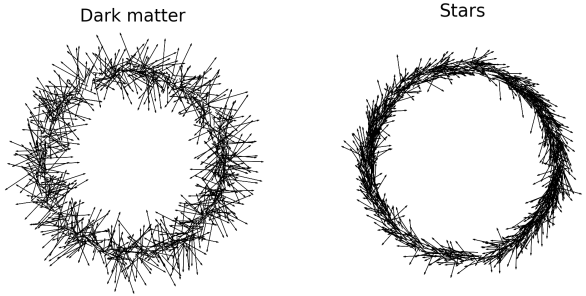
Dark matter capture by the Sun: revisiting velocity distribution uncertainties

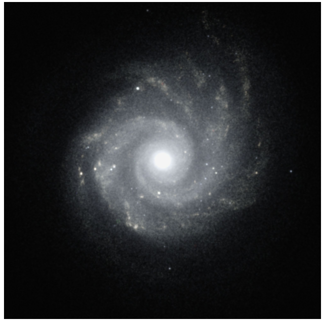
A. Nuñez-Castiñeyra
V. Bertin, E. Nezri

[arXiv:1906.11674]

PPNT19, Uppsala, October 2019

DM capture by the Sun





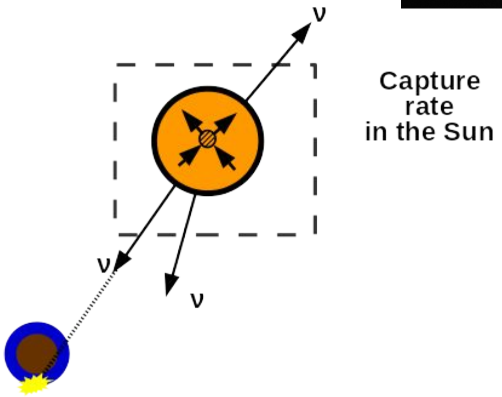
The number of captured WIMPs evolved as

$$\frac{\mathrm{d}N_\chi}{\mathrm{d}t} = C - 2\Gamma_A = C - C_A N_\chi^2$$

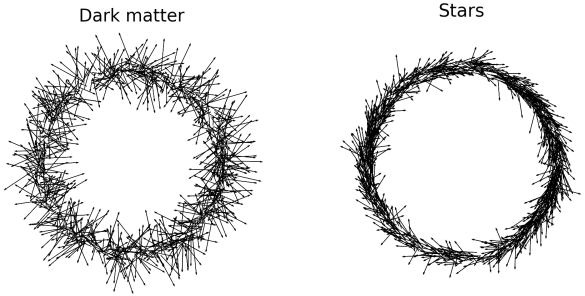
Once you solve it, it can be proved that

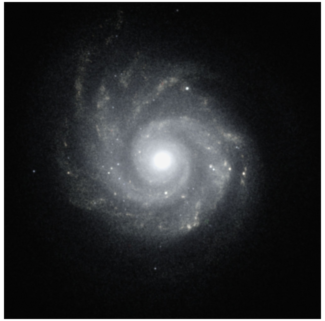
$$\Gamma_A = \tfrac{1}{2} C \tanh^2(t/\tau)$$

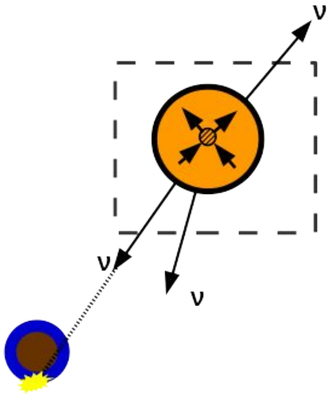
(A. Gould 1987)
(Jungman, Kamionkowski 1996)



DM capture by the Sun





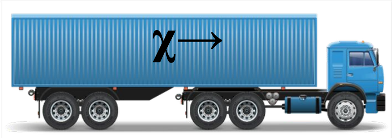


Capture rate in the Sun

$$\frac{dC}{dV} = \frac{\rho}{M_\chi}\int_0^{u_m} du\, \frac{f(u)}{u}\, w\Omega(w)$$

Astrophysics and Particle Physics come together

(A. Gould 1987)
(Garani & Palomares-Ruiz 2017)



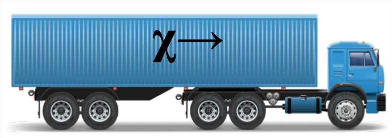
←(n/p)

DM capture by the Sun

$$\frac{dC}{dV} = \frac{\rho}{M_\chi} \int_0^{u_m} du \frac{f(u)}{u} w\Omega(w)$$

Astrophysics and **Particle Physics** come together

Capture in Sun: Low velocity part
Direct Detection: High velocity tail



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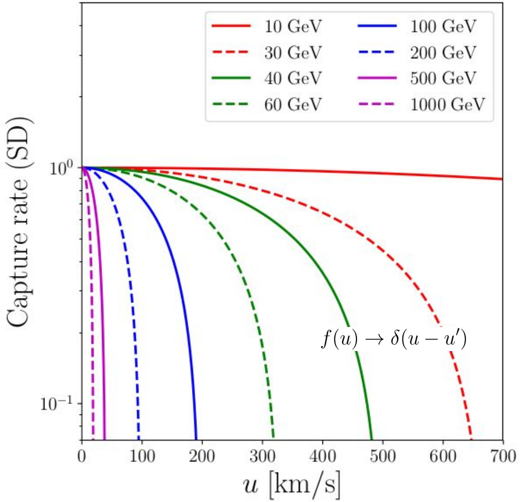

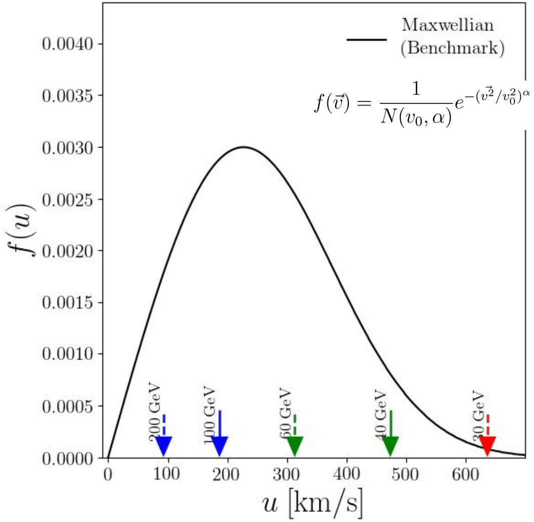

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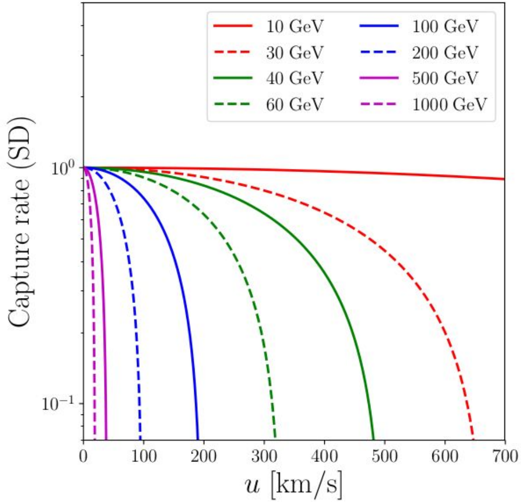
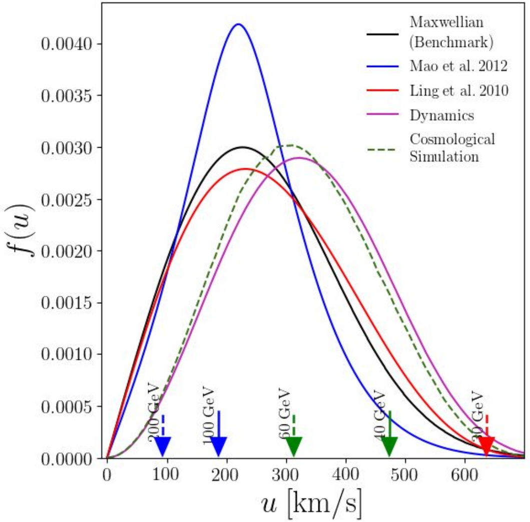
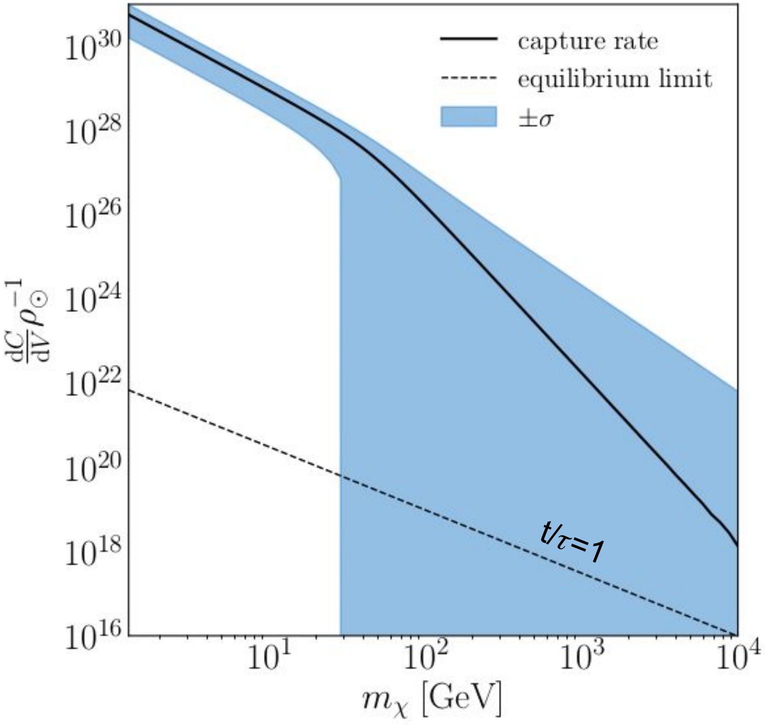


