Discovery of starspots on Vega

First spectroscopic detection of surface structures on a normal A-type star

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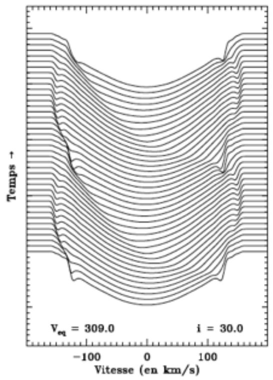
Rotation, pulsation and magnetism of standard A type stars

Our understanding of A-type stars until 2009:

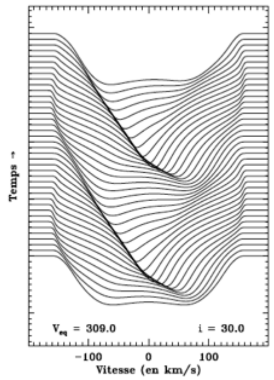
Radiative envelopes:

- **no magnetic field generation**
- **no surface structures**

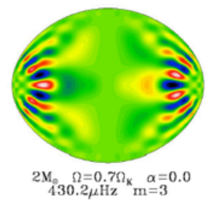
Meridian cut:



Complet



Perturbatif

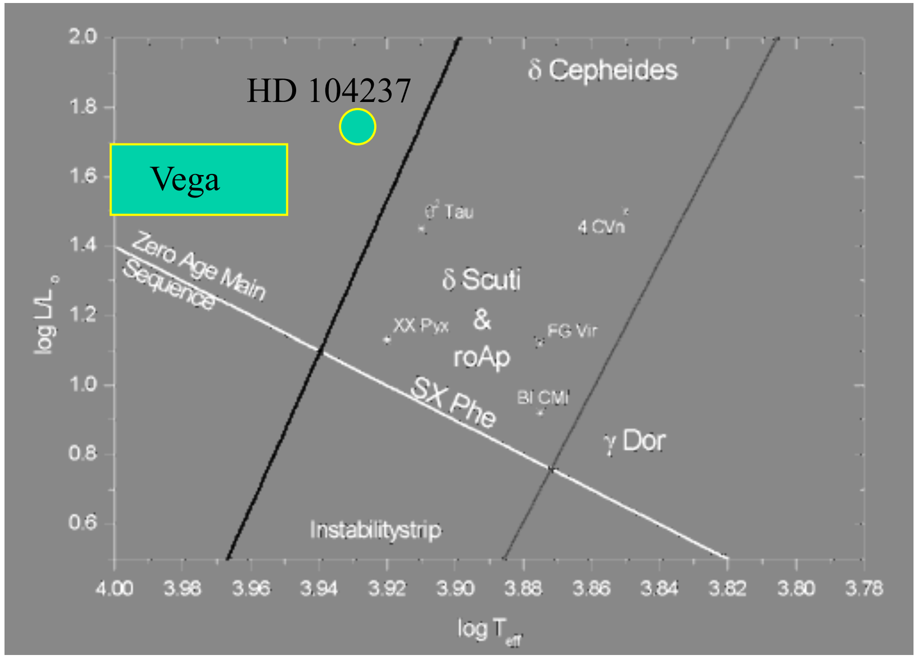


$(\tilde{n}, \tilde{\ell}, m) = (12, 0, 3)$

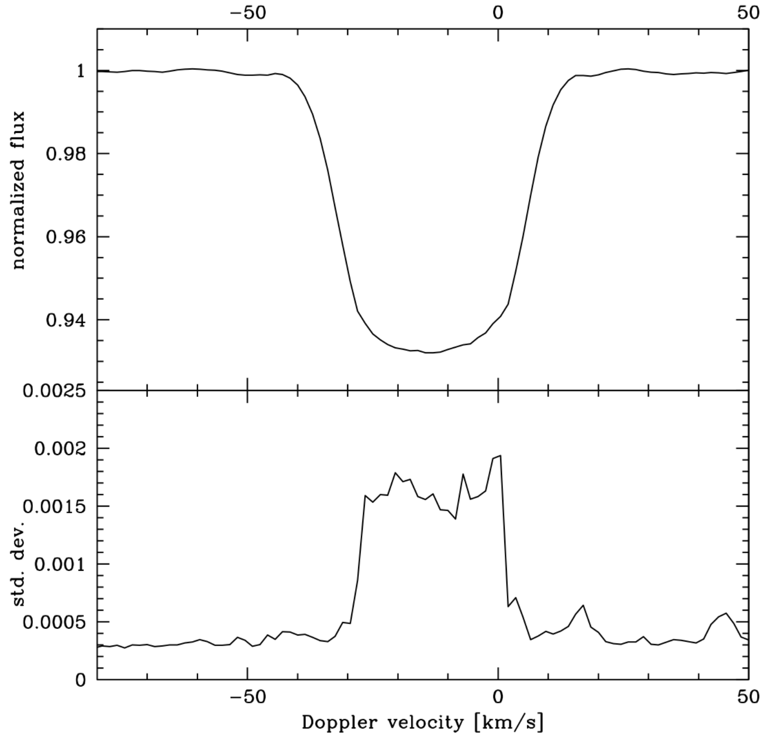
The “Vega” Project:

- search for stellar oscillations in rapidly rotating A stars – new theoretical approach
- search for weak magnetic fields in standard A-type stars
- velocimetry: are there signs of activity, rotational modulation?

Is Vega the ideal candidate? …



Vega is bluewards the δ Scuti instability strip…



Sophie/OHP data set (2012)
Signs of variations in equivalent photospheric profiles

Bright, rapidly rotating standard A-type star

Takeda's best fit model (Takeda et al. 2008, ApJ, 678, 446): :

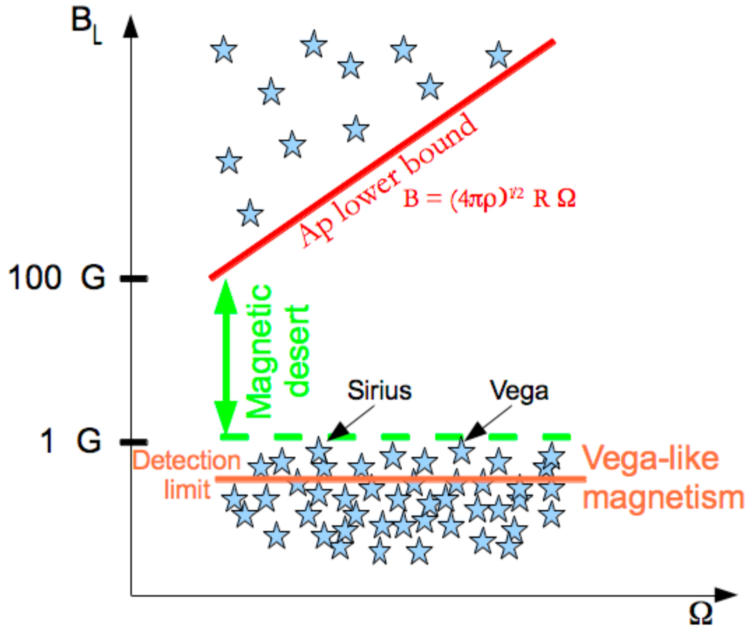
Model No.	v_e (km s^{-1})	Ω	i (deg)	R ($R_\odot$)	θ (mas)	log g (cm s^{-2})	T_{eff} (K)	
4................	175	0.44	7.2	2.520	3.308	3.997	9867	← Pole
				2.763	3.313	3.823	8931	← Equator

M ≈ 2.3 Msol

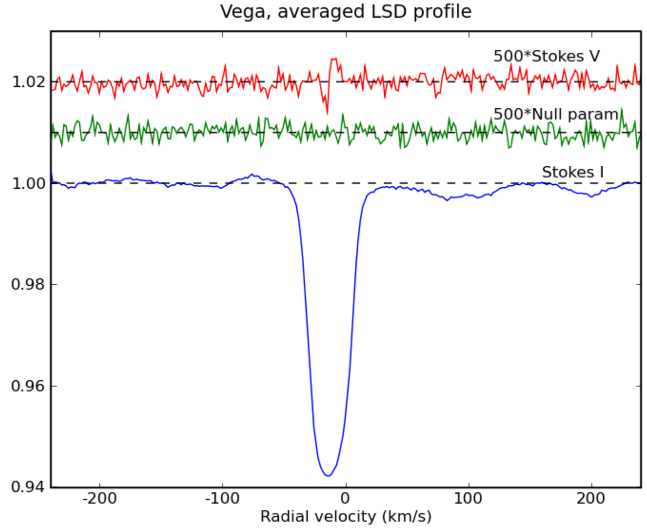
High resolution spectroscopy of Vega…
… the beginning

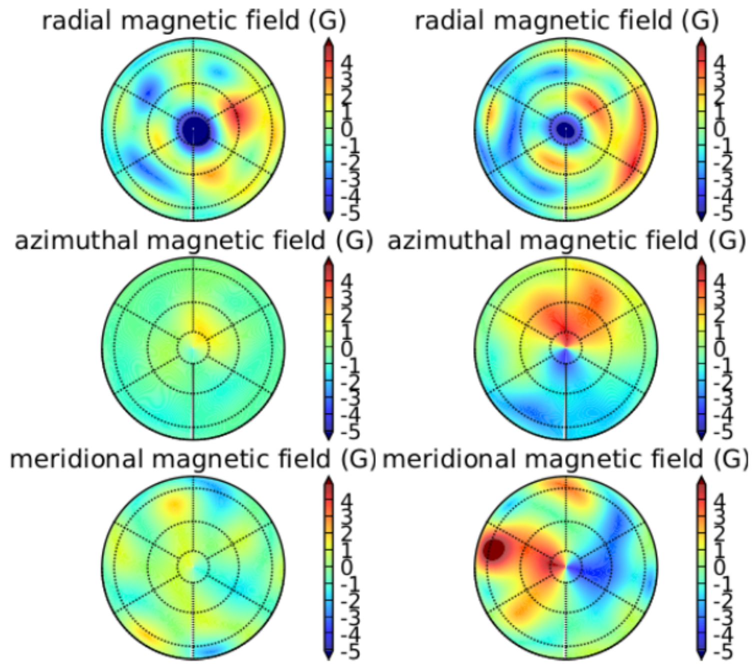
- 4500 polarimetric spectra
  (3 nights NARVAL/TBL 2008 - 3 nights ESPADONS/CFHT 2009 - 5 nights TBL 2010)
- Spectral resolution of R = 65000 - 75000 (depending on the instrument)
- very short exposure times: 4 - 13 seconds
- ESPADONS/NARVAL in Polarimetric mode (discovery of a weak magnetic field)
  - (Lignières et al., 2009, A&A 500, L41)
- Data reduction with ESPRIT software and LSD profile calculation (Donati, 1997)
- Telluric lines used for radial velocity calibration (precision close to 5-10 m/s)

Discovery of a new class of magnetic A type stars: "Vega-like"



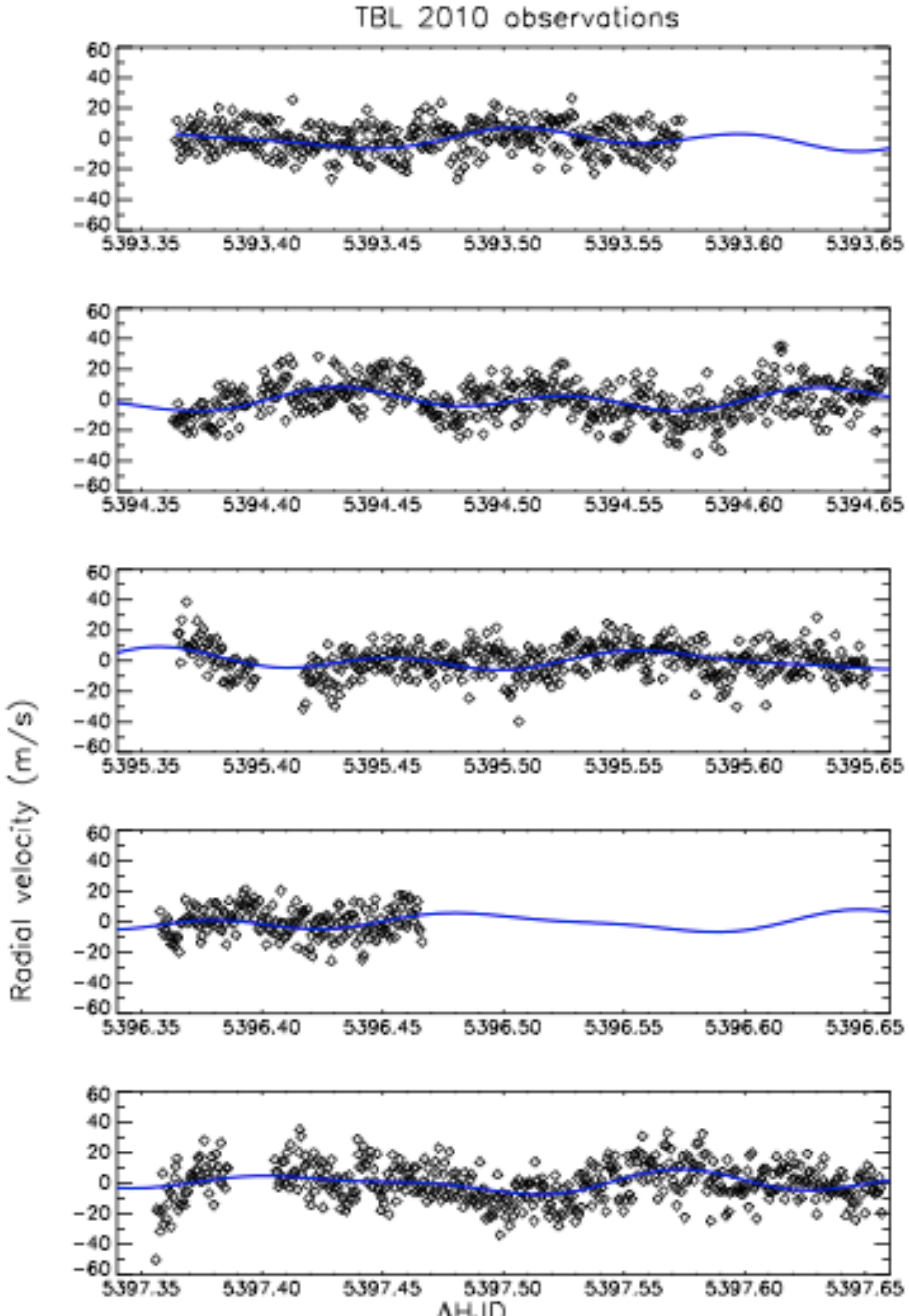
- B = - 0.6 +/- 0.3 G disk averaged line of sight component of the surface magnetic field
- Maximum B (spots) = 7G



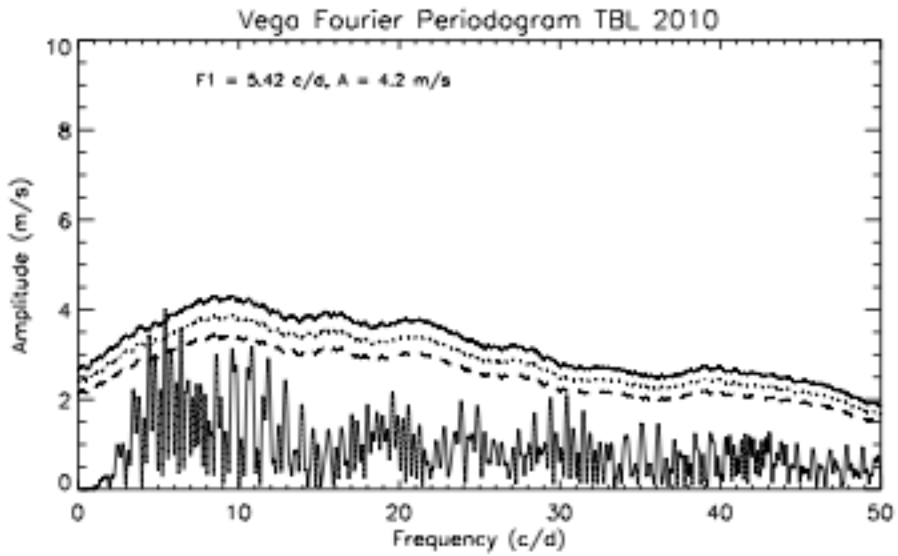


2008 2009

Ultrafaint pulsation signatures in a rapid rotator? Result of a high-res spectroscopic analysis of 4500 spectra



radial velocity variations



ID	freq. d^{-1}	A $m\,s^{-1}$
$F1_{2008}$	9.19	5.8
$F2_{2008}$	5.32	5.9
$F1_{2009}$	12.71	7.3
$F2_{2009}$	13.25	7.6
$F1_{2010}$	5.42	4.2
$F2_{2010}$	10.82	3.3

