# EXTRACTING SCIENCE FROM SURVEYS OF OUR GALAXY

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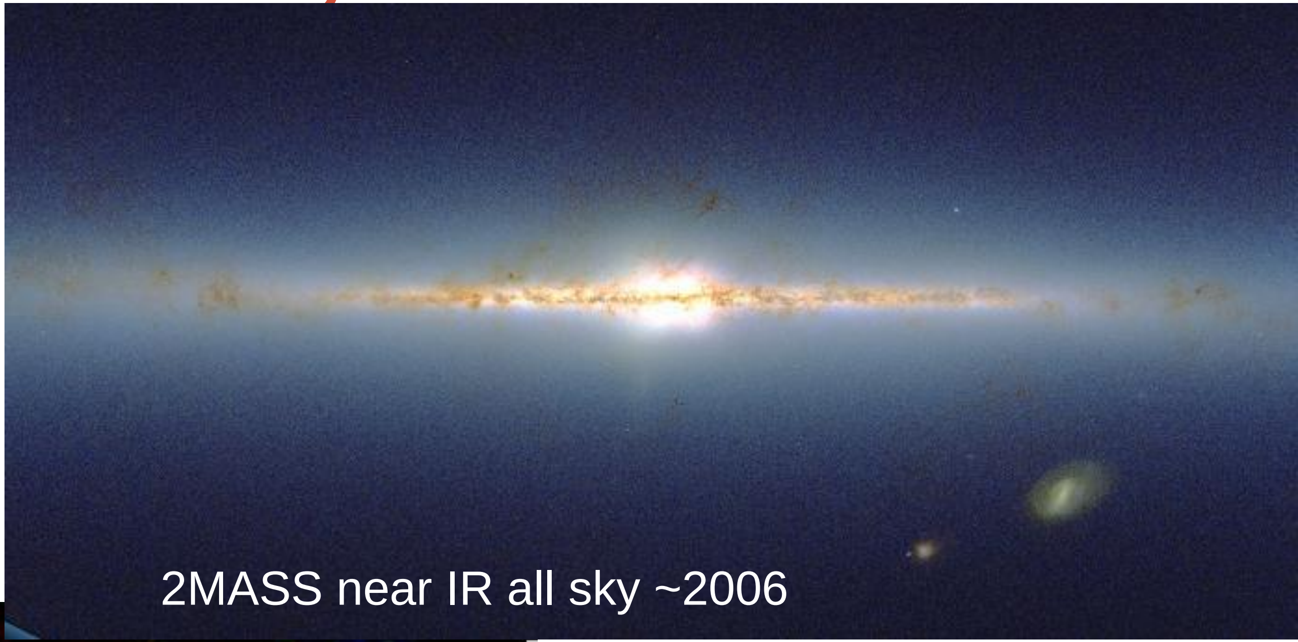
# Outline

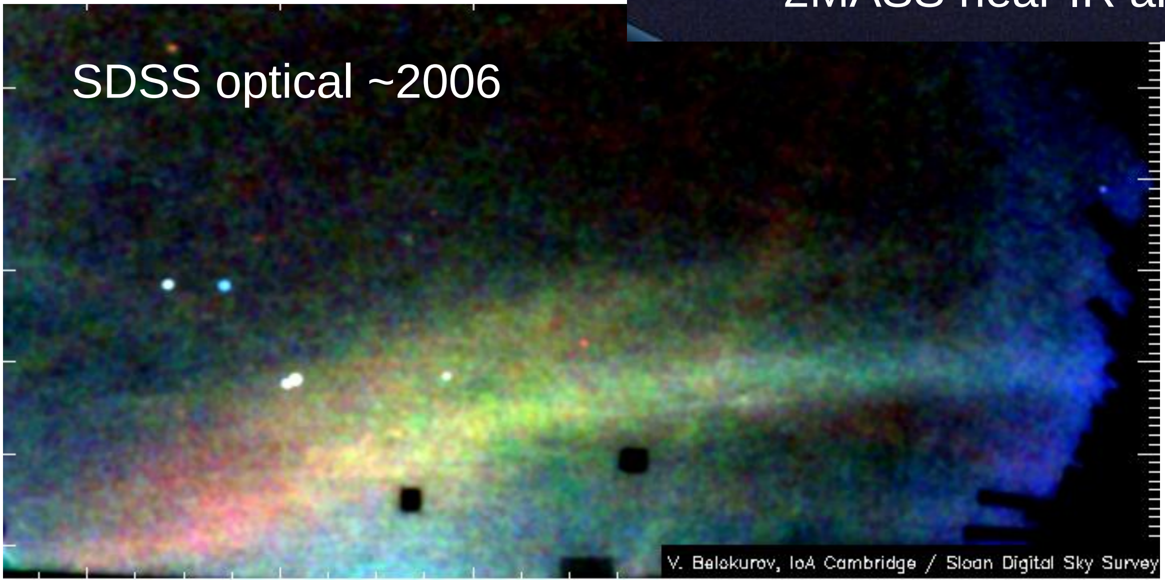
- Galaxy surveys
- Goals
- Why models will be key
- Modelling tecnologies
- Simple examples
- The path ahead
- Conclusions

