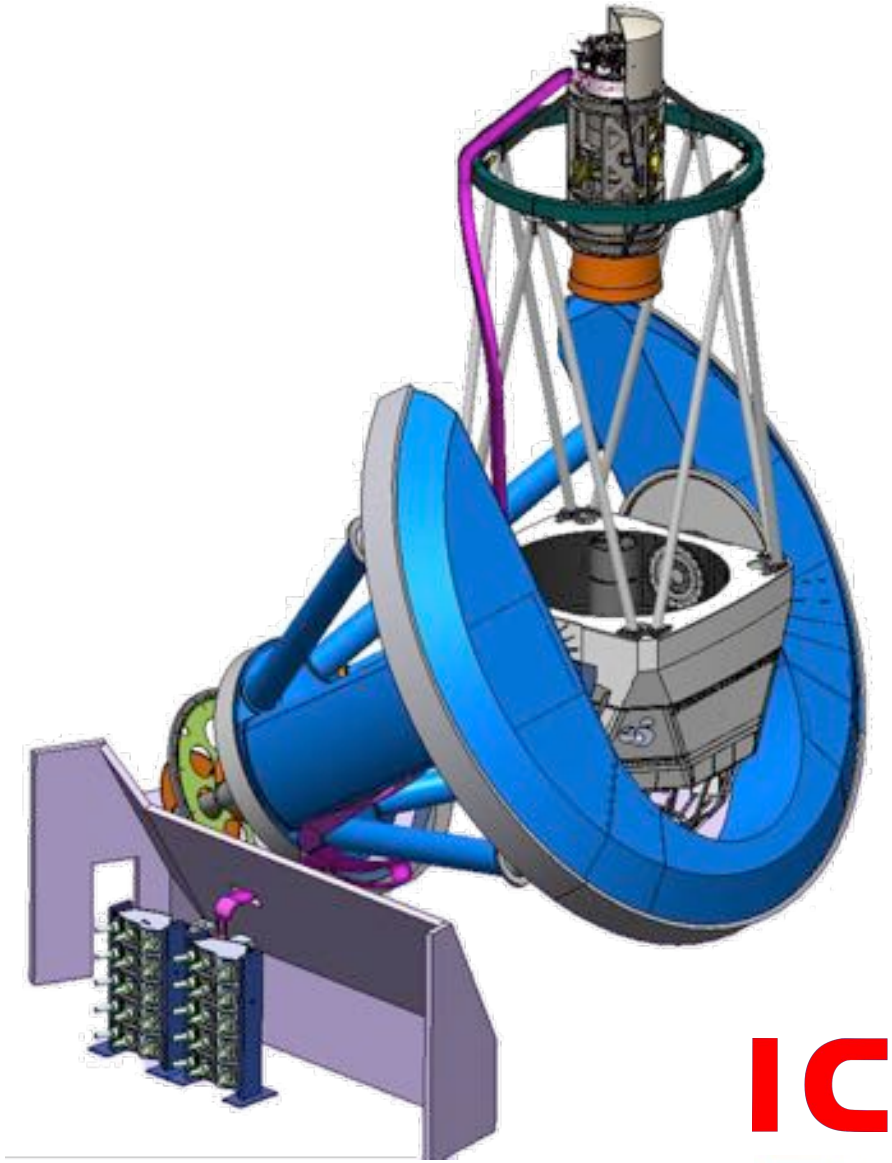


DESI

Dark Energy Spectroscopic Instrument

Francisco Javier Castander

and the Barcelona-Madrid Regional Participation Group

on behalf of the DESI collaboration

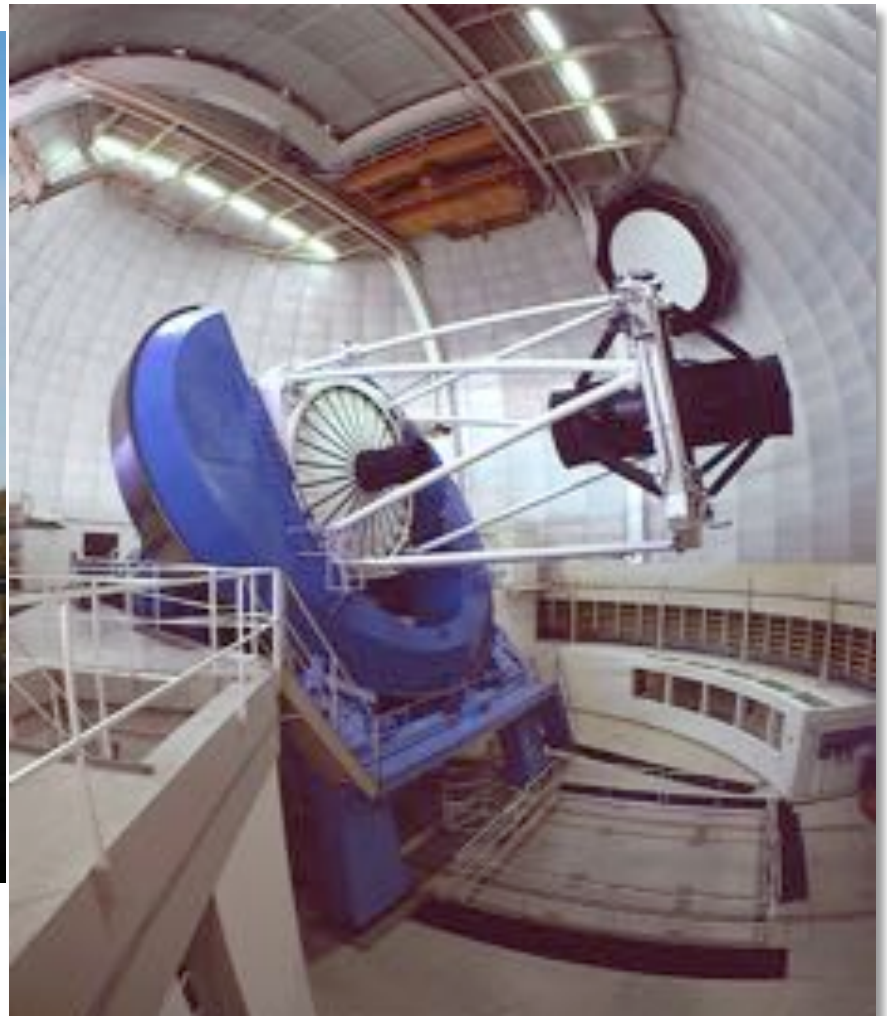
ICE IEEC IFAE Institut de Física d'Altes Energies

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

ift Instituto de Física Teórica UAM/CSIC

DESI Concept

- DESI is the Dark Energy Spectroscopic Instrument
- A new multi-fibre spectrograph
- DESI will be installed at the Mayall Telescope on Kitt Peak, AZ
- Kitt Peak is operated by NOAO for the NSF



DESI Concept

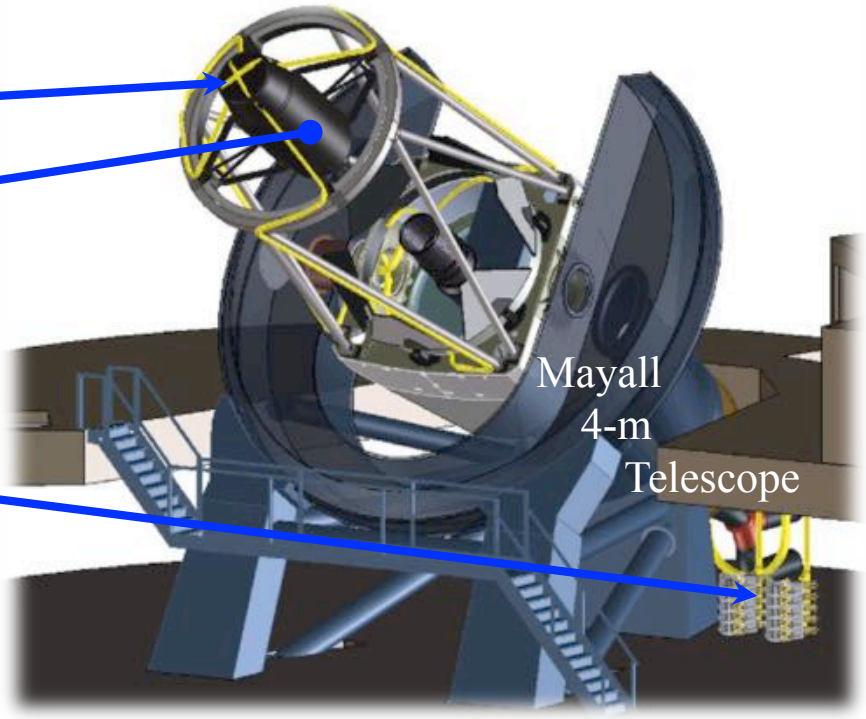
- Scale up BOSS to a massively parallel fiber-fed spectrometer with 5x more fibers, larger telescope aperture, robotic fiber positioners
- Stage-IV BAO over a broad redshift range: $z < 3.5$
- Sky area: 14,000 square degrees
- Number of galaxy redshifts: 30 million
- Medium resolution spectroscopy, R ~ up to 5500

Three main hardware components:

5000 fiber actuators

New 8 deg^2 field-of-view corrector
DES heritage

10 New spectrographs
BOSS heritage

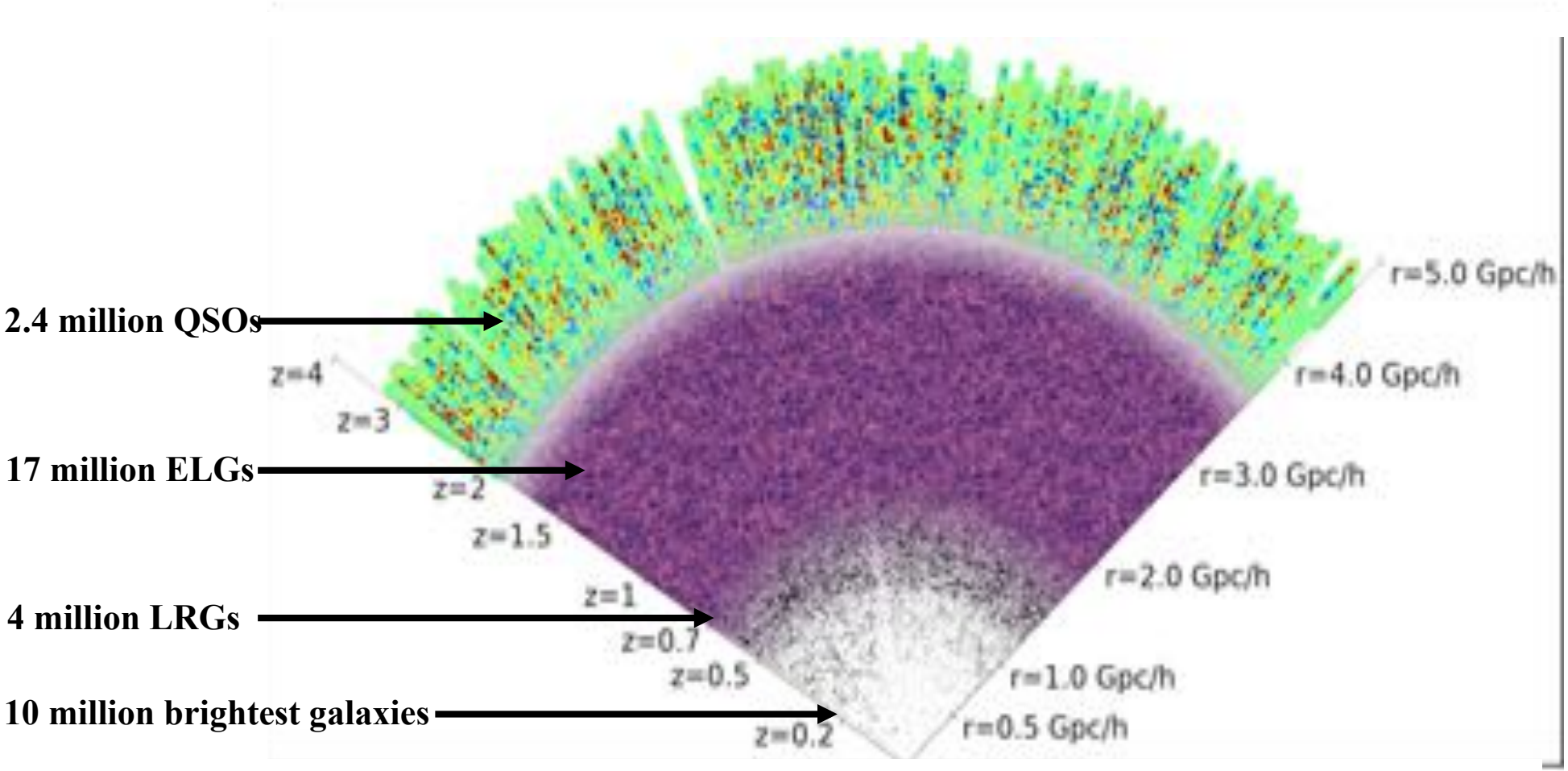


DESI Science Objectives

- **Is cosmic expansion accelerating because of a breakdown of General Relativity (GR) on cosmological scales or because of a new energy component that exerts repulsive gravity within GR?**
- **If the latter, is it consistent with a cosmological constant or does it evolve in time?**
- **Any answers to this will point to new physics!**
- **Measure the expansion rate of the Universe**
  - **The distance-redshift relation $D_A(z)$**
  - **Directly measure H(z)**
- **Measure the rate at which structures grow in the Universe**
  - **Growth function and its derivatives**
- **DESI will do both in one survey**

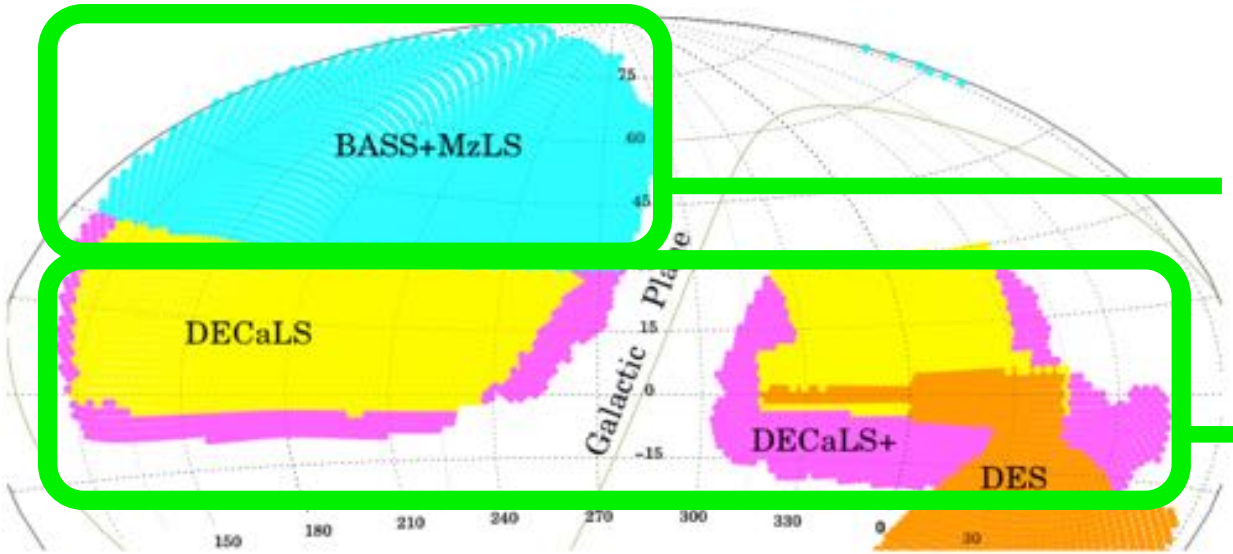
DESI survey

Five target classes spanning redshifts z=0 ➔ 3.5.
~34 million redshifts over 14,000 sq. degrees (baseline survey).



