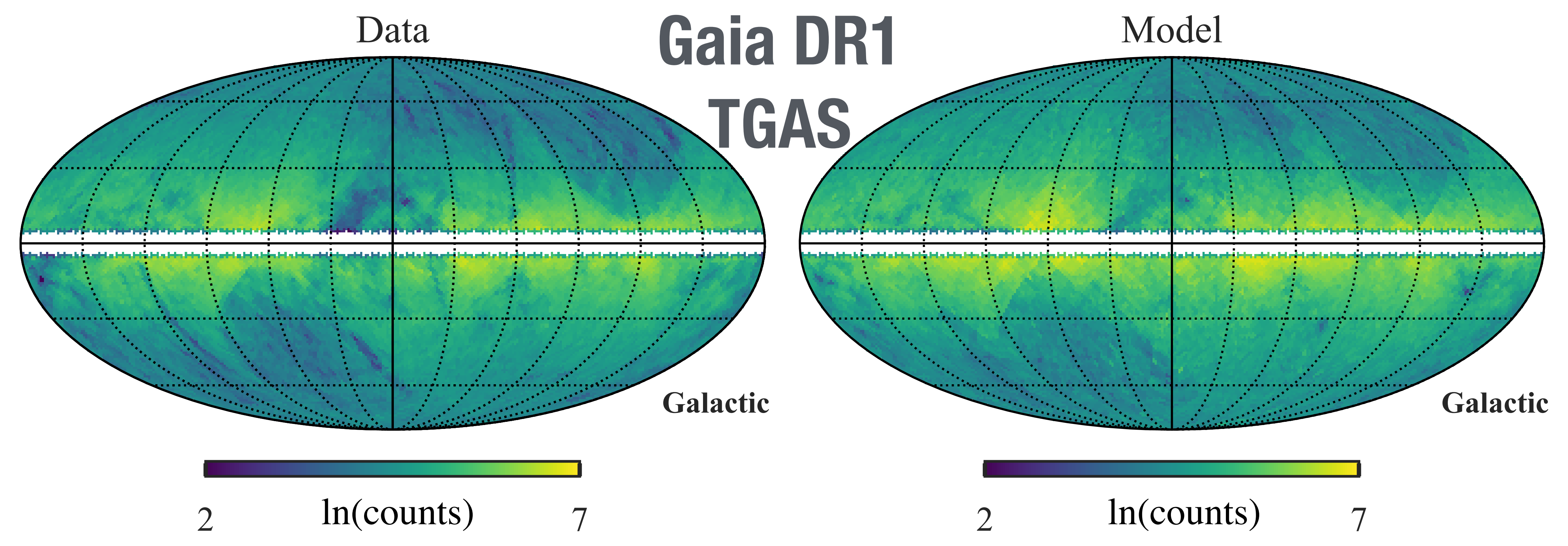


HEATING HISTORY OF THE SOLAR NEIGHBOURHOOD WITH GAIA DR1

JASON SANDERS, INSTITUTE OF ASTRONOMY, CAMBRIDGE

THE SCIENCE OF GAIA AND FUTURE CHALLENGES, LUND

OUTLINE

1. Background
2. Before Gaia
3. With Gaia
4. Modelling
5. Solar motion
6. Round-up

INTRODUCTION: HEATING HISTORY OF THE GALAXY

- Long been known that older disc populations are dynamically hotter (e.g. Roman 1950, Parenago 1950)
- Non-axisymmetries in the potential scatter stars from circular orbits to eccentric (Spitzer & Schwarzschild, 1953). The older stars undergo more scattering.
- Non-axisymmetric features
  1. Spiral arms —> primarily radial scattering/radial heating
  2. Giant Molecular Clouds —> can convert radial to vertical motion
  3. bar (less important at Sun)
  4. satellites/dark-matter sub halos (less important at Sun — maybe important in outer disc)
- Or are older stars born hotter

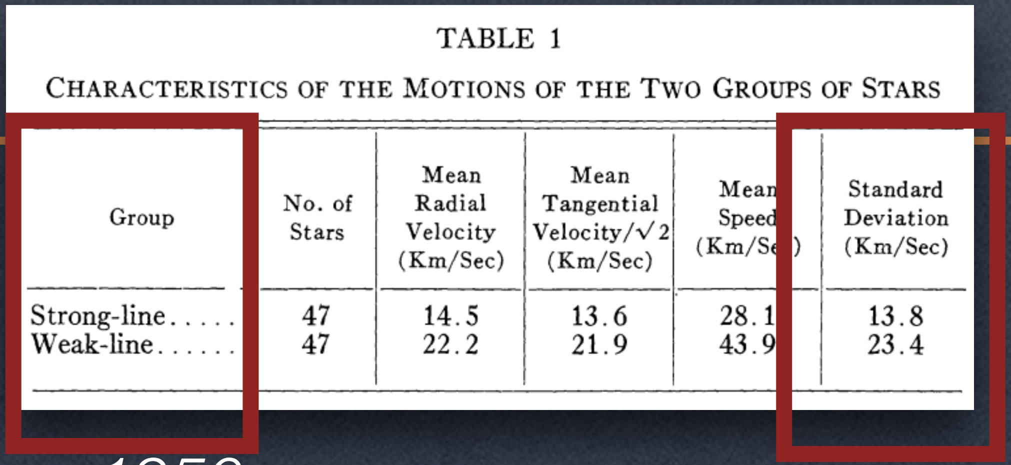


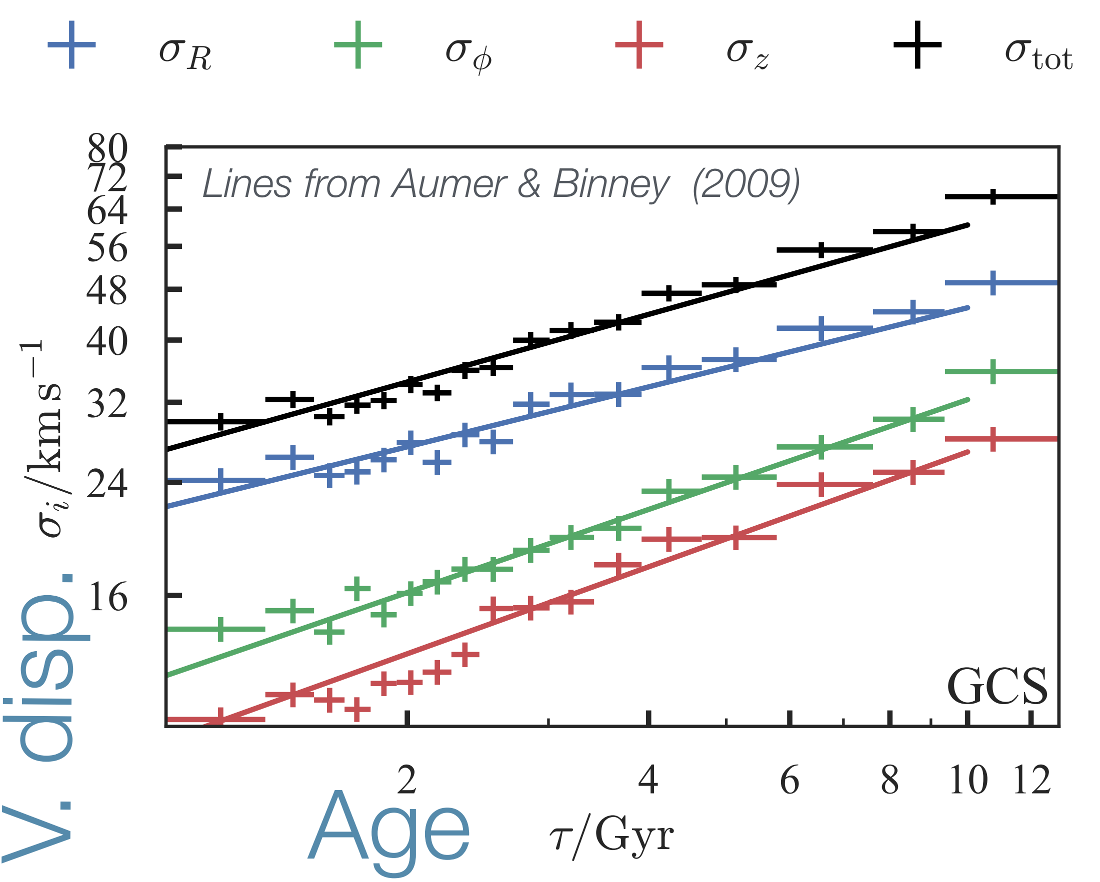
TABLE 1

CHARACTERISTICS OF THE MOTIONS OF THE TWO GROUPS OF STARS

Group	No. of Stars	Mean Radial Velocity (Km/Sec)	Mean Tangential Velocity/√2 (Km/Sec)	Mea Speed (Km/Se)	Standard Deviation (Km/Sec)
Strong-line.....	47	14.5	13.6	28.1	13.8
Weak-line......	47	22.2	21.9	43.9	23.4

Roman 1950

HEATING HISTORY OF THE GALAXY — PRE-GAIA



Spectroscopic

Geneva-Copenhagen survey

Casagrande et al. (2011)

Biased to younger stars

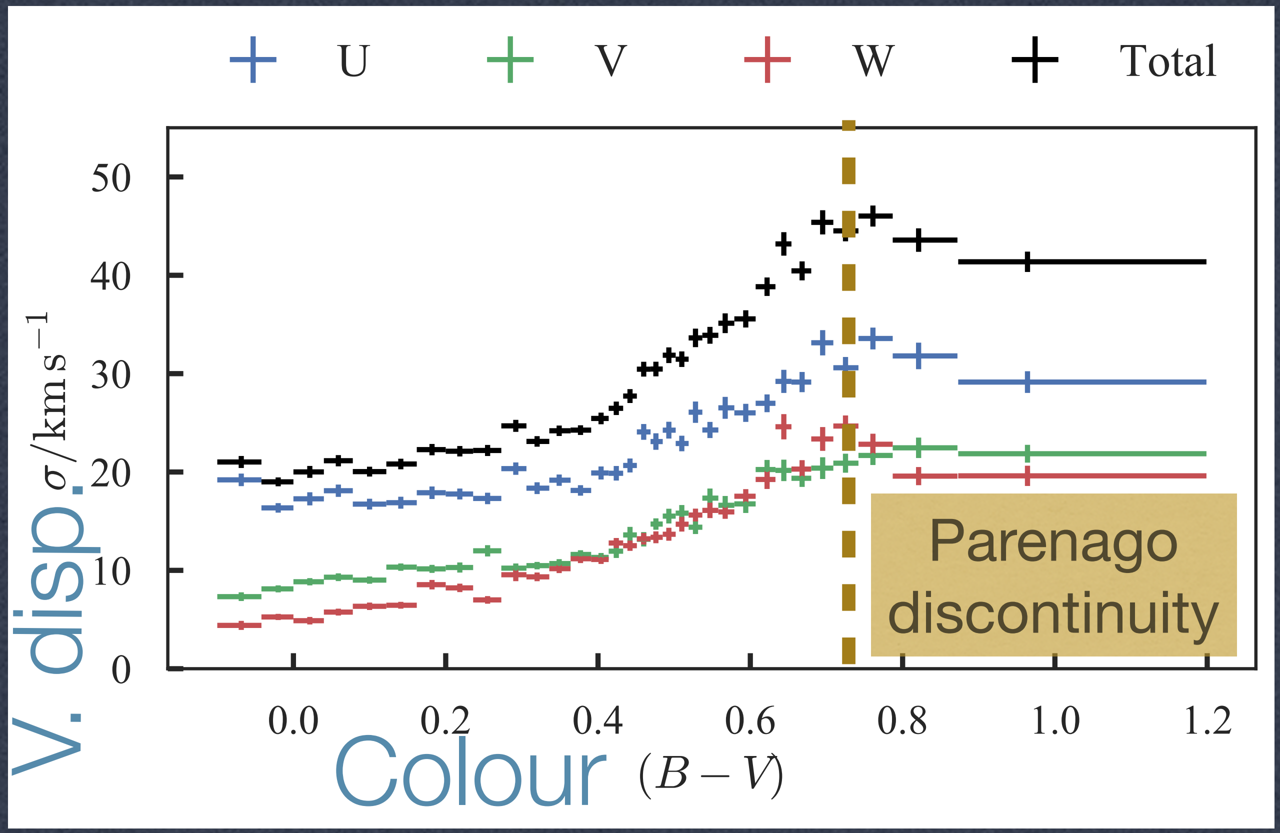
10,000 stars

In the solar neighbourhood, the velocity dispersion is approx. power-law with age, $\sigma \sim \tau^\beta$

Slope ~gives rate of heating although velocity dispersion vs. age ≠ heating rate with time (Aumer, Binney & Schoenrich 2016b)

Confused by age uncertainties — non-trivial but typically constant relative age error.

HEATING HISTORY OF THE GALAXY — PRE-GAIA



Astrometric

Hipparcos + Tycho-2

Dehnen & Binney (1998)

Aumer & Binney (2009)

15,000 stars

Alternative perspective using main-sequence stars.

Redder populations contain older stars

Superposition of different age populations beyond turn-off colour for oldest populations. Parenago discontinuity gives max. age.

Locally, with only proper motions, we can reconstruct full 3D distribution by using full sampling over the sphere.

Aumer & Binney (2009) find β_R=0.31, β_z=0.45

WHAT WILL GAIA SHED LIGHT ON?

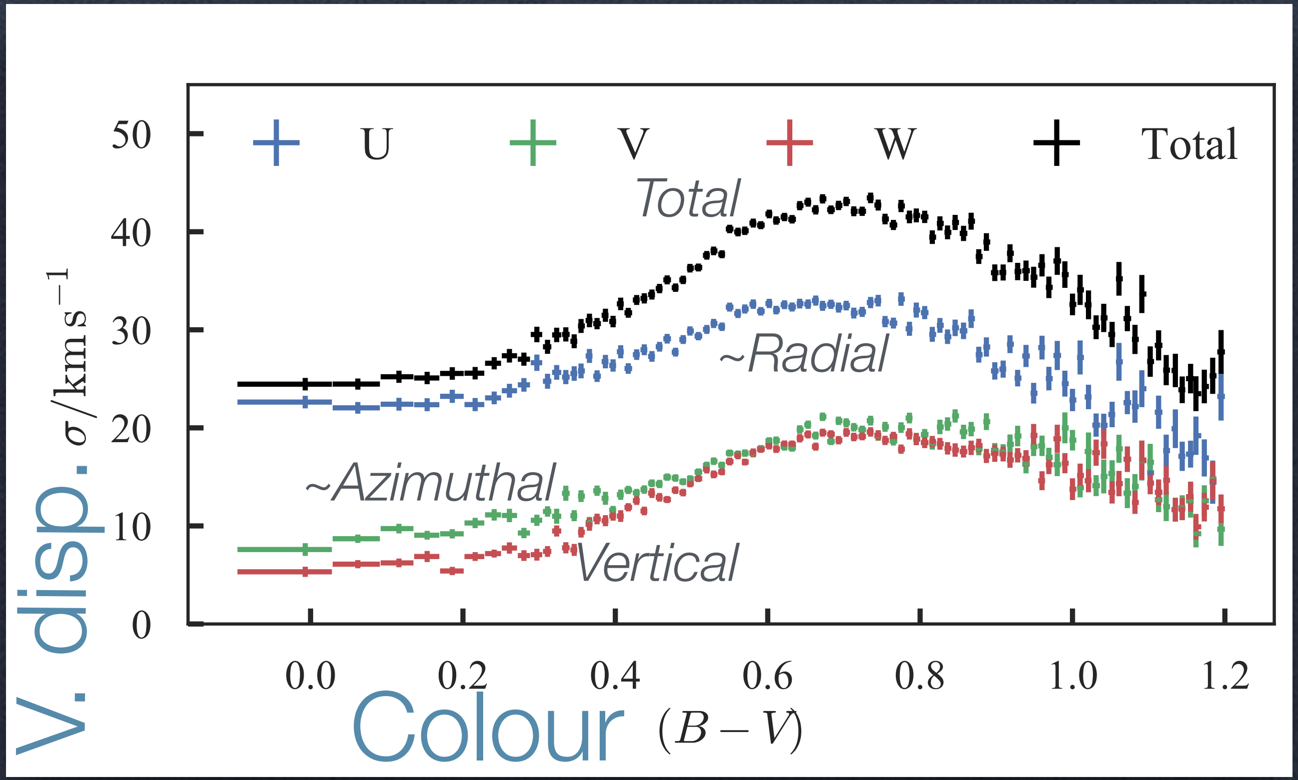
How does ‘thick disc’ fit into the picture?

