Non-seismic (and Non-LTE) stellar parameters for the PLATO core sample

Maria Bergemann
Max Planck Institute for Astronomy
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PLATO WP 122

More than 70 scientists with expertise in model atmospheres (HE, 3D RHD and MHD), spectral modelling, (spectro)photometry, interferometry, SED fitting, Bayesian methods and astro-statistics, and analysis of fundamental stellar parameters of FGKM stars

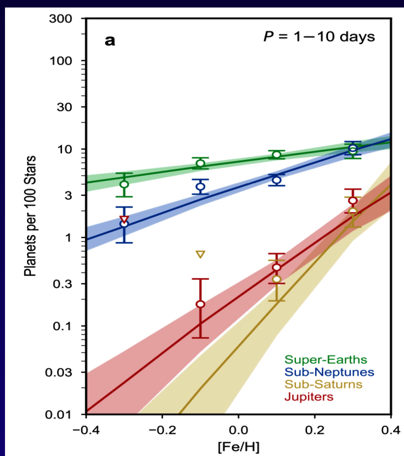
Outline

- **Intro: why non-seismic stellar parameters for PLATO?**
- **Methods: SAPP**
- **Models: why 3D Non-LTE**
- **Solar chemical composition**

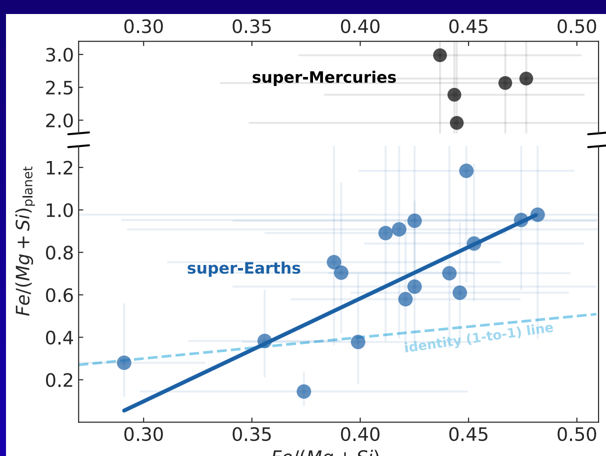
Classical stellar parameters for PLATO

T_{eff}, [Fe/H]
chemical abundances,
V*sini*…

Exoplanets
structure, formation, populations

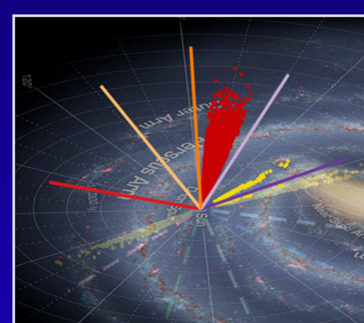


Petigura+ 2018



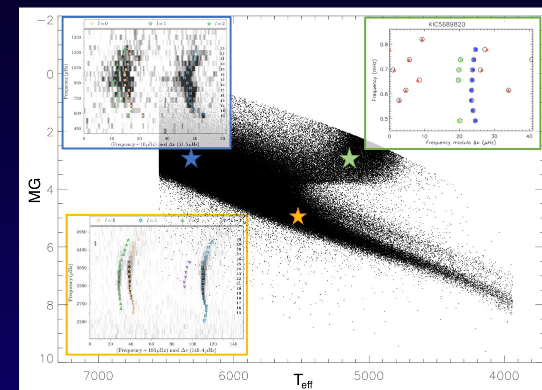
Adibekyan+ 2021

Population statistics



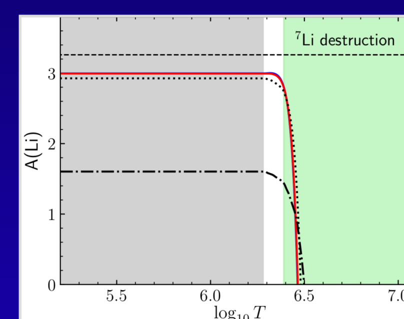
Davies & Miglio 2018

Asteroseismology
masses, radii, ages



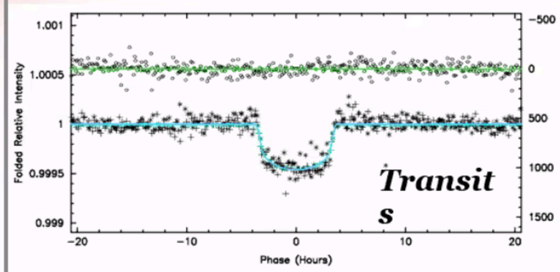
Lund et al. 2017, Deheuvels et al. 2014

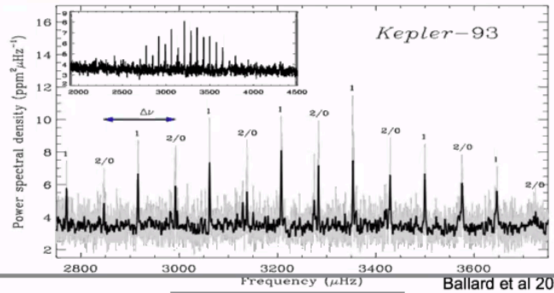
Stellar structure and evolution



Deal+ 2018, 2021; Semenova+2020

Methods





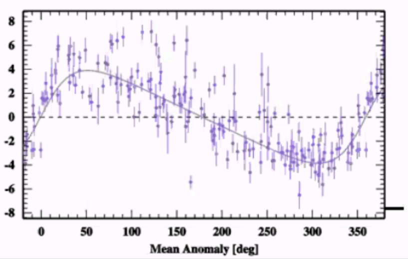
Ballard et al 2014

High-precision photometry

Planet radius
Period,
inclination

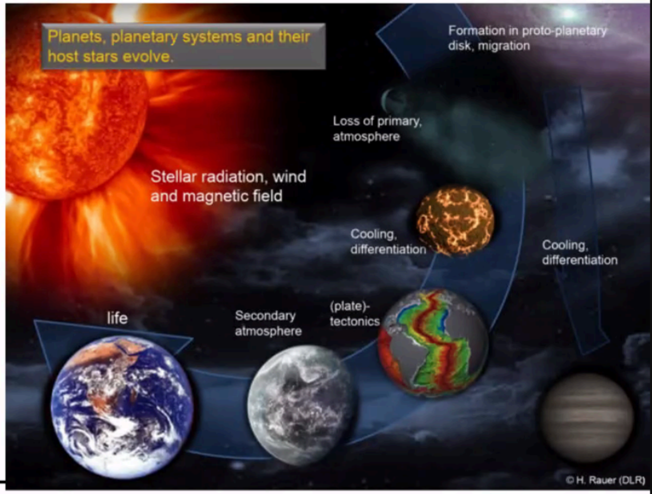
R⋆, M⋆
age

High precision radial velocity



Planet mass
Eccentricity

- Radius ~3%
- Mass ~10%
- Age ~ 10%

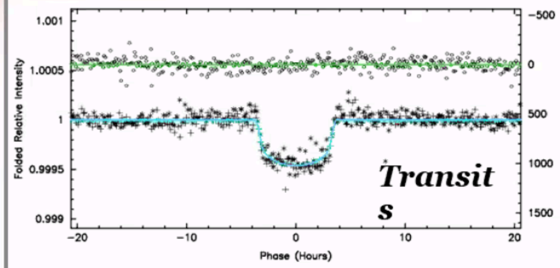


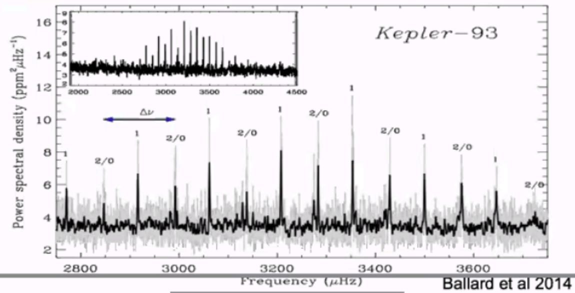
+ orbital parameters + architecture

5

Talk by Heike Rauer

Methods





Ballard et al 2014

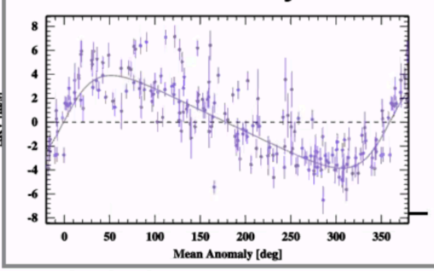
High-precision photometry

+ T_{eff}, [Fe/H]

