UKIRT PLANET FINDER / M DWARF DETECTABILITY

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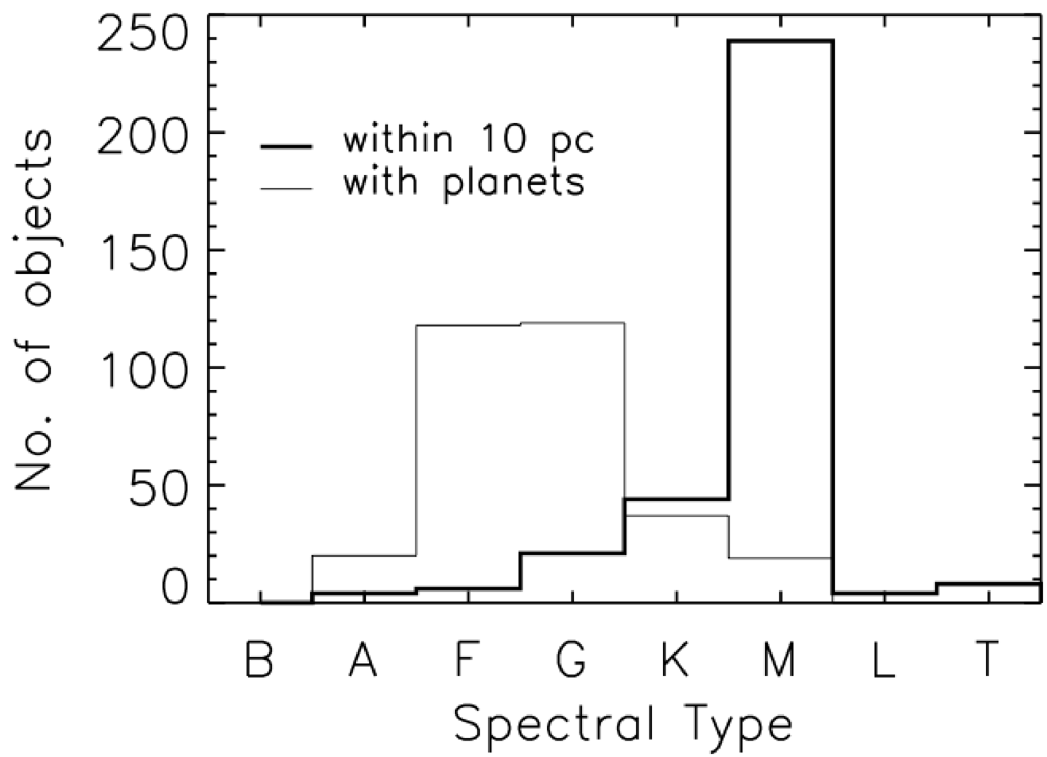
Astronomy of Exoplanets with Precise Radial Velocities

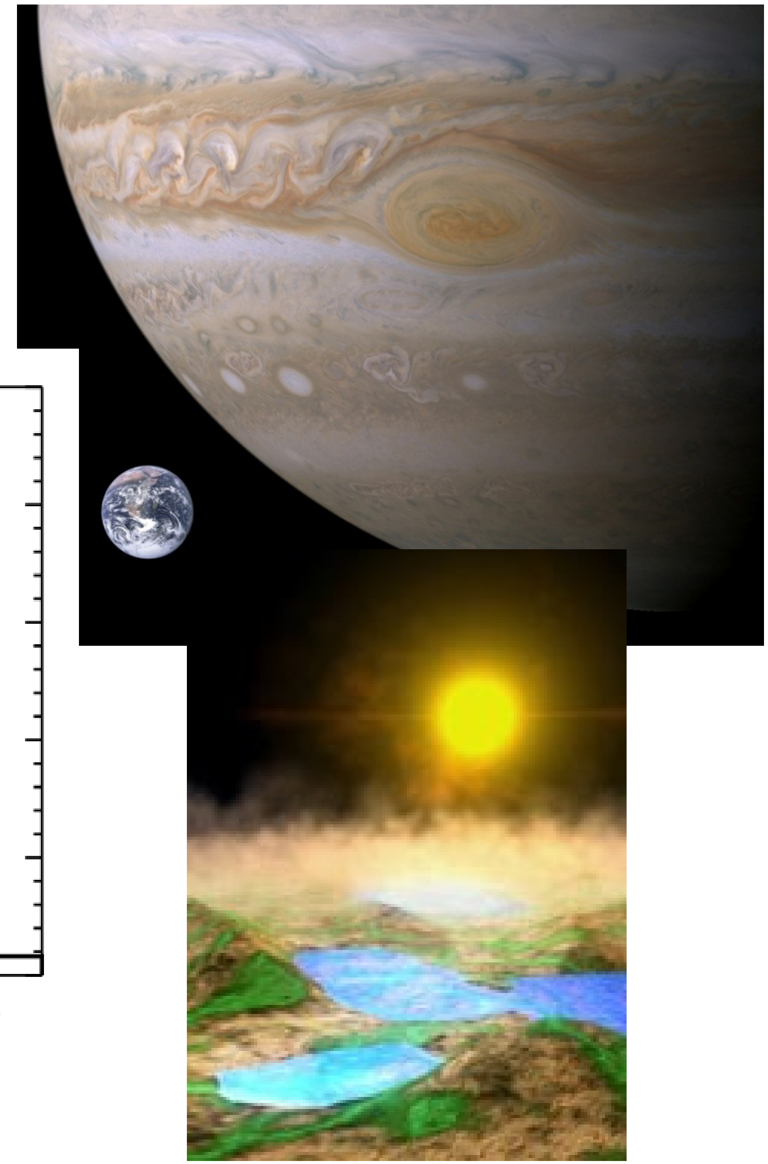
PSU

17th August 2010

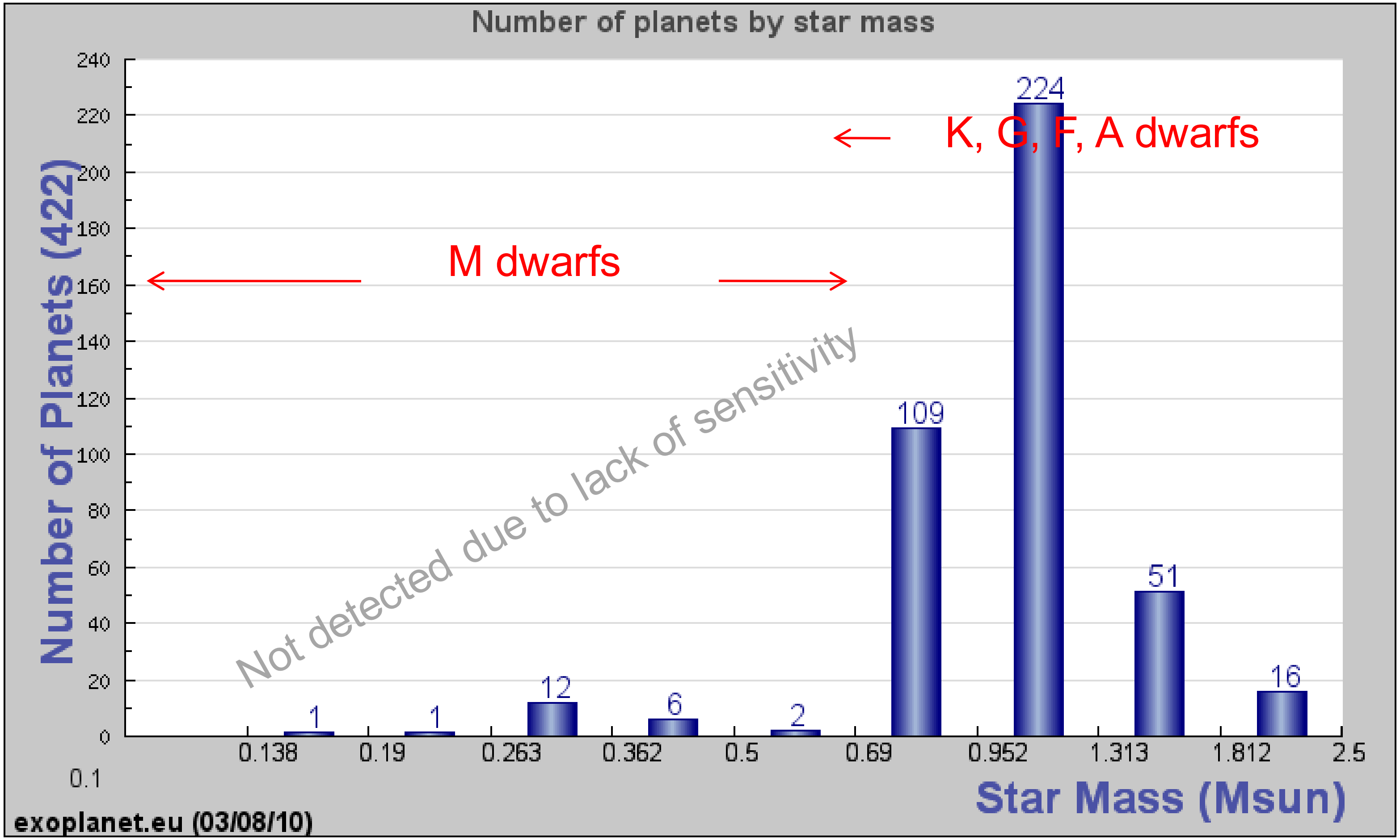
The holy grail of exoplanet hunting – Earth-mass planets