# Photometric surveys

- Also PanStarrs
- IR
  - UKIDS ~2011
  - VISTA ~2014
- Dark Energy surveys…



2MASS near IR all sky ~2006



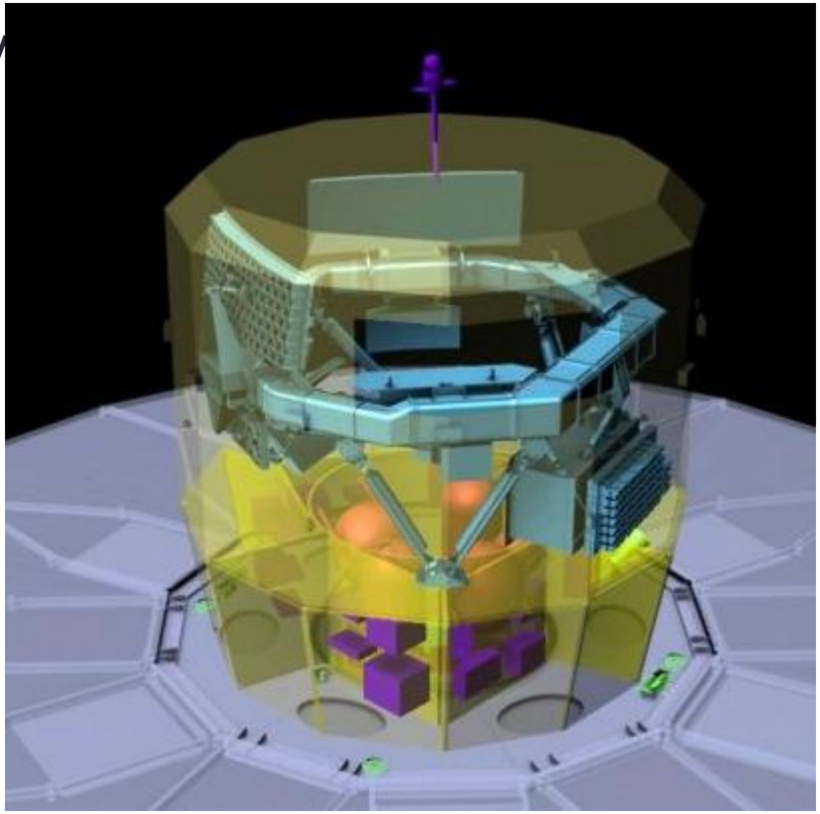

SDSS optical ~2006

# Spectroscopic surveys

- From spectra get $v_{los}$, ability to distinguish giants from dwarfs & more complete chemical information
  - SEGUE optical to ~2011 (~ 0.5 m spectra @ R=2500)
  - RAVE red to ~2013 (~0.5 m spectra @ R=7500)
  - LAMOST
  - APOGEE near IR from 2012 @ R=20,000
  - ESO-Gaia optical from 2012 @ R=20,000 and 40,000
  - Galah optical from 2013

# Gaia (astrometry, photometry & spectroscopy)

- ESA "cornerstone mission" set for launch on Soyuz Sept 2013 to Earth/Sun Lagrange pt L2
- Will catalogue $10^9$ stars over 5yrs
- Parallax, proper motion, photometry for all stars
- Line-of-sight velocity for ~1/5
- Will detect parallax movement equal to diameter of penny 12,000 miles away
- Telemetry fused into catalogue ~late 2016 and ~2019
- Then free-for-all
- Better have your tools prepared!



# Huge expenditures

- Custom spectrographs for APOGEE & Galah ~m$10 each
- Telescope time for ESO-Gaia valued at ~mEu 60
- Gaia project ~mEu 650
- We need to make good use of the harvested data!

# Goals

- Our Galaxy is typical of the galaxies that currently dominate star formation
- How does it work?
  - How is its DM distributed?
- How was it assembled?
- How is it evolving?

# Role of models

- Data always dominated by selection effects – you see what you can see because it’s near/luminous/not shrouded in dust
- Observational errors never negligible for the majority of (faint!) stars
- Extremely hard to work back from the data to what’s out there
- Much better to use a model plus “selection function” to predict what should be in the catalogue

# Chemical evolution

- Primordial gas almost pure H/He mixture
- ISM first enriched/polluted by massive, short-lived stars
  - $\rightarrow$ high $\alpha$ /Fe abundances
- After ~1 Gyr significant enrichment by deflagration SNe (type 1a SNe) which produce almost pure Fe
- So old stars metal-poor, oldest stars Fe poor
- Many (all?) stars born on near circular orbits in equatorial plane. Fluctuations in grav field cause them to diffuse from there – radially & vertically
- Consequence: older stars have larger random motions
- Consequence: we need to model fluctuations in $\Phi$ as well as mean value
- Major problem: accretion of metal-poor gas has always been important but we don't know the distribution of this gas in (R, $L_z$)

# Curse of high dimension

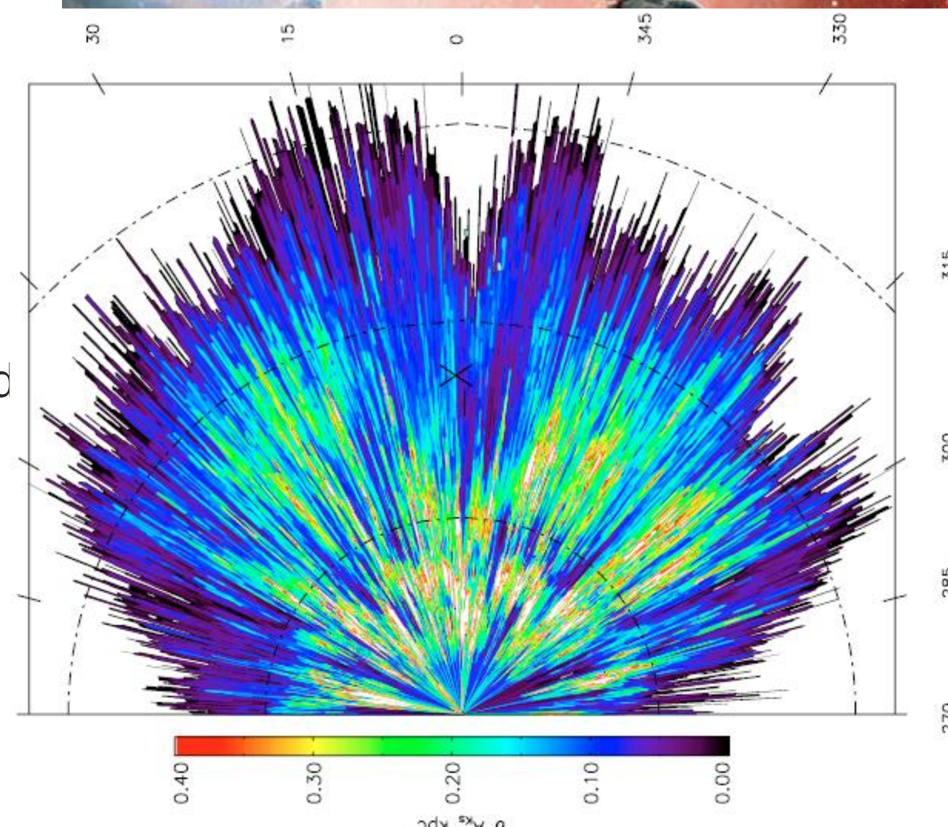
- The data live in space with 10+ dimensions
  - Sky coords + parallax (3)
  - Proper motions + $v_{los}$ (3)
  - Brightness in > 2 bands (2+)
  - Abundances Fe/H and $\alpha$/Fe + (2+)
  - Surface gravity (log g), $T_{eff}$ (2+)
- Correlations between kinematics and chemistry are key for unravelling history and understanding dynamical evolution
- Correlations lost when you project data into lower d
- The Galaxy is a discrete realisation & we want the underlying pdf
- Even with $10^9$ objects you lose almost all information if you bin in 10+ dimensions
  - Say 10 bins in each spatial coordinate (1000), 5 in each cpt of v (125), 10 in brightness, 5 in colour (50), 5*3 in chemistry, 2*2 in log(g) $T_{eff} \rightarrow 4\times10^8$ bins so with Gaia mostly only 1 star per bin!

