The (unknown) dark matter halo of the Milky Way

Some propositions for future work (for Marie 👍)

Emmanuel Nezri
Laboratoire d'Astrophysique de Marseille

2eme reunion IPhU: Direct Dark Matter Search

18 october 2021, CPPM Marseille

Outline

- *DM in galaxies*
  - *Success*
  - *Issues*

- *The case of the MW*

- *Direct detection rate: astrophysical assumptions*

  - *the Standard Halo Model and a parameters*

  - *Local density*

  - *Alternative velocity distributions*

Dark matter in a nutshell

- Cold Dark Matter works well in cosmology, CMB, structure formation
+ candidates (WIMPs ,axions, PBHs ...) can accommodate the cosmological abundance

Dark matter in a nutshell

- *Cold Dark Matter works well in cosmology, CMB, structure formation*
  - *+ WIMPs can accommodate the cosmological abundance*

- *Dark Matter in galaxies :*

Dark matter in a nutshell

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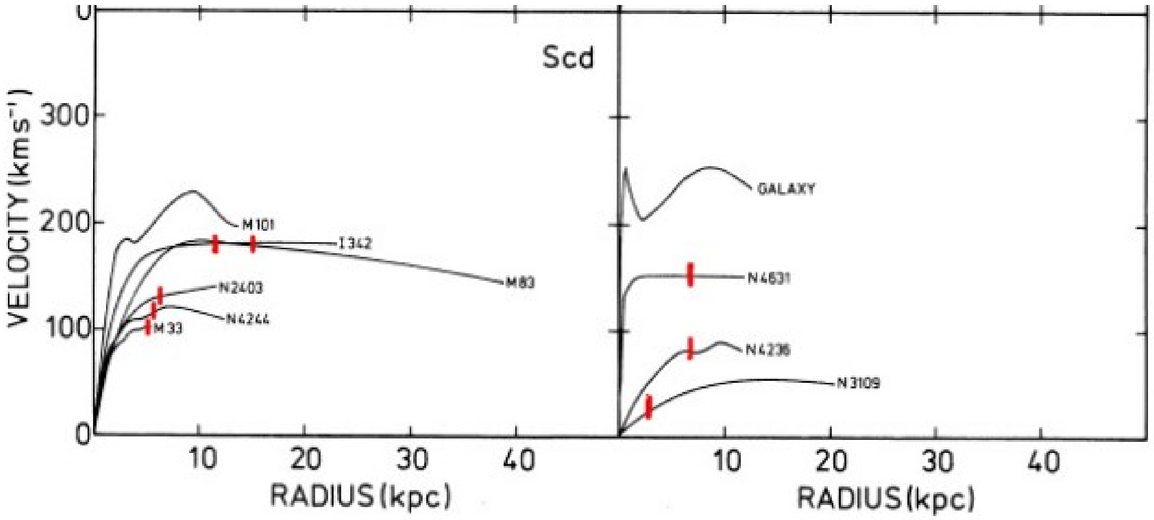
- Dark Matter in galaxies :

Success (vanilla picture) :

Rotation curves



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- Cold Dark Matter works well in cosmology, CMB, structure formation
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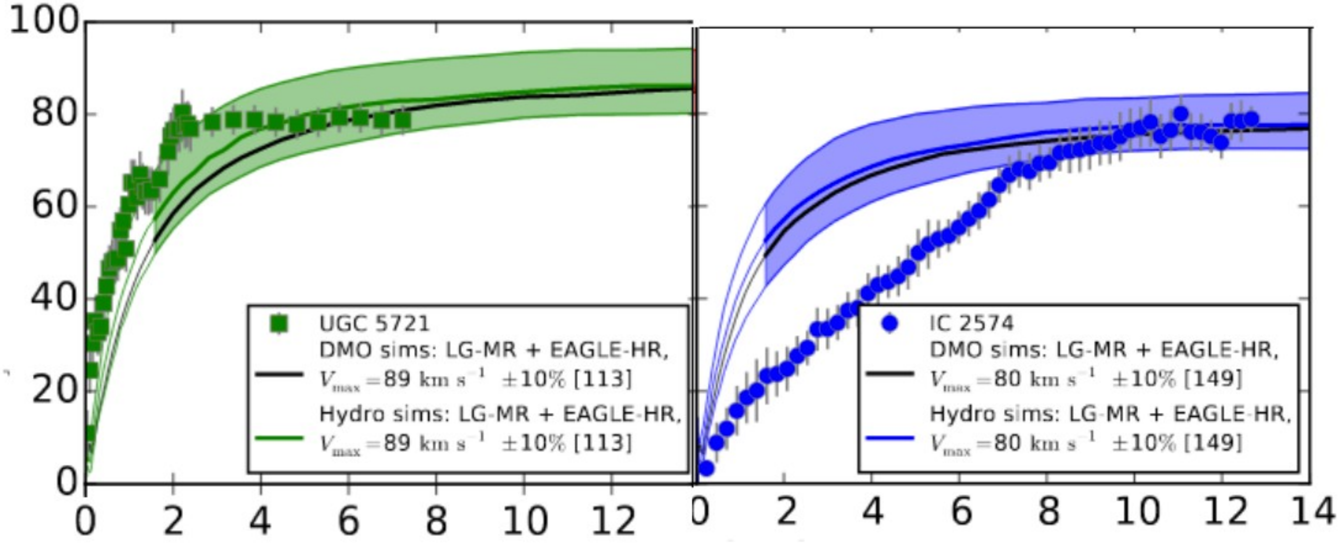
Issues:

Rotation curves – core/cusp – diversity (driven by surface density of the baryons), BF

Satellites – To-big-to-fail – phase space correlation (plane)

Bar, Bulge/stellar halo



Ohman et al 2015

Apostole/Eagle simulations

Dark matter in a nutshell

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- Dark Matter in galaxies :

Success, vanilla picture :

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Bar, Bulge/stellar halo

Among solutions :

Baryonic physics in cosmological simulations ? Star formation, Feedback (SN,AGN ..)

More complex dark matter at least at small/galactic scales ?

The Milky Way:

The Milky Way:

Dynamical modelling of the Galactic bulge and bar: the Milky Way's bar pattern speed, stellar, and dark matter mass distribution

Matthieu Portail[1]*, Ortwin Gerhard[1]†, Christopher Wegg[1] and Melissa Ness[2]

[1] *Max-Planck-Institut für Extraterrestrische Physik, Gießenbachstraße, D-85741 Garching, Germany*

[2] *Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany*

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ABSTRACT

We construct a large set of dynamical models of the galactic bulge, bar and inner disk using the Made-to-Measure method. Our models are constrained to match the red clump giant density from a combination of the VVV, UKIDSS and 2MASS infrared surveys together with stellar kinematics in the bulge from the BRAVA and OGLE surveys, and in the entire bar region from the ARGOS survey. We are able to recover the bar pattern speed and the stellar and dark matter mass distributions in the bar region, thus recovering the entire galactic effective potential. We find a bar pattern speed of $39.0 \pm 3.5\,\mathrm{km\,s^{-1}\,kpc^{-1}}$, placing the bar corotation radius at 6.1 ± 0.5kpc and making the Milky Way bar a typical fast rotator. We evaluate the stellar mass of the long bar and bulge structure to be $M_{\mathrm{bar/bulge}} = 1.88 \pm 0.12 \times 10^{10}\,\mathrm{M}_{\odot}$, larger than the mass of disk in the bar region, $M_{\mathrm{inner\ disk}} = 1.29 \pm 0.12 \times 10^{10}\,\mathrm{M}_{\odot}$. The total dynamical mass in the bulge volume is $1.85 \pm 0.05 \times 10^{10}\,\mathrm{M}_{\odot}$. Thanks to more extended kinematic data sets and recent measurement of the bulge IMF our models have a low dark matter fraction in the bulge of $17\% \pm 2\%$. We find a dark matter density profile which flattens to a shallow cusp or core in the bulge region. Finally, we find dynamical evidence for an extra central mass of $\sim 0.2 \times 10^{10}\,\mathrm{M}_{\odot}$, probably in a nuclear disk or disky pseudobulge.

Key words: methods: numerical – Galaxy: bulge – Galaxy: kinematics and dynamics – Galaxy: structure – Galaxy: centre

1 INTRODUCTION

Although it is well established that the Milky Way hosts a central barred bulge which causes non-axisymmetric gas flow (Peters, III 1975; Binney et al. 1991) and asymmetries in the near-infrared light (Blitz & Spergel 1991; Weiland et al. 1994) and star counts (Nakada et al. 1991; Stanek et al. 1997); our understanding of this structure has dramatically improved in the last decade. The discovery of the so-called split red clump in the galactic bulge (Nataf et al. 2010; McWilliam & Zoccali 2010) and the later 3D mapping of the

hypothesis of a double bar system in the inner Milky Way (Benjamin et al. 2005; López-Corredoira et al. 2005; Cabrera-Lavers et al. 2008; but see also Martinez-Valpuesta & Gerhard 2011). Recently, Wegg et al. (2015, hereafter W15) demonstrated by combining the VVV, UKIDSS, GLIMPSE and 2MASS catalogues that the galactic bulge smoothly segues into the long bar. Both components appear at a similar angle, showing that the galactic bulge and the long bar in the Milky Way are consistent with being a single structure that became vertically thick in its inner part, similarly to the

The Milky Way:

Dynamical modelling of the Galactic bulge and bar: the Milky Way's bar pattern speed, stellar, and dark matter mass distribution

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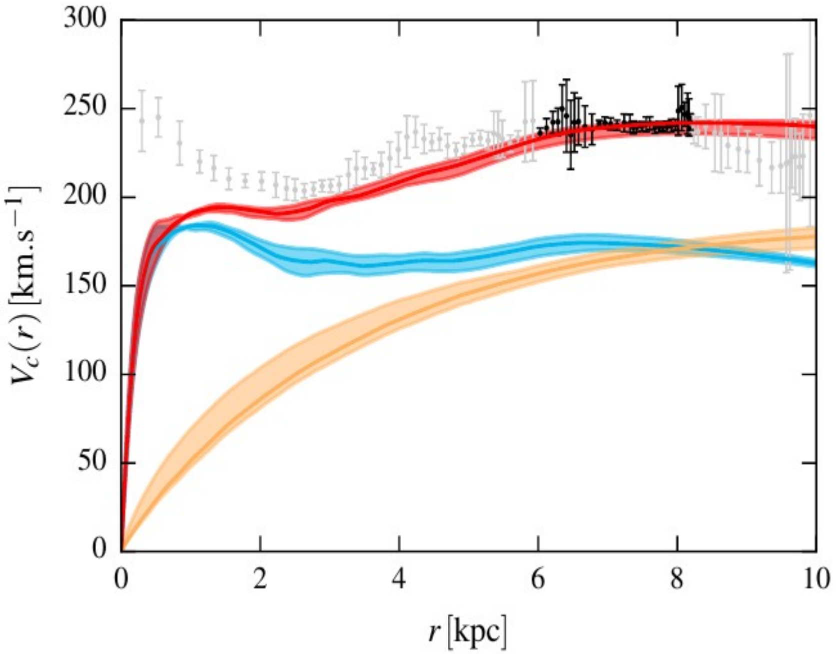
Sharp falloff to keep the RC constant between 6 kpc and 8 kpc => cored profile at the center
:



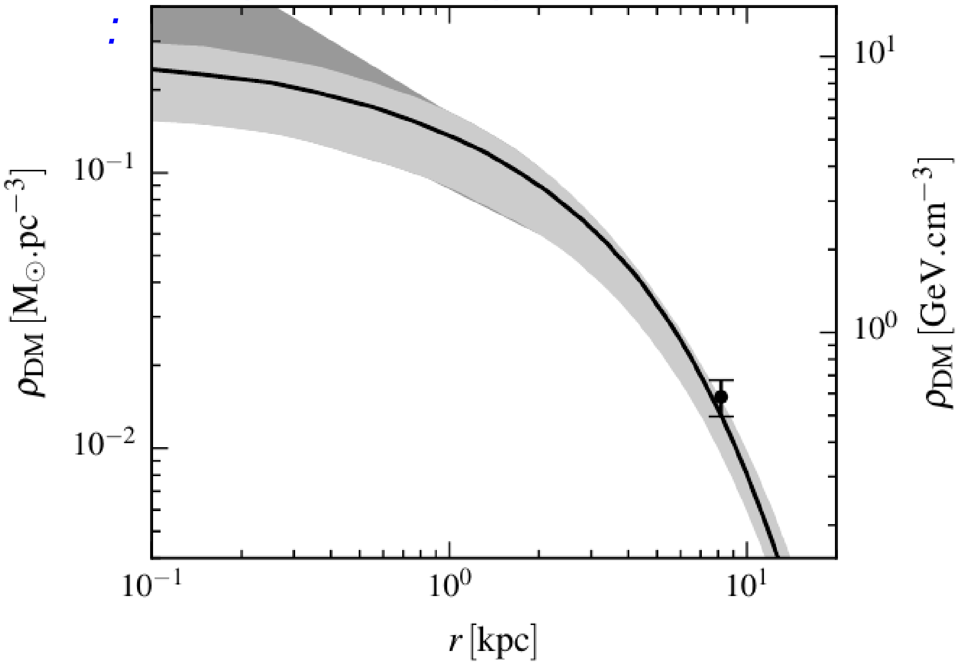


Figure 23. Rotation curve o
for evaluation of systematic
surements from Sofue et al.
respectively the baryonic, c
that the totality of the additi

The presence of a core in our best model halo density thus appears as a consequence of the constraint on the flat shape of the total circular velocity in the 6 – 8 kpc range, which for our baryonic mass distribution requires the dark matter density to fall off more steeply than $\rho_{\mathrm{DM}}(r) \propto r^{-1}$. In order to then not overpredict the dark matter mass in the bulge, the dark halo density is forced to become shallower further in.

ur best model (black line), range
rey span) and range of possible
ld keep constant the dark matter
n). Under the assumption of an
core to account simultaneously
nd the rotation curve at the solar
measurement of the dark matter
from Piffl et al. (2014), in good

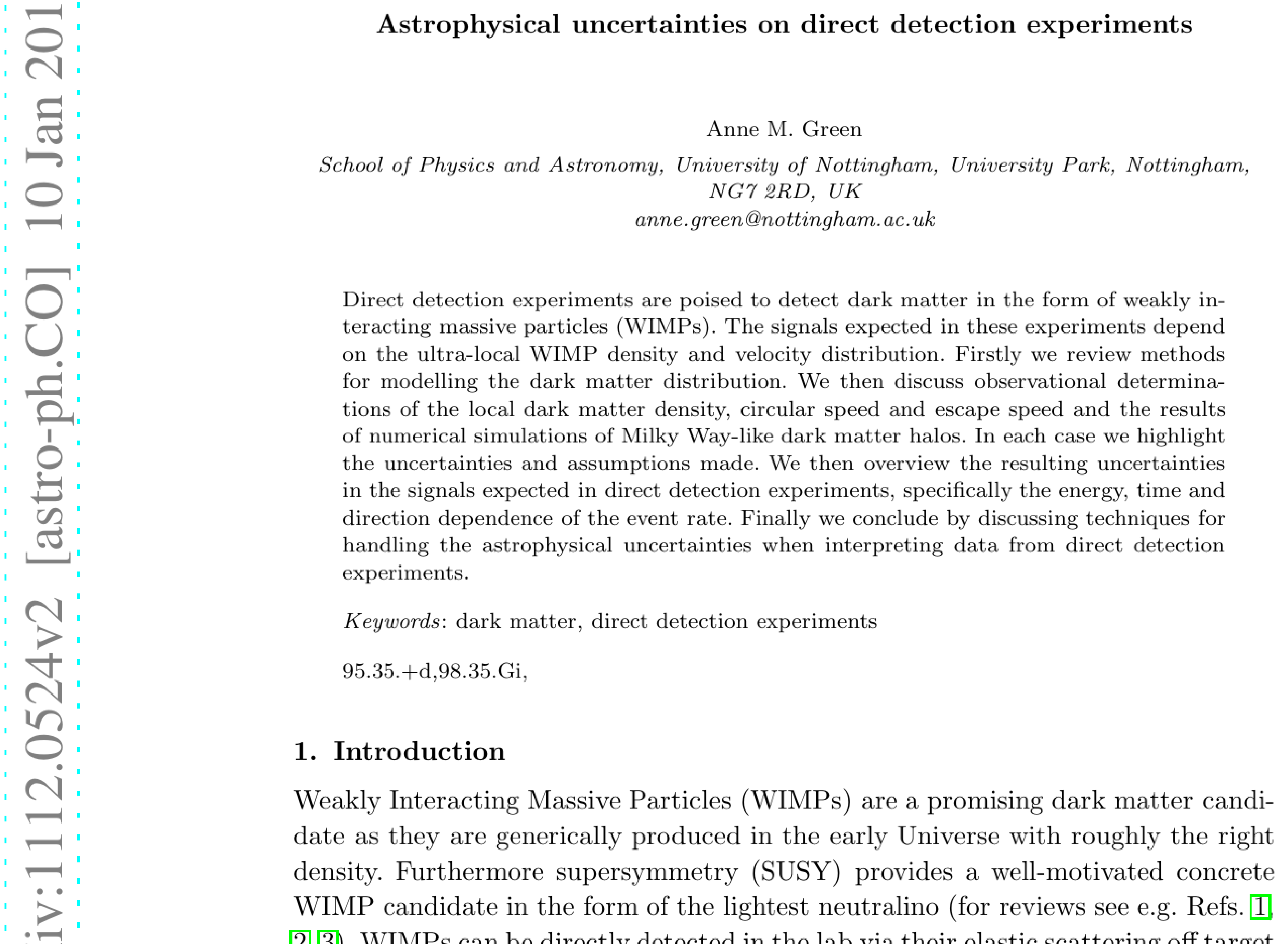
WIMP dark matter direct detection

$$\frac{d\mathcal{R}}{dE_R} = \frac{\rho_{\odot}}{M_{DM}} \frac{d\sigma}{dE_R} \int_{v_{min}}^{v_{esc}} d^3\vec{v}\ \frac{\mathrm{f}(\vec{v}(t))}{v}$$

