

# Distance calculations!

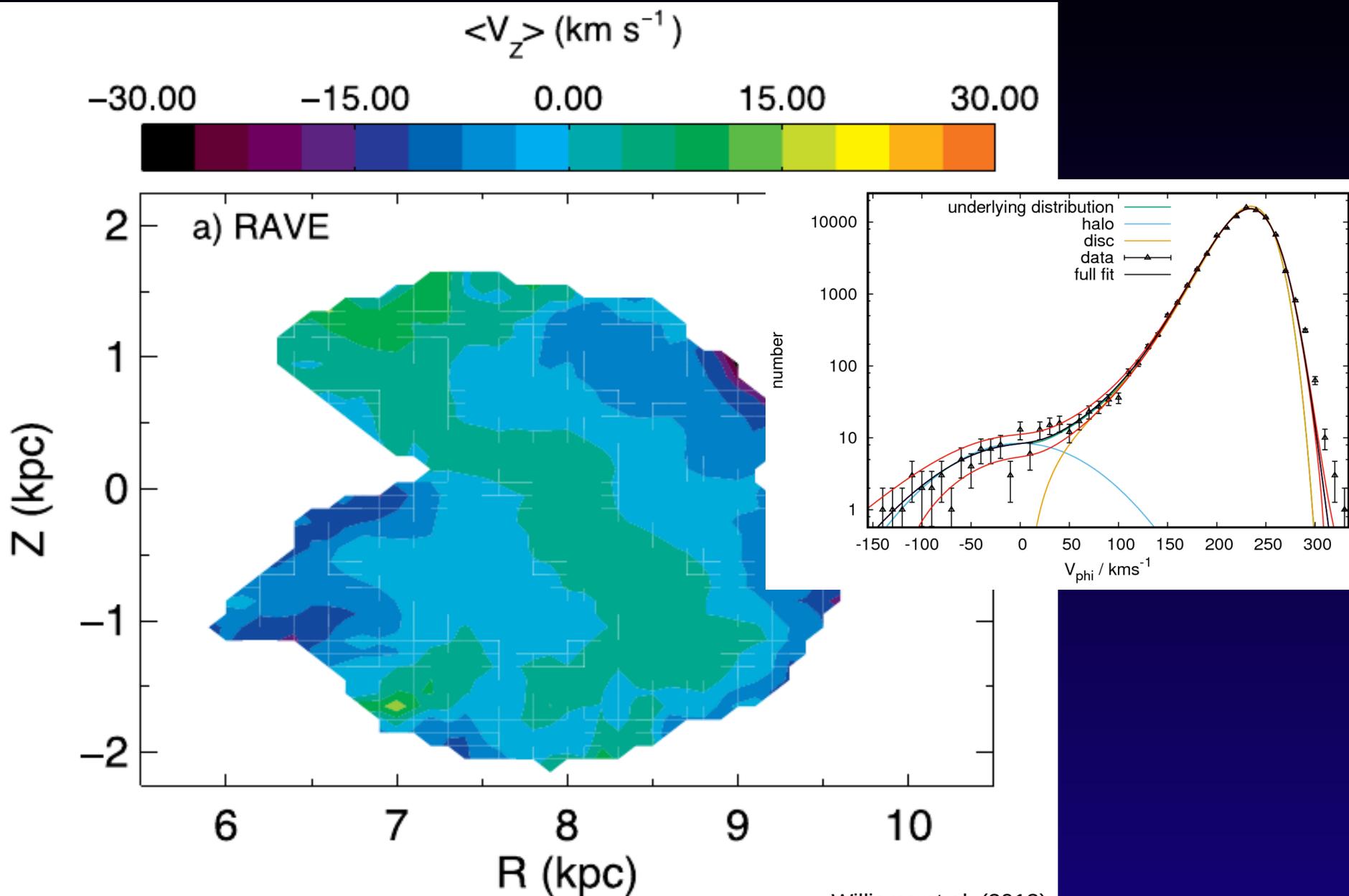
Ralph Schönrich (Oxford)

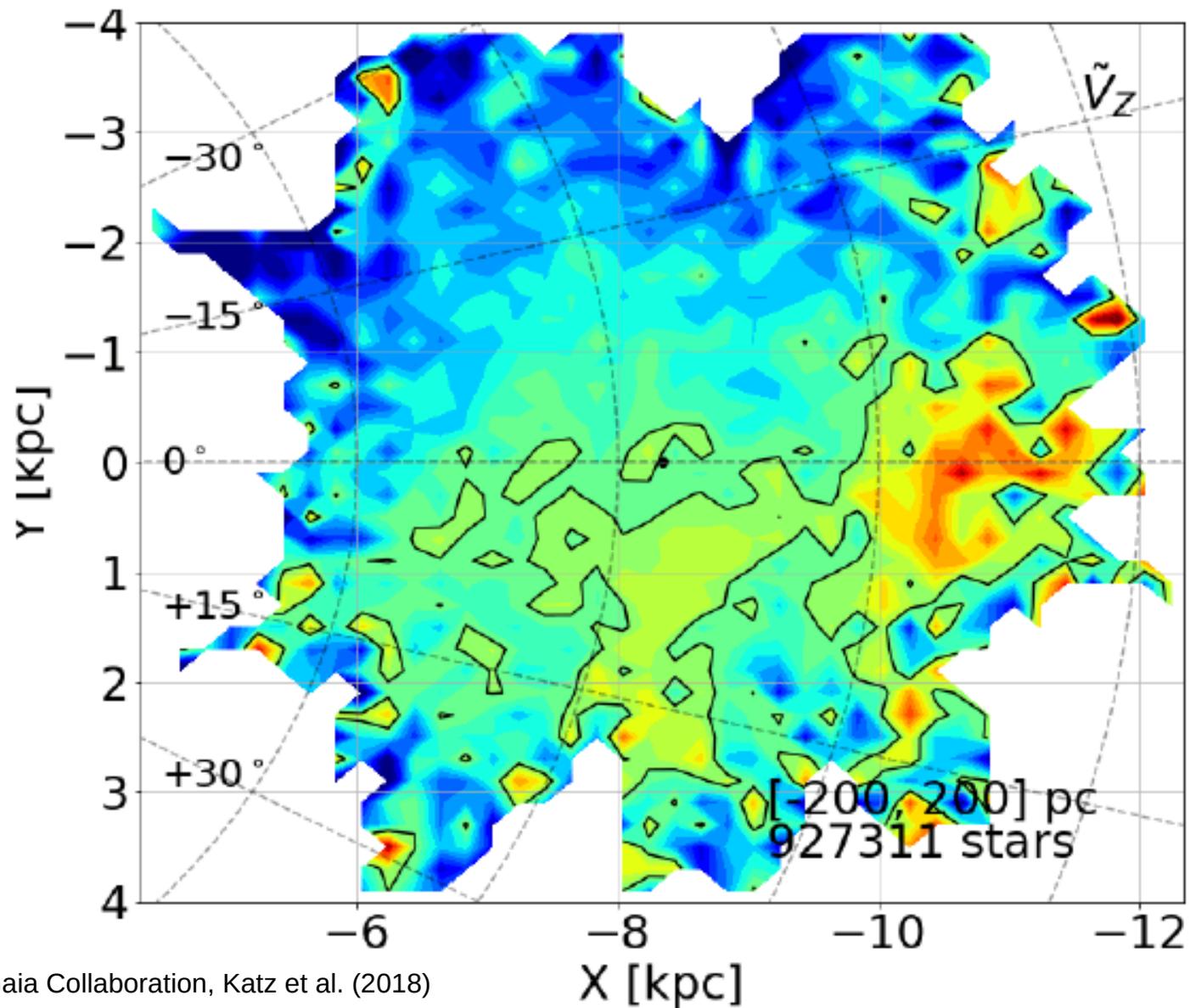
James Binney, Martin Asplund,  
Paul McMillan, Laurent Eyer, Walter Dehnen  
Michael Aumer

# Plan for today

Get Gaia distances

# Why we need tests on our samples



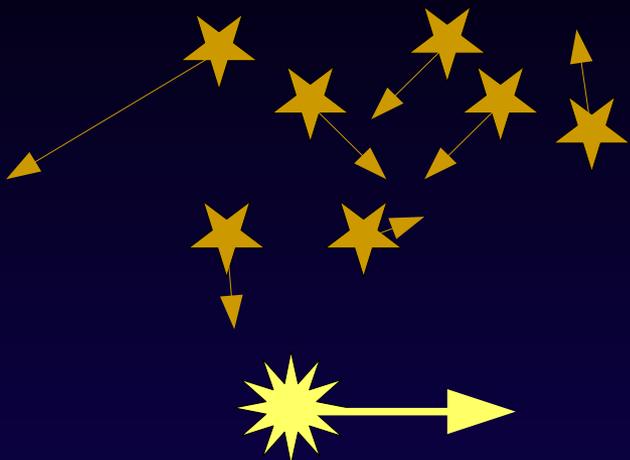


Gaia Collaboration, Katz et al. (2018)

# Statistical classics

see e.g. Popowski & Gould (1998)

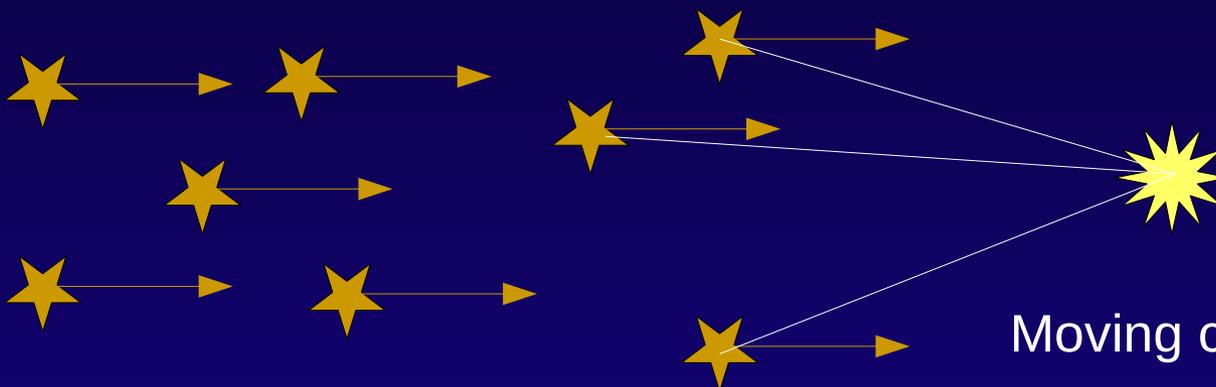
Secular and statistical parallax



Assume zero average motion

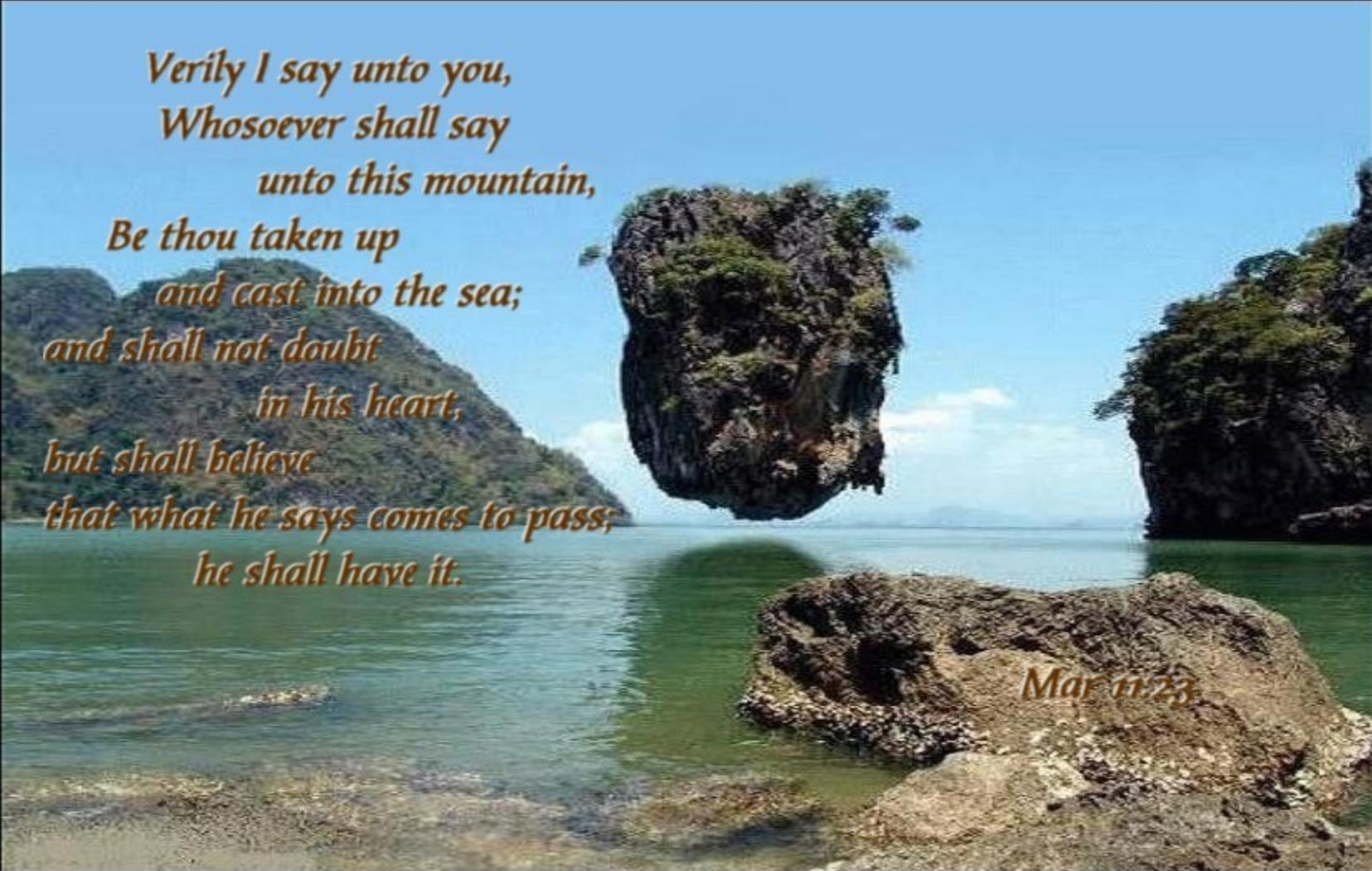


Assume specific, constant velocity ellipsoid



Moving cluster parallax

# How to move a mountain



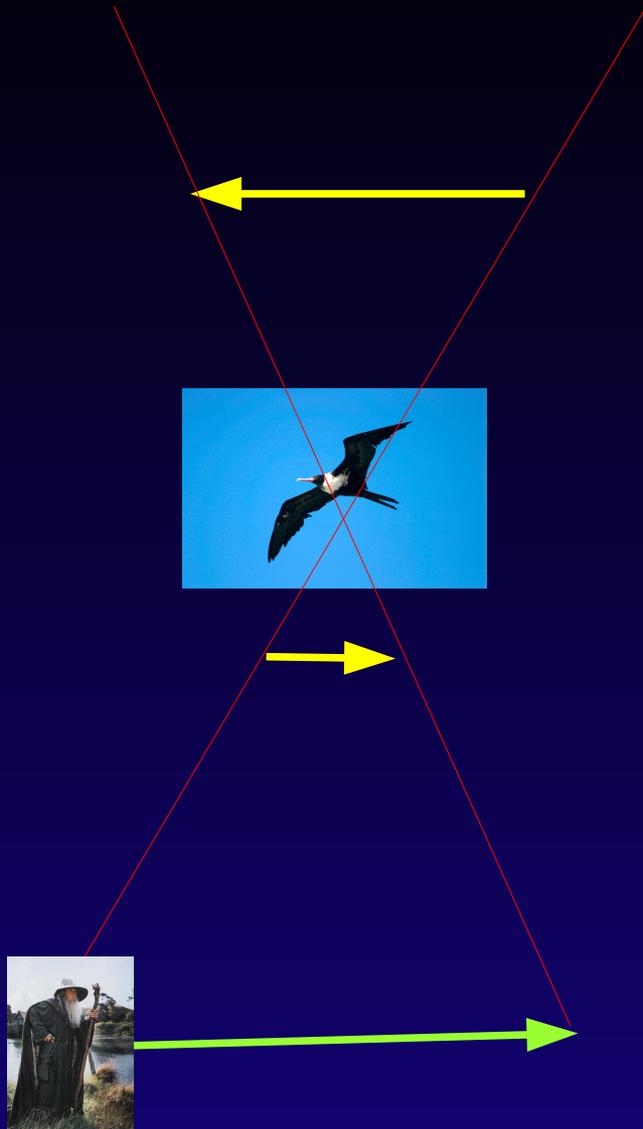
*Verily I say unto you,  
Whosoever shall say  
unto this mountain,  
Be thou taken up  
and cast into the sea;  
and shall not doubt  
in his heart,  
but shall believe  
that what he says comes to pass;  
he shall have it.*

