Magnetic field in low–mass X–ray binaries and Dark Matter signals

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Based on:

A. Kar, H. Kim, S. P. Kim, S.S., "*WIMP constraints from black hole low--mass X-ray binaries*", *JCAP 03 (2024) 030* (2311.16539)

K. Choi, I. Jeong, S.Kang, A. Kar and S.S., "Sensitivity WIMP bounds on the velocity distribution in the limit of a massless mediator", JCAP 01 (2025) 007 (2408.09658)

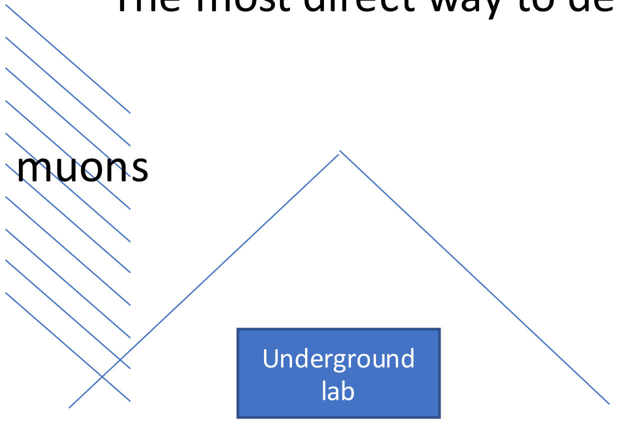
P. Gondolo, S. Kang, A. Kar, H. Kim and S. S., "Magnetic field equipartition in low–mass X–ray binaries", in preparation

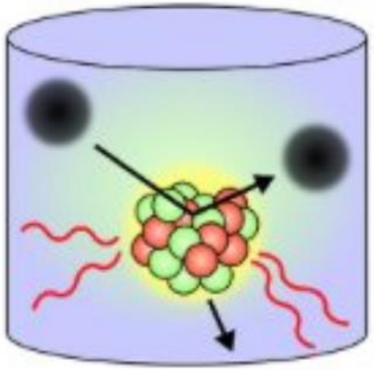
The visible part of Galaxies (including ours) is strongly believed to be embedded in a halo of invisible Dark Matter particles (the only alternative: modify gravity)

WIMPS (Weakly Interacting Massive Particles) are the most popular Dark Matter candidates (but many other possibilities…):

- few GeV < WIMP mass< few TeV
- No electric charge, no colour
- Weak-type interactions with ordinary matter keep WIMPS in thermal equilibrium in the early Universe and can provide the correct relic abundance through thermal decoupling ("WIMP miracle")

The most direct way to detect WIMPs: direct detection of its interaction with ordinary matter (it's all in the name!)

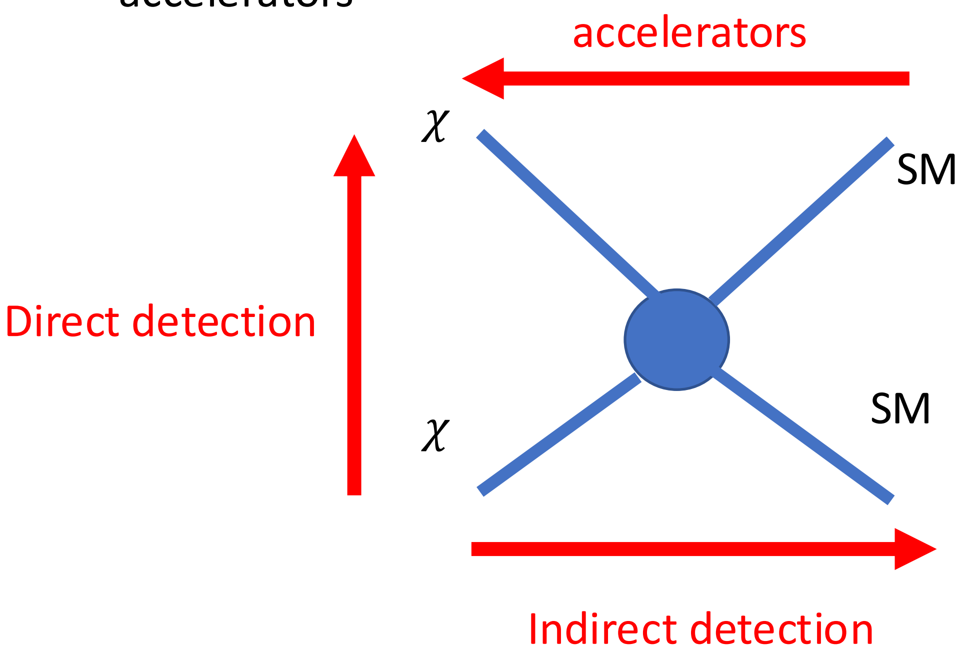




Measure nuclear recoil (~ keV range) from WIMP-nucleus elastic scattering in ionizator, scintillator, bolometer, bubble chamber, etc.

WIMP searches:

- Direct detection
- Indirect detection
- accelerators



Indirect detection:

- WIMP annihilation to photons/neutrinos/antiprotons/positrons in tha halo of our Galaxy
- Enhanced wherever the DM density is large (e.g. Galactic Center)
- Celestial bodies can accumulate WiMPs in their interior through their gravitational potential

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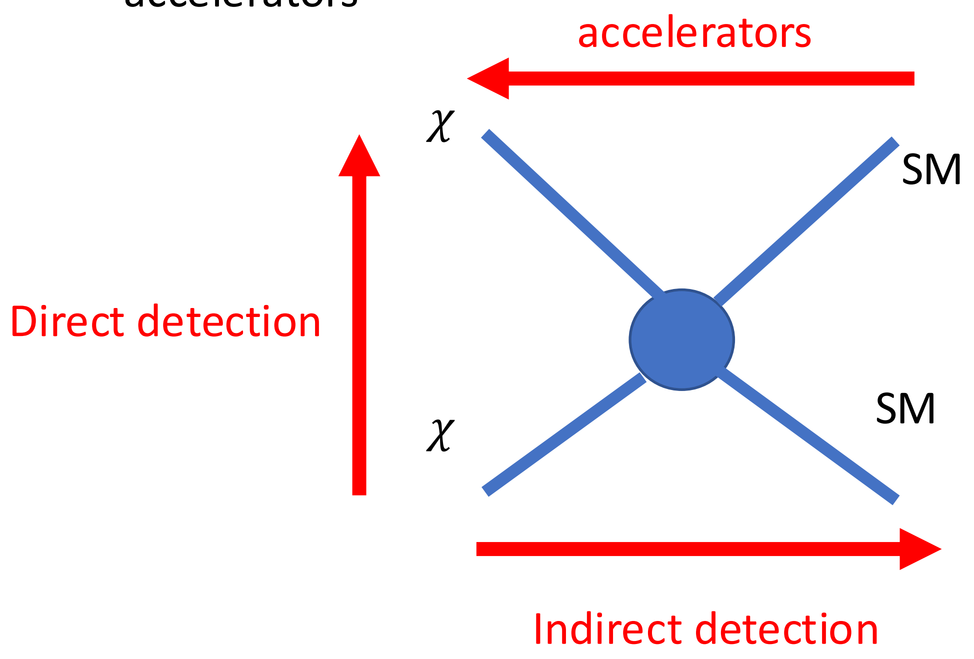

$<\sigma_{ann} v> \sim 3 \times 10^{-26}\ cm^3\ s^{-1}$ "standard thermal value"

Indirect detection:

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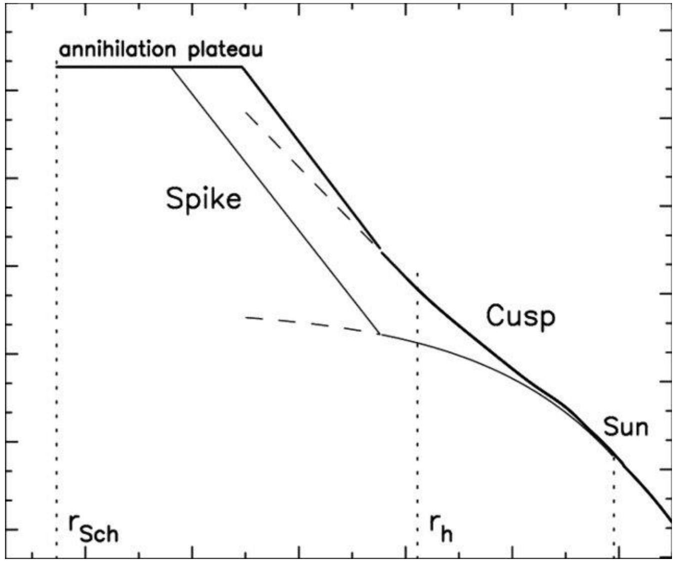
Dark Matter density profile at the Center of Galaxies

In cosmological simulations of cold and collisionless dark matter, a dark matter halo has a density profile that rises toward the center with a power index of −1 to −1.5 → cusp
This is not observed (cusp-core problem) but simulations do not include the effect of baryons.

