The LAMOST-Kepler project

Past, present and future

Peter De Cat

Royal Observatory of Belgium
Ringlaan 3
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&

LAMOST-Kepler consortium

J.N. Fu, et al. (BNU, Beijing, China)
Shi J.R., Luo A.L., Zhang H.T., et al. (NAOC, Beijing, China)
A. Frasca, G. Catanzaro (INAF, Catania, Italy)
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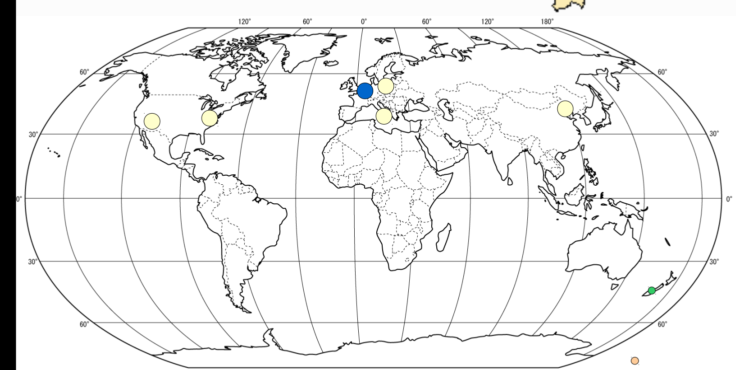

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Past, present and future

Lamost **O**bservations in the **K**eplerfield

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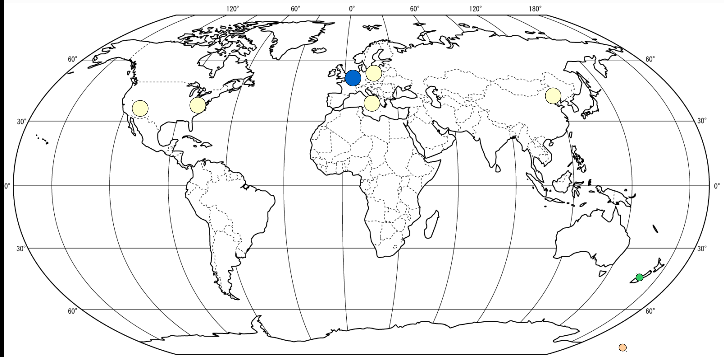
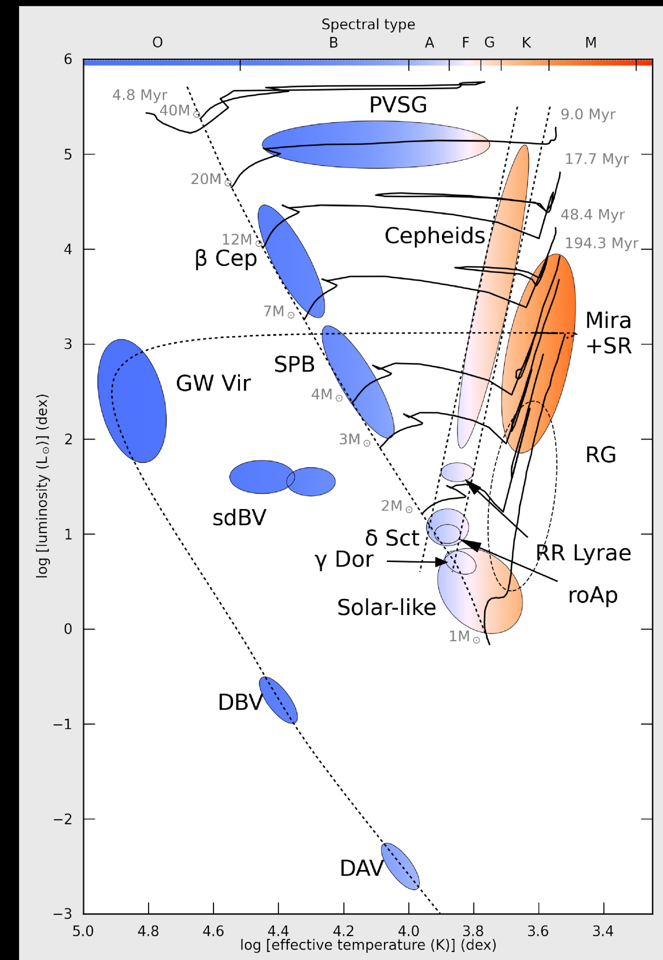


NASA mission Kepler

- *primary mirror: 1.2-m*
- *launch on 7 March 2009*
  - *Earth-trailing heliocentric orbit*
  - *lifetime ~3.8 years (failure on 14 May 2013)*
- *continuous monitoring of 1 star field i*
  - *about 200,000 stars*
  - *roll 90° about line-of-sight every 3 months*
  - *short (1 min.) or long (32 min.) cadence*
  - *broad band photometry with accuracy of few ppm*
- *main scientific goals*
  - *discover Earth-size planets (transit method)*
  - *characterizing planet-hosting stars by means of asteroseismic methods*
  - *opportunity for asteroseismic investigation of stars covering H-R diagram*



Kepler Asteroseismic Science Consortium (KASC)

need for accurate stellar parameters

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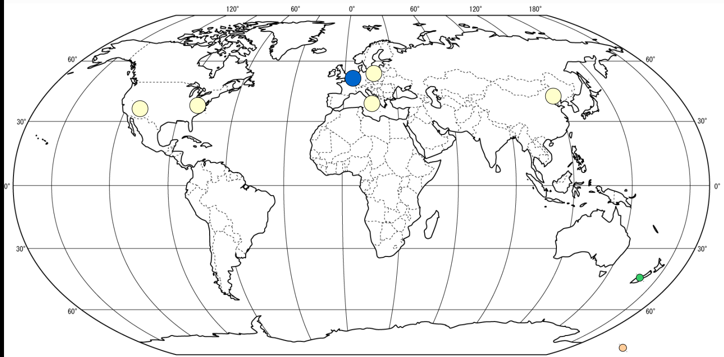


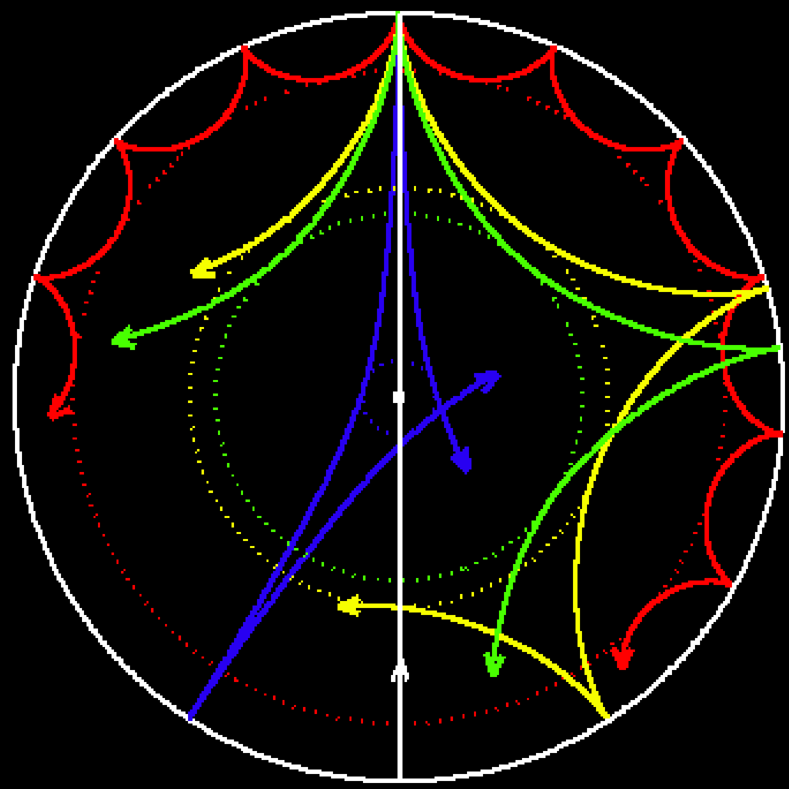
Asteroseismology

- *science in which stellar (aster) oscillations (seismo) are studied (logy) to gain information of stars*
  - *only way known to probe internal structure*
  - *derive stellar parameters with unprecedented precision (R, M, age,...)*
  - *direct tests to modeling of complex dynamical processes in stellar interiors (e.g. diffusion, convective overshoot)*
  - *improve understanding of stellar evolution*

Requirements for asteroseismology?

Requirements for asteroseismology

- *large number of pulsation frequencies*



Requirements for asteroseismology

- *large number of pulsation frequencies*
  - *time series with sufficiently long time base*
  - *high-quality observations: photometry, radial velocities, line-profile variations*

MOST

Kepler and K2

TESS

CoRoT

BRITE

Gaia

Requirements for asteroseismology

- *large number of pulsation frequencies*
  - *time series with sufficiently long time base*
  - *high-quality observations: photometry, radial velocities, line-profile variations*
- *identification of the pulsation modes*
  - *Echelle diagram (in frequency for p-modes, in period for g-modes)*
  - *multi-colour photometry*
  - *high-resolution high-SNR spectroscopy*

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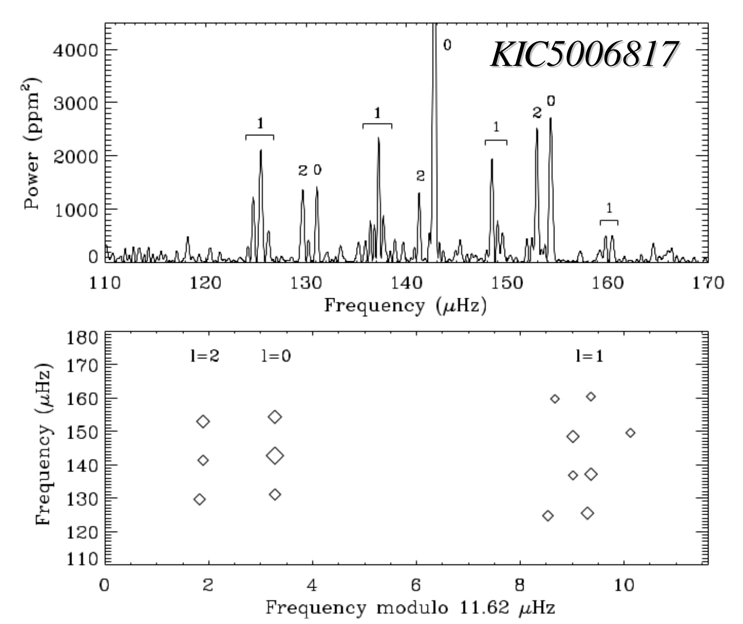
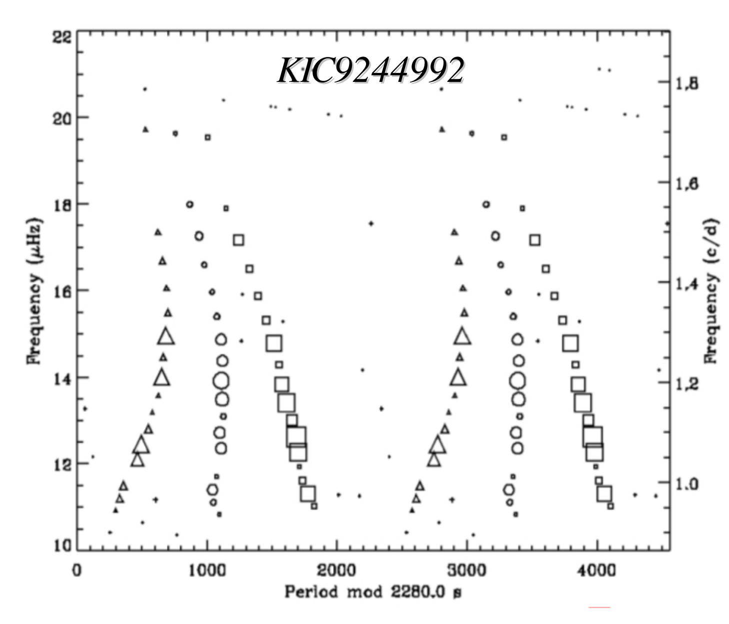


Bedding et al., 2010, ApJL 713, L176



Bedding et al., 2015, EPJW 101, 01005

Requirements for asteroseismology

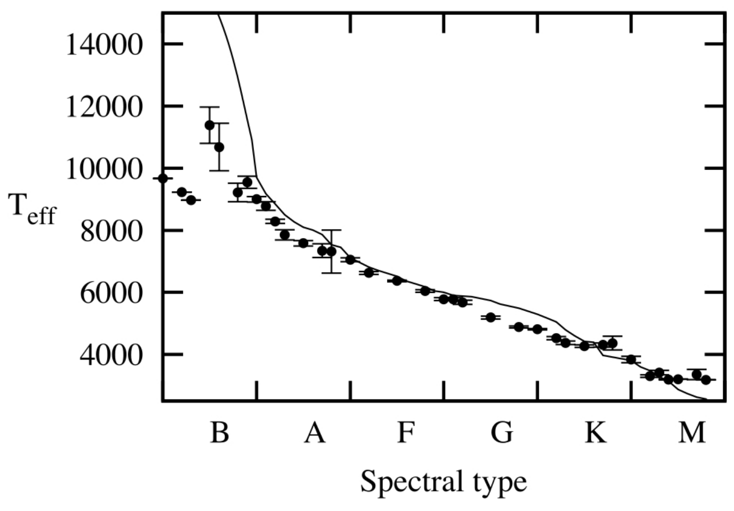
- *large number of pulsation frequencies*
  - *time series with sufficiently long time base*
  - *high-quality observations: photometry, radial velocities, line-profile variations*
- *identification of the pulsation modes*
  - *Echelle diagram (in frequency for p-modes, in period for g-modes)*
  - *multi-colour photometry*
  - *high-resolution high-SNR spectroscopy* → in general large spectroscopic surveys not sufficient

Requirements for asteroseismology

- *large number of pulsation frequencies*
  - *time series with sufficiently long time base*
  - *high-quality observations: photometry, radial velocities, line-profile variations*
- *identification of the pulsation modes*
  - *Echelle diagram (in frequency for p-modes, in period for g-modes)*
  - *multi-colour photometry*
  - *high-resolution high-SNR spectroscopy*
- ***accurate stellar parameters***
  - ***temperature (T_{eff}), surface gravity (logg), metallicity ([M/H])***
  - ***projected rotational velocity (vsini)***
  - ***abundances***

Requirements for asteroseismology

- *…ion frequencies*
  - *…tly long time base*
  - *…ns: photometry, radial velocities, line-profile variations*
- *…ion modes*
  - *…ncy for p-modes, in period for g-modes)*
  - *…y*
  - *…R spectroscopy*



Balona et al. (2011, MNRAS 413, 2403)

- ***accurate stellar parameters***
  - ***temperature** (T_{eff}), **surface gravity** (logg), **metallicity** ([M/H])*
  - ***projected rotational velocity** (vsini)*
  - ***abundances***

one good spectrum needed

⇒
- accurate position in H-R diagram
- confirmation of pulsating class members
- search for unknown pulsating class members

Requirements for asteroseismology

- *large number of pulsation frequencies*
  - *time series with sufficiently long time base*
  - *high-quality observations: photometry, radial velocities, line-profile variations*
- *identification of the pulsation modes*
  - *Echelle diagram (in frequency for p-modes, in period for g-modes)*
  - *multi-colour photometry*
  - *high-resolution high-SNR spectroscopy*
- *accurate stellar parameters*
  - *temperature (T_{eff}), surface gravity (logg), metallicity ([M/H])*
  - *projected rotational velocity (vsini)*
  - *abundances*
- ***radial velocities** can give extra constraints*
  - ***multiple systems*** → few spectra needed

Requirements for asteroseismology

- *large number of pulsation frequencies*
  - *time series with sufficiently long time base*
  - *high-quality observations: photometry, radial velocities, line-profile variations*
- *identification of the pulsation modes*
  - *Echelle diagram (in frequency for p-modes, in period for g-modes)*
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  - *high-resolution high-SNR spectroscopy*
- *accurate stellar parameters*
  - *temperature (T_{eff}), surface gravity (logg), metallicity ([M/H])*
  - *projected rotational velocity (vsini)*
  - *abundances*
- ***radial velocities** can give extra constraints*
  - *multiple systems*
  - *cluster membership* ► one spectrum needed ⇒
    - age & composition
    - distance
    - etc.

Requirements for asteroseismology

- *large number of pulsation frequencies*
  - *time series with sufficiently long time base*
  - *high-quality observations: photometry, radial velocities, line-profile variations*
- *identification of the pulsation modes*
  - *Echelle diagram (in frequency for p-modes, in period for g-modes)*
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- *accurate stellar parameters*
  - ***temperature** (T_{eff}), **surface gravity** (logg), **metallicity** ([M/H])*
  - ***projected rotational velocity** (vsini)*
  - *abundances*
- *radial velocities can give extra constraints*
  - ***multiple systems***
  - ***cluster membership***

what can LAMOST offer?