# Must fit in the space of the data

- Quantities we measure ($\alpha$, $\delta$, $\varpi$, $\mu_\alpha$, $\mu_\delta$, $v_{los}$, $V_B$ ,..) are far removed from the physics
- Gaussian errors in these variables yield highly correlated and non-Gaussian error distributions in the physical variables (x, v, L,..) because $s=1/\varpi$ , $v_\perp = \mu s$, …
- So we must carry the model (folded through the selection function) into the space of observables
- Major problem:
  - By maximum likelihood we can choose the best model in a class
  - But does this model provide an acceptable fit?
  - If not, in what respects is it deficient?
- To use max likelihood either the model or the data must be converted to a pdf
- If our model is a discrete realisation, how do we do that without binning?

# The interstellar medium (ISM)

- Probability of an optical photon reaching us from the GC ~exp(-30)
- At $\lambda$ =2$\mu$m probability much higher, but still significantly less than one
- Consequence: can get large-scale structure of disc only if the ISM is modelled in parallel with stars
- Current models crude
- Gaia will deliver millions of stars with trig determined positions & measured extinction
- How to weave data into a map of the fractal ISM?



# Galactic dynamics

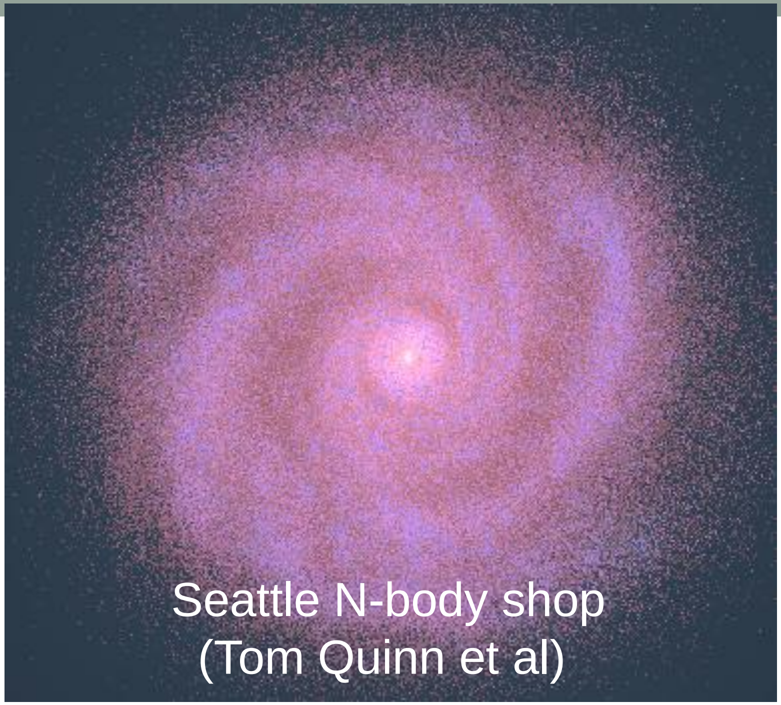
- Galaxies essentially collisionless: stars move in collective gravitational field with effects of star-star scattering negligible over Hubble time
- From any initial condition fluctuations in collective gravitational field decay to small values in 2-5 dynamical times
  - Fluctuations associated with collective modes *are* important, but only over hundreds of dynamical times
- So work with slowly evolving equilibrium models + Fokker-Planck diffusion
- Jeans thm: DF of equilibrium model can be assumed to be f(consts of motion)
- Numerical work in 1960s+ $\rightarrow$ most orbits admit 3 approx consts of motion $\rightarrow$ quasi-period motion
- Major exception: near end of (rotating) Galactic bar orbits have fewer consts of motion $\rightarrow$ chaotic orbits
- We focus on the quasiperiodic regime (which dominates near Sun)

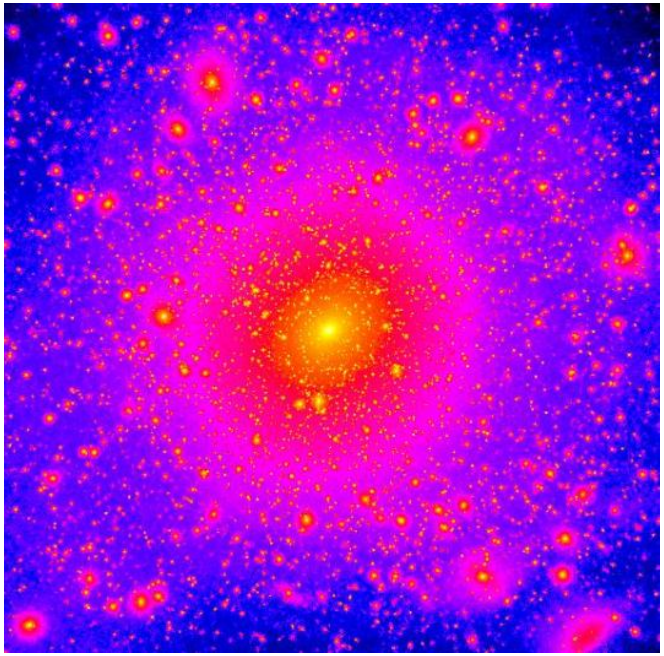
# Actions

- Any $f(I_1,..I_3)$ is a const of motion so there is much choice
- But some consts are more equal than others – the most equal are action integrals $J_r$, $J_z$, $J_\phi = L_z$
- They alone can be taken as momenta & complemented by (angle) variables
- They are adiabatic invariants, so slow change of grav field leaves f(J) invariant
- They provide faithful compression of phase space:
  - $d^3x\, d^3v = d^3J\, d^3\theta \to (2\pi)^3\, d^3J$
  - Galaxy can be significantly understood in 3d action space
- For these reasons best to specify f(J) rather than $f(E,L_z,..)$

# Types of model

- Cosmological N-body
  - Computationally costly ($10^5$ CPU hr)
  - Impossible to produce specific end point by adjusting initial conditions
  - Much realism but also fudged “sub-grid” physics
  - They are discrete realisations of unknown pdf
  - Cumbersome & highly non-unique model specification (6N numbers)



# Orbit-based models

- Schwarzschild
  - Choose $\Phi(x)$, integrate orbits, fit data by weighting orbits
  - Building orbit library non-trivial
- Made-to-measure
  - Adapt weights while integrating orbits
- In both cases we get a discrete realisation of unknown pdf and highly non-unique model specification
- But good ability to steer model to pre-determined goal