Direct detection

$$\frac{d\mathcal{R}}{dE_R} = \frac{\rho_\odot}{M_{DM}} \frac{d\sigma}{dE_R} \int_{v_{min}}^{v_{esc}} d^3\vec{v}\, \frac{\mathrm{f}(\vec{v}(t))}{v}$$

A review : Anne Green, arXiv:1112.0524



Astrophysical uncertainties on direct detection experiments

Anne M. Green

School of Physics and Astronomy, University of Nottingham, University Park, Nottingham, NG7 2RD, UK

anne.green@nottingham.ac.uk

Direct detection experiments are poised to detect dark matter in the form of weakly interacting massive particles (WIMPs). The signals expected in these experiments depend on the ultra-local WIMP density and velocity distribution. Firstly we review methods for modelling the dark matter distribution. We then discuss observational determinations of the local dark matter density, circular speed and escape speed and the results of numerical simulations of Milky Way-like dark matter halos. In each case we highlight the uncertainties and assumptions made. We then overview the resulting uncertainties in the signals expected in direct detection experiments, specifically the energy, time and direction dependence of the event rate. Finally we conclude by discussing techniques for handling the astrophysical uncertainties when interpreting data from direct detection experiments.

Keywords: dark matter, direct detection experiments

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1. Introduction

Weakly Interacting Massive Particles (WIMPs) are a promising dark matter candidate as they are generically produced in the early Universe with roughly the right density. Furthermore supersymmetry (SUSY) provides a well-motivated concrete WIMP candidate in the form of the lightest neutralino (for reviews see e.g. Refs. [1, 2, 3]). WIMPs can be directly detected in the lab via their elastic scattering off target

Direct detection

$$\frac{d\mathcal{R}}{dE_R} = \frac{\rho_\odot}{M_{DM}} \frac{d\sigma}{dE_R} \int_{v_{min}}^{v_{esc}} d^3\vec{v}\, \frac{\mathrm{f}(\vec{v}(t))}{v}$$

The Standard Halo Model (SHM)

Maxwellian velocity distribution

(self-grav isothermal sphere)

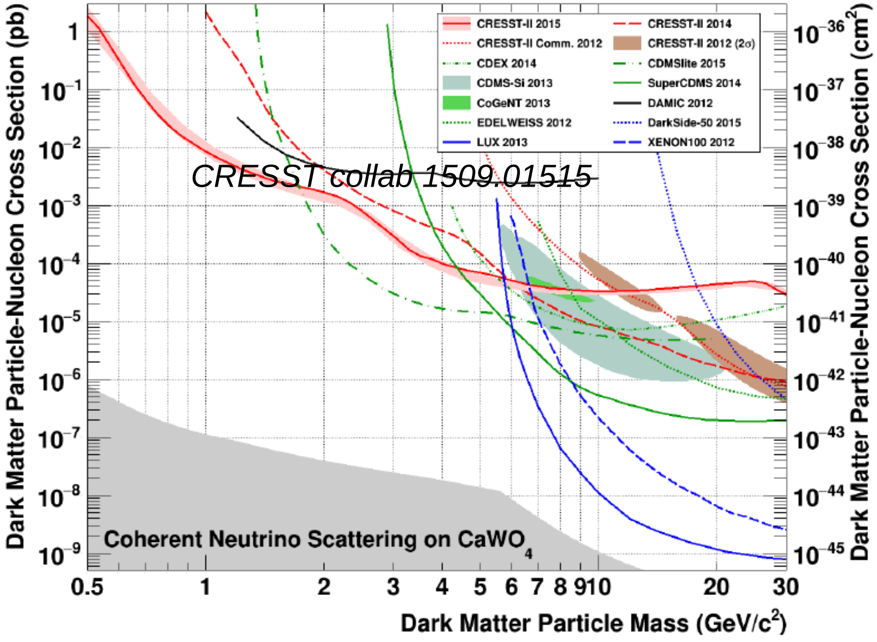
$$f_{\vec{v}}\left(\vec{v}\right) = \frac{1}{v_0^3 \pi^{3/2}} \exp\left(-\frac{|\vec{v}|^2}{v_0^2}\right)$$

$$v_c = 220\ \mathrm{km/s}, \quad v_0 = v_c$$

$$\rho_\odot = 0.3\ \mathrm{GeV/cm^3}$$

Escape velocity (Piffl+ 2014 from RAVE and simus)

$$v_{esc} = 544\ \mathrm{km/s}$$



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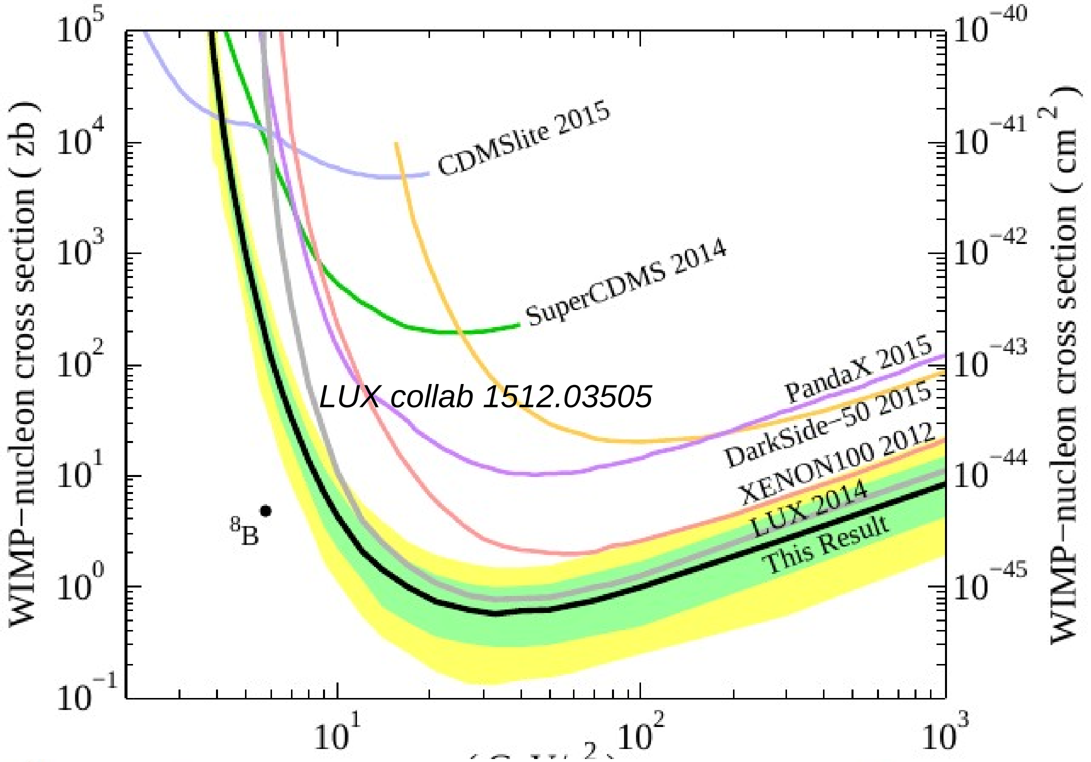

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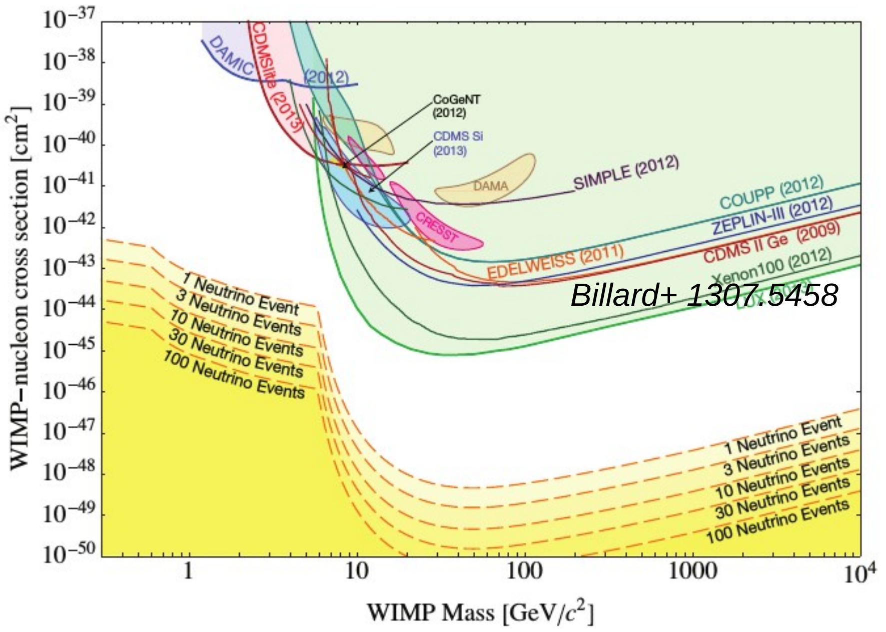
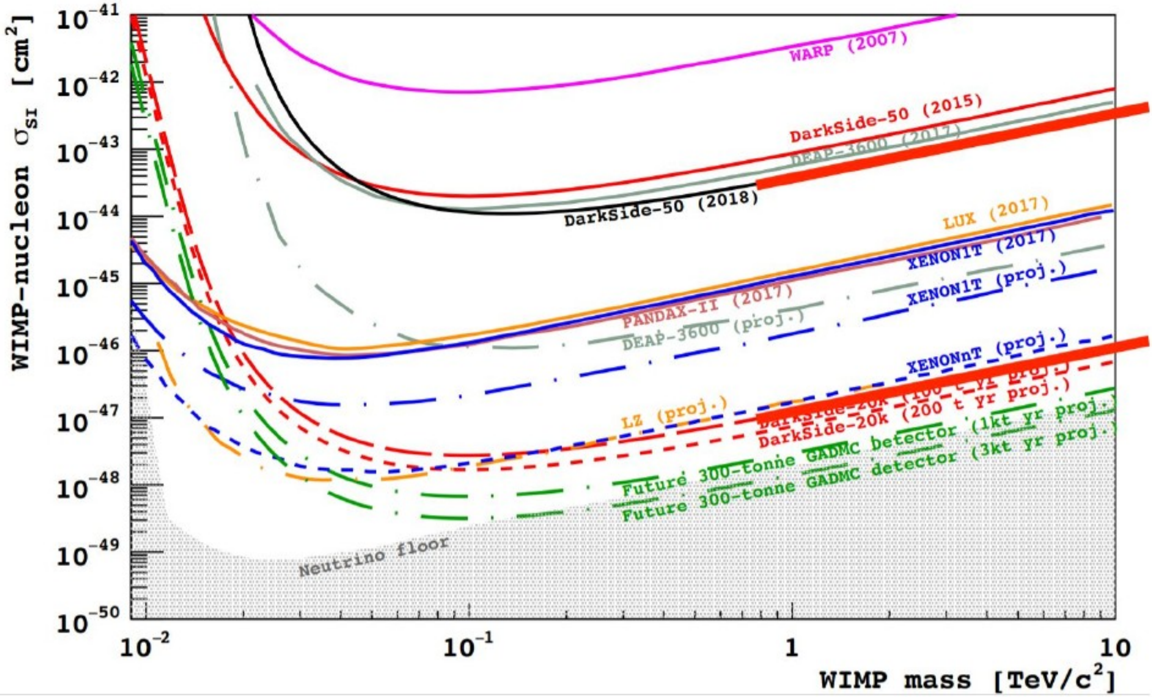


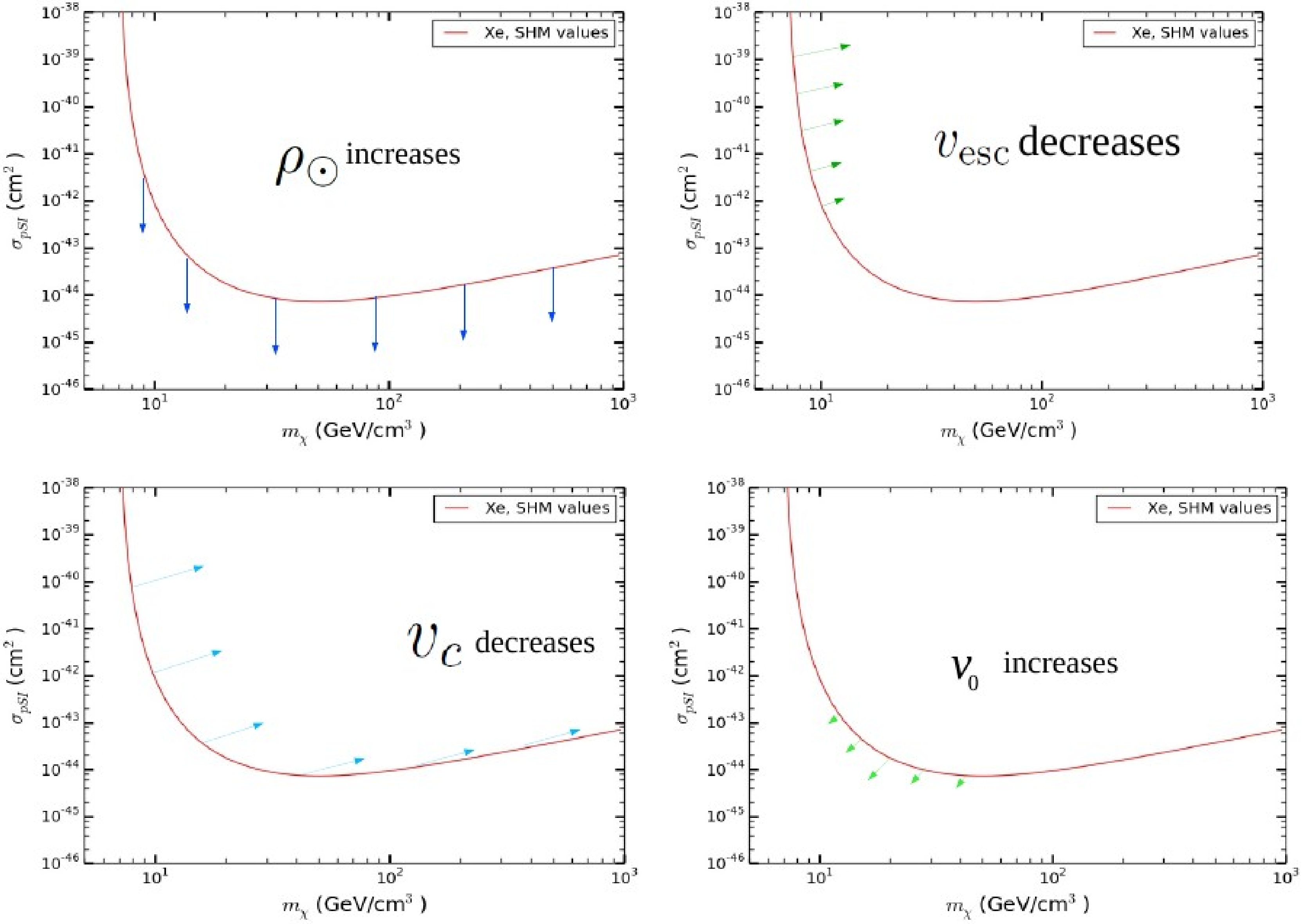
Billard+ 1307.5458



Parameters of the SHM

Stefano Magni thesis 2015 (Supervisor Julien Lavalle)

$$v_{\rm min}\left(E_T, m_{\chi{\rm min}}, m_A\right) = v_{\rm esc} + v_c + V_{\odot}$$



