A Holy Grail for stellar wind analysis
zeta Puppis seen by XMM

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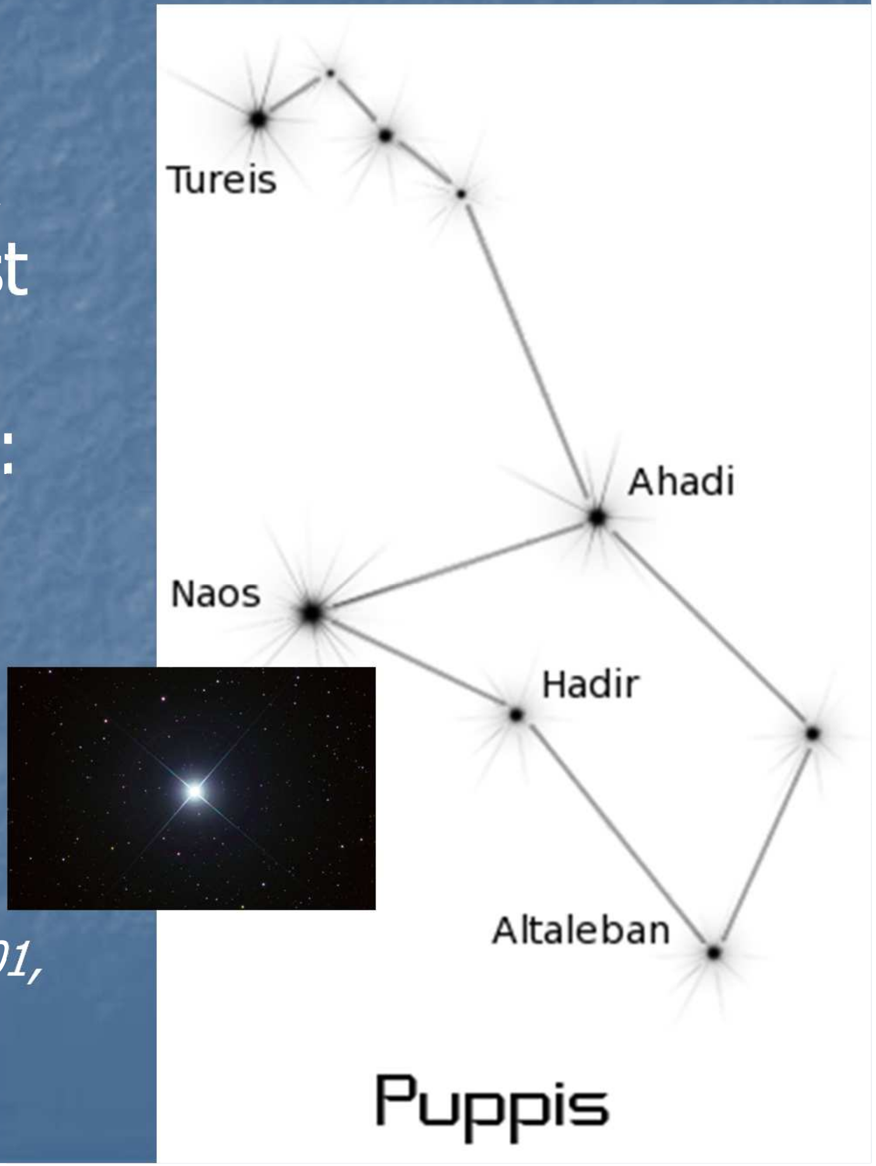
Zeta Puppis

- One of the closest (335pc), earliest (O4I), and brightest massive stars
- Many intriguing properties : runaway star, chemical enrichment, fast rotation (post RLOF+SN ? Ejection from cluster ?)
- The first one observed by Chandra & XMM *(Kahn et al. 2001, Cassinelli et al. 2011)*



