PLATO Hare-and-Hounds exercise

Modelling main sequence stars

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Goal

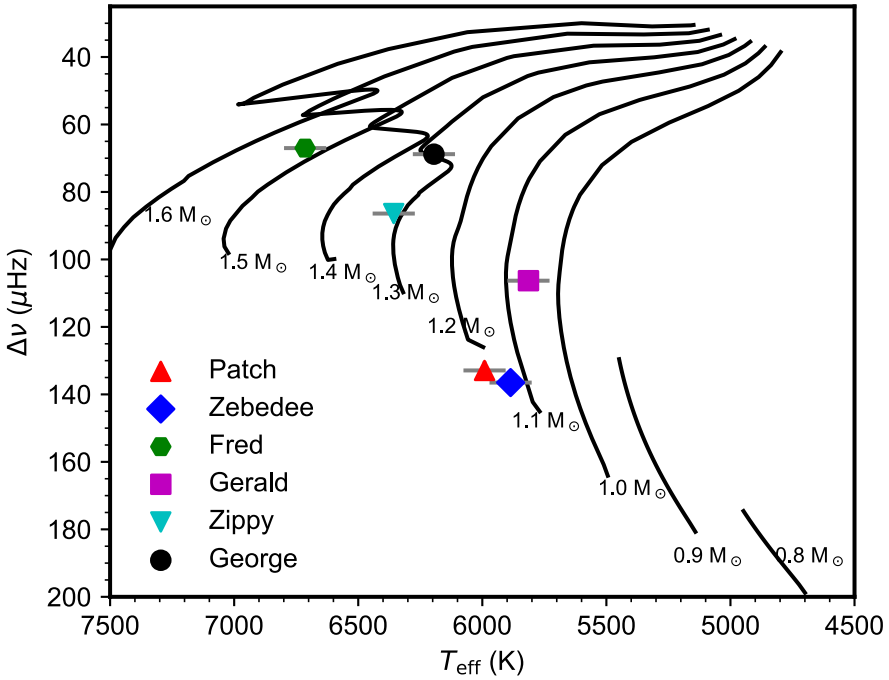
Definition of the best/possible approach to determine stellar properties (mass, radius, and age) for stars for which PLATO is expected to provide seismic data.

- Establish the accuracy limit with which stellar properties may be derived from given sets of asteroseismic data, based on a pre-computed grid of models;
- Compare different methods available in the community;
- Understand the impact from changing key aspects of the modelling: surface corrections, weights, etc;
- Understand the impact from changing the quality and characteristic of the classic and seismic data.

Hare and Hounds

Simulations

- 2yr observations, V~9 (six simulated stars)
- T_{eff} and [Fe/H] spectroscopic-like uncertainties
- Fixed model grid
- **5 different pipelines**



Targets	$L/L_\odot$	T_{eff} (K)	[Fe/H]	ν_{max} (μHz)	$\Delta\nu$ (μHz)
Patch	1.03 ± 0.03	5991 ± 85	-0.28 ± 0.09	2906 ± 143	132.9 ± 2.7
Zebedee	0.98 ± 0.03	5886 ± 85	0.10 ± 0.09	3254 ± 167	136.5 ± 2.8
Fred	5.42 ± 0.16	6714 ± 85	-0.04 ± 0.09	1393 ± 69	67.0 ± 1.4
Gerald	1.50 ± 0.05	5814 ± 85	0.03 ± 0.09	2207 ± 108	106.3 ± 2.1
Zippy	2.85 ± 0.09	6357 ± 85	-0.17 ± 0.09	1660 ± 85	86.4 ± 1.7
George	3.67 ± 0.11	6195 ± 85	0.35 ± 0.09	1284 ± 68	68.8 ± 1.4

