Asteroseismic inference for populations of stars

Talk @ *Getting ready for PLATO*

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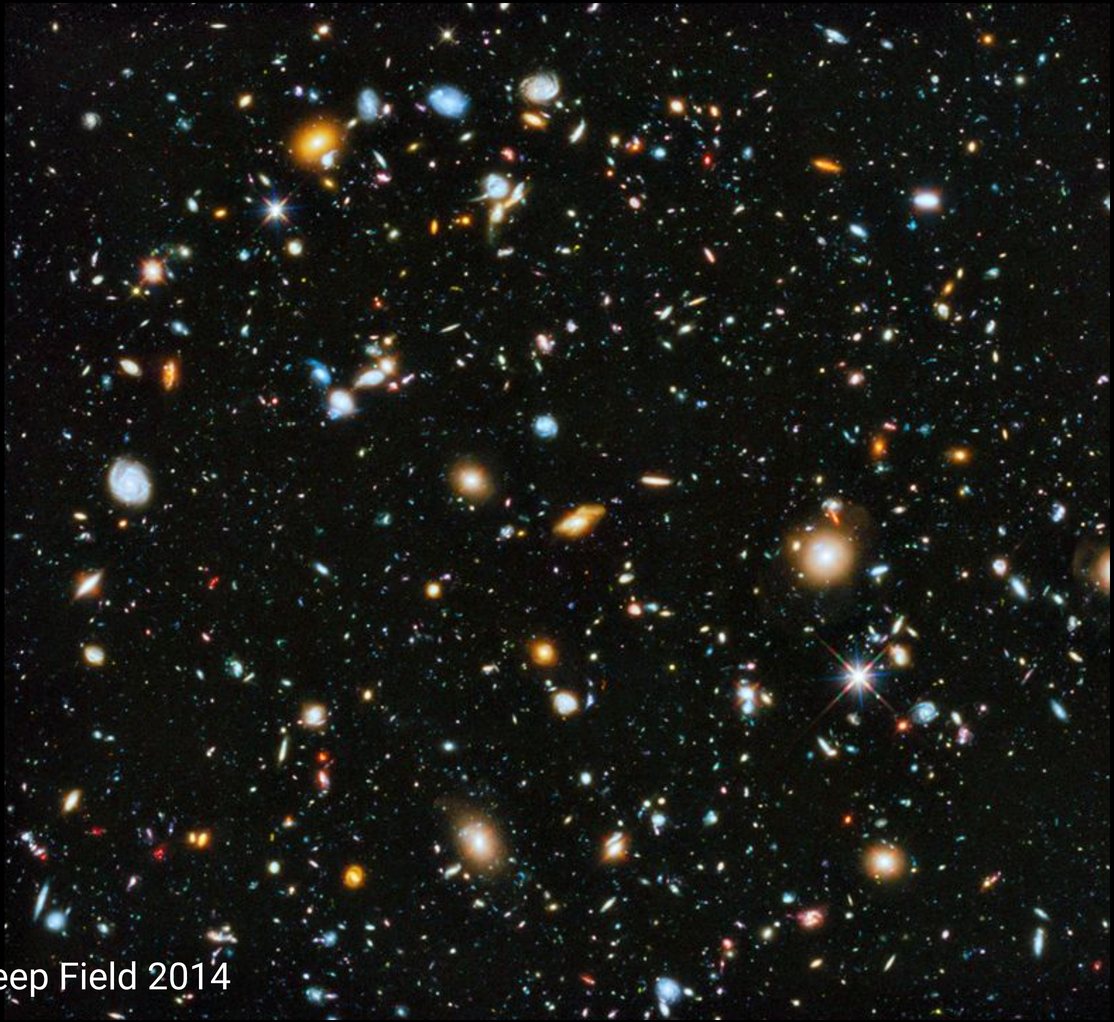


Hubble Ultra Deep Field 2014

The Milky Way is at the same time both **generic** and **unique**.

Generic: similar structural components as other disc-type galaxies[1]

Unique: Our position within the Galaxy allows us to study the Milky Way and its stellar populations to a different level of detail than for similar studies in other galaxies.

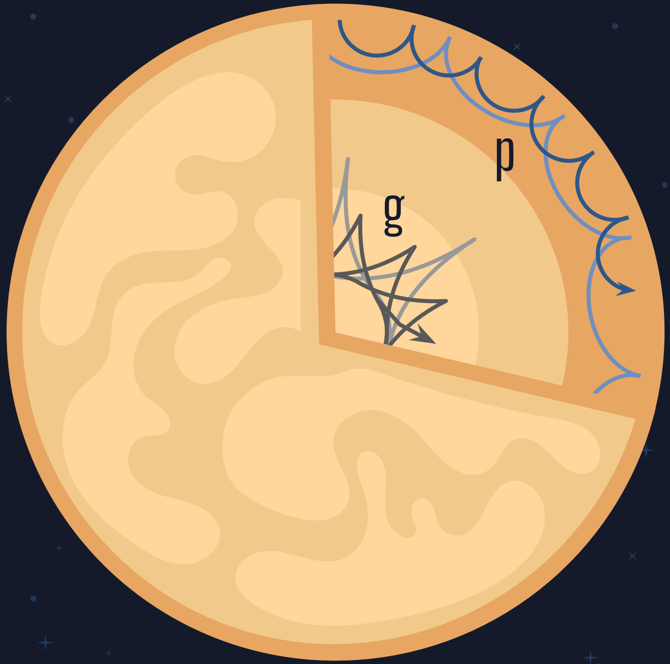
[1] *e.g. SAGA survey II, Mao et al. 2020*

The Milky Way as seen by its stars

p(chemical composition, orbit, age)

I.

Solar-like Oscillations



p-modes

Restoring force is the pressure gradient. Generally confined to the outer regions.

g-modes

Restoring force is buoyancy. Typically confined within the deep radiative interior.

Three quantum numbers:

Radial order n

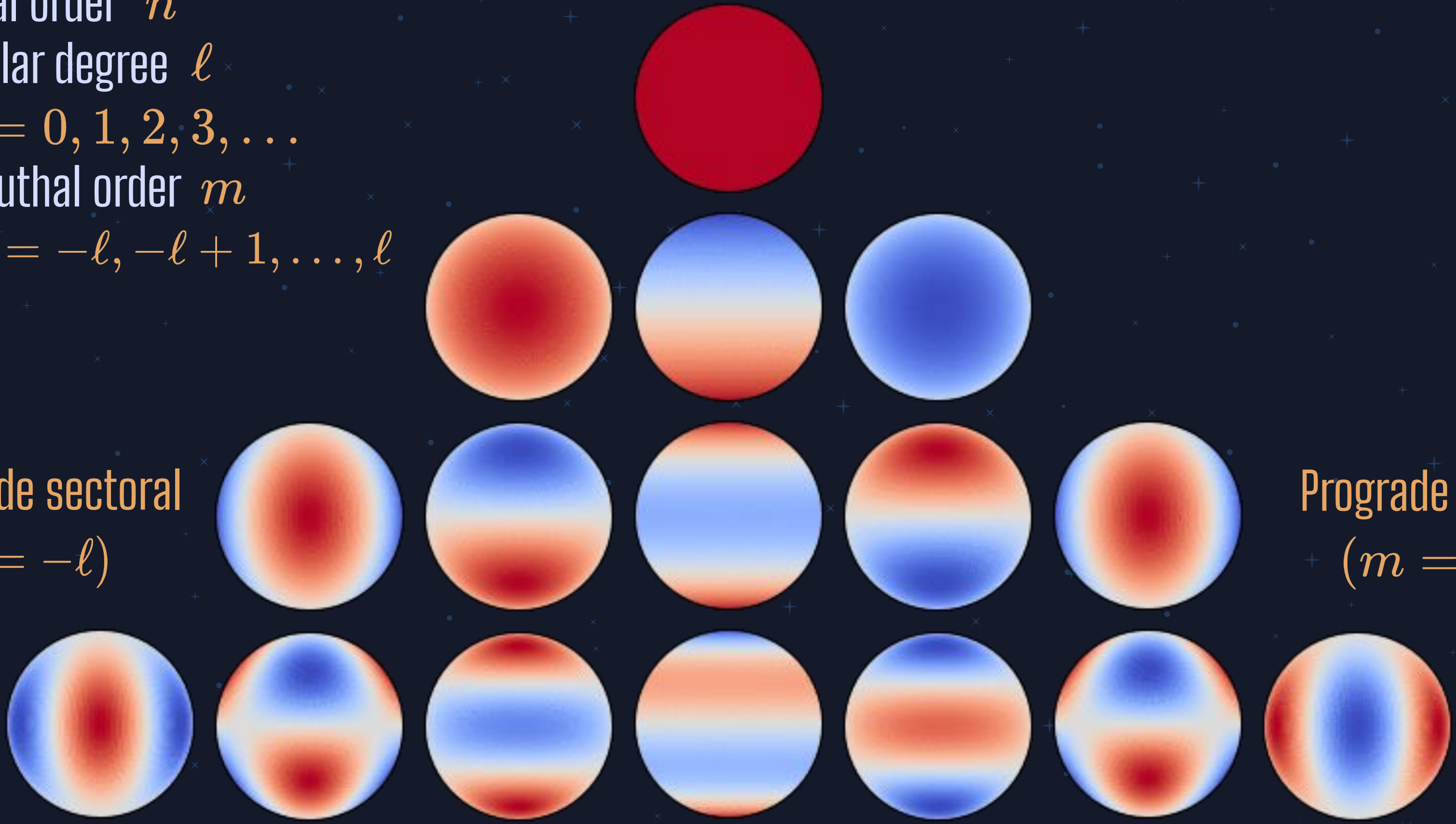
Angular degree ℓ

$\ell = 0, 1, 2, 3, \ldots$

Azimuthal order m

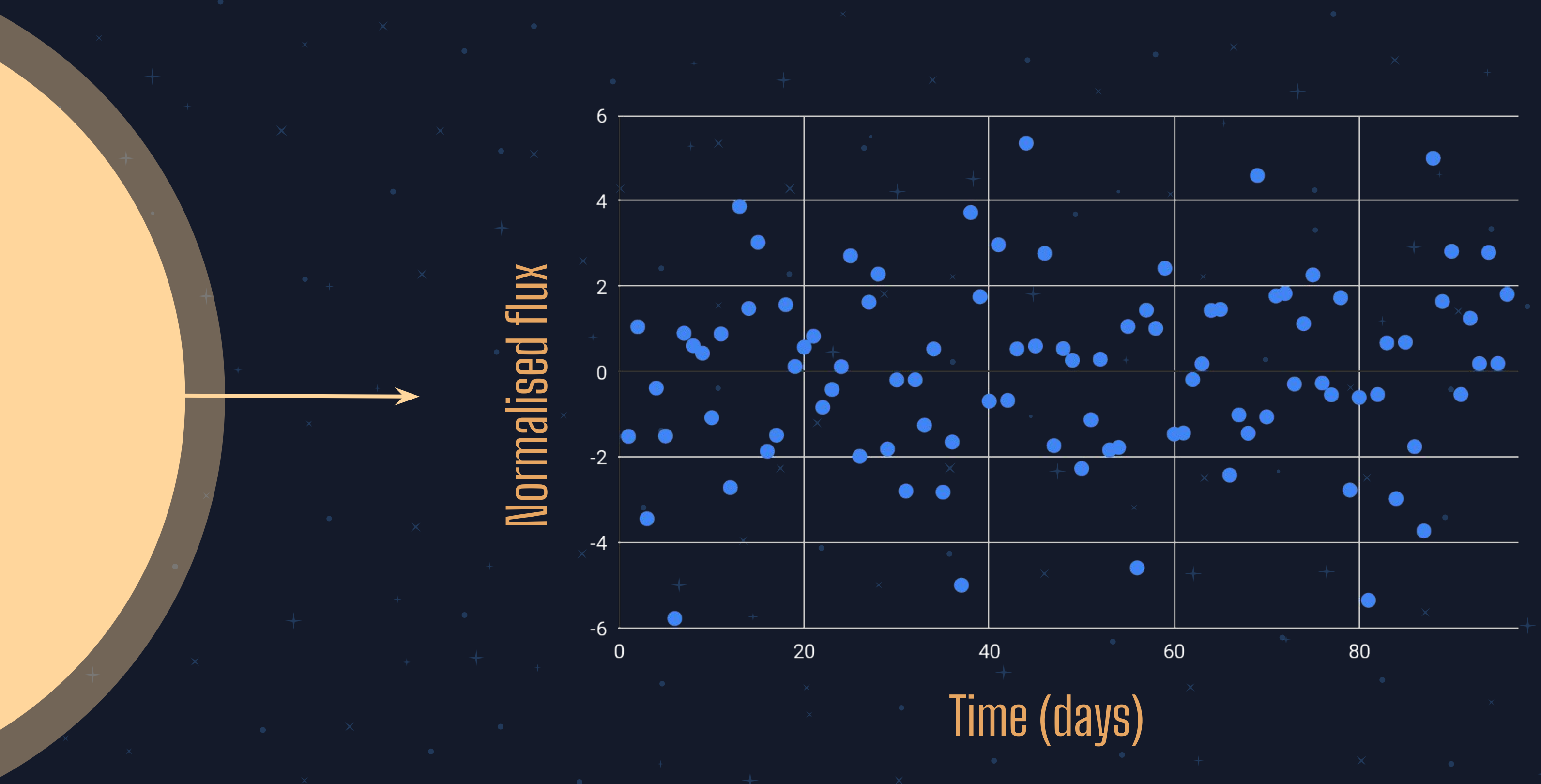
$m = -\ell, -\ell + 1, \ldots, \ell$

Zonal $(m = 0)$

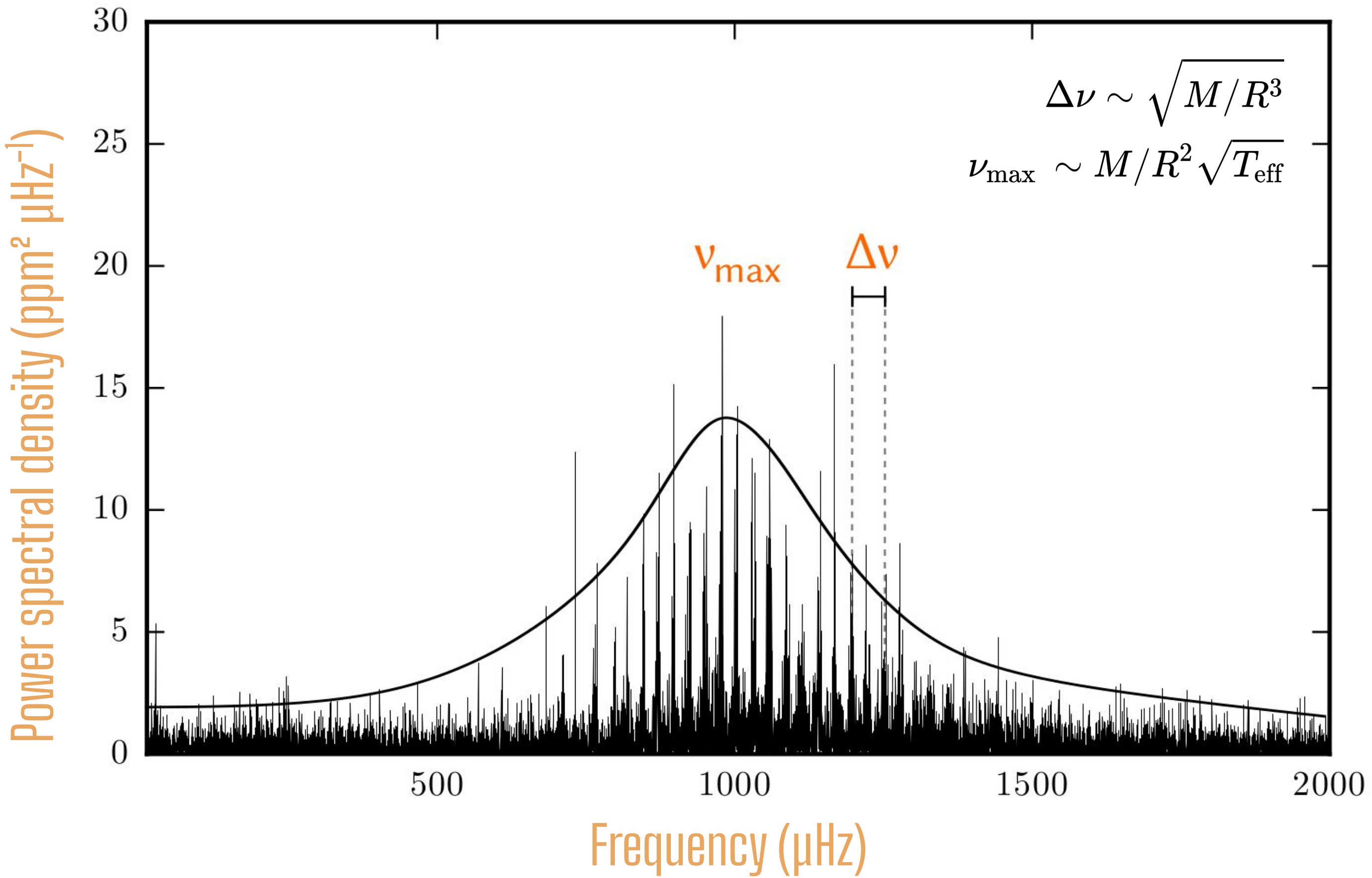


Retrograde sectoral $(m = -\ell)$

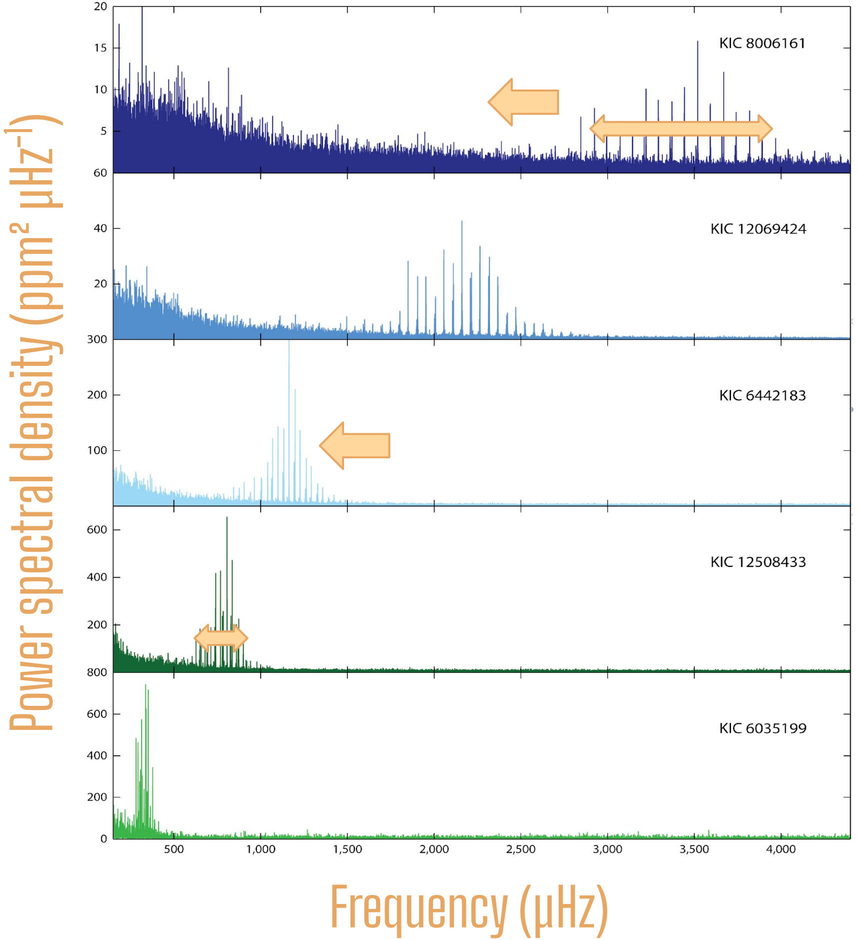
Prograde sectoral $(m = +\ell)$

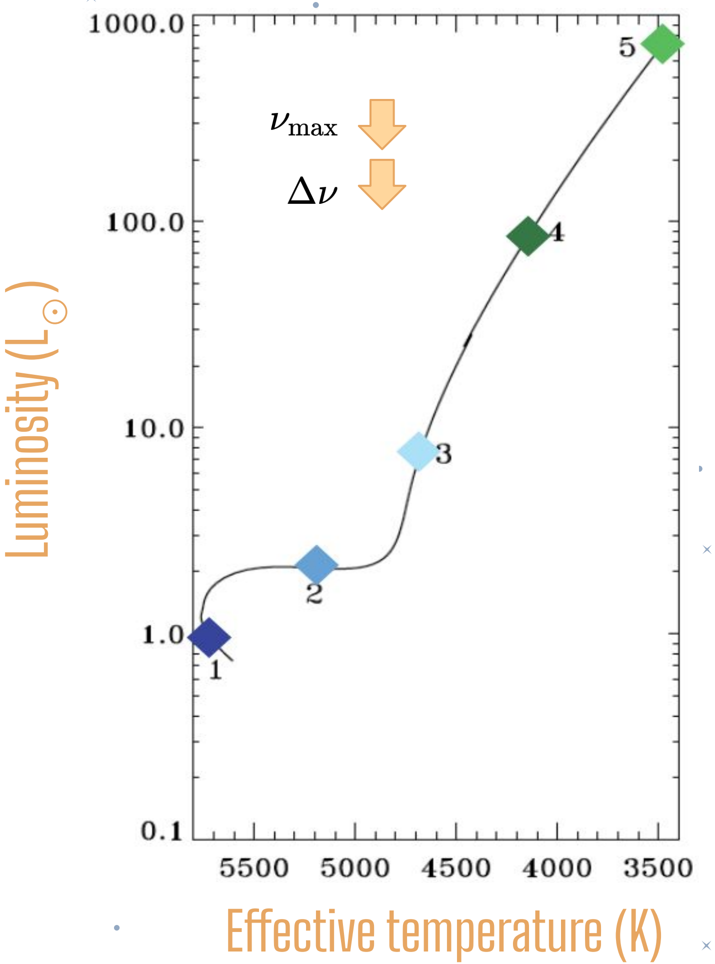


Normalised flux
6
4
2
0
-2
-4
-6
0
20
40
60
80
Time (days)

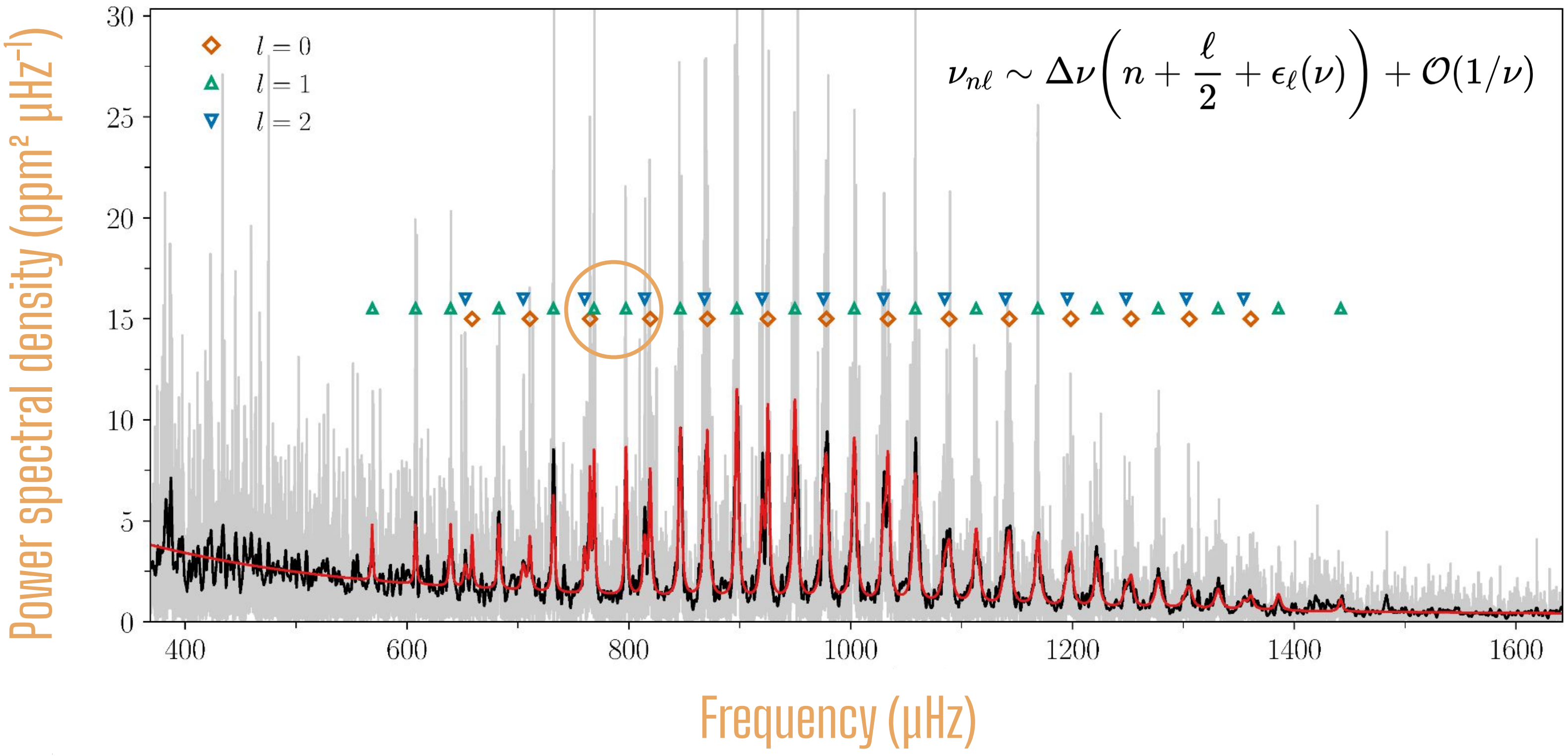


