Gaia DR2 and the Hubble Constant

Victor Chan & Jo Bovy

Manuscript *in prep*

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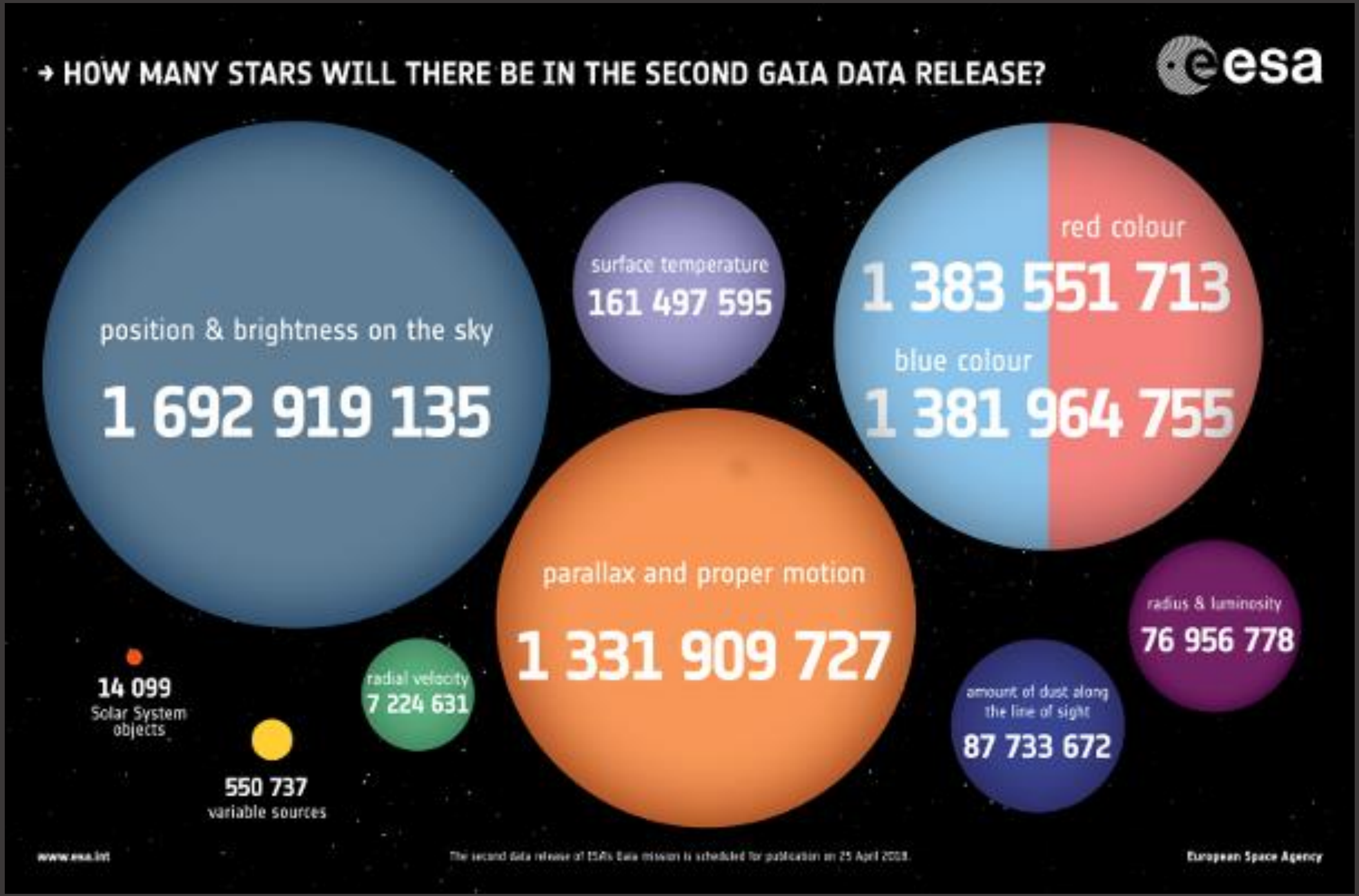
KITP – Tensions between Early & Late Universe

Astronomy & Astrophysics
UNIVERSITY OF TORONTO

Gaia is a fantastic resource!



Courtesy of ESA

… but the parallaxes are a bit too small

Lindegren++ 2018; *Gaia* Data Release 2: The Astrometric Solution

Results. For the sources with five-parameter astrometric solutions, the median uncertainty in parallax and position at the reference epoch J2015.5 is about 0.04 mas for bright ($G < 14$ mag) sources, 0.1 mas at $G = 17$ mag, and 0.7 mas at $G = 20$ mag. In the proper motion components the corresponding uncertainties are 0.05, 0.2, and 1.2 mas yr^{-1}, respectively. The optical reference frame defined by *Gaia* DR2 is aligned with ICRS and is non-rotating with respect to the quasars to within 0.15 mas yr^{-1}. From the quasars and validation solutions we estimate that systematics in the parallaxes depending on position, magnitude, and colour are generally below 0.1 mas, but the parallaxes are on the whole too small by about 0.03 mas. Significant spatial correlations of up to 0.04 mas in parallax and 0.07 mas yr^{-1} in proper motion are seen on small (<1 deg) and intermediate (20 deg) angular scales. Important statistics and information for the users of the *Gaia* DR2 astrometry are given in the appendices.

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Riess++ 2018; 2018ApJ...861..126R

of 5 millimags per observation. We use the new *Gaia* DR2 parallaxes and *HST* photometry to simultaneously constrain the cosmic distance scale and to measure the DR2 parallax zeropoint offset appropriate for Cepheids. We find the latter to be $-46 \pm 13\,\mu$as or $\pm$ 6 μas for a fixed distance scale, higher than found from quasars, as expected, for these brighter and redder sources. The precision of

The offset varies with magnitude, colour

Khan++ 2019; 2019gaia.confE..13K

−52 and −48 μas for RGB and RC stars, respectively. The trends with G are also relatively flat, resulting in small fluctuations as we move from low to high G magnitudes: from −58 to −51 μas for stars on the RGB, and from −46 to −52 μas in the clump.

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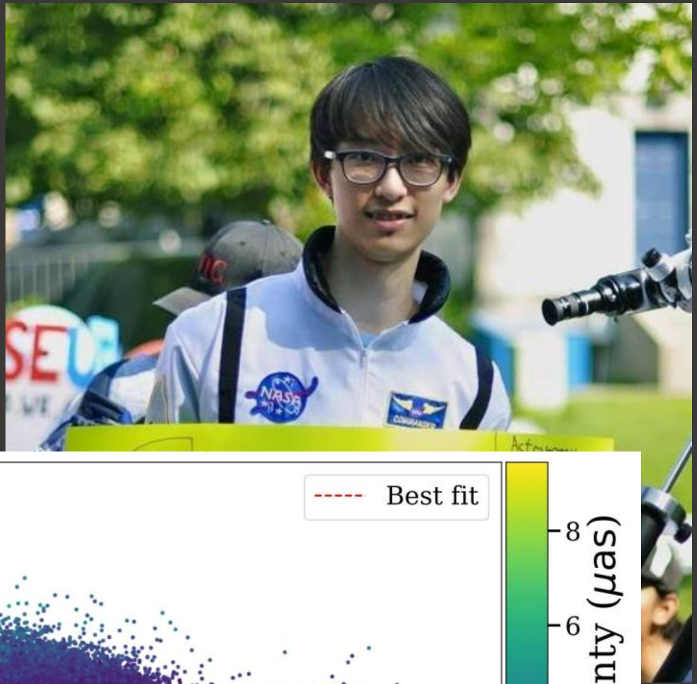
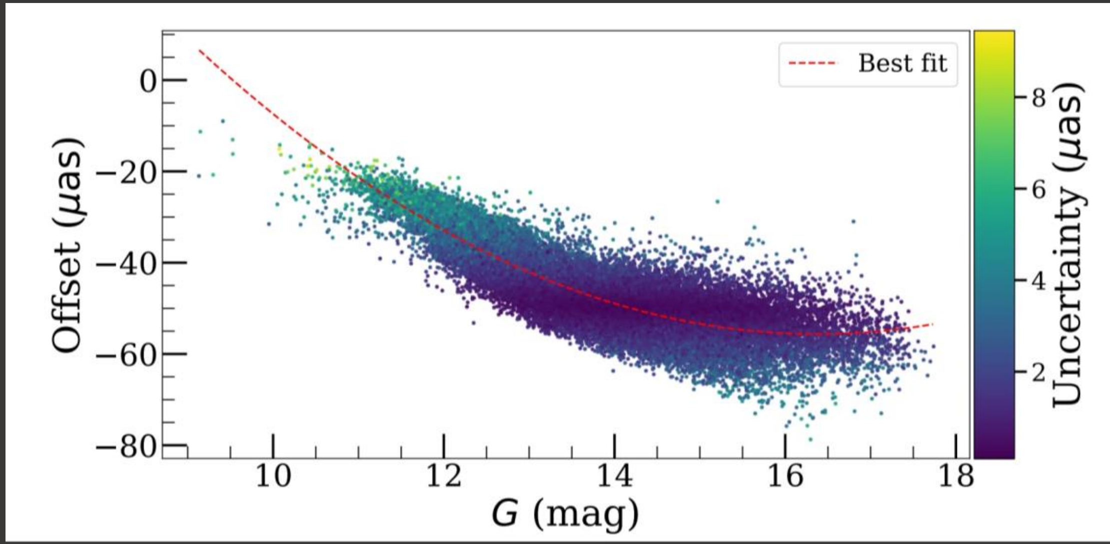
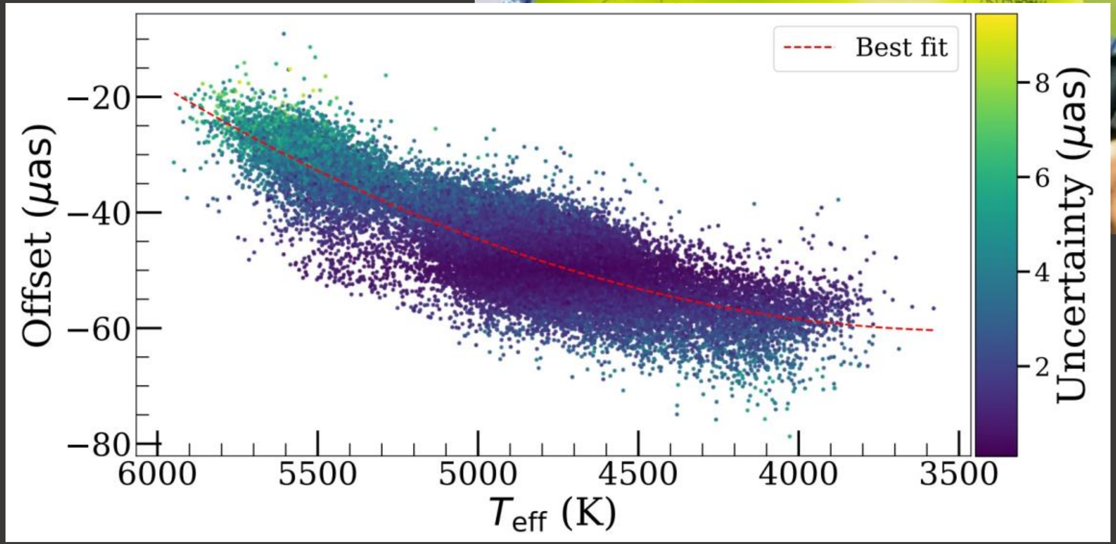


Leung & Bovy 2019; arXiv:1902.08634 (Submitted to MNRAS)





