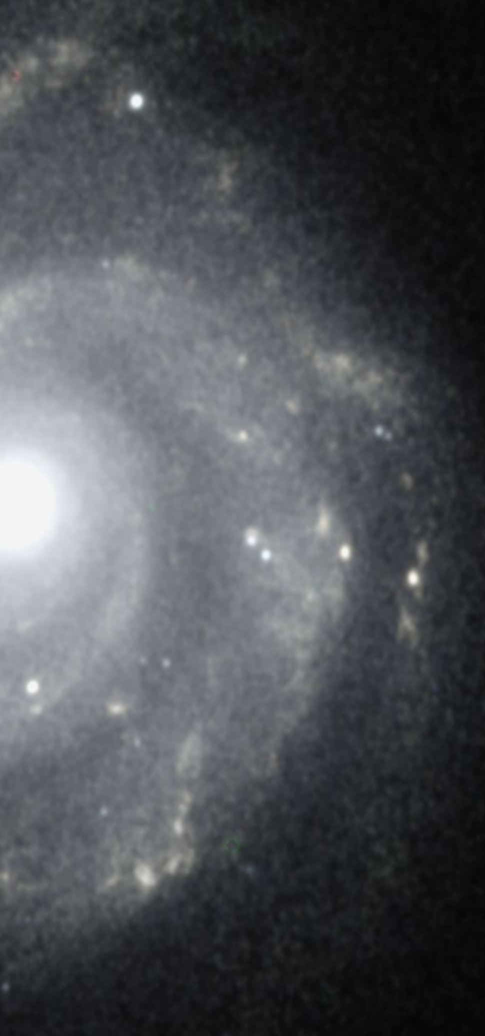
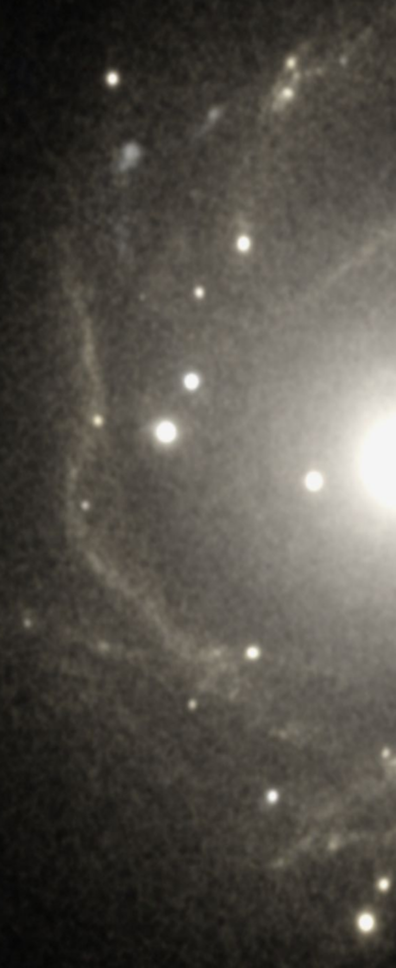




Revisiting velocity distribution uncertainties (application to capture by the Sun)

A. Nuñez-Castiñeyra

V. Bertin, E. Nezri

[arXiv:1906.11674]

Lacroix, Nunez-Castineyra, Stref, Lavalle,Nezri in prep

Nunez-Castineyra, Nezri, Devriendt, Teyssier in prep

Marseille, October 2019

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/cm³; v_{esc}=544 km/s ; f(v)=Maxwellian distribution)

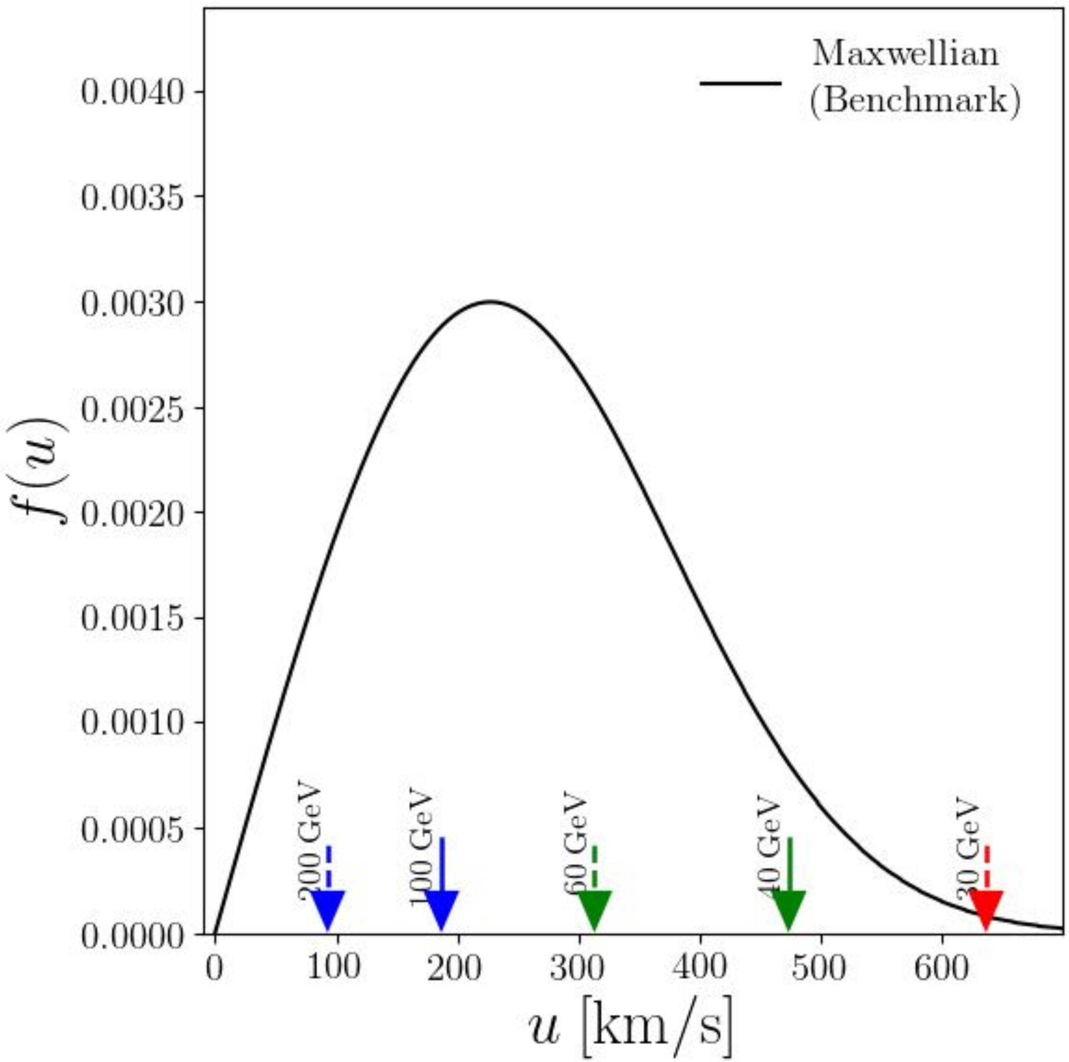
- Direct extrapolation by fiting f(v) from Cosmological "Milky-Way like" simulations

- Dynamical phase space prediction using MW macro features

e.g Eddington (Eddington, lacroix 2018), Action angle (Binney , Posti) etc.

1. SHM

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



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2. Cosmological simulations

To extrapolate data o use fits on f(v) obtained in simulations of "MW-like galaxy"**

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

Ingredients

Different fluids are modelled using different techniques.

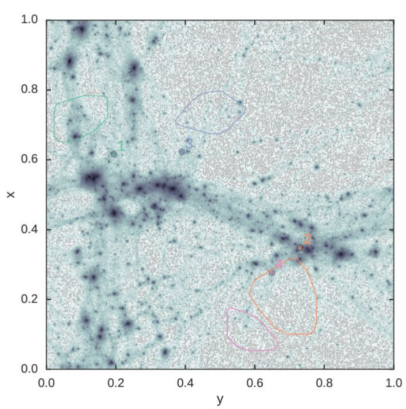
1. **Dark matter** as a collisionless fluid (Vlasov equation)
2. **Gas** as a compressible ideal gas (Euler equations)
3. **Stars** as a collisionless fluid (Vlasov equation)
4. Various chemical species as passive scalars and associated reactions

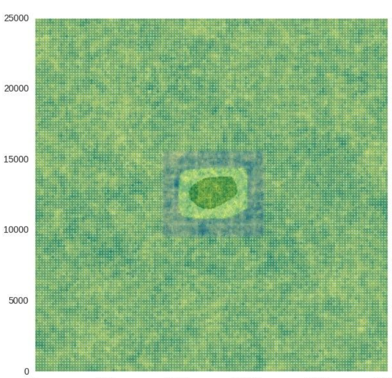
Possible extra ingredients:

5. Metals and dust grains as passive scalars or as new fluids
6. Massive neutrinos as a quasi-relativistic fluid
7. Magnetic fields as a divergence free vector field
8. Supermassive black holes as individual accreting particles
9. Cosmic rays as an additional energy variables or as a new fluid

Zoom-in Simulations

1. detect one halo of interest in a cosmological simulation.
2. compute the Lagrangian volume in the low resolution IC
3. generate high-resolution IC by adding high frequency waves to the low resolution initial Gaussian random field
4. use the Lagrangian volume as a map to initialize high resolution particles.
5. do the high resolution simulation and check for contamination
6. eventually, compute a better initial Lagrangian volume and re-do the simulation





z=0

z=100

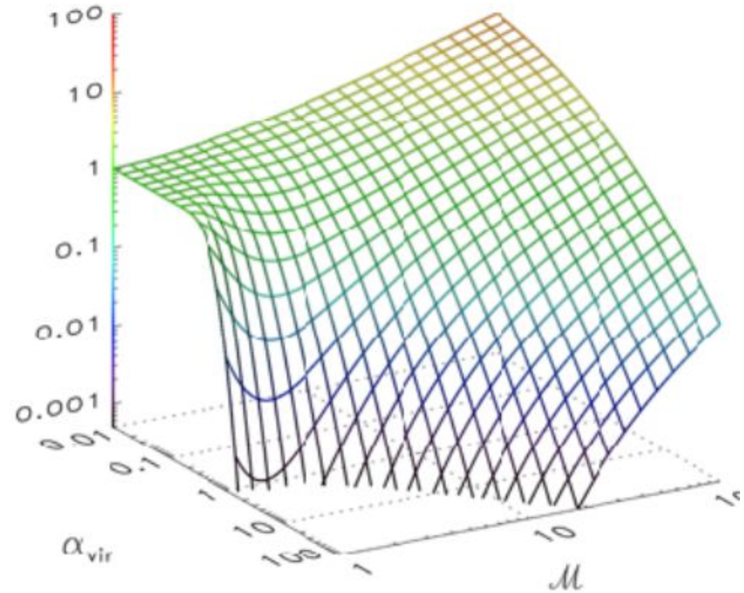
Star formation

Schmidt law for star formation:

$$\dot{\rho}_* = \epsilon_* \frac{\rho_g}{t_{\rm ff}} \text{ for } \rho > \rho_*$$

Option 1: constant efficiency (Krumholz & Tan (2007))

Option 2: calculated efficiency (Federrath & Klessen (2012))



$$p(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left(-\frac{\left(s + \frac{1}{2}\sigma_s^2\right)^2}{2\sigma_s^2}\right)$$

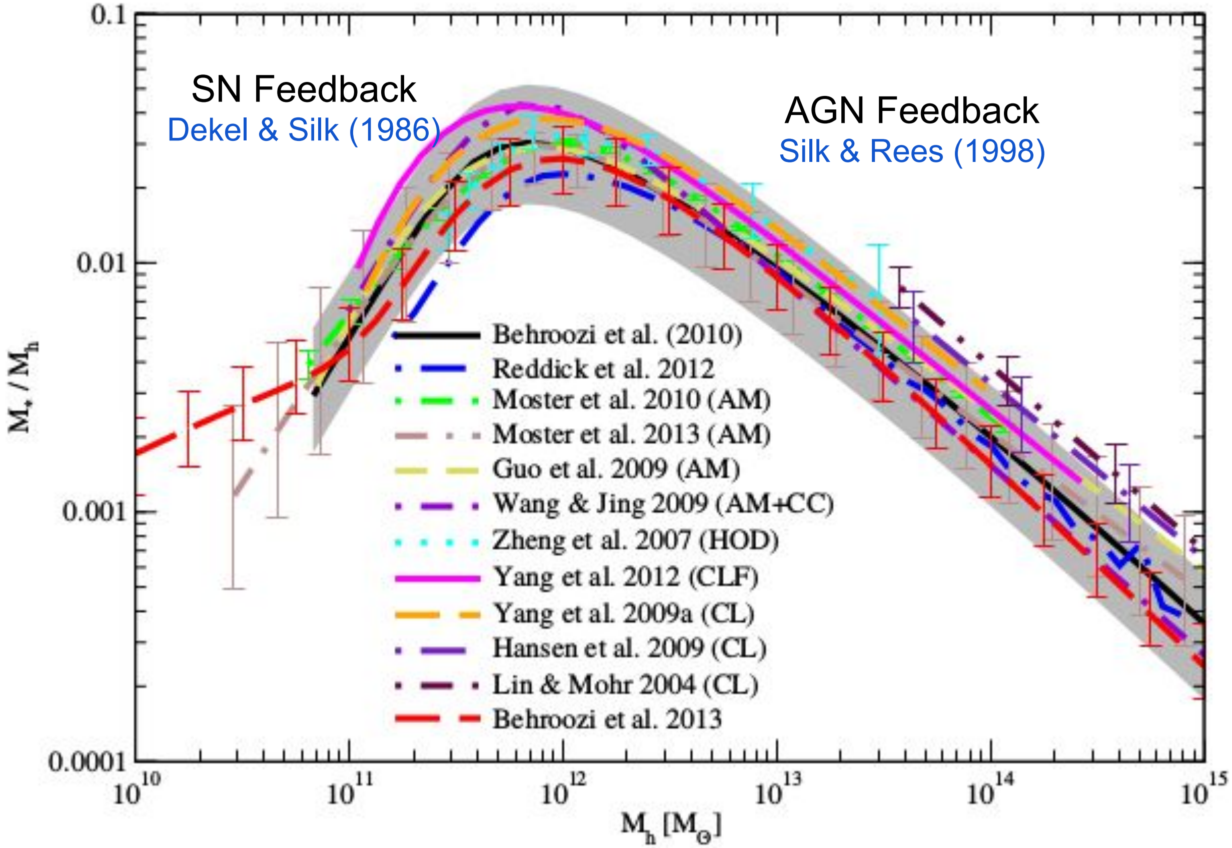
Among some of the models we use: Krumholz & McKee (2005)

$$\sigma_s^2 = \ln\left(1 + b^2 \mathcal{M}^2\right) \qquad \mathcal{M} = \frac{\sigma_{\rm T}}{c_s}$$