Supermassive black hole (SMBH) with mass $M_{BH} \sim 3 \times 10^6 M_\odot$ located very close to the dynamical center of the Galaxy, and most likely associated to the compact radio source labeled Sgr A



The dark matter at the galactic center can be redistributed by the black hole into a cusp with density profile $r^{\gamma_{sp}}$ and $1.5 \lesssim \gamma_{sp} \lesssim 2.5$ (adiabatic compression, Gondolo, Silk, PRL83(1999)1719)

→ stong enhancement of the WIMP annihilation signal

very sensitive on the cups index γ_{sp}

Dark Matter Spike density profile

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

with:

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

spike index

and

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

constant value of the annihilation plateau

horizon radius:

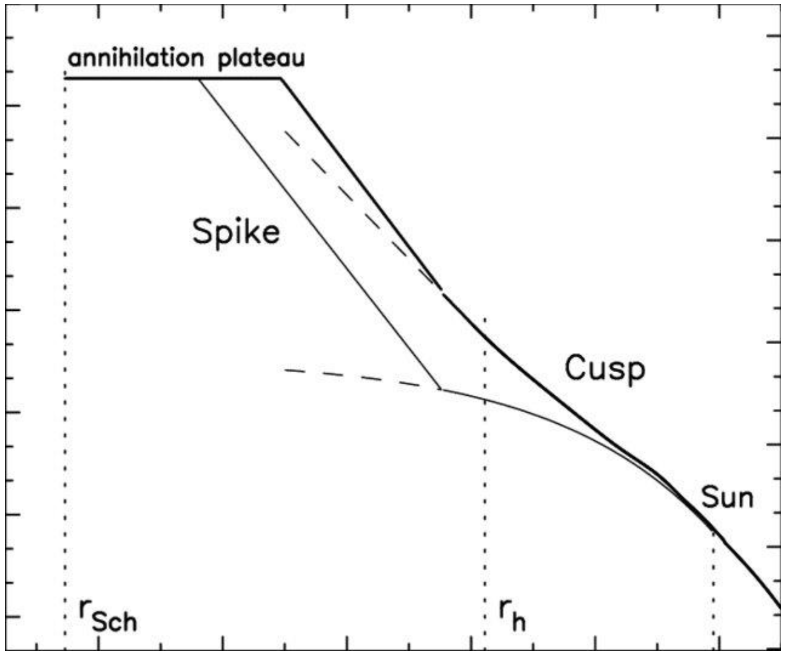
$$R_s = 2GM_{\rm BH}/c^2$$

spike radius:

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

radius of influence r_{in} defined by the relation:

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



WIMP annihilation signals are extremely sensitive to the spike index γ_{sp}.

What is the value of the spike index γ_{sp}?

Adiabatic contraction of the spike (Gondolo, Silk, PRL83(1999)1719)

Beyond the influx of the Black Hole the DM density profile is predicted by models of Galaxy formation (NFW, Moore, Einasto, etc). Suppose that:

$$\rho(r) = \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma}$$

$0<\gamma<2$

corresponding to the phase distribution f(E,L) (E=energy, L=angular momentum)

Locally, the presence of the BH redistributes the DM density as:

$$\rho'(r) = \int_{E'_m}^{0} dE' \int_{L'_c}^{L'_m} dL' \frac{4\pi L'}{r^2 v_r} f'(E', L')$$

with

$$v_r = \left[2\left(E' + \frac{GM}{r} - \frac{L'^2}{2r^2}\right)\right]^{1/2},$$

$$E'_m = -\frac{GM}{r}\left(1 - \frac{4R_S}{r}\right),$$

$$L'_c = 2cR_S\,,$$

$$L'_m = \left[2r^2\left(E' + \frac{GM}{r}\right)\right]^{1/2}.$$

(all particles with $L<L_c'$ are captured by the BH)

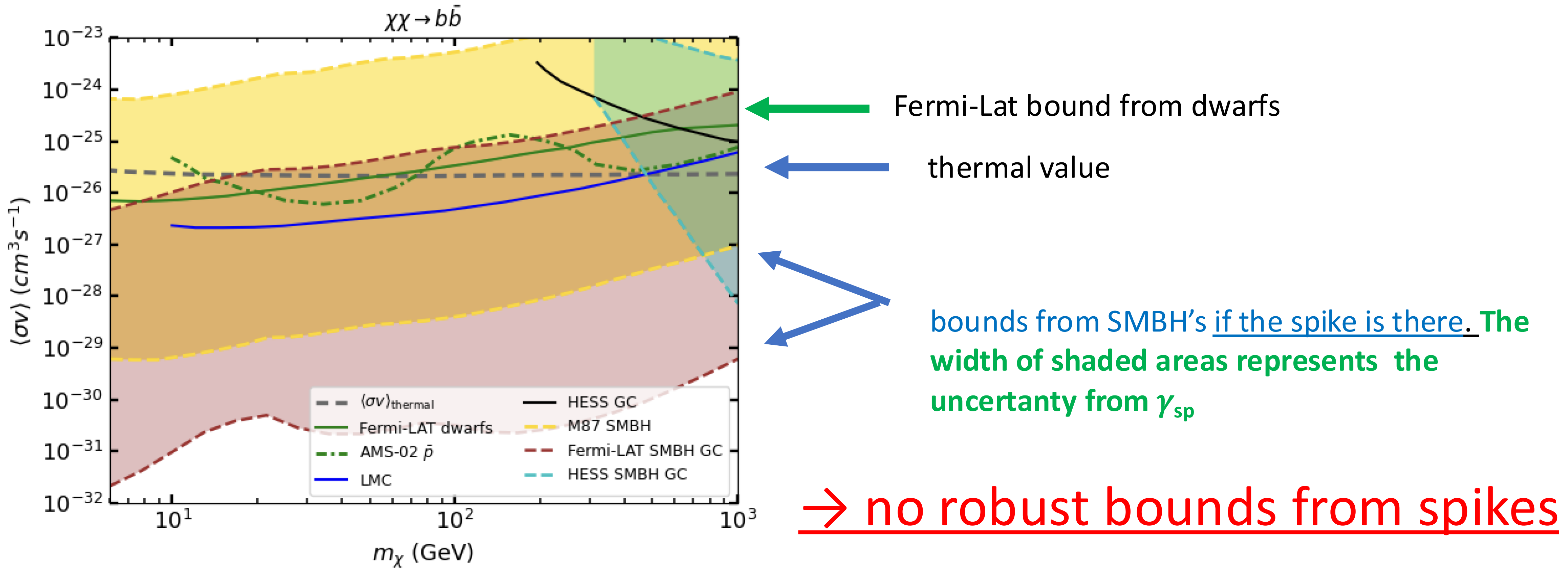
Adiabatic assumption: f'=f, L'=L, E=E'

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

Very uncertain.

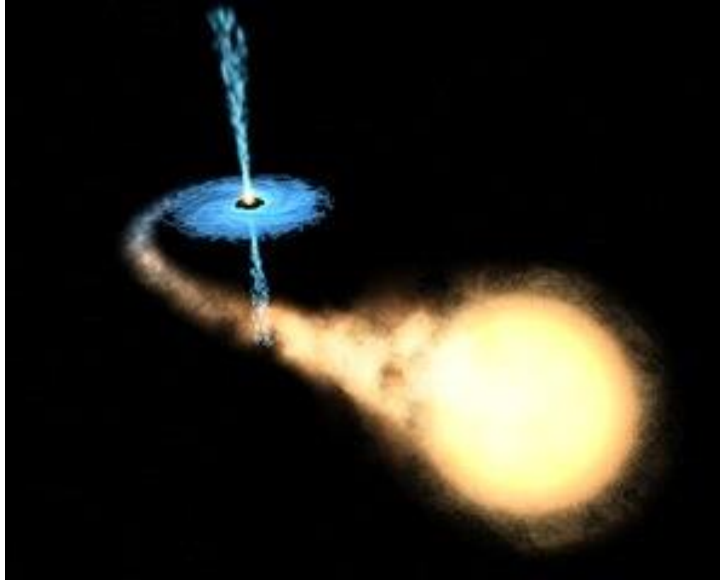
1. No cusp → no spike
2. Even if the cusp is there, the spike could not have been formed (BH or hosting galaxy experienced a non-adiabatic merger, or BH not exactly at the center)
3. Even if the spike is initially formed, it can be smoothed out by DM scattering off stars