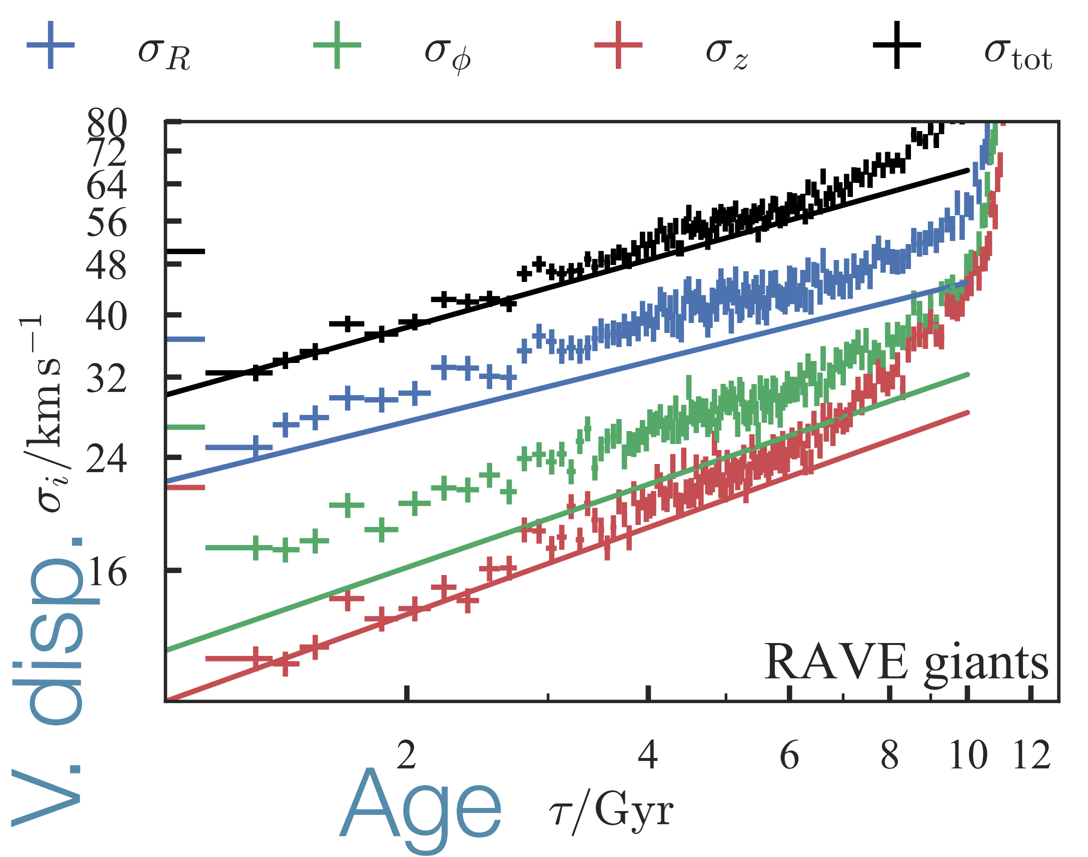
can $\sigma(\tau)$ be explained by continuous thin disc heating or is there space for step in σ + age errors

What is the spatial dependence of heating?

can we detect variation in β due to relative importance of different heating mechanisms?

HEATING HISTORY OF THE GALAXY — WITH GAIA





Astrometric

Gaia DR1: TGAS (Tycho-Gaia Astrometric solution)

APASS photometry

400,000 stars

Spectroscopic

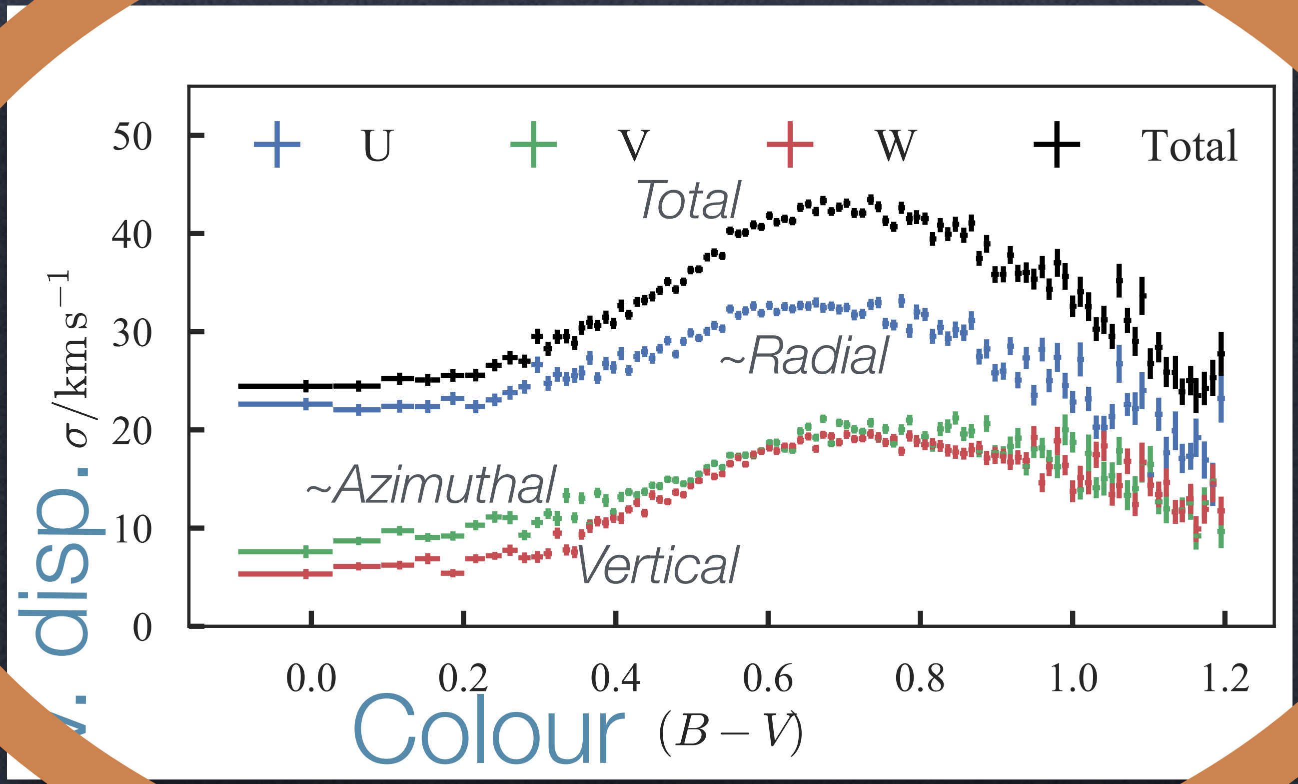
RAVE DR5 (-on)+TGAS

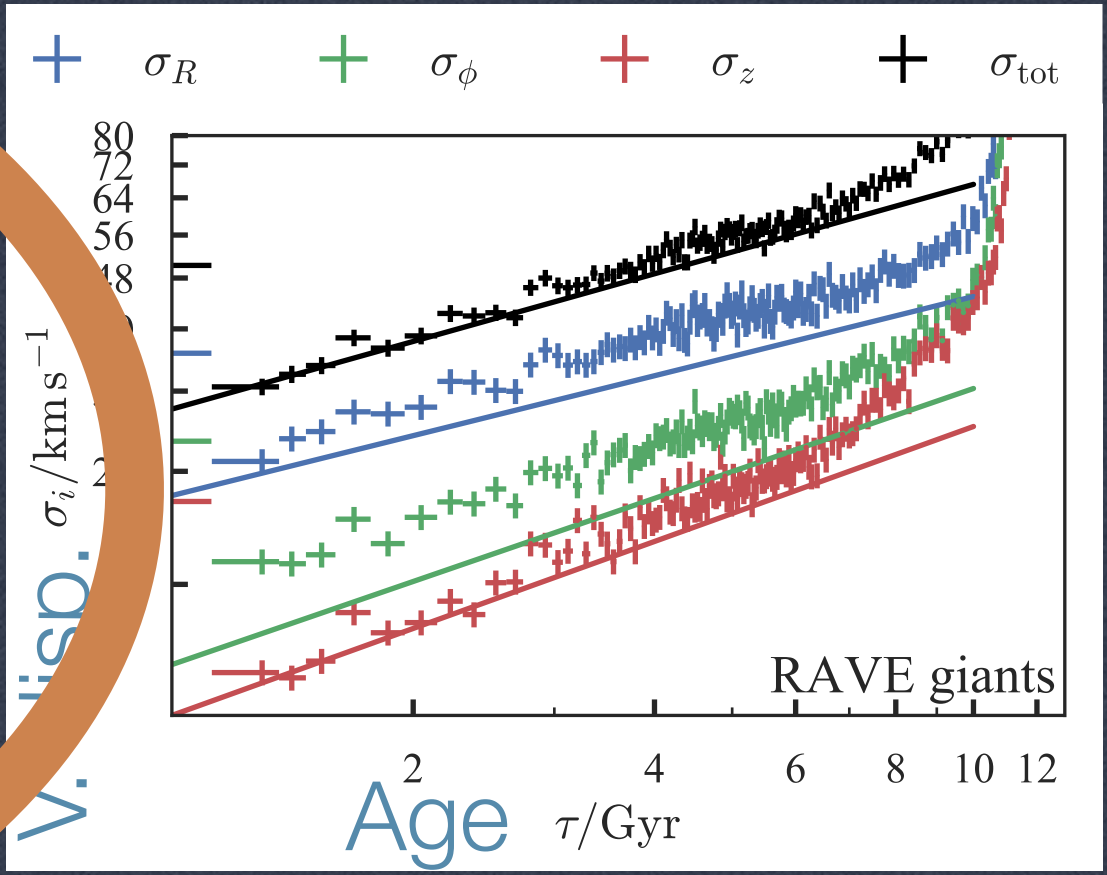
Kunder et al. (2017), Casey et al. (2017)

Ages from isochrones

80,000 stars

HEATING HISTORY OF THE GALAXY — WITH GAIA





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80,000 stars

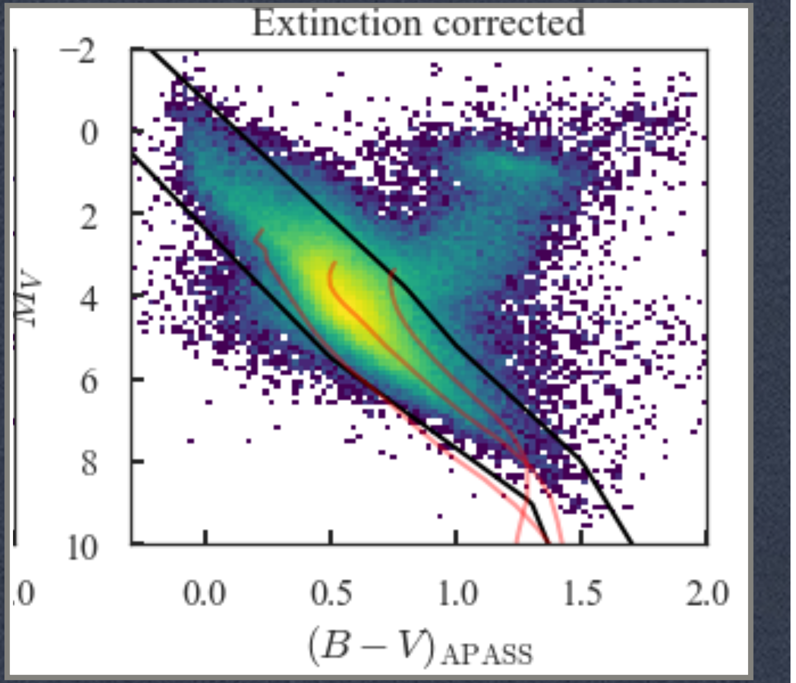
DETAILS — TGAS MAIN SEQUENCE

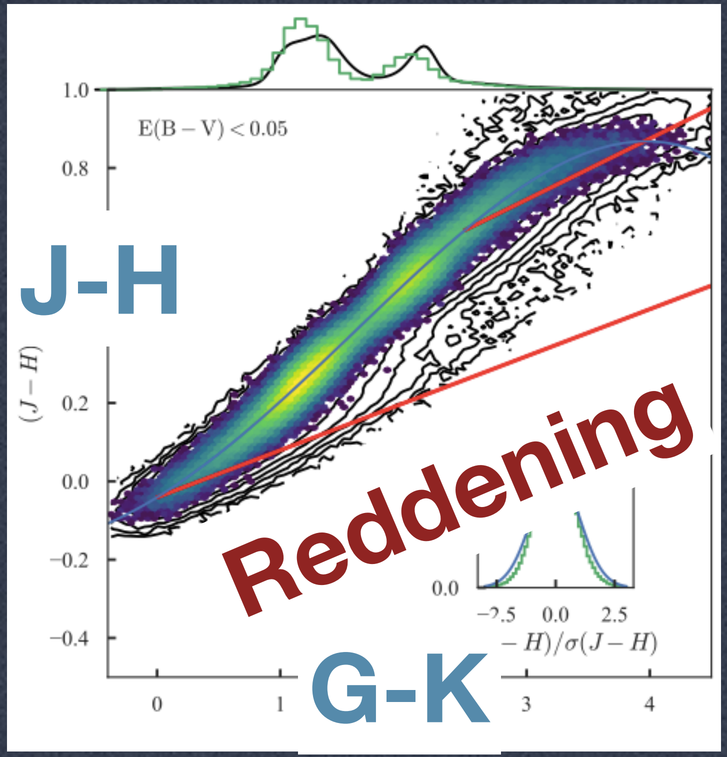
Method

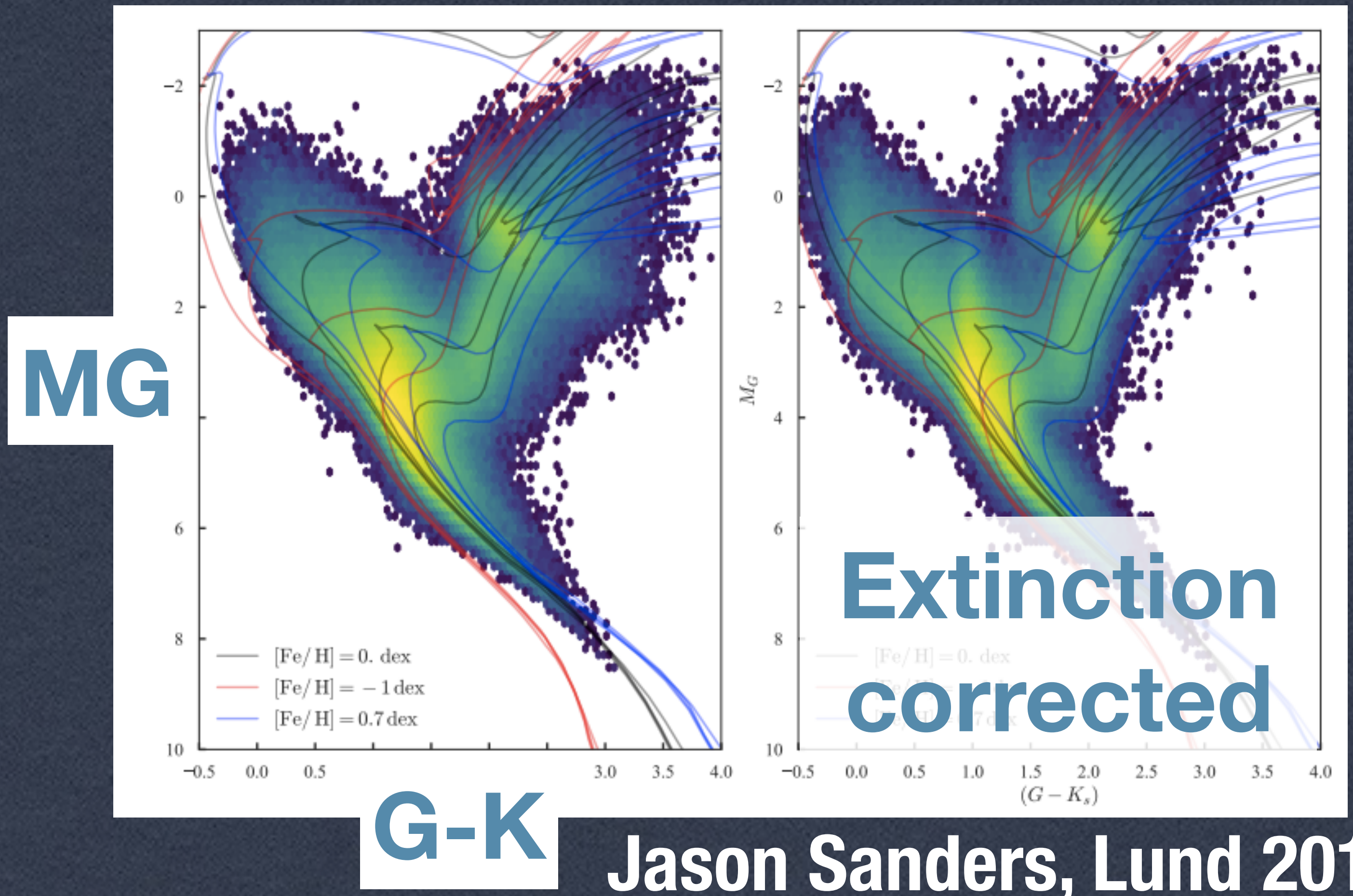
- Cut out main sequence.
- Correct for rotation field using Oort constants.
- Average projected proper-motions over sphere to find dispersions [Dehnen & Binney 1998]

Extinction correction

- Reddening vector in (G-K) vs. (J-H) offset from stellar locus (also noted by Poggia et al. 2017).
- Extinction estimated from this offset folded with a 3d extinction prior from Green et al. (2015) [where available] and an isochrone prior.







