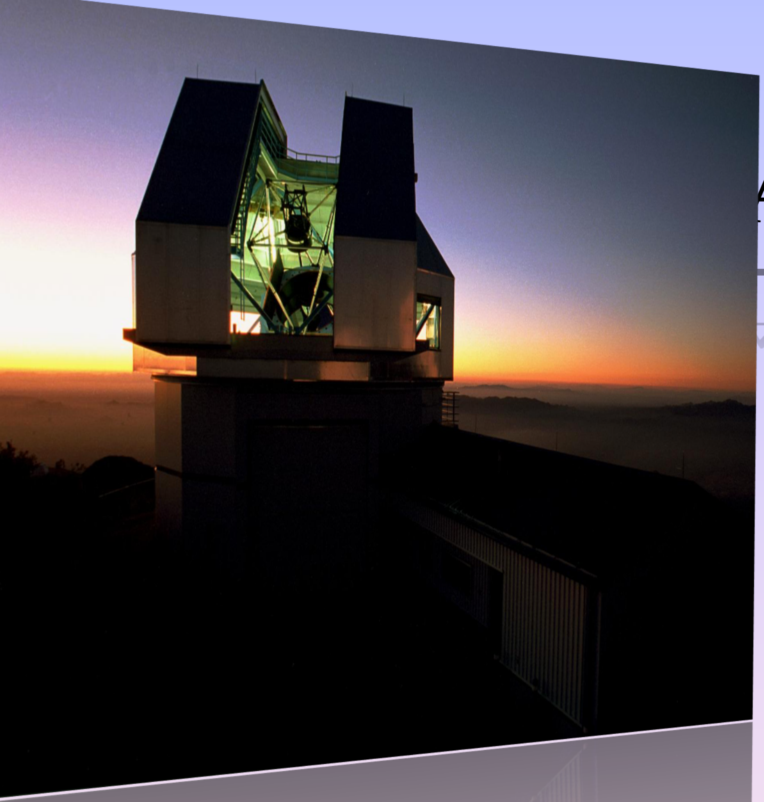


Astro 500

Techniques of Modern Observational Astrophysics

Matthew Bershady

University of Wisconsin

Lecture Outline

Spectroscopy from a 3D Perspective

- ✓ Basics of spectroscopy and spectrographs
- ✓ Fundamental challenges of sampling the data cube
- Approaches and example of available instruments
  - ➢ I: Grating-dispersed spectrographs
    - ➢ Echelles
    - ➢ Bench Spectrograph
  - ➢ II: Fabry-Perot interferometry
  - ➢ III: Spatial heterodyne spectroscopy

Review

Spectral Resolution

- $R=\lambda/\Delta\lambda$
- For slit spectra, depends on slit width and grating choice.

What is the effective slit-width of a circular fiber?

What is the effective slit-width of a tilted slit?

Review

LRIS (Keck Obs WWW page)

Typical information provided:

Grating Name	Grooves (l/mm)	Blaze Wave (Å)	Dispersion (Å/pix)	Spectral coverage (Å/2048 pix)
150/7500	150	7500	4.8	9830
300/5000	300	5000	2.55	5220
400/8500	400	8500	1.86	3810
600/5000	600	5000	1.28	2620
600/7500	600	7500	1.28	2620
600/10000	600	10000	1.28	2620
831/8200	831	8200	0.93	1900
900/5500	900	5500	0.85	1740
1200/7500	1200	7500	0.64	1310

What order?

What else do you need to know in order to calculate resolution?

Review

Spectral Resolution

- Examples:
  - V filter: 5500Å/1000Å = 5.5
  - LRIS-R: 1″ ~4 pixels FWHM
    - 150 l/mm grating: $R \sim 6500/20 \sim 325$
    - 600 l/mm grating: $R \sim 6500/5 \sim 1300$
    - 1200 l/mm grating: $R \sim 6500/2.6 \sim 2600$

Review

Spectrometer Throughput

- Spectrometer throughput ranges from a few percent to ~50%. The losses accumulate fast. Dispersing elements are usually a big hit, then the losses at multiple surfaces go like $(\text{transmission})^n$ where n is the number of surfaces in the collimator and camera elements (n can be pretty big).

$$0.98^8 * 0.7 * 0.8 = 0.47$$

Camera/coll
with 8 surfaces

grating

ccd

(often more)

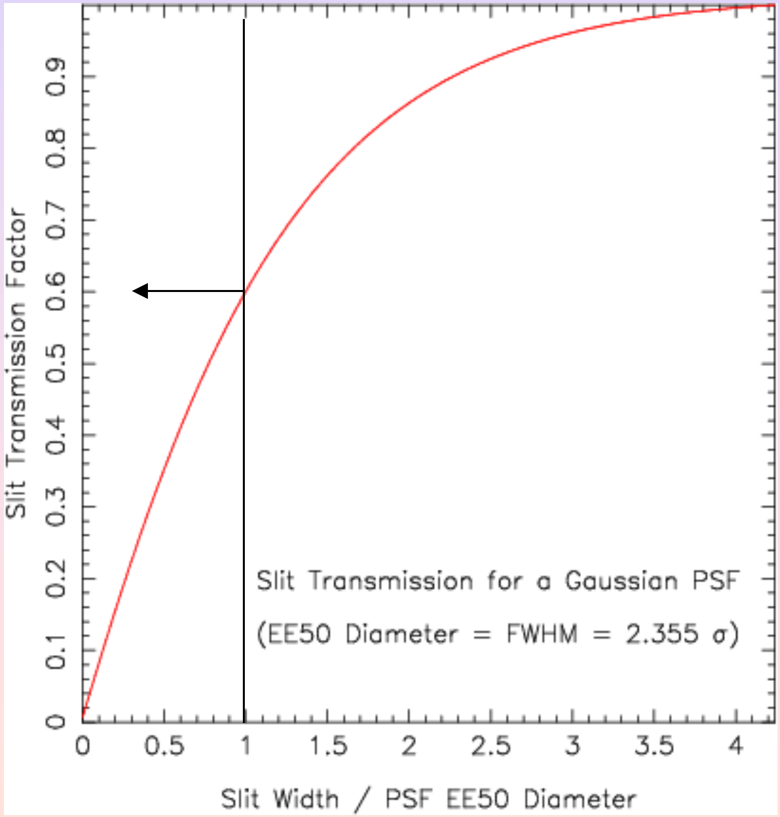
What’s missing?

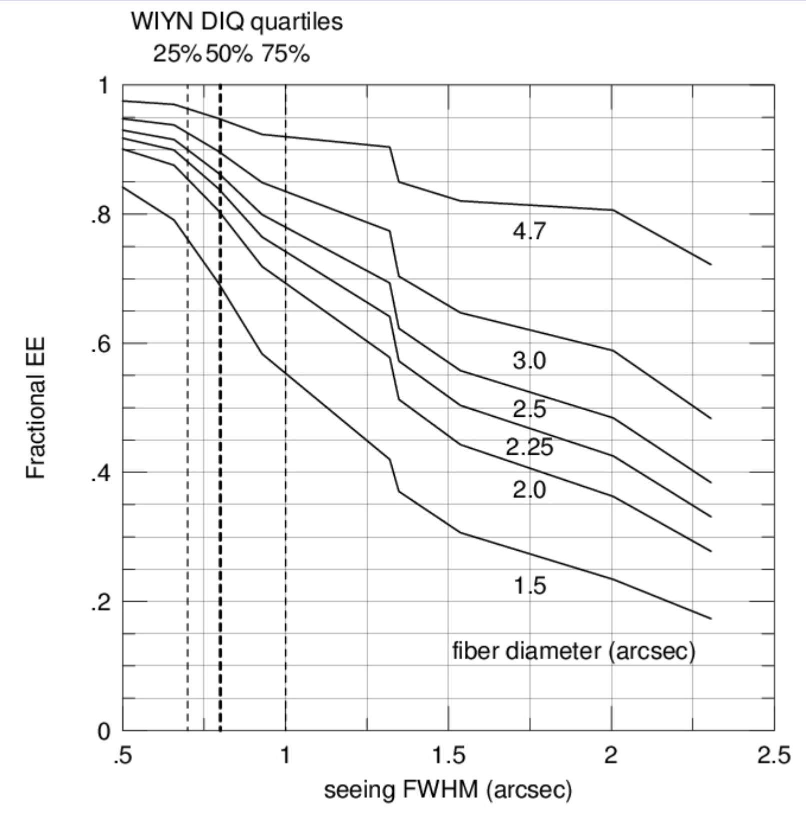
Review

Slit Losses

Another throughput issue: slit losses can be very significant!

Applies to fibers too.





Review

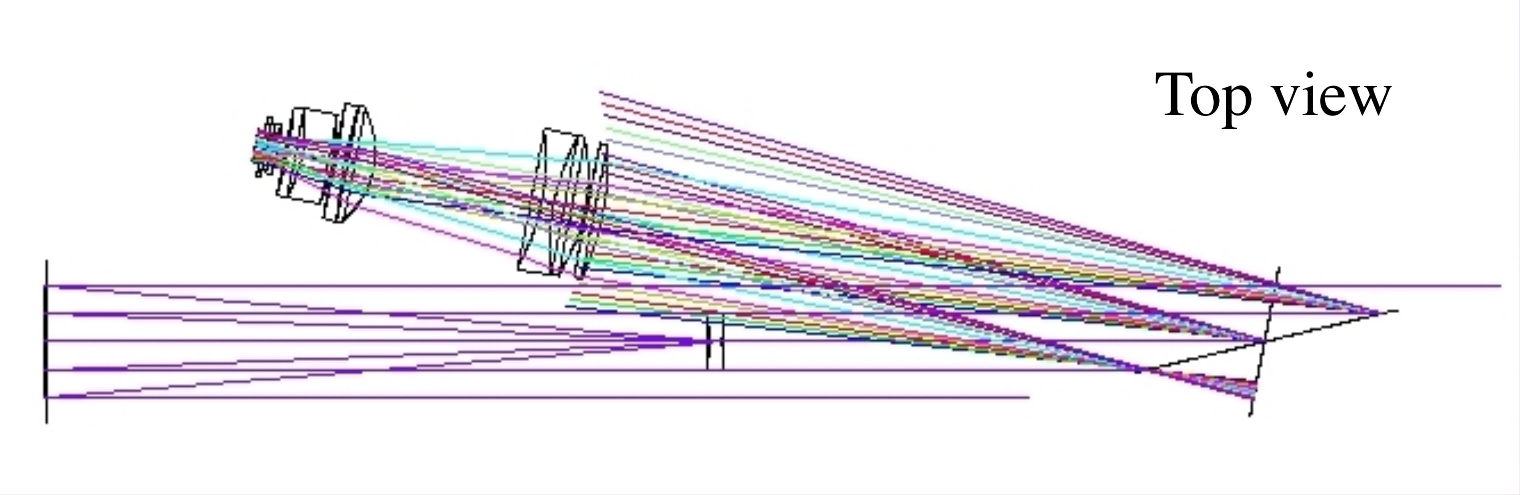
Other Losses

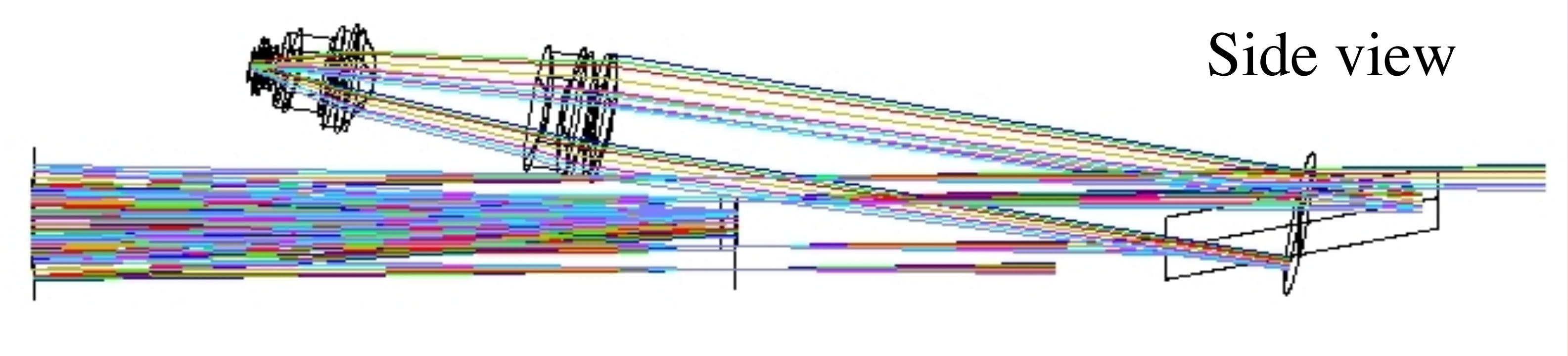
- Lens absorption (particularly in blue/NUV)
- Beam over-fill or blockage (vignetting)
- Fiber losses (transmission and surfaces)
- Slicer losses (optical surfaces)
- Telescope losses (mirrors)
- ADC losses
- Atmospheric absorption

Other???

