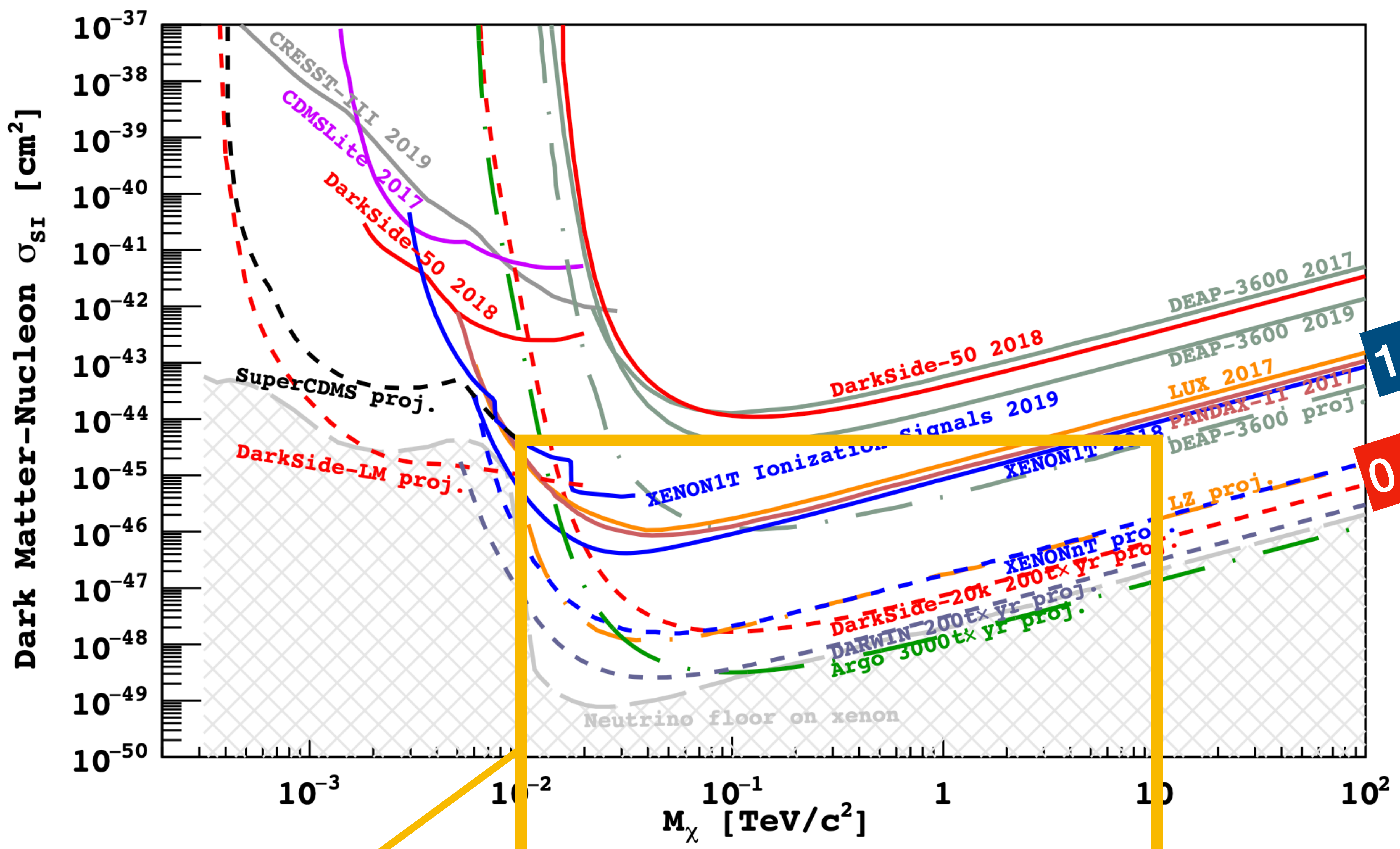
Direct search for Dark Matter with the DarkSide-20k experiment

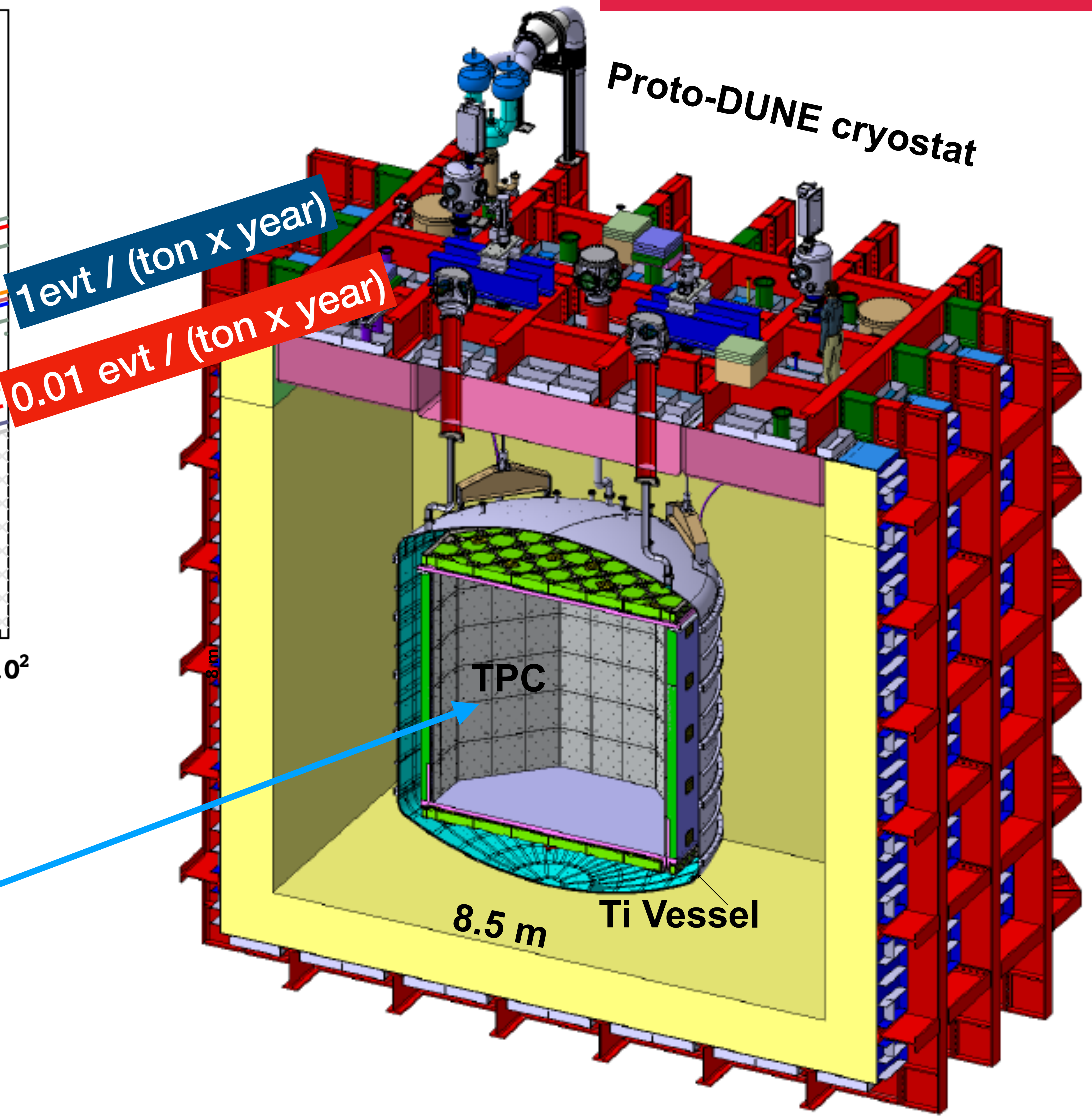
Marie van Uffelen - CPPM, LAM - IPhU days 2023

PhD supervisors: Emmanuel Nezri (LAM), Fabrice Hubaut (CPPM)

The experiment I work on: DarkSide-20k

Cf. talk P. Pralavorio for more details





- Strong discovery potential in the 10GeV-10TeV range
- Next Argon experiment: DarkSide-20k
  - 200 t x year exposure
  - Argon double phase TPC

Will be the largest TPC ever built for dark matter search purpose

↓

needs to be properly calibrated

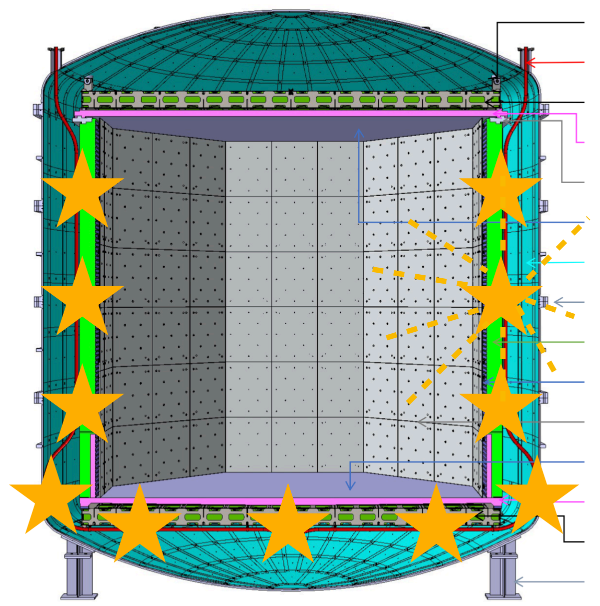
Last year's presentation (link)

Declaration of my PhD thesis purpose and first results

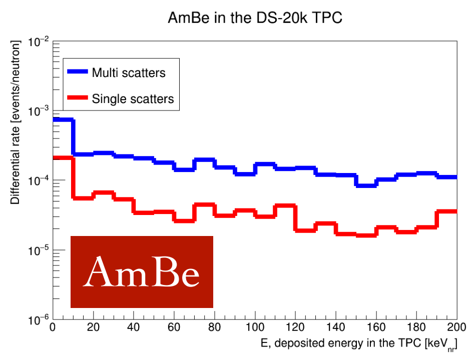
Particle physics

Now over (internal note written for the collab)

My first commitment and results: the ***simulation*** of DarkSide-20k's ***TPC calibration***

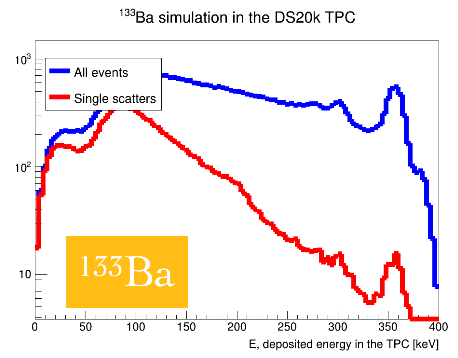


NR calibration, **neutron** sources (most important)



✅ *in 1 month*

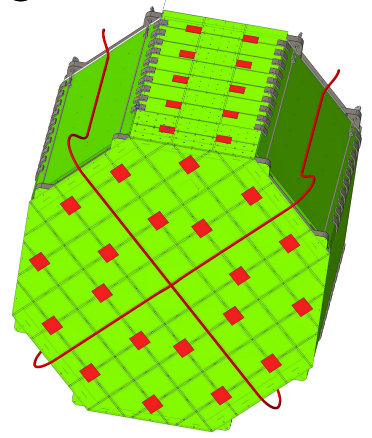
ER calibration, γ sources



✅ *in 1 week*

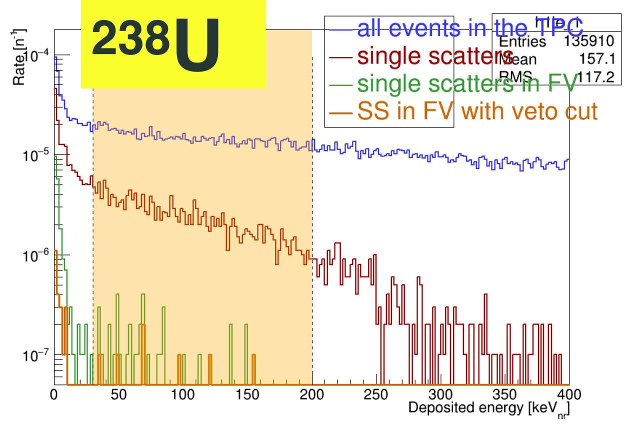
Simulations of the ***impact*** of the calibration system on the rest of the detector

Veto's light collection efficiency



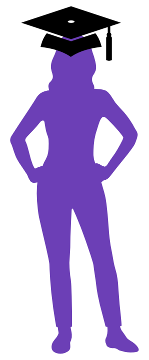
✅ *No impact on the veto's LCE !*

Induced background

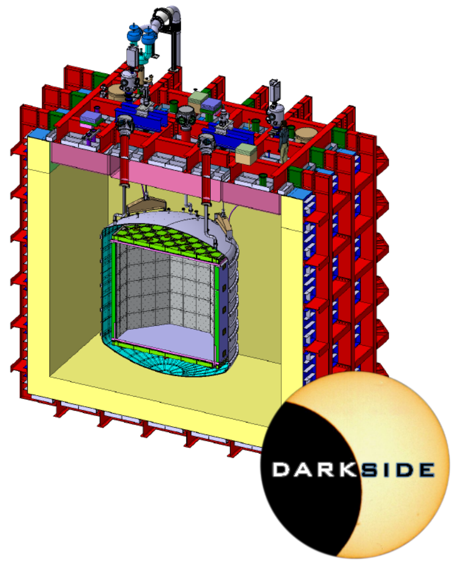


✅ *Represents < 0.01% of DS20k bgd budget*

My thesis



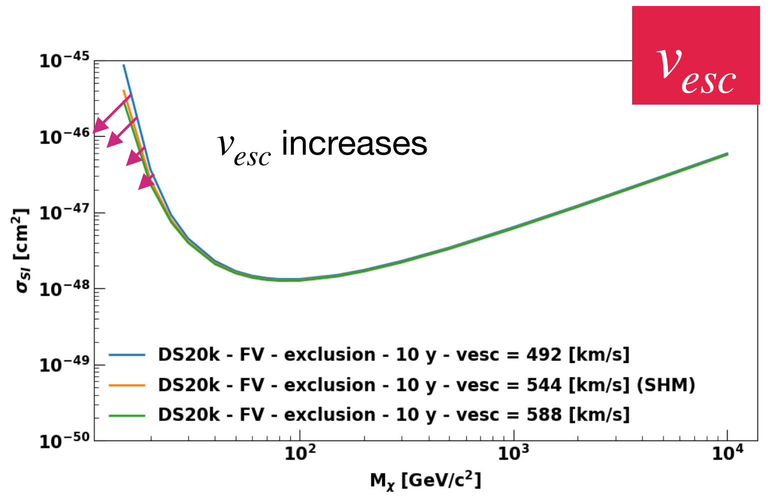
The detector

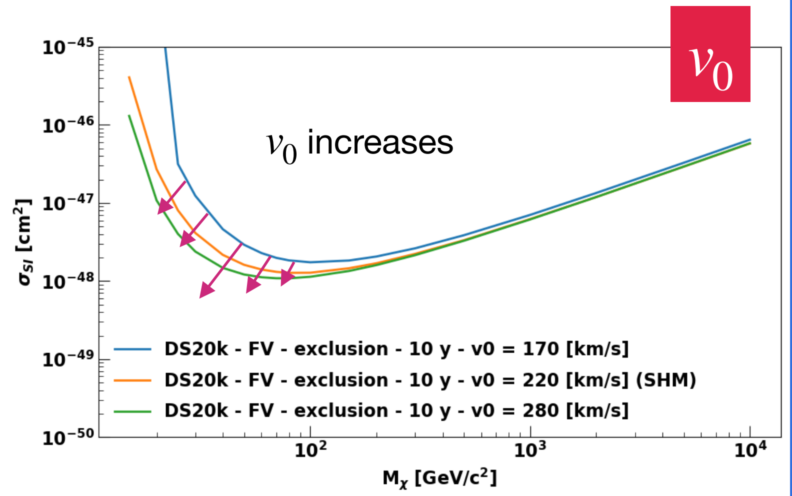


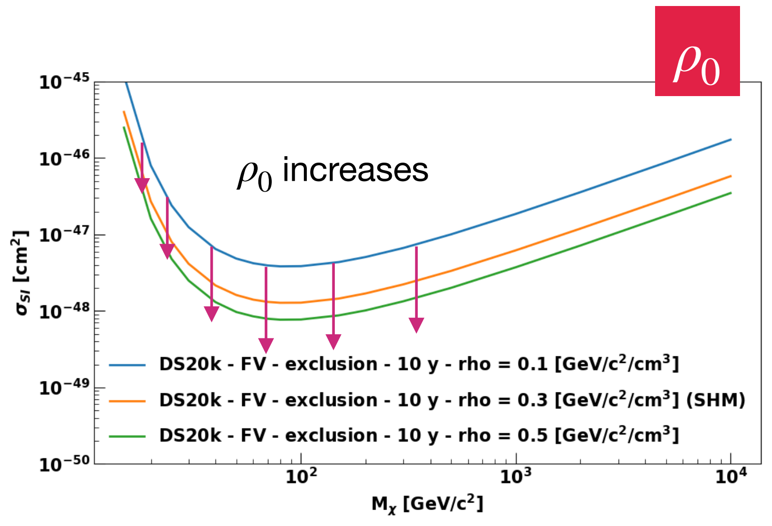
Astrophysics

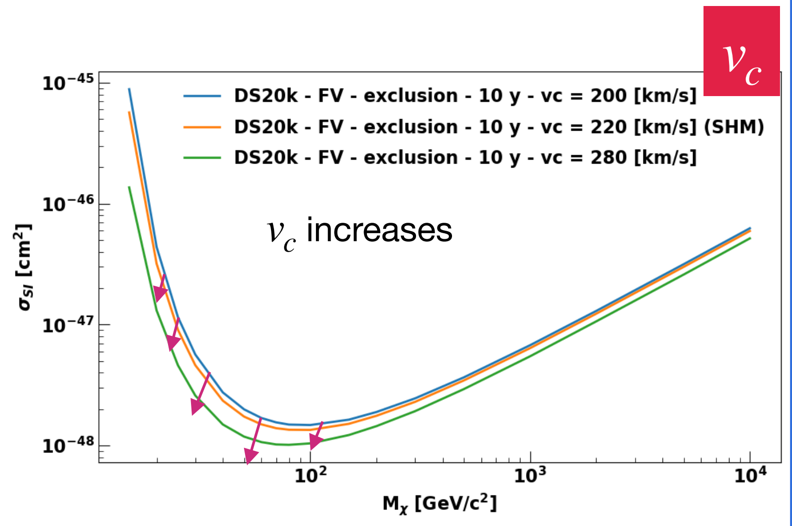
2022 commitment

Assess the ***impact*** of ***astrophysical uncertainties*** on DS20k ***exclusion limit***









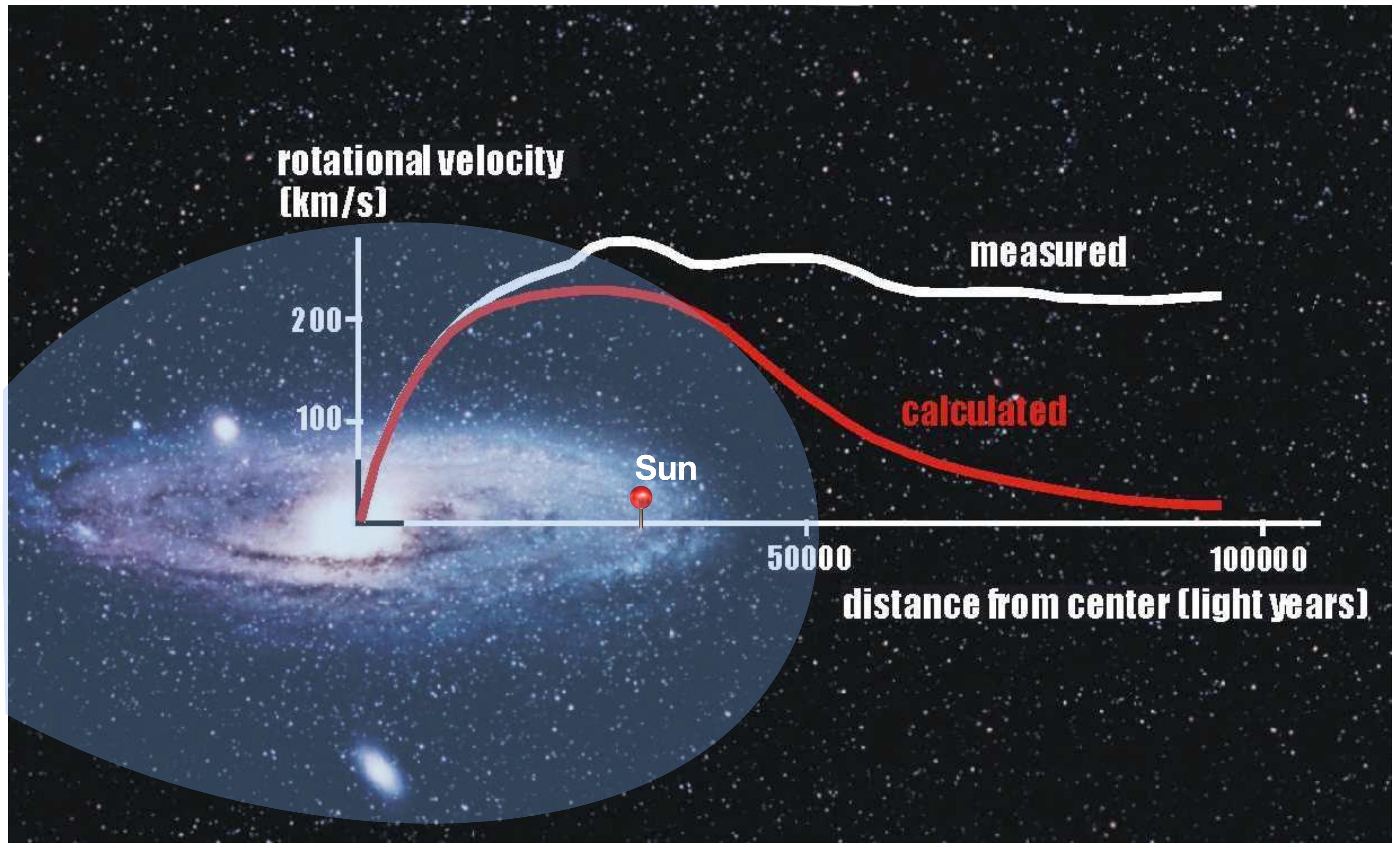
$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} \frac{d\sigma}{dE_R} d\vec{v}$$

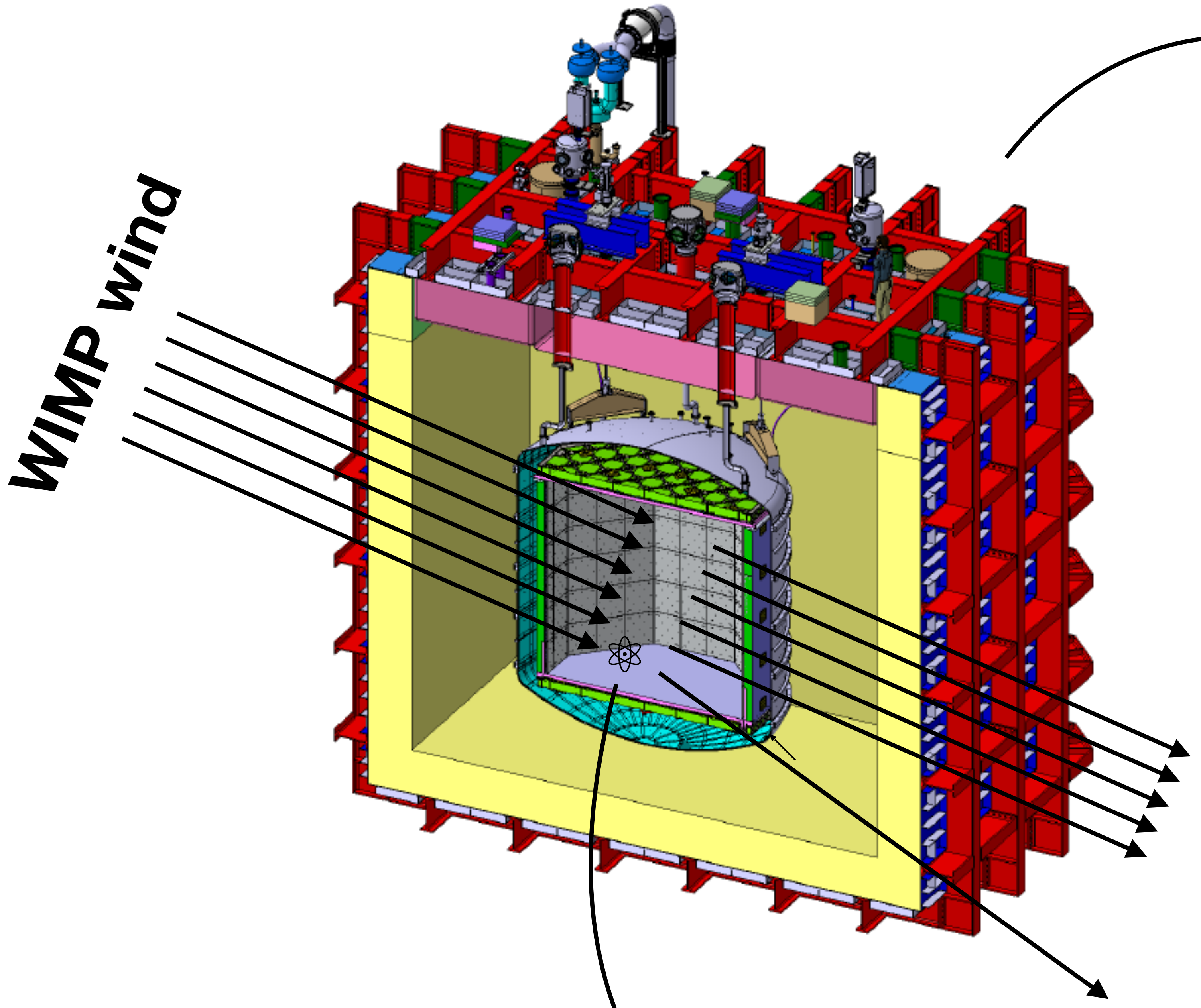
HEP

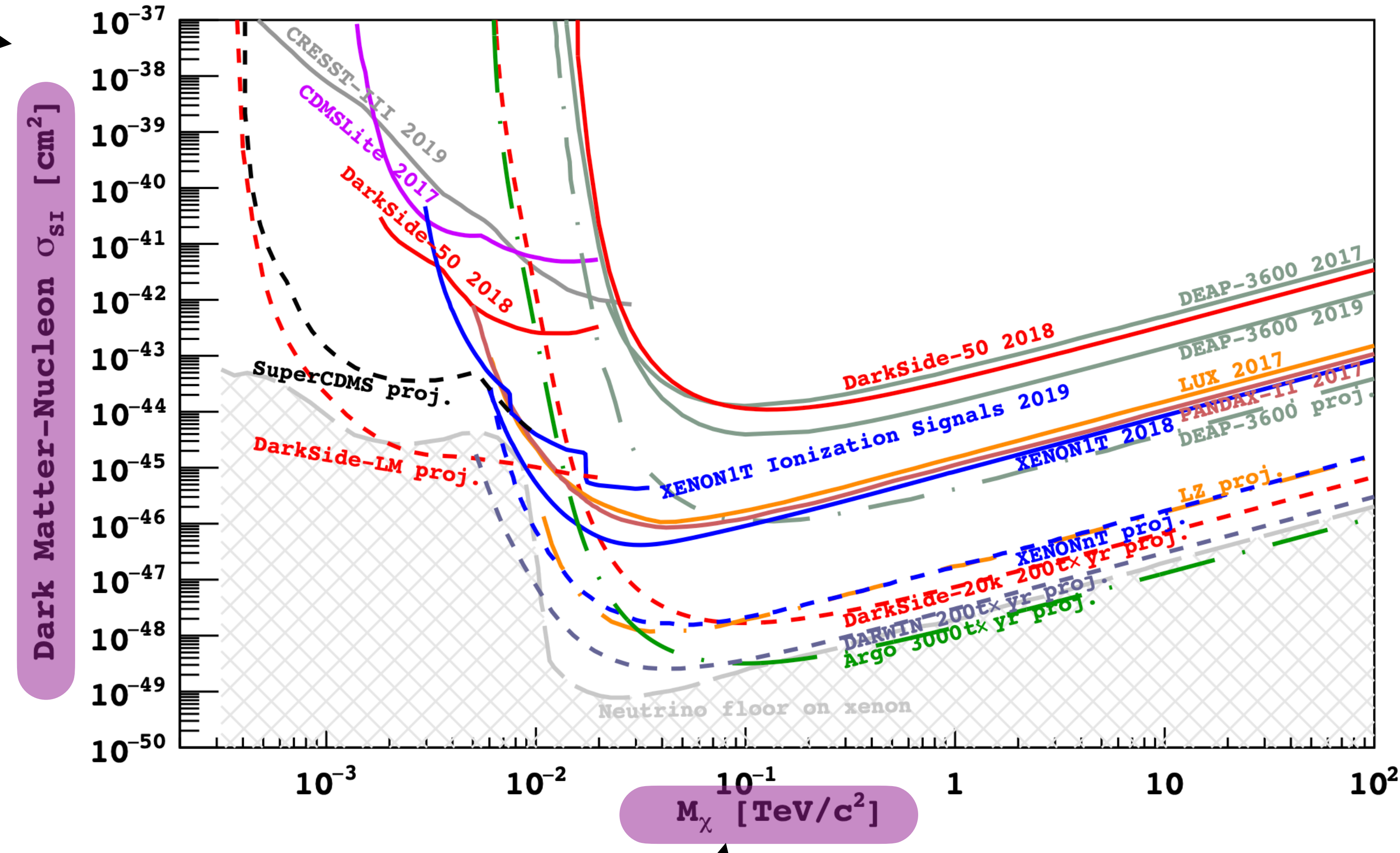
Astro

Dark Matter Direct Detection (DMDD)