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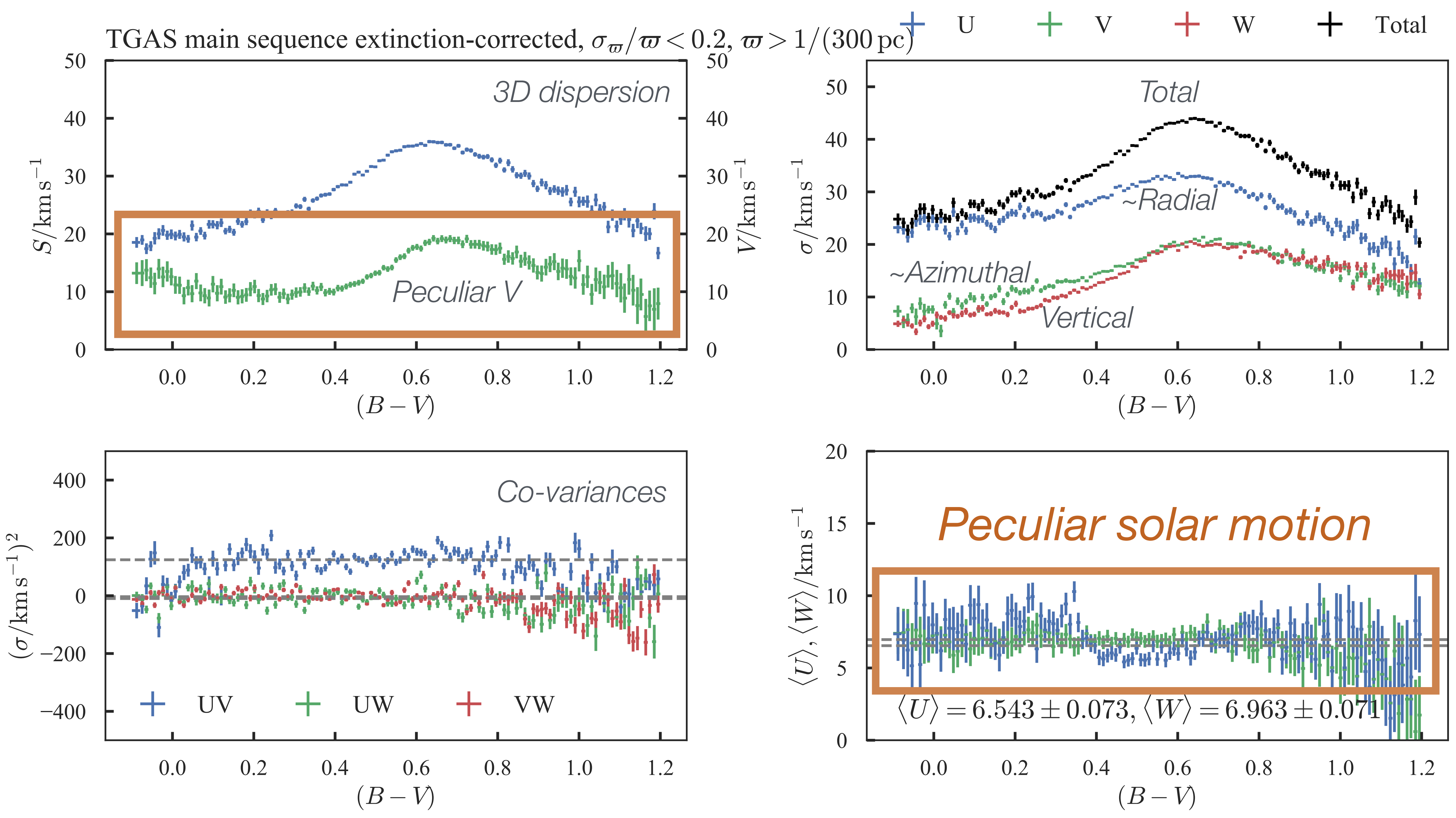
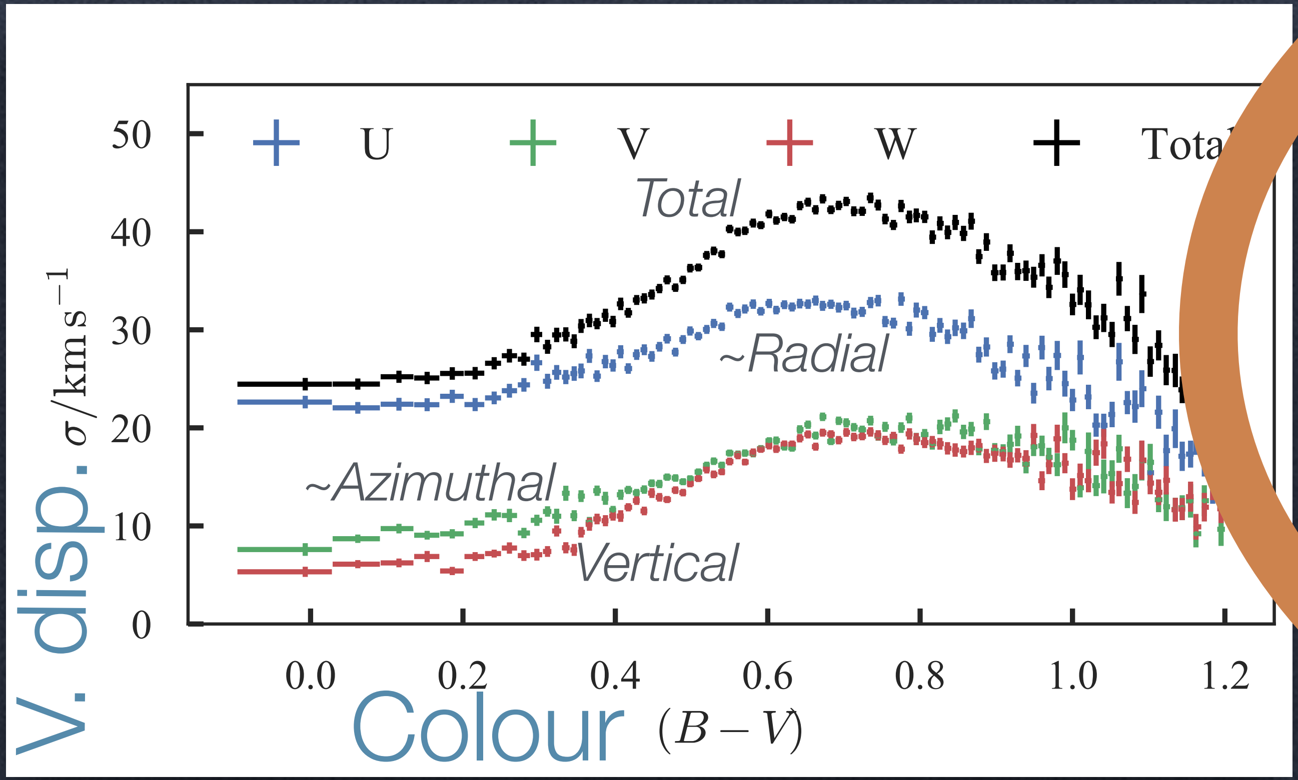
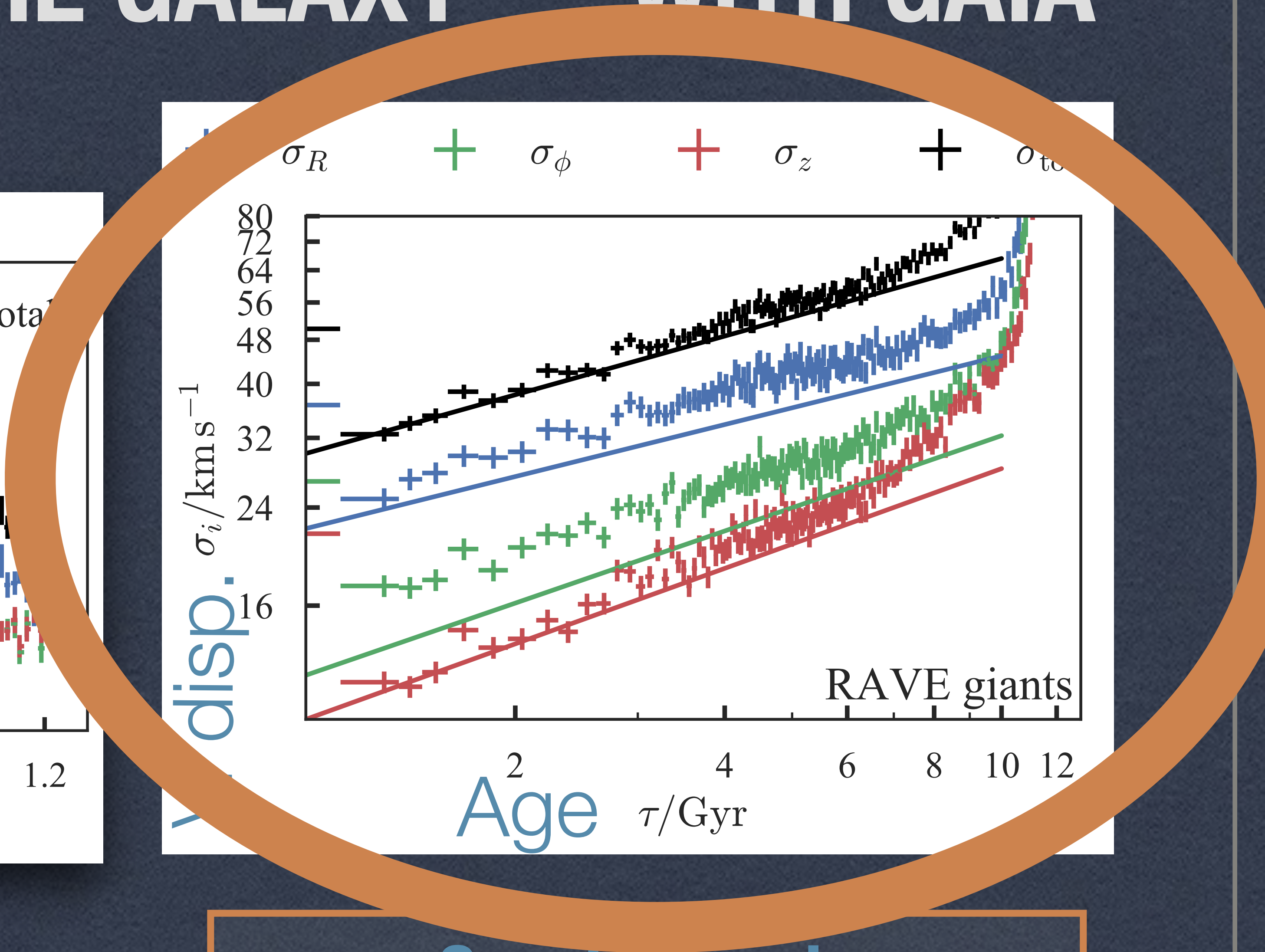
RESULTS — TGAS MAIN SEQUENCE



HEATING HISTORY OF THE GALAXY — WITH GAIA





Astrometric

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400,000 stars

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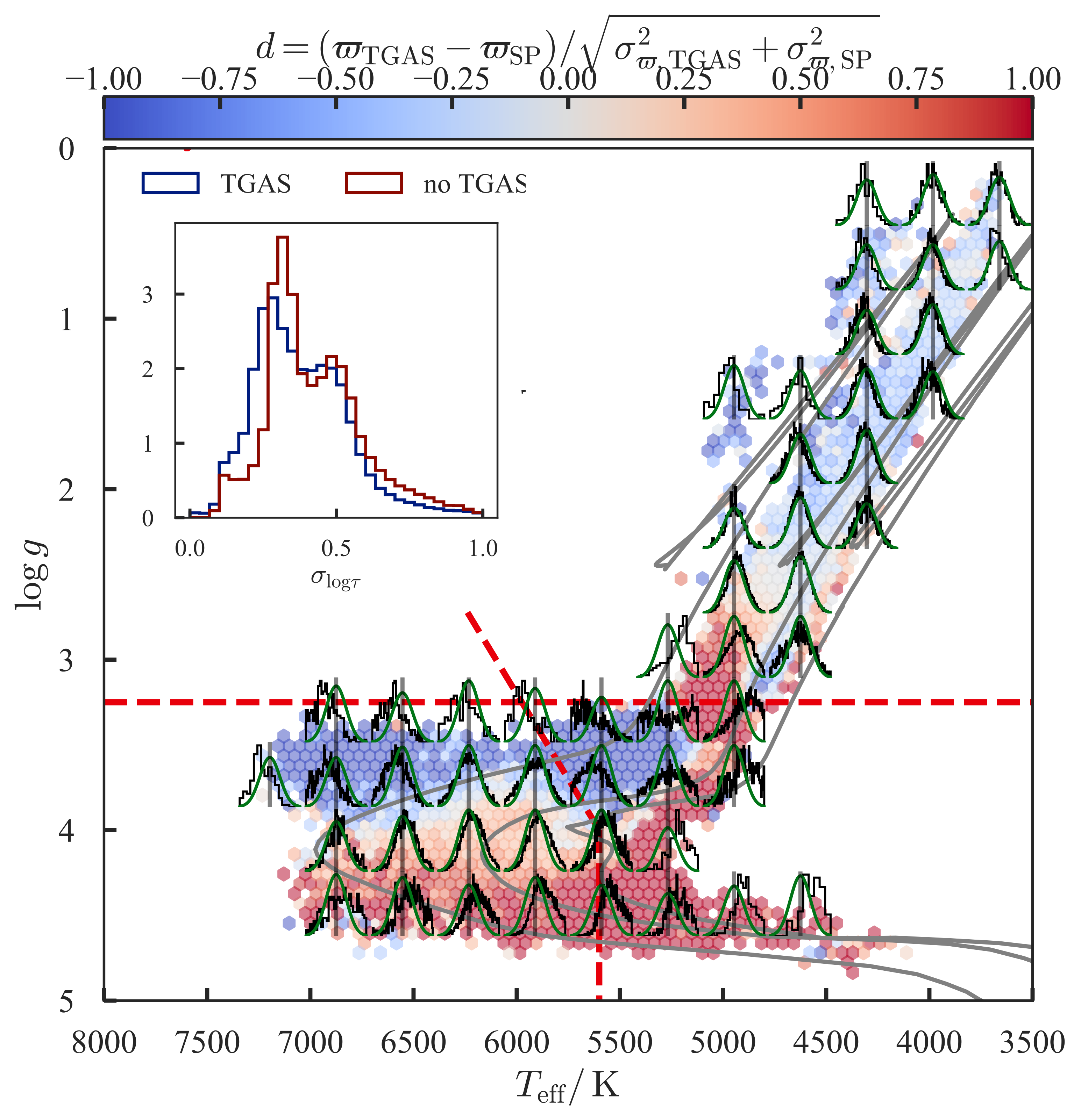
Ages from isochrones

