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Summary

Key word list

Instrumentation: high angular resolution

Instrumentation: interferometers

Instrumentation: spectrographs

Techniques: high angular resolution

Techniques: imaging spectroscopy

Definitions and acronyms

Acronyms	Definitions
ALMA	Atacama Large Millimeter/sub-millimeter Array
AGN	Active Galactic Nuclei
CND	Circum-nuclear Disk
E-ELT	European Extremely Large Telescope
ESA	European Space Agency
ESO	European Southern Observatory
CG	Galactic Center
HARMONI	High Angular Resolution Monolithic Optical & Near-infrared Integral field spectrograph
IRAM	Institut de Radioastronomie Millimétrique
JWST	James Webb Space Telescope
METIS	Mid-infrared E-ELT Imager and Spectrograph
MICADO	Multi-AO Imaging Camera for Deep Observations
MIRI	Mid-Infrared Instrument (JWST)
NACO	NaCo Nasmyth Adaptive Optics System (NAOS) Near-Infrared Imager and Spectrograph (CONICA) (ESO-VLT)
NASA	National Aeronautics and Space Administration
NIRCAM	Near Infrared Camera (JWST)
NIRSPEC	Near Infrared Spectrograph (JWST)
PdBI	Plateau de Bure Interferometer (IRAM)
SINFONI	Spectrograph for INtegral Field Observations in the Near Infrared
SPECS	Submillimeter Probe of the Evolution of Cosmic Structure
SPIRIT	Space Infrared Interferometric Telescope
VLT	Very Large Telescope (ESO)

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1 Introduction

1.1 General context

In the 2000 Decadal Report “Astronomy and Astrophysics in the New Millennium” there was a strong recommendation to the scientific community for the development of space optical and infrared astronomy. For the infrared a far-IR *kilometer baseline* interferometer, SPECS (Submillimeter Probe of the Evolution of Cosmic Structure), was studied as a NASA “vision mission” in its Science Plan for astrophysics. In 2003 the Community Plan for Far-IR/Submillimeter Space Astronomy recommended SPIRIT, a *structurally-connected* interferometer, as a practical step toward to the more ambitious SPECS mission.

Following these studies, in October 2004 the ESA AWG (Astronomy Working Group) of the Science Directorate recommended a study of a far infrared interferometer mission (FIRI), in preparation of the Cosmic Vision program. To investigate the feasibility of such a far infrared mission a technology reference study (TRS) has been performed to investigate the critical aspects of such a mission. The ESA Concurrent Design Facility (CDF)[1] was requested and financed by ESA/ESTEC/SCIAM to carry out the assessment study of a Far-InfraRed Interferometer Technology Reference Study (FIRI).

As base reference for the work here presented are considered the two studies before cited:

- SPIRIT
- FIRI

The two missions considered an assembly of two 1.0m diameter telescope, separated to a common hub collector by means of a mechanical structure, permitting to vary the inter-telescope distance or baseline.

In 2007, the “FIRI: A Far-Infrared Interferometer for ESA” Proposal for the ESA Cosmic Vision 2015 – 2025 has been developed by a large team of astronomers in more than 50 research institutes from Europe, USA and Canada and submitted to the European Space Agency (Helmich & Ivision, 2007, arXiv:0707.1822). On May 2013, a white paper titled “Sub-arcsecond far-infrared space observatory: a science imperative”

[1] http://sci.esa.int/future-missions-preparation-office/40738-firi-cdf-study-report/#

has been submitted in response to the ESA's Call for Science Themes for the L2 and L3 Missions. This proposal has been presented at the Paris meeting on September 3-4th 2013.

1.2 Why the need of high resolution (0.1") in the Far-IR (40-200μm)

Astrophysics and cosmology can make a substantial progress only if we can study in detail, both photometrically and spectroscopically, the *astrophysical objects within the spatial scales of the phenomena responsible of their emission.* In the 2020's we will experience the advent of high (milli-arcseconds) resolution at both optical and near-to-mid-infrared wavelengths from the ELT's on ground and the JWST from space. Moreover the completion of ALMA in the next years will allow very high angular resolution (down to 5 mas) in the submillimeter atmospheric windows above 350μm. The intermediate wavelengths (FIR=30-300μm) are therefore those that will suffer mostly in the near future the lack of high resolution facilities. These wavelengths are among the most important ones in astronomy, because they carry at least half of the energy emitted in the Universe. Most energetic processes – such as star formation and, often, black hole accretion – happen in dust enshrouded environments, which can be observed only at FIR wavelengths, many atomic and molecular transitions, tracing most of the astrophysical regimes, occur in the MIR-to-FIR. It is therefore imperative for Astrophysics to make a real progress that high resolution in the FIR became a reality.

1.3 Comparison of the resolving power of different facilities from the near-IR to the submm

In the following, we compare these resolutions with those that will be achieved by the other facilities: Table 1 shows the ALMA performances, Table 2 the E-ELT and Table 3 the JWST predicted resolutions and sensitivities.

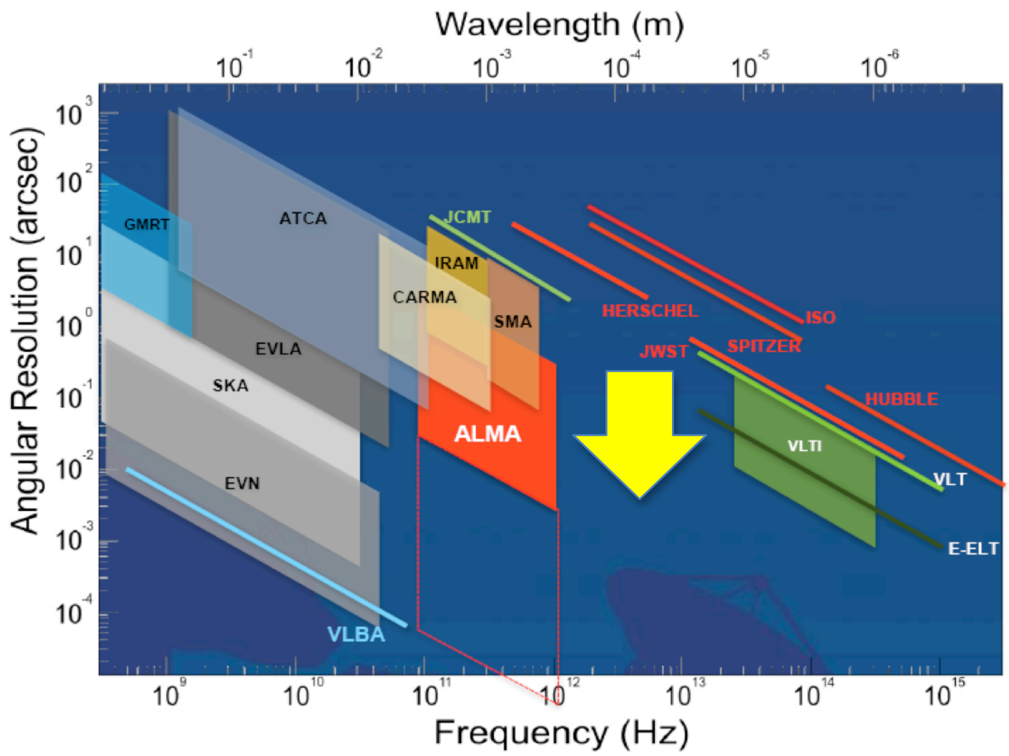

FIGURE 1: ANGULAR RESOLUTIONS REACHED BY CURRENT OR PLANNED FACILITIES, ILLUSTRATING THE GROWING "FIR GAP" (COURTESY OF TH. DE GRAAW).

1.3.1 ALMA

ALMA			Ang. Res.(")	Sensitivity (mJy)		Primary Beam	max scale
Band	Freq(GHz)	λ (mm)	min – max*	line	cont.	(")	(")
6	211-275	1.1-1.4	1.3 ... 0.014	13	0.14	27	18
7	275-373	0.8-1.1	1.0 ... 0.011	21	0.25	18	12
8	385-500	0.6-0.8	0.7 ... 0.008	63	0.86	12	9
9	602-720	0.4-0.5	0.6 ... 0.006	80	1.4	9	6
10	787-950	0.3-0.4	0.5 ... 0.005	93	1.2	7	5

*min Baseline=0.2km – max B=18km

TABLE 1: PERFORMANCES OF THE ALMA INTERFEROMETER, IN THE WAVELENGTH RANGE 0.350-1.3MM.(http://almascience.eso.org/call-for-proposals/sensitivity-calculator)

1.3.2 E-ELT

E-ELT: 39m	@1.25µm	@2.2µm	@3.6µm	@10µm
diffraction limit(FWHM):	8mas	12mas	23mas	64mas

E-ELT Instrument	λ range	FoV	R
METIS* Mid-IR imager	3.5-20μm	18”	
METIS* L, N band slit spectrograph	3.6μm, 10.6μm	18”	< 5000
MICADO#: J,K imaging	1.25, 2.2μm	30”	
HARMONI§: NIR spectrograph	1.25-2.2μm	1-10”	~4000, 10000, 20000

* http://www.strw.leidenuniv.nl/metis
\# http://www.mpe.mpg.de/ir/instruments/micado/micado.php
§ http://www.roe.ac.uk/~cje/ras/HARMONI.ppt

TABLE 2: PERFORMANCES OF THE E-ELT TELESCOPE, IN THE WAVELENGTH RANGE 1.25-20μM. ABOVE ARE LISTED THE RESOLUTION AT THE DIFFRACTION LIMIT. BELOW THE WAVELENGTH COVERAGE, FIELD OF VIEW AND SPECTRAL RESOLUTION OF THE PLANNED INSTRUMENTS

1.3.3 JWST

JWST: 6.5m	@0.6μm	@2.2μm	@5.0μm	@25.5μm
diffraction limit (FWHM):	23mas	85mas	193mas	1 arcsec

JWST Instrument	λ range	FoV	Sensitivity	@λ	R
	(μm)		(S/N=10, t=10^4 sec.)	(μm)	
MIRI*: imager	5.6-10	84”x113”	0.2-0.28-0.7μJy	5.6-7.7-10	
	11.5-15		1.7-1.4-1.8μJy	11.3-12.8-15	
	18-25		4.3-8.6-28 μJy	18-21-25.5	
MIRI* spectrograph	5.6-28		0.7 10^{-20} W m^{-2}	6.4μm	2200-3500
			1.0 10^{-20} W m^{-2}	9.2μm	
			1.2 10^{-20} W m^{-2}	14.5μm	
			6 10^{-20} W m^{-2}	22.5μm	
NIRCAM# imaging	0.6-2.3	30”	11.2nJy	1.5μm	
	2.4-5		12.3nJy	2.8μm	
			29.7nJy	3.6μm	
			55.7nJy	4.6μm	
NIRSPEC § spectrograph	1.25-2.2	3’x3’	5.7 10^{-22} W m^{-2} (t=10^5 sec. At R=1000)	2.0μm	~100, 1000, 2700

* http://www.stsci.edu/jwst/instruments/miri/sensitivity/
\# http://www.stsci.edu/jwst/instruments/nircam/sensitivity/table
§ http://www.stsci.edu/jwst/instruments/nirspec/sensitivity/

TABLE 3: JWST PERFORMANCES: ABOVE ARE LISTED THE DIFFRACTION LIMITS, BELOW THE PERFORMANCES OF THE THREE MAIN INSTRUMENTS: MIRI, NIRCAM AND NIRSPEC.

