Characterising stars with AIMS and SPInS

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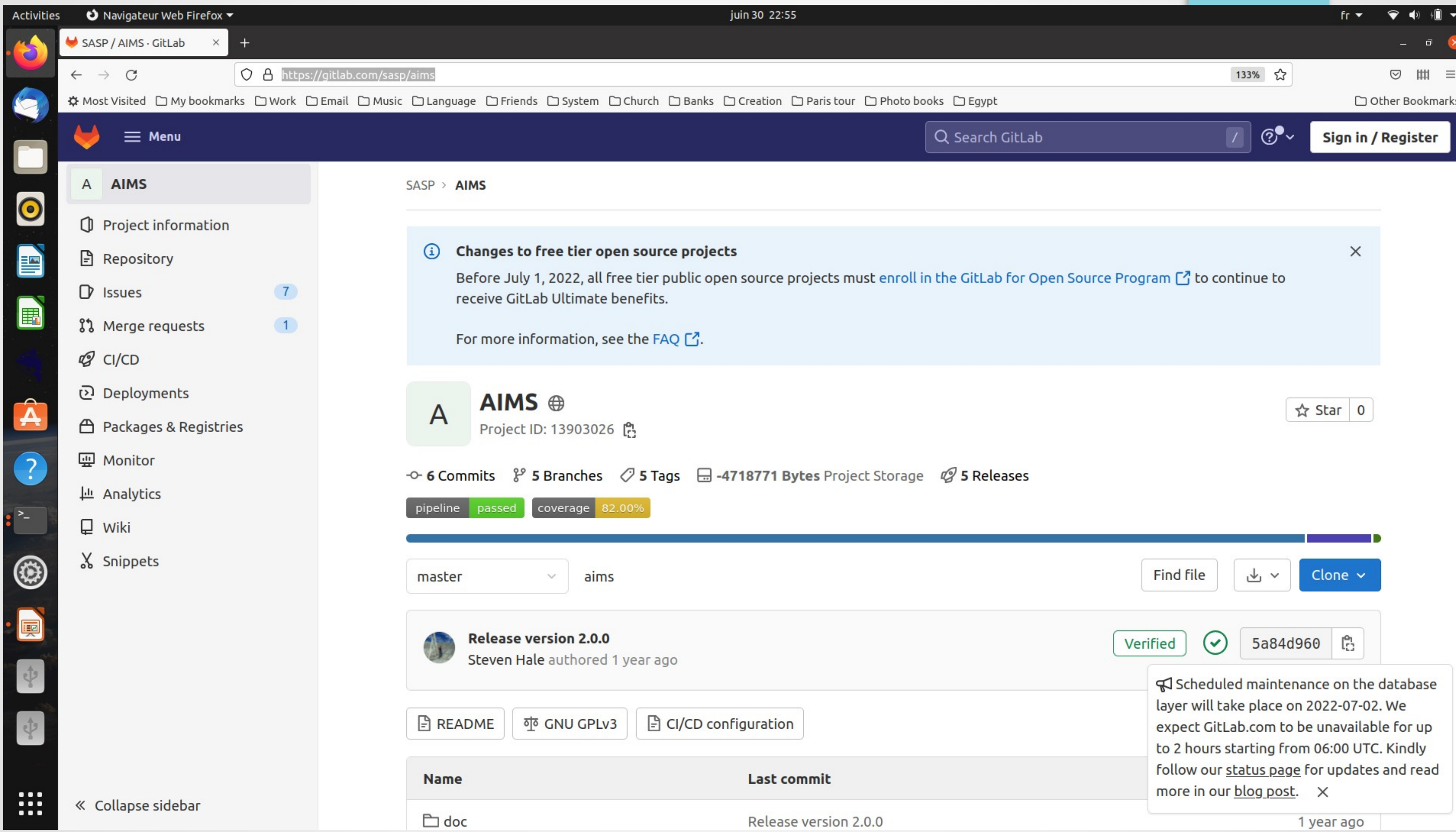
Introduction

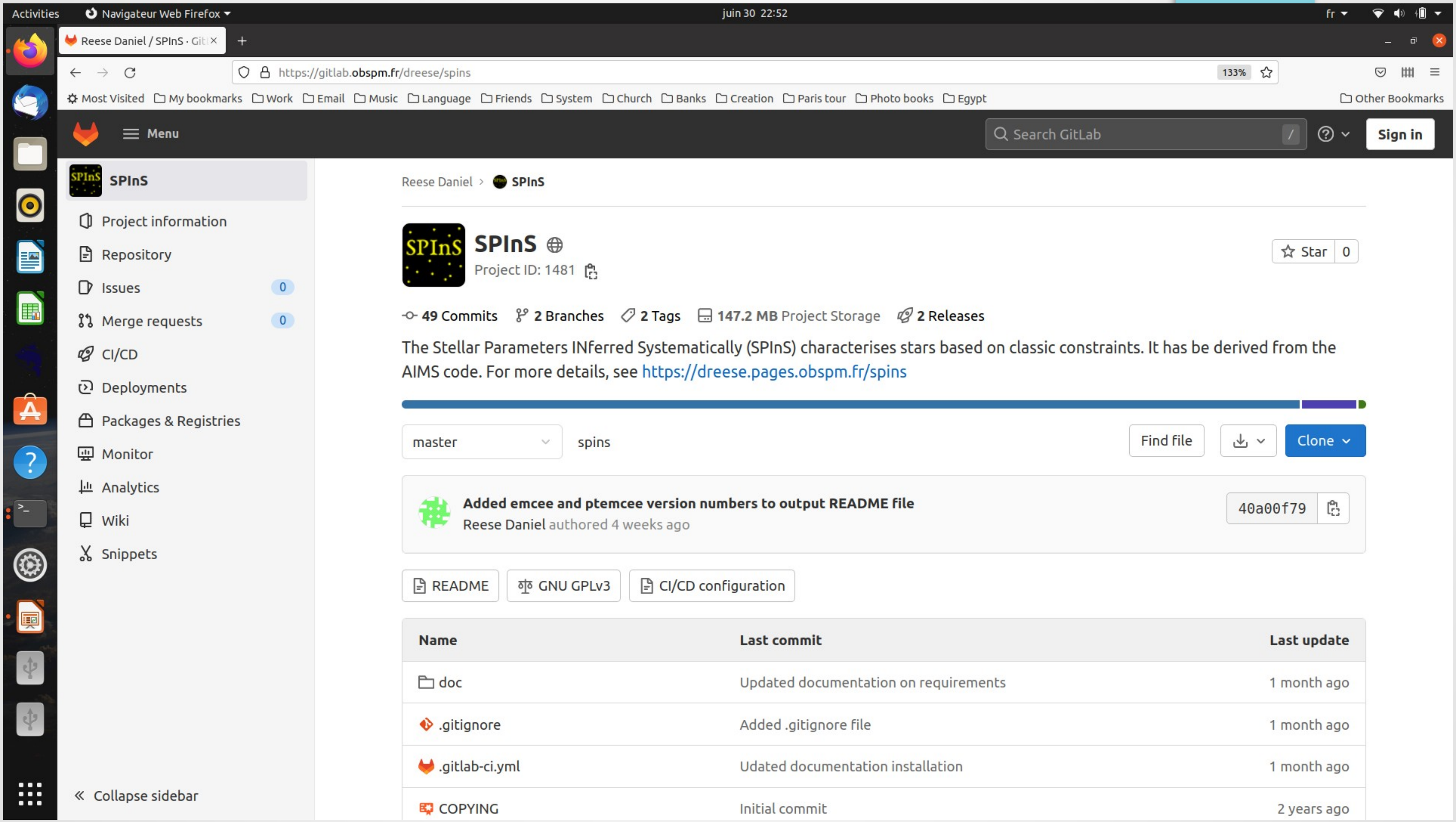
- AIMS = Asteroseismic Inferences on a Massive Scale
  - goal: obtain probability distribution functions (PDFs) for stellar properties, from a set of classic (Teff, log g, [M/H]) and seismic constraints
- SPInS = Stellar Parameters INferred Systematically
  - basically the same as AIMS without the seismic constraints
  - can be seen as a spin-off of AIMS

AIMS website



https://gitlab.com/sasp/aims

SPInS website



https://gitlab.obspm.fr/dreese/spins

Some history – AIMS

- 2015: initial version written during my postdoc in Birmingham
  - written in python in order to make it easier for others to contribute to the code
- 2016: tutorial on AIMS with Mikkel Lund
  - various parts of the code are translated to Fortran to speed up calculations
- 2019: publication of Rendle et al. (2019, MNRAS 484, 771)
- 2021: inclusion of age parameter (in addition to physical age)
- 2019, 2022: inclusion of seismic indicators based on WhoSGlAd method (Farnir et al. 2019)
  - method based on Gram-Schmidt orthogonalisation

AIMS – contributors

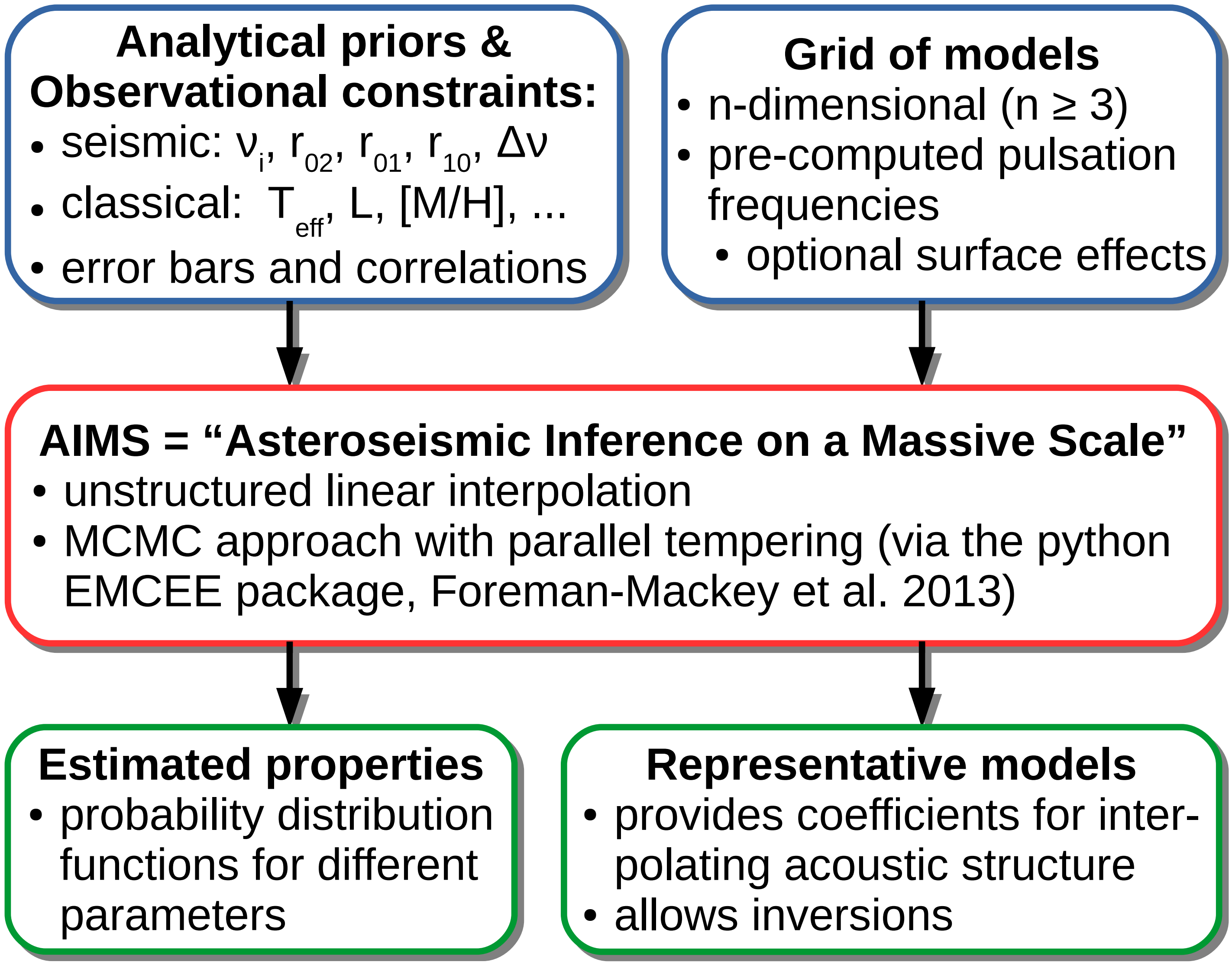
- Daniel R. Reese
- Andrea Miglio
- Benoît D. C. P. Herbert
- Ben Rendle
- Gael Buldgen
- Guy R. Davies
- Martin Farnir
- Martin W. Long
- Mikkel N. Lund
- Tiago L. Campante

