Modelling our Galaxy

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Outline

- Surveys
- Cosmological simulations
- Our alternative

Surveys

- Photometry
  - 2MASS, SDSS, Vista, PanStarrs, Sky Mapper
- Spectroscopy
  - Geneva-Copenhagen S, RAVE, SEGUE, LAMOST, Gaia-ESO, Galah, LSST
- Astrometry
  - Gaia (2017, 2019,..)
- A massive job to synthesise into
  - a working model of Galaxy
  - a picture of how the Galaxy was assembled
  - Chemodynamical models are central to this effort

Cosmological simulations

- Outside Oxford efforts focus on cosmological simulations
  - Huge N-body + hydrodynamic computations
  - One simulation requires many months of hundreds of CPUs
- Simulations of Dark-Matter clustering form bedrock of cosmology
  - Physics incredibly simple but took 15 yrs for simulations to get basic picture right (over-merging problem sorted ~2000)
- For 15 years the community has struggled with simulations that include gas & star formation
  - Without powerful feedback from star formation galaxies become too luminous and too spheroidal
  - There is direct observational evidence for powerful outflow from star-forming galaxies but the mechanisms of gas exchange between inter-galactic and interstellar media not really understood
  - Consensus is that core problem is ~ fractal structure of ISM, which extends to scales that won't be resolved numerically any time soon
- So cosmological simulations lack predictive power
  - They are far too costly to fit to data
  - It's hard even to characterise them

Orbits

- Most orbits in plausible Φ(R,z) are quasiperiodic
  - $\Rightarrow \exists$ angle-action coords (θ,J)
  - The momenta J are consts of motion
    - J_r quantifies excursions in r
    - $J_\phi = L_z$ angular momentum
    - J_z quantifies excursions $\perp$ Galactic plane
- We have developed techniques for computing J(x,v), θ(x,v) and x(θ,J), v(θ,J)

(Extended) Distribution Functions

- Any non-negative f(J) defines an equilibrium dynamical model
- We think of galaxies as built up out of components/populations
- DFs $f_i(J)$ can be straightforwardly added
- $f(J) = \sum_i f_i(J)$
- Our basic DF for disc is “quasi isothermal”

$$f(J_r, J_z, L_z) = f_{\sigma_r}(J_r, L_z) f_{\sigma_z}(J_z, L_z),$$

$$f_{\sigma_r}(J_r, L_z) \equiv \frac{\Omega\Sigma}{\pi\sigma_r^2\kappa}[1 + \tanh(L_z/L_0)]\mathrm{e}^{-\kappa J_r/\sigma_r^2}$$

$$f_{\sigma_z}(J_z, L_z) \equiv \frac{\nu}{2\pi\sigma_z^2}\,\mathrm{e}^{-\nu J_z/\sigma_z^2} \qquad \Sigma(L_z) = \Sigma_0 \mathrm{e}^{-R_c/R_d}$$

Metallicity-blind models

- 2010 – 2012 we demonstrated good fits to GCS stars (s<120 pc) with superposition of a quasi-isothermal for stars of each age
- 2014 we showed that these models could predict to good (but imperfect) accuracy kinematics of stars with s~2000 pc (RAVE data)
- 2015 we fitted DF to kinematics of RAVE stars and from vertical density profile determined by SDSS determined parameters of dark halo under assumption that it is a (flattened) NFW model

The thin disc DF

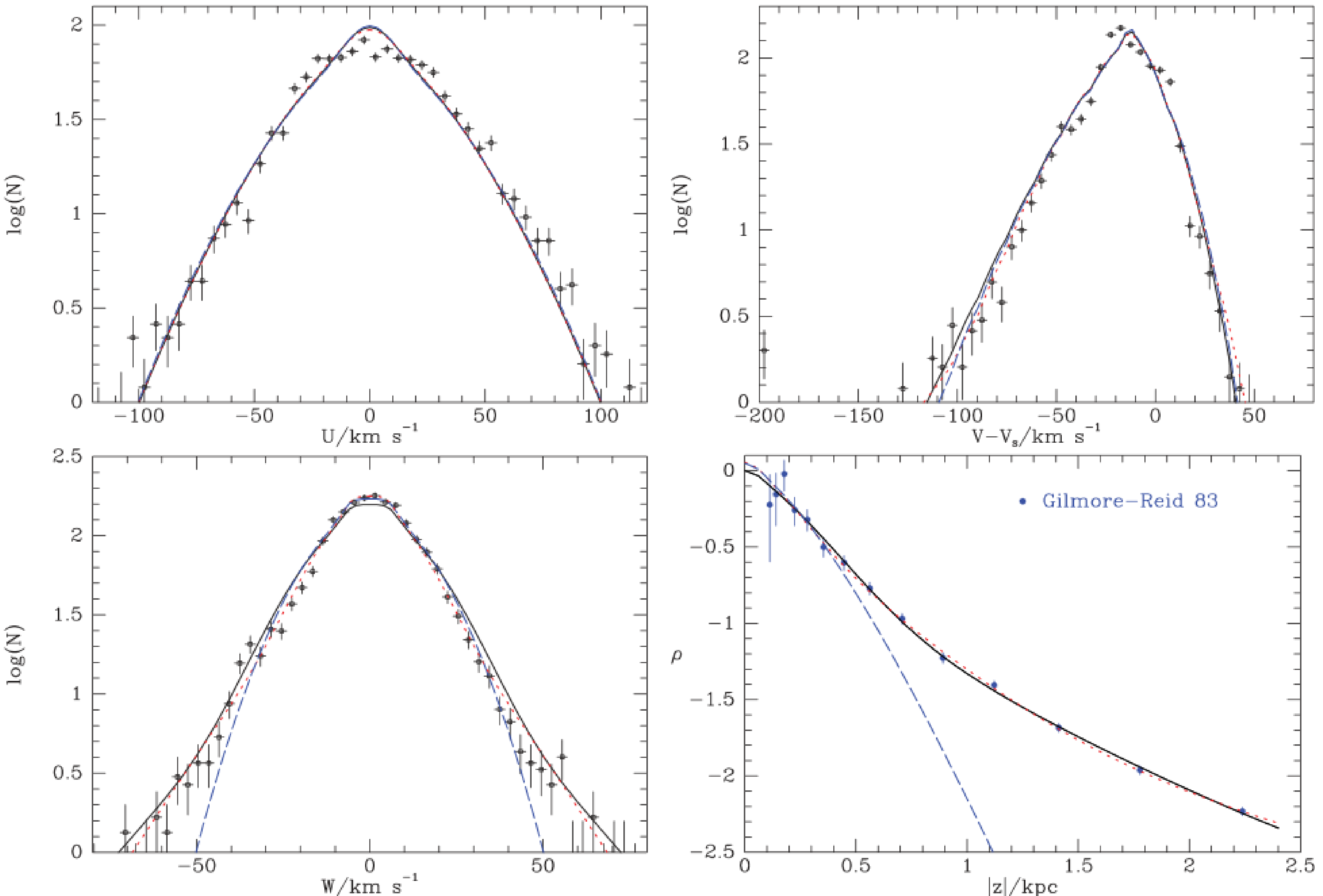
- A sum over ages of stars with velocity dispersion increasing with age