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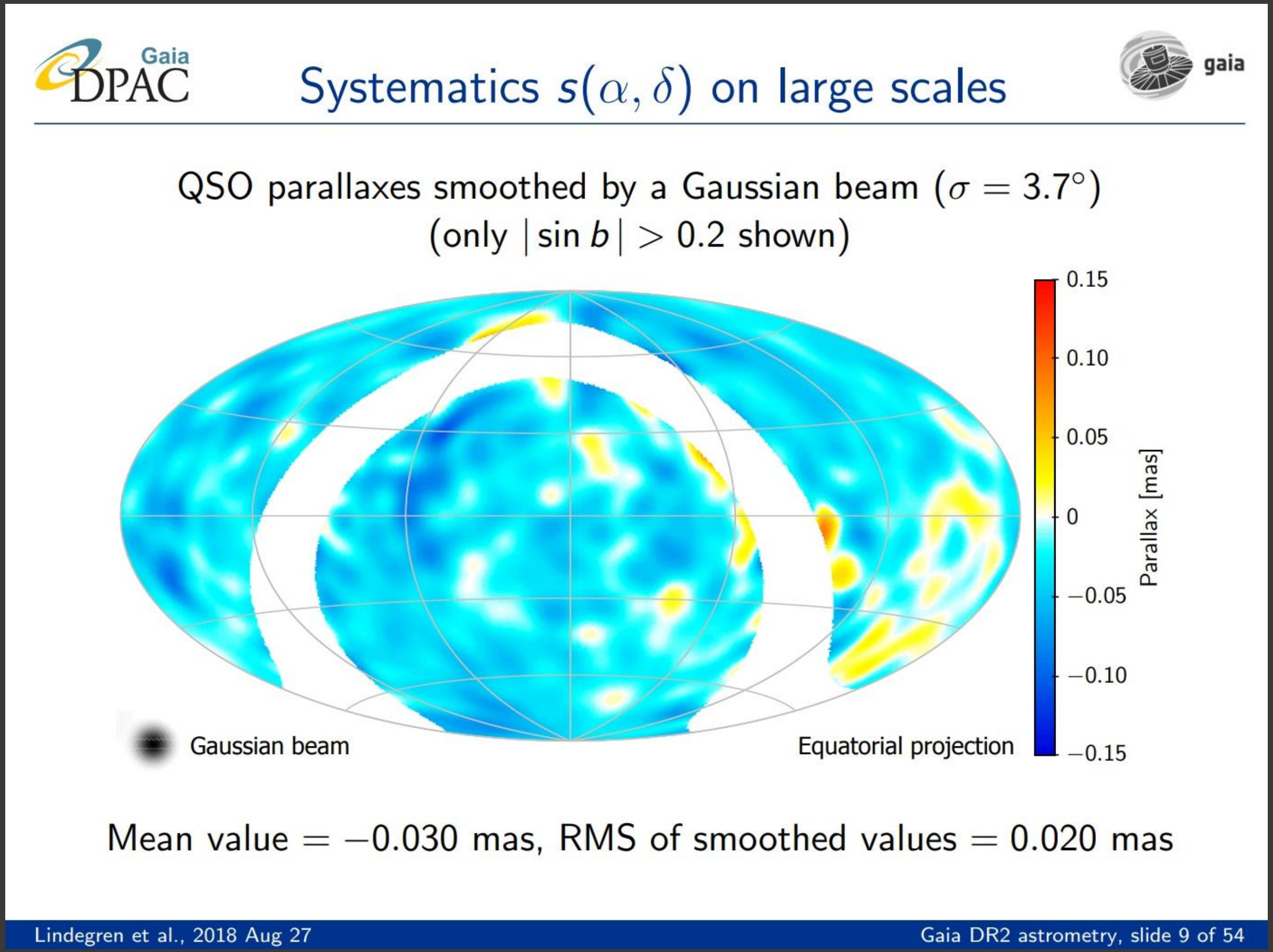
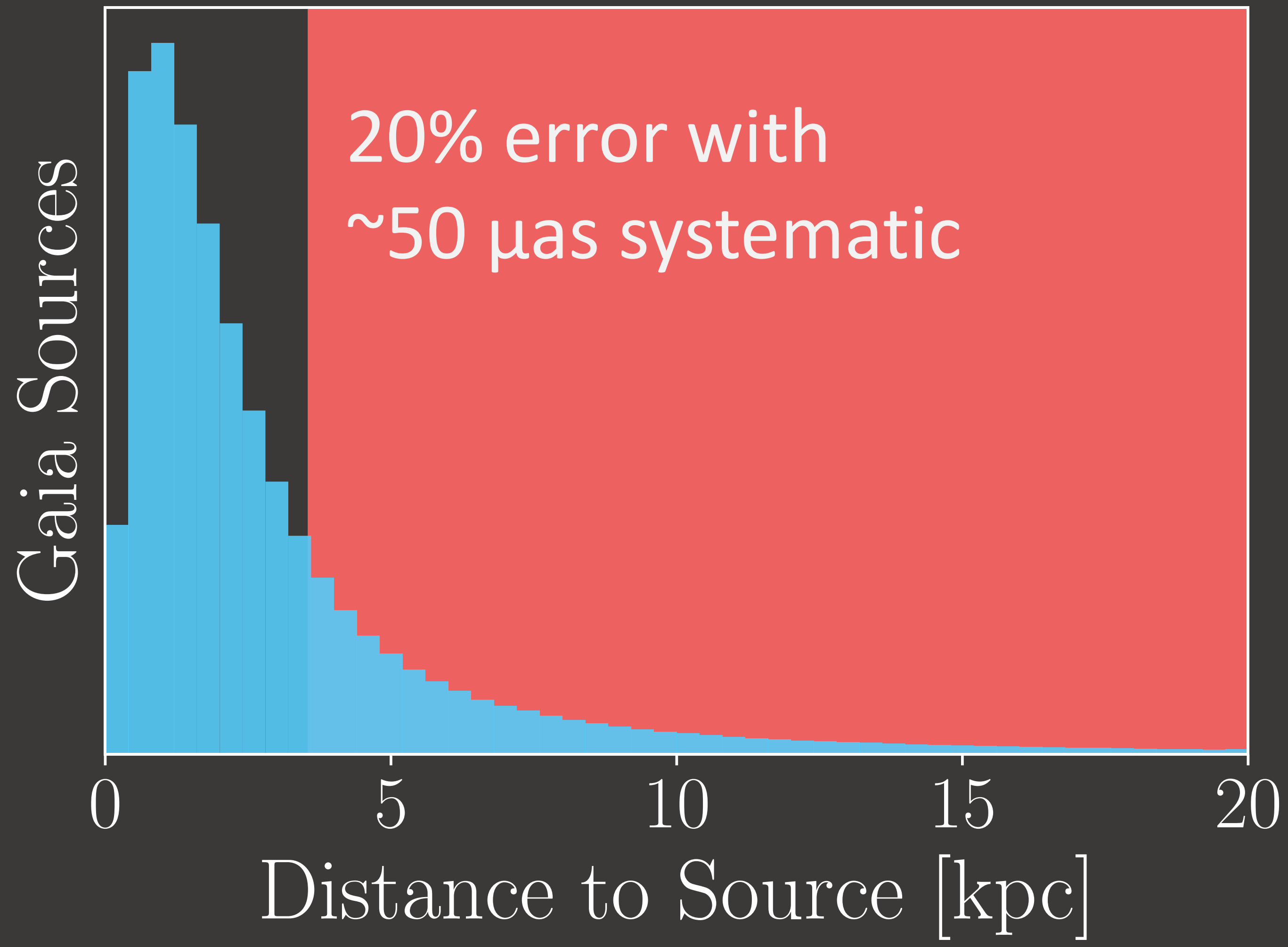
The offset varies with sky position!



Close to 25% of DR2 parallaxes are affected…



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Accurate distance anchors are essential to local H_0 measurements

Table 6. Recent H_0 Error Budgets (%)

Term	Description	Riess+ (2016)			Here		
		LMC	MW	4258	LMC	MW	4258
$\sigma_{\mu,\mathrm{anchor}}$	Anchor distance	2.1	2.1	2.6	1.2	1.5	2.6
$\sigma_{\mathrm{PL,anchor}}$	Mean of P–L in anchor	0.1	...	1.5	0.4	...	1.5
$R\sigma_{\lambda,1,2}$	zeropoints, anchor-to-hosts	1.4	1.4	0.0	0.1	0.7	0.0
σ_Z	Cepheid metallicity, anchor-hosts	0.8	0.2	0.2	0.9	0.2	0.2
	subtotal per anchor	2.6	2.5	3.0	1.5	1.7	3.0
All Anchor subtotal			1.6			1.0	
$\sigma_{\mathrm{PL}}/\sqrt{n}$	Mean of P–L in SN Ia hosts		0.4			0.4	
$\sigma_{\mathrm{SN}}/\sqrt{n}$	Mean of SN Ia calibrators (# SN)		1.3 (19)			**1.3 (19)**	
σ_{m-z}	SN Ia m–z relation		0.4			0.4	
σ_{PL}	P–L slope, $\Delta \log P$, anchor-hosts		0.6			0.3	
statistical error, σ_{H_0}			2.2			1.8	
Analysis systematics[a]			0.8			0.6	
Total uncertainty on σ_{H_0} [%]			2.4			**1.9**	

Riess++, 2019

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Riess++, 2019

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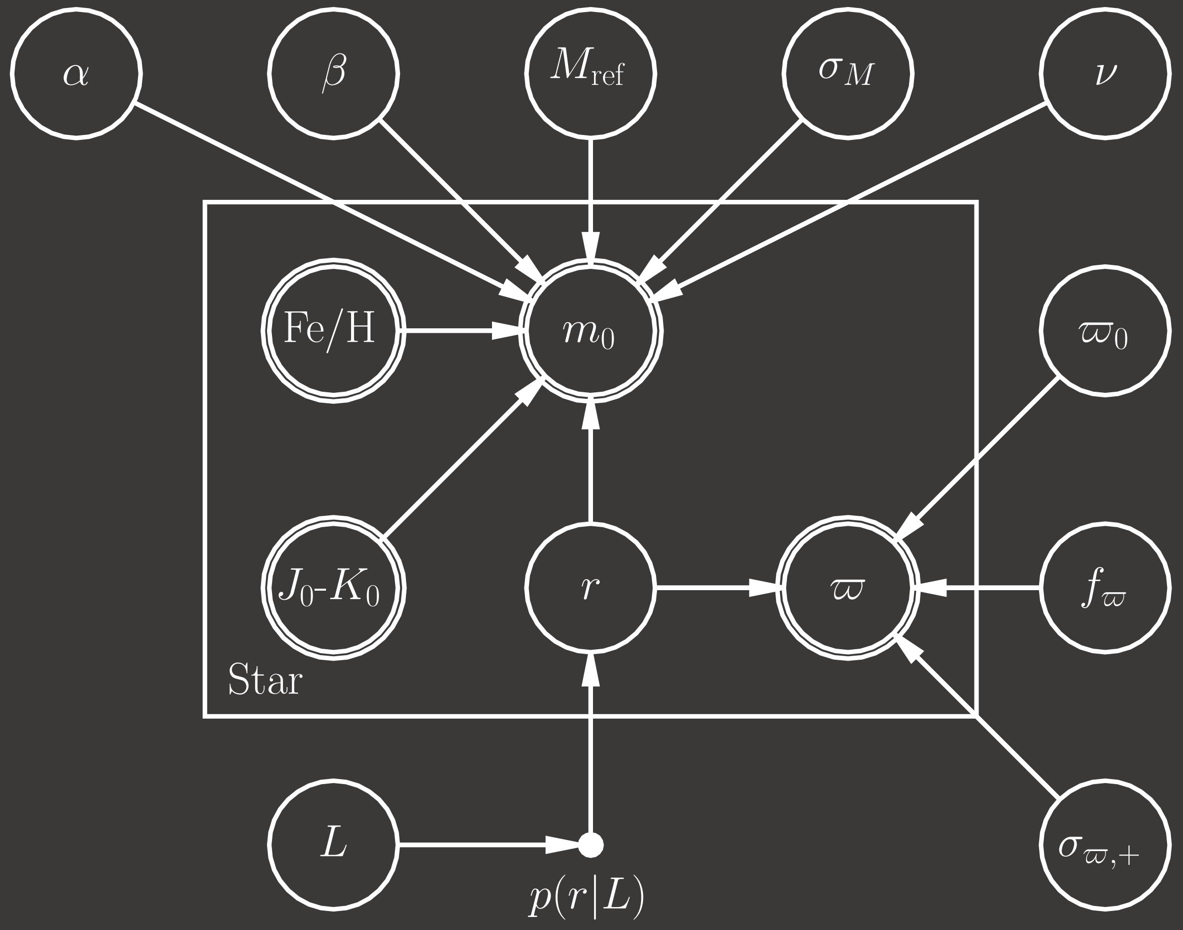
Typical MW Cepheid $r \sim 3\ \mathrm{kpc}$ $N \sim 2500$

$$\varpi = 1/r \approx 333\ \mu\mathrm{as}$$

$$\sigma_{\varpi,\mathrm{sys}} < 5\ \mu\mathrm{as}$$

We build a model describing *Gaia* parallaxes



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How is the zero-point parallax modelled?

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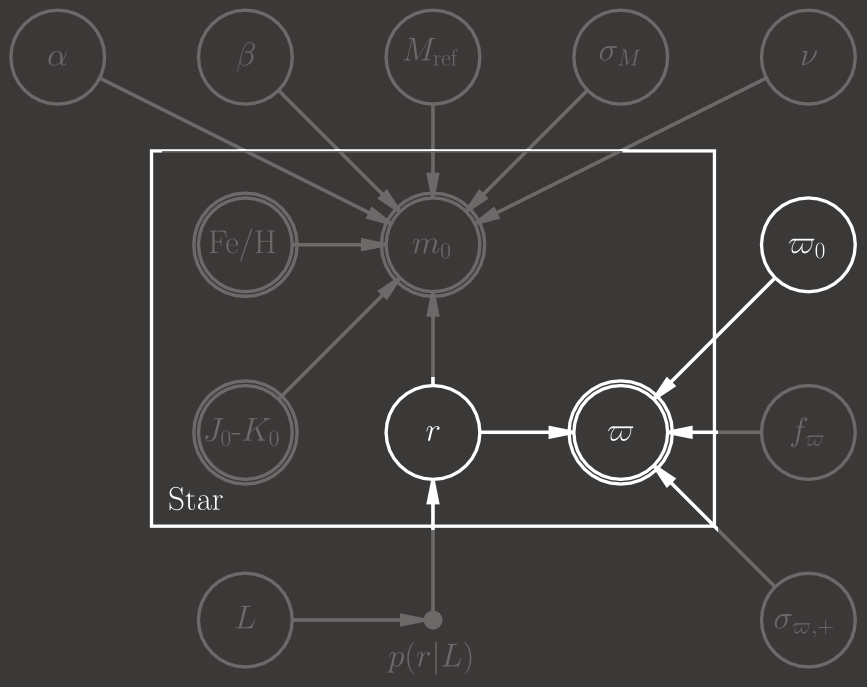

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Hierarchical models can validate *Gaia* parallax errors

$$\sigma_{\varpi}^2 = (f_{\varpi} \varsigma_{\varpi})^2 + \sigma_{\varpi,+}^2$$

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Reported errors

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$$\sigma_{\varpi}^2 = (f_{\varpi} s_{\varpi})^2 + \sigma_{\varpi,+}^2$$

Correction parameters

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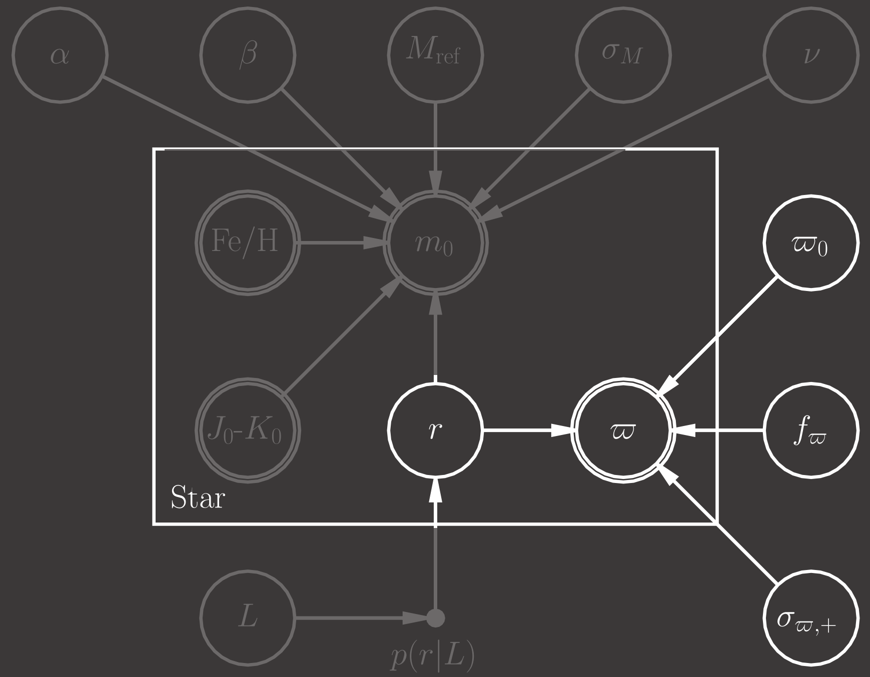