*Mar 11:23*

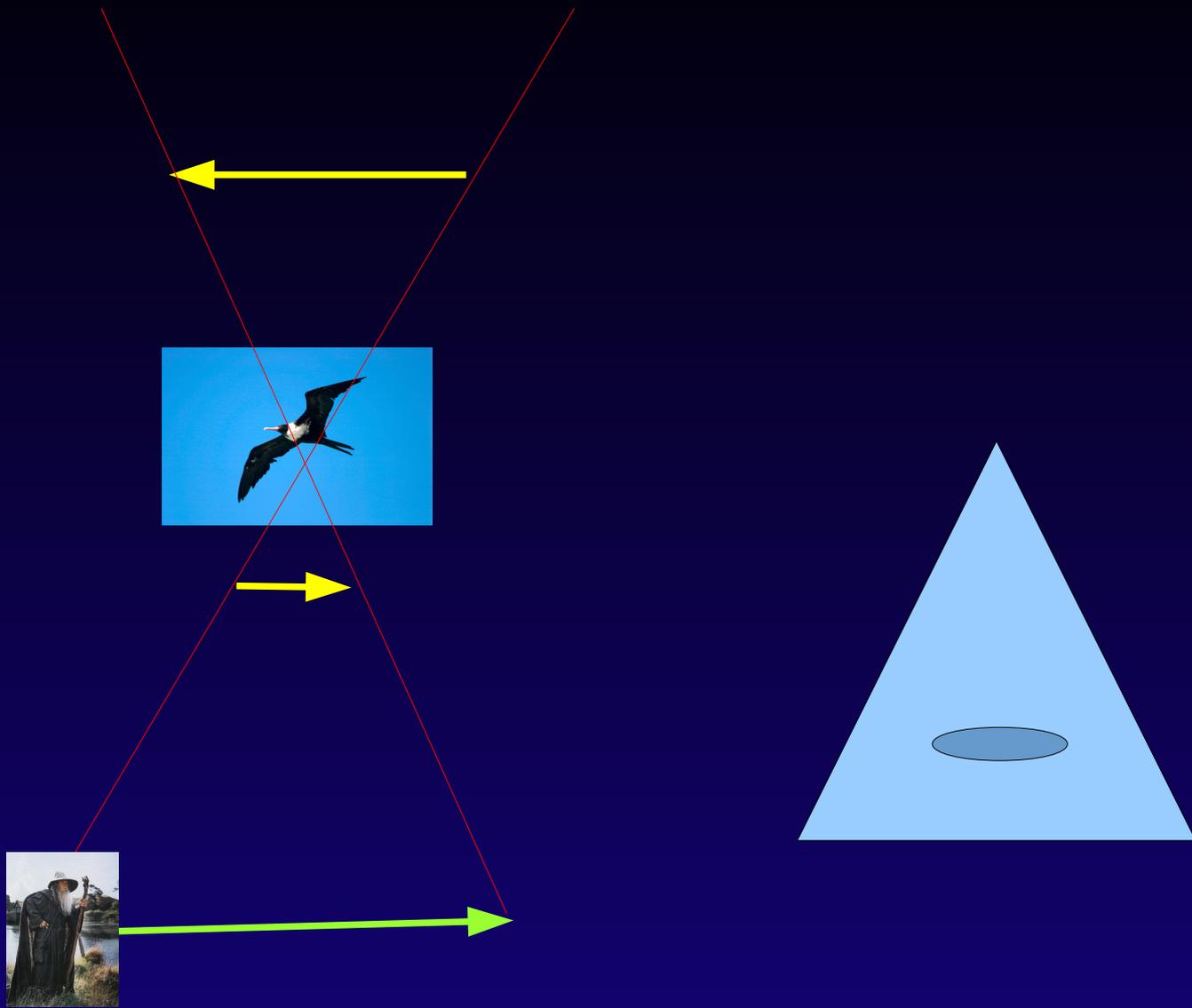
No, that's dumb



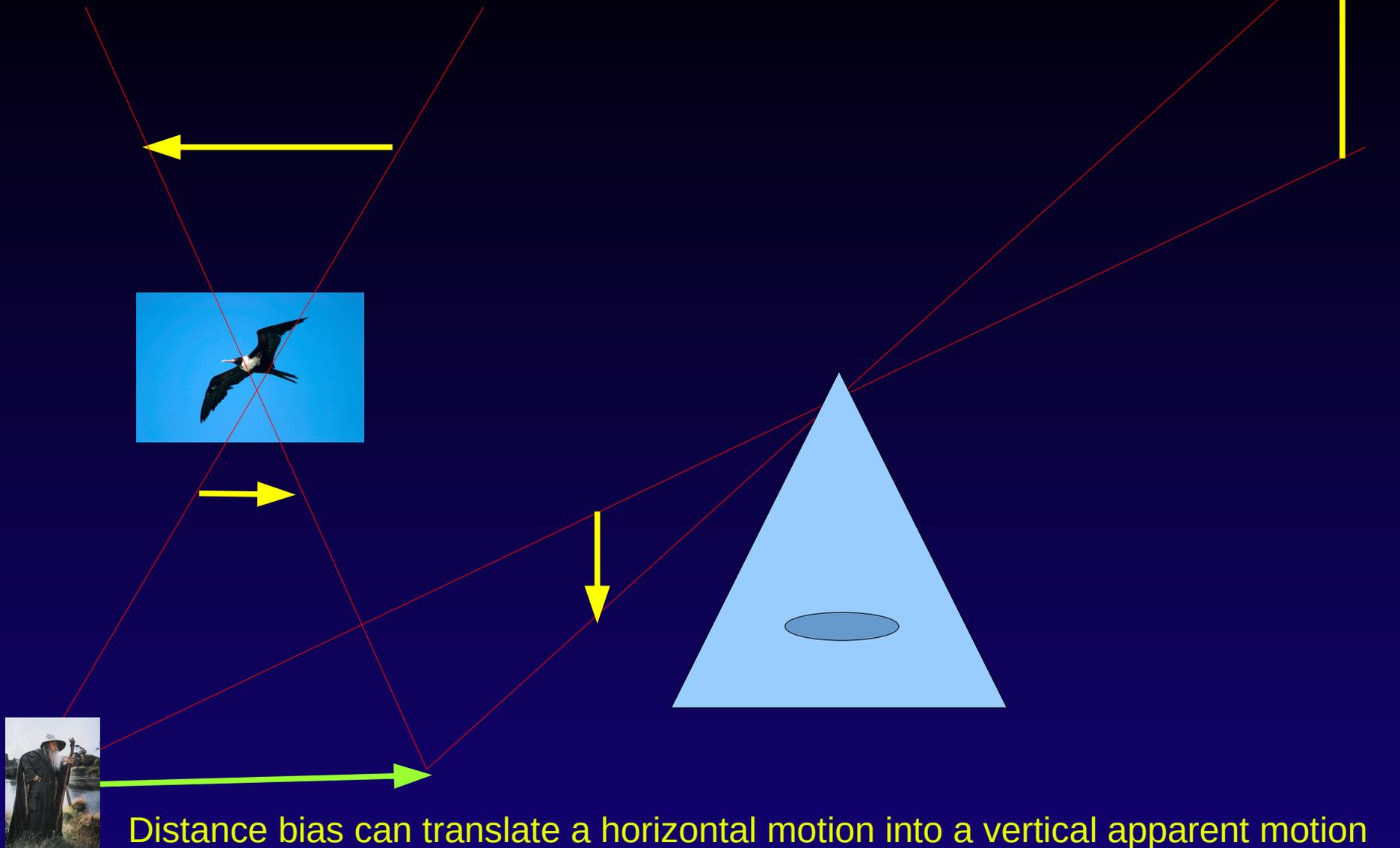
# Another dumb way



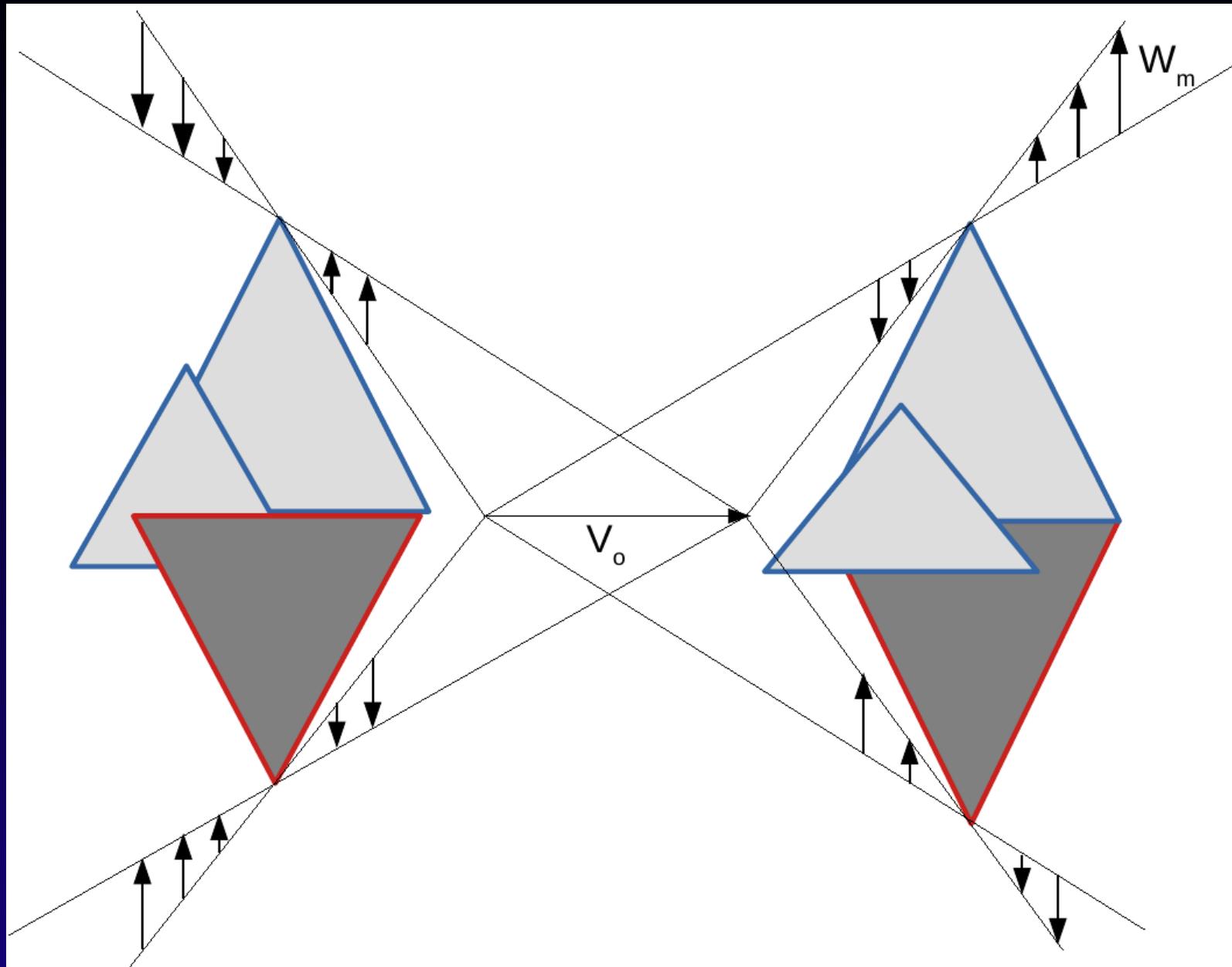
# Another dumb way



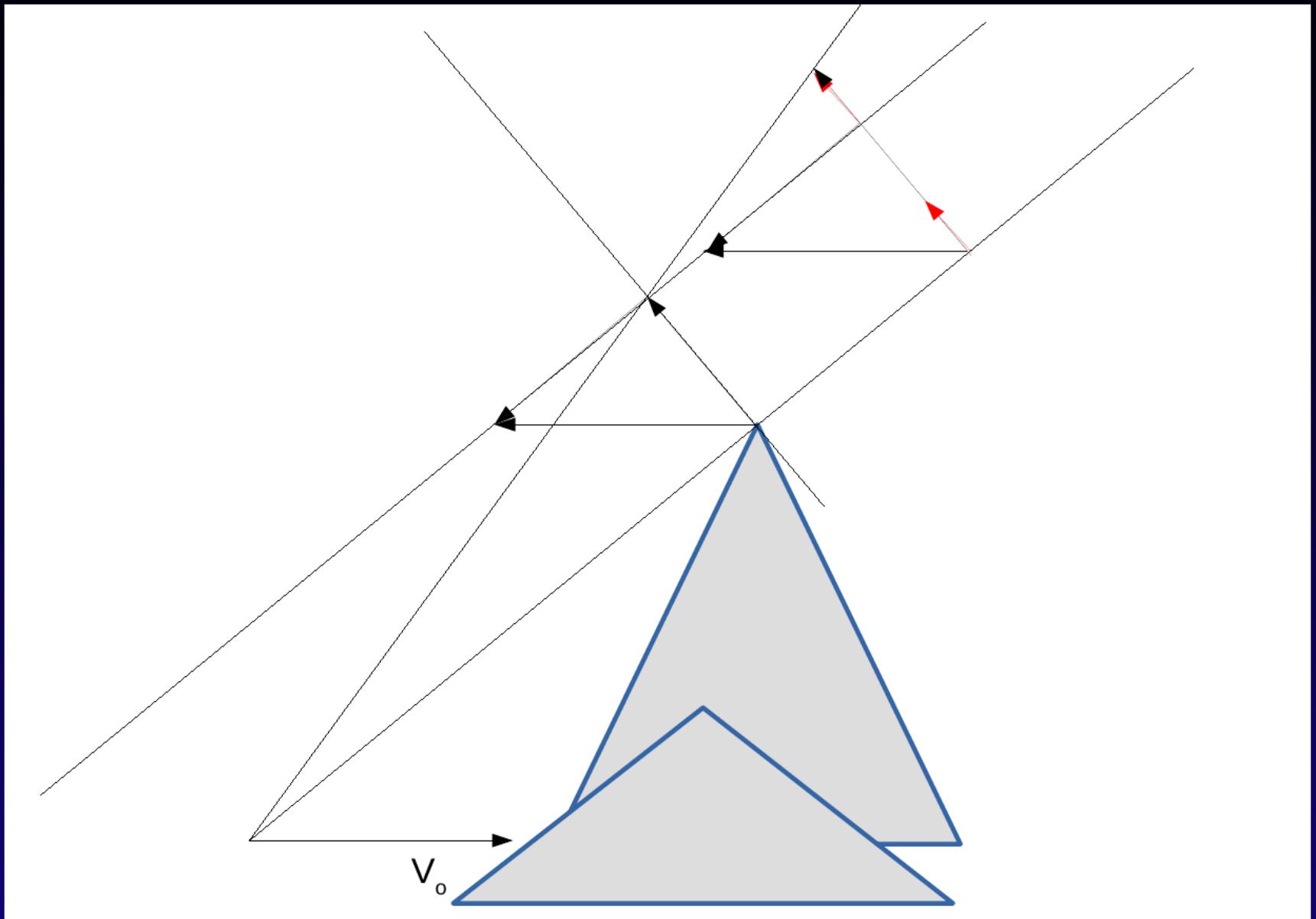
# Another dumb way



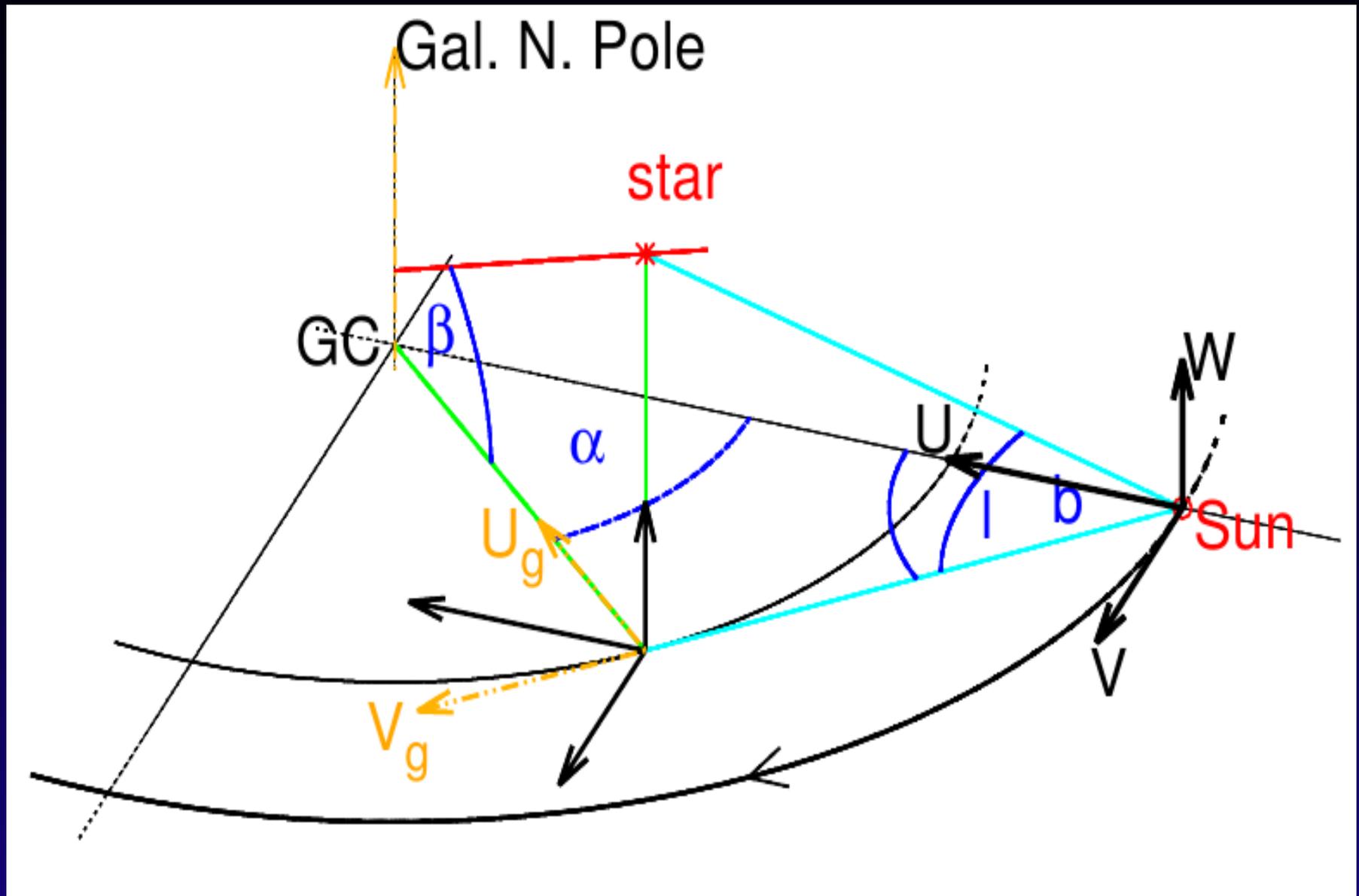
# The pattern changes sign



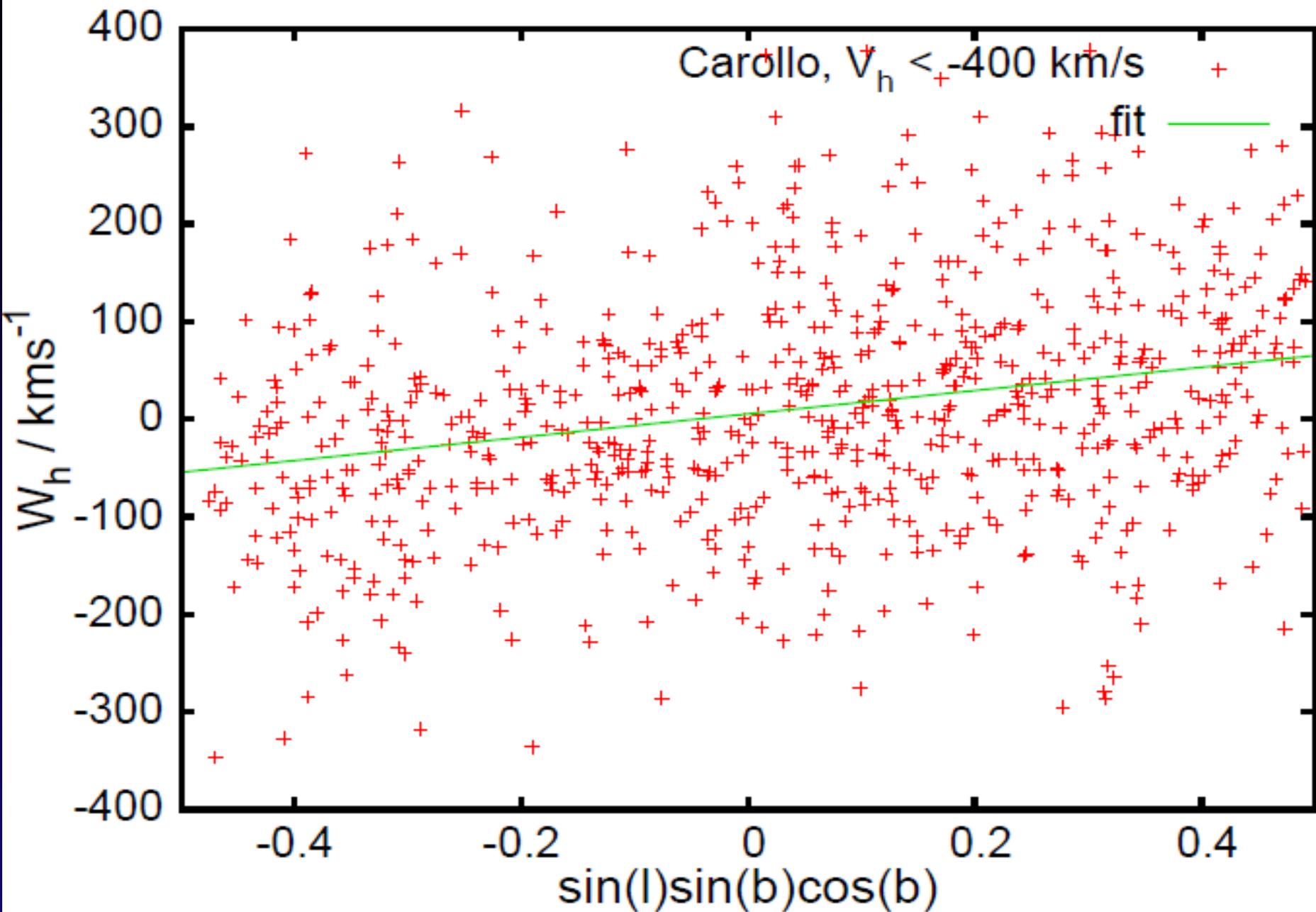
# How to construct the velocity bias



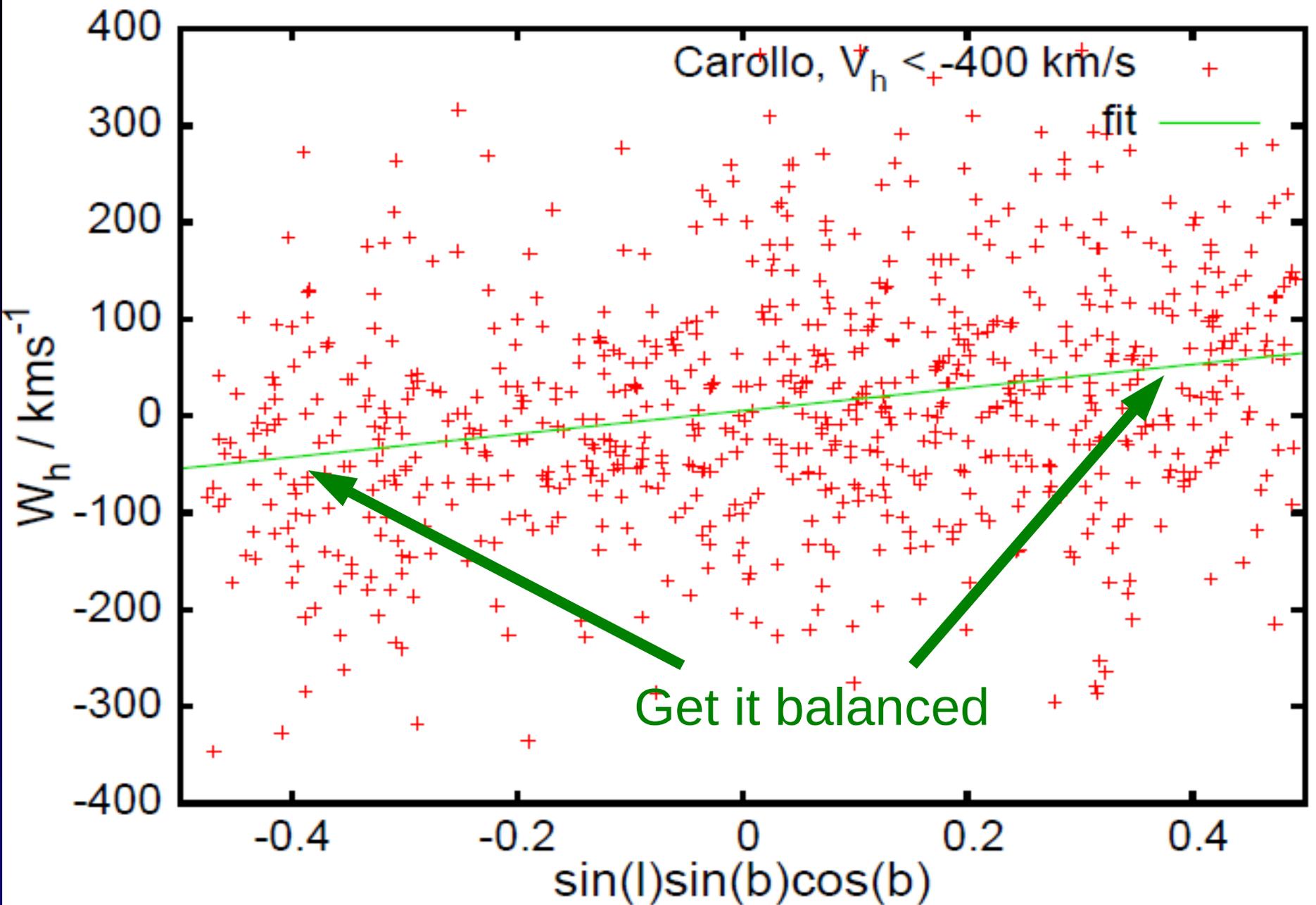
# Galactic Coordinates



# The skies are falling!



But that's not all .....



# A simple estimate

Get a simple linear relationship  $W = f T_{VW} V + e$

→ Can set up a linear least squares estimator

Precision:

$$e_f = \frac{1}{\sqrt{N}} \frac{\sigma_W}{\sigma_T V}$$

0.2

250 km/s

80 km/s

as-observed  
dispersion!

# Distance bias, formally

$$\begin{pmatrix} U_0 \\ V_0 \\ W_0 \end{pmatrix} = \mathbf{M} \begin{pmatrix} s\mu_b \\ s\mu_l \\ v_{\parallel} \end{pmatrix} \quad \mathbf{M} \equiv \begin{pmatrix} -\sin b \cos l & -\sin l & \cos b \cos l \\ -\sin b \sin l & \cos l & \cos b \sin l \\ \cos b & 0 & \sin b \end{pmatrix}$$

See also Johnson & Soderblom (1987)

$$\begin{pmatrix} U \\ V \\ W \end{pmatrix} = \mathbf{M}(\mathbf{I} + f\mathbf{P})\mathbf{M}^T \begin{pmatrix} U_0 \\ V_0 \\ W_0 \end{pmatrix} = (\mathbf{I} + f\mathbf{T}) \begin{pmatrix} U_0 \\ V_0 \\ W_0 \end{pmatrix}$$

$$\mathbf{T} = \mathbf{M}\mathbf{P}\mathbf{M}^T = \begin{pmatrix} 1 - \cos^2 b \cos^2 l & -\frac{1}{2} \cos^2 b \sin 2l & -\frac{1}{2} \sin 2b \cos l \\ -\frac{1}{2} \cos^2 b \sin 2l & 1 - \cos^2 b \sin^2 l & -\frac{1}{2} \sin 2b \sin l \\ -\frac{1}{2} \sin 2b \cos l & -\frac{1}{2} \sin 2b \sin l & \cos^2 b \end{pmatrix}$$

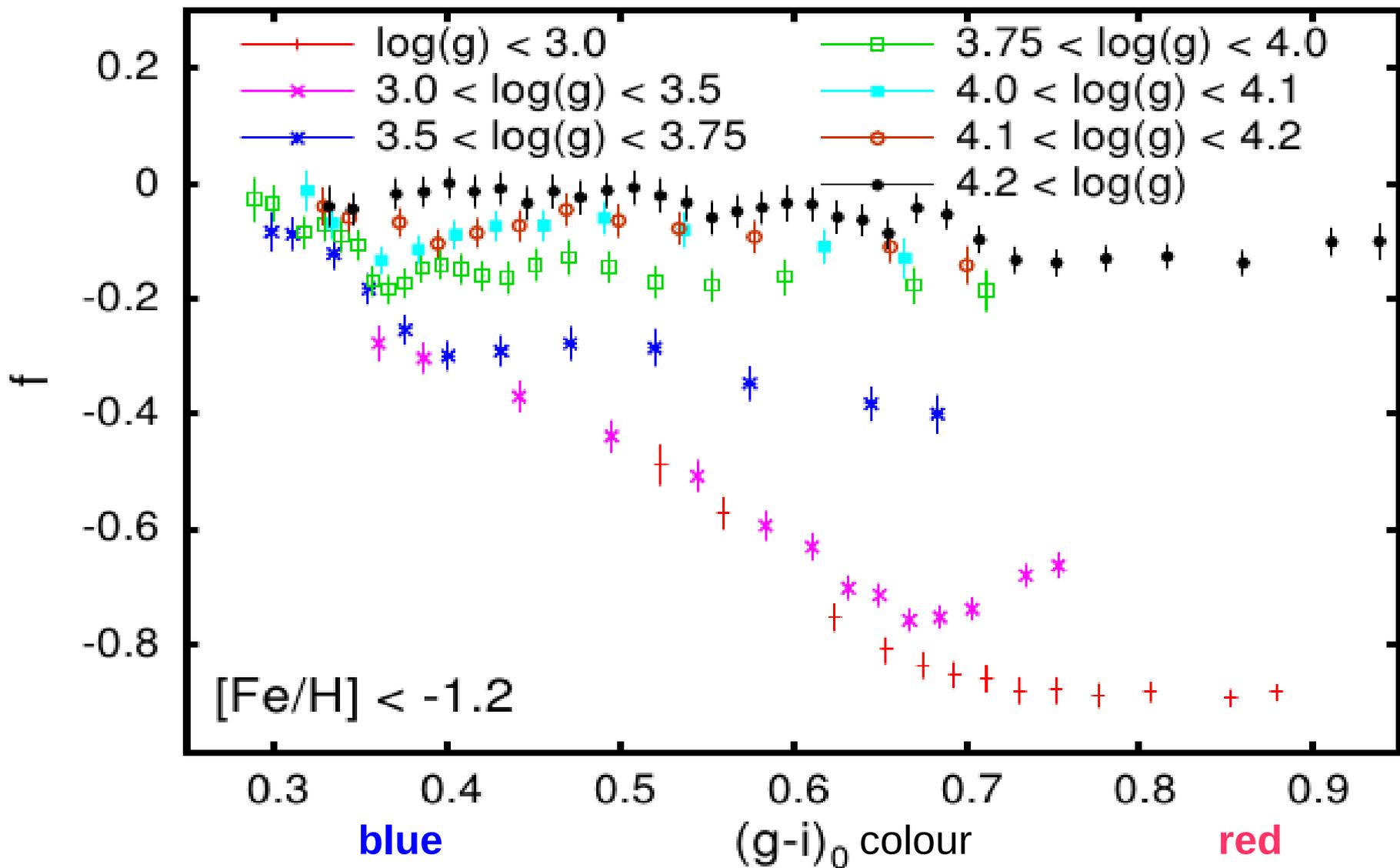
$$\sum_i [U_i - \langle U \rangle - f(x_i - \langle x \rangle)] x_i = \sum_i (1 + fT_{UU_i}) \delta U_i x_i$$

$$\sum_i [W_i - \langle W \rangle - f(y_i - \langle y \rangle)] y_i = \sum_i (1 + fT_{WW_i}) \delta W_i y_i$$