$$f_{\rm thn}(J_r, J_z, L_z) = \frac{\int_0^{\tau_{\rm m}} {\rm d}\tau\, {\rm e}^{\tau/t_0} f_{\sigma_r}(J_r, L_z) f_{\sigma_z}(J_z, L_z)}{t_0({\rm e}^{\tau_{\rm m}/t_0} - 1)}$$

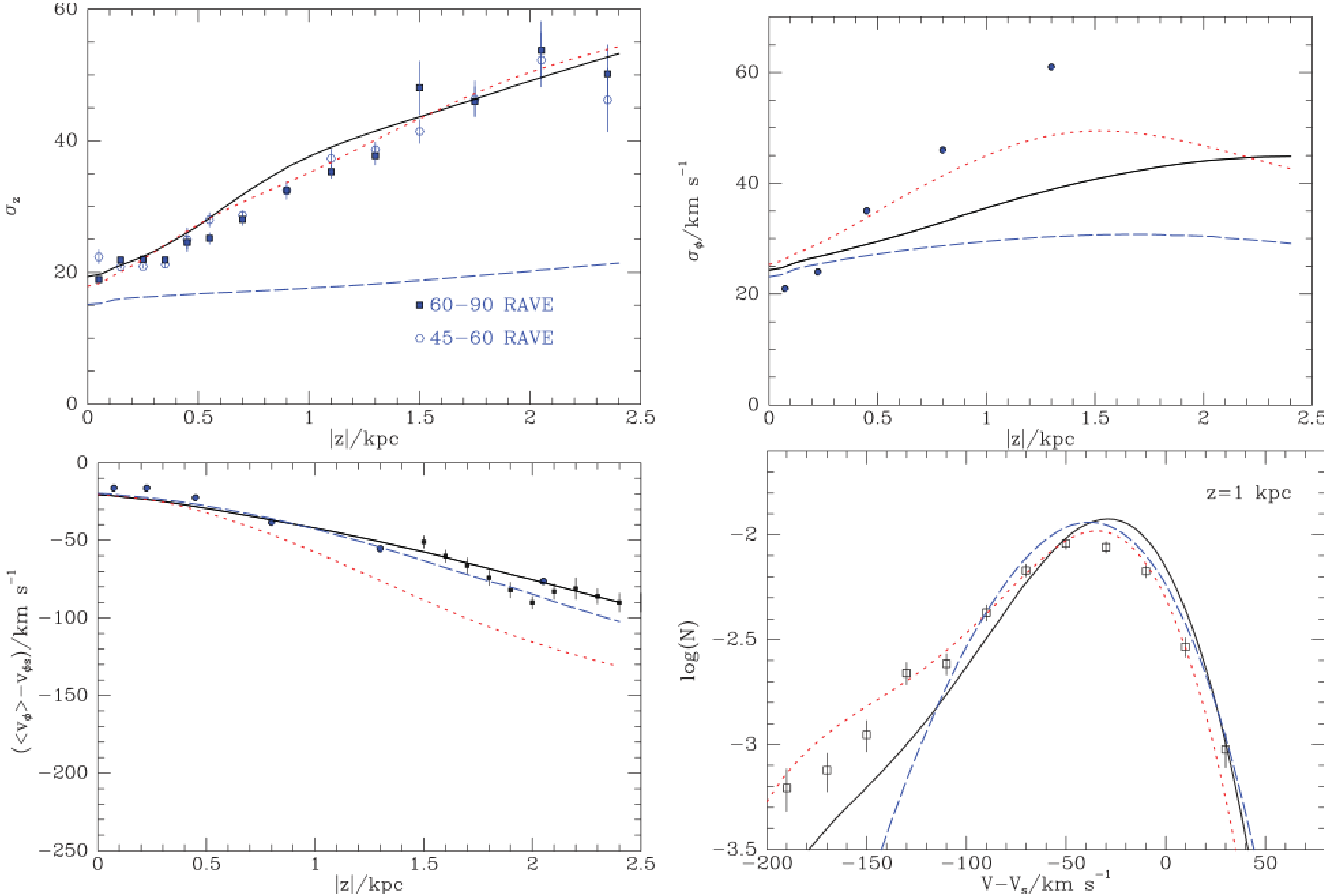
$$\sigma_r(L_z, \tau) = \sigma_{r0} \left(\frac{\tau + \tau_1}{\tau_{\rm m} + \tau_1}\right)^{\beta} {\rm e}^{q(R_0 - R_{\rm c})/R_{\rm d}}$$

$$\sigma_z(L_z, \tau) = \sigma_{z0} \left(\frac{\tau + \tau_1}{\tau_{\rm m} + \tau_1}\right)^{\beta} {\rm e}^{q(R_0 - R_{\rm c})/R_{\rm d}}.$$