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Gaia Data Release 1
Lindegren++ 2016

$$f_\varpi = 1.4 \qquad \sigma_{\varpi,+} = 200\ \mu\text{as}$$

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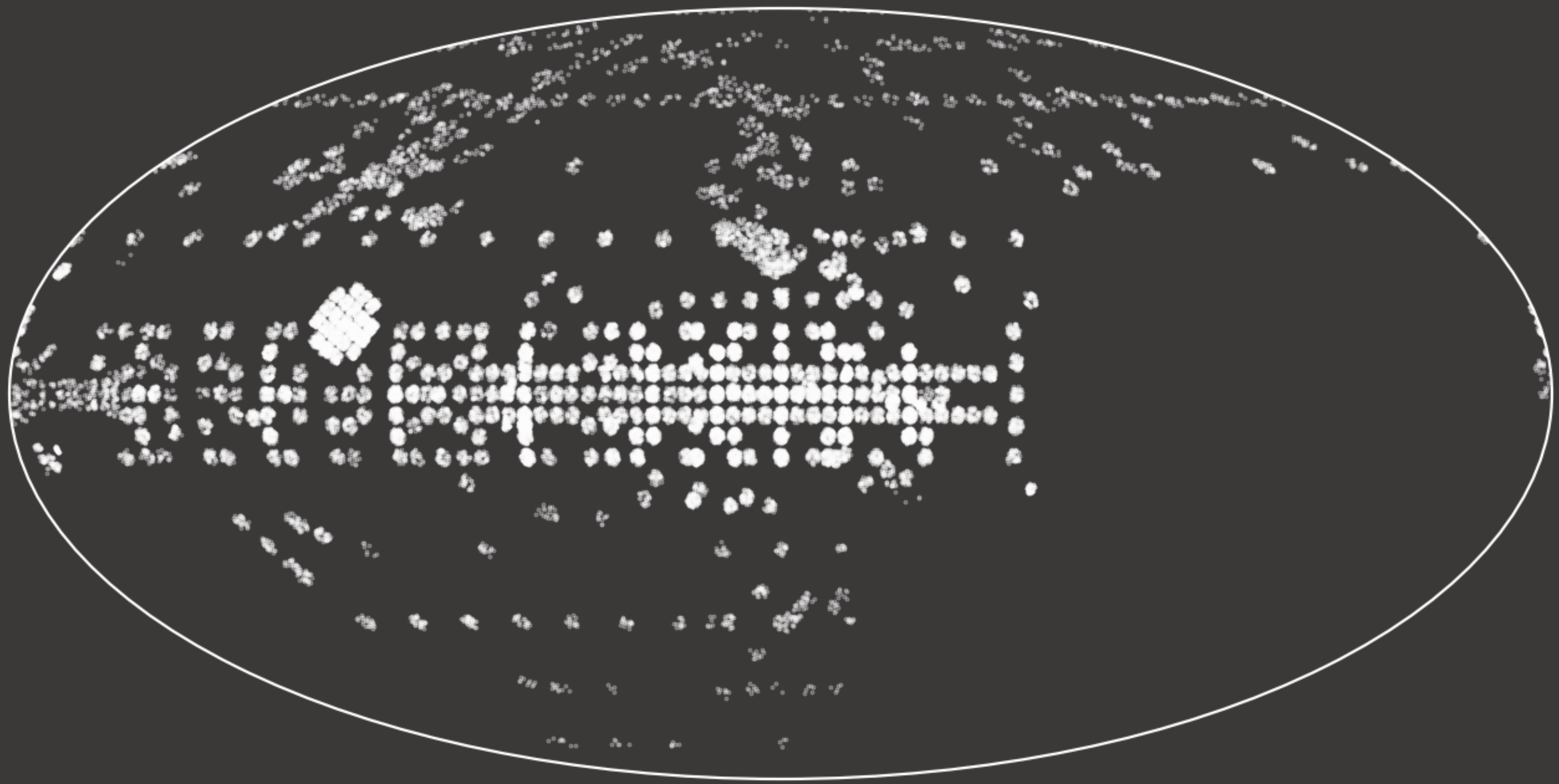
Gaia Data Release 1
Lindegren++ 2016

$f_{\varpi} = 1.4$ $\sigma_{\varpi,+} = 200\ \mu\text{as}$

Gaia Data Release 2
Lindegren++ 2018
(Tentative)

$f_{\varpi} = 1.08$ $\sigma_{\varpi,+} = 21 - 43\ \mu\text{as}$

Measuring the zero-point requires lots of data



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Red clump stars are standard candles

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Luminosity is modelled with stellar properties

$$M \sim \alpha(J_0 - K_0) + \beta[\mathrm{Fe/H}] + M_{\mathrm{ref}}$$

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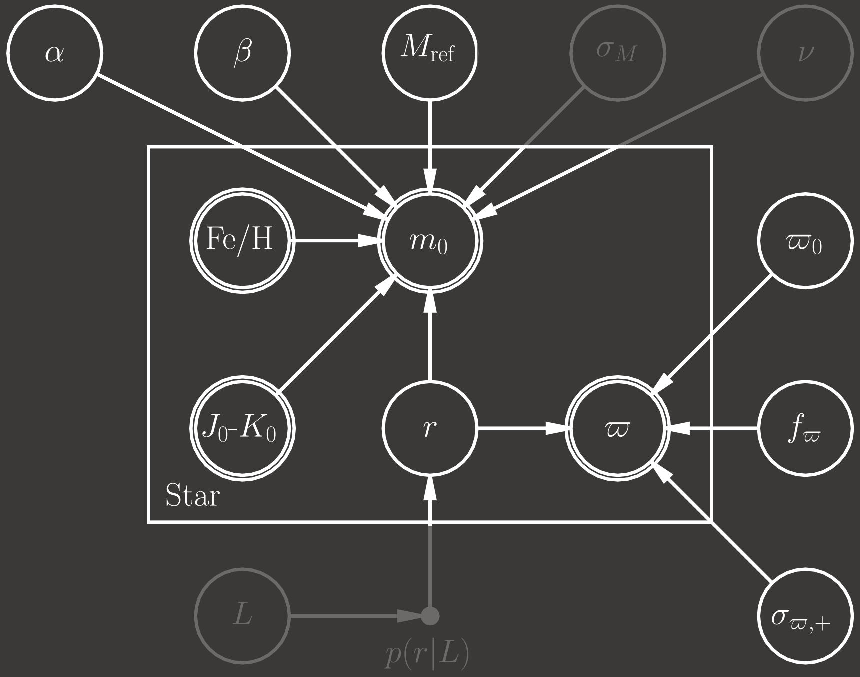

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Model uncertainties outweigh photometric uncertainties (?)

$$\mu_m = m - A_m - M = 5\log r - 5 = \mu_r$$

$$p(\mu_m|\mu_r)$$

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$$p(\mu_m | \mu_r) = \mathcal{S}(\mu_m | \mu_r, \sigma_M^2, \nu)$$

Student’s t-distribution

Model uncertainties outweigh photometric uncertainties (?)

VICTOR READ THIS

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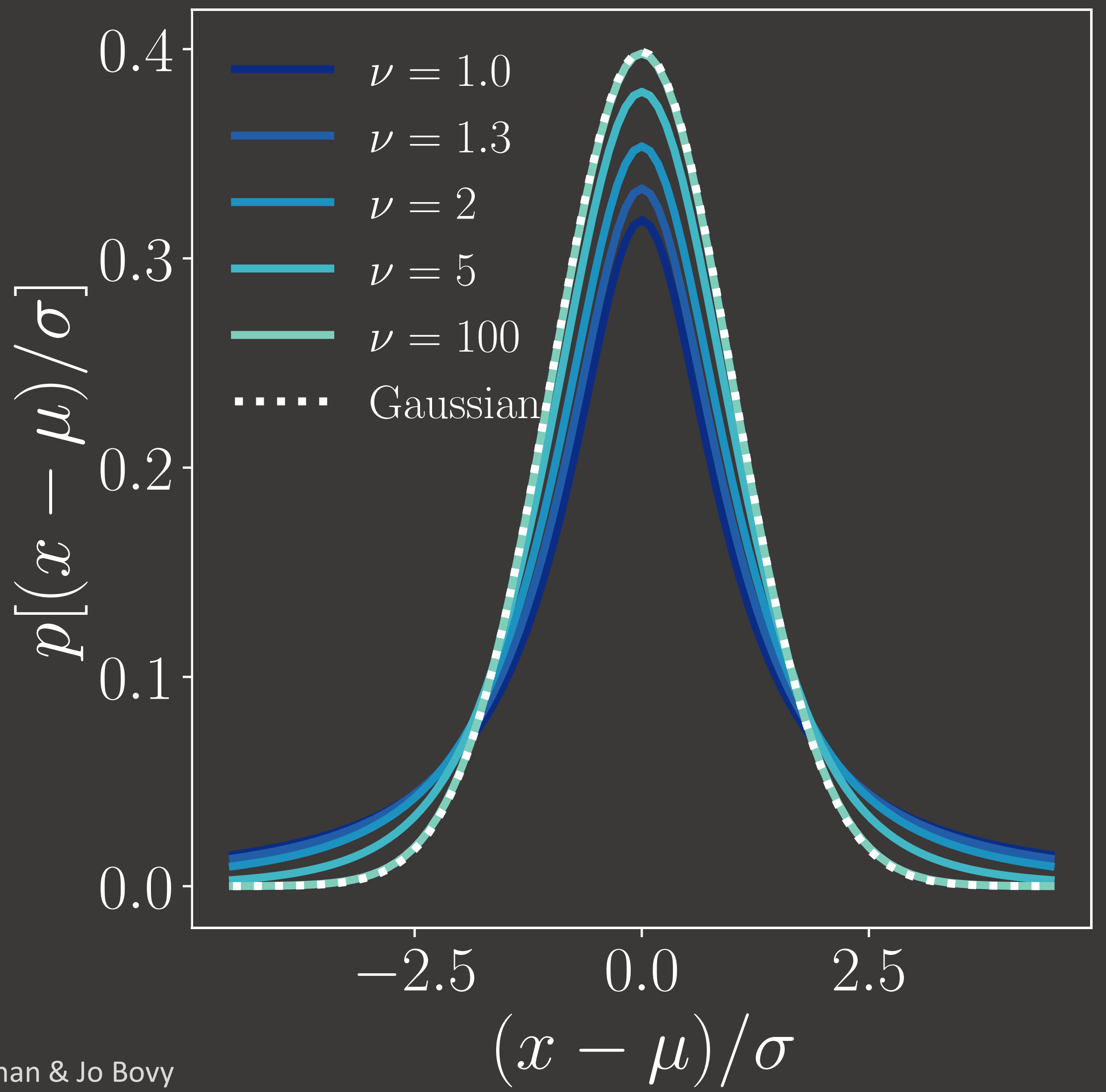
Student's t-distribution

The Student's t-distribution catches potential photometric outliers



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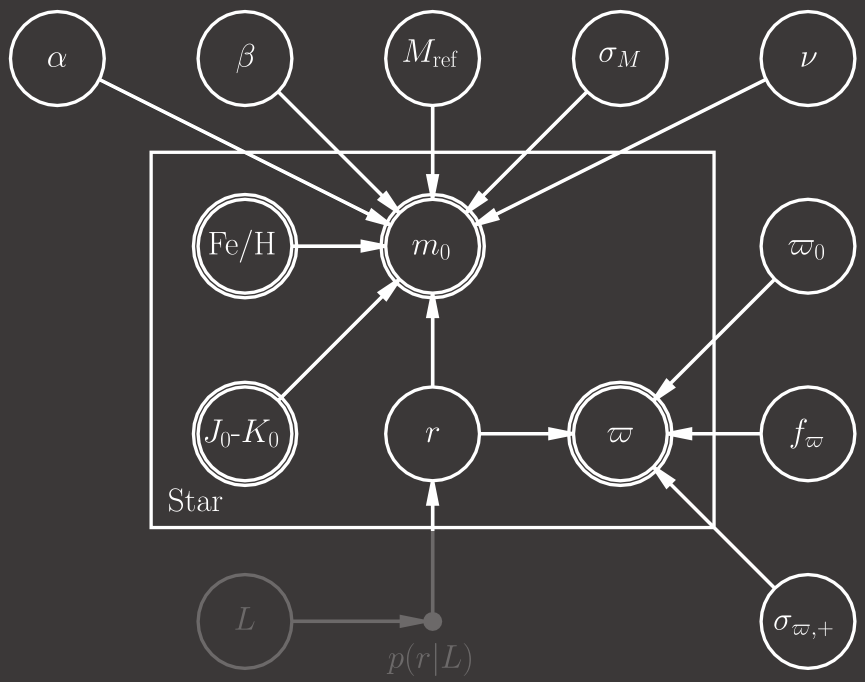