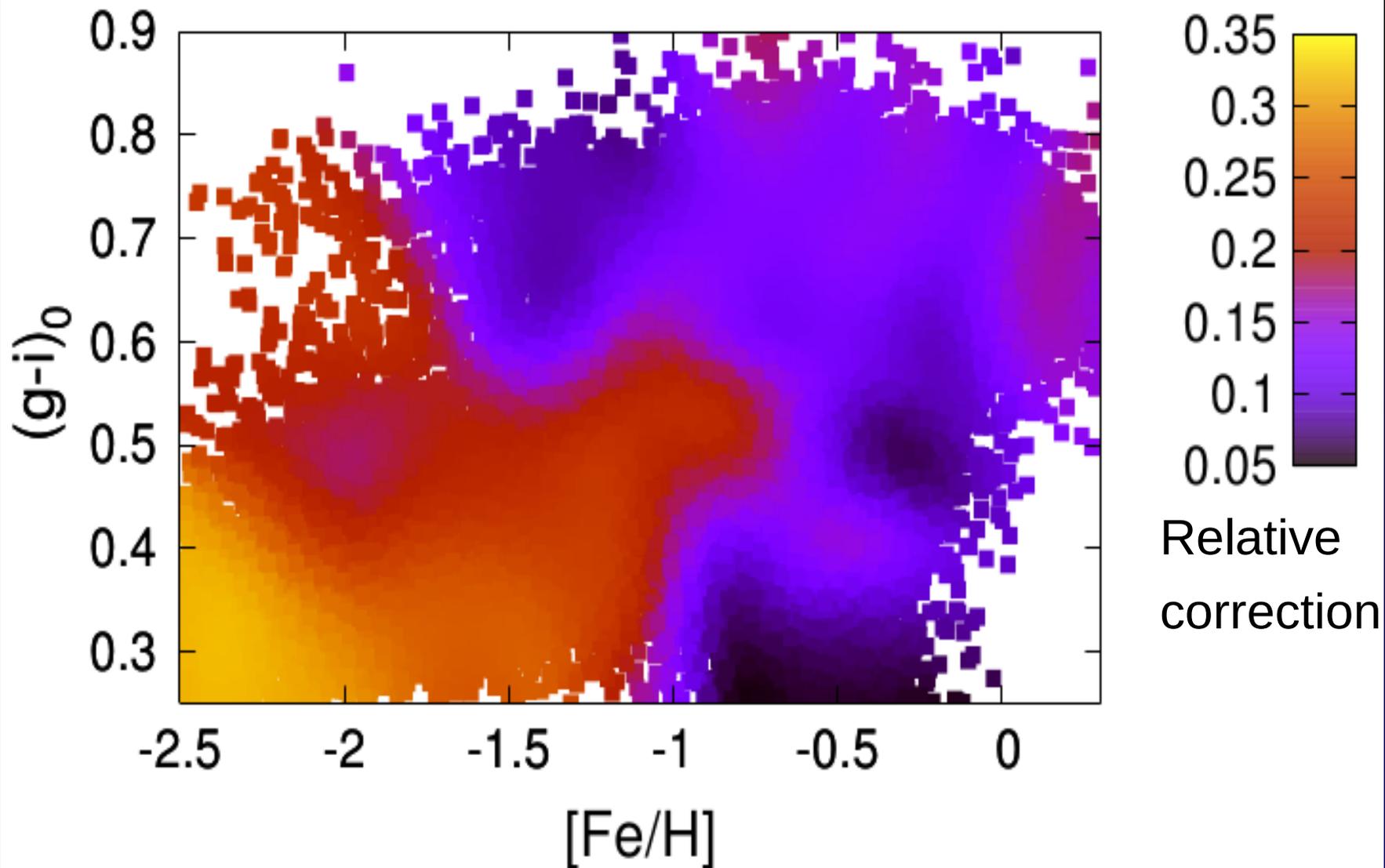
$$x \equiv -T_{UU}U_{\odot} + T_{UV}V + T_{UW}W$$

$$y \equiv -T_{WW}W_{\odot} + T_{WU}U + T_{WV}V$$

# Gravity selection on samples

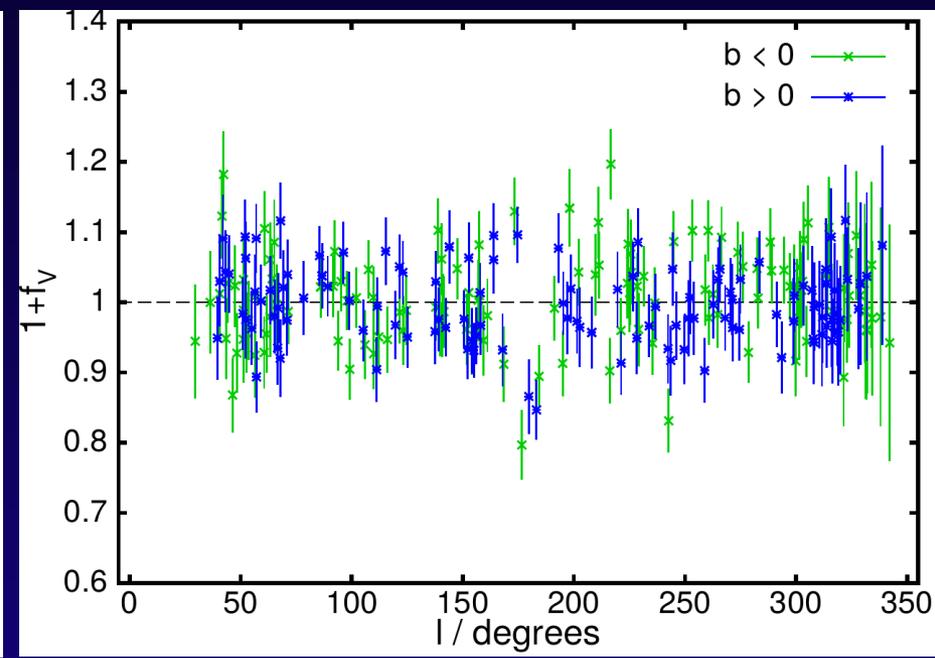
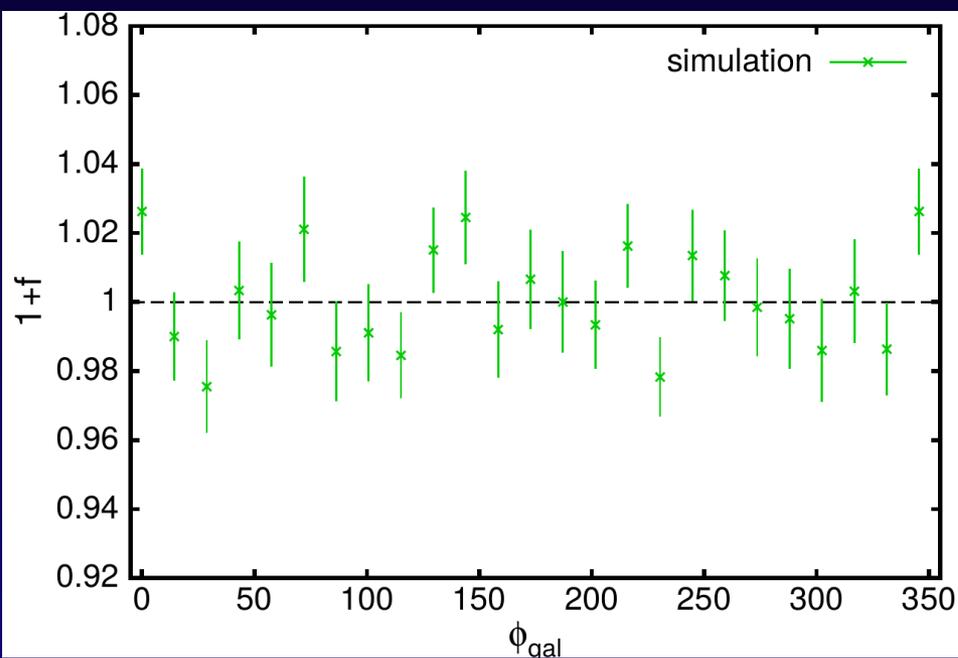


# Distance corrections



# Validation on N-body discs

model	$\langle f \rangle$	$\sigma_f$	$\sigma_{f,\text{st}}$	$f_V$	$\sigma_{f,V}$	$\sigma_{f,V,\text{st}}$
$V\alpha 9s8\lambda\zeta$	-0.0004	0.014	0.014	0.0015	0.033	0.022
$V\alpha 5\lambda$	-0.0073	0.018	0.013	-0.0064	0.024	0.019
$M\alpha 1\zeta^*$	0.0026	0.019	0.017	-0.0013	0.030	0.027
P2	-0.0064	0.020	0.017	-0.0066	0.035	0.028
EHR2	-0.0072	0.010	0.008	0.0009	0.014	0.013



Start with Gaia DR 1

# Divide et impera!

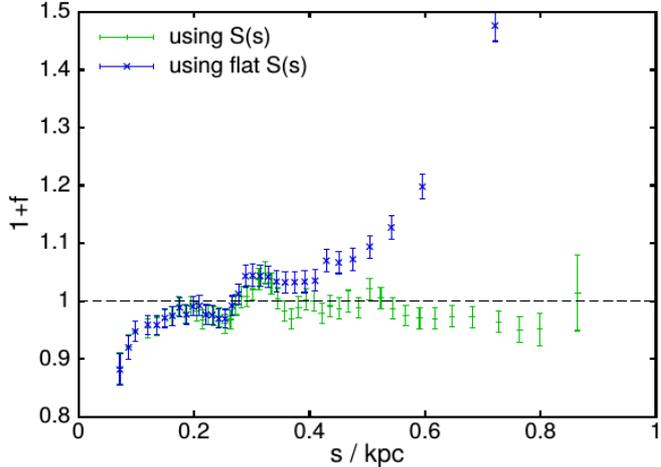
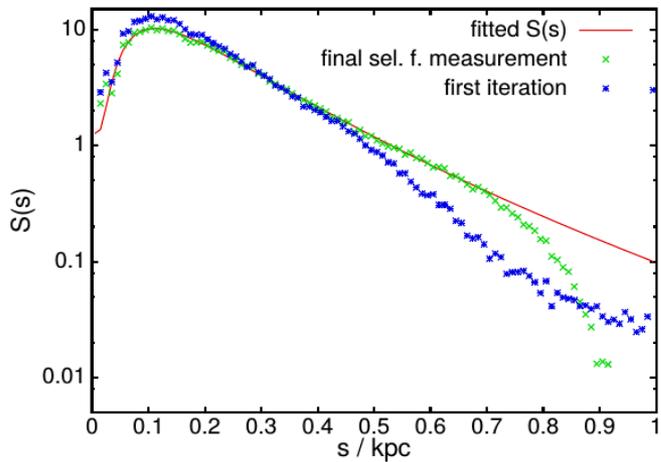
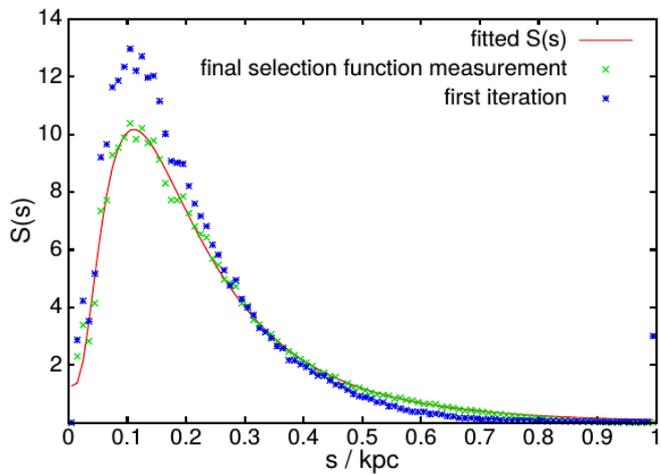
Detect trends within sample

$$\langle s \rangle = N^{-1} \int ds s^3 G(p, p_0, \sigma_p) \rho(s(p), l, b) S(s(p))$$

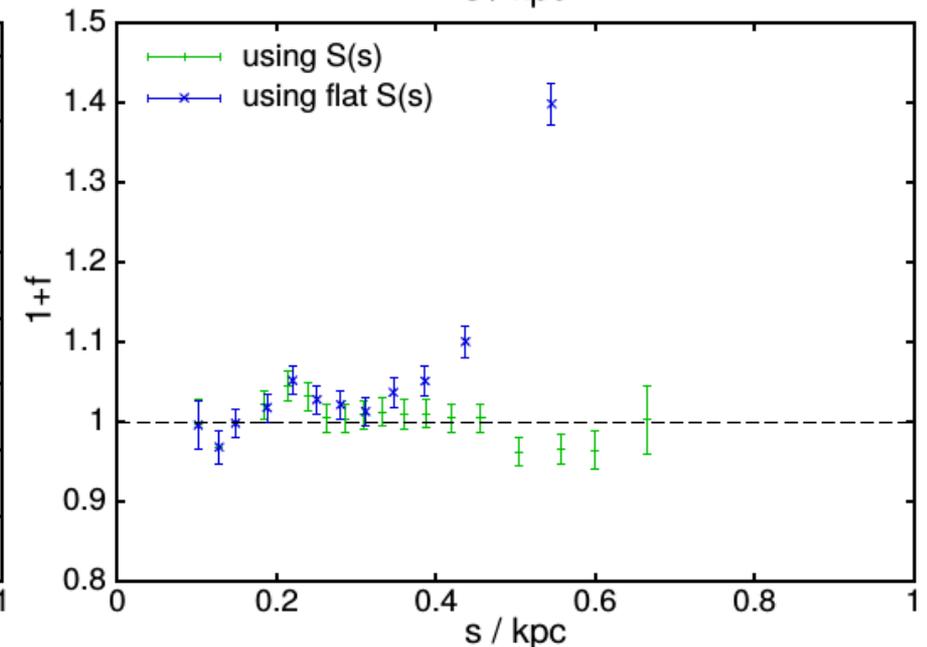
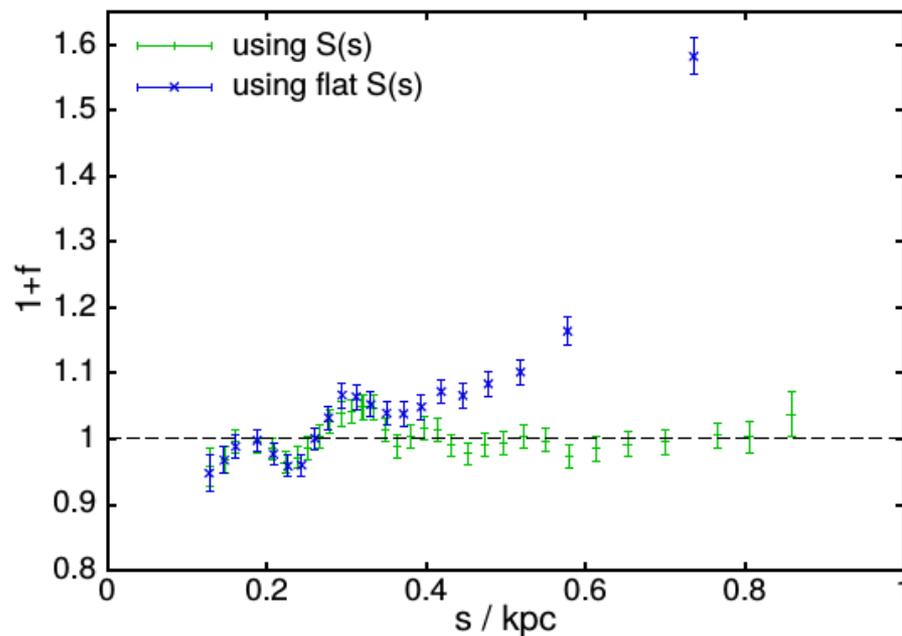
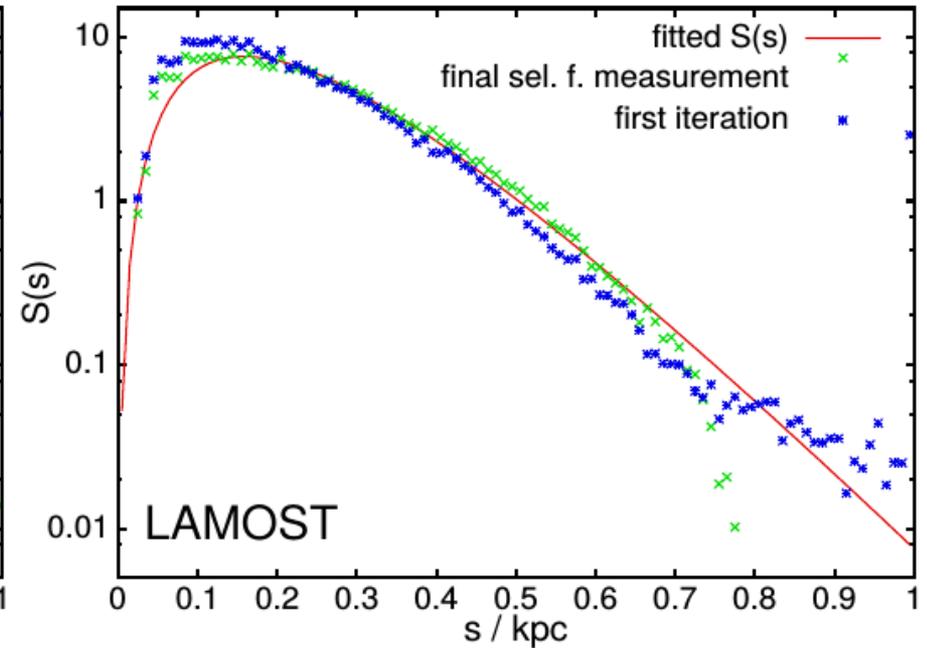
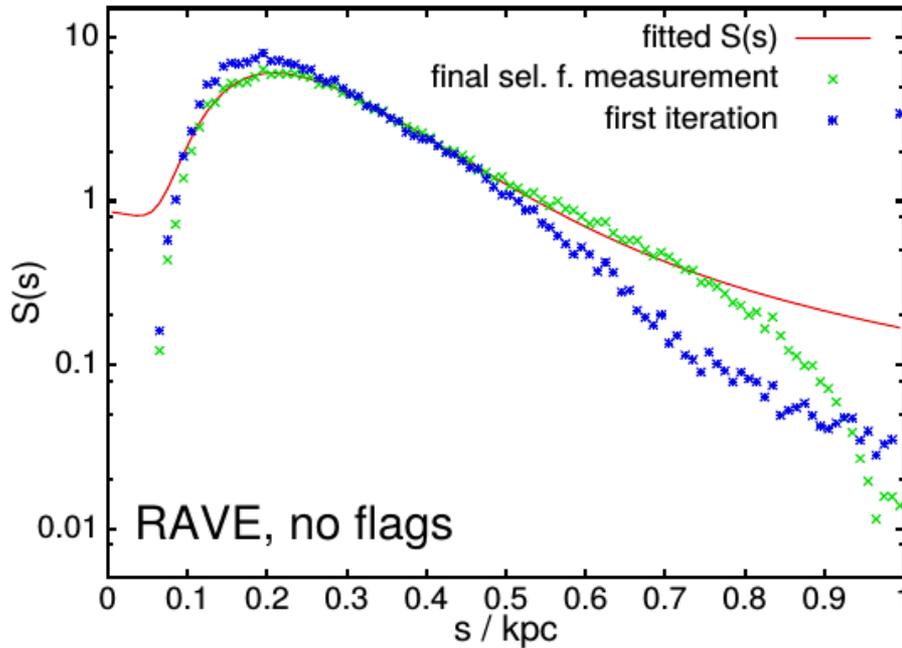
$$N = \int ds s^2 G(p, p_0, \sigma_p) \rho(s(p), l, b) S(s(p))$$

Solve for  $S(s)$  by iteration  
→ convergence within 5 steps

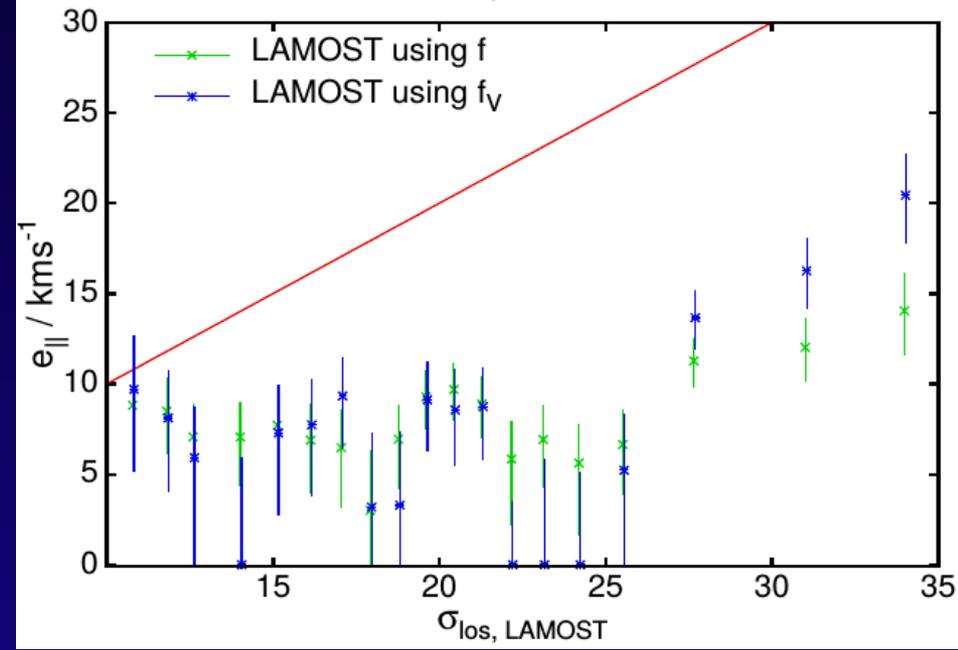
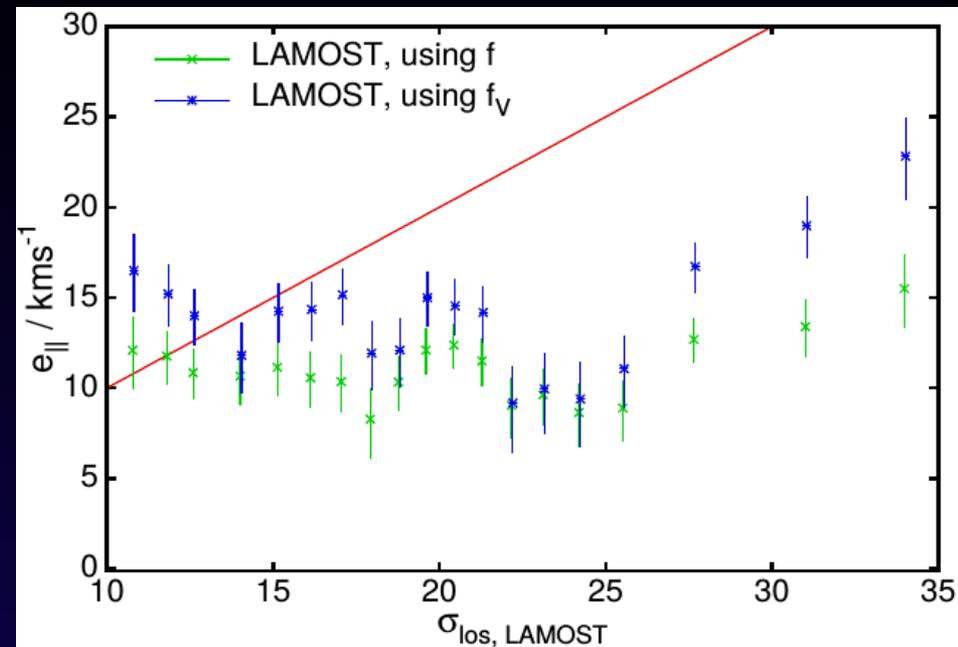
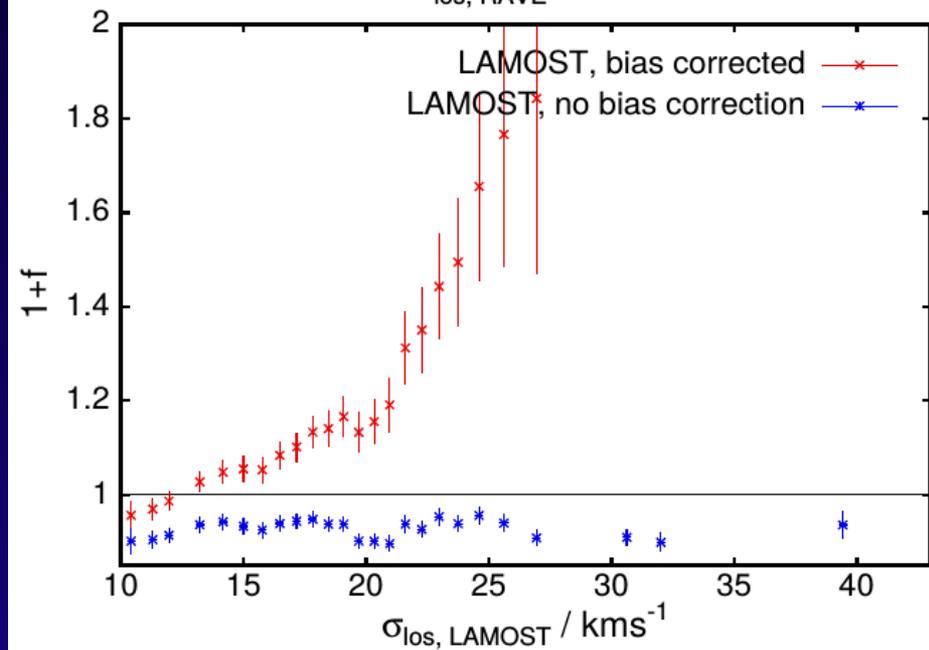
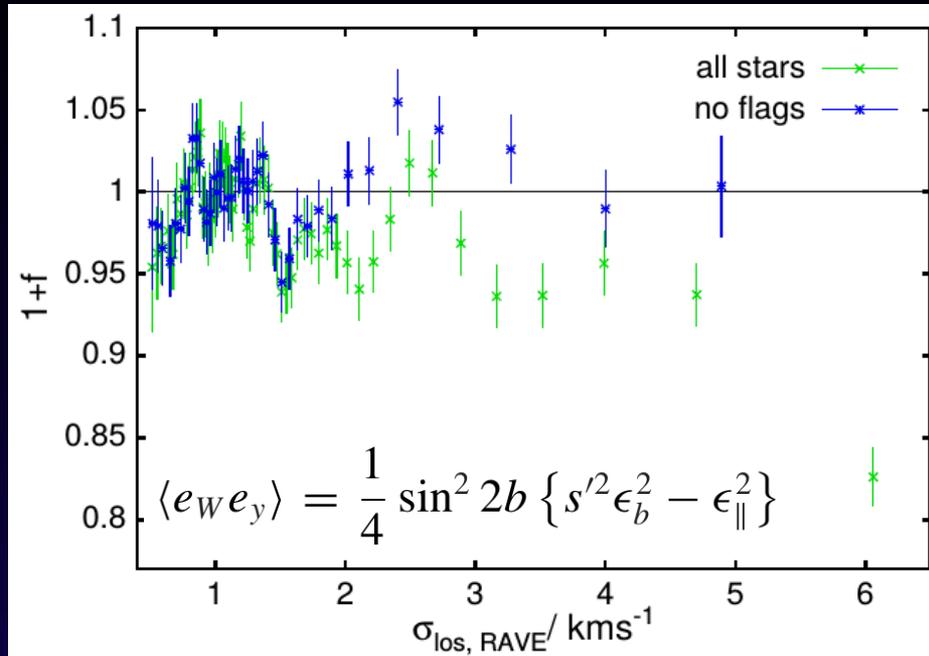
Validate via distance test



