4MOST – 4m Multi-Object Spectroscopic Telescope

4MOST: ESO's wide-field, high-multiplex optical spectroscopic survey facility

Cescutti Gabriele

S3 and S4 member

Osservatorio Astronomico di Trieste
Astronomical Observatory of Trieste

AstroFIt 2
Astronomy Fellowships in Italy

13 November 2018

www.4MOST.eu

VISTA at Paranal Observatory, Chile

Science Themes

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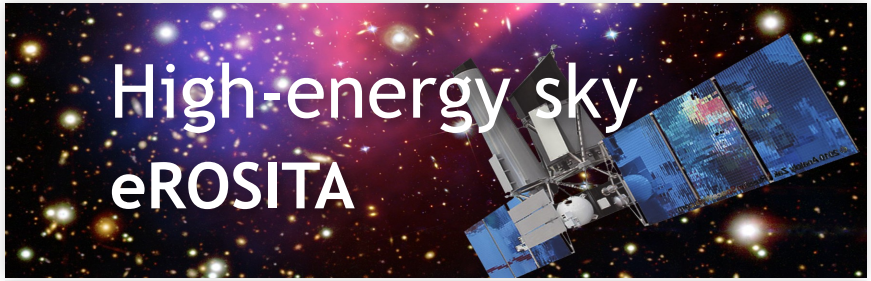

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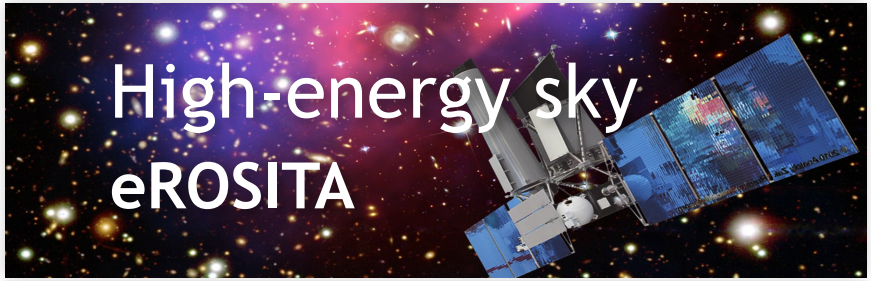

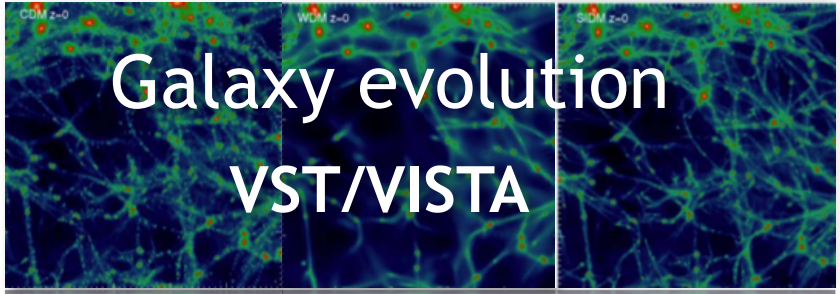

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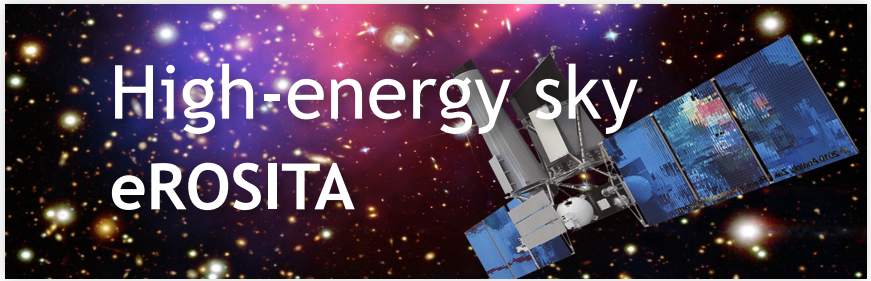
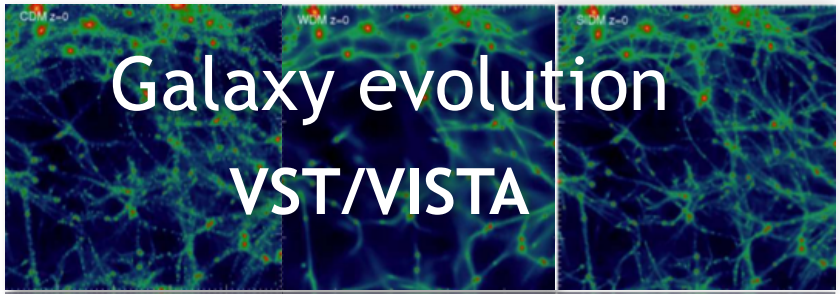
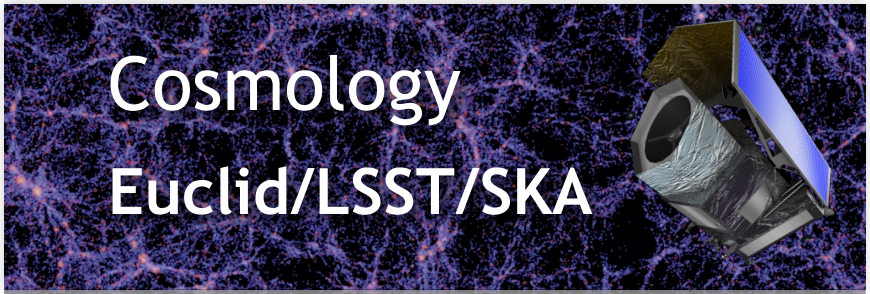
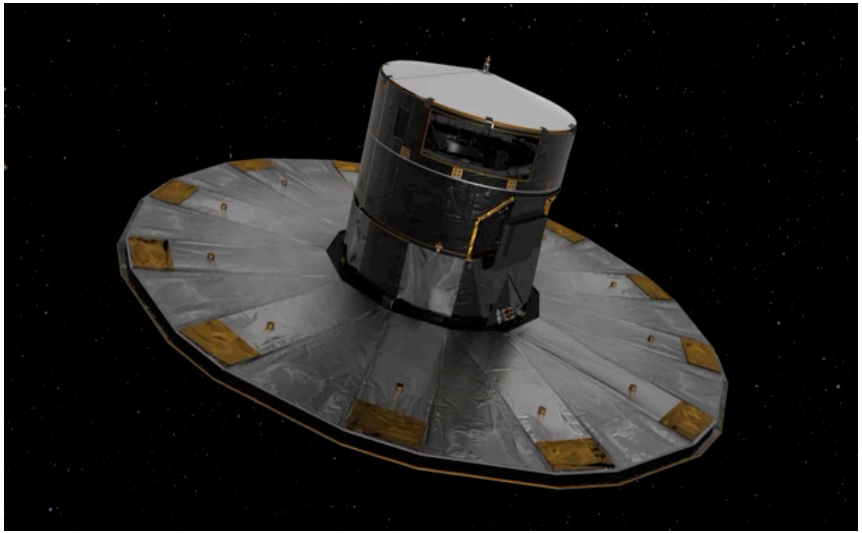






Galactic Archeology: Gaia

- The chemical composition and kinematics of stars are strongly coupled to birth environment
- Gaia measures distances and proper motions for >2 billion stars
- 4MOST will complement Gaia with radial velocities and chemical composition for faint stars
- 4MOST targets selected on Gaia parallax with sometimes color constraints



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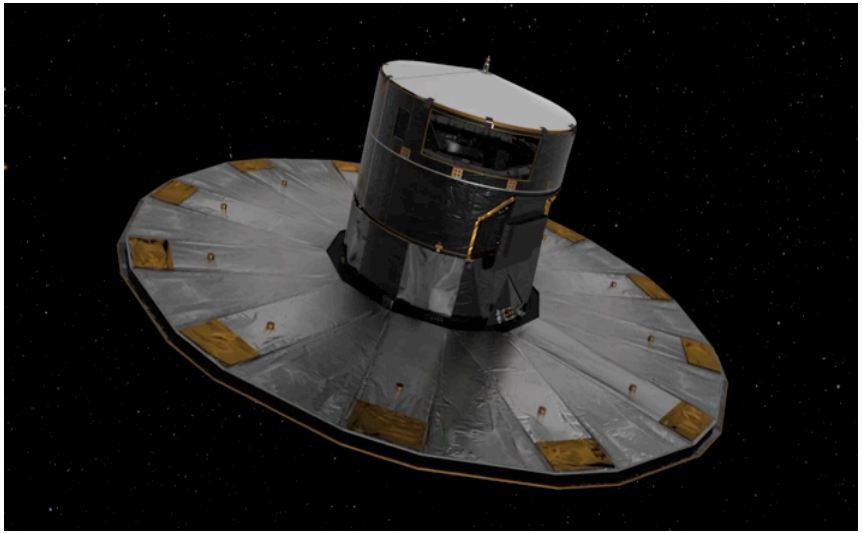

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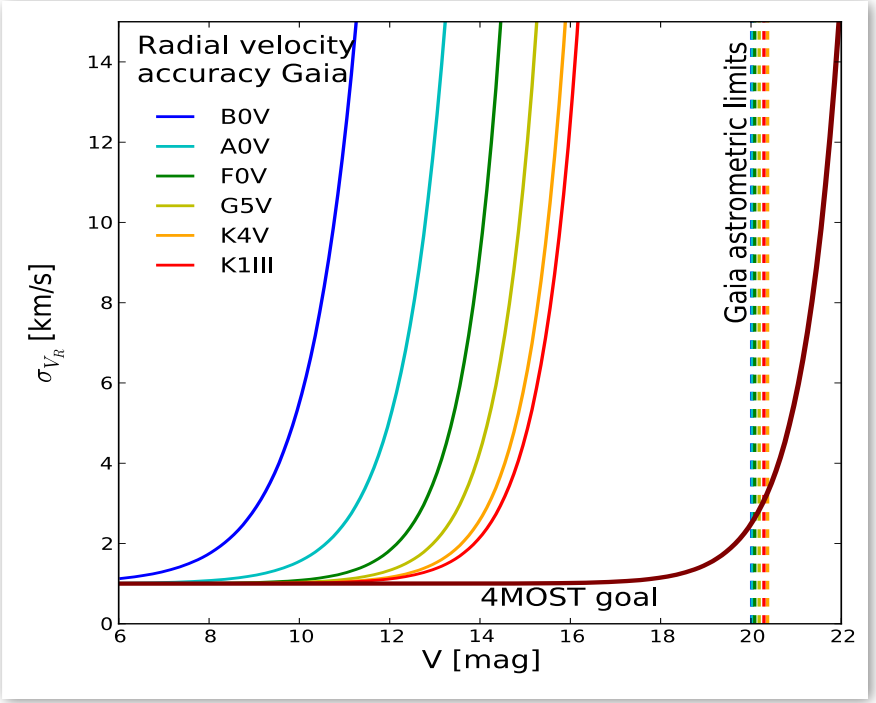

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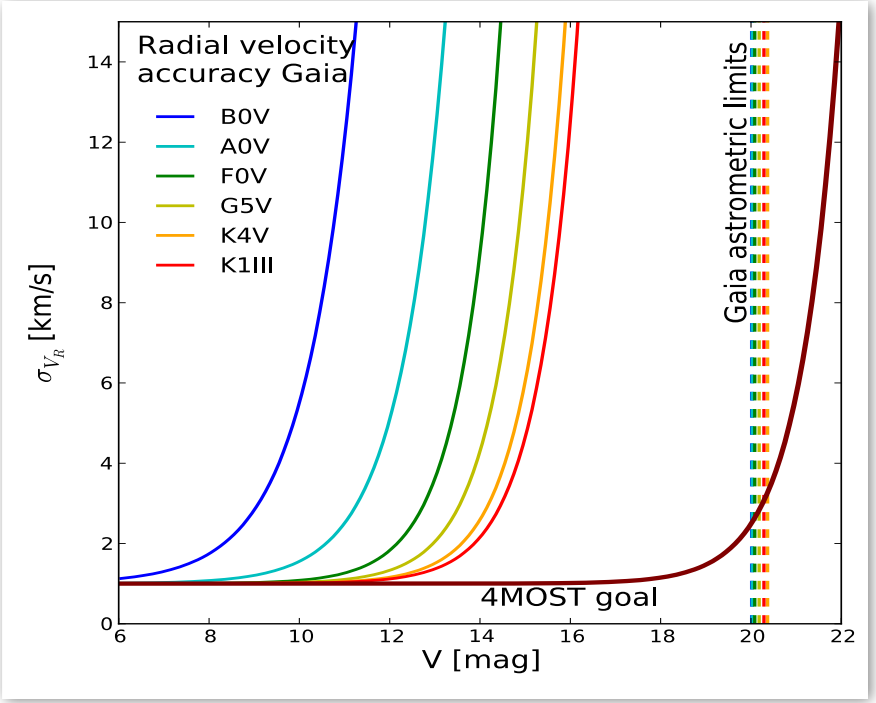

- *Unique capability in the South (Milky Way bulge and MCs)*

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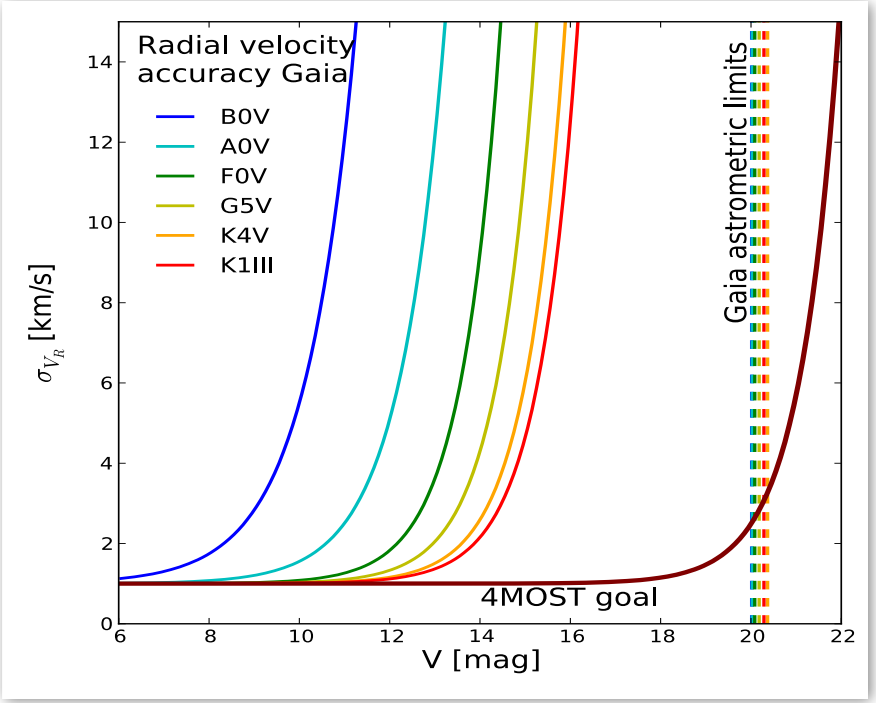
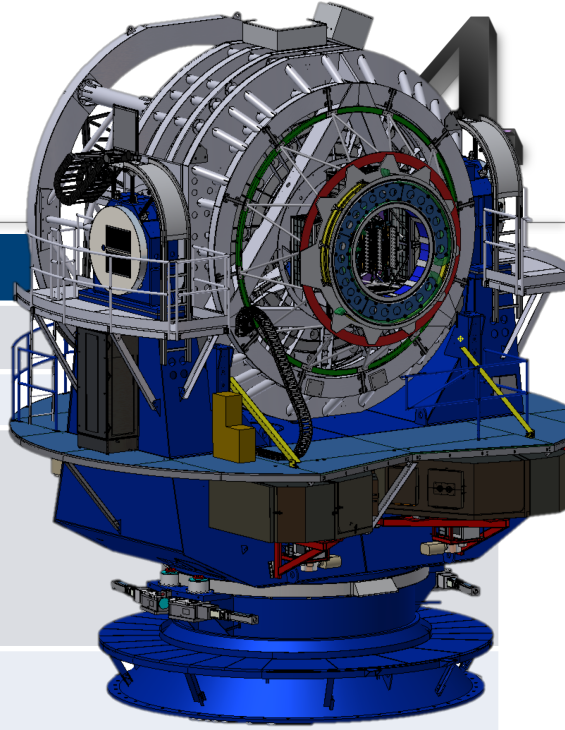


- *Unique capability in the South (Milky Way bulge and MCs)*

Science Requirements

- 4MOST shall be able to obtain:
  - *Radial velocities* of ≤1 km/s accuracy and
    Stellar parameters of <0.15 dex accuracy of any Gaia star
    - R~5000 spectra of 20 r-mag stars with S/N=10 per Ångström
  - *Abundances* of up to 15 chemical elements
    (Li, CNO, Mg, Ca, Ti, Si, Cr, Mn, Fe, Ni, Sr, Ba, Eu).
    - R~20000 spectra of 16 V-mag stars with S/N=140 per Ångström
  - *Redshifts* of AGN and galaxies (also in clusters)
    - R~5000 spectra of 22 r-mag targets with S/N=5/Å with >3 targets in ⌀=2'
- In a 5 year survey 4MOST shall obtain:
  - *15 (goal 30) million targets* at R~5000
  - *1.0 (goal 3.0) million targets* at R~20,000
  - *16,000 (goal 23,000) degree²* area on the sky at least two times

Instrument Specification



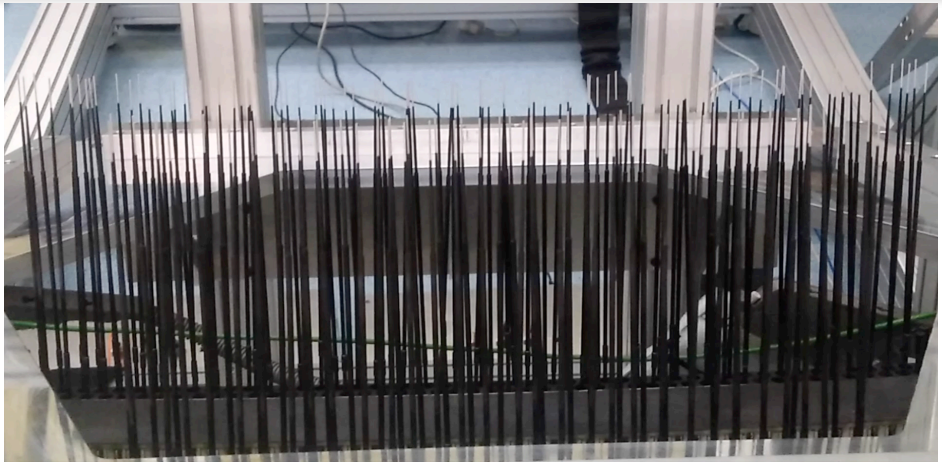
Specification	Design value
Field-of-View (hexagon)	~4.2 degree^2 (⌀>2.6˚)
Multiplex fiber positioner	2436
Medium Resolution Spectrographs (2x) # Fibres Passband Velocity accuracy	R~4000–7500 812 fibres (2x) 370-950 nm < 1 km/s
High Resolution Spectrograph (1x) # Fibres Passband Velocity accuracy	R~20,000 812 fibres 392.6–435.5 nm, 516–573 nm, 610–679 nm < 1 km/s
# of fibers in ⌀=2’ circle	>3
Fibre diameter	⌀=1.45 arcsec
Area (first 5 year survey)	>2h x 18,000 deg^2
Number of science spectra (5 year)	~75 million of 20 min

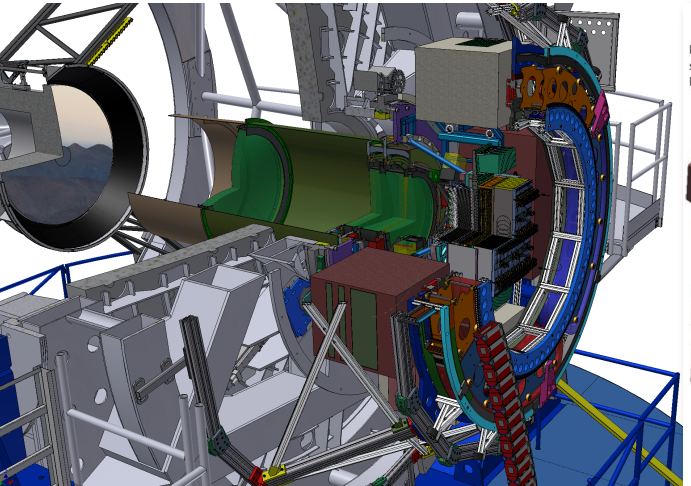
AESOP Fiber Positioner

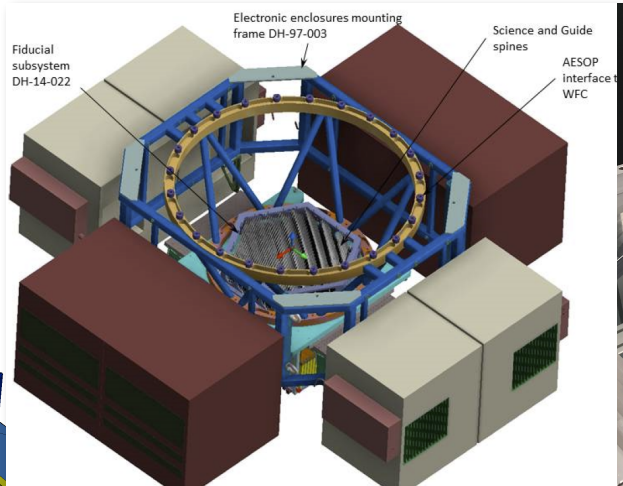
2436 Fiber Probes
-patrol diameter 2.4x pitch
-minimum separation ~20”
-reconfiguration time <2 min during CCD readout

24 Fiducials

12 Guide Probes







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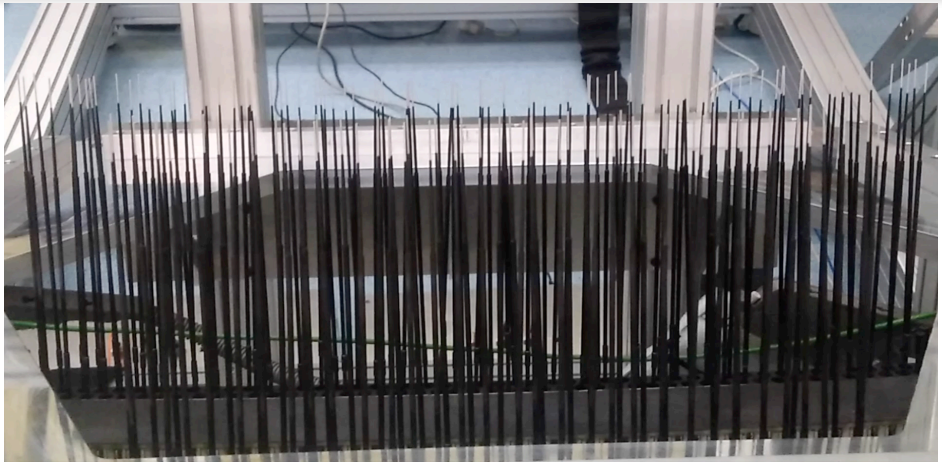

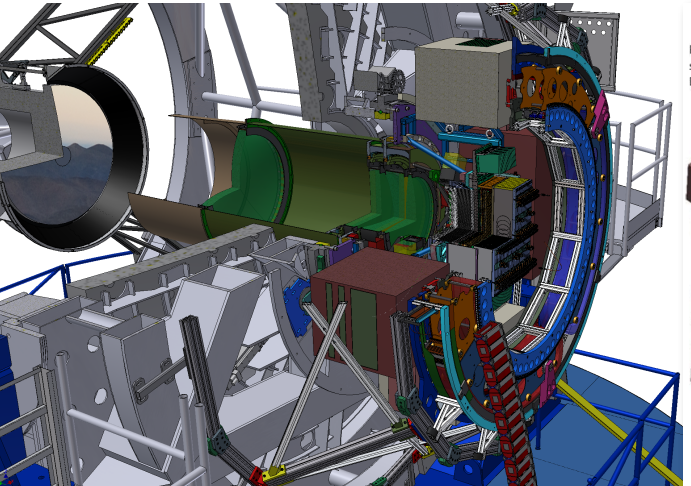

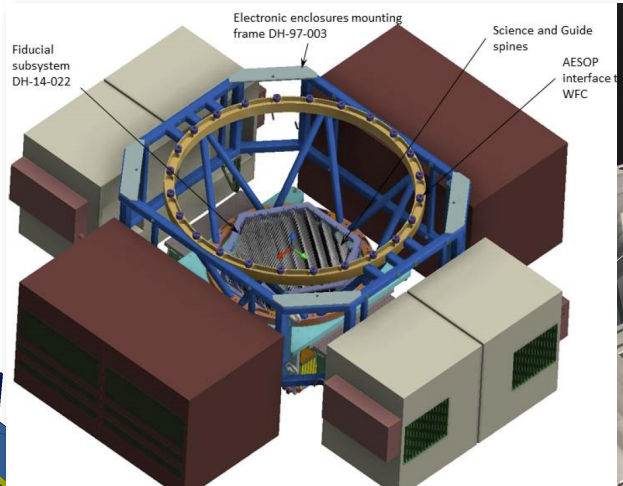

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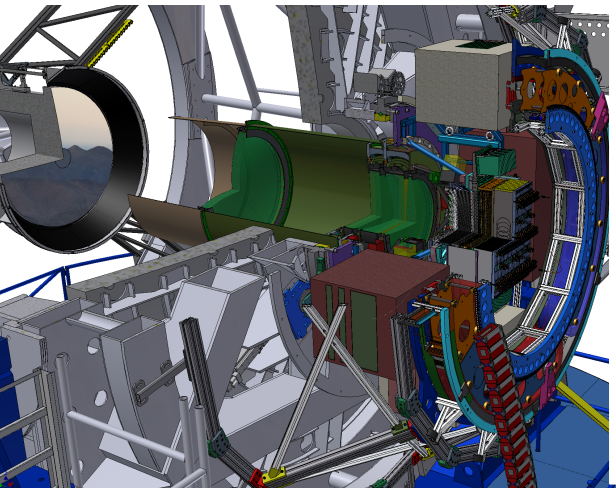

