Indirect search for Dark Matter by looking at Jupiter

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INTRODUCTION

In my work I have looked for gamma-ray signals from **Jupiter** by studiying FermiLAT data.
No signal has been found, but upper limits on gamma-ray flux by Jupiter can be «translated» into upper limits on **cross section** for DM-nucleon interaction.

DATA ANALISYS: settings

Jupiter's **path** on the sky from 1/1/2009 to 31/12/2023 (**15 years** of FermiLAT data) has been **partitioned** into **1202** steps (each one being a 0.5 deg displacement on the sky).
Inside each step, Jupiter can be considered a **stationary point-source** in the **centre of ROI**.

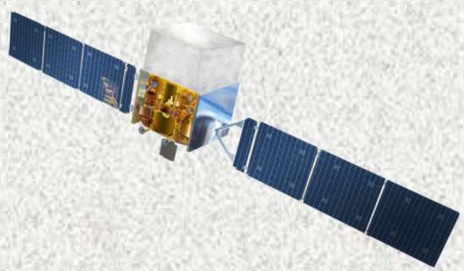
NB: We have **EXCLUDED** data corresponding to Jup-Sun proximity (30 deg theshold), Jup-Moon proximity (15 deg theshold), Jup-GalPlane proximity (15 deg theshold).

CONFIG PARAMETERS

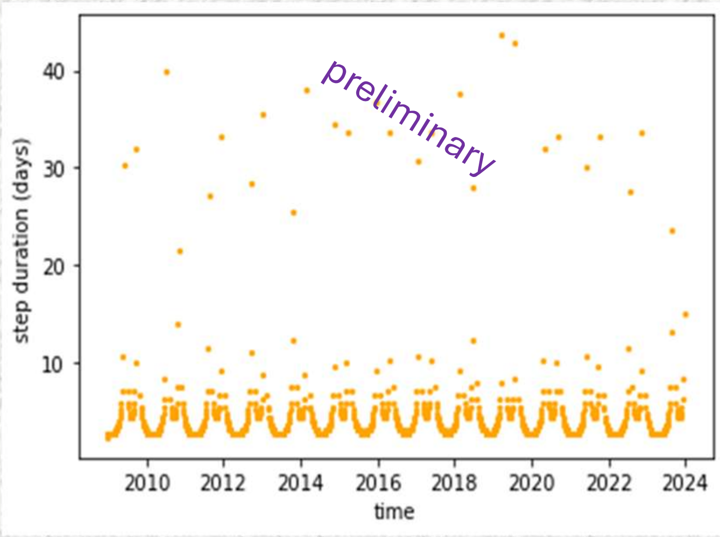
binning:
 roiwidth : 20 deg
 binsz : 0.5 deg
 binsperdec : 8

selection :
 emin : 56 MeV
 emax : 2000 GeV

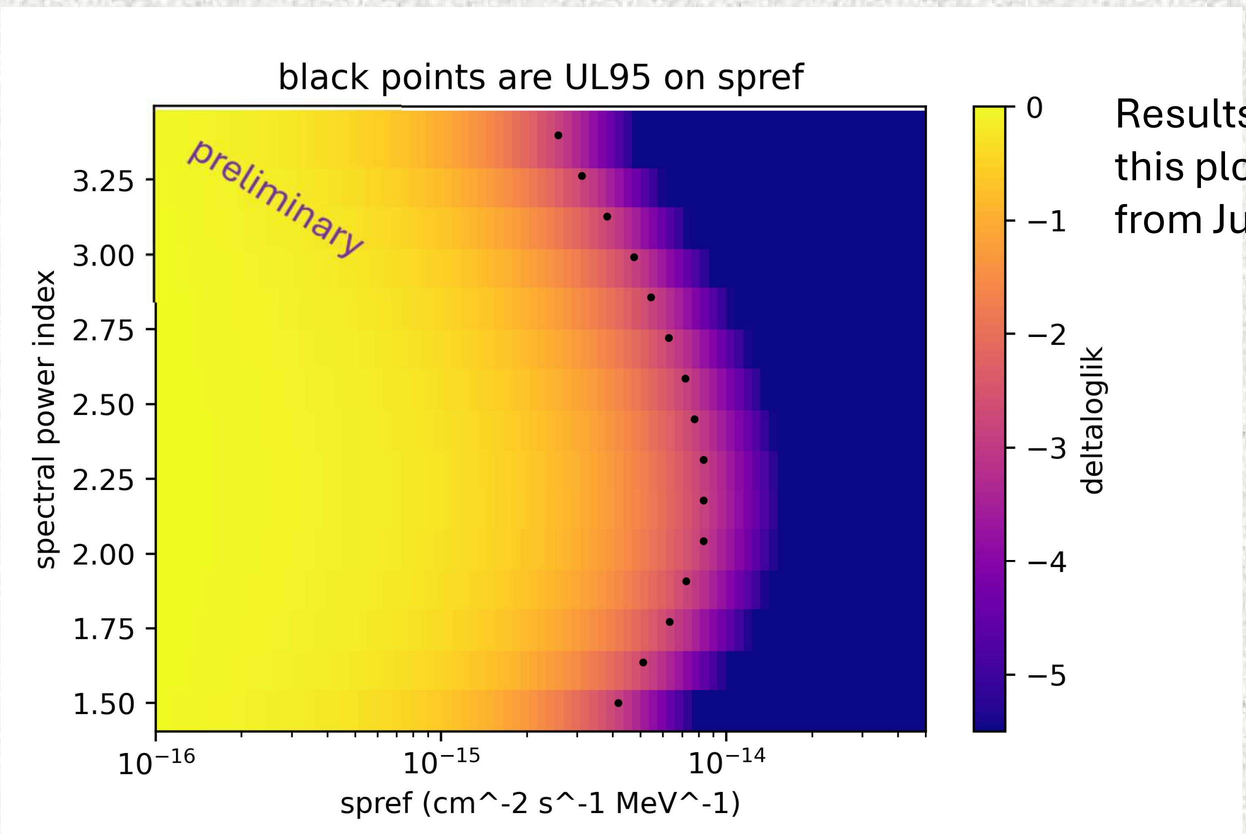
<u>Fermipy and Fermitools</u> packages have been used to perform this analisys.



