ARRAKIHS

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Analysis of Resolved Remnants of Accreted galaxies as a Key Instrument for Halo Surveys

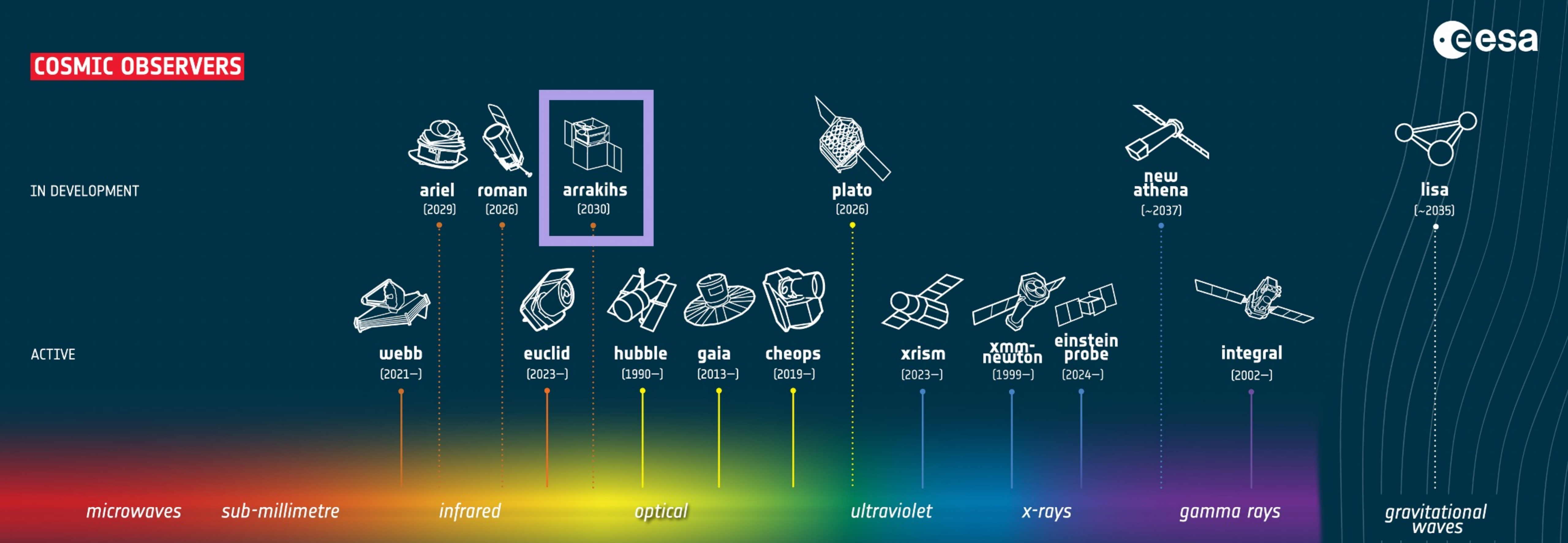
Sociedad Española de Astronomía

Granada, July 15-19, 2024

Rafael Guzmán, ARRAKIHS Mission Consortium Lead (IFCA & UF)

ARRAKIHS: ESA F2 Astrophysics Mission

- ESA Fast Class Mission
- Call of opportunity Dec 2021
  - 19 F-class proposals submitted
  - Successfully passed phase 1 with 4 other missions
  - ARRAKIHS proposal *(Guzmán, Serrano + AMC)* selected as the F2 Mission in Nov 2022



ARRAKIHS

COSMIC OBSERVERS

IN DEVELOPMENT

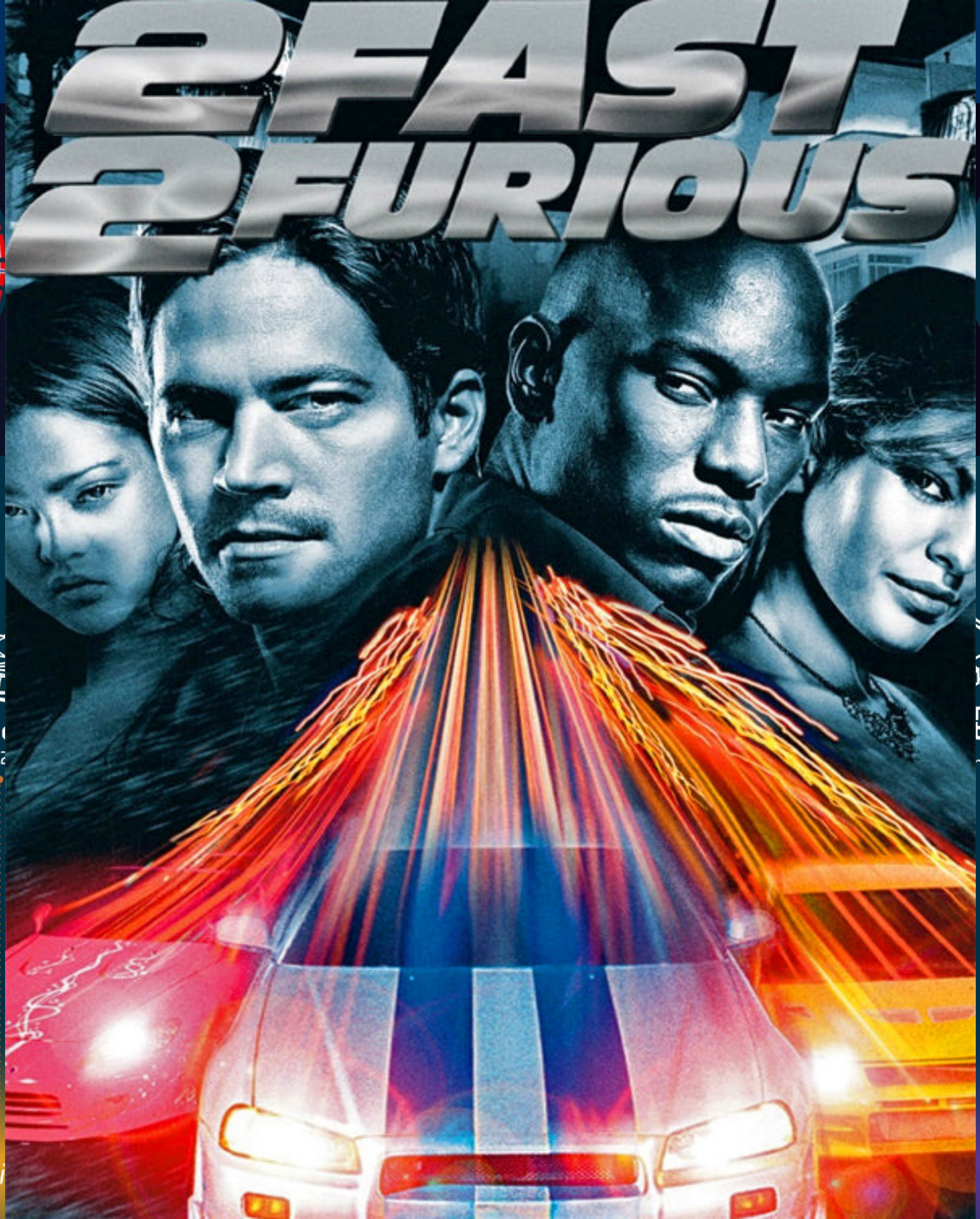
ari
(202

ACTIVE

webb
(2021–)

microwaves

sub-millimetre



new
thena
(~2037)

lisa
(~2035)

integral
(2002–)

gamma rays

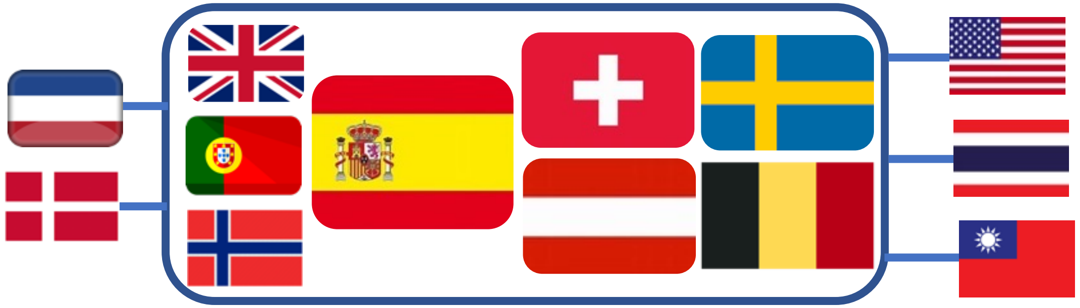
gravitational
waves


ARRAKIHS
esa
2 FAST
esa
arrakihs
COSMIC OBSERVERS
esa
IN DEVELOPMENT
lisa
[~2035]
ACTIVE
microwaves
sub-millimetre
gravitational waves

Consortium, Organization and Timeline

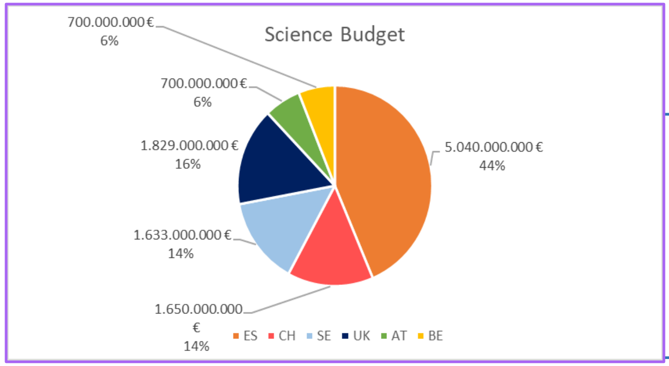
ARRAKIHS

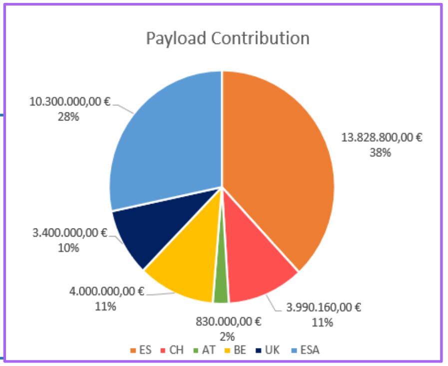
ESA/F2-Mission (CoC 175M EUR)



CONSORTIUM (PAYLOAD + GROUND SEGMENT + SCIENCE)

	A/B	C/D/E	TOTAL	
Research Centers	3.691.000 €	13.801.000 €	17.492.000 €	
Industry	3.474.860 €	17.104.100 €	20.578.960 €	
			38.070.960 €	TOTAL





Over 120 scientists and engineers from over 20 research institutions and industrial partners worldwide.

Consortium, Organization and Timeline

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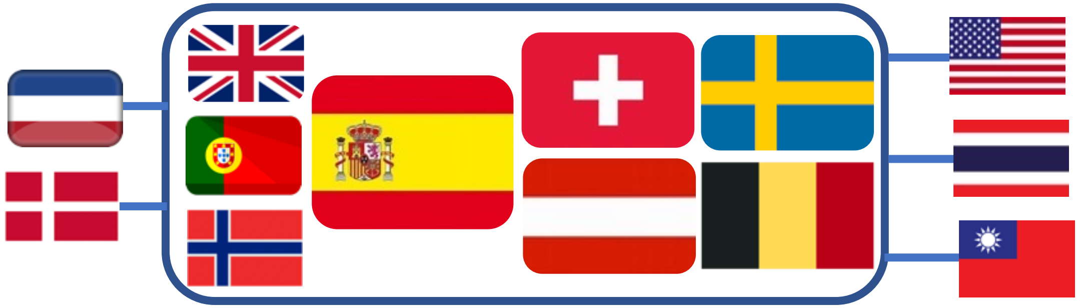

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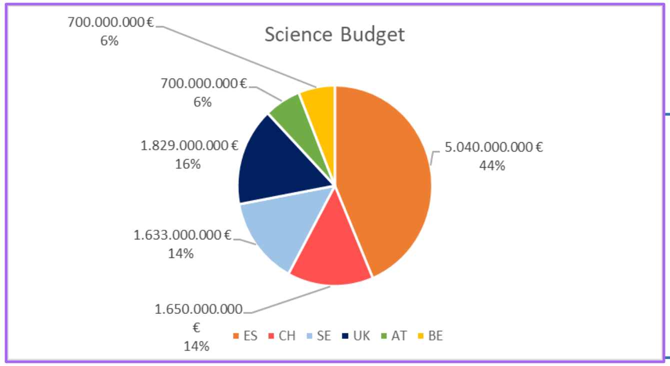

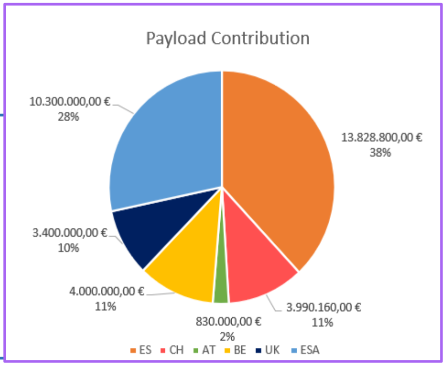

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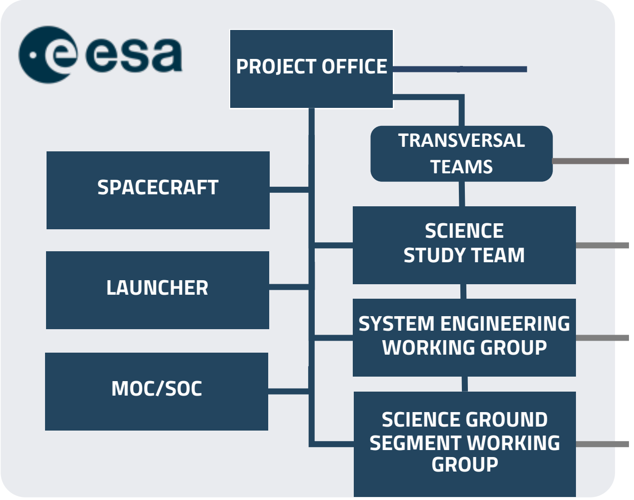
European Space Agency (ESA)

ARRAKIHS Mission Org.



Consortium, Organization and Timeline

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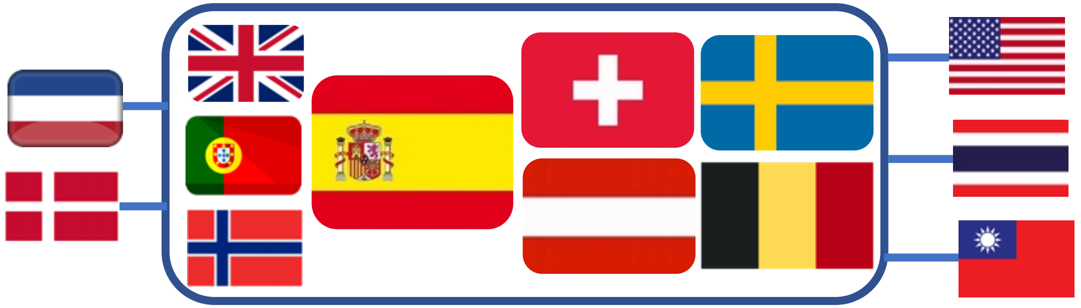

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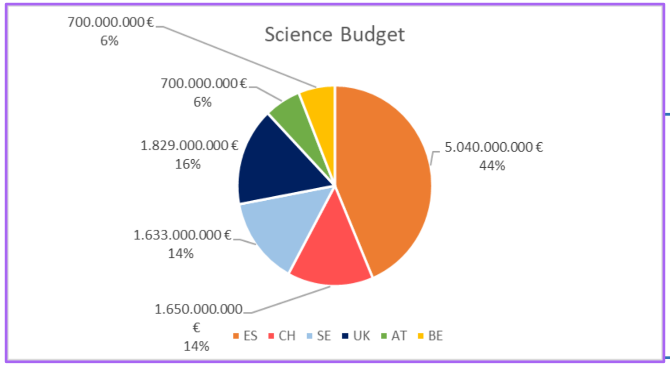

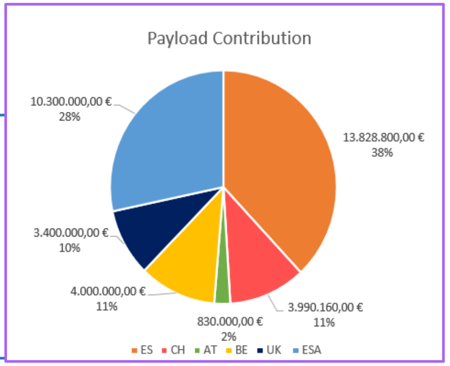

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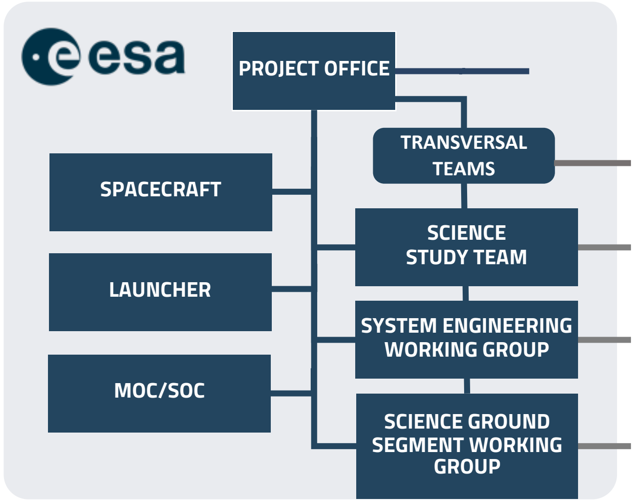

IFCA CSIC Consejo Superior de Investigaciones Científicas

CEFCA Centro de Estudios de Física del Cosmos de Aragón

IEEC Institut d'Estudis Espacials de Catalunya

Universidad Complutense Madrid

Universidad de Valladolid

Instituto de Astrofísica de Canarias

IAA Instituto de Astrofísica de Andalucía

Consortium, Organization and Timeline

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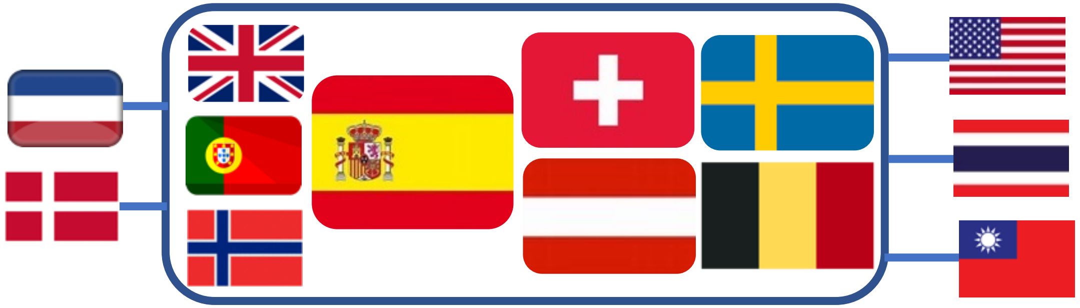

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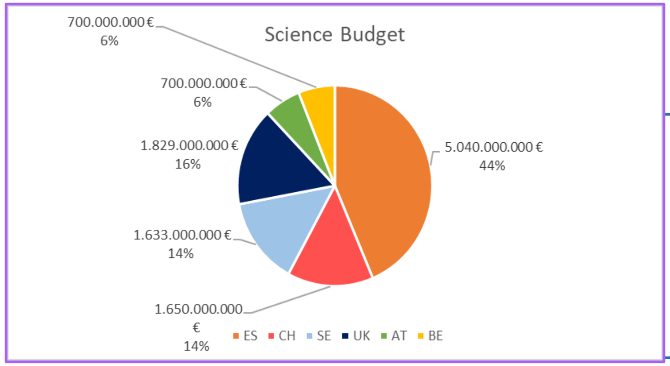

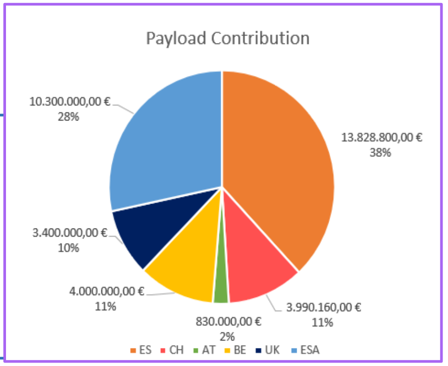

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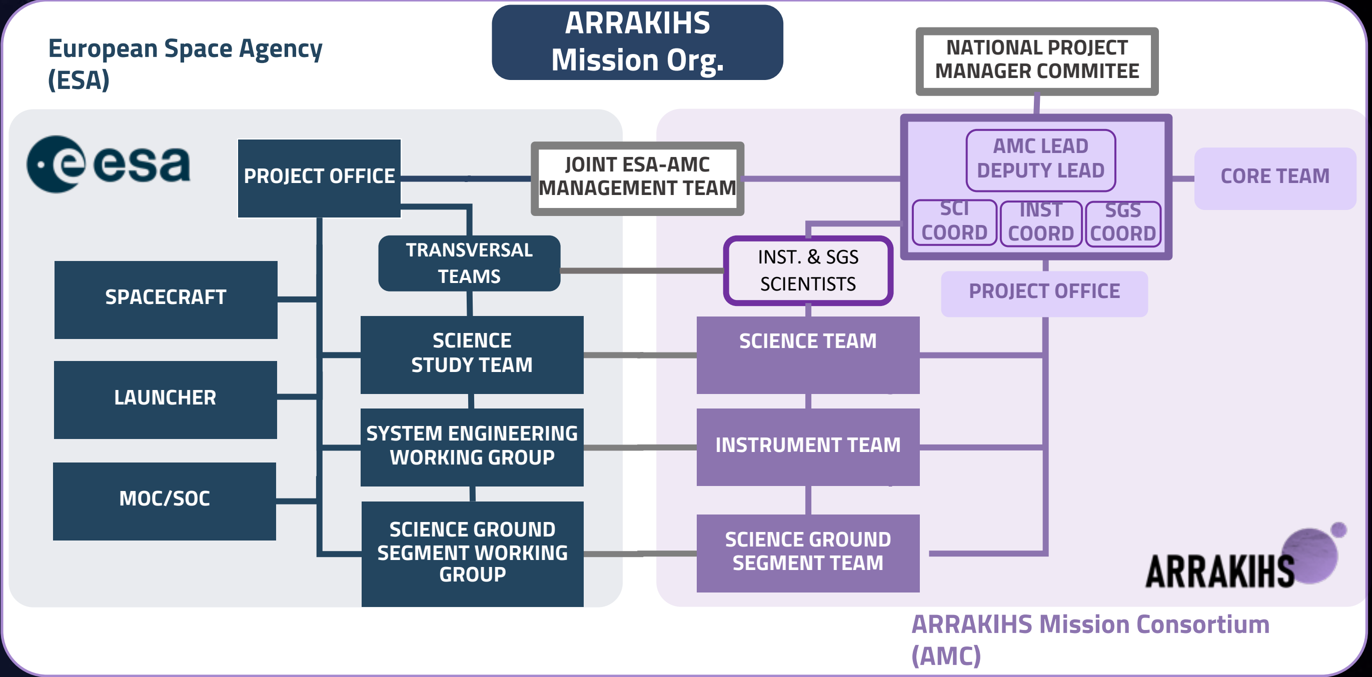

Consortium, Organization and Timeline

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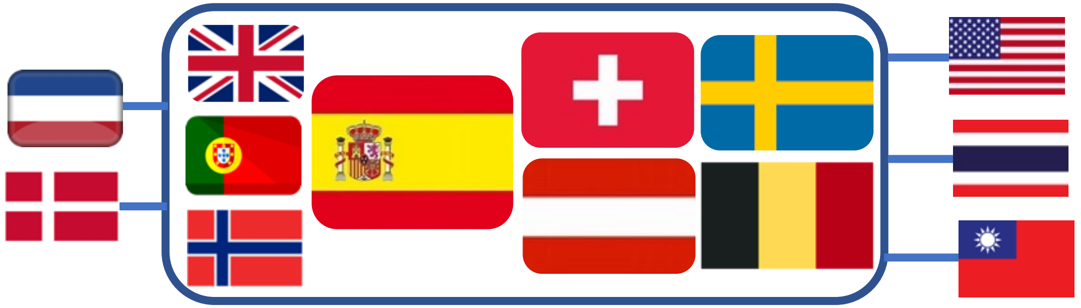

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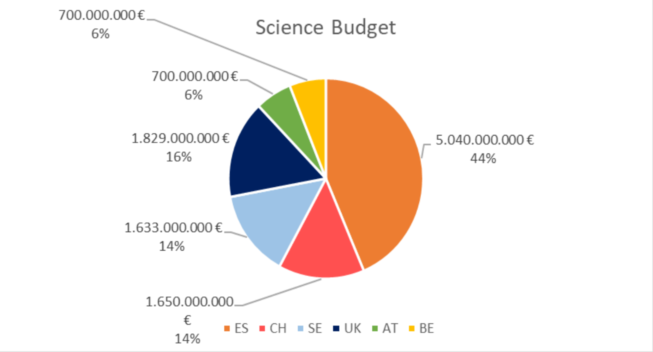

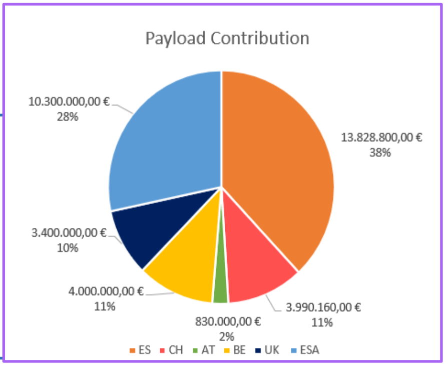

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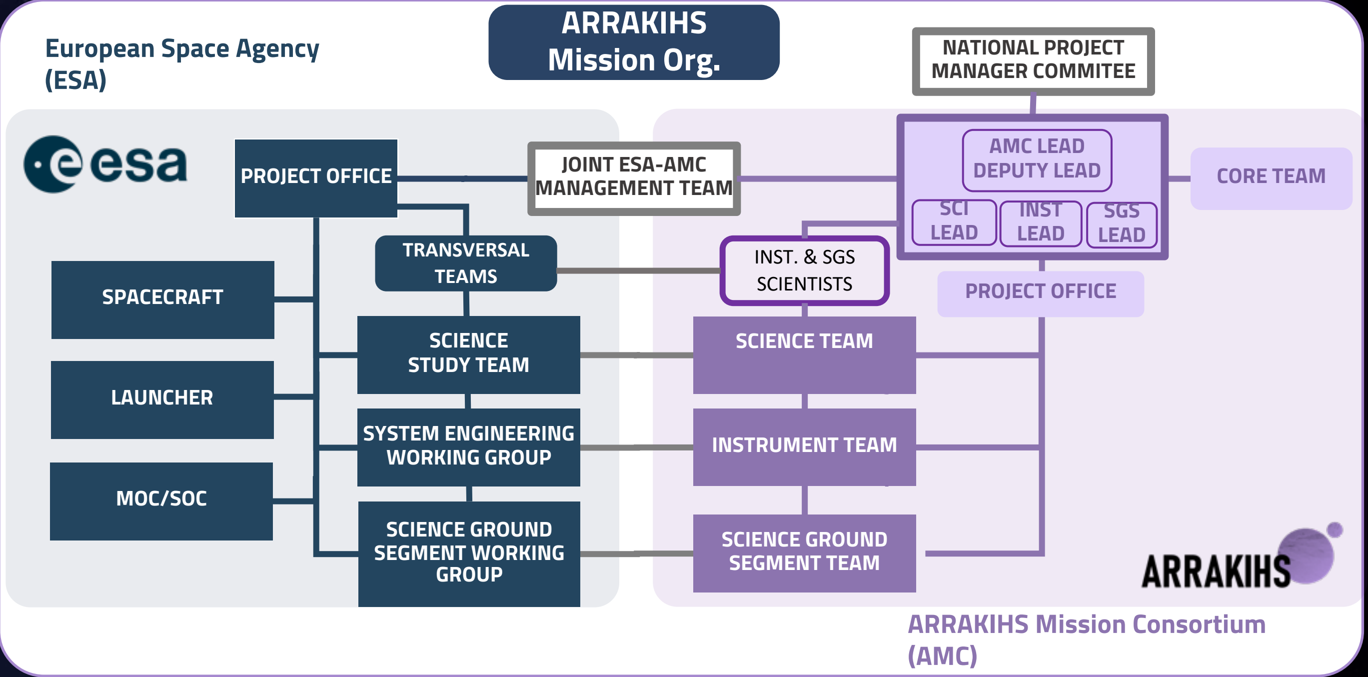
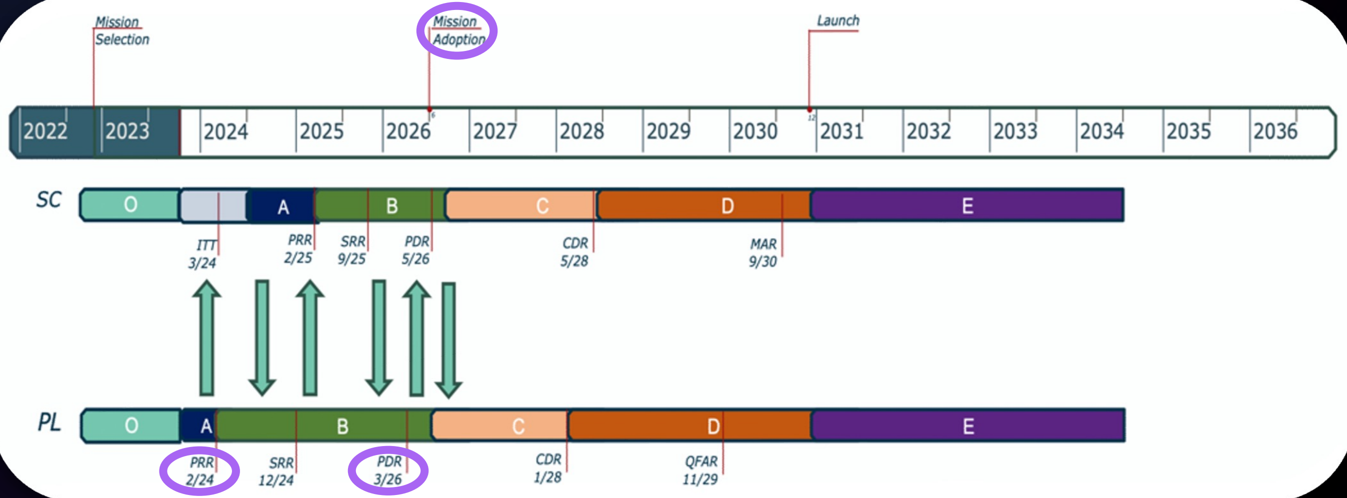
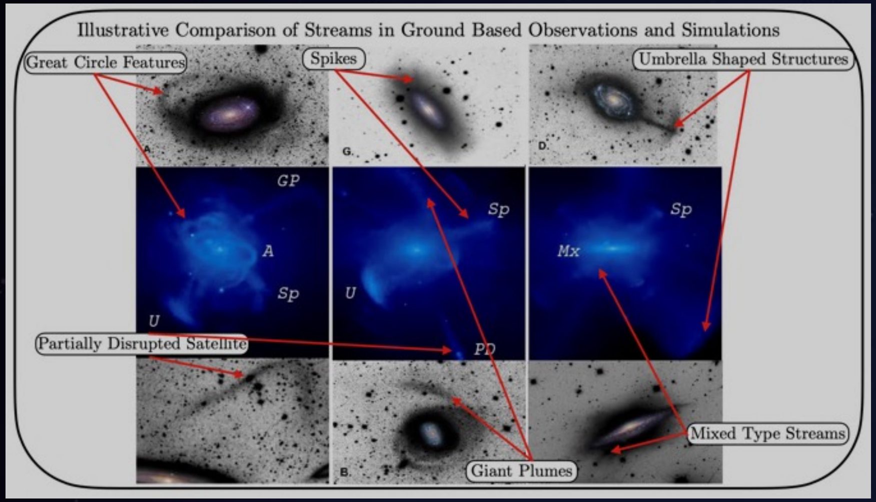