$\Delta\nu \sim \sqrt{M/R^3}$
$\nu_{max} \sim M/R^2\sqrt{T_{eff}}$
ν_{max}
$\Delta\nu$
30
25
20
15
10
5
0
500
1000
1500
2000
Power spectral density (ppm² μHz⁻¹)
Frequency (μHz)

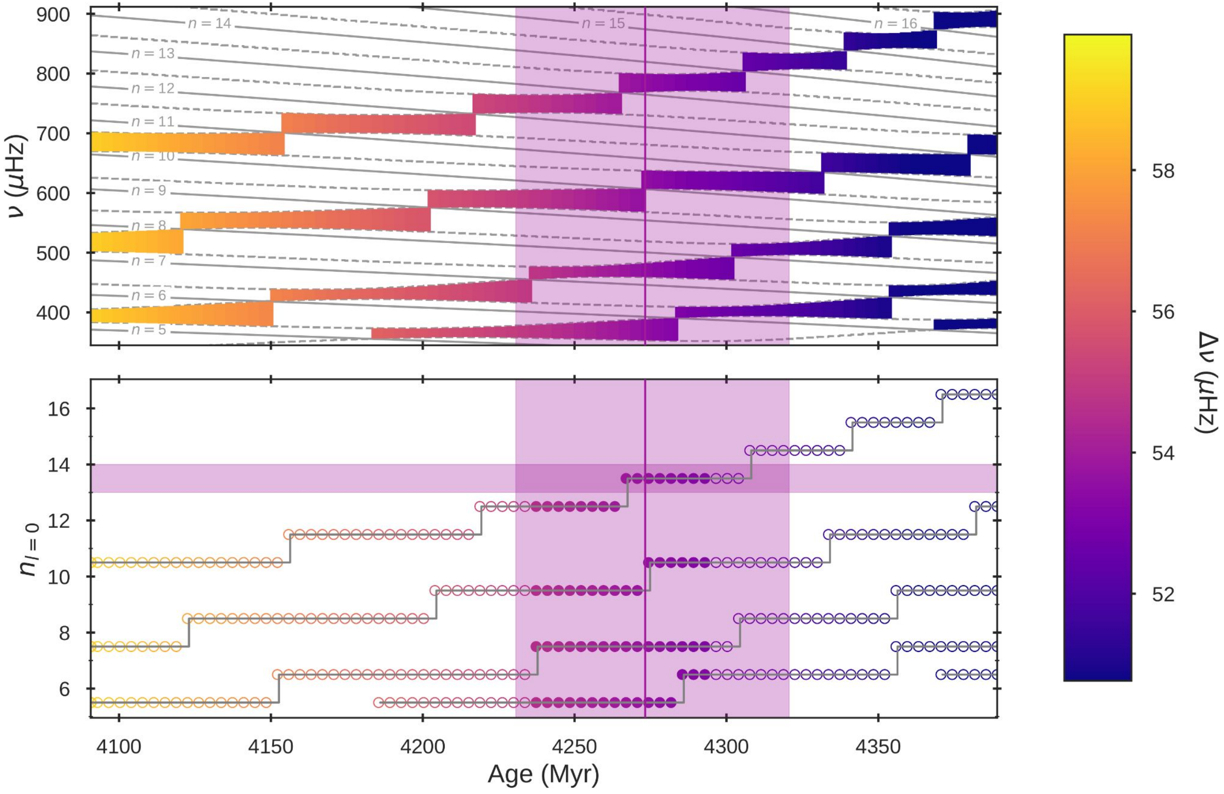




Chaplin WJ, Miglio A. 2013.
Annu. Rev. Astron. Astrophys. 51:353–92



$l = 0$
$l = 1$
$l = 2$
$\nu_{n\ell} \sim \Delta\nu\left(n + \frac{\ell}{2} + \epsilon_\ell(\nu)\right) + \mathcal{O}(1/\nu)$
Power spectral density (ppm² μHz⁻¹)
30
25
20
15
10
5
0
400
600
800
1000
1200
1400
1600
Frequency (μHz)



