Galactic model fitting

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14th June 2019

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Gaia DPAC Data Processing & Analysis Consortium

gaia

Vetenskapsrådet

Rymdstyrelsen Swedish National Space Agency

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Model of the Galaxy

???

Charge is measured from a Gaia (or other) CCD

So this is a broad question…

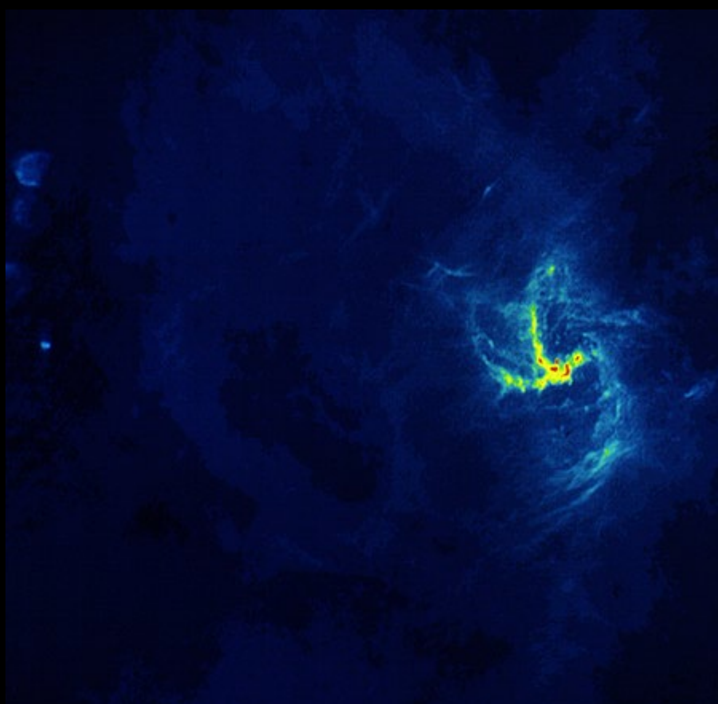
I'm going to focus on fitting dynamical models to learn what the gravitational potential is.

Mostly the disc.

Therefore local dark matter density, orbits of everything, etc etc all that good stuff.

Some basic knowledge

Proper motion of the Galactic centre



$$\mu_{\mathrm{SgrA}^*} = (-6.379 \pm 0.026)\ \mathrm{mas\ yr^{-1}}$$
$$= (-30.24 \pm 0.12)\ \mathrm{km\ s^{-1}\ kpc^{-1}}$$

$\mu_{\mathrm{Sgr\ A}^*} = (v_0 + V_\odot)/R_0$

So we need to know $V_\odot$

(in so far as that is a valid approximation)

e.g. 12.24 ± 2 km/s (Schönrich, Binney, Dehnen 2012)

Distance to the Galactic Centre

There's really useful information gained from these tadpoles

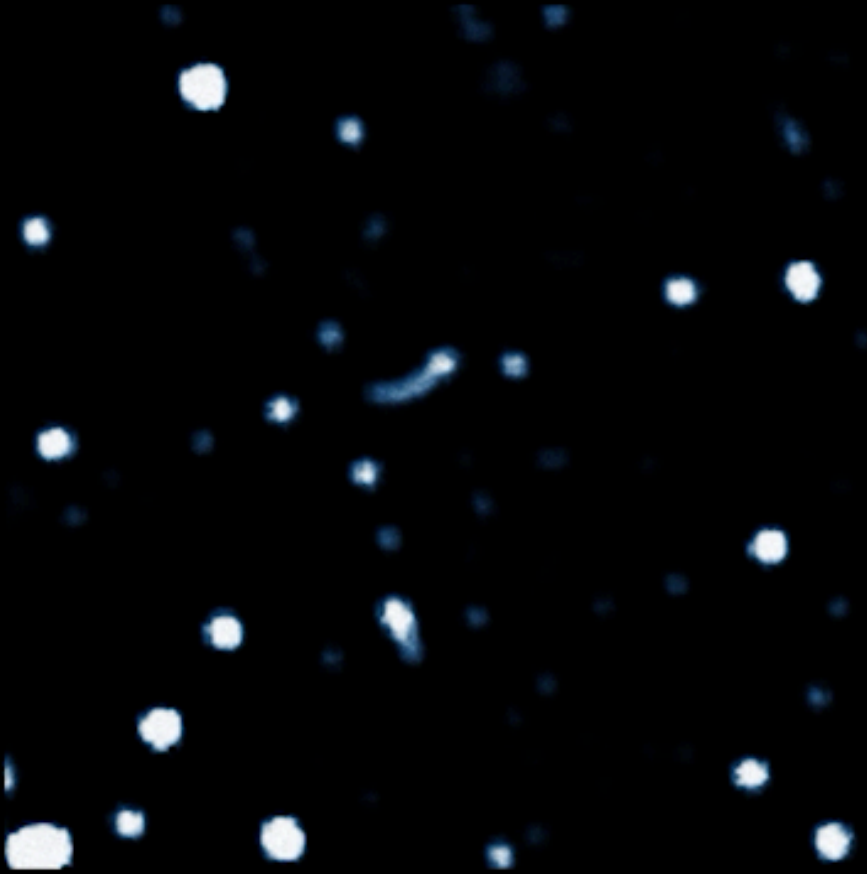
Gravity Collaboration et al (2019):

R0 = 8178 ± 13 (stat) ± 22(sys) pc

Gravity Collaboration et al (2018):
(using most of the same data)

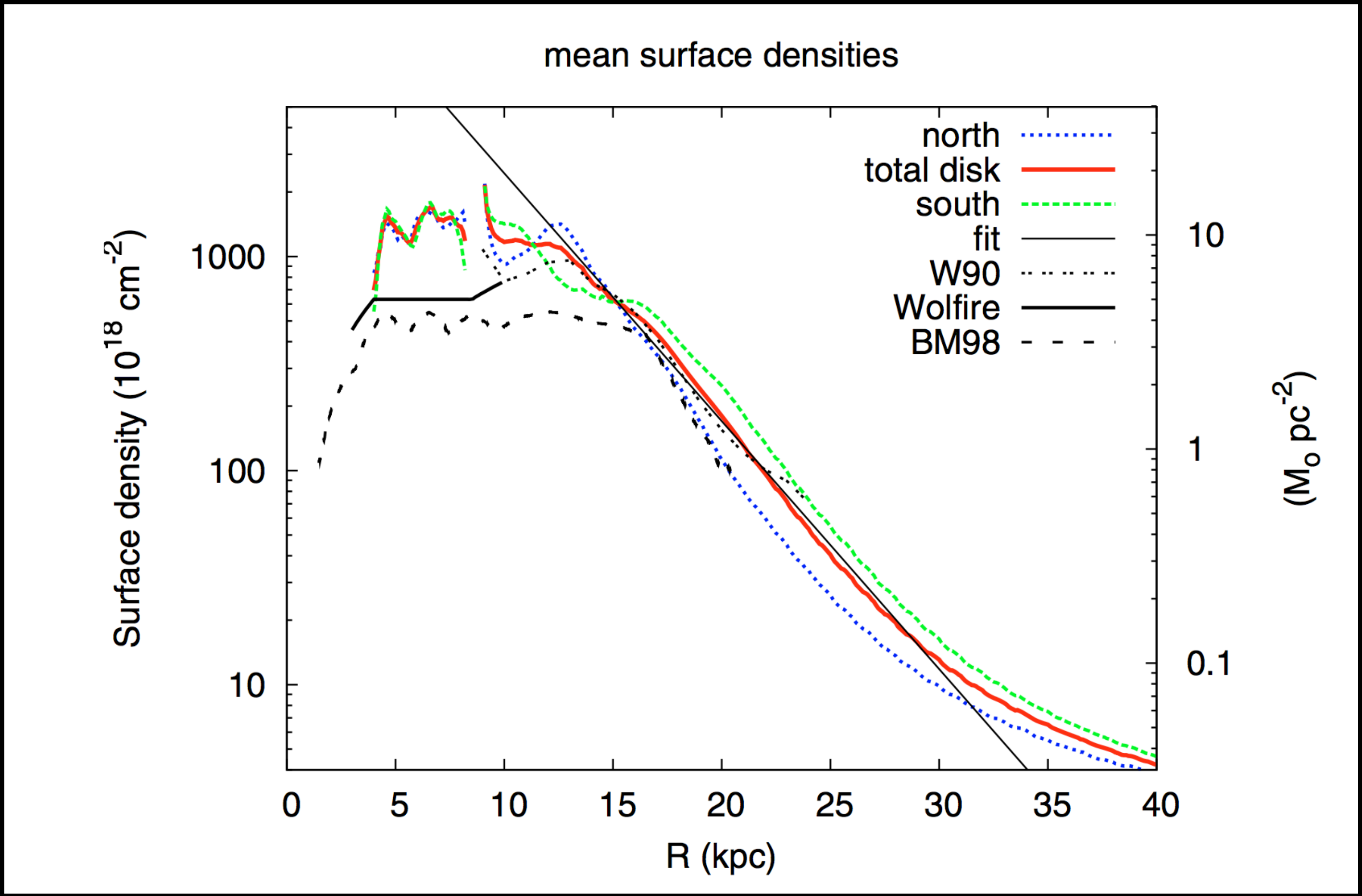
R0 = 8122 ± 31 (stat)

Systematics??



