Spectral extraction of BOSS
fully-depleted CCD data

Workshop on Precision Astronomy with Fully Depleted CCDs
BNL Nov. 2013

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on behalf of the BOSS collaboration

(slides "borrowed" from S. Bailey, D. Schlegel, A. Font-Ribera, N. Roe, P. Jelinski +many papers)

Outline

Brief description of :
- Science with BOSS
- BOSS spectrograph (Smee et al., arXiv:1208.2233)
- Data reduction pipeline

Data reduction challenges (in relation with CCDs):
- Optimal extraction for Emission Line Galaxies
- Characterization of the PSF

CCD effects in BOSS :
- Clock phase mismatch at boundary of amplifiers
- Scattering on the back side of the CCD for the longest wavelength
- PSF width as a function of signal intensity
- Impact on PSF of diffusion in CCD and large incidence angles

Science with SDSS-III / BOSS

- 3D (angle, redshift) catalogs of
    - 1.3(*) million galaxies (Large Red Galaxies) at redshifts 0.3-0.6
    - 160 thousand quasars (QSO) at redshifts 2.2-3.5   (*) +200k from SDSS-II

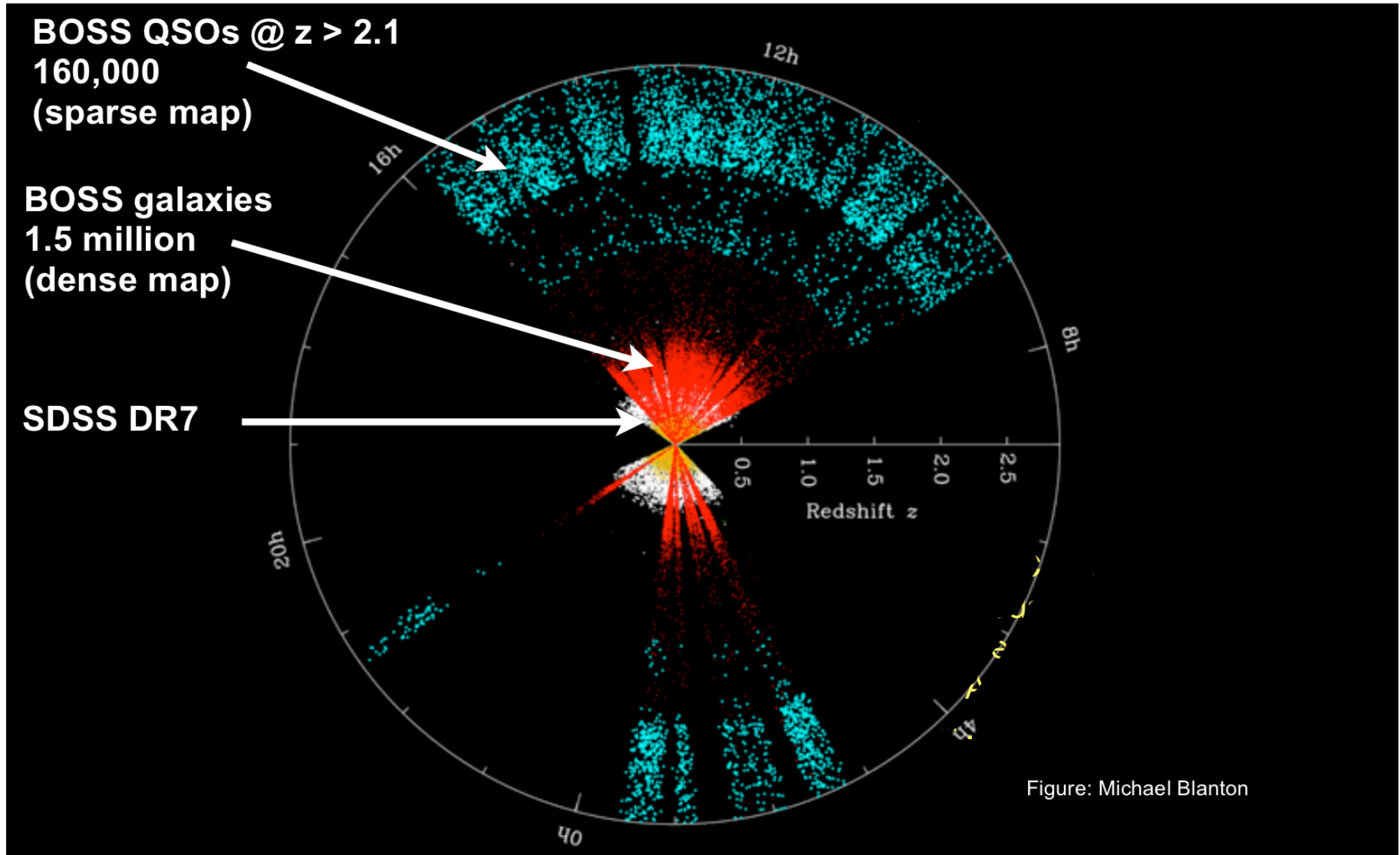   - needs an input multi-band photometric catalog, a target selection method
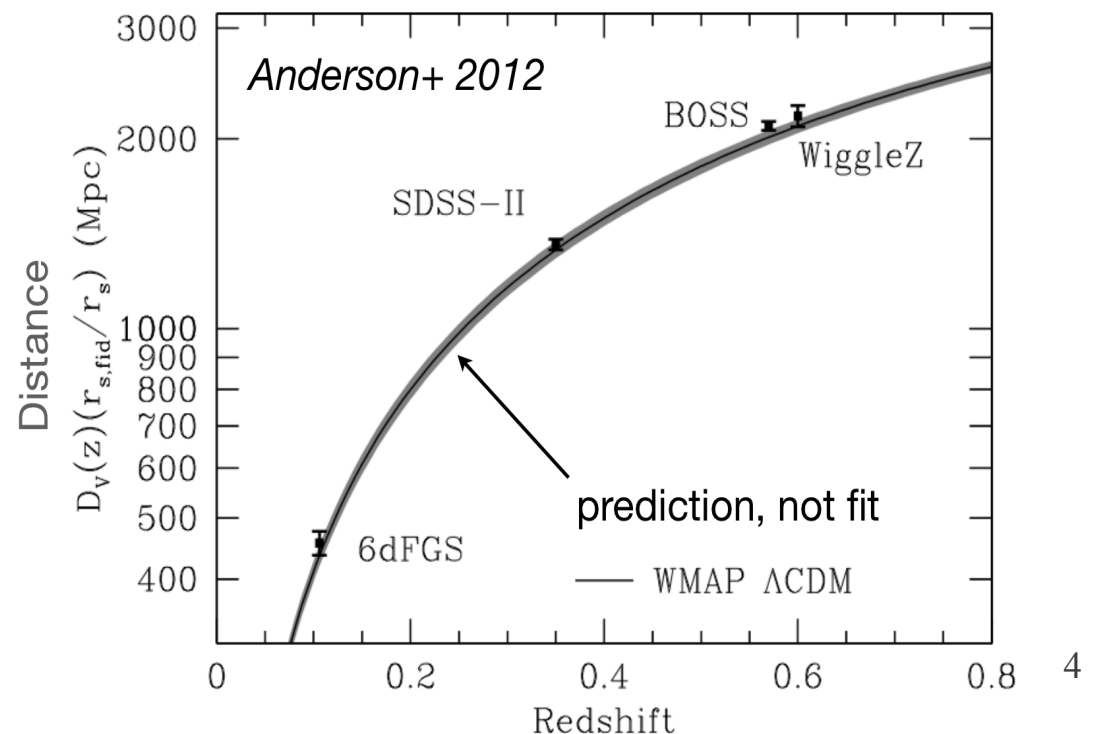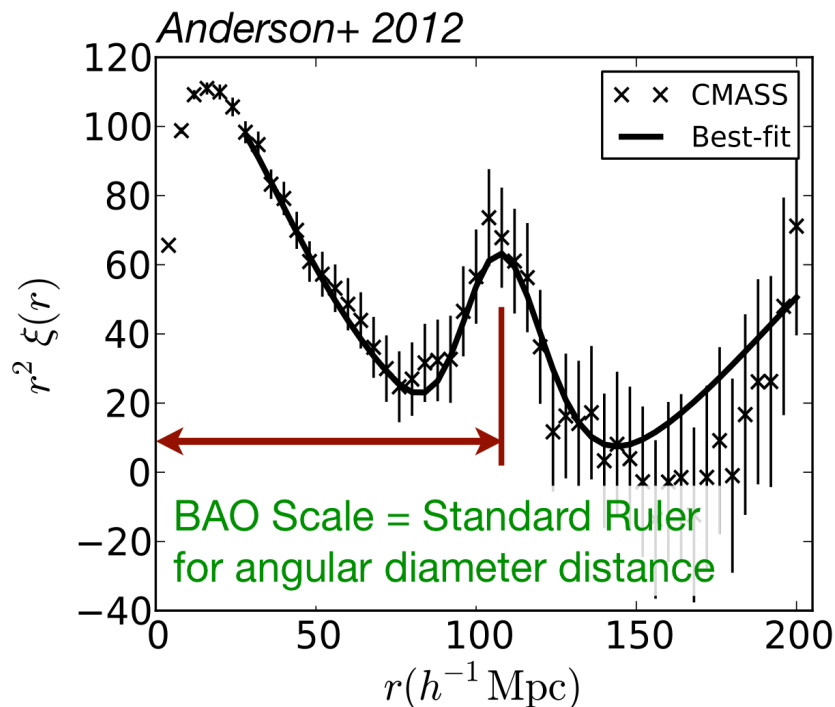

BOSS QSOs @ z > 2.1
160,000
(sparse map)

BOSS galaxies
1.5 million
(dense map)

SDSS DR7

Figure: Michael Blanton

Science with SDSS-III / BOSS

- Based on galaxy catalog (BOSS data: redshifts)
  - **Baryon acoustic oscillations** (measure of angular distance, H(z)) at z~0.6
  - Matter power spectrum
  - Redshift space distortions (measure of growth rate of structures)

- Lyman-alpha forest (BOSS data: spectra)
  - Baryon acoustic oscillations at z~2.2
  - Matter power spectrum at small scales : constraints on ns, neutrino mass

Very successful results :

Science with SDSS-III / BOSS

- Based on galaxy catalog (BOSS data: redshifts)
    - Baryon acoustic oscillations (measure of angular distance, H(z)) at z~0.6
    - Matter power spectrum
    - **Redshift space distortions** (measure of growth rate of structures)

- Lyman-alpha forest (BOSS data: spectra)
    - Baryon acoustic oscillations at z~2.2
    - Matter power spectrum at small scales : constraints on ns, neutrino mass
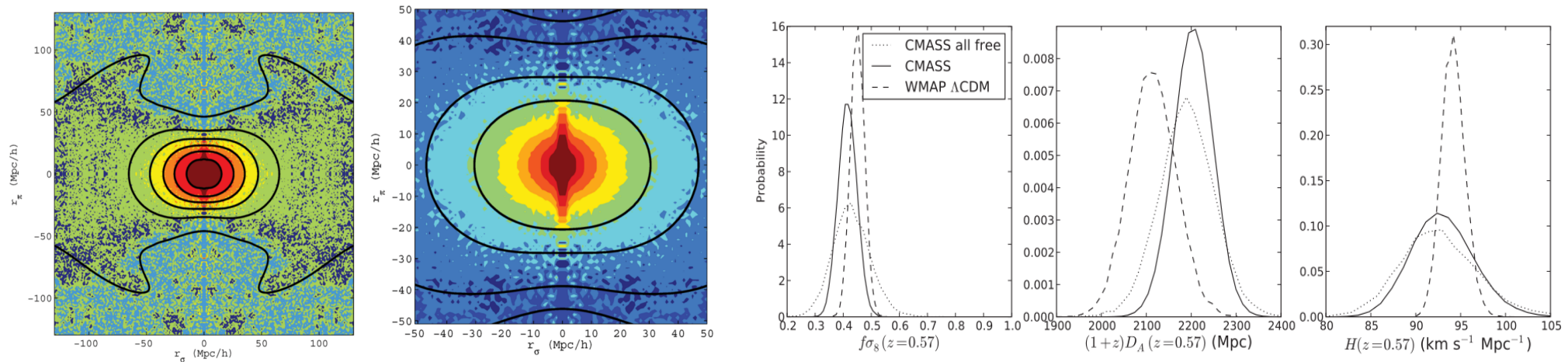
Very successful results :

Figure 3. Left-hand panel: two-dimensional correlation function of CMASS galaxies (colour) compared with the best-fitting model described in Section 6.1 (black lines). Contours of equal ξ are shown at [0.6, 0.2, 0.1, 0.05, 0.02, 0]. Right-hand panel: smaller-scale two-dimensional clustering. We show model contours at [0.14, 0.05, 0.01, 0]. The value of ξ_0 at the minimum separation bin in our analysis is shown as the innermost contour. The $\mu \approx 1$ 'finger-of-God' effects are small on the scales we use in this analysis.

Reid et al. 2012

Science with SDSS-III / BOSS

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- Lyman-alpha forest (BOSS data: spectra)
  - **Baryon acoustic oscillations** at z~2.2
  - Matter power spectrum at small scales : constraints on ns, neutrino mass
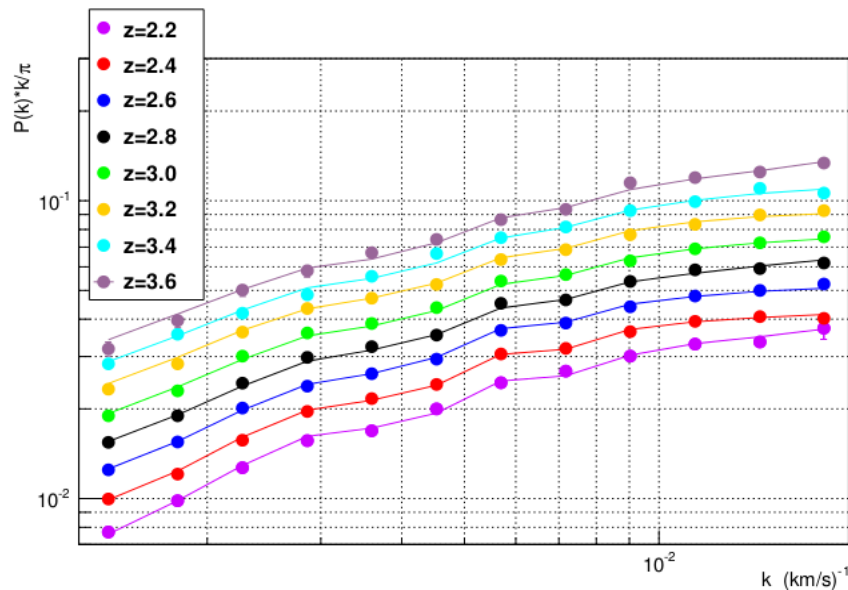
Very successful results :

