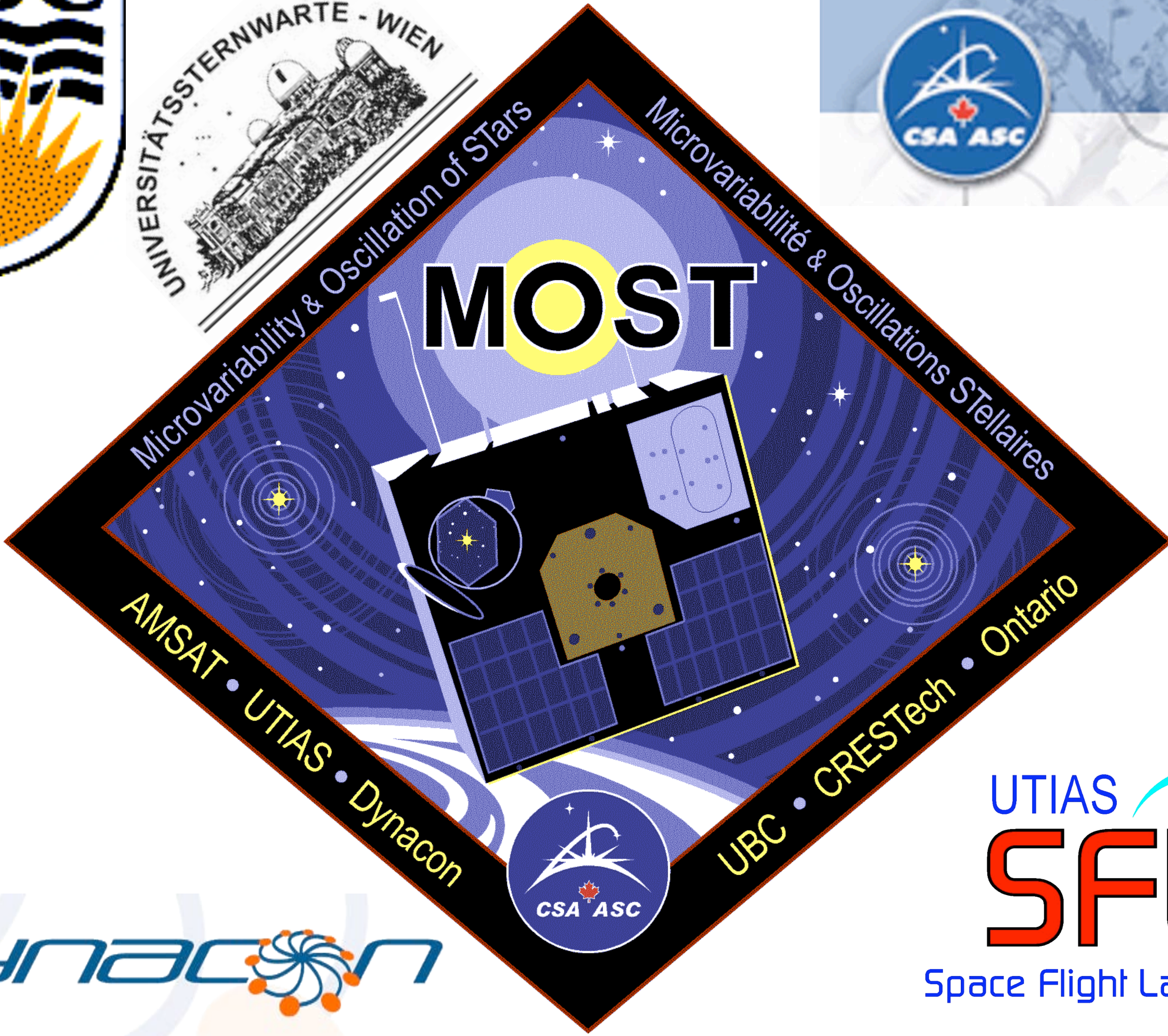
UBC

UNIVERSITÄTSSTERNWARTE - WIEN

Agence spatiale canadienne
Canadian Space Agency
CSA ASC

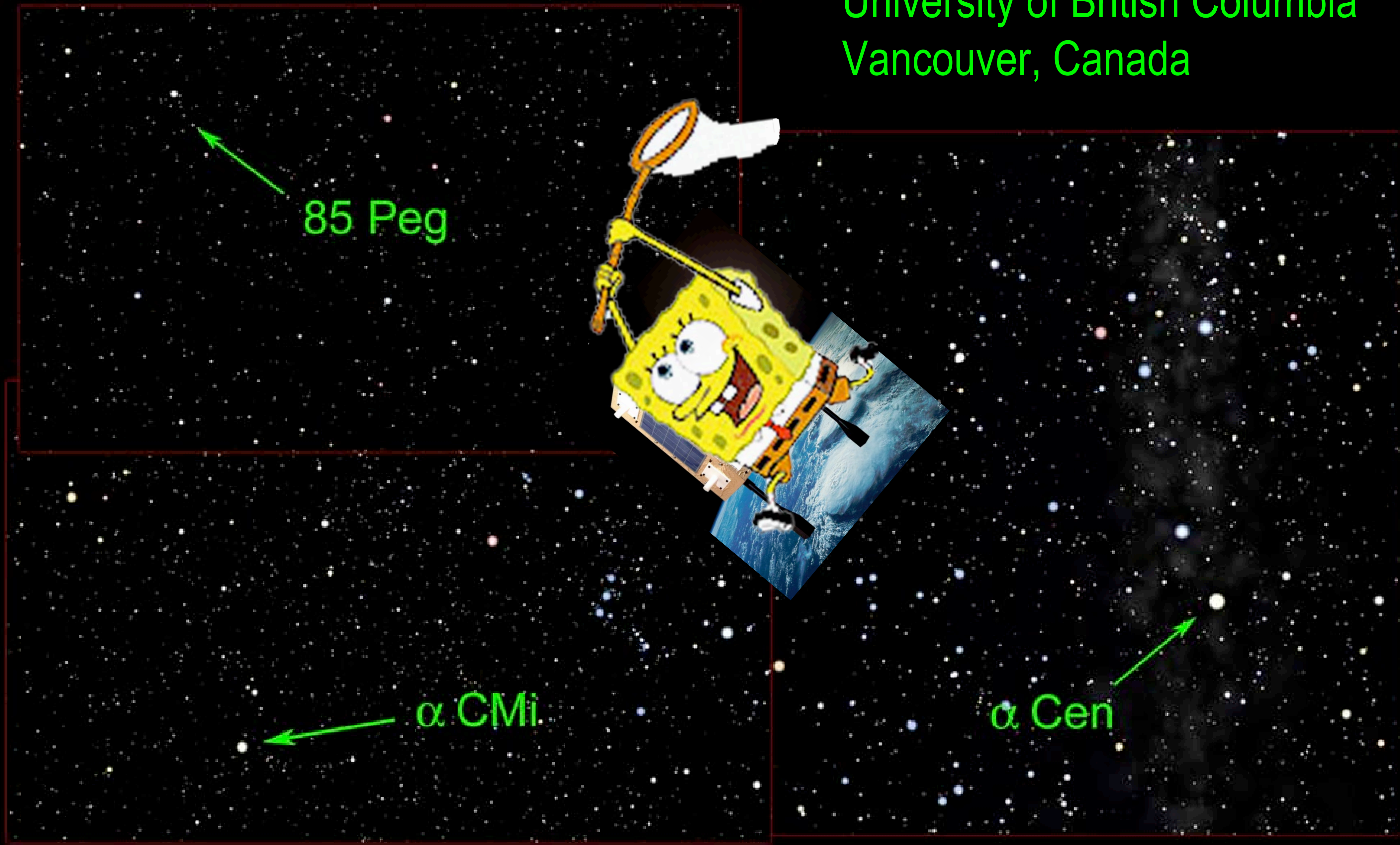


dynacon

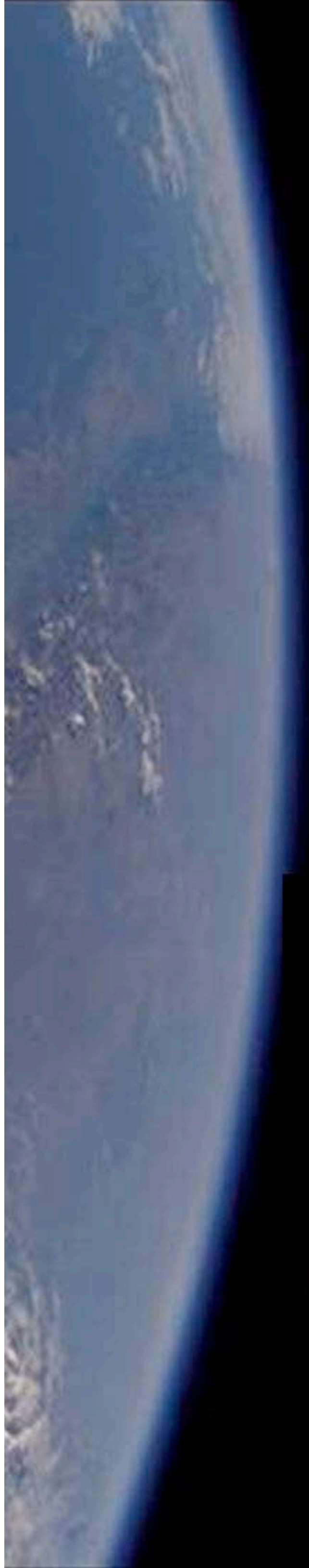
UTIAS
SFL
Space Flight Laboratory

The MOST data pipeline:
Lessons for Kepler?

Jaymie M. Matthews
University of British Columbia
Vancouver, Canada



Observing modes



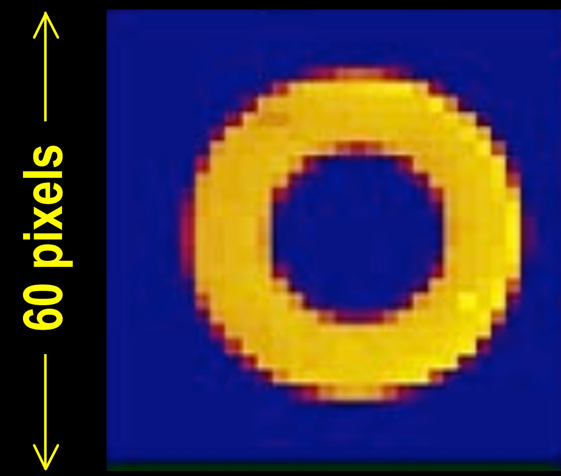
✓ *Fabry Imaging*

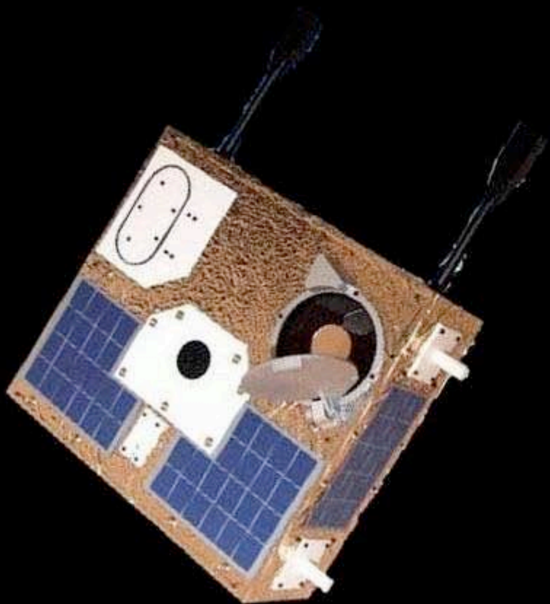
Targets: *0 < V < 6*

Pupil image:

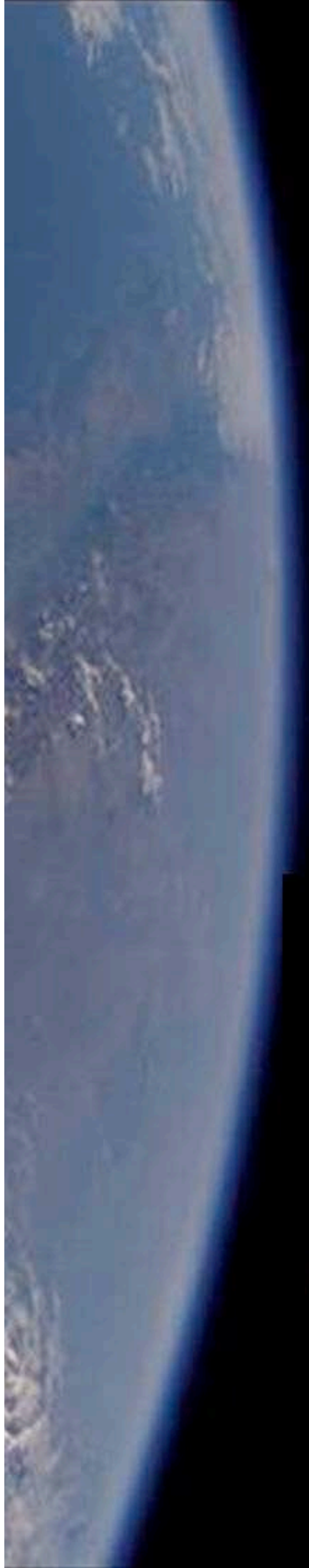
~1500 pixels

fixed to < 0.01 pixel





Observing modes



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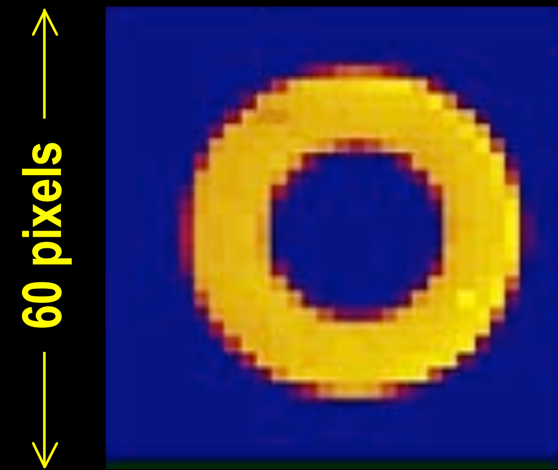
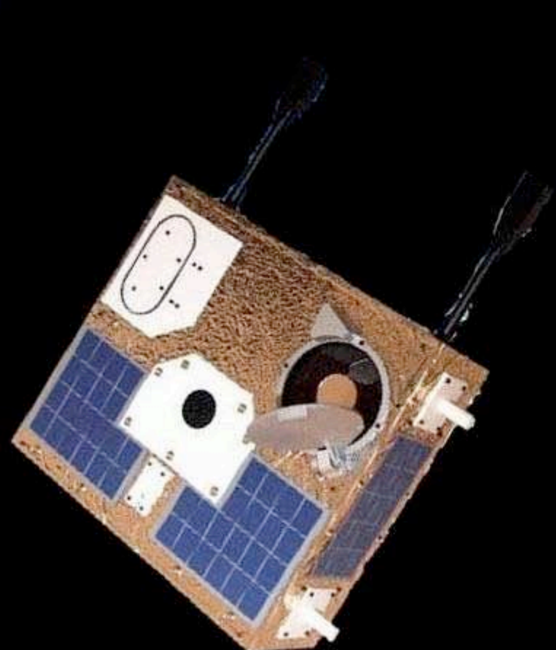
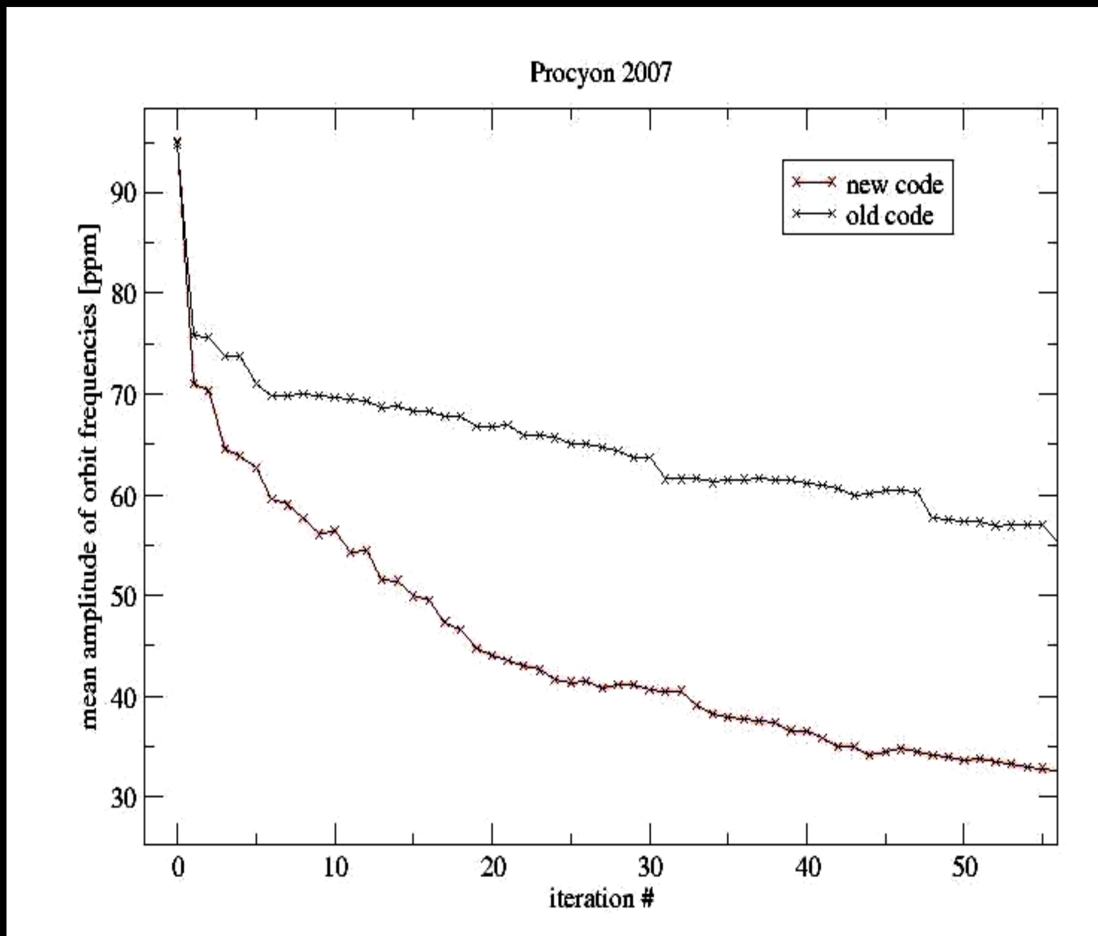