ESO/GRAVITY

Pieces of the puzzle: Gas discs

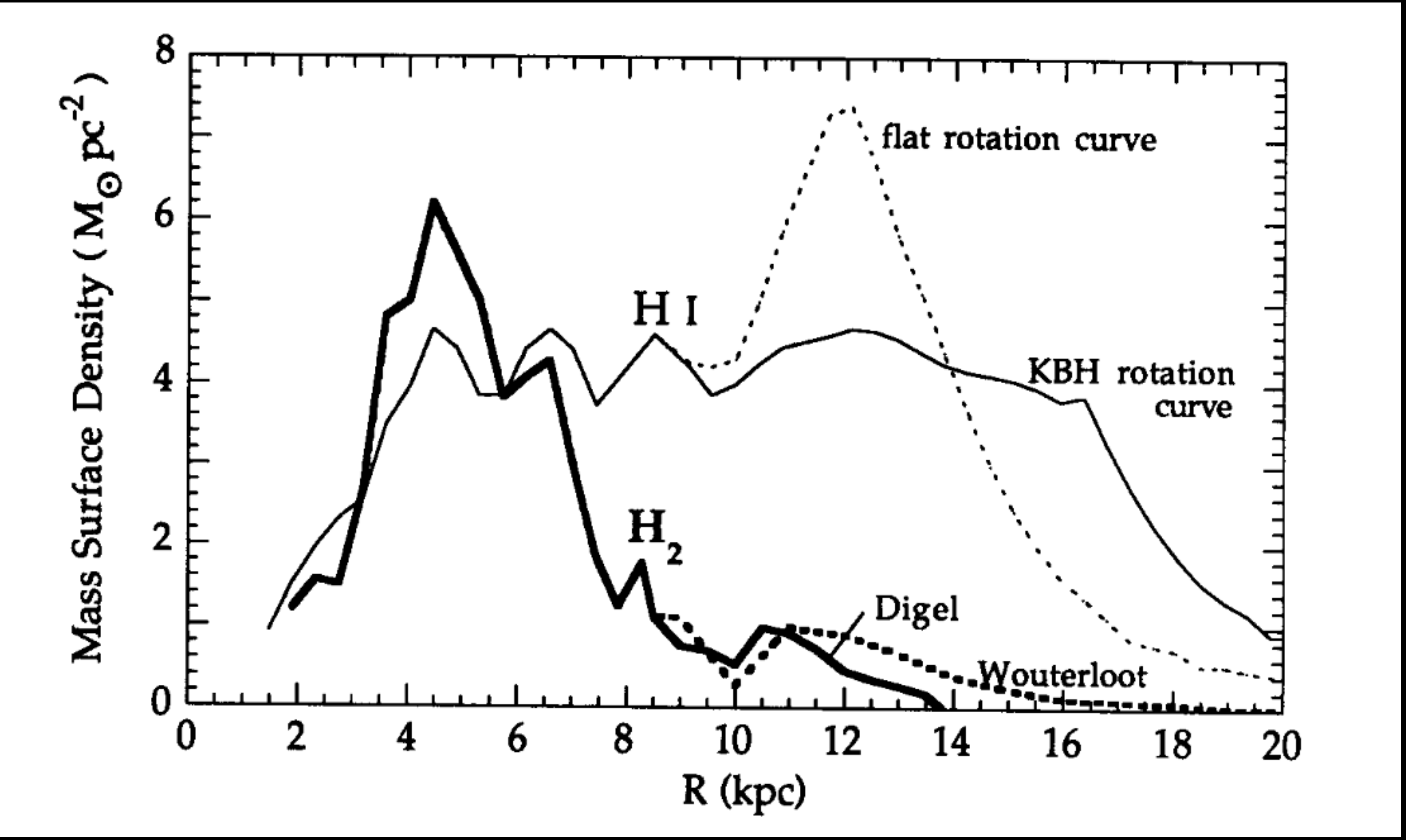


H I

(and associated helium)

Kalberla & Dedes (2008)

Pieces of the puzzle: Gas discs



Dame (1993)

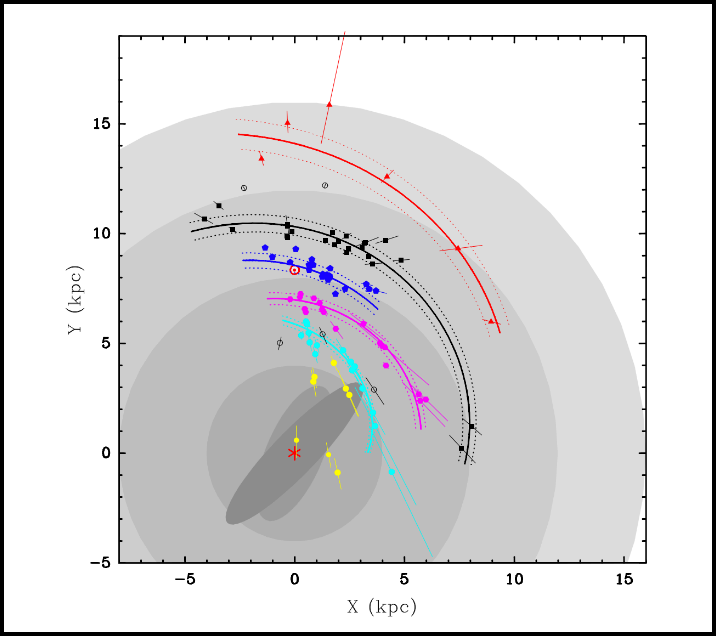
Arbitrary rescaling by factor 2 to match at $R=R_\odot$

Sources on near circular orbits

Maser sources are on near circular orbits in the Milky Way, and we can measure parallaxes and proper motions with high accuracy

Combine all this (and a few other things) in a Bayesian framework and you can get an estimate for the properties of the Milky Way

(McMillan 2011, 2017)



Reid et al 2014

But we can want to do more…

We're seeing (effectively) a snapshot

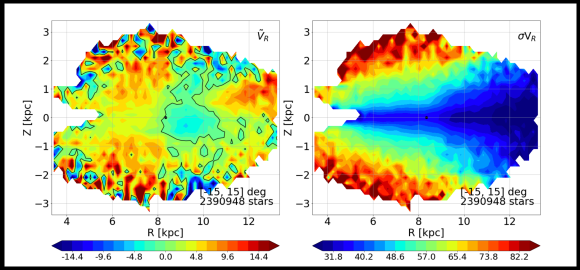
10yr ≪ 200 Myr

Gaia mission — Orbital period in Milky Way

Acceleration is not measured (~cm/s/yr)

We see the current positions & velocities of stars

These are short-lived properties of stars (on Galactic timescales).



Gaia collaboration, Katz et al. (2018)

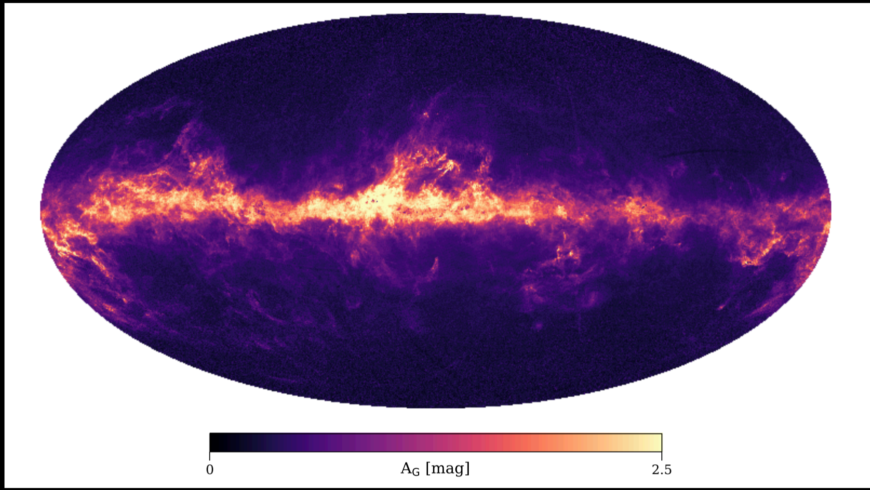
Our data will have selection effects

We also need to allow for the fact that there are serious, complicated selection effects on our data

Inevitably distance dependant, line-of-sight dependant, luminosity depandant,…

If we're unlucky, whim-of-the-input-catalogue-decision-maker dependant

And there's dust



Andrea et al 2018

We need a model that relates position & velocity to gravitational field

For example, everything is in equilibrium (f(J))