2 Science case studies

We will focus in the following on various science cases where only high resolution FIR imaging and spectroscopy will allow breaking-through achievements in astrophysics and cosmology.

2.1 Star and planet formation

It has long been established that new stars are formed in dense, often optically invisible, regions of molecular clouds. With the stellar radiation being absorbed by dust and gas, studying the very earliest phases of star formation can only be done at far-IR and submm wavelengths.

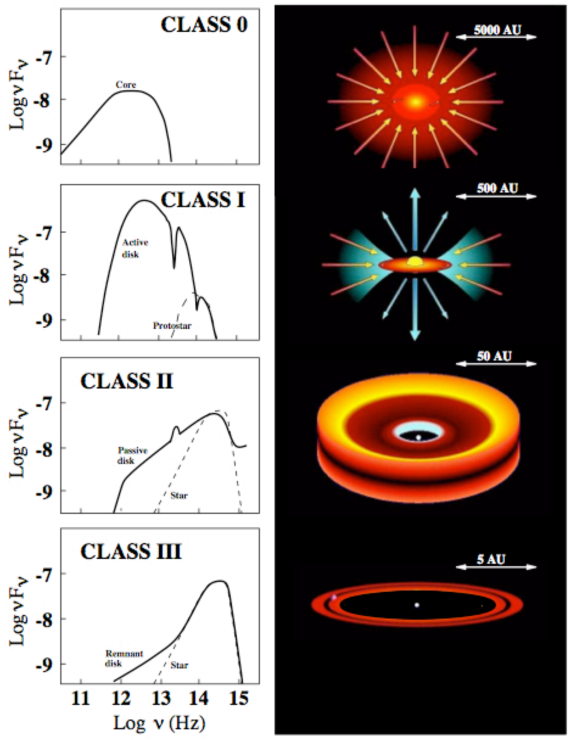

FIGURE 2: A SCHEMATIC SEQUENCE ILLUSTRATING THE PROCESS OF STAR FORMATION, FROM THE DENSE MOLECULAR CORES TO THE FORMATION OF A CENTRAL STAR AND A PLANETARY SYSTEM

As shown in Fig.2, the evolution that brings matter from a dense protostellar core into a forming low-mass star follows a sequence of spectral energy distributions where the peak emission moves from submillimeter to far-infrared and only when the circumstellar envelope and most of its circumstellar disk are removed the star shines in the optical. The spatial scales over which such evolution occurs decrease from a typical dense core radius of 0.1pc (~1000AU) (e.g. Simpson et al. 2011) in the prestellar phase, down to a disk radius of ~100 AU (e.g. DG Tau, Simon et al. 2000), in the pre-main sequence phase, corresponding to an angular size of 0.75 arcsec at the distance of the closest star forming regions in the Milky Way (D=140pc, Ophiuchus and Taurus). This latter *spatial scale of 100AU* is very important also in the early protostellar evolution as it indicates the *transition between the optically thin prestellar envelope and the optically thick protostellar source*. Observing this spatial scale is critical to fully understand the process of star formation. This scale corresponds to an angular size of 0.4” at the distance of Perseus and 0.25” at the distance of Orion, among the most representative star forming regions in the Milky Way. To study protostellar evolution, which also brings to the formation of planets out of the circumstellar disks, *subarcsecond resolution imaging spectroscopy together with continuum imaging at the peak emission wavelengths (50-200µm) is therefore needed*.

2.1.1 Observables needed to study the properties of disks and stellar envelopes

Besides the observations of the thermal continuum in the far-infrared, due to dust emission, of the various phases, from the prestellar cores, through the Class 0 and I, to the Class II, where the disk is still energetically important, a wealth of atomic and molecular transitions will be crucial to study in detail the physics and the chemistry of the whole evolutionary sequence, from prestellar cores to protoplanetary disks. Imaging spectroscopy at a spectral resolution R≥3000, to be able to detect emission and absorption lines in velocity fields of the order of ~100 km/sec, typical of protostellar outflows, complemented by observations of the continuum (in broad-band photometric channels with R~5) in the wavelength region from 50 to 200µm will be essential to characterize this unexplored phase of the early stellar evolution. Examples include the H_2O lines from the envelope, the OH and high-J CO lines from the accreting gas disk, the molecular hydrogen at 28µm and the lines from outflows and shocks: such as [CII]158µm and [OI]63 and 145µm, as well as the strong molecular lines from OH and H_2O. Figure 3 shows, as an example, the structure and the spatial scale of a protoplanetary disk: the FIRI resolution of 0.1” will allow the observations of outer disk regions at the distance of the closest star forming regions (140pc).

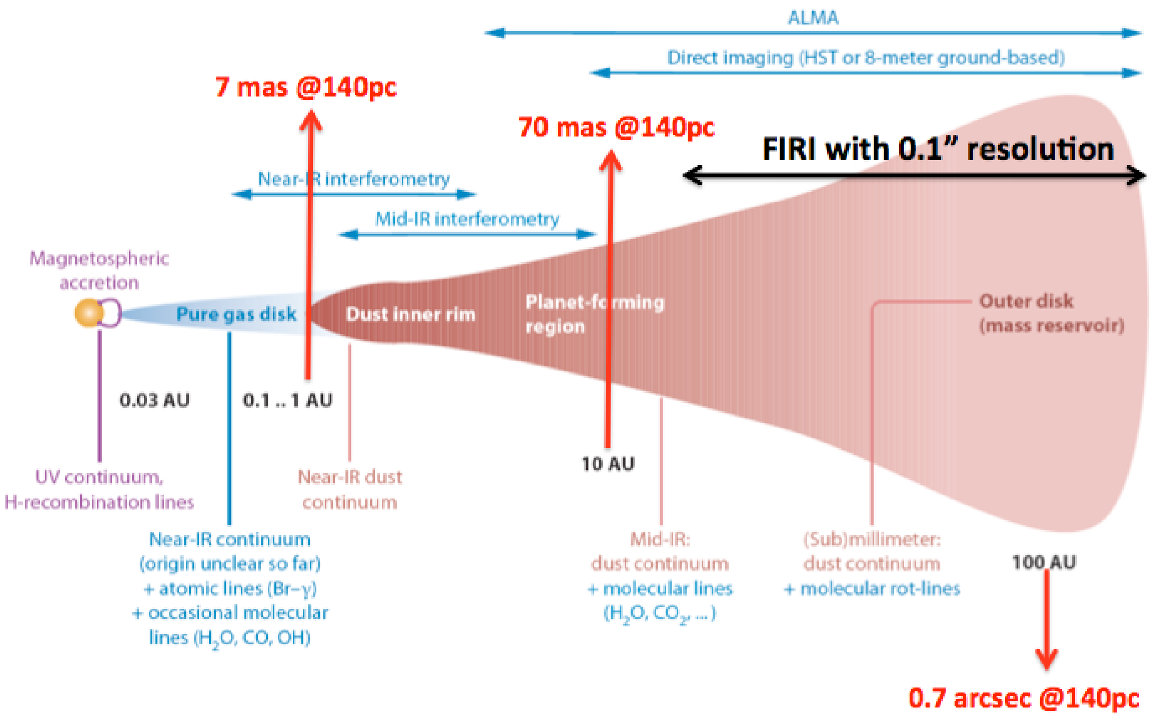

FIGURE 3: STRUCTURE AND SPATIAL SCALES OF A PROTOPLANETARY DISK. ABOVE ARE SHOWN THE TECHNIQUES THAT CAN SPATIALLY RESOLVE WHICH SCALES. BELOW IT SHOWS WHICH KIND OF EMISSION ARISES FROM WHICH PARTS OF THE DISK. ANGULAR SIZES ARE ALSO SHOWN FOR A DISTANCE OF 140PC. (ADAPTED FROM DULLEMOND & MONIER, 2010).

2.1.2 Massive star formation

Unlike low-mass star formation, for which a well established theory (e.g. Shu 1977) can predict the various evolutionary phases, the origins of massive star formation are still largely unknown. There are a number of unsolved key questions that could be resolved by the advent of FIR interferometry. Among these is the role of clustering: why are massive stars only born in clusters? and why are massive stars primarily seen in the center of clusters? There are two competing theories which need robust observational tests: *the competitive accretion versus the monolithic collapse* (e.g. Tan et al. 2014). If massive stars form via accretion, why is the high accretion rate not become quenched by radiation pressure? Or, if massive stars form from the collapse of a single cloud, as in the case of low-mass star formation, why doesn't the cloud fragment into smaller clumps? Do merging of stars play a central role in the build-up of mass? (Zinnecker & Yorke 2007; Beuther et al. 2007). Trying to give definitive answers to these questions will need important experimental verifications and FIR high resolution imaging and spectroscopy is crucial. To give two examples, angular resolution of better than 0.5" is needed to observe sub-structure in clumps at 40-200μm in the continuum; the study of evolutionary phase of cloud cores and pre-stellar clusters requires spectroscopy of far-IR high-density molecular line tracers (e.g., high-J CO, H_2O and OH transitions, as well as the major ISM coolants, such [CII]158μm and [OI]63μm) at a relatively high spectral resolution (R≥ 3000).

