4MOST – 4m Multi-Object Spectroscopic Telescope

4MOST Spectroscopic Surveys & Asteroseismology

Roelof de Jong (AIP)
4MOST PI

Reconstructing the Milky Way's History, 1–5 June 2015, Bad Honnef

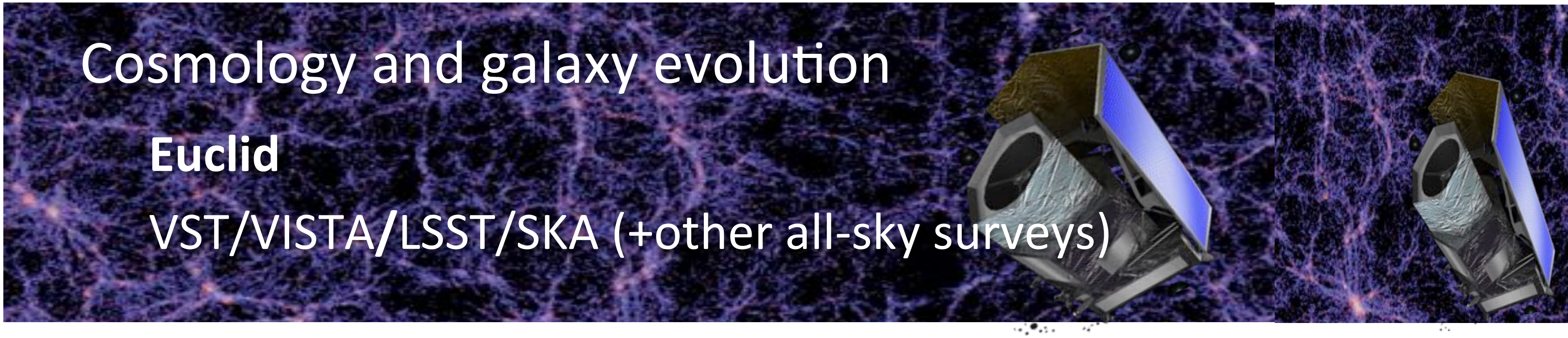
www.4MOST.eu

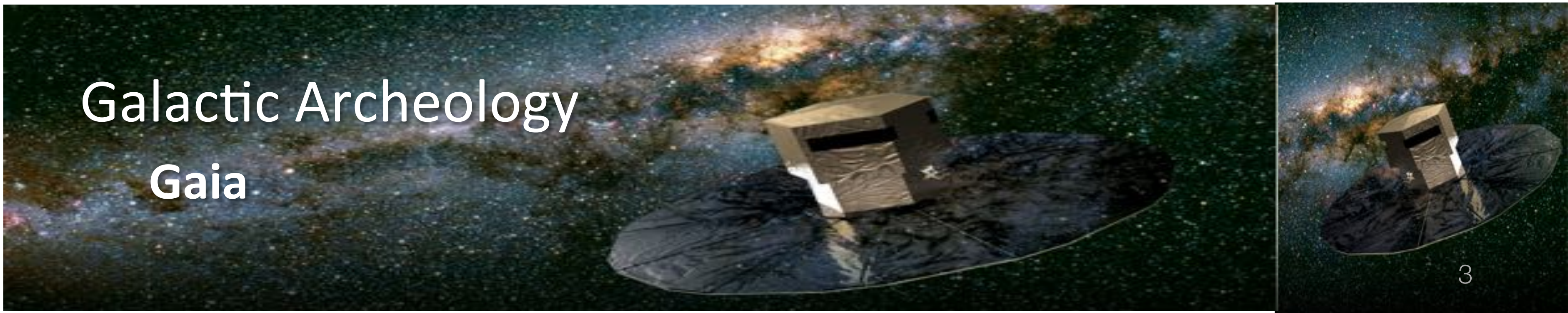
4MOST: Wide-field, high-multiplex optical spectroscopic survey facility for ESO

- Status:
  - Preliminary Design Phase started Jan 2015
  - ESO Council approval expected June 2015
  - Operations start on **VISTA** telescope 2021 (at least 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 in coordination with community
  - Add-on surveys from community through ESO peer-reviewed applications

Main science drivers

A 5 year 4MOST survey provides





Main science drivers

A 5 year 4MOST survey provides

- Euclid/LSST/SKA (and other surveys) complement:
  - Dark Energy & Dark Matter (BAO, RSD, lensing, Lyα forest)
  - Galaxy evolution (groups & clusters)
  - Transients (SNe Ia, GRB)
  - >13 $\times 10^6$ spectra of m_V~20-22.5 mag LRGs & ELGs
- eROSITA complement:
  - Cosmology with x-ray clusters to z~0.8
  - X-ray AGN/galaxy evolution and cosmology to z~5
  - Galactic X-ray sources, resolving the Galactic edge
  - 2 $\times 10^6$ spectra of AGN and galaxies in 50,000 clusters
- Gaia complement:
  - Chemo-dynamics of the Milky Way
  - Stellar radial velocities, parameters and abundances
  - 13 $\times 10^6$ spectra @ R~5000 of m_V~15-20 mag stars
  - 2 $\times 10^6$ spectra @ R~20,000 of m_V~14-16 mag stars

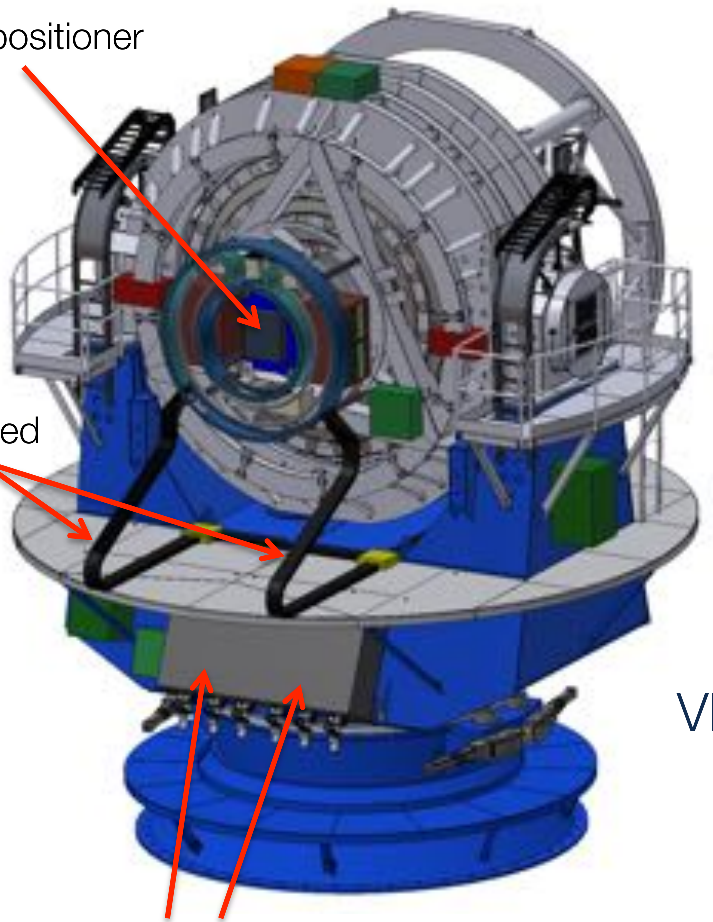
+ ~15 million spectra for community proposals

4MOST is a general purpose spectroscopic survey facility serving many astrophysical communities

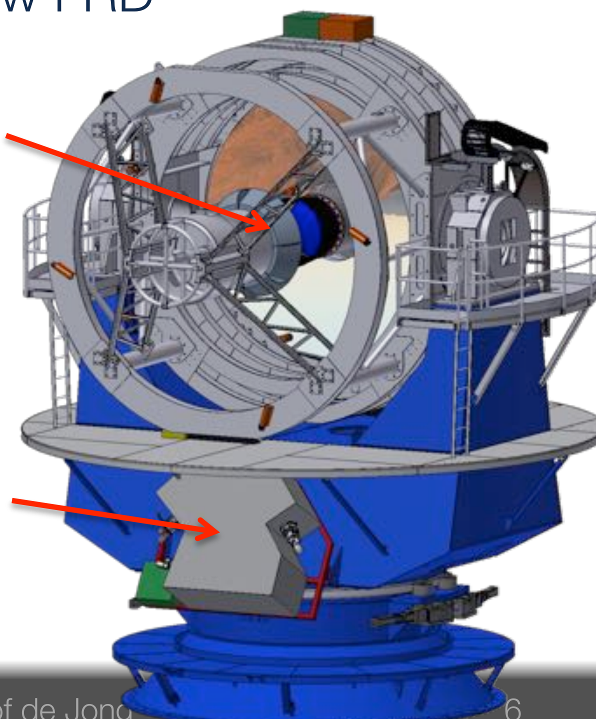
Science Requirements

- 4MOST shall be able to obtain:
  - *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’
  - *Radial velocities* of ≤2 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
    - R~20000 spectra of 16 V-mag stars with S/N=140 per Ångström
- 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) degree^2* area on the sky at least two times

4MOST instrument overview



- New Wide-field Corrector, fibre positioner and three spectrographs
- Spectrographs mounted on telescope fork (gravitation invariant)
- Short fibre run (~15 m), prototype shows very low FRD



VISTA telescope

Instrument Specification

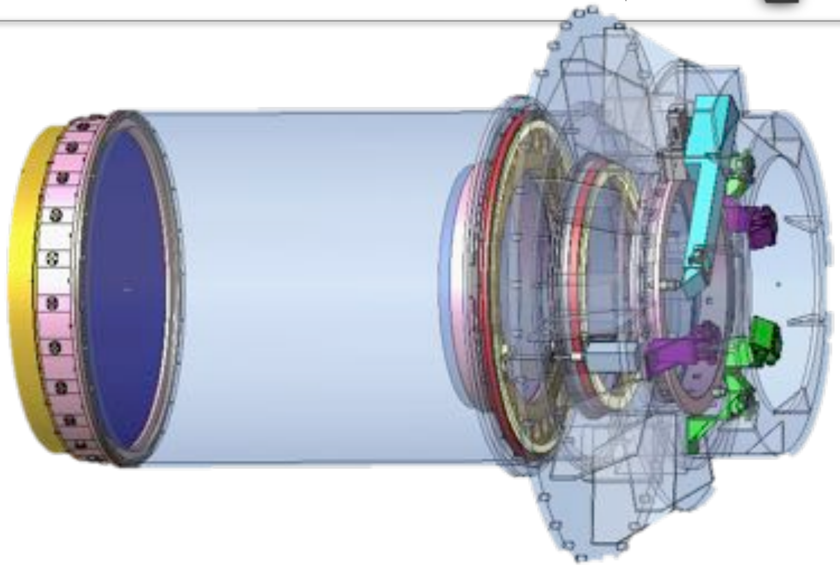
Specification	Design value
Field-of-View (hexagon)	~4.1 degree^2 (⌀>2.5°)
Multiplex fiber positioner	~2400

Medium Resolution Spectrographs (2x)
  # Fibres
  Passband
  Velocity accuracy
	R~5000–7000
	  1600 fibres
	  390-930 nm
	  < 2 km/s

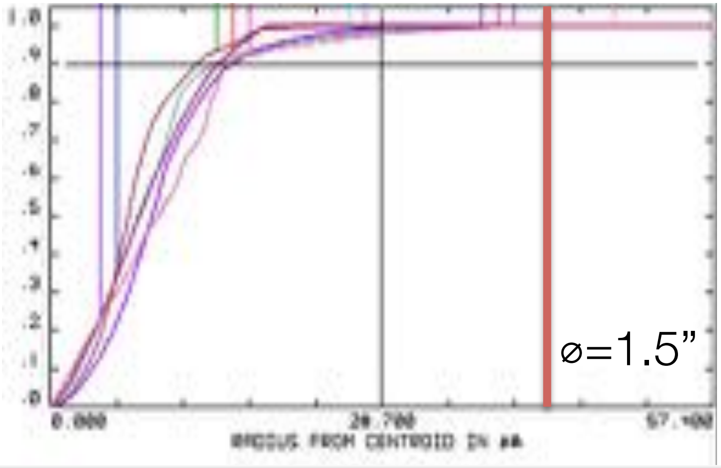
High Resolution Spectrograph (1x)
  # Fibres
  Passband
  Velocity accuracy
	R~20,000
	  800 fibres
	  392-437 & 515-572 & 605-675 nm
	  < 1 km/s

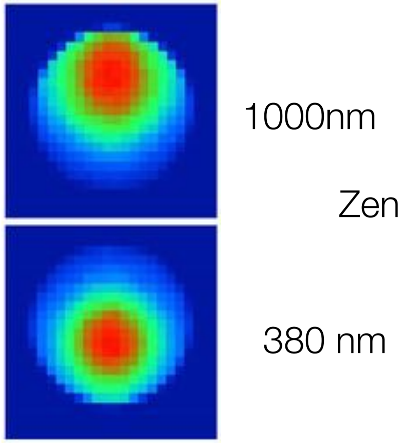
# of fibers in ⌀=2' circle	>3
Fibre diameter	⌀=1.4 arcsec
Area (first 5 year survey)	>2h x 18,000 deg^2
Number of science spectra (5 year)	~75 million of 20 min

Wide-field corrector VISTA ⌀=2.5°
includes an ADC, A&G, and WFS



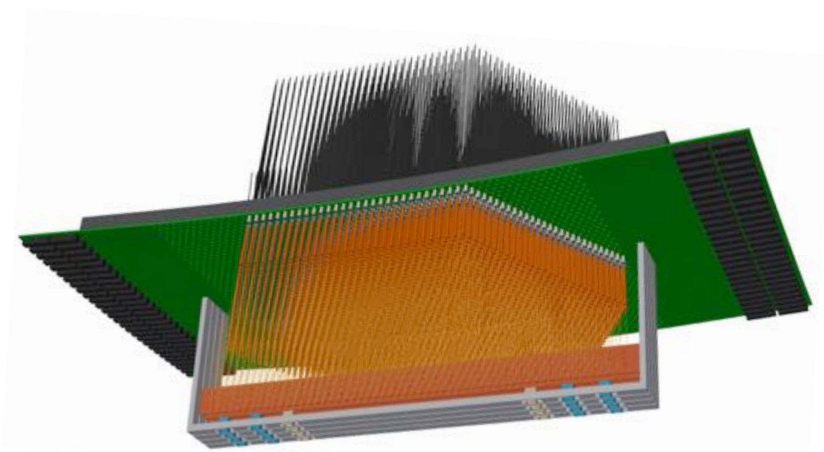
Development AIP responsibility





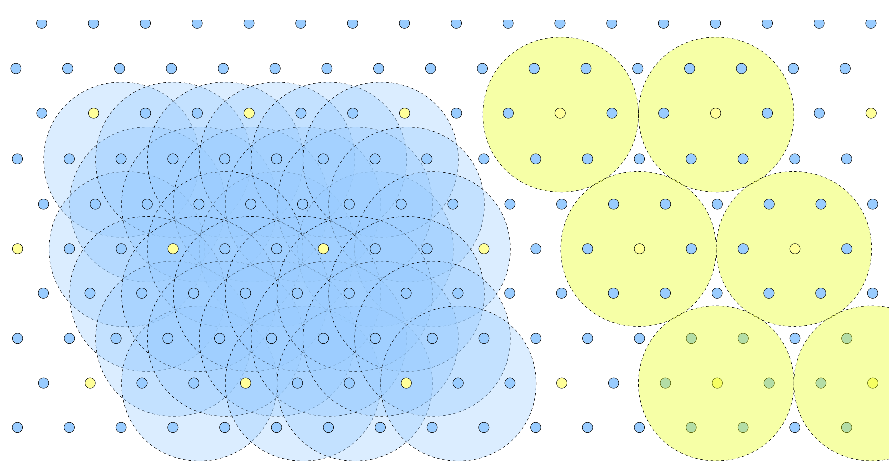
Field-edge position
Zenith Distance: 55 degree
Seeing: 0.7 arcsec
Fibre: 1.5 arcsec