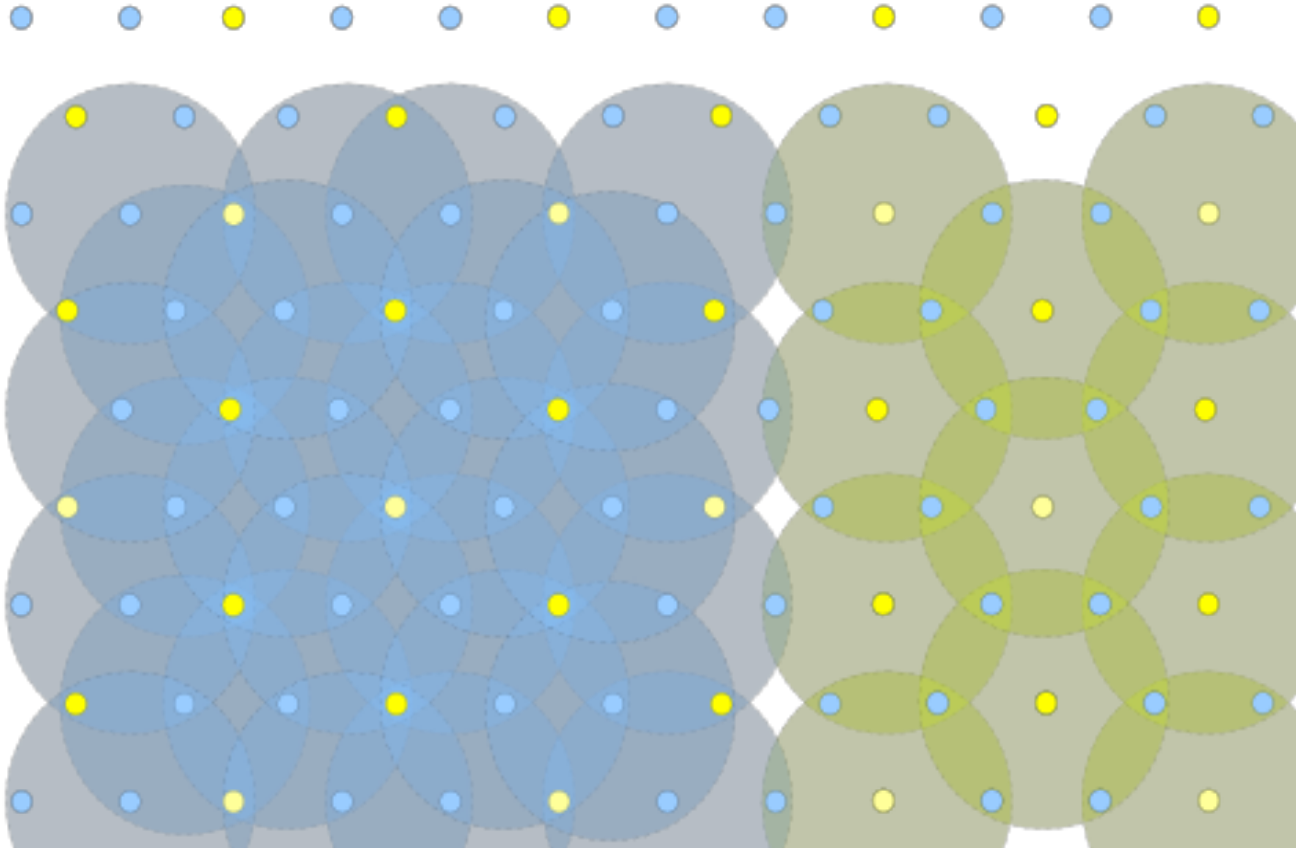

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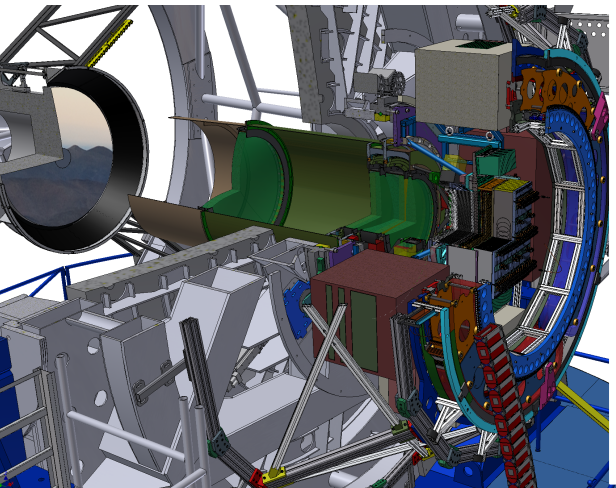
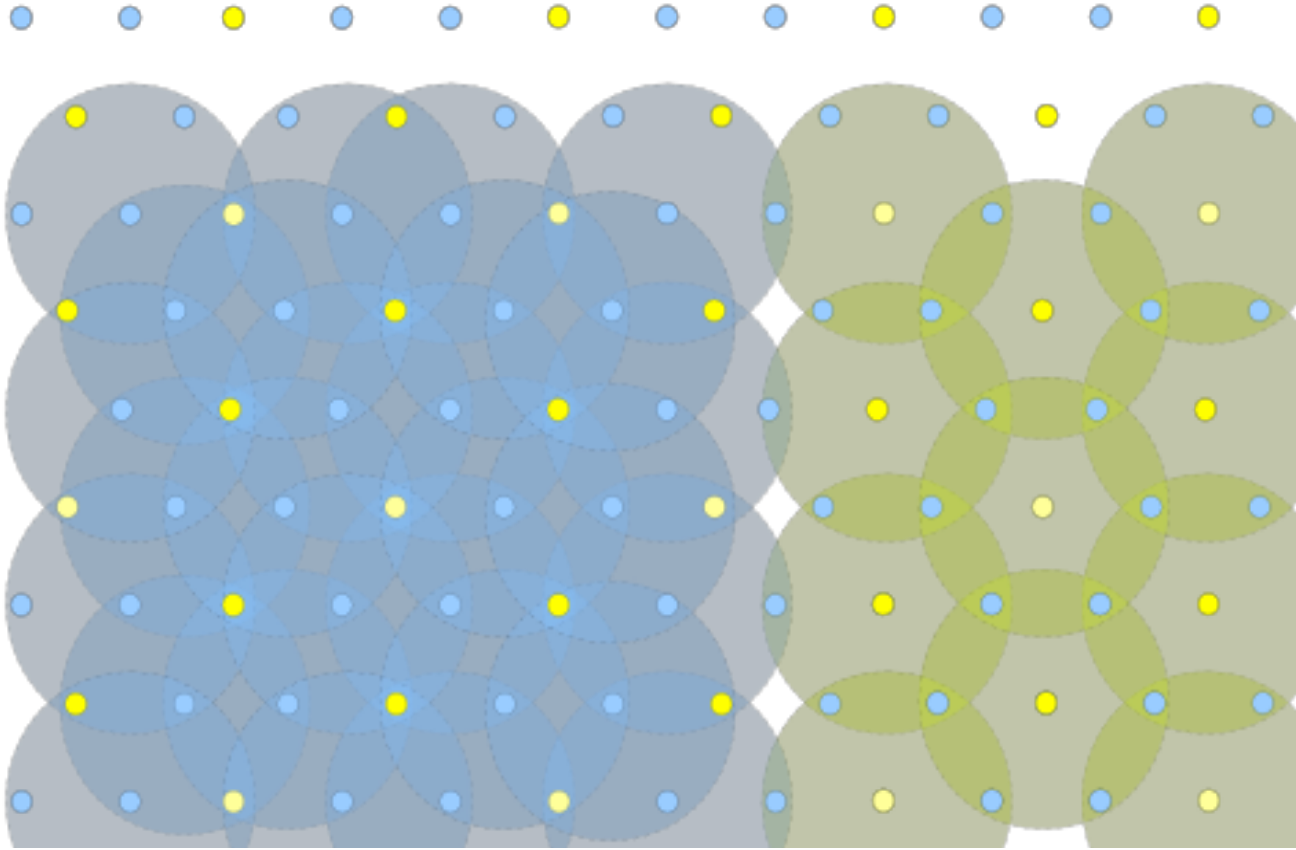
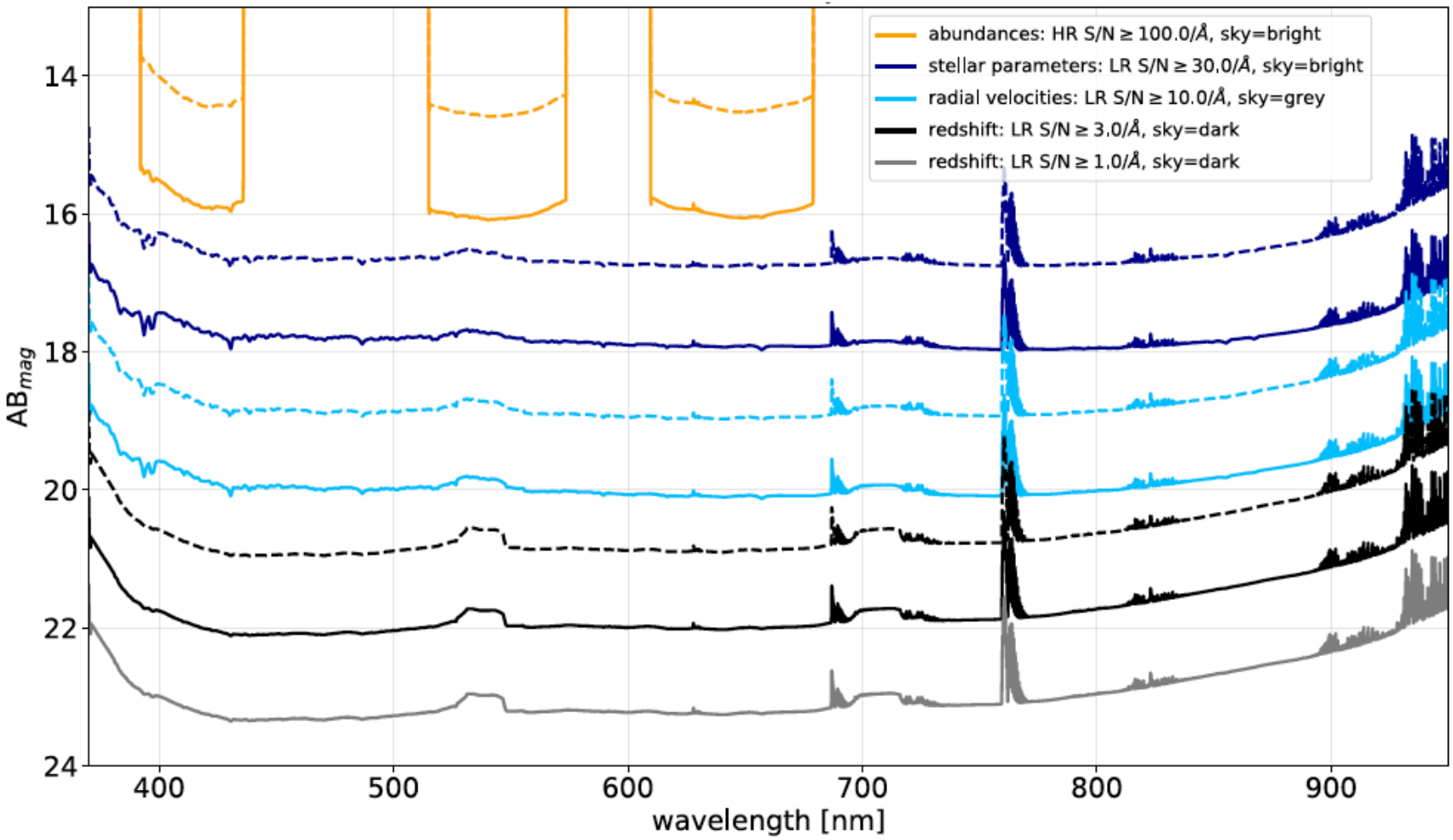


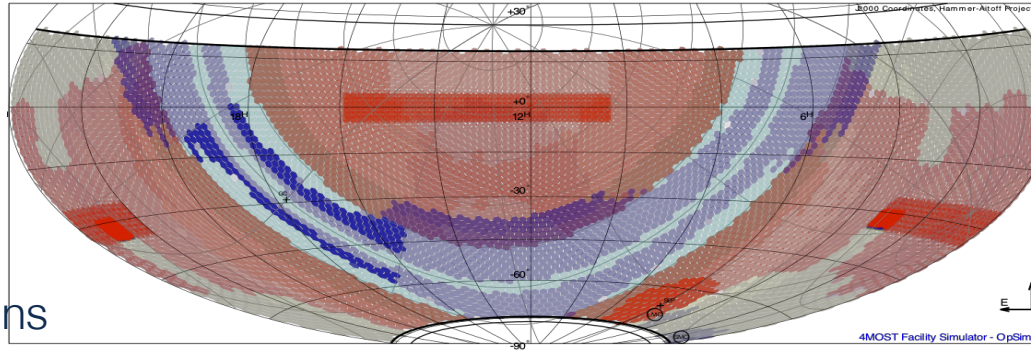


20 minutes — 120 minutes



4MOST Operations

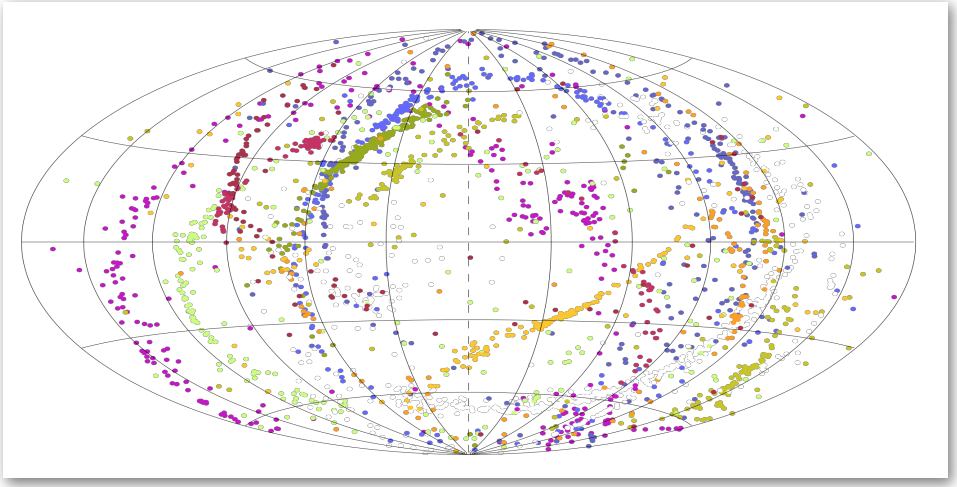
- Unique operations model for MOS instruments suitable *for most* science cases
- 4MOST program defined by *Public Surveys* of 5 years
- Surveys will be defined by *Consortium* and *Community*
- All Surveys will run ***in parallel***
  - Surveys share fibres per exposure for increased efficiency
- *Consortium Key Surveys* will define observing strategy
  - Millions of targets all sky
  - Fill all fibres
- *Add-on Surveys* for smaller surveys
  - Small fraction fibers all sky or
  - dedicated small areas
  - 10^3 to 10^6 targets
- Several passes of sky with 10, 20, 30 mins

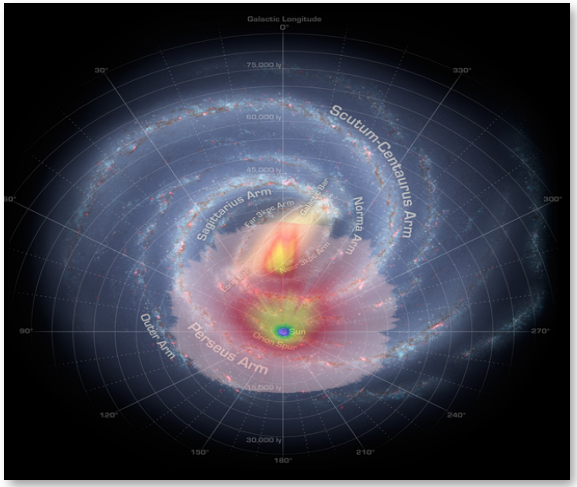


Ten Consortium Surveys

No	Survey Name	Survey (Co-)PI
S1	Milky Way Halo LR Survey	Irwin (IoA) , Helmi (RuG)
S2	Milky Way Halo HR Survey	Christlieb (ZAH)
S3	Milky Way Disk and Bulge LR Survey	Chiappini, Minchev, Starkenburg (AIP)
S4	Milky Way Disk and Bulge HR Survey	Bensby (LU), Bergemann (MPIA)
S5	Galaxy Clusters Survey	Finoguenov (MPE)
S6	AGN Survey	Merloni (MPE)
S7	Galaxy Evolution Survey (WAVES)	Driver (USW), Liske (HHU)
S8	Cosmology Redshift Survey	Richard (CRAL), Kneib (EPFL)
S9	Magellanic Clouds Survey	Cioni (AIP)
S10	Time-Domain Extragalactic Survey (TiDES)	Sullivan (Southampton)

Galactic Archeology

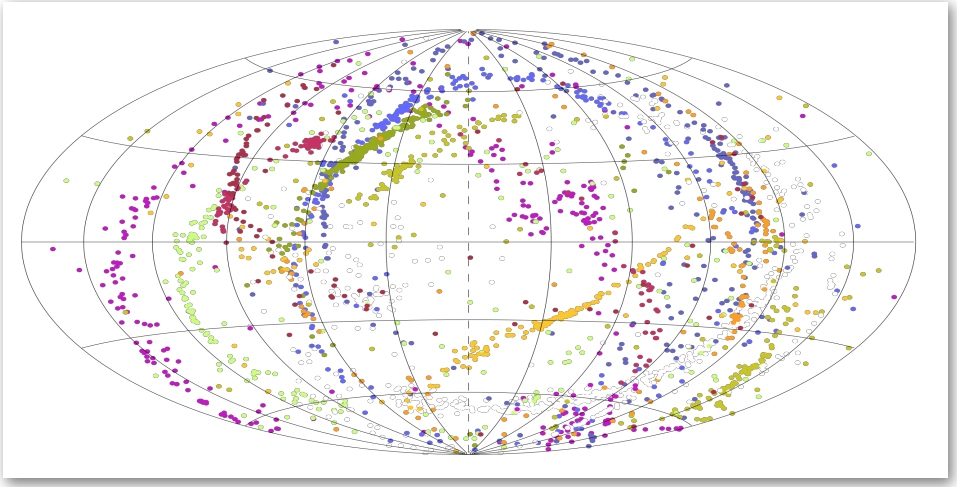


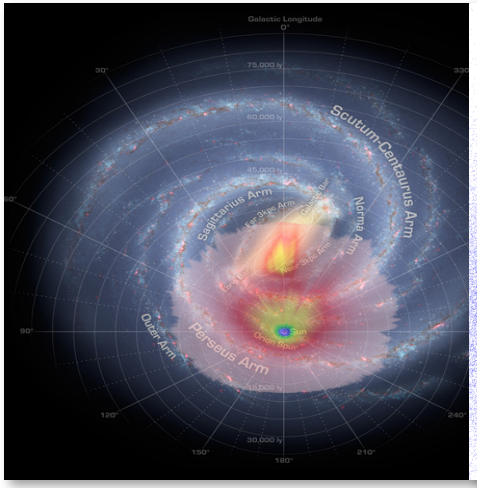


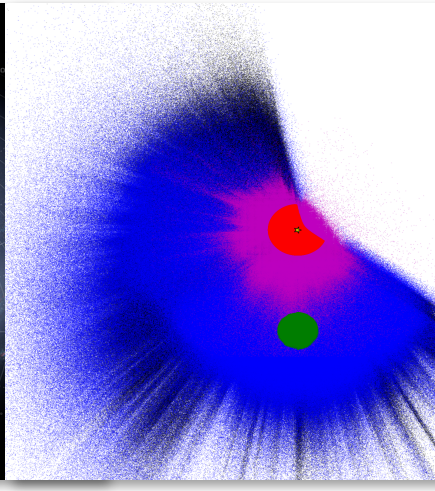
- Map the Dark Matter substructure of the Milky Way and Magellanic Clouds halos
- Chemo-dynamical substructure of the halo: Accreted versus in situ formation
- Importance of population migration

- Formation and dynamical evolution of the Milky Way disk and bulge components
- Constraints on the very first populations of stars (Pop III, IMF, rotation)
- Properties of exoplanet host stars

Galactic Archeology







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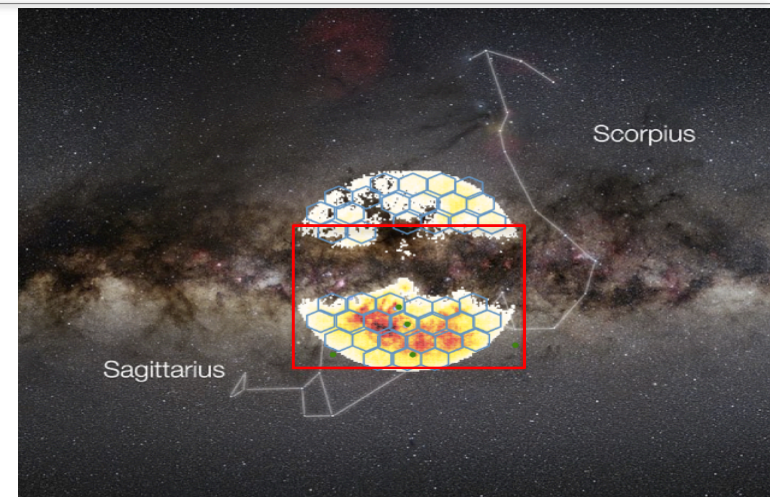
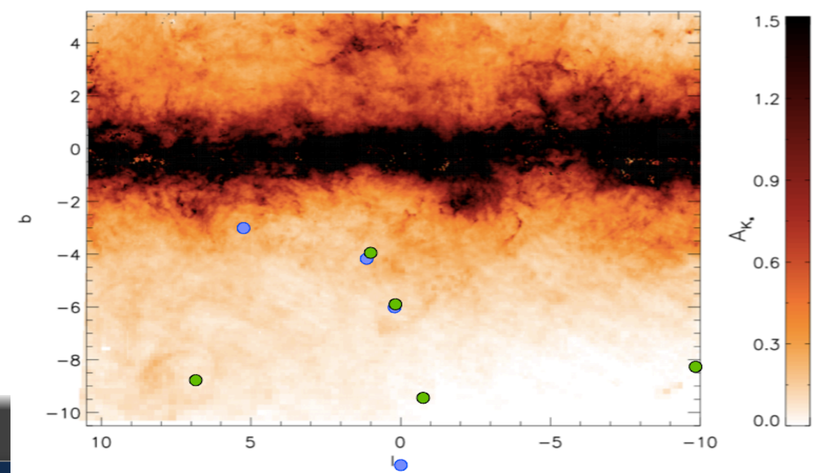
Milky Way bulge chemo-dynamics

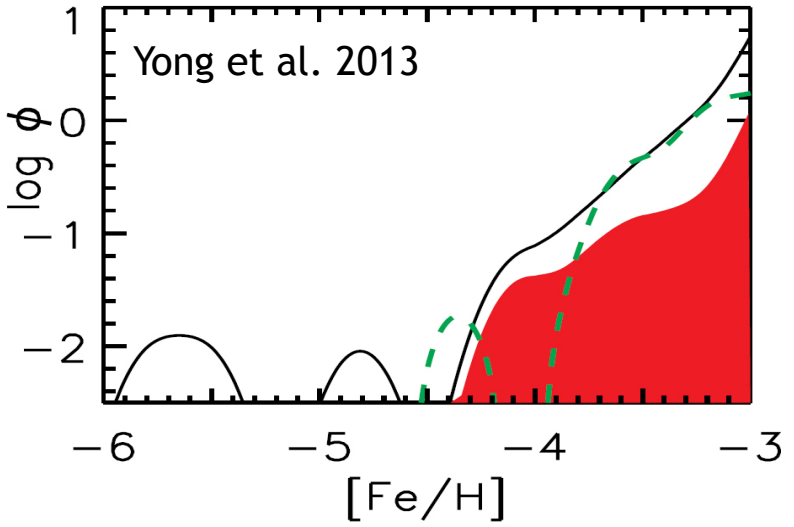
- Two formation scenarios:
  - Collapse/merging of proto-galaxies
  - Bar instability, disk buckling
- Observe ~150,000 giants, covering inner 1.5 kpc of the Milky Way
- Full coverage to understand effects of reddening and substructure
- Bulge-halo-thick disk connection?
- Search for chemo-dynamical substructures

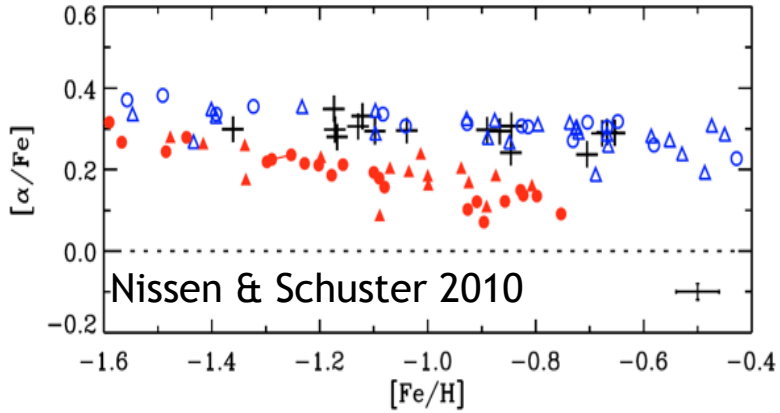




High Res: Milky Way halo

- Observe ~100,000 halo stars with HR spectrograph
- Metallicity distribution function
  - Find most metal-poor stars
  - Constraints on Pop III stars (IMF, rotation)
- Chemo-dynamical substructure
  - Identify stream of tidally disrupted dwarfs
  - Early chemical enrichment of streams (depends on a few stars)
  - Accreted versus in situ formation
- Sample:
  - All stars m_V<15.5 and |b| ≳ 40°





4MOST: Wide-field, high-multiplex optical spectroscopic survey facility for ESO

- Status:
  - ESO Council approved 4MOST in June 2015, ESO contract signed
  - Long-Lead-Items being constructed, Final Design Review 1 May 2018 (FDR-2 Jan 2019)
  - Operations start on **VISTA** telescope late-2022 (at least 2x 5 year)
- Science:
  - Cosmology, galaxy evolution, high-energy, transients, and Galactic science
  - Complement large-area space missions: Gaia, eROSITA, Euclid, PLATO
  - Complement ground-based surveys: VISTA, VST, DES, LSST, SKA, etc.
- Survey facility:
  - Consortium delivers instrument, science operations, data products, science
  - Run all-sky 5 year public surveys in parallel, with yearly data releases
  - Key surveys organised by consortium in coordination with community
  - **Add-on surveys from community and Chile through ESO peer-reviewed applications**

Preparing for 4MOST

http://www.eso.org/sci/meetings/2019/4MOST.html

Garching 5-6 May 2019

Community workshop introducing
ESO's next-generation spectroscopic survey facility.

