Direct Detection and Astronomical Data

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Outline

- Dark matter direct detection
  - main aim
  - formalism
  - link to astronomical data $\Leftrightarrow \rho_\chi$, f_χ
- Local dark matter density, ρ_χ
- Local dark matter velocity distribution, f_χ

Dark matter direct detection

- It searches for nuclear recoil events induced by the non-relativistic scattering of Milky Way dark matter particles in low-background detectors

- Rate of nuclear recoil events:

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \sum_T \xi_T \frac{\rho_\chi}{m_T\, m_\chi} \int_{v > v_{\min}(E_R)} f_\chi(\mathbf{v} + \mathbf{v}_e(t))\, v\, \frac{\mathrm{d}\sigma_T}{\mathrm{d}E_R}(v^2, E_R)\, d^3 v$$

astronomical data

particle and nuclear physics input

Determination of ρ_χ and f_χ

- ρ_χ from astronomical data
  - local methods
  - global methods

- f_χ from astronomical data
  - global methods plus assumptions on the dark matter phase-space density F_χ

- They rely on the Jeans-Poisson system:

$$\Sigma(R,Z) = -\frac{1}{2\pi G}\left[\int_0^Z \mathrm{d}z\,\frac{1}{R}\frac{\partial(RF_R)}{\partial R} + F_z(R,Z)\right]$$

$$F_z(R,Z) = \frac{1}{\nu}\frac{(\nu\sigma_z^2)}{\partial z} + \frac{1}{R\nu}\frac{\partial(R\nu\sigma_{Rz})}{\partial R}$$

with

$$\Sigma(R,Z) = \int_{-Z}^{Z}\mathrm{d}z\sum_j \rho_j(R,z)$$

$$F_R(R,Z) = -\frac{\partial\Phi}{\partial R}$$

$$F_z(R,Z) = -\frac{\partial\Phi}{\partial z}$$

- Assume a mass model for the Milky Way:
  - $\mathbf{x} \to \rho_j(\mathbf{x}, \mathbf{p})$ — j mass densities at $\mathbf{x}$
  - $\mathbf{p} = (p_1, p_2, \dots)$ — model parameters

- Compute physical observables, e.g.:
  - Terminal velocities
  - Radial velocities
  - Velocity dispersion of stellar populations
  - Oort's constants
  - Sun's rotational velocity
  - Surface density
  - Optical depth for microlensing events

- Compare theory and observations

- Infer $\rho_\chi(\mathbf{x}_\odot, \mathbf{p})$ from $\mathbf{p}$

- Emphasis on correlations
  - Large number of model parameters, e.g. $\sim \mathcal{O}(10)$
  - One mass model
  - It allows to assess / identify correlations between parameters / observables
- Emphasis on systematics
  - Few model parameters, e.g. $\sim 2/3$
  - Many mass models can be tested
  - It allows to estimate the systematic error / theoretical bias that might affect the first approach

Determination of f_χ / Self-consistent methods

- Solve for F_χ the system:

$$\rho_\chi(\mathbf{x},\mathbf{p}) = \int \mathrm{d}\mathbf{v}\, F_\chi(\mathbf{x},\mathbf{v};\mathbf{p})$$

$$\mathbf{v}\cdot\nabla_{\mathbf{x}}F_\chi - \nabla_{\mathbf{x}}\Phi\cdot\nabla_{\mathbf{v}}F_\chi = 0 \qquad \text{(Vlasov)}$$

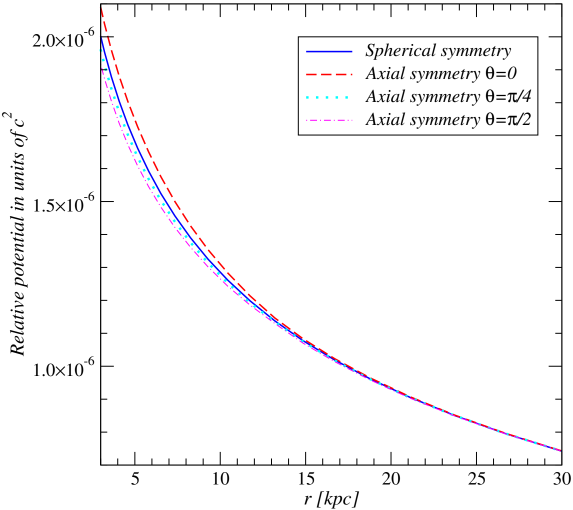
$$\nabla^2\Phi = 4\pi G\sum_j \rho_j \qquad \text{(Poisson)}$$

- Then: $f_\chi(\mathbf{v}) = F_\chi(\mathbf{x}_\odot,\mathbf{v};\mathbf{p})/\rho_\chi(\mathbf{x}_\odot,\mathbf{p})$

- If $\rho_\chi(r)$ and $\Phi(r)$ are **spherically symmetric**, and $F_\chi(\mathbf{x},\mathbf{v}) = F_\chi(\mathbf{x},|\mathbf{v}|)$ is **isotropic**, then:
  - $F_\chi(\mathbf{x},\mathbf{v}) = F_\chi(\mathcal{E})$, where $\mathcal{E} = -1/2|\mathbf{v}|^2 + \psi$ and $\psi = -\Phi + \Phi_{vir}$
  - There is a unique self-consistent solution for F_χ

- It is given by

$$F_\chi(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2}\left[\int_0^{\mathcal{E}} \frac{d^2\rho_\chi}{d\psi^2}\frac{d\psi}{\sqrt{\mathcal{E}-\psi}} + \frac{1}{\sqrt{\mathcal{E}}}\left(\frac{d\rho_\chi}{d\psi}\right)_{\psi=0}\right]$$

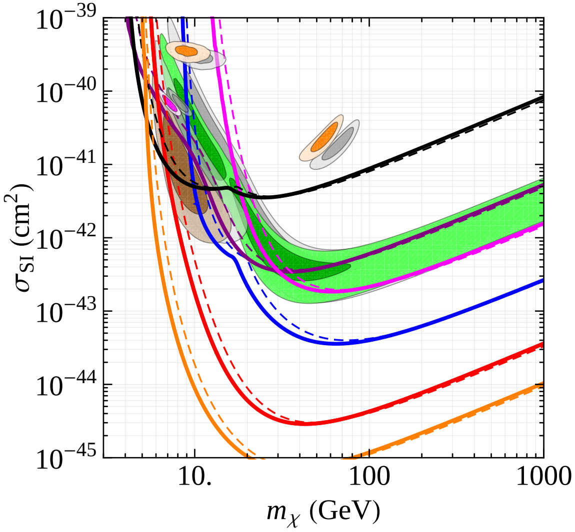

2.0×10^-6
1.5×10^-6
1.0×10^-6
Relative potential in units of c^2
5
10
15
20
25
30
r [kpc]
Spherical symmetry
Axial symmetry θ=0
Axial symmetry θ=π/4
Axial symmetry θ=π/2

- If $\rho_\chi(r)$ and $\Phi(r)$ are **spherically symmetric**, and $F_\chi(\mathbf{x}, \mathbf{v})$ is **anisotropic**, then:
  - $F_\chi(\mathbf{x}, \mathbf{v}) = F_\chi(\mathcal{E}, L)$
  - There is not a unique self-consistent solution for F_χ

- Solutions exist if, e.g.
  - $F_\chi(\mathcal{E}, L) = G(\mathcal{E}) L^{2\gamma}$
  - $F_\chi(\mathcal{E}, L) = F\left(\mathcal{E} - \frac{L^2}{2r_a^2}\right)$

- If $\rho_\chi(R, z)$ and $\Phi(R, z)$ are **axisymmetric** then:
  - $F_\chi(\mathbf{x}, \mathbf{v}) = F_\chi(\mathcal{E}, L_z)$
  - ρ_χ only determines the even part of F_χ under $\mathbf{v} \to -\mathbf{v}$
  - Moments $\int \mathrm{d}^3\mathbf{v}\, v_i^\alpha F_\chi$, α odd, fix the odd part of F_χ under $\mathbf{v} \to -\mathbf{v}$
- Formal solutions exist but are numerically unstable. Progress has to be done!