- Earth-mass planets in the habitable zones of the nearest stars





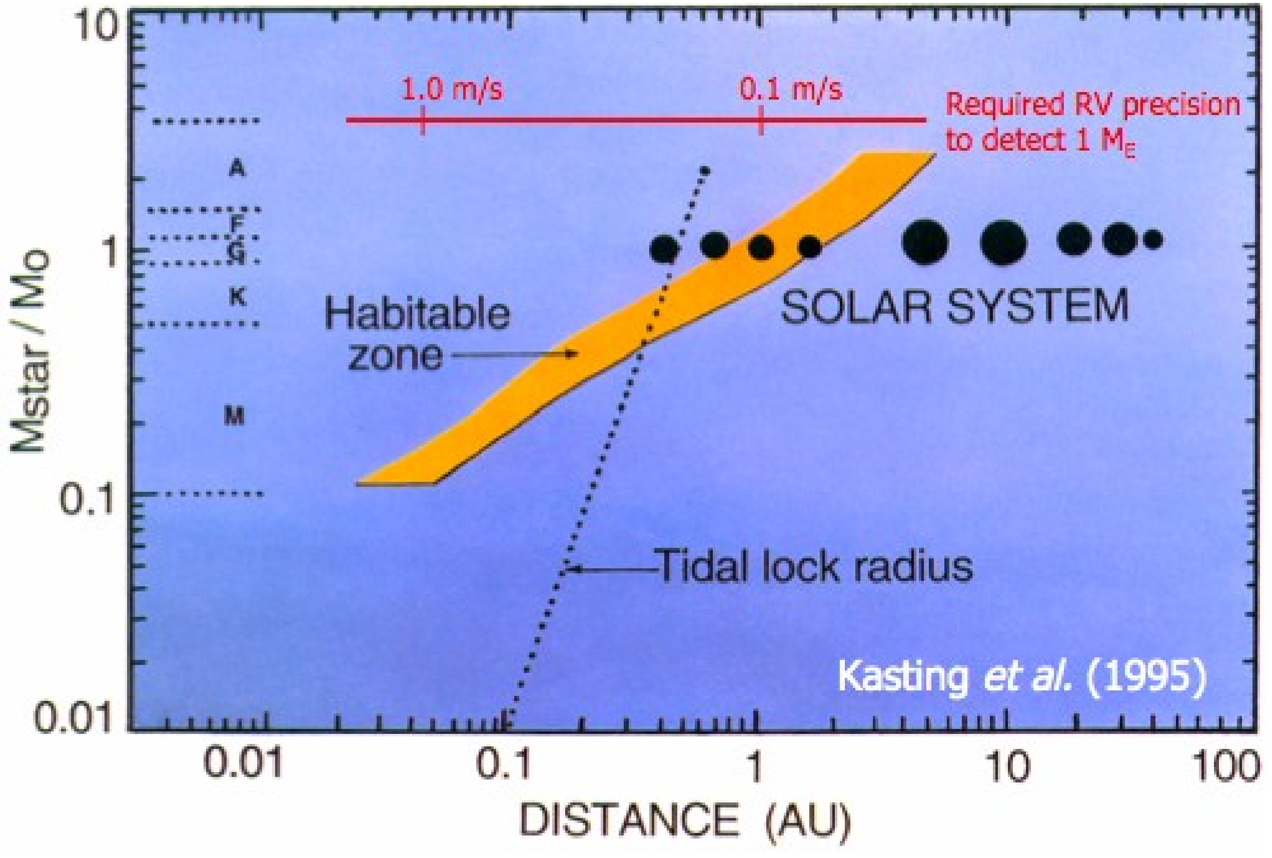
Astrophysically …unexplored



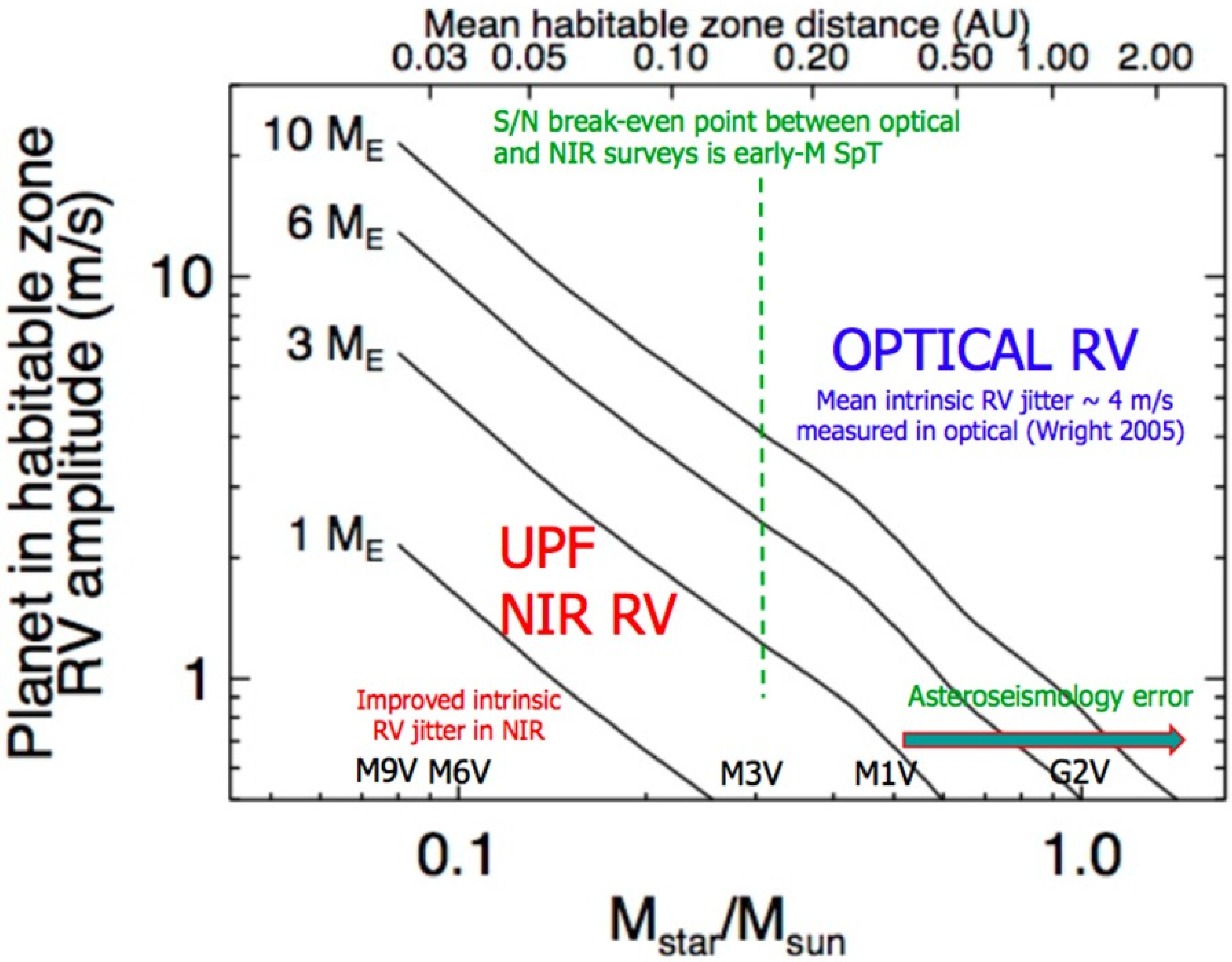
Accessible habitable zones

Habitable zone inside 0.3 AU for M dwarfs

Impact of tidal locking unclear



The potential in the infrared



UPF Design Baseline Concept

- Design inherited from Gemini PRVS
- Scaled down to 3.8m UK InfraRed Telescope
- Instrument similar to HARPS, UVES
- Cross dispersed échelle spectrograph
  - White pupil collimator design
  - Refractive camera
  - No mechanisms (in main optical path)
- Fibre fed
  - Fibre deployment system located on WFCAM cryostat
- Spectrograph and calibration unit located in UKIRT basement