DM in the form of WIMPs (Weakly Interacting Massive Particles)







Rate of nuclear recoils events -> rely on a halo model

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} \frac{f(v)}{v} \frac{d\sigma}{dE_R} d\vec{v}$$

HEP

Astro

Background estimates

Data & MC Simulations

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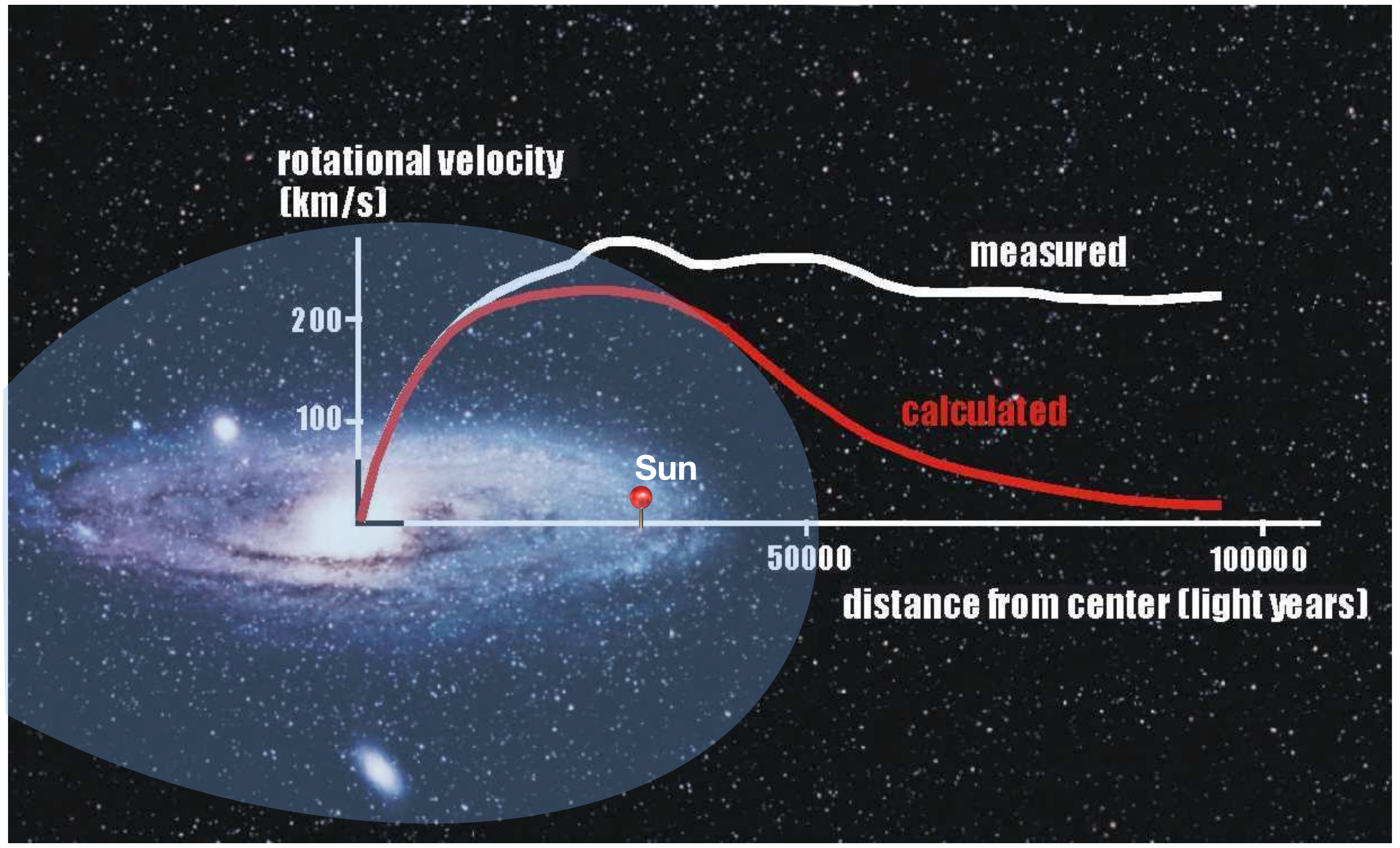

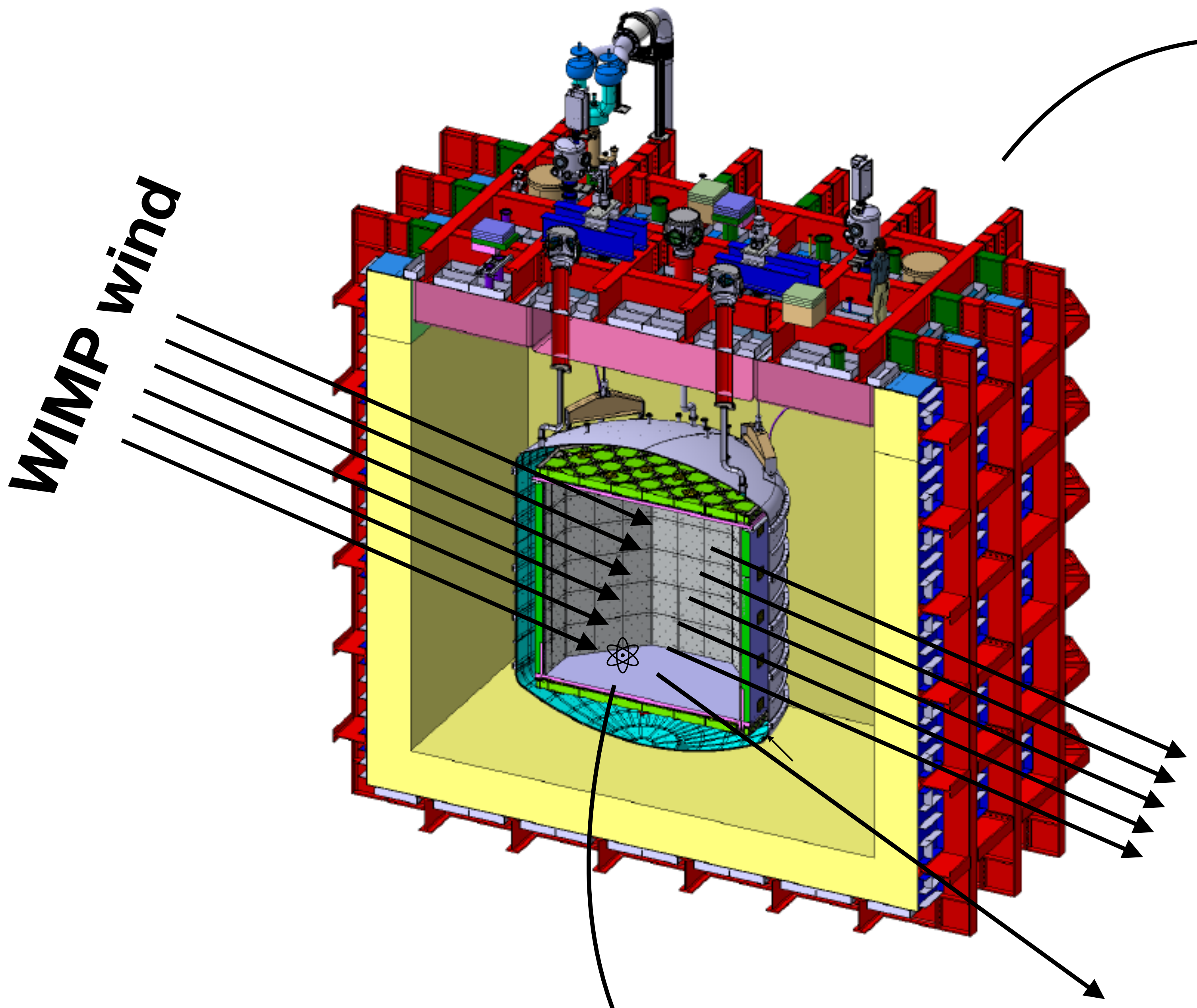

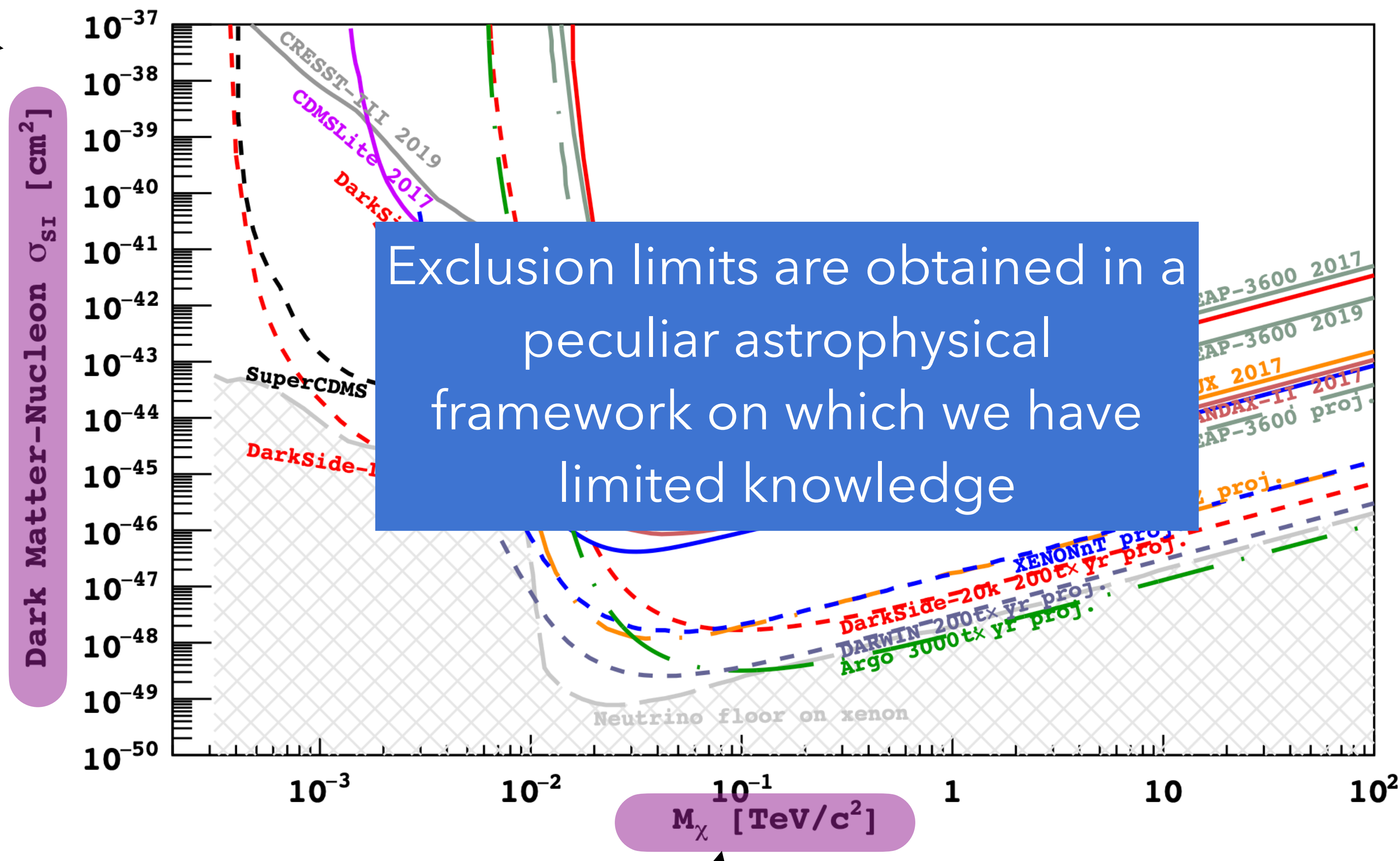

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HEP

Astro

Background estimates

Data & MC Simulations

Phenomenological part of the thesis

Assess the effects of astrophysical uncertainties on DS20k exclusion limit

- The exclusion limit of an experiment allows to:
  - Compare experiment between themselves and assess the competitiveness of each of them in different WIMP mass regions
  - Claim for the rejection of a phase space region in (m_χ, σ) after null-result

Need a ground model to describe the WIMP galactic halo influencing the rate of events one has in its detector

Every DMDD uses the so-called **Standard Halo Model (SHM)**, a very handy halo model derived from very simple assumptions (non-collisionnal, isotropic and isothermal halo)

Need a realistic model relying on reasonable assumptions in order not to incorrectly accept or reject phase space

To do so, one needs to rely on trustworthy cosmological simulations and good estimates of the astrophysical parameters of interest $(v_0, v_c, v_{esc}, \rho_0)$

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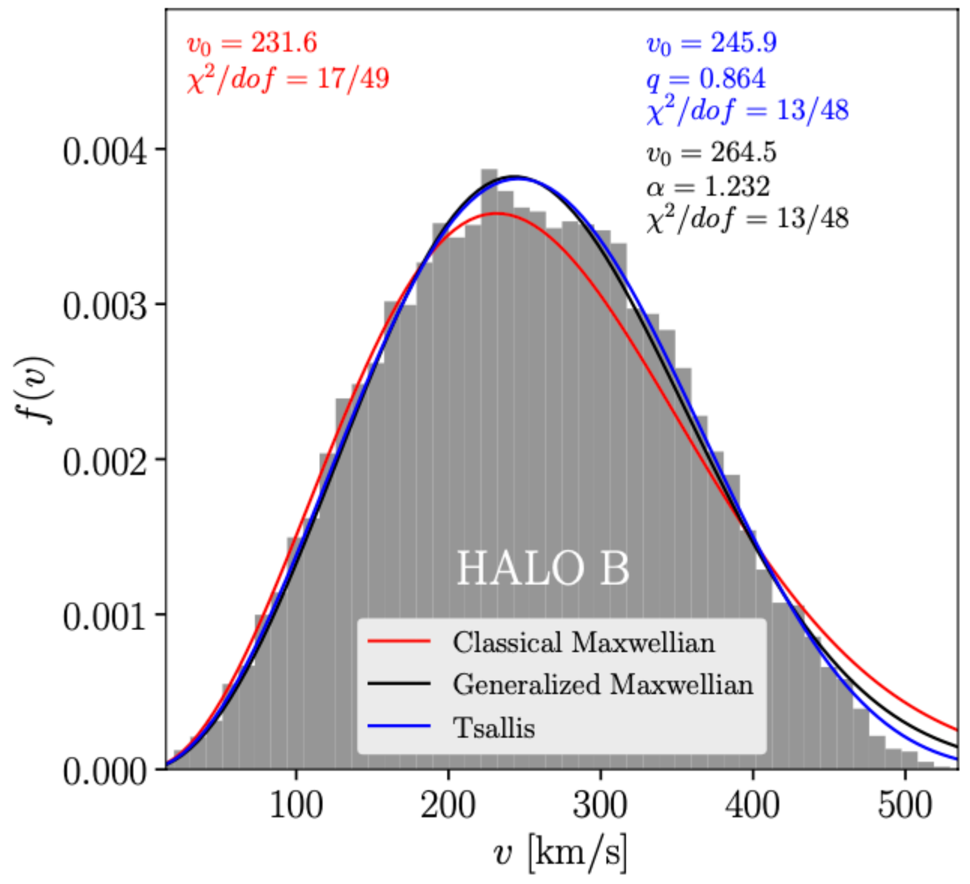
$(v_0, v_c, v_{esc}, \rho_0)$

My 2022 study

Take better suited velocity distributions

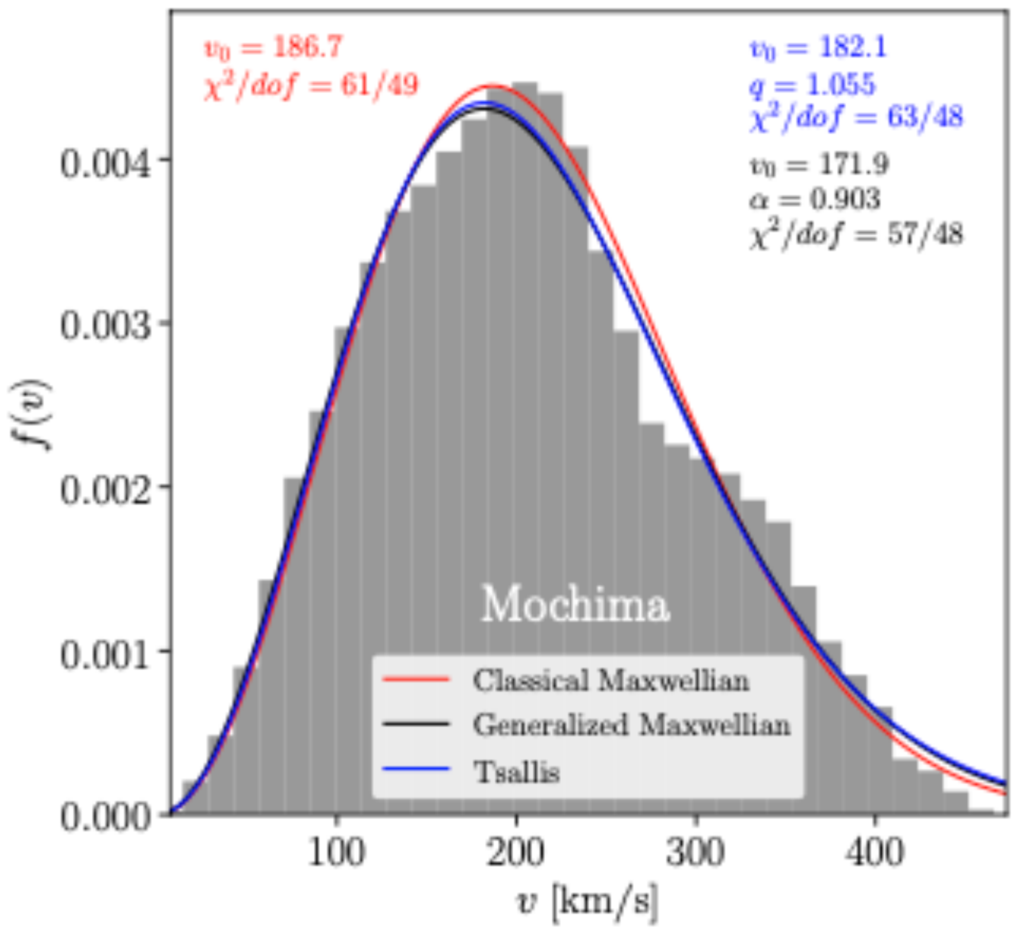
Play on $f(\vec{v})$ in the rate of events, hint from cosmological simulations

Starters



(a) Halo B

Fig. From A. Nuñez thesis
Simu. By P. Mollitor et. al.



(b) Mochima

Fig. From A. Nuñez thesis
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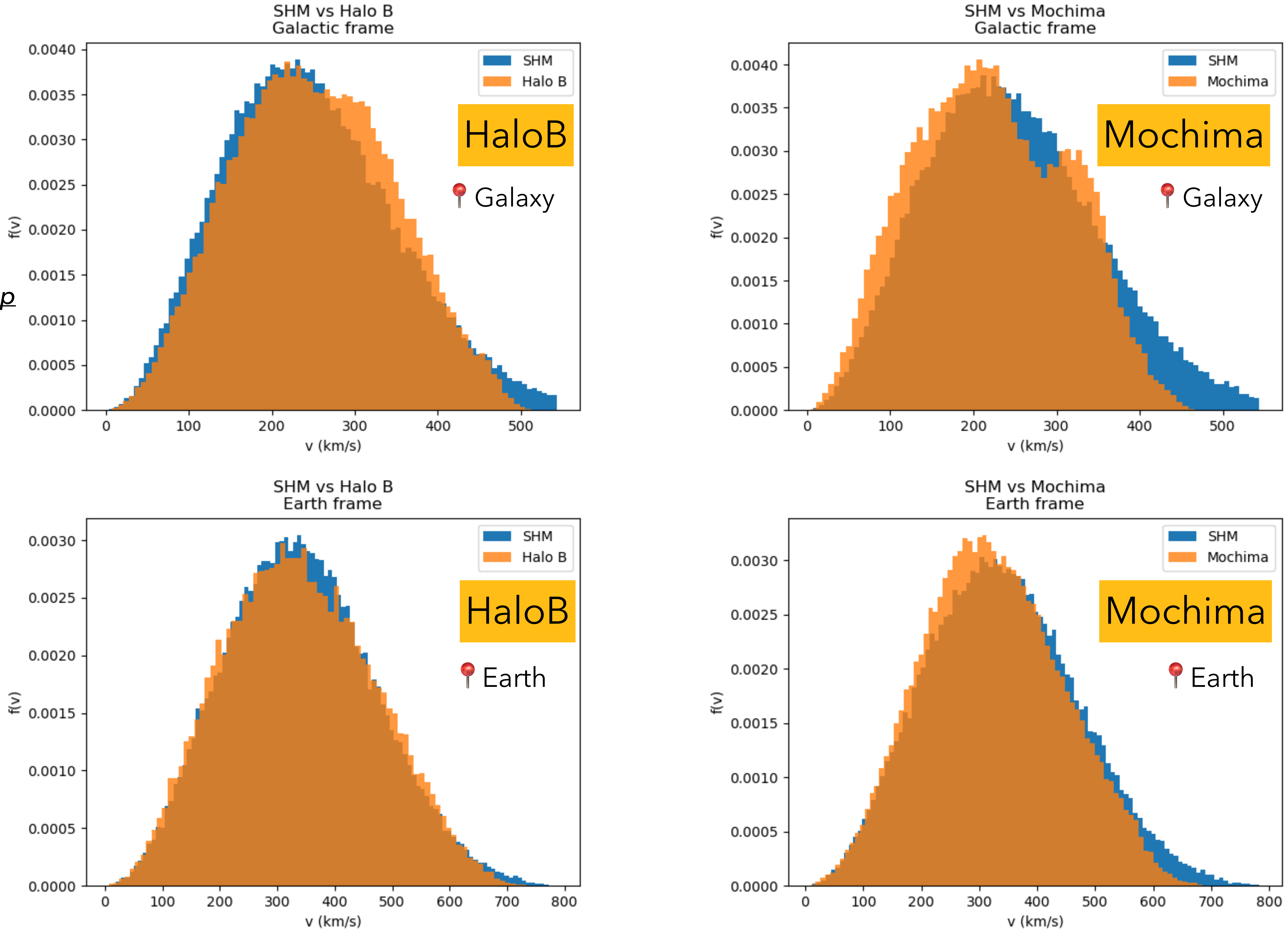
Development of different methods to integrate these f(v)

Directly take the simulation result as input 📚 *See more in back up*



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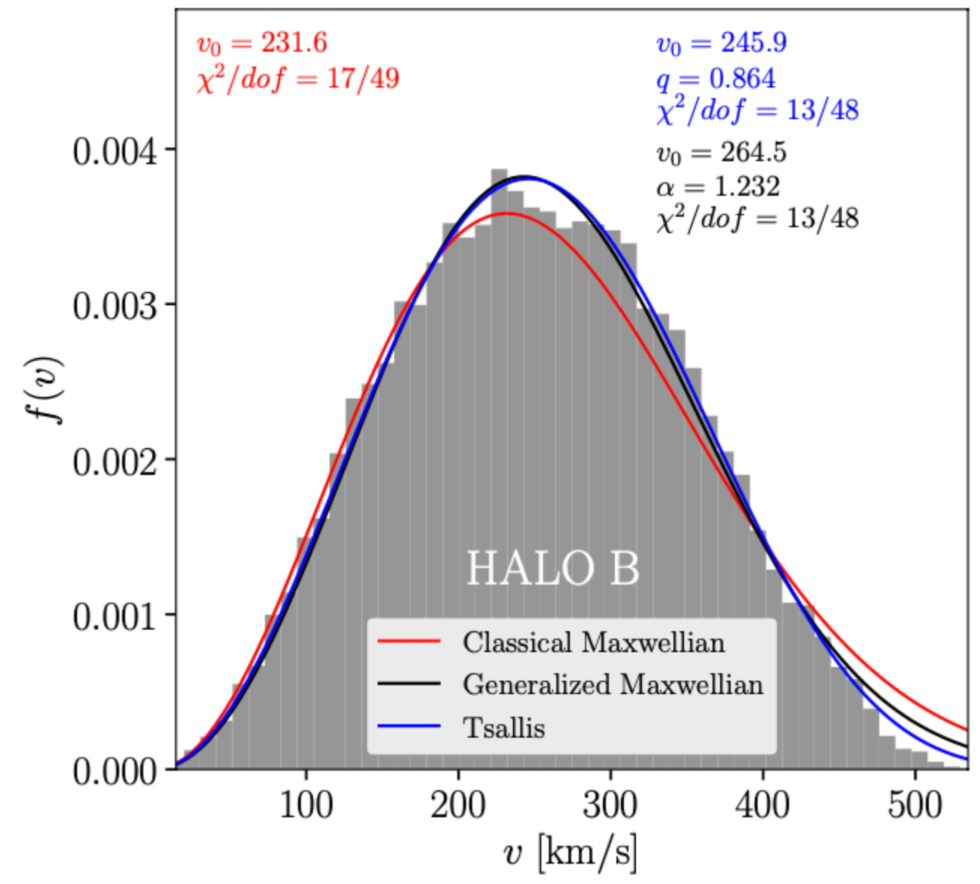

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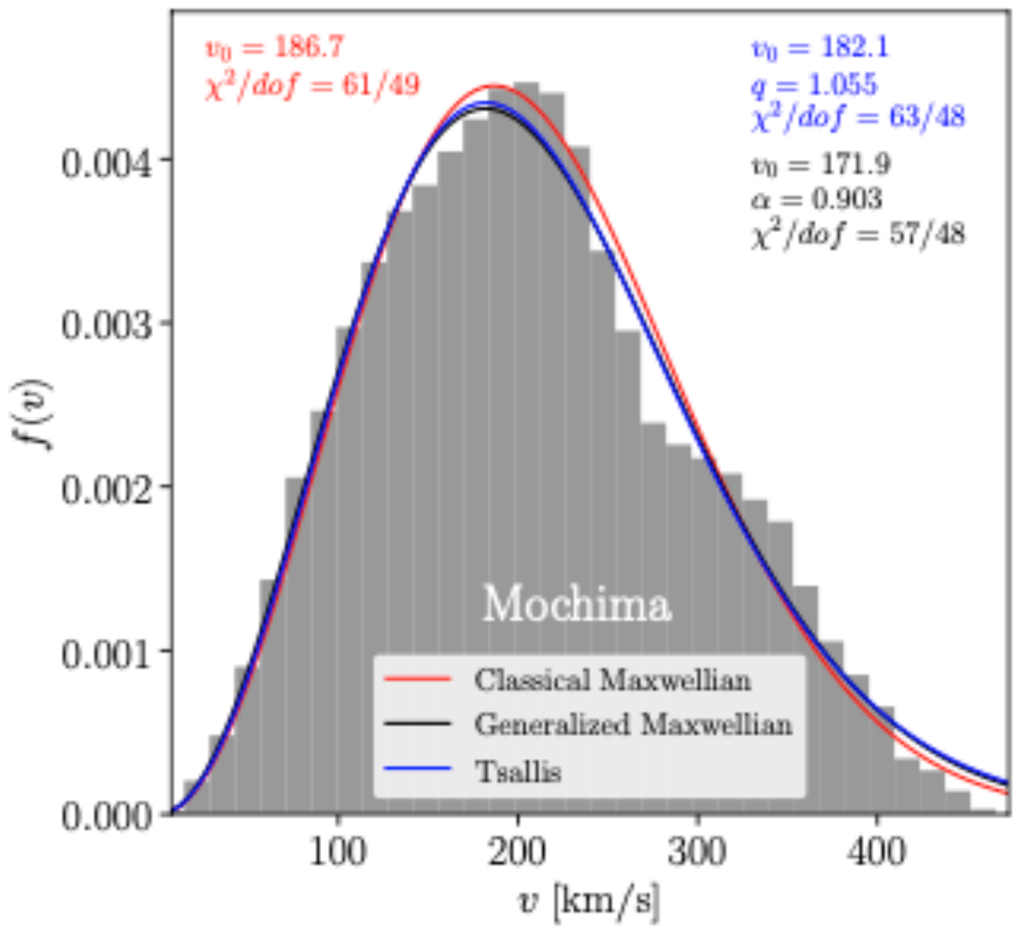