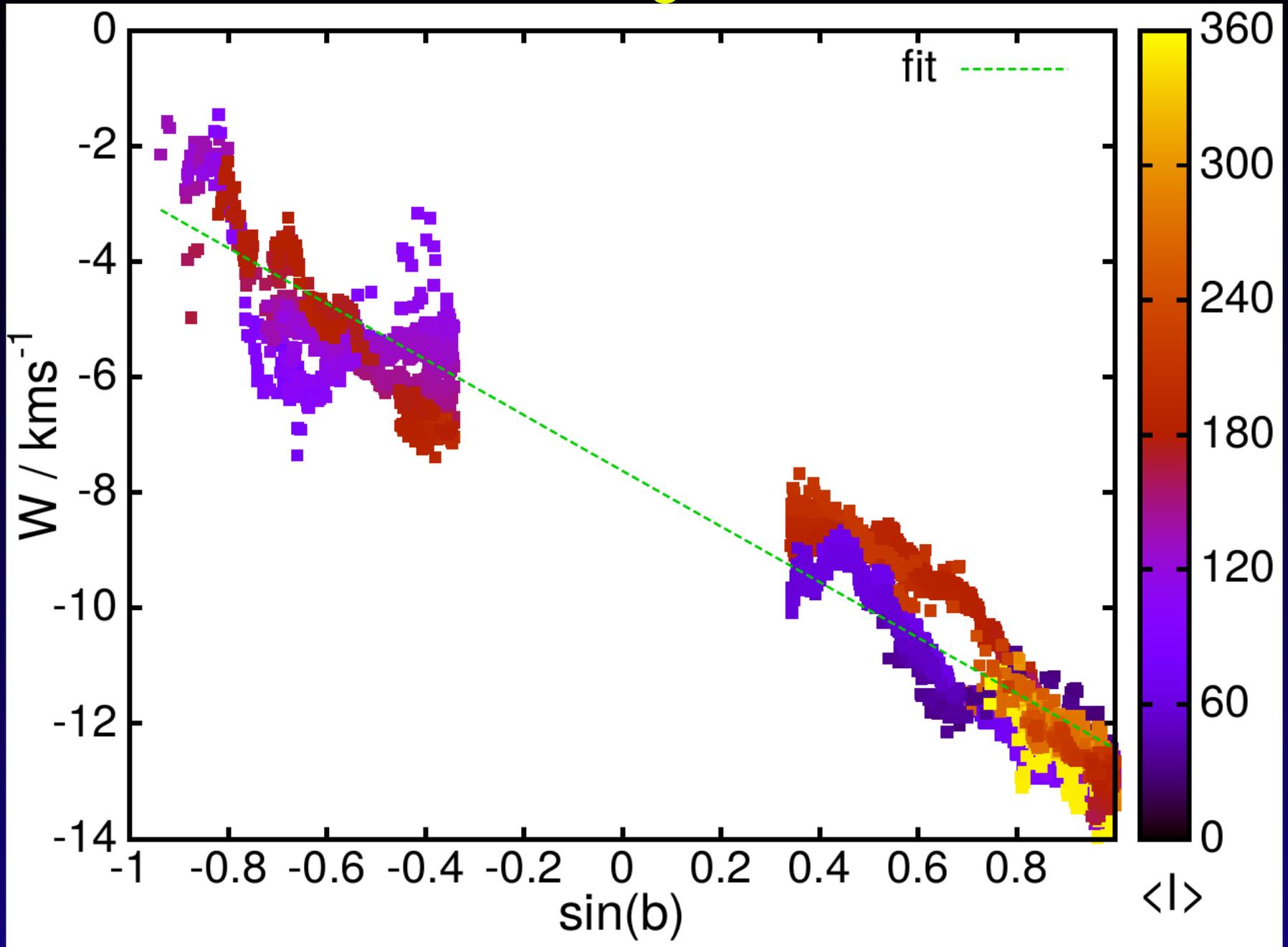
# Testing selection function



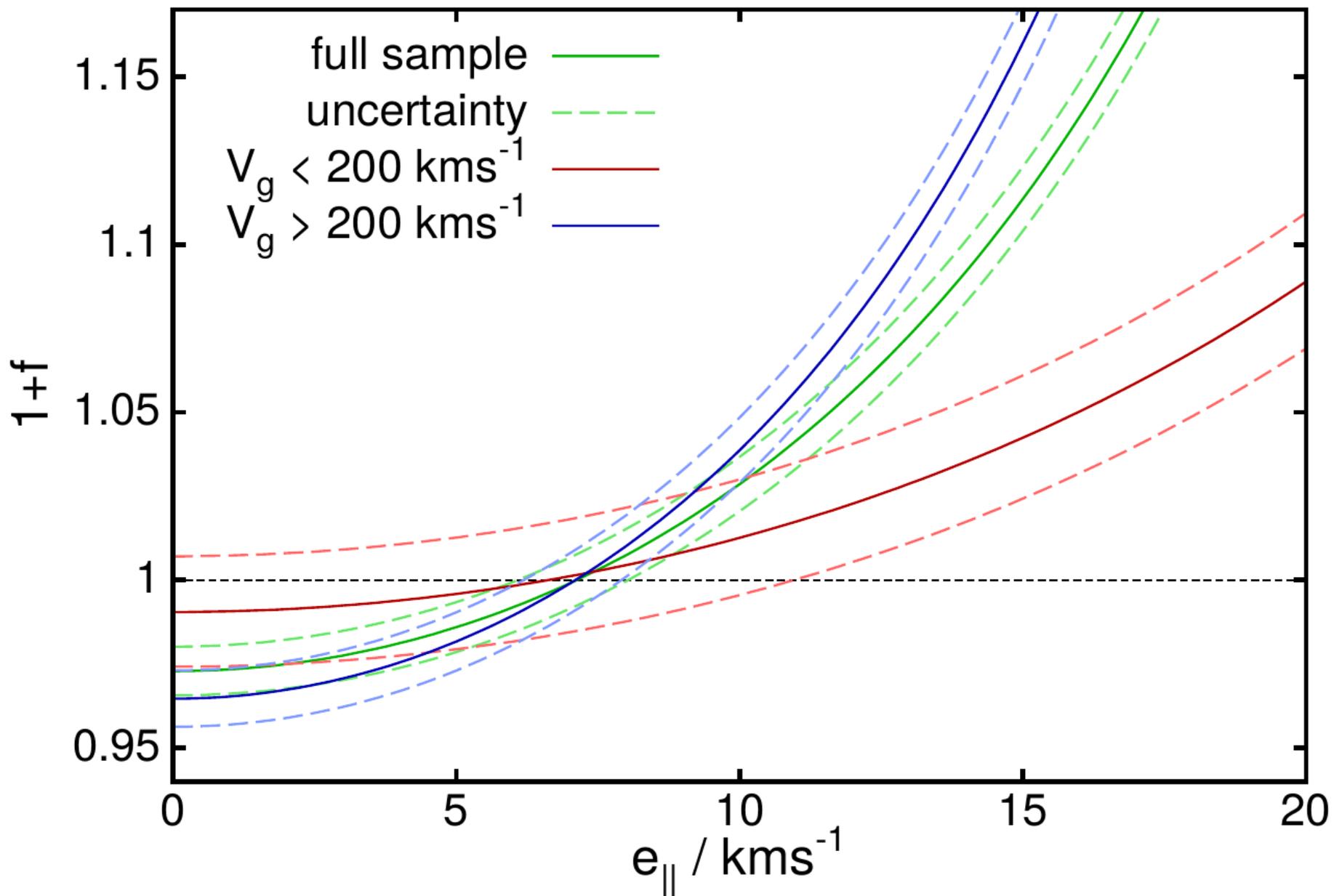
# Testing for RV errors



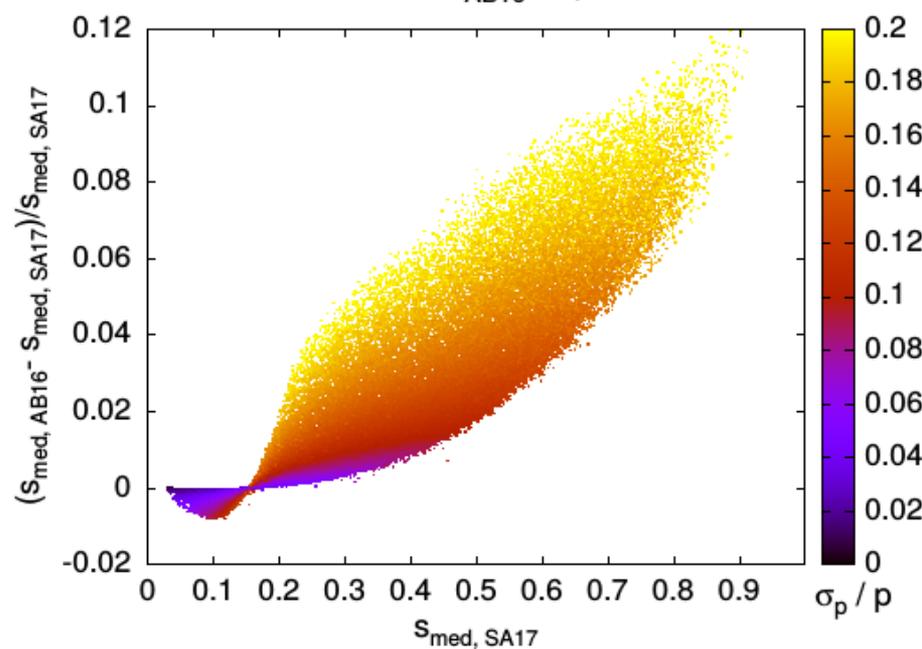
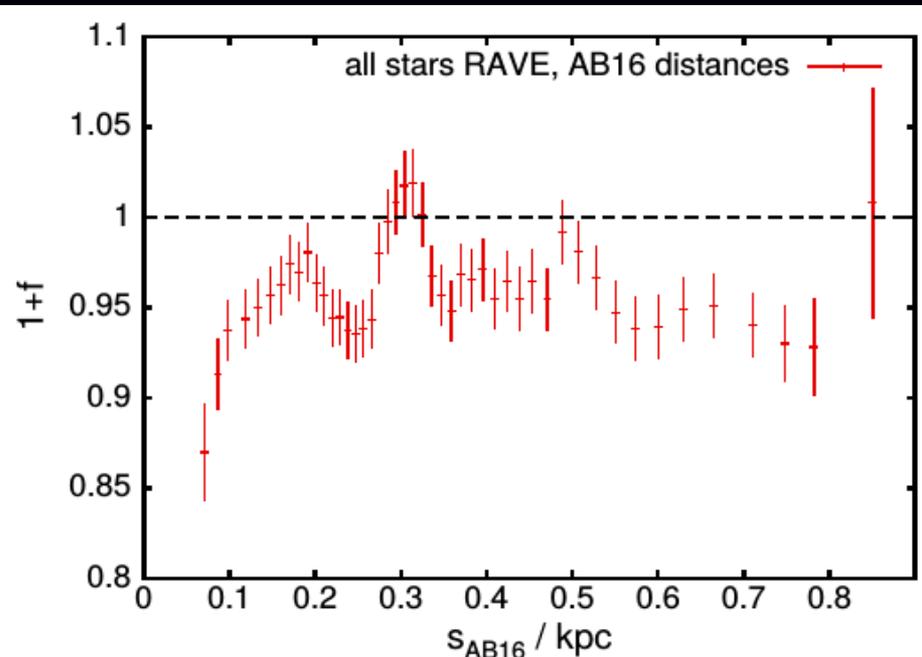
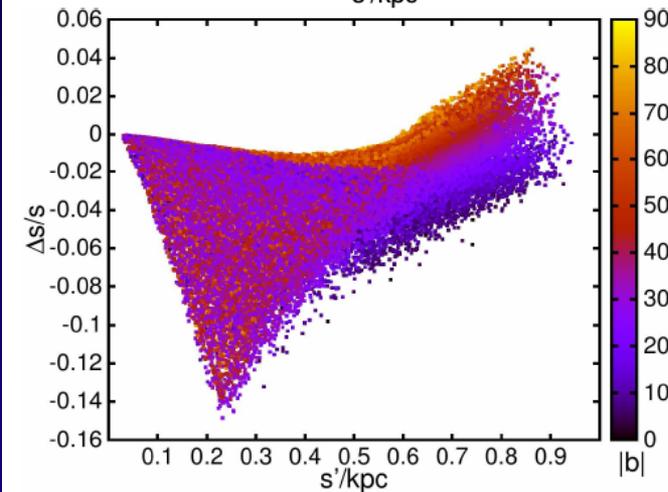
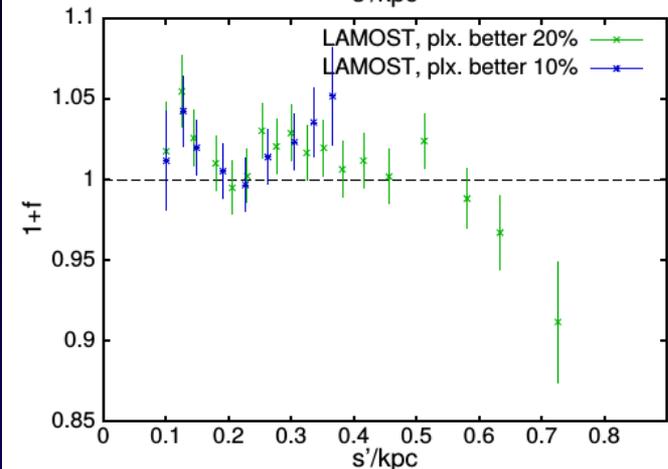
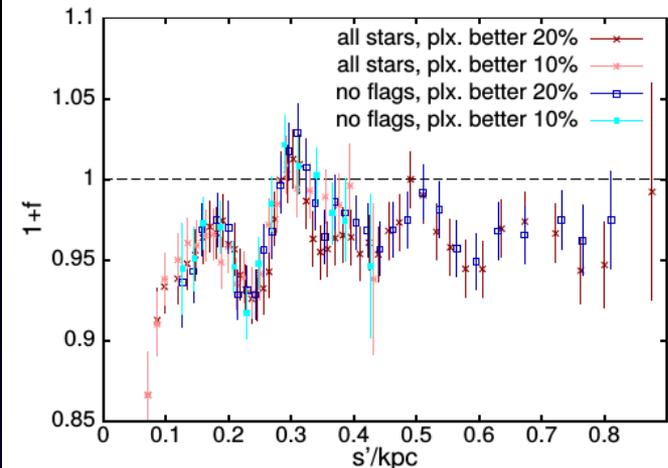
# Testing RV