Review : Read, arXiv:1404.1938

The Local Dark Matter Density

J. I. Read[1*]

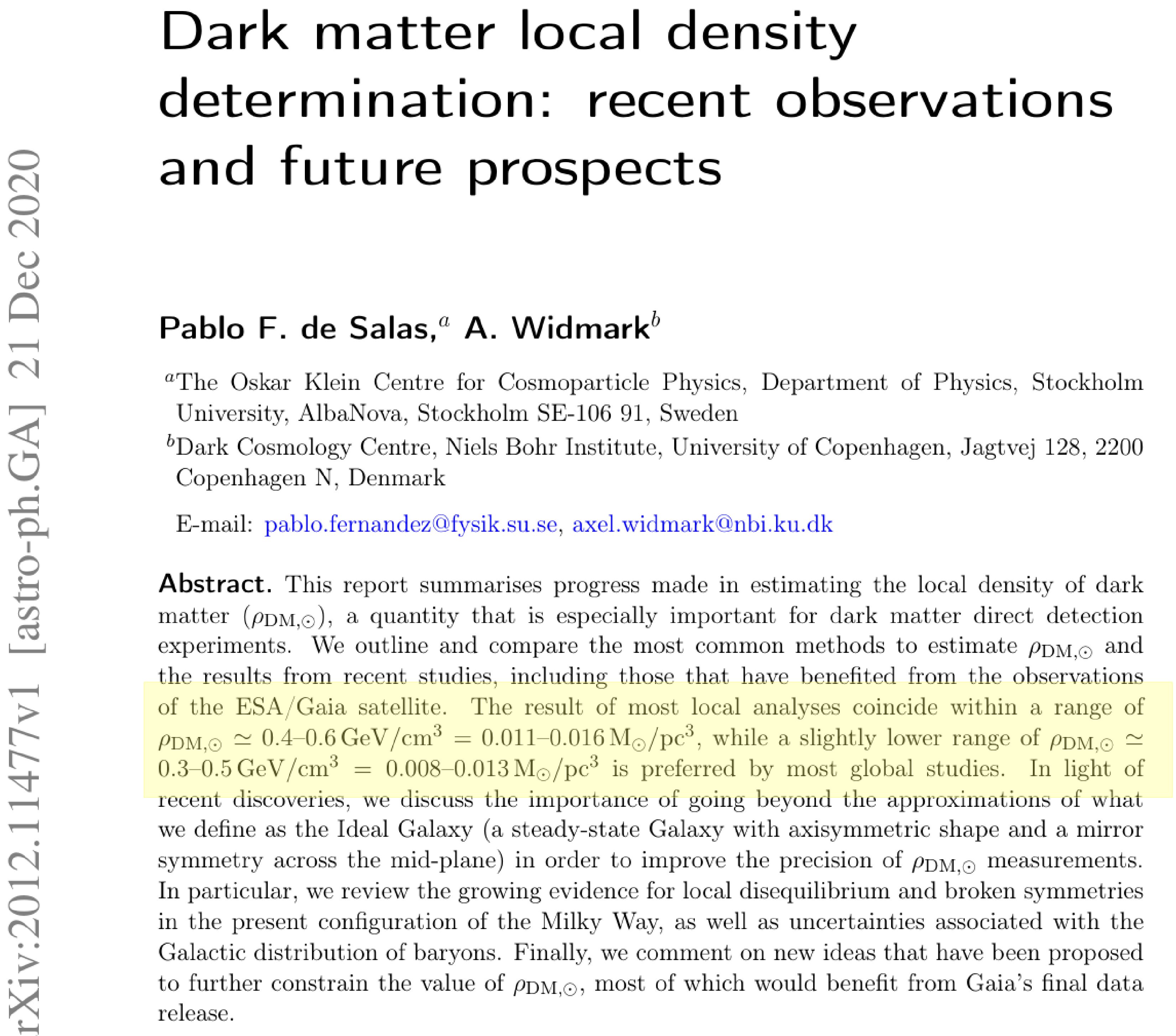
[1]Department of Physics, University of Surrey, Guildford, GU2 7XH, Surrey, UK

Abstract

I review current efforts to measure the mean density of dark matter near the Sun. This encodes valuable dynamical information about our Galaxy and is also of great importance for ‘direct detection’ dark matter experiments. I discuss theoretical expectations in our current cosmology; the theory behind mass modelling of the Galaxy; and I show how combining local and global measures probes the shape of the Milky Way dark matter halo and the possible presence of a ‘dark disc’. I stress the strengths and weaknesses of different methodologies and highlight the continuing need for detailed tests on mock data – particularly in the light of recently discovered evidence for disequilibria in the Milky Way disc. I collate the latest measurements of $\rho_{\rm dm}$ and show that, once the baryonic surface density contribution Σ_b is normalised across different groups, there is remarkably good agreement. Compiling data from the literature, I estimate $\Sigma_b = 54.2 \pm 4.9\,{\rm M}_\odot\,{\rm pc}^{-2}$, where the dominant source of uncertainty is in the HI gas contribution. Assuming this contribution from the baryons, I highlight several recent measurements of $\rho_{\rm dm}$ in order of increasing data complexity and prior, and, correspondingly, decreasing formal error bars (see Table 4). Comparing these measurements with spherical extrapolations from the Milky Way’s rotation curve, I show that the Milky Way is consistent with having a spherical dark matter halo at $R_0 \sim 8\,{\rm kpc}$. The very latest measures of $\rho_{\rm dm}$ based on $\sim 10,000$ stars from the Sloan Digital Sky Survey appear to favour little halo flattening at R_0, suggesting that the Galaxy has a rather weak dark matter disc (see Figure 9), with a correspondingly quiescent merger history. I caution, however, that this result hinges on there being no large systematics that remain to be uncovered in the SDSS data, and on the local baryonic surface density being $\Sigma_b \sim 55\,{\rm M}_\odot\,{\rm pc}^{-2}$.

I conclude by discussing how the new Gaia satellite will be transformative. We will obtain much tighter constraints on both Σ_b and $\rho_{\rm dm}$ by having accurate 6D phase space data for millions of stars near the Sun. These data will drive us towards fully three dimensional models of our Galactic potential, moving us into the realm of precision measurements of $\rho_{\rm dm}$.

A recent review : Salas, Widmark, arXiv:2012.11477



Dark matter local density determination: recent observations and future prospects

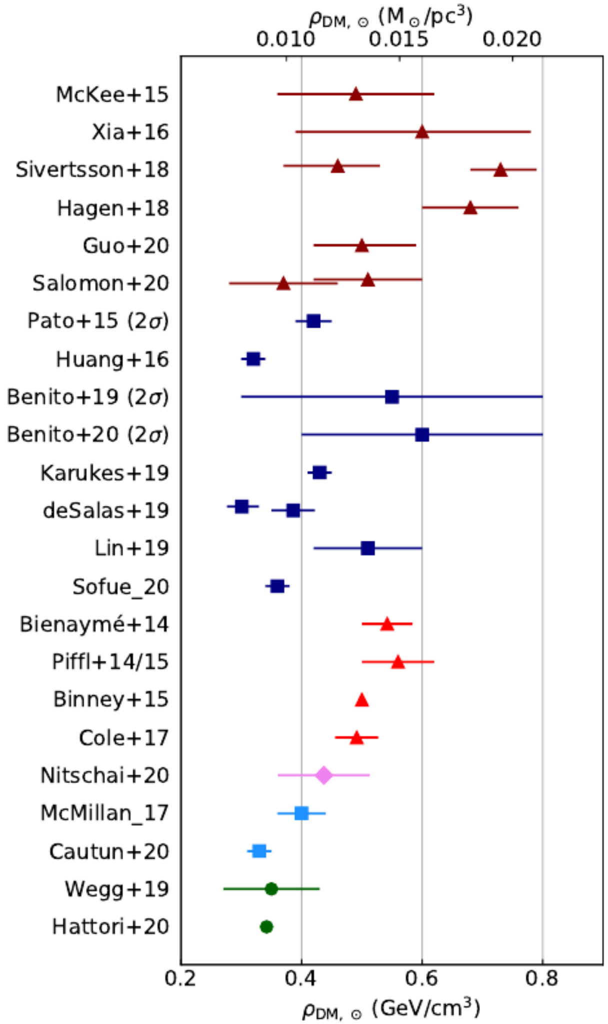
Pablo F. de Salas,[a] **A. Widmark**[b]

[a]The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, AlbaNova, Stockholm SE-106 91, Sweden
[b]Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Jagtvej 128, 2200 Copenhagen N, Denmark

E-mail: pablo.fernandez@fysik.su.se, axel.widmark@nbi.ku.dk

Abstract. This report summarises progress made in estimating the local density of dark matter ($\rho_{\mathrm{DM},\odot}$), a quantity that is especially important for dark matter direct detection experiments. We outline and compare the most common methods to estimate $\rho_{\mathrm{DM},\odot}$ and the results from recent studies, including those that have benefited from the observations of the ESA/Gaia satellite. The result of most local analyses coincide within a range of $\rho_{\mathrm{DM},\odot} \simeq 0.4$–$0.6\,\mathrm{GeV/cm^3} = 0.011$–$0.016\,\mathrm{M_\odot/pc^3}$, while a slightly lower range of $\rho_{\mathrm{DM},\odot} \simeq 0.3$–$0.5\,\mathrm{GeV/cm^3} = 0.008$–$0.013\,\mathrm{M_\odot/pc^3}$ is preferred by most global studies. In light of recent discoveries, we discuss the importance of going beyond the approximations of what we define as the Ideal Galaxy (a steady-state Galaxy with axisymmetric shape and a mirror symmetry across the mid-plane) in order to improve the precision of $\rho_{\mathrm{DM},\odot}$ measurements. In particular, we review the growing evidence for local disequilibrium and broken symmetries in the present configuration of the Milky Way, as well as uncertainties associated with the Galactic distribution of baryons. Finally, we comment on new ideas that have been proposed to further constrain the value of $\rho_{\mathrm{DM},\odot}$, most of which would benefit from Gaia's final data release.

A recent review : Salas, Widmark, arXiv:2012.11477

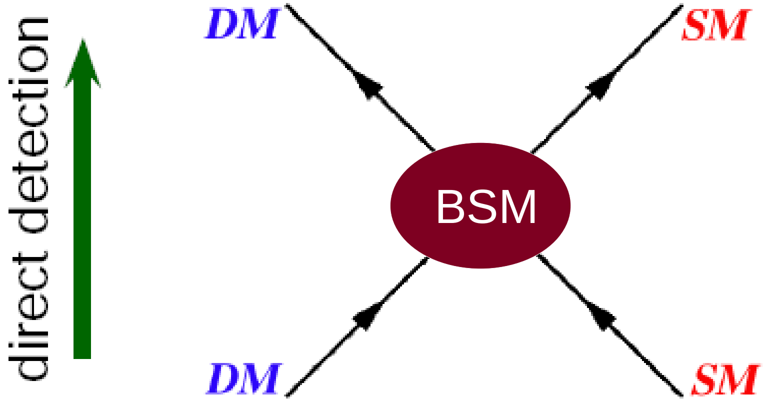


More to come soon with GAIA
=> Improve statistics

But reach the limits of current modeling
=> systematics

Figure 1: Summary of recent $\rho_{\mathrm{DM},\odot}$ estimates. The marker type indicates the main observation of the analyses: triangles for local observations, squares for circular velocities, a diamond for disc stars in an extended local region, and circles for halo stars. From top to bottom: the brown triangles correspond to the local studies presented in section 4.1.1; the dark blue squares to the circular velocity analyses from section 4.2; the red triangles to the Galactic mass models based on local observations, discussed in section 4.3.1; the pink diamond to the Jeans anisotropic modelling of disc stars presented in section 4.3.2; the cyan squares to the circular-velocity-based Galactic mass models included in section 4.3.3; and the green circles to the analyses of halo stars from section 4.3.4. We do not include the very local analyses from section 4.1.2 because of their large error bars.

Dark matter detection



$$\frac{d\mathcal{R}}{dE_R} = \frac{\rho_\odot}{M_{DM}} \frac{d\sigma}{dE_R} \int_{v_{min}}^{v_{esc}} d^3\vec{v}\, \frac{f(\vec{v}(t))}{v}$$

Astrophysics:

Dark matter distribution in the halo

Density profile
Cusp/core
Clump spectrum

Local dark matter features ?
Density
Phase space distribution
Escape velocity
Dark disk ?
Inhomogeneities ? Clumps, Streams ?

- *Alternatives to the SHM :*

Dark matter detection calculations rely on DM distribution features :

- Vary parameters

- A priori : test more or less motivated/justified assumptions

- Obs

- Mass models

- semi analytic approaches

- cosmological simulations as consistent galactic framework from first principles(+some recipes)

but no numerical Milky Way !