Impact of ρ_χ and f_χ on exclusion limits / preferred regions



Summary

- The interpretation of direct detection experiments depends on astronomical data through ρ_χ and f_χ
- ρ_χ can be inferred from astronomical data using local and global methods
- f_χ requires a global method and additional assumptions on F_χ

Outline

Riccardo:

1. Astrophysical uncertainties: local DM density and velocity distribution
2. Effect on direct detection observables
3. How to measure the local DM density
4. How to measure the local DM velocity distribution

Mattia:

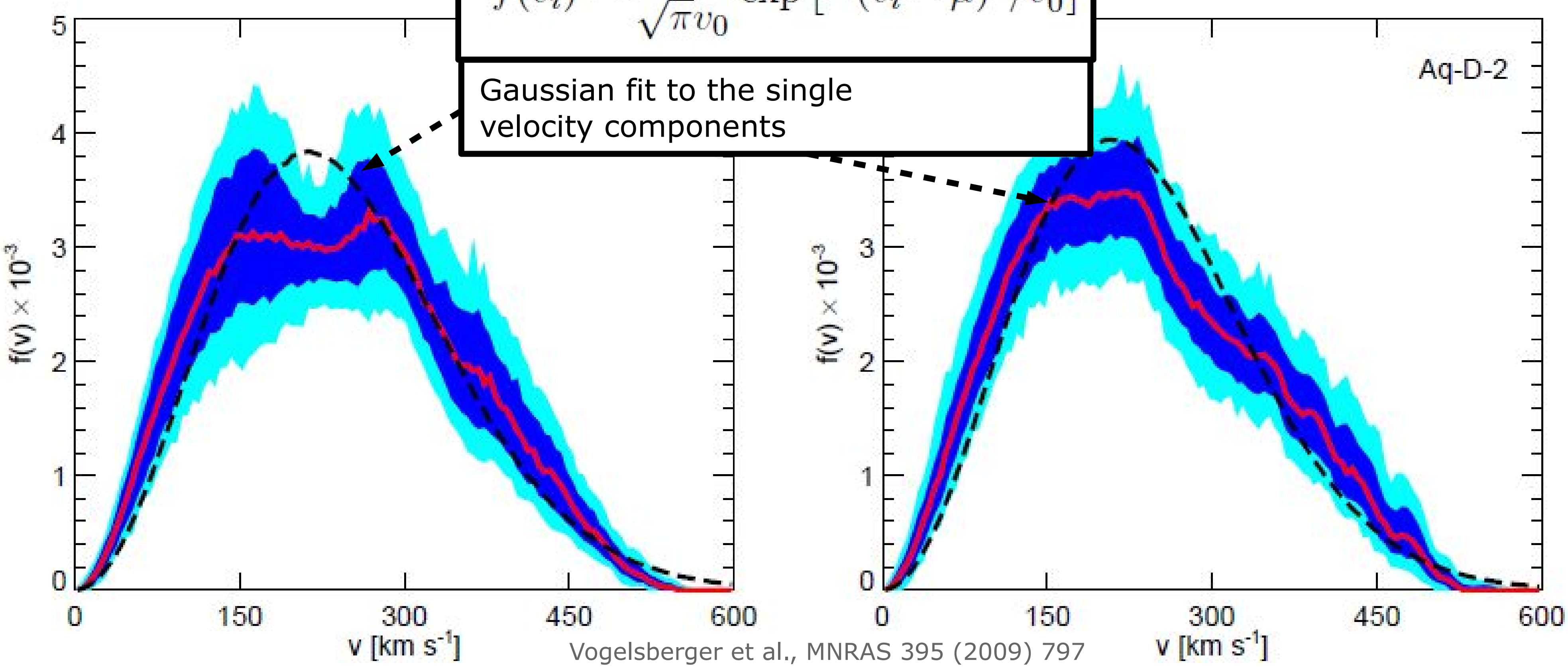
5. What simulations tell us about local DM density and velocity distribution
6. Future prospects for the local DM density
7. Future prospects for the local velocity distribution

Dark-Matter-only simulations

- *f*(*v*) from boxes with a size of 2 kpc between 7 and 9 kpc
- less DM particles in the peak and more with a larger speed
- local spikes position-independent and related to the history of the halo

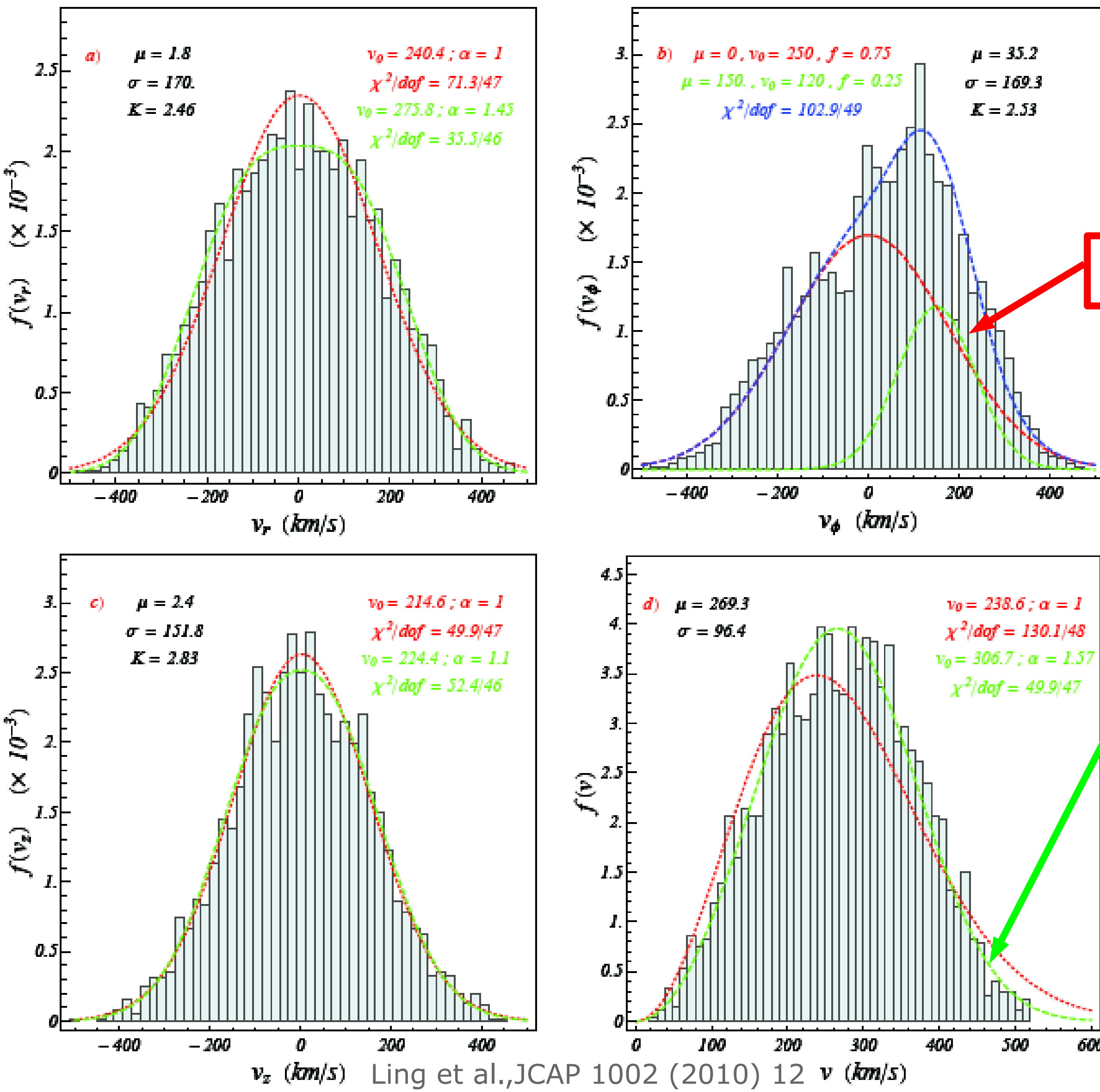
$$f(v_i) = \frac{1}{\sqrt{\pi} v_0} \exp\left[-(v_i - \mu)^2 / v_0^2\right]$$

Gaussian fit to the single velocity components



Vogelsberger et al., MNRAS 395 (2009) 797

Hydrodynamical sim. (Ling et al. 2010)



