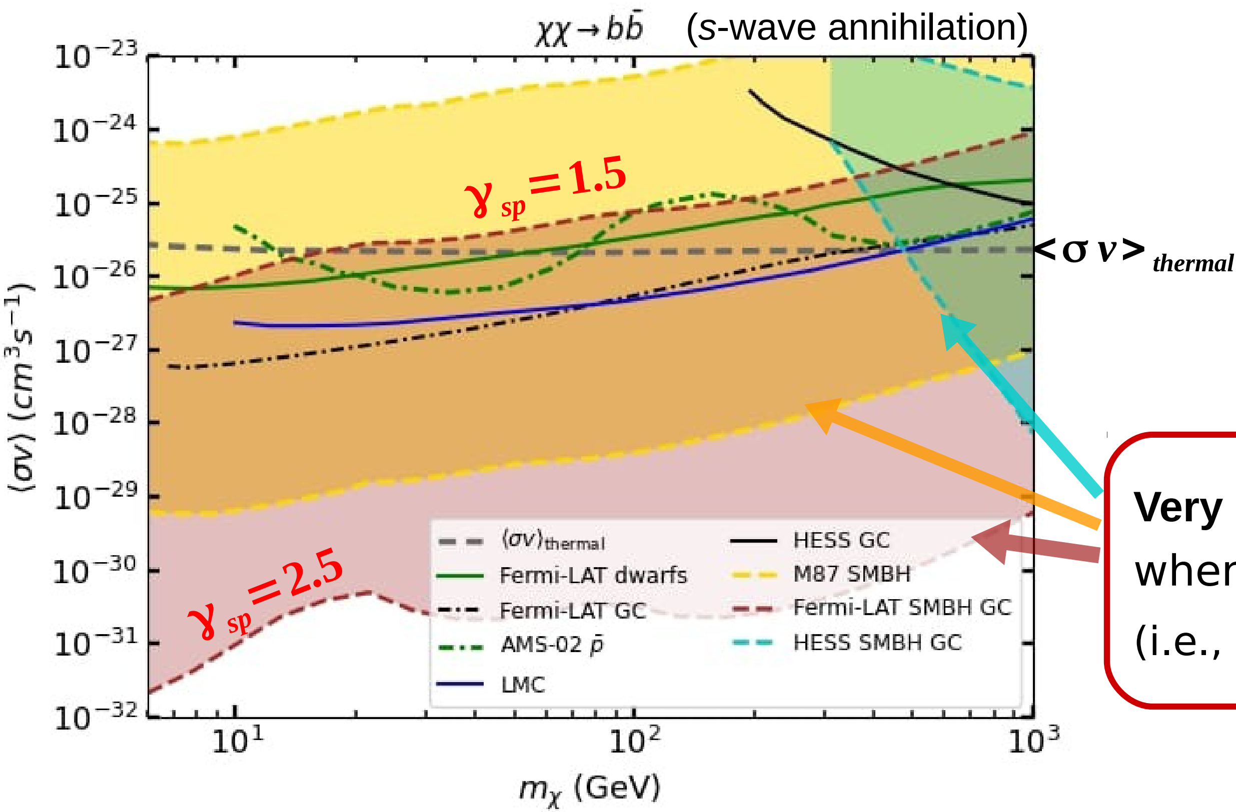
Examples of spike in the Galaxy

[Gondolo & Silk, PRL 83, 1719 (1999)]



- For DM spike around SMBHs at the center of galaxies $\mathbf{1.5 \lesssim \gamma_{\rm sp} \lesssim 2.5}$

Bounds on WIMP annihilation from SMBHs



Multi-frequency searches from the SMBH at M87
[Lacroix *et al.*, PRD 92, 043510 (2015)]

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Fermi-LAT γ-ray search from the SMBH at the GC
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Very strong bounds on $<\sigma v>$ from SMBHs when the spike index γ_{sp} is large, $\gamma_{sp} \sim 2.5$ (i.e., when an initial "cusp" halo is assumed)

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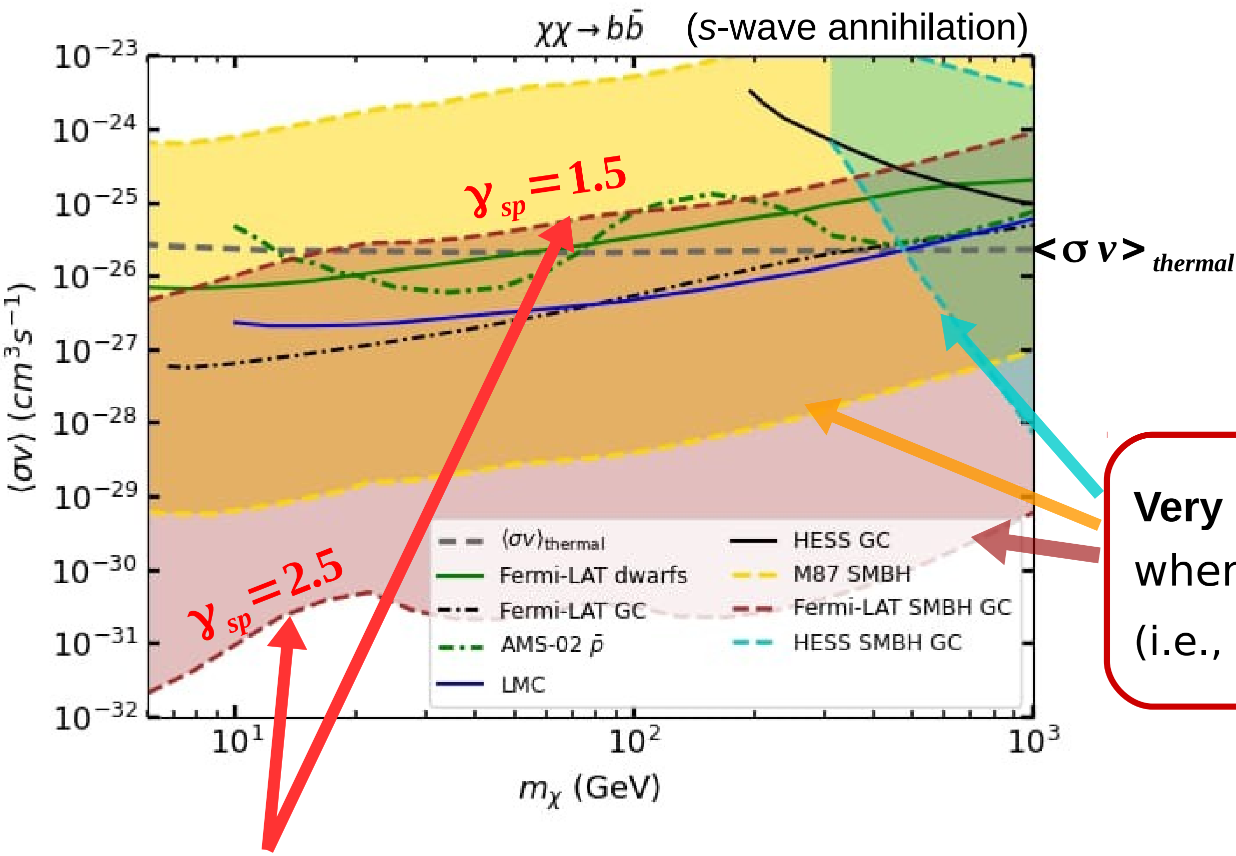

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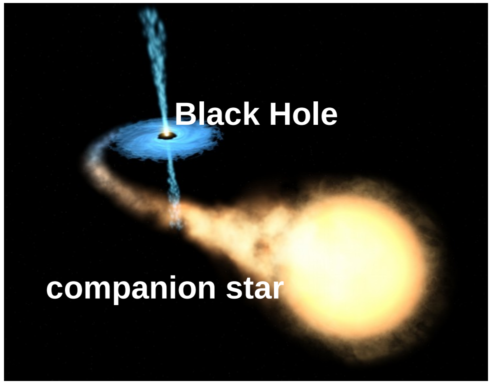
- Bounds from SMBHs are **very uncertain** depending on the uncertainty $1.5 \lesssim \gamma_{sp} \lesssim 2.5$
  - No initial "cusp" → Small spike ($\gamma_{sp} \simeq 1.5$) → very weak bound (may not even reach $\langle\sigma v\rangle_{thermal}$)
- Lack of observational supports to constrain γ_{sp} for DM spikes around the SMBHs
- **Bounds on WIMP annihilation from SMBH spikes are not robust !**

Black Hole low-mass X-ray binaries (BH-LMXBs)

- BH-LMXB is a binary system made of a low mass Black Hole and an orbiting star (companion star)
  - Lot of studies for such systems **in X-Ray, Optical, Infrared and Radio observations**
  - Many of such systems are observed in the Milky Way (e.g., *XTE J1118+480*, *A0620-00*, etc.)