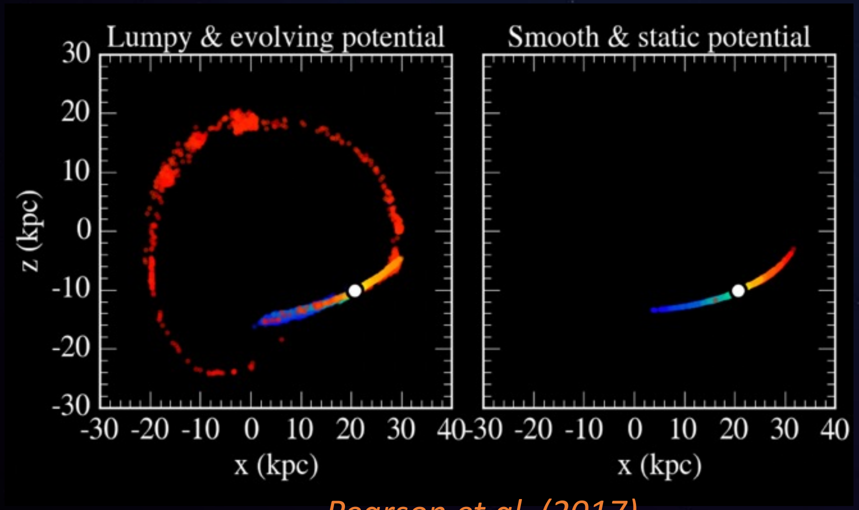
Science Goal: Resolve the Tensions with CDM at Galaxy Halo Scales

ARRAKIHS

1) Stellar Streams: Statistics and Shapes

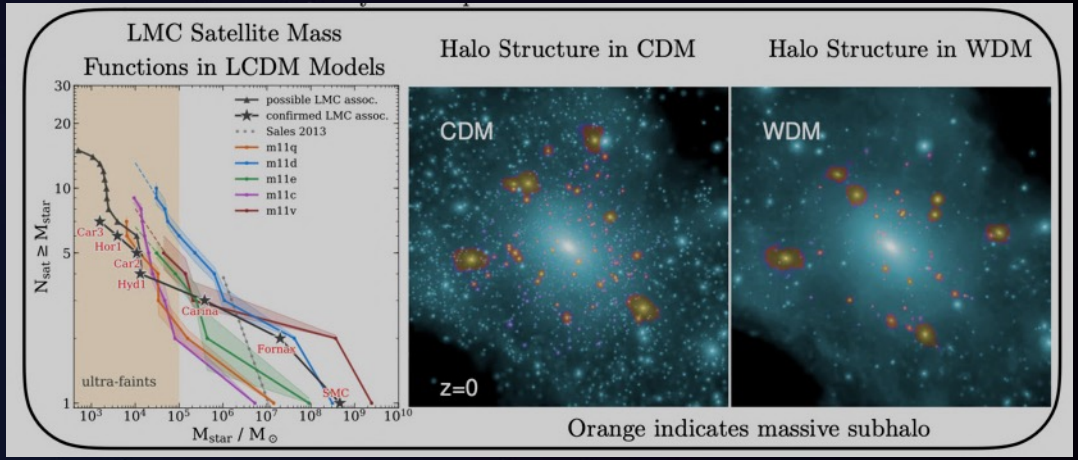


Martínez-Delgado et al. (2010, 2012, 2015, 2021)

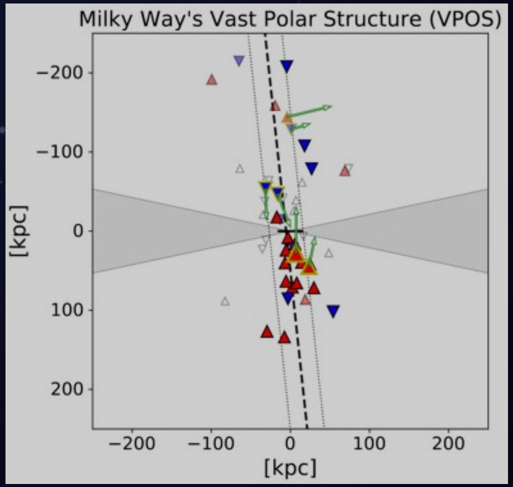


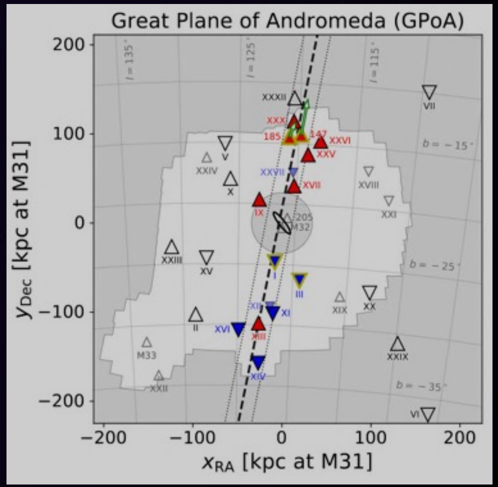
Pearson et al. (2017)

2) "Missing Satellites" and "Satellite Planes" problems:



Jahn et al. (2019)





Pawlowski (2021)

VIS+NIR Observations of MW-type Galaxy Halos at Ultra-Low SB

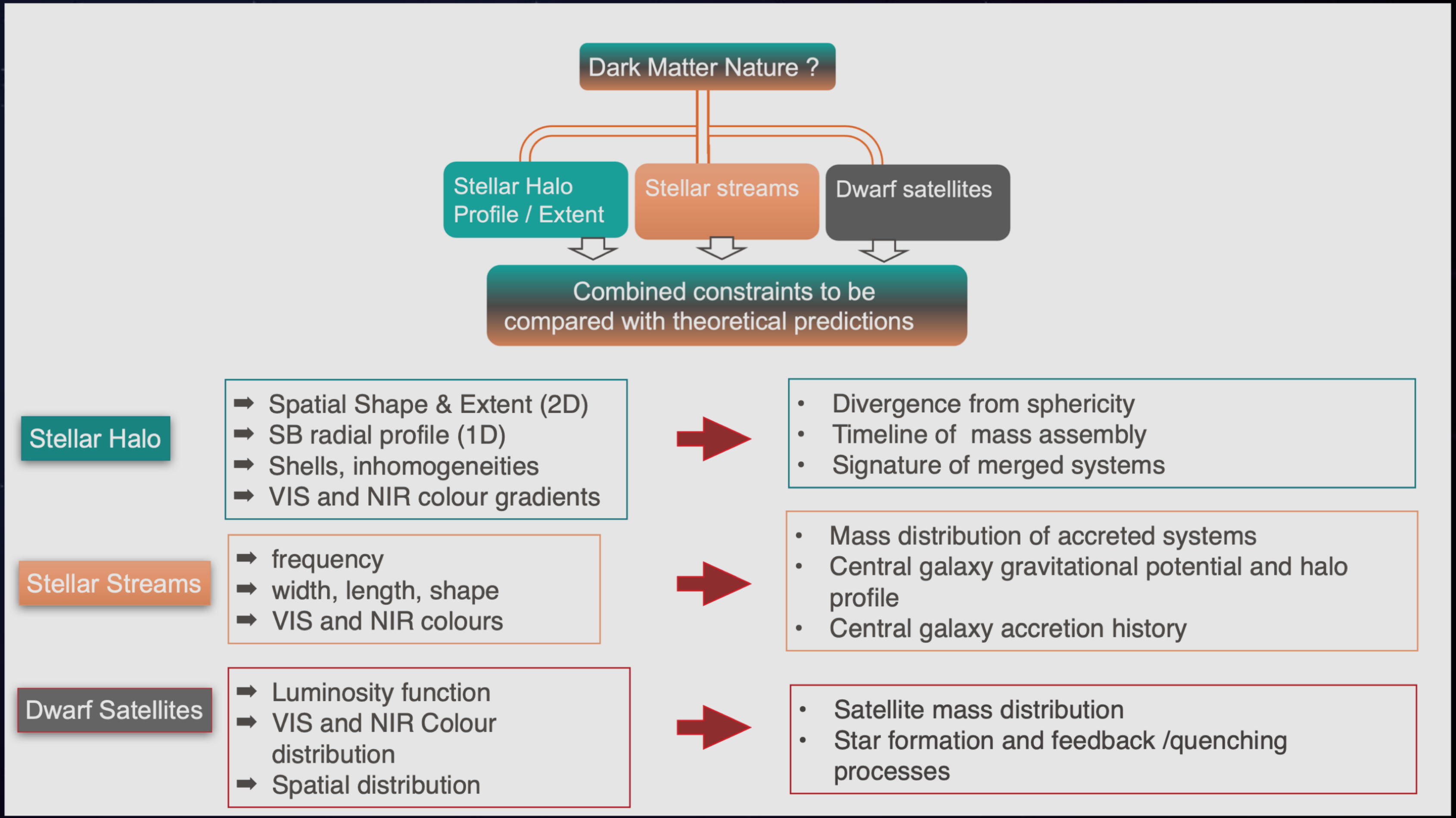
ARRAKIHS

Mission Statement: "ARRAKIHS will assess the significance of reported tensions between predictions of the Cold Dark Matter (CDM) cosmological model at galaxy halo scales, the current implementation of baryon physics (BP) in galaxy formation models and the observed properties of the haloes of the Milky Way (MW) and Andromeda galaxies. To test the predictions of the CDM+BP models, ARRAKIHS will obtain deep, simultaneous, visible and infrared imaging of a statistically representative sample of nearby haloes of MW-type galaxies in the local universe, down to unprecedented low surface brightness."

ARRAKIHS if the first mission specifically designed to explore the Ultra-Low SB features of the halos of MW-type galaxies through the optimization of:

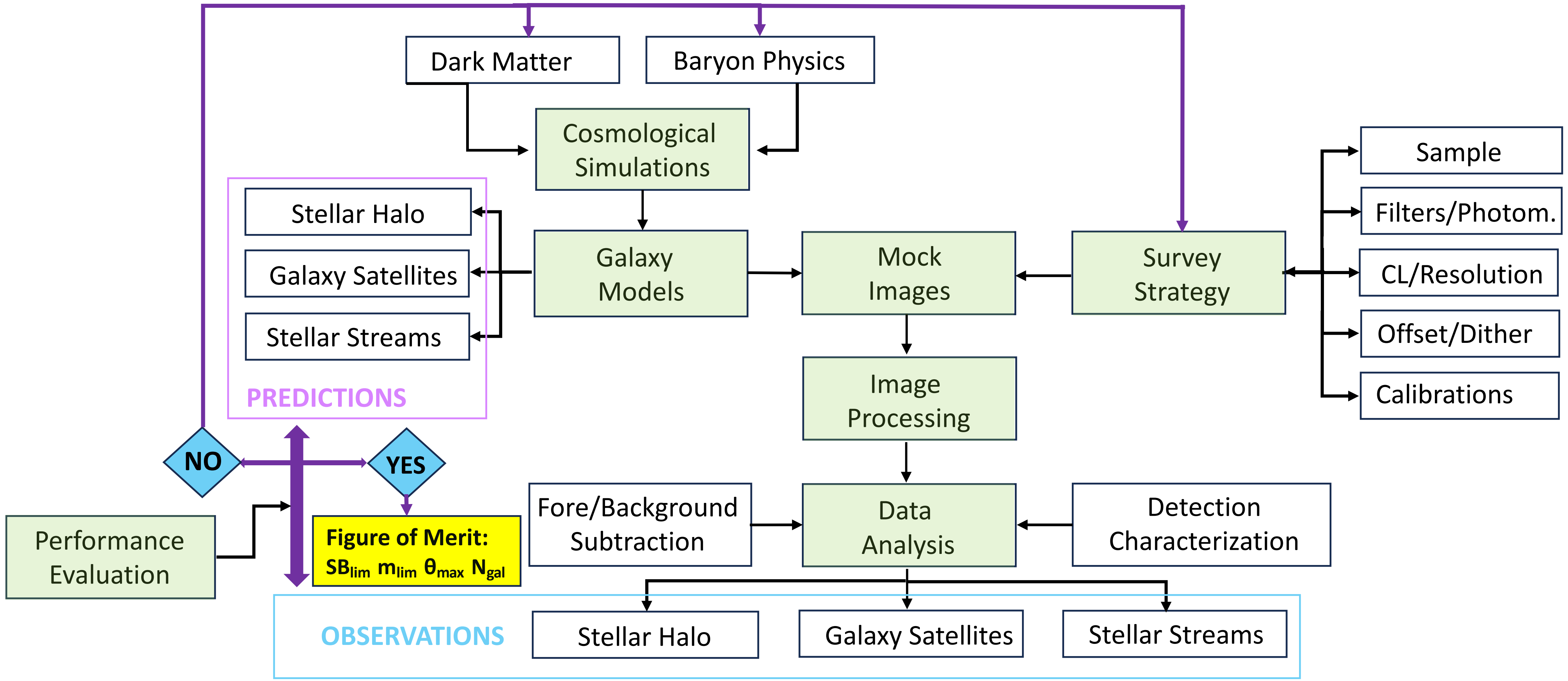
(1) Instrument
(2) Observational Strategy
(3) Image Processing Algorithms.

In addition, ARRAKIHS will run **extensive cosmological simulations** to provide state-of the art predictions on the Ultra-Low SB features of the halos of MW-type galaxies for different combinations of DM+BP.



SciRD: Guzmán, Jablonka, Isaac + AMC (2023)

Science Project Flow Chart

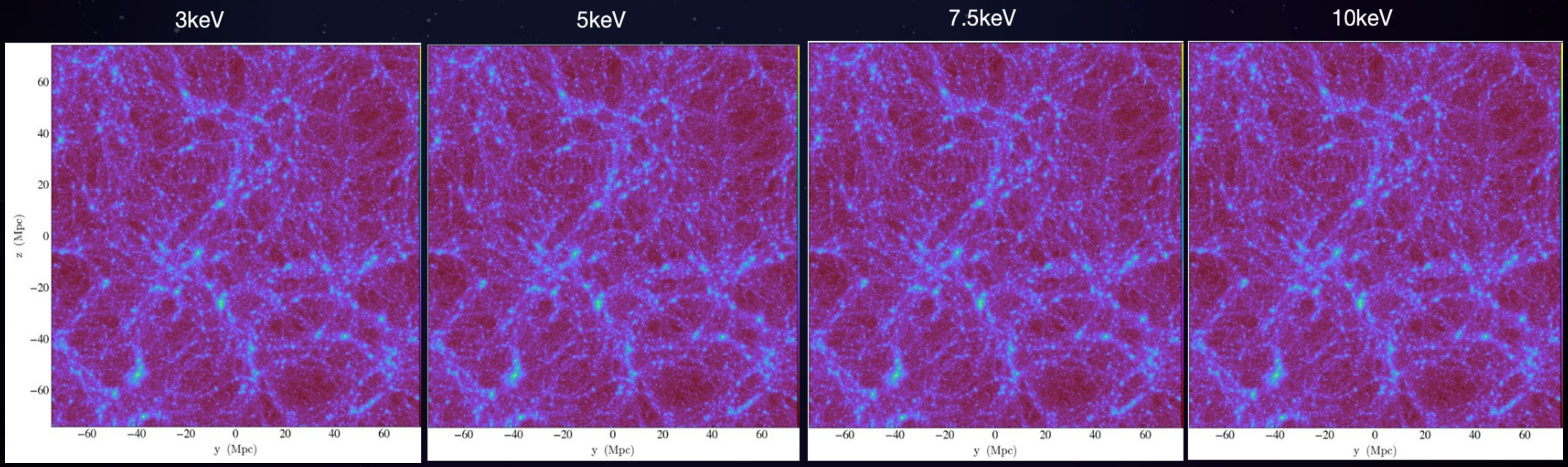


The ARRAKIHS Cosmological Simulations (Harkonens Models)

ARRAKIHS

Cosmological models HARKONENS (Horizon-ARraKihs ONset of Enlightening New Simulations):

1. 30 cosmological zoom-in simulations (~30 pc) to resolve the formation of small satellites and the thickest streams, in six different dark matter flavours (3, 5, 7.5, 10, 30, self-interacting) - Dark matter only first, with baryons later with the same cosmology (Planck+2018) using "Swift", the fastest and more flexible code available. We will rely on the cosmological box already simulated at intermediate resolution by the HorizonAGN group, and that has been extensively tested against observations.

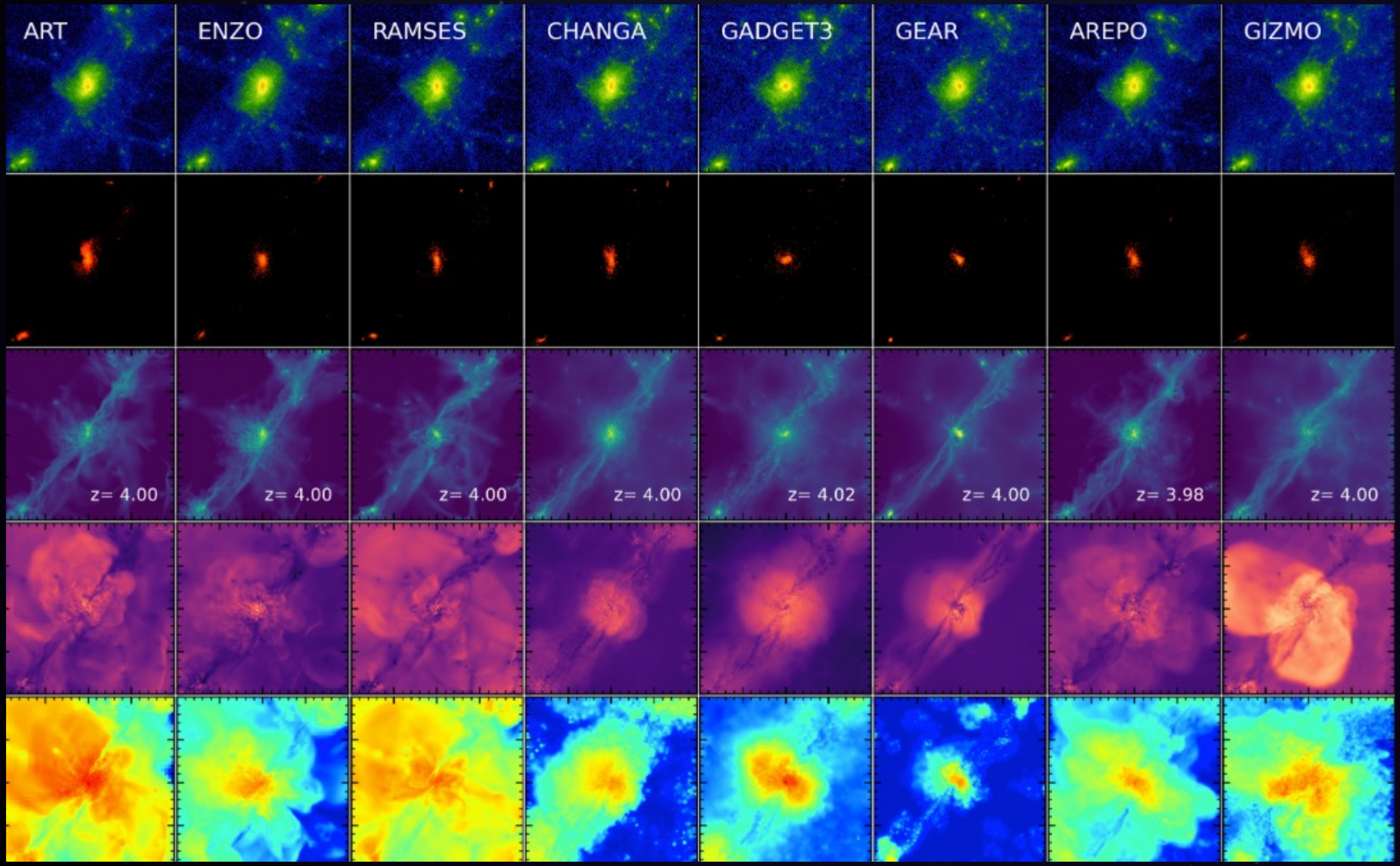


Dubois et al. 2016
Roca-Fábrega + AMC 2024

The ARRAKIHS Cosmological Simulations (Harkonens Models)

ARRAKIHS

2 Two additional zoom-in simulations with the AGORA initial conditions will be ran. The AGORA halo has been ran already using all the most widely used numerical codes in the community. Thus a direct comparison will allow us to find out which parameters are code-dependent.



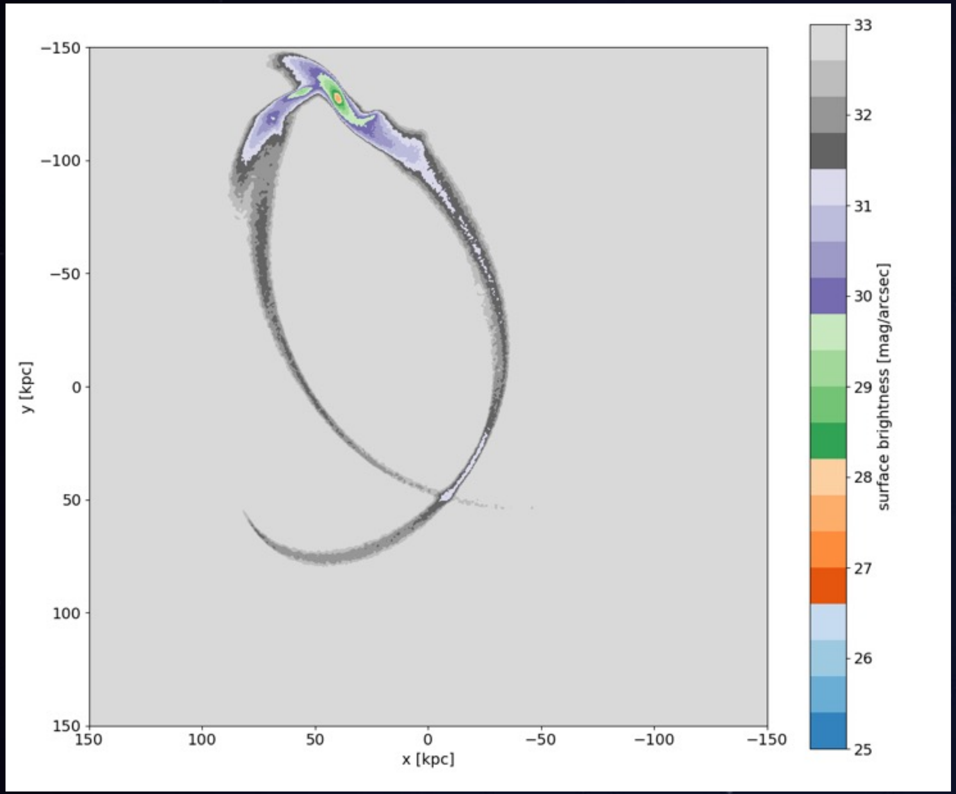
Roca-Fàbrega et al. 2024, 2021; Jung et al. 2024; Strawn et al 2023; Kim et al. 2014, 2016

The AGORA CDM halo will be ran with small variations in the baryonic physics recipes to see the effect each has on the distribution and properties of satellites and streams, including:

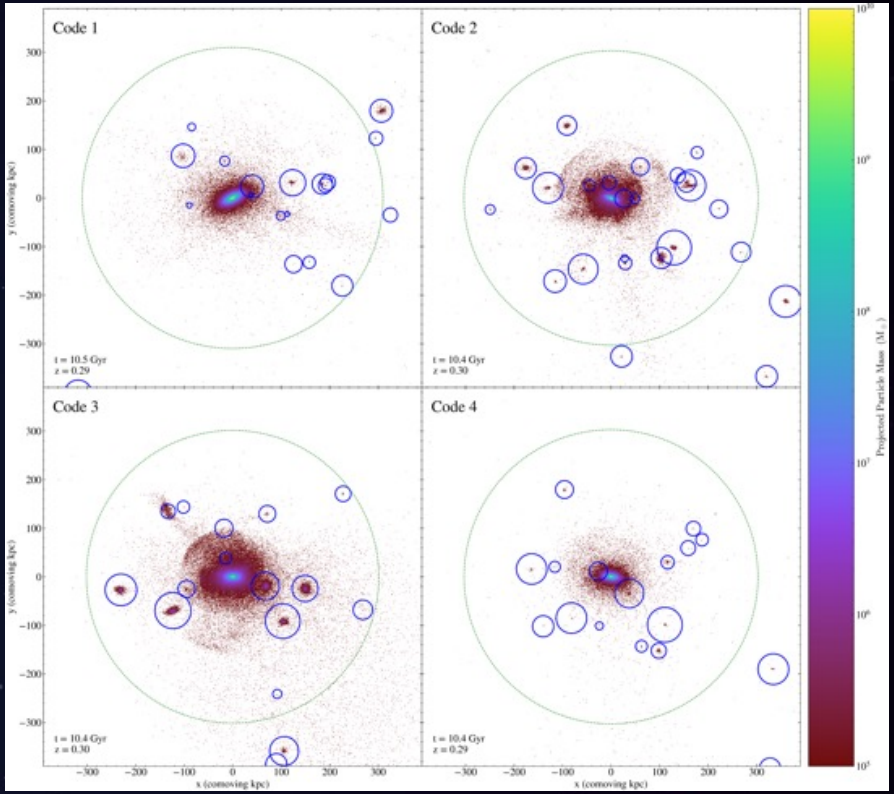
- Stellar Feedback
- UV-background reionization
- Star Formation
- Cooling/Heating
- AGN feedback
- Magnetic fields

These models will also allow to determine the degeneracy between dark matter flavor and baryonic physics and their effect on the properties of the three halo observables in ARRAKIHS.

The ARRAKIHS Cosmological Simulations (Harkonens Models)



Revaz, Erkal + AMC (2024)



Rodríguez-Cardoso + AMC (2024)

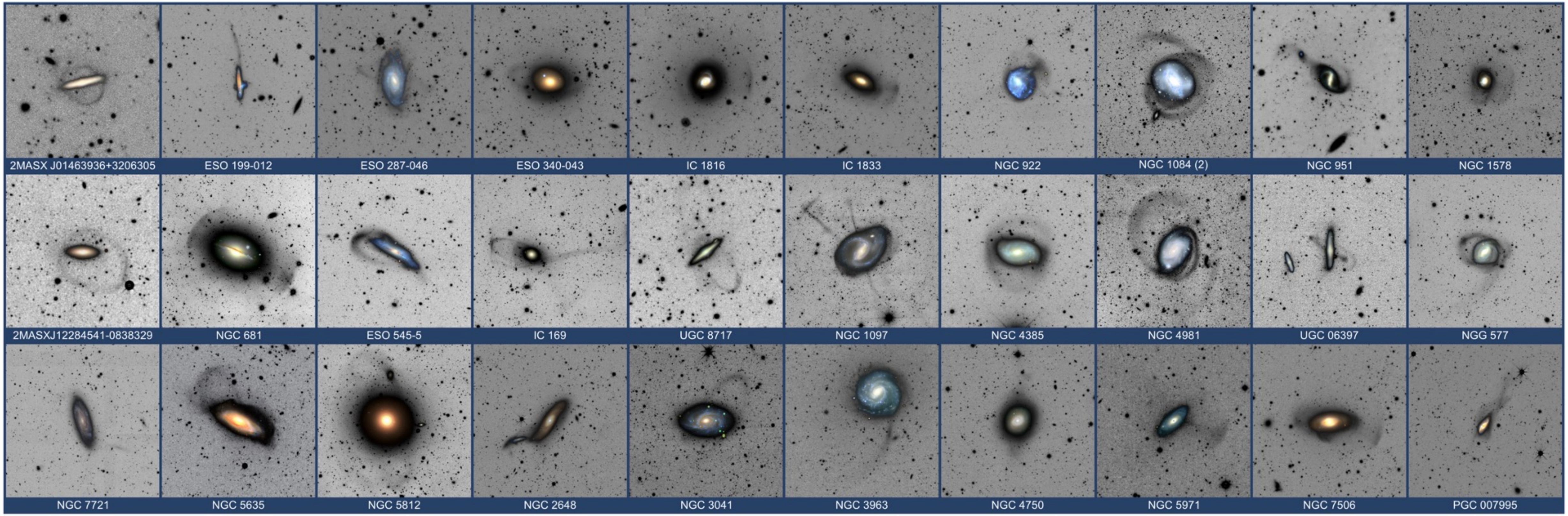
3

- The potential of the halos simulated in the zoom-in cosmological simulations with different dark matter flavors and baryonic physics will be extracted.
- Higher resolution halo models than in the cosmological models (~real stellar mass) will be run to resolve the thinnest stellar streams and the smallest satellites.
- The orbits of the satellites will be derived from the cosmological simulations
- Finally, we will inject the dwarfs to the frozen potential of the realistic halos, with a large number of particles and high spatial and temporal resolution.
- The properties of the three halo observables will be characterized from cosmological simulations and under different dark matter flavors and baryonic physics.