A decade of XMM observations

ObsID	Rev.	Mid-exp. Date	JD	EPIC-MOS1				EPIC-pn				RGS1		
			−2 450 000.	Mode	Sched.	Perf.	Real	Mode	Sched.	Perf.	Real	Sched.	Perf.	Real
0095810301	0091	2000-06-08T09:32:39	1703.898									57.4 ks	57.4 ks	36.2 ks
0095810401	0156	2000-10-15T06:43:44	1832.780	LW+thick	37.7 ks	37.7 ks	37.3 ks	LW+medium	35.7 ks	35.7 ks	33.4 ks	40.6 ks	40.6 ks	39.9 ks
0157160401	0535	2002-11-10T23:40:41	2589.487	LW+thick	42.2 ks	42.2 ks	41.7 ks	LW+thick	13.0 ks	13.0 ks	12.1 ks	42.4 ks	42.4 ks	41.6 ks
								LW+medium	24.4 ks	24.4 ks	22.7 ks			
0157160501	0538	2002-11-17T07:03:34	2595.794	LW+thick	43.4 ks	41.1 ks	32.2 ks	LW+thick	15.7 ks	15.7 ks	14.6 ks	43.6 ks	42.5 ks	29.8 ks
								LW+medium	23.0 ks	23.0 ks	12.2 ks			
0157160901	0542	2002-11-24T20:26:10	2603.352	LW+thick	43.4 ks	43.4 ks	42.9 ks	LW+thick	14.1 ks	14.1 ks	13.2 ks	43.6 ks	43.6 ks	43.0 ks
								LW+medium	24.6 ks	24.6 ks	20.9 ks			
0157161101	0552	2002-12-15T04:53:31	2623.704					LW+medium	24.2 ks	24.0 ks	11.5 ks	45.6 ks	38.9 ks	26.9 ks
0159360101	0636	2003-05-30T19:28:01	2790.311	LW+thick	66.8 ks	62.7 ks	18.8 ks	SW+thick	42.8 ks	42.7 ks	24.3 ks	72.9 ks	69.2 ks	56.2 ks
0163360201	0731	2003-12-07T02:47:04	2980.616					LW+thick	61.2 ks	52.6 ks	32.4 ks	62.9 ks	53.6 ks	35.8 ks
0159360301	0795	2004-04-12T17:33:58	3108.232	LW+thick	63.9 ks	41.8 ks	19.0 ks	SW+thick	30.2 ks	30.2 ks	17.4 ks	64.1 ks	61.3 ks	21.1 ks
0159360401	0903	2004-11-14T01:57:57	3323.582	LW+thick	21.9 ks	21.9 ks	21.6 ks	SW+thick	29.8 ks	29.8 ks	20.9 ks	77.0 ks	63.0 ks	48.2 ks
0159360501	0980	2005-04-16T14:39:28	3477.111	LW+thick	29.3 ks	29.3 ks	29.0 ks	SW+thick	63.8 ks	63.8 ks	22.1 ks	64.2 ks	64.2 ks	31.0 ks
				SW+thick	34.1 ks	27.7 ks	13.4 ks							
0159360701	1071	2005-10-15T04:04:52	3658.670					SW+thick	59.6 ks	22.2 ks	15.5 ks	60.0 ks	30.0 ks	27.5 ks
0159360901	1096	2005-12-04T01:14:14	3708.552	SW+thick	59.8 ks	53.5 ks	46.2 ks	SW+thick	59.6 ks	53.3 ks	33.1 ks	60.0 ks	53.5 ks	43.1 ks
0159361101	1164	2006-04-17T21:48:48	3843.409	LW+thick	58.0 ks	42.9 ks	40.1 ks					58.2 ks	52.9 ks	40.5 ks
0414400101	1343	2007-04-09T22:49:29	4200.451	SW+thick	63.7 ks	63.7 ks	47.3 ks	SW+thick	63.5 ks	63.5 ks	34.2 ks	63.9 ks	63.9 ks	48.8 ks
0159361301	1620	2008-10-14T01:15:08	4753.552	SW+thick	66.2 ks	61.2 ks	53.3 ks	SW+thick	66.0 ks	61.0 ks	38.3 ks	66.4 ks	61.5 ks	54.7 ks
0561380101	1814	2009-11-04T06:17:00	5139.762	SW+thick	64.1 ks	64.1 ks	62.1 ks	SW+thick	63.9 ks	63.9 ks	44.7 ks	64.3 ks	64.3 ks	60.5 ks
0561380201	1983	2010-10-07T23:09:52	5477.465	SW+thick	76.7 ks	76.7 ks	74.3 ks	SW+thick	76.5 ks	76.5 ks	53.5 ks	76.9 ks	76.9 ks	65.9 ks
Total exposure time					771.2 ks	679.9 ks	579.2 ks		791.6 ks	734.0 ks	477.0 ks	1066.7 ks	979.7 ks	750.7 ks

Data reduction

- The best dataset available for a massive star (~1/2 Ms for EPIC, 3/4 Ms for RGS)
- 18 observations taken in different modes (timing, full frame, large window, small window), with different filters (medium, thick), sometimes off-axis
- Bright $\rightarrow$ slight pile-up (~limit of large window mode)
- Extraction with pattern=0, keeping the same circular regions for source and bkgd (*NB: annular source = KO!*)
- New RGS pipeline (SAS 10) solved the flux/shift issues

