Cosmic Visions:
New Technology Development

Nov 2017 summary

Technology List

- **Proof of principle development of Ground Layer adaptive optics (GLAO) for LSST, DESI, future spectroscopic platforms**
- **Germanium CCDs -- cost-effective extension of wavelength range to 1.35 micron for imaging + spectroscopy**
- **Low-noise readout with Skipper CCDs -- spectroscopy, esp. in low S/N regime**
- **Ring Resonators -- OH line suppression for low-resolution infrared spectroscopy of SNe**
- **Fiber Positioners -- smaller format and/or more cost-effective**

Other discussions

- **Proof of principle for sky-subtraction of faint object spectroscopy**
- **Studies of enhancement of LSST photo-z from cross-correlations**
- **Develop narrow-band imaging for Lyman-alpha emitters for DESI-2 at z=2–3.5**
- **Quantum sensors (Chattopadhya)**

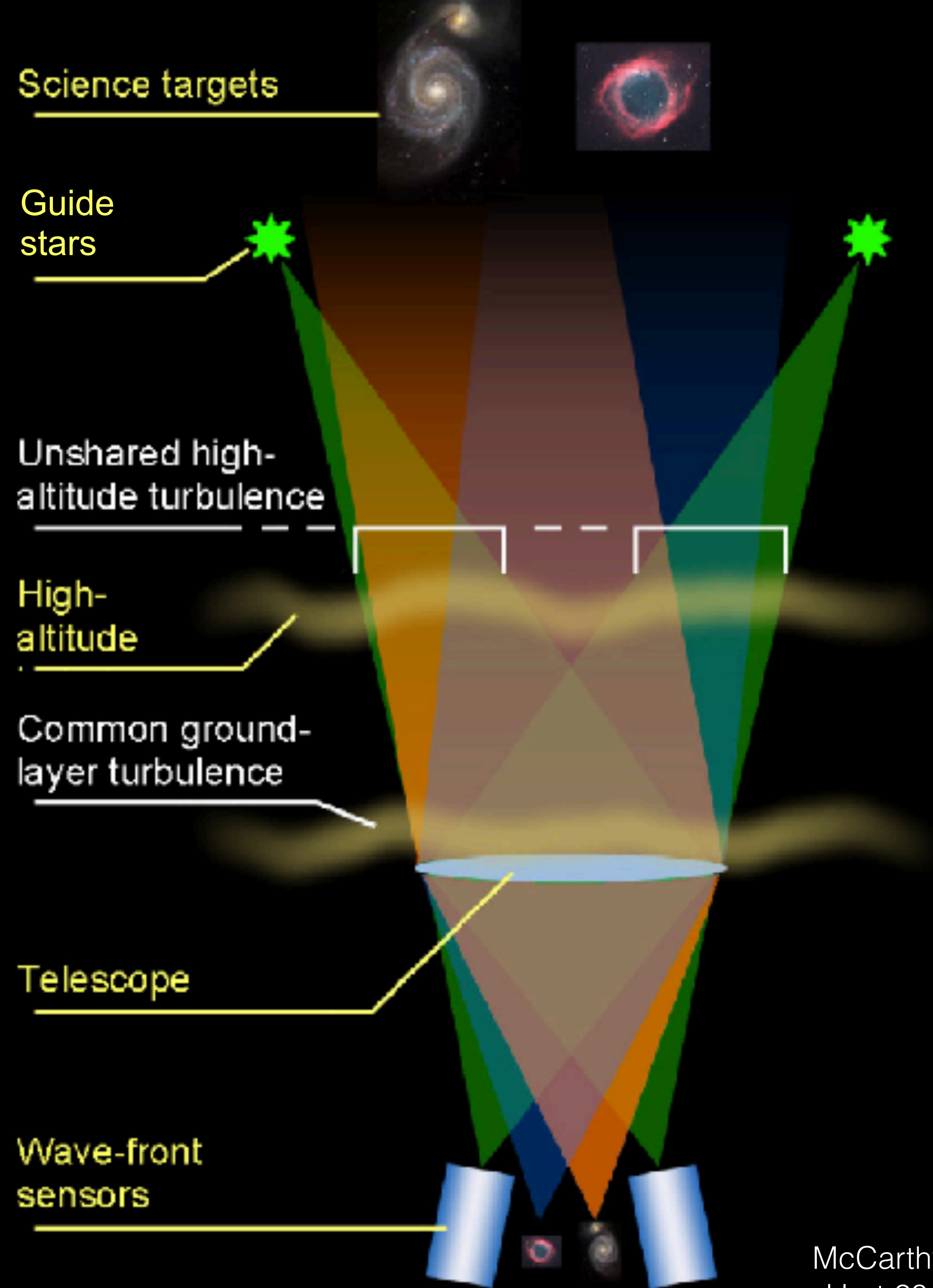
Presentations:
https://indico.hep.anl.gov/indico/conferenceDisplay.py?confId=1267

Google doc notes:
https://docs.google.com/document/d/1UIouMgDaCzTFyYBguC1gUm6-lbJrrCW9Zpsgts67fXg/edit#