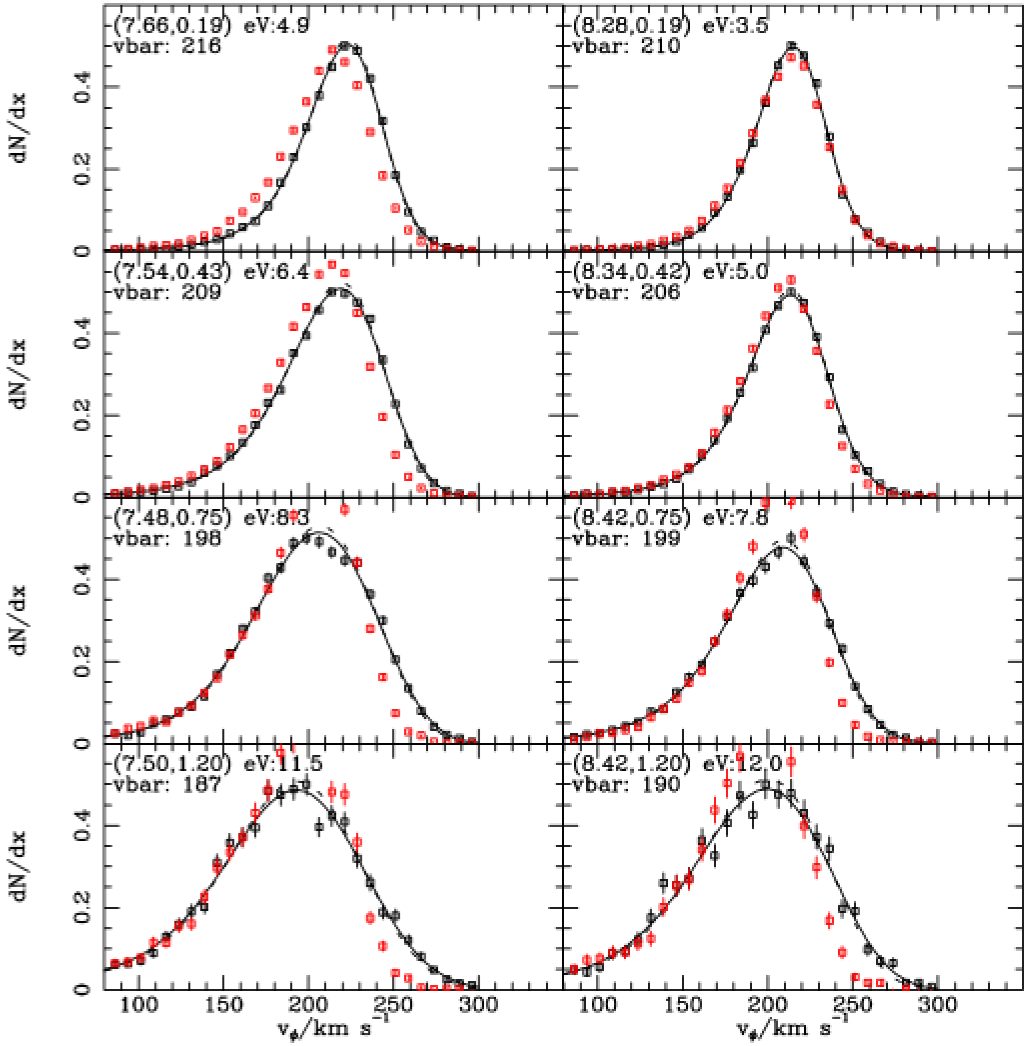
GCS kinematics (+ Gilmore Read density)