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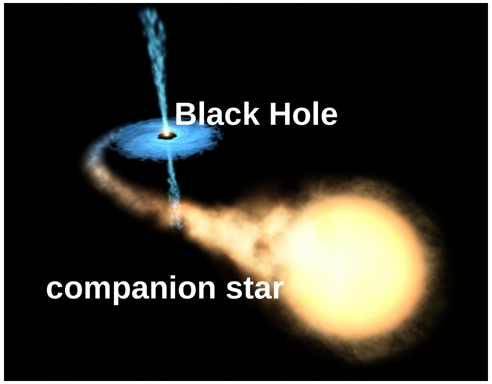

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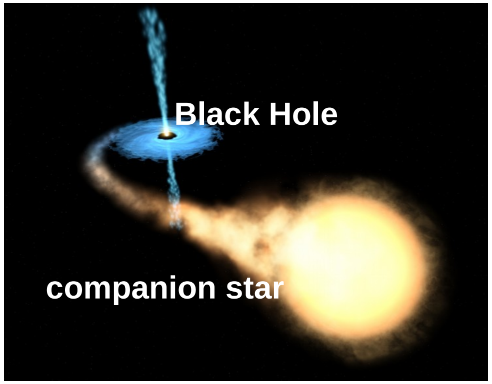

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	Measured Parameters	XTE J1118+480
	$M_{\rm BH}$	$7.46^{+0.34}_{-0.69} M_\odot$ (Gonzalez Hernandez et al. 2014)
star mass / BH mass →	q **= *m* / *M*$_{BH}$**	0.024 ± 0.009 (Khargharia et al. 2013)
star radial velocity →	K (km s^{-1})	708.8 ± 1.4 (Khargharia et al. 2013)
orbital inclination →	i	$73°5 \pm 5°5$ (Khargharia et al. 2013)
orbital period →	P (day)	0.16993404(5) (Gonzalez Hernandez et al. 2014)
orbital decay rate →	$\dot{P}$ (ms yr^{-1})	-1.90 ± 0.57 (Gonzalez Hernandez et al. 2014)
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A low mass Black Hole system $\boldsymbol{M_{BH}}$ ~ a few $\boldsymbol{M_\odot}$

table. from [Chan & Lee, ApJL, 943, L11 (2023)]

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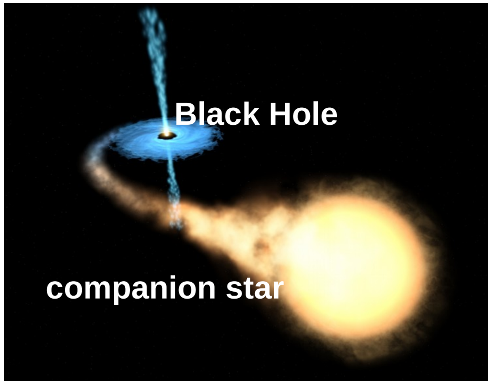

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A low mass Black Hole system $M_{BH} \sim$ a few $M_\odot$

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- **An abnormally fast decay of the orbital period is observed, $\dot{P} \simeq -2$ ms yr $^{-1}$!**

Possible explanations of the observed orbital decay in BH-LMXB

- Possible explanations from Standard theories:
  - **Predicted orbital decays from Standard theories (including Gravitational-Wave radiation) are ~2 orders of magnitude smaller than the Observed one !**

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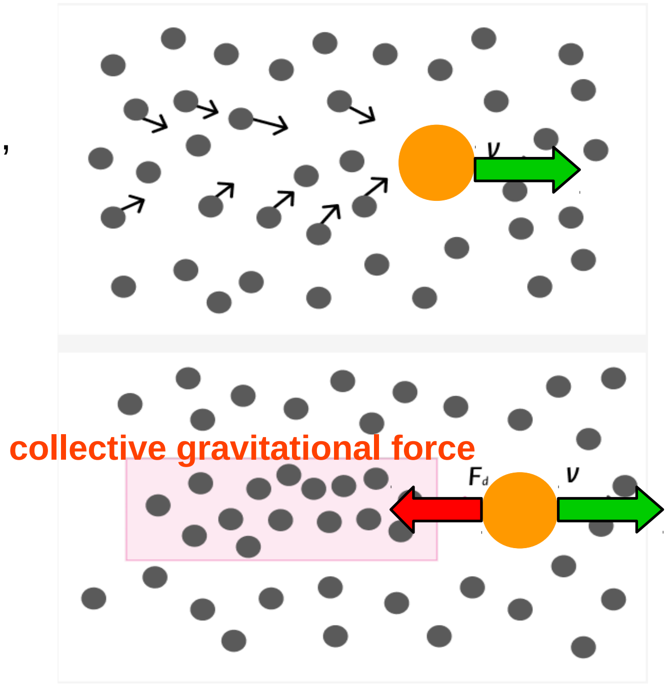
- **Alternative explanation:** The dynamical friction between dark matter and the companion stars may explain the abnormally fast orbital decays

Dynamical friction: if the star is moving in a dense spike of DM particles, it gravitationally pulls the DM particles toward it. This leads to a concentration of DM particles behind the star, which slows down the star by the collective gravitational force



Orbital decay in BH-LMXB due to dynamical friction between DM and companion star

$$\dot{P} = -\frac{12\pi q G P \ln\Lambda}{(1+q)^2 (K/\sin i)} \left[\frac{G M_{\rm BH}(1+q) P^2}{4\pi^2}\right]^{1/3} \rho_\chi$$

DM spike model around BH-LMXB:

$$\rho_{\rm sp}(r) = \rho_0 \left(\frac{r}{r_{\rm sp}}\right)^{-\gamma_{\rm sp}}$$

$r_{\rm Sch} = 2GM_{\rm BH}/c^2$

for $2\,r_{\rm Sch} < r \leq r_{\rm sp}$

$\rho_0 \simeq 0.3\,{\rm GeV\,cm^{-3}}$

(local halo DM density)

$r_{\rm sp} = 0.2\,r_{\rm in}$

$$M_{\rm DM}(r \leq r_{\rm in}) = \int_0^{r_{\rm in}} dr\, 4\pi r^2 \rho_\chi = 2\,M_{\rm BH}$$

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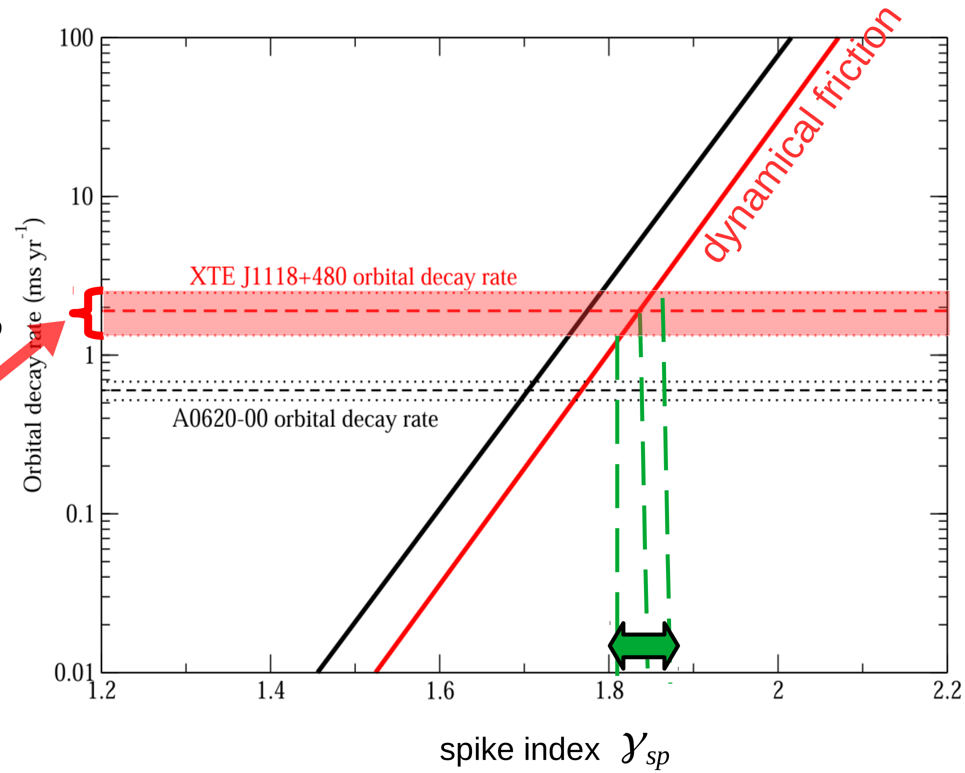

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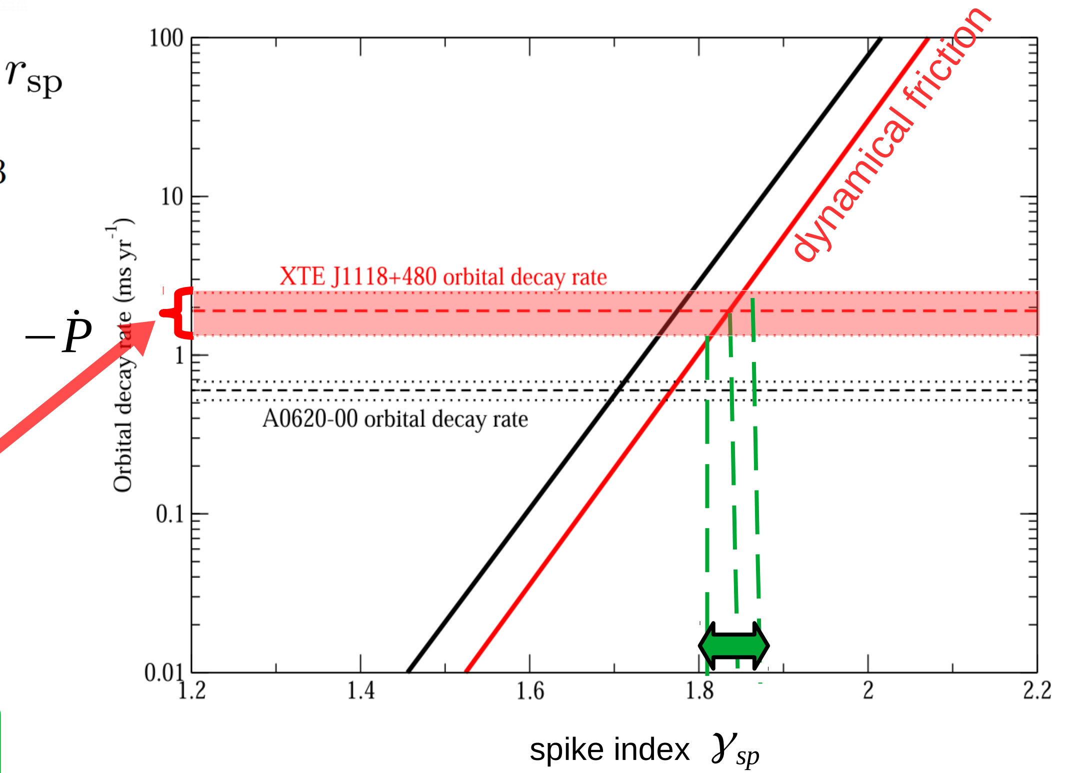