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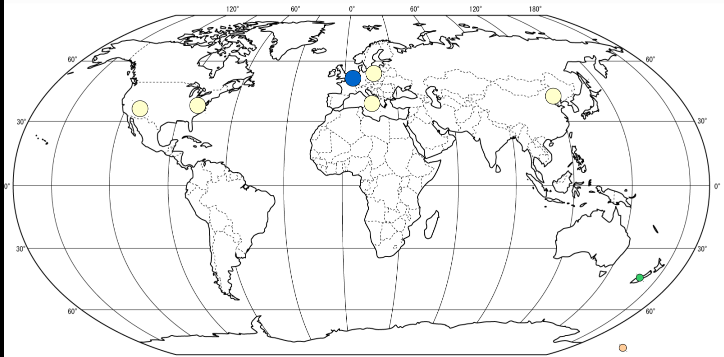
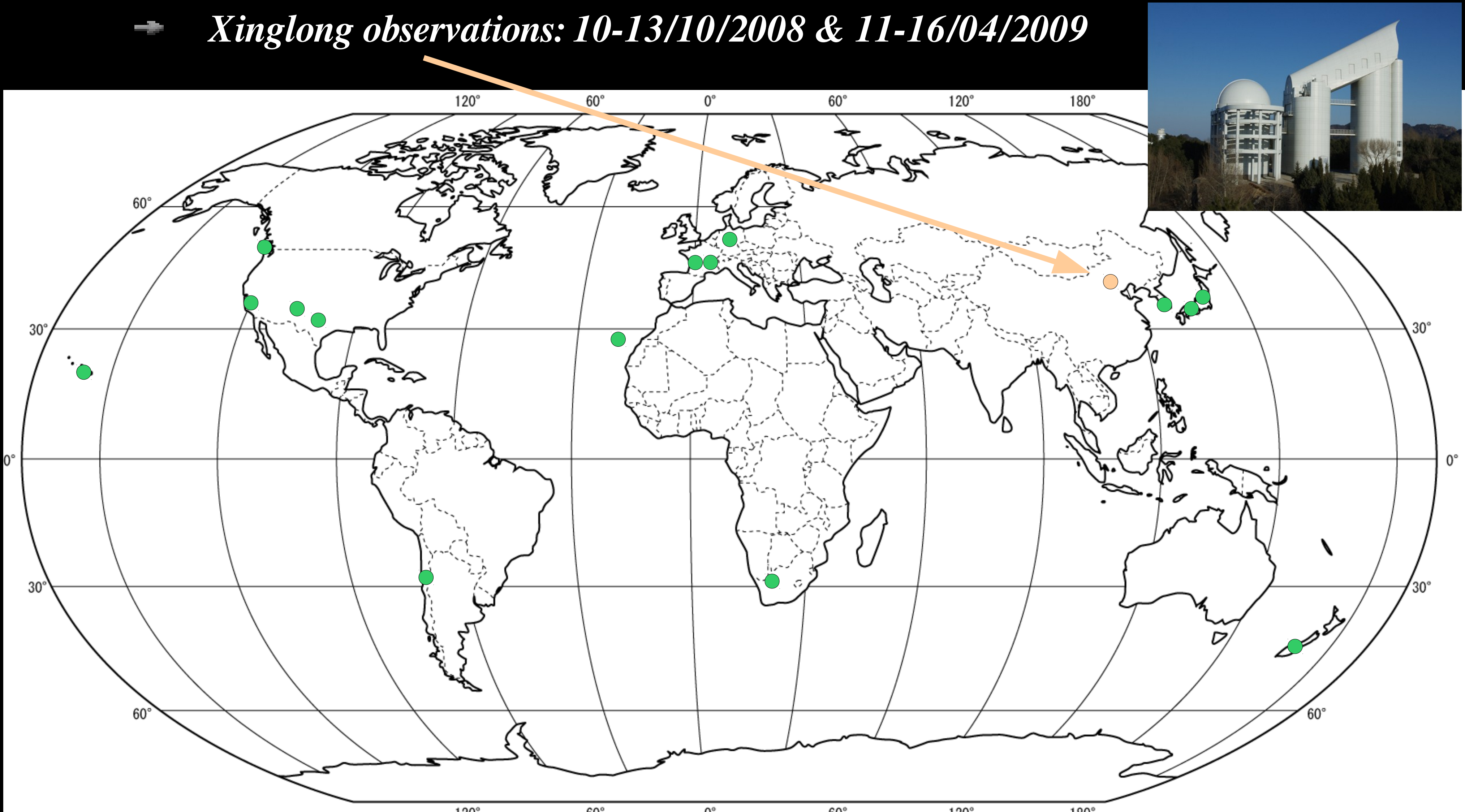


History of LAMOST-Kepler project

- *20/10/2003: first contact with Jiannning Fu (Dubrovnik)*

History of LAMOST-Kepler project

- *20/10/2003: first contact with Jianning Fu (Dubrovnik)*
- *since 2008: collaboration with Jianning Fu*
  - → *Xinglong observations: 10-13/10/2008 & 11-16/04/2009*

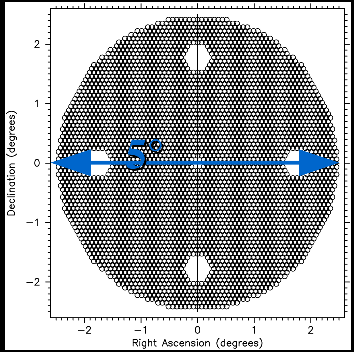


History of LAMOST-Kepler project

Large Sky Area Multi-Object Fiber Spectroscopic Telescope

http://www.lamost.org
Cui et al., 2012, RAA 12, 1197
Luo et al., 2015, RAA 15, 1095

- **Specifications:**
  - Fibers: #4000
  - Telescope: 4.0-m Guo Shou Jing Telescope
    northern hemisphere (Xinglong Observatory, China)
  - Wavelengths: 370 – 900 nm
  - Resolution: 1000-2000 (low) / 5000-10000 (medium)
  - Field of View: ~20 deg^2 (5°; circular)
  - Targets: >5,000,000 (stars, galaxies, QSOs)
  - Science case:
    - LEGAS: LAMOST Extragalactic Survey
    - LEGUE: LAMOST Experiment for Galactic Understanding and Exploration
      → survey of Milky Way stellar structure (halo and disk components)



unique combination of large aperture with wide field of view

History of LAMOST-Kepler project

- 20/10/2003: first contact with Jiannning Fu (Dubrovnik)
- since 2008: collaboration with Jianning Fu
- 23/10/2009: introduction idea to Jianning Fu
  - to cover whole Kepler field-of-view
  - to characterize targets in homogeneous way
    - spectral type
    - any peculiarities
    - logg, T_{eff}, metallicity
  - with low resolution spectroscopy
    - radial velocity ⇒ binaries, cluster membership
    - rotation velocity ⇒ restriction on $v\sin i$
  - because it is the only instrument to observe thousands of targets efficiently
    - brightest targets (Kp ≤ 10.5): with 2-m class telescopes
    - LAMOST: focus on fainter targets

with KASC subchairs

History of LAMOST-Kepler project

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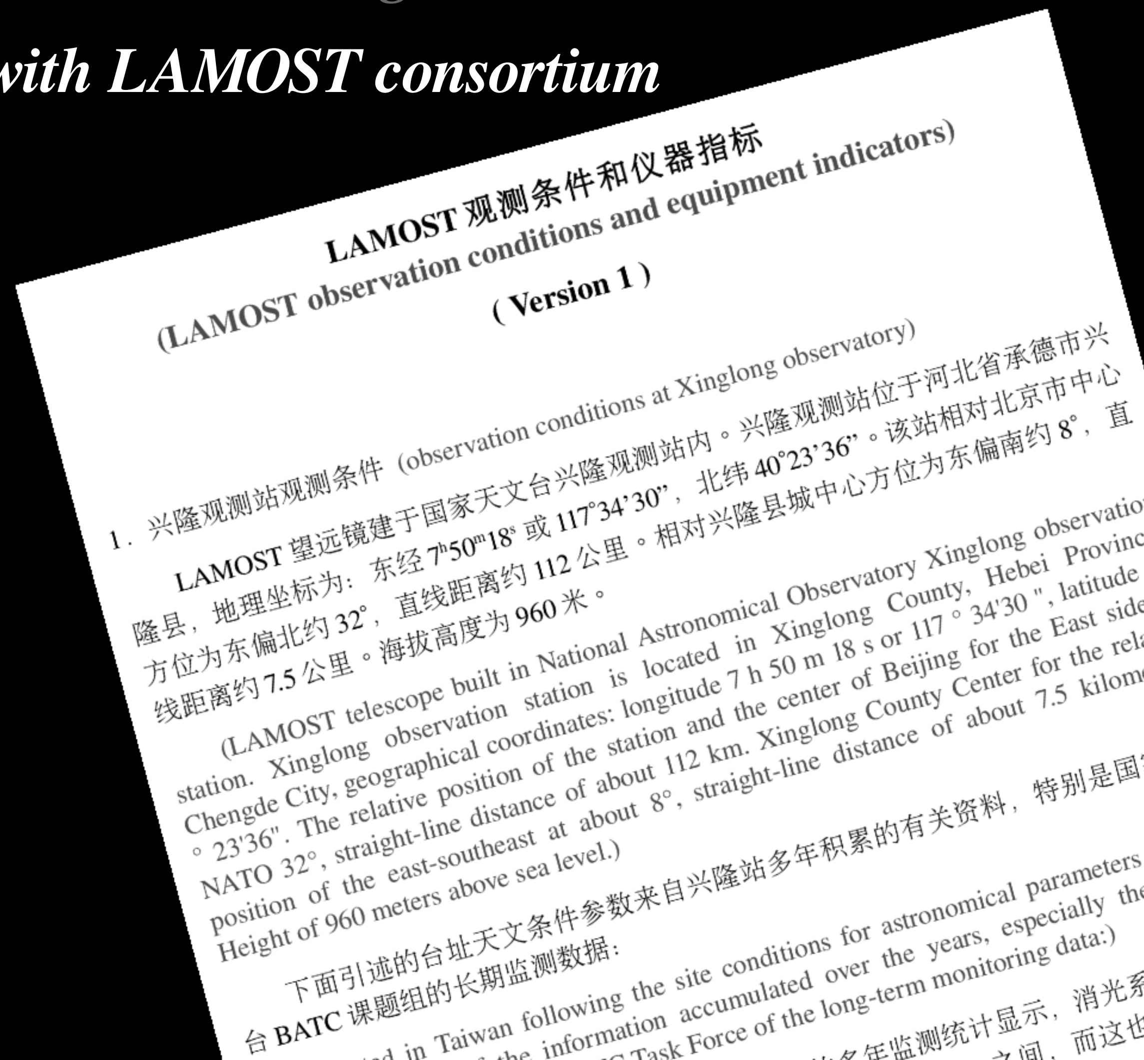

LAMOST 观测条件和仪器指标
(LAMOST observation conditions and equipment indicators)
(Version 1)

1．兴隆观测站观测条件 (observation conditions at Xinglong observatory)

LAMOST 望远镜建于国家天文台兴隆观测站内。兴隆观测站位于河北省承德市兴隆县，地理坐标为：东经 7h50m18s 或 117°34'30"，北纬 40°23'36"。该站相对北京市中心方位为东偏北约 32°，直线距离约 112 公里。相对兴隆县城中心方位为东偏南约 8°，直线距离约 7.5 公里。海拔高度为 960 米。

(LAMOST telescope built in National Astronomical Observatory Xinglong observation station. Xinglong observation station is located in Xinglong County, Hebei Province Chengde City, geographical coordinates: longitude 7 h 50 m 18 s or 117 ° 34'30 ", latitude ° 23'36". The relative position of the station and the center of Beijing for the East side NATO 32°, straight-line distance of about 112 km. Xinglong County Center for the rela position of the east-southeast at about 8°, straight-line distance of about 7.5 kilom Height of 960 meters above sea level.)

下面引述的台址天文条件参数来自兴隆站多年积累的有关资料，特别是国台 BATC 课题组的长期监测数据：

(... in Taiwan following the site conditions for astronomical parameters ... the information accumulated over the years, especially the ... Task Force of the long-term monitoring data:)

... 多年监测统计显示，消光系 ... 之间，而这

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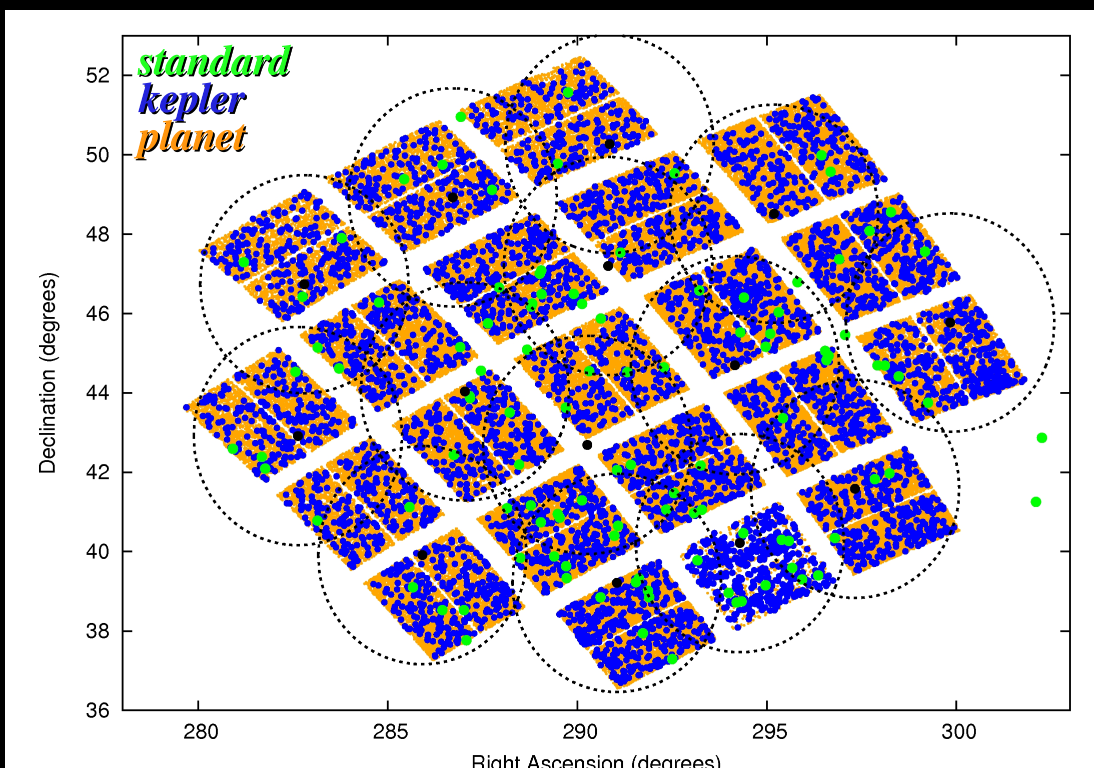

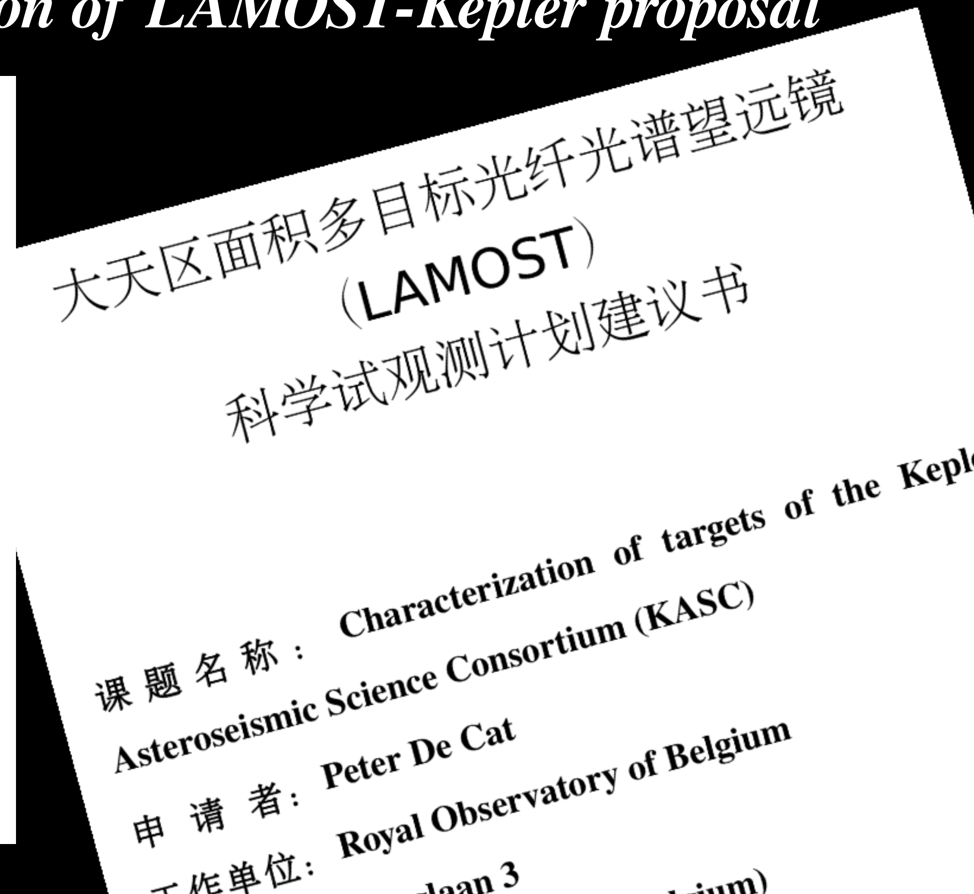

大天区面积多目标光纤光谱望远镜
（LAMOST）
科学试观测计划建议书

课 题 名 称： Characterization of targets of the Kepl
Asteroseismic Science Consortium (KASC)
申 请 者： Peter De Cat
工作单位： Royal Observatory of Belgium