Astrophysical Uncertainties:

- Assumptions on the Sun's composition (Wikström & Edjso 2009)
- Assumptions on the galactic DM features (Choi 2014 , A. Green 2017)
- DM velocity distribution. (Ling 2010, Mao 2012)
- Intrinsic uncertainty of capture ([arxiv:1906.11674])



Intrinsic uncertainty



Nunez-Castineyra, Nezri & Bertin
[arxiv:1906.11674]

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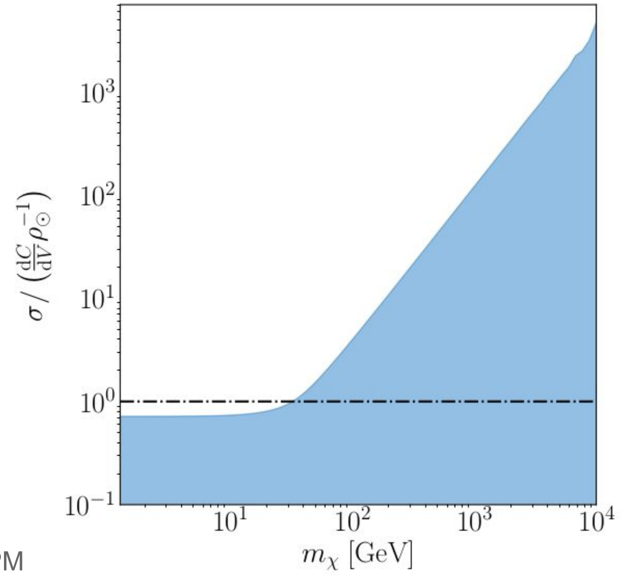
Astrophysics and **Particle Physics** come together



Three main ways to approach f(v)

- Take the standard halo model (SHM)

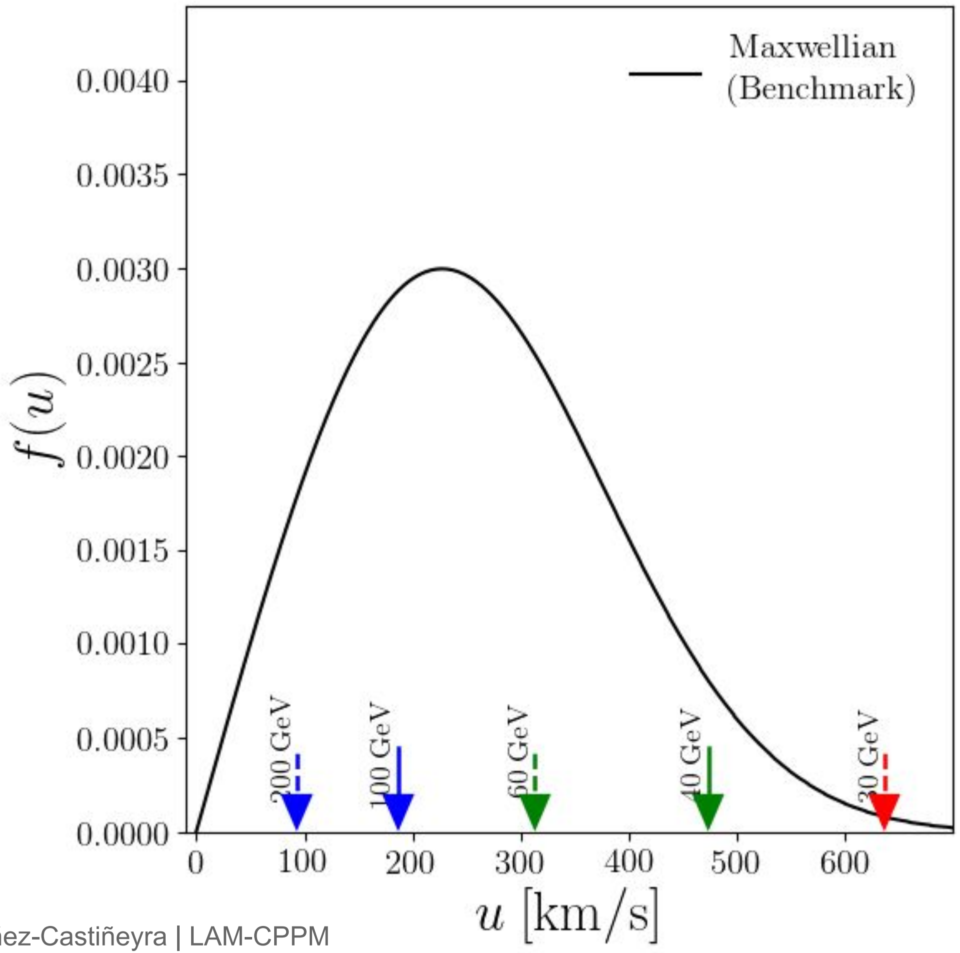
(V_sun=220 km/s ; ρ_{sun} ~ 0.4-0.3 GeV/cm^3; v_{esc}=544 km/s ; f(v)=Maxwellian distribution)

- Direct extrapolation by fiting f(v) from Cosmological "Milky-Way like" simulations

- Dynamical phase space prediction using MW macro features

1. SHM

Takes standard assumptions as they are and use them to generate the f(v)



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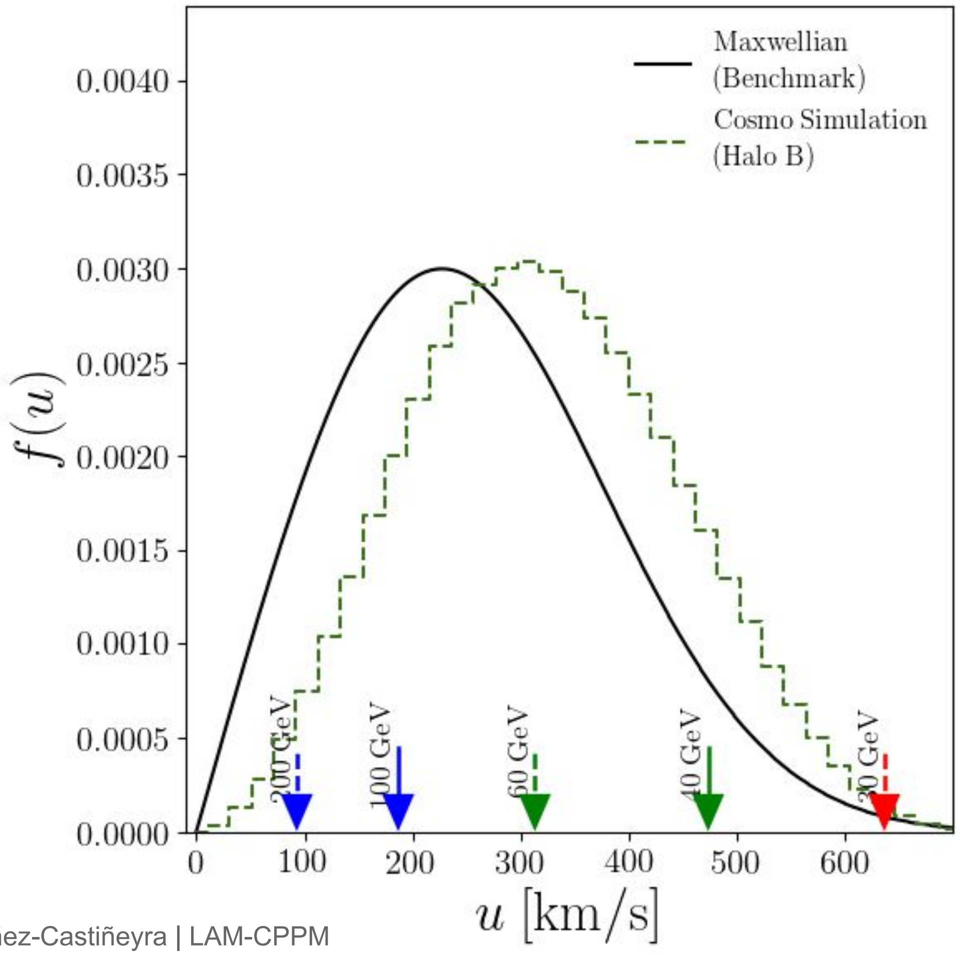
  e.g Eddington (Eddington 1916, Lacroix 2018), Action angle (Posti 2015) etc.