Jupiter position in the sky at different times has been computed by exploiting Python libraries dedicated to calculation of ephemerides (**astropy.coordinates**).



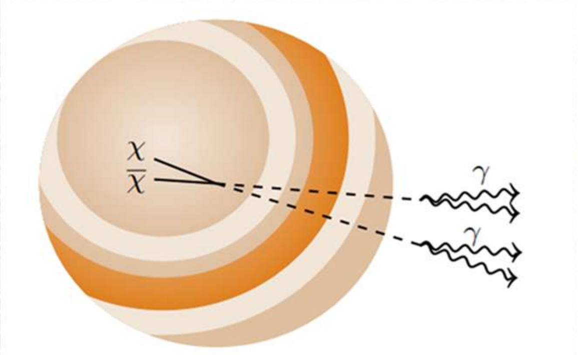
DATA ANALISYS: summary plot



Results of all stackings are summarized in this plot, showing that **no signal** is observed from Jupiter.

DM MODEL: the annihilation model

Then I have hypothesized a **simple scenario** in which eventual signals from Jupiter are all produced by annihilation between **dark matter** particles.
In order to make annihilation possible, DM particles should be **Majorana particles**.



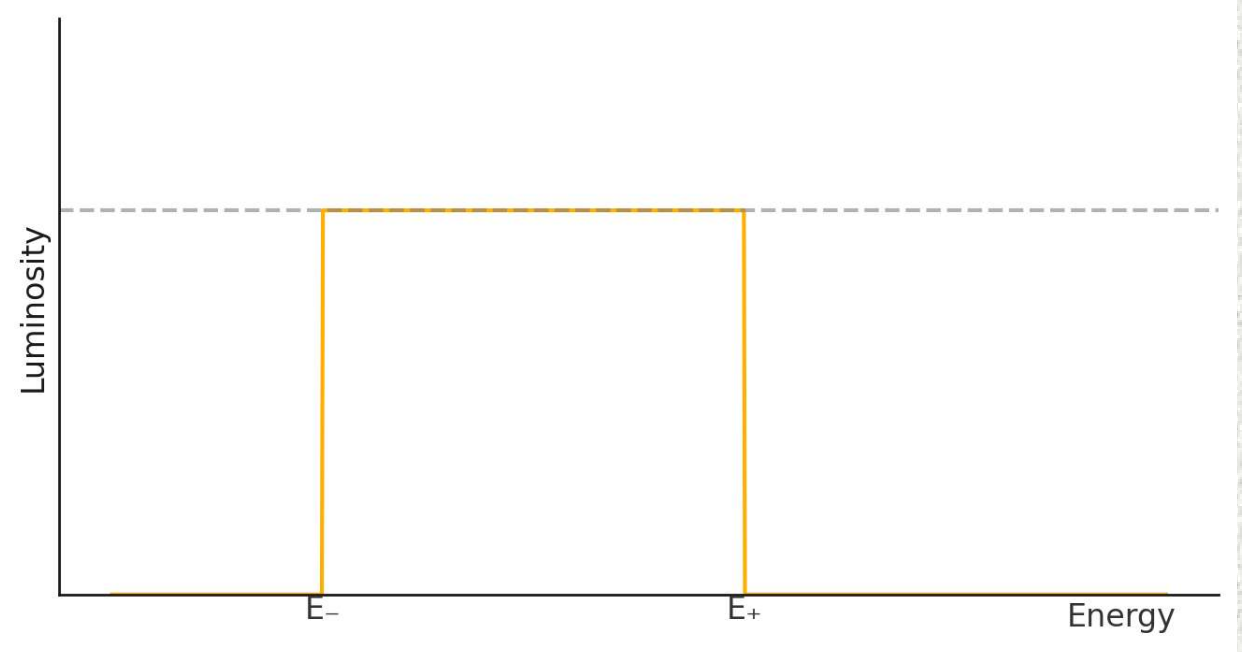
Schematic of DM annihilation to long-lived particles in Jupiter. The long-lived particles can decay outside the Jovian surface, producing a new source of γ-rays.

$$X\,\overline{X} \rightarrow \phi\,\phi \rightarrow 4\gamma$$

The emission model I have considered assumes that annihilation produces two mediator scalar particles ϕ (so 0-spin mediators) *[S.Profumo, ISBN:978-1786340016]* **.**
These mediators then decay producing **4 gamma-ray photons** (2 for each ϕ).

