4MOST – 4m Multi-Object Spectroscopic Telescope

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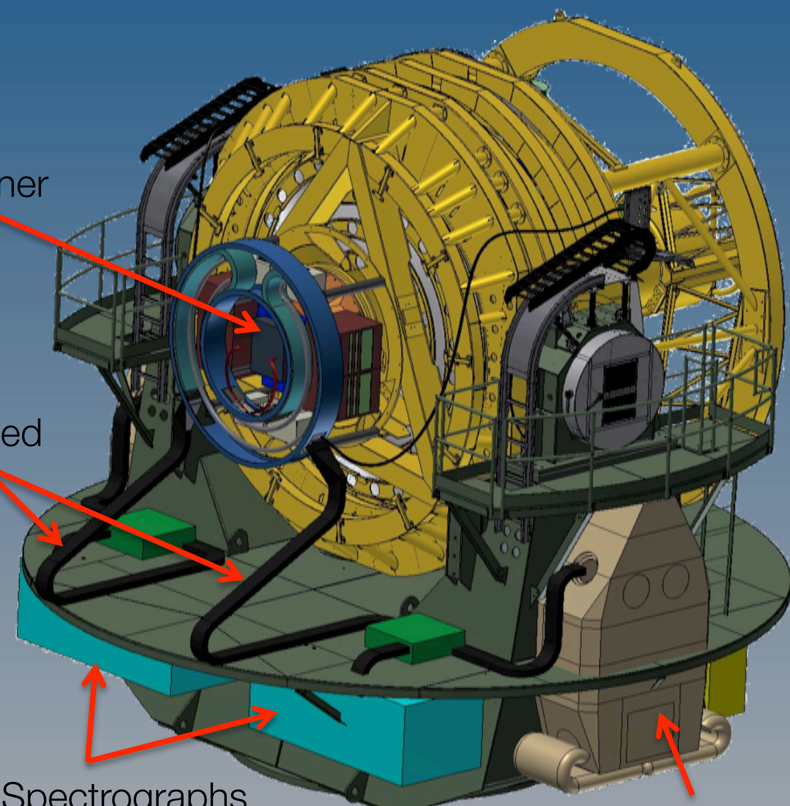
4MOST PI

www.4most.eu



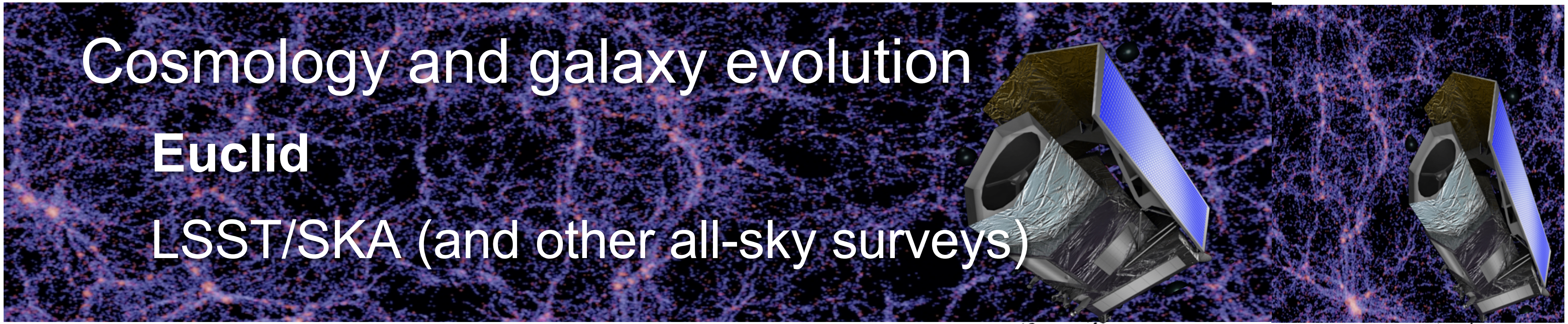
VISTA telescope

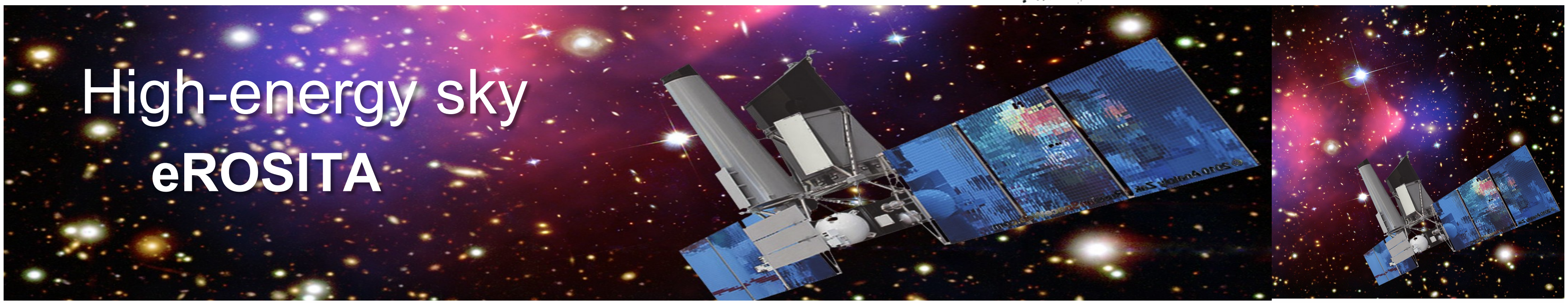
Wide-field, high-multiplex optical spectroscopic survey facility for ESO

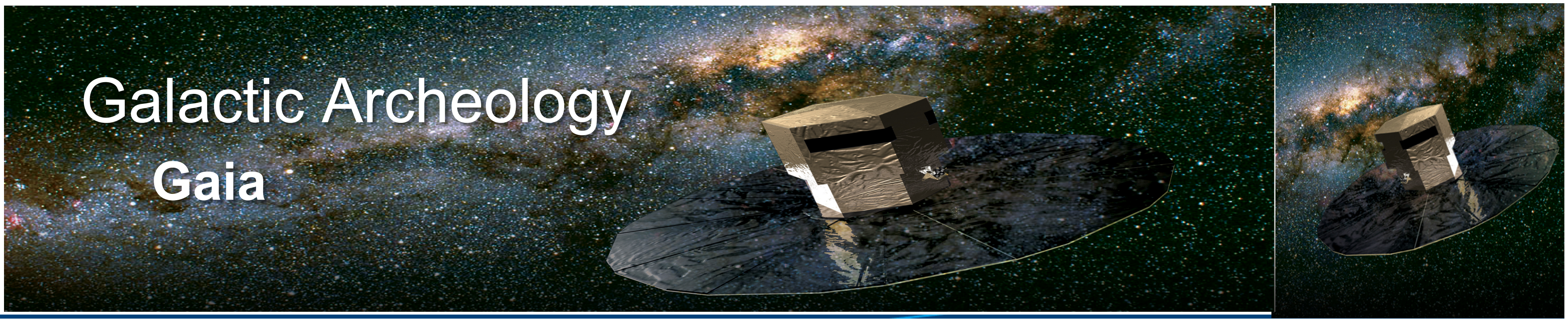
- Status:
  - Project approved by ESO, preliminary design phase starts fall 2014
- Science:
  - Cosmology, galaxy evolution, high-energy and Galactic science
  - Complement all-sky space missions: Gaia, eROSITA, Euclid
  - Complement ground-based surveys: VISTA, VST, DES, LSST, SKA, etc.
- Survey facility:
  - Instrument, science operations, data products, science
  - Run all-sky public surveys in parallel, starting in 2019 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:
  - Very high multiplex: ~1600 fibres to R~5000 + 800 fibres R~20,000 in parallel
  - Wavelength range: LR: 390-930 nm, HR: 395-456.5 & 587-673 nm
  - Large field-of-view on VISTA, 4m-class telescope: ⌀=2.5°

Main science drivers

A 5 year 4MOST survey provides







Main science drivers

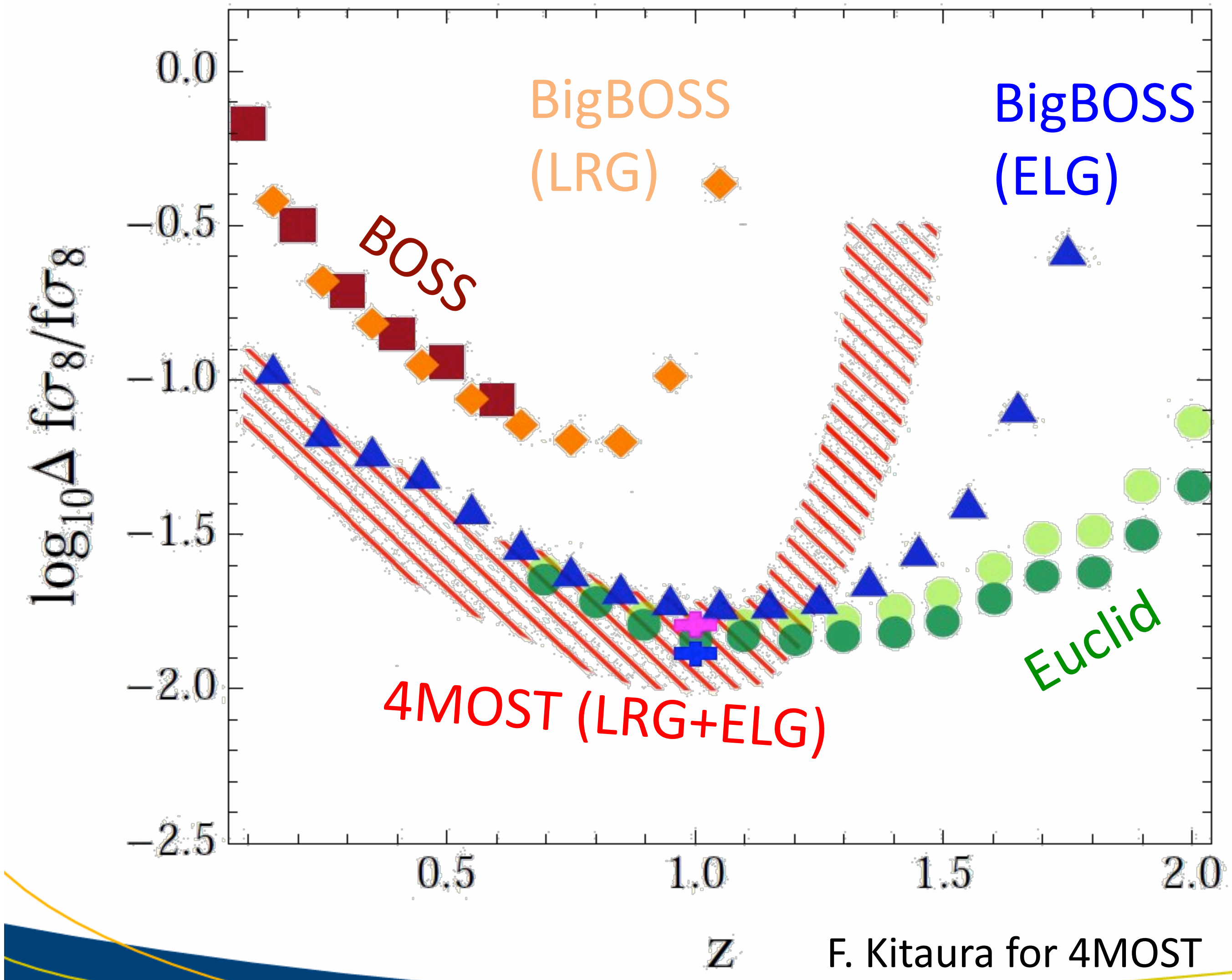
A 5 year 4MOST survey provides

- **Euclid/LSST/SKA** (and other surveys) complement:
  - Dark Energy & Dark Matter
  - Galaxy evolution
  - Transients
  - >13 ×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 ×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 ×10^6 spectra @ R~5000 of m_V~15-20 mag stars
  - 2 ×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