2. Cosmological simulations

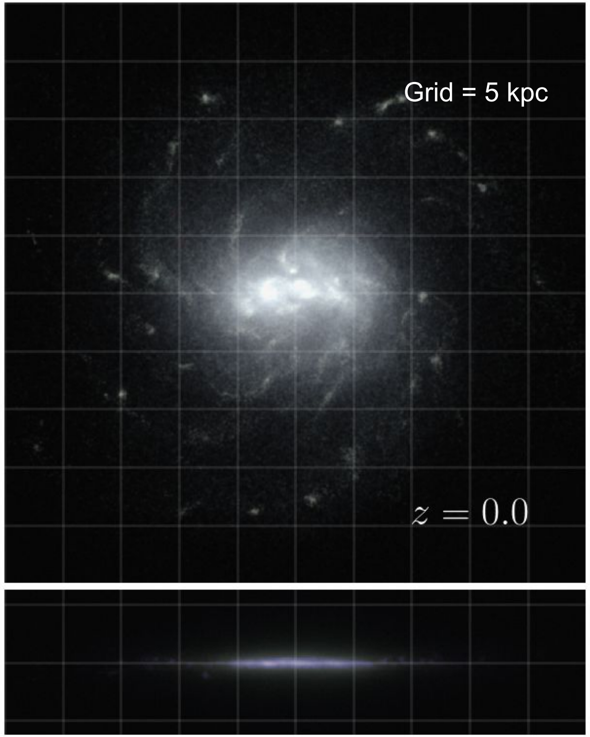
Extrapolate data o use fits on f(v) obtain in simulations of "MW-like galaxy"**

**: how MW-like can a simulation be?



We use 2 cosmological simulations of spiral galaxies in a **MW size halo**

- Simulated with AMR code RAMSES
- Similar baryonic physics implementation
  - Star formation
  - SN feedback
- Ingredients:
  - Dark Matter
  - Gas
  - Stars
- Usual comparisons with MW are done in their respective publications: RC, TF, SHMR, SFR.. we present here extra checks



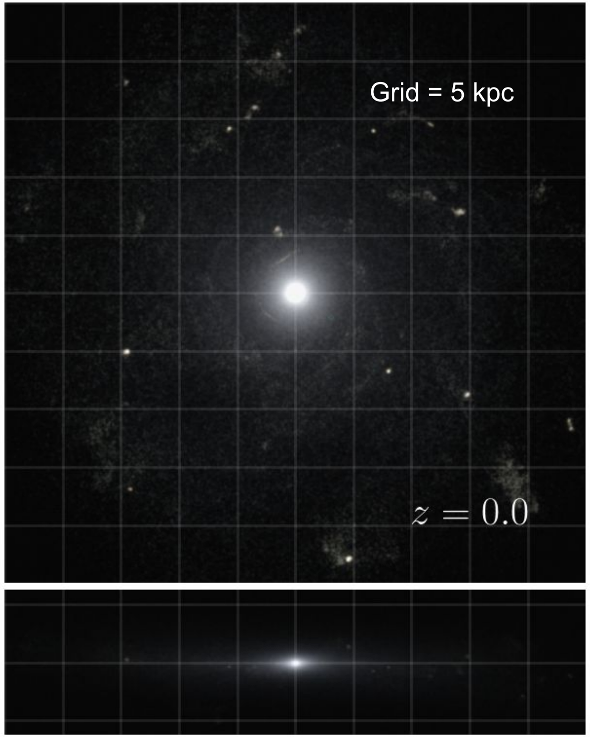
Halo B

Boxsize = 20 Mpc

M_{DM}=0.6x10^{12} M_{star}=7x10^{10}

Resolution = 150 pc

Mollitor et al [arXiv:1405.4318]



Mochima

Boxsize = 36 Mpc

M_{DM}=0.9x10^{12} M_{star}=3x10^{10}

Resolution = 35 pc

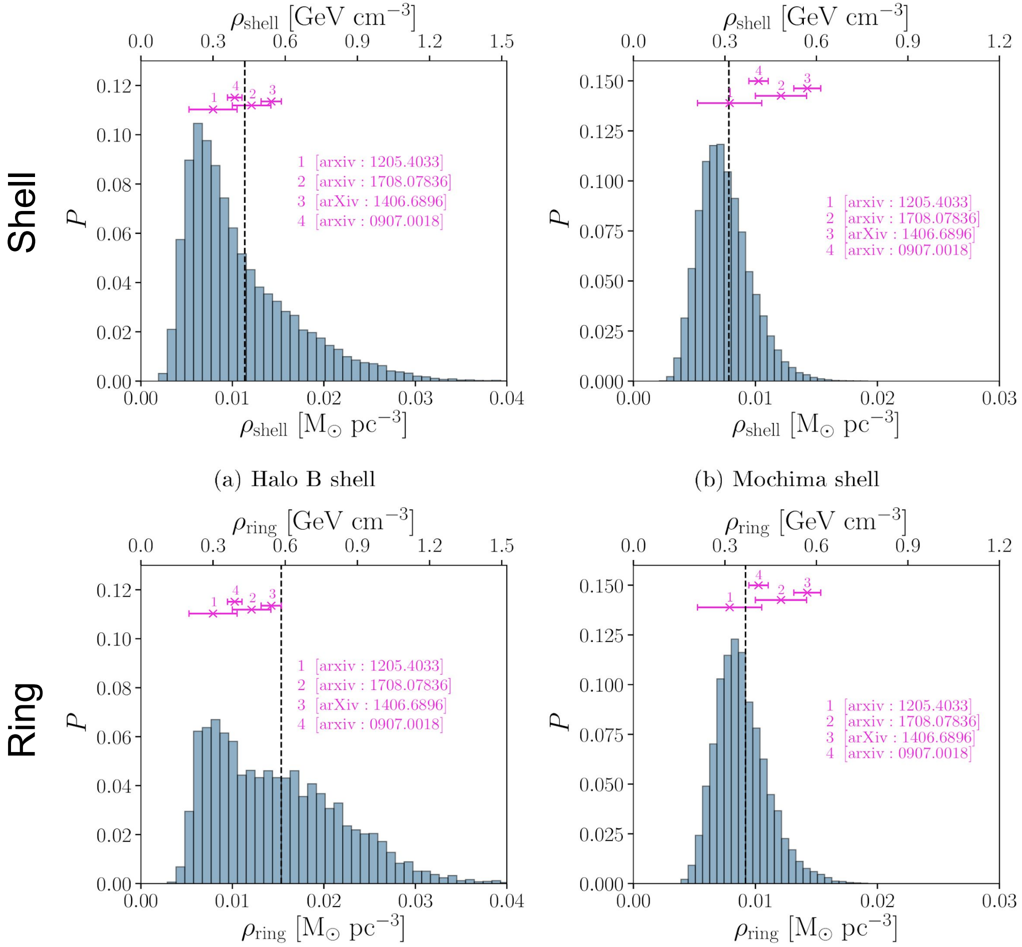
Nunez-Castineyra et al. in prep

Local DM density

Check of the local density value in the simulation with analytical predictions and observations in two volumetric selection