DM MODEL: a box-shape spectra

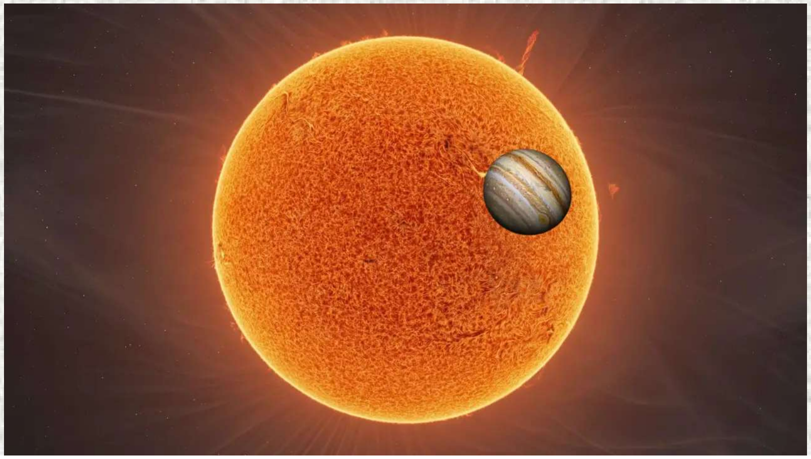
It can be demonstrated that this model implies a box-shape emission.
In particular: hypothetical emission by Jovian dark matter should be **constant** between:
$E_- = \frac{m_X}{2} \cdot [1 - \sqrt{1 - r^2}]$ and $E_+ = \frac{m_X}{2} \cdot [1 + \sqrt{1 - r^2}]$
where $\boldsymbol{r} = \frac{\boldsymbol{m_\phi}}{\boldsymbol{m_X}}$ and X indicates the DM particle.



DM MODEL: why Jupiter

Making this study on Jupiter instead of the Sun has **two advantages** and **one disadvantage**:
- Jupiter has not the strong gamma-ray background that our Sun has (**advantage**);
- Jupiter is colder than our Sun, so that evaporation is negligible (**advantage**);
- Jupiter is less massive than our Sun (**disadvantage**), so it should contain less dark matter.

Evaporation is the escape rate of DM particles from the planet/star.
Escape happens when velocity of a particle is higher than **escape velocity of the planet/star**.
It can be showed that evaporation is negligible (for Jupiter) if $m_X > 0.1\ GeV$.
Thesold for our Sun is $1\ GeV$.



DM MODEL: assuming equilibrium

I have assumed that planet has reached **equilibrium** between capture of dark matter particles and annihilation.
So total **number of DM particles** inside the planet is assumed to be **constant**.

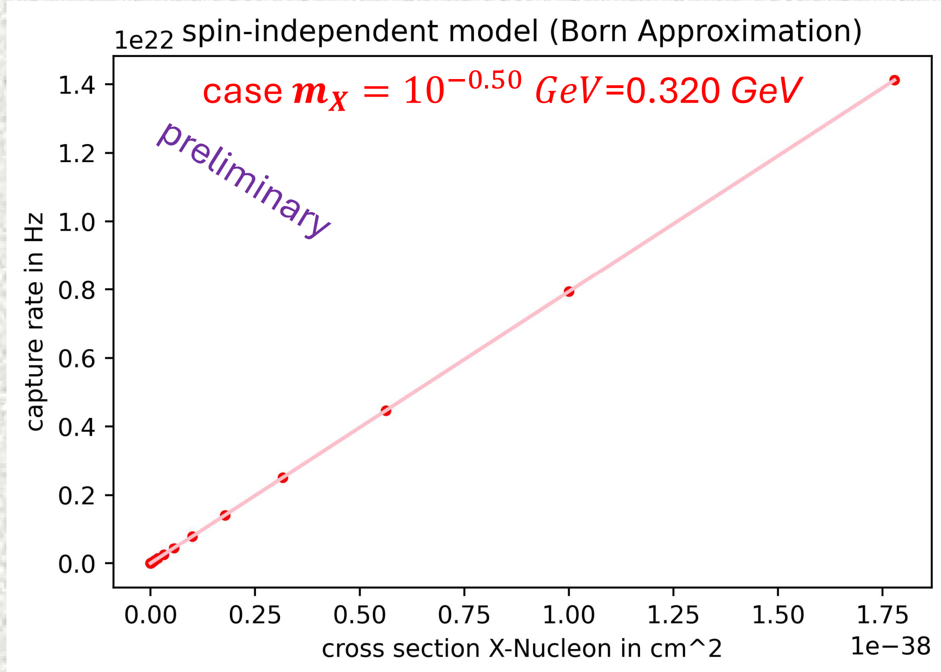
So:
- gamma-ray luminosity of the planet depends on **annihilation rate** inside it;
- **annihilation rate is equal to capture rate divided by two**;
- capture rate can be computed with **ASTERIA** Python Package.

DARKSUSY tool takes as input DM **density in solar system environment and other parameters** to compute capture rate for Jupiter *[T.Bringmann et al., DOI:10.1088/1475-7516/2018/07/033]* **.**

DM MODEL: the factor ‘a’

DARKSUSY tool shows that Capture rate is **always proportional** to Cross section (for **Nucleon-DM** interaction):

$C_{[Hz]} = \boldsymbol{a}_{[Hz/cm\text{^}2]} \cdot \sigma_{X\leftrightarrow N\ [cm^2]}$.