Tilting Spine (Echidna) positioner



FMOS Echidna on Subaru

- ~2400 fibres
- Large, overlapping patrol areas enables dense target packing and special high-resolution fibres
- Closest separation ~15 arcsec
- Reconfiguration time <2 min during science CCD readout

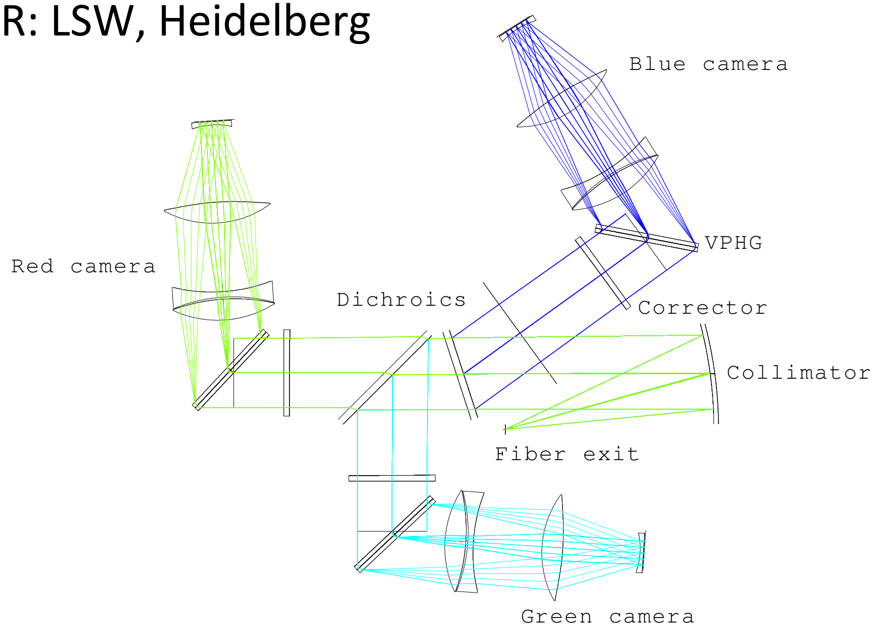


AAO, Sheinis et al.

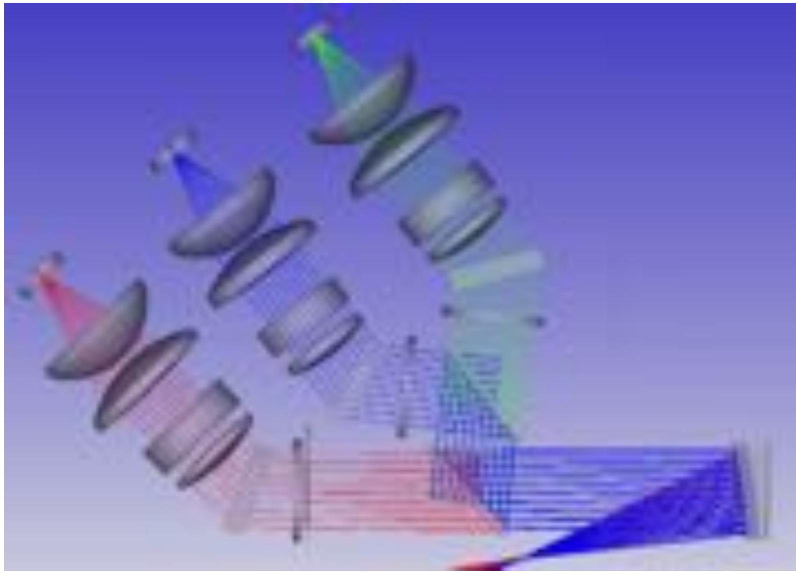
Dedicated HR and LR spectrographs

- Fixed configuration spectrographs, high throughput with VPH gratings
- 3-arm designs with 6k x 6k detectors for both high- and low-resolution

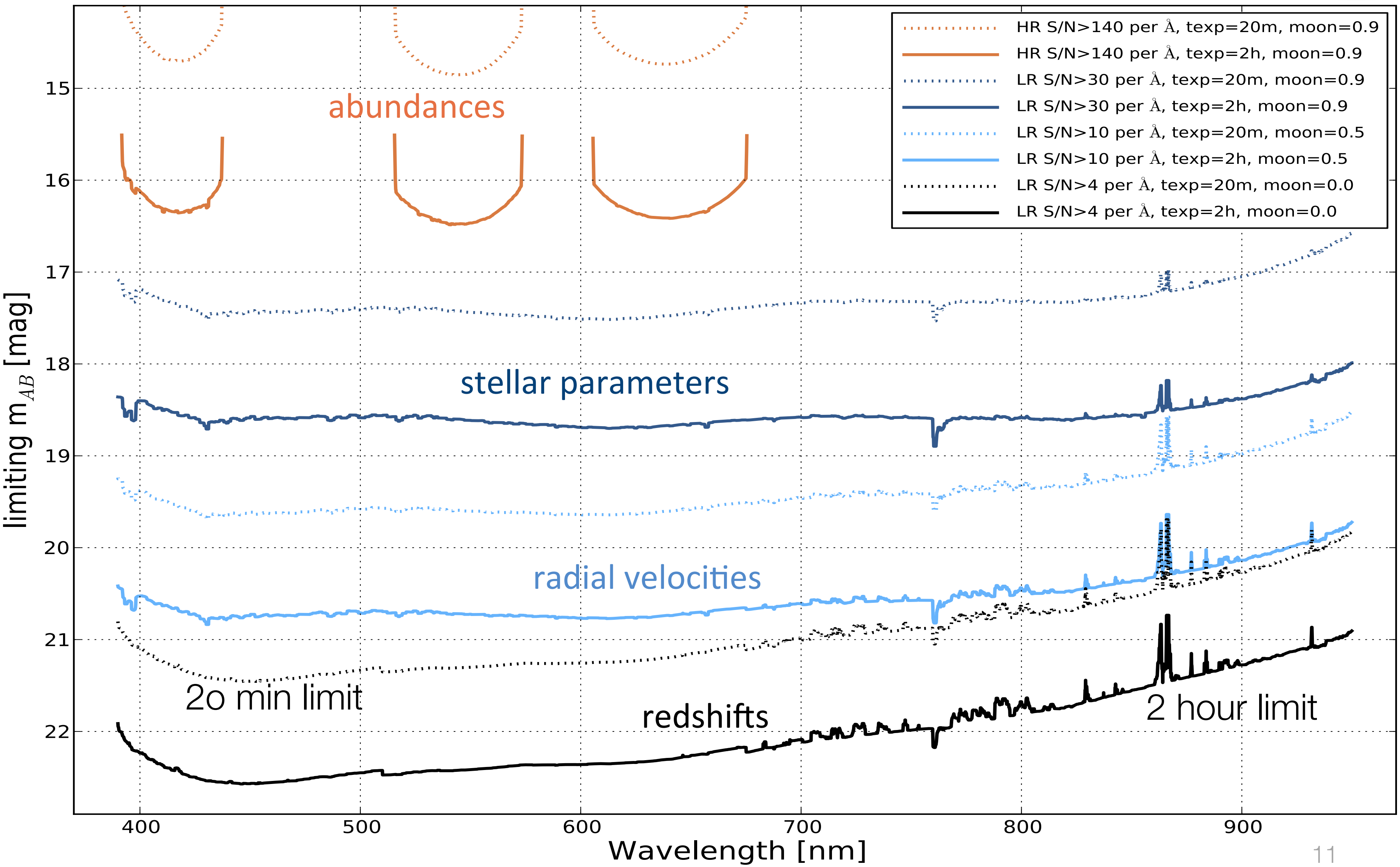
HR: LSW, Heidelberg



LR: CRAL, Lyon

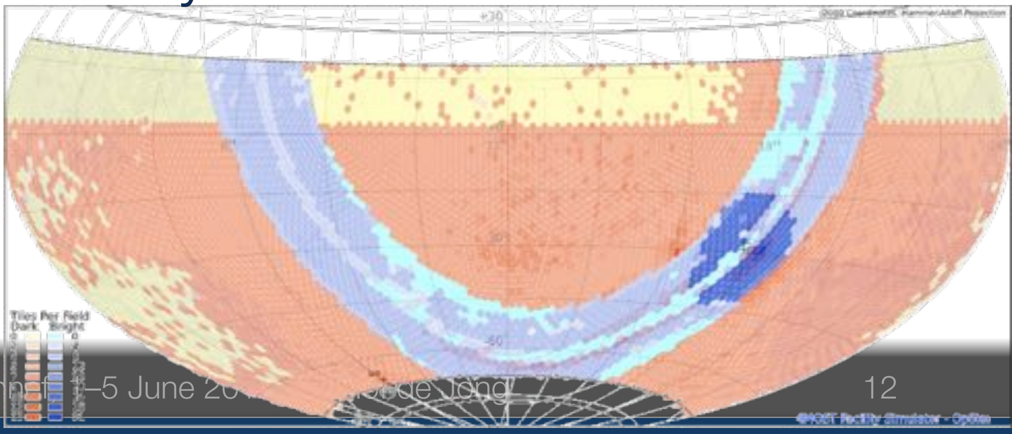


Magnitude limits for typical science cases



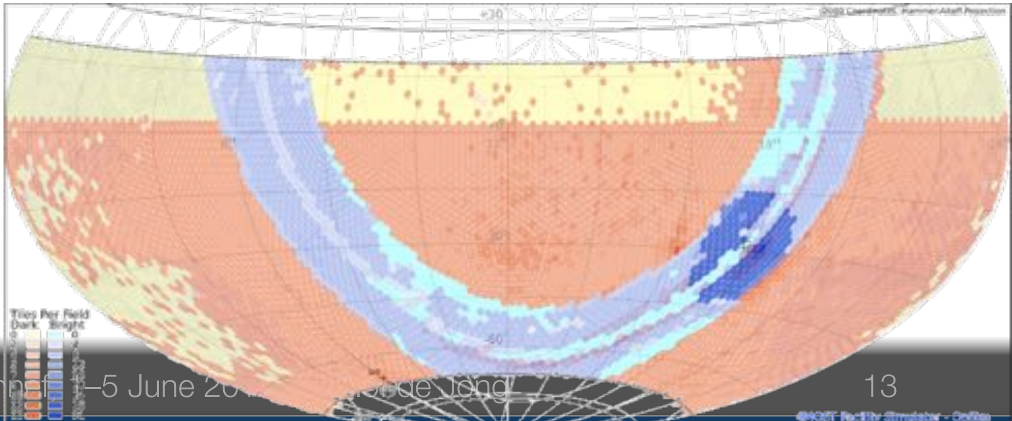
How are we going to run 4MOST?

- Unique operations model for MOS instruments that allows observations *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
- ***Key Surveys*** will define observing strategy
  - Millions of targets all sky
- ***Add-on Surveys*** for smaller surveys
  - Small fraction fibers all sky
  - Dedicated small area
  - 10^3 to 10^6 targets



How are we going to run 4MOST?

- Consortium Surveys will ensure whole hemisphere covered with at least ~120 minutes total exposure time
- Each exposure 20 minutes, repeats possible
- Total exposures times per target between 20 and 120 min (and more) possible till required S/N
- Areas with more targets get visited for more than 120 min
- All decided at least ~2 days in advance. Current ESO operations models does not allow ToOs for 4MOST