Predictions

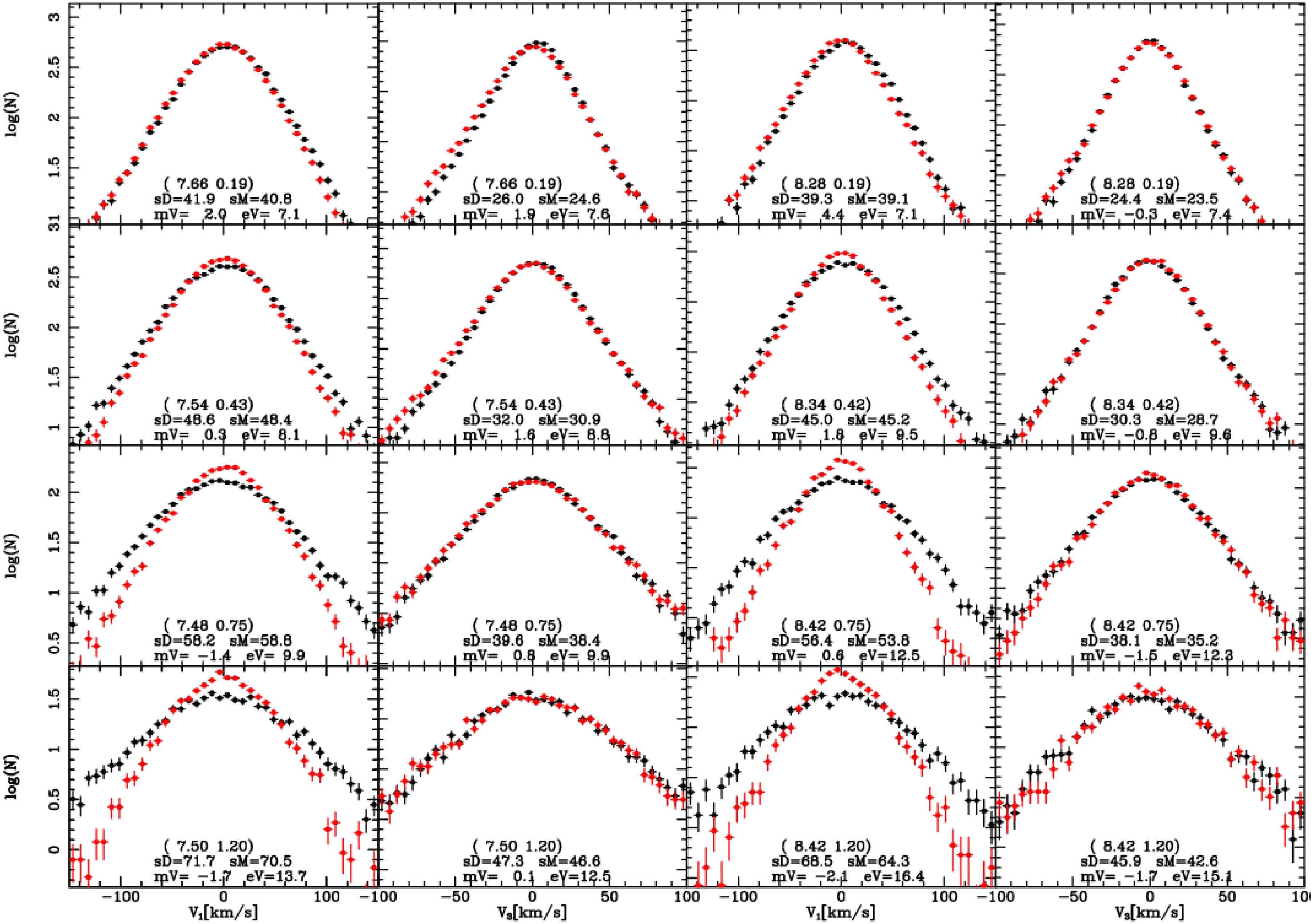


More predictions

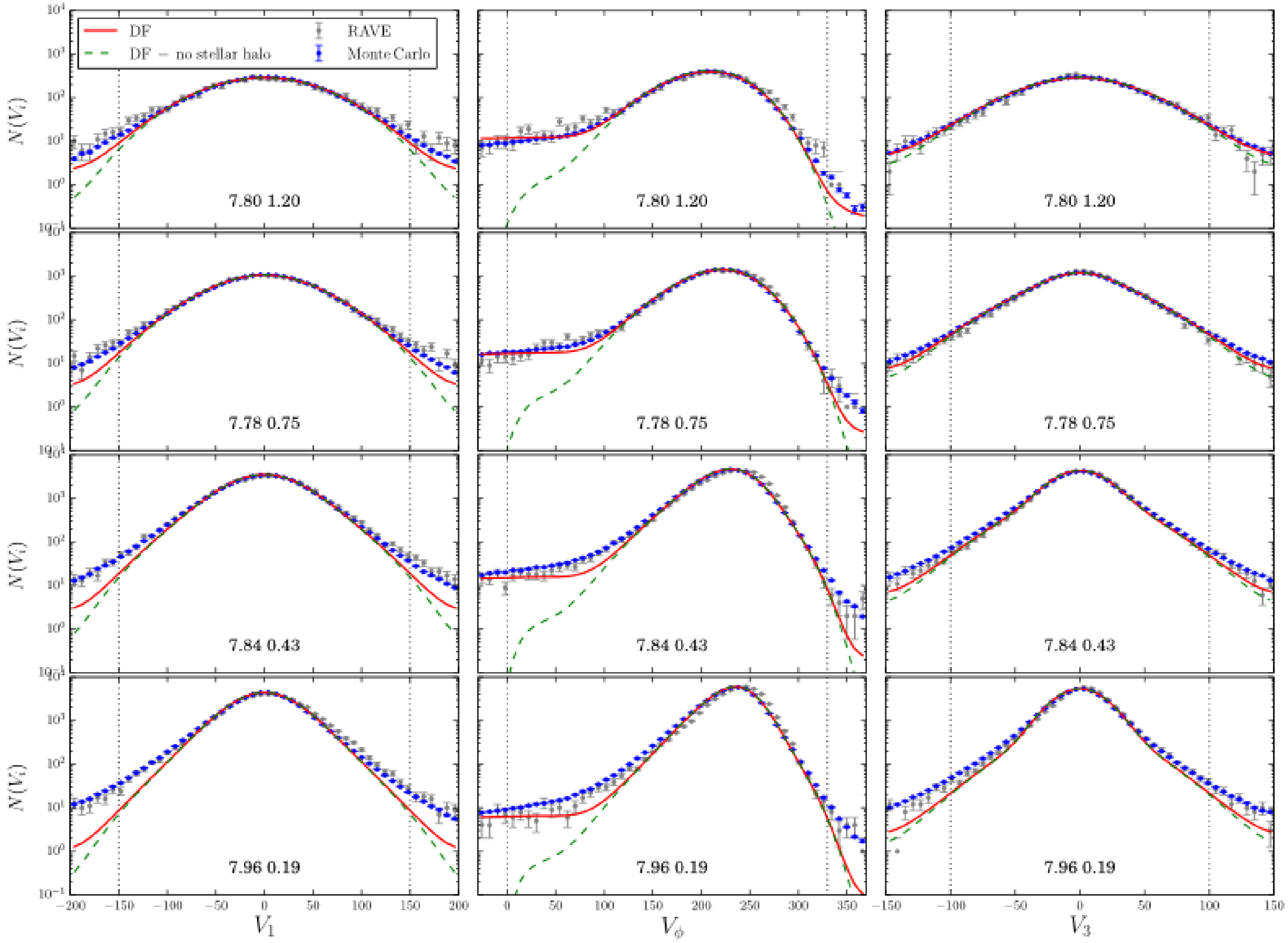


V_phi

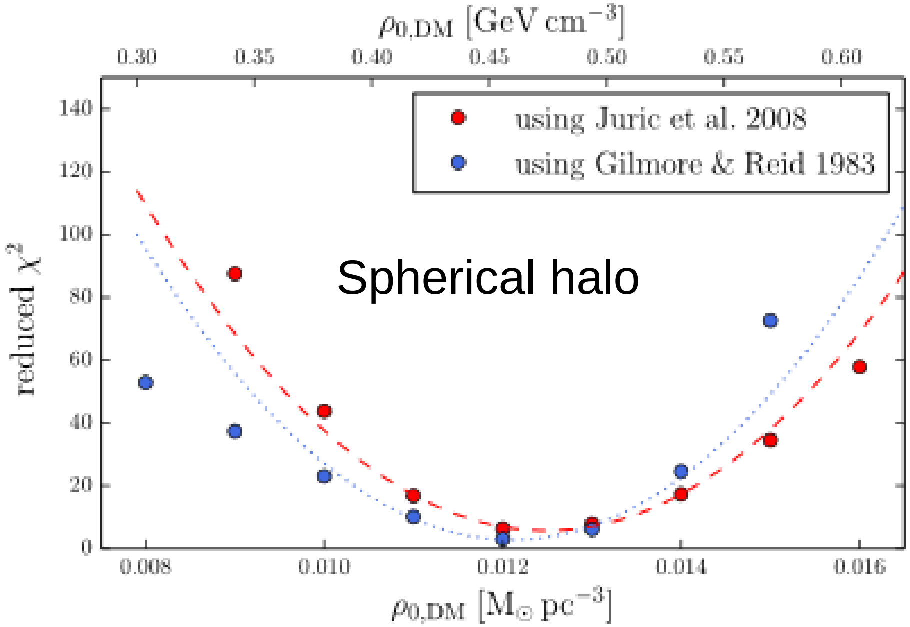
More predictions (V_R, V_z)