OVER 200M of CPU HOURS IN HPC (led by Sweden and Switzerland)

Ground Observations: SB_{lim} = 28.5 mag arcsec^{-2} in r-band

ARRAKIHS



STELLAR STREAM LEGACY SURVEY

Martínez-Delgado et al. (2023); Miró-Carretero et al. (2024)

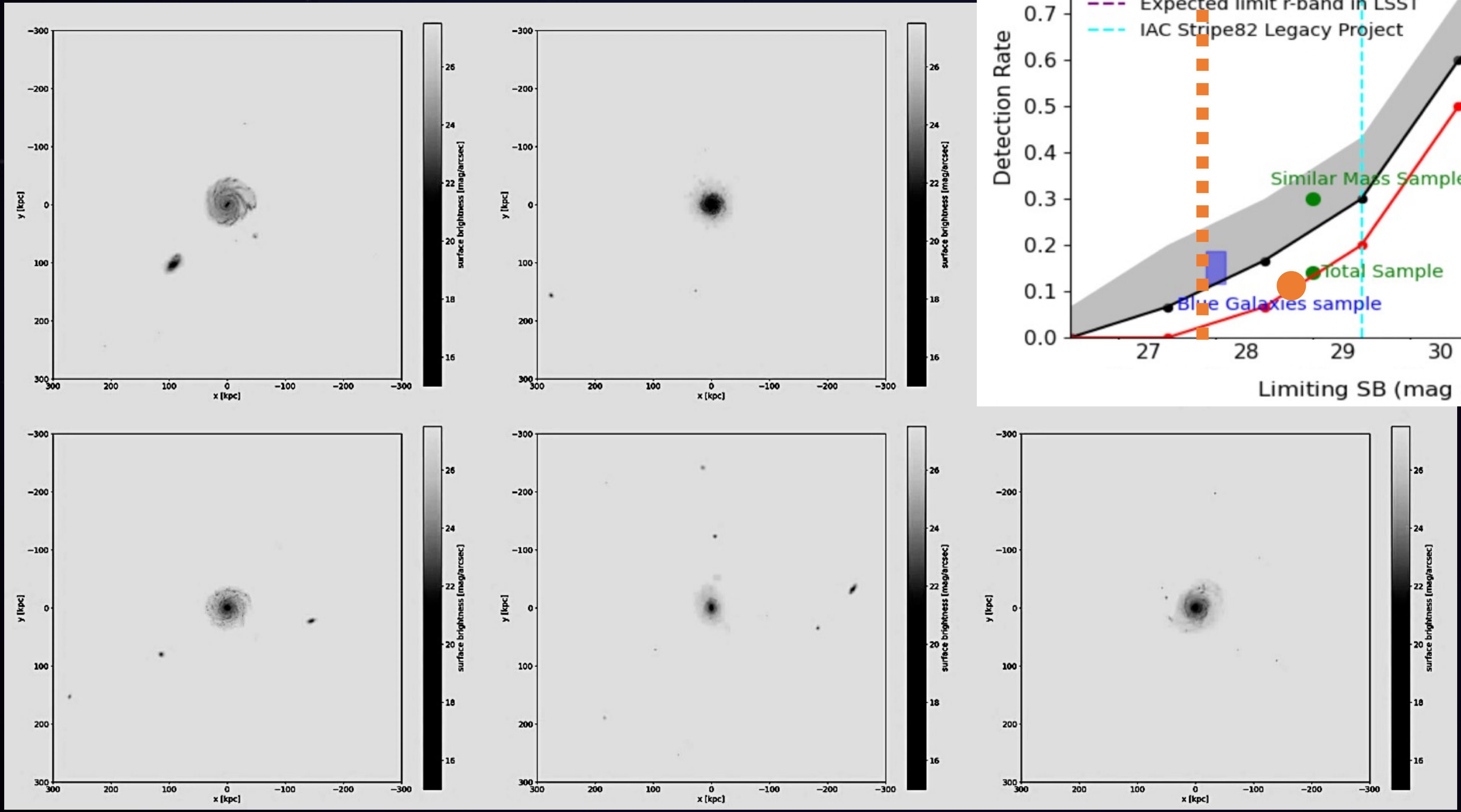
DARK ENERGY SPECTROSCOPIC INSTRUMENT

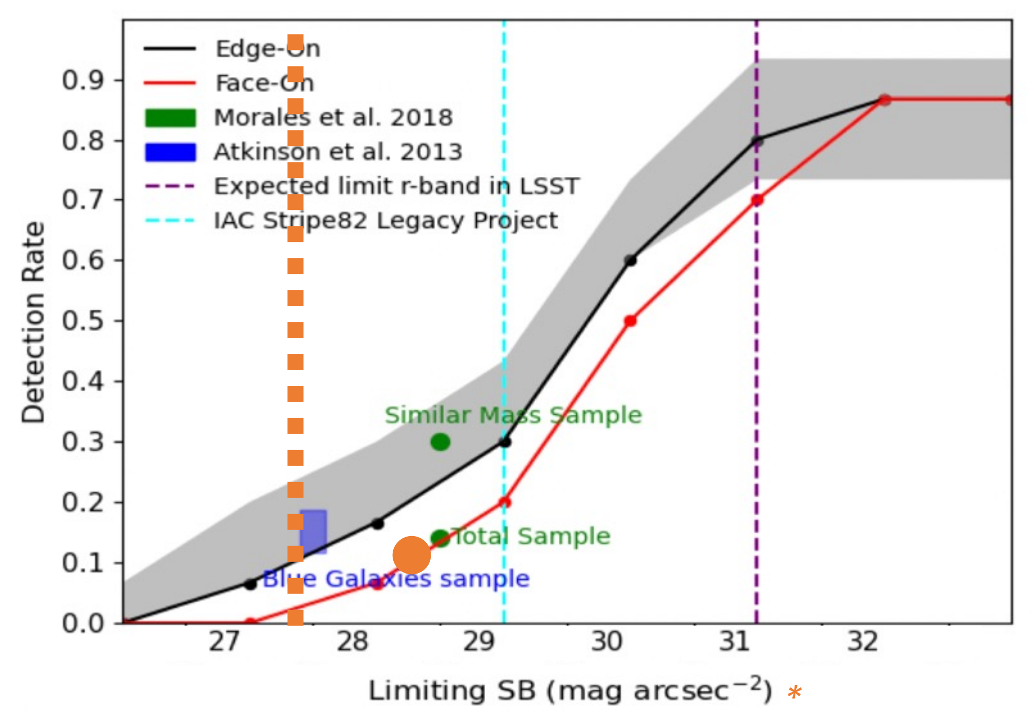
ARRAKIHS SB_{lim} = 31.5 (VIS), 30.5 (NIR) mag arcsec^{-2}

ARRAKIHS

Miró-Carretero et al. (2024)
Vera-Casanova et al. (2022)

AMC (2024): SB_{lim} = 27.5 mag arcsec^{-2}





** SB_{lim} scaled to 100 arcsec^2*

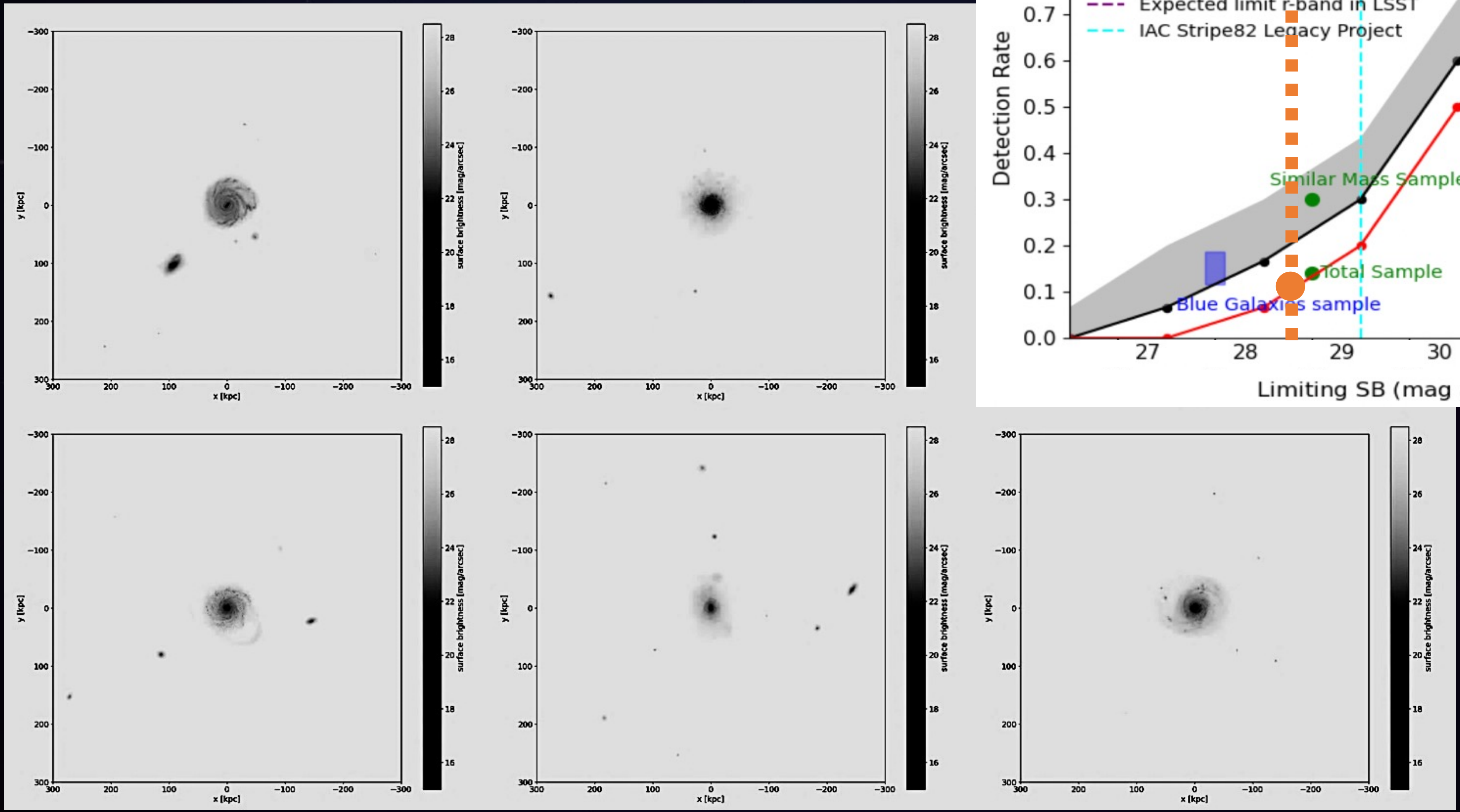
Revaz, Roca-Fábrega + AMC (2024)

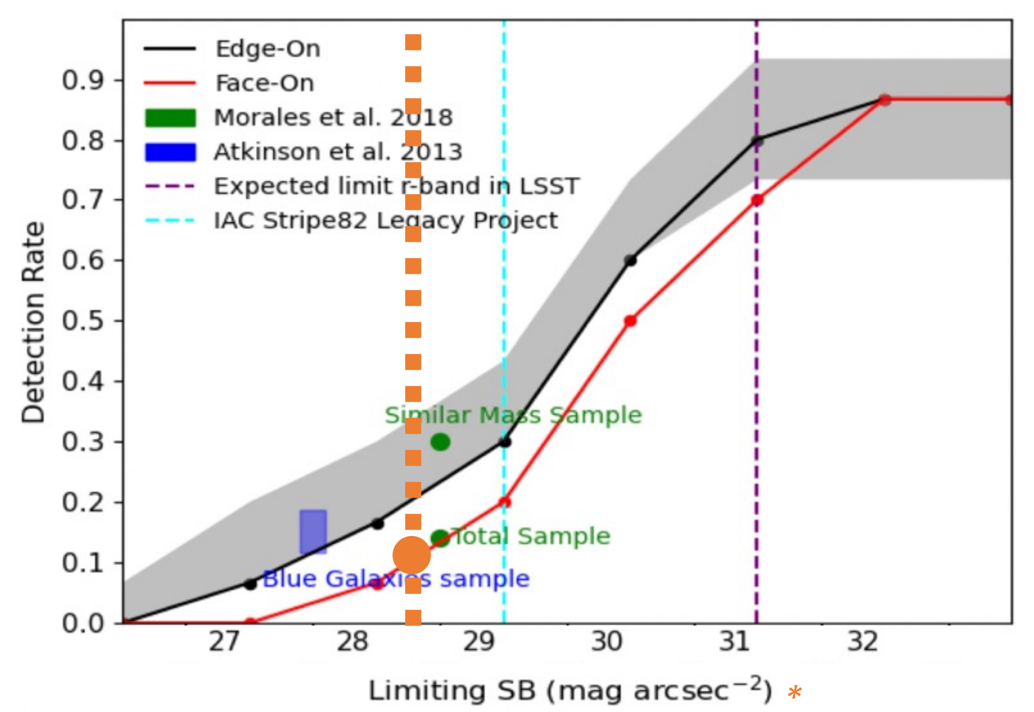
ARRAKIHS SB_{lim} = 31.5 (VIS), 30.5 (NIR) mag arcsec^{-2}

ARRAKIHS

Miró-Carretero et al. (2024)
Vera-Casanova et al. (2022)

AMC (2024): SB_{lim} = 28.5 mag arcsec^{-2}





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Revaz, Roca-Fábrega + AMC (2024)

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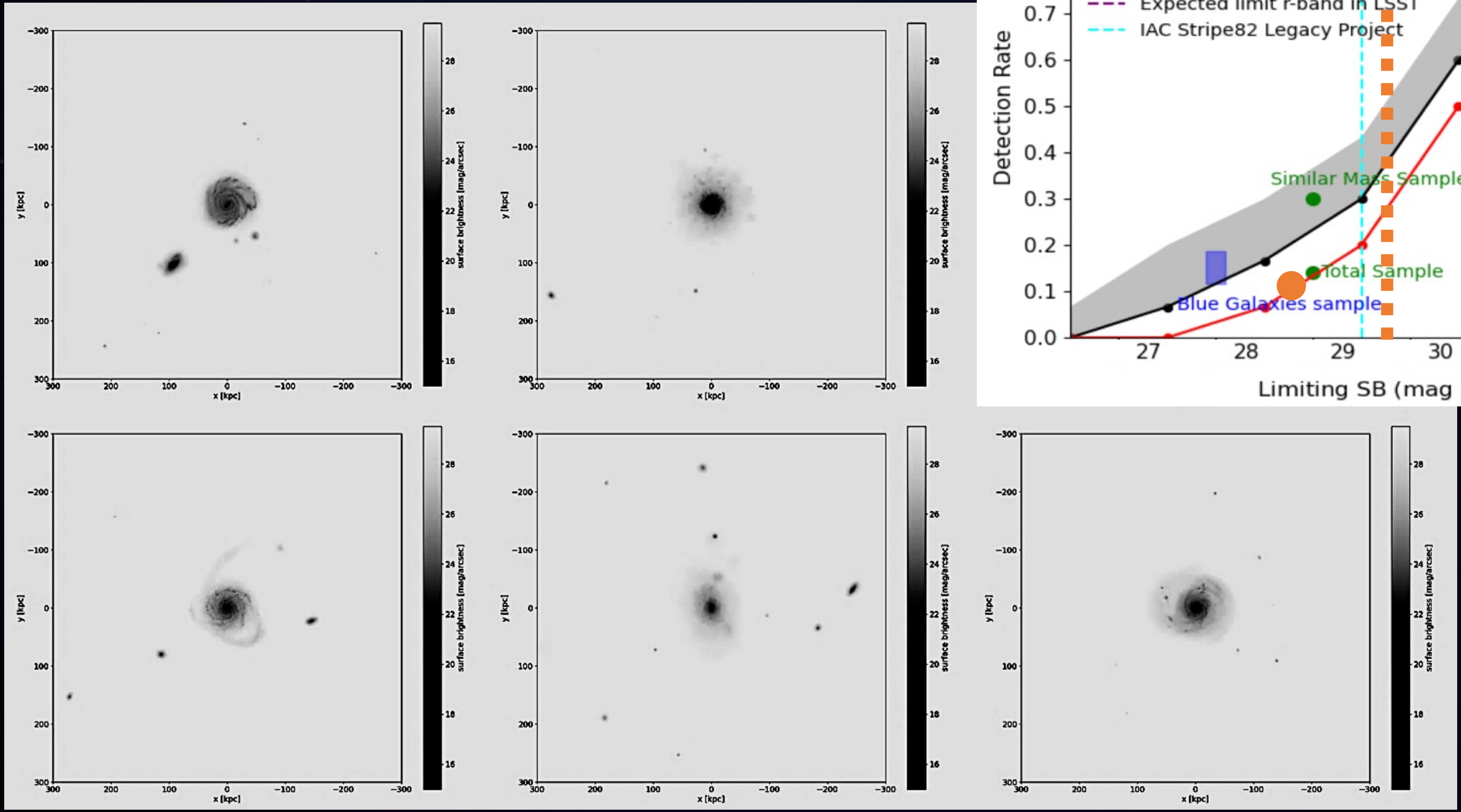
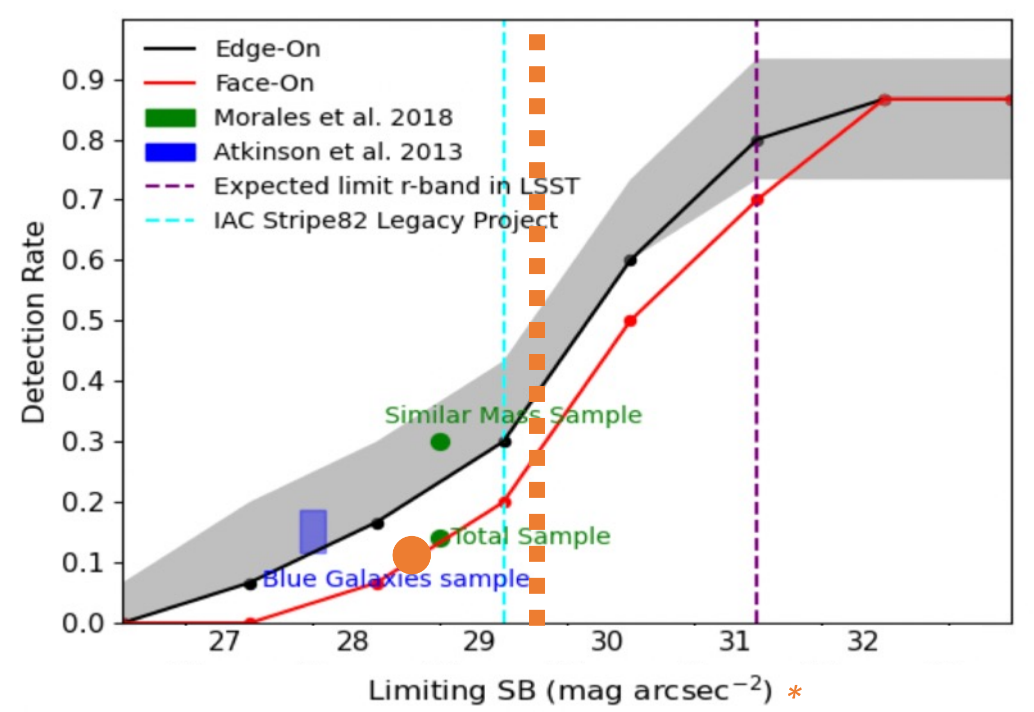
ARRAKIHS

Miró-Carretero et al. (2024)
Vera-Casanova et al. (2022)

AMC (2024): SB_{lim} = 29.5 mag arcsec^{-2}





** SB_{lim} scaled to 100 arcsec^2*

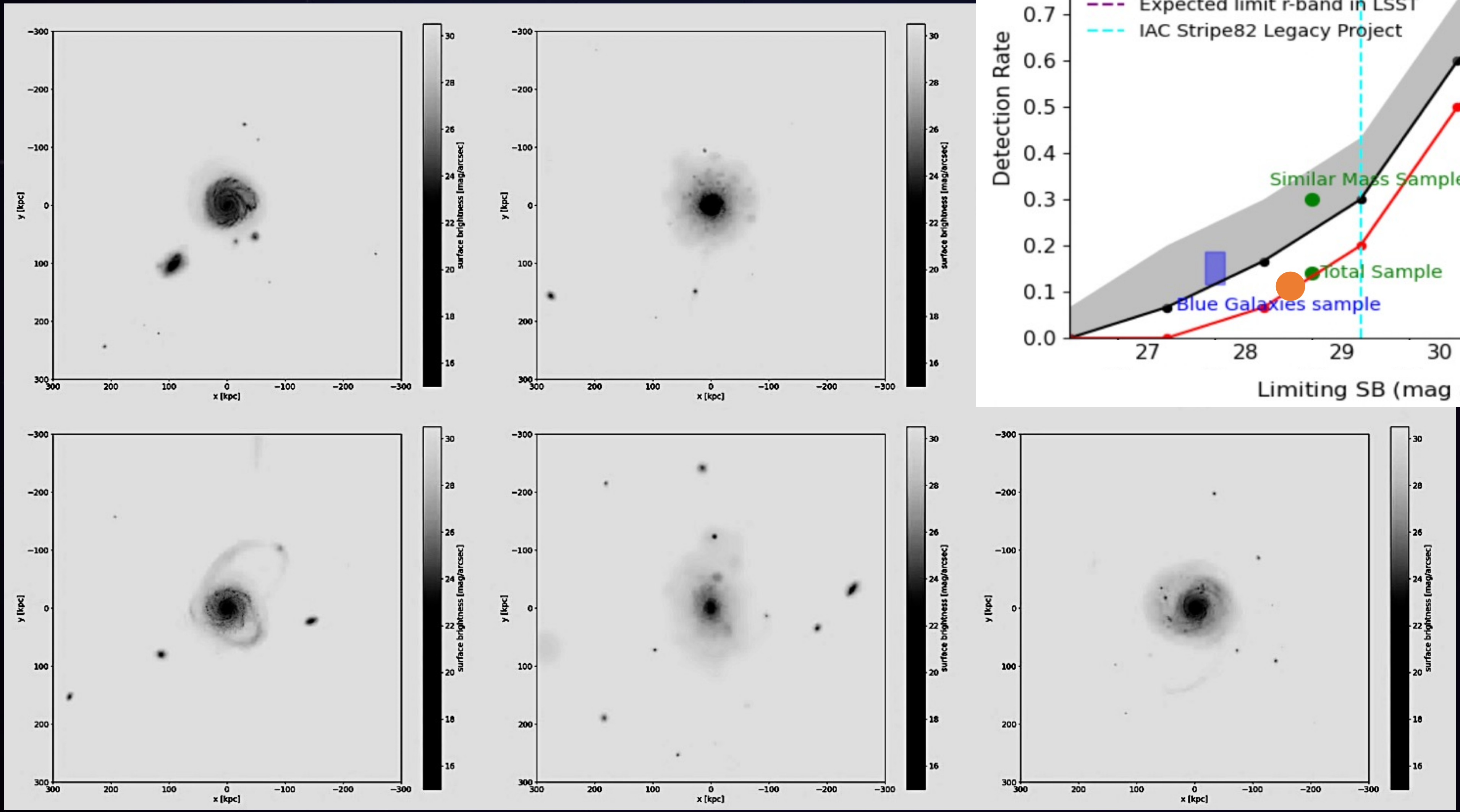
Revaz, Roca-Fábrega + AMC (2024)

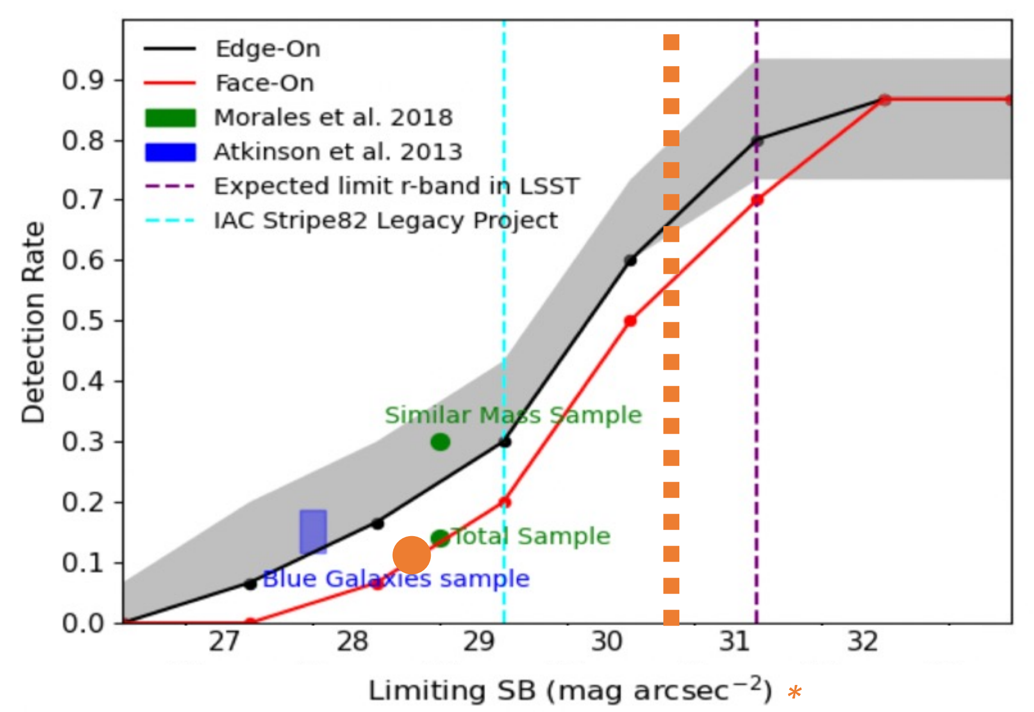
ARRAKIHS SB_{lim} = 31.5 (VIS), 30.5 (NIR) mag arcsec^{-2}

Miró-Carretero et al. (2024)

Vera-Casanova et al. (2022)

AMC (2024): SB_{lim} = 30.5 mag arcsec^{-2}





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Revaz, Roca-Fábrega + AMC (2024)

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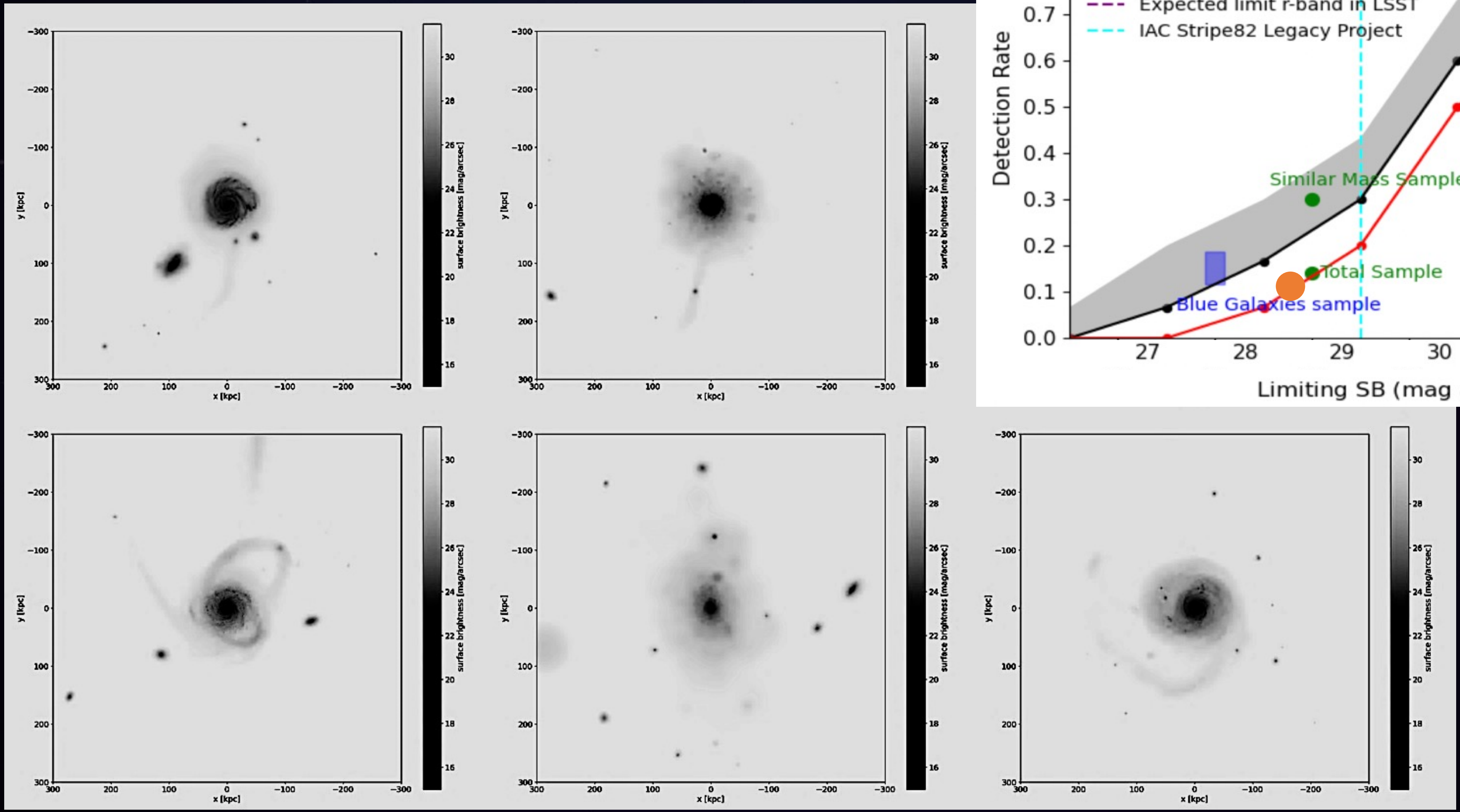
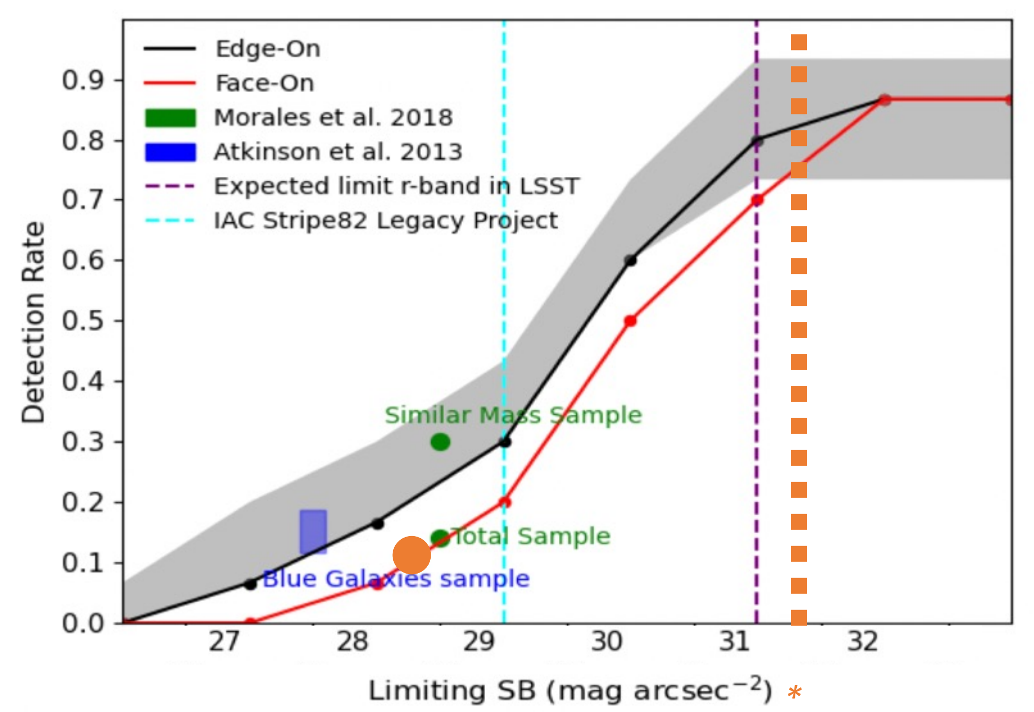
AMC (2024): SB_{lim} = 31.5 mag arcsec^{-2}