- Ring
- Shell

Centered at r = 8 kpc and a thickness of 2 kpc



(a) Halo B shell

(b) Mochima shell

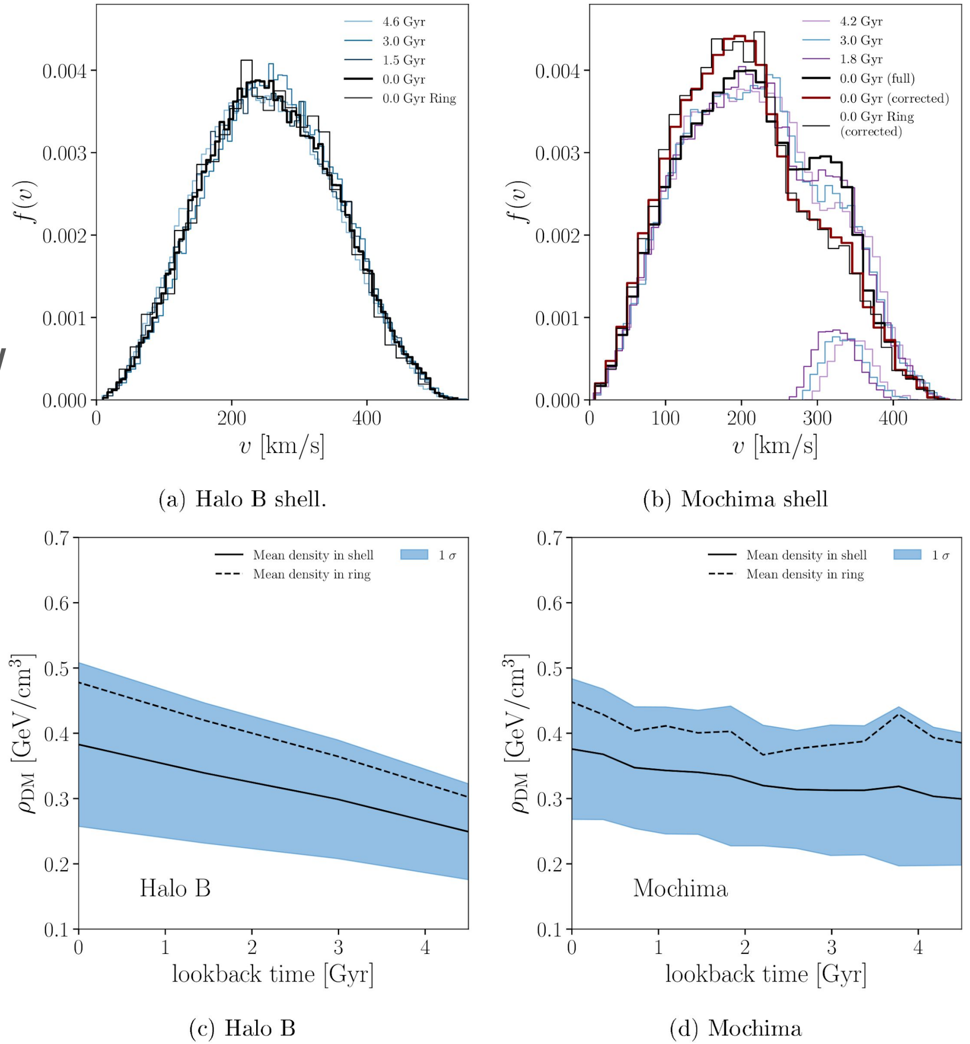
(c) Halo B ring

(d) Mochima ring

Check for equilibrium

Usually assumed for the MW

- Local density over time
- f(v) over time



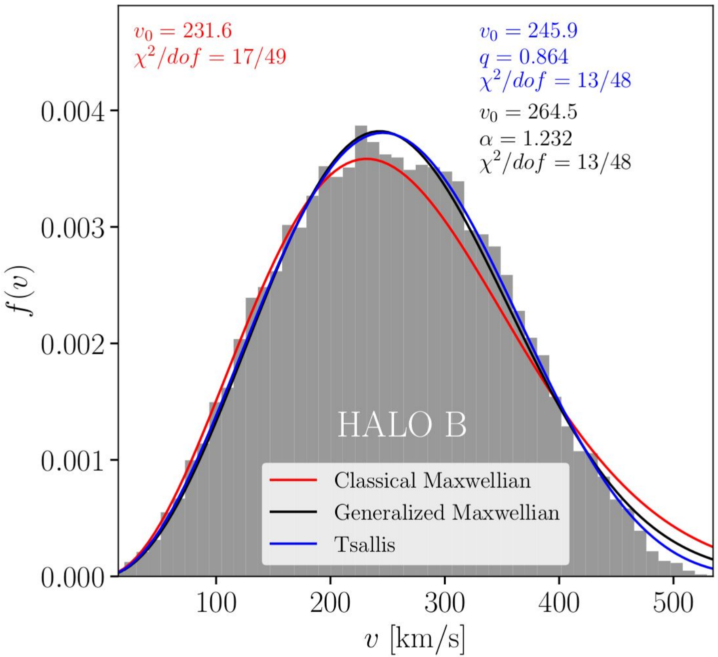
(a) Halo B shell.

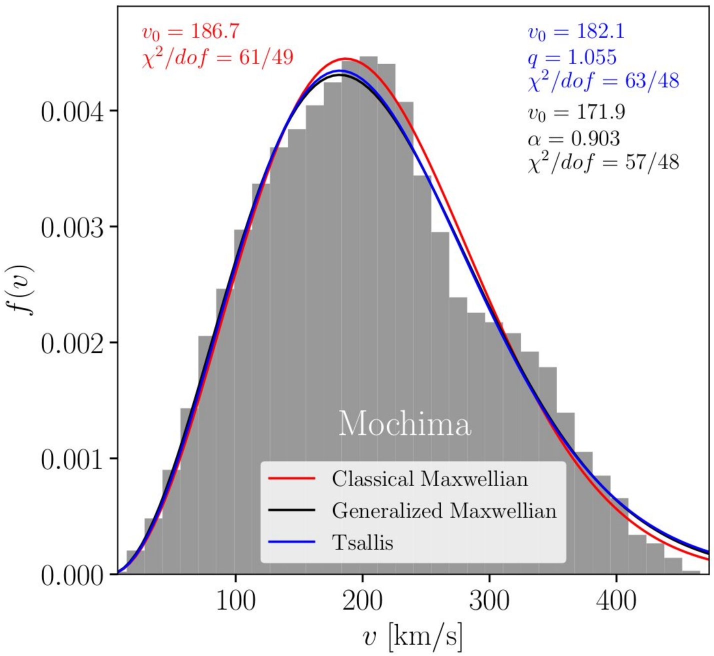
(b) Mochima shell

(c) Halo B

(d) Mochima

Then we can fit





Take your favorite fitting formula and go ahead...

$$f(\vec{v}) = \frac{1}{N} e^{-(\vec{v}^2/v_0^2)}$$

Classical Maxwellian

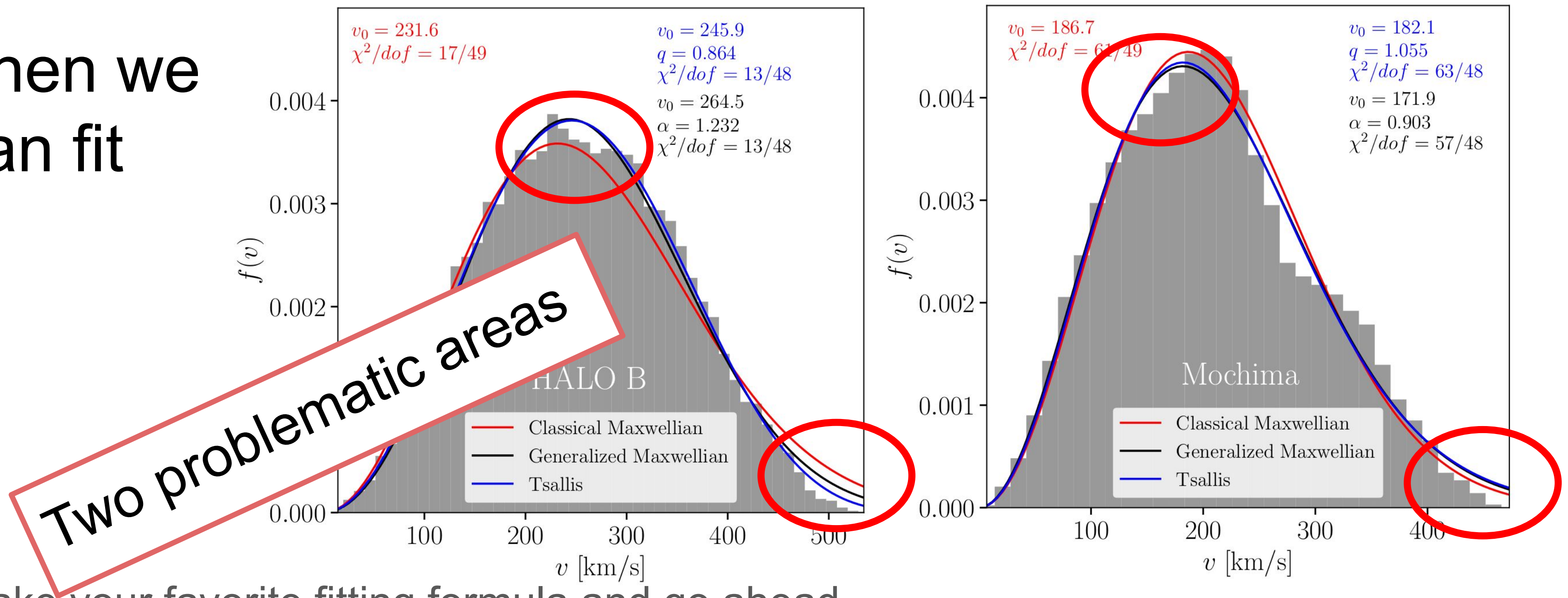
$$f(\vec{v}) = \frac{1}{N} e^{-(\vec{v}^2/v_0^2)^\alpha}$$

Generalized Maxwellian

$$f(\vec{v}) = \frac{1}{N} \left(1 - (1-q)\frac{\vec{v}^2}{v_0^2}\right)^{q/(1-q)}$$

Tsallis

Then we can fit



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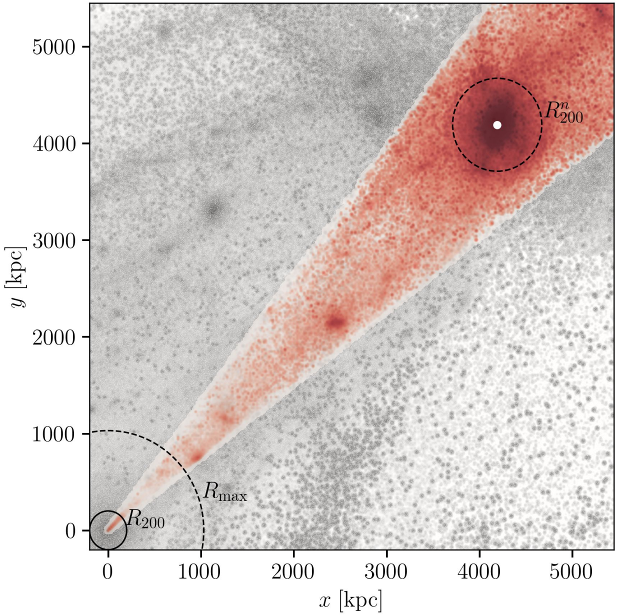
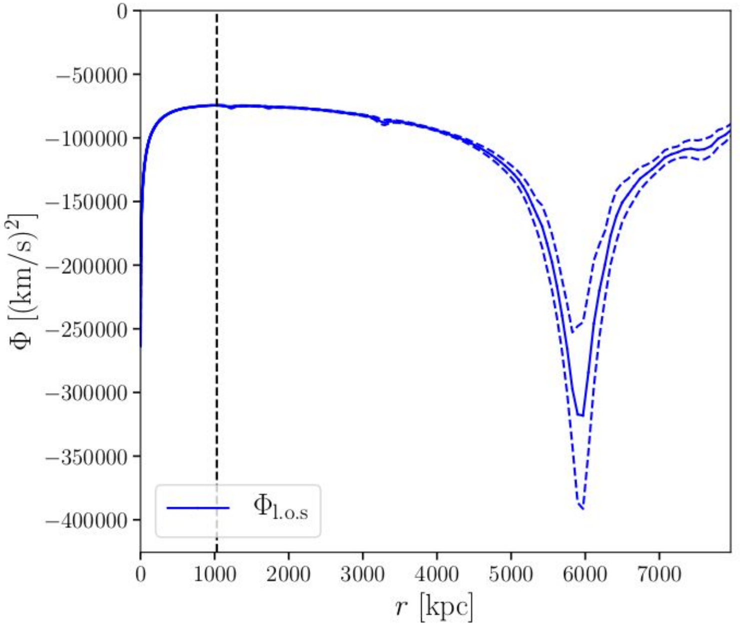
Tsallis