So ***a-values*** have been computed for each value of hypothetical m_X.

m_X (GeV)	a (10^{59} Hz/cm^2) Spin-Ind	a (10^{59} Hz/cm^2) Spin-Dep
10^{-1}	6	4
$10^{-0.75}$	7	4
$10^{-0.50}$	9	6
$10^{-0.25}$	15	11
10^{0}	18	11
$10^{0.25}$	20	3
$10^{0.50}$	37	0.5
$10^{0.75}$	25	0.1
10^{1}	21	0.03
$10^{1.25}$	21	0.01
$10^{1.5}$	21	0.003
$10^{1.75}$	18	0.001
10^{2}	7	0.0003

preliminary

DM MODEL: the main equation

It can be demonstrated that, in this model:
- assuming that **all emission is given by DM** annihilation (no cosmic-ray-induced signals)
- assuming that scalar **mediators ϕ are fast enough** to decay outside Jupiter
  (from energy conservation: $m_\phi \ll 0.99999990 m_X$)

$$\sigma_{X-N} = \frac{2\pi}{a_{(m_X)}} \cdot (Flux \cdot d^2)$$

where *Flux* is gamma-ray integral flux (between E_- and E_+) by FermiLAT and *d* is average distance between Jupiter and Earth.

Since we can only obtain upper limits for emission by Jupiter,
it means that **we can only obtain upper limits for $\boldsymbol{\sigma_{X-N}}$.**

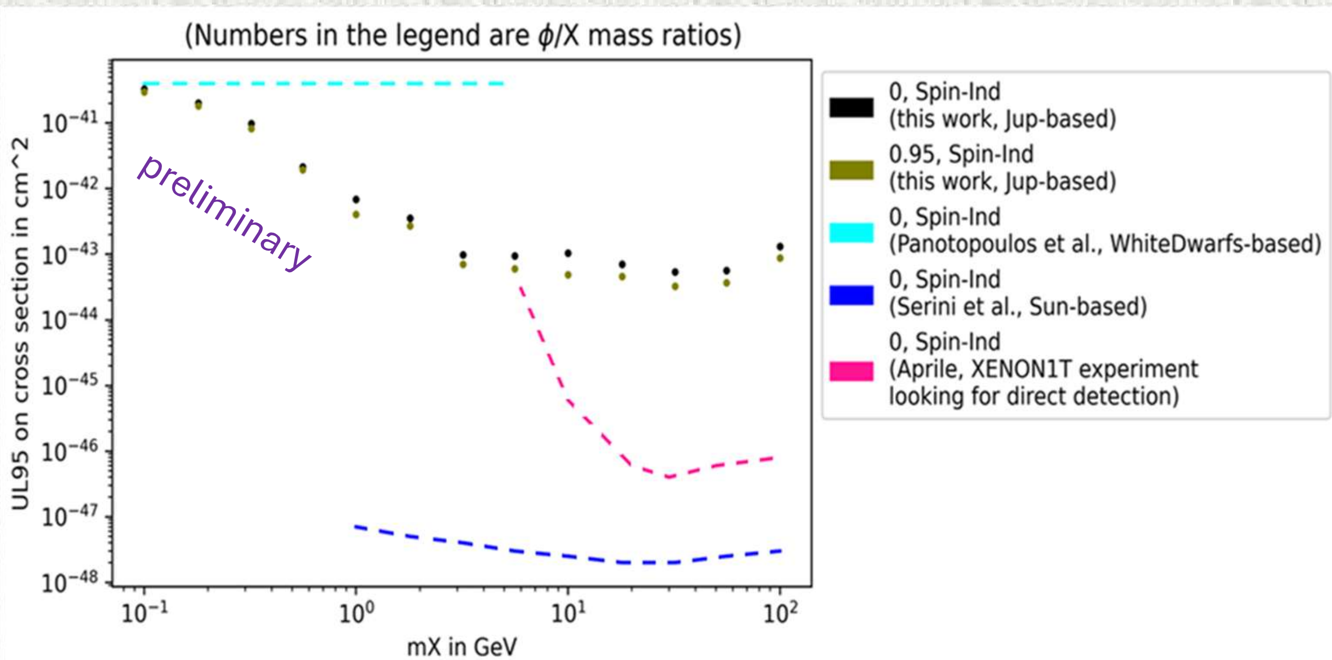
DM MODEL: demonstration of MAIN EQUATION

$$Flux = \frac{Luminosity}{4\pi d^2} = Yield \cdot A_{rate} \cdot \frac{1}{4\pi d^2} = 4 \cdot \frac{C_{rate}}{2} \cdot \frac{1}{4\pi d^2} = \frac{C_{rate}}{2\pi d^2} = a(m_X) \cdot \sigma_{X-N} \cdot \frac{1}{2\pi d^2} \rightarrow$$