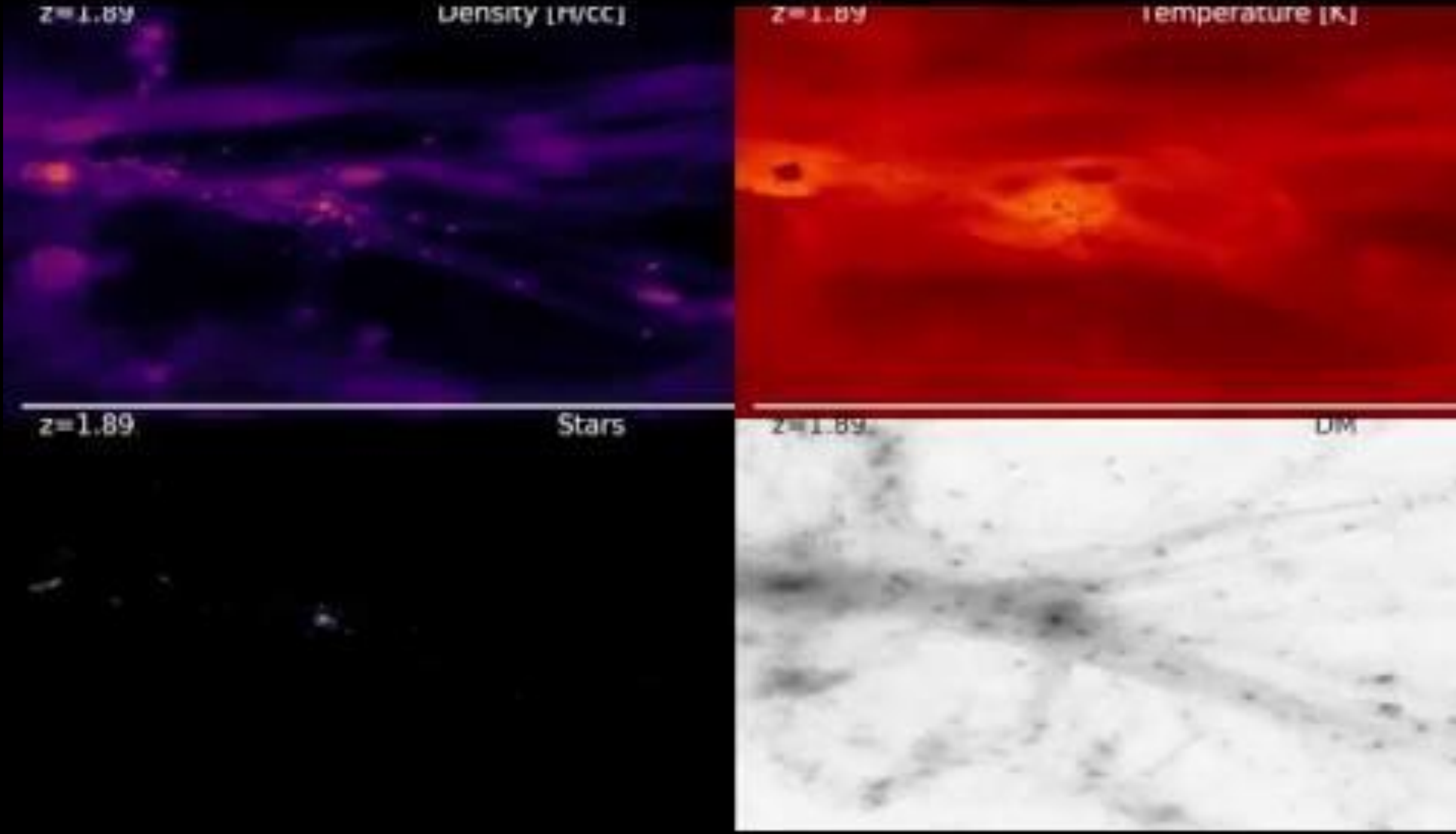
$$\rho_{\rm crit} \propto \alpha_{\rm vir} \mathcal{M}^2 \qquad \alpha_{\rm vir} = \frac{\sigma_{\rm T}^2}{G\rho_0\Delta^2}$$

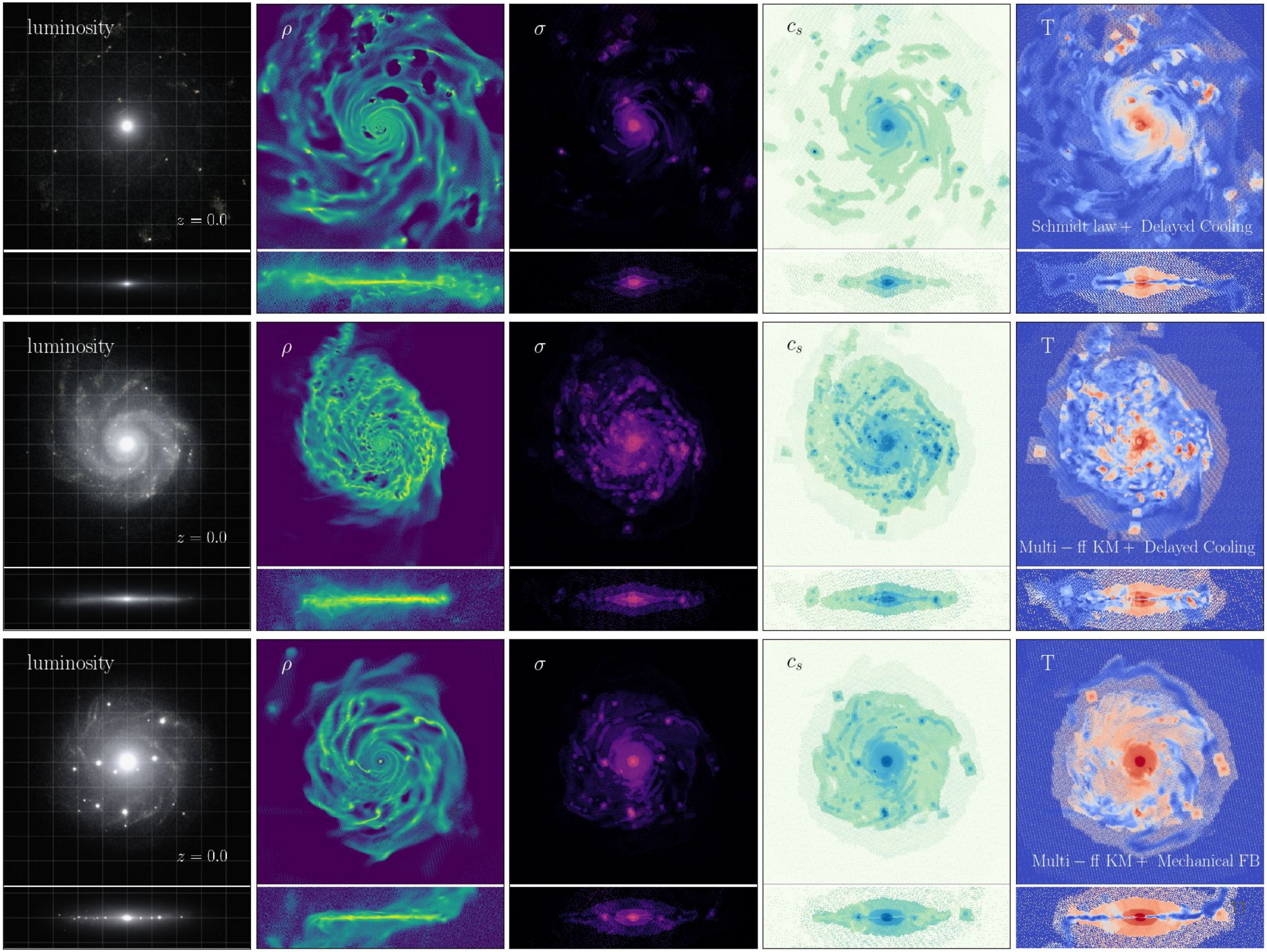
$$\epsilon_{ff} = \exp\left(3/8\sigma_s^2\right)\left(1 + {\rm erf}\left(\frac{\sigma_s^2 - s_{\rm crit}}{\sqrt{2\sigma_s^2}}\right)\right)$$

Feedback



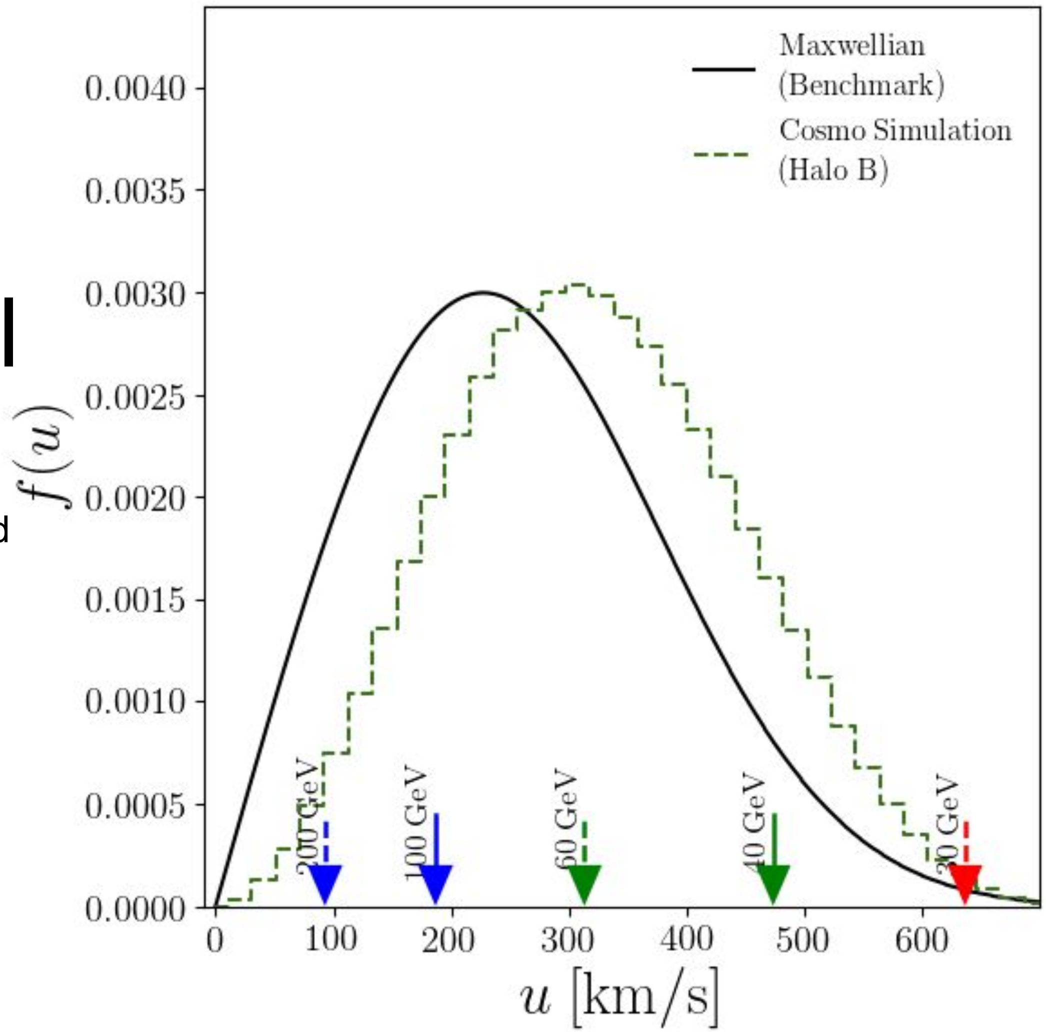
Behroozi et al. (2013)


z=1.89
Density [H/cc]
z=1.89
Temperature [K]
z=1.89
Stars
z=1.89
DM


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

2. Cosmological simulations

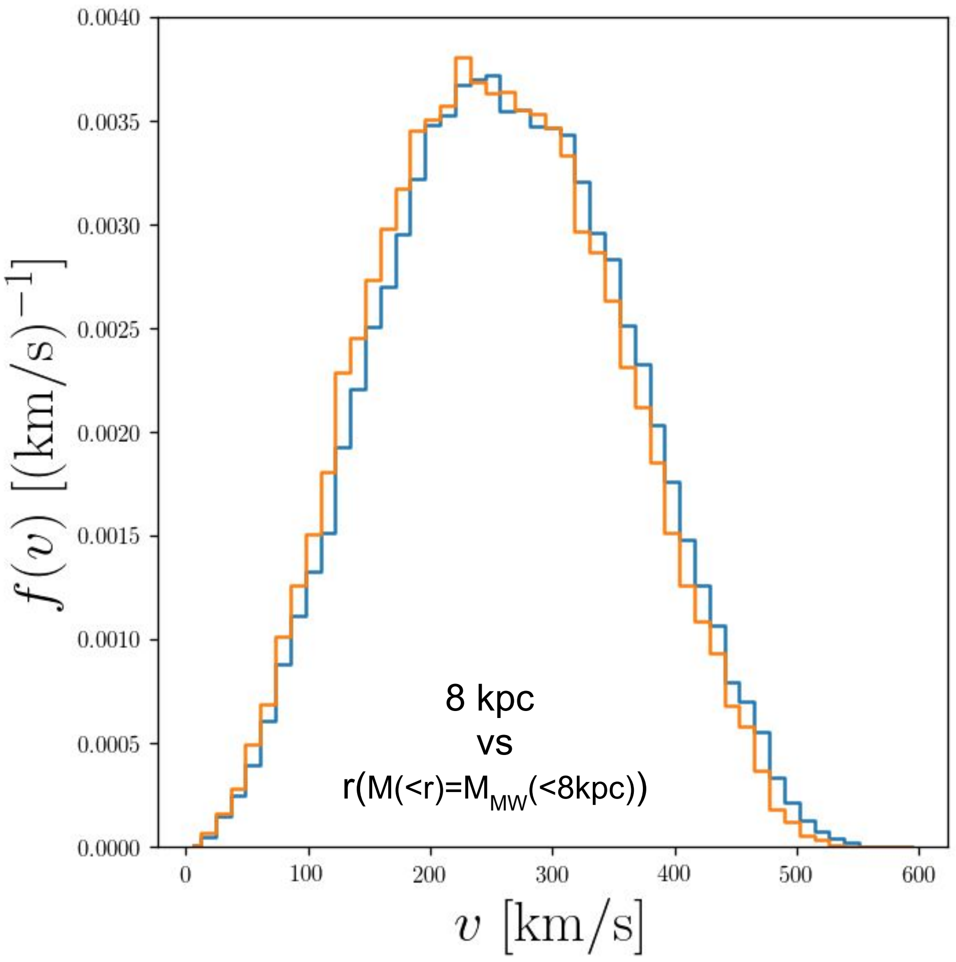
Extrapolate data o use fits on f(v) obtained in simulations of "MW-like galaxy"**



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

2. Cosmological simulations

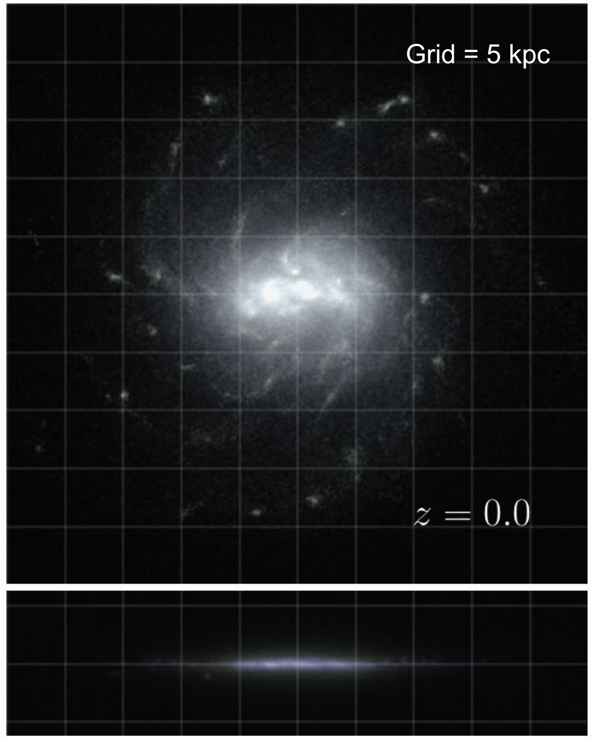
Extrapolate data o use fits on f(v) obtain in simulations of "MW-like galaxy"** at 8 kpc**