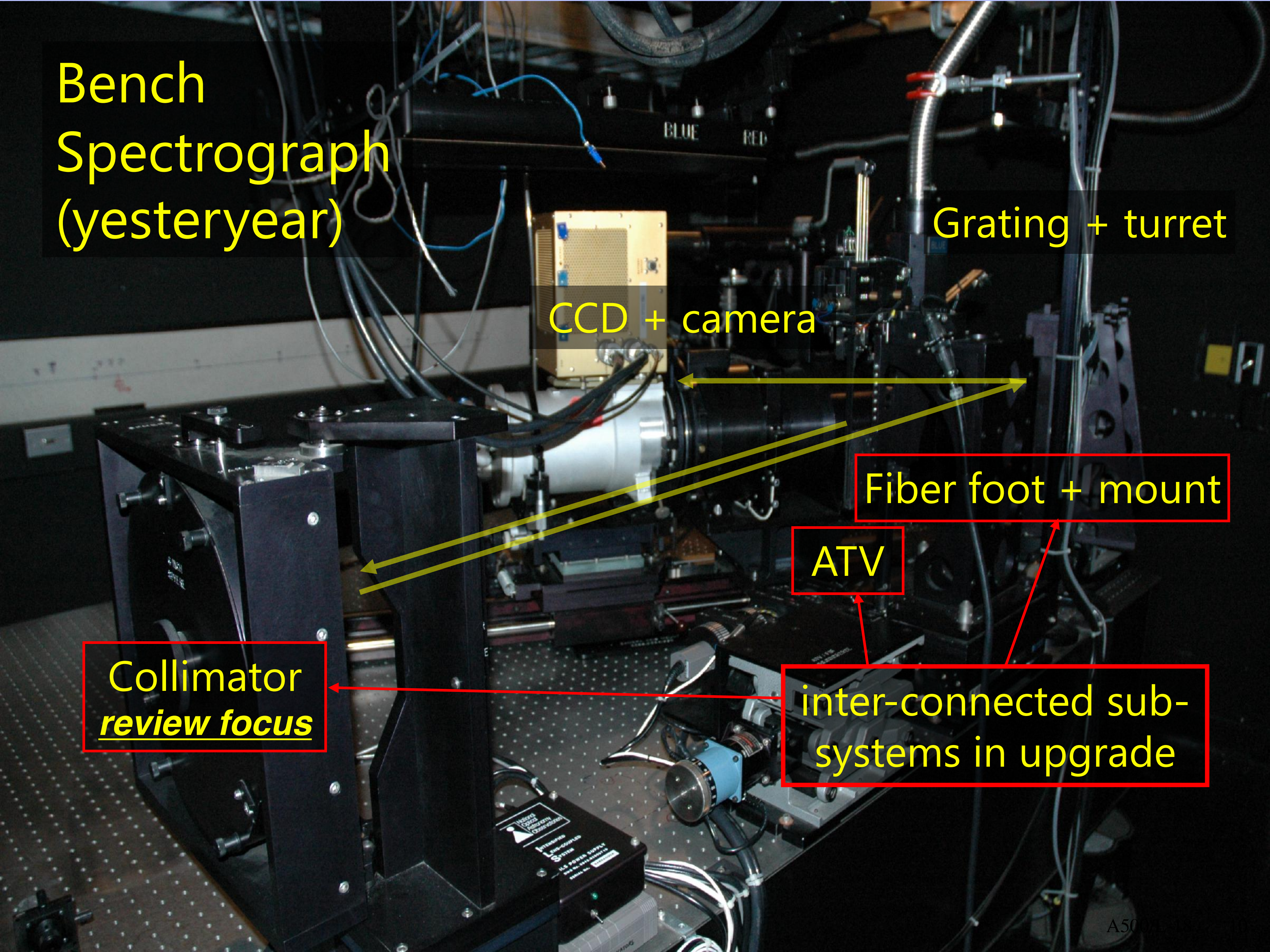
An Example: The Old WIYN Bench

Echelle setup





Bench Spectrograph (yesteryear)



Grating + turret

CCD + camera

Fiber foot + mount

ATV

Collimator

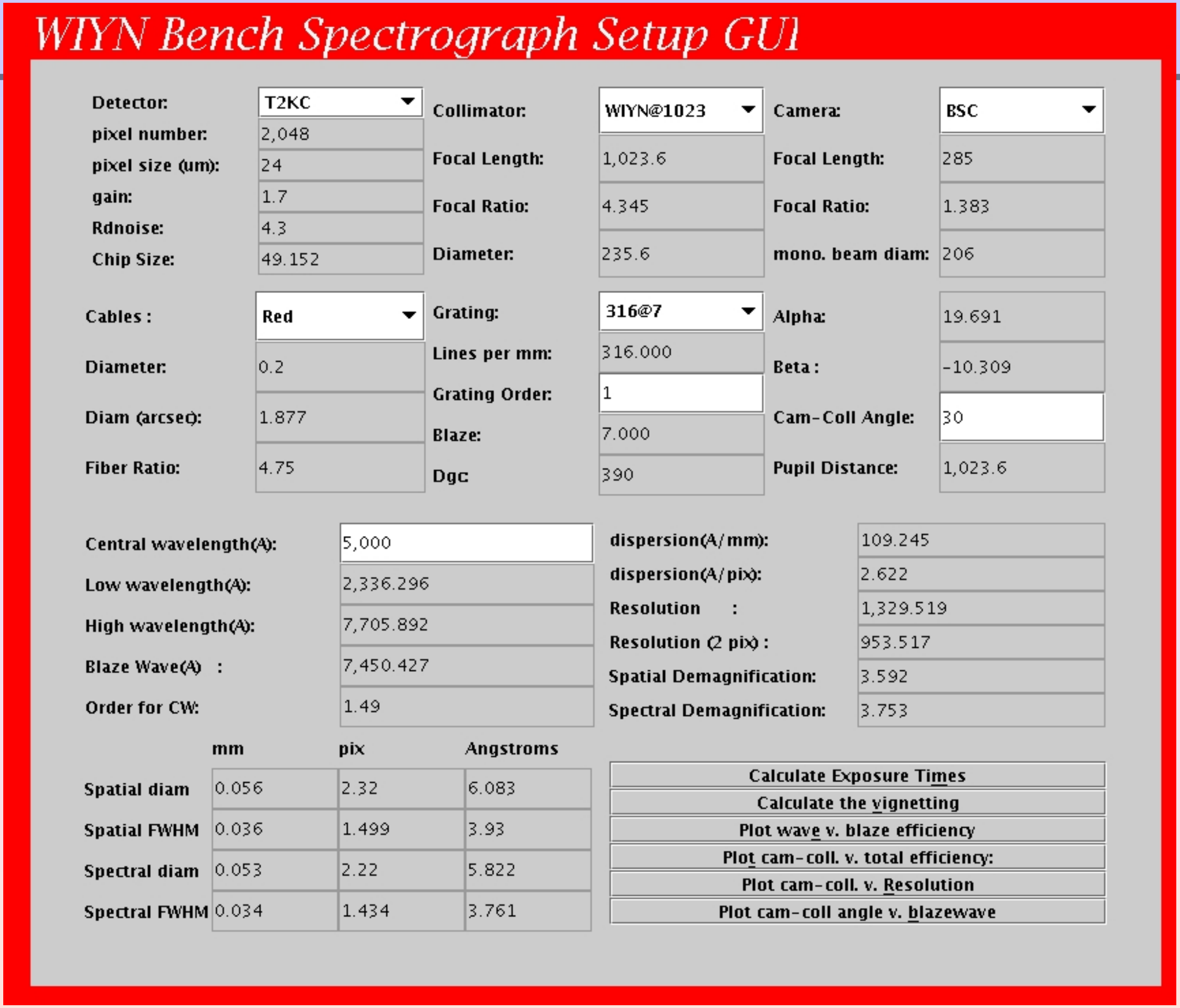
review focus

inter-connected sub-systems in upgrade

Spectrograph characteristics

- Fiber feeds: 75 mm slit, 80-100 fibers
  - Hydra (200μ,300μ), (DensePak, 300μ), SparsePak (500μ)
- Collimator: on-axis parabola, 1021 mm fl ← old system
- Grating suite:
  - SRg echellettes (316-1200 l/mm), R2 echelle, VPHg (740, 3300 l/mm); camera-collimator angles of $11^o < \theta_{cc} < 150^o$
  - Delivered instrumental resolutions $500 < \lambda/\delta\lambda < 25{,}000$
- Cameras:
  - BSC (all-refractive, 285 mm fl), Simmons (catadioptric)
- CCD: T2KC/T2KA (24μ) –> STA 1042 (12μ)
- System demagnification: 3.58 (BSC) + anamorphic factors
  - Re-imaged fiber sizes (spatial): 56μ, 84μ, 140μ
  - Re-imaged fiber sizes (spectral): down to 2/3 spatial
  - Re-imaged fiber separation: 112μ (edge-to-edge)

Performance Quantification



WIYN Bench Spectrograph Setup GUI

Detector: T2KC
pixel number: 2,048
pixel size (um): 24
gain: 1.7
Rdnoise: 4.3
Chip Size: 49.152

Collimator: WIYN@1023
Focal Length: 1,023.6
Focal Ratio: 4.345
Diameter: 235.6

Camera: BSC
Focal Length: 285
Focal Ratio: 1.383
mono. beam diam: 206

Cables : Red
Diameter: 0.2
Diam (arcsec): 1.877
Fiber Ratio: 4.75

Grating: 316@7
Lines per mm: 316.000
Grating Order: 1
Blaze: 7.000
Dgc: 390

Alpha: 19.691
Beta : -10.309
Cam-Coll Angle: 30
Pupil Distance: 1,023.6

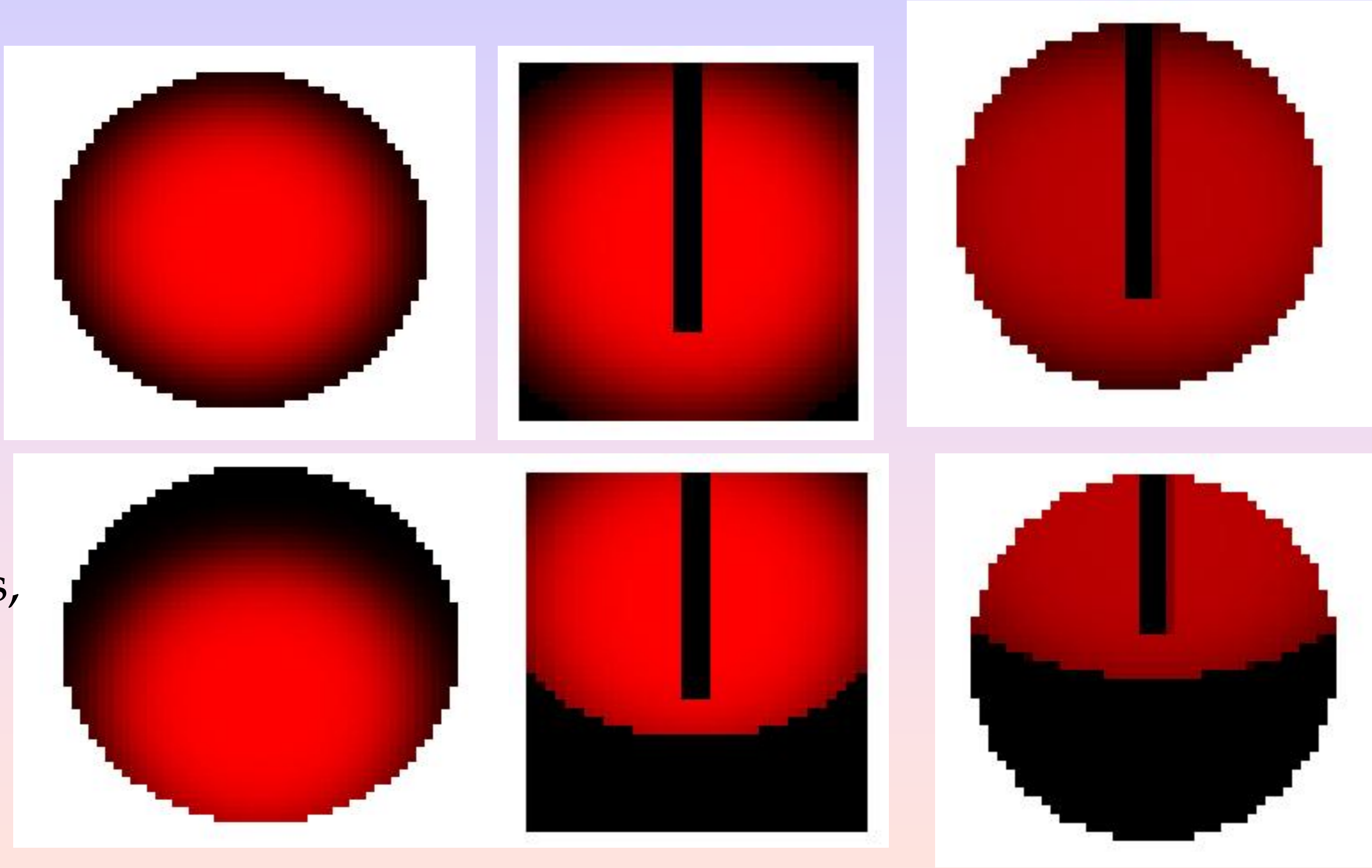
Central wavelength(A): 5,000
Low wavelength(A): 2,336.296
High wavelength(A): 7,705.892
Blaze Wave(A) : 7,450.427
Order for CW: 1.49

dispersion(A/mm): 109.245
dispersion(A/pix): 2.622
Resolution : 1,329.519
Resolution (2 pix) : 953.517
Spatial Demagnification: 3.592
Spectral Demagnification: 3.753

	mm	pix	Angstroms
Spatial diam	0.056	2.32	6.083
Spatial FWHM	0.036	1.499	3.93
Spectral diam	0.053	2.22	5.822
Spectral FWHM	0.034	1.434	3.761

Setup optimization - written by Steve Crawford - go to www.astro.wisc.edu/~crawford/Spectrograph/intro.html

Bench GUI Vignetting Model



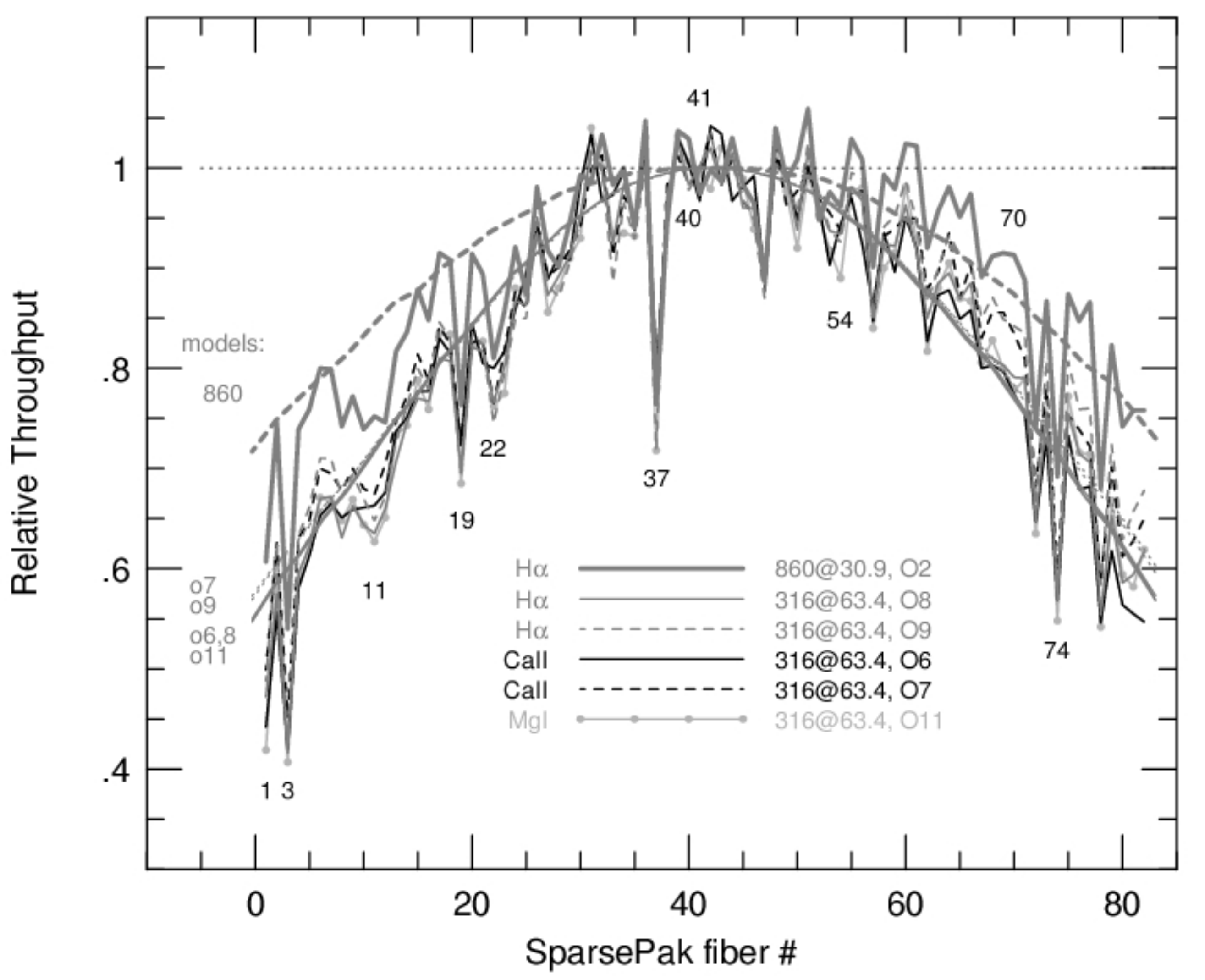
collimator grating camera

On axis

Off axis, Central wave

Echelle order 8 (8.41), cwl 669nm

It works!