# Oxford models

- Models have specified DF f(J) that is a function of action integrals
- Consequently can specify pdf of stars
- Unique and compact model specification
- Q “what would this model look like in a different $\Phi$?” has a well-defined answer

# How to calculate actions?

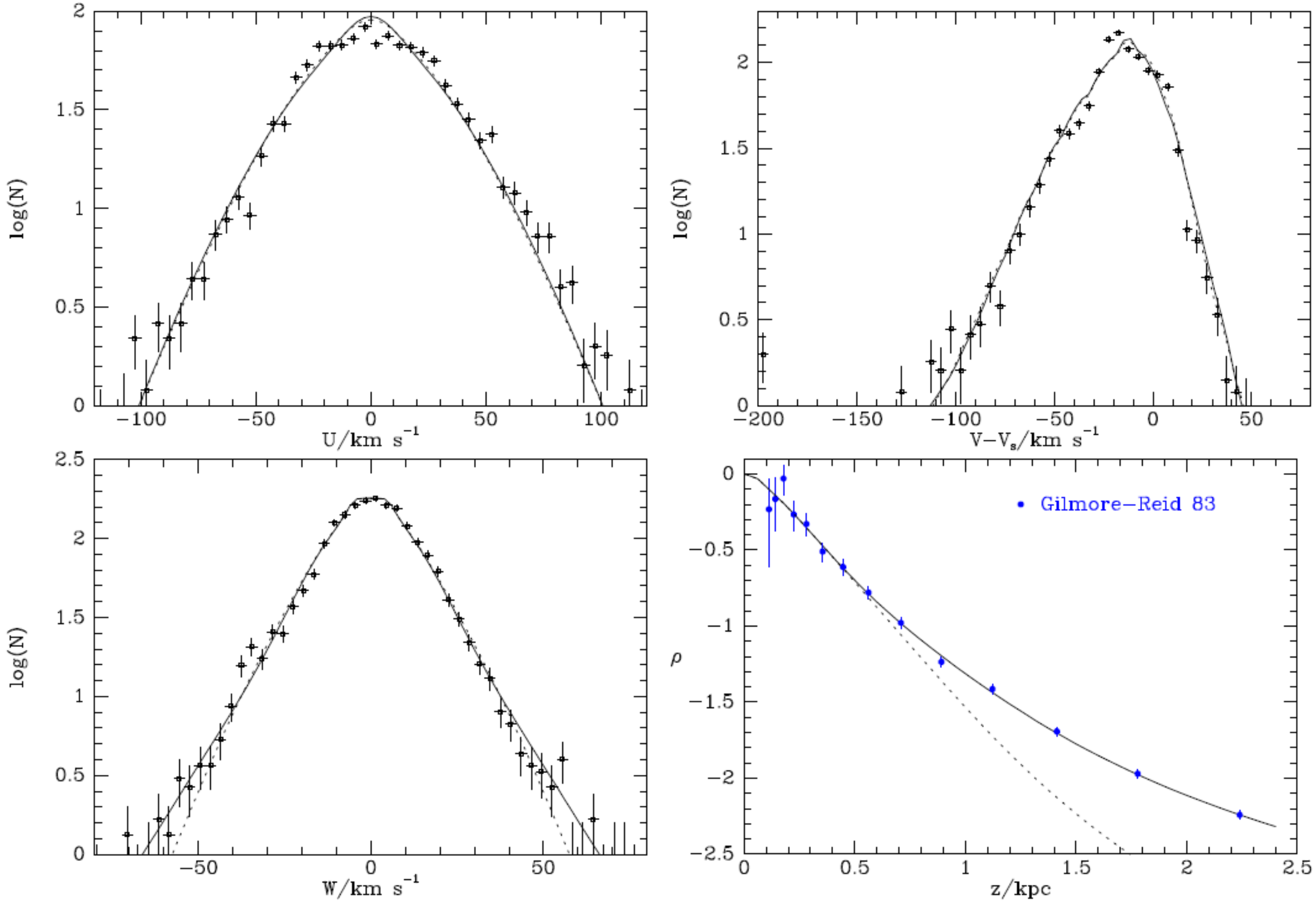
- By Fourier decomposition of time series of numerically integrated orbits (Binney & Spergel 1982, 1984)
- By mapping analytic phase-space tori into target phase space (McGill & Binney 1990, Kaasalainen & Binney 1994)
- By exploitation of adiabatic invariance for thin-disc orbits (Binney 2010)
- By fitting separable (Staeckel) potentials (Sanders 2012)
- By pretending $\Phi$(R,z) is a Staeckel potential (Binney 2012)
- By  averaging the action of s.h.m (Fox 2013)
- We now have serviceable schemes for both directions
- (x,v) $\rightarrow$ (J,$\theta$) and (J,$\theta$) $\rightarrow$ (x,v)
- But the last word hasn't been written yet

# The general programme

- Construct equilibrium models with DFs f(J) that depend on parameters
- Construct selection functions of principal surveys
- Fit DFs folded through selection function to principal surveys, first alone & then together
- Determine extent to which these models constrain $\Phi$(R,z)
- As data improve, fit separate DFs to several chemically distinct populations
- Use N-body models to determine diffusion coefficients
- Study impact of diffusion on fitted DFs
- Build models of cosmic accretion, star-formation and chemical evolution & make these models consistent with fitted DFs