Planet radius
Period,
inclination

R⋆, M⋆
age

High precision
radial velocity



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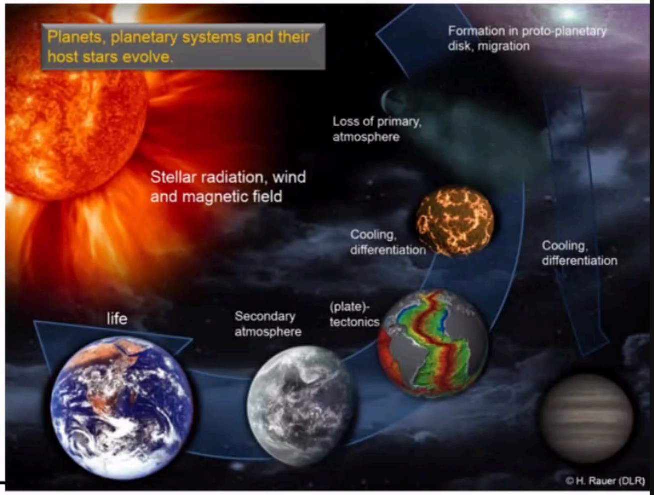
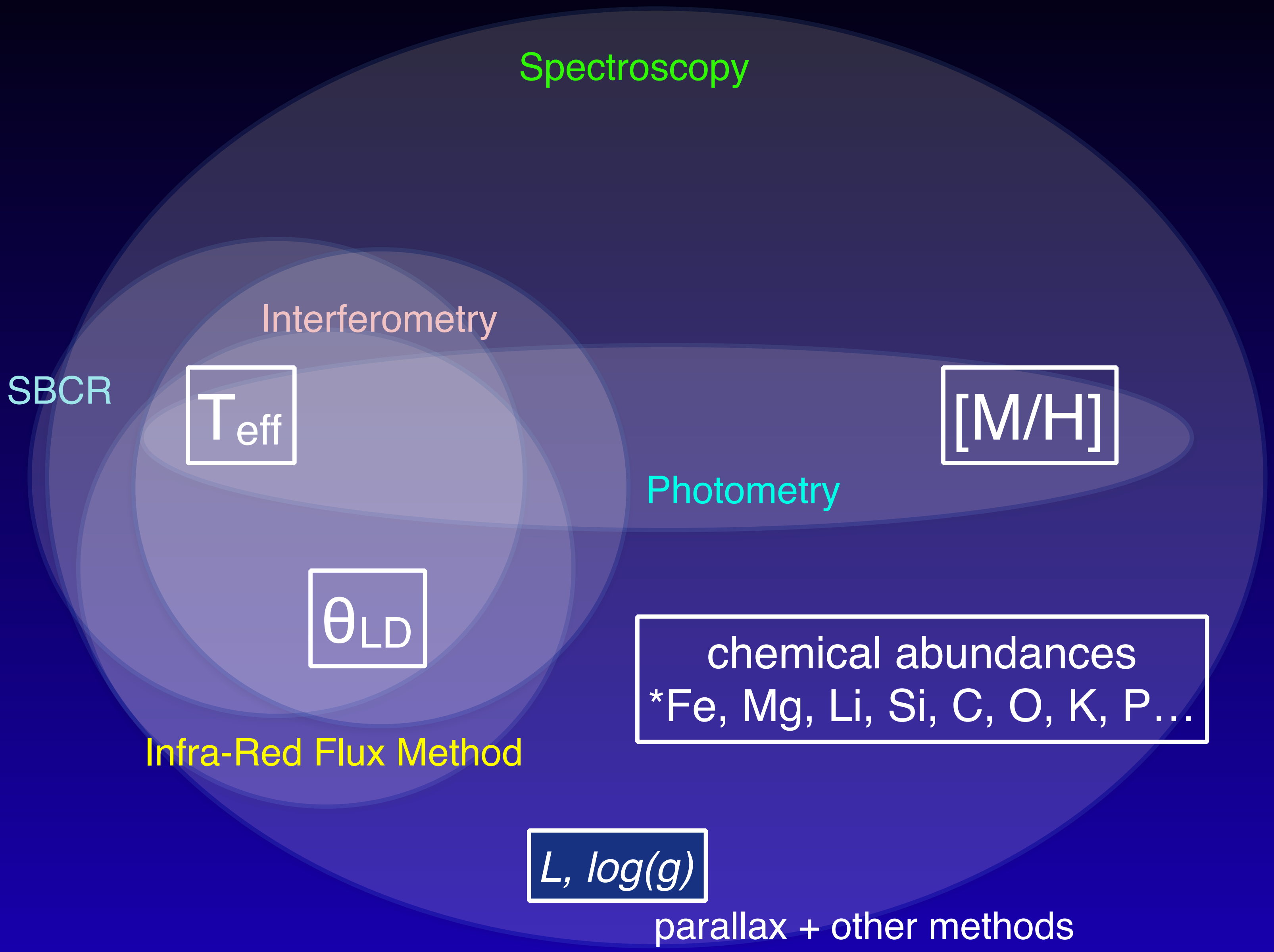


+ orbital parameters + architecture

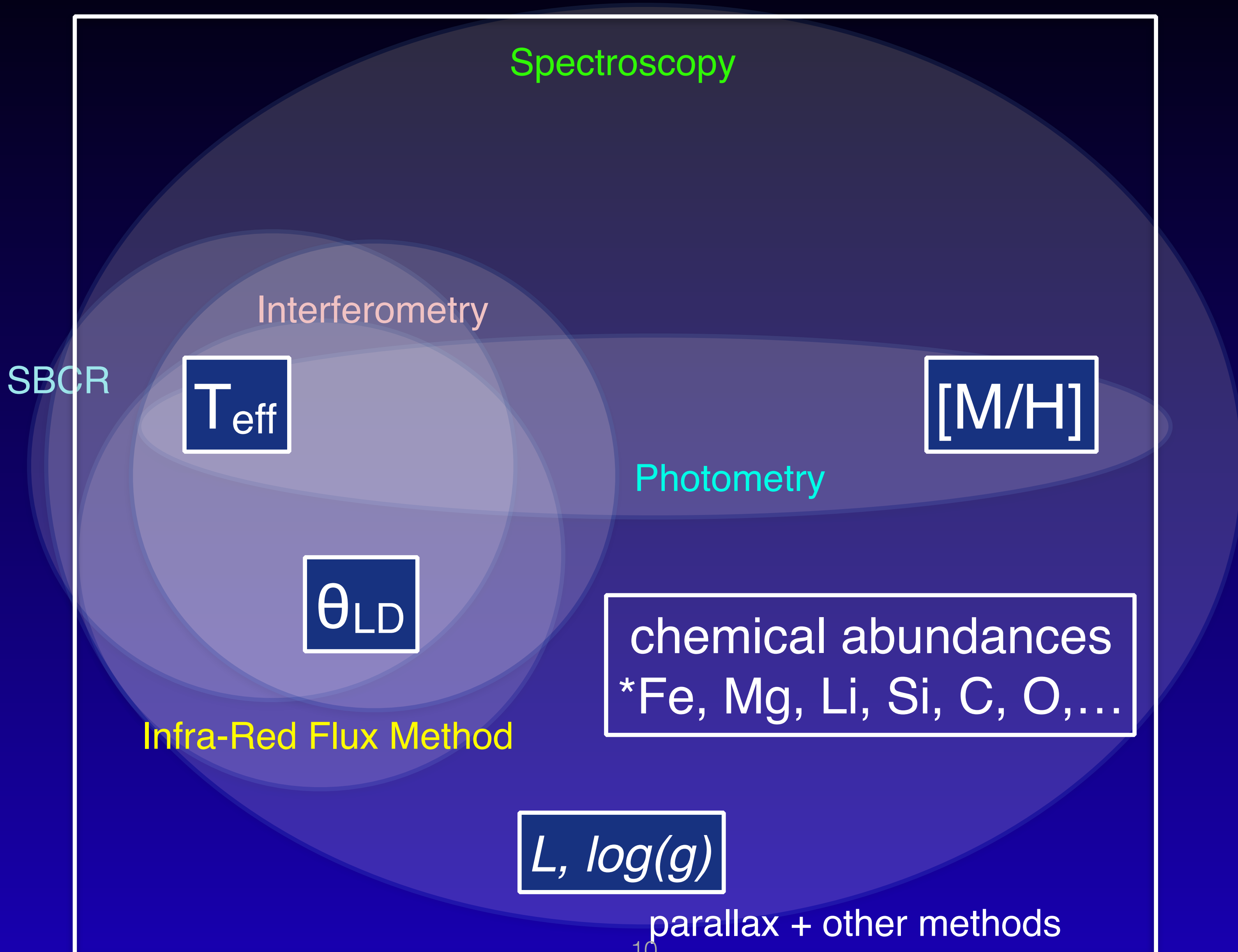
	Goal	Impact error of spectroscopic parameters	
		ΔT_{eff} = 100 K (~2%)	Δ [Fe/H] = 0.1 dex
ΔR/R (radius)	2 %	1 %	1 %
ΔM/M (mass)	10 %	3 %	3 %
Δτ/τ (age)	10 %	10 %	5 %