Ling et al.,JCAP 1002 (2010) 12

- $f(v)$ from particles with 7 kpc < R < 9 kpc and |z|<1 kpc

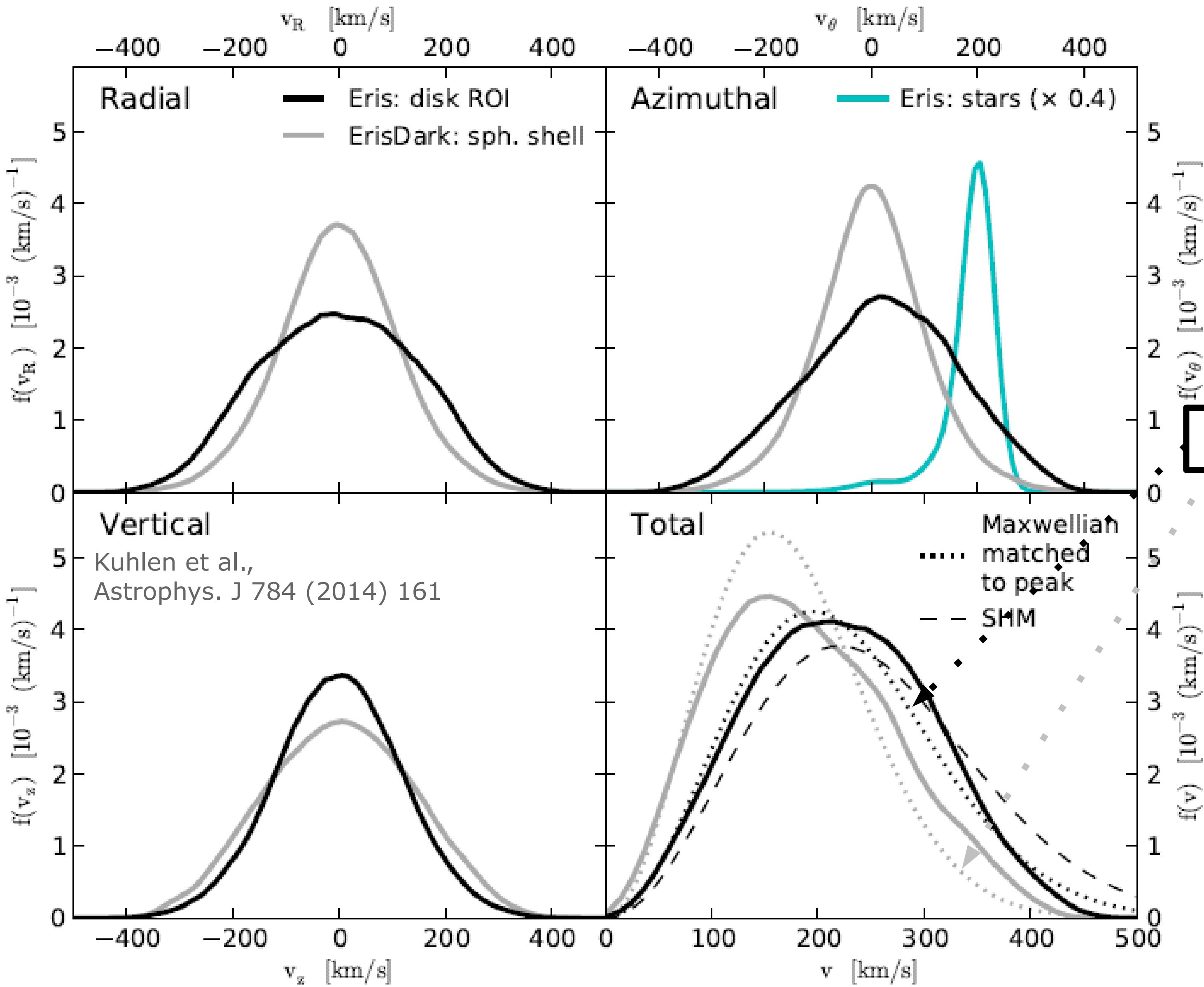
Gaussian or Maxwellian fit

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

Generalised Gaussian or Maxwellian fit

- generalised Maxwellian provides a better fit than standard one
- tangential velocity not symmetrical

Eris hydrodynamical simulation



- $f(v)$ from particles with 7 kpc < R < 9 kpc and |z|<2 kpc
- $f(v)$ in a spherical shell with 4 kpc < r < 12 kpc

Matched Maxwellian

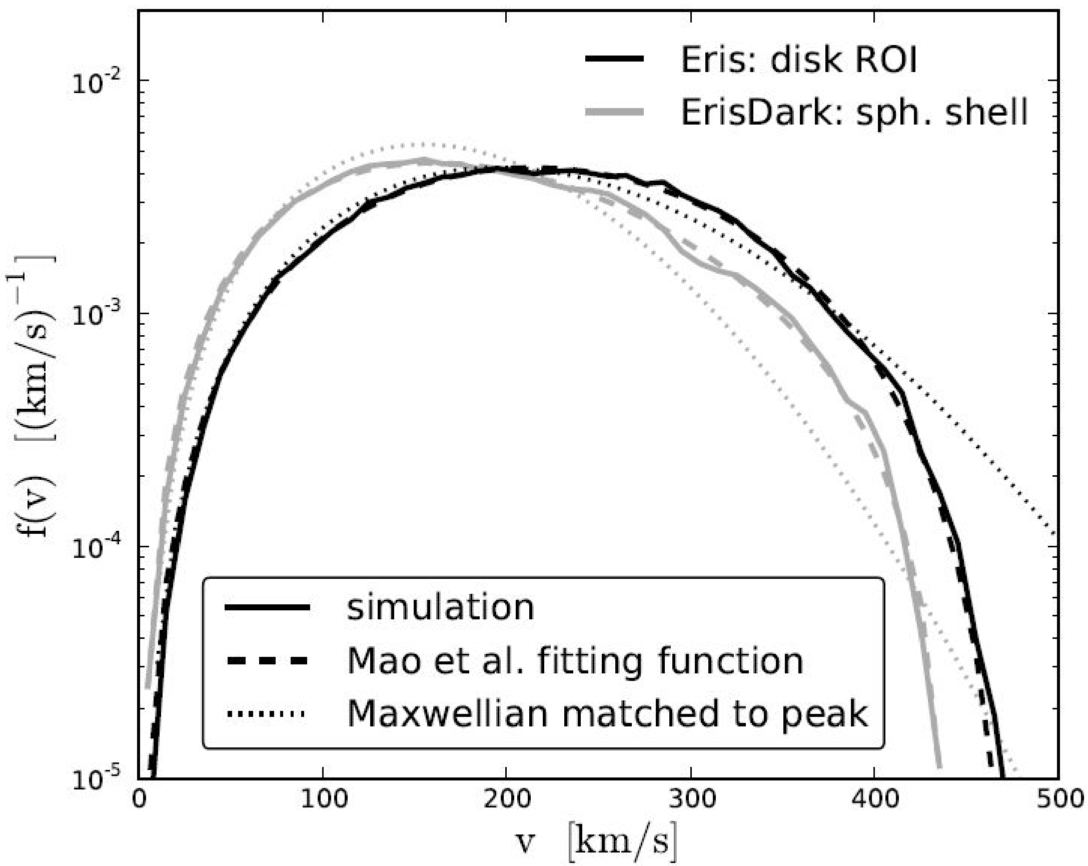
- Maxwellian provides better fits if baryons are included
- though not the best one

Eris hydrodynamical simulation

- best-fit description provided by the function in Mao et al., Astrophys. J. 764 (2013) 35

$$f(v) = \begin{cases} A\, v^2 \exp(-v/v_0) \, \left(v_{\rm esc}^2 - v^2\right)^p & \text{if } v \le v_{\rm esc}, \\ 0 & \text{otherwise,} \end{cases}$$

Kuhlen et al., Astrophys. J 784 (2014) 161



Dark disk

- the dark disk has a $\rho(R_0)$ from 0.25 and 1.5 times the density of the non-rotating DM component
- its lag velocity with respect to stars is between 0 and 150 km/s

Read et al., MNRAS 397 (2009) 44

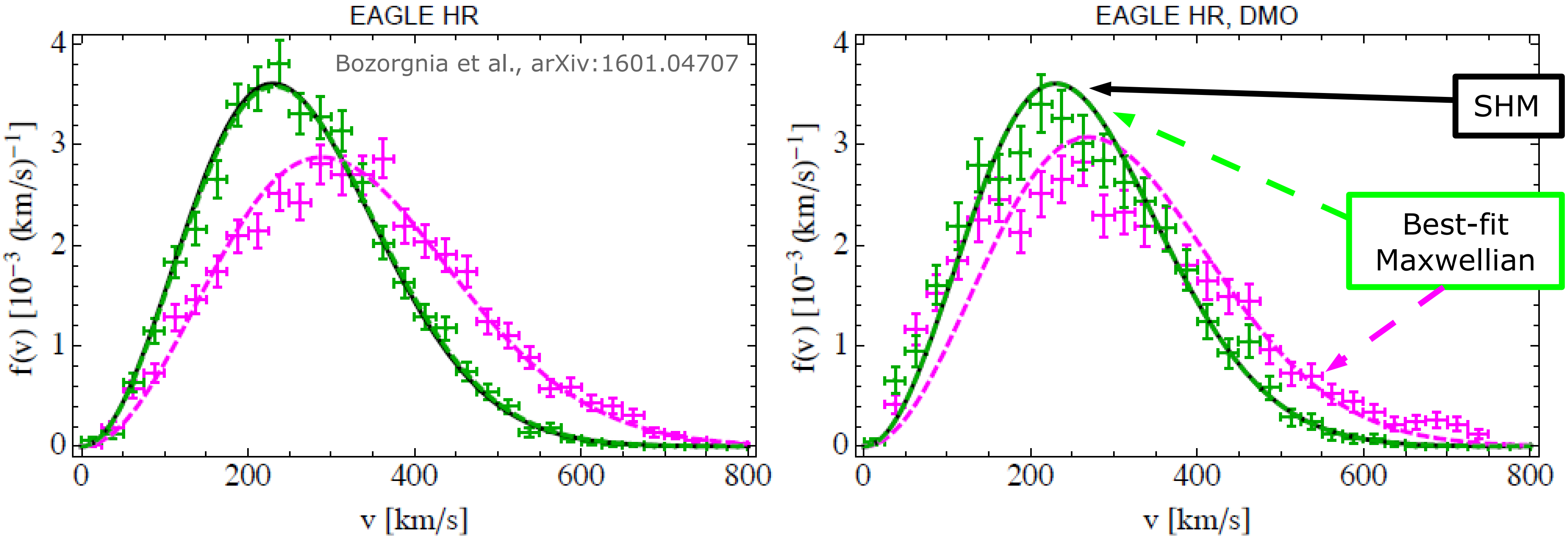
- Ling et al.: $\rho(R_0)$=0.31 GeV/cm^3 (in a spherical shell between 7 and 9 kpc) and 0.39 GeV/cm^3 in the "torus"
- Ling et al.: dark disk contributes 25% of $\rho(R_0)$ and v_{lag}=75 km/s

Ling et al.