Or we can treat things as a simple perturbation from this equilibrium

Or, e.g., all the stars came from the same place and can be treated as a tracer (e.g. stream fitting, N.B. not as orbits)

Fitting

$$P(\text{observation}|\text{Model}) = \int P(\text{observation}|\mathbf{x},\mathbf{v}) \times P(\mathbf{x},\mathbf{v}|\text{Model})\ \mathrm{d}^3\mathbf{x}\,\mathrm{d}^3\mathbf{v}$$

Non-negligible for very small volume in phase space,
Because what we have are line-of-sight dependant

e.g. f(J) in Φ

If one does this integral with an orbit library (evaluate at δ-functions in J), the number of relevant orbits for a given observation is small. (Can still fit the dynamics in a fixed potential – McMillan & Binney, 2012)

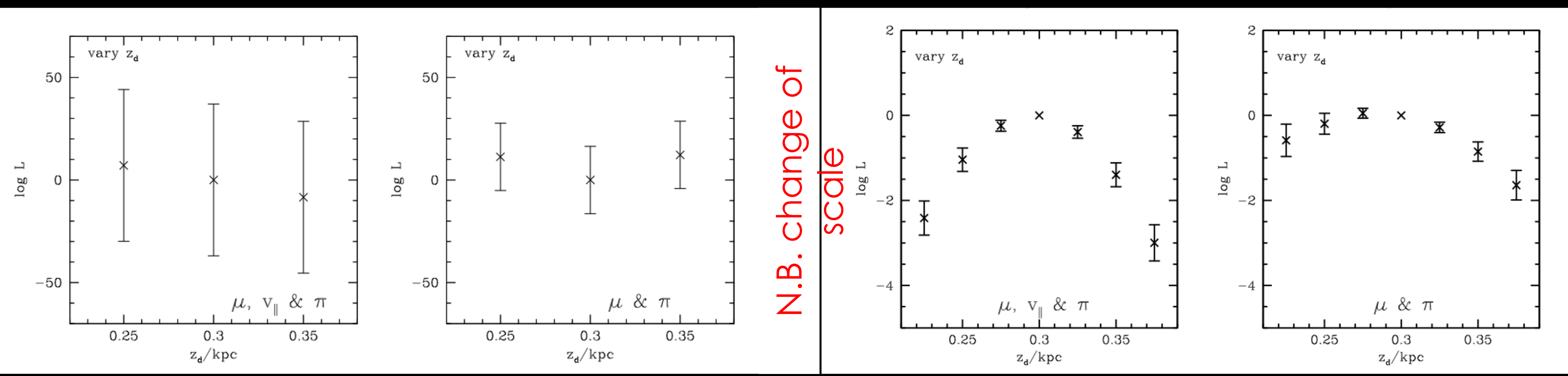
When you change Φ, number of relevant orbits changes in uncontrolled way – shot noise.

If instead you fix x,v at which you evaluate integral, this noise is greatly reduced

We can't do this with a discrete orbit library

Torus (orbit) library

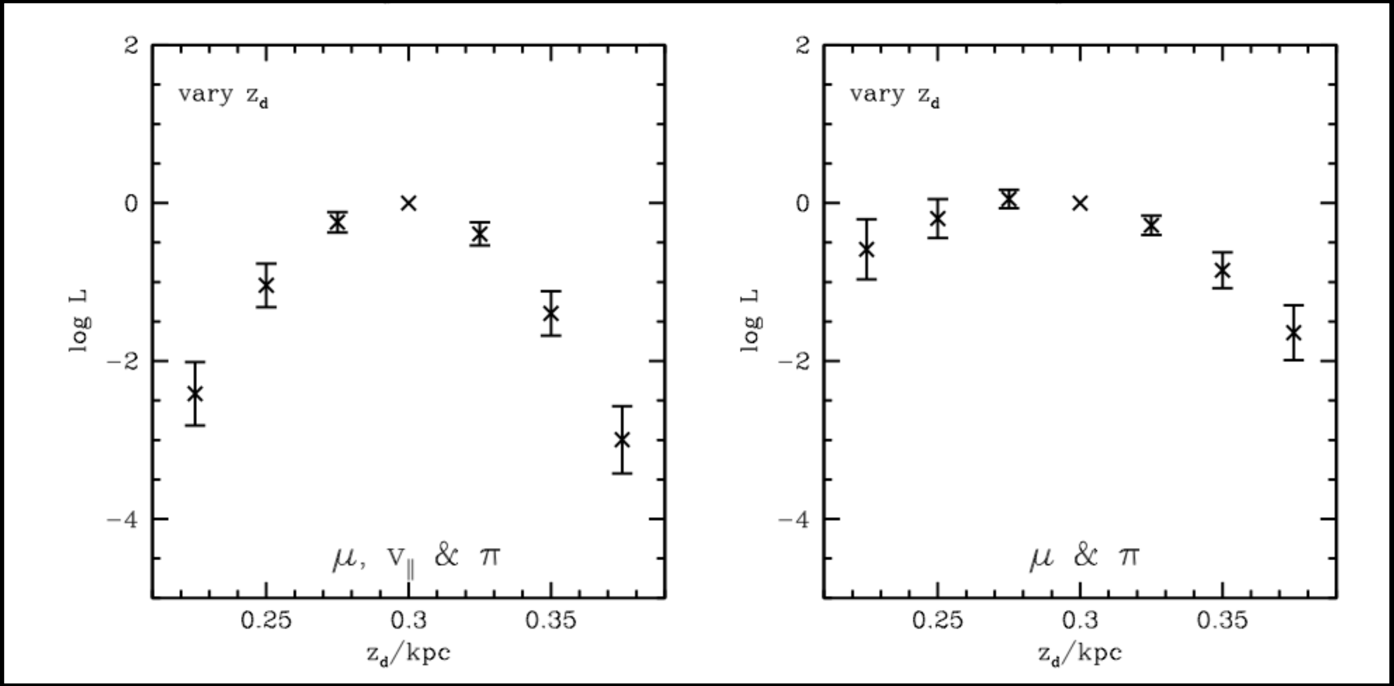
Calculation of $\underline{J}(\underline{x},\underline{v})$



Error bars: numerical uncertainty

McMillan & Binney (2013)

We showed that with only 10^4 stars (and even with only their proper motions), this is possible



Fitting f(**J**) models to 'realistic' data

McMillan & Binney 2013

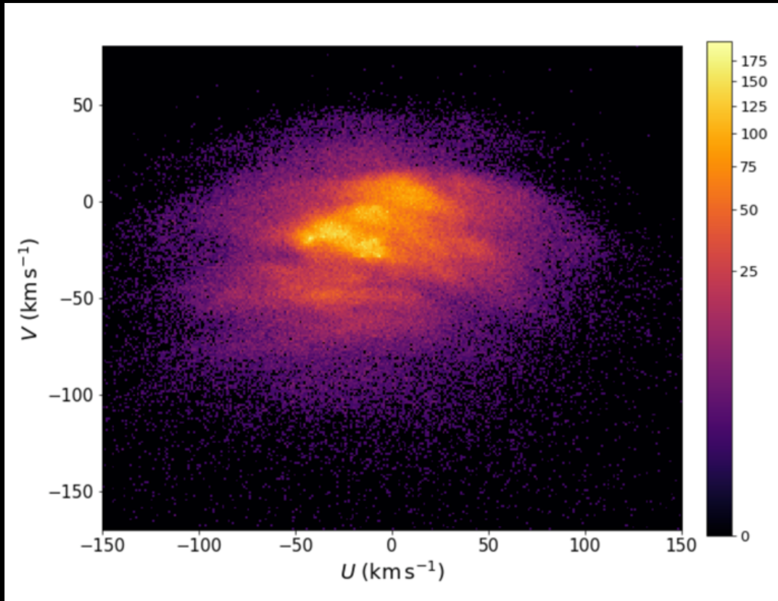
Need a df for the disc, a simple choice:
(in keeping with past ideas e.g. Shu 1969, Dehnen 1999)

$$f(\mathbf{J}) \propto \Sigma(R_c(J_\phi)) \prod_{i=z,r} \exp(-\frac{\omega_i J_i}{\sigma_i^2})$$

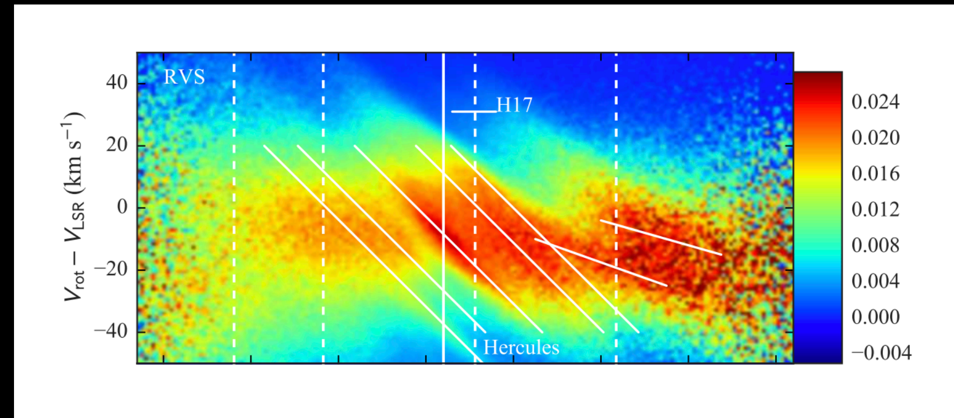
"quasi-isothermal"