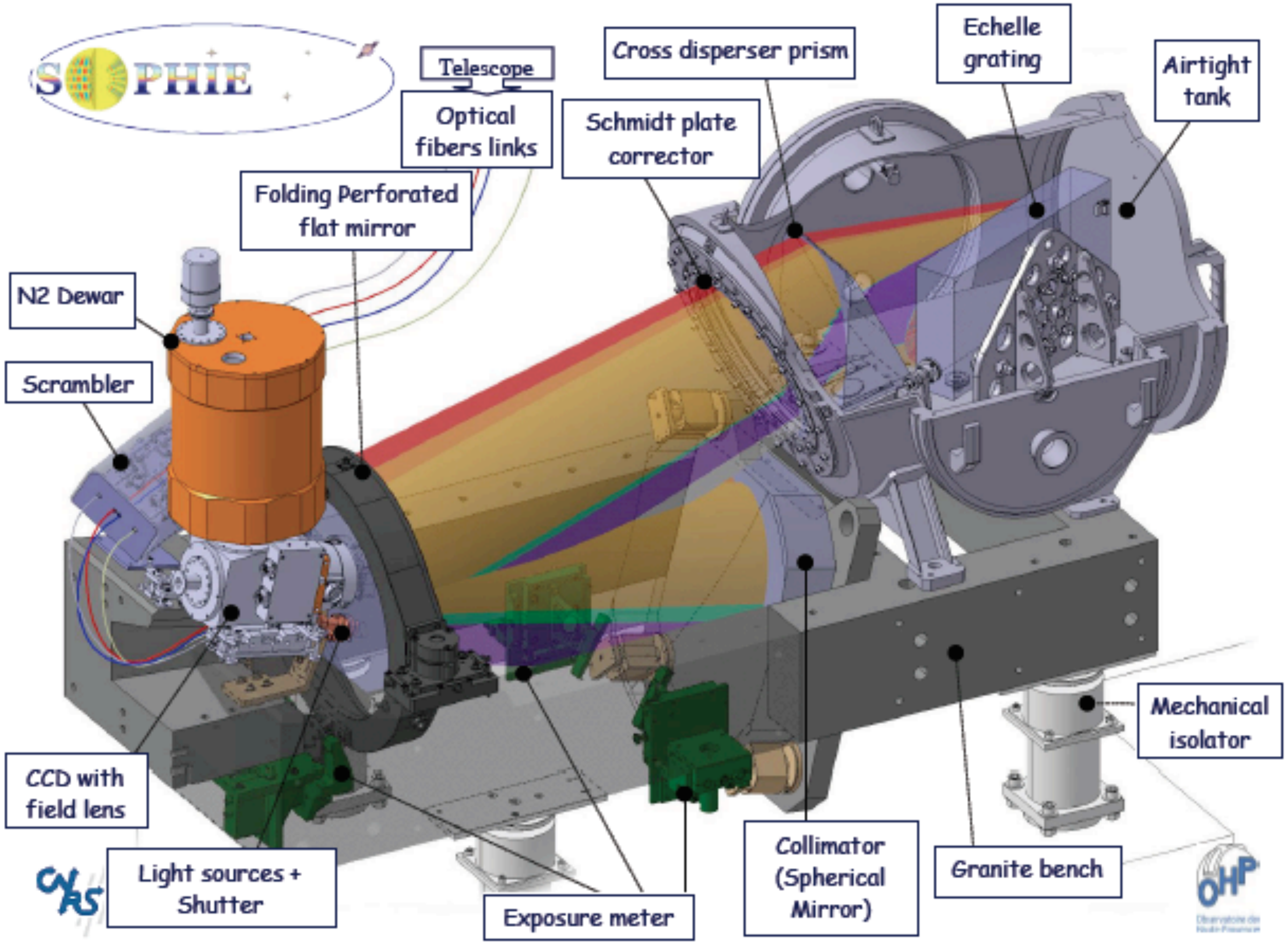
(Böhm et al. 2012)

Search for line profile variations in Vega

- First indications for pulsations inVega (CFHT, TBL, 4500 spectra in 2008,9,10)
- spectrographs Narval/TBL and Espadons/CFHT unstable – no access to low frequencies
- indications of some higher frequencies– pulsations?
- Vega needed to be re-observed with a stable instrument – SOPHIE/OHP

Need for observations in high precision velocimetry…

- 5 nights with SOPHIE/OHP August 2012 (2600 spectra)
- Intrinsic stability of 2 m/s
- High resolution echelle spectrograph



High-resolution velocimetry with SOPHIE/OHP 2012

Date (1)	BJD_{first} (2)	BJD_{last} (3)	N_{spec} (4)	t_{exp} (sec) (5)	t_{cov} (hrs) (6)	S/N (7)
Aug. 2 2012	6142.3308	6142.6238	425	17-30	7.0	884±202
Aug. 3 2012	6143.3528	6143.6436	629	10-15	7.0	925±145
Aug. 4 2012	6144.3412	6144.6423	628	10-17	7.2	850±121
Aug. 5 2012	6145.3788	6145.6442	402	13-17	6.4	766±103
Aug. 6 2012	6146.3444	6146.6423	504	17-25	7.1	808±115

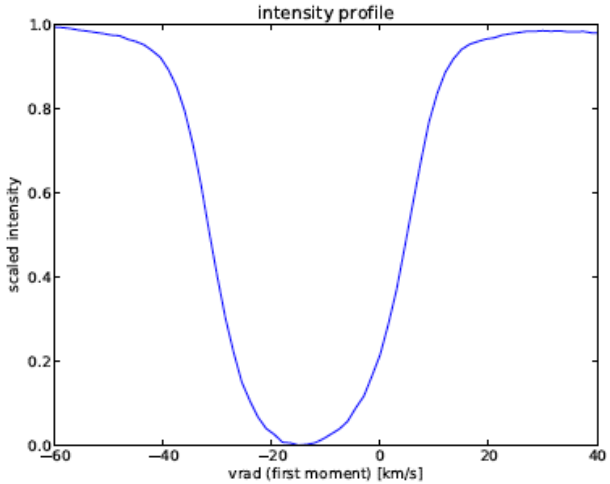
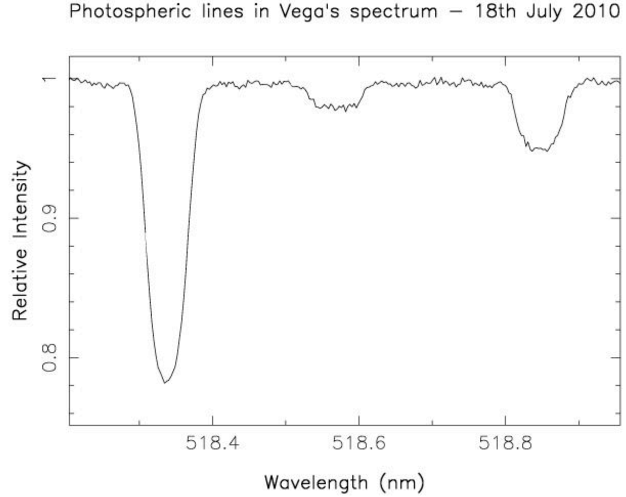
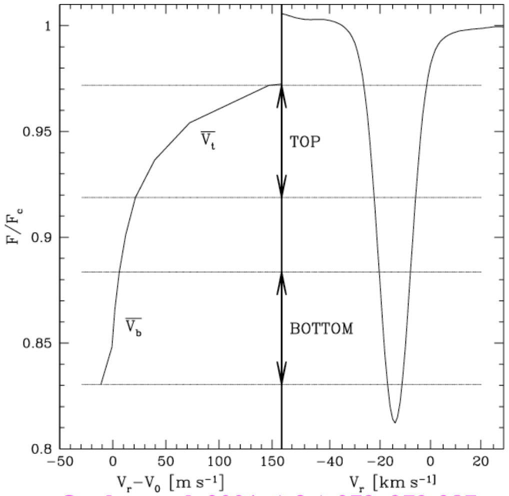


Fig. 1. mean equivalent photospheric (LSD) profile of Vega, stronger lines only, rescaled in depth.

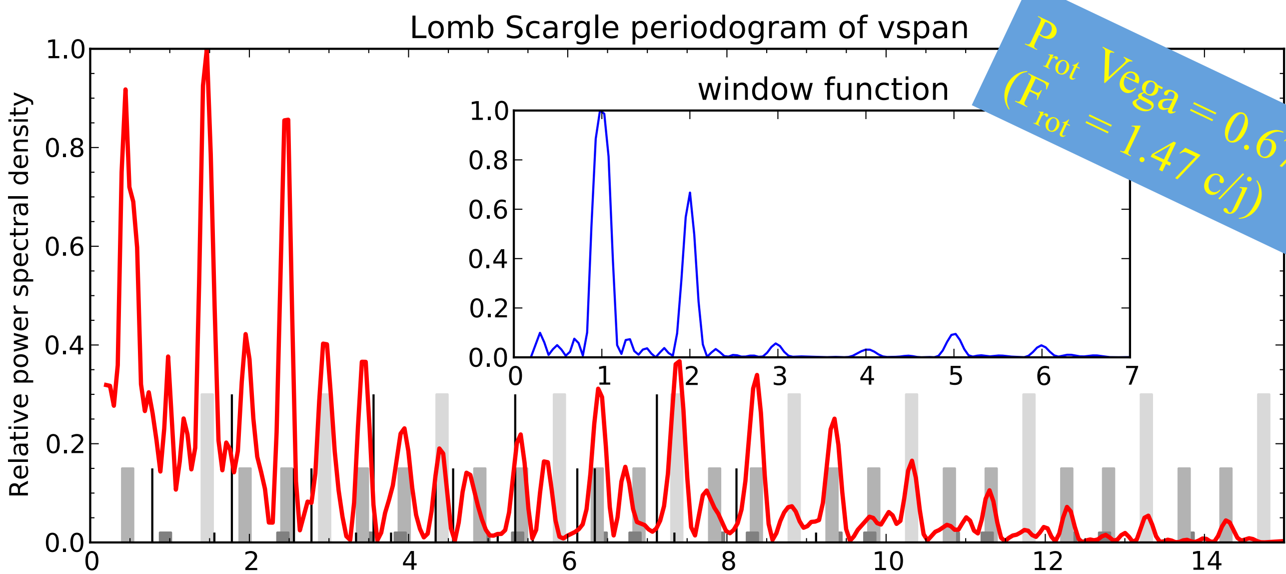


- Line selection above certain threshold (gravitational darkening)
- Esprit data reduction pipeline (Donati). Calculation of LSD profiles.
- Calculation of bisectors, radial velocities, vspan, moments, correlations…
- Search for periodicities, Lomb Scargle analysis, Multi-sine leastsquare fitting, 2D methods