Instrument Concept

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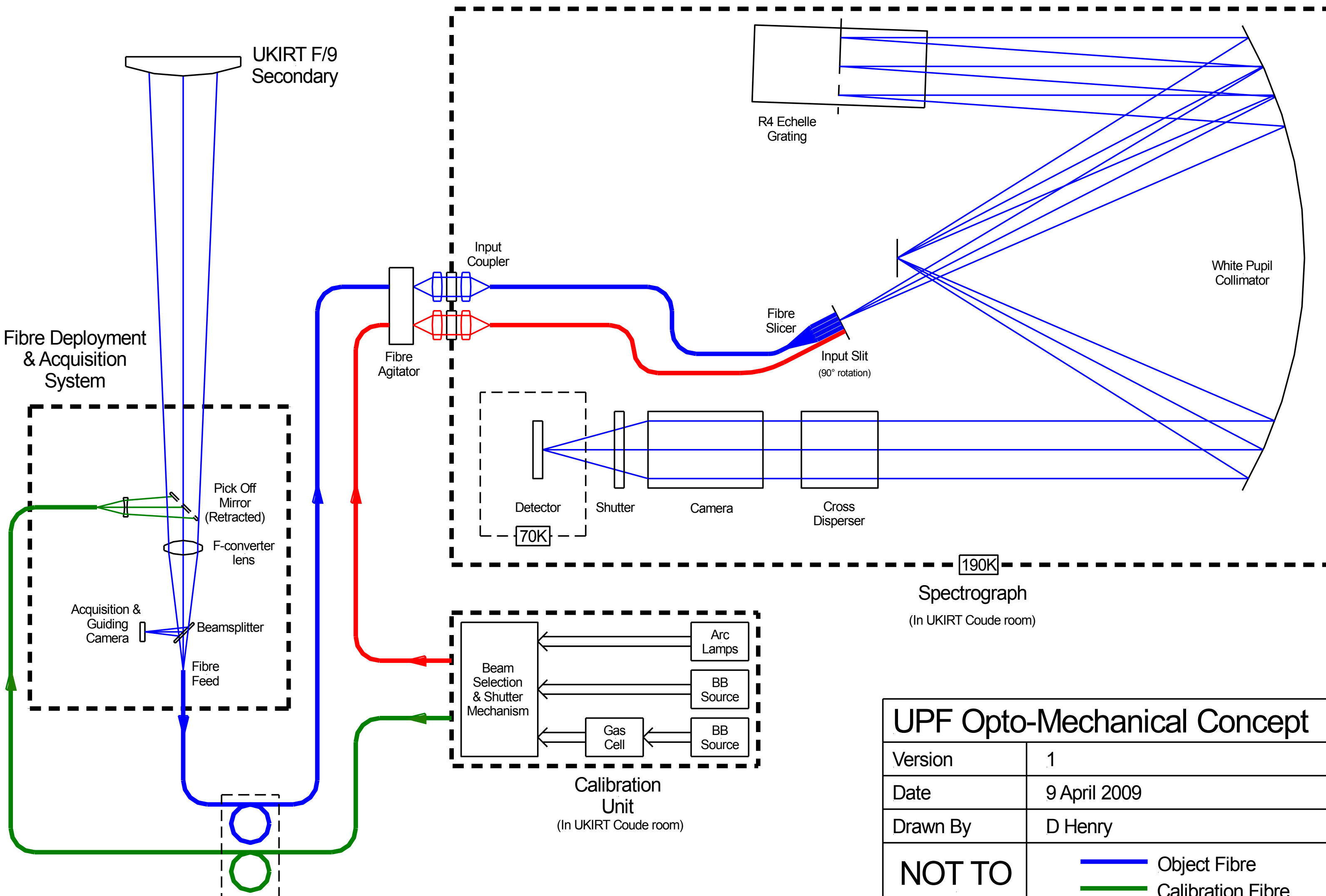
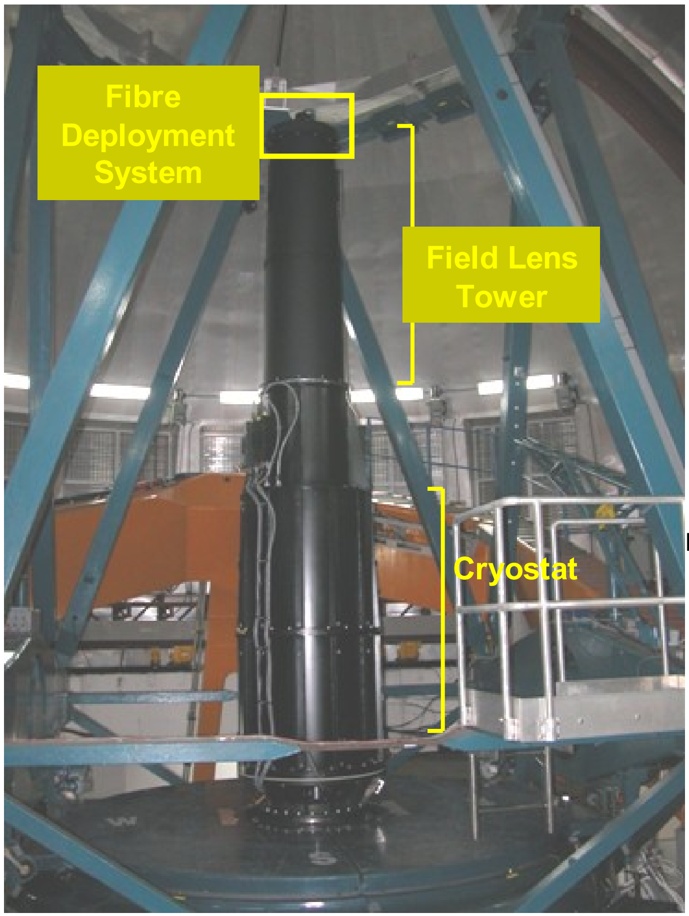
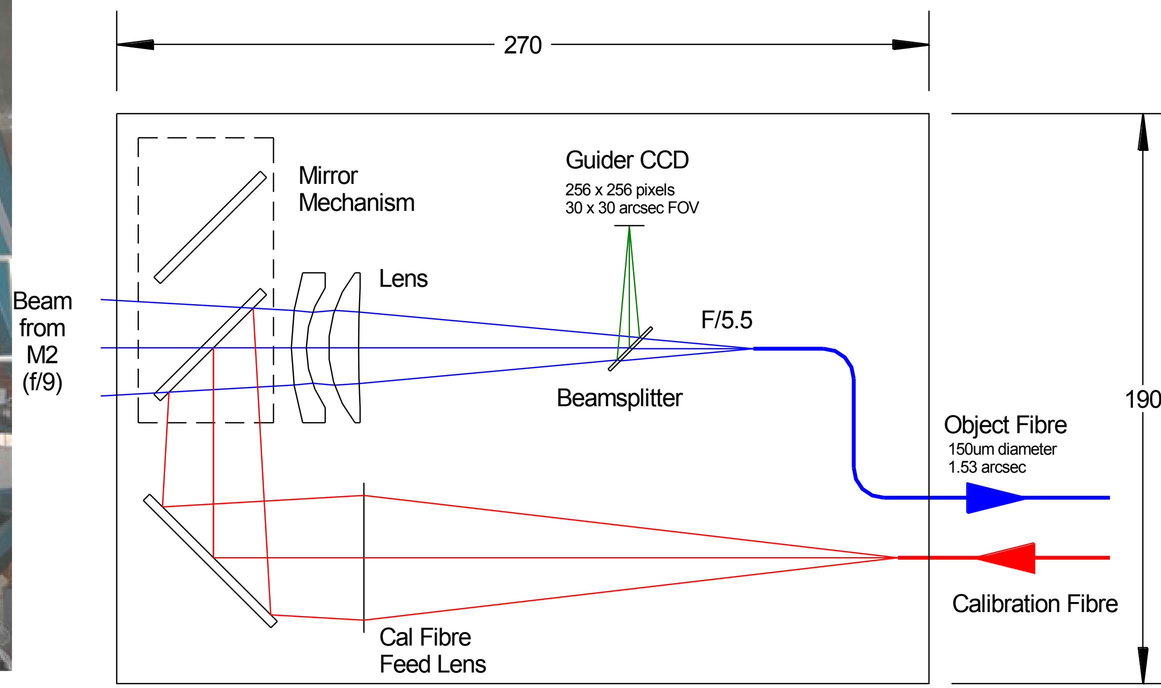


UPF Opto-Mechanical Concept	
Version	1
Date	9 April 2009
Drawn By	D Henry
NOT TO SCALE	Object Fibre Calibration Fibre Reference Fibre

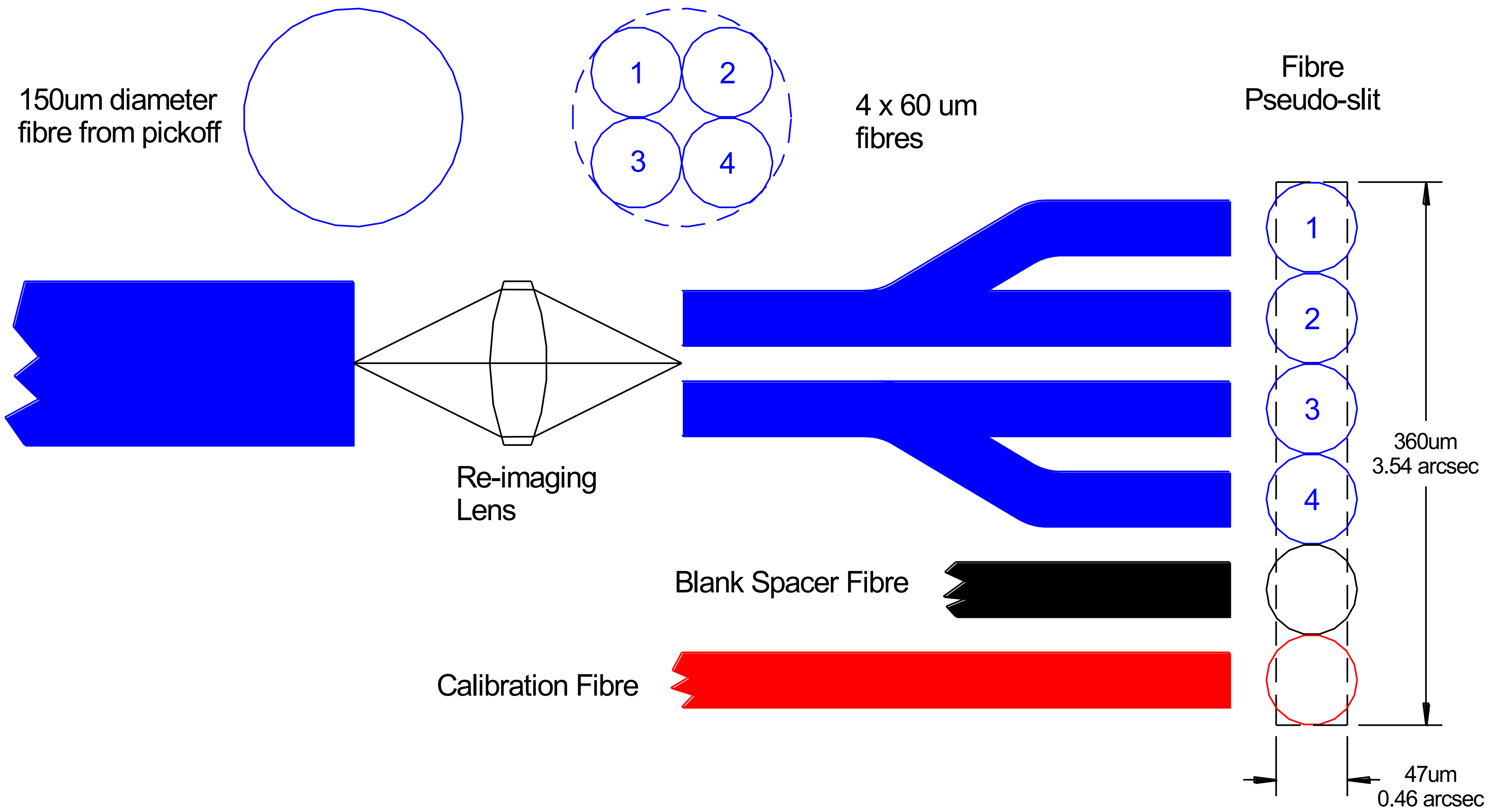
Fibre deployment and acquisition

- Remove field lens tower (normal operation for WFCAM installation/removal)
- Cryostat remains in place
- Fit second tower containing fibre pickoff & guiding assembly at f/9 focus