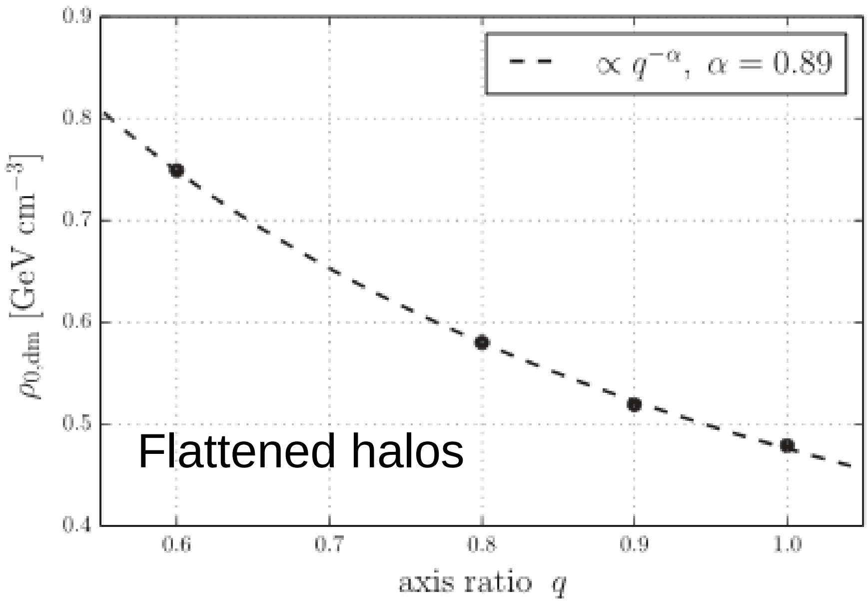


Model fitted to RAVE

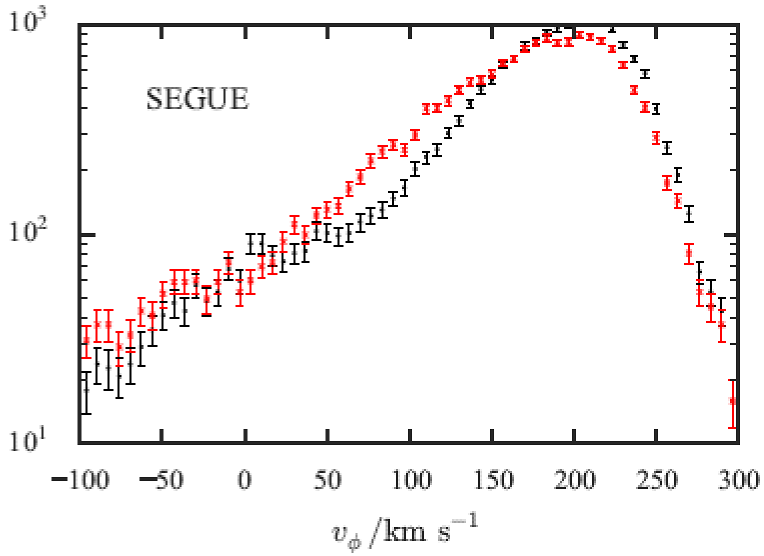


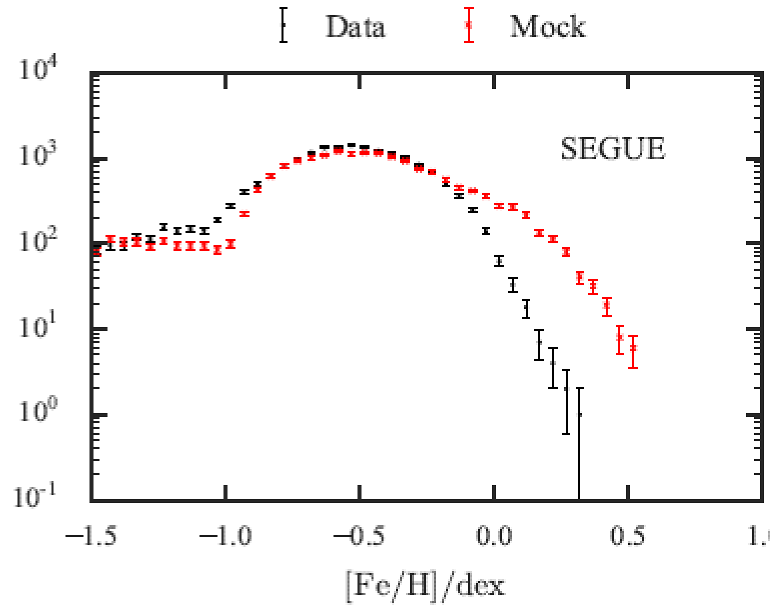
Strongest constraints yet on local DM density (Piffl + 2014)