Some history – SPInS

- 2018: initial version written for the 5th International Young Astronomer's School (Paris)
  - derived from AIMS
  - included a physical age and an age parameter from the start
- 2020:
  - official release
  - improved treatment of age
  - possibility of handling multiple systems
  - publication of Lebreton & Reese (2020, A&A 642, 88)

- Main contributors: Daniel R. Reese & Yveline Lebreton

Flowchart


Analytical priors & Observational constraints:
• seismic: ν_i, r_{02}, r_{01}, r_{10}, $\Delta\nu$
• classical: T_{eff}, L, [M/H], ...
• error bars and correlations
Grid of models
• n-dimensional (n ≥ 3)
• pre-computed pulsation frequencies
• optional surface effects
AIMS = “Asteroseismic Inference on a Massive Scale”
• unstructured linear interpolation
• MCMC approach with parallel tempering (via the python EMCEE package, Foreman-Mackey et al. 2013)
Estimated properties
• probability distribution functions for different parameters
Representative models
• provides coefficients for inter-polating acoustic structure
• allows inversions

Observational constraints

- classic constraints (typically Gaussians)

```
log_Luminosity 0.00 0.05
log_Teff 3.76 0.0075
MoH 0.0 0.10
```

  - may apply elementary functions (e.g. log)
  - may also specify other distributions (uniform, truncated gaussian)
- seismic constraints (AIMS only)
  - individual frequencies with ℓ and with or without n
  - error distributions are assumed to be Gaussian and independant
  - frequency combinations (e.g. separations/ratios) are calculated subsequently and correlations are calculated analytically

Grid of models

- made of evolutionary tracks characterised by a set of parameter (e.g. M, X, Y)
  - model parameters read from list file by AIMS/SPInS
  - AIMS/SPInS will reconstruct the evolutionary tracks

grid.txt - /media/dreese/lacie/SPACEINN/AIMS/project/

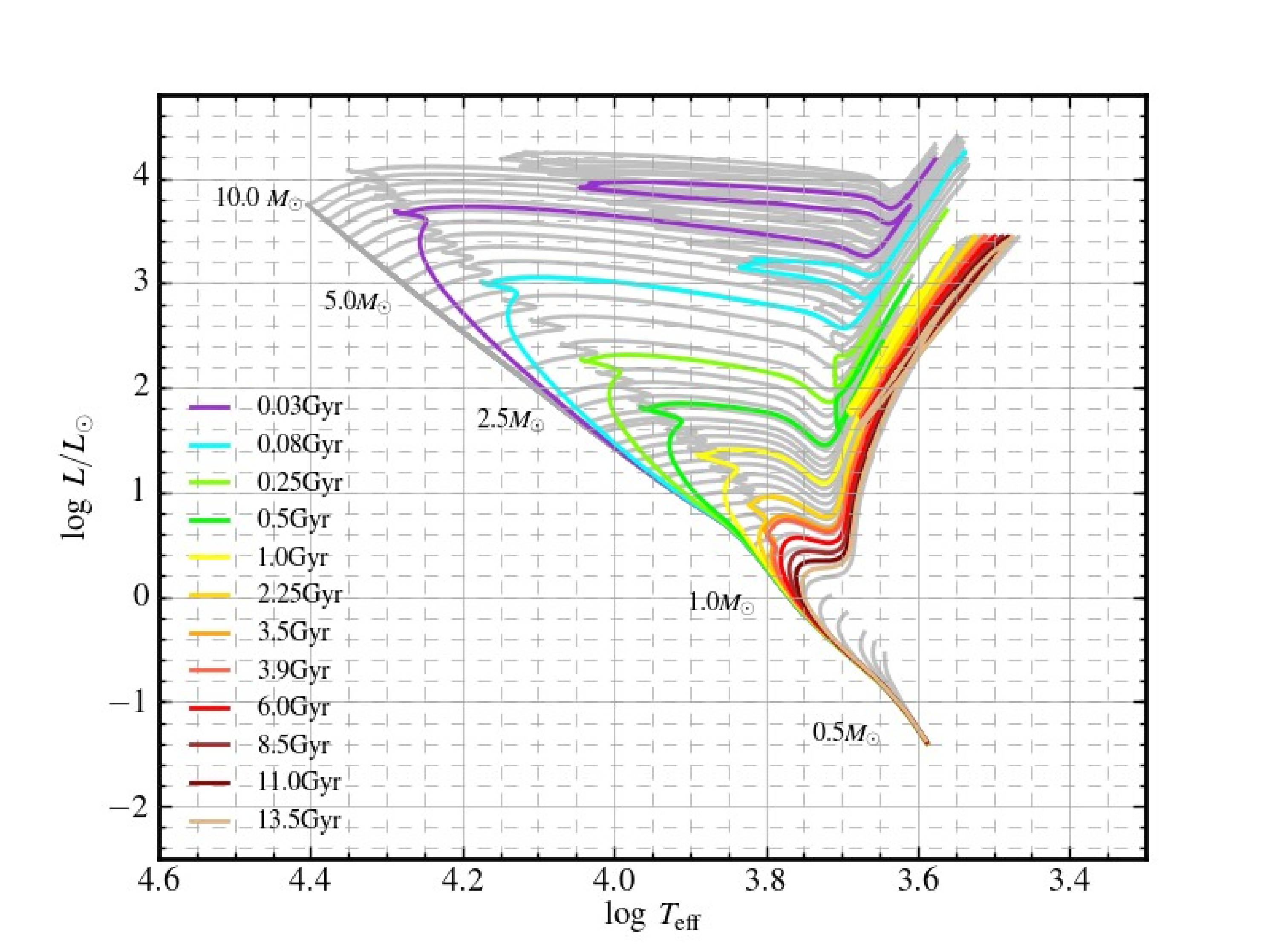
File Edit Search Preferences Shell Macro Windows Help

/media/dreese/lacie/SPACEINN/AIMS/project/grid.txt byte 380 of 544 L: 4 C: 0

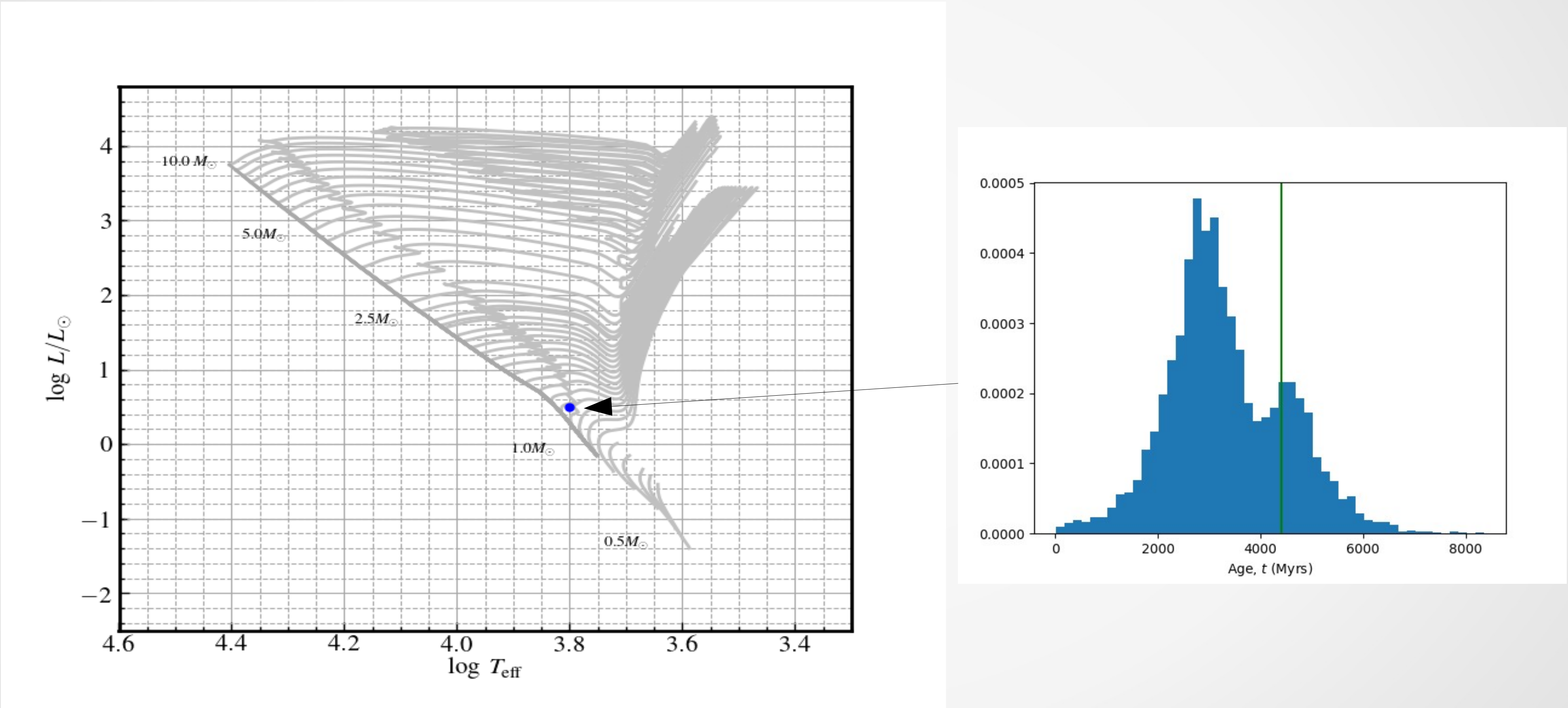
```
1 /home/dreese/models_inversions/Grid_mesa_MS/  .freq
2 m0.80Y0.2536Z0.0028a1.8ovh0.2ovhe0_n1.profile.FGONG  1.59136E+33  5.02248266E+10  2.33097993E+33  0.0028
3 m0.80Y0.2536Z0.0028a1.8ovh0.2ovhe0_n2.profile.FGONG  1.59136E+33  4.86716596E+10  1.94640636E+33  0.0028
4 m0.80Y0.2536Z0.0028a1.8ovh0.2ovhe0_n3.profile.FGONG  1.59136E+33  4.89176532E+10  1.97545563E+33  0.0028
5
```

  - *for AIMS only:* model frequencies stored in individual files (their paths are specified in the list file)
- a first run is necessary to generate a binary grid file with all of the models parameters, frequencies, and grid tessellation (see interp.)