Introducing v_{esc}

To find v_{esc} we first find R_{max}

Radius at the point where the potential in the line between the halo and the biggest neighbour reach a maximum

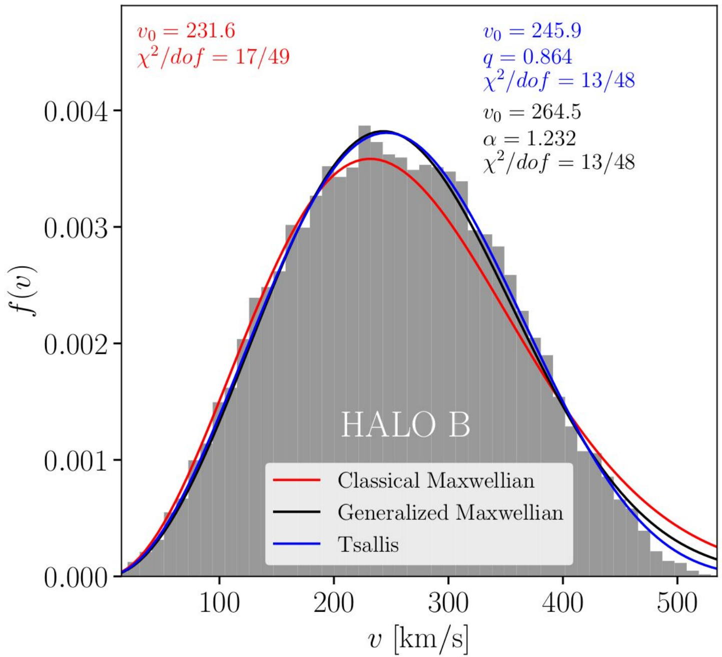


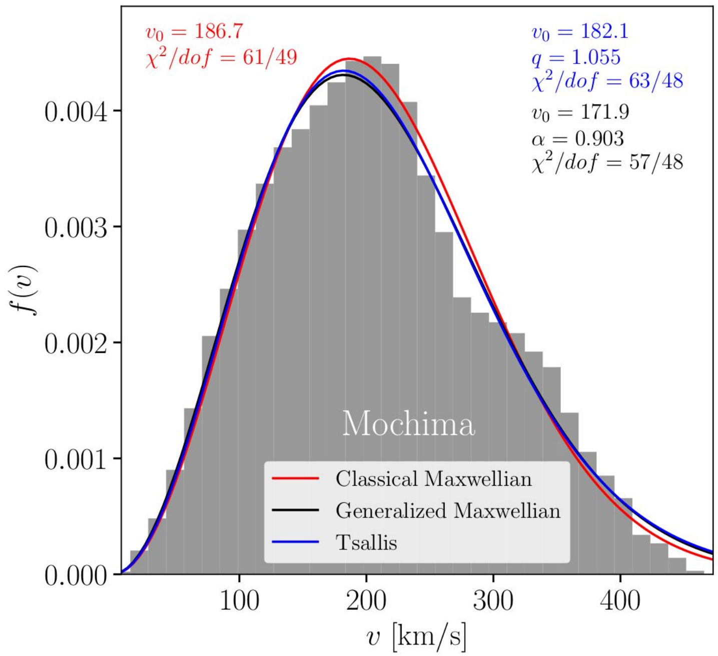


$$v_{esc} \equiv \sqrt{2\Psi(r)}$$

$$\Psi(r) = \Phi(R_{max}) - \Phi(r)$$

Then we can fit





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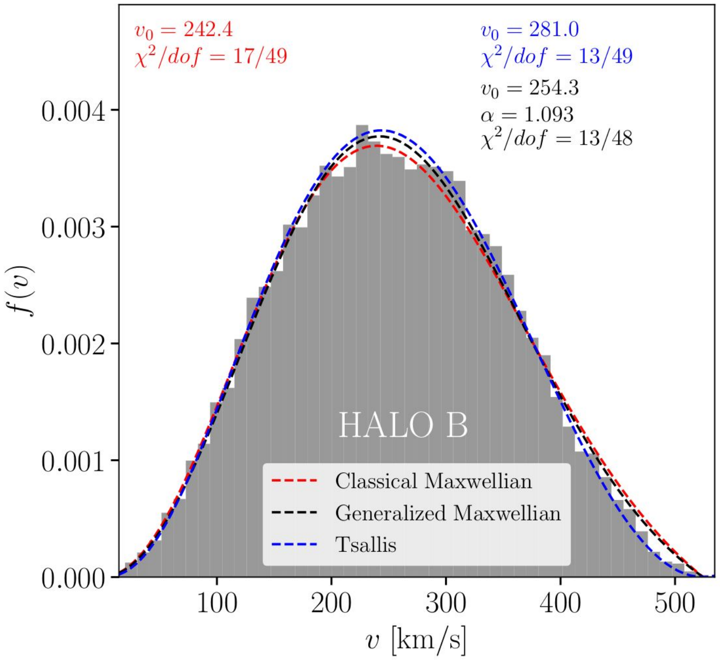

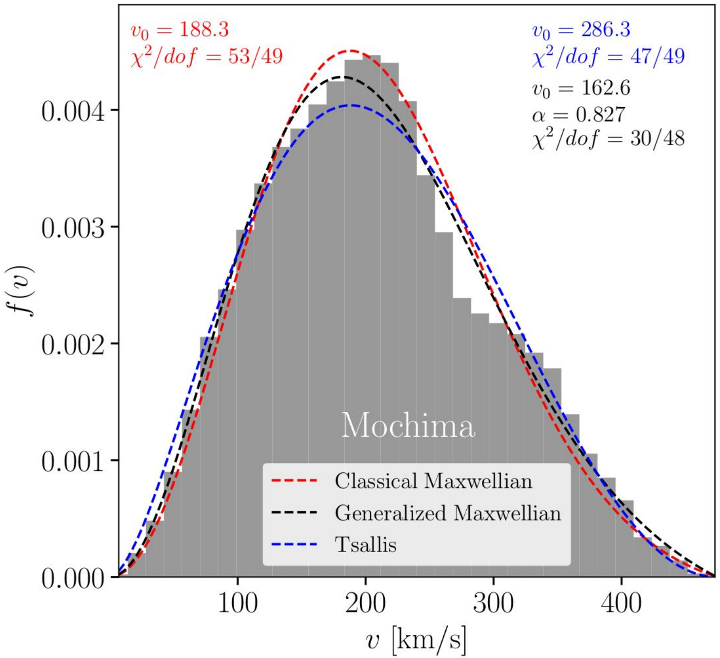

Take your favorite fitting formula and go ahead… now including v_{esc}

$$f(\vec{v}) = \frac{1}{N}\left(e^{-(\vec{v}^2/v_0^2)} - e^{-(v_{\rm esc}^2/v_0^2)}\right)$$

Classical Maxwellian

$$f(\vec{v}) = \frac{1}{N}\left(e^{-(\vec{v}^2/v_0^2)^\alpha} - e^{-(v_{\rm esc}^2/v_0^2)^\alpha}\right)$$

Generalized Maxwellian

$$f(\vec{v}) = \frac{1}{N}\left(1-(1-q)\frac{\vec{v}^2}{v_0^2}\right)^{q/(1-q)}$$