Relative Throughput
SparsePak fiber #
1
.8
.6
.4
0
20
40
60
80
models:
860
o7
o9
o6,8
o11
1 3
11
19
22
37
40
41
54
70
74
Hα 860@30.9, O2
Hα 316@63.4, O8
Hα 316@63.4, O9
CaII 316@63.4, O6
CaII 316@63.4, O7
MgI 316@63.4, O11

Photon Budget-1: Top End

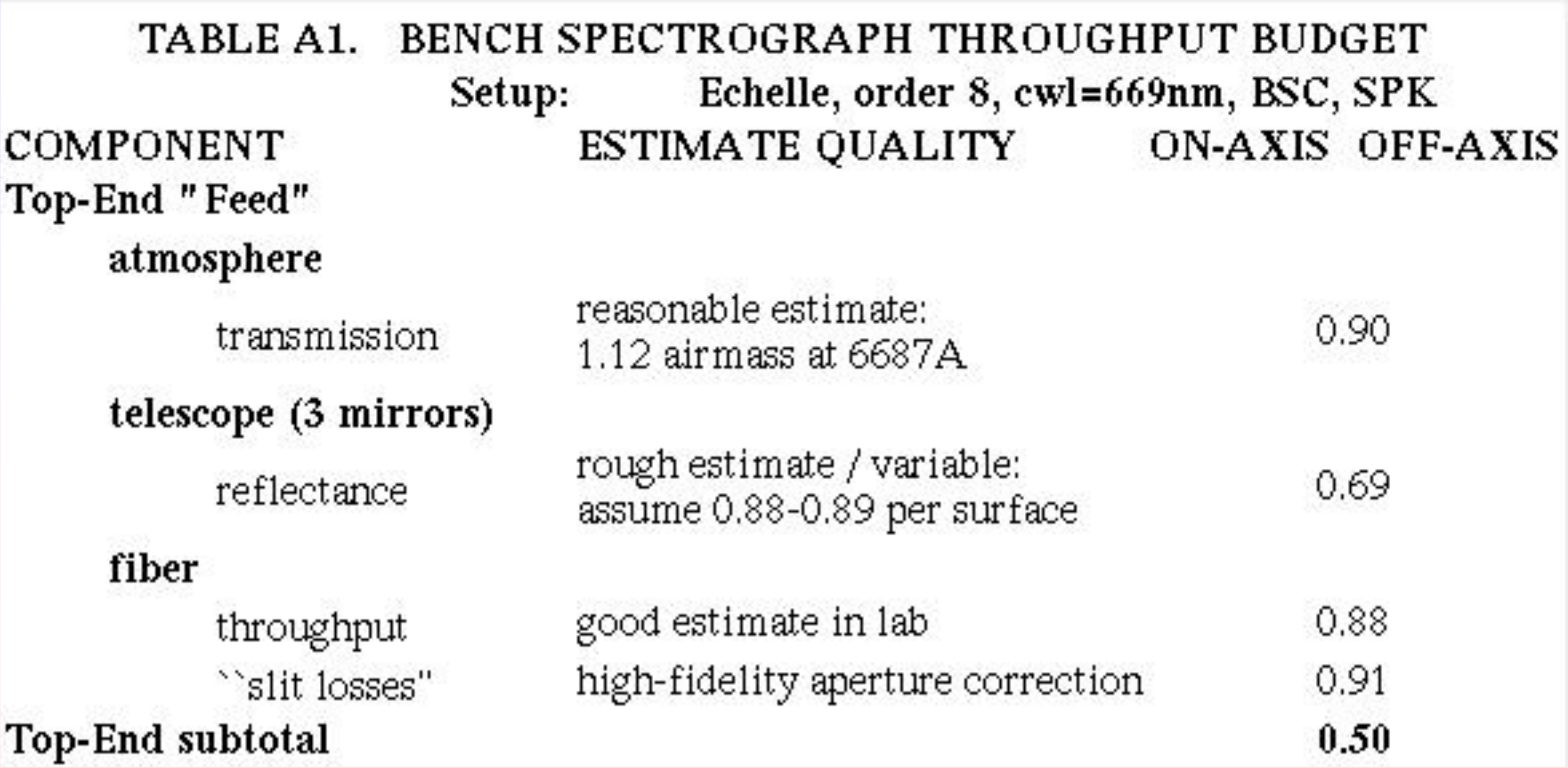


TABLE A1. BENCH SPECTROGRAPH THROUGHPUT BUDGET

Setup: Echelle, order 8, cwl=669nm, BSC, SPK

COMPONENT	ESTIMATE QUALITY	ON-AXIS	OFF-AXIS
Top-End "Feed"			
atmosphere			
transmission	reasonable estimate: 1.12 airmass at 6687A	0.90	
telescope (3 mirrors)			
reflectance	rough estimate / variable: assume 0.88-0.89 per surface	0.69	
fiber			
throughput	good estimate in lab	0.88	
``slit losses''	high-fidelity aperture correction	0.91	
Top-End subtotal		**0.50**	

Photon Budget-1a

- *Half the light is lost before the spectrograph!*
- Over-coating secondary and tertiary (LLNL-type) will yield significant gains -- 16%. **[RECOMMEND but not done]**
- More frequent re-aluminization may pay for itself in total photons collected per year. Explore?
- AR coating fibers gains 4% -- a lot of effort.

Photon Budget-2: Spectrograph

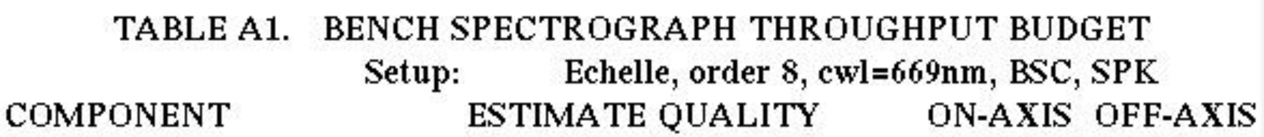
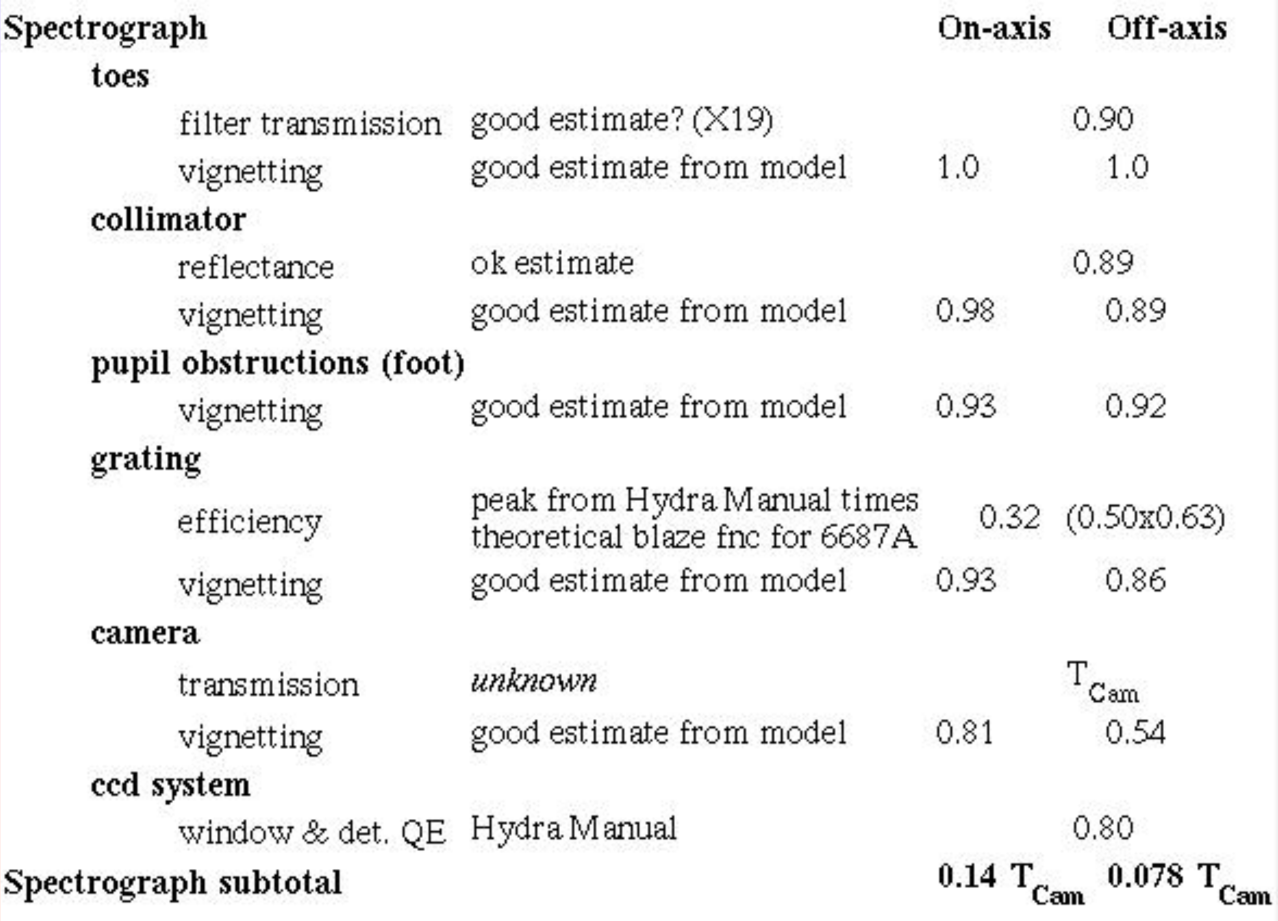


TABLE A1. BENCH SPECTROGRAPH THROUGHPUT BUDGET

Setup: Echelle, order 8, cwl=669nm, BSC, SPK

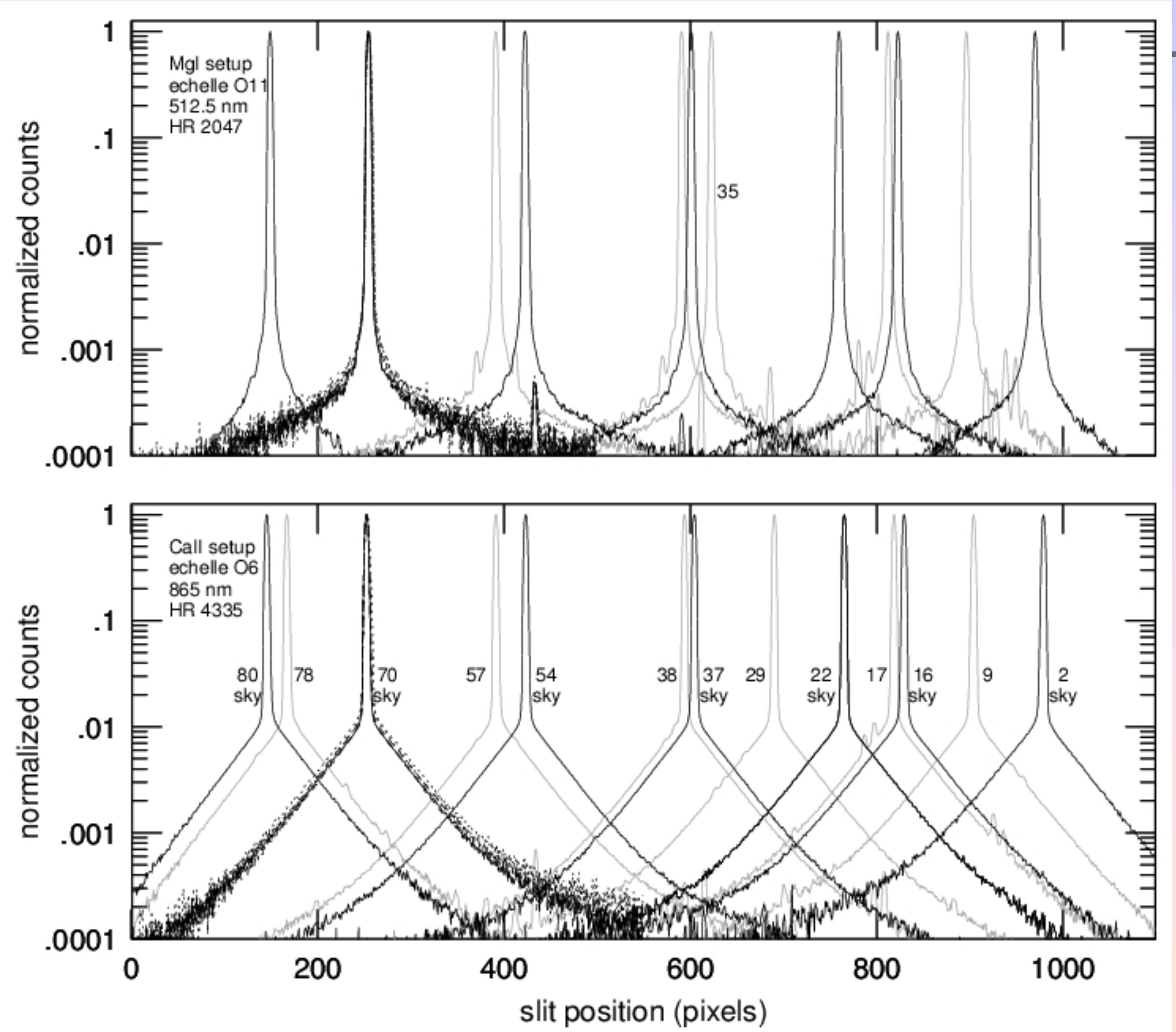


COMPONENT	ESTIMATE QUALITY	ON-AXIS	OFF-AXIS
Spectrograph		**On-axis**	**Off-axis**
toes			
filter transmission	good estimate? (X19)		0.90
vignetting	good estimate from model	1.0	1.0
collimator			
reflectance	ok estimate		0.89
vignetting	good estimate from model	0.98	0.89
pupil obstructions (foot)			
vignetting	good estimate from model	0.93	0.92
grating			
efficiency	peak from Hydra Manual times theoretical blaze fnc for 6687A	0.32	(0.50x0.63)
vignetting	good estimate from model	0.93	0.86
camera			
transmission	*unknown*		T_{Cam}
vignetting	good estimate from model	0.81	0.54
ccd system			
window & det. QE	Hydra Manual		0.80
Spectrograph subtotal		**0.14 T_{Cam}**	**0.078 T_{Cam}**