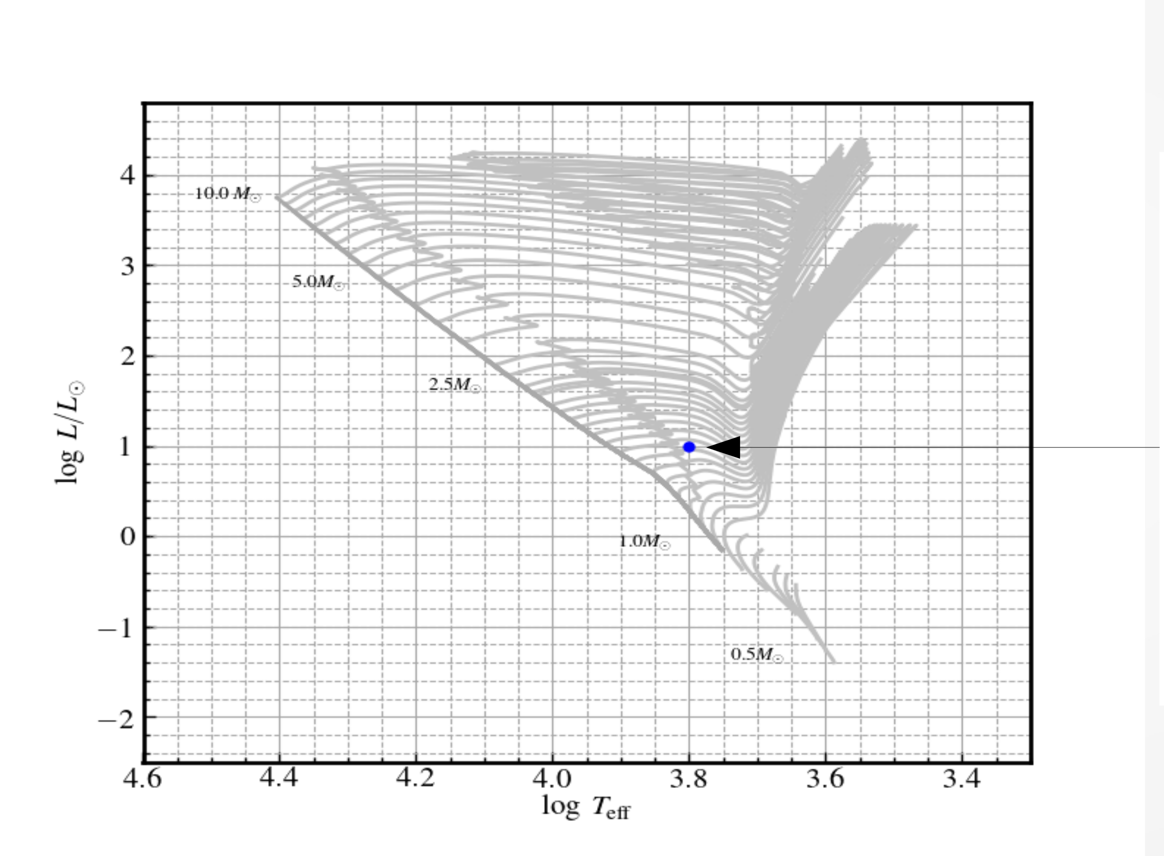
A Bayesian approach

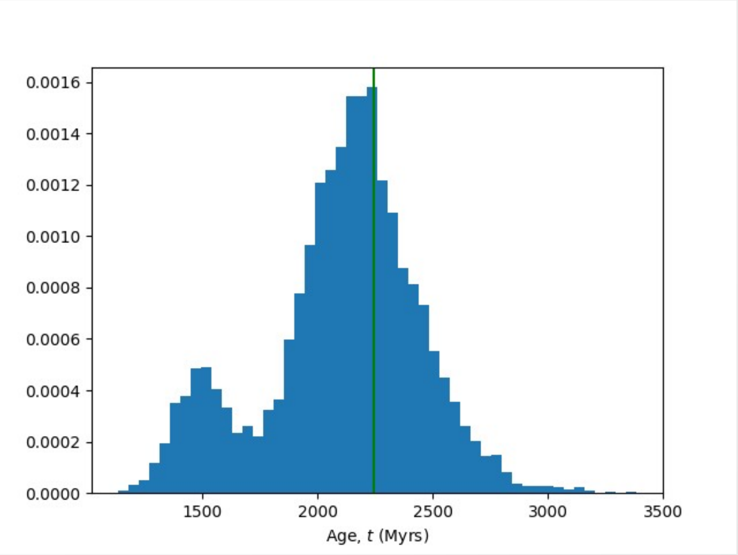


A Bayesian approach

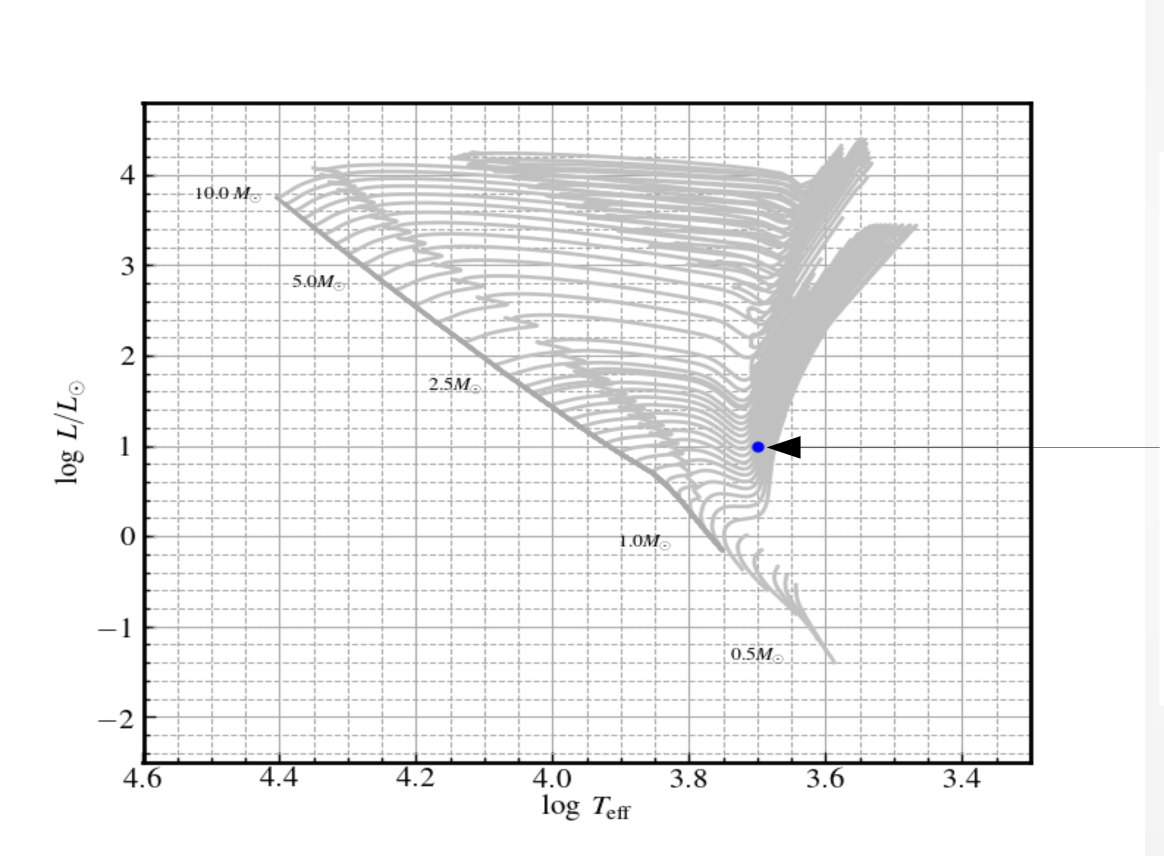


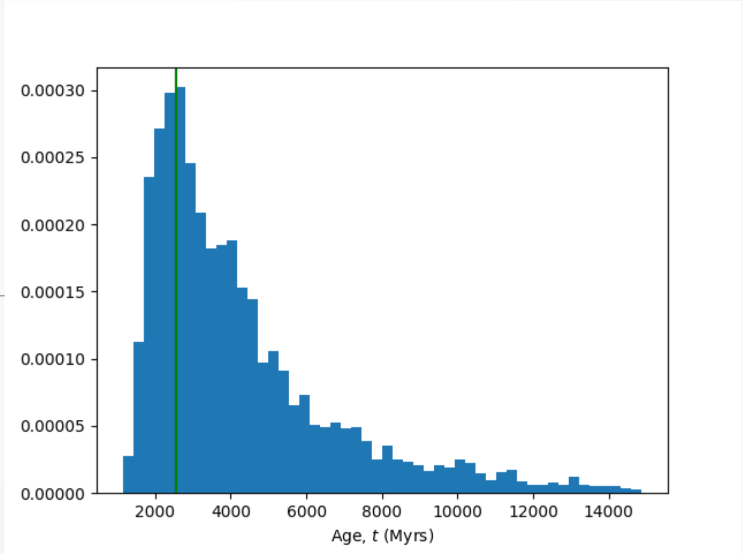
A Bayesian approach



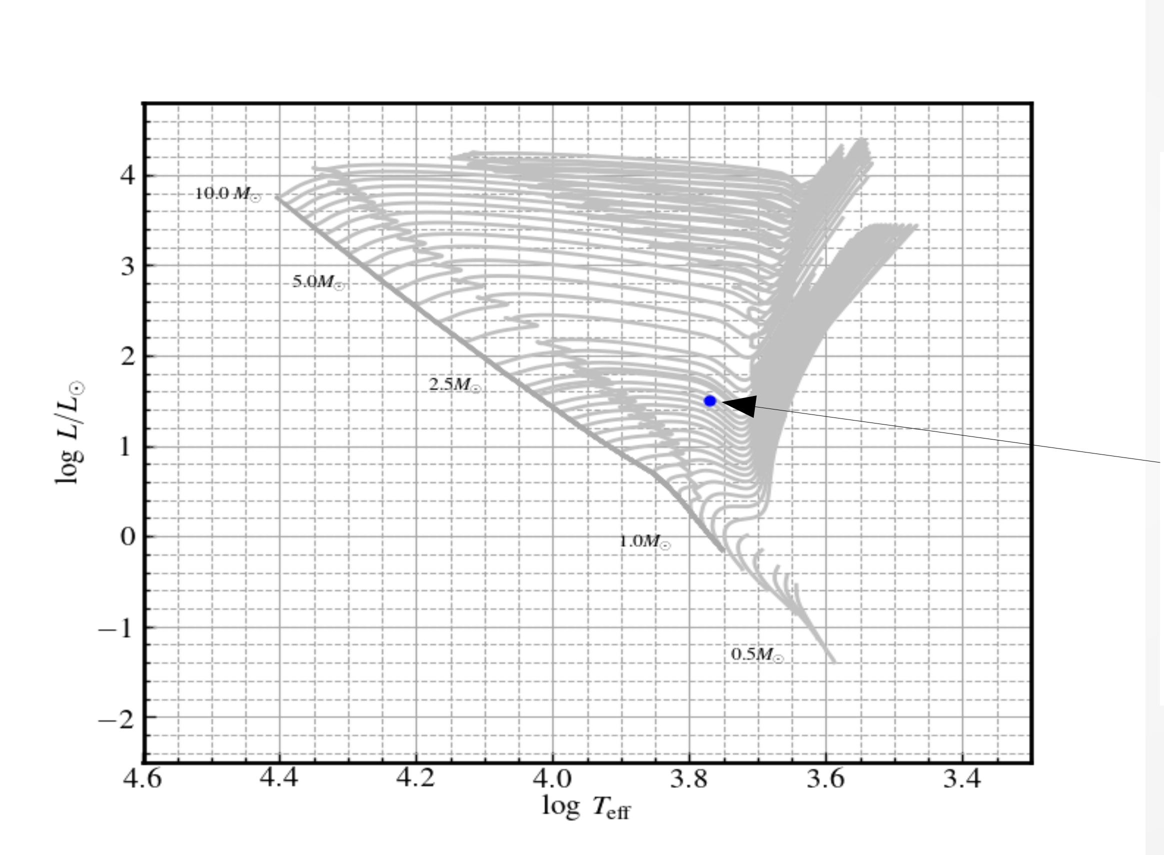


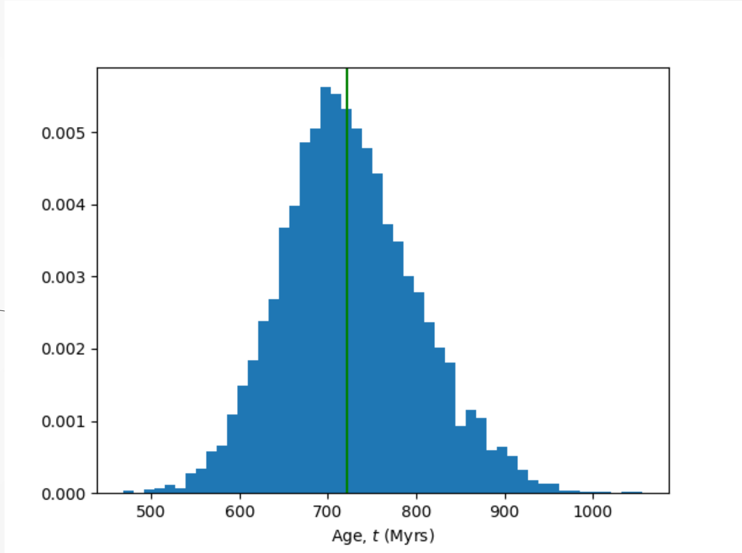
A Bayesian approach



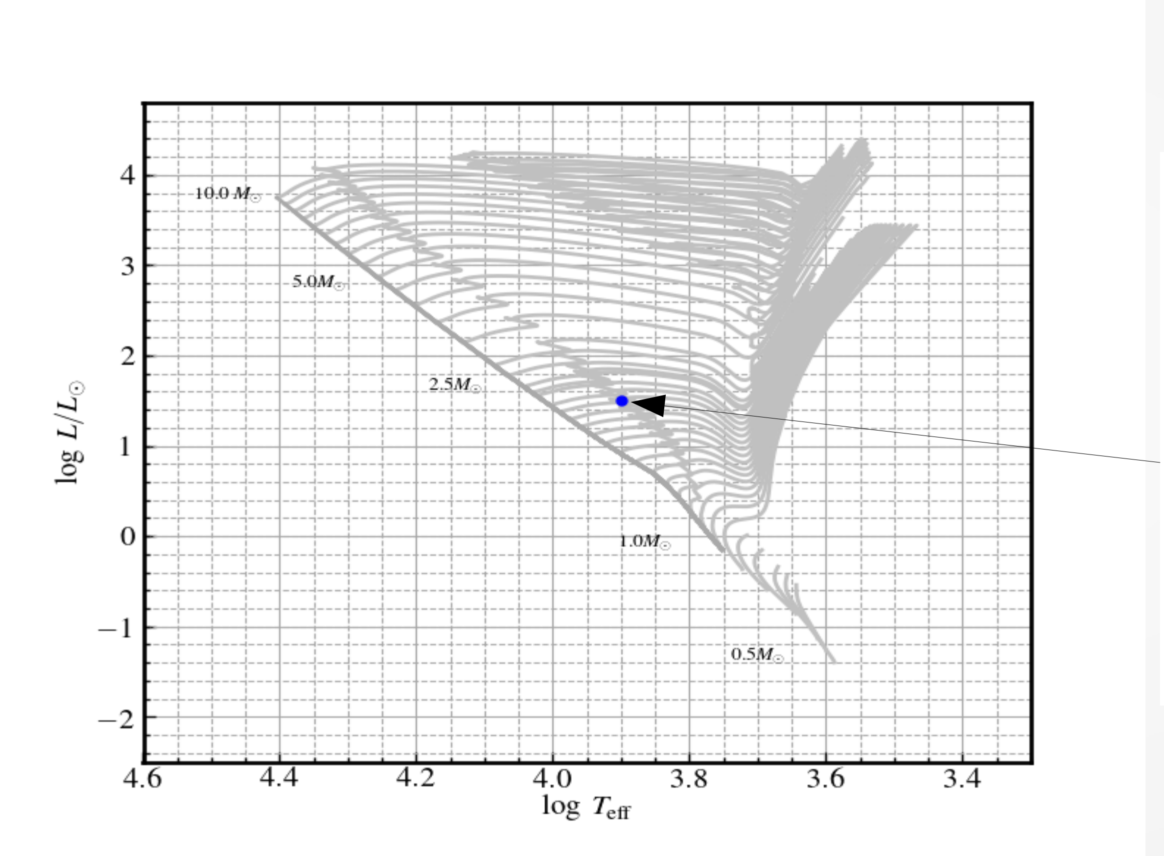


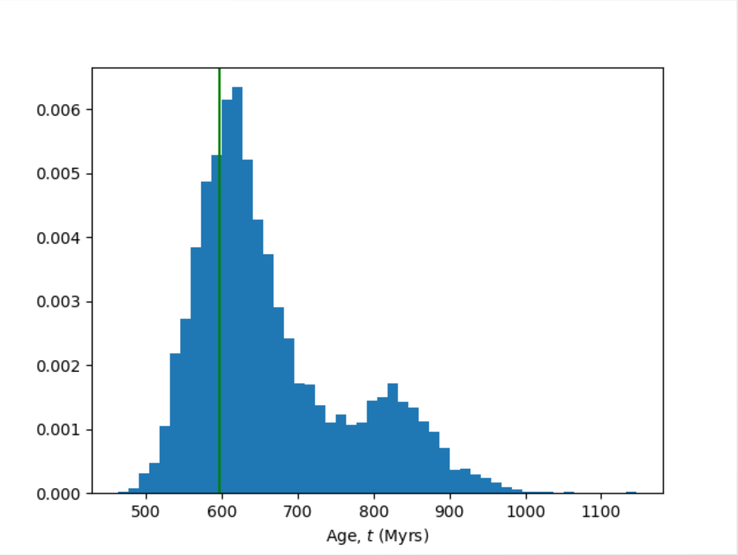
A Bayesian approach



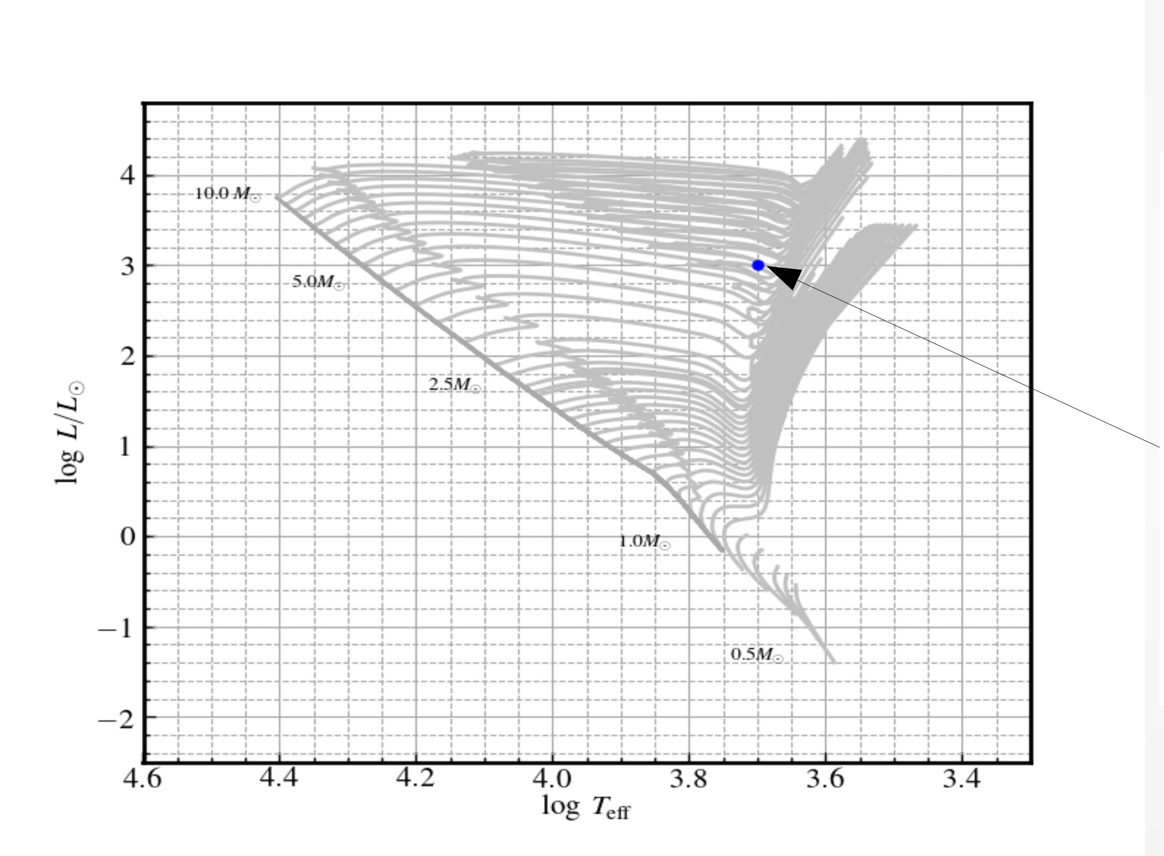