The 4MOST survey programme will consist of **both** Consortium Surveys **and Community Surveys,** ideally with a high degree of complementarity, both scientifically and in terms of observing efficiency.

The process of selecting the Community Surveys will be initiated by a "Call for Letters of Intent for Public Spectroscopic Surveys", to be issued by ESO in mid-2019.

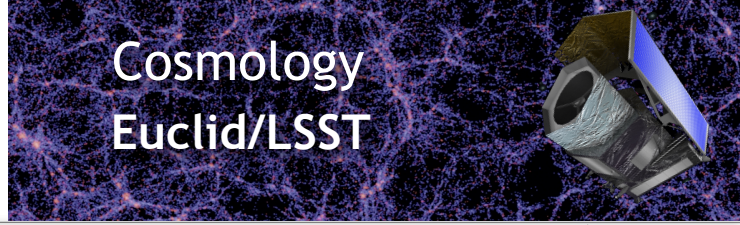
Community Surveys

- Fibre-hour share 30%, all surveys ESO Public Surveys

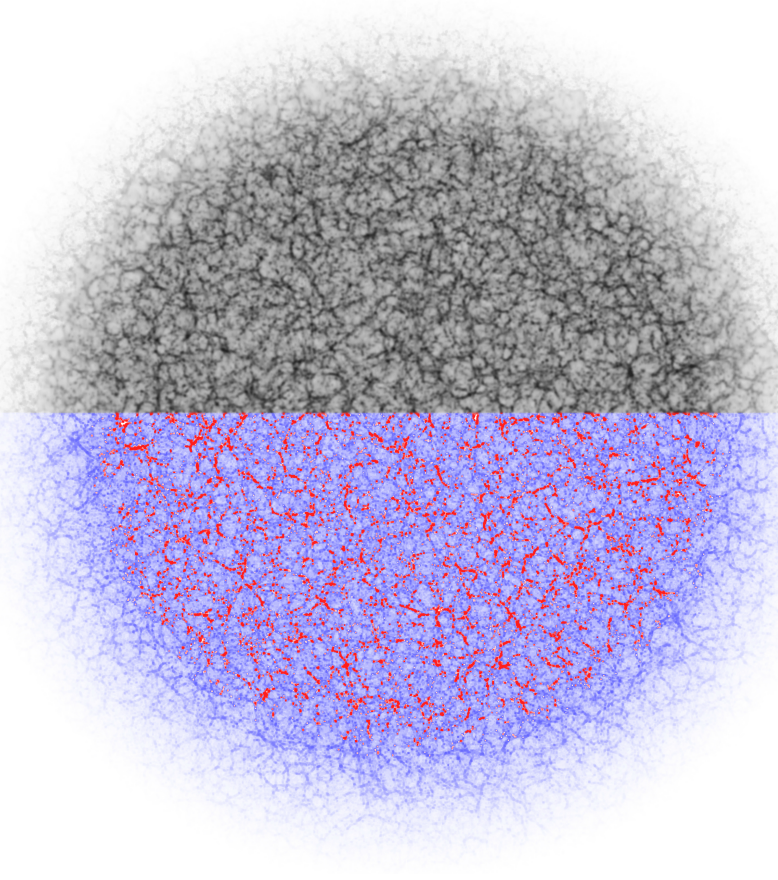
- Participating Surveys:
  - Become equal partner in Science Team with Consortium Surveys
  - Share survey strategy, OBs, L1 data products, selection function analysis, and optionally L2 data reduction pipelines
  - Can use all Consortium data (and vice versa), but core science protected

- Non-participating Surveys:
  - Receive own observing nights
  - Prepare own OBs, receive only L1 data products
  - Have no access to Consortium and Community Participating Survey data
  - Target duplication policy TBD

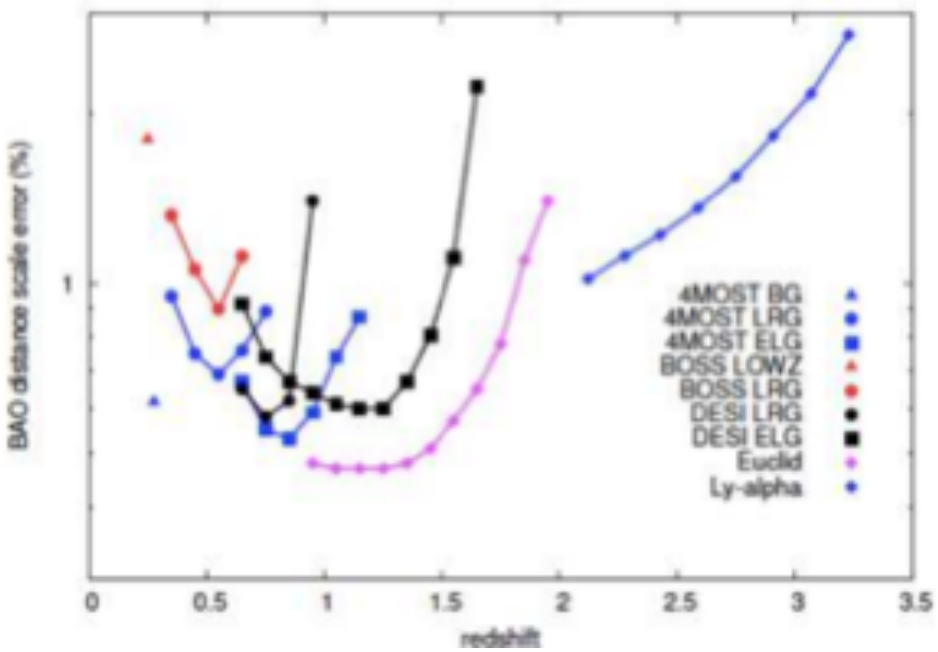
Cosmology

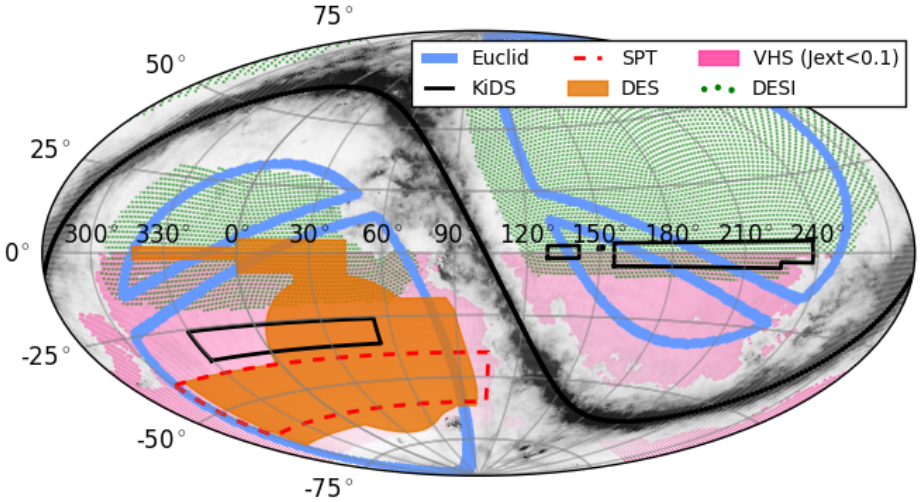


- *Dark Energy* and *General Relativity* constraints by measuring cosmic expansion history and growth of structure:
  - **BAO and RSD**: LRGs, ELGs, AGN, Lyα forest
  - **Weak Lensing**: Photo-z calibrations, characterize the foreground, combine with RSD to reduce uncertainties
  - **Galaxy Clusters**: Redshifts and velocity dispersions of Galaxy Clusters
  - **CMB synergies**: kinetic Sunyaev-Zel'dovich (kSZ) effect, and weak gravitational lensing of the CMB
  - **SNe Ia**: DES/LSST live SNe Ia and host galaxies (50k transients/year)
- Concentrate on redshifts z<~1 and z>2.4 to complement Euclid



Cosmology Survey





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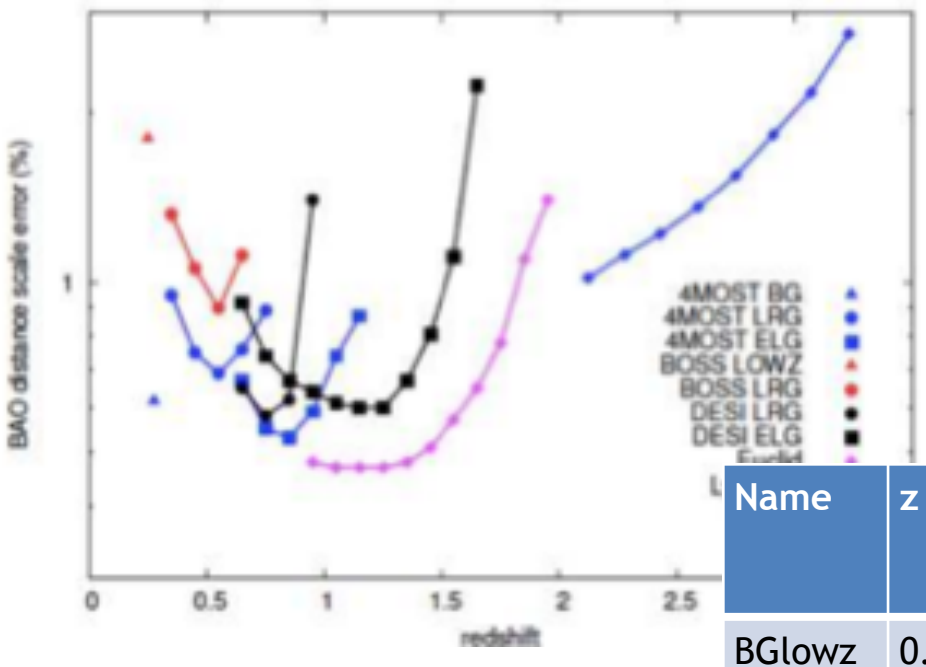
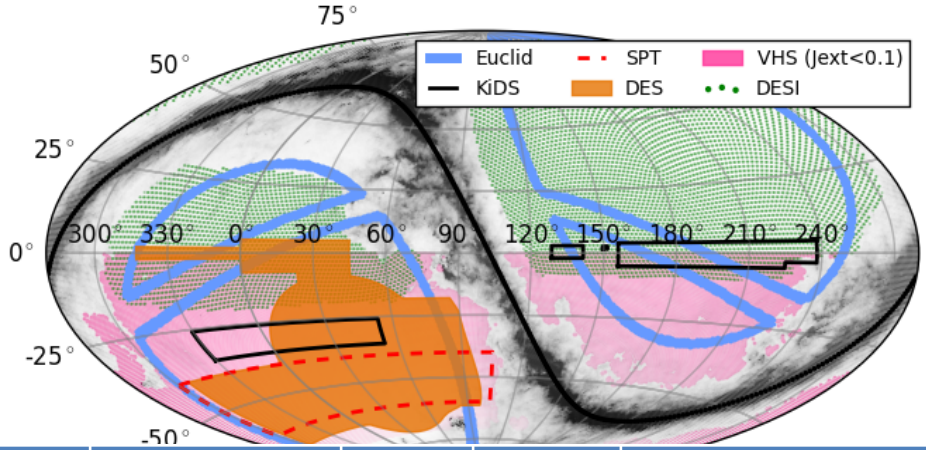
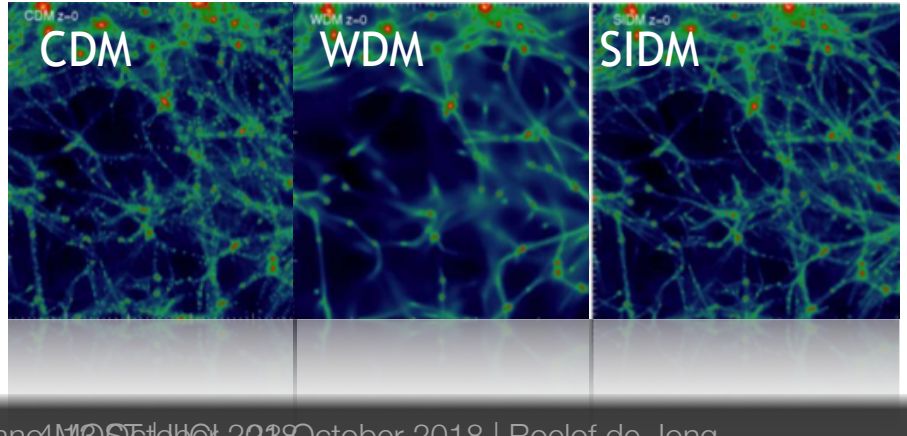


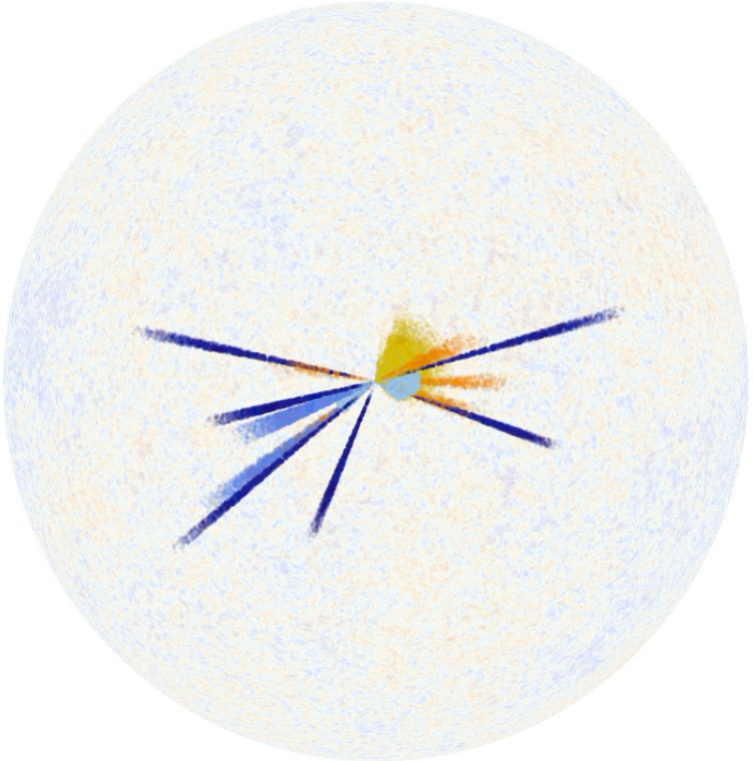


Name	z	Mag. range	Area (deg^2)	Density (deg^{-2})	Color selection
BGlowz	0.15-0.4	16.0 < J < 18.0	7500	250	*J–Ks*, *J–W1*
BGhighz	0.4-0.7	18.5 < J < 19.5	7500	400	*J–Ks*, *J–W1*
ELG	0.6-1.1	22.0 < g < 23.6	5000	1200	*g–r*, *r–i*

Galaxy and Dark Matter Evolution

- Galaxy formation to dwarf satellite scale, halo occupation
- Evolution of mass & energy budget for z<1
- Growth of structure on 1kpc-10Mpc scales for z<1





Galaxy and Dark Matter Evolution

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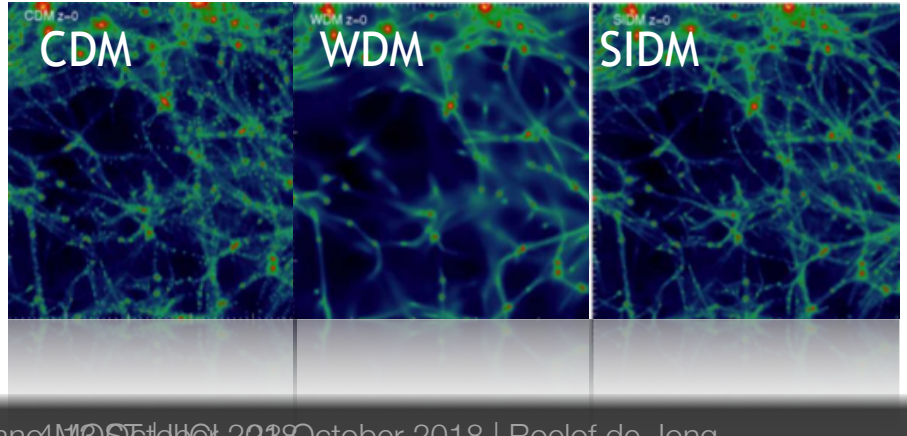

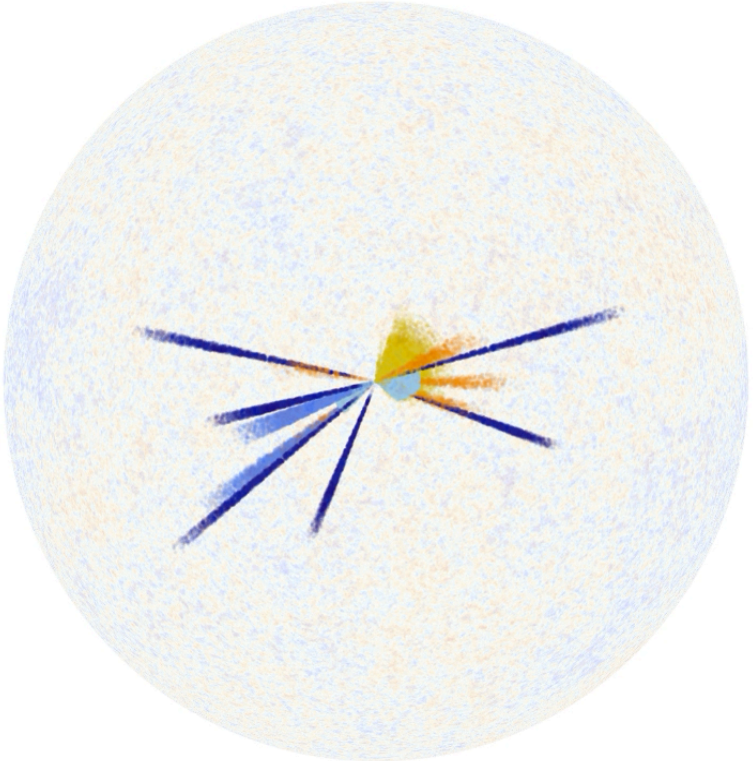

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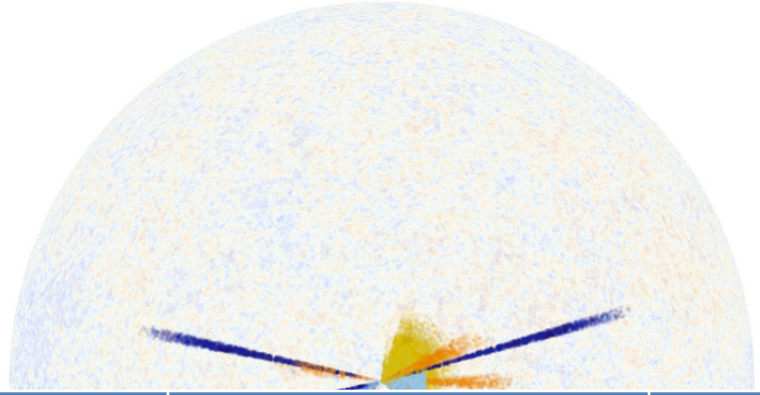

Survey Name	RA (degrees)	Dec (degrees)	Selection	Targets
Wide(North)	157 < RA < 225	−3 < Dec < +4	m_z< 21.5 mag, z_{phot} < 0.23	500,000
Wide (South)	−30 < RA < 52.5	−35.9 < Dec < −27	m_z < 21.5 mag, z_{phot} < 0.23	500,000
Deep(G23)	−21 < RA < −9	−35 < Dec < −30	m_z < 21.5 mag, z_{phot} < 0.85	500,000
Deep(DDF1/ELIAS-S1)	8.95	−43.70	m_z < 21.5 mag, z_{phot} < 0.85	100,000
Deep(DDF2/XMMLSS)	35.50	−5.70	m_z < 21.5 mag, z_{phot} < 0.85	100,000
Deep(DDF3/ECDFS)	52.90	−28.00	m_z < 21.5 mag, z_{phot} < 0.85	100,000
Deep(DDF4/E-COSMOS)	150.12	+2.34	m_z < 21.5 mag, z_{phot} < 0.85	100,000
High S/N	DDF2/DDF3/DDF4	DDF2/DDF3/DDF4	$M_* > 10^{9.5} M_\odot$, z_{DEVILS}	8000

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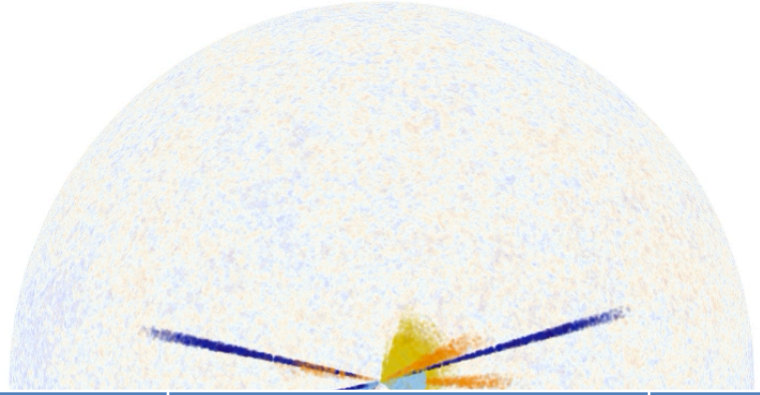

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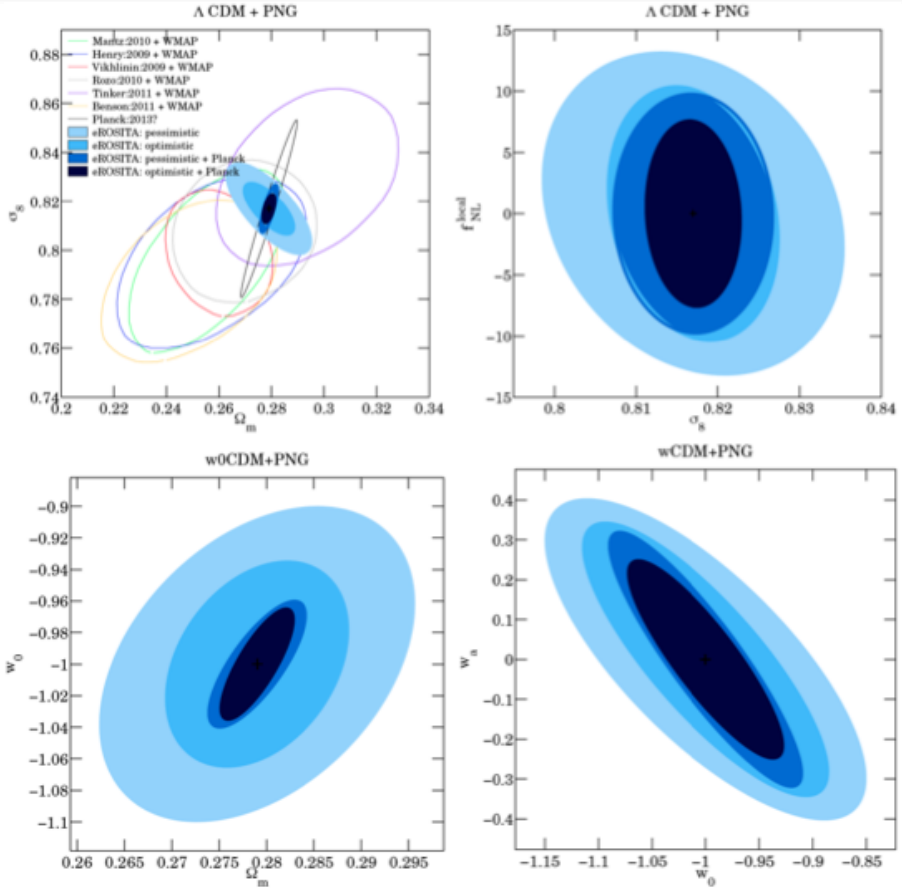
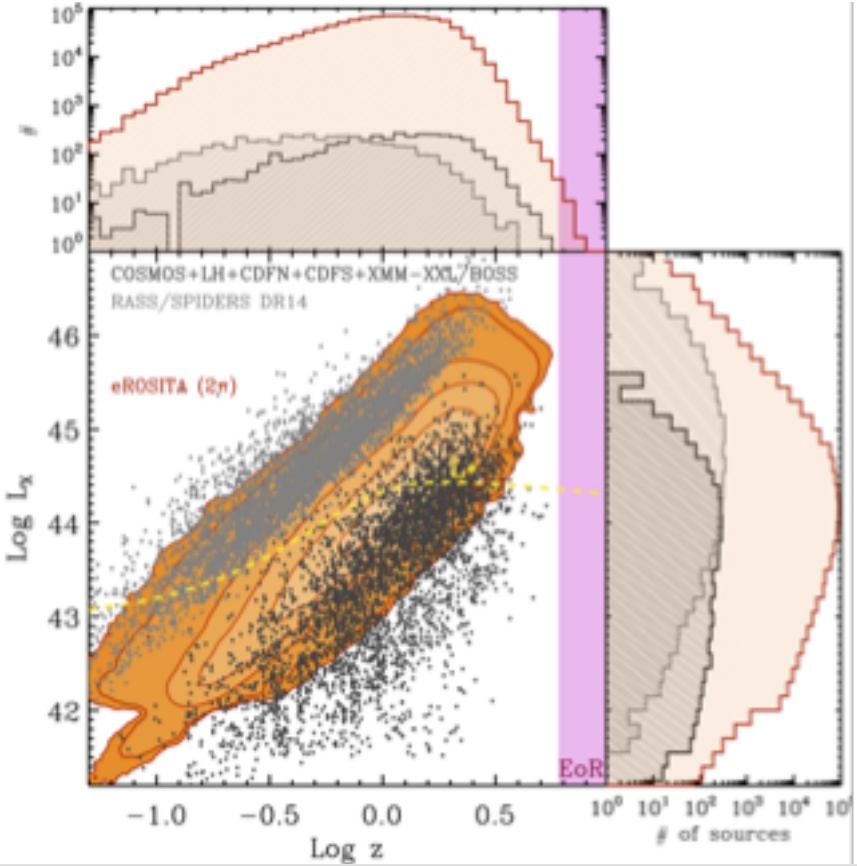
High-energy sky

