Early LIME DM limit estimation

Motivation and Goals

We are able to take data with the LIME prototype for a long period in stable conditions.

Therefore it is interesting to start studying what we can achieve in the context of DM detection from all the available meauramente and to start to campare with other experiments which work and worked in similar conditions.

--> I started to study the assumptions and methodologies used to evaluate the exclusion limits with the LIME prototype

Physics

- For a given WIMP mass value, the cross-section has to be evaluated;
- For the Spin-Independent case the relation which links the number of expected events to the cross-section is:

$$N_{DM_{evt},i} = tV\frac{P}{P_{atm}}\frac{T}{T_0}\rho_i\frac{N_0}{A_{mol,i}}\frac{2\rho_0\sigma_{n,SI}}{m_\chi^2 r_i}\frac{\mu_{A,i}^2}{\mu_n^2}A_i^2 I_i^{E\gamma}(m_\chi, E_{thr,i})$$

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Integral form for the velocity distribution

$$I^{E\gamma}(m_\chi, E_{thr}) = \int_{E_{thr}}^{E_{max}} dE \int_{-1}^{1} dcos\gamma S(E)\pi \frac{v_p^3}{v_{lab}} \alpha' \left(e^{-\frac{\left(\frac{\sqrt{2m_A E}}{2\mu_A} - v_{lab}cos\gamma\right)^2}{v_p^2}} - e^{-\frac{v_{esc}^2}{v_p^2}} \right)$$

- The region of interest [E_{thr}, E_{max}] defines the range in which DM interactions are expected to be detected;
  - E_{max} is set by the kinematics of WIMP-nucleus scattering for each element in the gas mixture
  - E_{thr} varies for each target material and it is influenced by the quenching effect

The expected number of DM-induced events for the Spin-Independent case is:

$$N_{DM_{evt},i} = tV \frac{P}{P_{atm}} \frac{T}{T_0} \rho_i \frac{N_0}{A_{mol,i}} \frac{2\rho_0 \sigma_{n,SI}}{m_\chi^2 r_i} \frac{\mu_{A,i}^2}{\mu_n^2} A_i^2 I_i^{E\gamma}(m_\chi, E_{thr,i})$$

for the Spin-Dependent case is:

$$N_{DM_{evt},i} = tV \frac{P}{P_{atm}} \frac{T}{T_0} \rho_i \frac{N_0}{A_{mol,i}} \frac{2\rho_0 \sigma_{p,SD}}{m_\chi^2 r_i} \frac{\mu_{A,i}^2}{\mu_n^2} \frac{4\langle S_p \rangle (J_i+1)}{3J_i} I_i^{E\gamma}(m_\chi, E_{thr,i})$$

Estimation of the exposure time

The sCMOS sensor is open for a total of 484 ms:

- 184 ms are required to open the sensor;
- 300 ms is the time interval during which the entire sensor remains exposed.
- 30 ms are needed to acquire the image

--> the camera for the 40% of the time is not total efficient

- Even if the PMTs data are not analized, they operate in parallel and each signal acquisition takes 0.01s

The effective exposure time T for each run can be defined as:

$$T = (dt - 0.01n)\varepsilon$$

dt= the total duration of the run

n = the number of PMT signals acquired

Quenching factor (QF)