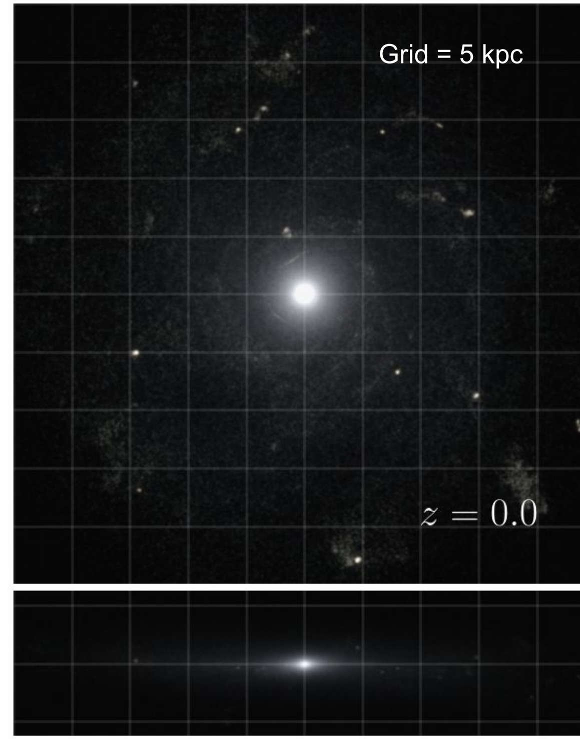


**: how MW-like can a simulation be?
***: what is the meaning of 8 kpc in your simulations with respect to 8kpc in the MW

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

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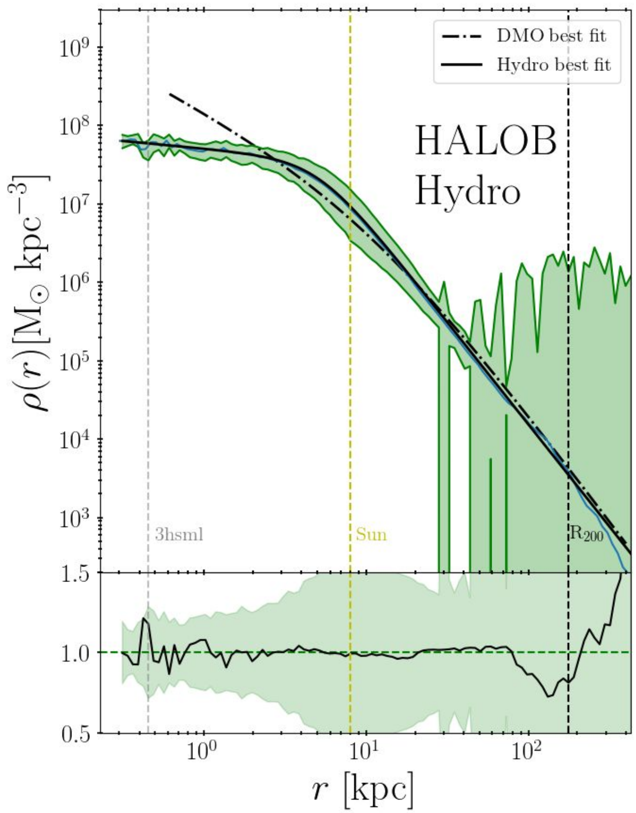

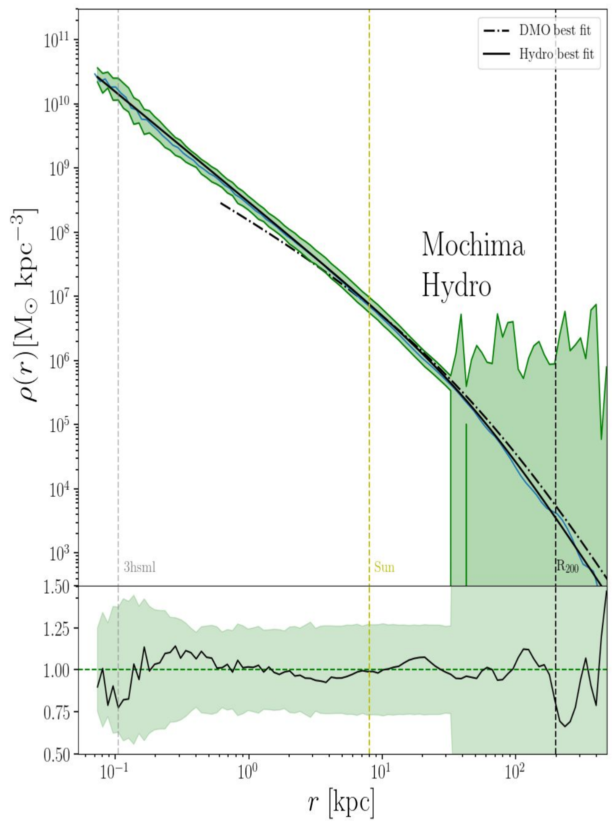

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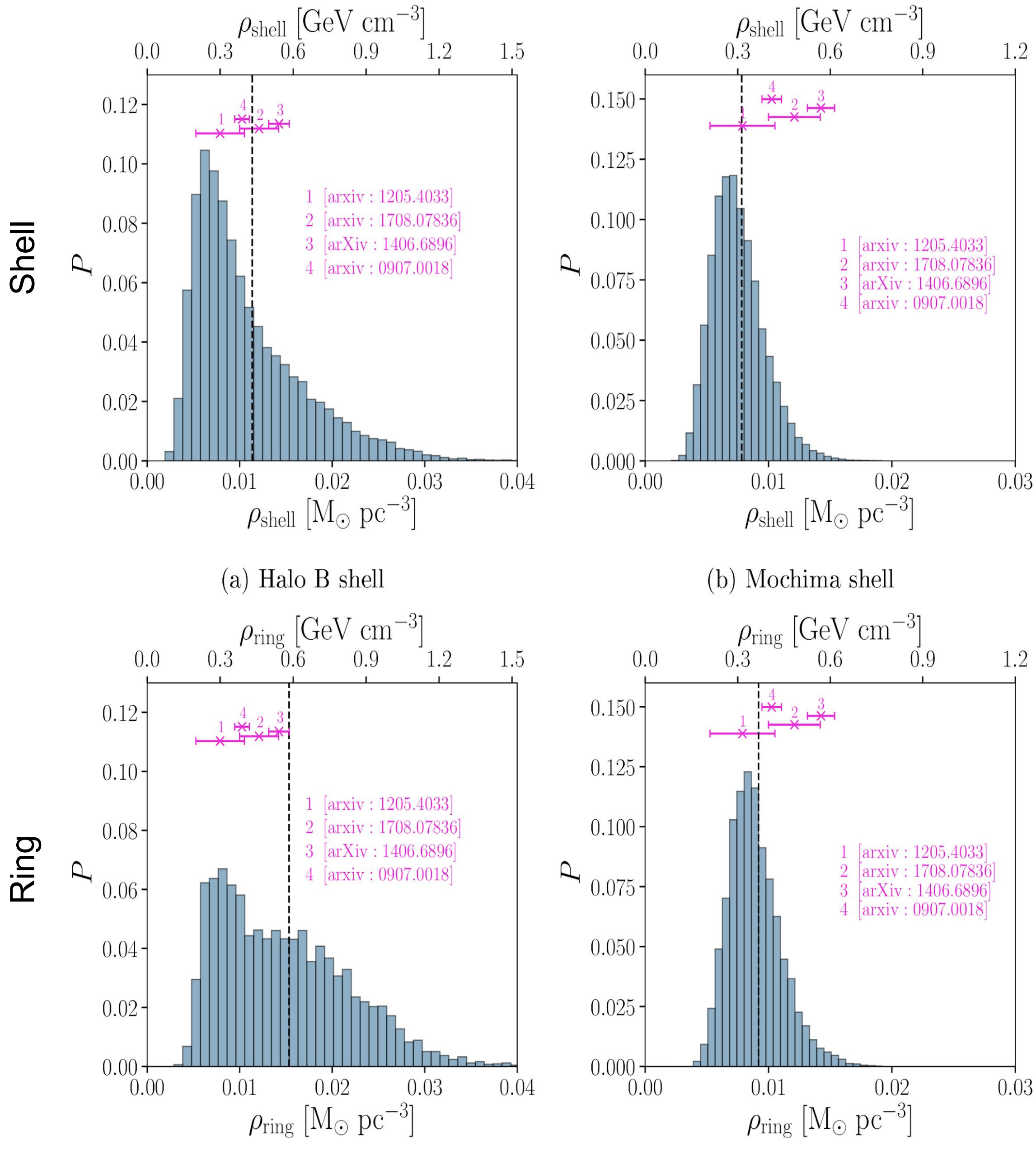
Local DM density

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

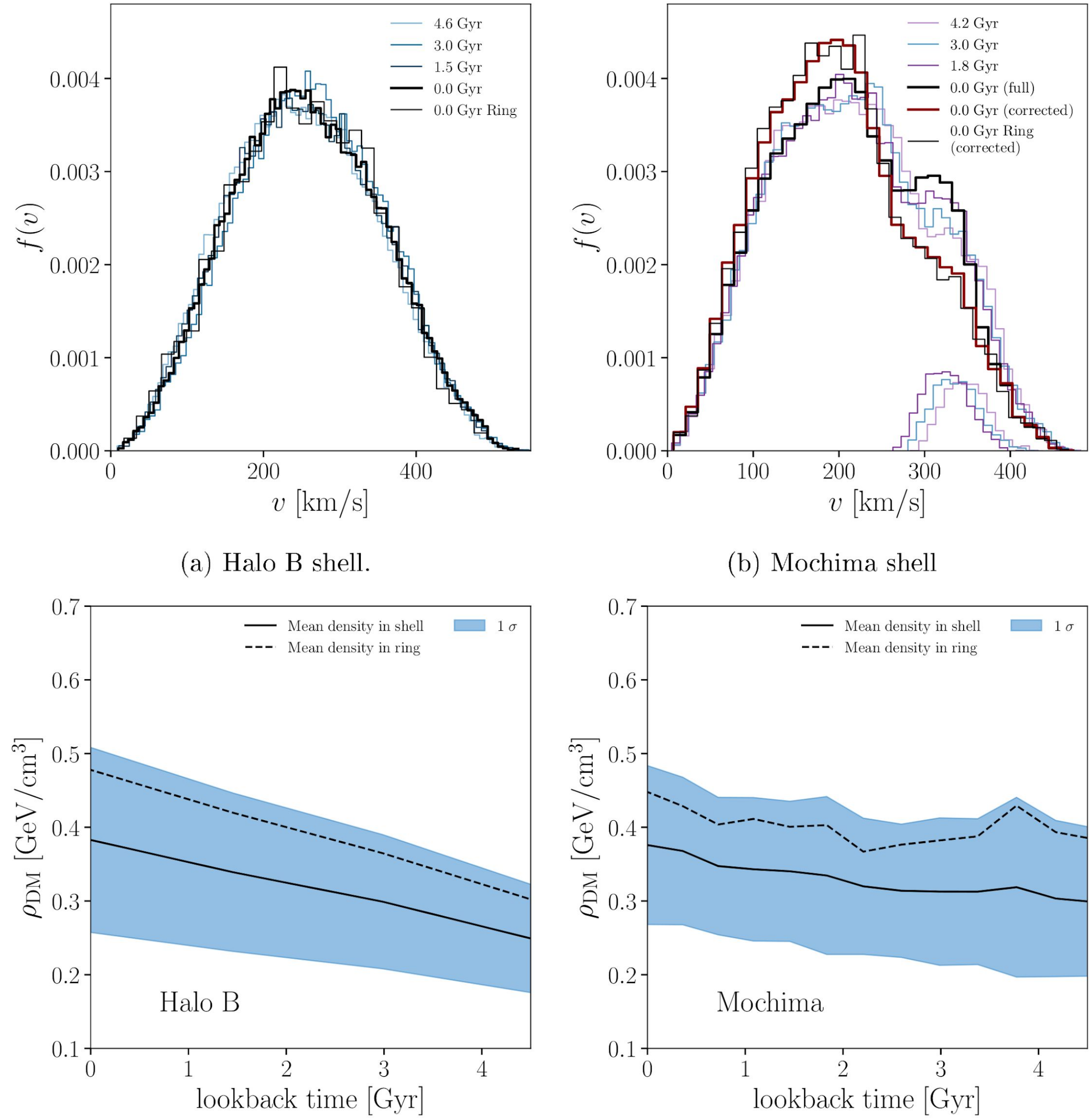
(c) Halo B ring

(d) Mochima ring

Check for equilibrium

Usually assumed for the MW

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

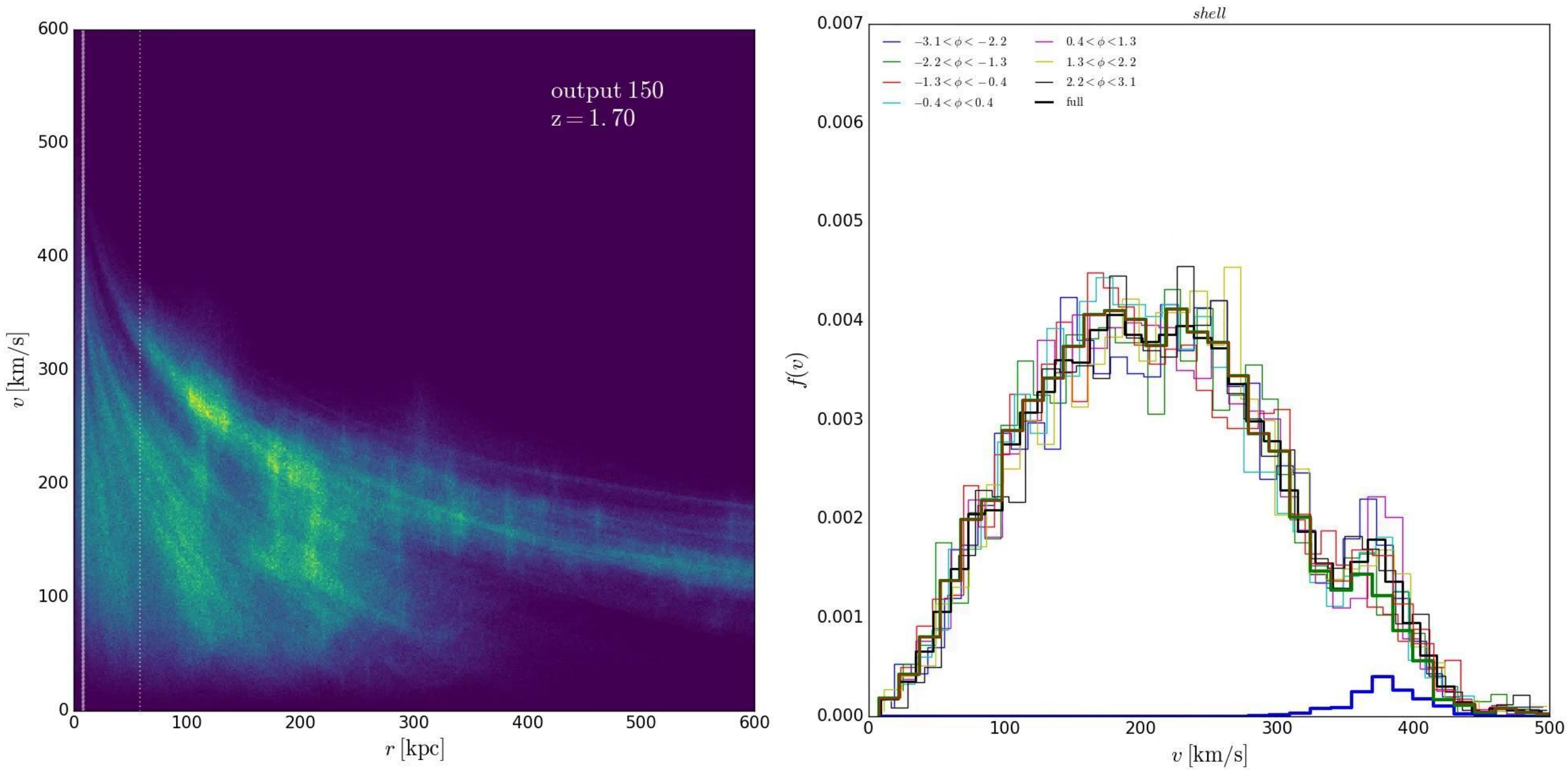


(a) Halo B shell.