In the literature, very strong bounds on $<\sigma v>$ have been published from the Super Massive Black Holes at the center of our Galaxy, or of the Large Magellanic Cloud, when the existence of the cusp is assumed, but they don't even reach the thermal value $<\sigma v>_{thermal} \sim 2.2 \times 10^{26}$ $cm^3 s^{-1}$ when the the uncertainty on δ_{sp} is taken into account



→ no robust bounds from spikes

XTE J1118+480: a low-mass X-ray binary in the constellation Ursa Major. Made of a Black Hole and a rotating star.
The study of the motion of the visible star allows an accurate measurement of the parameters of the system

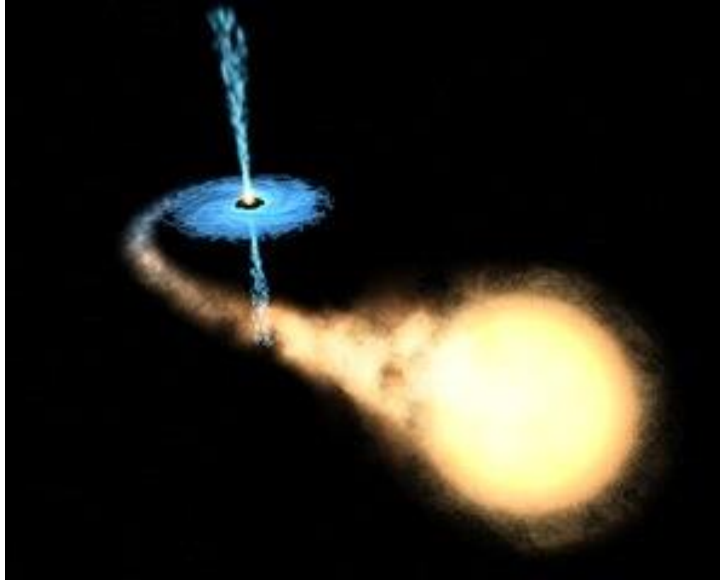


M_{BH}	$7.46^{+0.34}_{-0.69} M_\odot$ (Gonzalez Hernandez et al. 2014)
q =m_{star}/M_{BH}	0.024 ± 0.009 (Khargharia et al. 2013)
K (km s^{-1})	708.8 ± 1.4 (Khargharia et al. 2013)
i	$73.°5 \pm 5.°5$ (Khargharia et al. 2013)
P (day)	0.16993404(5) (Gonzalez Hernandez et al. 2014)
$\dot{P}$ (ms yr^{-1})	-1.90 ± 0.57 (Gonzalez Hernandez et al. 2014)
d (kpc)	1.70 ± 0.10 (Gonzalez Hernandez et al. 2011)

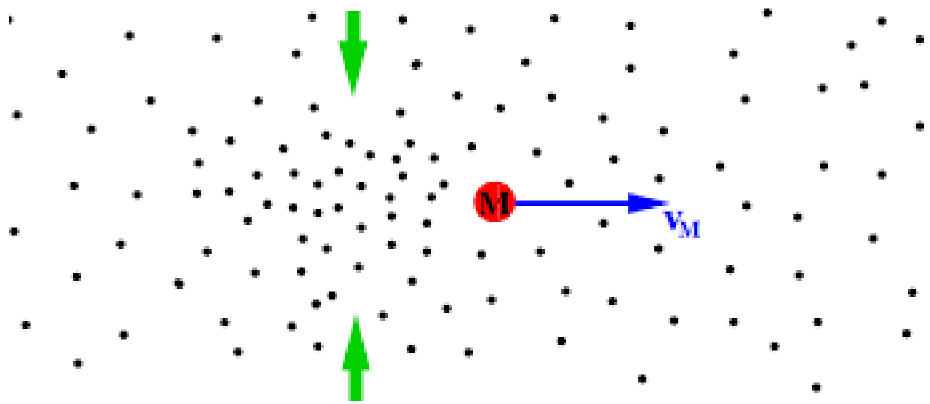
low-mass black hole (few solar masses) + visible star ~2% of that

Change of rotational period abnormally high: -1.9 ms/year

- Difficult to explain $\dot{P}$ = -1.9 ms/year in XTE J1118+480, **2 orders of magnitude larger** than the one expected with gravitational-wave radiation
- Two possible explanations:
  - ❑ orbital period reduced by coupling between the magnetic field and the 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



Alternative explanation: the star is slowed down by the dynamical friction with a steep dark matter density spike close to the Black Hole



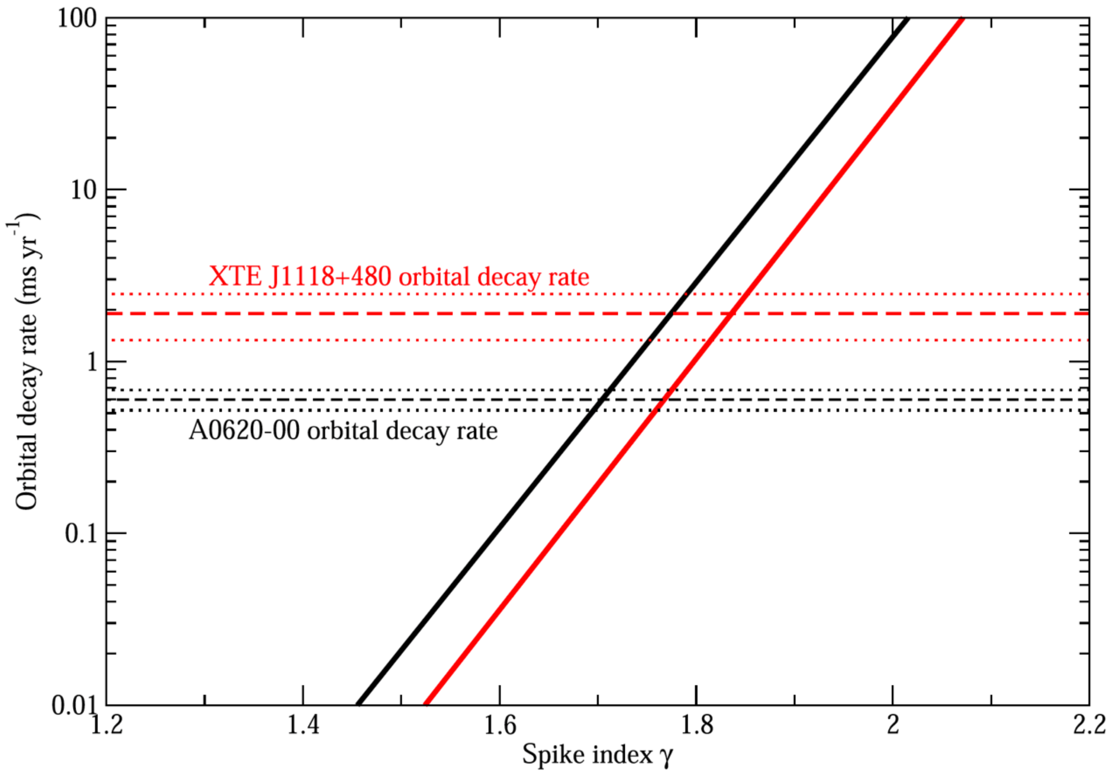
Dynamical friction: if the star is crossing a very dense spike of DM particles, a concentration of DM particles develops behind the rotating star, slowing it down

Orbital decay due to dynamical friction between DM and the star

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

depends on the observed parameters of the BH–LMXB and the spike density. The only free parameter is the spike index $\gamma_{\rm sp}$ → **can determine $\gamma_{\rm sp}$ from observation**

M.H.Chan and C.M.Lee, Astrophys. J. Lett. 943, no.2, L11 (2023)



using observed value of $\dot{P}$:

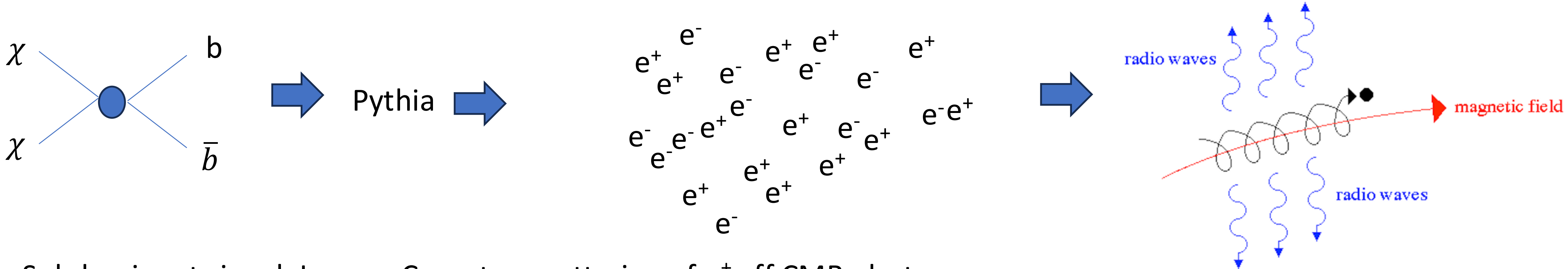
$\gamma_{\rm sp} = 1.85 \pm 0.04$ for XTE J1118+480

at variance with SMBH in the Galactic Center, or in LMC

very small uncertainty → **much smaller uncertainty in the calculation of DM signals**