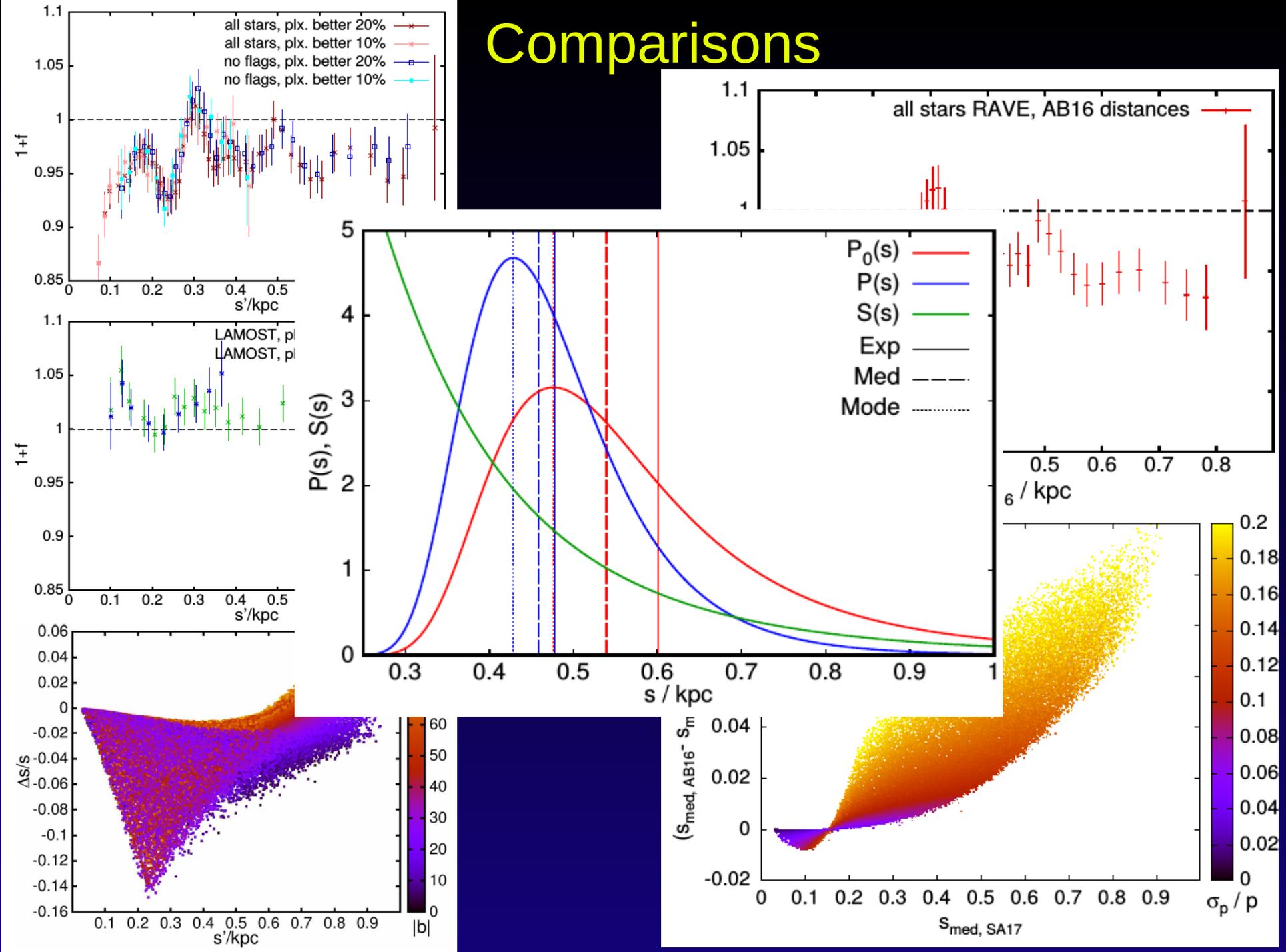
# Using kinematic differences



# Comparisons

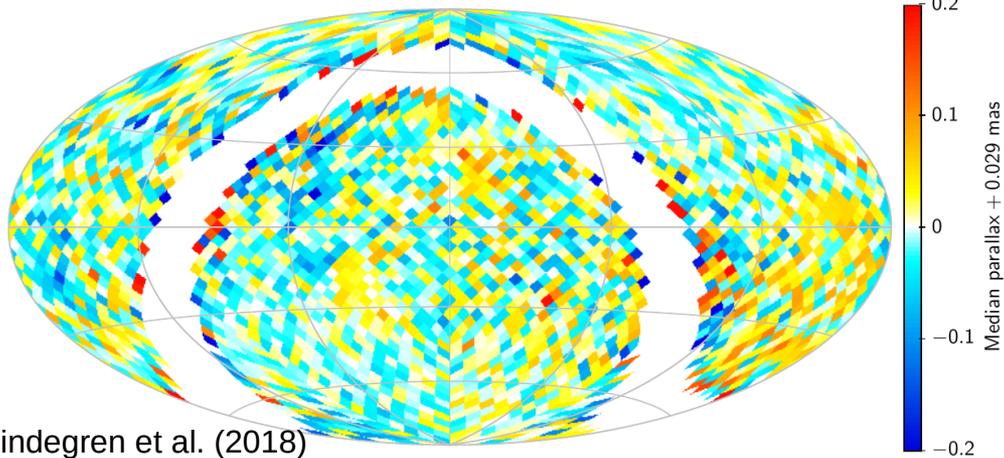


# Comparisons

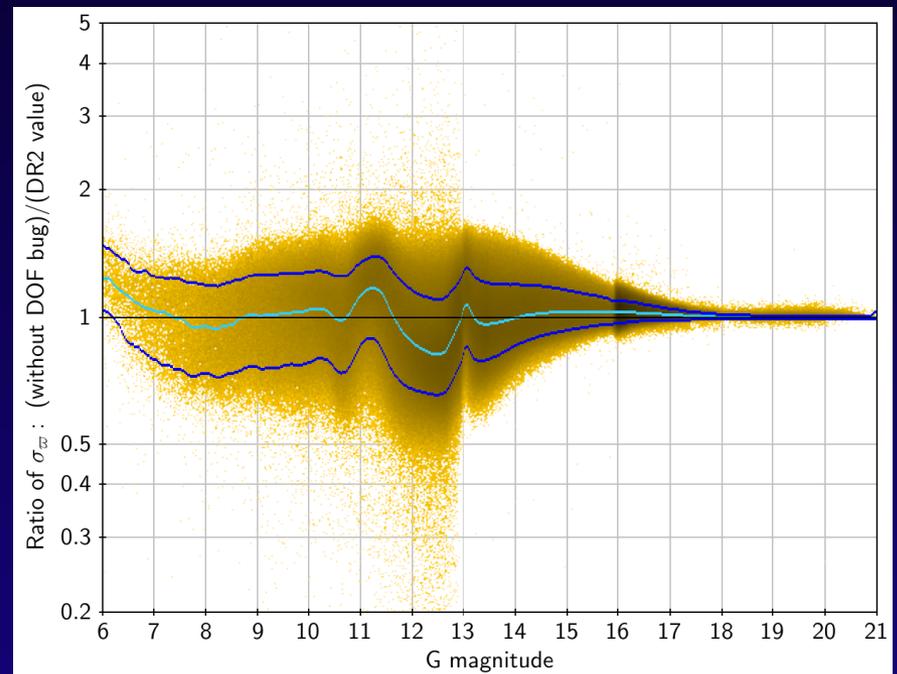
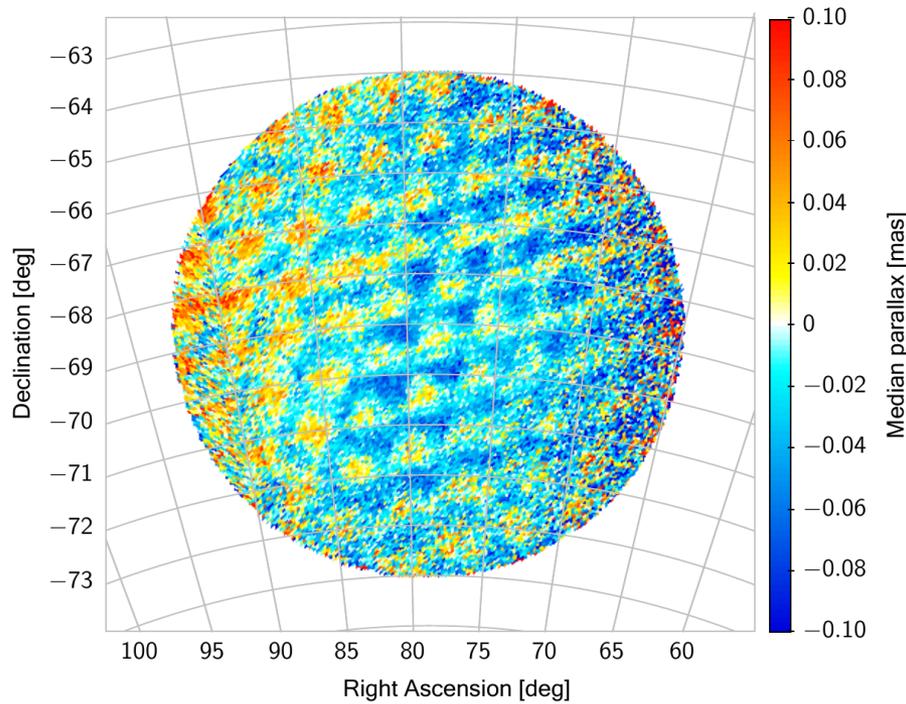
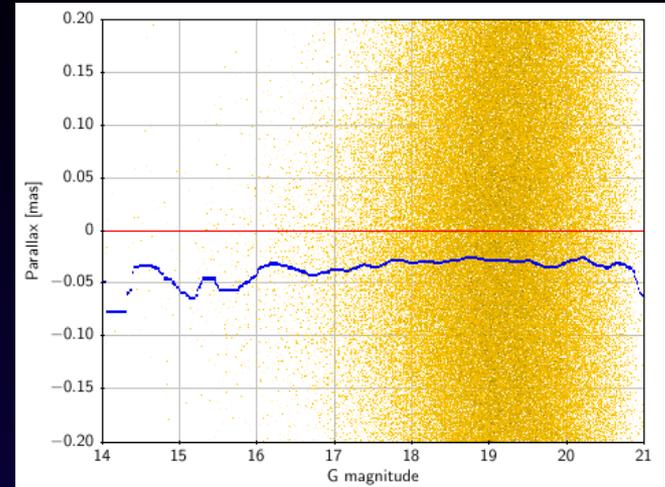


# Gaia DR2

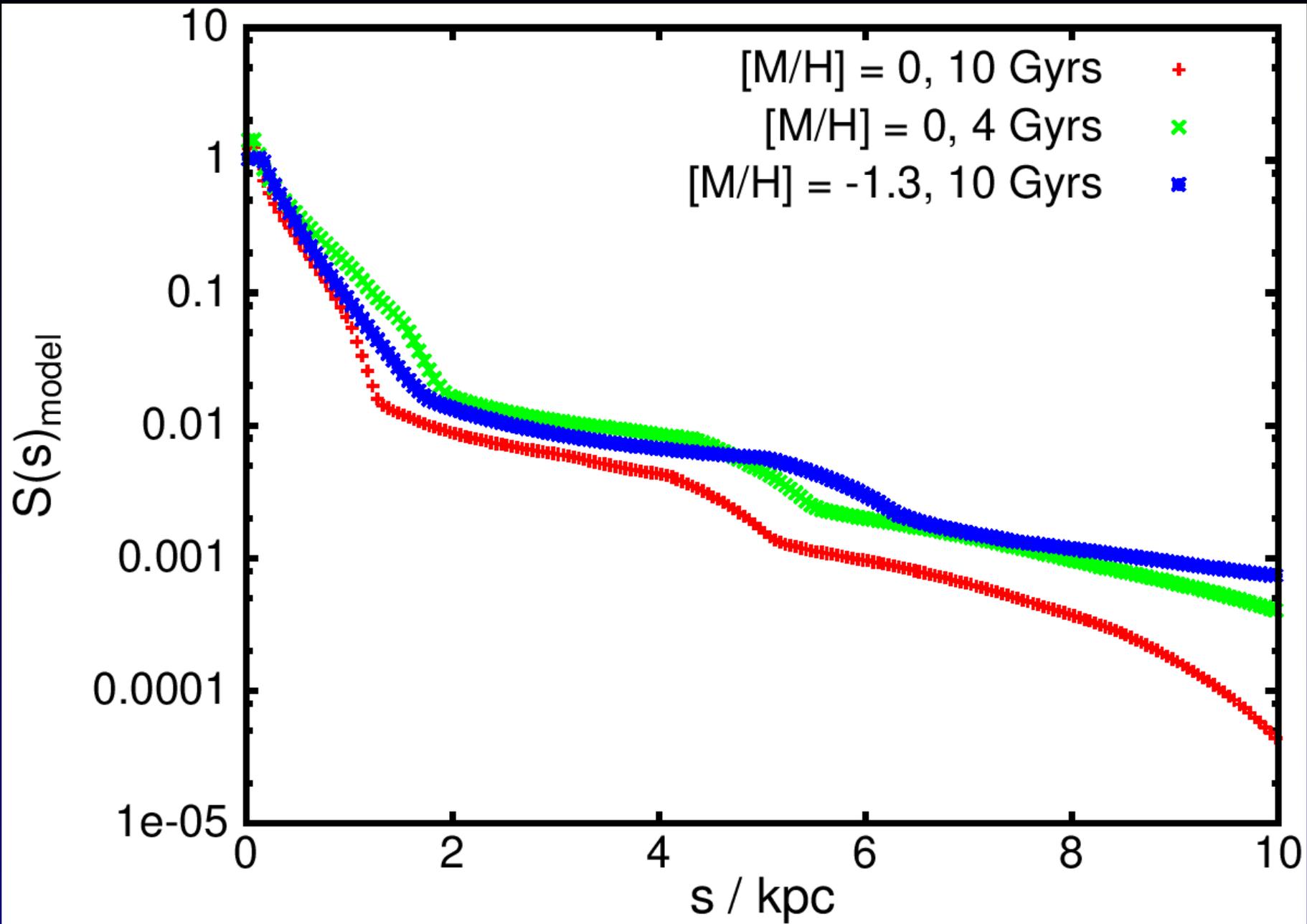
# Known issues



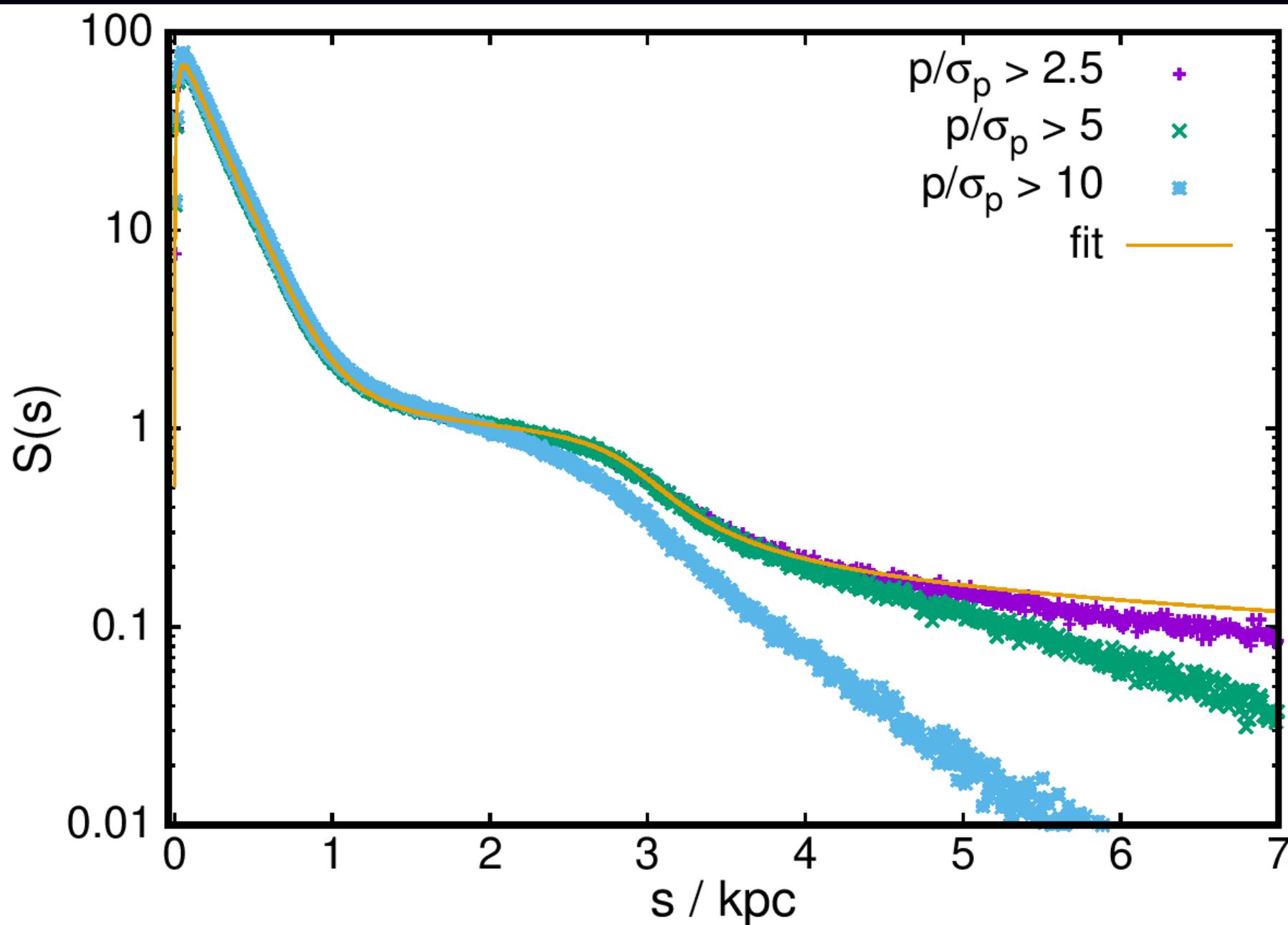
Lindgren et al. (2018)



# The selection function

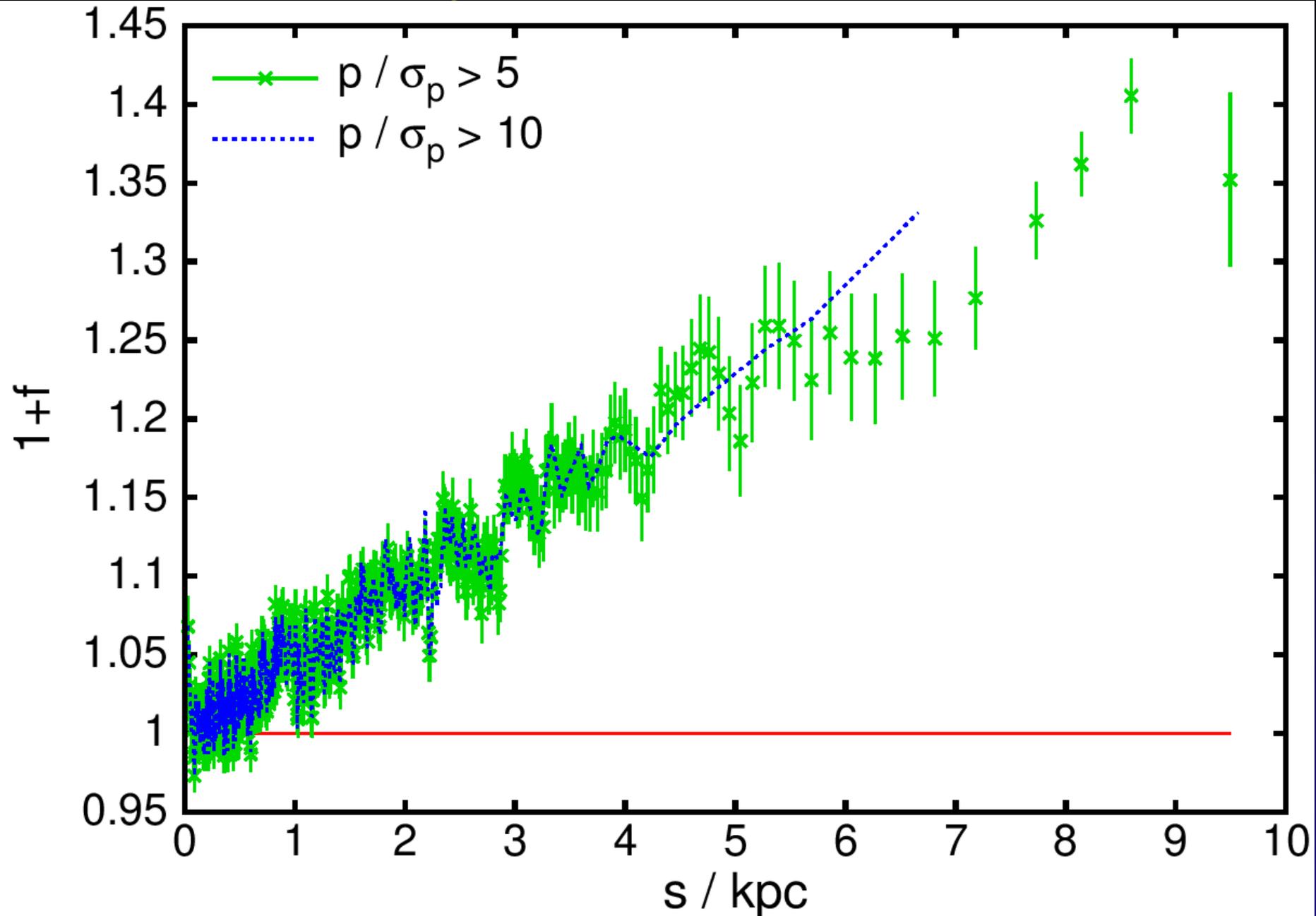


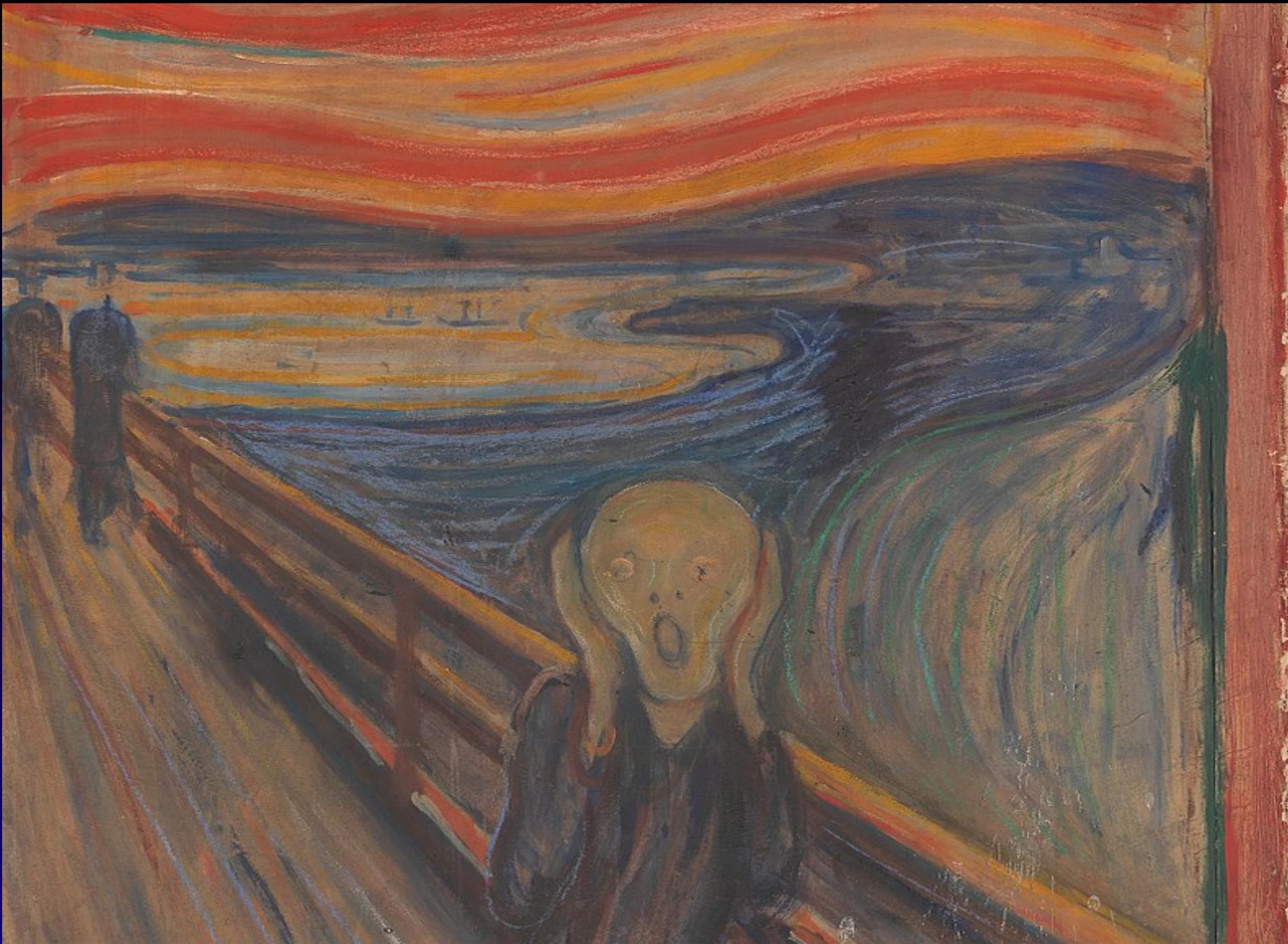
# The selection function



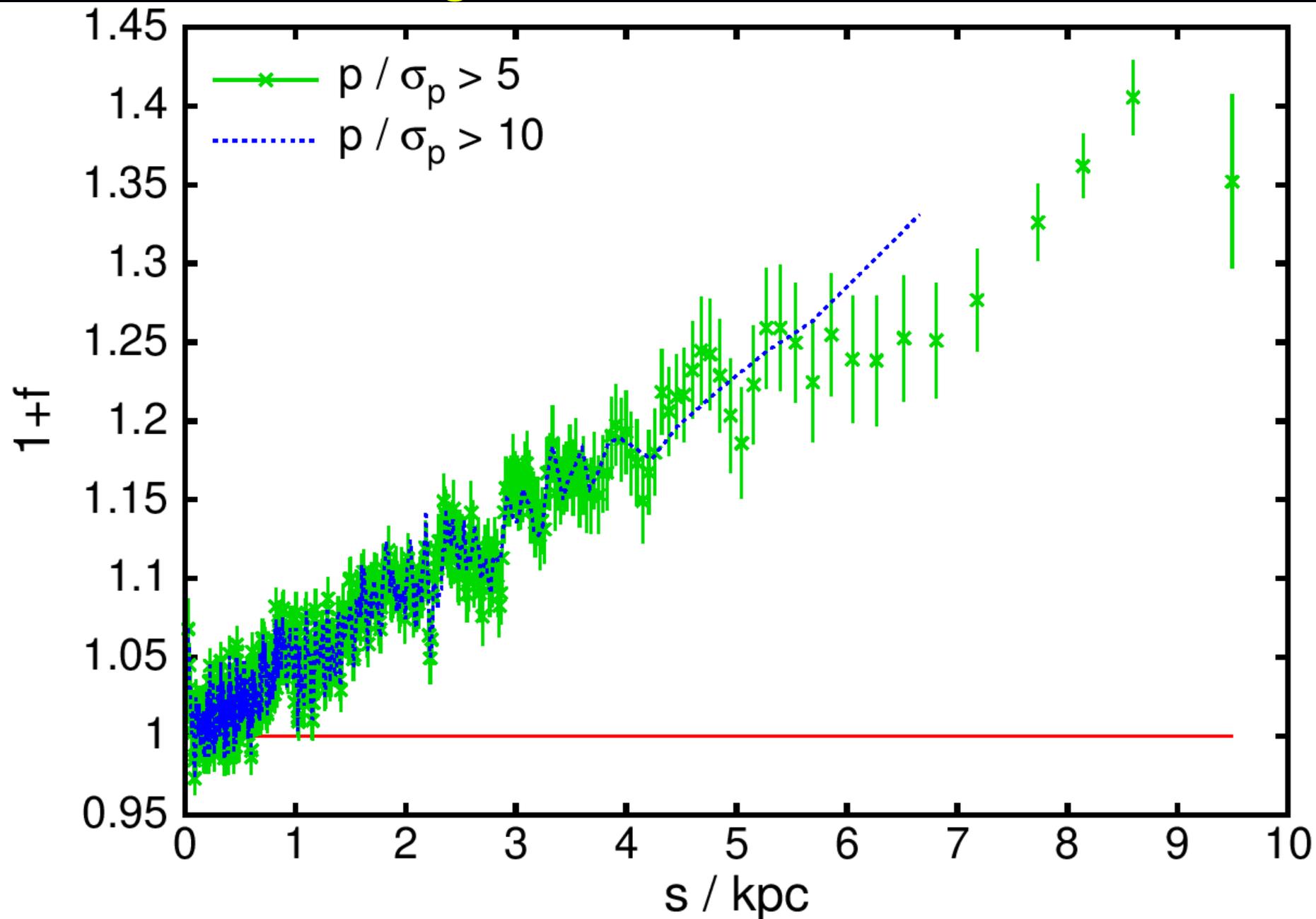
Plug this into distances

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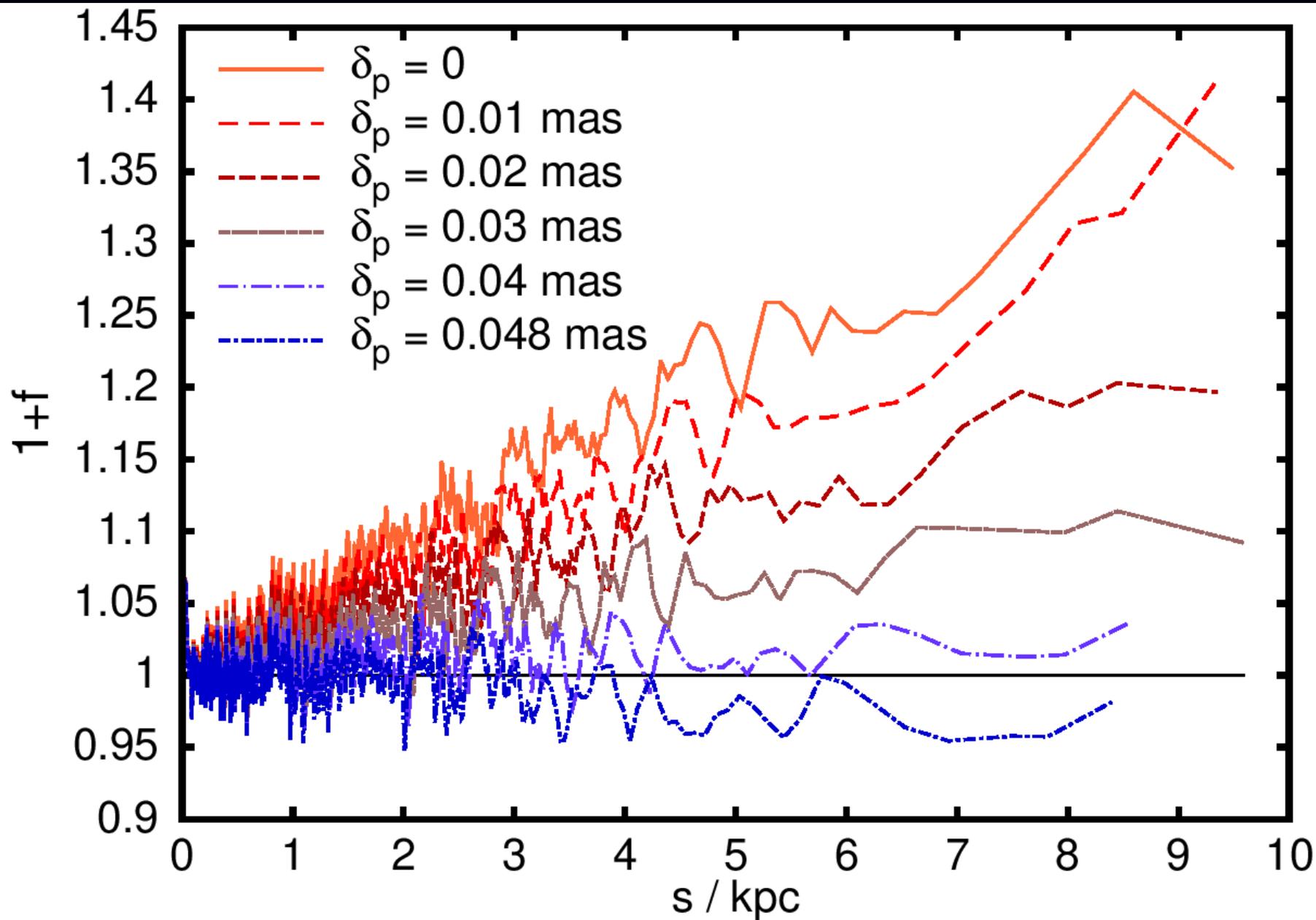