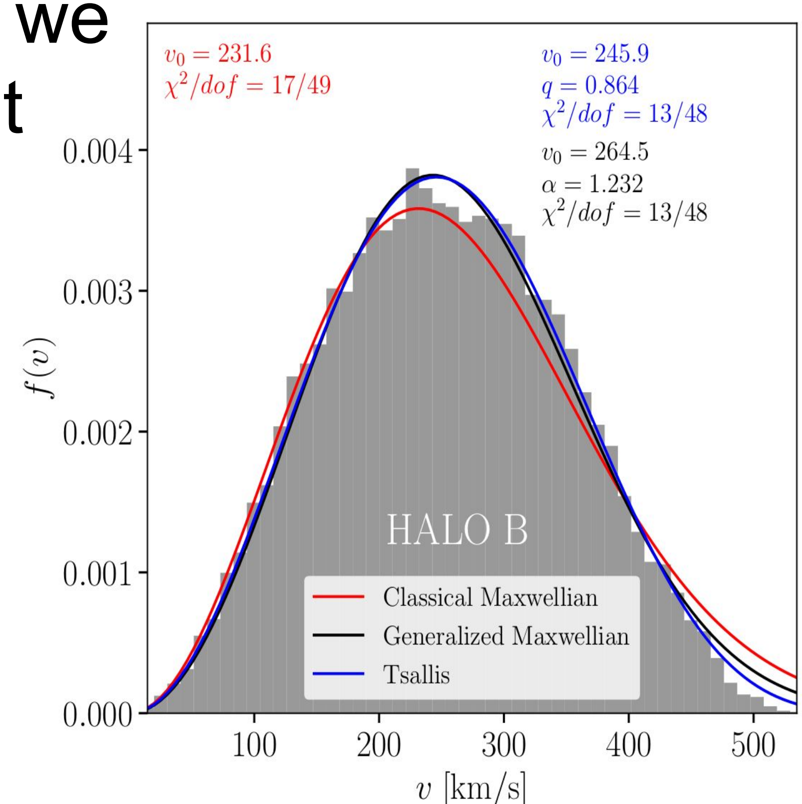
(b) Mochima shell

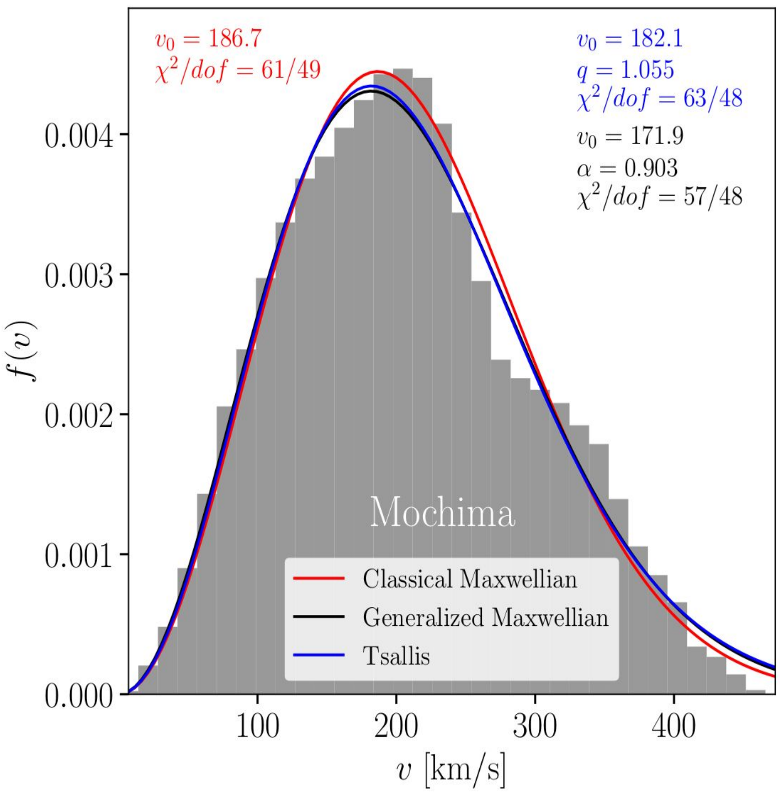
(c) Halo B

(d) Mochima


output 150
z = 1.70
v [km/s]
r [kpc]
shell
$-3.1 < \phi < -2.2$
$-2.2 < \phi < -1.3$
$-1.3 < \phi < -0.4$
$-0.4 < \phi < 0.4$
$0.4 < \phi < 1.3$
$1.3 < \phi < 2.2$
$2.2 < \phi < 3.1$
full
$f(v)$
v [km/s]

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

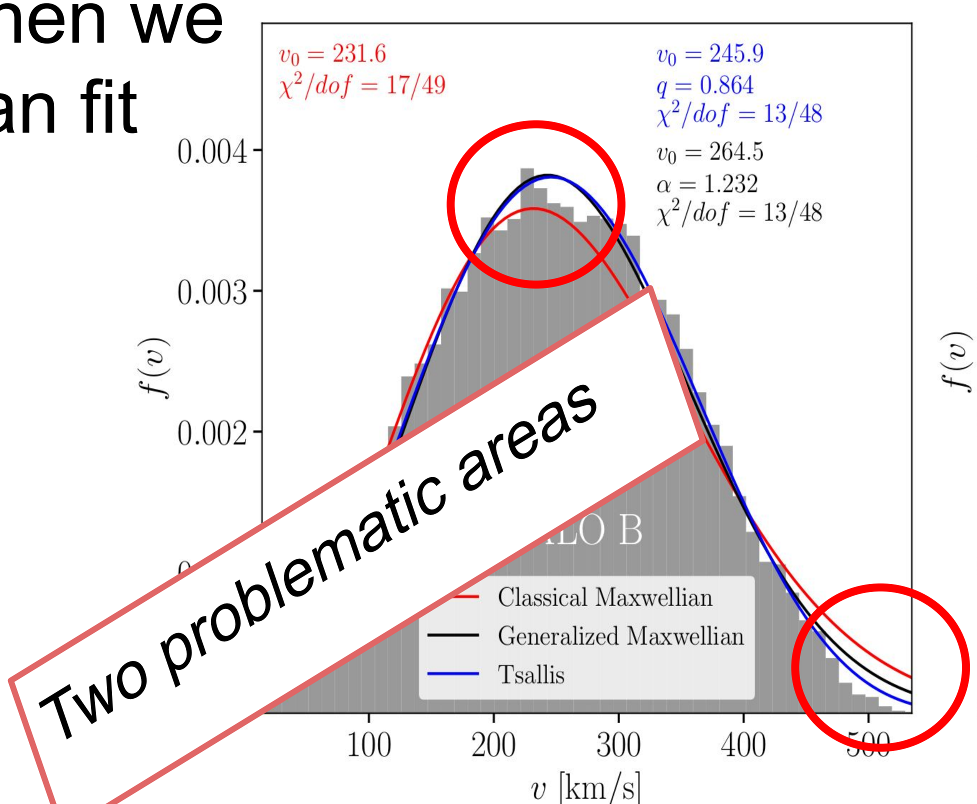
$$f(\vec{v}) = \frac{1}{N} e^{-(\vec{v}^2/v_0^2)^\alpha}$$

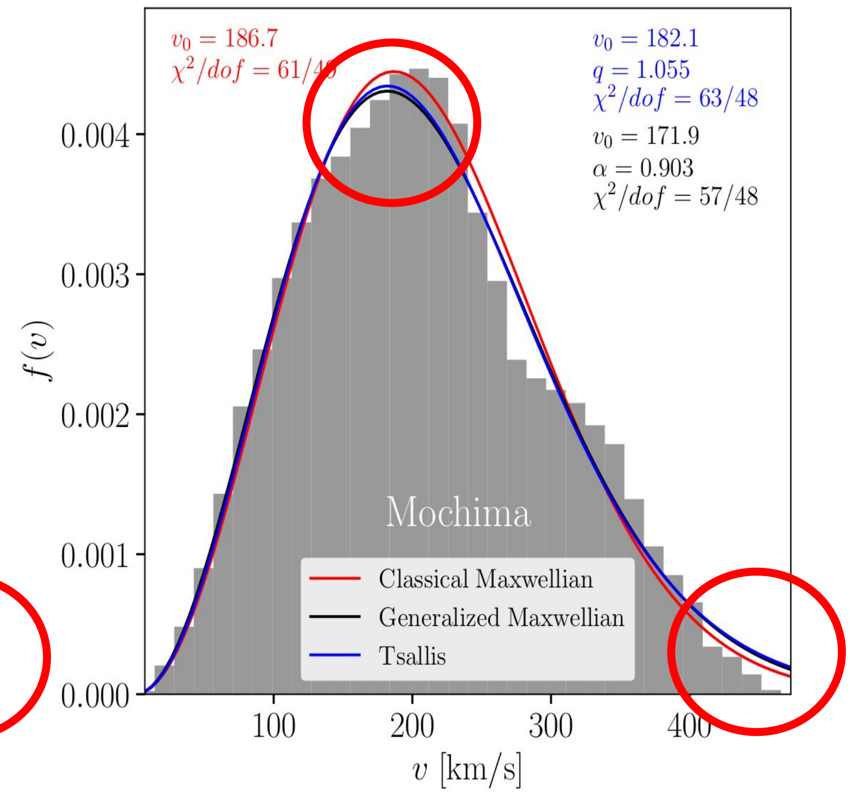
Generalized Maxwellian

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

Tsallis

Then we can fit





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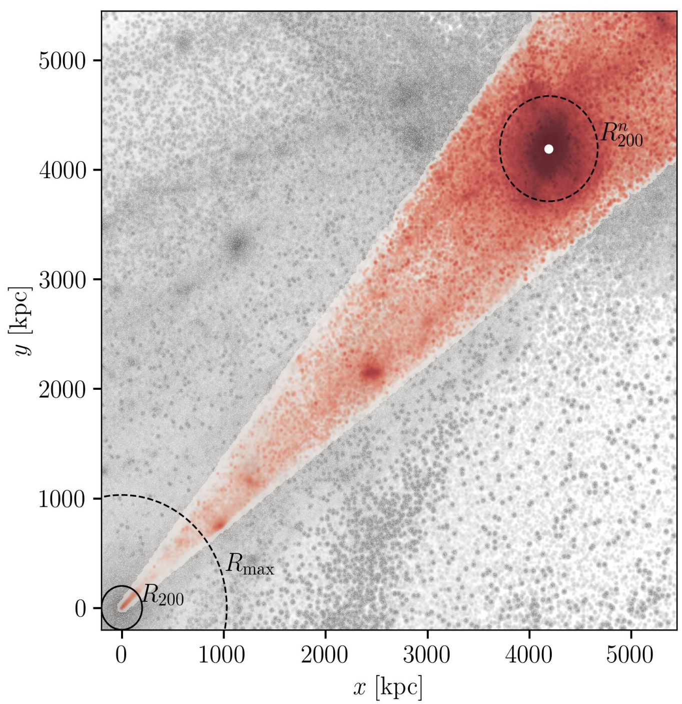
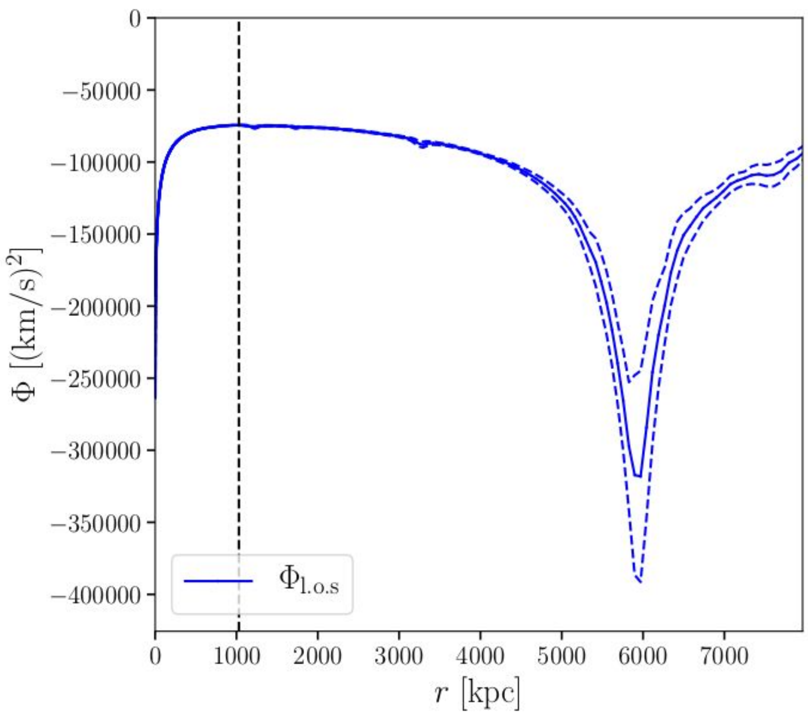
Tsallis

Introducing v_{esc}

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

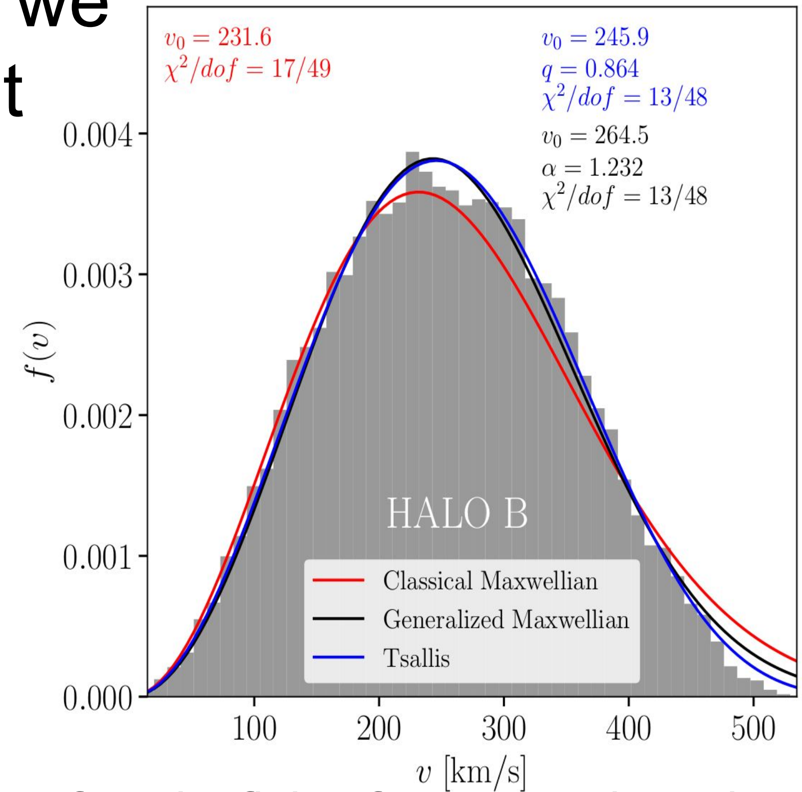
Radius at the point where the potential in the line between the halo and the biggest neighbour reach a maximum