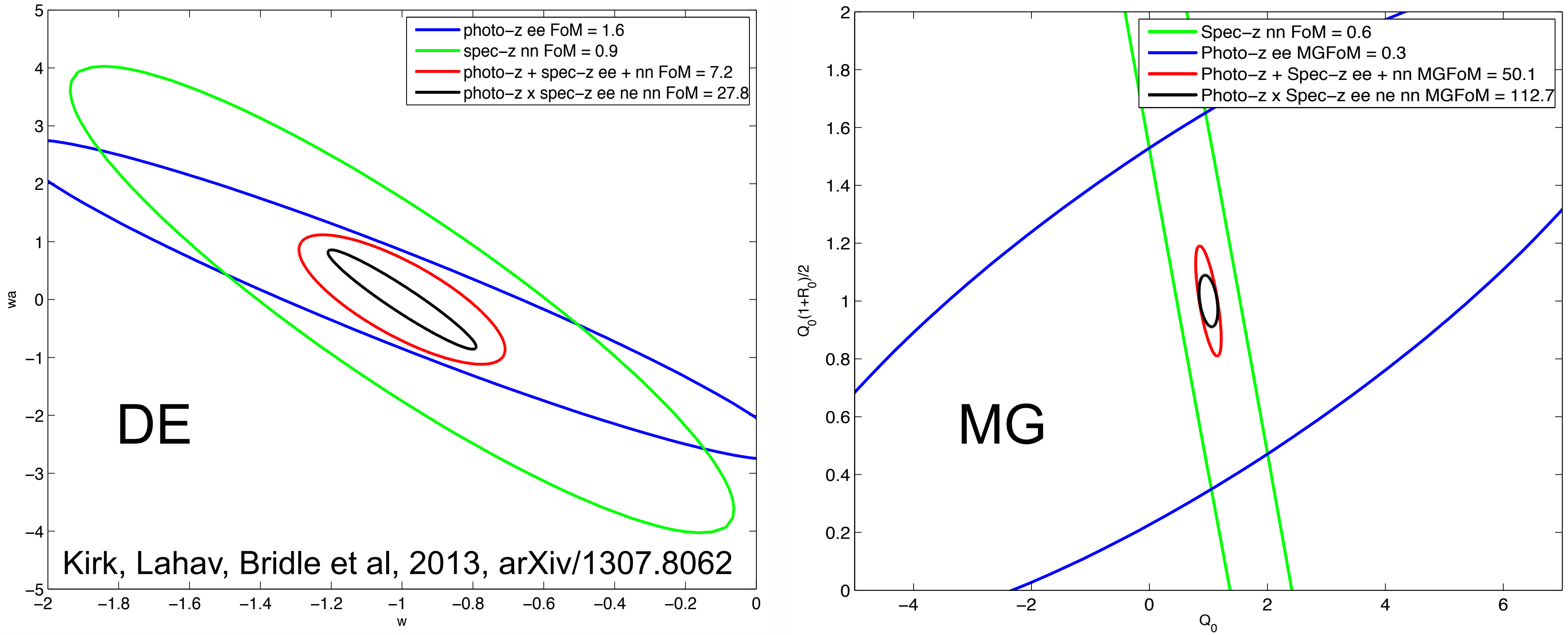
4MOST BAO + RSD (>12M objects)



F. Kitaura for 4MOST

- Concentrate on redshifts z<~1, maximize area to increase number of targets by going less deep
- Complement Euclid in redshift range and by providing redshifts of lensing populations

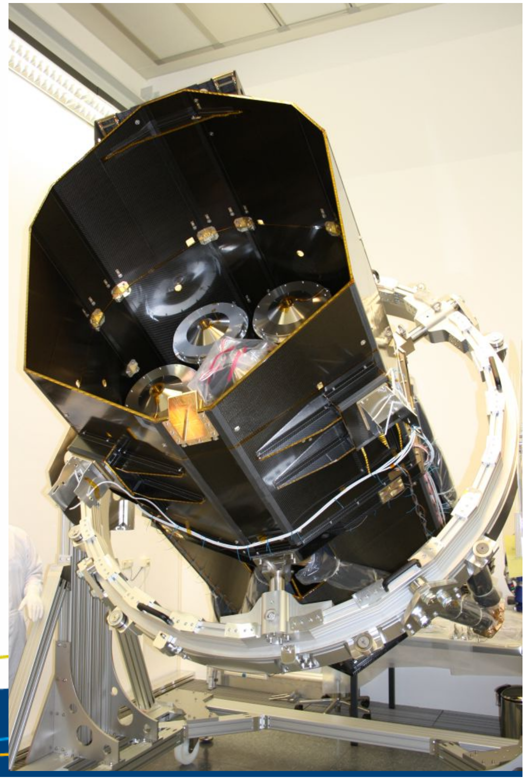
Constraints on Dark Energy (DE) & Modified Gravity (MG) Combined Spectroscopic and Deeper Imaging surveys



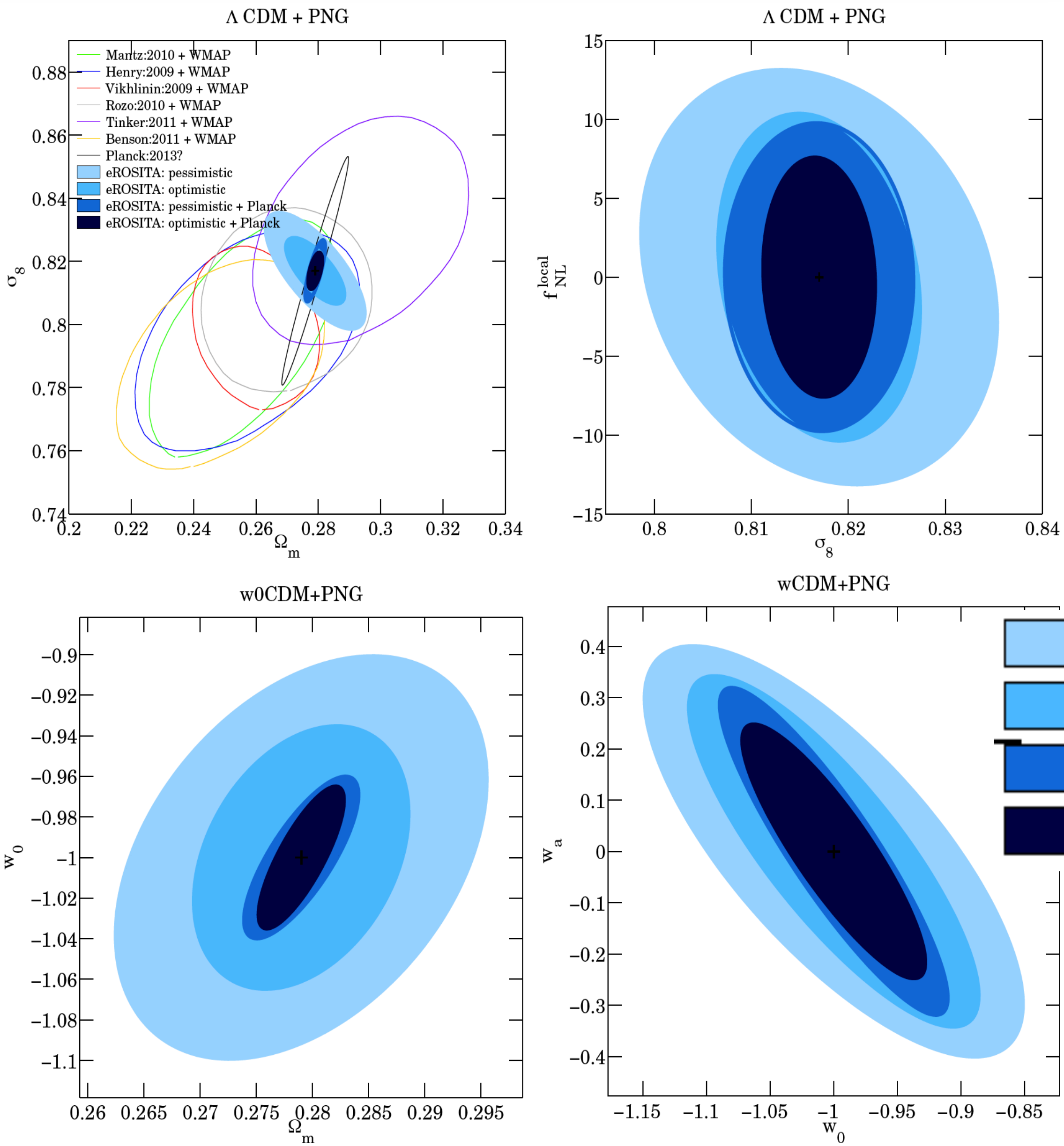
- Full combination including **cross-correlations** using same sky
- Same-sky benefit substantial: **x4** for DE, **x2** for MG vs different skys
- For 15,000 deg^2 LSST+4MOST FOM=54 (DE), 383 (MG) (Kirk, Private Communication)

eROSITA follow-up

- German - Russian mission
- 0.5 –10 keV, beam ~25”
- 8x all sky survey (4 year) + 3 years pointed observations
- Sky divided in two, German and Russian half
- Launch 2015
- Mission goals:
  - Dark Matter and Energy, growth of structure
  - X-ray detection of 100000 galaxy clusters
  - X-ray detection of 3 million point sources (AGN and Galactic)
- Spectroscopic follow-up needed!



Cosmological constraints by obtaining redshifts and velocity dispersions of galaxy clusters



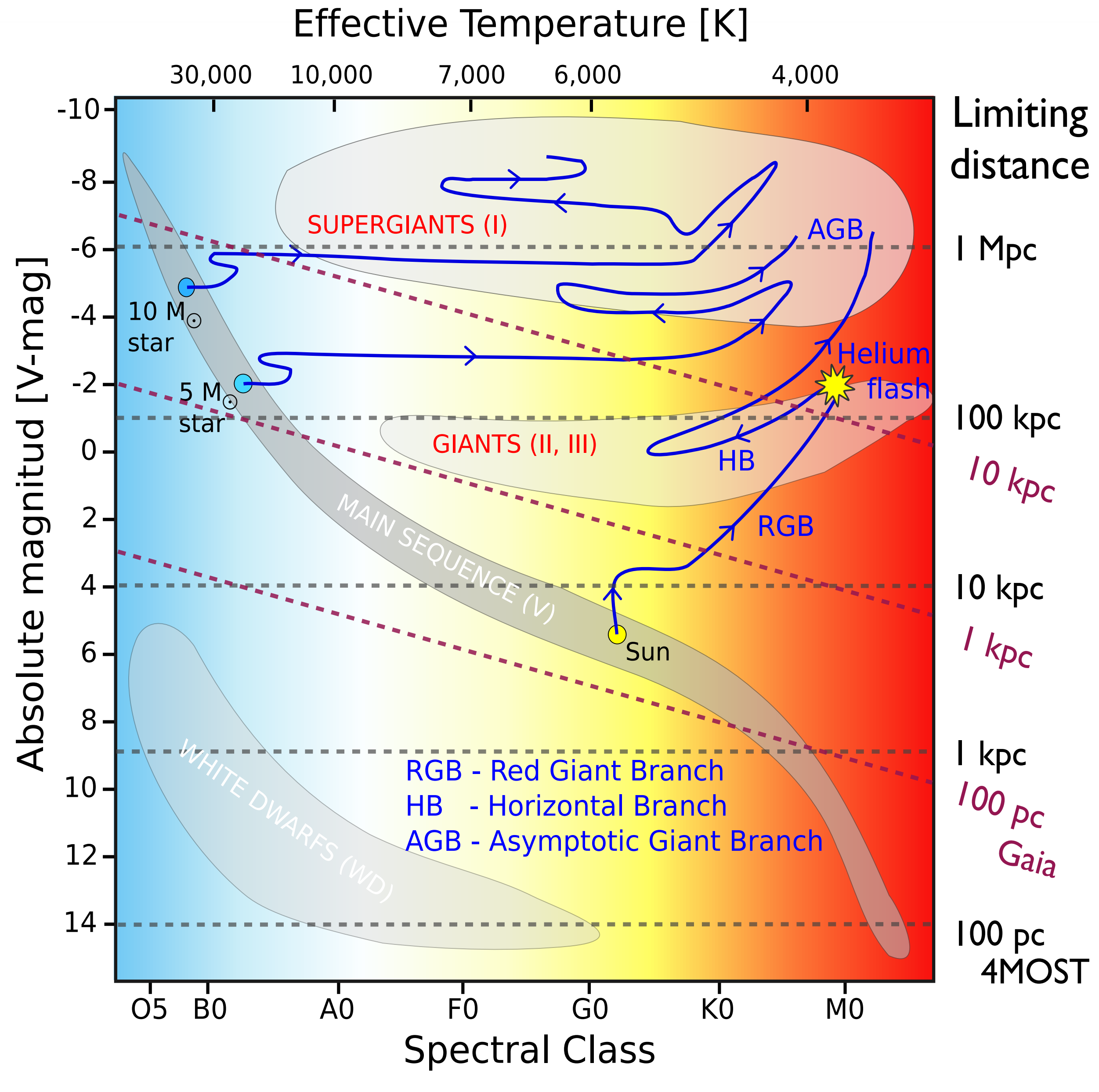
- X-ray (eROSITA) selection - Redshift determination
- Mass calibration
  - (dedicated follow-up)
- Cluster Mass function vs. z
- Cluster Power Spectrum vs. z