DESI Survey Area & Imaging

- 14,000 sq. degree footprint defined by low Galactic and atmospheric extinction
- DESI targeting requires new imaging over this area



"North cap":

Accessible from Northern telescopes only

Bok (gr) + Mayall (z)

"Equatorial":

Accessible from Northern or Southern telescopes

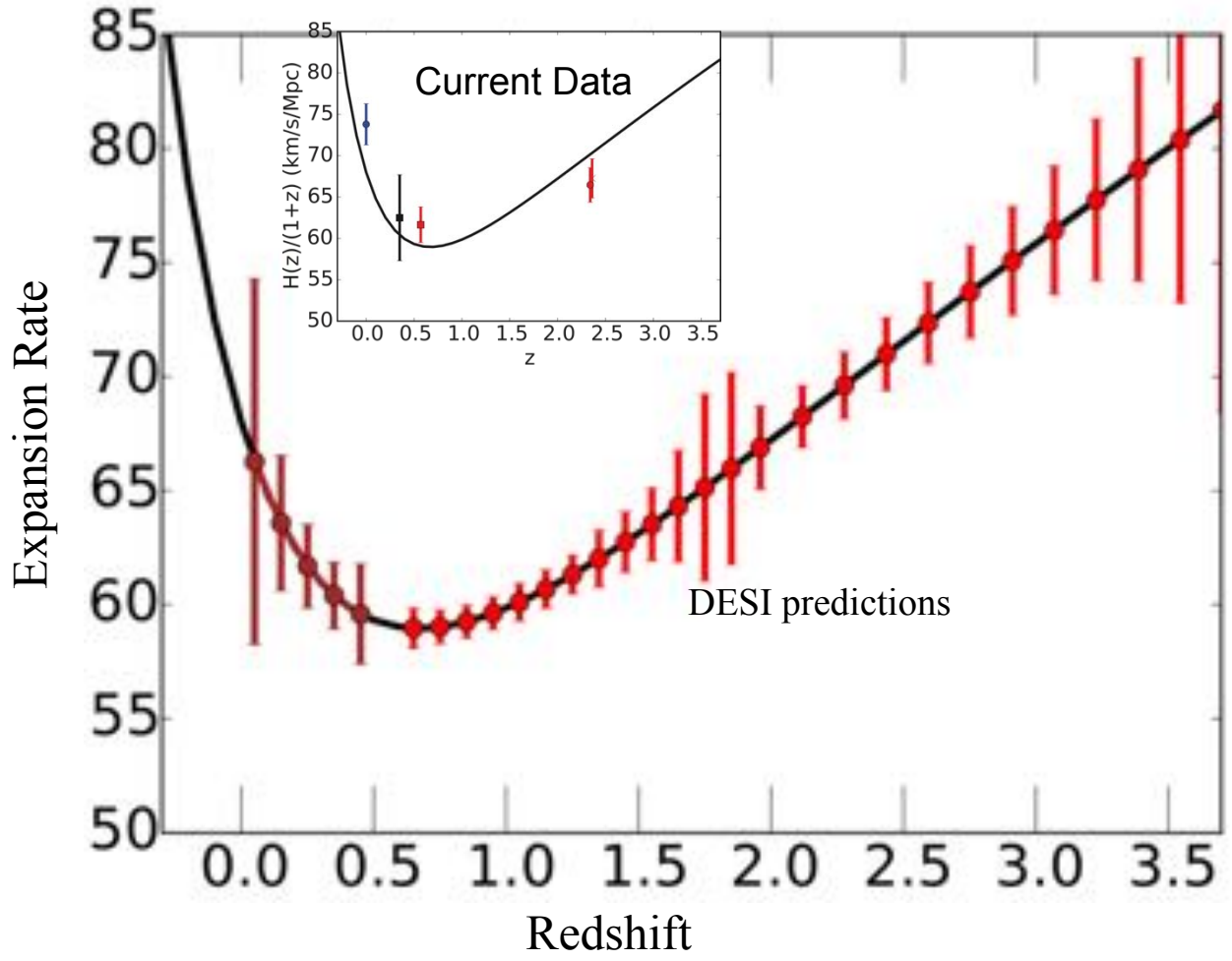
DECam, including DECALS project started August 2014, first data release of ~800 sq. deg. May 2015

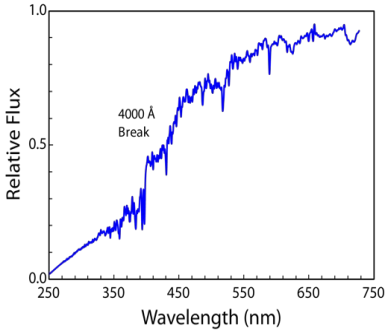
- **Combined imaging: g=24.0, r=23.6, z=23.0**

  (compare to SDSS g=22.2, r=22.2, z=20.5)

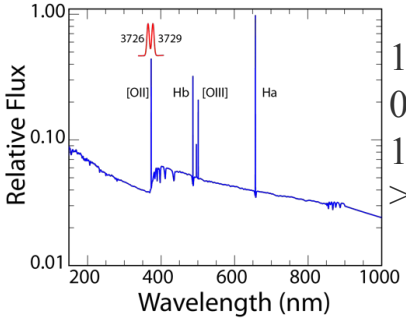
DESI Hubble Diagram

Target type	z range	Target density deg^{-2}	Good z density deg^{-2}	Δz/(1+z) precision	Δz/(1+z) systematic	Bad z assignment	Complete-ness
LRG	0.4–1.0	350	300	0.0005	0.0002	< 5%	> 95%
ELG	0.6–1.6	2400	1280	0.0005	0.0002	< 5%	> 90%
QSO	< 2.1	170	120	0.0025	0.0004	< 5%	> 90%
Ly-α	> 2.1	90	50	0.0025	-	< 2%	> 72%

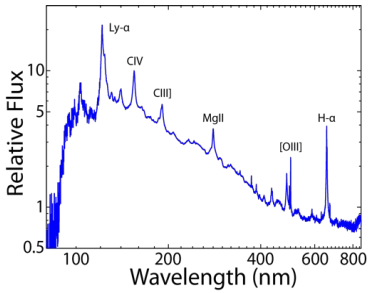




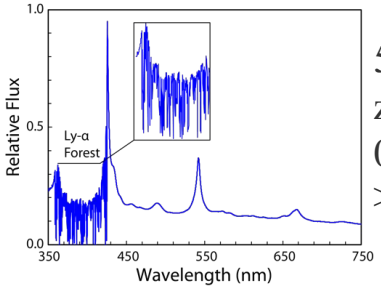
300/sq. degree
0.4 < z < 1.0
4.2 M
>95% completeness



1280/sq. degree
0.6 < z < 1.6
17.9 M
>90% completeness

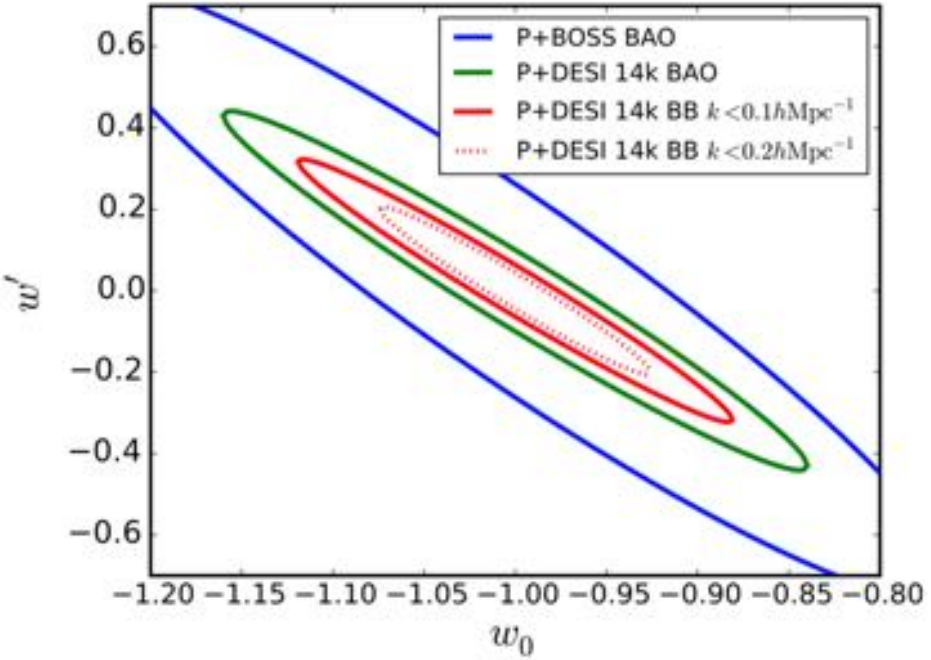


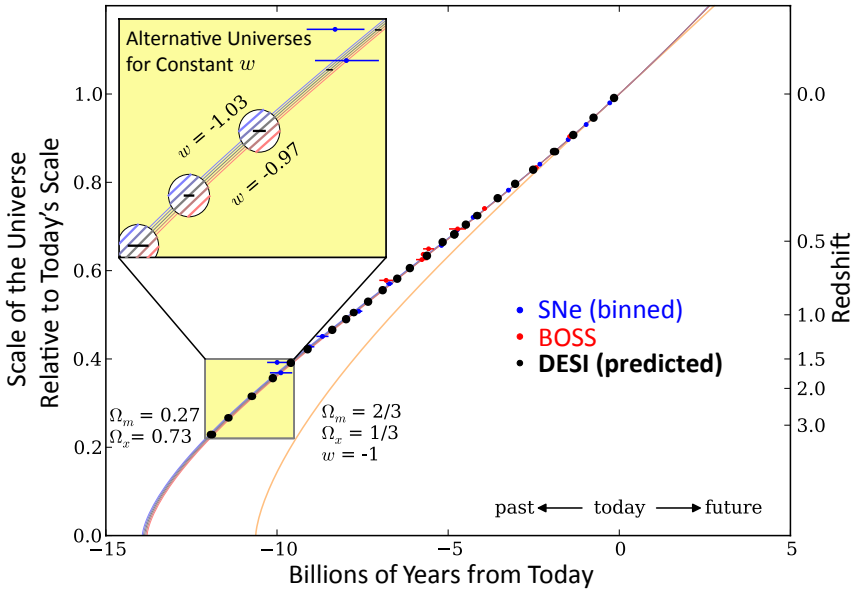
120/sq. degree
0.9 < z < 2.1
1.7 M
>90% completeness



50/sq. degree
z > 2.1
0.7 M
>70% completeness

DESI is a Stage IV DE Experiment



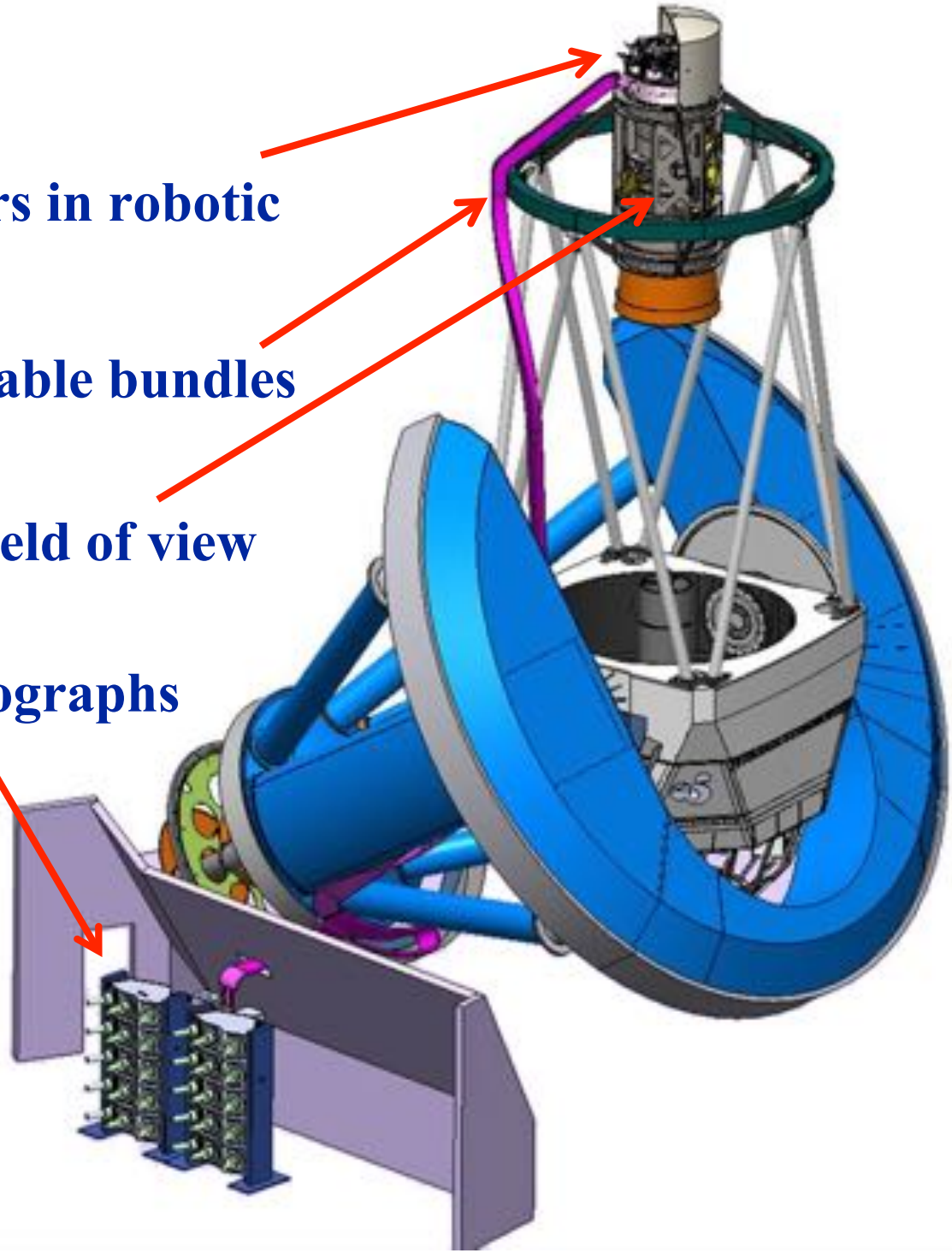


- **BAO FOM for baseline survey = 143**
- **Significant improvement when adding additional information from DESI and when adding external constraints**
- **DESI will discriminate DE models**