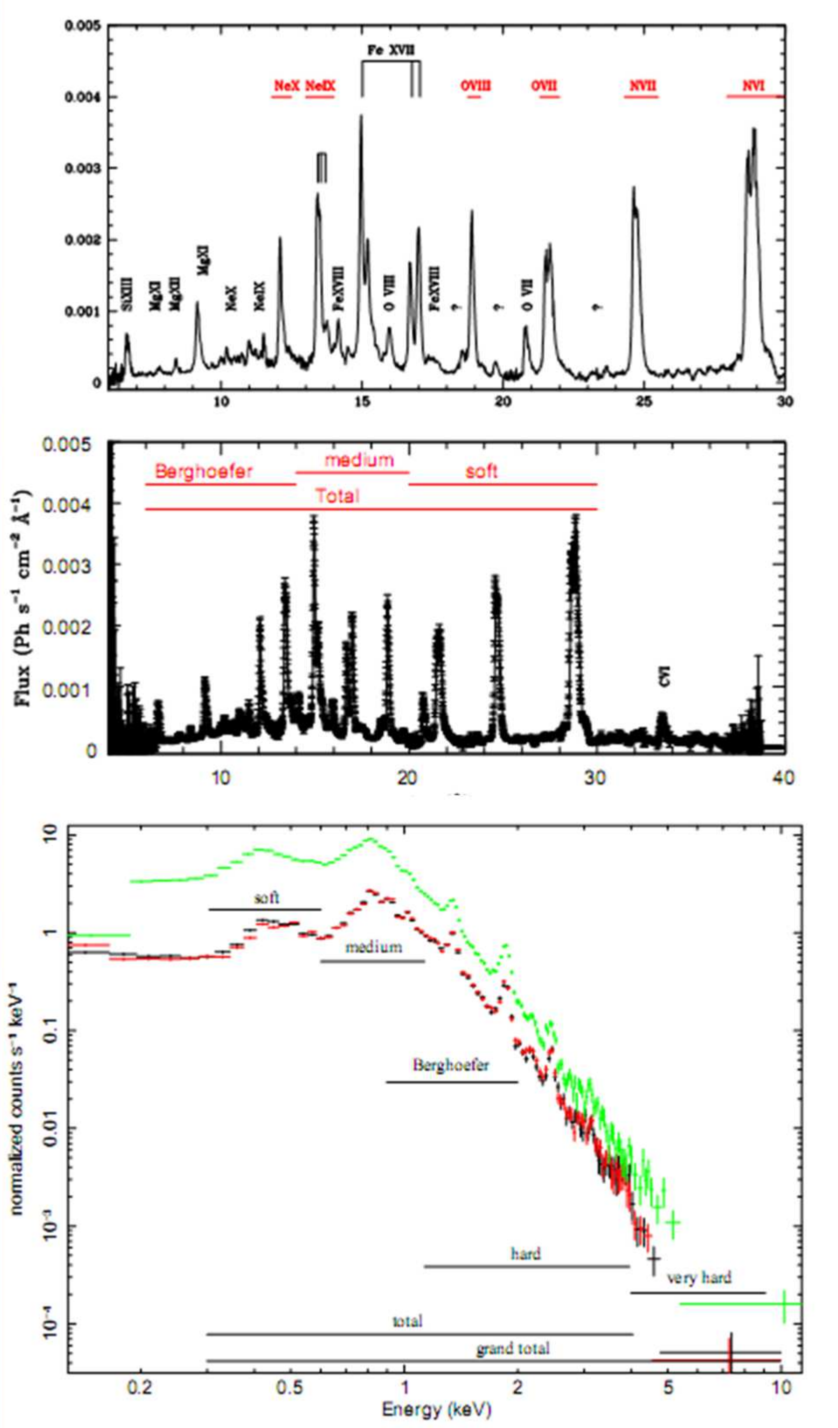
Variability of zeta Puppis

- In optical :
  - long-term changes *(Conti & Niemela 1976)*
  - 5d variations *(e.g. Moffat & Michaud 1981)*
  - a few h pulsations *(e.g. Reid & Howarth 1996)*
- In X-rays :
  - Einstein - nothing
  - ROSAT revealed a small modulation (2% amplitude) of 17h period in 0.9-2 keV band *(Berghöfer et al. 1996)*
  - Chandra, XMM (1 dataset) – nothing

(Kahn et al. 2001, Oskinova et al. 2001)

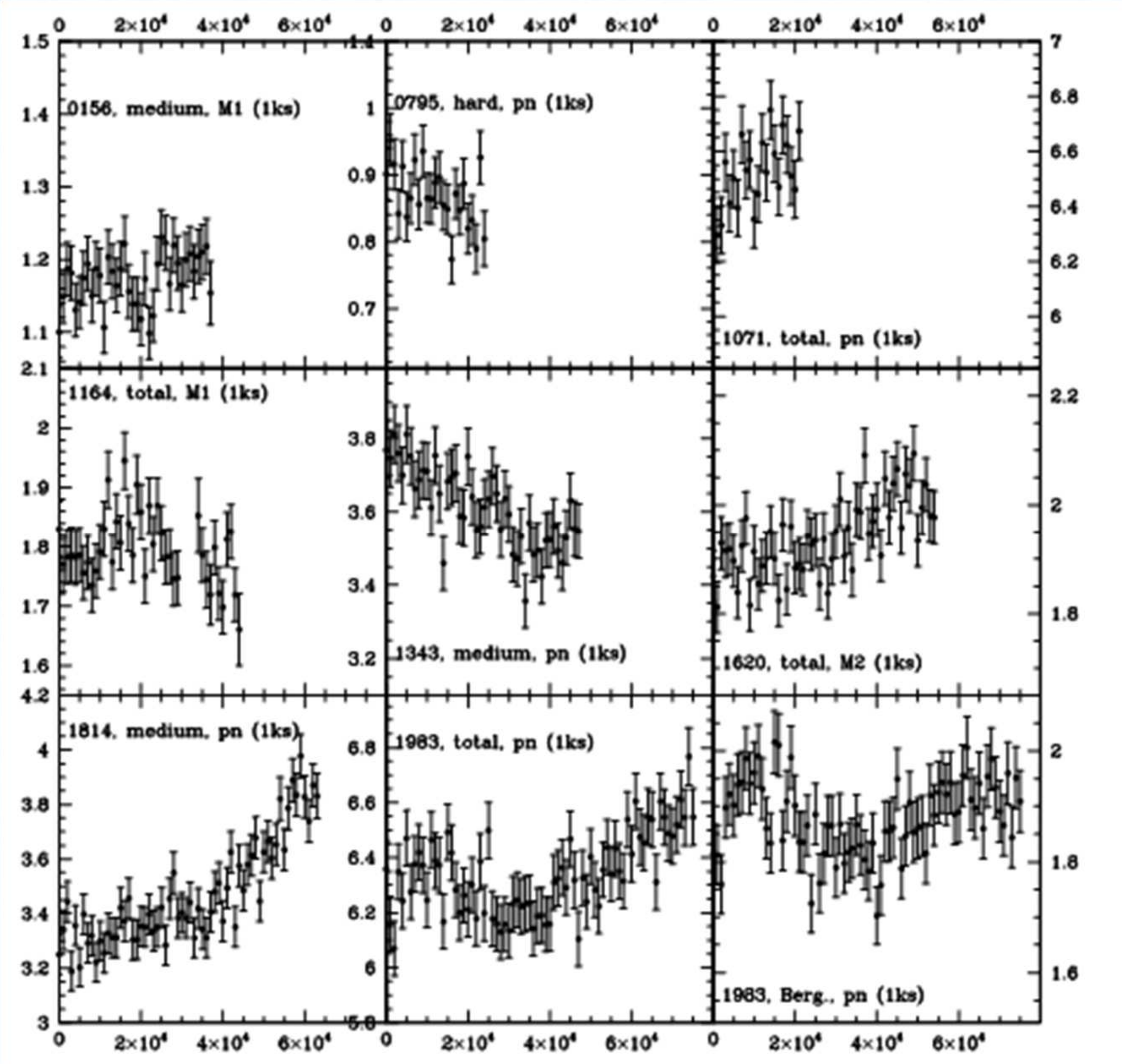
Variability: the XMM view

- Several energy bands
- Several time bins (200s to 5ks EPIC, 500s to 10ks RGS)
- Chi-2 tests (constant, line, parabola); Fourier; Autocorrelation
- Results :
  - Background is variable
  - Instruments do not agree



Variability: short & mid-term

- The longest you observe or the longer the time bin, the more variable it is $\Rightarrow$ no obvious short term variations but mid-term ones exist (with timescales > Texp : rotation ?)