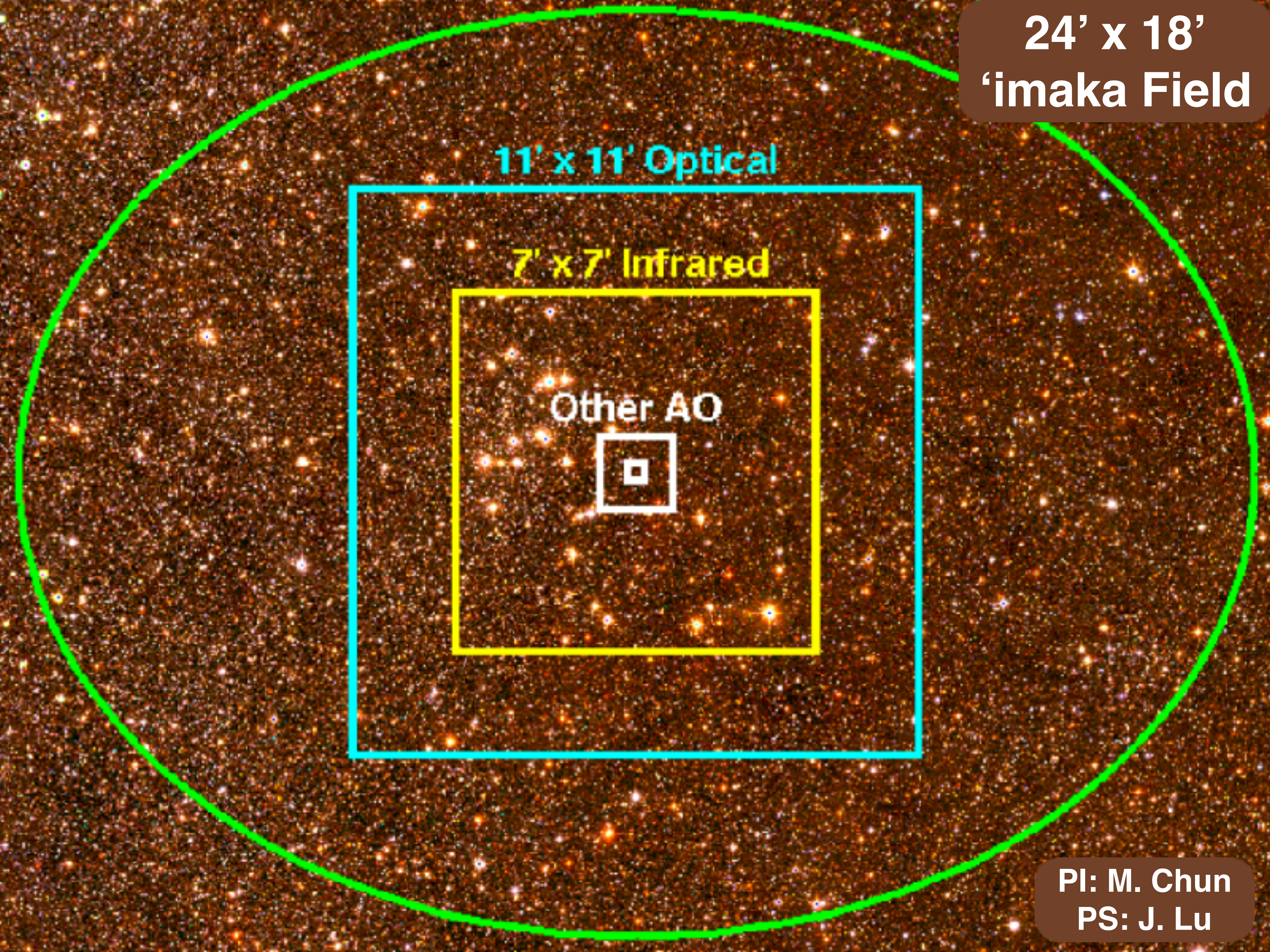
Ground Layer Adaptive Optics

Multiples Guide Stars

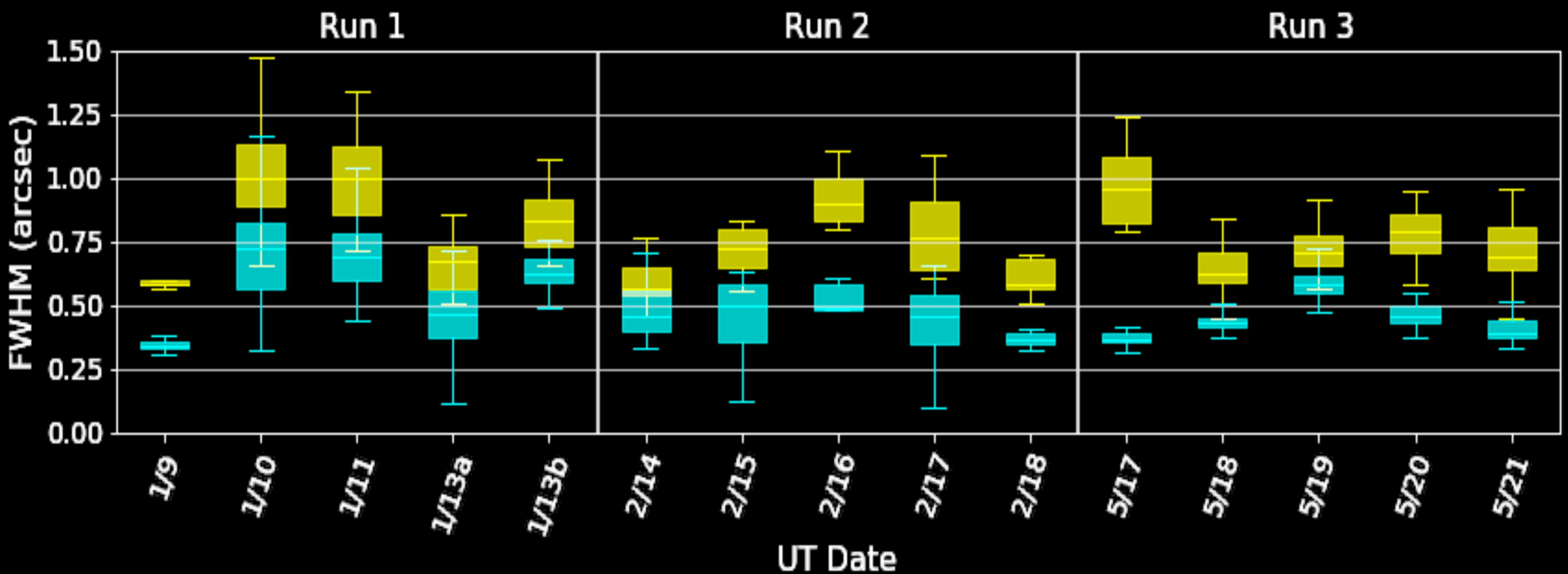
Correct Lowest Turbulence



McCarthy & Hart 2010


24’ x 18’
‘imaka Field
11’ x 11’ Optical
7’ x 7’ Infrared
Other AO
PI: M. Chun
PS: J. Lu

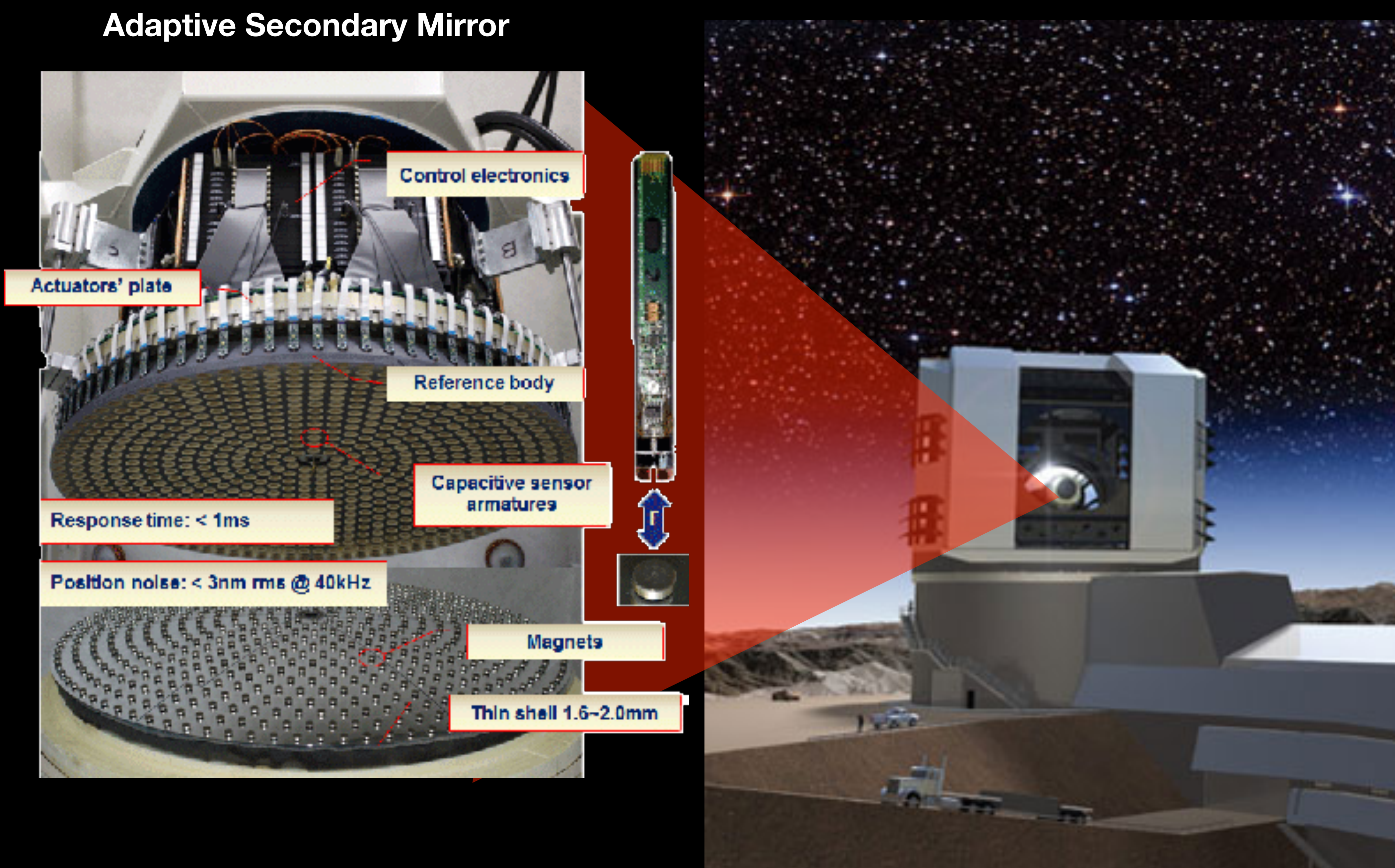
GLAO improves PSF stability for long-duration exposures.