Serenelli+2017, Valle+2018, Bellinger+2019
Cunha, Roxburgh+ 2021 …

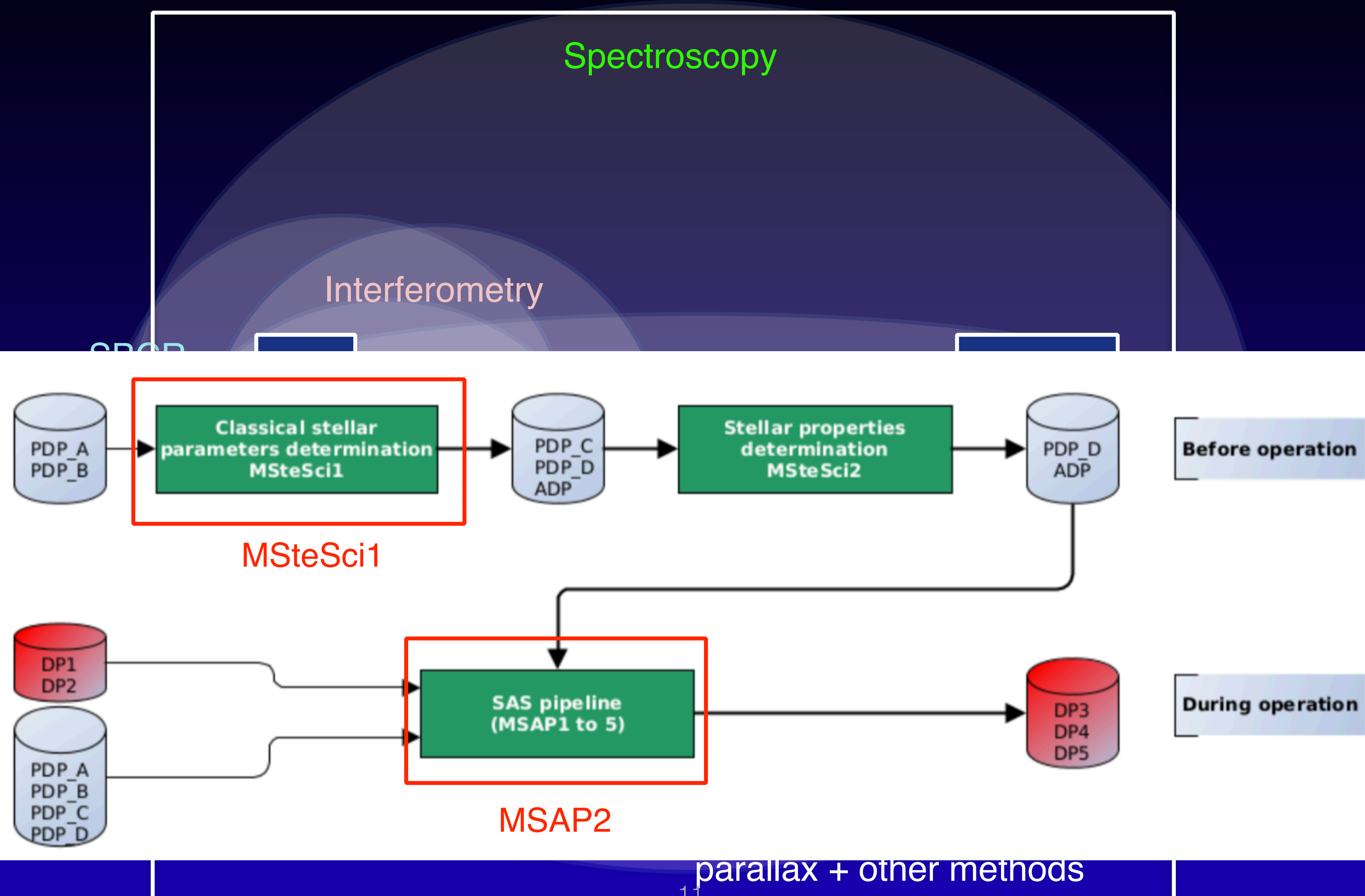
Methods to determine stellar parameters



This is what PLATO pipeline does



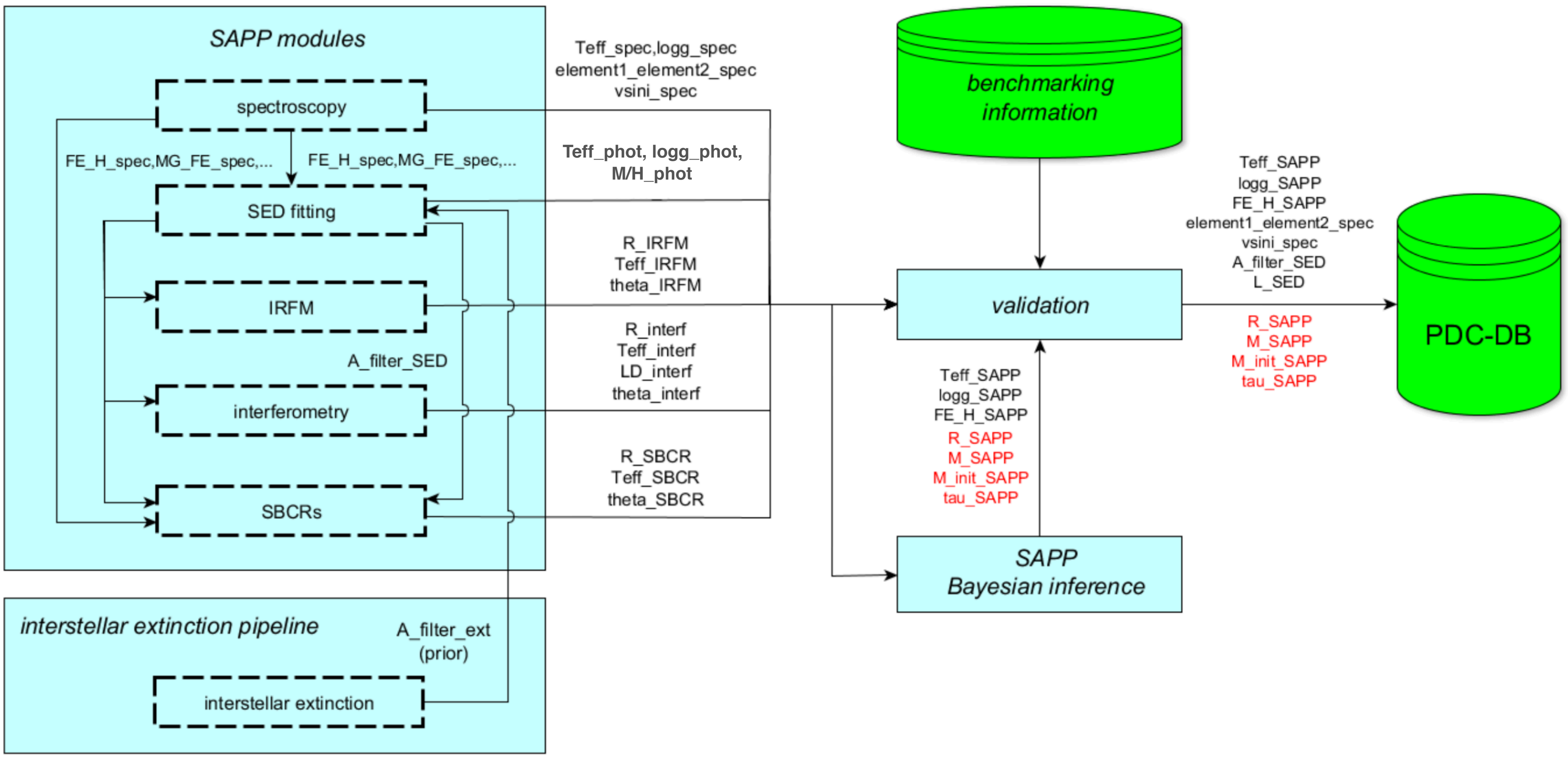
This is what PLATO pipeline does



SAPP

Stellar Abundances and atmospheric Parameters Pipeline

also MSteSci1, MSAP2…



SAPP

Stellar Abundances and atmospheric Parameters Pipeline

Astronomy & Astrophysics manuscript no. output
October 11, 2021

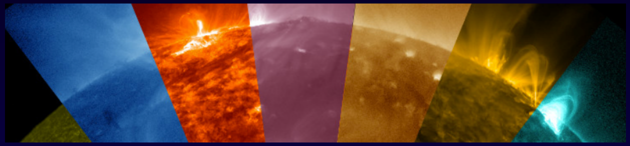
The SAPP pipeline for the determination of stellar abundances and atmospheric parameters of stars in the core program of the PLATO mission

Matthew Raymond Gent[1], Maria Bergemann[1], Aldo Serenelli[2, 3, 1], Luca Casagrande[7], Jeffrey Gerber[1], Ulrike Heiter[5], Mikhail Kovalev[1, 22], Thierry Morel[4], Nicolas Nardetto[6], Vardan Adibekyan[10, 12], Víctor Silva Aguirre[23], Martin Asplund[18], Kevin Belkacem[13], Carlos del Burgo[14, 15], Lionel Bigot[6], Andrea Chiavassa[6], Luisa Fernanda Rodríguez Díaz[23], Marie-Jo Goupil[13], Jonay I. González Hernández[15, 16], Denis Mourard[6], Thibault Merle[8], Szabolcs Mészáros[9, 10, 11], Douglas J. Marshall[19, 20], Rhita-Maria Ouazzani[13], Bertrand Plez[21], Daniel Reese[25], Regner Trampedach[24], and Maria Tsantaki[17]

Stellar parameters for PLATO: how-to

✓ **Combination of heterogeneous data**

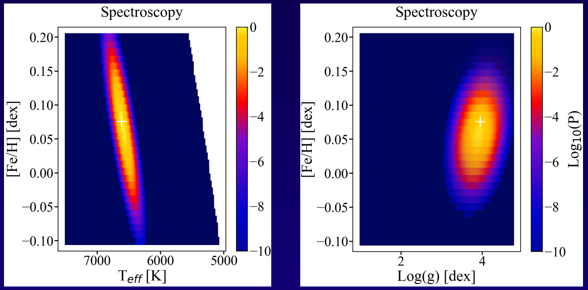
spectra, photometry, parallaxes, interferometry
+ PLATO data (photometry, global oscillation parameters)



(C) GSFC Scientific Vizualisation Studio, NASA

✓ **Efficiency and robust parameters**

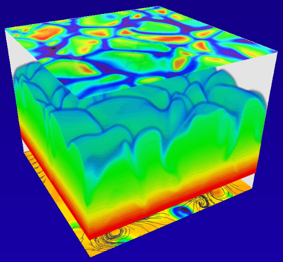
parameter correlations and probability distribution functions



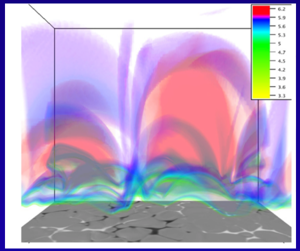
(c) M. Gent

✓ **Flexibility**

ability to rapidly update models,
based on new physics
stellar atmospheres, synthetic spectra
opacities, atomic data
M-RHD, Non-equilibrium modelling



(c) A. Nordlund



Hansteen et al 2015

Observations

Stellar parameters for PLATO: how-to

T_{eff}, θ_{LD} to ~2% precision
+ log(g)

IRFM

$$\frac{\mathcal{F}_{\text{Bol}}(\text{Earth})}{\mathcal{F}_{\lambda_{\text{IR}}}(\text{Earth})} = \frac{\sigma T_{\text{eff}}^4}{\mathcal{F}_{\lambda_{\text{IR}}}(\text{model})}$$

$$T_{\text{eff}} = \left(\frac{4\,F_{\text{bol}}}{\sigma\theta^2}\right)^{1/4}$$

+ relationships calibrated on Gaia
Casagrande et al. 2021

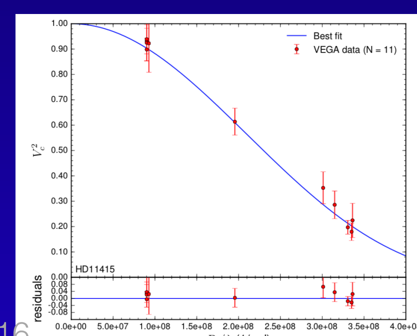
SBCR

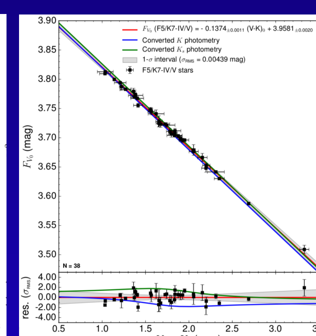
$$\theta_{LD} = 10^{8.4392-0.2V_0-2F_{V_0}}$$

R=1/9.3004*θ / π(arcsec)

Photometry

$$P_{i,\alpha,\beta} = P_i(O_{\text{mag,dist}}|\mathbf{m},d,r) \times \exp\left[-\frac{(\mu_\alpha-\mu(d))^2}{2\delta\mu(d)^2}\right] \times \exp\left[-\frac{(A_{k_1,\beta}-A_{k_1}(r))^2}{2\delta A_{k_1}(r)^2}\right],$$





Salsi et al. 2020, 2021

Stellar parameters for PLATO: how-to

T_{eff}, θ_{LD} to ~1% precision

- SPICA - new visible instrument for the CHARA Array (angular resolution of ~0.2 mas)
- Designed for completing a survey of fundamental parameters of ~1000 stars in 3 years, and possible extension for P2
- Direct R & T_{eff} *(σ ~ 30 K)*, new accurate SBCR, direct measurement of the limb darkening for 10^2 stars