→ *let's have an educated use of those numerical galaxies/halos*

test semi analytical approaches
test fit functions (general Maxwellian, Tsallis …)
use f(v) to estimate uncertainties on detection rate/experiment sensitivities

Cosmological simulations

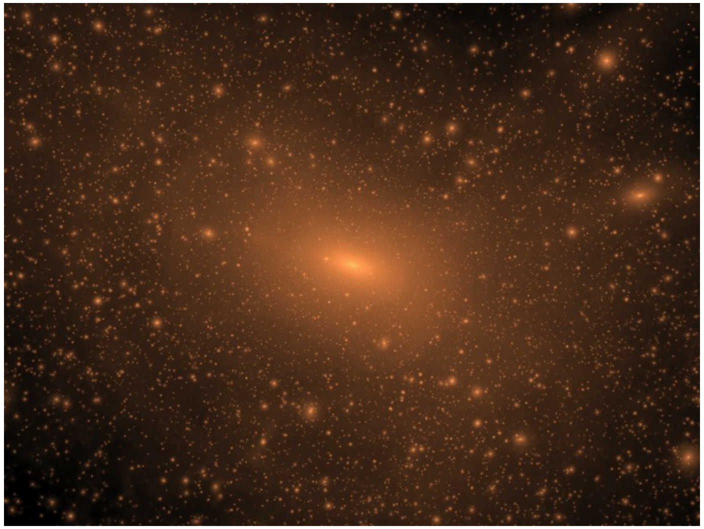
Cosmological Dark Matter Only (DMO) simulations

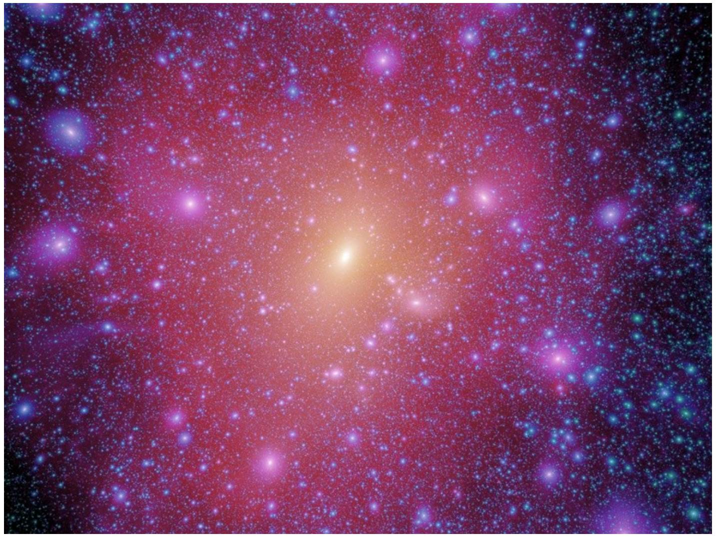
Via Lactea , GHALO

Aquarius

ZOOM on MW sized halos
Billion of particles

Select particles ~ 8 kpc from the center





DARK MATTER (and STARS)

- Gravity : Vlasov and Poisson equations

$$\nabla^2\Phi = 4\pi G\left[\rho + (n-2)\rho_X\right]$$

Direct detection

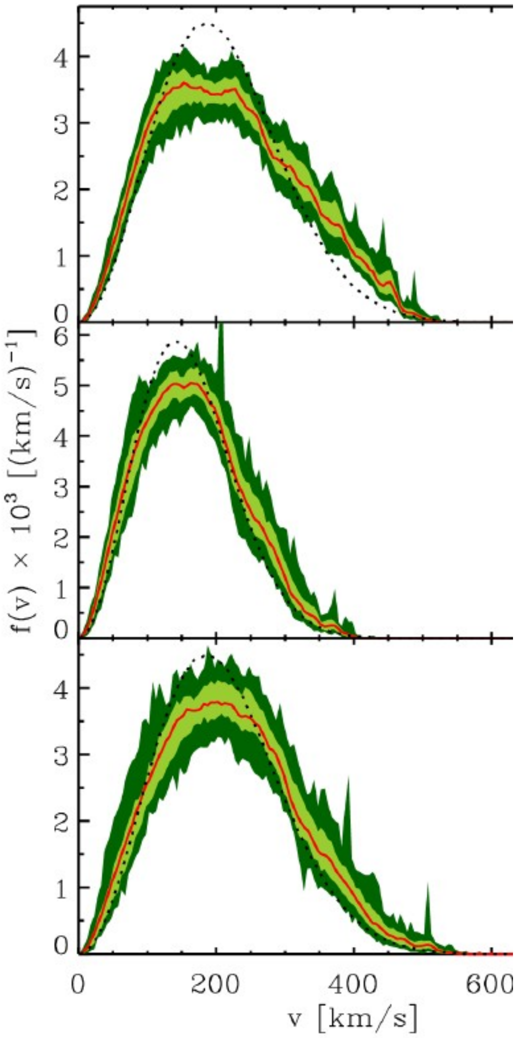
Via Lactea , GHALO

Khulen +0912.2358

DM only simulations:

Aquarius

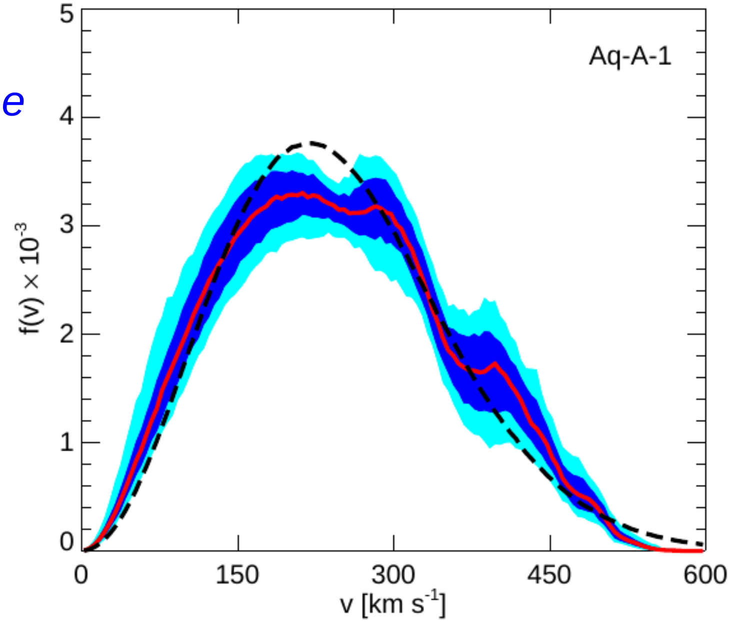
Vogelsberger+ 0812.0362

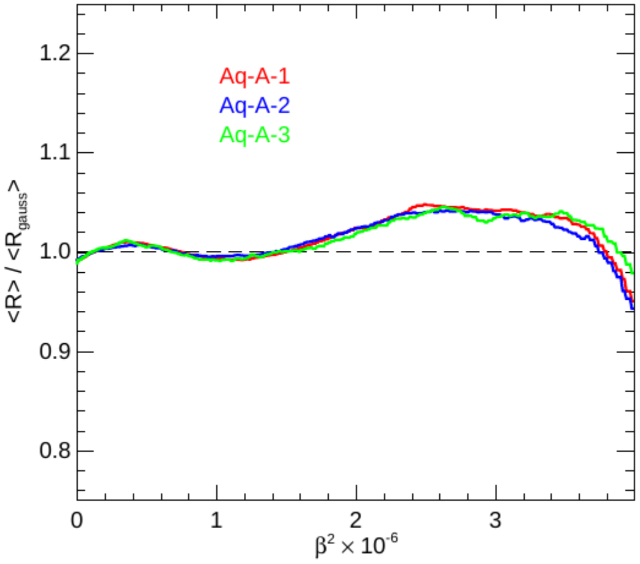


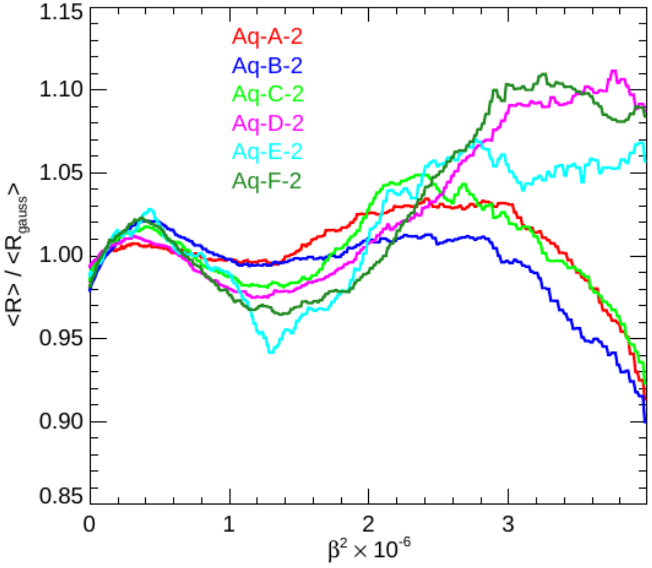
Select particles ~ 8 kpc from the center

Departure from maxwellian
Satellites acretion

10% on detection rate







Adding baryons

DARK MATTER (and STARS)

$$\nabla^2\Phi = 4\pi G\left[\rho + (n-2)\rho_X\right]$$

- Gravity : Vlasov and Poisson equations

GAS

$$\frac{\partial\rho}{\partial t} + \nabla\cdot(\rho\boldsymbol{u}) = 0,$$

$$\frac{\partial\boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = -\nabla\Phi - \frac{\nabla p}{\rho},$$

$$\frac{\partial\varepsilon}{\partial t} + \boldsymbol{u}\cdot\nabla\varepsilon = -\frac{p}{\rho}\nabla\cdot\boldsymbol{u},$$

- Hydrodynamics : Euler equations
- + Gravity

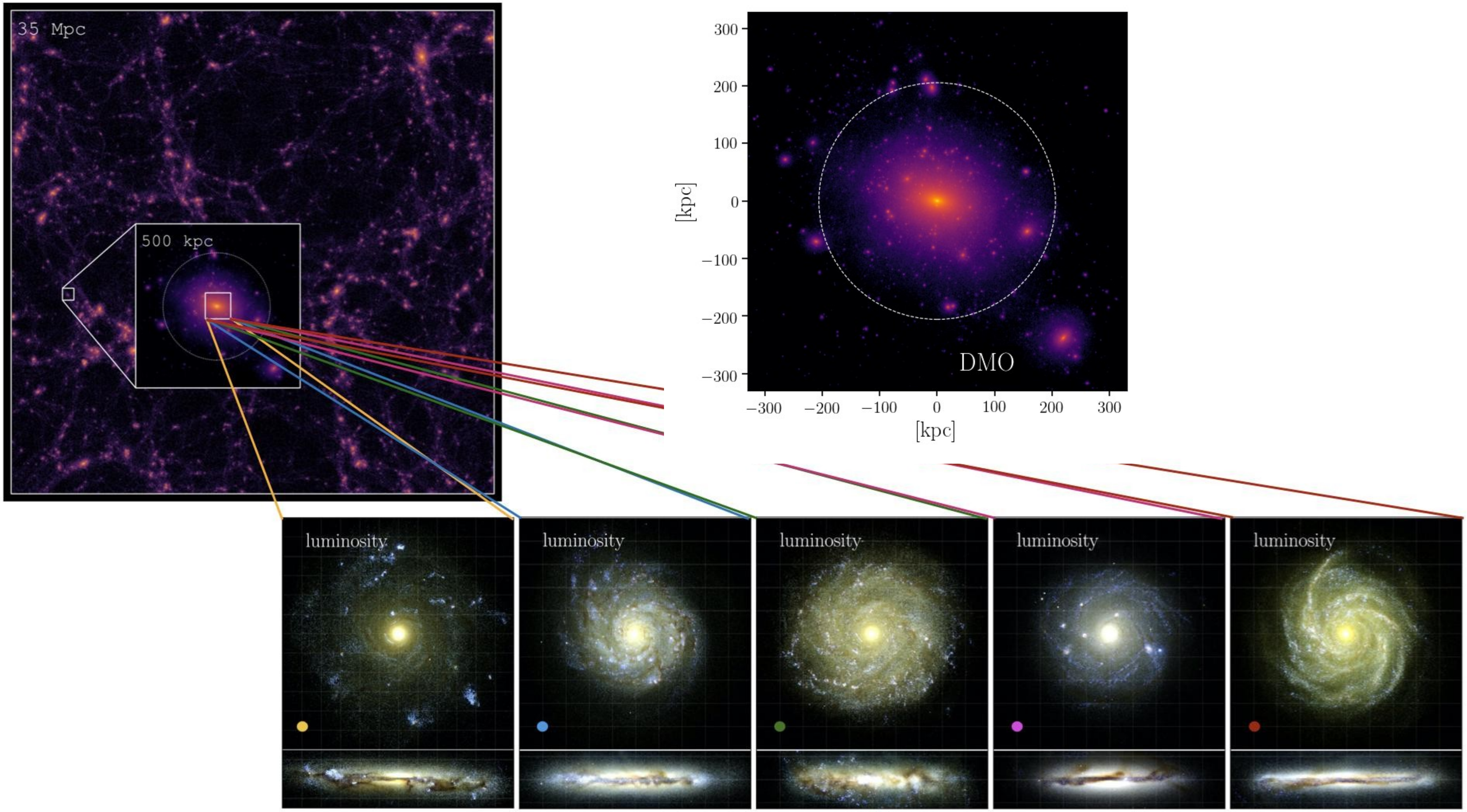
- Baryonic physics (sub grid)

- Star formation
- Feedback (SN, AGN ...)

Adding baryonic physics: Cosmological (zoom-in) hydro simulations Auriga, Apostole, NIHAO, Fire-2, Vintergatan, Mochima ...

Mochima (Nunez-Castineyra,EN,Devriendt,Teyssier)

arXiv:2004.06008



Adding baryonic physics: Cosmological (zoom-in) hydro simulations Auriga, Apostole, NIHAO, Fire-2, Vintergatan, Mochima ...