Vspan - bisector analysis

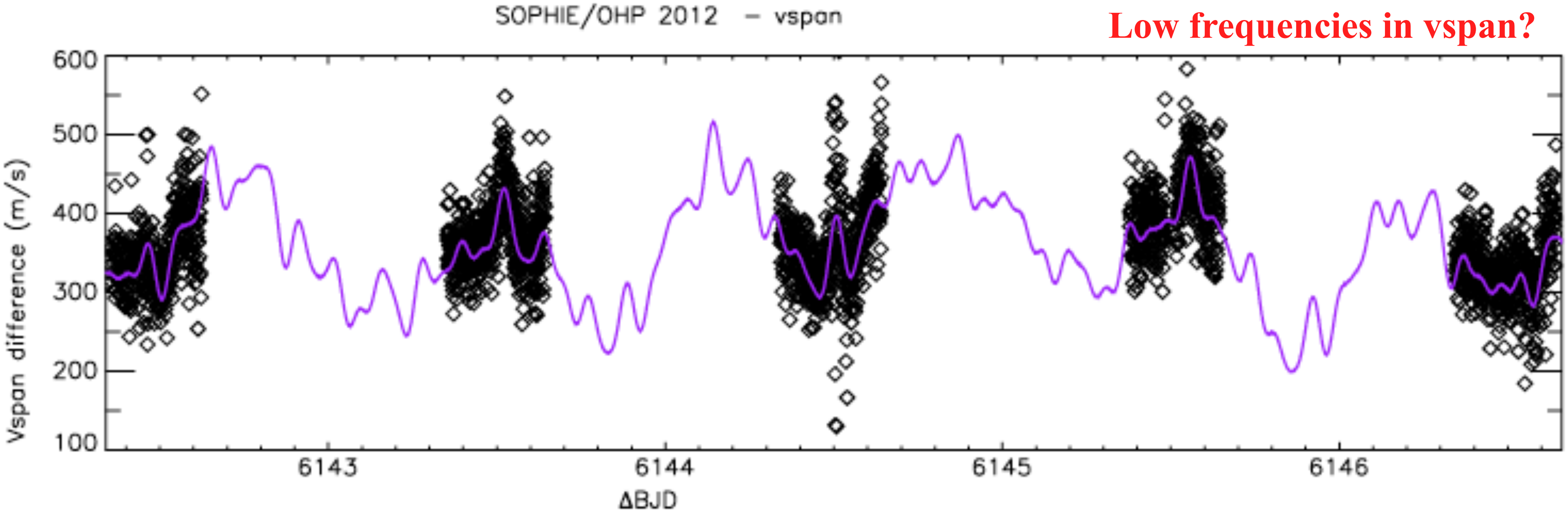


Queloz et al. 2001, A&A 379, 279-287

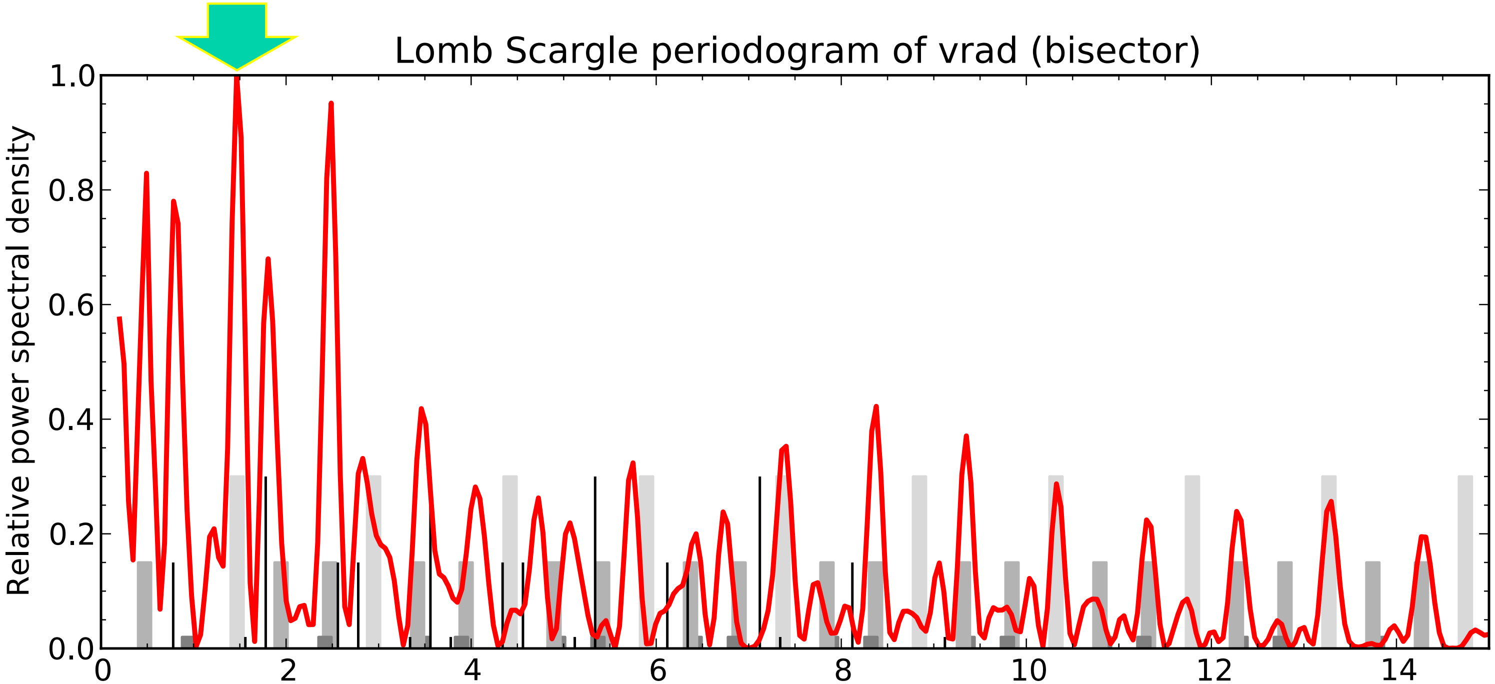


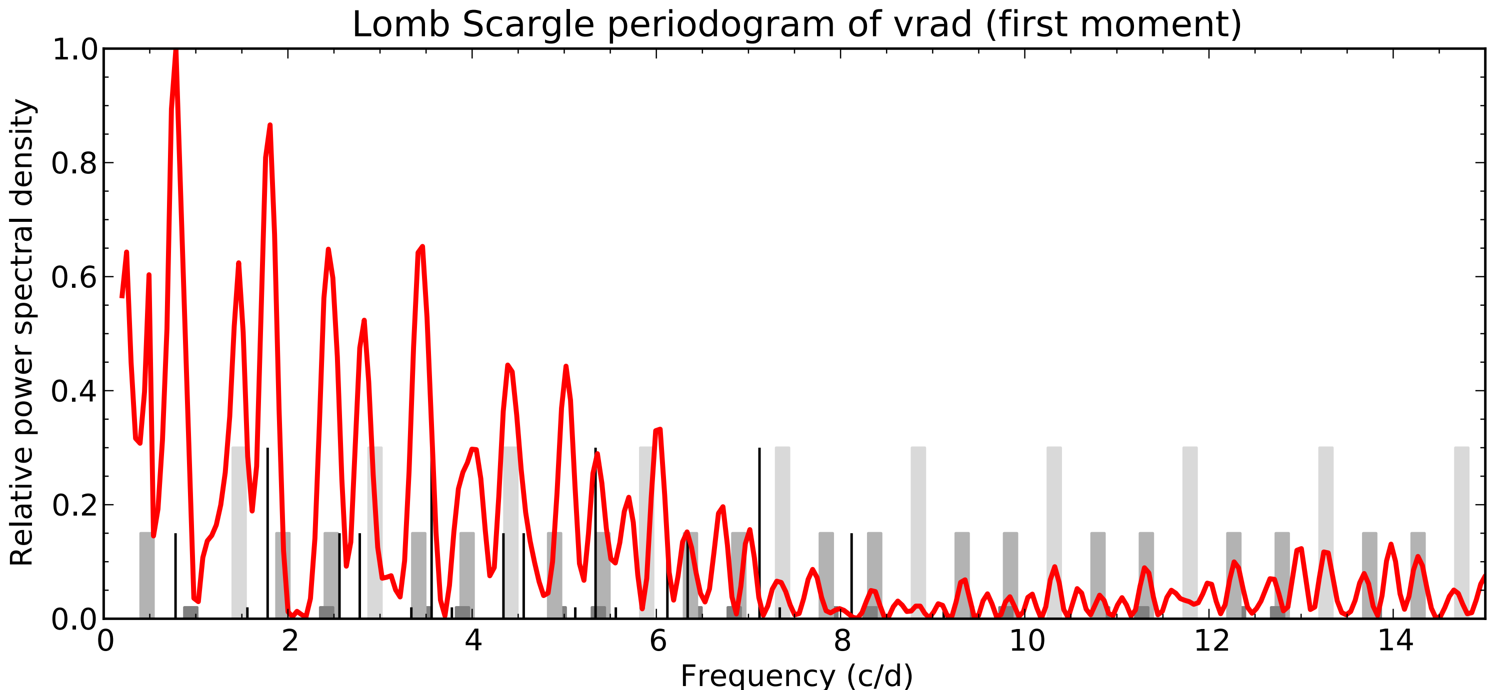
P_{rot} Vega = 0.678j
(F_{rot} = 1.47 c/j)

Low frequencies in vspan?



Radial velocity - different estimators



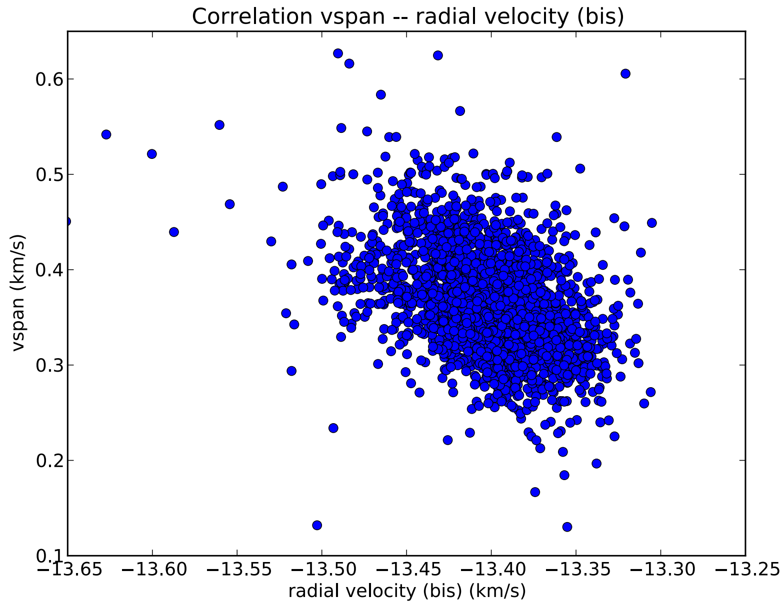


Rotational modulation!
Indications of a structured surface?

vspan

ID	freq. d^{-1}	A $m\,s^{-1}$	Comment
F1	1.457	69.32	F_{rot}
F2	2.02	22.93	2 F_{rot}-1.
F3	0.40	47.52	
F4	8.34	13.30	5 F_{rot} + 1.
F5	11.31	14.17	7 F_{rot} + 1.
F6	5.78	14.09	4 F_{rot}
F7	8.04	12.59	
F8	16.21	8.23	11 F_{rot}
F9	5.43	9.05	3 F_{rot}+1
F10	10.70	8.92	9 F_{rot}-1

Anticorrelation vspan - vrad



Vrad_first moment

ID	freq. d^{-1}	A $m\,s^{-1}$	Comment
F1c -1	0.77	6.16	F1c = 1.77
F2c	3.34	4.32	3F_{rot} - 1? $F2_{2008}$ -2 ? $F1_{2010}$ -2 ?
F3c	4.97	3.78	4F_{rot} - 1?
F4c	1.48	4.01	F_{rot}
F5c	24.47	2.17	16F_{rot} + 1?
F6c	14.24	2.42	$F2_{2009}$ +1 ?
F7c	8.29	2.12	5F_{rot} + 1?
F8c	5.53	2.30	
F9c	11.78	2.61	$F1_{2009}$ -1 ? $F2_{2010}$ +1 ?
F10c	14.67	2.68	10F_{rot}

Radial velocity variations induced by a starspot on Vega

60°

8°

0°

-6°

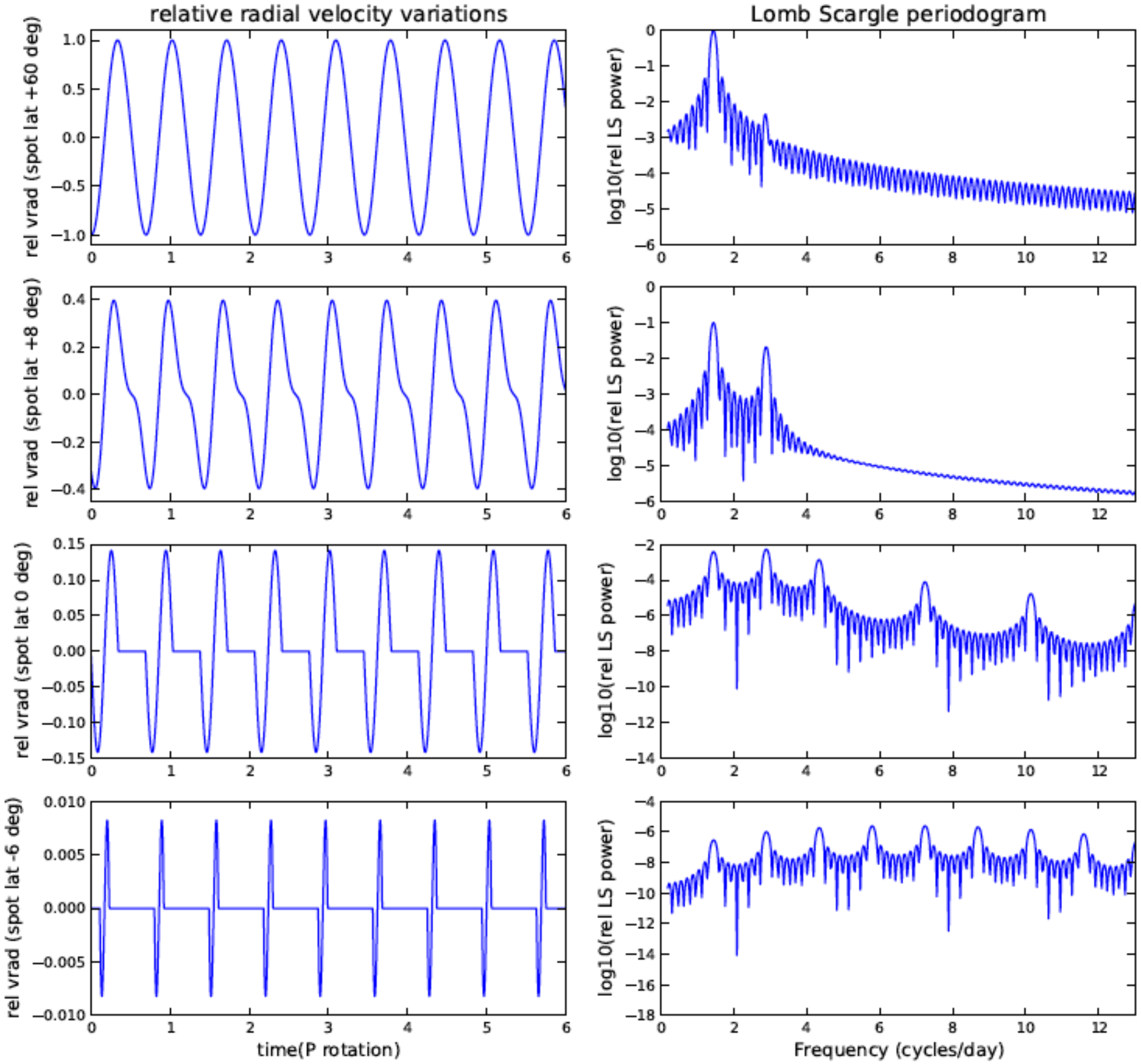


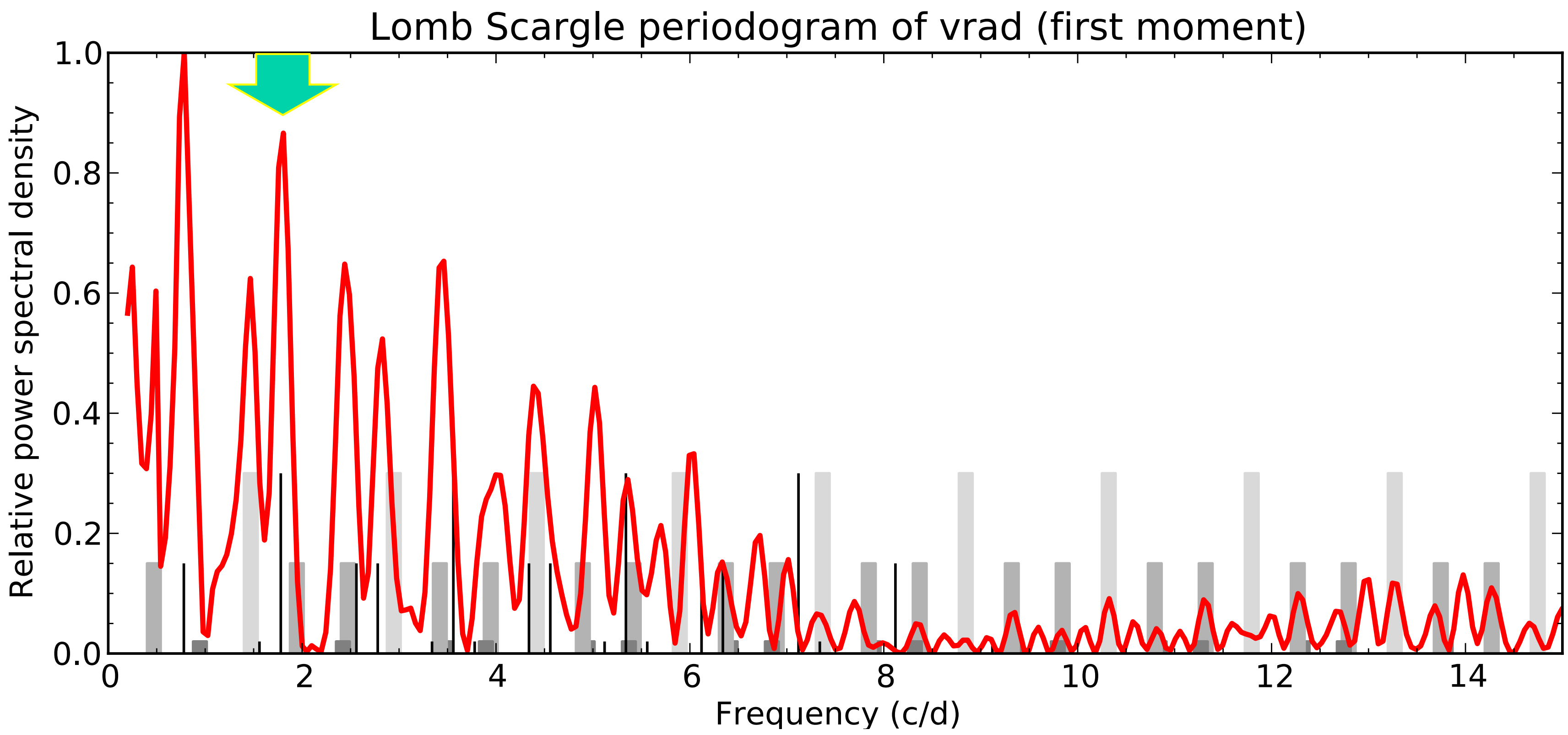
Fig. 5. Simulation of the relative radial velocity variations induced by a spot (of same size) located at latitude (figures left, top to bottom): +60°, +8°, 0° and -6° for Vega (inclination angle i= 7° (the star is seen almost pole-on). Figures right, top to bottom show the respective Lomb Scargle periodograms. The spot position at latitude +60° is taken as the reference with respect to the radial velocity and Lomb Scargle power spectrum amplitude.

Presence of an exoplanet (F = 1.77 c/j) ?