- Eris: $\rho(R_0)$=0.42 GeV/cm^3 (in the disk) and it is 34% larger than the density in the spherical shell at R_0, and 31% larger than $\rho(R_0)$ from ErisDark
- following accretion of subhalos, estimate of dark disk is 9.1% of $\rho(R_0)$, i.e. 1/3 of the excess in the local density in Eris

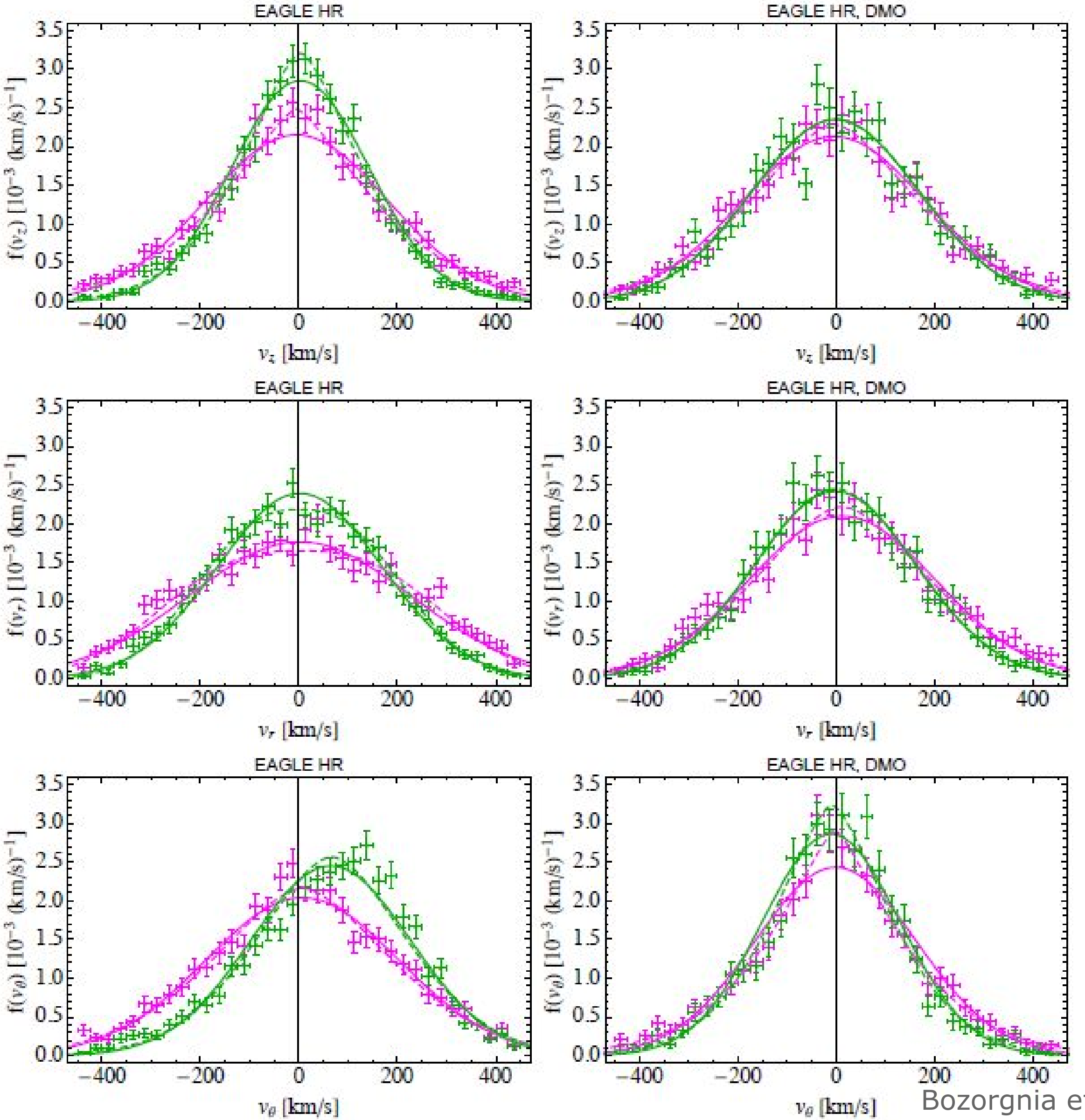
Eris

EAGLE and APOSTLE hydro. simulations



- $f(v)$ from particles with 7 kpc < R < 9 kpc and |z|<2 kpc
- gives some sense of halo-to-halo scatter (14 halos in EAGLE and 2 halos in APOSTLE)
- closest or further away from SHM
- Maxwellian fits better simulations with baryons than without
- Mao et al. $f(v)$ is still the one with the best-fit solution

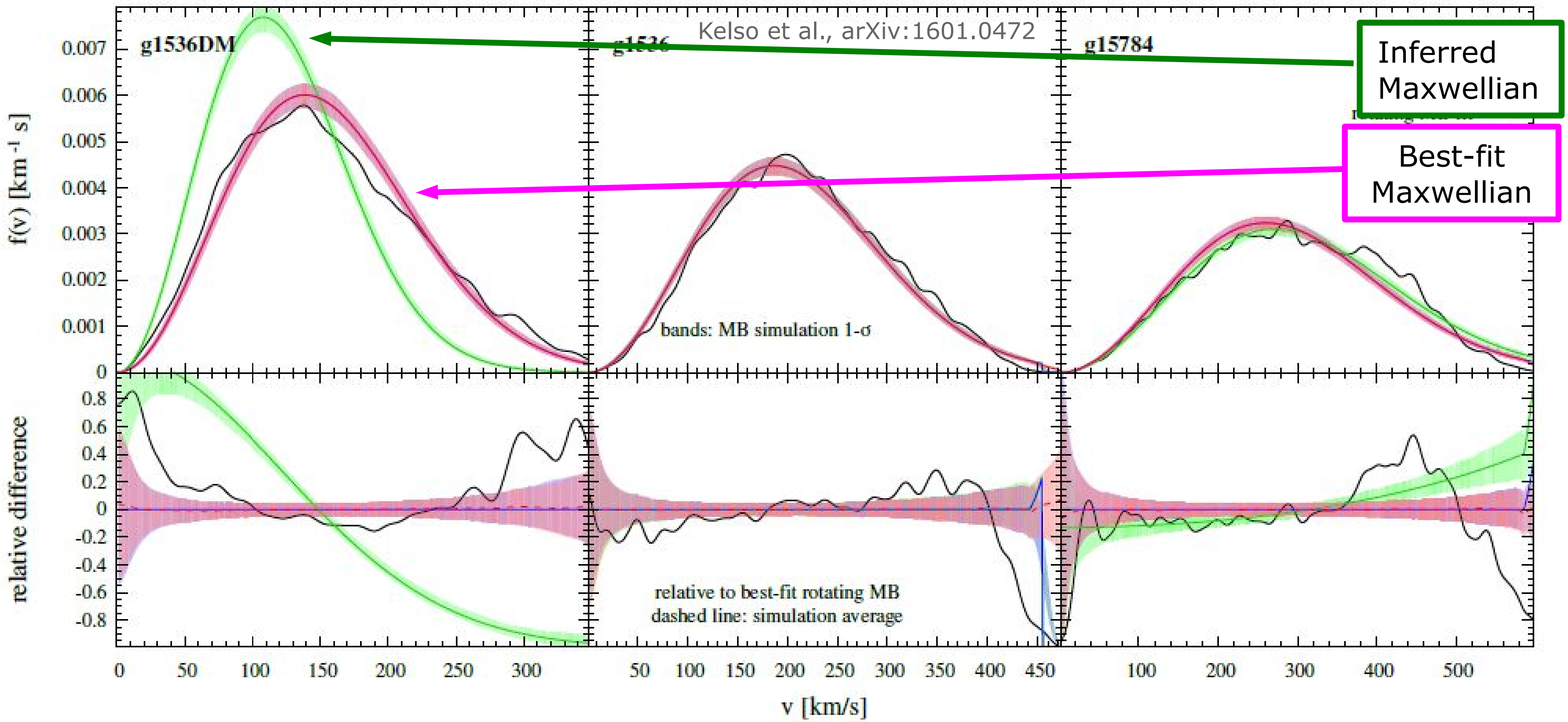
EAGLE and APOSTLE hydro. simulations



- tangential velocity is not symmetric: |μ| is different from zero at more than 3σ for 4 of the 14 halos in EAGLE
- only 2 of those halos have a DM component co-rotating with stars at the same velocity
- $\rho(R_0)$=0.42-0.73 GeV/cm^3
- enhancement with respect to spherical shell is >10% for 5 halos and >20% for 2 halos