Miró-Carretero et al. (2024)
Vera-Casanova et al. (2022)





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Revaz, Roca-Fábrega + AMC (2024)

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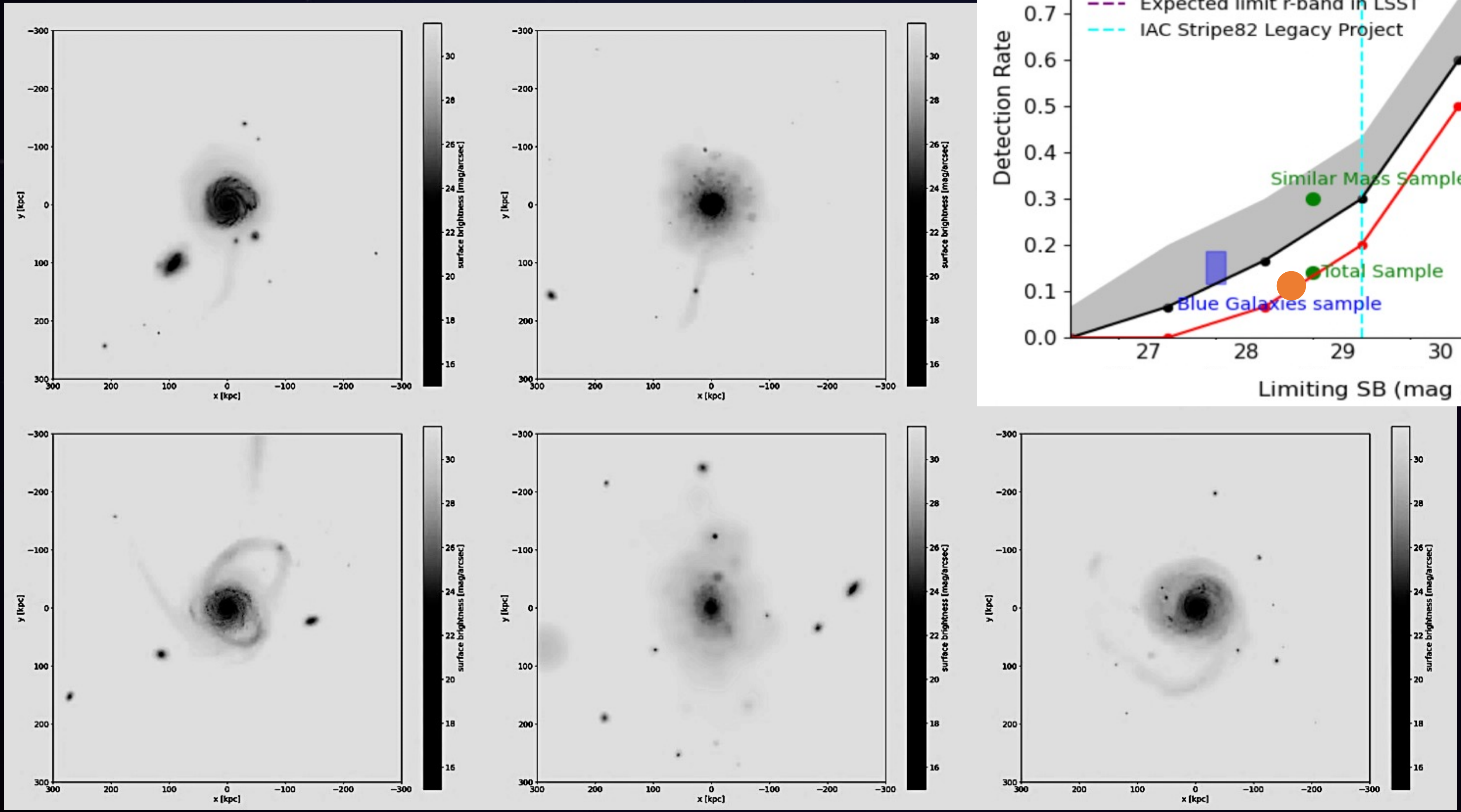
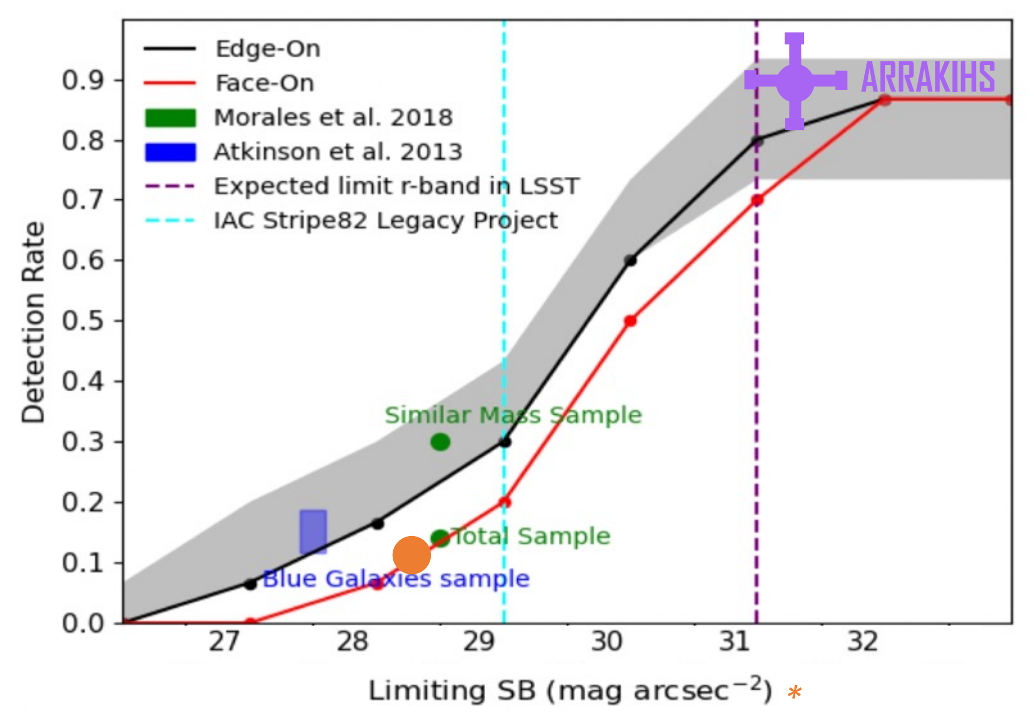
Miró-Carretero et al. (2024)
Vera-Casanova et al. (2022)

AMC (2024): SB_{lim} = 31.5 mag arcsec^{-2}





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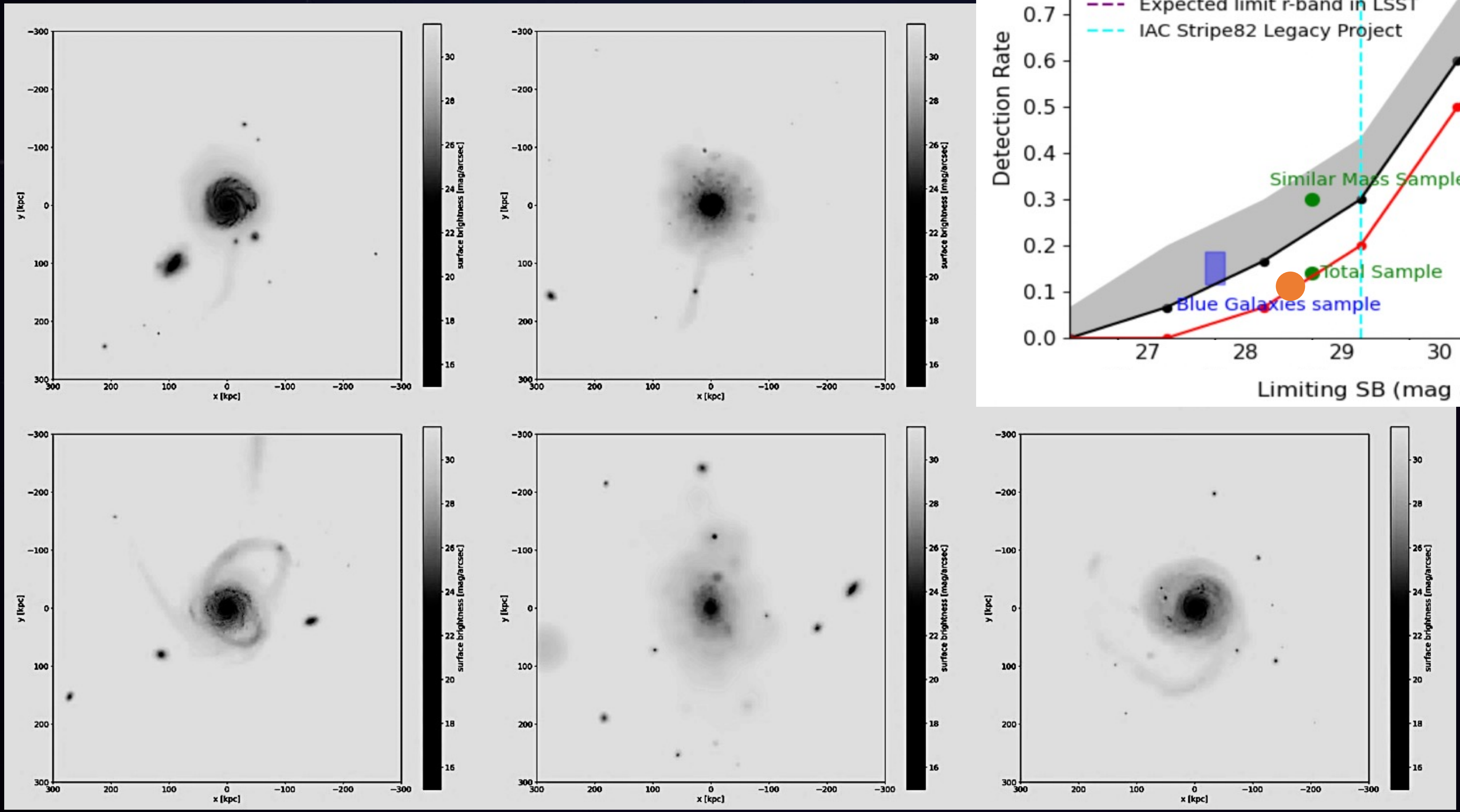
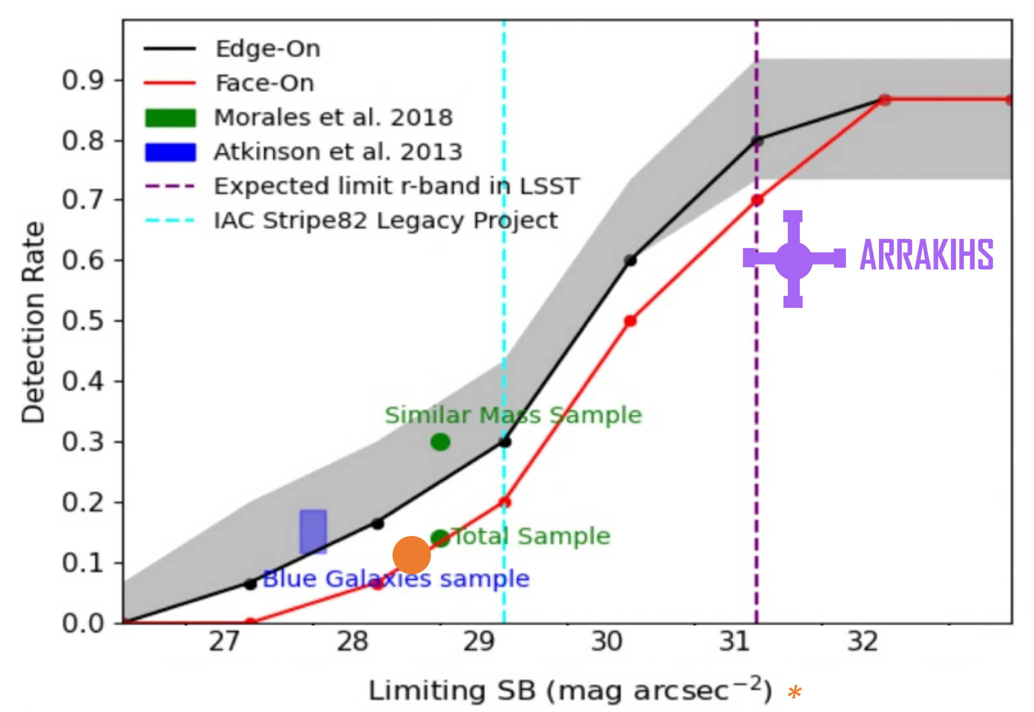




** SB_{lim} scaled to 100 arcsec^2*

HARKONEN cosmological simulations to break the degeneracy between DM and BP: Roca-Fábrega, Revaz + AMC (2024)

Revaz, Roca-Fábrega + AMC (2024)

Payload Overview

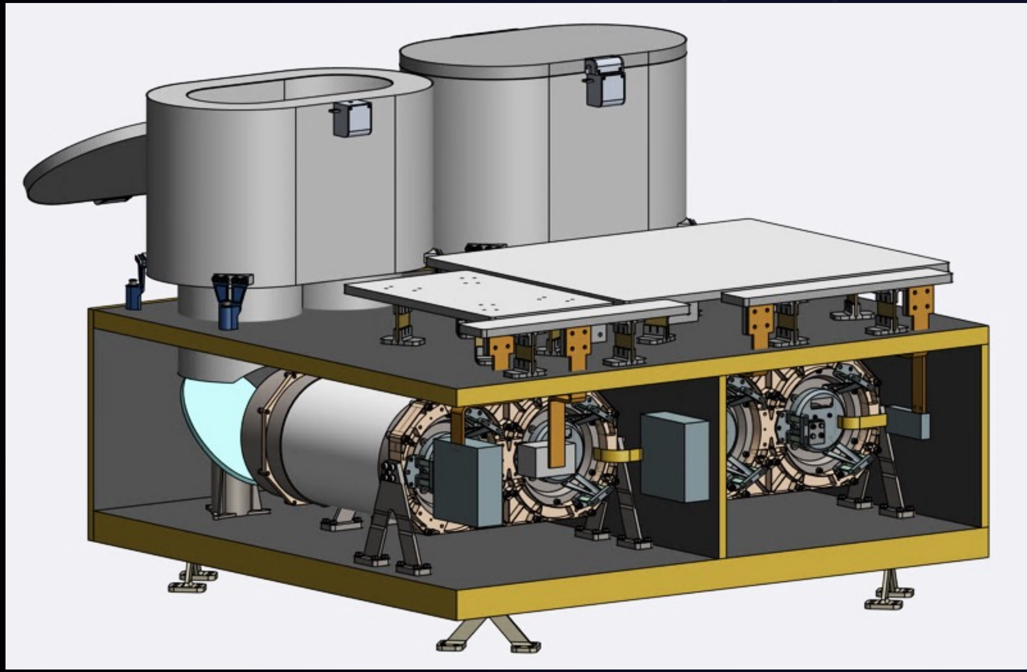
ARRAKIHS

SATLANTIS

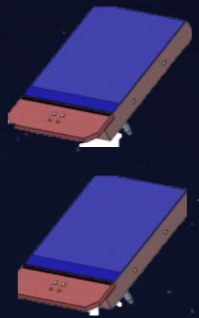
OPTO MECHANICS

2x iSIM170

iPRR: Serrano, Guzmán, Prod'homme + AMC (2024)



ELECTRONICS



SATLANTIS

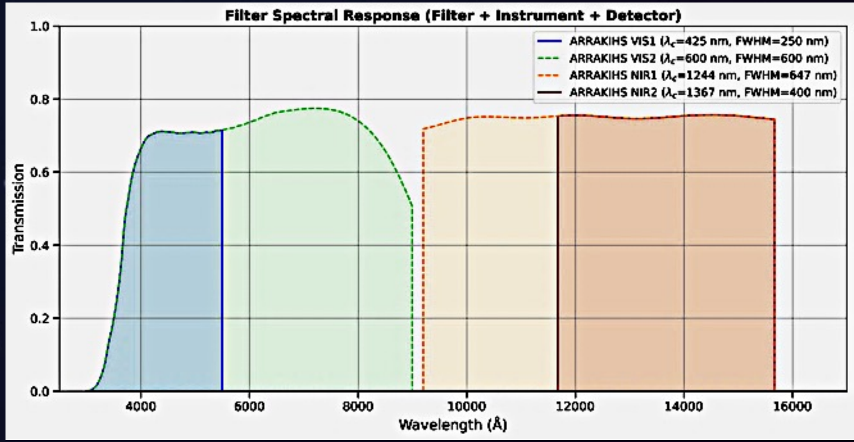
universität wien

TELEDYNE DALSA Everywhereyoulook™

2x **CMOS-304**

CDPU

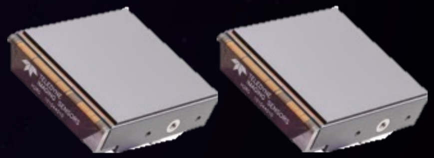
IWF INSTITUT FÜR WELTRAUMFORSCHUNG



DETECTORS

TELEDYNE e2V Everywhereyoulook™

2x **H2RG-10**



KOEGL SPACE — POLITÉCNICA — University of Zurich

Thermo-Mech. Structure

CEFCA — IEEC — LIDAX — HSLU

Detector & Filter Characterization

SATLANTIS — CEFCA

Payload Ground Tests

IFCA

Data Management & Analysis

CSL

Straylight & Baffles

Payload Overview

ARRAKIHS

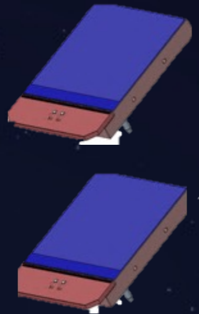
SATLANTIS

OPTO MECHANICS

2x iSIM170

iPRR: Serrano, Guzmán, Prod'homme + AMC (2024)

ELECTRONICS



SATLANTIS

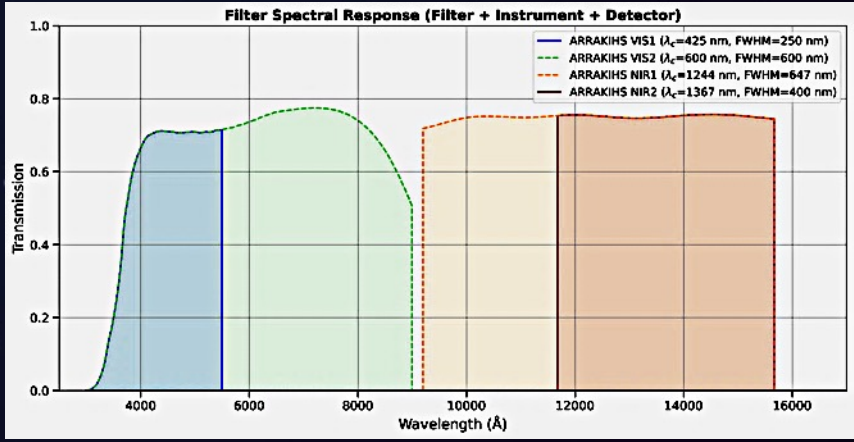
universität wien

TELEDYNE DALSA Everywhereyoulook™

2x CMOS-304

CDPU

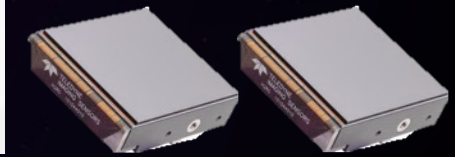
IWF INSTITUT FÜR WELTRAUMFORSCHUNG



DETECTORS

TELEDYNE e2v Everywhereyoulook™

2x H2RG-10



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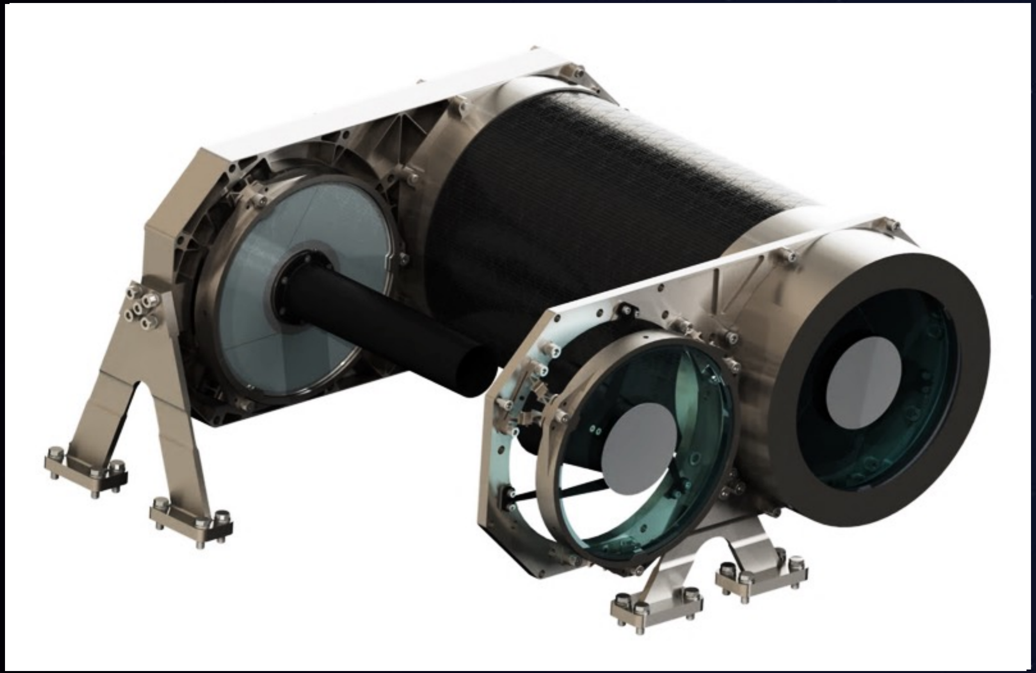

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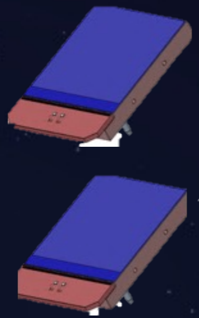


SATLANTIS

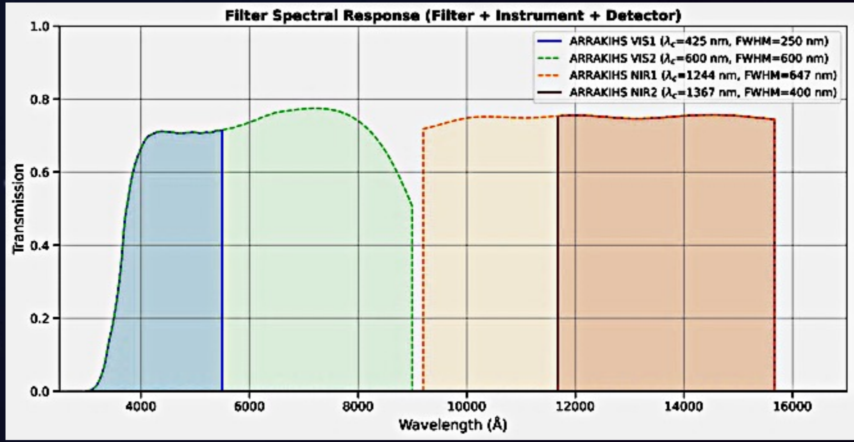
universität wien

TELEDYNE DALSA Everywhereyoulook™

2x **CMOS-304**

CDPU

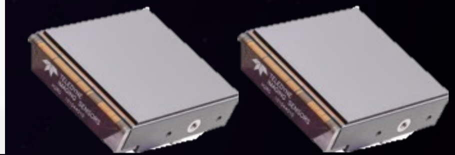
IWF INSTITUT FÜR WELTRAUMFORSCHUNG



DETECTORS

TELEDYNE e2V Everywhereyoulook™

2x **H2RG-10**



KOEGL SPACE · University of Zurich

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SATLANTIS

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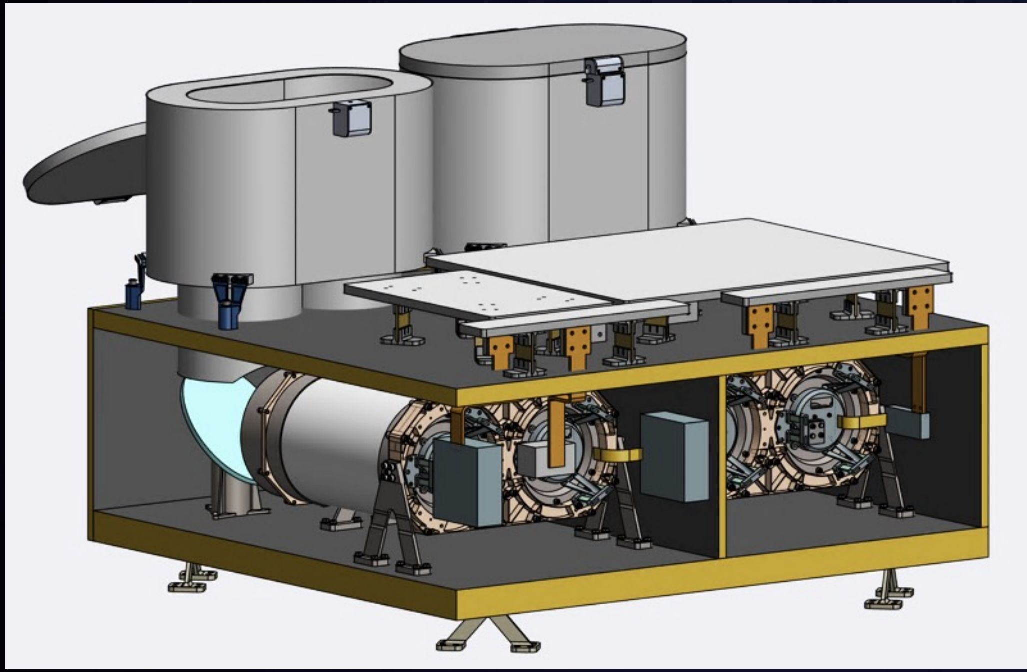
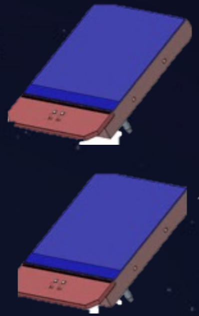


ELECTRONICS



SATLANTIS

universität wien

TELEDYNE DALSA Everywhereyoulook™

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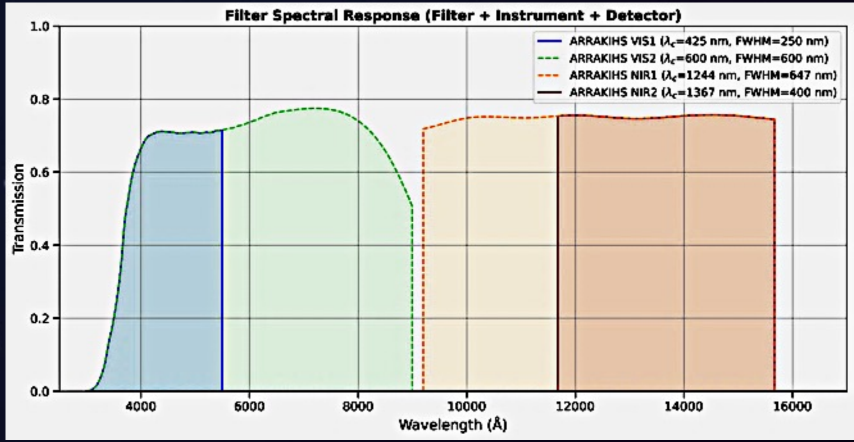
CDPU

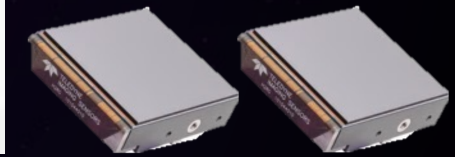
IWF INSTITUT FÜR WELTRAUMFORSCHUNG



DETECTORS

TELEDYNE e2V Everywhereyoulook™

2x **H2RG-10**



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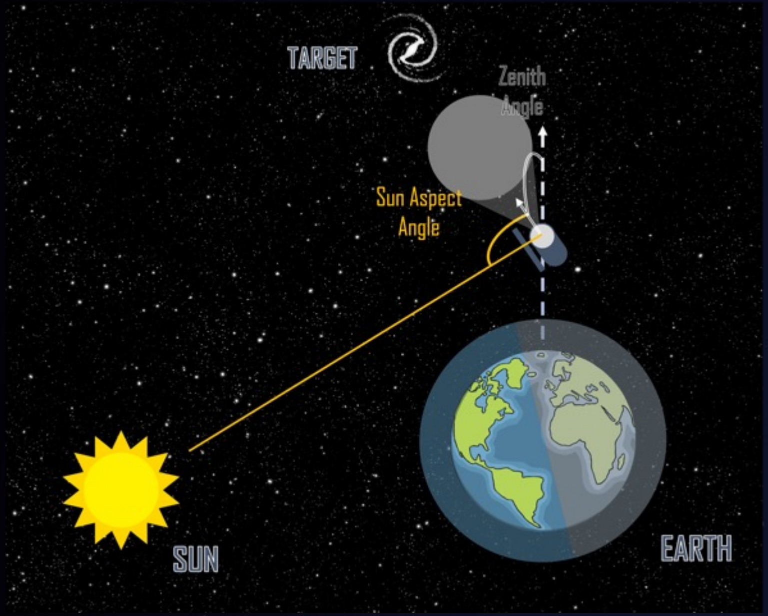
CONOPS & Mission Analysis