DM signal from XTE J1118+480

Main source of signal: syncrotron radiation from $e^{\pm}$ produced from DM annihilation in BH magnetic field



Subdominant signal: Inverse Compton scattering of $e^{\pm}$ off CMB photons

Solve diffusion equation (f=density of $e^{\pm}$ assumed in equilibrium) :

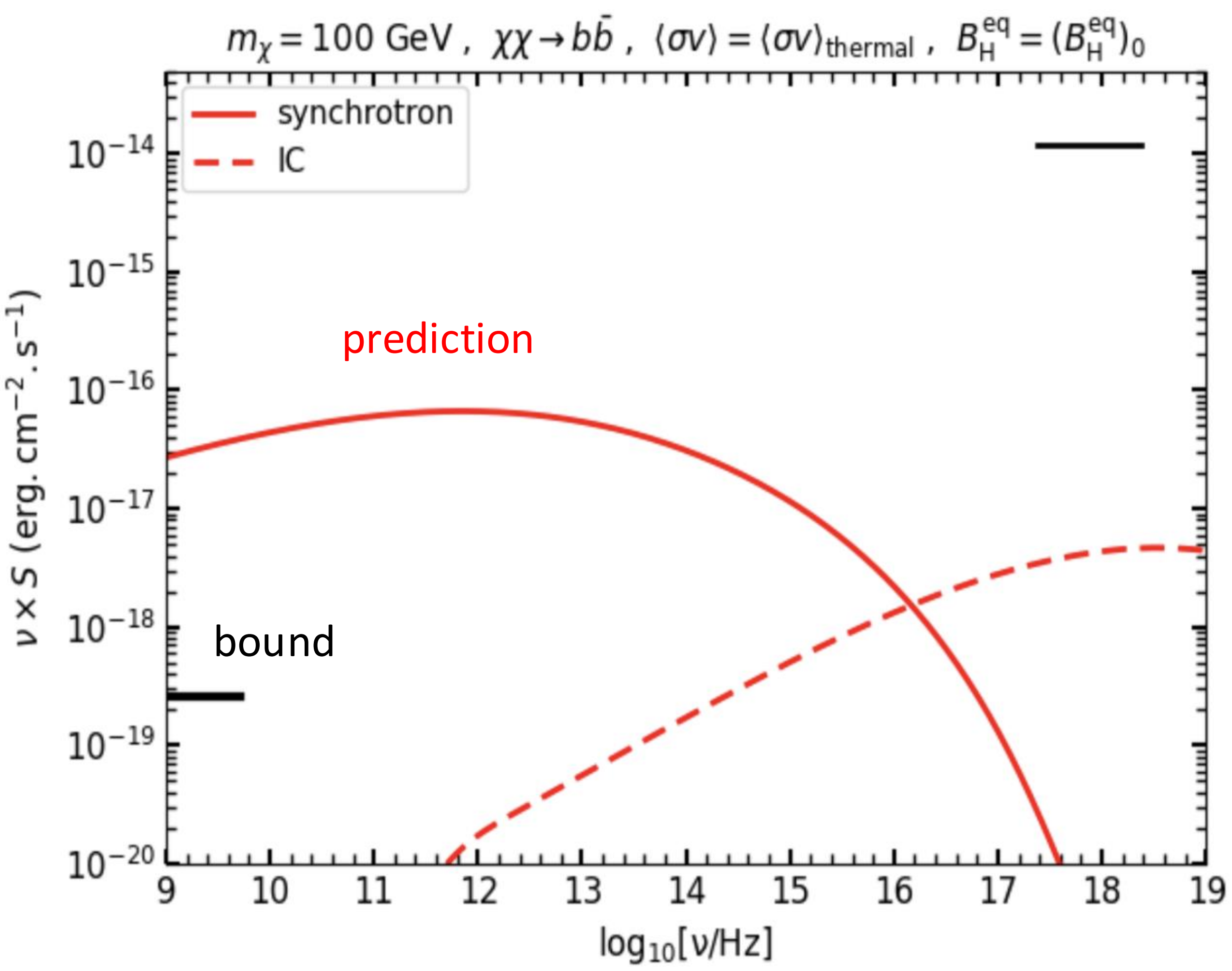
$$-\frac{1}{r^2}\left[r^2 D\frac{\partial f}{\partial r}\right] + \frac{1}{p^2}\frac{\partial}{\partial p}(\dot{p}p^2 f) = q(r,p)$$

diffusion coefficient

source from DM annihilation

$D(r,p)=(1/3)\, r_g v_e$ with $r_g=E/(eB)$ (the $e^{\pm}$ gyroradius and v_e ~c the electron velocity (assuming Bohm diffusion, i.e. that the coherence length of the magnetic field is comparable or greater that r_g)

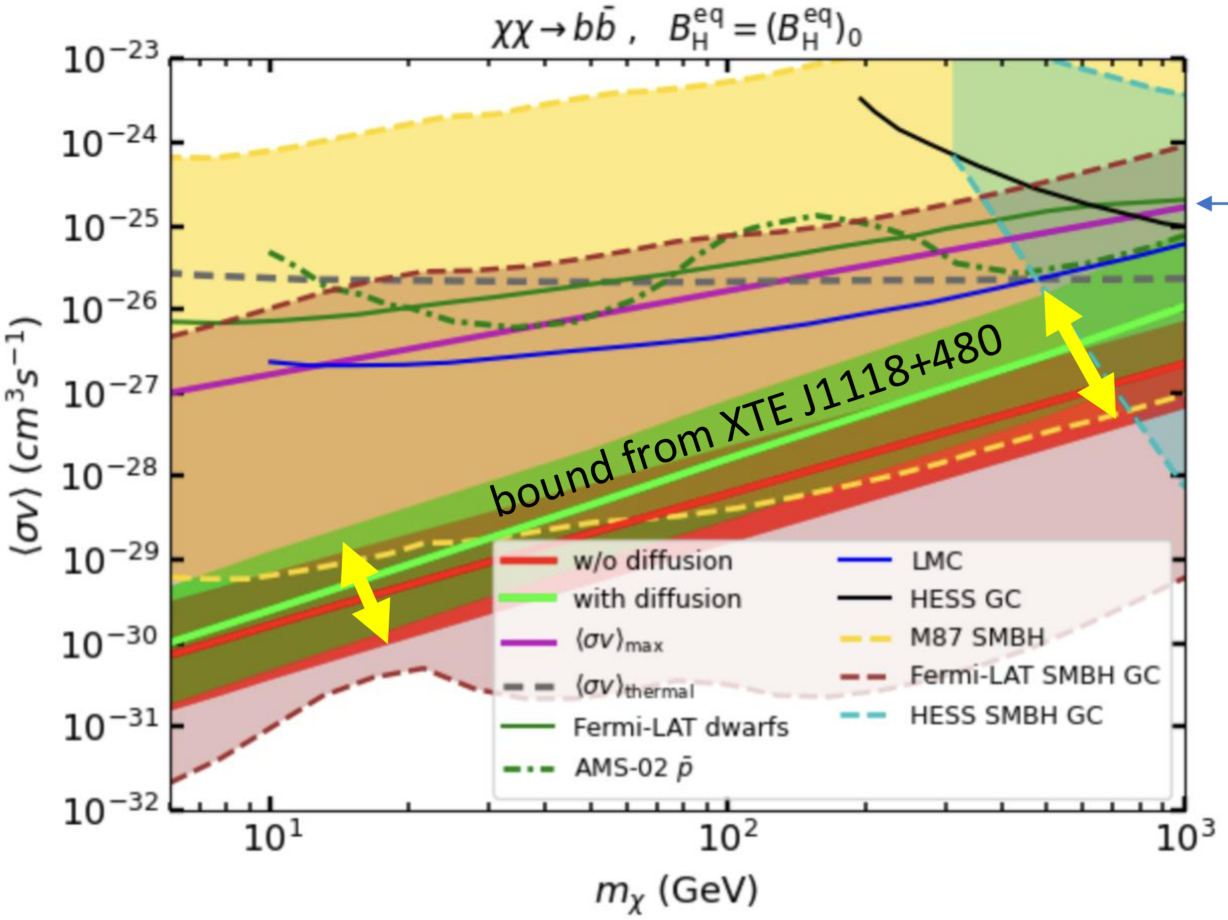
DM signal from XTE J1118+480



strong constraint!