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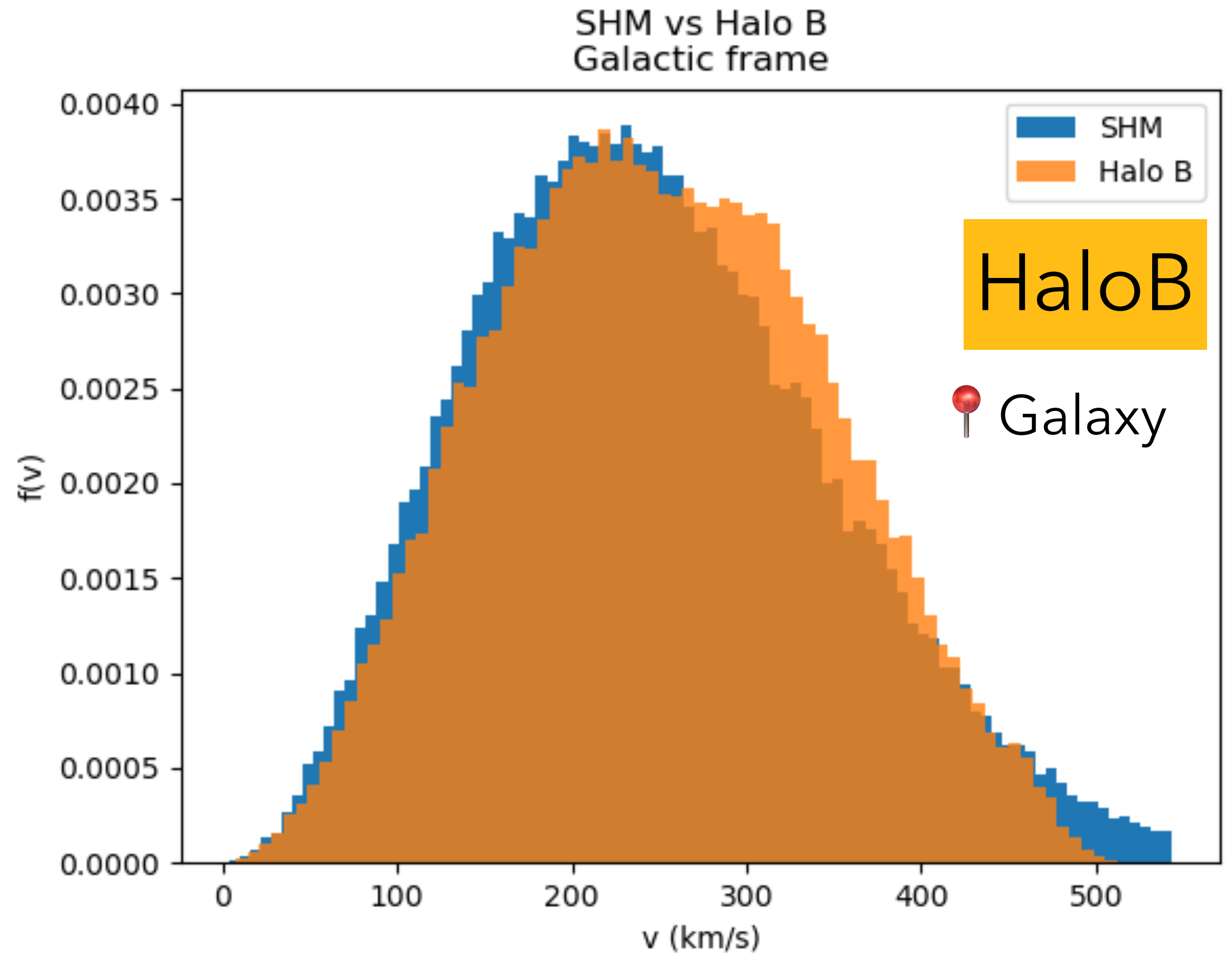

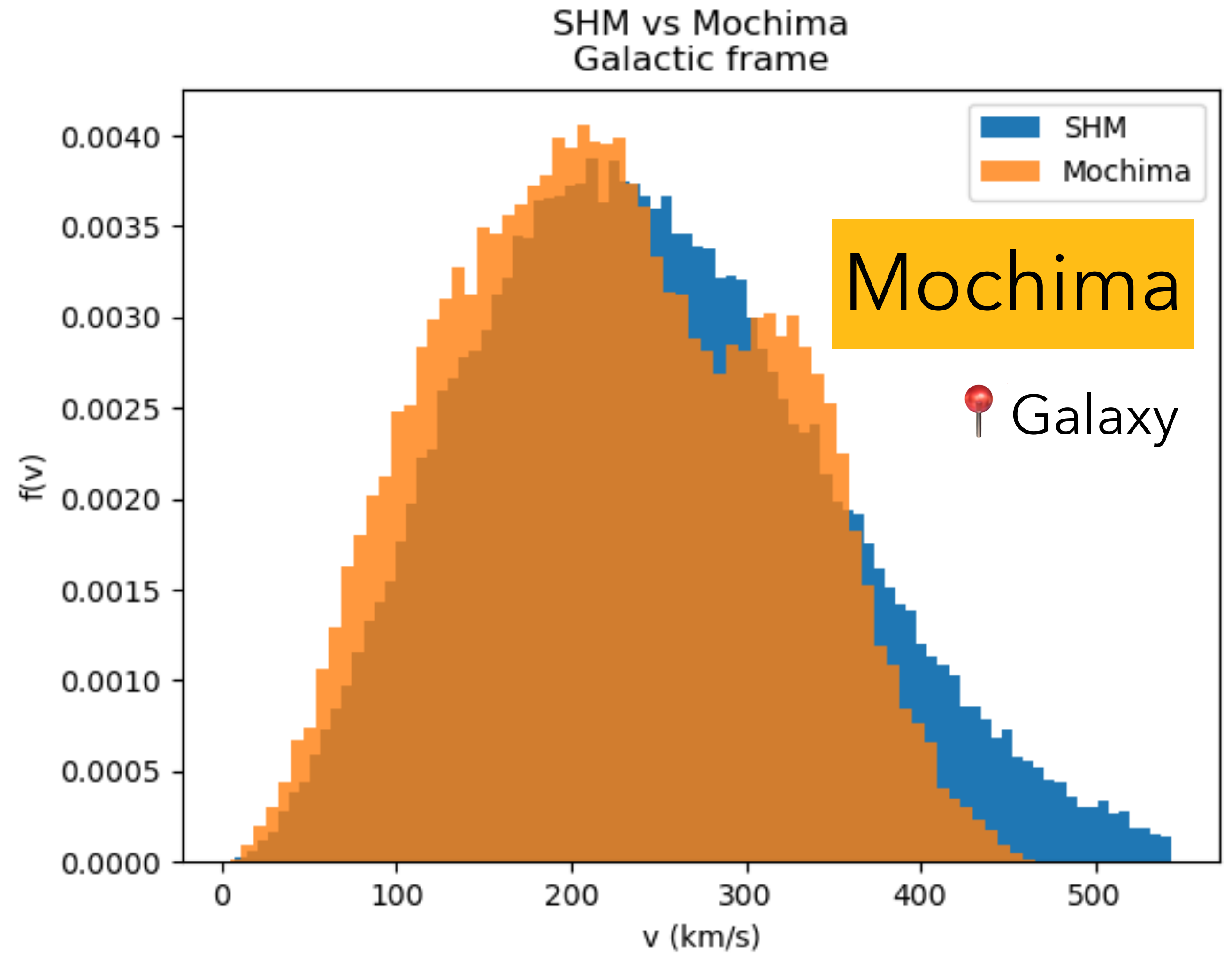

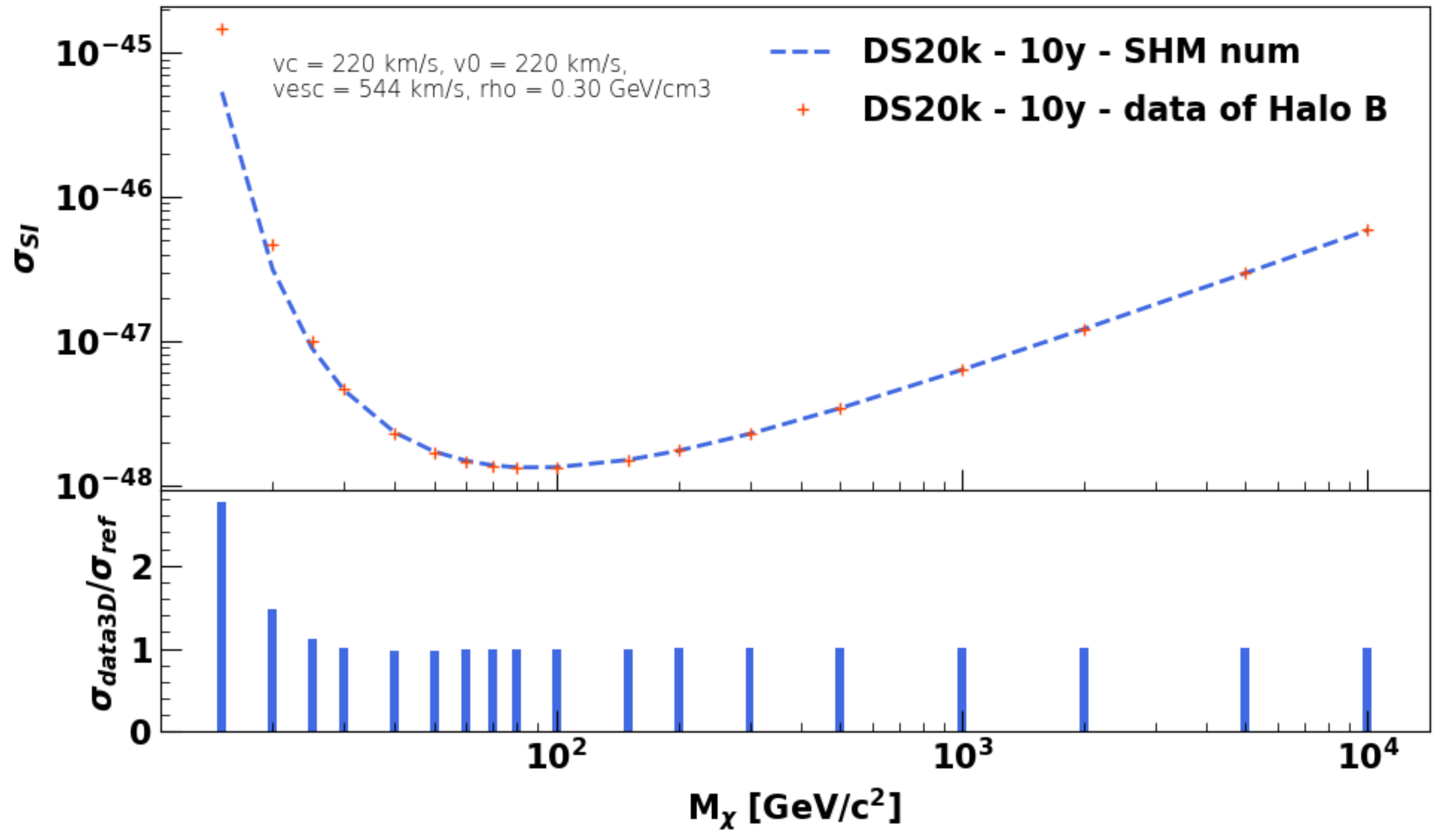

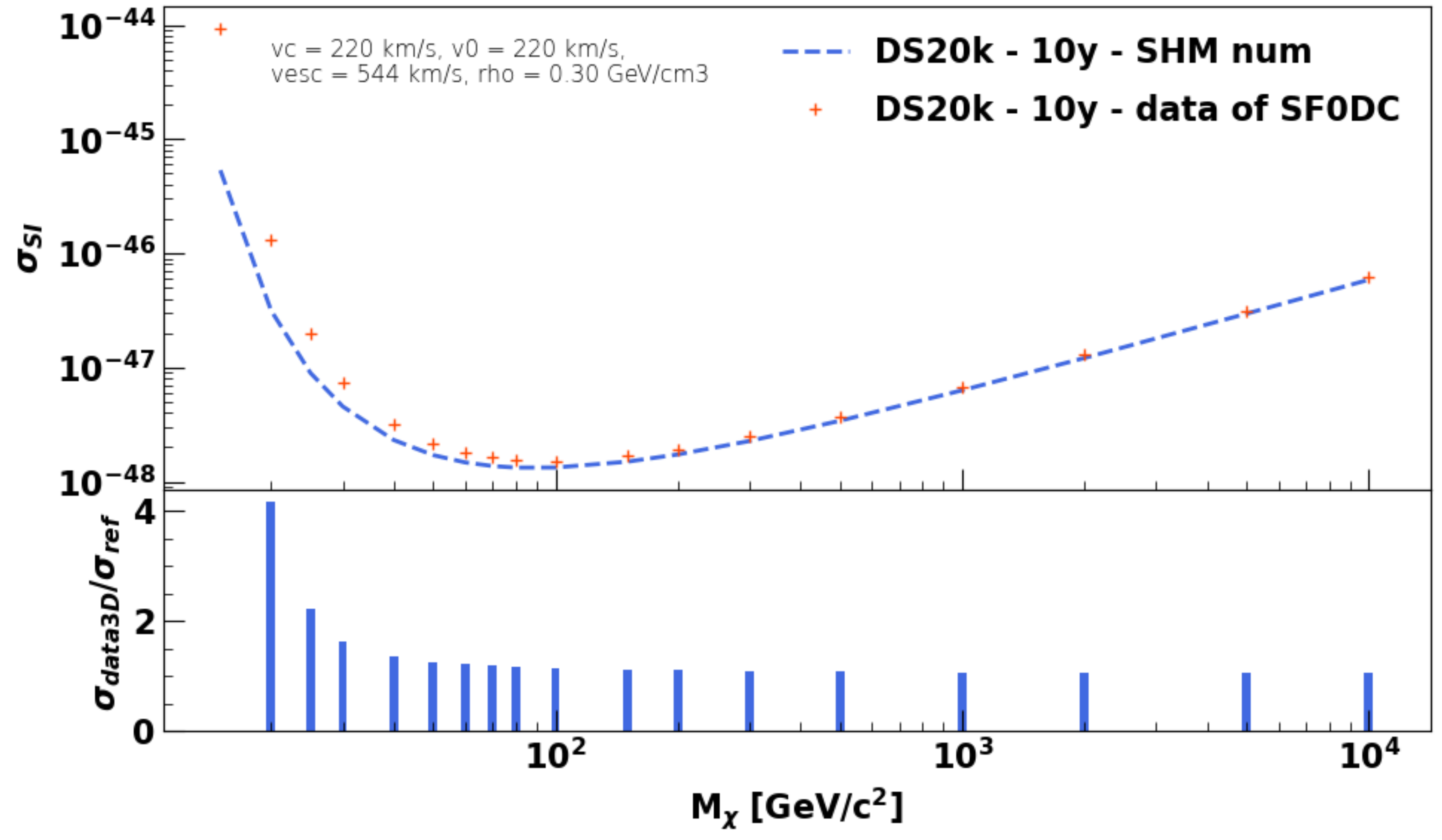

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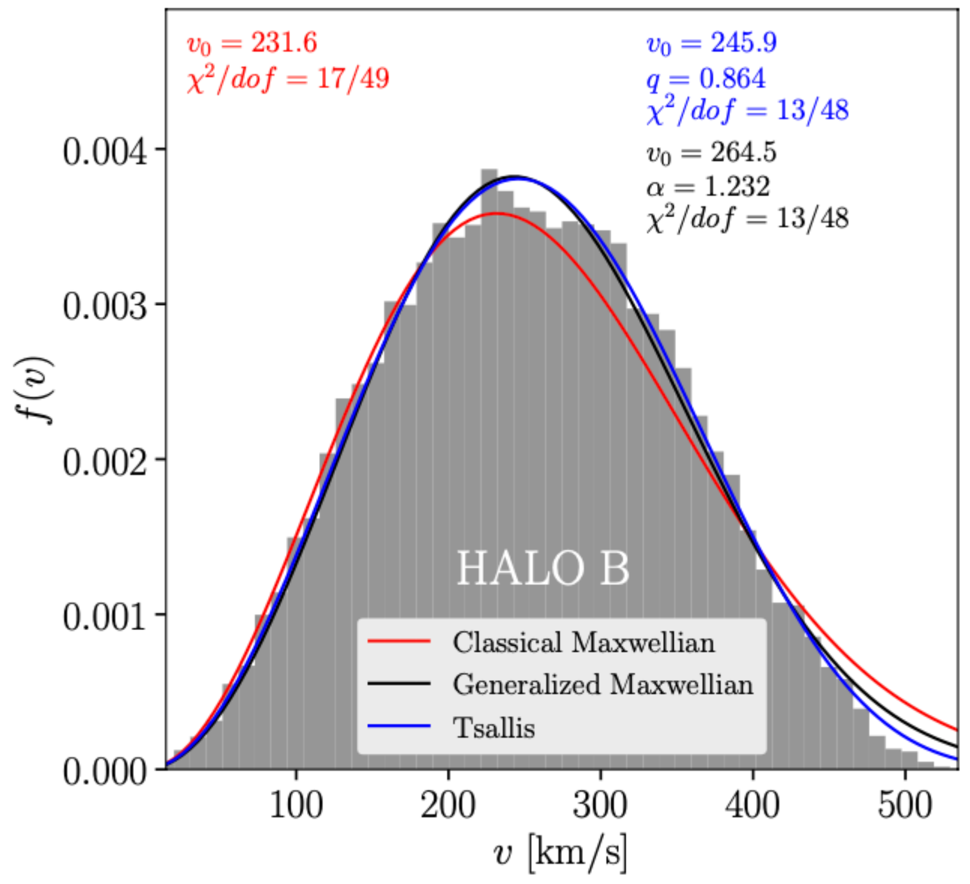

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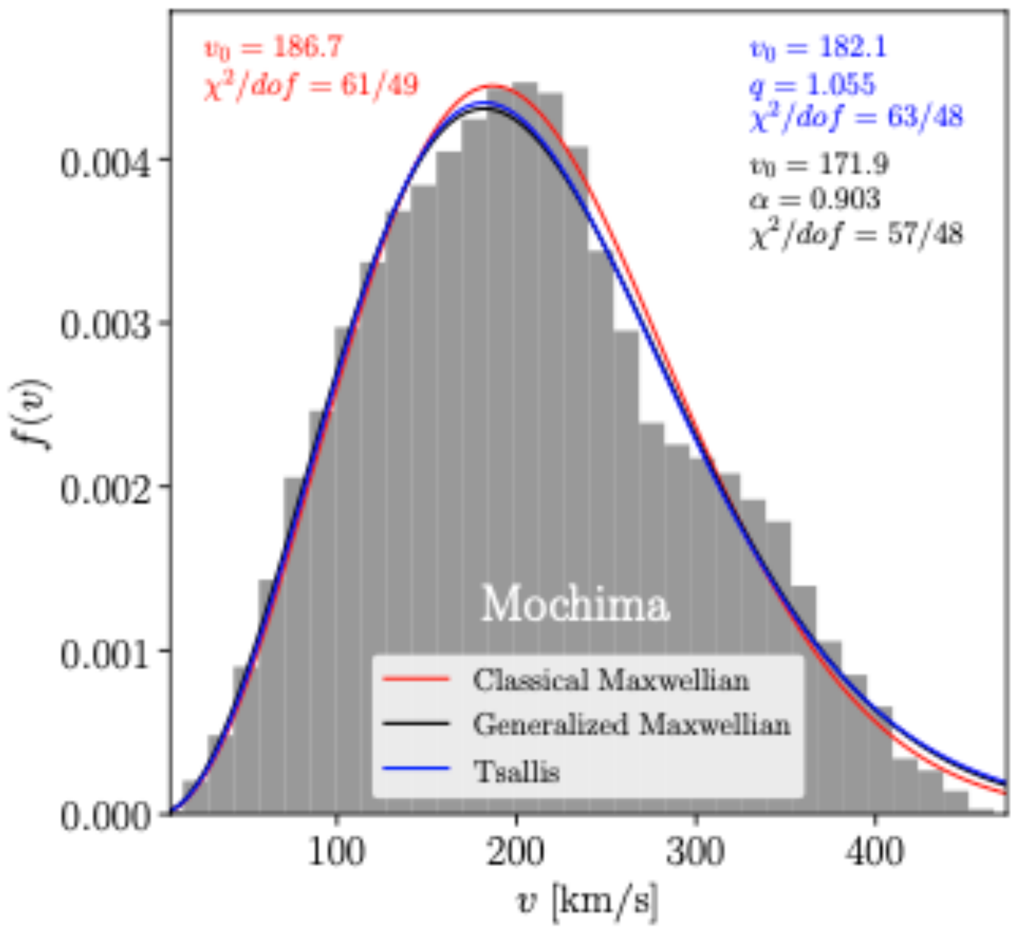

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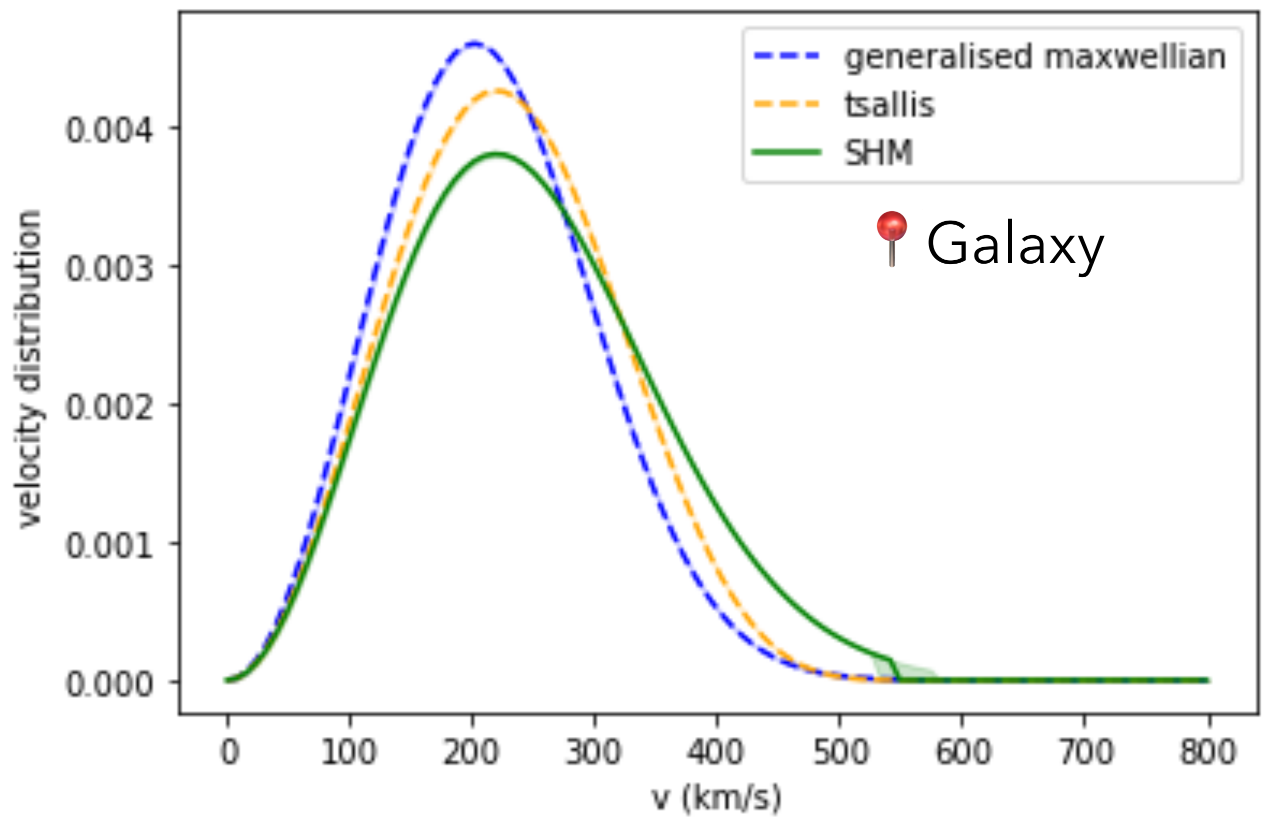
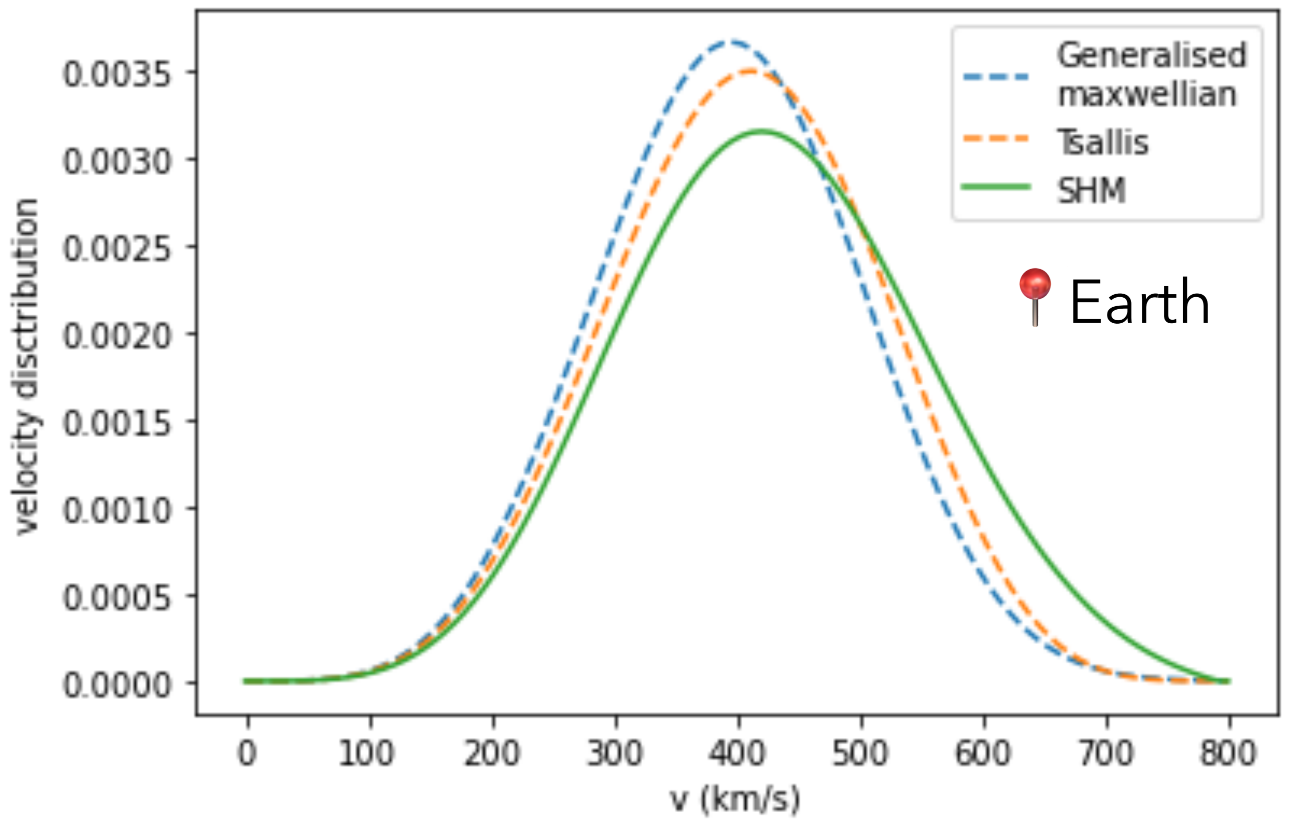
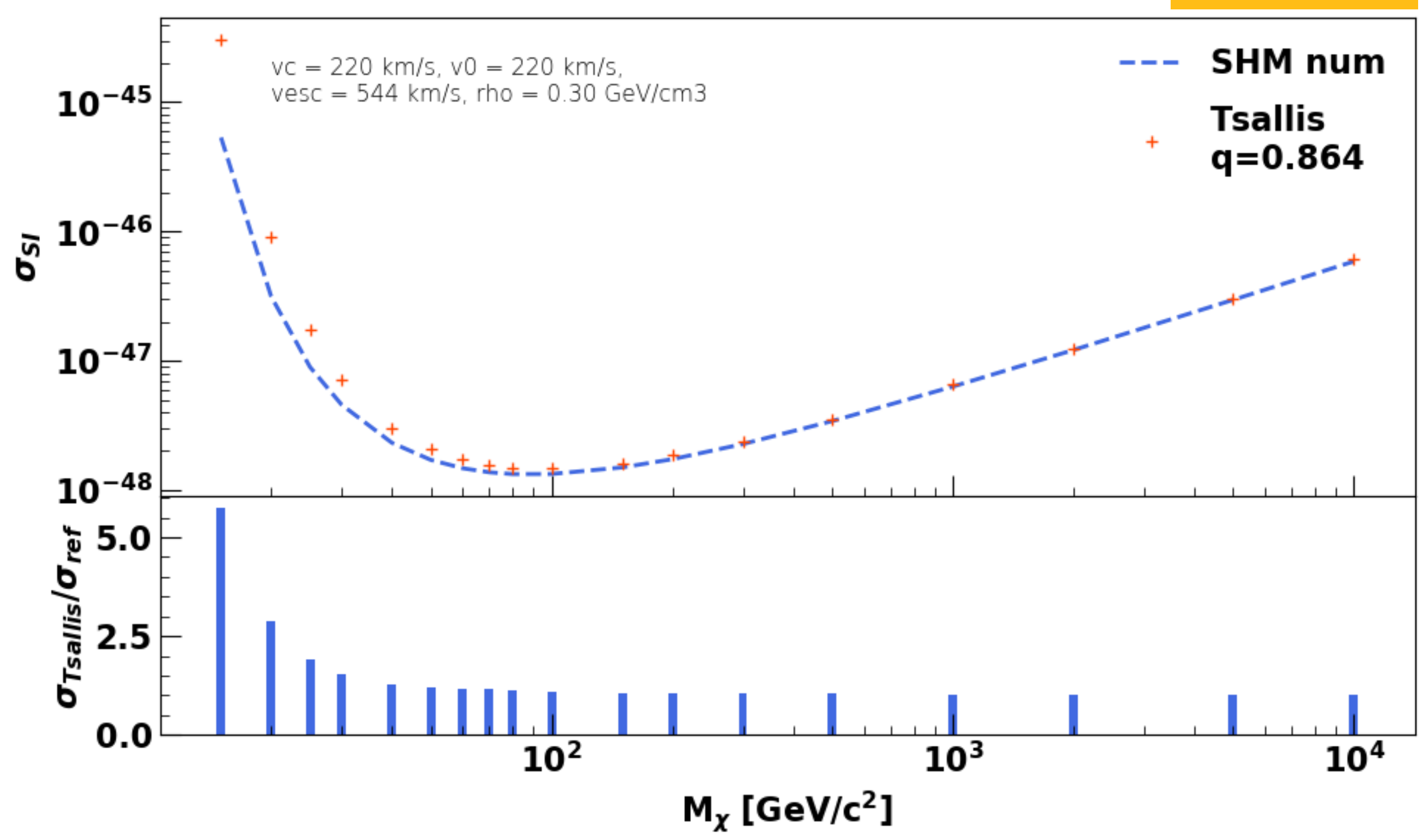
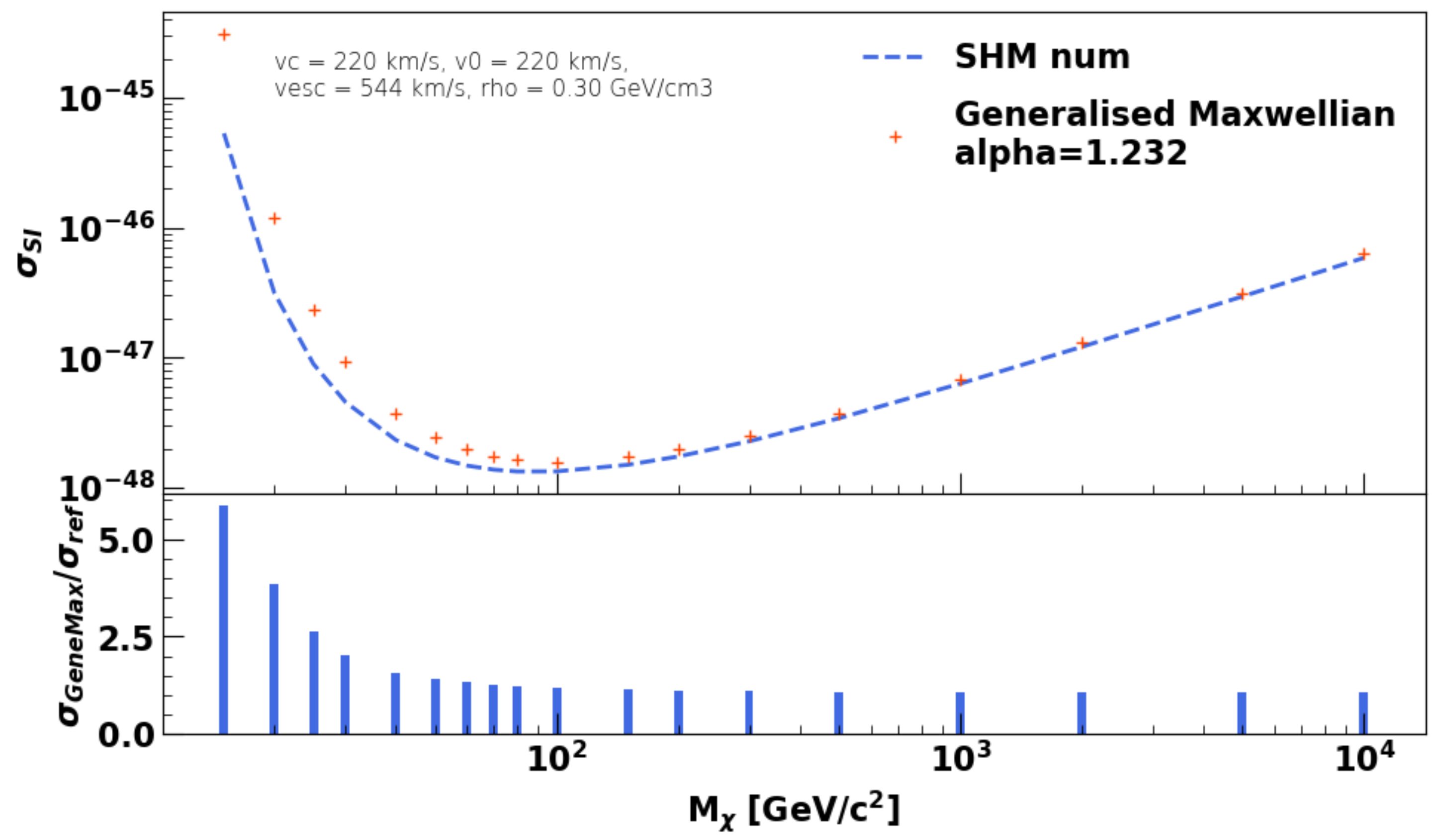