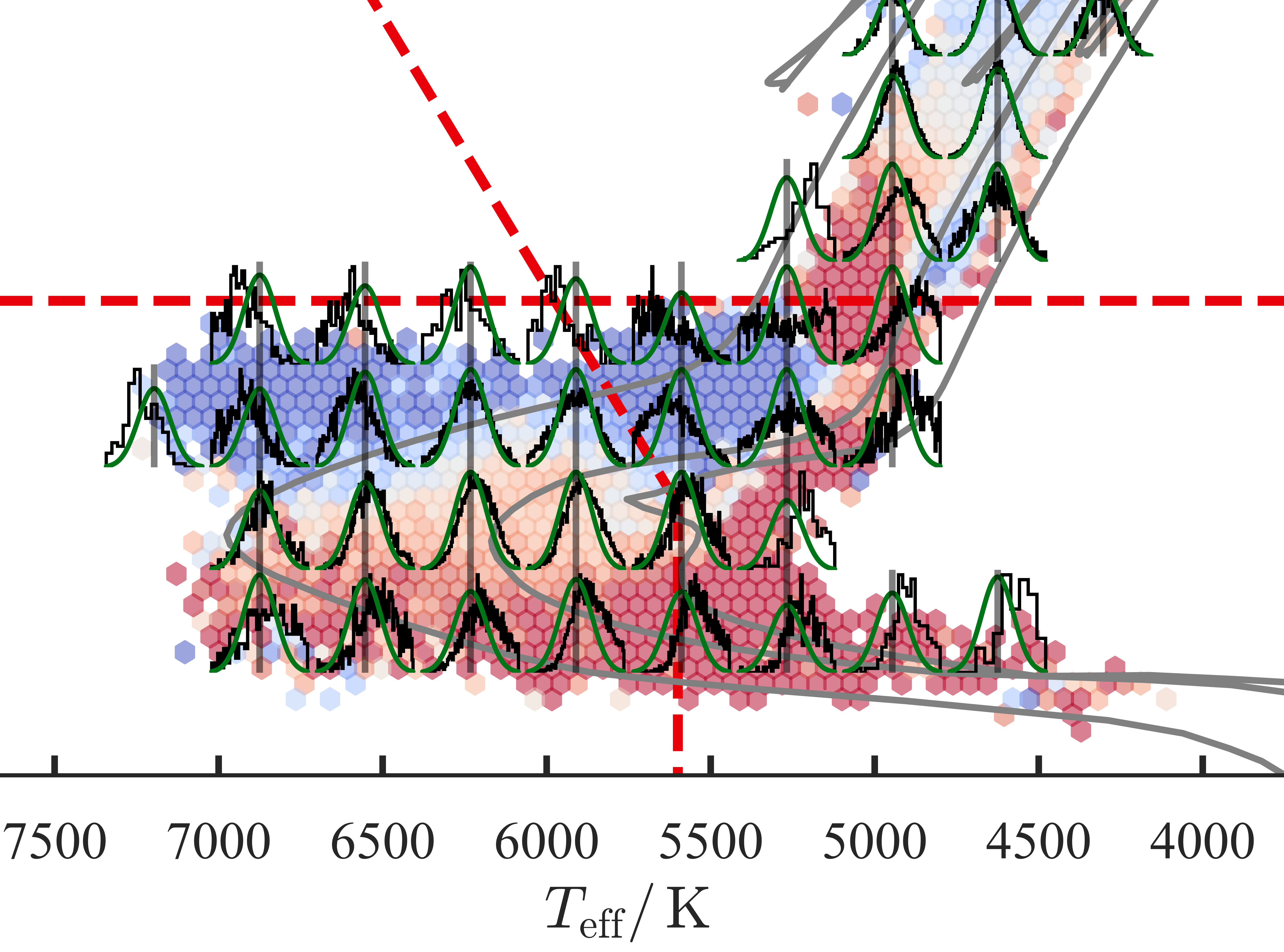
80,000 stars

DETAILS — TGAS+RAVE AGES



Method

- Spectro-photometric Bayesian distance computation from Burnett & Binney (2010) using parallaxes from TGAS — age is a by-product
- Using RAVE-on spectroscopic parameters from Casey et al. (2017) (obtained using Cannon approach)
- using spectroscopic parameter correlations — important for data-driven results as follow training dataset
- c.f. McMillan et al. (2017) for similar using RAVE DR5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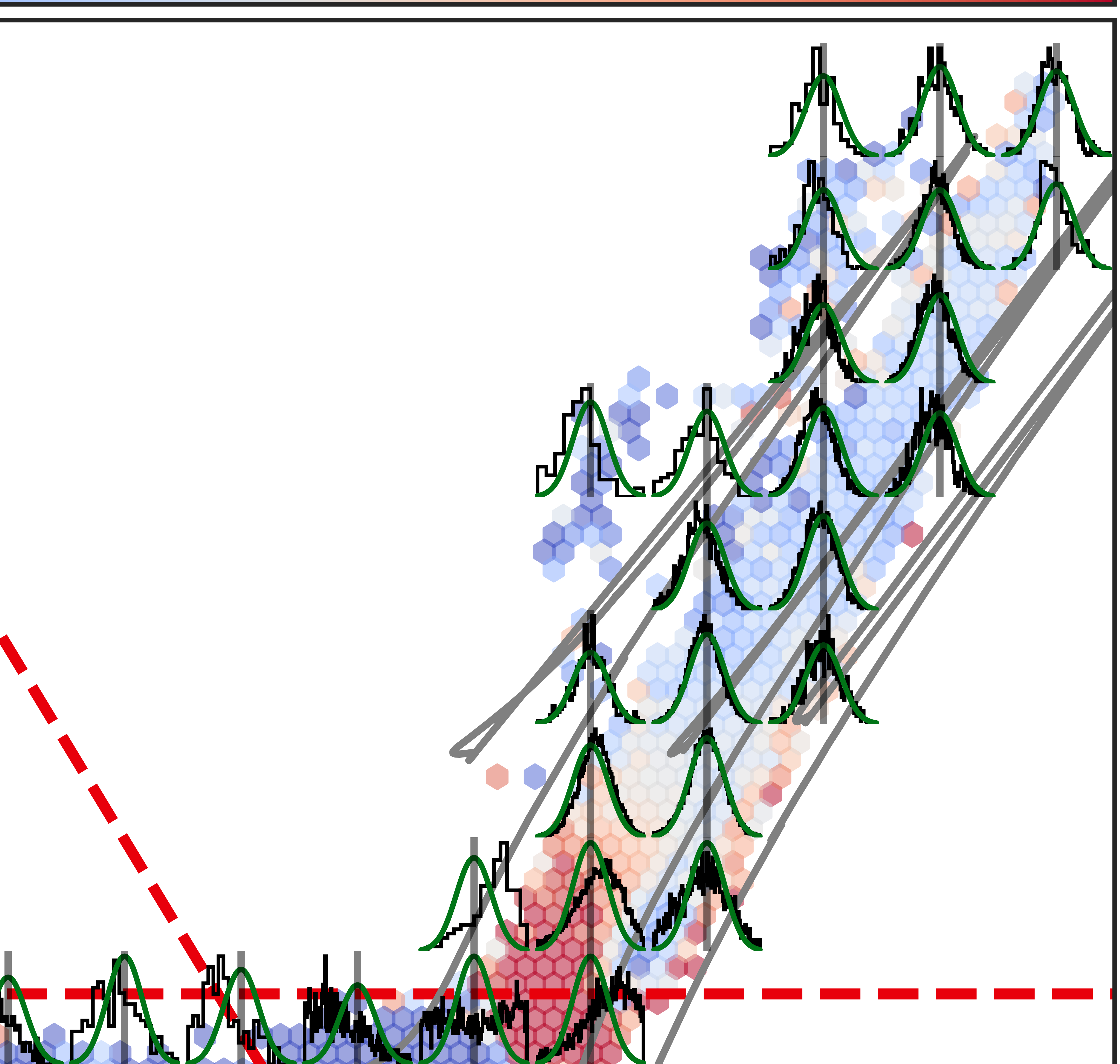

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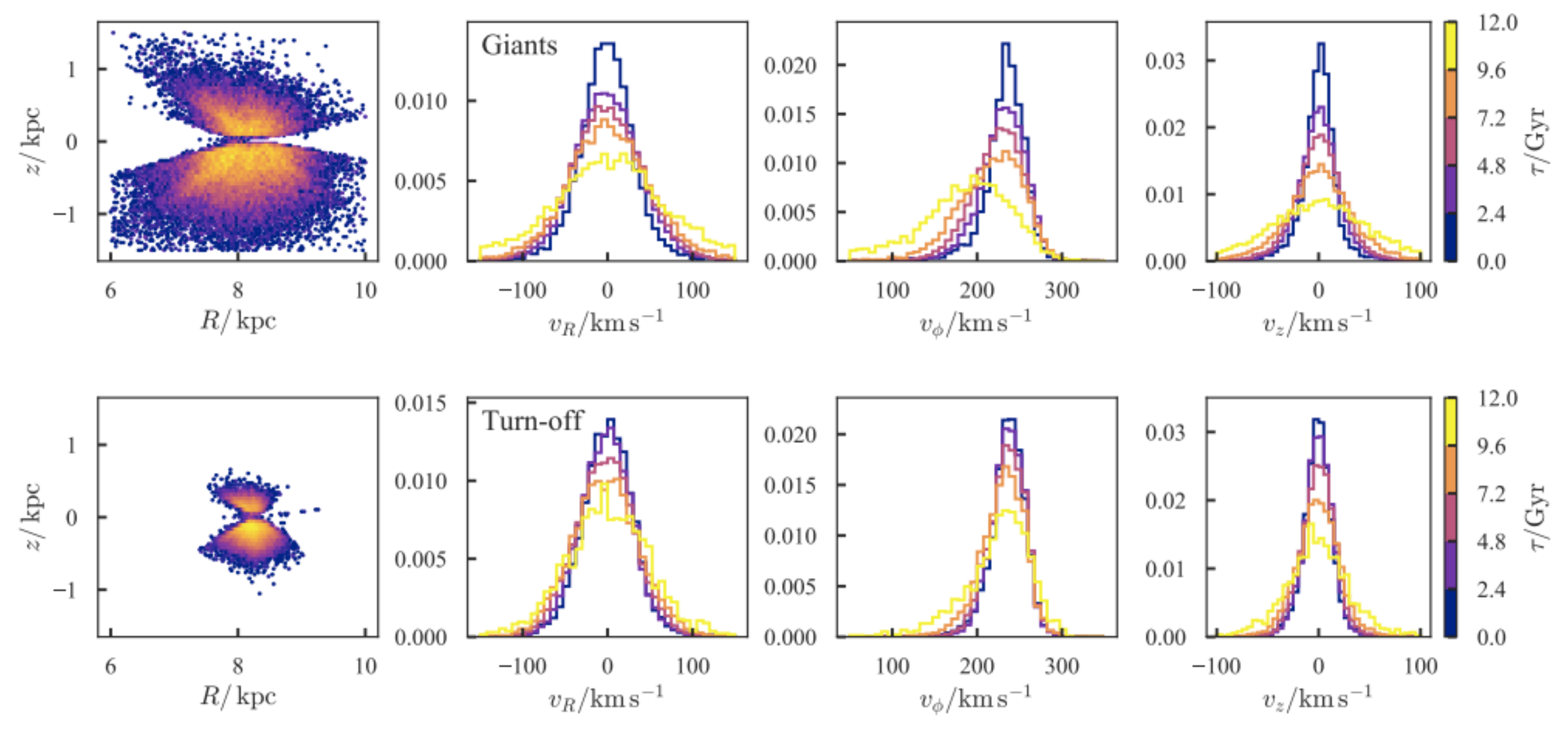
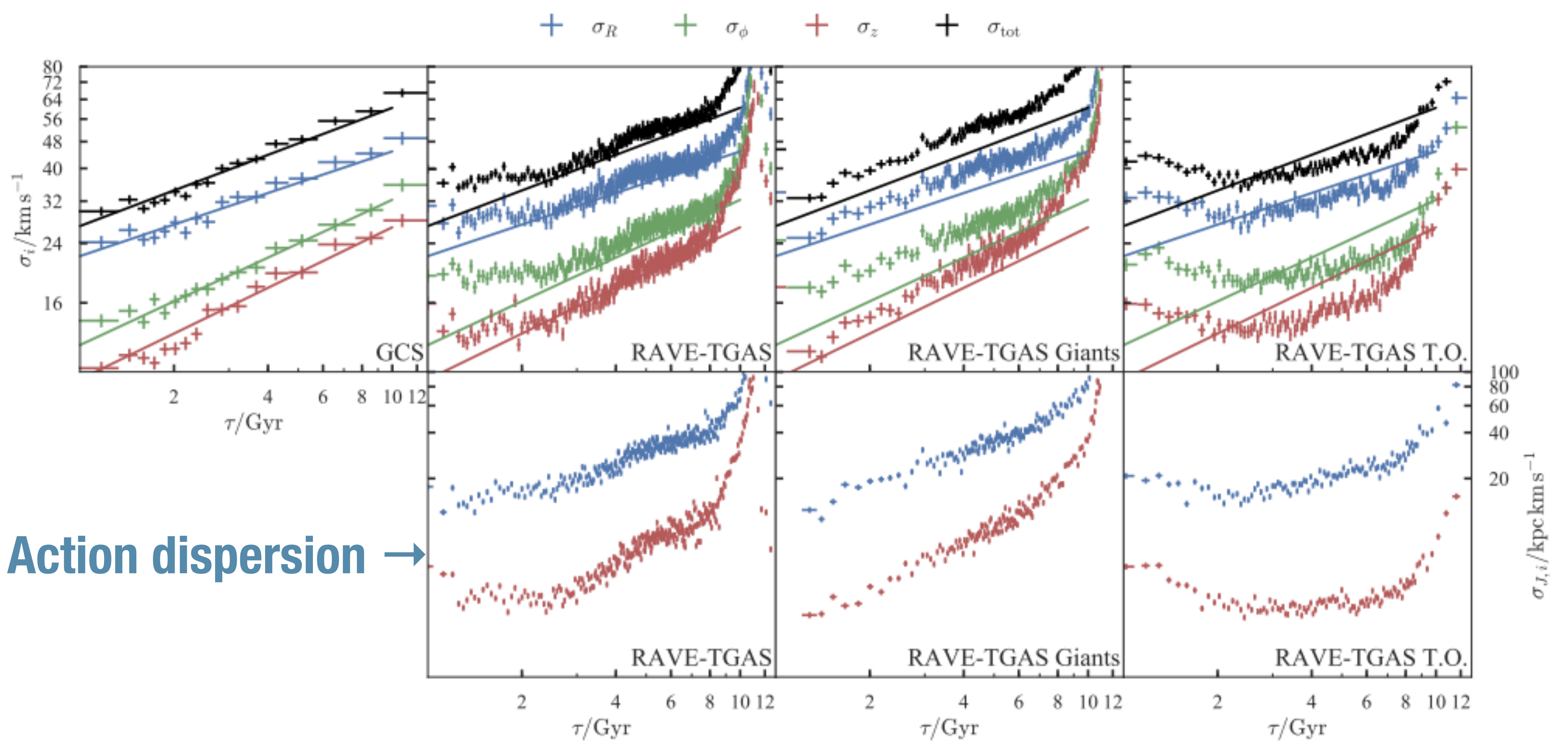
RESULTS — TGAS+RAVE AGES