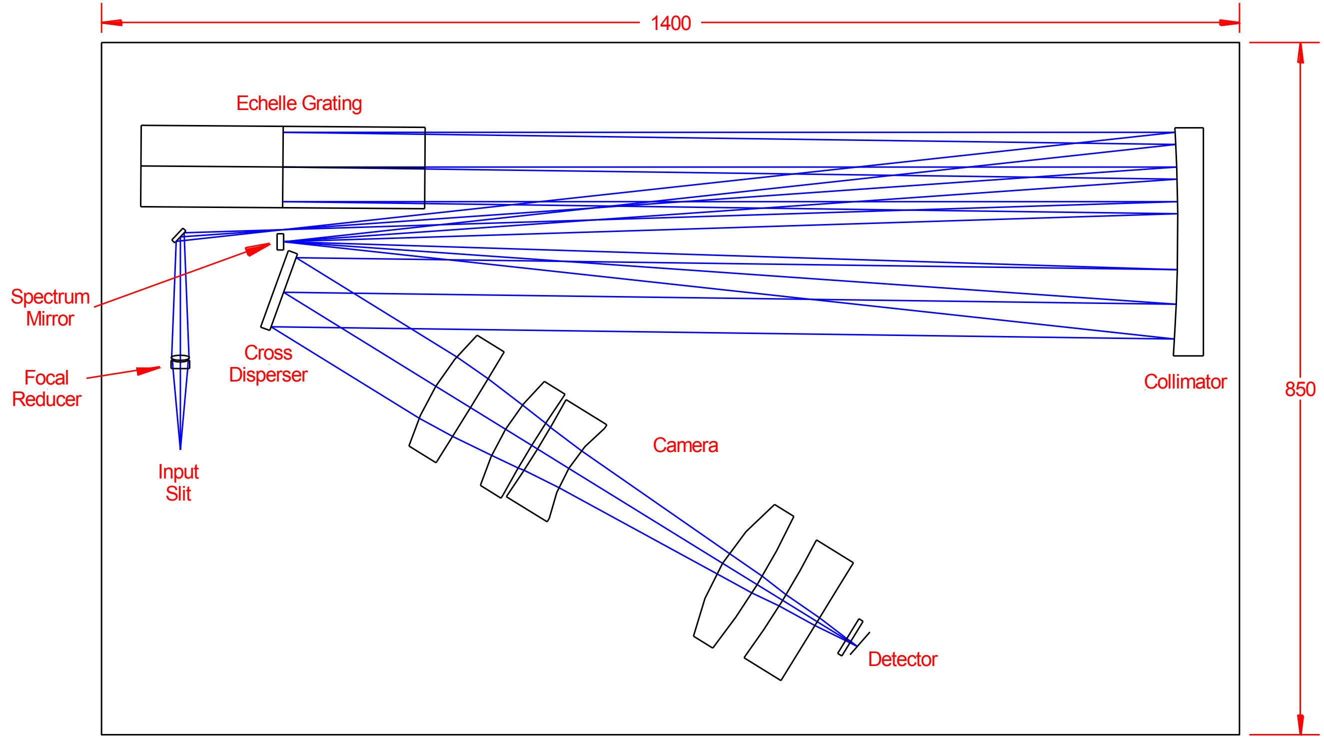




Fibre Slicer Concept



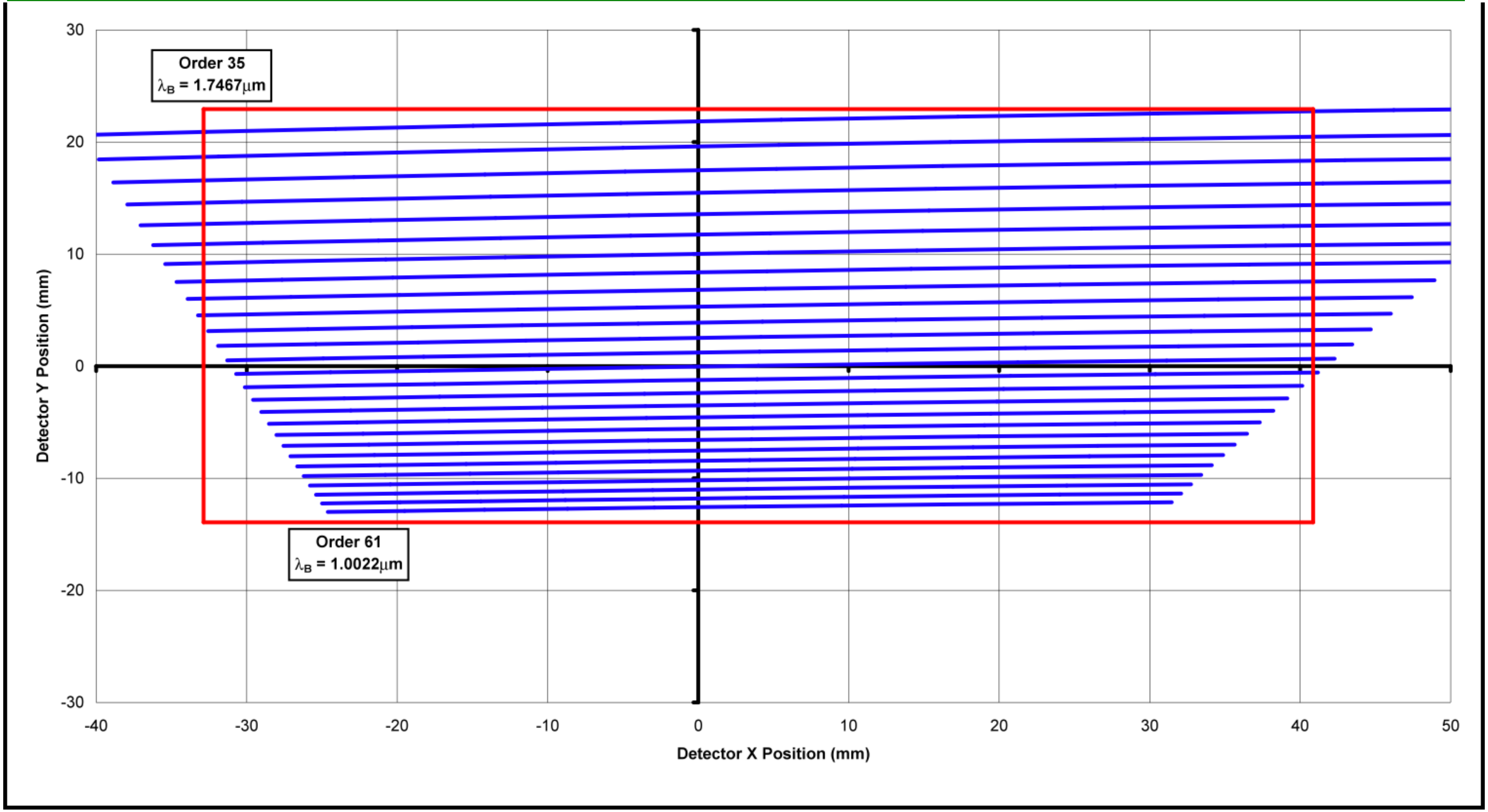
Spectrograph Optical Layout



- Input slit
  - 0.46 arcsec wide, 0.36 x 0.047mm effective size, f/5
- Focal reducer
  - Convert from f/5 to f/13
- Single collimator
  - Parabolic mirror, f=1100mm, 85mm collimated beam diameter
- Spectrum mirror
  - Spectrally dispersed image at intermediate focal plane

- Echelle
  - 31.6 lines/mm, R4 (75° blaze angle)
- Cross disperser
  - Reflective grating
- Camera
  - f=450mm, f/5.3
- Detector
  - 2 x 2K^2 HAWAII-2RG arrays

UPF Spectral Format



Detector array footprint
2 x 2K² HAWAII-2RG arrays
73.728 x 36.864mm

Achieving metre per second precision

UPF

- Metre per second RV precision is equivalent to <0.001 of a pixel
- Large wavelength coverage in single exposure
  - Hundreds of spectral features
- Highly stable instrument
  - Guiding at fibre input
  - Fibre scrambling
  - Fibre agitator – reduces modal noise in fibres
  - No other mechanisms (fixed focus, single grating, single filter)
  - Floor mounted instrument – gravitationally stable, so no flexure
  - Under vacuum – removes effects of pressure and humidity variation
  - Located in Coude room or instrument lab
    - Less than 2K annual temperature variation
  - Active temperature stabilisation of spectrograph optical bench
    - $\pm$0.05K over 24 hours
- Combination of these measures gives <0.1 pixel drift over 1hr integration

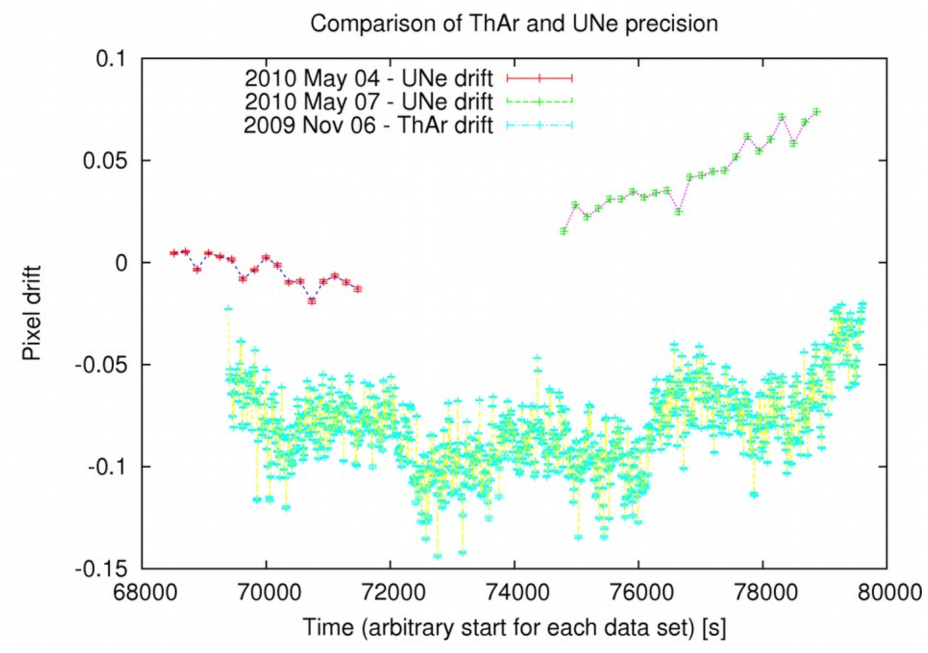
Achieving metre per second precision

UPF

- Calibration needed to increase precision by 2 orders of magnitude to achieve 0.001 pixels
  - Simultaneous calibration via reference fibre – tracks drift in wavelength scale over an integration
  - Off line (daytime) calibration via gas cell – absolute calibration of wavelength scale
  - Off line measurement of spectral response function (PSF * fibre slit) – mitigates against small changes causing spurious centroid shifts

Reference fiducial in the NIR

- Use of a laser comb not currently within UPF budget.
- Use simultaneously exposed arcs (Th-Ar, Kr, Ne, Xe)
- UNe lamp promising – gives more lines than ThAr → 3-3.5x improvement in Y band precision