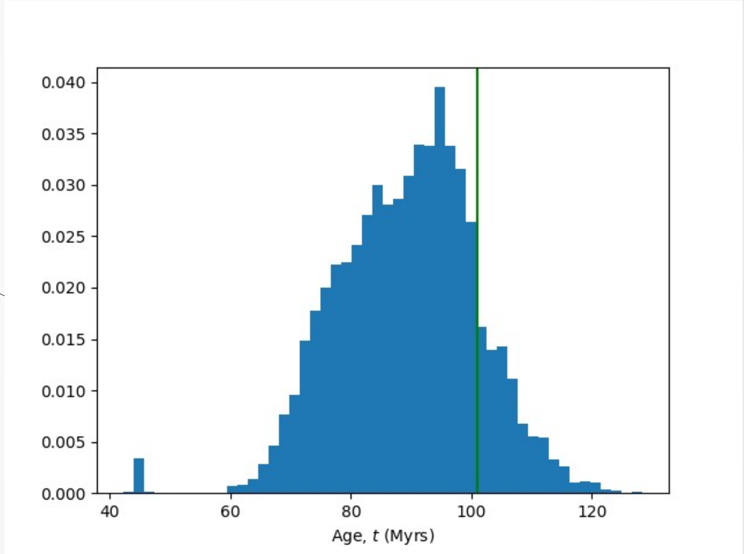
A Bayesian approach



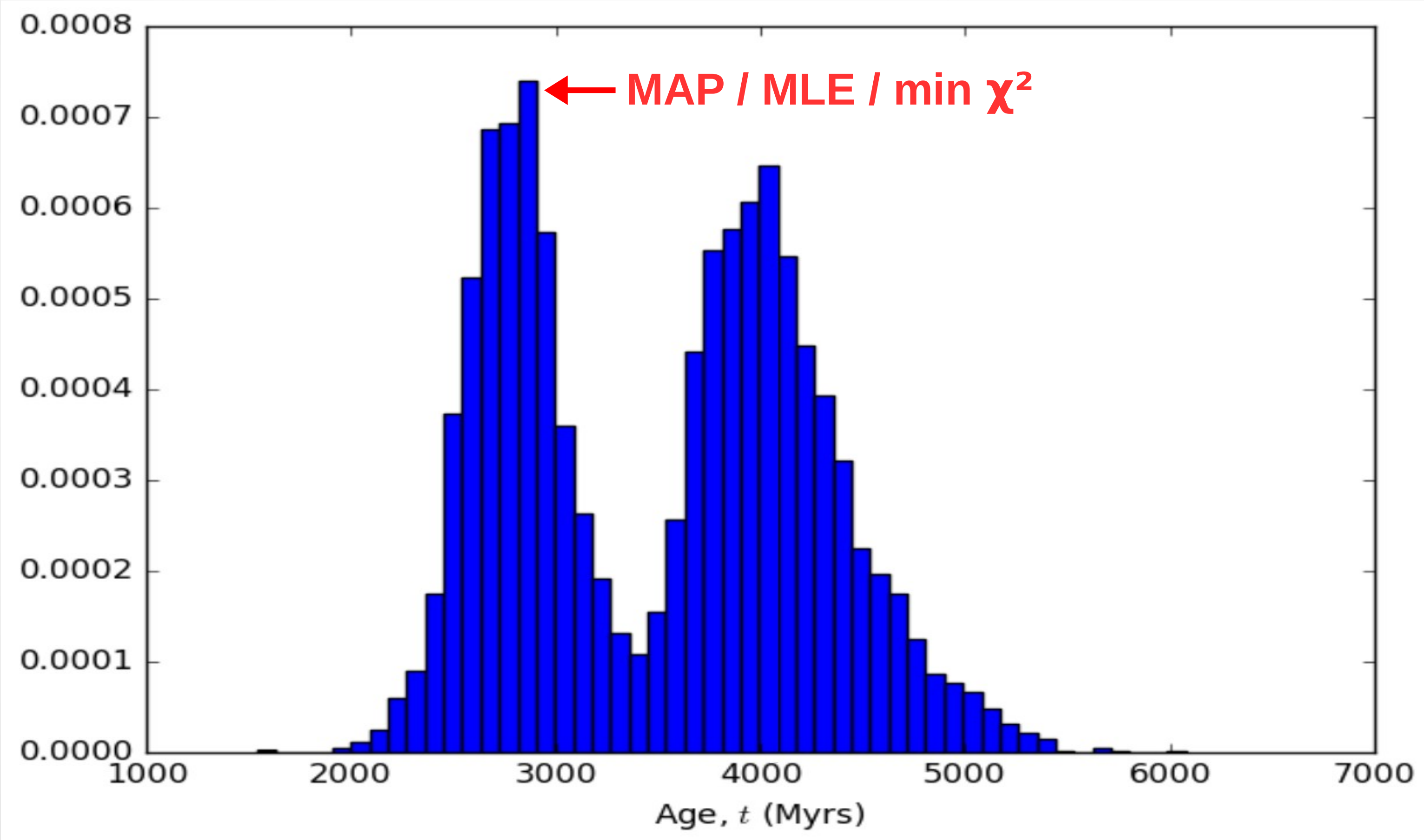


A Bayesian approach





A Bayesian approach



A Bayesian approach

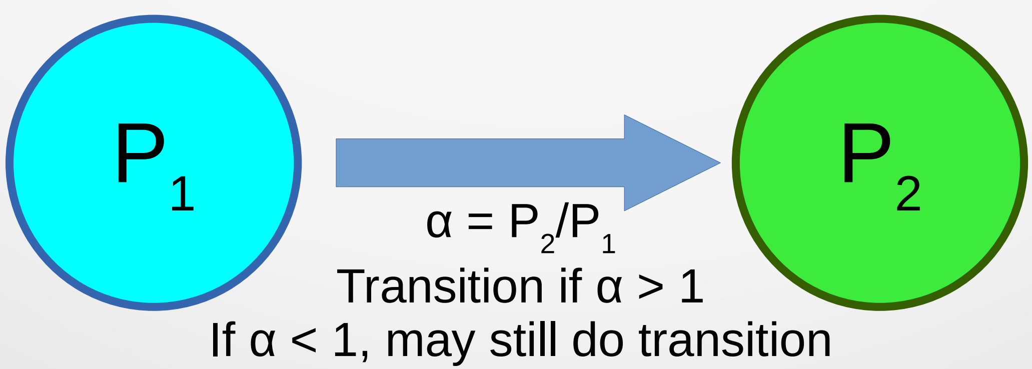
- Bayes' theorem: $P(model|data) \propto \underbrace{P(data|model)}_{Likelihood\ \ function} \underbrace{P(model)}_{Prior}$

- Priors: initial mass function (IMF), metallicity distribution function (MDF), star formation rate (SFR)

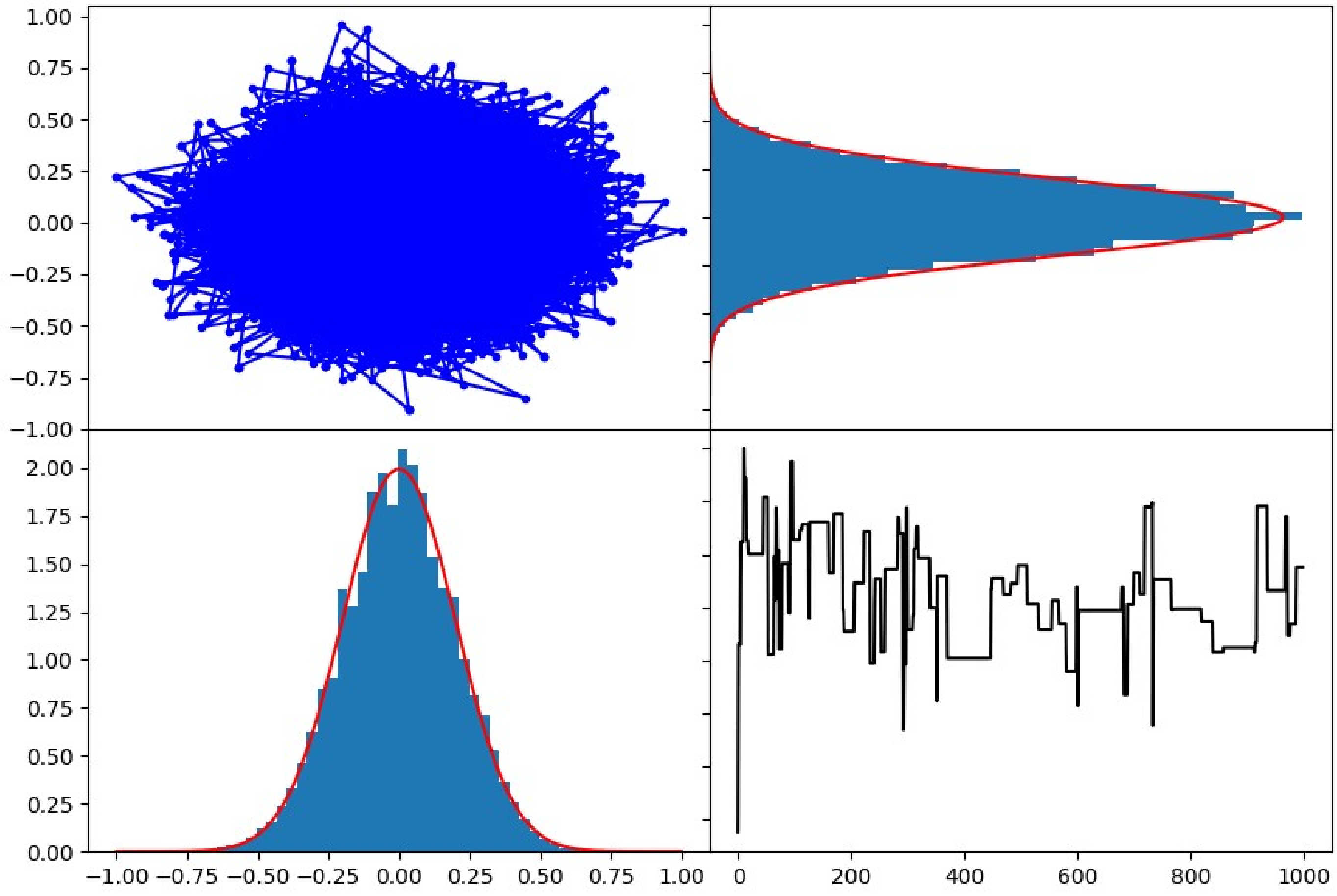
- Likelihood function: observational constraints