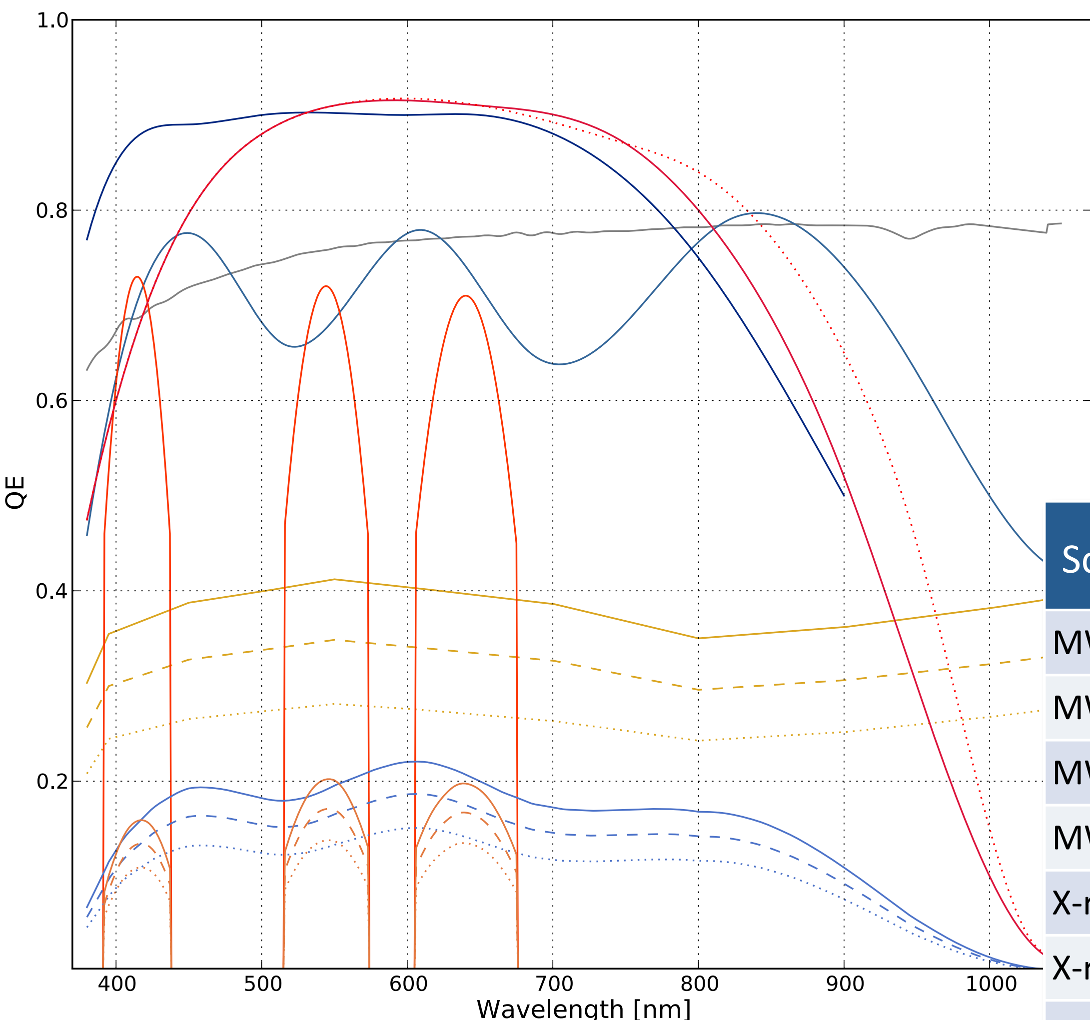


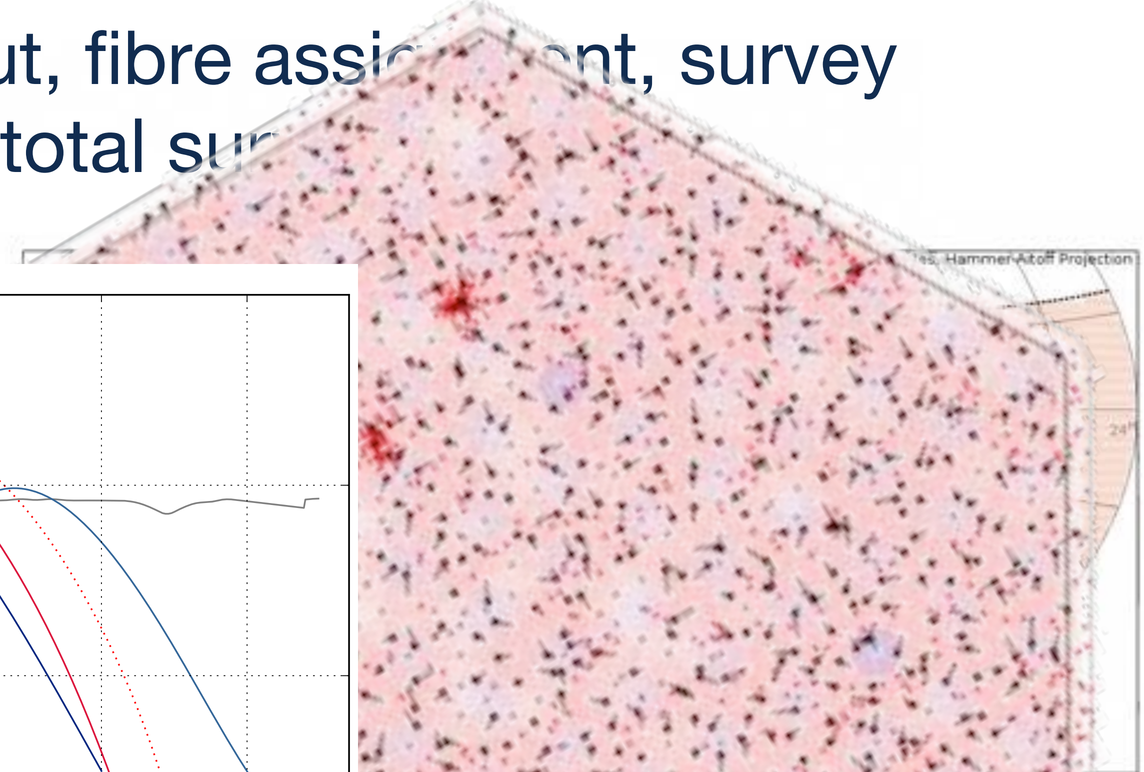
Science verification with full 4MOST simulator: Design Reference Surveys

Surveys implemented with ~60M objects (coordination Feltzing & McMahon)

- Milky Way halo R>5000 (~3M objects) Helmi, Irwin
  - Chemo-dynamics streams
- Milky Way halo R>20,000 (~ 0.2M objects) Christlieb
  - Chemical evolution of accreted components
- Milky Way disks/bulge R>5000 (~25M objects) Chiappini, Minchev, Starkenburg
  - Chemo-dynamics of bulge/disks
- Milky Way disks/bulge R>20,000 (~2.5M objects) Bergemann, Bensby
  - Chemical evolution in situ components
- eROSITA galaxy clusters (~50,000 clusters, ~2.5M objects) Merloni (acting)
  - Dark Energy and galaxy evolutions
- eROSITA AGN (~1M objects) Merloni
  - Evolution of AGN and the connection to their host galaxies
- Galaxy evolution WAVES (~1.5M objects) Driver, Liske
  - Dense magnitude/redshift limited galaxy survey
- Fundamental cosmology science (~23M objects) Kitaura
  - Luminous red, blue galaxies, and AGN survey

Simulate throughput, fibre assi ent, survey strategy and verify total su





Science case	S/N / Å	r_{AB}-mags	Targets (Millions)
MW halo HR	140	12–15.5	0.07
MW halo LR	10	16–20.0	1.5
MW disk/bulge HR	140	14–15.5	2.1
MW disk/bulge LR	10–30	14–18.5	10.7
X-ray galaxy clusters	4	18–22.0	1.4
X-ray AGN	4	18–22.0	0.7
BAO+RSD galaxies	4	20–22.5	12.8
Total			>29

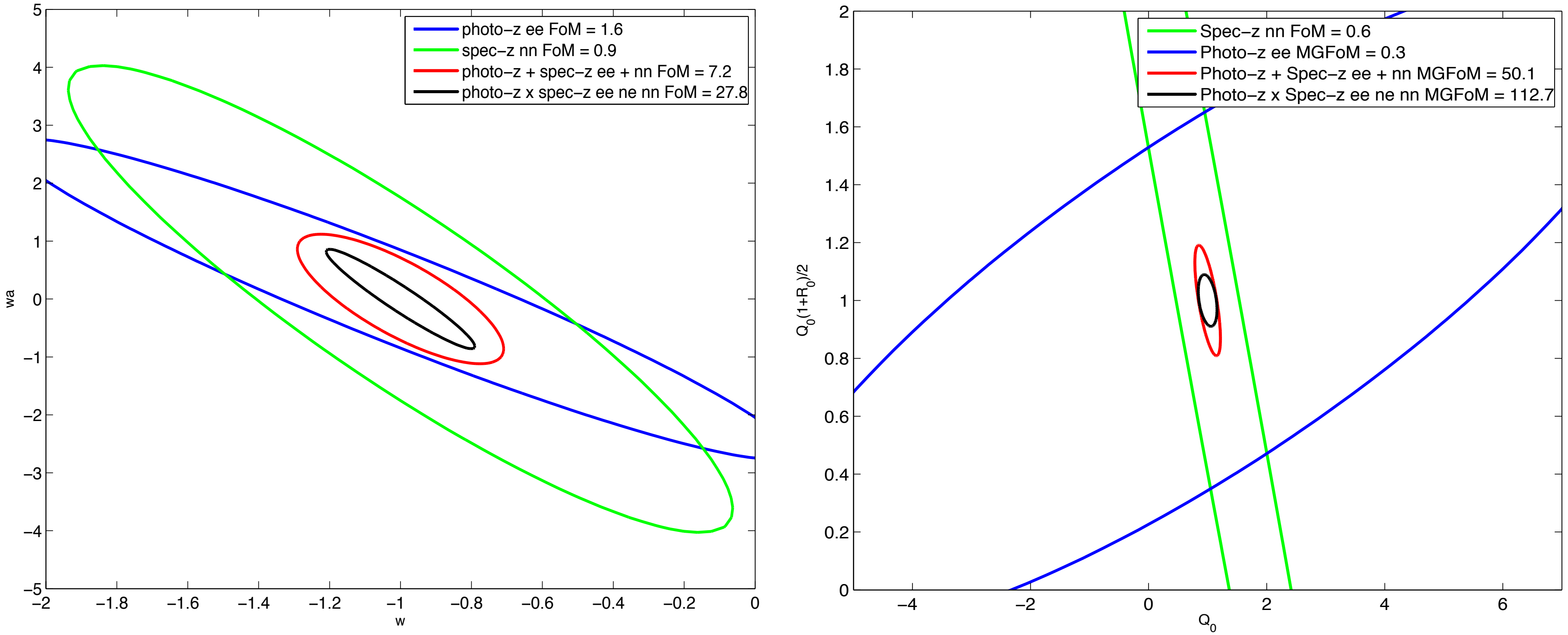
MPE, Garching, Boller, Dwelly et al.

Cosmology surveys (~15M objects)

- *Dark Energy* and *General Relativity* constraints by measuring cosmic expansion history and growth of structure:
  - Weak Lensing: Photo-z calibrations and characterize the foreground lensing populations for KIDS, DES, LSST and Euclid. Same sky cross-correlation of foreground density field & lensing improves constraints 2–4x
  - Galaxy Clusters: Redshifts and velocity dispersions of Galaxy Clusters provides strong constraints on growth rate of structure.
  - SNe Ia: Follow-up DES Sne Ia host galaxies and later LSST transients to measure expansion. 10s of LSST transients per pointing -> 100k transients/year
  - BAO and RSD: Use different populations (LRGs, ELGs, AGN, Lα forest) and their cross-correlation to measure expansion and structure growth

- Concentrate on redshifts z<~1 to complement Euclid, maximize area to increase number of targets for 4m telescope

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

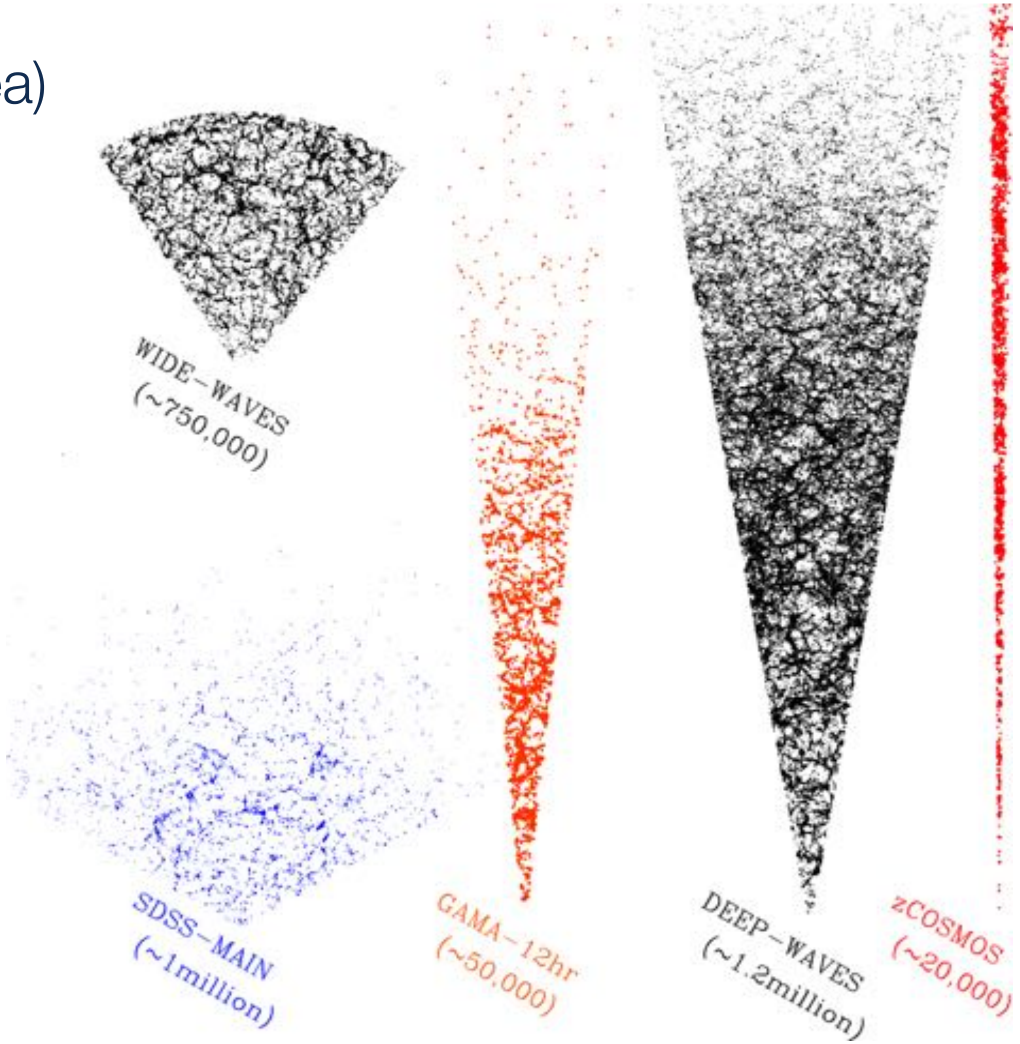


- Full combination including **cross-correlations** using same sky
- Same-sky benefit substantial: **x4** for DE, **x2** for MG vs different hemispheres
- For 15,000 deg^2 LSST+4MOST FOM=54 (DE), 383 (MG) (Kirk, Private Communication)

Galaxy+DM evolution (WAVES)

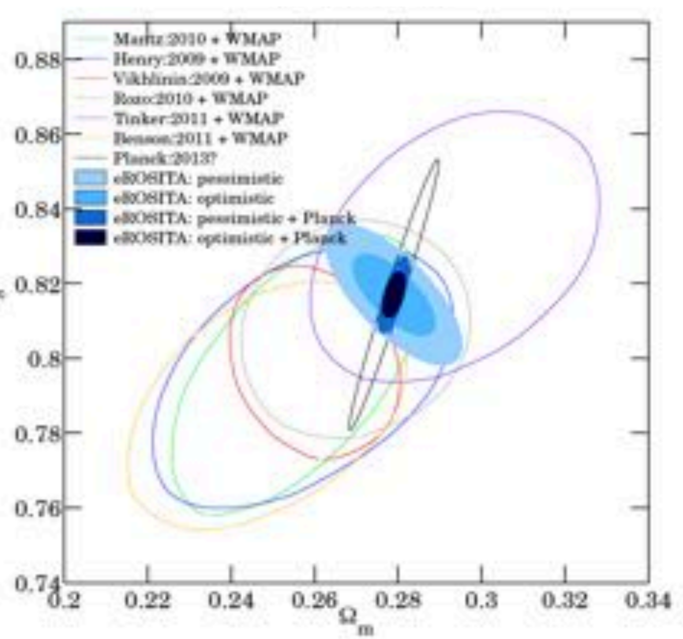
- Wide-WAVES (VST KiDS area)
  - 750 deg^2, 0.8M galaxies, z<0.2
- Deep-WAVES
  - 100 deg^2, 1.2M galaxies, z<1.0