Surveys	FoM	a_p	σ_{w_p}	σ_{Ω_k}
BOSS BAO	37	0.65	0.055	0.0026
DESI 14k galaxy BAO	112	0.72	0.025	0.0013
DESI 14k galaxy and Ly-α forest BAO	143	0.74	0.024	0.0011
DESI 14k BAO + gal. broadband to $k < 0.1\ h\ Mpc^{-1}$	303	0.75	0.016	0.0009
DESI 14k BAO + gal. broadband to $k < 0.2\ h\ Mpc^{-1}$	687	0.74	0.011	0.0007

DESI

- 5000 fibers in robotic actuators
- 10 fiber cable bundles
- 3.2 deg. field of view optics
- 10 spectrographs



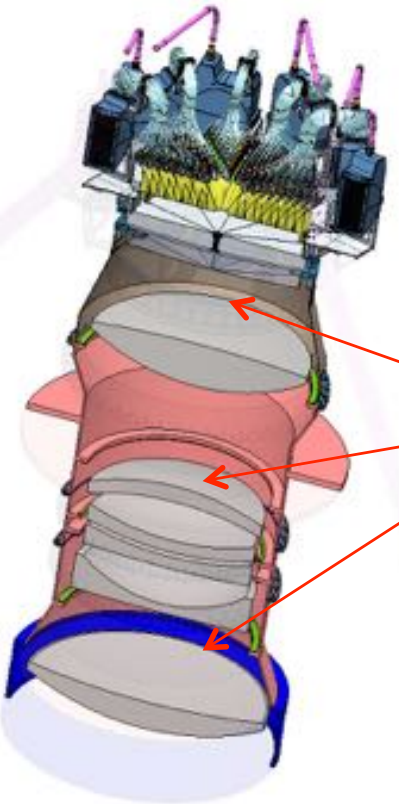
Mayall 4m Telescope
Kitt Peak
Tucson, AZ

Readout & Control

DESI Instrument

The DESI project will build:

- A new instrument to study dark energy
- **To be installed and commissioned on the Mayall Telescope**
- **A** new corrector for the telescope (creating an **8 deg^2 FOV**)



Corrector
Heritage: DECam

6 Lenses

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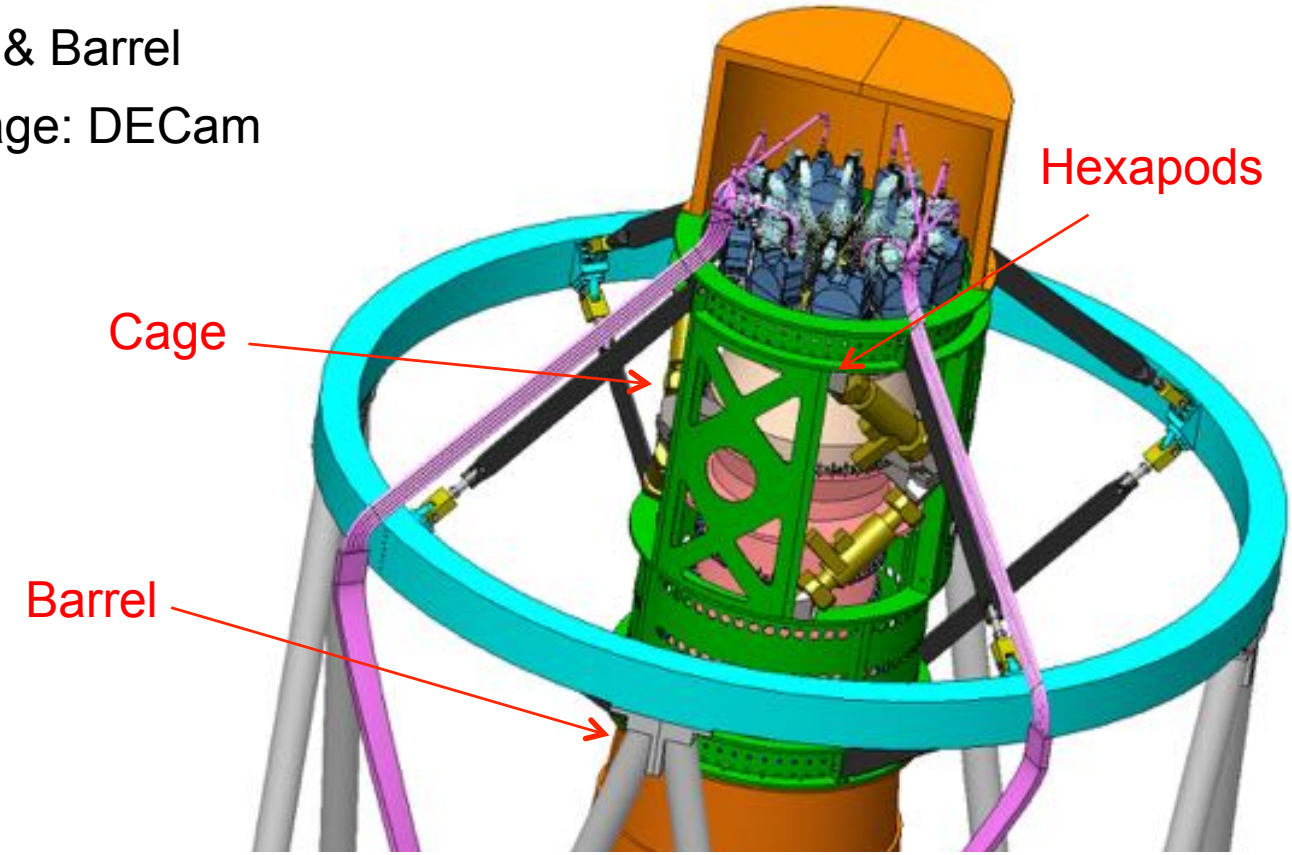
- A new top ring and cage, barrel and hexapod assembly

Cage & Barrel

Heritage: DECam



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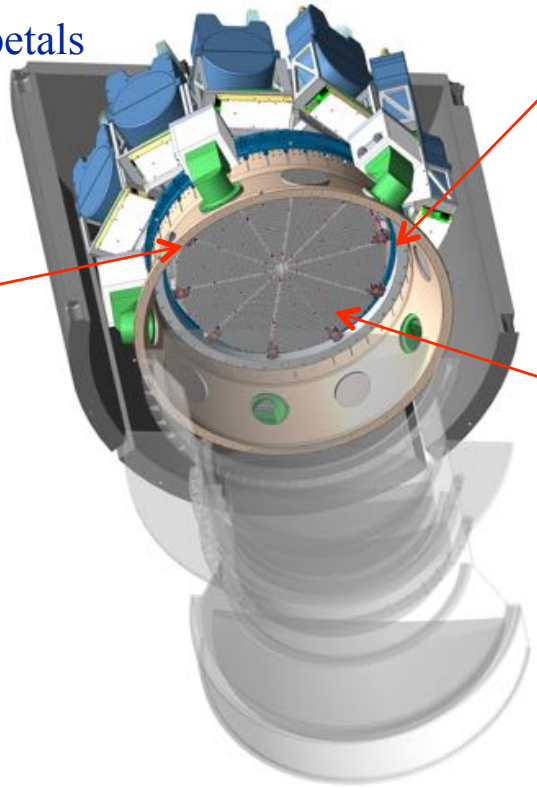
- A focal plane with 5000 fiber positioner robots in 10 petals



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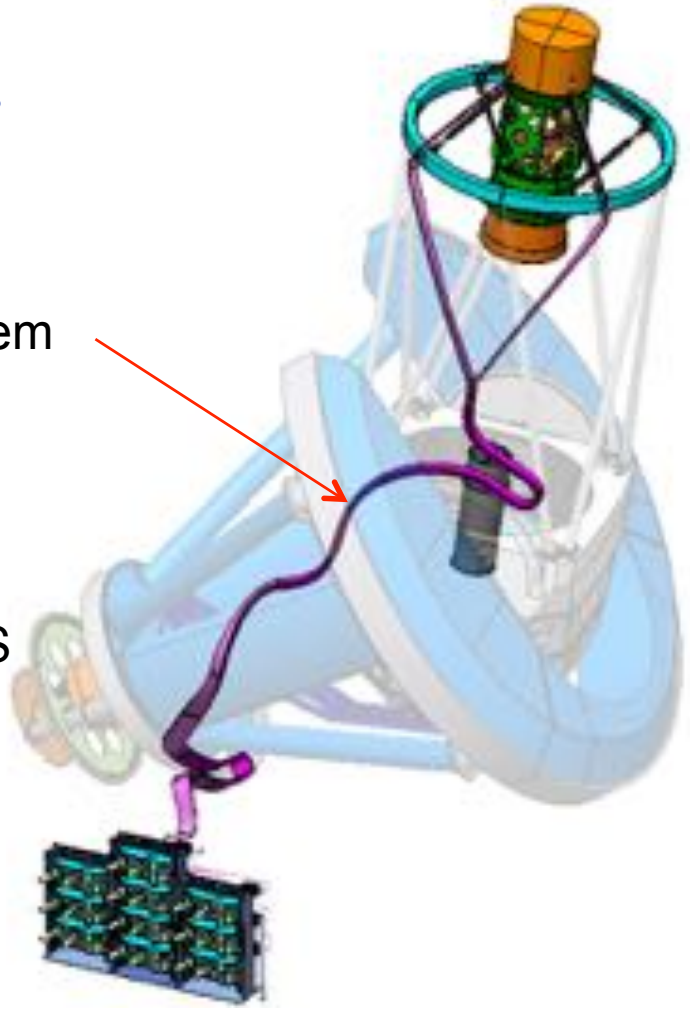

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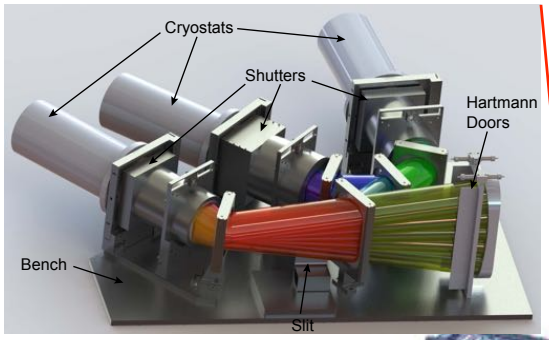
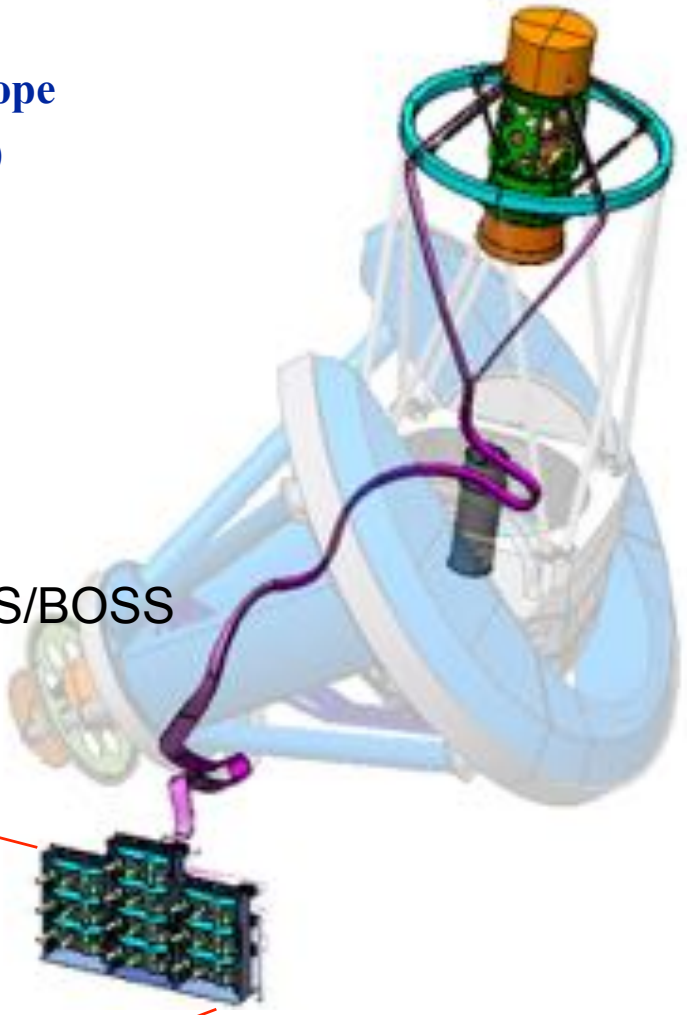
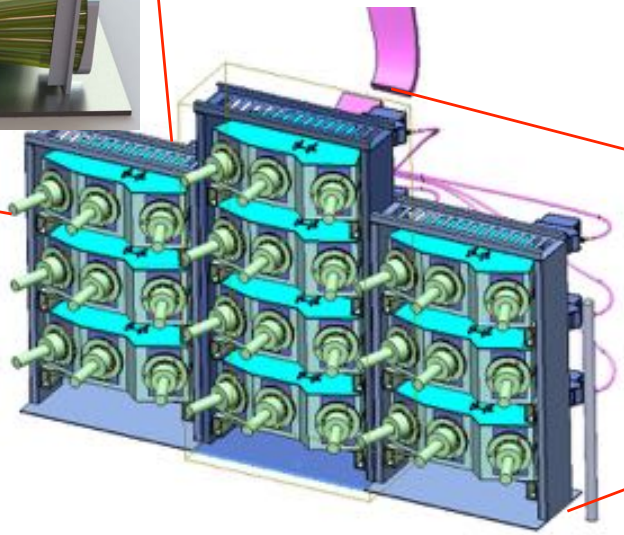