Preliminary analysis

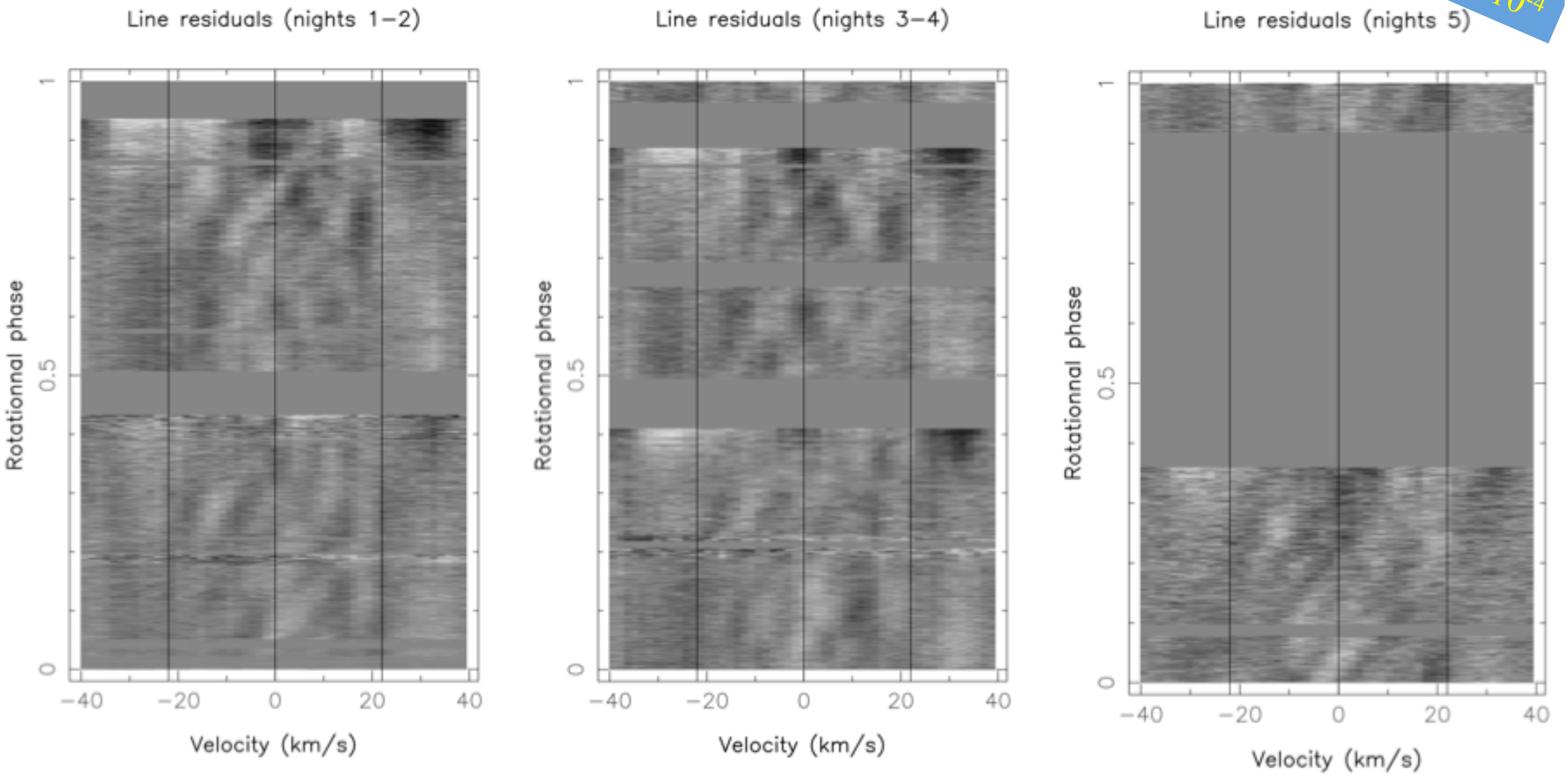
An additional frequency is seen in the Lomb Scargle periodicity analysis of Vrad!

- close to jupiter mass
- $R_{orbit} \sim 1.36\ R_{vega}$
- close to co-rotation radius
- Exoplanet migration?

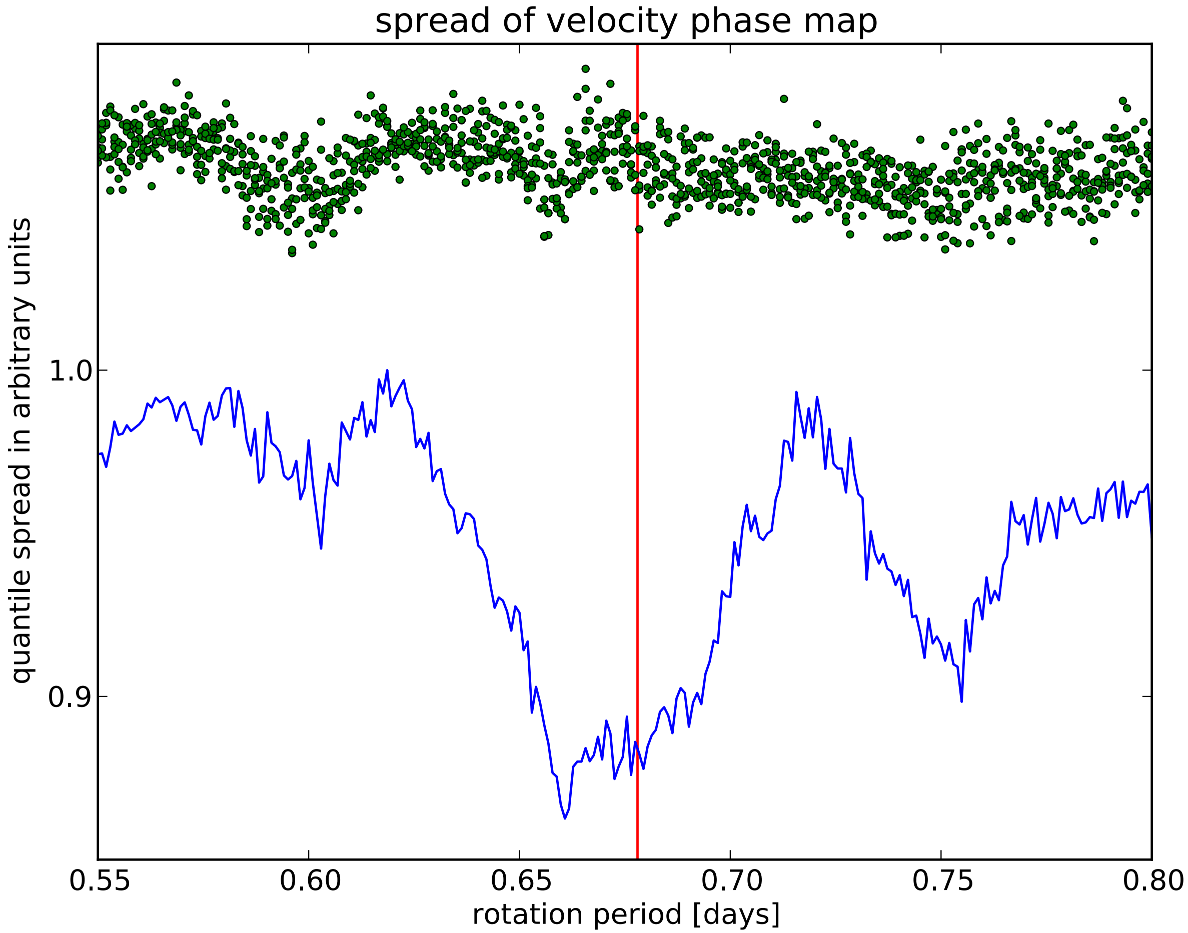


Vega's surface is indeed structured!
…an A star should not show this structure…

$\Delta F/Fc < 7\ 10^{-4}$



Minimum dispersion with Vega's rotation period of 0.678d



…after a tough refereeing process…

First referee A&A:

« If this finding is real, we would have to make a fundamental review
on the nature of superficially normal A stars »

...press releases

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Détection de taches sur la surface de l'étoile de masse intermédiaire Vega

Mercredi, 6 mai 2015

Pour la première fois une équipe internationale de scientifiques a pu mettre en évidence l'existence de taches sur la surface de l'étoile de masse intermédiaire Vega. Ce résultat inattendu amène de nouvelles

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ASTRONOMY

Spots spotted on Vega star

Nature **521**, 262 (21 May 2015) | doi:10.1038/521262b
Published online 20 May 2015

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Issue	A&A **Volume** 577, May 2015
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Number of page(s)	12
Section	Stellar structure and evolution
DOI	http://dx.doi.org/10.1051/0004-6361/201425425
Published online	06 May 2015

A&A 577, A64 (2015)

Discovery of starspots on Vega
First spectroscopic detection of surface structures on a normal A-type star

Pulsation, magnetism and rotation of intermediate mass stars

What is the role of stellar rotation and magnetism in stellar evolution?

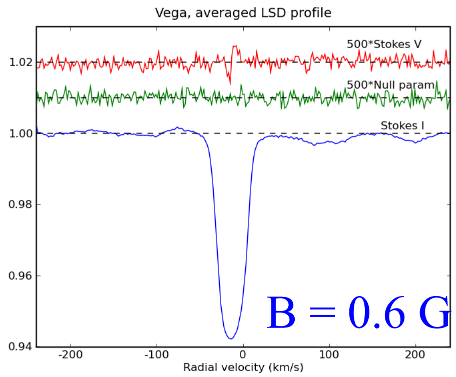
Our recent work on Vega:

7000 spectra

- Spectro-polarimetric and velocimetric obserations of Vega
  (4500 spectra NARVAL/TBL and ESPADONS/CFHT (2008-10)
- **Discovery and confirmation of a new class of weakly magnetic A type stars**
  INSU/CNRS press release; Lignières, Petit, Böhm & Aurière, 2009
- **Strong indications for stellar pulsations in Vega** **Böhm et al., 2012**
- (initial data set + 2500 SOPHIE/OHP spectra)
- **Solving a long-term « fight »:** spectroscopy – interferometry on the rotation period of Vega: $P_{rot} = 0.69$ j **Böhm et al., 2015**

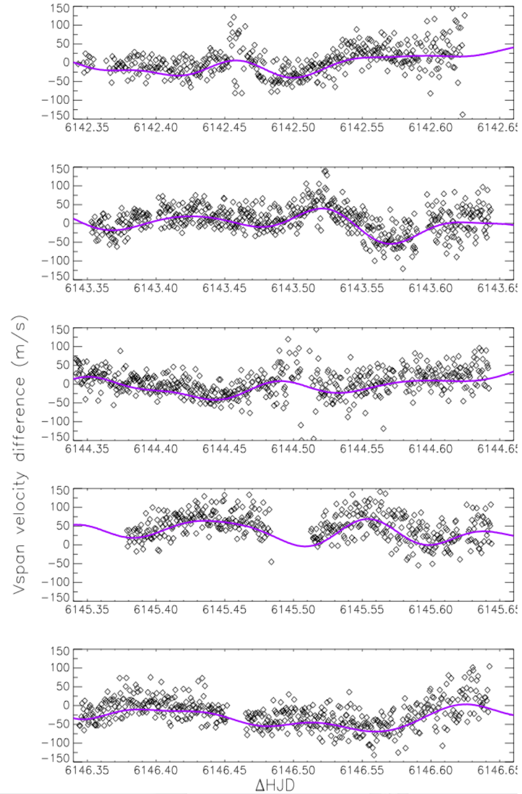
Hypothesis: all intermediate mass stars show stellar oscillations and magnetic fields, it's only a matter of scale/amplitude!

Böhm 2012



Vega

Oscillations



Vega is "active" - and the others?

- What is the implication on the magnetic fields of intermediate mass stars?
- DI - ZDI What is the link between active plages and magnetic field regions?
- What is the origin of the magnetic field of "normal" A-type stars?

A&A 577, A64 (2015)
DOI: 10.1051/0004-6361/201425425

Astronomy & Astrophysics

Discovery of starspots on Vega*

First spectroscopic detection of surface structures on a normal A-type star

T. Böhm[1,2], M. Holschneider[3], F. Lignières[1,2], P. Petit[1,2], M. Rainer[4], F. Paletou[1,2], G. Wade[6], E. Alecian[5], H. Carfantan[1,2], A. Blazère[1,2], and G. M. Mirouh[1,2]

Neo-Narval

Neo-Narval, spectropolarimetry and velocimetry at TBL

Torsten Böhm

Séminaire Nice OCA,
2 Février 2016

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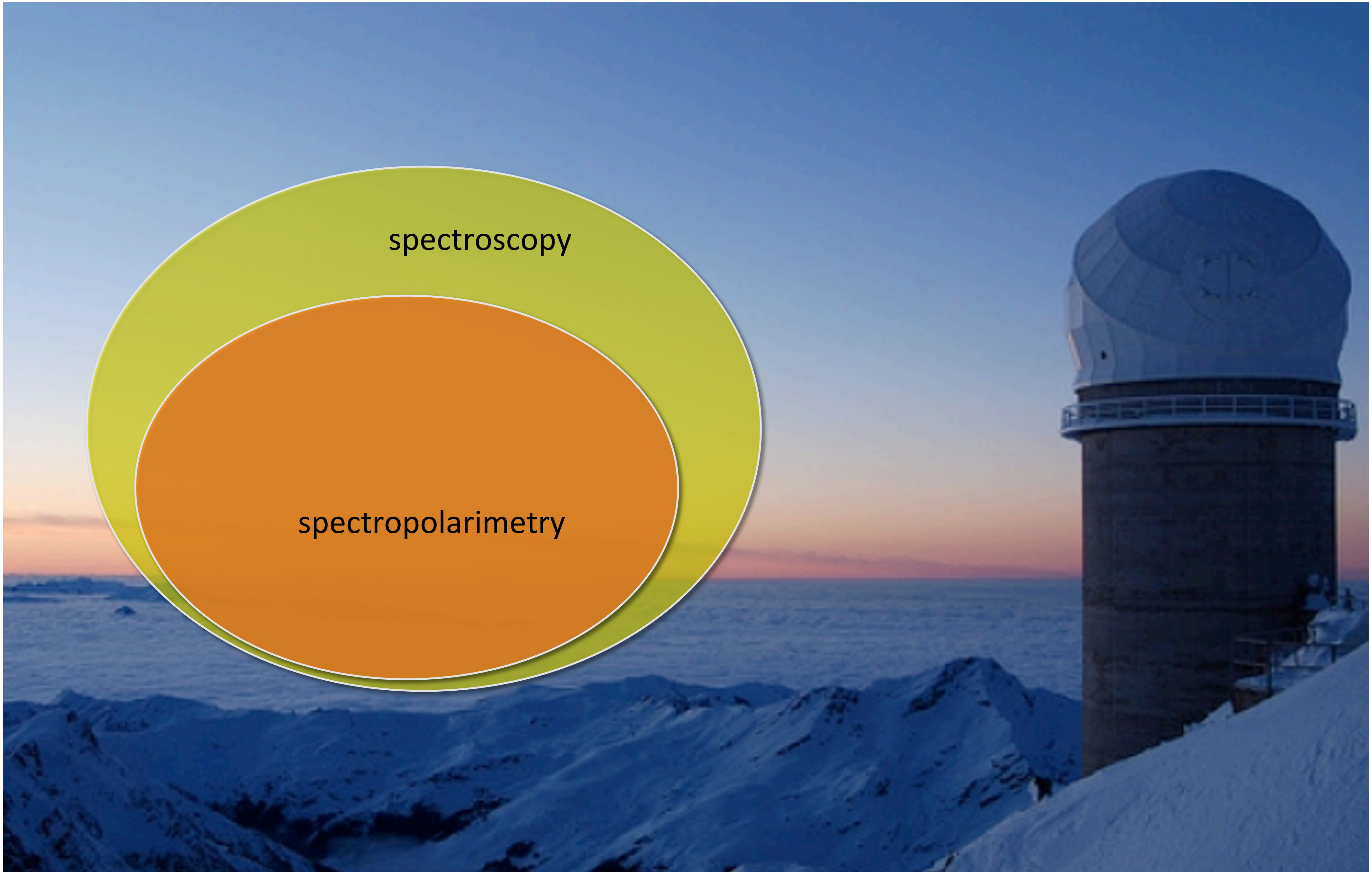
Narval at TBL/Pic du Midi - today