ARRAKIHS

AMC (2023)



CONOPS

iPRR: Camazón, Guzmán, Corral + AMC (2024)

Height: **800 Km**

Orbit: **Sun-Synchronous, 6am-6pm**

Field of Regard:

- **90^0 < Solar Angle < 130^0**
- **0^0 < Zenith Angle < 60^0**

Calibrations:

- **Darks, Flats**
- **Flux, PSF, Ghosts, etc.**

MISSION ANALYSIS

Sample: **≥75 MW-like galaxies** (ext-SAGA; Mao +2020)

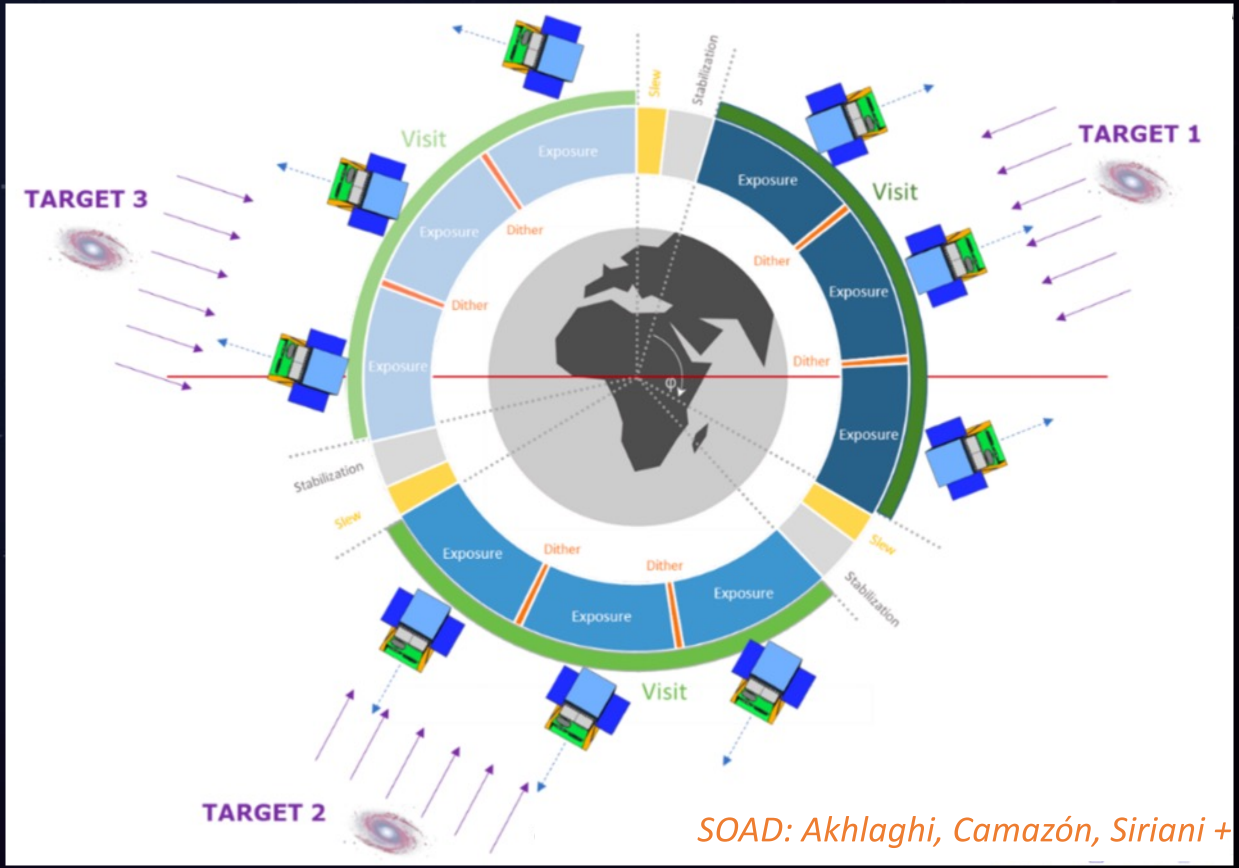
- $1 \leq M / 10^{10}$ Mo ≤ 5; $25 \leq d/\mathrm{Mpc} \leq 50$
- Zodiacal Light ≥ 22 J-mag arcsec^{-2}
- E(B-V) < 0.1

Gómez-Flechoso + AMC (2024)

Total Observing time: ≥ **150 hrs/gal**

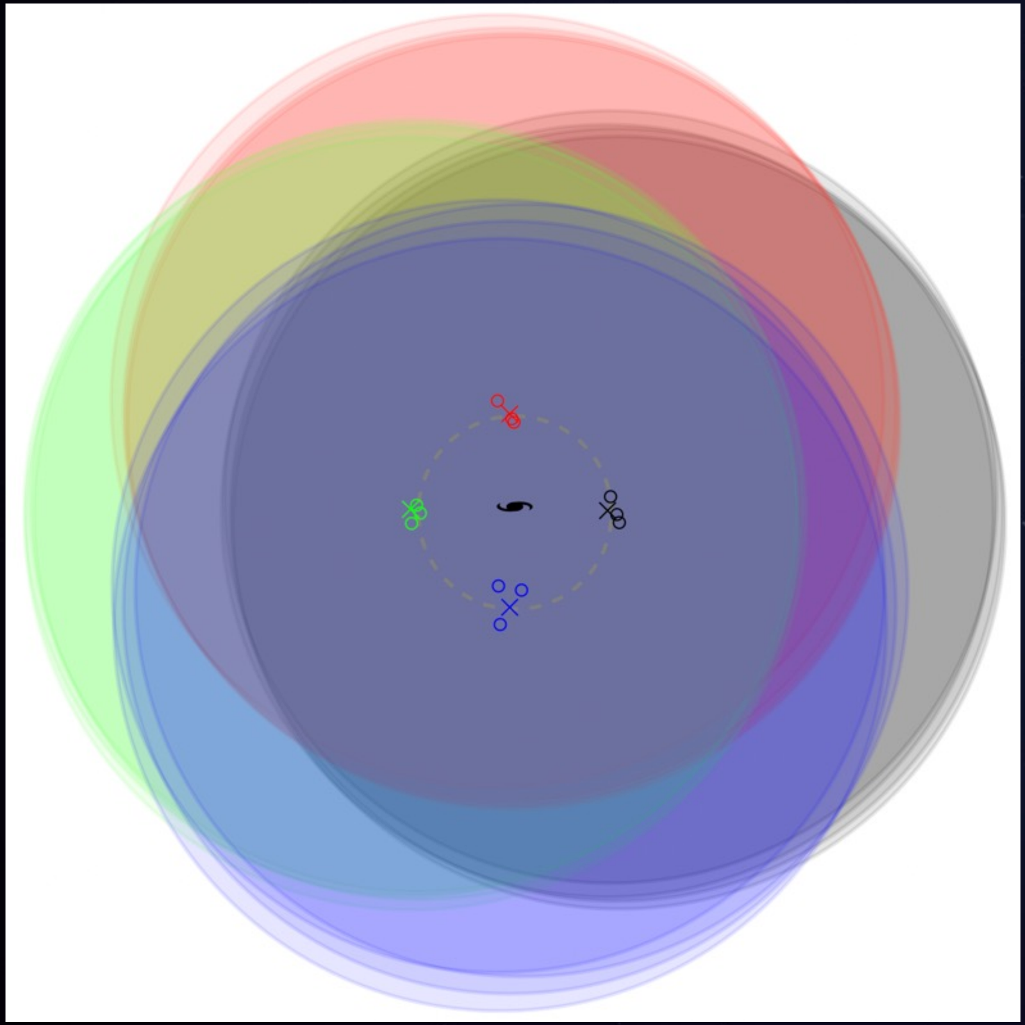
Single exposure time: ≤ **10 minutes**

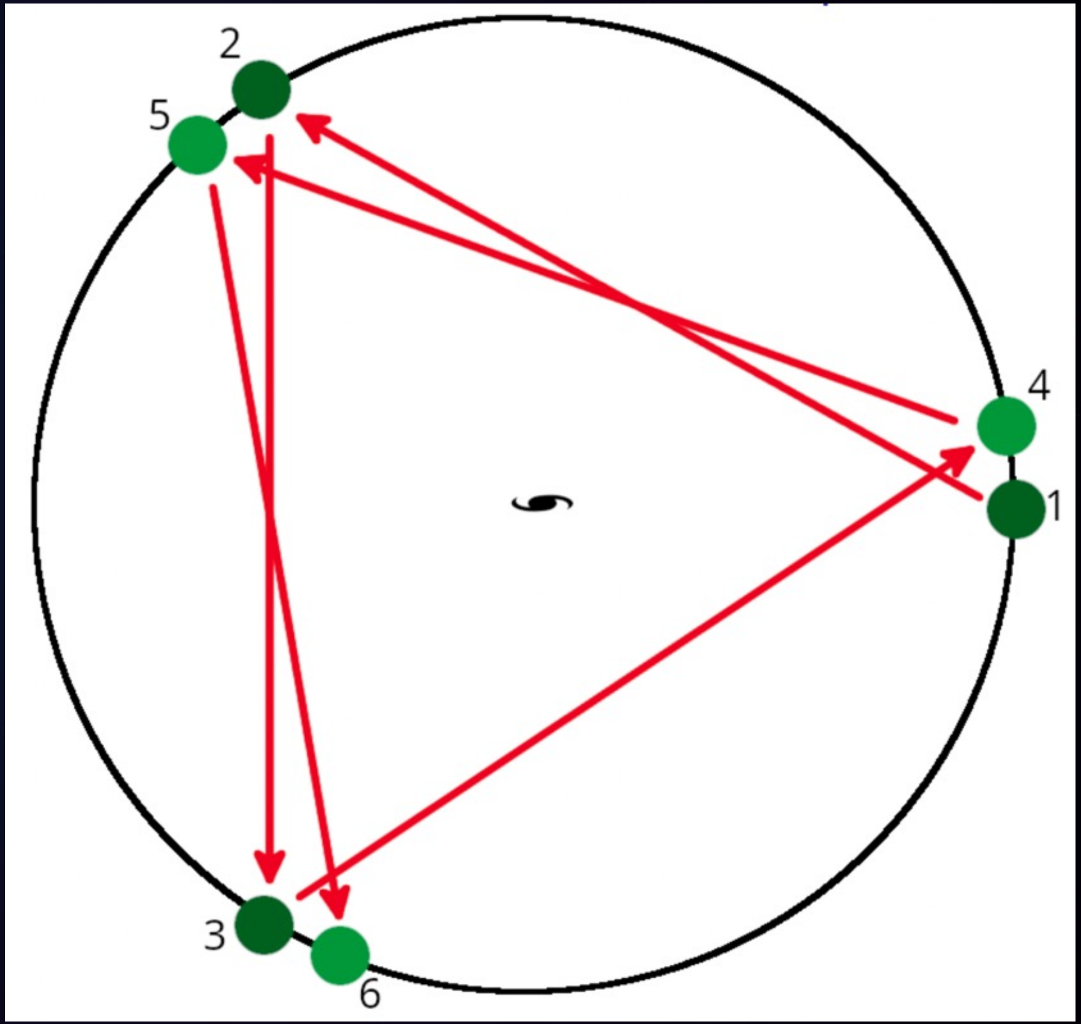
Camazón, Guzmán + AMC (2024)



SOAD: Akhlaghi, Camazón, Siriani + AMC (2024)

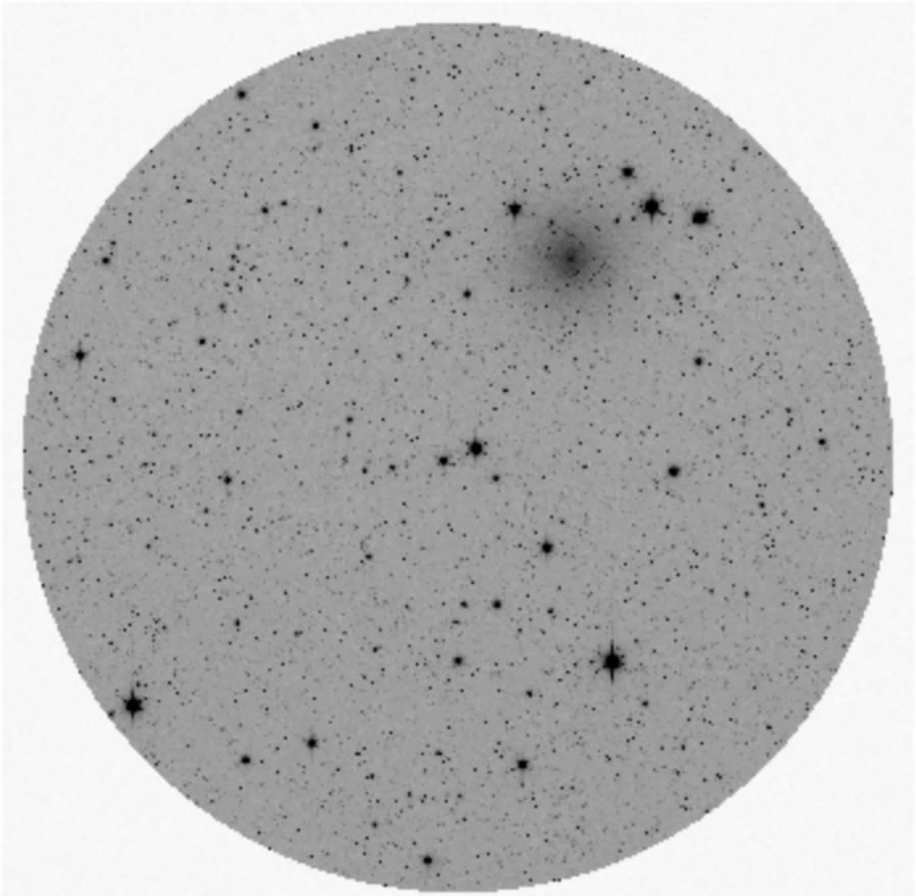
Observational Strategy: Dithers & Offsets

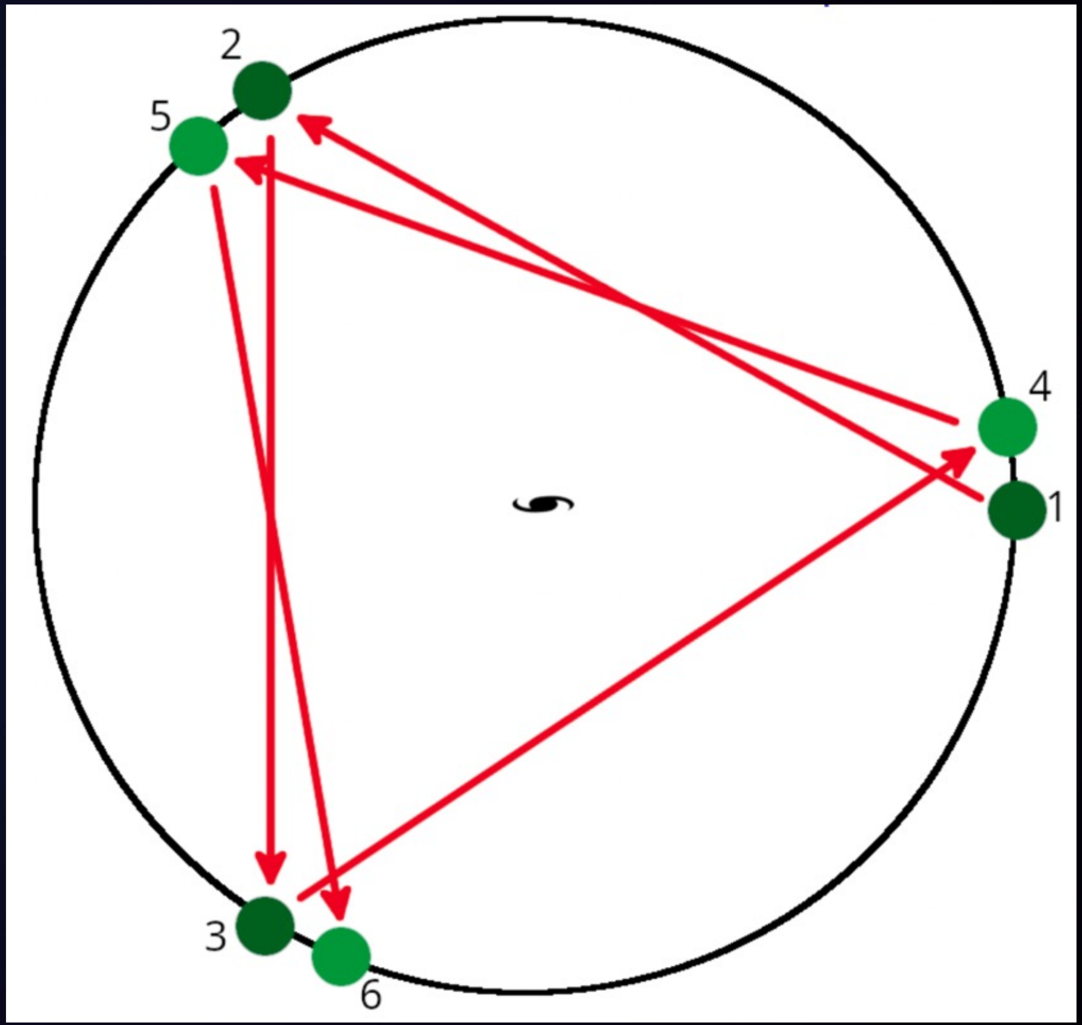




Akhlaghi + AMC (2024)

Observational Strategy: Dithers & Offsets

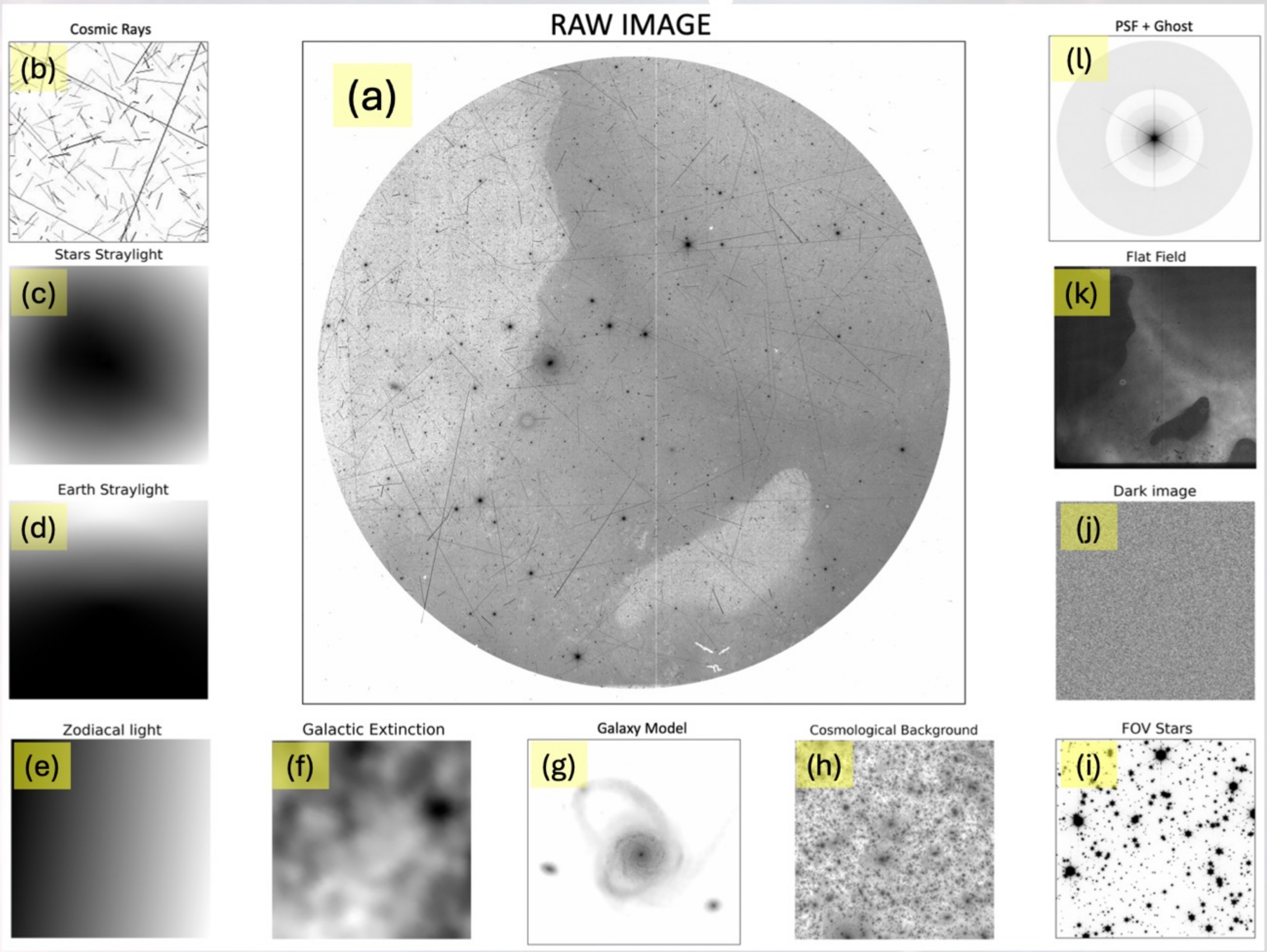




Akhlaghi, Camazón + AMC (2024)

Mock Simulations (ATREIDS Code)

ARRAKIHS



Full description in Alex Camazón's poster (ATREIDS) #P142

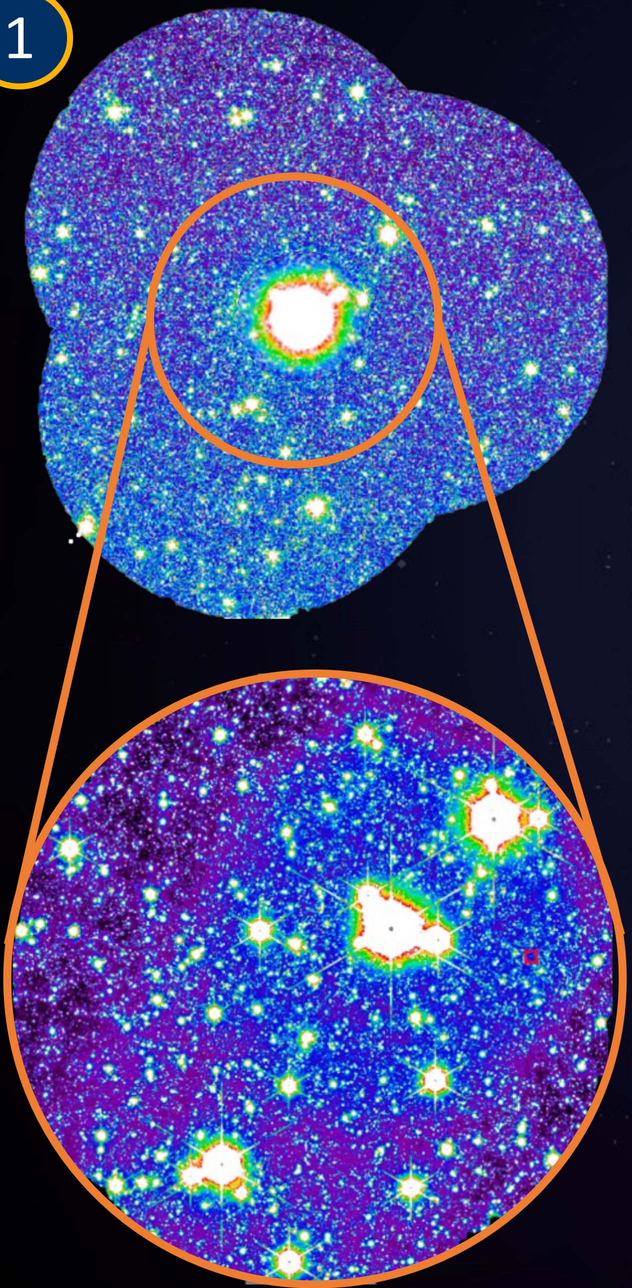
ARRAKIHS Telescope Realistic Exploration and Imaging Detection Simulations (ATREIDS)

Camazón, Guzmán + AMC (2024)

Image Processing Algorithms (Modified NoiseChisel Code)

ARRAKIHS

1



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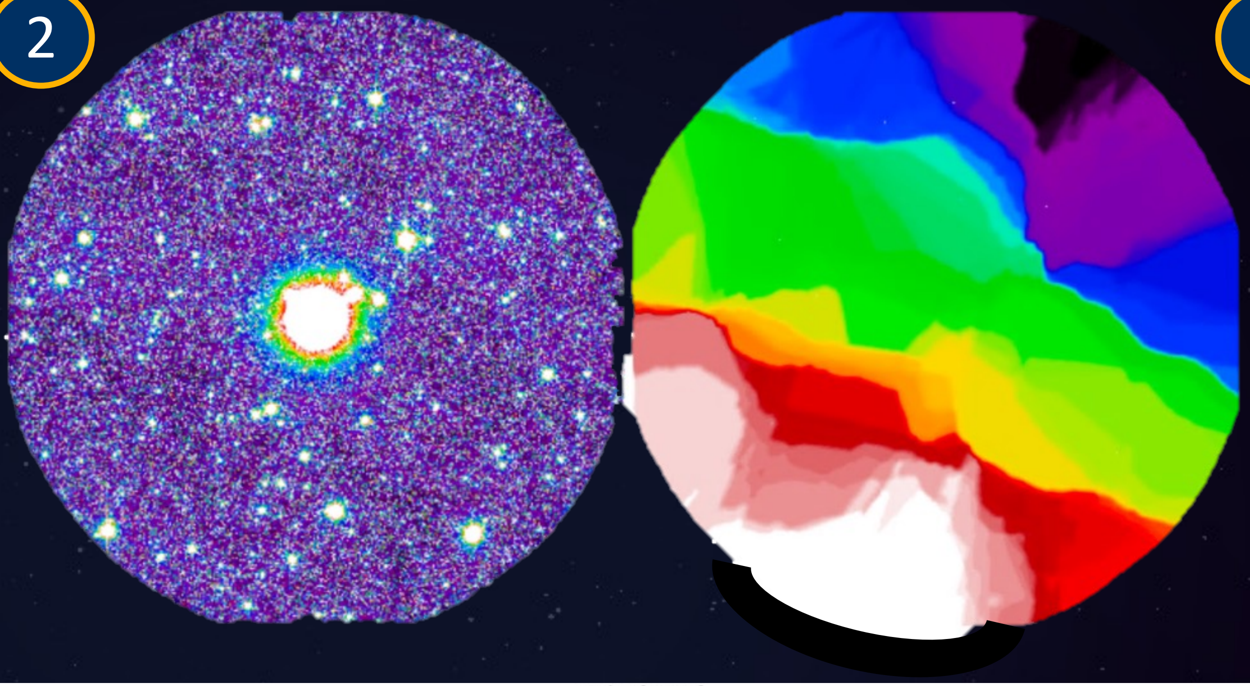
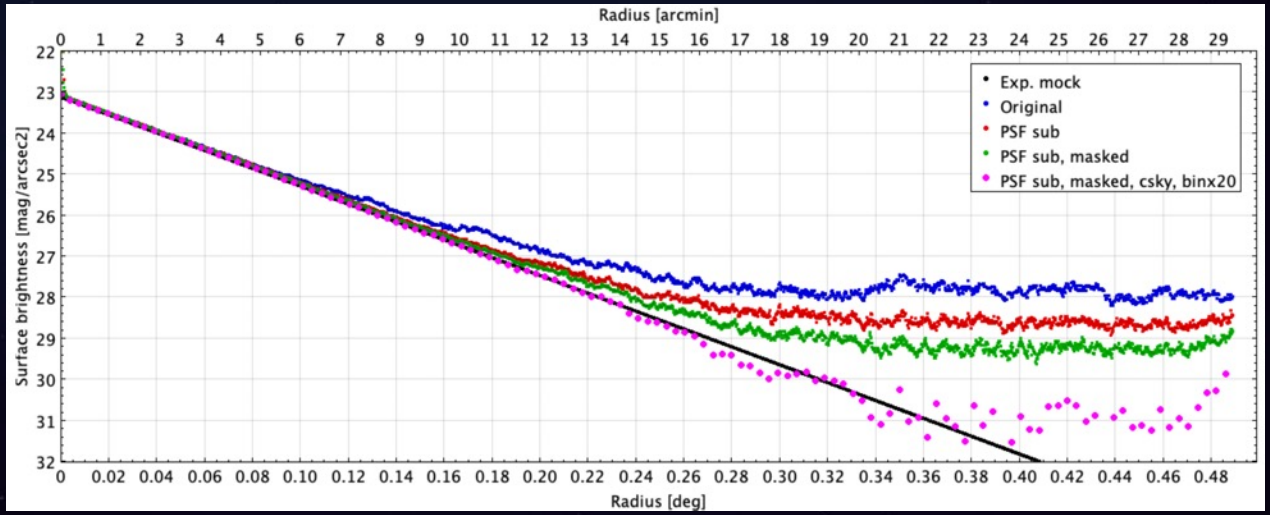
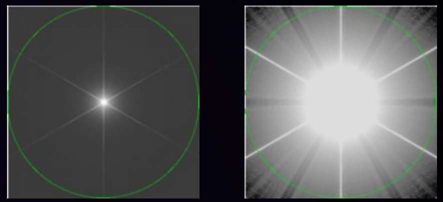