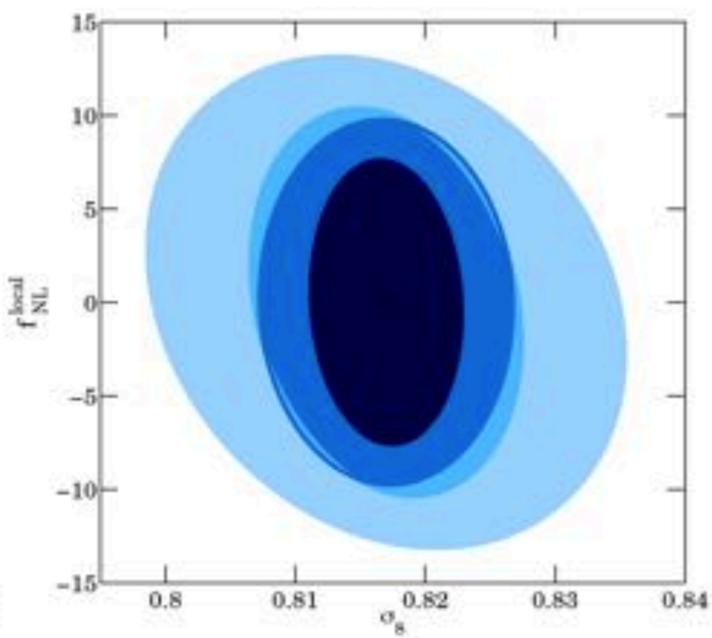
- Goals:
  - Galaxy formation to dwarf satellite scale, halo occupation
  - Evolution of mass & energy budget for z<1
  - Growth of structure on 1kpc-10Mpc scales for z<1



eROSITA complement

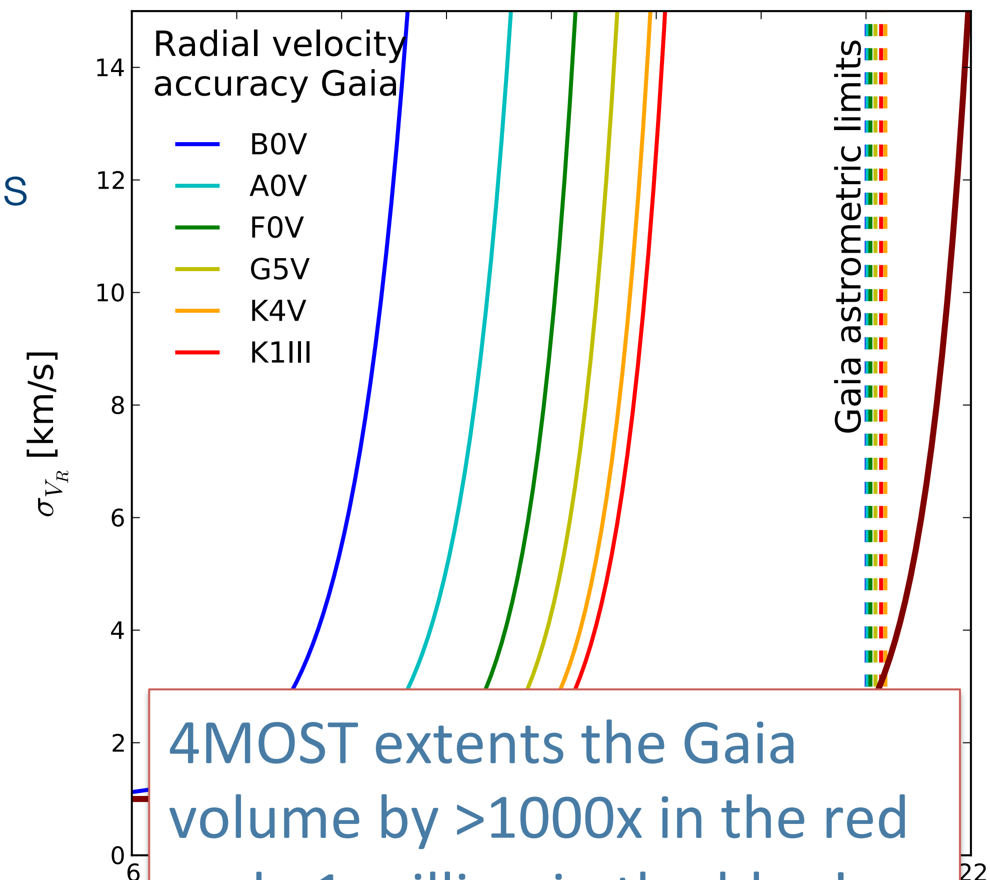
- German - Russian X-ray mission, Launch late-2015
- 8x all sky survey, 0.5 –10 keV, beam ~25”
- Mission goals: Dark Matter and Energy, growth of structure
- 10^5 galaxy clusters with >20 redshifts per cluster
- 10^6 AGN, 10^6 Galactic sources
- Strong cosmology constraints by cross-calibrating different tracers
- AGN evolution and Galaxy-Black Hole connection





Gaia needs spectroscopic follow-up to achieve its full potential

- Gaia astrometric mission launched Dec-2013
  - paralaxes and proper motions for ~1 billion stars to m_G<20 mag
  - spectra for radial velocities and metallicities for 150 million stars to m_G<~15 mag

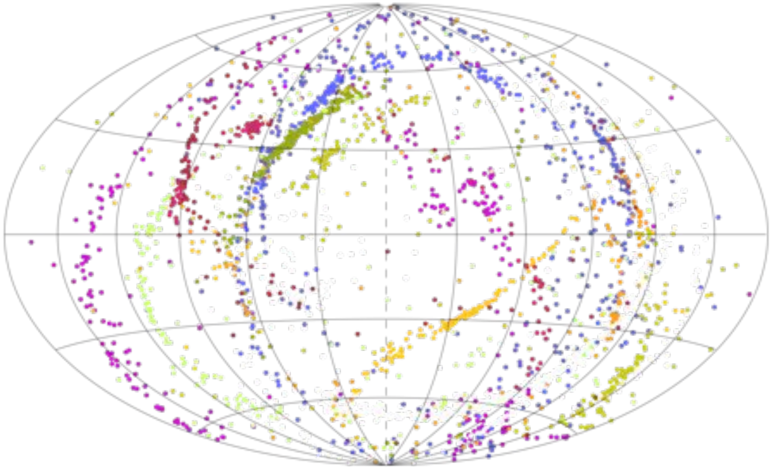


In South so cover the bulge, disk, halo and the Magellanic Clouds

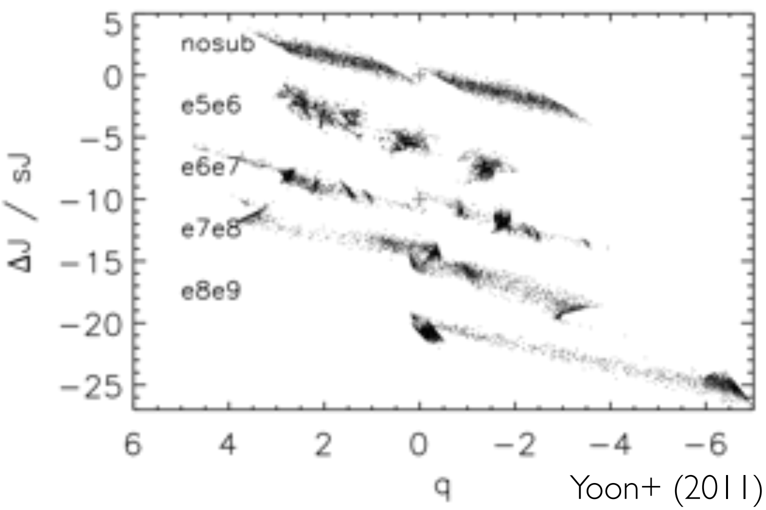
4MOST extents the Gaia volume by >1000x in the red and >1 million in the blue!

Testing cosmology with Milky Way dynamics

- Obtaining R~5000 spectra of $>10^6$ stars at $|b|>30°$ allows us to:
  - Determine the Milky Way 3D potential from streams to ~100kpc
  - How is DM reacting to baryons:
    - has there been significant adiabatic contraction?
    - is there a disk-like DM component?
    - does the DM respond to the bar?
  - Determine the mass spectrum of Dark Matter 10^3–10^5 $M_\odot$ halo substructure by the kinematic effects on cold stellar streams



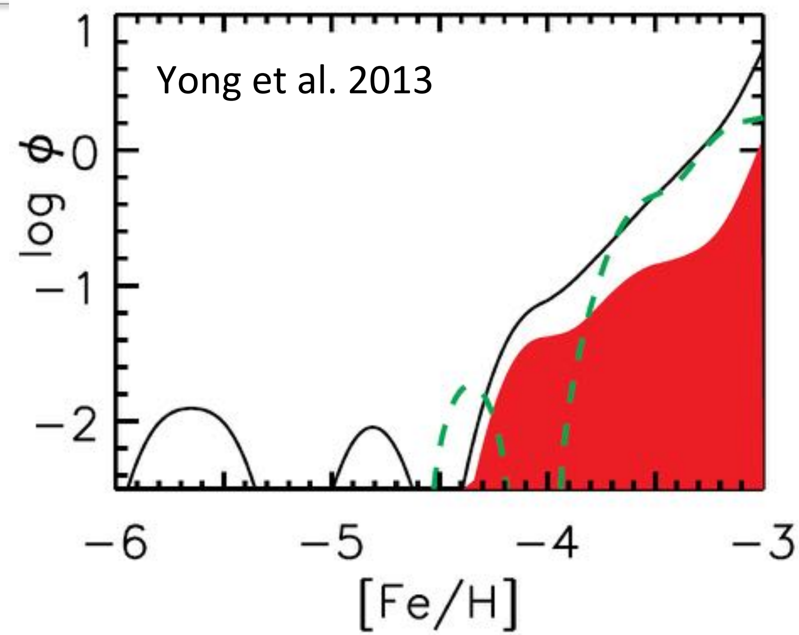
Cooper+ (2010)

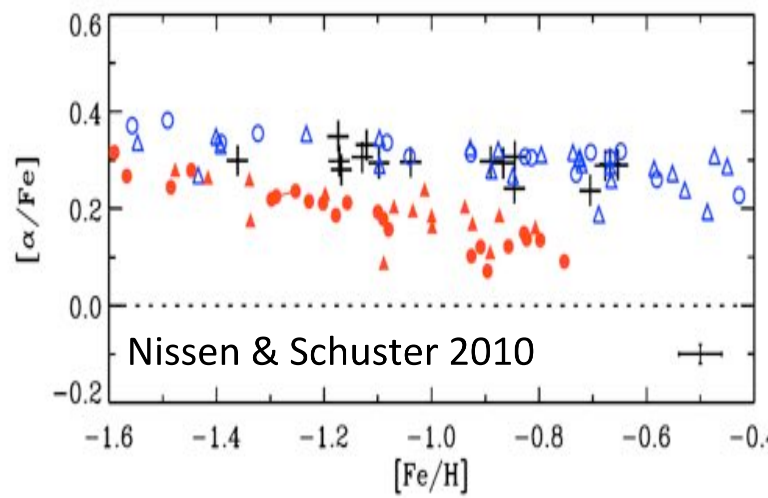


Yoon+ (2011)

HR: Milky Way halo

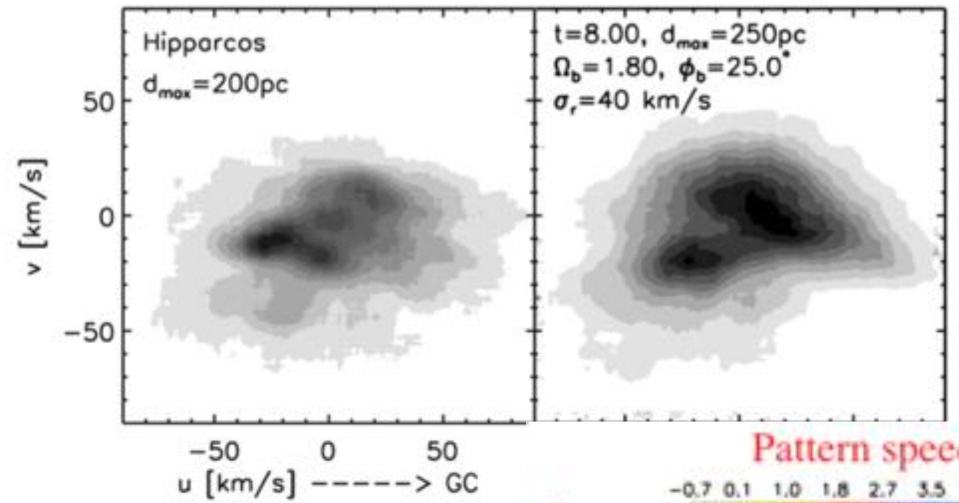
- Observe ~100,000 halo stars with HR spectrograph
- Metallicity distribution function
  - Constraints on Pop III stars (IMF, rotation)
- Chemo-dynamical substructure
  - Identify stream of tidally disrupted dwarfs
  - Early chemical enrichment of streams (depends on a few stars)
  - Accreted versus in situ formation
- Include LMC & SMC + stream

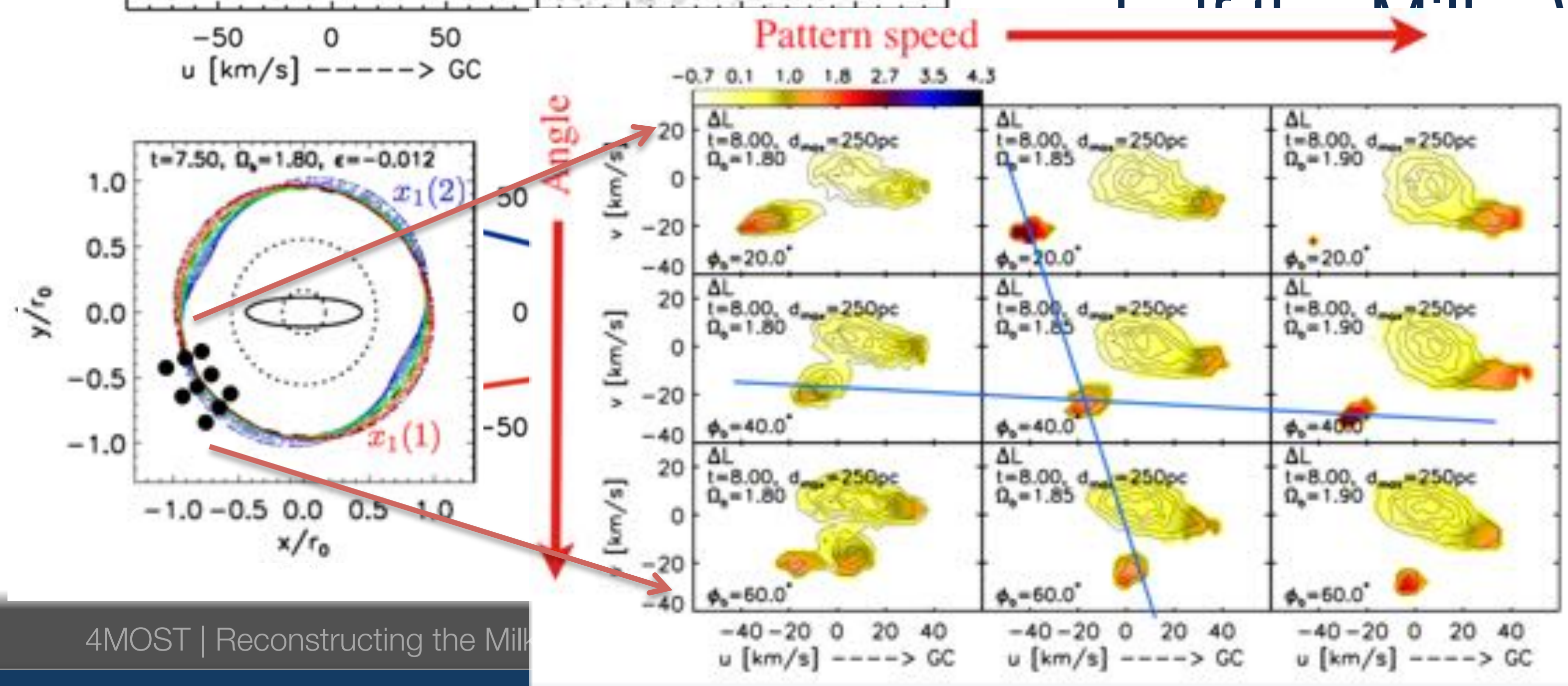




Milky way bar creates moving groups in velocity distribution

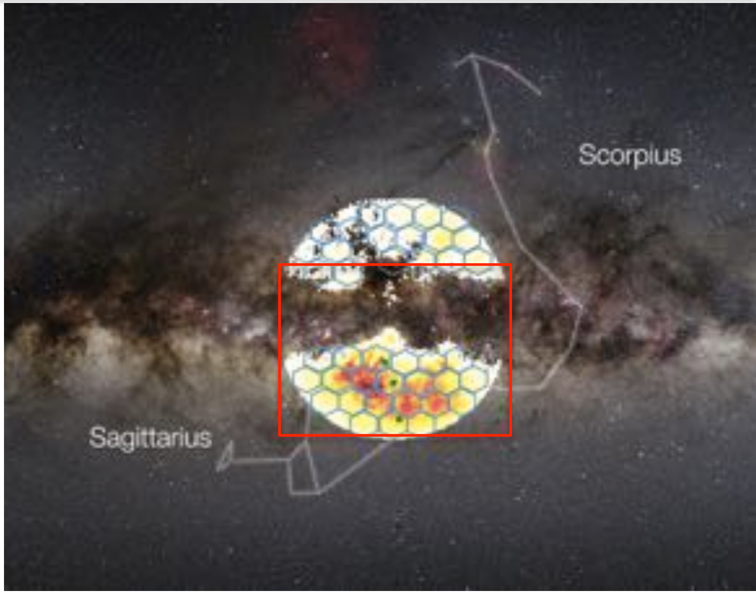
- So far only done out to 200 pc with Hipparcos
- Gaia combined with 4MOST can do this to ~10 kpc, i.e. in almost half the Milky Way