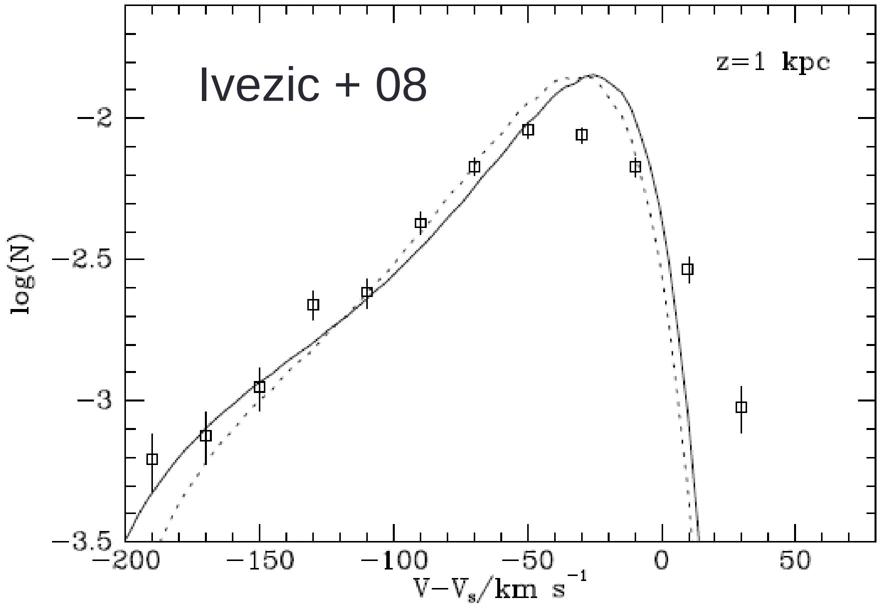
# A simple example

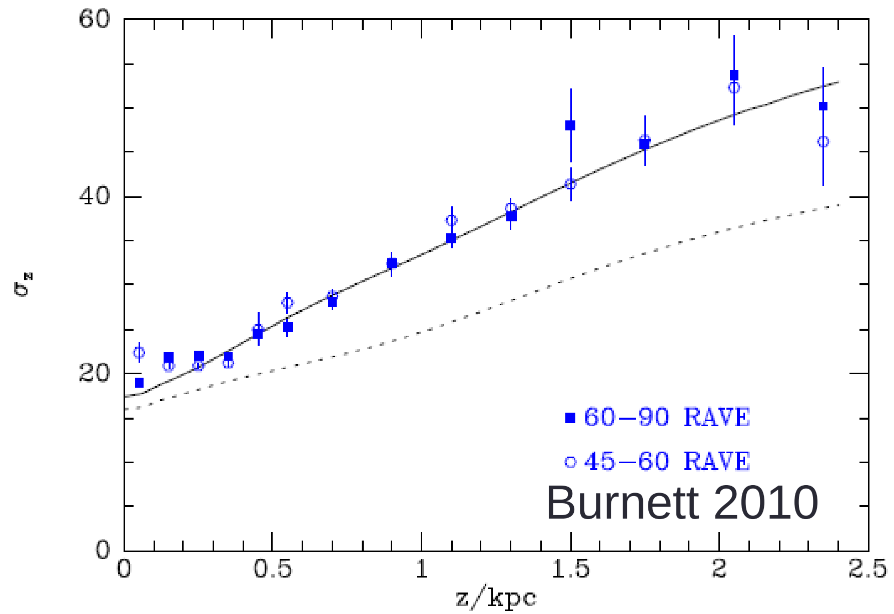
- $f(L_z,J_r,J_z)$ has 4 parameters for each of thin/thick disc



# More predictions

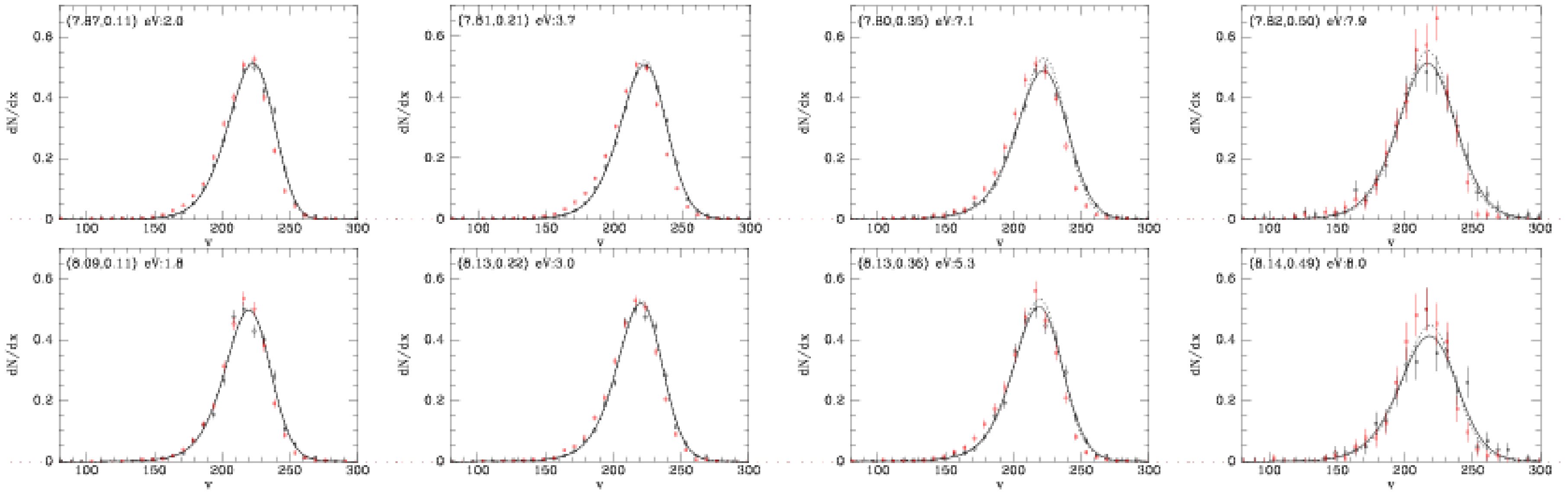
- Get essentially perfect fits to given data and good predictions for N(V) at z=1 kpc and $\sigma_z$(z)