BAO at z=2.4
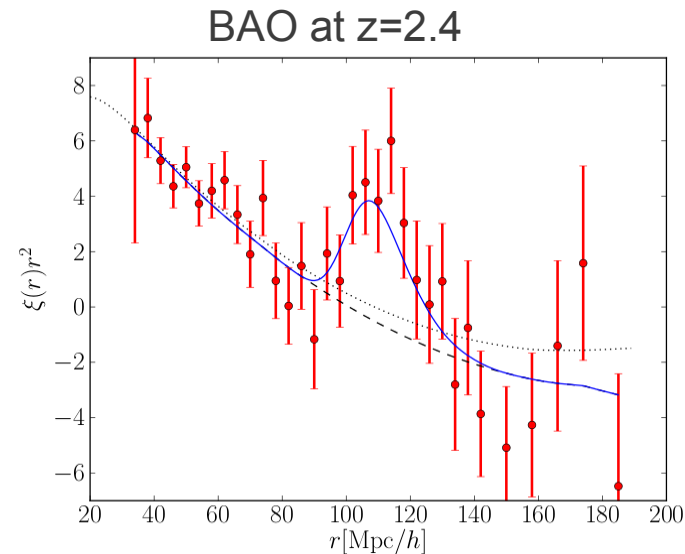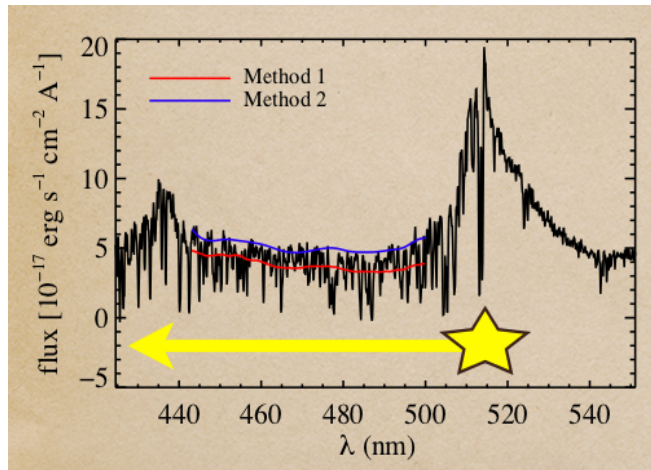
Busca 2013, Slosar 2013

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Science with SDSS-III / BOSS

- Based on galaxy catalog (BOSS data: redshifts)
  - Baryon acoustic oscillations (measure of angular distance, H(z)) at z~0.6
  - Matter power spectrum
  - Redshift space distortions (measure of growth rate of structures)

- Lyman-alpha forest (BOSS data: spectra)
  - Baryon acoustic oscillations at z~2.2
  - **Matter power spectrum** at small scales : constraints on ns, neutrino mass

Very successful results :

Fig. 23: *Fit of the power spectrum measured with BOSS in the range $z = [2.1 - 3.7]$; the z and k binning of McDonald et al. (2006) is adopted.*
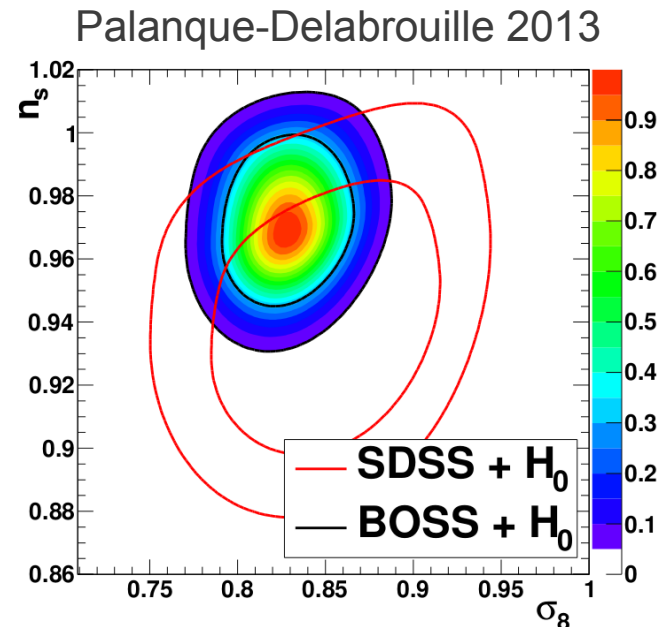

Palanque-Delabrouille 2013

Fig. 26: *2D confidence level contours for the σ_8 and n_s cosmological parameters with a frequentist interpretation. The red and black curves are obtained respectively for SDSS and BOSS measurements of the power spectrum.*

The BOSS spectrograph

2.5m telescope on
Apache Point Obs.
New Mexico

Two double-spectrographs
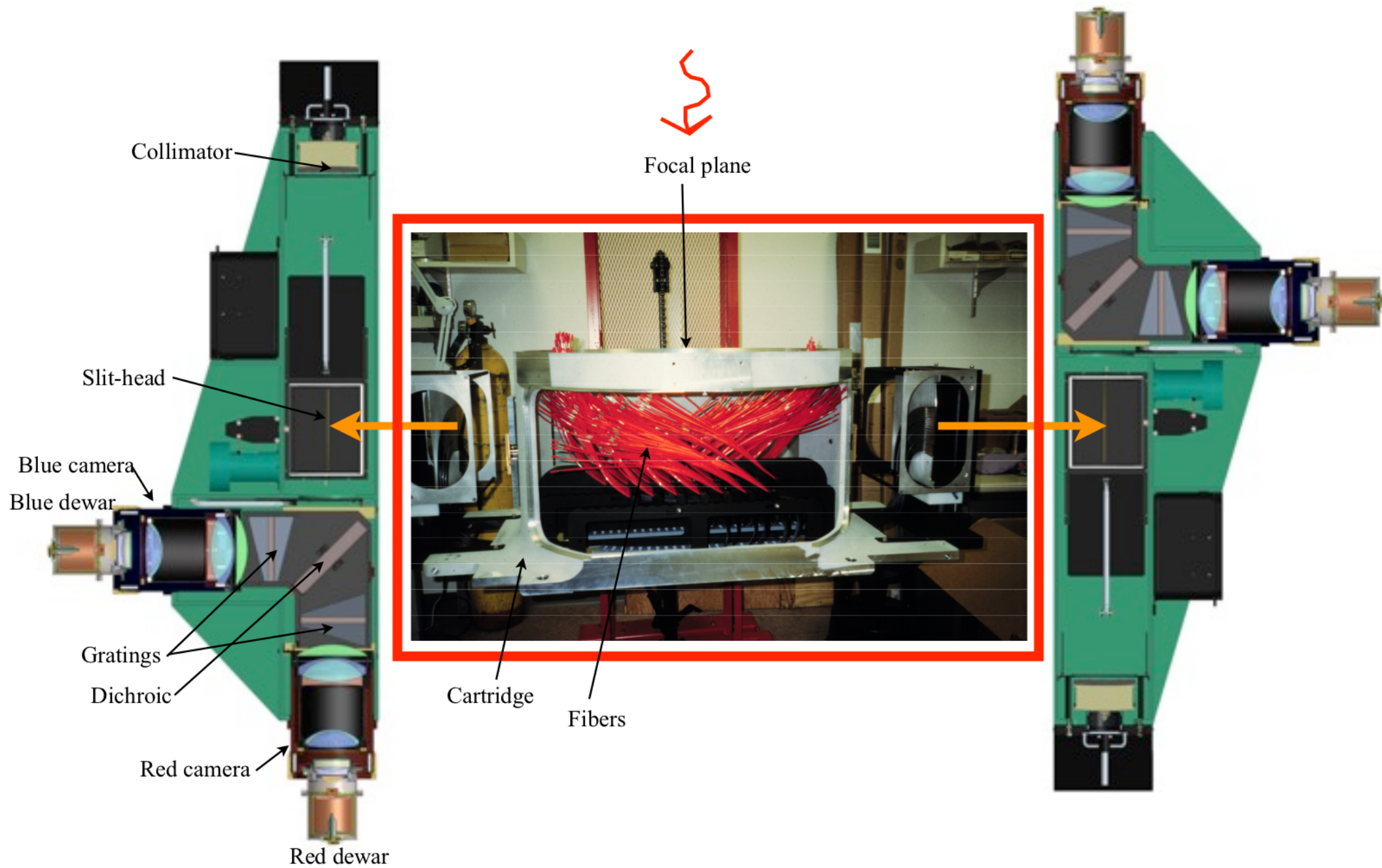(permanently mounted)

3° focal plane:
Either imaging camera
or 1 of 8 spectro cartridges
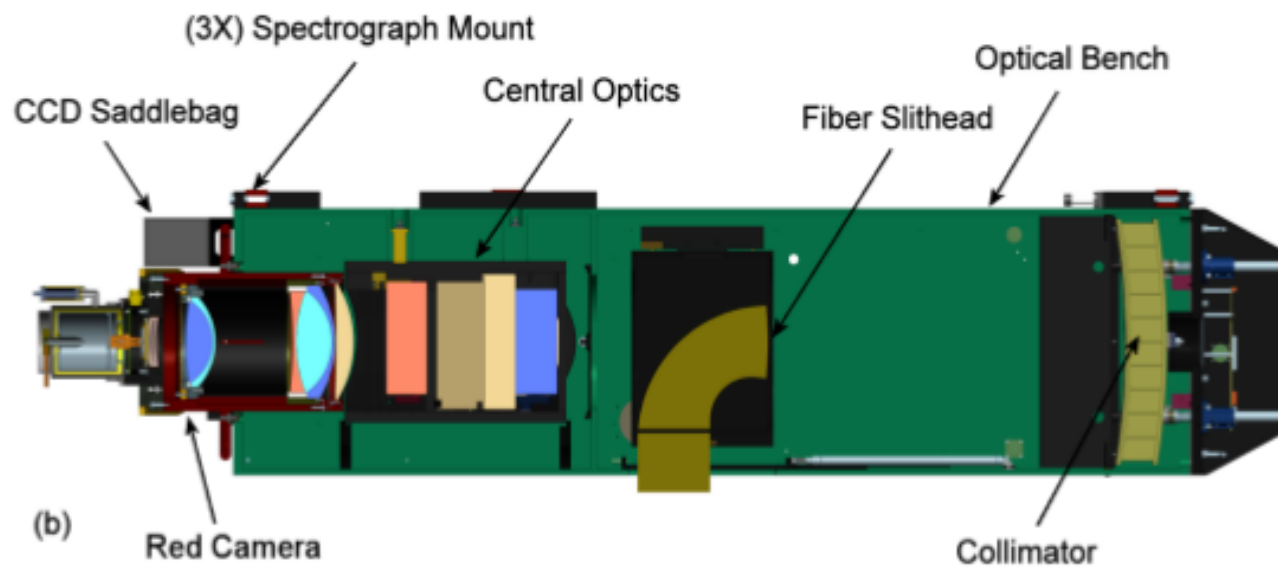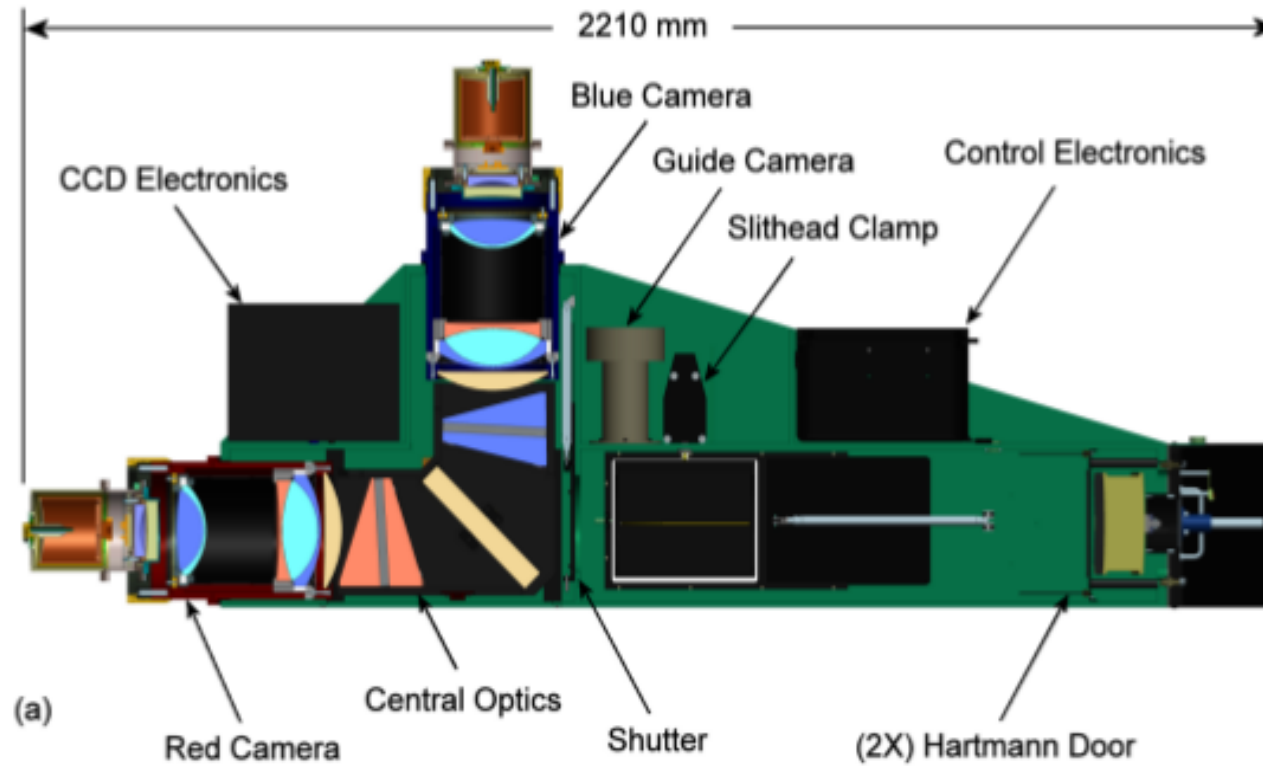(swapped during night)

"Doghouse":
Stores imaging camera
when not in use
(now removed from
telescope)

6. 12. 2000

The BOSS spectrograph

Collimator

Focal plane

Slit-head

Blue camera
Blue dewar

Gratings

Dichroic

Red camera

Cartridge

Fibers

Red dewar

SDSS-III / BOSS spectrograph

(a) Labels: 2210 mm, CCD Electronics, Blue Camera, Guide Camera, Control Electronics, Slithead Clamp, Central Optics, Shutter, (2X) Hartmann Door, Red Camera

(b) Labels: (3X) Spectrograph Mount, CCD Saddlebag, Central Optics, Optical Bench, Fiber Slithead, Red Camera, Collimator

1000 fibers holes drilled
on aluminum plate

Zoom on fiber
split-end
(bundle of 20 fibers)
25 bundles per CCD

Hand plugging of fibers on cart-ridge
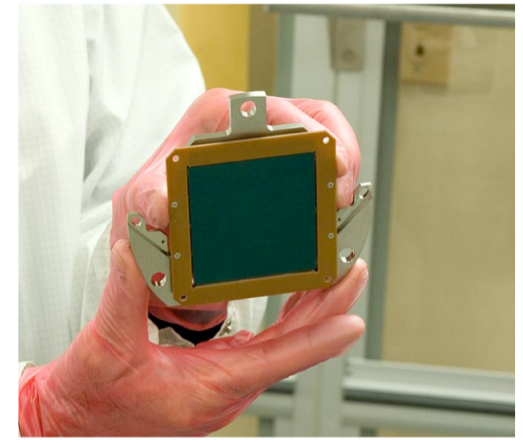
BOSS CCDs