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- *12/2010: observation details of LAMOST-Kepler proposal*

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- *05/2011: first observations for LAMOST-Kepler project*

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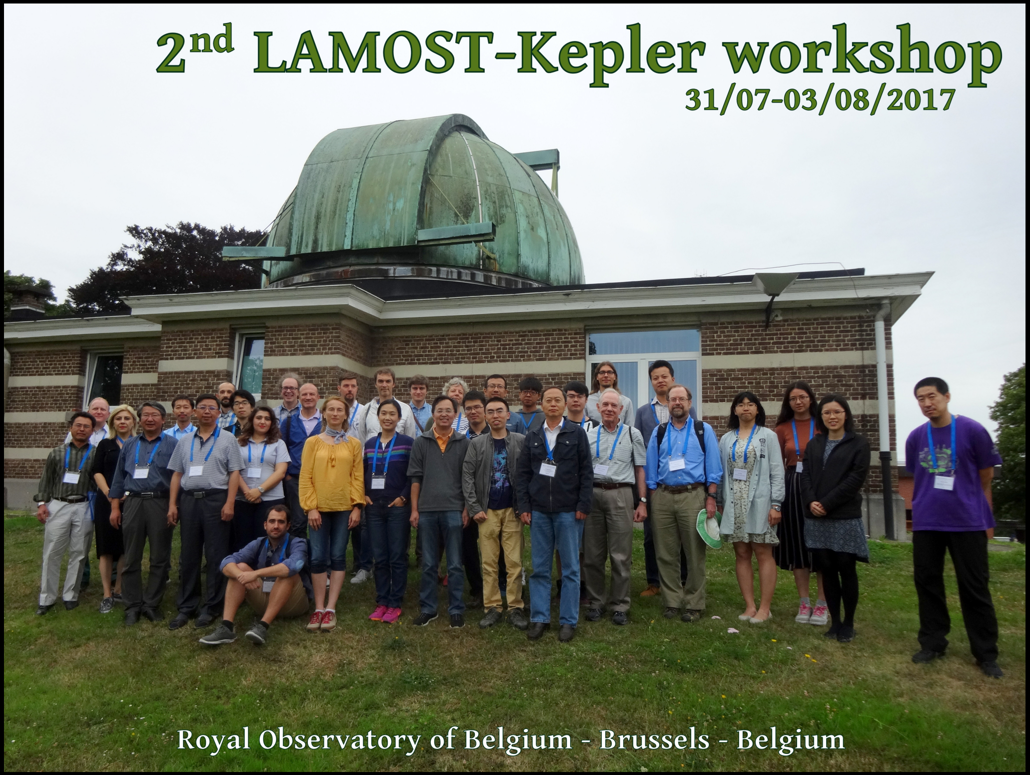
- 05/2011: first observations for LAMOST-Kepler project
- 05/2012: first spectra distributed and start of analysis
  - Asian team (Fu et al.)
  - European team (Frasca et al.)
  - American team (Gray & Corbally et al.)

History of LAMOST-Kepler project

- *18/08-22/08/2014: 1st LAMOST-Kepler workshop (Beijing)*
  - *present the LAMOST facility and the opportunities it opens for the international scientific society*
  - *highlight its usefulness for large observational surveys*
  - *present results obtained for the targets observed by the Kepler space mission*
  - *create/strengthen international collaborations with the LAMOST*

History of LAMOST-Kepler project

- *18/08-22/08/2014: 1st LAMOST-Kepler workshop (Beijing)*
- *31/07-03/08/2017: 2nd LAMOST-Kepler workshop (Brussels)*
  - *evaluation of first regular survey of 5 years*
    - *Importance of LAMOST as large spectroscopic survey*
      - *What is current status of LAMOST and the LAMOST-Kepler project?*
      - *What are the main scientific achievements in different fields based on LAMOST observations?*
    - *What can we still expect from LAMOST in the future?*



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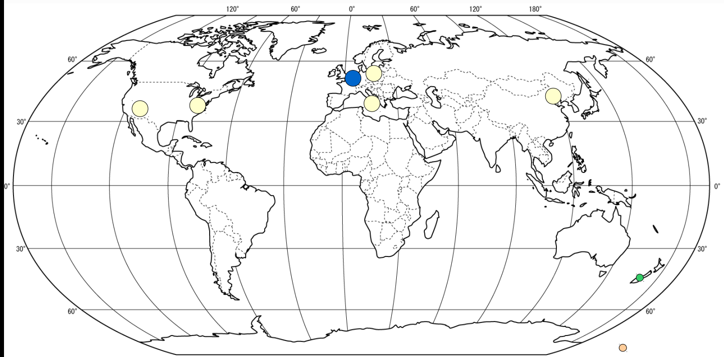


Database

Database

De Cat et al., 2015, ApJ 220, 19

- *First round*
  - *selection of targets*
    - *type of targets*

      without parameters high to low T_{eff}

      - *~250 standard targets (MK secondary standards)*
      - *~7,000 KASC targets (KIC10; scientific interest for KASC)*
      - *~150,000 planet targets (KIC10; scientific interest for planet search group)*
      - *~1,000,000 extra targets (KIC10; no scientific interest)*
      - *field stars (USNO-B catalog; no scientific interest)*
    - *brightness of targets*
      - *brightness intervals of maximum 5 magnitudes*
      - *bright targets (9.0 < Kp < 14.0)*

        from faint to bright (avoid saturation)
      - *faint targets (Kp > 14.0)*

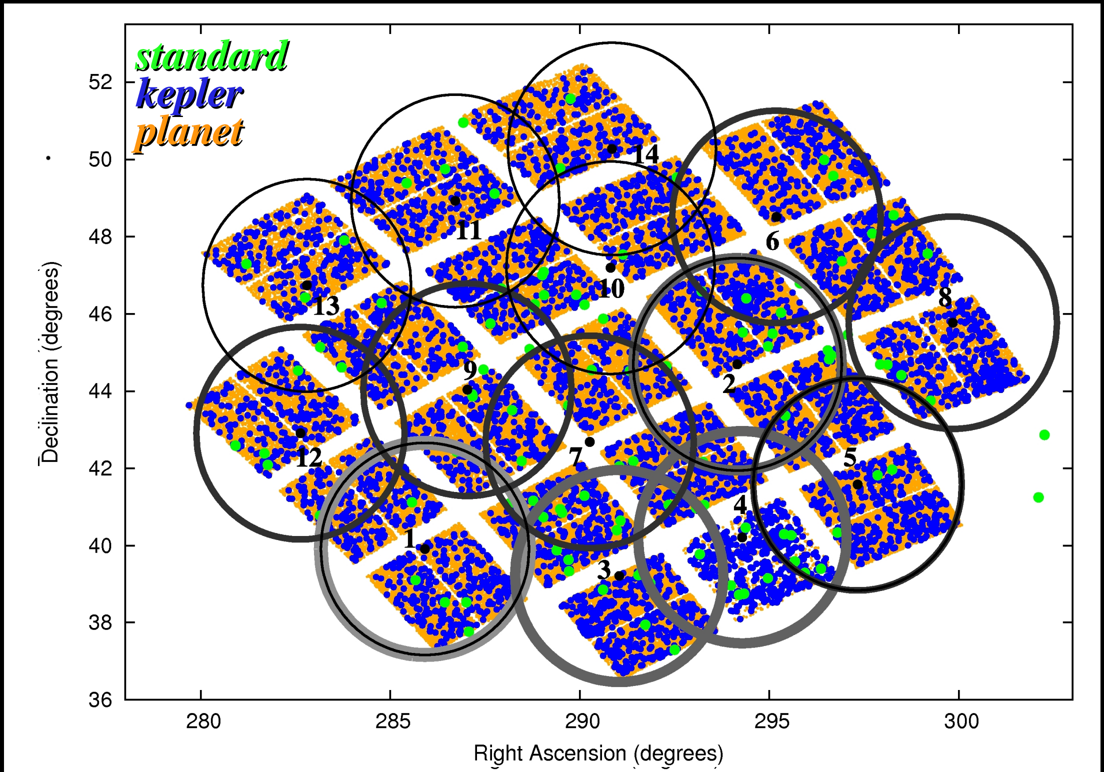
        from bright to faint (avoid too low flux)

Database

De Cat et al., 2015, ApJ 220, 19

- *First round*
  - *selection of targets*
  - *selection of fields*
  - *observations*

Year	#Fields	#Plates	#Spectra
2011	1	3	2,543
2012	3	7	19,903
2013	6	14	40,918
2014	7	14	37,722
total	*17*	*38*	*101,086*



	#Objects	#Kepler
Total	101,086	55,906
Unique	80,447	42,209
1×	63,333	31,147
2×	14,186	8859
3×	2483	1870
4×	332	258
+5×	113	75

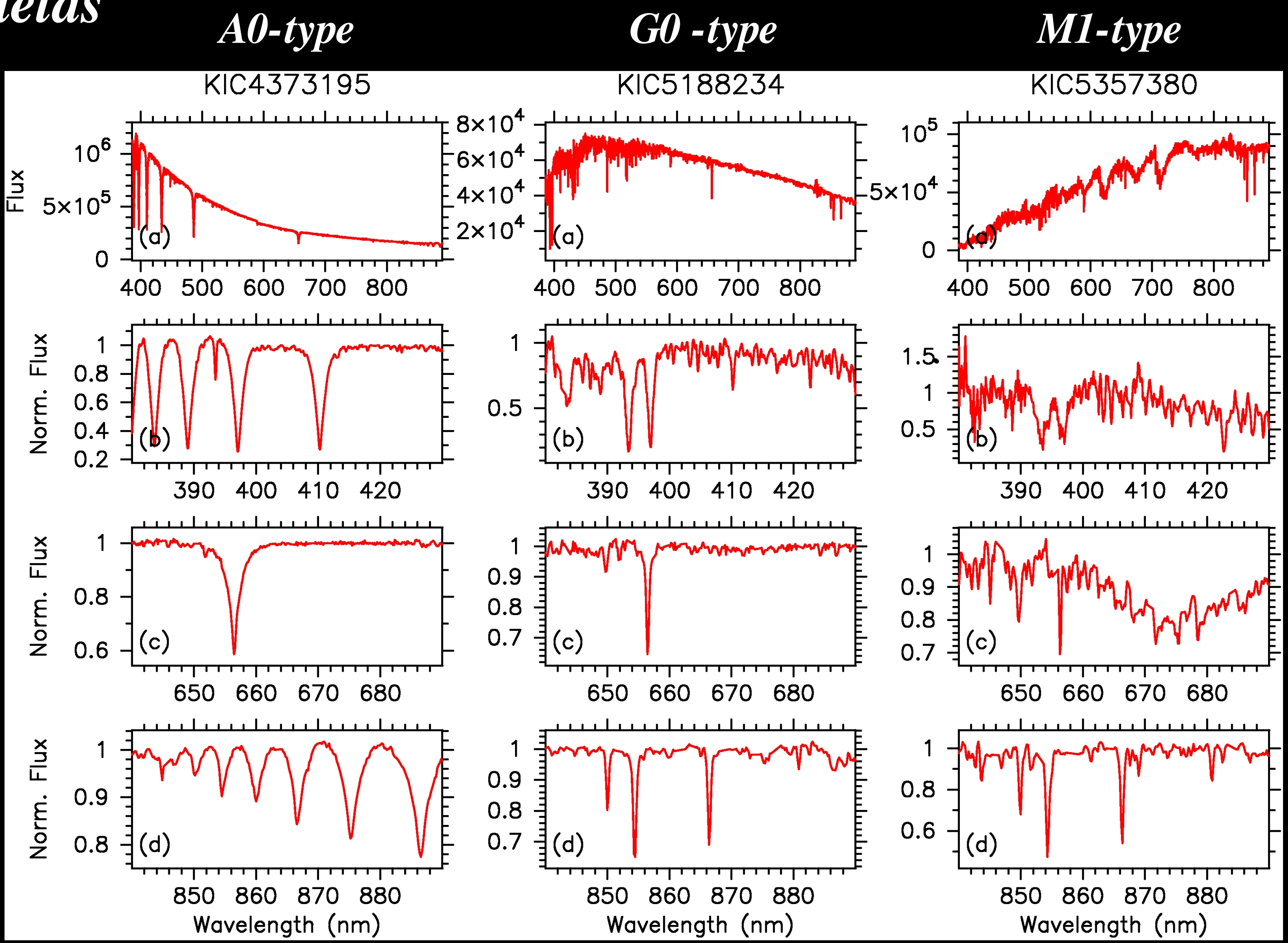
- *21.1% of Kepler stars observed*
- *17K objects with multiple observations*

⇒ ideal for validation methods

Database

De Cat et al., 2015, ApJ 220, 19

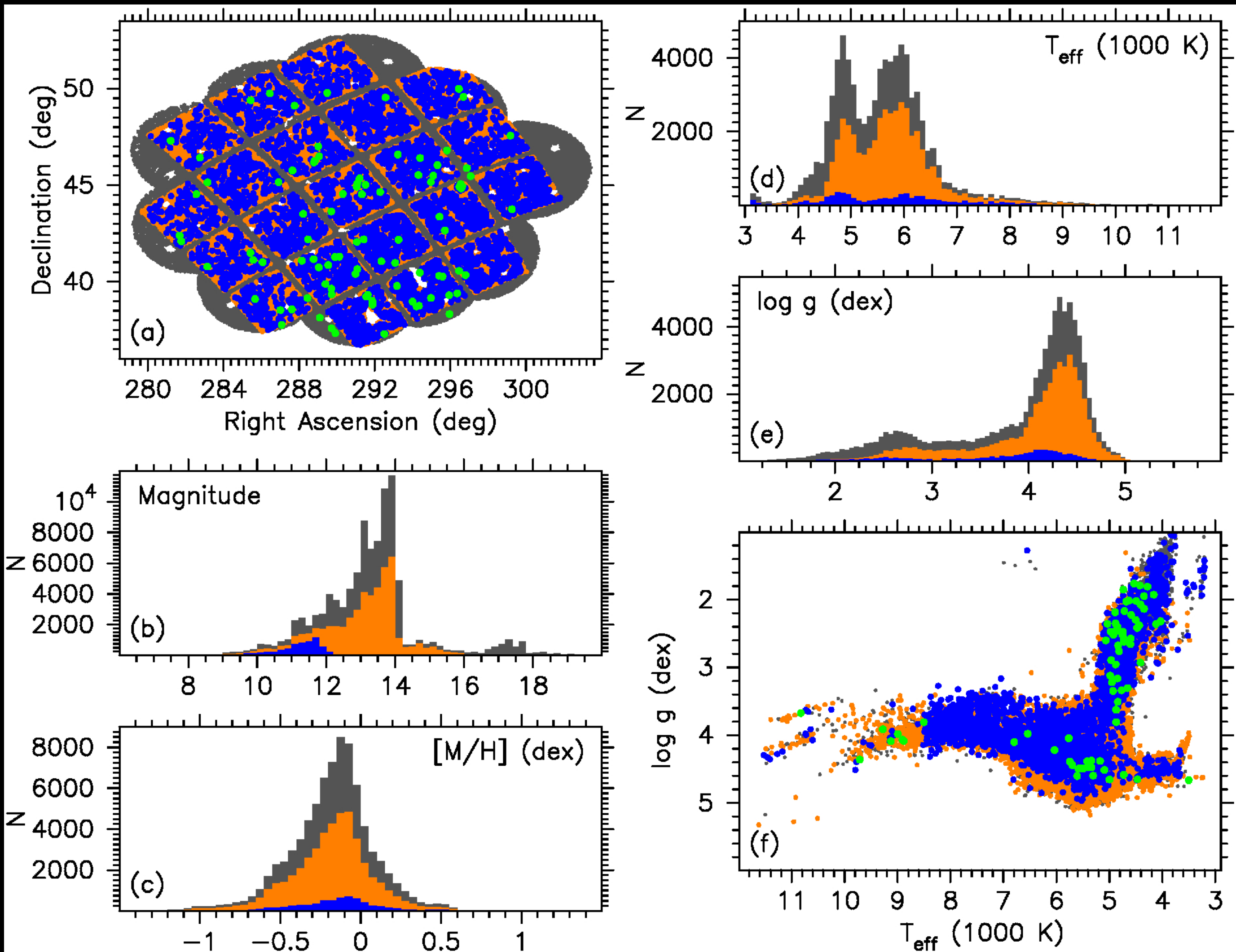
- *First round*
  - *selection of targets*
  - *selection of fields*
  - *observations*



