CHRONOSTAR: UNSUPERVISED, BLIND DISCOVERY AND AGEING OF STELLAR ASSOCIATIONS

Timothy Crundall

Prof. Michael Ireland (Masters supervisor)

Prof. Mark Krumholz (Masters supervisor)

Prof. Christoph Federrath

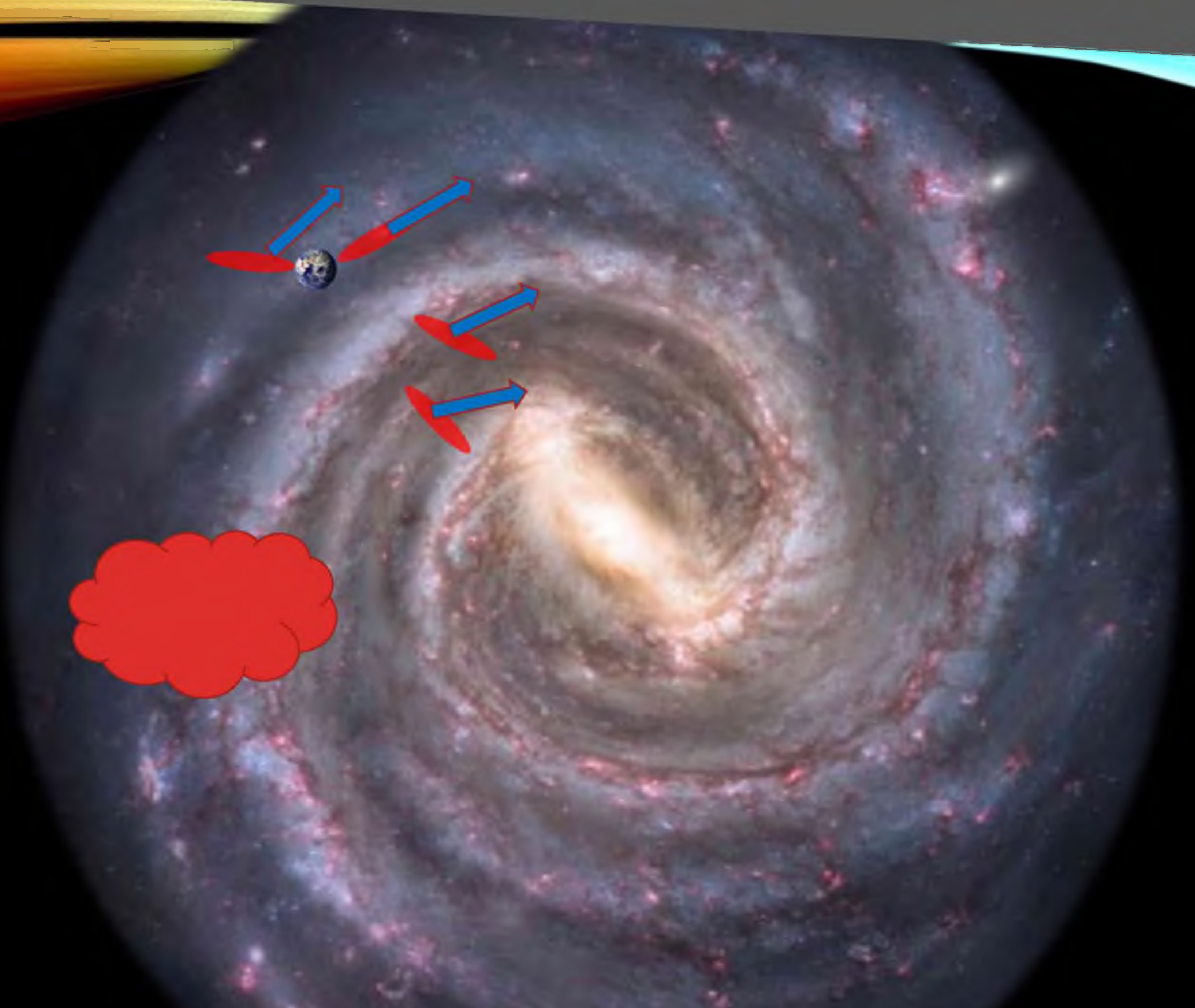
Dr. Maruša Žerjal

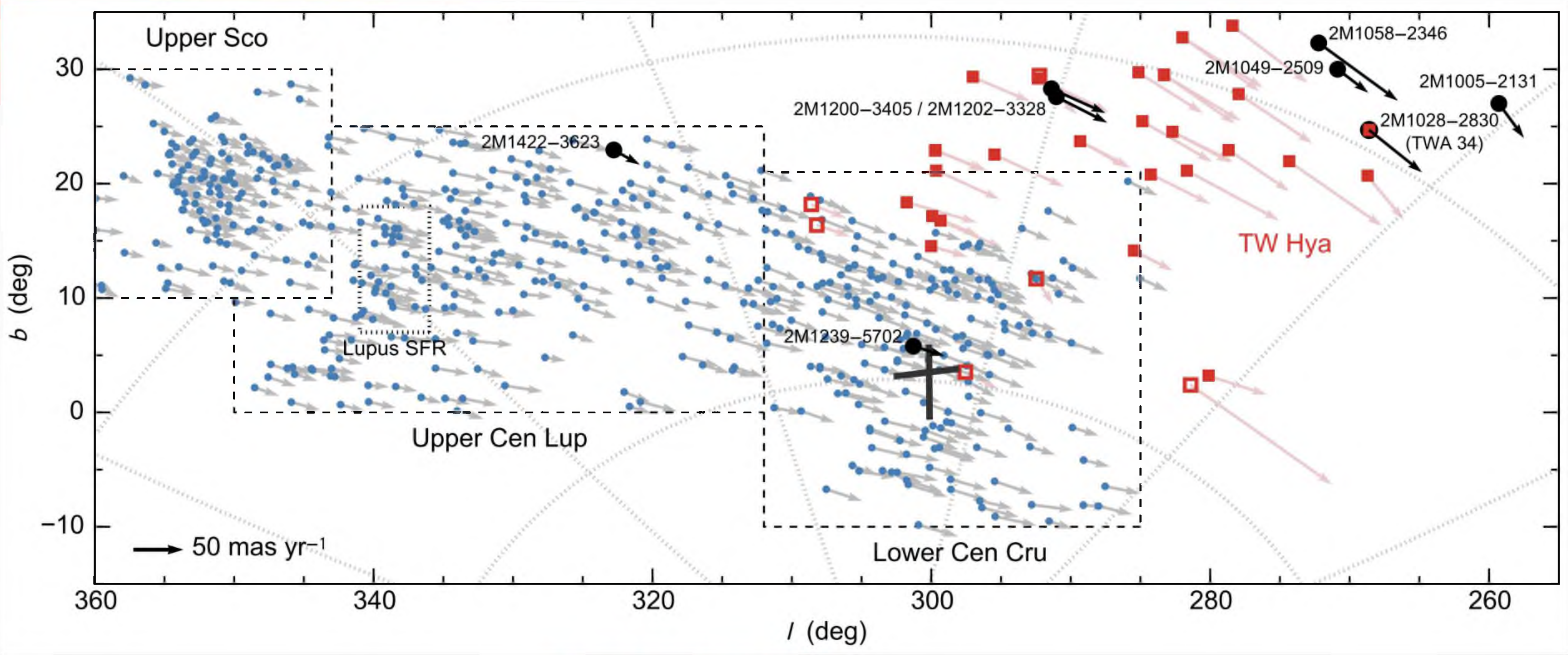
Jonah Hansen

"… practically didn't do anything" - J. Hansen

Australian National University

Universität zu Köln





Murphy et al. 2015

MOTIVATION

- Vast majority of young-ish (<200 Myr) stars are unbound
- Kinematic analysis promises to find the origins of all these stars and assign an age