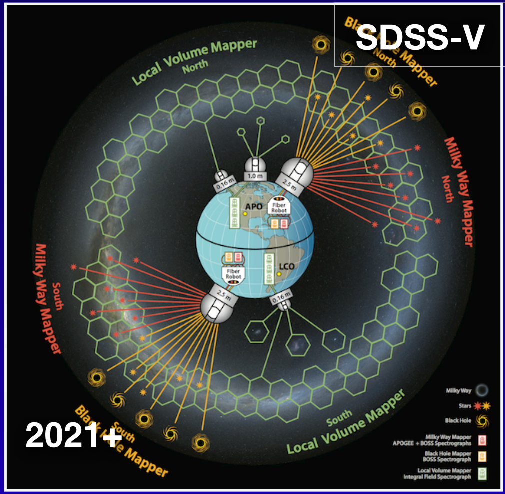
Dwarfs	Challouf			Salsi-1			Salsi-2		
SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4
V // V-K	-2	-1	0	1	2	3	4	5	6
0	0,10	1,00	3,35	6,28	11,82	22,25	39,94	70,70	125,14
1	0,06	0,63	2,11	3,96	7,46	14,04	25,20	44,61	78,96
2	0,04	0,40	1,33	2,50	4,71	8,86	15,90	28,14	49,82
3	0,02	0,25	0,84	1,58	2,97	5,59	10,03	17,76	31,43
4	0,02	0,16	0,53	0,99	1,87	3,53	6,33	11,20	19,83
5	0,01	0,10	0,33	0,63	1,18	2,23	3,99	7,07	12,51
6	0,01	0,06	0,21	0,40	0,75	1,40	2,52	4,46	7,90
7	0,00	0,04	0,13	0,25	0,47	0,89	1,59	2,81	4,98
8	0,00	0,03	0,08	0,16	0,30	0,56	1,00	1,78	3,14
9	0,00	0,02	0,05	0,10	0,19	0,35	0,63	1,12	1,98
10	0,00	0,01	0,03	0,06	0,12	0,22	0,40	0,71	1,25

Mourard et al 2018, Pannetier et al. 2021

Stellar parameters for PLATO: how-to

Extensive efforts to collect high-quality spectra for P1, P2, P4 P5 samples
optical, near-IR, med- & high-resolution

T_{eff}, [Fe/H] to a few ~1% precision



Observations

Data + model comparison

Bayesian approach

homogeneous full-scale quantitative probabilistic analysis of distributions in the multi-D parameter space

$$P(R|O_{sp}, O_{ph}) \sim P(O_{sp}|R) \cdot P(O_{ph}|R) \cdot P_{mod}(R) \cdot P_{pr}(R) \cdot P_{i,ph,astr}$$

Gaia

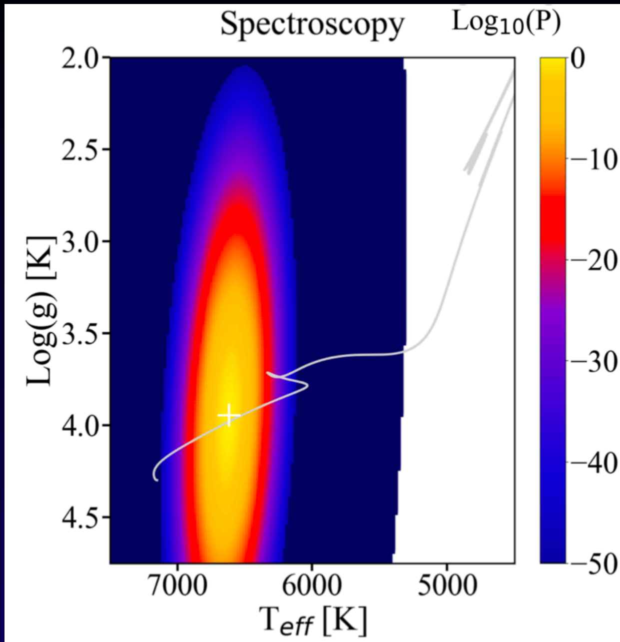
Other constraints

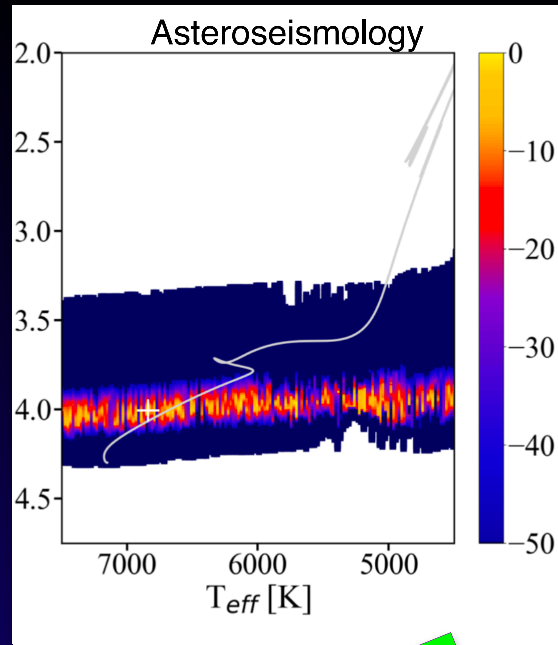
priors: e.g., mass function

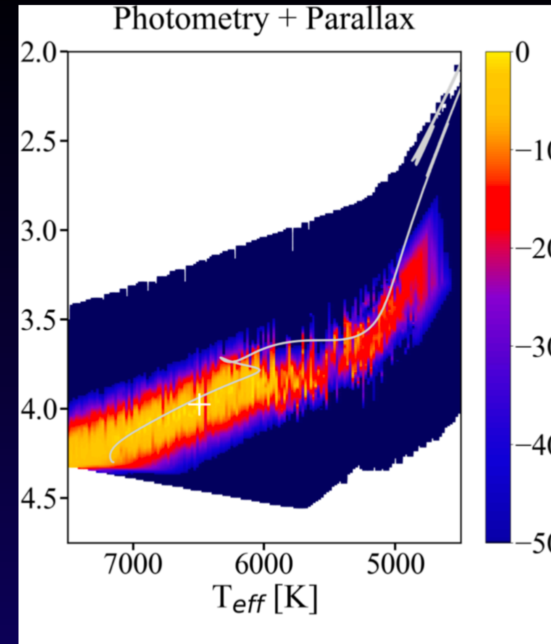
Spectra + photometry:
VLT, Gaia, APOGEE, ...
Future: WEAVE, 4MOST, MSE

- Combine P (***O*|*R***) based on data taken with <u>different facilities</u> at once
- Systematic model differences can be directly accounted for

Serenelli et al. 2013, Schoenrich & Bergemann 2014, Gent et al. subm.

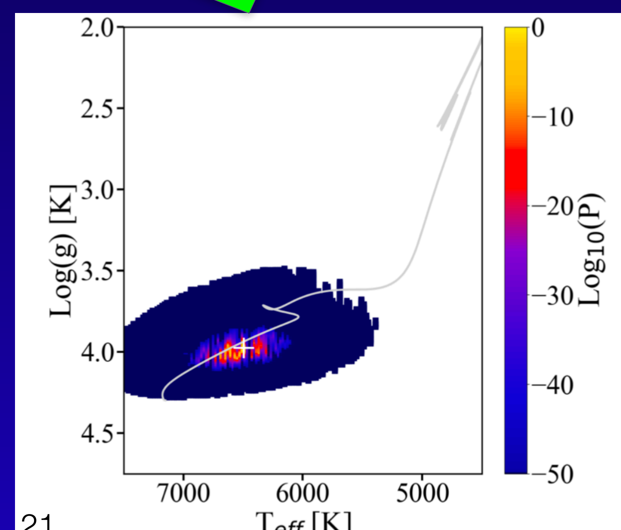






Spectroscopy, nu_max, and photometry yield orthogonal constraints, but in the Bayesian framework complete correlations in the multi-D space are preserved.

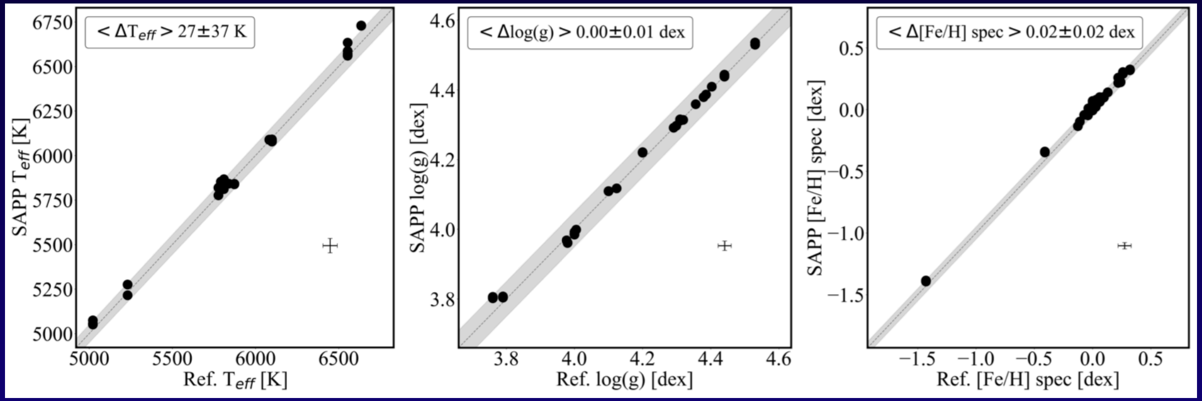
Combined solution

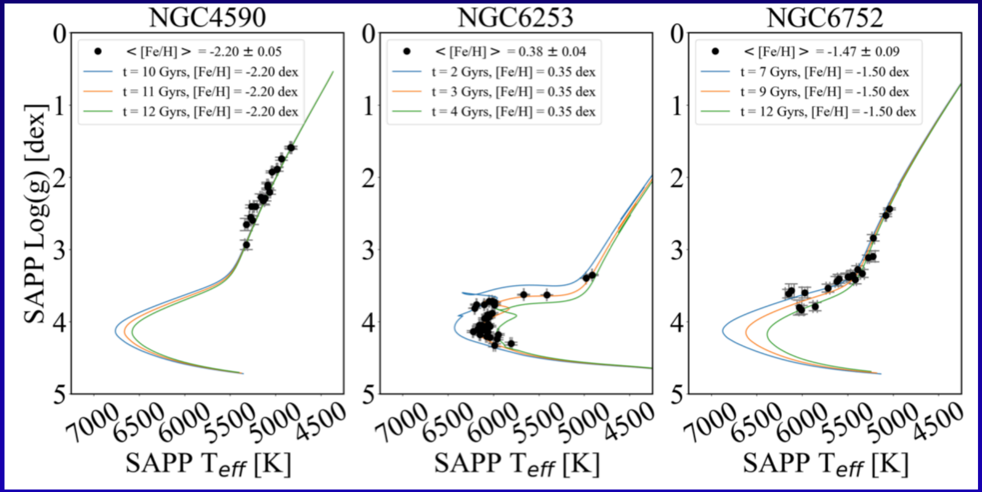


Gent et al. subm.

SAPP

- ✓ tested and verified against independently determined parameters of PLATO ‘golden standards’ (benchmark stars, Heiter+ 2015, Jofre+ 2018), WP125500 by O. Creevey & P. Maxted
- ✓ excellent performance for FGKM stars + red giants





Gent et al. subm.

SAPP

Parameter / SNR	Star, mag	Error caused by the internal precision of the code	
		Gaia GSP-Spec pipeline*	PLATO SAPP*
T_{eff} / 125	G=10.3	62 K	18 K
T_{eff} / 40	G=11.8	178 K	24 K
[Fe/H]	G=10.3	0.06 dex	0.00 dex
[Fe/H]	G=11.8	0.16 dex	0.01 dex
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* based on noised-up models

Bergemann et al. PLATO TN in prep.