Database

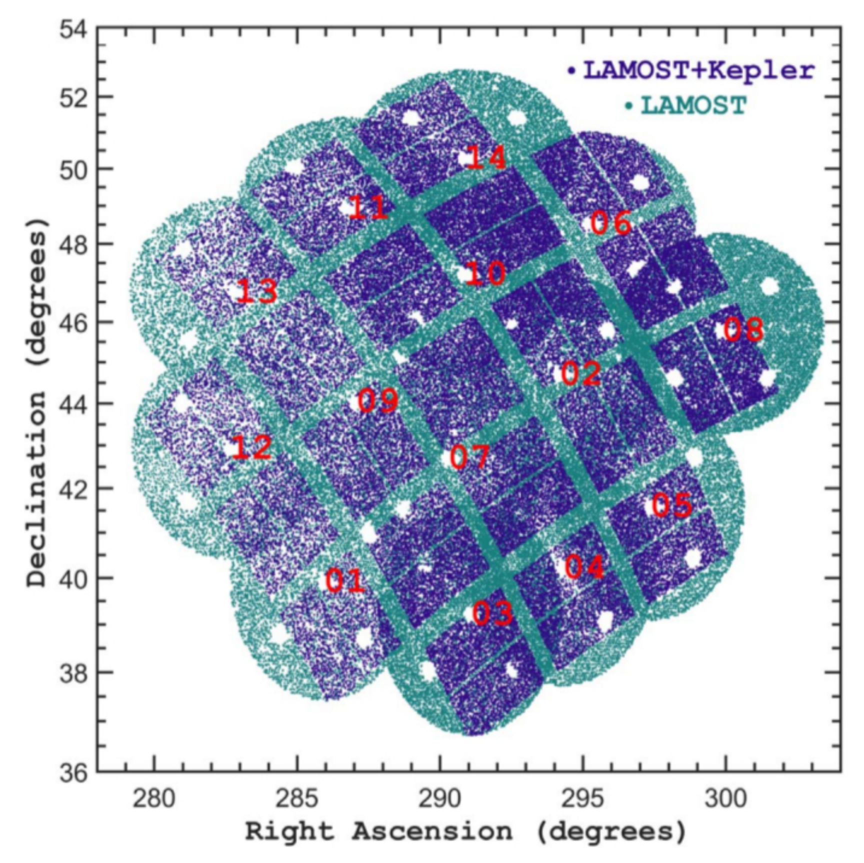
De Cat et al., 2015, ApJ 220, 19

- ***First round***
  - *selection of targets*
  - *selection of fields*
  - *observations*



Database

- ***Second round***
  - ***selection of targets***
    - ***focus on stars with***
      - ***Kepler data***
      - ***LAMOST data***



Zong et al., 2018, ApJ 238, 30

Year	#Fields	#Plates	#Spectra
2011			
2012	3	7	17,659
2013	6	14	39,309
2014	7	14	38,516
2015	11	32	97,247
2017	6	16	35,139
total	*33*	*83*	*227,870*

	#Objects	#Parameters
Total	227870	173971
Unique	104887	89570
2×	37482	28077
3×	10552	6613
4×	2293	1429
+5×	1176	483

- ***number of observations more than doubled***
- ***38.2% of Kepler stars observed***

European team

ROTFIT

Frasca et al., 2016, A&A 594, A39

European team

ROTFIT

Frasca et al., 2016, A&A 594, A39

goals

- calculation of stellar parameters with independent method
- search for active stars

method

- code ROTFIT (e.g. Frasca et al., 2010, A&A 518, 48)
  adapted to LAMOST spectra
  - semi-automatic normalisation with IRAF
  - librabry of 1150 stars with known stellar parameters (T_{eff}, logg, [Fe/H]) from Indo-U.S. Library of Coude Feed Stellar Spectra
    (Valdes et al., 2004, ApJS 152, 251)
  - degrading to match low-resolution LAMOST spectra
  - comparison for segments of 50 nm of the spectra
  - stellar parameters derived as weighted mean of parameters from best 10 templates for each segment

European team

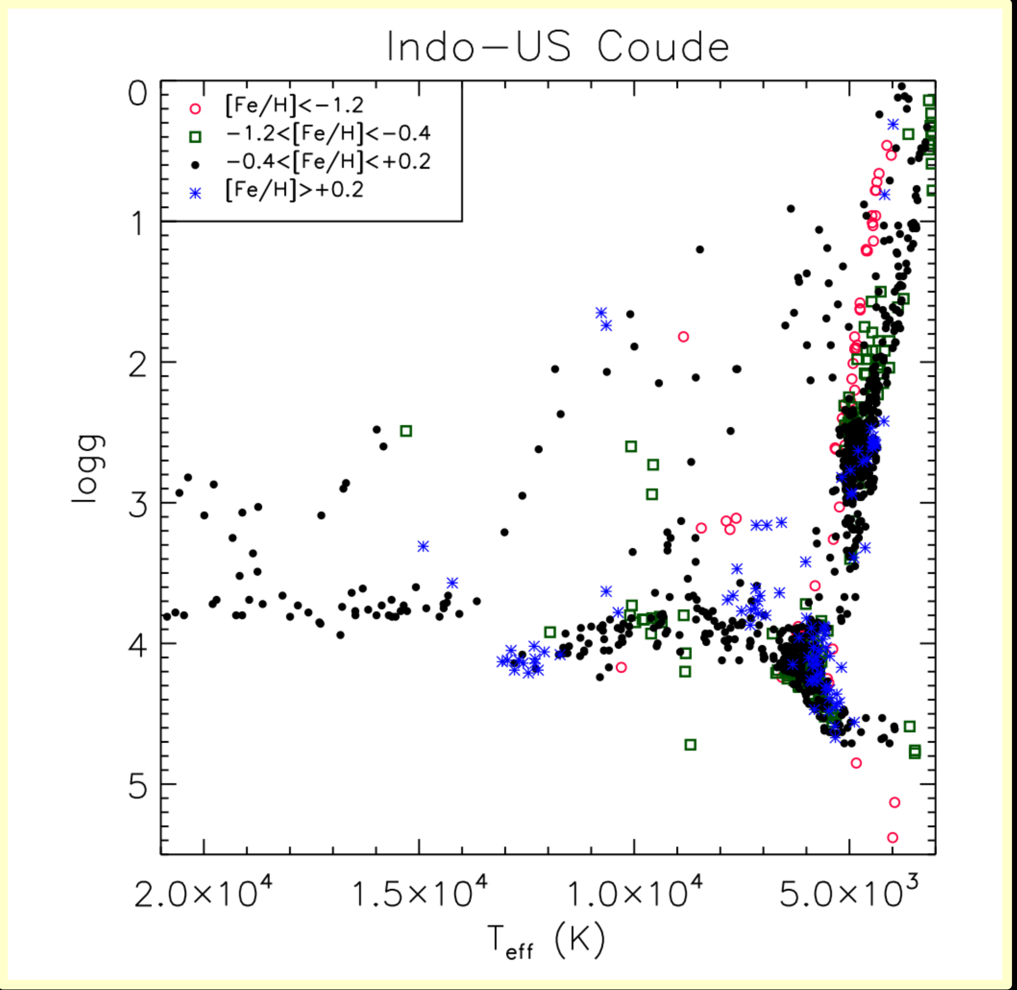
goals

- *calculation of stellar param*
- *search for active stars*

method

- *code* ***ROTFIT*** *(e.g. Frasca et al., 20*
  adapted to LAMOST spectr
  - *semi-automatic normalisation*
  - *librabry of 1150 stars with kno*

    Indo-U.S. Library of Coude Feed Stellar Spectra
    (Valdes et al., 2004, ApJS 152, 251)
  - *degrading to match low-resolution LAMOST spectra*
  - *comparison for segments of 50 nm of the spectra*
  - *stellar parameters derived as weighted mean of parameters from best 10 templates for each segment*



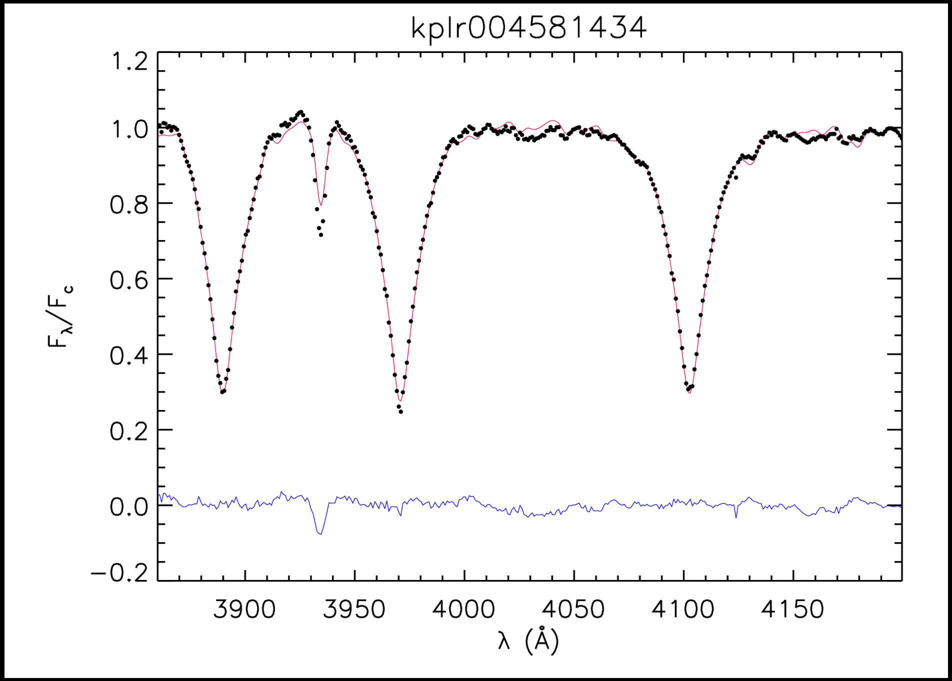
European team

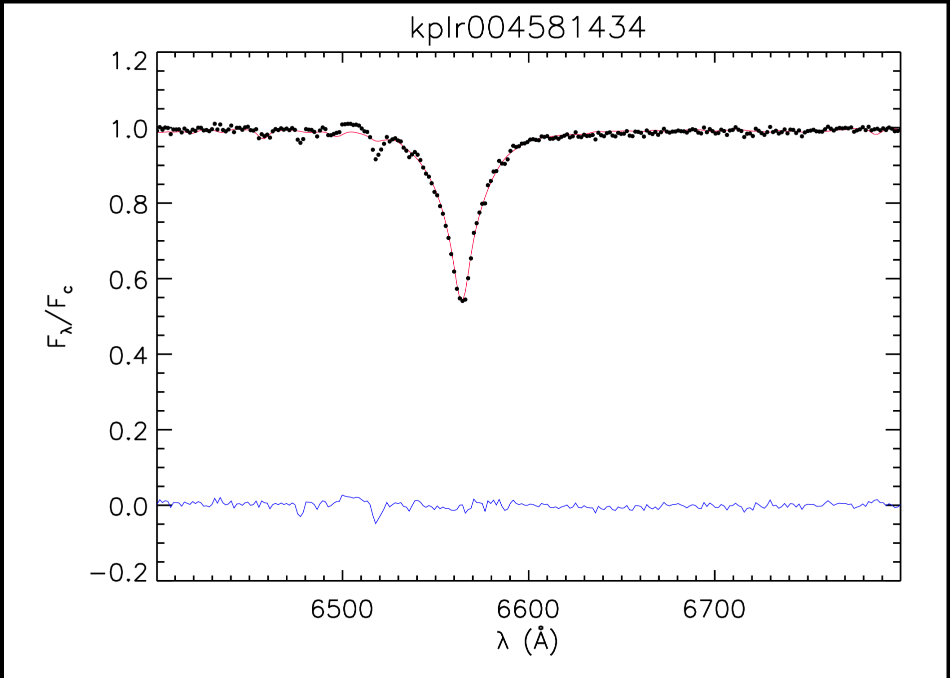
ROTFIT

Frasca et al., 2016, A&A 594, A39

examples

	target	SpT	Teff	logg	[Fe/H]
✯	KIC4581434	A1V	9307(91)	3.81(12)	-0.25(14)





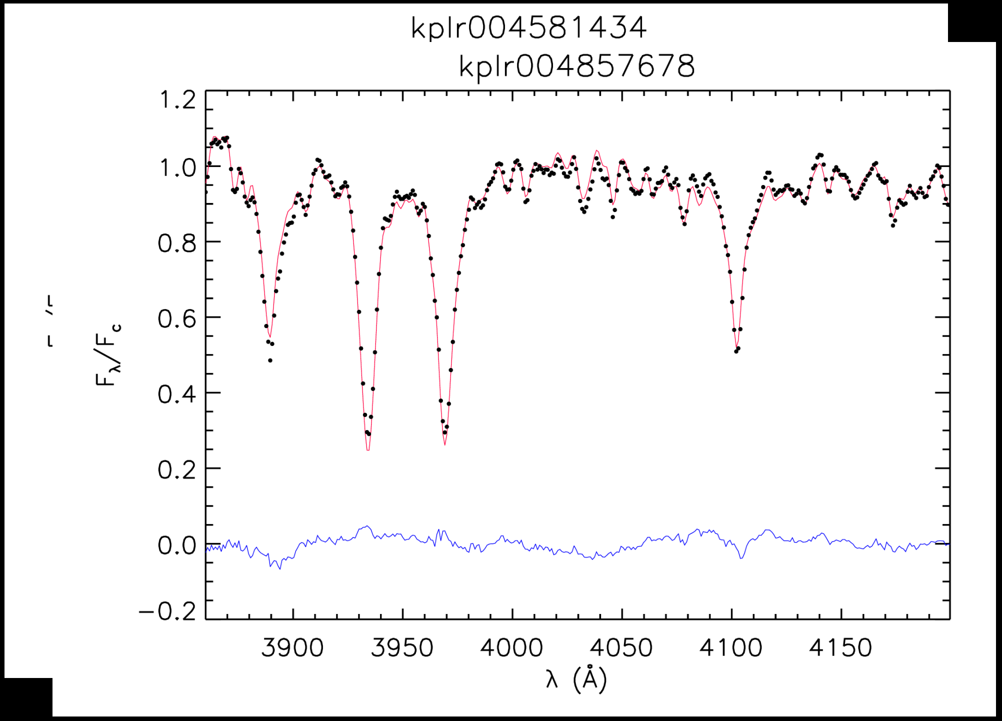
European team

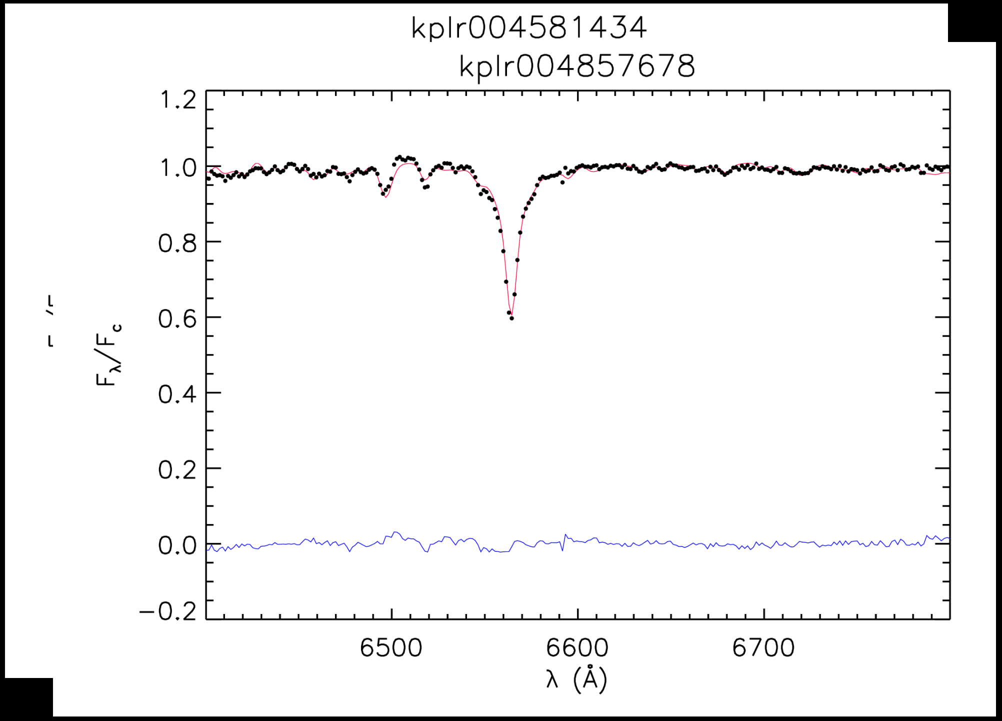
ROTFIT

Frasca et al., 2016, A&A 594, A39

examples

	target	SpT	Teff	logg	[Fe/H]
✯	KIC4581434	A1V	9307(91)	3.81(12)	-0.25(14)
✯	KIC4857678	F3V	6464(80)	4.13(11)	-0.24(13)