Tsallis



Generalised maxwellian



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Play on $f(\vec{v})$ in the rate of events, hint from cosmological simulations

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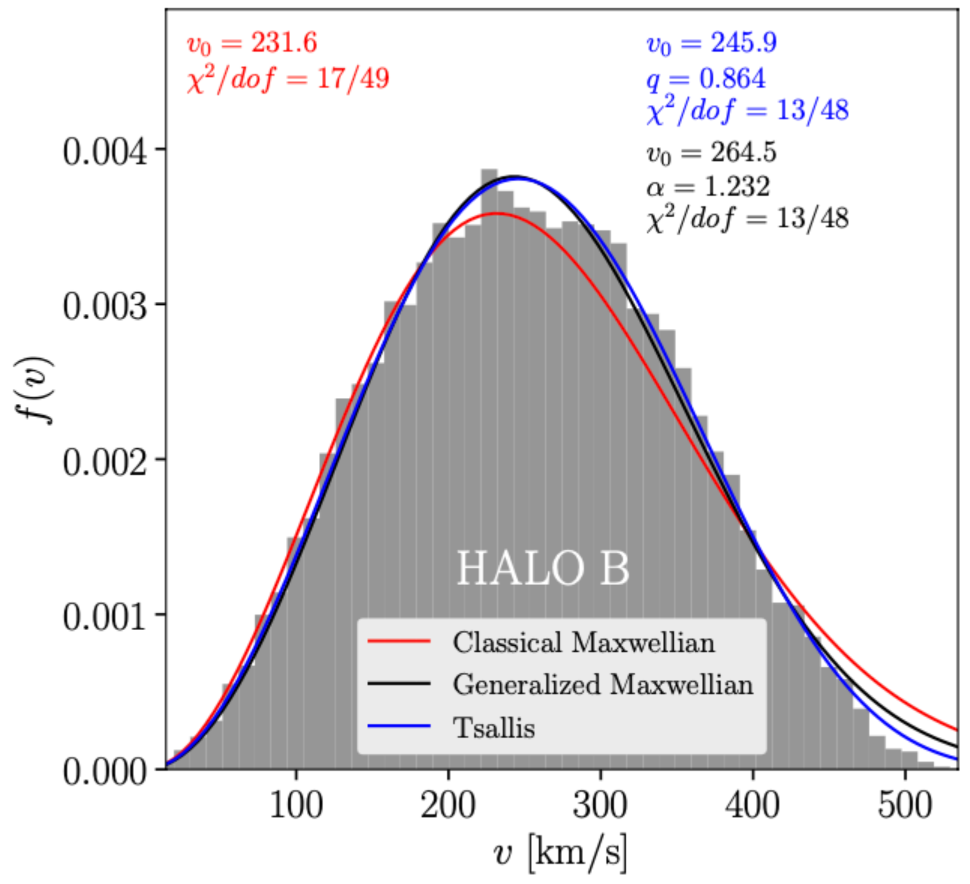

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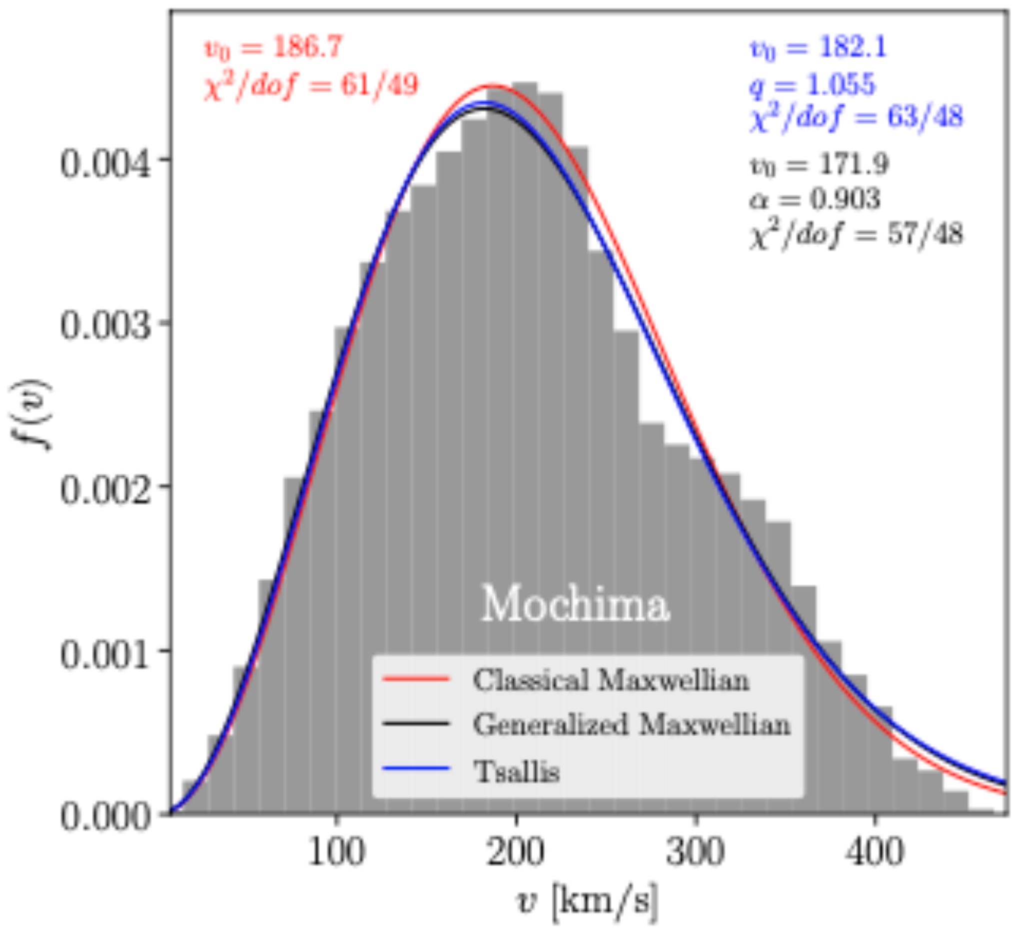

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Development of different methods to integrate these f(v)

Directly take the simulation result as input

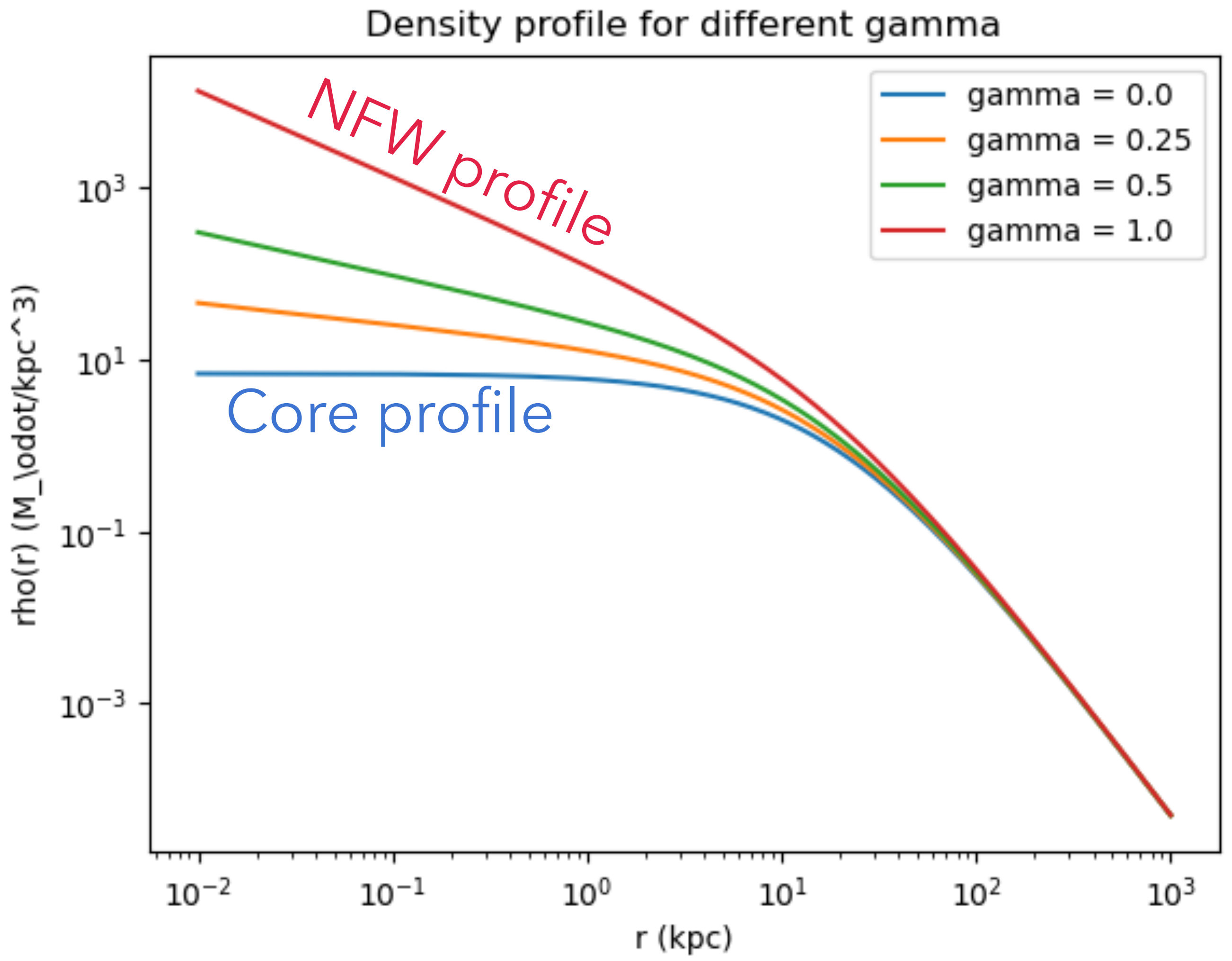
📚 *See more in back up*

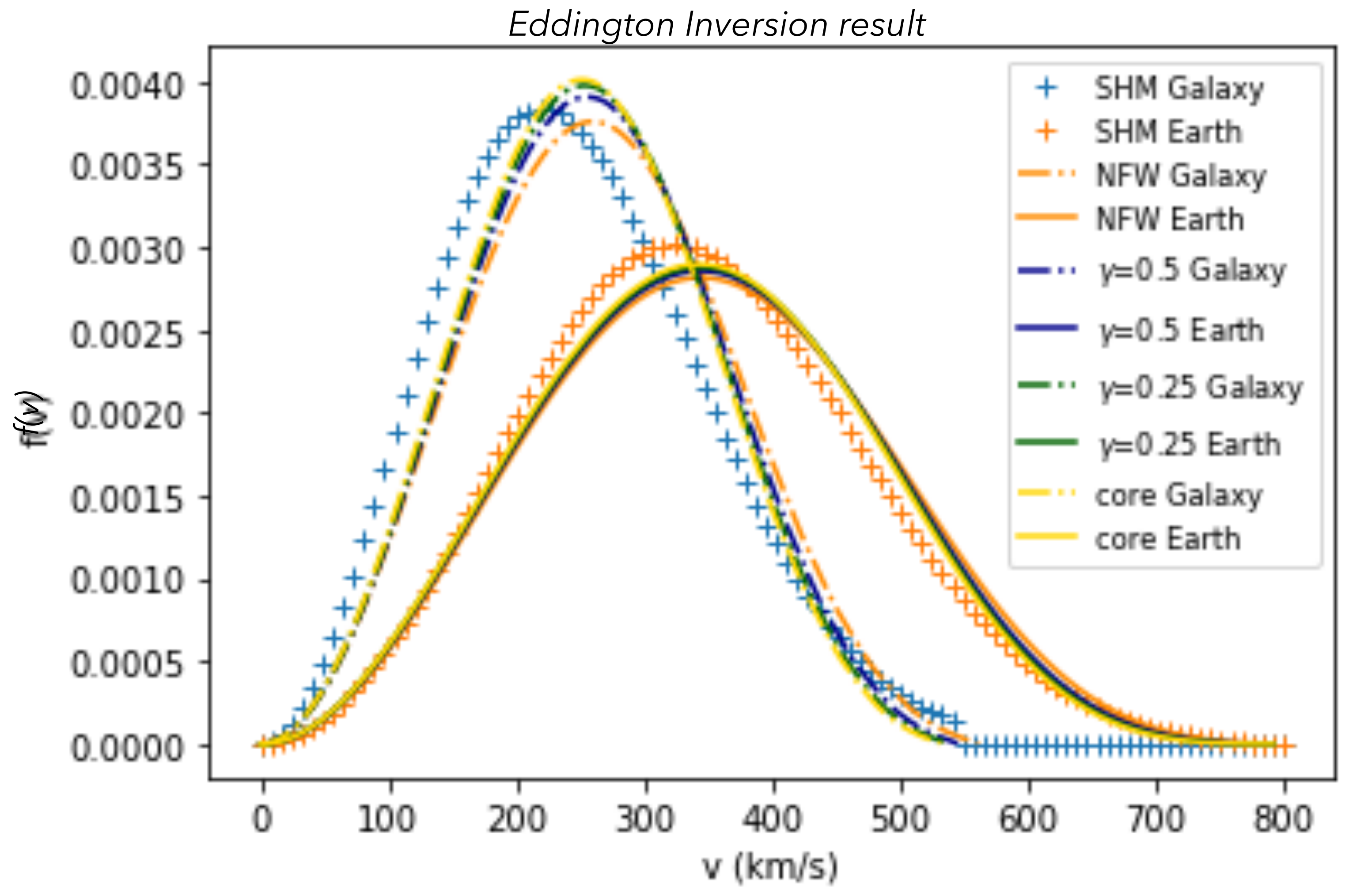
Fit the simulation result with known distributions

📚 *See more in back up*

Fit the mass distribution and perform Eddington Inversion

📚 *See more in back up*





Eddington procedure

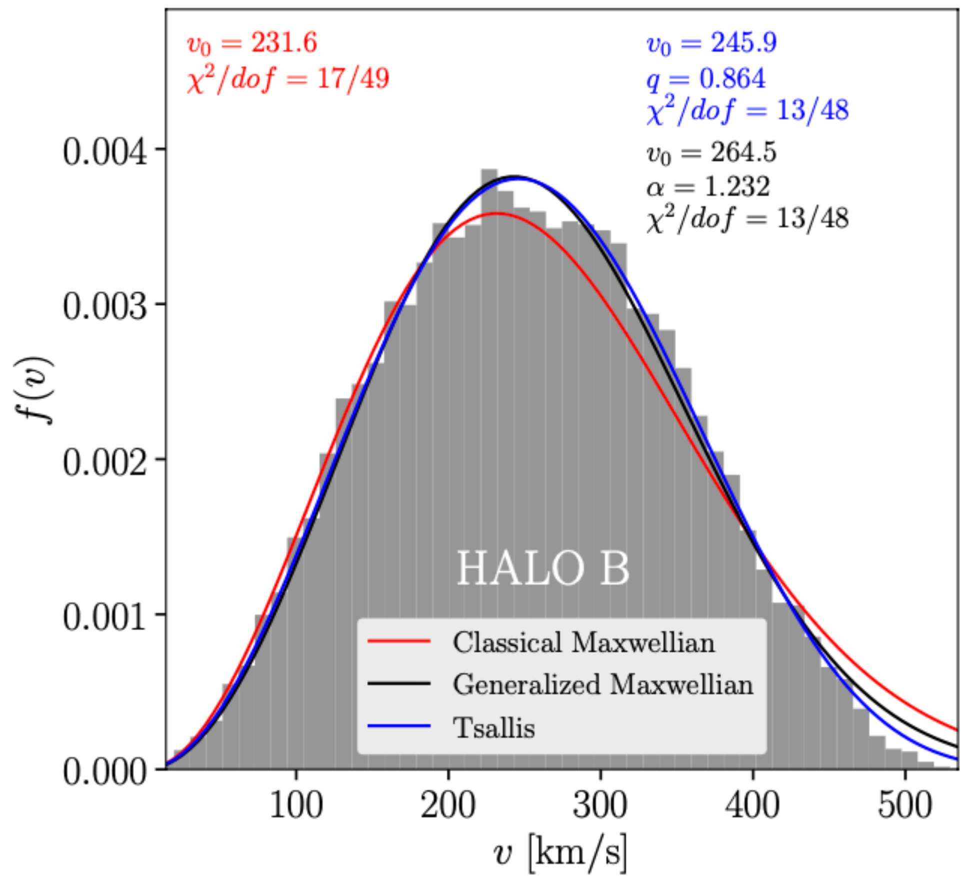
📚 *See more in back up*

Future: perform rates and exclusion limits computations

Take better suited velocity distributions

Play on $f(\vec{v})$ in the rate of events, hint from cosmological simulations

Starters



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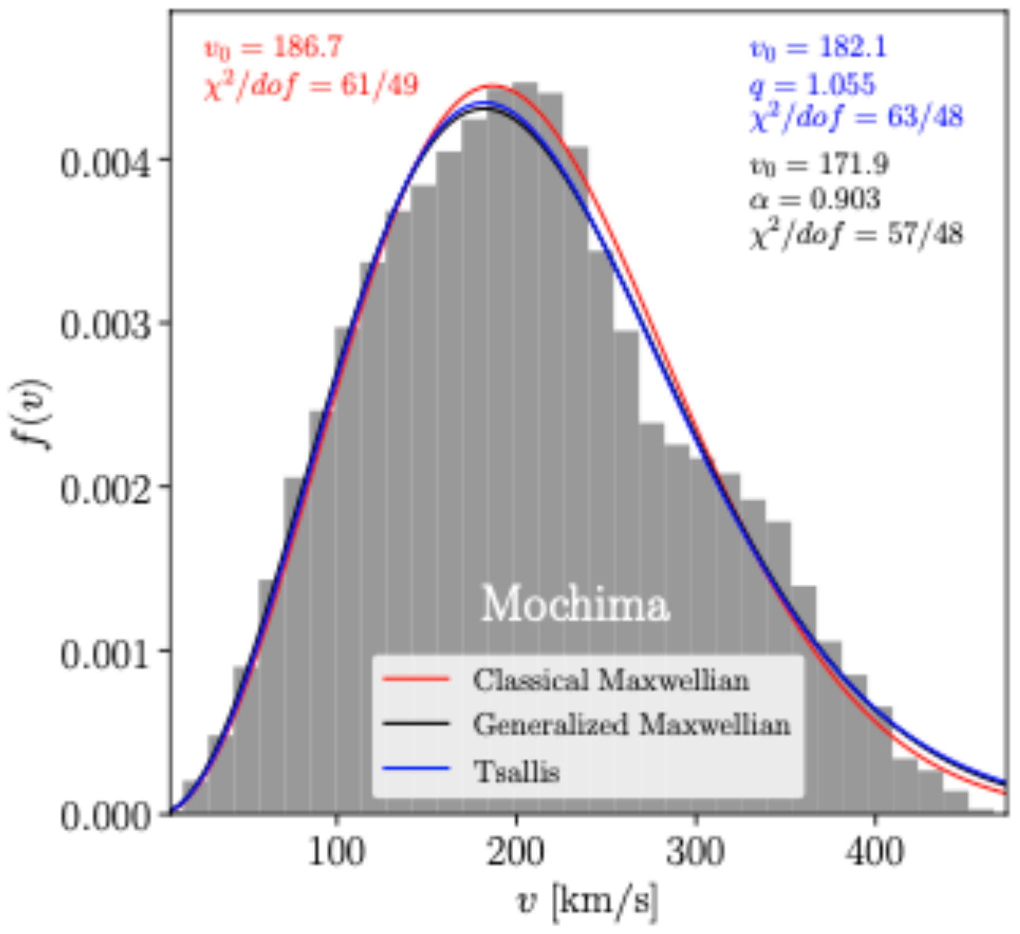

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📚 *See more in back up*

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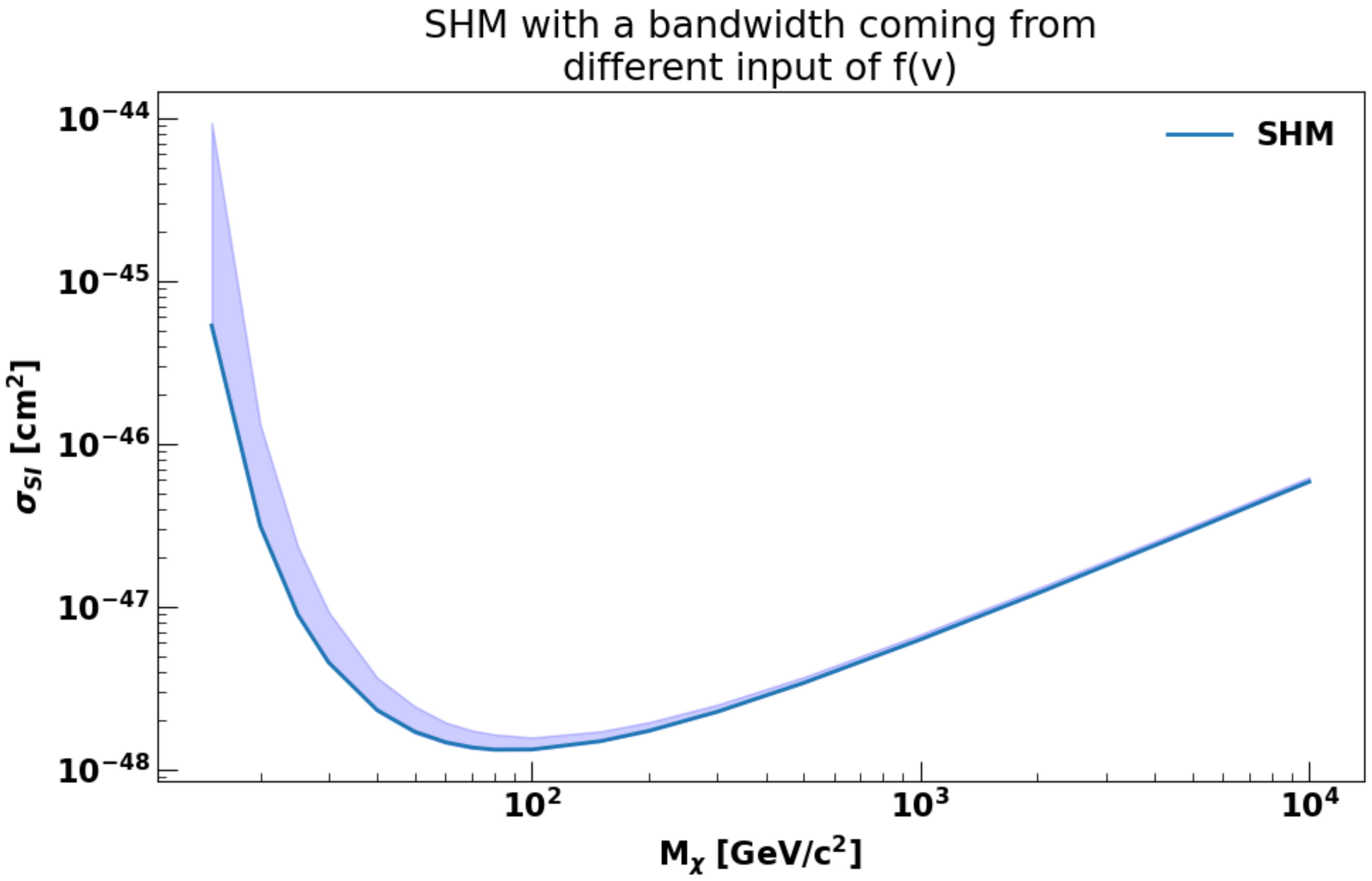
Global result



Take better estimates for the astrophysical parameters of interest

Play on $v_{esc}, v_0, v_c, \rho_0$ in the rate of events, hint from galaxy surveys

Litterature survey of parameters estimate

2011 - 2022 estimates of astrophysical parameters computed from galactic surveys data analysis

$v_0 \in [178{,}252]$ km/s

$v_c \in [178{,}252]$ km/s

$v_{esc} \in [432{,}693]$ km/s

$\rho_0 \in [0.13{,}0.44]$ GeV/cm³

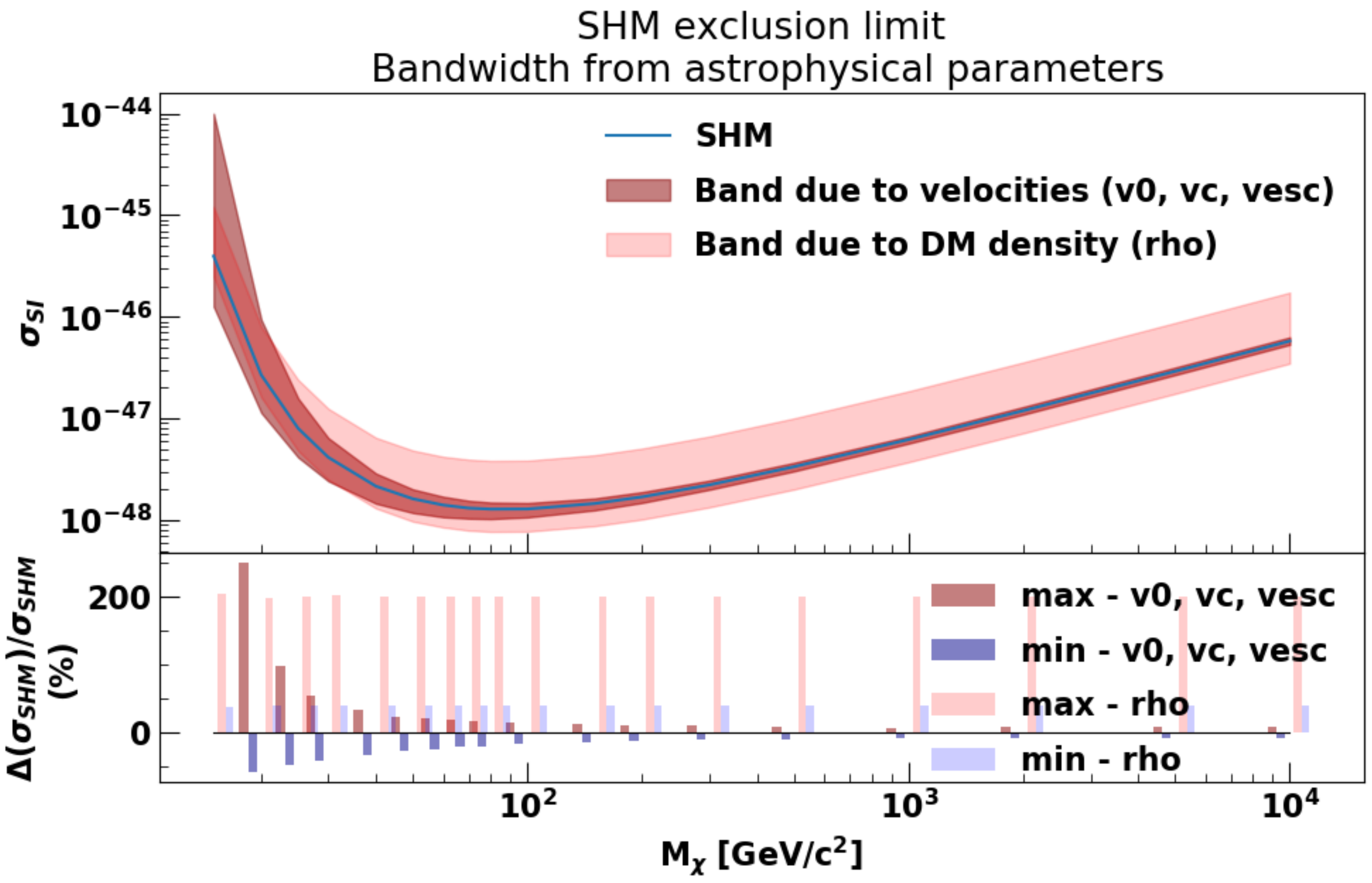
📚 *See more in back up*

Blue line: reference (published) exclusion limit computed with SHM and $v_{esc} = 544$ km/s, $v_c = 220$ km/s, $v_0 = 220$ km/s, $\rho_0 = 0.3$GeV/cm³