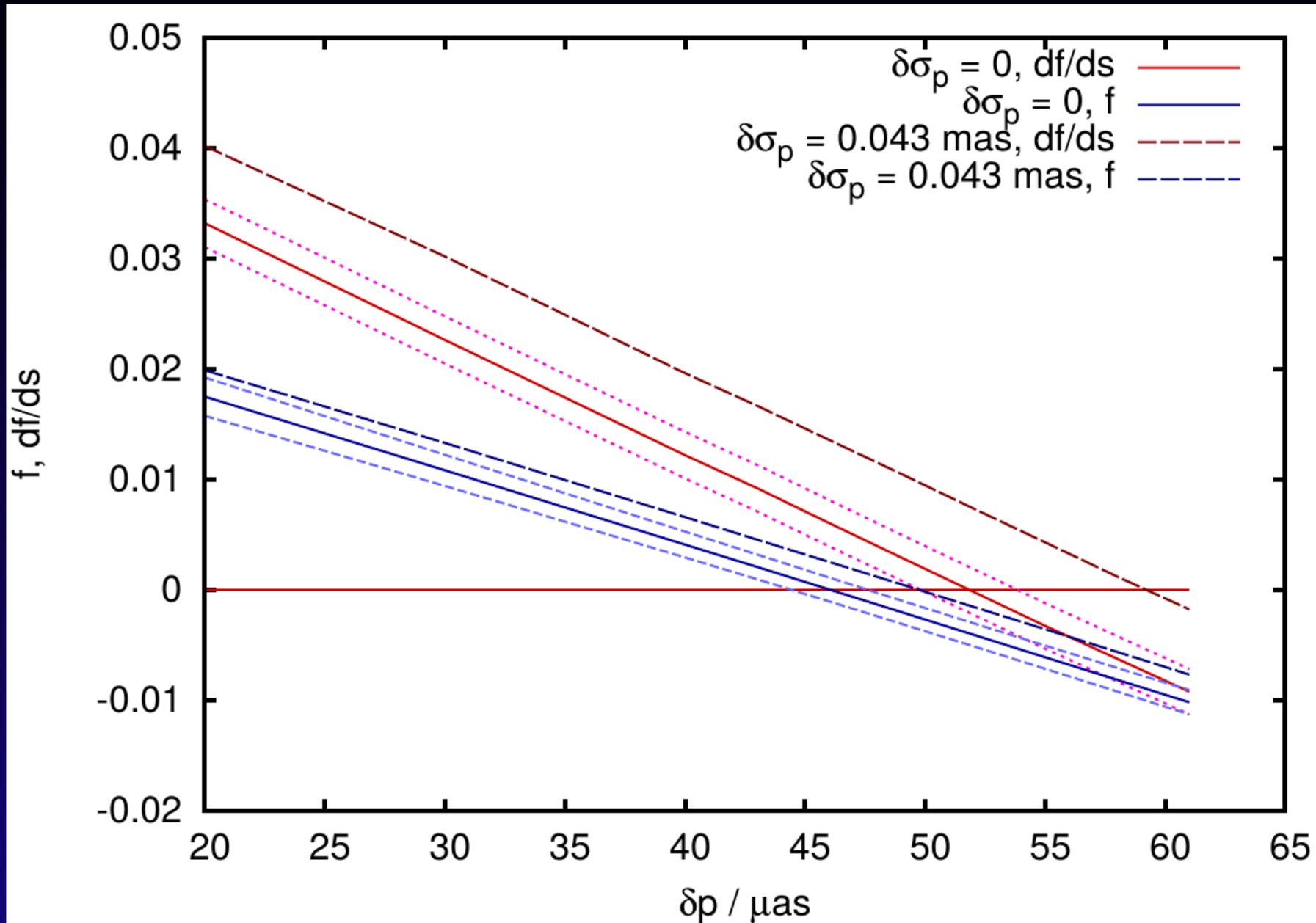
# Plug this into distances



# Parallax offset?



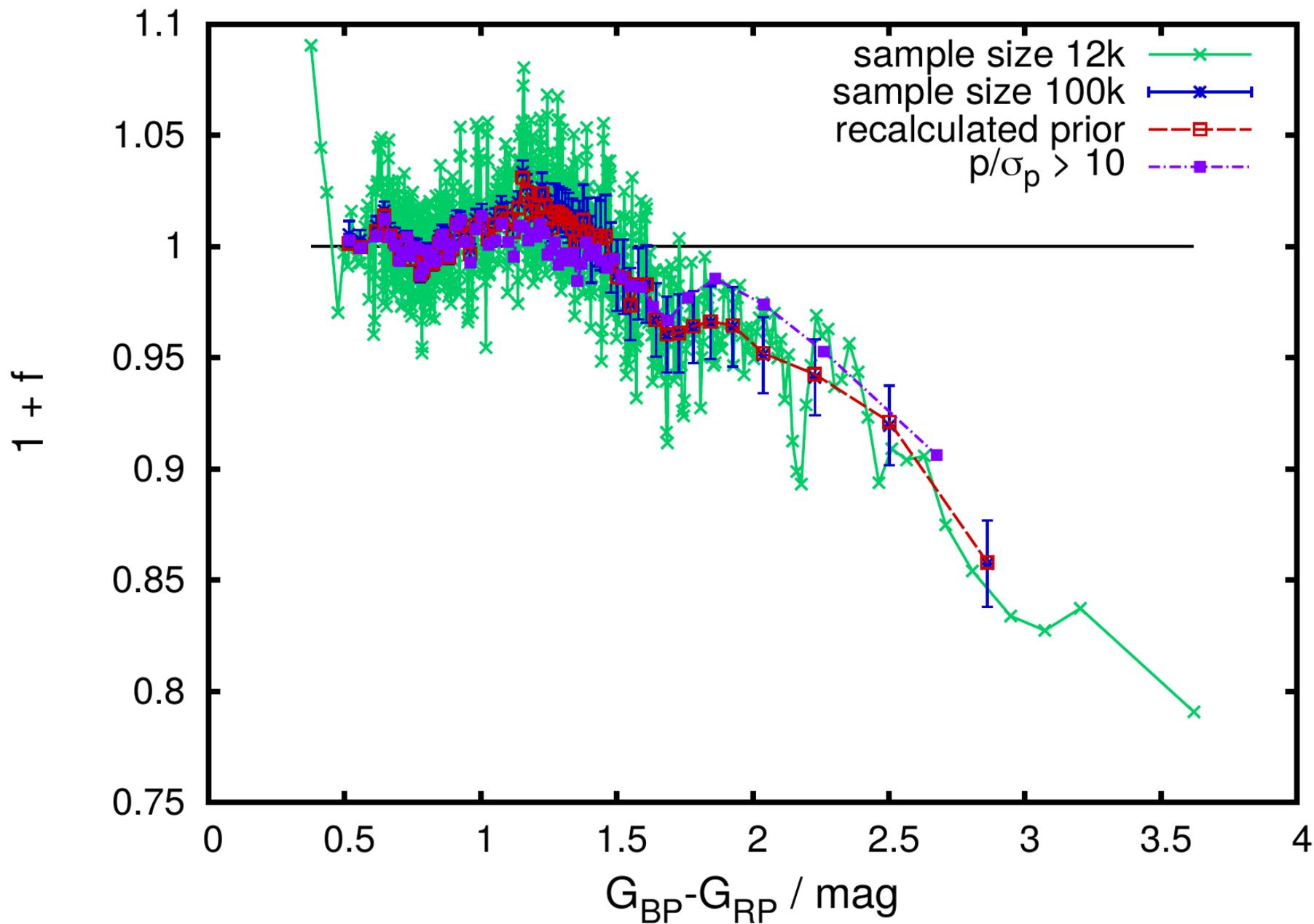
# Offset quantified



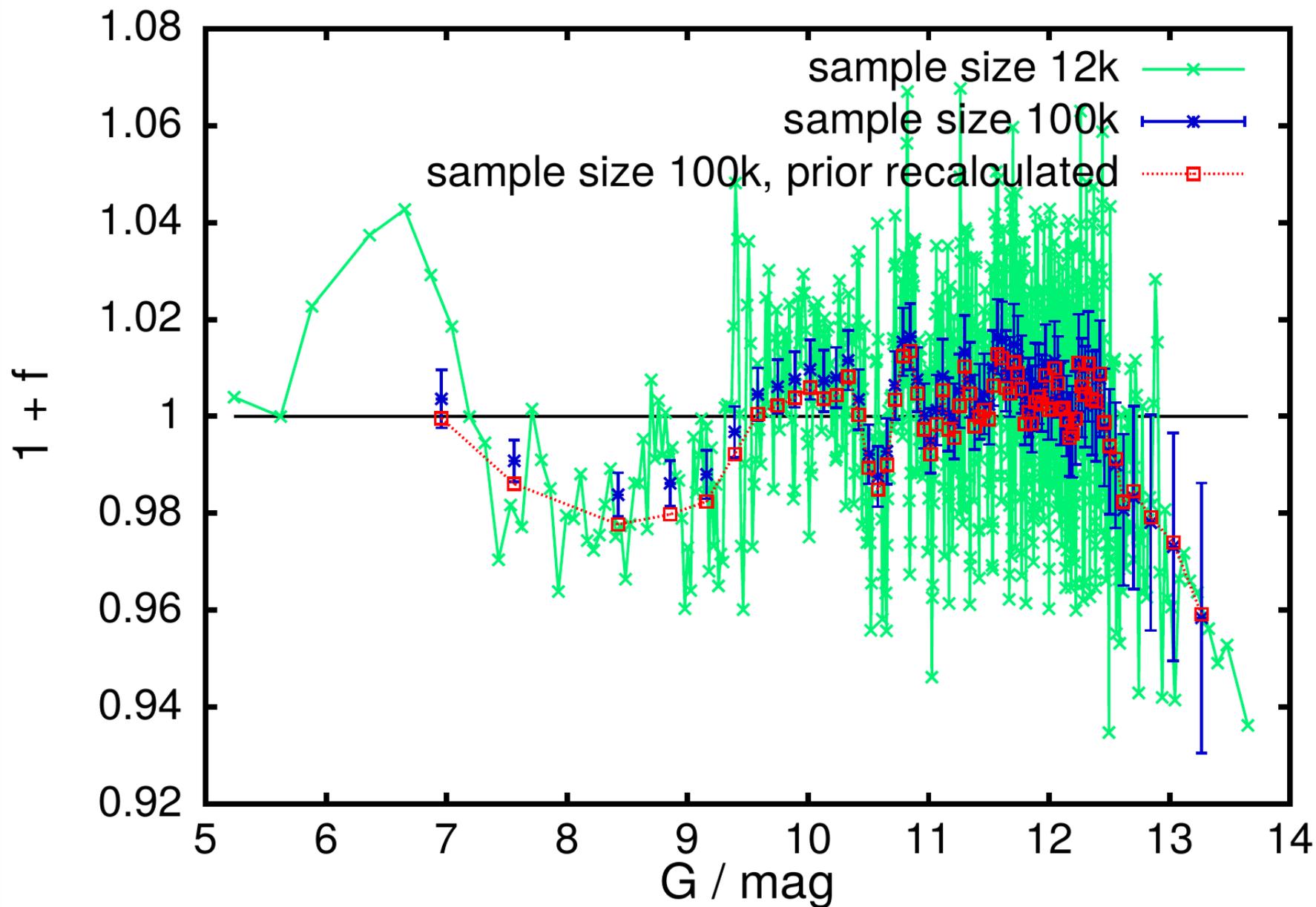
Is there more?

Is there more?

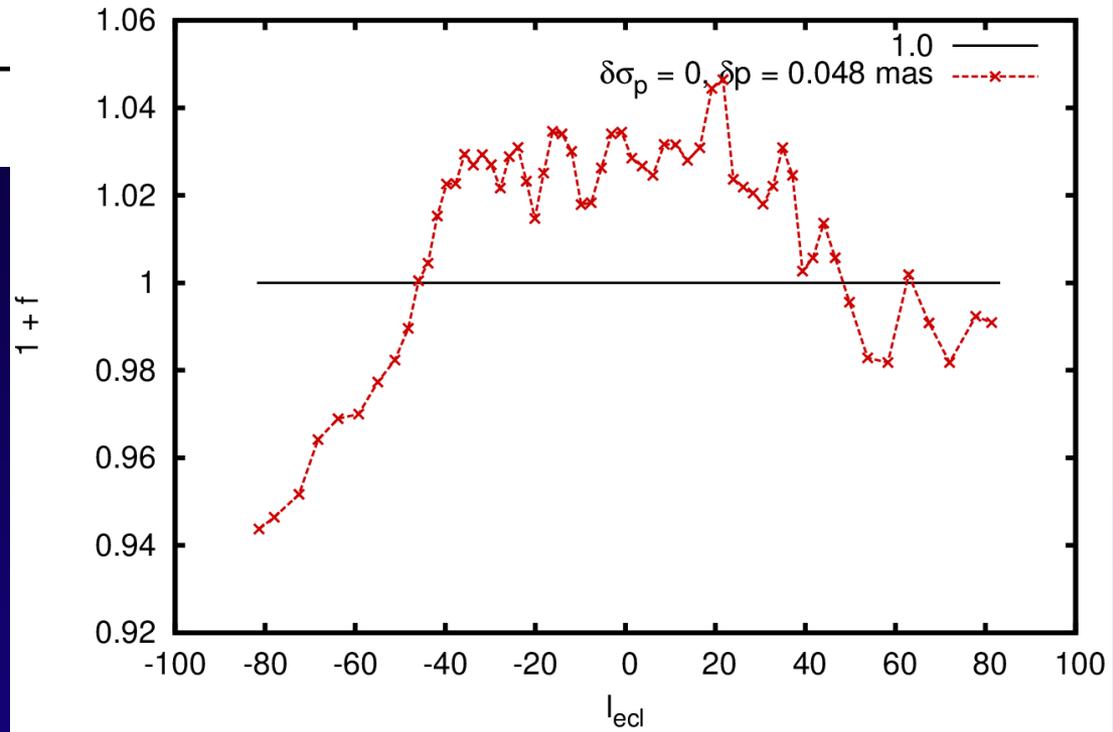
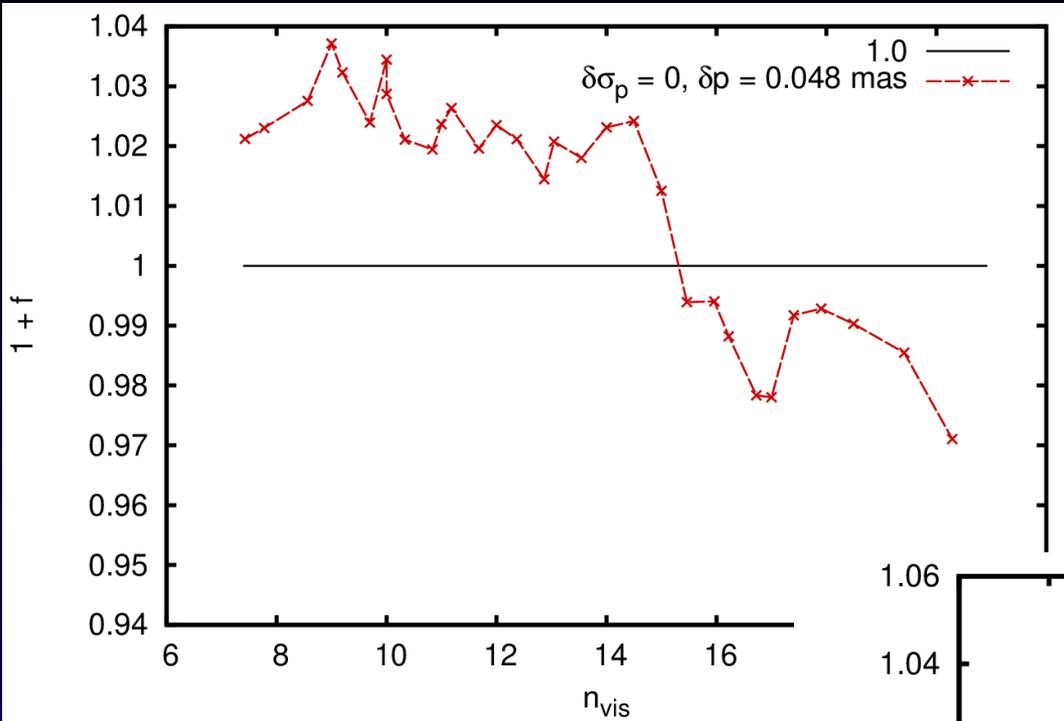
# Colour



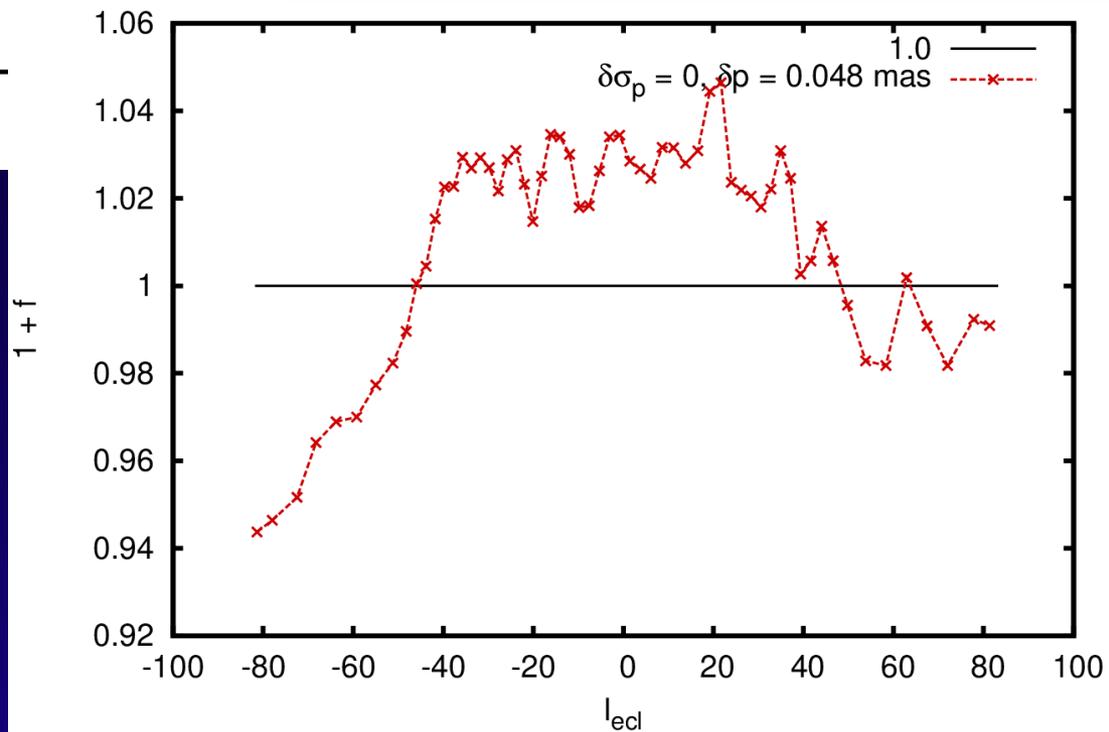
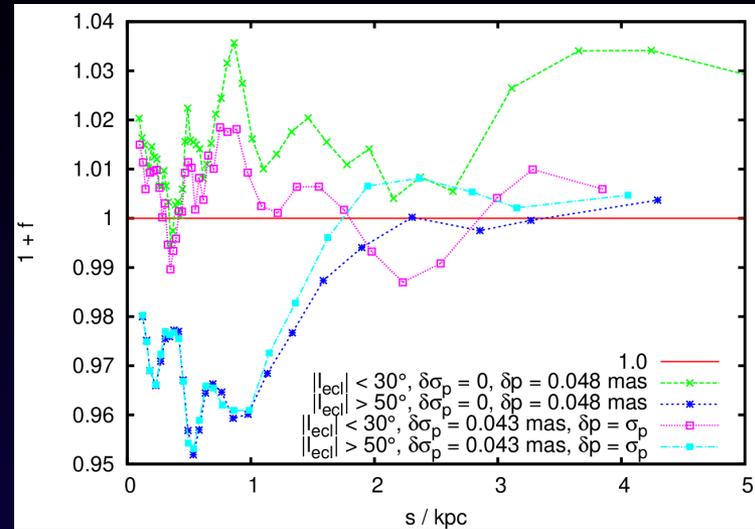
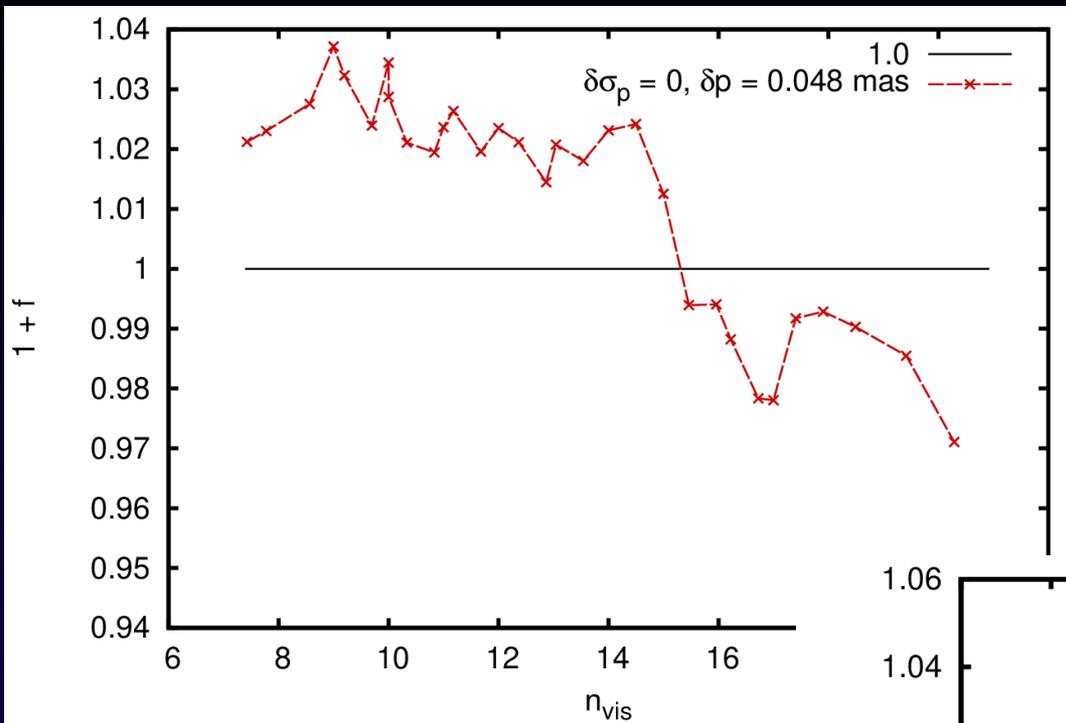
# Magnitudes