2.1.3 Fragmentation

One of the questions that can directly be answered by FIR interferometric imaging is the following: do massive clumps form only one massive star or do they break up? High angular resolution is the key observational technique. We take as an example the low-mass protostellar source L1448 at a distance of 250pc: the separation between the two components observed with the IRAM PdB Interferometer at 1.3mm is about 2.4 arcsec, which corresponds to 600AU. The resolution of 0.1 arcsec provided by FIRI allows to separate 100AU at the distance of 1kpc and 300AU at the distance of 3kpc, this latter encloses most high mass star forming regions visible from Earth in our galaxy. Imaging interferometry in the FIR is able to study the fragmentation of molecular clouds cores into fragments, bringing to the formation of binary or multiple stellar systems.

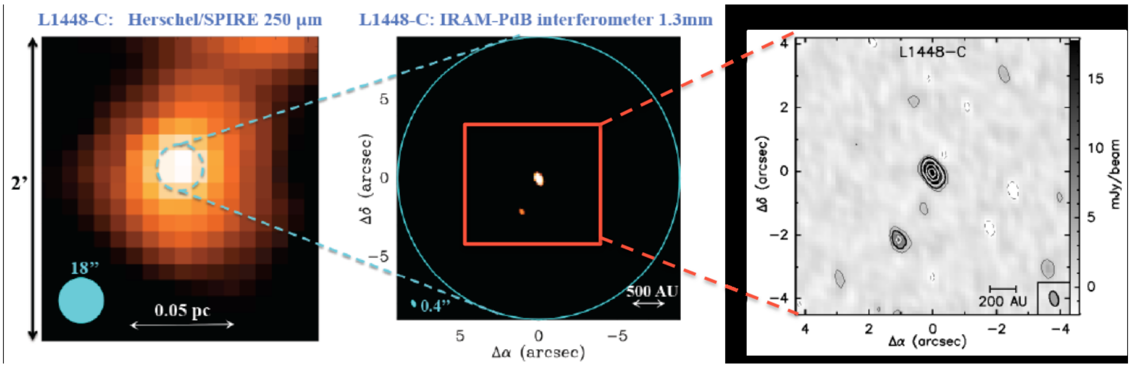

FIGURE 4: THE CLASS 0 PROTOSTELLAR OBJECT AS IT APPEARS AT INCREASING RESOLUTION: ON THE LEFT THE HERSCHEL SPIRE IMAGE AT 250MM IS SHOWN (COURTESY OF THE HERSCHEL GOULD BELT SURVEY, ANDRÉ ET AL. 2010, AND PEZZUTO ET AL. IN PREP.) , WHILE AT THE CENTER AND ON THE RIGHT THE IRAM PDBI OBSERVATIONS AT 1.3MM, WITH A HPBW BEAM OF 0.48”×0.27”, SHOWING THAT THE SOURCE IS IN REALITY MADE OF TWO COMPONENTS (MAURY ET AL. 2010)

2.2 The Galactic Center

The Galactic Center (GC), with its central black hole of 4.4 x 10^6 $M_\odot$, is an excellent laboratory for studying phenomena and physical processes that may be occurring in many other galactic nuclei (Genzel et al. 2010). At a distance d = 8.0±0.5 kpc (Reid 1993), the nucleus of our galaxy is a few hundred times closer than the nearest active galactic nuclei (AGN), thus allowing high spatial resolution studies. The distribution of gas and dust toward the GC (Genzel et al. 2010) consists of a central cavity of radius ~1.5 pc containing warm dust and gas heated and ionized by the central cluster of massive stars orbiting close to the black hole (SgrA* radio source position). Between ~1.5 pc and ~5 pc, a disk of denser molecular gas exists (the circum-nuclear disk or CND; Guesten et al. 1987). However, it is not yet clear whether all the material in the CND is stable against the strong tidal forces in the region or has a more transient nature (Bradford et al. 2005; Montero-Castaño et al. 2009; Requena-Torres et al. 2012). The neutral gas component toward the central cavity has been less studied, first because high angular resolution is required to separate the different components and also because column densities are inevitably lower and emission lines are intrinsically weak. Owing to the lower dust extinction at far-IR wavelengths and because of the strong emission from the interstellar component related to AGN and star formation activity, the relevance of far-IR imaging spectroscopy at the highest possible resolution of the GC is therefore extraordinary. In Fig.5 are shown some of the results from *Herschel* (Goicoechea et al. 2013) indicating the richness of the far-IR spectra of the SgrA* source and of the CND.

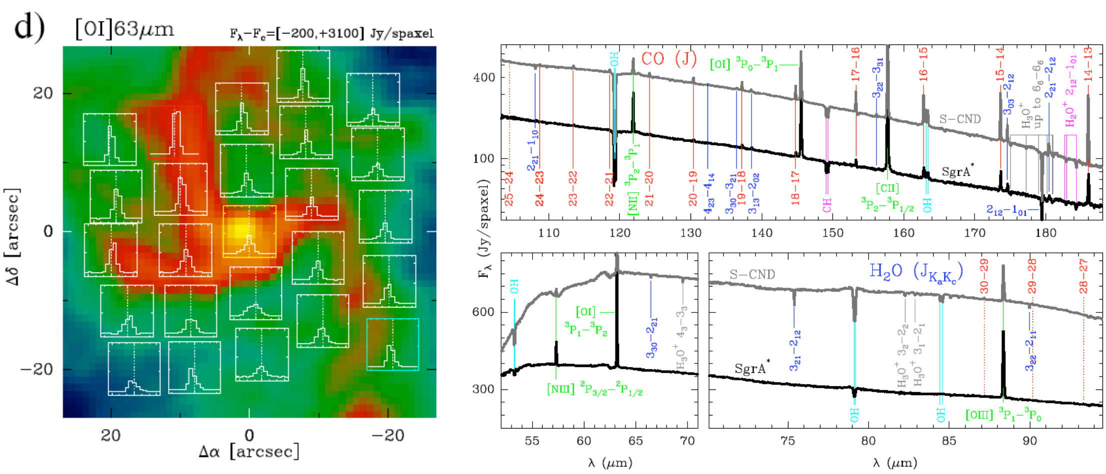

FIGURE 5: HERSCHEL FAR-INFRARED SPECTROSCOPIC OBSERVATIONS OF THE GALACTIC CENTER. LEFT: THE [OI]63μM MAP, OVERLAID ON THE 6CM RADIO CONTINUUM MEASURED WITH THE VLA AT 3'' RESOLUTION (YUSEF-ZADEH & MORRIS 1987). RIGHT: THE COMPLETE 53-190μM PACS SPECTRUM OF SGRA* AND THE CND (GOICOECHEA ET AL. 2013)

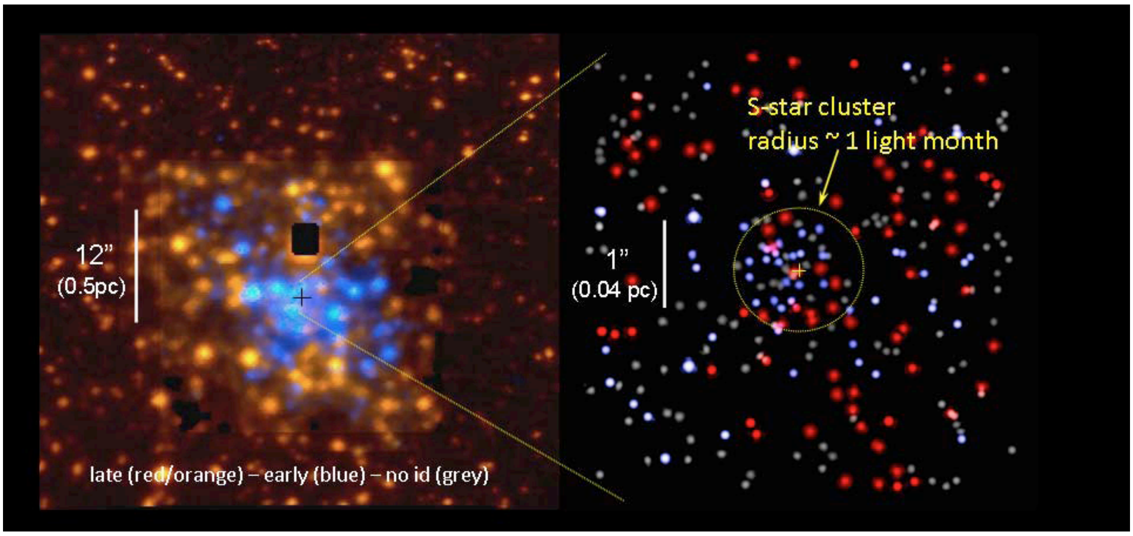

FIGURE 6: DISTRIBUTION OF EARLY-TYPE STARS (BLUE) AND LATE-TYPE STARS (ORANGE/RED), AS OBTAINED FROM SINFONI INTEGRAL FIELD SPECTROSCOPY IN THE CENTRAL $P \sim 1$ PC (LEFT) AND CENTRAL $P \sim 0.08$ PC (RIGHT) (FROM GENZEL ET AL. 2010).

At the distance of the Galactic Center (~8kpc) an angular distance of 0".25 corresponds to 0.01 pc, i.e. ~2000 AU. We can see, in Fig.6 (from NACO and SINFONI observations at the VLT, ESO), the spatial distribution of early and late-type stars, colored in blue and red, respectively, showing a steep increase in the density (and brightness) of bright early-type stars (Genzel et al. 2010). *A similar spatial resolution in mid- to far-IR imaging spectroscopy would be able to overcome the obscuration that might affect the field and "see" through the innermost region of the Galactic Center.*

2.3 Stars and local galaxies

In the Milky Way and in local galaxies, the resolution of 0.1 arcsec in the FIR will allow for the first time to study in detail massive disks at the distance of our Galactic centre and massive molecular cores in the Magellanic Clouds, as well as star forming filaments in nearby galaxies, such as Andromeda and the giant molecular clouds at the edge of the local group. The following table shows a few examples of what we can "see" with a resolution of 0.1 arcsec.