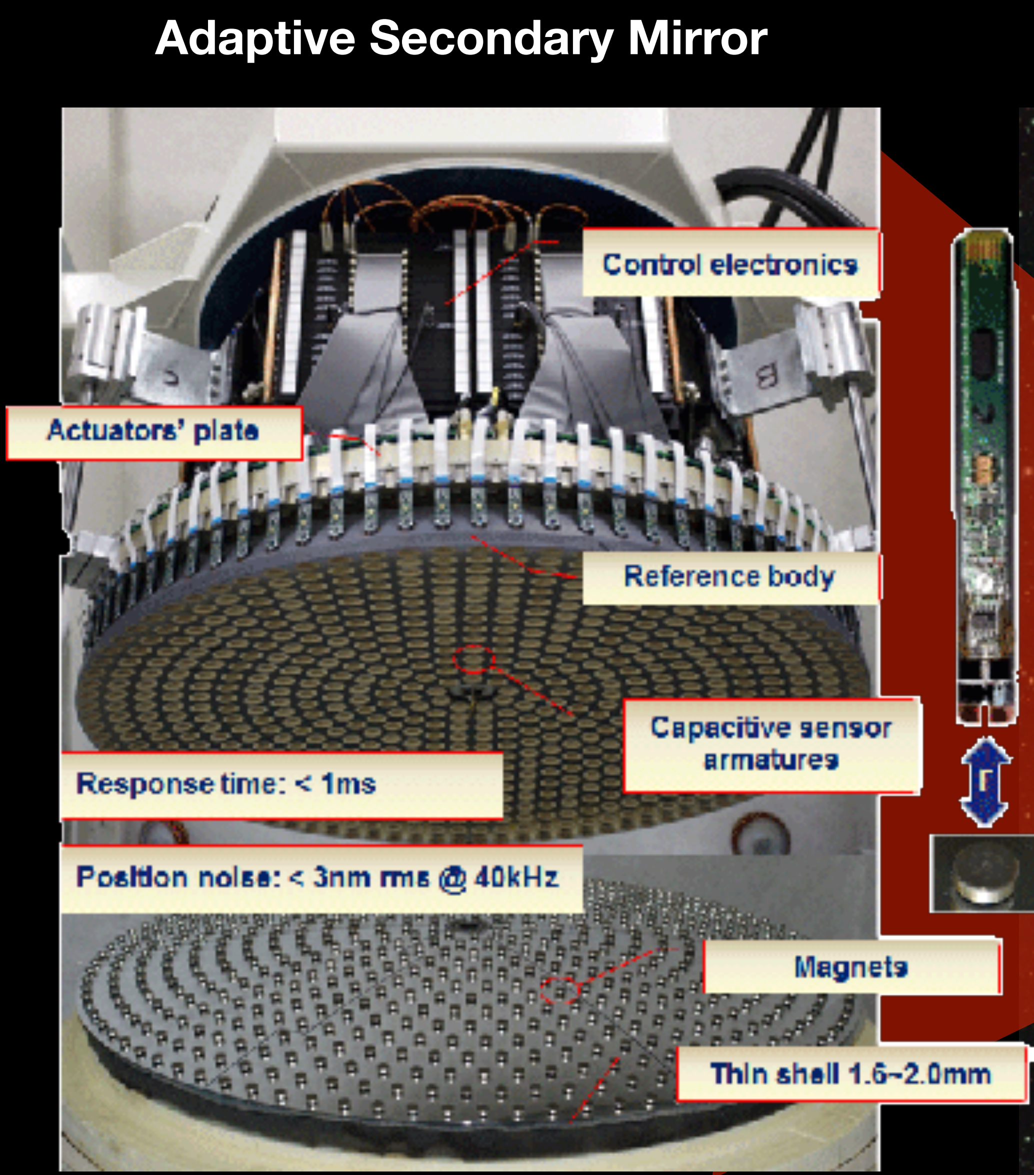
Many different conditions over 15 nights.