For "XTE J1118+480" : $\gamma_{sp} = 1.85 \pm 0.04$

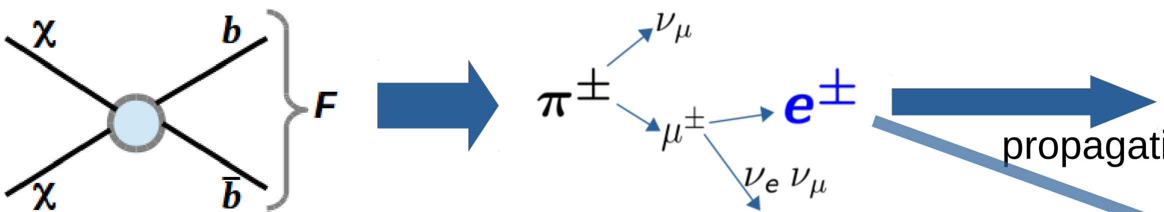
(uncertainty within ~ 4% !)

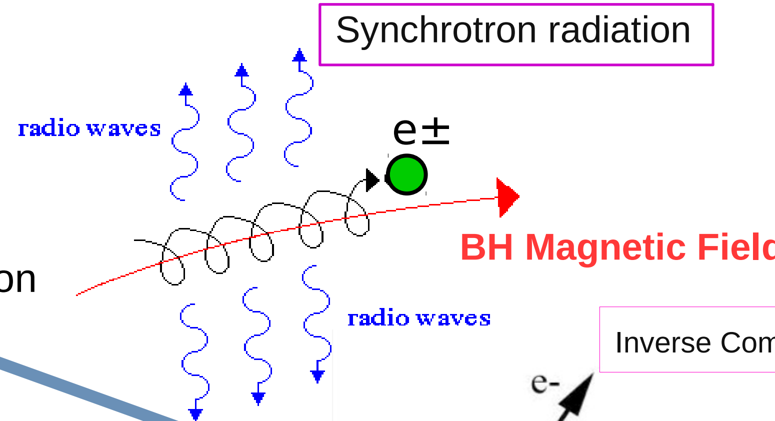
→ **Much smaller uncertainty in the DM annihilation signals compared to those from SMBHs !**

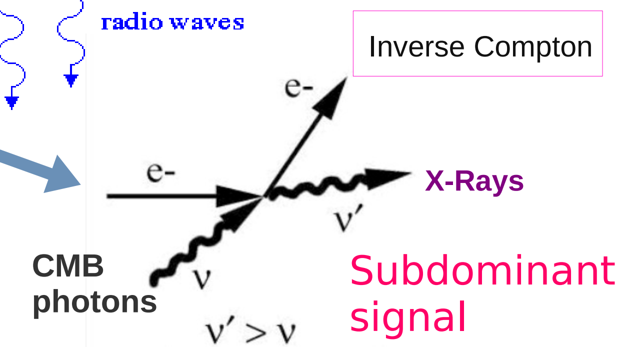
WIMP annihilation signal from XTE J1118+480

- **Main source of signal** : Synchrotron radiation from e± produced from WIMP annihilation in Black Hole magnetic field

Annihilation in the DM spike







e± source :

$$Q_e(E,r) = \langle \sigma v \rangle \underbrace{\left\{ \frac{\rho_\chi^2(r)}{2m_\chi^2} \right\}}_{\text{no. density of DM pairs}} \left\{ \sum_F B_F \frac{dN_e^F}{dE} \right\}$$

$\frac{dN_e^F}{dE}$ ⇨ e± spectra per annihilation in channel *F*

ρ_χ ⇨ DM spike density profile

Propagation of DM induced e±:

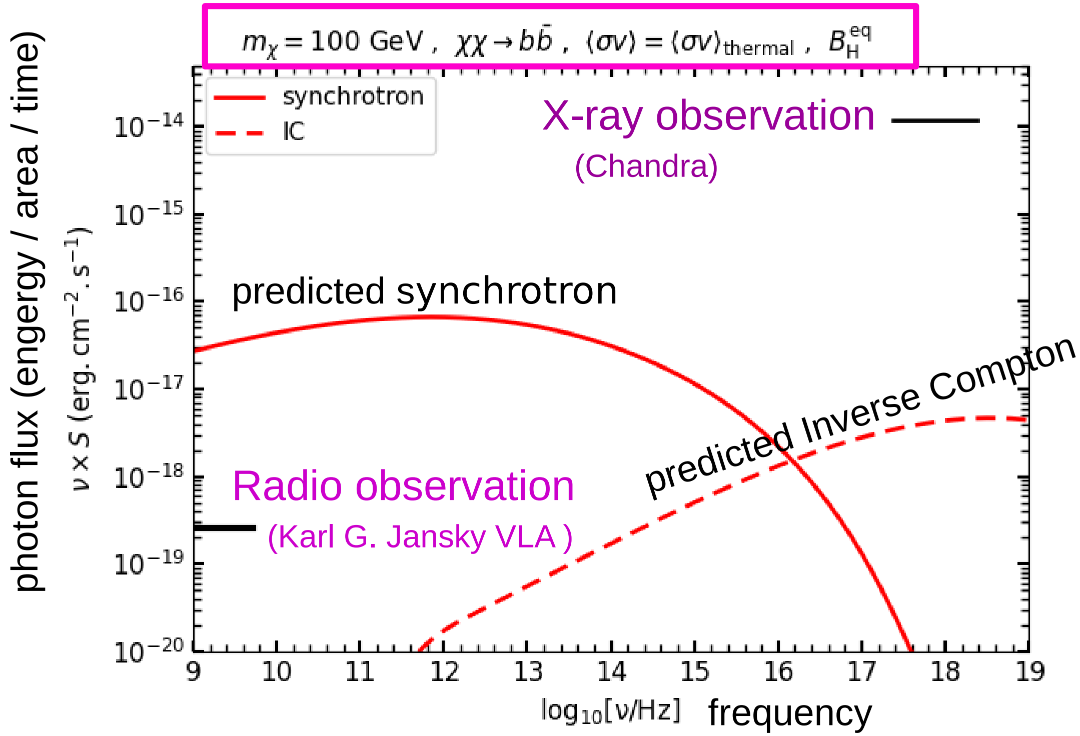
$$\underbrace{-\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D \frac{\partial f}{\partial r}\right]}_{\text{Diffusion}} + \underbrace{\frac{1}{p^2}\frac{\partial}{\partial p}(\dot{p}p^2 f)}_{\text{Energy loss}} = \underbrace{q(r,p)}_{\text{e± source from DM}}$$

f (r,p) = e± distribution at equilibrium

p : momentum $p \simeq E$

$$Q_e(r,E) = 4\pi p E q(r,p)$$

WIMP annihilation signal from XTE J1118+480



$\langle\sigma v\rangle_{\rm thermal} \simeq 2.2\times10^{-26}\ {\rm cm^3\ s^{-1}}$

A.K, H. Kim, S. P. Kim, S. Scopel, JCAP 03 (2024) 030

Strong constraint from Radio observation !