Gaia end-of-mission data taken from Recio-Blanco et al. A&A 585, A93, 2016

typical G-type main-sequence star at intermediate metallicity

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SAPP

Gaia RVS will not be sufficient to achieve PLATO goal of 2% in R, 10% in M and τ as the internal error <u>does not include</u> model error + error of actual RVS data

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Is Gaia RVS + SAPP sufficient for PLATO?

unfortunately no, because

σ_tot = σ_internal + **σ_model** + **σ_data**

.93, 2016

SAPP

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…93, 2016

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Observations

Data + model comparison

Models

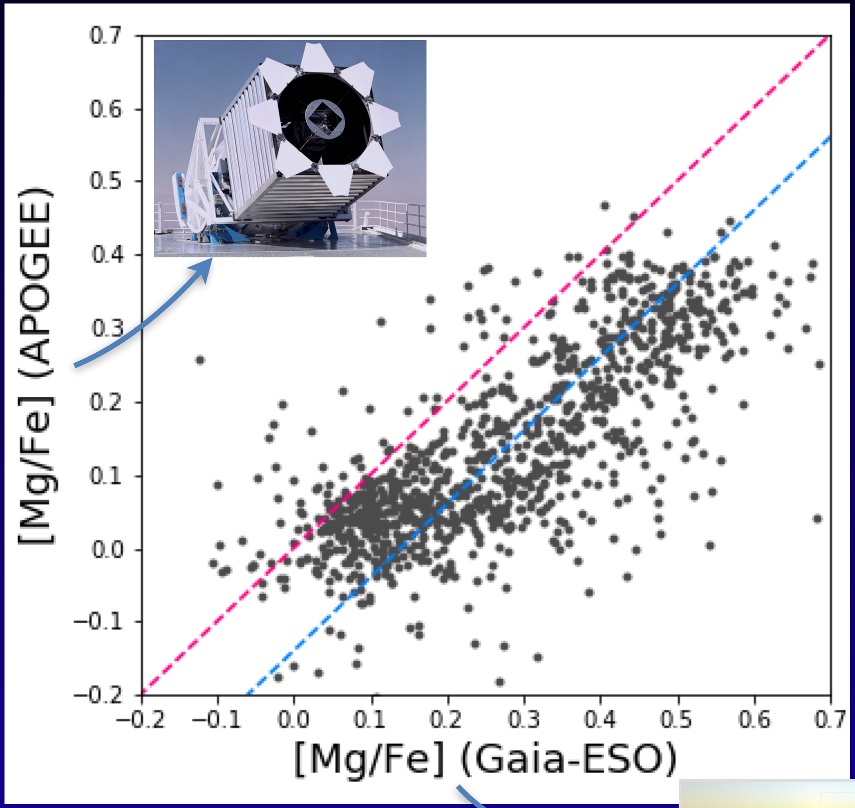
Observations

Data + model comparison

Models

models must be as good as observations to allow results limited by observational uncertainties

Same stars observed by APOGEE and Gaia-ESO surveys



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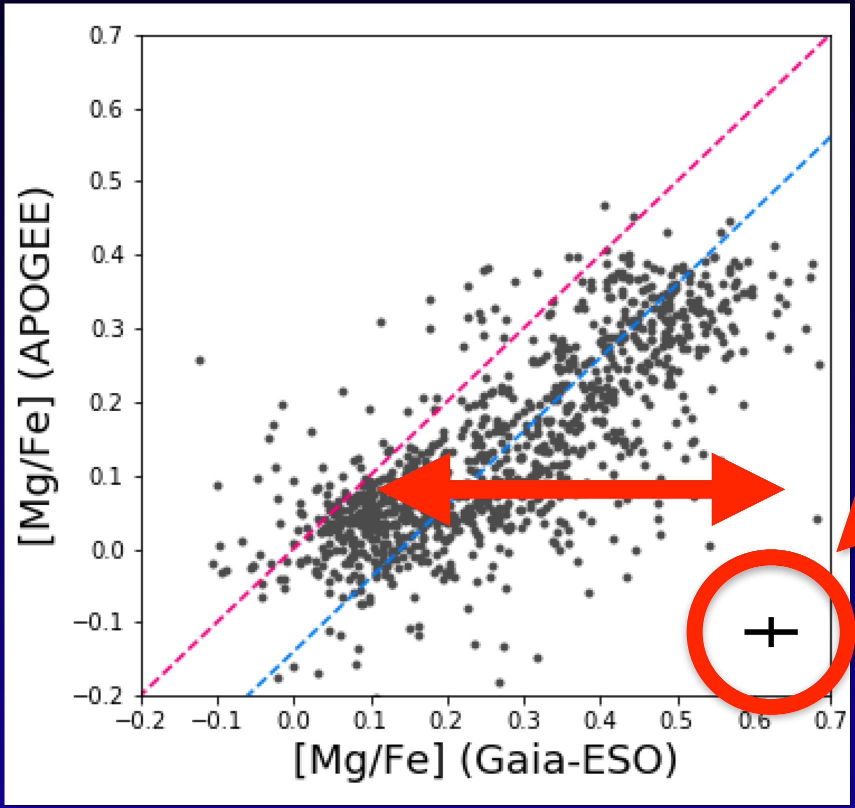
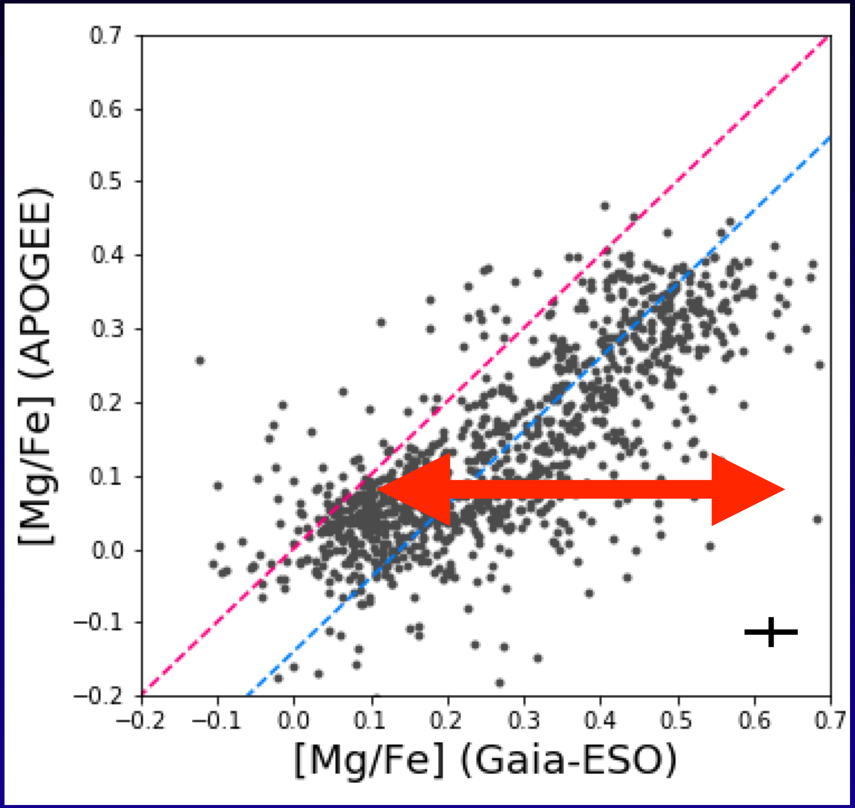


- up to a factor of 3 differences
- the differences are not caused by data quality

error caused by observational uncertainties (statistical error)

Same stars observed by APOGEE and Gaia-ESO surveys

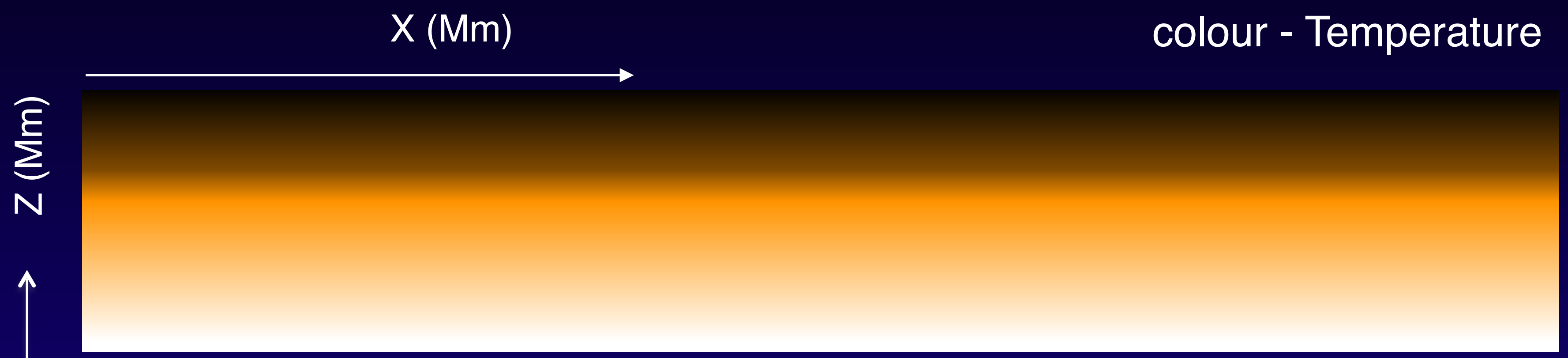


- up to a factor of 3 differences
- the differences are <u>not</u> caused by data quality
- The differences are caused by **models**

error caused by observational uncertainties
(statistical error)