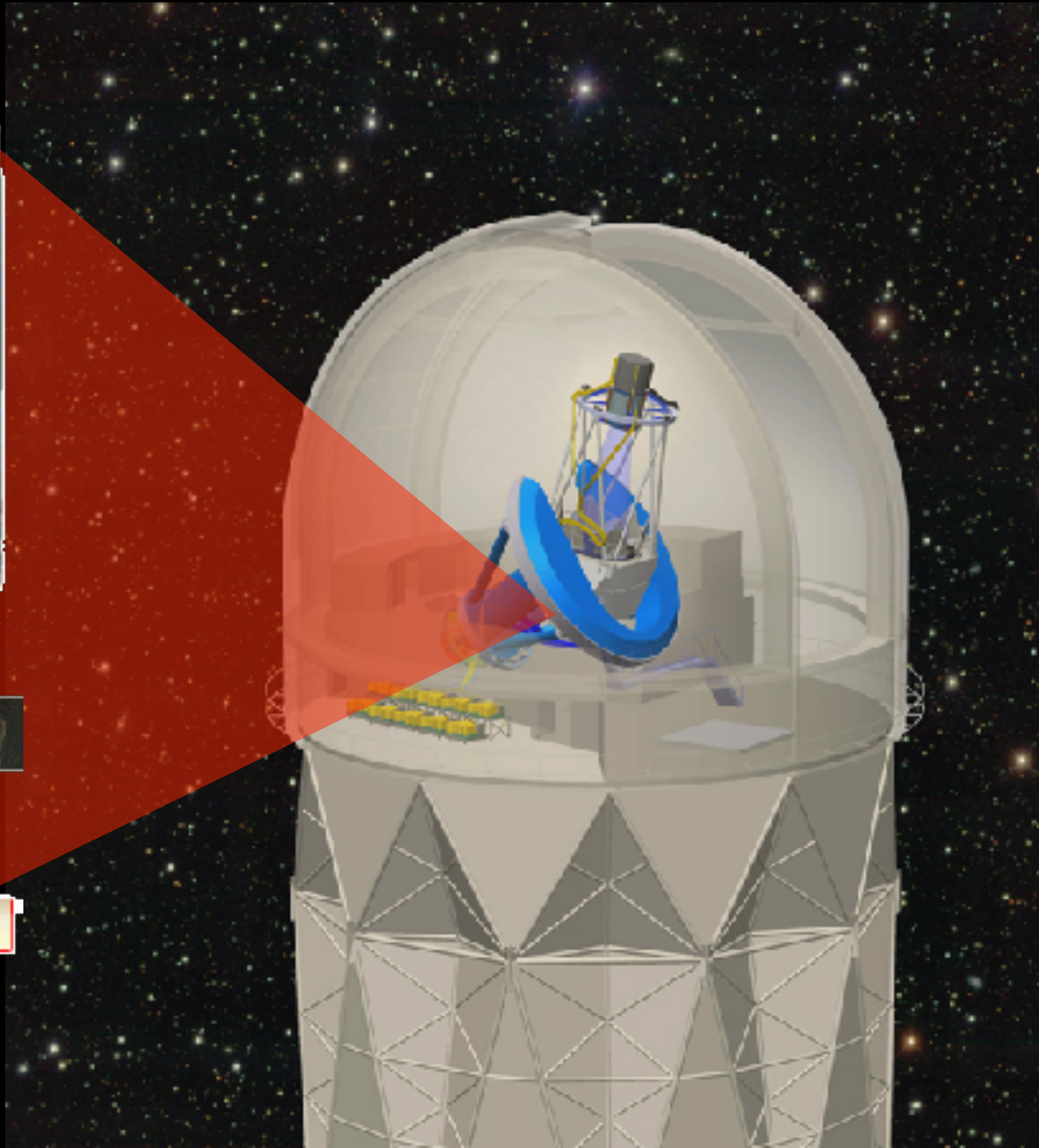
FWHM projected to λ = 500 nm
Observations mostly at R (~650 nm) and I (~800 nm)

GLAO on LSST secondary mirror
– Weak lensing galaxies counts increase as 1/seeing^power

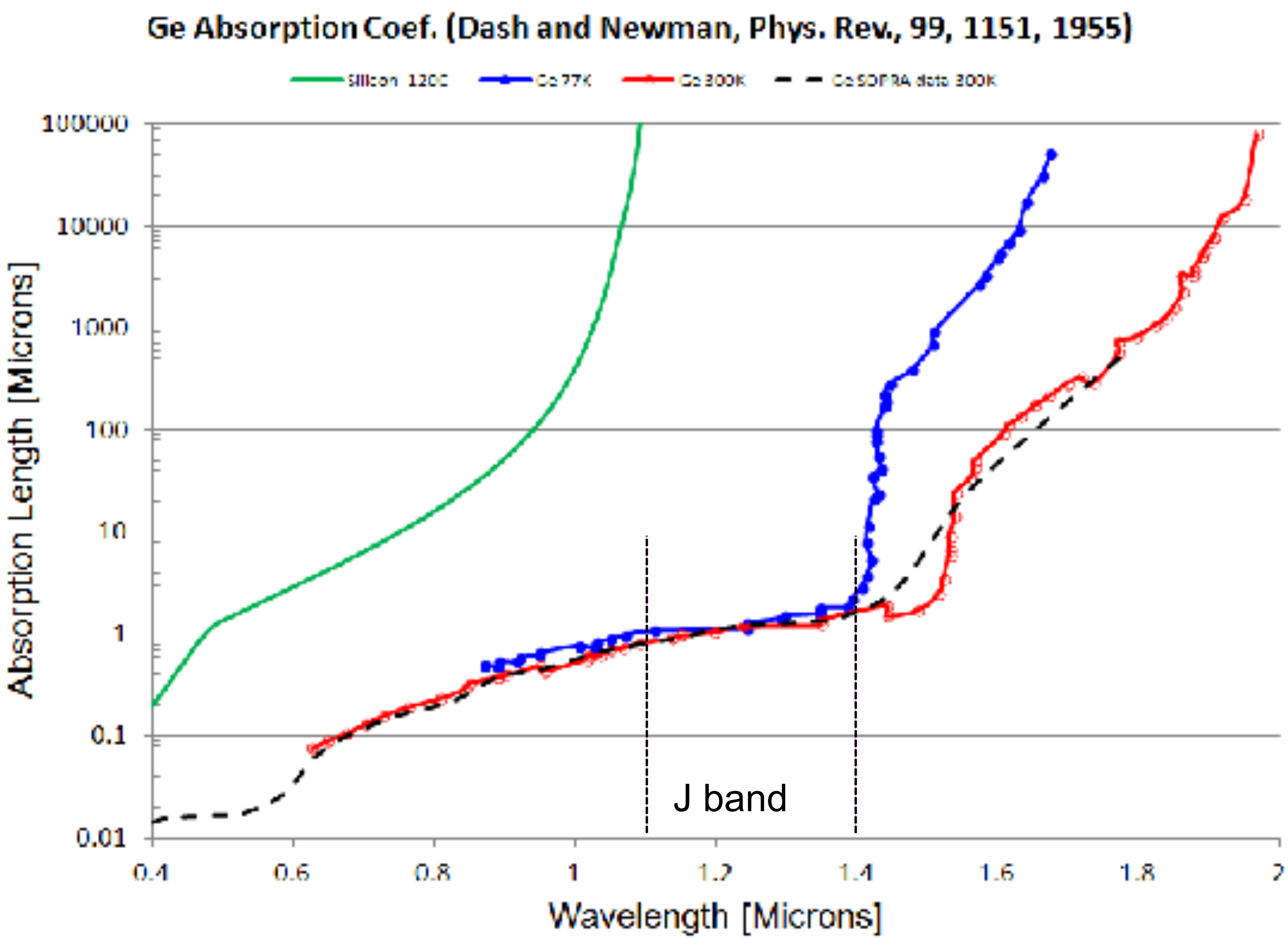


GLAO on DESI primary mirror
– More light in the same fibers –> fainter galaxies + quasars