A. Kar, H. Kim, Sang Pyo Kim, S.S, JCAP 03 (2024) 030

DM signal from XTE J1118+480



bound from Fermi-LAT dwarfs

thermal <σv>

strong constraint, small uncertainty!

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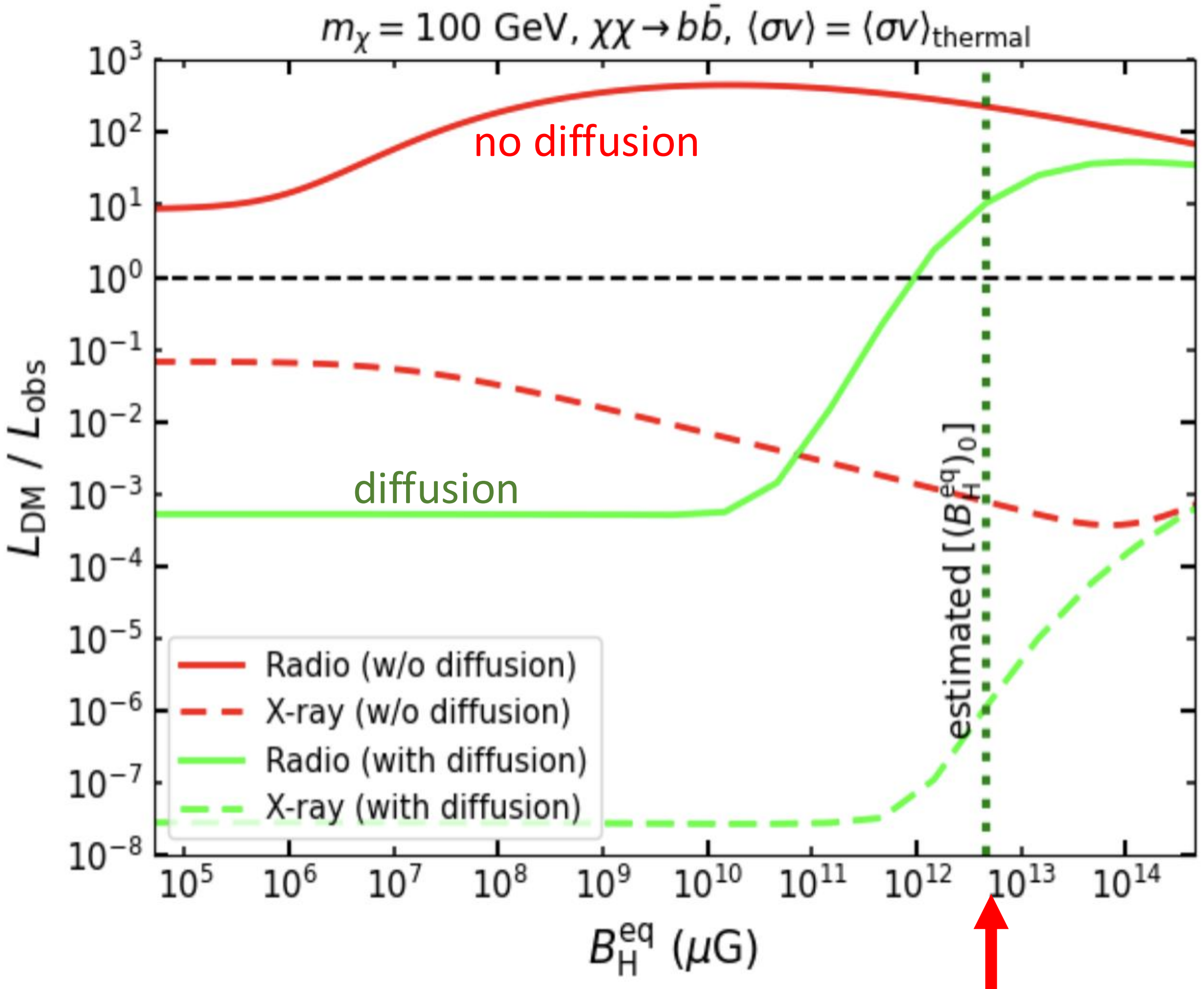
However, large uncertainty in the DM signal calculation **from the magnetic field**



equipartition

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

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

No direct access to B^{eq}_H parameter. Assuming equipartition of energy:

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

with $\dot{m} \sim 10^{-4}$

On general grounds B~10^{10} μG for supermassive black hole ($M_{BH} \simeq 10^9 M_\odot$) and B~$10^{14}$ μG for a stellar mass one (as in XTE J1118+480)

predictions are sensitive to the intensity of the magnetic field when the effect of diffusion is included

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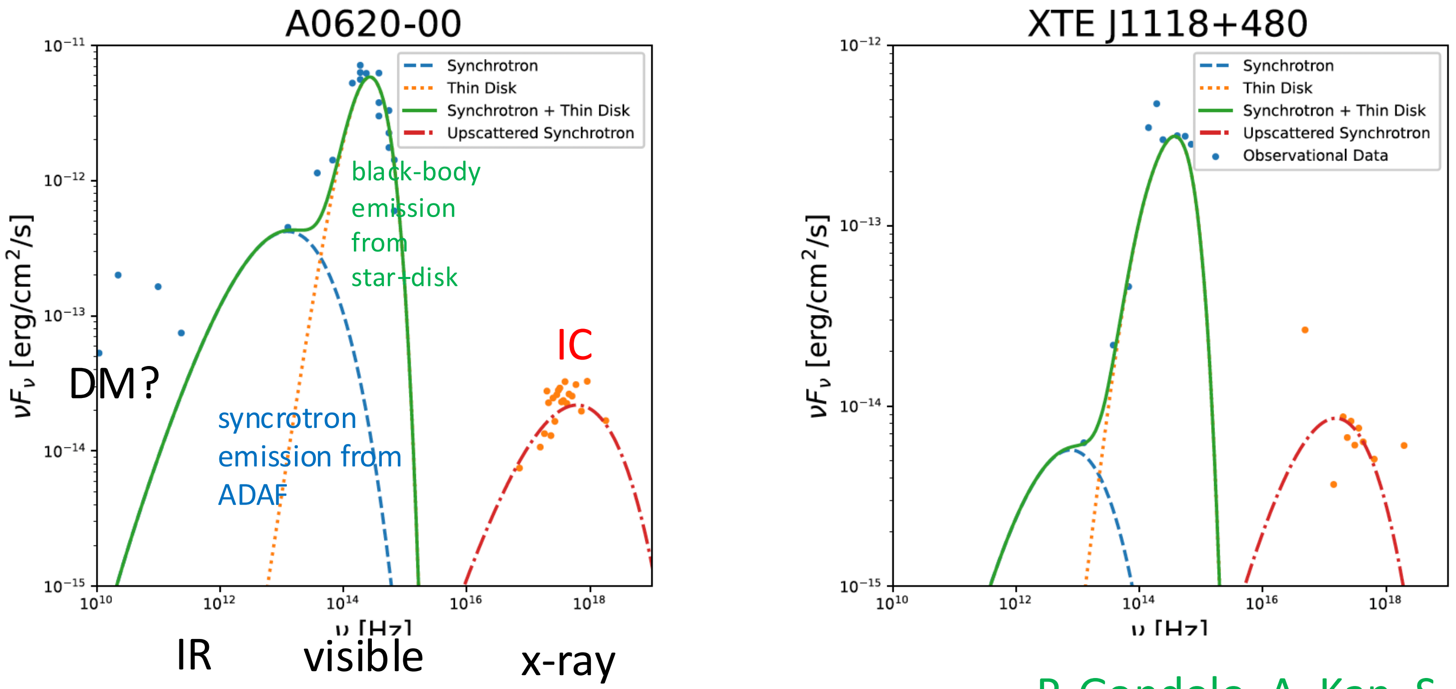
the bottom line: we have traded the uncertainty on the spike profile index for another one: the intensity of the magnetic field….

can we better estimate the magnetic field from the emission data?