Hare and Hounds

Simulations

- 2yr observations, V~9 (six simulated stars)
- T_{eff} and [Fe/H] spectroscopic-like uncertainties
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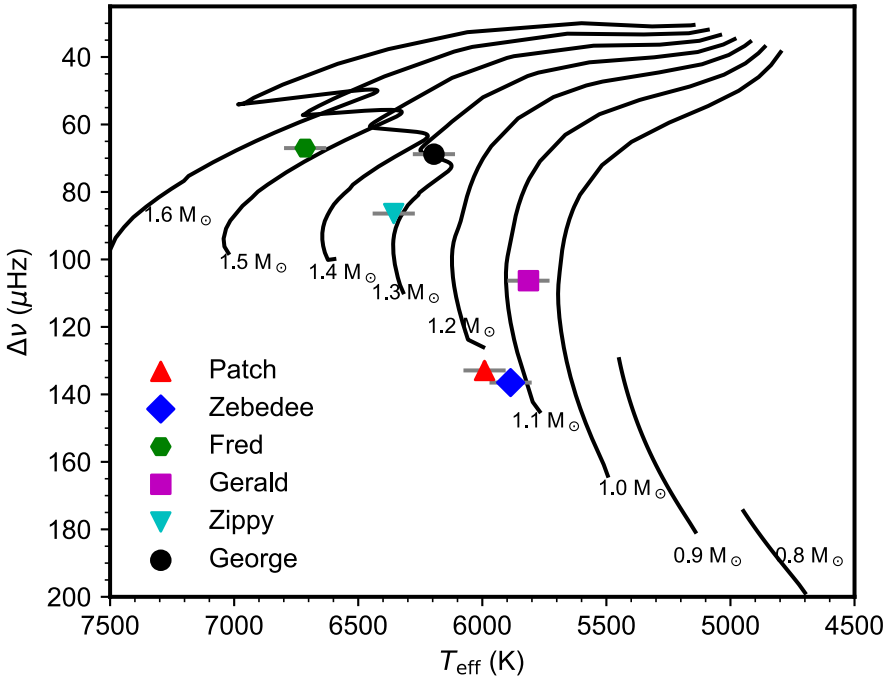
Also: relaxed the quality and extent of the data



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Grid properties

- Model grid with a total of 9000 evolutionary tracks containing about 3.5 million models
- $M \in [0.8,1.5]\ M_{\odot}$; [Fe/H] $\in [-0.5,0.5]$dex
- $\alpha_{mlt} \in \{1.6,1.7,1.8,1.9,2.0\}$, $f_{ov} \in \{0.0,0.015,0.030\}$ and dY/dZ $\in \{1,2,3\}$
- No gravitational settling (or any other type of chemical transport)

Inference Methods

Fit observations $O_i \in \{T_{\rm eff}, [Fe/H], L, \nu_{\rm i}\}$

Classical constraints

seismic constraints (frequencies or their combinations.)

to model observables $\mathcal{m}_i(p_1, p_2, p_3, \ldots)$

where $p_i \in \{M, Y_0, Z_0, \alpha_{\rm mlt}, f_{\rm ov}, {\rm age}, \ldots\}$

Inference Methods

Fit observations $O_i \in \{T_{\rm eff}, [Fe/H], L, \nu_{\rm i}\}$

Classical constraints

seismic constraints (frequencies or their combinations.)

Key differences

- Sampling of the parameter space
- Estimates of properties and their uncertainties
- Surface dependent/independent approaches

to model observables $m_i(p_1, p_2, p_3, \ldots)$

where $p_i \in \{M, Y_0, Z_0, \alpha_{\rm mlt}, f_{\rm ov}, \text{age}, \ldots\}$

In addition, for any given method

- Consider different surface corrections (when applicable)
- Consider different weights of the observations