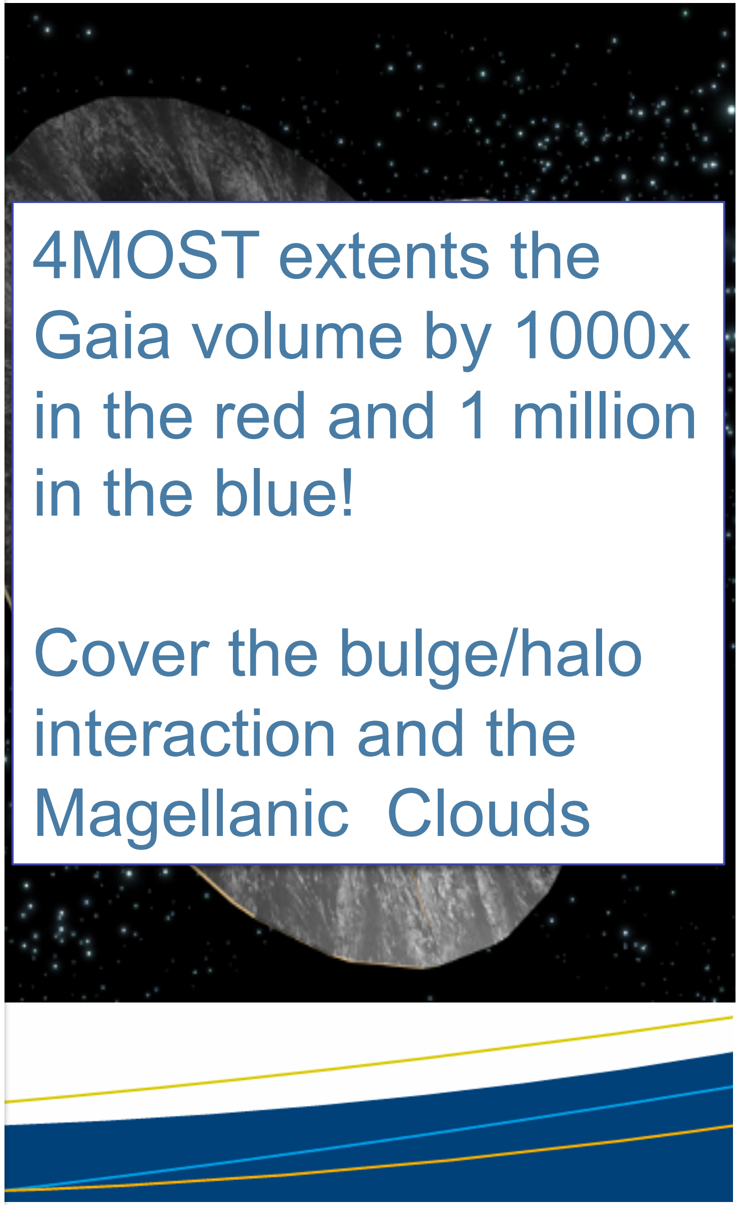
	DETF FoM
eROSITA: pessimistic (photo-z)	57
eROSITA: optimistic (spec-z)	103
eROSITA: pessimistic + Planck	174
eROSITA: optimistic + Planck	263

Merloni et al. 2012

Pillepich et al. 2012

Gaia needs spectroscopic follow-up to achieve its full potential



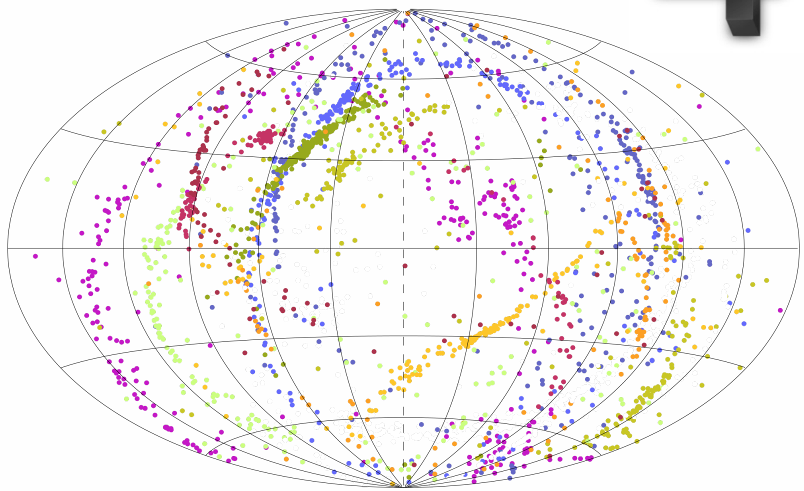


4MOST extents the Gaia volume by 1000x in the red and 1 million in the blue!

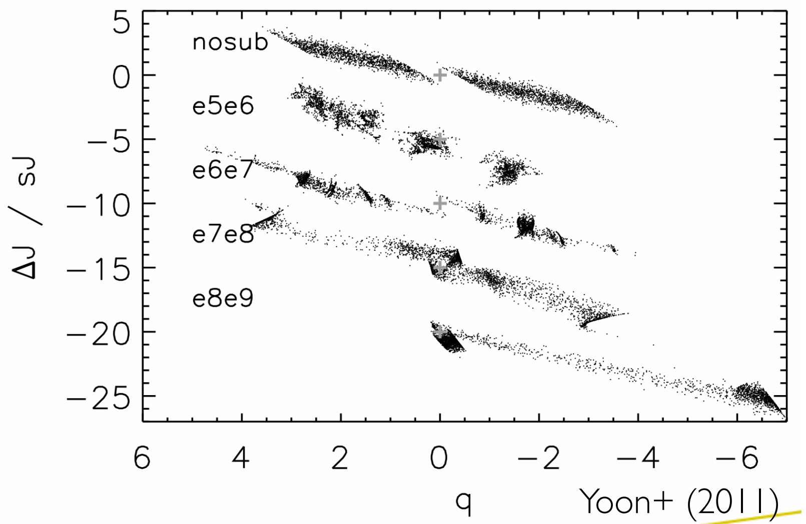
Cover the bulge/halo interaction and the Magellanic Clouds

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
  - Measure the effect of 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 halo substructure by the kinematic effects on cold streams of 10^3–10^5 $M_\odot$

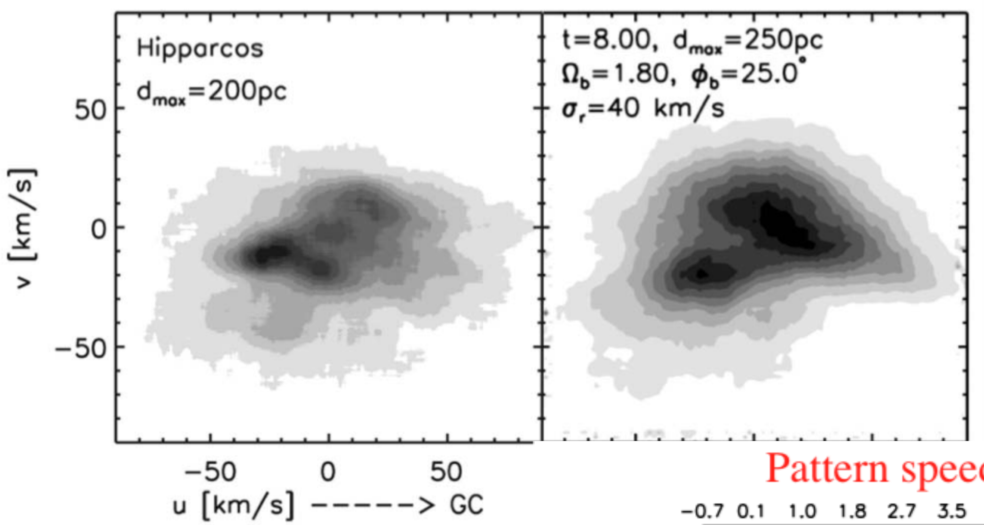


Cooper+ (2010)

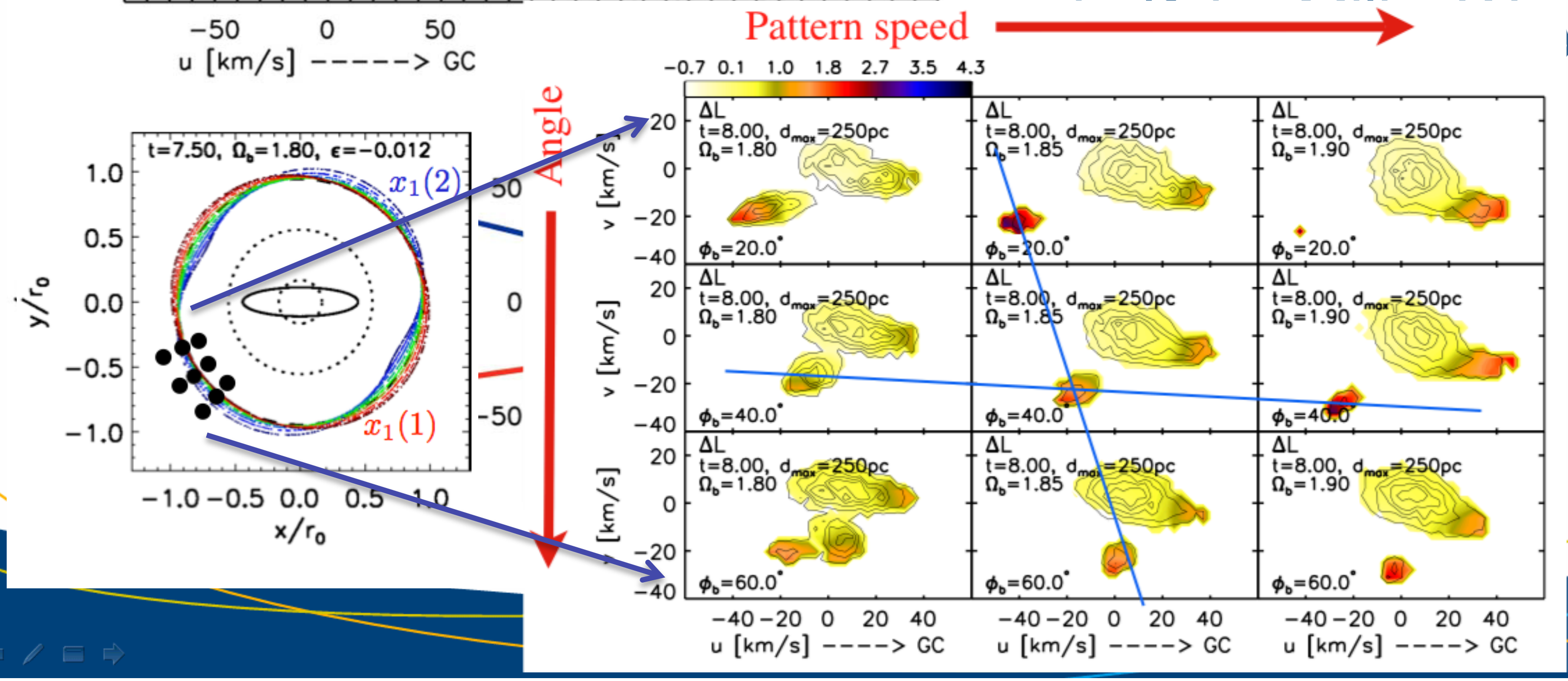


Yoon+ (2011)