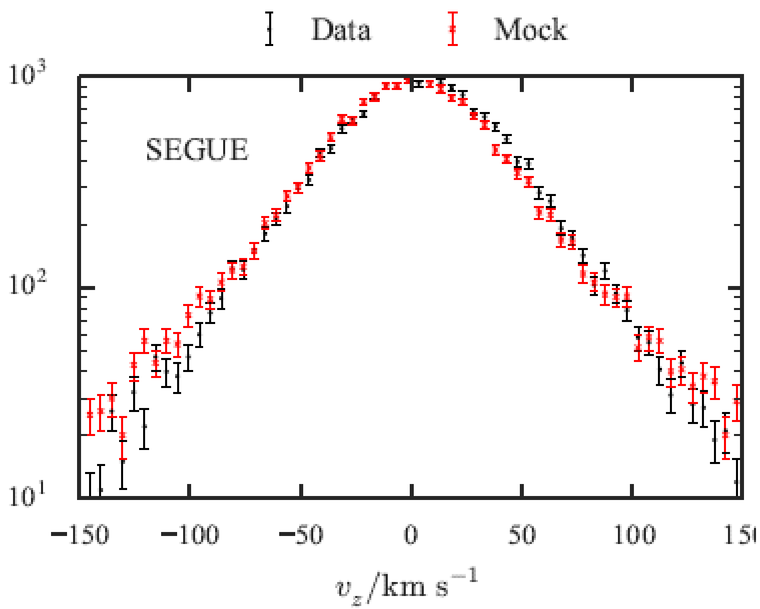


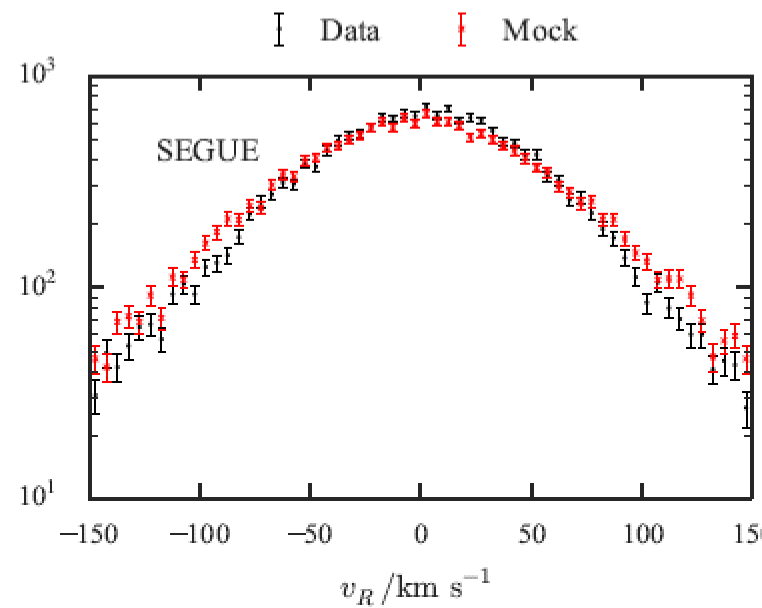


Predictions









Self-consistency

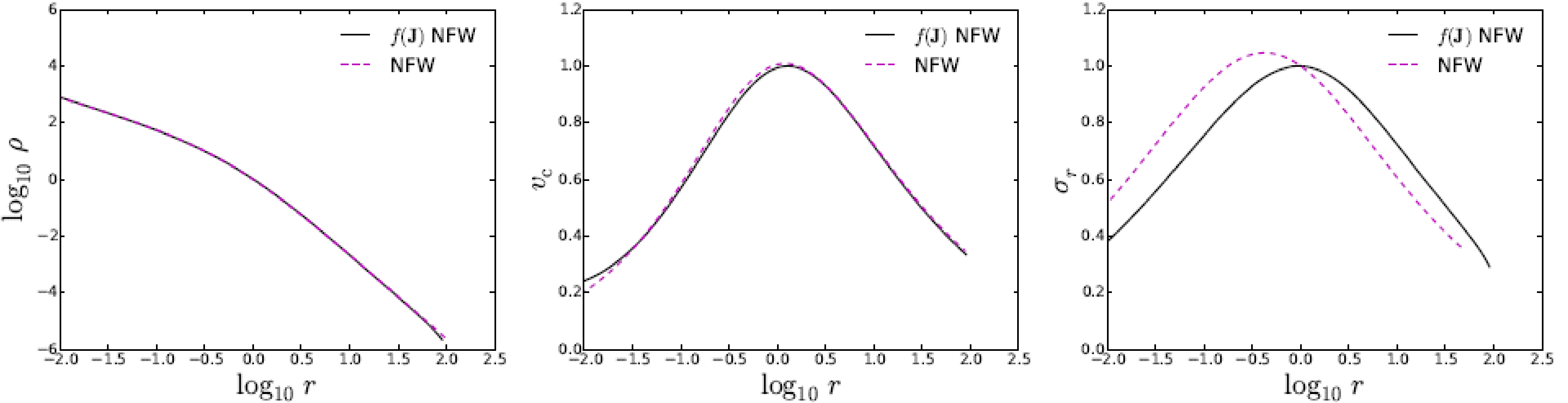
- This work all done with $\Phi(R,z)$ computed from specified $\rho(R,z)$
- ρ_{disc} assumed to be exponential in R and double exponential in z
- The disc self-consistent with its assumed contribution to $\Phi(R,z)$ only to extent that DF produces roughly exponential + double exponential $\rho(R,z)$
- Current models specify dark halo by f(J) rather than $\rho(R,z)$ and we compute the potential self-consistently generated by $f_{total}(J)$

A live NFW halo (Posti + 2015)