WE NEED A METHOD THAT

Can derive

- Initial location
- Initial distribution
- A consistent age

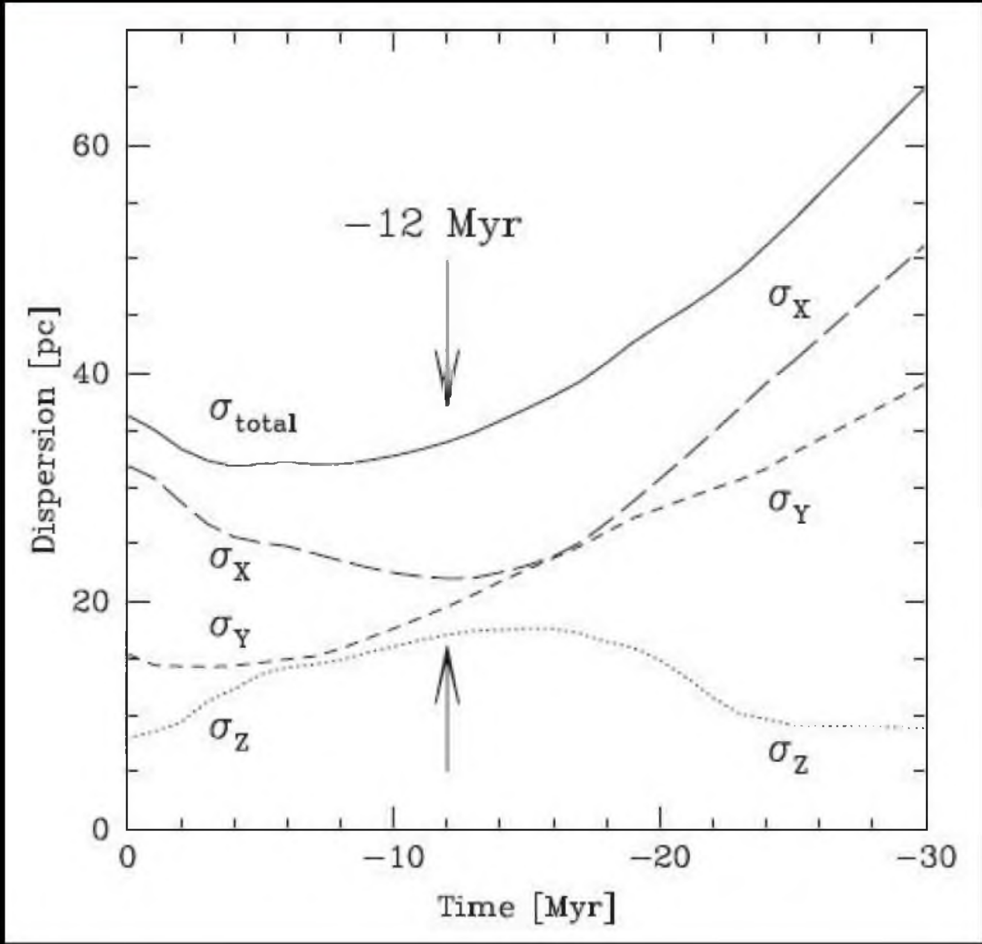
But also

- Is not sensitive to membership selection
- Can handle partial memberships
- Can handle complicated formation histories
- Is robust to measurement uncertainties