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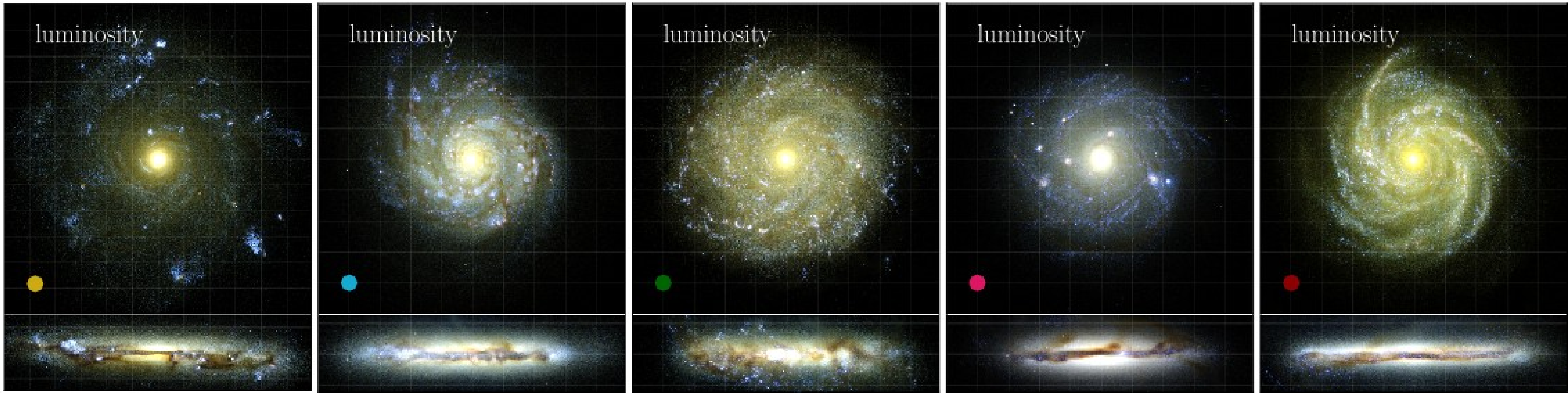
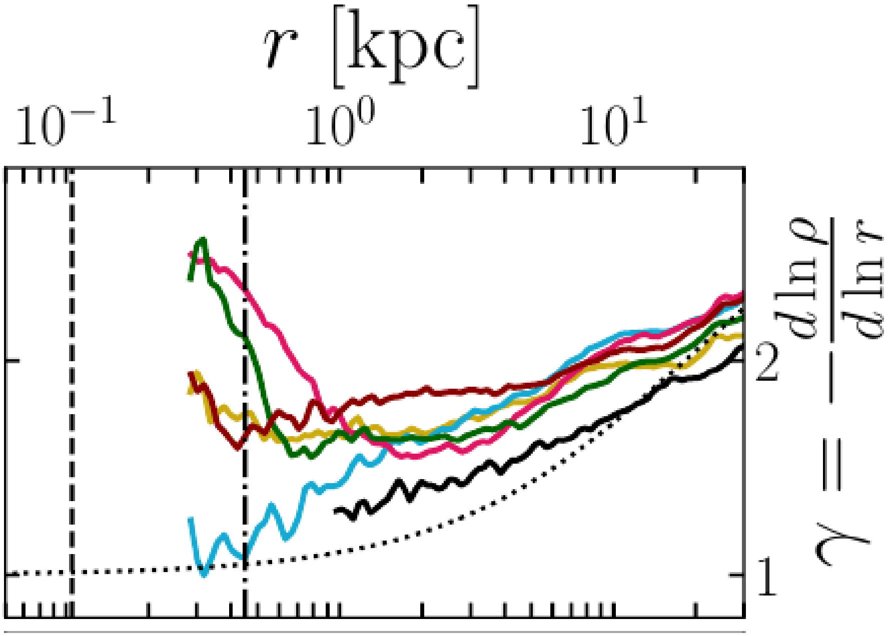
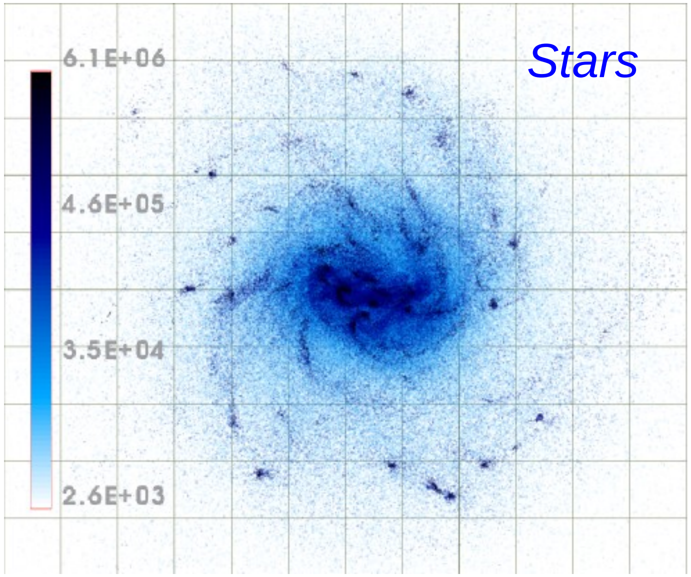
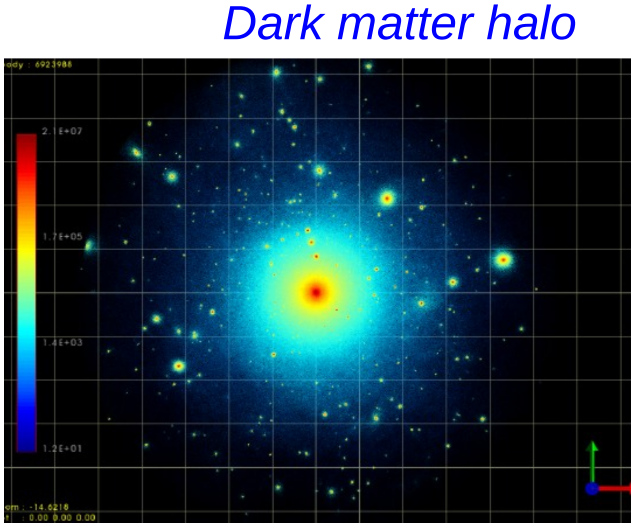
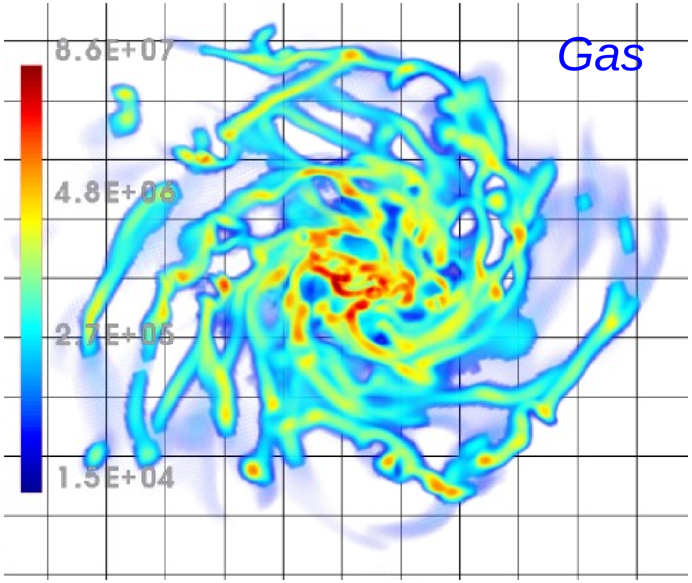
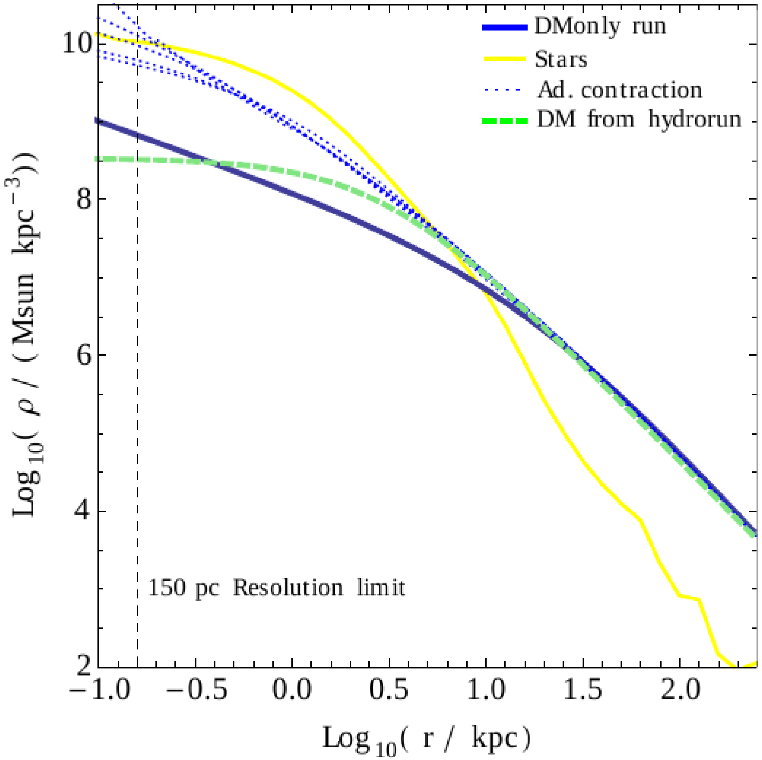






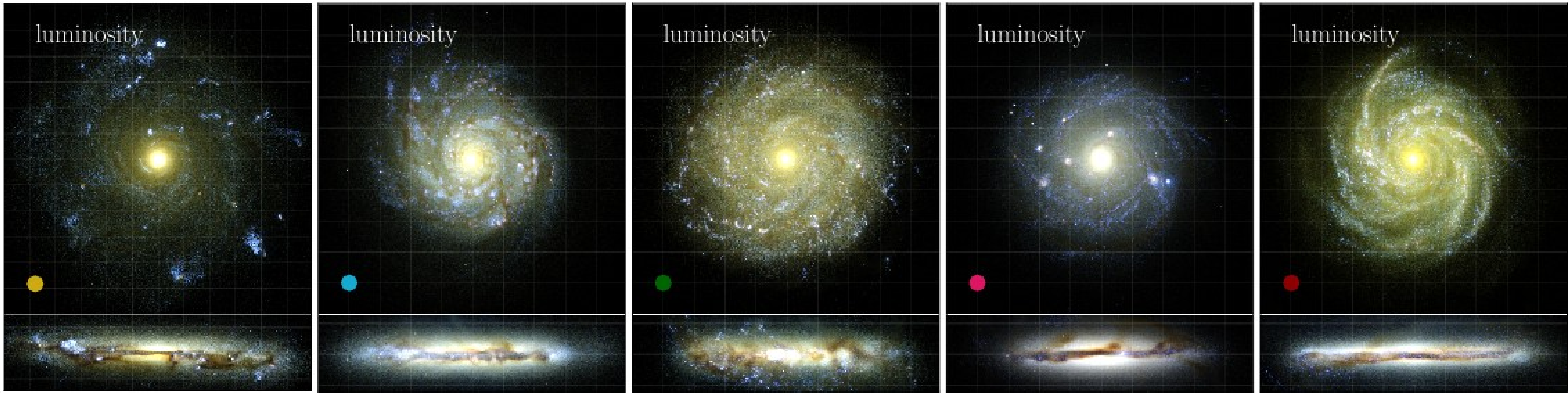




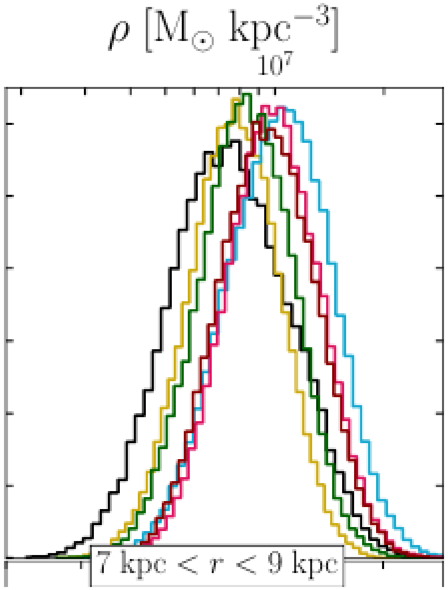


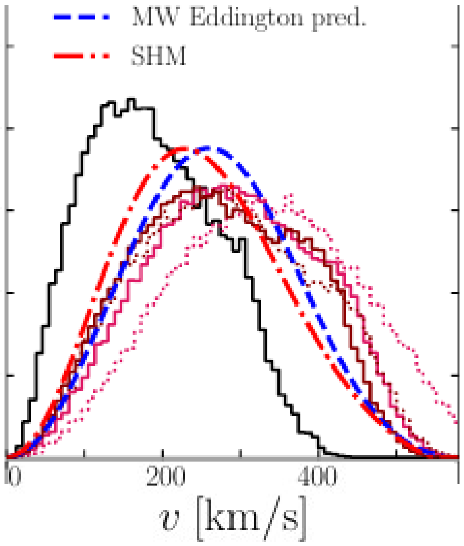
Mollitor,EN,Teyssier
arXiv:1405.4318

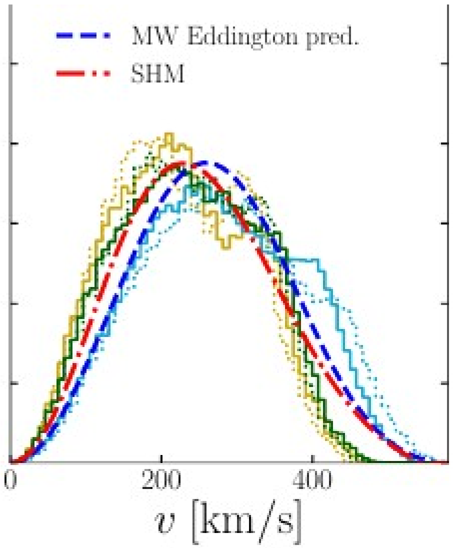
Contraction + flattening



Select dark matter particles around 8 kpc and look at distribution



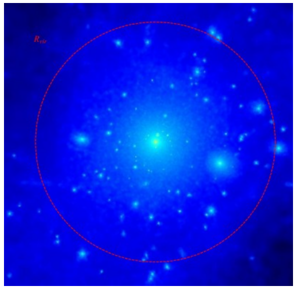


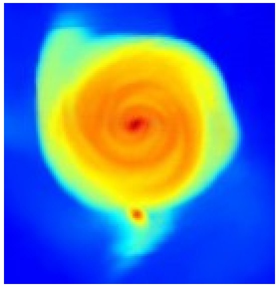


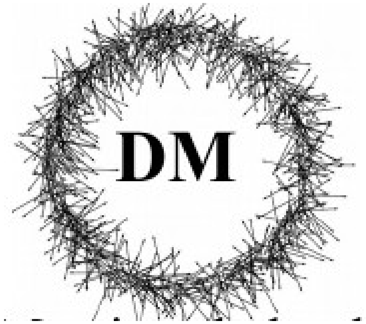
Direct detection

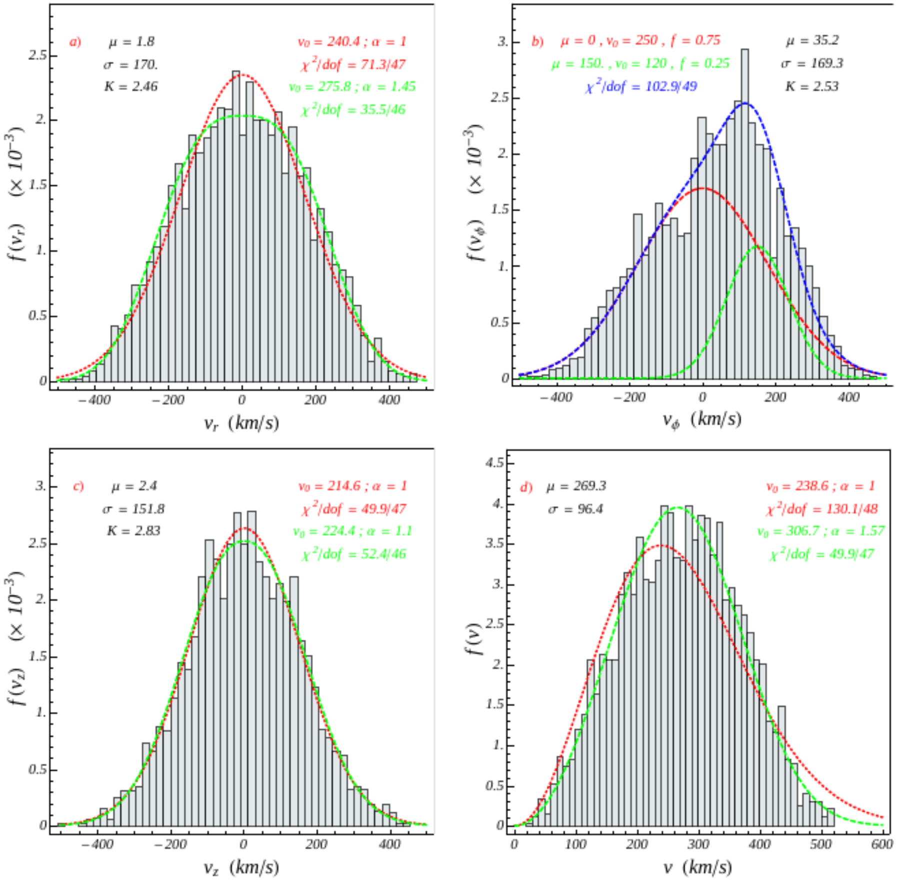
Horizon *Ling,EN+ 0909.2028*

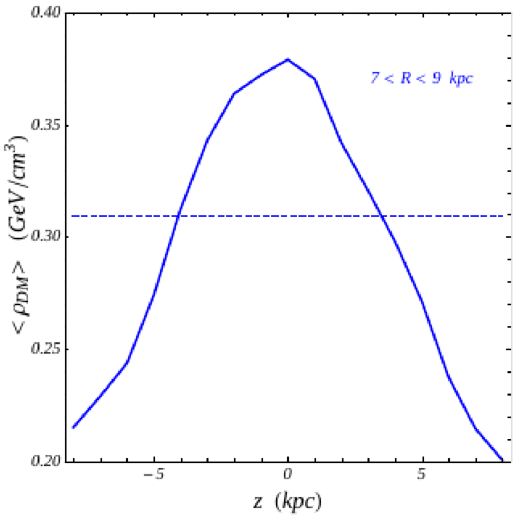
Hydro simulations:
Include a galaxy
Stellar disk, azimuthal velocity
Dark disk ?