BOSS Throughput

Lauren Anderson
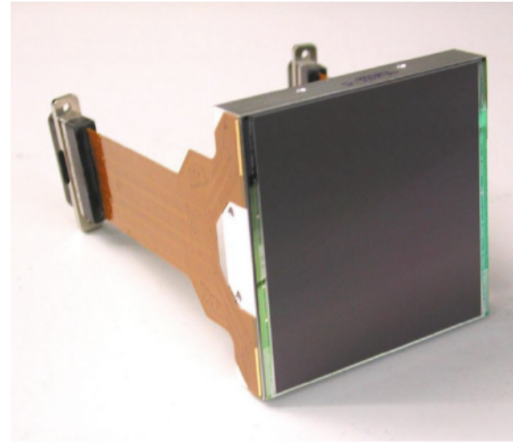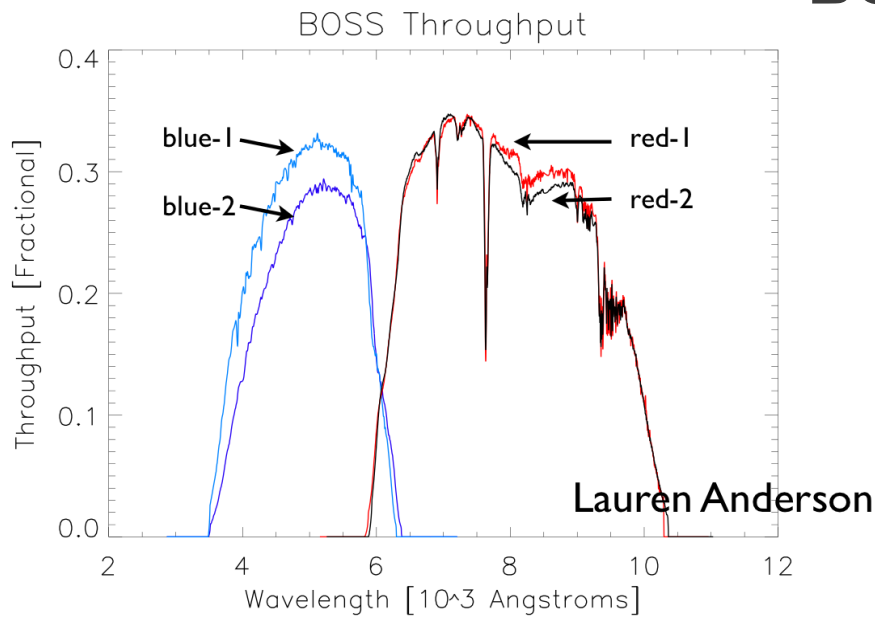
E2v CCD 231-84 BI
4k x 4k Broadband Coating,
low noise outputs

LBNL 4kx4k
Fully Depleted,
Red Sensitive

Blue CCDs
- 2 + 1 spare 231-84 BI CCDs from e2v
– 4096 x 4112 15 um pixels
– Low read noise ~ 1.8-2.0 e- at 88kHz, especially important for QSO studies

Red CCDs
- 2 + 1 spare red 4k x 4k CCDs from LBNL
- Fully depleted 250 um thick for improved red response,reduced fringing
- Window-frame style package
- Read noise ~ 2.4-2.8 e- at 88 kHz

CCD performances

TABLE 4
### CCD Performance for SDSS and BOSS

	read noise (e^-)	dark current (e^-/pix/15 min)	gain (e^-/ADU)	number of bad columns	fraction of bad pixels
SDSS					
b1	2.8–3.8	1.05–1.10	1.05–1.10	4	
b2	3.2–3.9	1.23–1.26	1.23–1.26	4	
r1	3.5–4.1	1.00–1.09	1.00–1.09	14	
r2	3.6–4.4	1.04–1.05	1.05	10	
Start of BOSS					
b1	1.79–1.98	0.64–0.68	1.01–1.05	0	2.0e-05
b2	1.74–2.04	0.61–0.65	0.99–1.04	2	2.1e-04
r1	2.36–2.72	0.88–1.10	1.54–1.97	5	1.4e-04
r2	2.42–2.99	0.95–1.97	1.54–1.96	3	1.8e-04
MJD 55300 (r2 replaced)					
b1	1.83–2.01	0.51–0.53	1.01–1.05	0	2.1e-05
b2	1.87–2.03	0.53–0.56	0.99–1.04	2	2.1e-04
r1	2.43–2.73	0.63–0.80	1.54–1.97	5	3.3e-04
r2	2.73–2.89	1.19–2.27	1.59–1.66	11	4.4e-04
MJD 55800 (r1 replaced)					
b1	1.77–2.02	0.46–0.49	1.01–1.05	0	2.1e-05
b2	1.86–2.01	0.56–0.59	0.99–1.04	2	2.1e-04
r1	2.45–2.82	0.57–0.82	1.47–1.93	1	3.3e-04
r2	2.85–2.88	1.30–1.56	1.59–1.66	11	2.5e-04

- Full-well depth much larger than 65k e-/pixel
- CTE > 1-10^-5 (see Dawson 2008, tested at LBNL with 55Fe source)
- readout time 55.6 sec
- overall overhead of 70 sec (pre-exposure flush+read)

BOSS data reduction pipeline (CCD level)

Standard extraction :

- bias subtraction
- bad pixels masking
- cosmic ray identification
- 1D Gaussian profile/PSF extraction perp. to the dispersion axis
- [follows a complex analysis (sky sub., redshift measurement)
    see Bolton et al. (2012)]
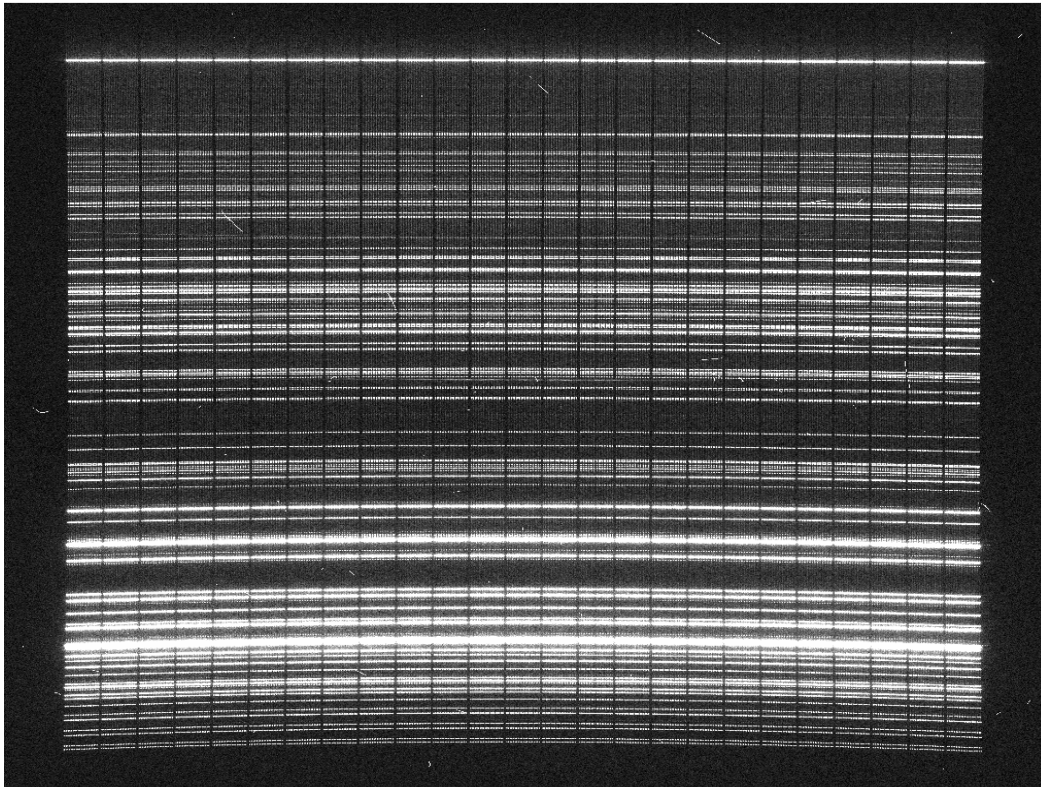
(this is an arc lamp image)

BOSS data reduction pipeline (CCD level)

Calibration sequence

- pixel to pixel flat fielding using lossy fiber

- fiber flat fielding using petals illuminated with 3100K quartz-iodine lamp.
     -> flat(fiber,wavelength) , X_ccd(fiber,wavelength) , PSF_x(fiber,wavelength)

- wavelength calibration using screen illuminated mercury-cadmium lamp for B channel, and Neon-Argon for R-channel.
     -> Y_ccd(fiber,wavelength) , PSF_xy(fiber,wavelength)

- trace coordinates shift (X,Y)=f(fiber,wavelength) reevaluated on
     each science image

- spectro-photometric calibration with fibers allocated to stars (modeled).
     -> flux(fiber,wavelength)

BOSS data reduction pipeline (CCD level)
Pixel to pixel flat fielding

with a lossy fiber
illuminated by a Deuterium Tungsten Halogen light source

one slit-plate
where 25 slit -heads
of 20 fibers are
aligned

location of the lossy fiber
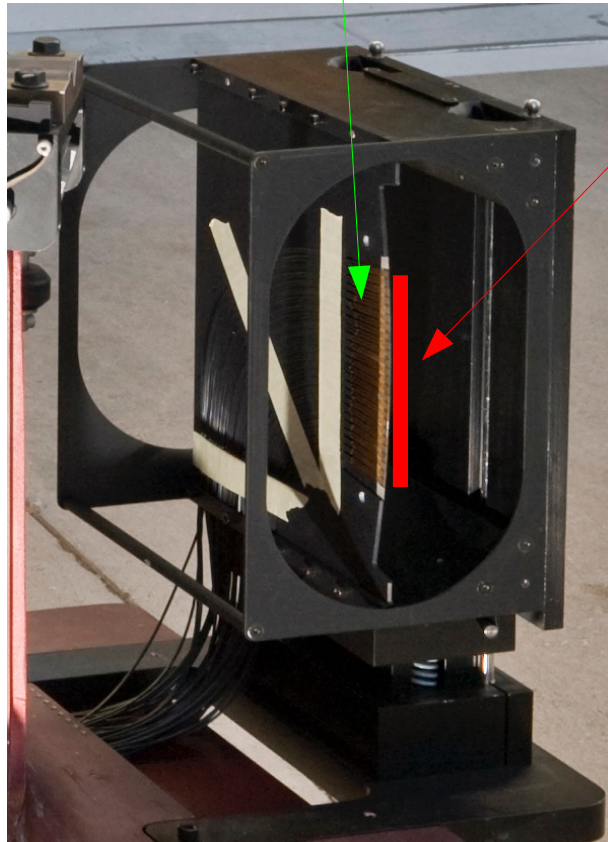
BOSS data reduction pipeline (CCD level)
Fiber flat fielding

Continuum lamp shining on telescope petals
mounted on wind baffle structure (Gunn et al 2006)
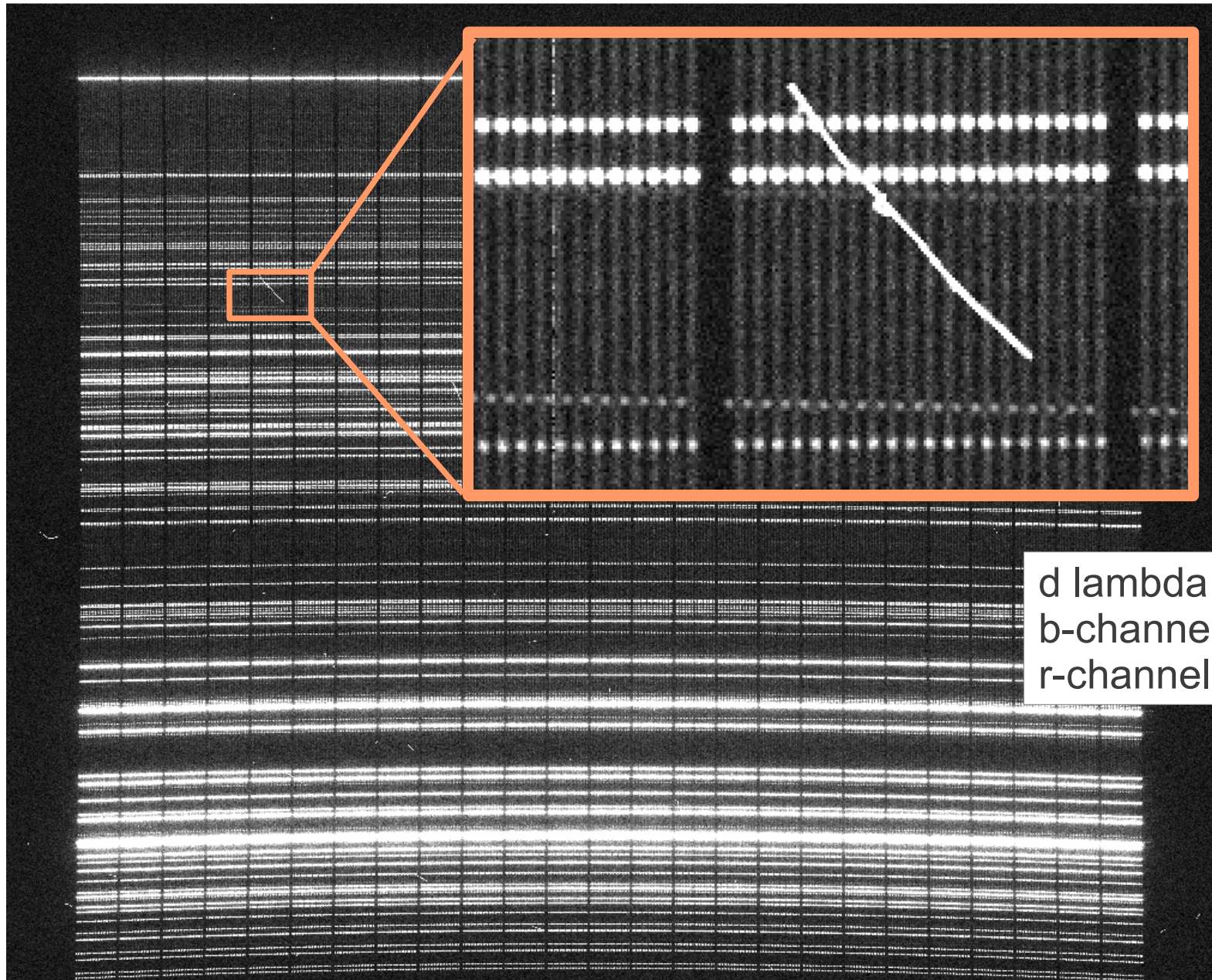
r1 CCD flat field image (zoom, log-scale)
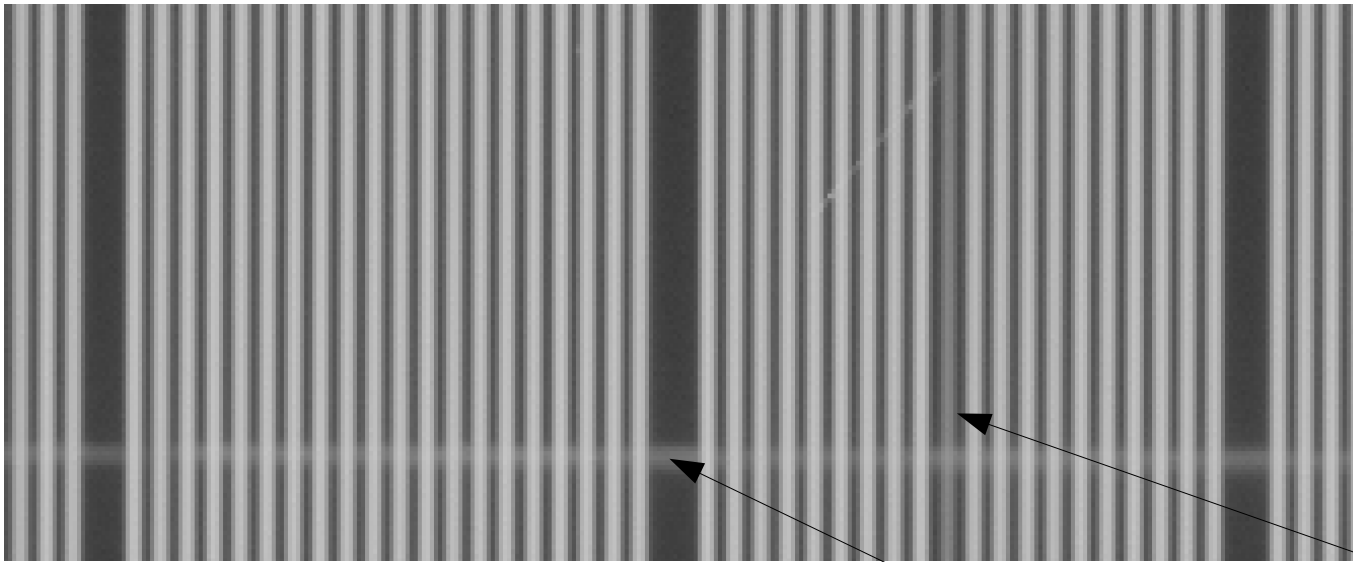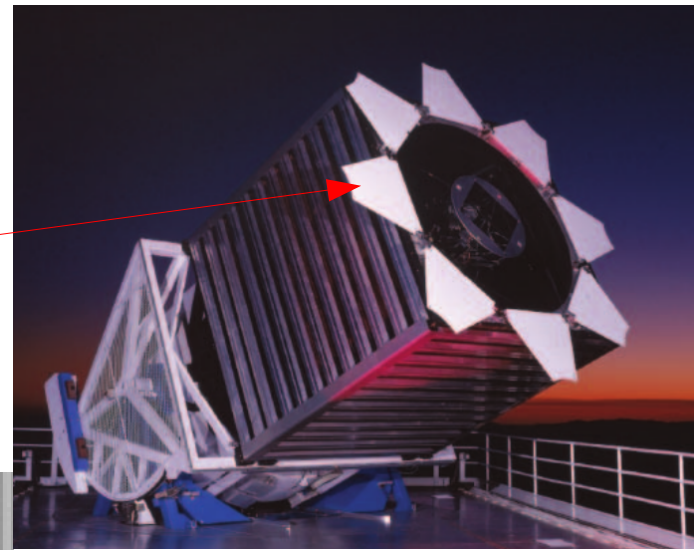
r-CCD :
fiber diameter on image: 3.1 pixels
distance between fibers: 6.7 pixels