Spectrograph
Heritage: SDSS/BOSS





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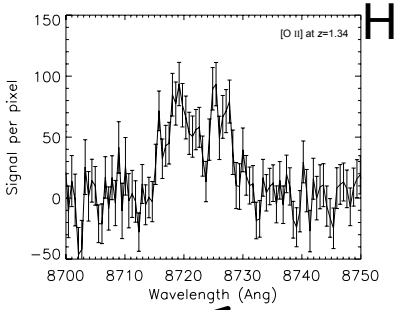
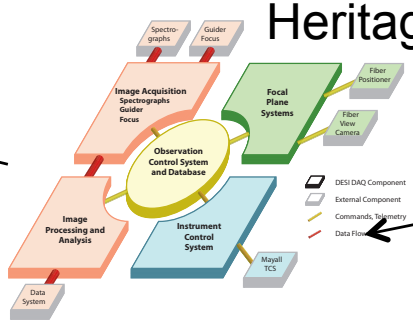
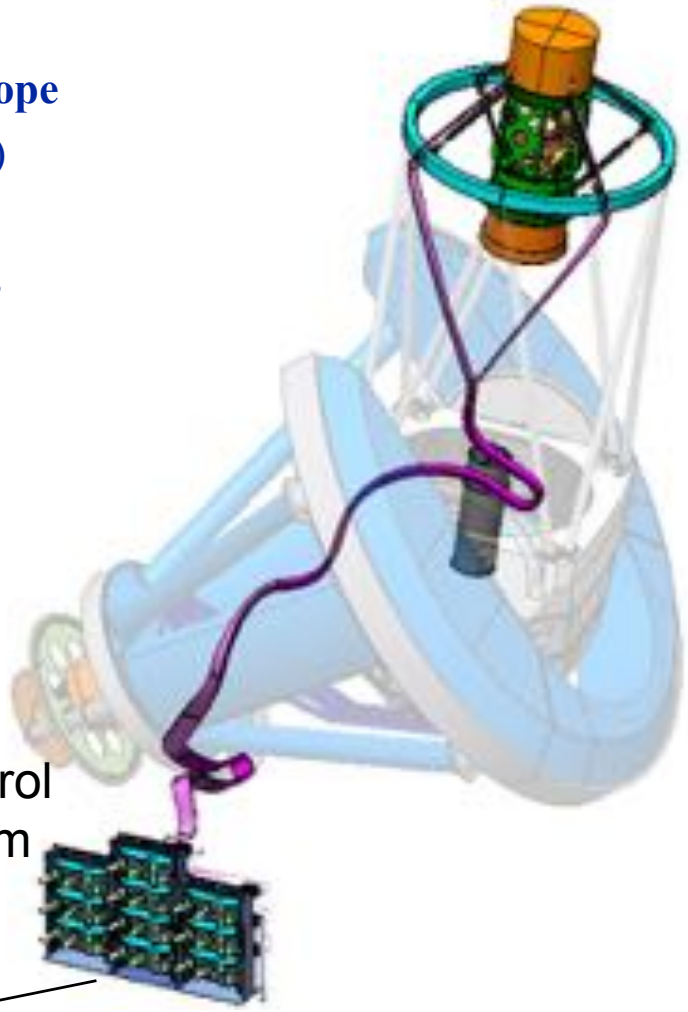
- Instrument controls and data processing



Data System
Heritage: BOSS



Instrument Control
Heritage: DECam



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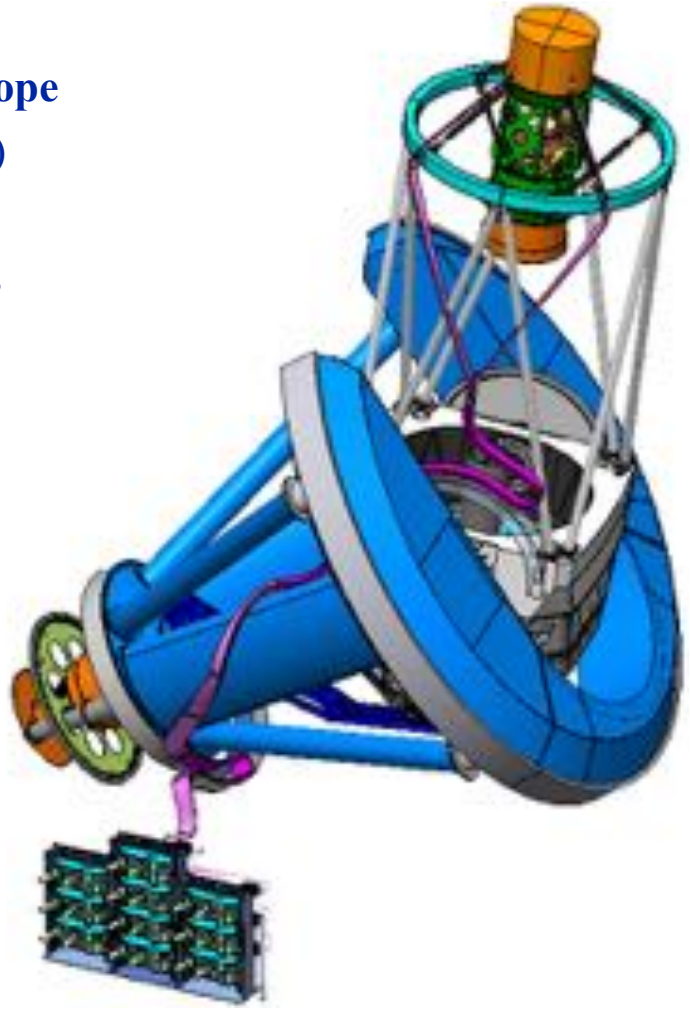

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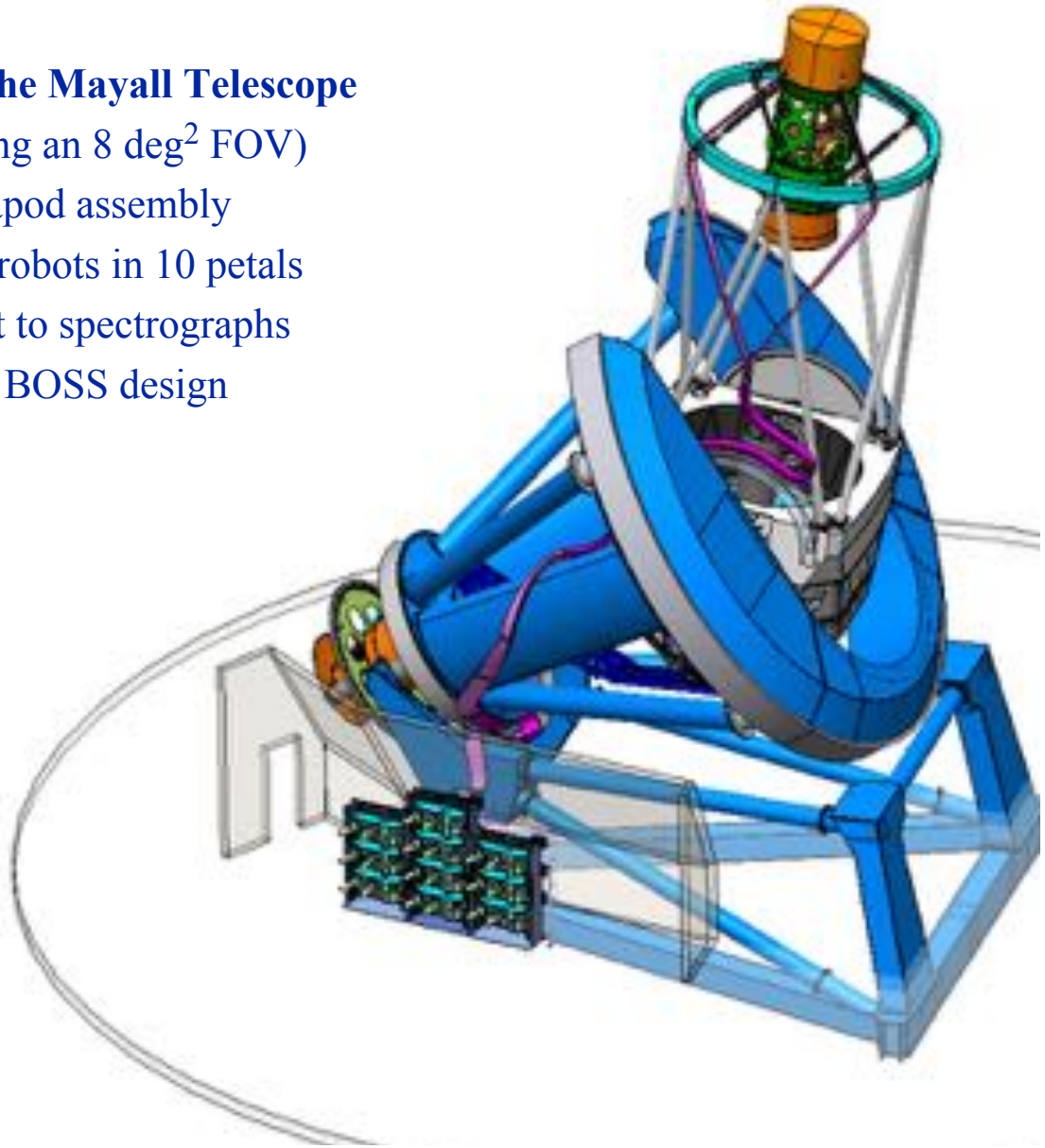

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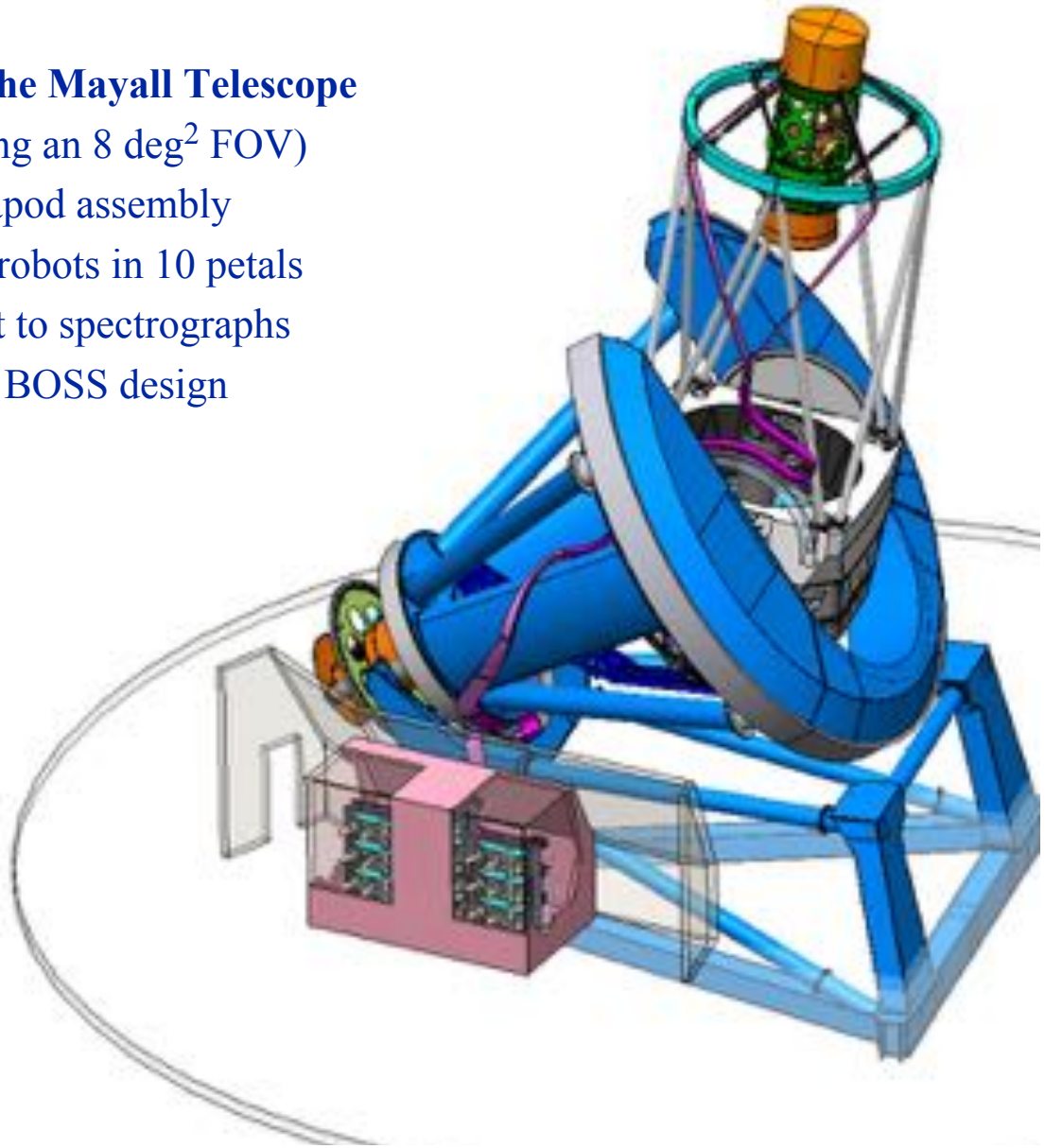