- Complement eROSITA German - Russian X-ray mission, Launch April 2019
  - 8x all sky survey, 0.5 –10 keV
  - *Dark Matter and Energy, growth of structure*
  - Strong cosmology constraints from Galaxy Cluster evolution
  - AGN evolution and Galaxy-Black Hole co-evolution
  - Active galactic compact objects to constrain stellar evolutionary channels

X-ray galaxy clusters and AGN

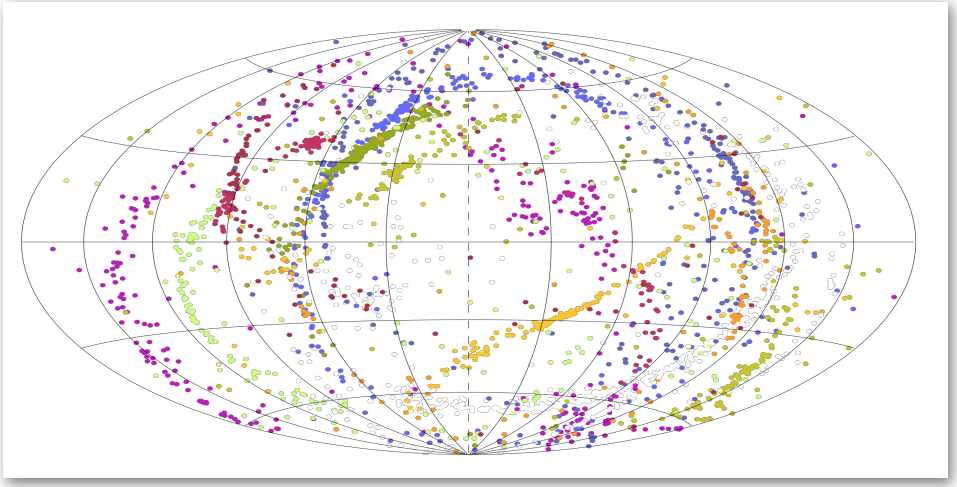


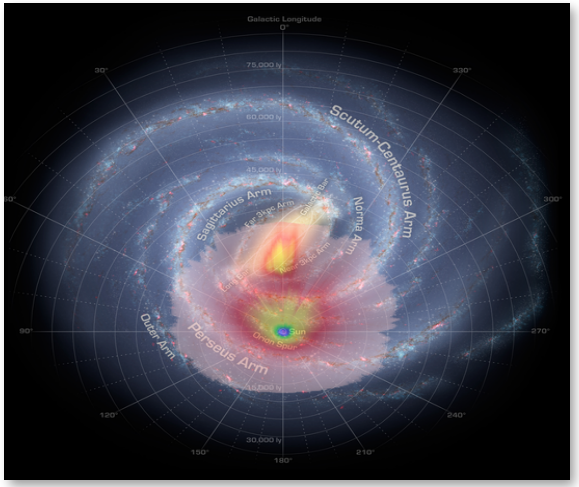


Time-Domain Extragalactic Survey (TiDES)

- Piggy-bag on existing exgal Surveys to:
  - Take spectra of “life” SN Ia candidates observed recently by LSST
  - Obtain redshifts of host galaxies of transients observed in the past
  - Perform reverberation mapping of AGNs in the 4MOST deep fields
- Expected to yield 10,000s of life transients and ~100,000 host redshifts
- Coordinating the sky coverage and cadence of LSST and 4MOST surveys is essential

Milky Way Archeology





- Map the Dark Matter substructure of the Milky Way and Magellanic Clouds halos
- Chemo-dynamical substructure of the halo: Accreted versus in situ formation
- Importance of population migration

- Formation and dynamical evolution of the Milky Way disk and bulge components
- Constraints on the very first populations of stars (Pop III, IMF, rotation)
- Properties of exoplanet host stars

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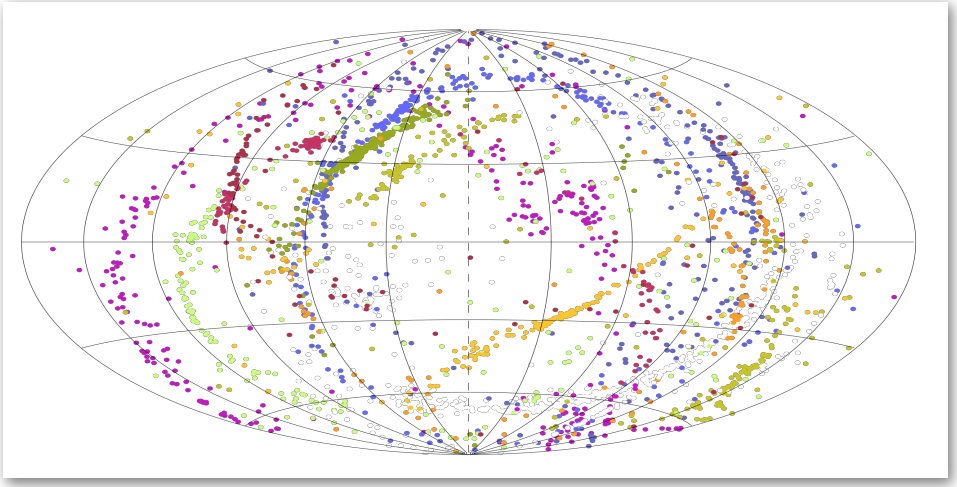

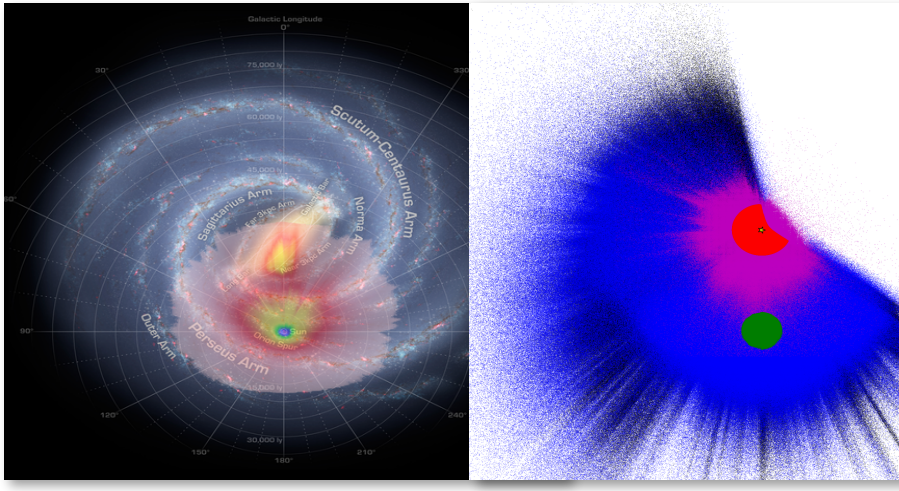

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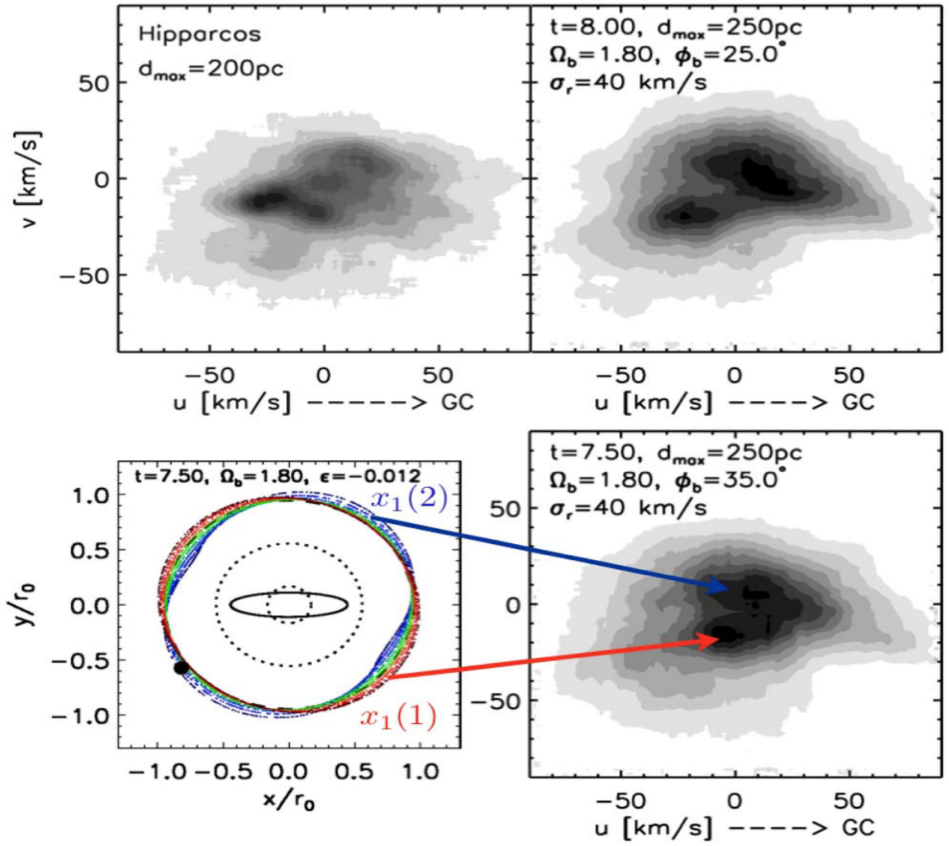
Milky way bar/spiral arms create moving groups in velocity distribution



- So far only done out to 200 pc with Hipparcos
- Gaia combined with 4MOST can do this to ~10 kpc, i.e. in almost half the Milky Way

Minchev et al. (2010)

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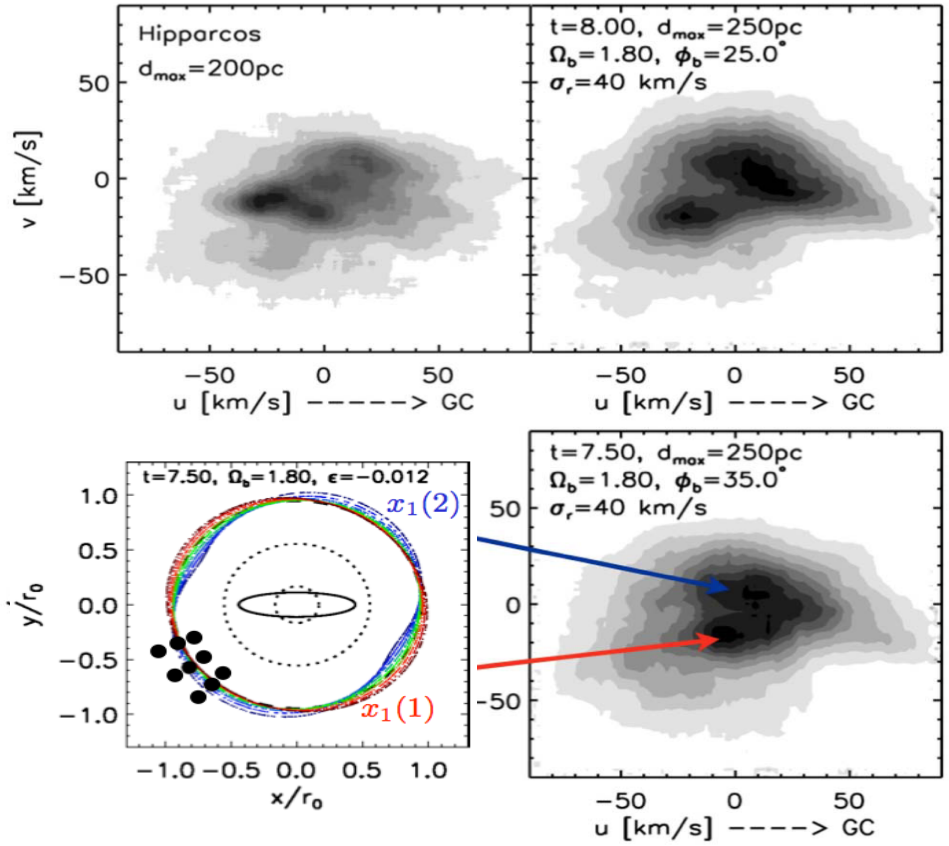

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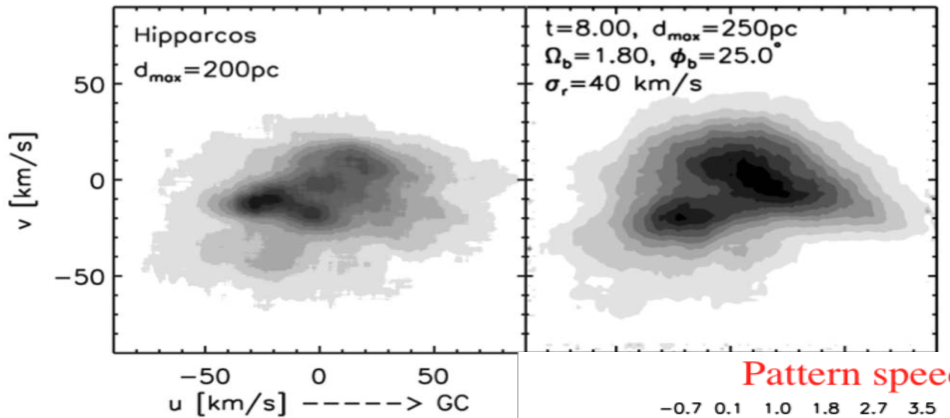
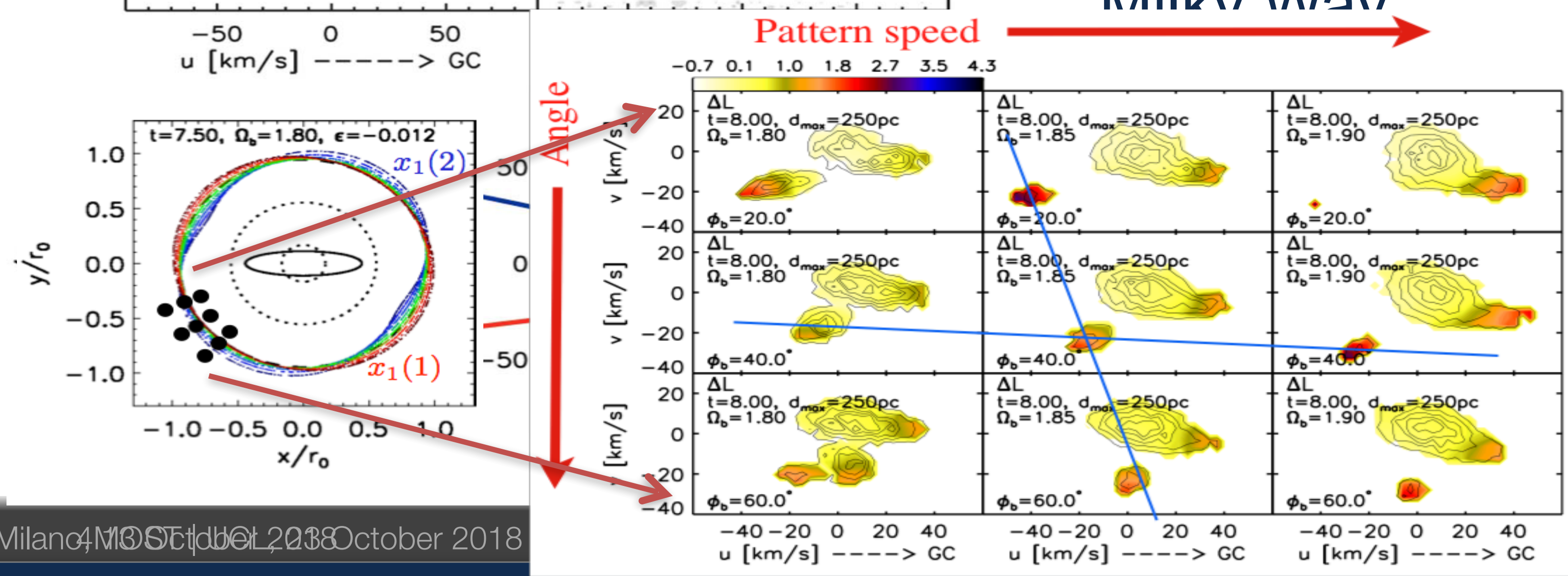
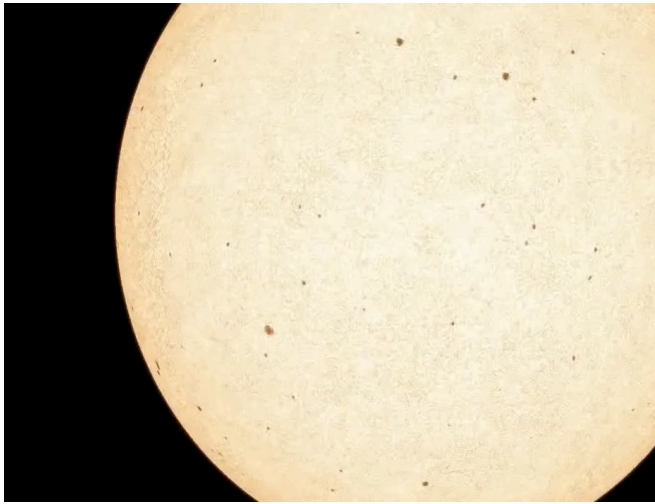
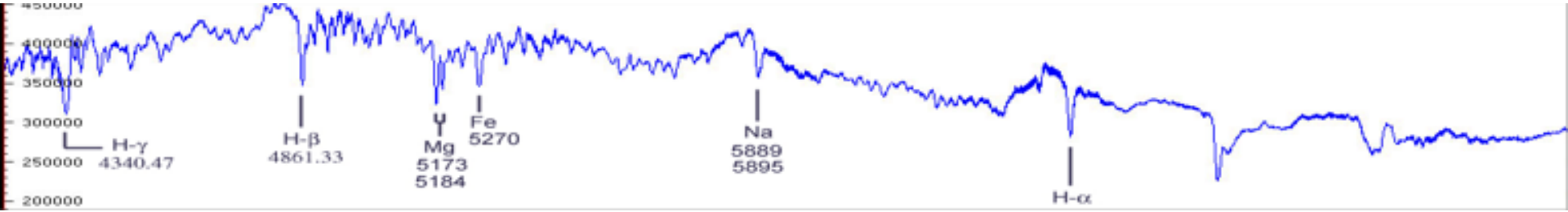




Exo-planet host stars

- In poor conditions 4MOST will take spectra of all bright stars (m_G<12) with DEC<30° every year to measure their chemical composition, velocity and activity
- Exoplanet survey satellite missions like the ESA PLATO mission will monitor 100,000s of stars every minute to find planets transiting and to measure seismic activity
- This allows us to determine the ages of these stars and their connection to other Milky Way stars





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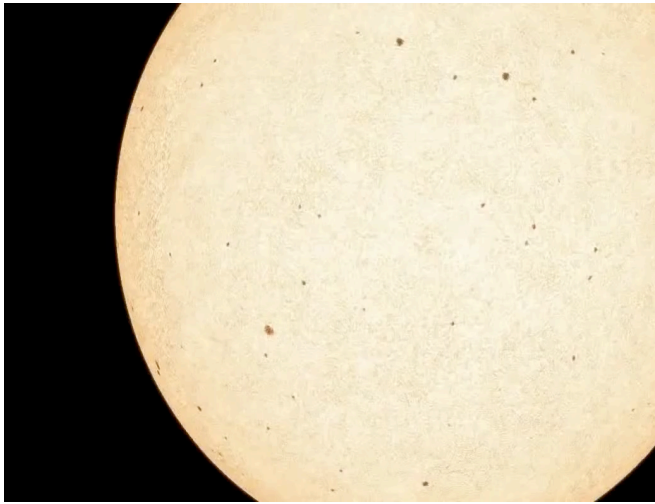

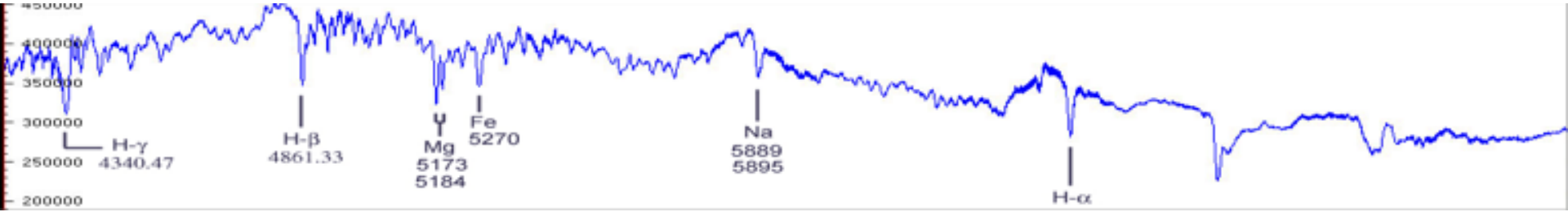

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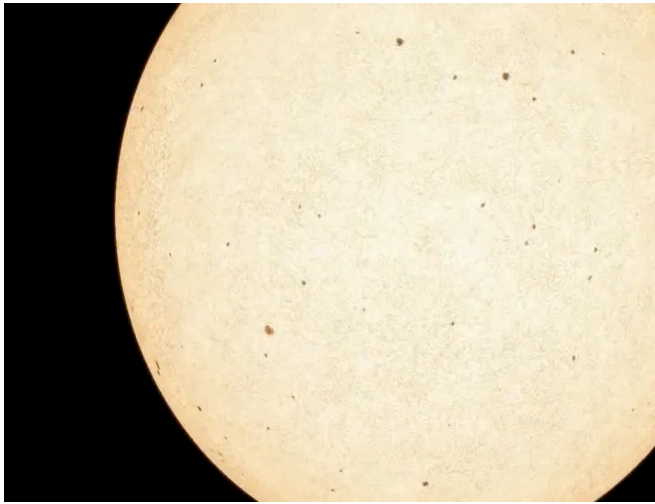
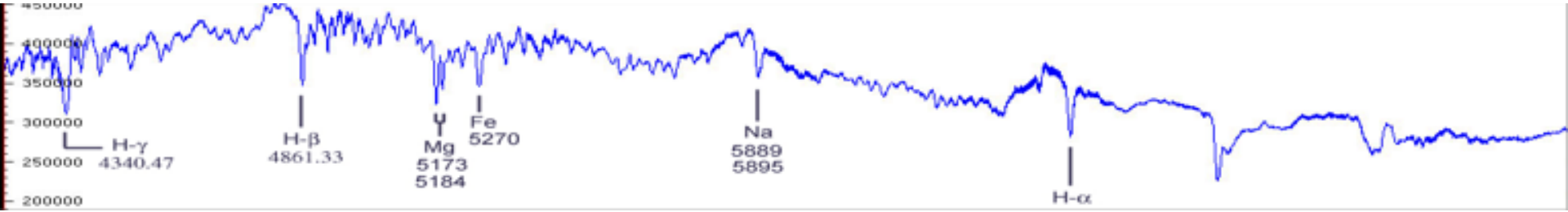
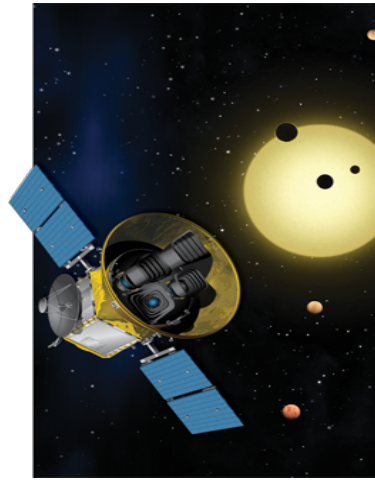
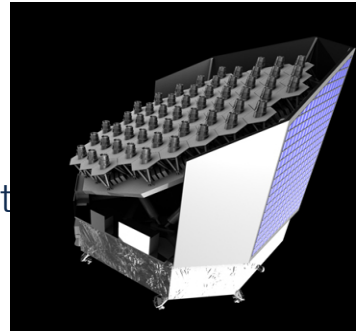