- <u>*B*-field near the BH :</u>

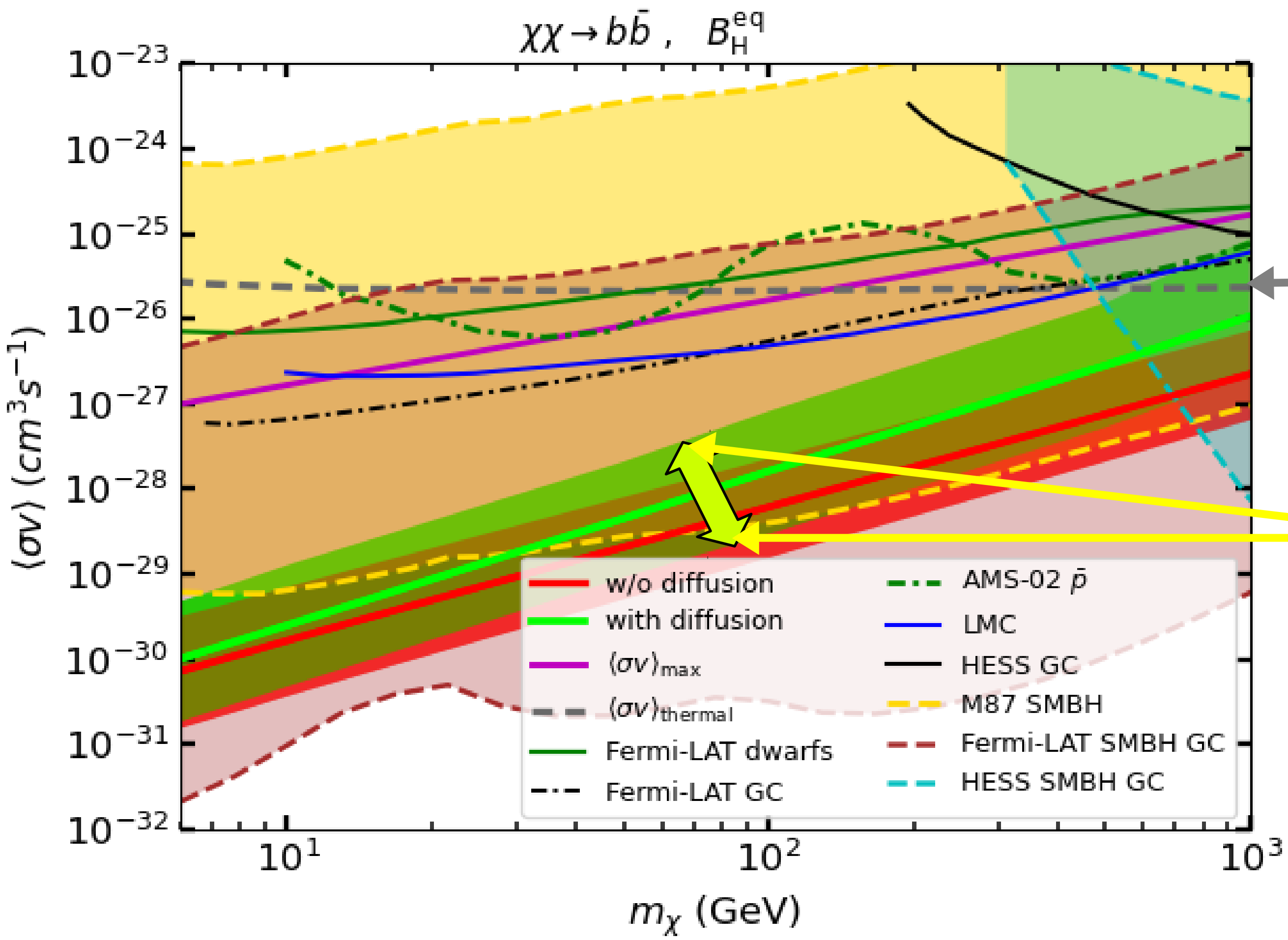
  We assume equipartition *B*-field : $\frac{B^2}{8\pi} = \frac{1}{2}\rho_c u_r^2 \quad \text{with} \quad u_r \sim c\sqrt{\frac{r_{\rm Sch}}{r}}$

  ρ_c → accreted density of charges

  (equipartition in magnetic, kinetic, and gravitational energy densities)

- Such a *B*-field profile is commonly used for the SMBHs

Constraints on WIMP annihilation from XTE J1118+480 BH-LMXB

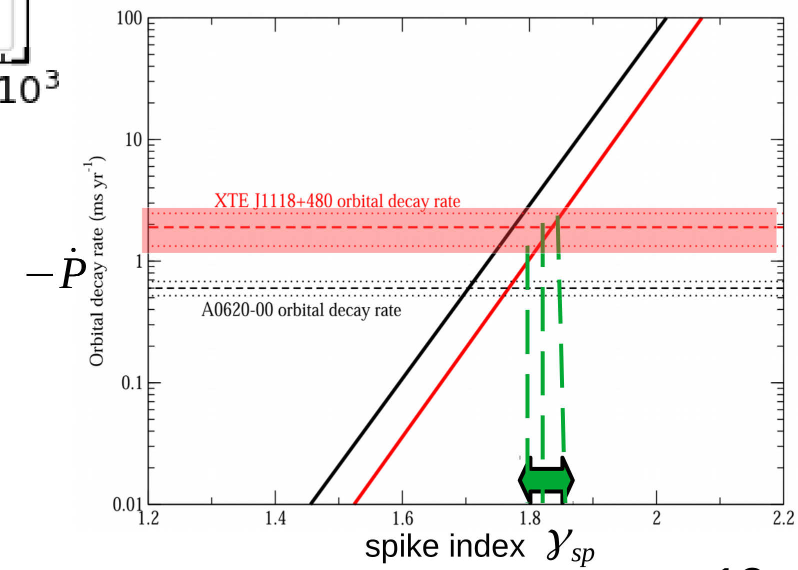


<σ v> ***thermal***

(*s*-wave annihilation)

[uncertainty due to spike index]

for "XTE J1118+480": $\gamma_{sp} = \mathbf{1.85 \pm 0.04}$

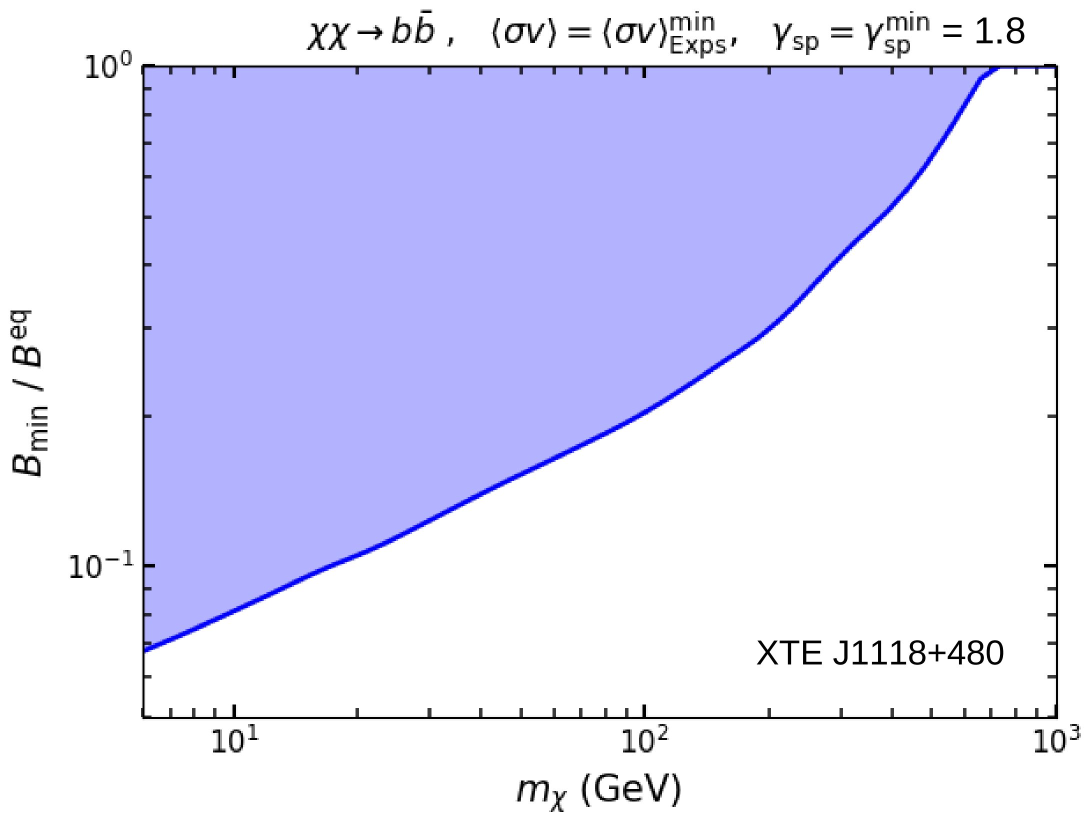


Strong constraint on <σ v> for m_χ up to TeV scale !

Much smaller uncertainty due to the spike index !

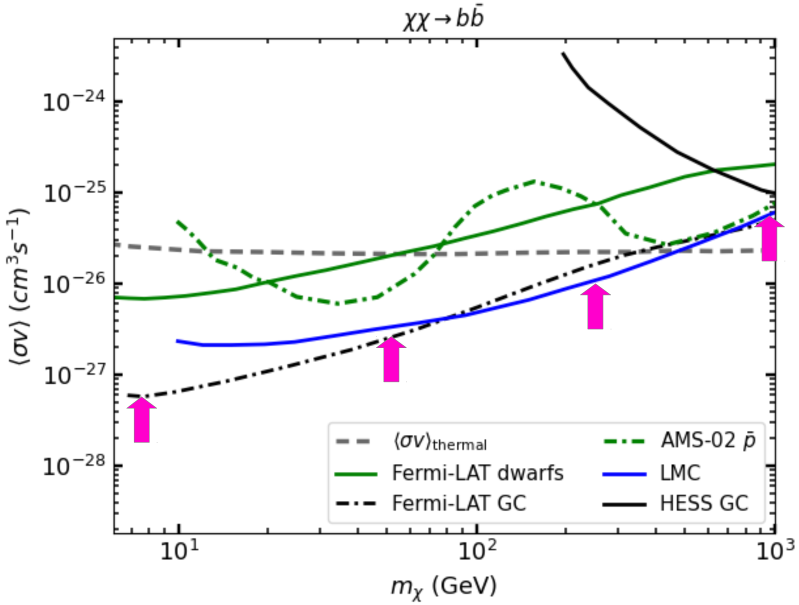
A.K, H. Kim, S. P. Kim, S. Scopel, JCAP 03 (2024) 030

Uncertainty in the DM signal from the magnetic field



Min. *B*-field (normalized to the equipartition field ***B^eq***) required to put bound on ⟨σv⟩ stronger than $\langle\sigma v\rangle^{\rm min}_{\rm Exps}$