Simulated stars

Outside the grid: min{dY/dZ} = 1

Targets	ID	Mass ($M_\odot$)	Radius ($R_\odot$)	Age (Gyr)	Y_{ini}	Z_{ini}	α_{mlt}	f_{ov}	Physics
Patch	Pa	0.8644	0.9557	9.898	0.25906	0.00784	1.931	0.0115	Default
Zebedee	Ze	1.0165	0.9646	3.085	0.26786	0.01734	1.872	0.0223	Default
Fred	Fr	1.4318	1.7225	1.839	0.26055	0.01638	1.688	0.0066	Default
Gerald	Ge	1.0242	1.2053	8.039	0.27566	0.02111	1.967	0.0274	Gravitational settling
Zippy	Zi	1.1278	1.3965	4.223	0.27784	0.01245	1.880	–	Step overshooting*
George	Go	1.3430	1.7069	3.757	0.28049	0.03001	1.770	0.0939	VAL C atmosphere

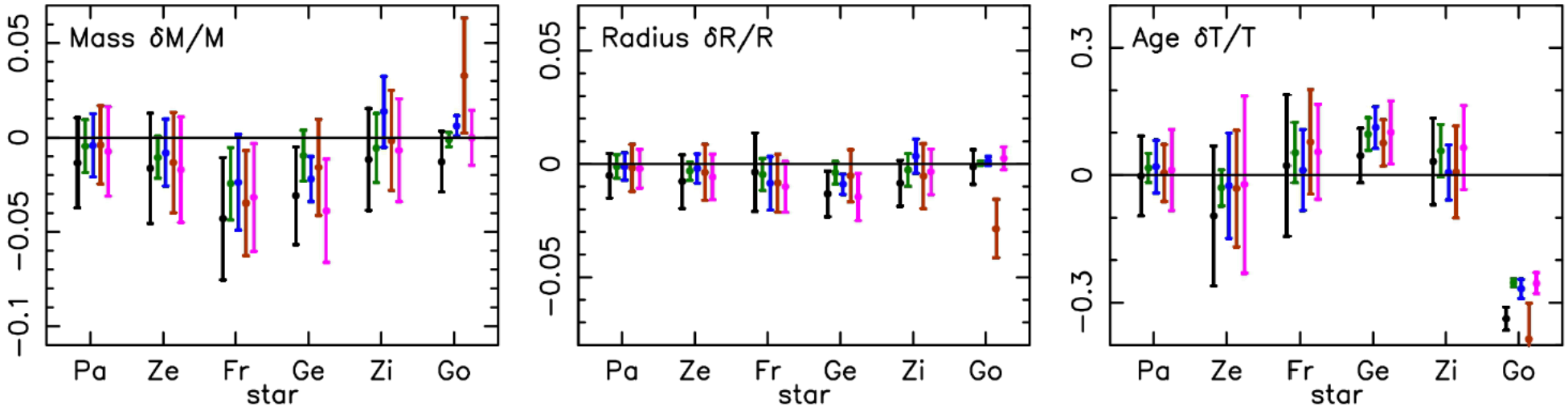
Outside the grid: max $\{f_{ov}\}$ = 0.03

Comparison between different Methods

Default
Patch: within parameter space
Zebedee: within parameter space
Fred: outside parameter space, dY/dZ

Different physics
Gerald: gravitational settling
Zippy: Step overshooting
George: outside parameter space, f_{ov}