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



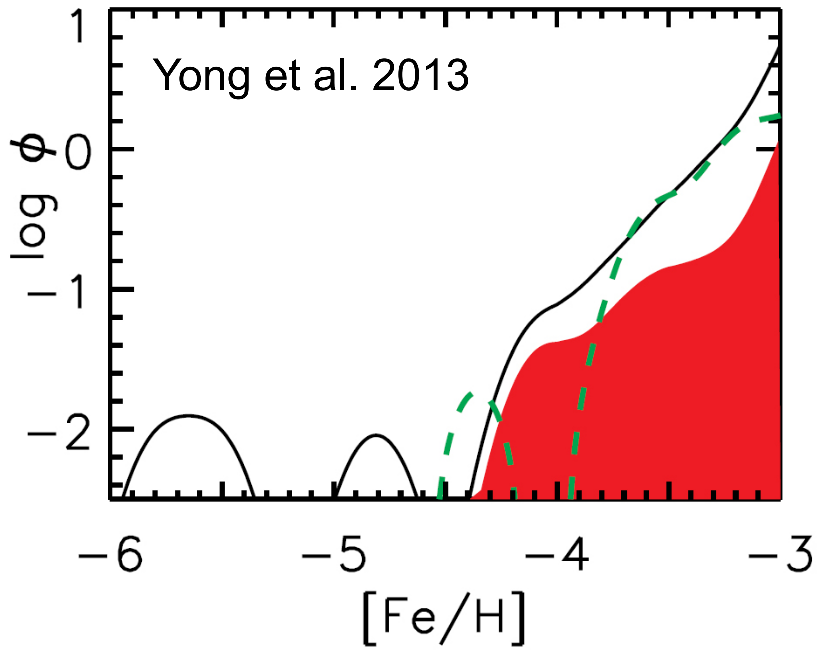
HR: Abundances, chemical clocks

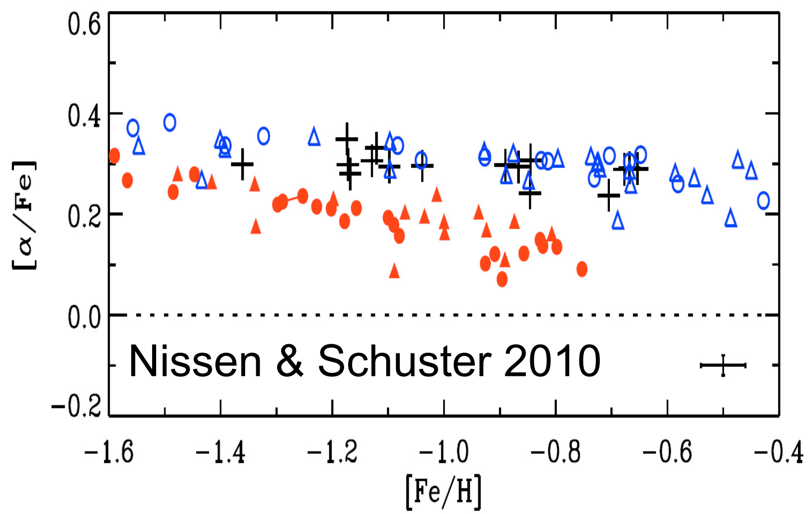
Element	Number of lines	[X/H]	σ
Na I	2	-3.13	0.03
Mg I	1	-2.55	
Al I	1	-2.99	
Si I	2	-2.42	0.20
Ca I	13	-2.60	0.04
Sc II	4	-3.11	0.20
Ti I/Ti II	15/19	-2.58/-2.57	0.08/0.07
V I	3	-2.96	0.02
Cr I	3	-2.97	0.05
Mn I/Mn II	7/1	-3.00/-2.93	0.05
Fe I/Fe II	63/4	-2.99/-2.84	0.07/0.11
Co I	4	-3.06	0.07
Ni I	4	-2.88	0.10
Sr II	1	-3.08	
Y II	1	-3.08	
Zr II	2	-2.81	0.29
Ba II	2	-3.02	0.07
La II	5	-2.92	0.23
Nd II	1	-2.93	
Eu II	1	-3.11	

- HR wavebands chosen to sample all the major nucleosynthesis channels:
  - light elements
  - α-elements
  - iron-peak elements
  - r-process element
  - heavy and light s-process elements
  - odd Z elements (Na, Al)
- Expected uncertainties between 0.1 and 0.2 dex (Caffau et al. 2013)
- Elements have different enrichment time scales depending on their origin
- Unlike ISM, stars maintain history

HR: Milky Way halo

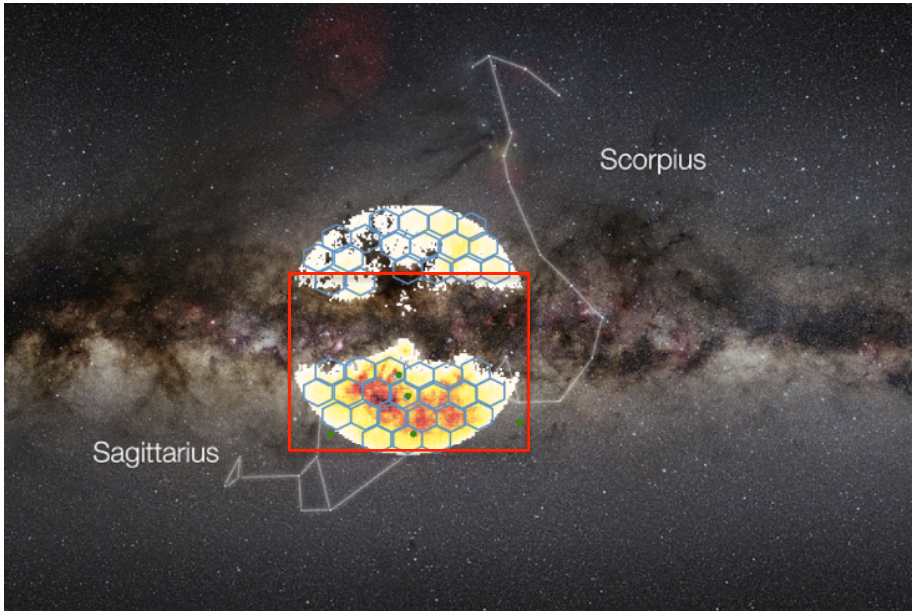
- Observe ~100,000 halo stars with HR spectrograph
- Metallicity distribution function
  - Constraints on Pop III stars (IMF, rotation)
- Chemo-dynamical substructure
  - Identify stream of tidally disrupted dwarfs
  - Early chemical enrichment of streams (depends on a few stars)
  - Accreted versus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

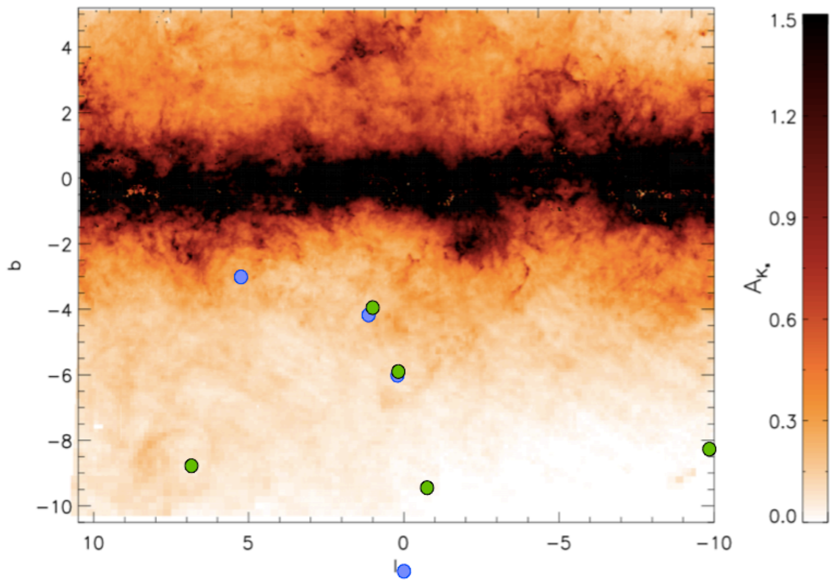




Milky Way bulge chemo-dynamics

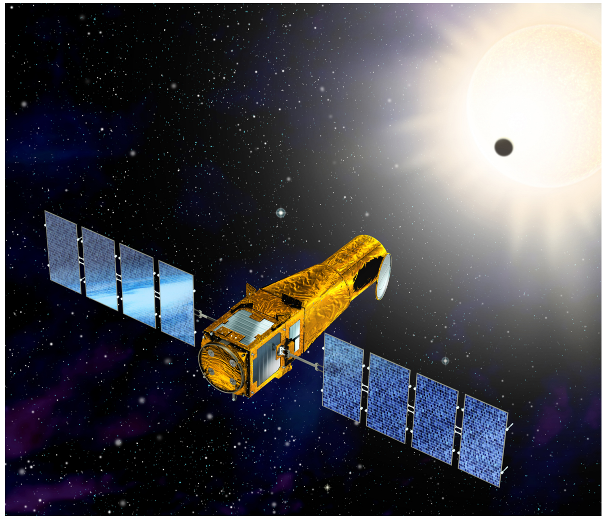
- Two formation scenarios:
  - Collapse/merging of proto-galaxies
  - Bar instability, disk buckling
- Observe ~150,000 giants, covering inner 1.5 kpc of the Milky Way
- Full coverage to understand effects of reddening and substructure
- Bulge-halo-thick disk connection?
- Search for chemo-dynamical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

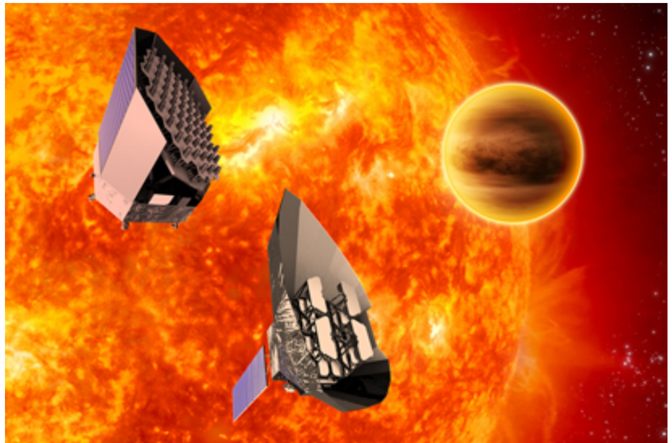




HR: Astro-seismology

- CoRoT+PLATO complement
- Masses and luminosity/distance can be derived with seismology of Red Giants
- Main uncertainty is metallicity dependence
- CoRoT fields currently being observed by Gaia-ESO
- PLATO is at the bright end for 4MOST
  - Dedicated repeat survey might help find most promising candidates
  - Can also characterize brown dwarfs, but may have to improve velocity calibration