$\langle\sigma v\rangle^{\rm min}_{\rm Exps}$



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Summary

- The fast orbital decay observed in Black Hole Low-Mass X-ray binaries (BH-LMXBs), e.g., XTE J1118+480, can be explained by the dynamical friction between DM and the companion star
  - Indirect evidence of DM spikes around such BHs ?
  - the DM spike index γ_{sp} can be pinned down with an accuracy of ≃ a few percent

- Study of radio synchrotron signal produced from such DM spikes around the BH-LMXBs can potentially put constraints on the WIMP annihilation better than the existing limits
  - such constraints have much smaller uncertainty due to the spike index
  - however, they are very sensitive to the BH magnetic field profile

- A better understanding of the B-fields near BH-LMXBs is needed in order to put a robust constraints on the WIMP annihilation

- One alternative way ⇨ study gamma-ray flux from WIMP annihilation in the BH-LMXB DM spikes
  - gamma-ray flux depends only on the spike → less uncertainty in the signal
  - presently not much dedicated observations are performed in gamma-rays for BH-LMXBs
  - new observation based studies of these systems in gamma-rays are needed

Backup slides

DM density spike model near Supermassive Black Holes

$$\rho_\chi(r) = \begin{cases} 0 & \text{for} \quad r \le 4\, r_{\rm Sch} \text{ , (capture of DM by the BH)} \\ \dfrac{\rho_{\rm sp}(r)\, \rho_{\rm sat}}{\rho_{\rm sp}(r) + \rho_{\rm sat}} & \text{for} \quad 4\, r_{\rm Sch} < r \le r_{\rm sp}\,, \\ \rho_{\rm halo}(r) & \text{for} \quad r > r_{\rm sp} \end{cases}$$

Schwarzschild radius: $r_{\rm Sch} = 2GM_{\rm BH}/c^2$

Spike radius: $r_{\rm sp} = 0.2\, r_{\rm in}$

radius of influence ($r_{\rm in}$) defined by:

$$M_{\rm DM}(r \le r_{\rm in}) = \int_0^{r_{\rm in}} dr\, 4\pi r^2\, \rho_\chi = 2\, M_{\rm BH}$$

$\rho_{\rm halo}(r)$ ⟹ the halo profile in which the Black Hole is grown adiabatically

Spike profile :

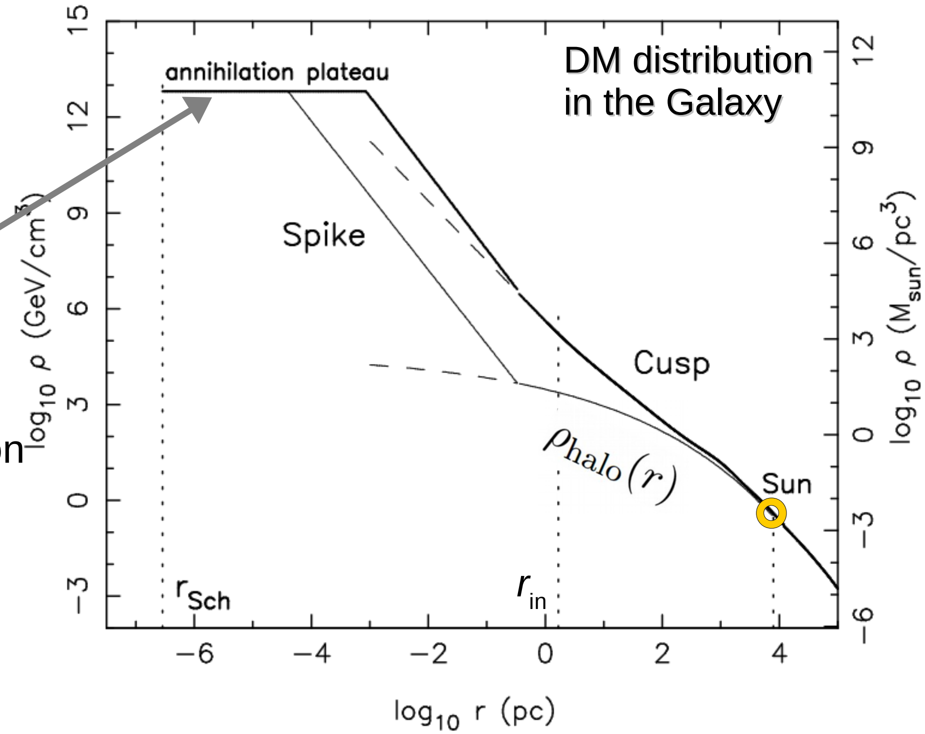
$$\rho_{\rm sp}(r) \sim r^{-\gamma_{\rm sp}} \qquad \text{for} \quad 4\, r_{\rm Sch} < r < r_{\rm sp}$$

$\gamma_{\rm sp}$ ⟹ Spike index (depends on $\rho_{\rm halo}(r)$)

$$\rho_{\rm sat} = \frac{m_\chi}{\langle \sigma v \rangle\, t_{\rm BH}}$$ ⟹ saturation due to WIMP annihilation

($t_{\rm BH}$: age of the BH)

$M_{\rm BH} \sim 3\times10^6 M_\odot$



Possible explanations of the observed orbital decay in BH-LMXB

- Possible explanations from Standard theories:

  - Gravitational-Wave radiation : the predicted decay is ~2 orders of magnitude smaller than the Observed one !

  - orbital period decay by the coupling between magnetic field and winds from the companion star through tidal torques. However, there should be a significant mass loss from the binary system, which has not been observed

  - the tidal torque between the circumbinary disk and the binary can efficiently extract the orbital angular momentum from the binary to cause the orbital decay. However, simulations show that the predicted mass transfer rate and the circumbinary disk mass should be much greater than the inferred values from observations

Orbital decay due to dynamical friction between DM and the star

Energy loss due to dynamical friction : $\dot{E} = -\frac{4\pi G^2 \mu^2 \rho_\chi \xi(\sigma) \ln\Lambda}{v}$ $E = -GM_{\rm BH} m/2a$

$P^2 = 4\pi^2 a^3 / G(M_{\rm BH} + m)$
(Kepler's law)

$\frac{\dot{P}}{P} = \frac{3\dot{a}}{2a} = -\frac{3\dot{E}}{2E}$

a ⇨ binary separation

$$\dot{P} = -\frac{12\pi q G P \ln\Lambda}{(1+q)^2 (K/\sin i)} \left[\frac{GM_{\rm BH}(1+q)P^2}{4\pi^2}\right]^{1/3} \rho_\chi$$

$q = m / M_{\rm BH}$

DM spike model :

$$\rho_{\rm sp}(r) = \rho_0 \left(\frac{r}{r_{\rm sp}}\right)^{-\gamma_{\rm sp}}$$

$r_{\rm Sch} = 2GM_{\rm BH}/c^2$

for $2\, r_{\rm Sch} < r \le r_{\rm sp}$

$\rho_0 \simeq 0.3\, {\rm GeV\, cm^{-3}}$
(local halo DM density)

$r_{\rm sp} = 0.2\, r_{\rm in}$

$$M_{\rm DM}(r \le r_{\rm in}) = \int_0^{r_{\rm in}} dr\, 4\pi r^2 \rho_\chi = 2\, M_{\rm BH}$$

γ_{sp} is the only free parameter

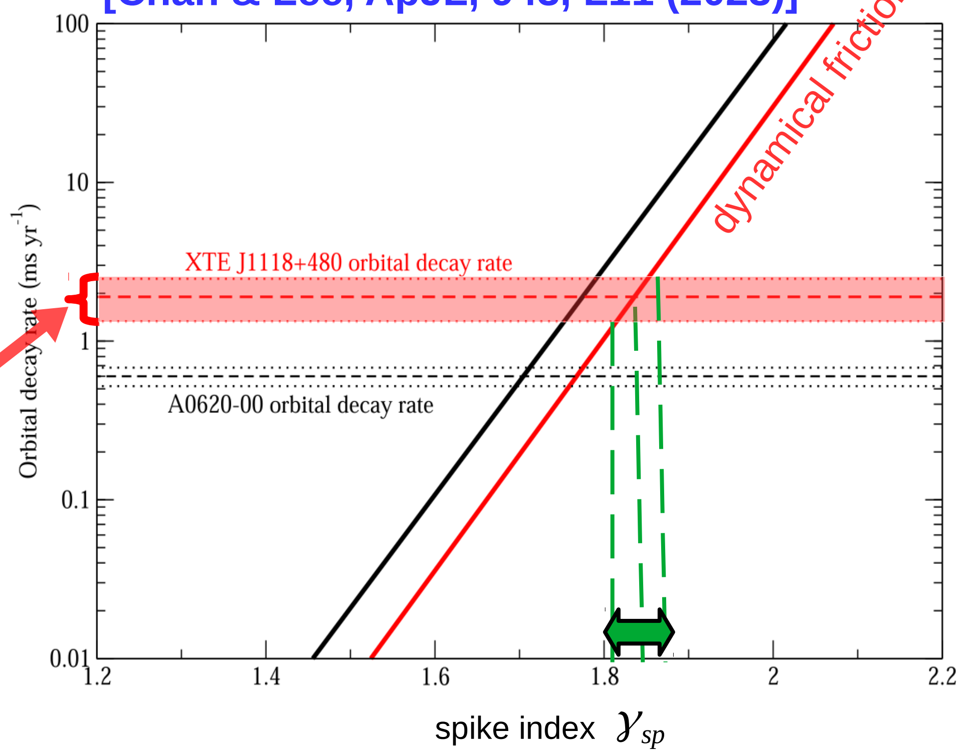
⇨ it can be constrained from the **observed $\dot{P}$**

For "XTE J1118+480" : $\gamma_{\rm sp} = \mathbf{1.85 \pm 0.04}$

(uncertainty within ~ 4% !)