900
800
700
600
500
400
ν (μHz)
n = 5
n = 6
n = 7
n = 8
n = 9
n = 10
n = 11
n = 12
n = 13
n = 14
n = 15
n = 16
16
14
12
10
8
6
$n_{l=0}$
4100
4150
4200
4250
4300
4350
Age (Myr)
58
56
54
52
Δν (μHz)

II.
Asteroseismic inference

The BAyesian STellar Algorithm

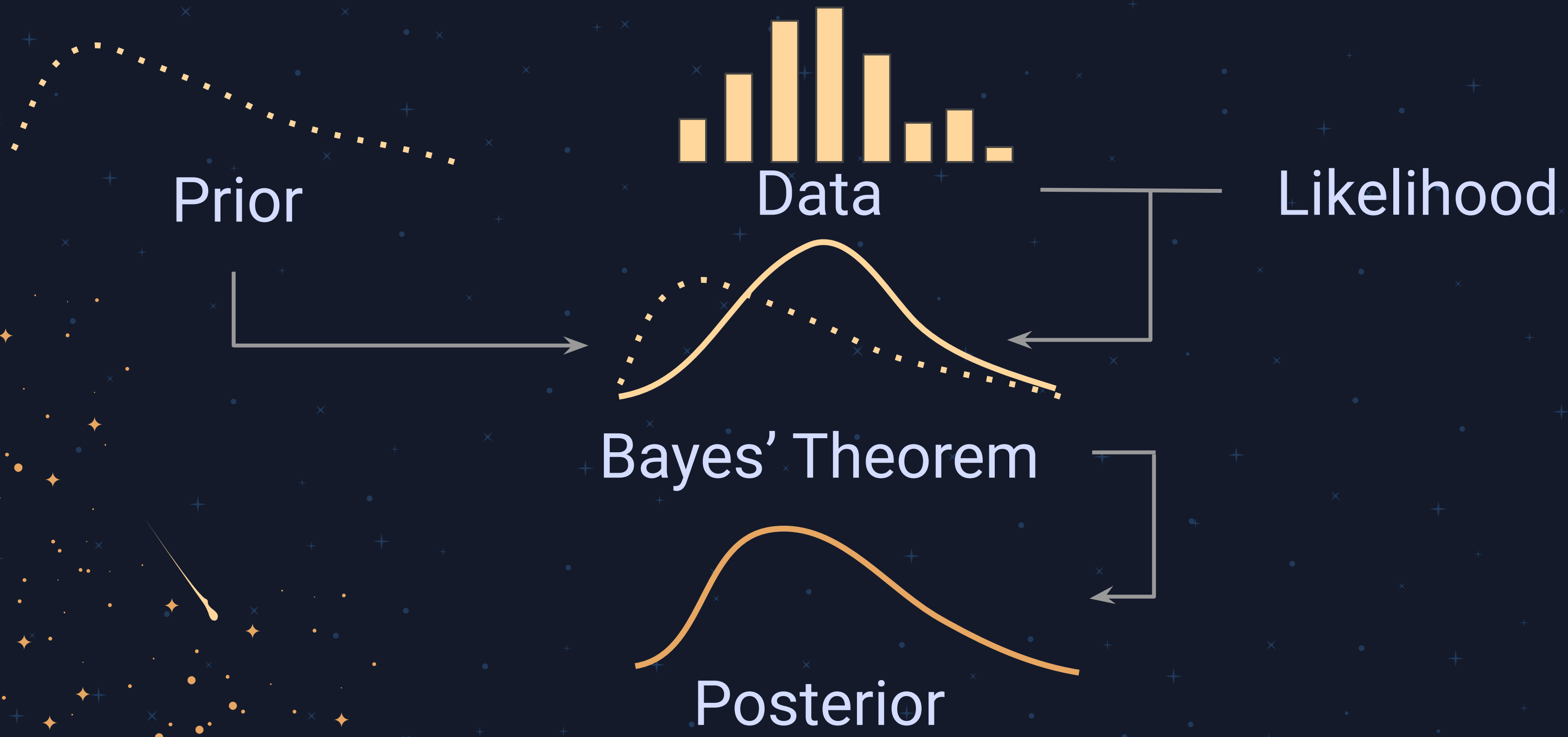
We wanted to create the most versatile pipeline for stellar properties determination

BASTA is fast and flexible in input and can fit observables from spectroscopy, photometry, astrometry, and asteroseismology and predict stellar properties.

BASTA can fit tens of thousands of stars even when not all have the same data (or quality of data) available.

BASTAcode/BASTA

What is Bayesian Inference?



BASTA is widely applied for

Exoplanet characterisation — e.g., Silva Aguirre et al. 2015 (MNRAS), Lundkvist et al. 2016 (Nat. Com.), Huber et al. 2019 (ApJ)

Asteroseismic fitting — e.g., Silva Aguirre et al. 2017 (ApJ), Stokholm et al. 2019 (MNRAS), Chaplin et al. 2020 (Nature)

Galactic archaeology — e.g., Casagrande et al. 2016 (MNRAS), Silva Aguirre et al. 2018 (MNRAS), Stokholm et al. 2023

Gyrochronology — van Saders et al. 2016 (Nature)

Cluster studies — e.g., Lund et al. 2016 (MNRAS), Stello et al. 2016 (ApJ),

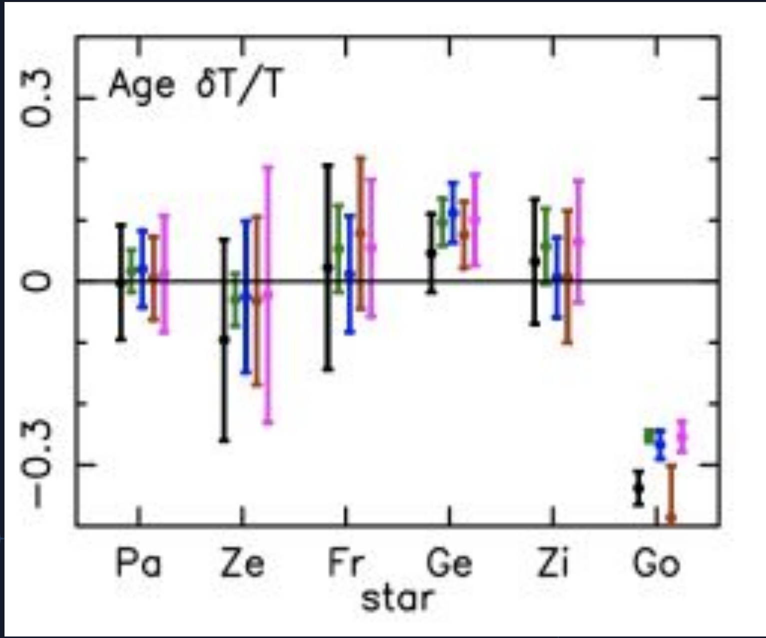
Parallaxes — e.g., Silva Aguirre et al. 2012 (AsNa), Huber et al. 2017 (ApJ)

See a non-exhaustive) list of papers using BASTA results at
https://ui.adsabs.harvard.edu/public-libraries/x2tCt52HR_yqG-oaUabo_A

What can we achieve?

Main-sequence solar-like pulsators with individual modes:

- Maximum relative difference between truth and inferred value in age: 11.25%
- However, bias when overfitting (~7%), not using appropriate macrophysics in stellar models (8.66 %) or when classical observations were shifted +/- 1 std (7%)