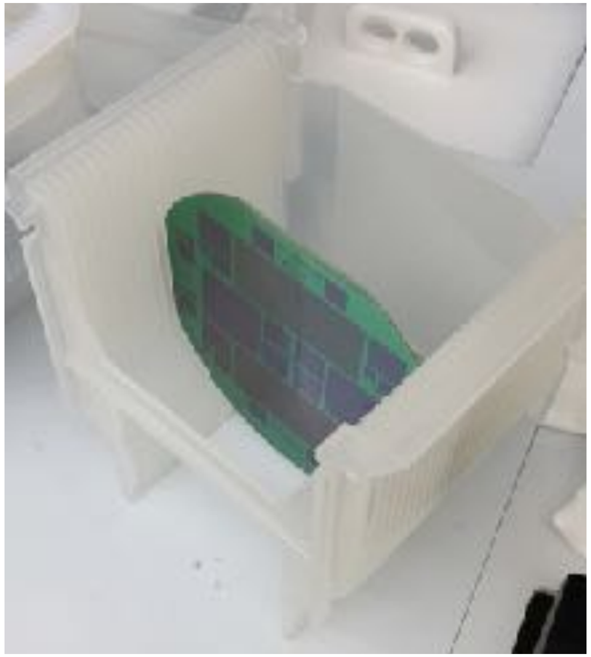
Germanium CCDs / Expected NIR benefits



- Extend near IR response with Ge
- Higher redshifts, e.g. z = 1.6 to 2.6 for DESI [O II] (Si to Ge)
    - 2x volume
- Ge CCD effort underway at Lincoln Laboratory

LBNL LDRD[1] CCD effort

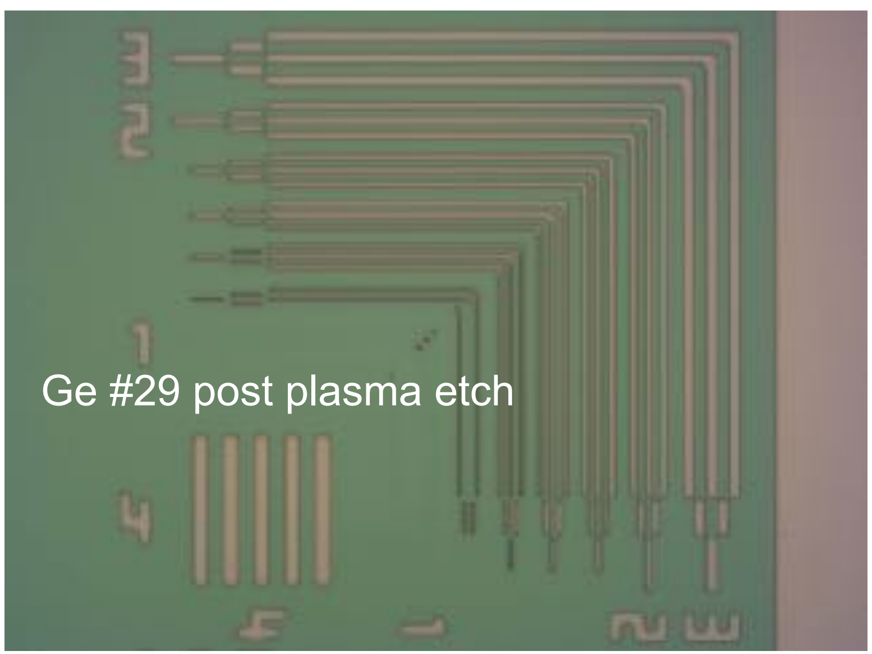
- Develop key components of Ge CCDs
  1) Buried channel MOSFETs on Ge
     » In progress
  2) Ge-compatible gate electrode
     » PolyGe doping vs deposition conditions
     » PolyGe etch development
     » Single versus multi-layer
- High purity Ge
- CCD process integration

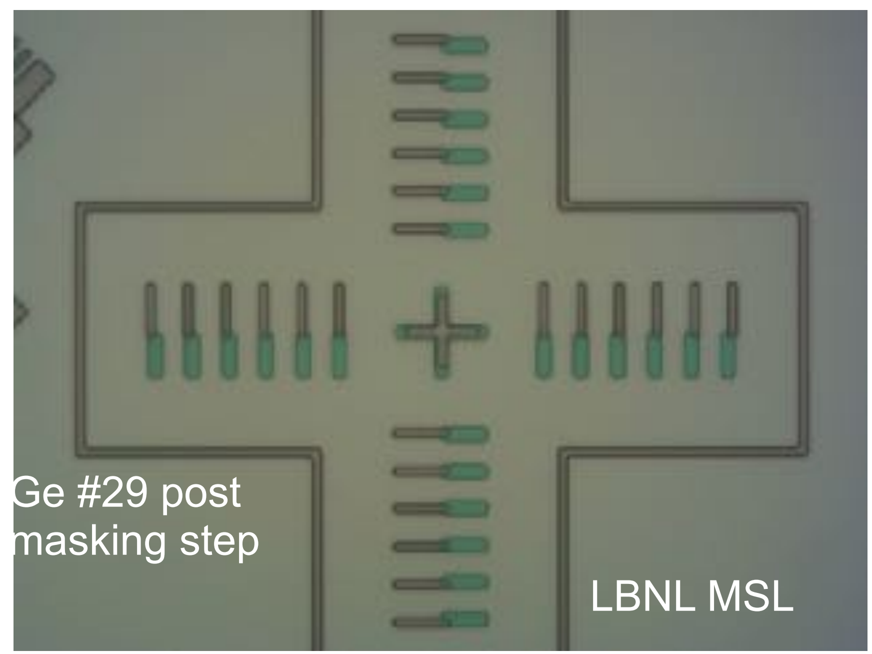


[1]Laboratory Directed R&D (internal LBNL Director's funds from the DOE)

LBNL LDRD[1] CCD effort

- Custom mask set contains many test structures, e.g.
  - » DALSA CCD process control monitors
    - MOS capacitors, contact chains, shorts structures, etc
  - » Structures to extract doping profiles (SRP / SIMS)
  - » In-process aids, e.g. resolution / alignment test structures