one fiber with lower
throughput

boundary between two amplifiers
with distorted pixels
(will talk about this later)

BOSS data reduction pipeline (CCD level)
Arc lamp images for wavelength calibration

d lambda / d y :
b-channel : 1.09 A/pixel
r-channel : 1.43 A/pixel

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Data reduction challenges (in relation with CCDs):
- Optimal extraction for Emission Line Galaxies
- Characterization of the PSF
    (spectro-photometry is irrelevant)

CCD effects in BOSS :
- Clock phase mismatch at boundary of amplifiers
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- PSF width as a function of signal intensity
- Impact on PSF of diffusion in CCD and large incidence angles

Data reduction challenges (at CCD level)
Optimal extraction : spectral PSF 2D features

- High redshift efficiency in BOSS
  for luminous galaxies
(LRG selected in mass: "CMASS" sample)

- on the plot scale is 0 - 12% .

- inefficiencies on edges of f.o.v. are
correlated to edges of spectrograph CCD
(because of fiber plugging constraints)

- 2D PSF extraction (will) help improve this

important for redshift measurement of
faint Emission Line Galaxies
        (Comparat et al. 2013)

In development :
Spectral extraction
      - using 2D PSF extraction
      - extracting simultaneously signal from 20 fibers
      (see Bolton & Schlegel, 2010)

Ross+ 2012

20
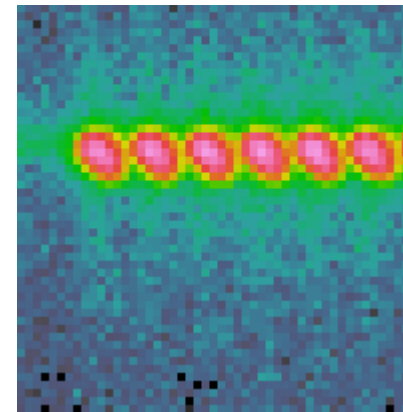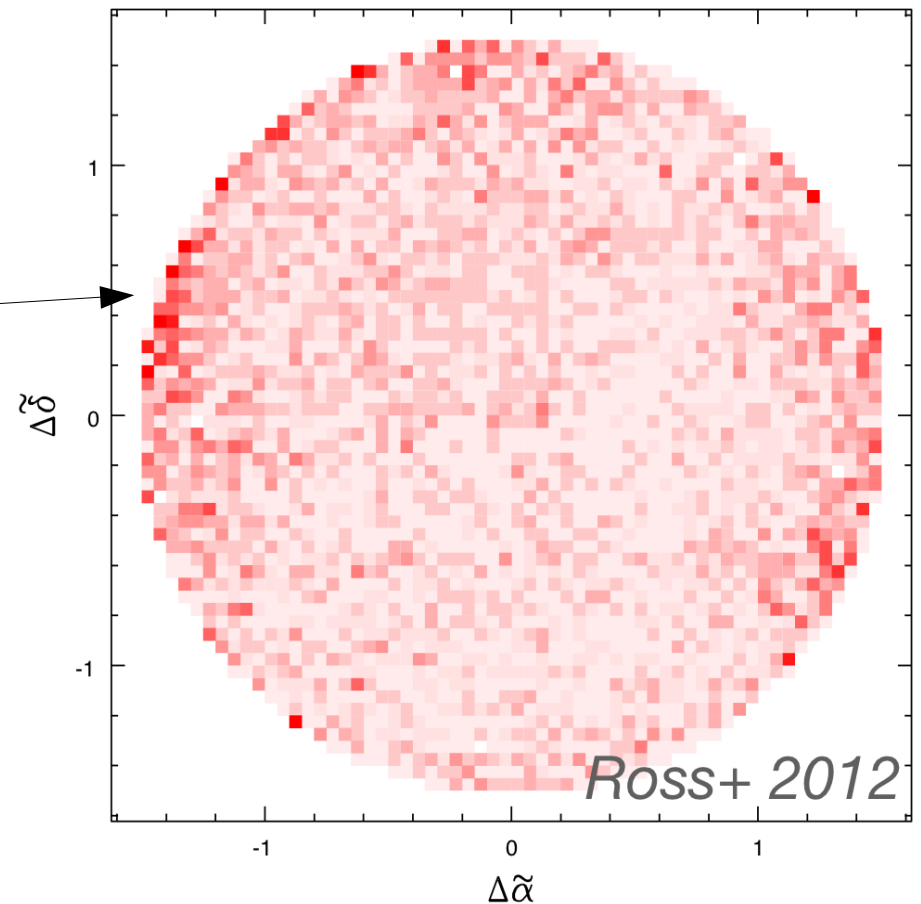
Data reduction challenges (at CCD level)
Optimal extraction : sky background substraction

- sky spectrum measured on specifically allocated fibers
- interpolated to the whole focal plane

Requires :
- a precise fiber flat fielding
- a precise PSF model (fiber to fiber variation)

Illustration : Comparat et al (2013)
redshift measurement of emission line galaxies (test run on BOSS spectrograph)

green to red : simulations

blue : data with successful redshift meas.

black: mean sky

21
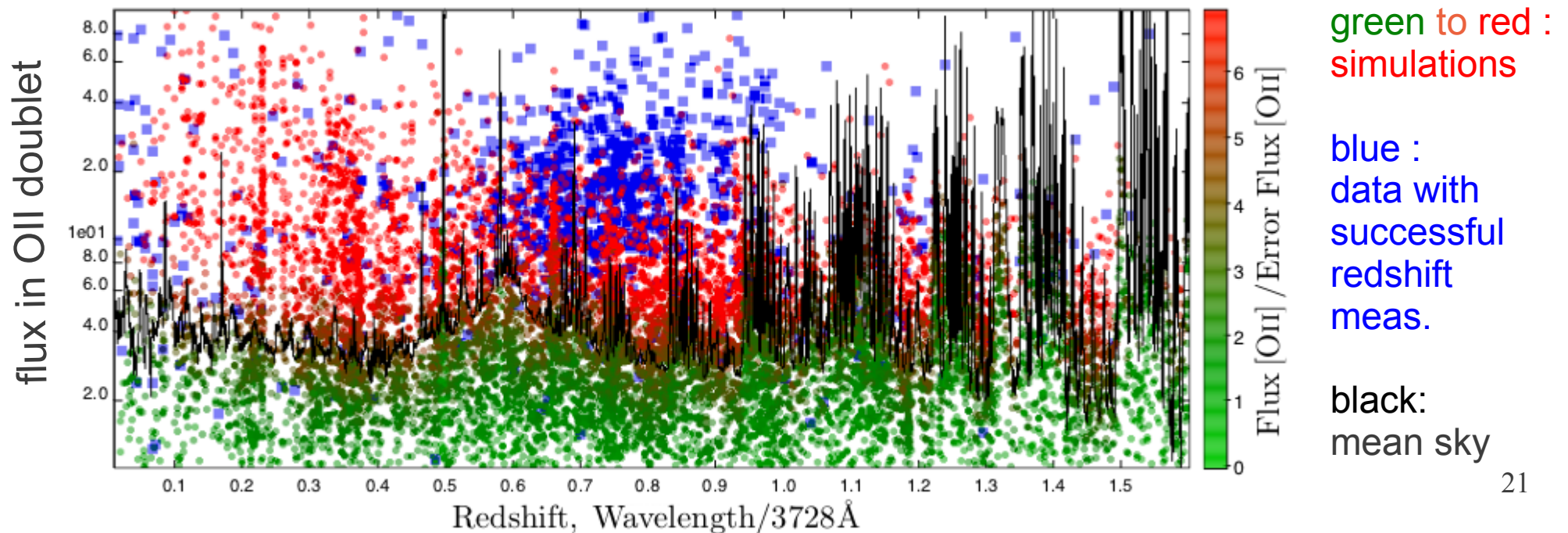
Data reduction challenges (at CCD level)
PSF calibration for Lyman-alpha power spectrum
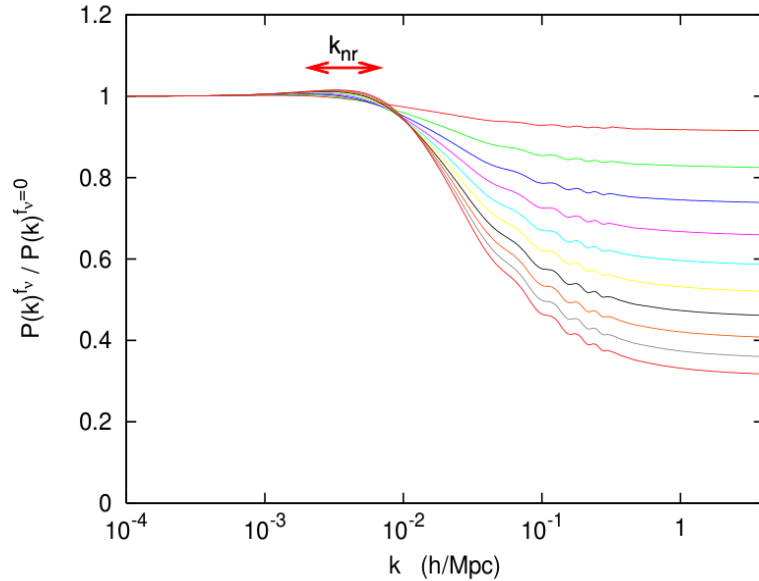
Fig. 13. Ratio of the matter power spectrum including three degenerate massive neutrinos with density fraction f_ν to that with three massless neutrinos. The parameters $(\omega_{\rm m}, \Omega_\Lambda) = (0.147, 0.70)$ are kept fixed, and from top to bottom the curves correspond to $f_\nu = 0.01, 0.02, 0.03, \ldots, 0.10$. The individual masses m_ν range from 0.046 eV to 0.46 eV, and the scale $k_{\rm nr}$ from $2.1 \times 10^{-3} h\,{\rm Mpc}^{-1}$ to $6.7 \times 10^{-3} h\,{\rm Mpc}^{-1}$

(Lesgourgues & Pastor 2006)
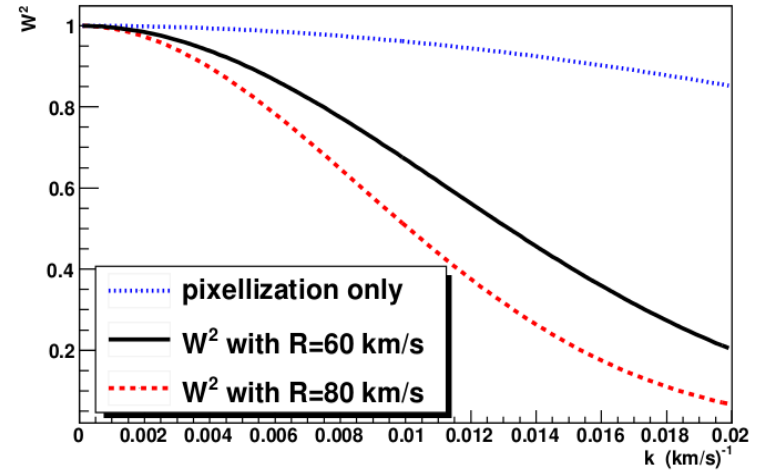
Fig. 10: *Window function $W^2(k, \bar{R}, \Delta v)$, with $\Delta v = 69\,{\rm km/s}$, reproducing the spectrum binning and the impact of the spectrograph resolution, for a resolution $\bar{R} = 60\,{\rm km/s}$ typical at $\lambda > 5000\,\AA$ and $\bar{R} = 80\,{\rm km/s}$ typical at $\lambda < 4300\,\AA$. For comparison, we also show the contribution from the pixellation only (equivalent to $\bar{R} = 0$).*

(Palanque-Delabrouille et al 2013)

at k=1 h/Mpc = 0.01 (km/s)^-1 $\dfrac{\partial \log P(k)}{\partial m_\nu} \sim 2\,{\rm eV}^{-1}$ $\dfrac{\partial \log P(k)}{\partial \log \sigma_{PSF}} \sim 1.2$ $\dfrac{\partial m_\nu}{\partial \log \sigma_{PSF}} \sim 0.6$