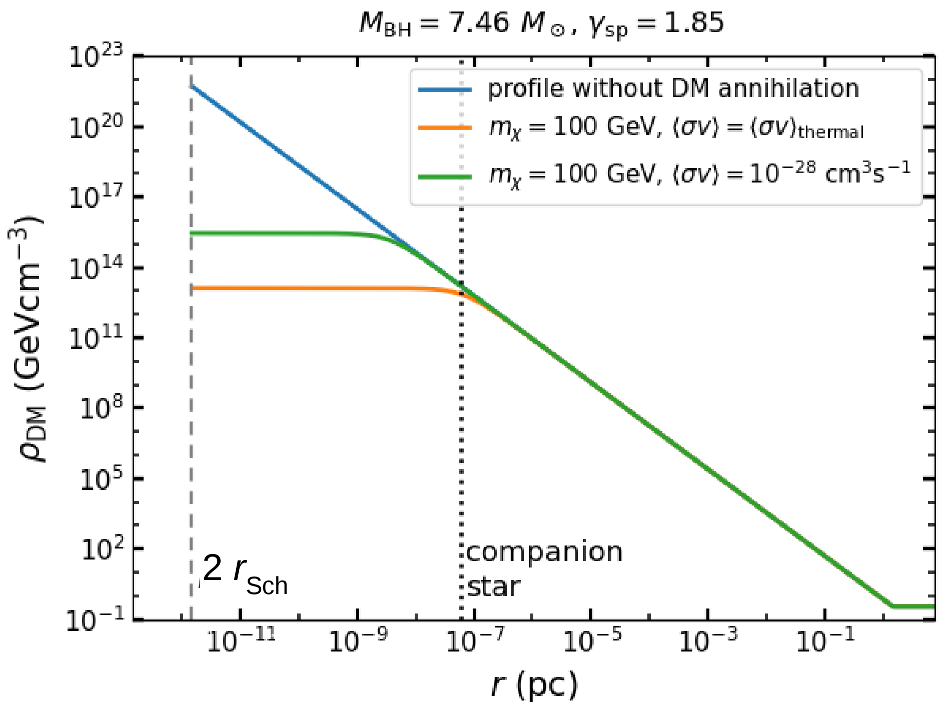
[Chan & Lee, ApJL, 943, L11 (2023)]

$-\dot{P}$



⇨ **Much smaller uncertainty in the DM annihilation signals compared to those from the SMBHs !**

DM density spike model near BH-LMXB XTE J1118+480



$$\rho_\chi(r) = \begin{cases} 0 & \text{for} \quad r \le 2\, r_{\rm Sch}\,, \\ \dfrac{\rho_{\rm sp}(r)\,\rho_{\rm sat}}{\rho_{\rm sp}(r) \,+\, \rho_{\rm sat}} & \text{for} \quad 2\, r_{\rm Sch} < r \le r_{\rm sp}\,, \\ \rho_{\rm halo} = \rho_0 & \text{for} \quad r > r_{\rm sp}\,, \end{cases}$$

$$\rho_{\rm sp}(r) = \rho_0 \left(\frac{r}{r_{\rm sp}}\right)^{-\gamma_{\rm sp}}$$

$$\rho_0 \simeq 0.3\,{\rm GeV\,cm^{-3}}$$

(local halo DM density)

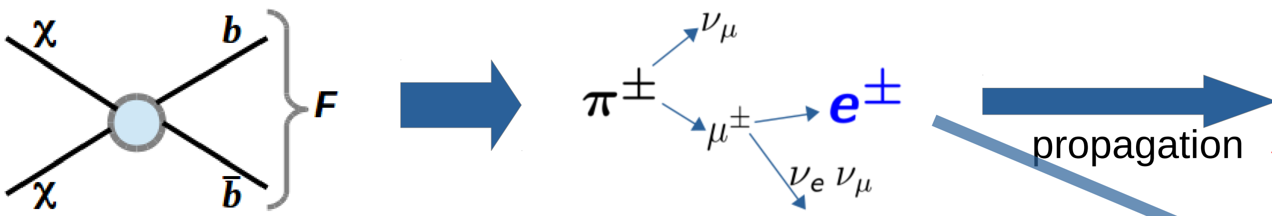
$$\rho_{\rm sat} = \frac{m_\chi}{\langle\sigma v\rangle\, t_{\rm BH}}$$

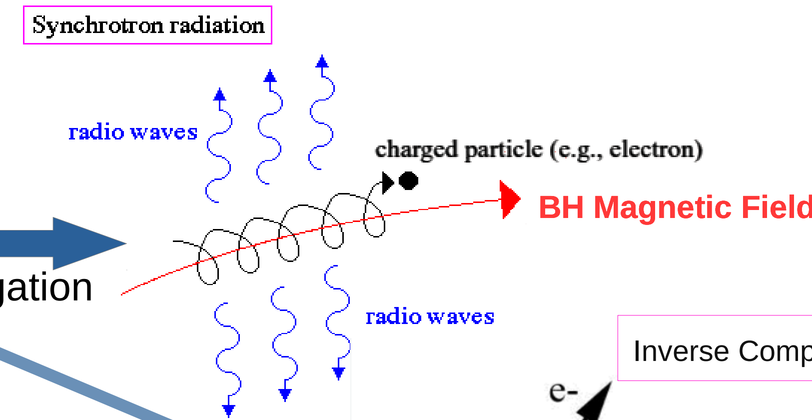
$t_{BH} < 3.5 \times 10^{14}$ s   for   XTE J1118+480

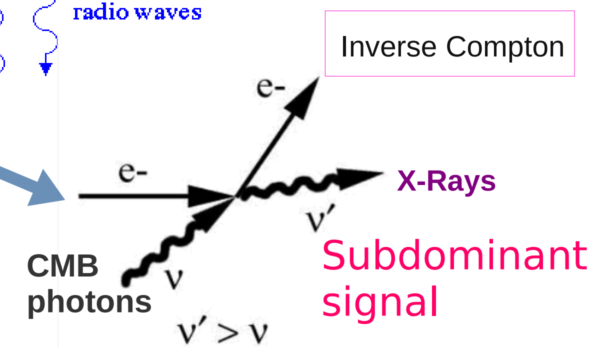
WIMP annihilation signal from XTE J1118+480

- **Main source of signal** : Synchrotron radiation from e± produced from WIMP annihilation in Black Hole magnetic field

Annihilation in the DM spike







e± source :

$$Q_e(E,r) = \langle \sigma v \rangle \left\{ \frac{\rho_\chi^2(r)}{2m_\chi^2} \right\} \left\{ \sum_F B_F \frac{dN_e^F}{dE} \right\}$$

$\frac{dN_e^F}{dE}$ ⇨ e± spectra per annihilation in channel F

Propagation of DM induced e±:

$$\underbrace{-\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D \frac{\partial f}{\partial r}\right]}_{\text{Diffusion}} + \underbrace{\frac{1}{p^2}\frac{\partial}{\partial p}(\dot{p}p^2 f)}_{\text{Energy loss}} = \underbrace{q(r,p)}_{\text{e± source from DM}}$$