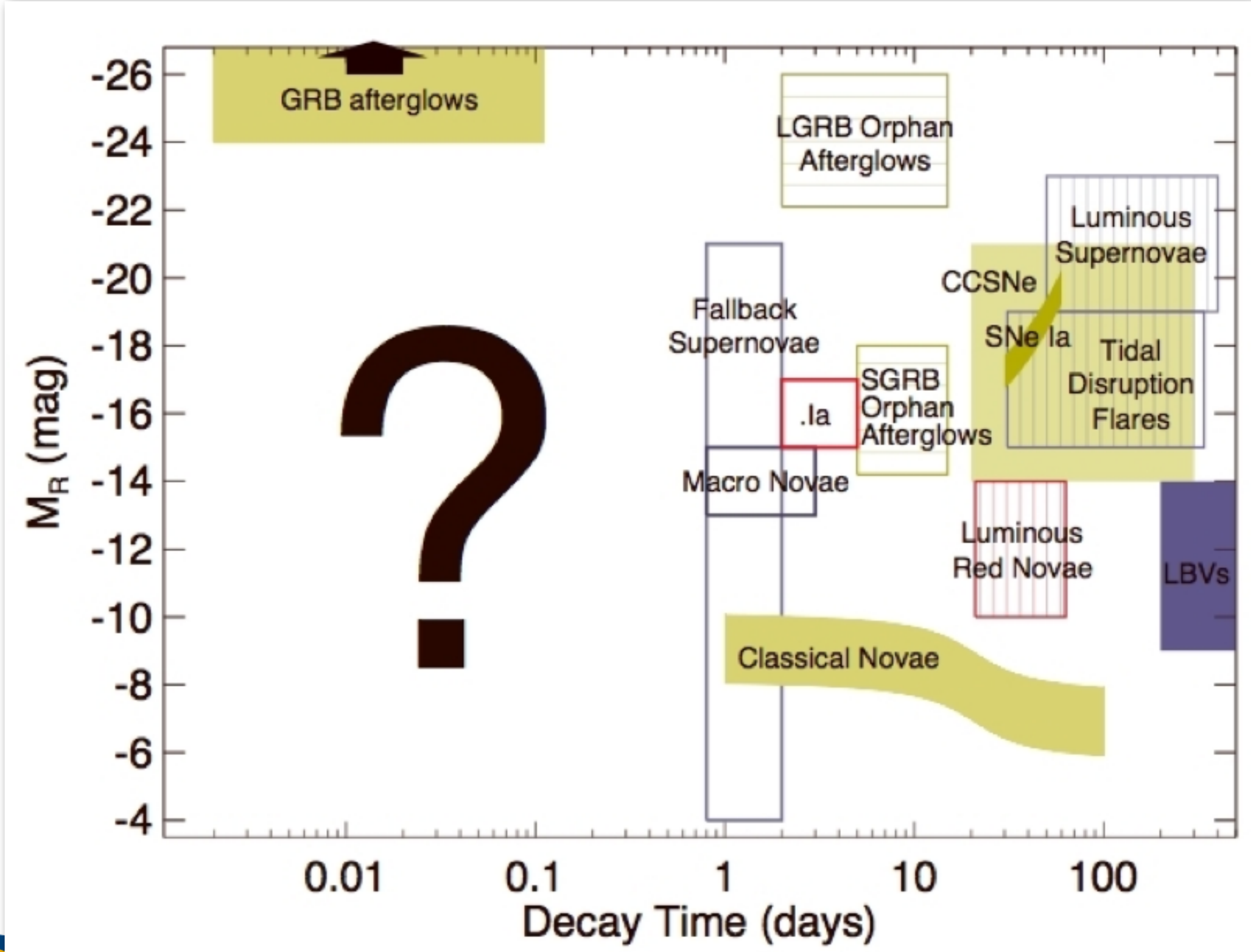




Other Science feasible with surveys with thousands to millions of objects

- Follow-up of LSST and Euclid variables/transients
- Nature of radio galaxies from SKA
- Support Euclid photometric redshift calibrations (for z<0.7 and measuring intrinsic alignment galaxies)
- Redshifts of Euclid strong galaxy lensing candidates
- Reverberation mapping of AGNs
- Galaxy evolution using HOD from redshift surveys to z~1.5
- Star formation history of the Milky Way from 100,000 White Dwarfs
- Ages of astro-seismology objects from e.g. CoRoT, PLATO
- Nature of peculiar variable stars discovered by Gaia, LSST, Euclid
- Chemo-dynamics of Magellanic Clouds and other satellites
- High resolution spectroscopy survey of Open Clusters
- Radial velocities time series of low mass binary systems
- Insert your idea here

LSST 100k transients/year



Science Requirements

- 4MOST shall be able to obtain:
  - *Redshifts* of AGN and galaxies (also in clusters)
    - R~500 spectra of 22 r-mag targets with S/N=5 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 19.5 r-mag stars with S/N=10 per Ångström
  - *Abundances* of up to 15 chemical elements
    - R~20000 spectra of 15.5 r-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

Instrument Specification

Specification	Concept Design value
Field-of-View (hexagon)	>4.0 degree^2 (⌀>2.5°)
Multiplex fiber positioner	~2400

Medium Resolution Spectrographs
  # Fibres
  Passband
  Velocity accuracy
	R~5000-8000
	  1600 fibres
	  390-930 nm
	  < 2 km/s

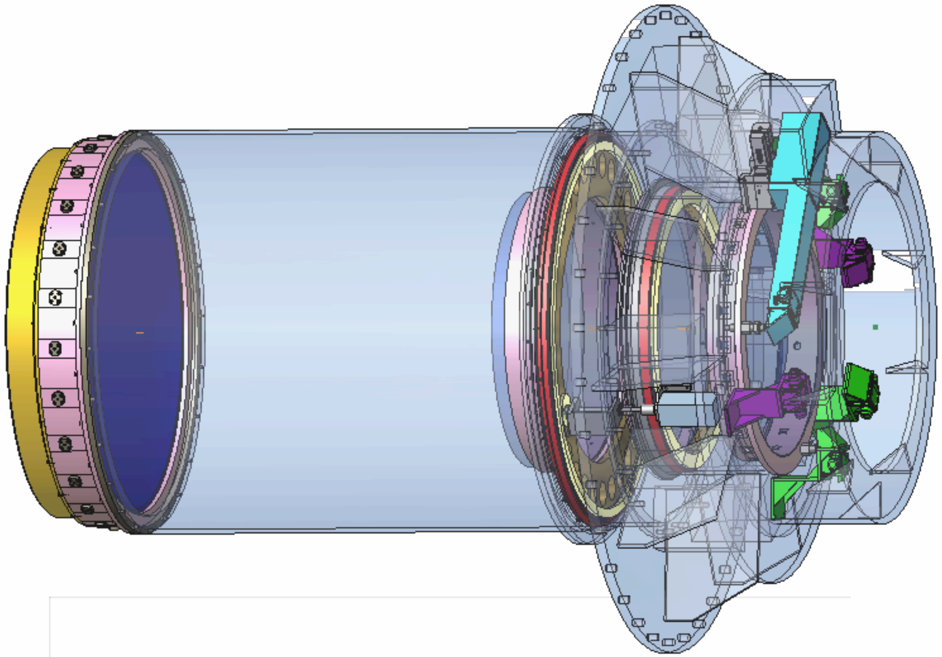
High Resolution Spectrograph
  # Fibres
  Passband
  Velocity accuracy
	R~20,000
	  800 fibres
	  395-456.5 & 587-673 nm
	  < 1 km/s

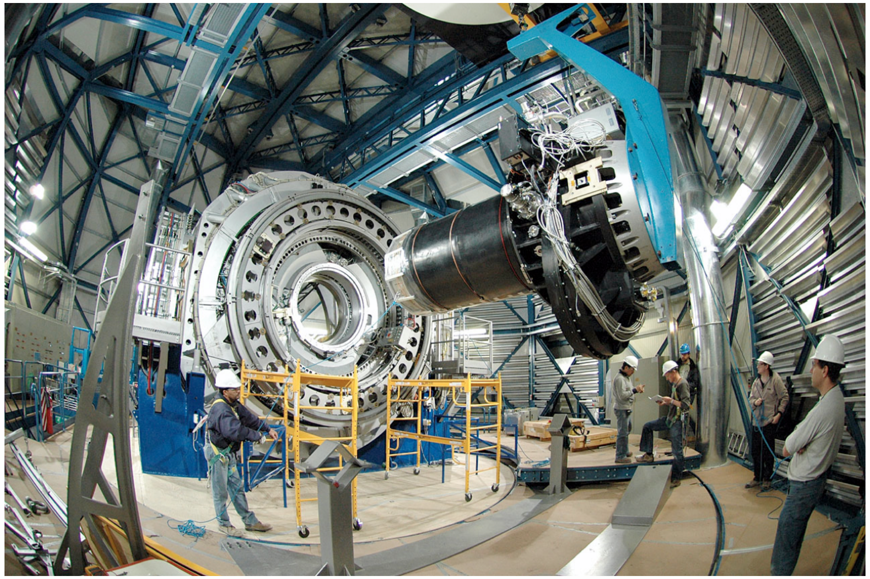
# of fibers in ⌀=2' circle	>3
Area (5 year survey)	>2h x 16,000 deg^2
Number of 20 min science spectra (5 year)	~100 million

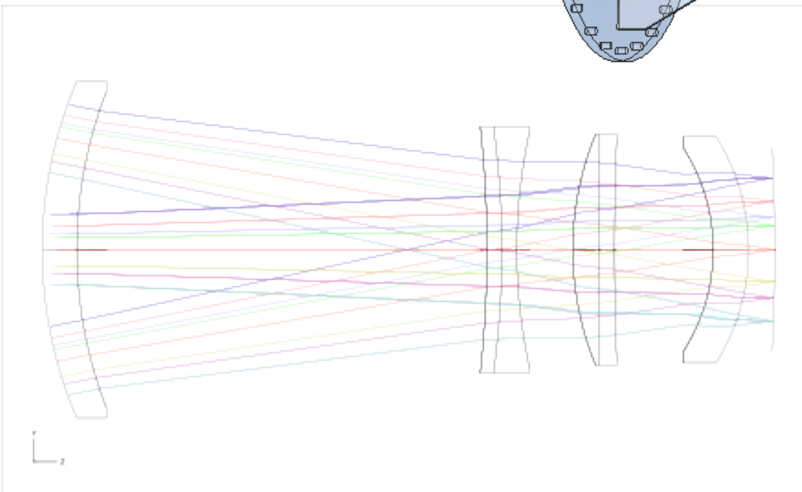
Wide-field Corrector can be inserted into VISTA like IR camera