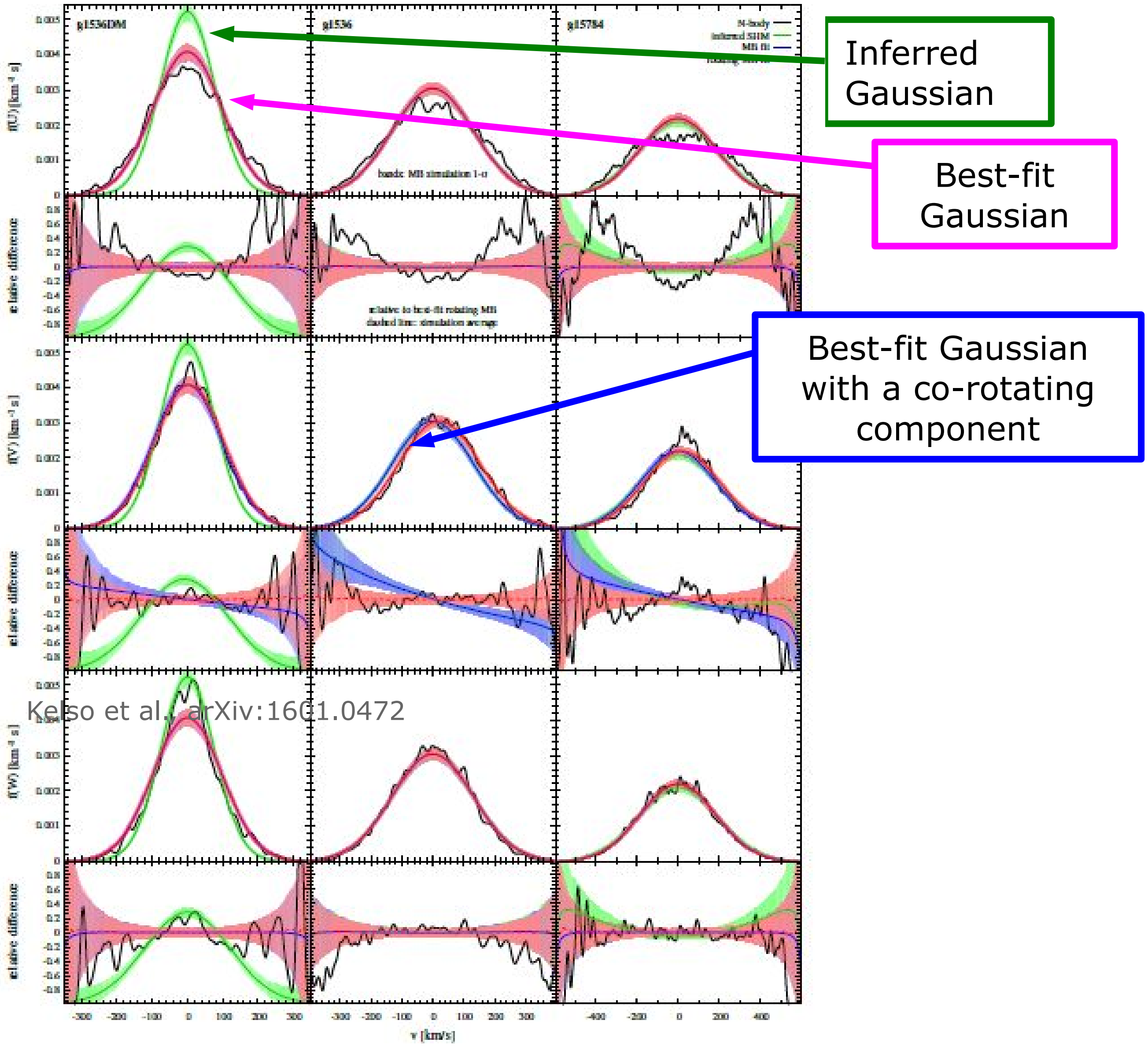
Bozorgnia et al., arXiv:1601.04707

MaGICC hydrodynamical simulations



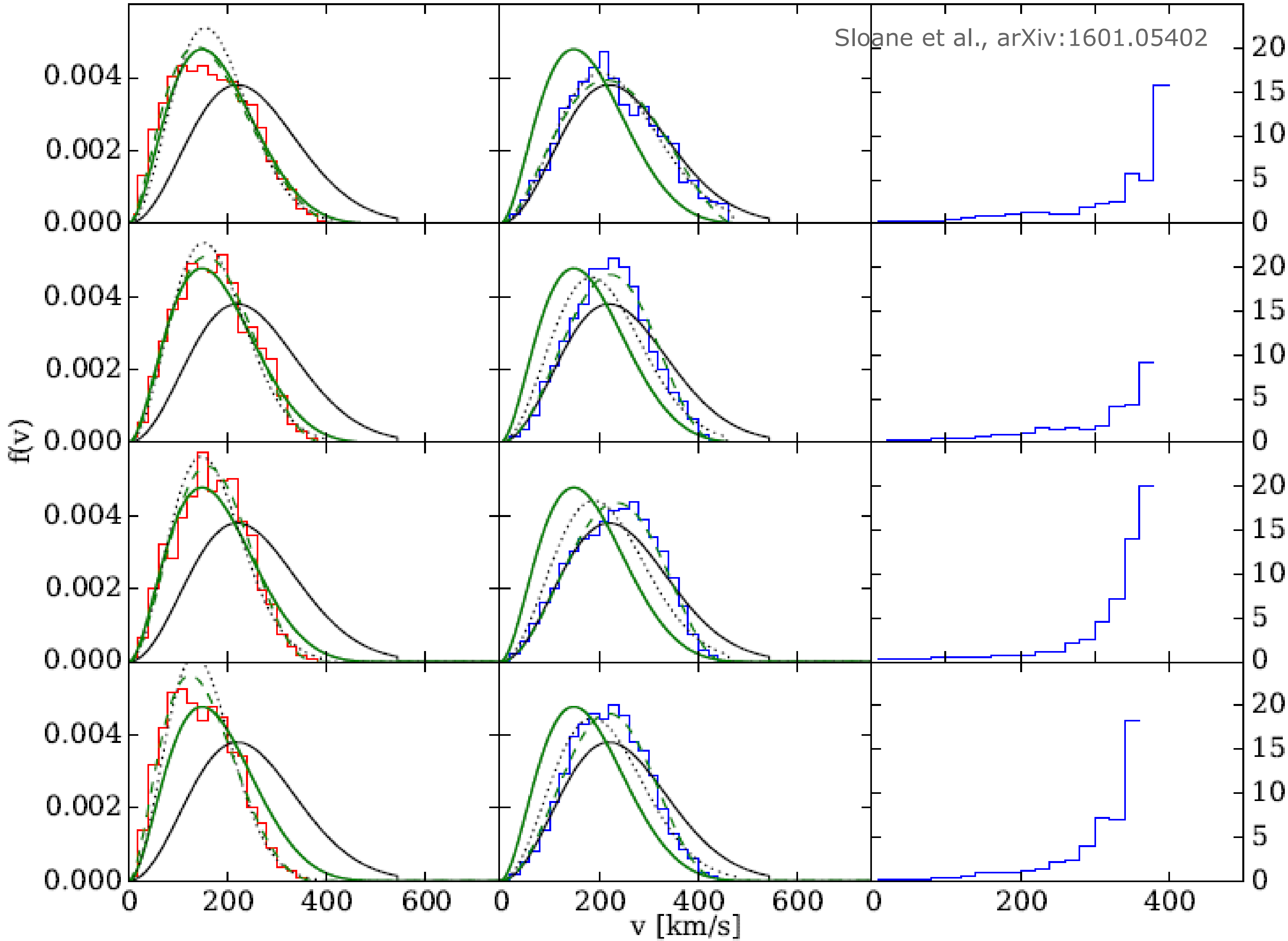
- $f(v)$ from particles within a torus on the disk, centred on 8 kpc and the section with a radius of 2kpc
- "inferred" Maxwellian: using a v_0 *inferred from the enclosed mass at* R_0

MaGICC hydrodynamical simulations



Kelso et al., arXiv:1601.0472

NIHAO hydrodynamical simulations



Silverhood et al., arXiv:1507.08581

$\rho(R_0)$ from vertical velocity dispersion

- Jeans analysis to reconstruct the local surface density in a direction perpendicular to the Galactic plan $\Sigma(z,R_0)$
- measurements exist up to 1.1 kpc
- data at larger *z* are needed to discriminate baryons and DM

$$\underbrace{\frac{1}{R\nu}\frac{\partial}{\partial R}(R\nu\sigma_{Rz})}_{\text{'tilt' term: }\mathcal{T}} + \underbrace{\frac{1}{R\nu}\frac{\partial}{\partial\phi}\left(\nu\sigma_{\phi z}\right)}_{\text{'axial' term: }\mathcal{A}} + \frac{1}{\nu}\frac{d}{dz}\left(\nu\sigma_z^2\right) = \underbrace{-\frac{d\Phi}{dz}}_{K_z}$$