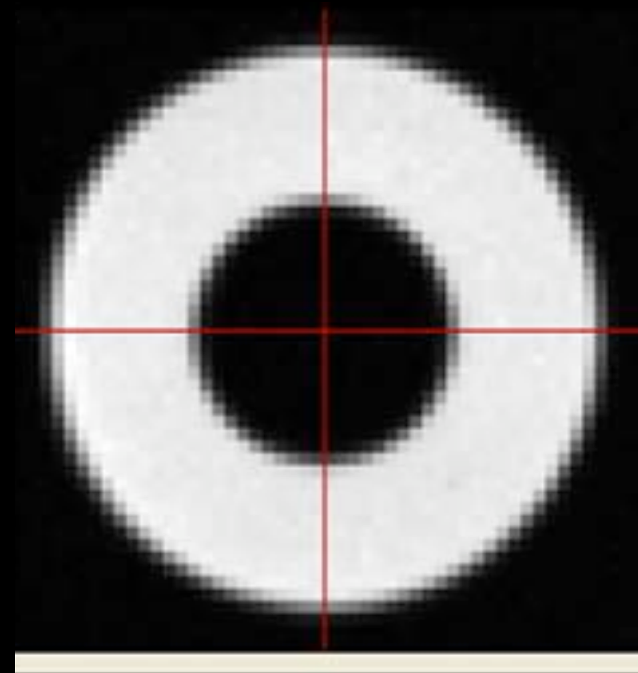
- decorrelation of Target and Background pixels
  - *Reegen et al 2006, MNRAS*
- very effective removal of stray light artifacts at the expense of slightly increased Poisson noise
- improved artifact identification
  - *Kallinger, Guenther, Matthews et al. 2007, CoAst*

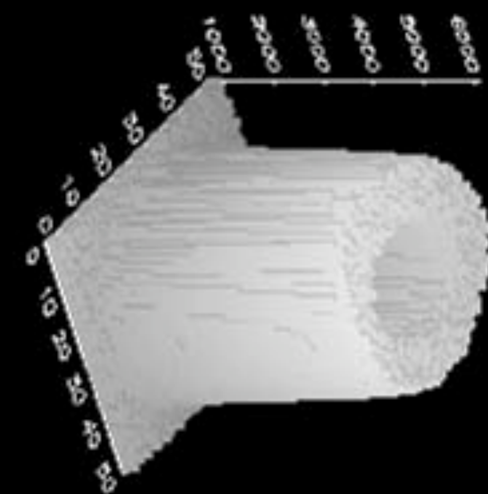


Observing modes

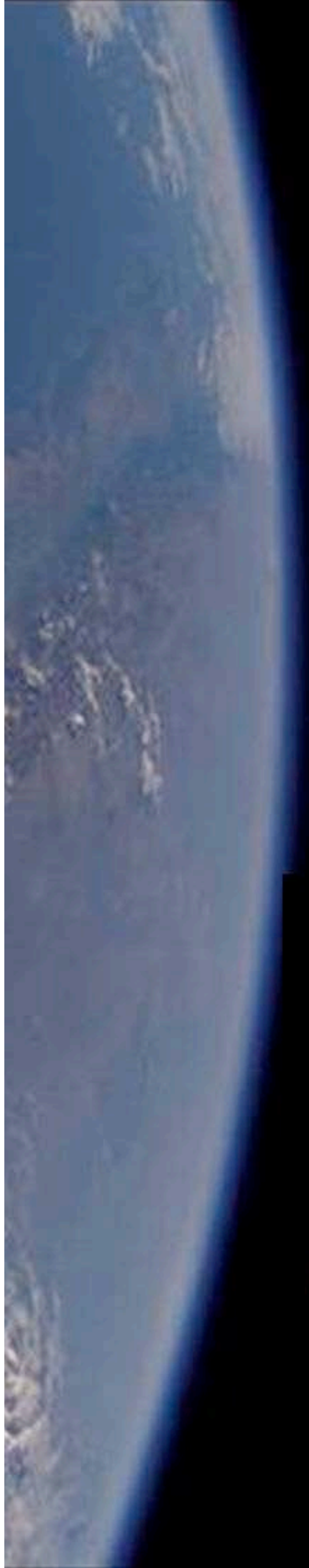
- ✓ *Fabry Imaging*







Decorrelation of target and background pixels



Observing modes

✓ Fabry Imaging

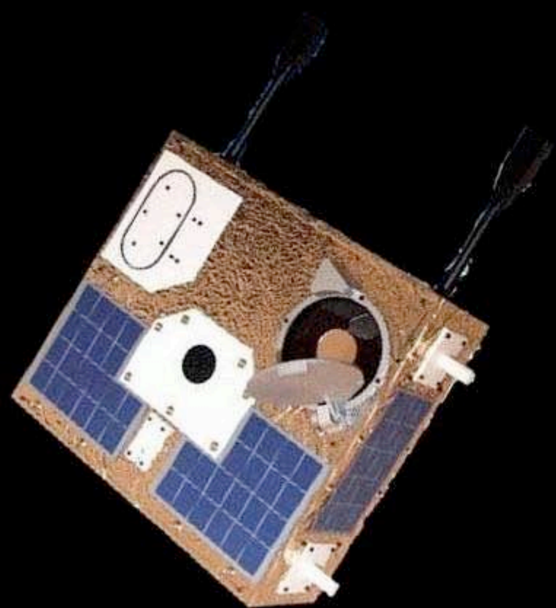
Targets: *0 < V < 6*

Pupil image:

~1500 pixels

fixed to < 0.01 pixel

✓ Direct Imaging



Targets: *6 < V < 13*

PSF FWHM:

~2.2 pixels

pointing stable to ~1/3 pix

Observing modes

✓ Guide Star photometry

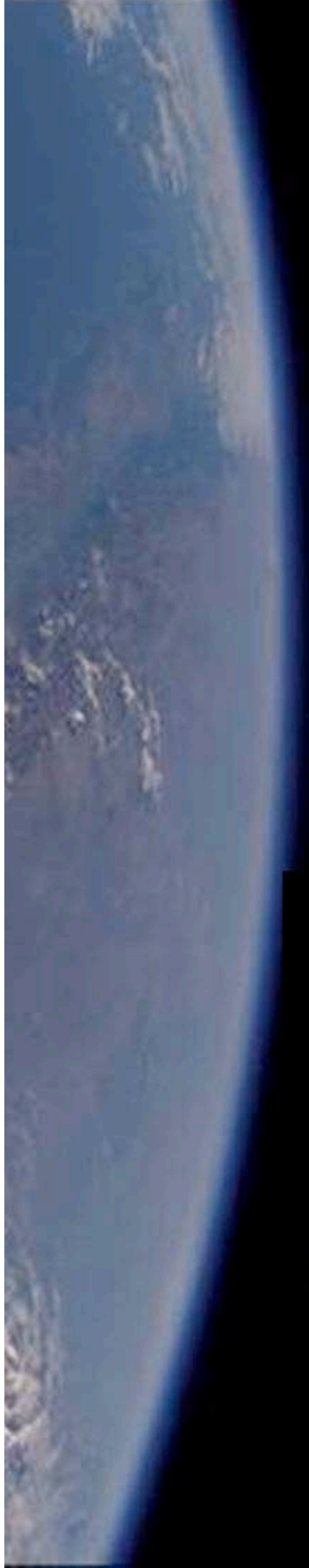
Targets: *8 < V < 11*

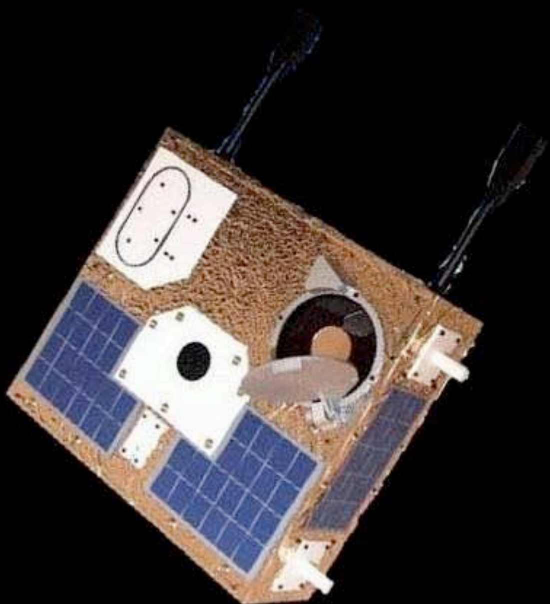
PSF FWHM:

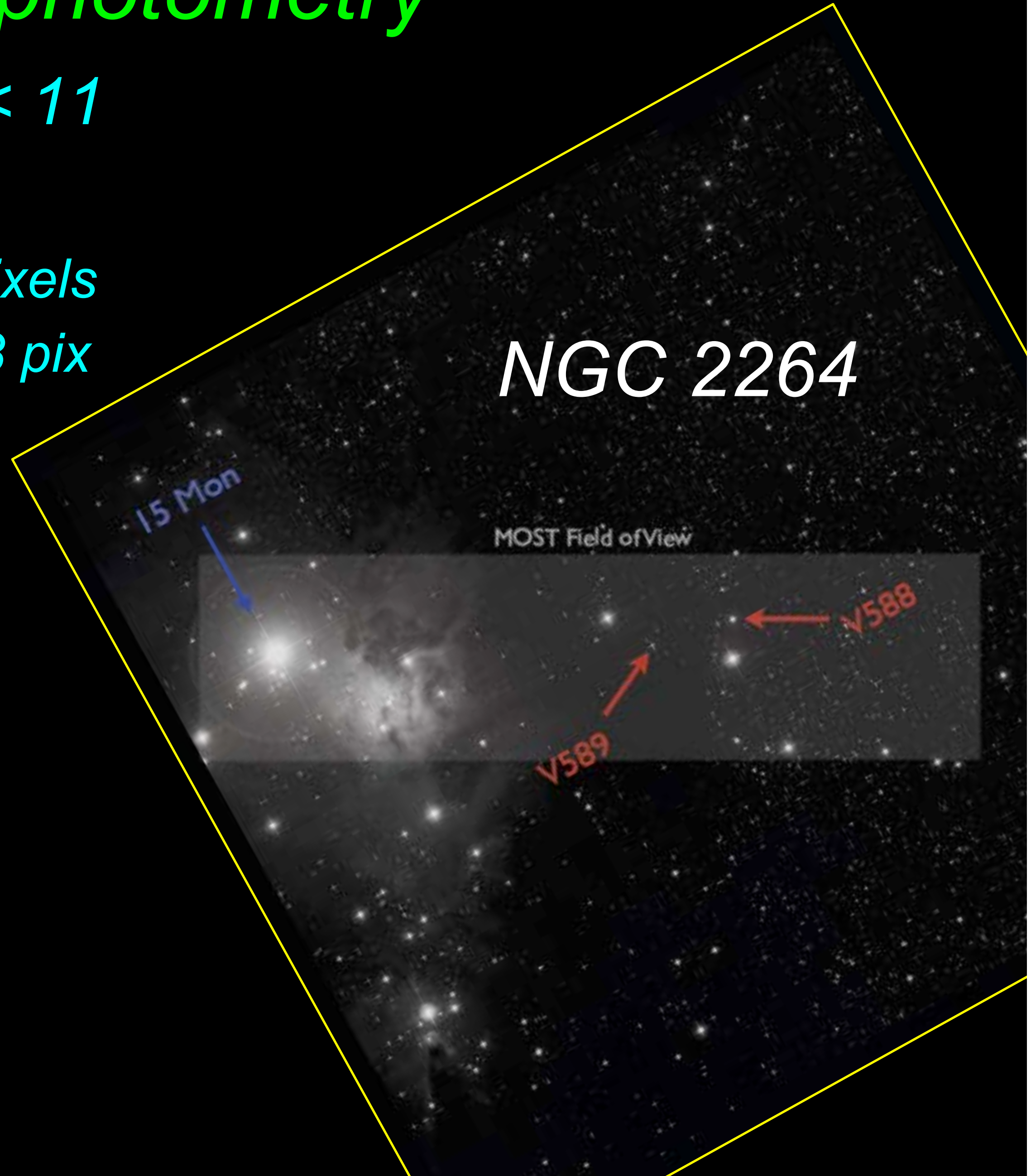
~2.2 pixels

pointing stable to ~1/3 pix

reduced on board automatically

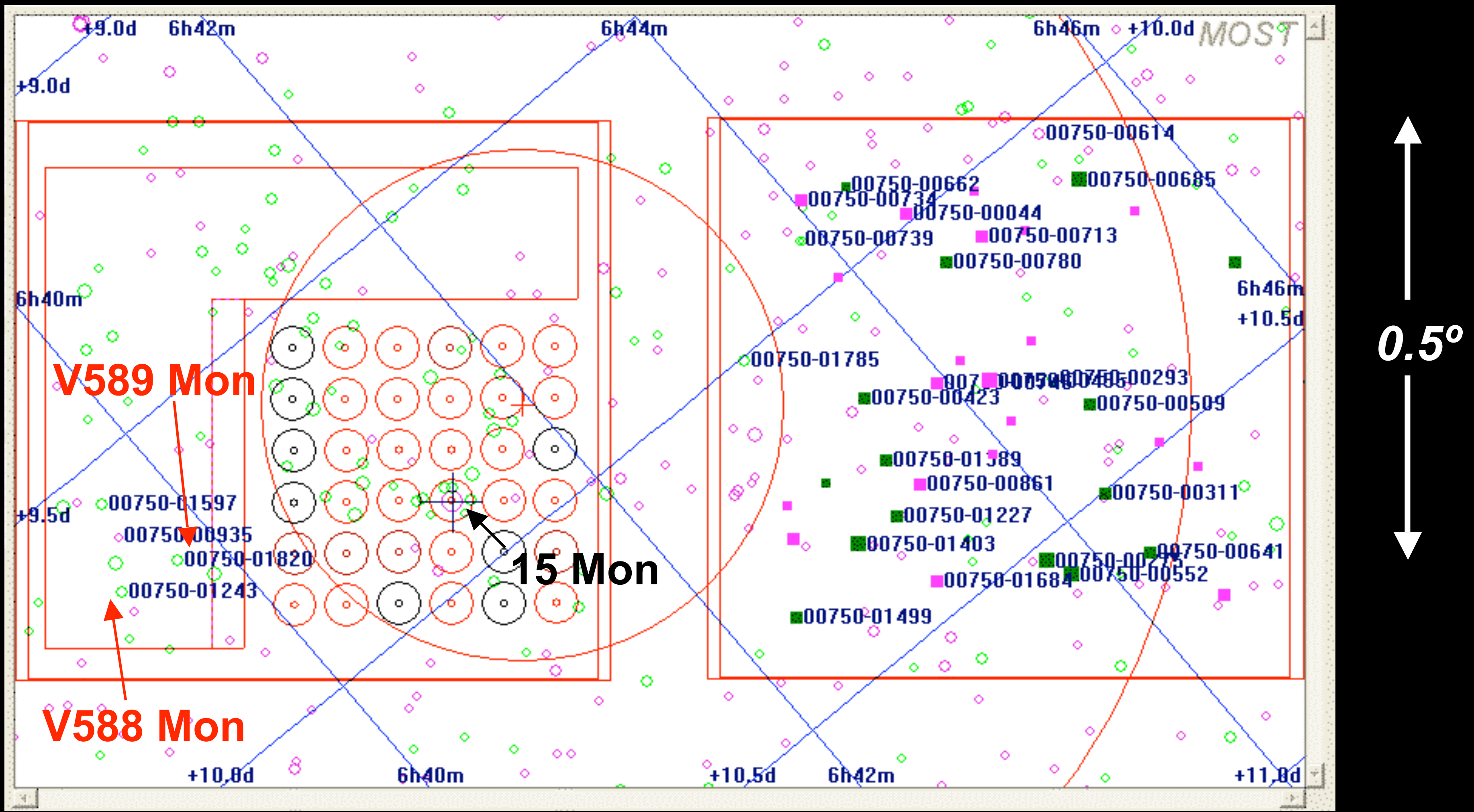






Observing modes

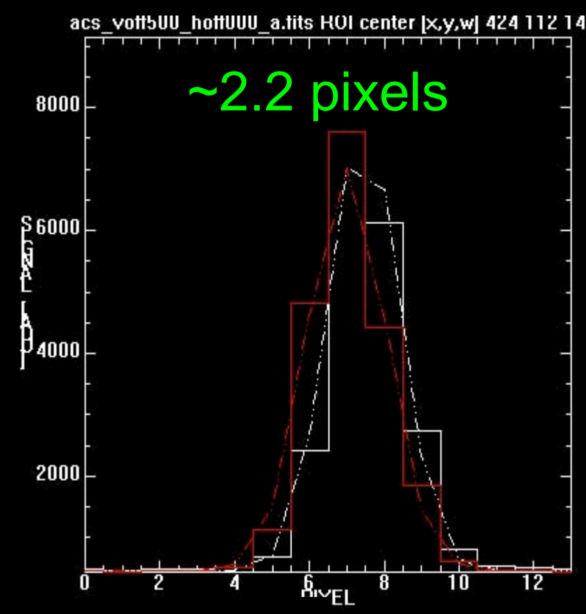
✓ *Guide Star photometry*



Photometry of up to 30-50 stars

NGC 2264

Photometric reductions



✓ Direct Imaging

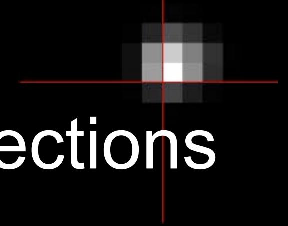
Targets: *6 < V < 13*

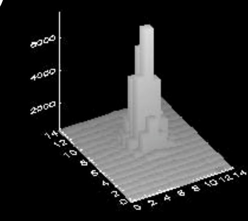
PSF FWHM:

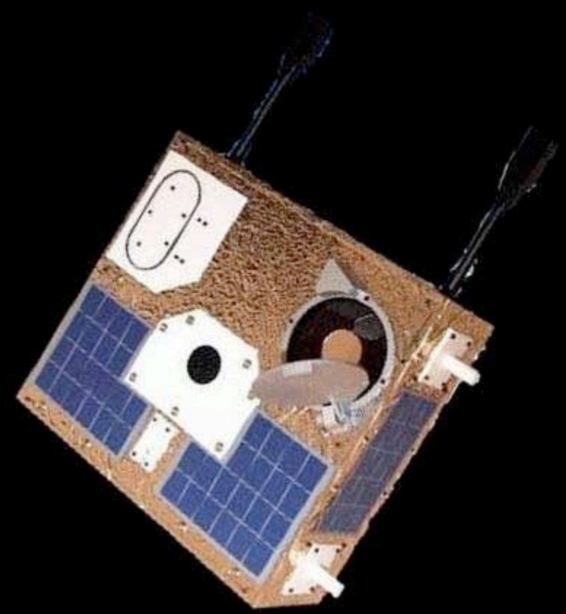
~2.2 pixels

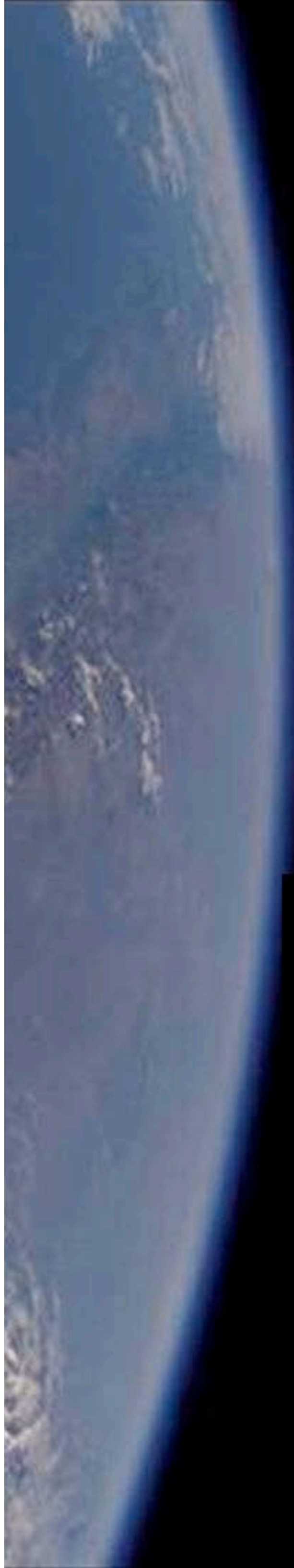
pointing stable to ~1/3 pix

- PSF & aperture photometry
- image stacking
- background corrections









Photometric reductions

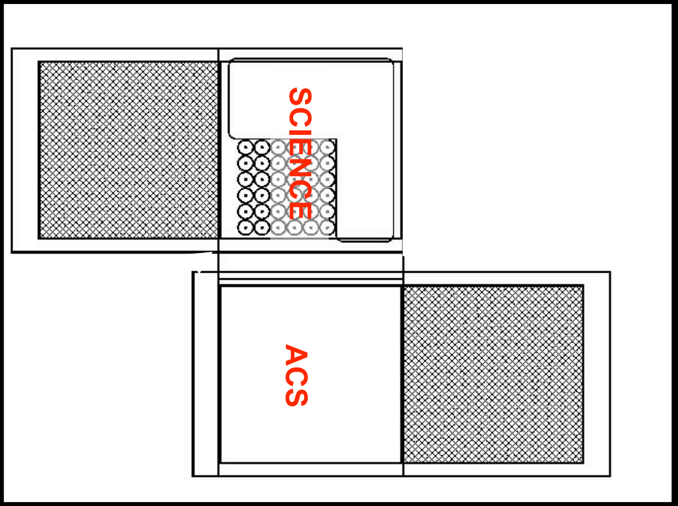
✓ Direct Imaging

Targets: *6 < V < 13*

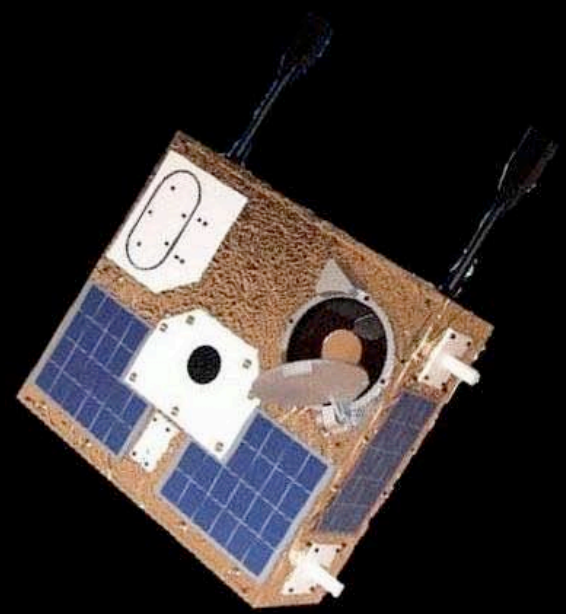
PSF FWHM:

~2.5 pixels

pointing stable to ~1/3 pix



- PSF & aperture photometry
- image stacking
- background corrections
- crosstalk between CCDs
  - *no longer an issue since we operate now only with Science CCD*
- no calibration source
  - *scattered Earthshine at certain seasons allows us to flatfield*



Photometric reductions

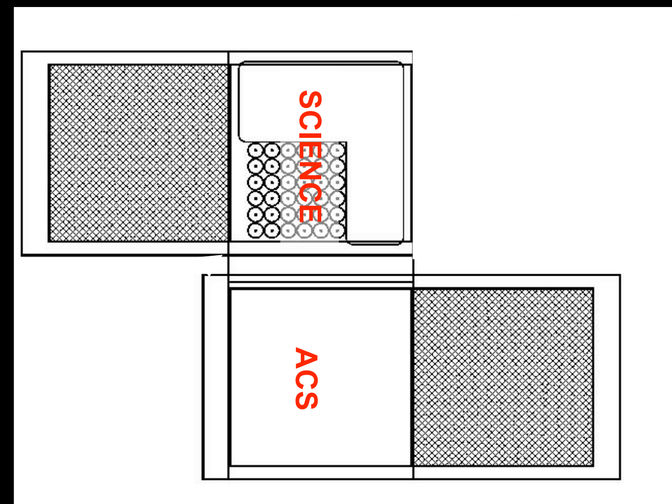
✓ *Direct Imaging*

Targets: *6 < V < 13*

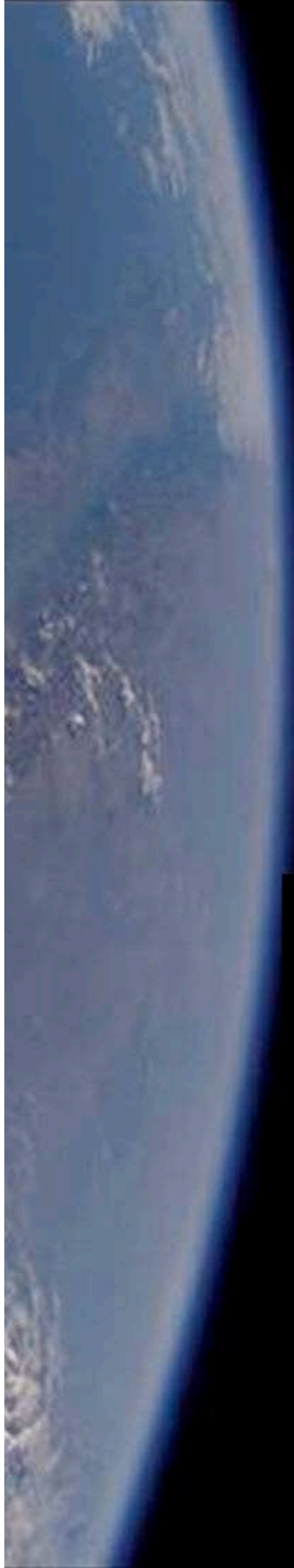
PSF FWHM:

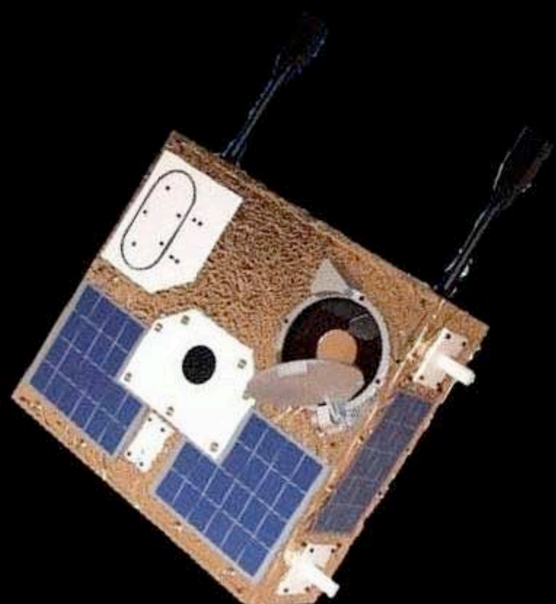
~2.5 pixels

pointing stable to ~1/3 pix



- reduction pipeline results in point-to-point precision within ~10% of Poisson noise limit