Variability: short and mid-term

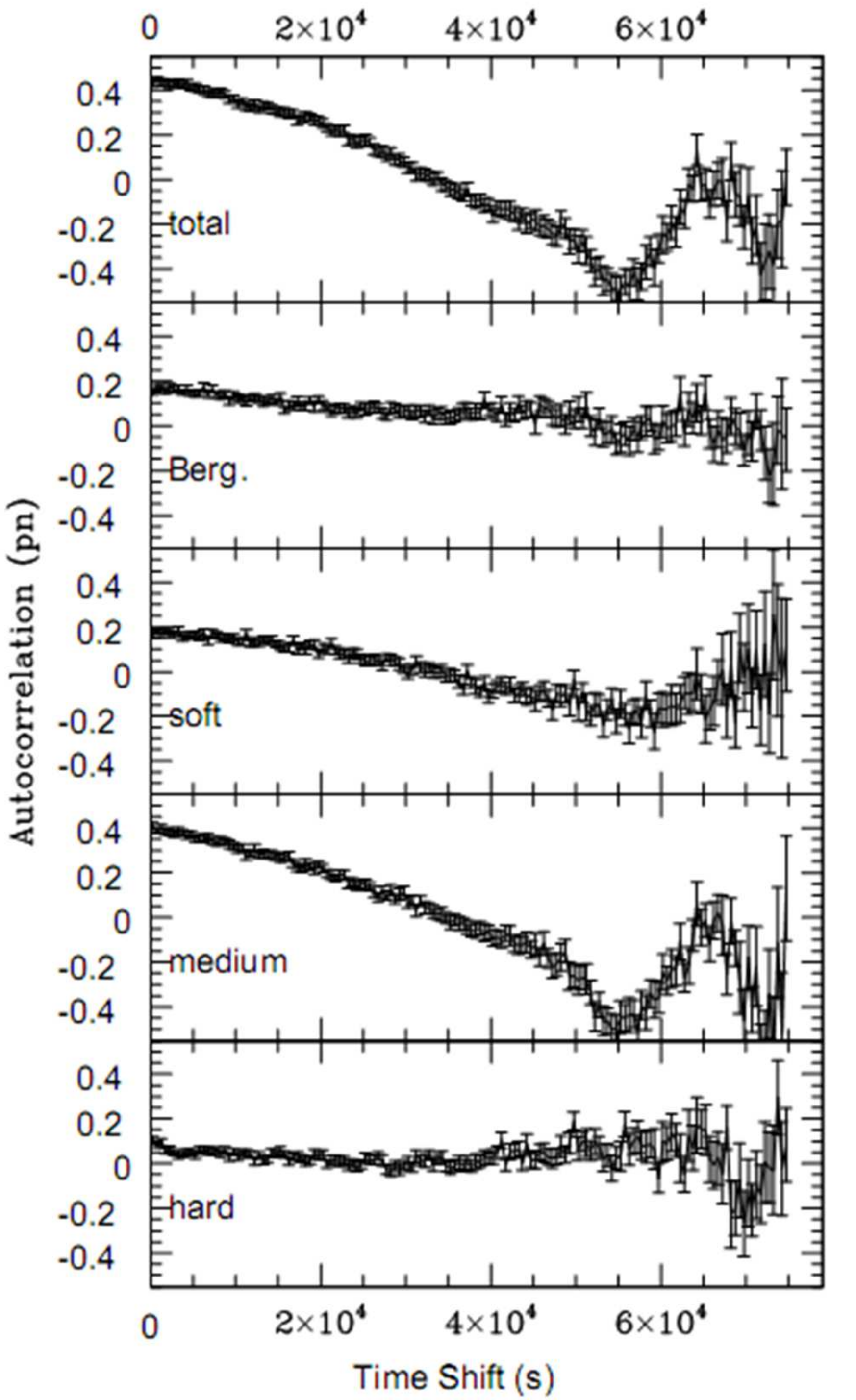
For the best data

(small window, thick filter)

- Fourier
  - 0.3-0.4/d + ~1/d ?
  - Rotation (5d) ????
- Autocorrelation
  - >0 if T<20ks, <0 @ 55ks
  - wind flow time ~5ks