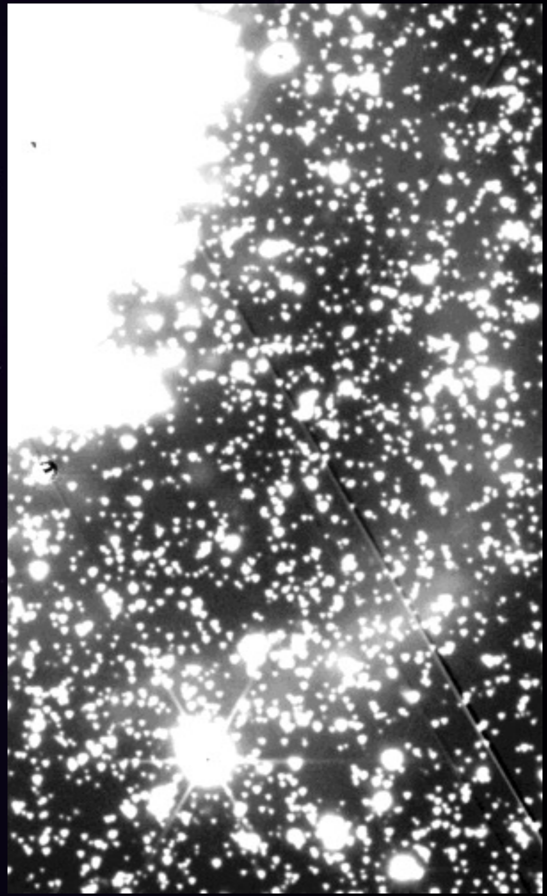


Akhlaghi, Infante + AMC (2024)

3



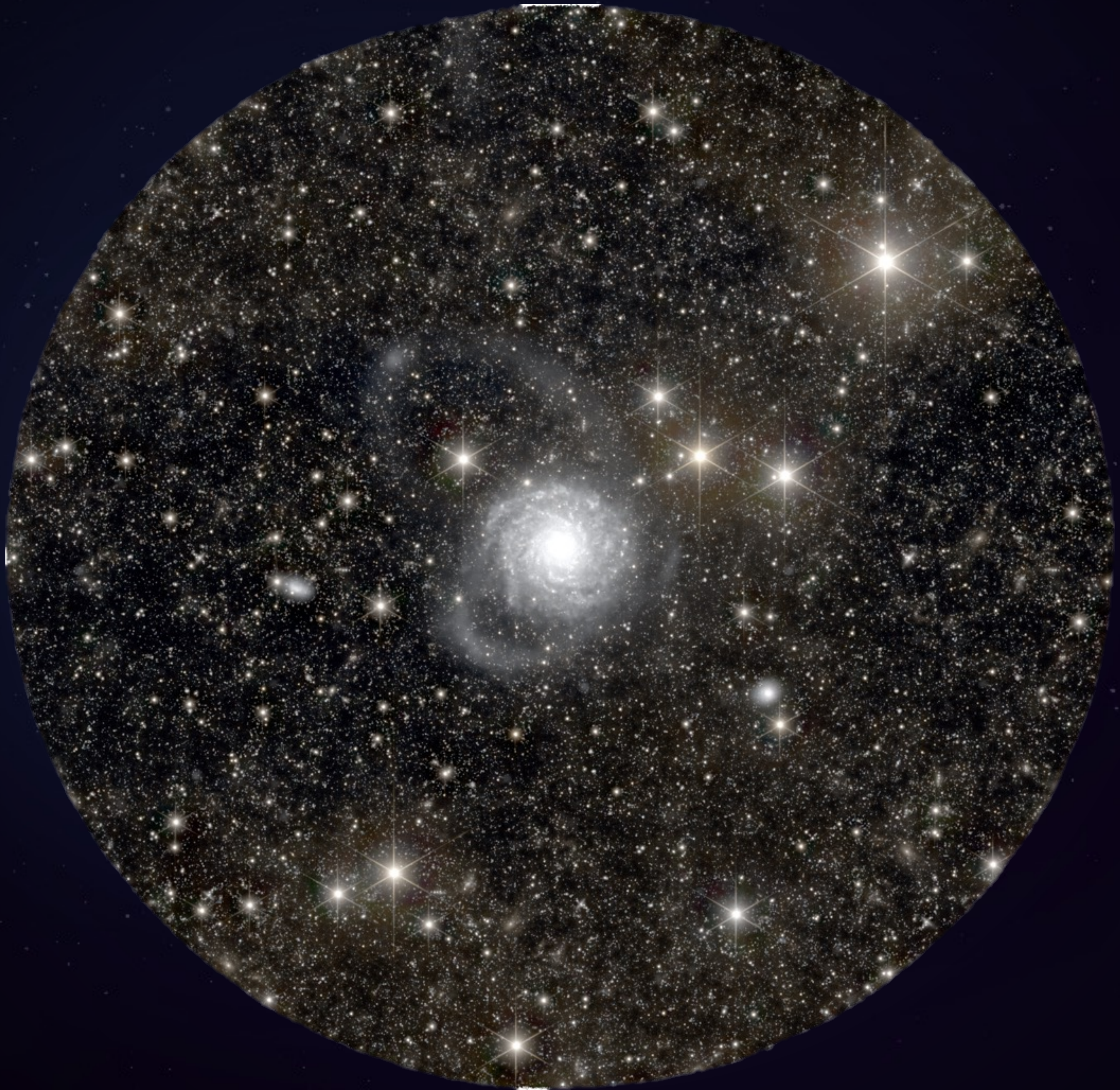
Infante + AMC (2024)



Infante-Sáinz & Akhlaghi (2024)

Mock End-to-End Simulations (ATREIDS Code)

ARRAKIHS



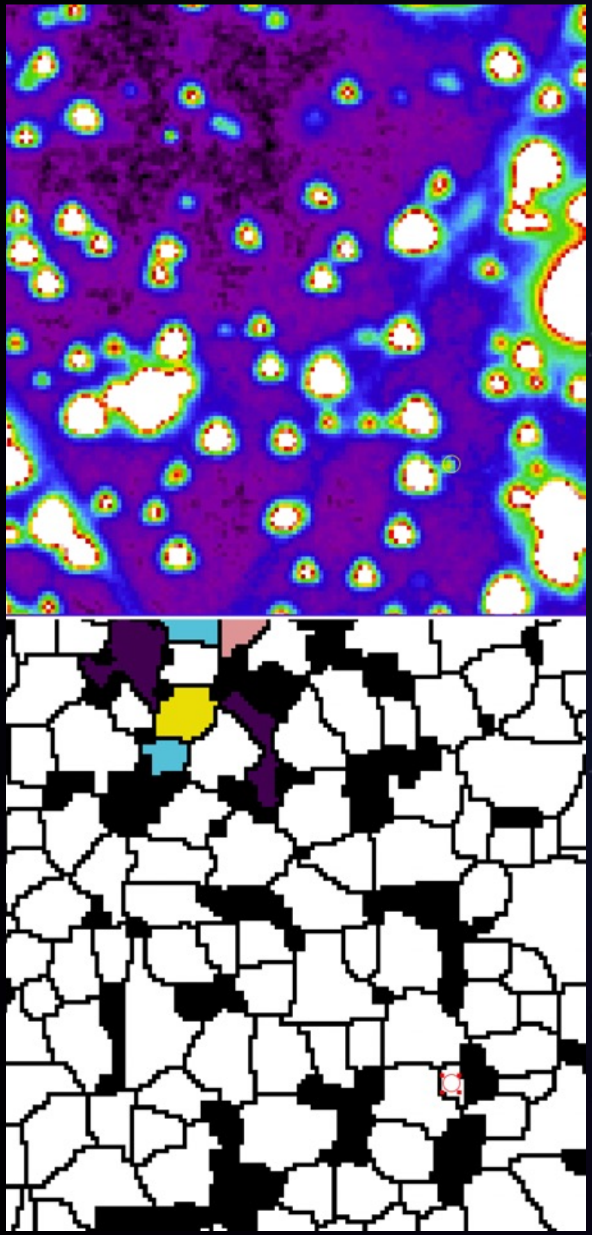
ARRAKIHS SB_{lim}

VIS1 = 31.36 mag/arcsec^2
VIS2 = 31.64 mag/arcsec^2
NIR1 = 31.02 mag/arcsec^2
NIR2 = 30.70 mag/arcsec^2

Akhlaghi, Camazón + AMC (2024)

Data Analysis (Gnuastro)

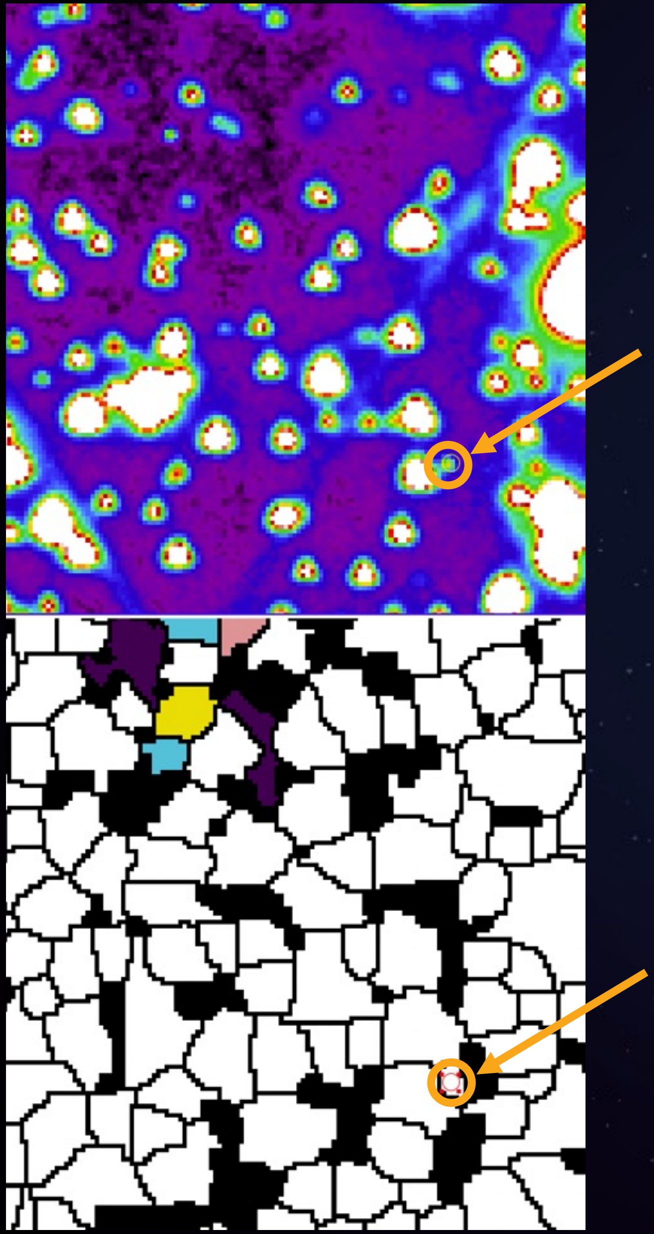
ARRAKIHS

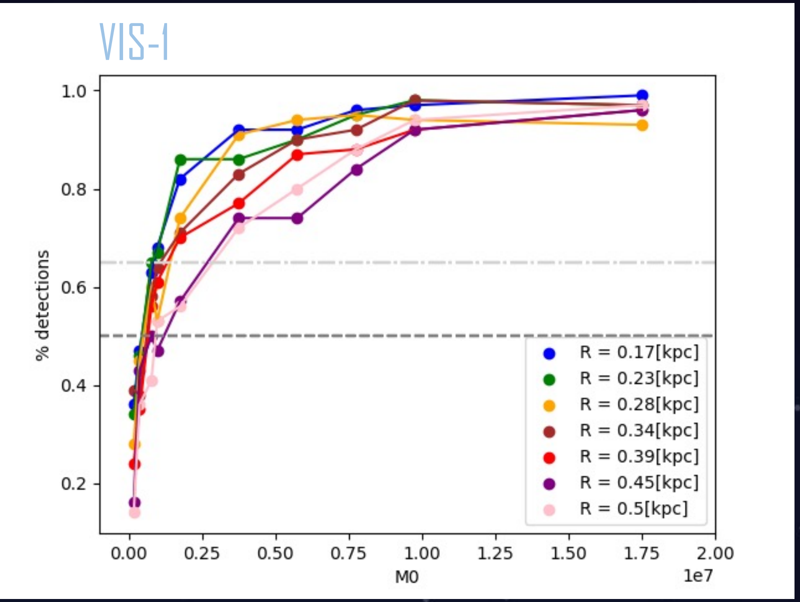


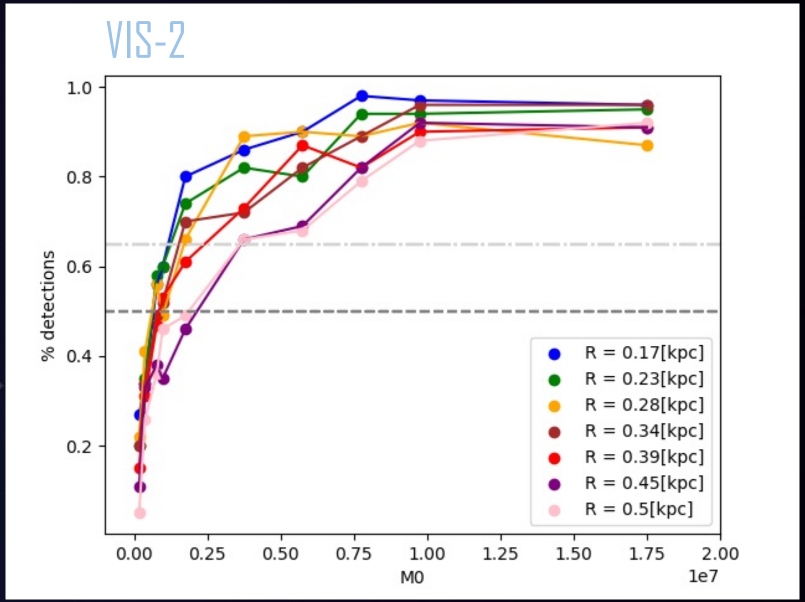
Domínguez + AMC (2024)

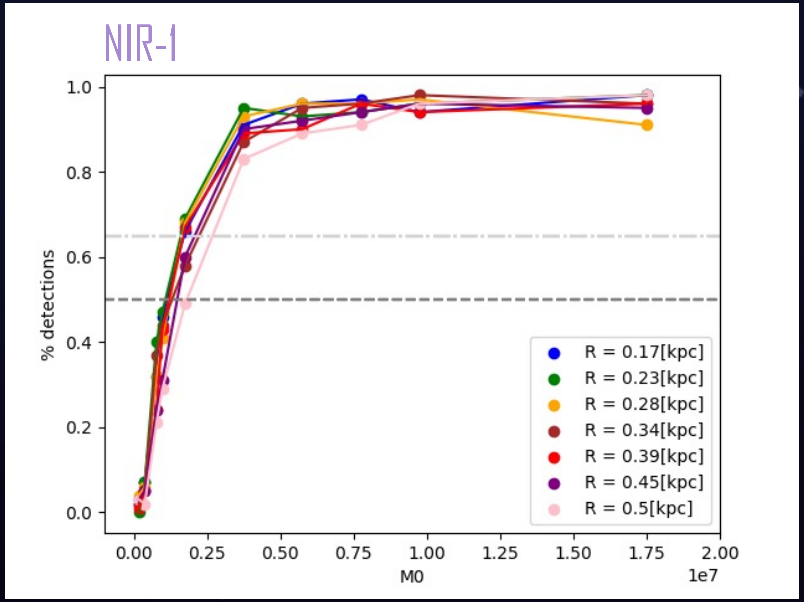
Data Analysis (Gnuastro)

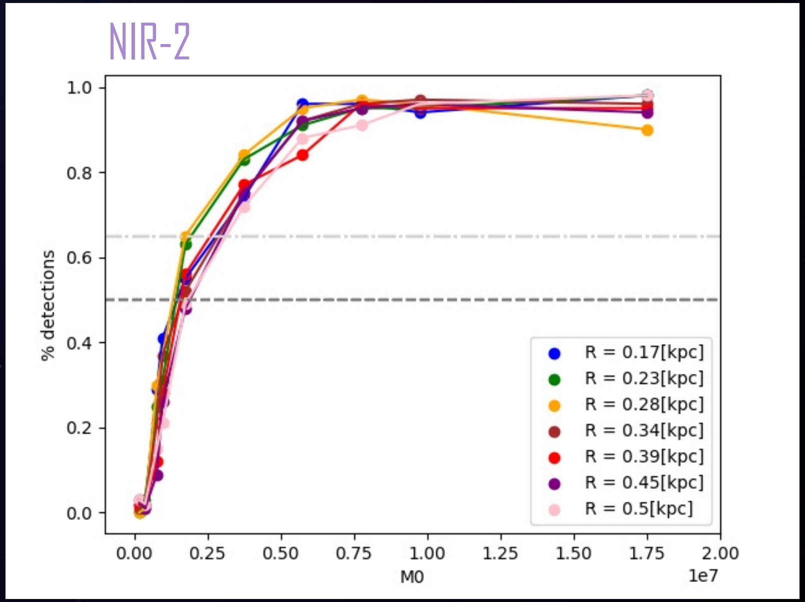
ARRAKIHS











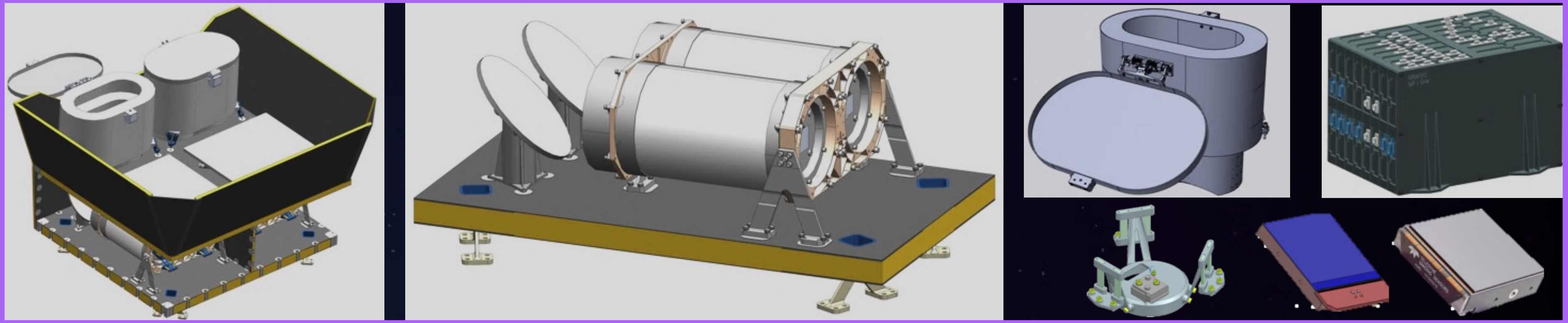
Domínguez + AMC (2024)

Phase B: On-going Work for PDR

ARRAKIHS

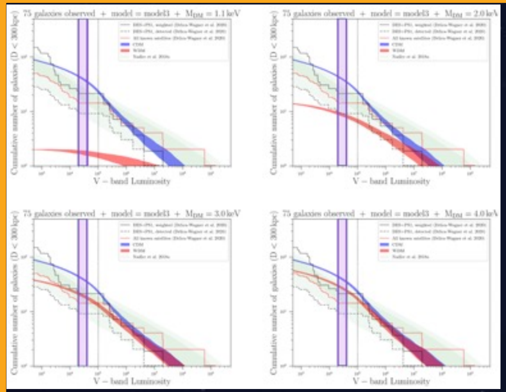
Instrumentation

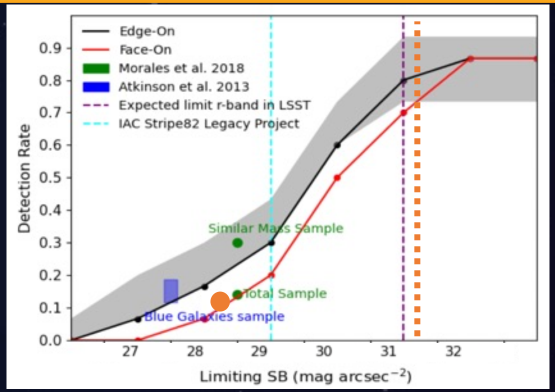
- Straylight
- Pointing stability
- Thermal Stability
- Filters & Detectors

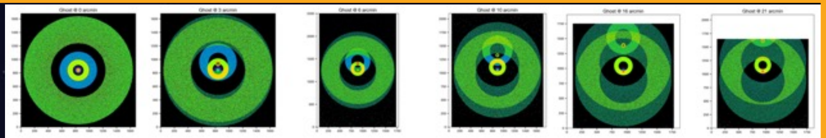


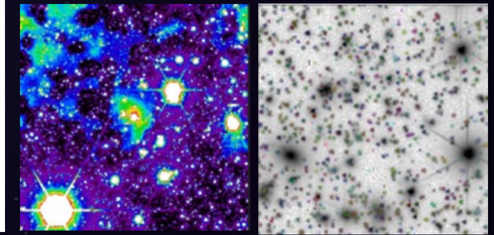
Science & SGS

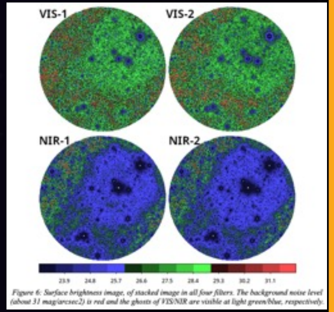
- Statistical descriptor for CDM & BP models
- Mock images
- Data processing
- Cirrus subtraction
- Background galaxy subtraction
- CONOPS
- Mission Analysis
- Complementarity with Euclid
- On-ground demonstrator

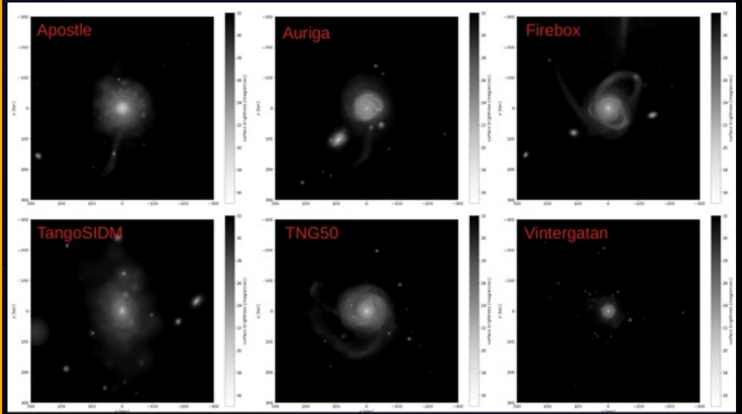


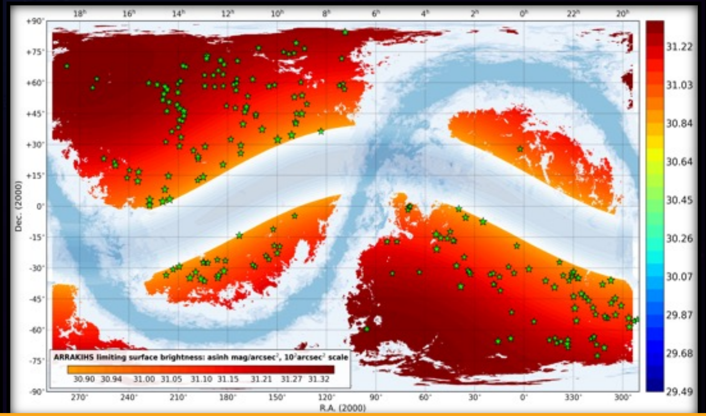


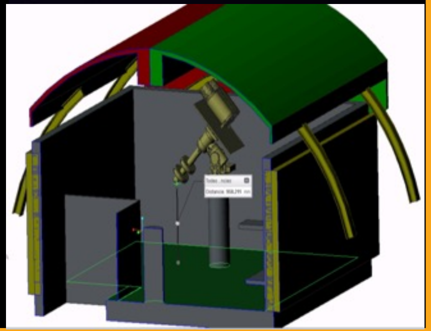










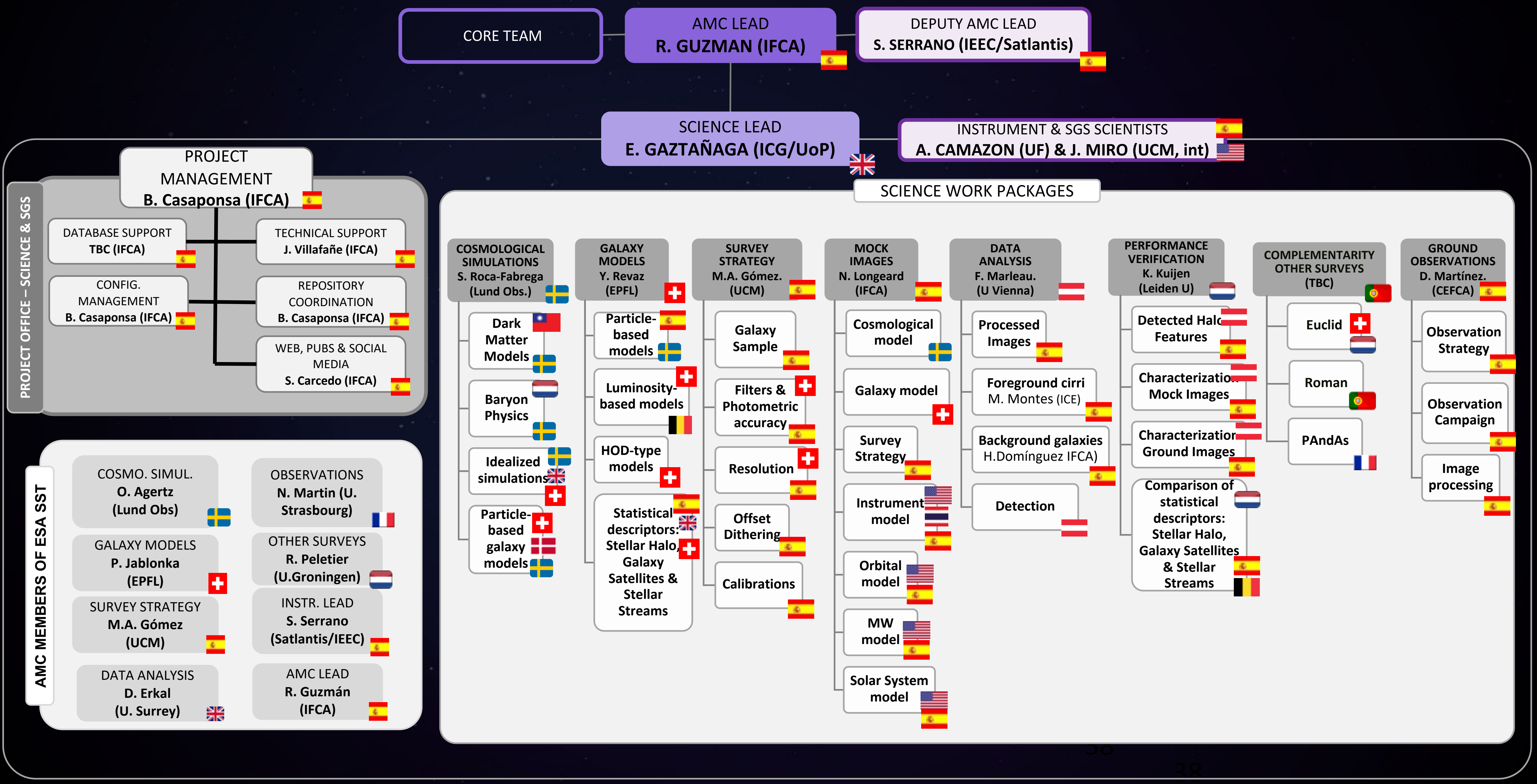


ARRAKIHS

Thanks!