Photon Budget-2a

- Vignetting accounts for most of losses in spectrograph.
  - On-axis: 69% throughput
  - Off-axis, central wave: 38% throughput
  - Off-axis: 20% throughput
- Grating efficiency 2nd largest loss (35-60%)
- Camera throughput ok, but scattering in red

Scattered light in the red



Photon Budget Summary

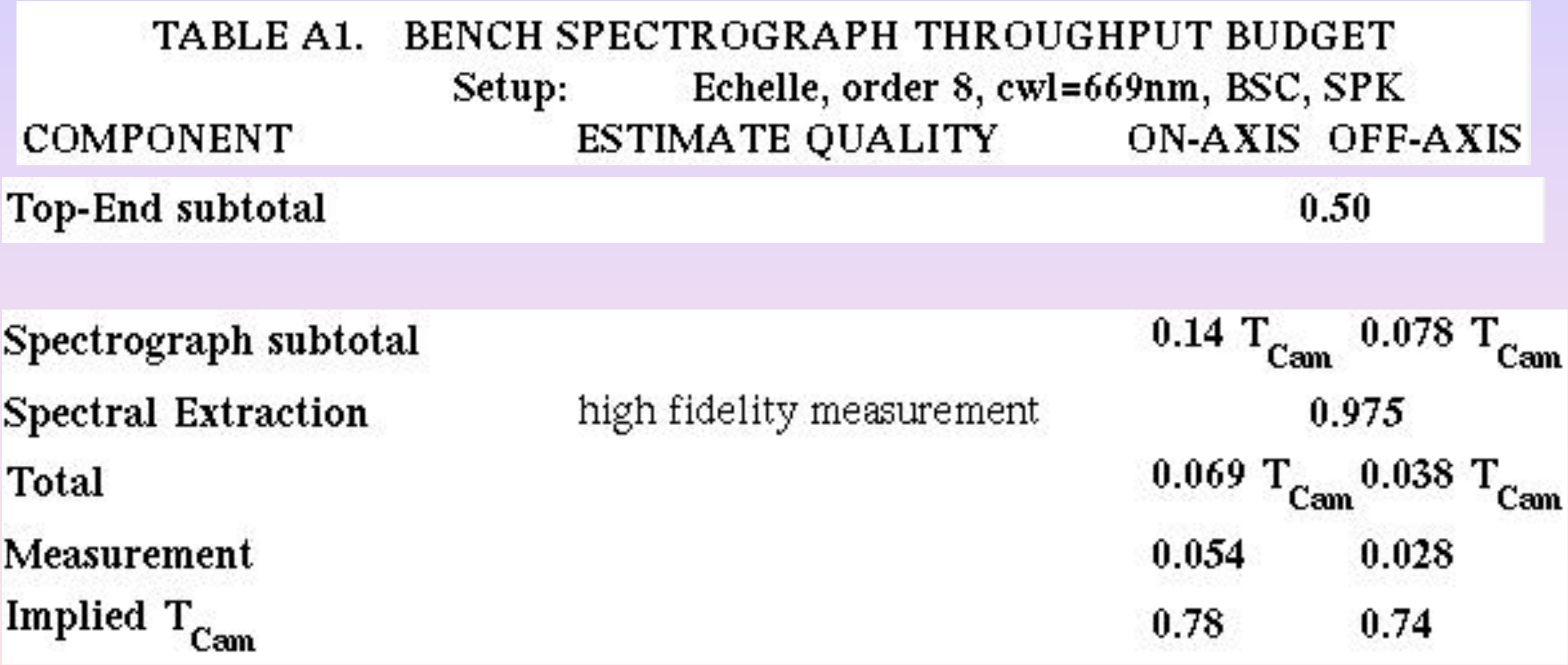


TABLE A1. BENCH SPECTROGRAPH THROUGHPUT BUDGET

Setup: Echelle, order 8, cwl=669nm, BSC, SPK

COMPONENT	ESTIMATE QUALITY	ON-AXIS	OFF-AXIS
Top-End subtotal		0.50	
Spectrograph subtotal		0.14 T_{Cam}	0.078 T_{Cam}
Spectral Extraction	high fidelity measurement	0.975	
Total		0.069 T_{Cam}	0.038 T_{Cam}
Measurement		0.054	0.028
Implied T_{Cam}		0.78	0.74

Motivation for Upgrade

- Spectrograph had very low throughput (3-5%).
- Generically uncompetitive by standards of 1980/1990’s cutting-edge systems (e.g., CryoCam).
- Read-noise-limited performance for many science-applications (background-limited work above λ/Δλ of a few thousand).

➢ Could we fix it with a modest-cost “upgrade” instead of starting from scratch? (ubetcha)

Problems to Solve

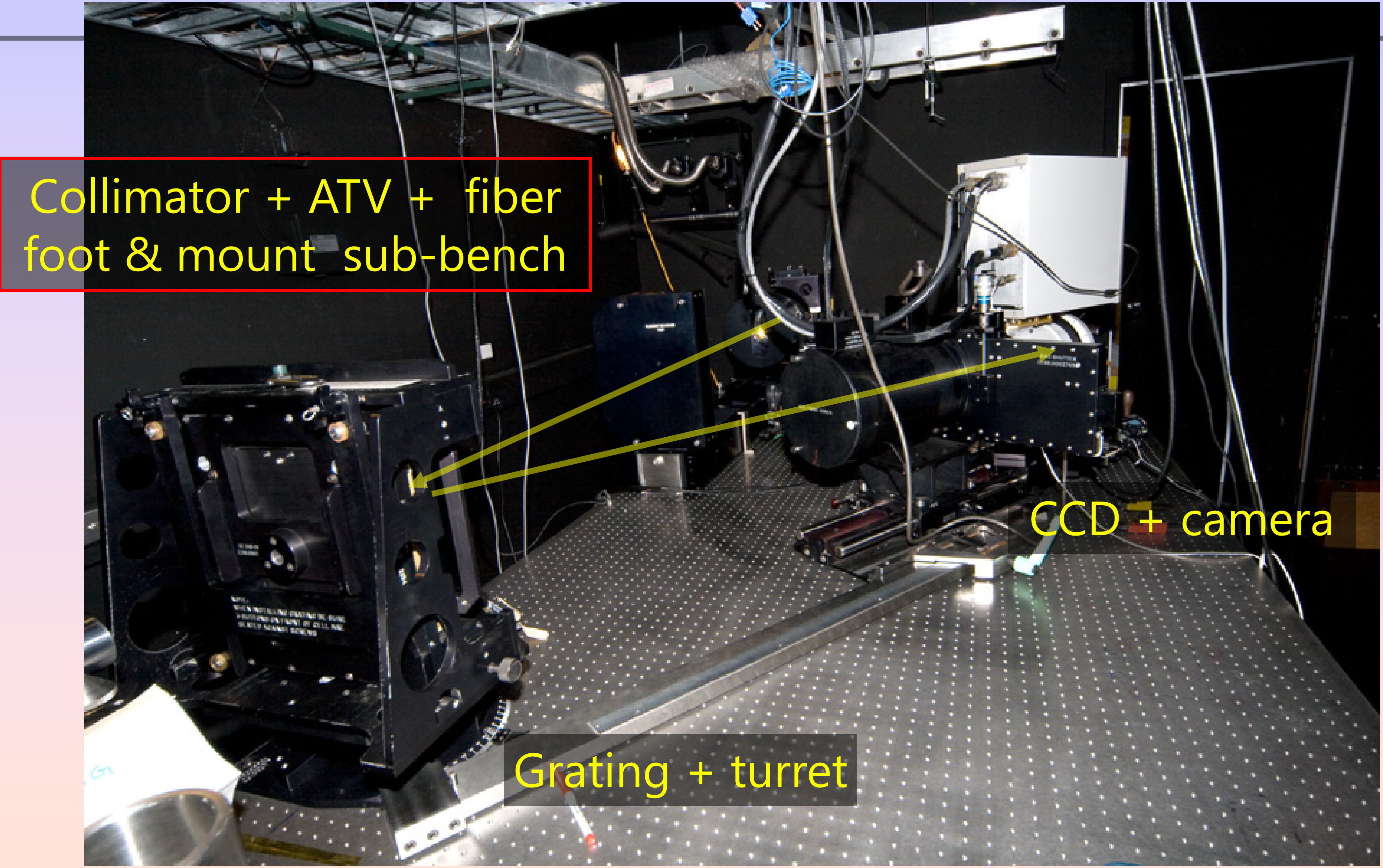
- Spectrograph not designed to handle fiber-output f-ratio.
  - ➢ Collimator too slow to capture fiber exit-beam (collimated beam too large; vignetted down-stream)
  - ➢ Toes vignette beam faster than f/5.7 (internal baffles)
- Entrance pupil is not re-imaged to minimize slit-function.

➢ Can be solved with proposed collimator design

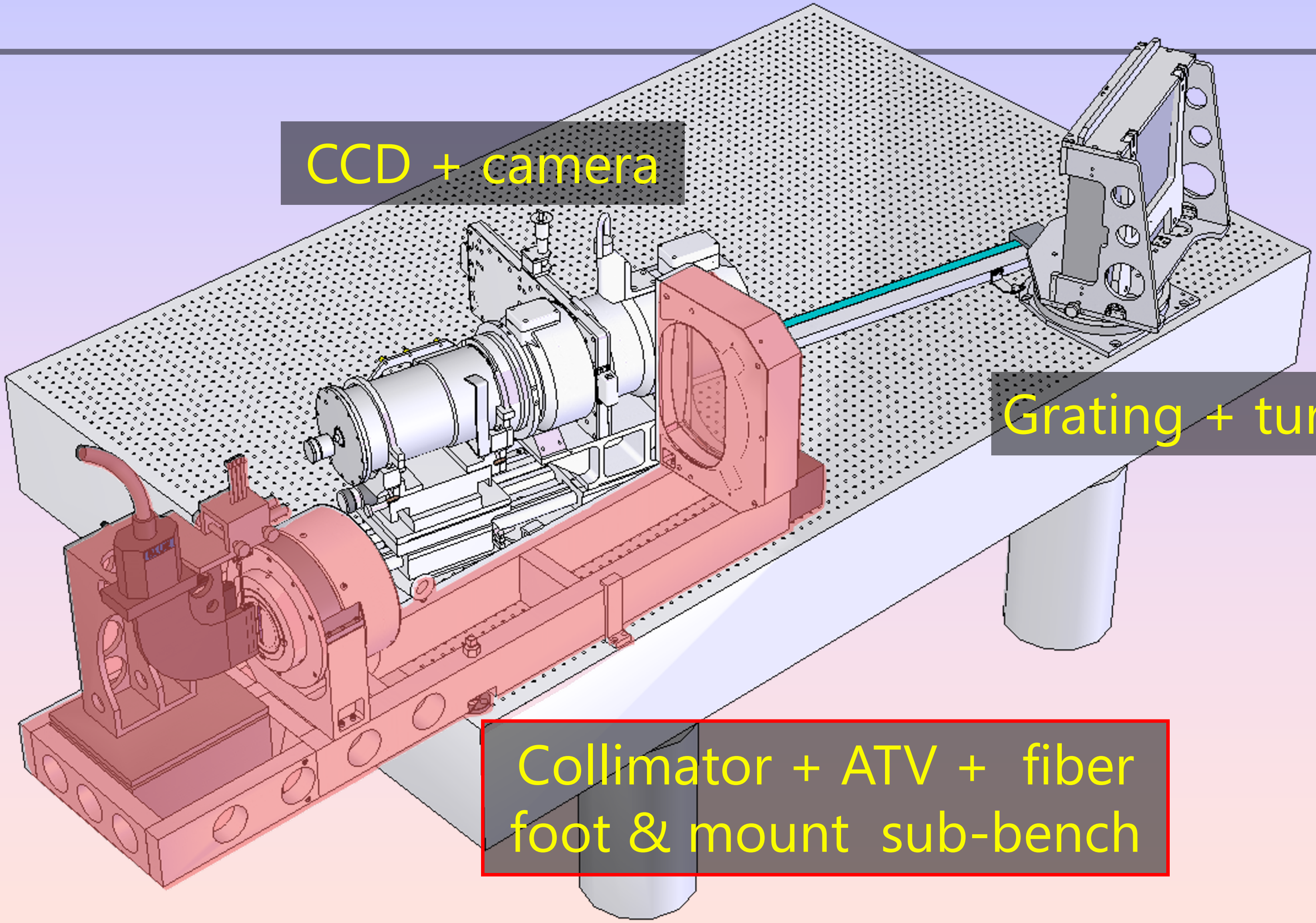
History: Options Considered

- Off-axis parabolic collimator + corrector
  - 3 tilted, all sph., FS lenses (C. Harmer)
    - Insufficient image quality; 7 surfaces
  - 4 tilted all sph., FS lenses (C. Harmer)
    - Good image quality; 9 surfaces; difficult to build
  - 3 displaced all sph., FS lenses (D. Blanco)
    - Good image quality; 7 surfaces; easier to build
- On-axis all-refractive collimator (M. Liang)
  - 4 all sph., one flint-glass, 3 FS -- 3 groups
    - Superior image quality; 6 surfaces; easiest to build

Bench Spectrograph (today)



Bench Spectrograph (today)