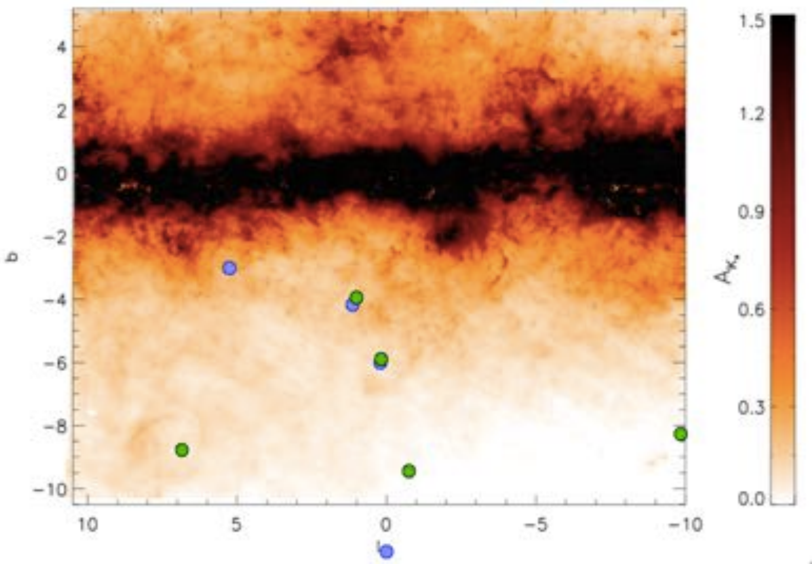




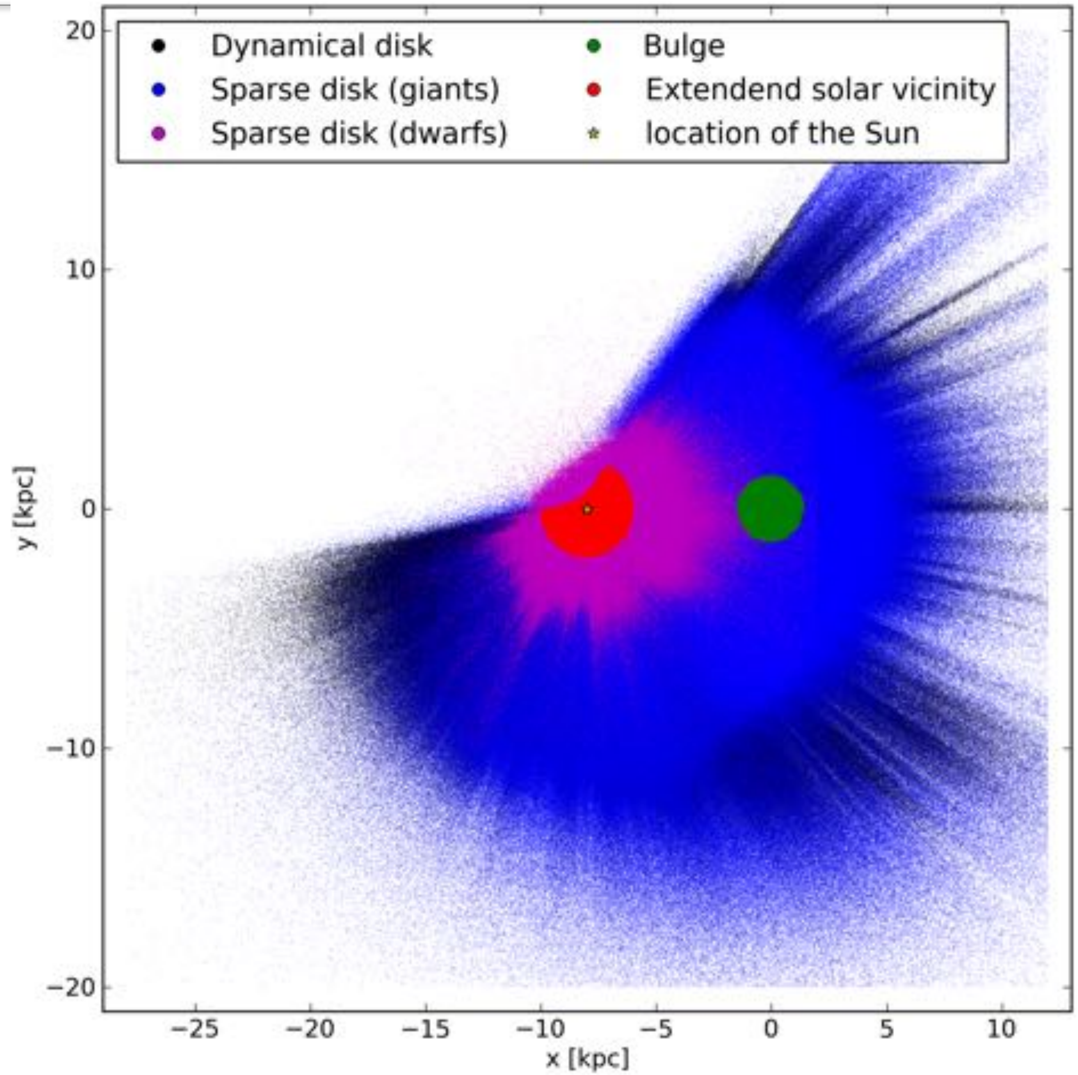
Milky Way bulge chemo-dynamics

- 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

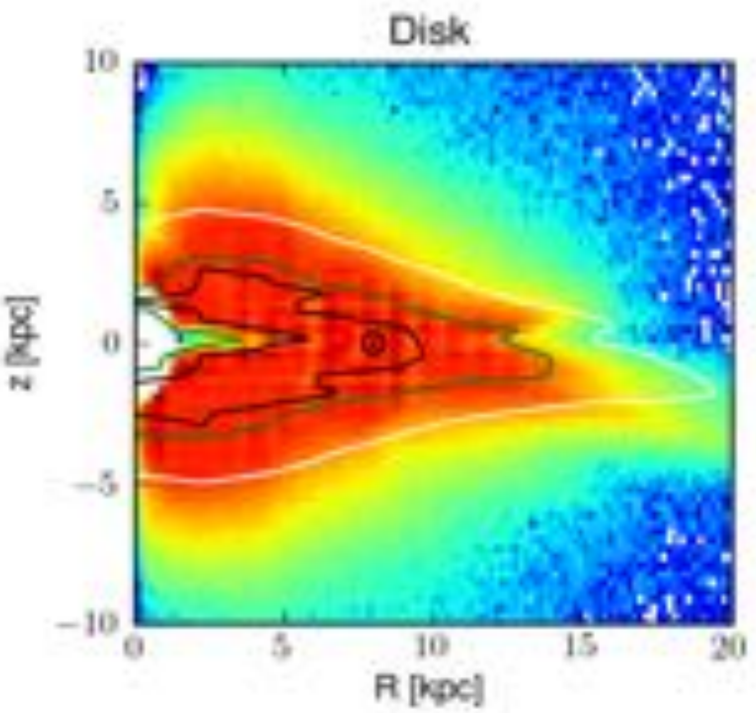




Galaxia based mock catalogues

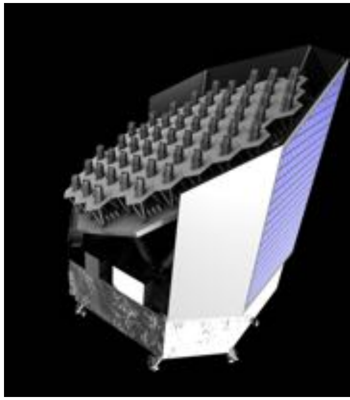


- Gaia based selection
- Cover all MW components

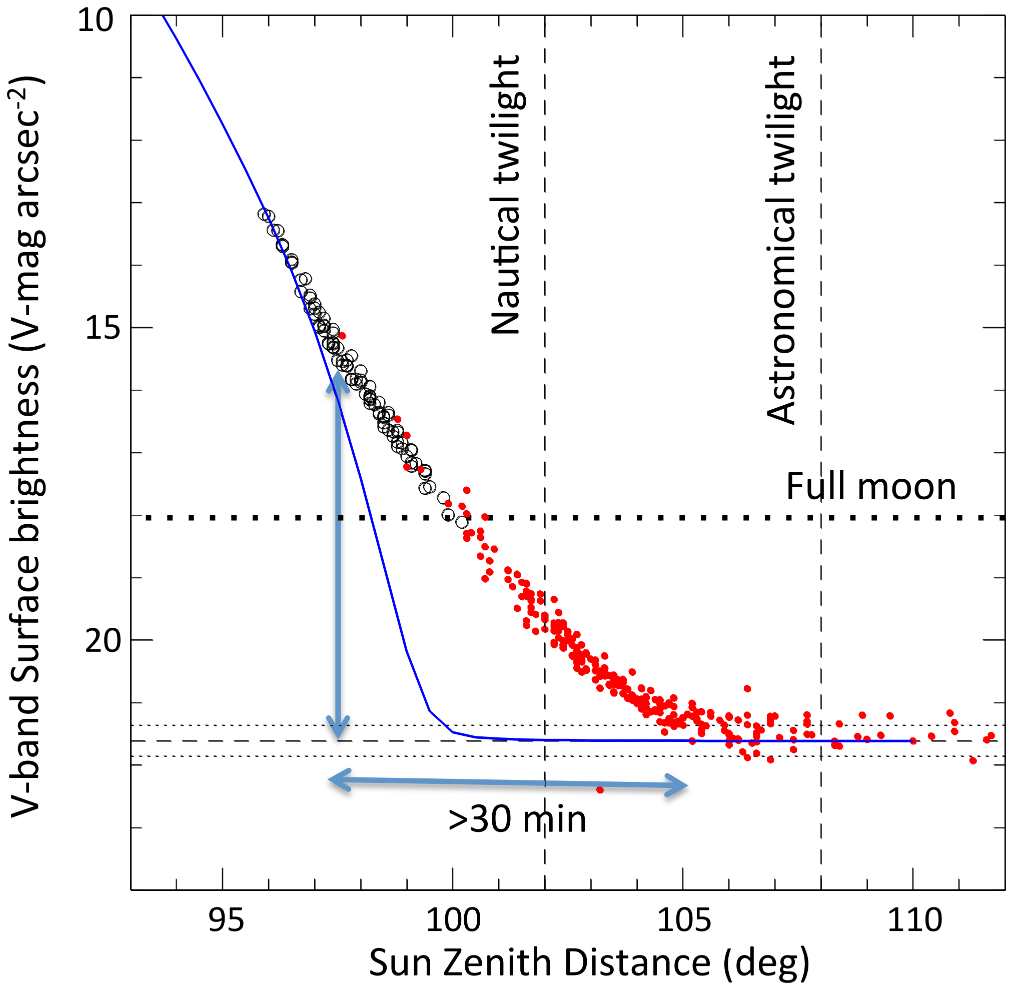


Observing TESS/PLATO bright sample

- 4MOST saturates for a 10th mag star in a default 20 min exposure in High Res Spectrograph (HR)
- With 2 min exposures we could 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 (early release?)
- 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
- Are repeats useful if we have velocity accuracy of 1 km/s? What if 400m/s, or 100 m/s?



TESS/PLATO stars in twilight?



- 20+ min at beginning and end of night for bright sample?
- ~8 exps/night -> full sky in <2 years
- At no cost to other 4MOST programs!

Other Science feasible with surveys with thousands to millions of objects

- High resolution spectroscopy survey of Open Clusters
- Radial velocities time series of low mass binary systems
- Star formation history of the Milky Way from 100,000 White Dwarfs
- Nature of peculiar variable stars discovered by Gaia, LSST, Euclid
- Chemo-dynamics of Magellanic Clouds and other satellites
- Follow-up of LSST and Euclid variables/transients
- Repeats on deep fields
- Reverberation mapping of AGNs
- Support Euclid photometric redshift calibrations (for $z<0.9$ and measuring intrinsic alignment galaxies)
- Redshifts of Euclid strong galaxy lensing candidates
- Nature of radio galaxies from SKA
- Characterisation of ~300k PLATO host stars
- Ages of astero-seismology objects from e.g. CoRoT, PLATO
- Insert your idea here

Consortium

- Facility Institutes
  - Leibniz-Institut für Astrophysik Potsdam (AIP) (D)
  - MPI für Extraterrestrische Physik, München (D)
  - Zentrum für Astronomie, Univ. of Heidelberg (D)
  - MPI für Astronomie, Heidelberg (D)
  - Institute of Astronomy, Cambridge University (UK)
  - Australian Astronomical Observatory (AU)
  - Centre de Recherche Astrophysique de Lyon (F)
  - NOVA/ASTRON (NL)
  - ESO, Garching (EU)
- Science Institutes
  - University of Lund (S)
  - University of Uppsala (S)
  - University of Groningen (NL)
  - L'Observatoire de Paris, GEPI, Paris (F)
  - University of Hamburg (D)

Your institute here?