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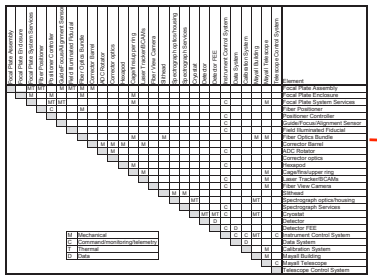
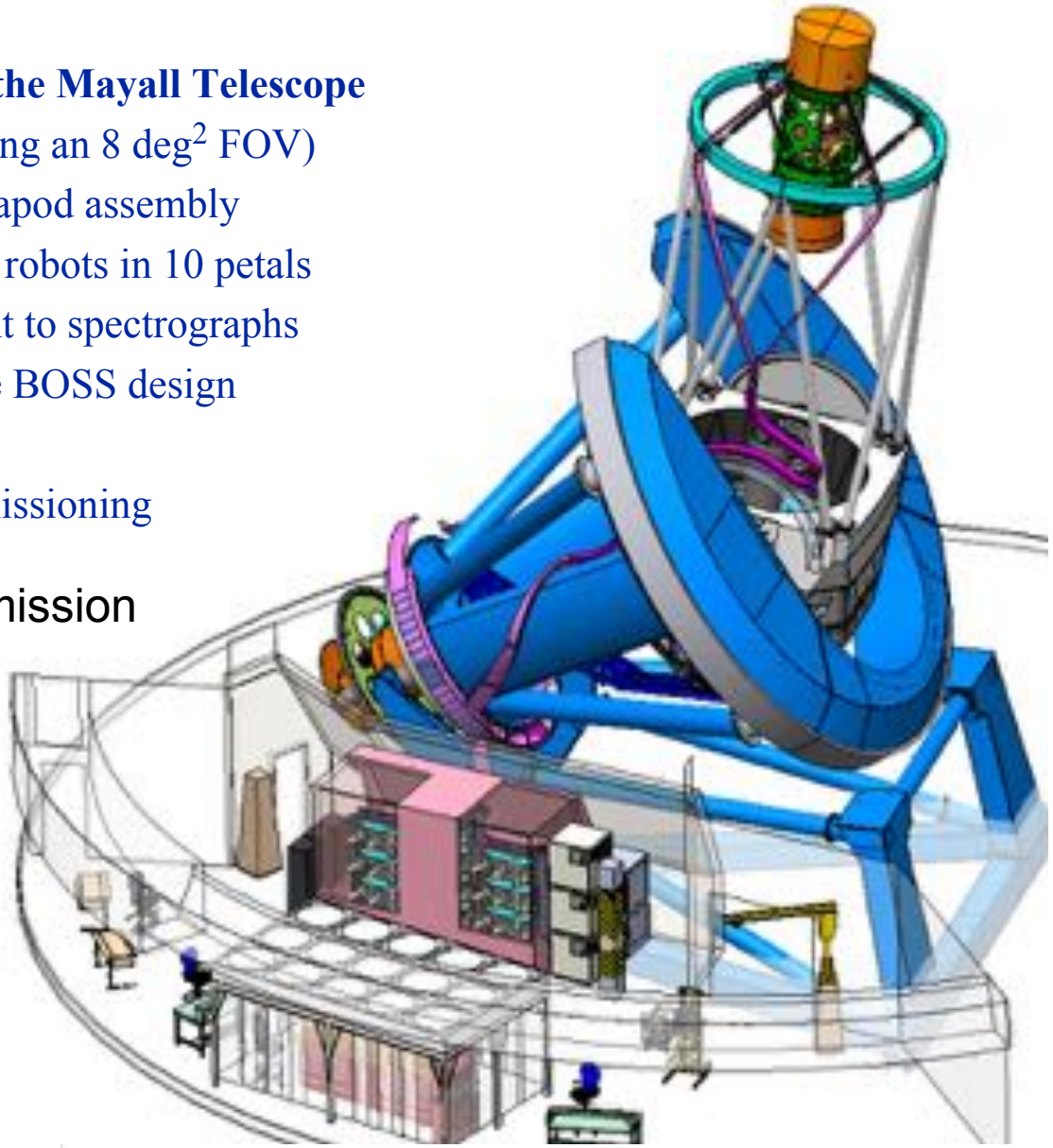
- Instrument controls and data processing
- Test and verification, installation, commissioning

Assembly, Integration, Test & Commission



Heritage: DECam



Project Status

- **CD-1 signed by DOE on March 19**
  - **Then executed "advanced procurement authority" (APA) to acquire the gratings for the spectrograph. Receiving TEC funds for this purpose.**
  - **Draft APA for early start on CCD fabrication**
- **Technical/Preliminary Design Reviews (Spring 2015):**
  - **Corrector, Barrel, Focal Plane, Fiber System, Spectrograph, Instrument Control, Data System, Installation and Commissioning**
- **CD-2 passed on July 2015, approved September 2015**
  - **Approved project scientific scope, schedule and funding profile**
- **CD-3 scheduled May 2016**

DESI Expert Collaboration

Partners are experienced

Barcelona: Guiders

DECam

Fermilab (U.S.): Telescope top-end + lens cell

w/ UCL (U.K.): Telescope optics

Dark Energy Survey top-end + optics

Durham: Fibers + testing

FMOS + Fibers for physics exp'ts

LAM + CPPM (France): Spectrographs

VIMOS spectrographs

CEA (France): Cryo systems

Megacam cryo

Berkeley Lab (U.S.): CCDs + electronics, optical design, project management

WFIRST/JDEM optical design

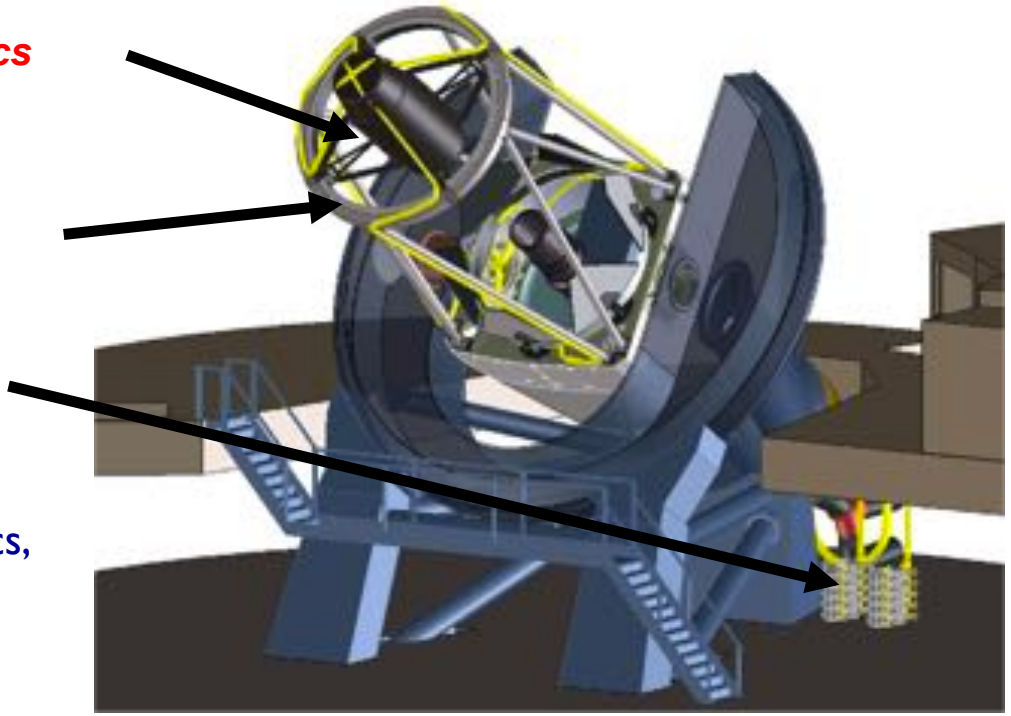
DES, BOSS, JDEM detectors

Yale: fiber view camera ***/ QUEST***

U Michigan: positioners ***/ DES***

SLAC, Ohio State: data acquisition + guiding ***BOSS, DES, LSST***

NOAO: telescope interface, operations ***DECam***



DESI Collaboration has grown to ~200 Participants and 43 Institutions

Institution	Membership
AMU RPG	RPG
Arizona	Full
Barcelona-Madrid RPG	RPG
CPG-NAOC	RPG
Durham	Full
EPFL	Full
FNAL	Full
LBNL	Full
Mexico RPG	RPG
Michigan	Full
NOAO	Full
OSU	Full
Portsmouth	Full
Saclay	Full
SLAC	Full
UK RPG	RPG
UCB	Full
UCL	Full
ANL	Assoc (3)
KASI	Assoc (3)
Penn	Assoc (3)
Yale	Assoc (3)

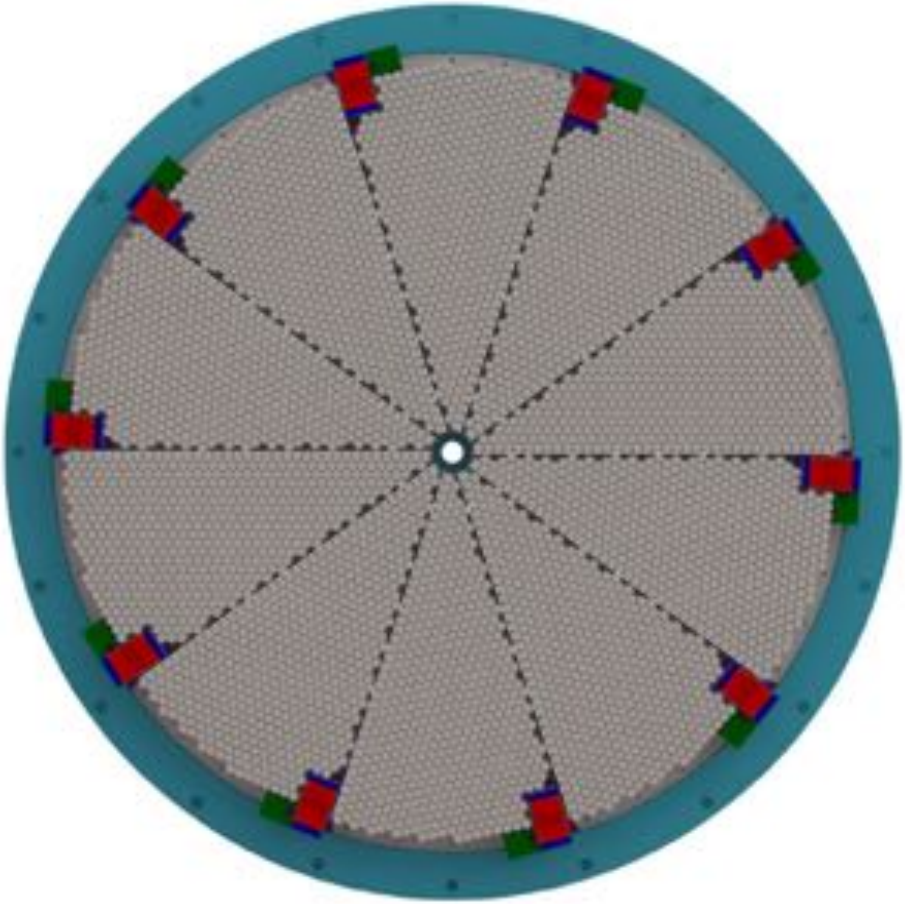
Institution	Membership
Andes	Assoc (1)
Barcelona (ICC)	Assoc (1)
BNL	Assoc (1)
BU	Assoc (1)
CMU	Assoc (1)
Cornell	Assoc (1)
ETHZ	Assoc (1)
Harvard	Assoc (2)
GMT RPG	Assoc (3)
Irvine	Assoc (1)
KIAS	Assoc (1)
LLNL	Assoc (1)
LPNHE	Assoc (1)
Pittsburgh	Assoc (2)
Queensland	Assoc (1)
Siena	Assoc (1)
SMU	Assoc (1)
Swinburne	Assoc (1)
Toronto	Assoc (1)
UCSC	Assoc (2)
Utah	Assoc (2)

Our Contribution

Barcelona-Madrid Regional participation Group

- **Institutions**
  - ICE, IEEC/CSIC
  - IFAE
  - CIEMAT
  - IFT/UAM
- **Instrumentation**
  - Guide Focus and Alignment Units
  - Guiding software
- **Science**
  - Working Group participation
  - Leading image validation task force
- **Management**
  - Part of Institutional Board
  - Member of several committees

Guide, Focus & Alignment



- Focal Plane composed of 10 petals
- Each petal contains a GFA
- GFA of two types:
  - 6 for guiding and field acquisition
  - 4 for focus and alignment
  - Identical except for optical filter