The MCMC algorithm

- MCMC = Monte Carlo Markov Chain
- one approach: Metropolis-Hastings algorithm
  - explores the model parameter space so as to
    - spend little time in unlikely regions
    - spend a lot of time in likely regions
    - the distribution of explored points corresponds to PDF



The MCMC algorithm



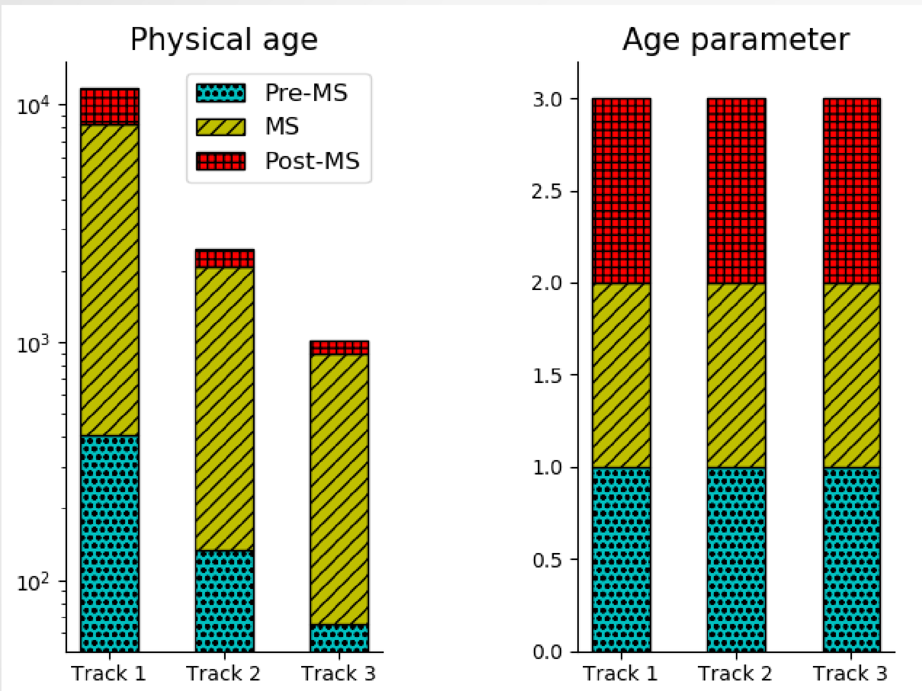
Model interpolation

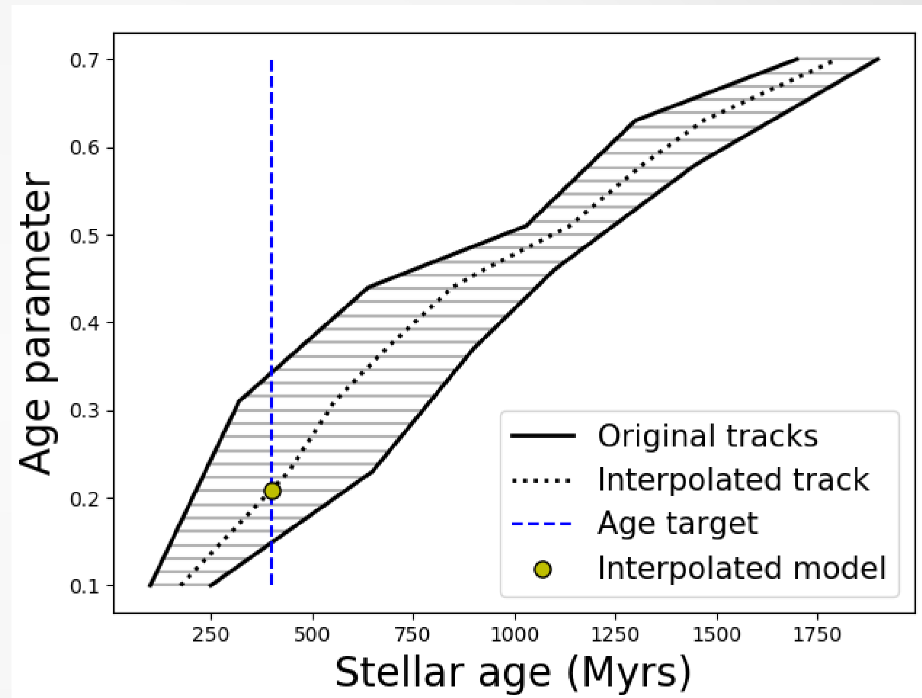
- two parts
  - age interpolation
  - track interpolation