Schedule and Milestones

- Jan 2015
  - Start Preliminary Design phase
- May 2016:
  - *Preliminary Design Review*, all concepts tested, evaluated, and costed
- Dec 2017:
  - *Final Design Review*, detailed designs finalized
- Jan 2020:
  - All subsystems manufactured, assembled, integrated and verified
- Oct 2020:
  - Full system integrated and verified at AIP, *preliminary acceptance Europe*
- Jun 2021:
  - System delivered and installed on telescope, *preliminary acceptance Chili*

Phase B (Jan 2015 – May 2016)

Phase C (May 2016 – Dec 2017)

Phase D (Dec 2017 – Jun 2021)

- Jun 2021 – Jun 2026:
  - First science survey of 4MOST, about 30% of targets determined by community surveys

Phase E

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

- Status:
  - Project approved by ESO, PD phase started, *operations 2021* (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 in coordination with community
  - Add-on surveys from community through ESO peer-reviewed applications
- Instrument specifications:
  - High multiplex: 1600 fibres to R~5000 + 800 fibres R~20,000 in parallel
  - Wavelength: LR: 390-930 nm, HR: 392-437 & 515-572 & 605-675 nm
  - Large field-of-view on VISTA, 4m-class telescope: ⌀=2.7°

Special message

The Galaxy is BIG

- America's Galaxy is BIG
- Africa's Galaxy is BIG
- Australia's is BIG
- Asia's Galaxy is BIG
- Europe's Galaxy is BIG

- Lot's of work for all of us to do!

rijksuniversiteit groningen

AIP

RAL Space

MPE

LMU USM

UPPSALA UNIVERSITET

LUND UNIVERSITY

ASTRON

ZAH

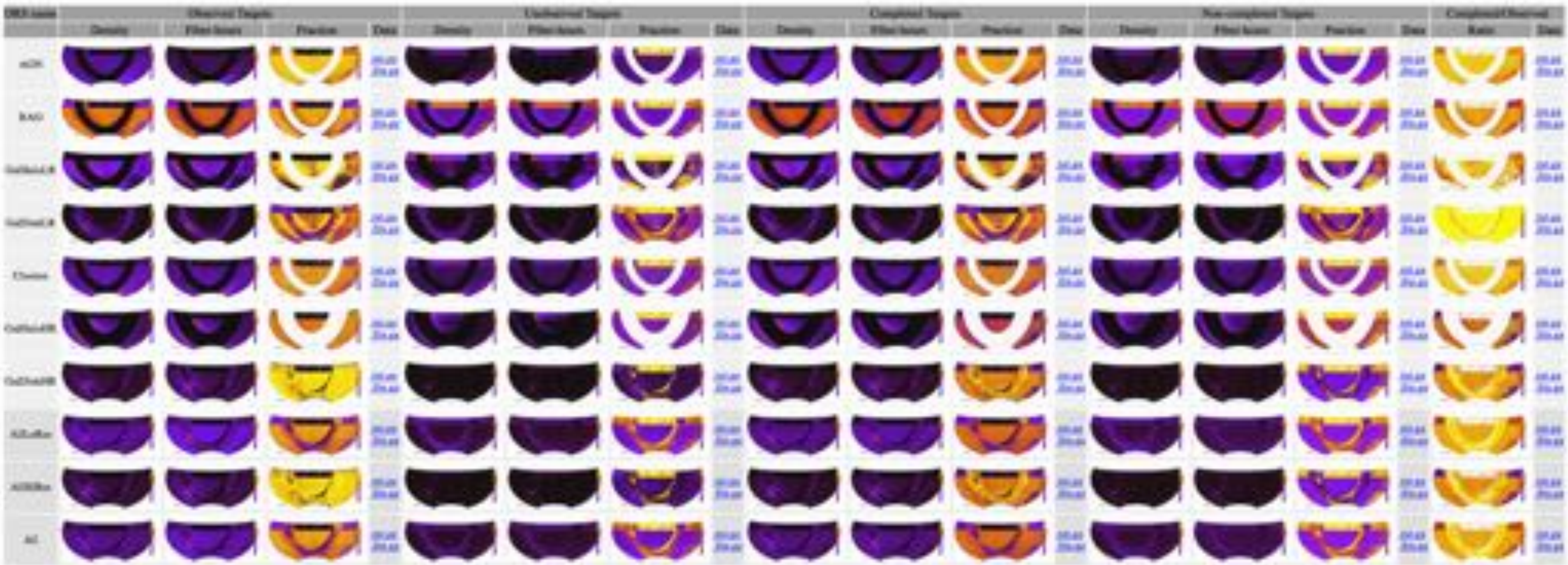
UNIVERSITY OF CAMBRIDGE

ESO

l'Observatoire de Paris | GEPI

Galaxies Étoiles Physique et Instrumentation

Diagnostic tools



Diagnostic tools

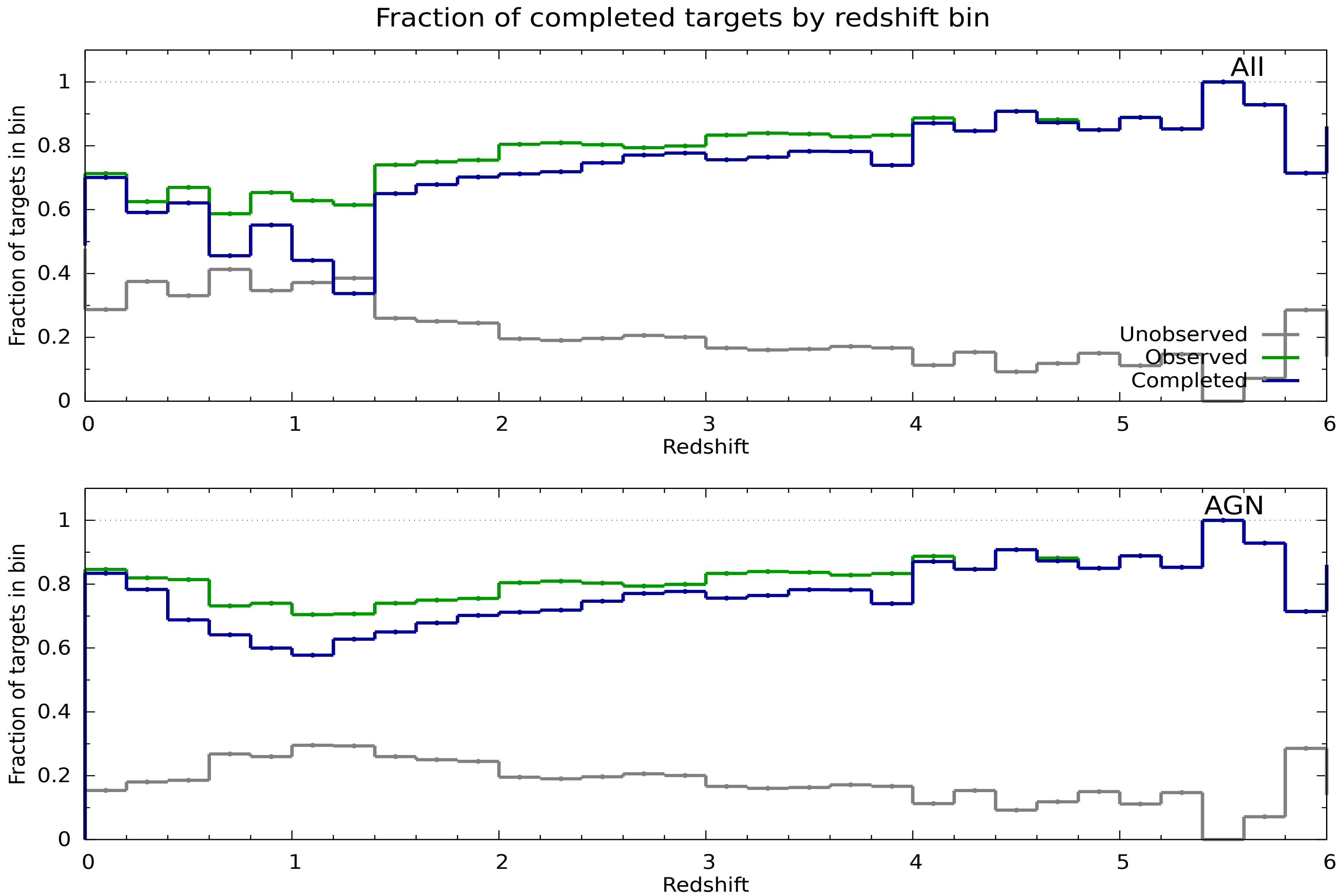
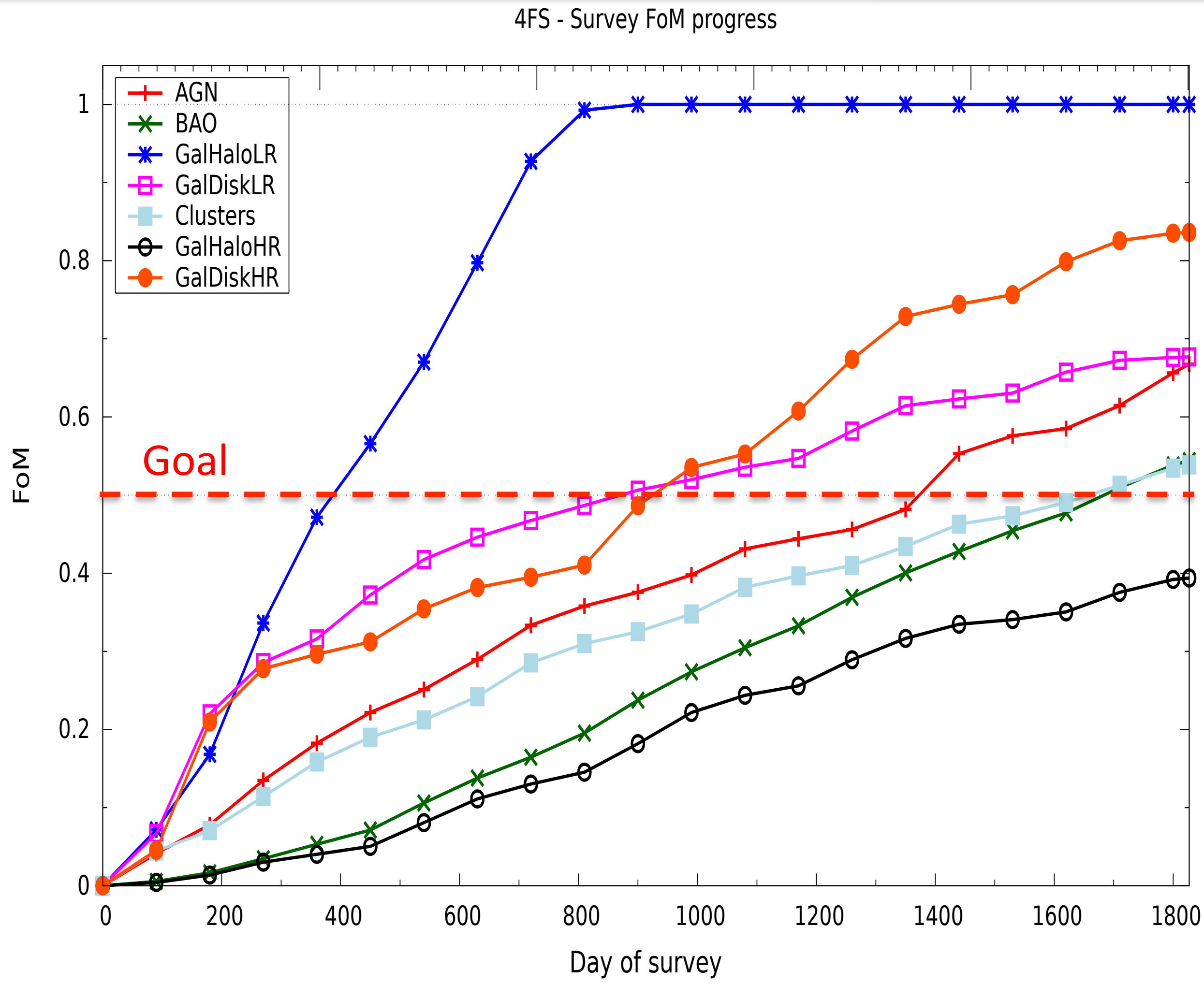
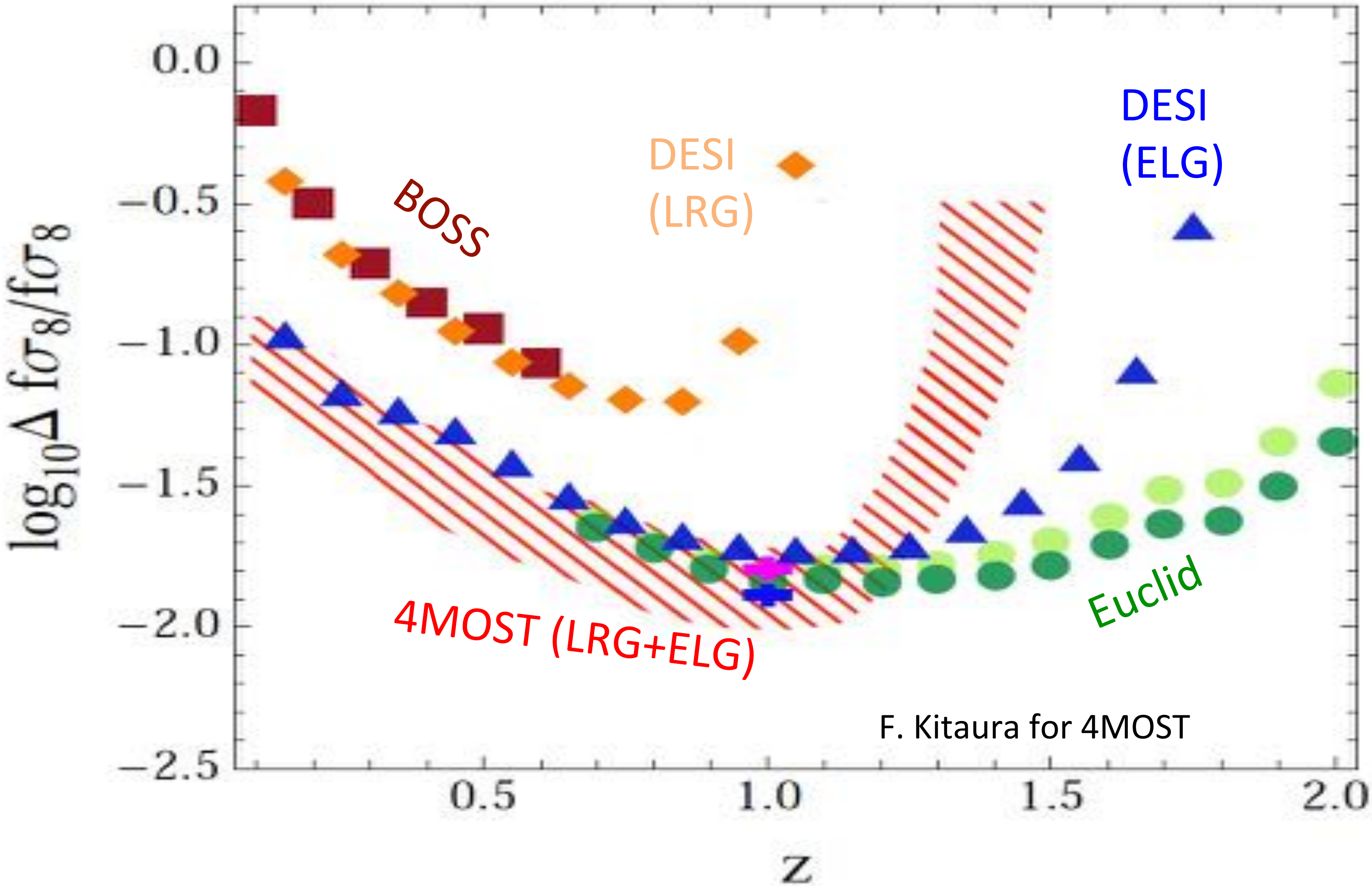


Figure-of-Merit (FOM = Metric)



- Monitor relative progress to assign proper weights

4MOST Facility Simulator - OpSim



- Concentrate on redshifts z<~1 to complement Euclid, maximize area to increase number of targets for 4m telescope

Planned Simulation and Analyses Tools

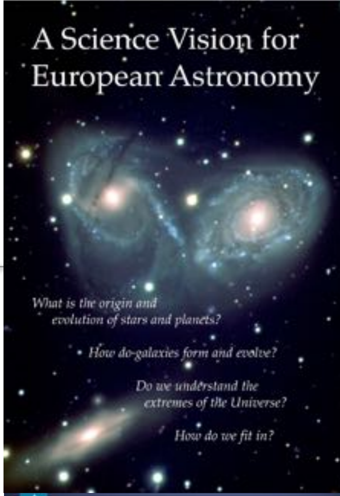
- Consortium provides full forward modelling tools:
  - Astronomer provides simulation with selection observables
  - Select targets as for real catalogue
  - Create fields and observing schedule including competition from other surveys
  - Apply (simplified?) atmosphere and instrument model
  - Apply (simplified?) data reduction and parameter extraction model
- Is full MCMC modelling needed?