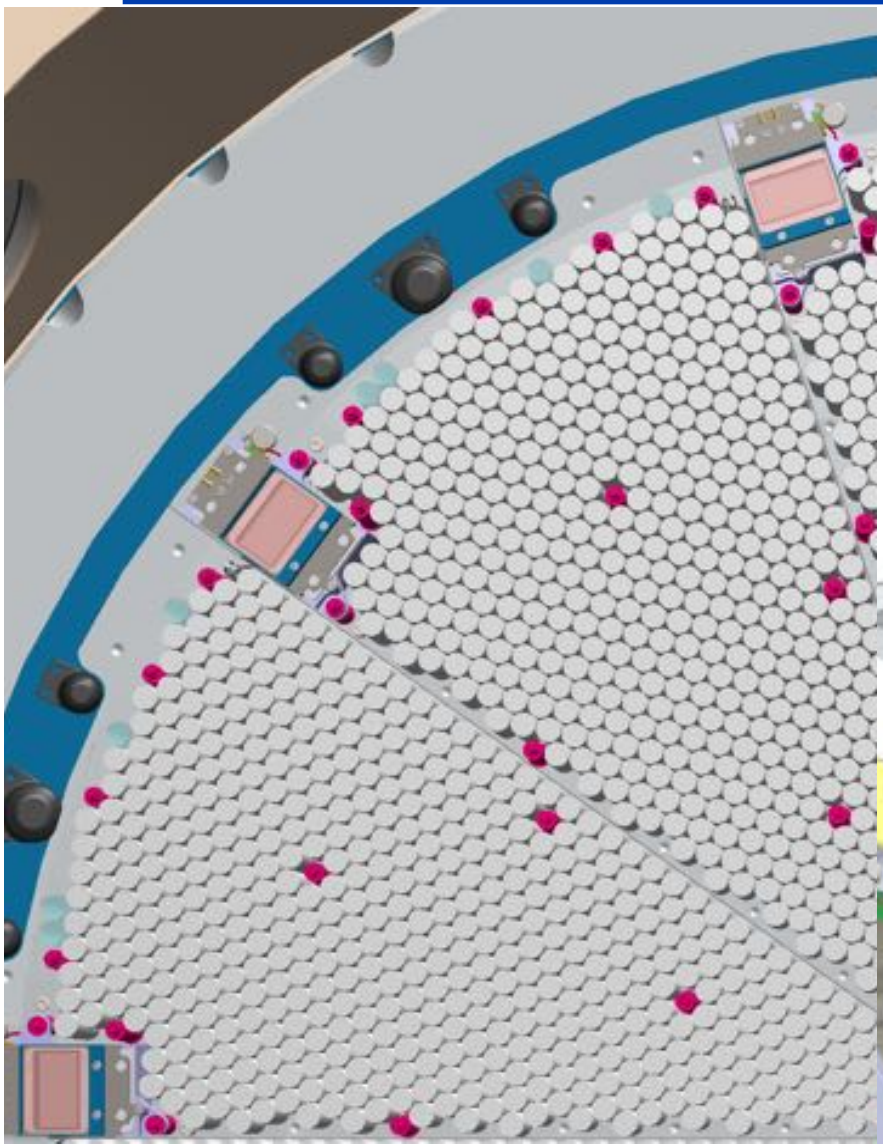
Guide, Focus & Alignment

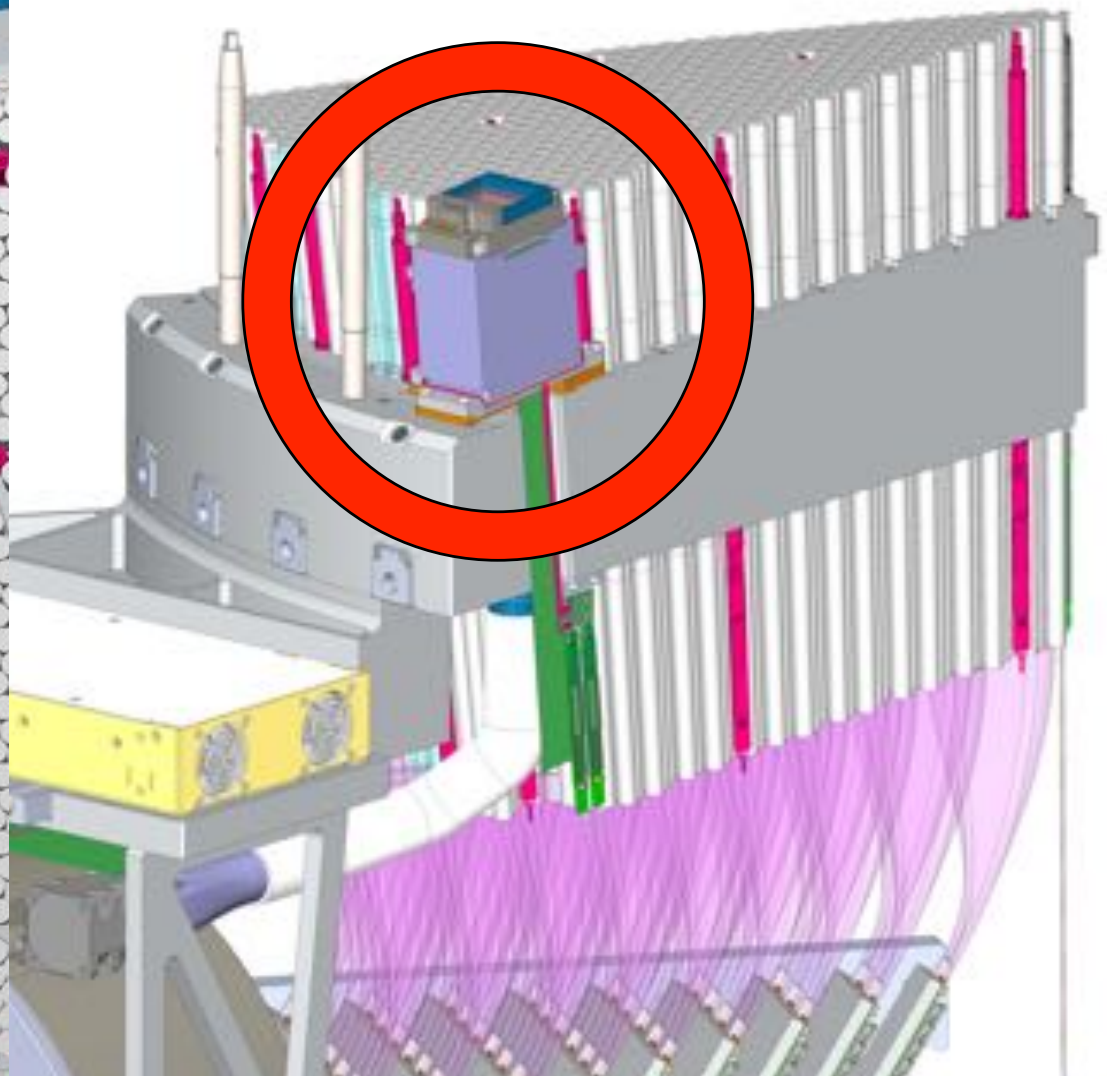
- GFA requirements DESI-0526:
- Guiding
  - Centroids with 0.03 arcsecond accuracy at 1 Hz (<0.5s latency).
  - At least 3 focus GFA with approximate symmetry around focal plane
  - 4 windowed star images and 1 windowed sky image archived per camera
- Environment
  - Must survive within DESI survival requirement (DESI-0583)
  - Shall operate (with degraded performance) under all observing conditions: galactic latitude, seeing, clouds
  - Function even when bright stars hit sensor

Guide, Focus & Alignment

- Field acquisition
  - Take acquisition exposure and determine current pointing within 20 seconds of slew.
  - Field acquisition images archived
  - Full frame images taken by any GFA on command.
- Focus and Alignment
  - Process at least 50 out of focus stars within 5 seconds
  - Determine barrel defocus relative to M1 within 30 um.
  - Determine barrel tip/tilt relative to M1 within 10 arcseconds

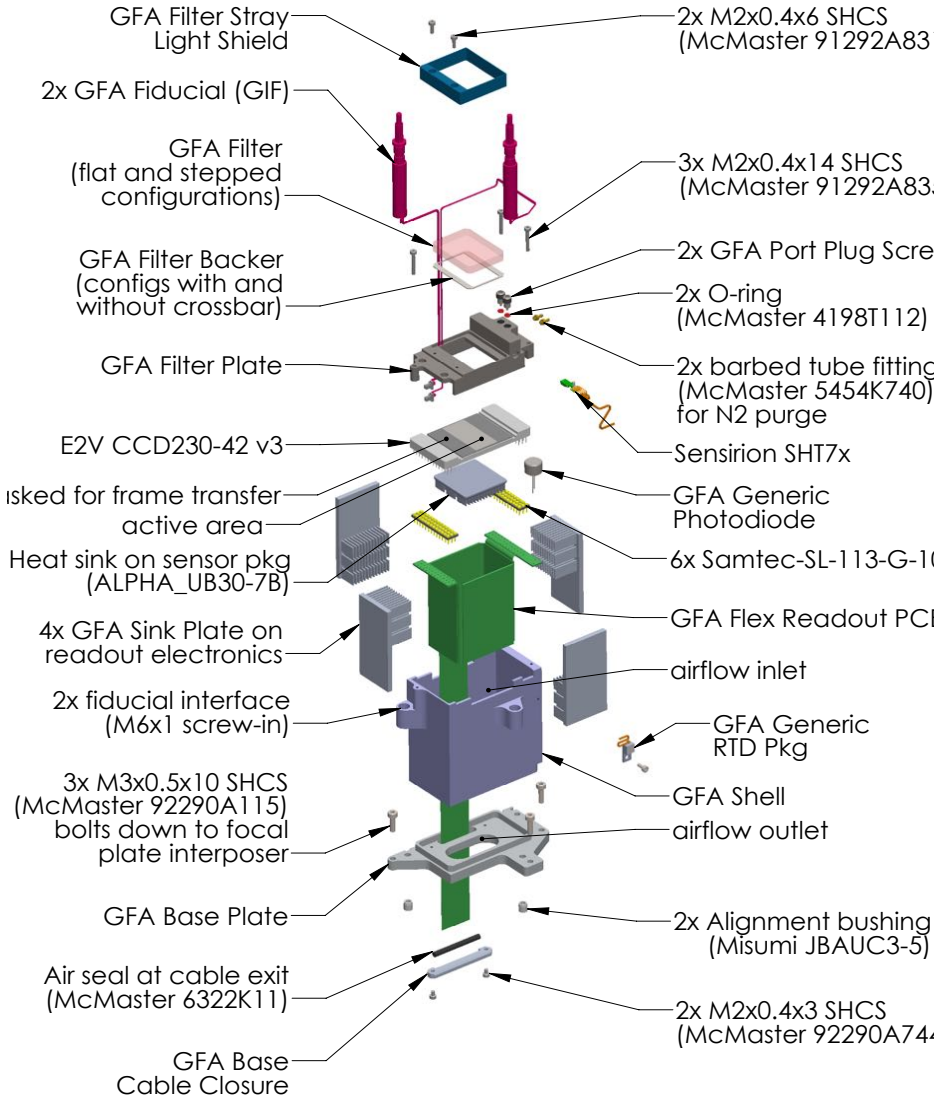
Guide, Focus & Alignment





Guide, Focus & Alignment

- Each petal has one camera.
- Light first passes through an optical filter (R)
- Central region of CCD is active.
- Edges are used for frame store.
- Electronics stays within unit allocated volume
- Thermal dissipation through air flow
- Integrate two fiducials
- Interface with FPA through a mount plate
- Implement a photodiode for unit safety

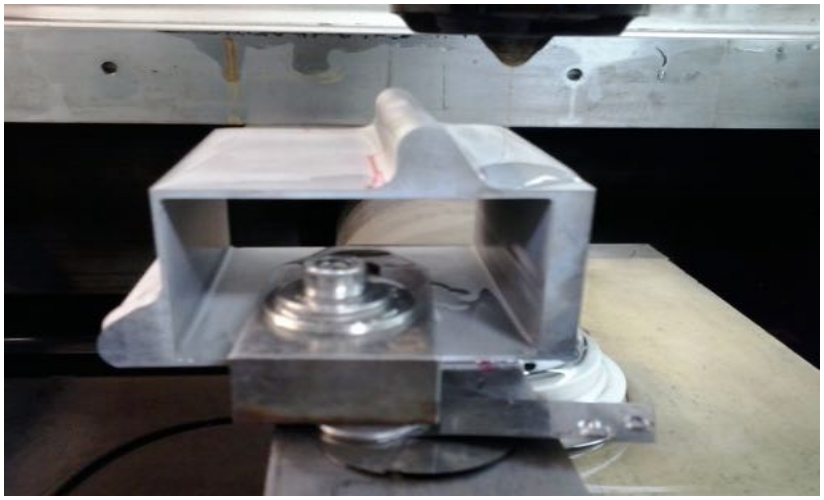


Guide, Focus & Alignment

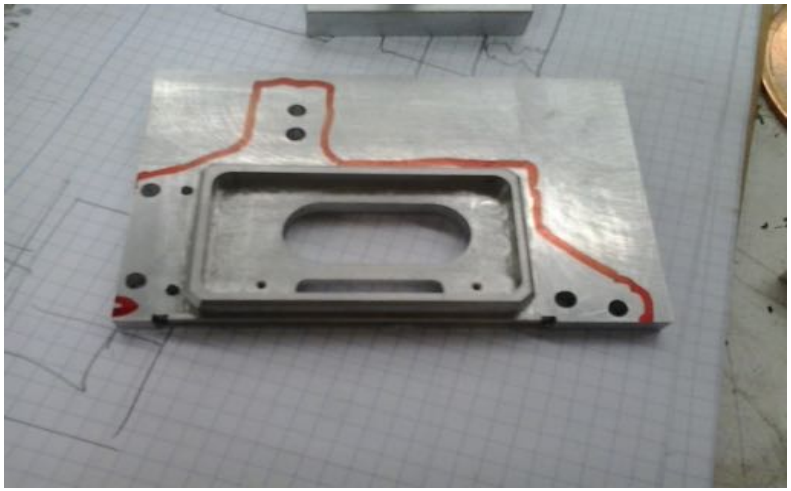
Work packages

- Mechanichs
- Electronics
- Gluing
- Software control
- Optics
- CCD characterization
- AIV