- SDSS-II measure (McDonald et al, Seljak etl al 2006)   **sum mu_nu < 0.17 eV (95%)**
- DESI goal (Font-Ribera et al 2013)   **sum m_nu < 0.02 eV (*)!**
(*) combining many probes, **not** dominated by Lyman-alpha

goal/challenge : spectral PSF calibration at 3%

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Tree rings in r1-CCD observed with the lossy fiber

varying wavelength!
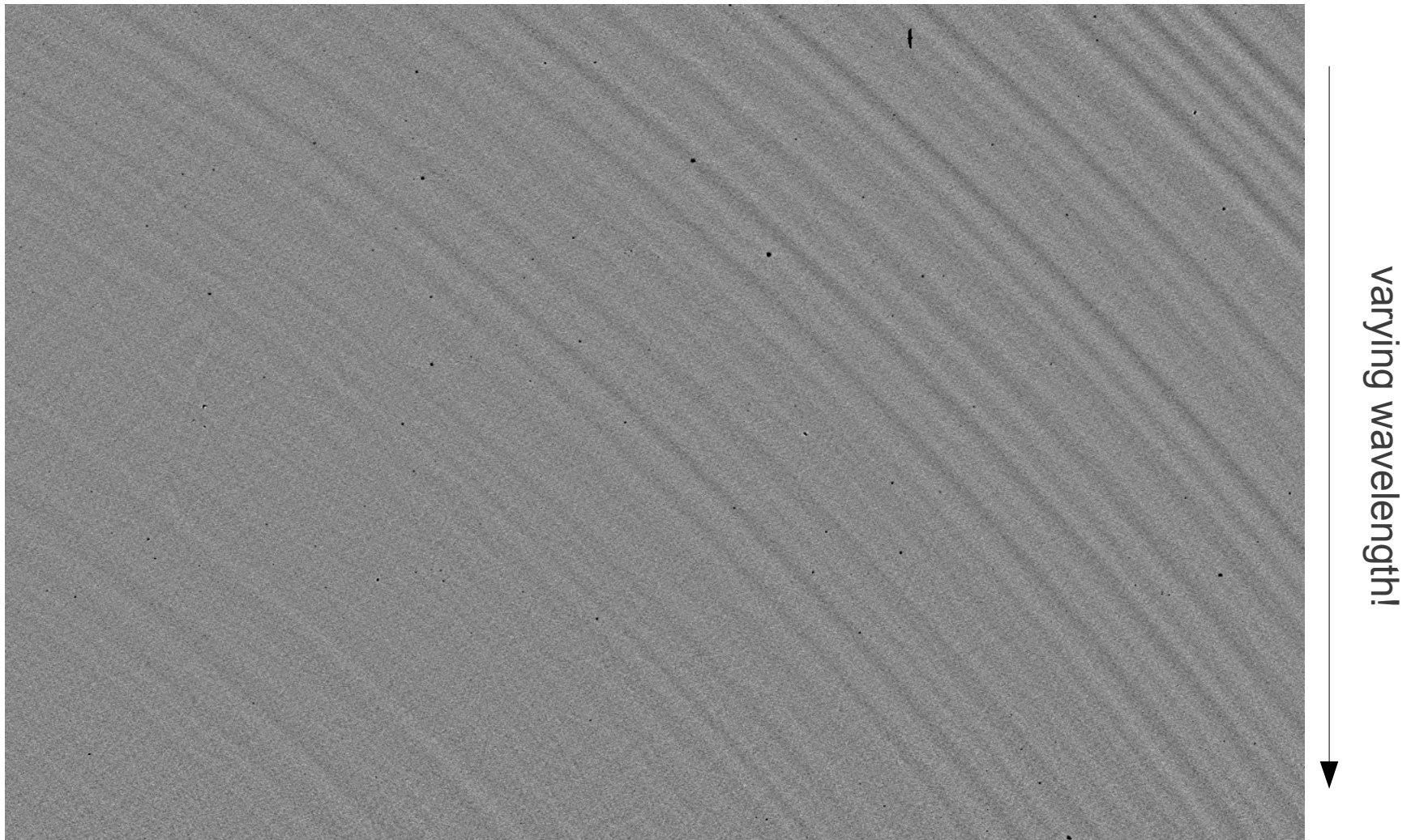
(but has been flattened to get mean_x = 1)

Do tree rings matter for spectroscopy ?

I learned at this workshop that the DES
astrometric bias from tree rings ~ 0.1 pixel (peak to peak).

Assuming this number for BOSS r CCDS,
with d lambda /d y = 1.4 A/pixel, at 8000 A,

the bias on redshift is of $2*10^{-5}$.

It's a negligible effect ....

Some artifacts in r-CCDs flat field images

r1-CCD

line separating two amplifiers

bubbles of glue
on the back side of the CCD

r2-CCD
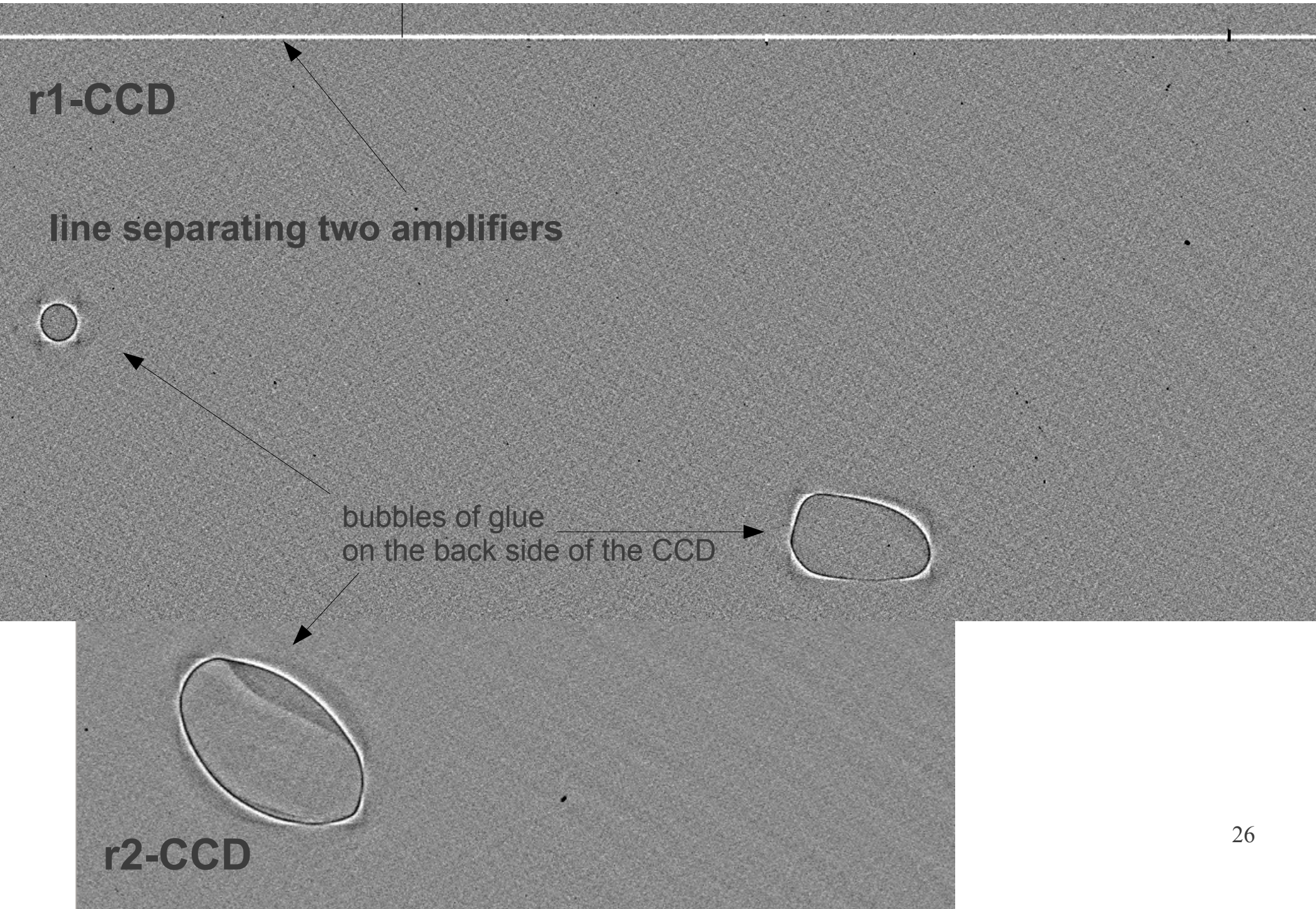
Discontinuity at the boundary of amplifiers on r-ccds (here r1)

2 pixel flat field images
with different clocks setups

(MJD=55056)   (MJD=55415)

sum=0.26
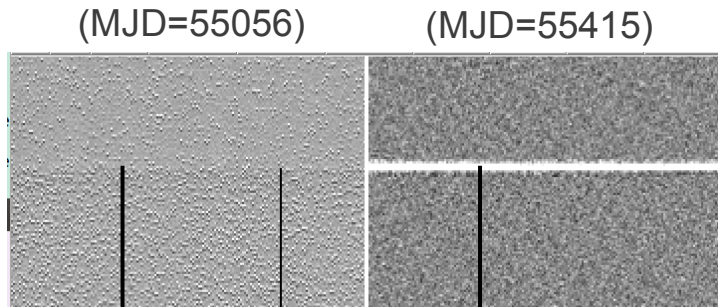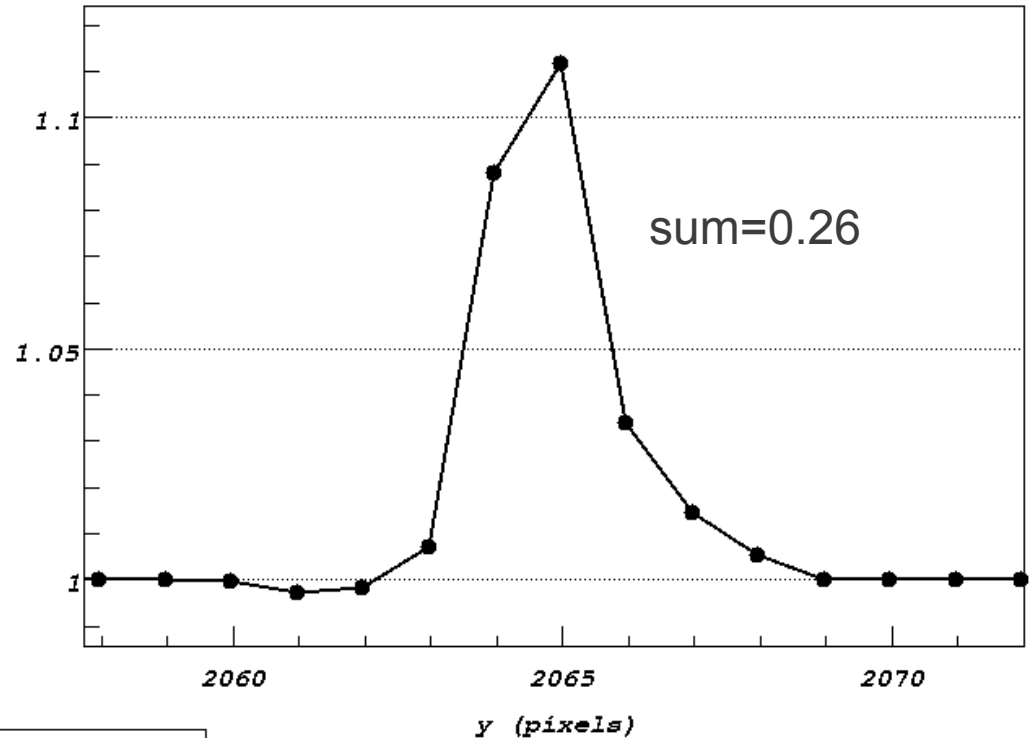
y=2065
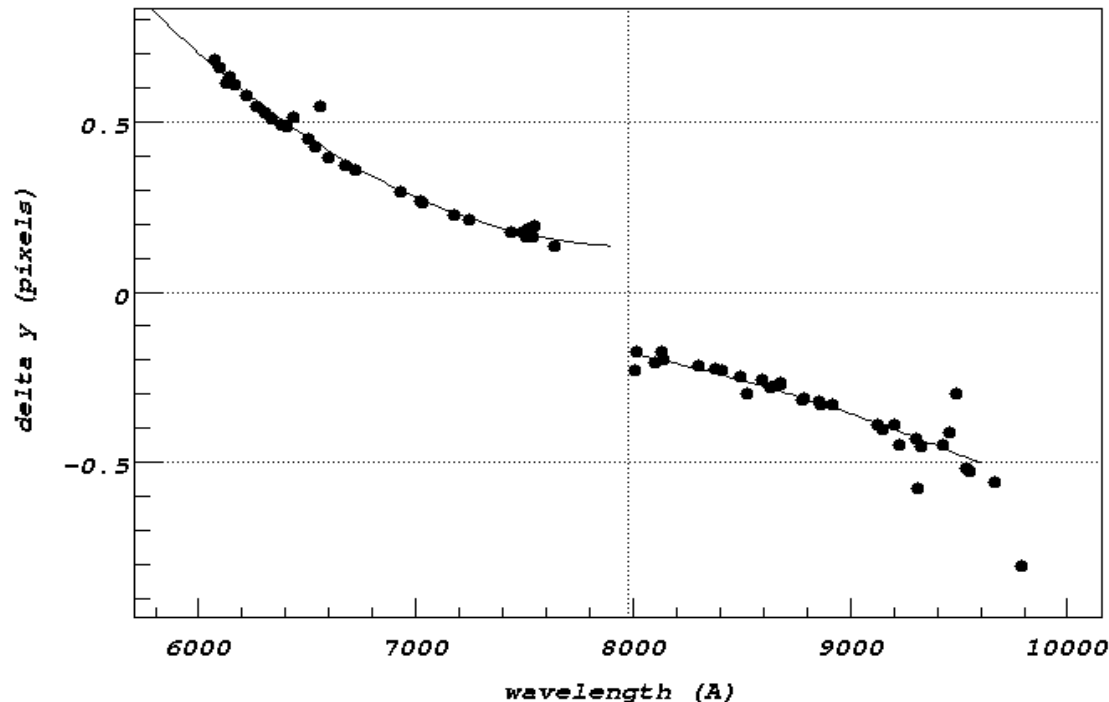
From the pixel coordinates of lamp line spots :

Discontinuity in y pixel(wavelength) of dy ~ 0.3.