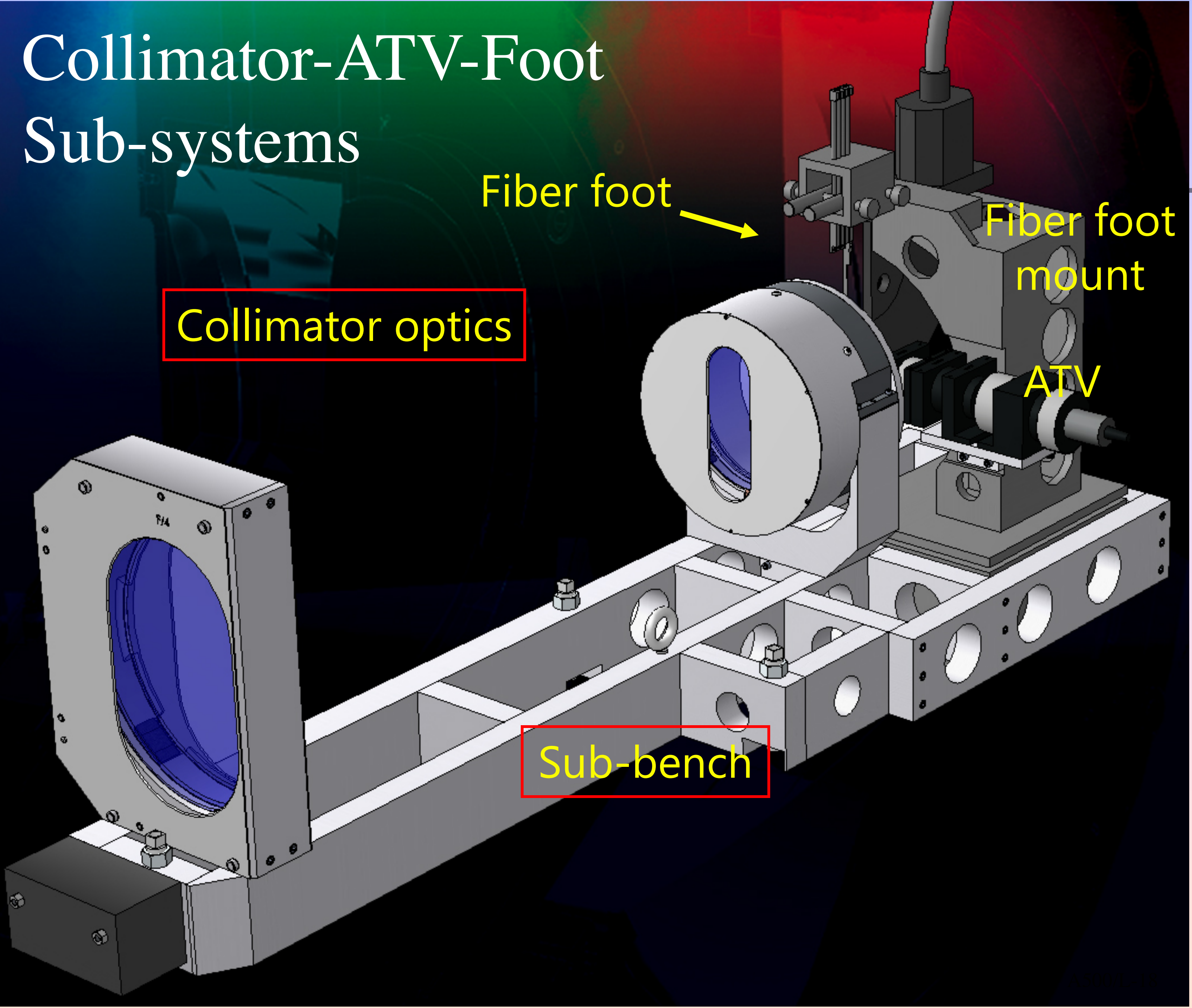


CCD + camera

Grating + turret

Collimator + ATV + fiber foot & mount sub-bench

Collimator-ATV-Foot Sub-systems



Fiber foot

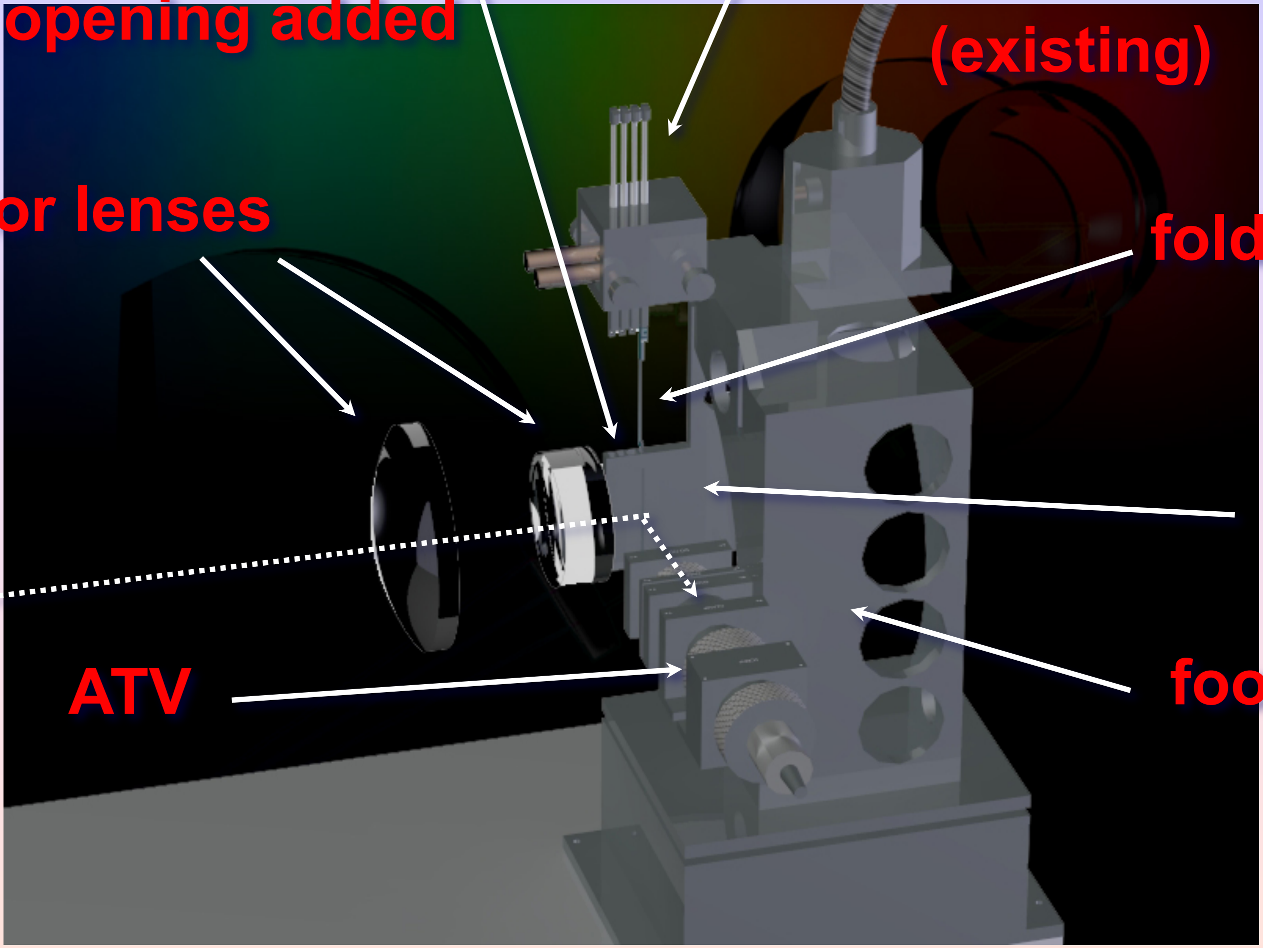
Fiber foot mount

Collimator optics

ATV

Sub-bench

ATV-Foot Sub-systems



toes w/ side-opening added

filter-insertion mechanism (existing)

Collimator lenses

fold-mirror

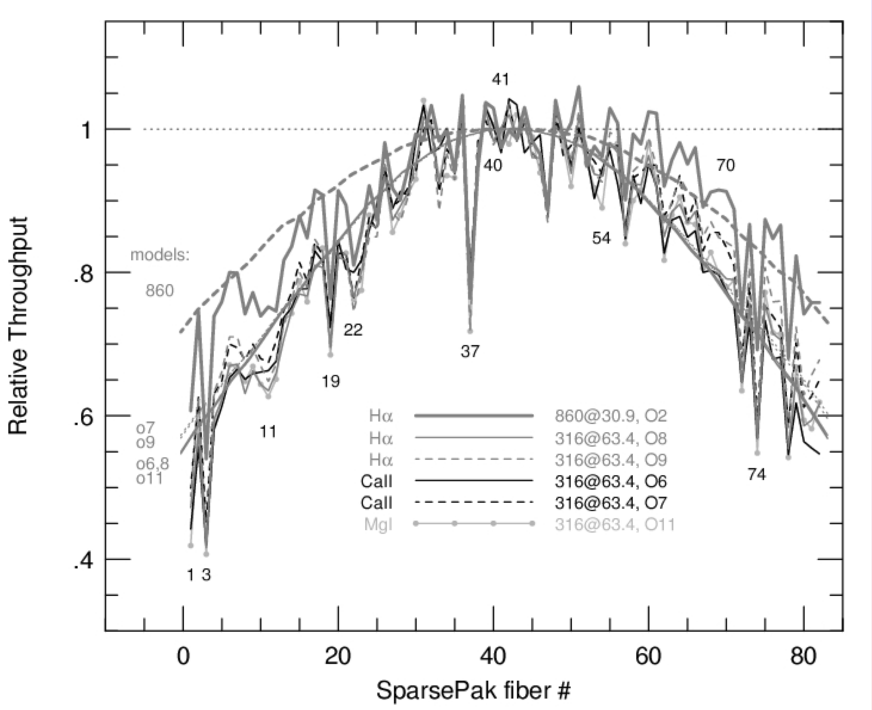
foot

foot mount

ATV

Preliminary Analysis

- Use custom beam-trace code. (Crawford)
- Examine throughput vs magnification trade as function of collimator fl.
- Find optimum pupil placement.



Bershady et al 200, ApJSupp, 156, 311

Preliminary Analysis

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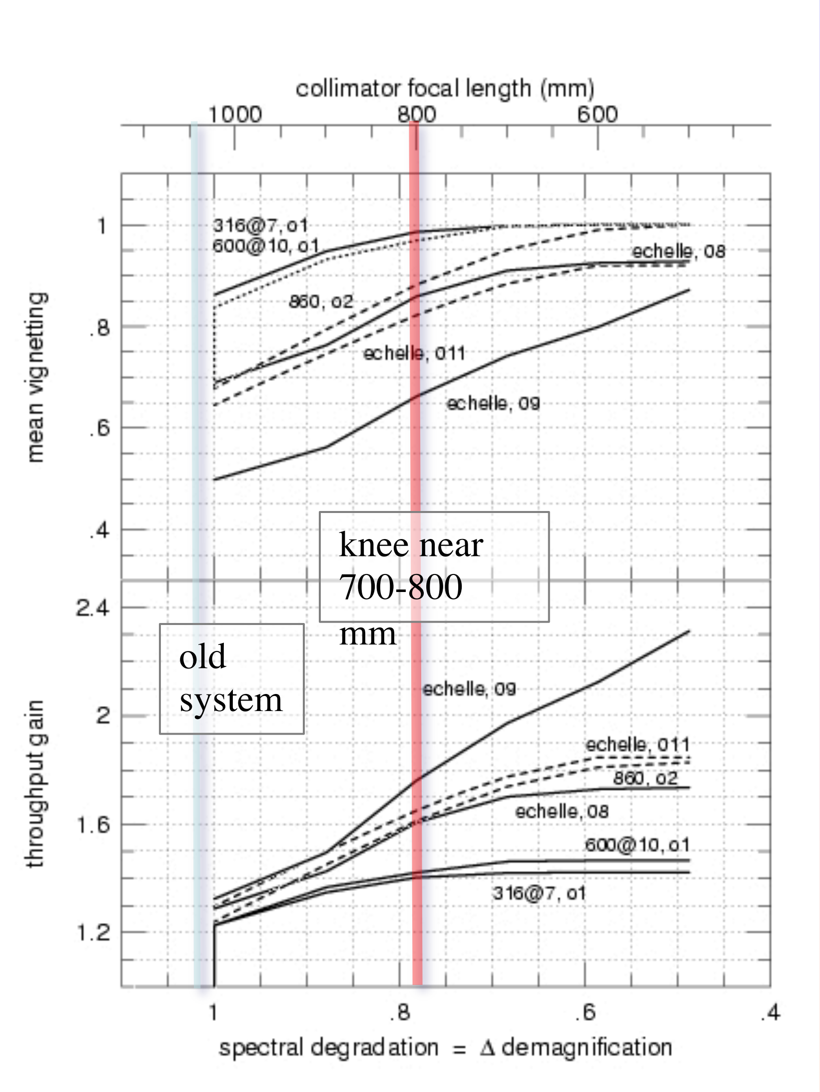


knee near 700-800 mm

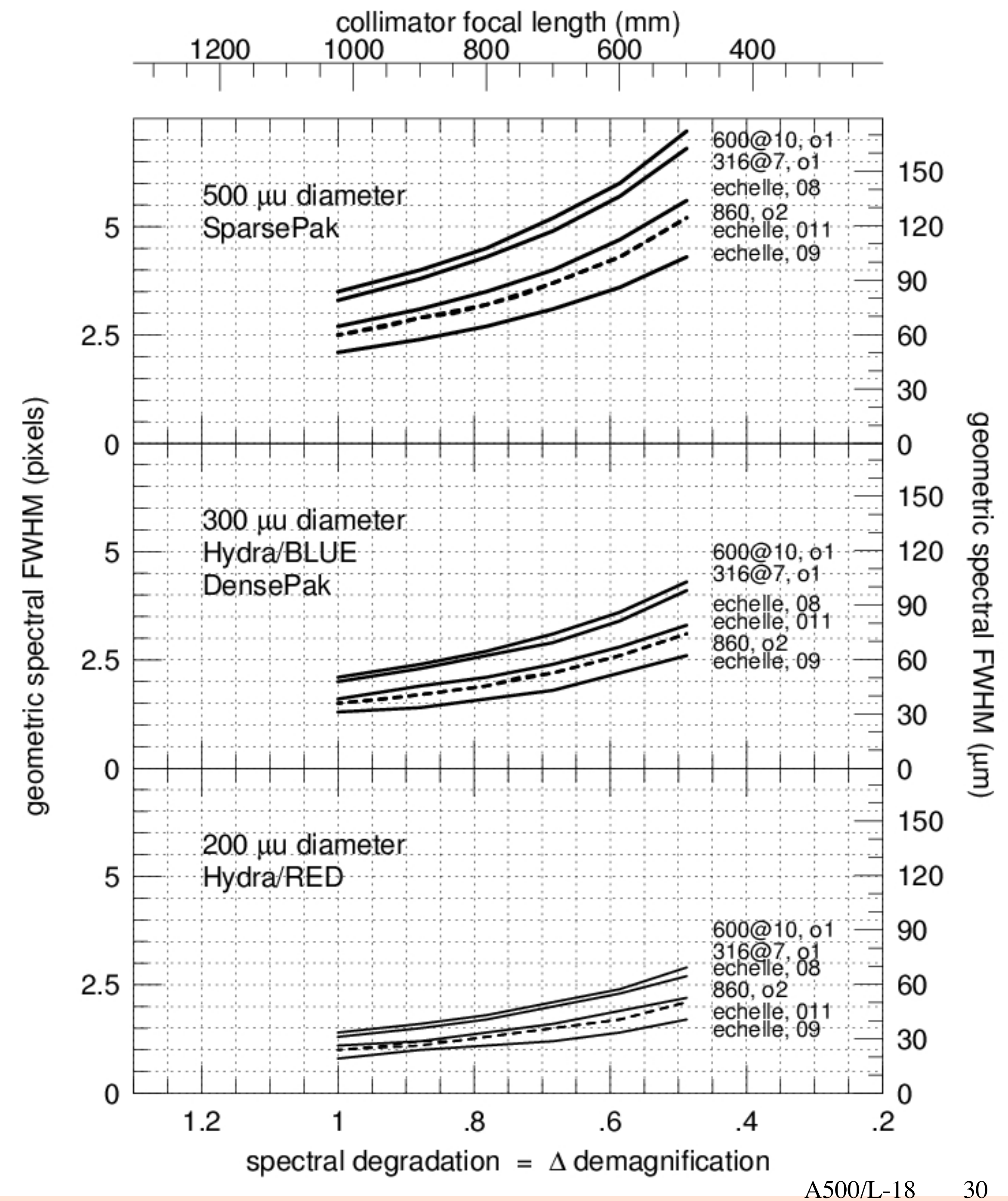
old system

Tradeoffs:
throughput vs resolution

Changes in geometric slit-width:

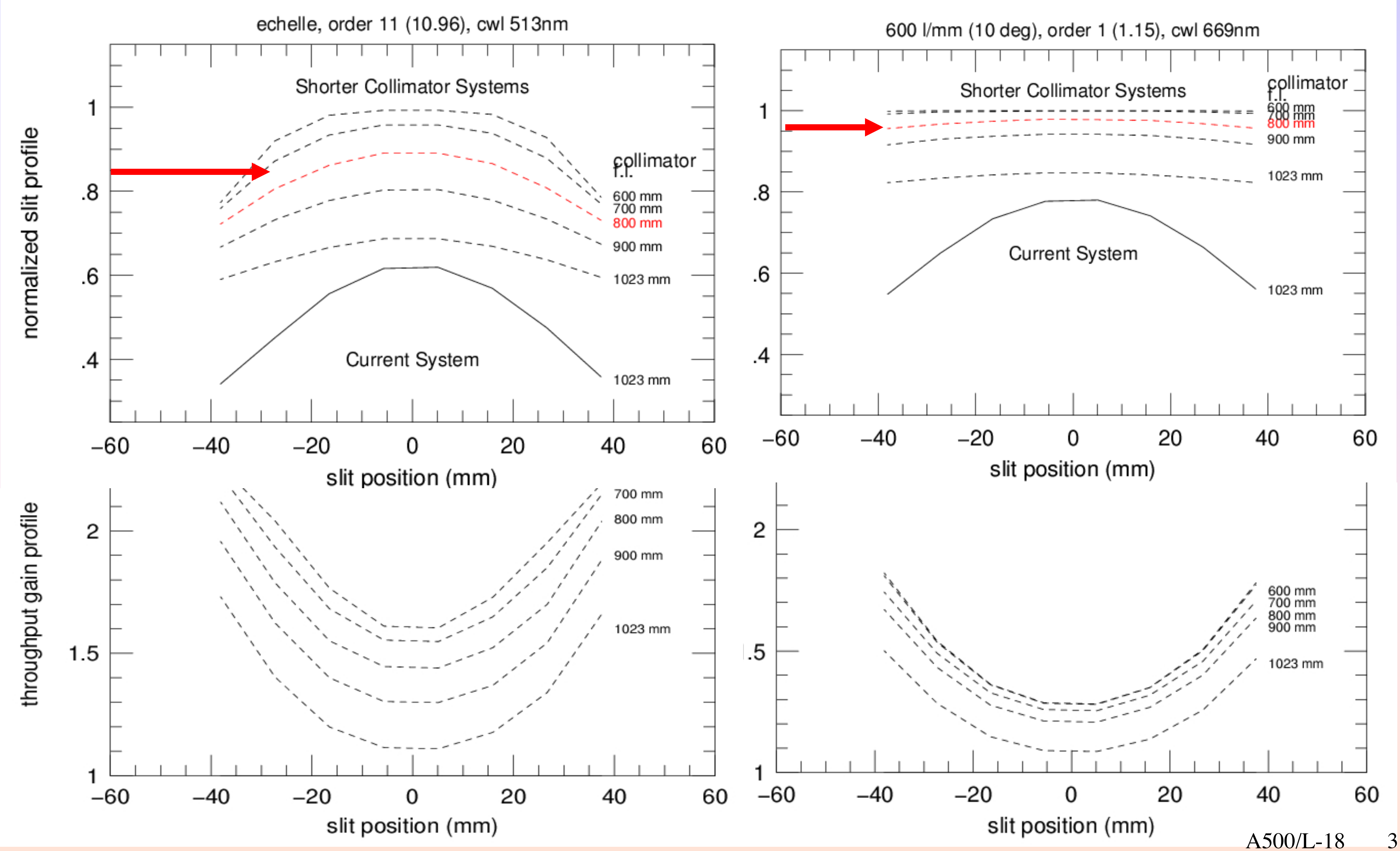
Decreased collimator f.l. *expands* image-size

At 800mm, smallest fibers still under-sampled



Preliminary Analysis

Estimated improvements in slit function



Preliminary Analysis

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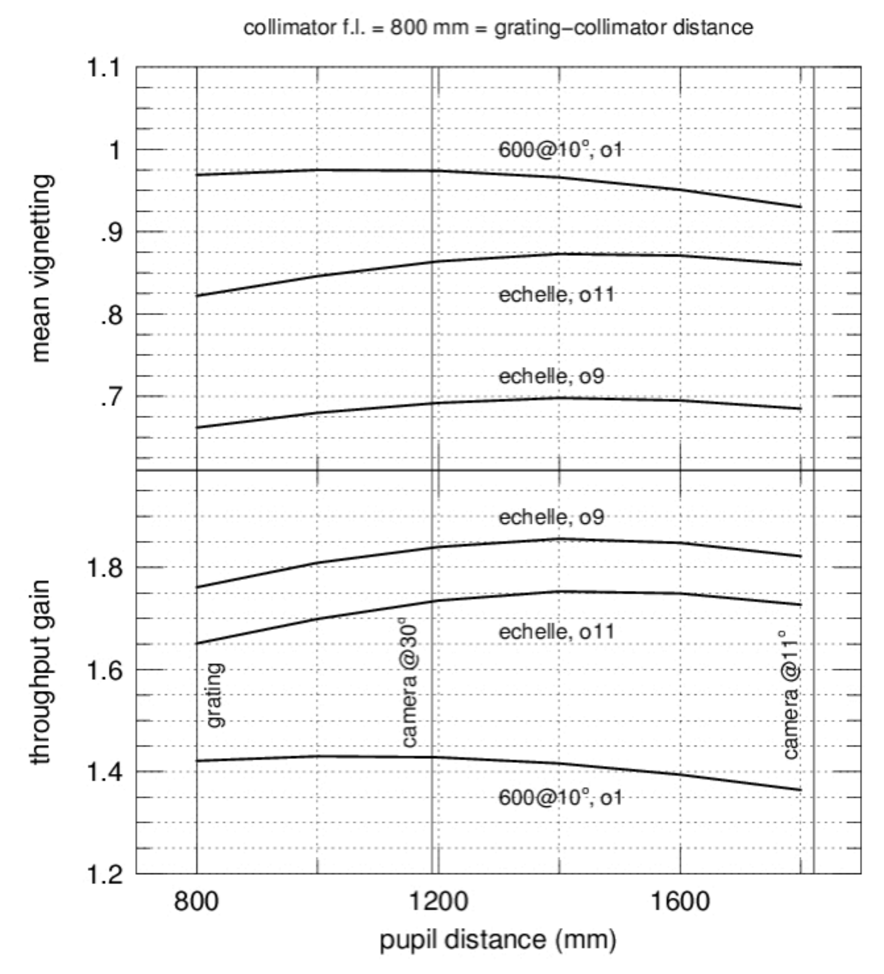
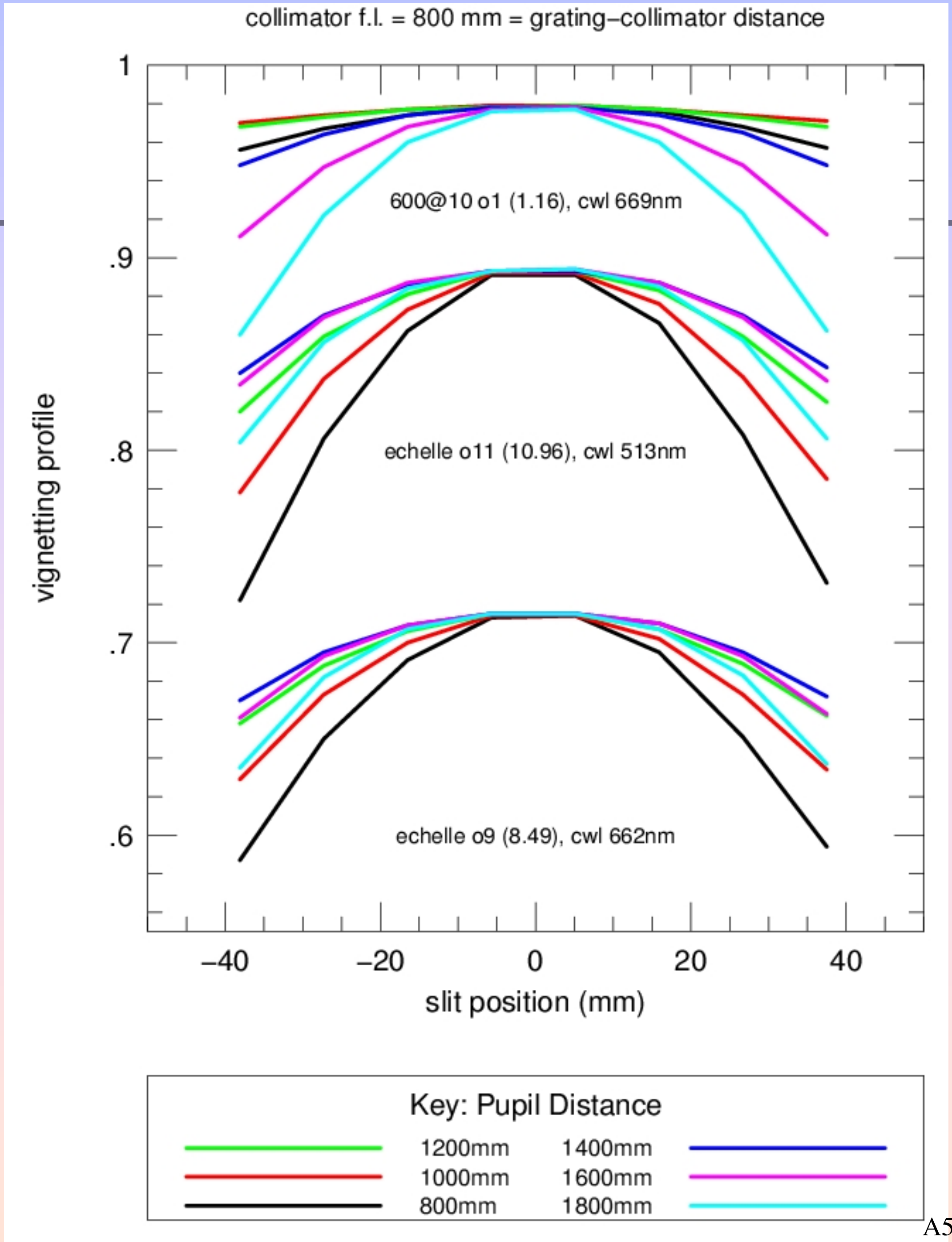
- Examine throughput vs magnification trade as function of collimator fl.
- Find optimum pupil placement.



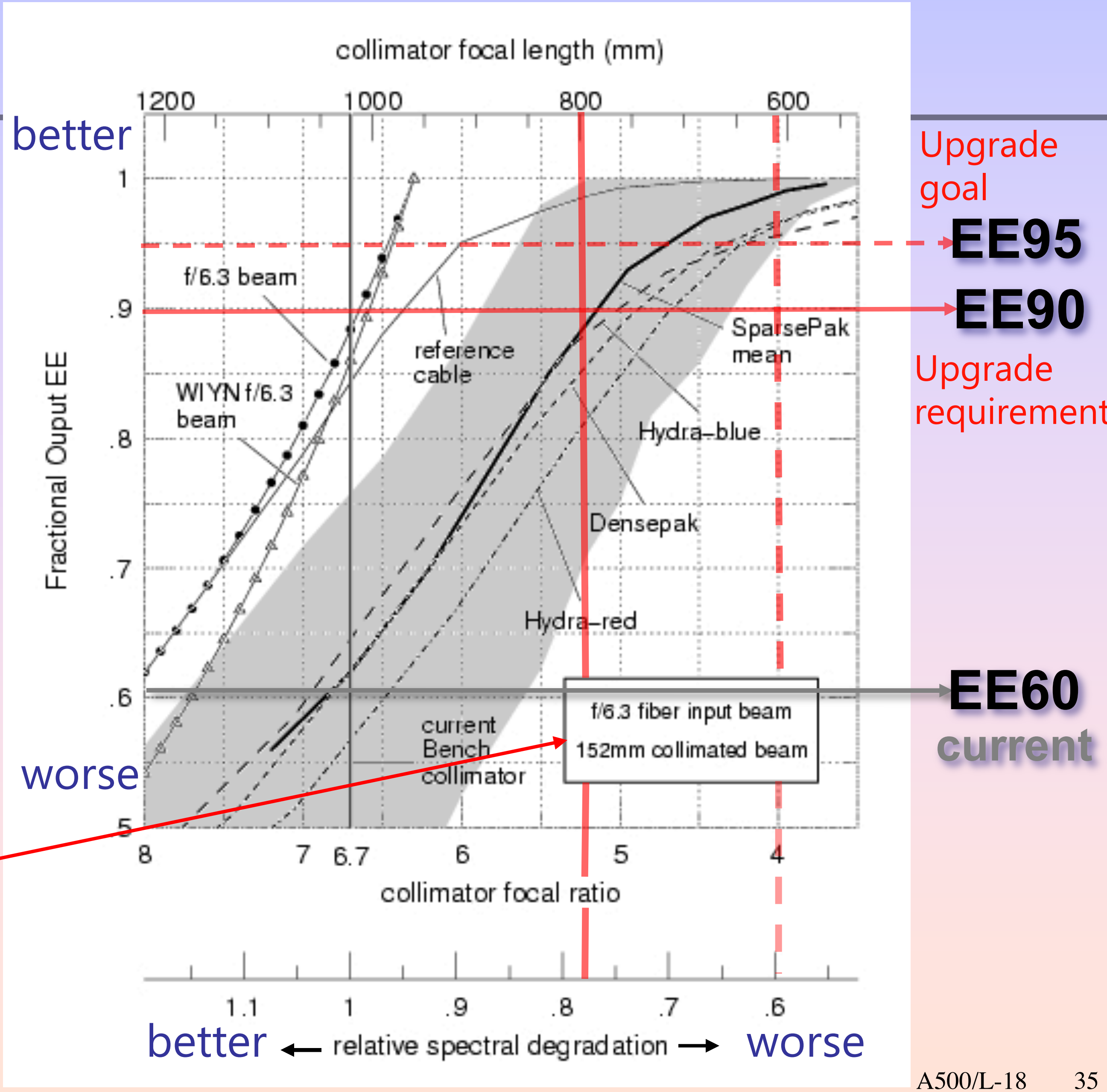
Effects of pupil placement on vignetting profile



Analysis Conclusions

- Collimator focal length:
  - ➢ decrease from 1021 mm to 800 mm.
- Pupil location:
  - ➢ increase from 1021 mm beyond collimator to 450 mm beyond first grating turret (over 1800 mm beyond collimator).
- Toes:
  - ➢ shorten and widen to accommodate f/5 with option for f/4.