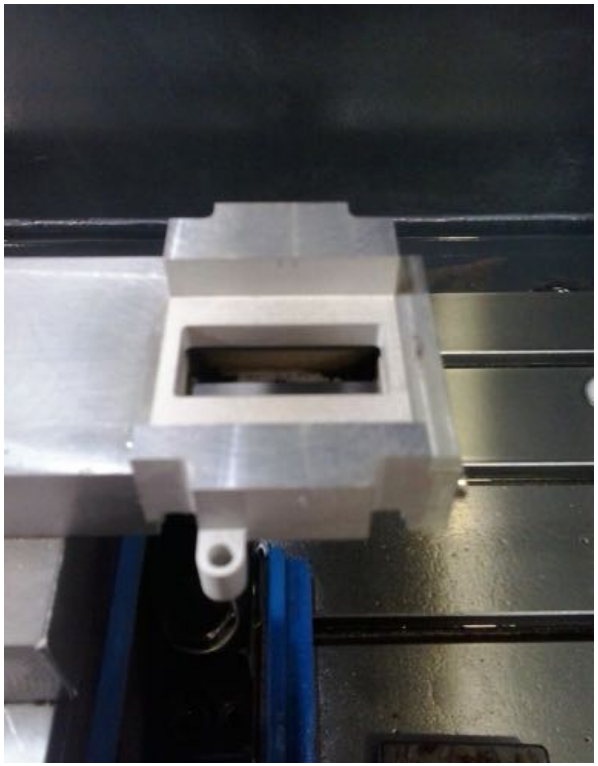
Guide, Focus & Alignment



GFA Shell

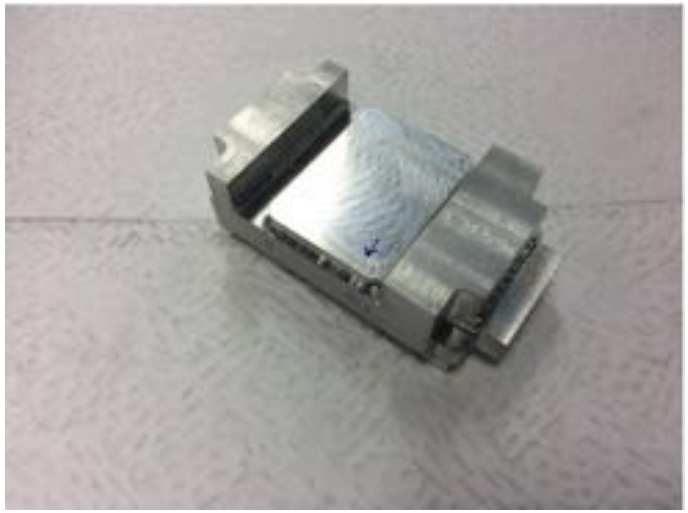


GFA Base Plate



GFA Filter Plate

Guide, Focus & Alignment

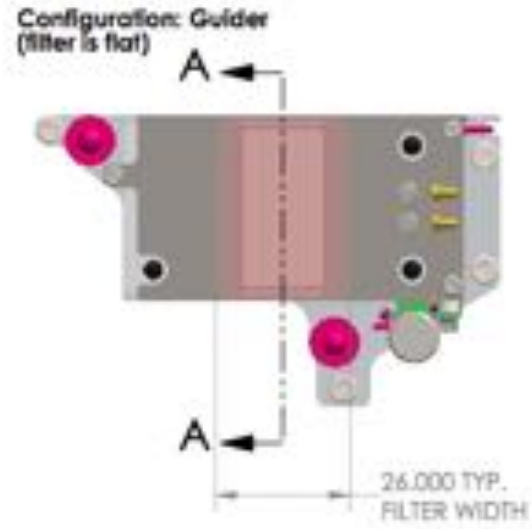


Gluing testing

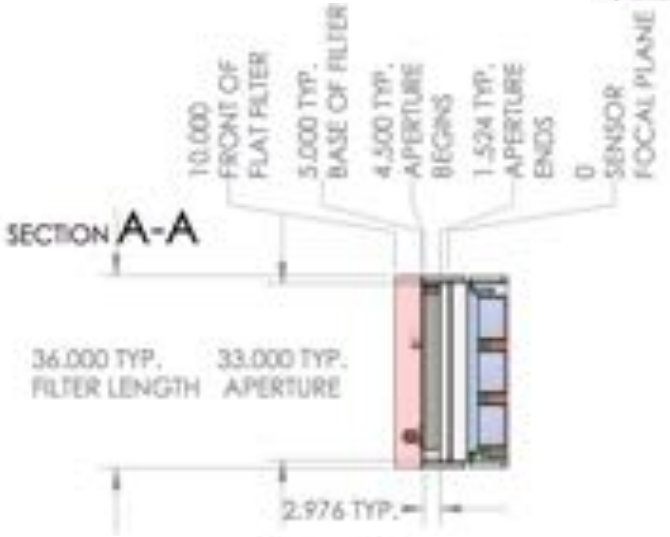
Leakage testing

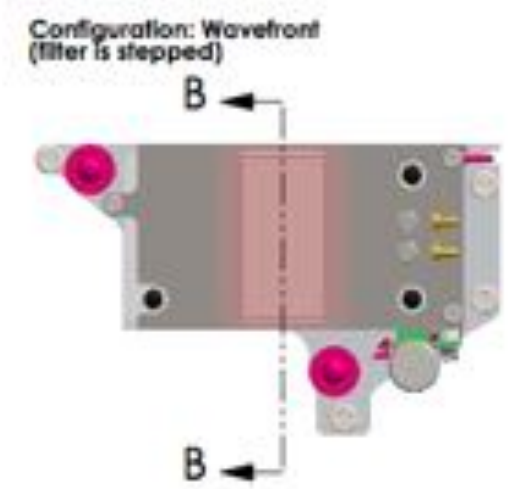
Alignment testing

Guide, Focus & Alignment

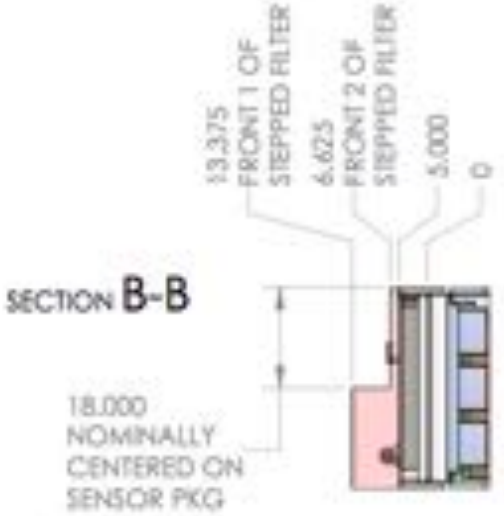


Guiding & Acquisition



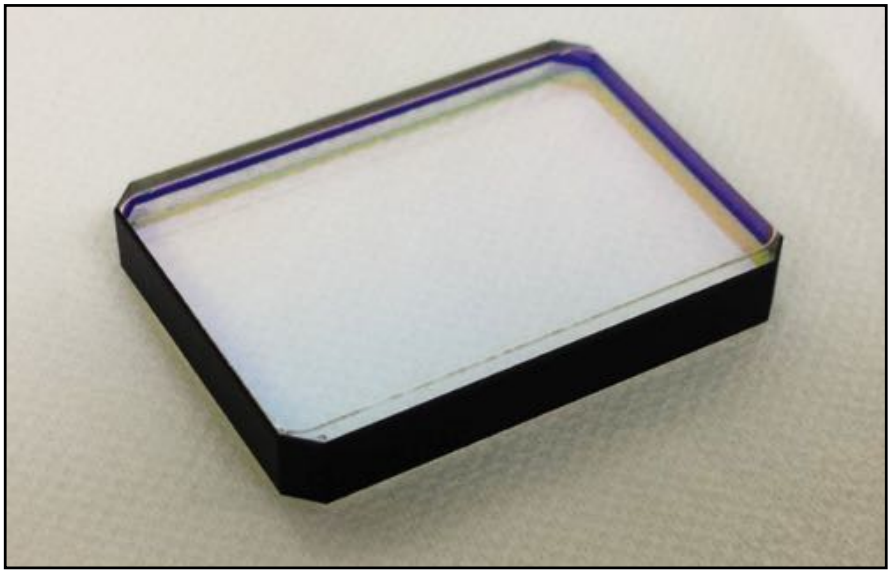


Focus & Alignment

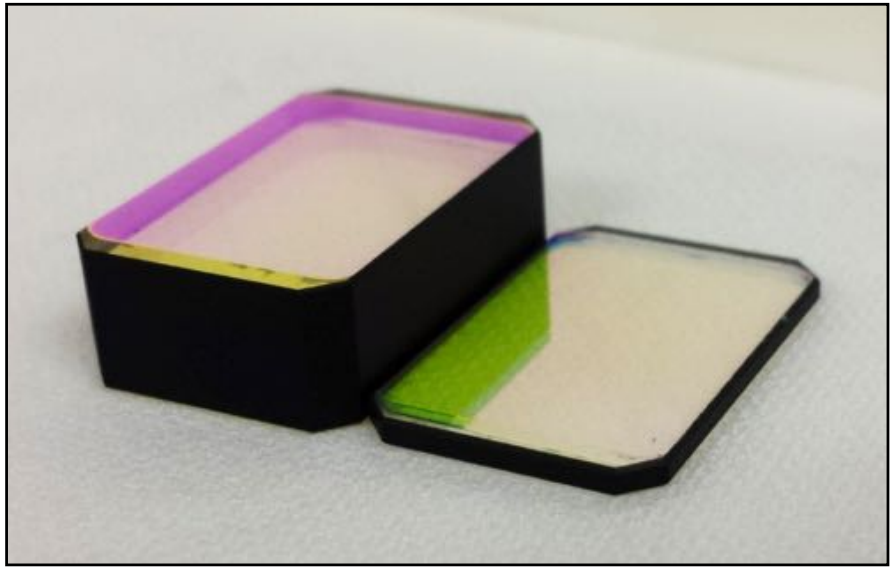


Guide, Focus & Alignment

Guider filter (flat)



Wavefront filter (stepped)

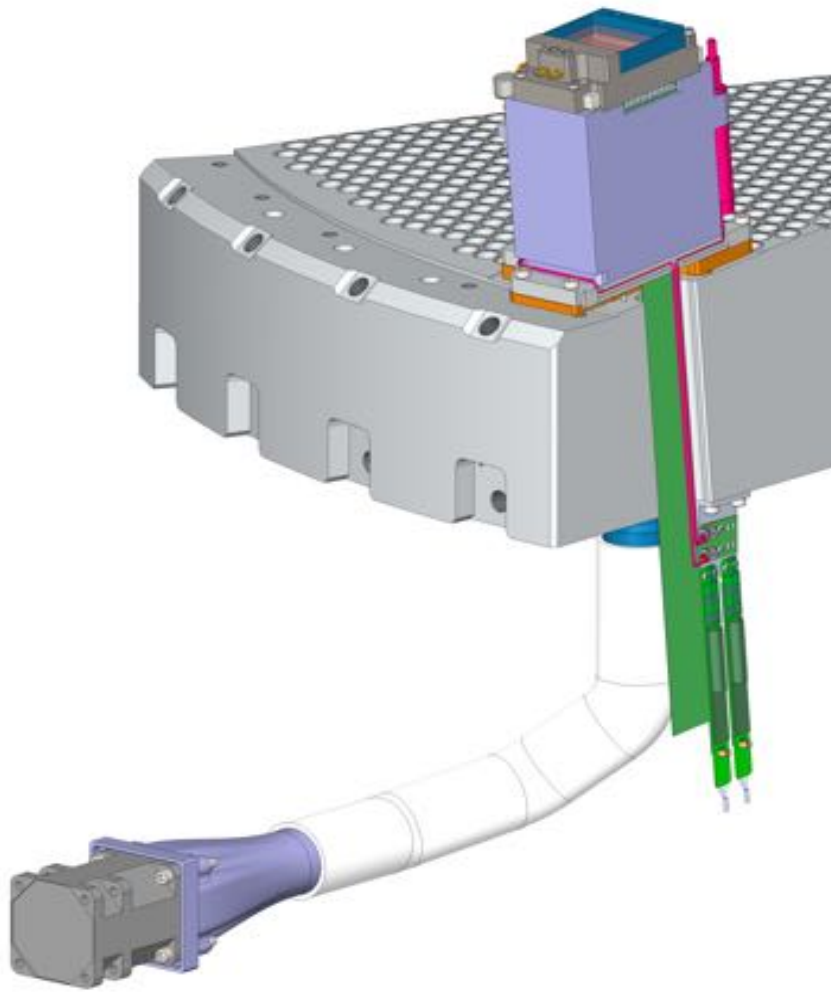


- 3 samples of each type were tested, all were coated in same batch
- Tests were made of:
  - transmission
  - wavefront
  - scratch-dig
  - temperature extremes
  - humidity extremes
  - bonding to Ti backer

Guide, Focus & Alignment

- GFA designed to operate at ambient temperature
- Advantages:
  - Greatly simplifies focal plane requirements having no cryogenics.
  - Removes condensation risk.
  - Thermoelectric cooling would consume significant fraction of system thermal budget.
  - Cooled by flow of air from a small fan.
    - flow rate requirement low, 5 cfm (DESI-0724)

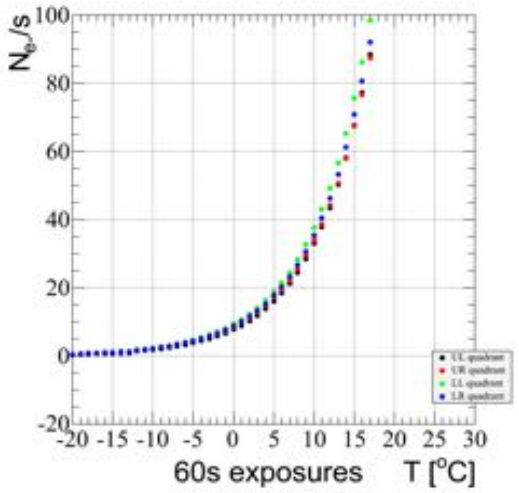
Fan Duty Cycle	Air speed (ft/min)	Flow Rate (CFM)
10%	174	5.568
20%	229	7.328
30%	273	8.736
40%	322	10.304
50%	355	11.36
60%	382	12.224
70%	404	12.928
80%	426	13.632

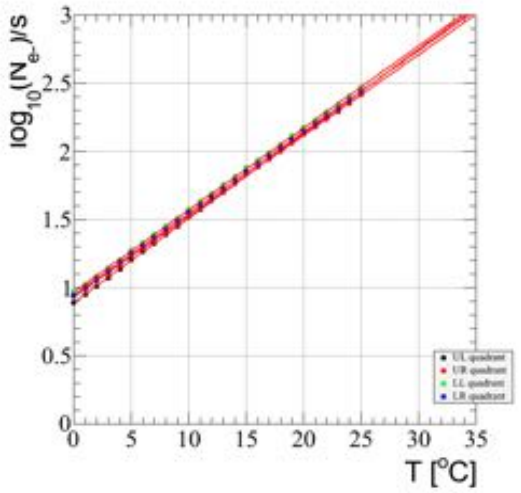


Flow test results: (DESI-1252)