(
obtained by the difference
of pixel coord. of spots between
two arc images.
MJD 55300 & 55506
)

Discontinuity at the boundary of amplifiers on r-ccds (here r1)

Explained by an inadequate phase difference of clocks between the two amplifiers.
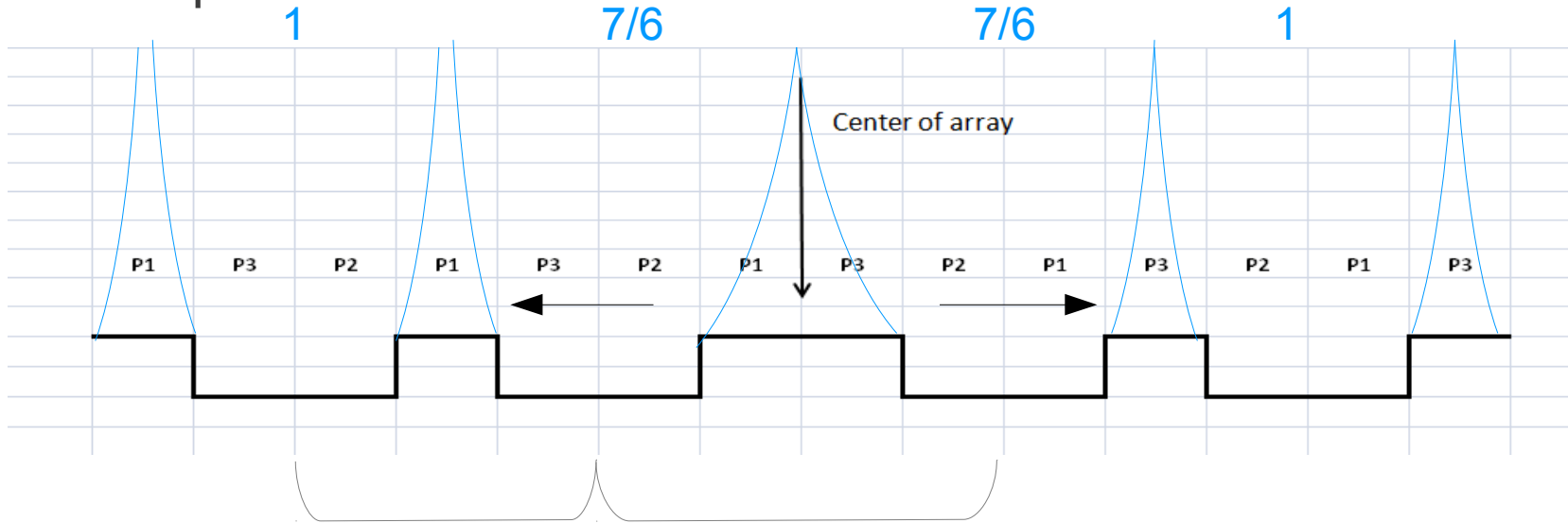
Distance between central pixels = 4/3 pixel

- expects a discontinuity of 1/3 pixel of wavelength mapping on CCD, consistent with obs.
- expects extra signal of 7/6 in the two central pixels, excess sum of 1/3.
- distorted electric field lines may dilute this effect on more pixels but without changing integral of 1/3 (no electron is lost).
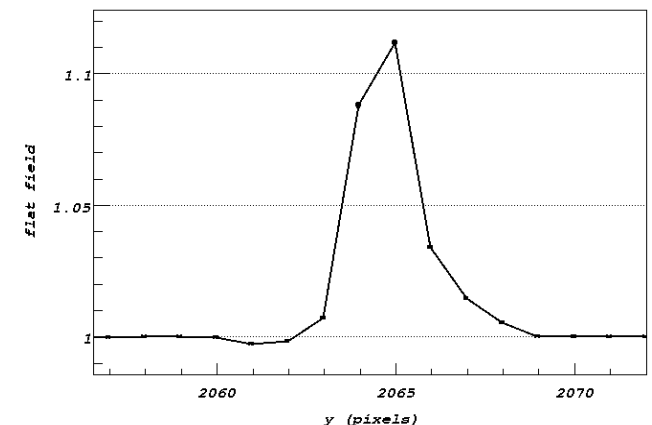
CCD effects affecting the PSF

I will address :

1) scattering on the back of the CCD for the longest wavelength
2) intensity-width effect
3) charge diffusion
4) incidence angle effect for long wavelength

Those effects are hard to disentangle with optical effects :

- fiber size
- optics aberrations
- diffraction due to entrance pupil
    (negligible for BOSS)
- diffraction of the grating
    (no evidence yet for this)
- scattered light due to roughness
    of optical surfaces

Simulation for DESI (P. Jelinski)
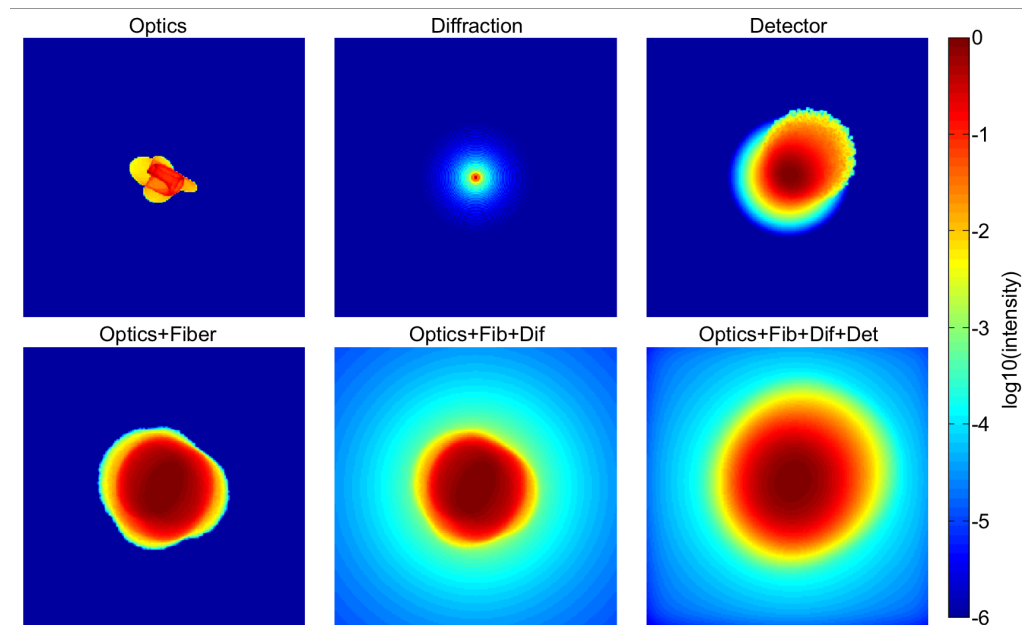
CCD effects affecting the PSF
Scattering on the back side of the CCD for the longest wavelength

Tests and analysis performed by N. Mostek & J. Thacker

long wavelength (1000nm-1050nm) spots (0.5 pix.) on a SNAP v2 BI device
(200 micron thick, 10.5 micron pixels)

Scattering in the direction of the CCD columns and rows
-> interaction with the vertical clock gate structure
        and channel stops (?)
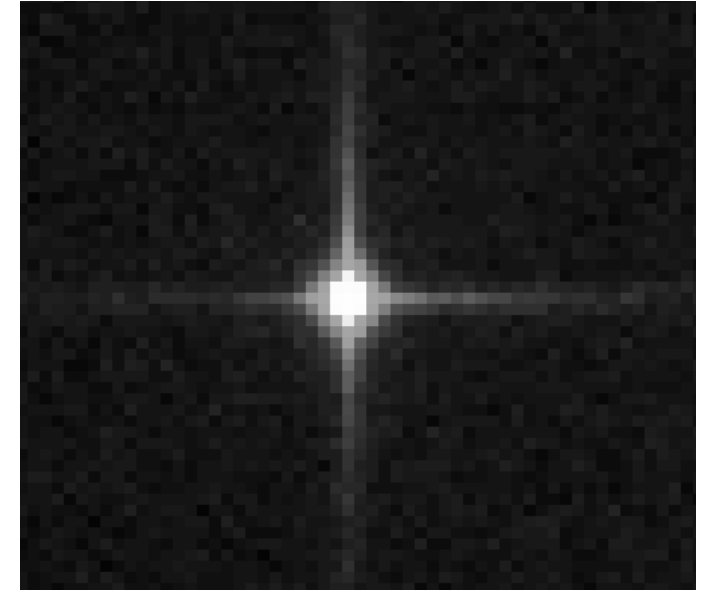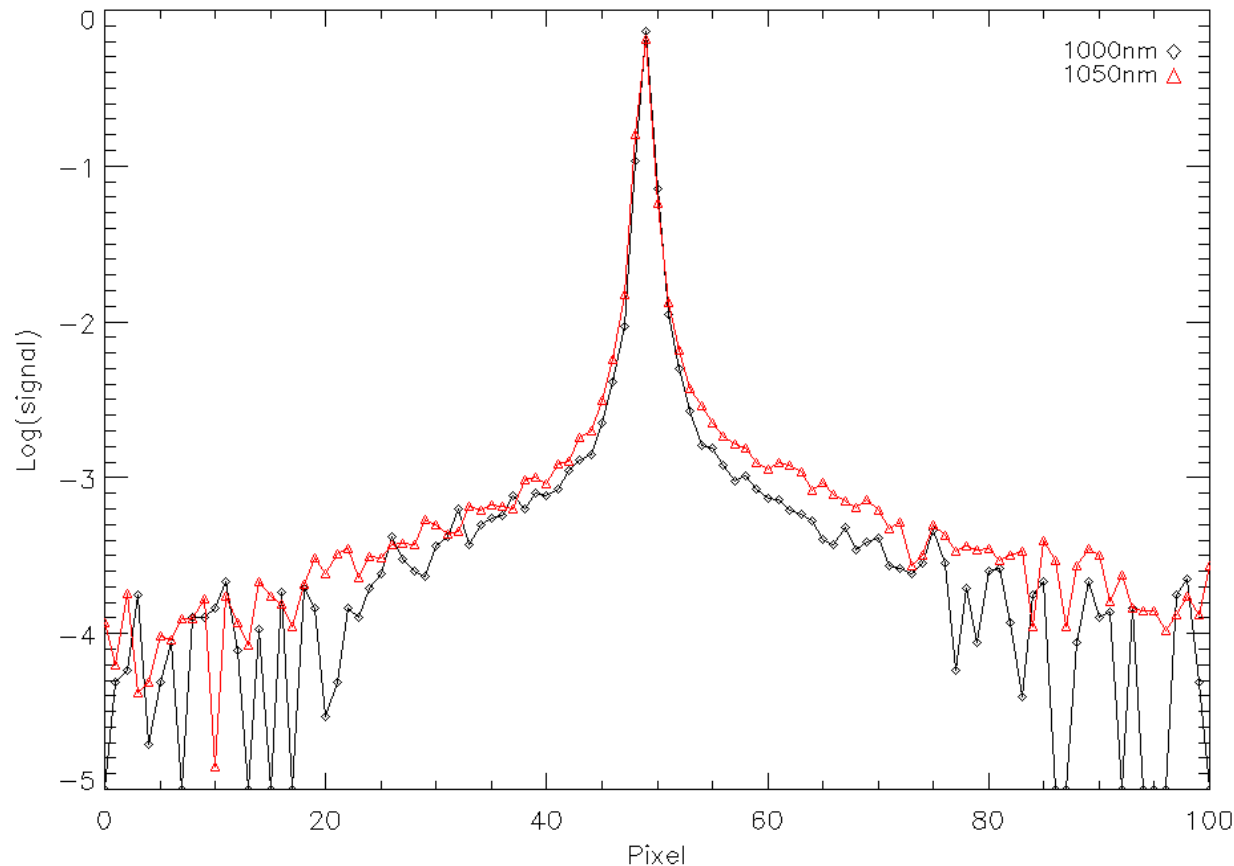
CCD effects affecting the PSF
Scattering on the back side of the CCD for the longest wavelength
We "may" be seeing this is BOSS arc lamp images

wavelength = 7200A
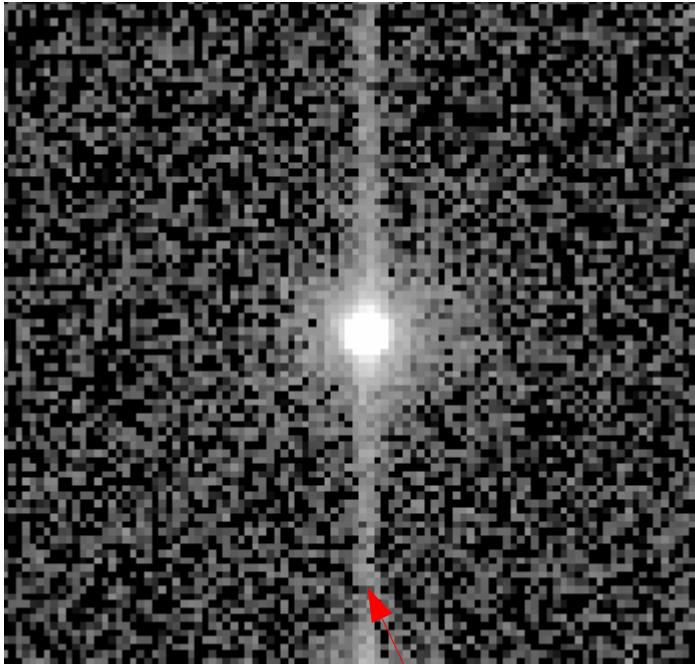
wavelength = 10000A

(this trace along wavelength
is not related to the PSF)
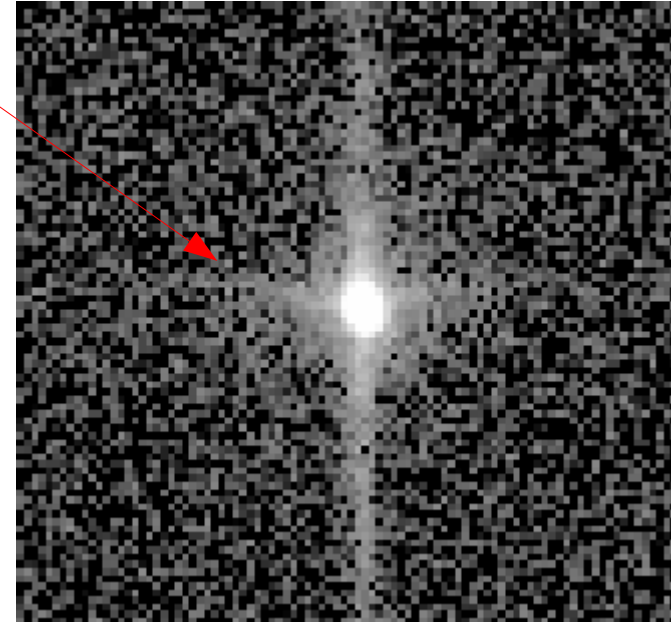
because not seen on laser data
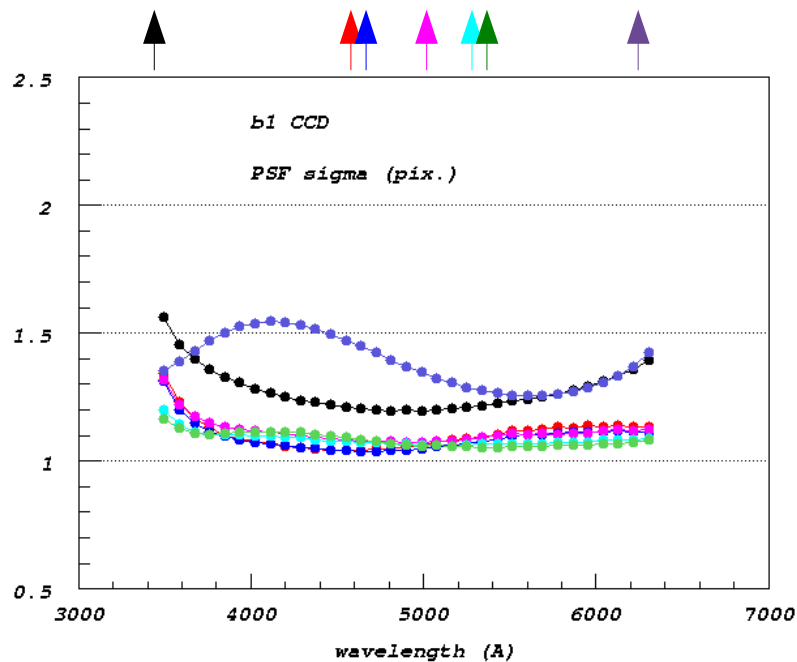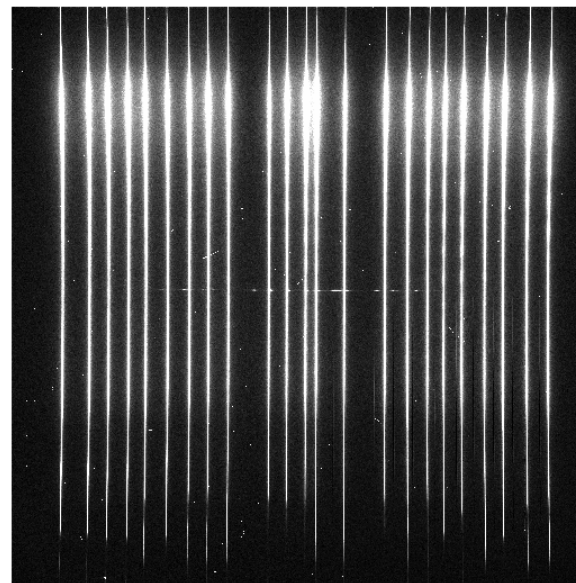(here at 9100A)
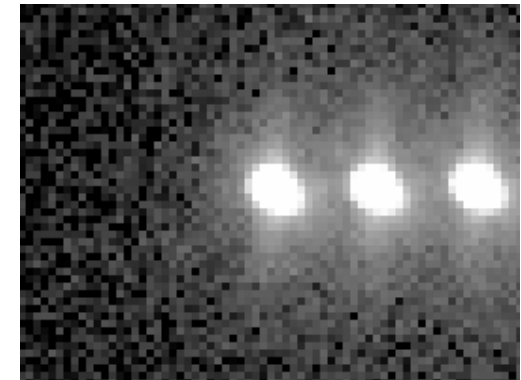
CCD effects affecting the PSF
PSF width vs Intensity

