Physical model of observable stellar kinematics in dwarf galaxies for indirect dark matter studies

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Premises & Motivation

Dwarf spheroidal satellite galaxies of the Milky Way:

ideal targets for Dark Matter (DM) indirect detection

- nearby
- DM dominated
- low γ-ray contamination
- low Galactic foregrounds

Searching for DM decay or annihilation products (e^+, e^-, γ…)

Photon flux from DM annihilation:

$$\Phi_\gamma(\Delta\Omega) = \underbrace{\frac{\langle\sigma v\rangle}{2m^2}\int_{E_{\min}}^{E_{\max}}\frac{\mathrm{d}N}{\mathrm{d}E_\gamma}\mathrm{d}E_\gamma}_{\text{particle physics factor}}\underbrace{\frac{1}{4\pi}\int_{\Delta\Omega}\int_{l.o.s}\rho^2(r(l))\mathrm{d}l\,\mathrm{d}\Omega}_{\text{J factor}}$$

(Bergström et al. 1998)

- **one of main uncertainties in the statistical analysis of the γ-ray data**
- **previously obtained via analysis of stellar motions via Jeans equation**

Approximate approach partially exploiting stellar kinematics information

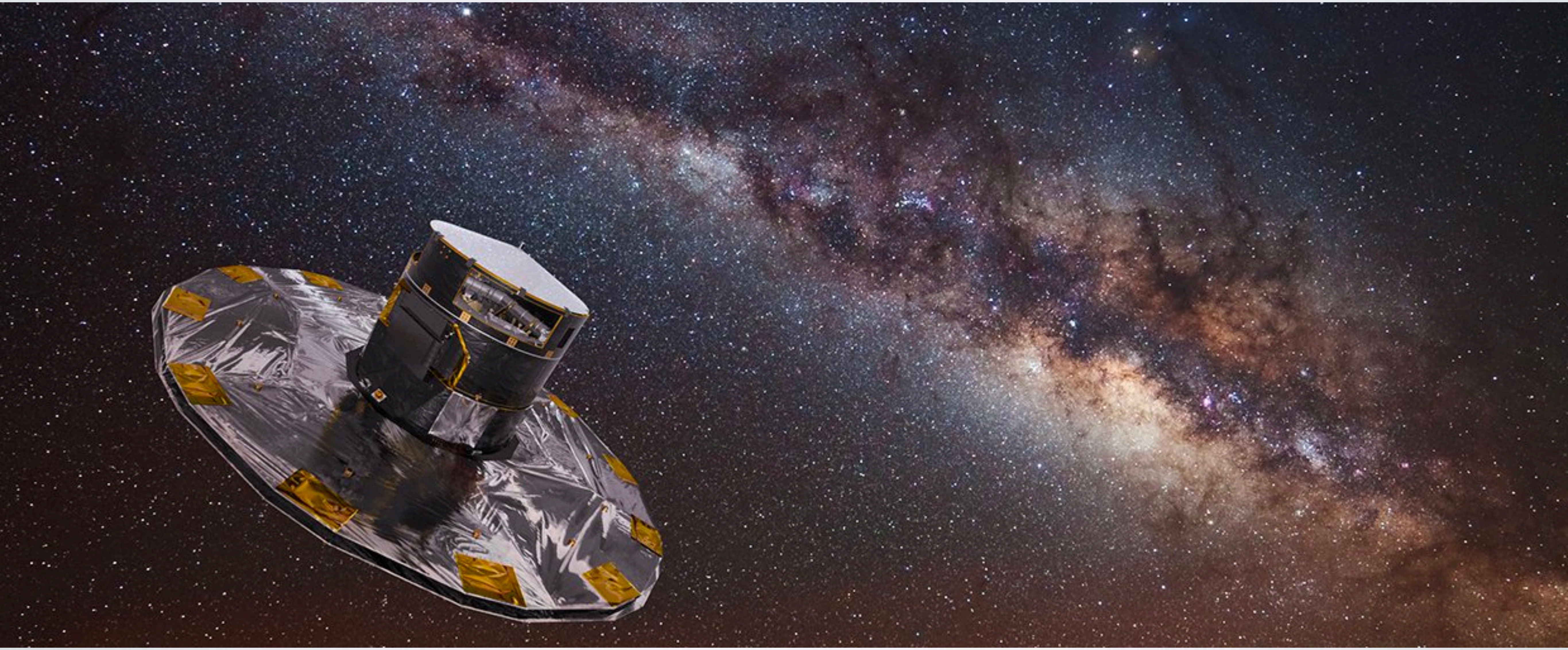
Objectives & Scope

- Build a physical model of stellar stellar kinematics in dwarf satellite galaxies
- Derive the expression of observable - projected - velocity distribution functions
- Use all available information on stellar motions from observational campaigns
- Use projected velocity distribution functions for model regression given the data
- Validate the method on a simulation suite and determine model systematics
- Apply the method on real stellar kinematics data to determine system configuration
- Characterise the underlying DM halo properties to estimate the ***J-factor***
- Employ *J*-factors to analyse high-energy data to search for particle DM

Stellar kinematic data: GAIA era

Old stellar kinematics: stellar *line-of-sight* velocities and position projected onto plane of the sky

GAIA astrometric mission:
- measurements of stellar 3D position and motion on plane of the sky
- observations of bright stars in dwarf spheroidal satellite galaxies
- census of 1 billion stars in the Milky Way
- operative until December 2022
- five public data releases scheduled



Physical model of stellar kinematics

Generalisation of Jeans Equation approach:
build physical model of stellar dynamics in a galaxy and derive its projections

$$f(\epsilon) = \frac{1}{\sqrt{8}\pi^2} \int_{\Psi^{-1}(\epsilon)}^{\infty} \frac{\mathrm{d}r}{\sqrt{\epsilon - \Psi(r)}} \left[\frac{\mathrm{d}\nu}{\mathrm{d}r} \frac{\mathrm{d}^2\Psi}{\mathrm{d}r^2} \left(\frac{\mathrm{d}\Psi}{\mathrm{d}r} \right)^{-2} - \frac{\mathrm{d}^2\nu}{\mathrm{d}r^2} \left(\frac{\mathrm{d}\Psi}{\mathrm{d}r} \right)^{-1} \right]$$

Eddington formula (Eddington 1911)

Physical model of stellar dynamics:
6-dimensional, phase-space distribution function of stellar velocities
depends on total gravitational potential **Ψ**
and on stellar density profile **ν**
(case of isotropic stellar velocities)