- A simple $f_{DM}(J)$ self-consistently produces a near NFW density profile

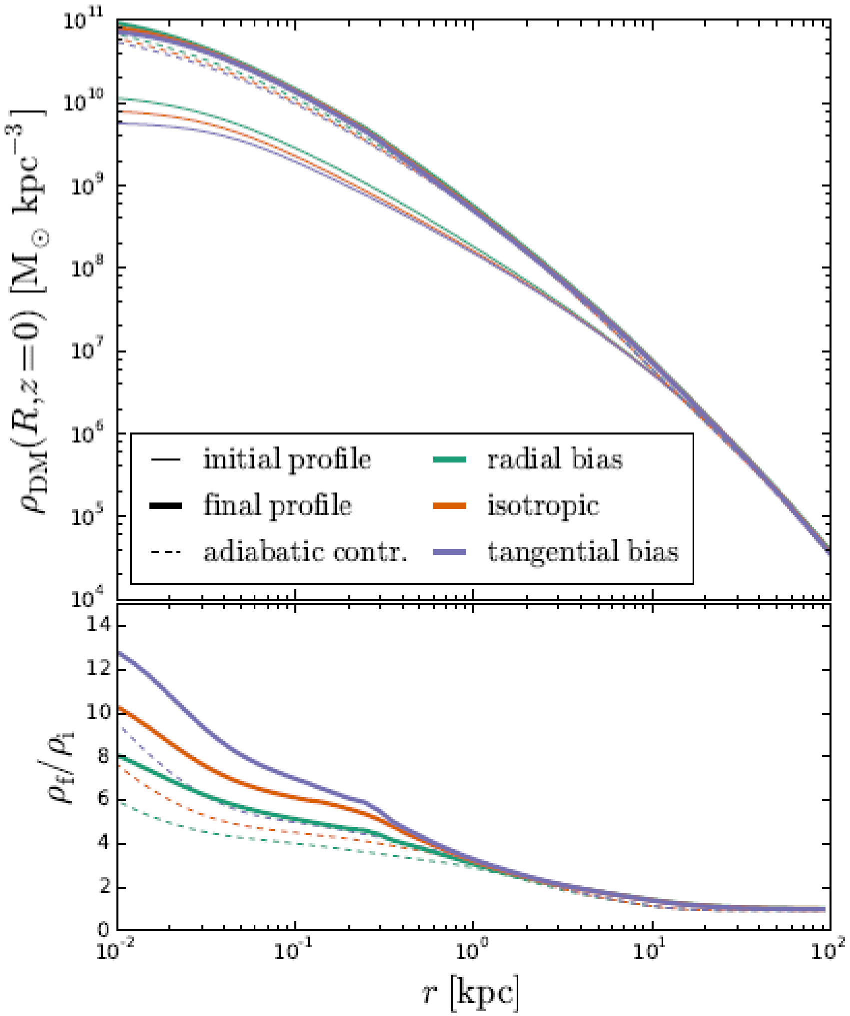
$$f(\mathbf{J}) = \frac{M_0}{J_0^3} \frac{[1 + J_0/h(\mathbf{J})]^{5/3}}{[1 + g(\mathbf{J})/J_0]^{2.9}}$$

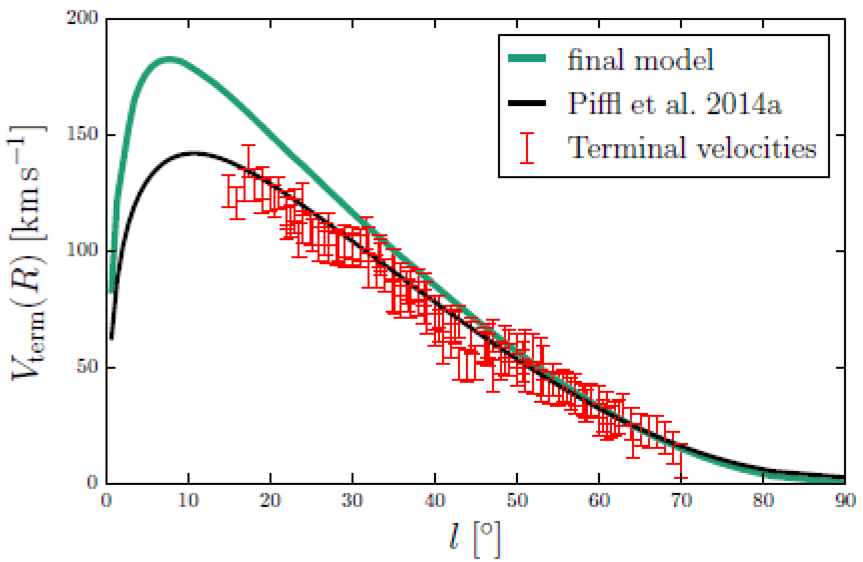
- g & h homogeneous fns of order unity – in spherical case the same linear function
- J_0 sets the linear scale



Adiabatic addition of the disc (Piffl + 2015)

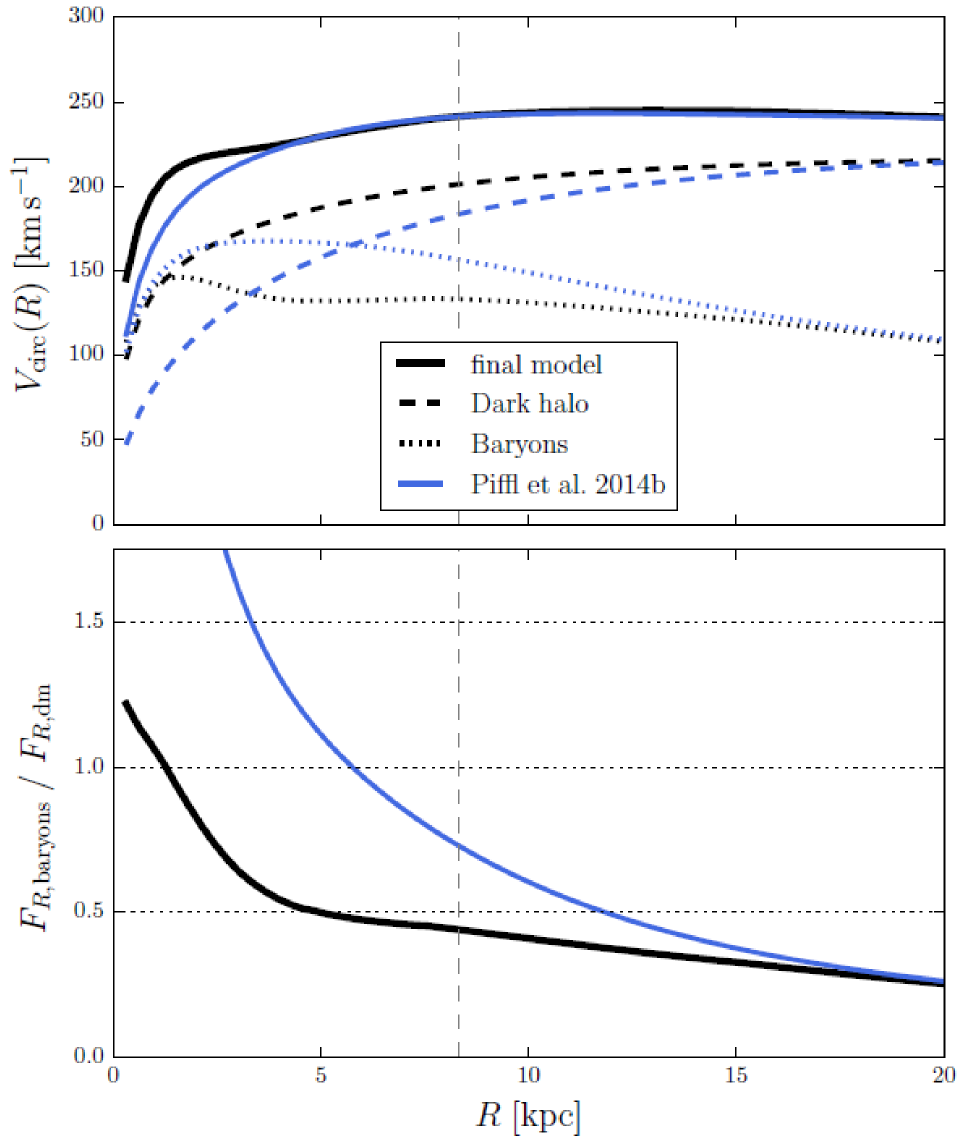
- The disc has grown over many dynamical times, and J_i adiabatic invariants, so perhaps $f_{DM}(J)$ same after disc growth as in DM-only simulation
- When we adopt this f_{DM} and f_{disc} fitted to RAVE data with NFW ρ_{DM}, we no longer match $v_c(R)$ curve because DM has been strongly compressed by gravity of disc