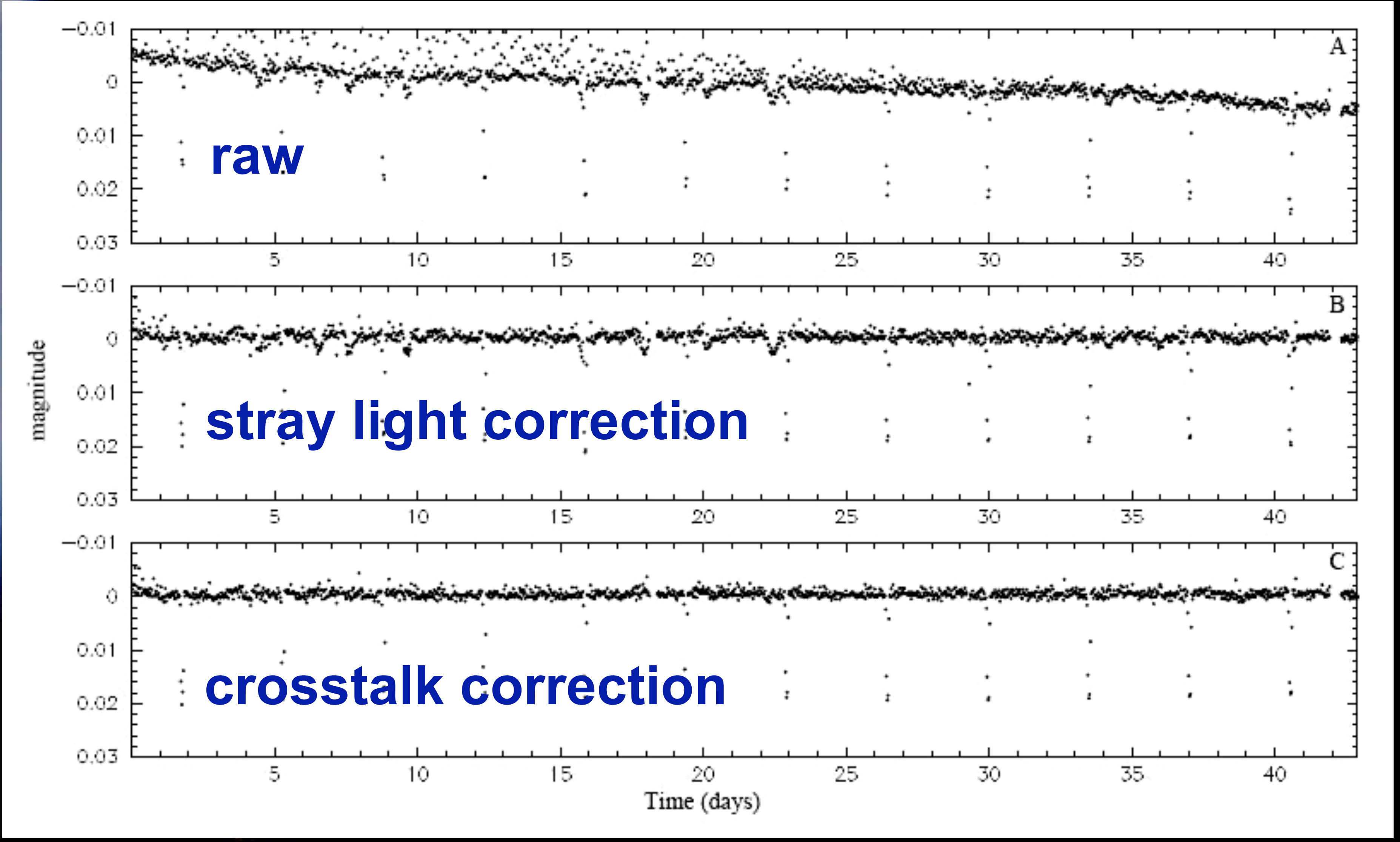


Photometric reductions

✓ Direct Imaging

HD 209458 *V ~ 7.5*

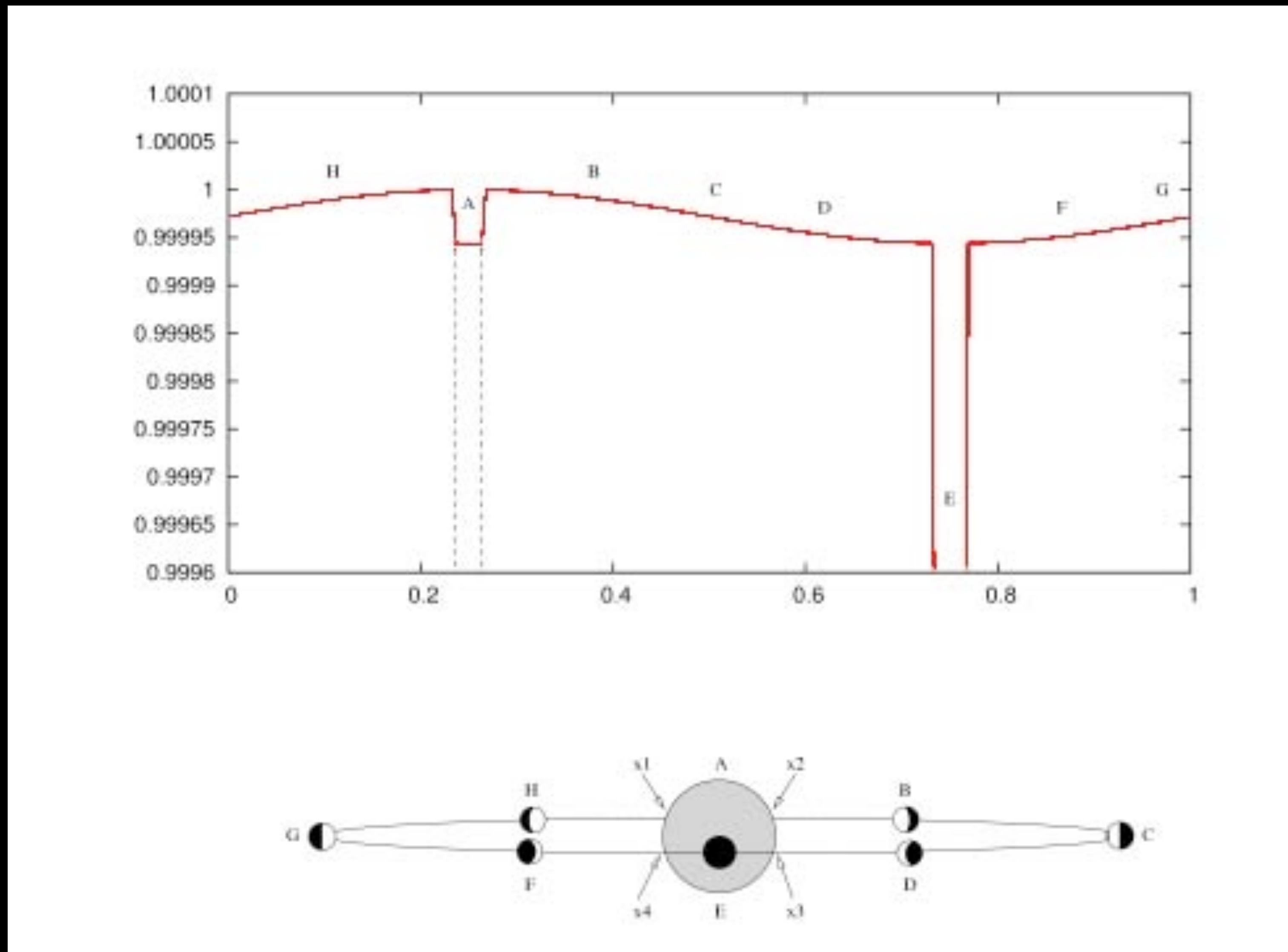
40-min bins



Light curve modeling

HD 209458 *V ~ 7.5*

✓ *Direct Imaging*

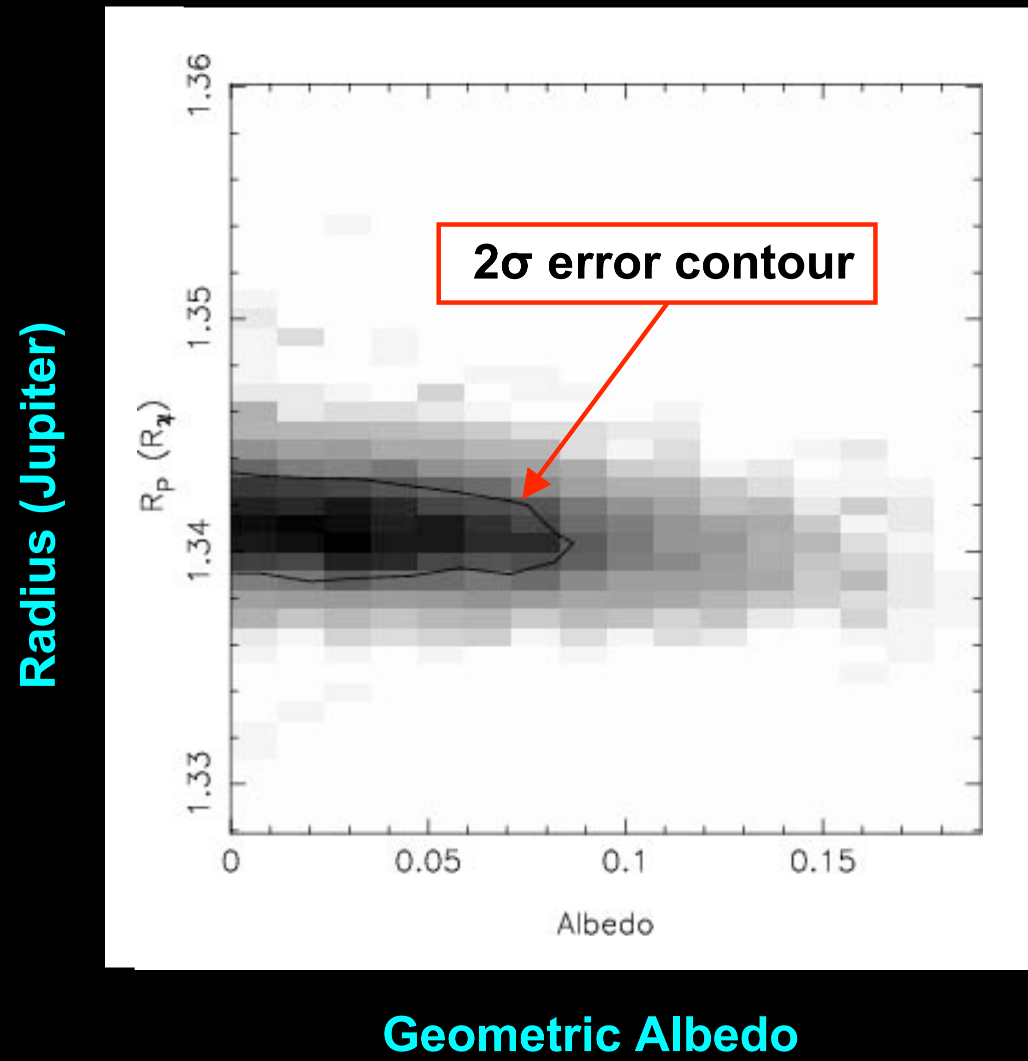


Light curve modeling

HD 209458 *V ~ 7.5*

✓ *Direct Imaging*

- Best fit:
  - *albedo : 0.04 ± 0.04*



Light curve modeling

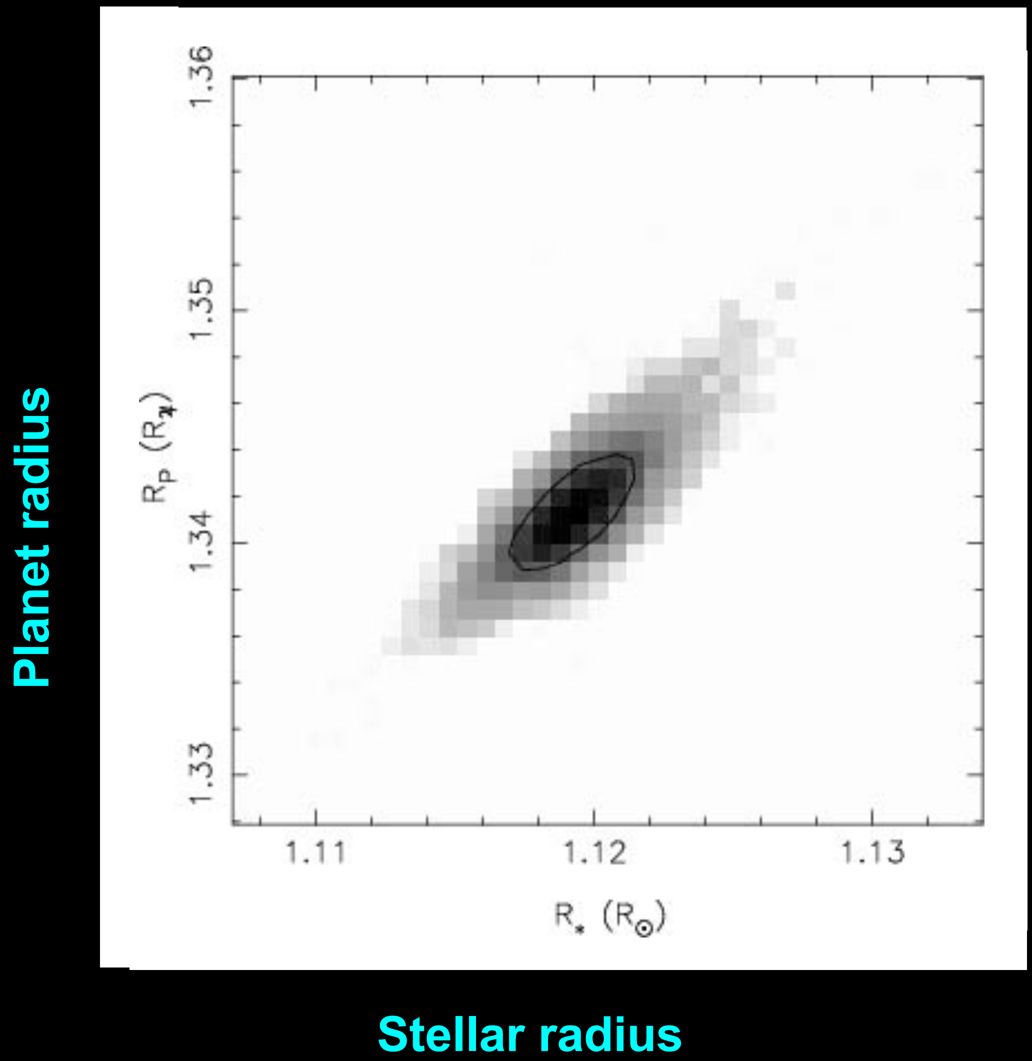
HD 209458 *V ~ 7.5*

✓ *Direct Imaging*

- Best fit:
  - *albedo : 0.04 ± 0.04*
  - stellar radius :
    1.339 ± 0.001 R_{Jup}
  - stellar mass
    1.084 ± 0.005 M_{Sun}

  i = 86.937° ± 0.003°
  P = 3.5247489 d

Rowe, Matthews et al. 2007
ApJ, submitted



Photometric reductions

✓ *Direct Imaging*

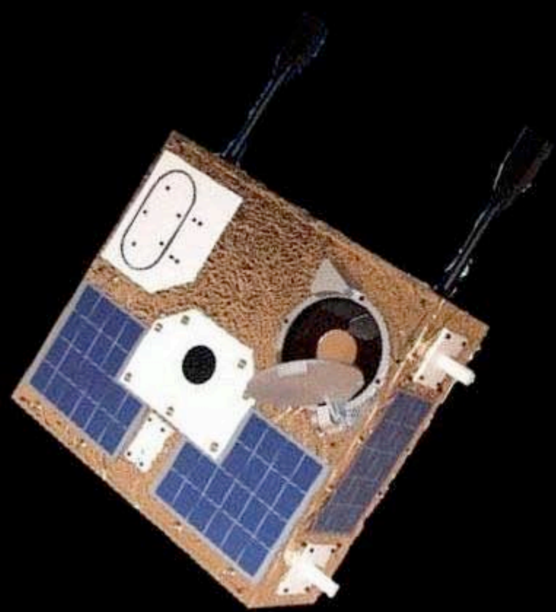
- UBC
- Vienna
- U Toronto (DDO)

✓ *Fabry Imaging*

- Vienna
- UBC

Parallel independent reduction streams

Convergence towards standardised pipelines



Photometric reductions

✓ *Direct Imaging*

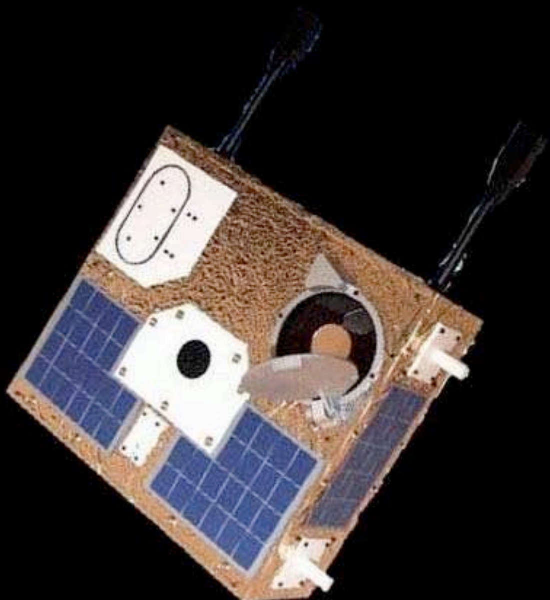
- <u>UBC</u>
- Vienna
- U Toronto (DDO)

✓ *Fabry Imaging*

- <u>Vienna</u>
- UBC

Parallel independent reduction streams

Convergence towards standardised pipelines



CCD stability

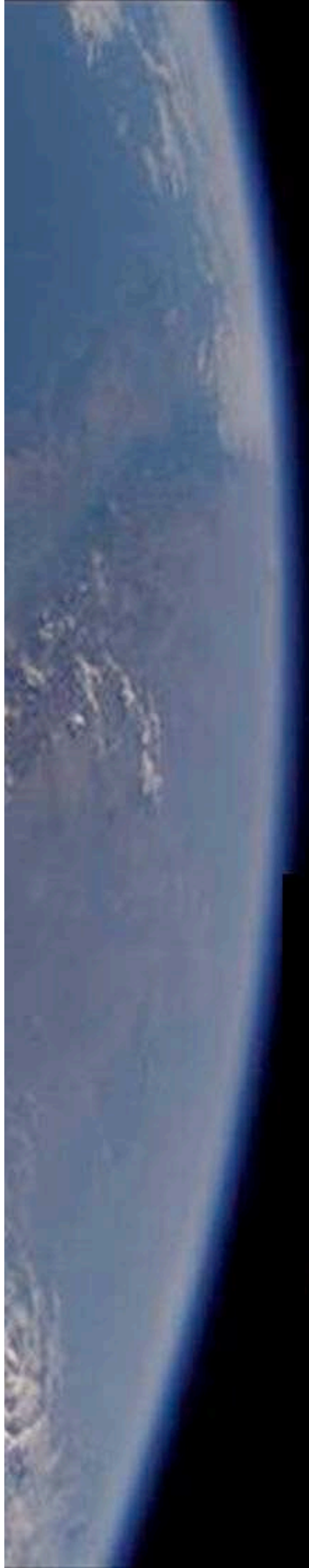
- ✓ *E2V 47-20 frame-transfer devices*
  - radiation tolerance
    - *warm pixels have not been a problem after almost 4.5 years in orbit*
  - CTI not an issue
  - gain stability
  - temperature regulation $\Delta T \sim 0.1$ C
  - temperature knowledge $\Delta T \sim 0.01$ C

- passive temperature regulation of CCD electronics
  $\Delta T \sim 2$ C during orbit

Stellar stability

✓ *difficult to do conventional <u>differential</u> photometry*

- intrinsic stellar variability at sub-mmag level
- \`ensemble' comparisons of only limited effectiveness for number of stars available in MOST field and brightness range
- comparison stars used only as \`canaries in the mineshaft' to recognise any subtle background artifacts



Stellar stability

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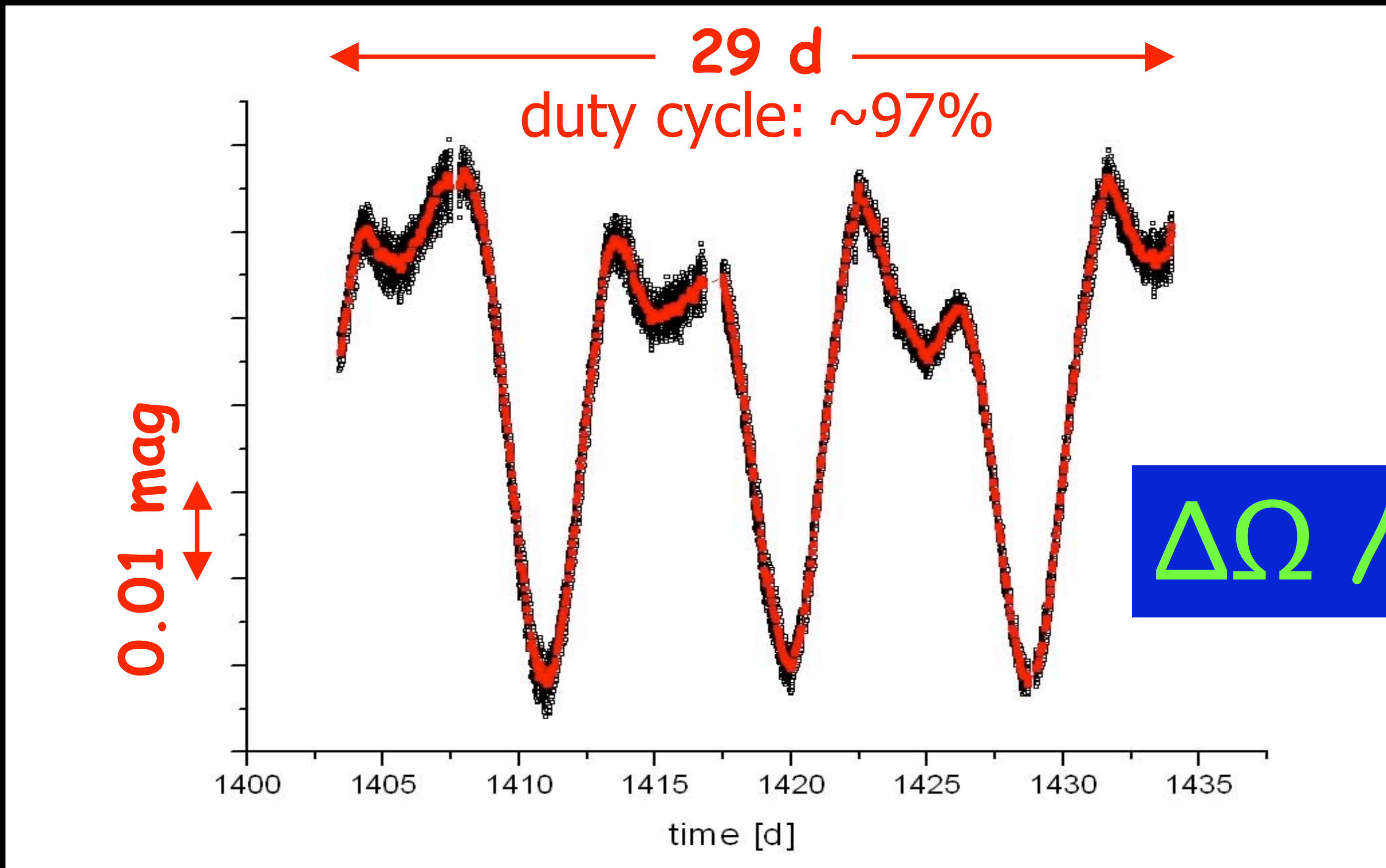
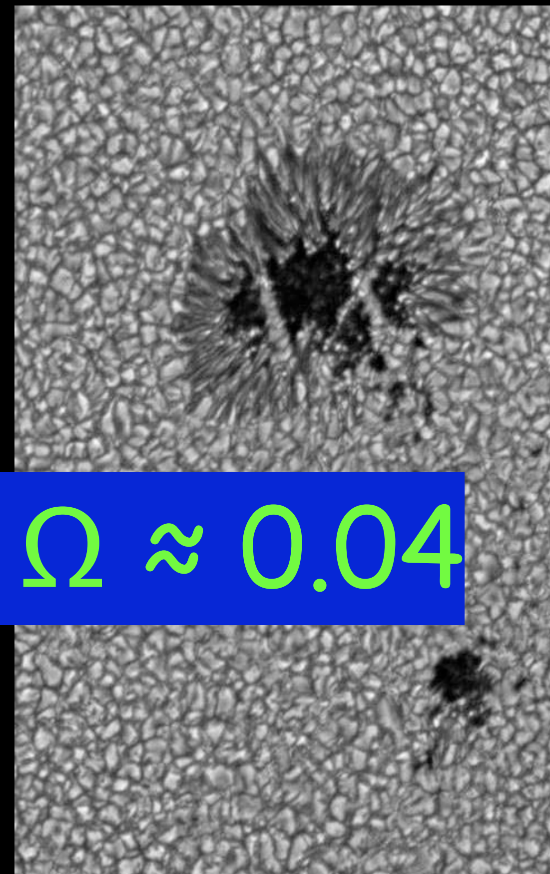
Differential rotation