1D LTE hydrostatic models

MARCS, Kurucz, MAFAGS



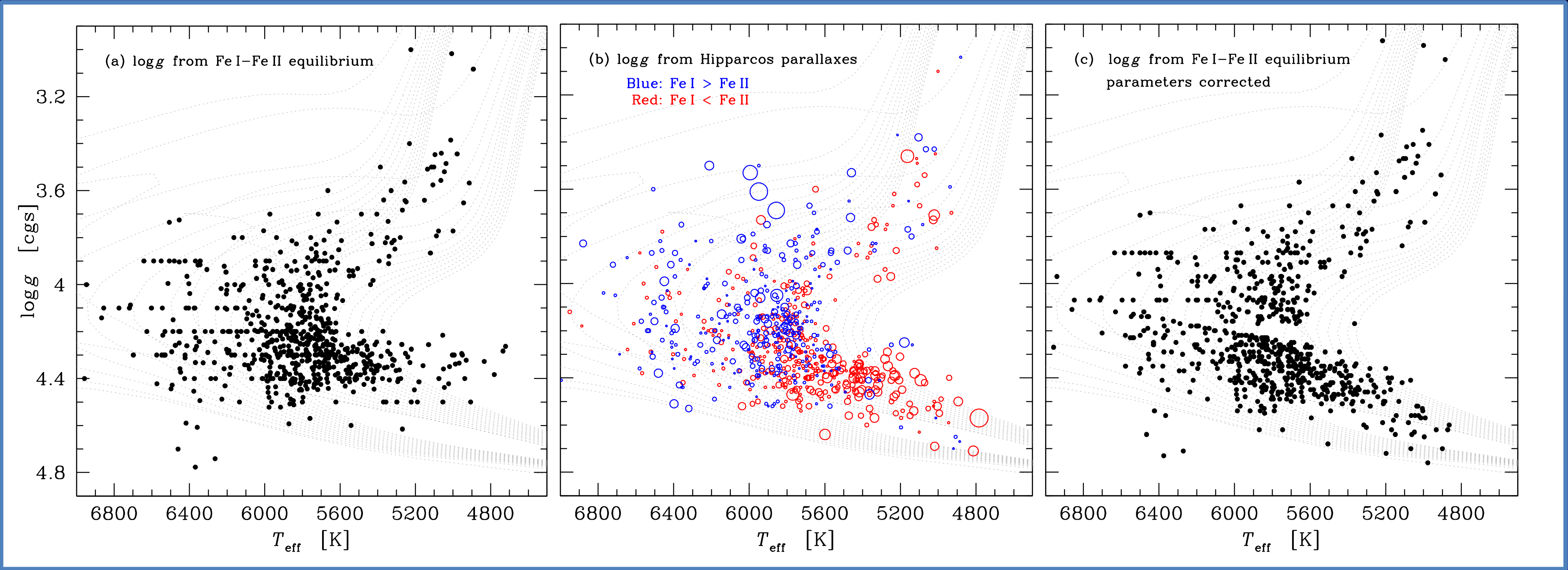
- dimensionality ➡ 1D
- convection ➡ mixing length
- turbulence ➡ **ad-hoc** correction to Doppler width
  (assuming isotropic Gaussian distribution)
- radiation ➡ LTE (Saha- Boltzmann equilibrium)

1D LTE codes usually work well for solar analogues,

but fail for stars which are hotter / cooler

more extended (lower log(g))

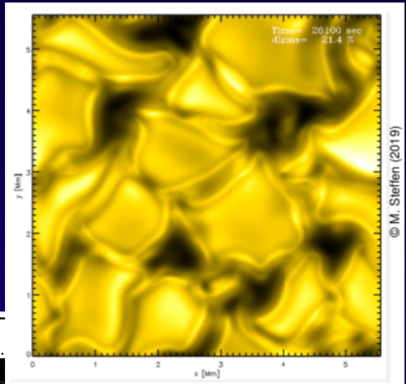
lower / higher metallicity

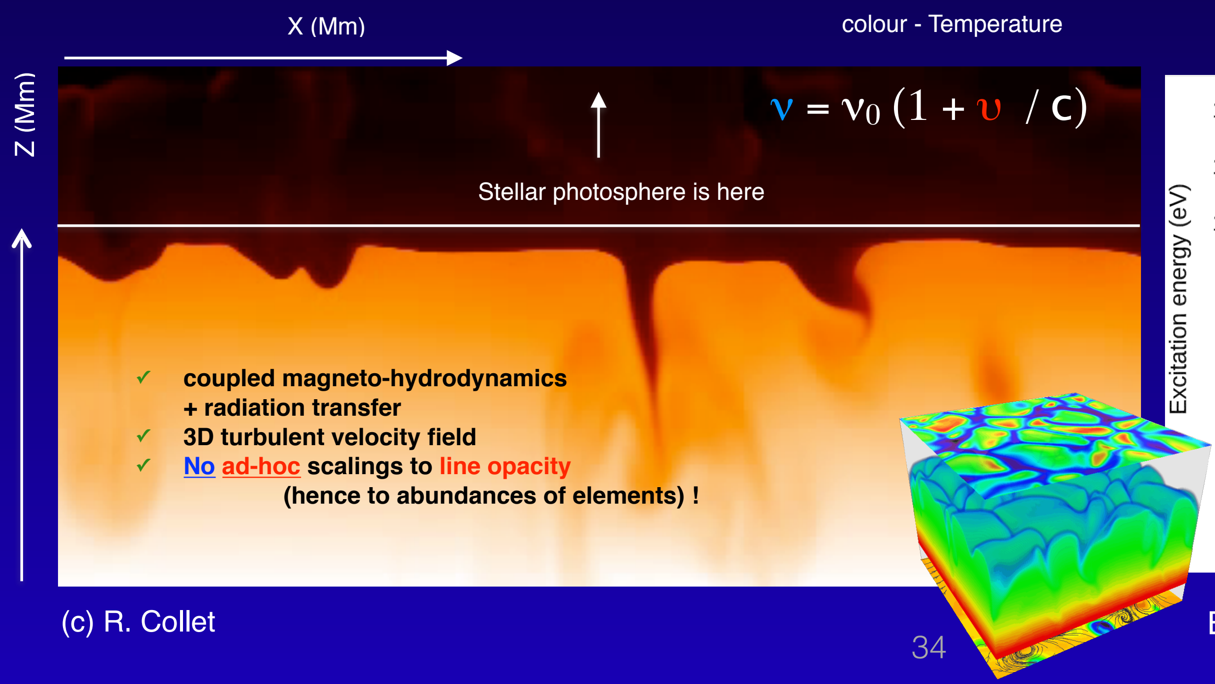


Bensby et al. (2014)

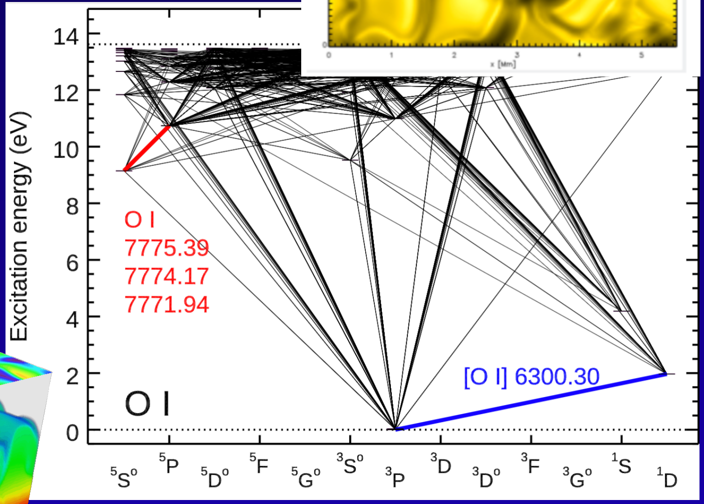
Stellar parameters for PLATO: how-to

- ✓ PLATO is the first survey that will rely on physical parameter-free model atmospheres & spectra
- ✓ Non-LTE synthetic spectra, 3D convective model atmospheres, MHD (*w. Vilnius group*), atomic and molecular data (*w. Michigan group)*
- ✓ Dedicated efforts to analyse M dwarfs (*Heiter, Olander+)*