$$\sigma_{X-N} = \frac{2\pi d^2}{a_{(m_X)}} \cdot Flux$$

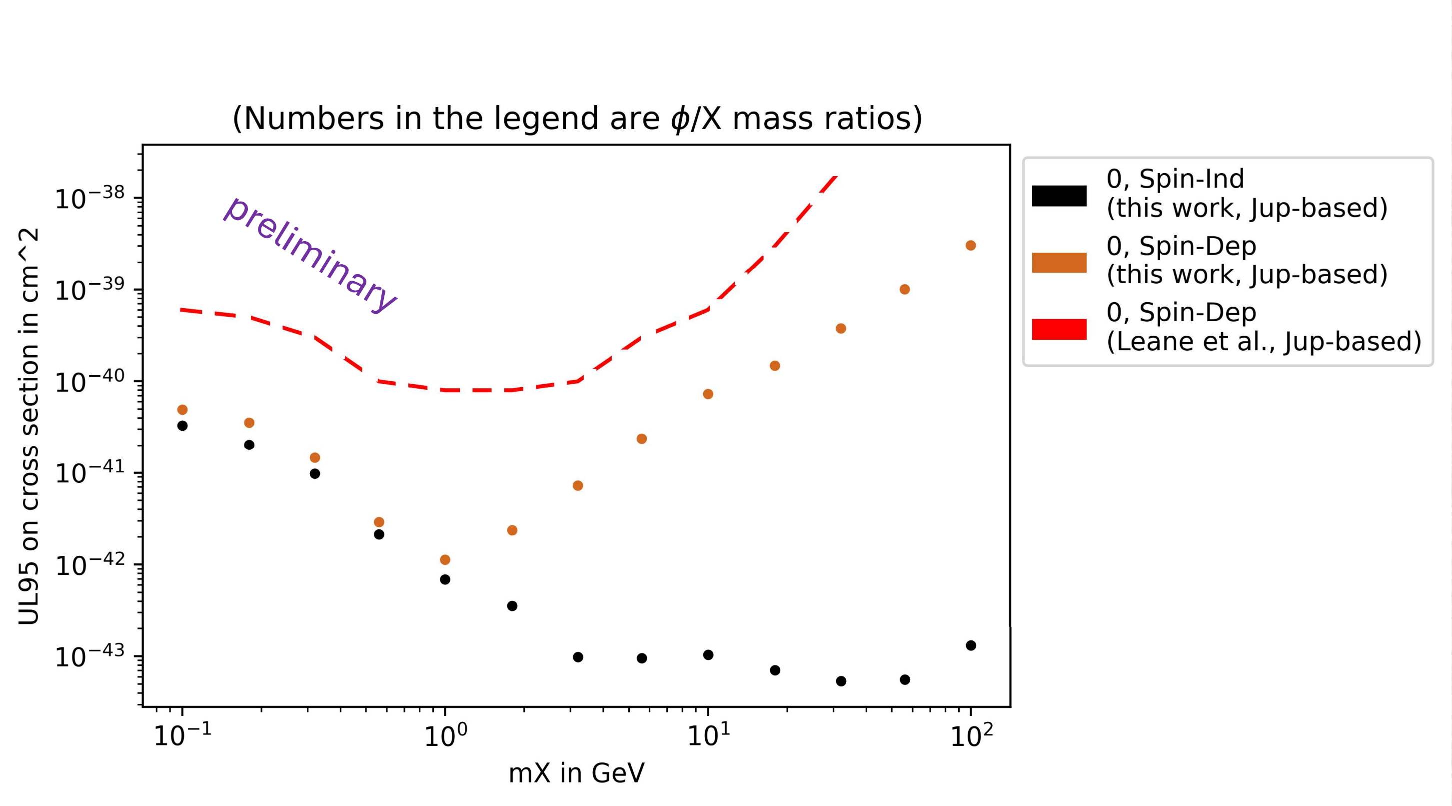
RESULTS: our Spin-Ind plot compared to other constraints found in recent literature

Now: in the DM-emission model (box-shape), called *k* the prefactor, we have:
$\boldsymbol{Flux = (E_+ - E_-)}$ **·k.**
Stacking of all 1202 ROIs has been performed with this box-shape-emission hypothesis**.**
Upper limits on *k* have been found, corresponding to values of stacked likelihood $\ln(L_{tot}) = MAX[\ln(L_{tot})] - 1.35$.
Following plot shows ULs with **95% C.L**. on cross section for DM-nucleon interaction, derived from computation of ULs on *k* and exploitation of the relation seen in the previous slide.



RESULTS: Spin-Dep plot

Also Spin-dependent capture rates have been computed with DarkSusy Fortran package *[T.Bringmann et al., DOI:10.1088/1475-7516/2018/07/033] .*



DM MODEL: where is dark matter supposed to accumulate in Jupiter?

All DM particles captured by Jupiter are expected to live in a **volume $\boldsymbol{V_X}$** surrounding the planetary centre. This volume is defined by a radius R_X which is the distance (from planetary centre) at which **gravitational energy and thermal energy of WIMPs are expected to be equal** (above this distance, thermal energy would prevail over gravity). *[S.Profumo, ISBN:978-1786340016]*

For Jupiter, we find that $\boldsymbol{R_X \sim 6 \cdot 10^8\ cm \cdot \sqrt{\frac{1\ GeV}{m_X}}}$ (remind that $R_{Jup} \sim 7 \cdot 10^9\ cm$).