Object	Distance	Size Scale	Structure
Galactic Centre	8.4 kpc	1000 AU	Massive disk
LMC	57 kpc	0.03 pc	Massive cores
Andromeda (M31)	780 kpc	0.44 pc	Filaments
Edge of local group	1.4 Mpc	0.8 pc	Molecular clouds

2.4 AGNs in the Local Universe

Active Galactic Nuclei (AGN) are very important astrophysical objects not only because their physics is interesting by itself, but also because of their crucial role in galaxy evolution. Since the discovery of the so-called Magorrian relation in the Local Universe (Magorrian et al. 1998; Ferrarese & Merrit 2000), between the mass of the black hole (BH) at the centre of bulge-dominated galaxies and the velocity dispersion of the stellar component of their galactic bulge, it was realized that the black hole growth in a center of a galaxy had to be intimately connected with the building of the galaxy stellar population. The enormous difference between the black hole Schwarzschild radius and the characteristic radius of the bulge indicates that this relation possibly reflects the coeval formation of the two in a common gravitational potential. It is therefore of crucial importance to study in the Local Universe not only the physical properties of AGNs, such as the accretion geometry and the line and continuum emission regions, the Narrow, Coronal and Broad Line regions as well as the molecular tori, but also the AGN feeding and the feedback from the AGN to the galaxy, in forms of winds, jets and atomic and molecular outflows. The recent discoveries from both Herschel FIR spectroscopy (Fischer et al 2010, Sturm et al 2011, Spoon et al 2013) and millimeter interferometry (Feruglio et al 2010, Aalto et al 2012, Cicone et al 2012, Maiolino et al 2012) seem to indicate that AGN outflow can have enough energy to quench star formation on a galaxy wide scale.

Emission Region	scales	6 Mpc	16 Mpc	50 Mpc
		Circinus	NGC1068	Local Universe
Outflows and jets	1kpc	34”	13”	4”.1
Narrow Line Region	100-500pc	3”.4-17”	1”.3-6”.5	0”.41-2”
Coronal Line Region	100pc	3.”4	1”.3	0”.41
Torus	10pc	0”.34	0”.13	0”.041
Broad Line Region	0.1pc	0”.034	0”.013	0”.004

TABLE 4: ANGULAR RESOLUTION NEEDED TO STUDY THE EMISSION REGIONS IN LOCAL AGNS. IN RED ARE SHOWN THE ANGULAR SCALES THAT CAN BE RESOLVED WITH FIRI

In Table 4, we have summarized the spatial scales of the emitting regions associated with the AGNs, which are shown in the picture of Fig.7, that gives an artist impression of the AGN stucture. Table 4 also reports the corresponding angular sizes of these emission regions at the distances of two nearby Seyfert galaxies, Circinus and NGC1068, and at the average distance of the Local Universe: most of the emitting regions, except the compact Broad Line Regions, can be resolved at an angular resolution of 0.1 arcsec, which can be provided by the FIRI 100m baseline interferometer.

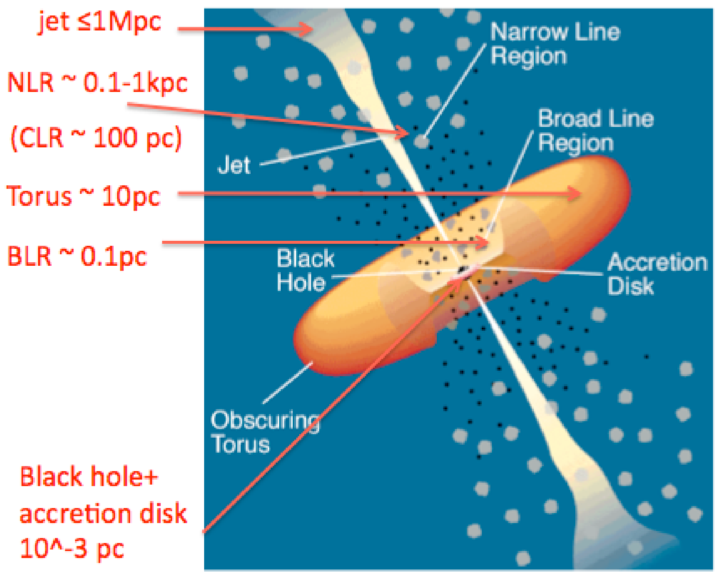

FIGURE 7: REPRESENTATION OF AN AGN, WHERE THE VARIOUS EMISSION REGIONS ARE INDICATED. ON THE LEFT THE MEAN SPATIAL SCALES OF THE EMISSION REGIONS ARE ALSO SHOWN (ADAPTED FROM URRY & PADOVANI, 1995).

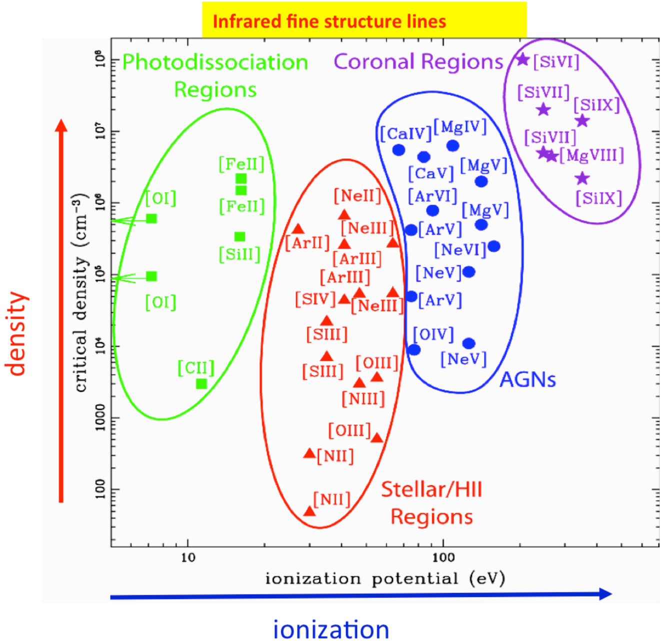

FIGURE 8: CRITICAL DENSITY OF THE FINE-STRUCTURE TRANSITIONS AS A FUNCTION OF THEIR IONIZATION POTENTIAL. FROM THE LEFT TO THE RIGHT ARE SHOWN THE DIFFERENT PHYSICAL REGIMES OF PHOTODISSOCIATION REGIONS, HII REGIONS, AGN EMISSION REGIONS AND CORONAL LINE EMISSION REGIONS (SPINOGLIO & MALKAN 1992).

A wealth of spectroscopic tracers, both atomic and molecular, occurs in the mid- to far-infrared. In particular ionic fine-structure lines trace a large range in physical conditions, as shown in Fig.8, where the critical density of the transitions is shown as a function of their ionization potential. Increasing the energy of the radiation field, we can cover from the neutral/low ionization photodissociation regions, to the HII regions, to the AGN emiting regions (Spinoglio & Malkan 1992). The best tracers to study the AGN emission line regions (Narrow Line Regions and Coronal Line Region) are the ionic fine-structure lines from various elements, e.g. [NeV]24μm, [OIV]26μm, [OIII]52 and 88μm, [NIII]57μm, [OI]63μm, etc. The study of outflows can be performed using far-IR OH and H_2O absorption lines. The needed resolution for studying line profiles and detect outflows in AGN is in the range of R=1500-3000, due to the need to map velocities of the order of 100-200 km/s. Complementary continuum observations with R~5 will also be very valuable.

2.5 Cosmology

2.5.1 Studying AGN vs Starburst evolution along cosmic times

Our perspective of galaxy evolution has greatly changed in recent years thanks to two main findings: the first is the the so-called *Magorrian relation* (see Section 2.4). The second is the evidence that most, if not all, galaxies during their evolution pass through a dust-obscured bright FIR/submillimetre phase. The first finding strongly suggests that in order to understand galaxy evolution in galaxies one has to study the evolution of the non-thermal nuclear activity (AGN) - on one side - and of star formation (SF) - on the other side. The second finding shows that the far-IR spectral domain is the most adequate to study galaxy evolution at the maximum of its activity - both AGN and SF - by overcoming dust obscuration and observing the peak continuum emission.

The starburst emission regions in galaxies has a linear size of 1-2 kpc and can be resolved at any redshift using FIR interferometry reaching an angular resolution of 0.1 arcsec. In fact, as shown in Fig.9, beyond the redshift z=2, due to the standard cosmology, the apparent size of astrophysical objects starts to increase as a function of redshift.We will therefore be able with FIRI to study both photometrically and specroscopically how the starburst components evolve in cosmic times. Whilst the AGN Narrow line Regions will not be resolved beyond z=0.1, spectroscopy will still allow to disentangle starburst and AGN components through bright fine structure lines.

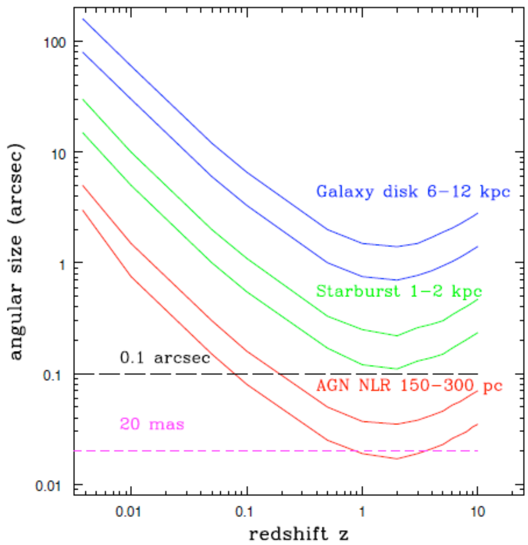

FIGURE 9: ANGULAR SIZES OF THE RELEVANT FIR EMITTING COMPONENTS OF GALAXIES AS A FUNCTION OF REDSHIFT, FOLLOWING THE STANDARD COSMOLOGICAL MODEL (SPERGEL ET AL. 2007).