$\delta P/P=(P_{fit}-P_{true})/P_{true}$



All hounds reported a problem fitting the data for George √

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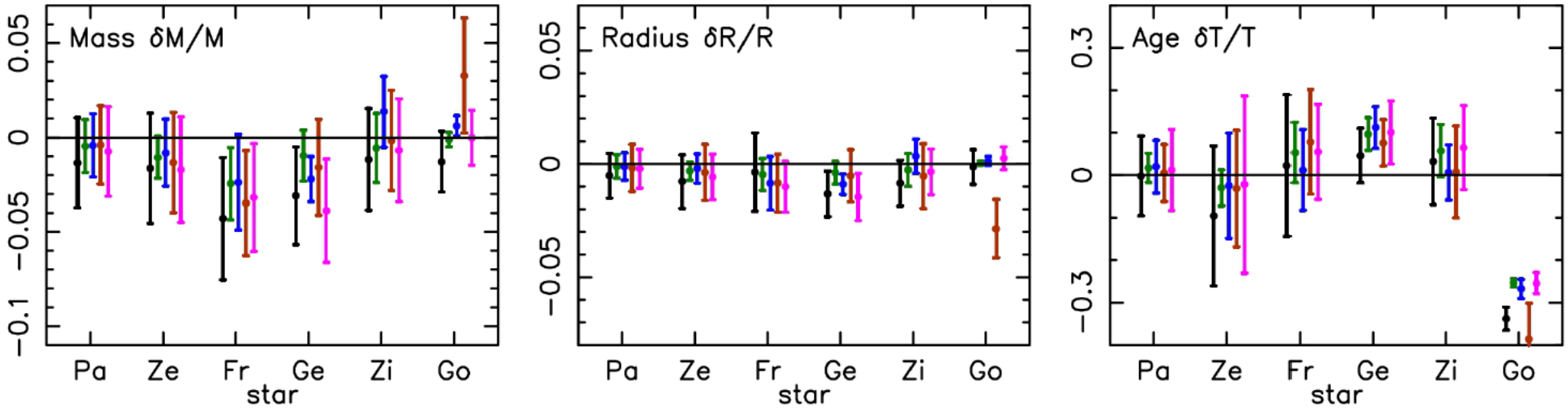

Average relative error (over all stars except George) for different methods
Mass: 1.31-2.61 %. Radius: 0.33-0.84%. Age: 5.07-6.01%

Similar performance

Worst accuracy performance

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Patch: within parameter space
Zebedee: within parameter space
Fred: outside parameter space, dY/dZ

Different physics
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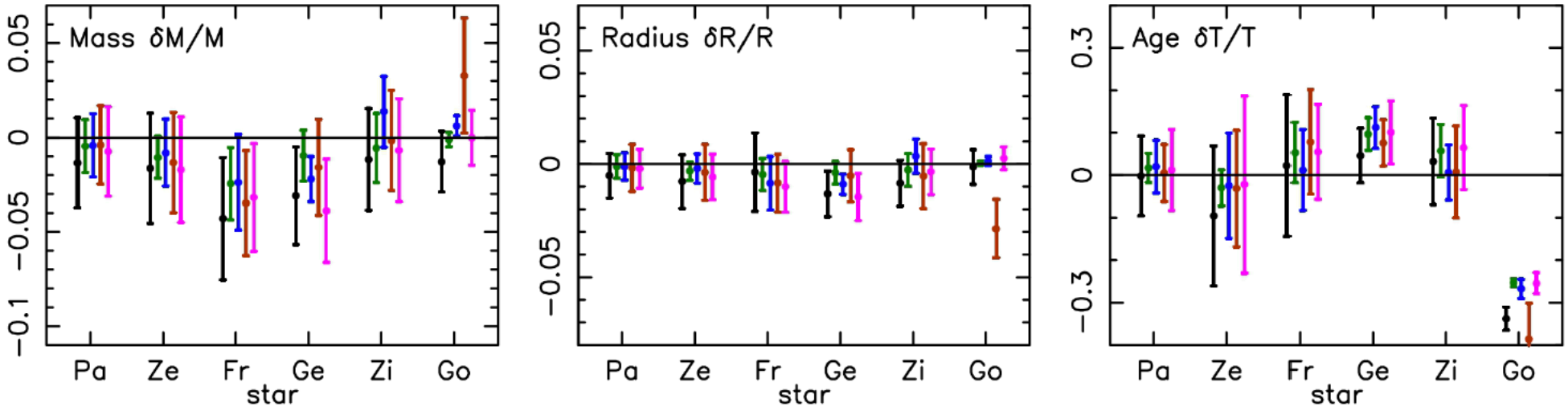


Maximum relative differences
Mass: 4.32% (Fred). Radius: 1.33% and Age: 11.25% (Gerald)