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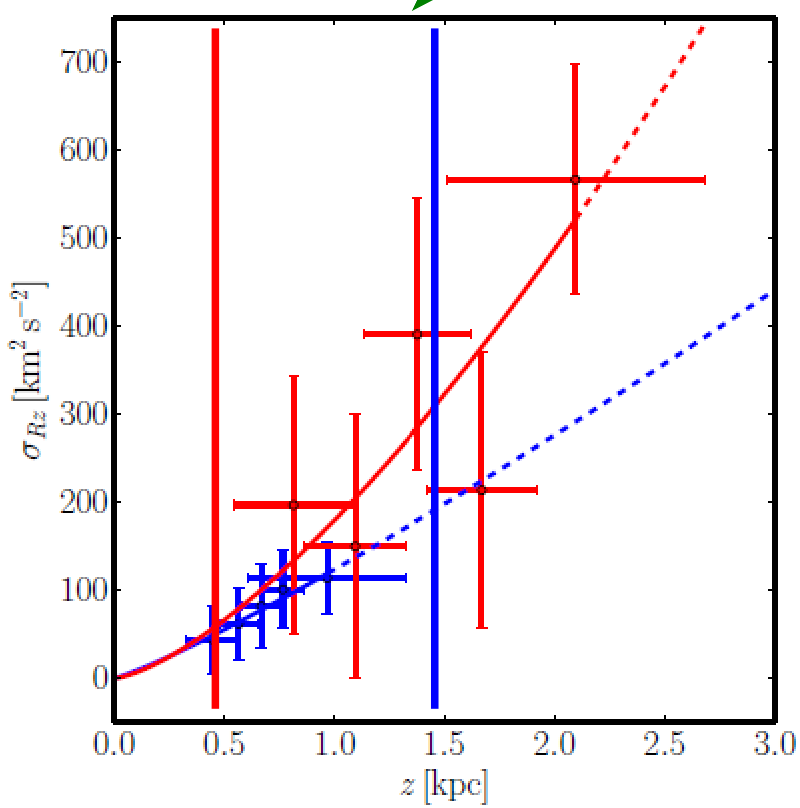
- Poisson equation
- model baryonic component $\rho_{\rm baryons}(z)$ and $\rho_{\rm DM}(z)$, e.g. a constant (i.e. $\rho(R_0)$) or a dark disk component

$$\frac{\partial^2\Phi}{\partial z^2} = 4\pi G\rho(z)_{\rm eff} \qquad \rho(z)_{\rm eff} = \rho(z) - \frac{1}{4\pi G R}\frac{\partial V_c^2(R)}{\partial R}$$

$$\rho_{\rm baryon}(z) = \frac{1}{4\pi G}\left|\frac{K_{\rm bn}D_{\rm bn}^2}{(D_{\rm bn}^2+z^2)^{1.5}}\right| \qquad \rho_{\rm DM}(z) = \rho_{\rm DM,const.} + \frac{1}{4\pi G}\sum_n\left|\frac{K_{{\rm DD},n}D_{{\rm DD},n}^2}{(D_{{\rm DD},n}^2+z^2)^{1.5}}\right|$$

ρ(R_0) from vertical velocity dispersion

$$\underbrace{\frac{1}{R\nu}\frac{\partial}{\partial R}(R\nu\sigma_{Rz})}_{\text{'tilt' term: }\mathcal{T}} + \underbrace{\frac{1}{R\nu}\frac{\partial}{\partial\phi}\left(\nu\sigma_{\phi z}\right)}_{\text{'axial' term: }\mathcal{A}} + \frac{1}{\nu}\frac{d}{dz}\left(\nu\sigma_z^2\right) = \underbrace{-\frac{d\Phi}{dz}}_{K_z}$$



Silverhood et al., arXiv:1507.08581

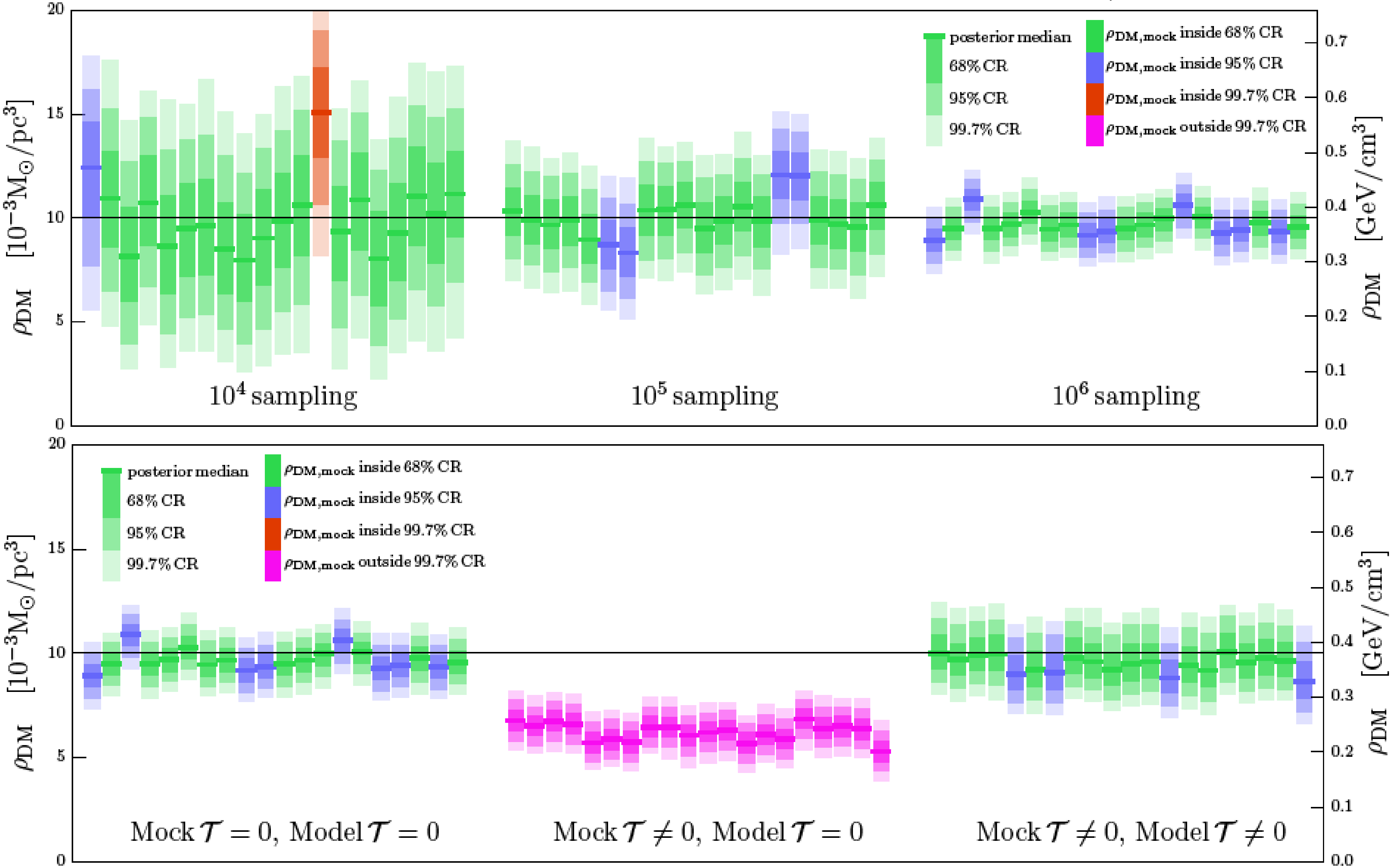
$$\rho_{\text{baryon}}(z) = \frac{1}{4\pi G}\left|\frac{K_{\text{bn}}D_{\text{bn}}^2}{(D_{\text{bn}}^2 + z^2)^{1.5}}\right|$$

$$\rho_{\text{DM}}(z) = \rho_{\text{DM,const.}} + \frac{1}{4\pi G}\sum_n \left|\frac{K_{\text{DD},n}D_{\text{DD},n}^2}{(D_{\text{DD},n}^2 + z^2)^{1.5}}\right|$$

- assuming you know tracers, parameters in the source term can be reconstructed by fitting data in σ^2_z
- tracer density and tilt term are modelled: more parameters but also more data!