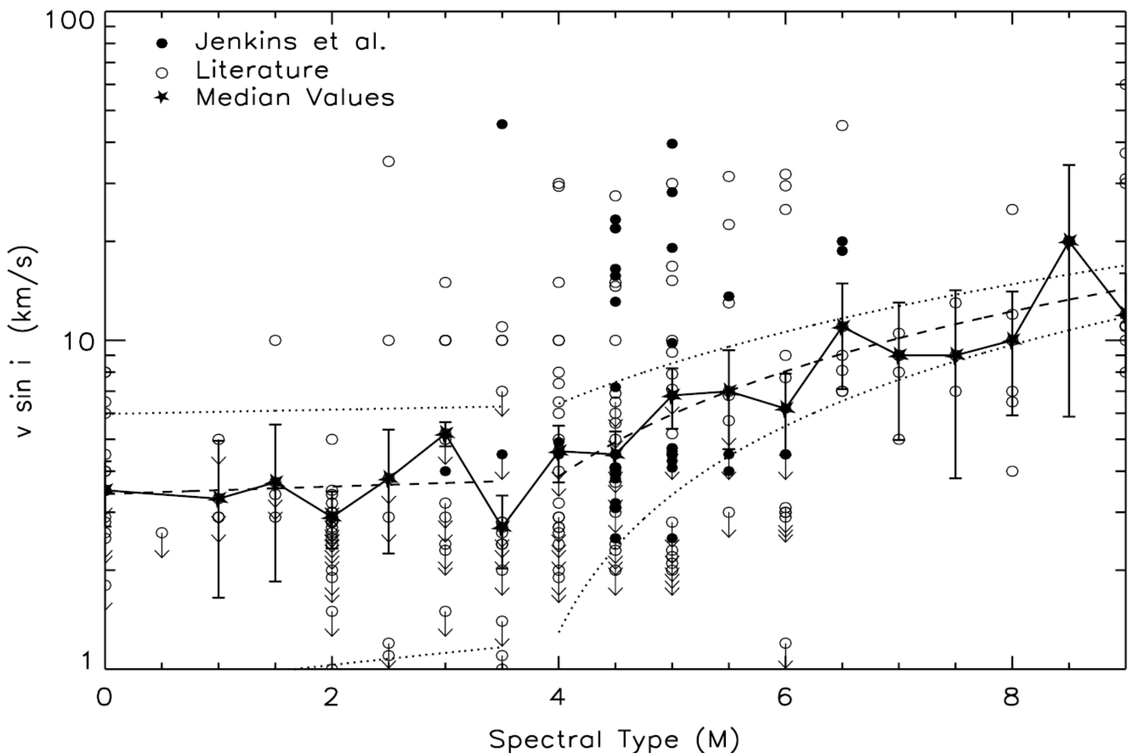


Instrument expectations

Error source	Contribution	Comment
Drift measurement with sim. arcs	< 0.2 m/s	~ 300 arc lines typically > 60 s
Wavelength calibration	< 0.1 m/s	> 1000 arc lines during daytime calibration
Instrument SRF measurement	< 0.3 m/s	> 1000 arc lines during daytime calibration
Photon-weighted centre of integration time	< 0.1 m/s	Median sky conditions (1m/s corresponds to 30s)
Opto-mechanical stability	< 0.3 m/s	< 0.1 pixel drift during an observation
Centring and guiding	< 0.3 m/s	Spatial scrambling of fibre and CCD guiding
Background subtraction	< 0.1 m/s	Stability of background, dark current, bias etc.
Total non-source noise	**< 0.6 m/s**	RMS
Source photon noise	0.8 m/s	m_Y=10.5 M6 V (*v*sin*i*=5 km/s) at 10 pc S/N=150 in 14 min
Source radial velocity jitter	(0-20 m/s)	Sources will be selected for minimum radial velocity jitter
Atmospheric noise	~0.5 m/s	
Total noise (1 σ)	**1.1 m/s**	For typical M6 V star at 10 pc (no radial velocity jitter)

M dwarf radial velocity planet searches

- How do rotation and starspot coverage limit precision?

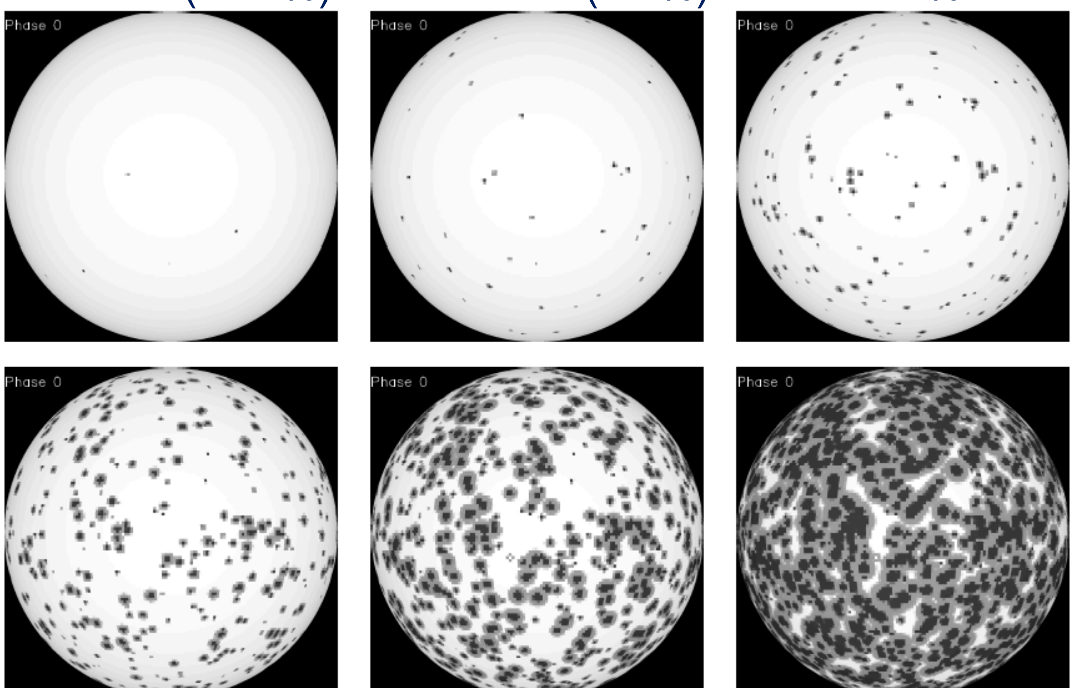


Jenkins et al. 2009, ApJ, 704, 975

M dwarf starspot patterns

- Doppler Images of (near fully convective) M dwarfs show uniform spot coverage – 10 % coverage (Barnes et al 2001, 2004)
- TiO band analysis indicates spot coverage: 20 to 40% (O'Neal et al 2004)
- Solar activity levels are extrapolated to active stars (Solanki 1999)
- Generate line profiles at multiple rot^{n} phases using a 3D stellar model

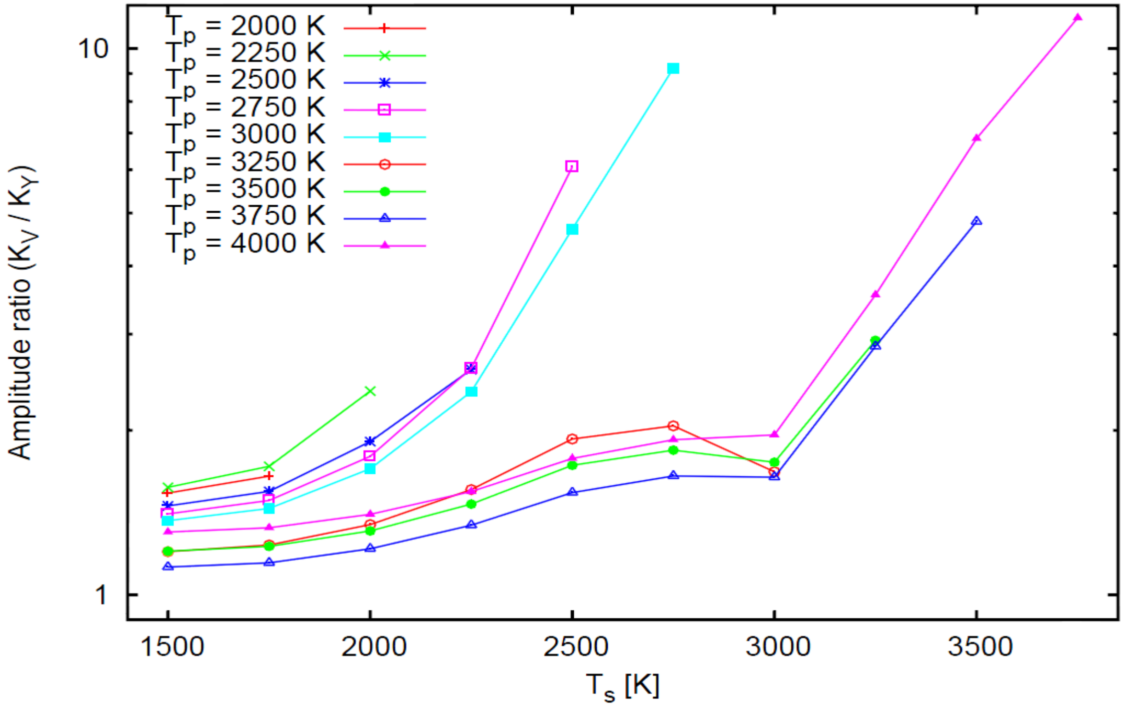
Solar min (0.03%) Solar max (0.3%) 1.9%



9% 30% 62%

How do spots impact RV curve?