Observing TESS/PLATO bright sample

- Asteroseismology provides core masses and ages (~10% accuracy) for many stellar types, prime calibrators for spectroscopic stellar survey (Miglio et al. 2017)
- Probably prime targets for early Science Verification release
- 4MOST saturates for a 10th mag star in a default 20 min exposure in High Res Spectrograph (HR)
- But 2 min exposures cover 7.5th-11th mag stars in HR
  - Target densities ~10s-600 per pointing
  - ~15 exposures/hour
  - 11th-13th mag stars in parallel LR, on average 400 stars/pointing
- PLATO FoV 2250 deg^2 = ~600 4MOST pointings = ~40 hours = ~4 bright nights
- Entire sky in 40 bright nights
  - Can be done in one year using only the 4 nights around full moon
  - ~1M HR, ~2M LR objects to 13th mag
- Large fraction can also be done in twilight and during poor seeing at no cost to the rest of the science program





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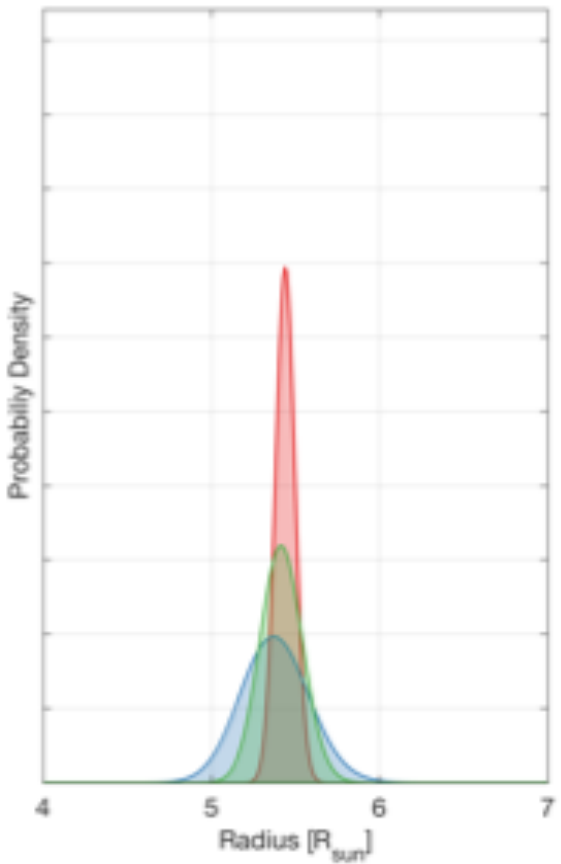
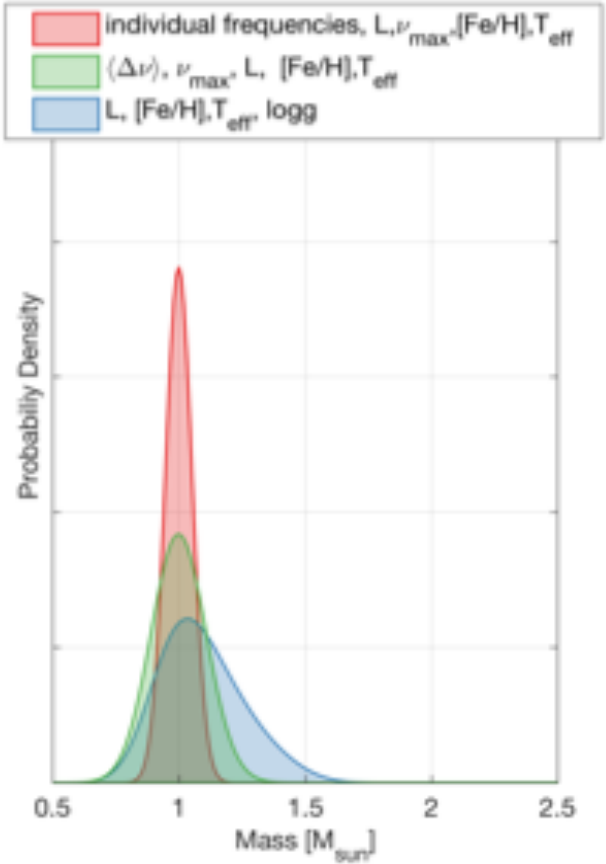
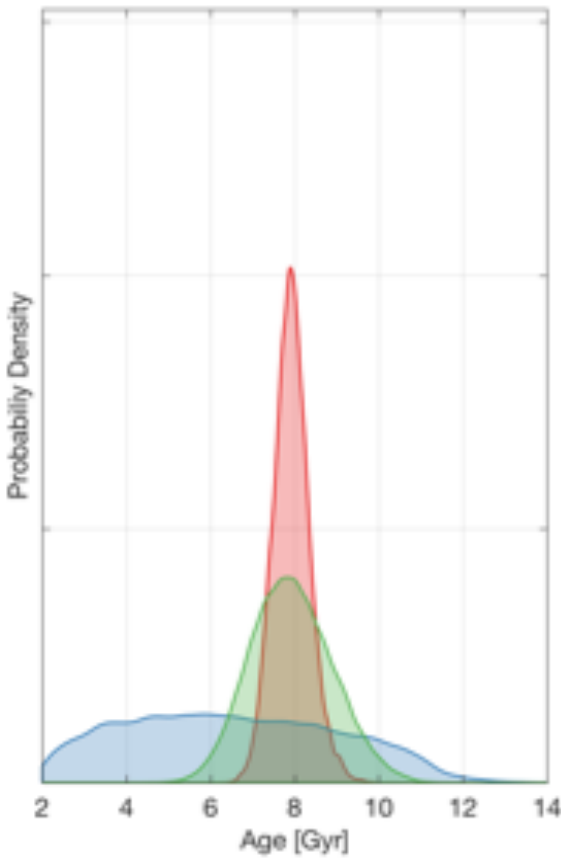
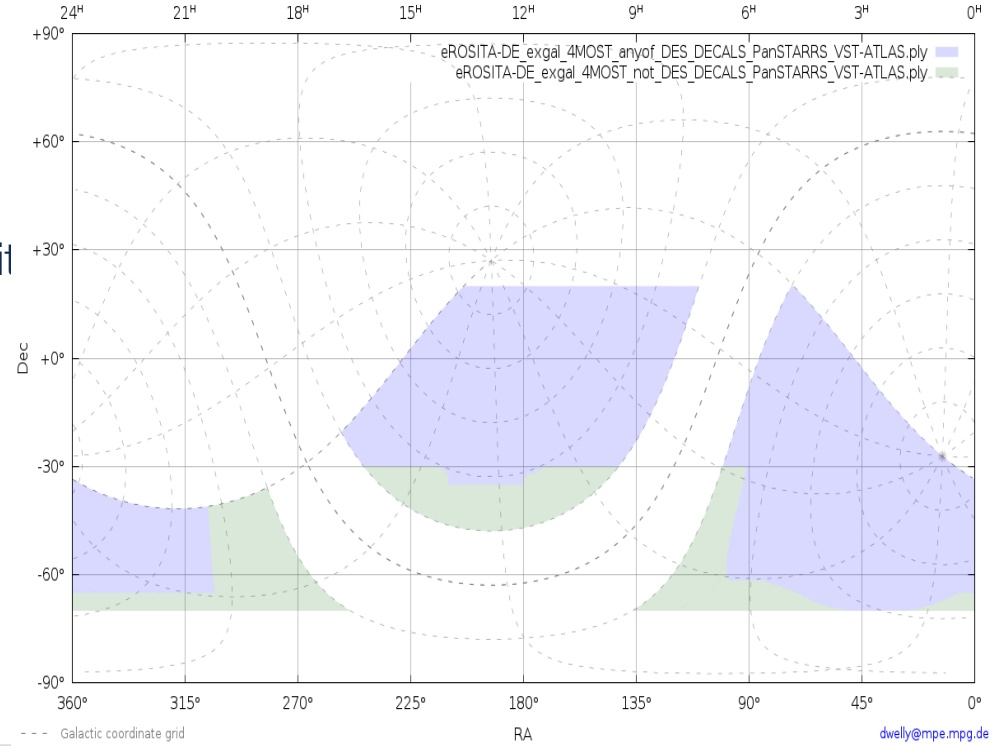






eROSITA galaxy clusters

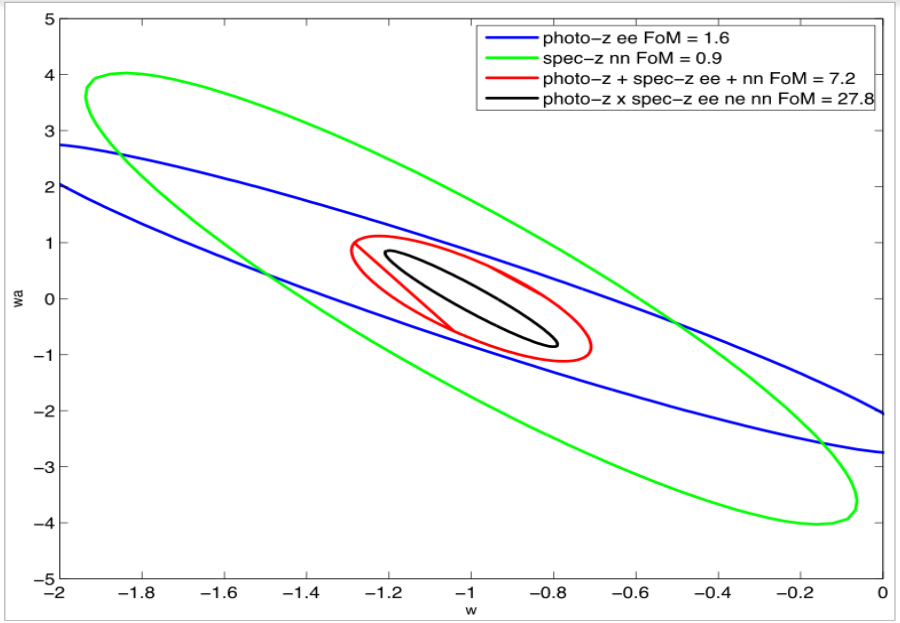
- Survey strategy
  - 13,000 degree^2
  - 200,000 X-ray clusters
  - 2M galaxies
- Primary science goals
  - Cluster mass function evolution wit redshift
  - Evolution of the cluster power spectrum
  - Galaxy evolution in dense environments

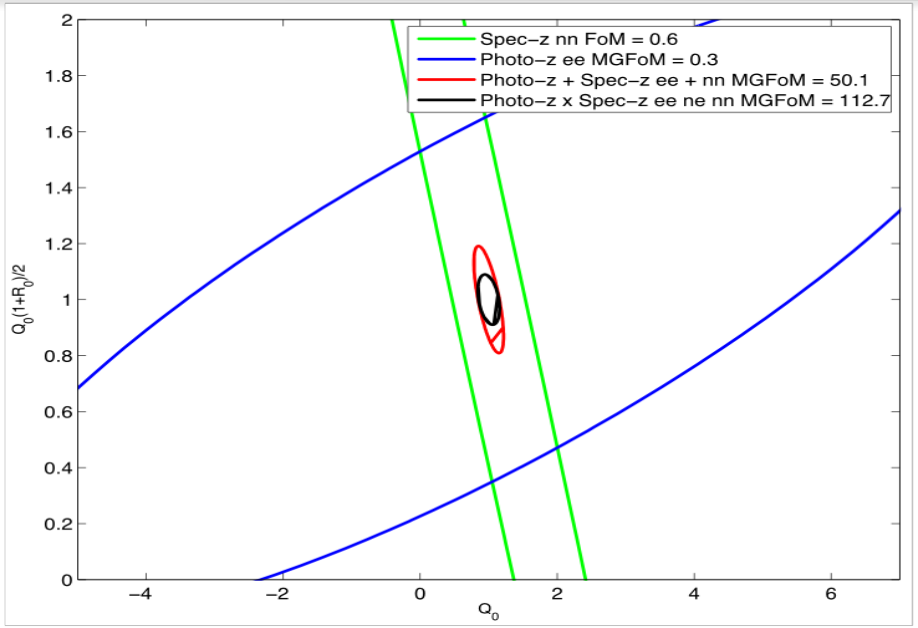


eROSITA AGN

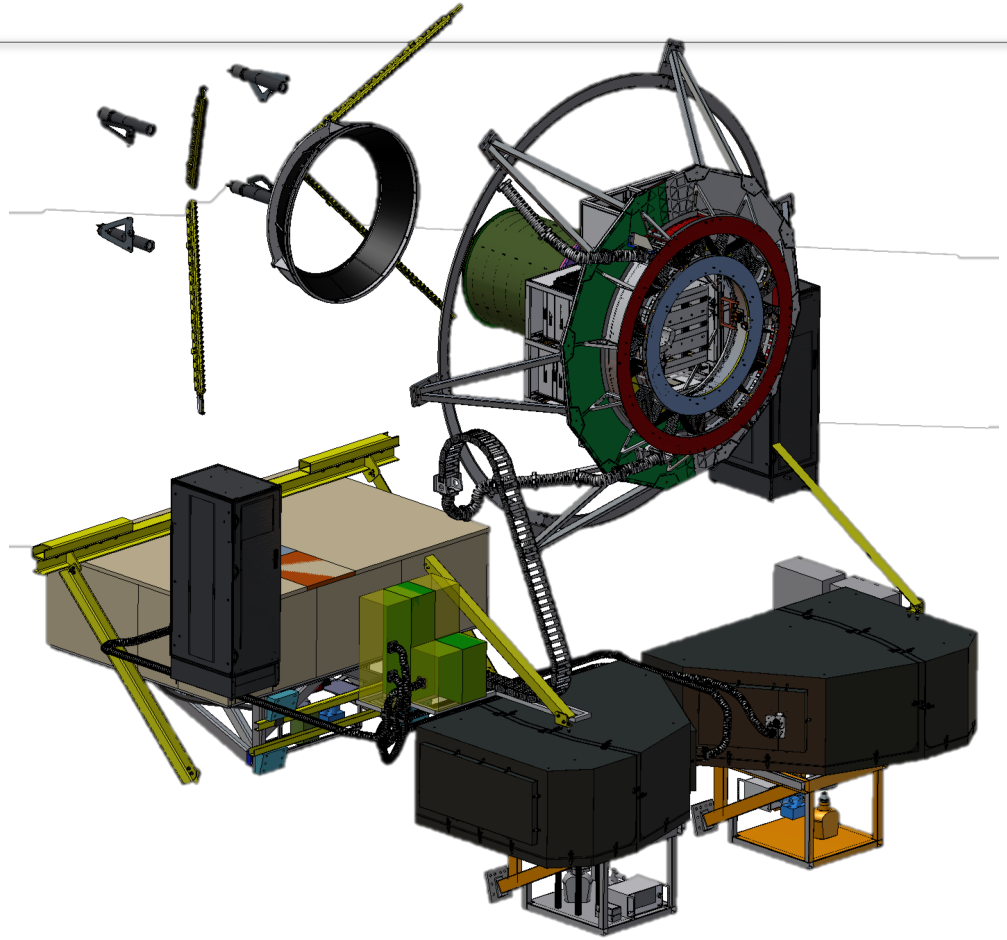
- Survey
  - >800,000 AGN (goal > 1.3 M) with 0<z<6.4
  - ≥ 10,000 (goal ≥13,500) degree^2
- Primary science goals
  - X-ray AGN luminosity function and SMBH evolution
  - Clustering of AGN to constrain the DM halo mass of their hosts
  - BAO with AGN tracers over z~0.9-2.5 to < 2%
  - BH – galaxy co-evolution statistics
  - AGN “standardizable” candles to study the expansion history of the Universe up to the high z

Constraints on Dark Energy (DE) & Modified Gravity (MG) Combined Spectroscopic and Deeper Imaging surveys

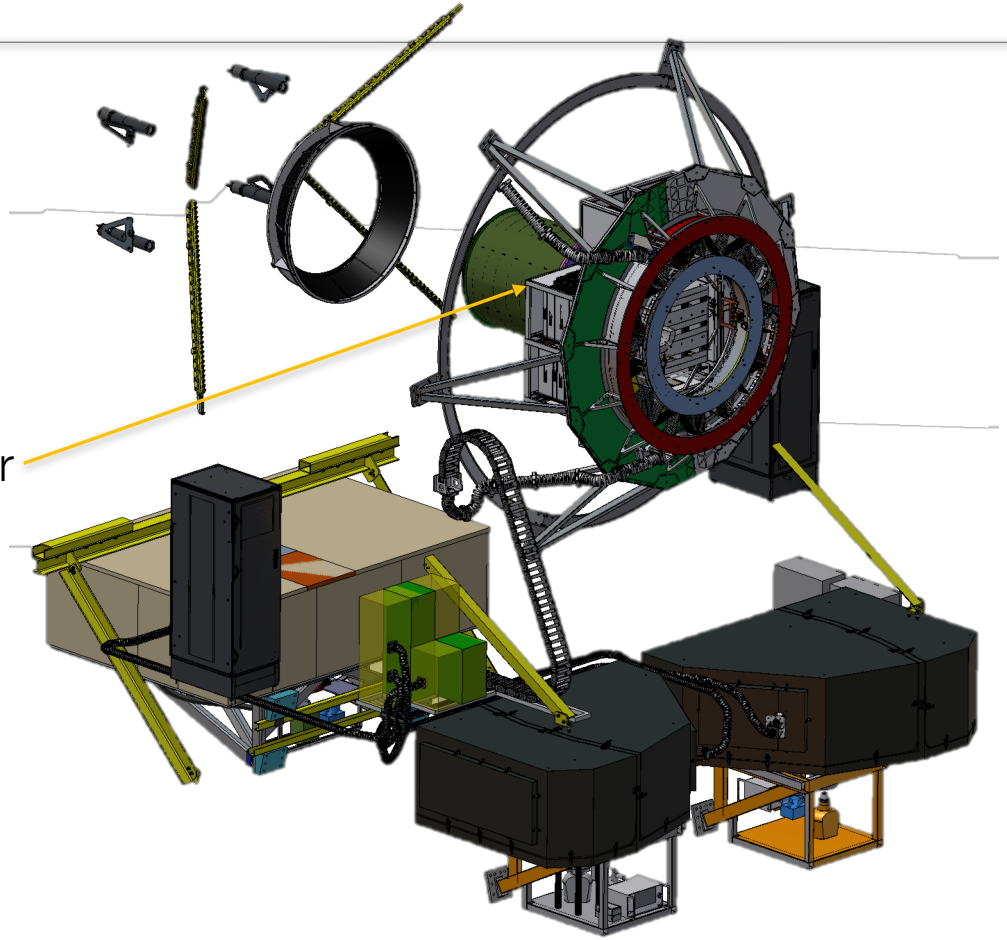


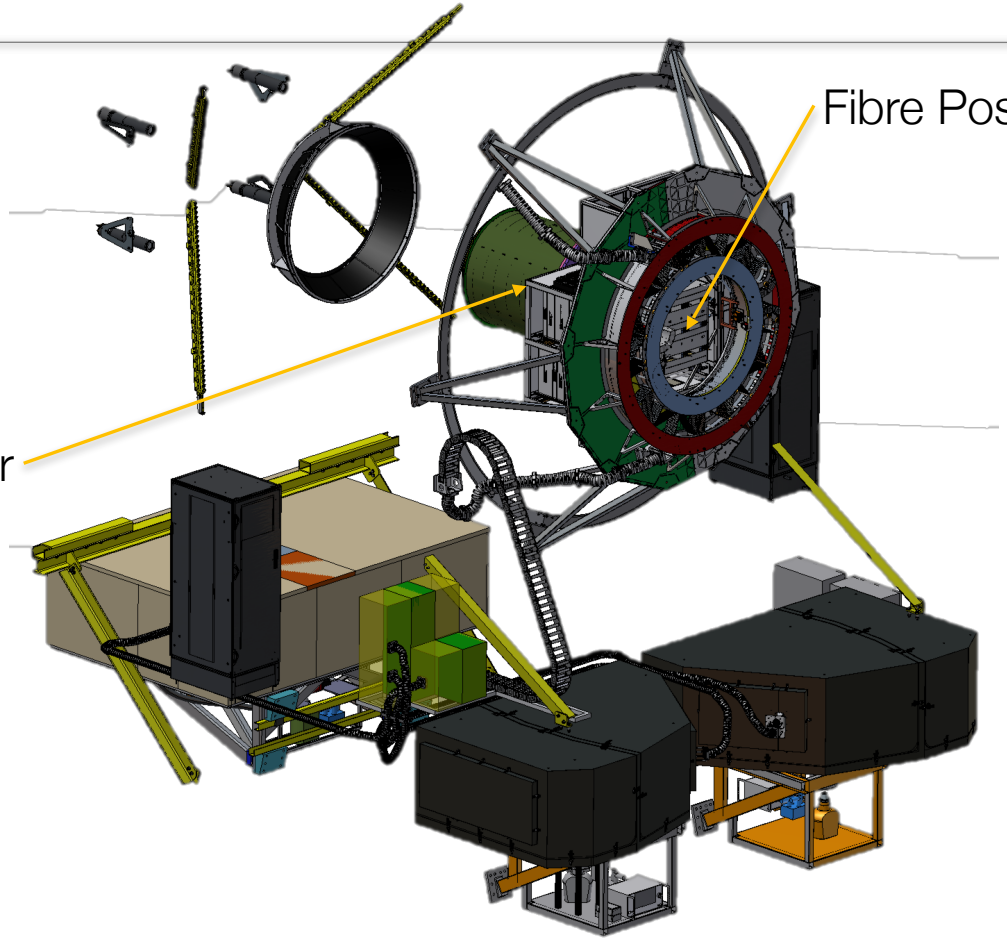


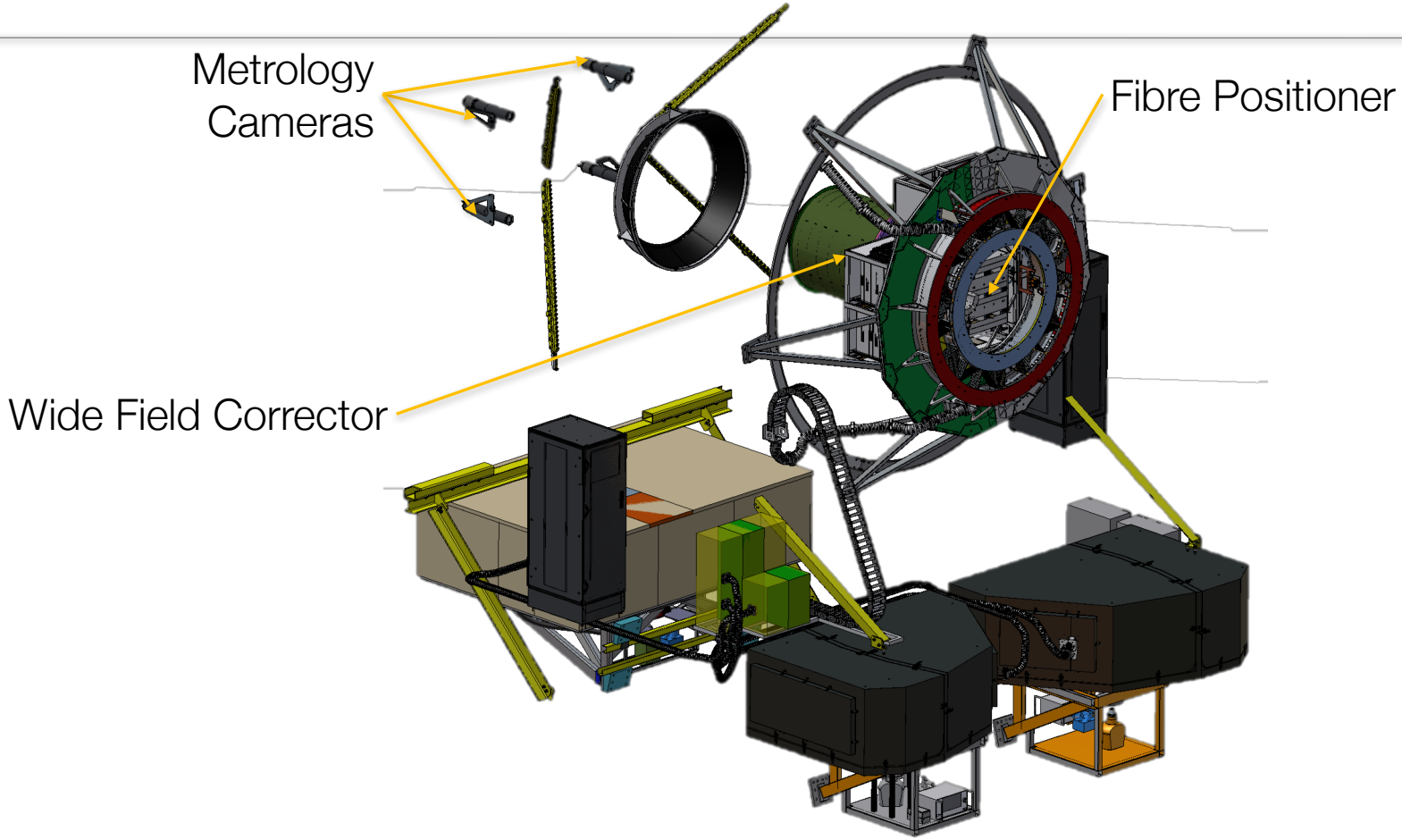
- Full combination including cross-correlations using multiple tracers same sky
- Same-sky benefit substantial: x4 for DE, x2 for MG vs different hemispheres
- For 15,000 deg^2 LSST+4MOST FOM=54 (DE), 383 (MG)
  (Kirk, Private Communication)