PRELIMINARY analysis based on fiber flat field images, with exposure times ranging from 6s to 80s.
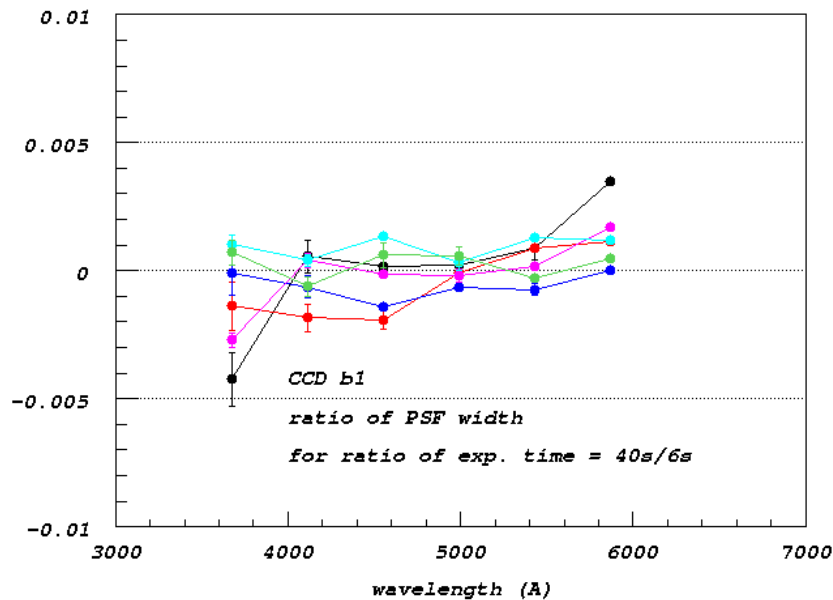

b1 CCD image
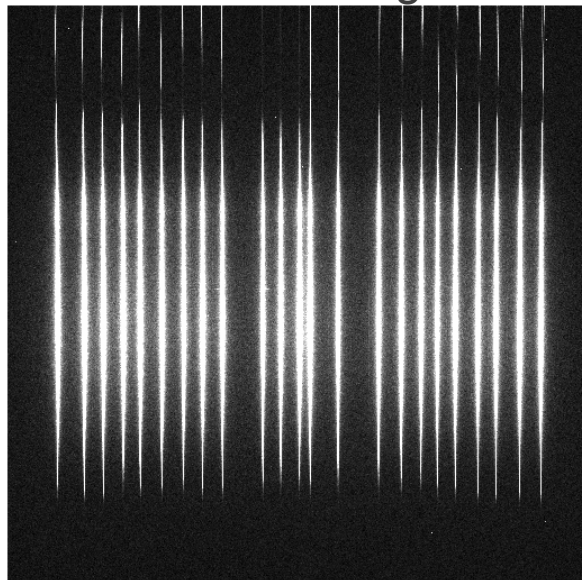
r1 CCD image
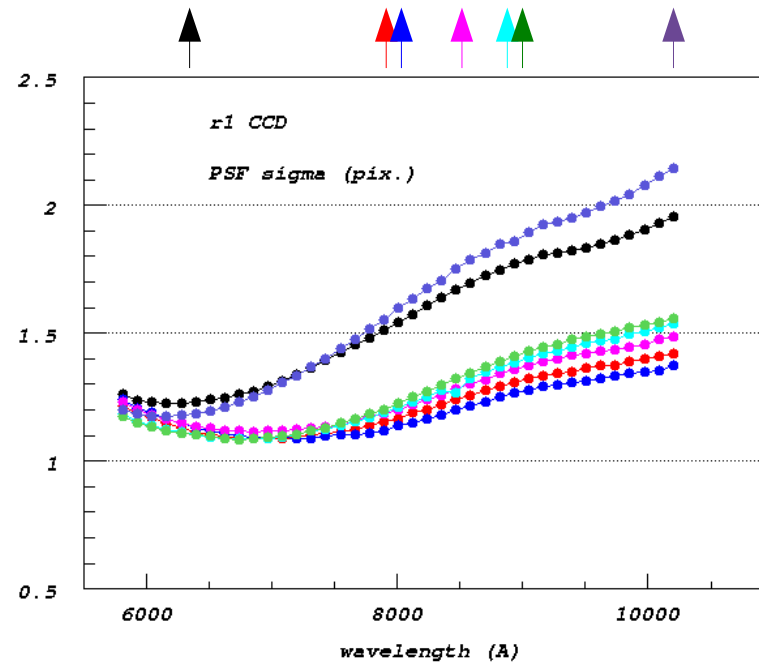
CCD effects affecting the PSF
PSF width vs Intensity (here exposure time)
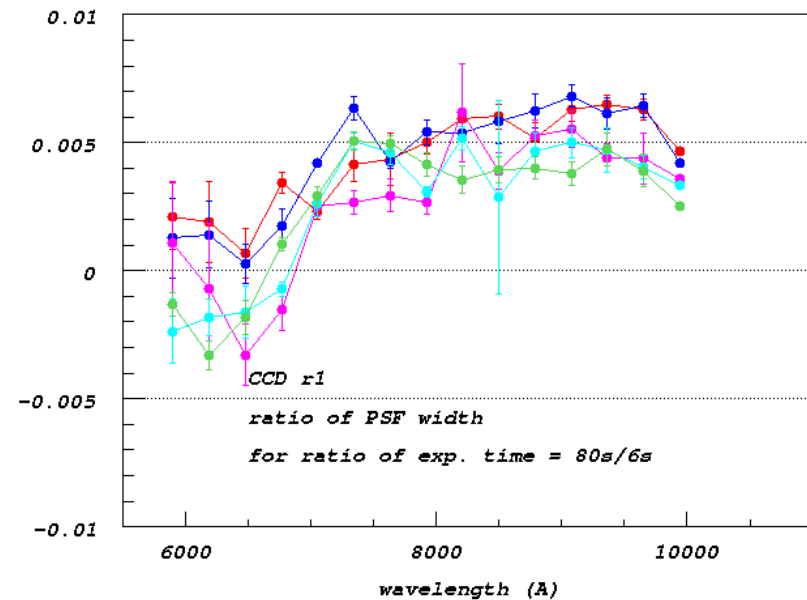
$$\frac{\sigma_x(T = 40\ s)}{\sigma_x(T = 6\ s)} - 1 \qquad\qquad \frac{\sigma_x(T = 80\ s)}{\sigma_x(T = 6\ s)} - 1$$

b1 CCD

r1 CCD

delta(width)/width ~ 0.15%
at wavelength = 5500A
for flux ratio ~ 6

delta(width)/width ~ 0.55%
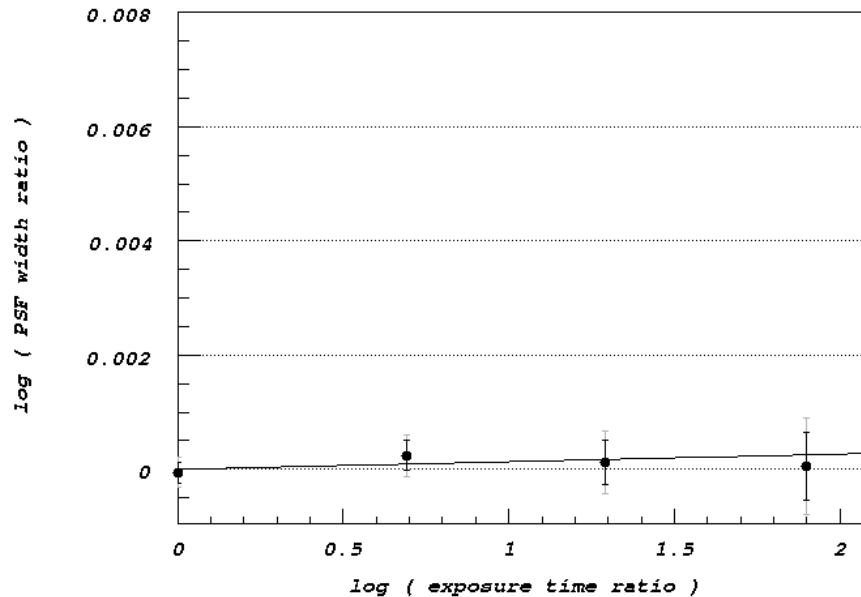at wavelength = 9000A
for flux ratio ~ 13

effect increases with wavelength but PSF shape varies with wavelength

CCD effects affecting the PSF

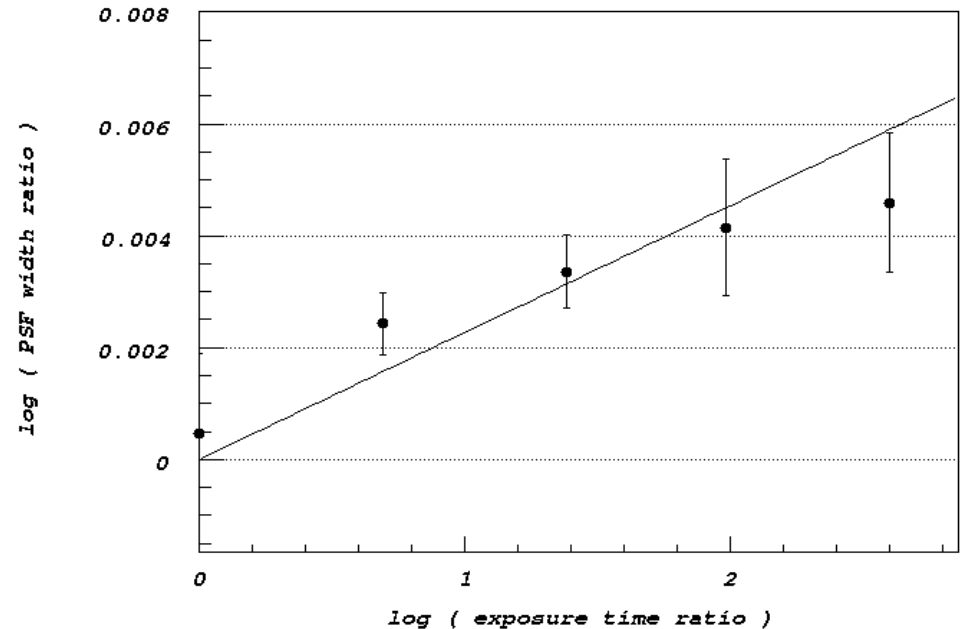## PSF width vs Intensity (here exposure time)

b1 CCD
for wavelength>4500A

r1 CCD
for wavelength>7000A

$$PSF\ width \propto (Counts)^{a}$$

b1 CCD : a = -0.0001 +- 0.0003
b2 CCD : a = 0.0002 +- 0.0003

r1 CCD : a = 0.0021 +- 0.0002
r2 CCD : a = 0.0020 +- 0.0002
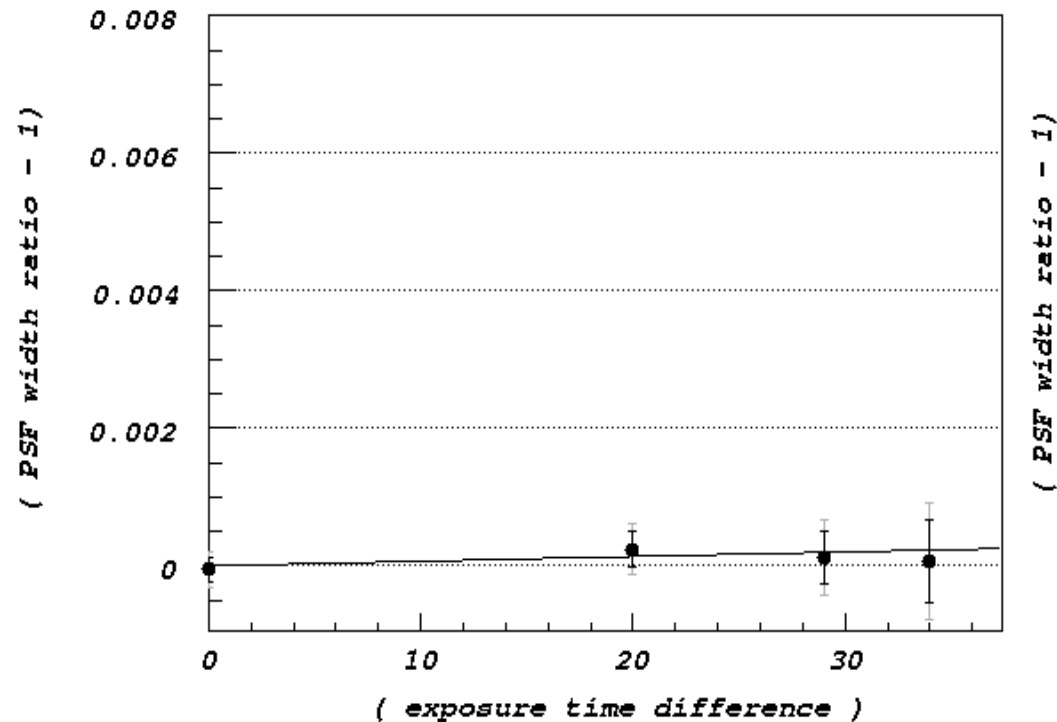
(this is still preliminary:
    - fluctuations from fiber to fiber not understood,
    - large change of PSF with fiber and wavelength
- measurements averaged over two series, which give consistent results)