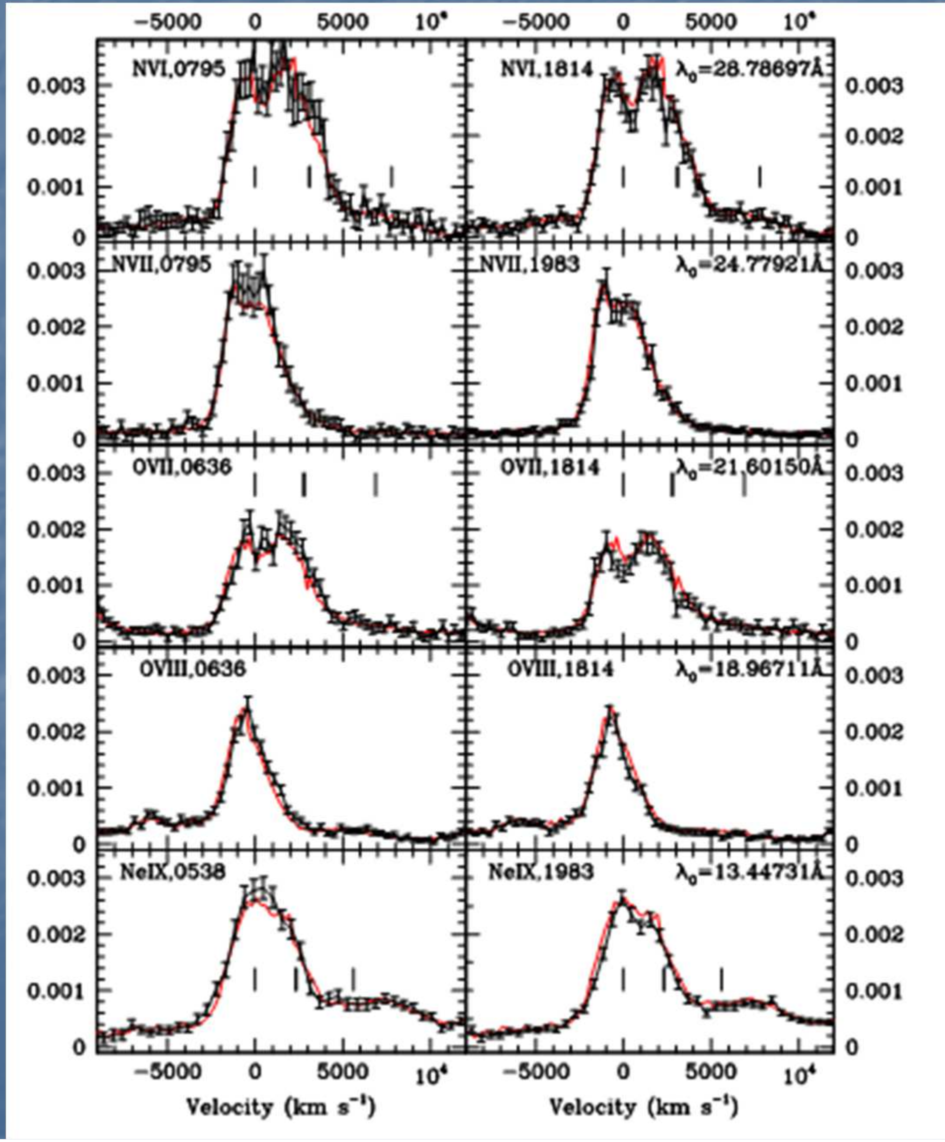
Not very significant anyway

Best case : pn data



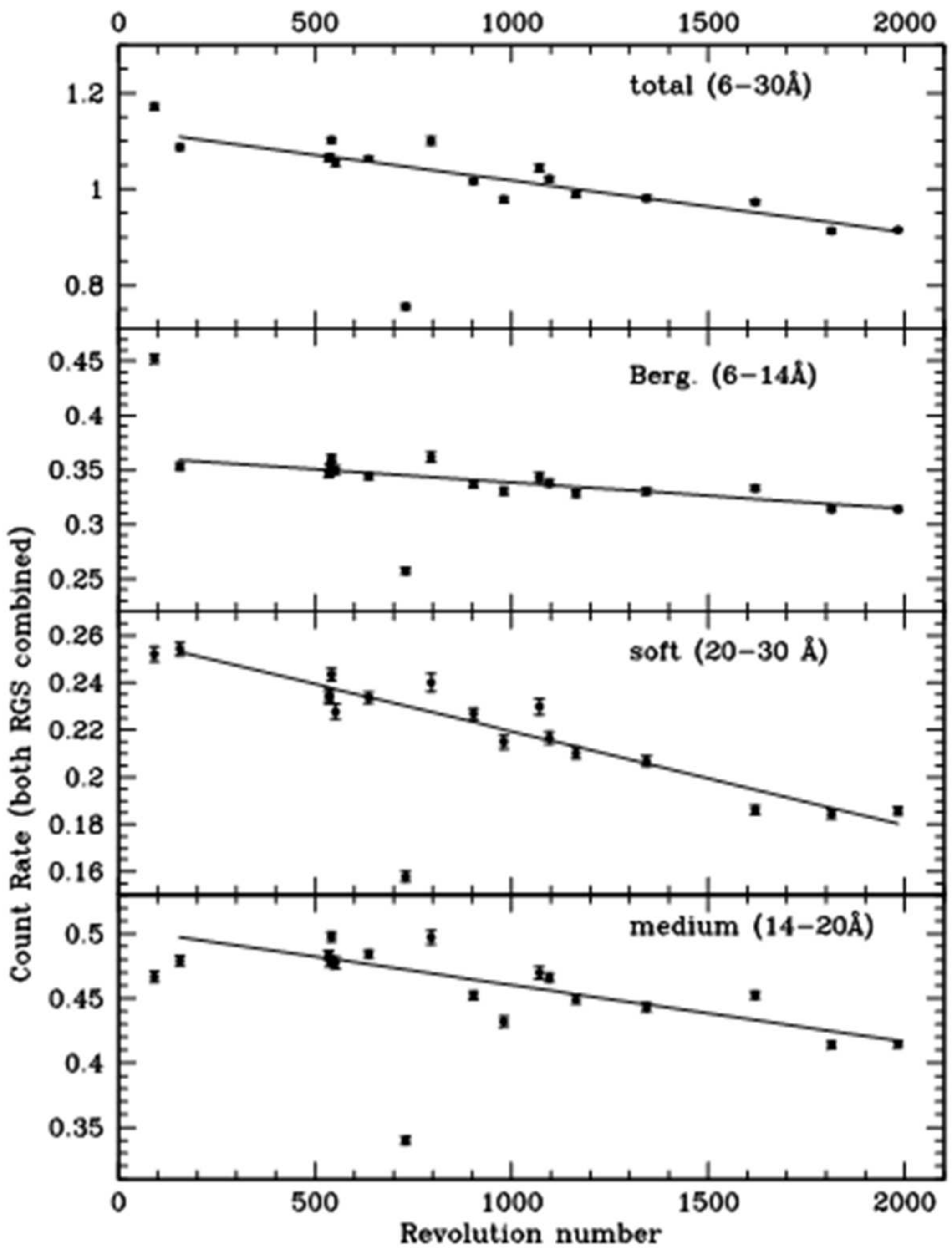
Variability: lines

- RGS data
  - TVS : nothing
  - Count rates and ratios : nothing
  - Comparison with average spectrum by eye : non-significant variations may exist but similar to optical…