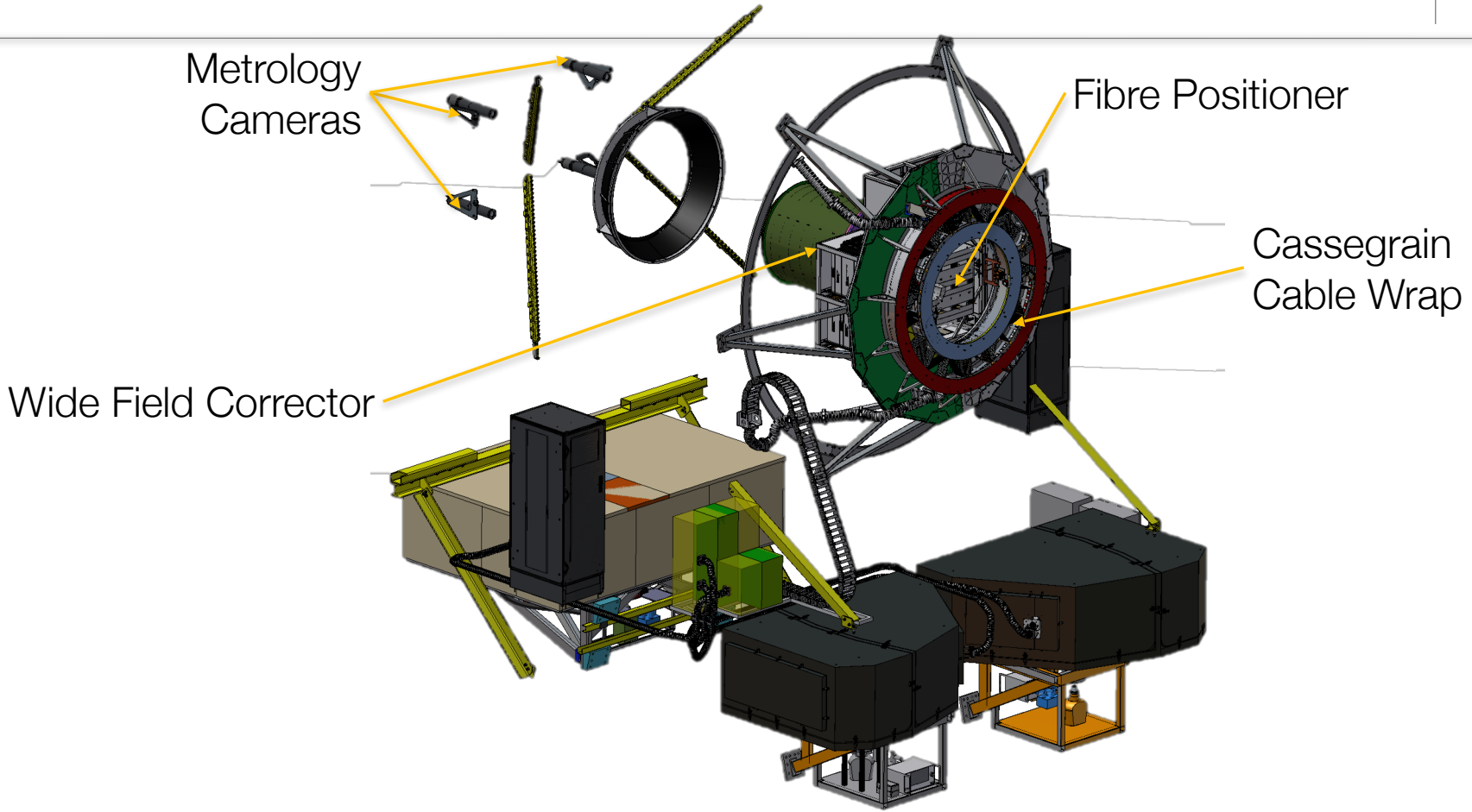


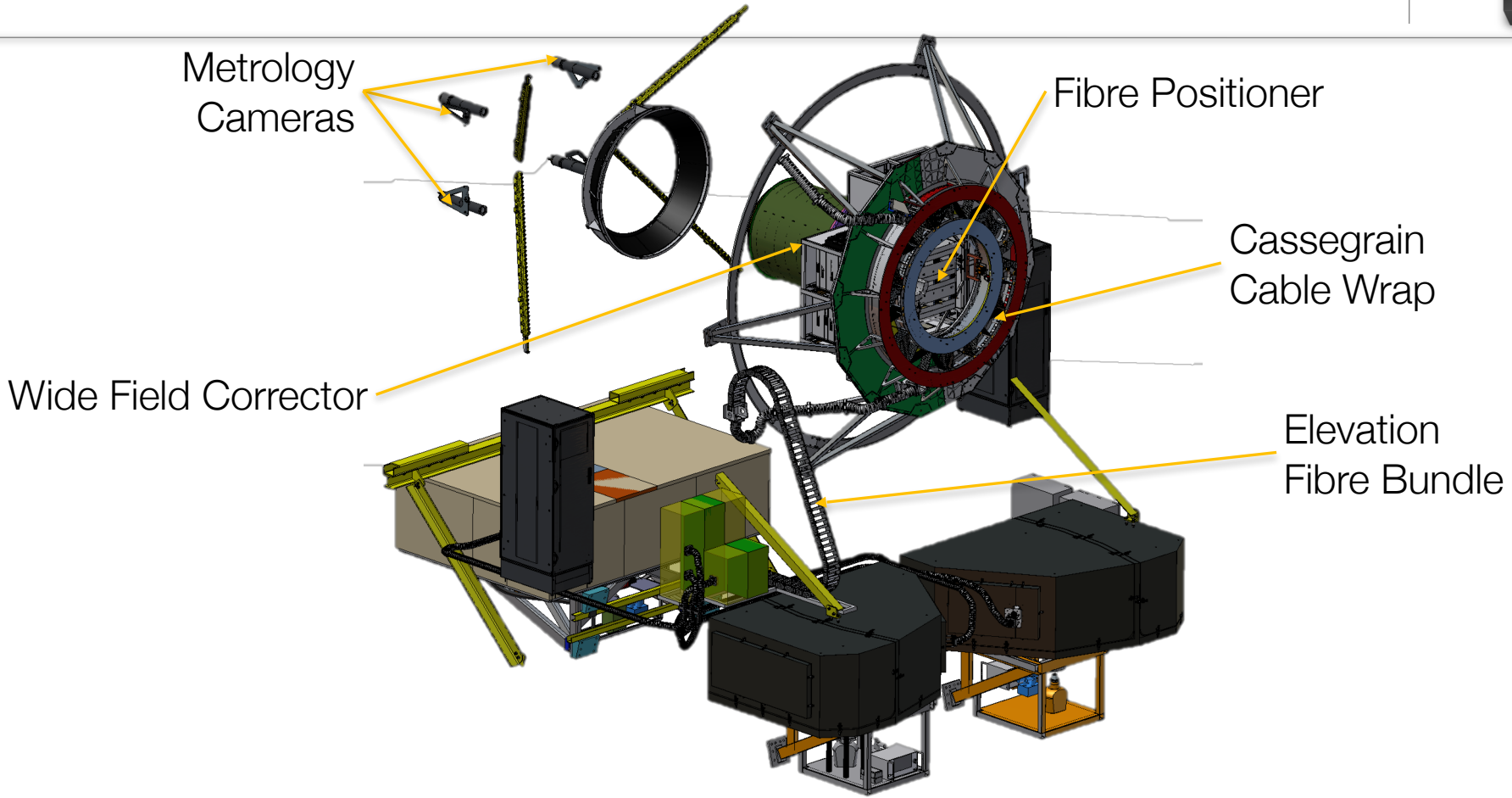
Wide Field Corrector

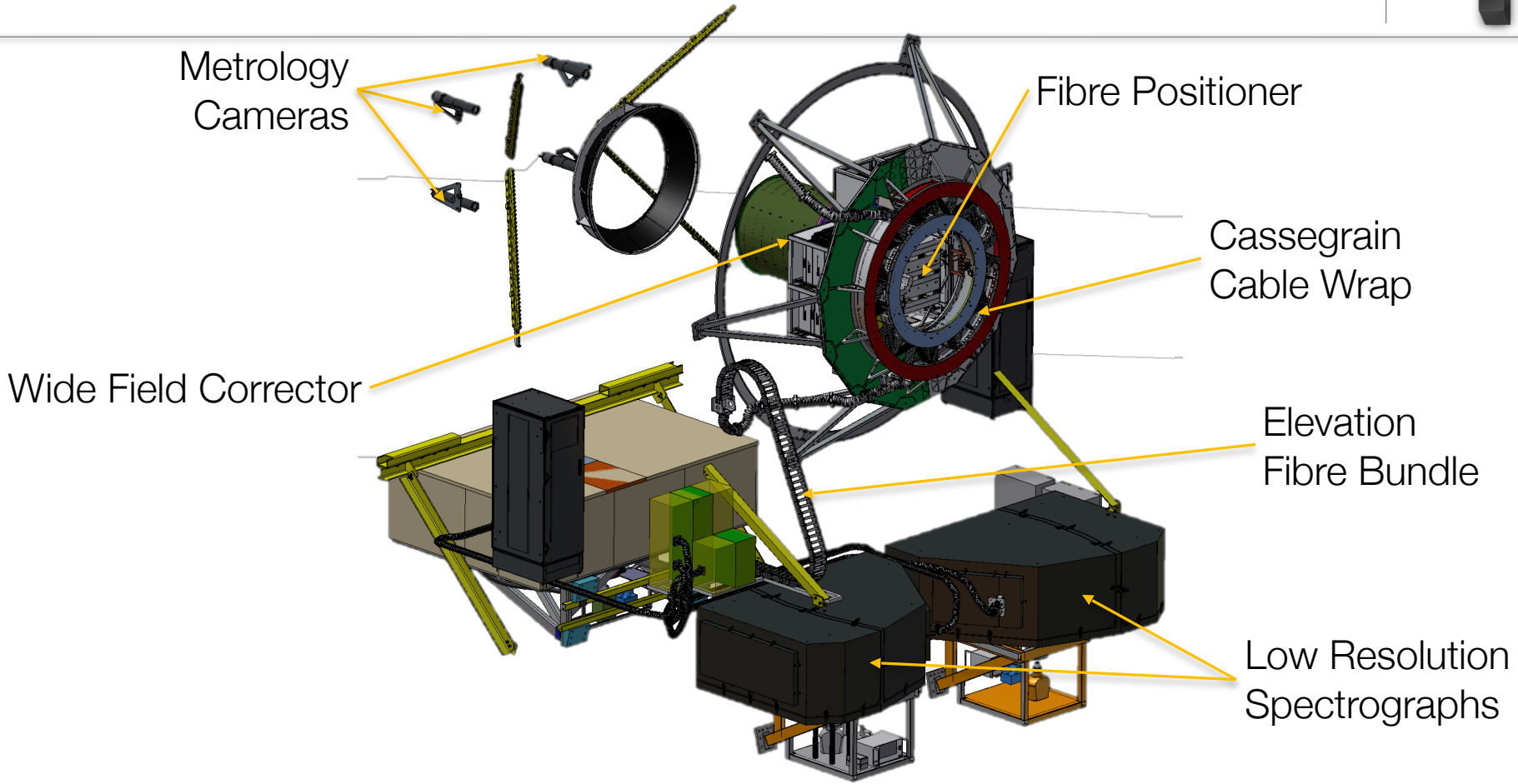


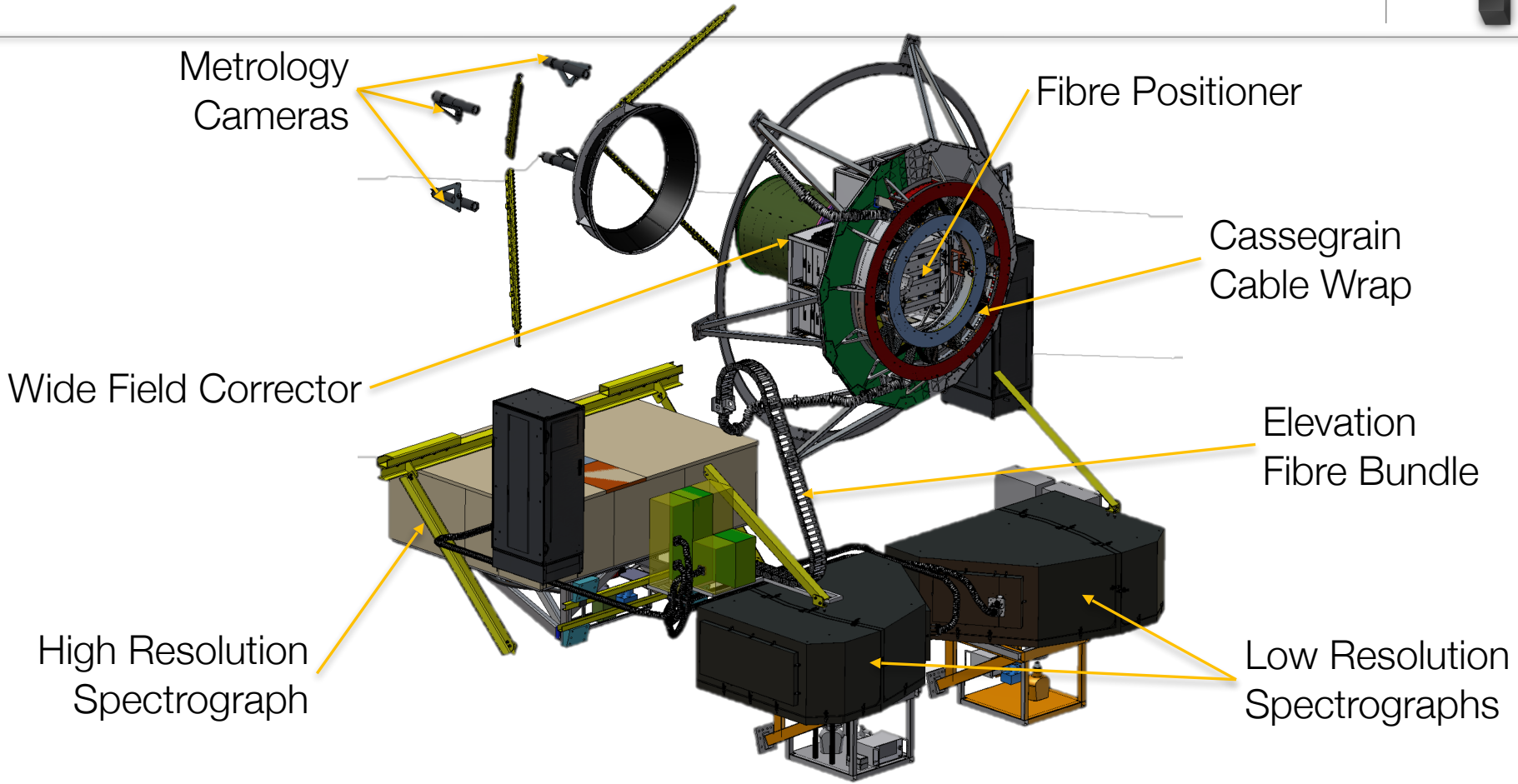

Fibre Positioner
Wide Field Corrector

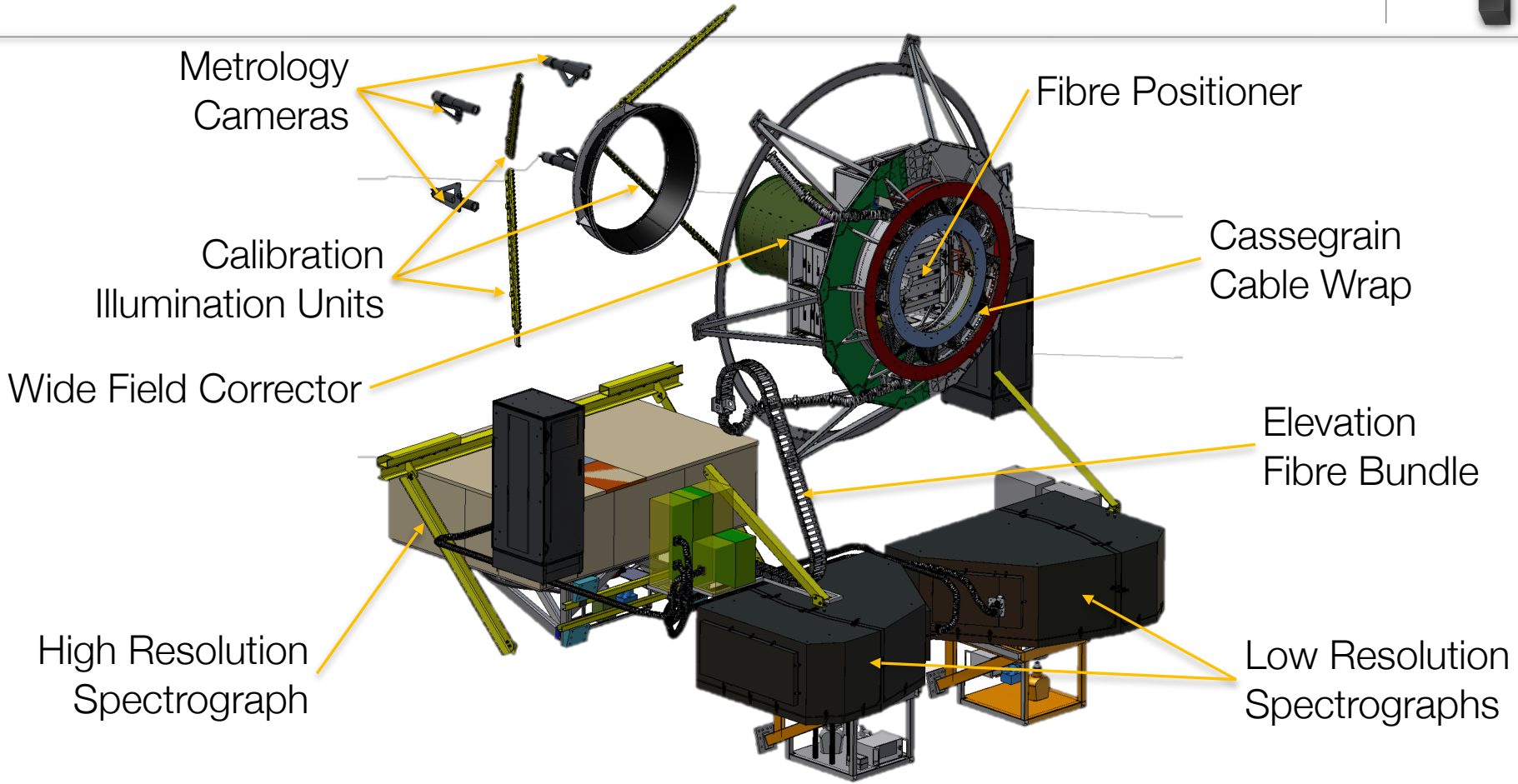

Metrology
Cameras
Fibre Positioner
Wide Field Corrector


Metrology
Cameras
Fibre Positioner
Cassegrain
Cable Wrap
Wide Field Corrector


Metrology
Cameras
Fibre Positioner
Cassegrain
Cable Wrap
Wide Field Corrector
Elevation
Fibre Bundle


Metrology
Cameras
Fibre Positioner
Cassegrain
Cable Wrap
Wide Field Corrector
Elevation
Fibre Bundle
Low Resolution
Spectrographs


Metrology Cameras
Fibre Positioner
Cassegrain Cable Wrap
Wide Field Corrector
Elevation Fibre Bundle
High Resolution Spectrograph
Low Resolution Spectrographs


Metrology Cameras
Calibration Illumination Units
Wide Field Corrector
High Resolution Spectrograph
Fibre Positioner
Cassegrain Cable Wrap
Elevation Fibre Bundle
Low Resolution Spectrographs

Wide Field Corrector and Atmospheric Dispersion Compensator (WFC/ADC)

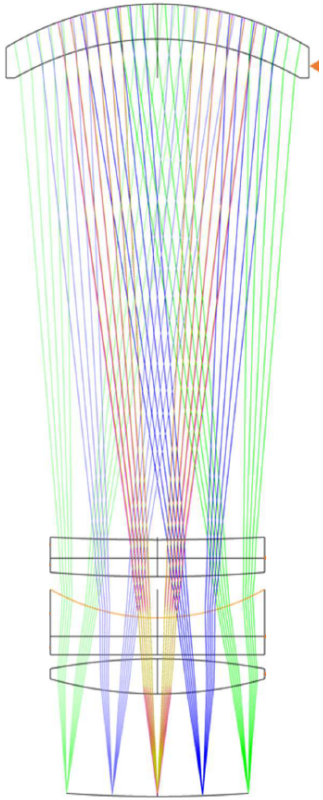
4 Lenses Groups with 2 counter-rotating prisms