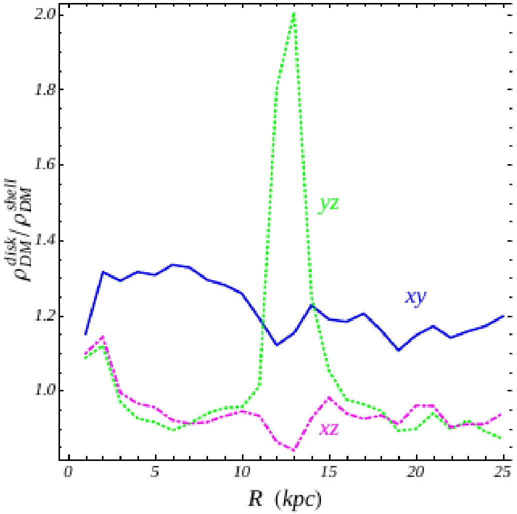








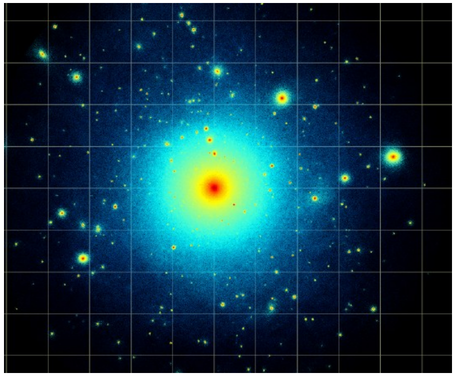


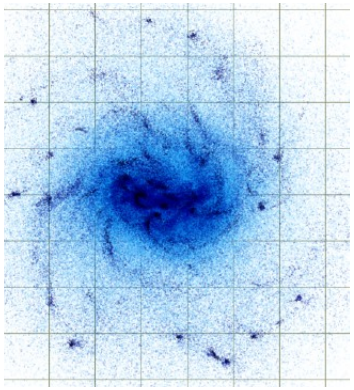


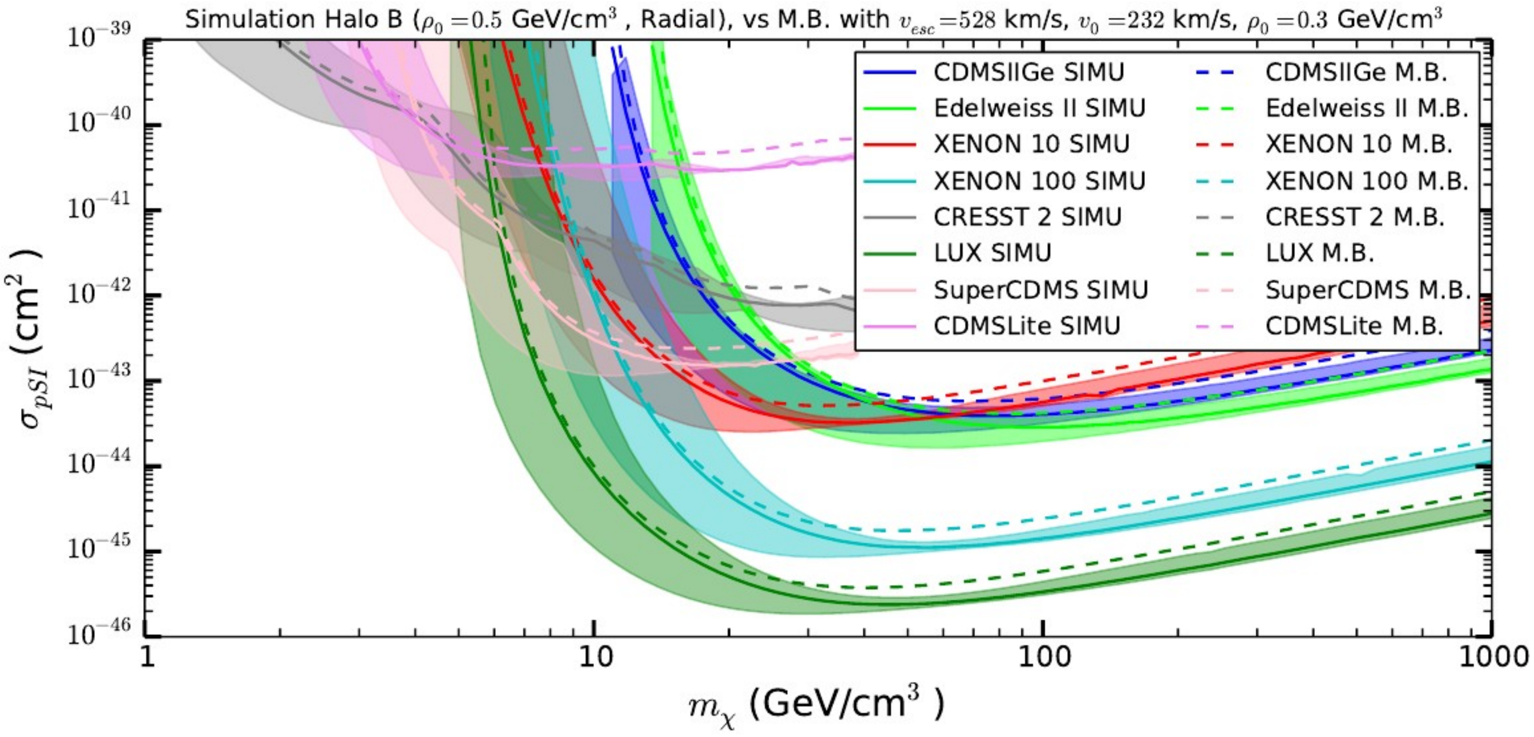
S.Magni PhD (Sup: Julien Lavalle)
P.Mollitor PhD (Sup: EN)

Direct detection

Hydro simulations:
Includes a galaxy
Stellar disk, azimuthal velocity
Dark disk ?

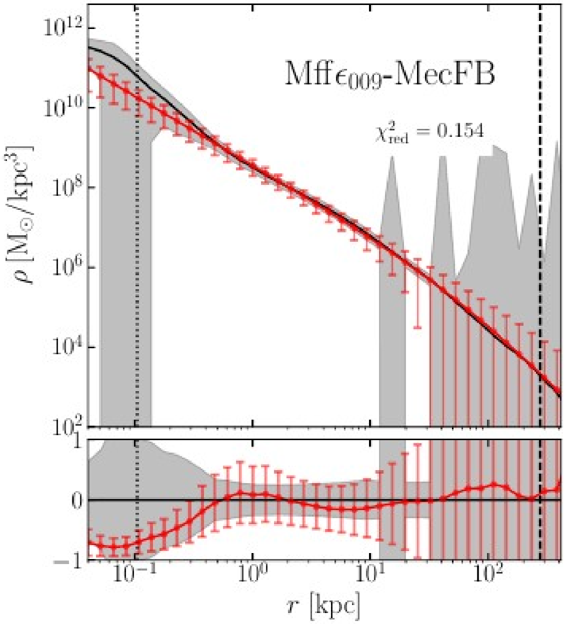


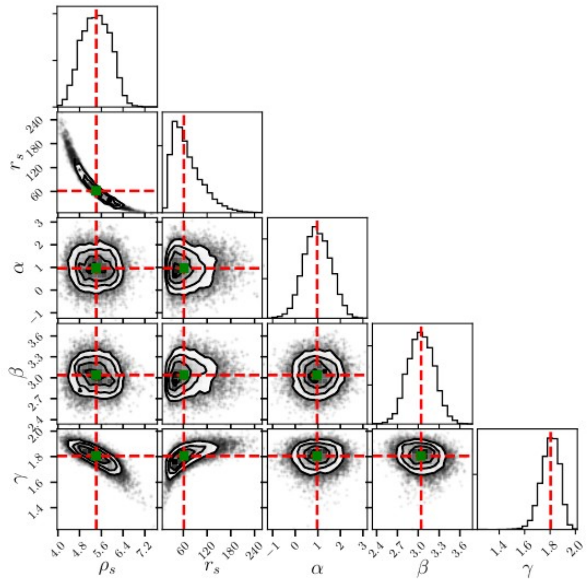


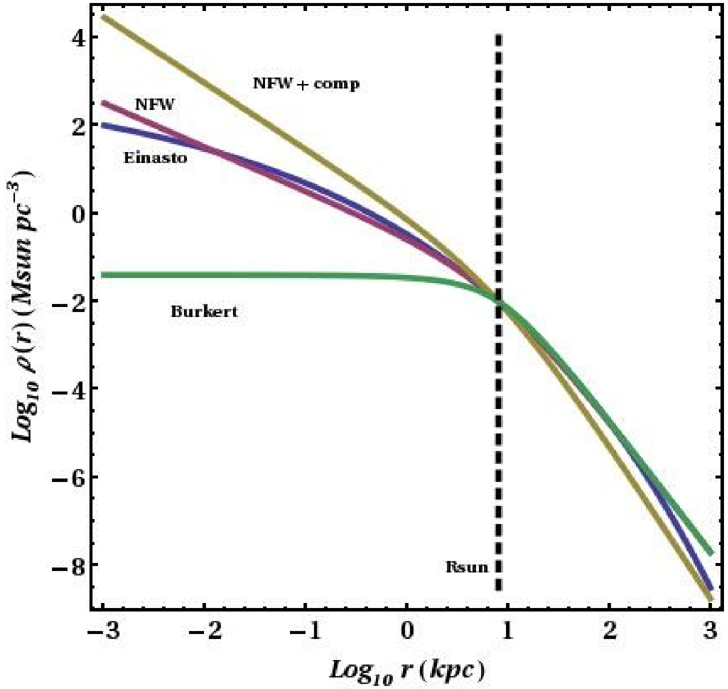


See also: Pillepich+ 1308.1703, Eagle/Apostle : Bozorgna + 1601.04707 ...

Back to DM haloes





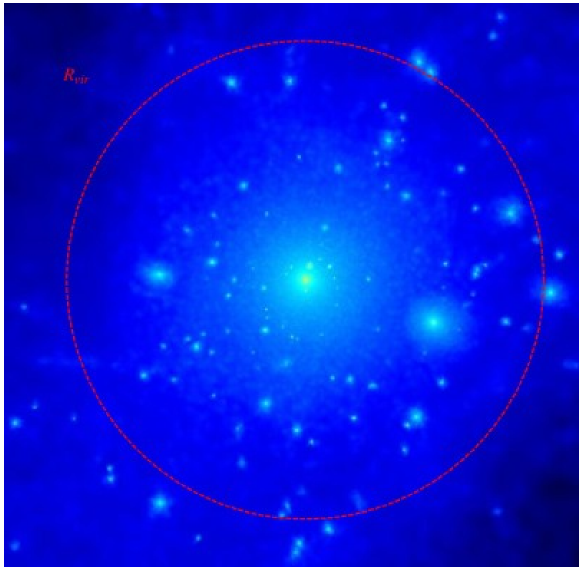


Clumps
Mas spectrum
Concentration
Spatial distribution

Streams ???

Density profile
Cusp/core
Baryons
Compression, Flattening

Stellar formation, feedback
…



$$\varrho^{SIS}(r) \doteq \frac{\sigma^2}{2\pi G_N r^2} \qquad \varrho(r) = \varrho_s \frac{a^2 + r_s^2}{a^2 + r^2}$$

$$\varrho^{NFW}(r) = \frac{\delta_c \varrho_{crit}}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

$$\varrho^{\alpha\beta\gamma}(r) = \frac{\varrho_s}{(r/a)^\gamma \left[1 + (r/a)^\alpha\right]^{\frac{\beta-\gamma}{\alpha}}}$$

$$\varrho^{Ein}(r) = \varrho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{a}\right)^\alpha - 1\right]\right\}$$

$$\varrho^{Bur}(r) = \frac{c}{(r+a)\left(a^2 + r^2\right)}$$

Halo modelling : Berezinsky+2014, Ando+2019, Stref, Lavalle 2017, Hutten, Maurin.Combet 2019(clumpy), Gioccoli(Moka) …

Semi analytical approaches

(Eddington inversion, Action-Angle ...)

Semi analytical methods

Eddington inversion

Lacroix,Stref,Lavalle

arXiv:1805.02403

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

$$\mathcal{E} \equiv \Psi(r) - v^2/2$$

$$f_{\vec{v}}(r,\vec{v}) \equiv \frac{f(\mathcal{E})}{\rho(r)}$$

$$f_v(r,v) \equiv v^2 \int \mathrm{d}\Omega_v\, f_{\vec{v}}(r,\vec{v})$$

$$f_v(r,v) = \frac{4\pi v^2}{\rho(r)} f\left(\mathcal{E} = \Psi(r) - \frac{v^2}{2}\right)$$

Spherical symmetry
Isotropy

arXiv:1805.02403v2 [astro-ph.G ’ Sep 2018

Anatomy of Eddington-like inversion methods in the context of dark matter searches

Thomas Lacroix, Martin Stref, and Julien Lavalle

Laboratoire Univers et Particules de Montpellier (LUPM),
Université de Montpellier & CNRS, Place Eugène Bataillon, 34095 Montpellier Cedex 05, France
E-mail: thomas.lacroix@umontpellier.fr, martin.stref@umontpellier.fr, lavalle@in2p3.fr

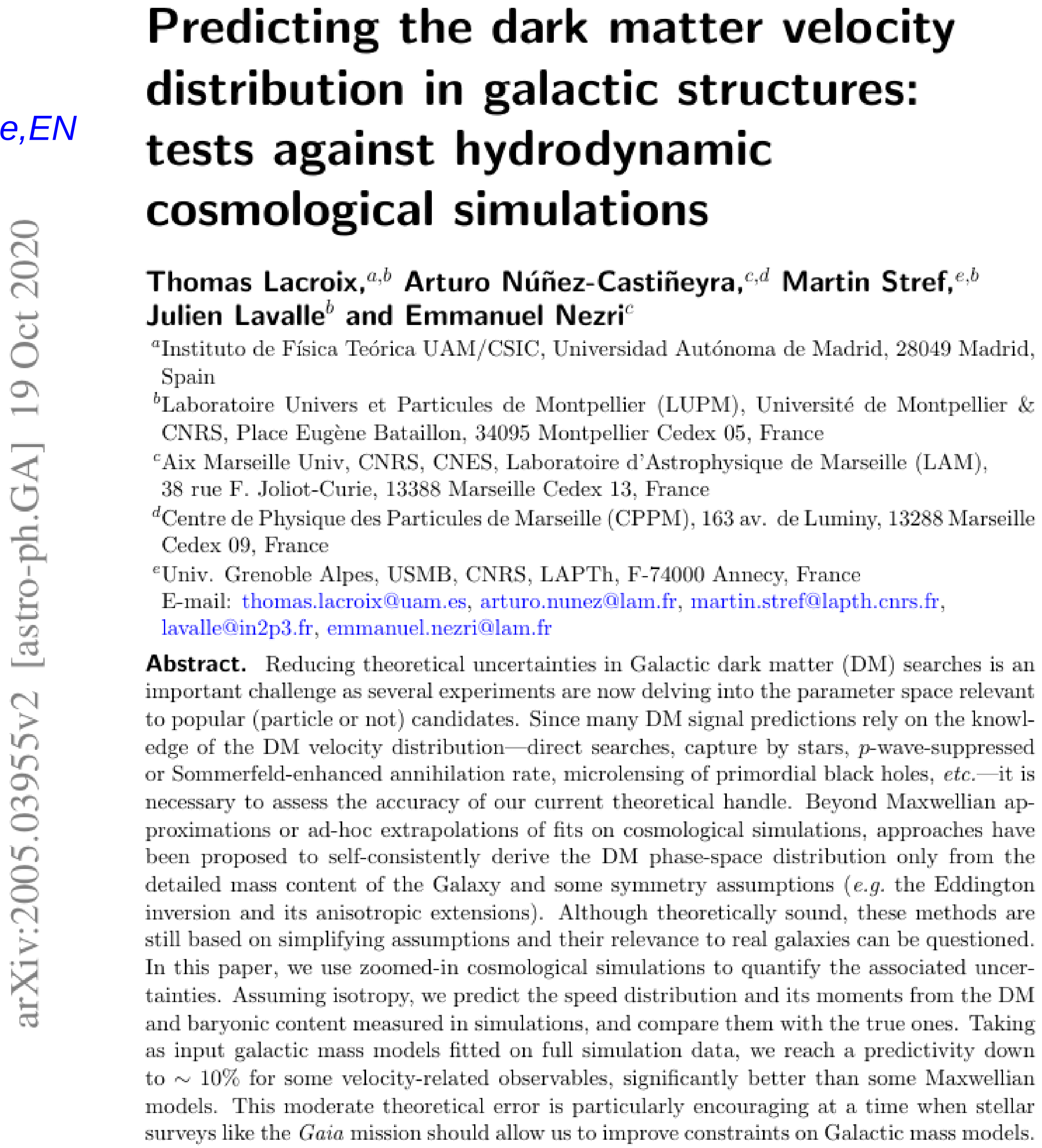
Abstract. Irrespective of the dark matter (DM) candidate, several potentially observable signatures derive from the velocity distribution of DM in halos, in particular in the Milky Way (MW) halo. Examples include direct searches for weakly-interacting massive particles (WIMPs), *p*-wave suppressed or Sommerfeld-enhanced annihilation signals, microlensing events of primordial black holes (PBHs), *etc.* Most current predictions are based on the Maxwellian approximation which is not only theoretically inconsistent in bounded systems, but also not supported by cosmological simulations. A more consistent method sometimes used in calculations for direct WIMP searches relies on the so-called Eddington inversion method, which relates the DM phase-space distribution function (DF) to its mass density profile and the total gravitational potential of the system. Originally built upon the isotropy assumption, this method can be extended to anisotropic systems. We investigate these inversion methods in the context of Galactic DM searches, motivated by the fact that the MW is a strongly constrained system, and should be even more so with the ongoing Gaia survey. We still draw conclusions that apply to the general case. In particular, we illustrate how neglecting the radial boundary of the DM halo leads to theoretical inconsistencies. We also show that several realistic configurations of the DM halo and the MW baryonic content entail ill-defined DFs, significantly restricting the configuration space over which these inversion methods can apply. We propose consistent solutions to these issues. Finally, we compute several observables inferred from constrained Galactic mass models relevant to DM searches (WIMPs or PBHs), *e.g.* moments and inverse moments of the DM speed and relative speed distributions.