Wide-field corrector VISTA ⌀=2.5°

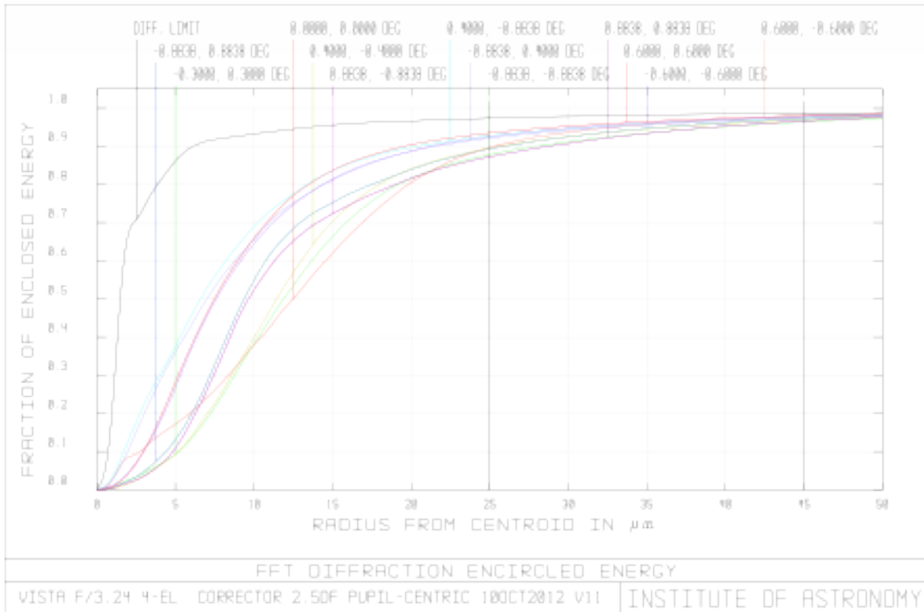
includes an ADC



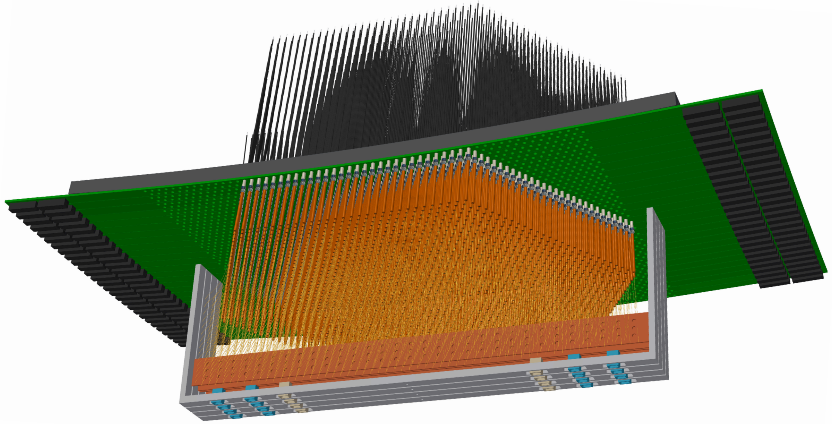




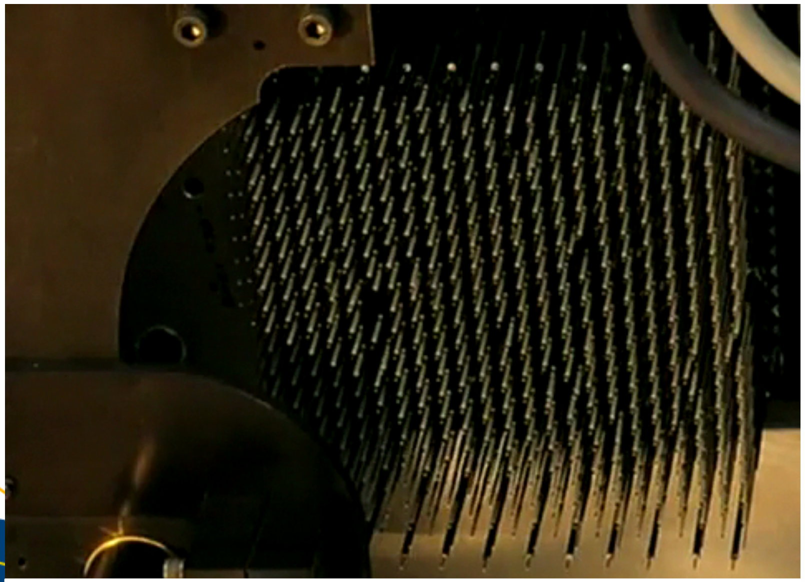
IoA Cambridge, King, Parry, Sun, et al.



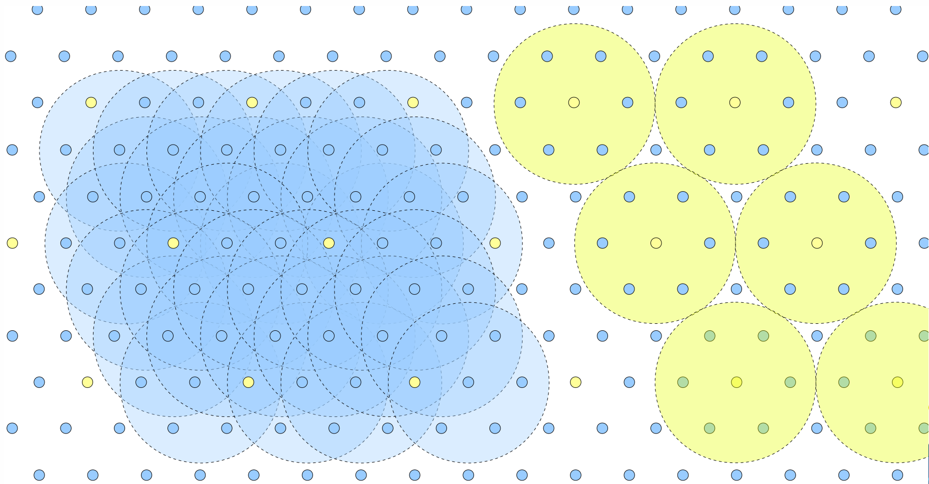
Echidna style positioner



- About 2400 fibres
- Large, overlapping patrol areas enables sparse fibres for high resolution spectrograph
- Pitch ~10 mm, Patrol R: ~1.2x pitch
- Closest separation ~10 arcsec
- Reconfiguration time <2 min



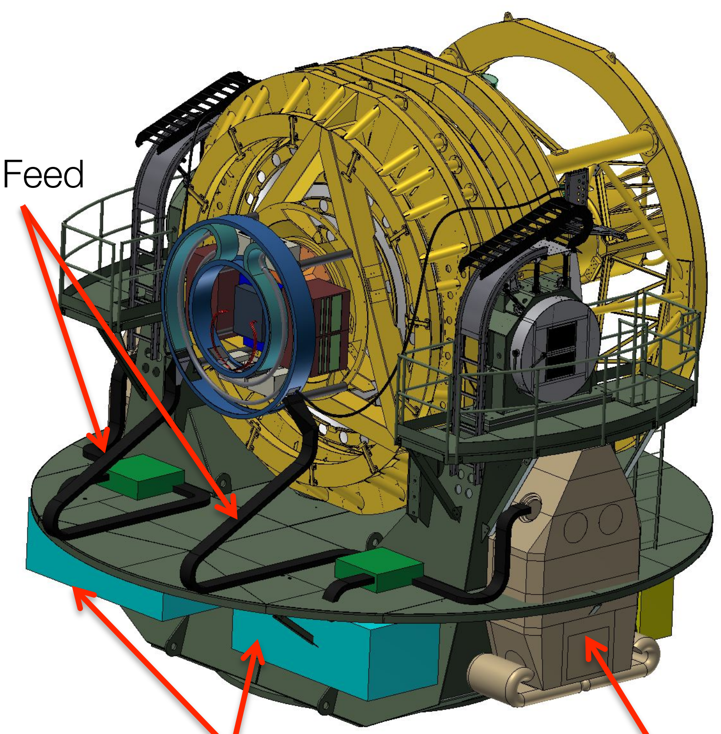
FMOS Echidna on Subaru

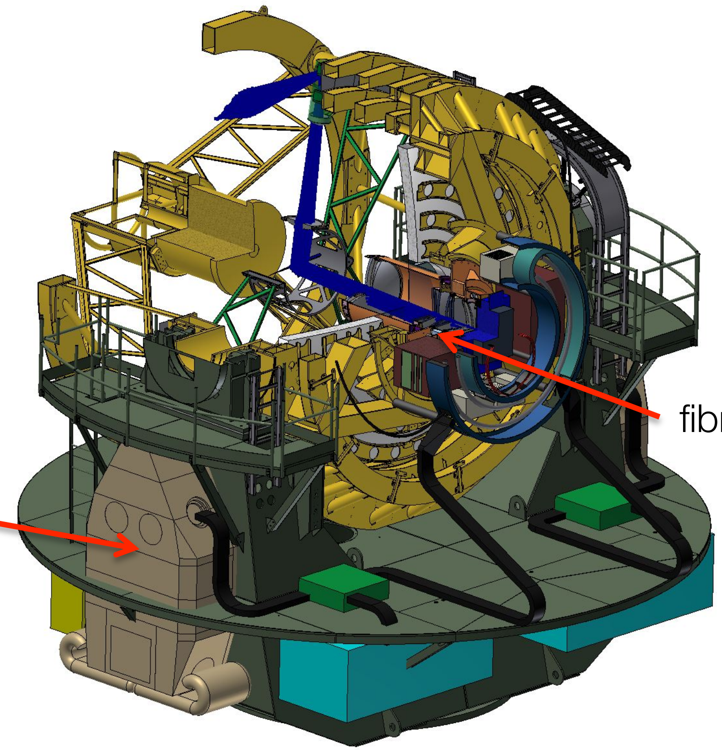


AAO, Saunders et al.

Spectrograph location and fibre routing

- Spectrographs mounted on telescope fork (gravitation invariant)
- Short fibre run (~15 m)
- Use commercial US Conec MTP connectors (Haynes et al. 2010)

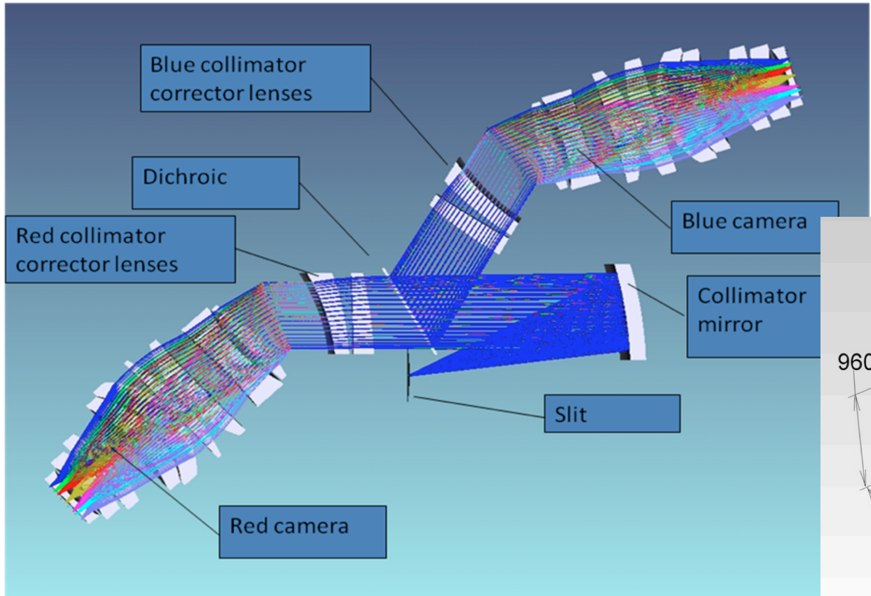


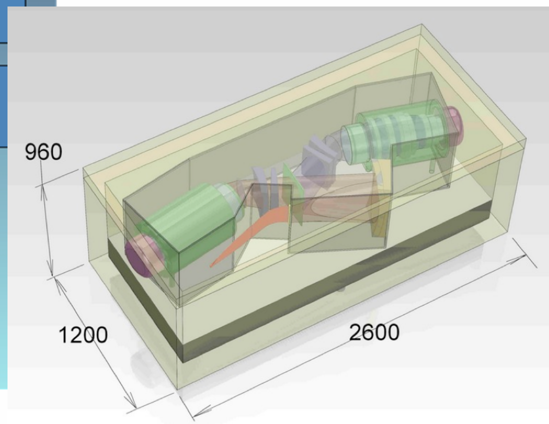


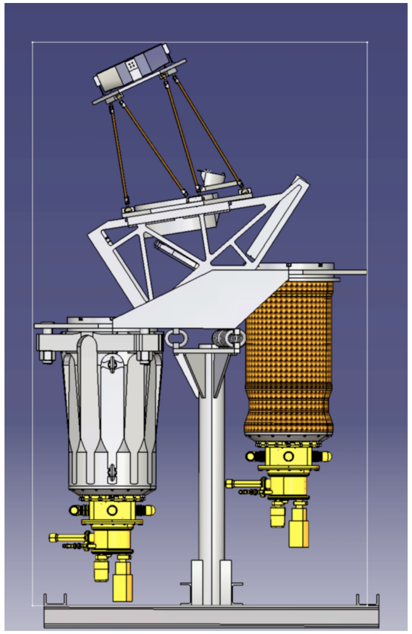
AIP, Potsdam, Haynes et al.