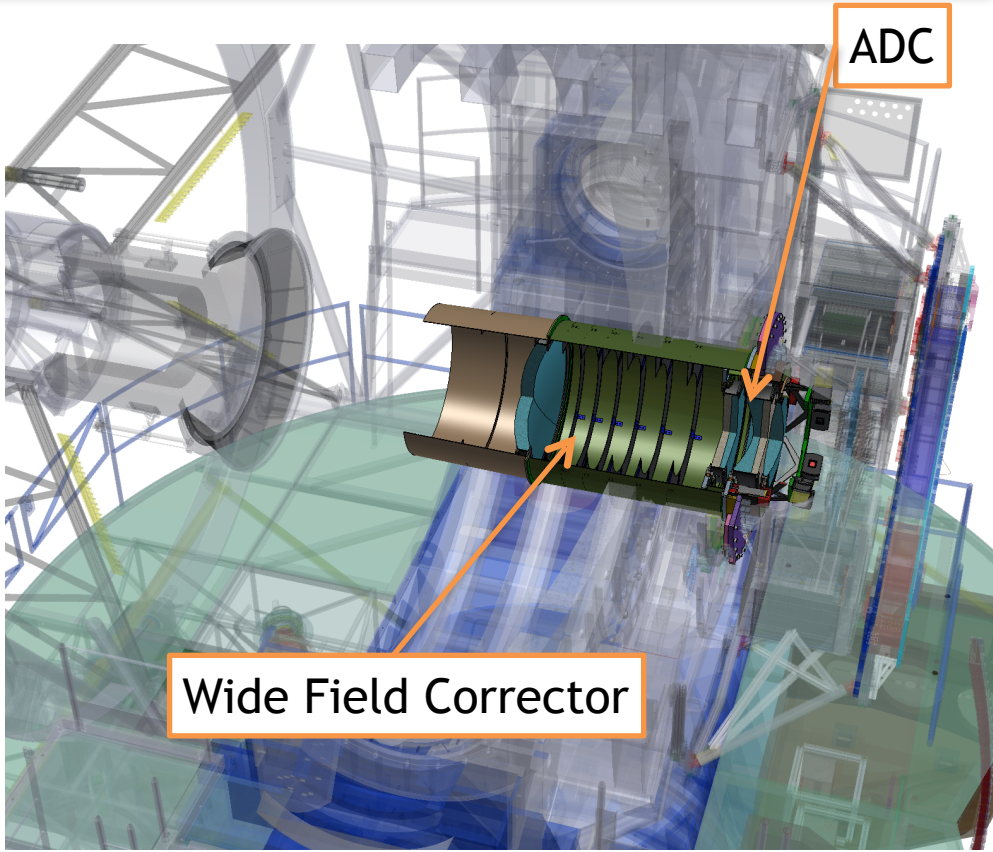
Field Ø = 2.6 degree

535 mm Focal Diameter
Largest lens ~950mm

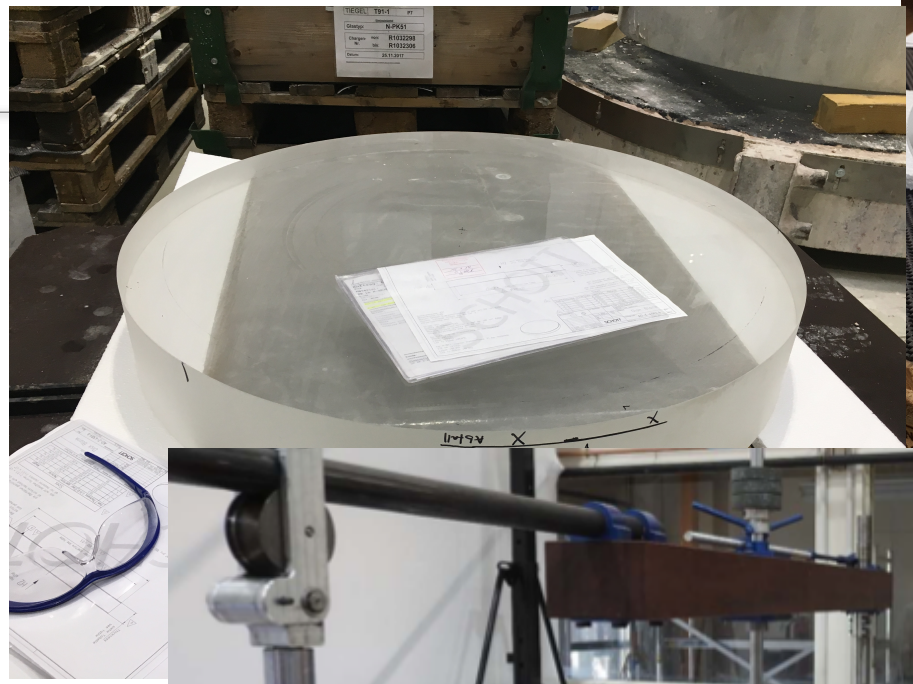
ADC functions to ZD=55°

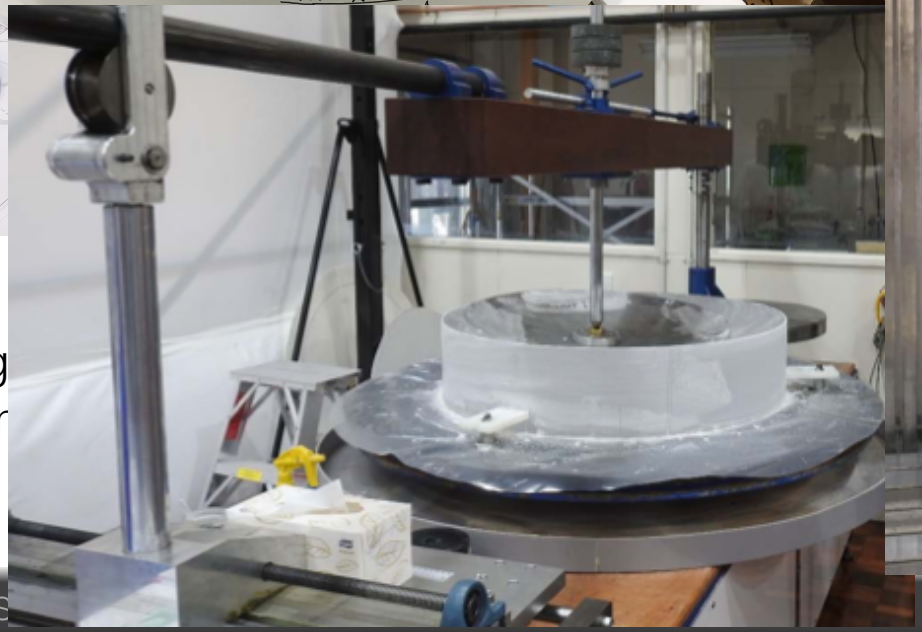
Design AIP
Assembly and alignment
UCL





Wide Field Corrector





Desig
Asser
UCL

4MOST Fibre Feed

Saviauk et al.
Wed 10702-225

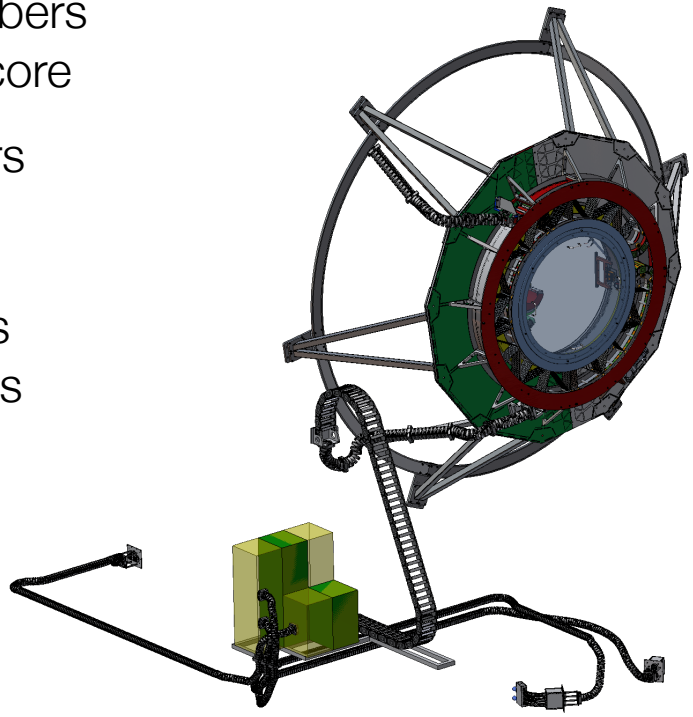
2436 Science Fibers
85 micron core

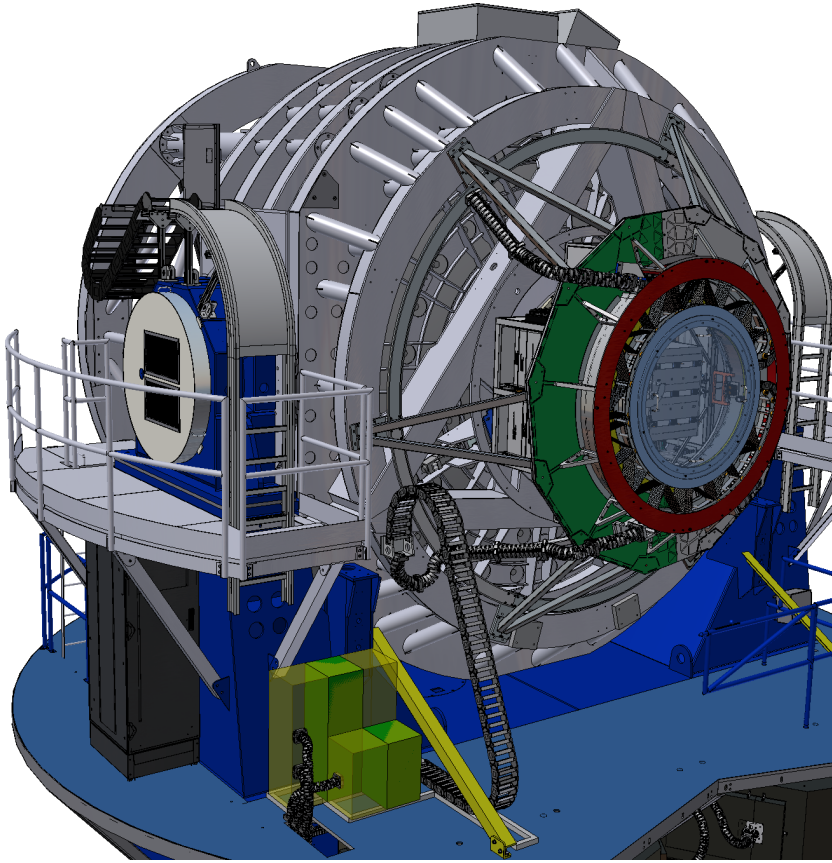
24 Fiducial Fibers

12 Guide Fibers

30 Simultaneous
Calibration Fibers

Fibre lengths:
HRS: 22m
LRS-A: 17m
LRS-B: 18m





Design and build at AIP

Low Resolution Spectrograph (LRS)

3 arms spectrograph
3 CCDs 6k x 6k

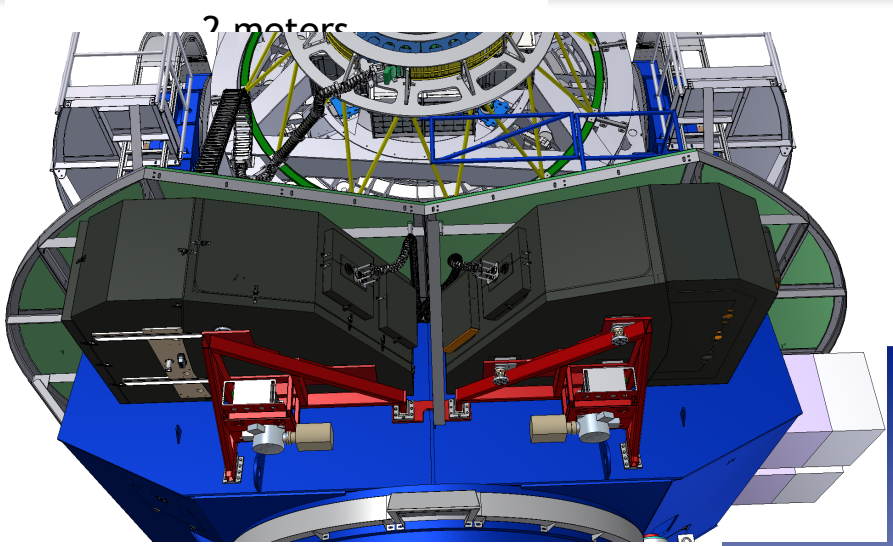
200 mm beam size

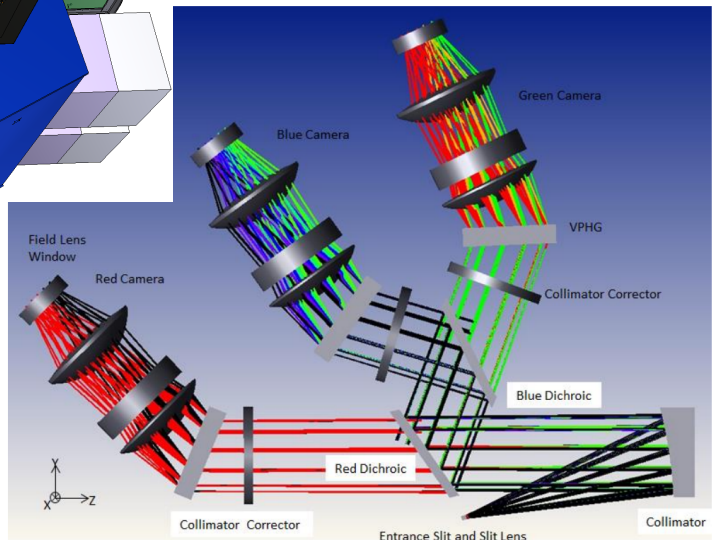
812 science fibers per spectrograph

2 mirrored spectrographs

Thermally stabilized

Design and build at CRAL in Lyon.





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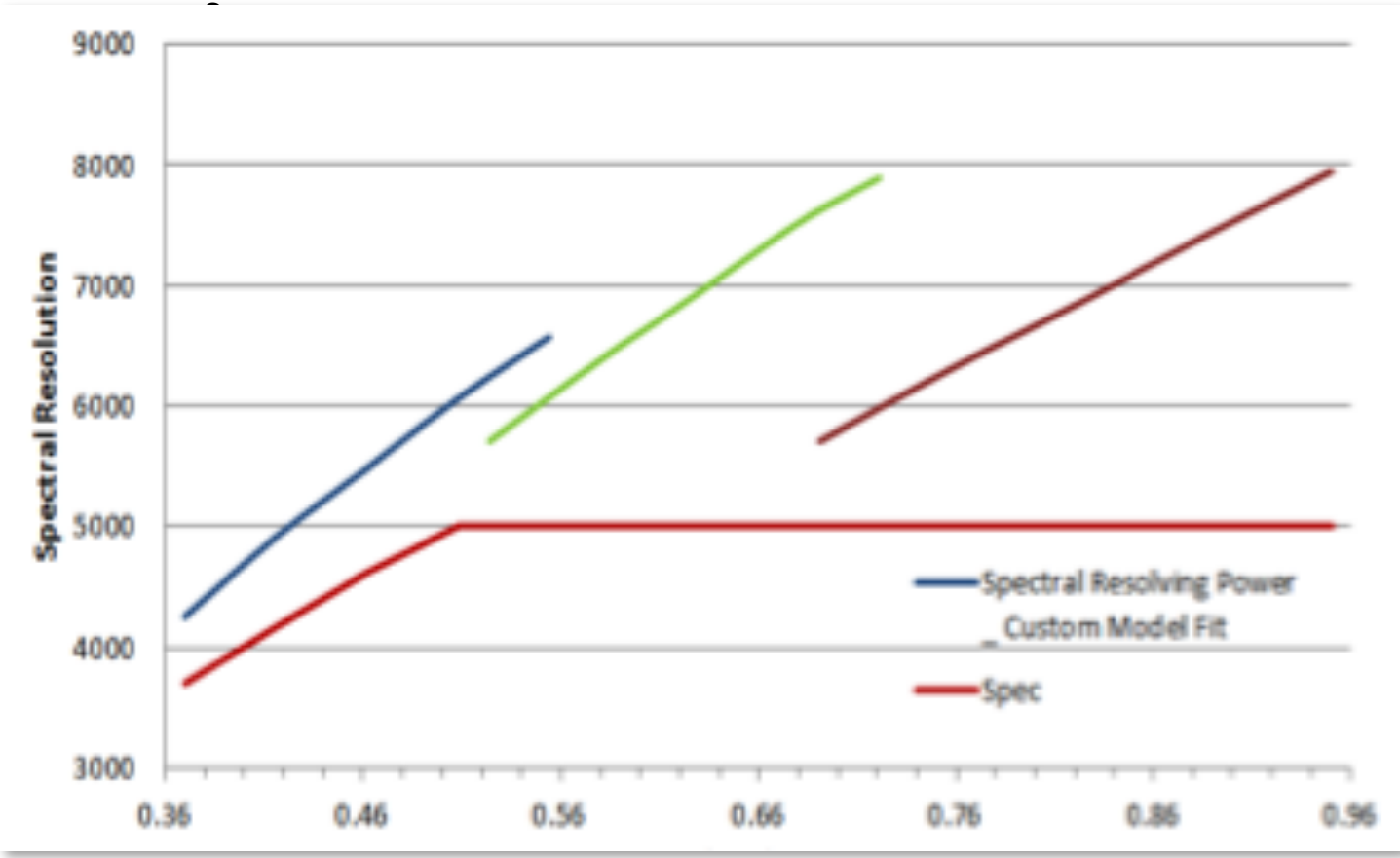


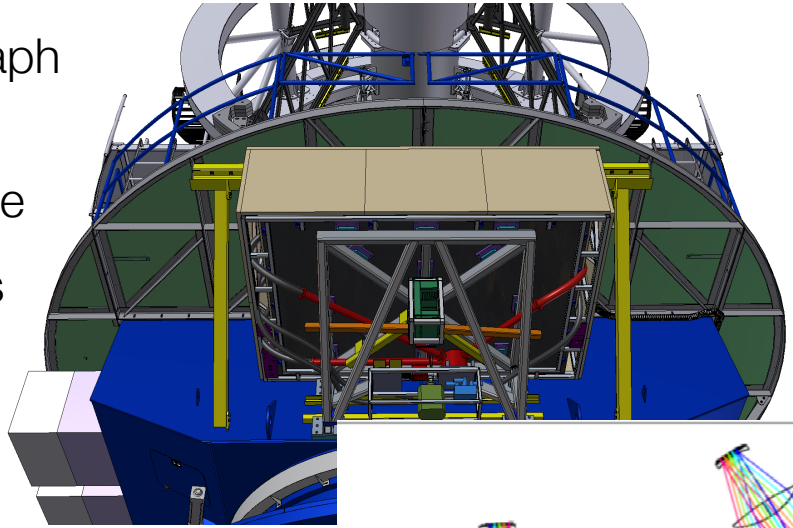
High Resolution Spectrograph (HRS)

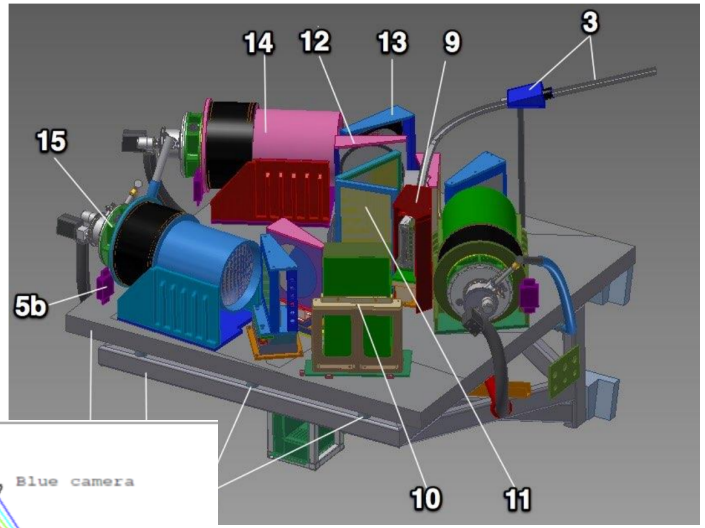
3 arms spectrograph
3 CCDs 6k x 6k

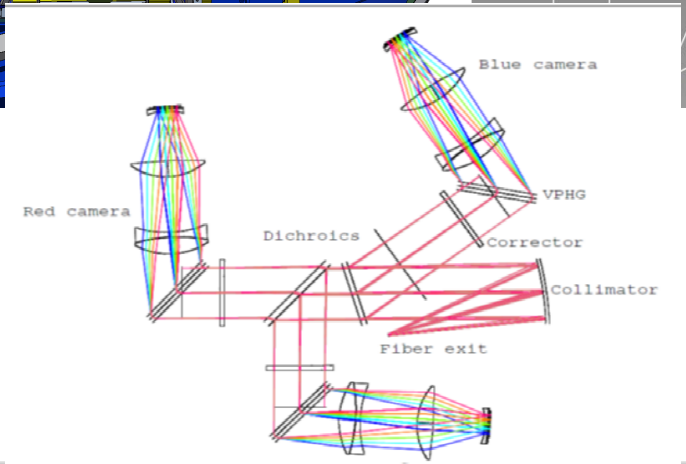
250 mm beam size

812 science fibers

1 spectrograph







Design and build at ZAH/LSW in Heidelberg.

High Resolution Spectrograph (HRS)

3 arms spectrograph
3 CCDs 6k x 6k

250 mm beam size

812 science fibers

1 spectrograph

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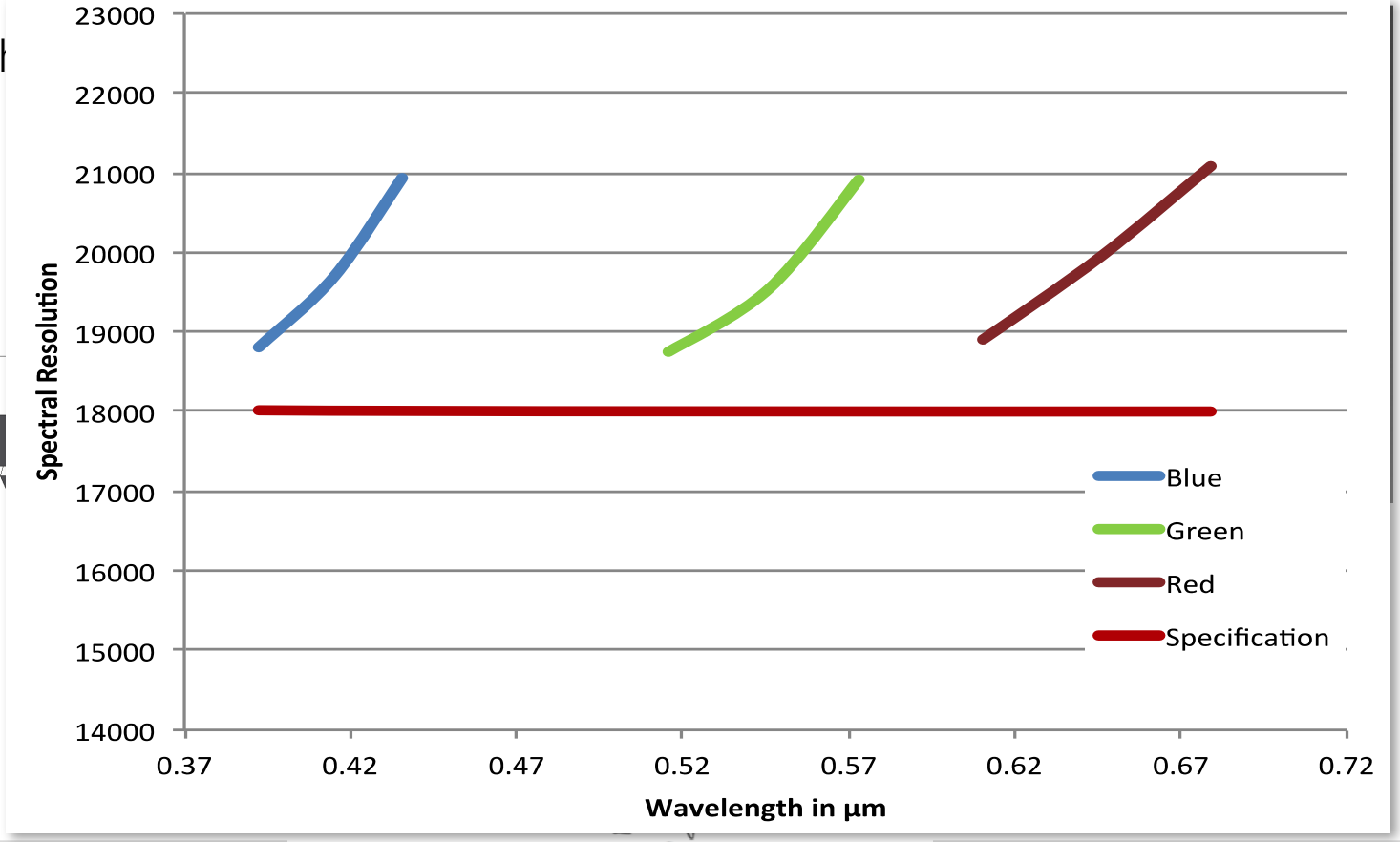

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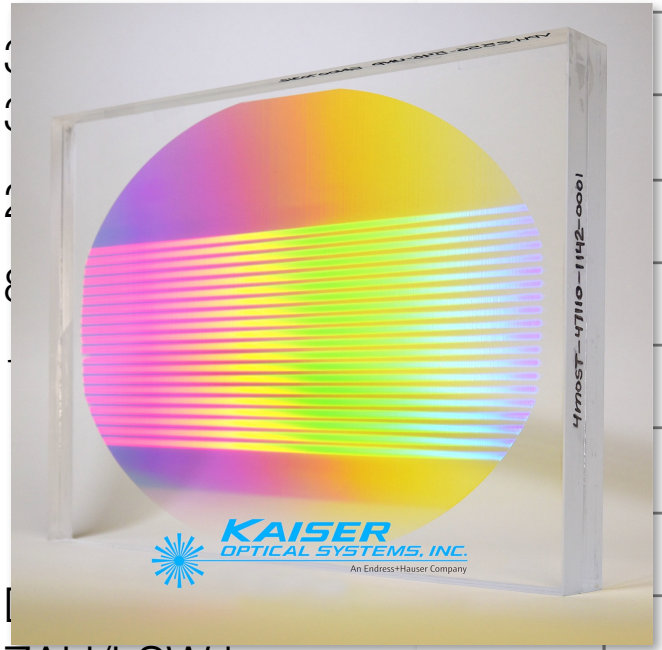
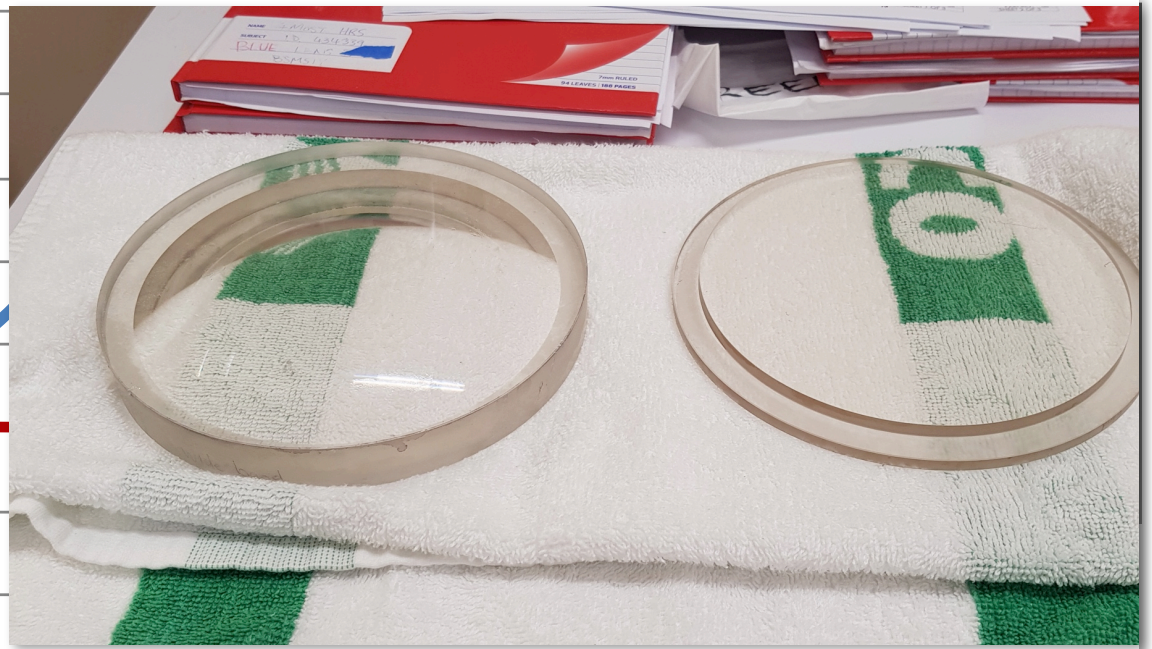
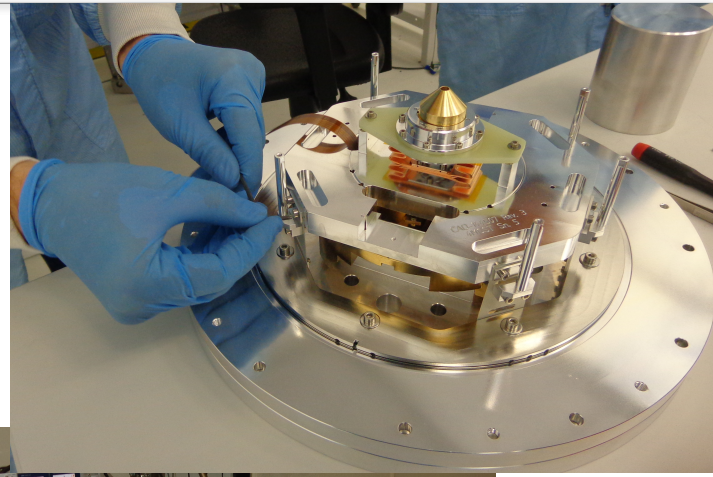


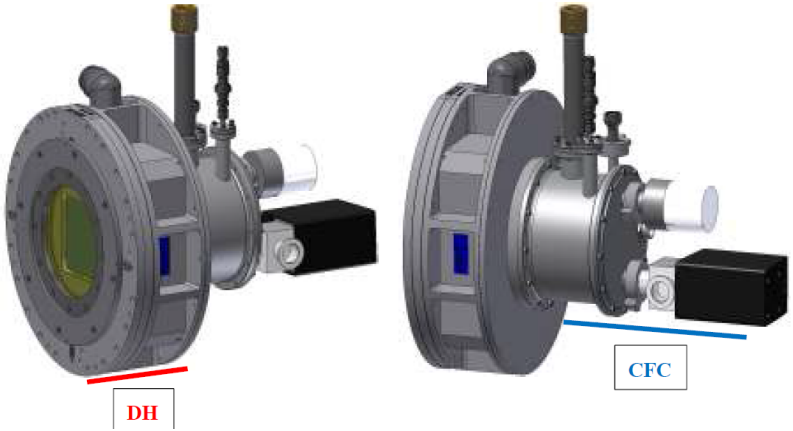


ZAH/LSW in Heidelberg.