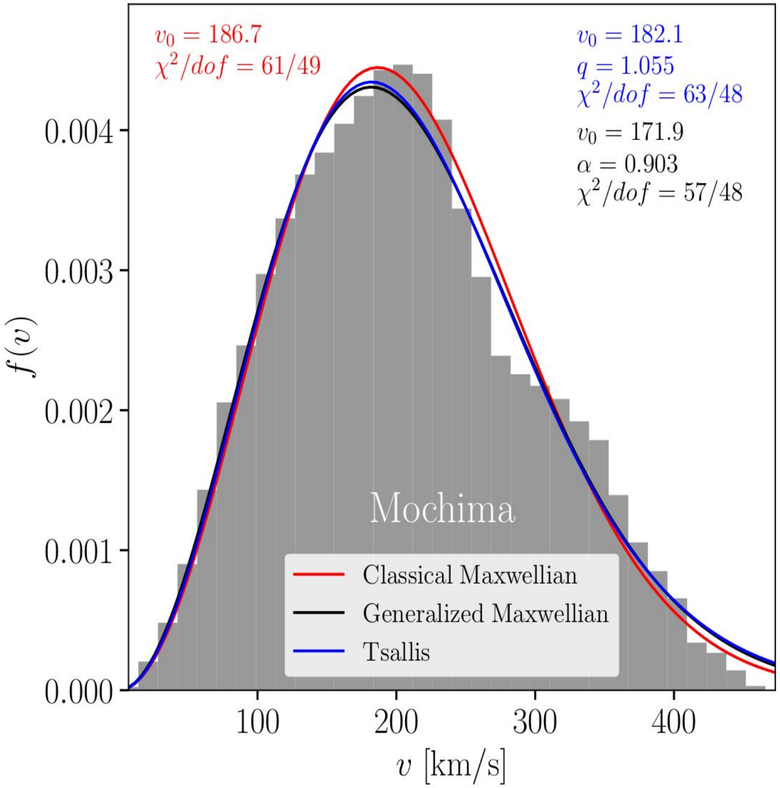




$$v_{\rm esc} \equiv \sqrt{2\Psi(r)} \qquad \Psi(r) = \Phi(R_{\rm max}) - \Phi(r)$$

Then we can fit





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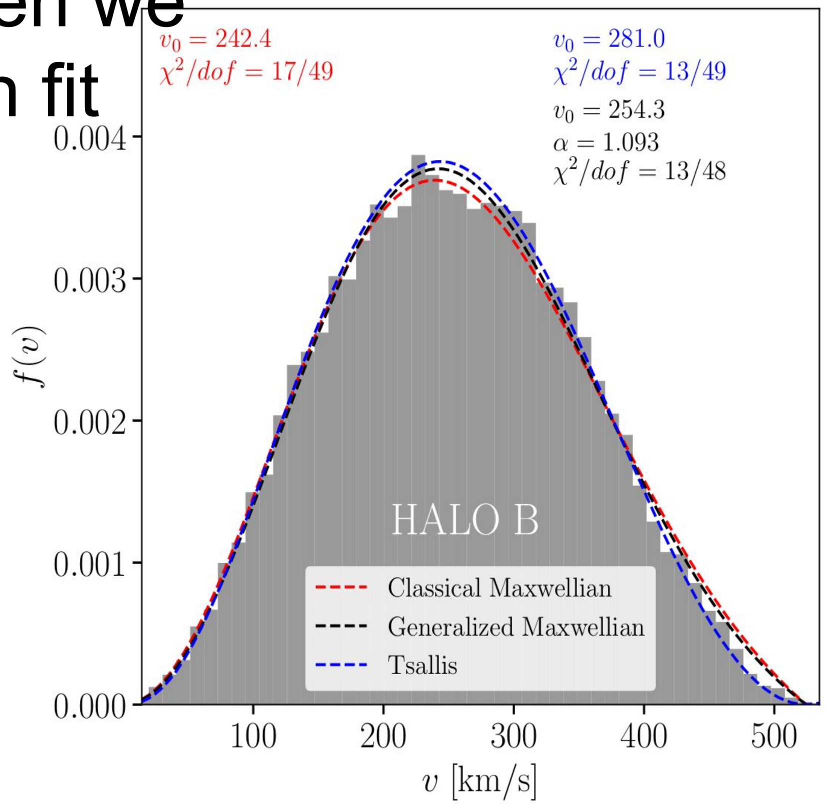

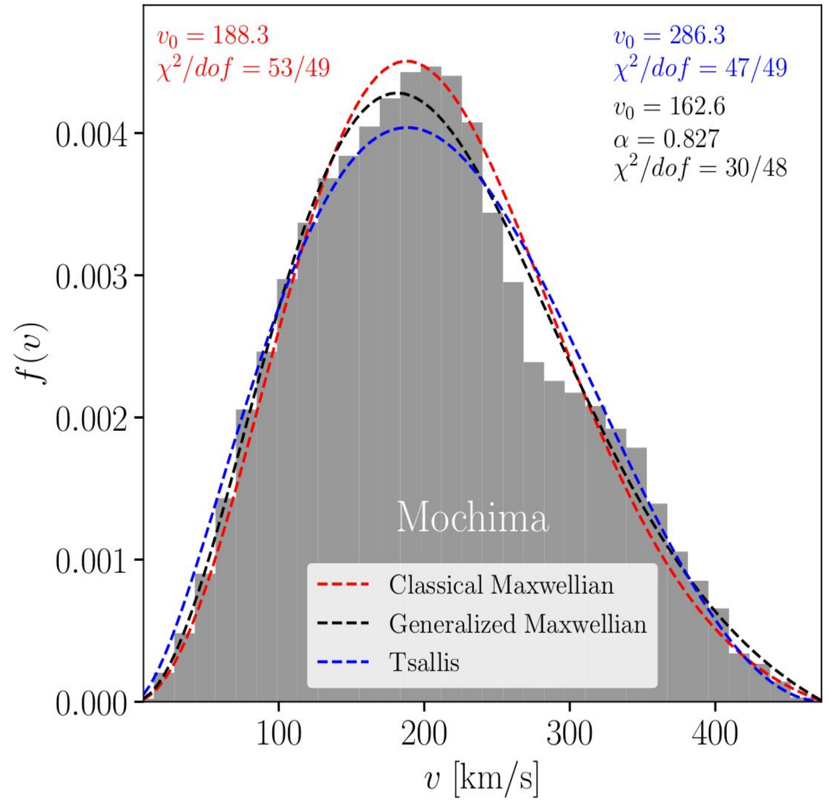

Take your favorite fitting formula and go ahead… now including v_{esc}

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

Classical Maxwellian

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Tsallis

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

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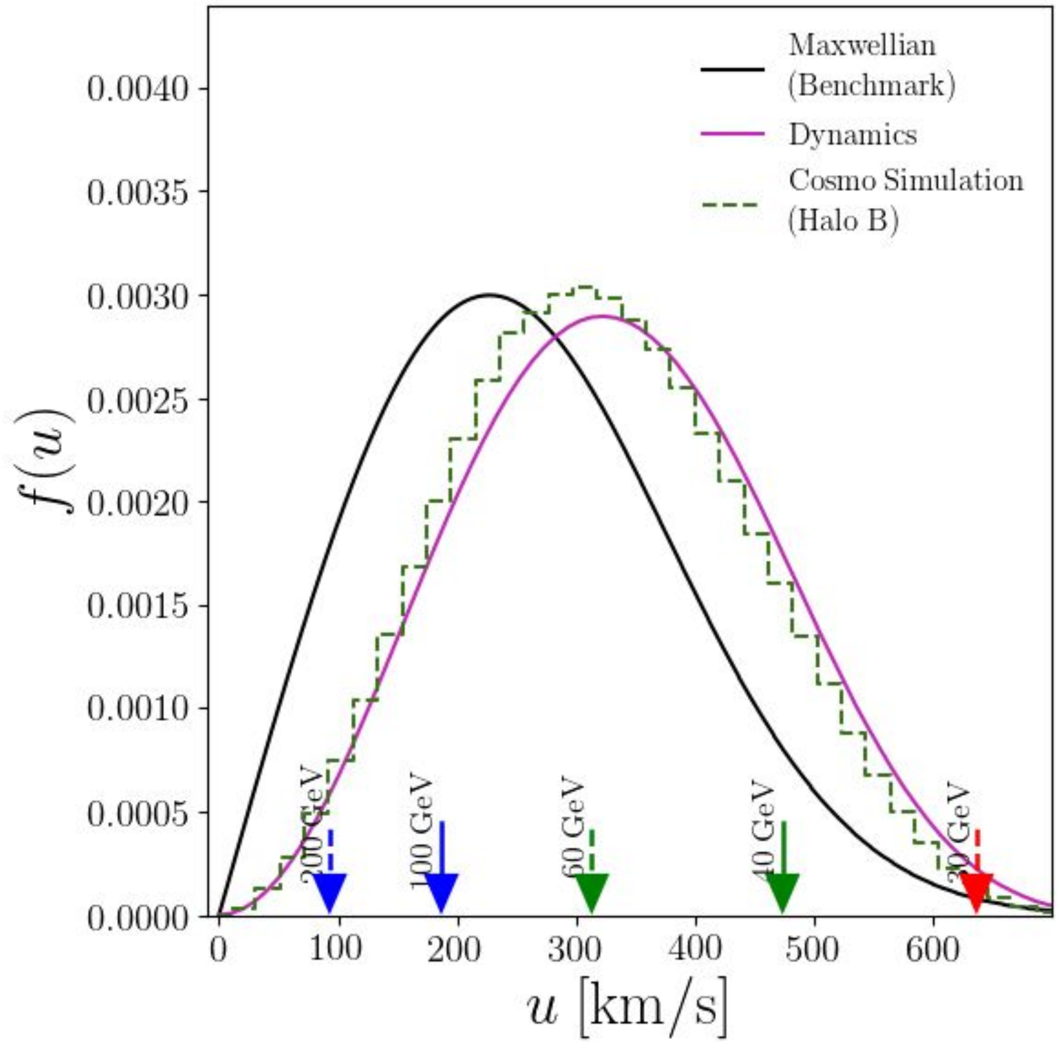
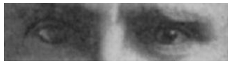
  - Degenerations in other values
- Direct extrapolation by fiting f(v) from Cosmological "Milky-Way like" simulations
  - No warranty that of the "Milky-way likeness" of the simulation
  - The meaning of 8kpc in the simulation
- Dynamical phase space prediction using MW macro features

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

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.

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

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

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

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

Assuming spherical symmetry and isotropy

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

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

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

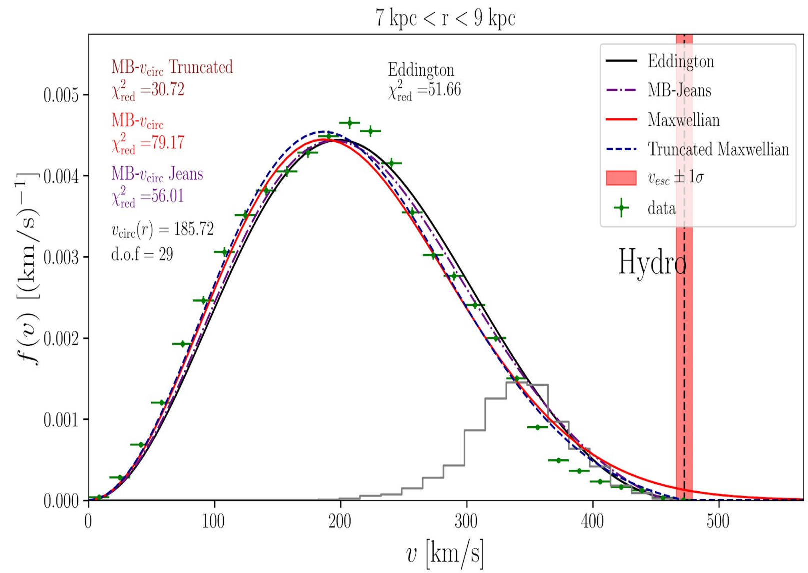
Eddington prediction vs Maxwellian approach