Gradually evolving (Binney 2010, Binney & McMillan 2011, Vasiliev 2019)

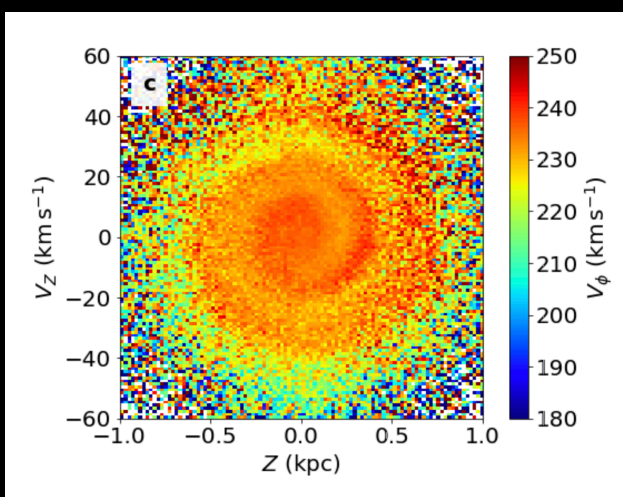
What do we need to add?



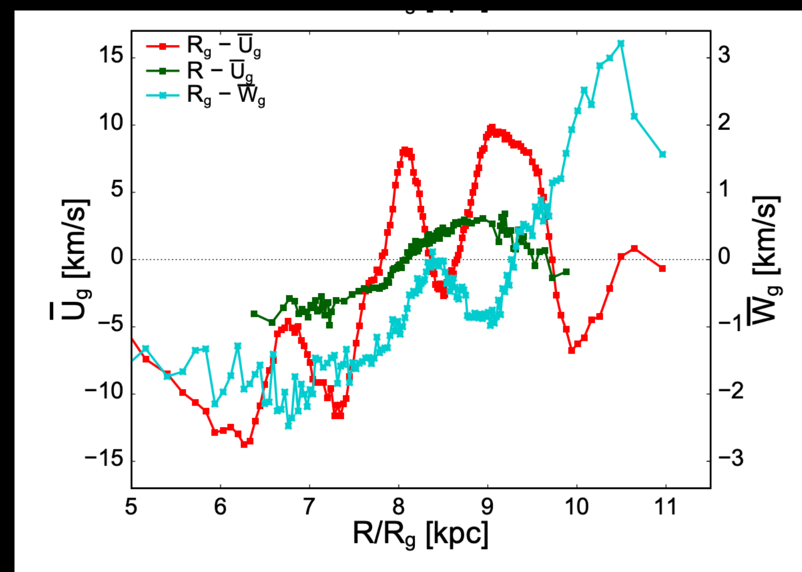
Gaia Collaboration Katz et al 2018



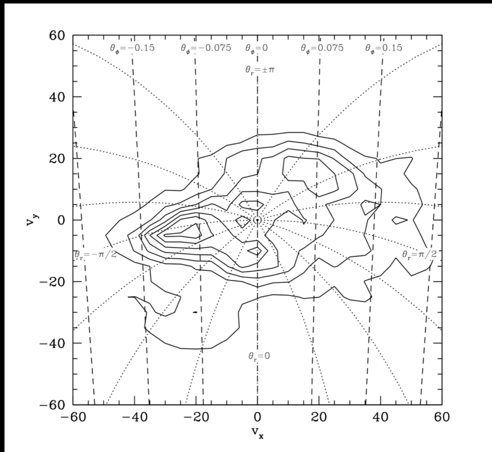
Kawata et al 18

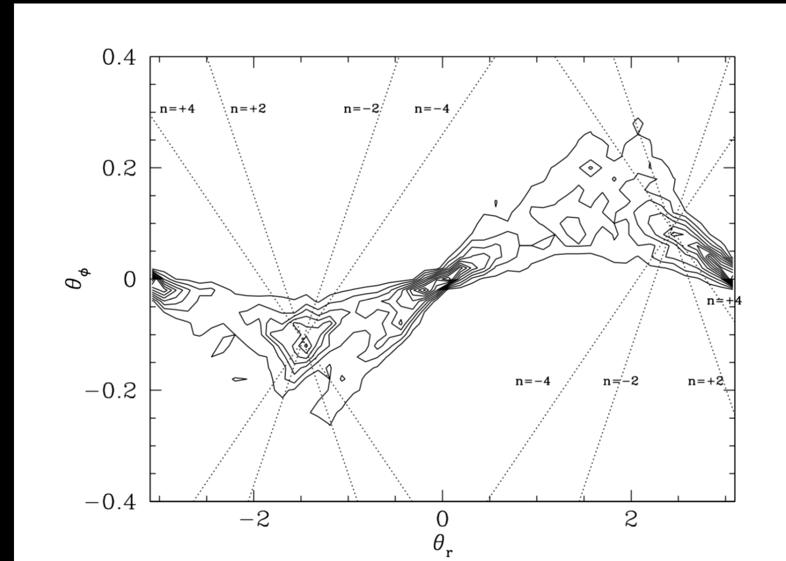


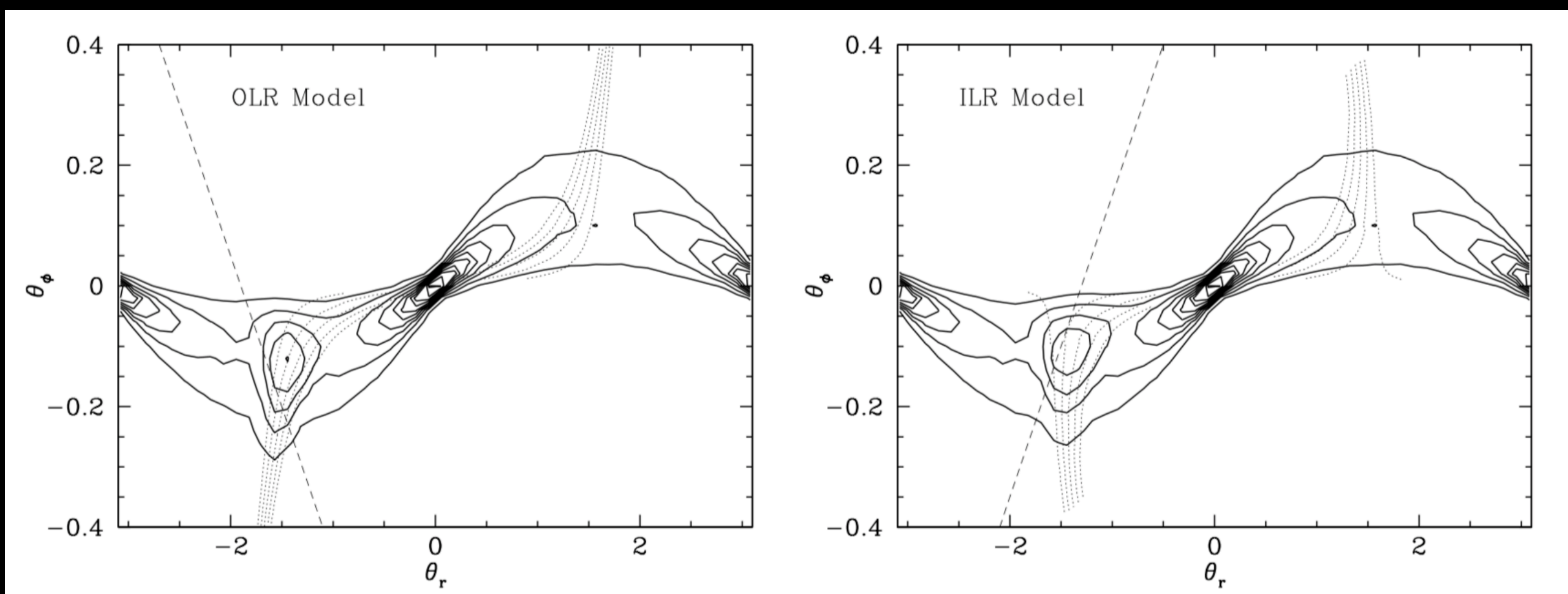
Antoja et al 2018