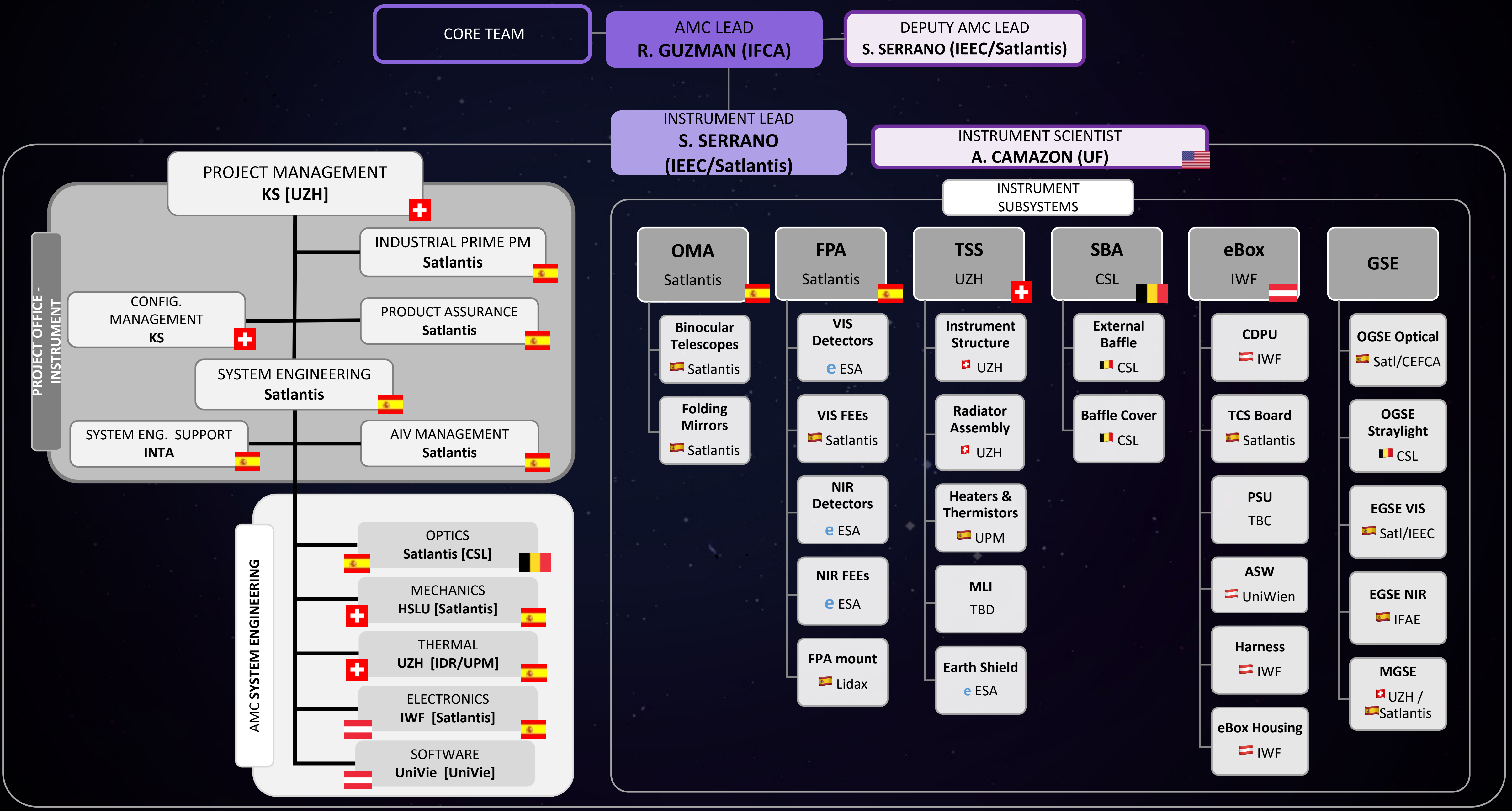
Phase B: AMC Science Team Organization Chart

ARRAKIHS

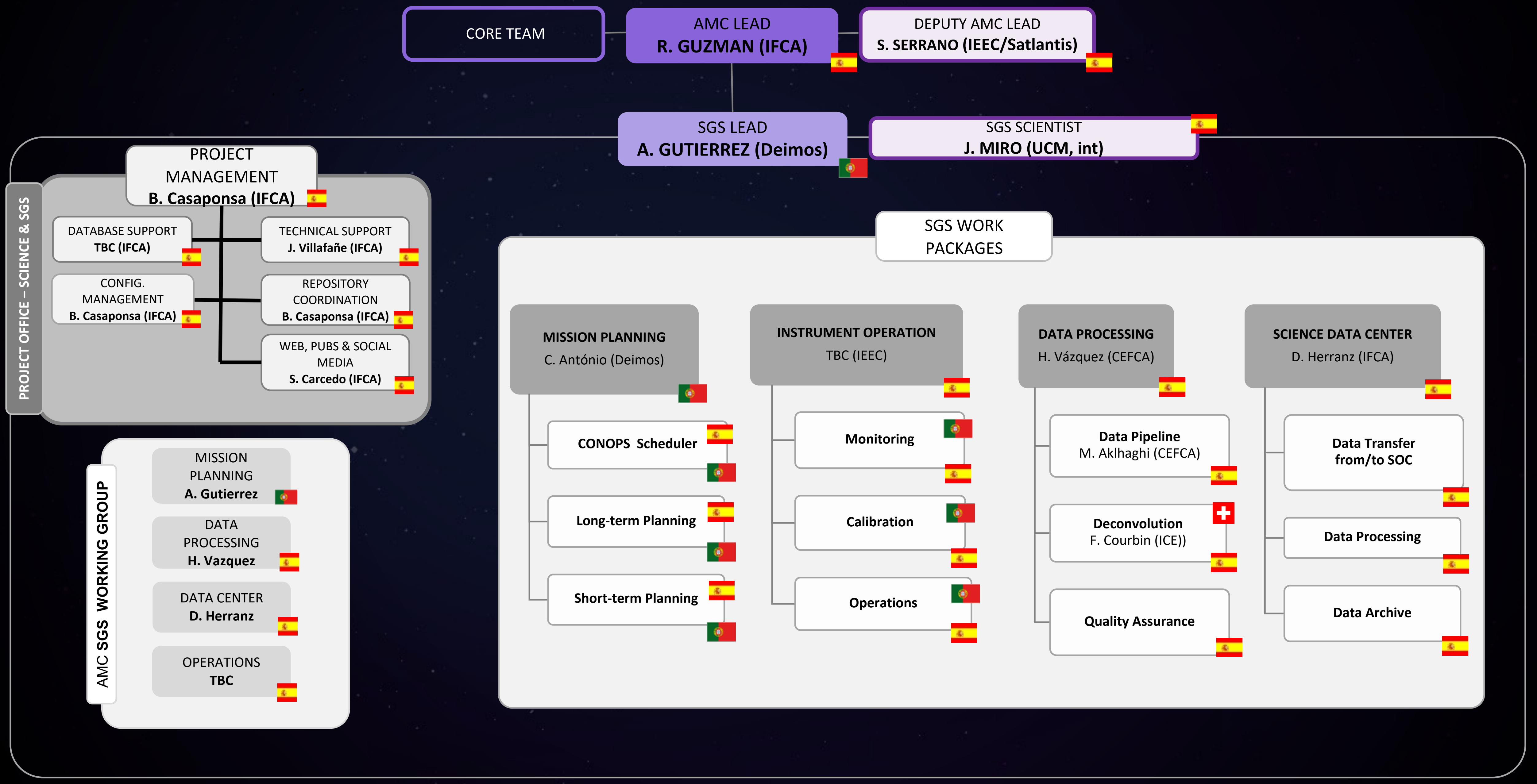


Phase B: AMC Instrument Team Organization Chart

ARRAKIHS



Phase B: AMC Science Ground Segment Team Organization Chart



Phase B: On-going Work for PDR

ARRAKIHS

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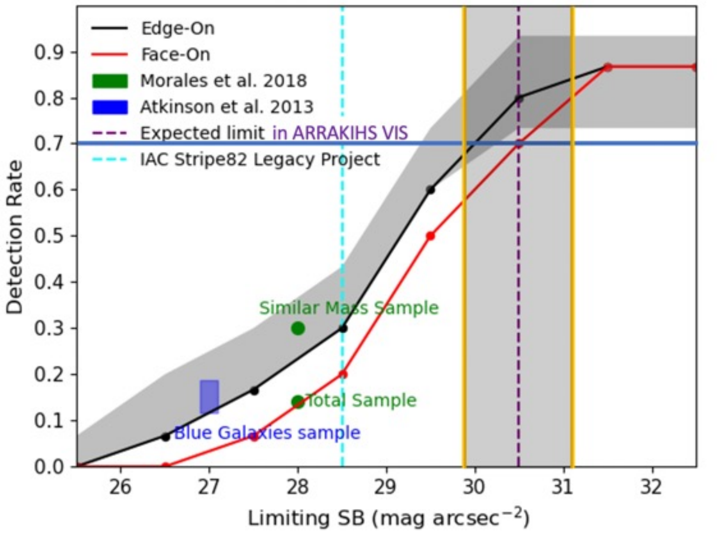
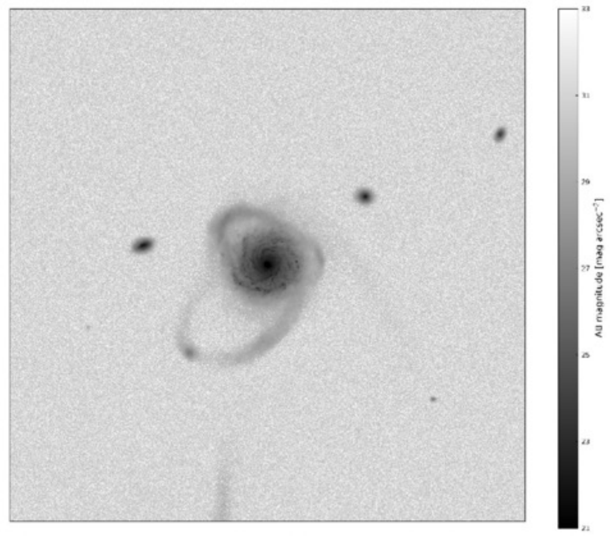


SB_{lim}	DR	N min
31	0.78	41
30.5	0.70	51
30	0.60	60
29.5	0.5	100

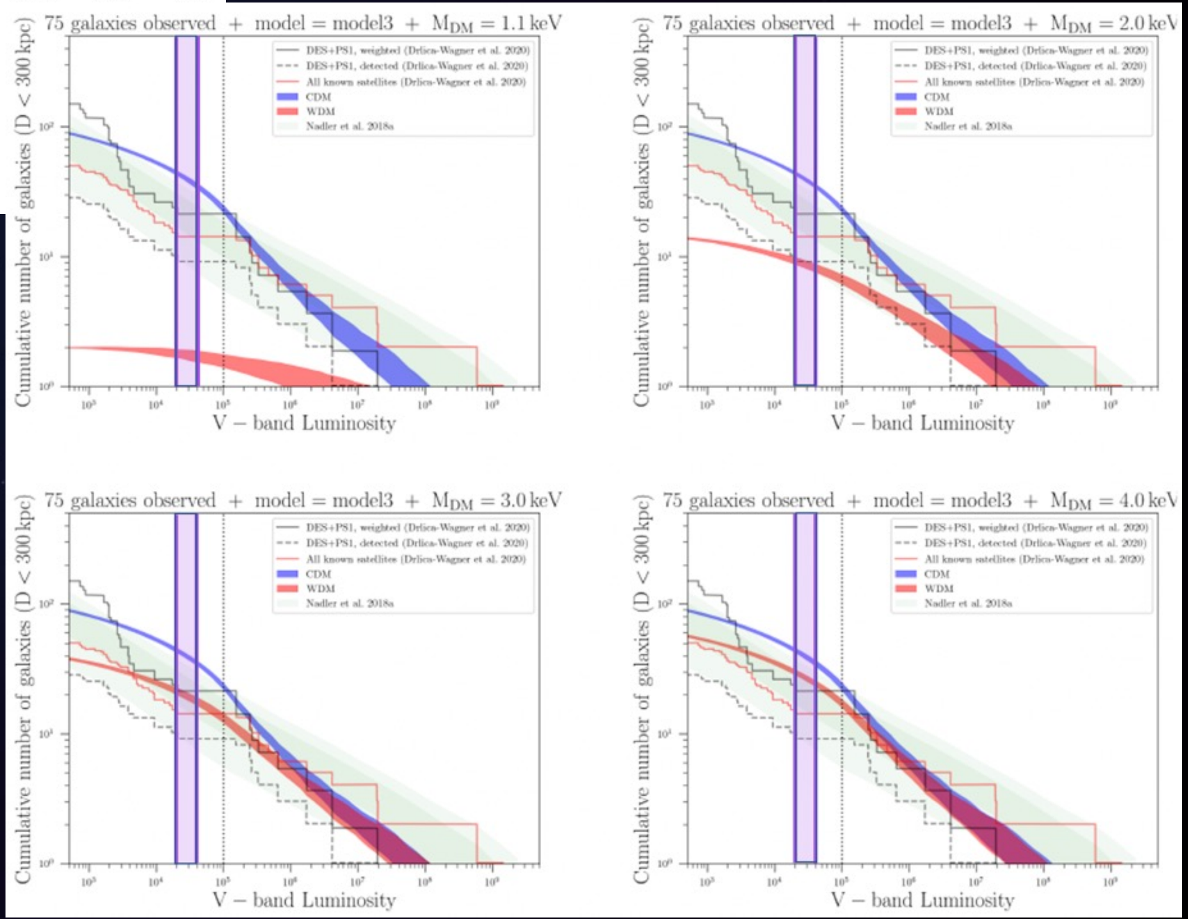
Vera-Casanova (2022)

Detection rate of stellar streams as a function of SB_{lim} (Vera-Casanova et al., 2022). Dashed vertical line and grey vertical area show the SB_{lim}=30.5±0.6 mag arcsec^{-2} in the ARRAKIHS survey (95% confidence level)

AMC (2023)



AMC (2024)



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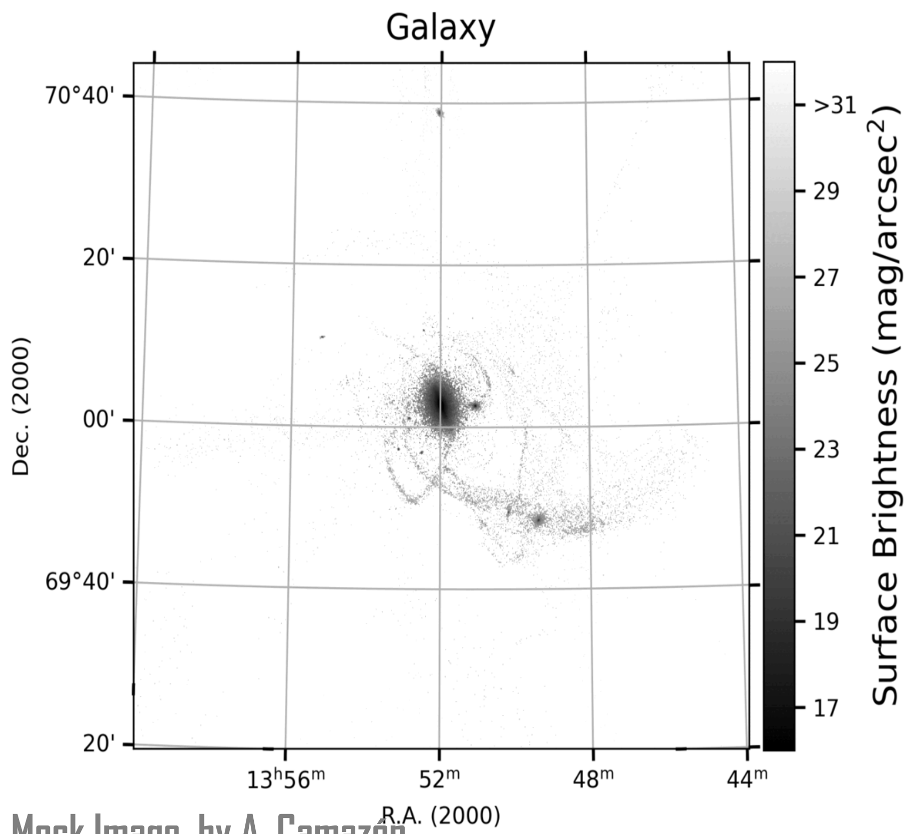
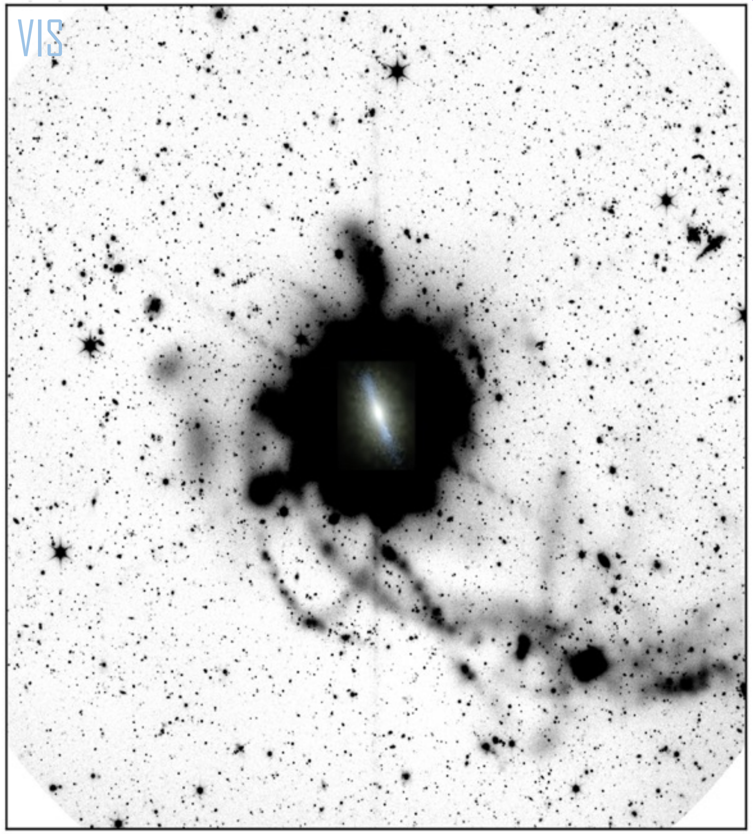
VIS-1: SB>30 mag arcsec^{-2}
Φ = 1.5 deg^2

VIS-2: SB>30 mag arcsec^{-2}
$\Theta \leq$ 1.4 arcsec in VIS-2.

NIR-1: SB>29 mag arcsec^{-2}
N=50 sq deg/yr

NIR-2: SB>29 mag arcsec^{-2}
Θ = $\leq$ 2.0 arcsec in NIR-2





Mock Image by A. Camazón

AMC (2023)

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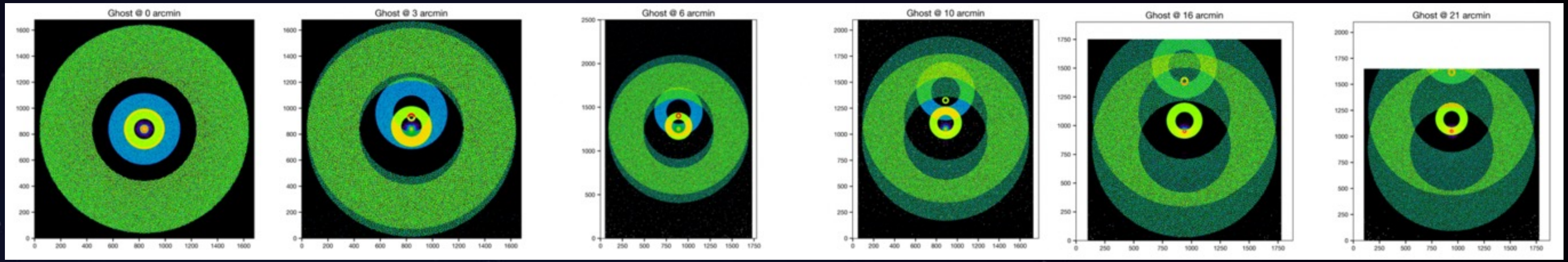

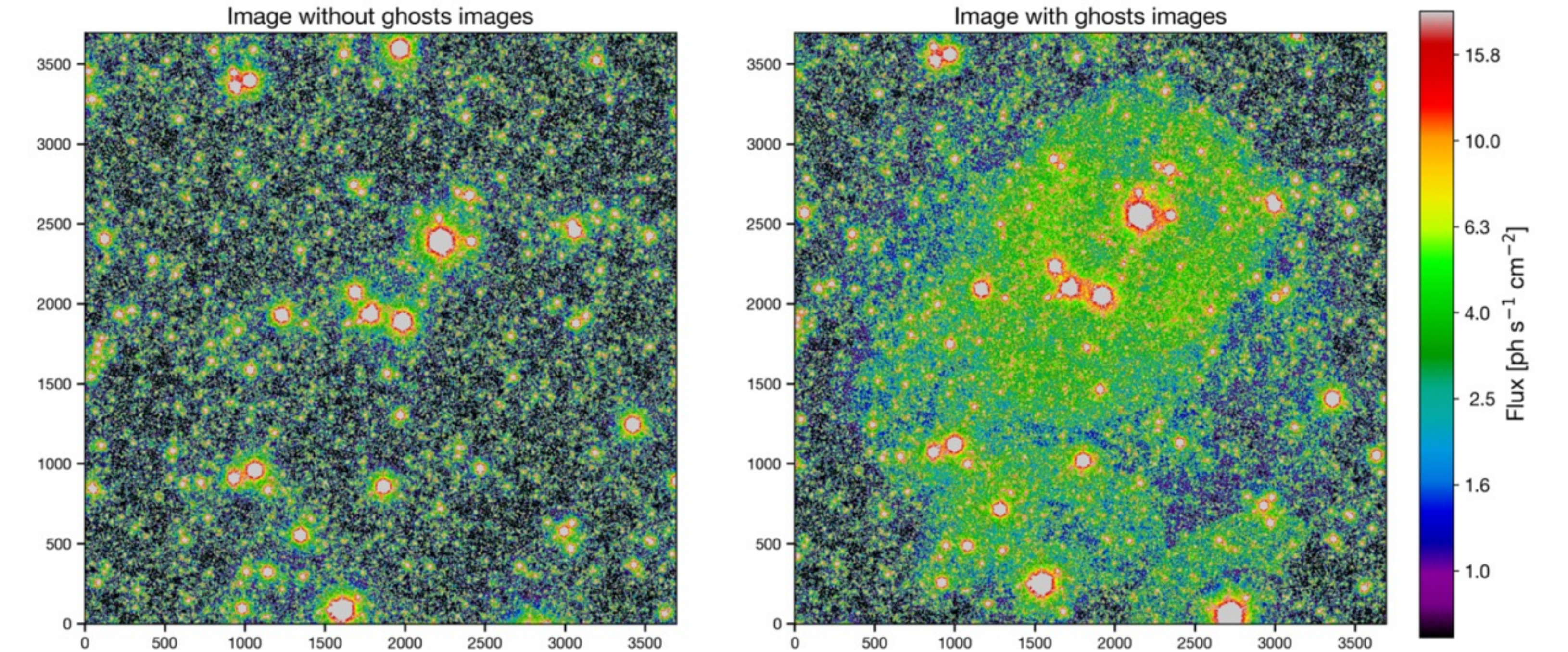

Figure 3: Comparison between two images in ARRAKIHS VIS-1 filter: left panel shows the image before the effects of the ghost images are included; right panel shows the image after the convolution with the ghost images. We haven't applied any sky or any noise in both images.

AMC (2024)

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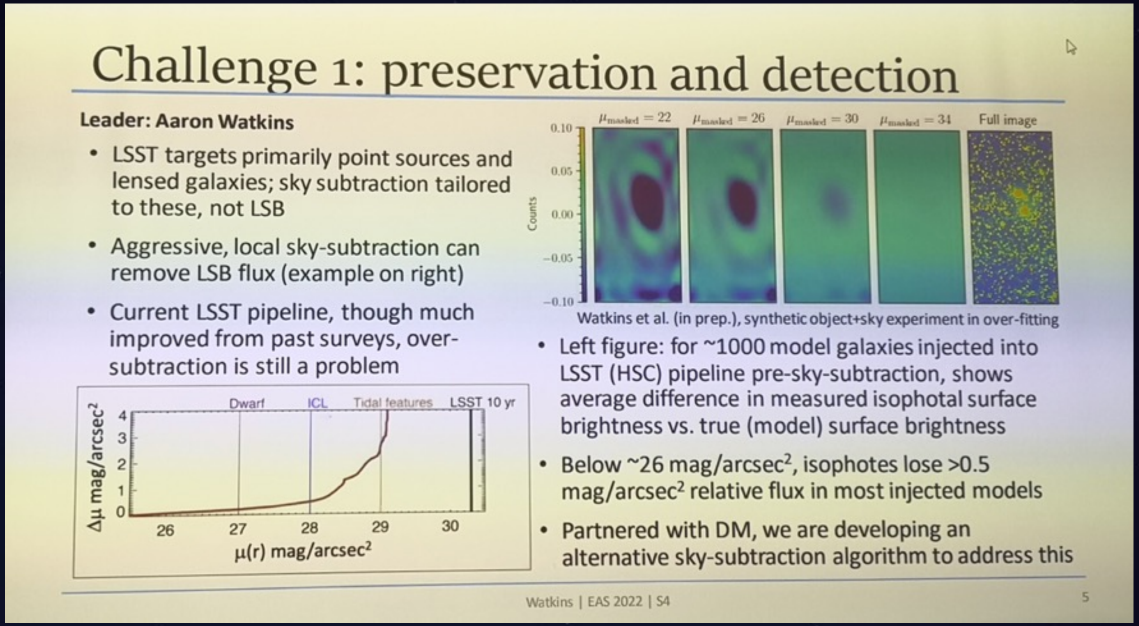
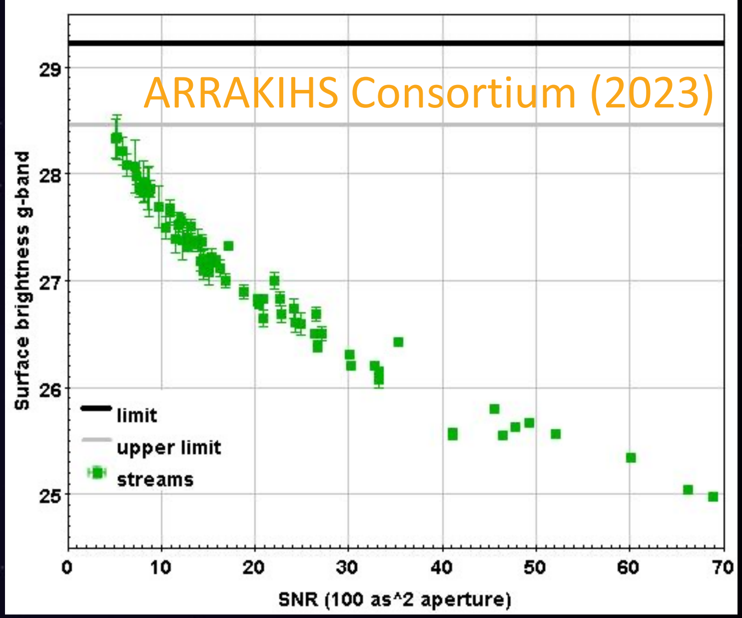
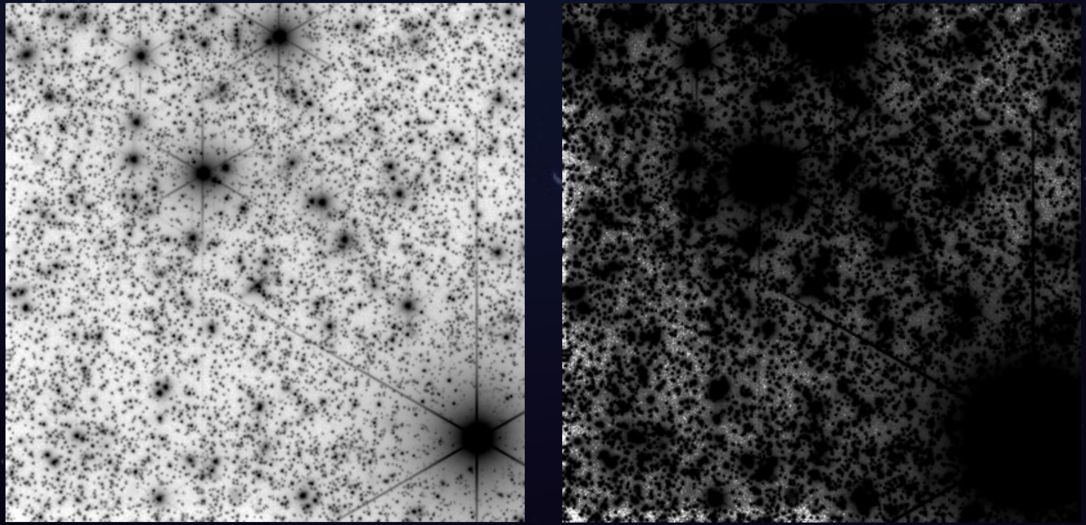
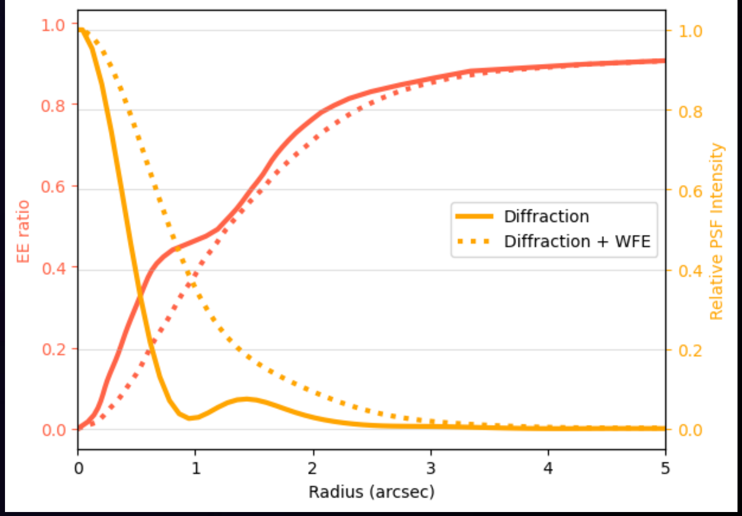
- **Data processing**
- Cirrus subtraction
- Background galaxy subtraction
- CONOPS
- Mission Analysis
- Complementarity with Euclid
- On-ground demonstrator







VIS2



PSF

Phase B: On-going Work for PDR

ARRAKIHS

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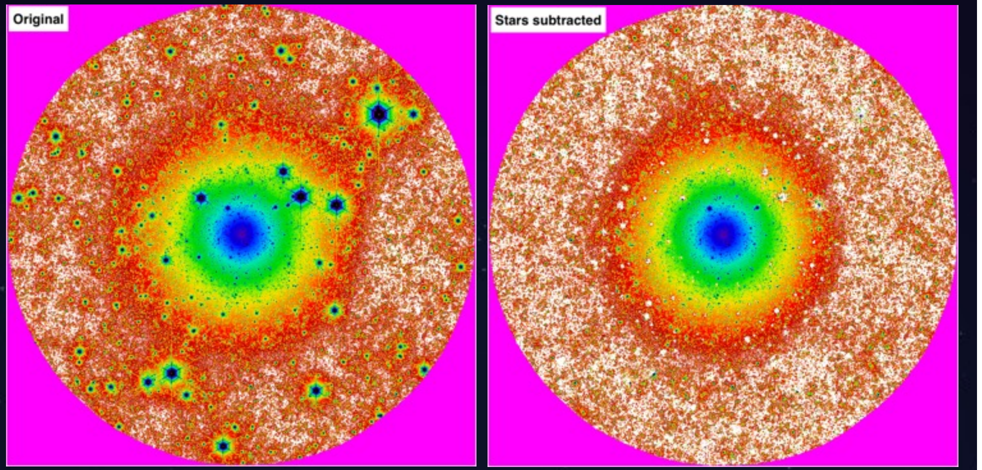

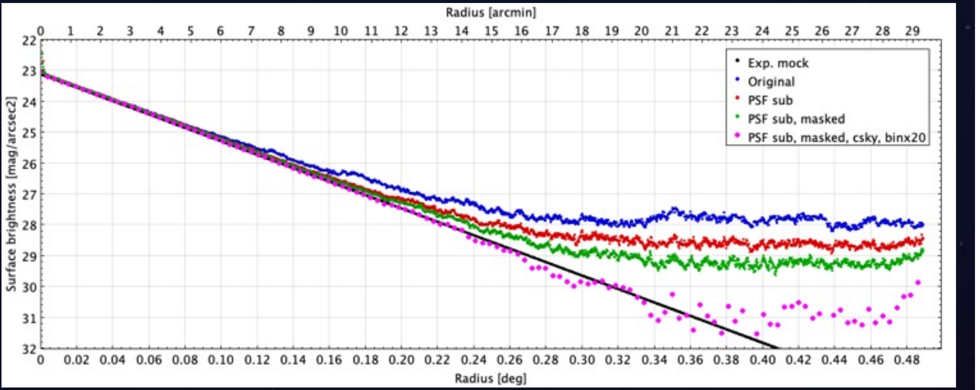

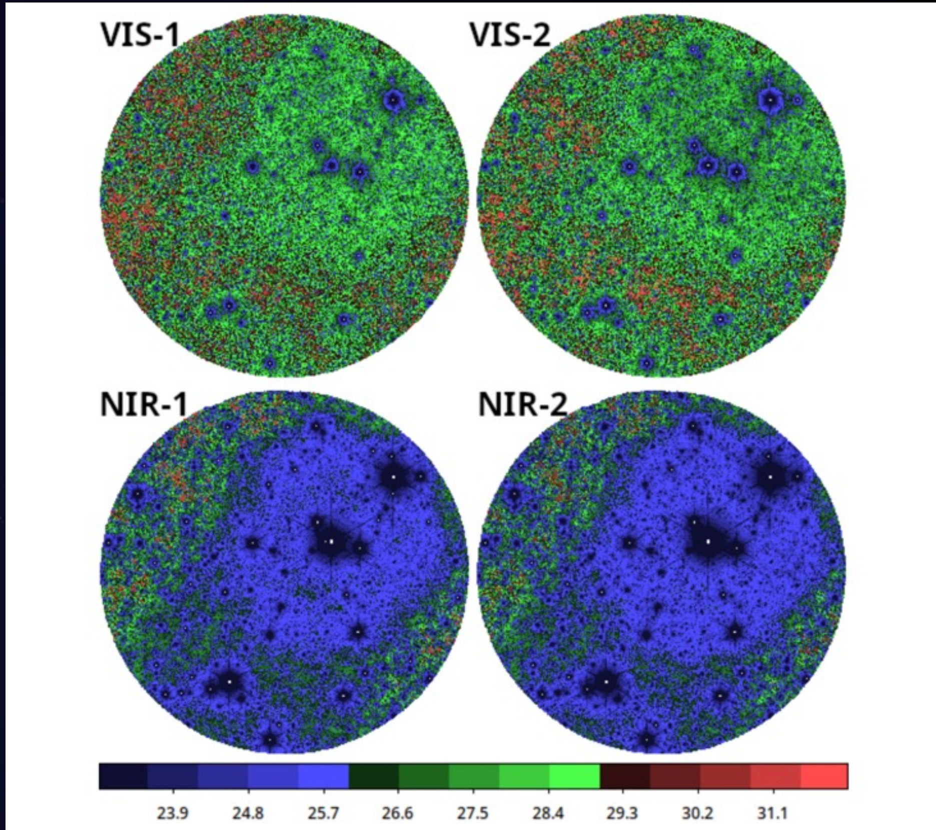

Figure 6: Surface brightness image, of stacked image in all four filters. The background noise level (about 31 mag/arcsec2) is red and the ghosts of VIS/NIR are visible at light green/blue, respectively.