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

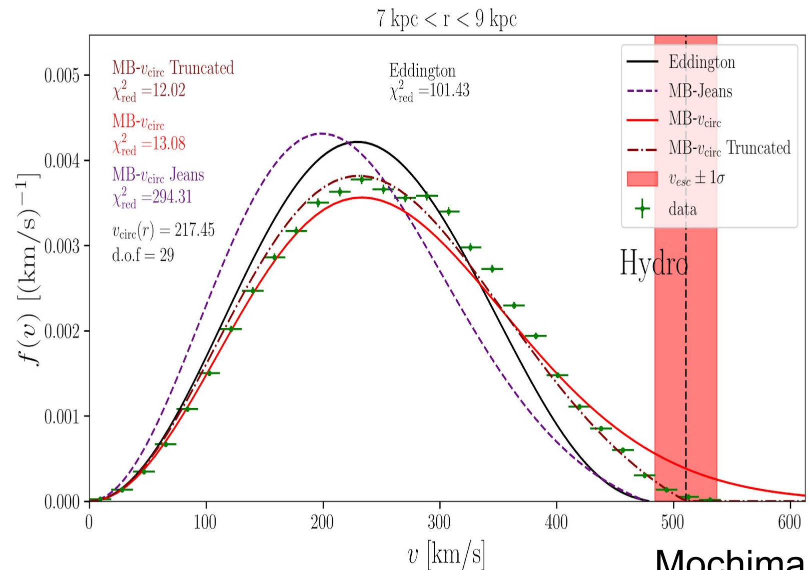
1) From the contained mass as

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

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

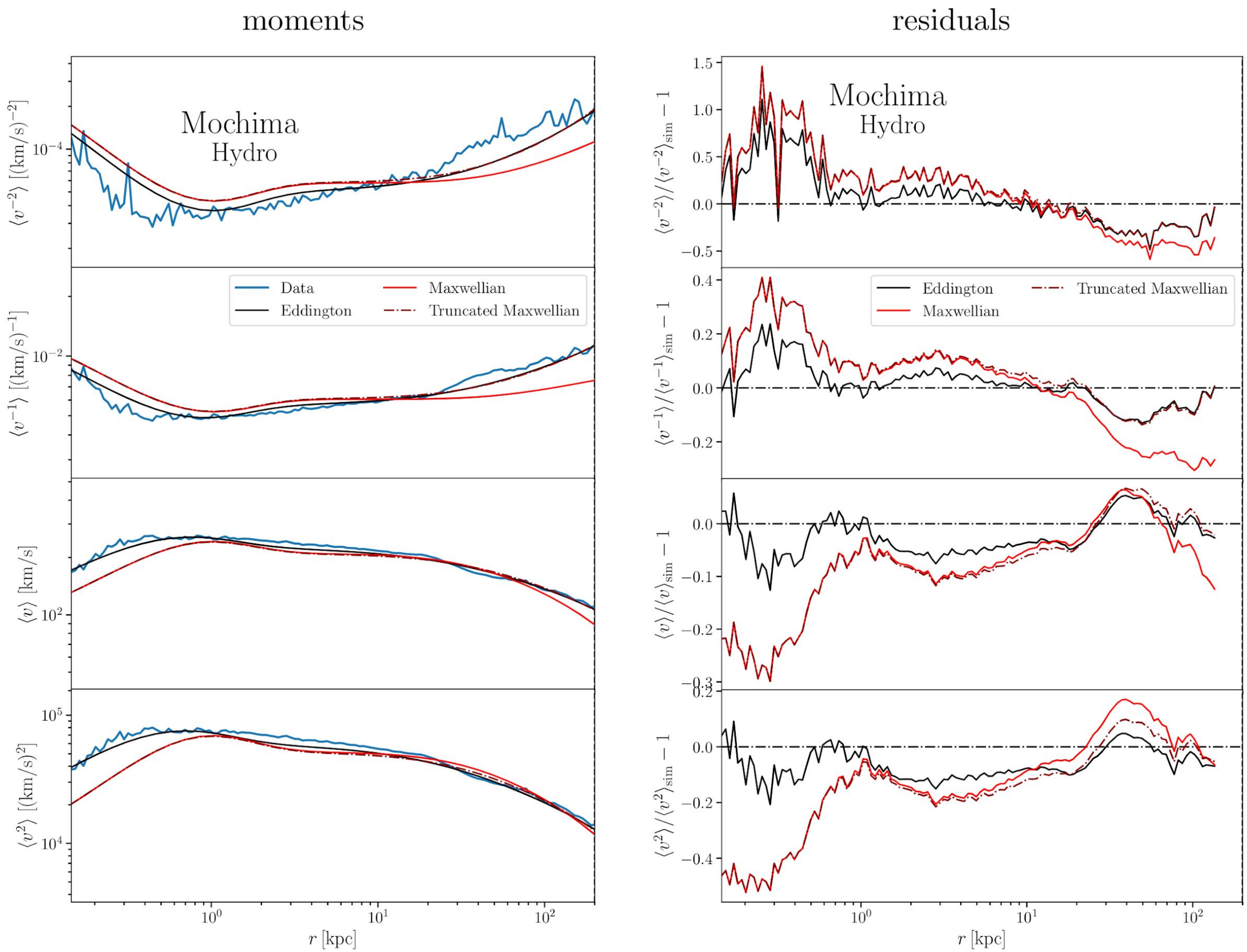


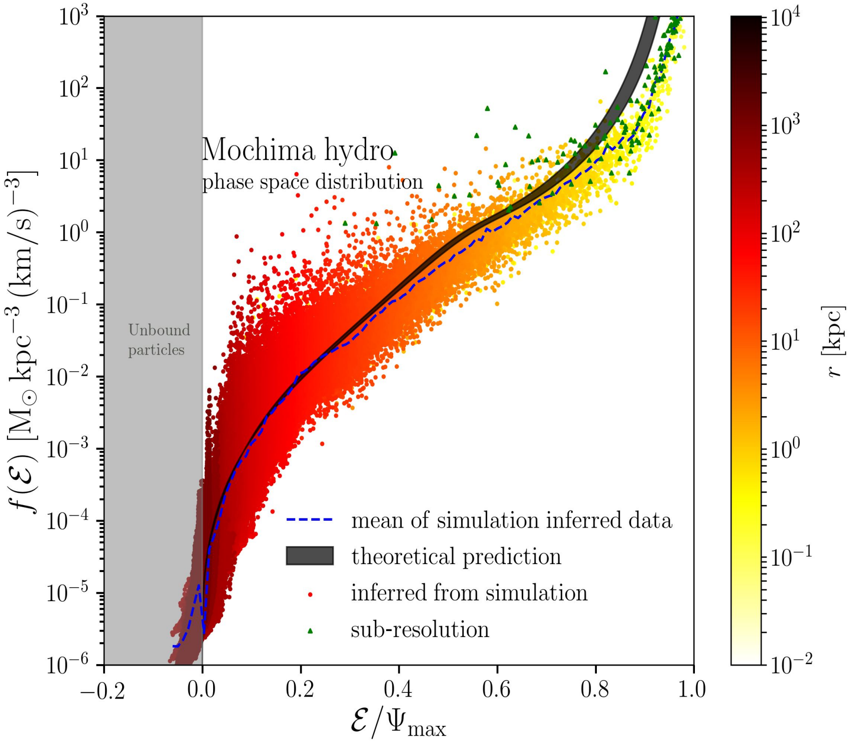
HALO B



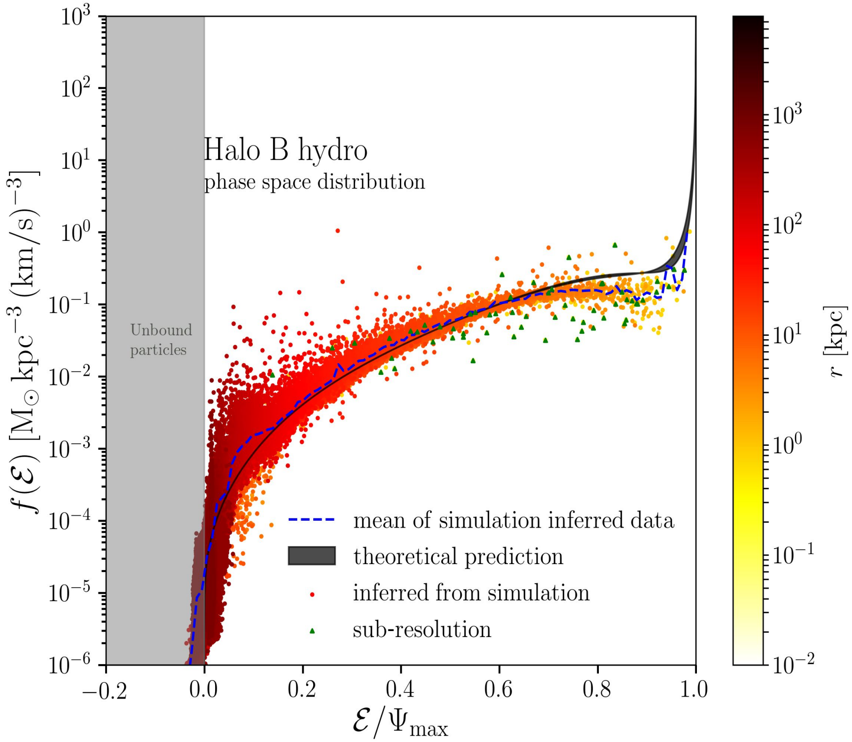
Mochima

Some more Eddington results





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



Halo B hydro
phase space distribution
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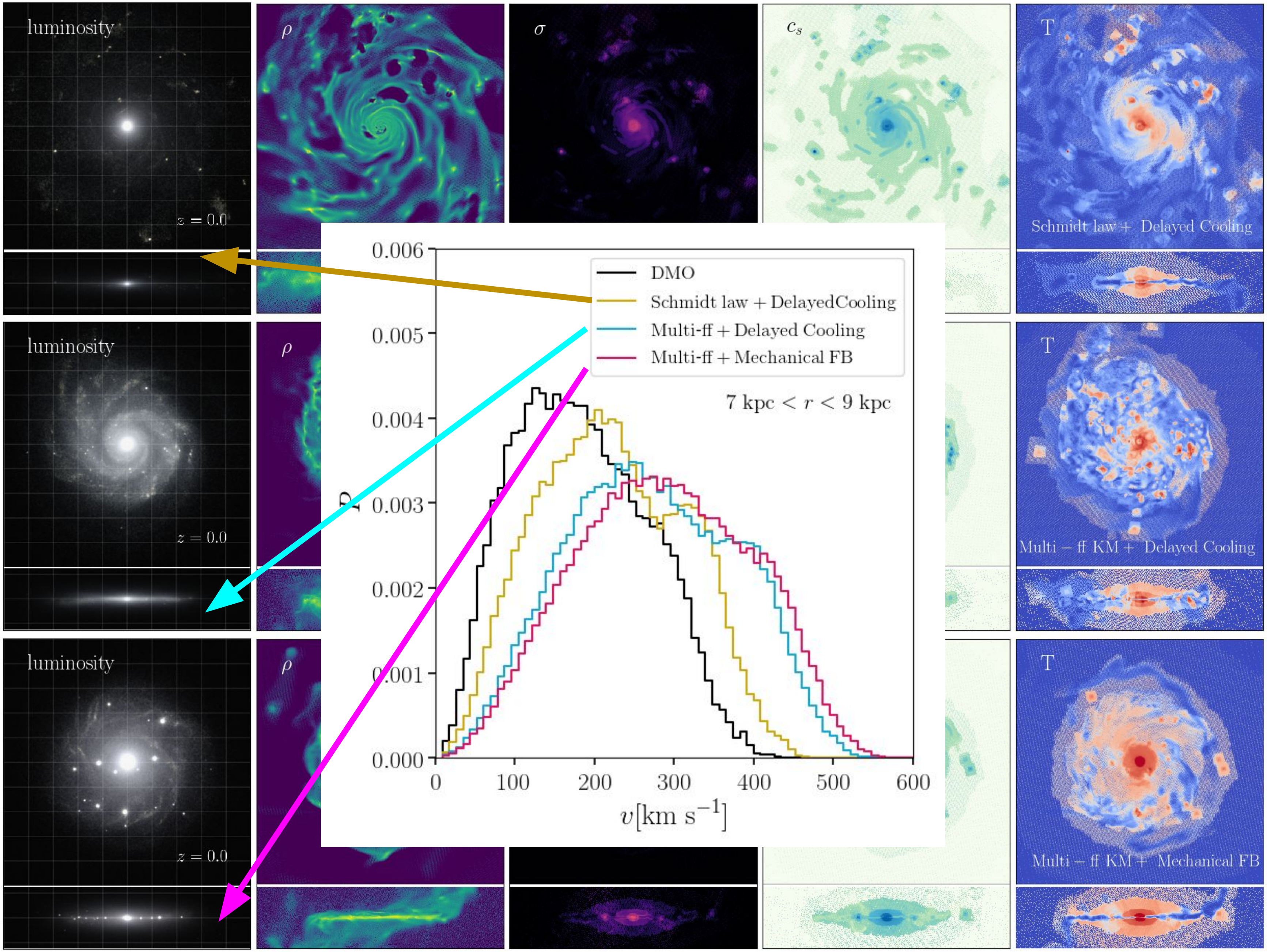
sub-resolution
$f(\mathcal{E})\ [\mathrm{M}_\odot\,\mathrm{kpc}^{-3}\,(\mathrm{km/s})^{-3}]$
$\mathcal{E}/\Psi_{\mathrm{max}}$
r [kpc]

What about baryonic physics in the simulation

(SF, Feedback)


luminosity
$z = 0.0$
ρ
σ
c_s
T
Schmidt law + Delayed Cooling
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Multi − ff KM + Mechanical FB
DMO
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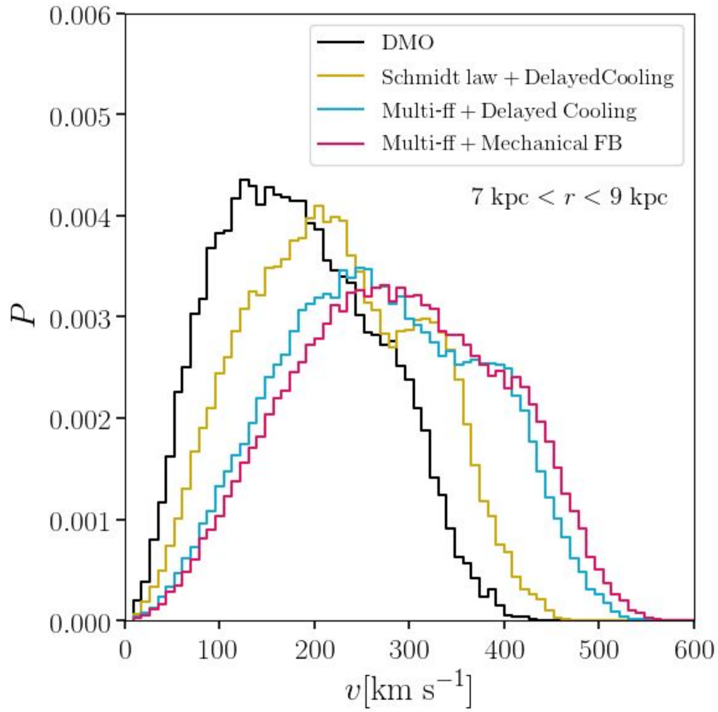
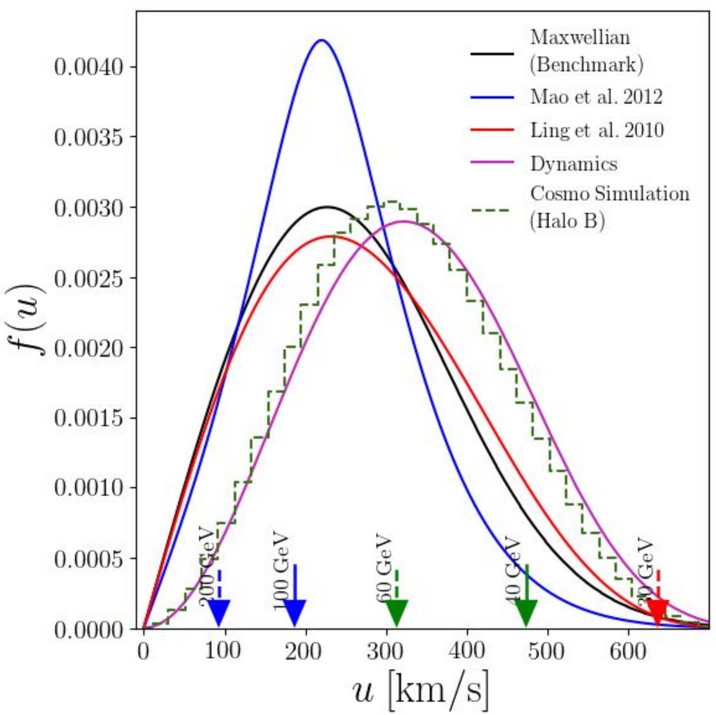
Multi-ff + Delayed Cooling
Multi-ff + Mechanical FB
7 kpc < r < 9 kpc
v[km s^{-1}]
0.000
0.001
0.002
0.003
0.004
0.005
0.006
0
100
200
300
400
500
600

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

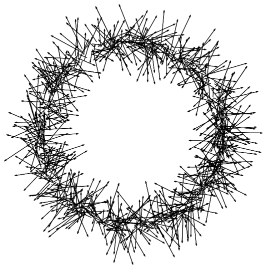


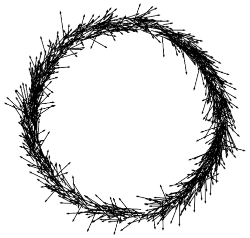
In simulations the implementation of baryonic physics will have an effect on the final distribution.
Nunez-Castineyra et al. in prep