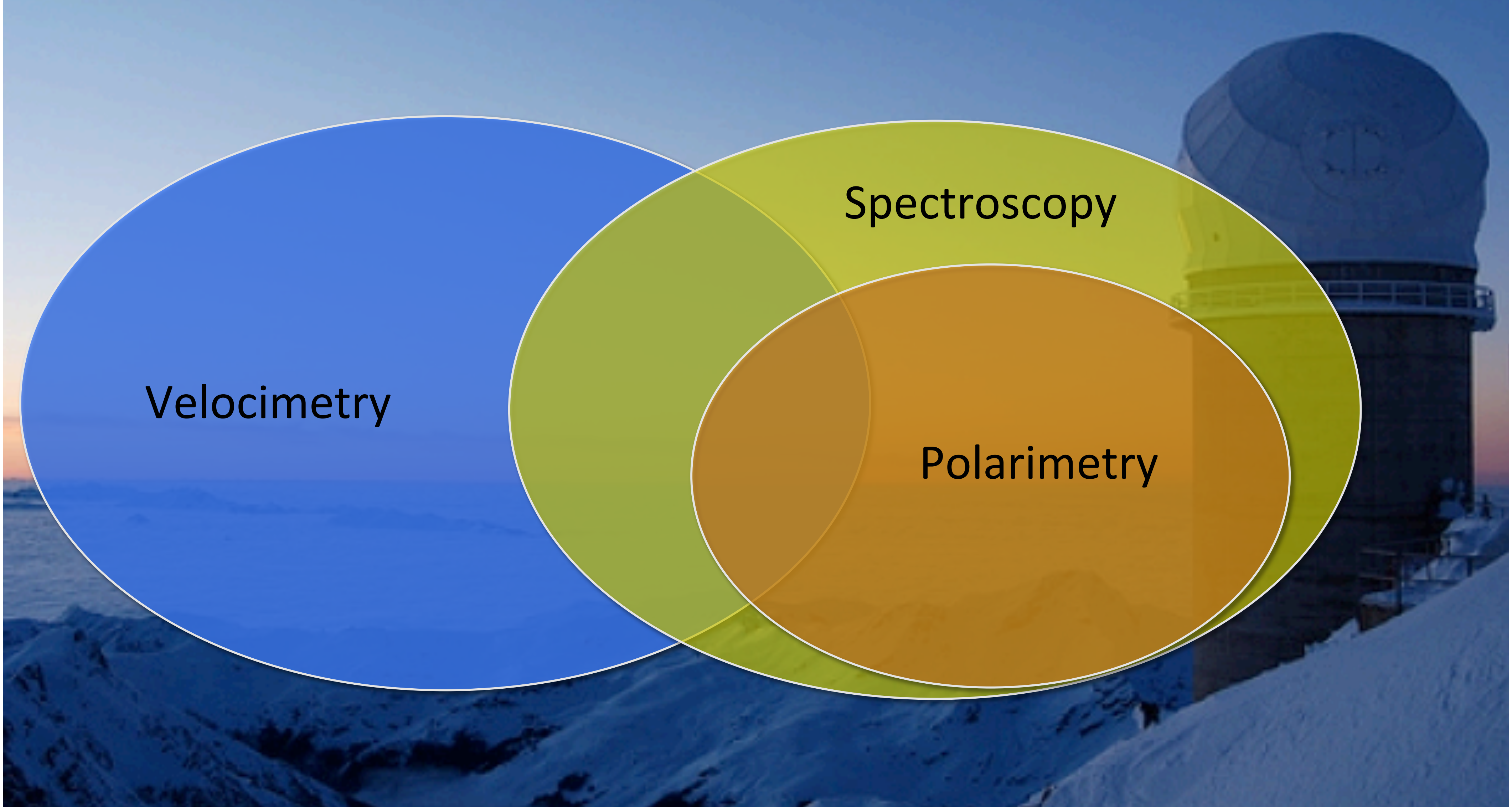
News from Neo-Narval

Torsten Böhm

- Neo-Narval:
  a spectropolarimeter stabilized in radial velocity at TBL/Pic du Midi
- Strongly supported by the community (prospective AA/INSU 2014)
- Financed by the CPER 2015+ (510k€)
- First light in 2018

Neo-Narval

Neo-Narval, a spectropolarimeter stabilized in radial velocity



Spectropolarimetric landscape - Narval/TBL

High-resolution spectrographs

Instrument	range 380-690nm	range 690-1000nm	POLAR QUV	Stability (< 5m/s) night - long term	Resolution
CHIRON (S1.5m)	from 415nm	up to 880nm	NO	7 - ?	up to 136000
HARPSPOL (S4m)	YES	NO	YES	0.2 - 0.2	120000
HARPSNorth (N2m)	YES	NO	NO	0.2 - 0.2	120000
HERMES (N1.2m)	YES	up to 900nm		2.5 - 60	85000
SOPHIE (N2m)	YES	NO	NO	2 - 2	76500
PEPSI (N2x8m)		In project		~3 - 100	up to 300000
Narval (N2m) & Espadons (N3.6m)	YES	YES	YES	30	65000 or 75000
Neo-Narval (N2m)	YES	YES	YES	<3 - <3	65000
UVES (S8m)	YES	YES	NO	~10 - 500	up to 110000
PSF (S6.5m)	YES	NO	NO	1 - 1	40000
HDS (N8m)	YES	NO	NO	5	55000
HIDES (N1.88m)	YES	NO	NO	6	67000

Availability:
100% at TBL!

International scientific context

Astronet Science Vision (european prospective, update 2013):

- Do we understand the extremes of the universe?
- How do galaxies form and evolve?
- What is the origin and fate of stars and planetary systems?
- How do we fit in?

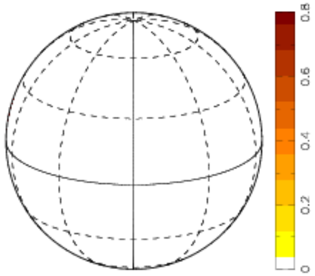
Neo-Narval

Which science with Neo-Narval?

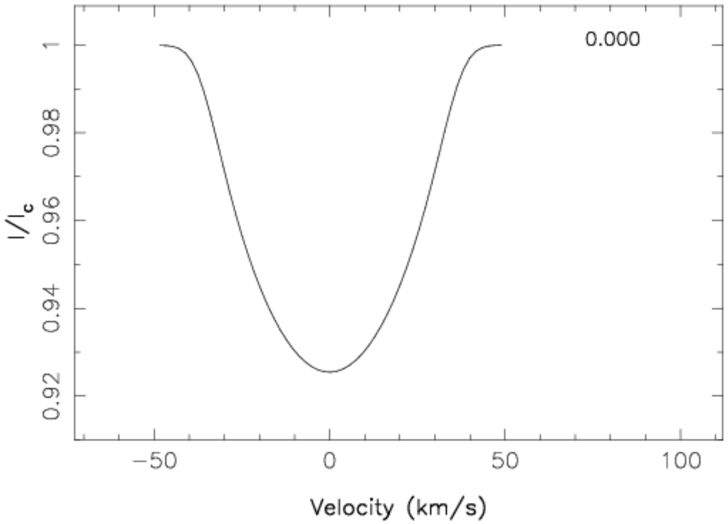
- **Stellar magnetism**
  - Origin of stellar magnetic fields (mecanisms)
  - Magnetic activity
  - Systematic study of the HR diagram
- **Birth and death of exoplanetary systems**
  - Exoplanets around magnetic stars
  - End of life of exoplanets around evolved stars
- **Ground based support to Gaia, Tess, Plato space missions**

Disentangling of observed physical effects

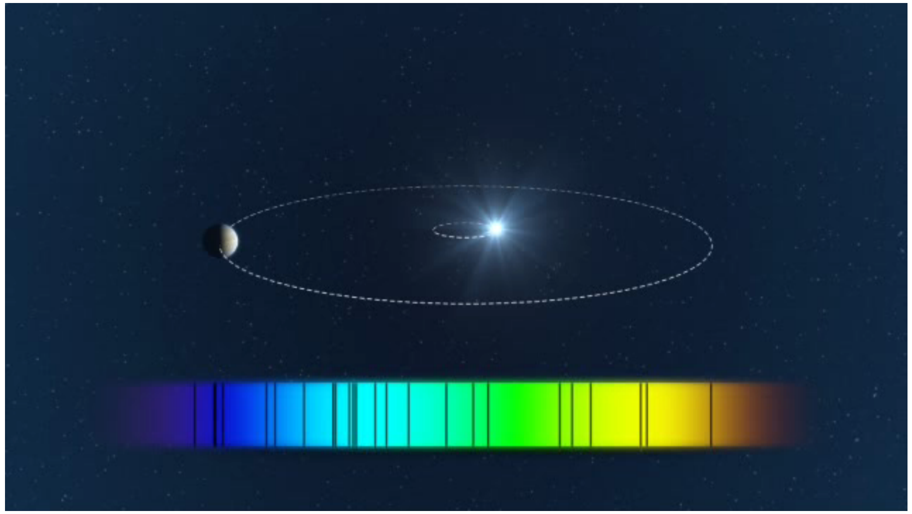
Stellar activity



+ granulation,...

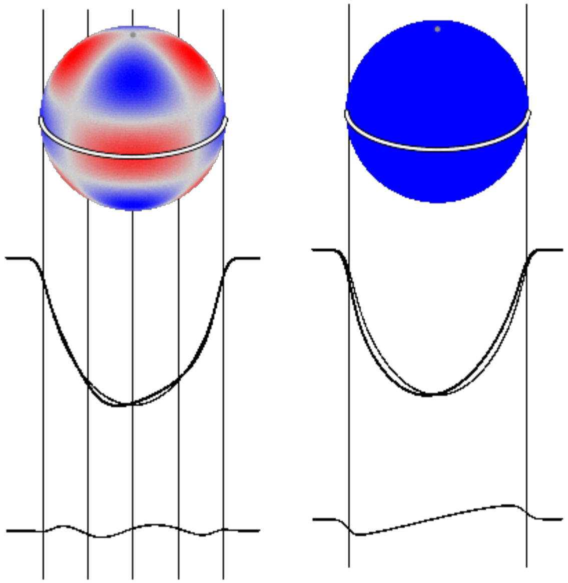


Simulation by J.F. Donati



©)ESO

Exoplanet or stellar companion?



Stellar oscillations

Simulation by J. Telting

Origin of magnetic field: the case of Vega (A0)

Narval/TBL 2009

Magnetic map

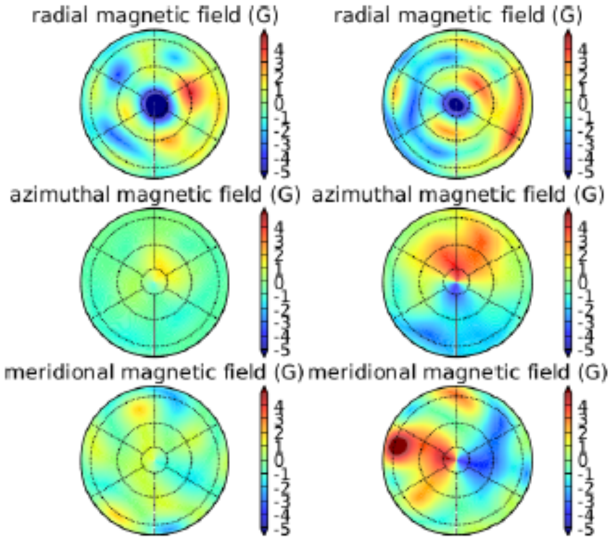


Fig. 1. Vectorial magnetic map of Vega for 2008 (*left*) and 2009 (*right*), in polar projection. The 3 rows illustrate the field projection onto one axis of the spherical coordinate frame with the radial, azimuthal, and meridional field components. The magnetic field strength is expressed in gauss. The phase origin is set at the bottom of each map and rotational phases are increasing in the clockwise direction.

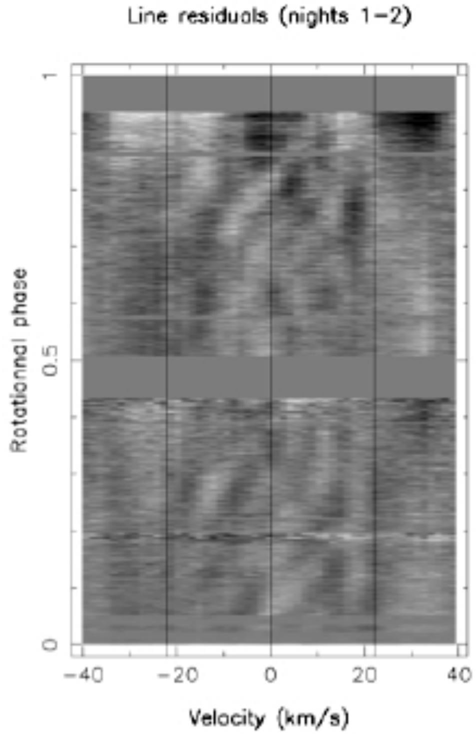
Petit et al. 2014, A&A 568, C2

simultaneous!

Neo-Narval

Sophie/OHP 2012

Surface brightness map *



Böhm et al. 2015, A&A 577, A64

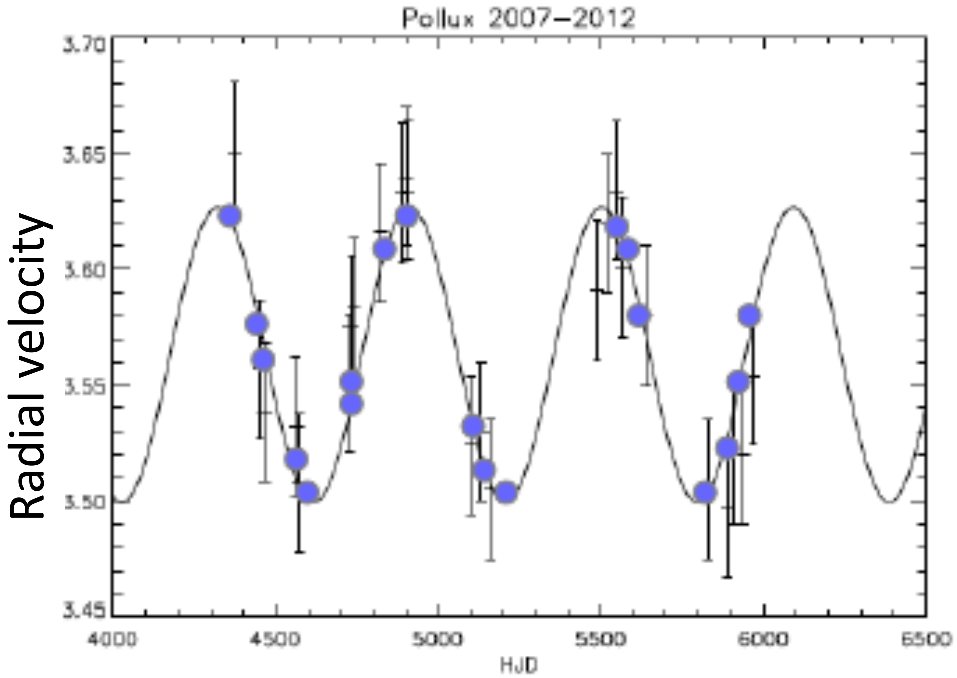
Study of the distribution and variation of magnetic field spots and brightness spots/plages

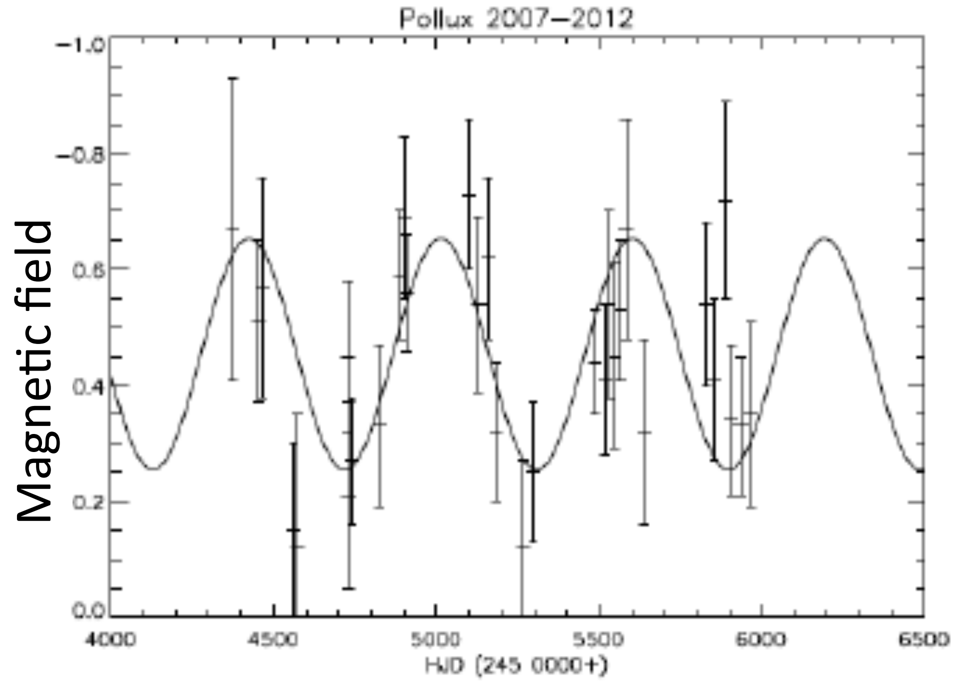
What is the origin of the magnetic field?