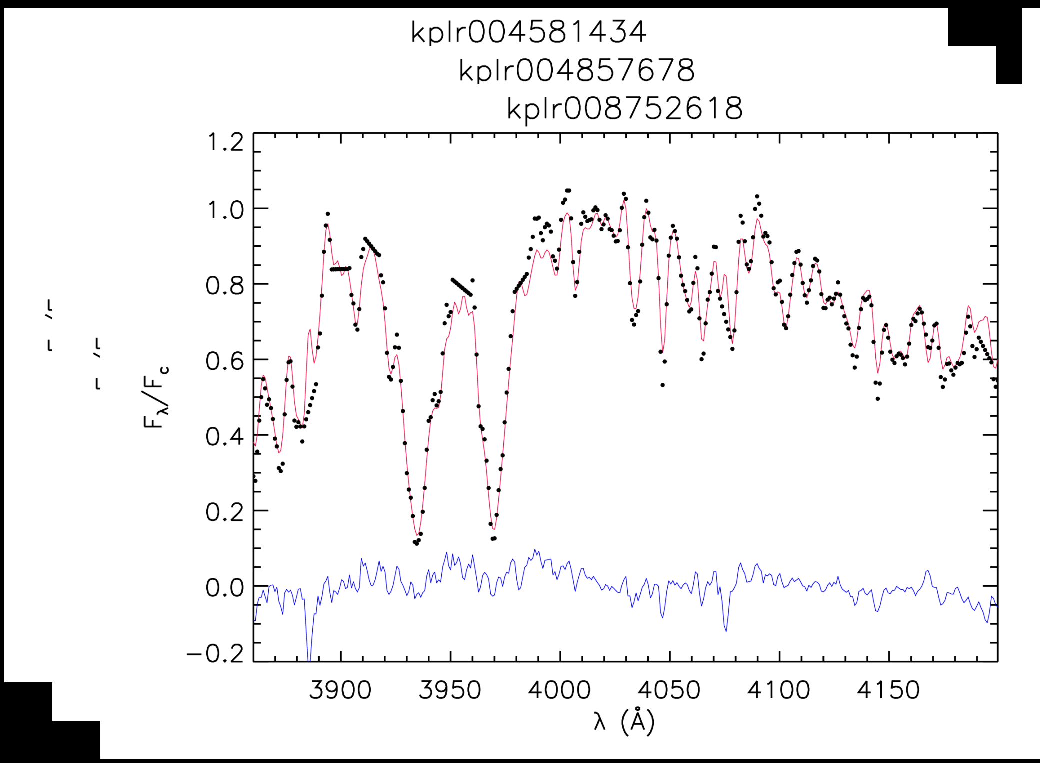
European team

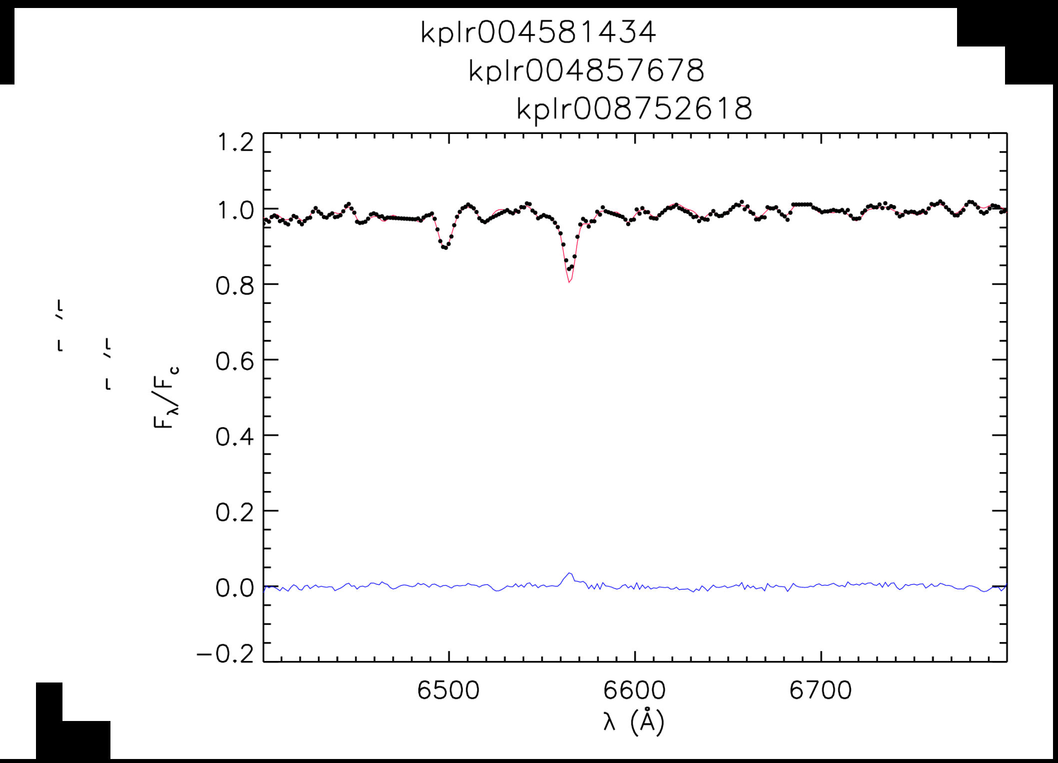
ROTFIT

Frasca et al., 2016, A&A 594, A39

examples

	target	SpT	Teff	logg	[Fe/H]
☆	KIC4581434	A1V	9307(91)	3.81(12)	-0.25(14)
☆	KIC4857678	F3V	6464(80)	4.13(11)	-0.24(13)
☆	KIC8752618	G8II	4734(104)	2.60(17)	-0.01(12)





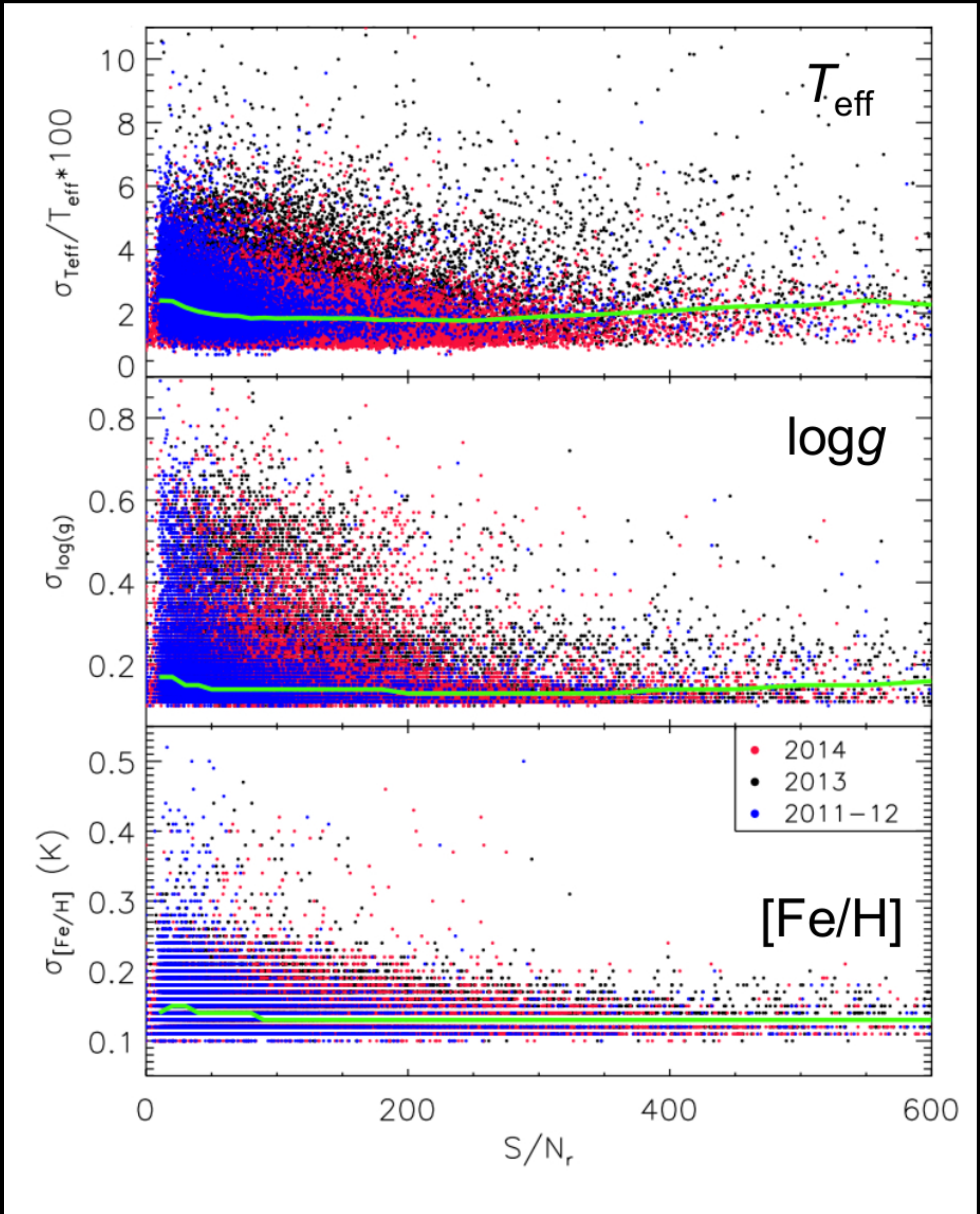
European team

ROTFIT

Frasca et al., 2016, A&A 594, A39

errors

- *single observations*
  - σ T_{eff} in the range 70-300 K, depending on S/N and T_{eff}
  - σ T_{eff}/T_{eff} = 2-3%
  - σ log(g) ≈ 0.2 dex
  - σ [Fe/H] ≈ 0.15 dex



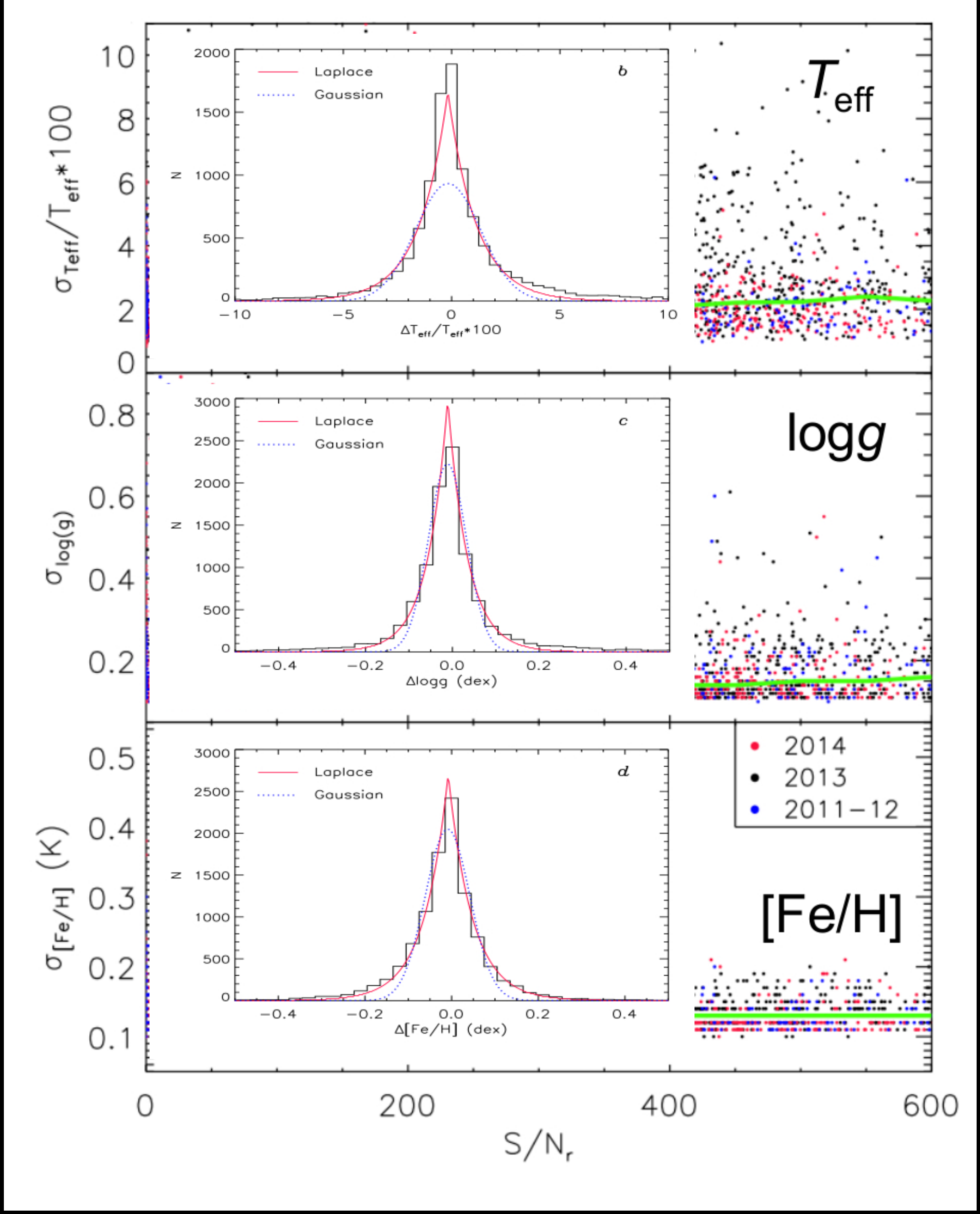
European team

ROTFIT

Frasca et al., 2016, A&A 594, A39

errors

- ***single observations***
  - $\sigma\, T_{eff}$ *in the range 70-300 K, depending on S/N and* T_{eff}
  - $\sigma\, T_{eff}/T_{eff}$ *= 2-3%*
  - σ *log(g) ≈ 0.2 dex*
  - σ *[Fe/H] ≈ 0.15 dex*
- ***multiple observations***
  - *distributions of differences repeated observations best fitted with Laplace function*
  - $b\, T_{eff}/T_{eff}$ *≈ 1.3%*
  - *b log(g) ≈ 0.05 dex*
  - *b [Fe/H] ≈ 0.05 dex*



ROTFIT errors overestimated?

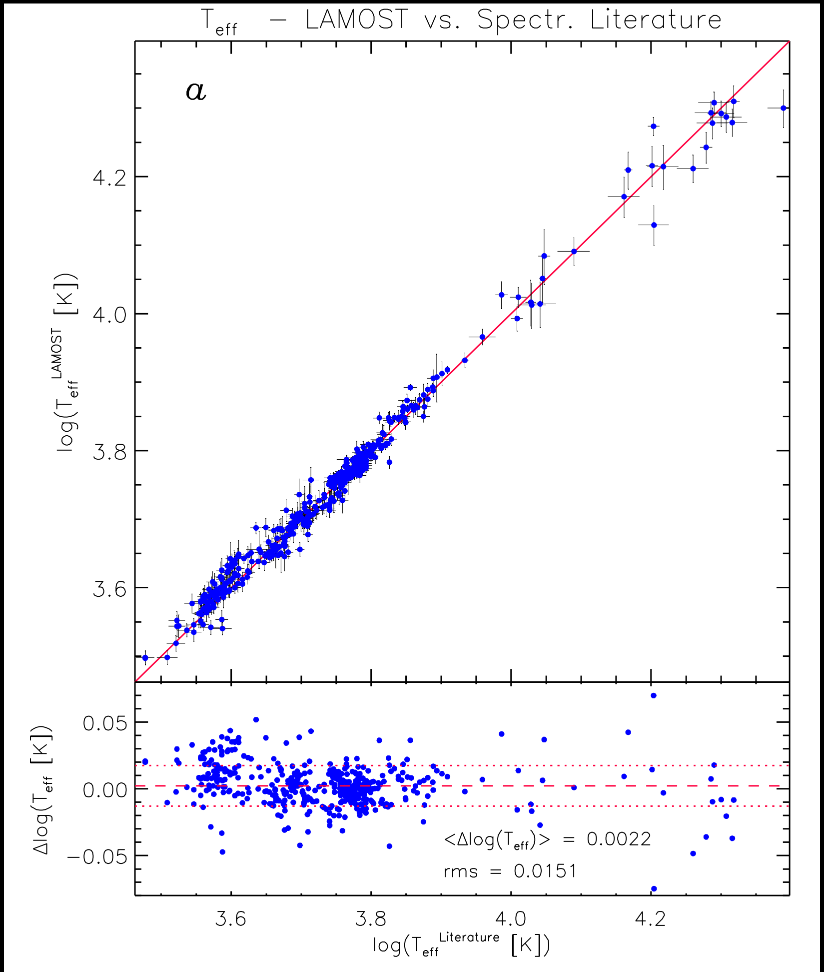
European team

ROTFIT

Frasca et al., 2016, A&A 594, A39

validation

effective temperature T_{eff}



- *comparison with literature values (468 stars)*
  - *high resolution spectra and/or asteroseismology*
  - *excellent agreement*
  - *very low scatter in log scale (~ 0.0151 dex)*
  - *$\sigma T_{eff}/T_{eff} \approx 3.5\%$*

European team

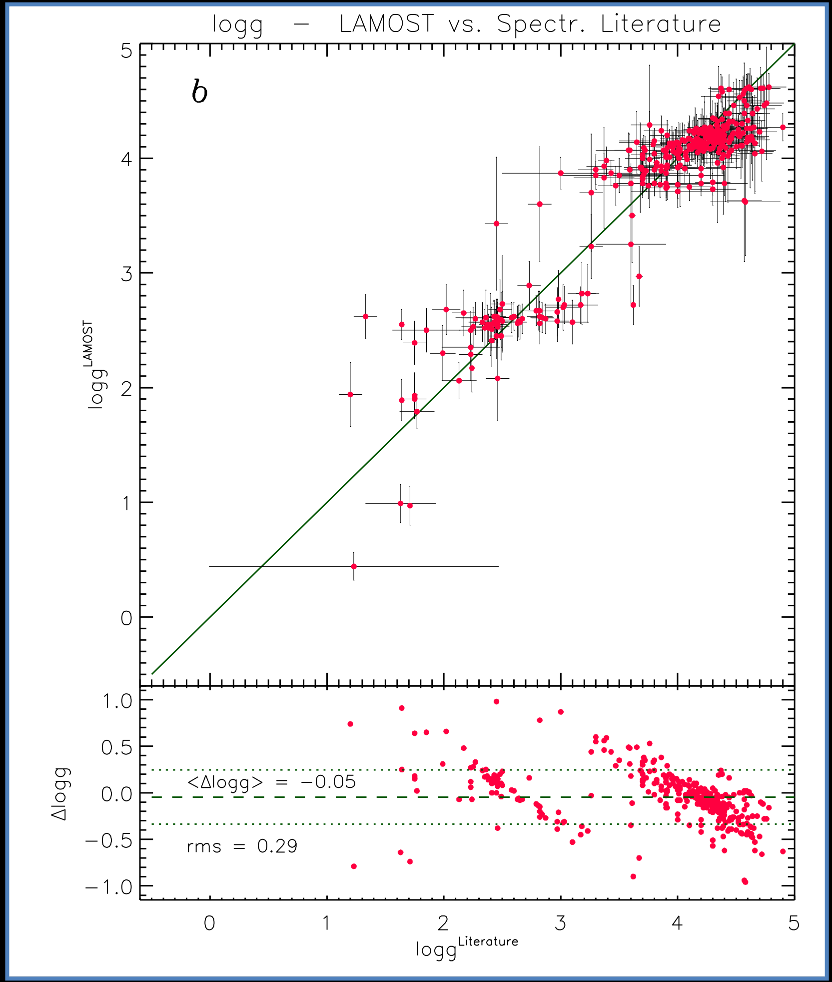
ROTFIT

Frasca et al., 2016, A&A 594, A39

validation

effective temperature T_{eff}

surface gravity logg



- ***comparison with literature values** (532 stars)*
  - ***overall good agreement***
  - ***larger scatter (~ 0.3 dex)***
  - ***tendency to cluster around gravity of RGB stars (≈ 2.5 dex) MS stars (≈ 4.5 dex)***

effect of non-uniform density of templates in logg?