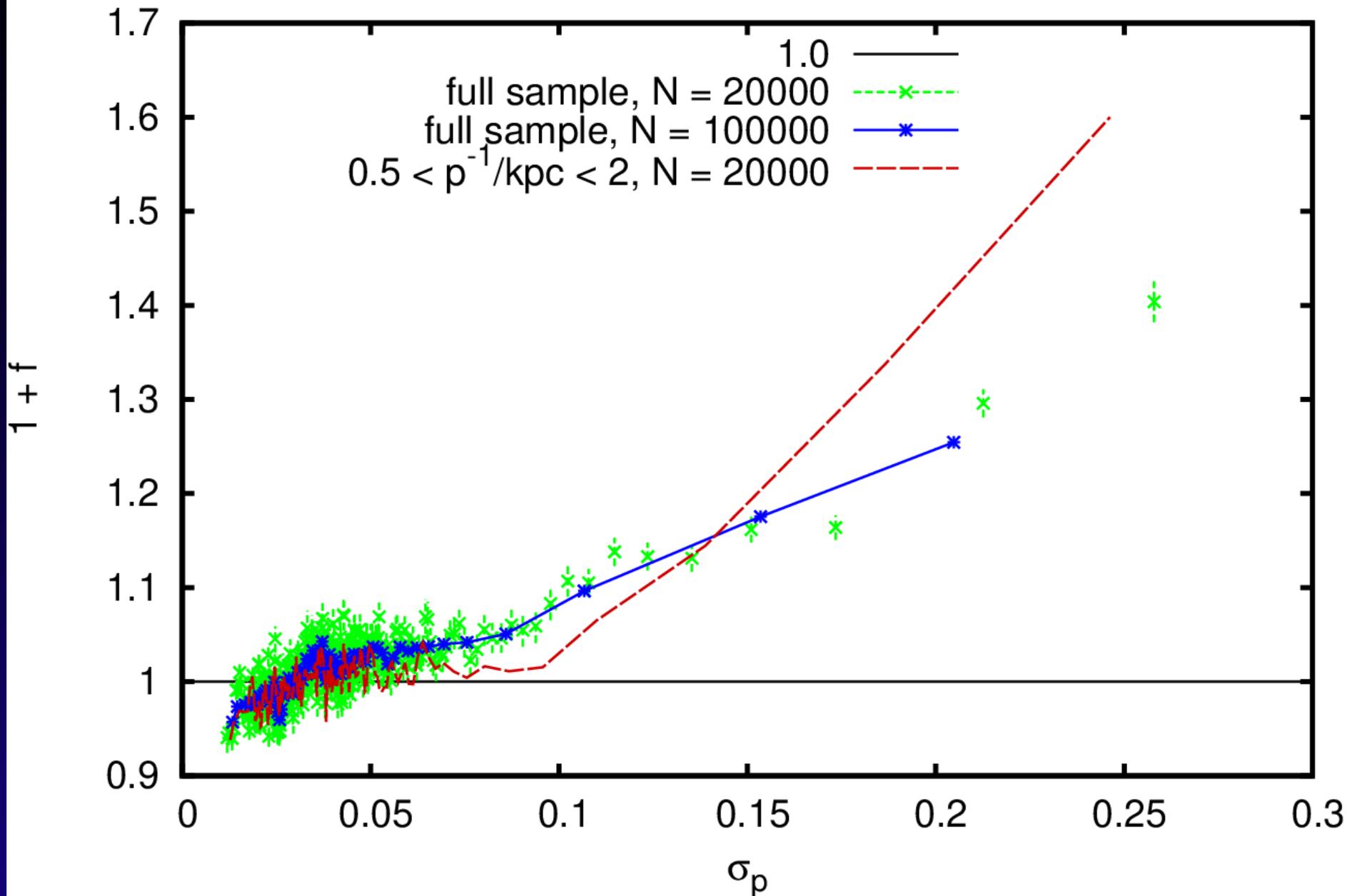
# Astrometric parameters



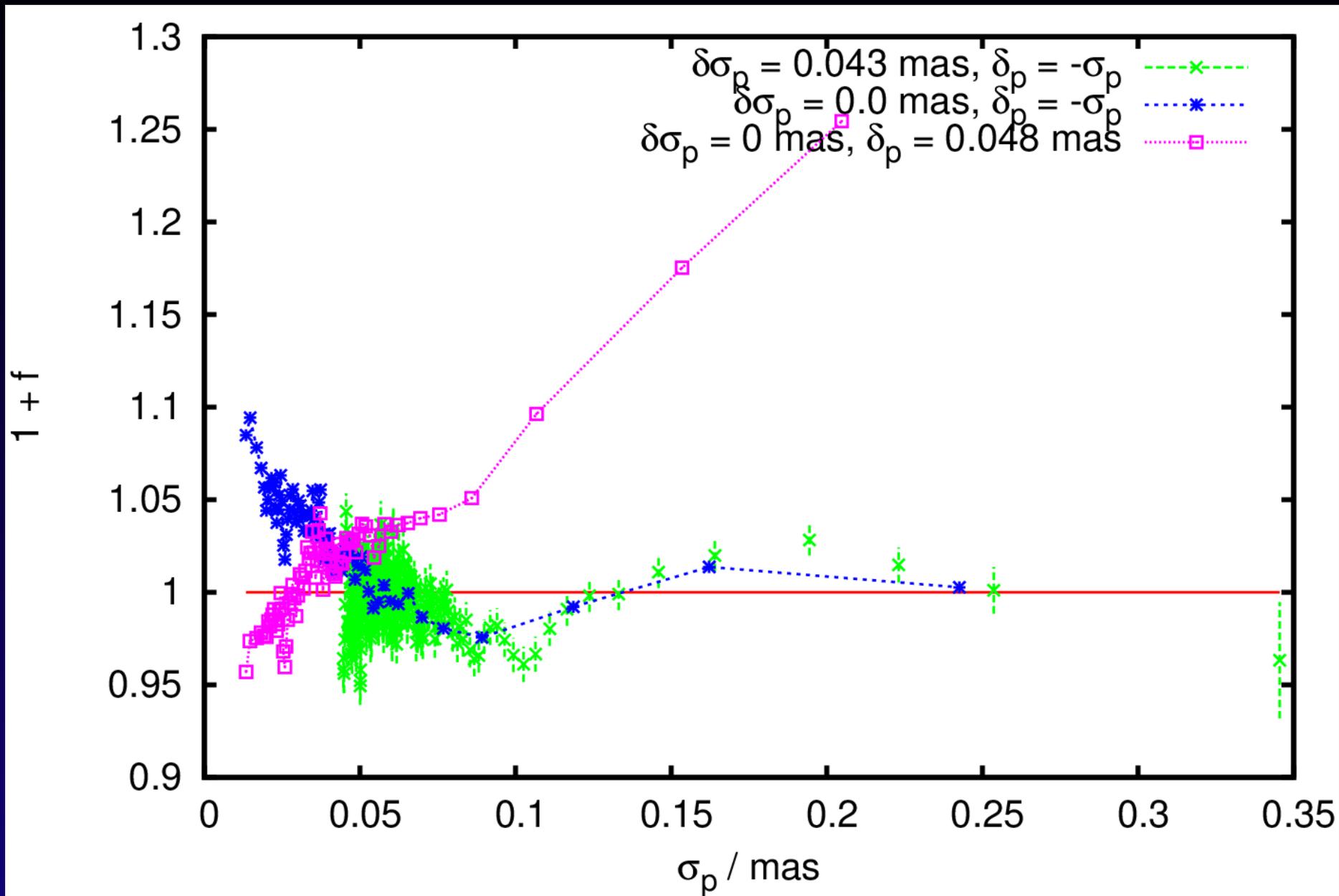
# Astrometric parameters



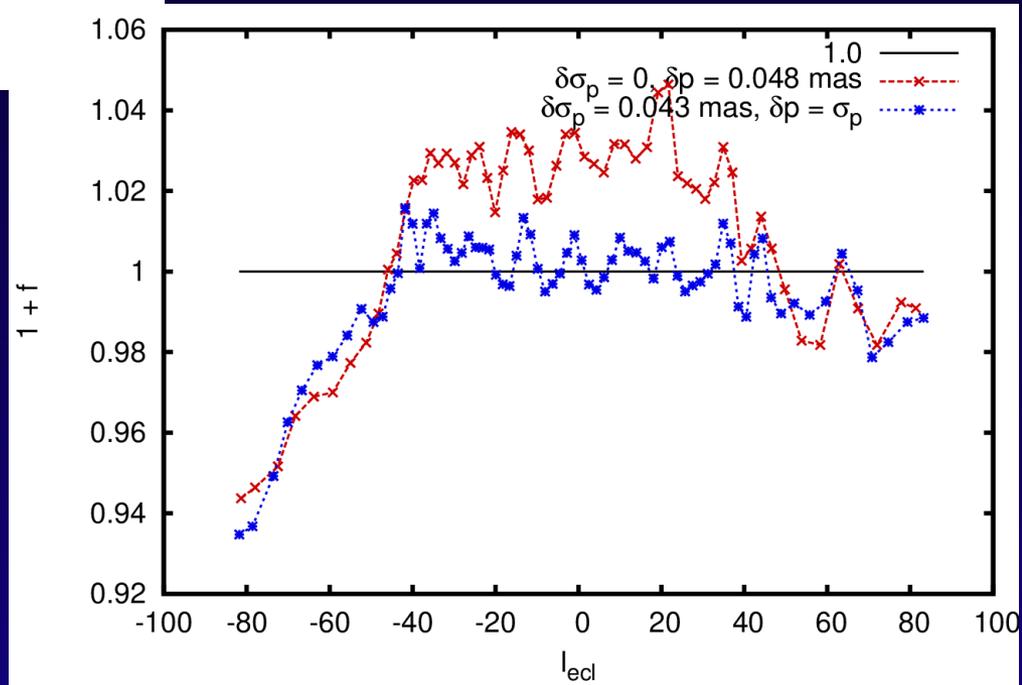
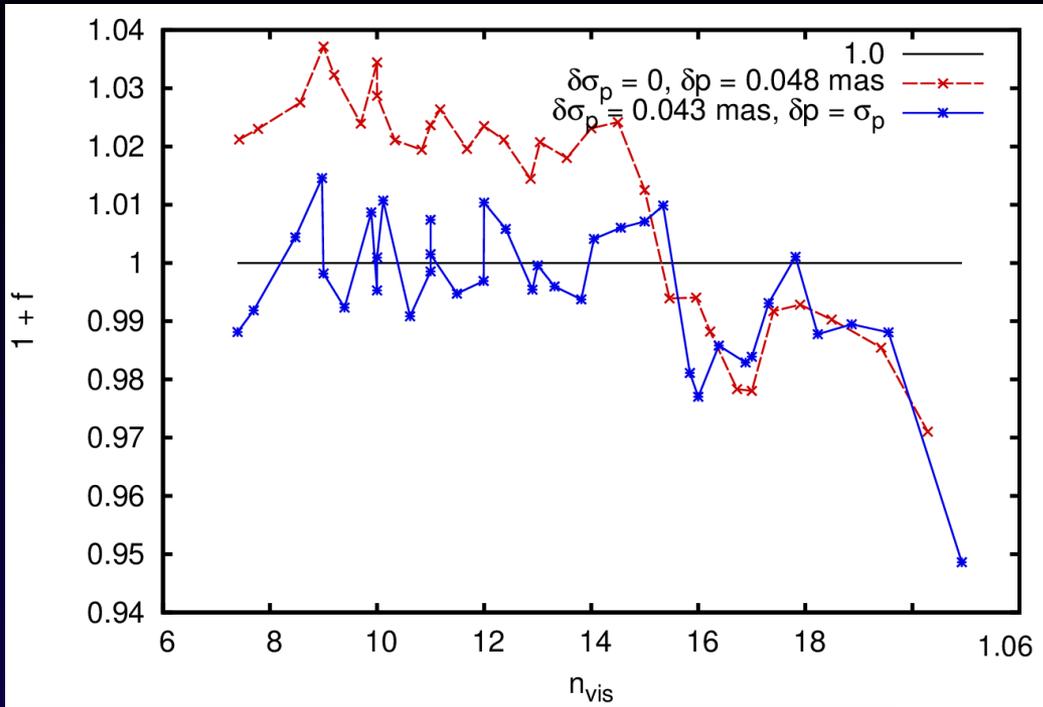
# Parallax quality