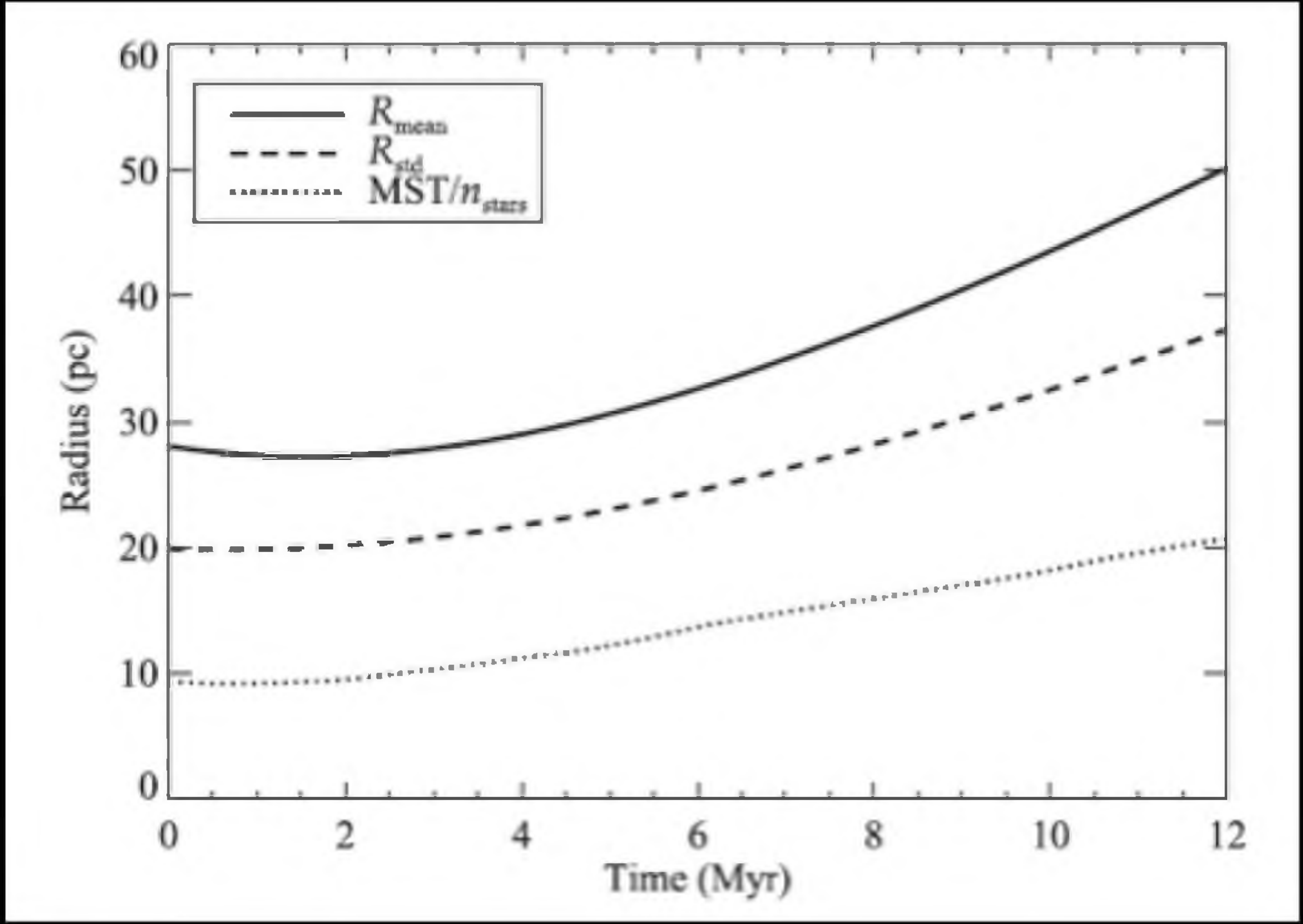
CLASSICAL APPROACH

CLASSICAL APPROACH

TRACEBACK



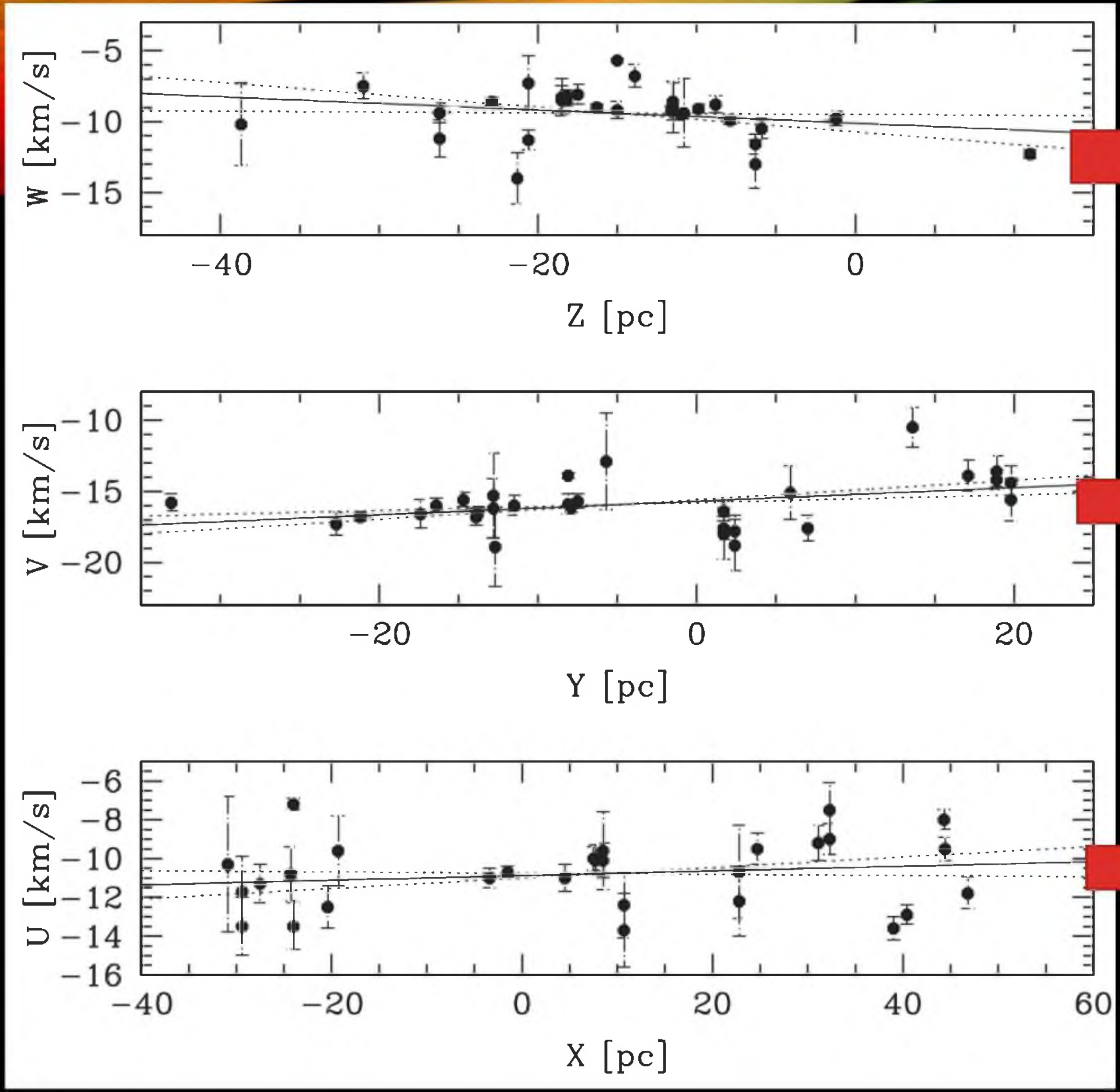
BPMG
Mamajek and Bell 2014



TWA
Donaldson et al. 2016

CLASSICAL APPROACH

EXPANSION AGES



$$\frac{\mathrm{km\ s^{-1}}}{\mathrm{pc}} \sim \frac{1}{\mathrm{time}}$$

BPMG
Mamajek and Bell 2014

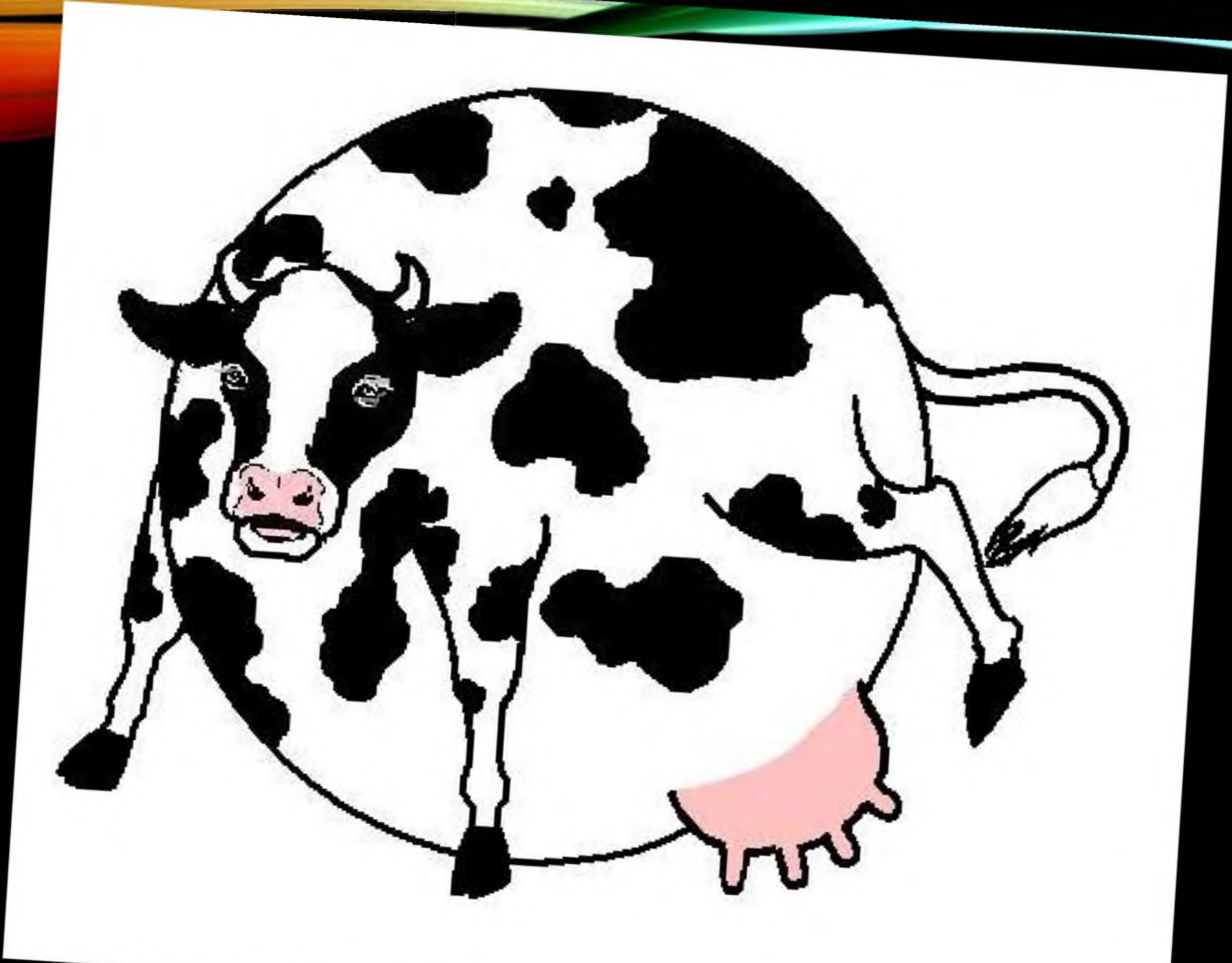
CLASSICAL APPROACH

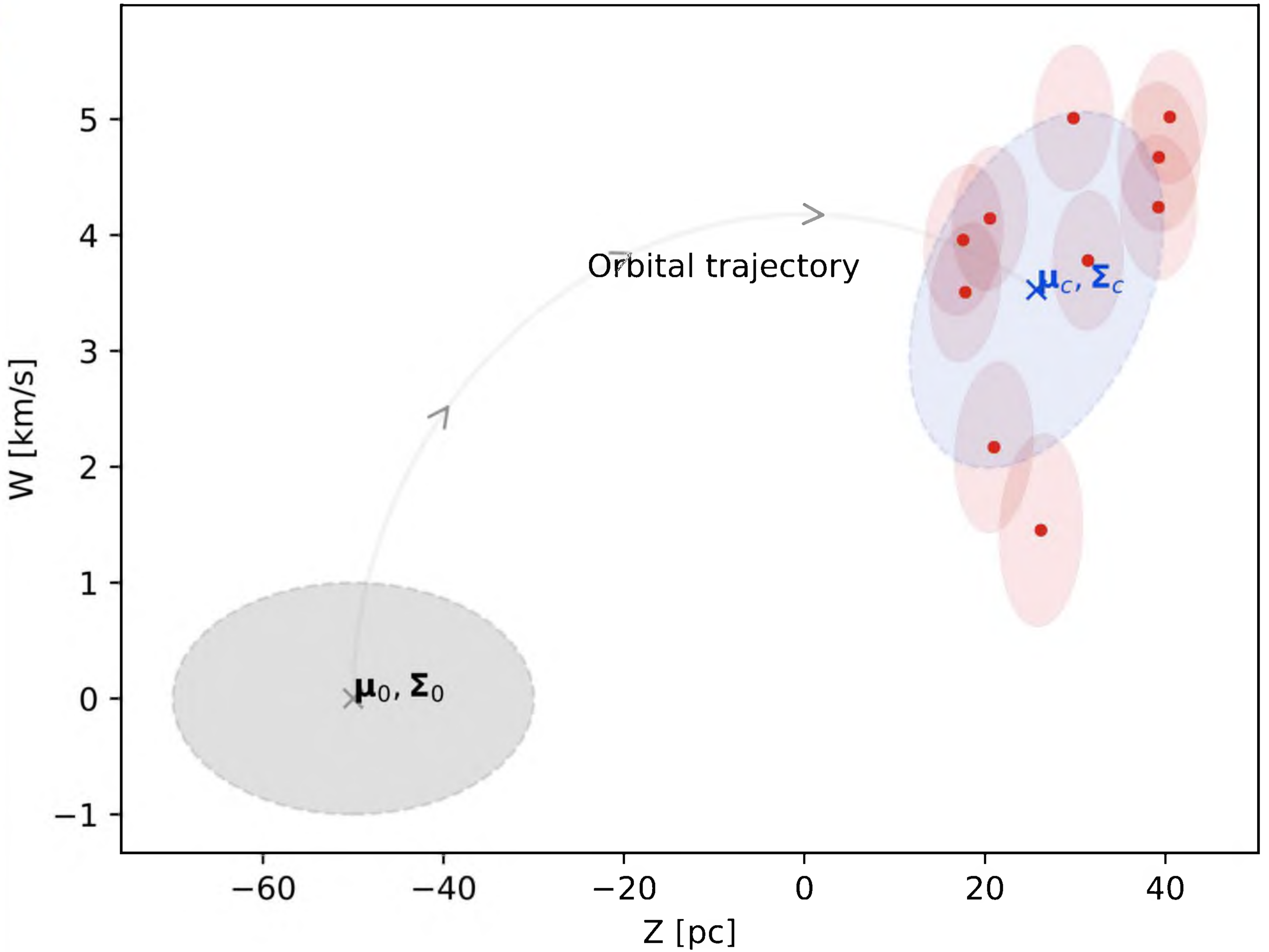
KINEMATIC AGES

Reference	Age	Method
–	(Myr)	–
Barrado y Navascués et al. (1999)	20 ± 10 Myr	CMD isochronal age (KM stars)
Zuckerman et al. (2001)	12^{+8}_{-4} Myr	H–R diagram isochronal age (GKM stars) + Li depletion
Ortega et al. (2002)	11.5 Myr	Traceback age
Song et al. (2003)	12 Myr	Traceback age
Ortega et al. (2004)	10.8 ± 0.3 Myr	Traceback age