2.6 Summary of science requirements

In the following Table 5, are reported the scientific objectives that have been taken as drivers to design the future FIR mission. In Table 6, we report the required parameters needed to observe each sientific objective.

	Science topic	Observing requirements	Instrument requirements
2.6.1	Star formation : Protostars	*Resolve 100AU, the transition between the optically thin prestellar envelope and the optically thick protostellar source: detection of the first hydrostatic cores*	At the closest star forming region of Taurus, 100AU correspond to 0.75 arcsec. However, this scale corresponds to an angular size of 0.4" at the distance of Perseus and 0.25" at the distance of Orion, among the most representative star forming regions in the Milky Way. Wavelength range needed is 40-200μm. Photometric imaging with R~5 and imaging spectroscopy at R ≥ 3000.
2.6.2	Star formation: Protoplanetary disks Formation of planetary systems	*Resolve the outer structure (10-100AU) of protoplanetary disks*	The planet forming region in a protoplanetary disk is expected to occur at ~10-15AU, corresponding to 0".075-0".11 at the distance of 140pc, the closest star forming region of Taurus. The outer disk, where most of the mass resides, is at a distance from the center of ~100AU (0".75@140pc). Wavelength range needed is 20-200μm. Spectroscopic resolution R ≥ 3000.
2.6.3	Star formation: Binary and multiple systems	*Resolve binary and multiple protostellar objects*	Three different types of multiple systems have been identified; separate envelope with separations larger than 6000 AU, common envelope with separation between 100-3000 AU and common disk with separation less than 100 AU. This latter separation can be reached in Orion with a resolution of 0".25. Wavelength range needed is 40-200μm. Photometric imaging with R~5 and imaging spectroscopy at R ≥ 3000.
2.6.4	Star formation: Massive star formation	*Answer to the question if massive clumps form only one massive star or stellar clusters*	At the distance of 3 kpc are included most high mass star forming regions in the Milky Way. A separation of 500-750 AU at this distance corresponds to an angular resolution of 0".17-0"25. Wavelength range needed is 40-200μm. Photometric imaging with R~5 and imaging spectroscopy at R ≥ 3000.
2.6.5	The Galactic Center	*Map the central thousands AU around the SgrA* Black Hole in extinction free continuum and lines*	At the distance of 8 kpc, a linear scale of 2000AU corresponds to 0".25, which will be needed to map the continuum and the lines in the inner region of the GC. Photometric imaging with R~5 and imaging spectroscopy at R ≥ 3000.
2.6.6	AGN in the local Universe	*Resolving the torus and the emission-line regions in the circumnuclear environment of local AGN*	With subarcsecond resolution (down to 0".1) the Narrow Line Regions of AGN could be mapped at a distance of ~50 Mpc. The molecular torus can be resolved for the closest AGN (d<20 Mpc). Photometric imaging with R~5 and imaging spectroscopy at R ≥ 1500.
2.6.7	Galaxy formation and Evolution	*Resolving starburst complexes and Narrow Line Regions along galaxy evolution*	Star formation rate and SMBH accretion rate for 1<z<5 can be measured through high sensitivity imaging spectroscopy from ~30-100μm.

TABLE 5: SCIENTIFIC OBJECTIVES TAKEN AS DRIVERS TO DESIGN THE INTERFEROMETRIC FIR MISSION.

	Topic	*Science Case*	*Required spatial res. (arcsec)*	*Required spec. res. (R)*	*Estimated Line Flux (W/m^2)*
2.6.1	Star formation : Protostars	*Resolve 100AU: detection of the first hydrostatic cores*	*0.25 " @400pc* *0.40" @250pc* *0.66" @150pc*	*≥3000* *R~5*	*2.1E-20** *5.4E-20** *1.5E-19**
2.6.2	Star formation: Protoplanetary disks/Formation of planetary systems	*Resolve the outer structure (10-100AU) of protoplanetary disks*	*0.20"* *30AU@140pc* *0.75"* *100AU @140pc*	*>5000*	*A: [OI]63µm: 2.4E-16#* *[OI]145µm: 1.2E-17 #* *B: [OI]63µm: 3.7E-16#* *[OI]145µm: 3.1E-17 #*
2.6.3	Star formation: Binary and multiple systems	*Resolve binary and multiple protostellar objects*	*0.25" @ 400pc*	*≥3000* *R~5*	*[OI]63µm: 9E-19 ^* *H_2O: 8E-19 - 4E-18^* *CO: 2E-19 - 4E-18^* *HDO: 4E-18***
2.6.4	Star formation: Massive star formation	*Answer to the question if massive clumps form only one massive star or stellar clusters*	*0.25" @3kpc*	*≥3000* *R~5*	*12^CO(10-9): 5E-18^^* *13^CO(10-9): 8E-19^^* *C^18O(10-9): 1E-19^^*
2.6.5	The Galactic Center	*Map the central thousands AU around the SgrA* Black Hole in extinction free continuum and lines*	*0.25" @ 8kpc*	*≥3000* *R~5*	*[OI]63µm: 2.4E-17 $* *CO(14-13)@186µm: 1.9E-19 $* *CO(24-23)@108µm: 2.0E-20 $*
2.6.6	AGN in the local Universe	*Resolving the torus and the emission-line regions in the circumnuclear environment of local AGN*	*0.10" @ 50Mpc*	*1500-3000* *R~5*	*min, ave, max* *[OIV]26µm:* *1E-19, 1E-18, 3E-18 §* *[NeV]24µm:* *3E-20, 2.8E-19, 9E-19 §* *[OI]63µm:* *6E-19, 2.6E-18, 7.6E-18§*
2.6.7	Galaxy formation and Evolution	*Resolving starburst complexes and Narrow Line Regions along galaxy evolution*	*0.10" starburst* *(0.02" NLR)*	*1500-3000*	*1E-21 < F < 1E-20*

TABLE 6: REQUIRED PARAMETERS FOR EACH SCIENTIFIC OBJECTIVE.

Notes:
*: H_2O lines predictions from the First Hydrostatic Cores models of Omukai (2007).
#: integrated flux predictions of protoplanetary disks models (Kamp et al. 2010, model A: R_{in}=0.5-R_{out}=30AU, model B: R_{in}=30- R_{out}=100AU) at 131pc and 45° incl.; in agreement with Herschel (Pinte et al. 2010).
^: flux scaled to an area of 0."25x0."25 of the proto-binary system NGC1333-IRAS4, assuming an emission region of 1000AU (Karska et al. 2013) (1/100 of the observed flux and scaled at a distance D=400pc).
**: Integrated flux observed in IRAS4A at HDO@893GHz with HIFI (Coutens et al 2013), scaled at D=400pc
^^: flux scaled to an area of 0."25x0."25 from HIFI observations in W3-IRS5 (San José-Garcìa et al. 2013) (10^-4 of the observed flux).
$: flux scaled to an area of 0."25x0."25 from Herschel observations of Goicoechea et al (2013).
§: scaled values, assuming a NLR extension of 500pc, from fluxes of local (D~50Mpc) Seyfert galaxies (Tommasin et al. 2010; Spinoglio et al. 2014, in prep.))(1/400 of the observed flux).
General note: If the true morphology is clumpy or composed of small sources diluted in the large single-dish beams the expected intensities with FIRI will be higher than assumed here.

2.7 Summary of Instrument Requirements

It appears clear from Table 6, which gives the instrument requirements for each of the scientific cases, that most scientific goals can be reached with an angular resolution of 0.1”- 0.25”, a spectral resolution in the range of R=1500-5000, able to perform emission and absorption line spectroscopy, a spectral range that covers 24-200μm and a sensitivity which allows detections of spectral lines with a flux of the order of a few in 10^{-19} W/m^2 . Complementary to imaging spectroscopy, also broad-band imaging will be required, with R~5. The field of view required for most programmes is 1 arcminute squared. For this latter requirement, we therefore need a 1σ line sensitivity of ~1x10^{-19} W/m^2. The “goal” sensitivity would be 1 order of magnitude better, i.e. 1x10^{-20} W/m^2, 1σ, 1 hr (~5σ, 24 hrs).

2.8 The Conceptual design

The scientific requirements, briefly discussed in the above sections, point to the need to spatially resolve in the sky astrophysical objects of an angular size of the order of 0.1-0.25 arcseconds. In order to reach such angular resolutions, an interferometer with a maximum inter-telescopes distance of 100m will be necessary.

To allow the required stability to such a configuration, the three foreseen technical solutions will be explored in this study:

- a tether connection between the two telescopes
- a SPIRIT type rigid boom connecting the two telescopes
- a free flying configuration

In the context of the FISICA study, the baseline FIR interferometer will consist of two 2m class cryogenically cooled telescopes performing aperture synthesis interferometry in both the continuum and the lines using the double Fourier spectro-imaging technique, operated at a maximum inter-telescopes distance of 100m.

The baseline interferometer will have the following angular resolutions (FWHM):

FIRI: 100m baseline	@30μm	@40μm	@100μm	@200μm
diffraction limit(FWHM) #:	0.07 arcsec	0.1 arcsec	0.25 arcsec	0.5 arcsec

(#) The angular resolution has been computed as the FWHM of the Airy disk: 1.22 λ/D.

2.9 Observing Modes

In this section are presented, for each of the science cases discussed, the relative observing modes and observational strategies to perform the needed observations. In the following, we have used an interferometer with 2m mirrors and, for computing the total integration time for each observing mode, we have assumed a scan duration of 30 sec. and a number of two scans per pair of u,v point. To compute the total number of u,v points we have assumed tangent positions of the mirrors.

2.9.1 Science case 1: Star Formation: Protostars

For this science case, we have chosen as target a protostar with a linear dimension of 100AU in the Perseus star forming region at a distance of 250pc. The needed resolution is 0.4 arcsec. Fig. 10 and 11 present the schematic view of the target and the (u,v) plane coverage needed to perform this observation. The total time needed on-source is ~21 hours, corresponding to 2600 u-v points with 2 scans per pair of u-v points.