Bench Input Beam



f/5
160mm
collimated beam

Project Goals

- Increase spectrograph throughput by 60% while minimizing resolution loss (< 20%).
    - Capture f/5 input beam (EE80 to EE90) into 160 mm collimated beam (collimator fl of 800 mm);
    - Minimize vignetting by optimizing pupil placement and opening toes and collimator optics to f/4 (EE95)
    - Tune image quality to BSC and commonly used and wide range of configurations.
- Accommodate new suite of VPHg
    - Restructure spectrograph layout to handle gratings at $10^o < \alpha < 70^o$ (incidence angle).

Specific Requirements

- Collimator efficiency as good or better than single Al-coated mirror (~92% reflectivity) between 350-950 nm (defined as “core” usable wavelength range).
    - AR coatings good to ~1.4% or better (feasible).
- Overall system throughput as good or better in full range 320-1000 nm.
- Delivered image-quality as good or better than existing rms spot-size in same range.
- Layout must prevent parasitic light entering camera.
- Ghosting must be <1e-4.

AR Coatings

- Collimator lens coatings must deliver < 1.4% reflectivity per surface from 350-950 nm (match/exceed existing collimator throughput) .
- Coatings must be durable, with performance longevity in excess of 10 years (useful lifetime of instrument).
- Two options considered:
  - ➢ Multi-layer broad-band AR coatings (Infinite Optics) proven on QUOTA (OTA mosaic CCD -- ODI precursor) fore-optics on WIYN.
  - ➢ Hardened Sol Gel (hybrid) AR coatings (Cleveland Crystals).
- Both options meet requirements.
  - ➢ Sol Gel hybrid significantly superior in performance.
  - ➢ Hardened Sol Gel (hybrid) deemed robust enough for Bench Spectrograph room environment (will require formal ISO spec met in accepted bid).

➢ Hardened Sol Gel hybrid preferred.

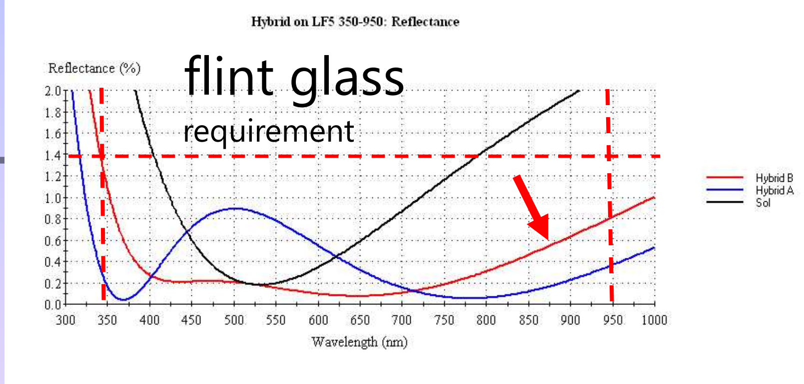
➢ Cleveland Crystals is capable of handling our optics (size and material) and interested to bid

➢ Lick Observatory could be alternative hardened Sol Gel vendor.

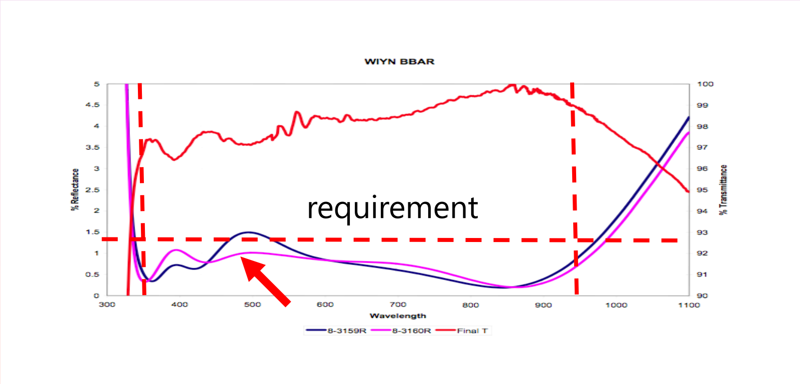
ISO 9211-
4-01-01
4-02-02
3-05-02
3-06-03

AR Coatings

<u>Prefered</u>
Hardened Sol Gel hybrid (Cleveland Crystals): ammonia-bath hardened Sol Gel over thin-film dielectric
<u>predicted performance</u>



<u>Alternative</u>
multi-layer broad-band (Infinite Optics): <u>measured performance</u>



Collimator-Doublet Cementing

- Collimator doublet (objective) consists of fused-silica plus flint glass (PBL25Y, an LF5 equivalent)
- NOAO has capacity to carry out cementing (Gary Poczulp)
- Sylgard 184 used in past with success
- Expect to coat optics first and then cement in-house

  - ➢ Ended up having bonding done by lens-polishing vendor (SESO)

Boundary Conditions

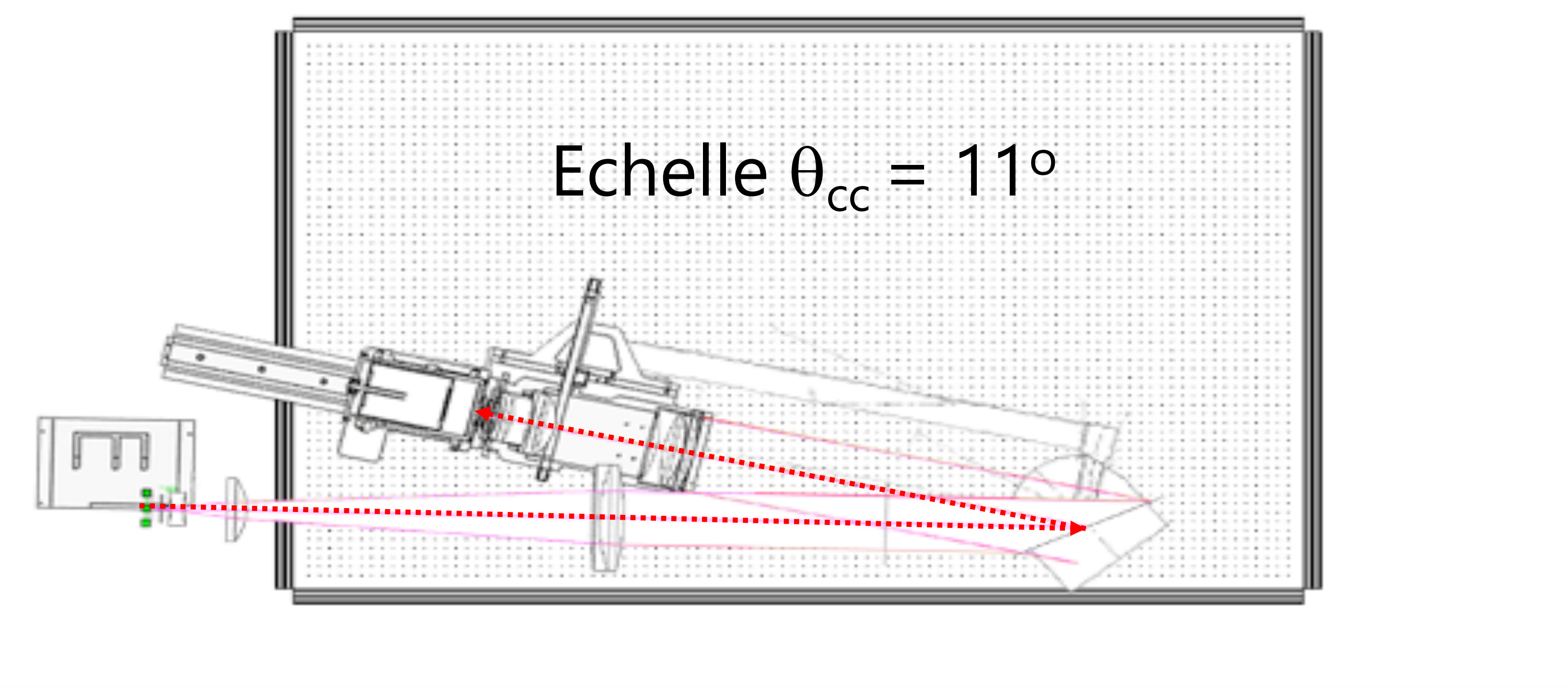
- Use existing camera(s), cables, room, and bench: modest-cost "Upgrade", not new system
- Maintain 11^o off-Littrow echelle configuration and low-order SRg with $20^o < \theta_{cc} < 45^o$.
- Maintain use of order-blocking filters
- Maintain or improve ergonomics:
  - Configuration changes & operations
- Maintain or improve ATV system
  - Source acquisition and fiber rear-illumination system.

Layout and Operation

- Allow for full range of used and anticipated spectrograph configurations.
  - Echelle: $\theta_{cc} = 11^o$
  - SRg: $20^o < \theta_{cc} < 45^o$
  - VPHg: $10^o < \alpha < 70^o$
    - folded or direct with 10-20^o overlap
- Keep moving parts on table
- Make ergonomic to reconfigure

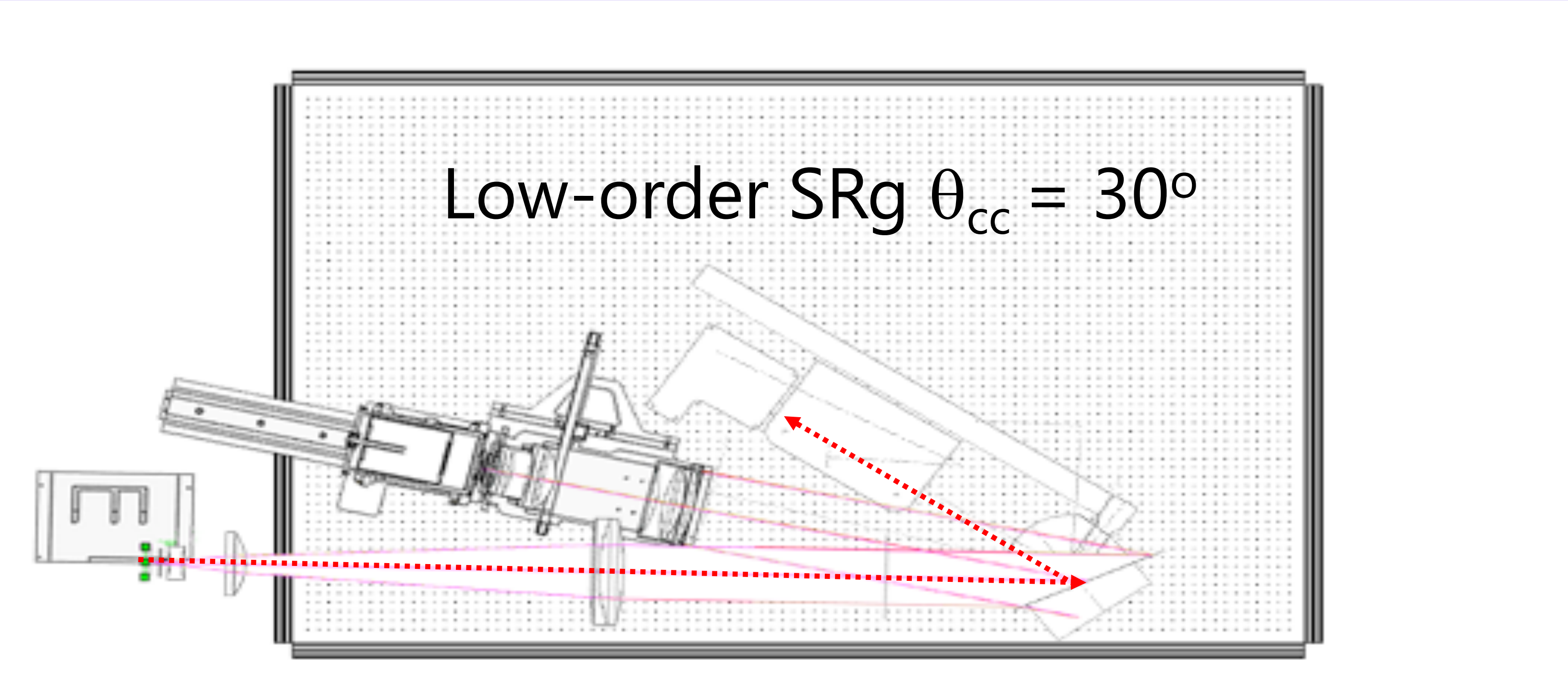
Spectrograph characteristics

- Highly versatile instrument used in many configurations



Spectrograph characteristics

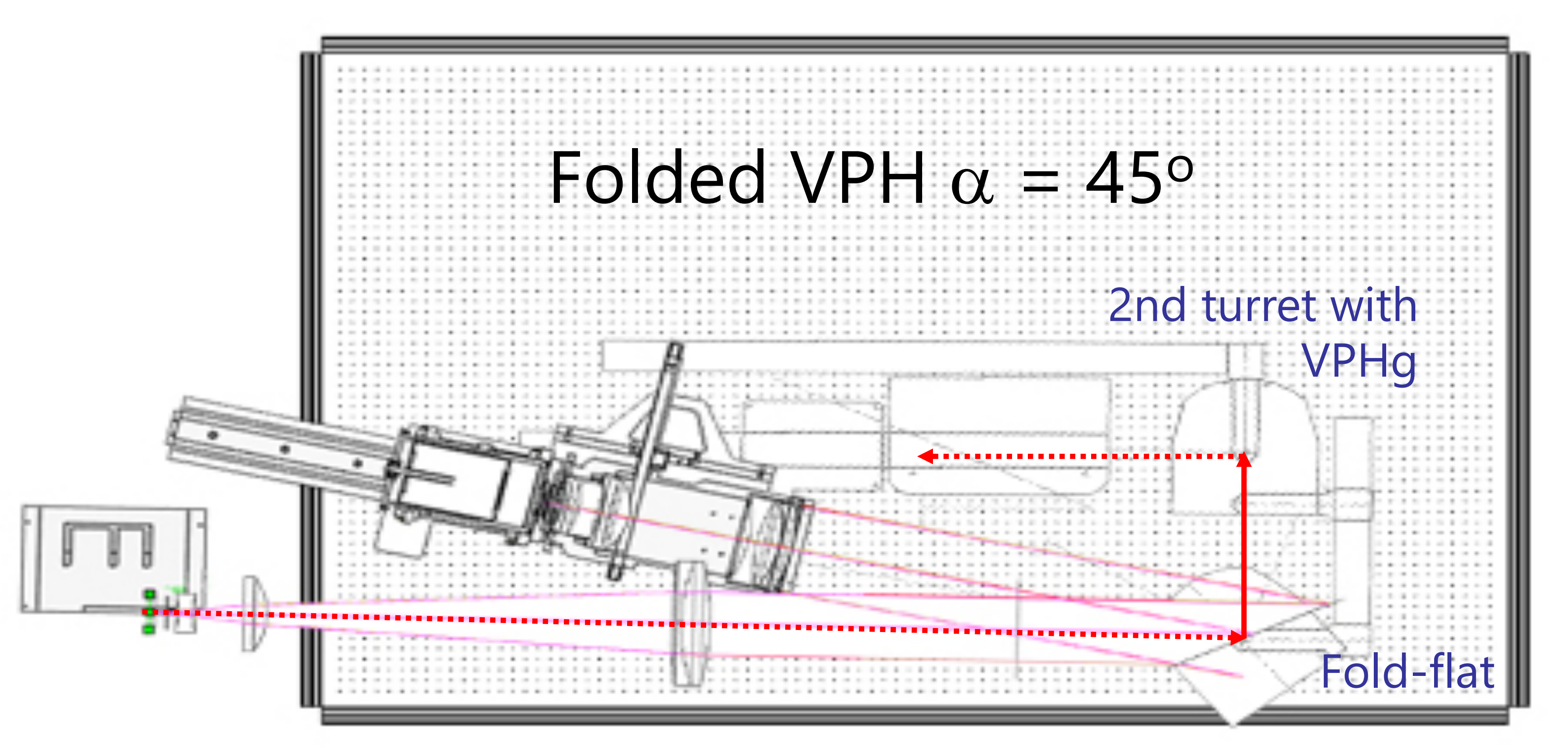
- Highly versatile instrument used in many configurations