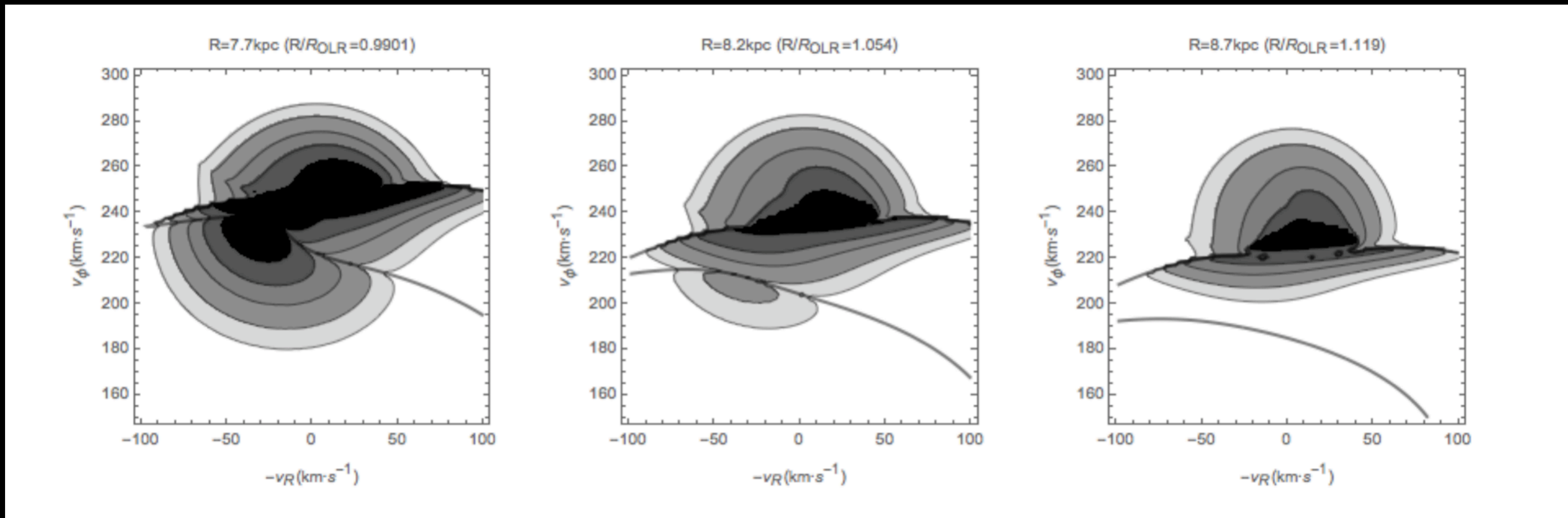
Friske & Schönrich 19





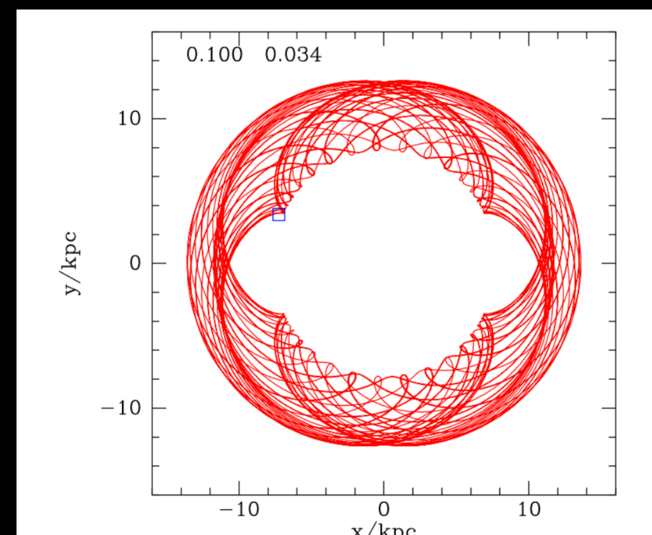


Sellwood 2010; McMillan 2011, 2013; but see also Sellwood et al 2018



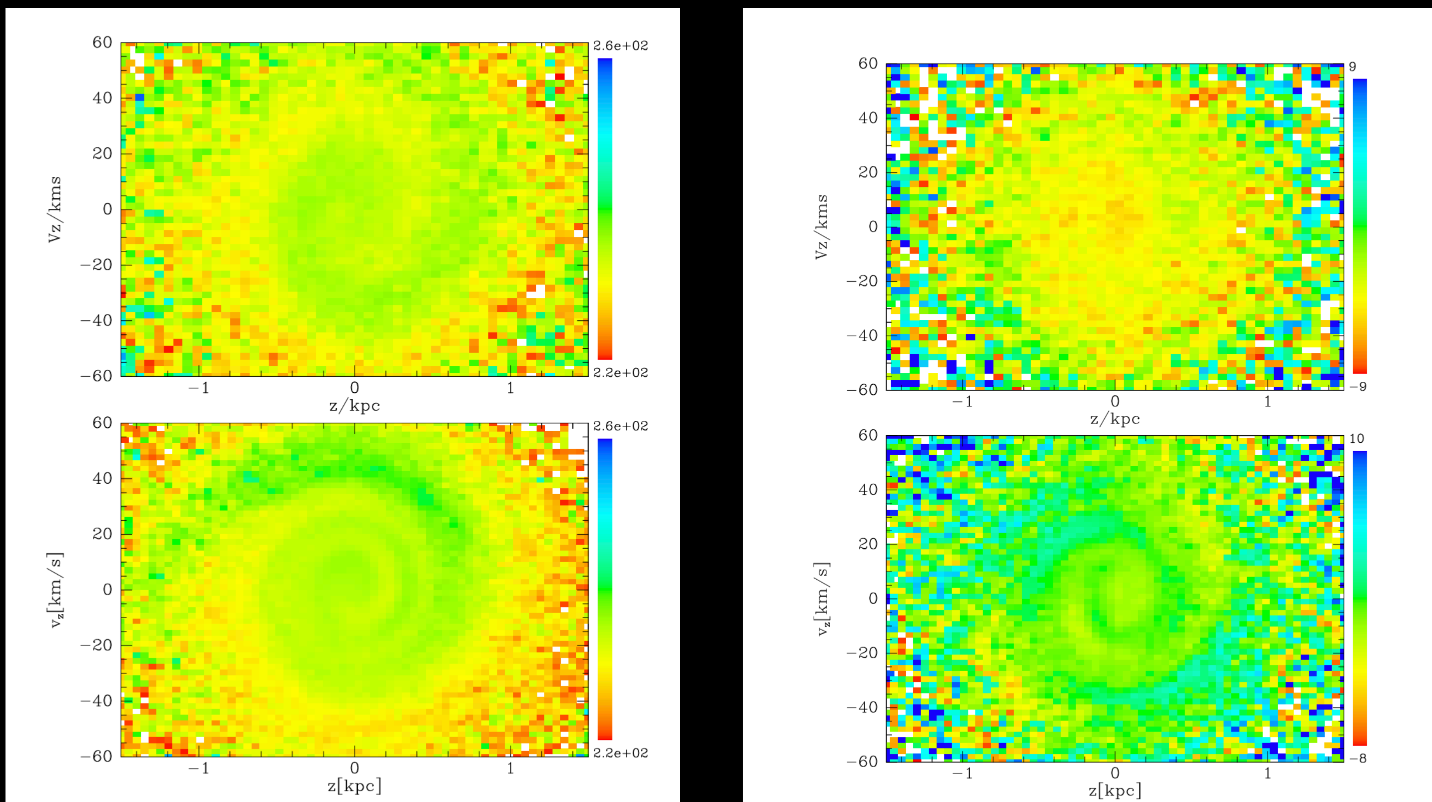
Monari et al 2017

More physically, apply to the df directly or to orbital tori directly



Binney 2017

Possible to model as perturbed f(J) model



Binney & Schönrich (2018)