$f\,(r,p)$ = e± distribution at equilibrium

p : momentum $p \simeq E$

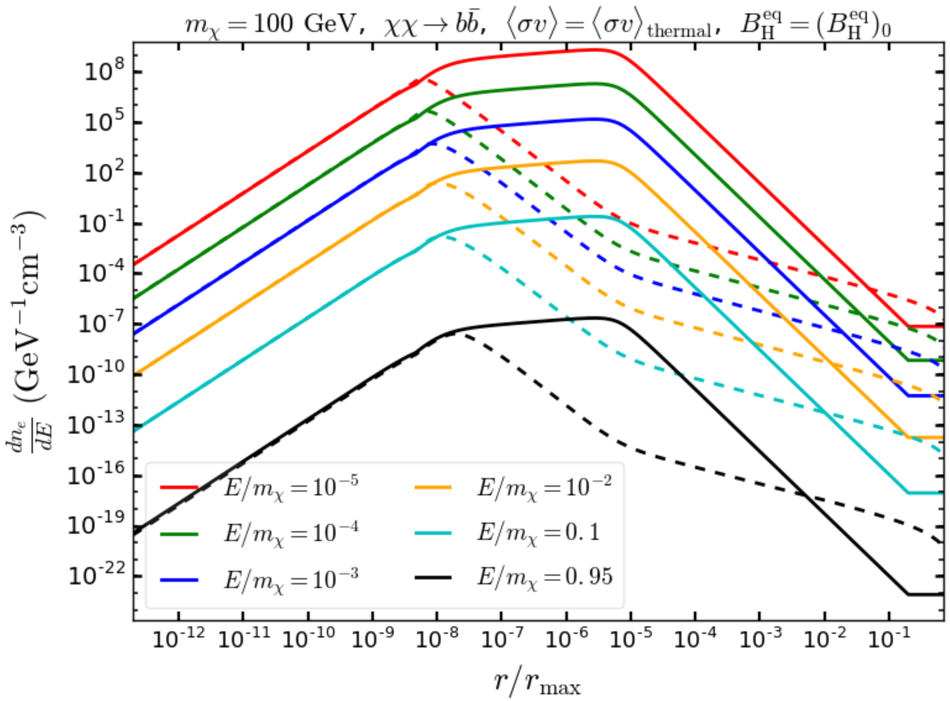
$$Q_e(r,E) = 4\pi p E q(r,p)$$

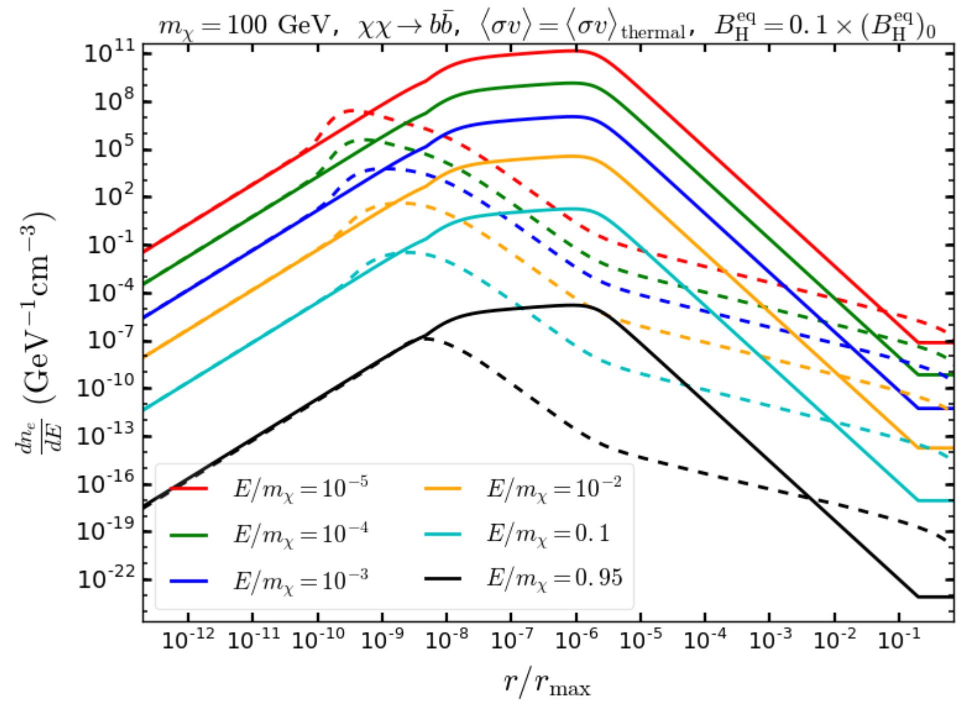
- Diffusion : $D\,(r,p) = 1/3\ r_g\ v_e$ with $r_g = E\,/\,eB(r)$ (gyroradius of e±) and $v_e \sim c \equiv$ velocity of e± (assuming "Bohm diffusion" , i.e., coherence length of the B-field $\gtrsim$ gyroradius of electrons)
- Energy loss of e± : due to radiative processes, e.g., Synchrotron radiation, Inverse Compton

Distribution of e±

dash line : w/o diffusion continues line : with diffusion

In XTE J1118+480

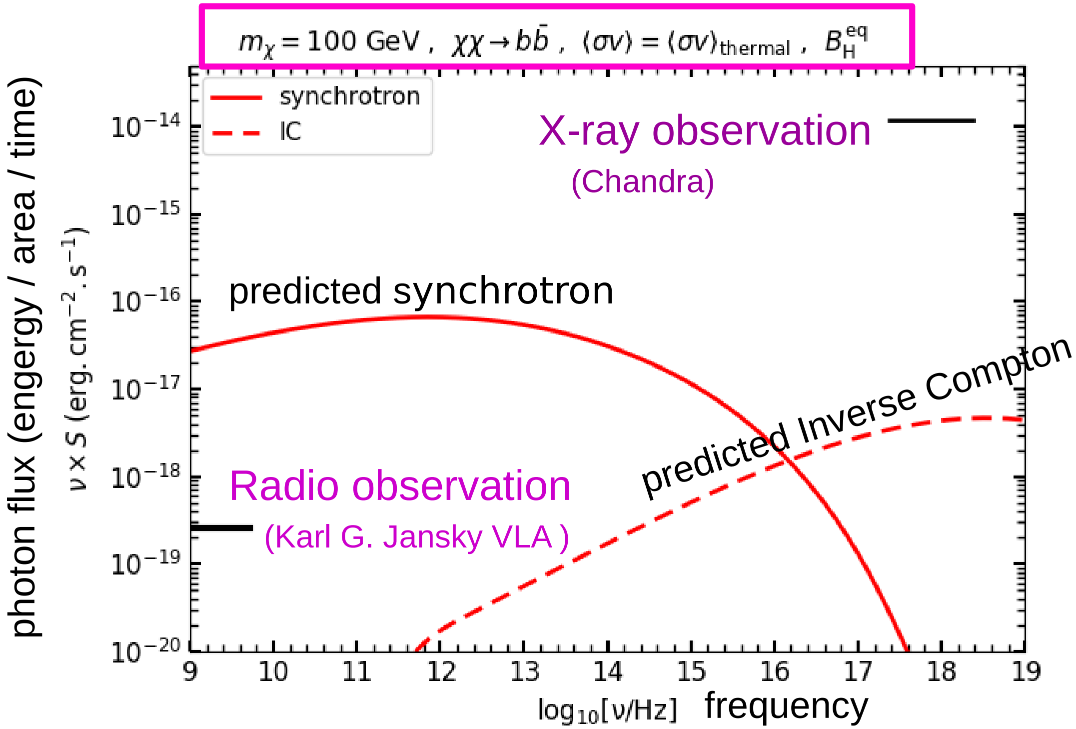




$$-\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 D\frac{\partial f}{\partial r}\right] + \frac{1}{p^2}\frac{\partial}{\partial p}(\dot{p}p^2 f) = q(r,p)$$

$$\frac{dn_e}{dE}(r,E) = 4\pi p E f(r,p)$$

WIMP annihilation signal from XTE J1118+480



$\langle\sigma v\rangle_{\rm thermal} \simeq 2.2\times10^{-26}\ {\rm cm^3\ s^{-1}}$

Strong constraint from Radio observation !

- <u>*B*-field near the BH :</u>

We assume equipartition *B*-field : $\frac{B^2}{8\pi} = \frac{1}{2}\rho_c u_r^2$ with $u_r \sim c\sqrt{\frac{r_{\rm Sch}}{r}}$

ρ_c → accreted density of charges

(equipartition in magnetic, kinetic, and gravitational energy densities)

$$B^{\rm eq}(r) = B_{\rm H}^{\rm eq}\left(\frac{r}{r_{\rm H}}\right)^{-5/4} \quad \text{for} \quad r_{\rm H} \le r < r_{\rm acc}$$

$r_{\rm H} = r_{\rm Sch} = 2GM_{\rm BH}/c^2$

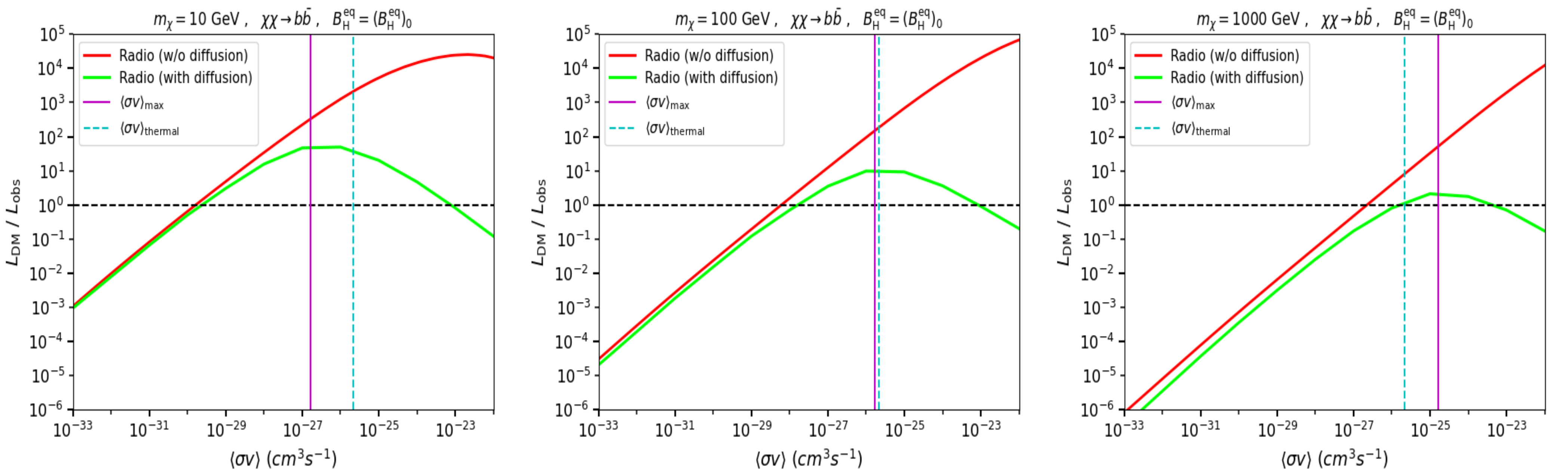
$r_{\rm acc}$ → accretion radius

$$B_{\rm H}^{\rm eq} \simeq 4\times10^{14}\,\dot{m}^{1/2}\left(\frac{M_{\rm BH}}{10M_\odot}\right)^{-1/2}\ [\mu G]$$

$\dot{m} \equiv \dot{M}/\dot{M}_{\rm Eddington}$ (accretion rate)