kappa 1 Ceti





$\Delta\Omega / \Omega \approx 0.04$

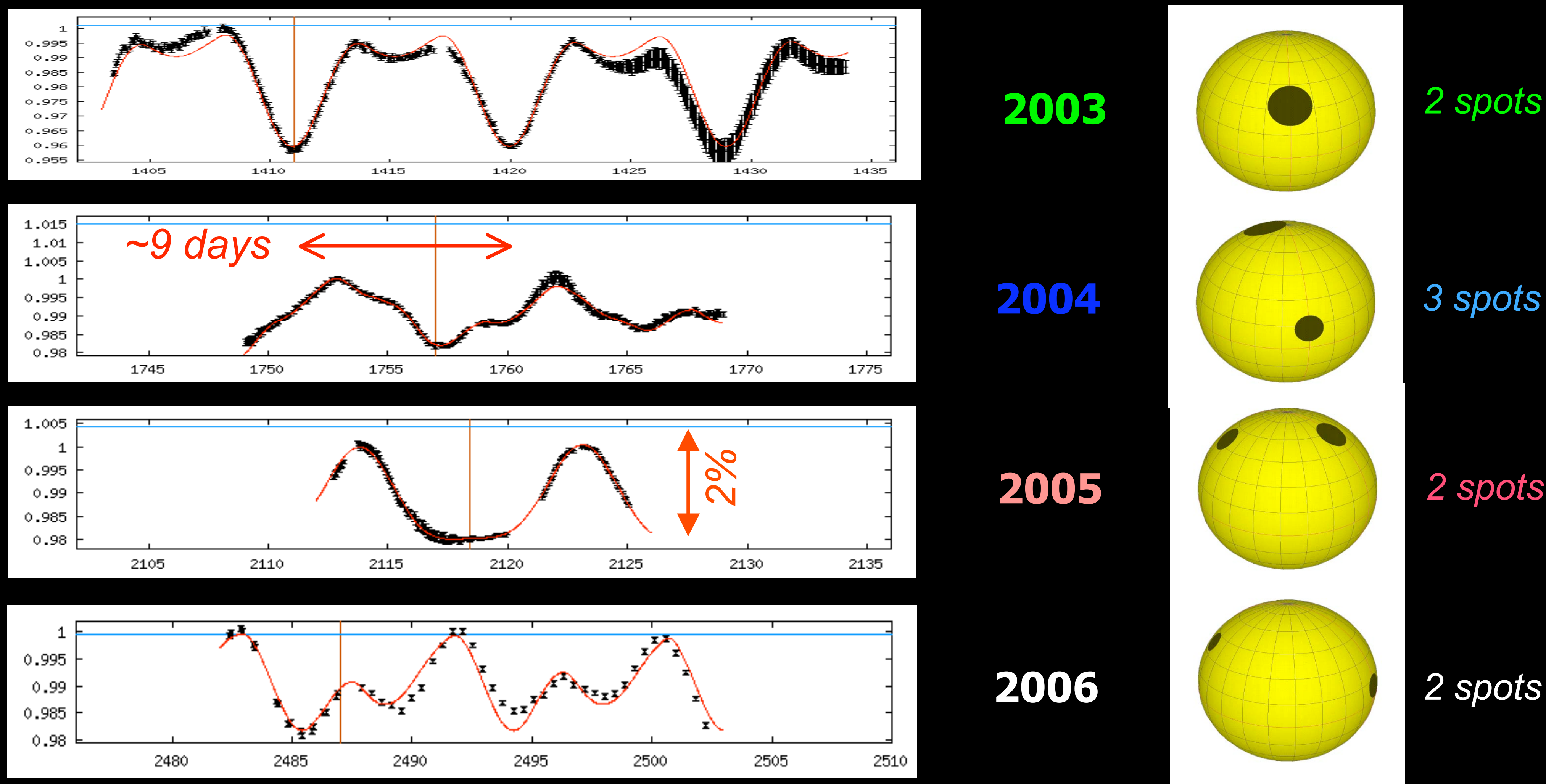
- kappa 1 Ceti light curve modeled by *differentially rotating* starspots at different latitudes

Rucinski, Walker, Matthews et al. 2004 PASP

kappa 1 Ceti

Differential rotation

MOST light curves and best-fitting spot models



HJD - 2451545

Walker, Croll, Matthews et al. ApJ 2007

kappa 1 Ceti

Differential rotation

A rotation profile
for a star other than the Sun

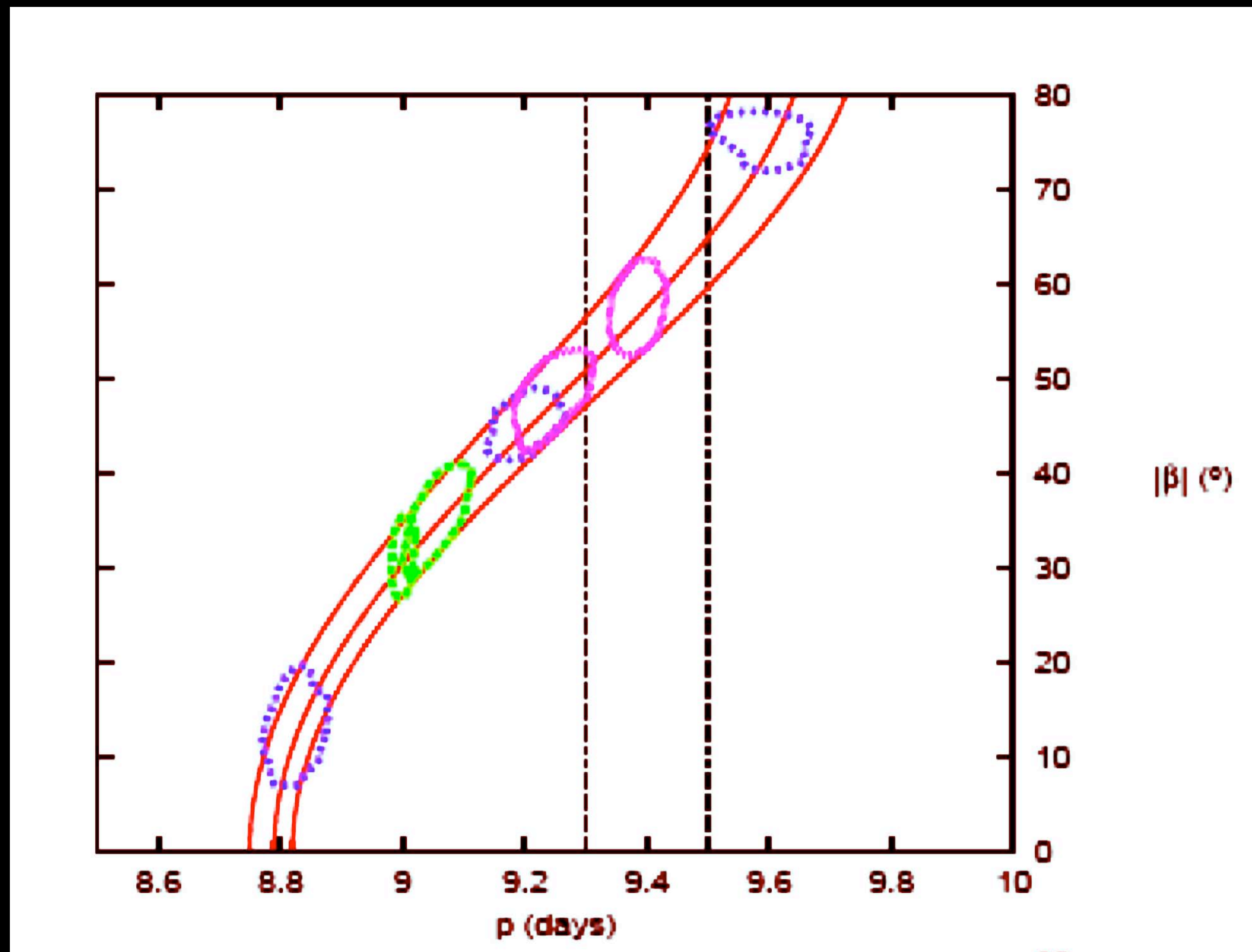
Best-fitting periods vs. star spot latitudes for three epochs.

Ellipses indicate 68% confidence limits

Red curves indicate <u>solar</u> period-latitude relation:

$$P_\beta = P_{eq} / (1 - k \sin^2 \boldsymbol{\beta})$$

for the confidence limits on P_{eq} *and k*

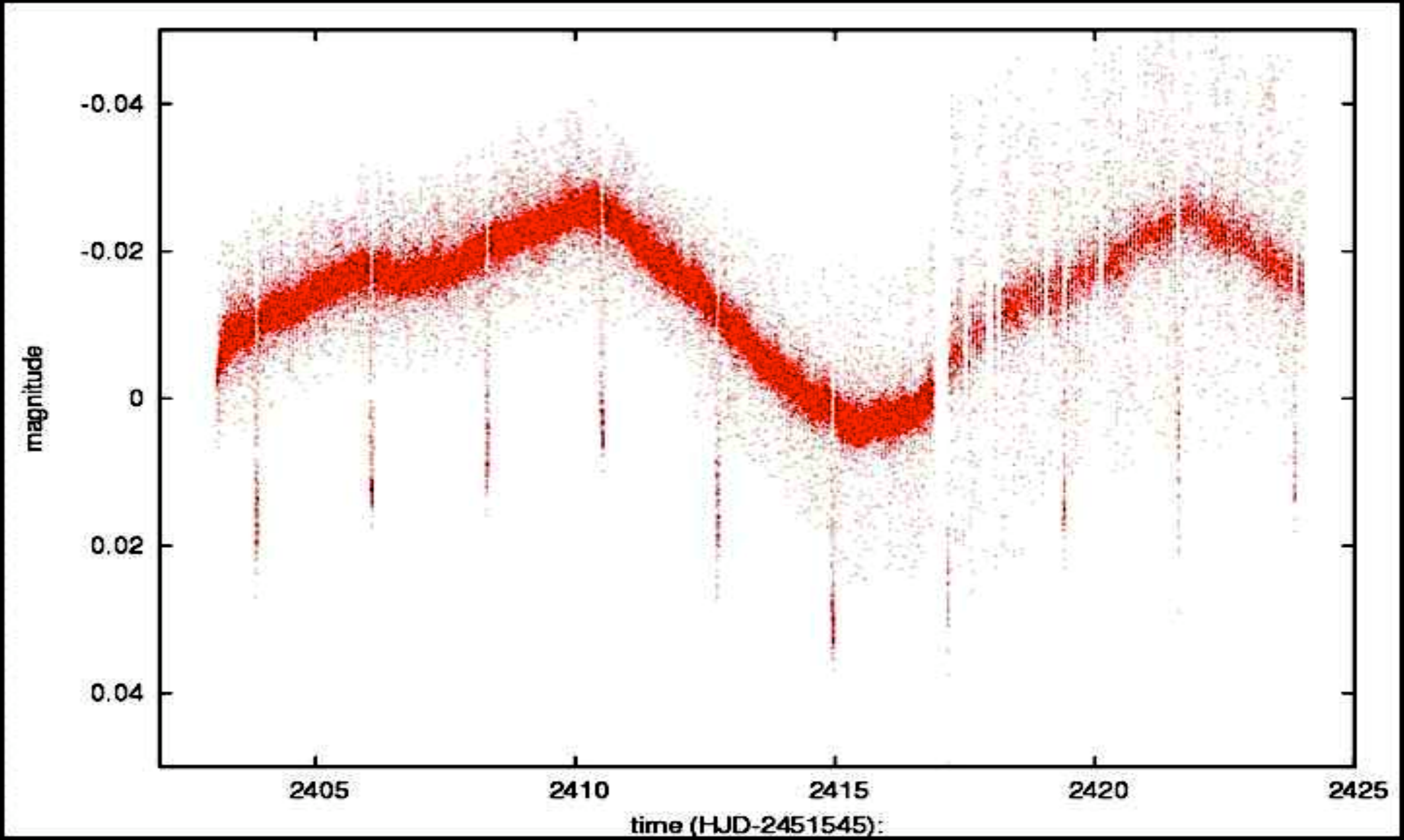


Walker, Croll, Matthews et al. ApJ 2007

HD 189733

HD 189733

- transiting exoplanet, with starspots

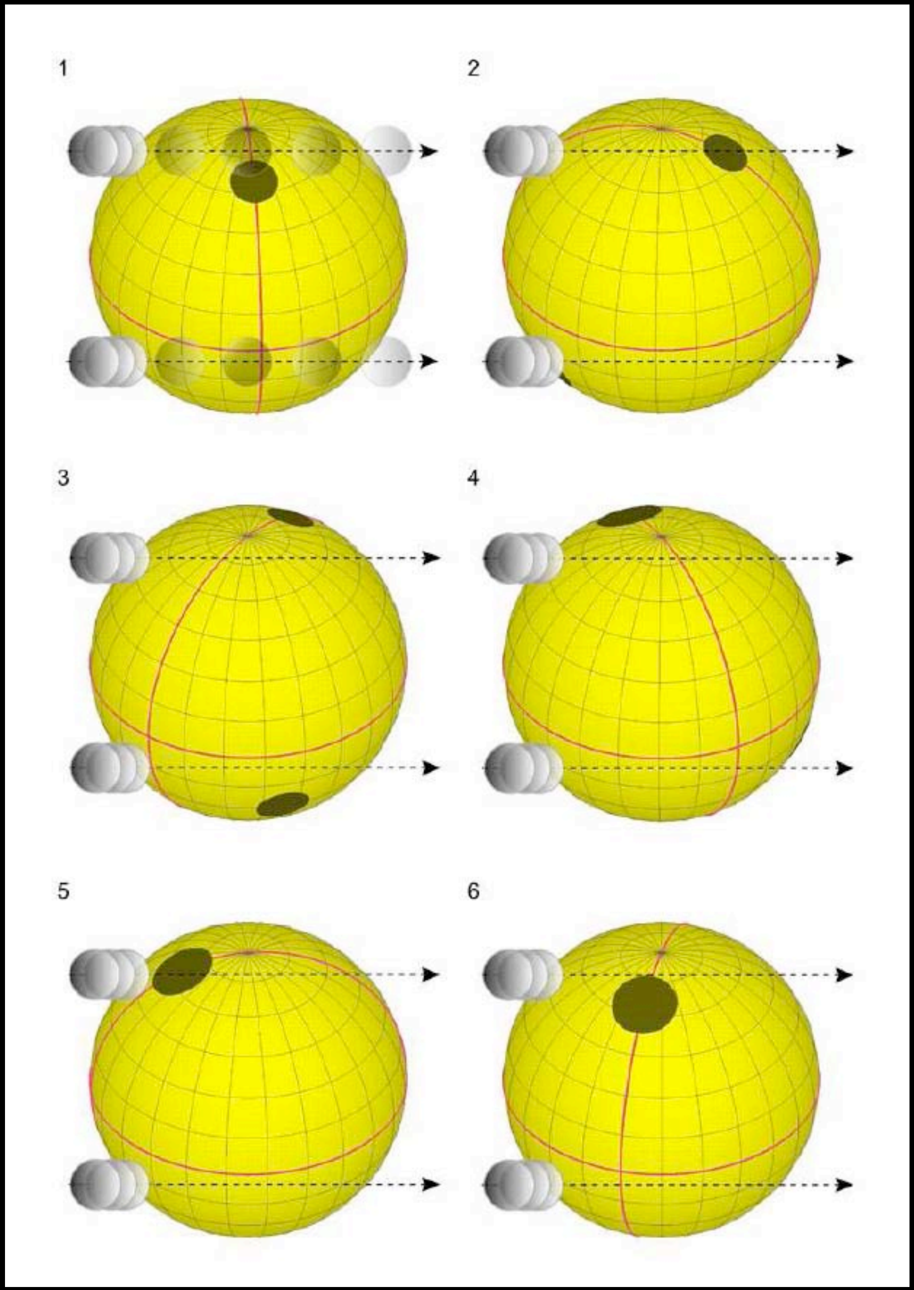


HD 189733

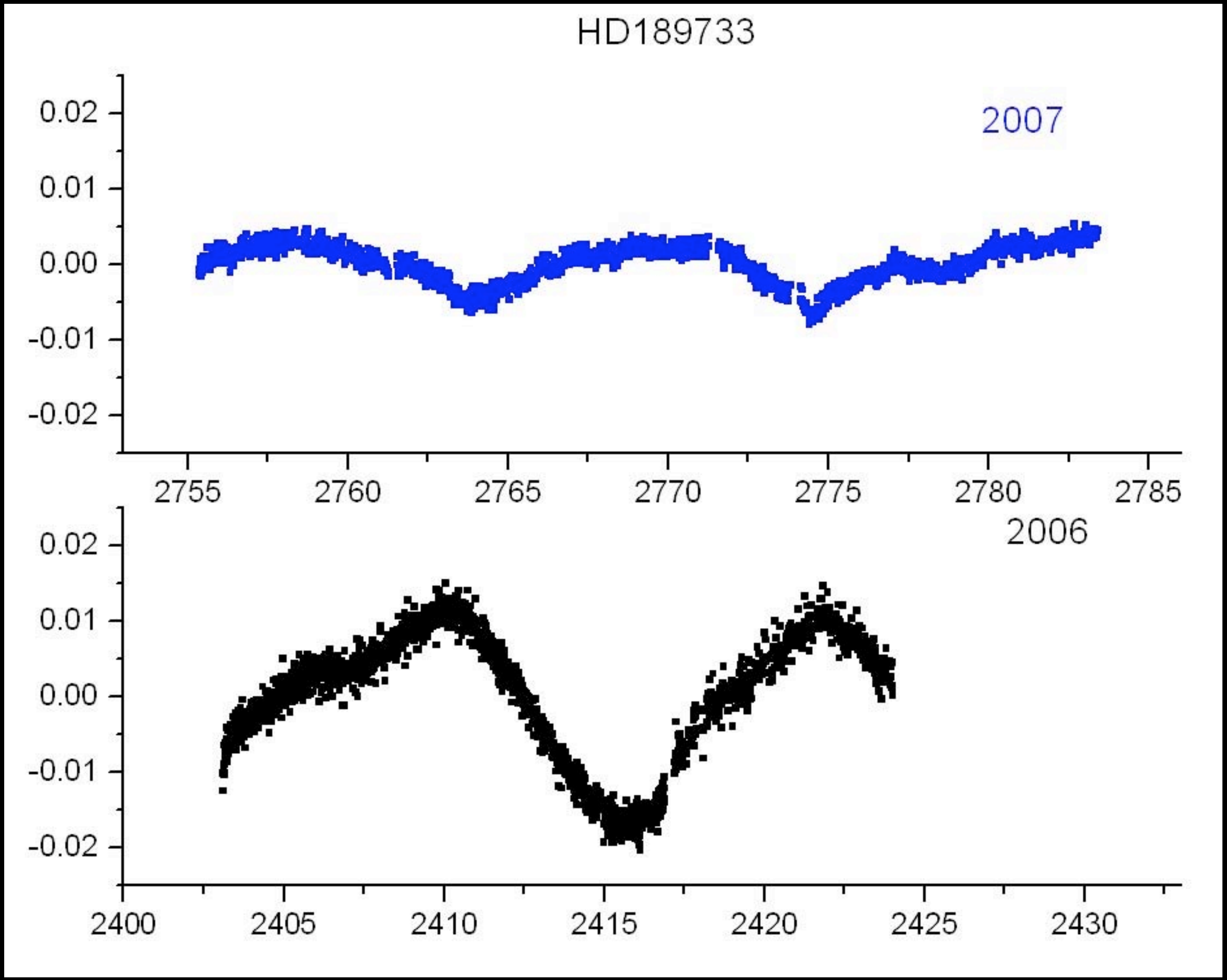
- transiting exoplanet with <u>starspots</u>

(Miller-Ricci et al. 2007)

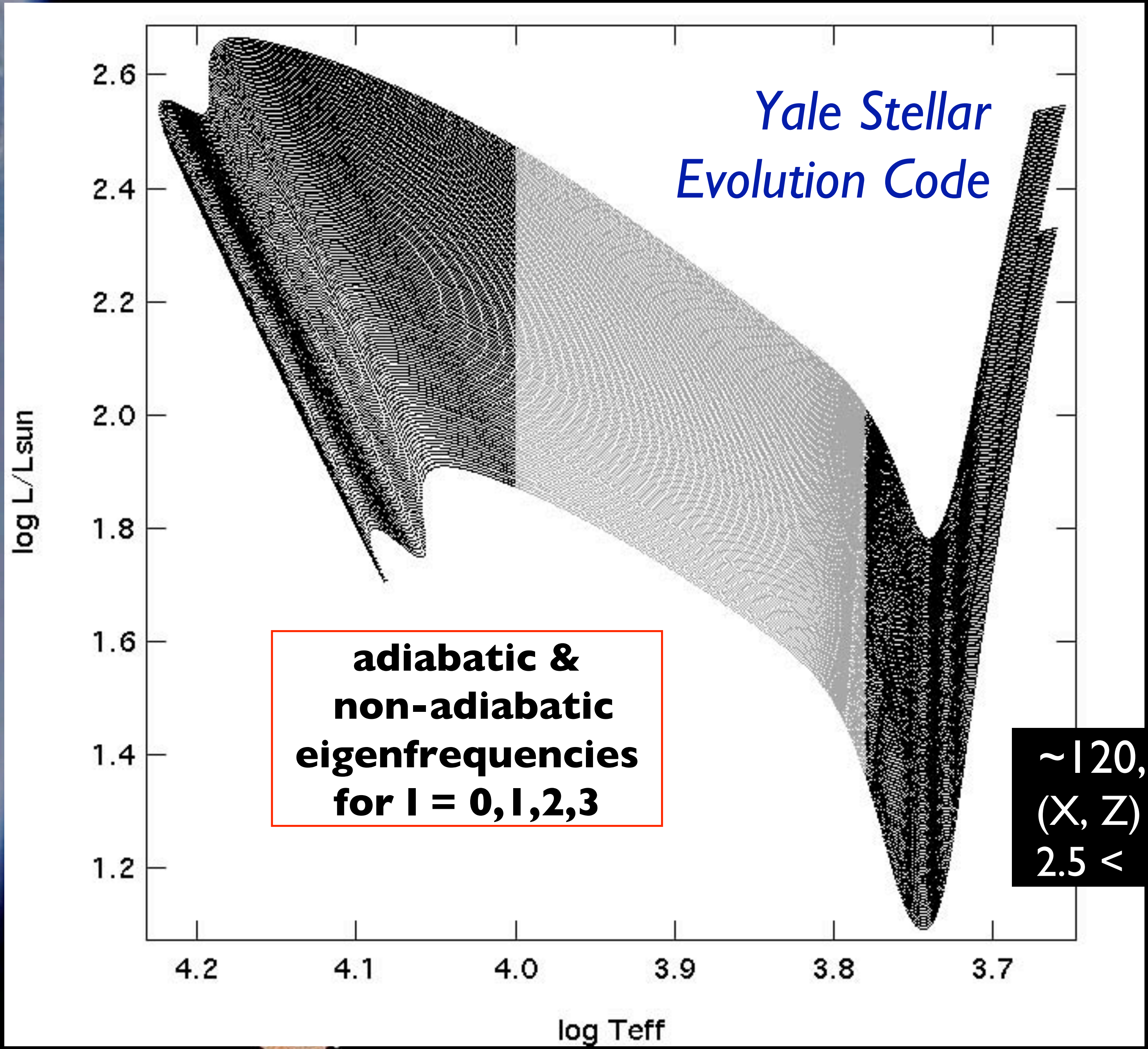
(Croll, Matthews et al. 2007)



HD 189733


HD189733
2007
0.02
0.01
0.00
-0.01
-0.02
2755
2760
2765
2770
2775
2780
2785
2006
0.02
0.01
0.00
-0.01
-0.02
2400
2405
2410
2415
2420
2425
2430

Light curve modeling



~120,000 models

(X, Z) = (0.71, 0.01)

$2.5 < M/M_{Sun} < 3.99$

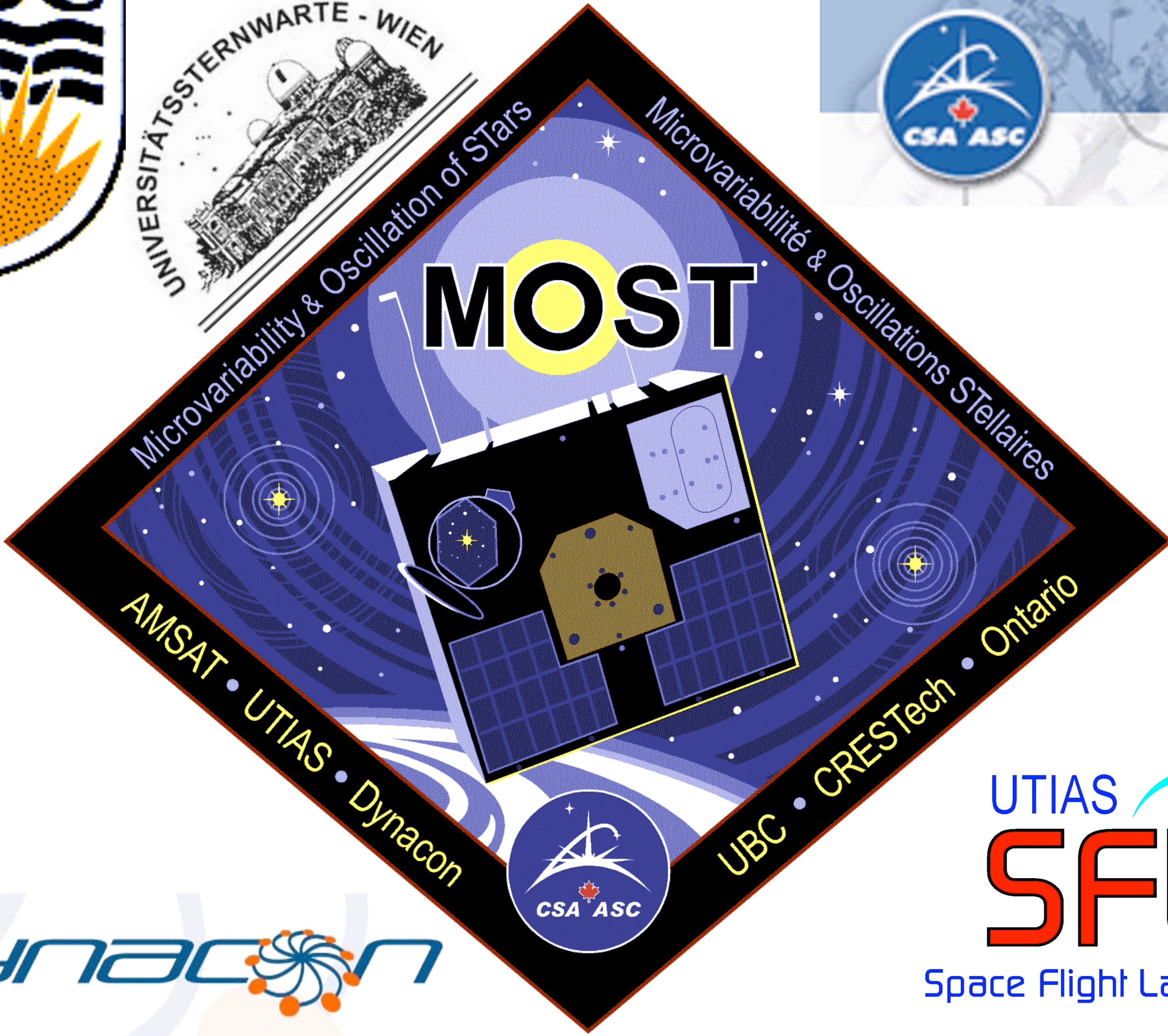
UBC

UNIVERSITÄTSSTERNWARTE - WIEN

Agence spatiale canadienne

Canadian Space Agency

CSA ASC



dynacon

UTIAS

SFL

Space Flight Laboratory

First results from MOST on Procyon

First results from MOST on Procyon

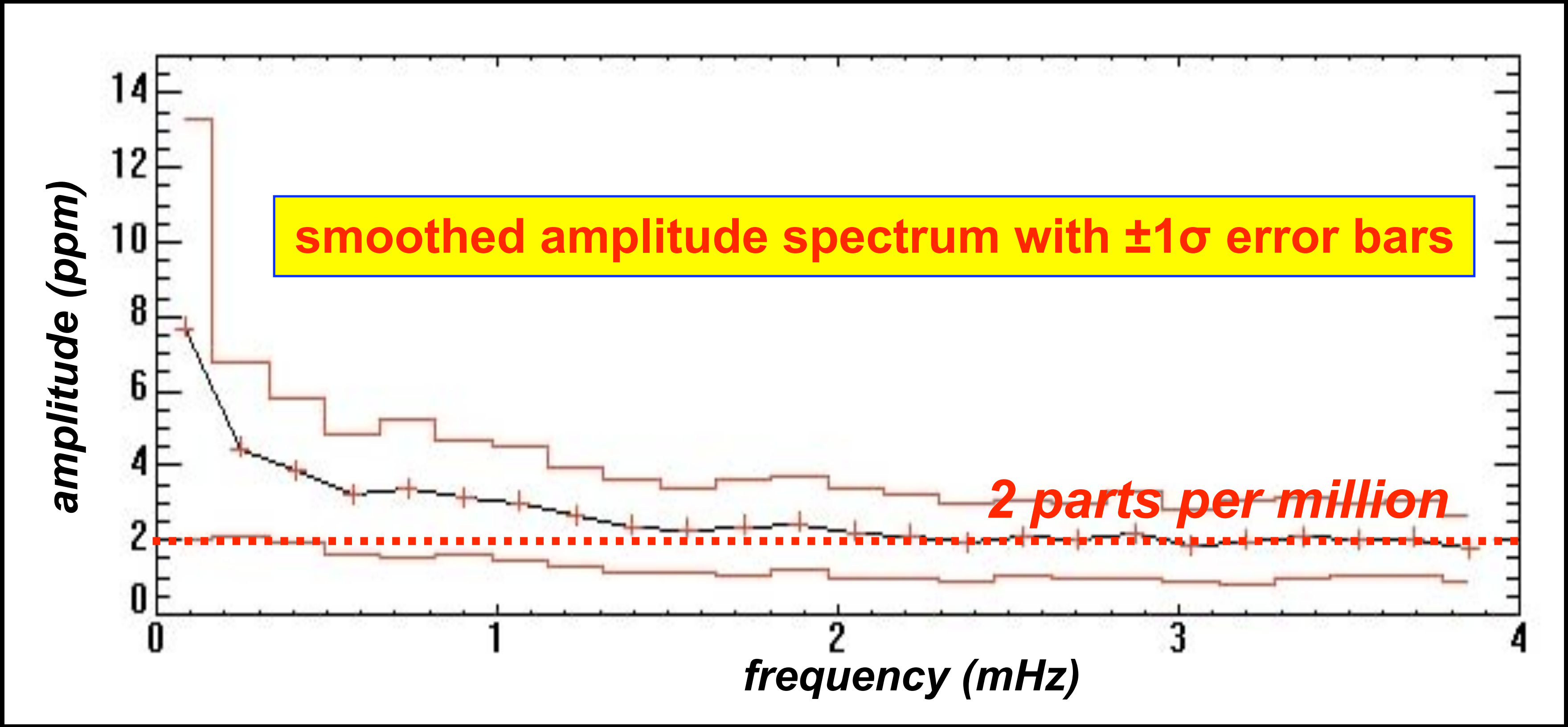
- reaction in the community

GONG-SOHO Meeting, New Haven, CT - July 2004

Much ado about nothing?