Dark red band: band coming from ρ_0 variation in its uncertainty interval: $\rho_0 \in [0.13{,}0.44]$ GeV/cm³ & $v_{esc} = 544$ km/s, $v_c = 220$ km/s, $v_0 = 220$ km/s

Light red band: band coming from v_{esc}, v_c and v_0 variation in their respective uncertainty interval *e.g : $v_0 \in [178{,}252]$ km/s & $v_{esc} = 544$km/s, $v_c = 220$ km/s, $\rho_0 = 0.3$GeV/cm³*

Independent variation of parameters



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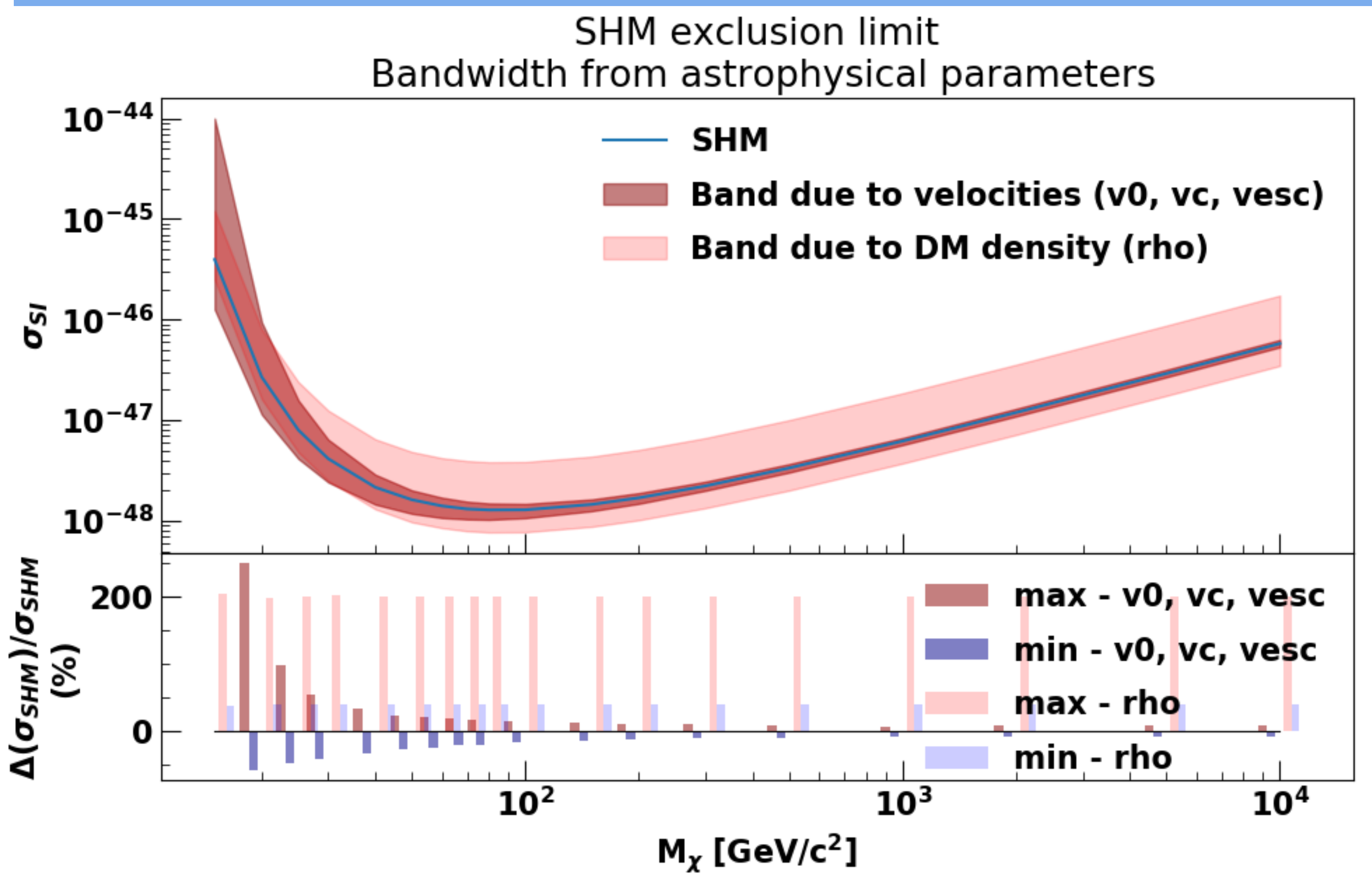


However, these four astrophysical parameters **depend on one another**. Future (and last) commitment on the phenomenological part of the thesis: **collaborate** with J. Lavalle (LUPM, Montpellier) to obtain consistent **sets of parameters** to take as input in the exclusion band computation

Last year's presentation (link)

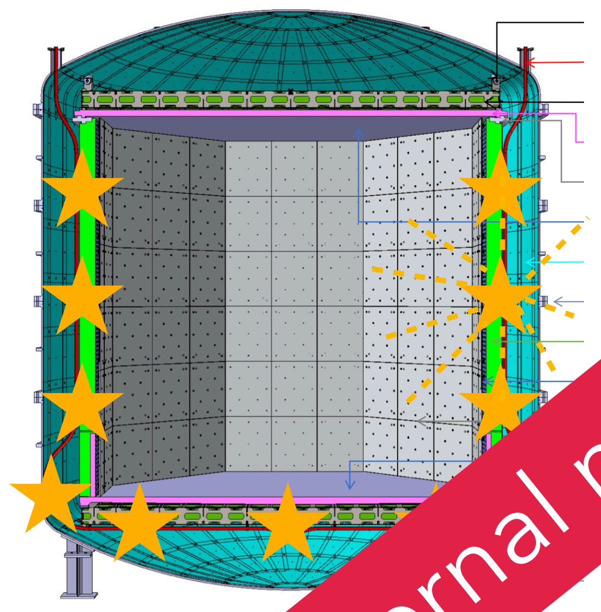
Declaration of my PhD thesis purpose and first results

Particle physics

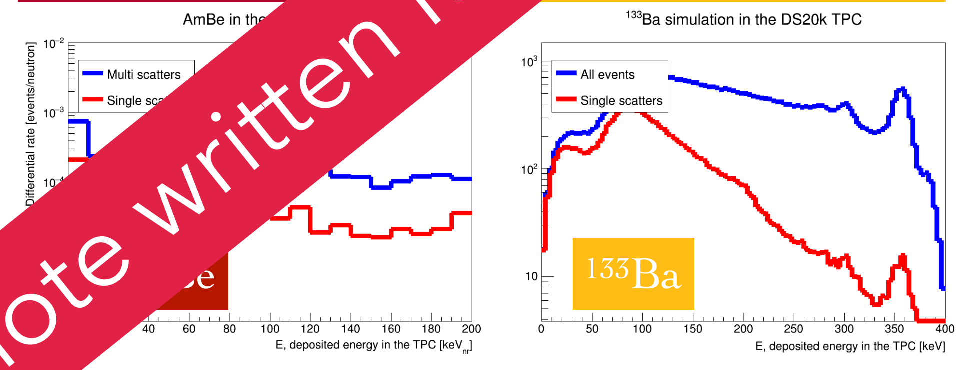
Now over (internal note written for the collab)

Over (internal note written for the collab)

My first commitment and results: the ***simulation*** of DarkSide-20k's ***TPC calibration***



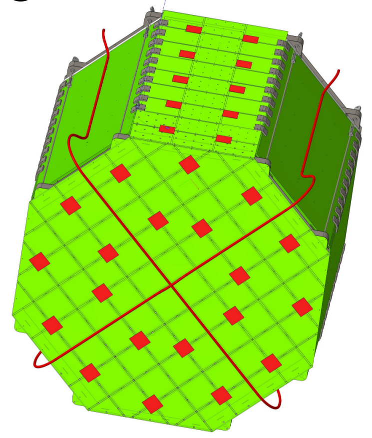
NR calibration, neutron sources (most important) | ER calibration, γ sources



✅ *in 1 month* ✅ *in 1 week*

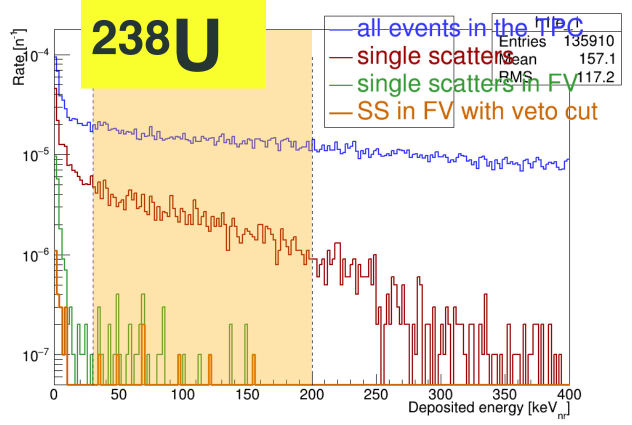
Simulation of the ***impact*** of the calibration systems on the rest of the detector

Light collection efficiency



✅ *No impact on the veto's LCE !*

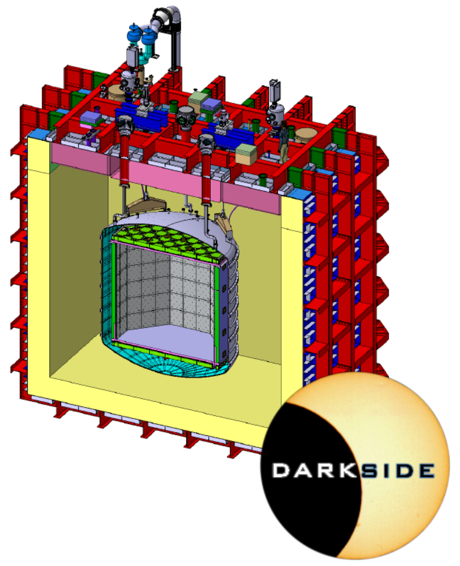
Induced background



✅ *Represents < 0.01% of DS20k bgd budget*

My thesis

The detector



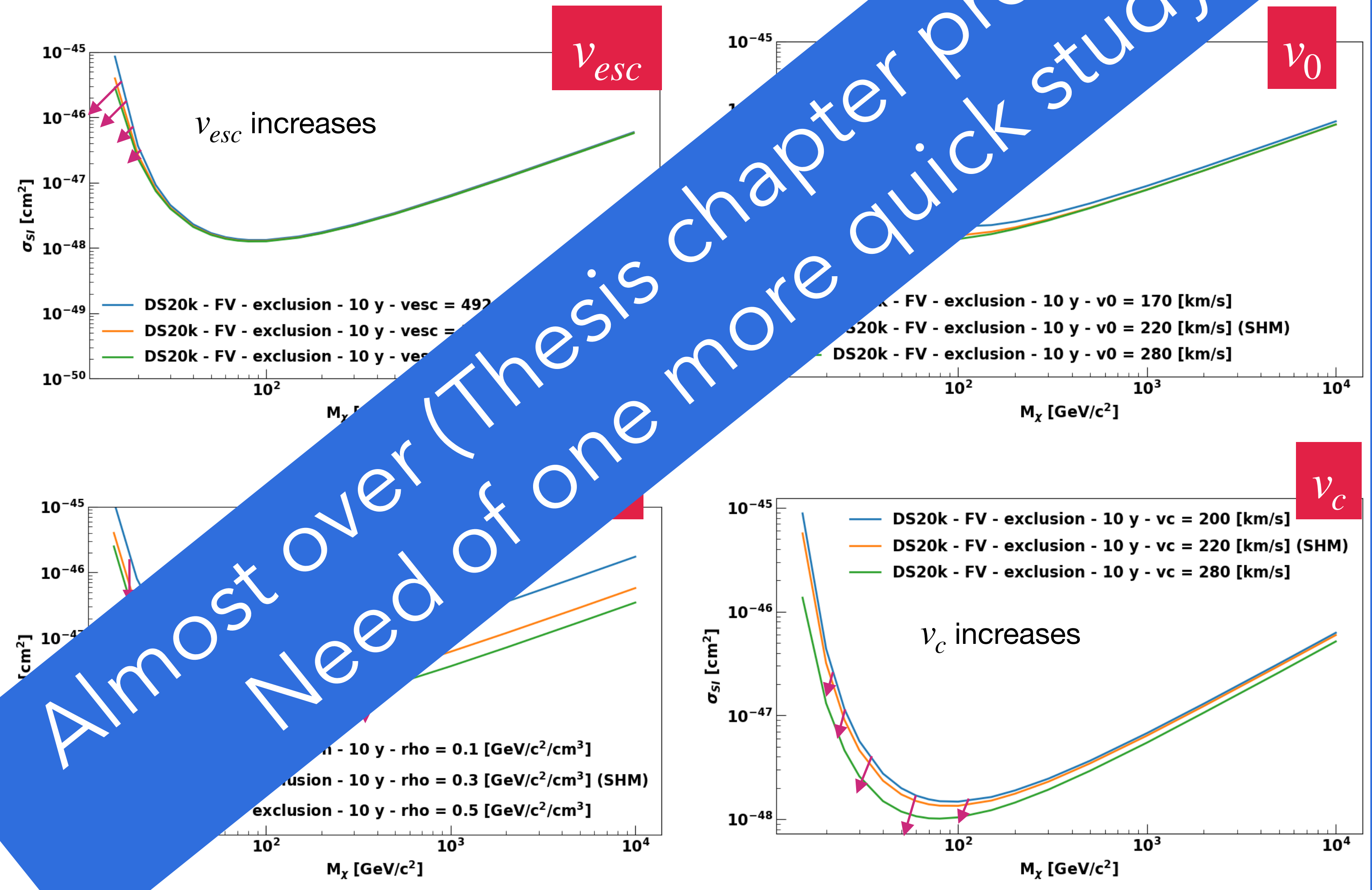
Astrophysics

2022 commitment

Almost over (Thesis chapter pre-written)

Need of one more quick study

Assess the ***impact*** of ***astrophysical uncertainties*** on DS20k ***exclusion***



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HEP

Astro

Global advancement of the PhD

- MC simulations
- Phenomenology
- Mock-up
- Signal reconstruction
- Teaching and communication

1st of October 2021: start of the PhD

Institut Physique de l'Univers Aix-Marseille Université

Internship

DS facilities visit at CERN

GDR DUPhy

End of 2021

IPhU day talk

Writing of a poster to present the mockup to visitors at CPPM

Presentation of CPPM implication in DM search at Fête de la science (Marseille) + Poster

Presentation of simulation studies to GDR DUPhy

DM lecture J. Lavalle

Present

Publication of DS sensitivity in low mass analysis

Presentation of phenomenological studies at national GDR

Presentation of the low-mass sensitivity at conferences

Simulations of the calibration in the previous geometry of DS20k

Hardware work on the mock up at CPPM:
- Tests at room temperature and cold
- Strain deformation vs temperature + data analysis

*Simulations of the calibration in the **frozen** geometry of DS20k*
- TPC calibration strategy
- Minimization of the guide tube system impact on the other parts of DS20k

Writing of an internal note presenting the simulation results

6 oral reports to the collaboration (including one in collaboration meeting)

Astrophysical impact on the DS20k exclusion limits
- Catalog recent estimates of astrophysical parameters
- Code development to include new models for WIMP velocity distribution in the galaxy and on Earth
- Production of uncertainties bandwidth around initial DS20k exclusion limit

Prospective writing of an internal note presenting the phenomenological results

Oral report to the collaboration

Hardware work on the mockup
- Prepare a calibration run
- Feasibility tests at cold

Teaching TPs

Hardware work on the mockups of the calibration system
- Giant mockup @CPPM
- Last cold tests
- Long tests @CERN

MC simulations of low-mass background in order to compute DS20k sensitivity at low WIMP mass

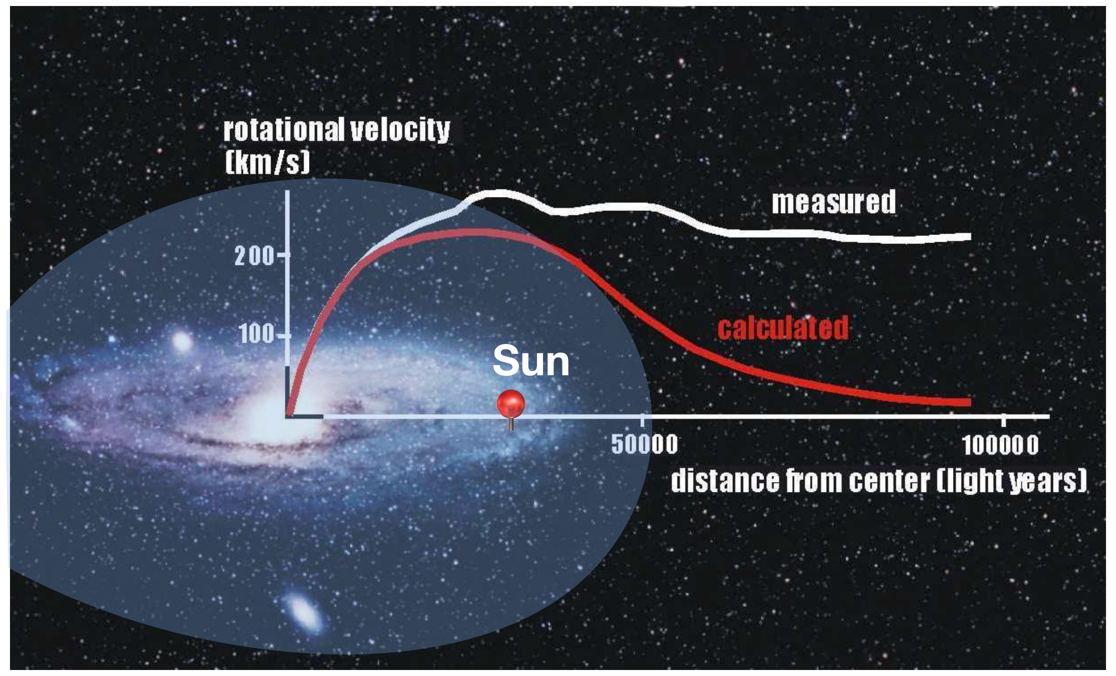
Astrophysical uncertainties applied to the low-mass sensitivity

Use AI to help signal reconstruction and optimize signal/background rejection

Back up

The Standard Halo Model (SHM) -1/2

Ground model to compute DMDD exclusion limits



- The SHM is a model derived from circular velocity measurements in galaxies (20th century):
  - Need to fit the velocity measurements adding a dark matter (i.e. mass component)
  - Data = v_c becomes constant
  - Isotropic gravitational potential :

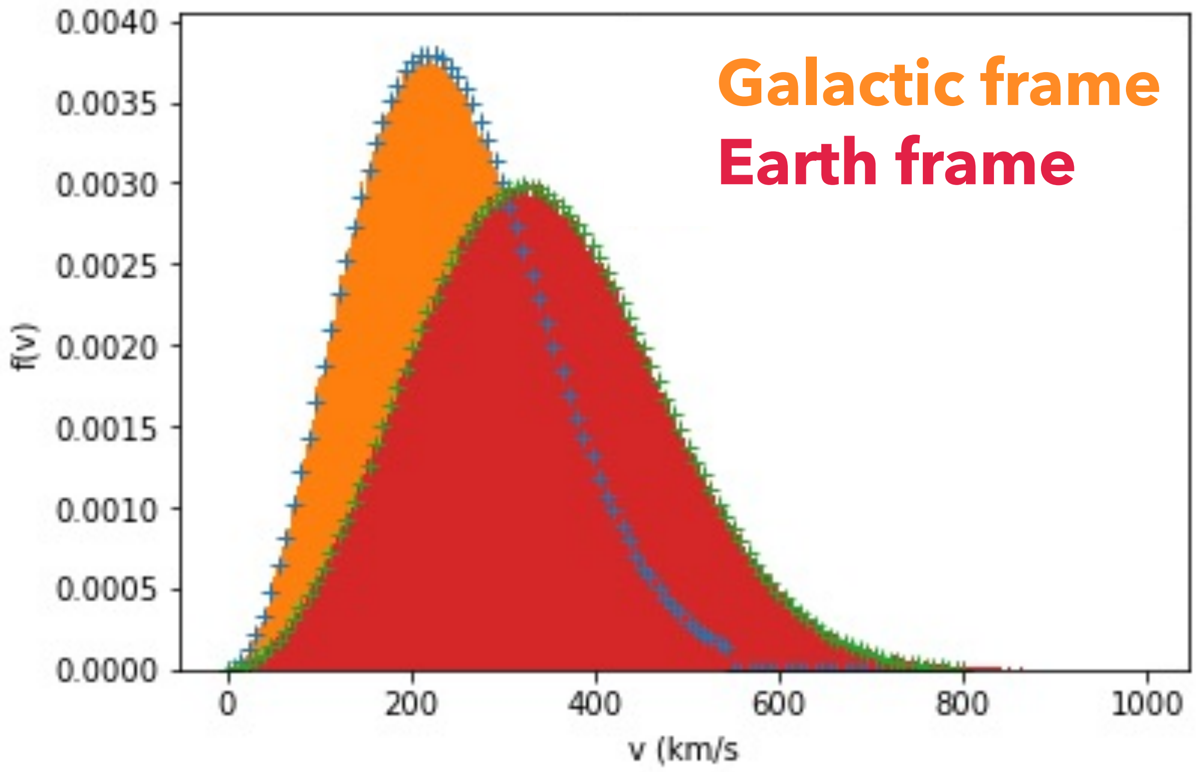
$$a = \frac{v_c^2}{r} = \frac{\mathcal{G}M(r)}{r^2} \Rightarrow v_c = \sqrt{\frac{\mathcal{G}M(r)}{r}} \sim \text{cst} \Rightarrow$$

$M(r) \sim r$

- $M(r) = \int_0^r \rho(r) d^3r = \int_0^r \rho(r) r^2 dr \sim r \Rightarrow \rho(r) \sim \frac{1}{r^2}$

<=>

- Assuming a model describing isotropic, spherically symmetric collisionless gas of DM particles
- Simple solution = describe the gas with Maxwell-Boltzmann distribution
  - Isothermal gas
  - $f(v_x) = f(v_y) = f(v_z) = \frac{1}{N} e^{-\frac{m_\chi v_x^2}{2k_B T}} = \frac{1}{N} e^{-\frac{v_x^2}{v_0^2}}$
  - $f(|\vec{v}|) = \frac{1}{N'} v^2 e^{-\frac{v^2}{v_0^2}}$

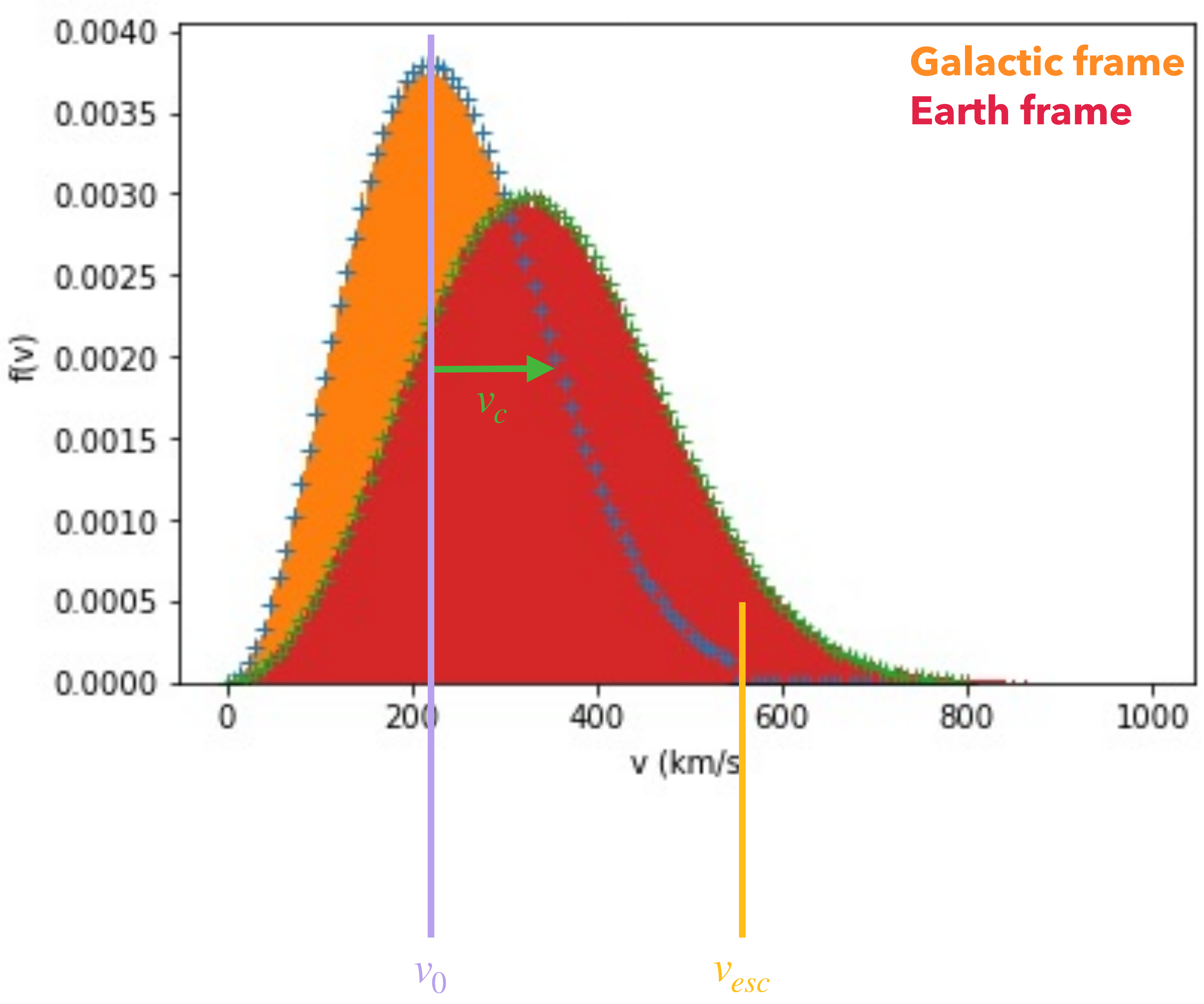


The Standard Halo Model (SHM) - 2/2

Ground model to compute DMDD exclusion limits

- In DMDD, one needs to estimate the number of NR events in the detection volume
- To compute it, one needs to estimate the velocity of the WIMP in the Earth frame
- Velocity composition:
- $\overrightarrow{v_{\chi/\oplus}}(t) = \overrightarrow{v_{\chi/\mathrm{gal}}} - \overrightarrow{v_{\oplus}}(t) = \overrightarrow{v_{\chi/\mathrm{gal}}} - \overrightarrow{v_{\oplus/\odot}}(t) - \overrightarrow{v_c} - \overrightarrow{v_{pec}}$
- Thus for DMDD, one needs to estimate the values of astrophysical parameters of interest to describe the halo AND to perform the change of frame
- The chosen values are the ones better-estimated in the 2010's:
  - $v_{esc} = 544$ km/s
  - $v_c = v_0 = 220$ km/s
  - $\rho_0 = 0.3$ GeV/cm³

Gives in the end



Take directly cosmological simulation data as input for $f(\vec{v})$

Data from Arturo Nuñez thesis

Cosmological simulations

Model gravitational interactions across time with a set of initial conditions (that are optimized)

The resolution of the simulation is increased in the Lagrangian volume after the first round of simulation