European team

ROTFIT

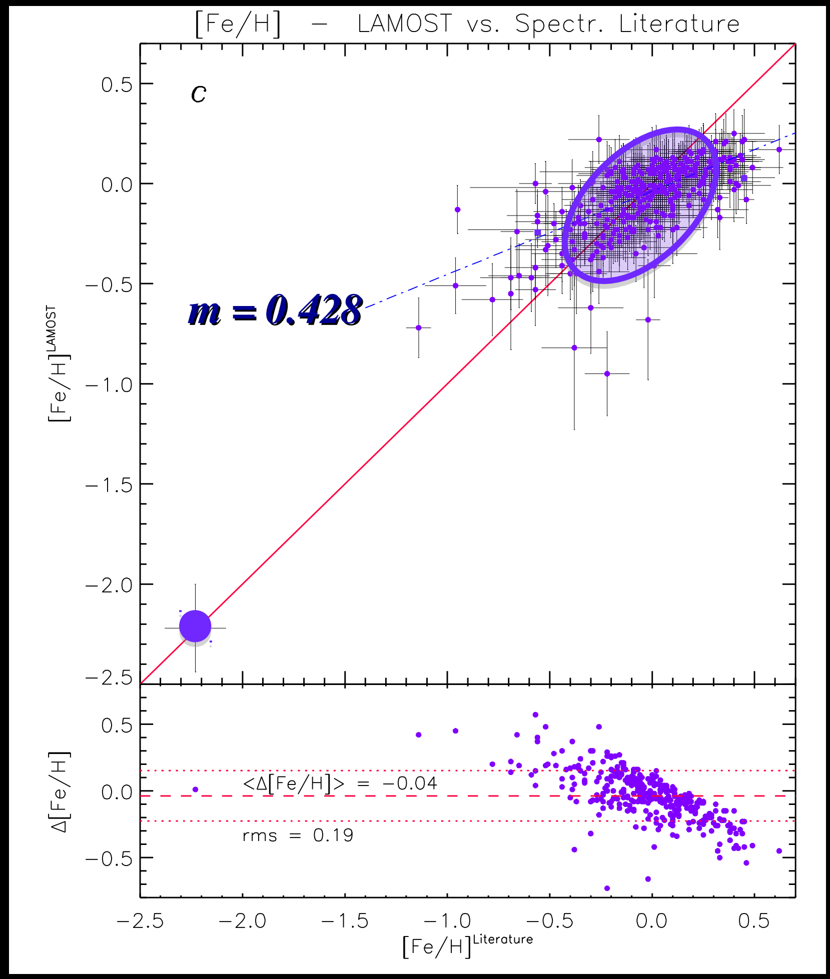
Frasca et al., 2016, A&A 594, A39

validation

effective temperature T_{eff}

surface gravity logg

metallicity [Fe/H]



- comparison with literature values (350 stars)
  - good agreement for -0.3 < [Fe/H] < +0.2 dex
- low metallicity star KIC9206432 has good [Fe/H] determination
  - negligible contamination by richer templates
- for $[Fe/H]^{Literature}$ > -1.5 dex
  - linear fit with slope m = 0.428

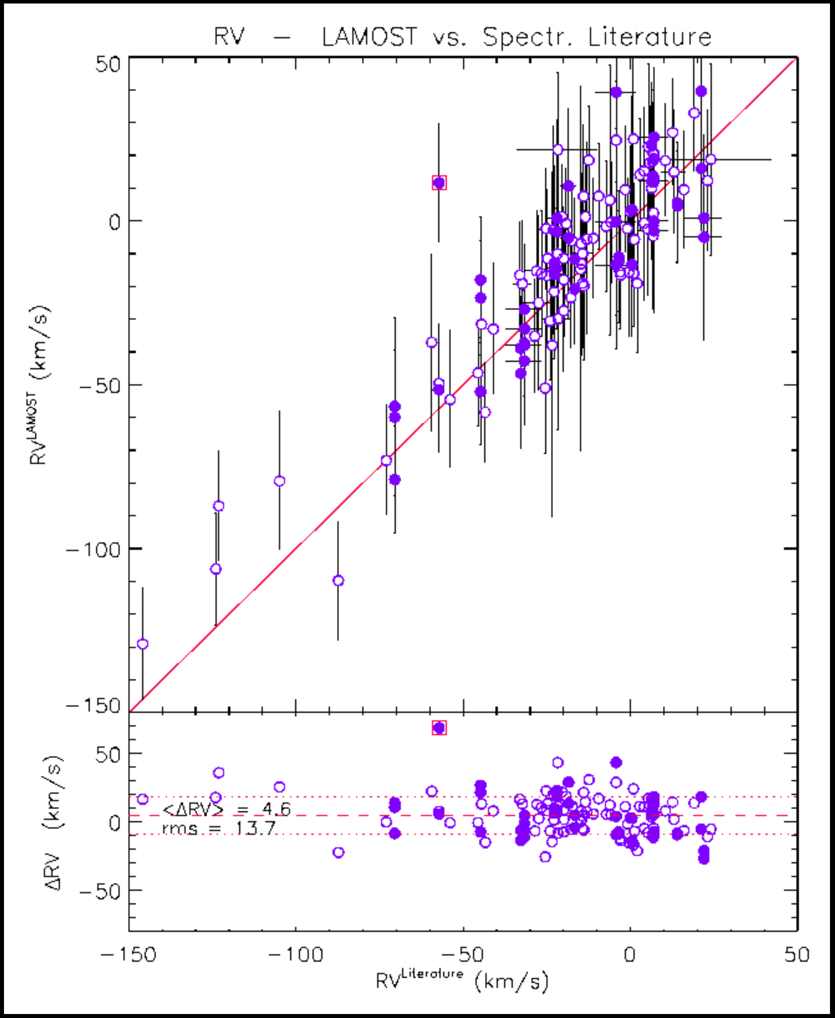
European team

ROTFIT

Frasca et al., 2016, A&A 594, A39

validation

- effective temperature T_{eff}
- surface gravity logg
- metallicity [Fe/H]
- radial velocity v_{rad}



- *by correlation (CC) between the target spectrum and best template from list of 20 spectra with different spectral types from the Indo US library*
  - *giving highest CC peak*
  - *Gaussian fit of CC peak*
- *comparison with literature values (104 stars)*
  - *agreement within 3σ*
  - *one exception*
    - *KIC 7599132 HD 180757*
    - *ellipsoidal variable in close spectroscopic binary (Catanzaro et al., 2018, MNRAS 477, 2020)*

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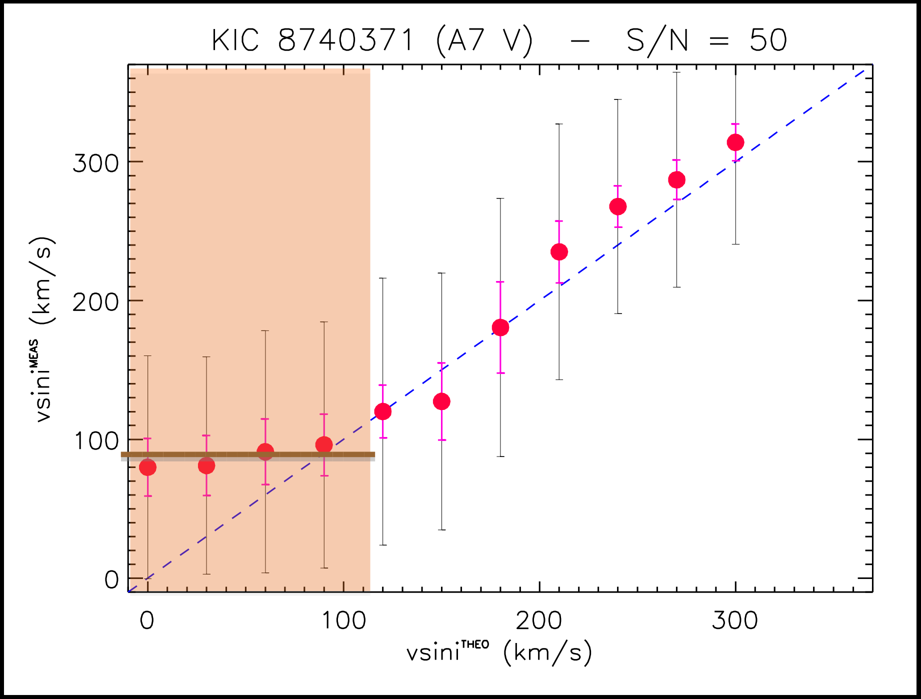
ROTFIT

Frasca et al., 2016, A&A 594, A39

validation

- *effective temperature $T_{\rm eff}$*
- *surface gravity logg*
- *metallicity [Fe/H]*
- *radial velocity $v_{\rm rad}$*
- ***prjected rotational velocity vsini***



- *alignment of template spectra with $v_{\rm rad}$*
- *broadening by convolution with rotational profile of increasing vsini*
  - *steps of 5 km/s*
  - *minimum in χ^2*

→ *Monte-Carlo simulations*

- *LAMOST spectra of slow rotator*
- *artificially broadened*
- *resampled on LAMOST points*
- *random noise added*

only stars with *v*sin*i* > 120 km/s can be detected

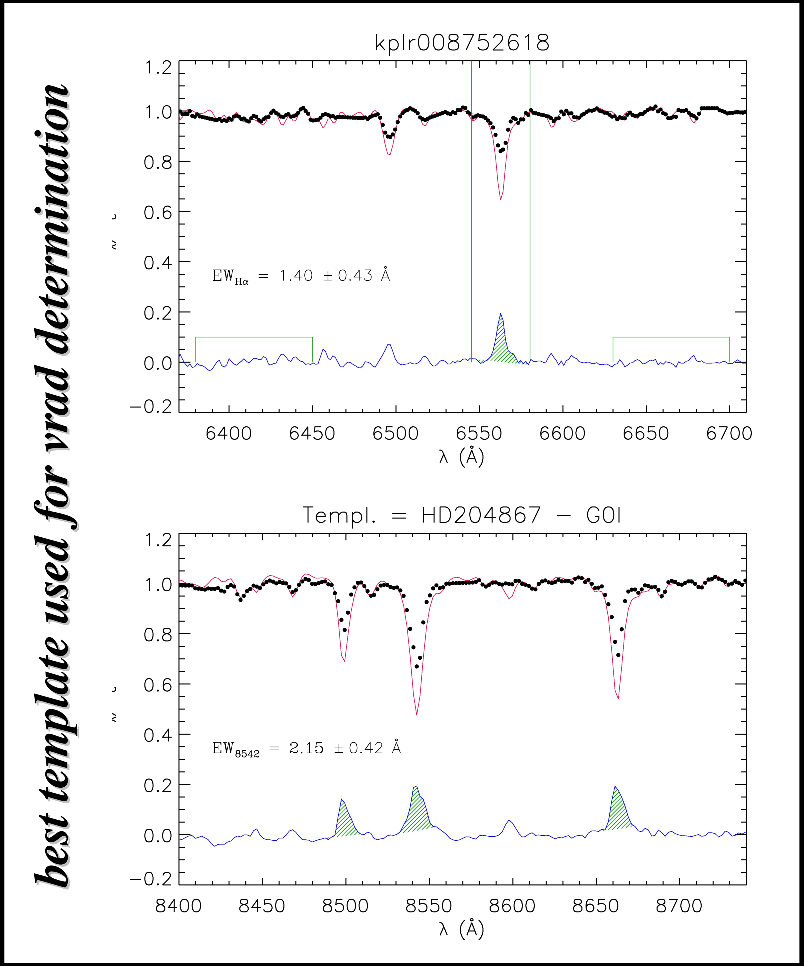
European team

ROTFIT

Frasca et al., 2016, A&A 594, A39

application

- search for active stars
  - filling/emission of Hα & CaII IRT



European team

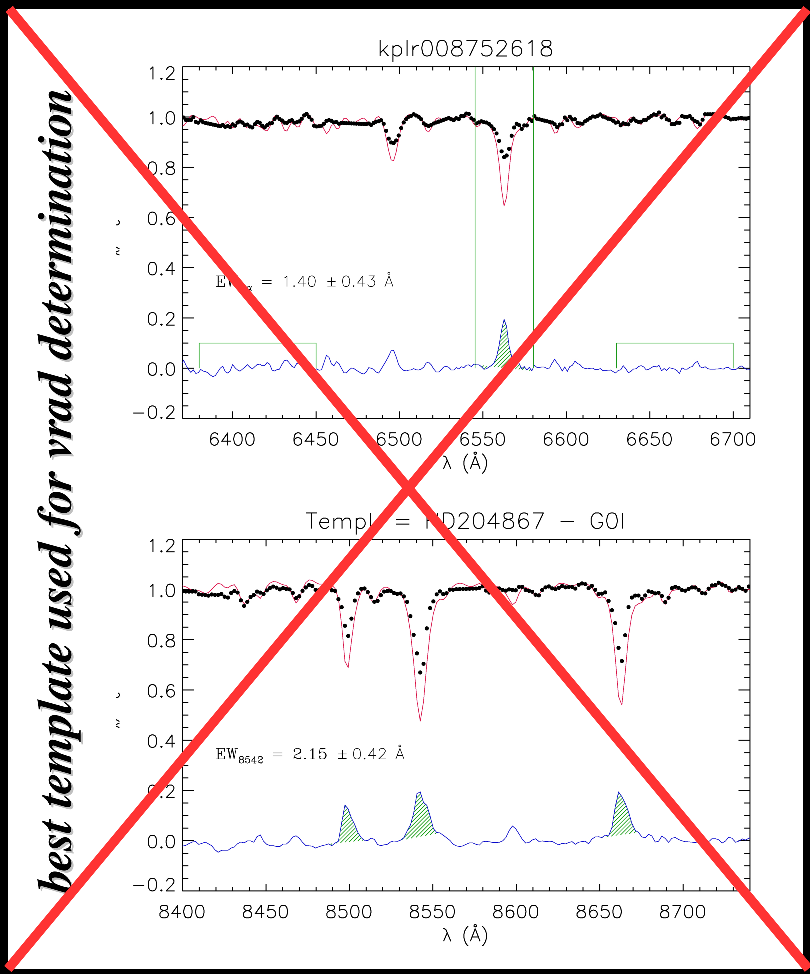
ROTFIT

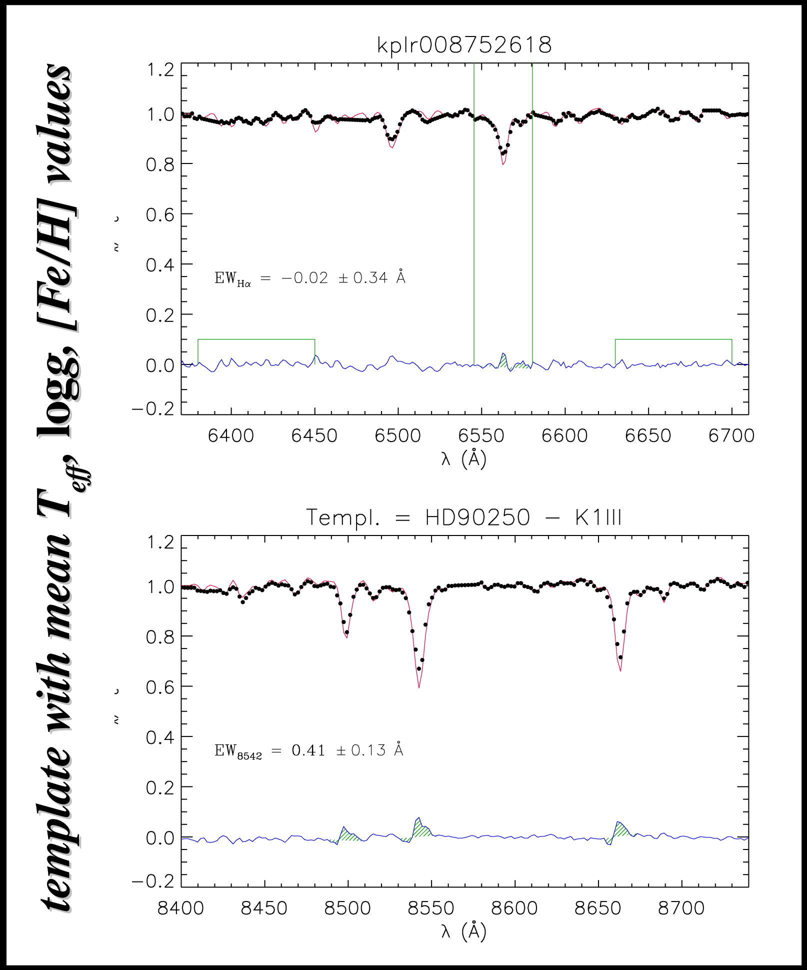
Frasca et al., 2016, A&A 594, A39

application

- *search for active stars*
  - *filling/emission of Hα & CaII IRT*

not an active star...