Age interpolation

- AIMS/SPInS uses 2 age parameters:
  - the physical age, t
  - the equivalent age parameter, τ (corresponds to evolutionary stage)
- MCMC according to age, t
  - this avoids introducing unwanted priors on age
  - components of multiple systems typically have the same *physical age*
- interpolation according to τ
  - this enables combining models at equivalent evolutionary stages when interpolating across tracks

Age interpolation

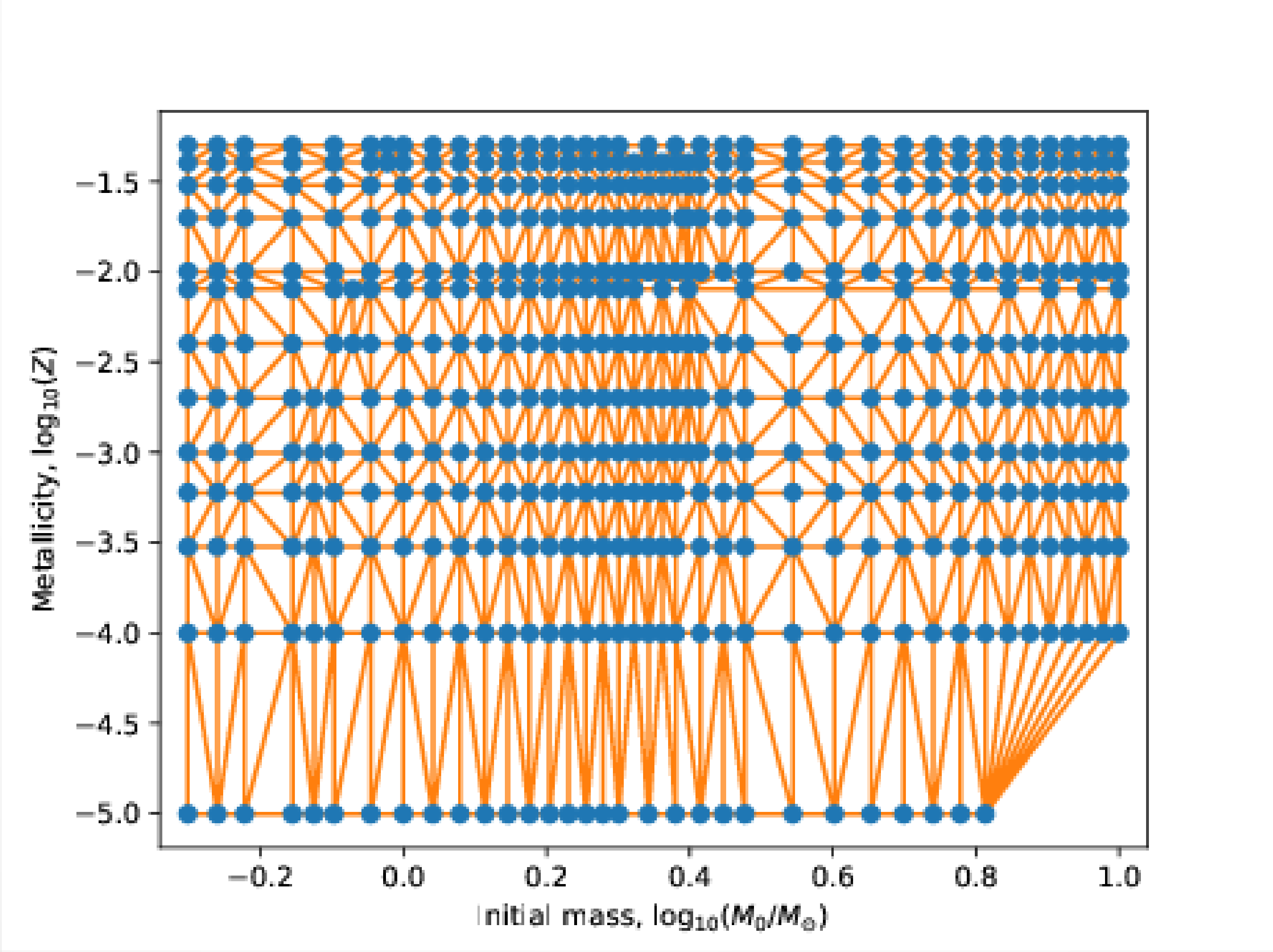




- AIMS/SPInS is constantly going back and forth between t and τ
  - need for efficient algorithm