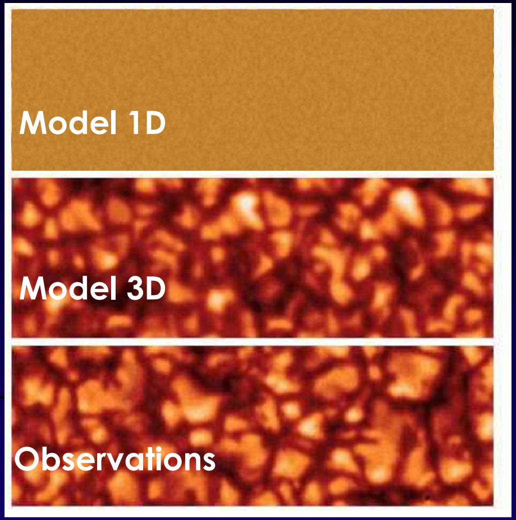
(c) R. Collet



Bergemann et al. 2021

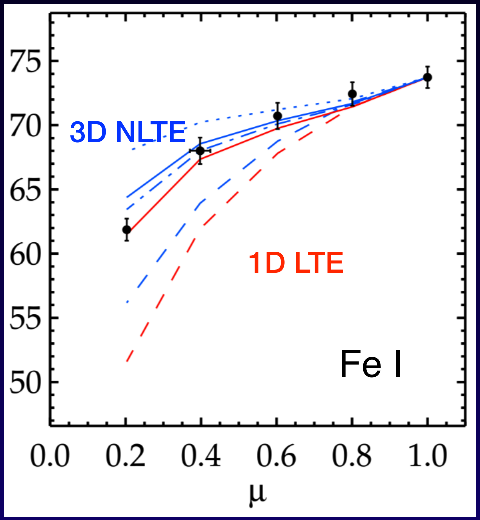
Testing 3D NLTE models

Observed granulation



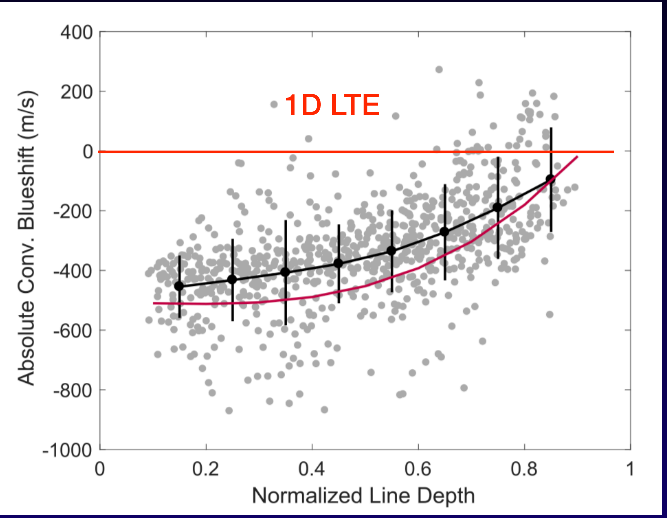
Nordlund et al. 2009

Center-to-limb variation



Lind et al. 2017

Convective line asymmetries

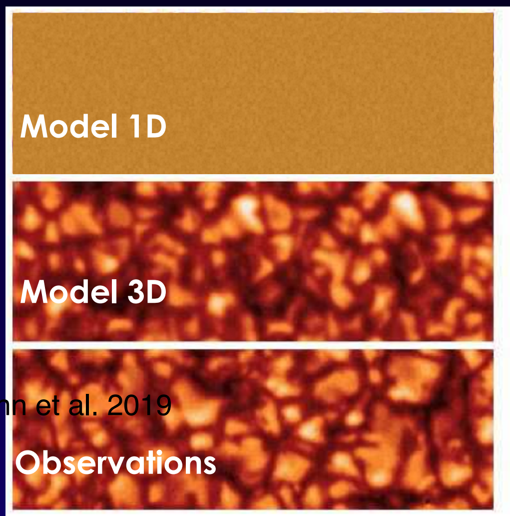


Dravins 2008, Miklos et al. 2020

gemar

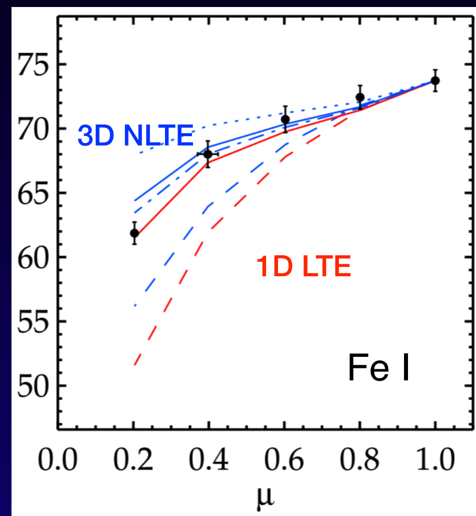
Testing 3D NLTE models

Observed granulation



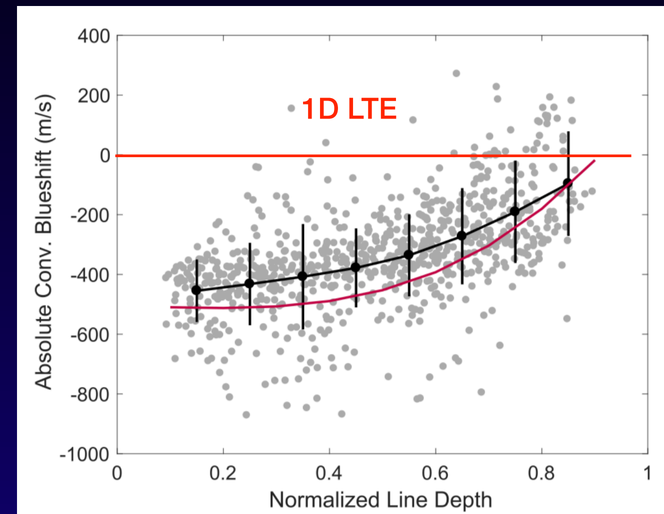
Nordlund et al. 2009

Center-to-limb variation



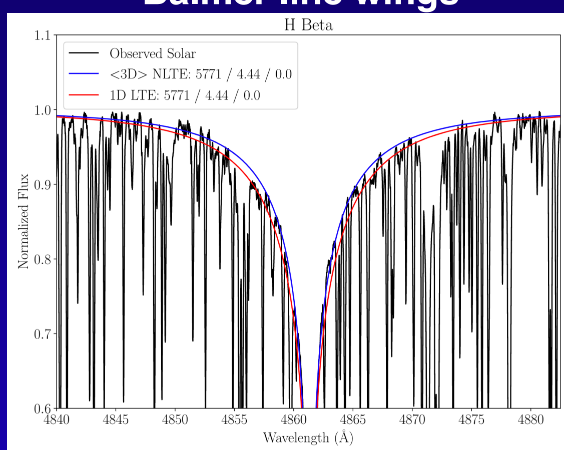
Lind et al. 2017

Convective line asymmetries



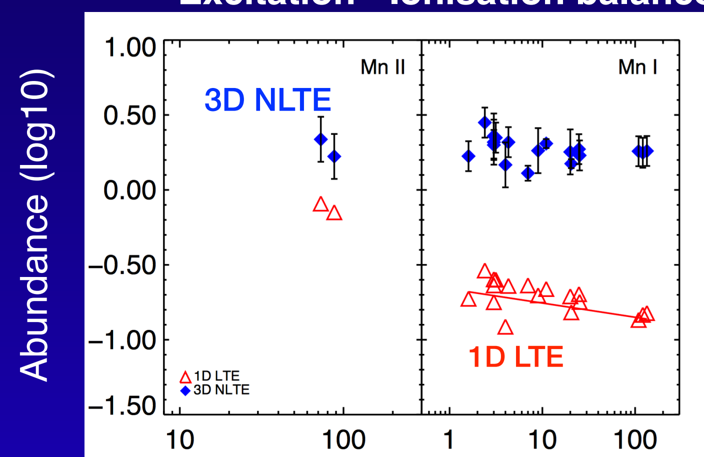
Miklos et al. 2020

Balmer line wings



Gerber et al. in prep

Excitation - Ionisation balance



Bergemann et al. 2019

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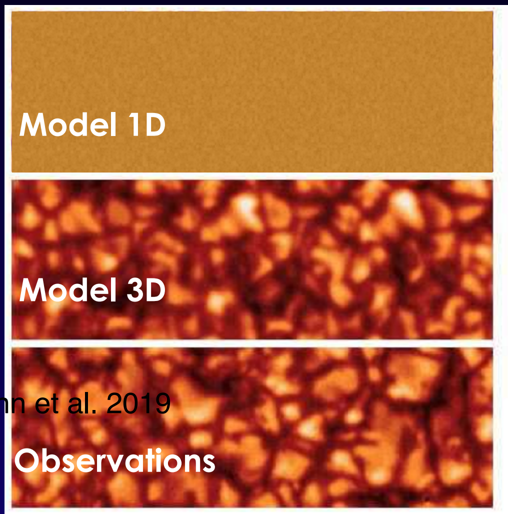

gemann et al. 2019

Nordlund et al. 2009

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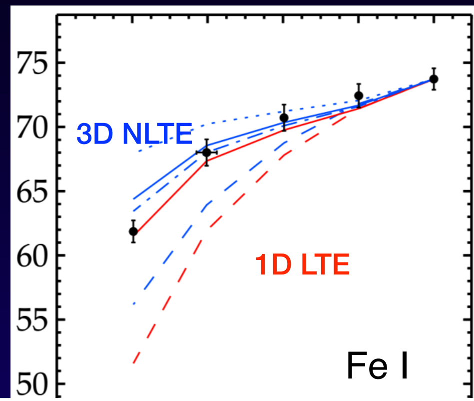

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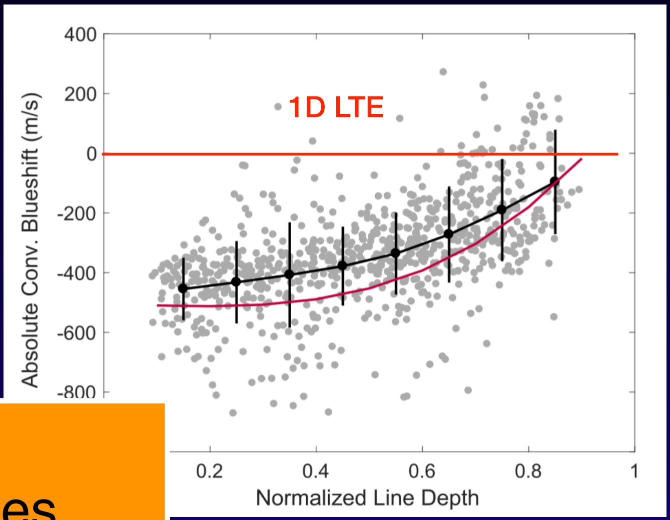
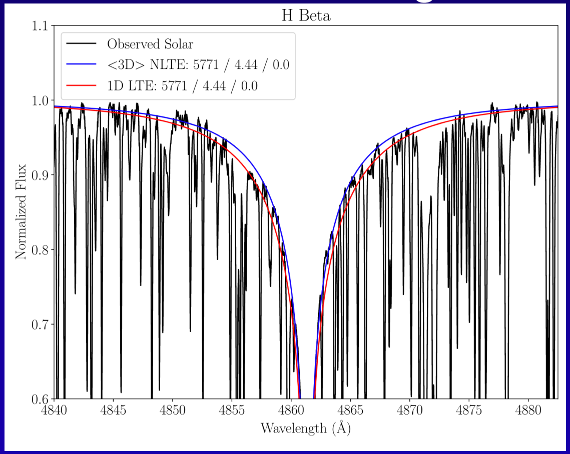


Miklos et al. 2020

PLATO
T_{eff}, [Fe/H], abundances
to a ~1% precision + **accuracy**

Balmer line wings



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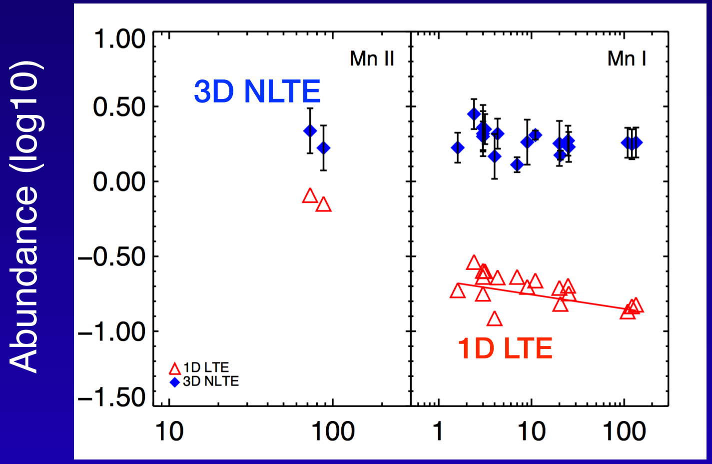


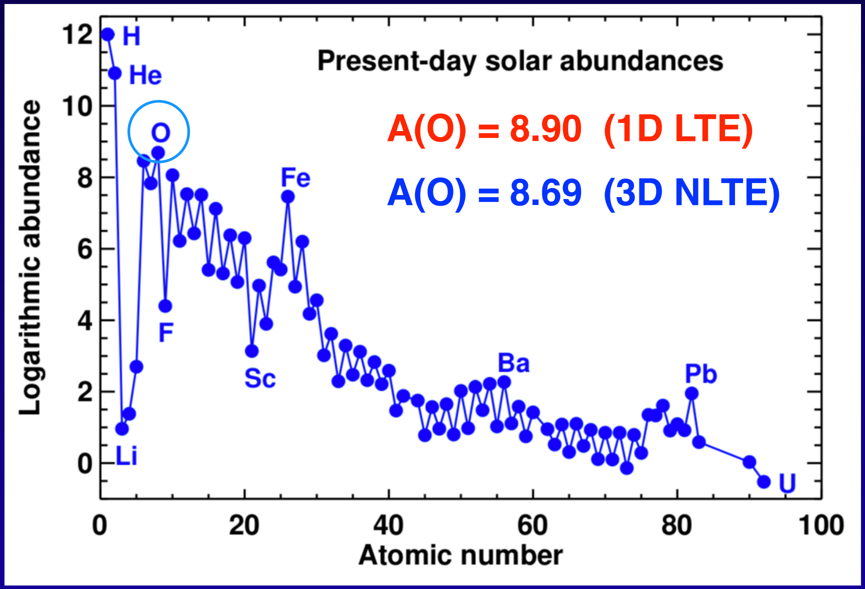
Bergemann et al. 2019

Oxygen ➡ Solar models ➡ Stellar evolution

Why better 3D NLTE models? Sun as a reference

Oxygen: cornerstone element in astrophysics

- ✓ Standard Solar Model + stellar evolution reference
- ✓ Galactic and extragalactic metallicity reference
- ✓ planet formation, exoplanet atmospheres