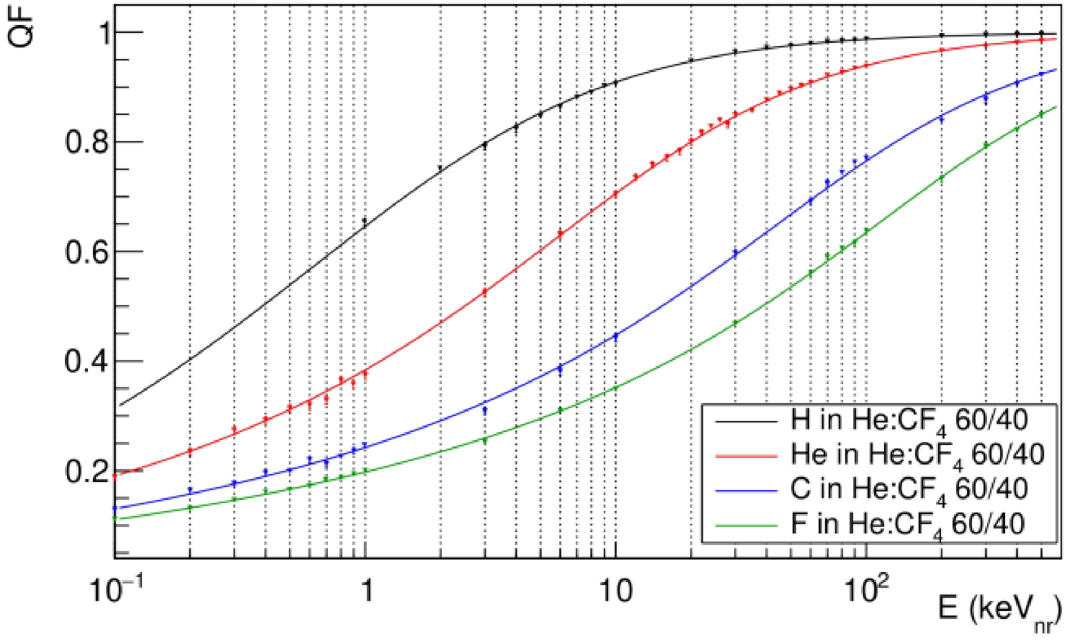
The quenching factor (QF) is used to describe the fraction of kinetic energy released through ionization by a nuclear recoil. The relationship between the observed nuclear recoil energy E_{ee} and the total kinetic nuclear recoil energy, E_{nr}, is:

$E_{ee} = QF \times E_{nr}$

The QF varies for each element in the gas mixture. It was evaluated using SRIM simulations.

The QF is modelled by the equation:

$$QF = \frac{a(E_{nr} + bE_{nr}^c)}{1 + a(E_{nr} + bE_{nr}^c)}$$



Definition of the selection cuts

For each image, the number of events are evaluated after applying the following cuts:

- Fiducial cuts:
  - sc_xmin [pixel] > 300;
  - sc_ymin [pixel] > 300;
  - sc_xmax [pixel] < 2000;
  - sc_ymax [pixel] < 2000;
- Quality cuts:
  - sc_rms [counts] > 6 to avoid the sensor nosily pixel;
  - $0.005 < \rho < 0.15$

$$\rho = \frac{\text{sc\_rms [counts]}}{\text{sc\_nhits [counts]}}$$

- sc_integral [counts] > 1500 or > 2500 if the energy threshold is 1 keV_{ee} or 1.5 keV_{ee}, respectively.

In the hypothesis that DM interactions have not been observed in this set of data,

Background: the 20% of the runs were randomly selected

Data: the remaining 80% were used as the main data set for event analysis.

--> This approach ensures that the background level is properly accounted for while maintaining the majority of the data for evaluating our exclusion limit.

Method

It consists in **counting** the number of detected events.

Data set: Run4 (10cm of copper + 40cm of water as shielding)

Run number[43887 - 55097] -> period [15/01/2024 - 08/04/2024]

1) After applying all the cuts, the number of events is evaluated
2) Data: the total number of events and exposure time is evaluated
3) Background: the total number of events and exposure time is evaluated, the number of events are rescaled to the data exposure time

Application of the Bayesian approach

To infer the posterior probability on expected signal (μ_s) and background (μ_b) events.

C.I. 90% on μ_s posterior.