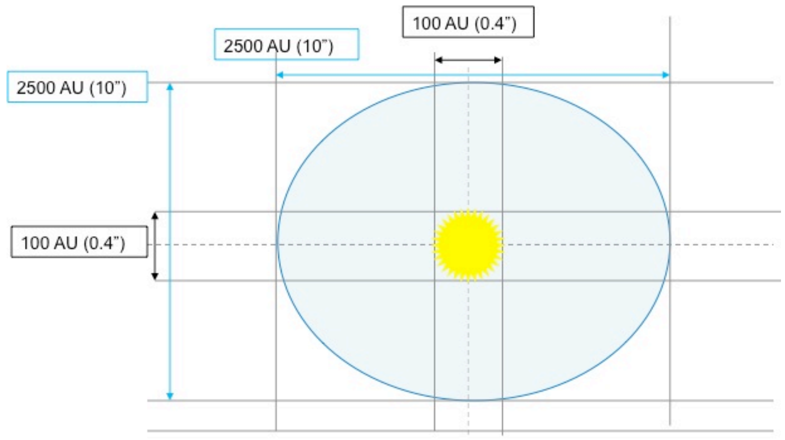

FIGURE 10: SCHEMATIC VIEW OF THE TARGET, INCLUDING THE CENTRAL SOURCE WITH A DIAMETER OF 100AU AND THE EXTENDED ENVELOPE WITH A SIZE OF 2500 AU

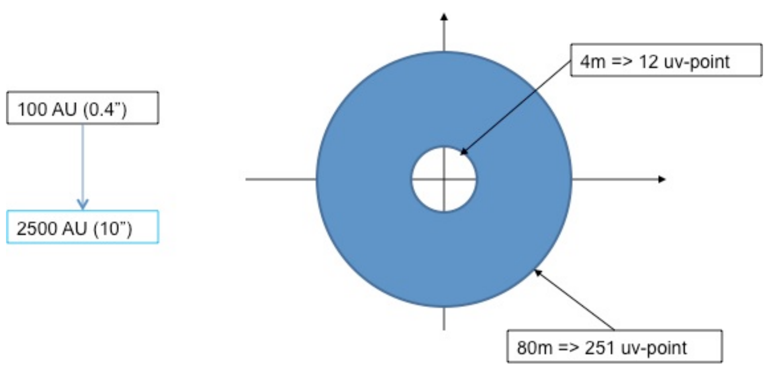

FIGURE 11: (U, V) PLANE COVERAGE FOR SCIENCE CASE 1.

2.9.2 Science case 2: Star Formation: Protoplanetary disk

For this science case, we have chosen as target a protoplanetary disk with a linear dimension to be explored from ~30AU to ~100AU in the Taurus star forming region at a distance of 140pc. The needed resolution ranges from 0.2 to 0.75 arcsec. Fig. 12 and 13 present the schematic view of the target and the (u,v) plane coverage needed to perform this observation. For an interferometer with 2m mirrors, the total time neeeded on-source is 30 hours, corresponding to ~3600 u-v points with 2 scans per pair of u-v points.

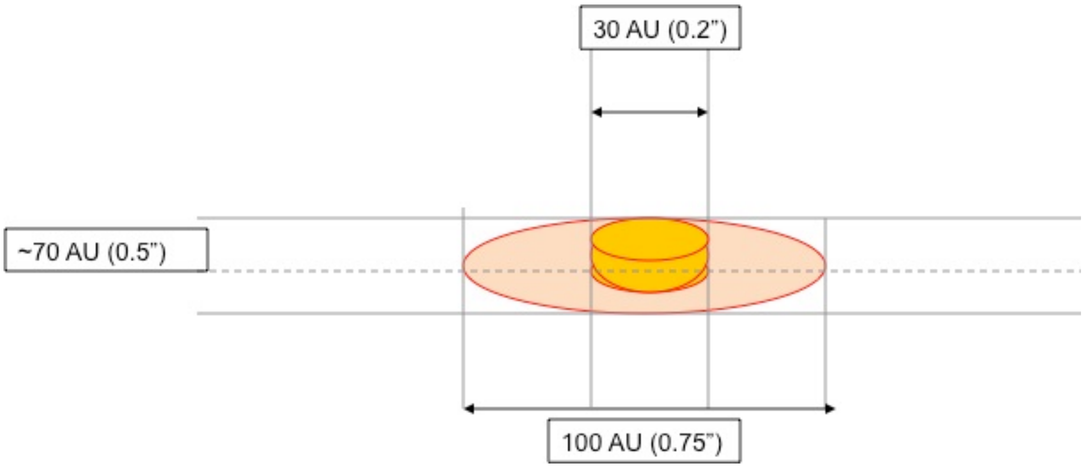

FIGURE 12: SCHEMATIC VIEW OF THE TARGET, A PROTOPLANETARY DISK WITH SIZES TO BE EXPLORED RANGING FROM 30 AU TO 100 AU.

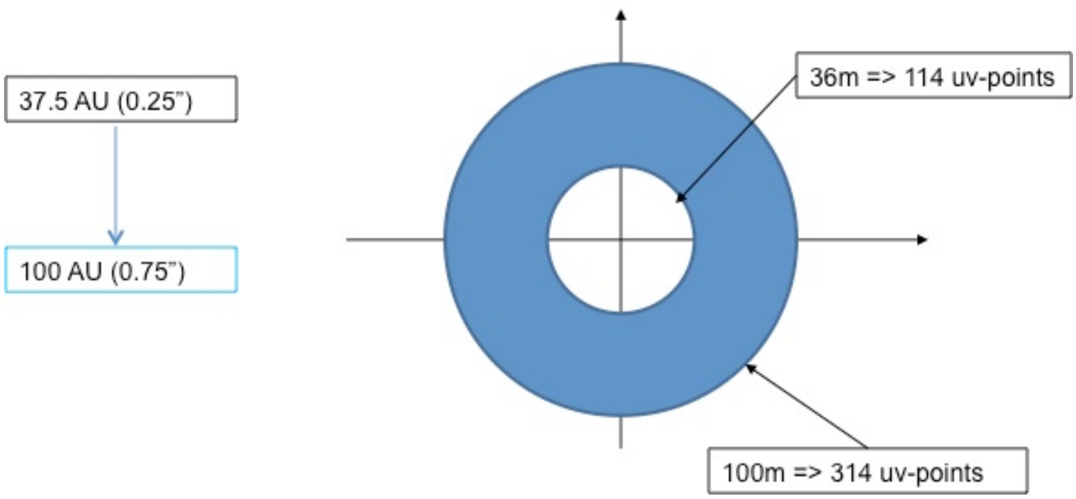

FIGURE 13: (U, V) PLANE COVERAGE FOR SCIENCE CASE 2.

2.9.3 Science case 3: Star Formation: Binary protostellar system

For this science case, we have chosen as target a binary protostellar system with a linear dimension to be explored of 100AU in the Orion star forming region at a distance of 400pc. The needed resolution is 0.25 arcsec. Fig. 14 and 15 present the schematic view of the target and the (u,v) plane coverage needed to perform this observation. For an interferometer with 2m mirrors, the total time neeeded on-source is 23 hours, corresponding to ~2700 u-v points with 2 scans per pair of u-v points.

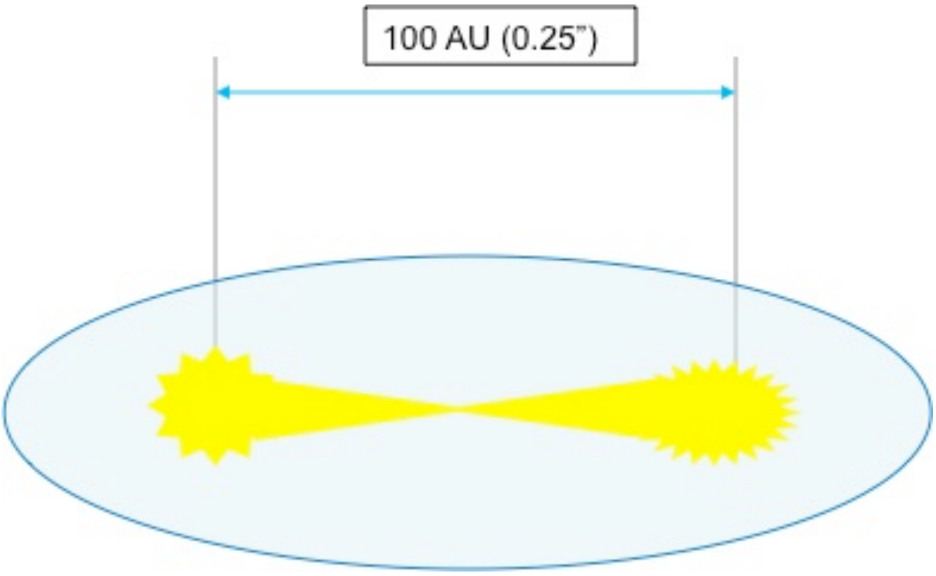

FIGURE 14: SCHEMATIC VIEW OF THE TARGET, COMPOSED OF A BINARY SYSTEM WITH A SEPARATION OF 100AU.