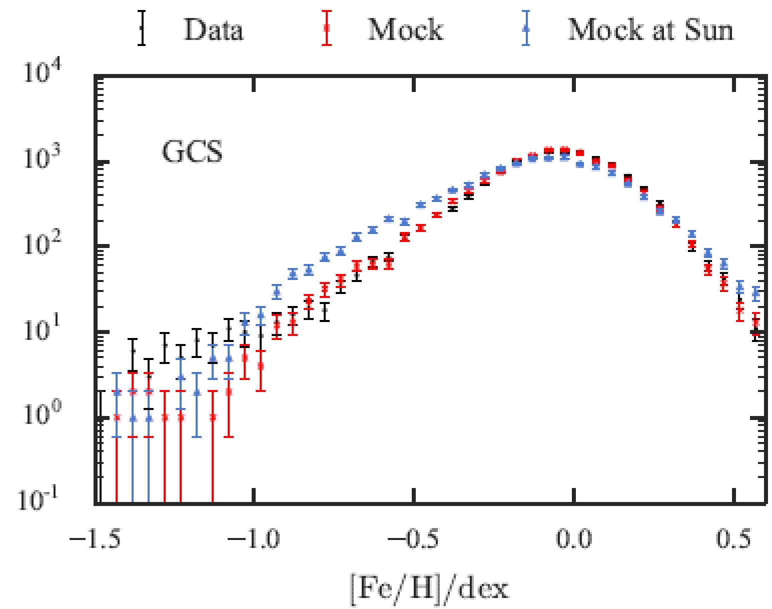
Currently (Piffl & B 2015)

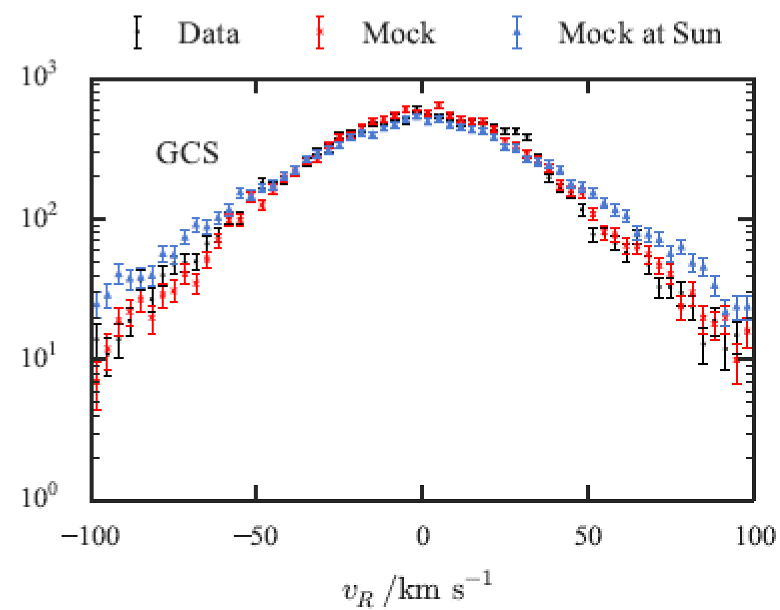
- Investigating whether data can be fitted using expected NFW f(J) – scale length of disc has to be increased and mass reduced. Then problematic to get $\rho_{\rm disc}$ sufficiently peaked to plane
- Likely that we have evidence for central heating of DM by bar/spiral structure…



EDFs (Sanders & B 2015)

- Luminosity and colour essential for predicted observables
  - They depend of [Fe/H] as well as age
  - So one has to extend to f(J,\tau,[Fe/H])
- Our choice of f(J,\tau,[Fe/H]) is motivated by a model of how spiral structure heats disc and drives “radial migration” (shifts in L_z)
  - But f(J,\tau,[Fe/H]) ultimately independent of model





Conclusions

- With analytic EDFs for disc and a DF for DM one can fit large bodies of data and successfully predict other data
- These models are cheaper than cosmological simulation by several orders of magnitude and no less/more rigorous
- Their physical content is much easier to appreciate & I believe the way forward is to fit our EDFs to simulations
- We are mapping the Galaxy's DM distribution in some detail
- We may soon have evidence of DM heating by baryons