Tsallis

$$q = 1-(v_0^2/v_{\rm esc}^2)$$

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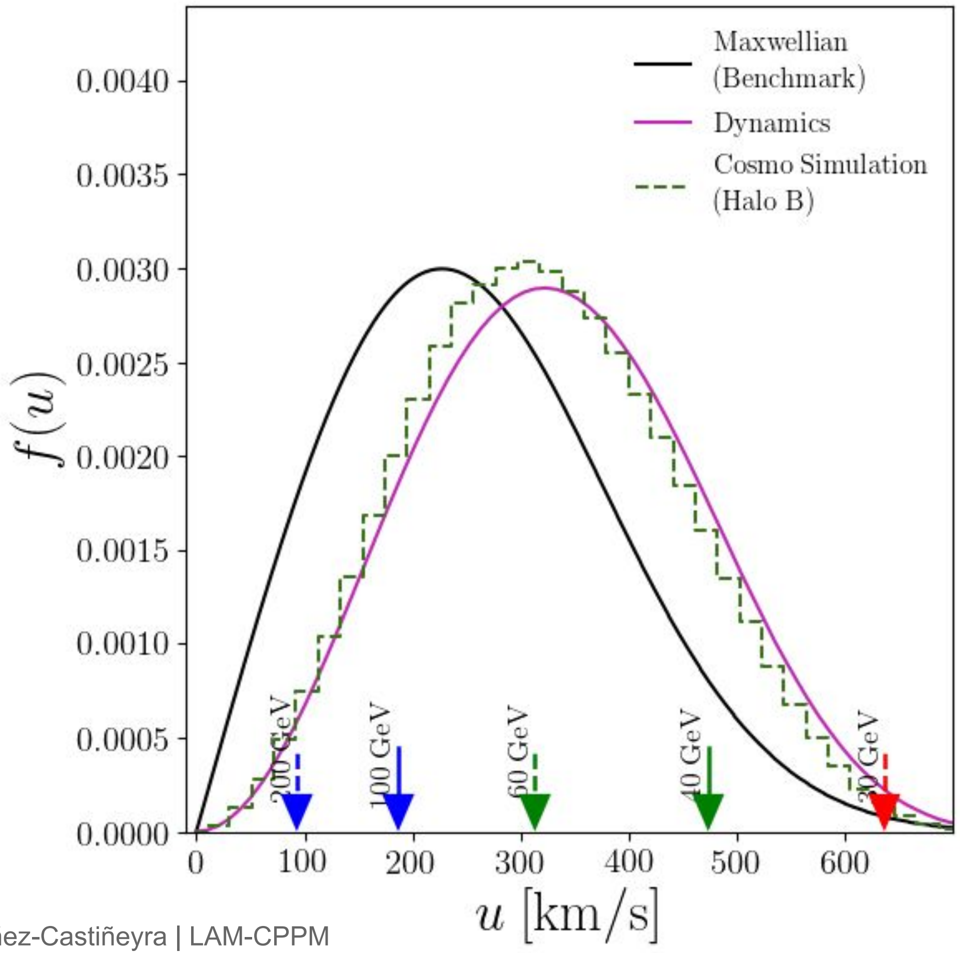
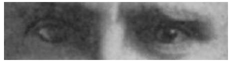
2. Predictions from dynamics



Eddington inversion



Predictions from the Eddington method as studied by Lacroix et al. (Binney - Tremaine) of f(v)

vs

fully consistent objects build in a Zoom-in Cosmological Simulation.

$$f(\vec{r}, \vec{v}) = f(\mathcal{E}, L)$$

Density profile → Eddington inversion → f(ε) → f(v)

$$\rho_{DM}(r) + \rho_{baryons}(r)$$

$$\frac{d\rho}{d\Psi}$$

Assuming spherical symmetry and isotropy

$$\mathcal{E} = \Psi(r) - \frac{v^2}{2}$$

$$\Psi = \Phi(r) - \Phi(r_{max})$$

$$f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2}\left(\frac{1}{\sqrt{\mathcal{E}}}\left[\frac{d\rho}{\Psi}\right]_{\Psi=0} + \int_0^{\mathcal{E}} \frac{d\Psi}{\sqrt{\mathcal{E}-\Psi}}\frac{d^3\rho}{d\Psi^3}\right)$$

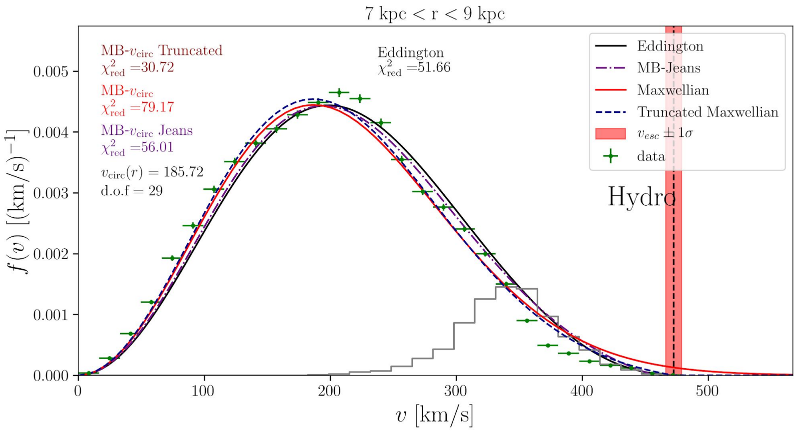
Eddington prediction
vs
Maxwellian approach

Two ways of building the mean of maxwellian f(v)

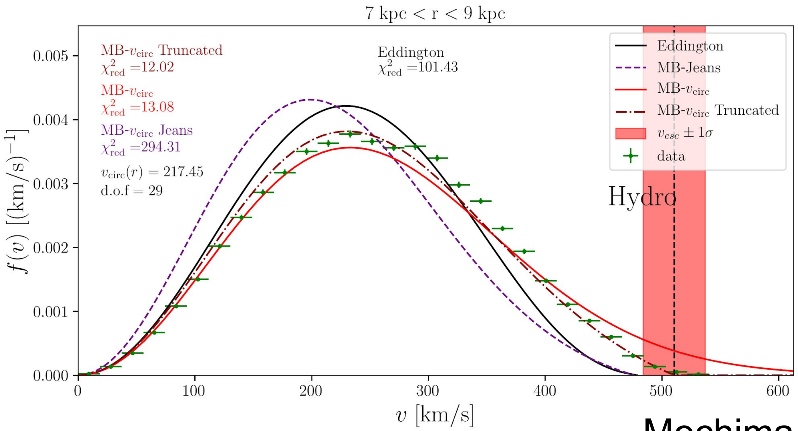
1) From the contained mass as

$$v_0 = v_c(r) = \sqrt{\frac{GM(r)}{r}}$$

2) By solving the **Jeans equation** for the velocity using the contain mass again.