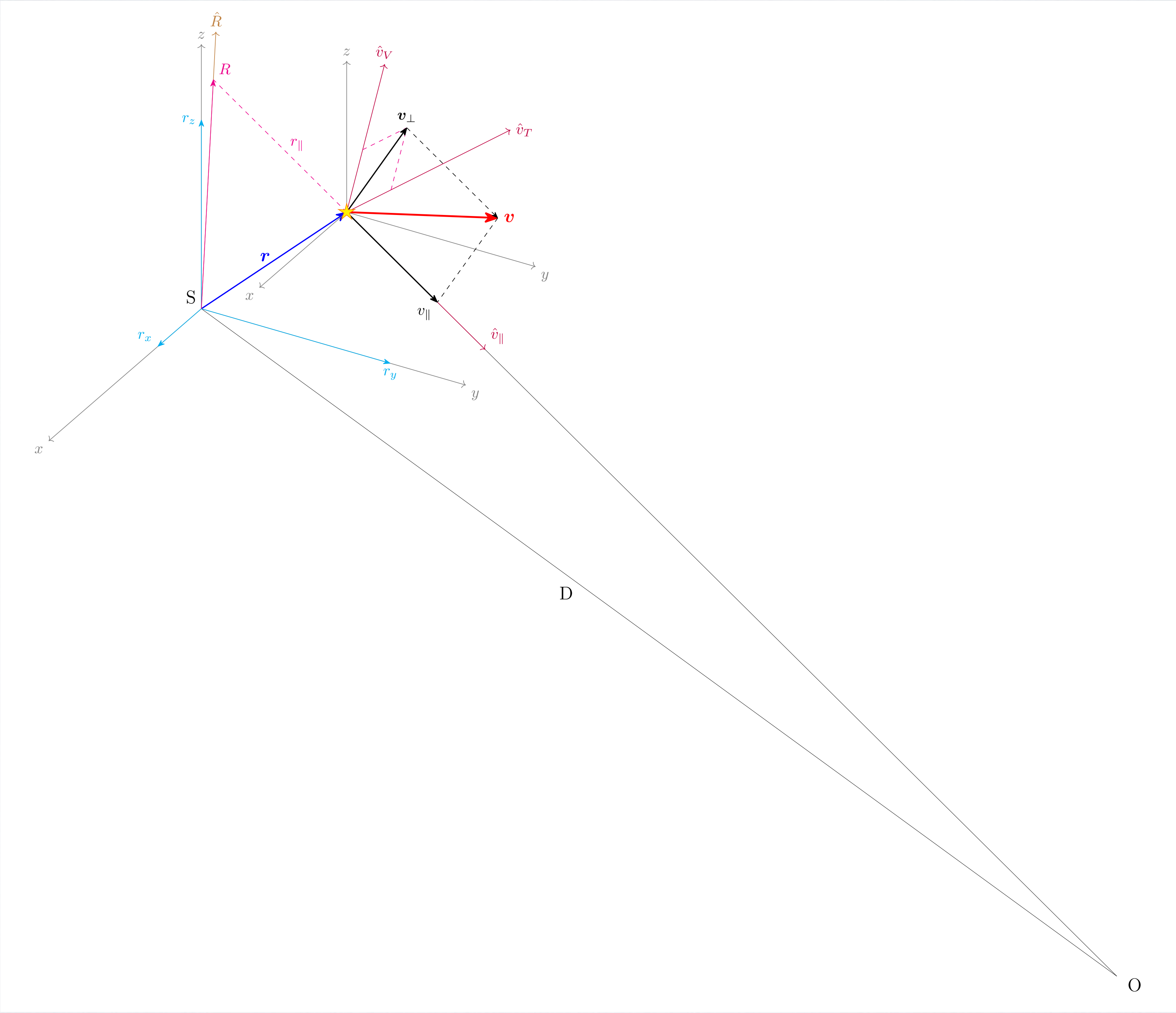
$$F_R(v_\parallel) = \frac{\int \mathrm{d}r_\parallel \, \mathrm{d}^2\boldsymbol{v}_\perp \, f(\boldsymbol{r}, \boldsymbol{v})}{\int \mathrm{d}r_\parallel \, \mathrm{d}^3\boldsymbol{v} \, f(\boldsymbol{r}, \boldsymbol{v})}$$

Distribution function of *line-of-sight* (*los*) stellar velocities: components of stellar velocities projected