Semi analytical methods

Eddington inversion

Lacroix,Nunez-Castineyra,Stref, Lavalle,EN

arXiv:2005.03955



Predicting the dark matter velocity distribution in galactic structures: tests against hydrodynamic cosmological simulations

Thomas Lacroix,[a,b] **Arturo Núñez-Castiñeyra,**[c,d] **Martin Stref,**[e,b]
Julien Lavalle[b] **and Emmanuel Nezri**[c]

[a]Instituto de Física Teórica UAM/CSIC, Universidad Autónoma de Madrid, 28049 Madrid, Spain
[b]Laboratoire Univers et Particules de Montpellier (LUPM), Université de Montpellier & CNRS, Place Eugène Bataillon, 34095 Montpellier Cedex 05, France
[c]Aix Marseille Univ, CNRS, CNES, Laboratoire d'Astrophysique de Marseille (LAM), 38 rue F. Joliot-Curie, 13388 Marseille Cedex 13, France
[d]Centre de Physique des Particules de Marseille (CPPM), 163 av. de Luminy, 13288 Marseille Cedex 09, France
[e]Univ. Grenoble Alpes, USMB, CNRS, LAPTh, F-74000 Annecy, France
E-mail: thomas.lacroix@uam.es, arturo.nunez@lam.fr, martin.stref@lapth.cnrs.fr, lavalle@in2p3.fr, emmanuel.nezri@lam.fr

Abstract. Reducing theoretical uncertainties in Galactic dark matter (DM) searches is an important challenge as several experiments are now delving into the parameter space relevant to popular (particle or not) candidates. Since many DM signal predictions rely on the knowledge of the DM velocity distribution—direct searches, capture by stars, p-wave-suppressed or Sommerfeld-enhanced annihilation rate, microlensing of primordial black holes, *etc.*—it is necessary to assess the accuracy of our current theoretical handle. Beyond Maxwellian approximations or ad-hoc extrapolations of fits on cosmological simulations, approaches have been proposed to self-consistently derive the DM phase-space distribution only from the detailed mass content of the Galaxy and some symmetry assumptions (*e.g.* the Eddington inversion and its anisotropic extensions). Although theoretically sound, these methods are still based on simplifying assumptions and their relevance to real galaxies can be questioned. In this paper, we use zoomed-in cosmological simulations to quantify the associated uncertainties. Assuming isotropy, we predict the speed distribution and its moments from the DM and baryonic content measured in simulations, and compare them with the true ones. Taking as input galactic mass models fitted on full simulation data, we reach a predictivity down to $\sim 10\%$ for some velocity-related observables, significantly better than some Maxwellian models. This moderate theoretical error is particularly encouraging at a time when stellar surveys like the *Gaia* mission should allow us to improve constraints on Galactic mass models.

Semi analytical methods

Eddington inversion

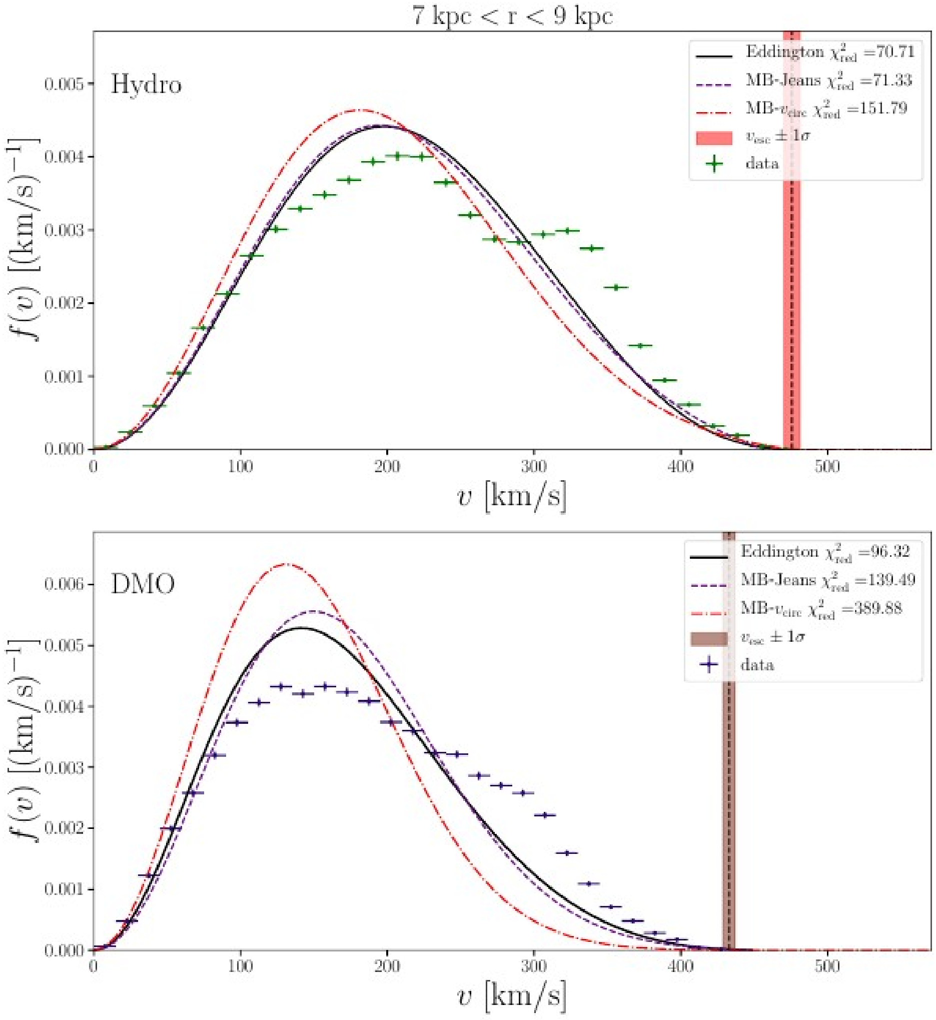
Lacroix,Nunez-Castineyra,Stref, Lavalle,EN

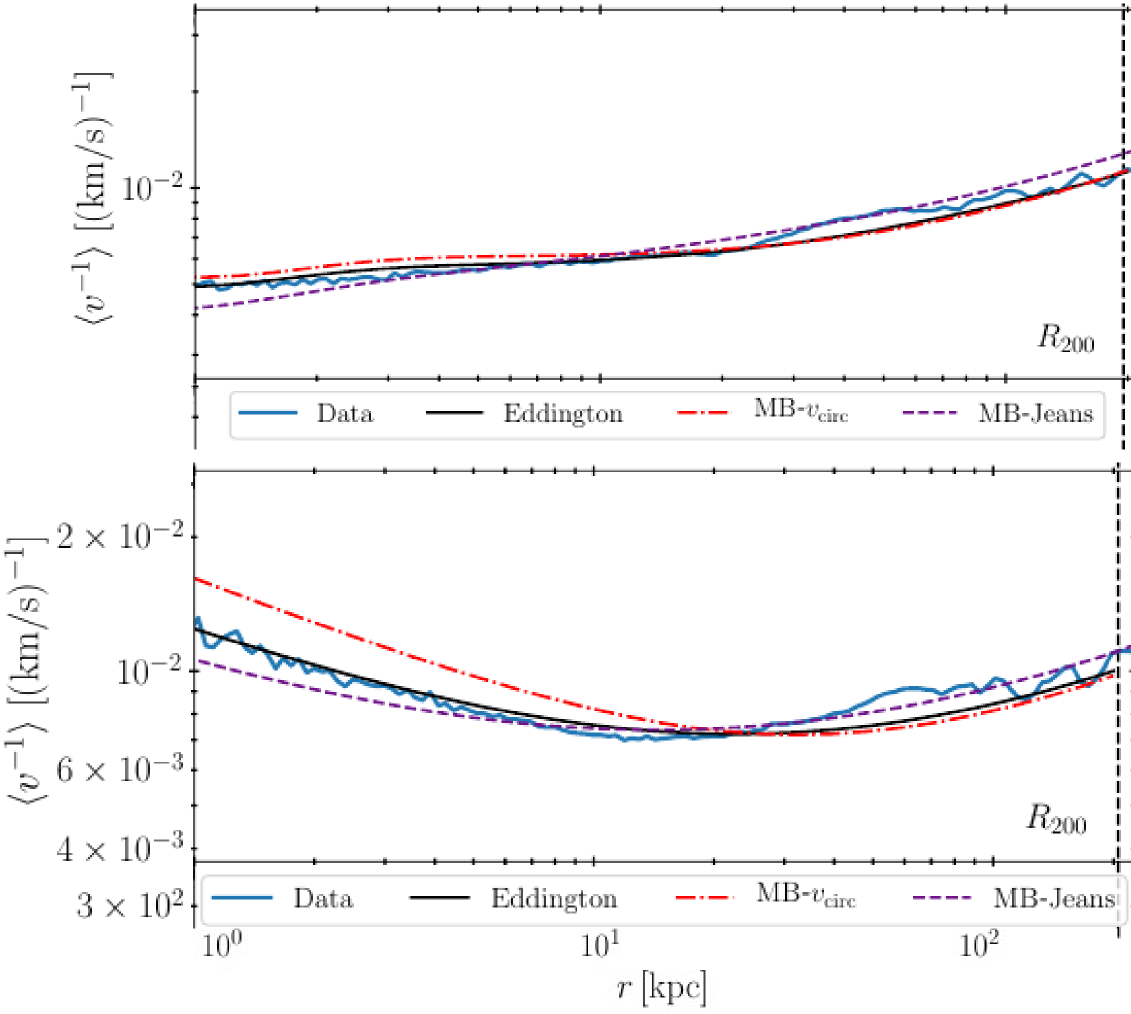
arXiv:2005.03955

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

$$\mathcal{E} \equiv \Psi(r) - v^2/2 \qquad f_{\vec{v}}(r,\vec{v}) \equiv \frac{f(\mathcal{E})}{\rho(r)}$$

$$f_v(r,v) \equiv v^2 \int \mathrm{d}\Omega_v\, f_{\vec{v}}(r,\vec{v}) \qquad f_v(r,v) = \frac{4\pi v^2}{\rho(r)} f\left(\mathcal{E} = \Psi(r) - \frac{v^2}{2}\right)$$



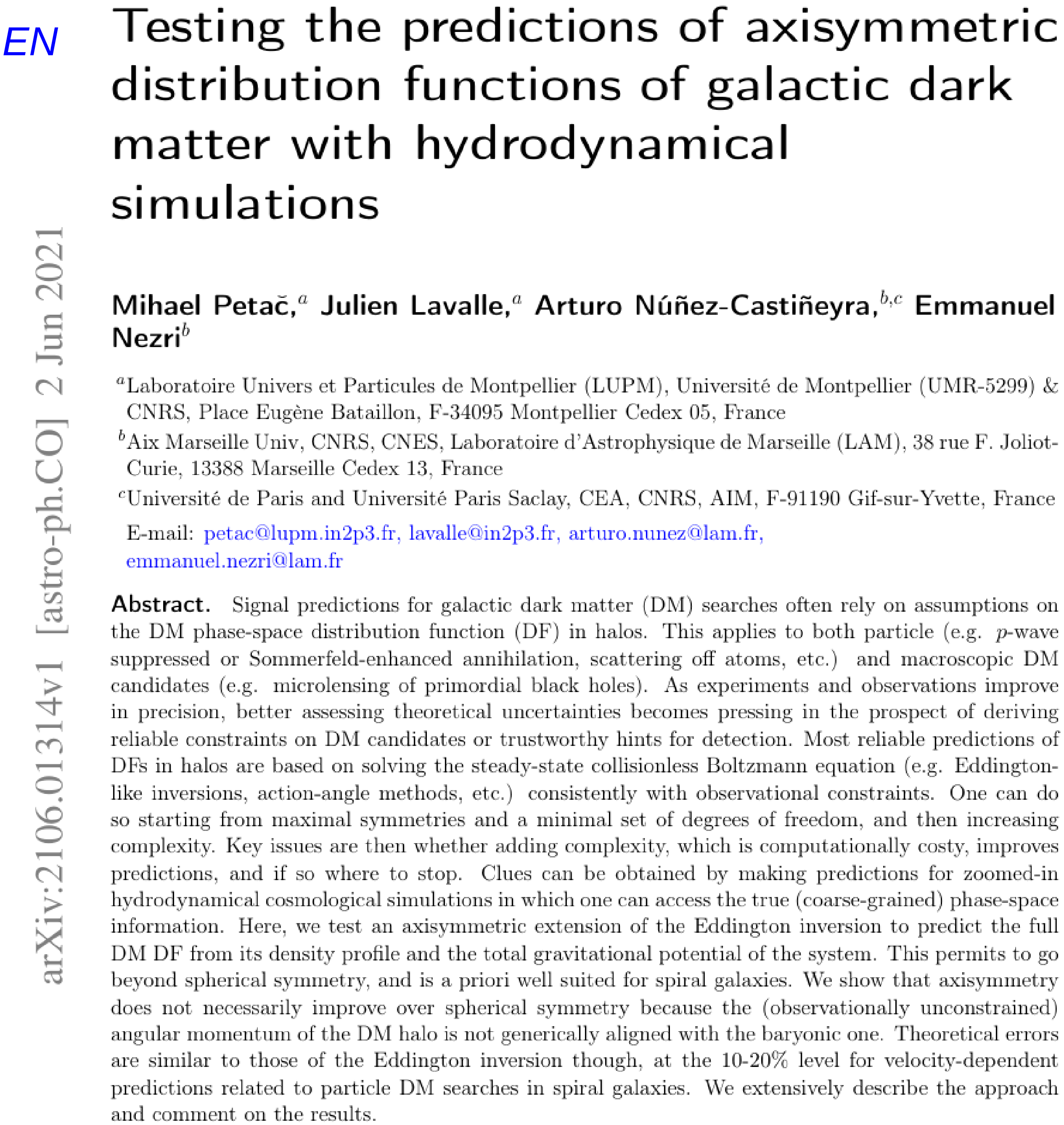


Semi analytical methods

Eddington inversion : axisymmetric extension

Petac, Lavalle, Nunez-Castineyra,EN

arXiv:2106.01314



Testing the predictions of axisymmetric distribution functions of galactic dark matter with hydrodynamical simulations

Mihael Petač,[a] **Julien Lavalle,**[a] **Arturo Núñez-Castiñeyra,**[b,c] **Emmanuel Nezri**[b]

[a]Laboratoire Univers et Particules de Montpellier (LUPM), Université de Montpellier (UMR-5299) & CNRS, Place Eugène Bataillon, F-34095 Montpellier Cedex 05, France

[b]Aix Marseille Univ, CNRS, CNES, Laboratoire d'Astrophysique de Marseille (LAM), 38 rue F. Joliot-Curie, 13388 Marseille Cedex 13, France

[c]Université de Paris and Université Paris Saclay, CEA, CNRS, AIM, F-91190 Gif-sur-Yvette, France

E-mail: petac@lupm.in2p3.fr, lavalle@in2p3.fr, arturo.nunez@lam.fr, emmanuel.nezri@lam.fr

Abstract. Signal predictions for galactic dark matter (DM) searches often rely on assumptions on the DM phase-space distribution function (DF) in halos. This applies to both particle (e.g. p-wave suppressed or Sommerfeld-enhanced annihilation, scattering off atoms, etc.) and macroscopic DM candidates (e.g. microlensing of primordial black holes). As experiments and observations improve in precision, better assessing theoretical uncertainties becomes pressing in the prospect of deriving reliable constraints on DM candidates or trustworthy hints for detection. Most reliable predictions of DFs in halos are based on solving the steady-state collisionless Boltzmann equation (e.g. Eddington-like inversions, action-angle methods, etc.) consistently with observational constraints. One can do so starting from maximal symmetries and a minimal set of degrees of freedom, and then increasing complexity. Key issues are then whether adding complexity, which is computationally costy, improves predictions, and if so where to stop. Clues can be obtained by making predictions for zoomed-in hydrodynamical cosmological simulations in which one can access the true (coarse-grained) phase-space information. Here, we test an axisymmetric extension of the Eddington inversion to predict the full DM DF from its density profile and the total gravitational potential of the system. This permits to go beyond spherical symmetry, and is a priori well suited for spiral galaxies. We show that axisymmetry does not necessarily improve over spherical symmetry because the (observationally unconstrained) angular momentum of the DM halo is not generically aligned with the baryonic one. Theoretical errors are similar to those of the Eddington inversion though, at the 10-20% level for velocity-dependent predictions related to particle DM searches in spiral galaxies. We extensively describe the approach and comment on the results.