*Study of vrad A ~ 3 - 60 m/s

Exoplanets around evolved stars…

Exo-planet or magnetic field?





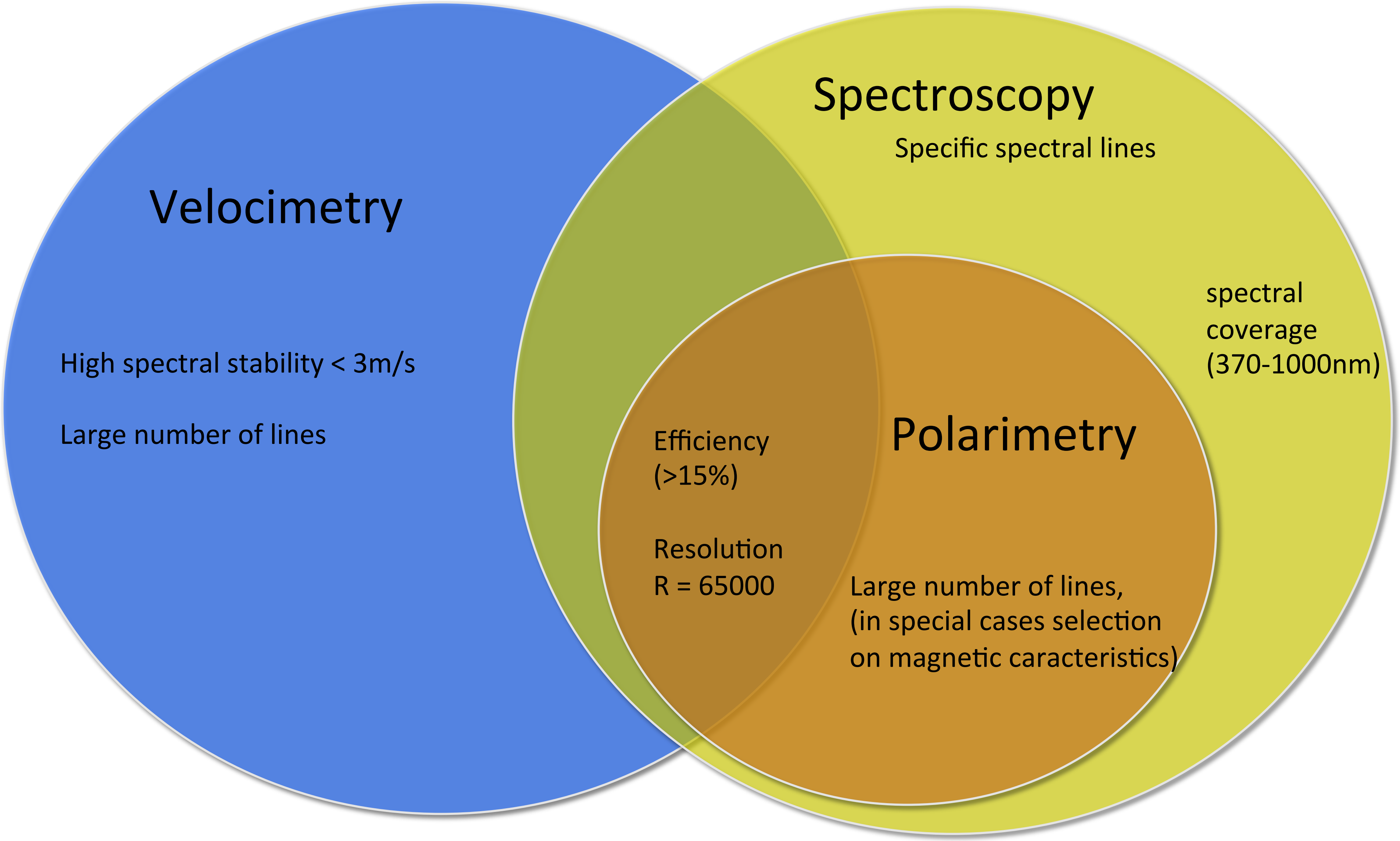
Ground based support of space missions

- Tess, Gaia et Plato: telluric planets around solar type stars
- Hot and warm Jupiters are detected in the same time:
  Neo-Narval could ideally do this follow-up!

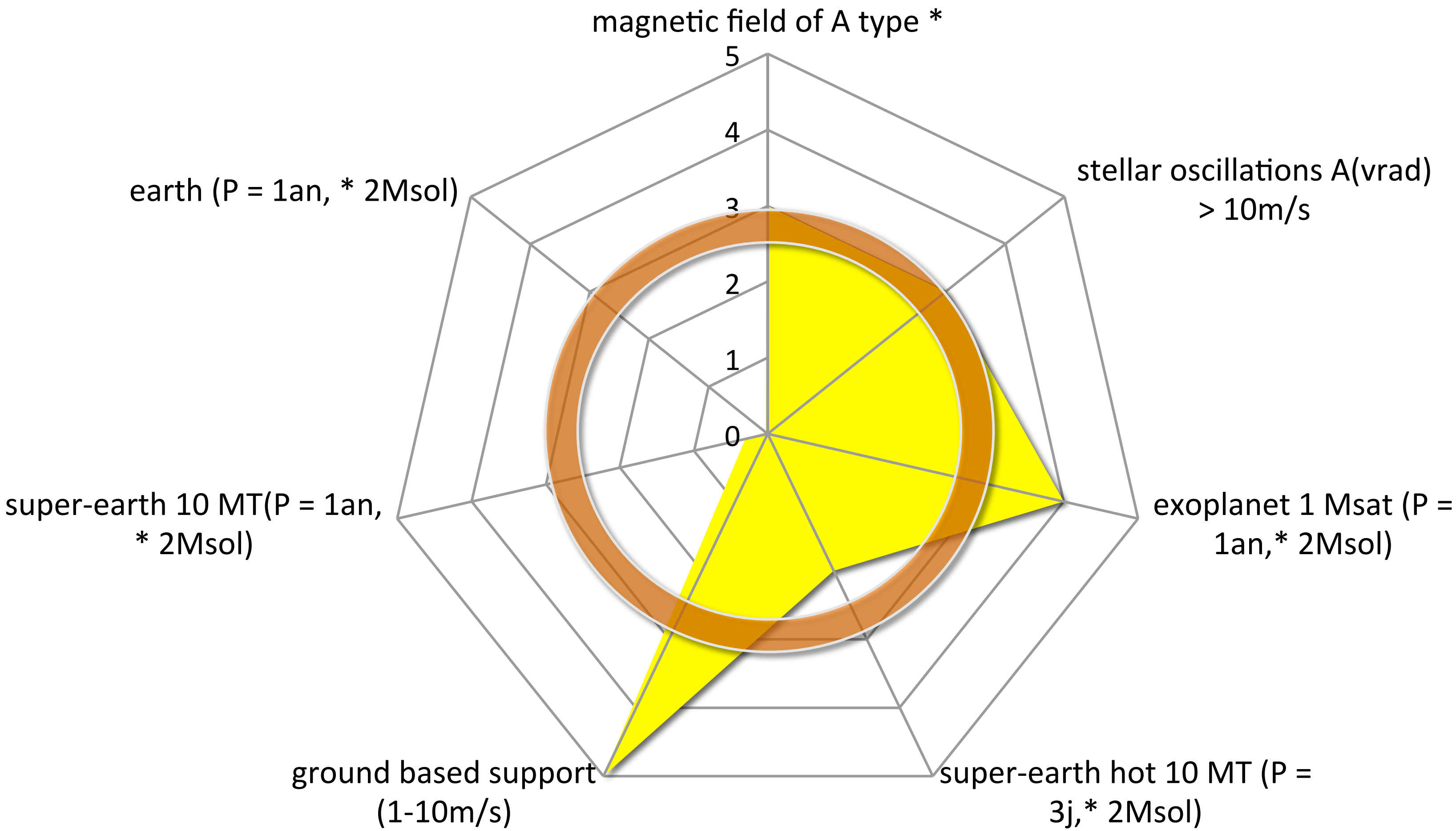
Radial velocity precision	Telescope size	Type of object	Required number of nights
10m/s	1-2m	Giant planets on short or intermediate orbits	50 nights/year for >3 tel., 6 yrs
1m/s	4m	Giant planets on long orbits. Super-earths on short and interm. orbits.	40 nights/year for 3 tel., 6 yrs
< 20cm/s	8m	Earths/Super-Earths on long orbits	40 nights/year for 1 tel, 6 yrs

Plato yellow book

Towards a veloci-spectro-polarimeter



Radial velocity precision: better than 3 m/s long-term



Neo-Narval project team

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+ external consultants (CS TBL, Observatoire Genève, ESO,..)

Different important constraints

- Versatile instrument (different communities), not a unique scientific focus
- Existing instrument, not a new construction
- Don't loose existing assets (throughput, coverage, resolution) …if possible
- Limited funding (500k€), manpower and time (mid 2018)
- Minimum telescope shutdown time (< 2 months if possible)
- Optimizing the duty cycle

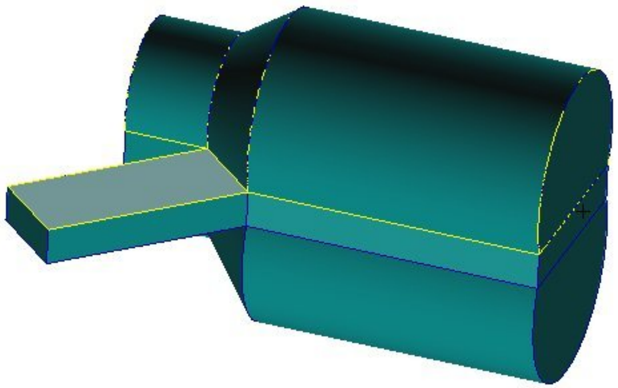
- How do we fit in?

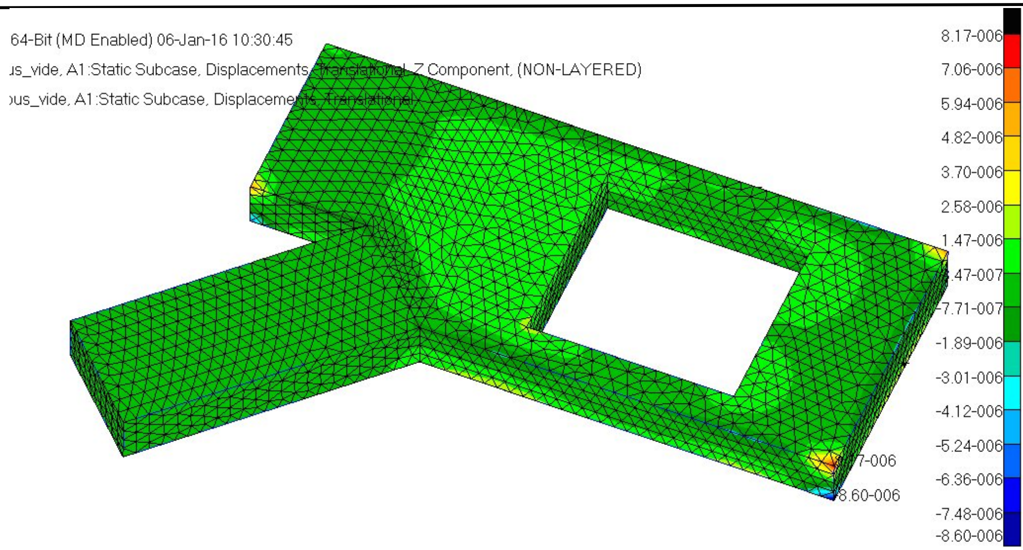
Main steps to high velocimetric stability

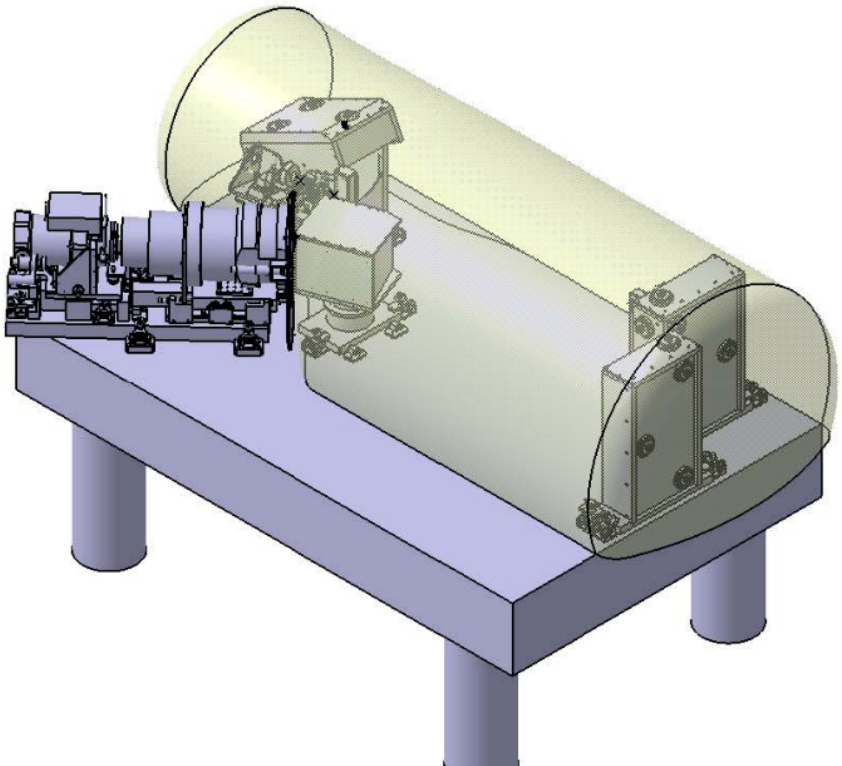
- ``Impossible'': symmetric mount of the optics, vertical design, in vacuum vessel

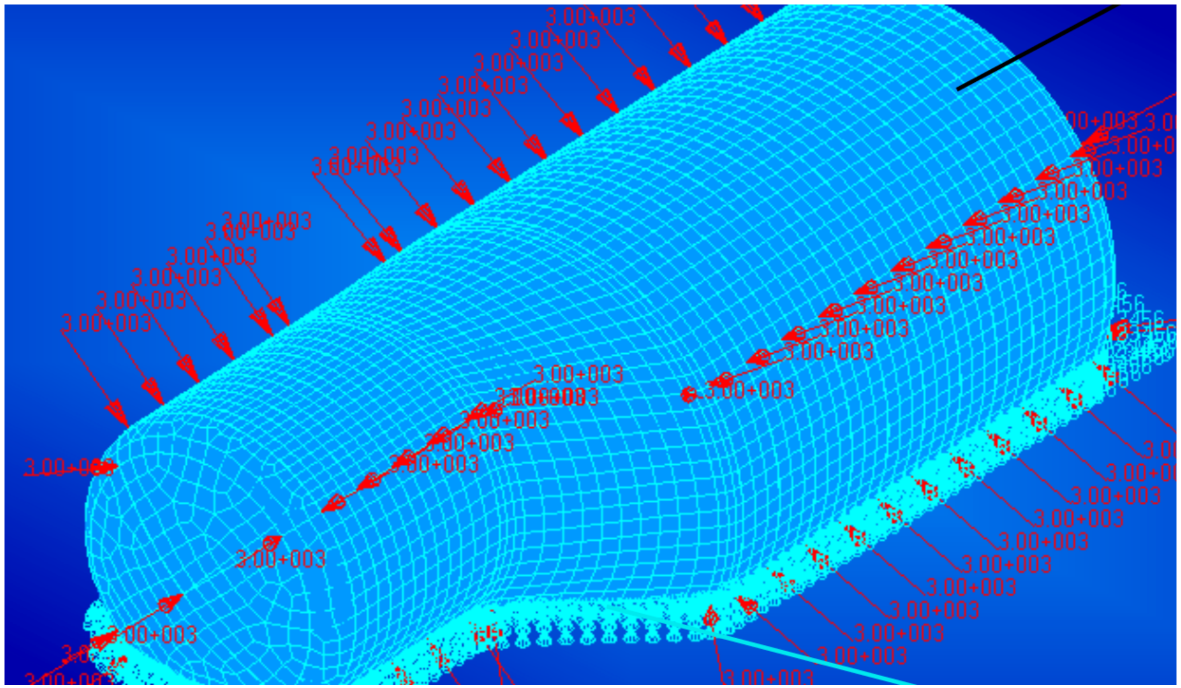
- Uniform light injection
  - Octogonal fibres + fibre scrambler
- Stabilizing the refractive index as seen by the dispersive elements
  - Grating (prisms, lens) in vacuum or constant pressure vessel ($\Delta P < 5\mu bar$)
- Thermalizing the environment ($\Delta T < 0.01K$) for maximum mecanical stability
- Simultaneous 3rd fibre for continuous calibration
  - Increased dispersion (additional prism + correction lens)?
  - Increased CCD size (4k4k EEV 15μm pixel size)?
  - Stabilized Fabry-Perot (stable to better than 1m/s long-term)
- New CCD (deeply depleted, without fringes in the R/IR)
- Optimized Data Reduction Software