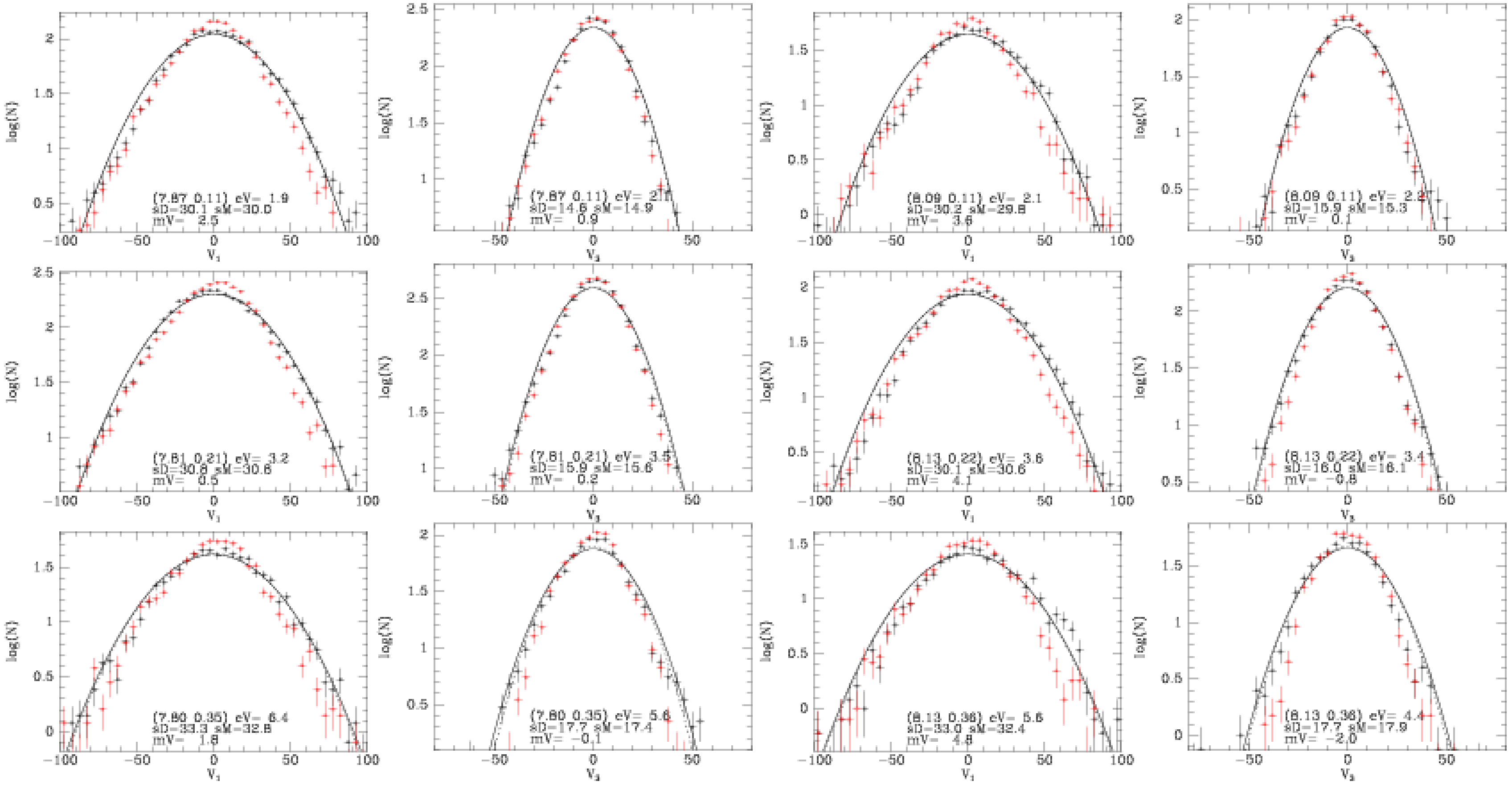

- The ability to fit simultaneously $\rho$(z) and $\sigma_z$(z) suggests $\Phi$ pretty accurate