onto the line of observation from Earth to the star, observed at a distance *R* from the centre of the system

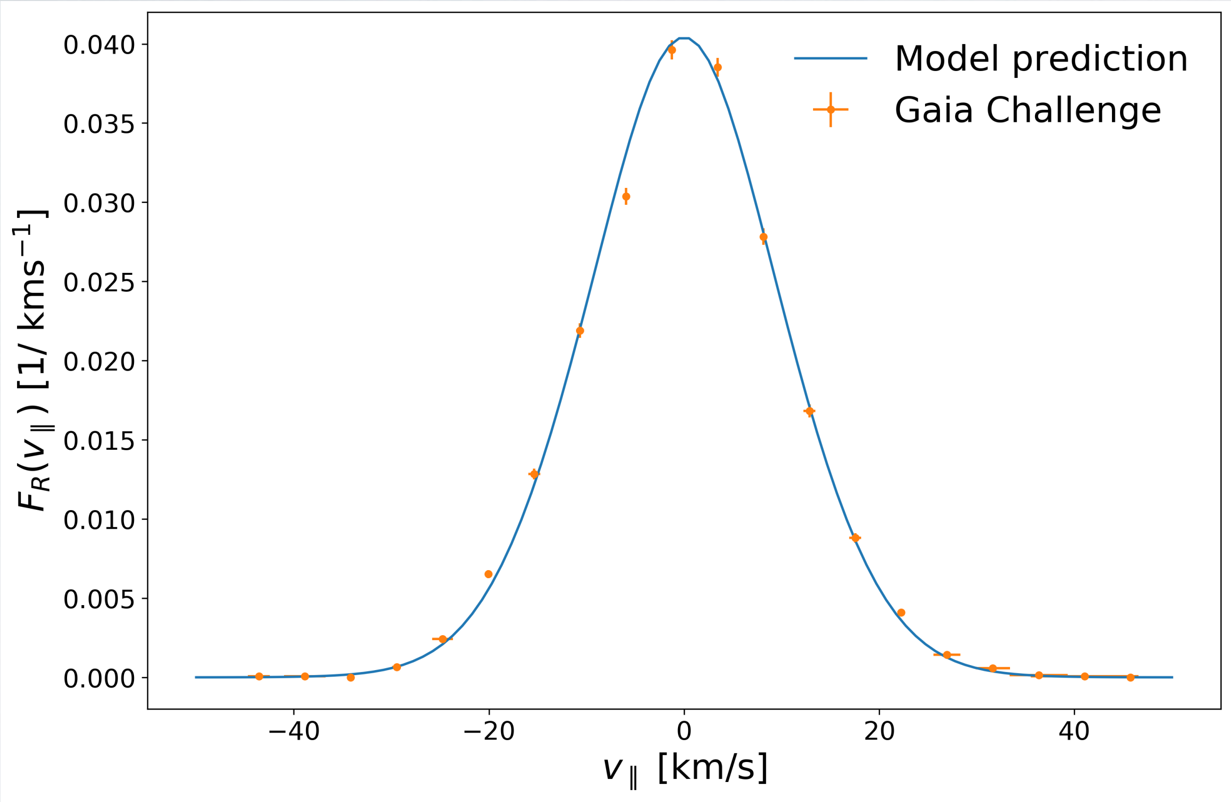
$$F_R(\boldsymbol{v}_\perp) = \frac{\int \mathrm{d}r_\parallel \, \mathrm{d}v_\parallel \, f(\boldsymbol{r}, \boldsymbol{v})}{\int \mathrm{d}r_\parallel \, \mathrm{d}^3\boldsymbol{v} \, f(\boldsymbol{r}, \boldsymbol{v})}$$