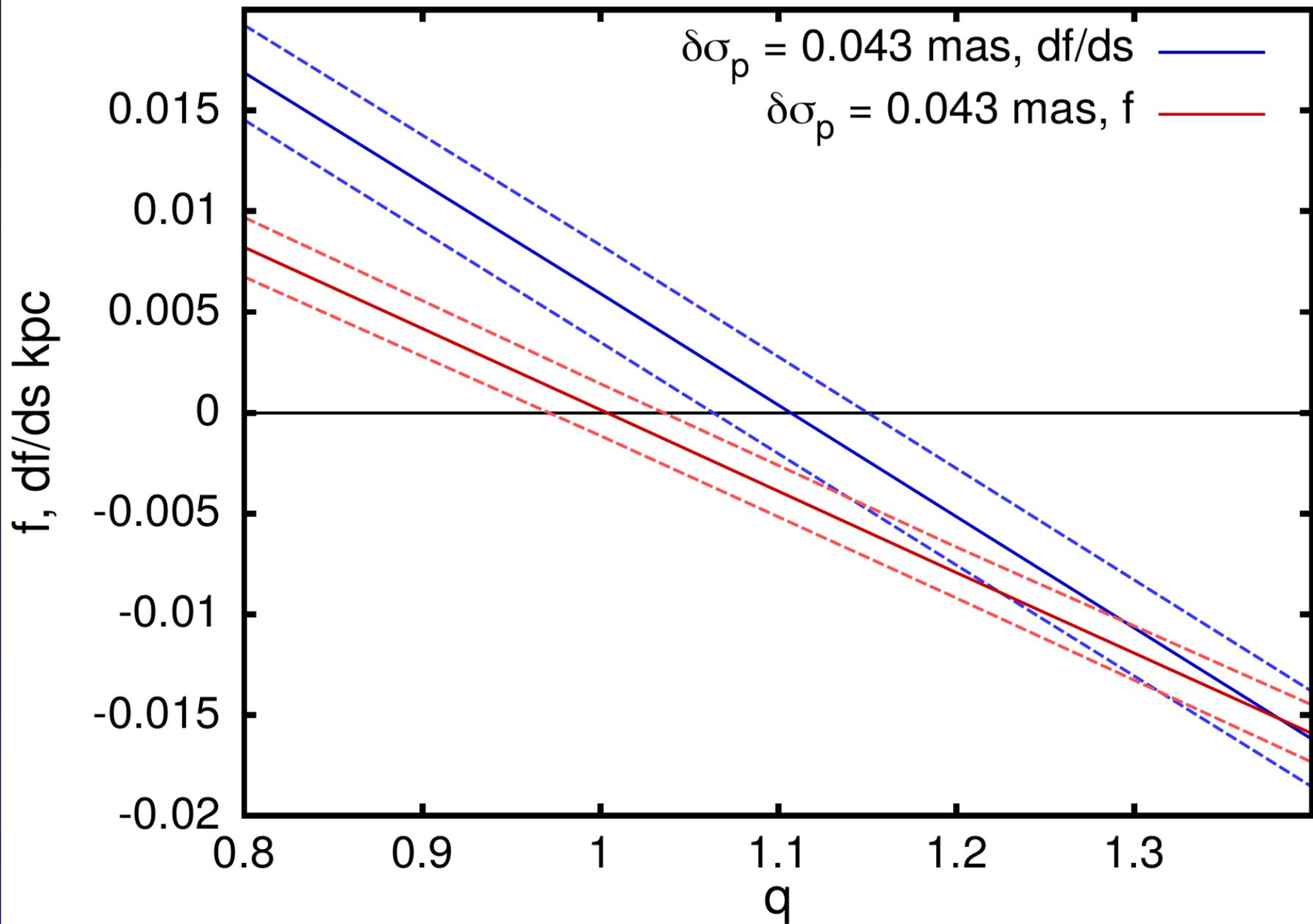
# Parallax error



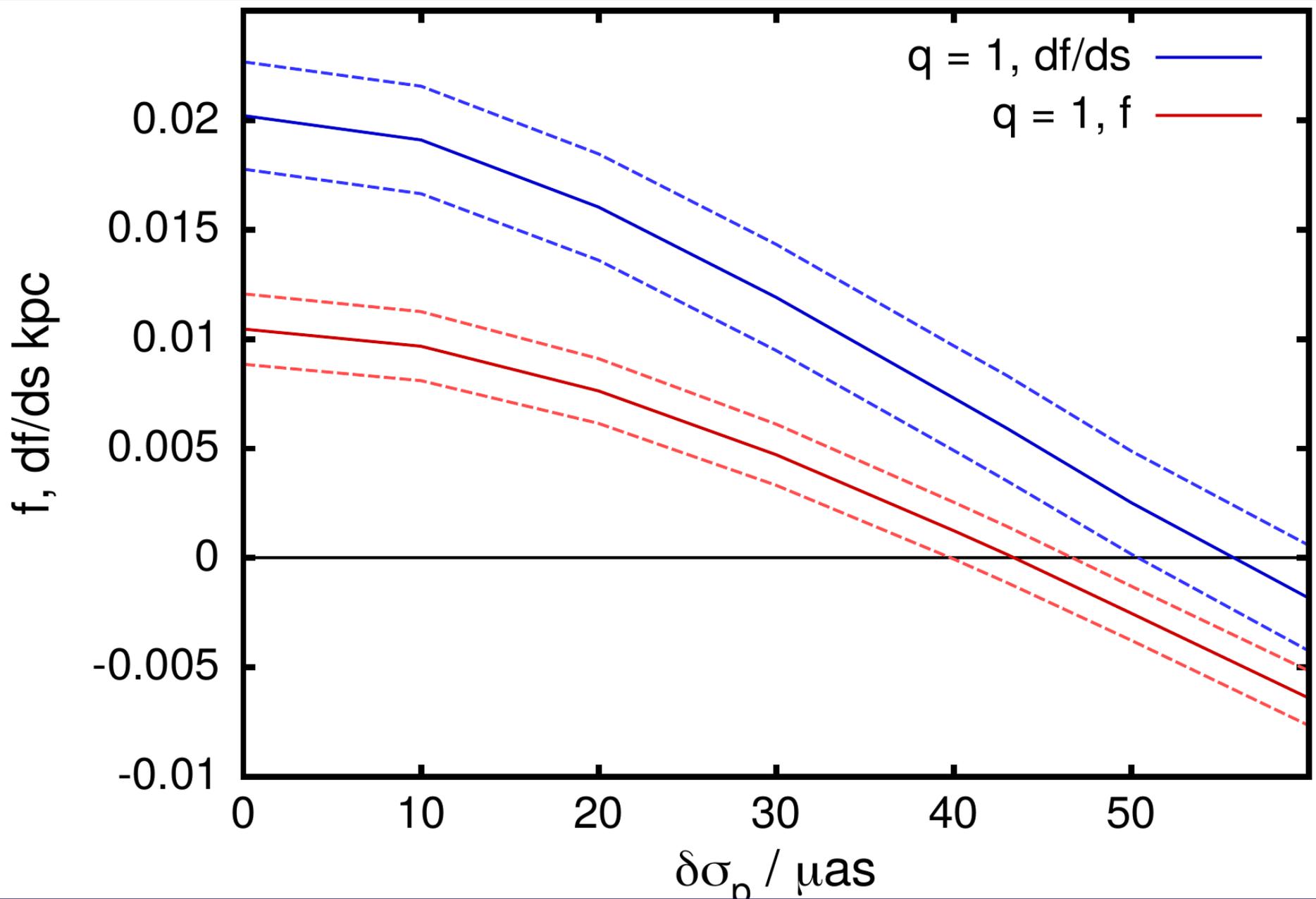
# Astrometric parameters



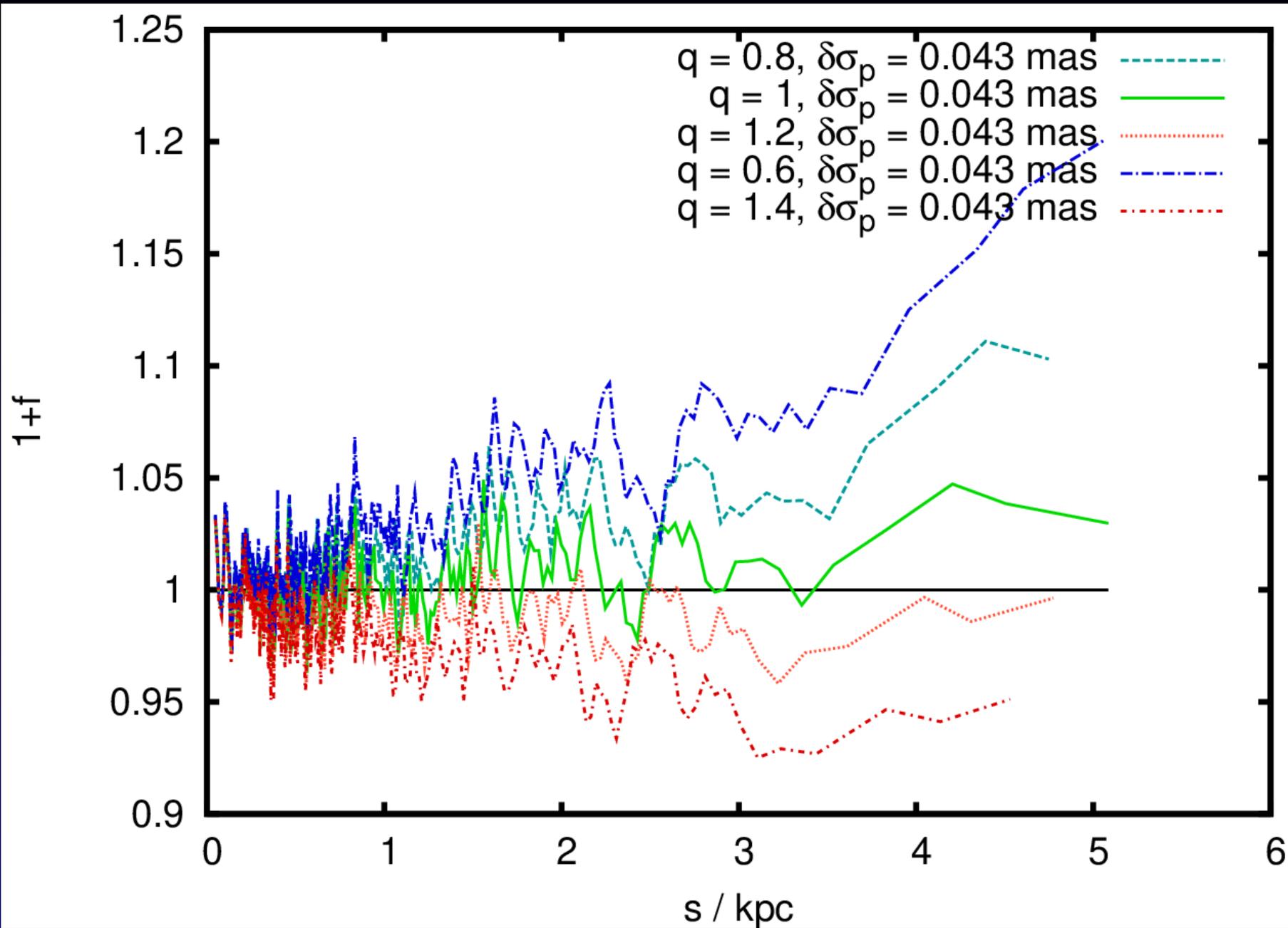
# Parallax bias quantified



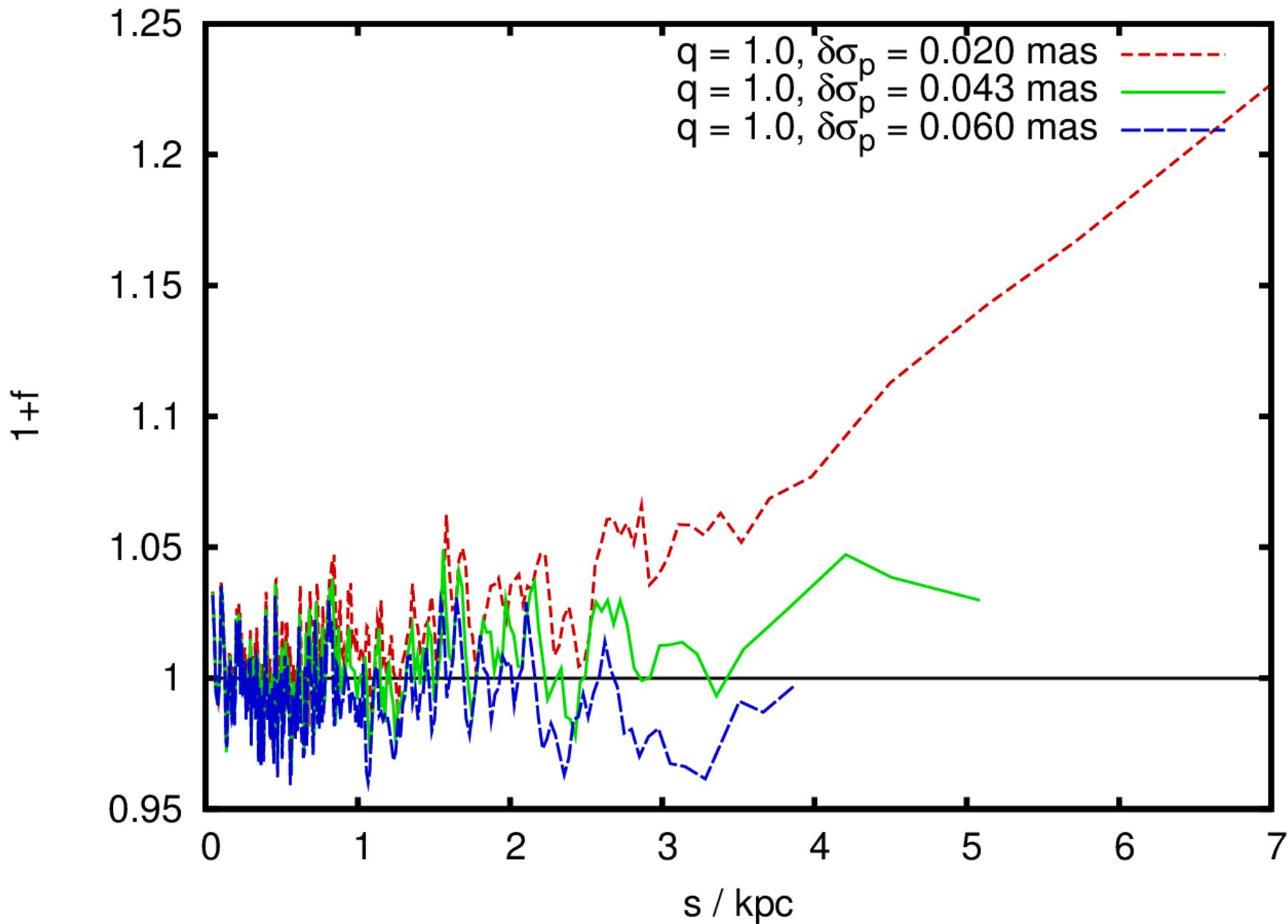
# Parallax error quantified



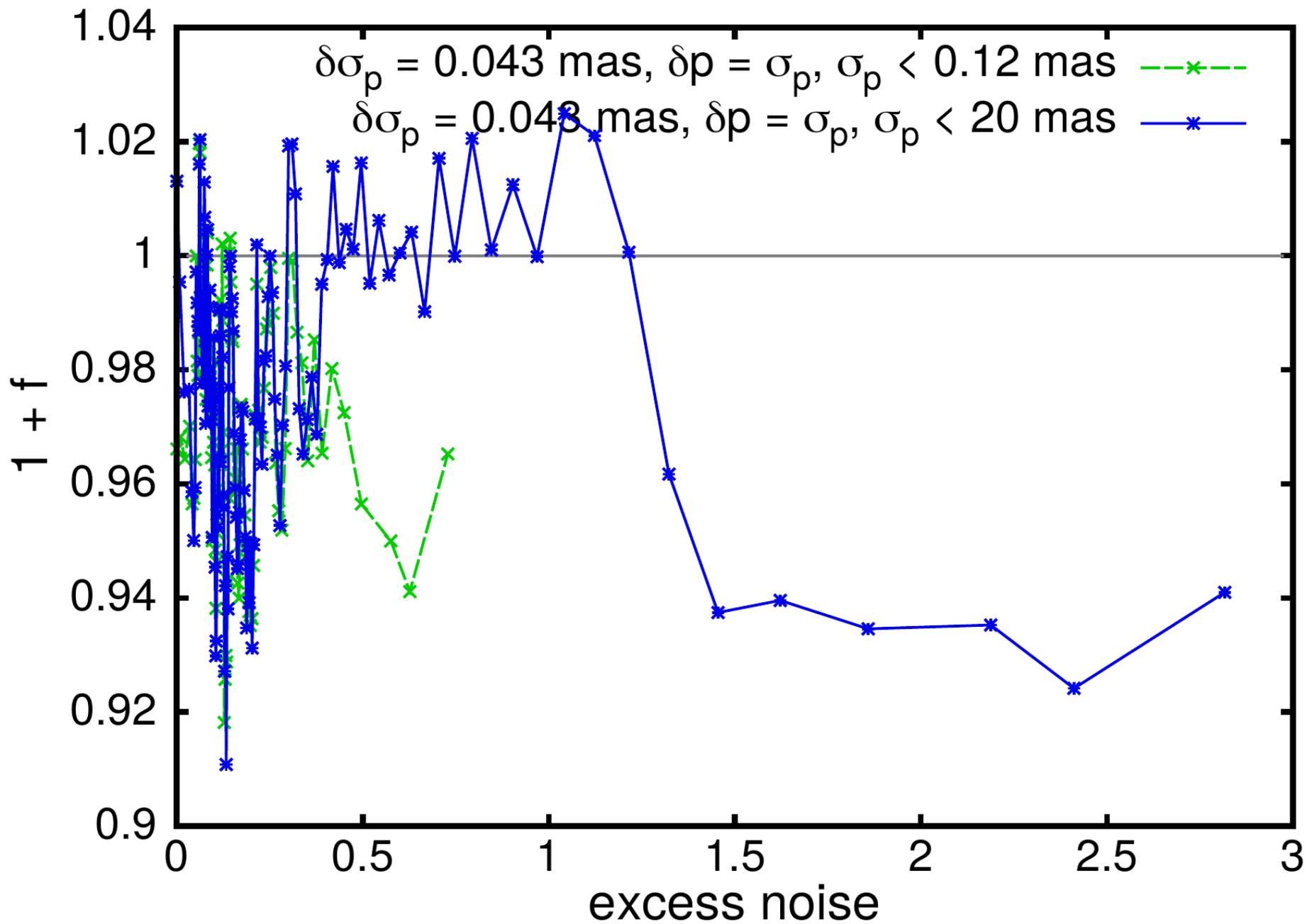
# Parallax error last look

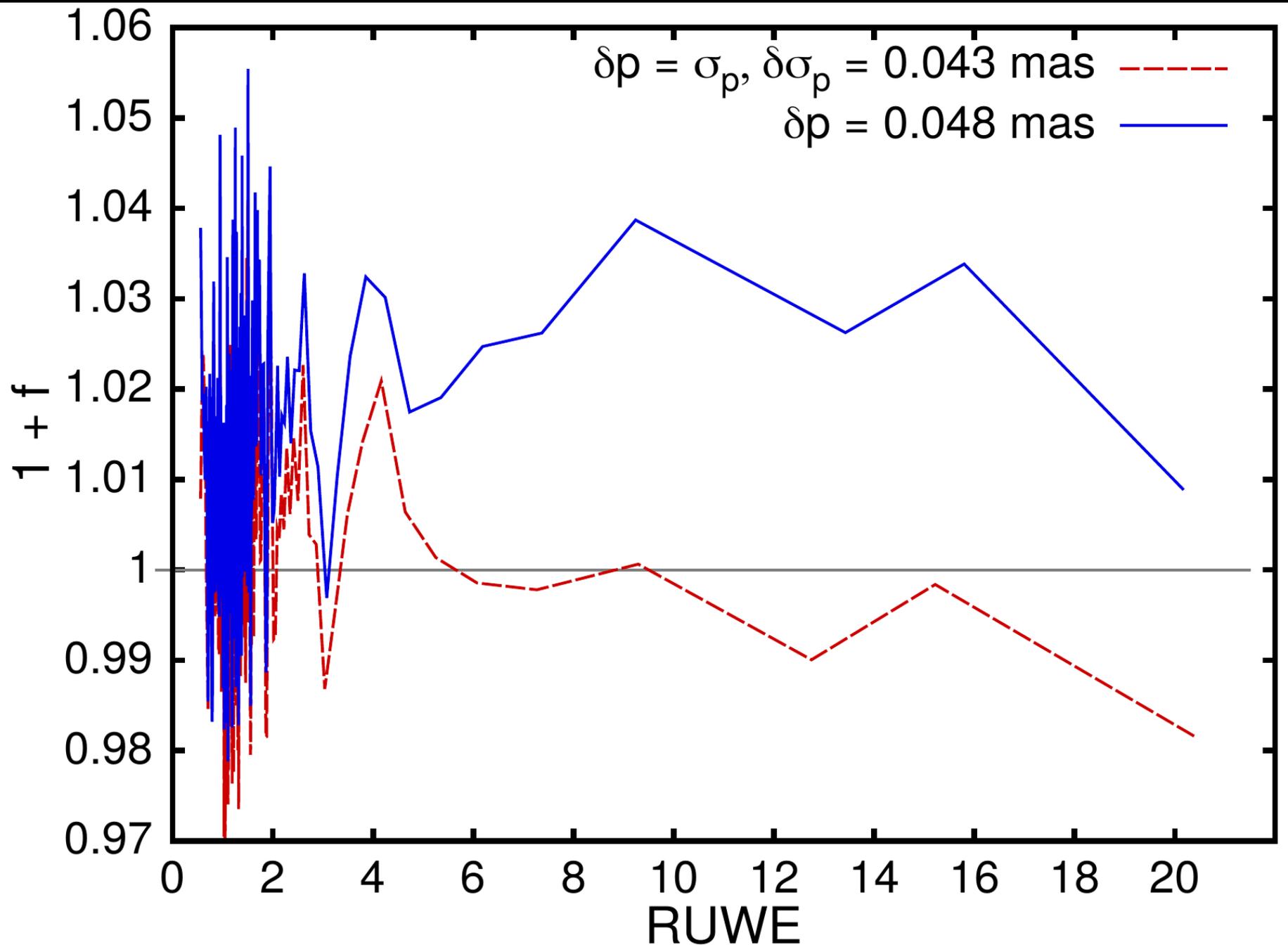


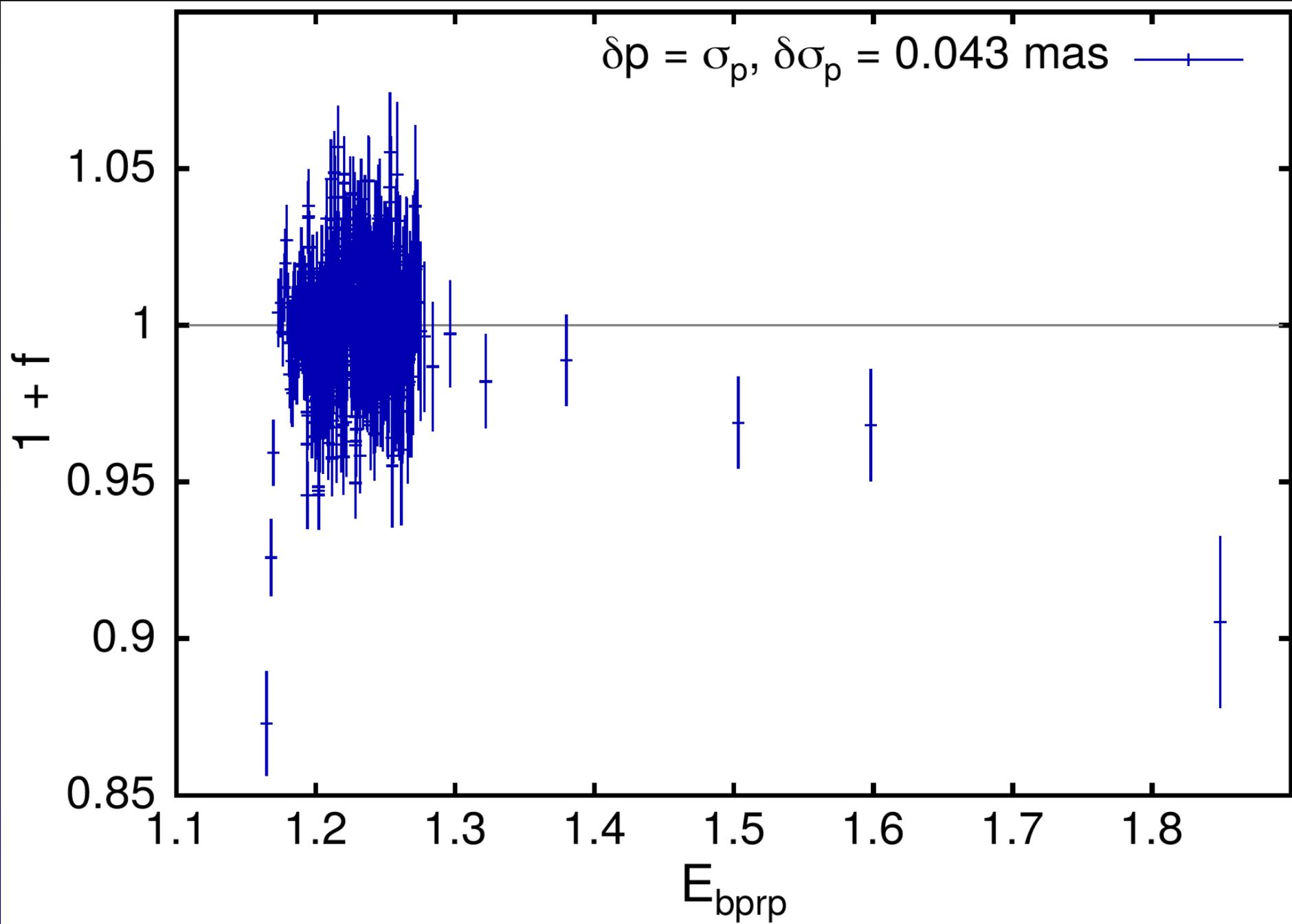
# Parallax error last look

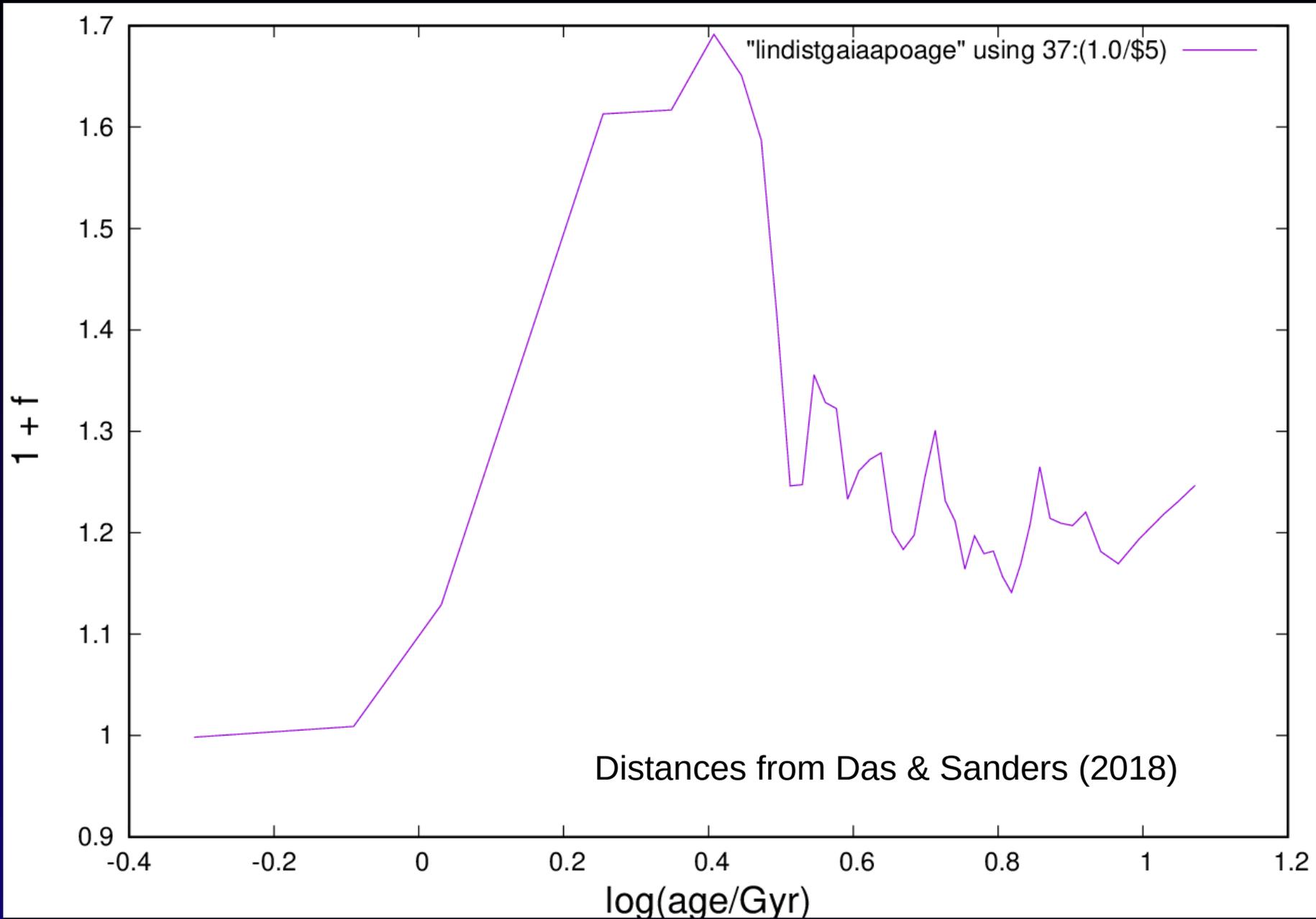


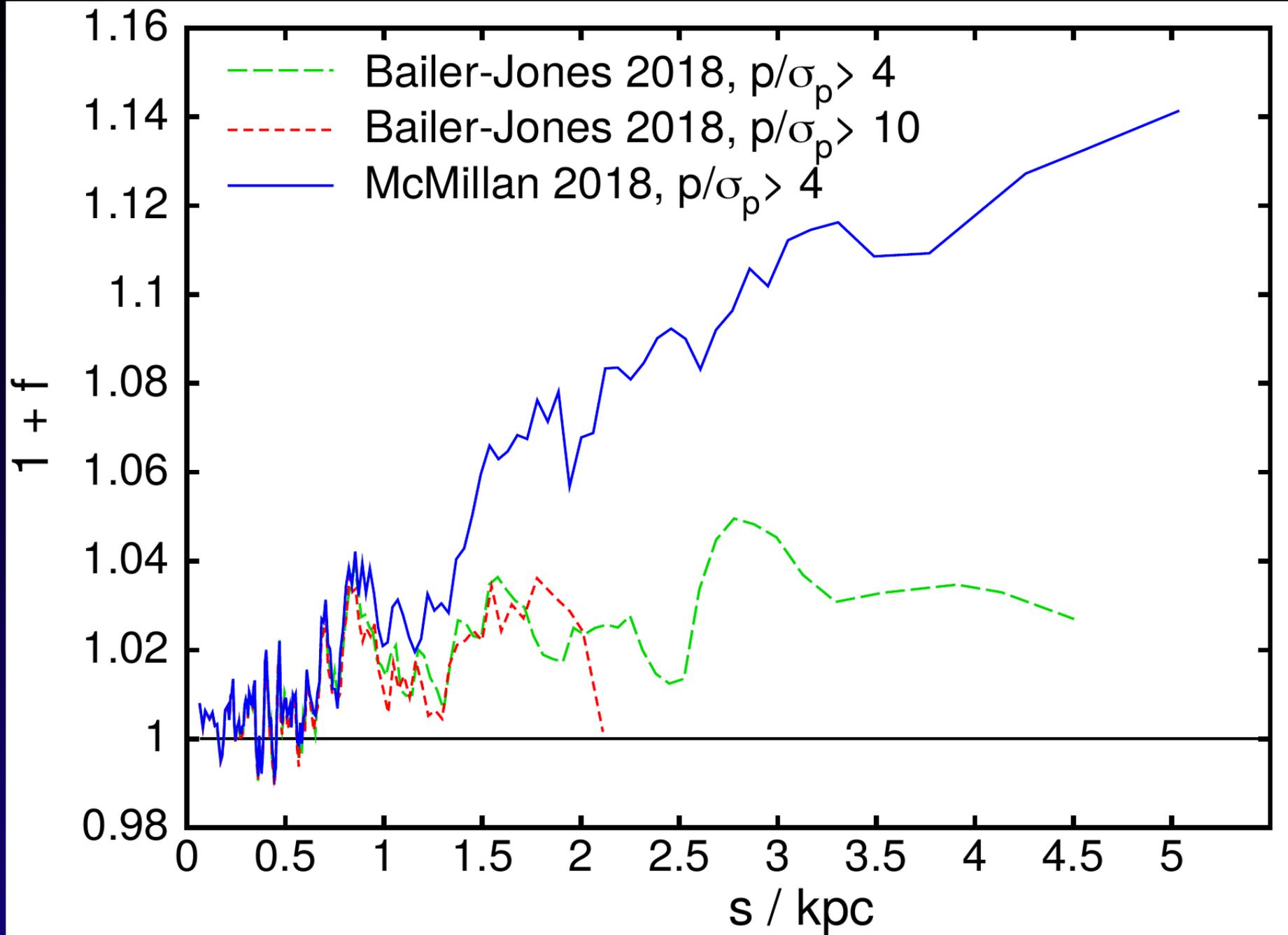
Gaia quality parameters?











# Quality cut suggestions

- A colour cut  $G_{\text{BP}} - G_{\text{RP}} < 1.5$  mag. To be entirely safe, we suggest  $0.5 < G_{\text{BP}} - G_{\text{RP}} / \text{mag} < 1.4$ .
- A magnitude cut for  $G < 14.5$  mag, and  $G_{\text{BP}}, G, G_{\text{RP}} > 0$ . A safer limit is  $G < 12.5$  mag and  $G_{\text{RP}} < 13.7$  mag.
- $p/\sigma_p > 4$ , safer is  $p/\sigma_p > 10$ .
- $\sigma_p < 0.1$  mas with  $\sigma_p$  as given by the Gaia pipeline, safer is  $\sigma_p < 0.07$  mas.
- $n_{\text{vis}} > 5$  as pointed out in [Lindegren et al. \(2018\)](#) and excess noise  $< 1$ .
- For the bp-rp excess noise factor, use  $1.172 < E_{\text{bprp}} < 1.3$ . Tighter cuts might apply if the number of outliers is important.
- $s > 80$  pc for studies that need assurance of distance systematics  $< 4\%$ . **BEWARE! This is for Gaia RV!**

# Summary

- Statistical distances demand line-of-sight velocities, proper motions and an initial distance estimate
- need to know observable uncertainties
- can get average distance bias down to  $\sim 1\%$  on all-sky sample
- the smaller the sky coverage, the larger the systematic uncertainties
- to calculate distances from parallaxes, you can use a self-informed prior for unbiased results
- code online – follow S & Aumer (2017), or for newer code → S, McMillan & Eyer (2019) (or best: ask me, I'll help)
- you should run this for every subsample you use!