CCD effects affecting the PSF
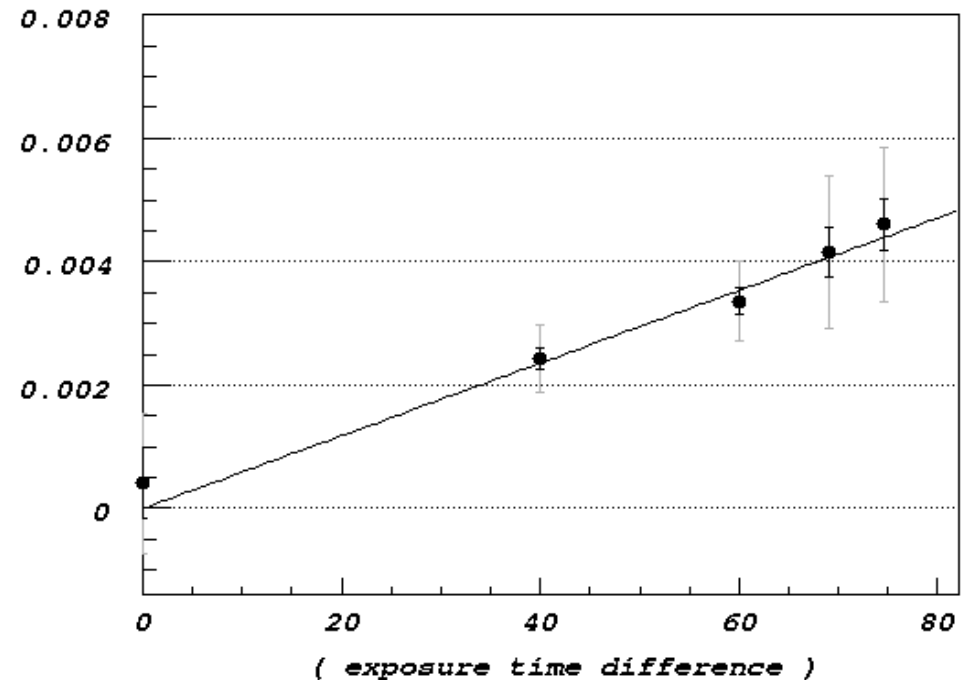## PSF width vs Intensity (here exposure time)

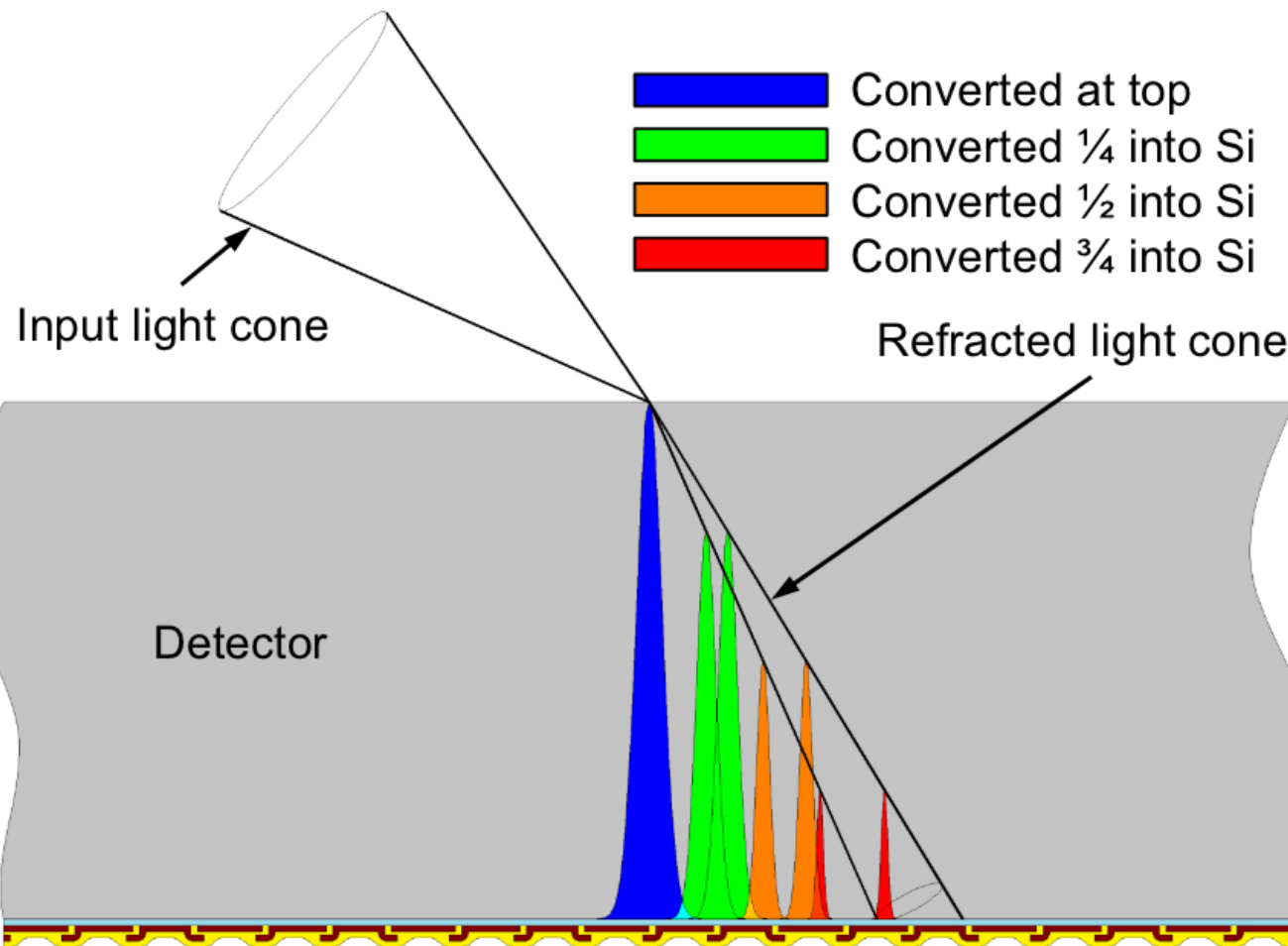b1 CCD
for wavelength>4500A

r1 CCD
for wavelength>7000A

(this is still preliminary:
- fluctuations from fiber to fiber not understood,
- large change of PSF with fiber and wavelength
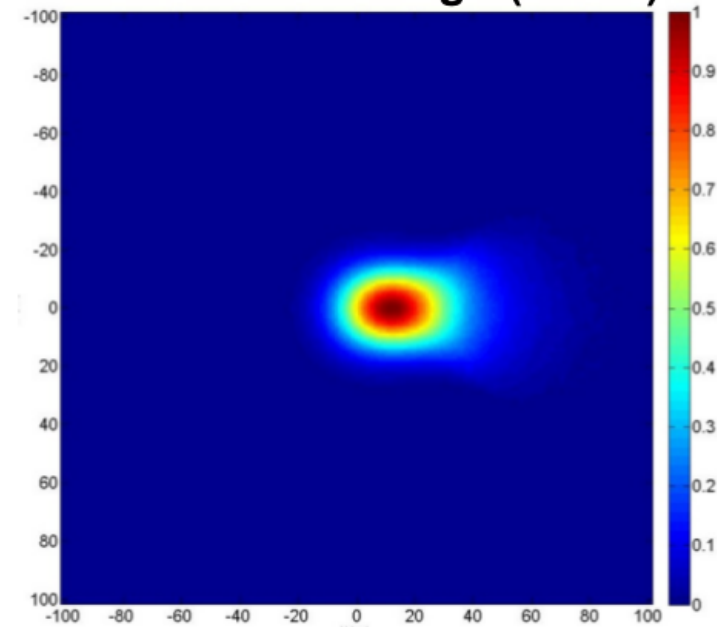- measurements averaged over two series, which give consistent results)

CCD effects affecting the PSF
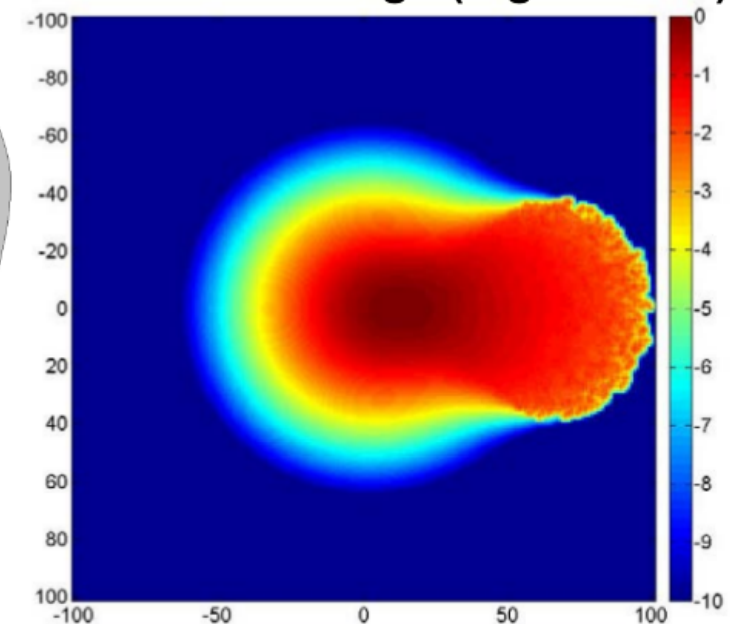## Diffusion and incidence angle effect

Detector Schematic

Converted at top
Converted ¼ into Si
Converted ½ into Si
Converted ¾ into Si

Input light cone

Refracted light cone

Detector

(P. Jelinski for DESI project)

Simulated Image (linear)

Simulated Image (logarithmic)

CCD effects affecting the PSF
Diffusion and incidence angle effect

For BOSS, the contribution of diffusion to the PSF is almost negligible

* For e2v **b-CCDs, sigma~5 um**, or ~1/3 pixel (fiber diameter is 3 pixels)

* For the LBL deep-depleted CCDs (see Holland et al. 2003)

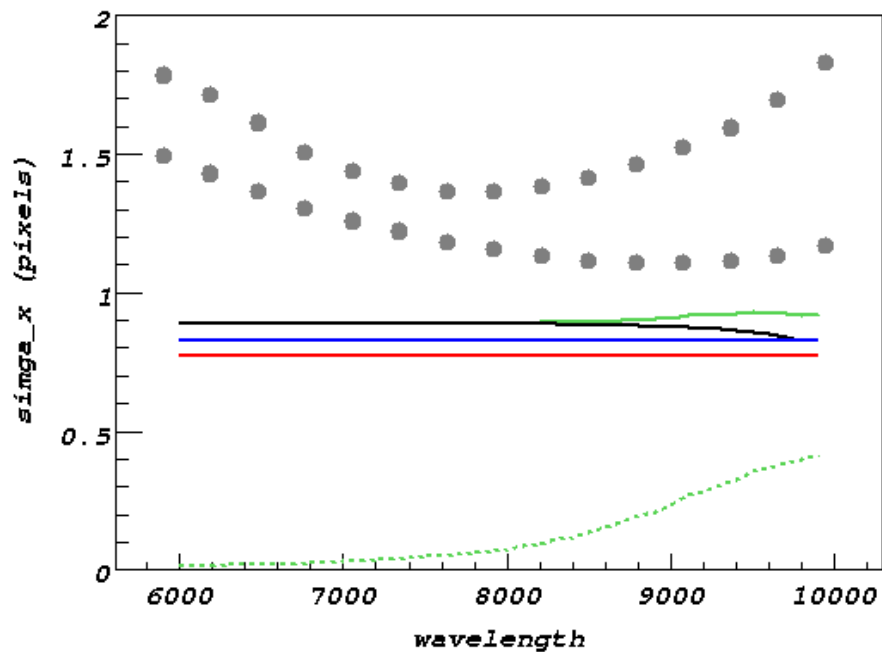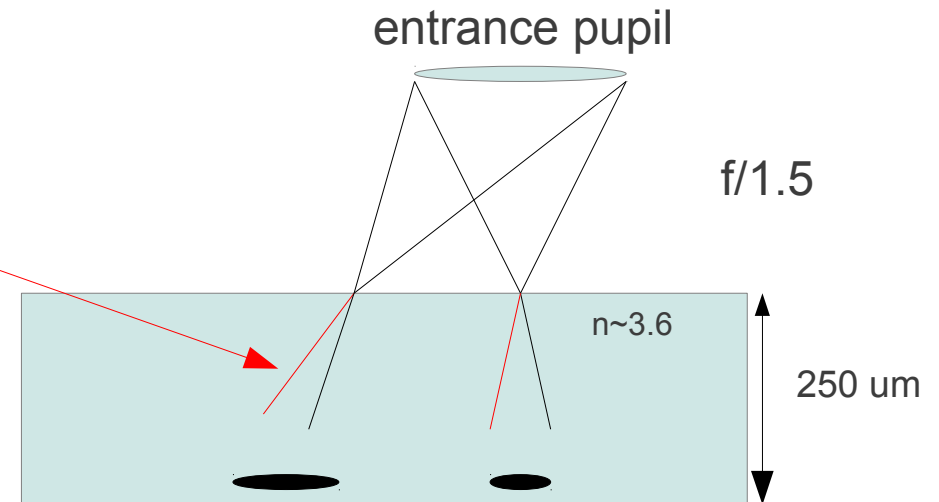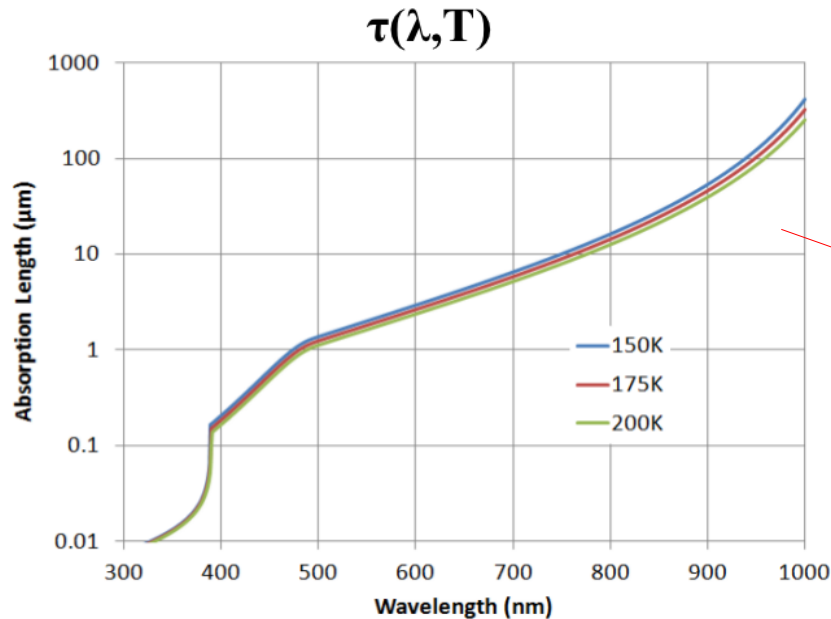$$\sigma_{max} = \sqrt{\frac{2kT}{qV} y_D}$$

   (yd is the thickness of the depleted region and V the difference of potential)

For BOSS **r-CCDs, sigma(max) ~ 5 um**, it is also negligible

CCD effects affecting the PSF
Incidence angle effect

(also quite negligible)

$\tau(\lambda, T)$

entrance pupil

f/1.5

n~3.6

250 um

grey dots: measured PSF
- edge fiber
- central fiber

green: with incidence angle effect
black: with diffusion
blue: with pixel size
red: fiber size

Concluding remarks

- CCD effects have little impact on science addressed by BOSS so far.

- New feature is the PSF width variation with the intensity of signal
    (requires a refined analysis and an evaluation of the impact for science)

- Some analysis are more demanding in terms of understanding of CCD-level data,
    in particular the PSF and noise
    (for Lyman-alpha forest analysis where sources are not resolved, and
    noise has to be subtracted from the power-spectrum)

- Upcoming e-BOSS survey and DESI project target Emission Line Galaxies
    where improved data reduction will improve the scientific outcome.