Data release and publication policies

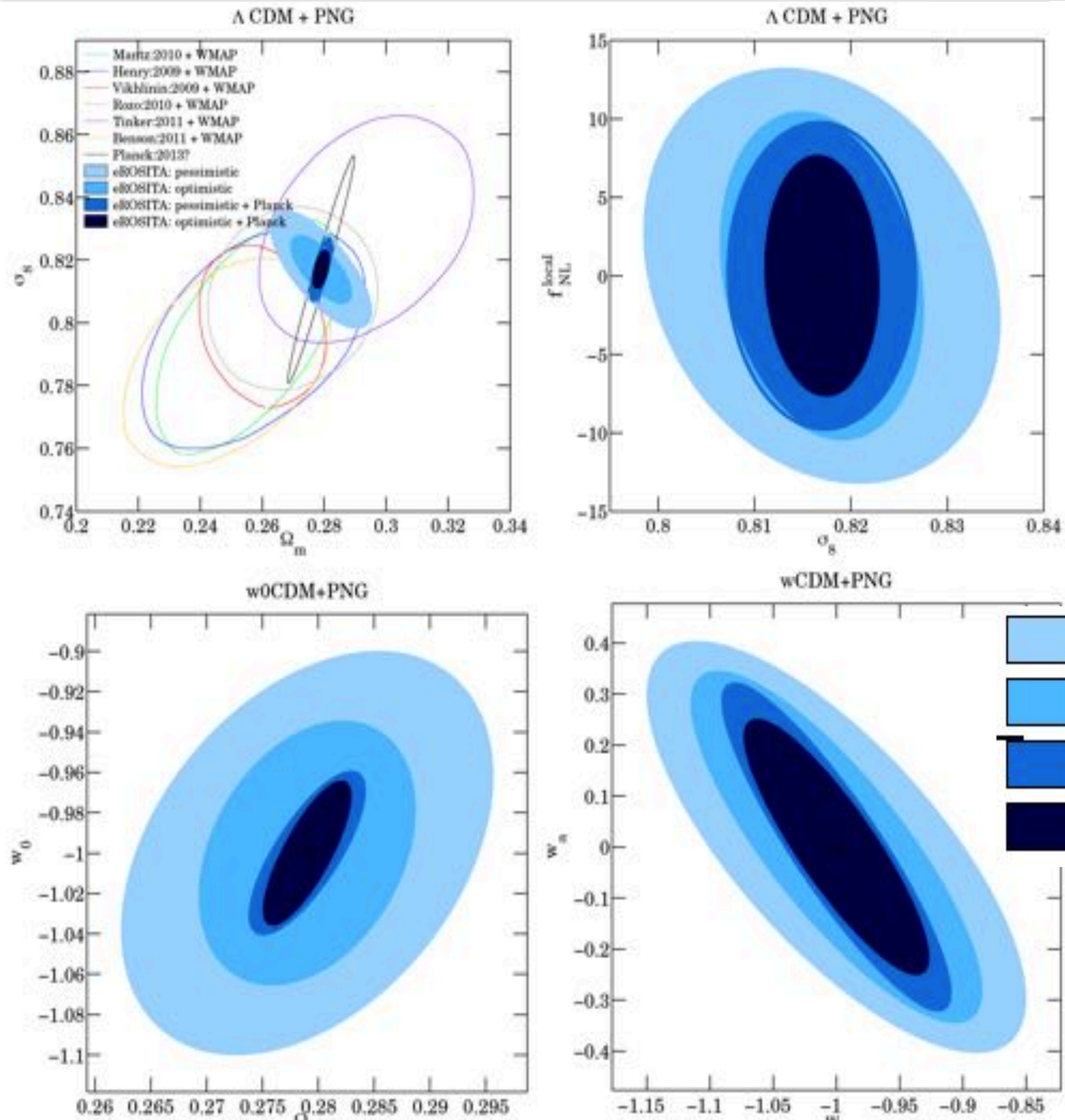
- All raw data immediately public
- All 1D spectra immediately available to all surveys
- 1D spectra released to external public in yearly DRs
- Higher level data products as agreed between individual surveys and ESO, probably yearly data releases after 1-1.5 yr
- Publication policies similar to Sloan
  - First announce science project and papers
  - "Builders" (both facility and survey) have opt-in option on papers
  - Surveys can have additional rules
- Valid for both Consortium and Community surveys

Background: EU strategic docs

- A Science Vision for European Astronomy (ASTRONET)
  - Extreme Universe (Dark Energy & Dark Matter, Black holes)
  - Galaxy Formation & Evolution
  - Origin of Stars and Planets
  - Solar System
- ASTRONET Infrastructure Roadmap
  „A smaller project, but again of high priority, is a wide-field spectrograph for massive surveys with large optical telescopes."
- ESA-ESO Working Group on Galactic populations, chemistry and dynamics
  „Blue multiplexed spectrograph on 4 or 8m class telescope"
- Strategic Review on Europe's 2-4m telescopes over the decade to 2020 (ASTRONET/OPTICON)
  „Optical wide-field spectrograph on 4m telescopes (N+S)"

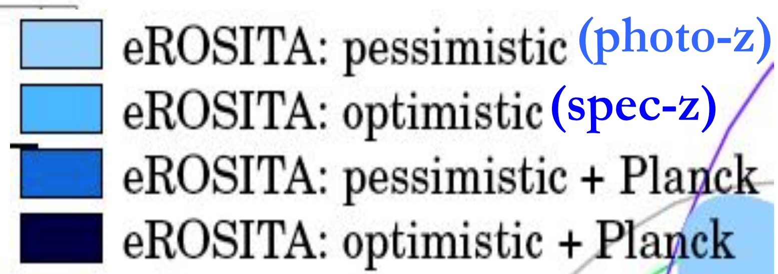


Cosmological constraints by obtaining redshifts and velocity dispersions of galaxy clusters



- X-ray (eROSITA) selection - Redshift determination
- Mass calibration
  - (dedicated follow-up)
- Cluster Mass function vs. z
- Cluster Power Spectrum vs. z

DETF FoM



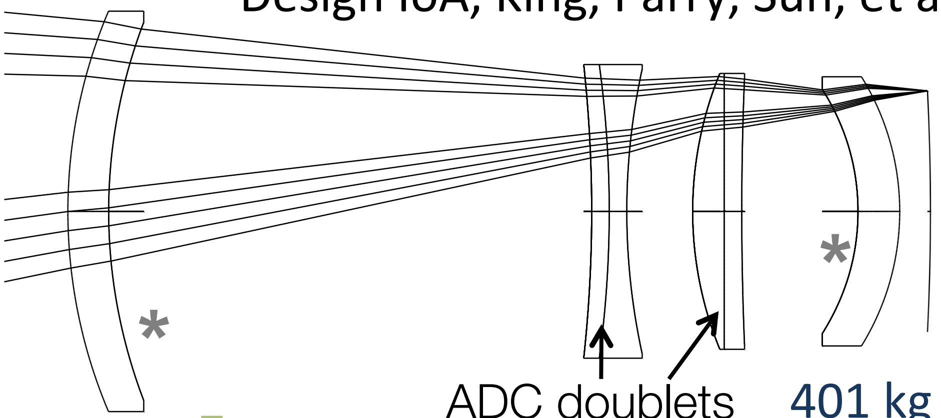
57
103
174
263

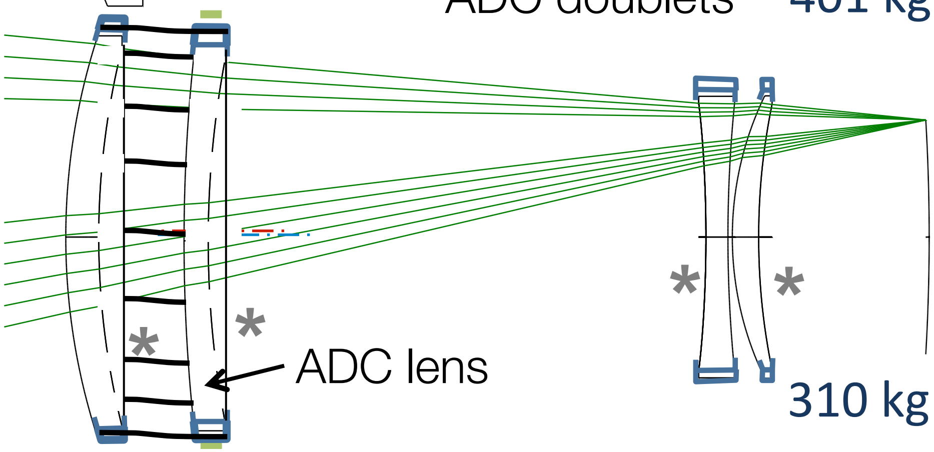
Merloni et al. 2012
Pillepich et al. 2012

Wide-field Corrector can be inserted into VISTA like IR camera

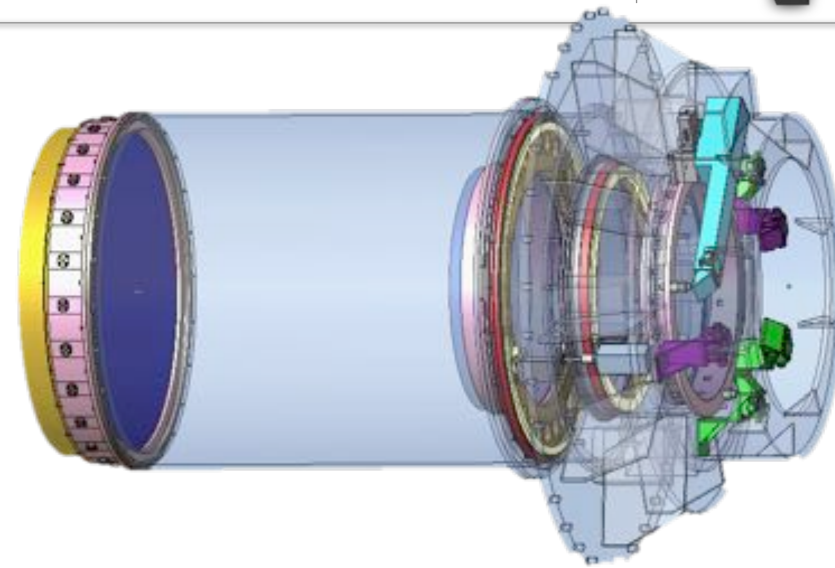
Wide-field corrector VISTA ⌀=2.5°
includes an ADC, A&G, and WFS

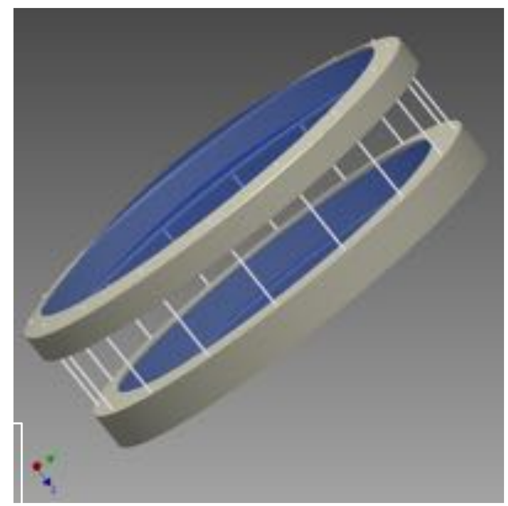
Design IoA, King, Parry, Sun, et al.

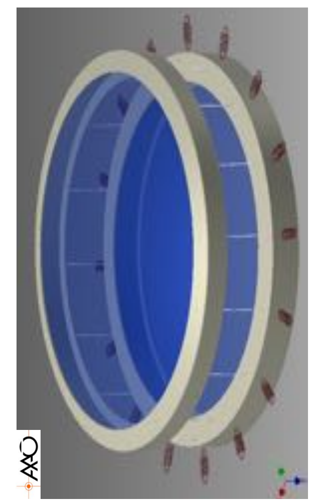




Design AAO, Gillingham et al.