V_ϕ V_R

But this misses the response of the disc potential

Closer to the data…

Model of the Galaxy

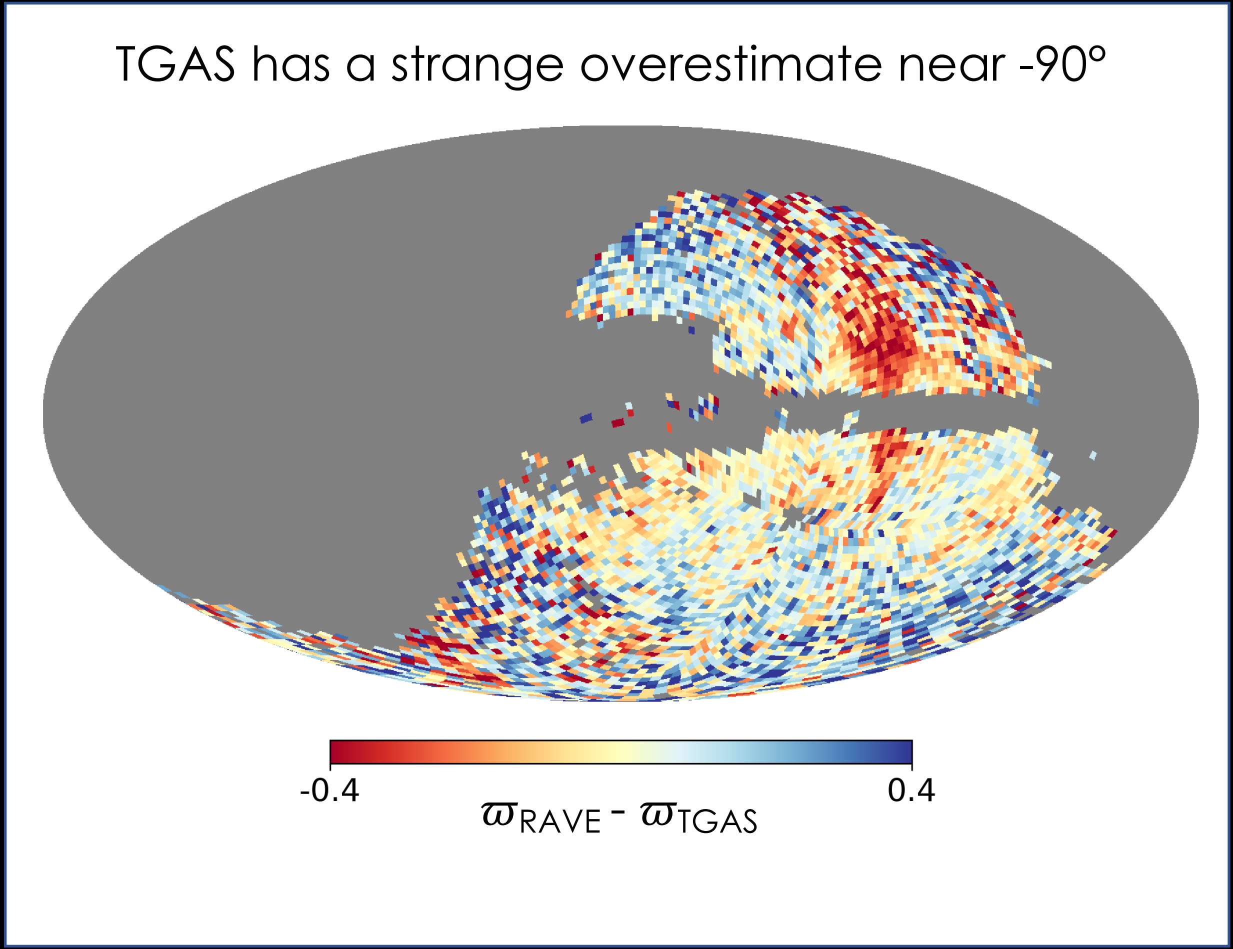
???

Stellar positions, proper motions, parallaxes

???