Giants

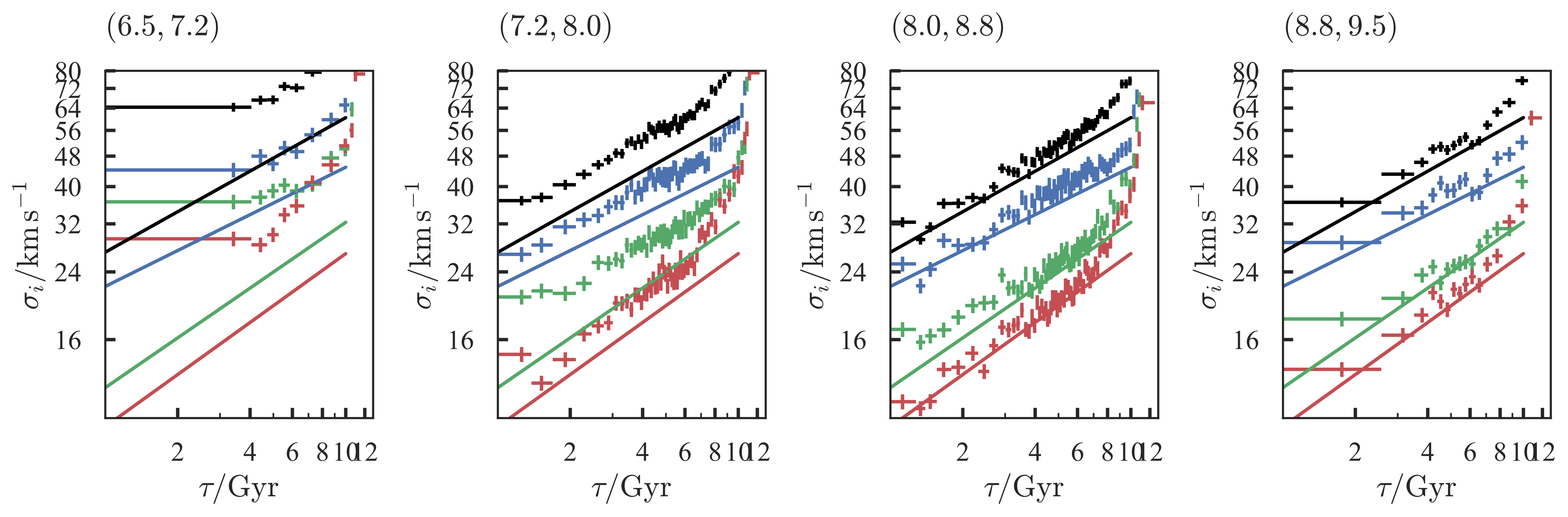


Turn-off



Action dispersion →

- Full RAVE+TGAS sample ~ match GCS
- **Except** have a hotter old component
- Giants sample show expected trends
- Turn-off sample shows flattening and rise below 2 Gyr —> not trustworthy



Split into radial bins

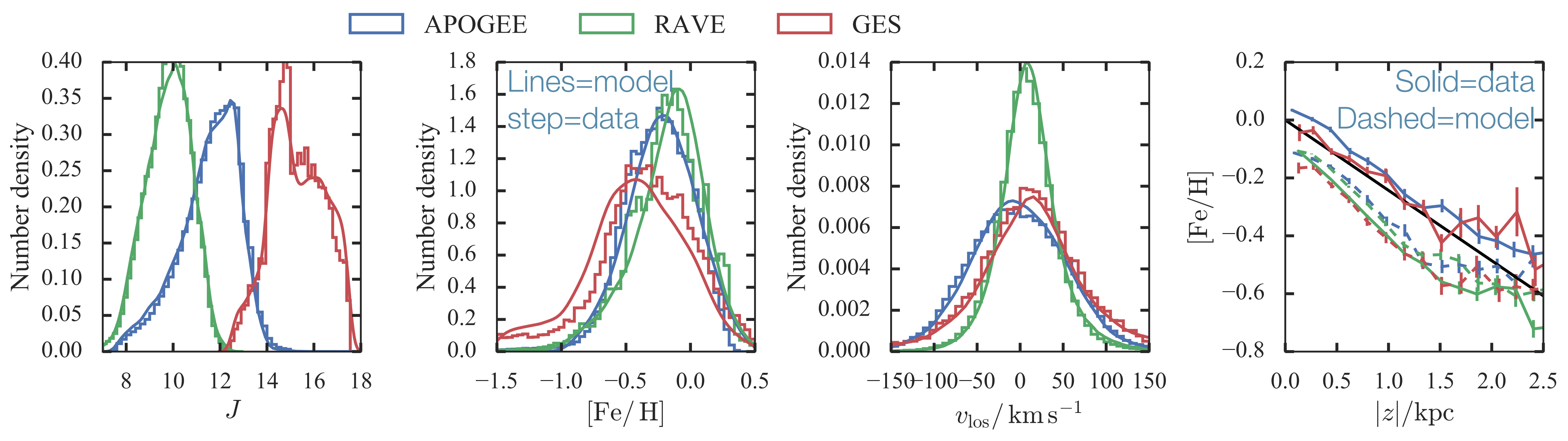
Difficult to interpret as

1. Each radial bin has a different selection in vertical height (e.g. we lose young cold stars in the innermost bin)
2. For a fixed age, the sampling in vertical height is non-trivial e.g. perhaps more distant stars —> higher vel. dips.

CHEMO-DYNAMICAL MODEL

$$f(\boldsymbol{J},\tau,Z,M)=\int \mathrm{d}J'_\phi\,\xi(M)\,\Gamma(\tau)\,K(J_\phi,J'_\phi,\tau)\,f(\boldsymbol{J}'|\tau)\,\delta[Z-Z(R'_c,\tau)]$$

Sanders & Binney (2015)



CHEMO-DYNAMICAL MODEL

Actions

$$f(\boldsymbol{J},\tau,Z,M)=\int \mathrm{d}J'_\phi\,\xi(M)\,\Gamma(\tau)\,K(J_\phi,J'_\phi,\tau)\,f(\boldsymbol{J}'|\tau)\,\delta[Z-Z(R'_c,\tau)]$$

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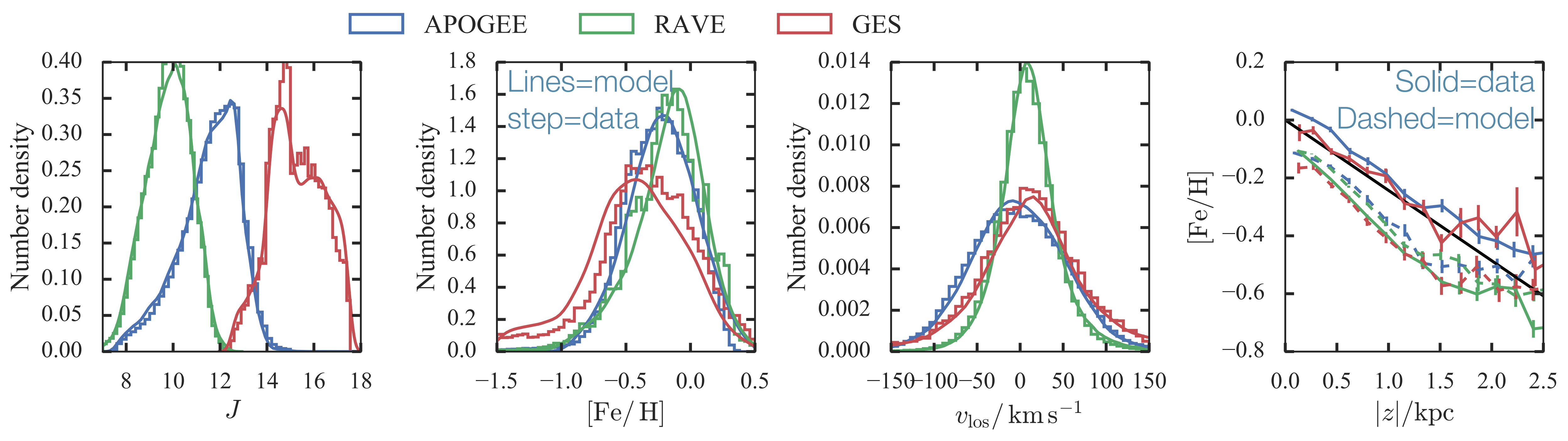
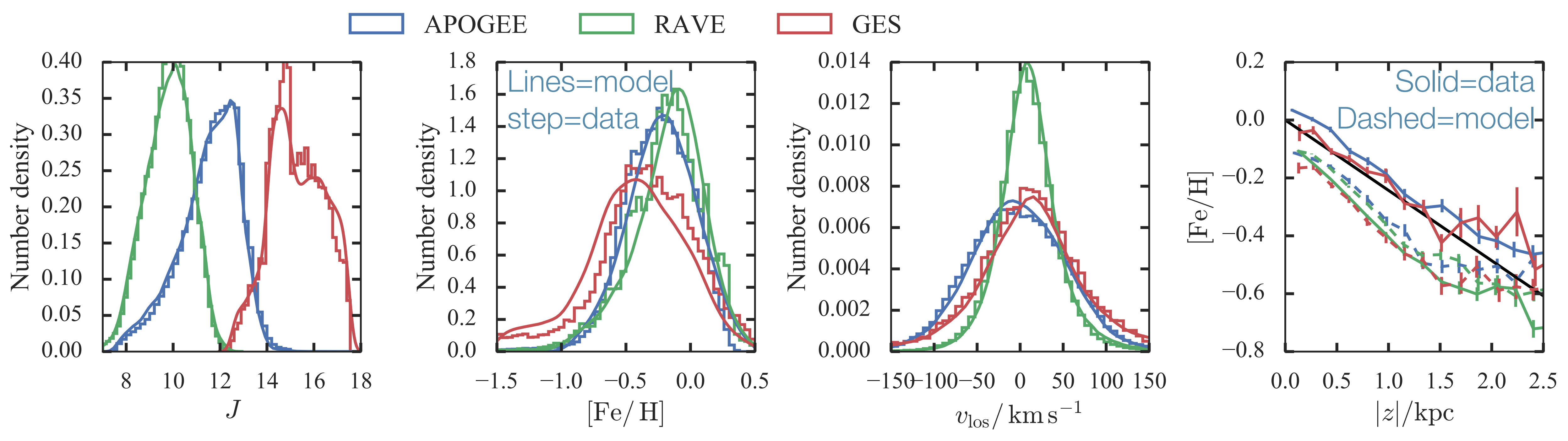


CHEMO-DYNAMICAL MODEL

Initial Mass Function

$$f(\boldsymbol{J},\tau,Z,M)=\int \mathrm{d}J'_\phi\,\xi(M)\,\Gamma(\tau)\,K(J_\phi,J'_\phi,\tau)\,f(\boldsymbol{J}'|\tau)\,\delta[Z-Z(R'_c,\tau)]$$

Sanders & Binney (2015)



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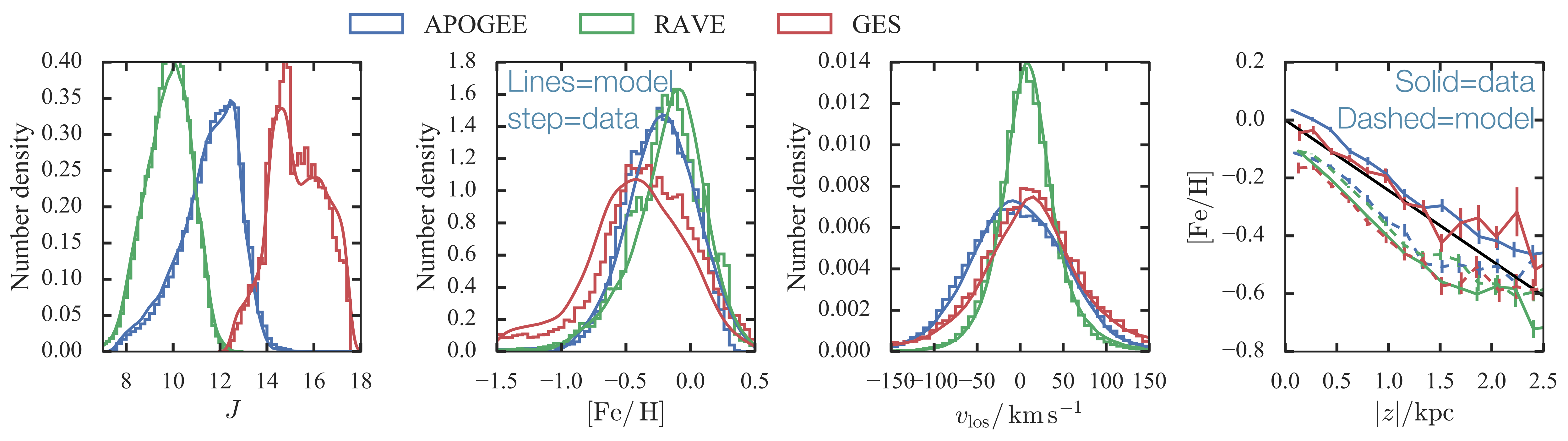
CHEMO-DYNAMICAL MODEL

Star formation rate

$$f(\boldsymbol{J},\tau,Z,M)=\int \mathrm{d}J'_\phi\,\xi(M)\,\Gamma(\tau)\,K(J_\phi,J'_\phi,\tau)\,f(\boldsymbol{J}'|\tau)\,\delta[Z-Z(R'_c,\tau)]$$

Sanders & Binney (2015)



CHEMO-DYNAMICAL MODEL

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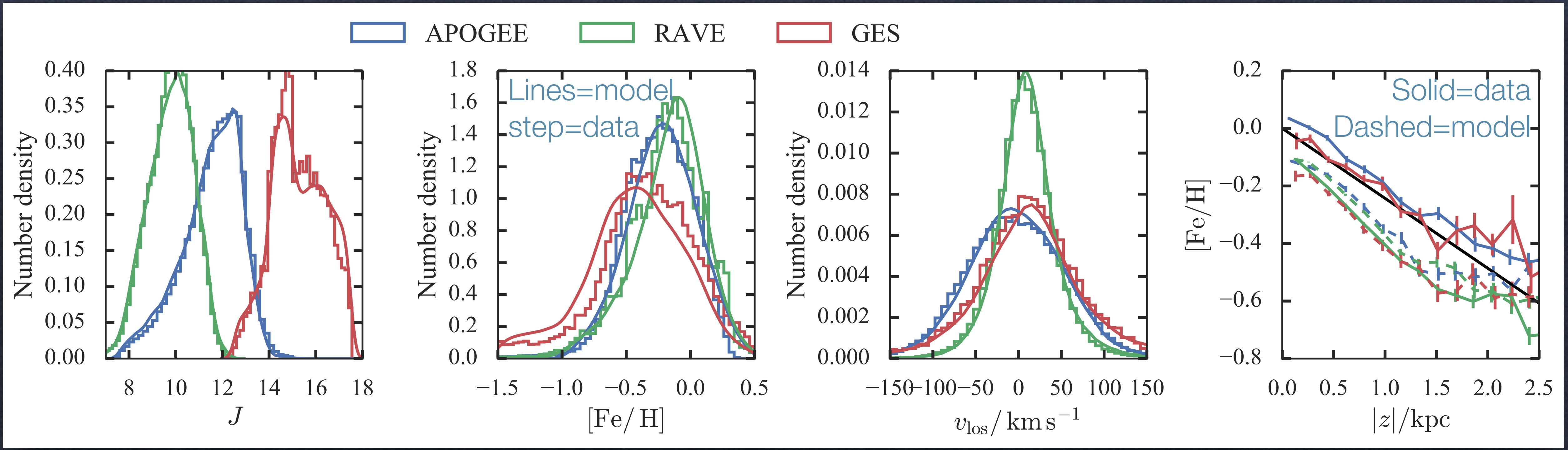
Sanders & Binney (2015)