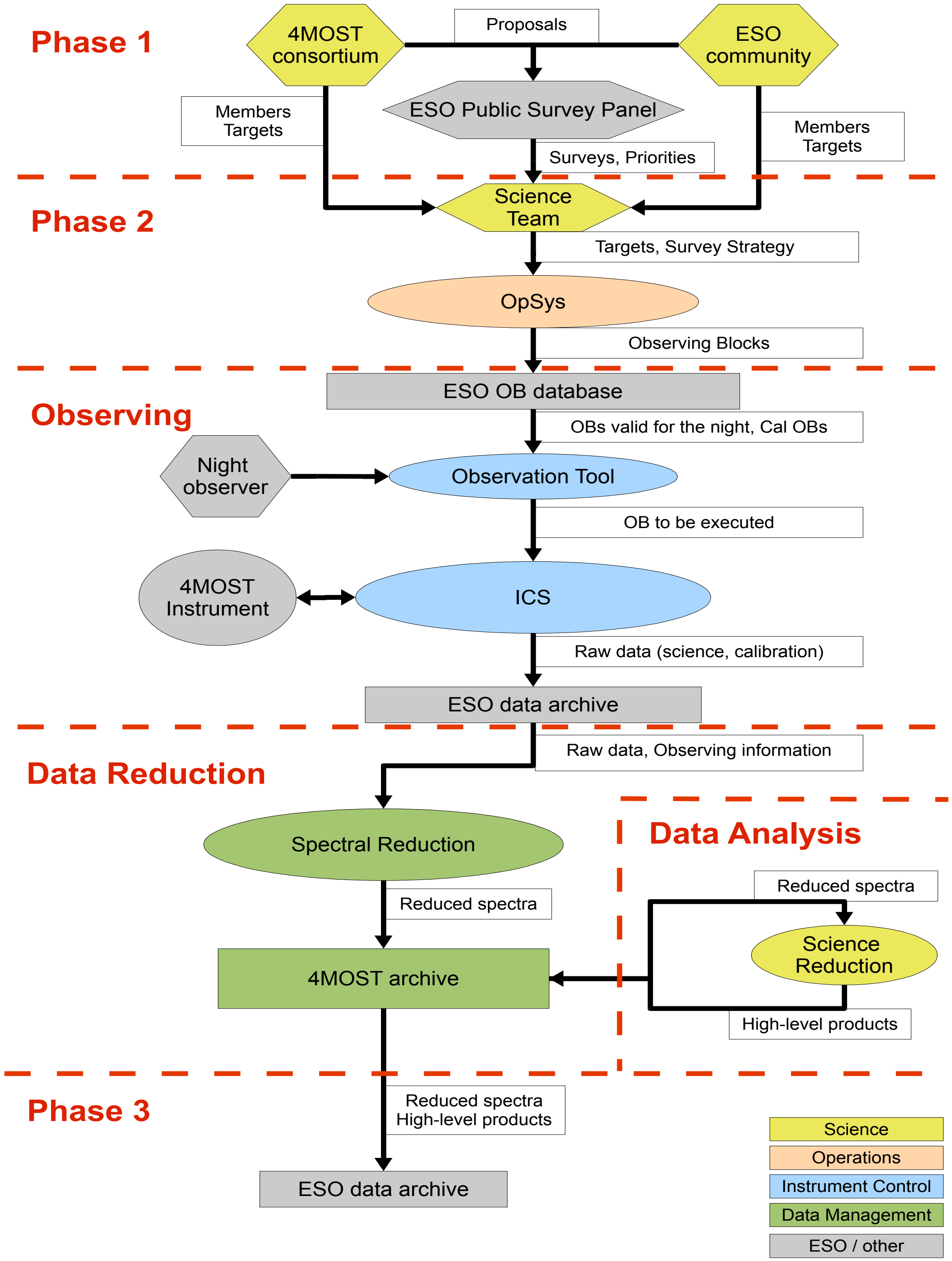






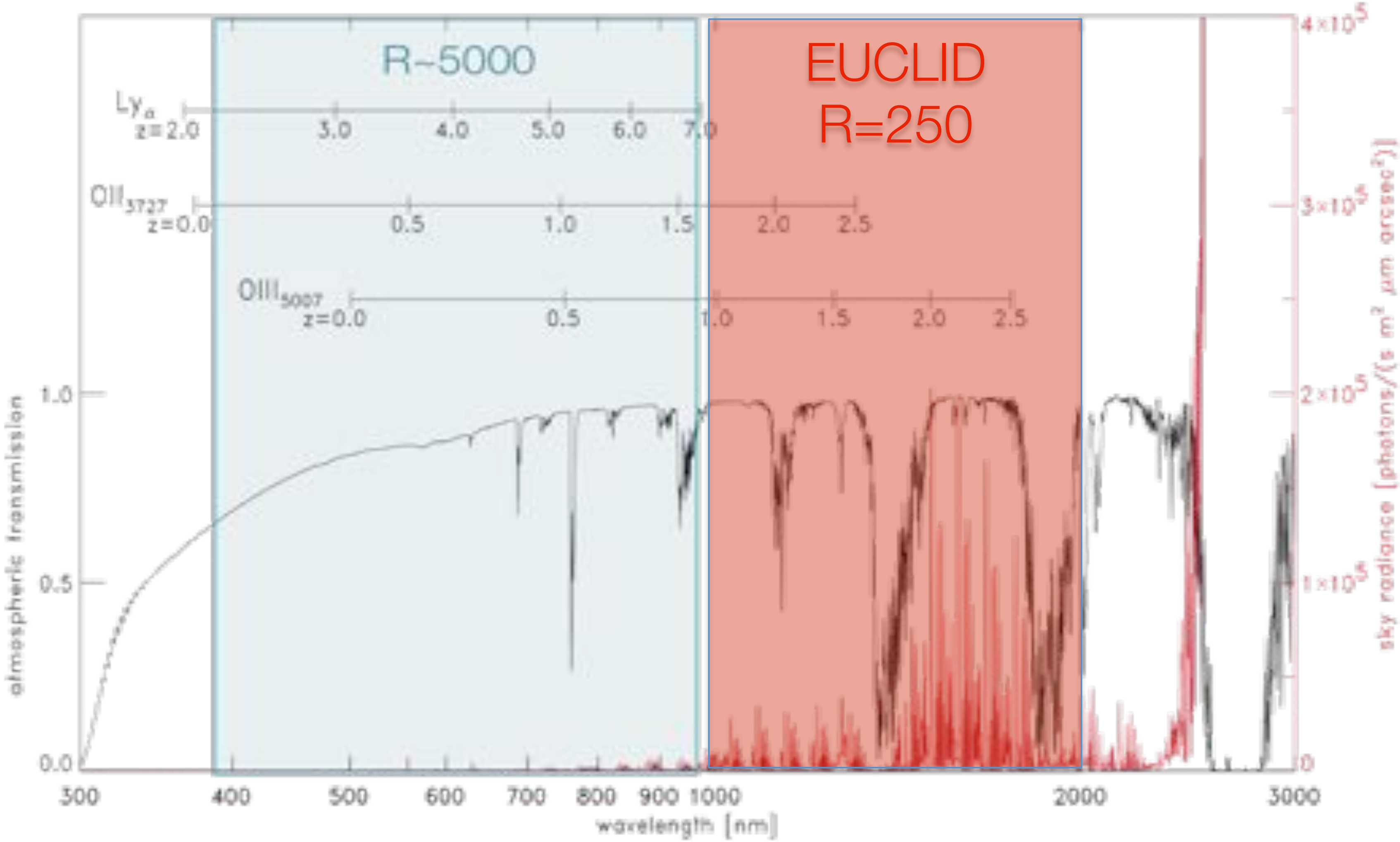
Unique operational aspects

- All observation preparation including target catalogs, survey strategy, observing block creation, calibrations are shared between Surveys
- All data reduction up to 1D calibrated spectra is shared
- Consortium is performing these tasks for both Consortium *and* Community Surveys
- We need to perform these tasks absolutely impartially to avoid conflicts with Community
- ESO requests we perform this for the lifetime of instrument (~10 years)
- *GTO return on this effort (second 5 years) still under negotiation with ES*
  – ESO proposes secondment at ESO for Science Operations



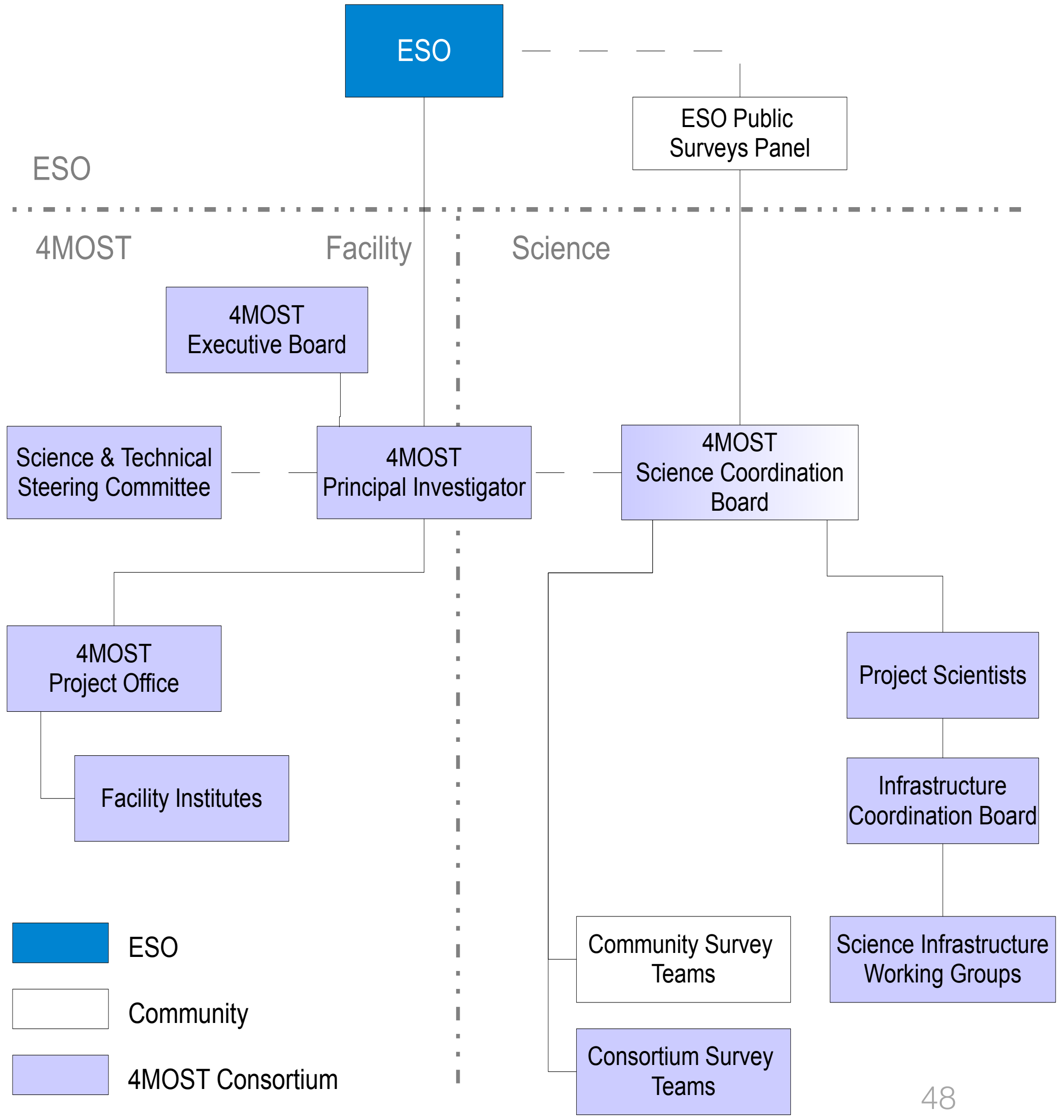
Phase 1
4MOST consortium
Proposals
ESO community
ESO Public Survey Panel
Members
Targets
Members
Targets
Surveys, Priorities
Phase 2
Science Team
Targets, Survey Strategy
OpSys
Observing Blocks
Observing
ESO OB database
OBs valid for the night, Cal OBs
Night observer
Observation Tool
OB to be executed
4MOST Instrument
ICS
Raw data (science, calibration)
ESO data archive
Raw data, Observing information
Data Reduction
Spectral Reduction
Reduced spectra
4MOST archive
Data Analysis
Reduced spectra
Science Reduction
High-level products
Phase 3
Reduced spectra
High-level products
ESO data archive
Science
Operations
Instrument Control
Data Management
ESO / other

Advantage of the optical wavelength range

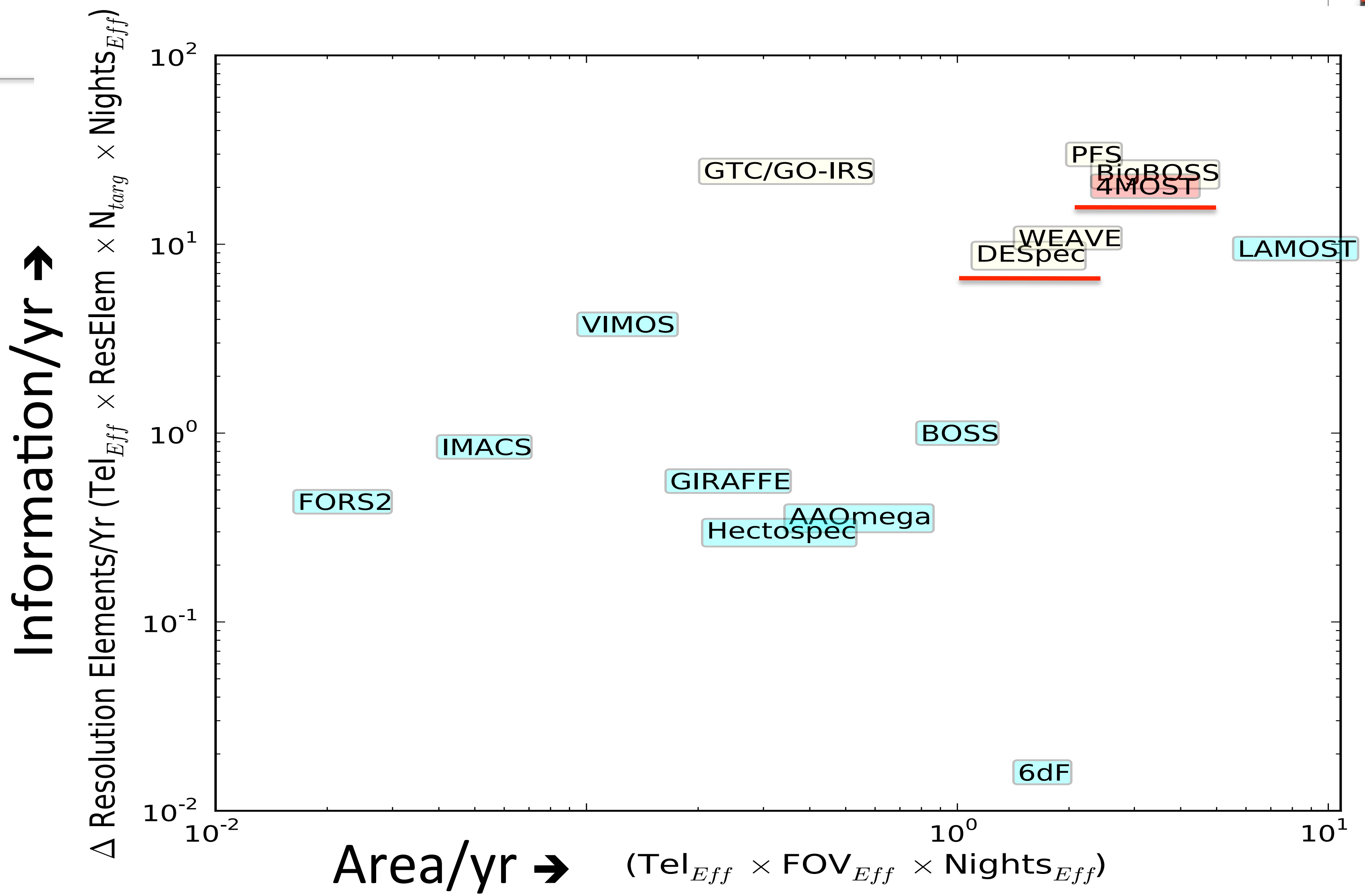


Proposed organisation breakdown

- Break work into Facility and Science part
- Science gets split between Survey Teams and Infrastructure Working Groups
- Science development overseen by the 4MOST Science Coordination Board (SCB)
- ESO Public Survey Panel approves all 4MOST Survey proposals



Competitiveness: Low-Resolution



Competitiveness: High-Resolution