Procyon: 2004

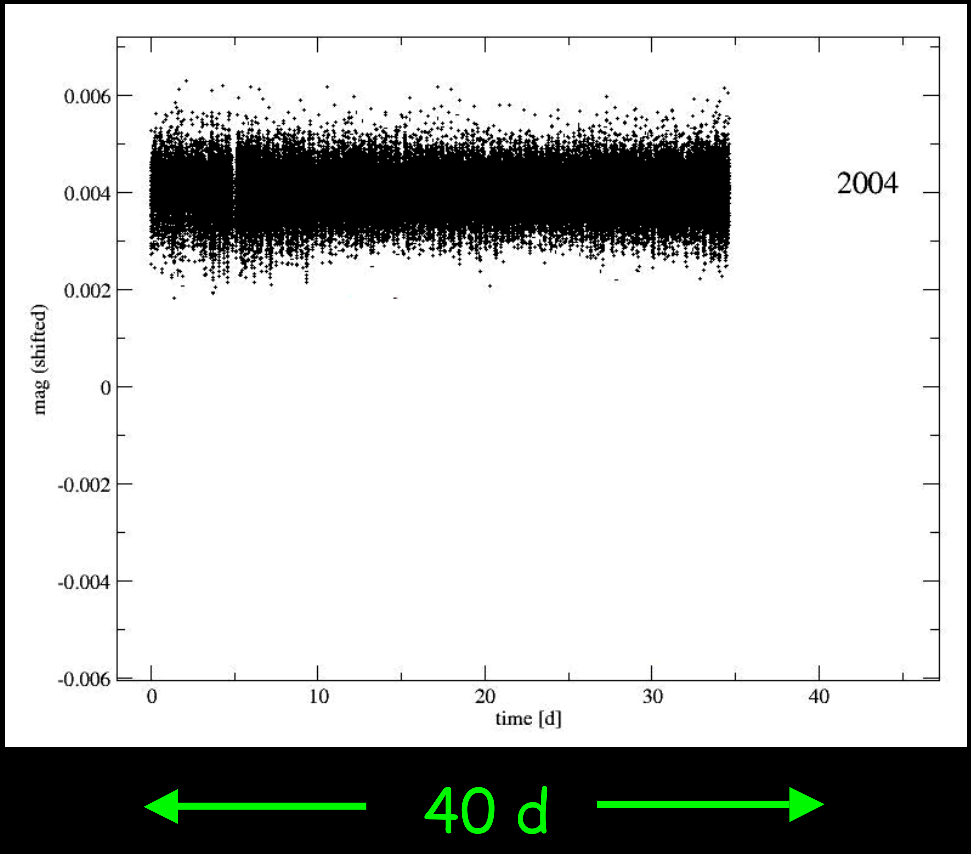
- Sampling: *average of 6× / min*
- Fabry Imaging
  - *32 days of coverage; 96% duty cycle*

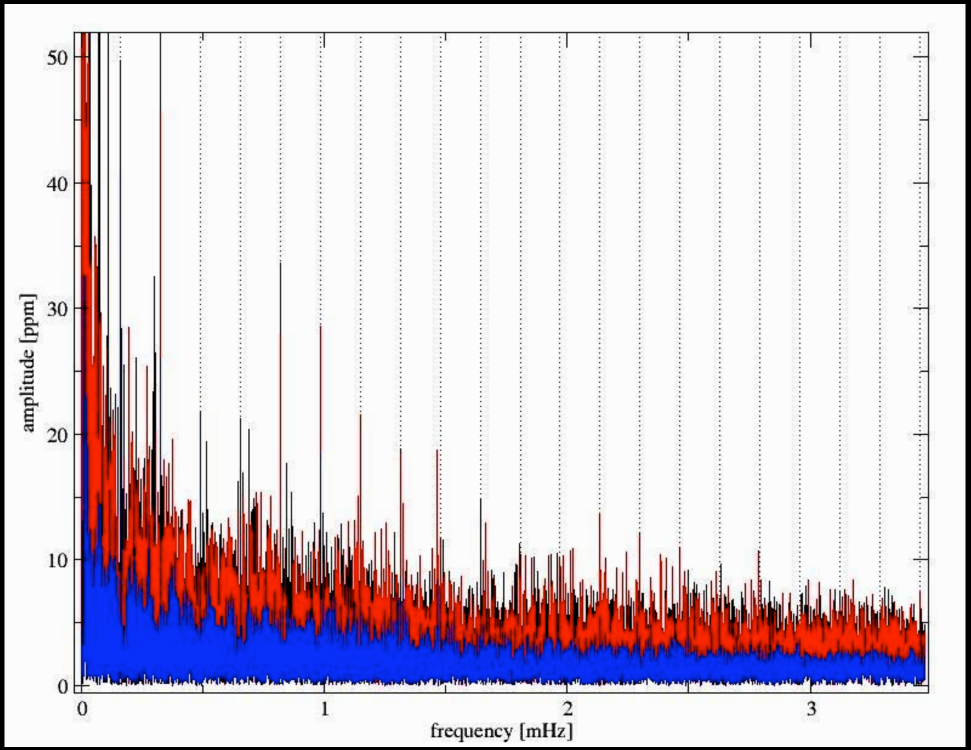


Matthews et al. 2004 Nature

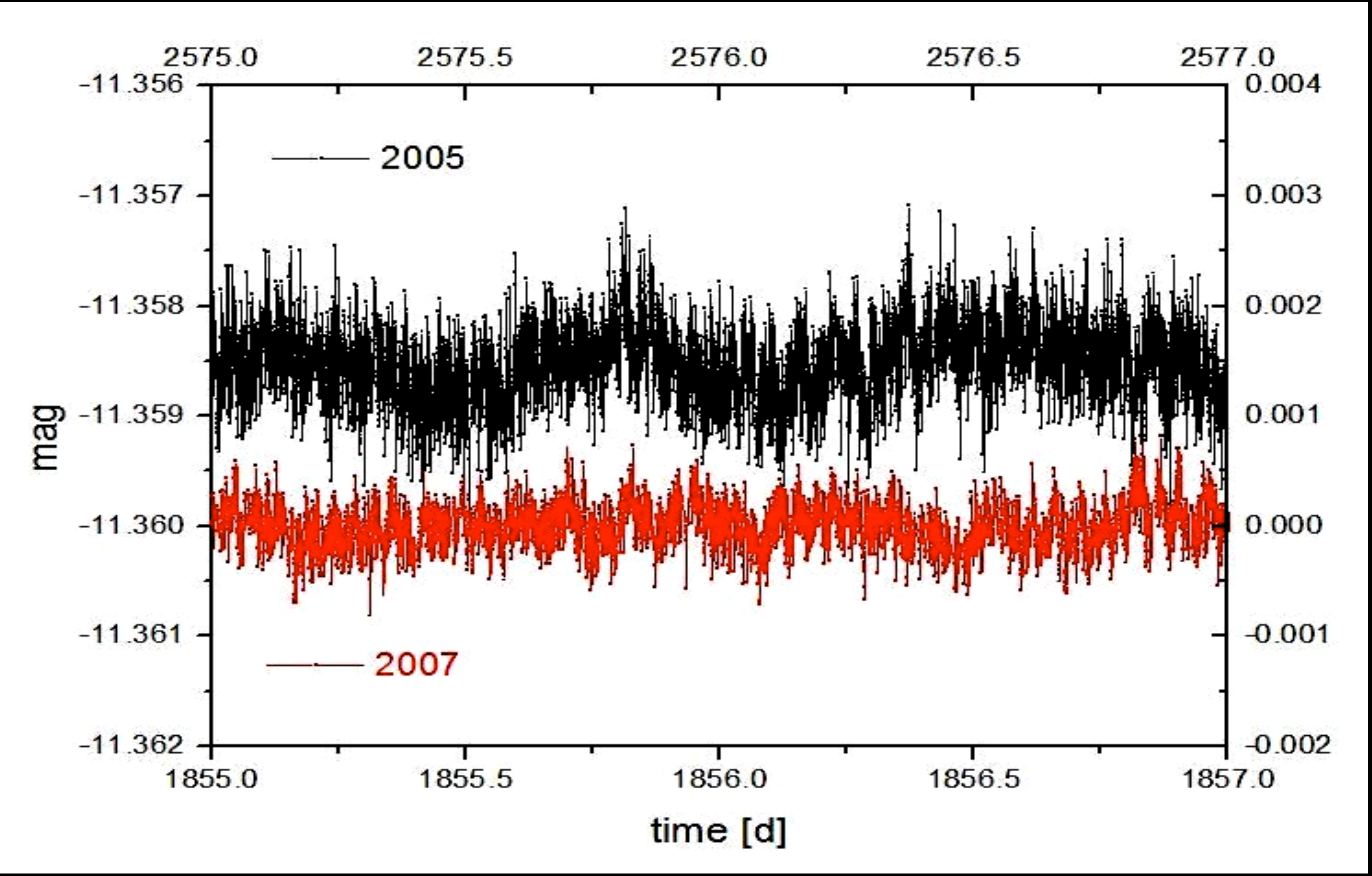
A nice place to visit

Year	Timespan [d]	Point-to-point scatter [ppm]	RMS [ppm]	noise (~ 1.5 mHz) [ppm]
2004	35	314	1245	3.0
2005	16	275	530	3.5
2007	38.5	155	230	1.5



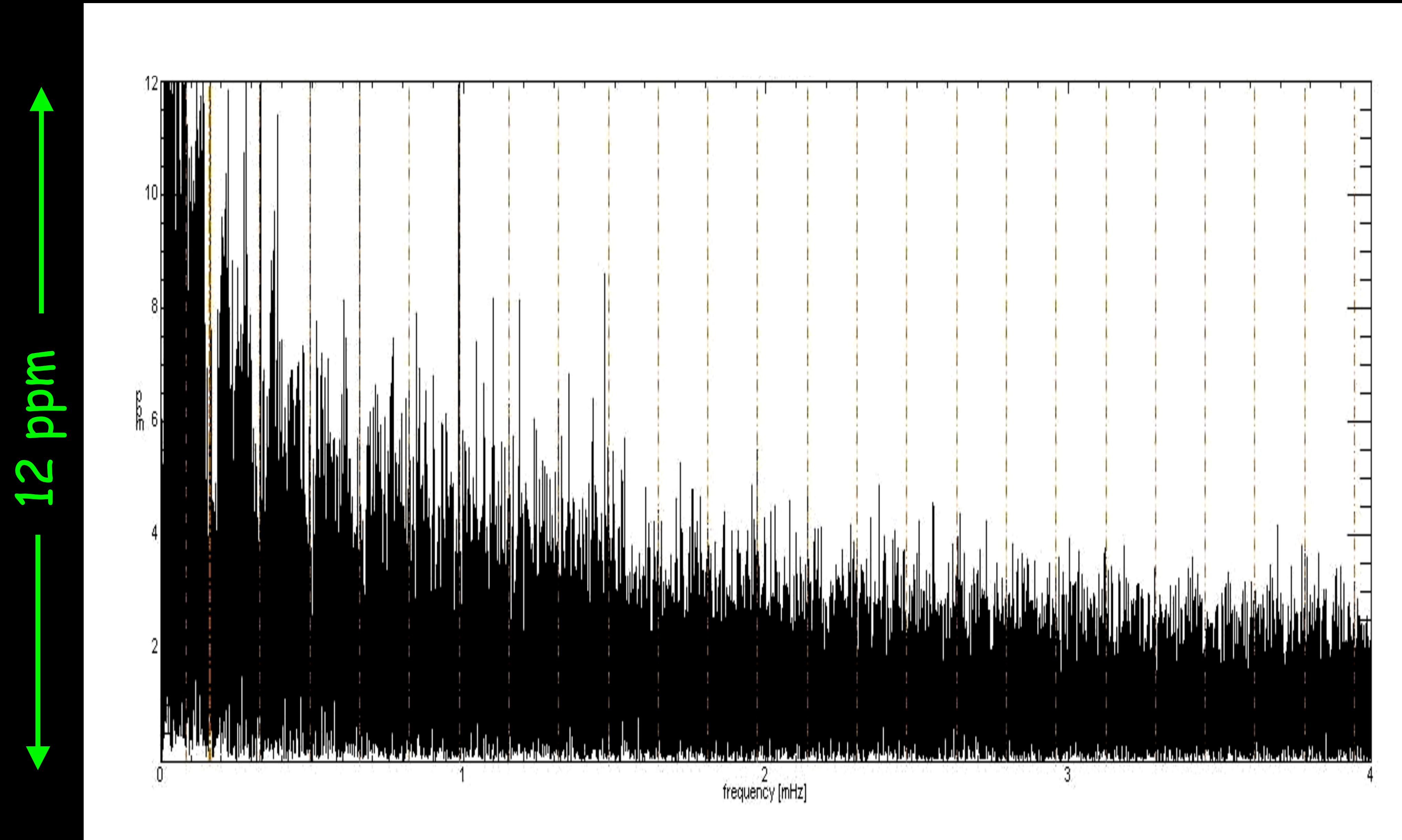


Improved photometry

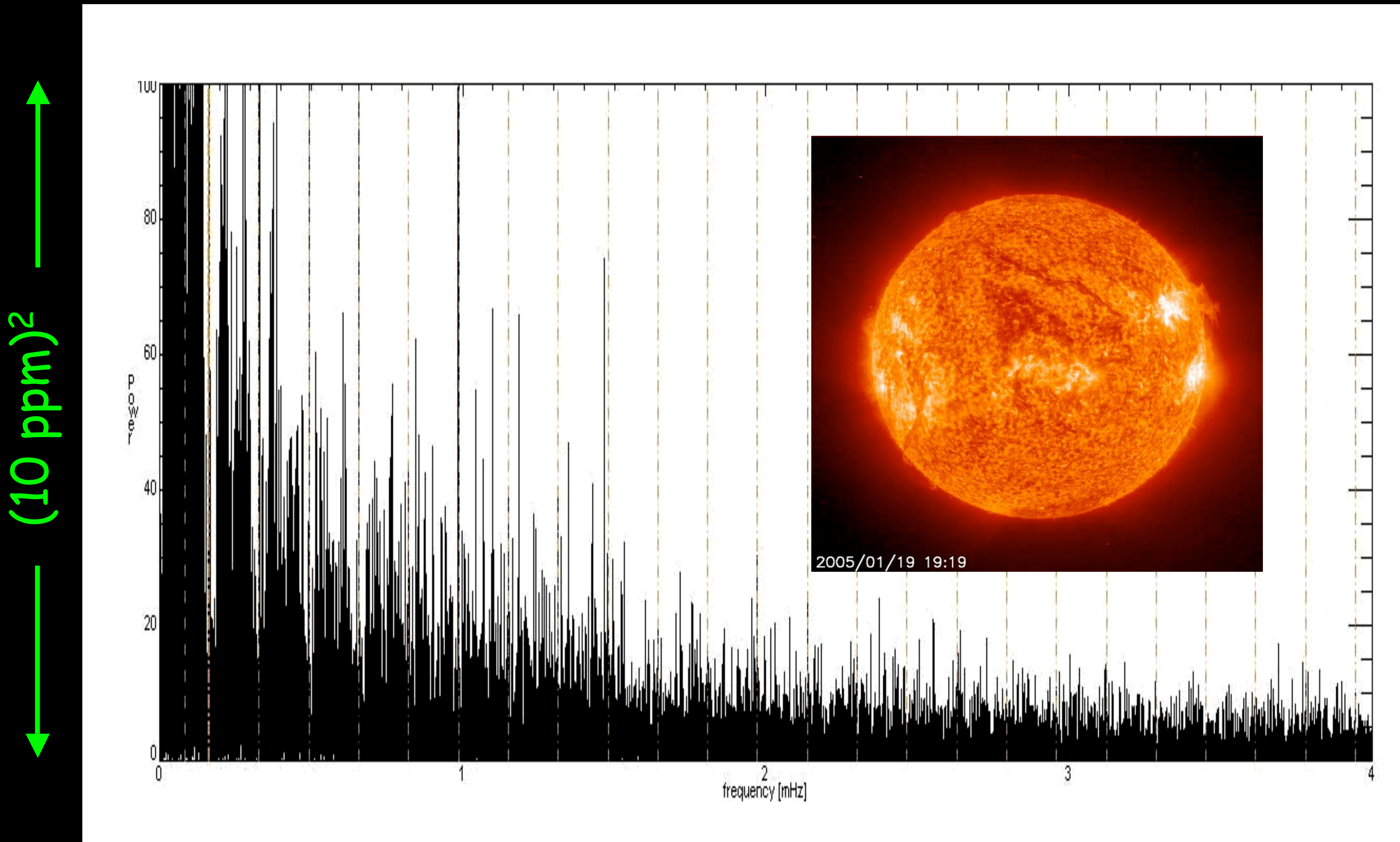


Sub-arcsec pointing, reduced scattered Earthshine

Improved sensitivity



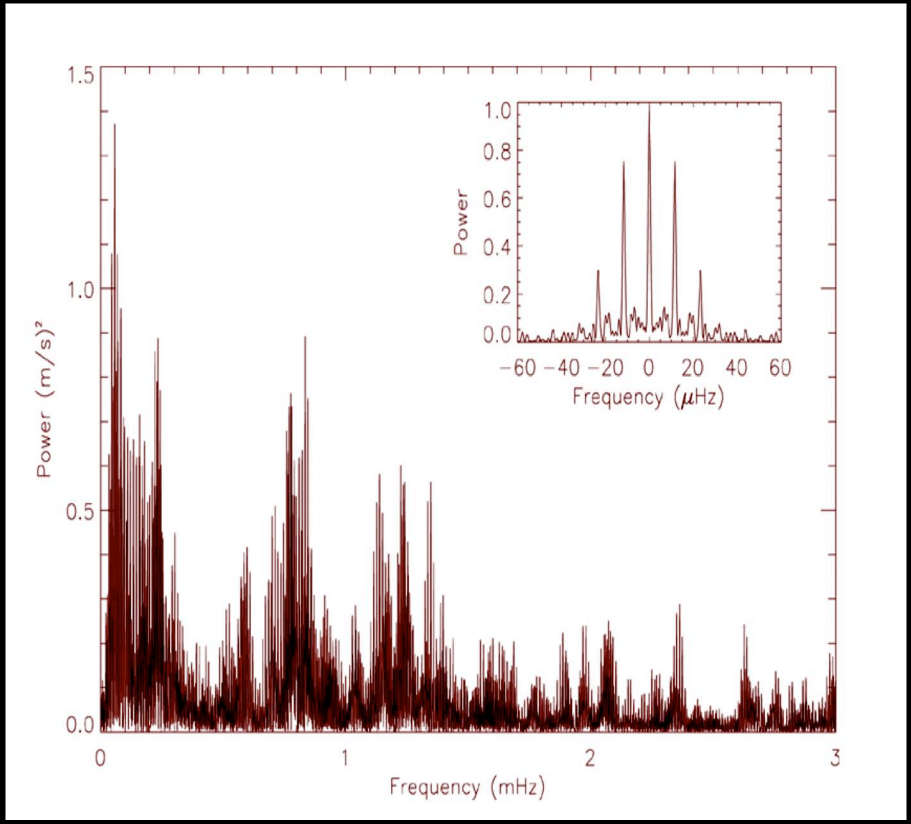
Improved sensitivity



p-mode 'hide and seek'