Cunha et al. 2022

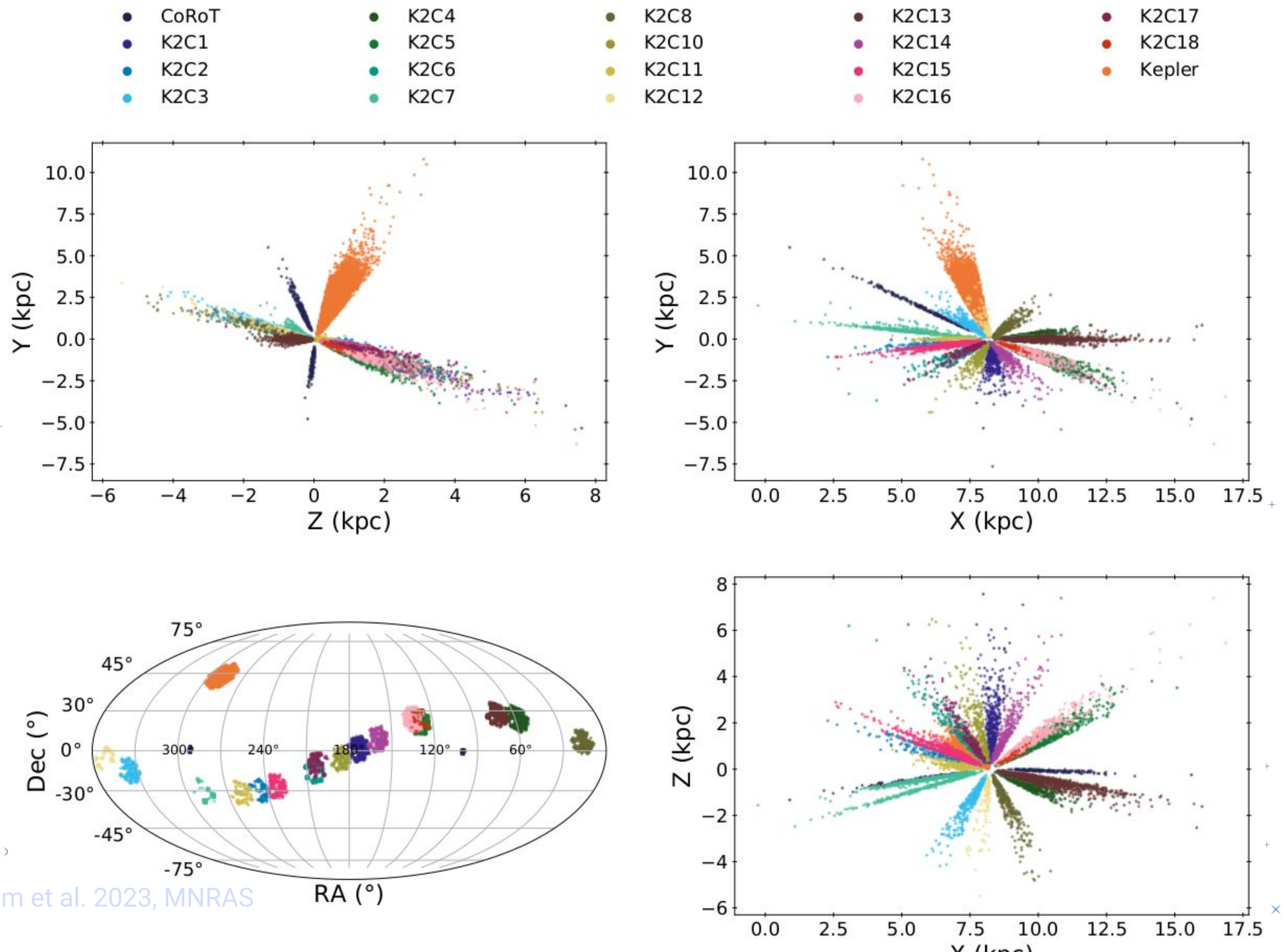
III. Populations of stars

Asteroseismic study of the Galactic discs

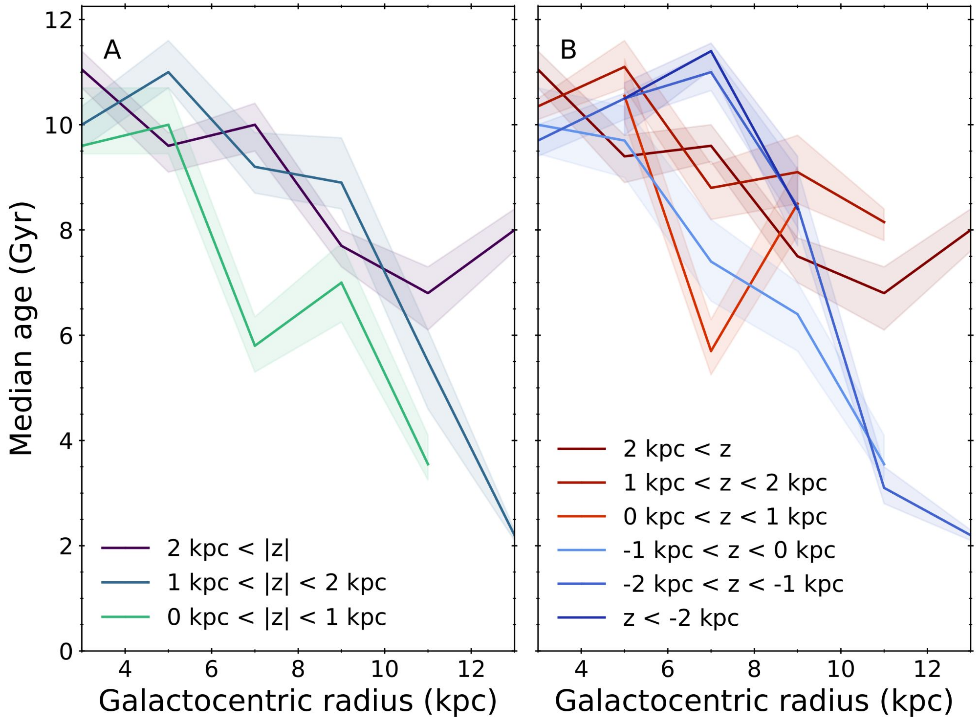
21.706 stars with

I. Asteroseismic quantities ($\Delta\nu$ + vmax)
II. 5D astrometric quantities
III. Chemical abundances and line-of-sight velocities
from different spectroscopic surveys
IV. Photometric magnitudes

Stokholm et al. 2023, MNRAS

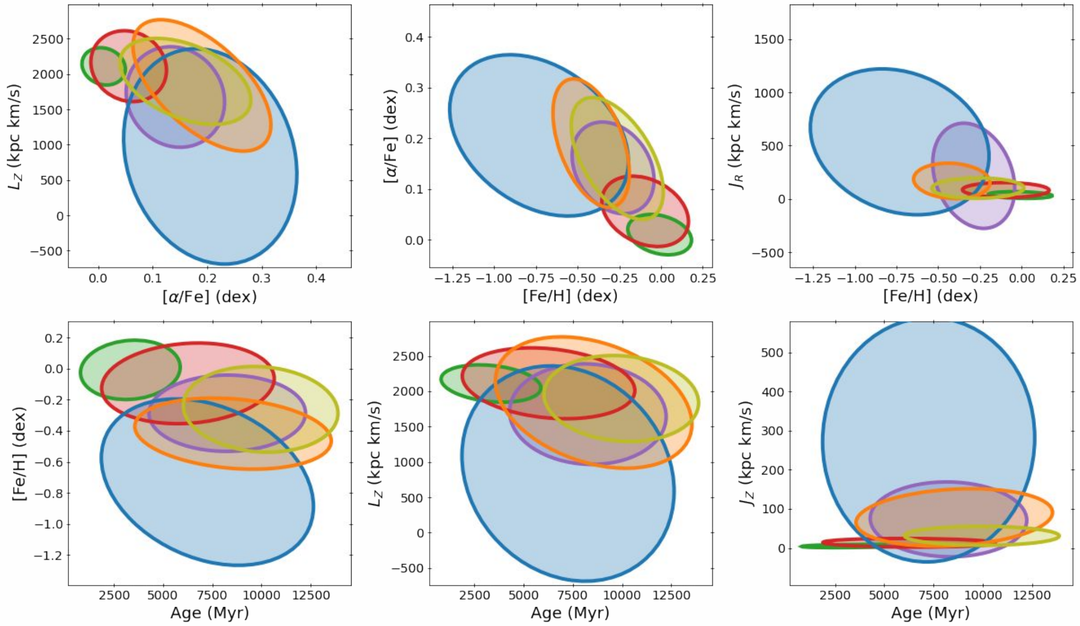


Stokholm et al. 2023, MNRAS



Stokholm et al. 2023, MNRAS

The six-component solution



Stokholm et al. 2023, MNRAS

Blue: halo

Olive and orange: thick disc

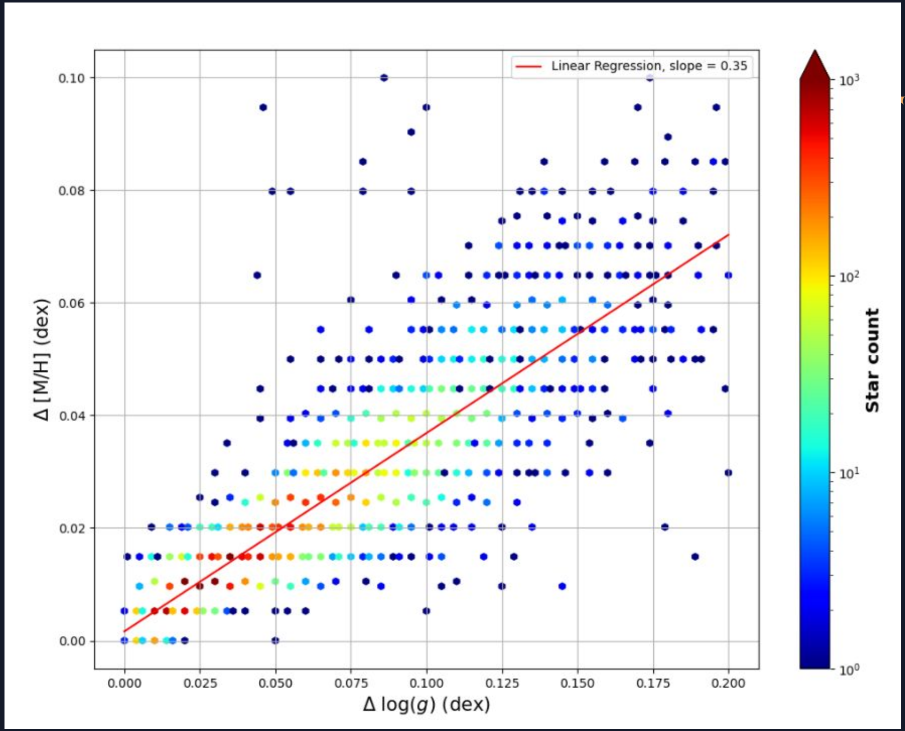
Red: Kinematically heated thin disc, possibly by gravitational interactions with satellite galaxies.