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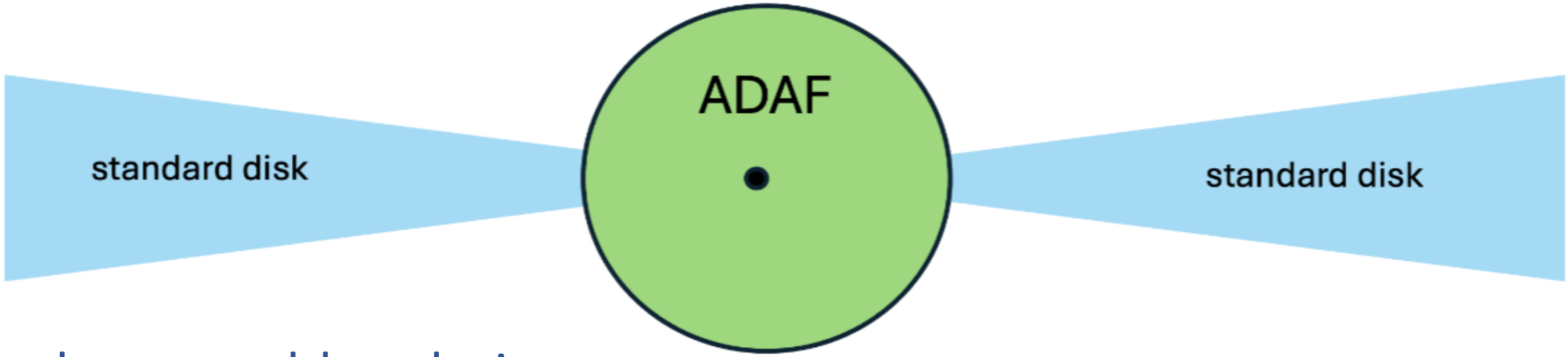
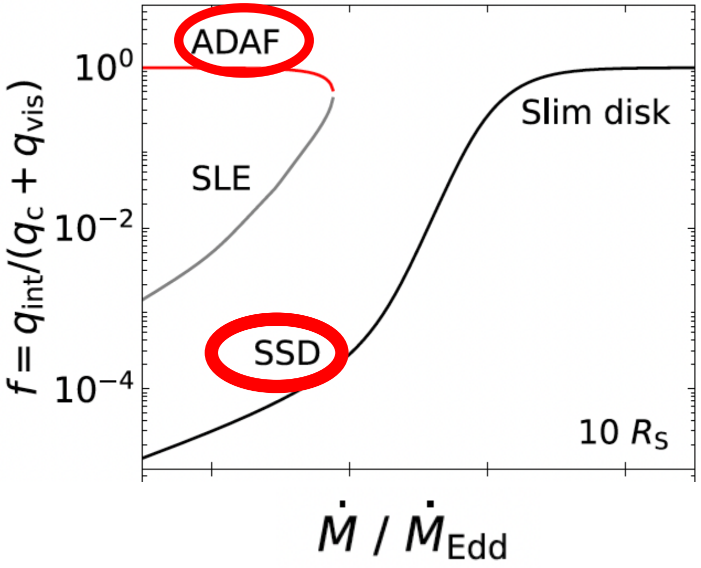
Schematic view of the accretion disk (Ichimaru 1977, Rees er al, 1982, Narayan and Yi 1994)



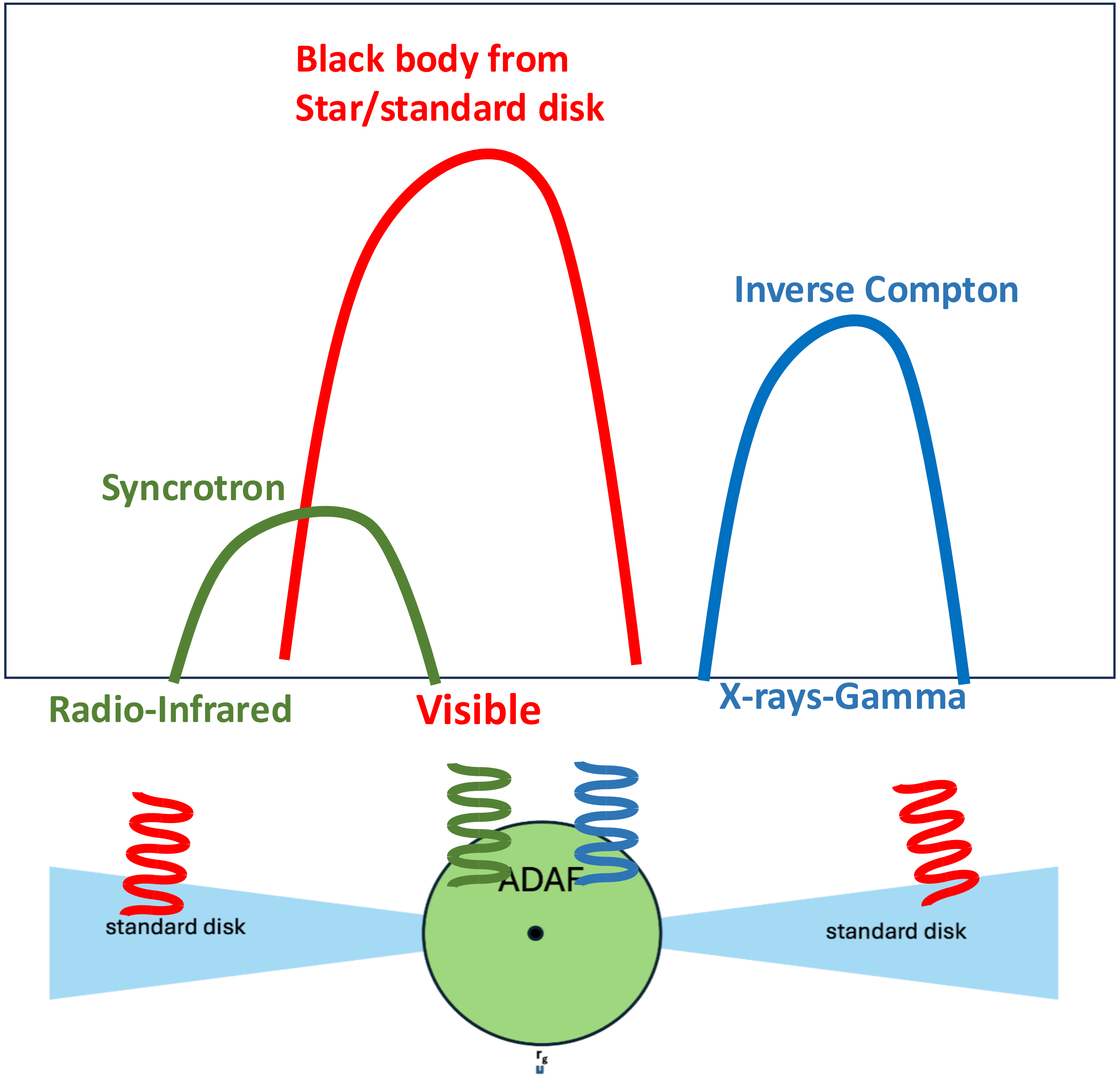


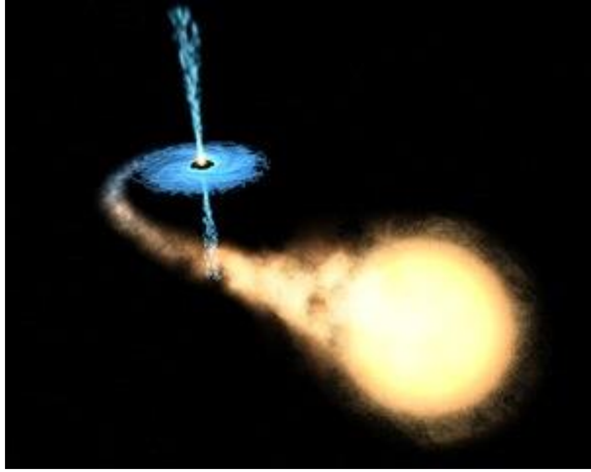
only two stable solutions:

Standard Shakura-Sunayev disk (SSD): geometrically thin, optically thick disk in thermal equilibrium. Produces black-body emission in the visible spectrum from its surface at the same temperature of the companion star

Advection Dominated Accretion Flow (ADAF): geometrically thick, optically thin disk of thermal electrons and protons falling inside the Black Hole → small scale stochastic magnetic field created by the charged particles of energy density up to that of the gas (equipartition) → synchrotron emission (infrared) emitted by electrons or electron-radiation inverse Compton (X-rays)

The emission from an LMXB in a nutshell





N.B. both Synchrotron and Inverse Compton from the ADAF are sensitive to the magnetic field and to the inner gas temperature T_c (that drives absorption)

Important point: at low T_c absorption dominates (the gas becomes optically thick – lower signal) while when T_c is high the gas becomes transparent (higher signals)

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An Observational Signature of Sub-equipartition Magnetic Fields in the Spectra of Black Hole Binaries

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X-Ray Spectra from Weakly Magnetized Accretion Flows

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In these papers T_c *assumed* ~ 5e10 K and a very strong upper bounds $\epsilon_B \lesssim 6 \times 10{-}5$ on the magnetic filed is found – **can the magnetic field be larger than that??**