Torres et al. (2006)	~18 Myr	Expansion age
Makarov (2007)	22 ± 12 Myr	Traceback age
Mentuch et al. (2008)	21 ± 9 Myr	Li depletion
Macdonald & Mullan (2010)	~40 Myr	Li depletion (magnetoconvection models)
Binks & Jeffries (2014)	21 ± 4 Myr	Li depletion boundary
Malo et al. (2014)	26 ± 3 Myr	Li depletion boundary
Malo et al. (2014)	21.5 ± 6.5 Myr (15–28 Myr)	H–R diagram isochronal age (KM stars)
This work	22 ± 3 Myr	CMD isochronal age (FG stars)
Final	**23 ± 3 Myr (1σ) [±2 Myr (statistical), ±2 Myr (systematic)]**	Li depletion boundary and isochronal age (FGKM stars)

Mamajek & Bell 2014

CHRONOSTAR
BAYESIAN APPROACH – TRACEFORWARD





Orbital trajectory
$\boldsymbol{\mu}_0, \boldsymbol{\Sigma}_0$
$\boldsymbol{\mu}_C, \boldsymbol{\Sigma}_C$
W [km/s]
Z [pc]
5
4
3
2
1
0
−1
−60
−40
−20
0
20
40

SCORING THE MODEL

$$p(C|D) \propto p_{\mathrm{prior}}(C)p(D|C)$$

$$p(D|C) \propto \prod_{i=1}^{N} \int \mathcal{N}(\boldsymbol{\theta}; \boldsymbol{\mu}_i, \boldsymbol{\Sigma}_i)\mathcal{N}(\boldsymbol{\theta}; \boldsymbol{\mu}_c, \boldsymbol{\Sigma}_c)\, d\boldsymbol{\theta} \equiv \prod_{i=1}^{N} \Omega_{i,c}$$

SYNTHETIC DATA

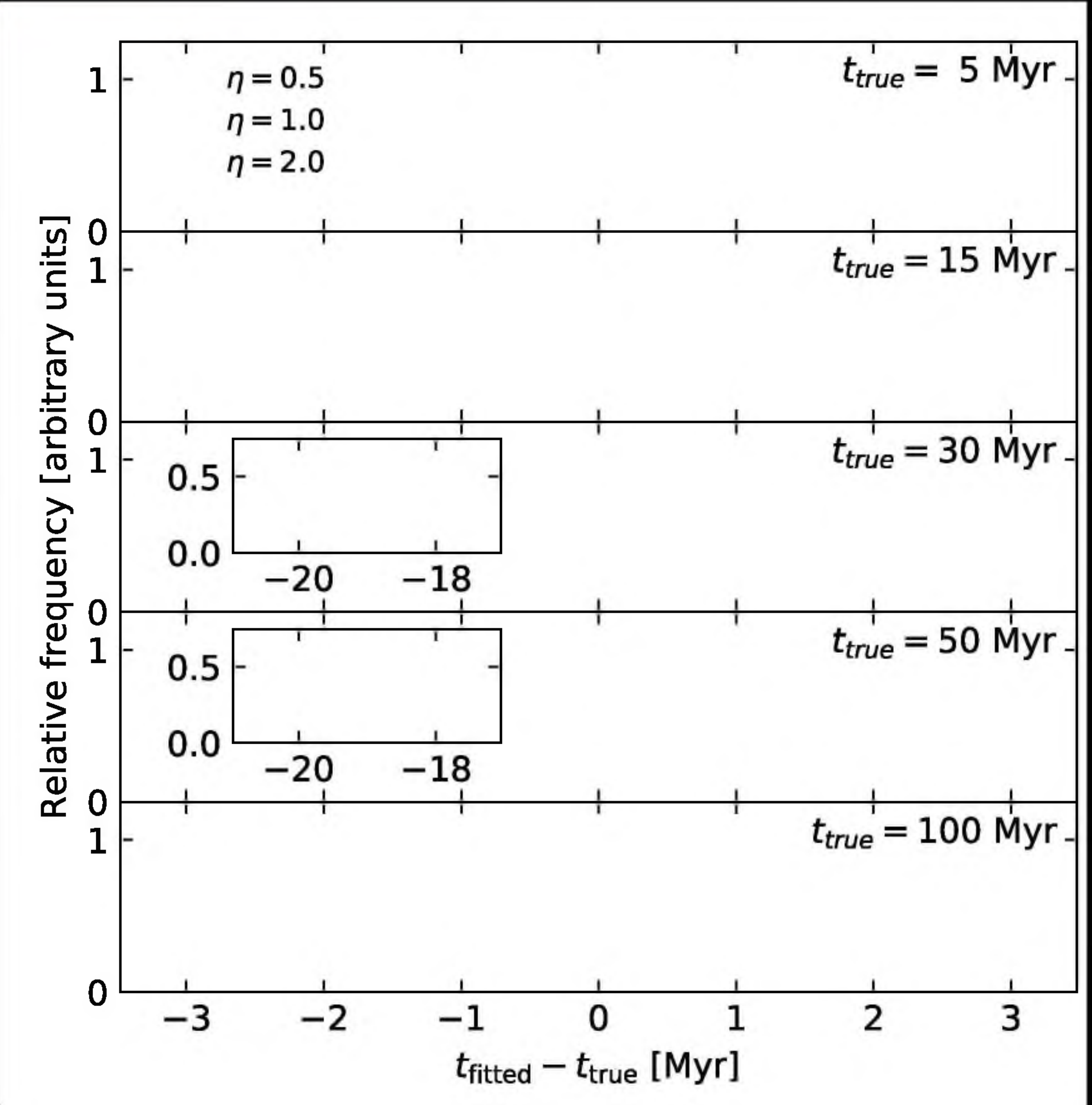
- Use synthetic data to test accuracy of this method

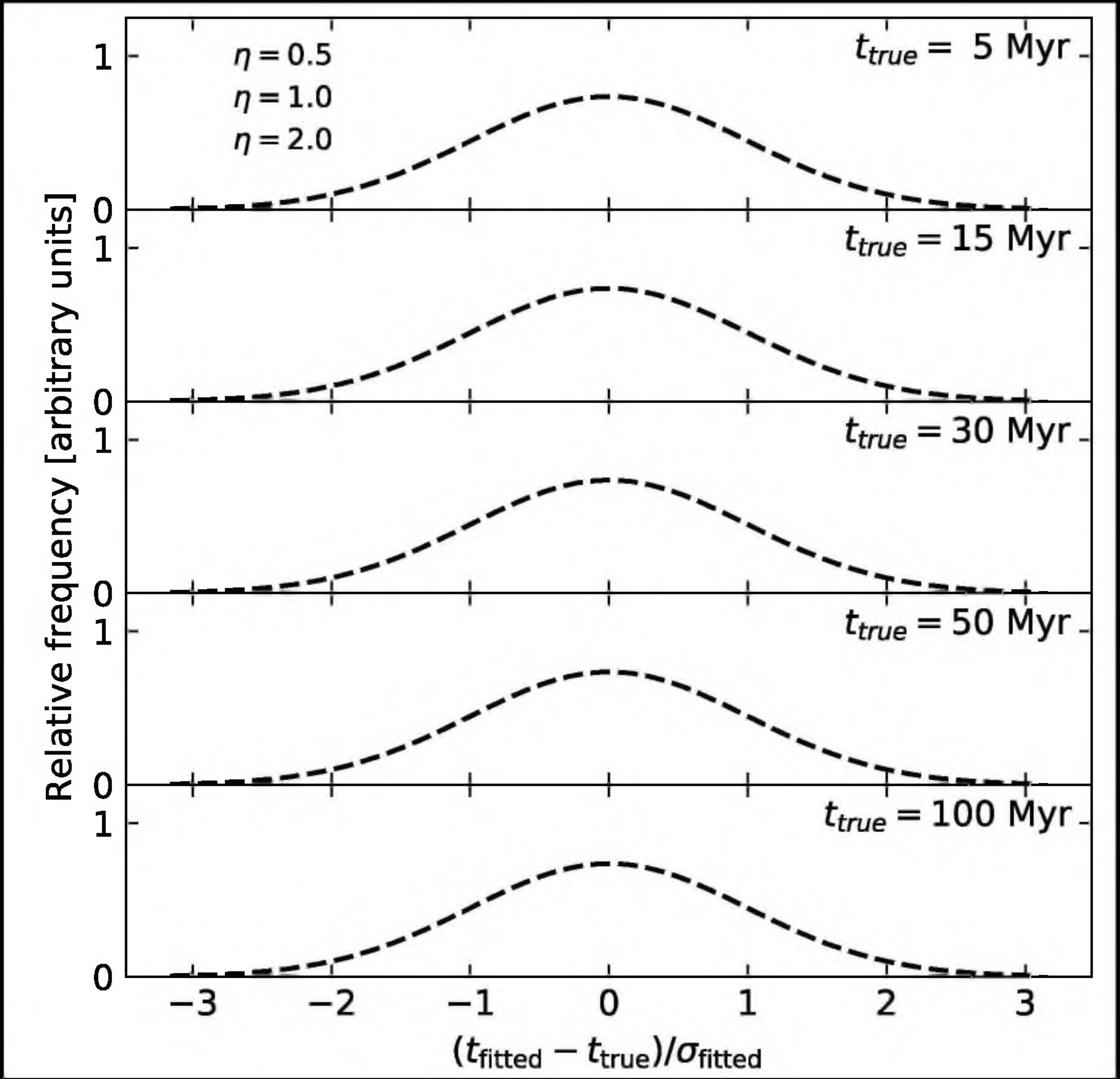
- Generate stars from a **6D Gaussian** (that matches assumptions)
- Project them forward in time through the **galactic potential**
- **Measure** stars in current epoch
  - Using median Gaia DR2 uncertainties as synthetic uncertainties