Isobaric vessels – pros and cons

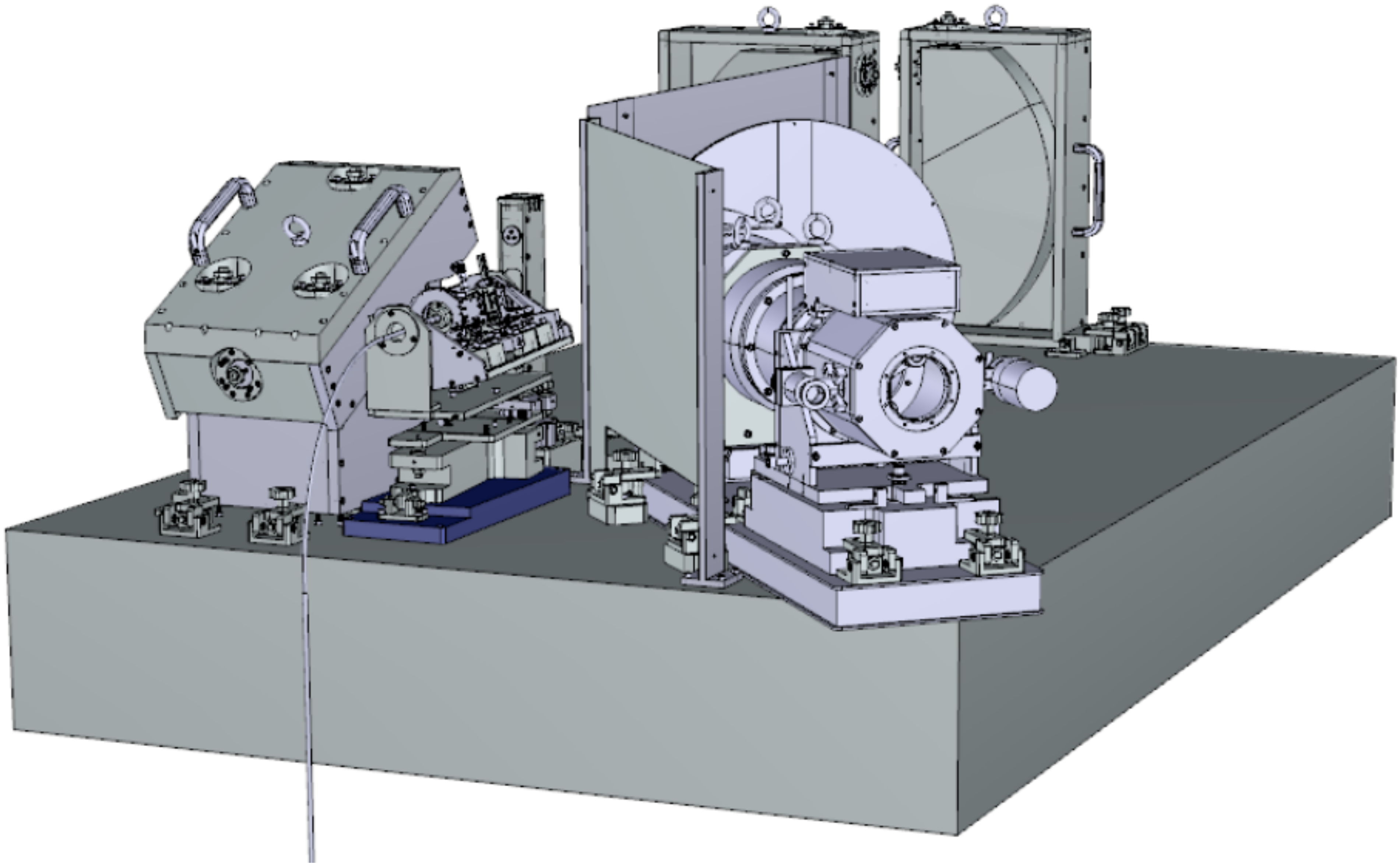




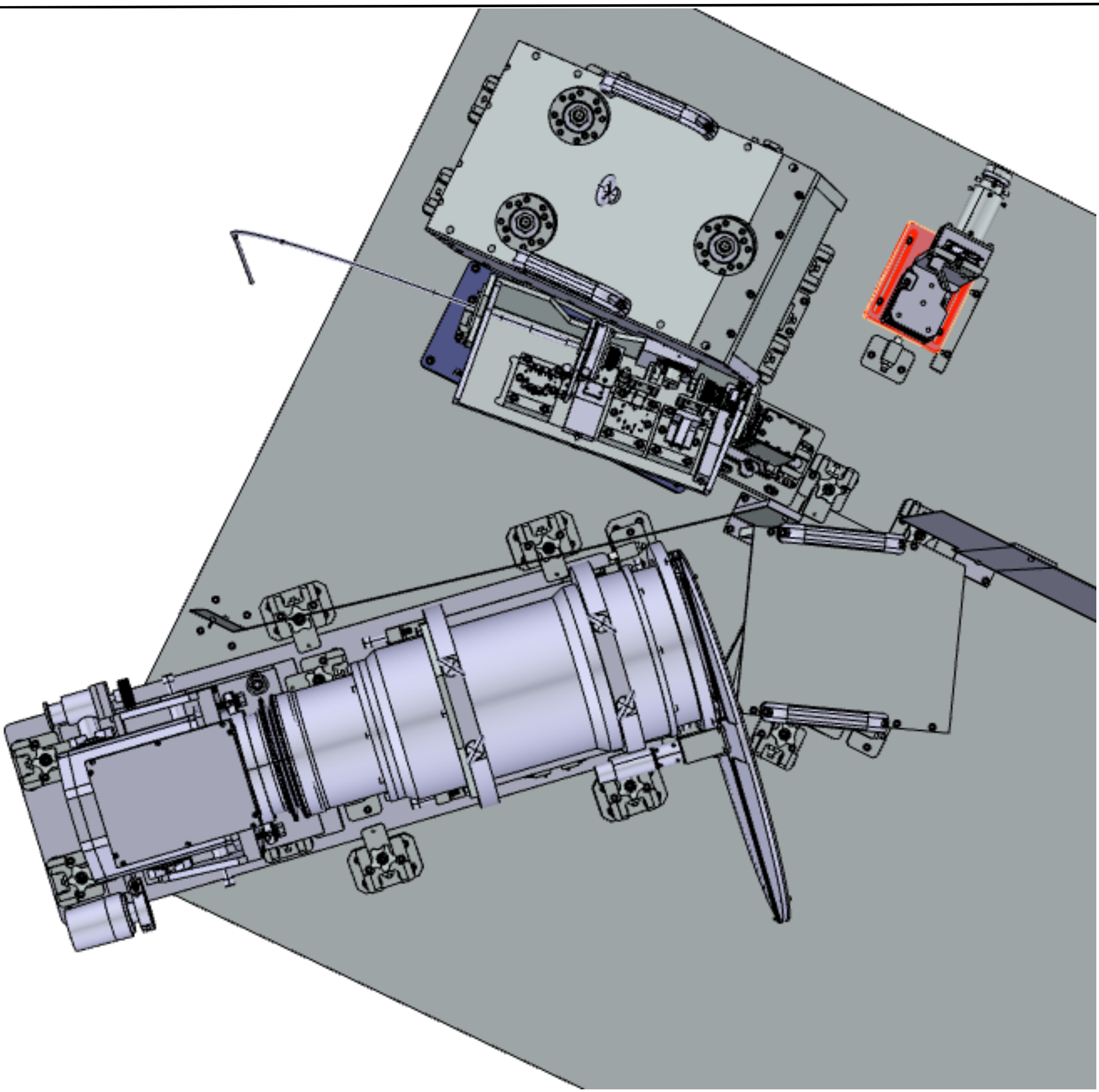




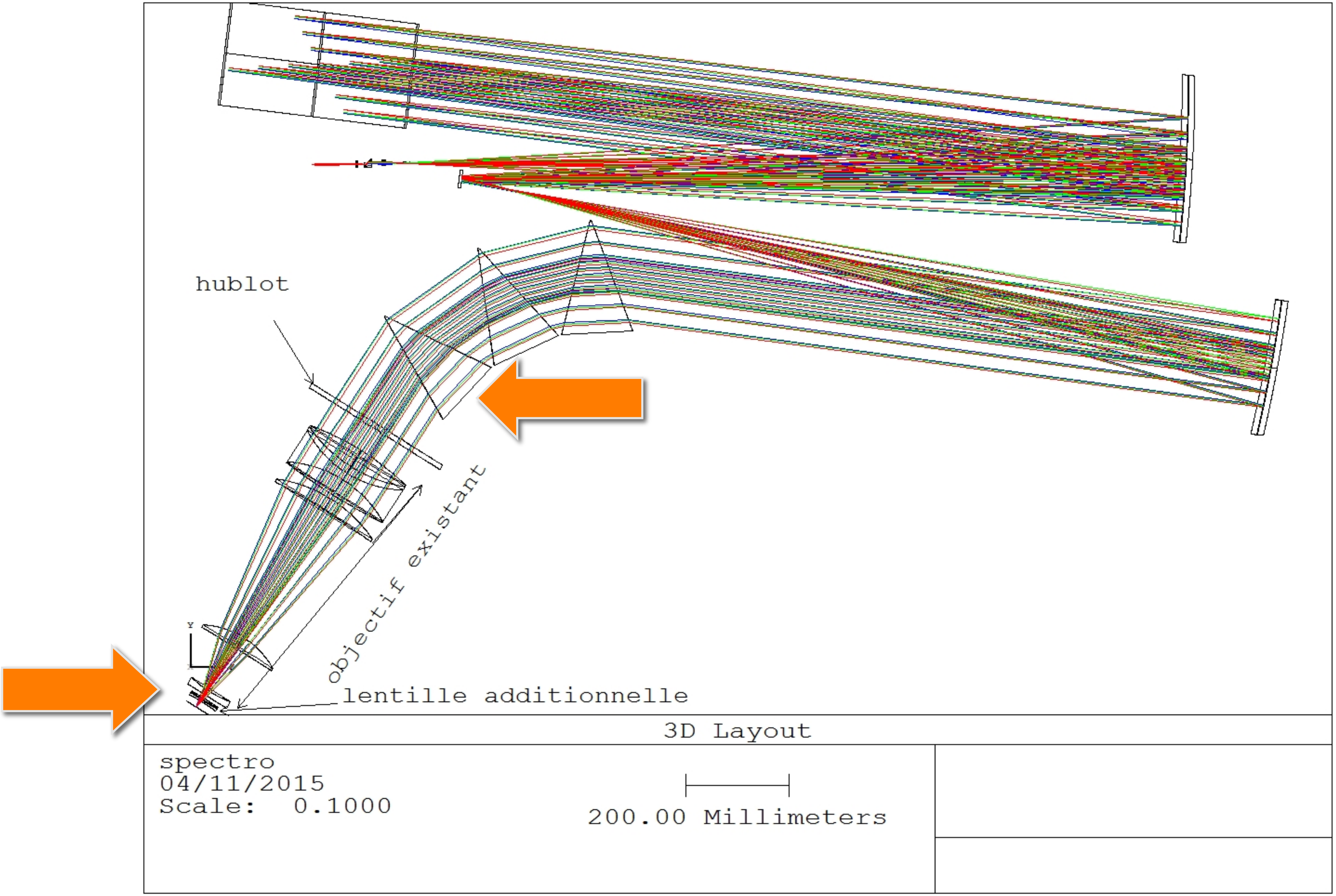
Dense mechanical layout – space for isobaric vessel?



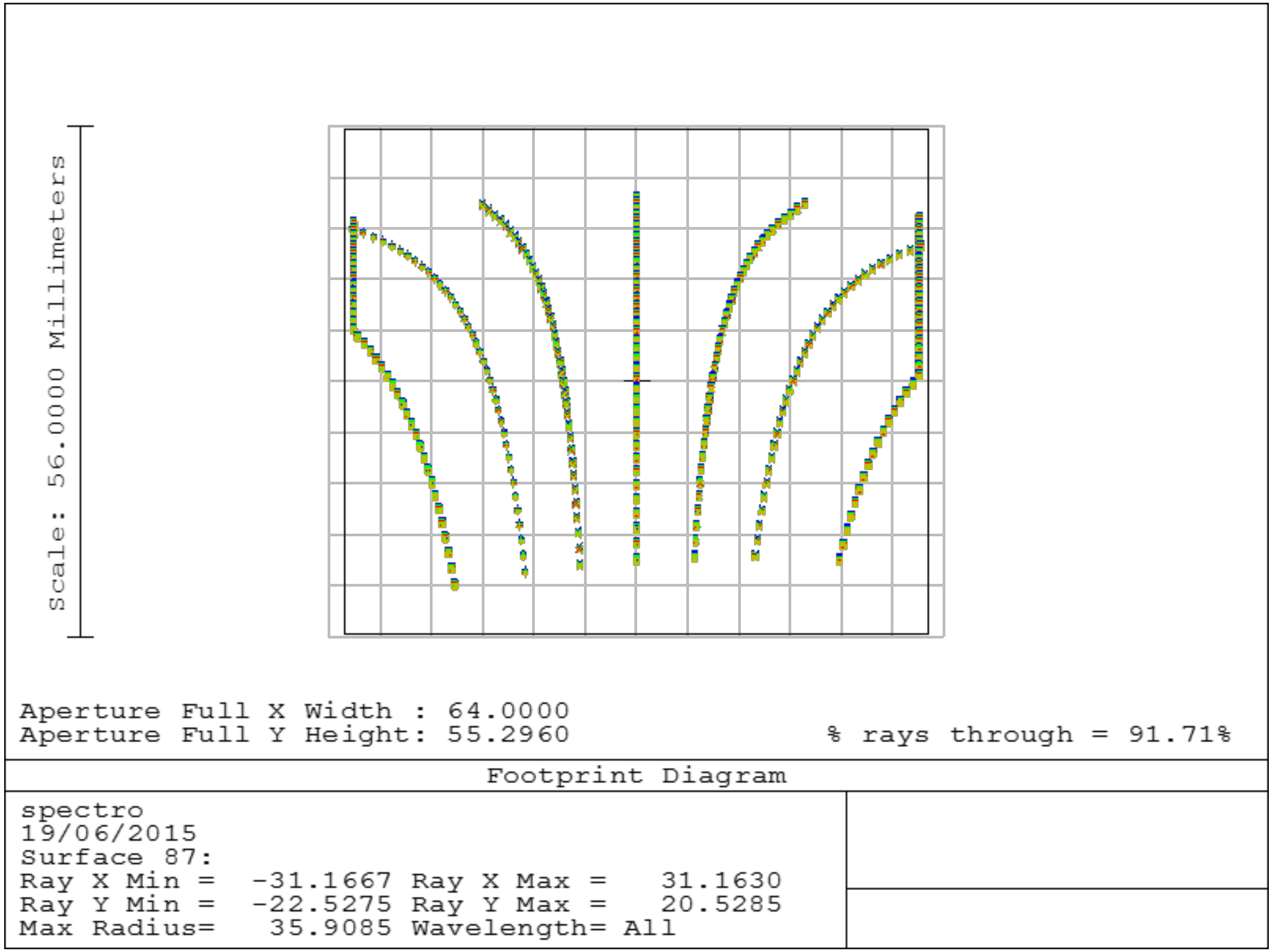
....where putting the isobaric vessel?