Intensity of the magnetic field in terms of its equipartition value

$$B(r) = \sqrt{\epsilon_B}\, B_{eq}(r)$$

$$B_{eq}(r) = 7.7 \times 10^8 \alpha^{-1/2} m^{-1/2} \dot{m}^{1/2} r^{-\frac{5}{4}} \text{ G.}$$

- α=0.3 = viscosity parameter
- m = BH mass in solar masses
- $\dot{m}$ = accretion rate in terms of Eddington value

our ignorance on the Magnetic field parameterized in the free parameter ε_B

We recalculate the full spectrum from the ADAF **without fixing a priori the gas inner temperature T_c**

- deep inside the ADAF electrons and ions have different temperatures T_e and T_i
- for values of the accretion rate $\dot{M} \gtrsim 10{-}3\ M_{eddington}$ (the Eddington accretion rate) electrons are known to be thermal
- the standard procedure to obtain the temperature of electrons is to assume energy balance between **the energy transfer rate q_{ie} from the ions to the electrons via Coulomb collisions** and the cooling rate q_{rad} of **radiative processes**:

$$q_{ie} = q_{rad}$$

q_{rad} takes contribution from all radiative processes: Bremsstrahlung, Syncrotron, Bremsstrahlung self-Compton, Syncrotron self-Compton:

primary Syncrotron radiation

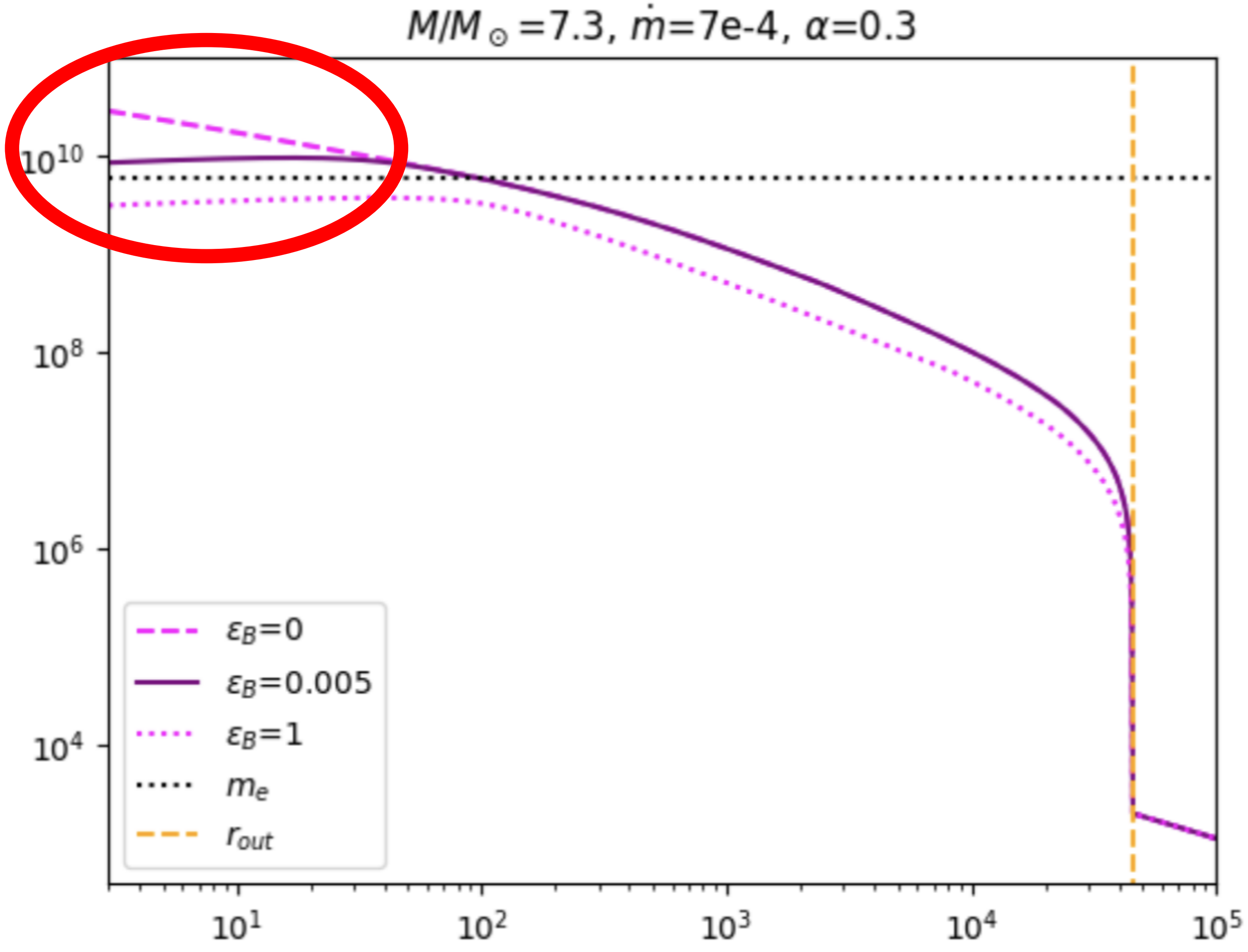
secondary processes: Compton and Bremsstrahlung from primary Syncrotron radiation

$$q_{rad} = q_{br} + q_{syn} + q_{syn,C} + q_{syn,\ br}$$

Synchrotron-induced processes quickly dominate if $B \neq 0$

N.B. increasing the magnetic field enhances radiative processes cooling down the gas!

Calculating the radial temperature profile with different values of ε_B (Magnetic field)



Indeed, when ε_B=1 the gas inner temperature T_c cannot reach 5e10 K in the first place.

two parameters in the calculation: the accretion rate $\dot{m}$ and ε_B

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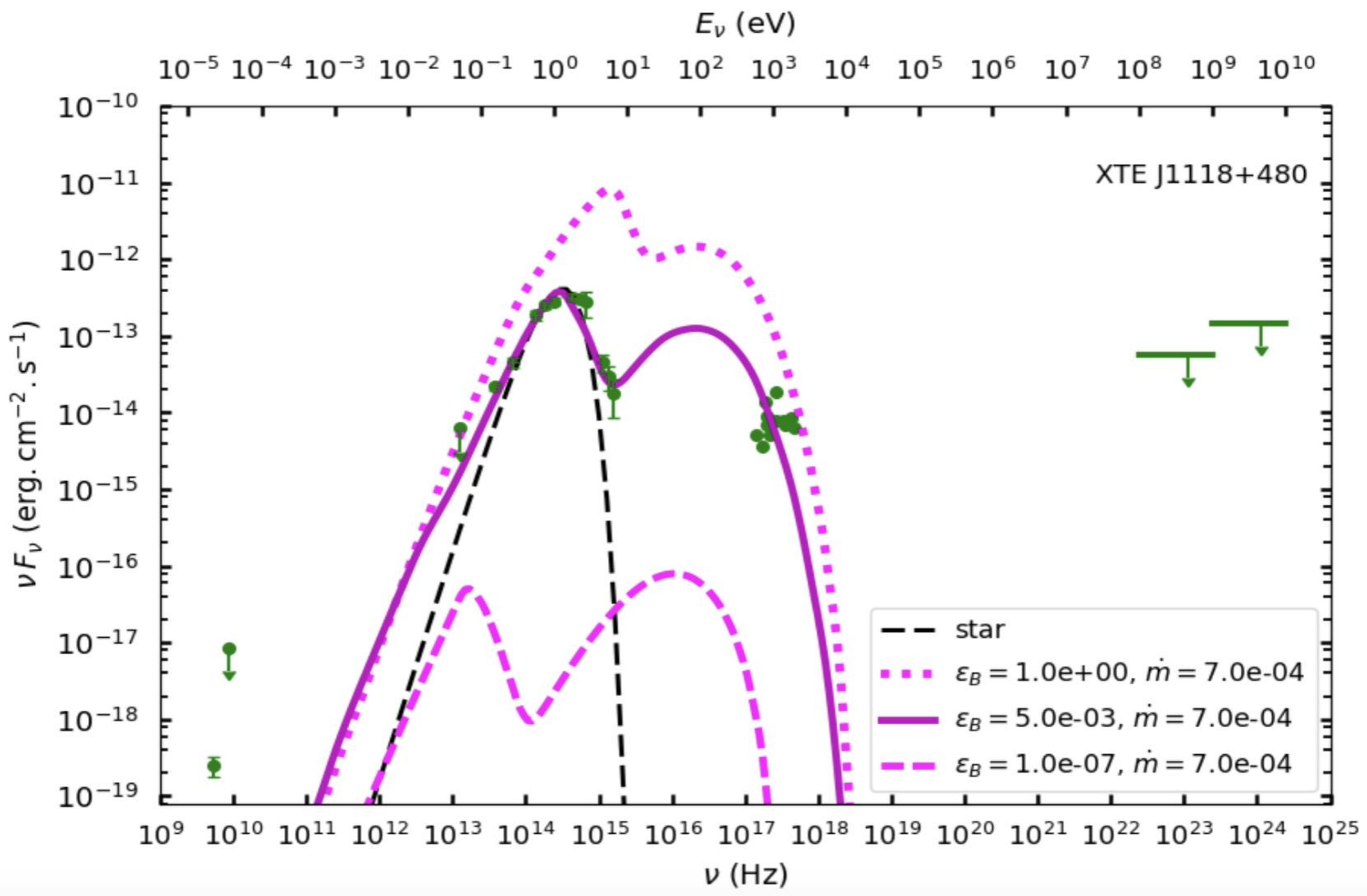
Calculated radial temperature profile with different values of ε_B (Magnetic field)