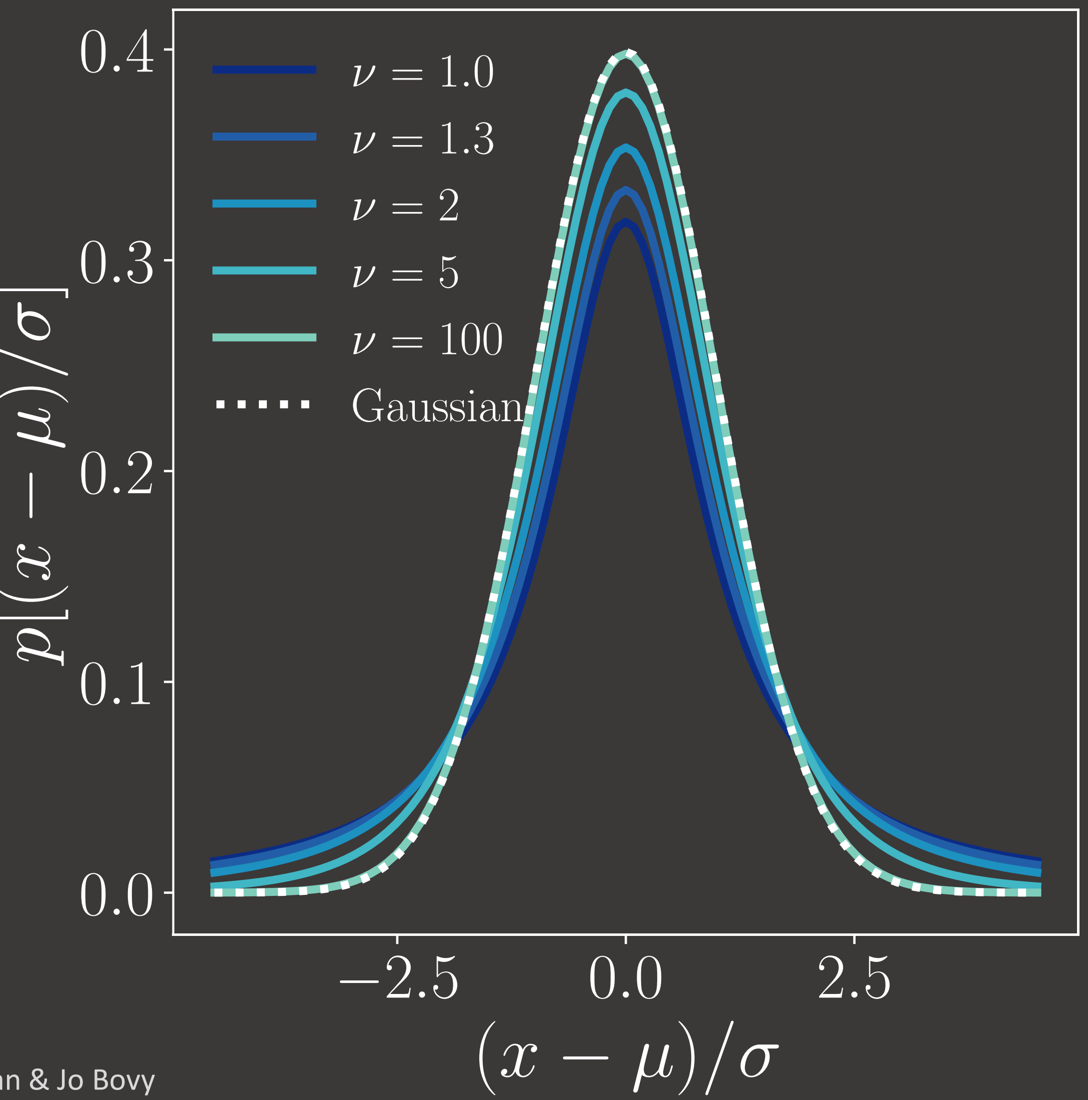

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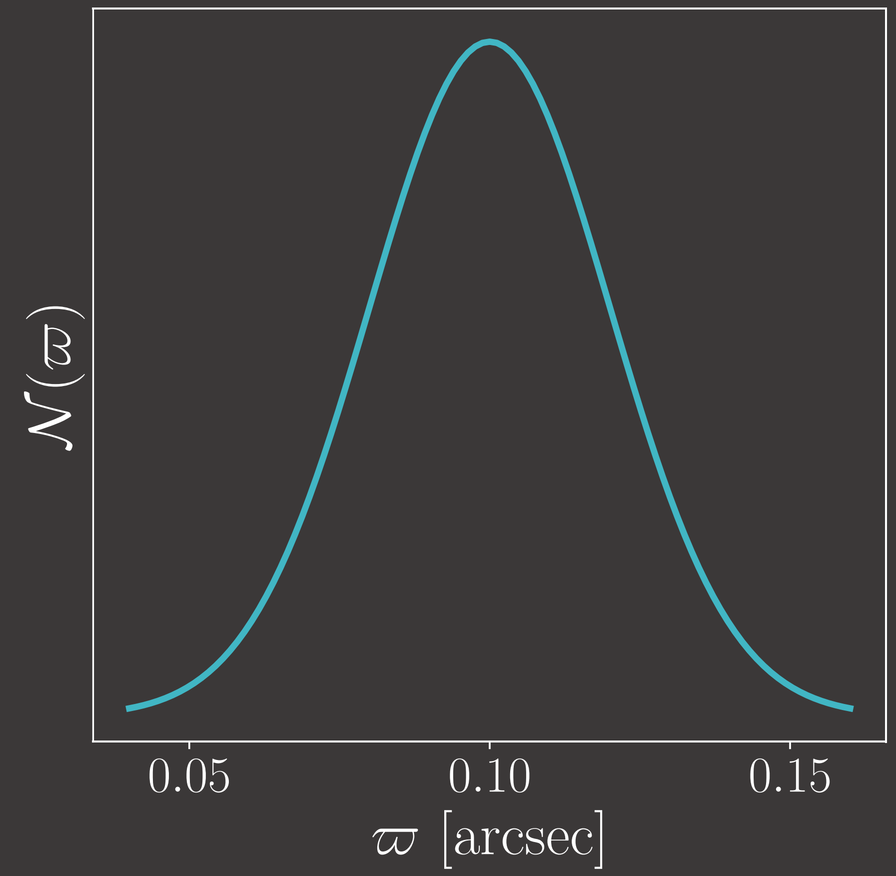
Red clump stars are standard(izable) candles

$$\mu = m - A_m - M = 5\log r - 5$$

$$\varpi = 1/r + \varpi_0$$

Inverting parallax is a biased estimator of distance



$$\varpi_{\mathrm{true}} = 0.1 \text{ arcsec}$$

$$\sigma_{\varpi} = 0.02 \text{ arcsec}$$

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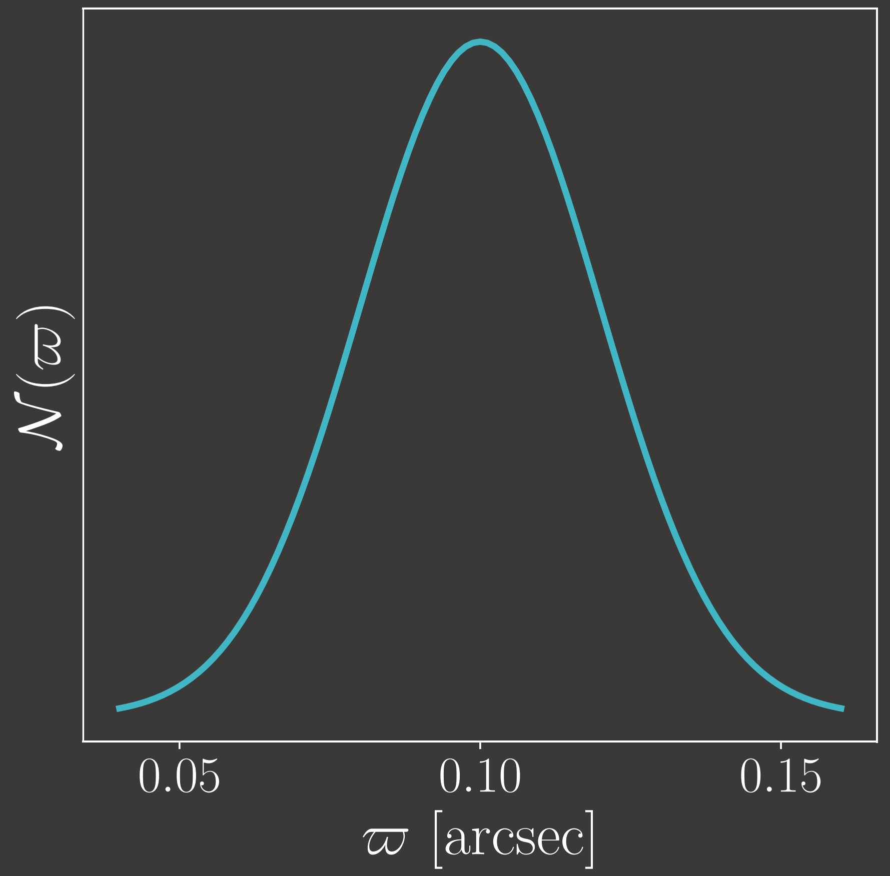

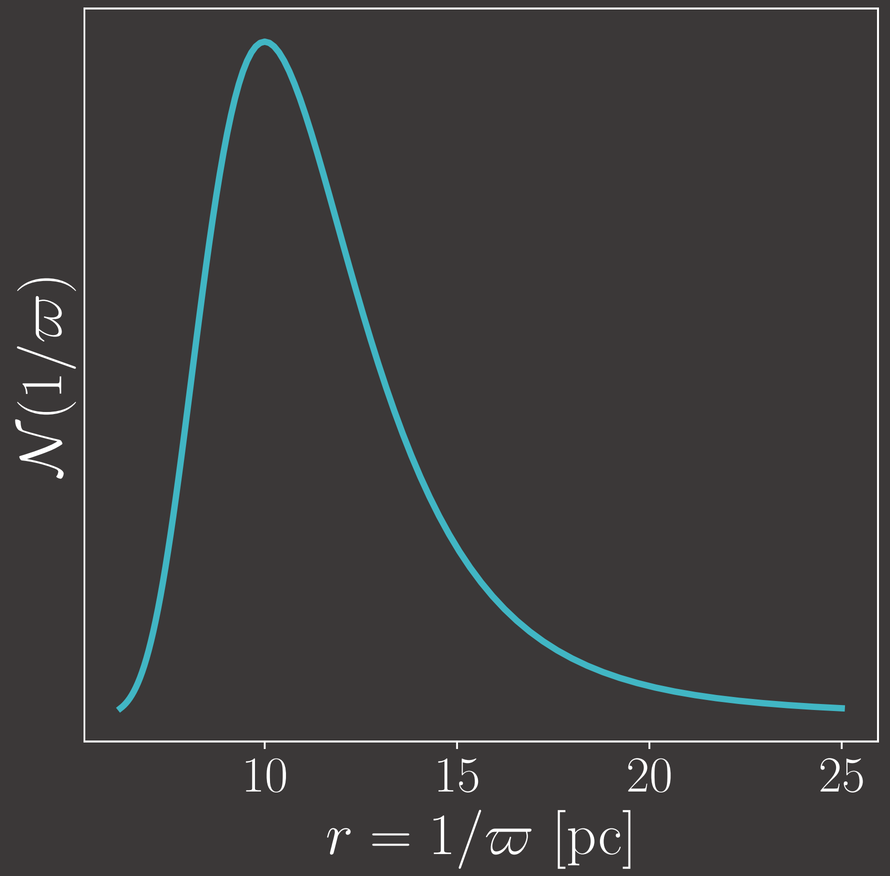

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An exponentially decreasing volume density prior resolves estimator bias

$$p(r|L) = \frac{r^2}{2L^3} \exp\left(\frac{-r}{L}\right)$$

Bailer-Jones 2015

In summary, the model relates photometric and parallax measurements through distance

Likelihood

$$\mathcal{N}(\varpi | 1/r + \varpi_0, \sigma_{\varpi}^2)$$

$$\mathcal{S}(\mu_m | \mu_r, \sigma_M^2, \nu)$$

Prior

$$p(r | L)$$

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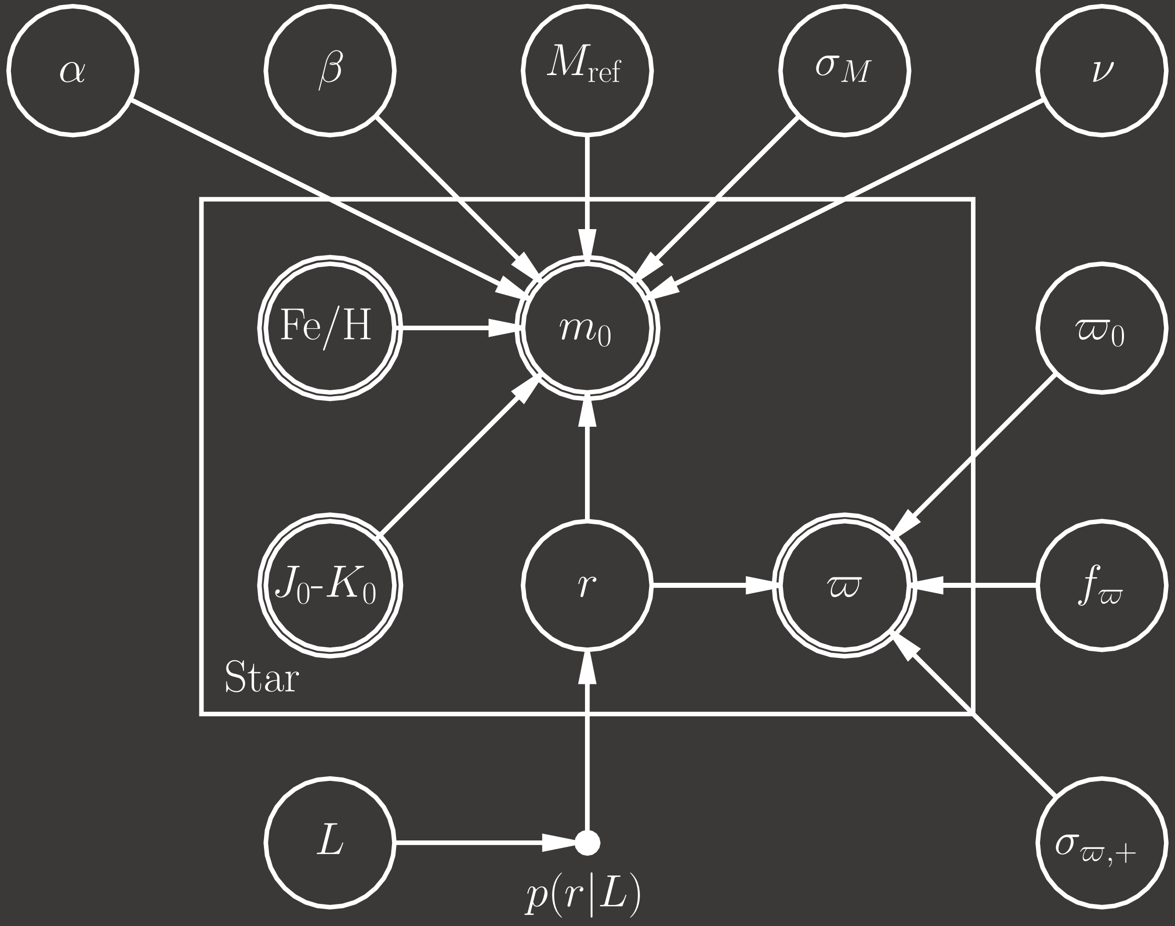
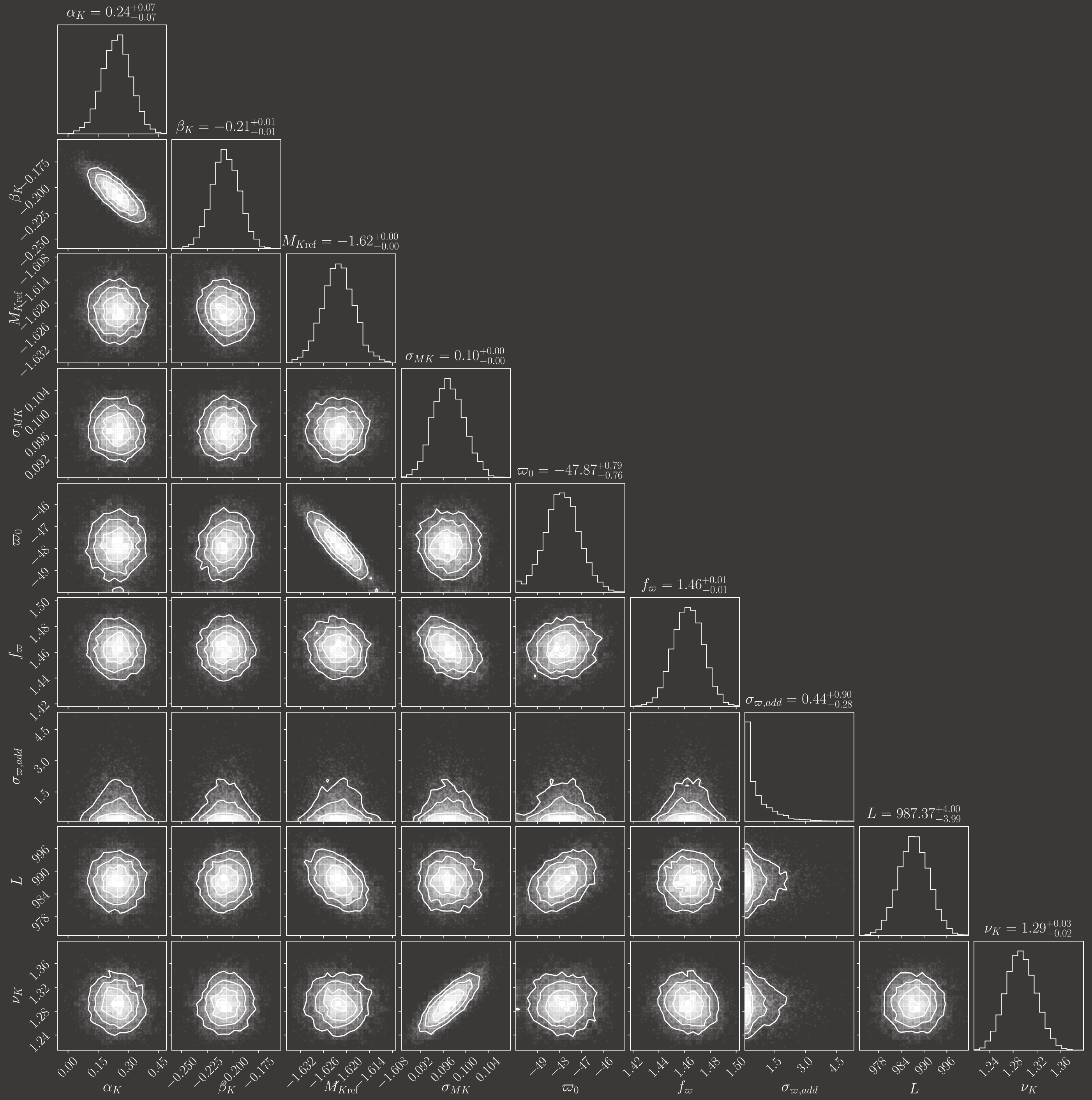