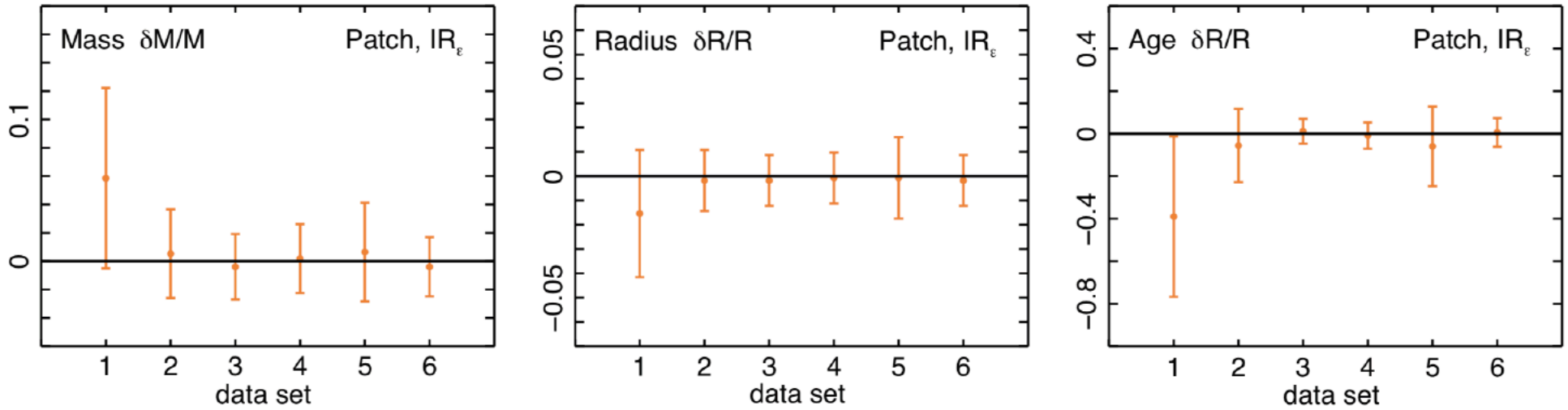
Model physics is key! Need tests on benchmark stars.

Decreasing the length of the seismic dataset

Datasets

Set	$l = 0$	$l = 1$	$l = 2$	Comments
1	0	0	0	no frequencies
2	2	2	0	
3	2	0	2	
4	2	2	2	
5	8	9	0	
6	8	9	6	full set

Patch: default, Age~9.9Gyr, M ~0.86$M_\odot$



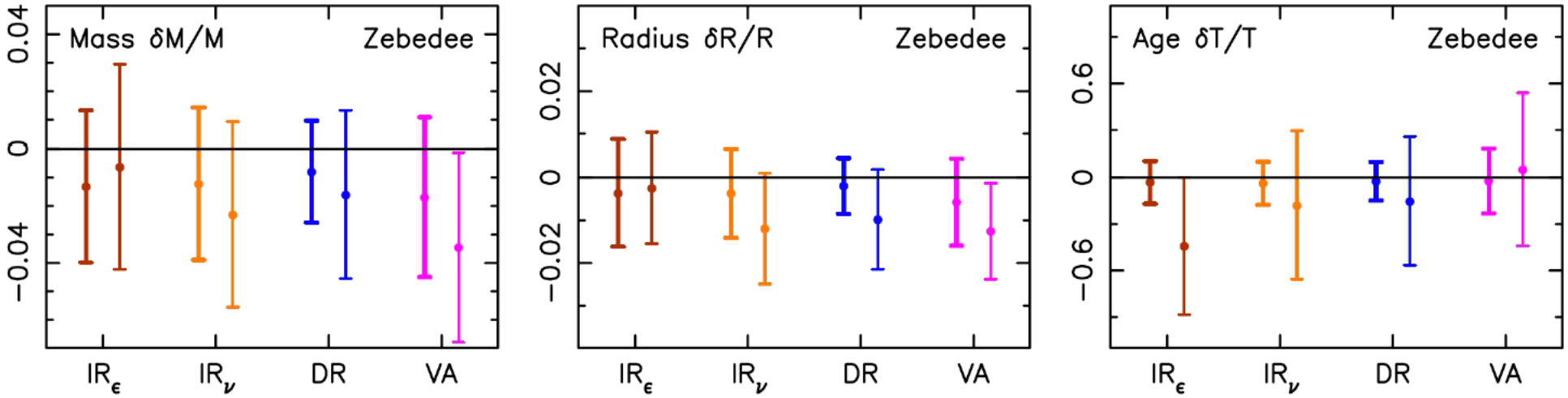
- Seismic data improves significantly both accuracy and precision on inferred properties
- Detection of just a few modes seems to be enough
- *l*=2 modes have a significant impact on age precision