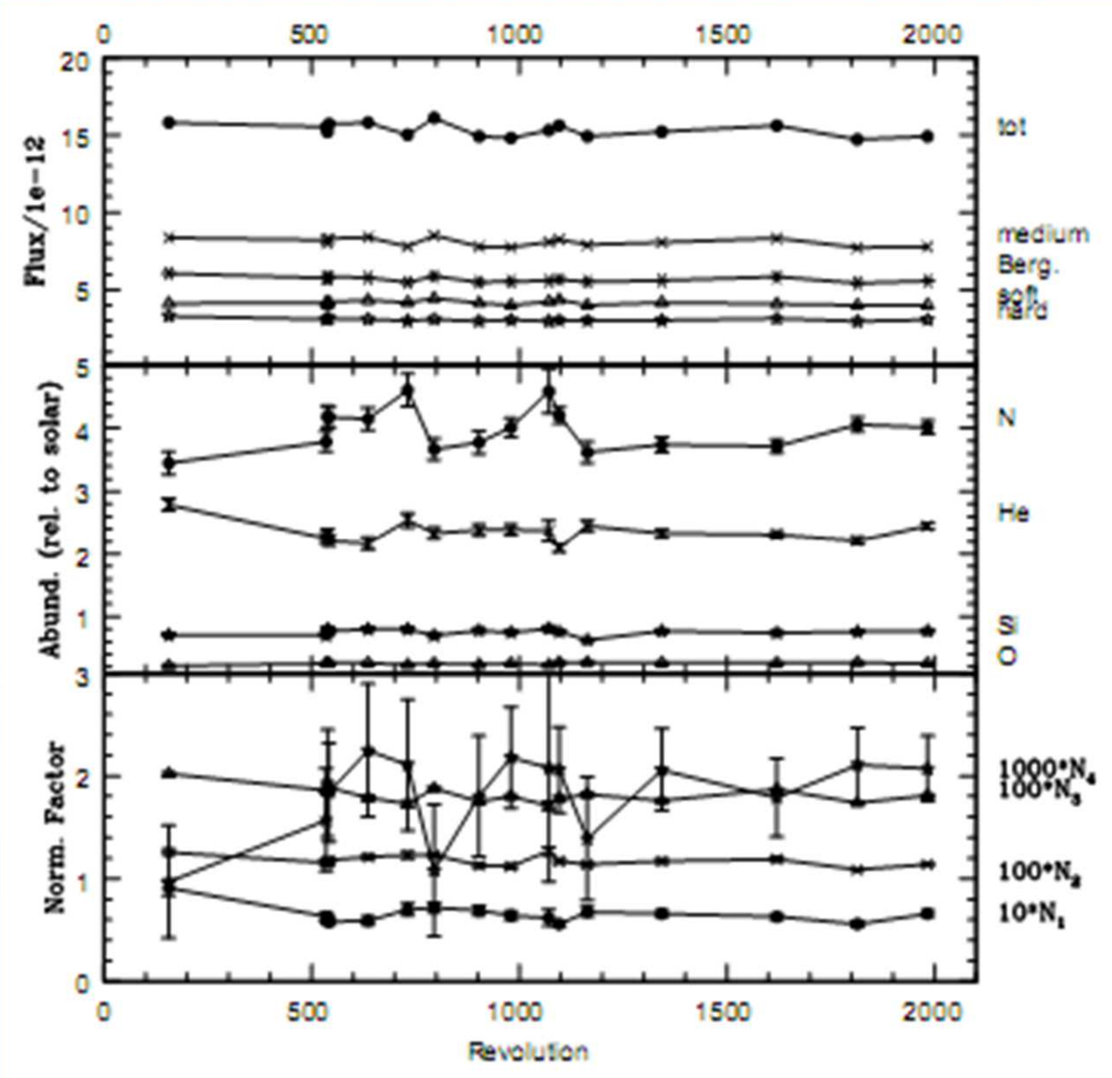
Variability: long-term

- EPIC, RGS : decrease !
  - *NB : Fourier, autocorrelation and relative dispersions calculated after detrending*