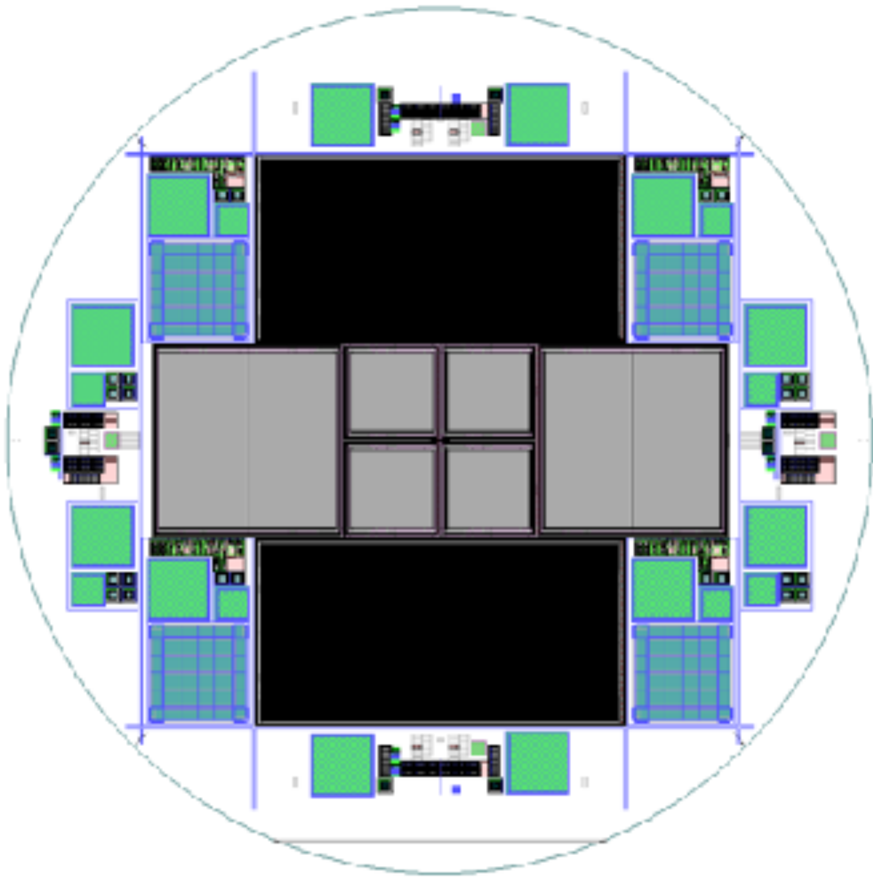




[1]Laboratory Directed R&D (internal LBNL Director's funds from the DOE)

LBNL LDRD[1] CCD effort

- Custom mask set also includes
  - Large format CCDs for yield studies and (hopefully) near-future (at least partially) functioning CCDs

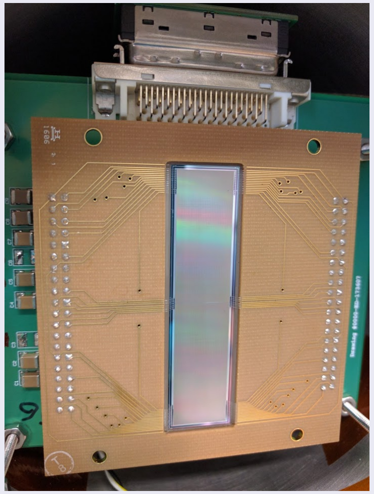


- Large format CCDs allow us to study yield issues early on
- 4k x 2k CCDs for multi-layer polyGe technology development
  - Etching, inter-polyGe isolation
- 2k x 2k and 1k x 1k CCDs compatible with e-beam and deep UV lithography
- All have 4-corner readout and frame-store clocks for partial CCD functionality (¼ serial / vertical short-free near corner)
- Designed for parallel process development

[1]Laboratory Directed R&D (internal LBNL Director's funds from the DOE)

SENSEI: First working instrument using SkipperCCD tech

Sensors



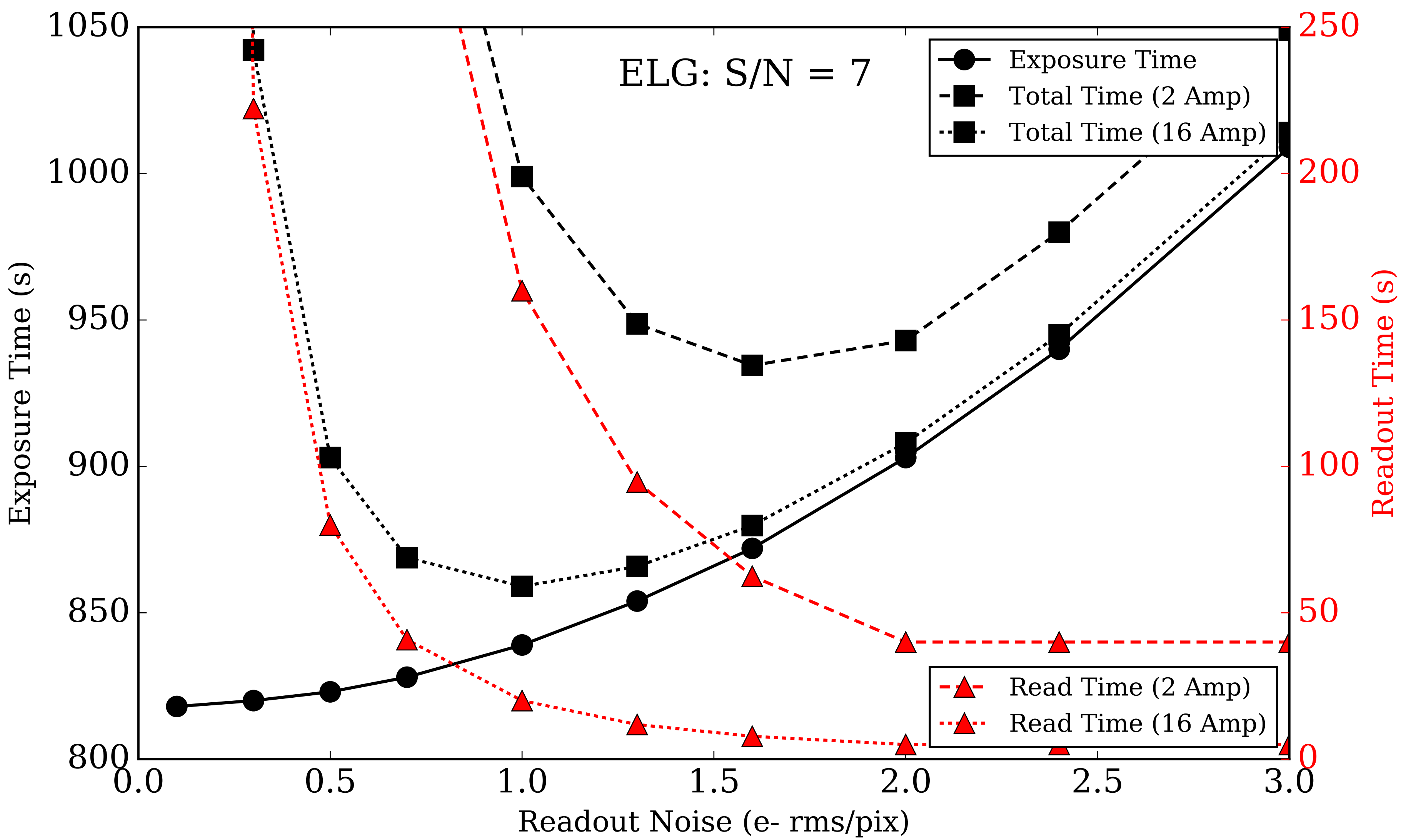
- Skipper-CCD prototype designed by **LBL MSL**
- 200 & 250 μm thick, 15 μm pixel size
- Two form factors 4k$\times$1k (0.5gr) & 1.2k$\times$0.7k pixels
- Parasitic run, optic coating and Si resistivity $\sim$10kΩ
- 4 amplifiers per CCD, three different RO stage designs

Instrument

- System integration done at Fermilab
- Custom cold electronics
- Modified DES electronics for read out
- Firmware and image processing software
- Optimization of operation parameters

DESI Exposure Time

Reduce time for DESI to observe ELGs at fixed $\mathrm{S/N} = 7$
DESI CCDs ($\sim 2\,\mathrm{e}^{-}\ \mathrm{rms/pixel}$) read with 2 amps in 42s
Explore decreased readout time with 16 amps