Impact of degrading the seismic data

Number of modes: decreased from 23 to 7 (no *l=2* mode)

Uncertainties on frequencies: increased by a factor of 3

Zebedee: default, Age~3Gyr, M ~1.01$M_\odot$



Change in average relative error (over 4 methods)
Mass: 1.32-2.25%; Radius: 0.4-1.01%; Age: 2.96-25.24%

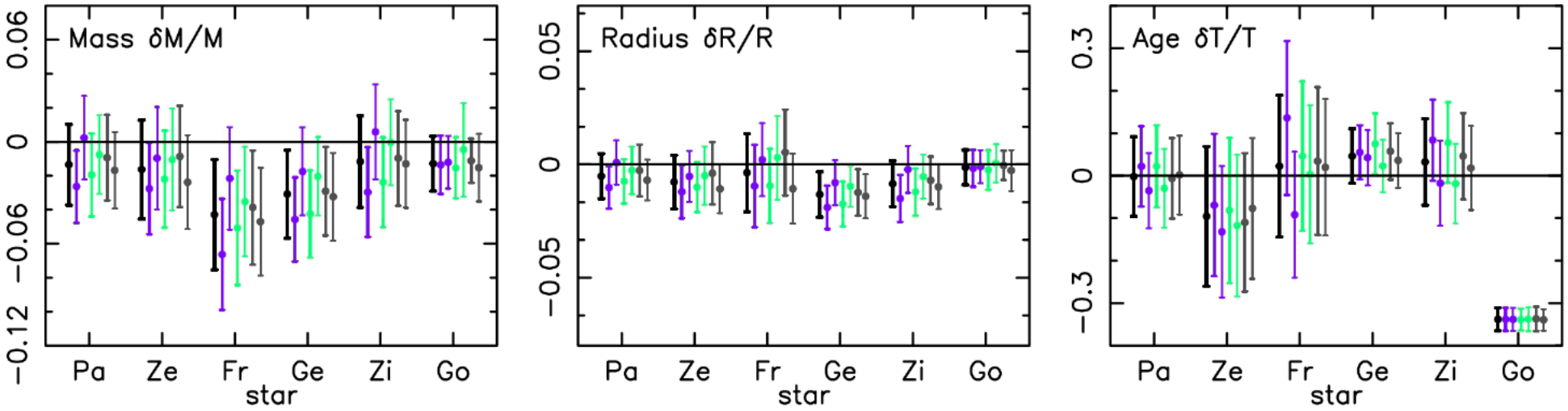
Need systematic study of impact of degrading the data!

Impact of degrading the classical data

Default
Patch: within parameter space
Zebedee: within parameter space
Fred: outside parameter space, dY/dZ

Different physics
Gerald: gravitational settling
Zippy: Step overshooting
George: outside parameter space, f_{ov}

Left to right: unchanged, [*Fe/H*]-+1σ, *L* -+1σ, T_{eff}-+1σ



Dispersion
Mass: 1.39% (Fred). Radius: 0.68% (Fred). Age: 6.7% (Fred)