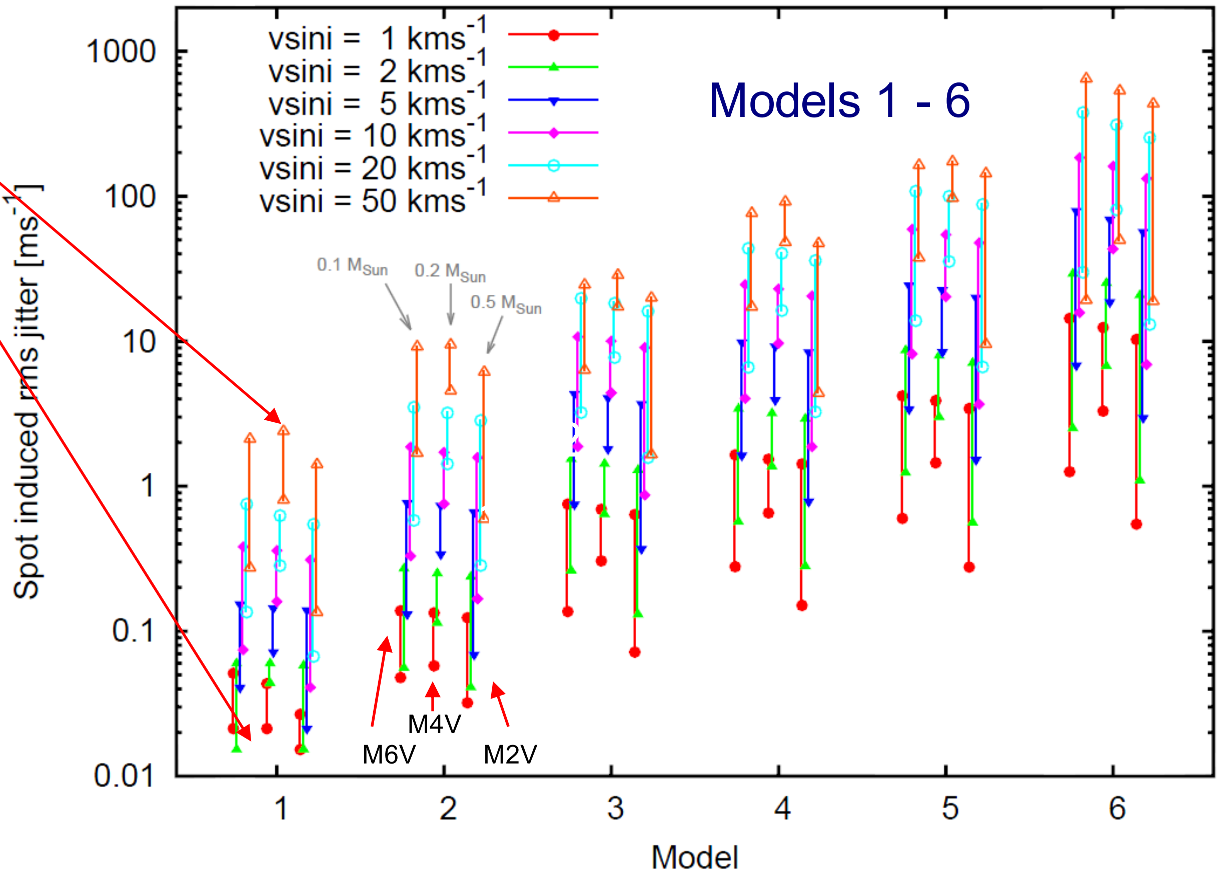
- Photosphere/Spot (T_p/T_s) contrast variations
- Amplitude induced in V vs Y band



- Once T_p/T_s is sufficiently high, spots in V and Y bands contribute negligible flux → little improvement in NIR over optical

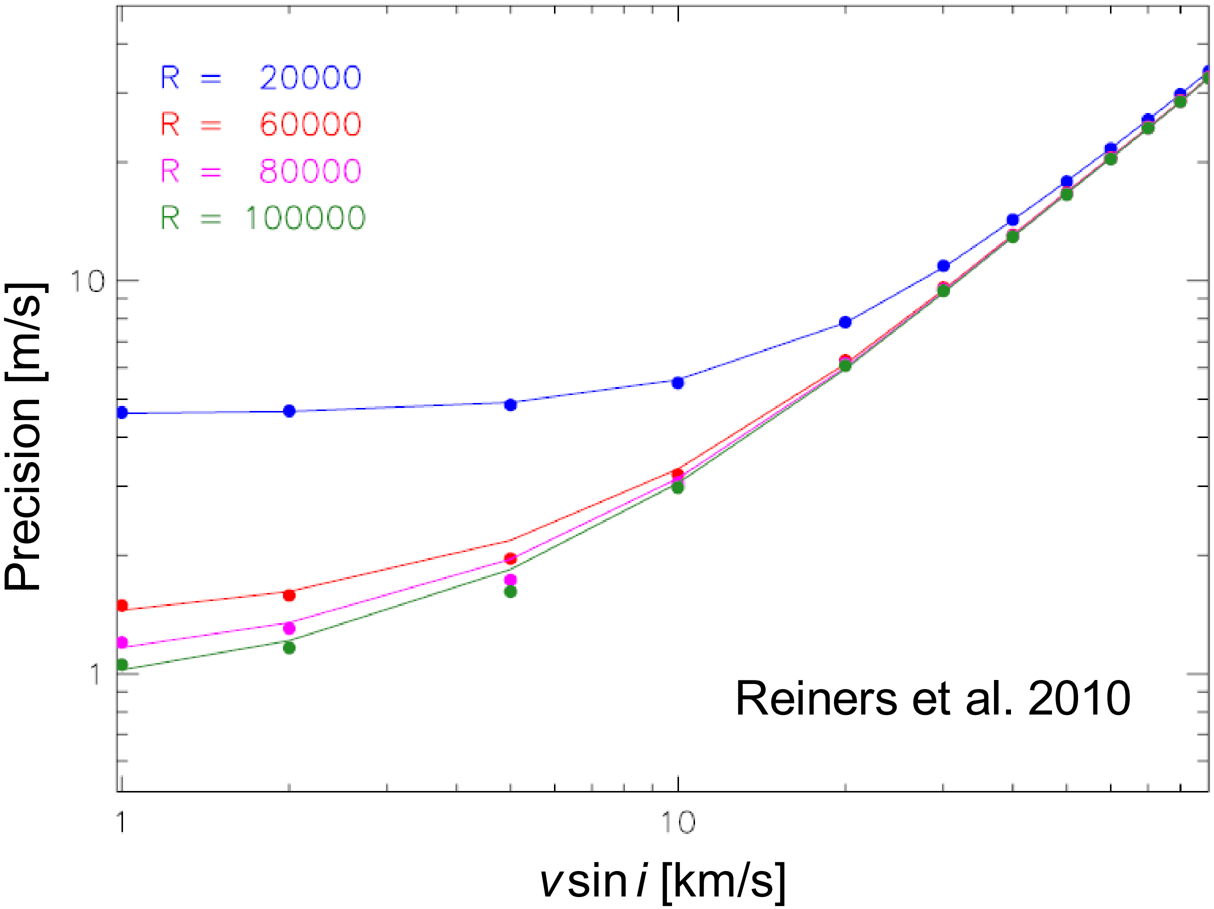
Radial Velocity – Random Spots

- $T_{s1} = 0.65\ T_p$
- $T_{s2} = T_p – 200K$
- Solar min + max models lowest RV jitter ~ 1m/s
- Placing spots randomly decreases jitter!



Precision as a function of rotation

$v\sin i$	Precision
2	1.5
5	2.0
10	3.0
20	6.0
50	11.0



Planet Detection

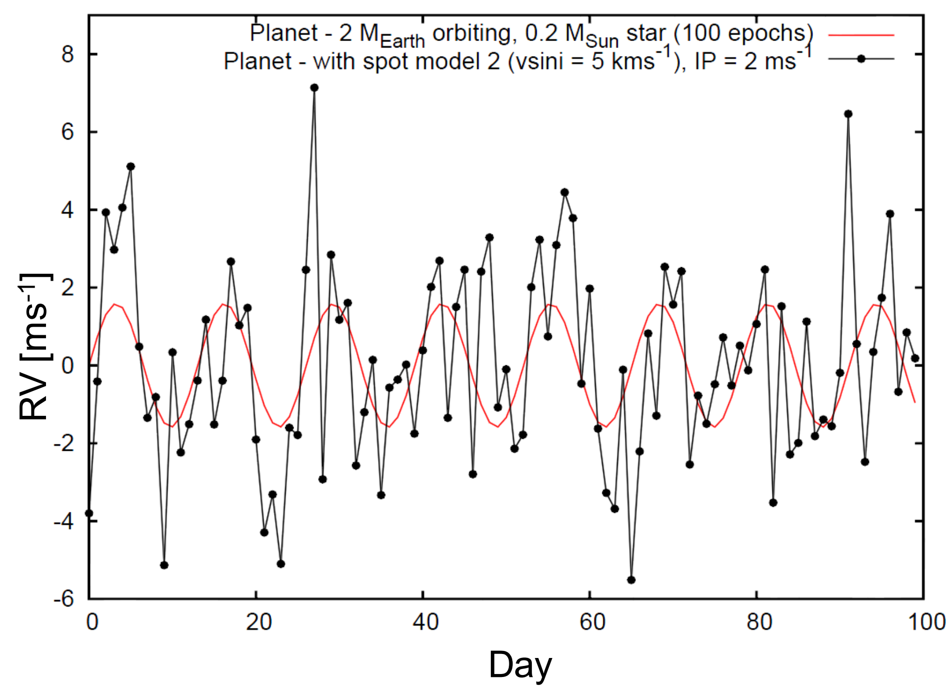
UPF

- Simulate detection thresholds for low-mass planets orbiting centre of habitable zone
- M_{star} = 0.1 (M6V), 0.2 (M4V) and 0.5 $M_{\odot}$ (M2V)
- M_{planet} = 1, 2, 5, 10 & 20 $M_{\oplus}$
- 10, 20, 50, 100, 200 & 500 epochs of observation (on consecutive nights)
- Radial Velocity Jitter:

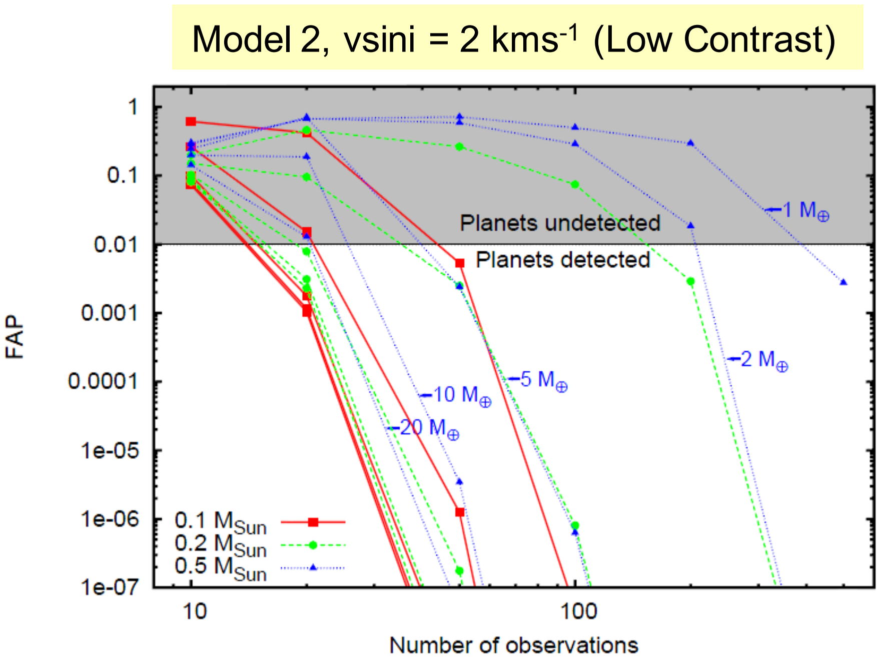
  (1) starspots

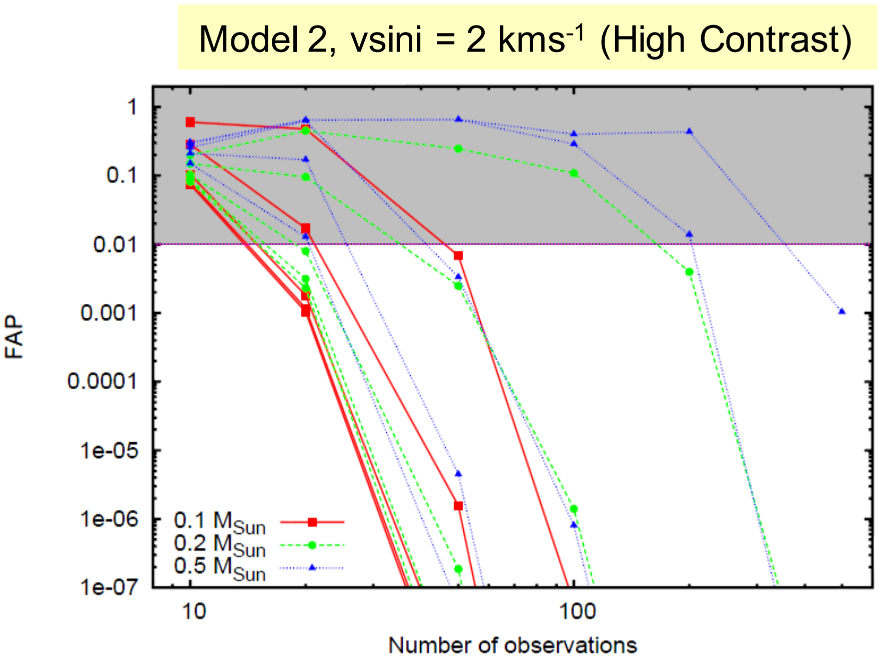
  (2) instrumental (1.5 – 6 ms^{-1} for Y band)

Lomb-Scargle periodogram analysis to detect periodicity



Planet Detection I – vsini = 2 kms^{-1}

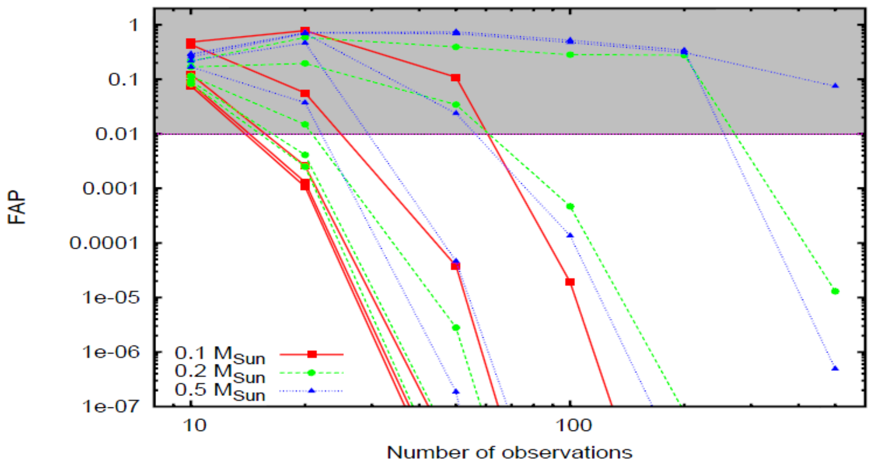




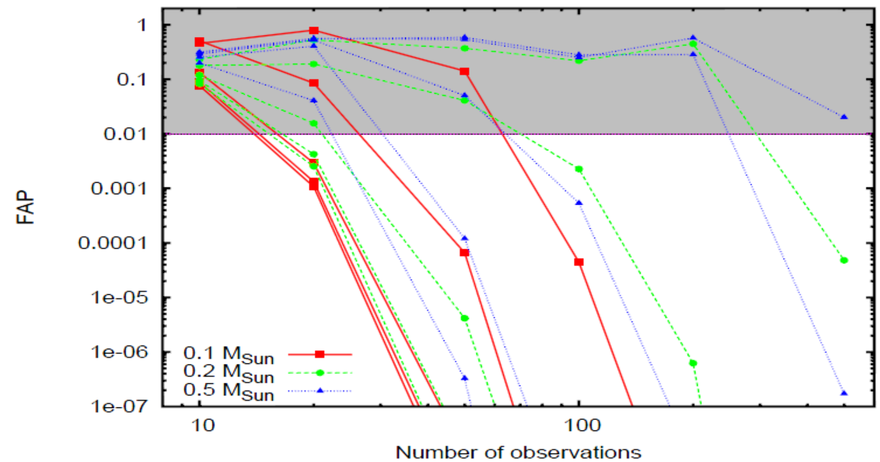
- Model 2 (Solar Max.) $v\sin i$ = 2 kms^{-1} (Meas. precsn. = 1.5 ms^{-1})
- 20 - 30 epochs required to detect 5 $M_\oplus$ planet orbiting 0.1 $M_\odot$ star
- 50 epochs required to detect 1 $M_\oplus$ planet orbiting 0.1 $M_\odot$ star
- 500 epochs required to detect 1 $M_\oplus$ planet orbiting 0.5 $M_\odot$ star
  (no significant variation for T_p/T_s contrast ratio as noise dominated by instrumental precision)

Planet Detection II – vsini = 5 kms^{-1}

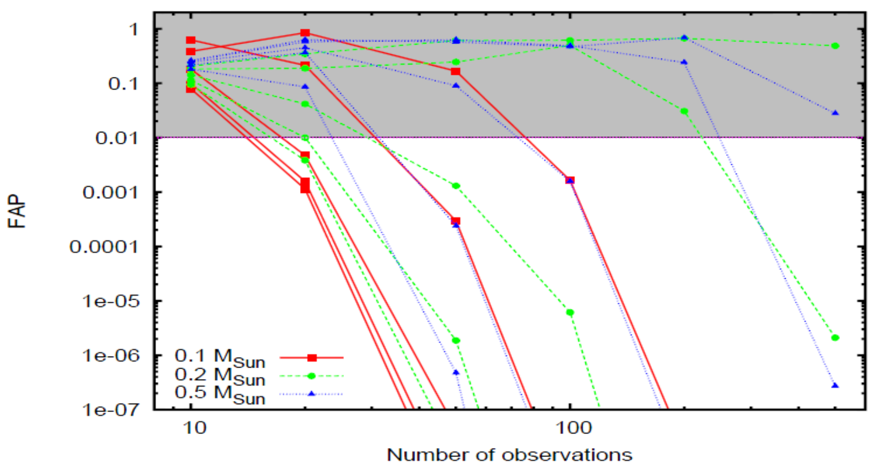
Model 2, vsini = 5 kms^{-1} (Low Contrast)



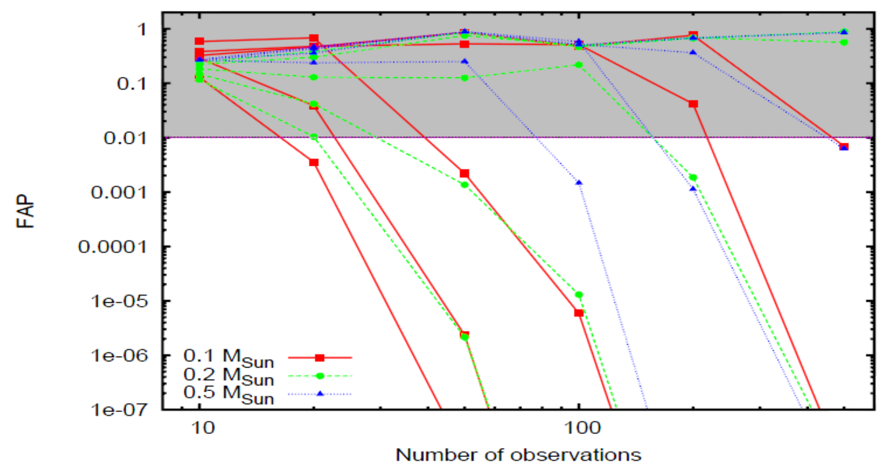
Model 2, vsini = 5 kms^{-1} (High Contrast)



Model 4, vsini = 5 kms^{-1} (Low Contrast)



Model 4, vsini = 5 kms^{-1} (High Contrast)



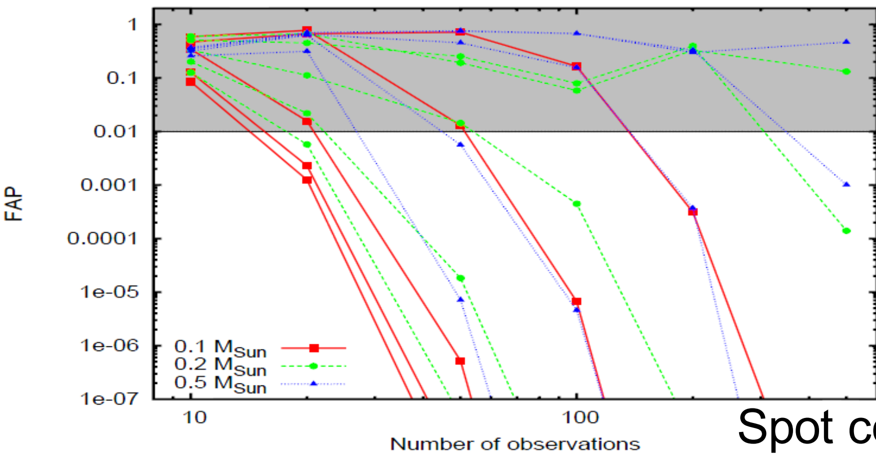
(Meas. precsn. = 2 ms^{-1})

Similar to 2 kms^{-1}

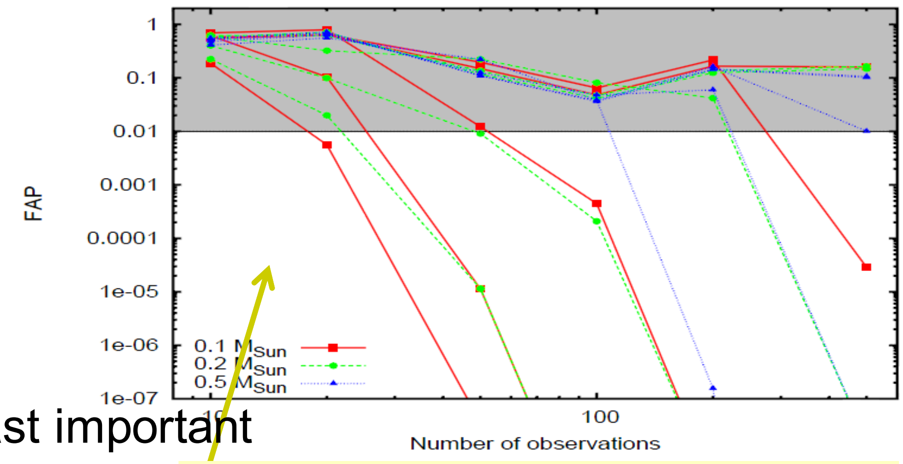
(R=70k $\equiv$ 4.3 kms^{-1} in Y-band)