Likelihood:

$$\mathcal{L}(\vec{x}|\mu_s, \mu_b, H_1) = \frac{(\mu_b + \mu_s)^{N_{evt}}}{N_{evt}!} e^{-(\mu_b+\mu_s)}$$

Prior:

- Background: poissonian distribution
- Signal: flat distribution

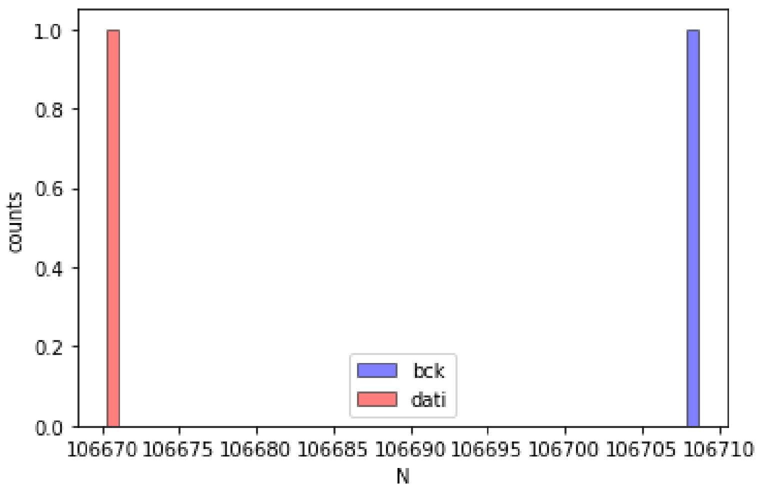
Posterior:

Evaluated thanks to the BAT software

Example (E_{thr} = 1keV$_{ee}$)

1) Evaluation of the number of data and background events

Exposure time ~ 17 days



bck: 106708.62824074163 +/- 326.6628663327707
data: 106670.33530598591 +/- 326.6042487567881

2) Posterior probability on expected signal (μ_s) and background (μ_b) events

3) Evaluation of the cross section SI

Prior background

Because the number of events of background has been rescaled to match the signal exposure time. This implies that the background uncertainty should be correctly scaled by the ratio data to background exposure.

Poissonian distribution --> Gaussian distribution with mean the number of events and sigma $2\sqrt{N}$

Example (E_{thr} = 1 keV$_{ee}$)

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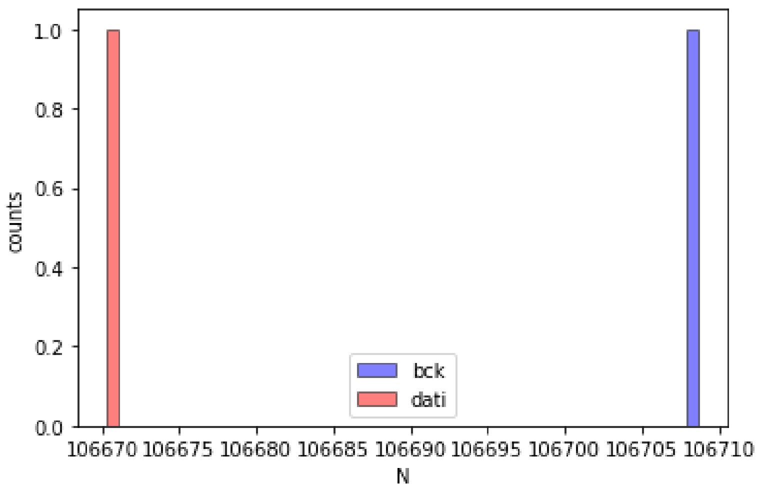