Purple and green: thin disc

This was with 20.000 stars – how about 200.000?

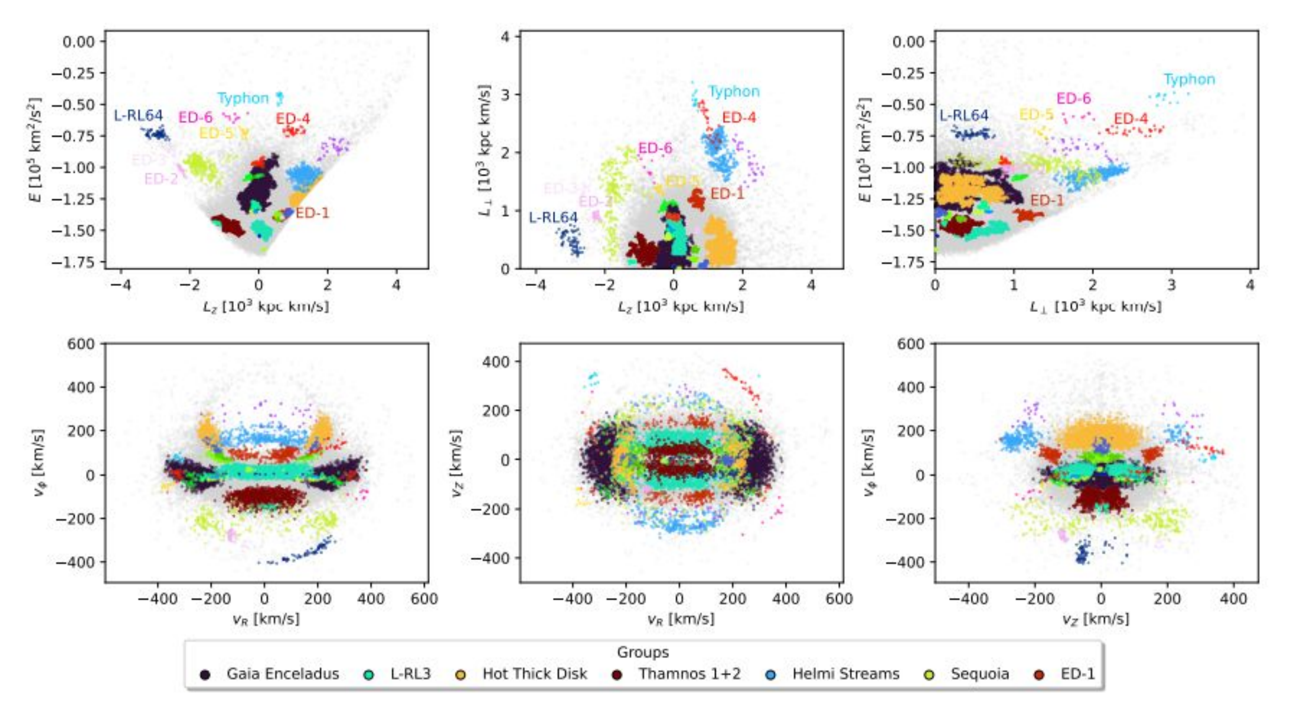
If we just want global asteroseismic parameters, the spectroscopic values are typically the bottleneck.

Work-in-progress: Use asteroseismic priors on the surface gravities to improve the precision in the spectroscopic solutions.



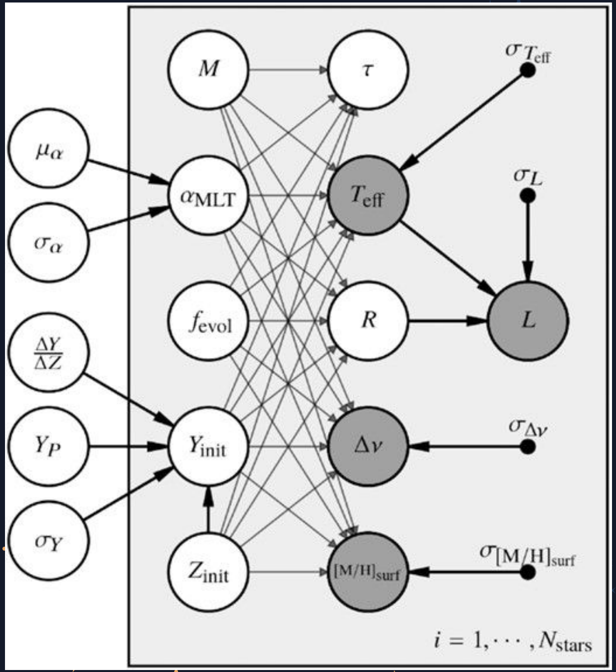
Elisa Denis et al. (in prep)

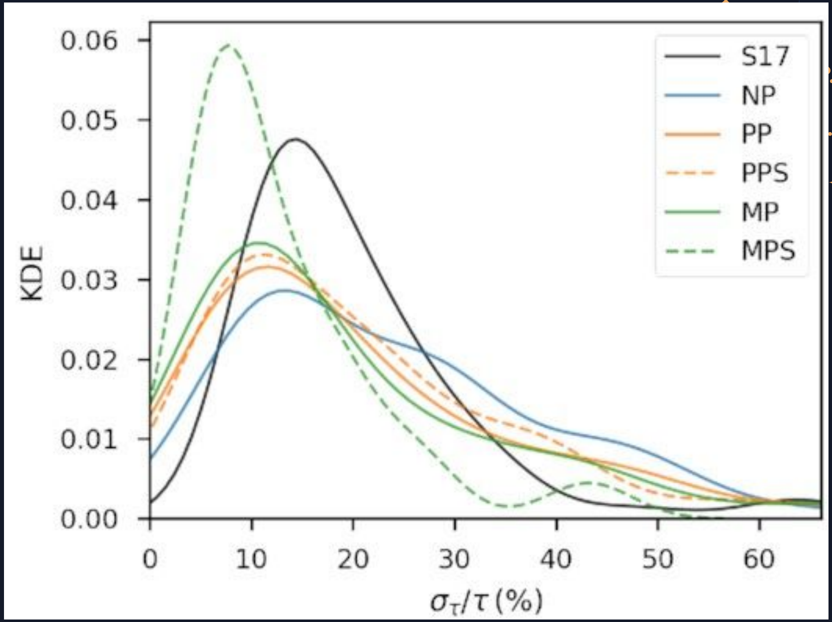
WIP: Adding age as a dimension for data-driven halo studies



Lövdal et al. 2022, Ruiz-Lara et al. 2022, Dodd et al. 2023, WIP

WIP: Bayesian Hierarchical Modelling of populations of stars





Lyttle et al. 2021

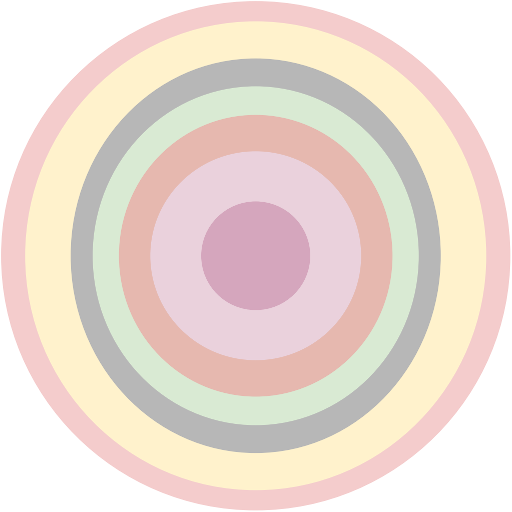
Take-home messages

- Stars works as time capsules and provide clues to processes and events in the Milky Way's past.
- Detailed studies of single stars can help us better understand issues in our theories for stellar structure and evolution.
- Ensemble studies of stars with known chemical compositions, orbits, and ages can help us understand the Galaxy we live within.

Thank you for your attention!

Chemical clocks

p(**chemical composition**, orbit, age)