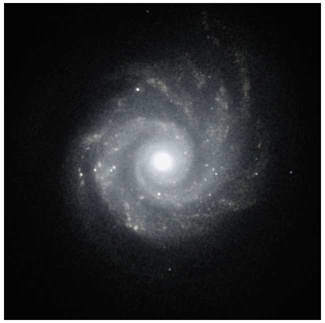


The discussed cases + some extra from the literature

DM capture by the Sun

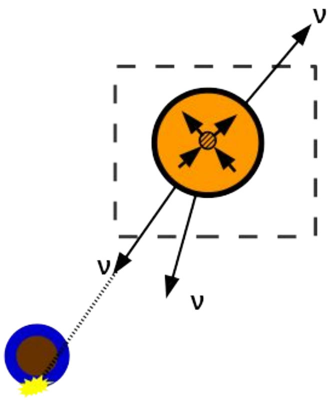






The number of captured WIMPs evolved as

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

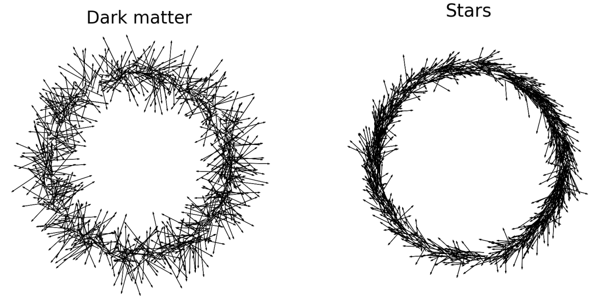


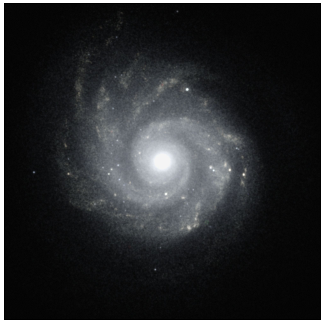
Once you solve it, it can be proved that

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

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

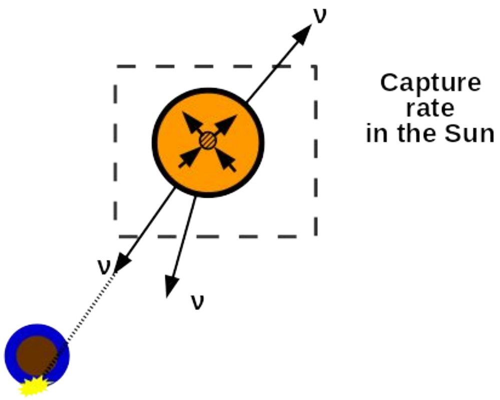
DM capture by the Sun



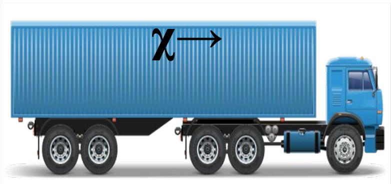


$$\frac{dC}{dV} = \frac{\rho}{M_\chi}\int_0^{u_m} du\,\frac{f(u)}{u}\,w\Omega(w)$$

Astrophysics and Particle Physics come together

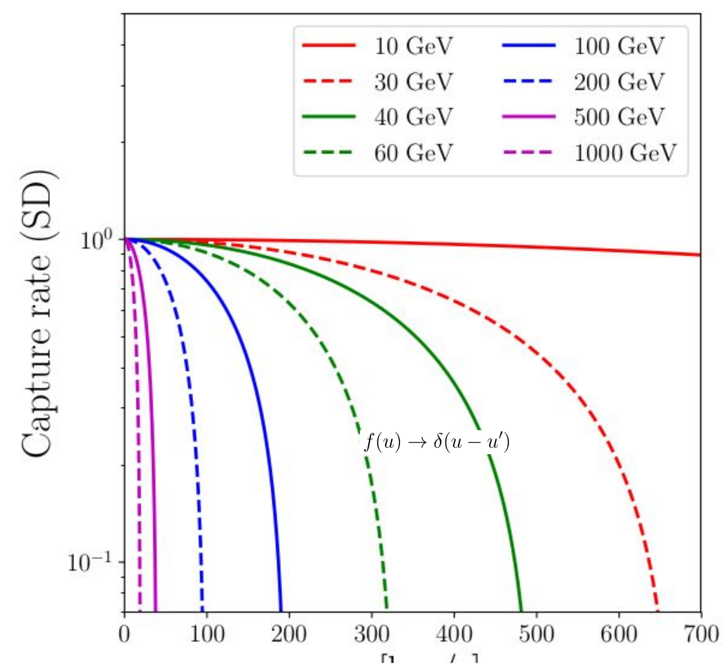


(A. Gould 1987)
(Garani & Palomares-Ruiz 2017)



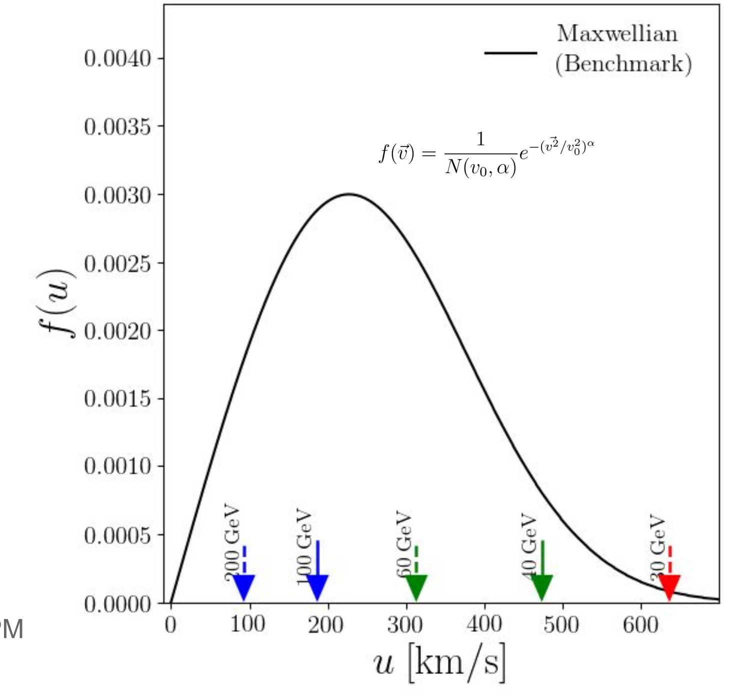
←(n/p)

DM capture by the Sun

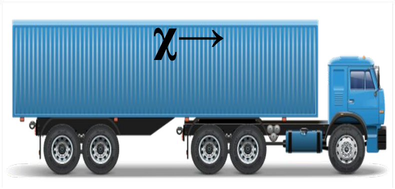


$$\frac{dC}{dV} = \frac{\rho}{M_\chi} \int_0^{u_m} du \frac{f(u)}{u} w\Omega(w)$$

Astrophysics and **Particle Physics** come together



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



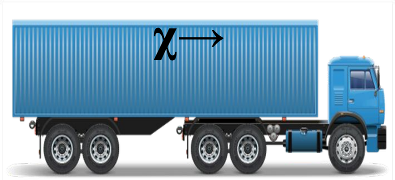
⟵(n/p)

DM capture by the Sun

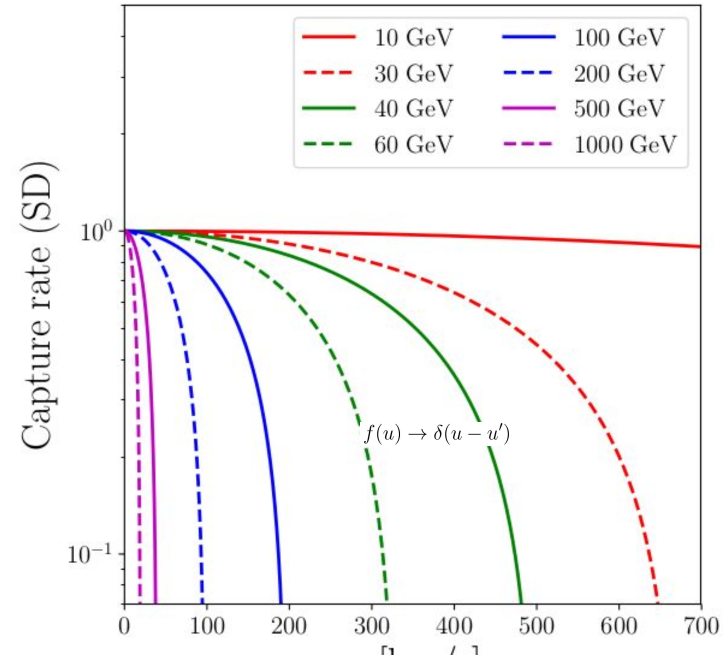
$$\frac{dC}{dV} = \frac{\rho}{M_\chi}\int_0^{u_m} du\,\frac{f(u)}{u}\,w\Omega(w)$$

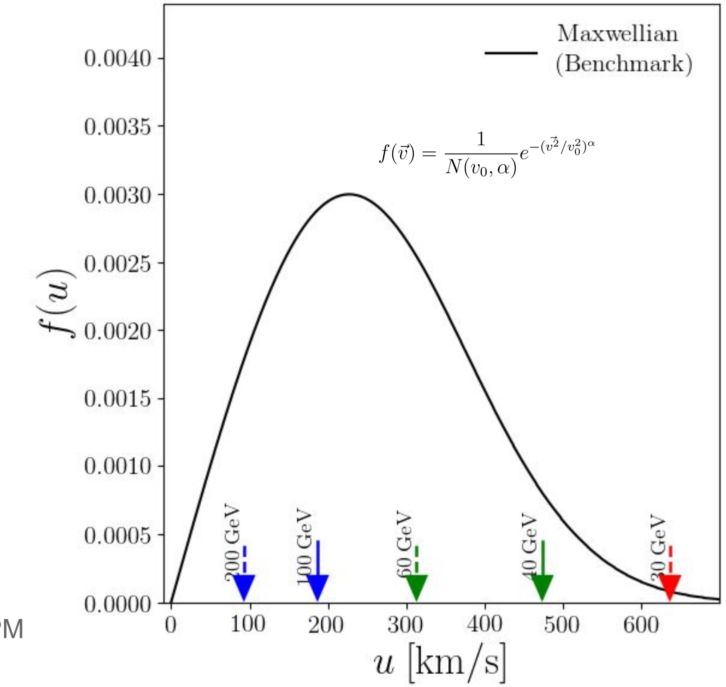
Astrophysics and **Particle Physics** come together

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



←(n/p)





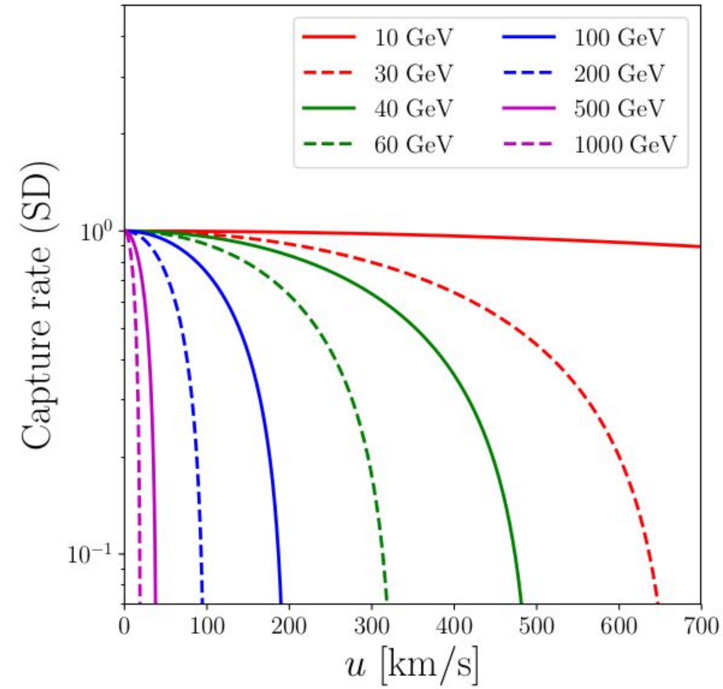
DM capture by the Sun

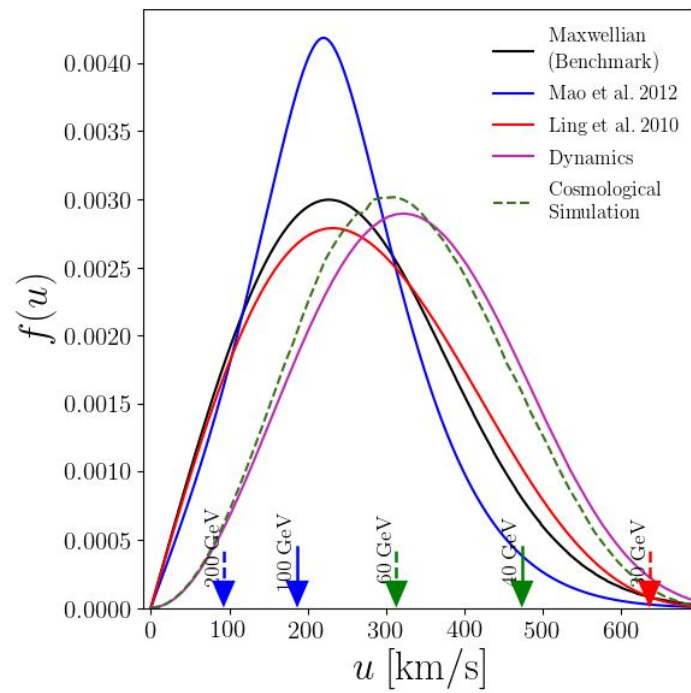
$$\frac{dC}{dV} = \frac{\rho}{M_\chi} \int_0^{u_m} du \frac{f(u)}{u} w\Omega(w)$$

Astrophysics and **Particle Physics** come together

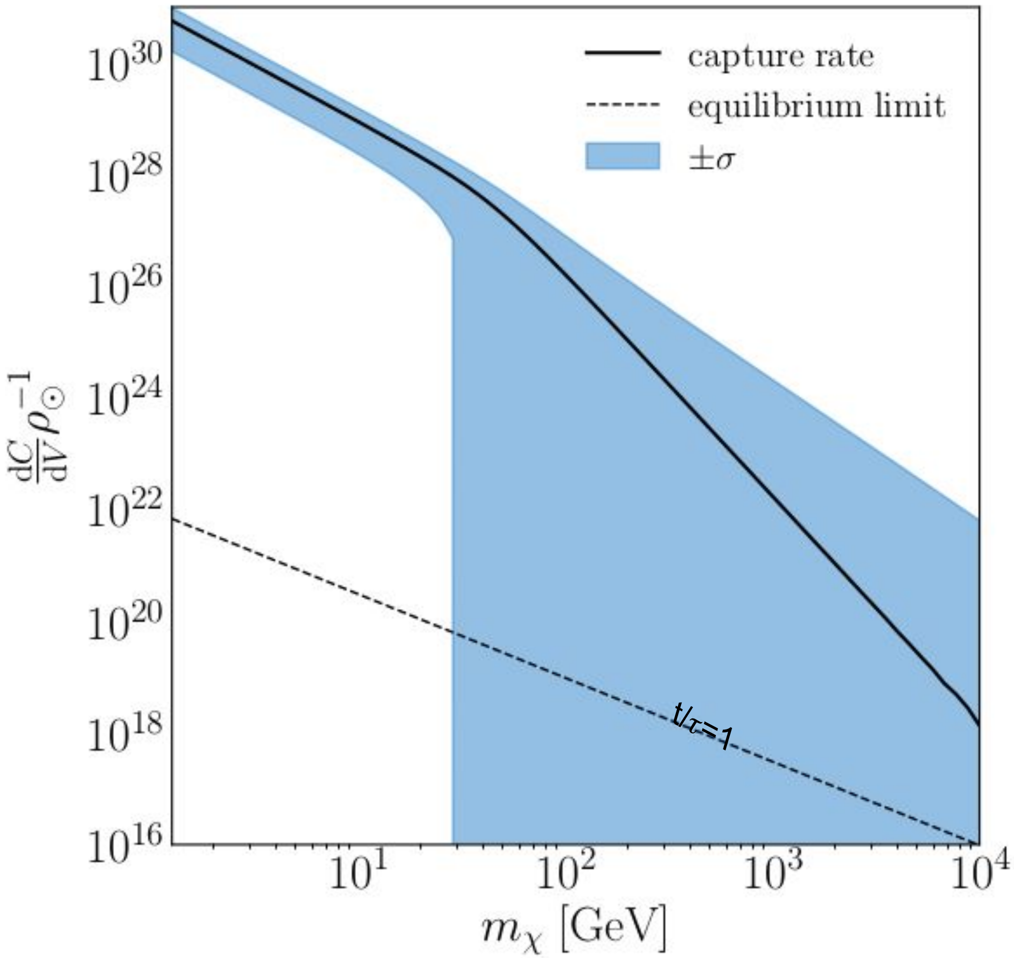
Astrophysical Uncertainties:

- 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])





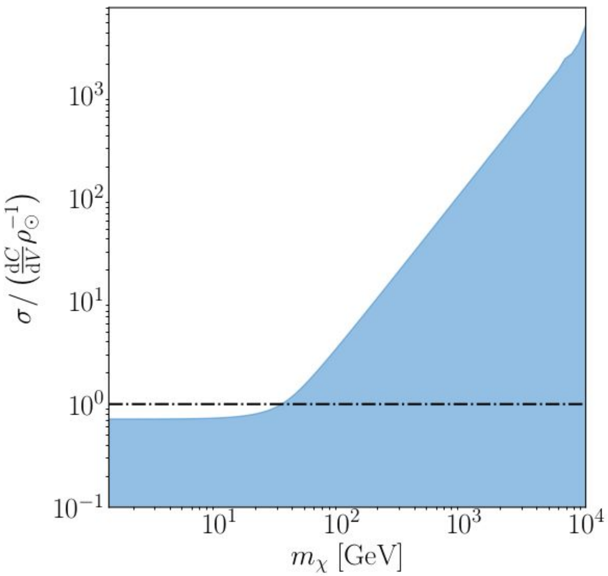
Intrinsic uncertainty



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

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

Astrophysics and **Particle Physics** come together



Results on Capture

− 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.