Since the equation describing the number of DM particles living in the planet is

$\frac{dN(t)}{dt} = C - A_{nnihilation\ parameter} \cdot N^2(t)$ ($\mathbf{C} = a_{(m_X)} \cdot \sigma_{X \leftrightarrow N}$ is capture rate),

then it is easy to infer that time necessary to achieve equilibrium is $\boldsymbol{\tau = \frac{1}{\sqrt{C \cdot A_{nnihilation\ parameter}}}}$,

where $\boldsymbol{A_{nnihilation\ parameter} \sim 10^{-26}\ cm^3 s^{-1}}\ /\boldsymbol{V_X}$ *[S.Profumo, ISBN:978-1786340016] .*

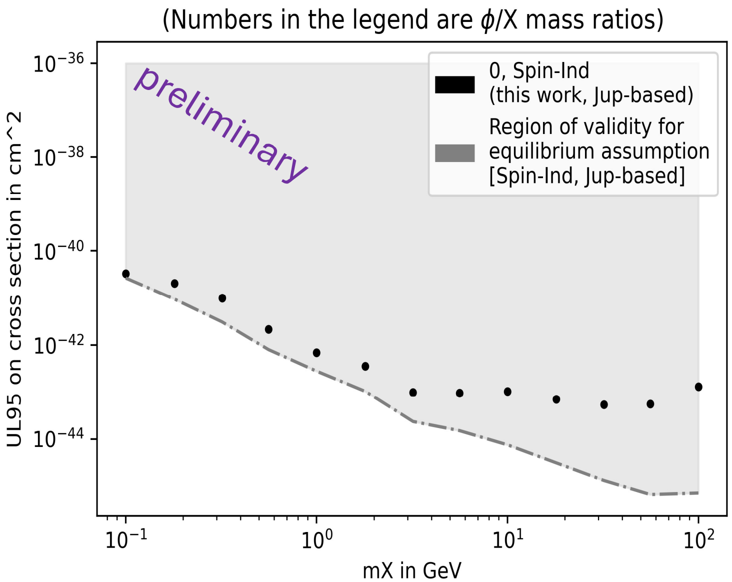
DM MODEL: about the capture-annihilation equilibrium

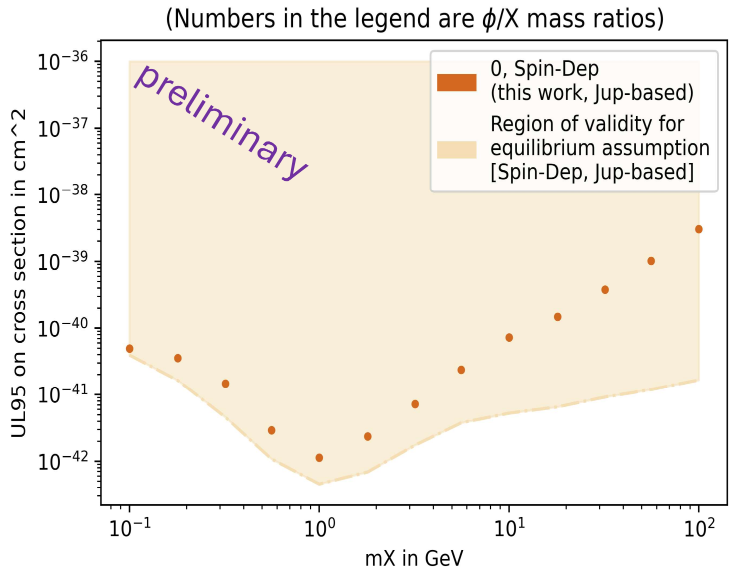
By adapting Profumo's calculation regarding the Sun to our source of interest (Jupiter), it can be showed that *[S.Profumo, ISBN:978-1786340016]* time necessary to achieve this equilibrium is:

$$\tau \sim \sqrt{\frac{10^{52}}{a_{(m_X)} \cdot \sigma_{X-N} \cdot m_X^{3/2}}}\ \text{s}$$

where $a_{(m_X)}$ is expressed in Hz/cm^2, σ_{X-N} in cm^2 and m_X in GeV.

In order to consider that equilibrium is already achieved, τ has to be significantly lower than age of Jupiter ($1.4 * 10^{17}$s). This gives us a condition (on validity of our model) corresponding to a lower limit on σ_{X-N}.





DM MODEL: other channels

The direct channel we have «explored» until now ($X\,\overline{X} \rightarrow \phi\,\phi \rightarrow 4\gamma$) is not the only possible one *[S.Profumo, ISBN:978-1786340016]* *[Serini et al., DOI:10.1088/1475-7516/2023/02/025]*.