Planet Detection III – vsini = 10 kms^{-1}

Model 3, vsini = 10 kms^{-1} (Low Contrast)

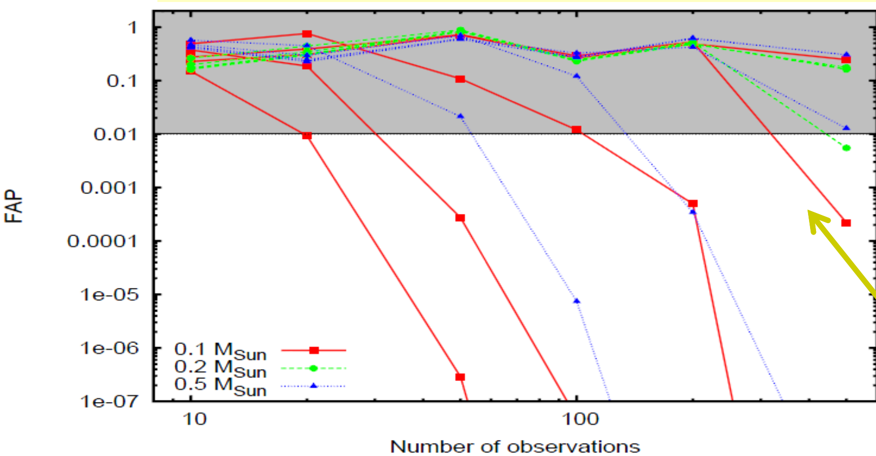


Model 3, vsini = 10 kms^{-1} (High Contrast)

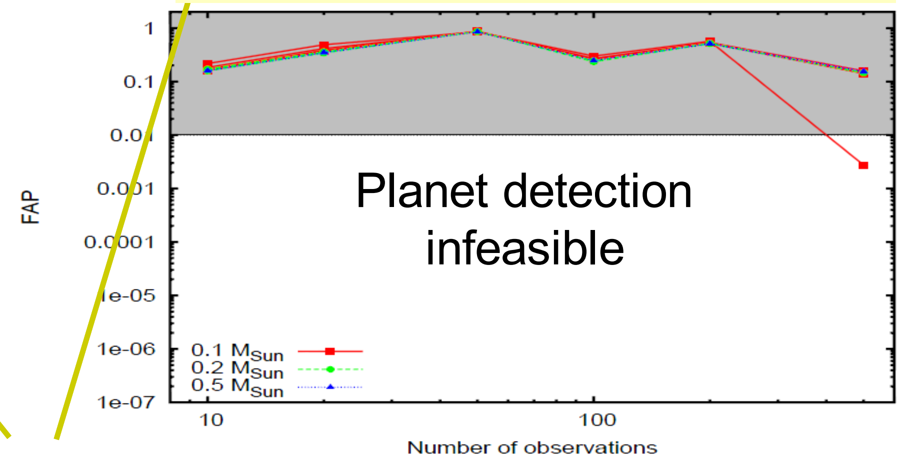


Spot contrast important

Model 6, vsini = 10 kms^{-1} (Low Contrast)



Model 6, vsini = 10 kms^{-1} (High Contrast)



(Meas. precsn. = 3 ms^{-1})

Only 10 & 20 $M_{\oplus}$ planets detected with 50 - 100 observations.

Planet Detection IV – vsini = 20 kms^{-1}

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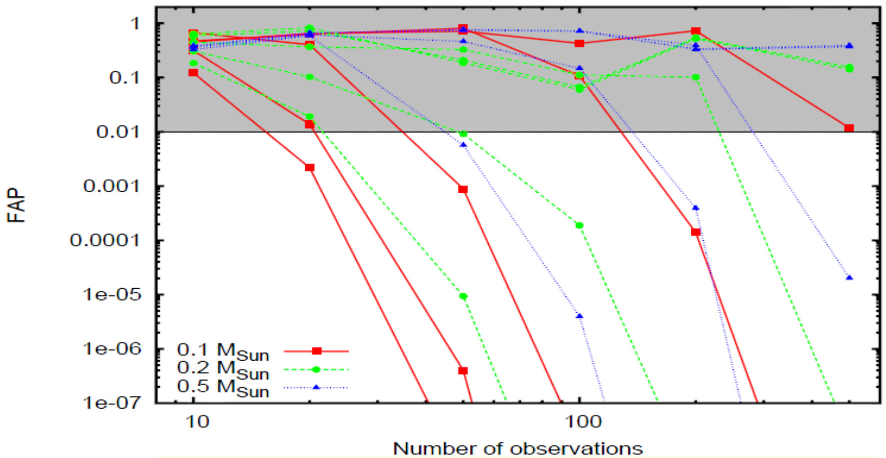
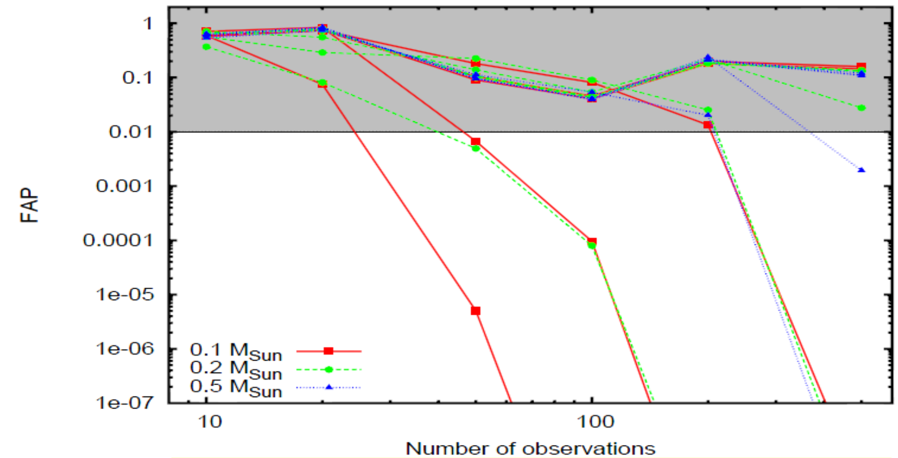
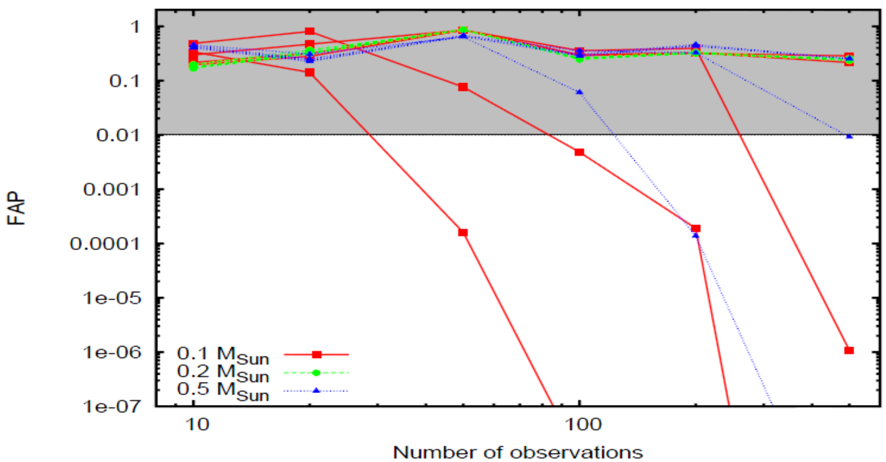
Model 3, vsini = 20 kms^{-1} (Low Contrast)



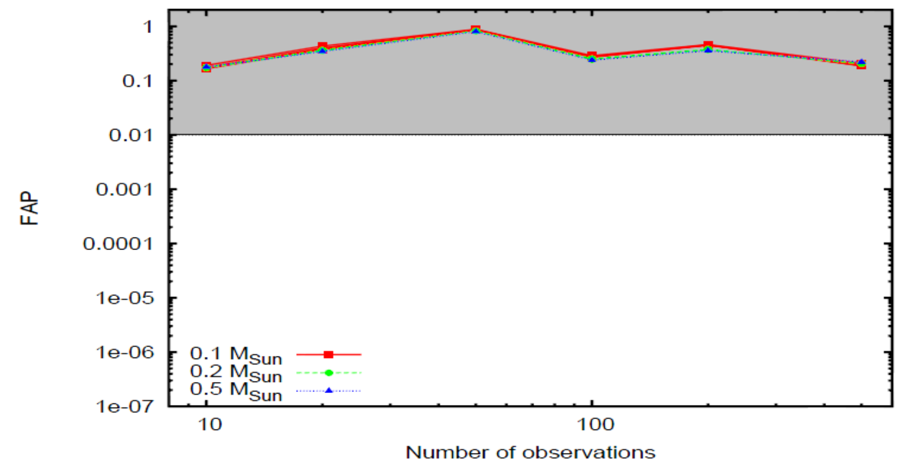
Model 3, vsini = 20 kms^{-1} (High Contrast)



Model 6, vsini = 20 kms^{-1} (Low Contrast)



Model 6, vsini = 20 kms^{-1} (High Contrast)



(Meas. precsn. = 6 ms^{-1})

Summary - UPF

- ~1 ms^{-1} precision in NIR (simultaneous Y,J & H) to enable detection of Earth-mass planets in habitable zones of the closest stars
- Low-risk design inherited from PRVS (Gemini)
- Low-cost: £4.6m ($7.2m) (baseline cost)
  of which £1.5m ($2.4m) is hardware/travel

Summary – M dwarf spot simulations

- With only several 10s of epochs detection of habitable zone Earth-like planets orbiting M dwarfs is possible
- Spot contrast important consideration for mid-late M dwarfs
- *v* sin *i* may be limiting factor if spot coverage low
- Removal of starspot jitter via line bisector analysis may be important for study of significant pop^{n} of moderat/fast rotators among mid-late M dwarfs
- Eccentric orbits: e = 0.5 → 2.5 x observations
  e = 0.9 → 5 x observations

(Barnes, Jeffers & Jones, MNRAS, submitted)