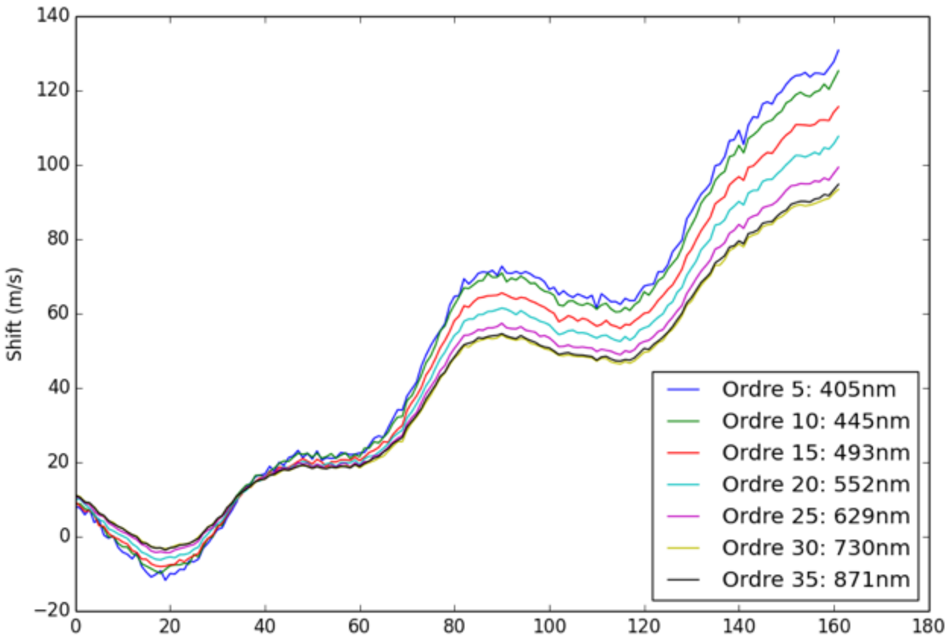
Simultaneous calibration – need for increased cross-dispersion….?

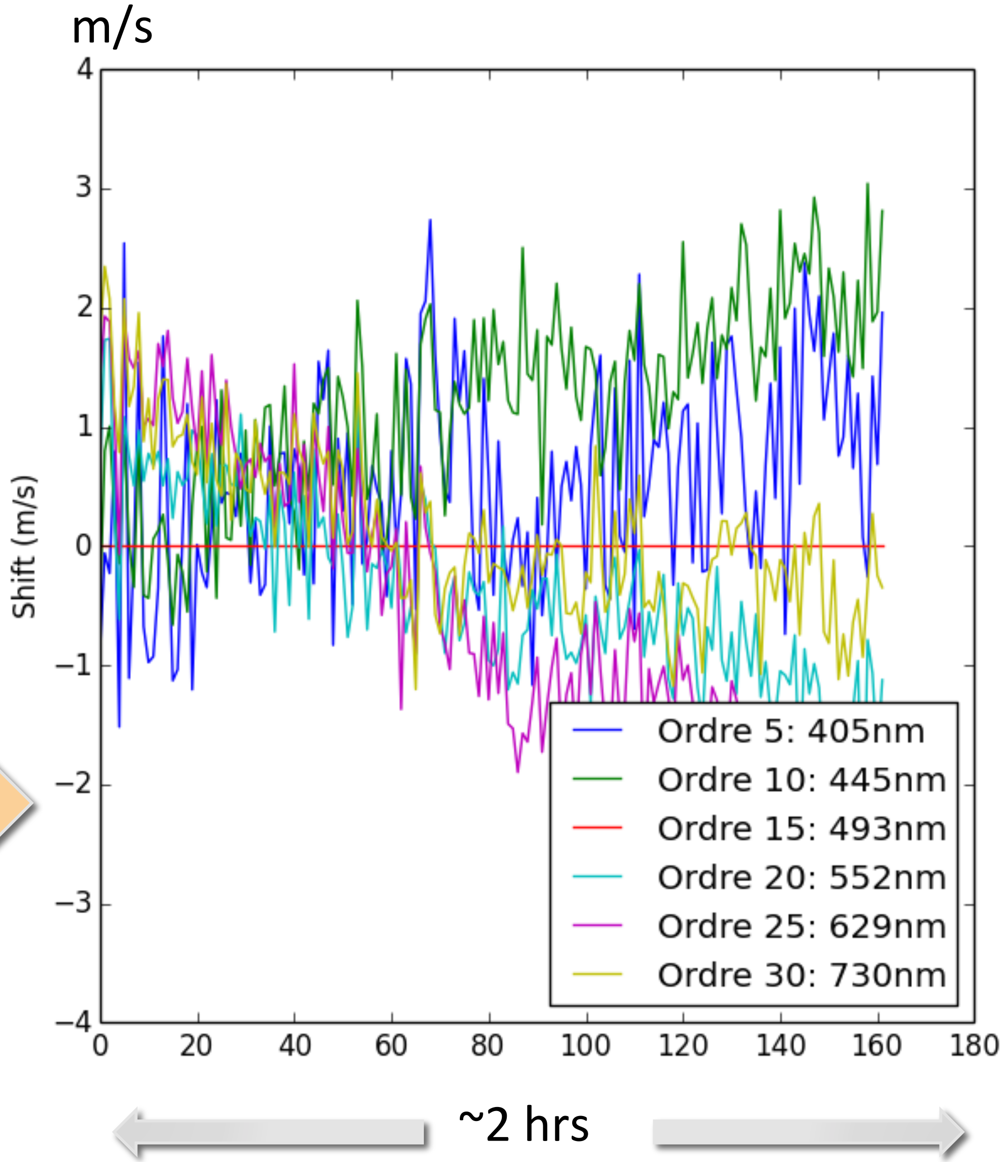


Echelle spectra layout in case of new CCD 4k4k



2k4.5k CCD – correcting the red by the blue?

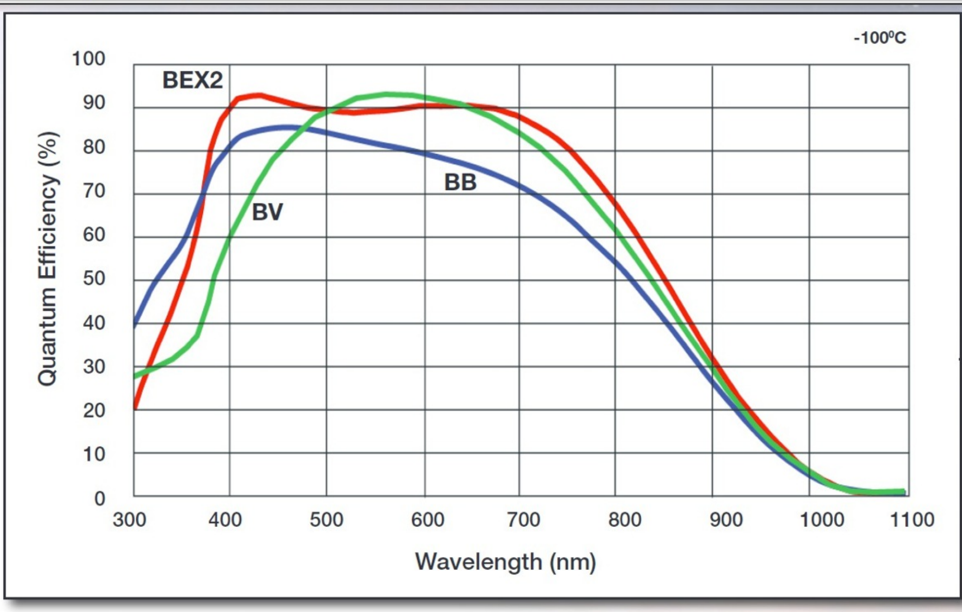




It seems possible,
at least on short-term!

New CCD: deeply depleted or not….?

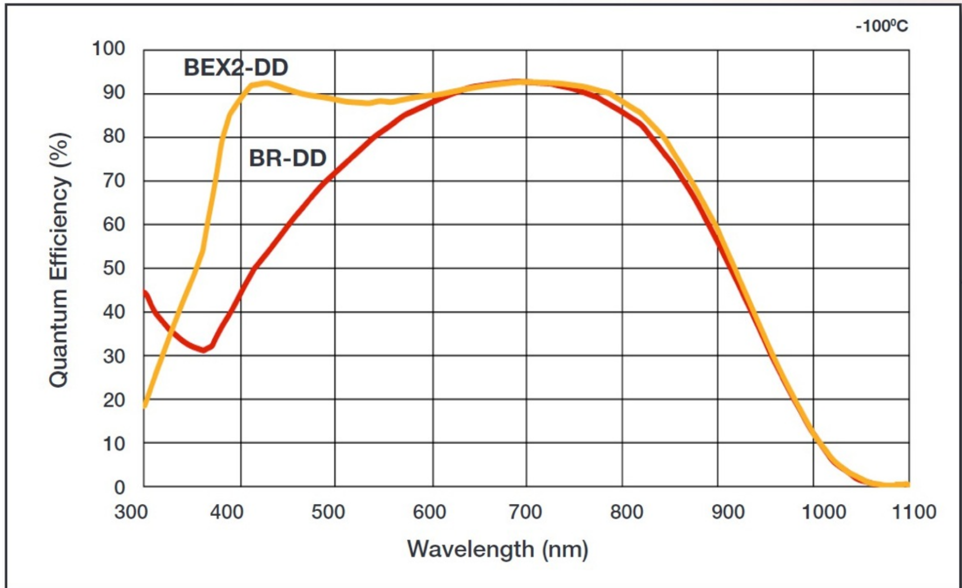
Andor_iKon-XL_231_Specifications.pdf



A range of sensor options are available for the iKon-XL 231 that provide high photon collection efficiency for maximising the SNR. Deep depletion (-DD) sensor options provide extended NIR sensitivity.

Standard Silicon Sensor Options

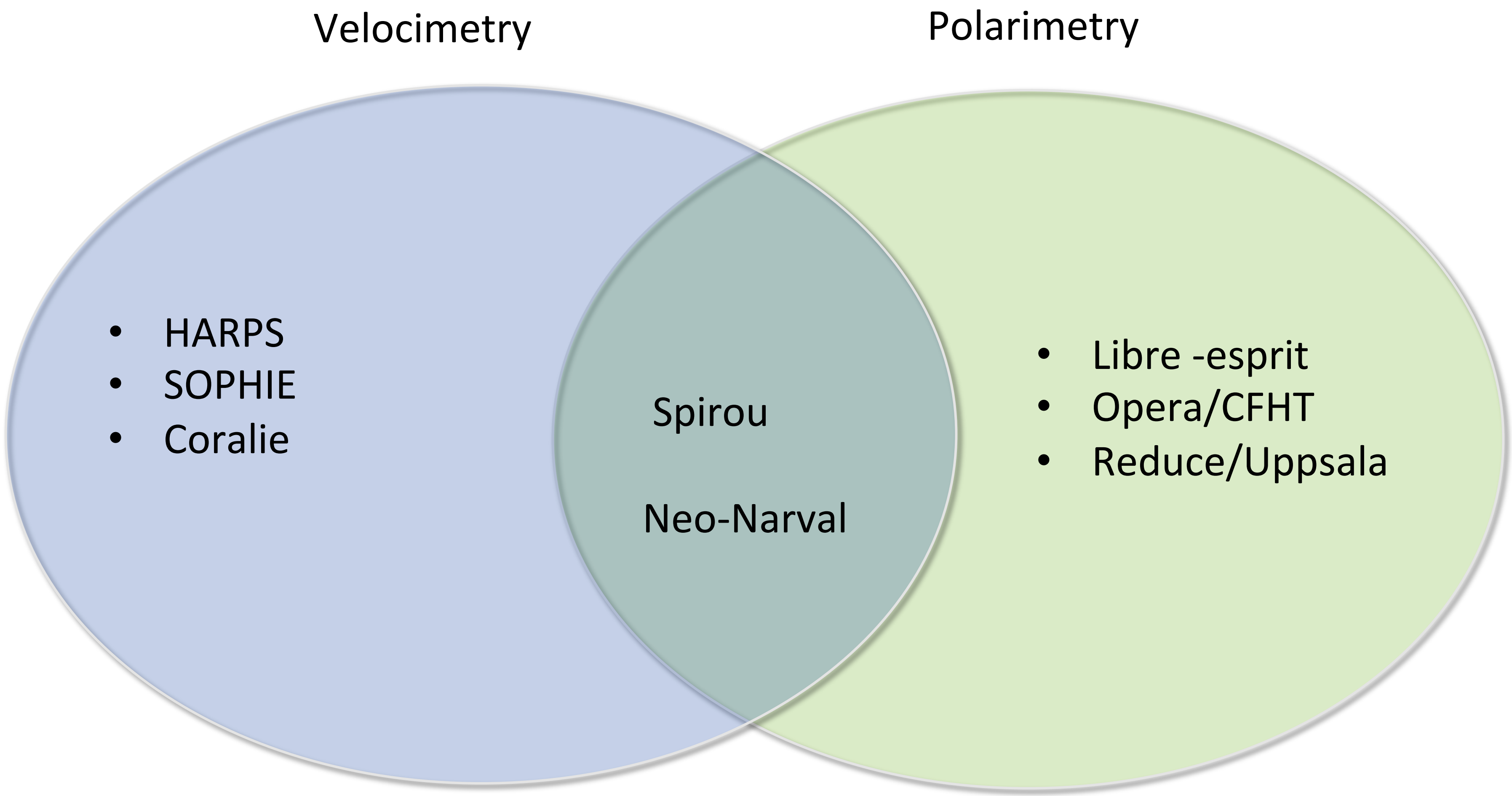
- **BV:** mid band AR coating
- **BB:** broad band AR coating (blue optimized)
- **BEX2:** dual AR coating (sensitivity extends to both the blue and NIR wavelength regions)



Deep Depletion Sensor Options

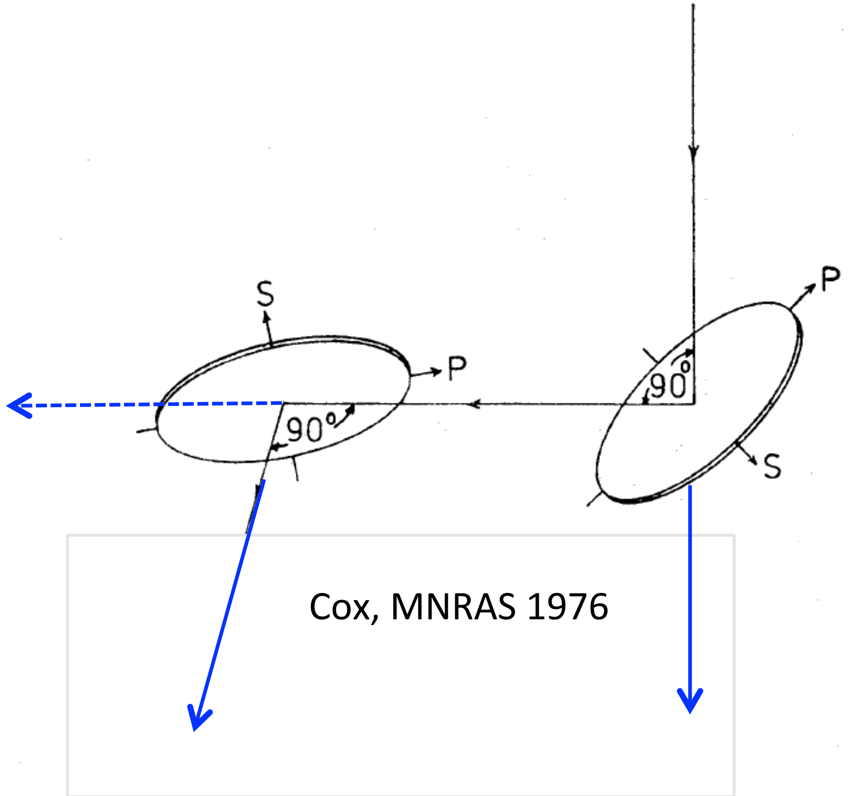
- **BR-DD:** deep depletion with fringe suppression (extended response in the NIR region)
- **BEX2-DD:** deep depletion with fringe suppression and dual AR coating (sensitivity extends to both the blue and NIR wavelength regions)

Data Reduction Software



Horizon 2020+:
Simultaneous observations Neo-Narval and SPIP?

identical
dichroic plate



dichroic plate

SPIP

near-IR
2020+

Neo-Narval

Visible
2018