Low-order SRg $\theta_{cc} = 30^{o}$

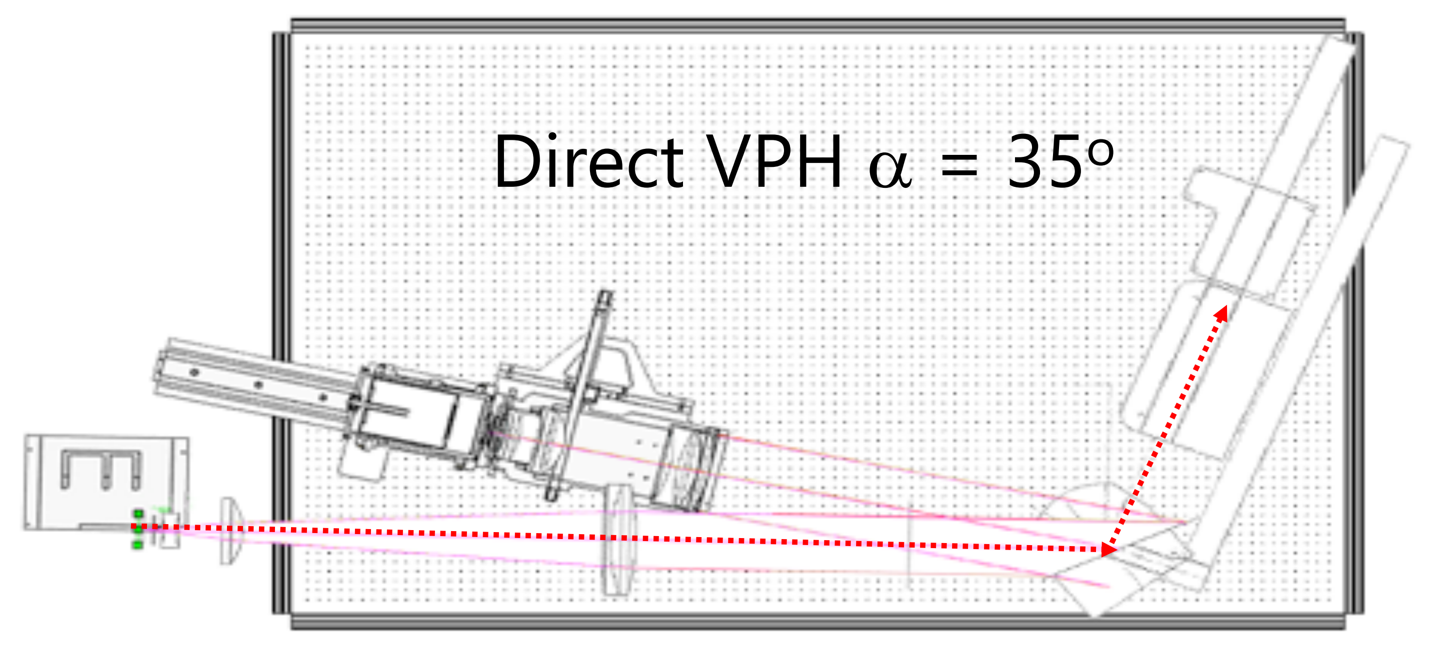
Spectrograph characteristics

- Highly versatile instrument used in many configurations



Spectrograph characteristics

- Highly versatile instrument used in many configurations

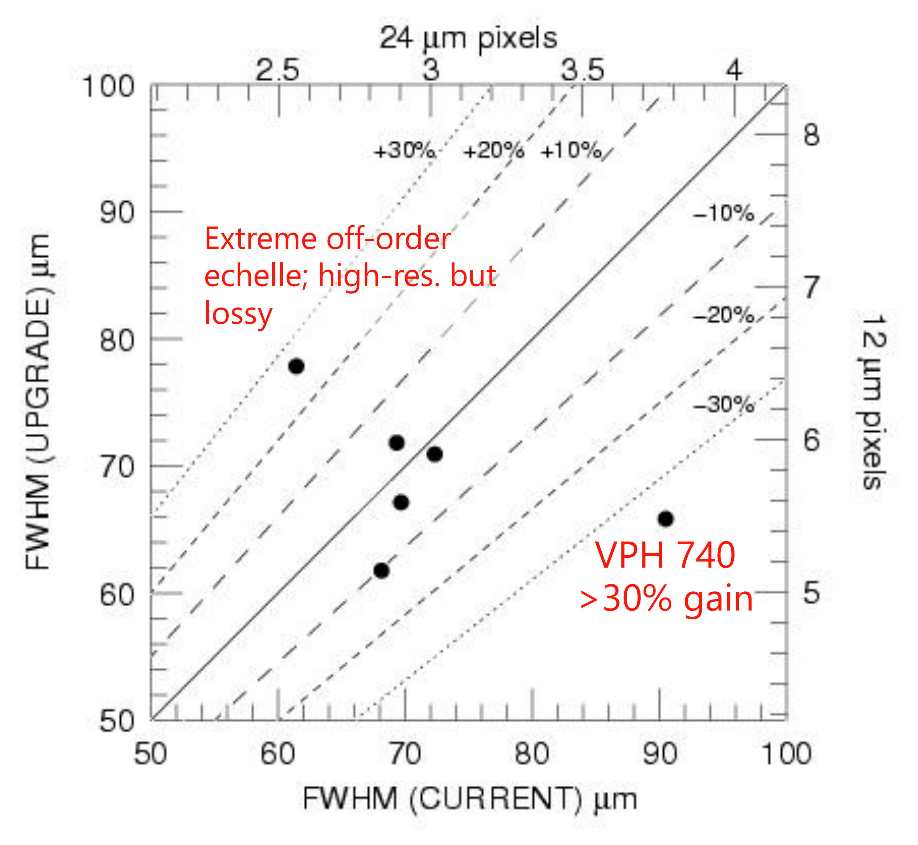


Additional Knowledge of “as built” System

- Image-quality well documented
  - reproduced by optical model in multiple configurations.
- No significant parasitics in standard setups.
- Low scattered light in visible
  - Increases significantly λ > 750 nm; likely due to BSC coatings.

Expected Performance: *Achieved*

- Image quality:
- Modest image magnification
  - +28%
- Improved image quality
  - 12-20% improvement typical;
  - as high as 3x improvement;
  - 30% degradation in one case
- Better pixel sampling
  - x2 -- 24 to 12 μm
- No loss in instrumental resolution for typical configurations with smallest (200μm) fibers
  - 0-15% loss 300μm fibers
  - 10-20% loss 500μm fibers



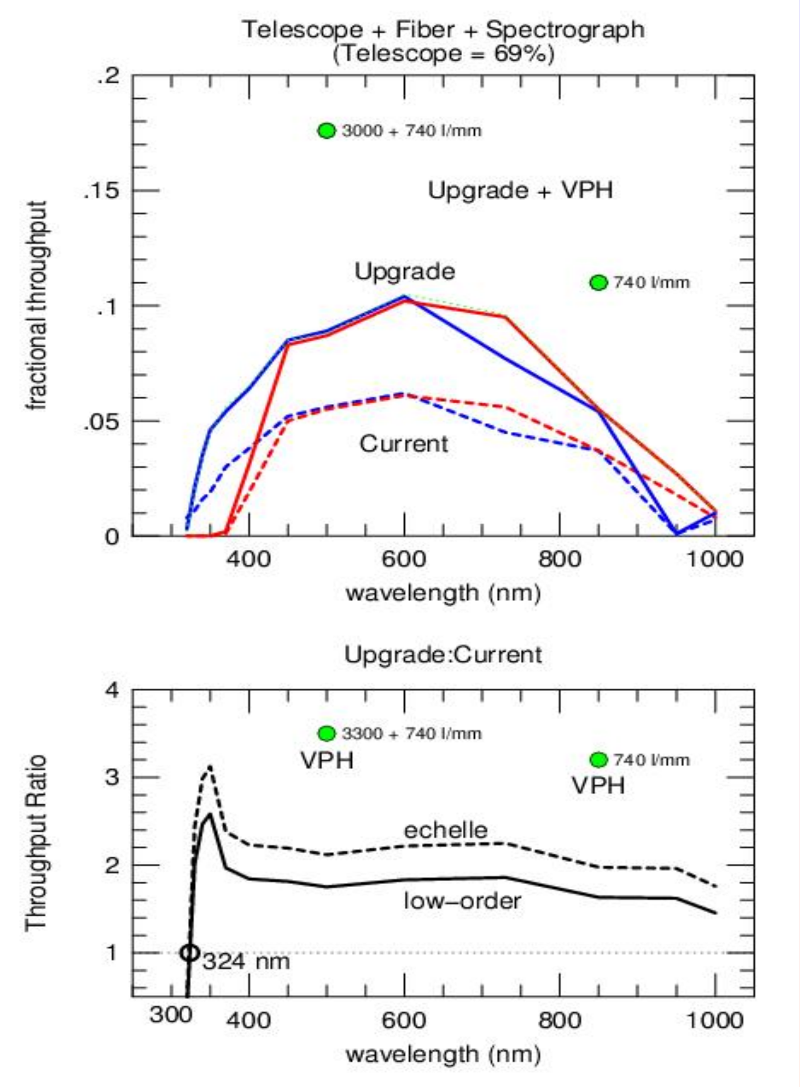
Extreme off-order echelle; high-res. but lossy

VPH 740 >30% gain

200 micron fibers

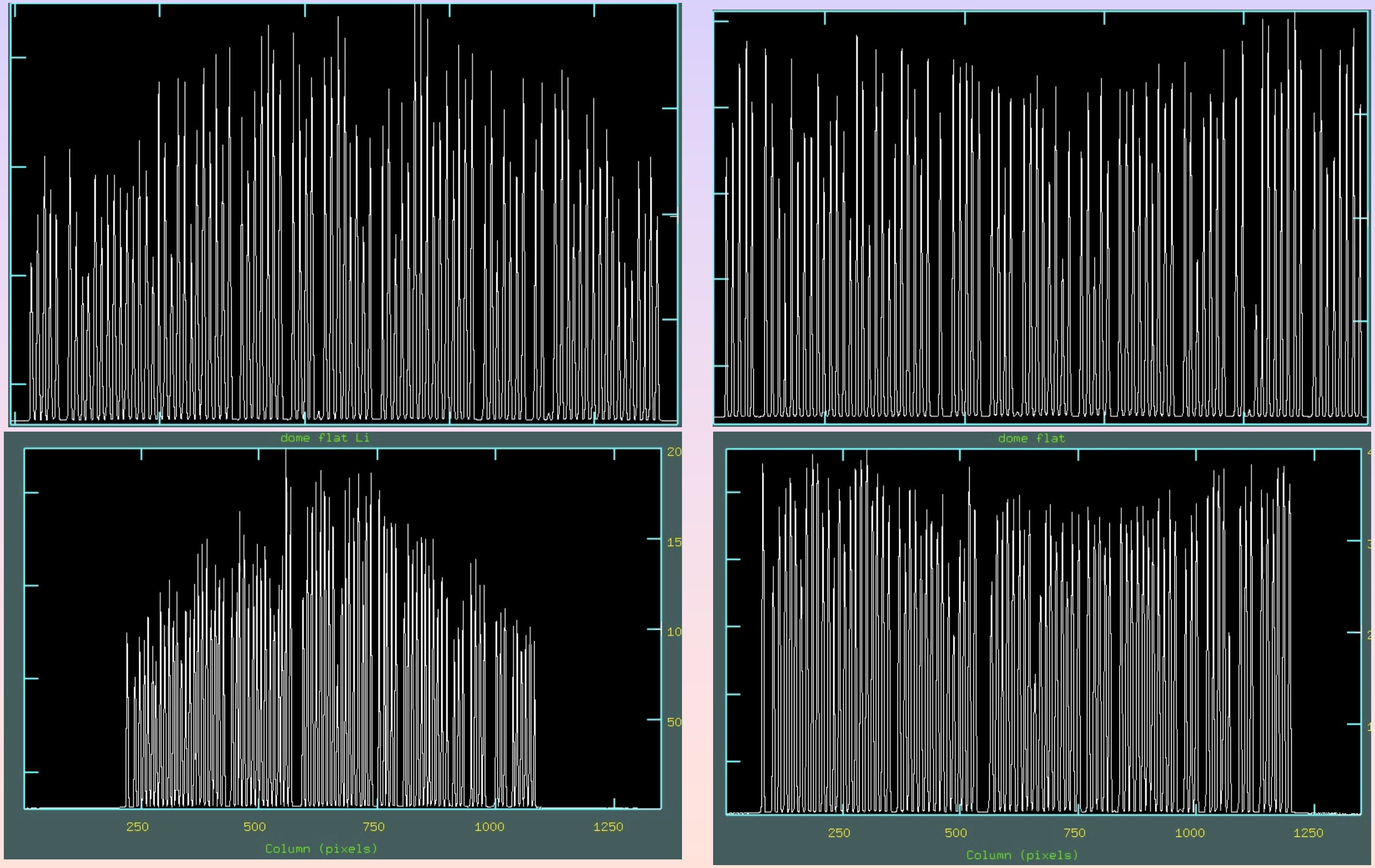
Expected Performanc: ***Achieved***

- Throughput gains: x2-3.5
- Fiber transmission curves + end reflection losses
- BBAR estimates for Sol Gel for refractive collimator
- Collimator glass transmission (LF5
- Fresh Al for the current collimator
- Relative vignetting:
    - + faster collimator
    - + optimized pupil location
    - + removal of fiber foot from beam (9%)
    - + opening of toes to let out f/4 (up to 30%)
- Relative CCD QE:T2KC vs STA
- Assumptions include a camera throughput of 74%, grating + filter throughput of 45% (estimated based on measurements of other components and total system throughput), and 3-mirror telescope efficiency of 69%. No atmosphere is included.



Delivered Performance

One example: field-dependent vignetting is gone



Low-
order
SRg

echelle

old

new