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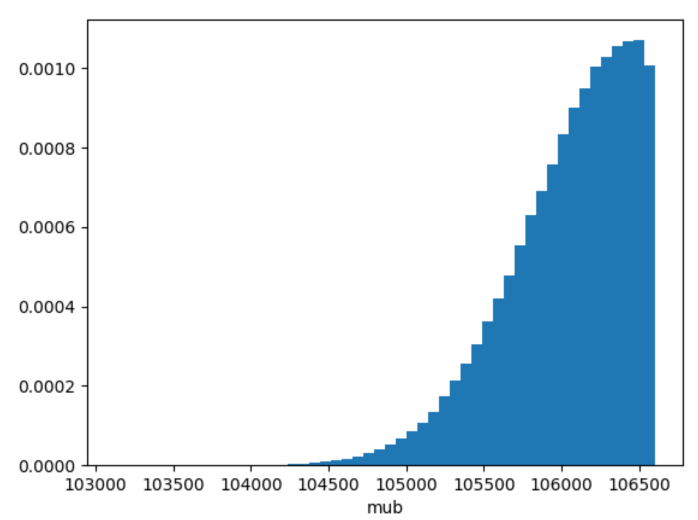
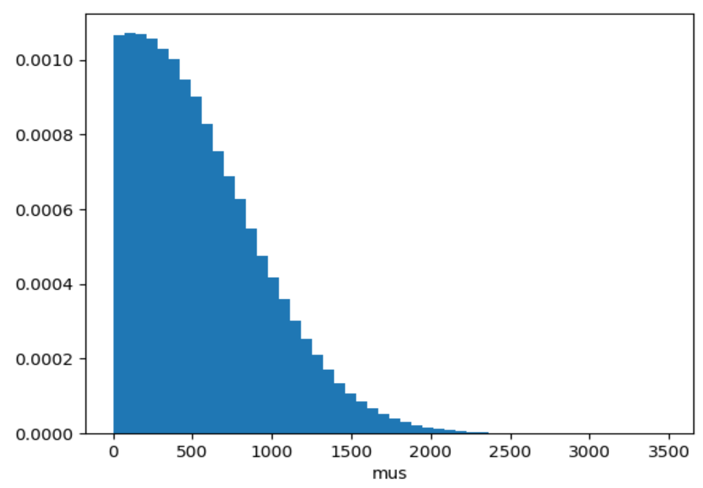




μ_s 90% C.I = 830

2) Evaluation of the cross section

$$N_{DM_{evt},i} = tV\frac{P}{P_{atm}}\frac{T}{T_0}\rho_i\frac{N_0}{A_{mol,i}}\frac{2\rho_0\sigma_{n,SI}}{m_\chi^2 r_i}\frac{\mu_{A,i}^2}{\mu_n^2}A_i^2 I_i^{E\gamma}(m_\chi, E_{thr,i})$$