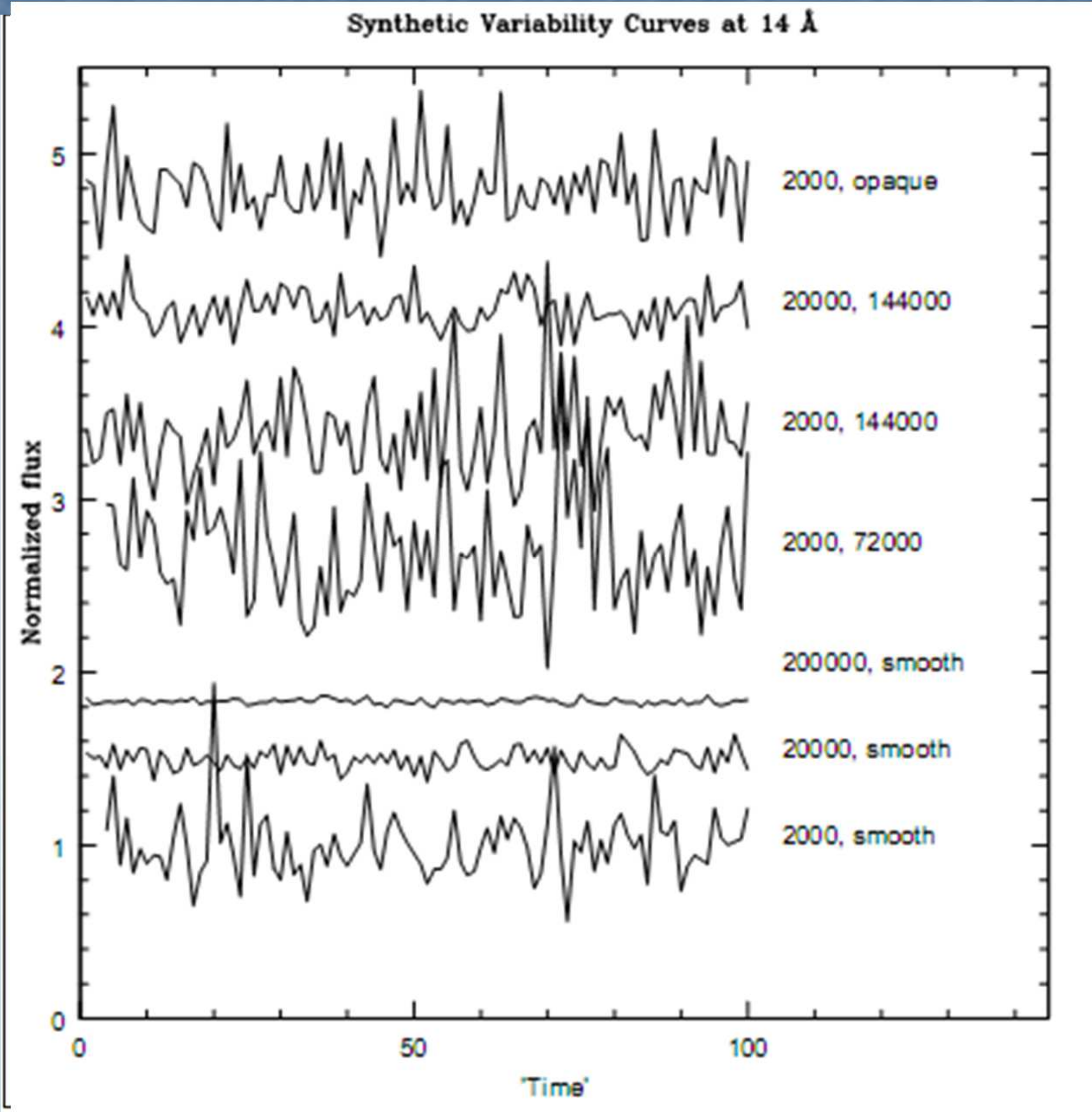
Variability: long-term

- EPIC spectra : fitted by tbabs (ISM, fixed) * sum of 4 thermal comp. (vphabs*vapec – Nh and kT fixed)
- Pile-up affects all data taken with medium filter
- Formally unacceptable fitting but missing physics and disagreement between instruments
- Flux appears quite constant (a few % decrease?) ⇒ count rate variations come from detector sensitivity changes



A simple model

- Features *(Oskinova et al. 2004)*
  - smooth wind or random absorbers
  - random emitters
  - solid angle conserved, outward motion (beta law)
- LCs less variable:
  - at high E
  - for smooth wind
  - For more emitting/absorbing clumps



How to compare with data?

- Relative dispersions calculated for each observation
  - for full LCs
  - for resampled LCs
- Poisson noise !
  - Relative dispersions in both cases ~ Poisson statistics !

$\Rightarrow$ If additional variability exists, it is hidden in noise... hence its amplitude is small, and emitting/absorbing clumps are many ($>10^5$) !