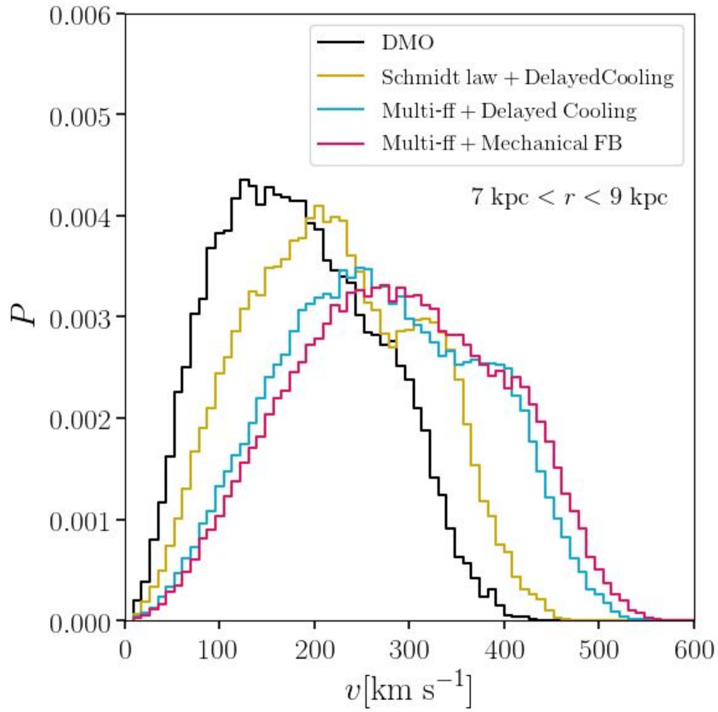
− The f(v)s obtained with the Eddington approach bring additional information on the possible distributions that can be assumed. (have better agreement with simulations data thand the standard Maxwellian VDF)

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

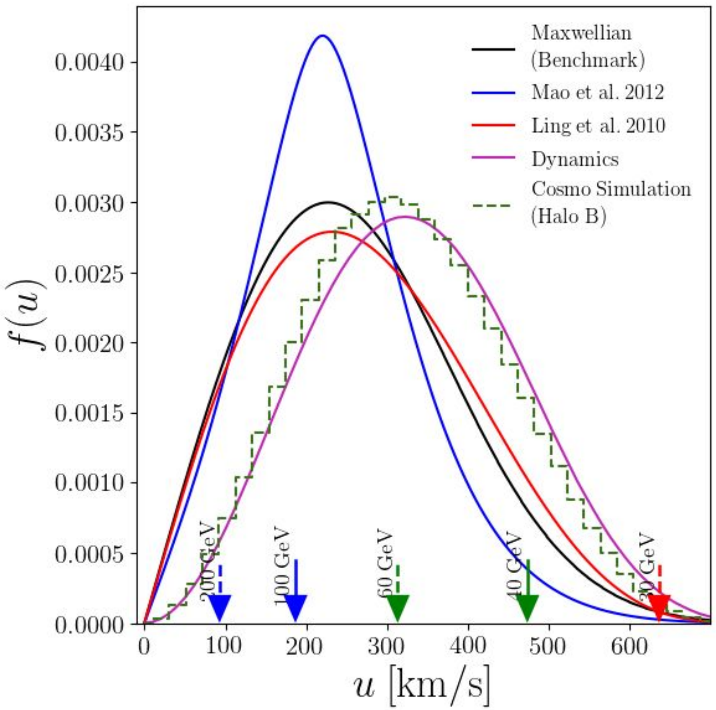
− The level of **variability** on the capture rate can reach up to 20% depending on the assumptions f(v)

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

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

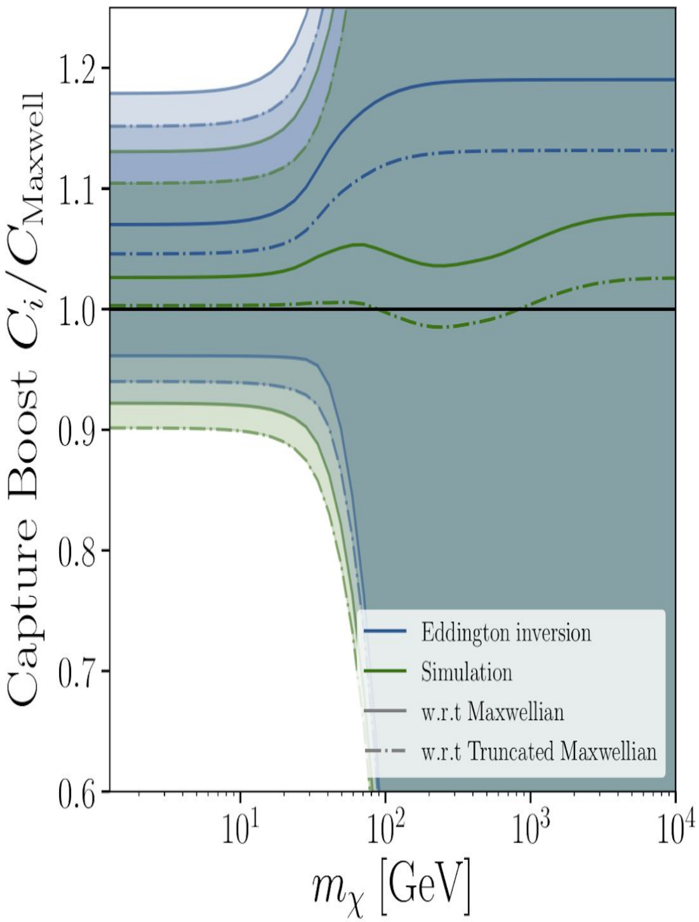
Three main ways to approach f(v)

- Take the standard halo model (SHM)
  - Maxwellian exhibit problems with the tail and hat of the f(v)
  - Assumes an isothermal halo density profile $\rho \propto r^{-2}$
  - Degenerations in other values
- Direct extrapolation by fiting f(v) from Cosmological "Milky-Way like" simulations
  - No warranty that of the "Milky-way likeness" of the simulation
  - The meaning of 8kpc in the simulation
- Dynamical phase space prediction using MW macro features
- e.g Eddington (Eddington 1916, lacroix 2018), Action angle (Posti 2015) etc.
  - Requires validation from simulations. Lacroix et al in prep

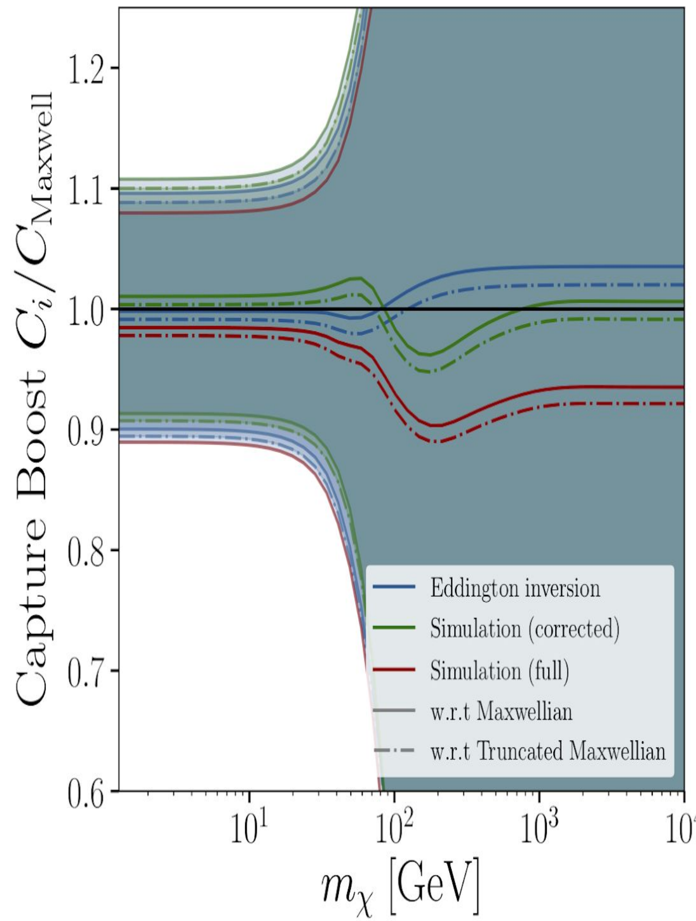
Perspectives: **GAIA era** will bring strong progresses + (directional) direct detection experiment and neutrino telescopes

Thank you

Capture boost

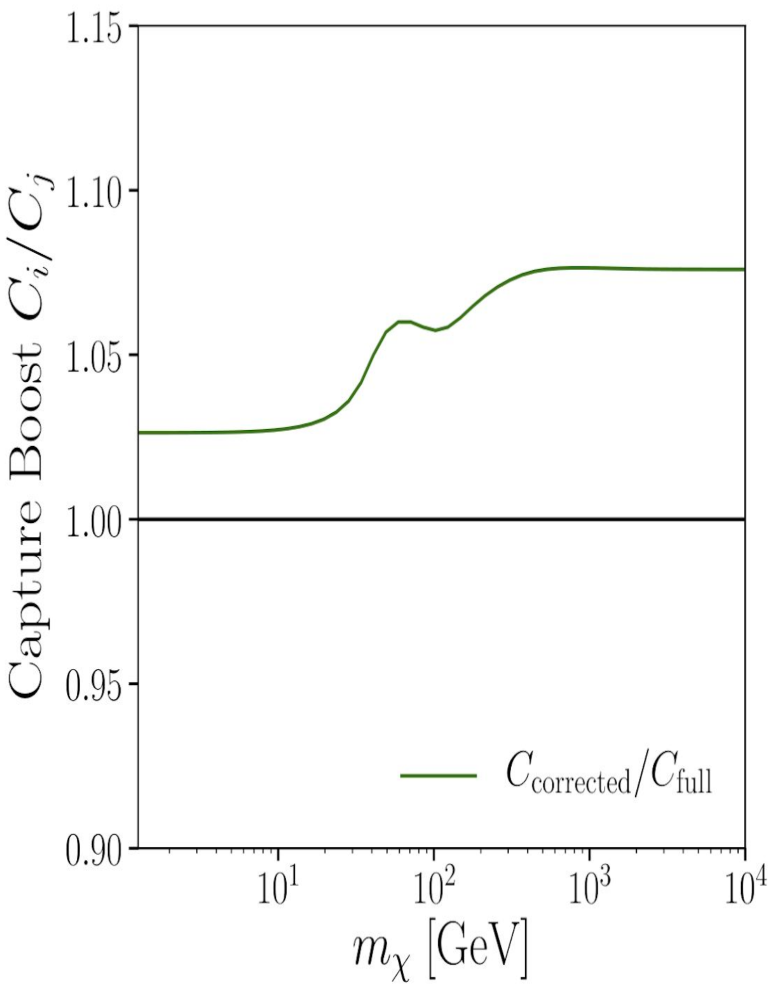


(a) Halo B shell

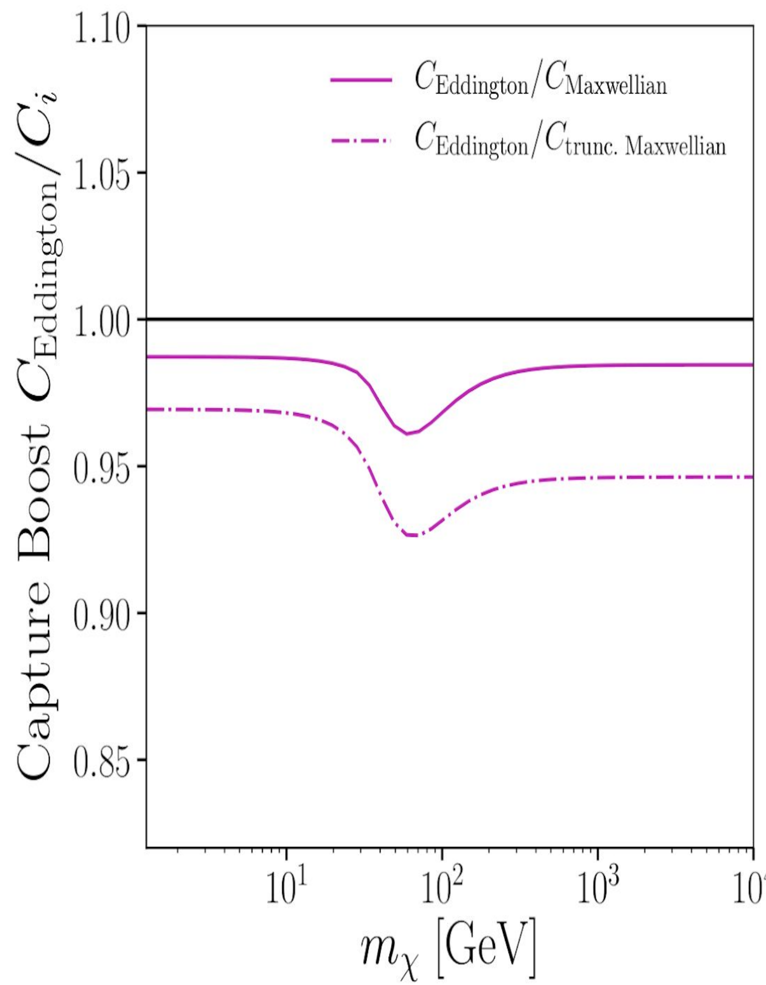


(b) Mochima shell

Capture boost



(c) Mochima



(d) Milky Way mass model