- Bedding et al. 2005:
  non-detection of p-modes
  in MOST 2004 data due to
  "non-stellar noise"
  in relevant frequency range

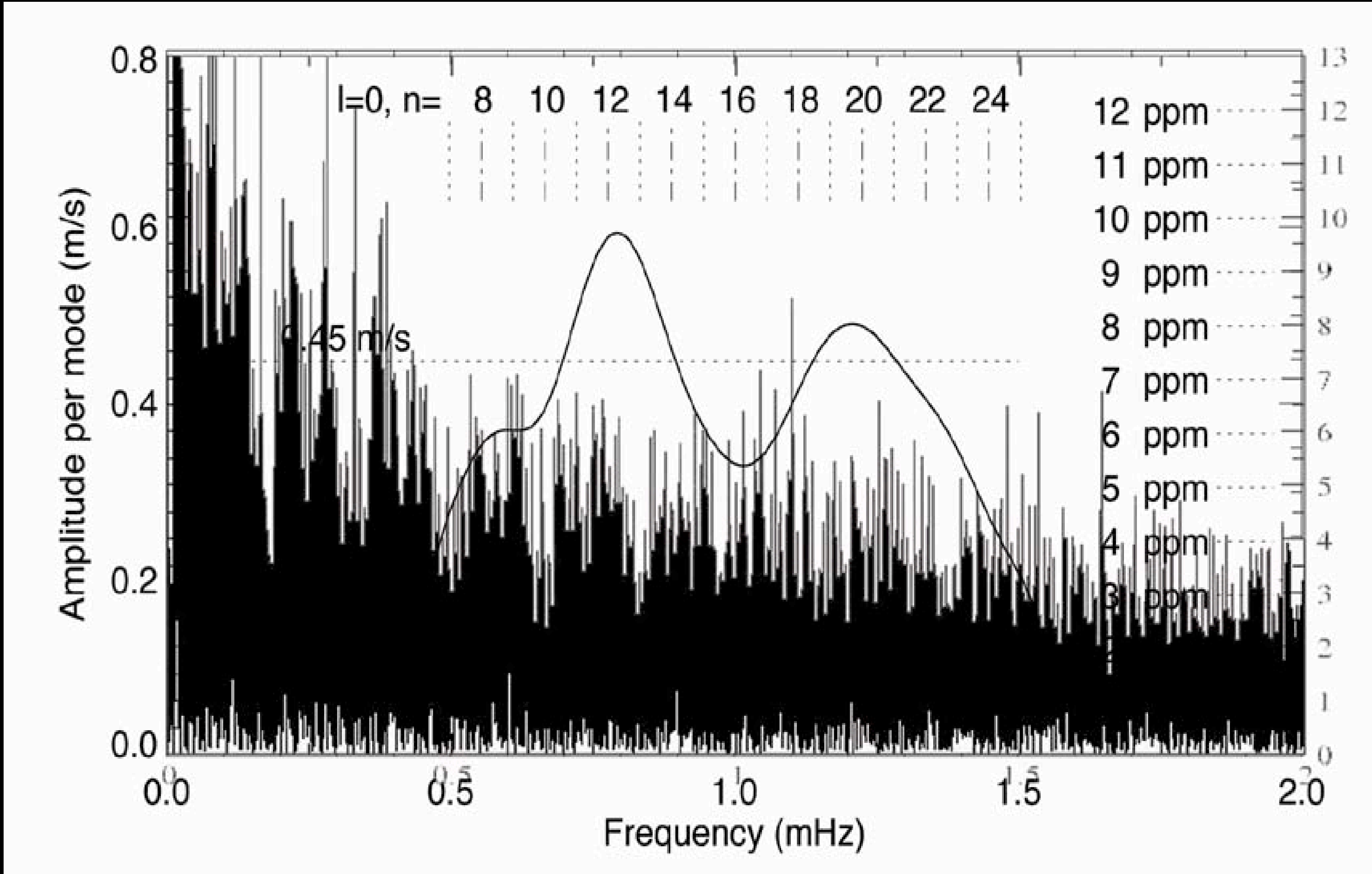
Leccia, Kjeldsen et al. (2006)



- Kjeldsen & Bedding scaling
  relation predicts
  peak amplitudes of ~8 ppm
- Leccia et al. 2006 predict
  mean amplitudes ~ 2 x solar

amplitudes of p-modes predicted to be ~8 ppm

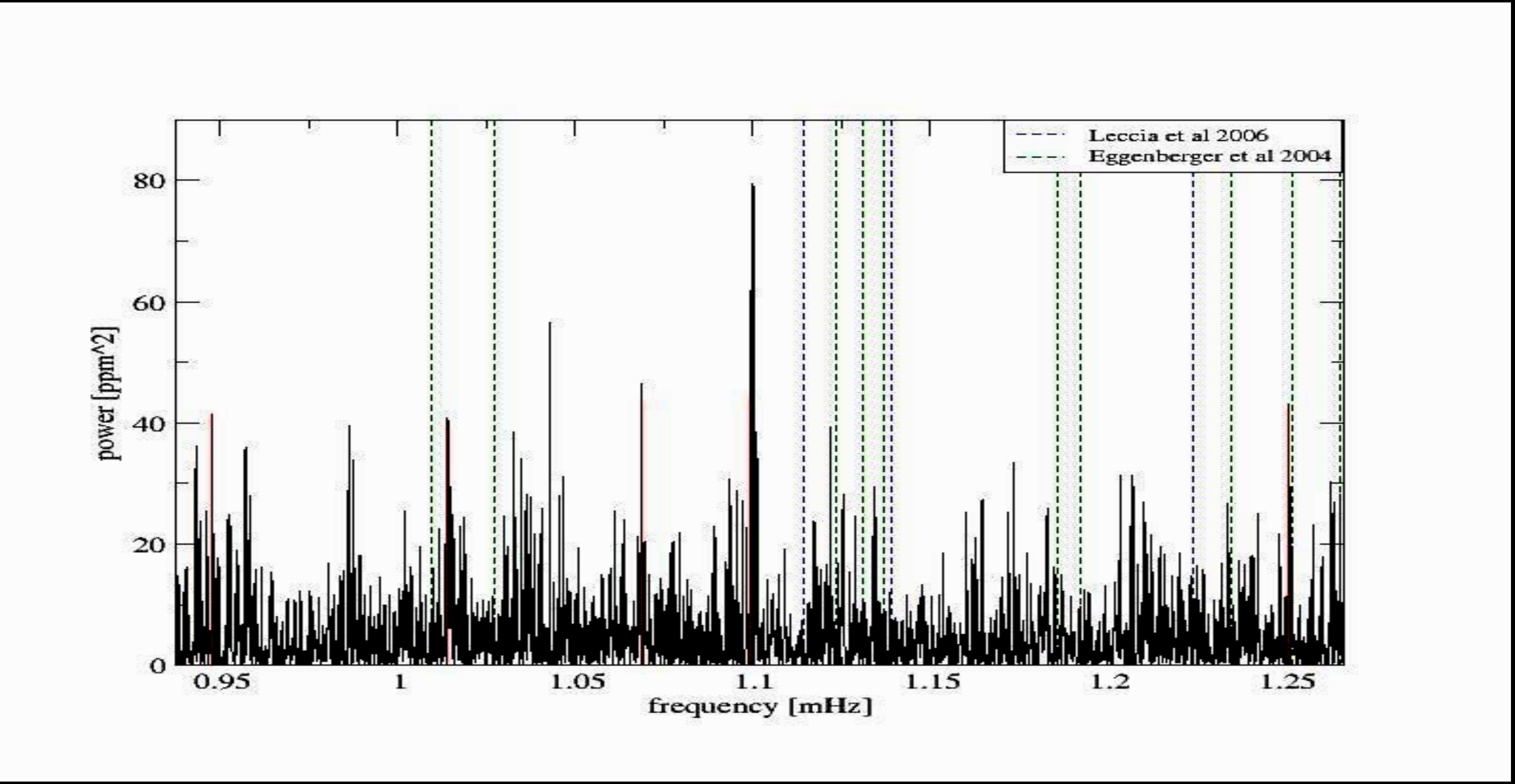
p-mode ‘hide and seek’



amplitudes of p-modes predicted to be ~8 ppm

Comparison to published frequencies

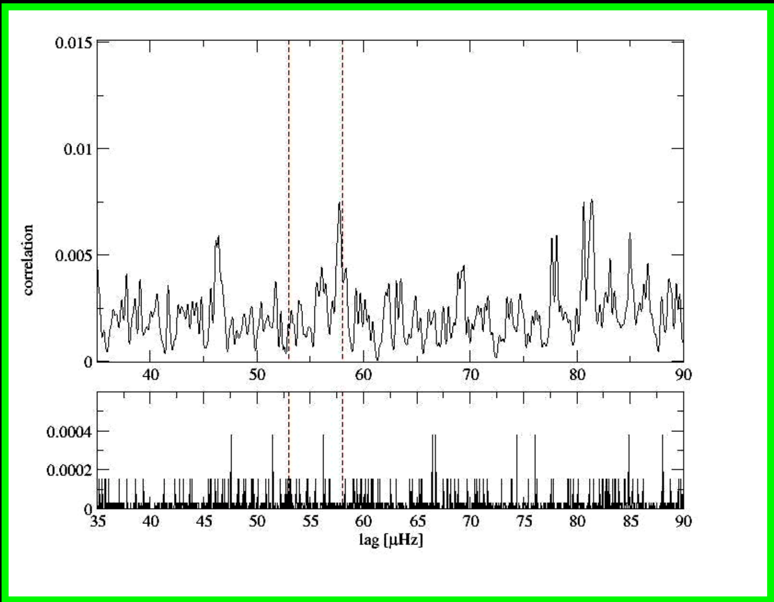
- Eggenberger et al. (2004):
  - 27 p-mode frequencies
- Leccia et al. (2006):
  - 10 p-mode frequencies

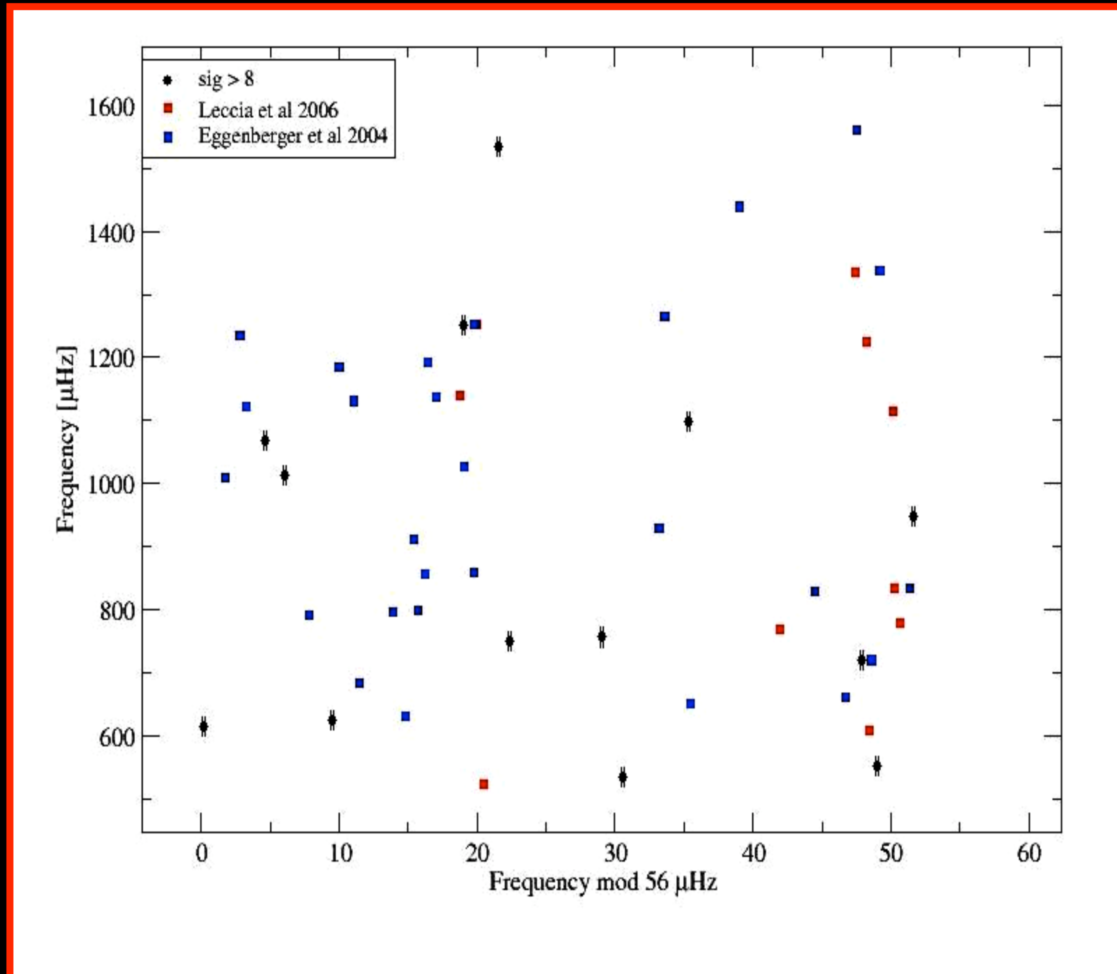


few matches to largest peaks in MOST spectrum

Climbing the echelle diagram

- Leccia et al. (2006):
  - $\Delta\nu$ = 56 μHz





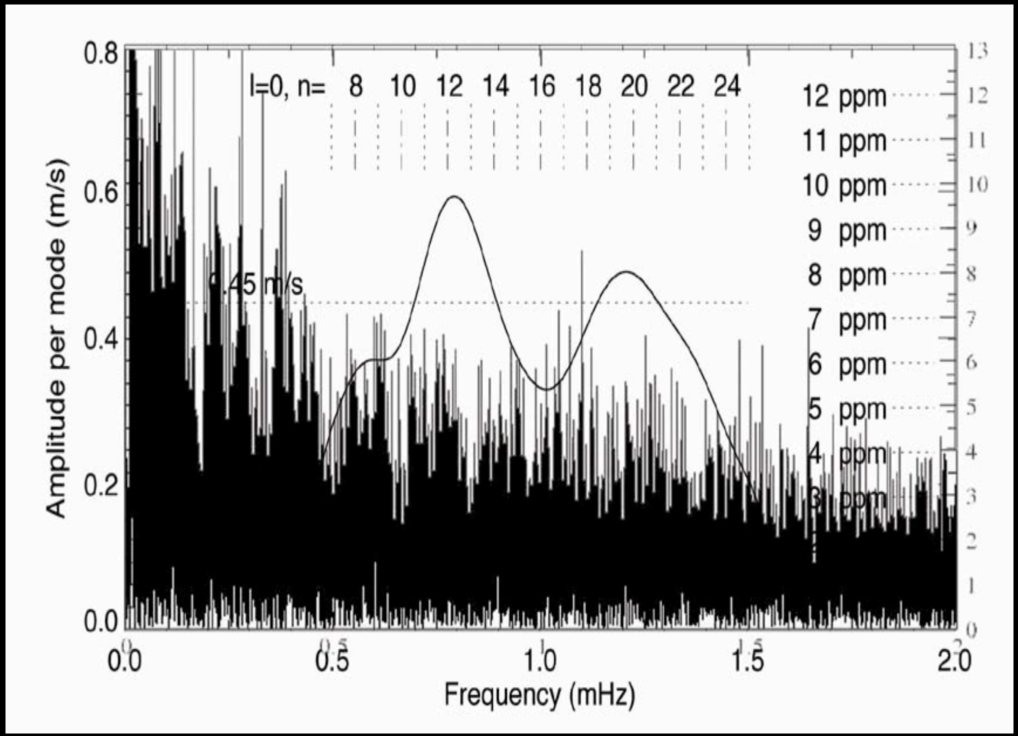
short mode lifetimes?

Procyon A?
Procyon eh?
Procyon why?

- still no evidence for p-modes in MOST photometry
  - amplitudes below 8 ppm

    or
  - mode lifetimes short

    or
  - both
- questions about scaling relation between p-mode velocity and luminosity amplitudes



The 2007 spectroscopy and photometry represent the best data set for p-mode studies of Procyon.