Mass distribution

Result

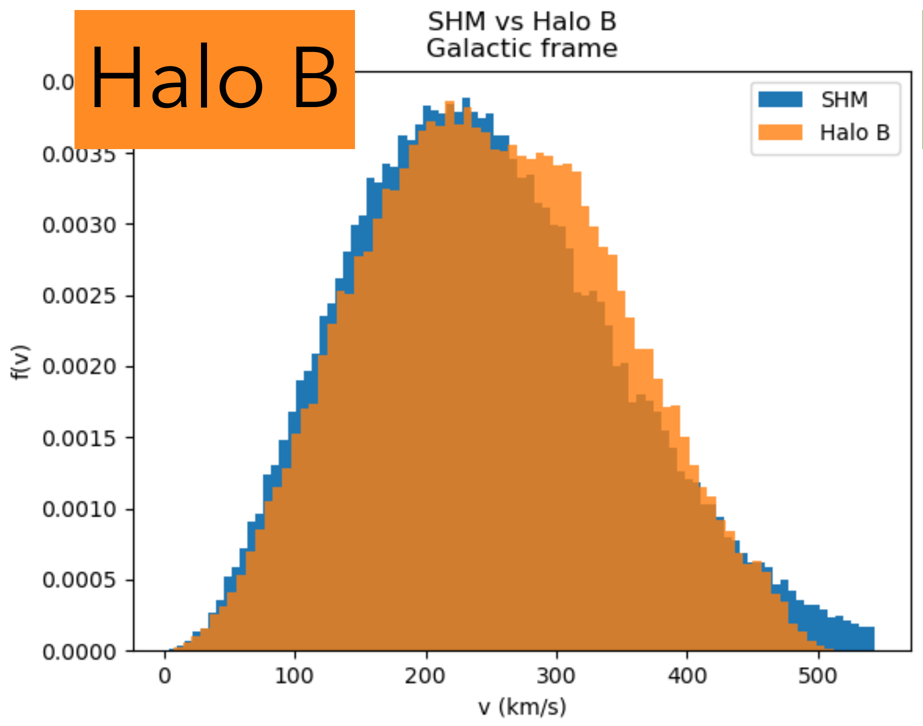
Velocity distribution

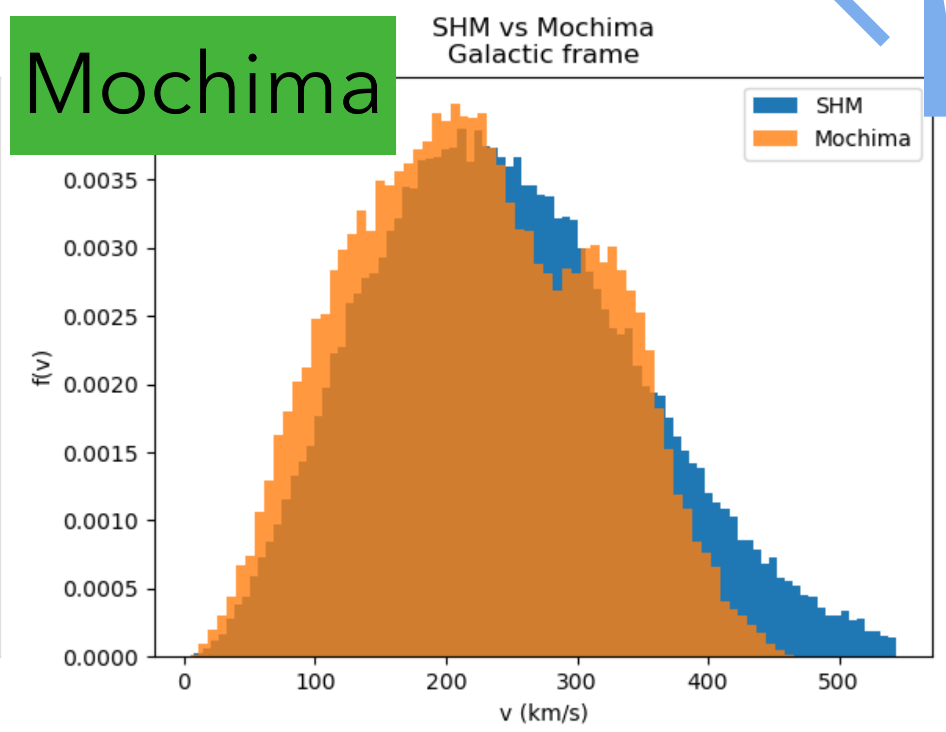
$v_{x,gal}, v_{y,gal}, v_{z,gal}$ in the galactic frame

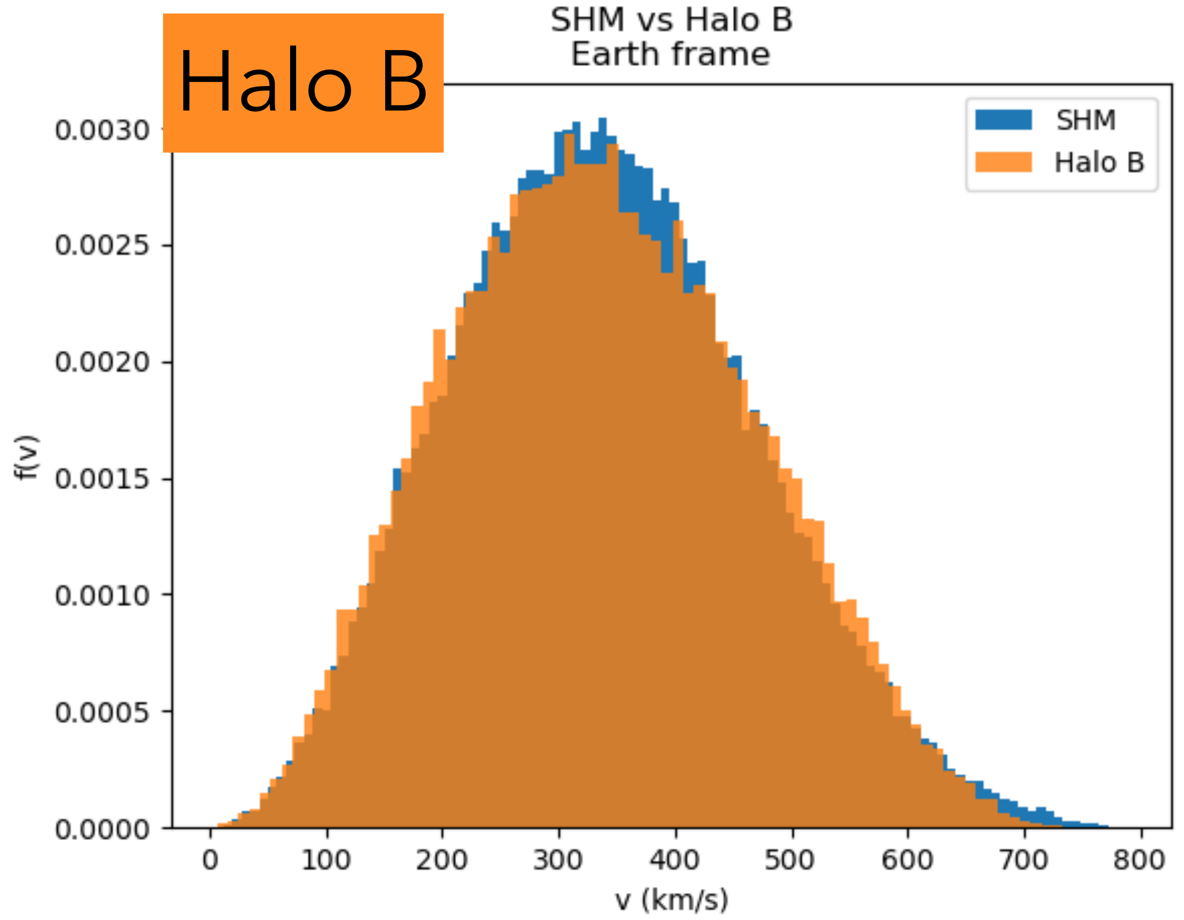
Change of frame

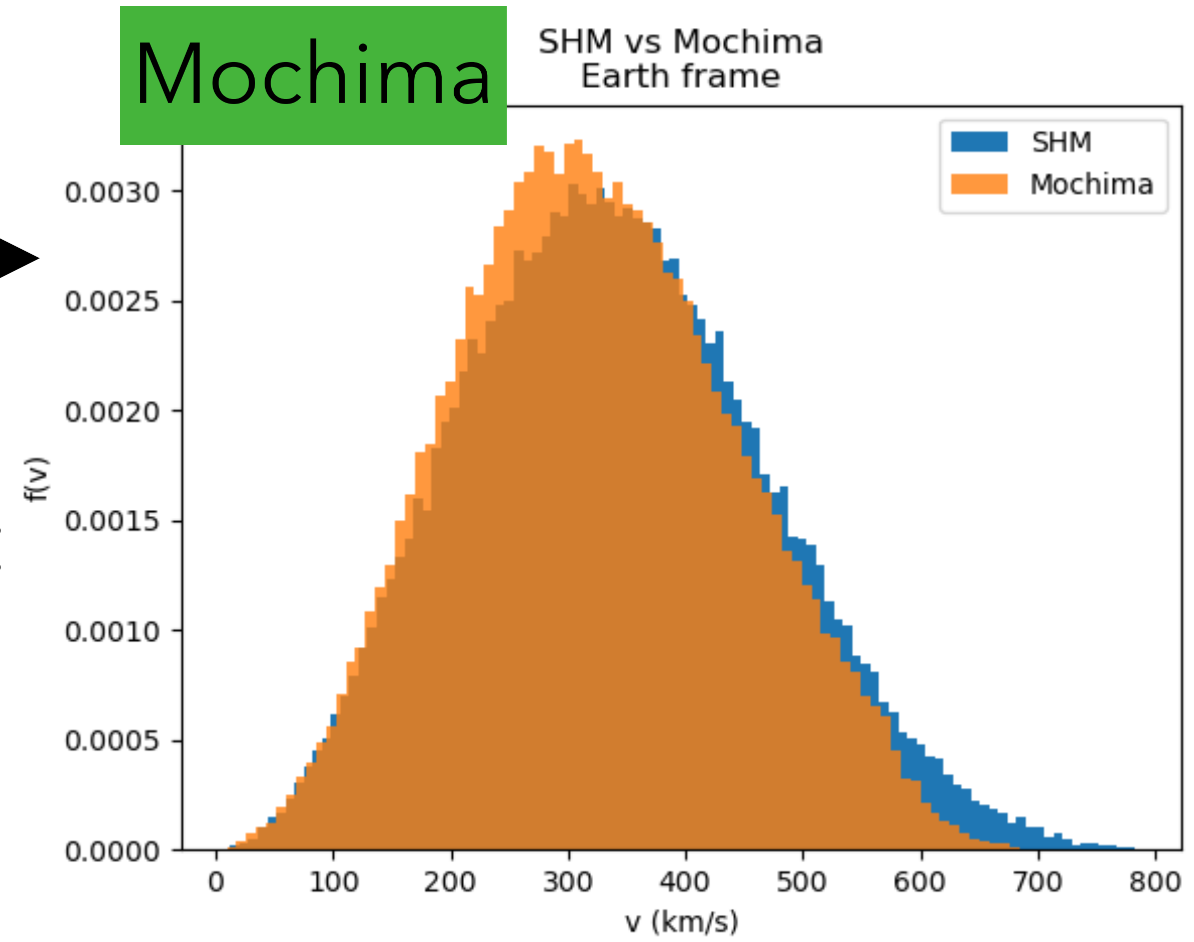
Galactic to Earth frame :

$v_{i,lab} = v_{i,gal} - v_{i,\oplus}(t)$
$i = x, y, z$





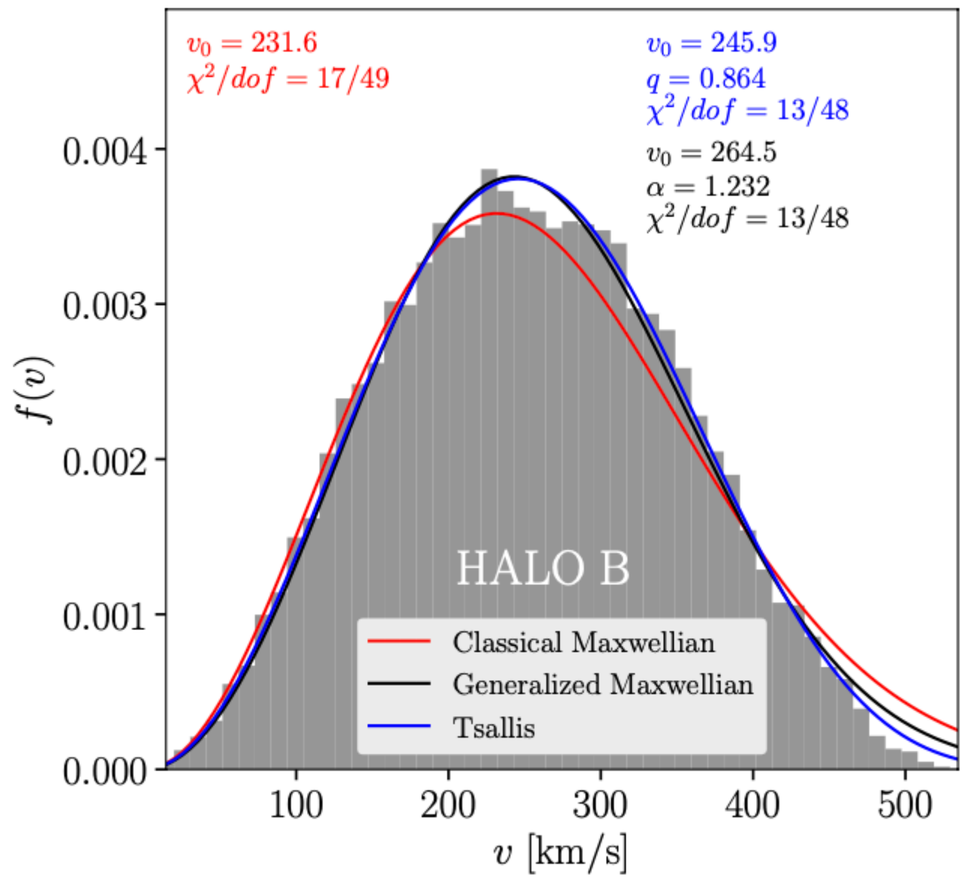




Take better suited velocity distributions

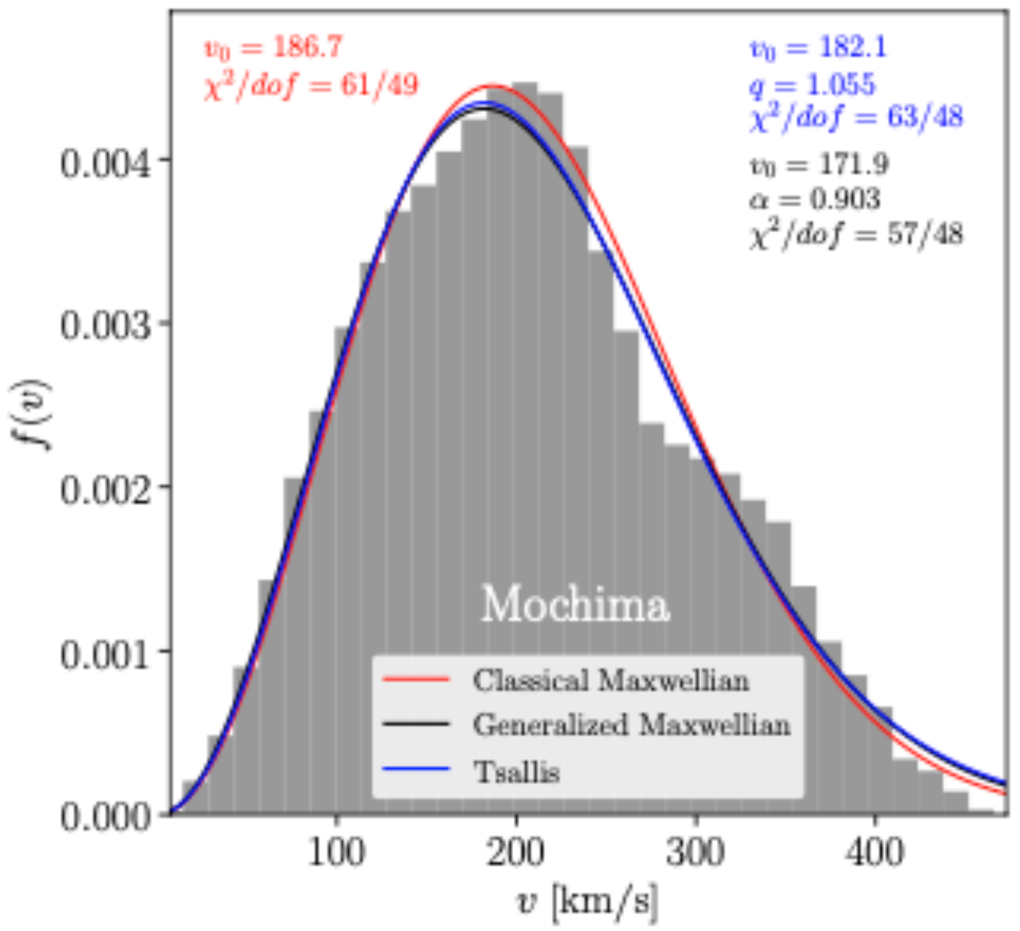
Play on $f(\vec{v})$ in the rate of events, hint from cosmological simulations

Starters



(a) Halo B

Fig. From A. Nuñez thesis
Simu. By P. Mollitor et. al.



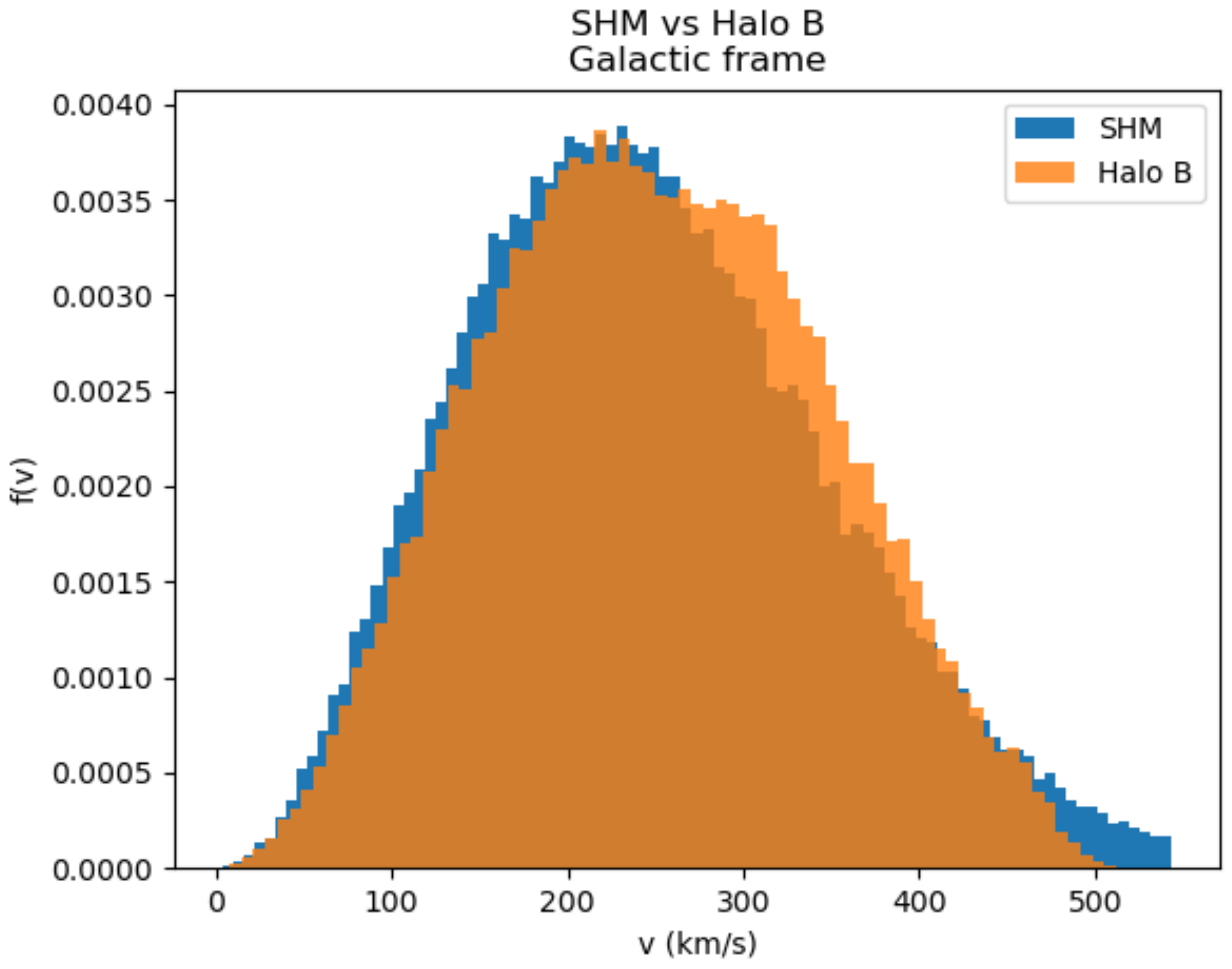
(b) Mochima

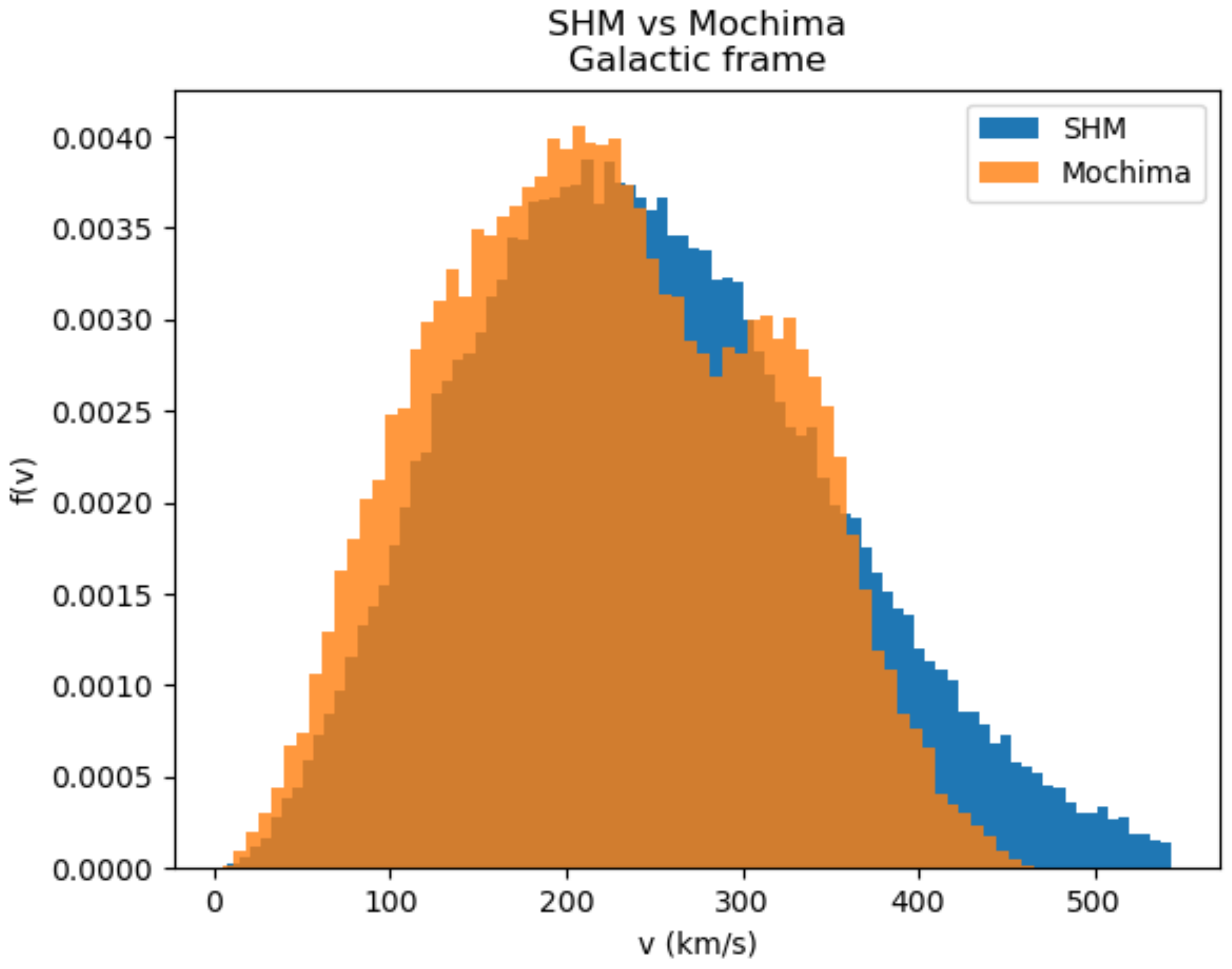
Fig. From A. Nuñez thesis
Simu. By A. Nuñez et. al.

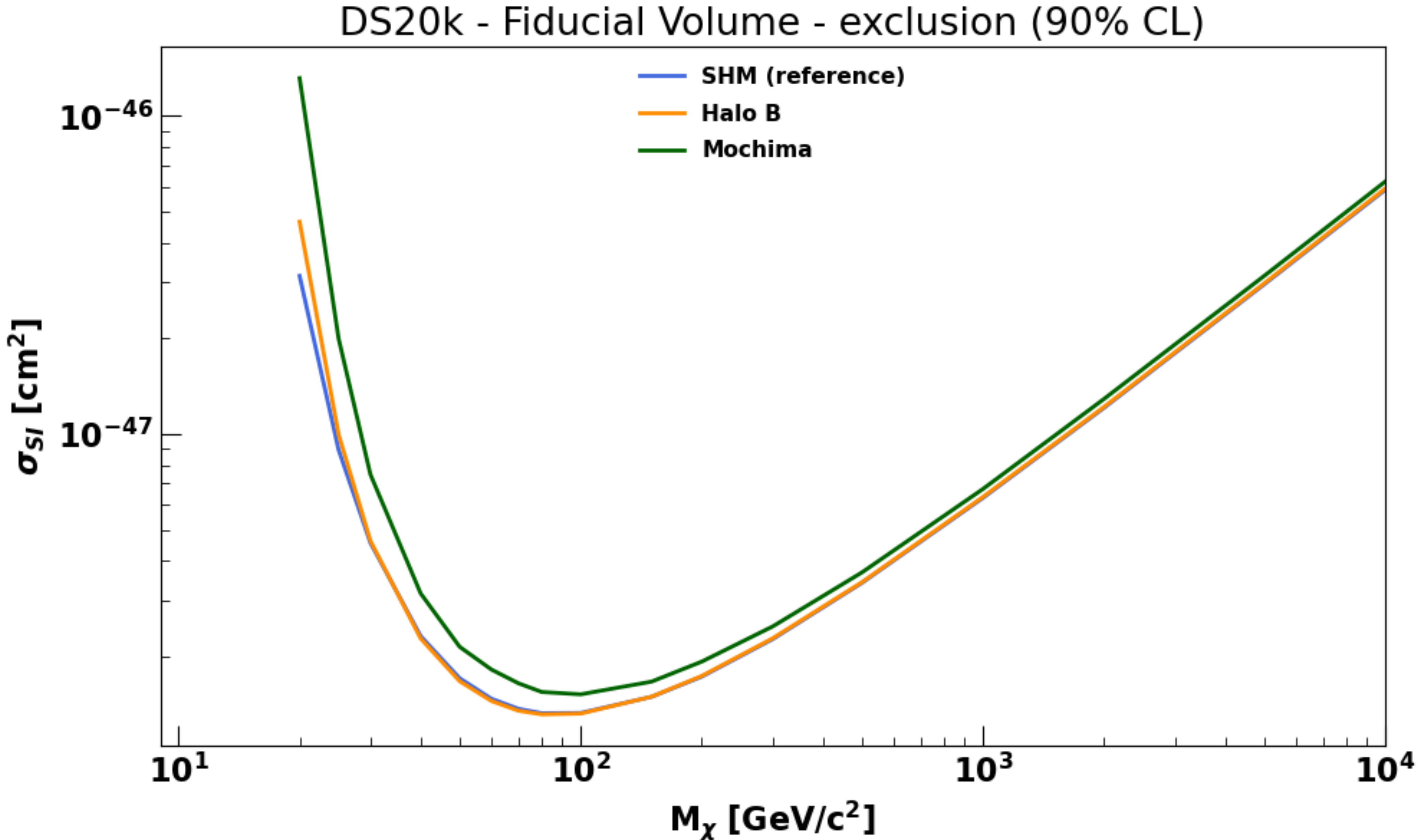
Development of different methods to integrate these f(v)

Directly take the simulation result as input

📚 *See more in back up*





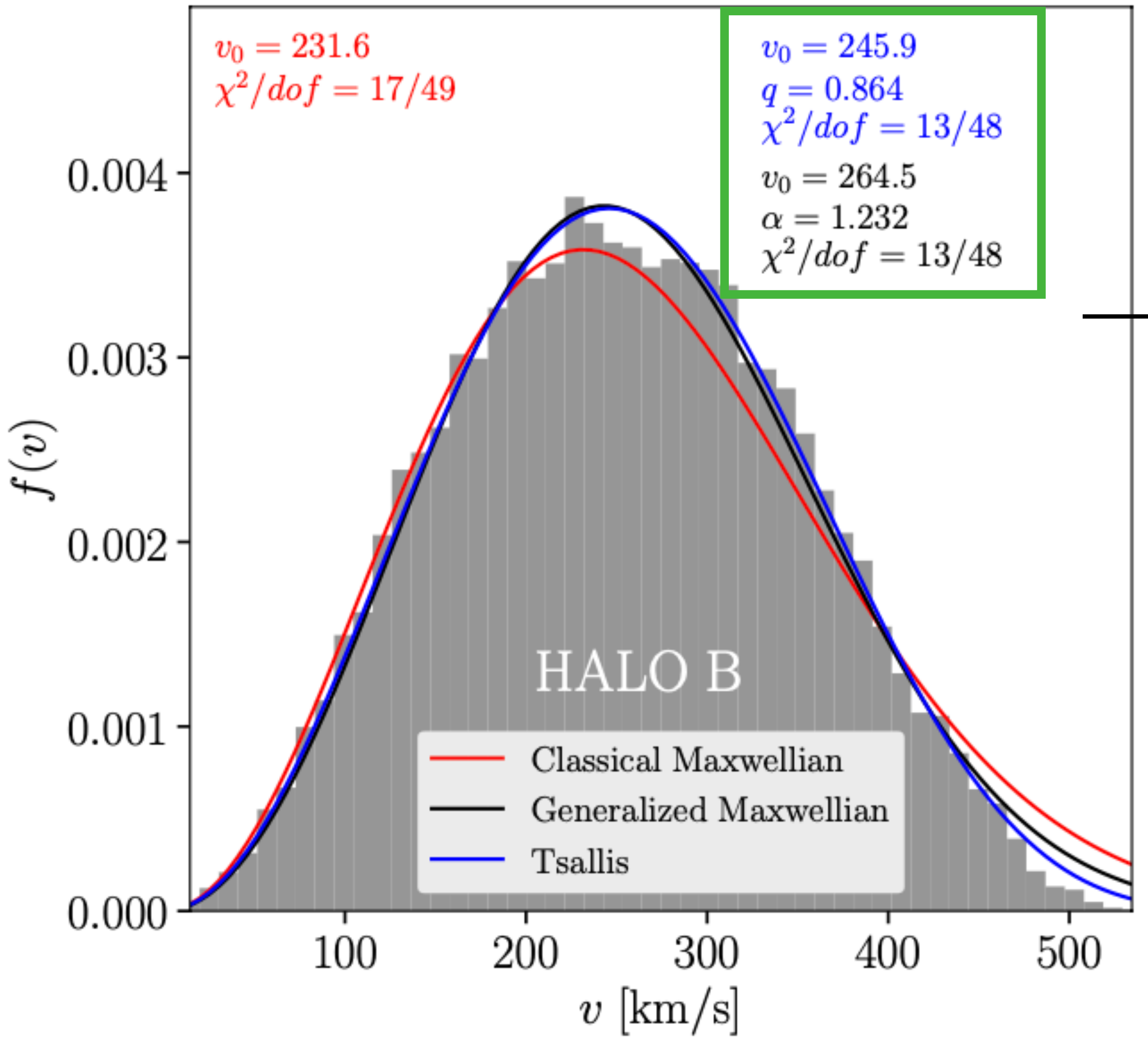


Description of a Tsallis distribution

Tsallis distribution

$$f_{gal}(v) = \frac{2\pi}{N_q} \cdot v^2 \cdot \left(1 - (1-q) \cdot \frac{|\vec{v}|^2}{v_0^2}\right)^{\frac{q}{1-q}}$$