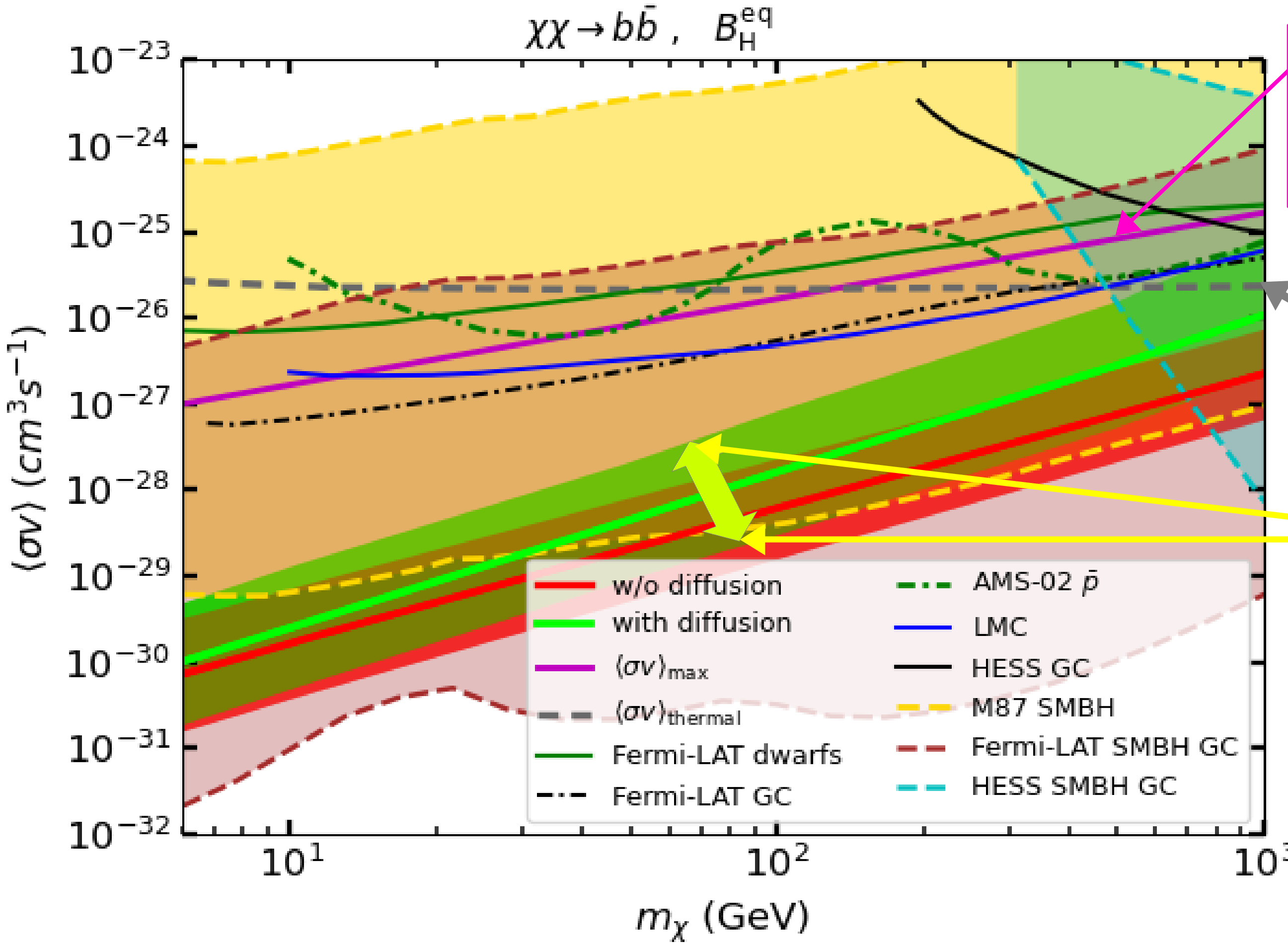
$$B_{\rm out}(r) = B^{\rm eq}(r_{\rm acc})\left(\frac{r}{r_{\rm acc}}\right)^{-2} \quad \text{for} \quad r \ge r_{\rm acc}$$

- Such a *B*-field profile is commonly used for the SMBHs for XTE J1118+480



DM induced radio luminosities (normalized to the observed one) as a function of ⟨σv⟩

Constraints on WIMP annihilation from XTE J1118+480 BH-LMXB

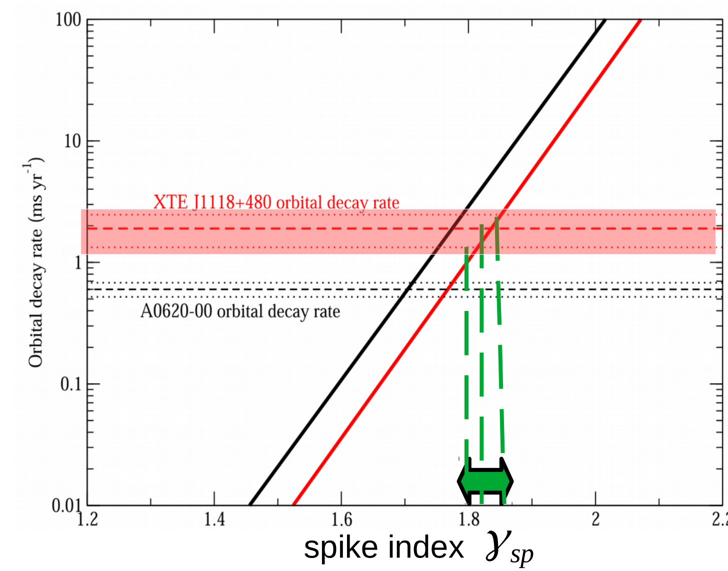


max **<σ v>** so that the annihilation saturation $\rho_{sat} = \frac{m_\chi}{\langle\sigma v\rangle\, t_{BH}} \geq \rho_{DM}(r_*)$ and the dynamical friction is active

$\langle\sigma v\rangle_{thermal} \simeq 2.2\times10^{-26}\ cm^3\ s^{-1}$
(*s*-wave annihilation)

[uncertainty due to spike index]

for "XTE J1118+480": $\gamma_{sp} = \mathbf{1.85 \pm 0.04}$

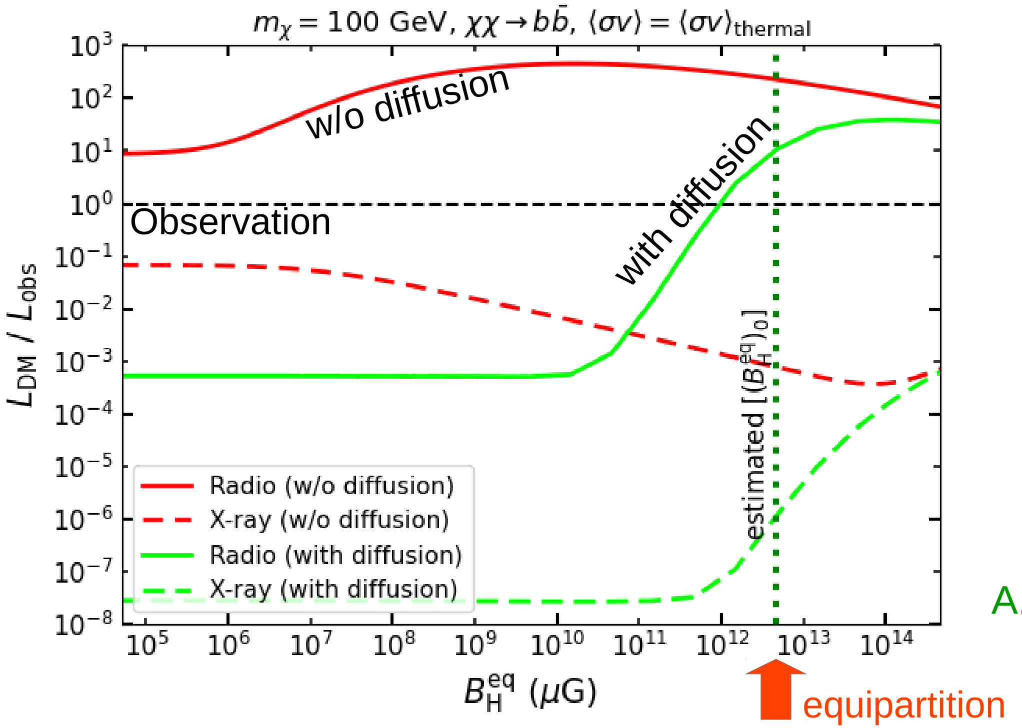


Strong constraint on <σ v> for m_χ up to TeV scale !

Much smaller uncertainty due to the spike index !

Uncertainty in the DM signal from the magnetic field

DM signal / observation



Signals are sensitive to the intensity of the *B*-field when the effect of diffusion is included

Much smaller uncertainty in the DM signal from the spike index

But, a large uncertainty from magnetic field

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$$B(r) = \begin{cases} B^{eq}(r) & \text{for} \quad r_H \le r < r_{acc} \\ B^{eq}(r_{acc}) \left(\frac{r}{r_{acc}}\right)^{-2} & \text{for} \quad r \ge r_{acc} \end{cases}$$

$r_H = r_{Sch} = 2GM_{BH}/c^2$

r_{acc} → accretion radius

$$B^{eq}(r) = B_H^{eq} \left(\frac{r}{r_H}\right)^{-5/4}$$

No direct access to the parameter B_H^{eq}

Assuming equipartition of energy :

$$B_H^{eq} \simeq 4 \times 10^{14}\, \dot{m}^{1/2} \left(\frac{M_{BH}}{10 M_\odot}\right)^{-1/2} \quad [\mu G]$$

$\dot{m} \sim 10^{-4}$ for XTE J1118+480

$\dot{m} \equiv \dot{M}/\dot{M}_{Eddington}$ (accretion rate)