Reducing Readout Time

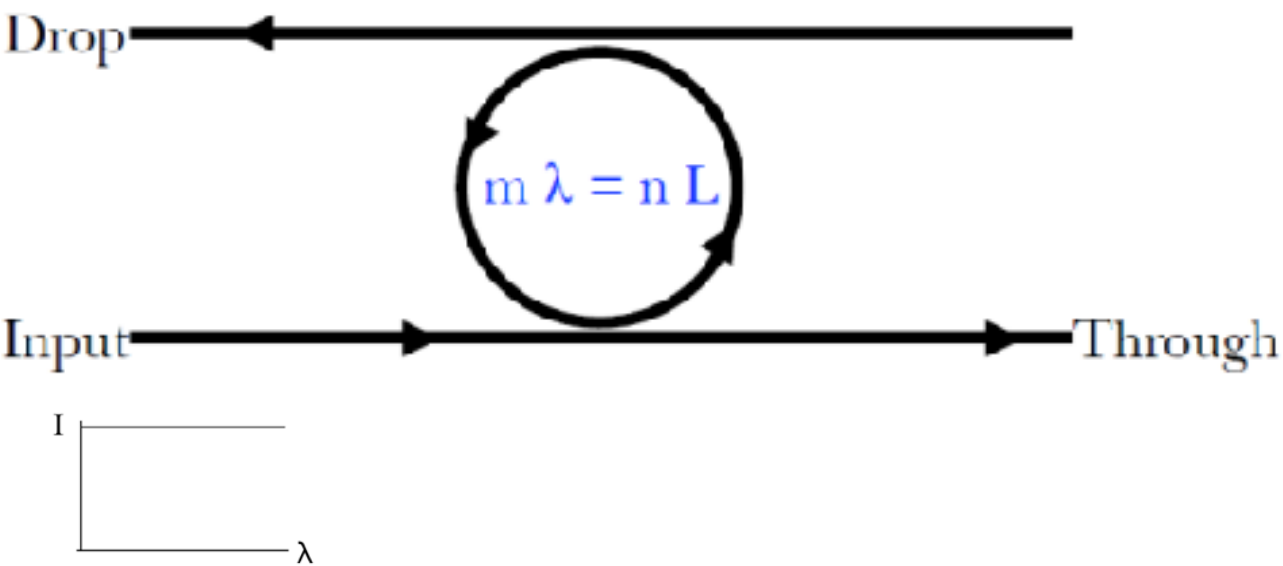
The Problem

- Current generation of Skipper-CCDs have single-read noise of $\sim 3.5\,\mathrm{e^-\,rms/pixel}$ which equates to a readout time:
  $100\,\mu\mathrm{s/\,pixel}$ with $\mathrm{RN} = 1\,\mathrm{e^-\,rms/pixel}$
  $10\,\mathrm{ms/\,pixel}$ with $\mathrm{RN} = 0.1\,\mathrm{e^-\,rms/pixel}$
- For a large format detector (2048×4096) with 4 amplifiers, this is 200 s and 2×10^4 s, respectively.

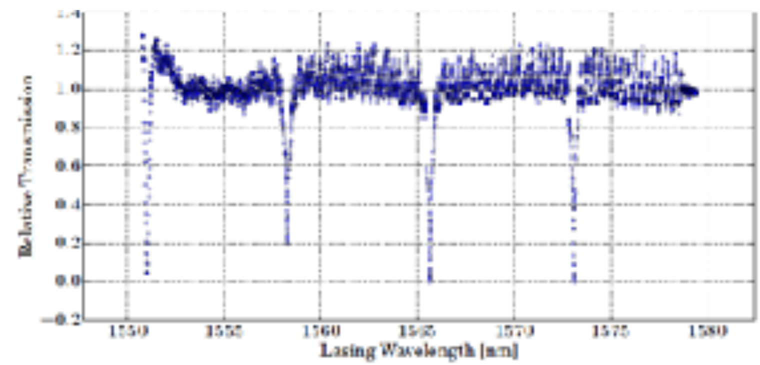
Paths for Development

- Reduce starting readout noise (DESI CCDs have $\sim 2\,\mathrm{e^-\,rms/pixel}$)
- Repeated readout for only a subset of pixels (known line position)
- Increase the number of readout channels/amplifiers (≥ 16 amps?)
- Use frame shifting to readout during subsequent exposure

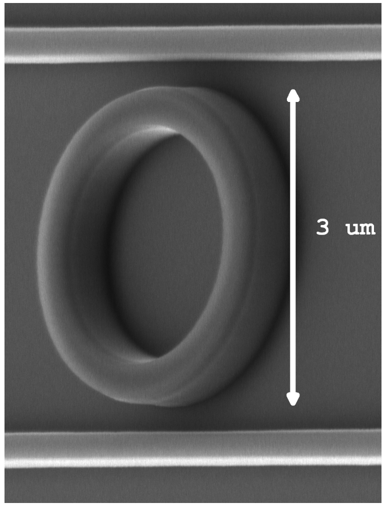
How Do Ring Resonators Work?



25μm single SiN ring with different modes (7nm gaps)