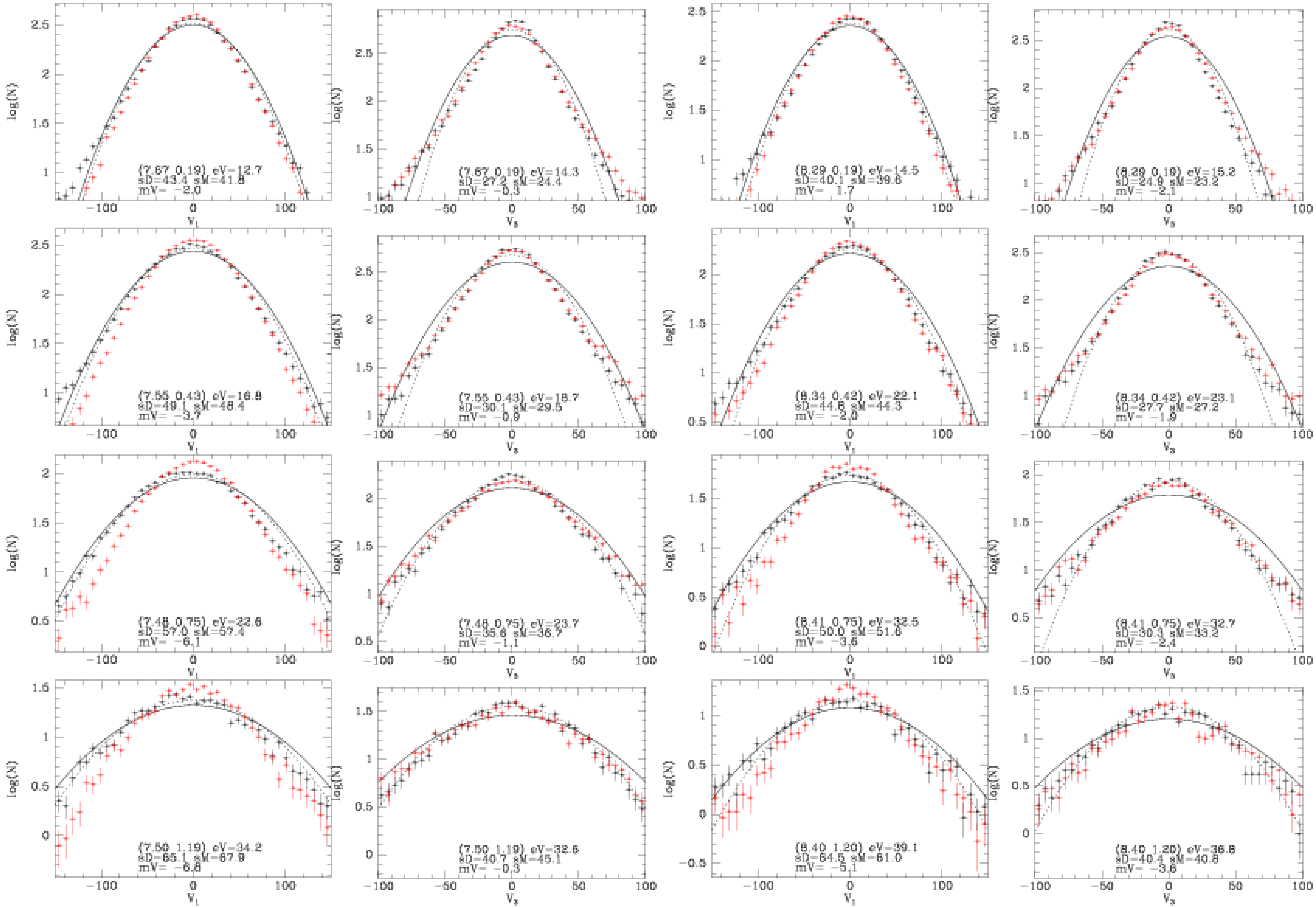
# Extending to RAVE survey




$V_\phi$ for hot dwarfs

# Hot dwarfs in RAVE

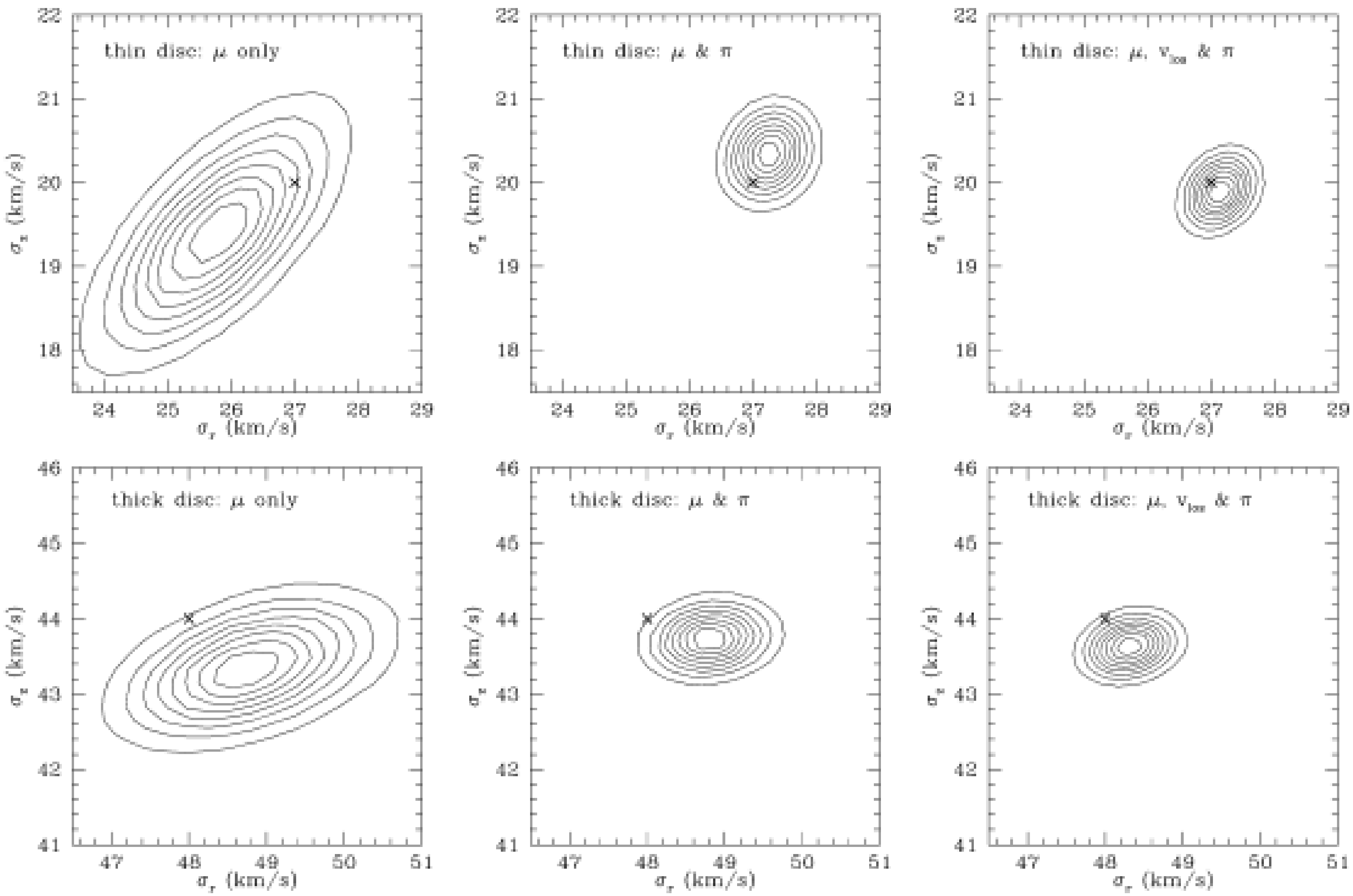




RAVE giants

# Fitting a catalogue: the DF

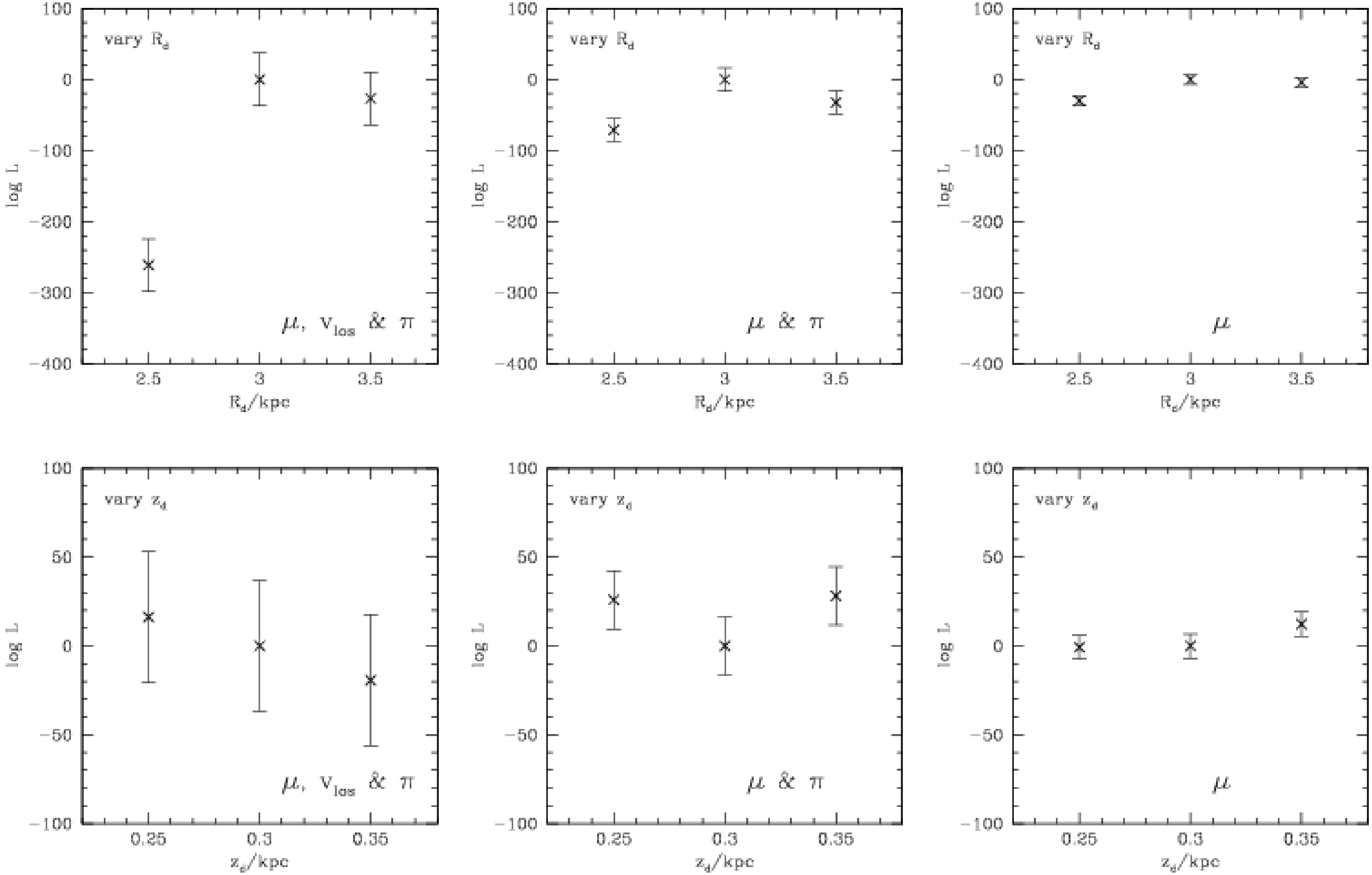
- McMillan & B (2012) showed that DF of thin+thick disc model could be recovered to good precision from catalogue of 10,000 stars with realistic errors