Parameters are inferred to very high precision

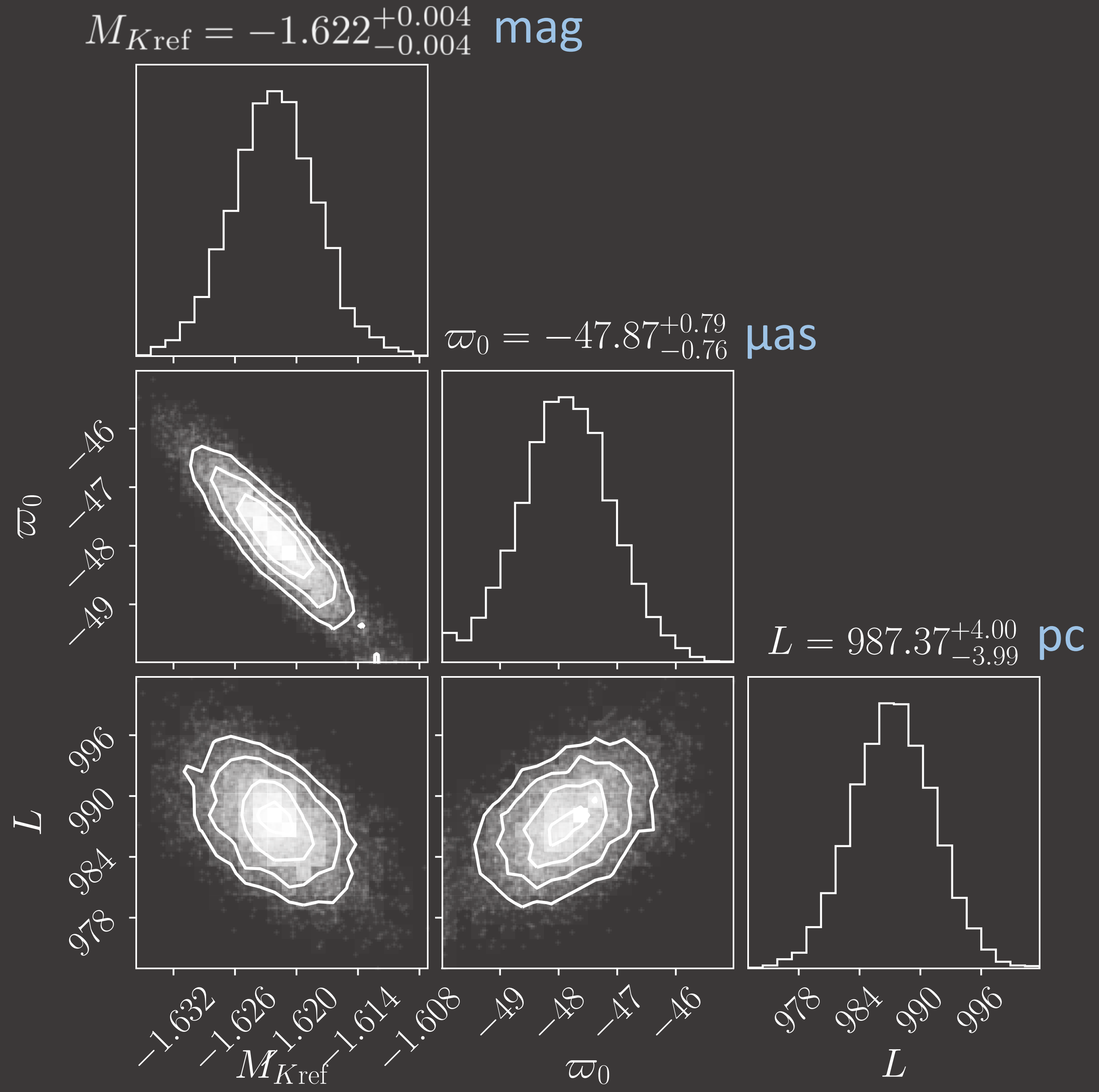
Photometry available:

2MASS: JHK_s

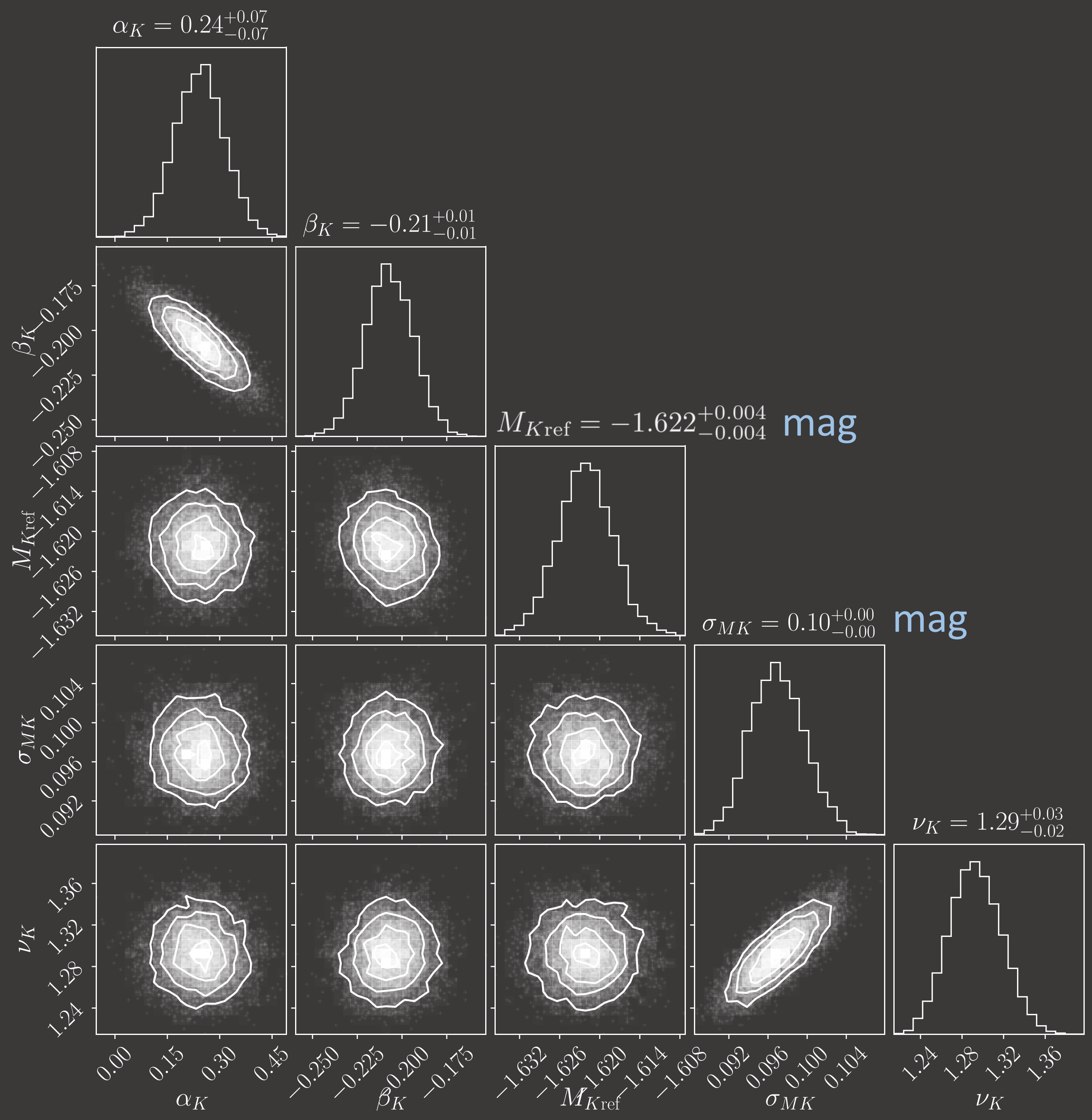
Gaia: G



The zero-point offset is constrained to within ~1 μas

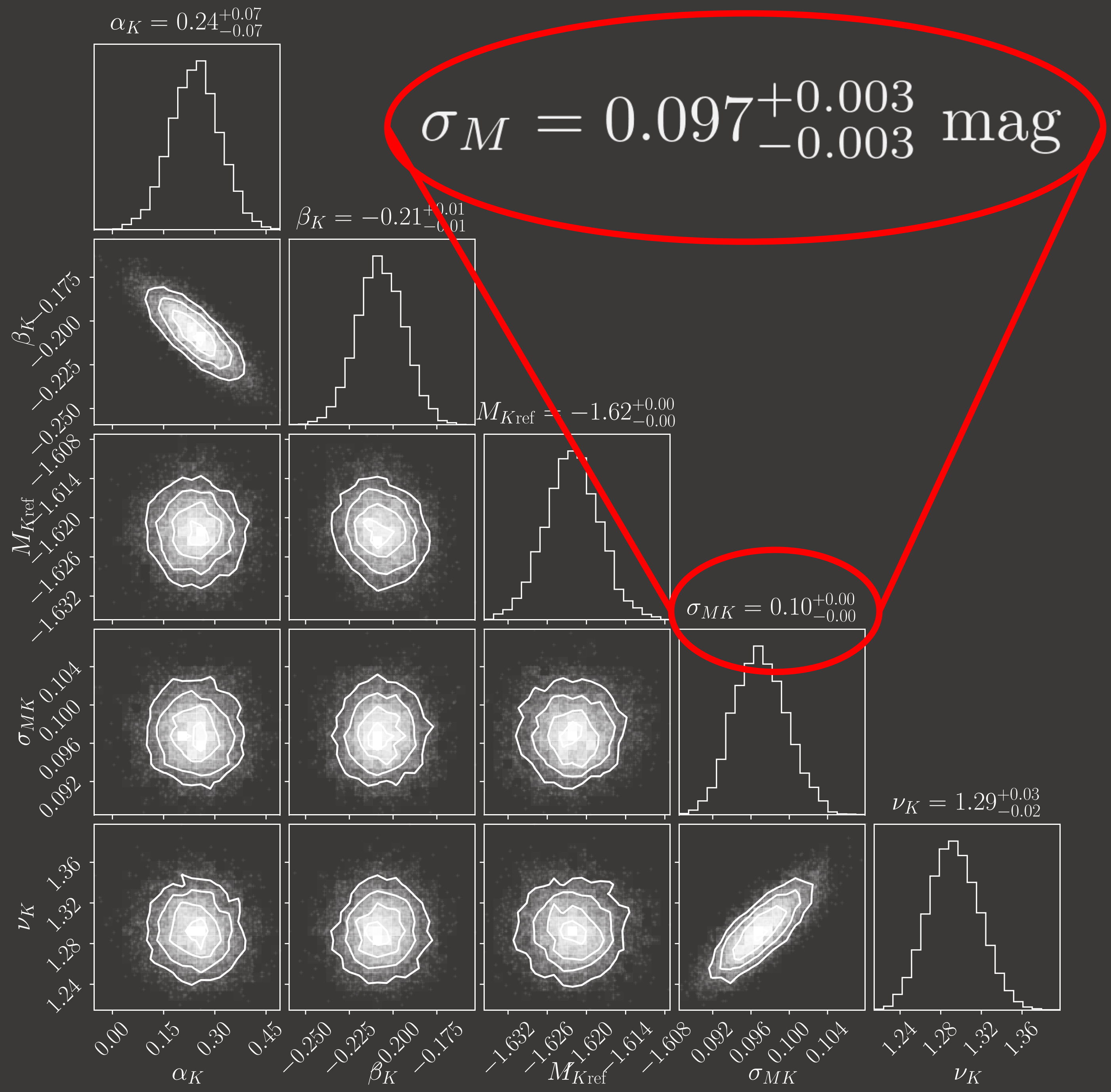


The red clump luminosity is inferred to have dependence on colour/metallicity



Model uncertainties outweigh photometric uncertainties

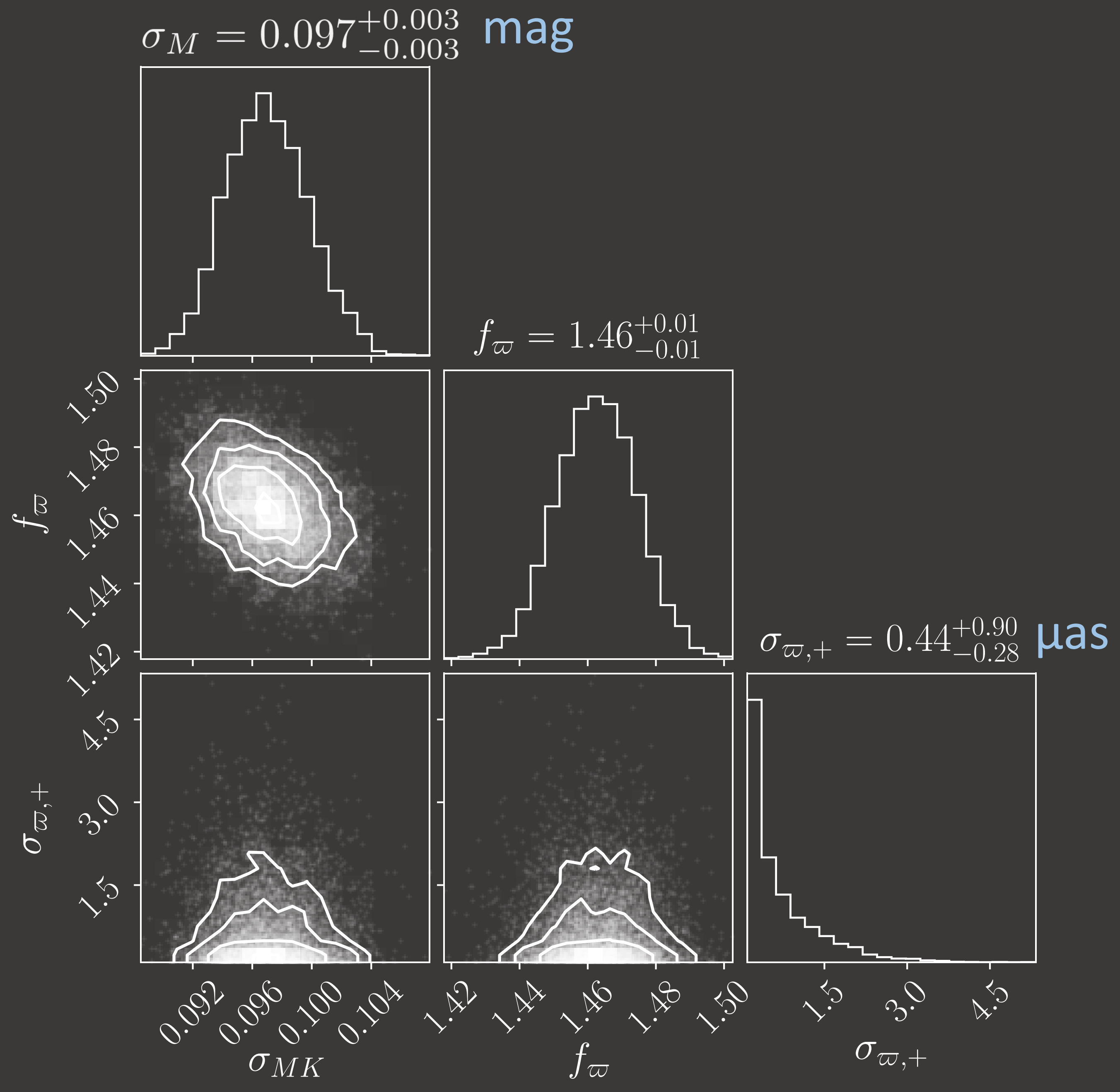
Typical K_s error ~ 0.02 mag



Gaia parallax error correction in disagreement with tentative values

$$f_\varpi = 1.08$$

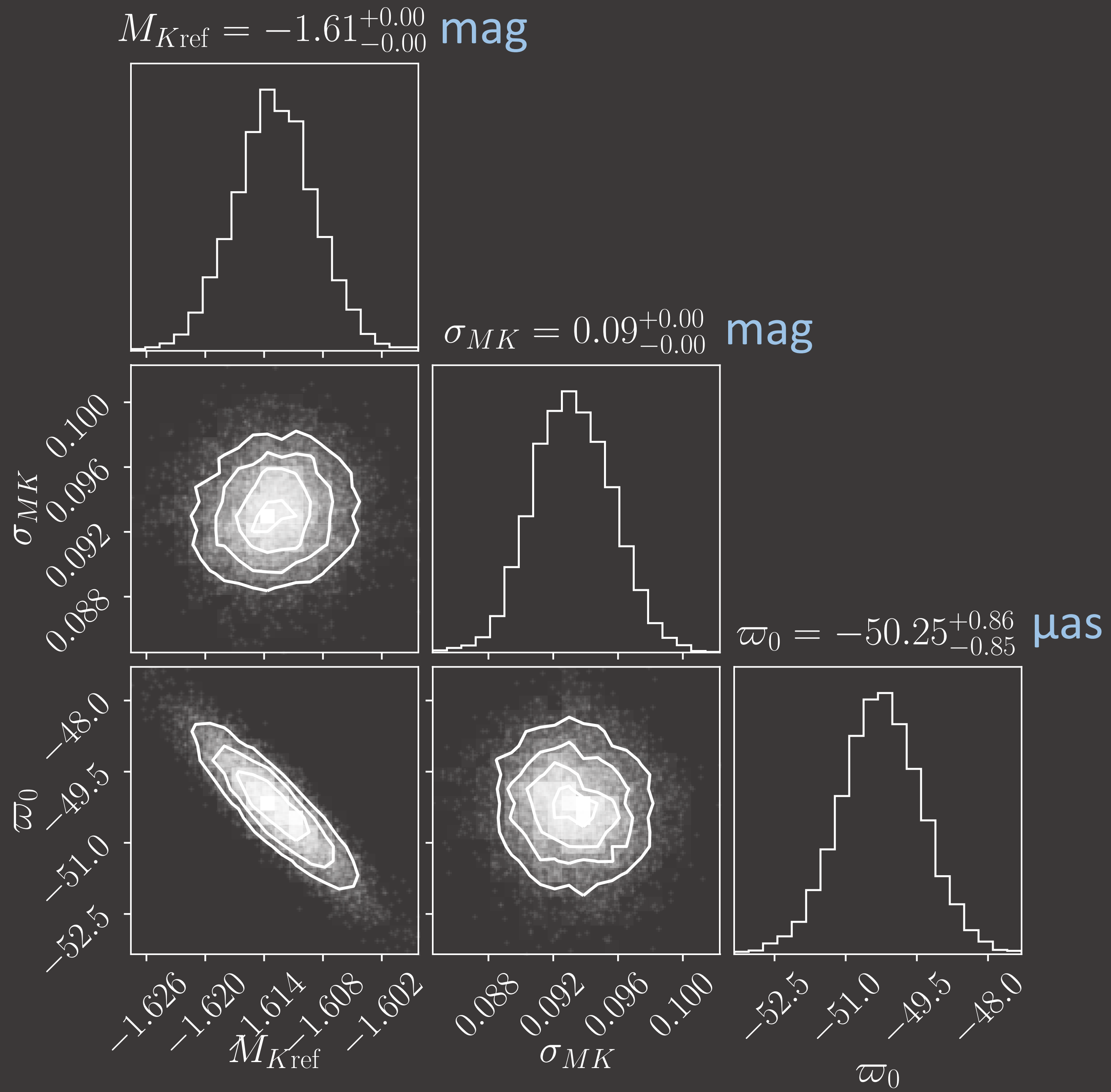
$$\sigma_{\varpi,+} = 21 - 43\ \mu as$$



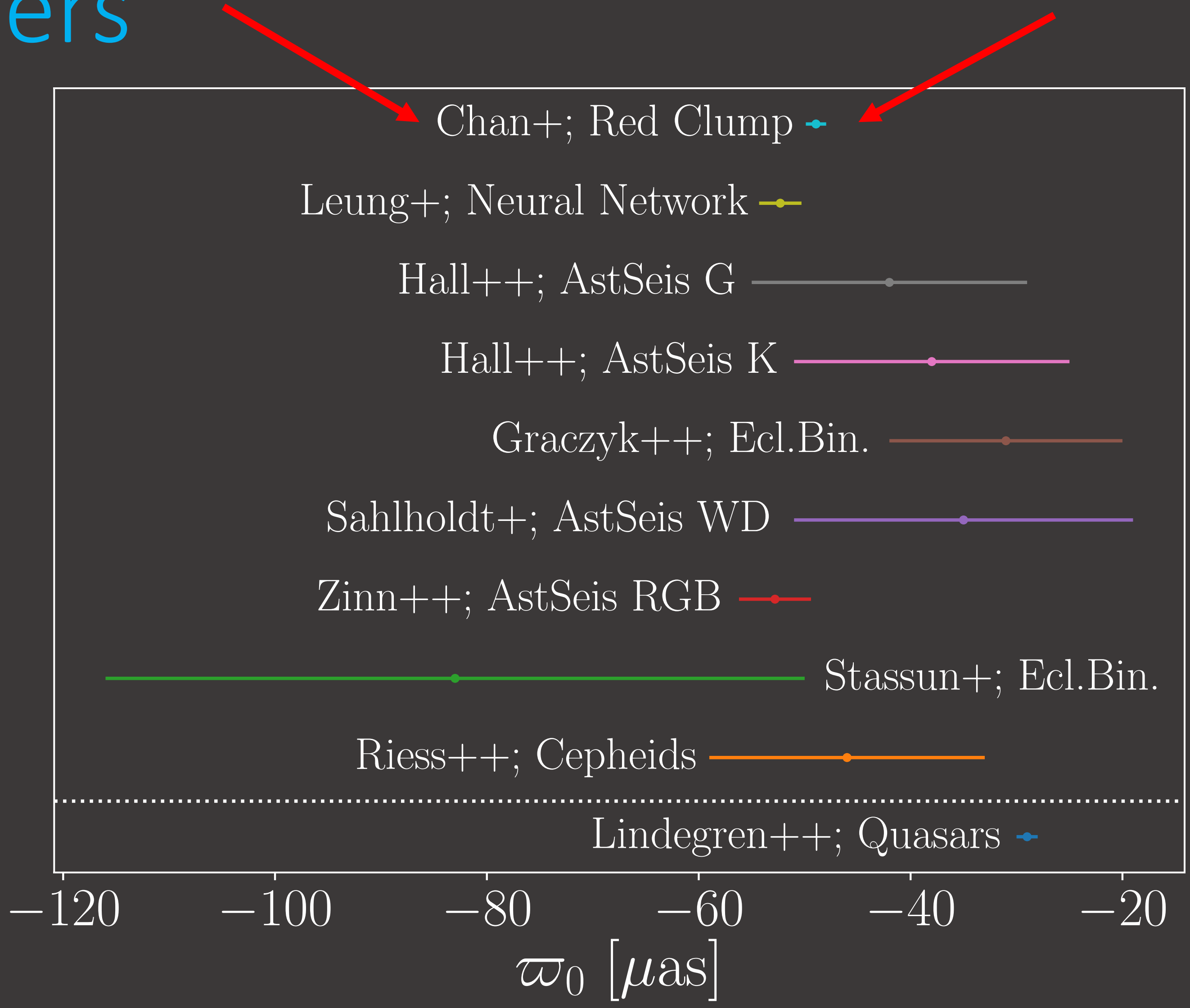
Fixing error correction to reported values changes results

$$f_\varpi = 1.08$$

$$\sigma_{\varpi,+} = 21 - 43\ \mu\text{as}$$



Constant zero-point results seem to agree with others

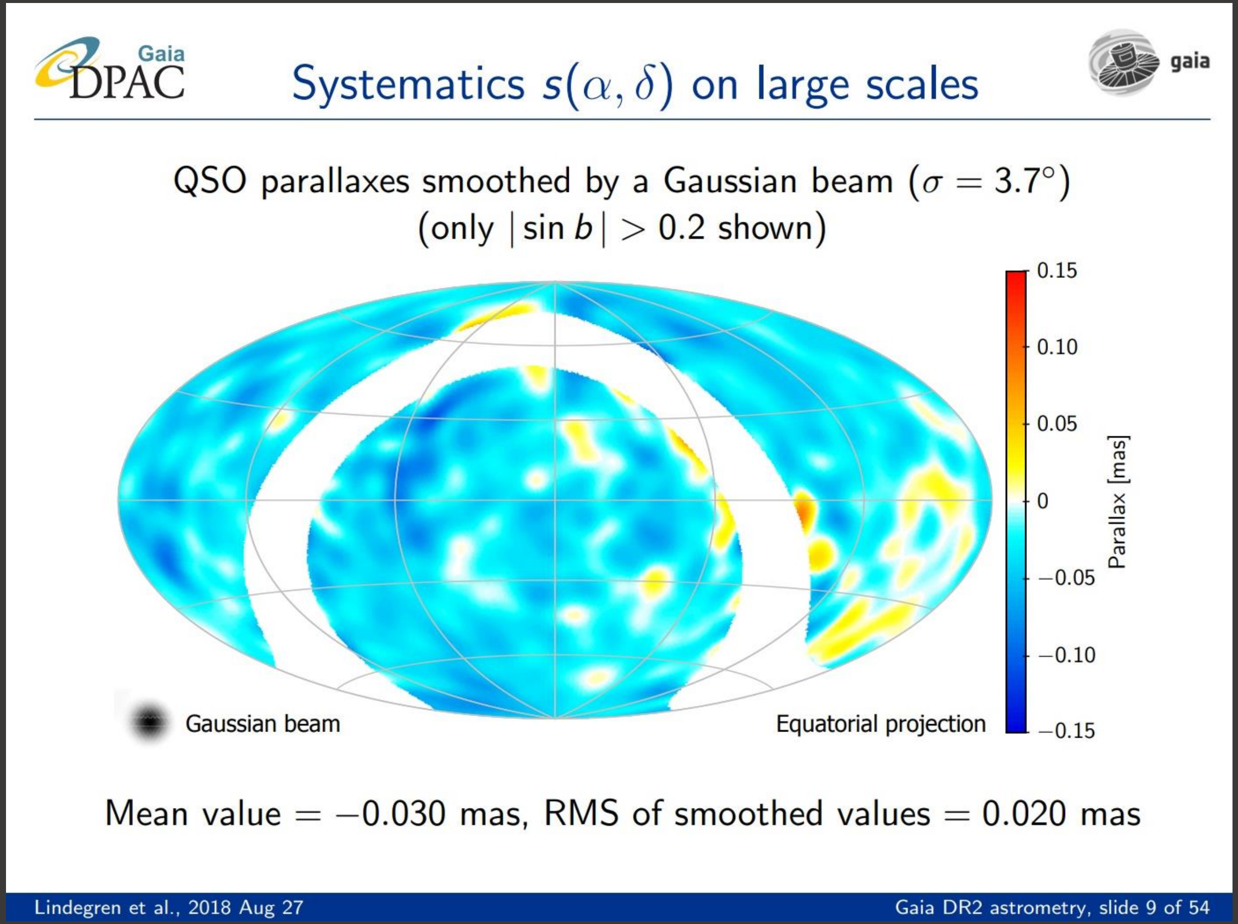


Adding zero-point dependences by including a functional form

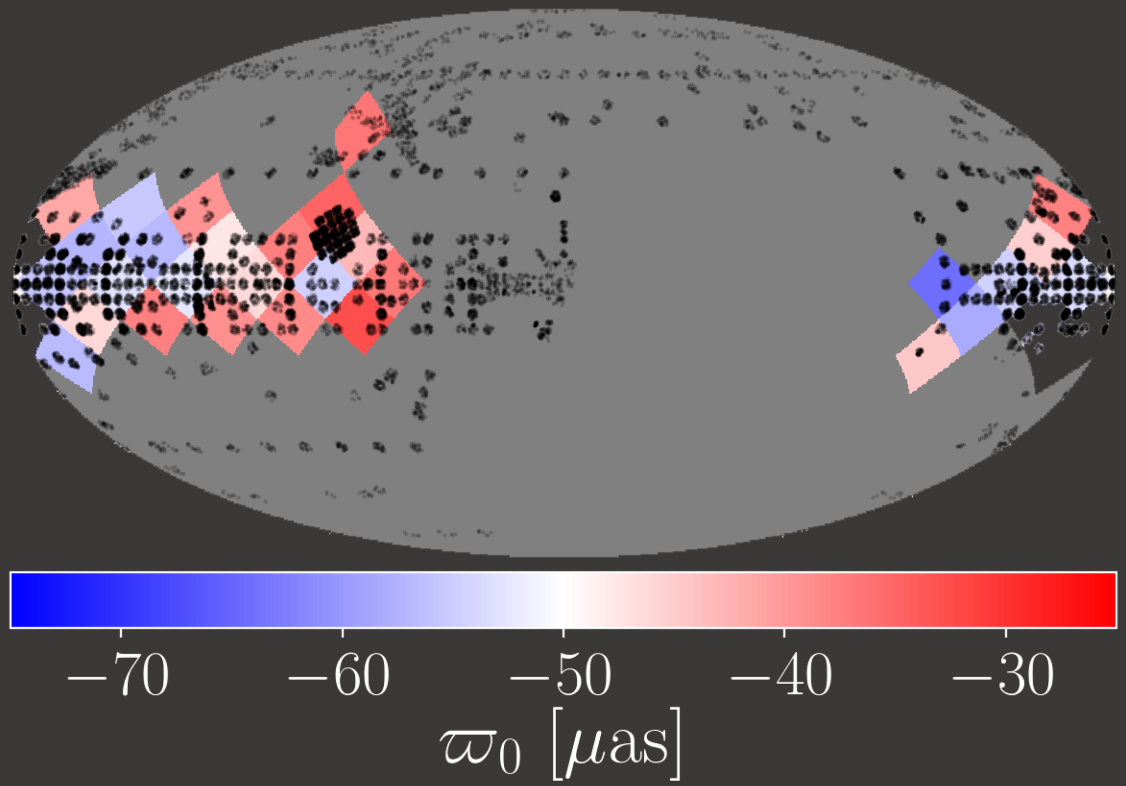
$$\varpi_0 \sim z_0 + z_1 G + z_2 G^2 + \ldots$$

Parameters

Reminder: The zero-point parallax may also vary across the sky



We can see variations across the MW disk



PRELIMINARY!!!