Quasi-isothermal

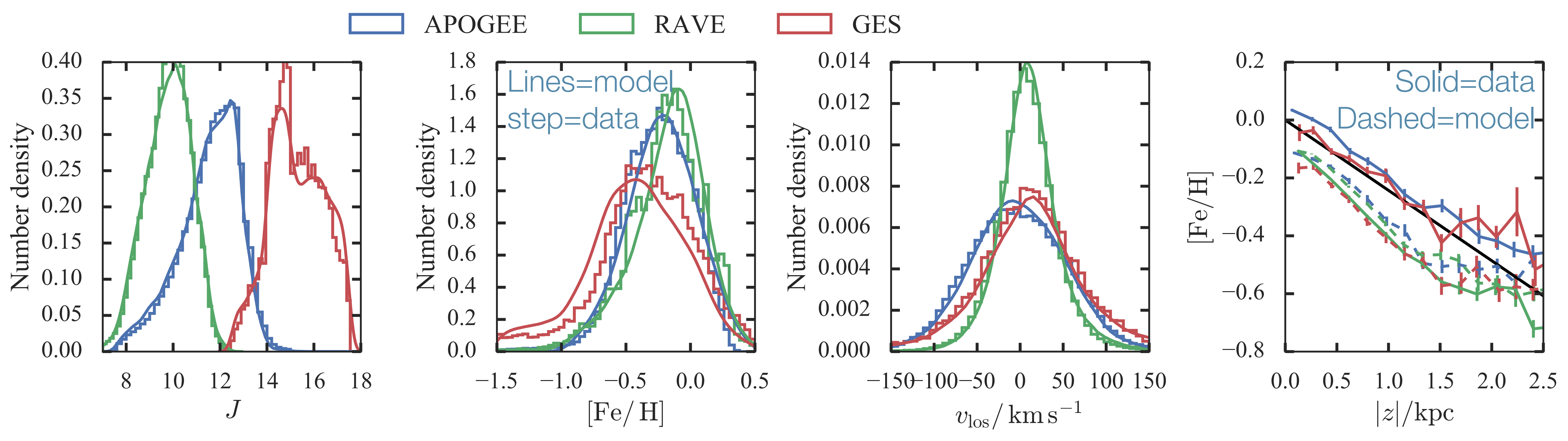


CHEMO-DYNAMICAL MODEL

$$f(\boldsymbol{J},\tau,Z,M)=\int \mathrm{d}J'_\phi\,\xi(M)\,\Gamma(\tau)\,K(J_\phi,J'_\phi,\tau)\,f(\boldsymbol{J}'|\tau)\,\delta[Z-Z(R'_c,\tau)]$$

Sanders & Binney (2015)

ISM metallicity



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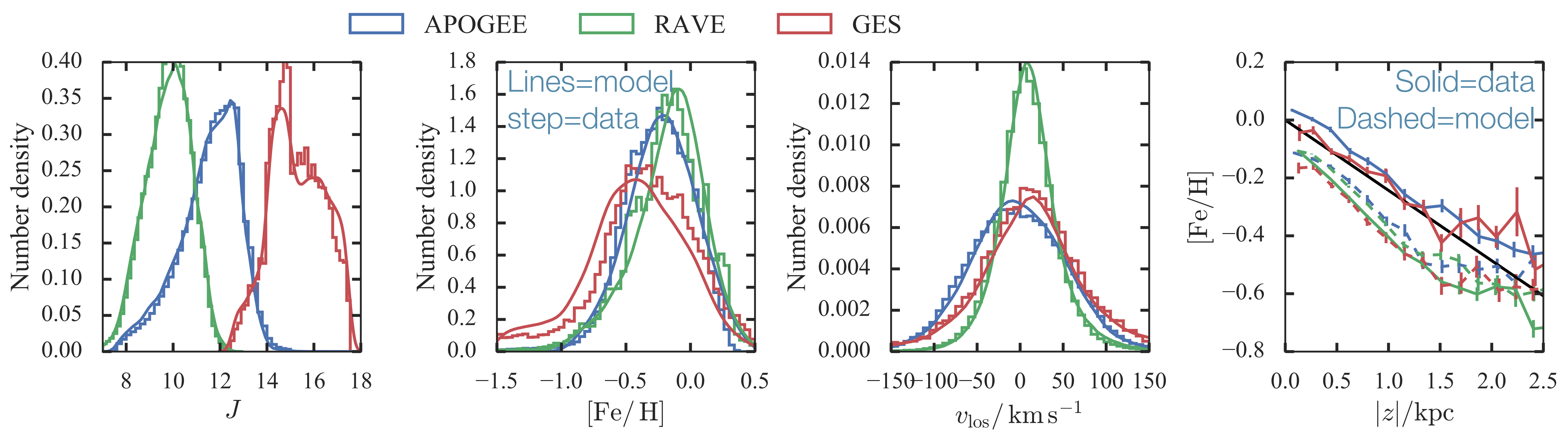
CHEMO-DYNAMICAL MODEL

Radial migration

$$f(\boldsymbol{J},\tau,Z,M) = \int \mathrm{d}J'_\phi\,\xi(M)\,\Gamma(\tau)\,K(J_\phi,J'_\phi,\tau)\, f(\boldsymbol{J}'|\tau)\,\delta[Z - Z(R'_c,\tau)]$$

Sanders & Binney (2015)

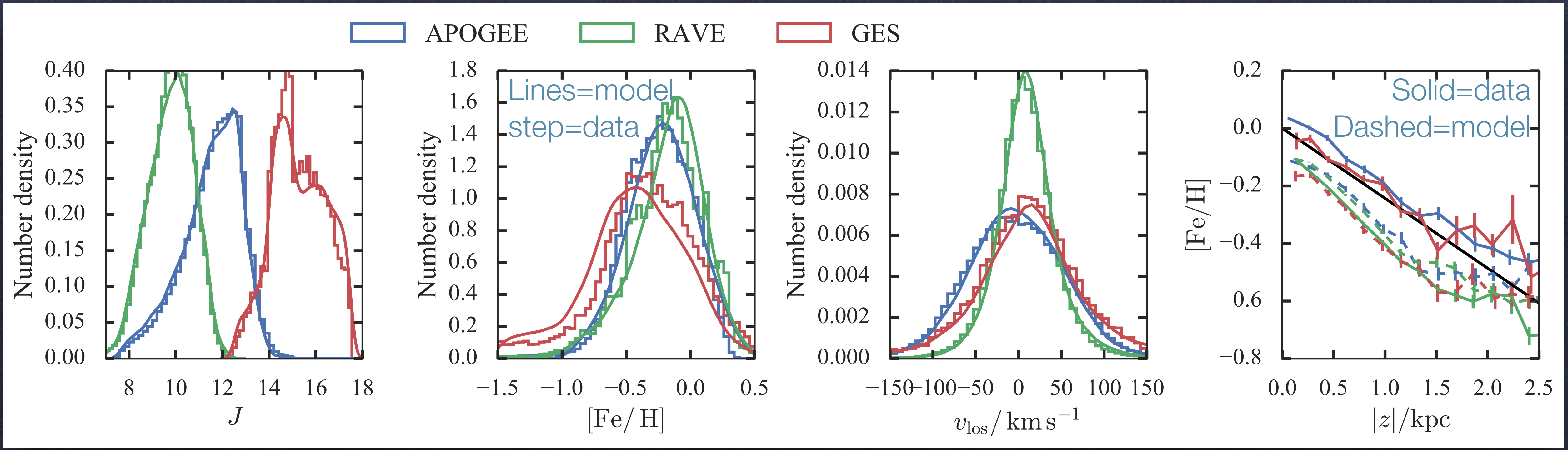


CHEMO-DYNAMICAL MODEL

$$f(\boldsymbol{J},\tau,Z,M)=\int \mathrm{d}J'_\phi\,\xi(M)\,\Gamma(\tau)\,K(J_\phi,J'_\phi,\tau)\,f(\boldsymbol{J}'|\tau)\,\delta[Z-Z(R'_c,\tau)]$$

Sanders & Binney (2015)

Fitted to local data — Geneva-Copenhagen & Gilmore & Reid density (1989)



Necessary for comparing surveys & incorporating survey selection function

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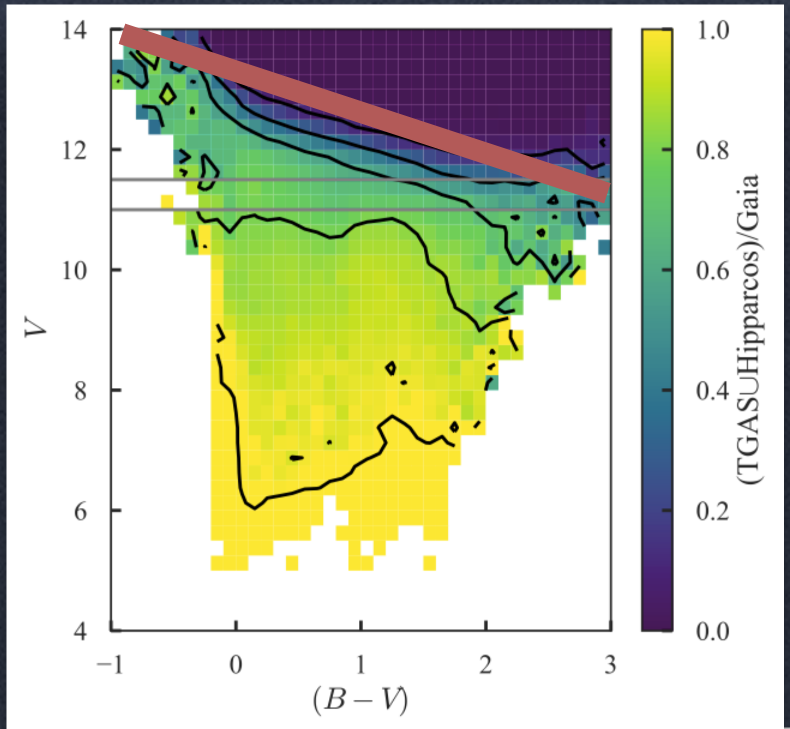
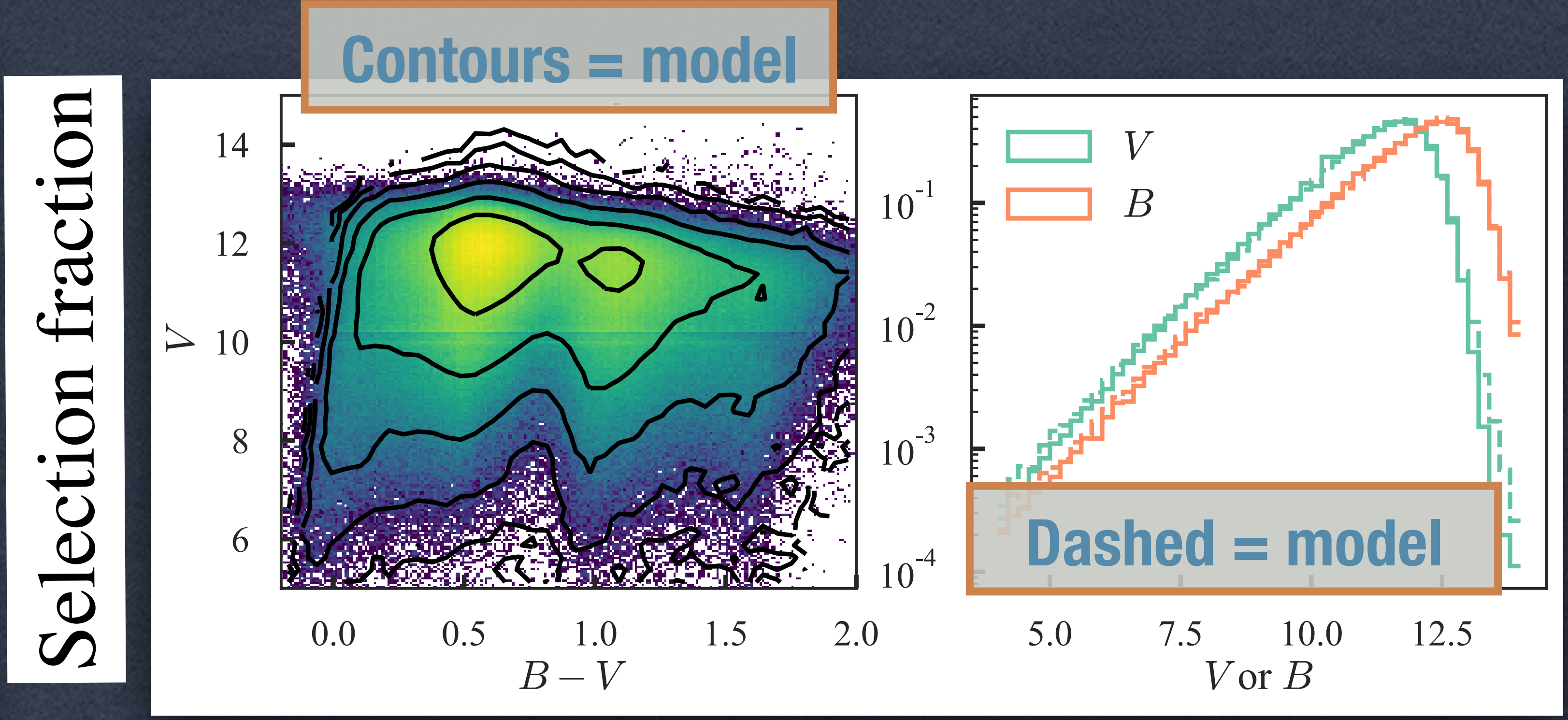
DETAILS — DATA — TGAS SELECTION FUNCTION

Comparison to APASS catalogue (filled in with Tycho-2 for V<10).

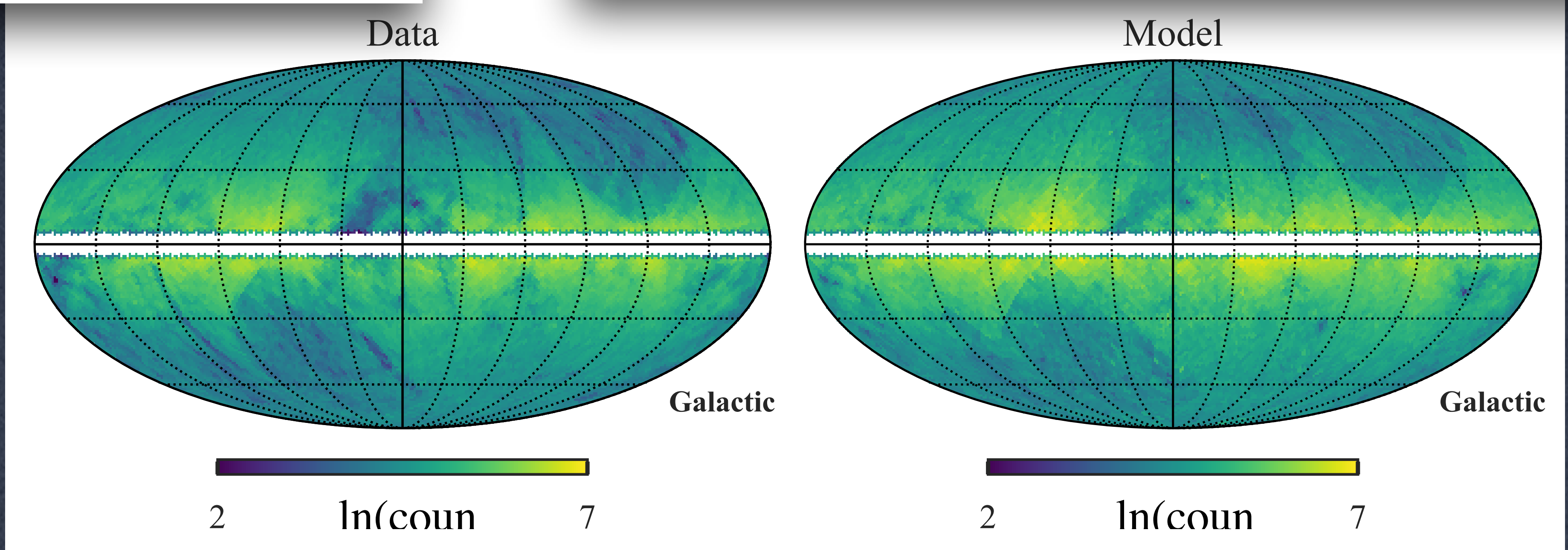
c.f. Bovy (2017) — comparison to 2-MASS but similar conclusions