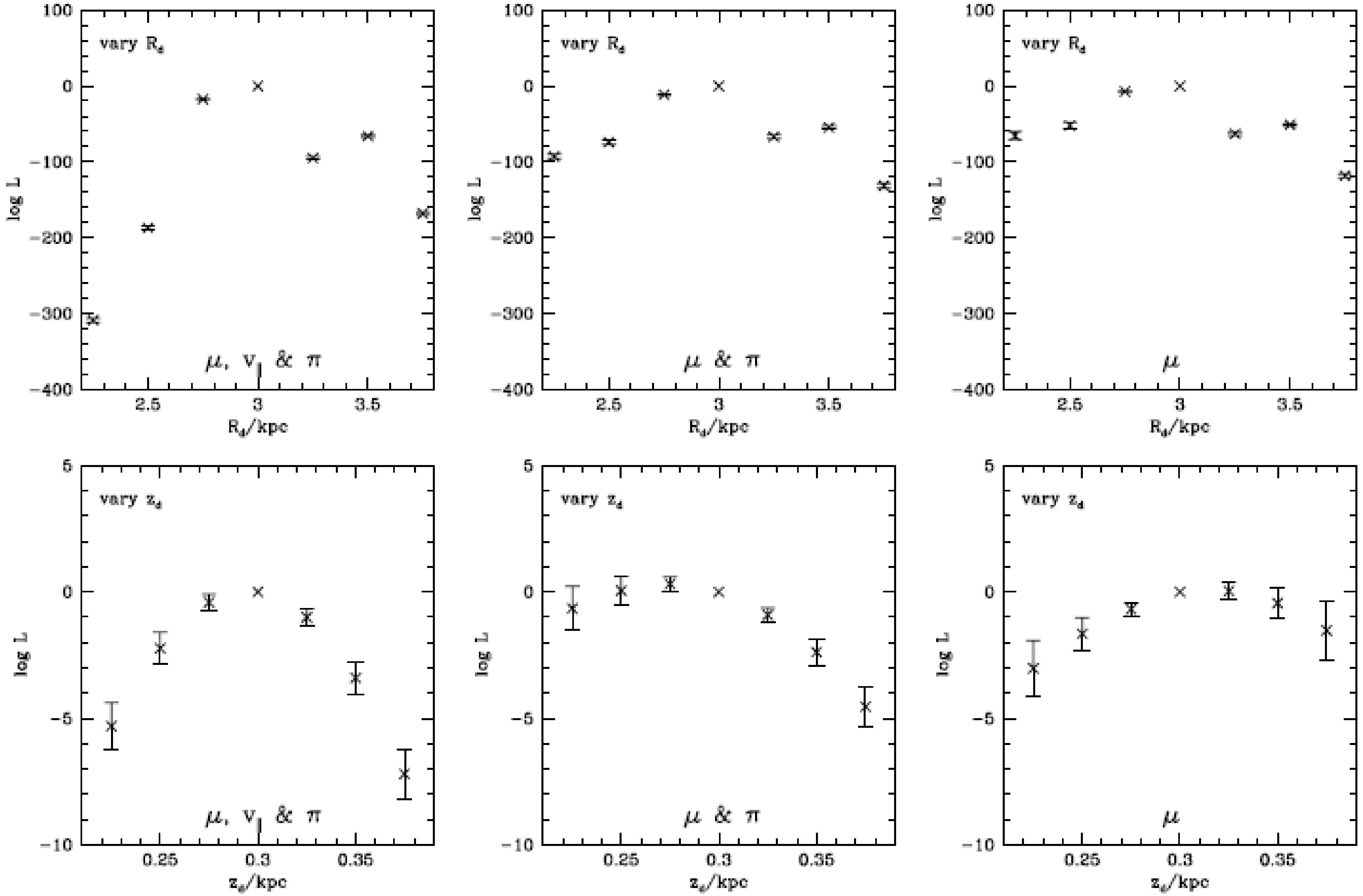
# Fitting a catalogue: II the potential

- To get $\Phi$: for a series of trial $\Phi$ determine likelihood of best-fitting DF: choose Phi that yields highest likelihood
- McMillan & B 2013 show that this scheme unfeasible with orbit (or torus) based models
- Problem is Poisson noise (which grows in importance with precision/completeness of data)
- Scheme can be made to work by using J(x,v) rather than v(J,$\theta$)
- In tests $\Phi$ has contributions from dark halo and exponential discs. Seek scale lengths of discs from 10,000 star catalogue

# Using tori


vary R_d
μ, V_los & π
μ & π
μ
vary z_d
log L
R_d/kpc
z_d/kpc
100
0
−100
−200
−300
−400
2.5
3
3.5
50
−50
−100
0.25
0.3
0.35

# With J(x,v)



# Extending the programme

- Identify respects in which data not fitted by equilibrium model
- Use perturbation theory to refine model by introduction of spiral structure & the warp in both stars and ISM; fit extended model
- Fit similar DFs to cosmological simulation and use these DFs as interface between data and those models (& between competing models)

# Conclusion

- Major observational efforts will be fruitless unless backed by an extensive model-building & fitting programme
- Models need to be chemo-dynamical
- N-body models lack flexibility
- Schwarzschild models available for triaxial configurations but lack uniqueness and are hard to work with
- Torus models currently only available for axisymmetric systems but benefit from unique and compact characterisation and are easiest to work with
- We must calculate likelihood of data in their native space
- Dimensionality of data space is high, so binning inadvisable
- & it's important for a model to deliver a DF and not a discrete realisation
- Models f(J) fitted to GCS make good predictions for RAVE catalogue
- Recovery of DF from catalogue straightforward
- Recovery of Phi from catalogue not possible with orbit/torus models