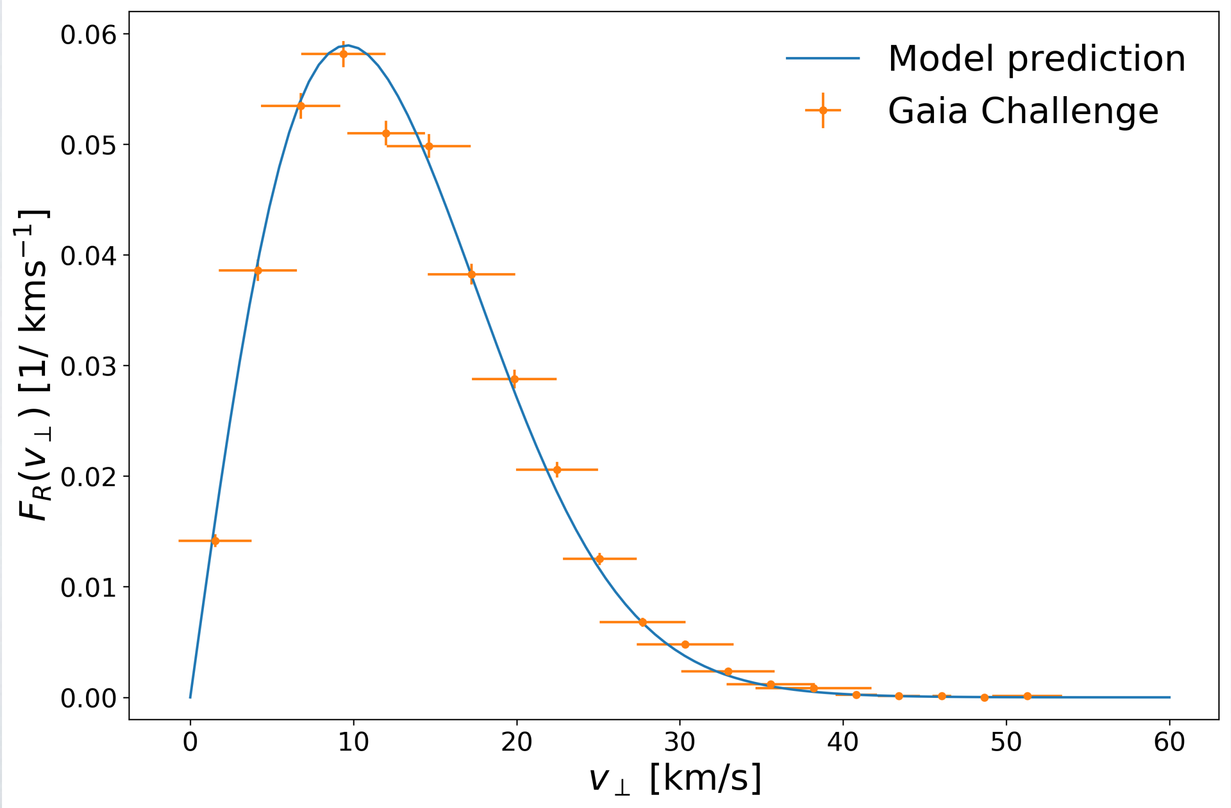
Distribution function of *orthogonal* stellar velocities: components of stellar velocities projected onto the plane on the sky orthogonal to the line of observation from Earth to the star, at a distance *R* from the centre of the system