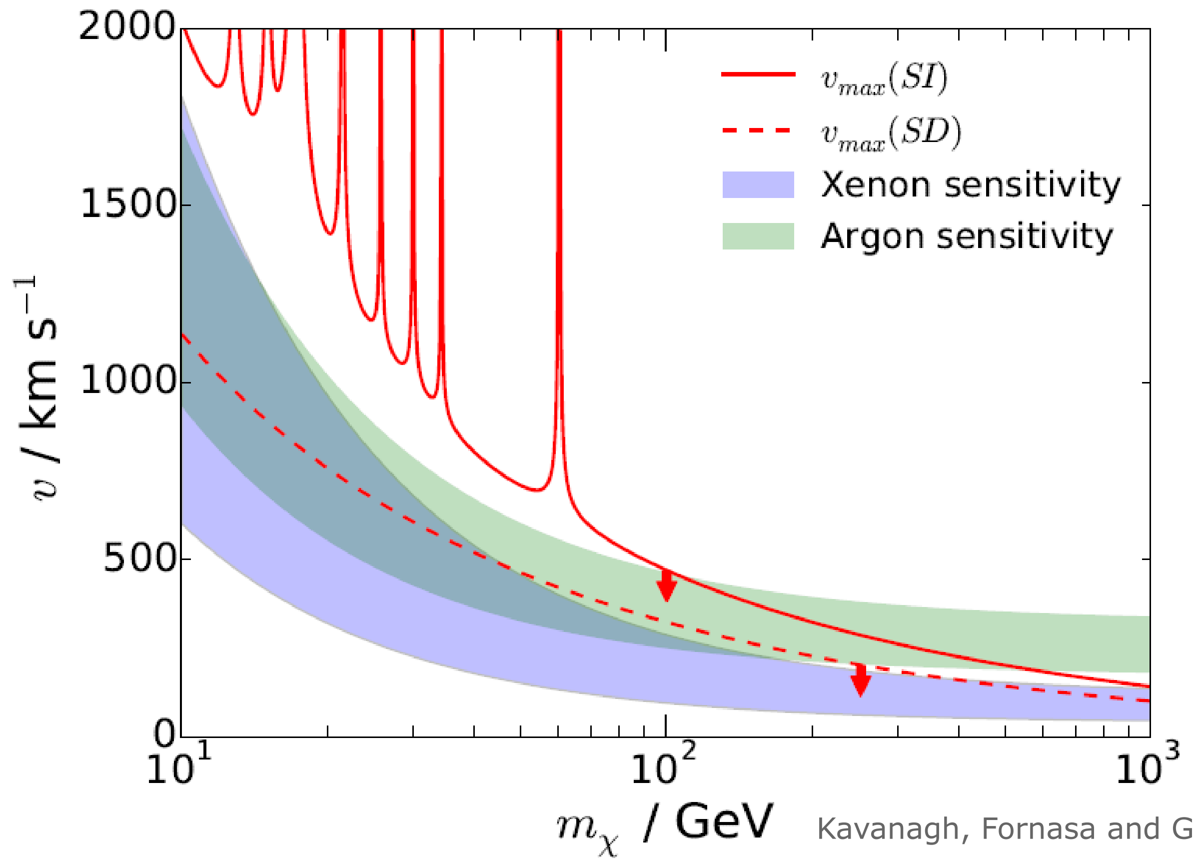
ρ(R_0) from vertical velocity dispersion

Silverhood et al., arXiv:1507.08581



Determine $f(v)$ with direct detection

- assume a certain number of recoil events is observed
- normally $f(v)$ is assumed (parametrised) to reconstruct DM properties (m_χ and $\sigma^{SI}_{p,\chi}$)
- use direct detection to determine the parameters of $f(v)$ alongside m_χ and $\sigma^{SI}_{p,\chi}$

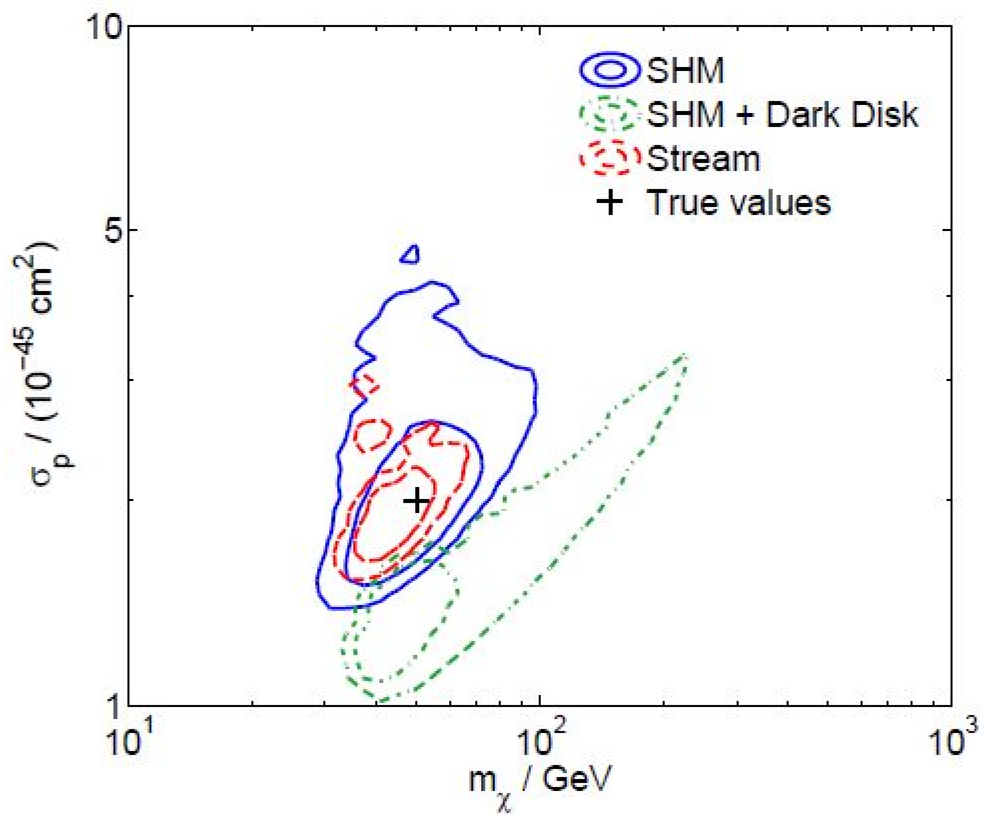


Kavanagh, Fornasa and Green, Phys. Rev. D91 (2015) 103533

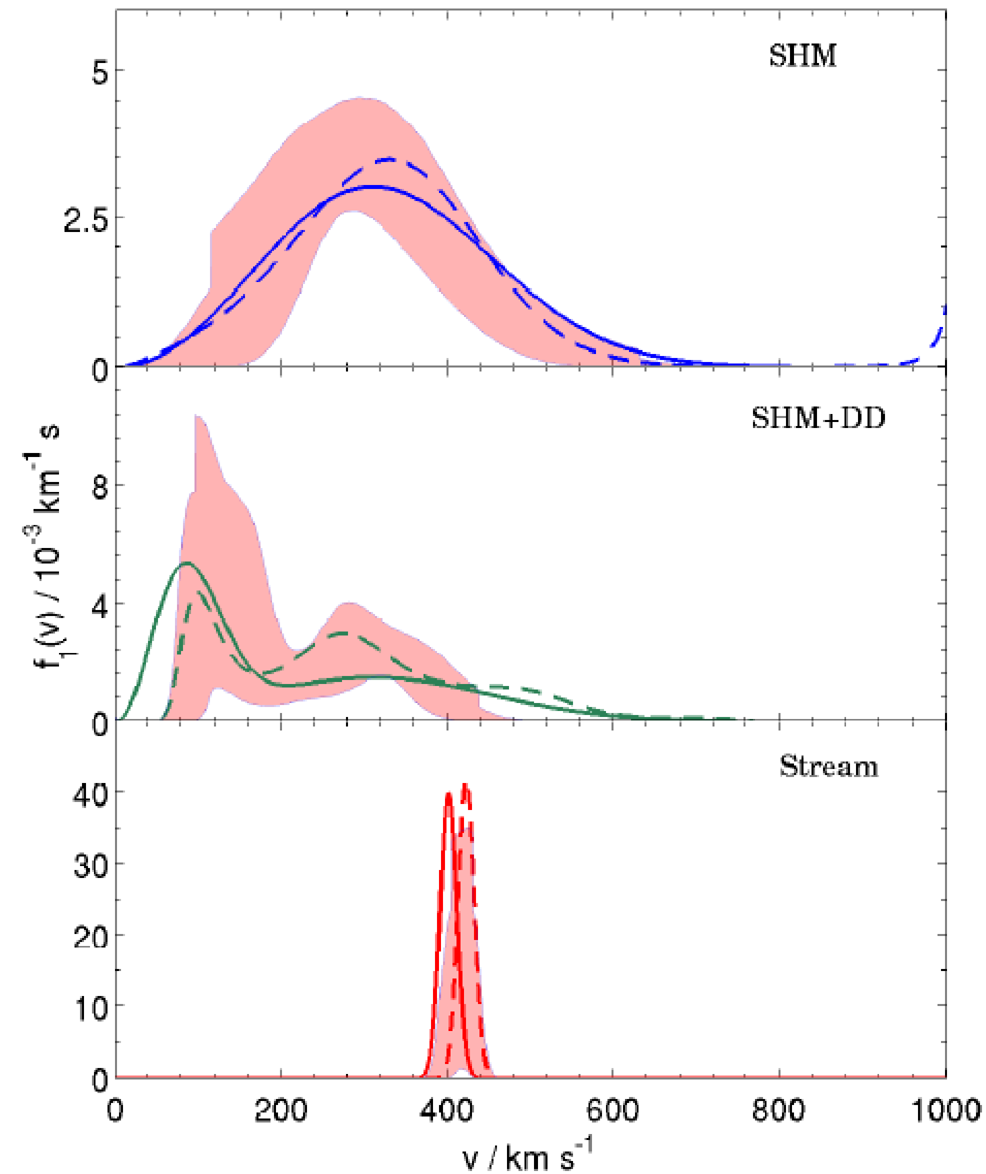
$$f(v) \propto \exp\left\{-\sum_{k=0}^{N} a_k \tilde{P}_k\left(\frac{v}{v_{\max}}\right)\right\}$$