- Variable star count, age, spread and velocity dispersion

TRACEFORWARD

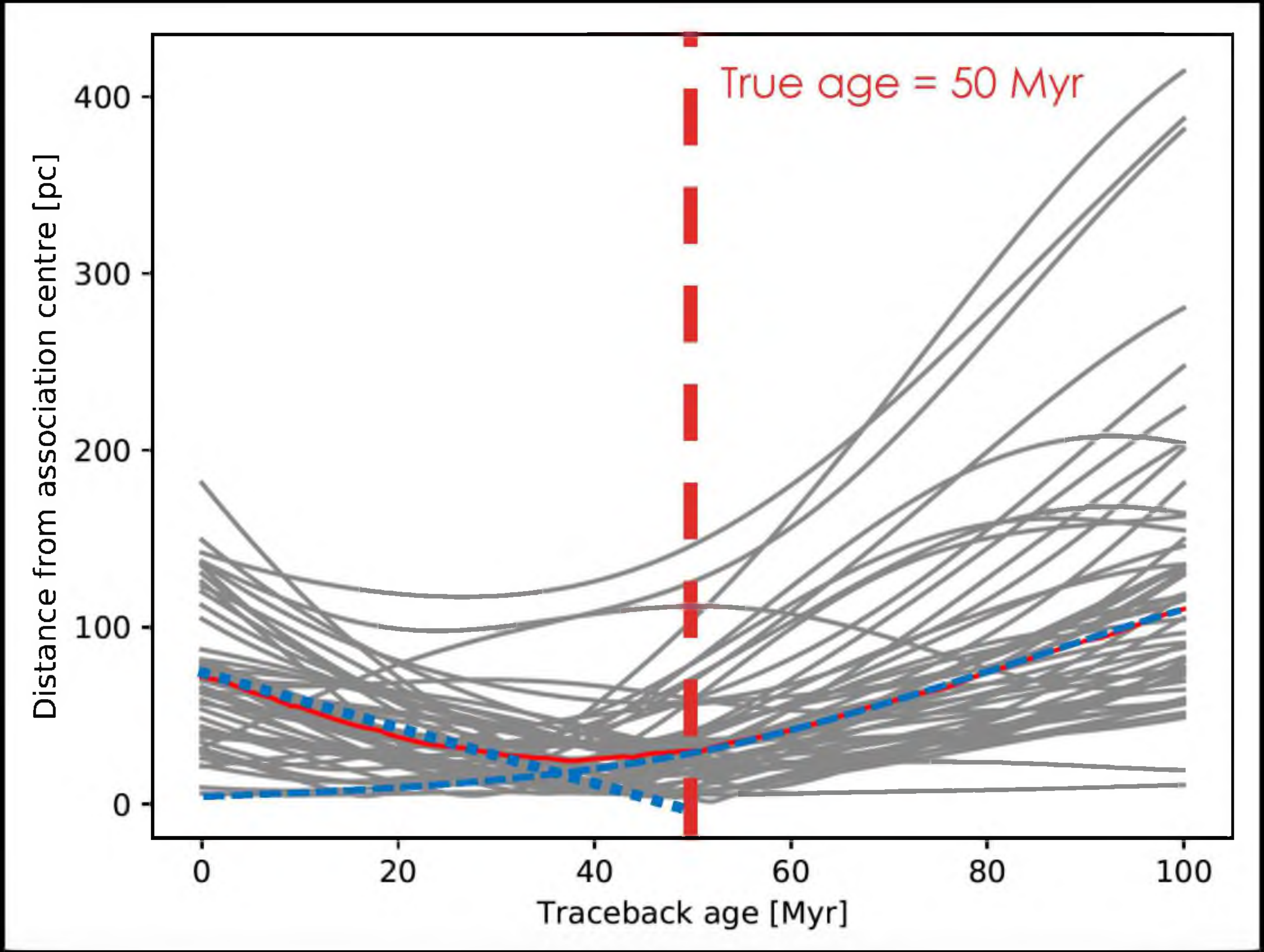
SYNTHETIC RESULTS

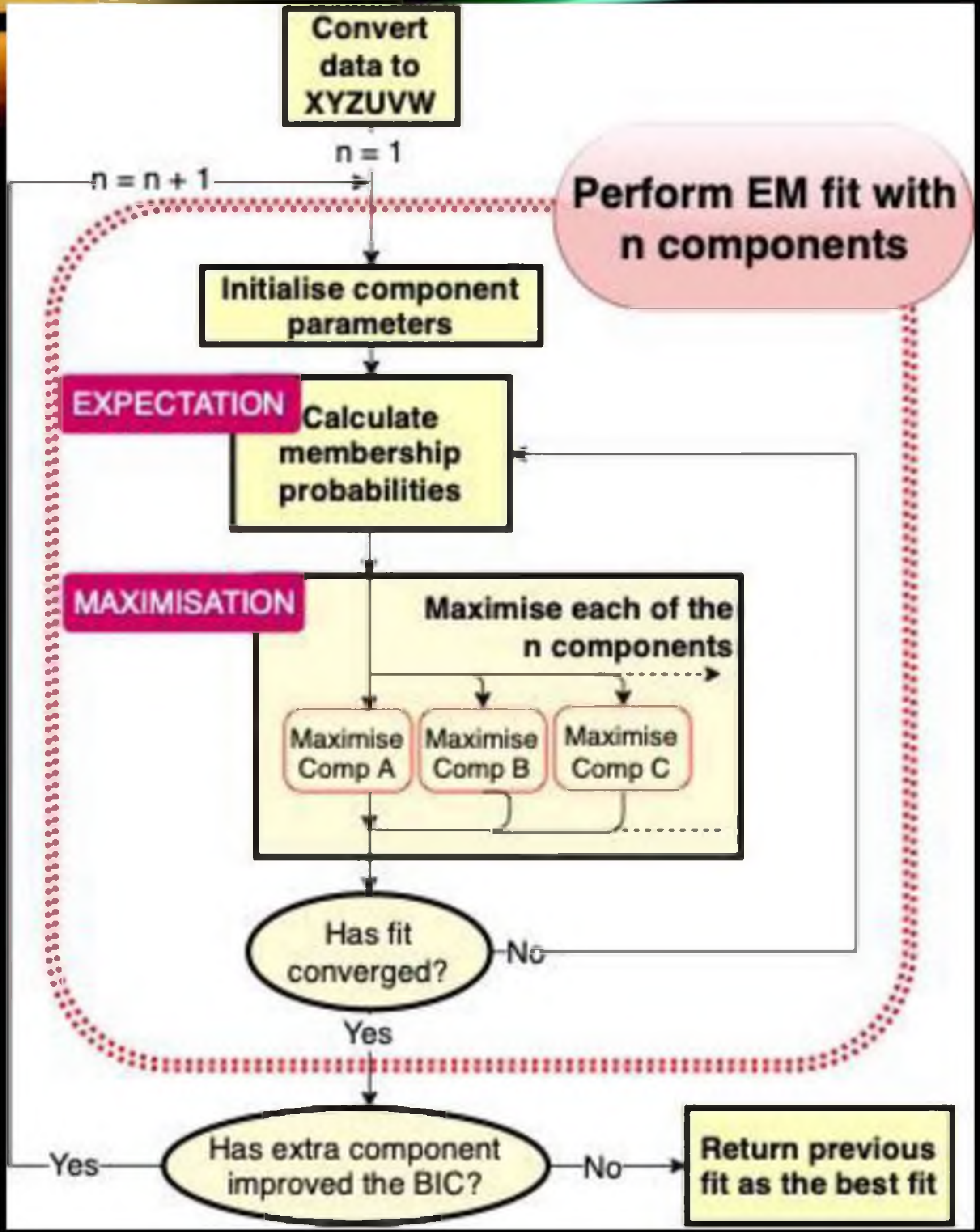


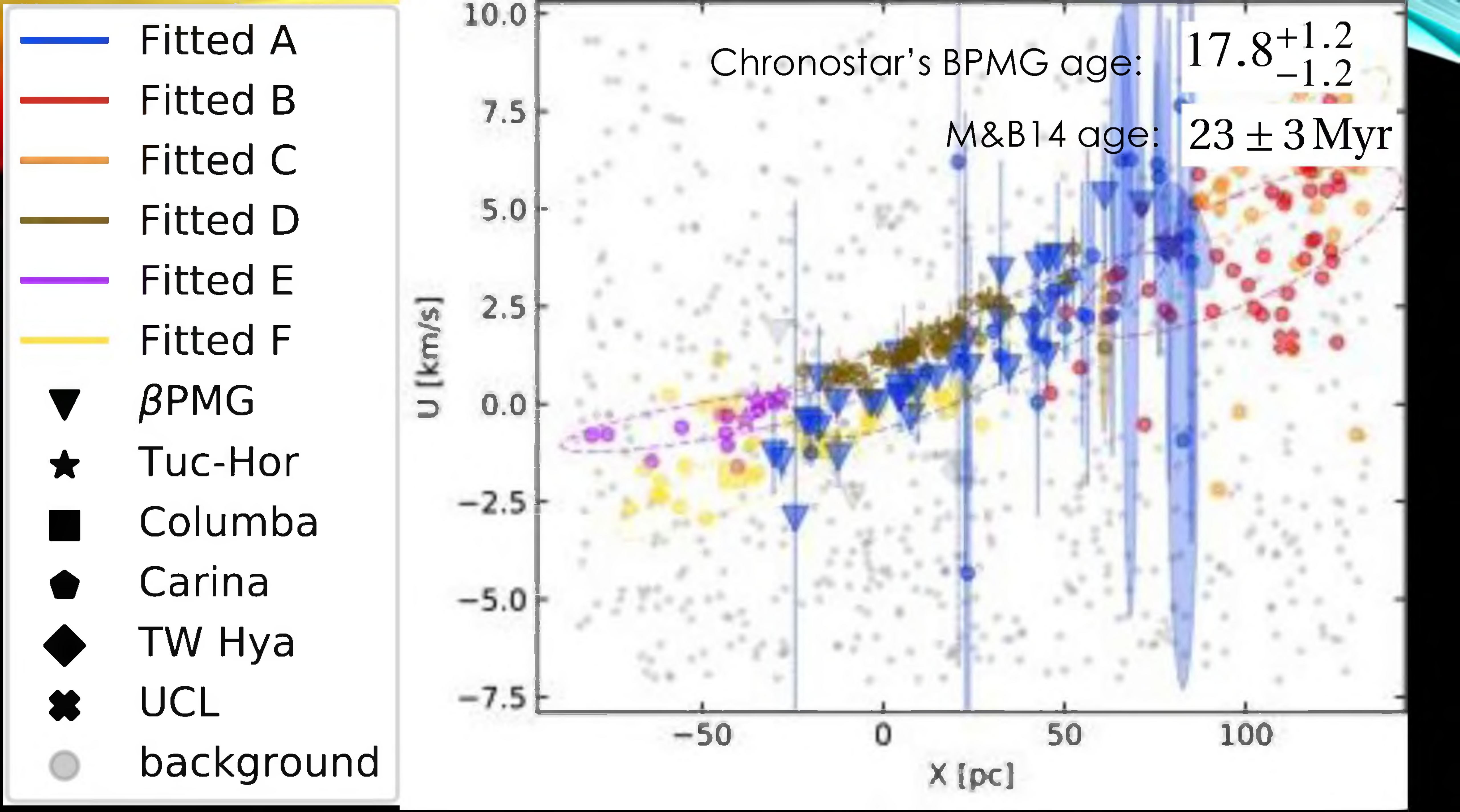


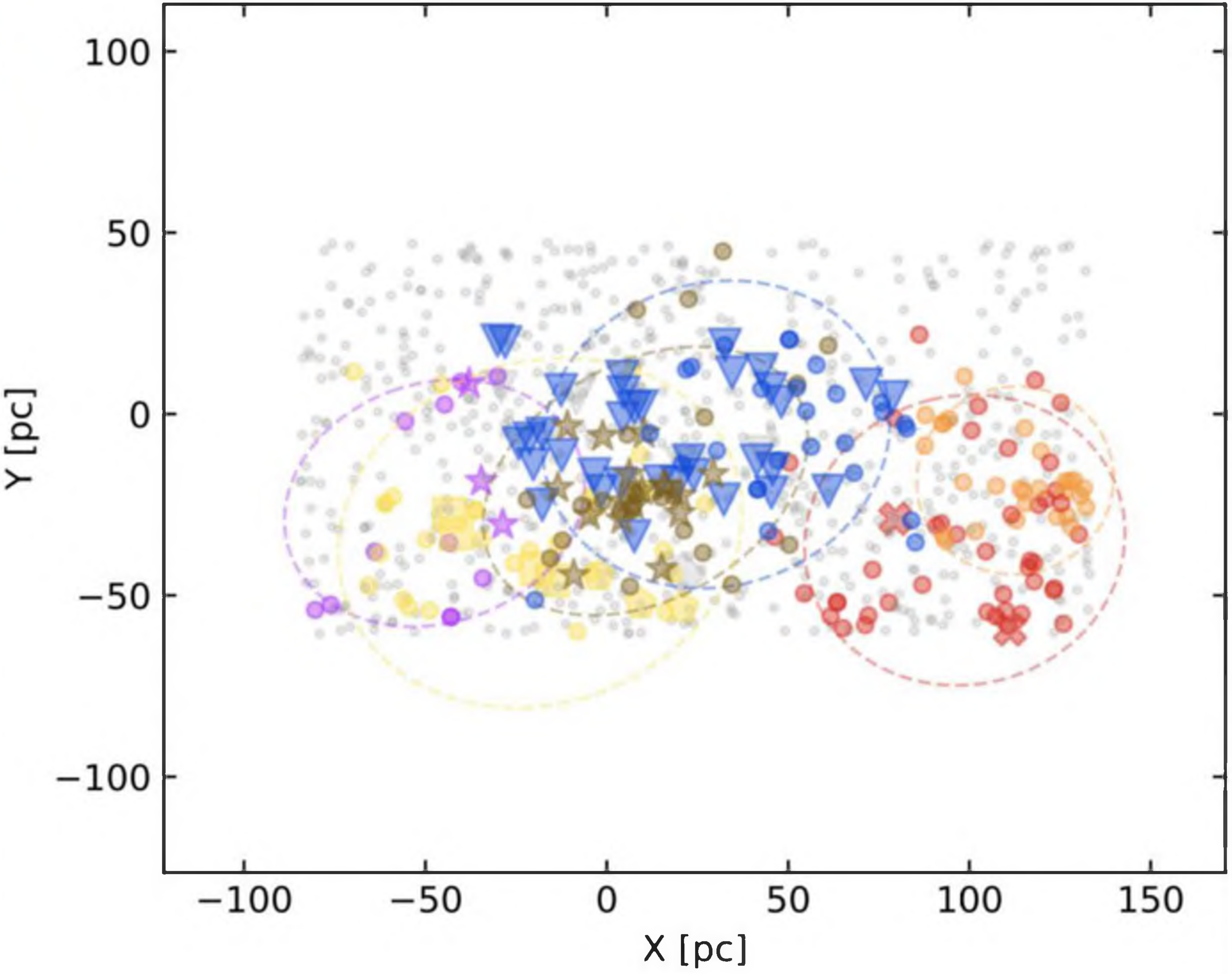
BAYESIAN APPROACH

COMPARISON TO CLASSICAL TRACEBACK

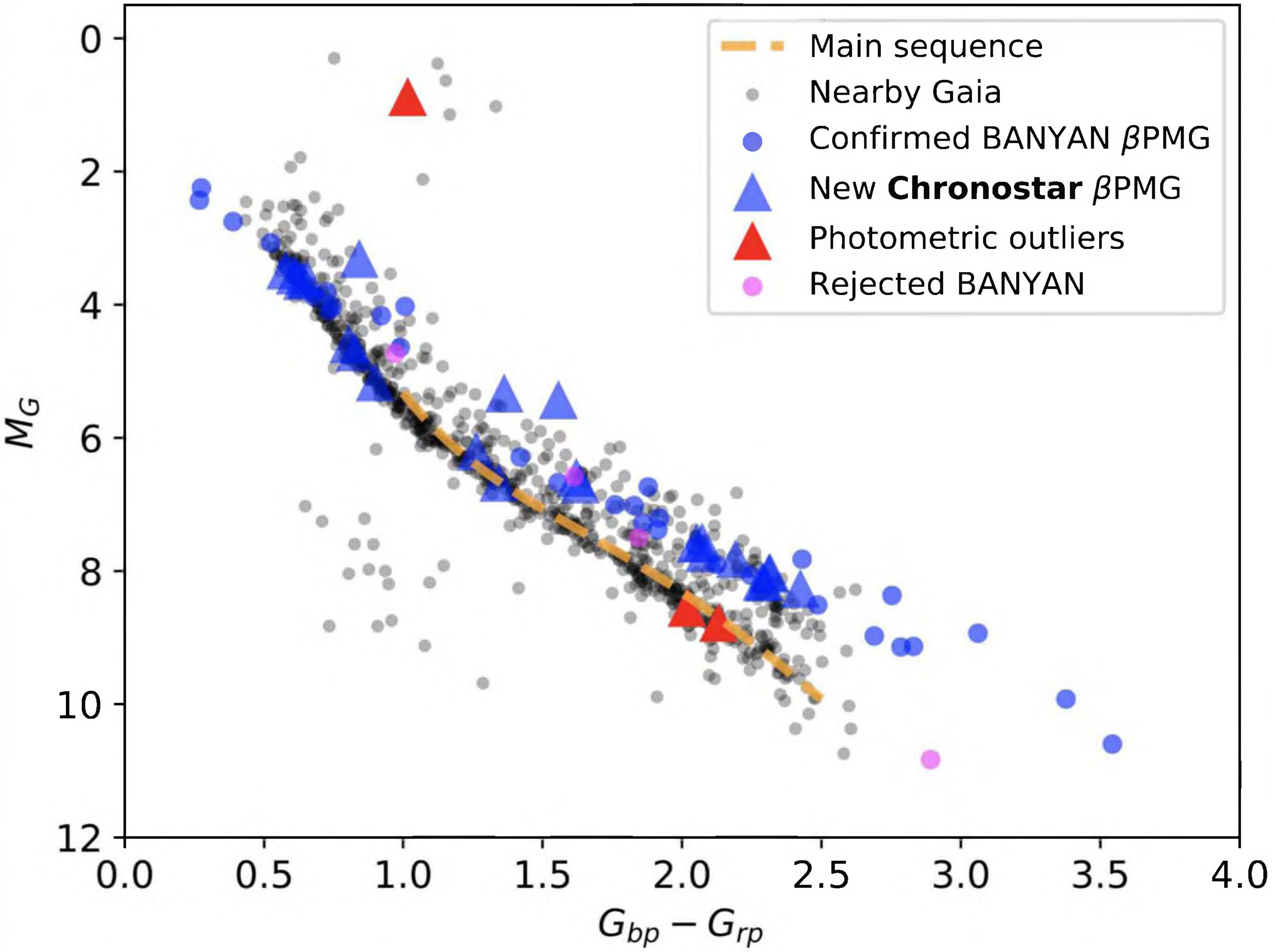



Convert data to XYZUVW
n = 1
n = n + 1
Perform EM fit with n components
Initialise component parameters
EXPECTATION
Calculate membership probabilities