For example, other possible channels are:

$X\,\overline{X} \rightarrow \phi\,\phi \rightarrow 2b\ \ 2\overline{b}$ (bottom quark channel)

$X\,\overline{X} \rightarrow \phi\,\phi \rightarrow 2t\ \ 2\overline{t}$ (top quark channel)

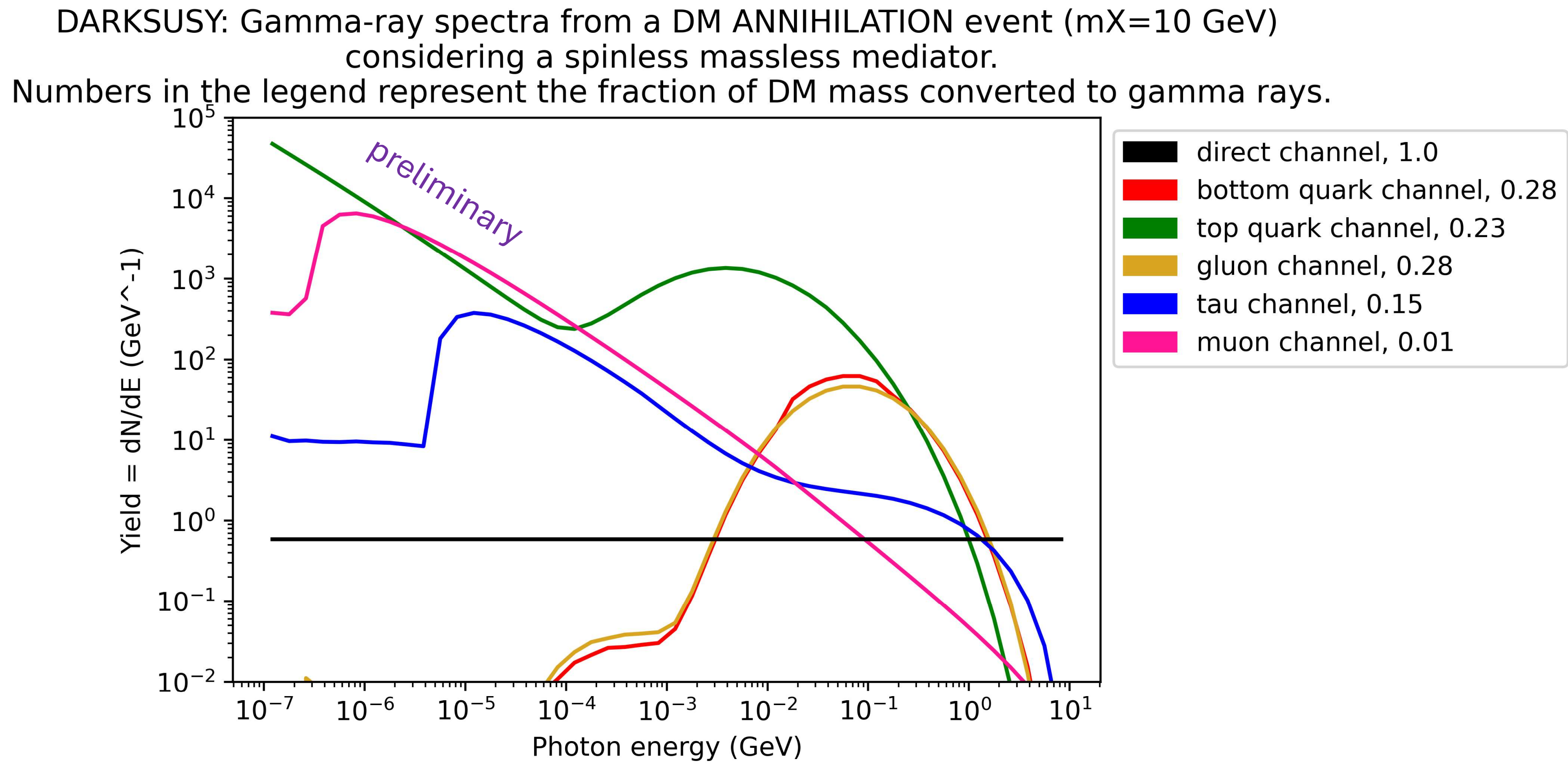
$X\,\overline{X} \rightarrow \phi\,\phi \rightarrow 4g$ (gluon channel)

$X\,\overline{X} \rightarrow \phi\,\phi \rightarrow \mu^+\mu^-$ (muon channel)

$X\,\overline{X} \rightarrow \phi\,\phi \rightarrow \tau^+\tau^-$ (tau channel).

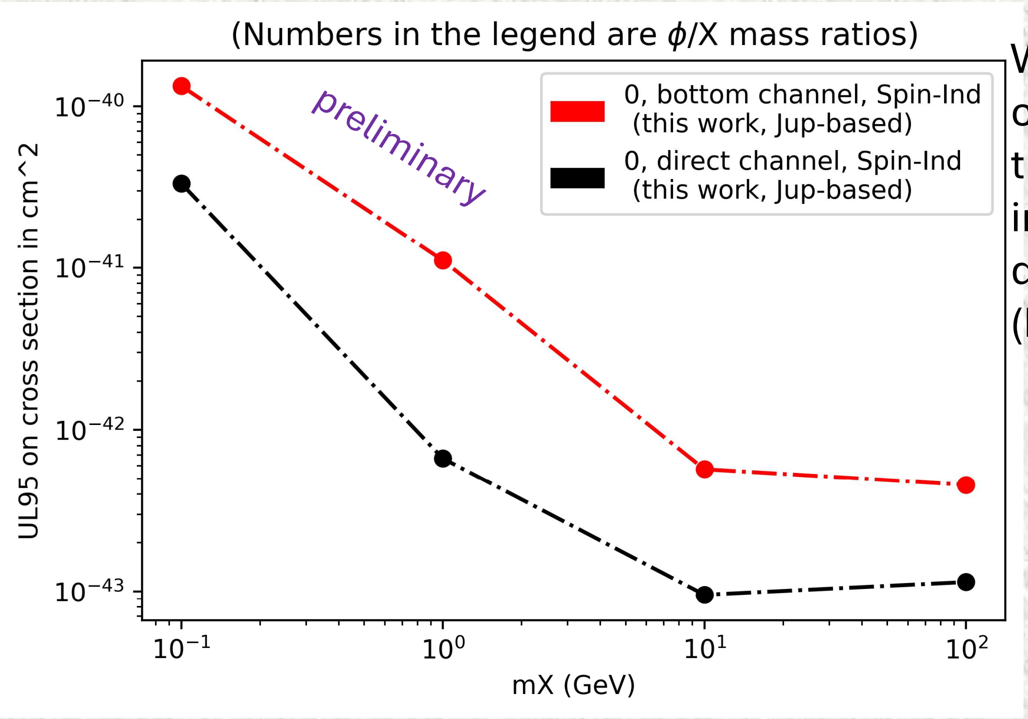
These are **indirect** channels, meaning that gamma-rays are **not primary** products of mediator's decay. Gamma rays are here generated as secondary particles, from decay or other processes affecting the produced primary particles.