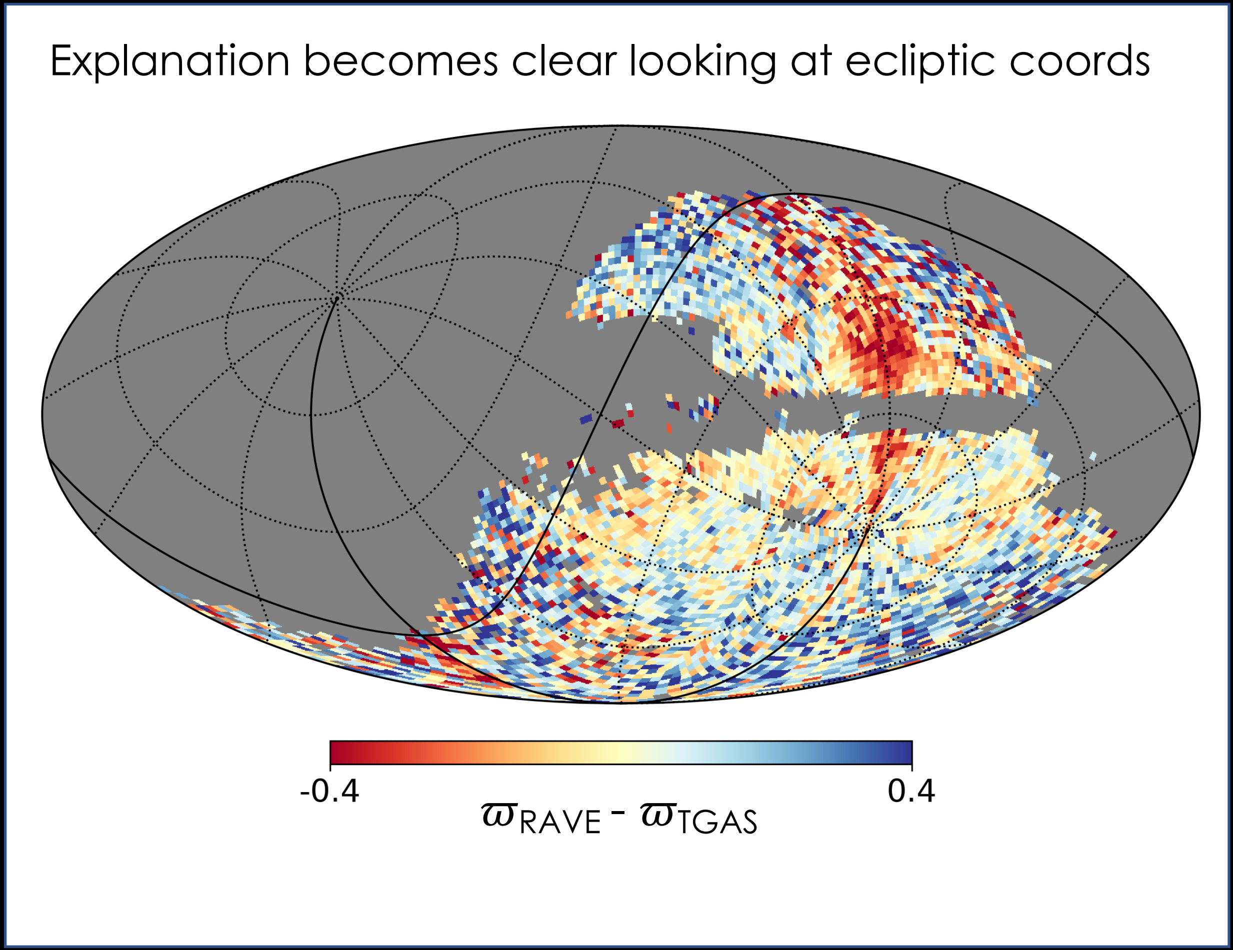
Charge on a Gaia CCD

Comparison to RAVE parallaxes



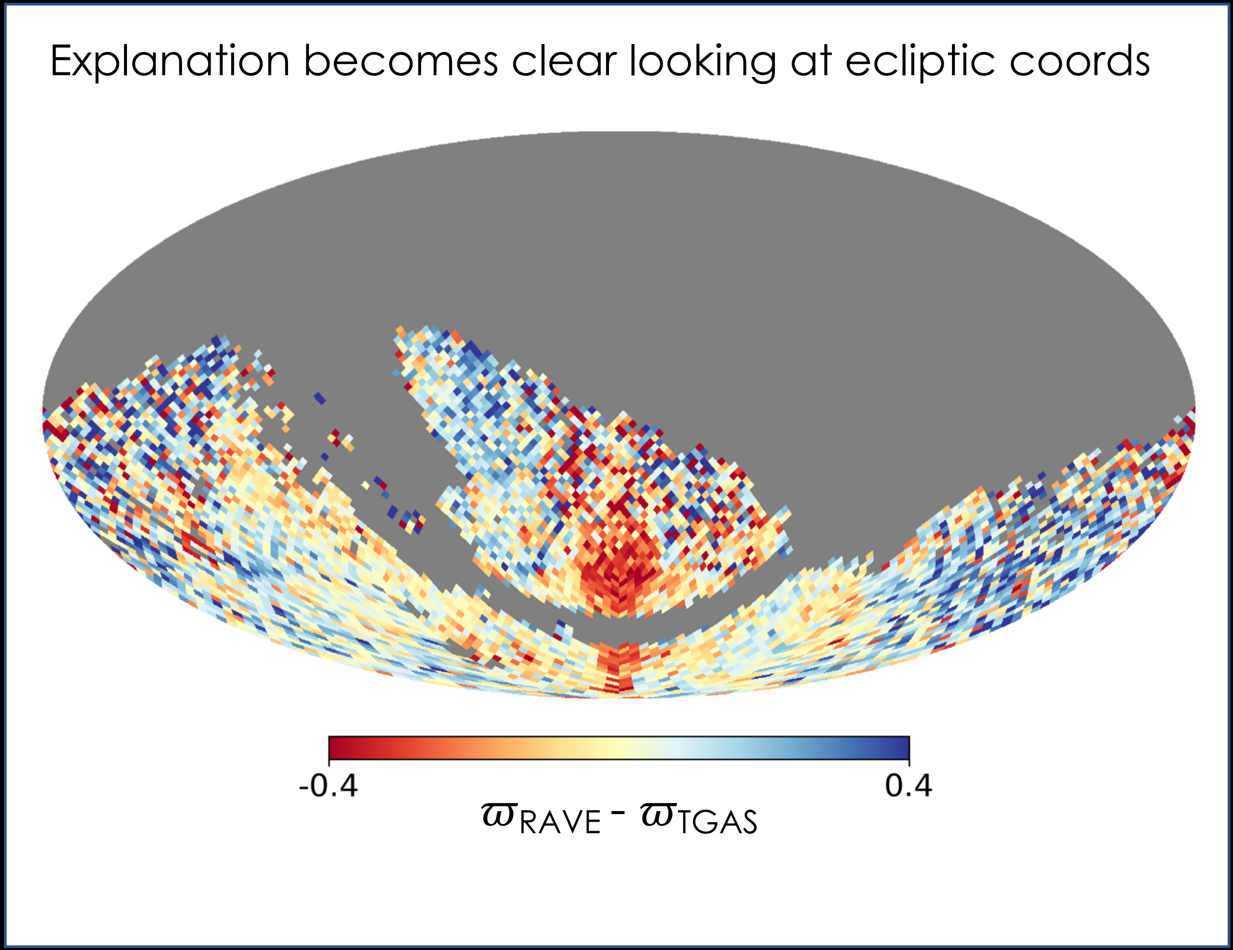
McMillan et al. 2018

Comparison to RAVE parallaxes



McMillan et al. 2018

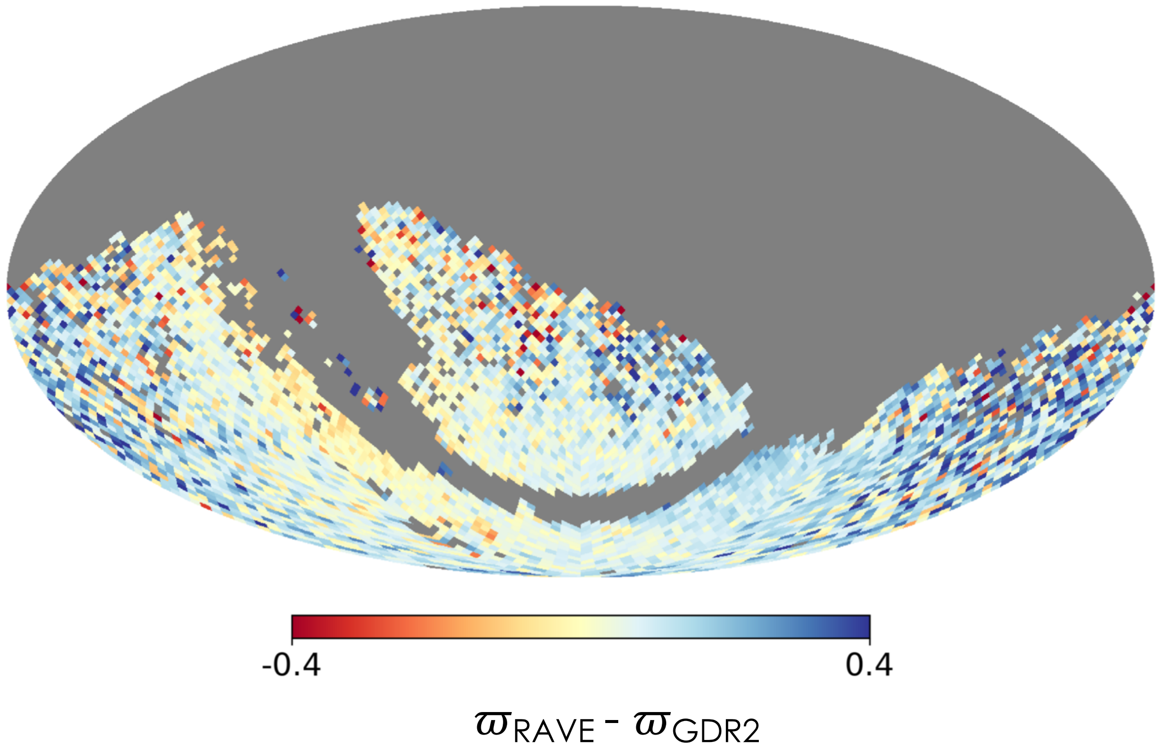
Comparison to RAVE parallaxes



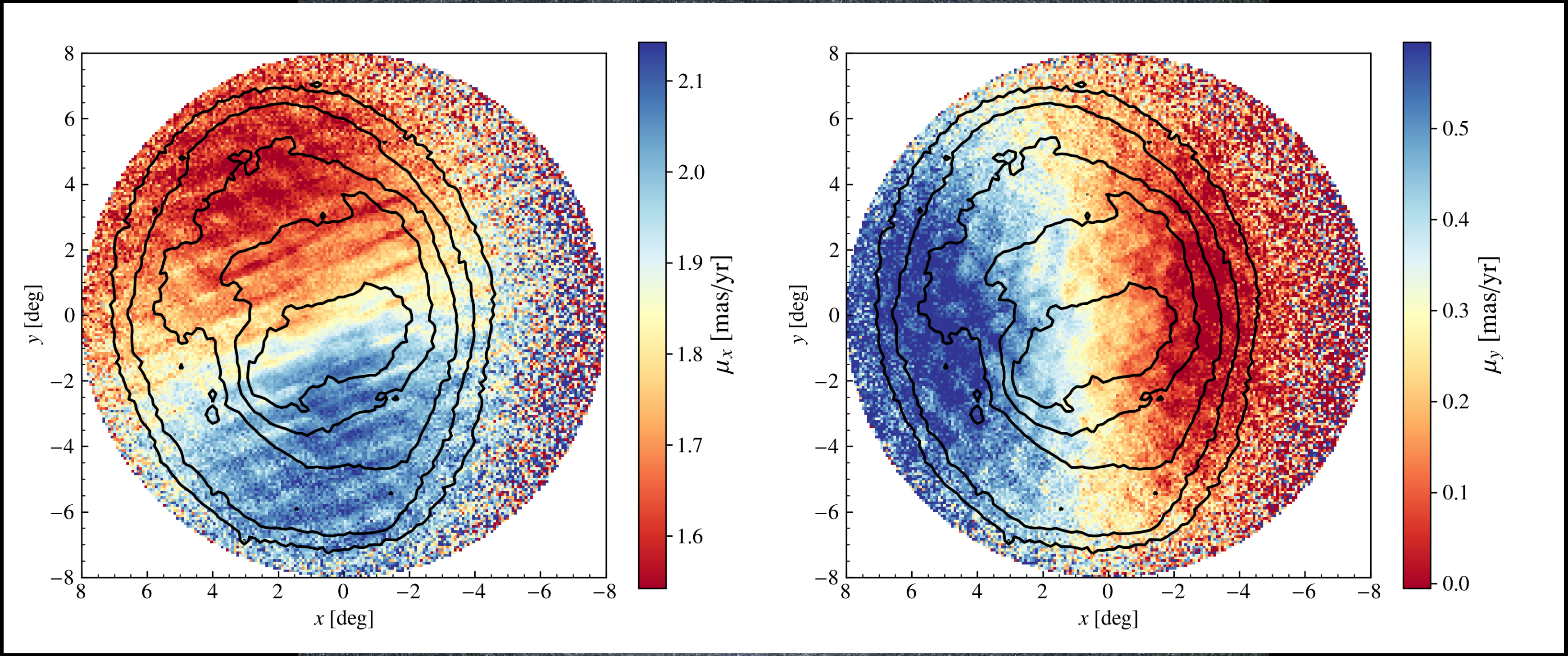
McMillan et al. 2018

Comparison to RAVE parallaxes

And the problem has been taken care of for Gaia DR2



Proper motions in, e.g. LMC



Gaia collaboration, Helmi, van Leeuwen, McMillan et al 2018

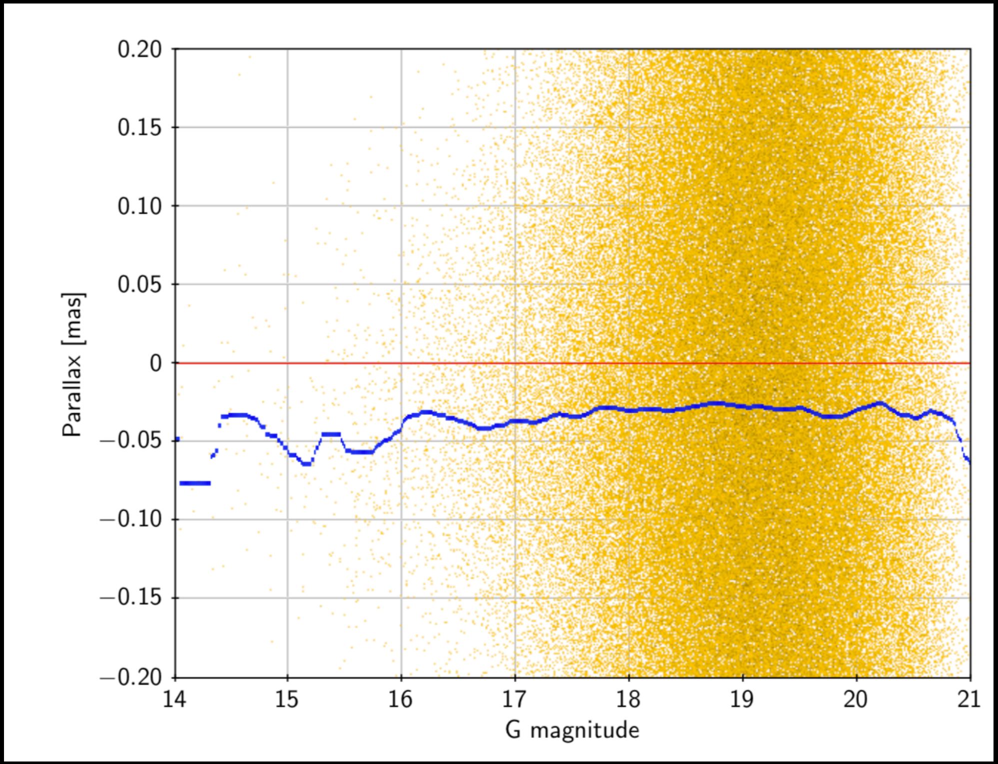
ESA/Gaia/DPAC

Systematic offset in Gaia data

We know that Gaia DR2 has a parallax zero-point offset that varies (including with apparent magnitude)

Can estimate using quasars, but these are faint (and do not have typical stellar SEDs)

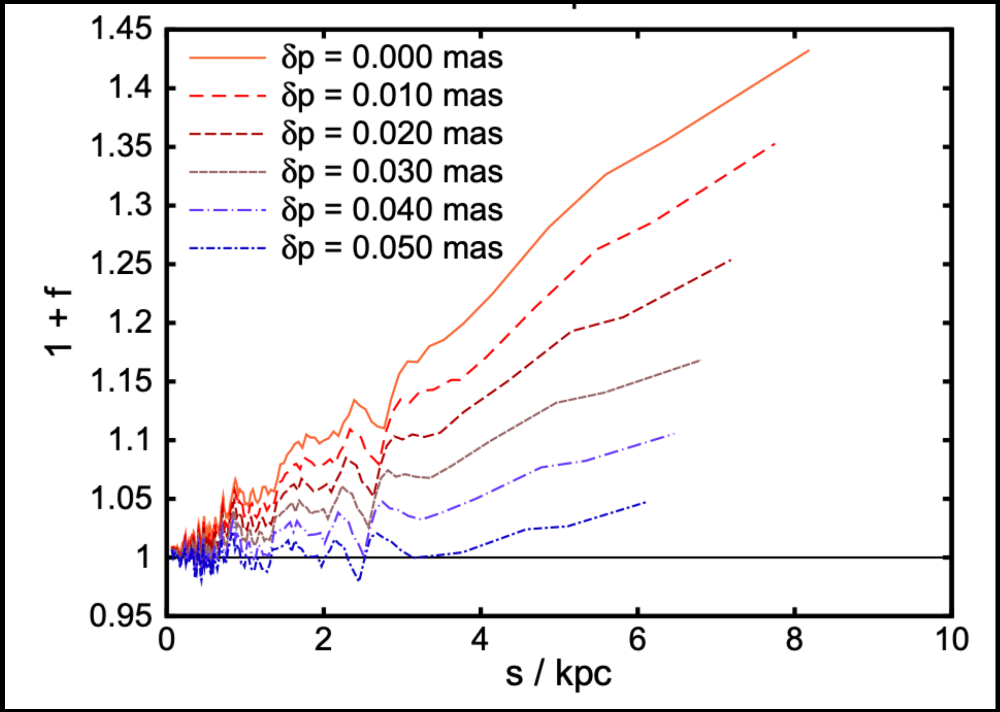
What can we do for the bright stars (i.e. the RV stars)?



Lindegren et al 2018

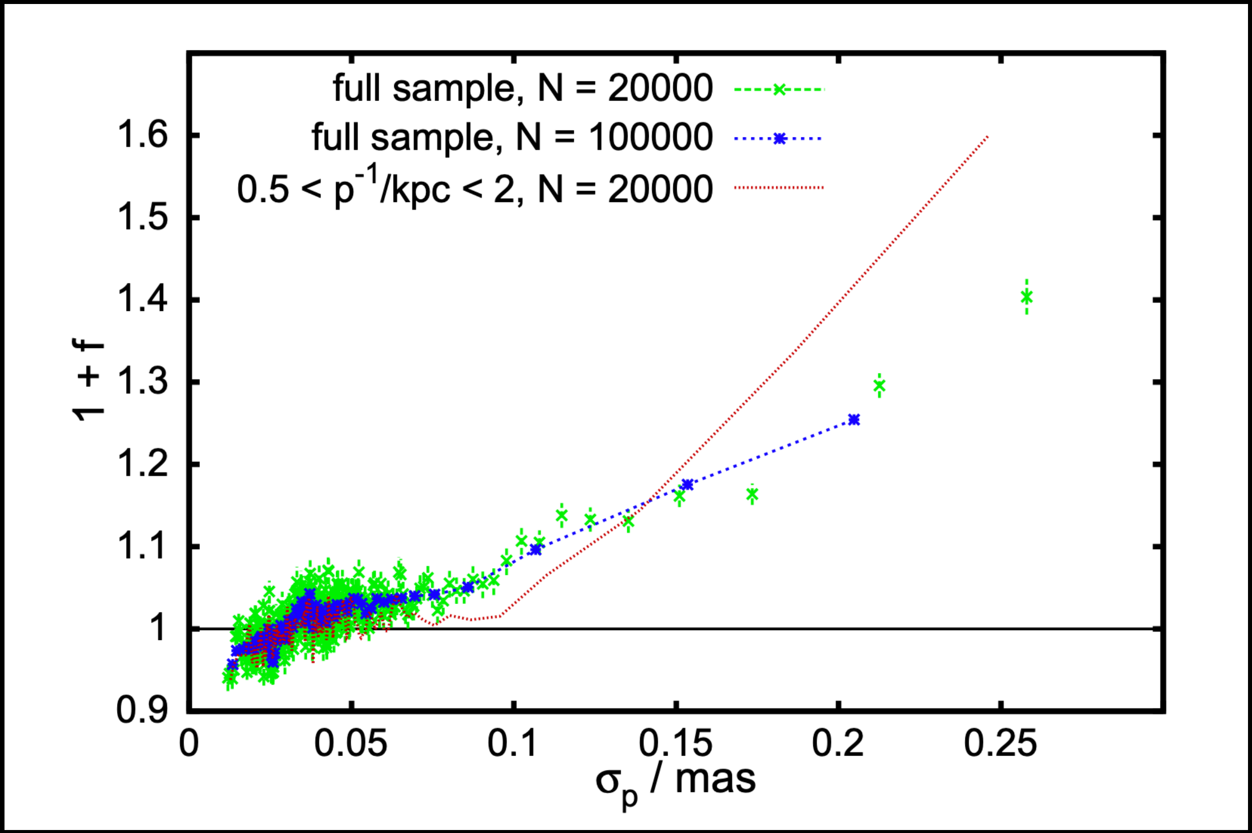
Systematic offset in Gaia data

Exploiting the impact of systematic errors in velocity introduced when you have systematic parallax errors, we can estimate them for stars with radial velocities.



Schönrich, McMillan & Eyer (2019)

Even correcting for this, there are trends with uncertainty for these bright stars



The wisdom of Lester Freamon (The Wire)

We're building something here...
All the pieces matter.

So we need to:

Respect the things we already know

Have models that
1) Predict x,v given potential
2) Capture the relevant dynamics
3) Are very finely grained

Make sure we understand what the data are really telling us.

Gaia DR2 was a preliminary release

EDR3: Q3, 2020
Improved astrometry, and photometry (integrated G, G_BP, G_RP)
Quasars and Extended Objects results

DR3: second half of 2021, adds
Object classification and astrophysical parameters
BP/RP spectra and/or RVS spectra they are based on, (for well-behaved objects).
Mean radial velocities (for stars with available atmospheric-parameter estimates).
Non-single stars.

DR4 (full release for nominal mission):
Full catalogue, including epoch data

DR++: Dependant on mission extension

Looking further ahead…

Many of you signed in support of a (successful!) proposal to look into the technological feasibility of sensors for a future GaiaNIR

Now, after the wealth of science from Gaia DR2, we are building a science case for:

Voyage 2050 White Paper

All-Sky Near Infrared Space Astrometry

5 times more stars (and much deeper in the plane).
Proper motions ~15 times more accurate (equiv ~2km/s at 100kpc).

Suggestions welcome!

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