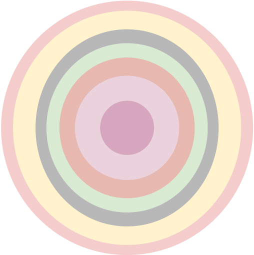


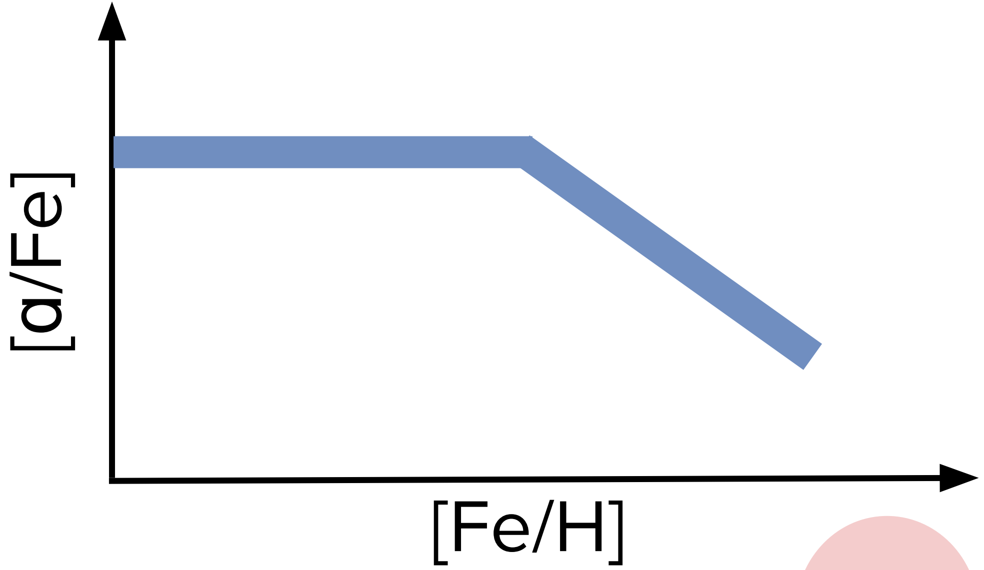
Supernova type II

Supernova type Ia

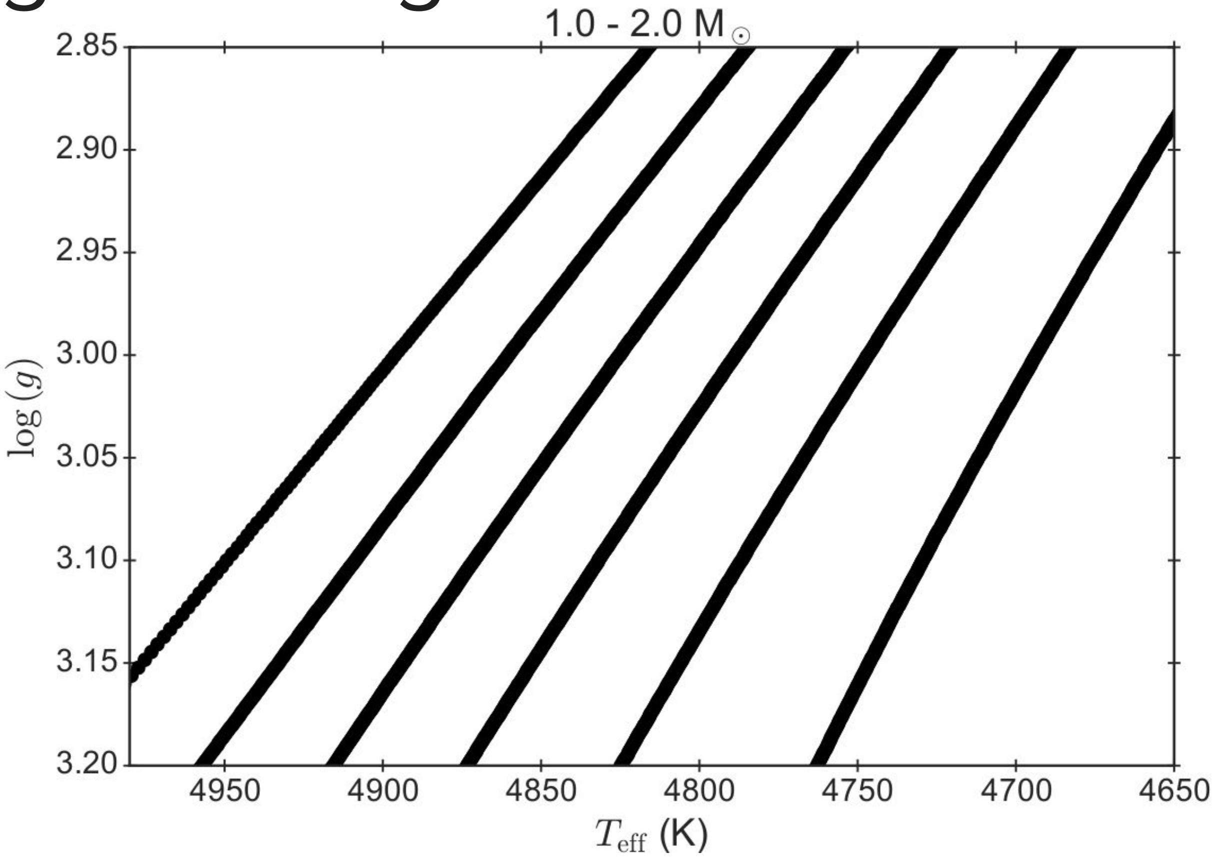
Chemical clocks

p(**chemical composition**, orbit, age)