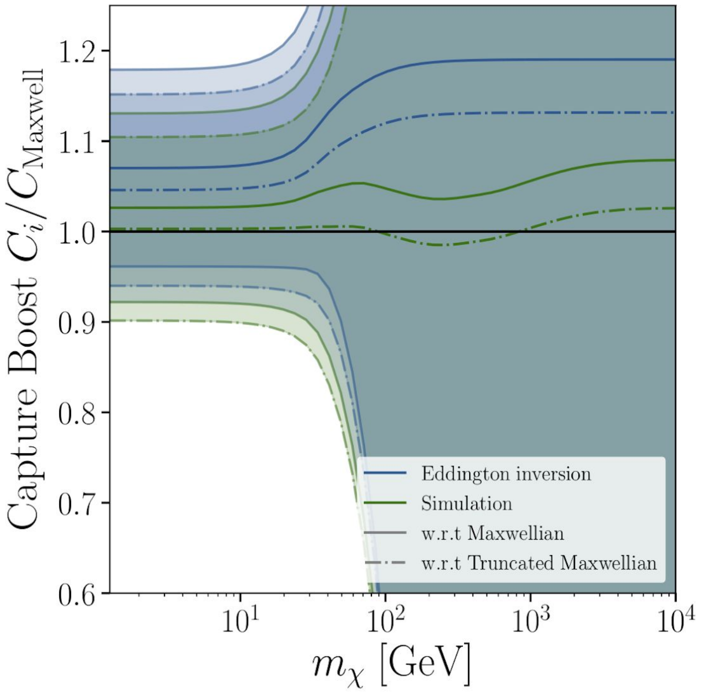


HALO B

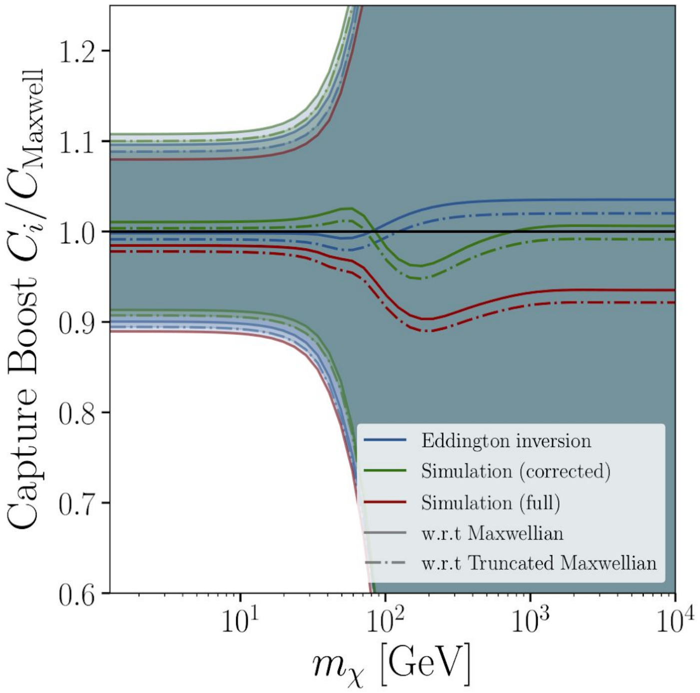


Mochima

Capture boost

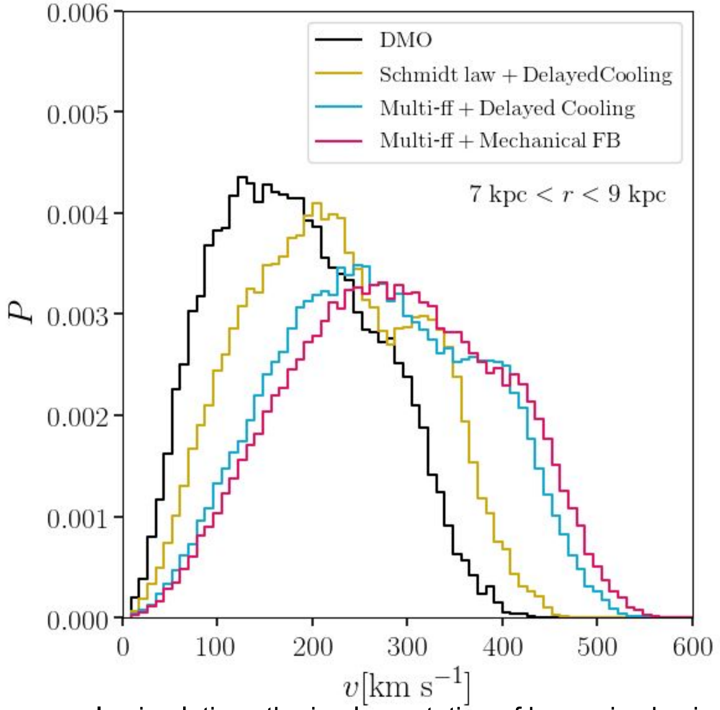


(a) Halo B shell

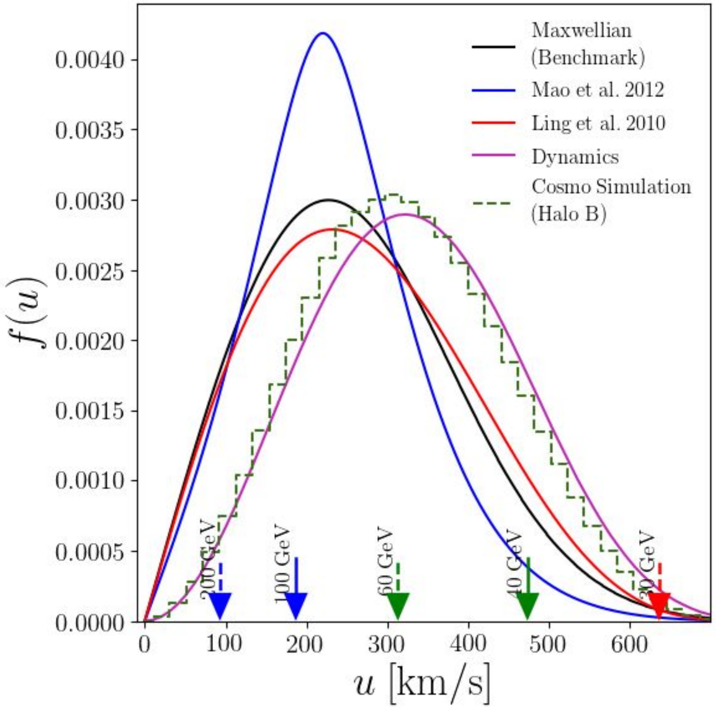


(b) Mochima shell

Point of emphasis on the variability of the f(v)



In simulations the implementation of baryonic physics will have an effect on the final distribution.
Nunez-Castineyra et al. in prep



The discussed cases + some extra from the literature

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  - Requires validation from simulations. Lacroix et al in prep

Conclusions

− Departure from capture/annihilation equilibrium during periods of low capture is an unlikely scenario. **The Sun is** safely in **equilibrium** for WIMPs with m χ . few TeV.

− The peak/hat and the tail of the simulations f(v) are usually hard to fit. Adding the escape velocity in the fits improves the consistency with the tail of the distribution.

− The f(v)s obtained with the Eddington approach bring additional information on the possible distributions that can be assumed. (have better agreement with simulations data thand the standard Maxwellian VDF)

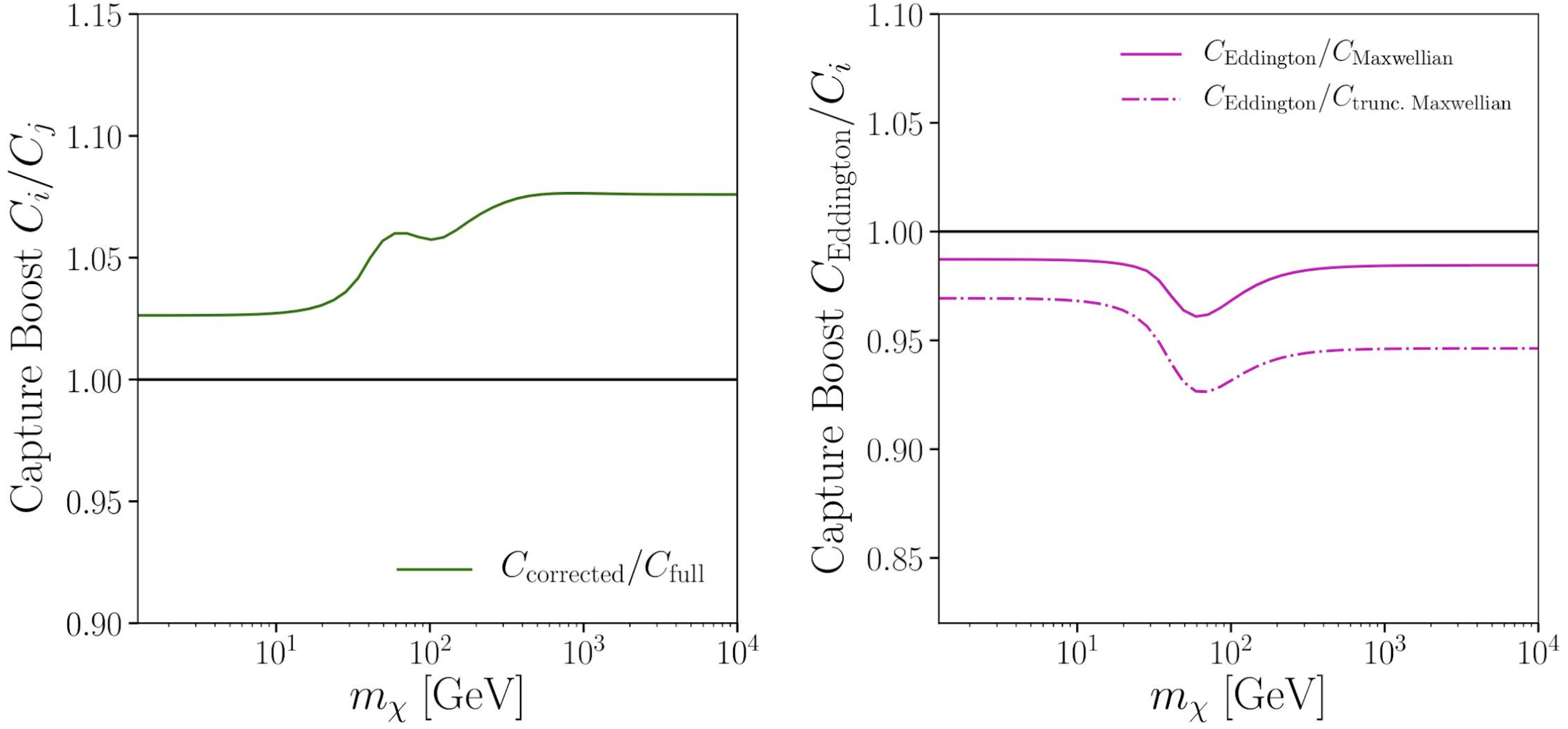
−The merger history of the halo could leave specific features in the f(v) that out of reach for usual functions.

− The level of **variability** on the capture rate can reach up to 20% depending on the assumptions f(v)

− The intrinsic errors, **the variance**, of the capture rate leads to dramatic uncertainties, especially for **m_χ>30 GeV.**