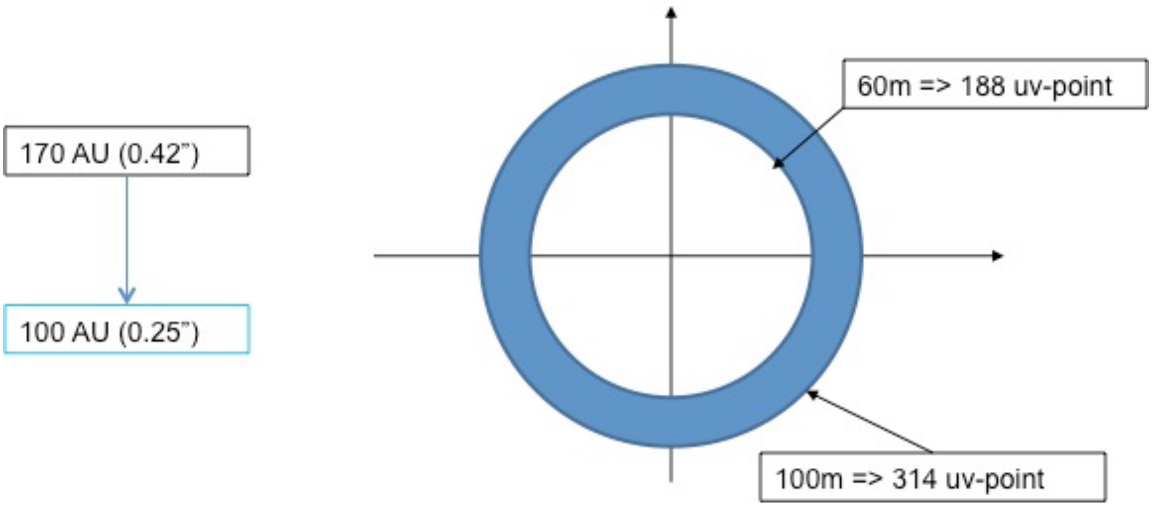

FIGURE 15: (U, V) PLANE COVERAGE FOR SCIENCE CASE 3.

2.9.4 Science case 4: Star Formation: Massive star formation

For this science case, we have chosen as target a protocluster with a linear dimension to be explored of 750AU in a generic massive star forming region at a distance of 3kpc. The needed resolution is 0.25 arcsec. Fig. 16 and 17 present the schematic view of the target and the (u,v) plane coverage needed to perform this observation. For an interferometer with 2m mirrors, the total time neeeded on-source is 33 hours, corresponding to ~4000 u-v points with 2 scans per pair of u-v points.

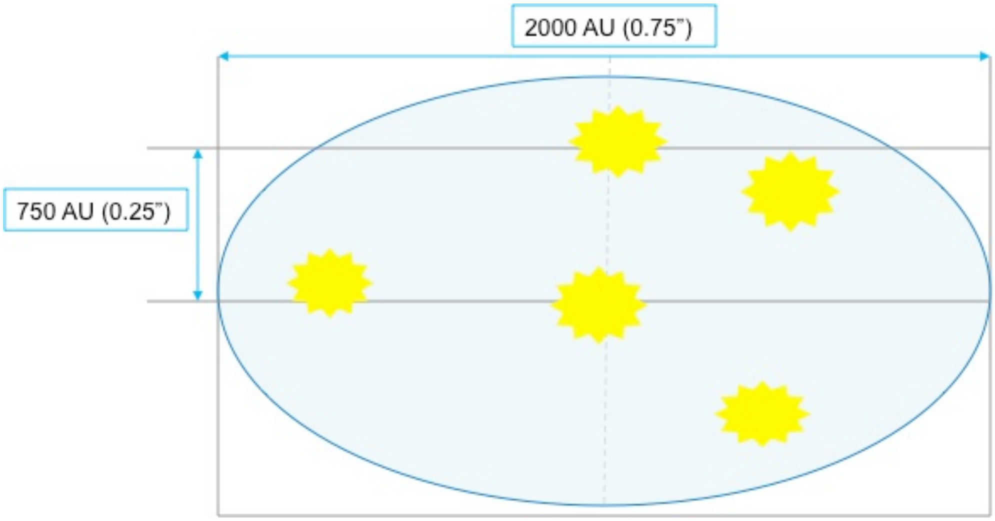

FIGURE 16: SCHEMATIC VIEW OF THE TARGET, COMPOSED OF CLUSTER OF STARS WITH A MEAN SEPARATION OF 750AU, COVERING A SIZE WITH DIAMETER OF 2000AU.

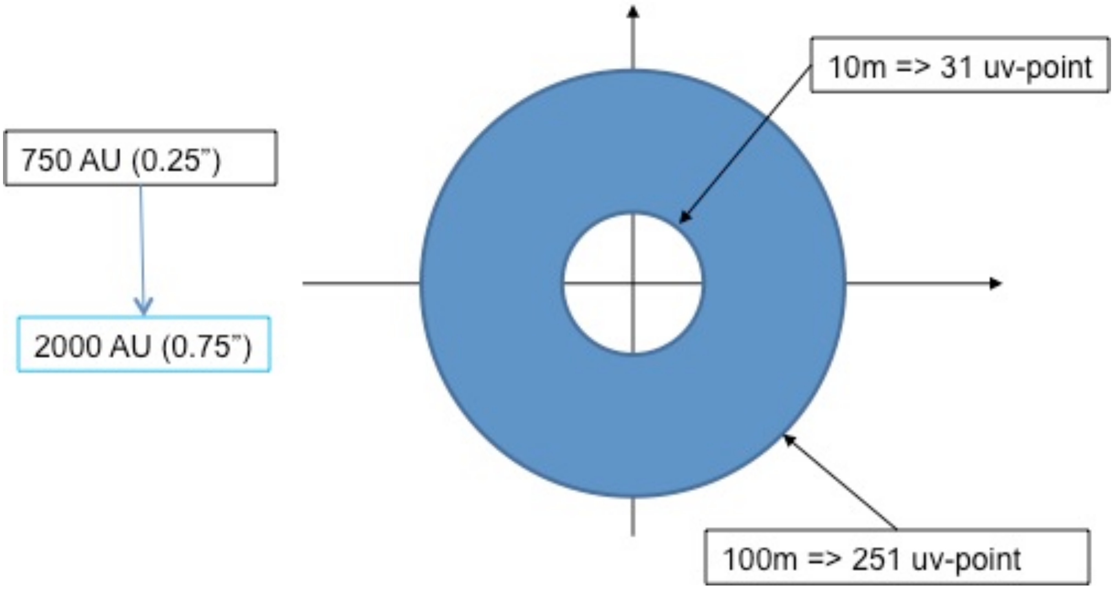

FIGURE 17: (U, V) PLANE COVERAGE FOR SCIENCE CASE 4.

2.9.5 Science case 5: The galactic Center

For this science case, we need to map a region of about 1 arcmin squared around the Galactic Center at a resolution of 2000AU at a distance of ~8kpc. The needed resolution is 0.25 arcsec. Fig. 18 and 19 present the schematic view of the target and the (u,v) plane coverage needed to perform this observation. For an interferometer with 2m mirrors, the total time neeeded on-source is 18 hours, corresponding to ~2200 u-v points with 2 scans per pair of u-v points.

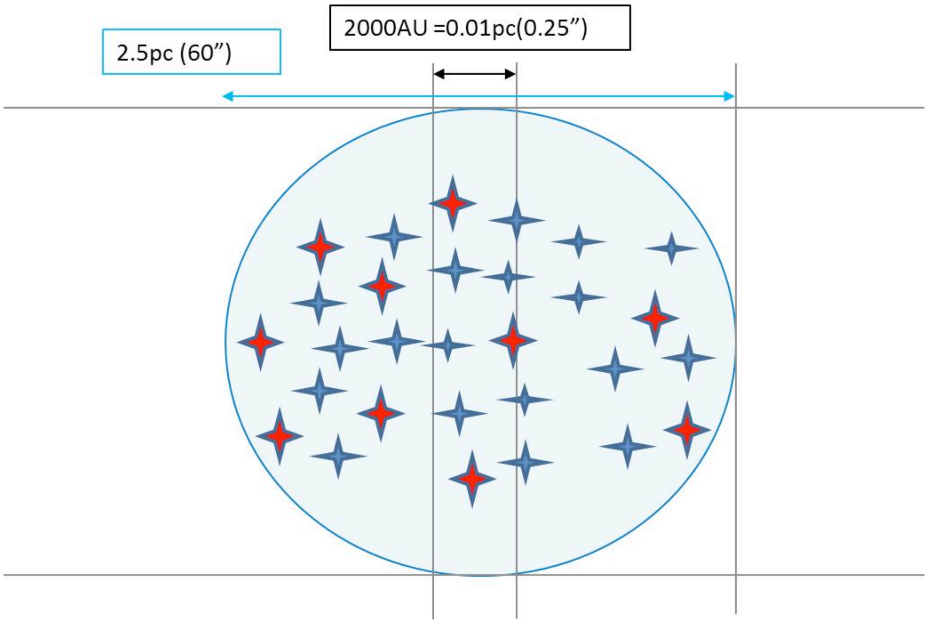

FIGURE 18: SCHEMATIC VIEW OF THE TARGET, COMPOSED OF CLUSTER OF STARS WITH A MEAN SEPARATION OF 2000AU (0.01 PC) COVERING A SIZE WITH DIAMETER OF 2.5 PC.

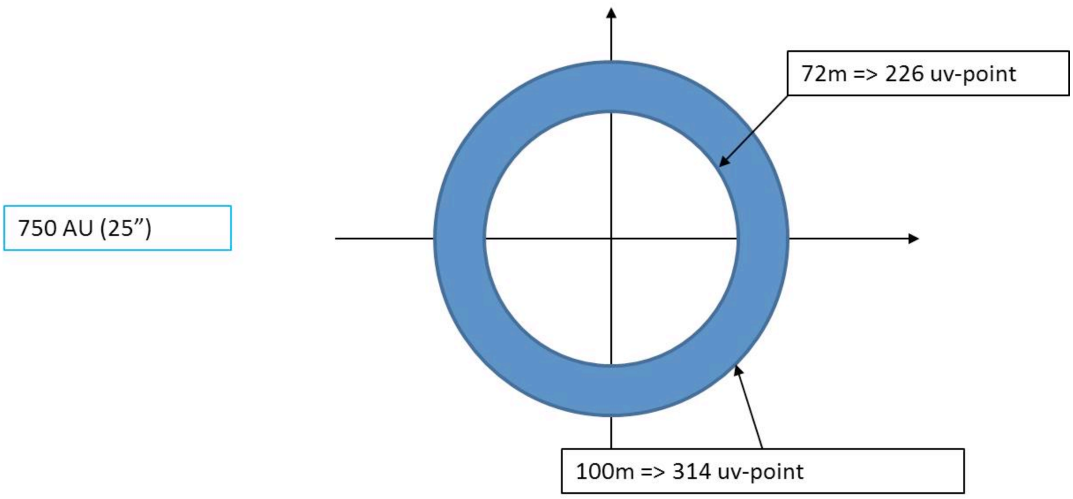

FIGURE 19: (U, V) PLANE COVERAGE FOR SCIENCE CASE 5.