Asplund et al. 2021

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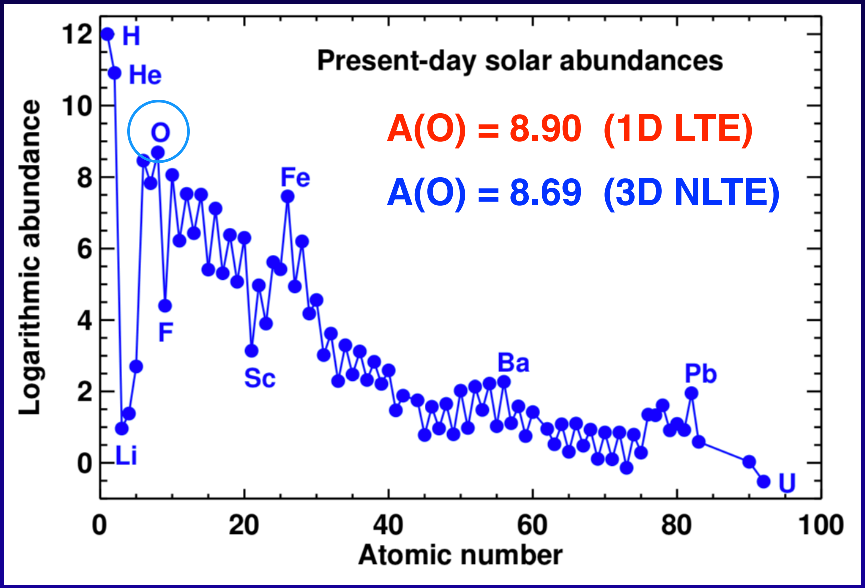
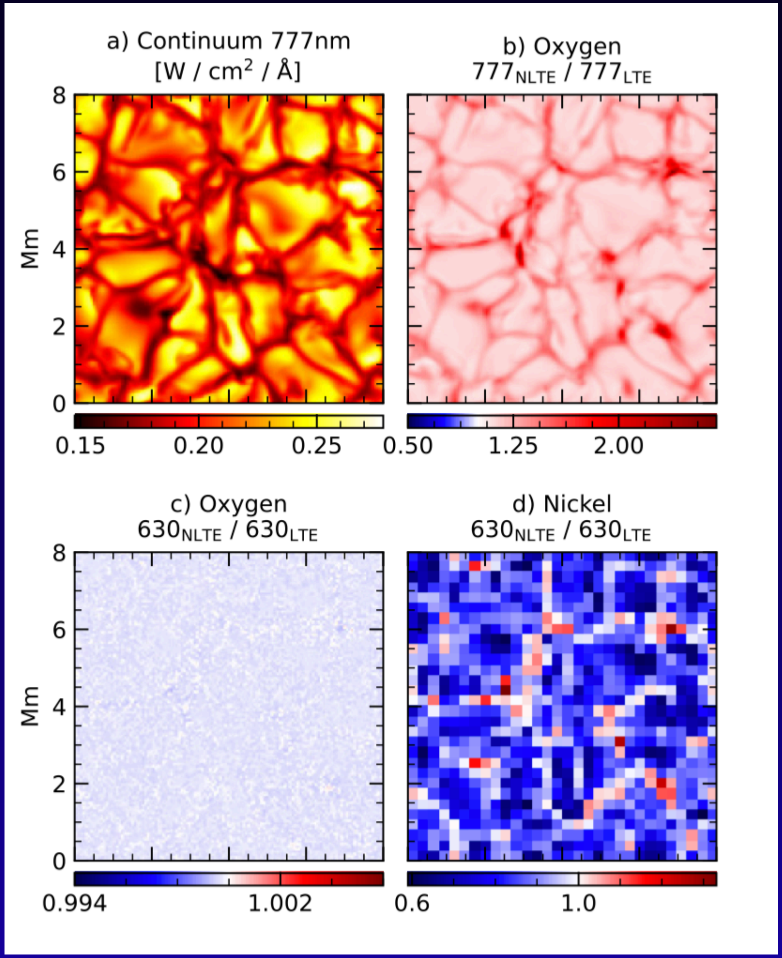


Asplund et al. 2021

But

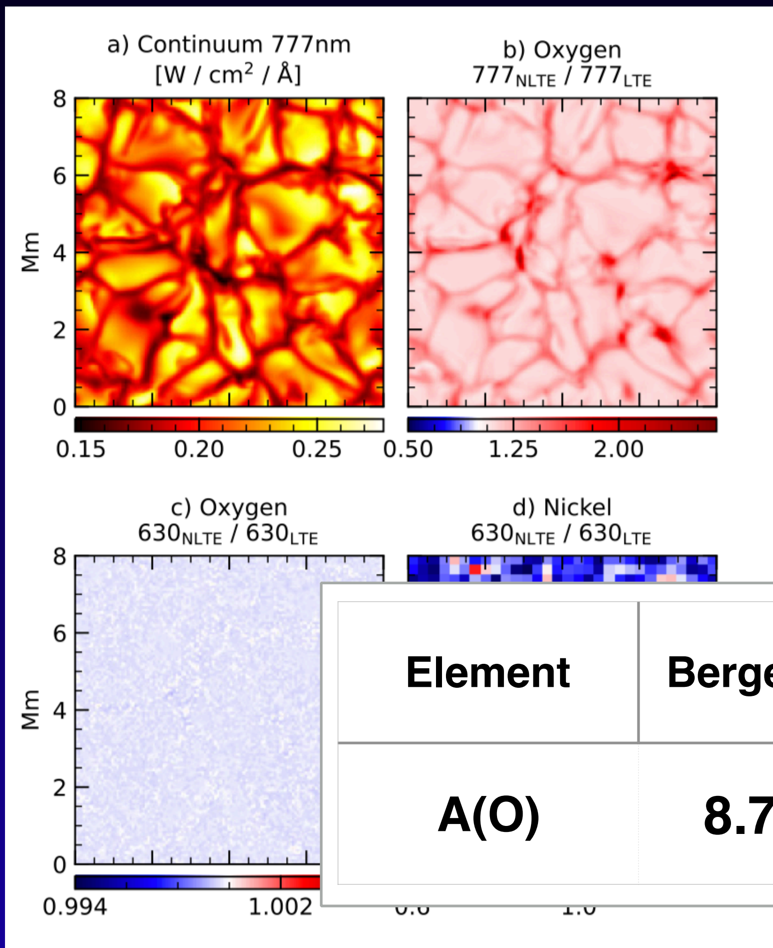
- ✓ Solar photospheric O still debated (*Caffau et al. 2008 but Asplund et al. 2009*)
- ✓ difficult to reconcile with solar models + helioseismology (*e.g. Serenelli et al. 2009, 2011, Delahaye & Pinsonneault 2006*)

Why better 3D NLTE models? Sun as a reference



- ✓ improved atomic data
  3D NLTE models for O *and* Ni (blend)
- ✓ realistic 3D NLTE radiative transfer
  with chromospheric effects
- ✓ highest resolution solar data
  IAG R = 700,000 data
  comprehensive error analysis

Why better 3D NLTE models? Sun as a reference



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Element	Bergemann+ 2021	Caffau+ 2008	Asplund+ 2021
A(O)	**8.75 ± 0.03**	8.76 ± 0.07	8.69 ± 0.04

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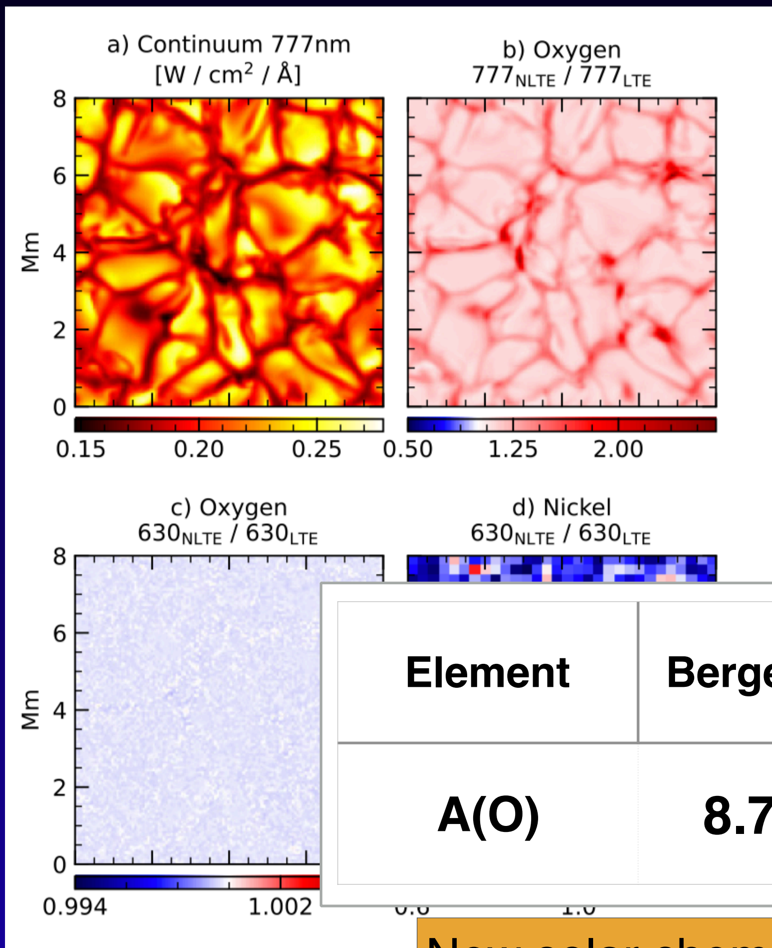

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New solar chemical composition for PLATO

Magg et al. in prep

Summary

PLATO best positioned to revolutionise stellar physics
=> all areas that rely on fundamental parameters of stars
*exoplanets, stellar populations, Galactic structure…

Challenges

- Combination of new data
  PLATO + CHARA / SPICA, 4MOST, WEAVE, Gaia …
  - with new models
    3D M*RHD model atmospheres + NLTE radiative transfer
    limb darkening, intensity profiles, synthetic spectra…
    - => new reference
      10.000s of stars at the level of detail so far
      only accessible to solar physics