Thank you

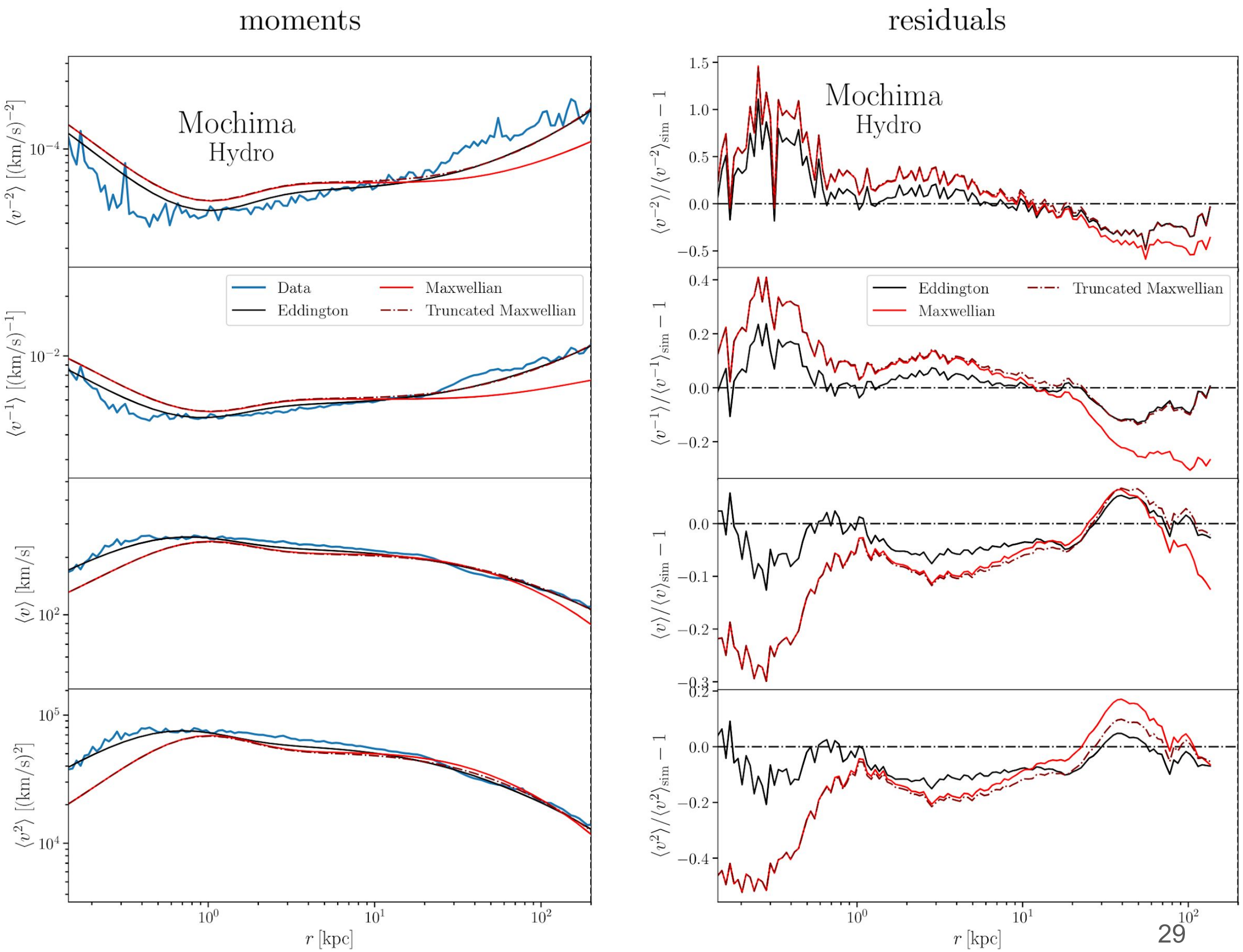
Capture boost

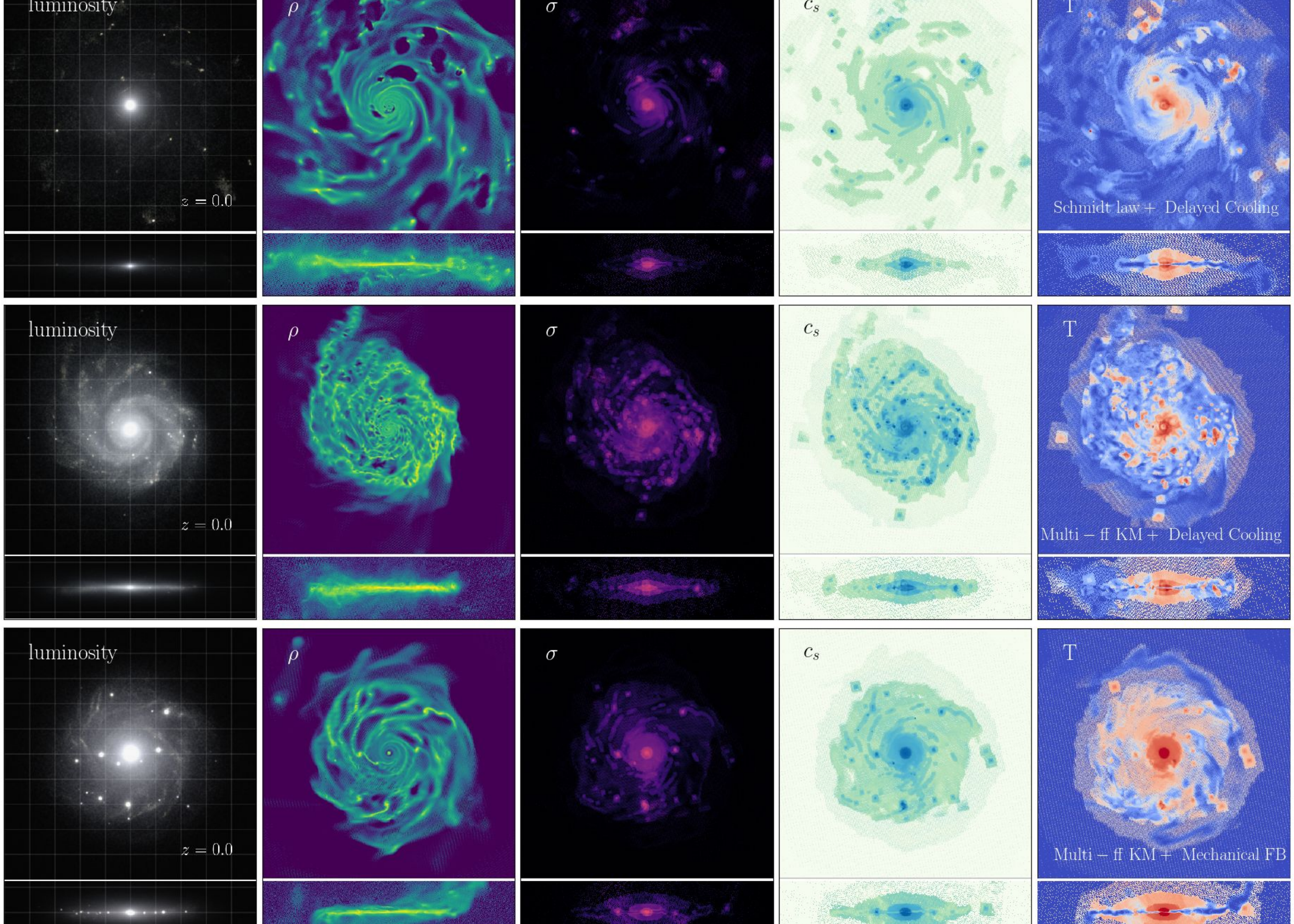


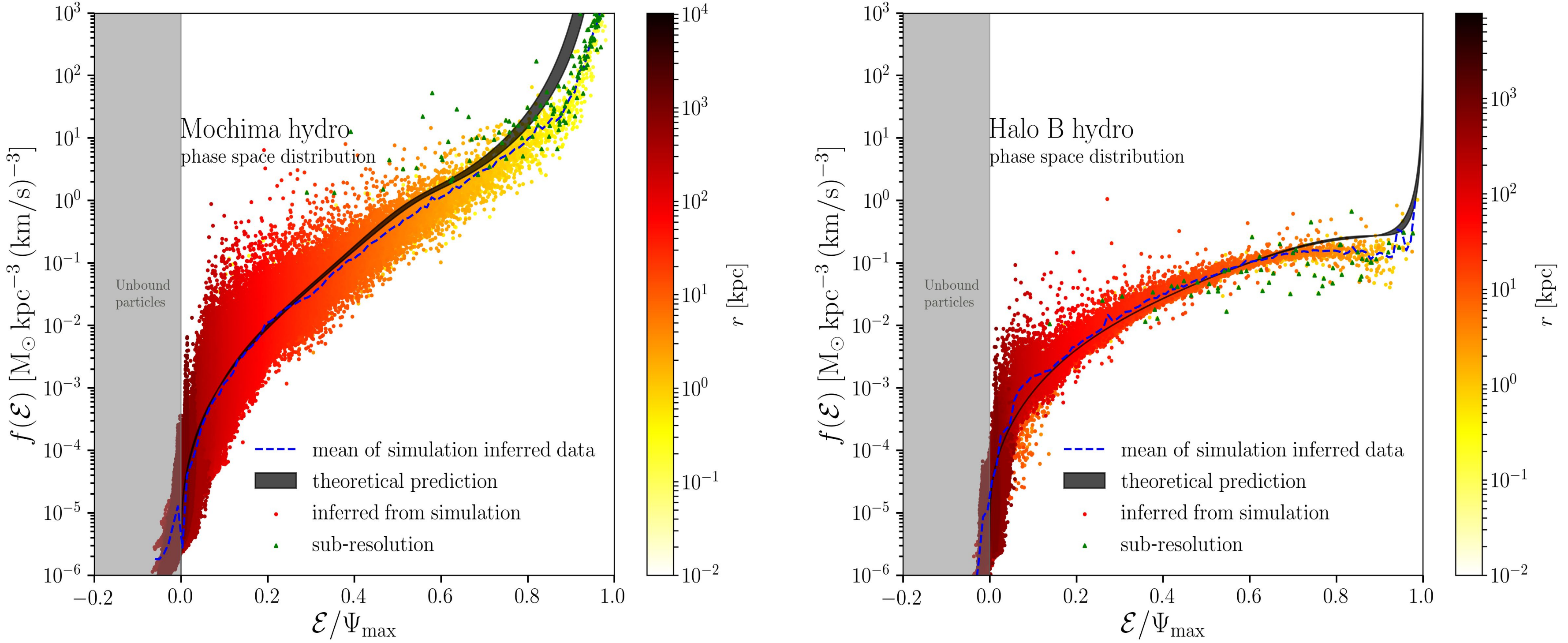
(c) Mochima

(d) Milky Way mass model

Some more Eddington results




luminosity
ρ
σ
c_s
T
$z = 0.0$
Schmidt law + Delayed Cooling
luminosity
ρ
σ
c_s
T
$z = 0.0$
Multi − ff KM + Delayed Cooling
luminosity
ρ
σ
c_s
T
$z = 0.0$
Multi − ff KM + Mechanical FB


Mochima hydro
phase space distribution
Unbound particles
mean of simulation inferred data
theoretical prediction
inferred from simulation
sub-resolution
$f(\mathcal{E})$ [$M_\odot$ kpc^{-3} (km/s)$^{-3}$]
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