European team

ROTFIT

Frasca et al., 2016, A&A 594, A39

application

- search for active stars
  - filling/emission of Hα & CaII IRT
  - detection of 547 active stars
  - 442 GKM stars classified as chromospherically active from the flux-flux relationship between Hα & CaII IRT
  - discovery of accreting star KIC8749284 (K1V)

European team

ROTFIT

Frasca et al., 2016, A&A 594, A39

future prospects

- ROTFIT
  - current version
    - DR3 versus DR5 for sample of LAMOST-Kepler data of first round
  - ideas for improvement of ROTFIT
    - evaluation of choice of segments?
    - evaluation of template spectra?
    - calculation of grid of synthetic spectra?
- iSPEC?

collaboration with Yang Pan & Jiantao Wang (BNU, Beijing, China)

work in progress

American team

MKCLASS

Gray et al., 2016, AJ 151, 13

American team

MKCLASS

Gray et al., 2016, AJ 151, 13

goals

- classification on MK system via direct comparison with MK standards
- identification of peculiar and astrophysically interesting stars

method

- code MKCLASS (http://www.appstate.edu/~grayro/mkclass)
  - reproduce steps of skilled human classifiers
  - input:
    - flux calibrated 370 – 900 nm R~1800 (LAMOST spectrum)
    - 2 standard libraries (0.8-m telescope @ Dark Sky Observatory; Appalachian State University)
      - normalised 380 – 460 nm R~2200 (GM spectrograph; 1200 g mm^{-1} grating)
      - flux calibrated 380 – 560 nm R~1100 (GM spectrograph; 600 g mm^{-1} grating)

    ⇒ auxiliary program: degrading LAMOST spectra to R~1100 and truncate
  - output:
    - spectral type: temperature type + luminosity class + peculiarities
    - quality evaluation based on χ^2 differences with best MK standard

American team

MKCLASS

Gray et al., 2016, AJ 151, 13

examples of output

LAMOST Spectrum Fits File	KIC Number	Header ID	g-band S/N	Spectral Type	Quality	Notes
spec-56094-kepler05B56094_2_sp01-167	KIC01865567	SDSS	278	B8 IV Si	vgood	...
spec-56094-kepler05B56094_sp01-167	KIC01865567	SDSS	319	B8 IV-V Si	vgood	...
spec-56094-kepler05B56094_2_sp07-213	KIC01873552	SDSS	104	A6 V Sr	vgood	...
spec-56094-kepler05B56094_sp07-213	KIC01873552	SDSS	125	A5 V Sr	vgood	...
spec-56811-KP190339N395439V01_sp01-180	KIC02284009	1275-10742685	21	F7 IV-V Fe-0.6	good	...
spec-56811-KP190339N395439V02_sp01-180	KIC02284009	kplr002284009	20	F7 IV Fe-0.6	good	...
spec-56811-KP190339N395439V01_sp01-181	KIC02142733 (3)	1275-10780735	31	G0 IV-V	vgood	...
spec-56811-KP190339N395439V02_sp01-181	KIC02142733	extra00015199	24	G1 V	vgood	...
spec-56811-KP190339N395439V02_sp01-189	KIC02284278	1275-10750999	62	K5 III	good	...
spec-56811-KP190339N395439V01_sp01-189	KIC02284278	kplr002284278	60	K5 III	vgood	...
spec-56094-kepler05B56094_2_sp14-028	KIC04145645	1275-10950670	20	M3 III	vgood	...
spec-56811-KP190339N395439V02_sp06-186	KIC04145645	1275-10950670	32	M2.5 III	vgood	...

temperature type *luminosity class* *peculiarities*

"excellent"

"vgood"

"good"

"fair"

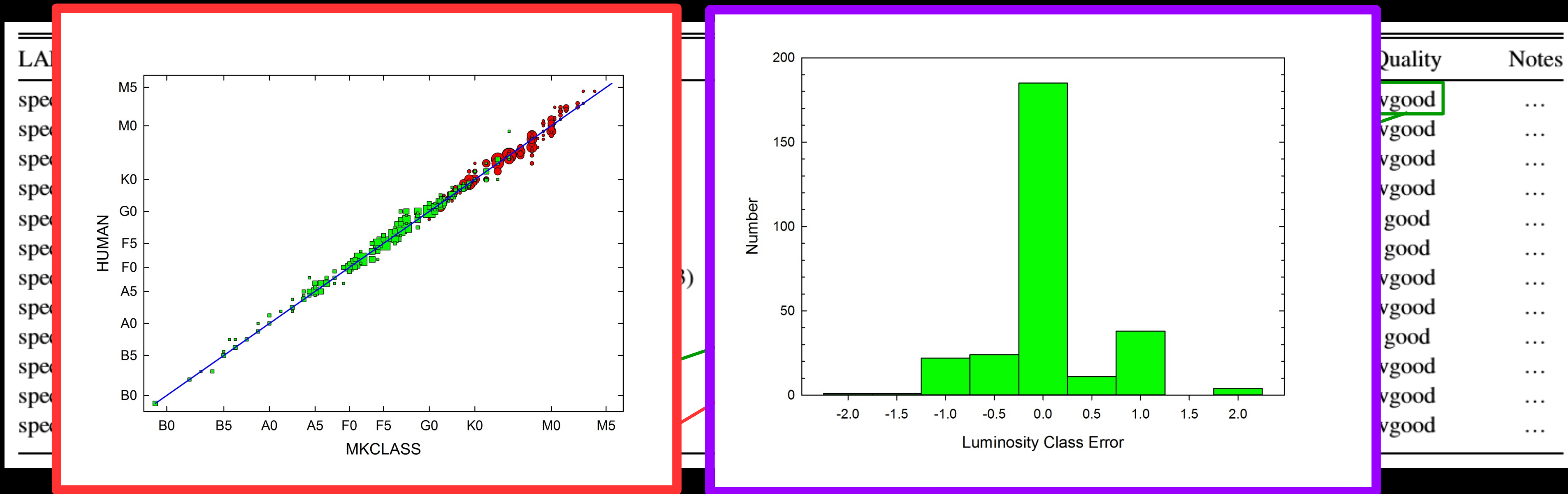
"poor"

American team

MKCLASS

Gray et al., 2016, AJ 151, 13

examples of output



temperature type *luminosity class* *peculiarities*

typical error in based on comparison with literature

"excellent"		
"vgood"	*~0.6 temperature subtype*	*~0.5 luminosity class*
"good"	*~1.2 temperature subtype*	*~1.0 luminosity class*
"fair"	*uncertain*	*uncertain*
"poor"	*unreliable*	*unreliable*

depends on temperature type

American team

MKCLASS

Gray et al., 2016, AJ 151, 13

application

- interesting stars in first round of LAMOST-Kepler data
  - 32 Barium dwarf candidates (s-process enhanced G-type dwarfs)
  - 34.6% of A stars are Am stars
  - 132 candidate λ Bootis stars
    - chemically peculiar stars on upper main-sequence (late-B to early-F)
      - fraction in instability stips of δ Scuti and γ Doradus stars
    - surface underabundances of most iron-peak elements (up to 2 dex)
    - near-solar abundances of C, N, O and S

accretion of metal-poor material from interstellar medium?

interaction with protoplanetary disks or planets?

- follow-up VATT spectra
  - confirmation of classification for 15 out of 34 observed candidates
  - 8 out of 11 with Kepler data pulsate (including 4 hybrid δSct/γDor stars)

Gray et al., 2017, AJ 154, 31

HERMES observations (collaboration with J. Molenda-Żakowicz)

American team

MKCLASS

Gray et al., 2016, AJ 151, 13

future prospects

- apply MKCLASS to LAMOST-Kepler data of second round

work in progress

Asian team

LASP

Ren et al., 2016, AJ 225, 28

Asian team

LASP

Ren et al., 2016, AJ 225, 28

goals

- *statistical analysis of stellar parameters provided by LAMOST*
- *calibration of stellar parameters*
- *comparison with literature (KIC10)*

method

- *code LASP (LAMOST Stellar Parameter Pipeline)*
  - *method: (Wu et al., 2011, RAA 11, 924; Luo et al., 2015, RAA 15, 1095)*
    - *step 1: Correlation Function Interpolation (CFI)*
    - *step 2: Université de Lyon Spectroscopic Analysis Software (ULySS)*
  - *sufficient quality:* $SNR_g > 6$
  - *final_class:* STAR
  - *final_subclass:* late A, F, G, K
  - *parameters:* T_{eff}, logg, [Fe/H], v_{rad}

Asian team

LASP

Ren et al., 2016, AJ 225, 28

validation

- external calibration
  - spectroscopic and asteroseismic parameters (Huber et al., 2014, ApJS, 211, 2)
  - giants ($\log g < 3.5$ dex) versus dwarfs ($\log g > 3.5$ dex)
  - deviation $\Delta = value_{LASP} - value_{Huber}$

	giants			dwarfs		
	meanΔ	stdΔ	range	meanΔ	stdΔ	range
T_{eff} (K)	34	131	3800 - 5300	5	104	4000 -7000
logg (dex)	0.13	0.19	1.5 – 3.5	-0.05	0.16	3.6 – 4.9
[Fe/H] (dex)	-0.04	0.15	-1.0 – 0.5	-0.01	0.10	-0.6 – 0.5

Asian team

LASP

Ren et al., 2016, AJ 225, 28

validation

- external calibration
- internal calibration
  - stars with multiple LAMOST observations
  - method of unbiased estimator (Xie et al., 2016, PNAS 113, 11431)

	$SNR_g \geq 6$	$SNR_g \geq 50$
T_{eff} (K)	91	68
logg (dex)	0.12	0.08
[Fe/H] (dex)	0.09	0.06

Asian team

LASP

Ren et al., 2016, AJ 225, 28

validation

- *external calibration*
- *internal calibration*
- *statistical analysis of stellar parameters*
  - *mean errors*
    - $T_{\rm eff}$ *2.75%*
    - logg *0.215 dex*
    - *[Fe/H]* *0.152 dex*
    - $v_{\rm rad}$ *18 km/s*

Asian team

LASP

Ren et al., 2016, AJ 225, 28

validation

- *external calibration*
- *internal calibration*
- *statistical analysis of stellar parameters*
- *comparison with KIC*
    - *conversion relations for giants and dwarfs*

Asian team

LASP

Ren et al., 2016, AJ 225, 28

future prospects

- similar analysis with inclusion of LAMOST-Kepler data of second round (Pan et al., in preparation)
- inclusion of missing stars
  - main-sequence stars
    - hot (OB-type)
    - cool (M-type)
  - white dwarfs
  - hot subdwarfs

Other teams

Other teams

Refereed papers

- *Dong et al., 2014, ApJL 789, L3*
- *Deheuvels et al., 2014, A&A 564, A27*
- *Liu et al. 2015, ApJ 807, 4*
- *Bostancı et al., 2015, MNRAS 453, 1095*
- *Chen et al., 2015, RAA 15, 1125*
- *Guzik et al., 2015, AstRv 11, 1*
- *Huang et al., 2015, RAA 15, 1240*
- *Xiang et al., 2015, RAA 15, 1209*
- *Ren et al., 2016, RAA 16, 45*
- *Yu et al., 2016, MNRAS 463, 1297*
- *Wang et al., 2016, AJ 152, 6*
- *Zhang et al., 2016, ApJL 821, 32*
- *Karoff et al., 2016, Nat Com 7, 11058*
- *Xie et al., 2016, PNAS 113, 11431*
- *Mulders et al., 2016, AJ 152, 187*
- *Murphy et al., 2016, ApJL 827, L17*
- *Zhu et al., 2016, ApJ 832, 196*
- *Chang et al., 2017, ApJ 834, 92*
- *Wu et al., 2017, RAA 17, 5*
- *Smalley et al., 2017, MNRAS 465, 2662*
- *Guo et al., 2017, ApJ 838, 25*
- *Mathur et al., 2017, ApJS 229, 30*
- *Yang et al., 2017, ApJ 849, 36*
- *Xiang et al., 2017, MNRAS 464, 3657*
- *Xiang et al., 2017, ApJS 232, 2*
- *Petigura et al., 2017, AJ 154, 107*
- *Balona et al., 2018, MNRAS 476, 4840*
- *Petigura et al., 2018, AJ 155, 89*
- *Hümmerich et al., 2018, A&A 619, A98*
- *Lampens et al., 2018, A&A 610, A17*
- *Zhang et al., 2018, ApJ 865, 115*
- *Zhu et al., 2018, AJ 156, 92*
- *Qian et al., 2018, ApJS 235, 5*
- *Qian et al., 2018, MNRAS 475, 478*
- *Vickers & Smith, 2018, ApJ 860, 91*
- *Wang et al., 2018, ApJ 860, 136*
- *Zhang et al., 2018, ApJ 854, 168*
- *Zhu et al., 2018, ApJ 860, 101*

Other teams

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- *Dong et al., 2014, ApJL 789, L3*
- *Deheuvels et al., 2014, A&A 564, A27*
- *Liu et al. 2015, ApJ 807, 4*
- *Bostancı et al., 2015, MNRAS 453, 1095*
- *Chen et al., 2015, RAA 15, 1125*
- *Guzik et al., 2015, AstRv 11, 1*
- *Huang et al., 2015, RAA 15, 1240*
- *Xiang et al., 2015, RAA 15, 1209*
- *Ren et al., 2016, RAA 16, 45*
- *Yu et al., 2016, MNRAS 463, 1297*
- *Wang et al., 2016, AJ 152, 6*
- *Zhang et al., 2016, ApJL 821, 32*
- *Karoff et al., 2016, Nat Com 7, 11058*
- *Xie et al., 2016, PNAS 113, 11431*
- *Mulders et al., 2016, AJ 152, 187*
- *Murphy et al., 2016, ApJL 827, L17*
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- *Chang et al., 2017, ApJ 834, 92*
- *Wu et al., 2017, RAA 17, 5*
- *Smalley et al., 2017, MNRAS 465, 2662*

- $[Fe/H]_{KIC} = -0.20 + 0.43[Fe/H]_{LAMOST}$

  LAMOST metallicities of 12,000 stars

  - *scatter ~0.25 dex*
  - *valid for $-0.3 < [Fe/H]_{LAMOST} < +0.4$*

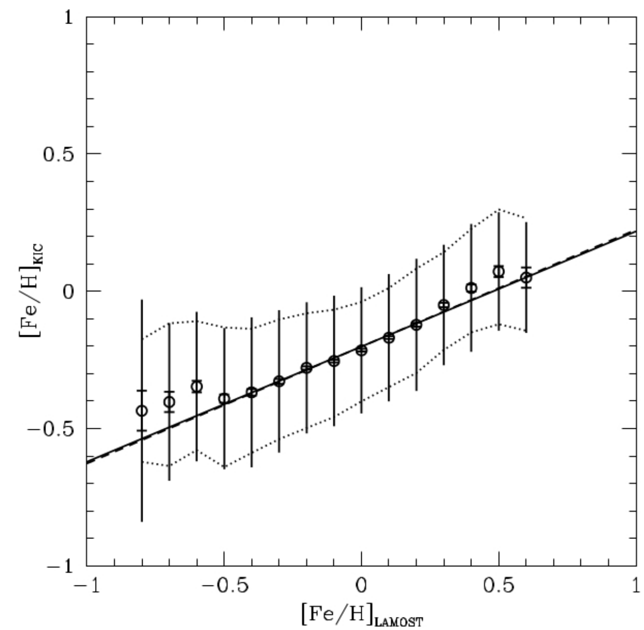

Figure 1. *Kepler* star metallicities as determined by KIC as a function of LAMOST spectroscopic metallicity. Outer error bars show standard deviations and inner error bars show standard errors of the mean. Dotted lines enclose the central 68.3% of the distribution. Solid line is fit to all the data, while dashed line removes the bins <200 stars. The remaining bins also coincide with the parameter regime where calibrations of LAMOST [Fe/H] with high-resolution spectroscopic [Fe/H] determinations are available ($-0.4 \lesssim [Fe/H]_{LAMOST} \lesssim +0.4$). They are essentially the same. The zero-point and slope are both detected at high significance, -0.203 ± 0.002 and 0.434 ± 0.011, respectively.