2.9.6 AGNs in the Local Universe

For this science case we need to map the emission line regions in local AGNs at an average distance of 50 Mpc. The maximum resolution of 0.10" is needed for this project, because we want to resolve the Narrow Line Region. This will be reached at wavelengths of < 50 µm, where many of the important AGN mid-IR fine structure lines lie, such as [OIV]26µm and [NeV]24µm. Fig. 20 and 21 present the schematic view of the target and the (u,v) plane coverage needed to perform this observation. For an interferometer with 2m mirrors, the total time neeeded on-source is 34 hours, corresponding to ~4100 u-v points with 2 scans per pair of u-v points.

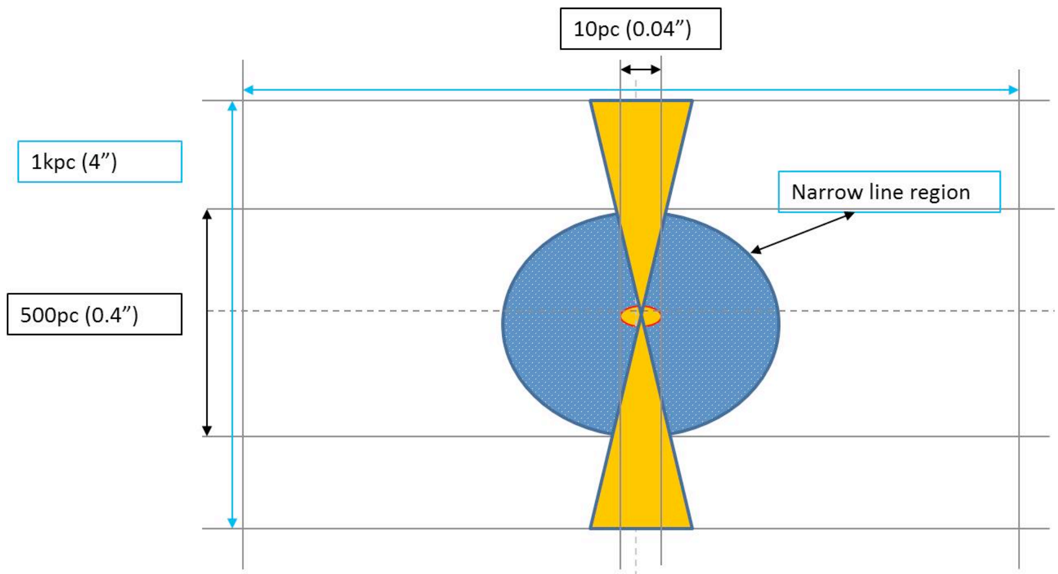

FIGURE 20: SCHEMATIC VIEW OF THE TARGET, COMPOSED OF THE EMISSION LINE REGIONS IN LOCAL AGNS AT AN AVERAGE DISTANCE OF 50MPC. THE SIZE OF THE JET IS ABOUT 1 KPC (4") AND THE NARROW LINE REGION EXTENDS FROM 100 TO 500PC (0."4 – 2").

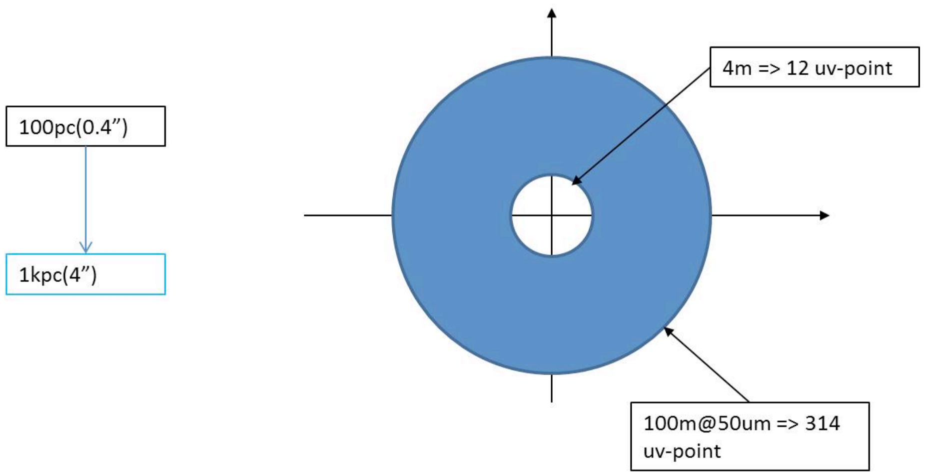

FIGURE 21: (U, V) PLANE COVERAGE FOR SCIENCE CASE 6.

2.9.7 Science case 7: Galaxy Formation and Evolution: Resolving Starburst structures at high redshift

For this science case we need to map the starburst and the galaxy disk of distant galaxies at a redshift of, e.g. z=2, corresponding to an average distance of ~16 Gpc. The maximum resolution of 0.10" is needed for this project, because we want to resolve the starburst structures. Fig. 22 and 23 present the schematic view of the target and the (u,v) plane coverage needed to perform this observation. For an interferometer with 2m mirrors, the total time neeeded on-source is 34 hours, corresponding to ~4100 u-v points with 2 scans per pair of u-v points.

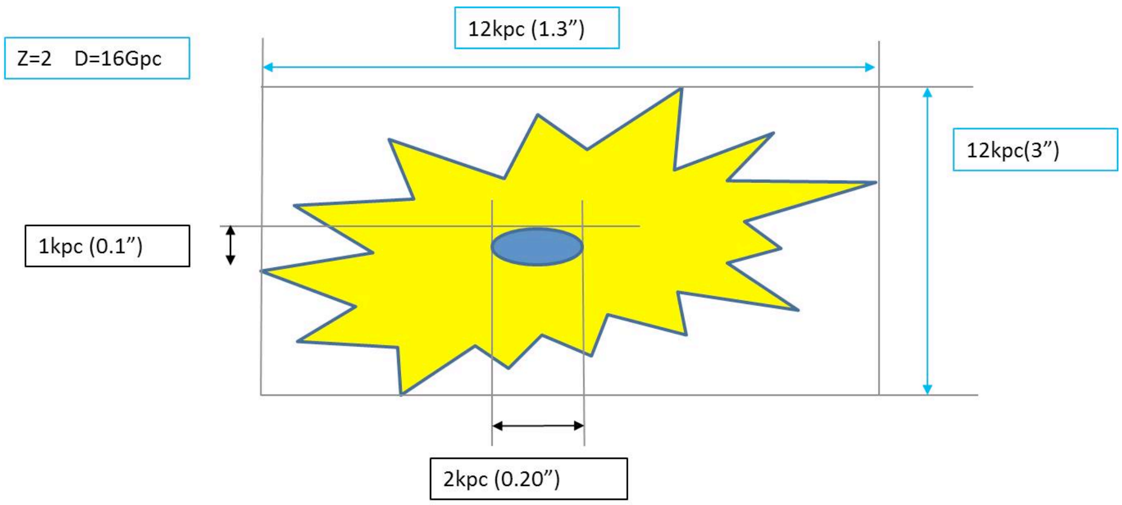

FIGURE 22: SCHEMATIC VIEW OF THE TARGET, COMPOSED OF A GALAXY DISK OF 6-12 KPC IN SIZE AND A STARBURT RING OF 1-2 KPC.

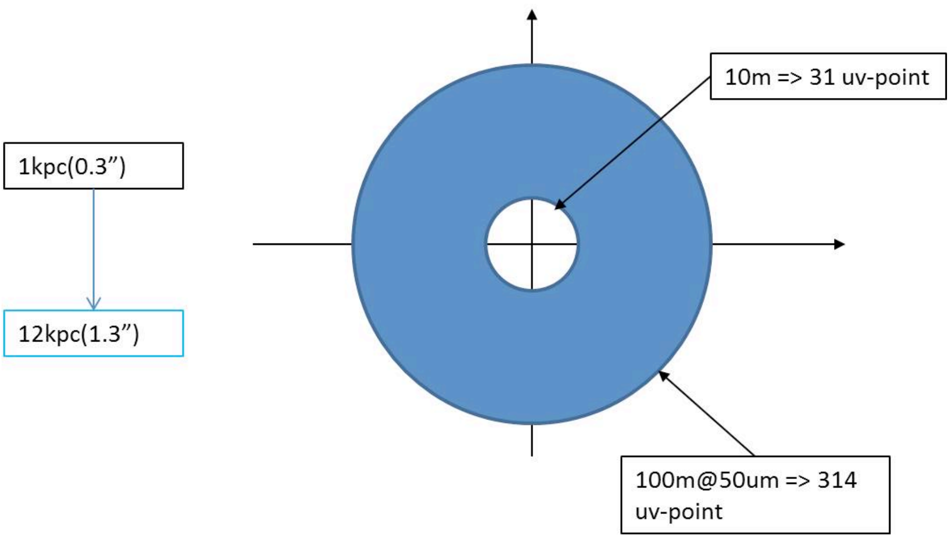

FIGURE 23: (U, V) PLANE COVERAGE FOR SCIENCE CASE 6.

3 Critical analysis

A critical analysis of the work done so far indicates that we have not been able to fully assess the observability of the targets of the considered science goals, because of the lack of any sensitivity model that could be used for this purpose. Moreover, an instrument simulator, fully compliant with the final characteristics and performances of the interferometer, which have been derived from the science requirements, has yet to be fully developed.

4 Conclusions and future steps

The conclusion of the results obtained indicates that, to be able to make a significant "break-through" progress in the astrophysics of most dust obscured processes, such as star formation in our Galaxy and in distant galaxies, obscured accretion processes in Active Galactic Nuclei, just to give two examples, a resolution of the order of 0.1 arcsec at ~40 µm and 0.25 arcsec at 100µm will be needed. These spatial resolutions can be reached with a maximum interferometric baseline of the order of 100 meters. Moreover, the most interesting wavelength range to study both ionic/atomic and molecular components which will never be accessible from the ground is the 25-200 µm spetral range.

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