MAXIMISATION
Maximise each of the n components
Maximise Comp A
Maximise Comp B
Maximise Comp C
Has fit converged?
No
Yes
Has extra component improved the BIC?
Yes
No
Return previous fit as the best fit

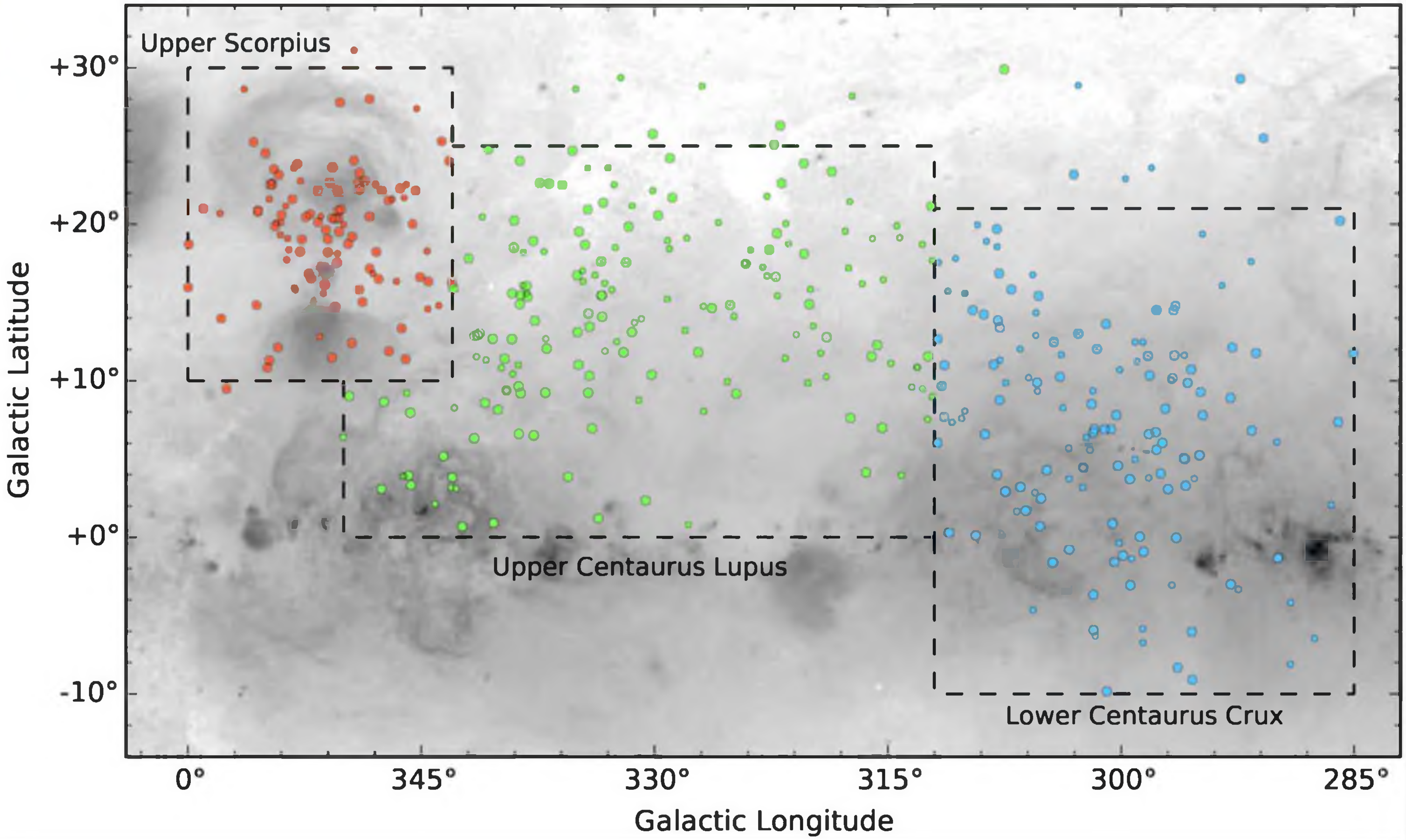

Fitted A
Fitted B
Fitted C
Fitted D
Fitted E
Fitted F
βPMG
Tuc-Hor
Columba
Carina
TW Hya
UCL
background
Chronostar's BPMG age: $17.8^{+1.2}_{-1.2}$
M&B14 age: $23 \pm 3\,\mathrm{Myr}$
U [km/s]
X [pc]
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−50
0
50
100