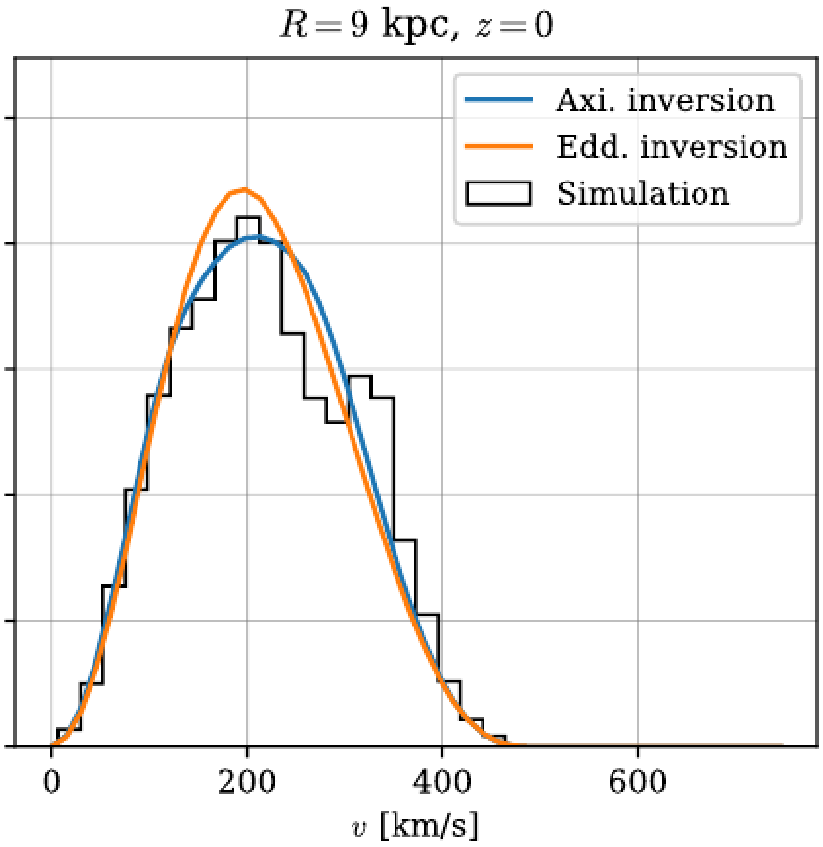
Semi analytical methods

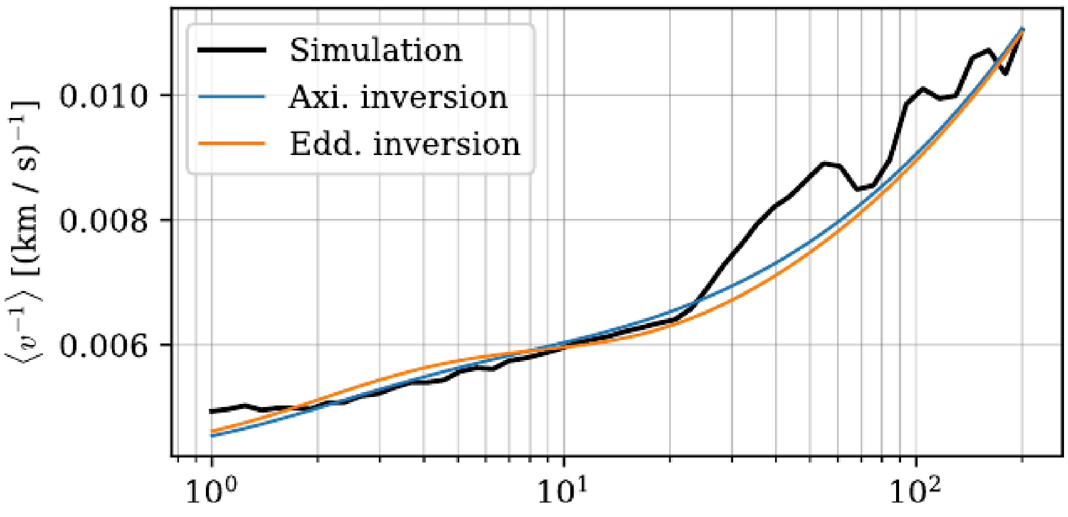
Eddington inversion : axisymmetric extension

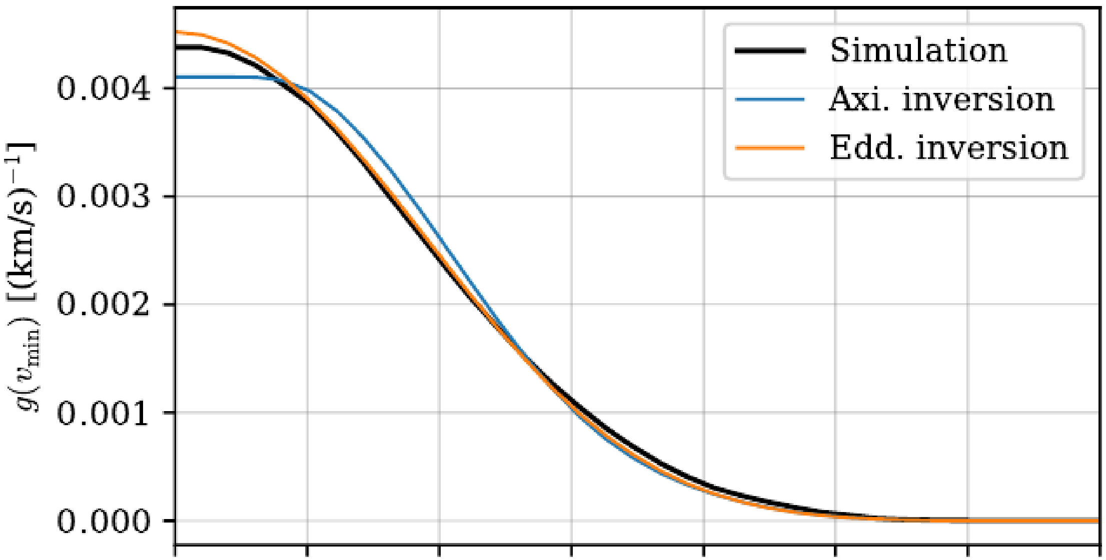
Petac, Lavalle, Nunez-Castineyra,EN

arXiv:2106.01314

$$f(\mathcal{E}) \longrightarrow f = f(\mathcal{E}, L_z)$$







Other ansatz, “ad hoc” approaches, fits ….

Test other assumptions for f(v)

Nunez-Castineyra,EN,Mollitor, Devriendt, Teyssier

In prep

Maxwellian

$$f(\vec{v}) = \frac{N}{2\pi v_0^2} \exp\left(-\frac{3|\vec{v}|^2}{2v_0^2}\right)$$

Generalized Maxwellian

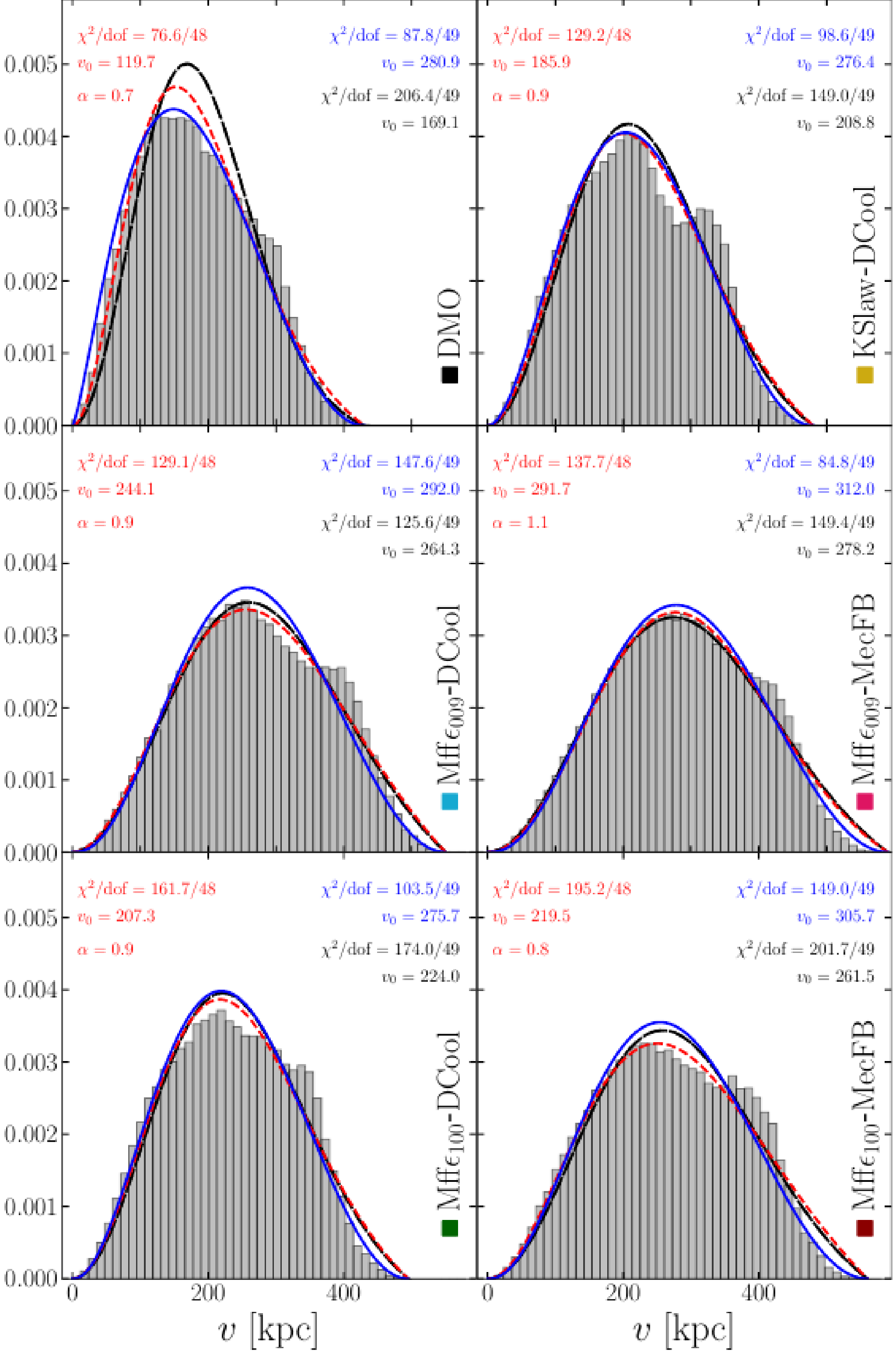
$$f(\vec{v}) = \frac{e^{-(\vec{v}^2/v_0^2)^{\alpha}}}{N(v_0,\alpha)}$$

Tsallis

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

Mao+ 2013

$$f(v, v_0, v_{\rm esc}, p) = \frac{1}{N} v^2 \exp^{-\frac{v}{v_0}} (v_{\rm esc}^2 - v^2)^p$$

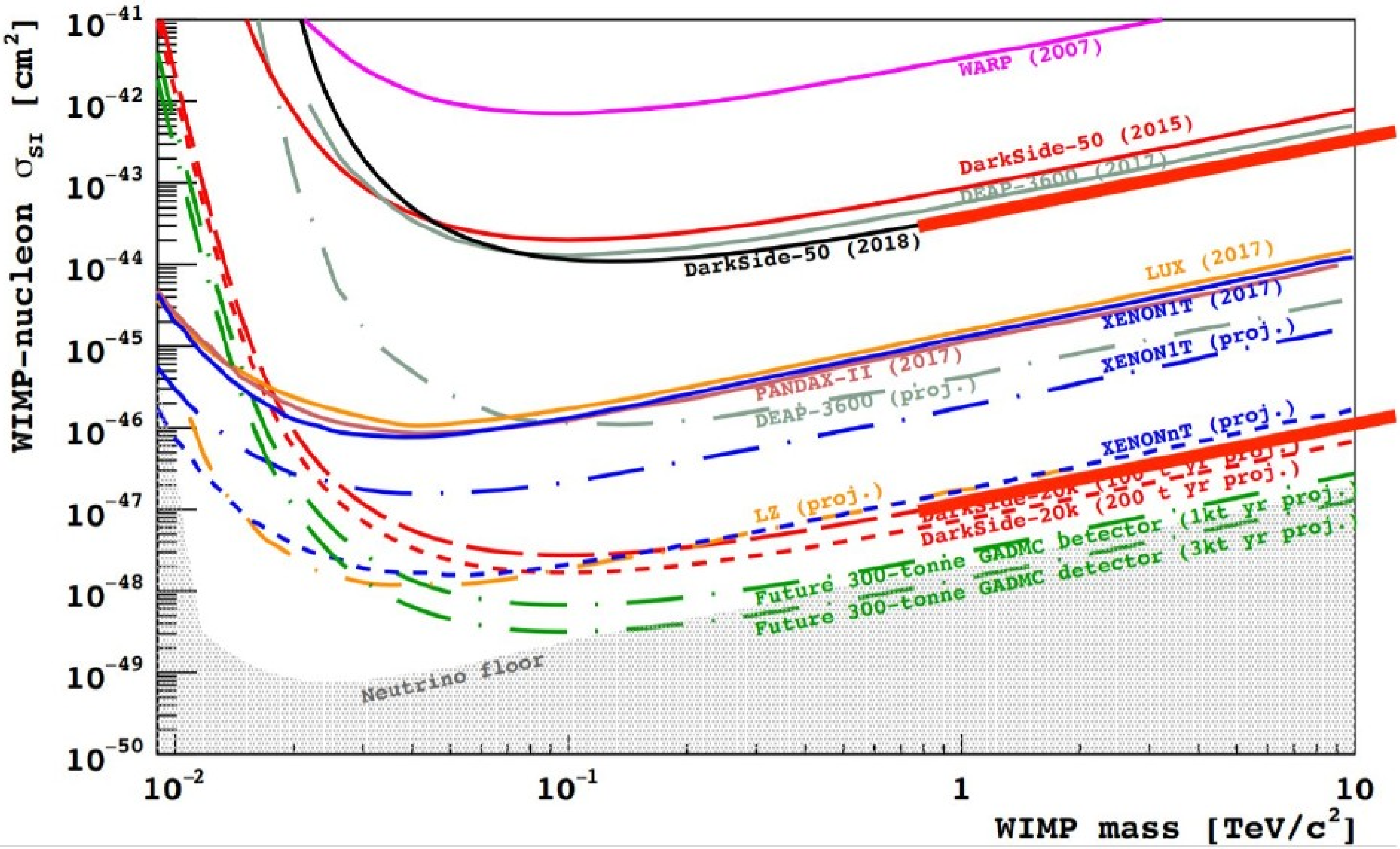


Conclusion - Work to do

→

Consider those approaches to vary f(v)

Add astrophysical uncertainties on Darkside sensitivity :



Conclusion - Work to do

Consider those approaches to vary f(v)

Add astrophysical uncertainties on Darkside sensitivity :