Impact of degrading the classical data

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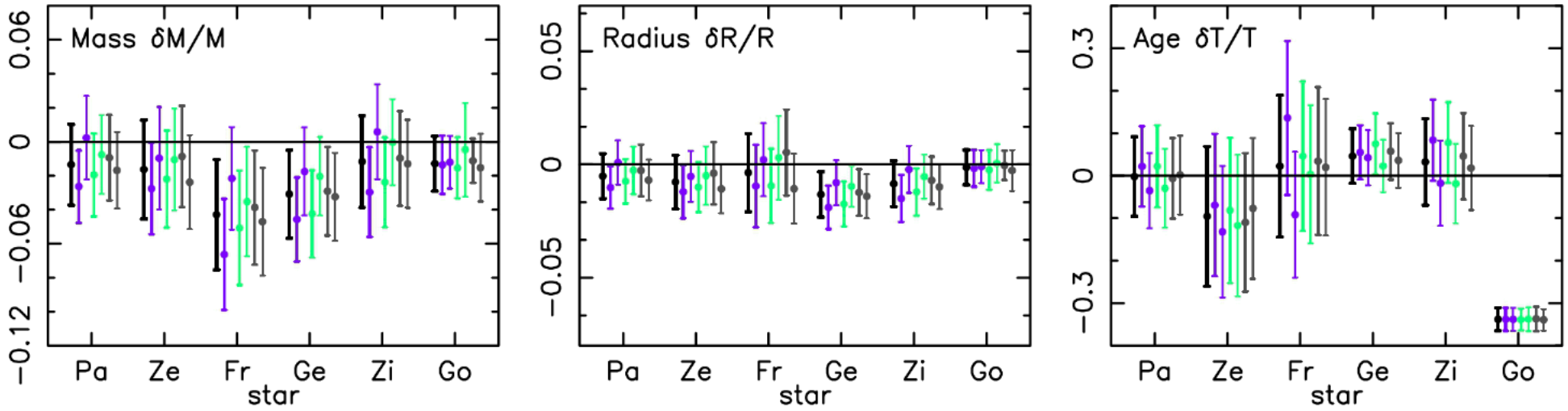
Patch: within parameter space
Zebedee: within parameter space
Fred: outside parameter space, dY/dZ

Different physics
Gerald: gravitational settling
Zippy: Step overshooting
George: outside parameter space, f_{ov}

Left to right: unchanged, [Fe/H]-+1σ, L -+1σ, T_{eff}-+1σ



Maximum difference between any two inferences
Mass: 2.34% and Age: 11.5%. shifting [Fe/H]
Radius: 1% shifting T_{eff}

It is important to determine the classical parameters to high accuracy!

Conclusions and future work

- **Maximum relative differences to the truth (i.e., worst over all methods and stars)**
  4.32% (Mass), 1.33% (Radius) and 11.25% (Age)

- **Average relative differences to the truth (i.e., average over all methods)**
  0.75-3.24% (Mass), 0.27-0.96% (Radius), 1.33-8.96% (Age)

- No significant difference found between methods, but more tests are required when seismic data becomes limited in extent and quality.

- Detection of just a few modes is enough to significantly improve accuracy and precision of results. The detection of an l=2 modes can improve significantly the age determination.

- Accuracy on classical parameters can have a significant impact on the results (specially [Fe/H] on age).

Conclusions and future work

- Need to test inferences against benchmark stars (boost after PLATO Launch).
- Perform new exercise focused on simulated stars near the threshold of detection of seismic data.
- Perform new exercise exploring a large set of simulated stars with different options for the physics to improve our understanding of the systematic errors.

PLATO Hare-and-Hounds exercise: Asteroseismic model fitting of main-sequence solar-like pulsators

M S Cunha ✉, I W Roxburgh, V Aguirre Børsen-Koch, W H Ball, S Basu, W J Chaplin, M-J Goupil, B Nsamba, J Ong, D R Reese, K Verma, K Belkacem, T Campante, J Christensen-Dalsgaard, M T Clara, S Deheuvels, M J P F G Monteiro, A Noll, R M Ouazzani, J L Rørsted, A Stokholm, M L Winther

Monthly Notices of the Royal Astronomical Society, stab2886, https://doi.org/10.1093/mnras/stab2886

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Thank you!