Projection of stellar velocity



Results on simulations I

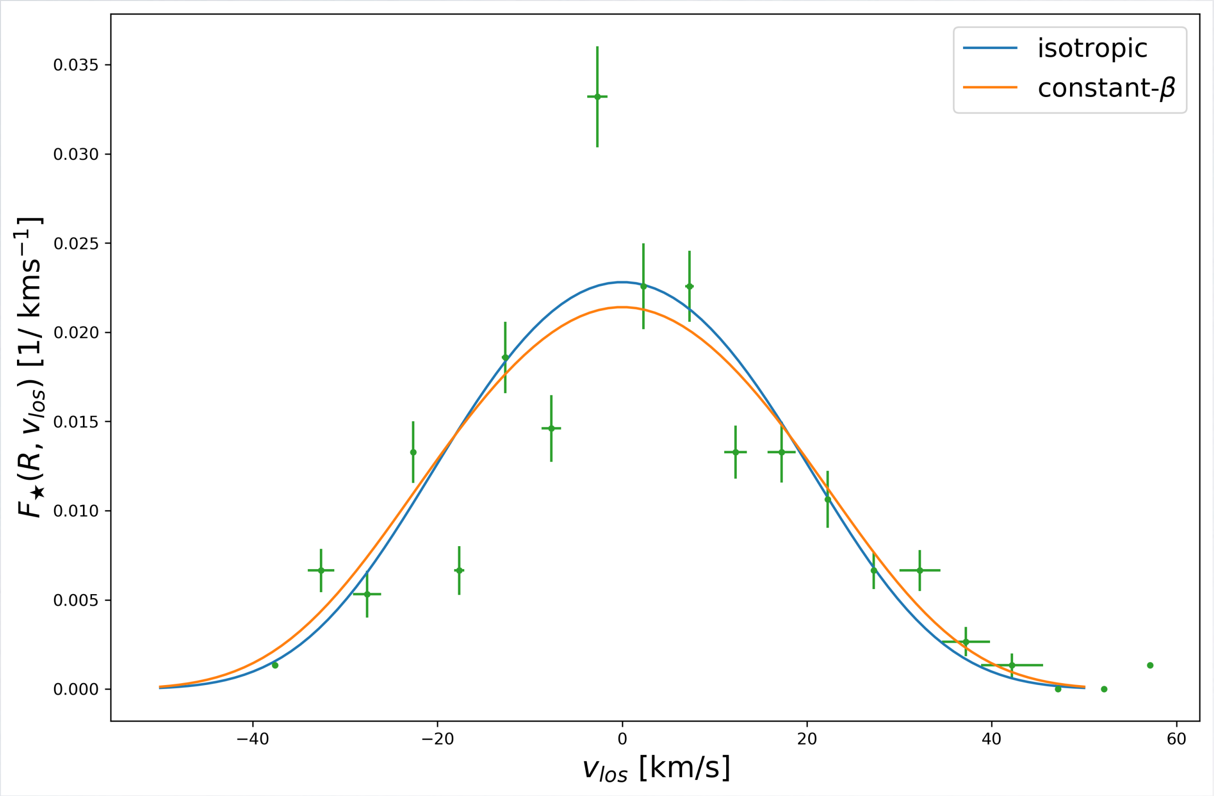


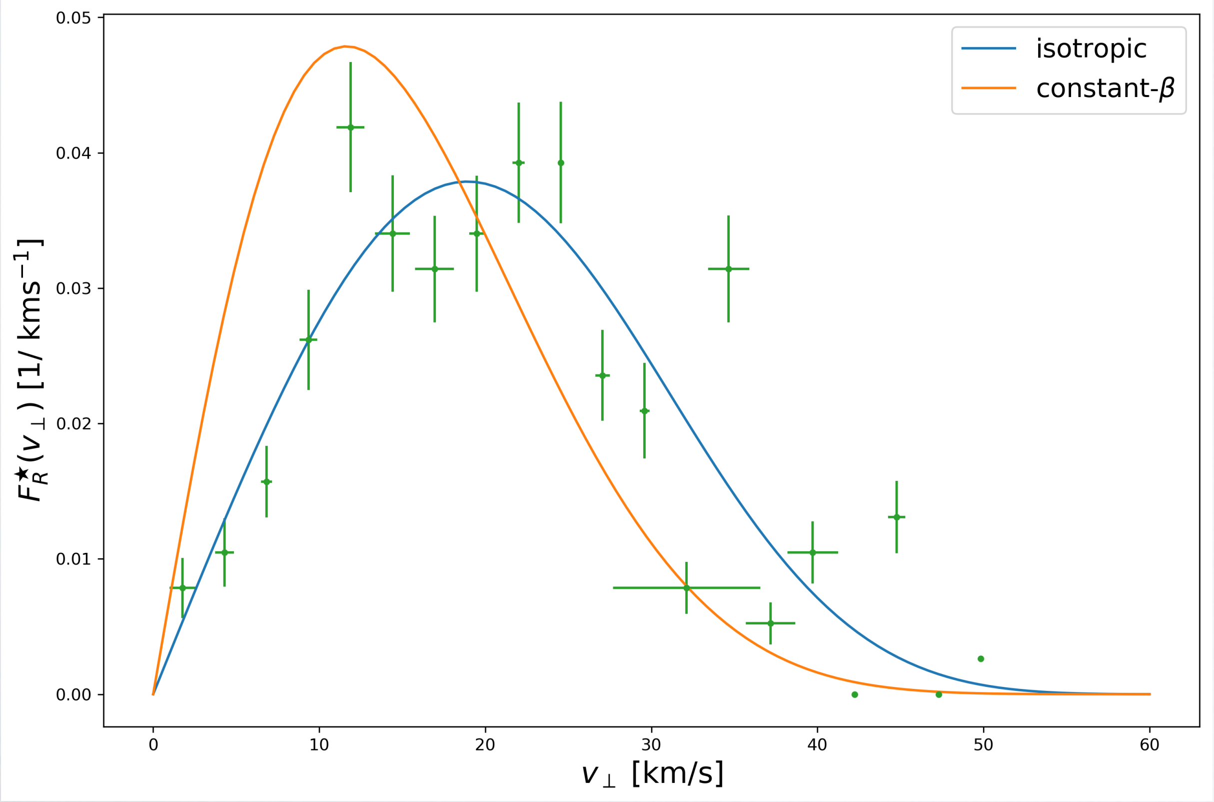


- Data points:
  Gaia Challenge simulation suite projected along an arbitrary *los* binned in R and in $v_\parallel$ (top) binned in R and in $v_\perp$ (bottom)
- Model prediction (blue curve): distribution function of *los* stellar velocities at the projected radial distance R (top)

  distribution function of *orthogonal* stellar velocities to the *los* at the projected radial distance R (bottom)
- Error bars: from simulated measurement uncertainties on the velocities

Results on simulations II





- Data points:
  APOSTLE simulation suite
  projected along an arbitrary *los*
  binned in *R* and in $v_{/\!/}$ (top)
  binned in *R* and in $v_\perp$ (bottom)

- Isotropic stellar velocities (blue):
  distribution function of *los* stellar velocities (top)
  distribution function of *orthogonal* stellar velocities (bottom)

- Constant-β velocity anisotropy (orange):
  distribution function of *los* stellar velocities (top)
  distribution function of *orthogonal* stellar velocities (bottom)

- Error bars: from simulated measurement uncertainties on the velocities

Future work

- Extend formalism to more general models of dwarf galaxies (Ψ, ν, anisotropy)
- Convolute the projected velocity distributions with the *pdf* of measurements
- Implement the expressions of the projected velocity distribution into fitting scheme
- Perform the validation on the *Gaia Challenge* simulation suite
- Perform model regression on real stellar kinematics data (latest **Gaia** data release)
- Infer the properties of dwarf satellite galaxies and the underlying DM halo
- Employ *J*-factors to analyse high-energy data to search for particle DM