Low- and High-Res Spectrographs

- Fixed configuration spectrographs, high throughput with VPH gratings
- Two R~5000 spectrographs similar to WEAVE design
- Two dedicated R~20,000 spectrographs for ~800 fibers
- Two arm spectrographs, one (HR) or two (LR) 3k x 8k CCDs per arm





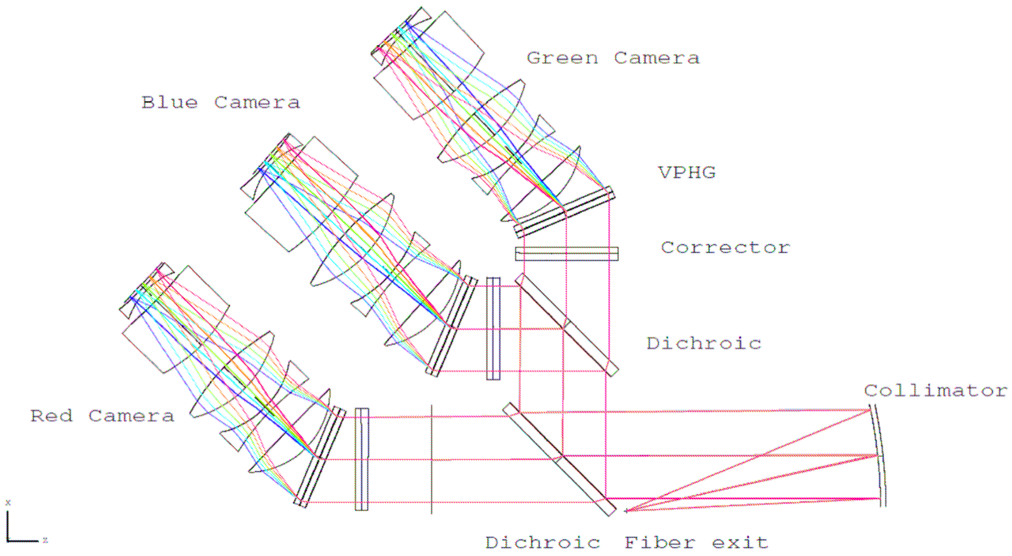


NOVA/ASTRON & RAL/Oxford (WEAVE), LSW
van der Pragt, Navaro, Dalton, Middleton, Seifert

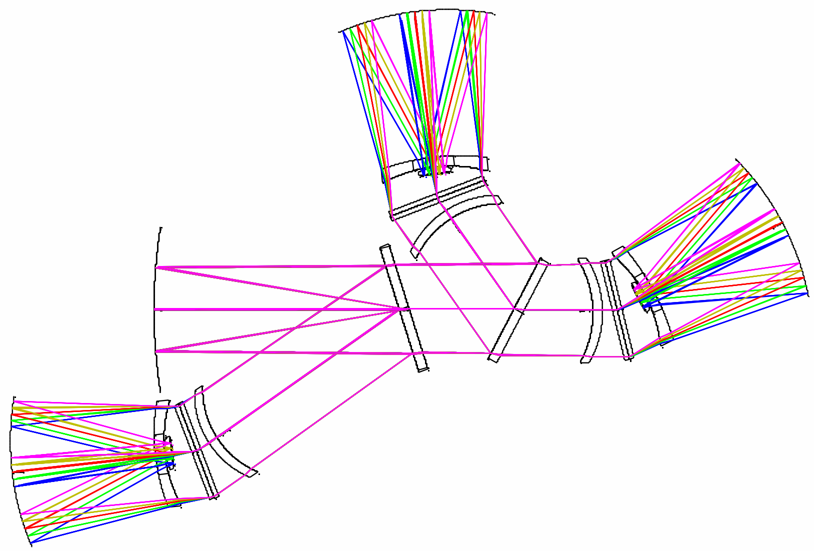
GEPI, Paris, Mignot,
Cohen, Bonifacio et al.

Spectrograph optimisation

- Optimisation on spectrographs in progress. Goals:
  - Reduce costs
  - Increase performance
  - Consider LR – HR switchable designs, other wavelength regions
- 3-arm designs with 6k x 6k or 4k x 4k detectors

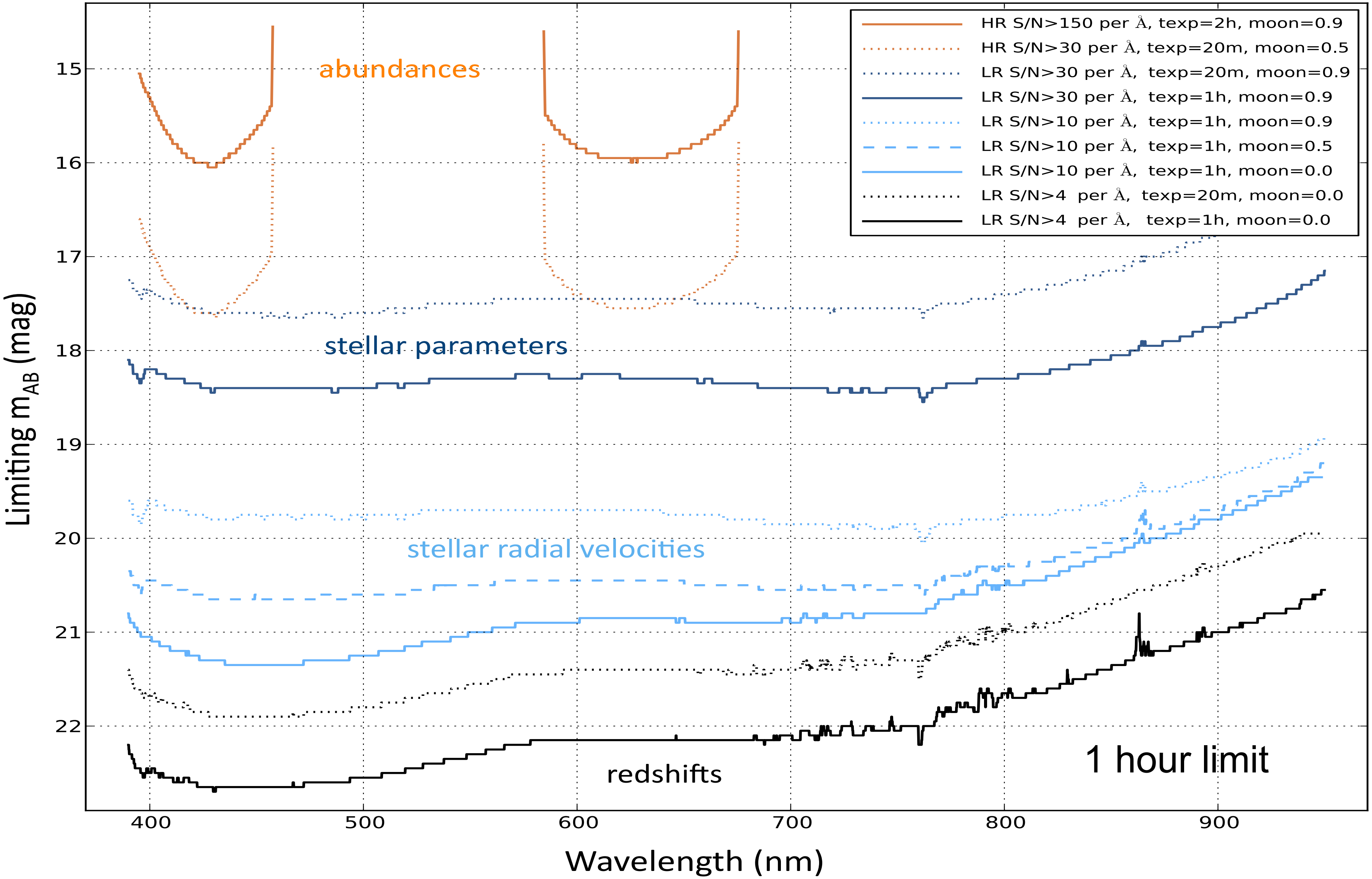


Seifert, Xu (LSW)



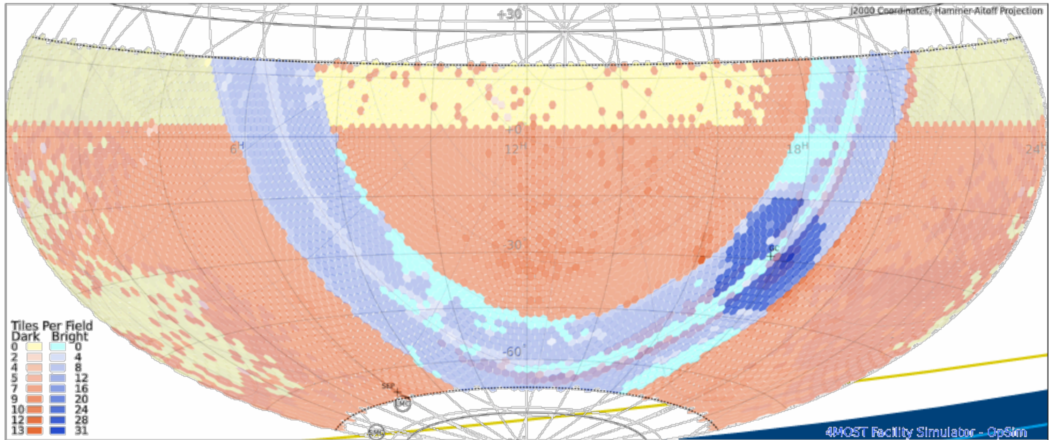
Saunders (AAO)

Magnitude limits for typical science cases



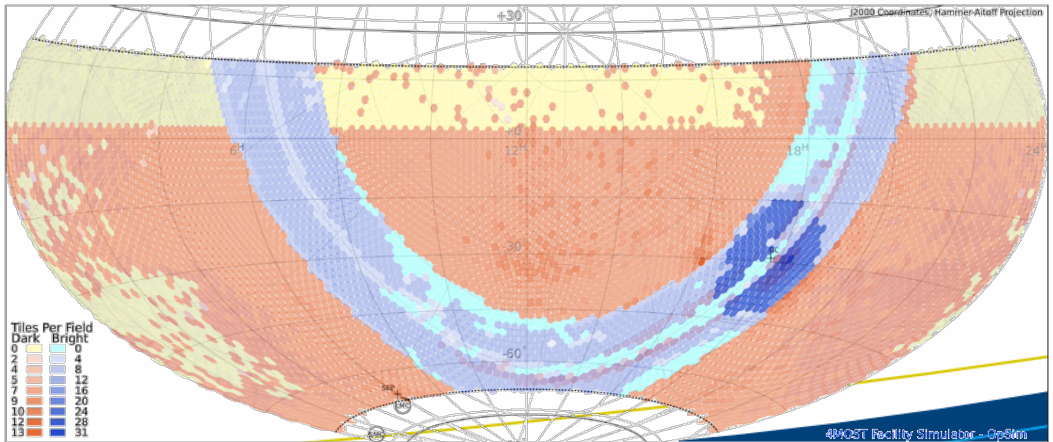
How are we going to run 4MOST?