- test procedure with mock data, i.e fix DM candidate and $f(v)$ and check if you reconstruct nominal values
- prove possible degeneracies and biases

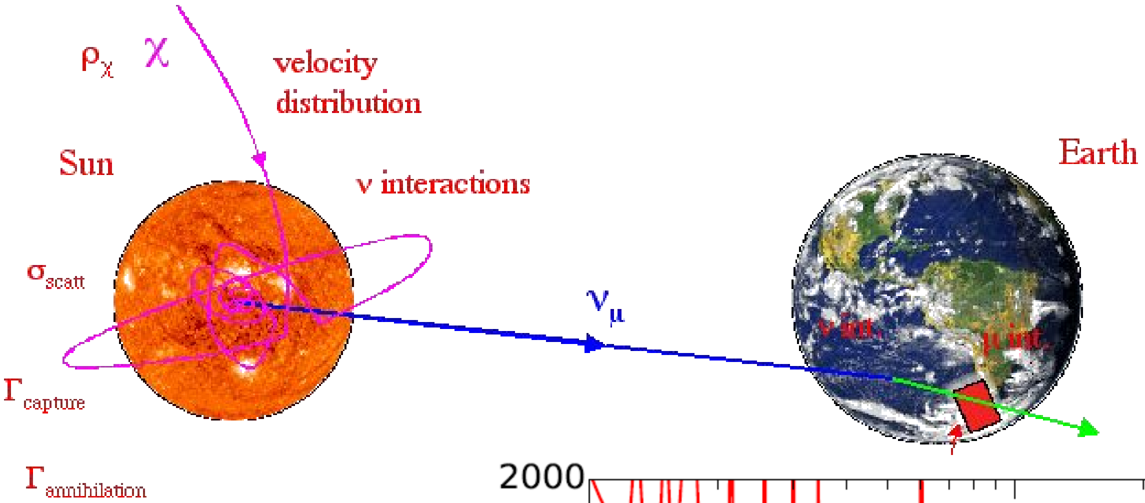
Model independent reconstruction of m_χ



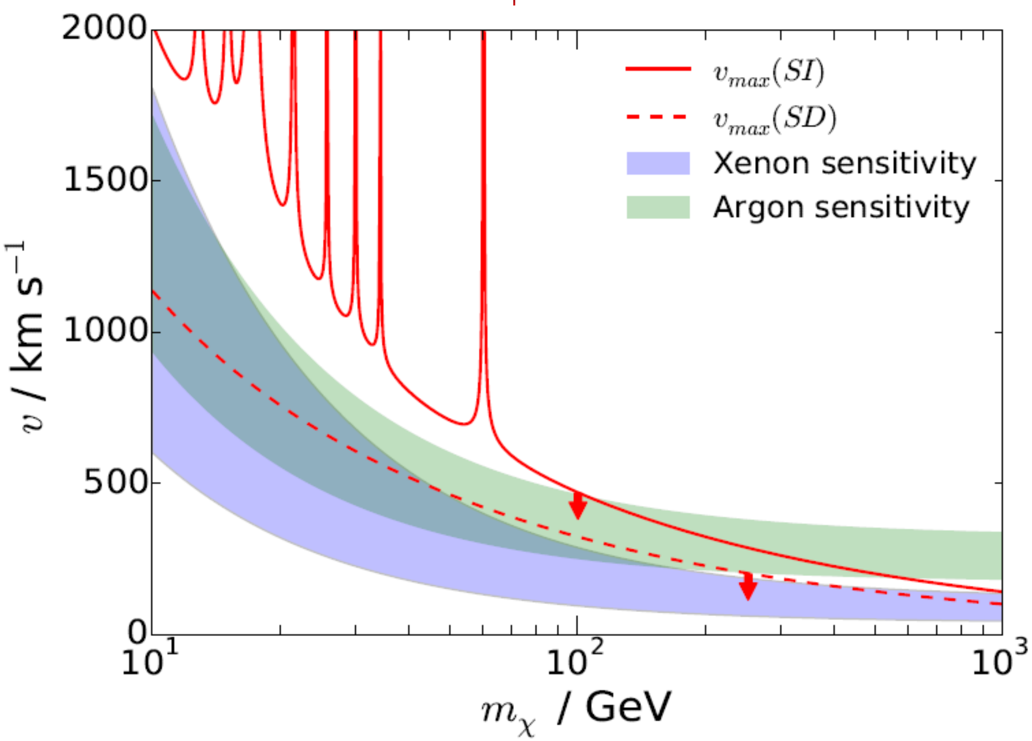
Kavanagh & Green, Phys. Rev. Lett. 111 (2013) 013302



Probing the low-*v* tail of *f*(*v*) with neutrino telescopes



- DM particles scatter with the Sun and gets capture
- their annihilations produce neutrinos that can be seen by IceCube



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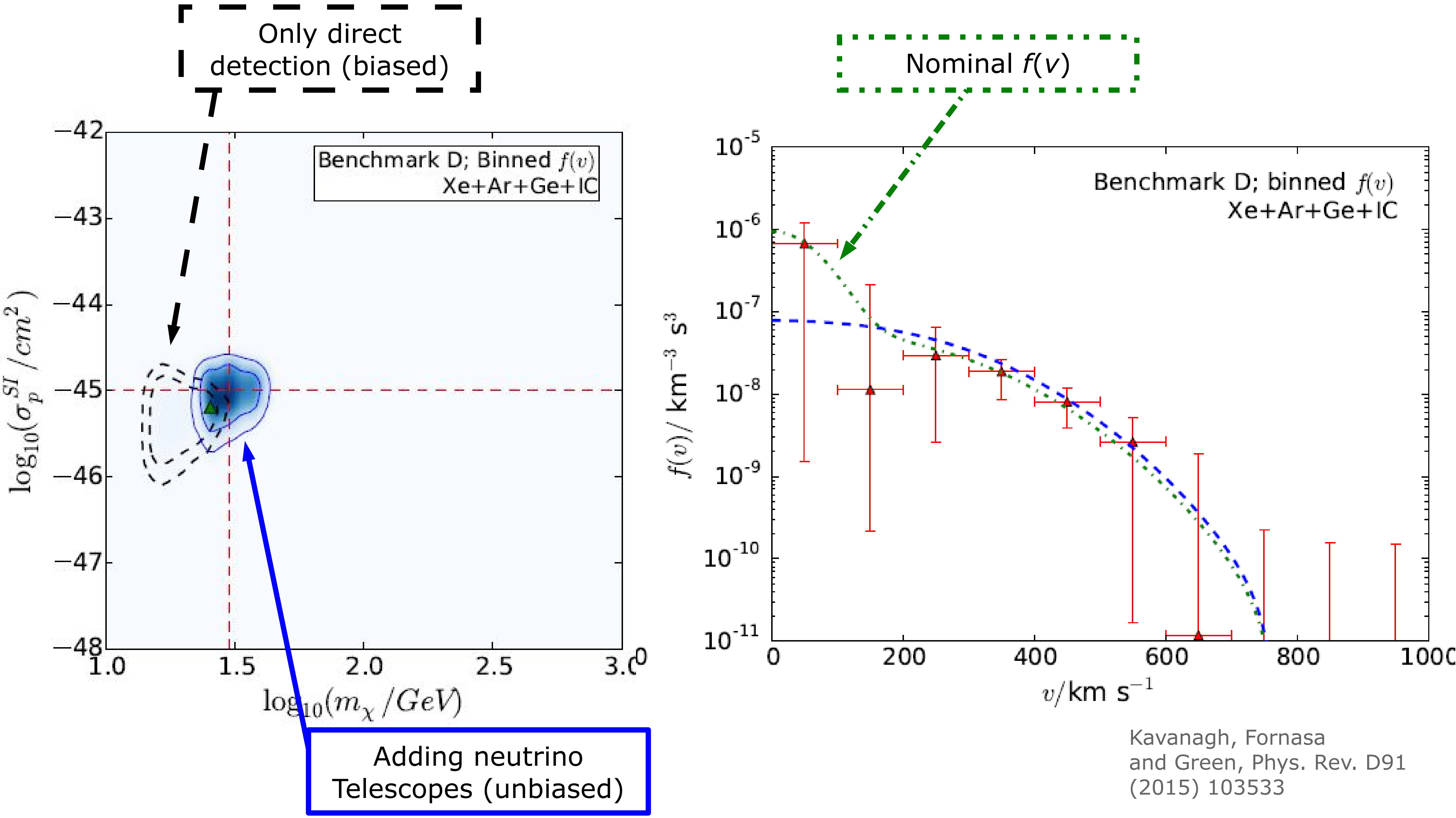

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Conclusions

- Simulations: $f(v)$ from hydrodynamical simulations peak at a higher speed but are well described by a Maxwellian $f(v)$
- Simulations: need for statistics (dark disk)
- Future: great expectations from Gaia (vertical velocity dispersion)
- Future: a signal in direct detection (and neutrinos from the Sun) would allow the beginning of WIMP astronomy