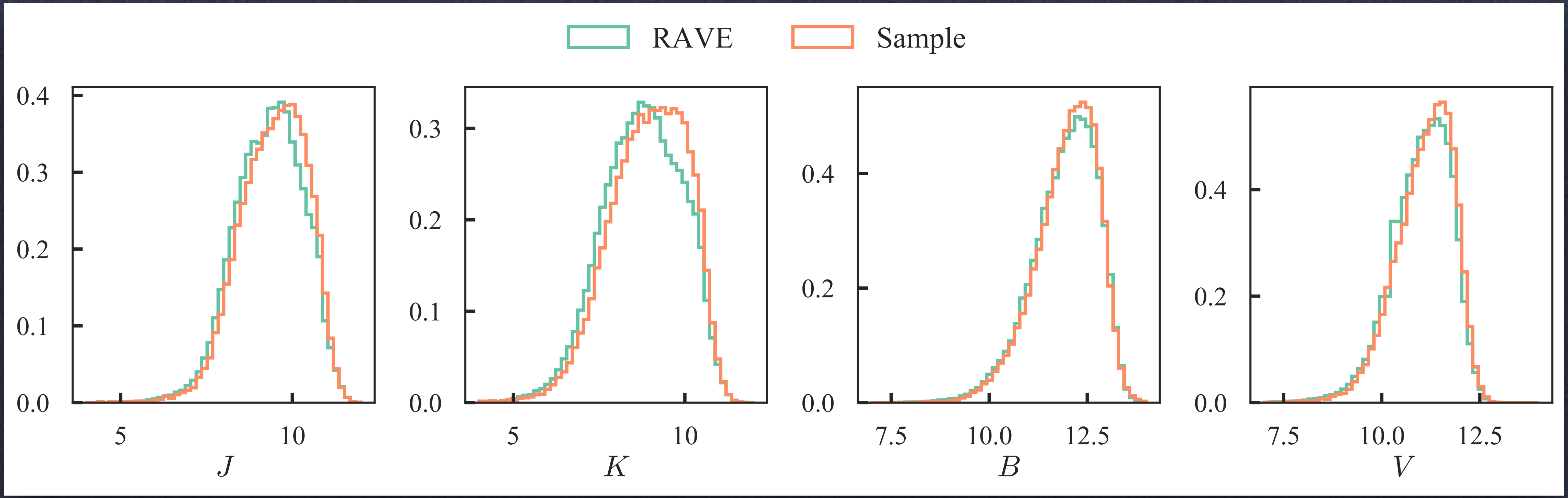
Contours = model

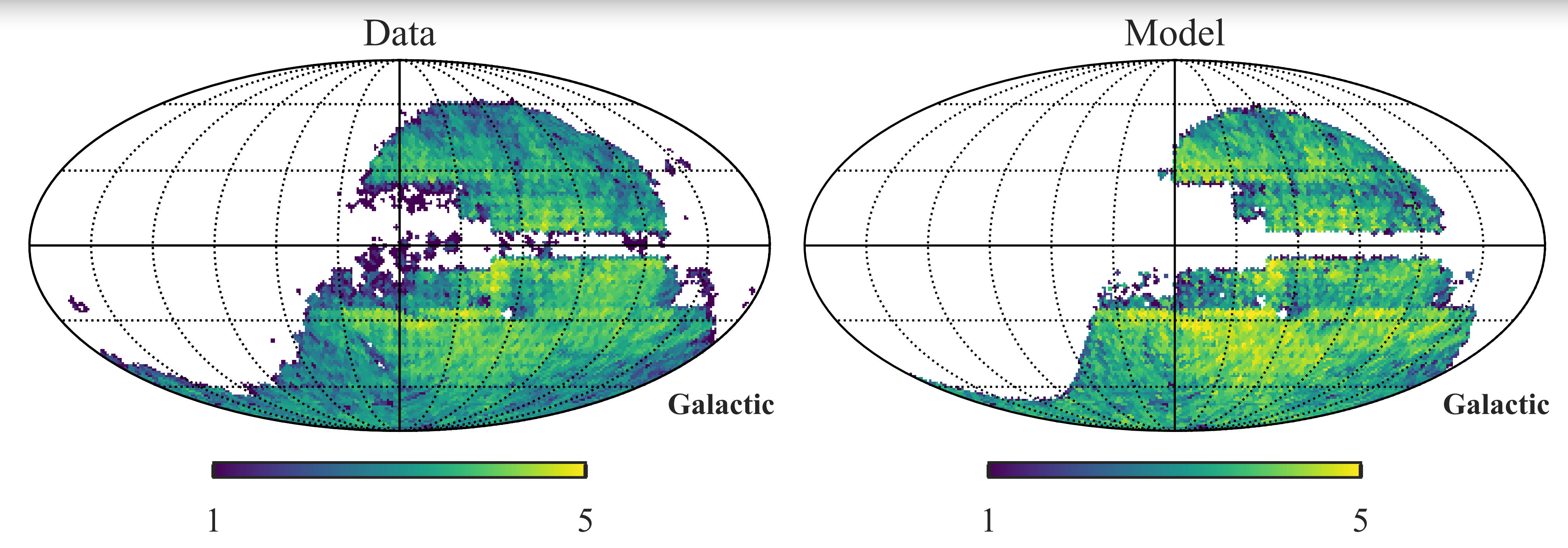
Dashed = model



DETAILS — DATA — RAVE SELECTION FUNCTION

Wojno et al. (2017) — selection in on-sky position and I-band mag





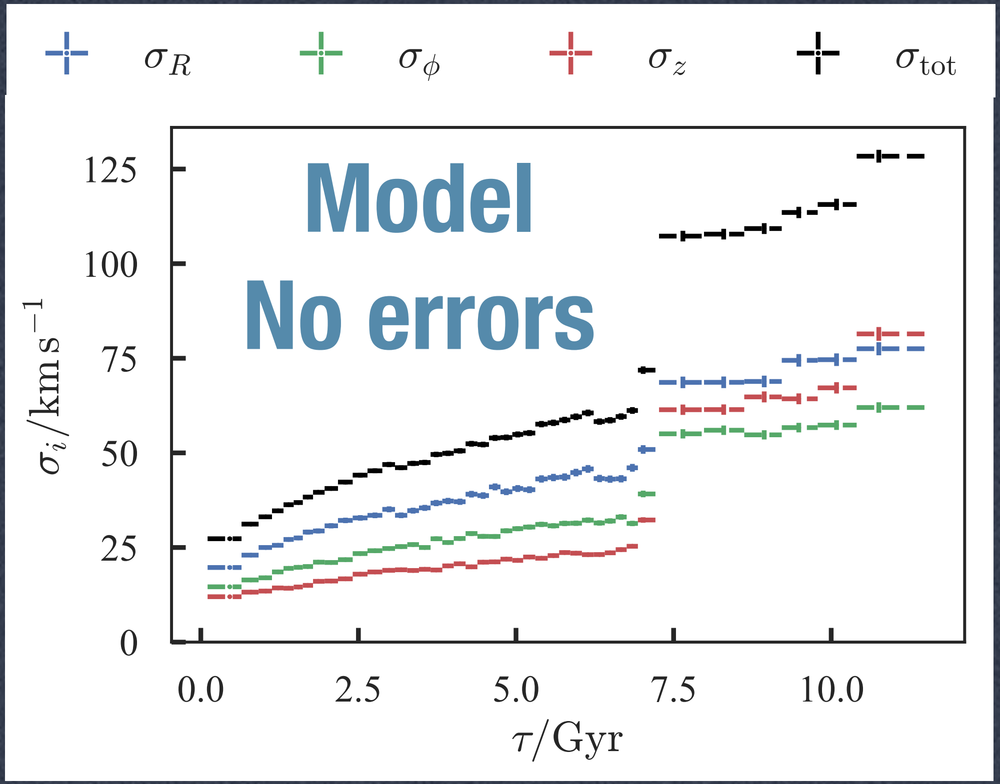
FITTING EDF TO TGAS+RAVE DATA

Sum over stars | **Error samples** | **Ratio of model to isochrone prior** | **Norm**

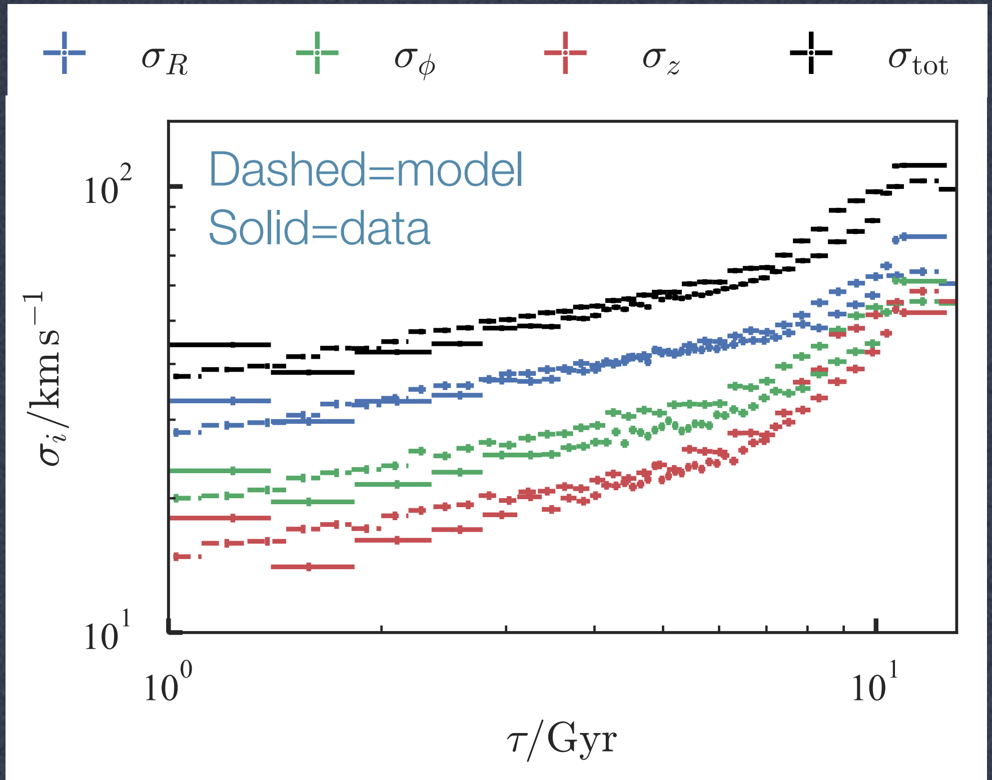
$$\log\mathcal{L} = \sum_i^{N_\star} \log \sum_n^{N_E} \frac{f(\boldsymbol{J}_{i,n},\tau_{i,n},Z_{i,n},\mathcal{M})}{f_{\mathrm{prior}}(\boldsymbol{x}_{i,n},\tau_{i,n},Z_{i,n},\mathcal{M})} - N_\star \log\mathcal{N}$$

- Log-Likelihood of TGAS+RAVE data — use [Fe/H], ages, positions, parallaxes, proper motions and radial velocities (8 dimensions)
- **Hard bit:** Normalize by computing integral of model folded with selection function (TGAS x RAVE) over 9D (including mass) — use a fixed set of samples from a base model (McMillan & Binney 2013). Uses isochrones and an extinction map.
- Using Galactic potential from McMillan (2017)

FITTING EDF TO TGAS+RAVE DATA — RESULTS

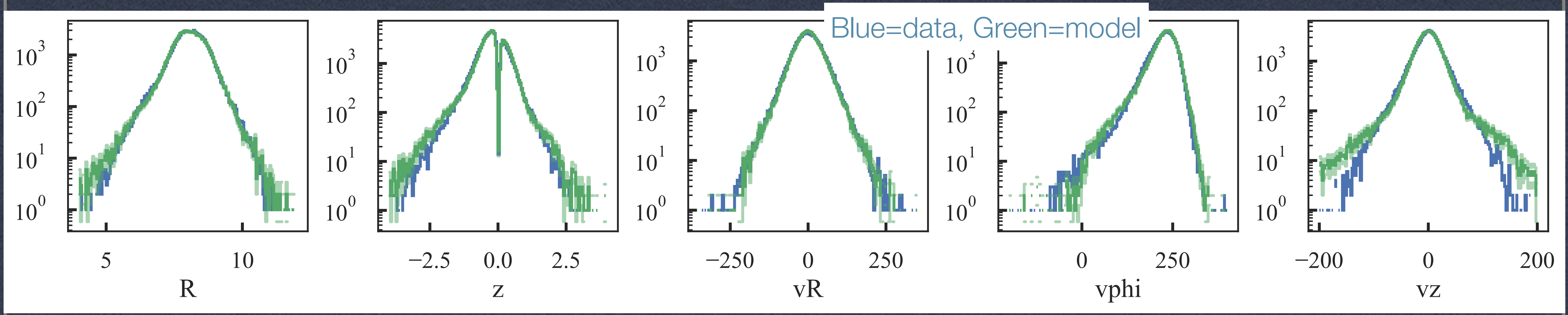

Model

No errors

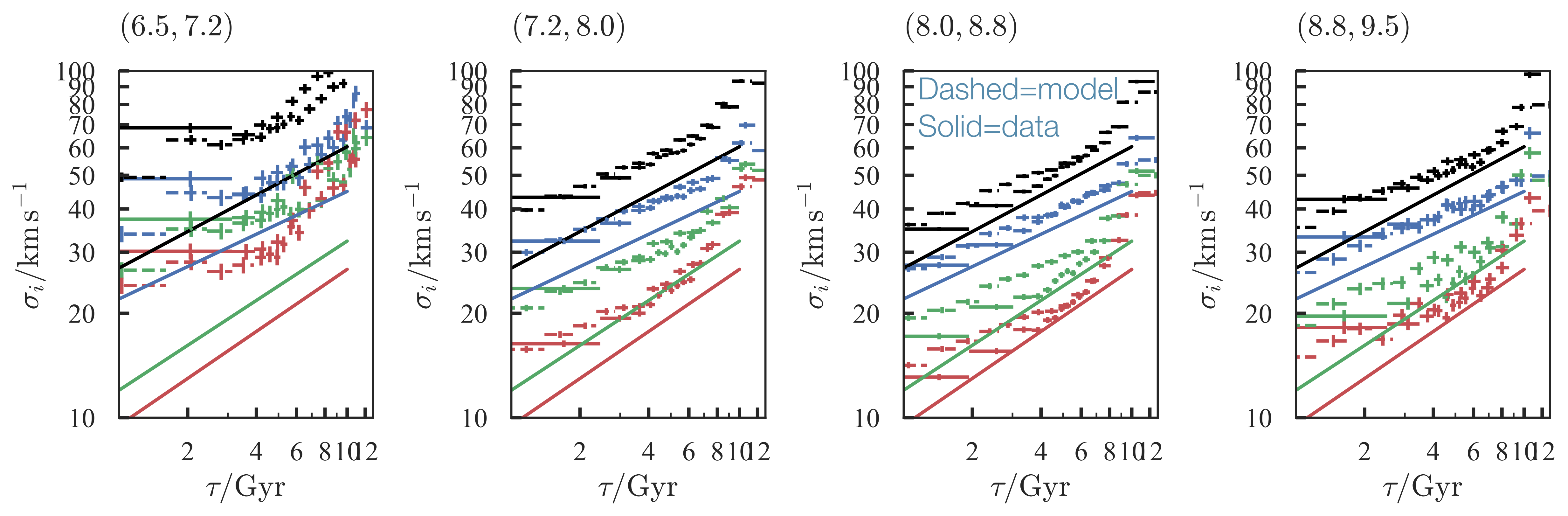

Dashed=model

Solid=data

- Rd(thick)=1.9 kpc, Rd(thin)=4 kpc, β_R=0.34, β_z=0.42
- σ(τ) discontinuous at ~7Gyr, **but** thick disc needs structure (particularly vertical)