Why ? Hint by cosmological simulations



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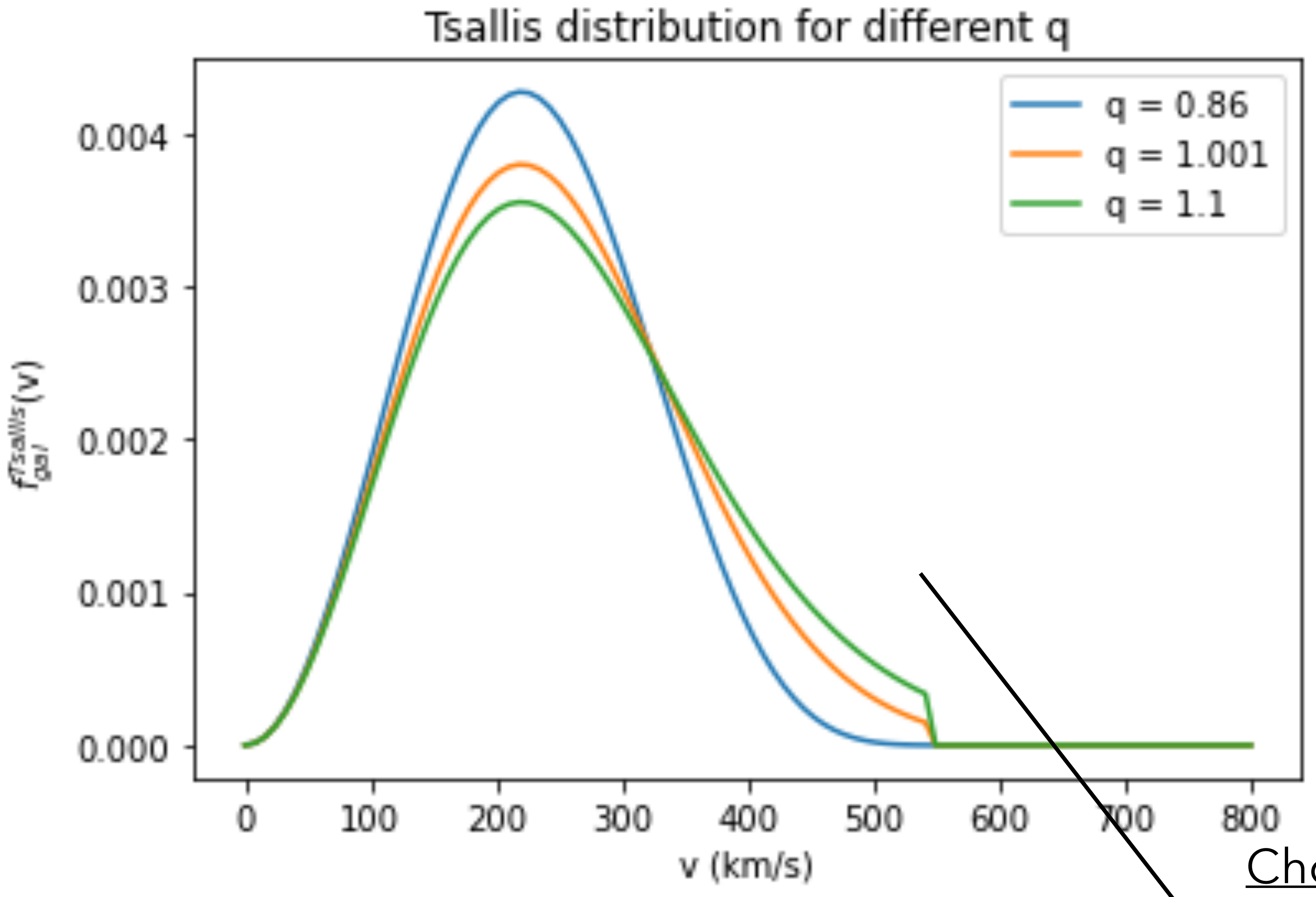
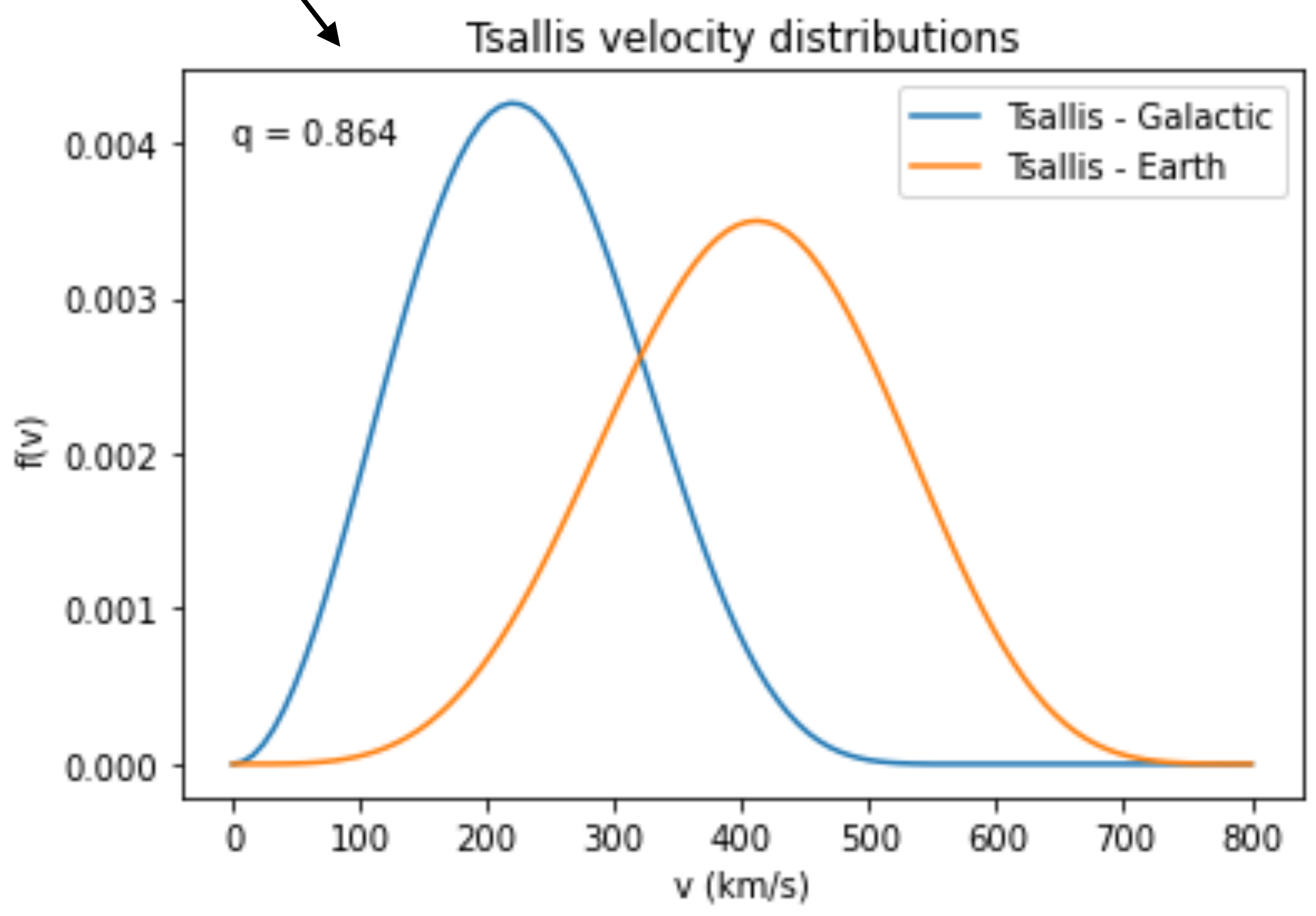


- q −−> 1 <=> Maxwell retrieved

Choose q = 0.864
And change frame to Earth



Description of a generalized Maxwellian distribution

$$f_{gal}(v) = \frac{2\pi}{N_\alpha} \cdot v^2 \cdot e^{-\left(\frac{|\vec{v}|^2}{v_0^2}\right)^\alpha}$$

Generalized maxwellian distribution

Why ? Hint by cosmological simulations

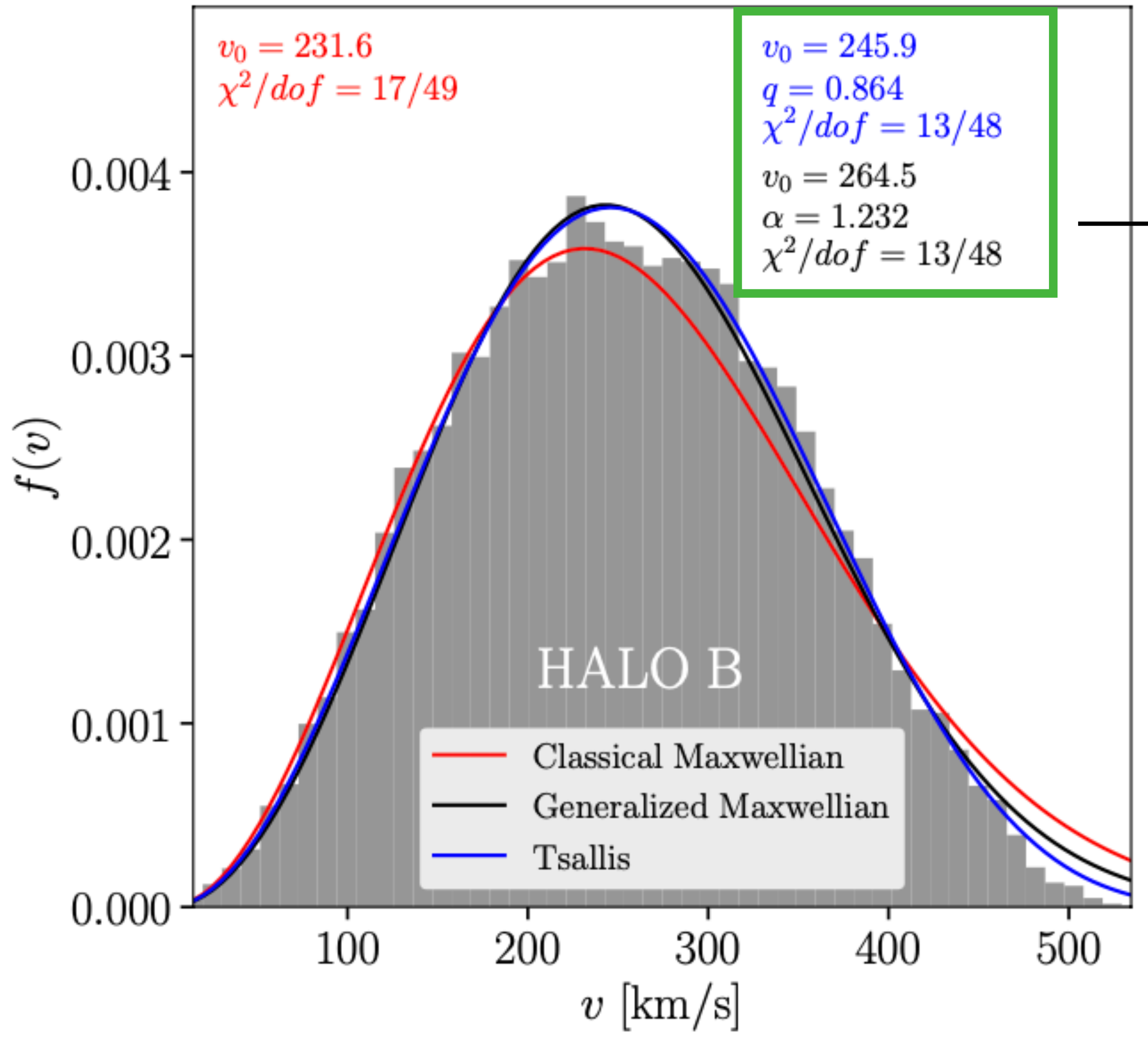


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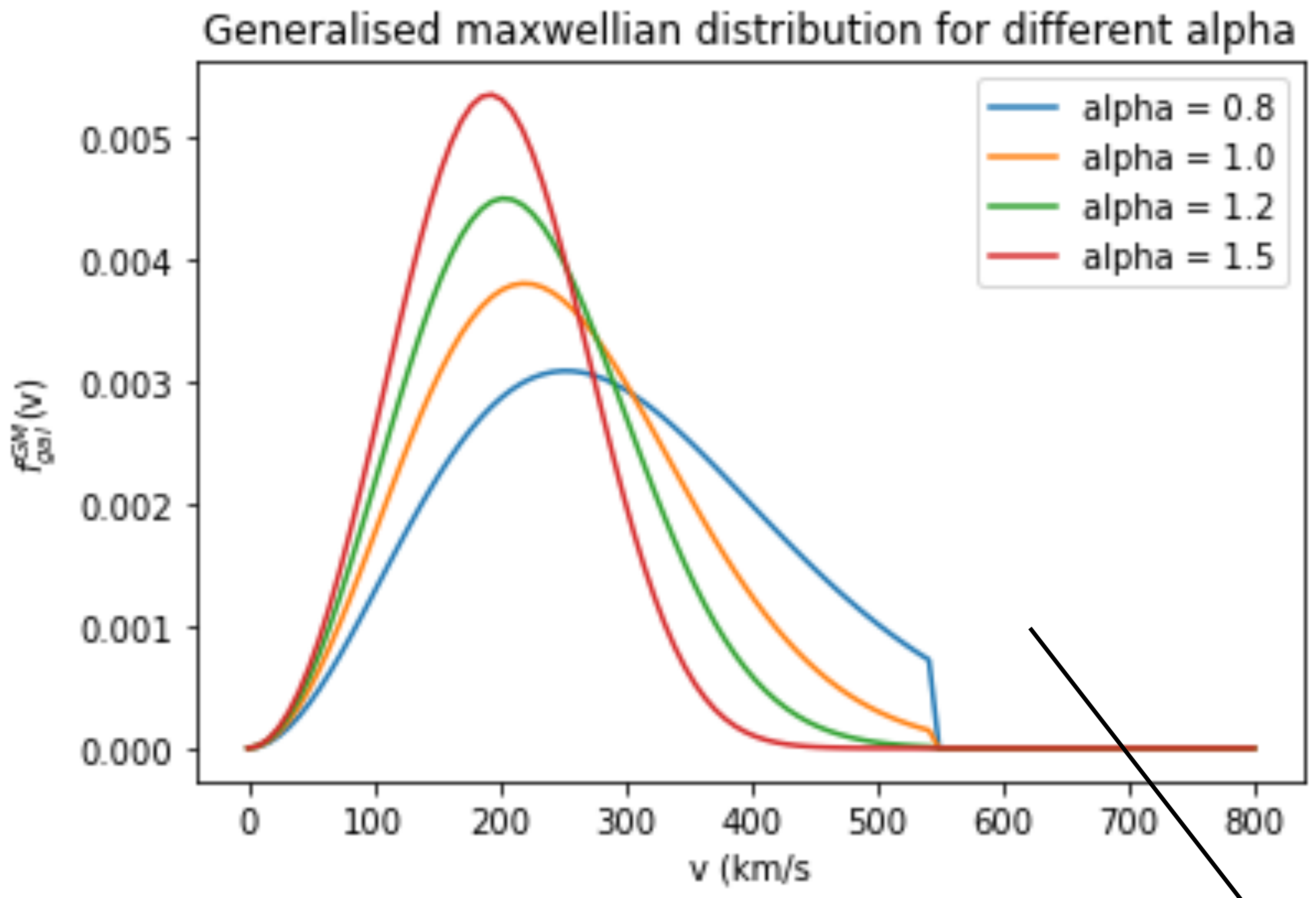
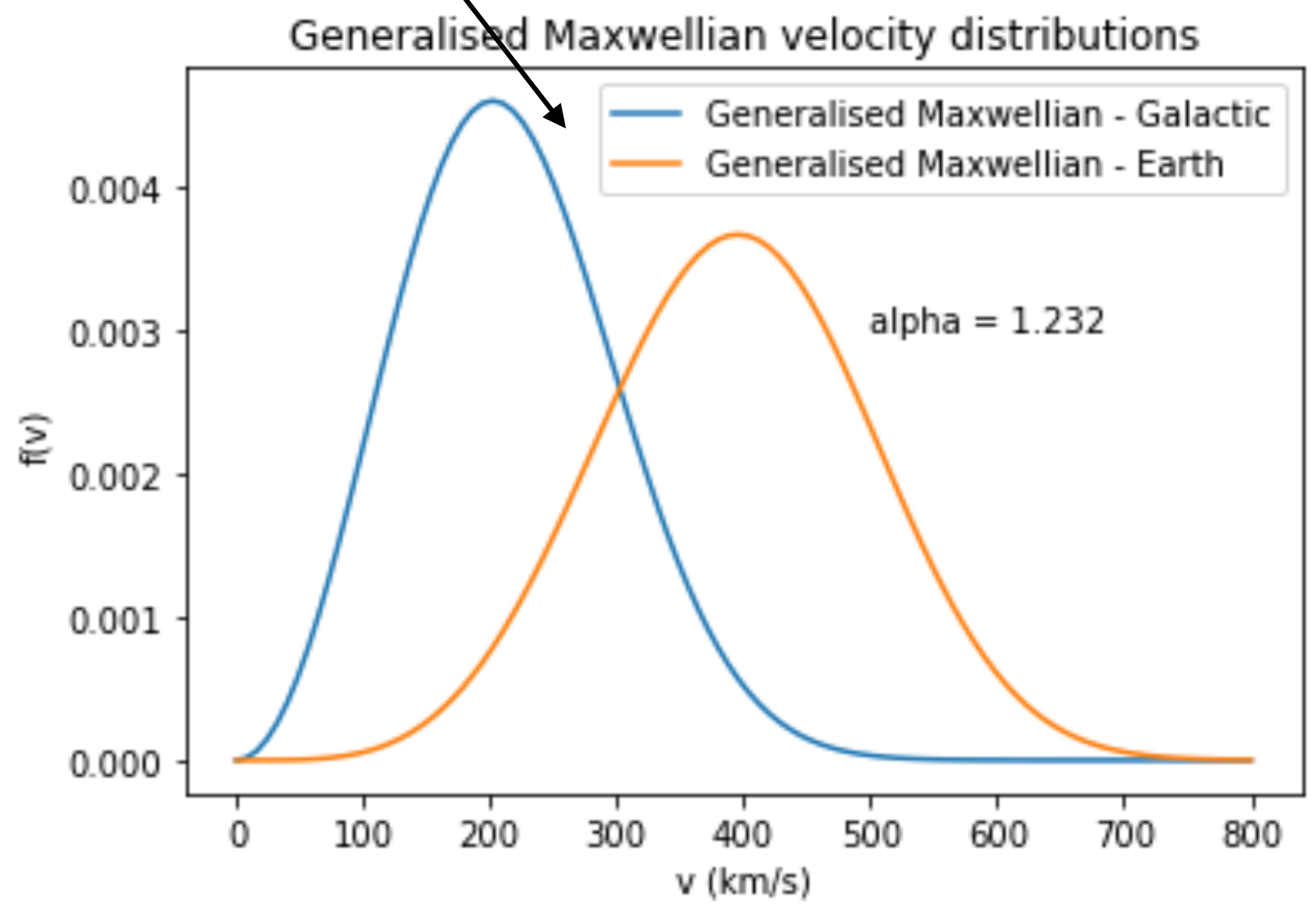
Fig. From A. Nuñez thesis



- Maxwellian distribution with the term inside the exponential set to the power α
- $\alpha = 1$ <=> Maxwell retrieved

Choose $\alpha = 1.232$
And change frame to Earth



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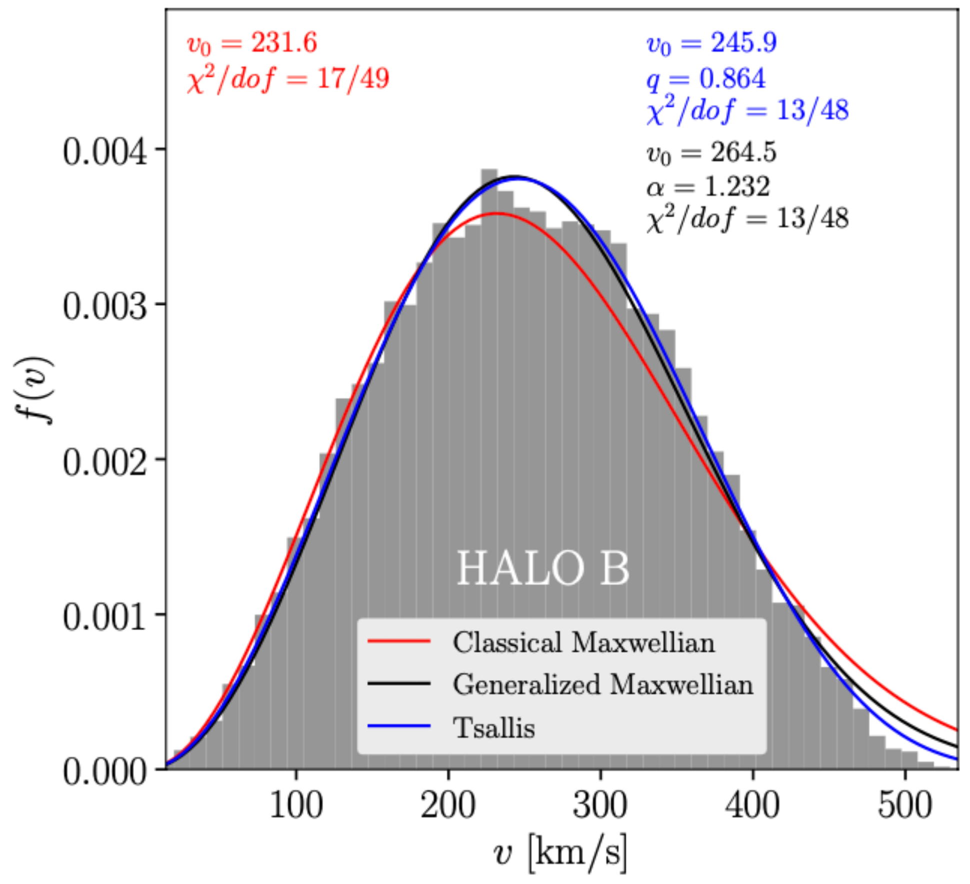

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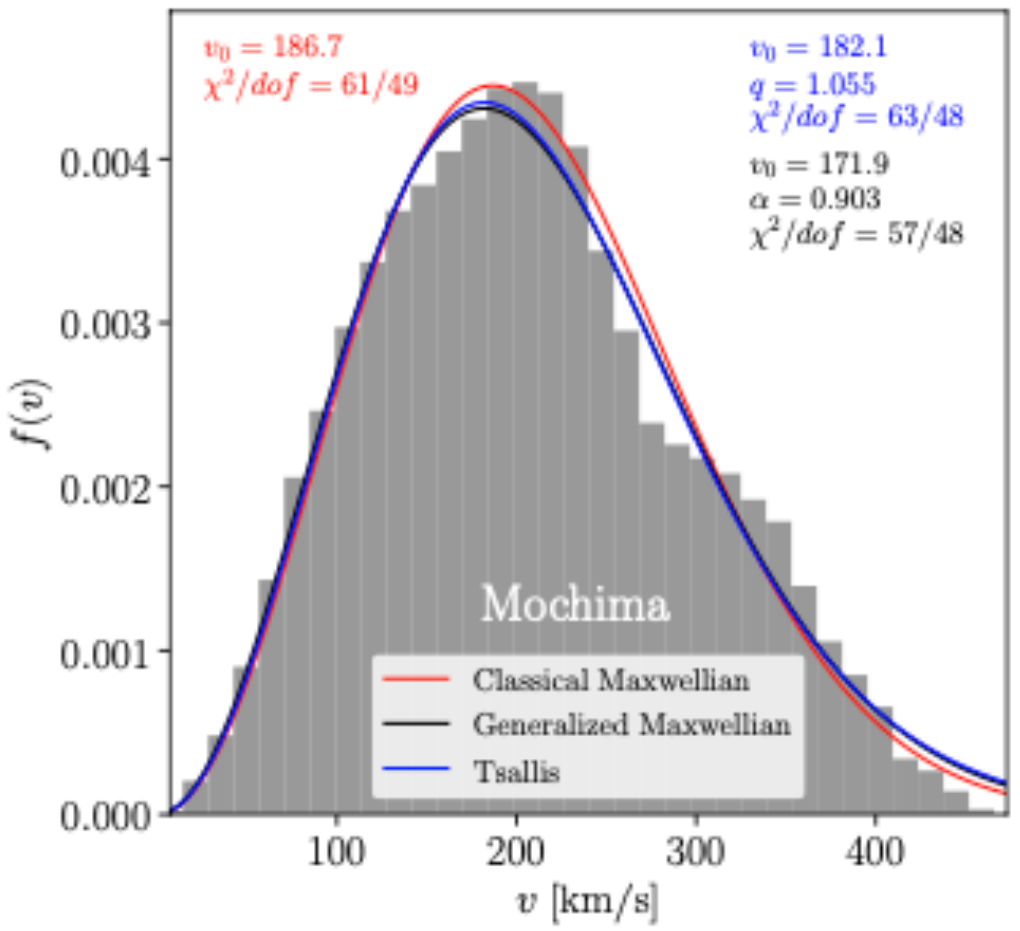

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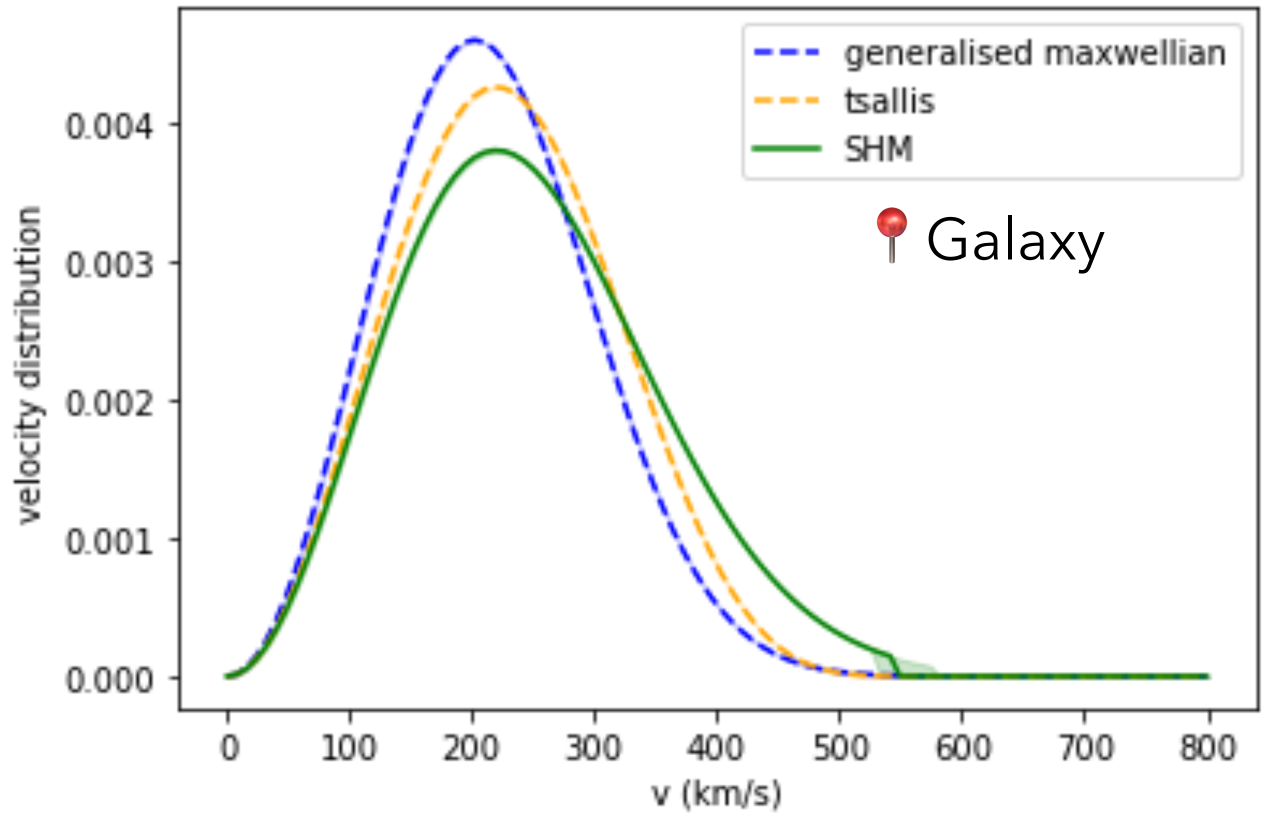
Development of different methods to integrate these f(v)