DM MODEL: other channels



DM MODEL: other channels

All indirect channels would be expected to generate less photons than the direct one, so they **give a weaker constraint**, i.e. a bigger upper limit on the X-nucleon cross section.



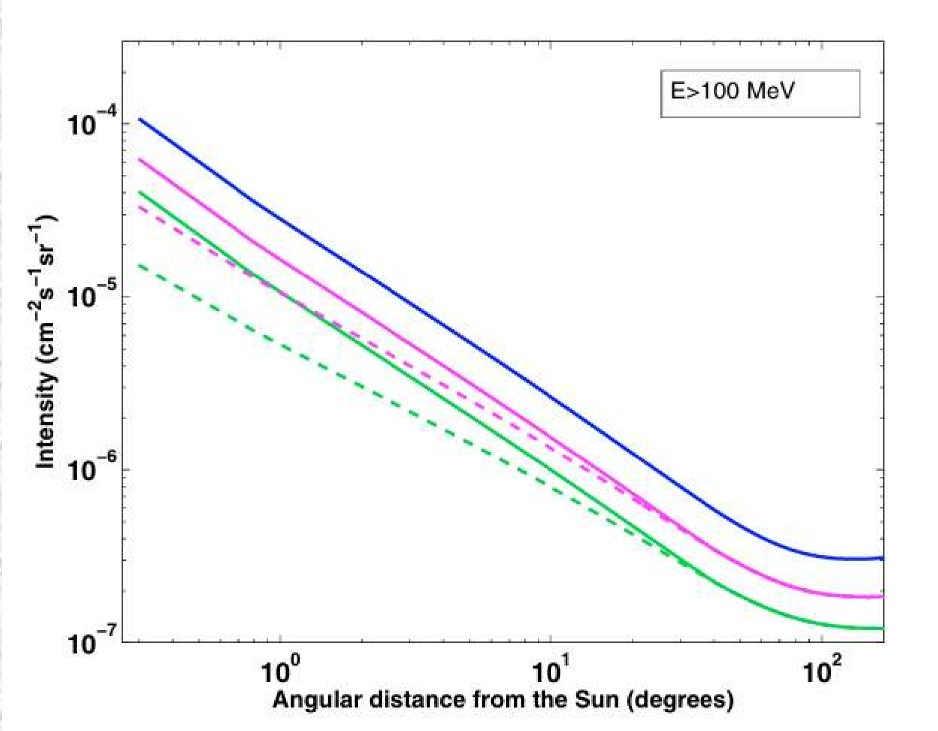
With current instrumental sensitivity and with current statistics **it is impossible to discriminate** the upper limits on cross section given by the different indirect channels, but we can discriminate between direct channel and one of indirect ones (bottom VS direct is shown on the left).

Thanks for your attention

BACKUP SLIDES

DATA ANALYSIS: why sun-jupiter proximity thesold is so high

Sun-Jupiter proximity thesold we have chosen is higher than other ones (regarding Moon and galactic plane). Indeed we want to avoid contamination from the Sun which (because of inverse Compton scattering) has a very large emitting disk in gamma-ray window (over 10°) *[E.Orlando et al., DOI: 10.1051/0004-6361:20078817]*.



DM MODEL: Darksusy input parameters

Density of dark matter in solar system environment: $0.4\,\frac{GeV}{cm^3}$

Average velocity of dark matter particles with respect to galactic center: $270\,\frac{km}{s}$

[Serini et al., DOI:10.1088/1475-7516/2023/02/025]

QUOTED REFERENCES

[E.Orlando et al., DOI: 10.1051/0004-6361:20078817]

[S.Profumo, ISBN:978-1786340016]

[R.Leane, J.Smirnov, DOI:10.48550/arXiv.2309.00669]

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[T.Bringmann et al., DOI:10.1088/1475-7516/2018/07/033]

REFERENCES FOR PLOT CURVES

[Serini et al., DOI:10.1088/1475-7516/2023/02/025]

[Panotopoulos et al., DOI:10.1142/S0218271820500583]

[R.Leane, T.Linden, DOI: 10.48550/arXiv.2104.02068

[E. Aprile, DOI: 10.1016/j.nuclphysb.2024.116463 *]*