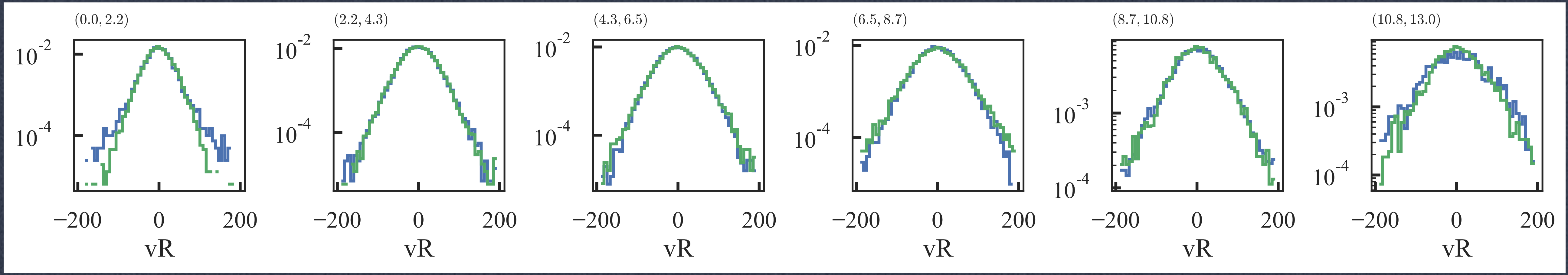

Blue=data, Green=model

FITTING EDF TO TGAS+RAVE DATA — RESULTS



Split into radial bins ↑

Split into age bins ↓



Blue=data, Green=model

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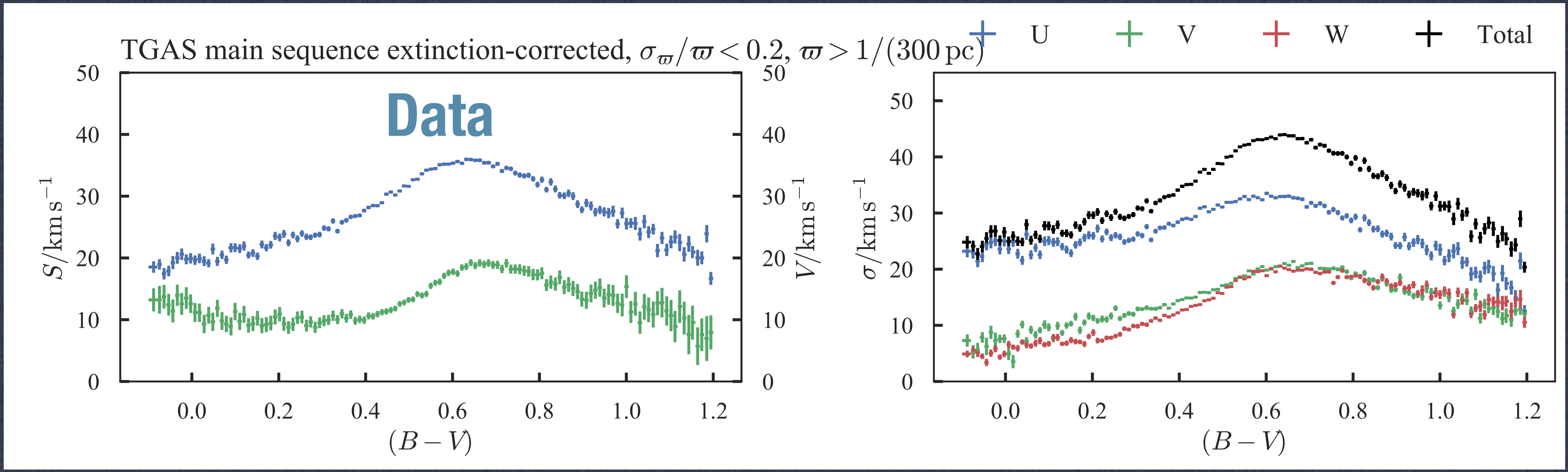
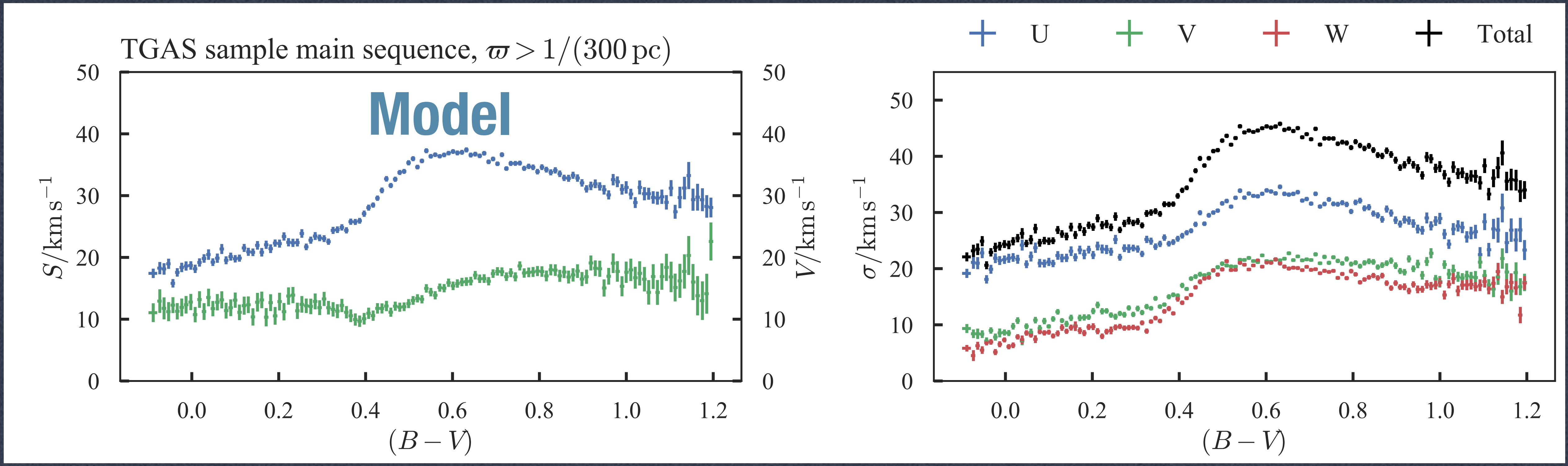
PREDICTIONS FOR TGAS MAIN SEQUENCE DATASET





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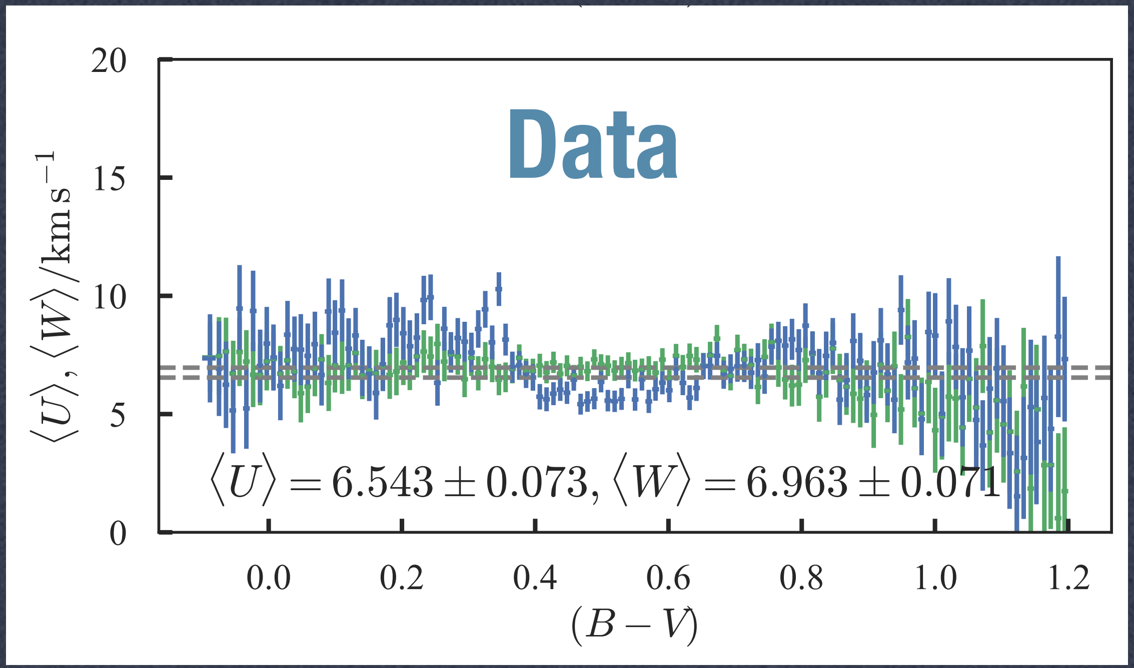
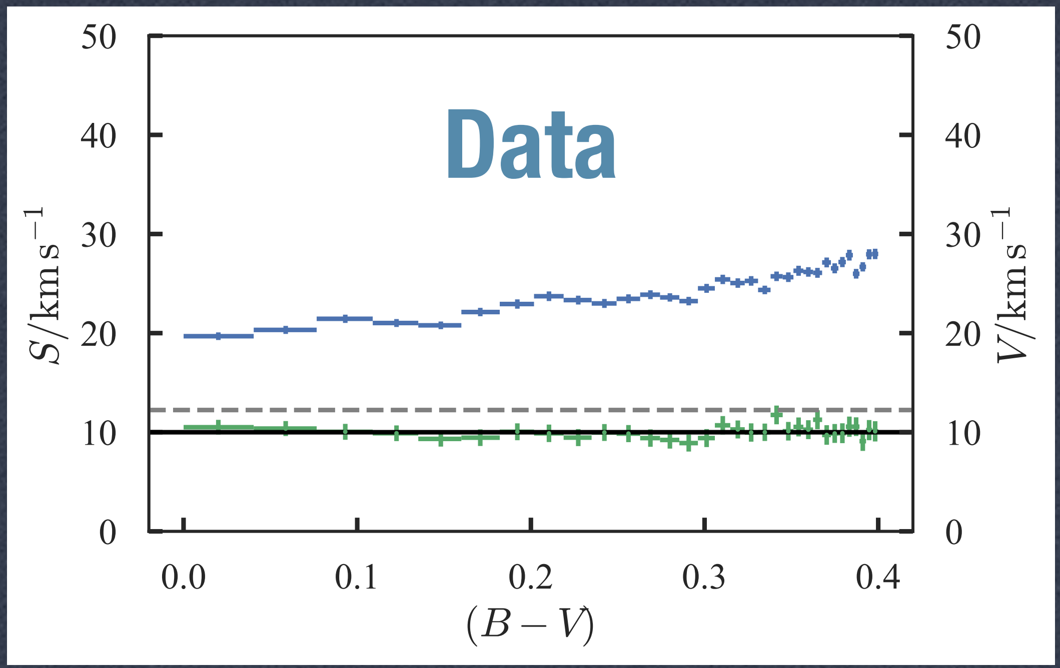
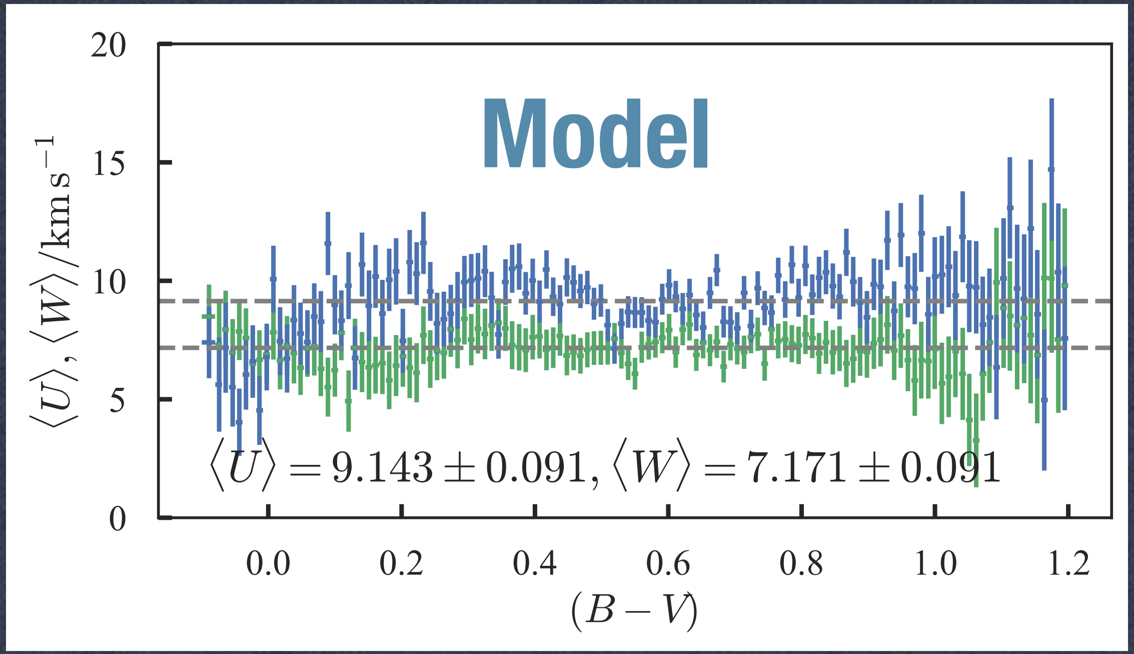
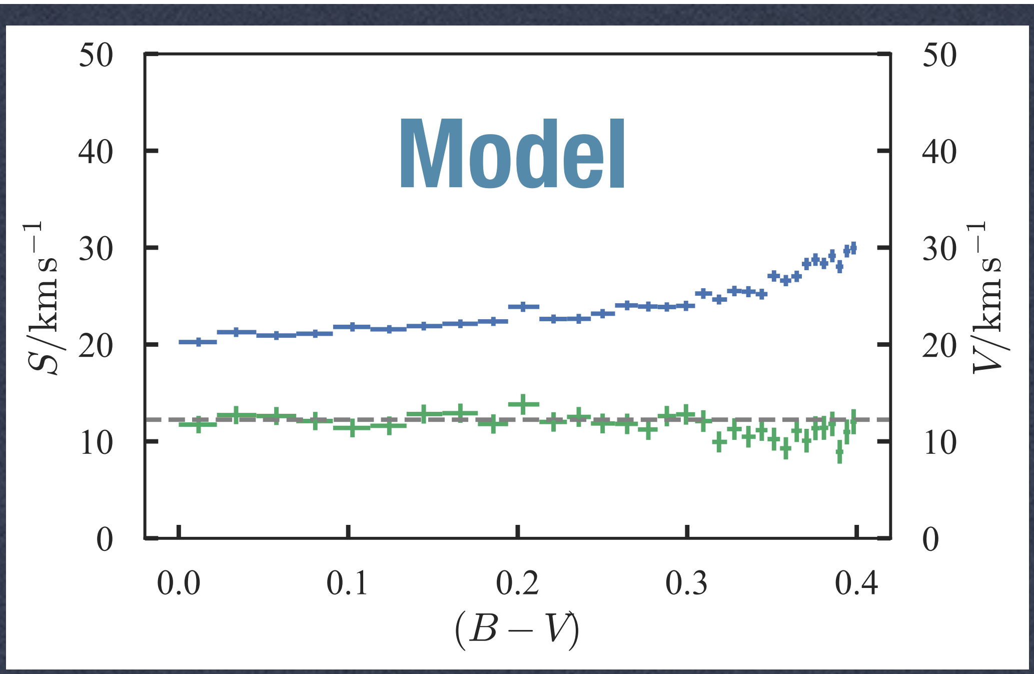
PECULIAR SOLAR MOTION

- Input model solar velocity is Schoenrich et al. (2012) (U,V,W)=(11.1,12.2,7.2) km/s
- Using Bovy (2017) Oort constants
- (U,V,W)=(8.5,10,7.0) km/s









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CONCLUSIONS

1. Heating with Gaia DR1

Ages for TGAS+RAVE giants give σ(τ) and full TGAS sample gives σ(B-V).

2. Models of TGAS+RAVE

Favour broken σ(τ), not smooth thin->thick disc transition, short thick disc scale

3. Peculiar solar motion

U~8.5 km/s V~10 km/s, W=(6.96±0.07) km/s (with Bovy 2017 Oort)

4. Future

Ages should be computed for all Gaia DR2 spectroscopic overlaps (then using Gaia DR3 spectroscopic parameters). Challenging to understand (systematic) errors.