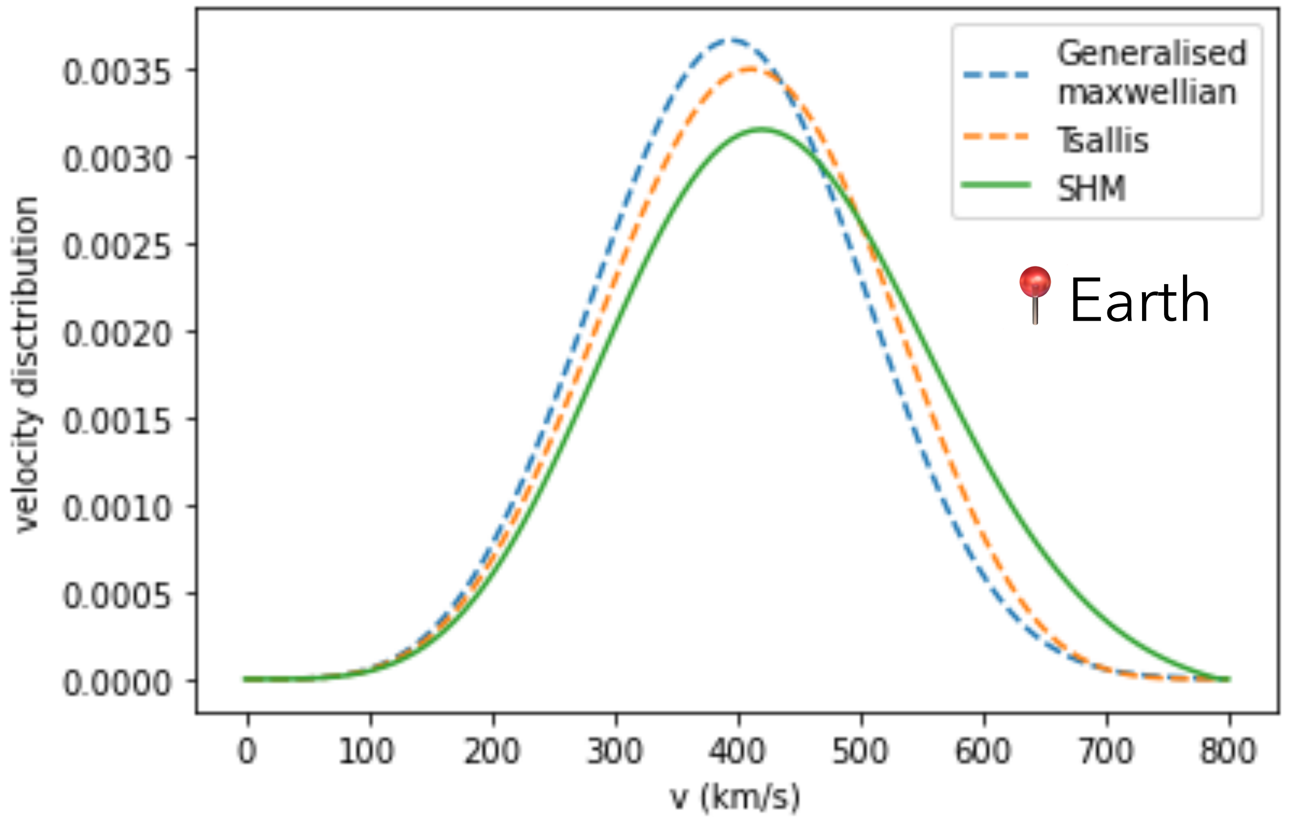
Directly take the simulation result as input

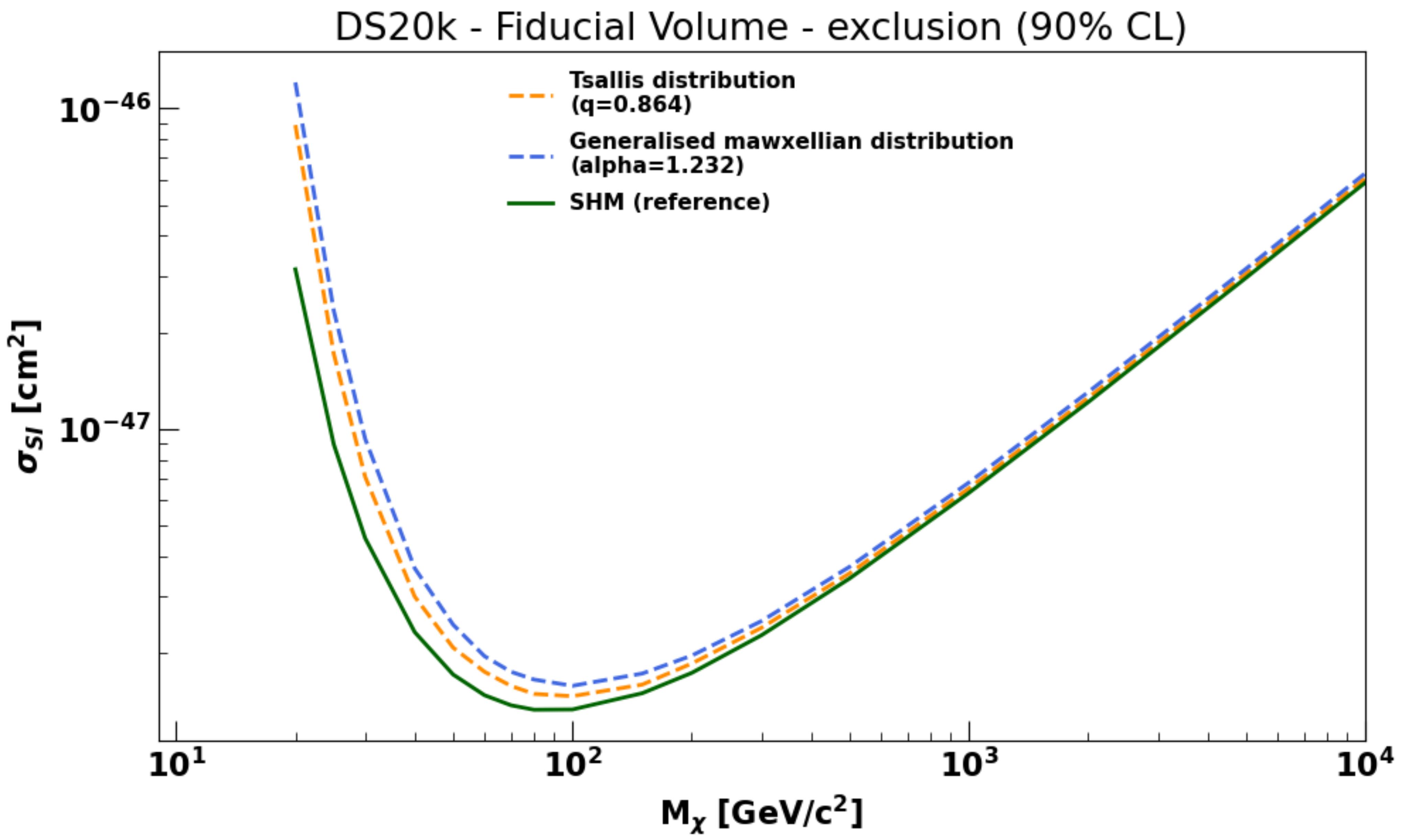
📚 *See more in back up*

Fit the simulation result with known distributions

📚 *See more in back up*







Take better estimates for the astrophysical parameters of interest

Play on $v_{esc}, v_0, v_c, \rho_0$ in the rate of events, hint from galaxy surveys

Litterature survey of parameters estimate

2011 - 2023 estimates of astrophysical parameters computed from galactic surveys data analysis

$v_0 \in [178{,}252]$ km/s

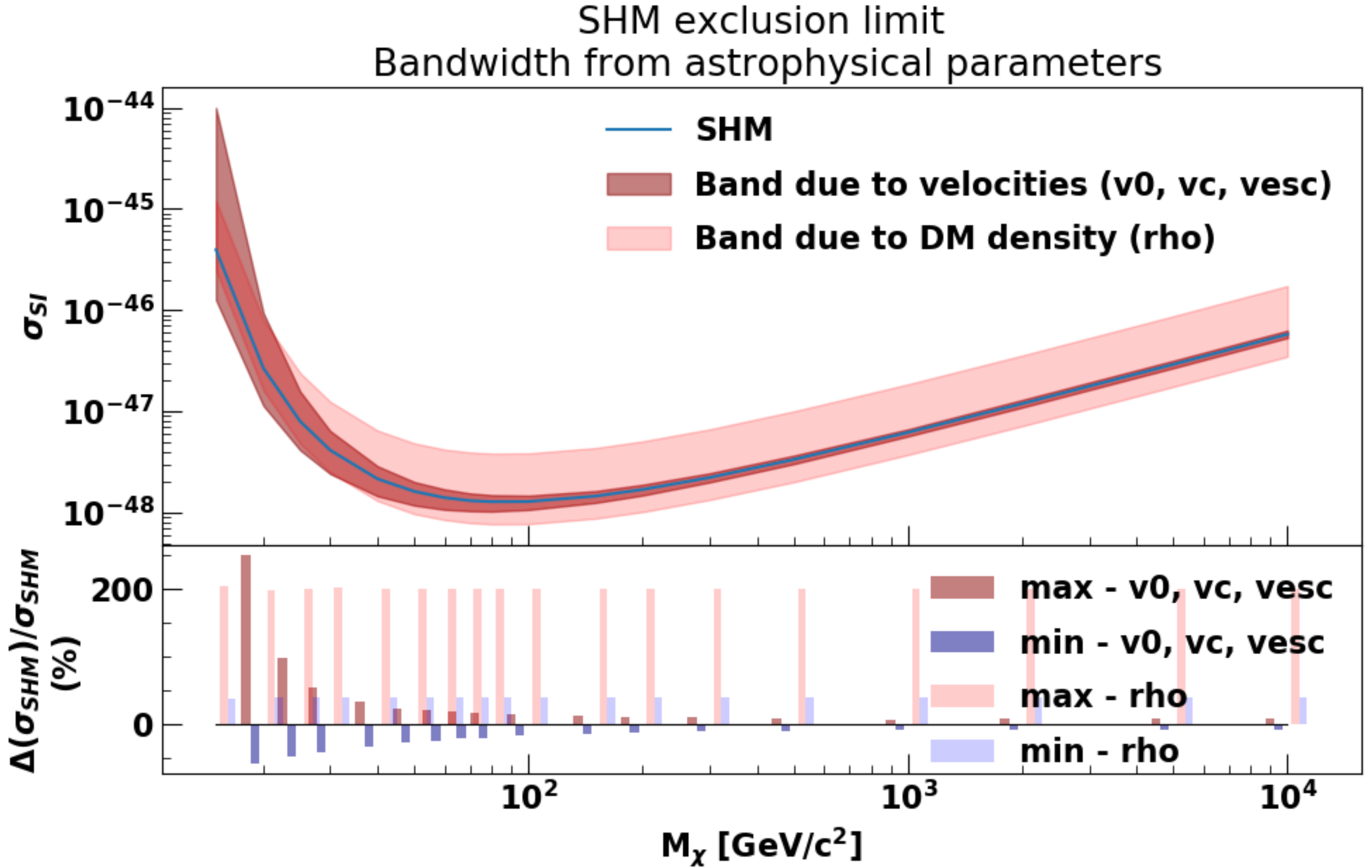
$v_c \in [178{,}252]$ km/s

$v_{esc} \in [432{,}693]$ km/s

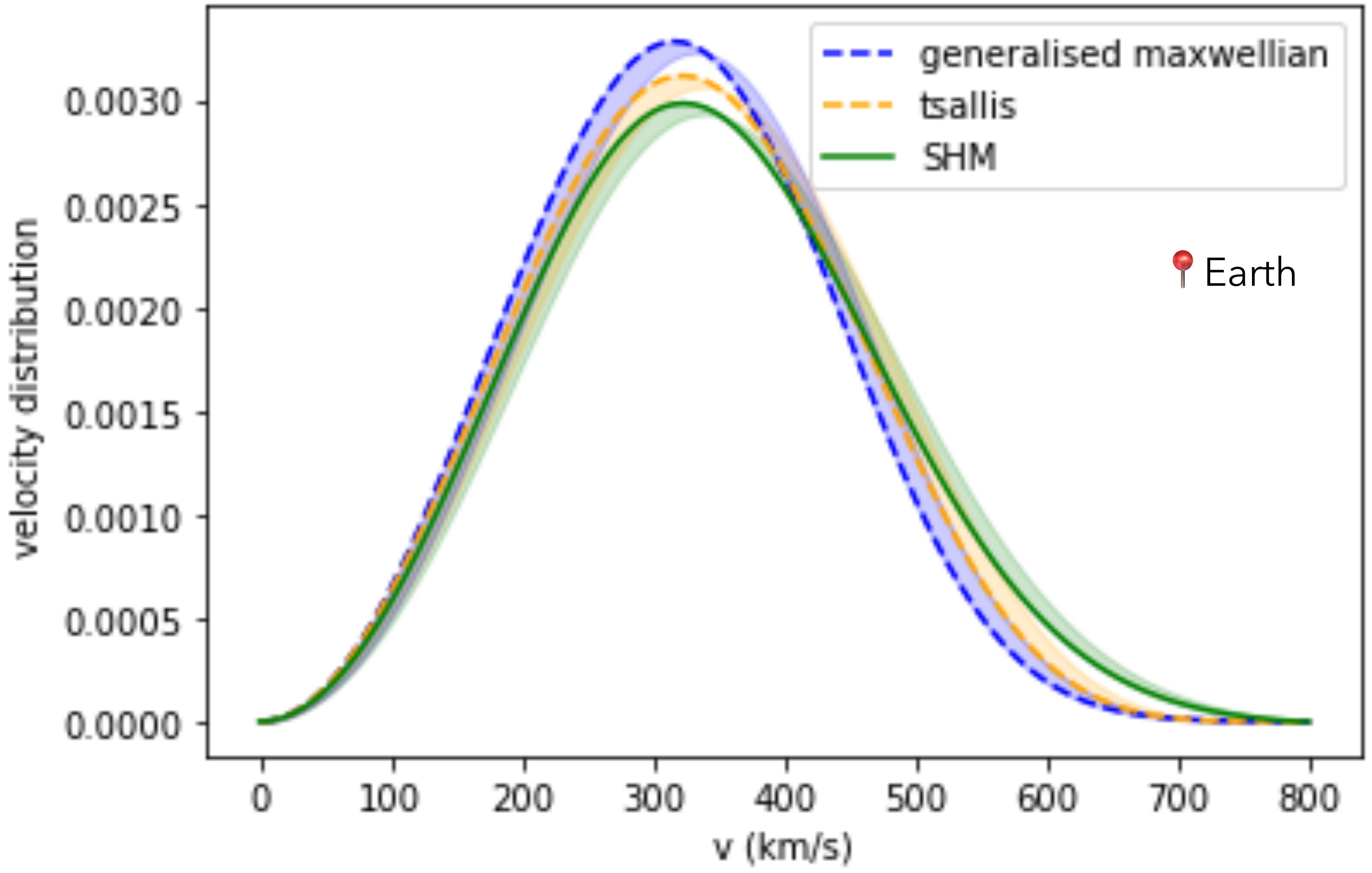
$\rho_0 \in [0.13{,}0.44]$ GeV/cm³

📚 *See more in back up*

Independent variation of parameters



Mix Tsallis / Generalised Maxwellian & parameters variation



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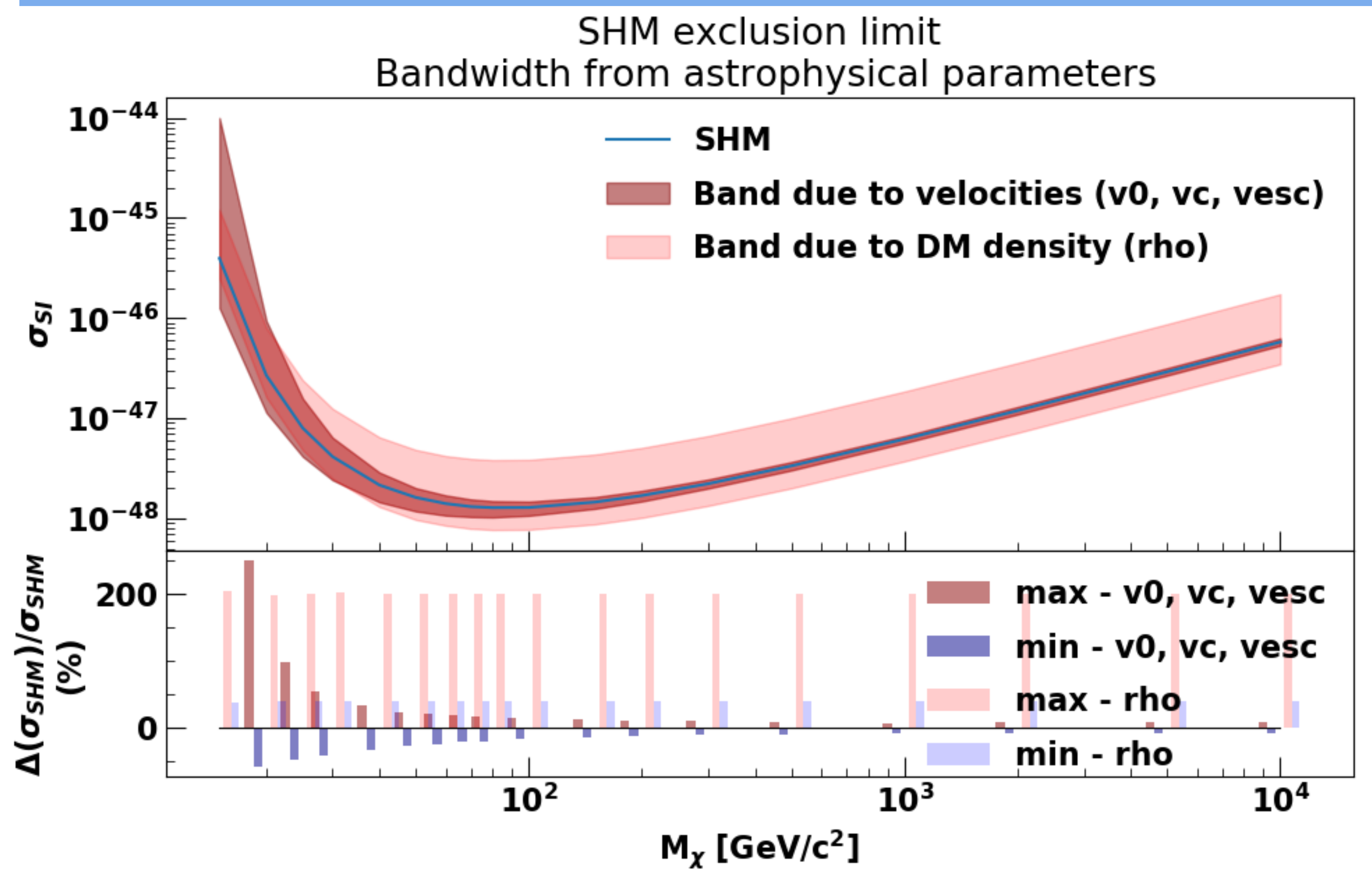

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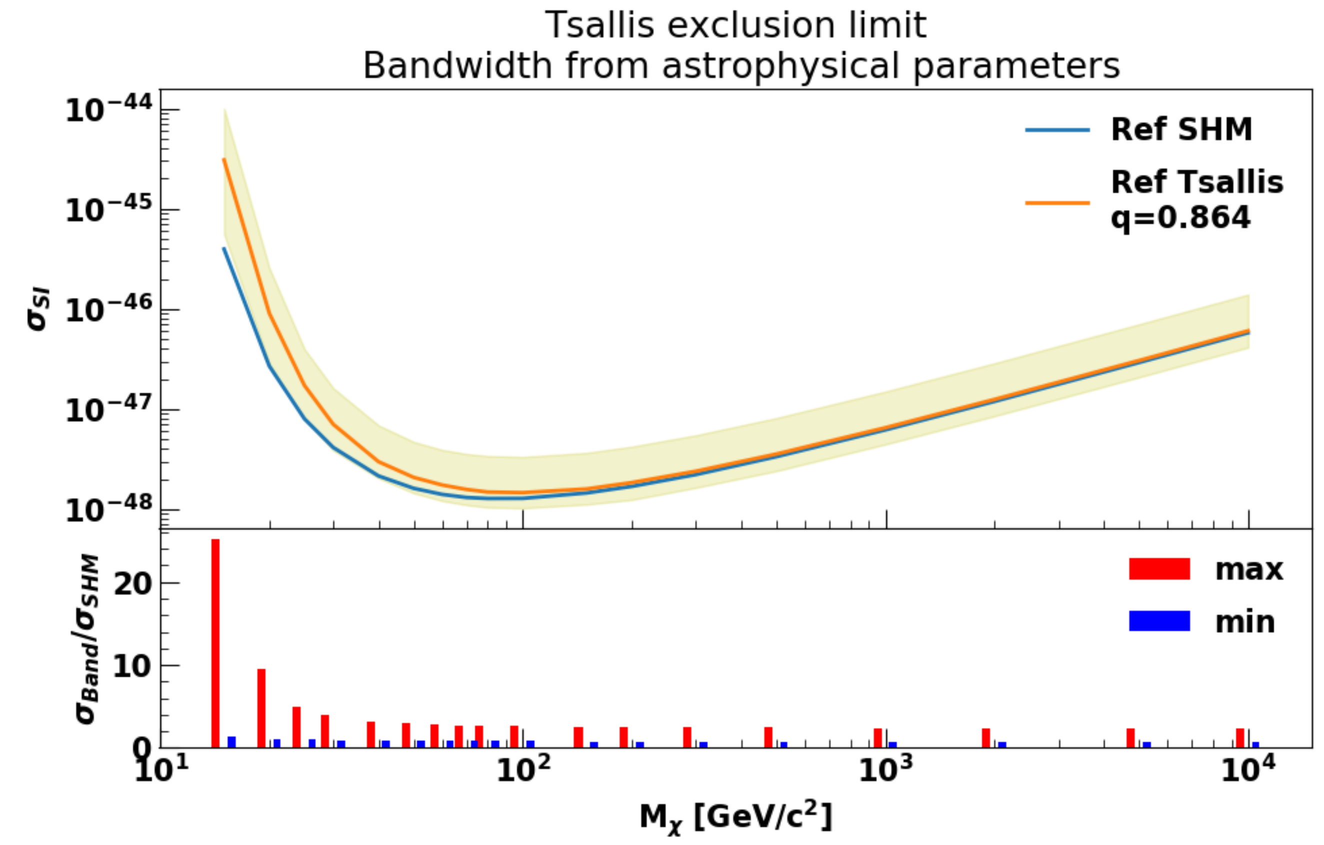

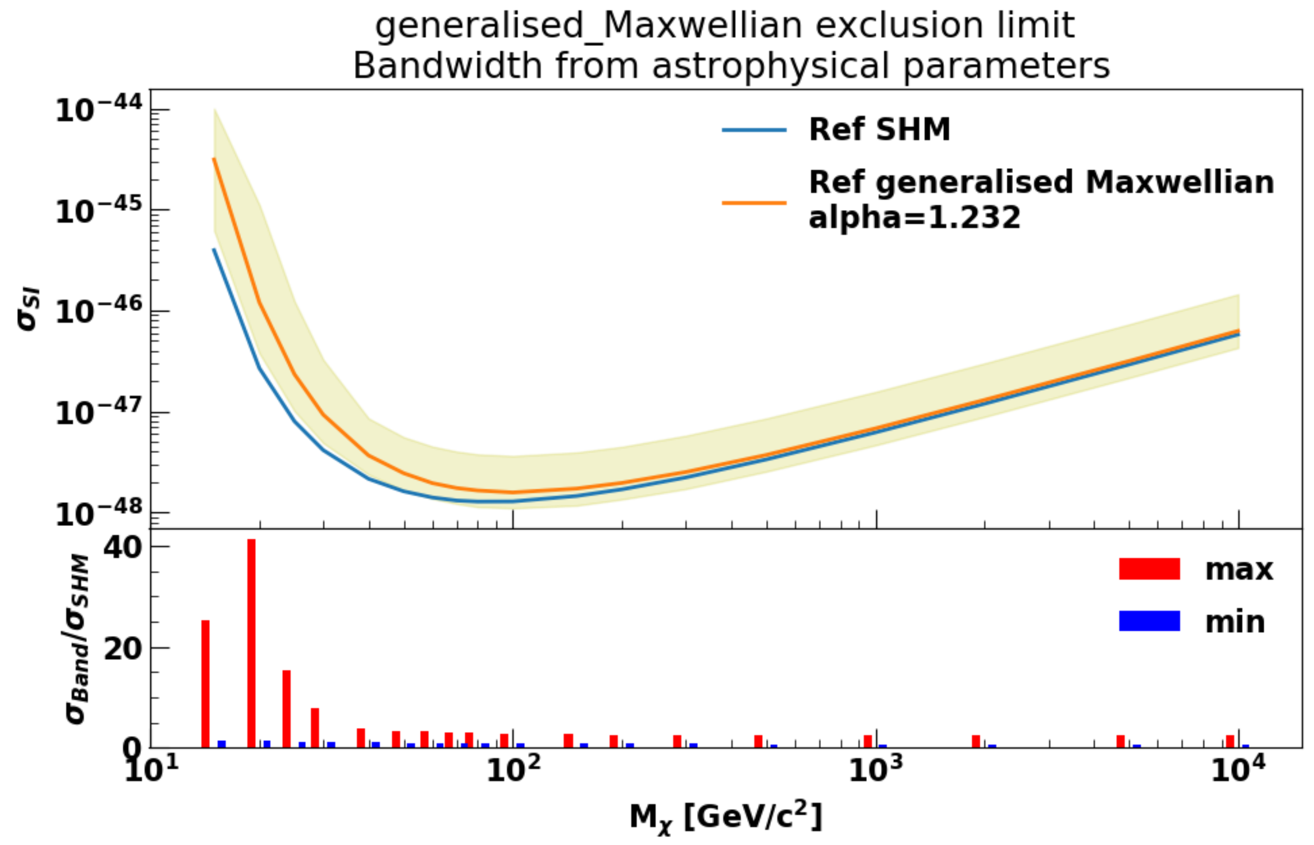

Eddington inversion procedure

Results from Arturo Nuñez thesis

Cosmological simulations

Models

Start with a mass density distribution $\rho(r)$

Add some assumptions:
- Isotropic problem
- Spherically symmetric system
- Search for a steady state solution

Solve collisionless Boltzmann equations

$$\vec{v} \cdot \frac{\partial f}{\partial \vec{r}} - \frac{\partial \Phi}{\partial \vec{r}} \frac{\partial f}{\partial \vec{v}} = 0$$

And Poisson equations

$$\Delta \Phi = 4\pi\rho(\vec{r})$$

+ Jeans' theorem

+ Abel inversion

Obtain a velocity distribution $f_{gal}(\vec{v})$

With 10-20% uncertainty

Handy if the only available input is $\rho(r)$

Non exhaustive list of articles where you can find estimates for the useful astrophysical parameters needed for DMDD

arXiv ou doi	Date	Auteurs	Vesc (km/s)	V0 (km/s)	Vc (km/s)	rho_0 (GeV/cm3)
10.1111/j.1365-2966.2011.18564.x	2011	Mc Millan	NS	NS	239+/-5	0.40+/-0.04
1608.00971v3	2016	Mc Millan	NS	NS	232,8+/-3	0.38+/-0.04
2012.02169	2021	Bovy	NS	NS	244+/-8	NS
10.1051/0004-6361/201833748	2018	Monari	580+/-63 * 593+/-76	NS	240	NS
2006.16283v2	2021	Koppelman Helmi	497+/-8	NS	232,8	NS
1309.4293v3	2013	RAVE	533+54-41	NS	220	NS
1309.4293v3	2013	RAVE	511+48-35	NS	240	NS
10.3847/1538-4357/ac4244	2022	Necib Lin (2 compo) Used Gaia eDR3	445+25-8	NS	235	NS

NS = Not specified

arXiv ou doi	Date	Auteurs	Vesc (km/s)	V0 (km/s)	Vc (km/s)	rho_0 (GeV/cm3)
10.3847/1538-4357/ac4244	2022	Necib Lin (single compo) Used Gaia eDR3	472+17-12	NS	235	NS
1901.02016v2	2019	Delson et al Using Gaia DR2	528+24-25	NS	230	NS
1901.02016v2	2019	Delson et al Using Gaia DR2	580+/-31	NS	230	NS
1411.1325v2	2015	Lavalle Magni	533+54+109-41-60	NS	220	0.37+0.02+0.04-0.03-0.04
1411.1325v2	2015	Lavalle Magni	511+48-35	NS	240	0,43+/-0,05
1411.1325v2	2015	Lavalle Magni	537+44-55	NS	196+26-18	0,25+0,14-0,12
1703.10102v2	2017	Green (Review of other)	NS	NS	NS	0.22->0.3 (best fit ranges)
1904.04781v3	2019	Wu, Freese, Kelso & al (review of others)	NS	NS	NS	0.2->0.6
10.3847/1538-4357/aaf648	2019	Eilers, Hogg, Rix, Ness	NS	NS	229+/-0,2	0.30+/-0.03