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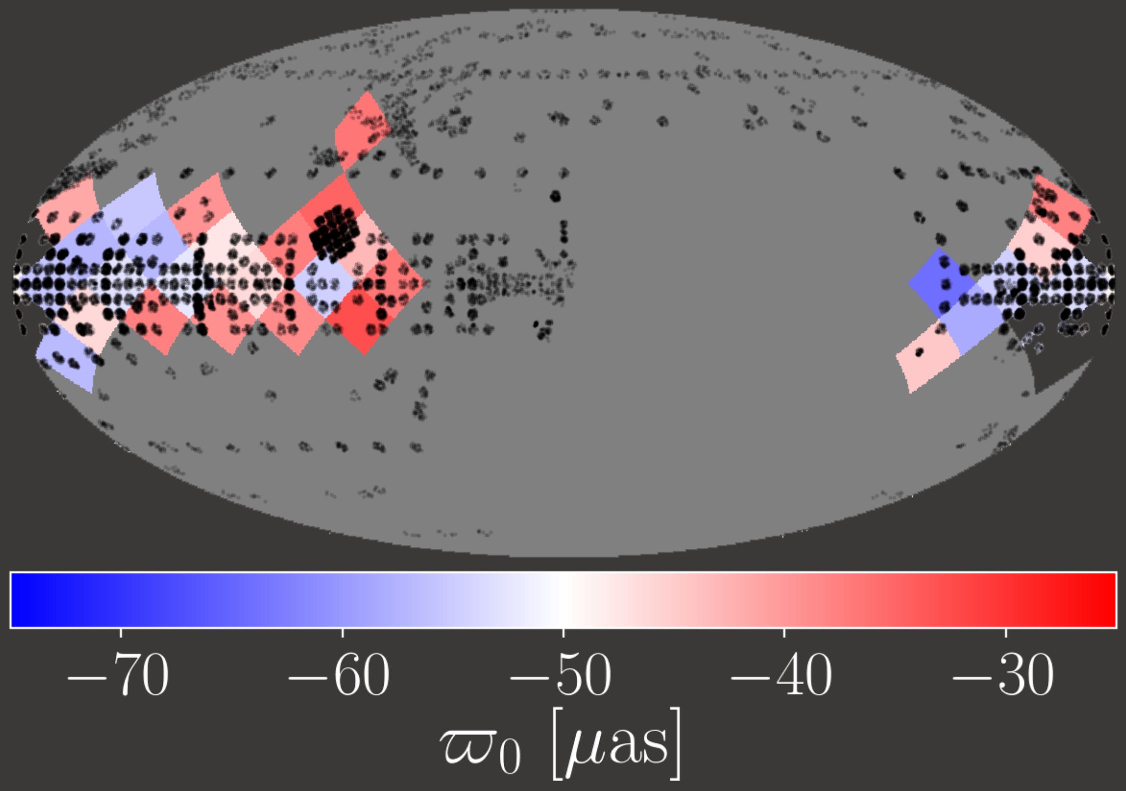
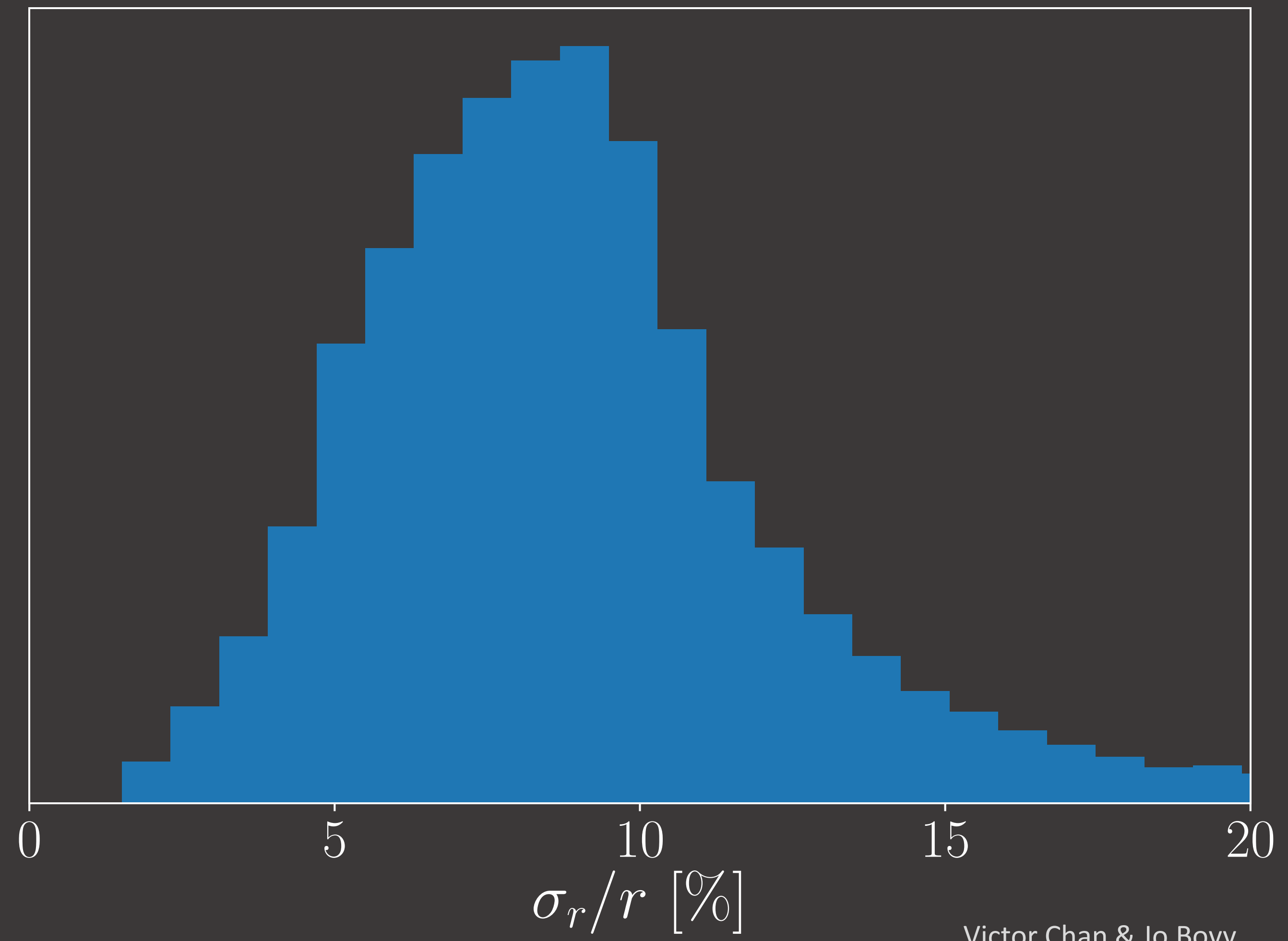


Even more sources coming in DR3 & future APOGEE data!

Good distance anchors improve our understanding of local H_0 measurements



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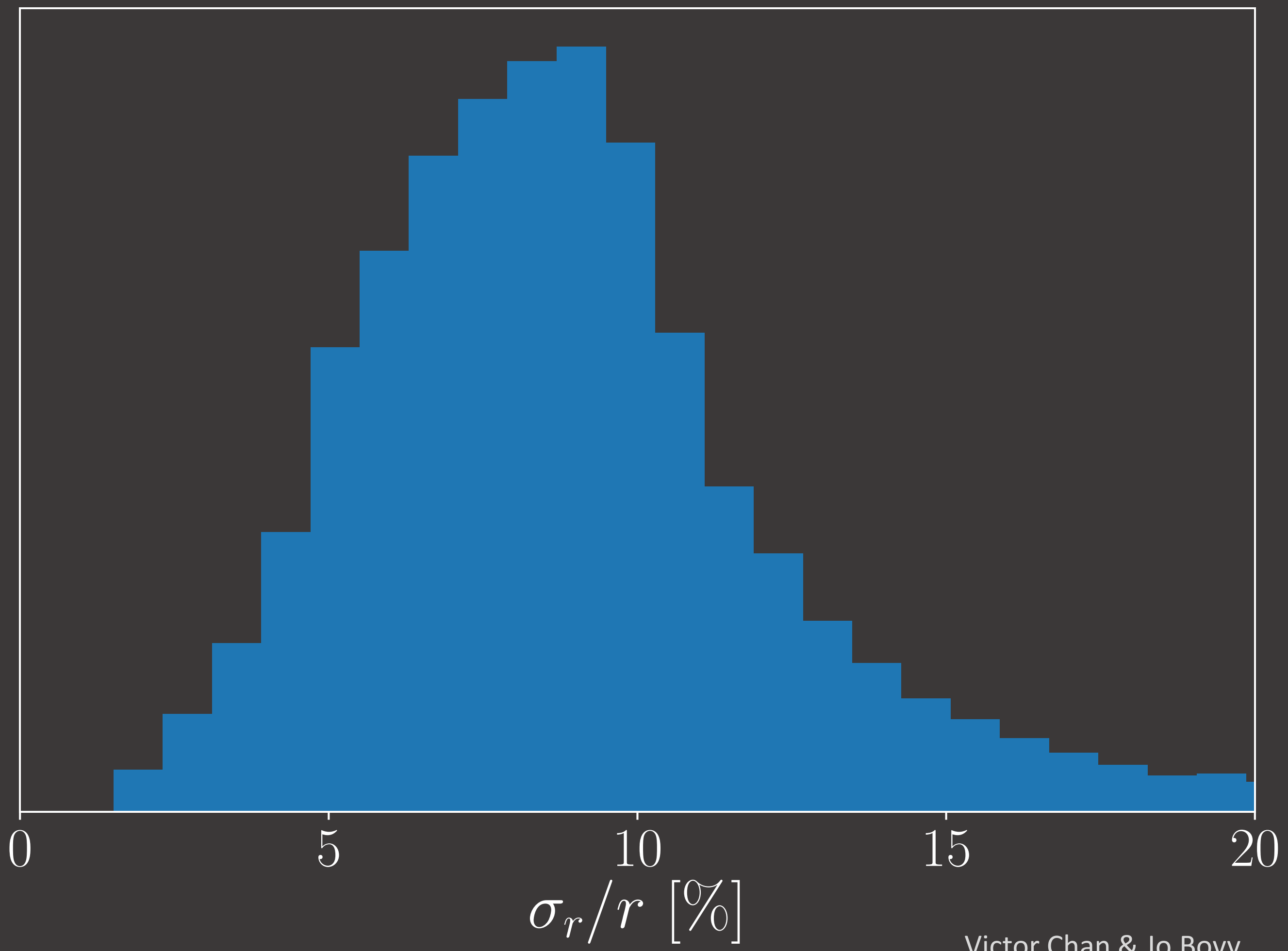

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$$\sigma_{\varpi_0} < 1\ \mu\text{as}$$

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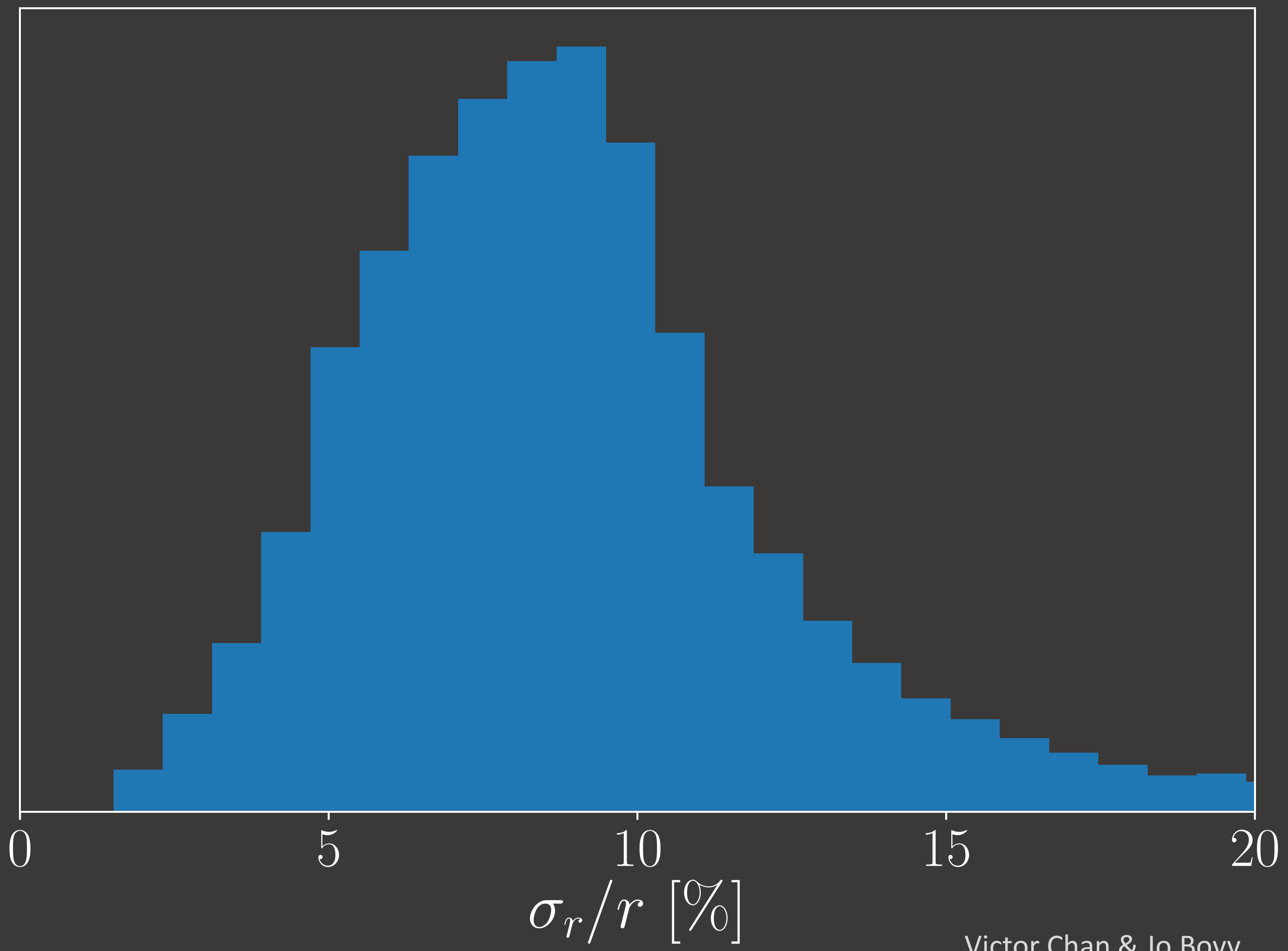