Guide, Focus & Alignment

- e2v ccd230-42 selected
  - Low dark current ~140 e-/s at operating temperature

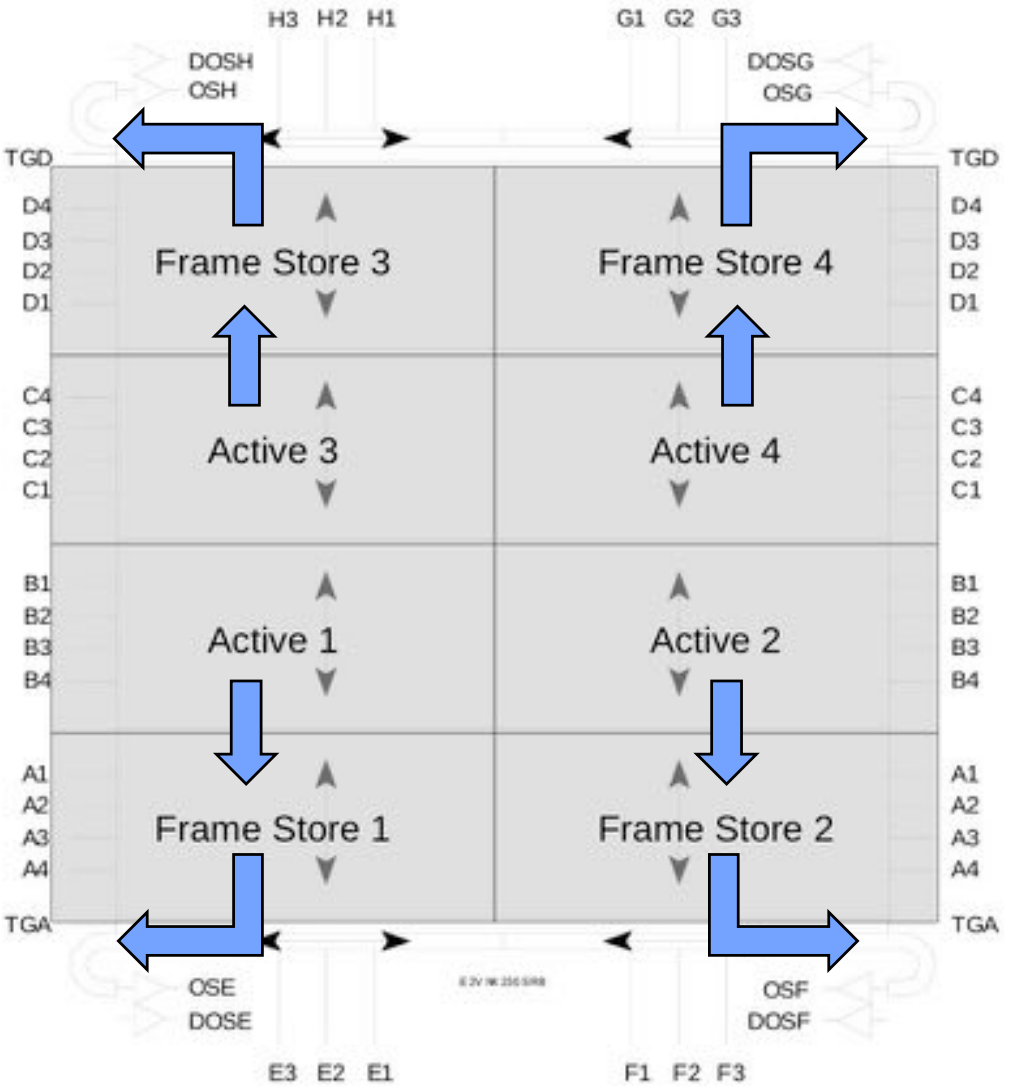




Temperature [°C]	Dark Current [e^-/s]	Temperature [°C]	Dark Current [e^-/s]
-21.0	<1	4.0	14.8
-20.0	<1	5.0	17.2
-19.0	<1	6.0	19.6
-18.0	<1	7.0	22.5
-17.0	<1	8.0	25.9
-16.0	<1	9.0	30.0
-15.0	<1	10.0	34.7
-14.0	1.0	11.0	39.7
-13.0	1.2	12.0	45.4
-12.0	1.5	13.0	52.3
-11.0	1.7	14.0	60.3
-10.0	2.0	15.0	69.9
-9.0	2.3	16.0	79.6
-8.0	2.7	17.0	91.0
-7.0	3.2	18.0	104.4
-6.0	3.7	19.0	120.3
-5.0	4.2	20.0	139.2
-4.0	4.9	21.0	158.1
-3.0	5.6	22.0	180.3
-2.0	6.4	23.0	206.1
-1.0	7.4	24.0	236.4
0.0	8.5	25.0	273.5
1.0	9.8	26.0	309.0
2.0	11.0	27.0	349.2
3.0	12.7	27.9	396.6

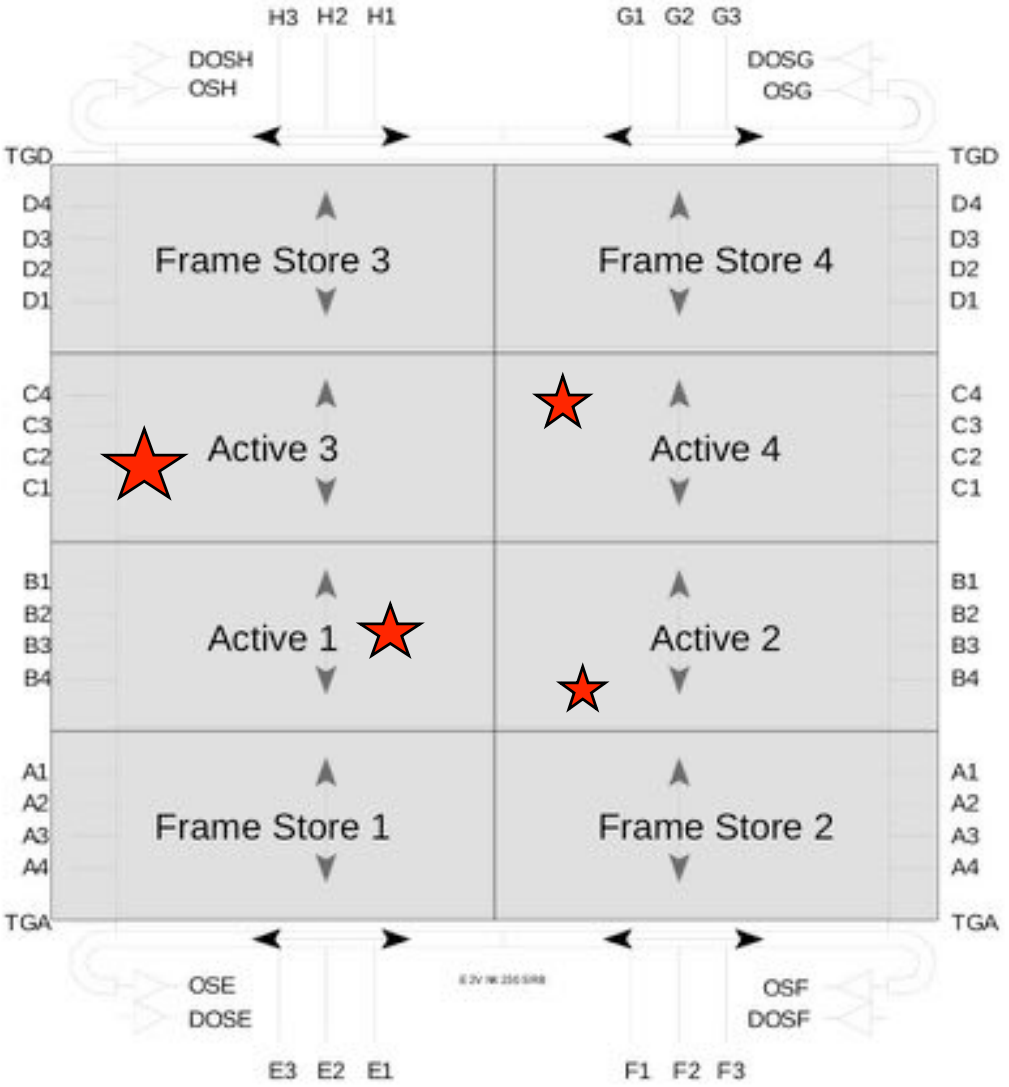
Guide, Focus & Alignment

- e2v ccd230-42 selected
  - Low dark current ~140 e-/s at operating temperature
  - 4 channel readout
  - 2M pixel active area with frame store
  - Can read out full frame in 0.5 seconds (1 MHz clocking)

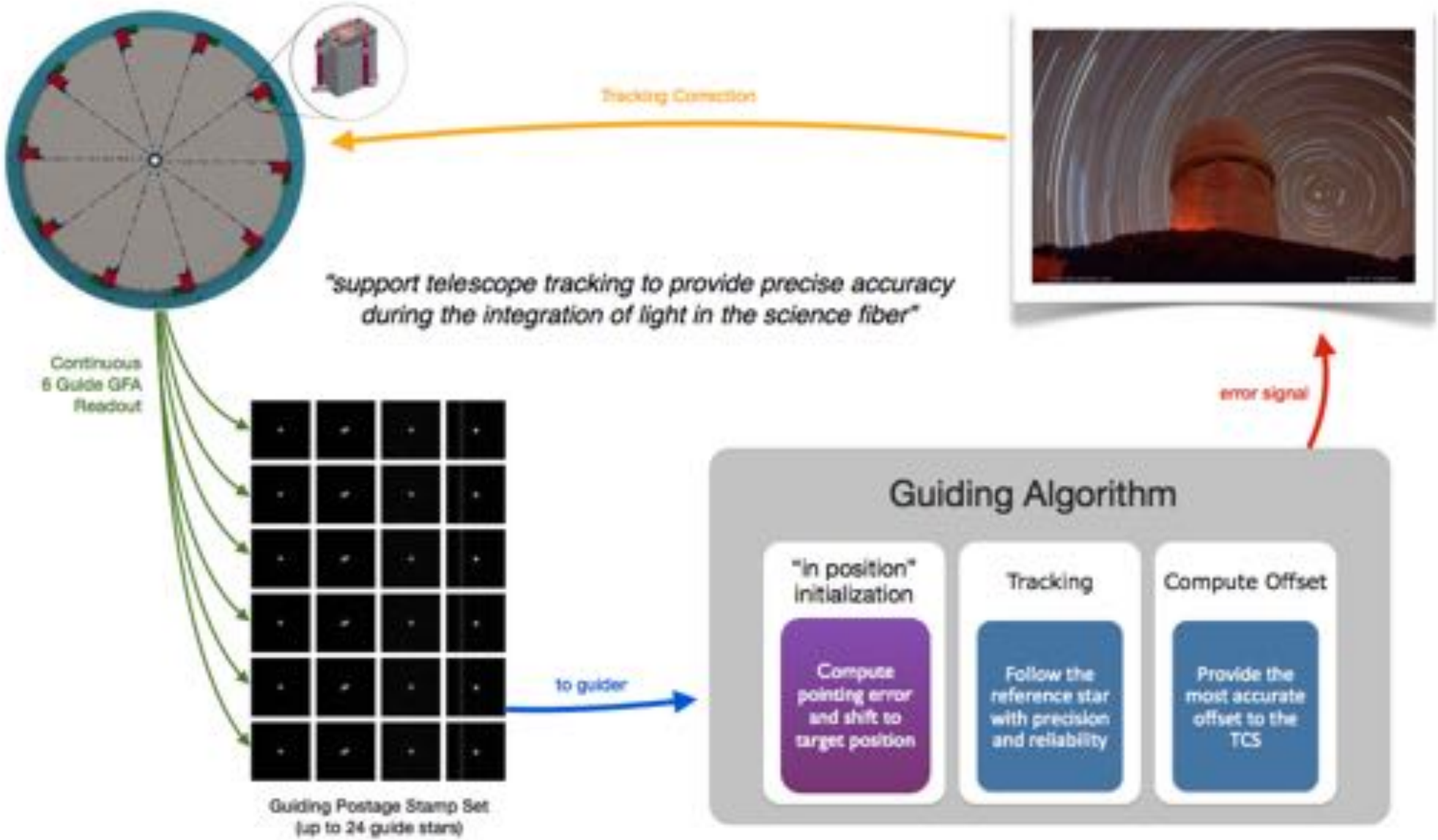


Guide, Focus & Alignment

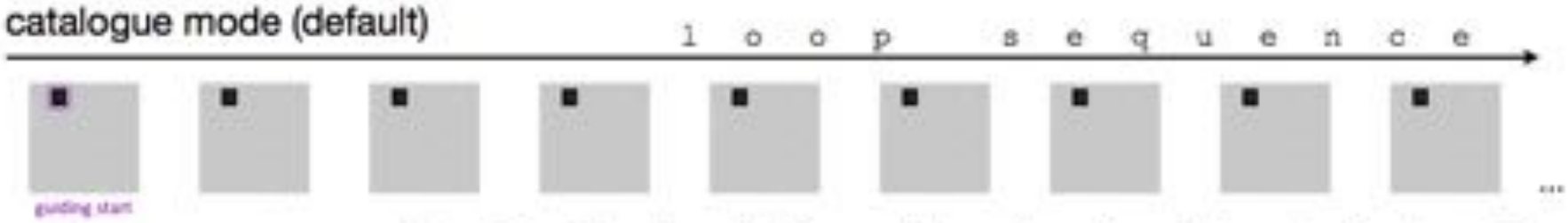
- e2v ccd230-42 selected
  - Low dark current ~140 e-/s at operating temperature
  - 4 channel readout
  - 2M pixel active area with frame store
  - Can read out full frame in 0.5 seconds (1 MHz clocking)
  - Can ROI each channel
    - all 4 channels clocked together so ROI star on one channel and 3 (mostly) sky ROI
    - enough stellar density for guiding targets
  - Many Hz readout possible in ROI mode



Guiding software

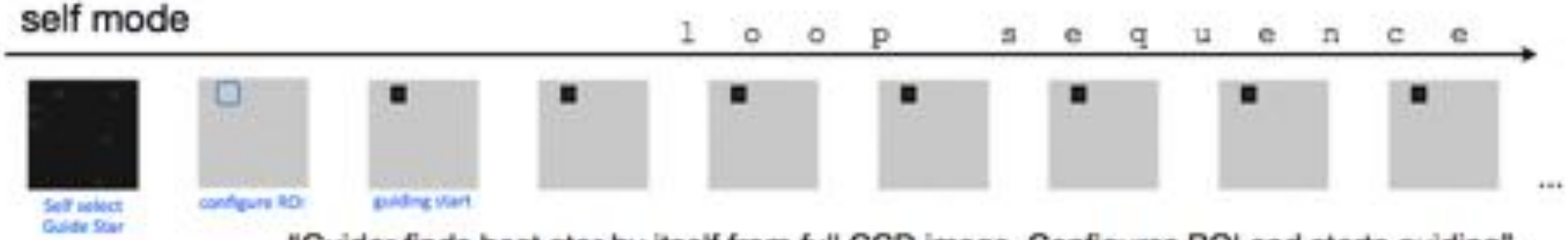


Guiding software



"The guider will receive a list of zero-point positions where the target guide stars are"

Default operation mode.



"Guider finds best star by itself from full CCD image. Configures ROI and starts guiding"

Starts guiding after 20s.

"User pick the guide star by itself from full CCD image. Configures ROI and starts guiding"

For specific cases or test use only.

Guiding software

Compute Offset
(every iteration)

For every CCD, measure the distance between the actual position of the reference star and the Zero Point

Single CCD

$$OutputOffset = \frac{\sum_{iCCD}^{activeCCDs} offset_{iCCD} \cdot GuideStarSN_{iCCD}}{\sum_{iCCD}^{activeCCDs} GuideStarSN_{iCCD}}$$

Centroids more accurate in stars with higher S/N → **Weighted Mean**

Multiple CCDs

Guiding software

Target SNR >10 on stars mag R < 17.5

11 stars meet the target SNR at NGP (worst-case scenario) in all guiding detectors

analysis study by K.Reil

Requirement:

Providing guide signals to the telescope at 1 Hz to a precision of <30 mas.

Simulation test:

10 SNR star measures the centroid within 0.1 pixel RMS precision using 4 ROIs of a single GFA. Assuming a scale of 0.27"/pix this provides 27 mas precision of centroid measurement.

Conclusion

- DESI builds on the long and successful experience of multiple collaborations in defining, building and executing wide area surveys to study the formation of our universe and the mystery of Dark Energy
  - SDSS, BOSS, DES…
- DESI will essentially complete BAO measurements in the northern sky out to redshift of 1.5.
- Technical design of DESI is very mature, Private/non-DOE funding being used for lenses and prototype spectrograph
- Strong support from HEP community and DOE: CD-2/3a baseline review passed and scope and funding profile approved.
- CD-3 Review May 2016
- On track for on-sky commissioning <4 years from now in 2019 and start of the survey in 2020
- Our group is actively involved