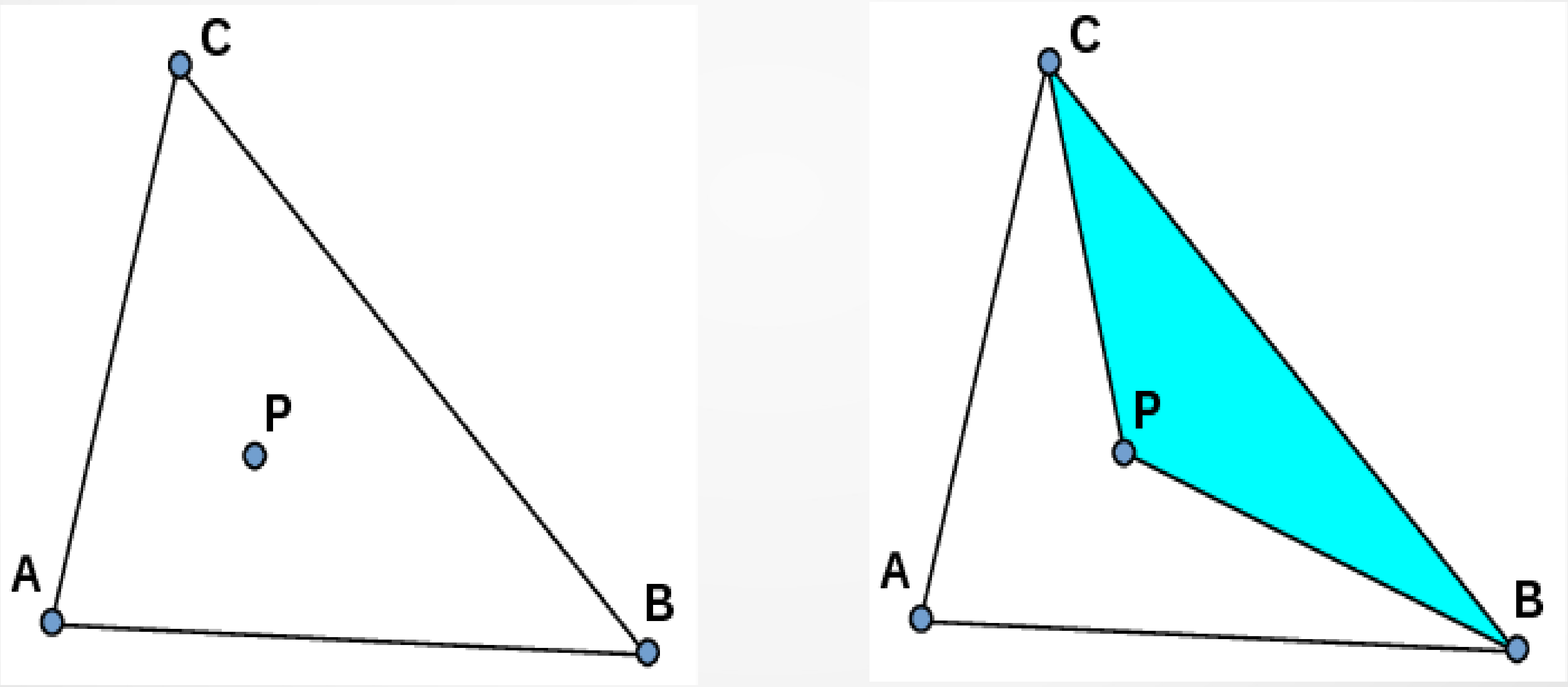
Track interpolation

- apply a Delaunay tessellation



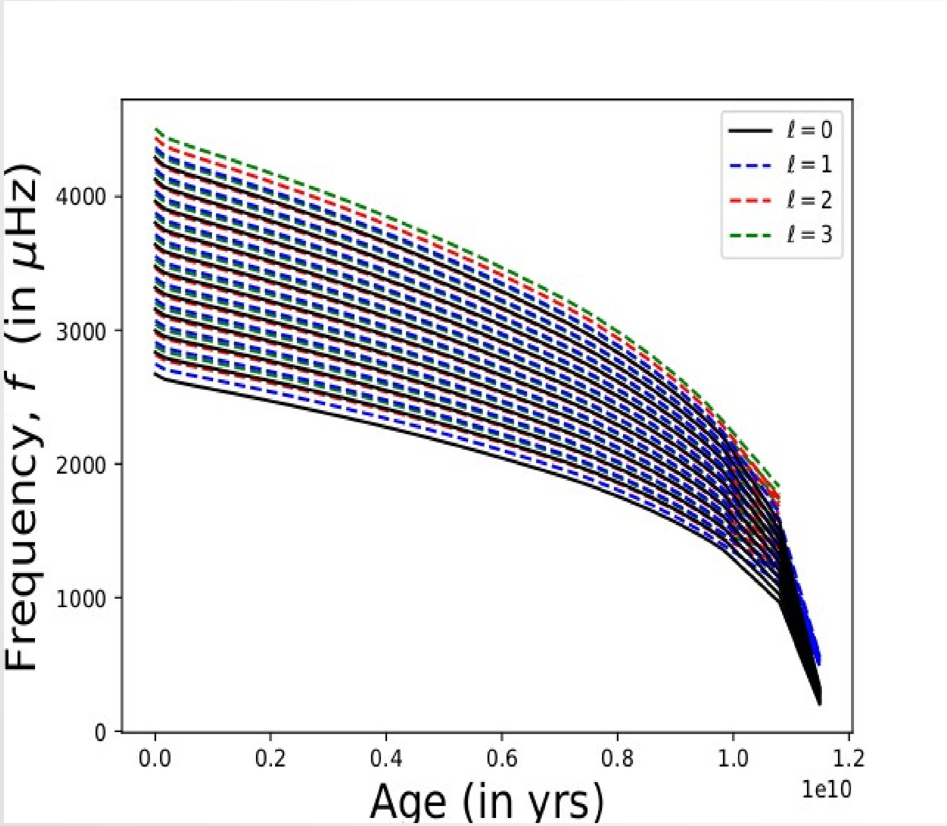
Track interpolation

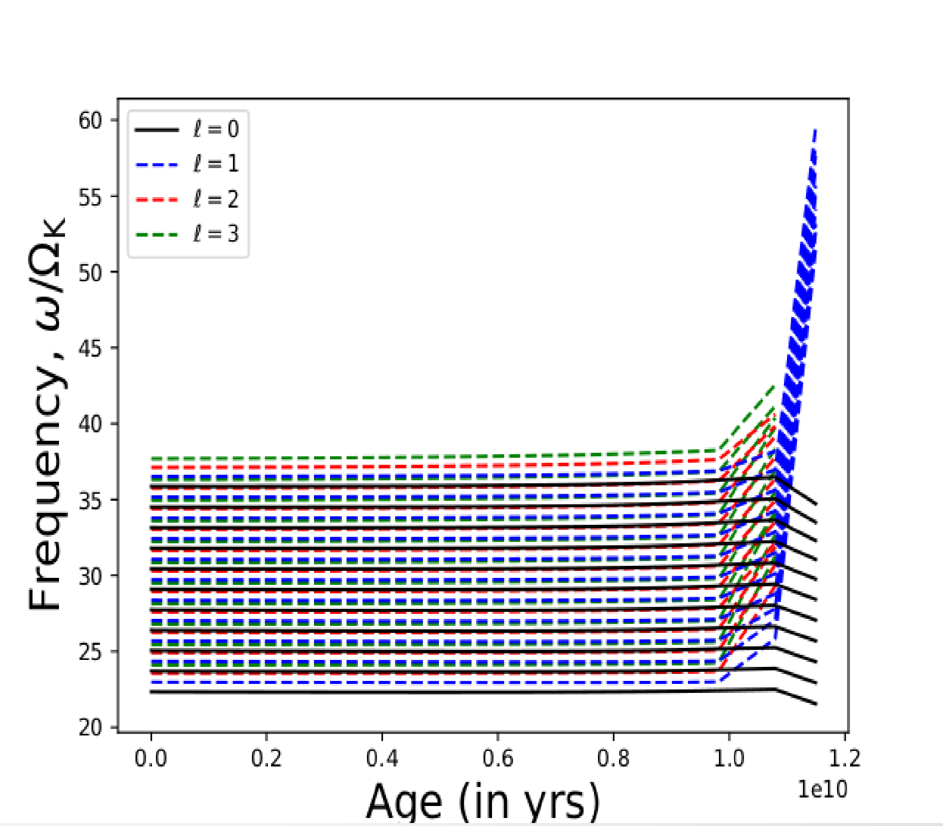
- calculate linear integration weights within selected simplex



Frequency interpolation (AIMS only)

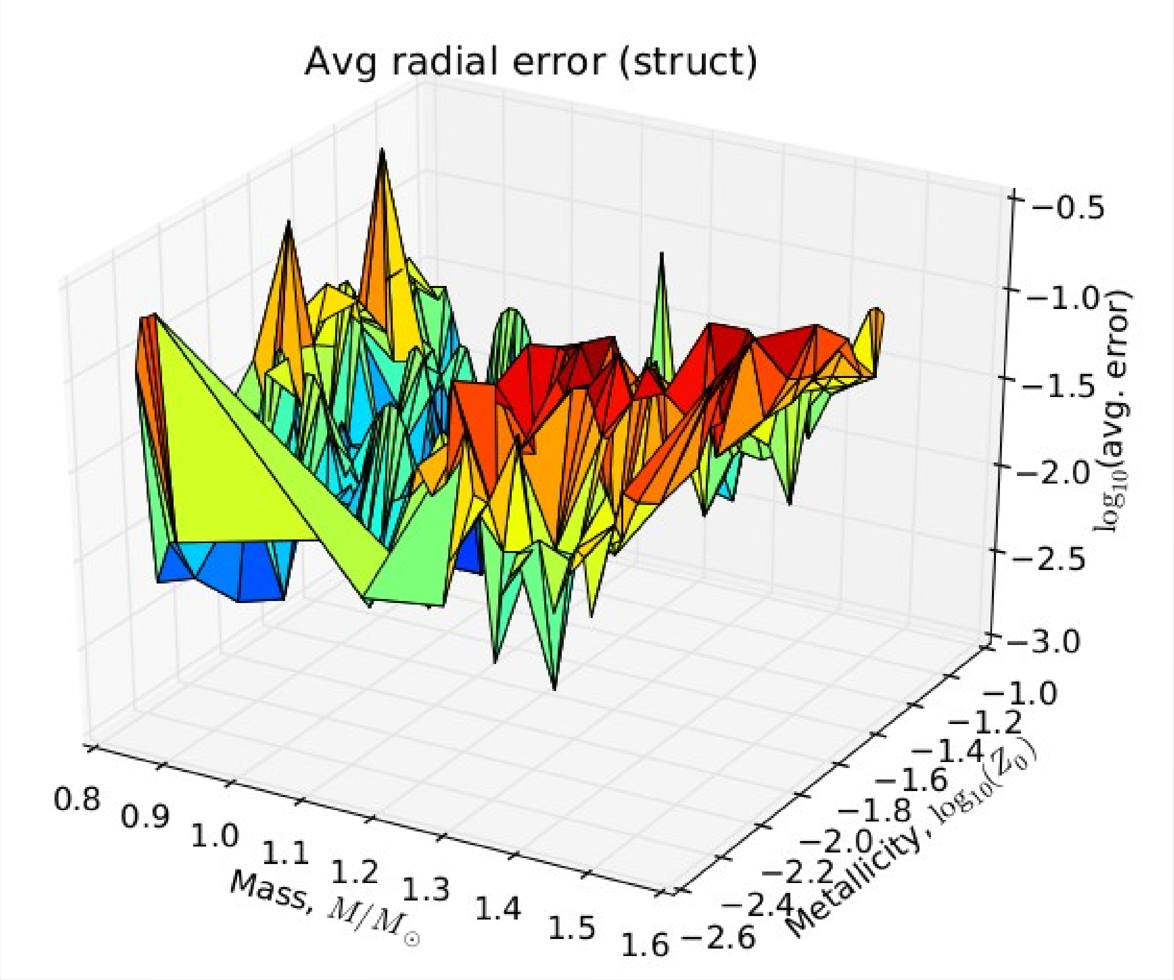
- non-dimensional frequencies are interpolated along tracks





Accuracy of the interpolation

- internal tests may be applied to analyse interpolation accuracy



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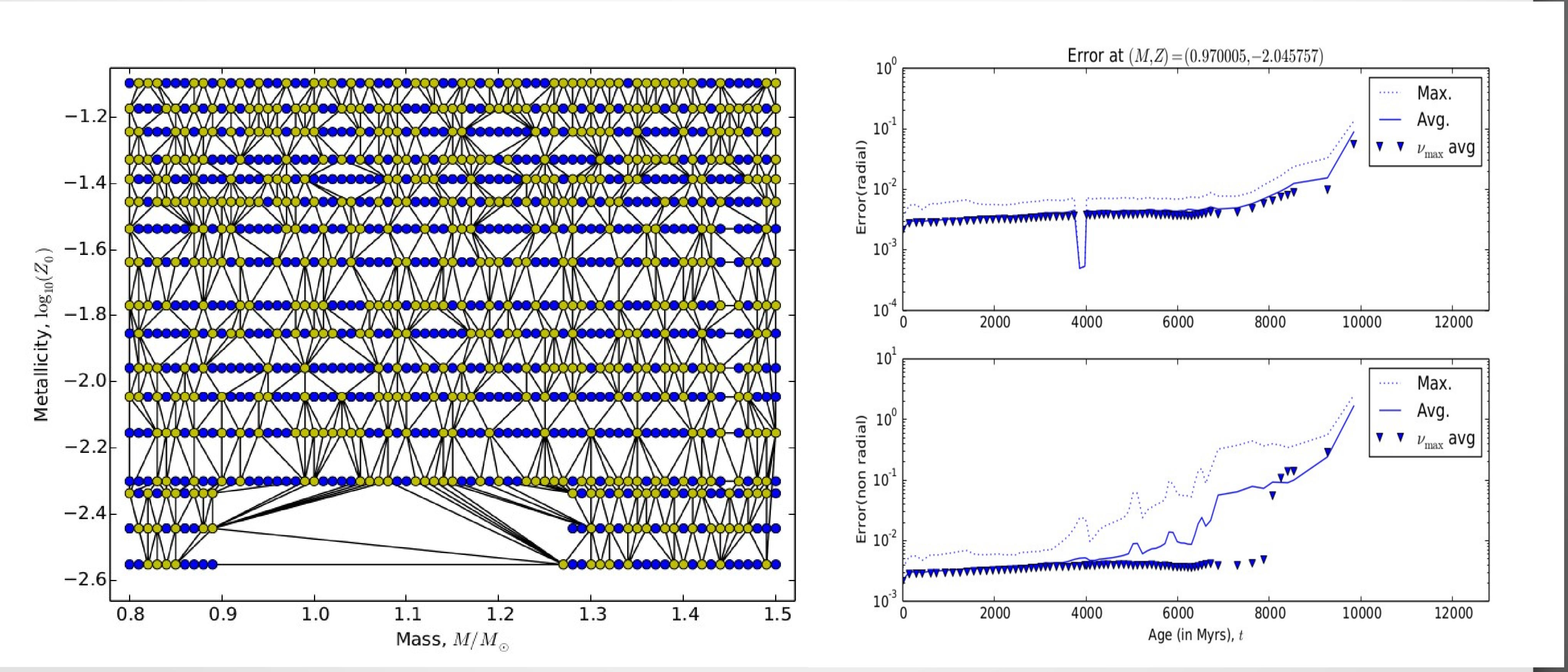
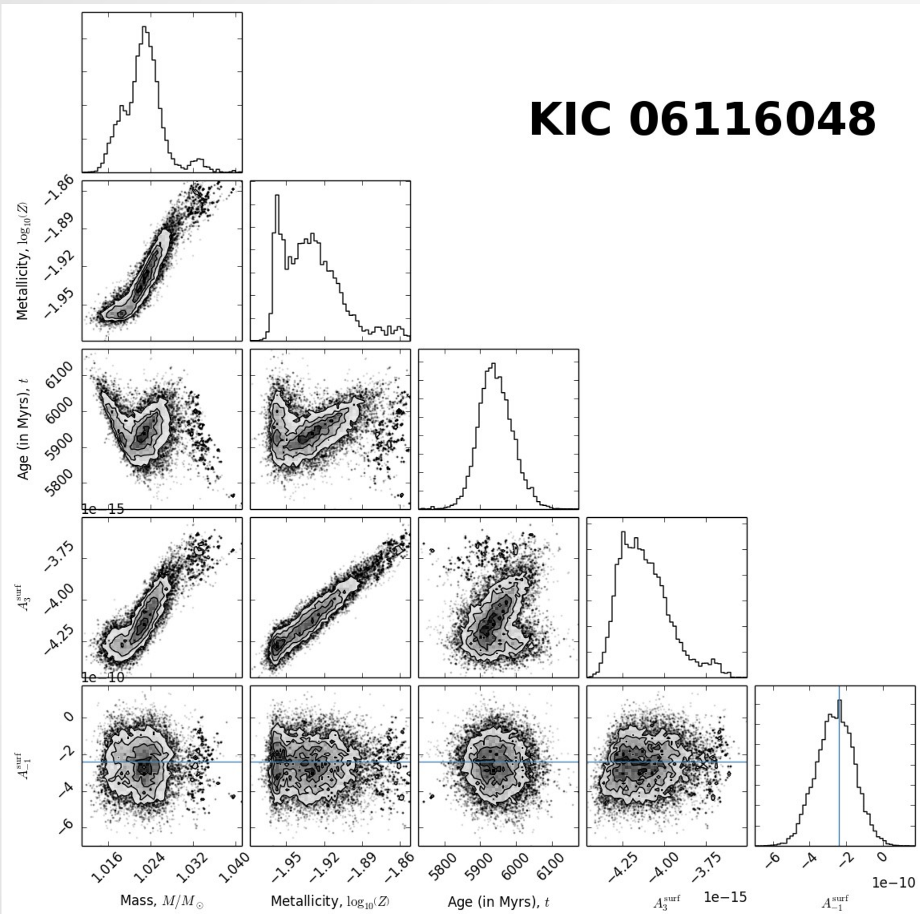
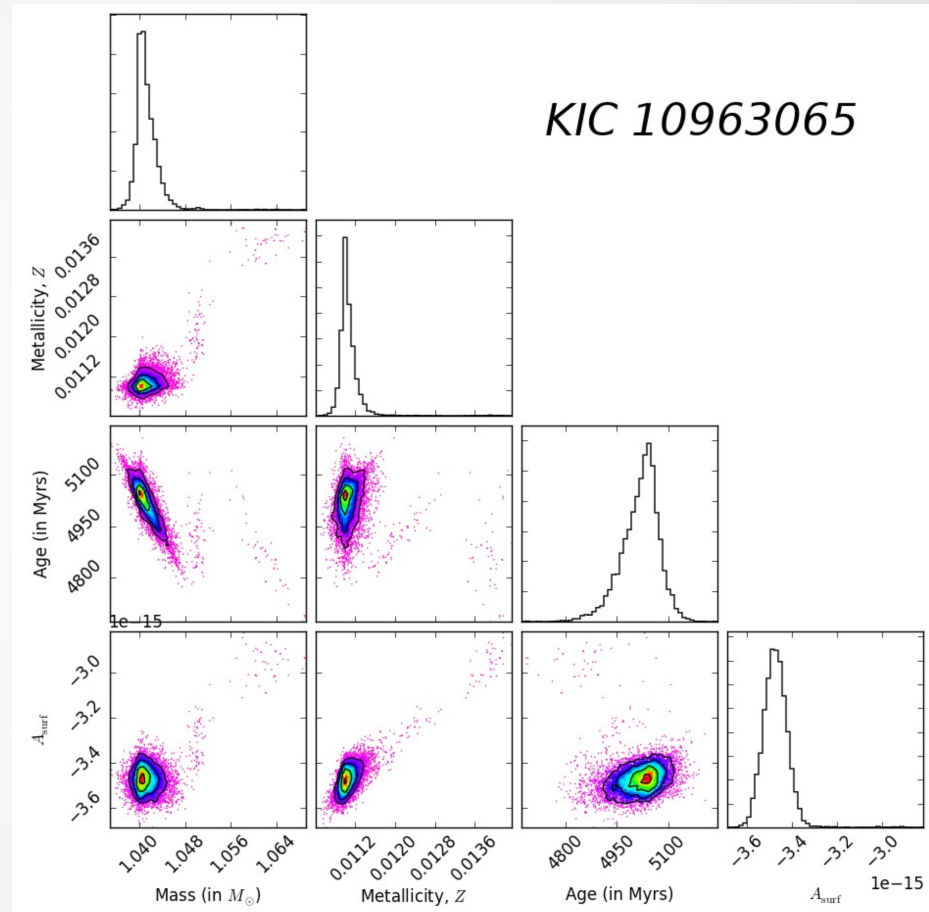