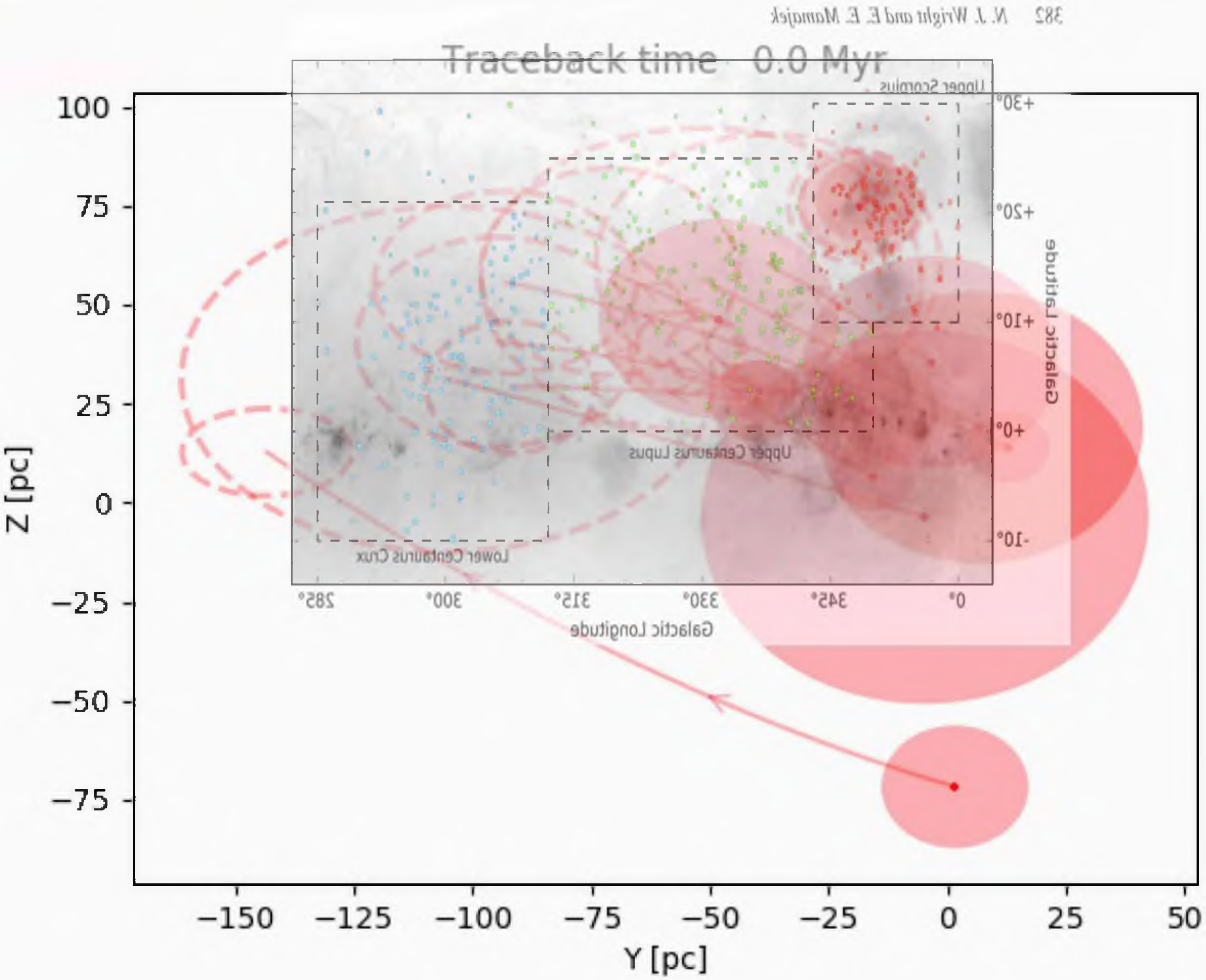


100
50
0
−50
−100
Y [pc]
−100
−50
0
50
100
150
X [pc]



Main sequence
Nearby Gaia
Confirmed BANYAN βPMG
New **Chronostar** βPMG
Photometric outliers
Rejected BANYAN
M_G
$G_{bp} - G_{rp}$
0
2
4
6
8
10
12
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0


Upper Scorpius
Upper Centaurus Lupus
Lower Centaurus Crux
Galactic Latitude
+30°
+20°
+10°
+0°
-10°
0°
345°
330°
315°
300°
285°
Galactic Longitude



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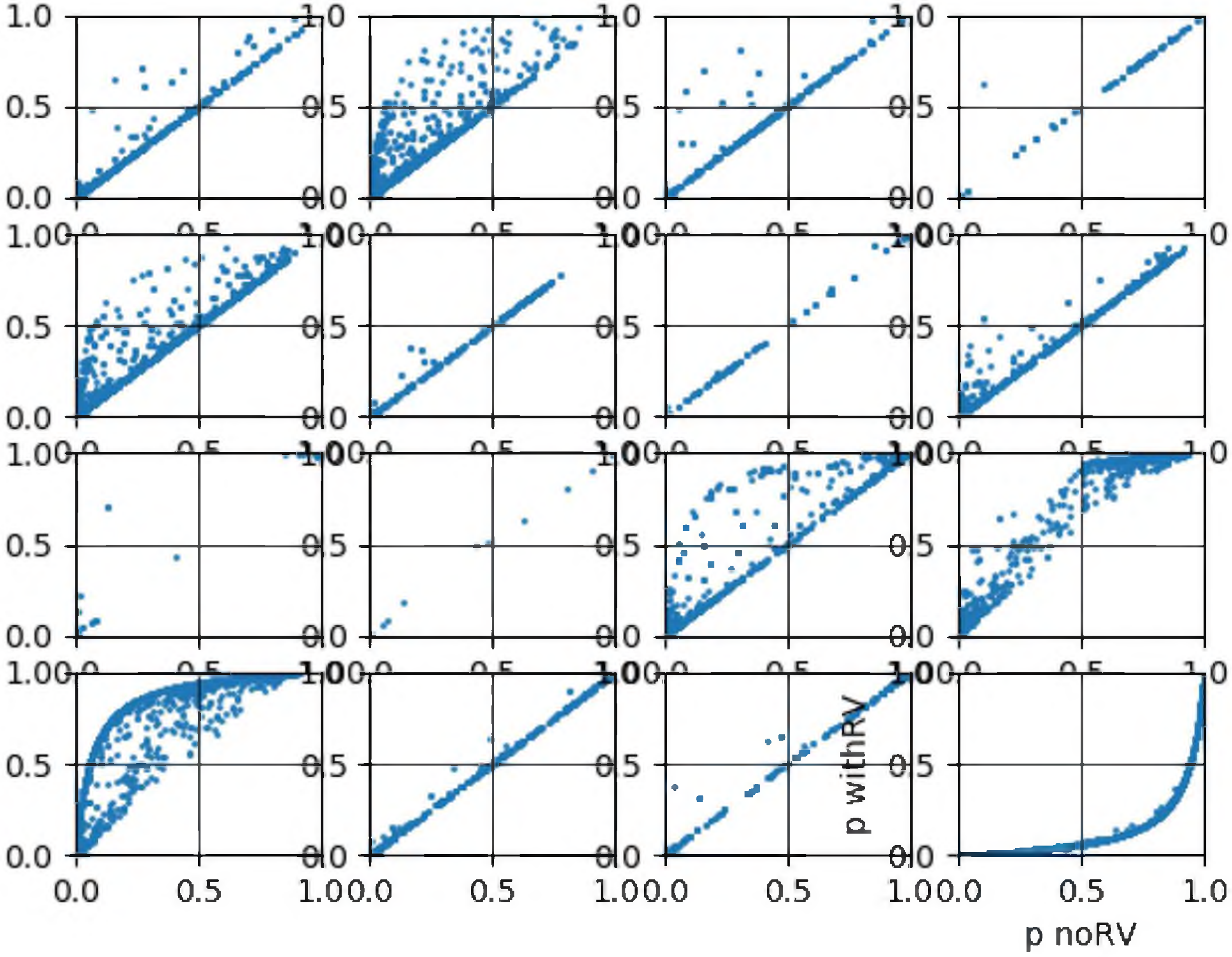
Traceback time 0.0 Myr
Upper Scorpius
Upper Centaurus Lupus
Lower Centaurus Crux
Galactic Latitude
Galactic Longitude
+30°
+20°
+10°
+0°
-10°
285°
300°
315°
330°
345°
0°
Z [pc]
100
75
50
25
0
−25
−50
−75
Y [pc]
−150
−125
−100
−75
−50
−25
0
25
50


1.0
0.5
0.0
0.0
0.5
1.0
p withRV
p noRV

SUMMARY

- Chronostar accurately and reliably retrieves kinematic ages from Gaussian initial conditions up to 100 Myr
- Can reliably decompose complicated combinations of synthetic associations
- First kinematic ages that are consistent with chemical ages
- Able to blindly rediscover BPMG (and Tucana Horolgium!)
- Able to decompose massive, complicated associations with sensible results
- RVs not needed!

NEXT STEPS

NEXT STEPS

- Allow for **non-isotropic** initial velocity dispersion
- Methodically go through all known moving groups/associations and calculate kinematic ages from current membership lists
- Decompose large complicated associations (e.g. Sco-Cen)
- Improve performance (epicyclic approximations, action space)
- Search through all of Gaia DR2