Global spectral fitting : preliminary results

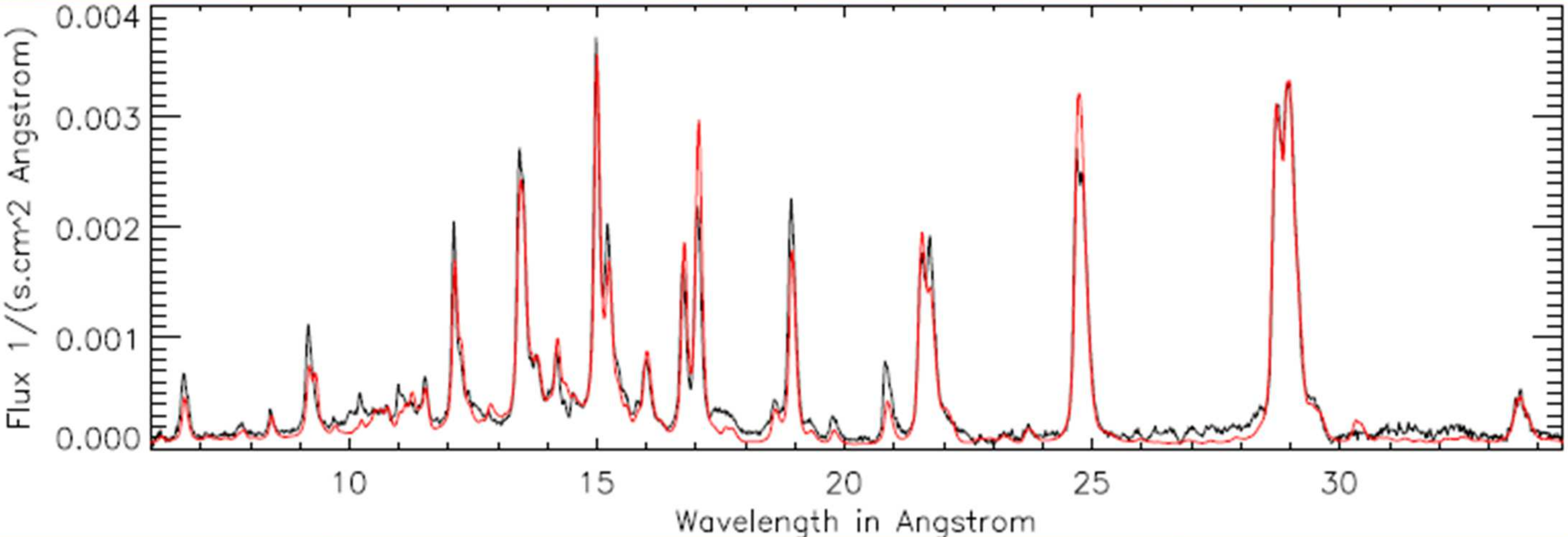


Table 1: Stellar and wind parameters for the fit of the RGS spectrum of ζ-Pup

T_{eff}	40kK
$\dot{M}$	$4.10^{-6}\ M_\odot$/yr
R_*	$18.6 R_\odot$
v_∞	$2250 km.s^{-1}$
$\frac{C_*}{C_\odot}$	0.10
$\frac{O_*}{O_\odot}$	0.35
$\frac{N_*}{N_\odot}$	4.00

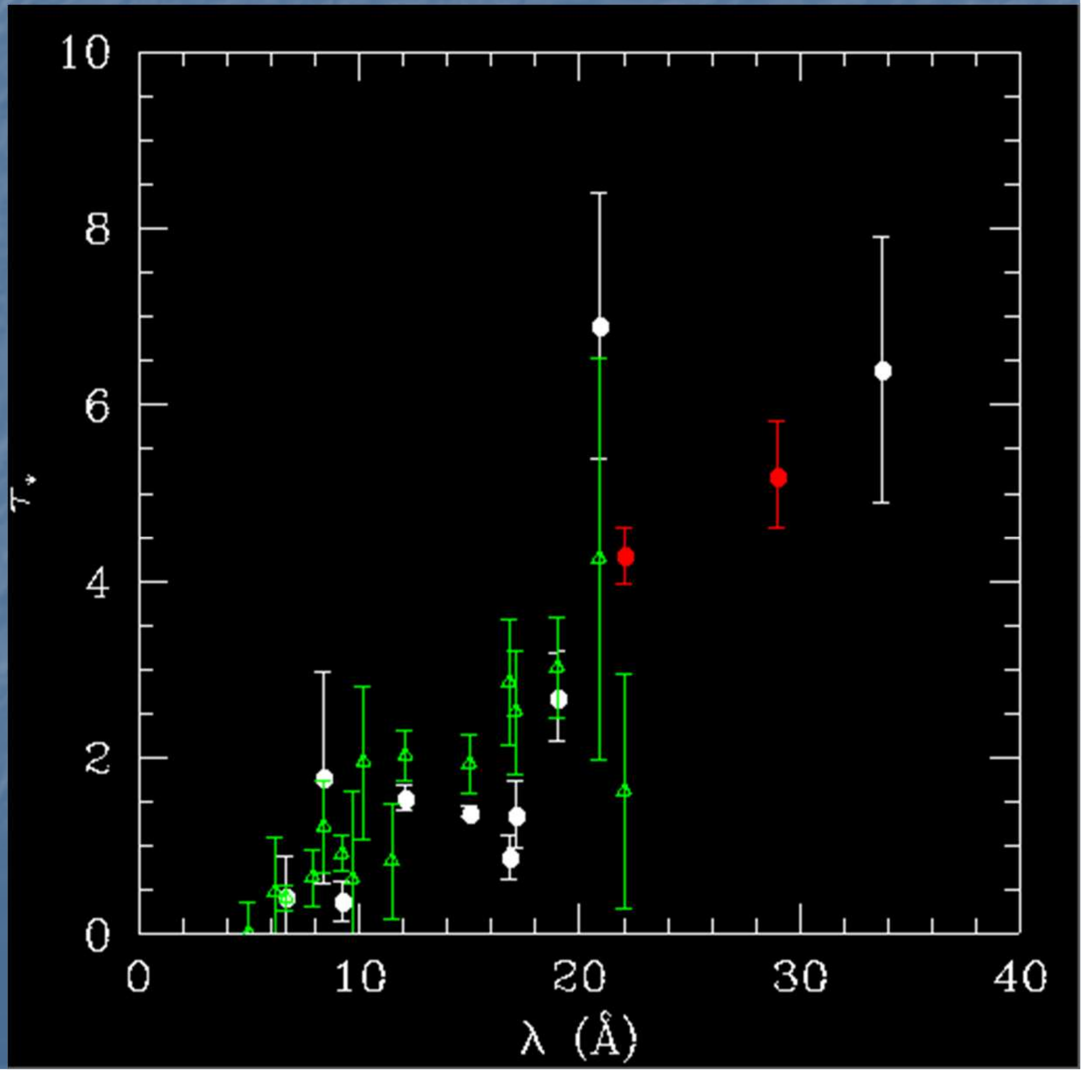
Table 2: Plasma parameters for the fit of the RGS spectrum of ζ-Pup

kT_{plasma} in keV	R_{inner} (in R_*)	R_{size} in (R_*)
0.108	5.	25.
0.175	2.2	5.
0.300	2	3.
0.684	3.	3.5

Line fitting : preliminary results

- Line profile fitting using Owocki & Cohen models : variation of tau with wavelength *(cf. Cohen et al. 2010, in green – NB with resonance scattering in red)*

BUT /!\ uniqueness of solution…



Conclusions

- A decade of XMM observations = best dataset !
- Variability
  - Only noise on short-term
  - Trends on mid-term (DACs ? But no link with rotation, cf. Fourier)
  - Long-term decrease due to detector degradation
  - Comparison with models : a lot of wind parcels needed !
- Lines
  - Multi-temperature needed
  - Typical optical depth varies with wavelength
- For the future…
  - Follow the star over its rotation period
  - Observe it with more sensitive detectors to decrease Poisson noise
  - Develop more detailed models