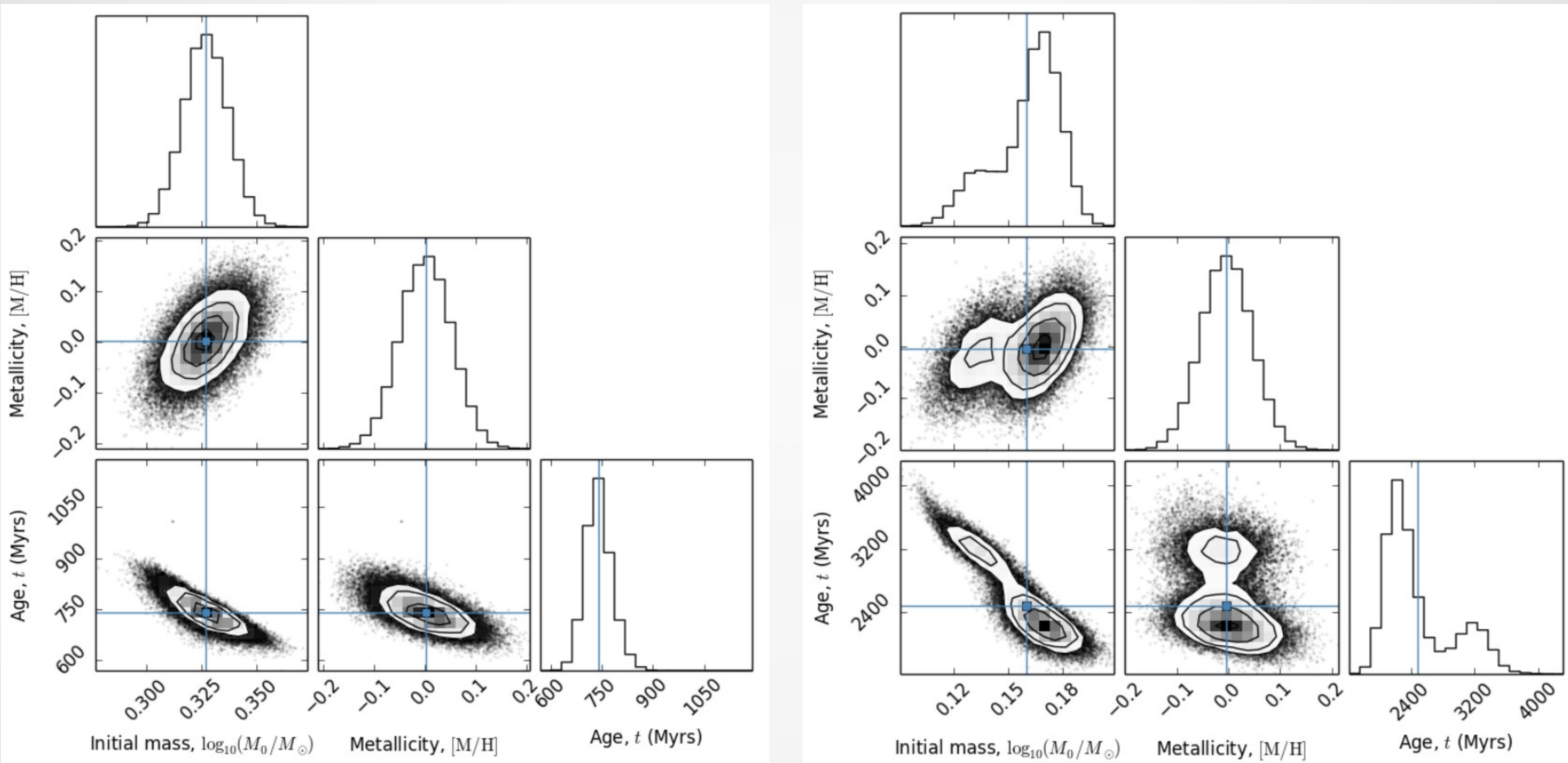
Some results with AIMS





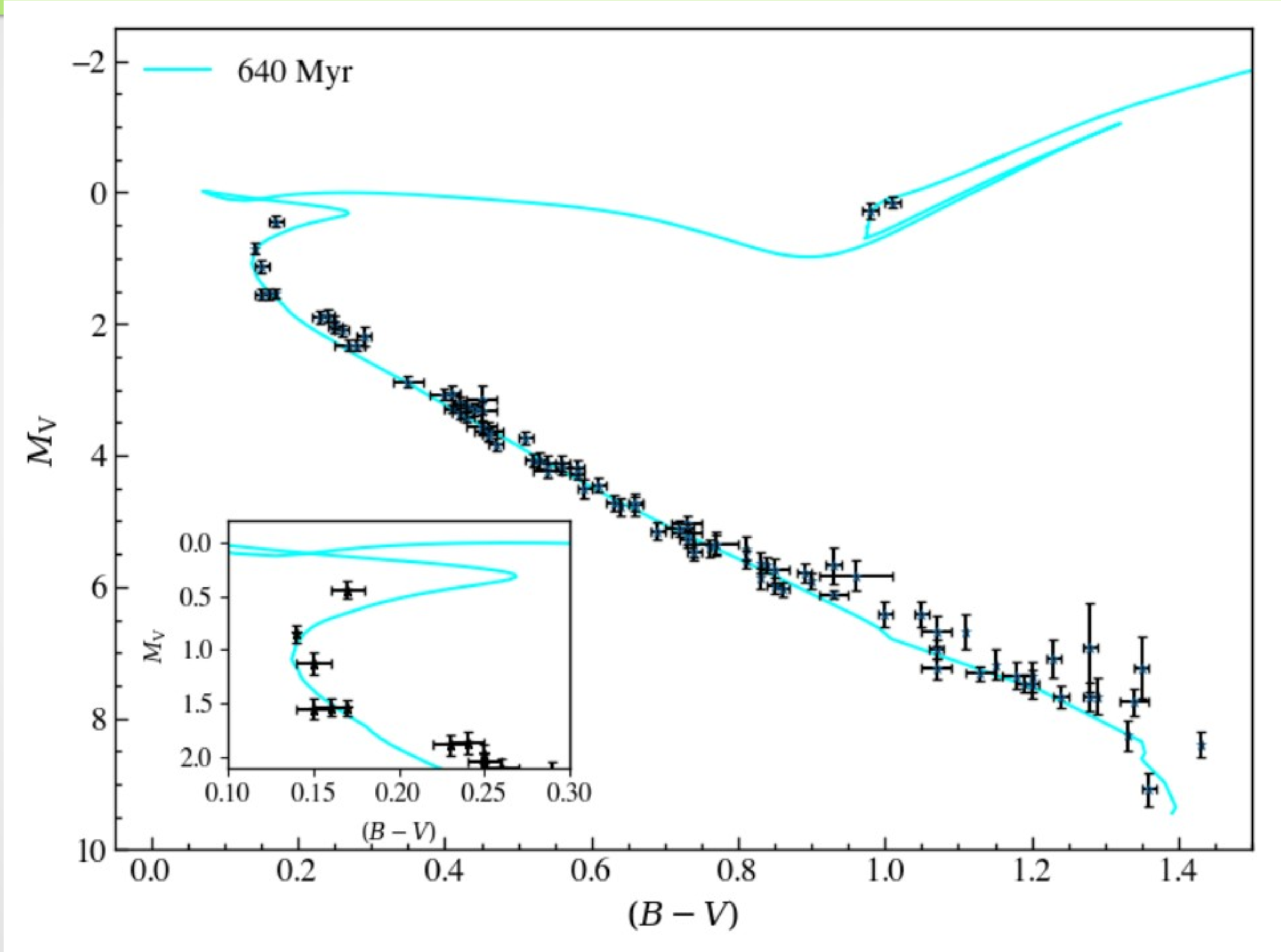
Solutions obtained with AIMS for Kepler LEGACY stars (Lund et al. 2017, Silva Aguirre 2017) – solutions are sometimes multimodal

Some results with SPInS



Results for some artificial stars

Some results with SPInS



Best fitting isochrone obtained with 92 stars from the Hyades cluster

Conclusion & perspectives

- AIMS and SPInS are helping to characterise stars and improve our understanding of various effects, e.g.:
  - AIMS: internal systematic effects and surface effects (Nsamba et al. 2018)
  - SPInS starting to be used extensively for the FLAME work package for Gaia and various other groups
- future improvements
  - automatic stopping criterion for the MCMC sampler
  - possibility of isolating separate modes in multimodal solutions
  - extend AIMS to handle multiple systems
  - extend AIMS to handle rotating stars