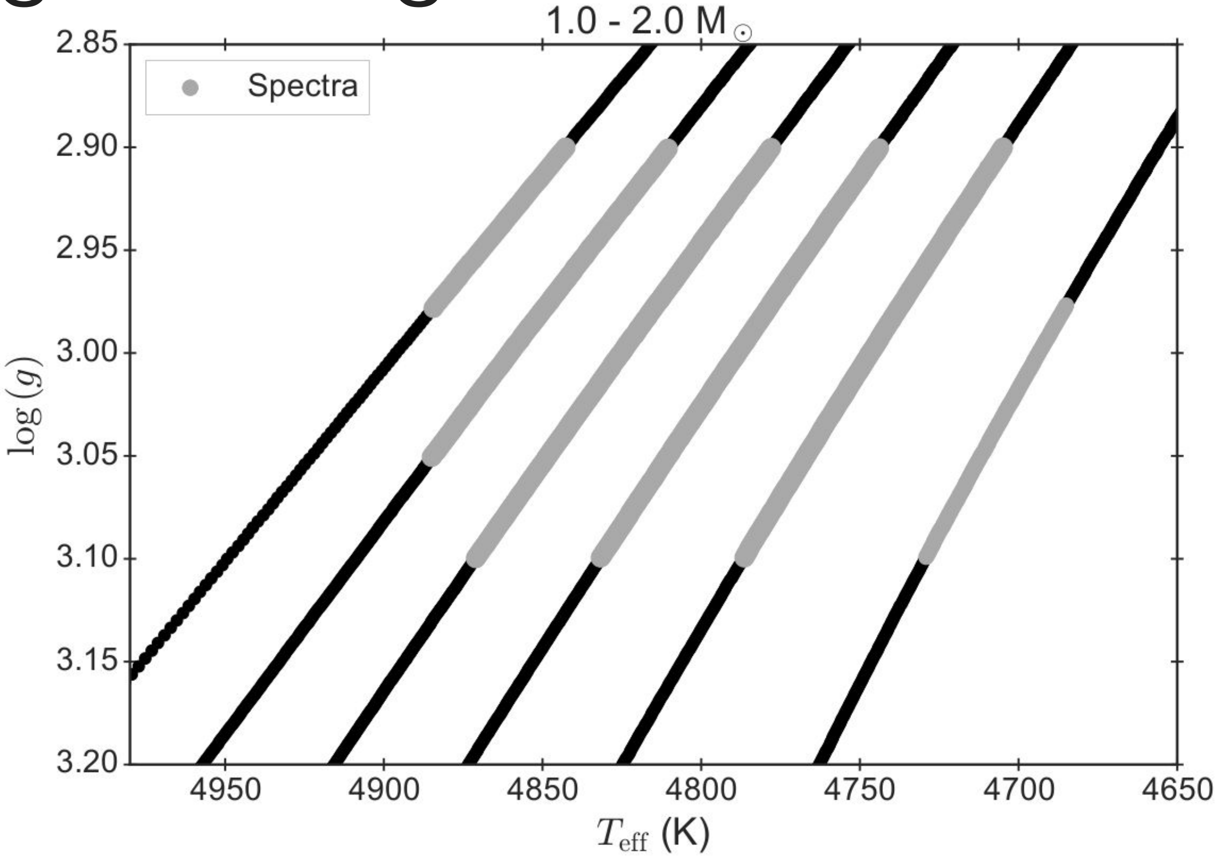




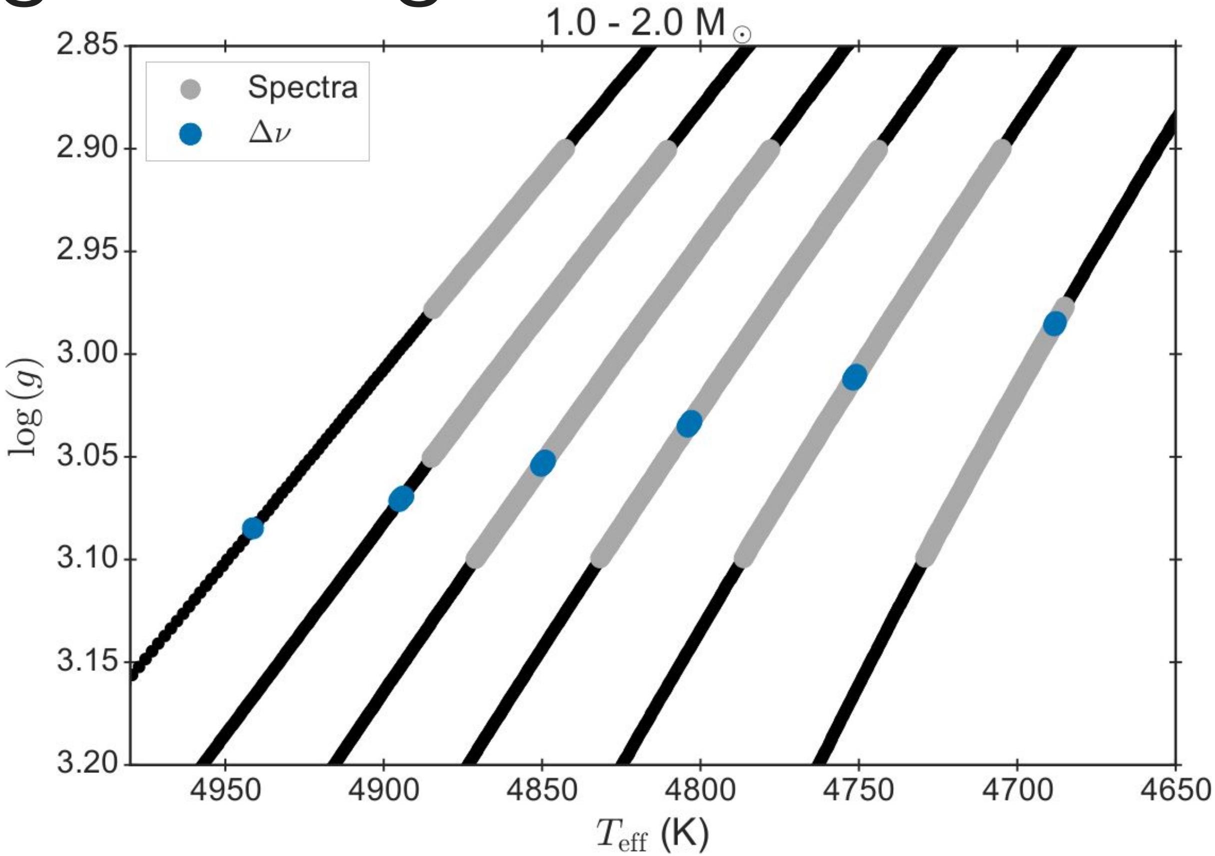
Ages from grid-based modelling



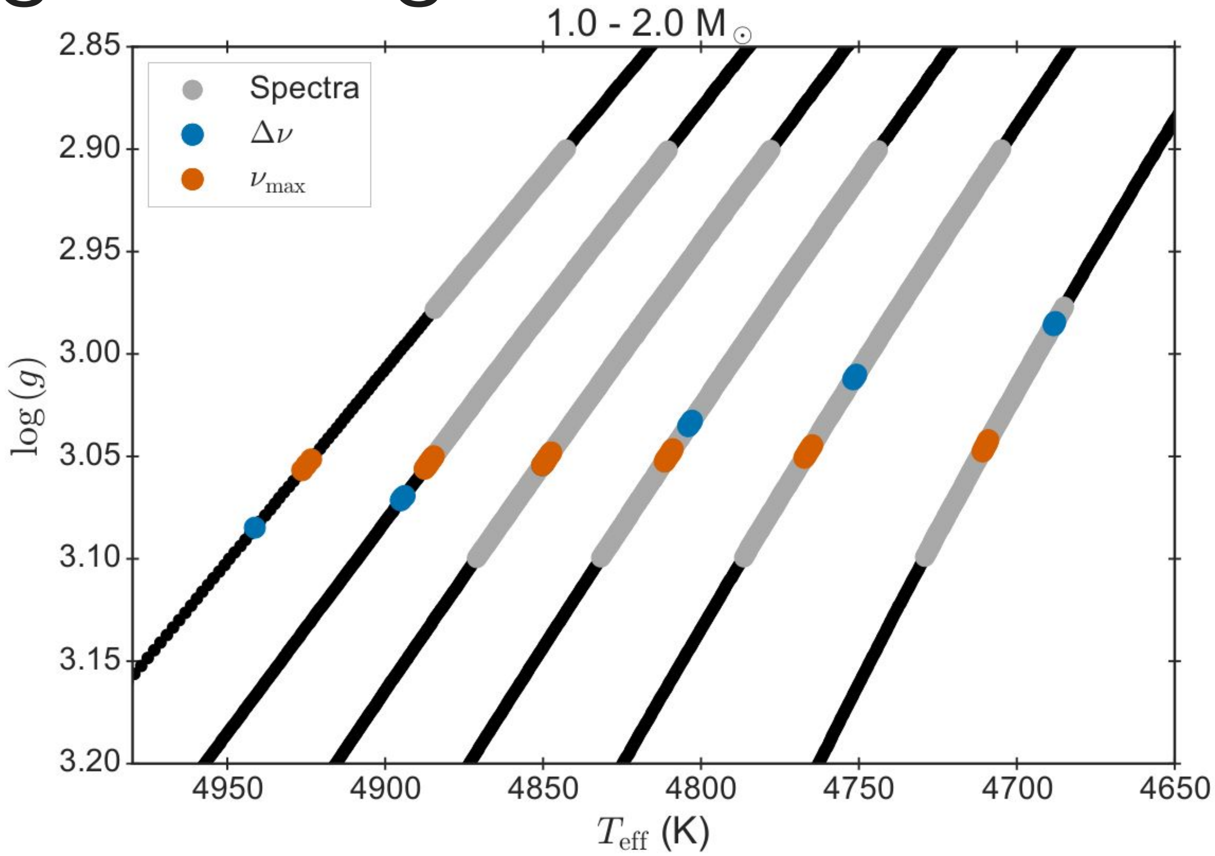
Ages from grid-based modelling



Ages from grid-based modelling

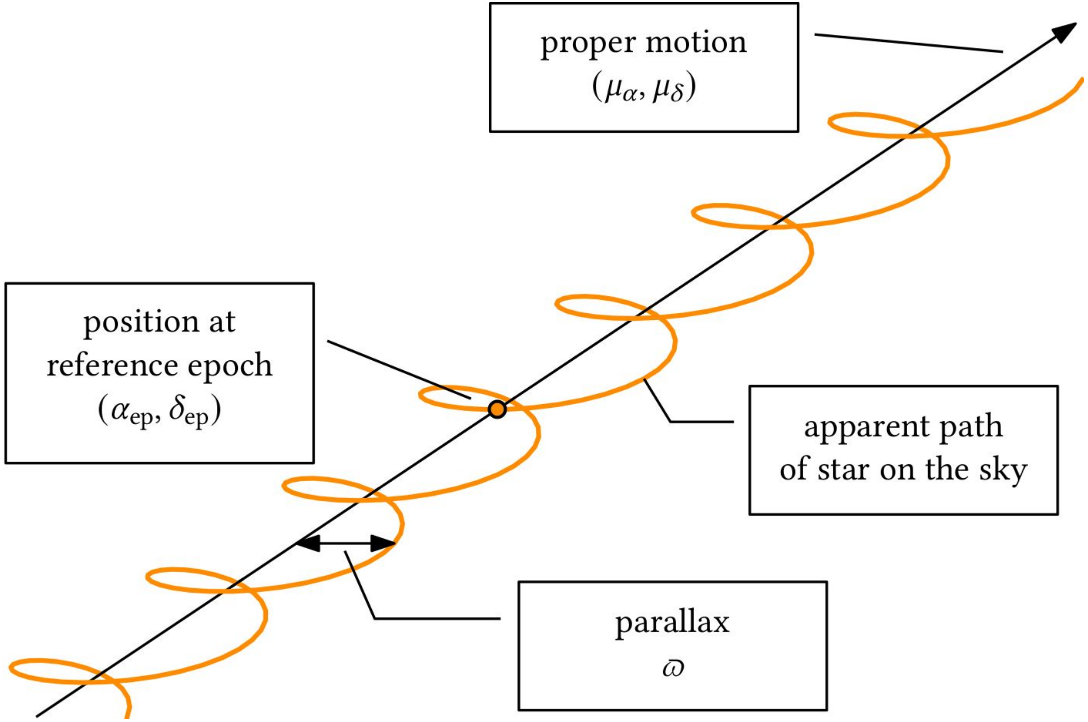


Ages from grid-based modelling



Orbits from astrometry

p(chemical composition, orbit, age)



Separating disk components

p(chemical composition, orbit, age)

A Unified Exploration of the Chronology of the Galaxy, Stokholm et al. 2023, MNRAS

Separating disk components

$$p([Fe/H], [\alpha/Fe], J_r, L_z, J_z, \text{age})$$

A Unified Exploration of the Chronology of the Galaxy, Stokholm et al. 2023, MNRAS

Actions

$$J_R \equiv \frac{1}{2\pi}\oint_{\mathrm{orbit}} v_R \ \mathrm{d}R$$

$$L_z \equiv \frac{1}{2\pi}\int_0^{2\pi} v_T \cdot R \ \mathrm{d}\phi$$

$$J_z \equiv \frac{1}{2\pi}\oint_{\mathrm{orbit}} v_z \ \mathrm{d}z$$

Actions are integrals of motions.
In a static, axisymmetric potential: conserved

A Unified Exploration of the Chronology of the Galaxy, Stokholm et al. 2023, MNRAS

Actions

$$J_R \equiv \frac{1}{2\pi} \oint_{\text{orbit}} v_R \, \mathrm{d}R$$

$$L_z \equiv \frac{1}{2\pi} \int_0^{2\pi} v_T \cdot R \, \mathrm{d}\phi$$

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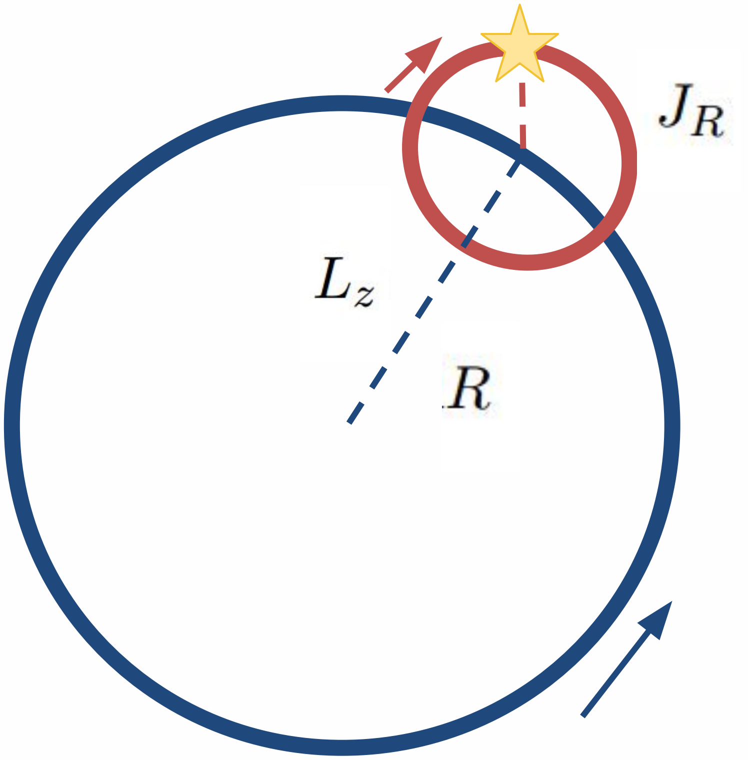

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