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$$N \approx 28000$$

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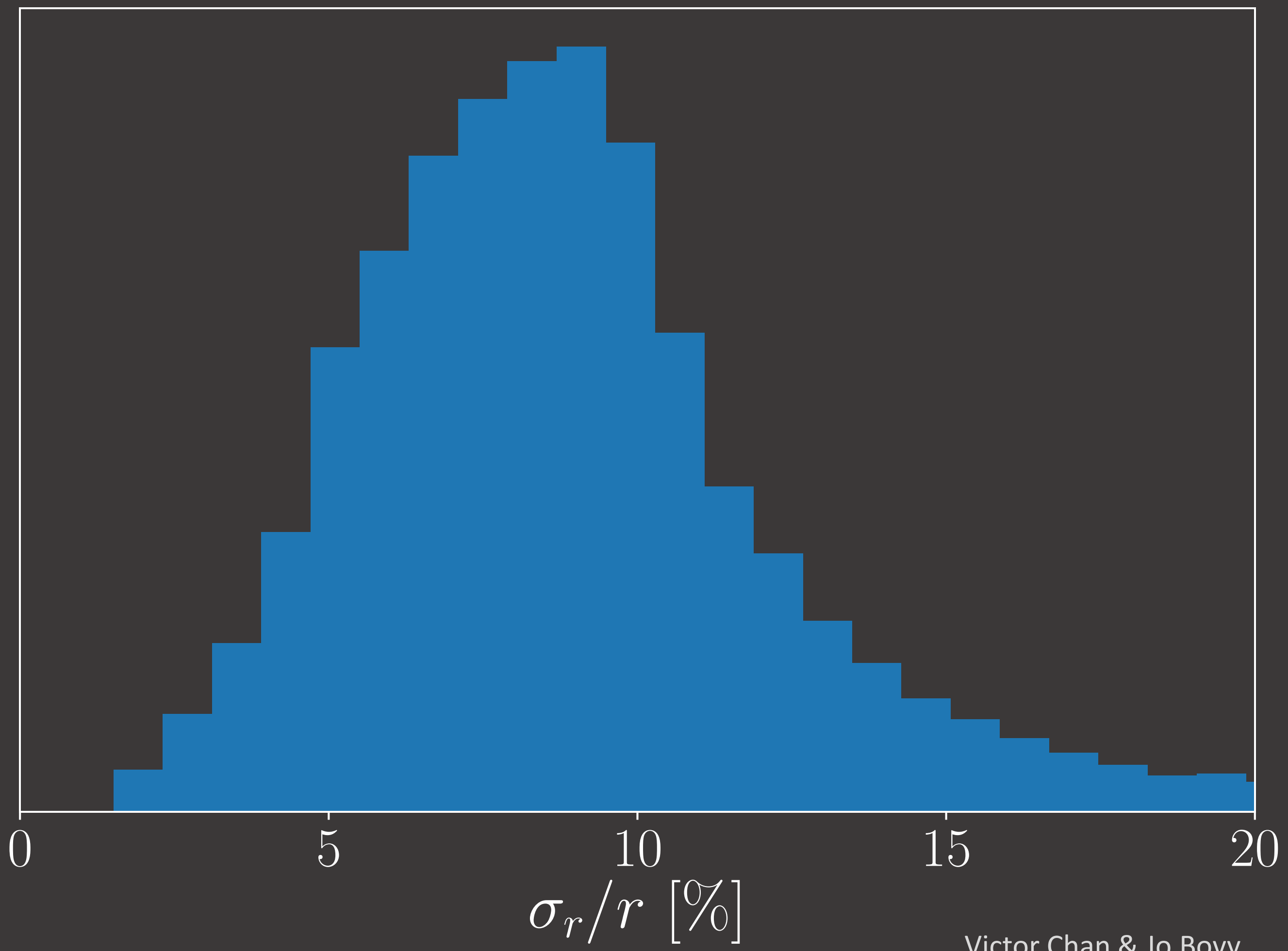

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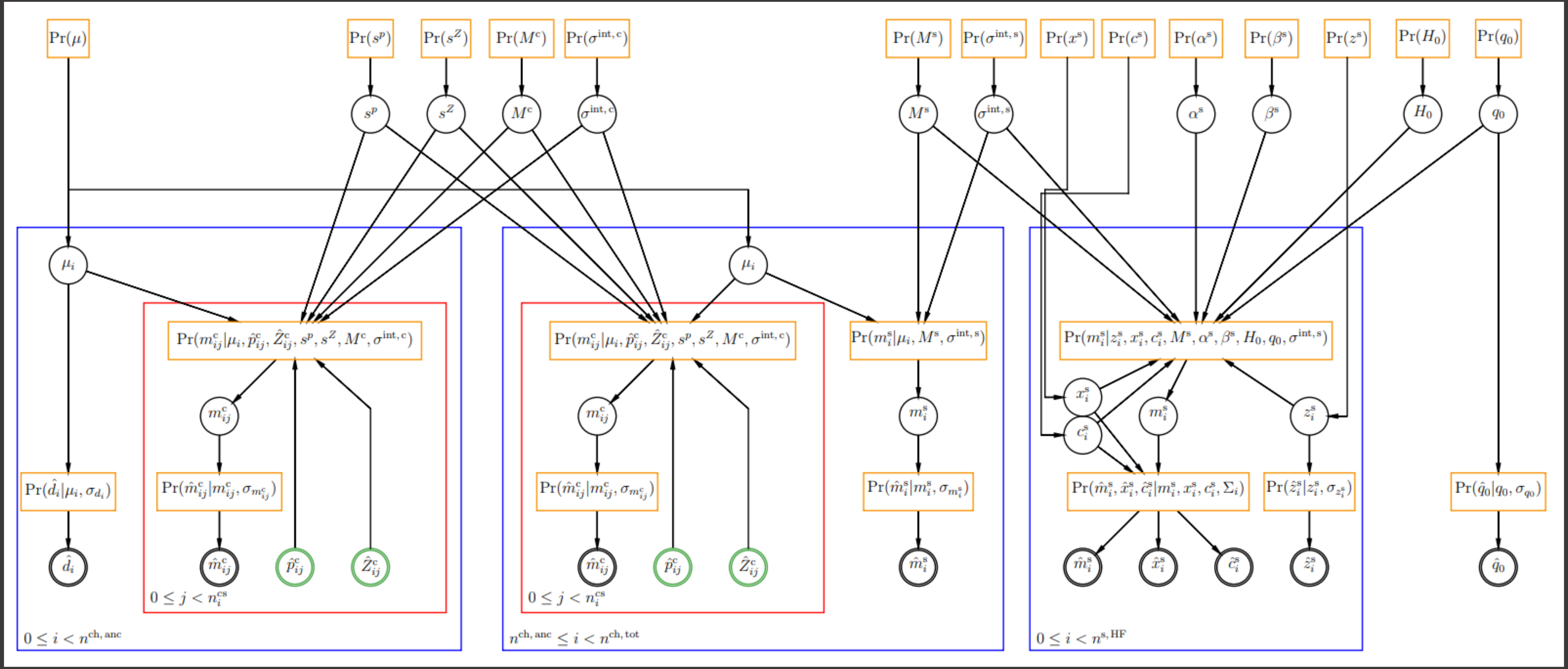
$$N \approx 28000$$

$$\frac{10\%}{\sqrt{N}} \ll 1\%$$

The probabilistic model can be adapted to a full Hubble parameter inference



Feeney++, 2017

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Zero-point expected in Data Release 3 as well

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More accurate astrometry

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Deeper/Dimmer sources

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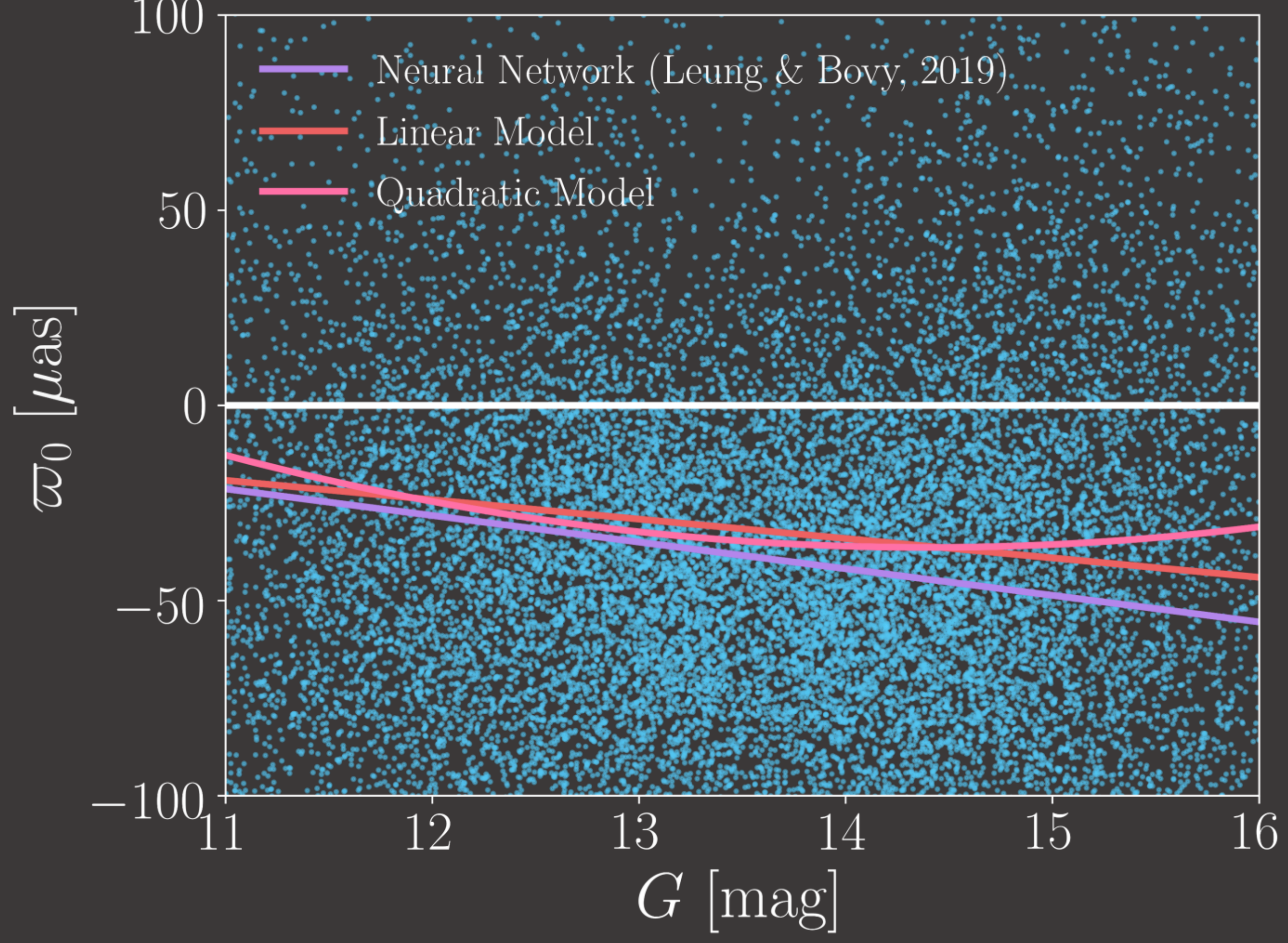
Spectra

In summary…

- *Gaia* has the potential to greatly improve local H_0 measurements
- We infer a zero-point parallax of -48.9 ± 0.9 µas if constant
  - Most precise to date
- Magnitude, colour, and sky position dependence can be included
- Probabilistic model can be extended to a full H_0 inference

The zero-point parallax appears to be more significant for dim sources



Preliminary!!!

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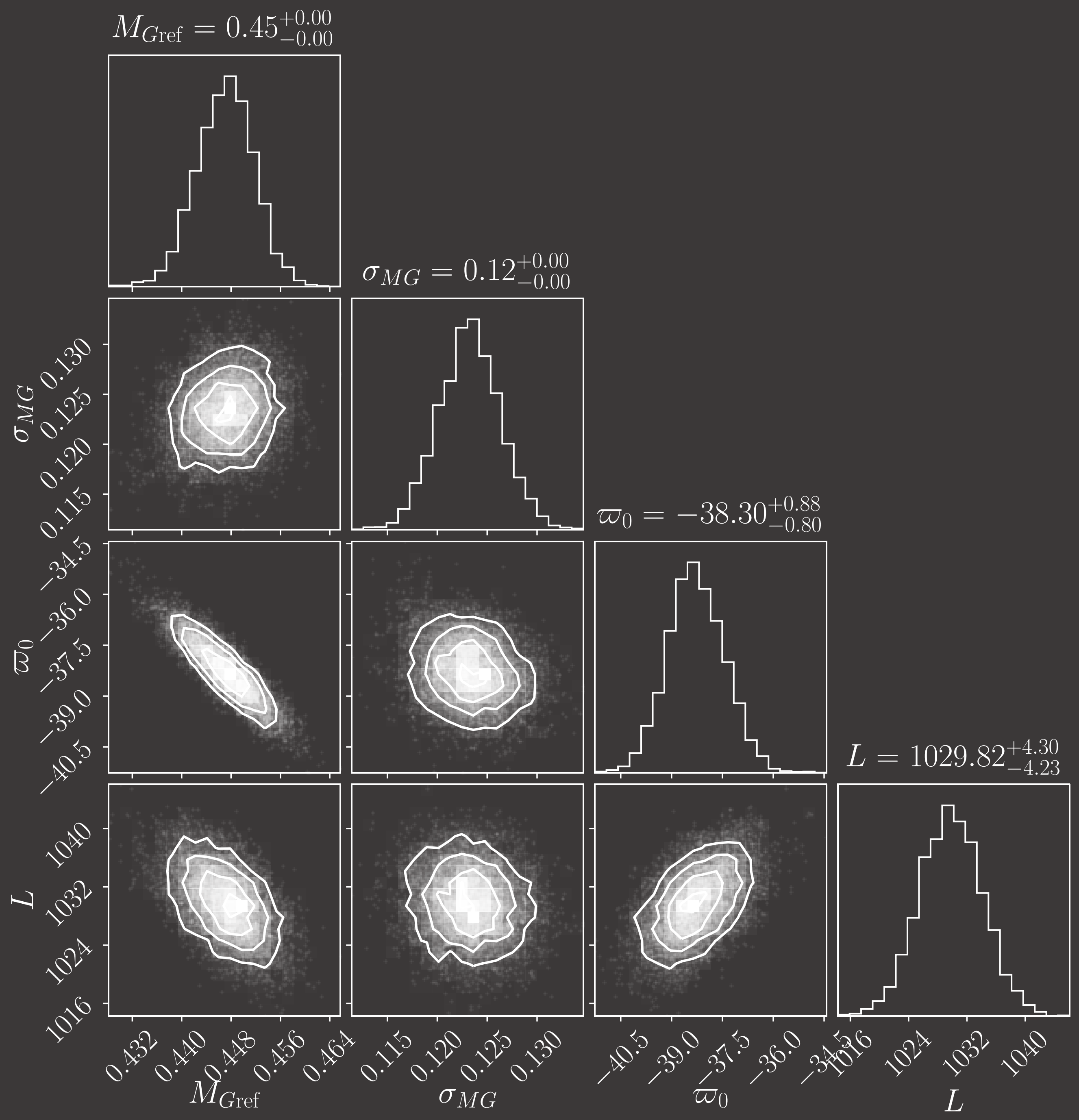
G band photometric inference



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Analogous to covariance matrix

The combined photometry model favours K_s band results