two parameters in the calculation: the accretion rate $\dot{m}$ and ε_B

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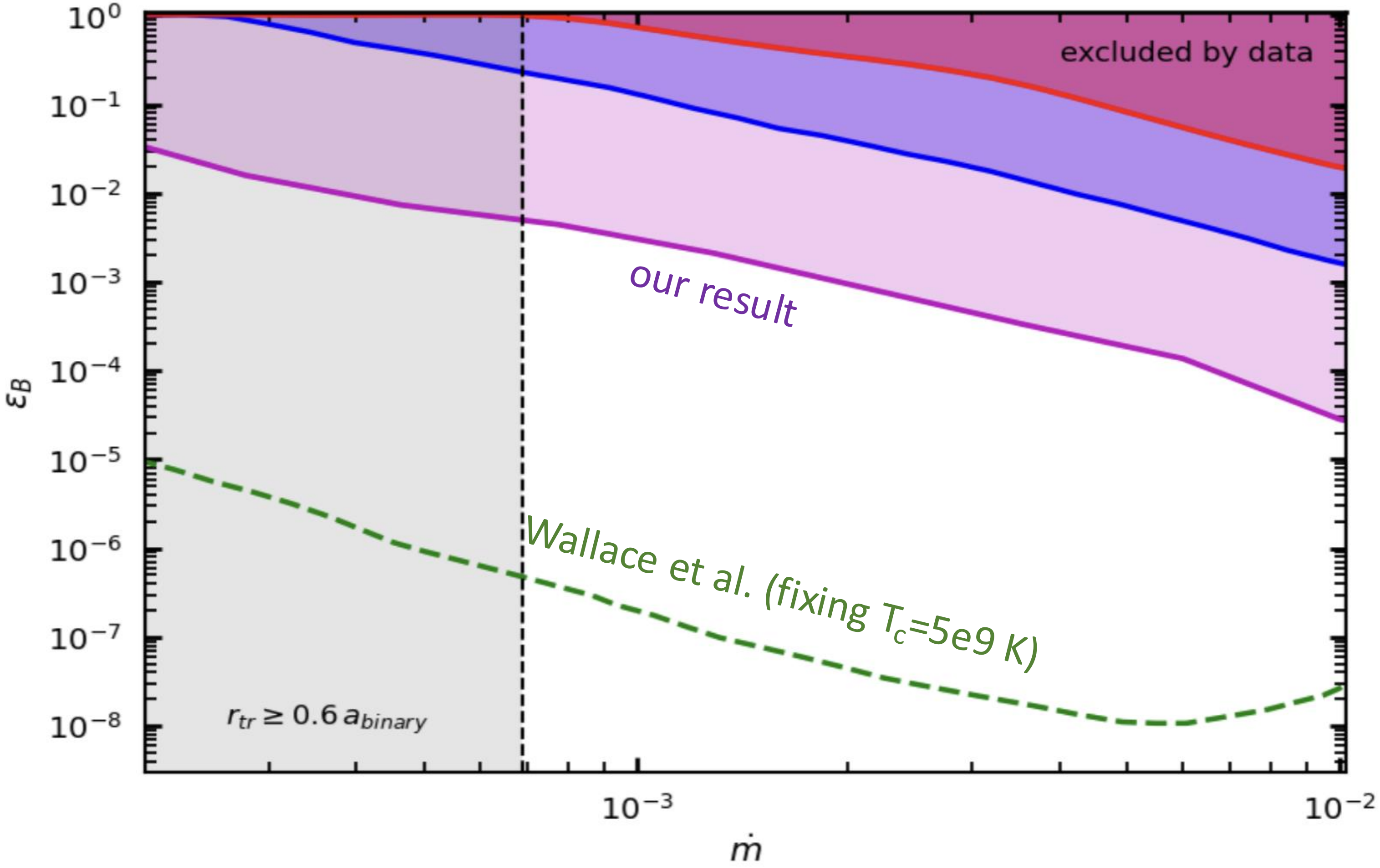
Upper bound on ε_B when the inner temperature is recalculated in a consistent way



The botton line: taking into account that a larger magnetic field cools the gas and suppresses the signal due to absorption **the observable upper bound on ε_B is less severe** than by fixing T_c to a high value – nevertheless the magnetic field compatible to observation **is still much lower than the equipartition value**.

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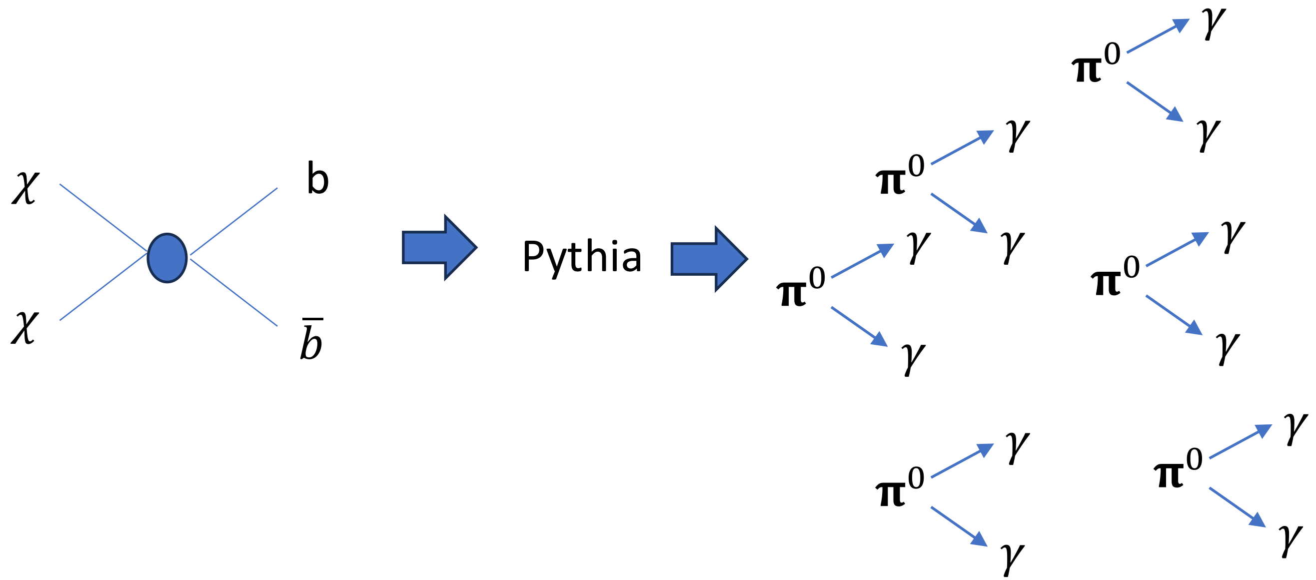
comment: looking directly for a signal in the gamma spectrum (~ tens of GeV) would be the simplest way to look for DM

- no dependence on the accretion disk details
- including no dependence on the magnetic field
- present bounds very weak (astronomers do not allocate telescope time to this part of the spectrum!)



continuum spectrum, up to $E=m_{DM}$

Conclusions

- The Dark Matter cusp in Low-Mass X-ray binaries can potentially put constraints on the WIMP annihilation cross section times velocity <σv> that exceed existing ones by several orders of magnitude (but we need to better understand the intensity and coherence of the magnetic field)
- Very strong upper limits on the magnetic field claimed in the literature (at fixed inner gas temperature)
- A careful reconstruction of the magnetic field in the low-mass X-ray binary XTE J1118+480 that recalculates the temperature including the cooling effects of the magnetic field leads to milder bounds still much lower than equipartition
- **→ rather than exclude a large magnetic field when the inner temperature is large: a large magnetic field cools the gas so that a high inner temperature is not possible in the first place.**
- looking directly for a signal in the gamma spectrum (~ tens of GeV) would be the simplest way to look for DM