Other teams

Refereed papers

- *Dong et al., 2014, ApJL 789, L3*
- *Deheuvels et al., 2014, A&A 564, A27*
- *Liu et al. 2015, ApJ 807, 4*
- *Bostancı et al., 2015, MNRAS 453, 1095*
- *Chen et al., 2015, RAA 15, 1125*
- *Guzik et al., 2015, AstRv 11, 1*
- *Huang et al., 2015, RAA 15, 1240*
- *Xiang et al., 2015, RAA 15, 1209*
- *Ren et al., 2016, RAA 16, 45*
- *Yu et al., 2016, MNRAS 463, 1297*
- *Wang et al., 2016, AJ 152, 6*
- *Zhang et al., 2016, ApJL 821, 32*
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- *Xie et al., 2016, PNAS 113, 11431*
- *Mulders et al., 2016, AJ 152, 187*
- *Murphy et al., 2016, ApJL 827, L17*
- *Zhu et al., 2016, ApJ 832, 196*
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- *Wu et al., 2017, RAA 17, 5*
- *Smalley et al., 2017, MNRAS 465, 2662*
- *Guo et al., 2017, ApJ 838, 25*

- *estimation of core rotation rates and upper limits to rotation in convective envelope for 6 Kepler subgiants and young red giants*
  - *LAMOST stellar parameters of 1 star*
  - *rotation contrast between core and envelope increases during subgiant branch*
  - *evidence for spin up of core of subgiants with time, while their envelope spins down*

- *Qian et al., 2018, ApJS 235, 5*
- *Qian et al., 2018, MNRAS 475, 478*
- *Vickers & Smith, 2018, ApJ 860, 91*
- *Wang et al., 2018, ApJ 860, 136*
- *Zhang et al., 2018, ApJ 854, 168*
- *Zhu et al., 2018, ApJ 860, 101*

Other teams

Refereed papers

- ★ Dong et al., 2014, ApJL 789, L3
- ★ Deheuvels et al., 2014, A&A 564, A27
- ★ Liu et al. 2015, ApJ 807, 4
- ★ Bostancı et al., 2015, MNRAS 453, 1095 →
- ★ Chen et al., 2015, RAA 15, 1125
- ★ Guzik et al., 2015, AstRv 11, 1
- ★ Huang et al., 2015, RAA 15, 1240
- ★ Xiang et al., 2015, RAA 15, 1209
- ★ Ren et al., 2016, RAA 16, 45
- ★ Yu et al., 2016, MNRAS 463, 1297
- ★ Wang et al., 2016, AJ 152, 6
- ★ Zhang et al., 2016, ApJL 821, 32
- ★ Karoff et al., 2016, Nat Com 7, 11058
- ★ Xie et al., 2016, PNAS 113, 11431
- ★ Mulders et al., 2016, AJ 152, 187
- ★ Murphy et al., 2016, ApJL 827, L17
- ★ Zhu et al., 2016, ApJ 832, 196
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- ★ Zhu et al., 2018, ApJ 860, 101

- comprehensive study of open cluster NGC 6866
  - LAMOST stellar parameters of 31 F- and G-type stars in cluster
  - [Fe/H] = −0.10 ± 0.13 dex
  - v_{rad} = 10.58 ± 31.83 km/s

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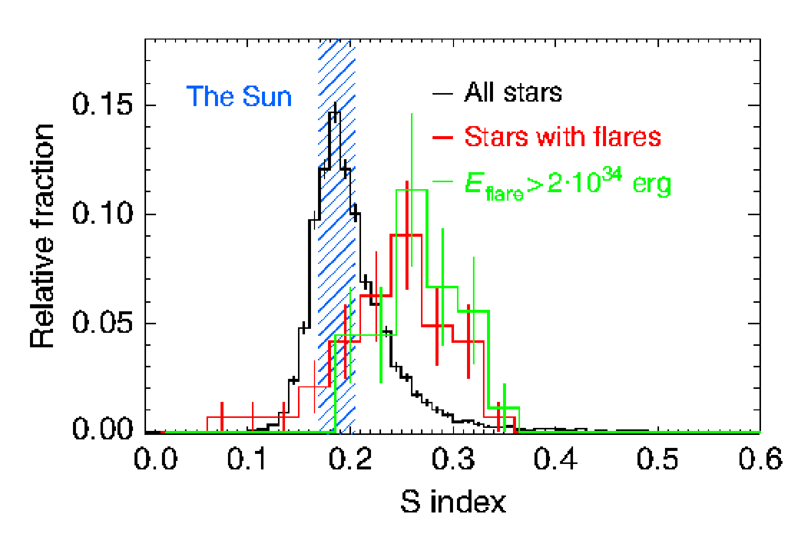
- Chang et al., 2017, ApJ 834, 92
- Wu et al., 2017, RAA 17, 5
- Smalley et al., 2017, MNRAS 465, 2662

- *observational evidence for enhanced magnetic activity of superflare stars*
  - *analysis of 5,648 LAMOST spectra of solar-like stars, including 48 superflare stars*
  - *superflare stars have larger chromospheric emission than others*
  - *superflare stars with activity levels lower than Sun exist*

  ⇒ *solar flares and superflares same origine?*



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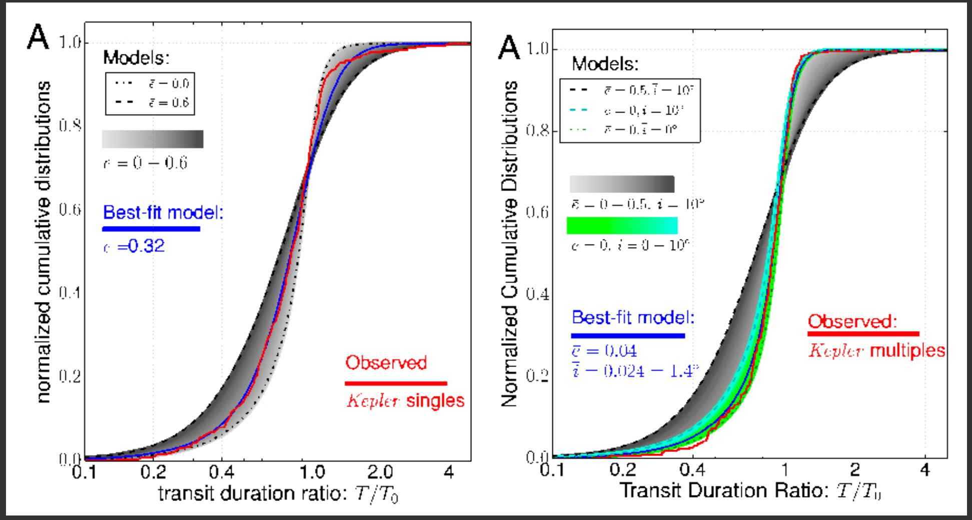
- *Yang et al., 2017, ApJ 849, 36*
- *Xiang et al., 2017, MNRAS 464, 3657*
- *Xiang et al., 2017, ApJS 232, 2*

- *exoplanet orbital eccentricities*
  - *LAMOST stellar parameters of 698 Kepler planet host stars*
  - *singles are on eccentric orbits (e≈0.3)*
  - *multiples are on nearly circular and coplanar orbits (cf. solar system)*



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- Guo et al., 2017, ApJ 838, 25

- pulsation versus metallicism in Am stars revealed by LAMOST and WASP
  - LAMOST spectral types of 30,282 A-type to early F-type stars & 67 Am stars in LAMOST DR1
  - δSct pulsations in Am stars are mostly confined to $6900 < T_{eff} < 7600$ K
  - incidence of pulsations in Am stars decreases with increasing degree of chemical peculiarity
  - maximum amplitude of pulsations in Am stars does not appear to vary significantly with metallicism
  - amplitude distributions of principal pulsation frequencies for A and Am appear very similar
  - evidence that suggests turbulent pressure is main driving mechanism in pulsating Am stars

Other teams

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- *Ren et al., 2016, RAA 16, 45*

> - *multi-technique investigation of binary fraction of A-F type candidate hybrid variable stars discovered by Kepler*
>   - *LAMOST T_{eff} of 22 A-F stars*
>   - *high-resolution HERMES and ACE spectra of 50 A-F stars*
>   - *orbital solutions for 7 new systems*
>   - *multiplicity fraction of ~27%*

- *Wu et al., 2017, RAA 17, 5*
- *Smalley et al., 2017, MNRAS 465, 2662*
- *Guo et al., 2017, ApJ 838, 25*
- *Mathur et al., 2017, ApJS 229, 30*
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- *Xiang et al., 2017, MNRAS 464, 3657*
- *Xiang et al., 2017, ApJS 232, 2*
- *Petigura et al., 2017, AJ 154, 107*
- *Balona et al., 2018, MNRAS 476, 4840*
- *Petigura et al., 2018, AJ 155, 89*
- *Hümmerich et al., 2018, A&A 619, A98*
- ← *Lampens et al., 2018, A&A 610, A17*
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Other teams

Proceeding papers

- *Molenda-Żakowicz et al., 2014, IAUS 301, 457*
- *Molenda-Żakowicz et al., 2015, IAUGA 225, 0365*
- *Fu et al., 2015, IAUGA 225, 5363*
- *De Cat et al., 2015, EPJWC 101, 01011*
- *Molenda-Żakowicz et al., 2016, IAUFM 29B, 514*
- *Fu et al., 2016, IAUFM 29B, 686*
- *Molenda-Żakowicz et al., 2016, pas conf, 59*
- *Fu et al., 2017, AAS 229, 305.02*
- *Molenda-Żakowicz et al., 2017, EPJWC 152, 04002*

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Proceeding papers

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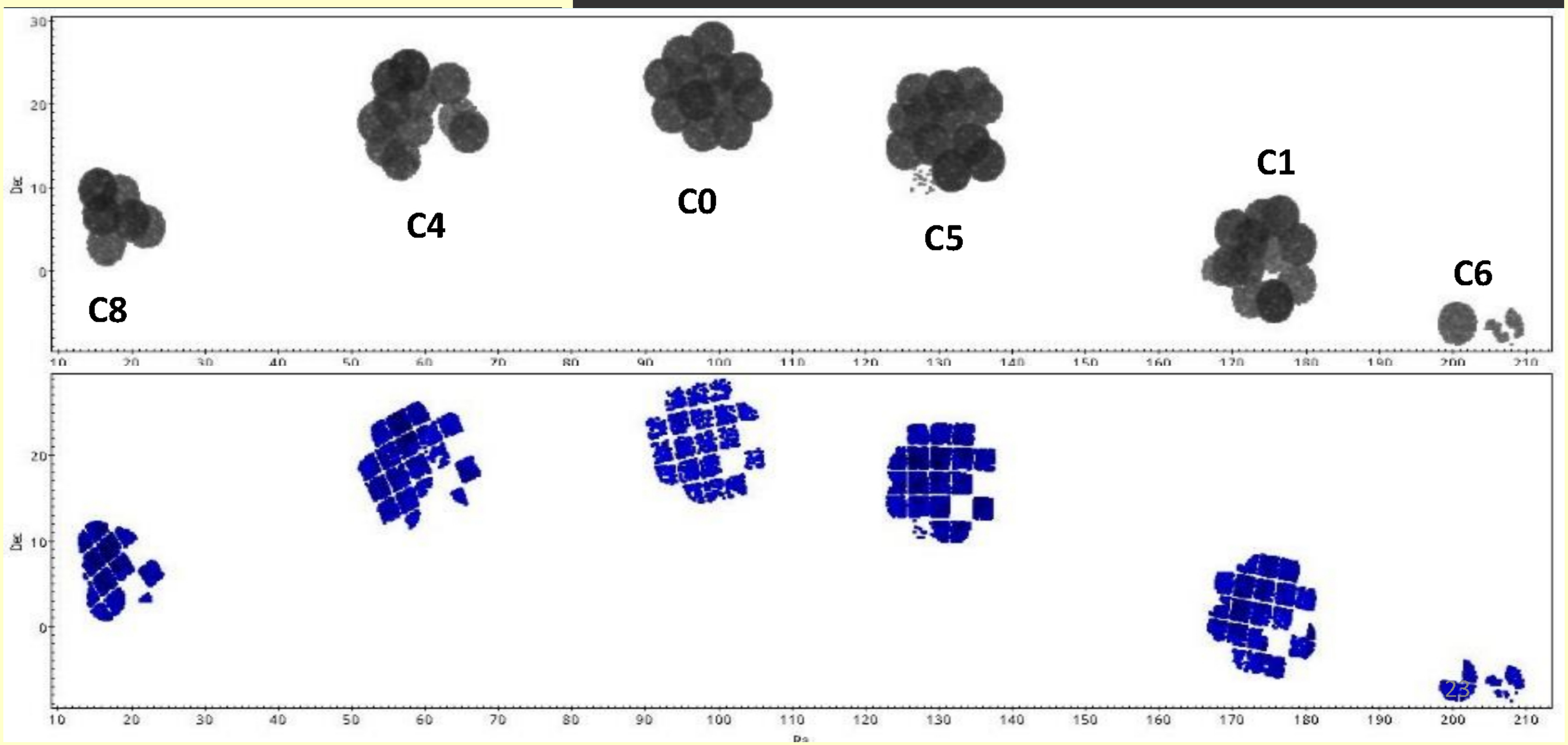
- Molenda-Żakowicz et al., 2015, IAUGA 225, 0365
- Fu et al., 2015, IAUGA 225, 5363
- De Cat et al., 2015, EPJWC 101, 01011
- Molenda-Żakowicz et al., 2016, IAUFM 29B, 514
- Fu et al., 2016, IAUFM 29B, 686
- Molenda-Żakowicz et al., 2016, pas conf, 59
- Fu et al., 2017, AAS 229, 305.02 → LAMOST observations in the K2 fields
- Molenda-Żako



Future prospects

Future prospects

Medium resolution LAMOST spectra

- *495 – 535 nm & 630 – 680 nm*
- *V < 15 mag*
- *R ~ 7500*
  - *improvement of accuracy*
  - *abundances of individual elements*

Mulitple observations of plates

- *Time-series analysis*
- *radial velocity variations (binaries, pulsations, rotation)*

Ground-based follow-up for space missions

- *ongoing: K2 (Fu, Smith, et al.)*
- *future: TESS, PLATO,...*

The LAMOST-Kepler project

Past, present and future

Lamost Observations in the Keplerfield

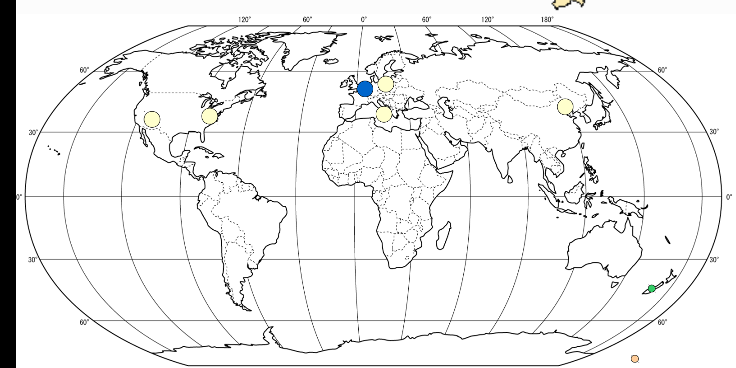
Peter De Cat

Royal Observatory of Belgium
Ringlaan 3
1180 Brussels
Belgium

&

LAMOST-Kepler consortium

J.N. Fu, et al. (BNU, Beijing, China)
Shi J.R., Luo A.L., Zhang H.T., et al. (NAOC, Beijing, China)
A. Frasca, G. Catanzaro (INAF, Catania, Italy)
J. Molenda- Żakowicz (University of Wrocław, Wrocław, Poland)
R. O. Gray (Appalachian State University, Boone, North Carolina, USA)
C. J. Corbally (Steward Observatory, Tucson, Arizona, USA)



Take away messages

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LAMOST is an excellent tool

- *for a homogeneous spectroscopic determination of basic stellar parameters* *($T_{\rm eff}$, log$g$, metallicity, $v_{\rm rad}$, $v$sin$i$)*
  - *in an efficient way*
  - *for fainter objects than most ground-based facilities (4-m telescope)*
- *for the detection of astrophysically interesting objects*
- *for follow-up observations of space missions*
  - *e.g. Kepler/K2 (past), TESS (present), PLATO (future)*

Kepler field is an excellent tool

- *for validation/calibration of LAMOST results*
  - *KIC*
  - *APOGEE*
  - *individual objects*

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THANK YOU!