- 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
- Areas with more targets visited more than 120 min

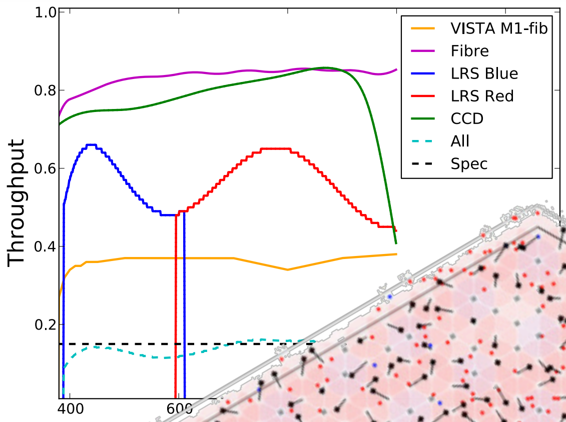


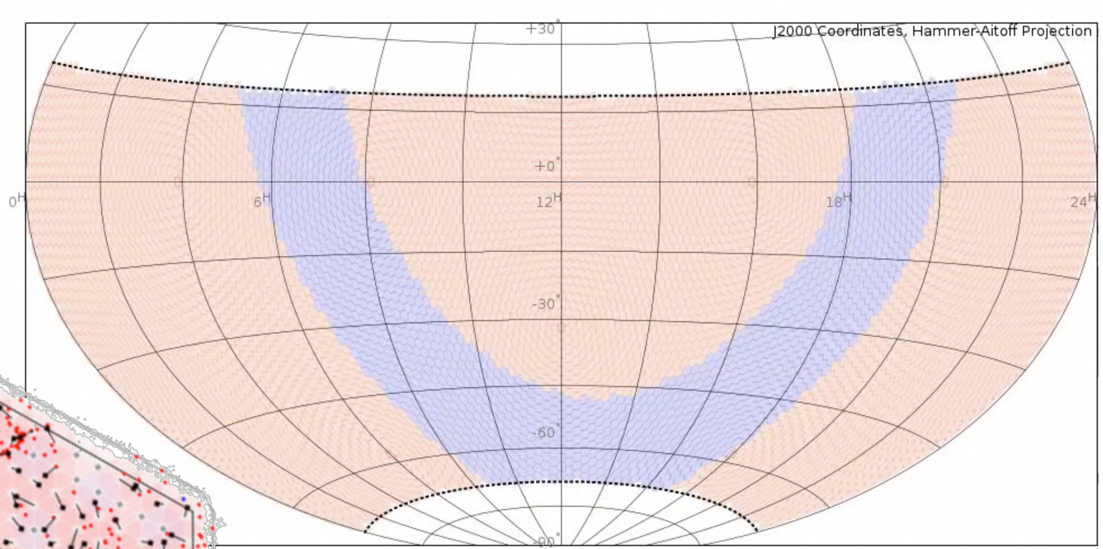
Science verification with full 4MOST simulator: Design Reference Surveys

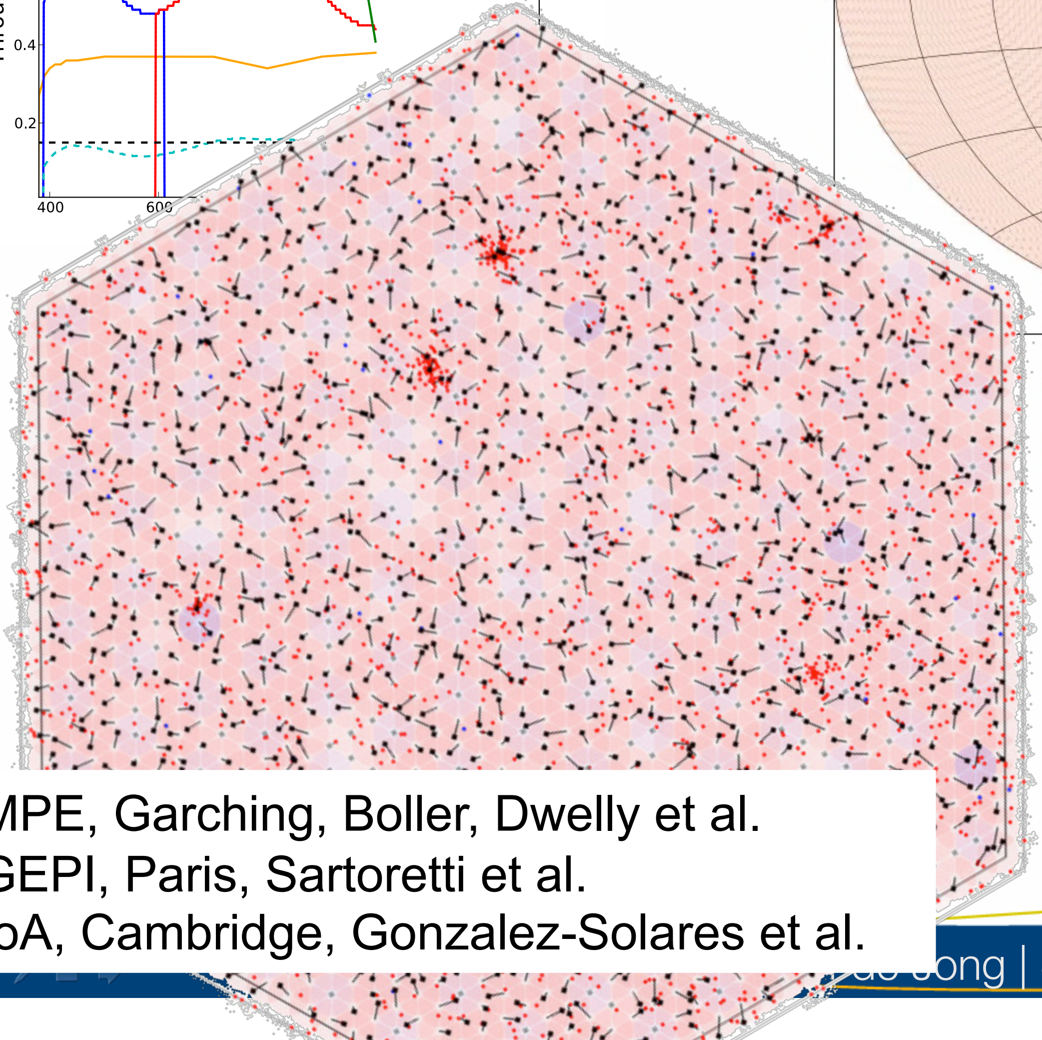
Surveys implemented with more than 40M objects:
(coordination C. Chiappini)

- Milky Way halo R>5000 (~3M objects) A. Helmi; M. Irwin
  - Chemo-dynamics streams
- Milky Way halo R>20,000 (~ 0.2M objects) N. Christlieb
  - Chemical evolution of accreted components
- Milky Way disks/bulge R>5000 (~15M objects) A. Koch; I. Minchev
  - Chemo-dynamics of bulge/disks
- Milky Way disks/bulge R>20,000 (~2.5M objects) E. Caffau
  - Chemical evolution in situ components
- eROSITA galaxy clusters (~50,000 clusters, ~2.5M objects) H. Boehringer
  - Dark Energy and galaxy evolutions
- eROSITA AGN (~1M objects) A. Merloni
  - Evolution of AGN and the connection to their host galaxies
- Fundamental cosmology science (~23M objects) F. Kitaura
  - Luminous red and blue galaxies survey

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







Science case	S/N per 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.
GEPI, Paris, Sartoretti et al.
IoA, Cambridge, Gonzalez-Solares et al.

Return on investment (TBC)

- First 5 year 4MOST survey:
  - 70% fibre hours for 4MOST consortium
  - 20% fibre hours for community
  - 10% fibre hours for Chile
- Second 5 year survey:
  - 30% fibre hours for 4MOST
  - 60% fibre hours community
  - 10% fibre hours for Chile
- Consortium surveys will have PIs based on institute interests
  - size will be approximate proportional to contribution (hardware, facility labor, science labor of broad interest: targeting, pipelines,)
- Consortium members can participate in all surveys
  - number of people within factor 2 proportional to contribution
  - Special limits for Australia as non-ESO partner probably required
- Community and Chile surveys are selected by Peer Review
- Considering fraction Community participation in Consortium

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

Schedule and Milestones

- Feb 2013:
  - Conceptual Design completed
- Jun 2013
  - *project selected, start concept optimization phase (new partners?)*
- Jun 2015:
  - Preliminary Design Review, all concepts tested, evaluated, and costed
- Jun 2016:
  - Final/Critical Design Review, detailed designs finalized
- Jun 2018:
  - All subsystems manufactured, assembled, integrated and verified
- Mar 2019:
  - Full system integrated and verified at AIP, preliminary acceptance Europe
- Oct 2019:
  - Delivery and installation at telescope, preliminary acceptance Chili
- Dec 2019 – Dec 2024:
  - First science survey of 4MOST, about 30% of targets determined by community surveys

- Phase A (Feb 2013 – Jun 2013)
- Phase B (Jun 2015)
- Phase C (Jun 2016)
- Phase D (Jun 2018 – Oct 2019)
- Phase E (Dec 2019 – Dec 2024)

4MOST Collaboration

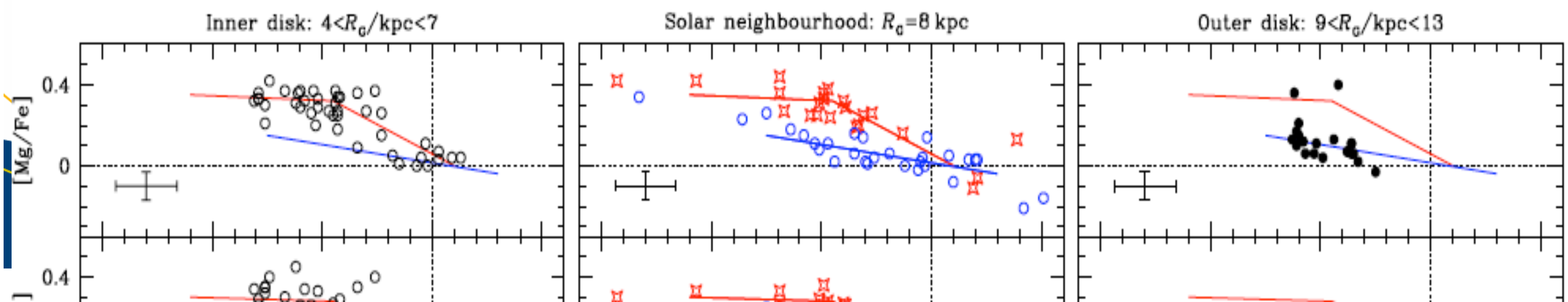
- Instrument Institutes
  - Leibniz-Institut für Astrophysik Potsdam (AIP) (D)
  - Zentrum für Astronomie, Univ. of Heidelberg (D)
  - Australian Astronomical Observatory (AU)
  - NOVA, Dwingeloo (NL)
  - MPI für Extraterrestrische Physik, München (D)
  - Institute of Astronomy, Cambridge University (UK)
  - ESO, Garching (EU)
- Science Institutes
  - University of Lund (S)
  - University of Uppsala (S)
  - University of Groningen (NL)
  - Rutherford Appleton Laboratory, Oxford (UK)
  - Ludwig-Maximilian Universität, München (D)
  - L'Observatoire de Paris, GEPI, Paris (F)

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

- Status:
  - Project approved by ESO, preliminary design phase starts 2014
- Science:
  - Cosmology, galaxy evolution, high-energy and Galactic science
  - Complement all-sky space missions: Gaia, eROSITA, Euclid
  - Complement ground-based surveys: VISTA, VST, DES, LSST, SKA, etc.
- Survey facility:
  - Instrument, operations, data products, science
  - Run all-sky public surveys in parallel, starting in 2019 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:
  - Very high multiplex: ~1600 fibres to R~5000 + 800 fibres R~20,000 in parallel
  - Wavelength range: LR: 390-930 nm, HR: 395-456.5 & 587-673 nm
  - Large field-of-view on VISTA, 4m-class telescope: ⌀=2.5°

HR: Milky Way disks

- Inside-out formation time scales and chemical evolution
- Importance of radial migration by bars/spiral structure
- Thick disk formation scenarios:
  - In situ formation from chaotic gas accretion at high redshift
  - Remnants of accreted satellites
  - Thin disk heating (satellites, dark matter halos, secular evolution)
- Use “chemical tagging” to link stellar populations of similar origin
  - Stars from same star cluster (age) have same chemical signature
- Even distribution in R and Z using ~ 1.5 million stars



HR: Binary stars contamination/opportunities

- Gaia / LSST will identify many binaries
  - Spatial resolved
  - Astrometric binaries (primary or both components)
  - Photometric properties (colour-colour or colour-magnitude outliers)
  - Eclipsing or tidal deformation variations
  - Spectroscopic multi-component
  - Spectroscopic radial velocity variations
- For Milky Way structure studies select against binaries or remove post facto
- Create large samples of well studied spectroscopic binaries:
  - Add velocities to eclipsing binaries constrains orbits, masses, radii
  - Add velocities to astrometric binaries constrains orbits
- Gaia and LSST will identify millions of eclipsing binaries!
- Cataclysmic and eruptive binaries could also be targets