4MOST Detectors

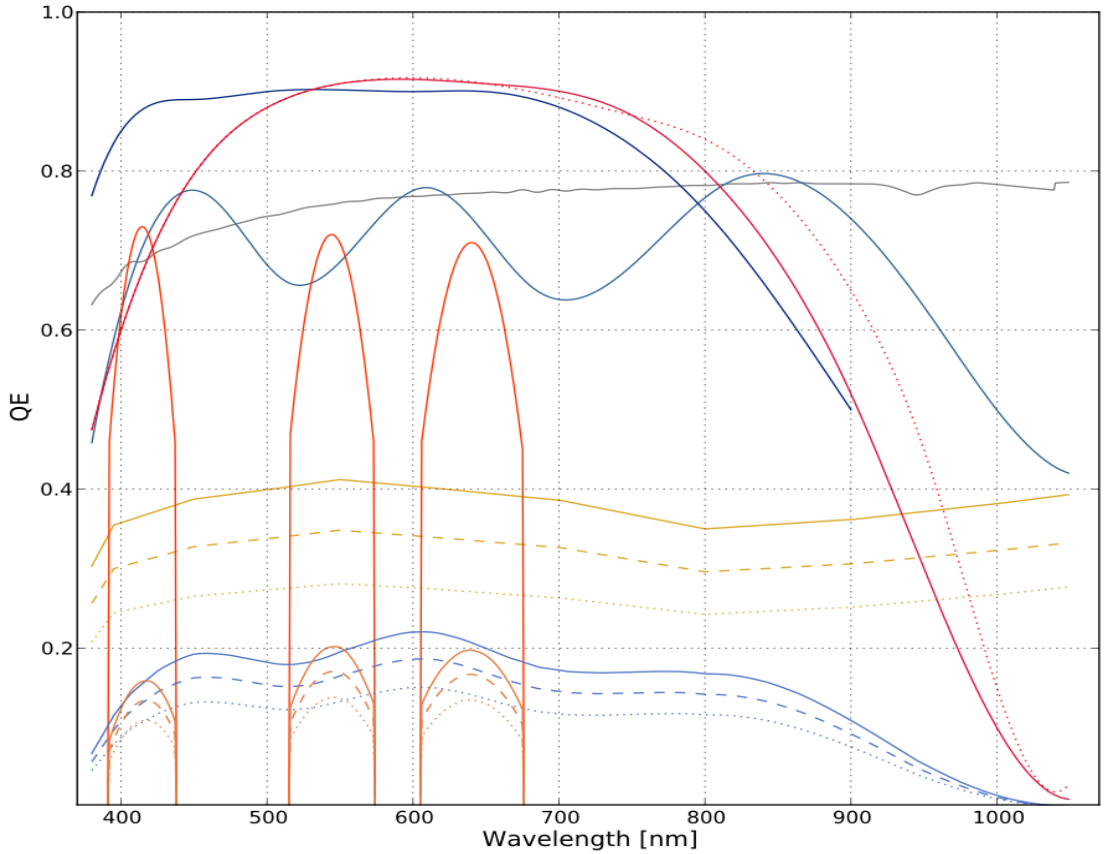
- 9 identical detectors
  (plus spares and engineering devices)
- E2V 6kx6k – Deep Depletion – Broad Band Coating
- Detector head based on ESPRESSO design
- Cooling and controls identical to MUSE design
- All to ESO standards

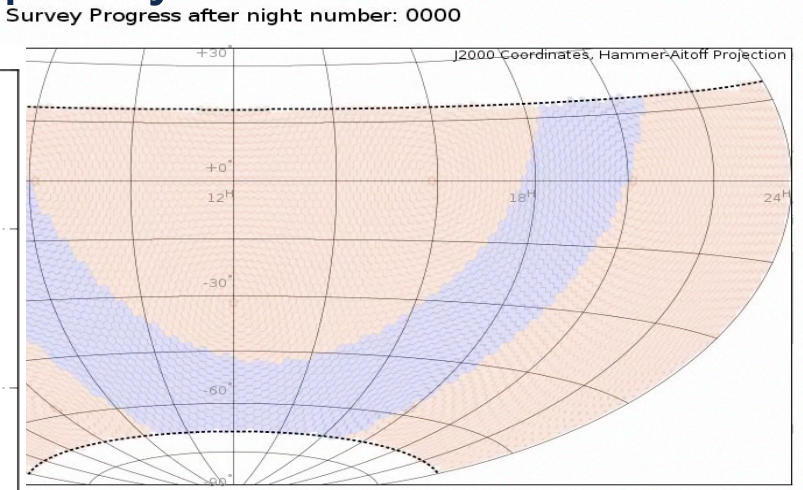




Design and build at ESO in Garching.

Simulate throughput, fibre assignment, survey strategy and verify total survey quality





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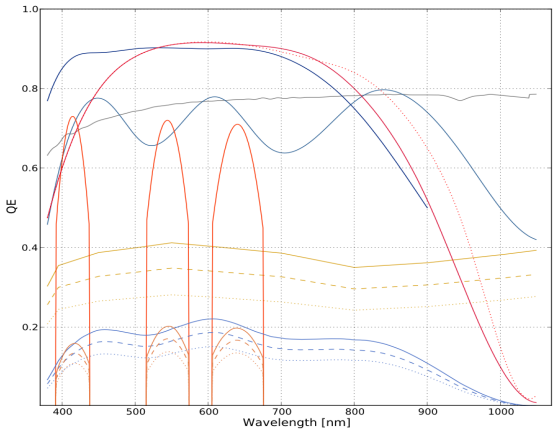

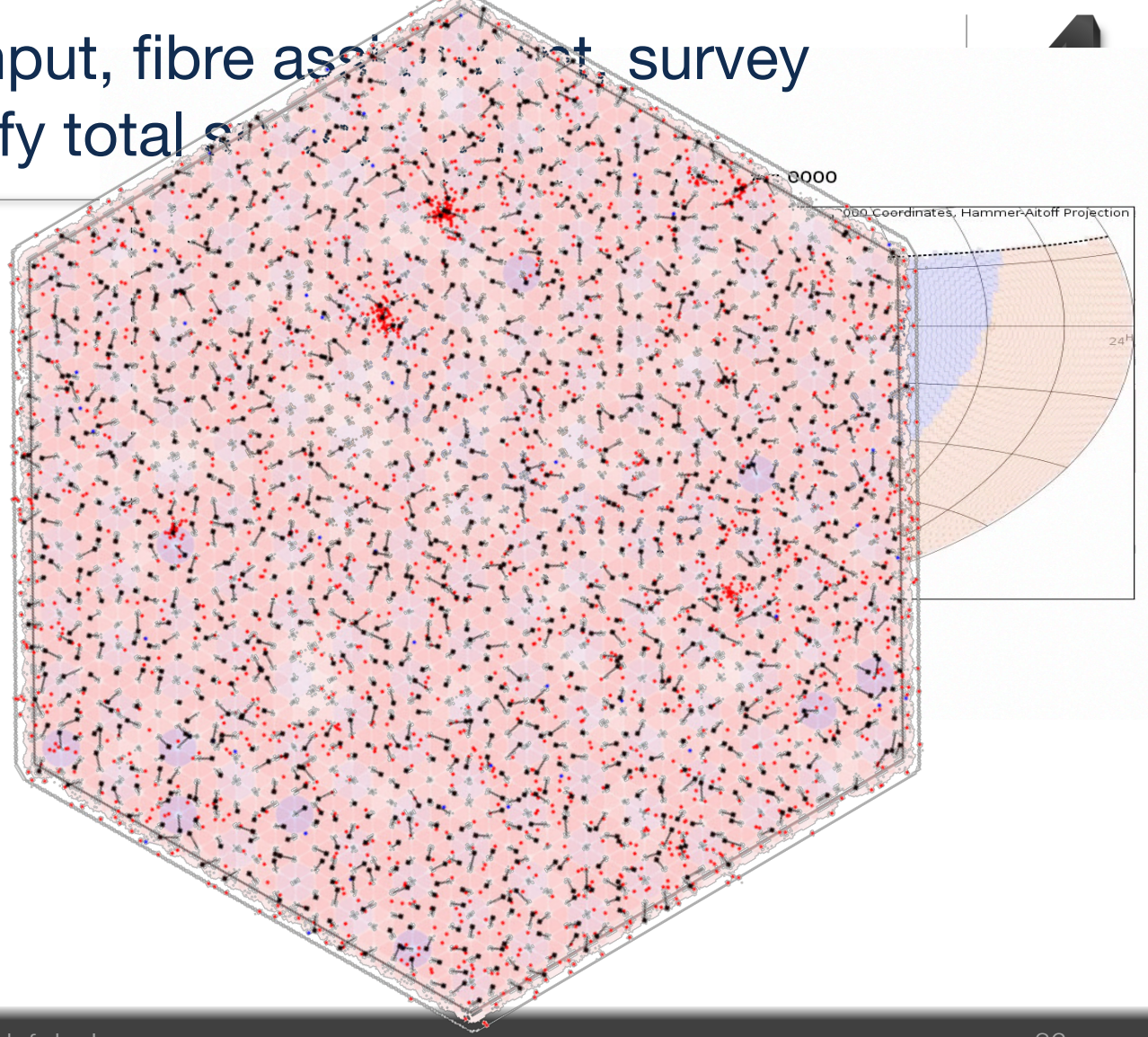

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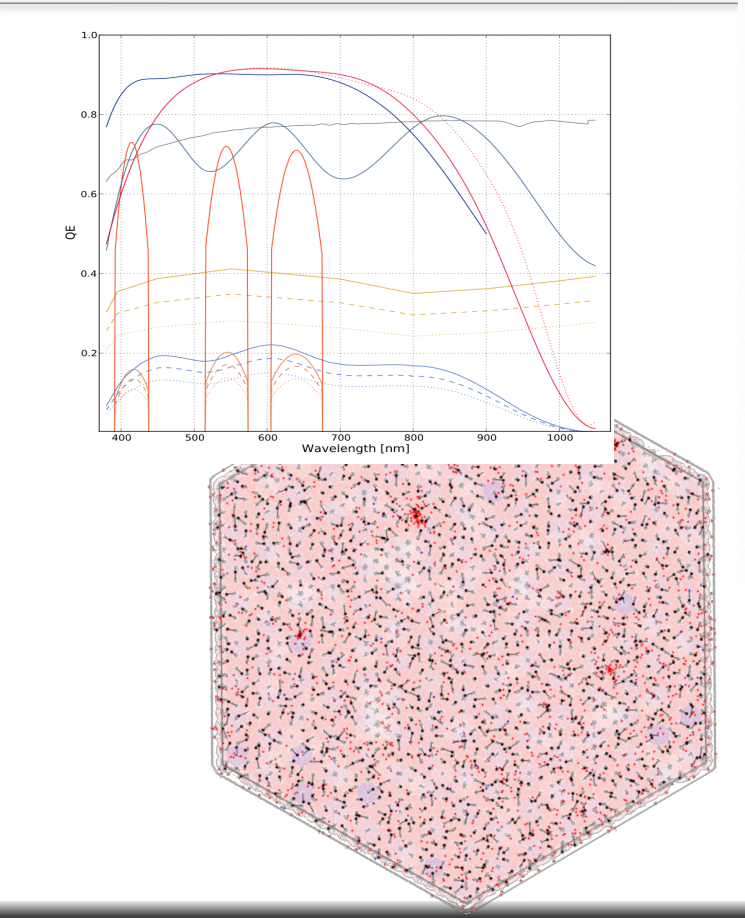

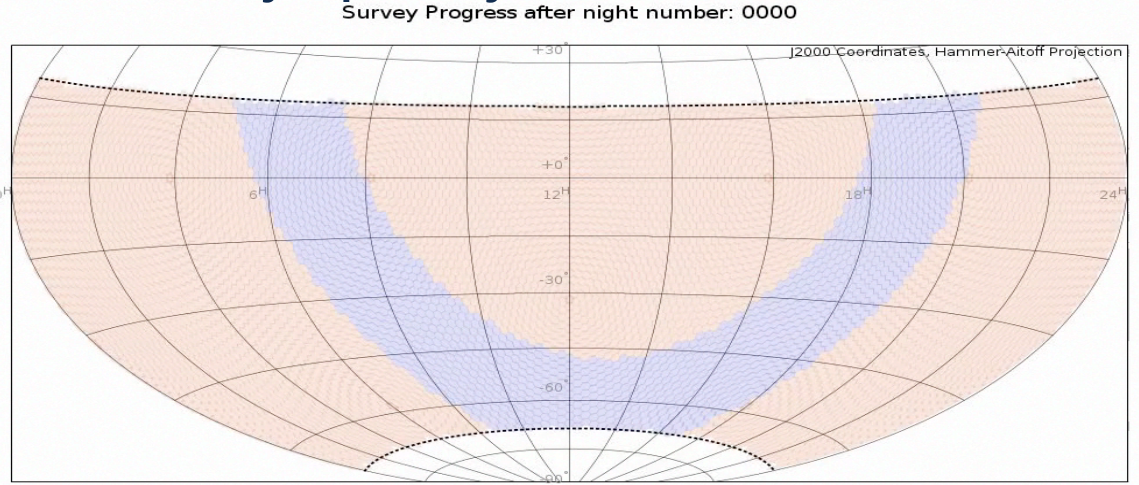

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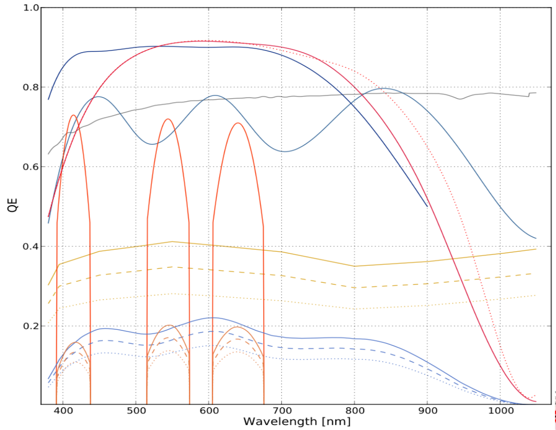
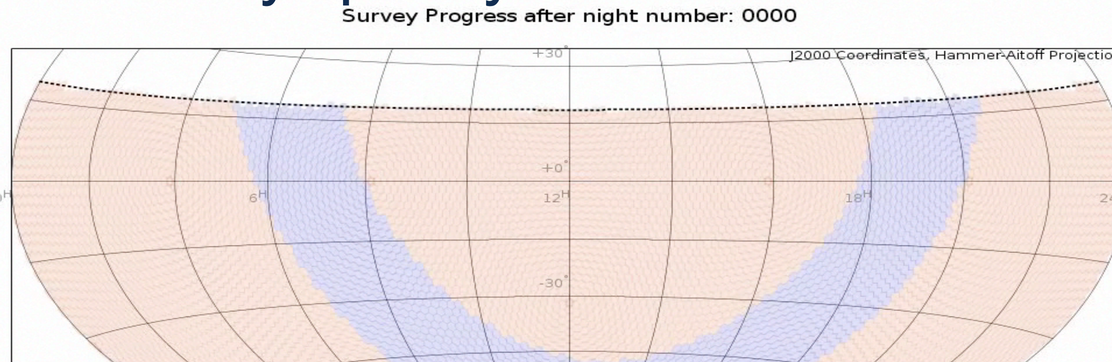
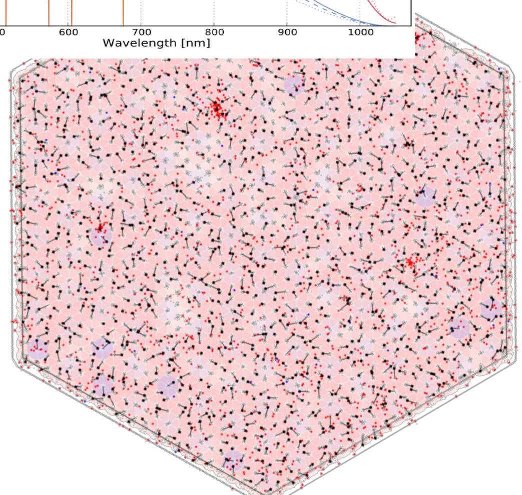






Science case	S/N / Å	r_{AB}-mags	Targets (Millions)
S1 Milky Way Halo LR Survey	10	16–20.0	1.4
S2 Milky Way Halo HR Survey	140	12–15.5	0.6
S3 Milky Way Disk and Bulge LR Survey	10–30	14–18.5	10.7
S4 Milky Way Disk and Bulge HR Survey	140	14–15.5	2.0
S5 Galaxy Clusters Survey	4	18–22.0	0.8
S6 AGN Survey	4	18–22.0	0.5
S7 Galaxy Evolution Survey (WAVES)	4	18–22.5	1.4
S8 Cosmology Redshift Survey	1	20–22.5	10.4
S9 Magellanic Clouds	10–30	16-20.0	0.3
S10 Transients Survey (TiDES)	4	18–22.5	0.3
Total			**>27**

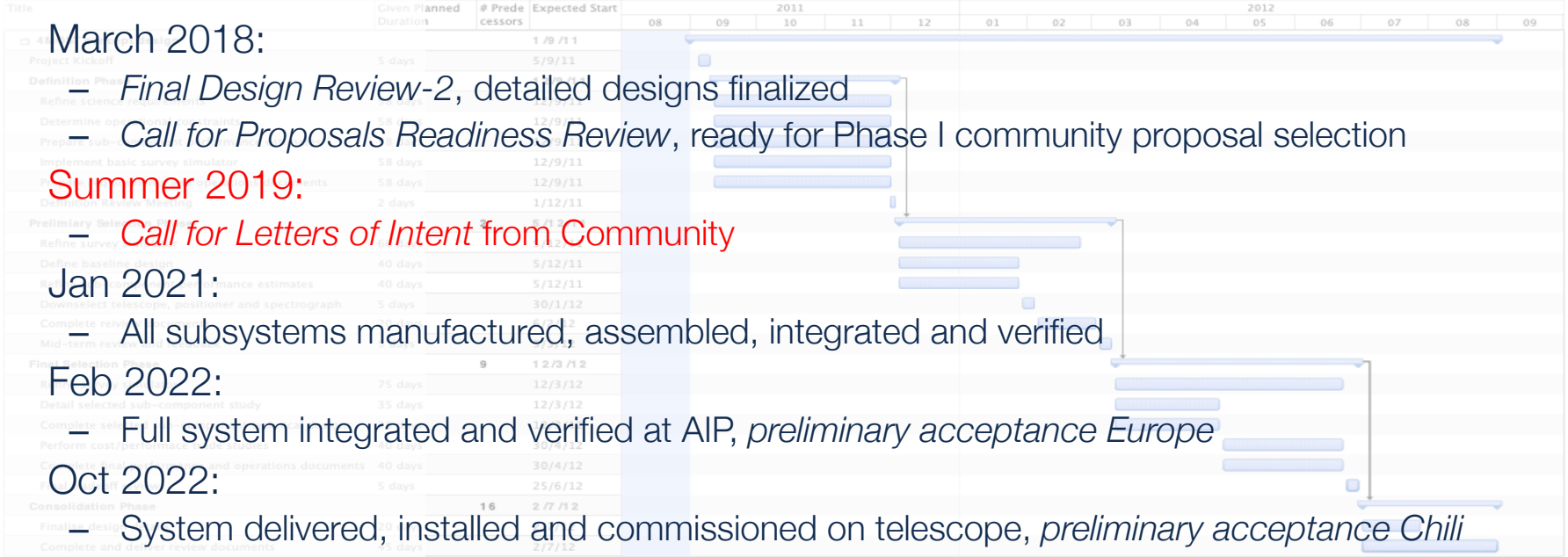
Policies: consortium membership

- Any Consortium institute member can sign up for the 4MOST Science Team (ST) through the 4MOST web site
- ST members can join any of the Consortium Surveys
  - Guideline is no more than two Surveys to encourage active memberships
- Surveys may admit limited set of external members based on needed expertise
- Permanent membership can be obtained by contributing 0.3 FTE (students), 0.4 FTE (post-docs), 0.8 FTE (staff). Otherwise, ST membership is normally lost when leaving a Consortium institute

Policies: data and publication rights

- Data releases:
  - L0 (raw data): public immediately
  - L1 (extracted, calibrated spectra): yearly
  - L2 (derived products): negotiated by each Survey with ESO
- All data of all Surveys are accessible to all ST members
- Publications are limited to approved Projects. Consortium Projects may be rejected if overlapping with Community Survey Core Science and vice versa (SDSS-like policy). Also PhD Projects extra protected

Schedule and Milestones



- March 2018:
  - *Final Design Review-2*, detailed designs finalized
  - *Call for Proposals Readiness Review*, ready for Phase I community proposal selection
- Summer 2019:
  - *Call for Letters of Intent* from Community
- Jan 2021:
  - All subsystems manufactured, assembled, integrated and verified
- Feb 2022:
  - Full system integrated and verified at AIP, *preliminary acceptance Europe*
- Oct 2022:
  - System delivered, installed and commissioned on telescope, *preliminary acceptance Chili*

- Nov 2022 – Oct 2027:
  - First science survey of 4MOST, 30% of targets available for Community Surveys

Wide-field, high-multiplex optical spectroscopic survey facility for ESO

www.4MOST.eu

- Status:
  - Contract signed with ESO, FDR-1 (almost) completed, *operations 2022* (≥2x 5 year)
- Science:
  - *Cosmology, galaxy evolution, high-energy and Galactic* science
  - Complement large area space missions: Gaia, eROSITA, Euclid, PLATO
  - Complement ground-based surveys: VISTA, VST, DES, LSST, SKA, etc.
- Survey facility:
  - Instrument, science operations, data products, science
  - Run all-sky 5 year *public* surveys in parallel with yearly data releases
  - Key surveys organized by consortium, add-on surveys from community through ESO
- Instrument specifications:
  - High multiplex: 1600 fibres to R~5000 + 800 fibres R~20,000 in parallel
  - Wavelength: LR: 370-950 nm, HR: 392-437 & 515-572 & 605-675 nm
  - Large field-of-view on VISTA, 4m-class telescope: ⌀=2.6°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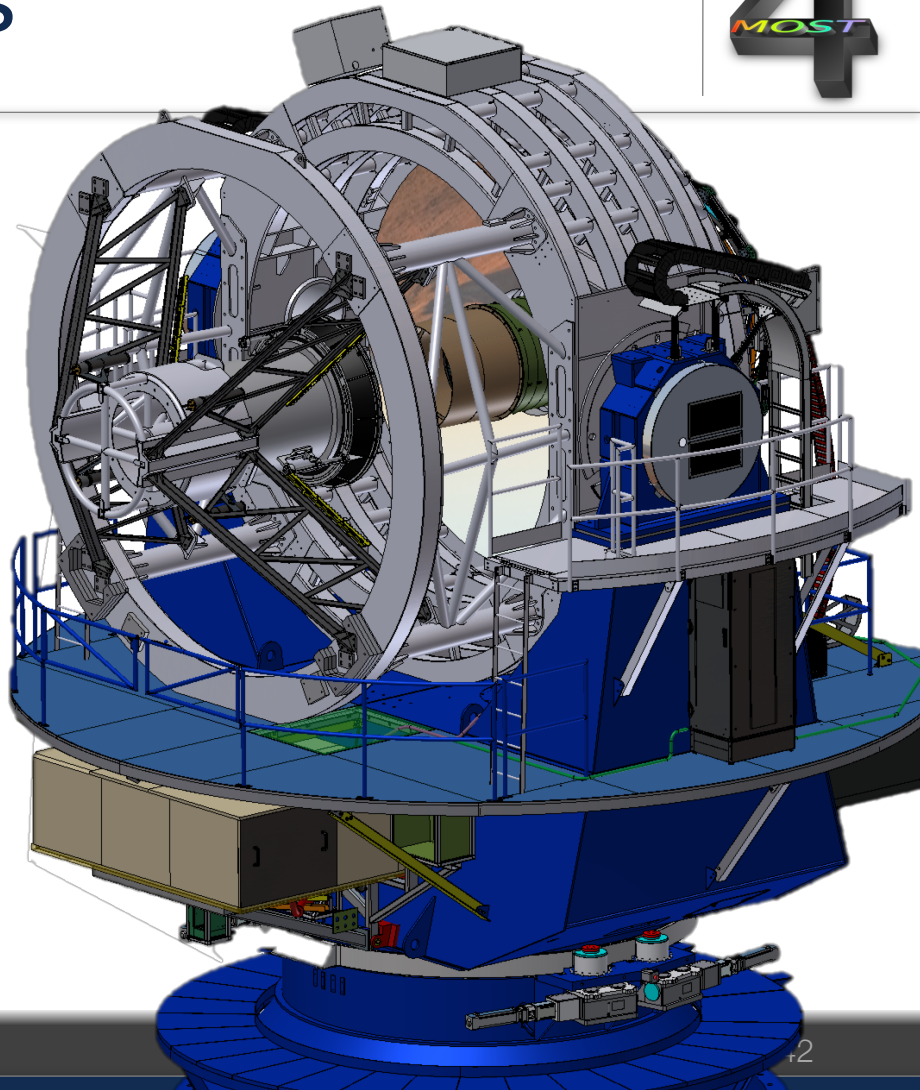
UH
CRAL
CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON
AAO
NOVA
ASTRON
ESO
EPFL
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

4MOST Components

To deliver the performance objectives of 4MOST, the facility requires:

1. WFC/ADC/Baffles (AIP)
2. Fiber Positioner (AAO)
3. Metrology System (AIP)
4. Fiber Feed (AIP)
5. Low Resolution Spectrograph (CRAL)
6. High Resolution Spectrograph (LSW)
7. Detectors/Cryostats (ESO)
8. ACQ/Guiding and WFS (AIP)
9. Calibration System (NOVA)
10. Facility Control (MPIA & LSW)
11. Data Management (IoA + AIP)



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