Silicon ring and waveguides fabricated at Argonne

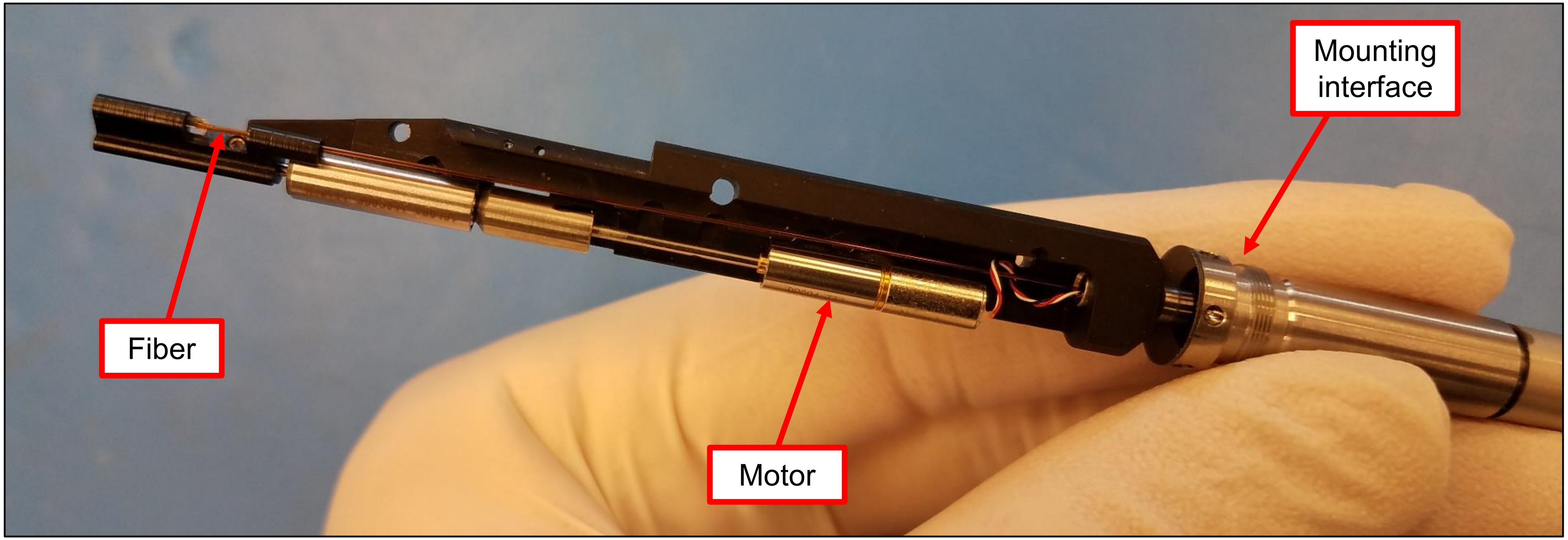


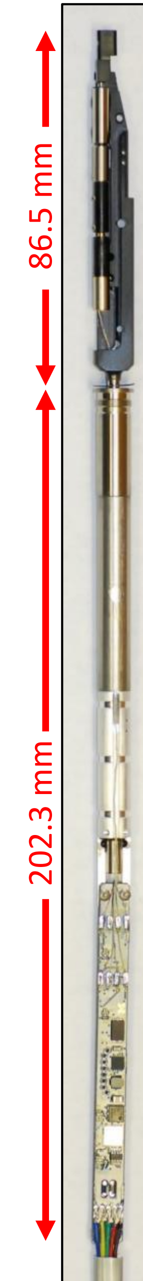
SEM image

Free Spectral Range (gap between modes):

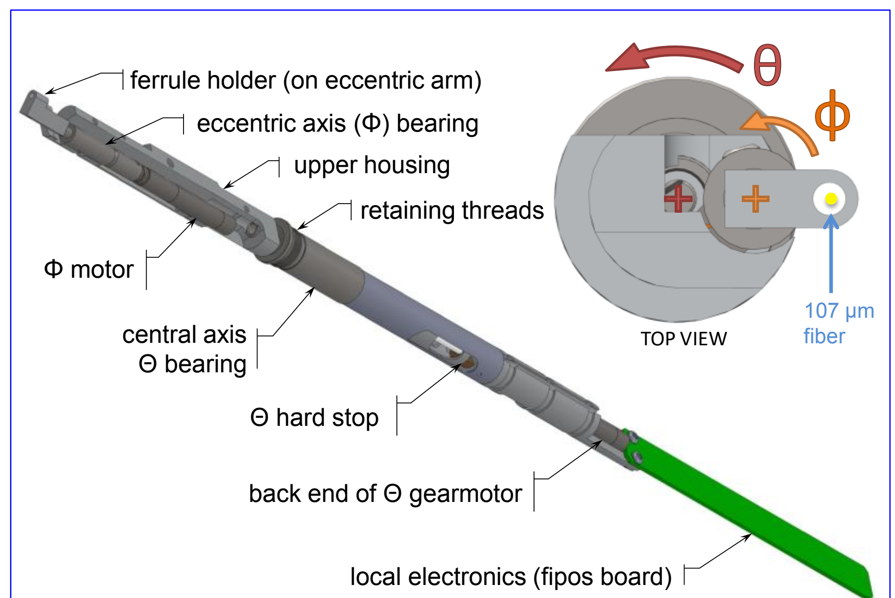
$$FSR_{\lambda_m} = \lambda_{m+1} - \lambda_m$$

DESI Fiber Positioners





- 10.4 mm pitch between neighboring units
- 2 rotational axes
- Driven by independent ø4 mm 337:1 gear motors
- Integrated drive electronics
- 20 parts + 10 fasteners
- Developed by Berkeley
- Production by University of Michigan
- Blind moves: 25-50 μm max error
- After correction move: 1-2 μm RMS error
- Tested to 600,000+ repositionings (and counting...)
- Have produced over 1000 units (and counting...)



Scaling of focal plane

- On DESI, we packed 5000 positioners at mean pitch of 10.525 mm into a ø812 mm aspheric focal surface
- Rough rule of thumb you could extract from the final DESI design:
  - ultimate # of science positioners = **0.84***(FP_diam / pitch)²
  - this 84% packing efficiency is obviously not some perfectly efficient HCP = 90.7%
  - instead it is a very real-world and practical number, that includes room for 100 fiducials, 10 guide/focus cameras, mechanical tolerances, aspherical geometry, mounting features, etc
- So if you wanted 25,000 positioners at say 11 mm pitch, you would need a focal surface that is ø1.9 m
- My personal intuition is that the right approach to scaling up in a next generation project is
  - don't try to squeeze positioners any smaller
  - instead focus on enabling a bigger ø focal surface
  - this focuses the "new technology" effort on what I consider the easy and monolithic stuff – a few ray traces done early on in the project
  - our DESI positioners work great and we truly now can manufacture 5000 of them in about 10 months – but it took 7 years and millions of $ to get to this point!

Focal plane layout summary

Patterning code and results files	-	https://desi.lbl.gov/svn/code/focalplane/	
Results files from patterning	-	https://desi.lbl.gov/svn/code/focalplane/	
Corrector Prescription	-	per DESI-0329-v15	
FOV	deg	3.2	
Focal Surface Diameter	mm	811.8	3.2deg FOV equivalent
Positioner Envelope	-	per DESI-595-v4	positioner envelope based
Patrol Radius	mm	6.0	
Area	deg²	8.042	
petals	-	10	
positioners	-	5000	
GFAs	-	10	
field fiducials (FIF)	-	100	
GFA fiducials (GIF)	-	20	
min pitch	mm	10.416	Note these tabulations of
max pitch	mm	15.605	
mean pitch	mm	10.525	
stdev pitch	mm	0.469	
mean uncovered area	-	0.067	Note these tabulations of
mean coverage density	-	1.103	value > 1 implies net over
positioner and fiducial coverage area	deg²	7.504	
positioner coverage density	1/deg²	666.3	i.e. positioners / deg²

DESI-0530 gives all the details, as well as summaries, of the DESI focal plane layout

Technology List

- **Proof of principle development of Ground Layer adaptive optics (GLAO) for LSST, DESI, future spectroscopic platforms**
  - **Jessica Lu demonstrating on ~1 deg field**
  - **opportunity for replacement of LSST secondary mirror (3.5-m)**
  - **opportunity for replacement of DESI primary mirror (3.8-m)**
  - **site testing may show different improvements at different sites**
  - **expensive item are voice-coil active mirrors, single vendor**
- **Germanium CCDs**
  - **cost-effective extension of wavelength range to 1.35 micron for imaging + spectroscopy**
  - **LDRD-supported in 2018-2019, SBIR-supported for high-purity Ge wafers**
- **Low-noise readout with Skipper CCDs**
  - spectroscopy, esp. in low S/N regime
- **Ring Resonators**
  - OH line suppression for low-resolution infrared spectroscopy of SNe
- **Fiber Positioners**
  - **smaller format either with DESI design or tilting spines**
  - **more cost-effective**
  - **injection-molding, …?**