t ~ 17 days

V = xyz = 0.03 m^3

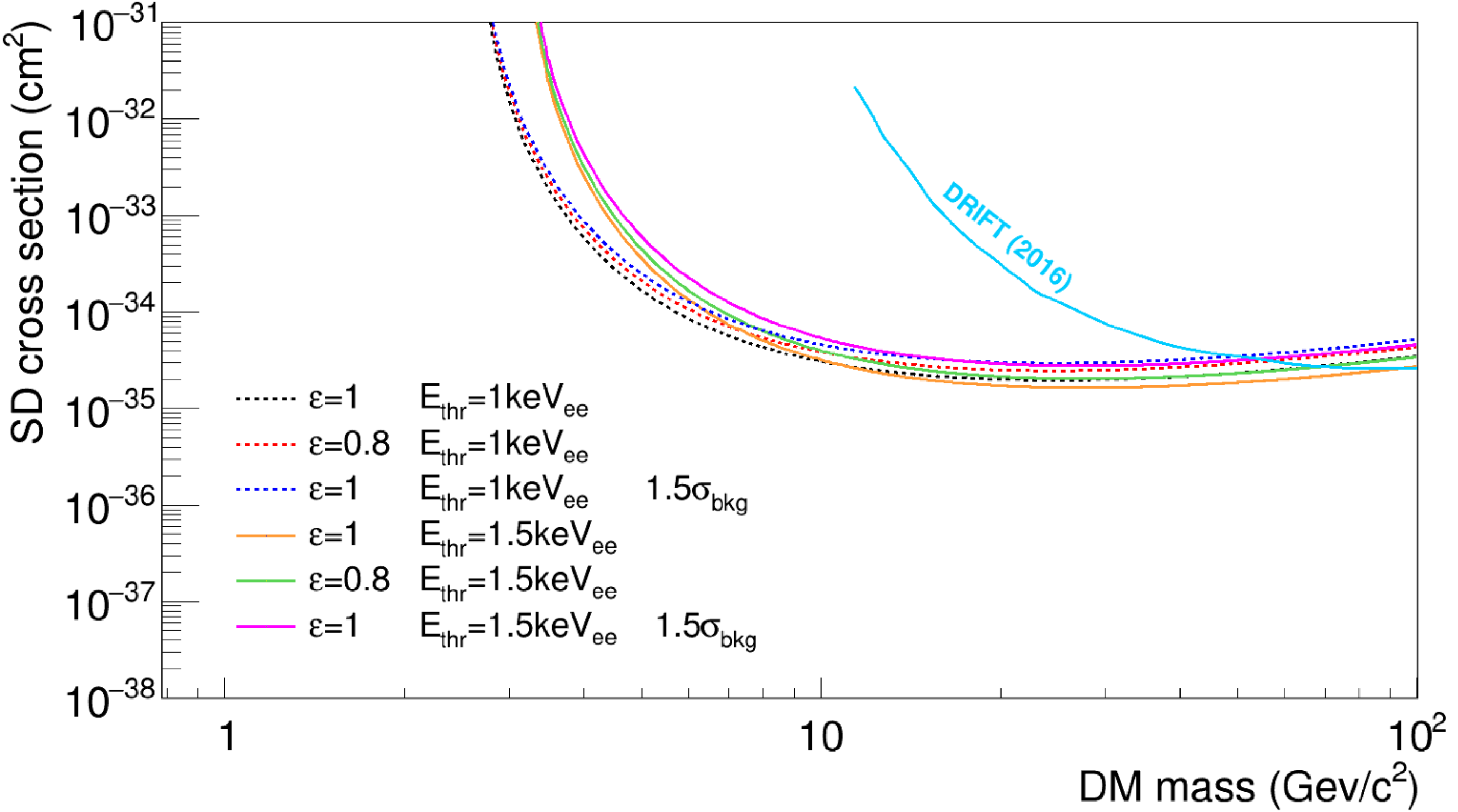
x = 1700 pixel * 152 μm = 0.25 m

y = 1700 pixel * 152 μm = 0.25 m

z = 0.48 m

P = 0.907 bar

Given by the average pressure



SD cross section (cm^2)
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
1
10
10^2
DM mass (Gev/c^2)
DRIFT (2016)
ε=1 E_{thr}=1keV$_{ee}$
ε=0.8 E_{thr}=1keV$_{ee}$
ε=1 E_{thr}=1keV$_{ee}$ 1.5σ_{bkg}
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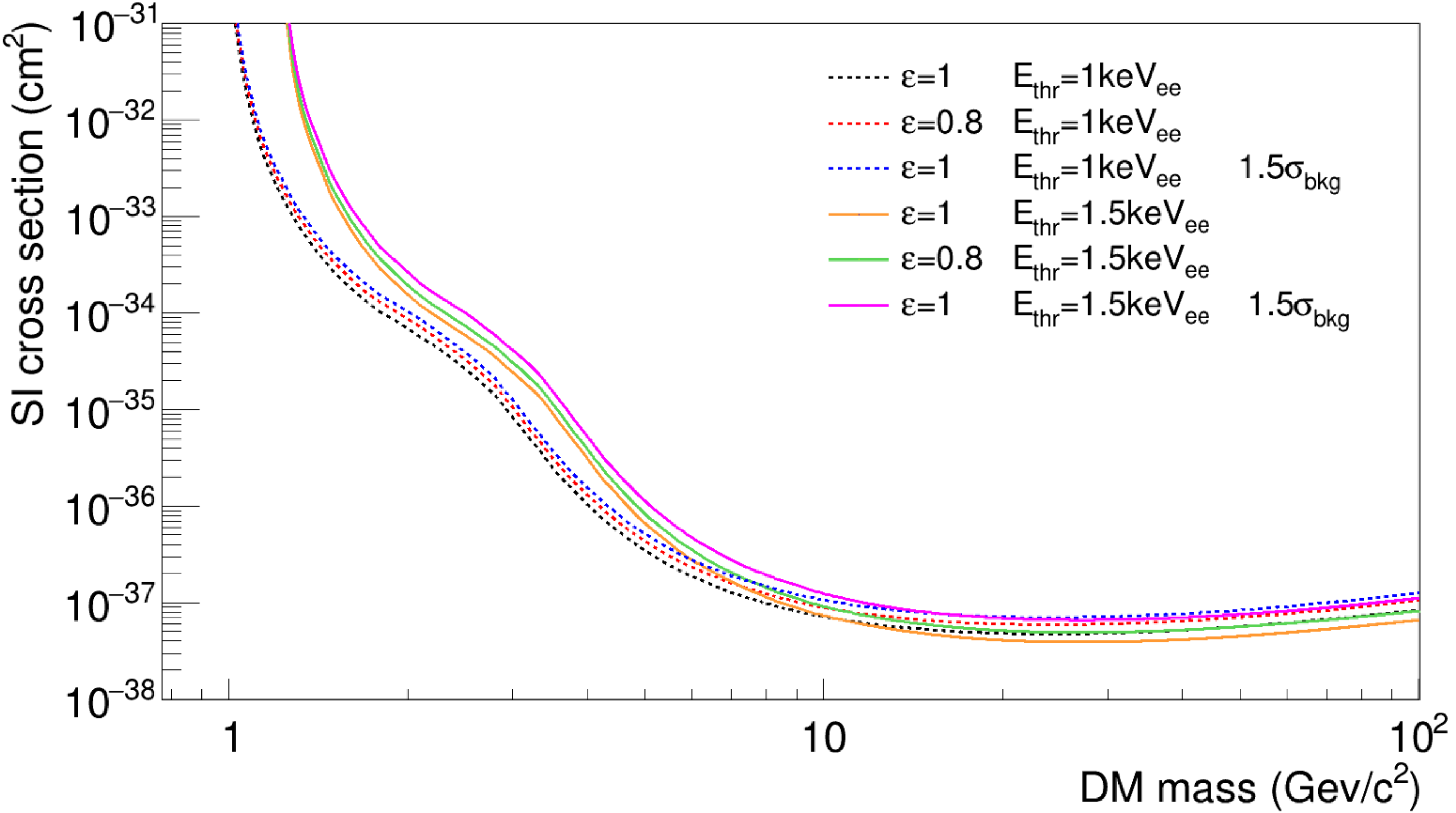
SI cross section (cm^2)
10^{-31}
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
1
10
10^2
DM mass (Gev/c^2)
ε=1 E_{thr}=1keV$_{ee}$
ε=0.8 E_{thr}=1keV$_{ee}$
ε=1 E_{thr}=1keV$_{ee}$ 1.5σ_{bkg}
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ε=1 E_{thr}=1.5keV$_{ee}$ 1.5σ_{bkg}

Conclusions

- We are assuming that not DM signal is observed and the background is computed from data --> it is better to usesimulated data for the background;
- Two different addition scenarios can be taken in exam:
  - E_{thr}= 500 eV & fiducial cut using a circle region with a radius of 800 pixel;
  - E_{thr}= 1.5 keV & not fiducial cut;

  These two scenarios correspond to our threshold estimates as a function of the fiducial cut caused by the electronic noise of the camera sensor and the vignetting correction, which amplifies pedestal fluctuations. The center region is less noisy and less suppressed by vignetting, resulting in fewer high-energy fake clusters, allowing for lower threshold values.
- In the presented analysis a single bin in energy has been taken in exam, the dependence on the energy and angle can taken in exam

Backup

Starting from

$$E_{max} = \frac{1}{2} m_\chi r (v_{lab} cos\gamma + v_{esc})^2$$

setting cosγ = 1 and replacing E_{max} with $E_{thr,nr}$

	1keV$_{ee}$		**1.5keV$_{ee}$**	
Element	**E$_{thr,nr}$ [keV$_{nr}$]**	**Min m$_\chi$ [GeV/c^2]**	**E$_{thr,nr}$ [keV$_{nr}$]**	**Min m$_\chi$ [GeV/c^2]**
He	2.1	1.0	3.4	1.3
C	3.1	1.9	5.5	2.6
F	3.8	2.5	6.8	3.5