	Surface brightness limit (3σ over 100 arcsec^2)	Detection limit (5σ in aperture with diameter equal to the PSF FWHM)
NIR-1	31.02 *mag/arcsec²*	26.09 *mag*
NIR-2	30.70 *mag/arcsec²*	25.78 *mag*
VIS-1	31.36 *mag/arcsec²*	27.43 *mag*
VIS-2	31.76 *mag/arcsec²*	27.82 *mag*

AMC (2024)

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AMC (2024)

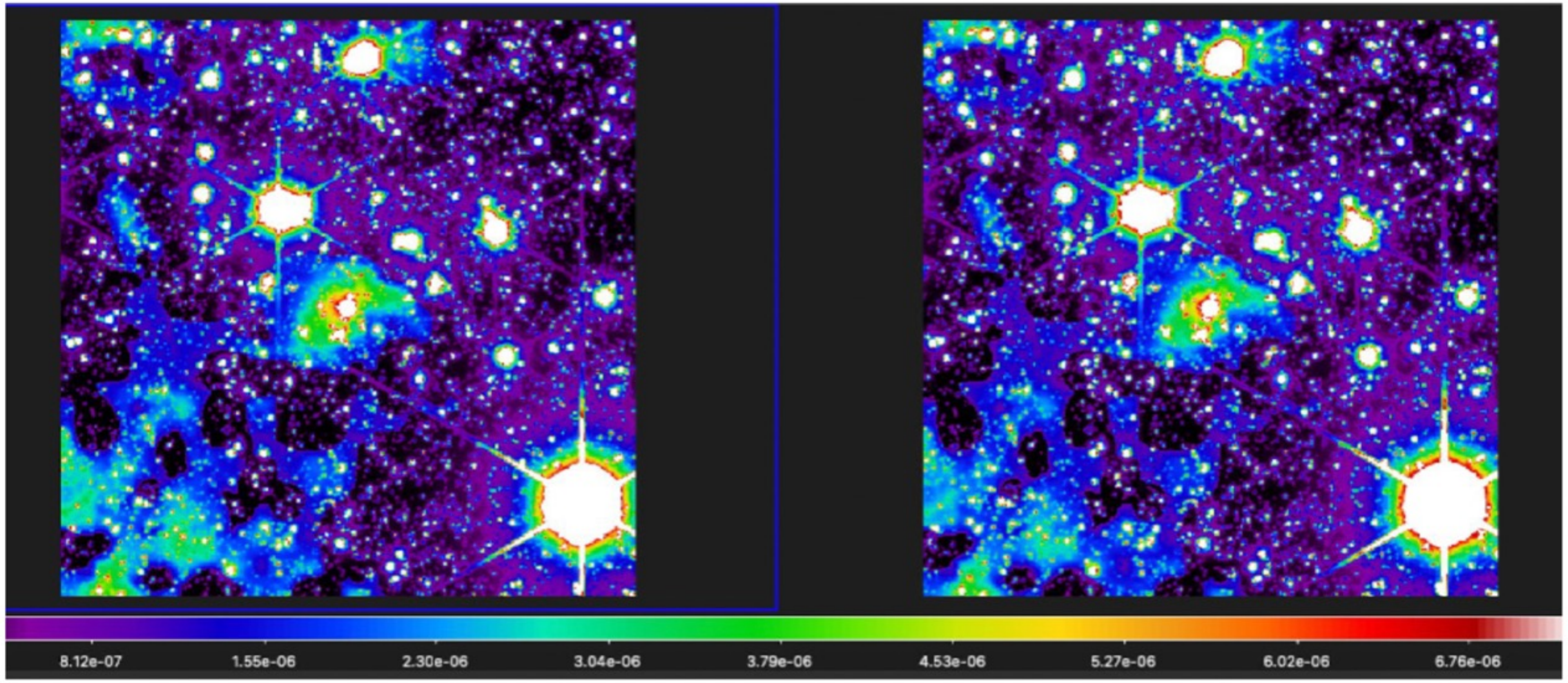
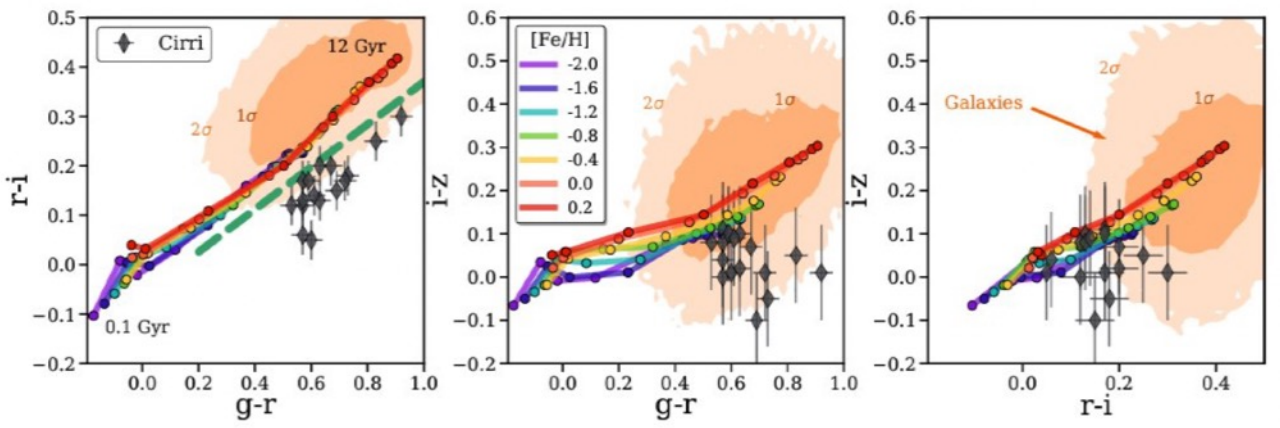


Fig 3.3.5. Example of the ARRAKIHS mock images with the simulated cirri NIR1 (left), NIR2 (right). The color scale is the same in both images.



Roman, Trujillo & Montes (2020)

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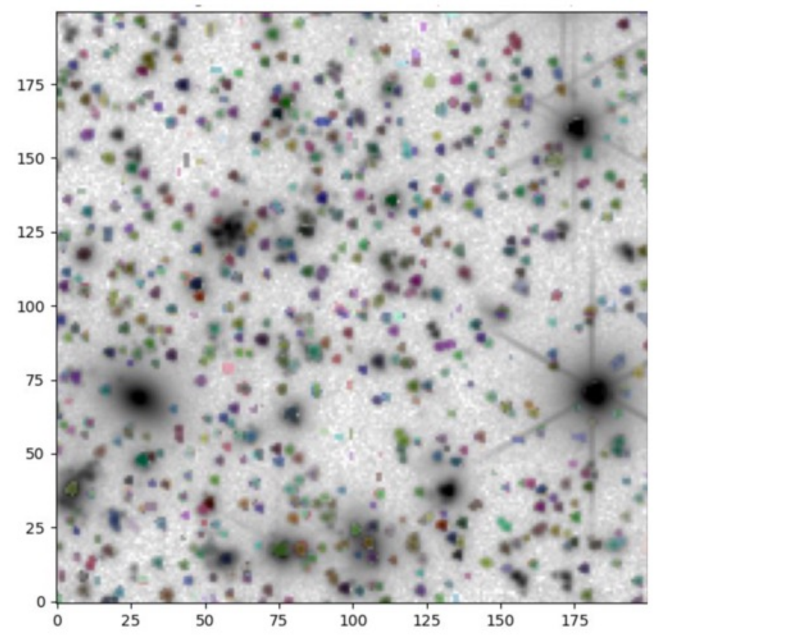


Fig 4.1.1 SAM is able to detect and segment all the faint and small sources observed by eye, even those close to bright stars.

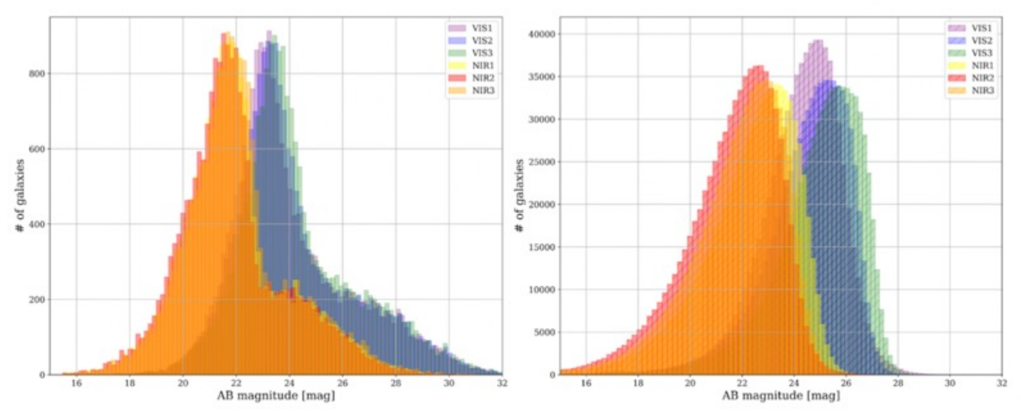
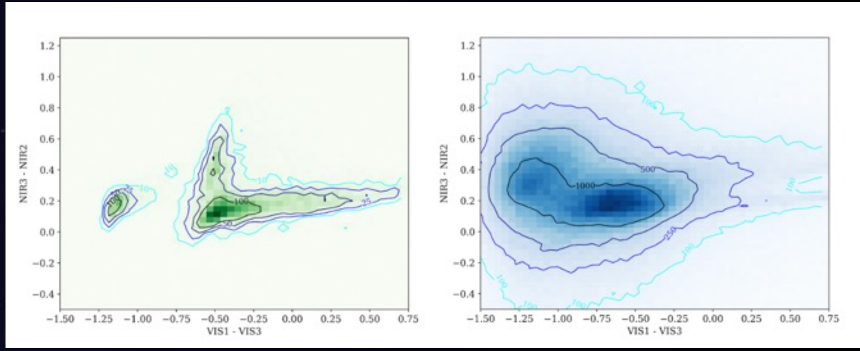
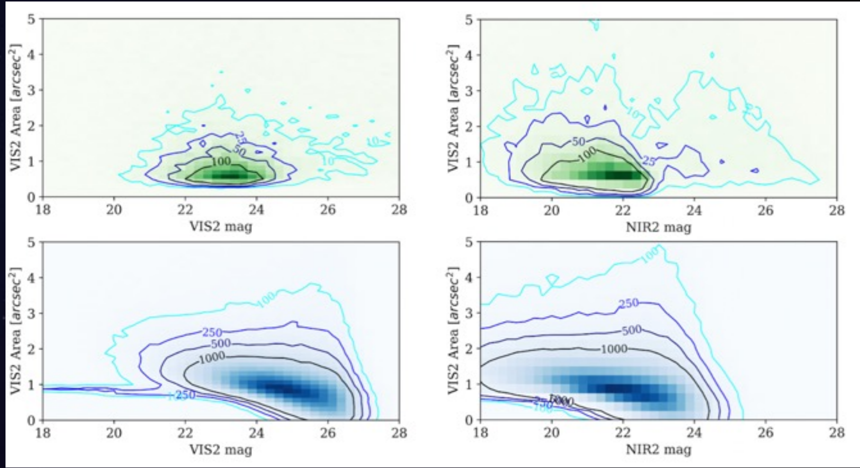
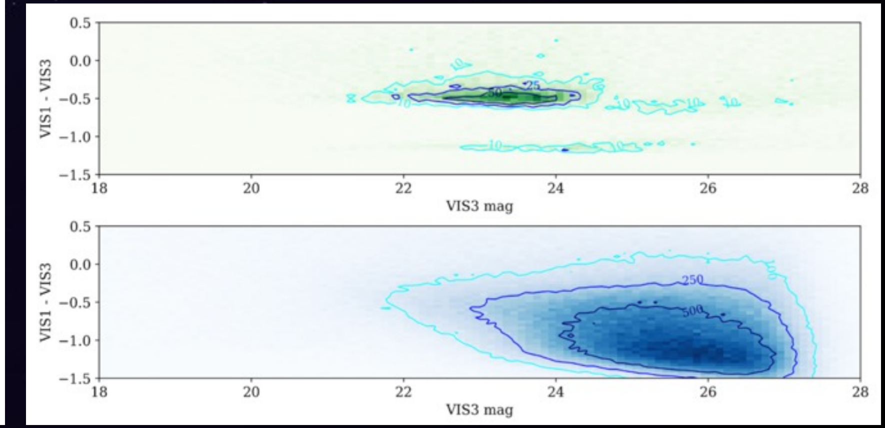


Figure 4: (Left) The magnitude histogram of IllustrisTNG300 in all 4 ARRAKIHS bands and 2 pseudo-filters (VIS3, and NIR3). (Right) The magnitude histogram of COSMOS2020 objects projected onto 4 ARRAKIHS bands and 2 pseudo-filters (VIS3, and NIR3).

AMC (2024)







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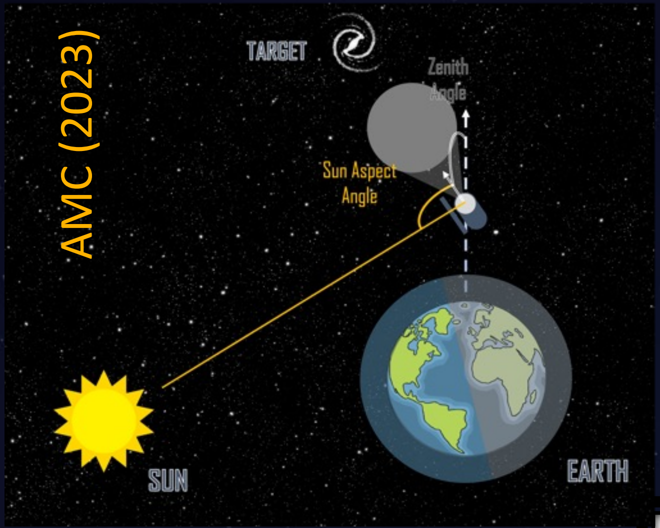


CONOPS

Height: **800 Km**

Orbit: **Sun-Synchronous, 6am-6pm**

Field of Regard:

- 90^0 < Solar Angle < 130^0
- 0^0 < Zenith Angle < 60^0

Calibrations:

- Darks, Flats
- Flux, PSF, Ghosts, etc.

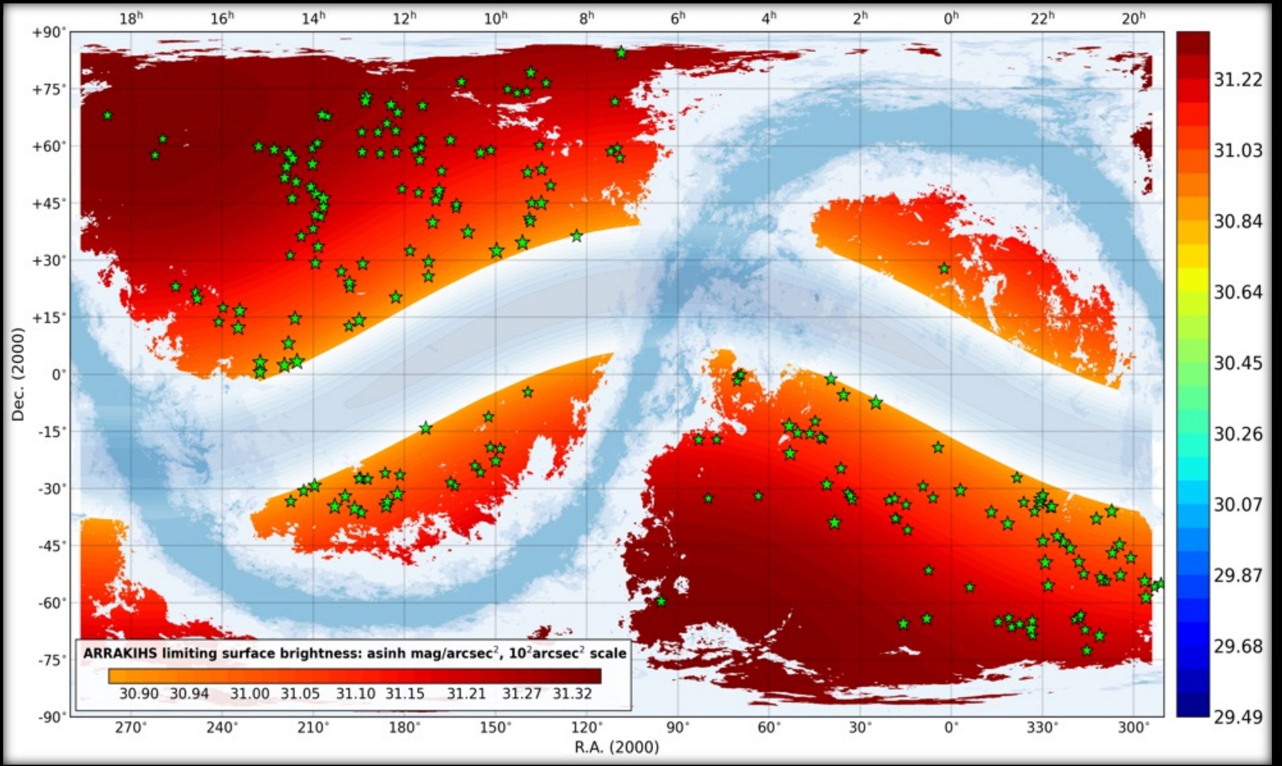
MISSION ANALYSIS

Sample: **≥75 MW-like galaxies** (ext-SAGA; Mao +2020)

- Zodiacal Light ≥ 22 J-mag arcsec^{-2}
- E(B-V) < 0.1

Total Observing time: **≥ 150 hrs/gal**

Single exposure time: **≤ 10 minutes**



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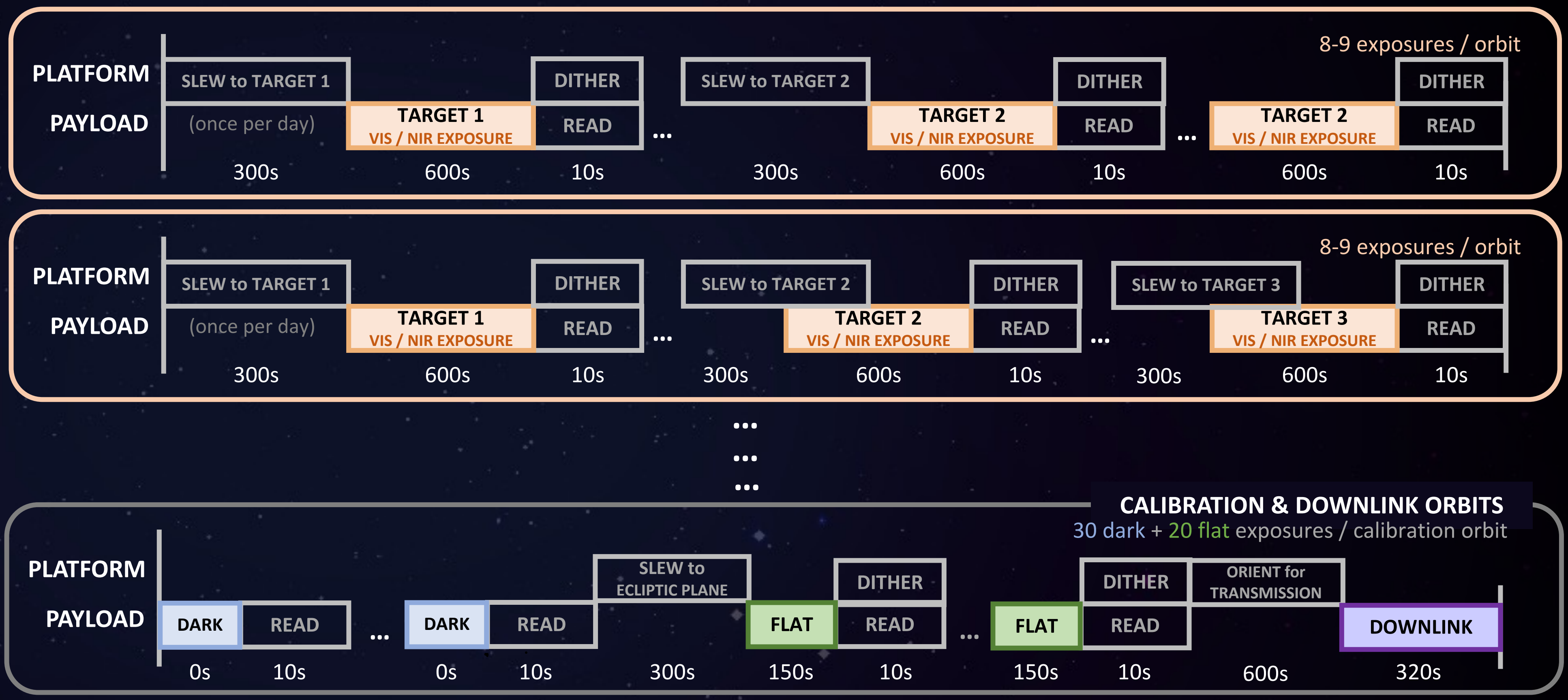

Data / Science Orbit: **4.8 Gbit**

Data / Calibration Orbit: **9.4 Gbit**

Total daily data (compressed): **40.8 Gbit (5.1 GB)**

Transmission time / day @ 15 Mbps: **45 min**

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Hunt et al. value at 3 sigma (in 100 $arcsec^2$)
VIS = 30.5 – 1.19 ~ 29.3 $mag/arcsec^2$
Y = 29.2 – 1.19 ~ 28. $mag/arcsec^2$
J = 29.4 – 1.19 ~ 28.2 $mag/arcsec^2$
H = 29.4 – 1.19 ~ 28.2 $mag/arcsec^2$

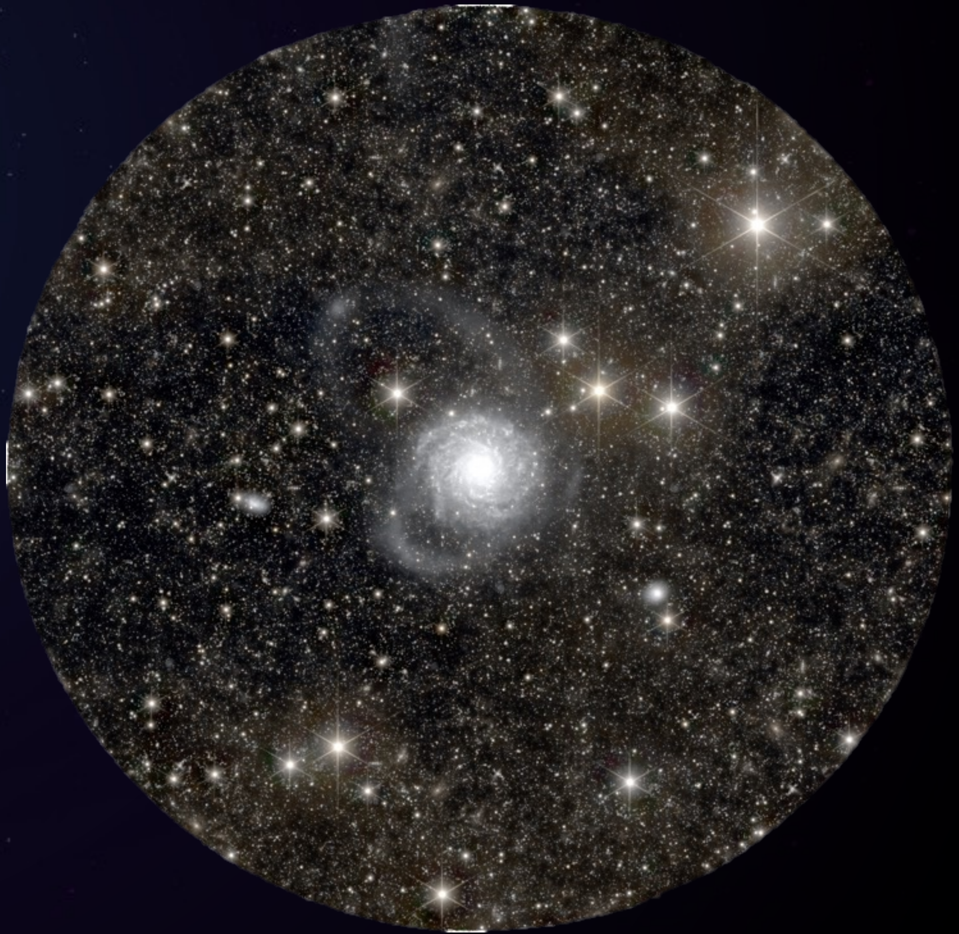
Euclid

Jablonka + AMC (2024)

Akhlaghi, Camazón + AMC (2024)

ARRAKIHS

VIS1 = 31.36 $mag/arcsec^2$
VIS2 = 31.64 $mag/arcsec^2$
NIR1 = 31.02 $mag/arcsec^2$
NIR2 = 30.70 $mag/arcsec^2$



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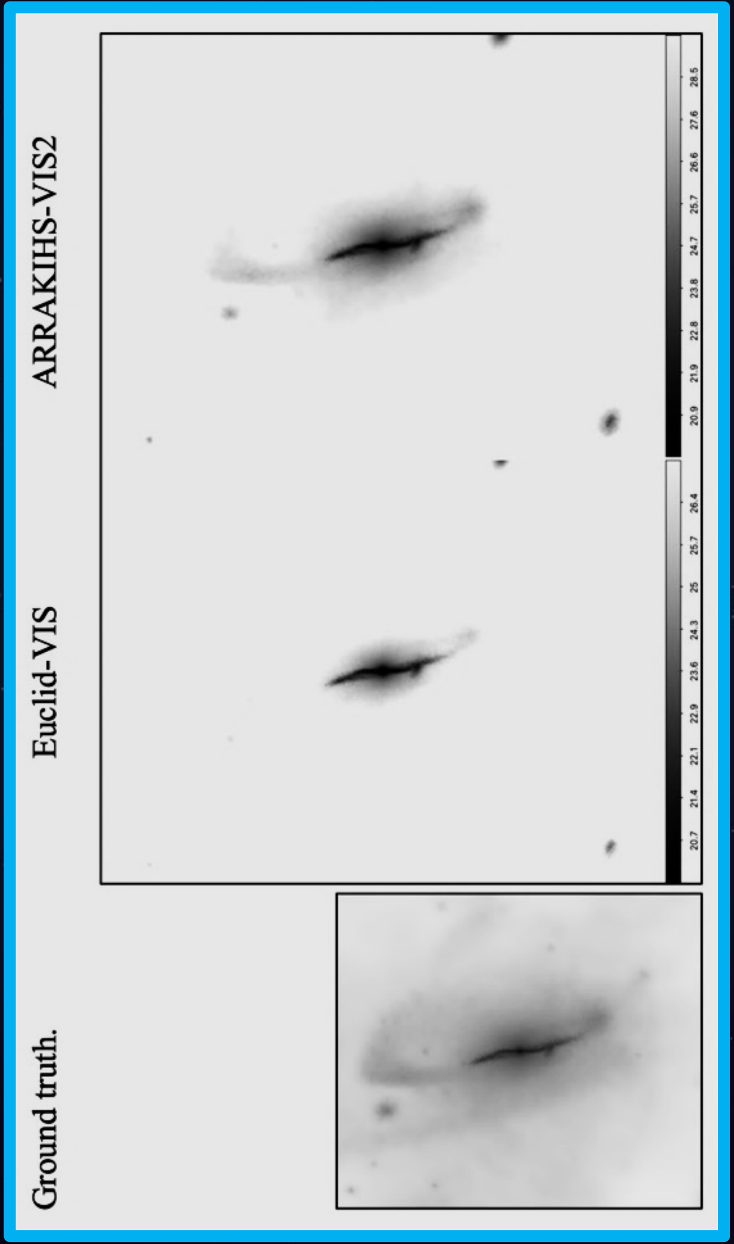

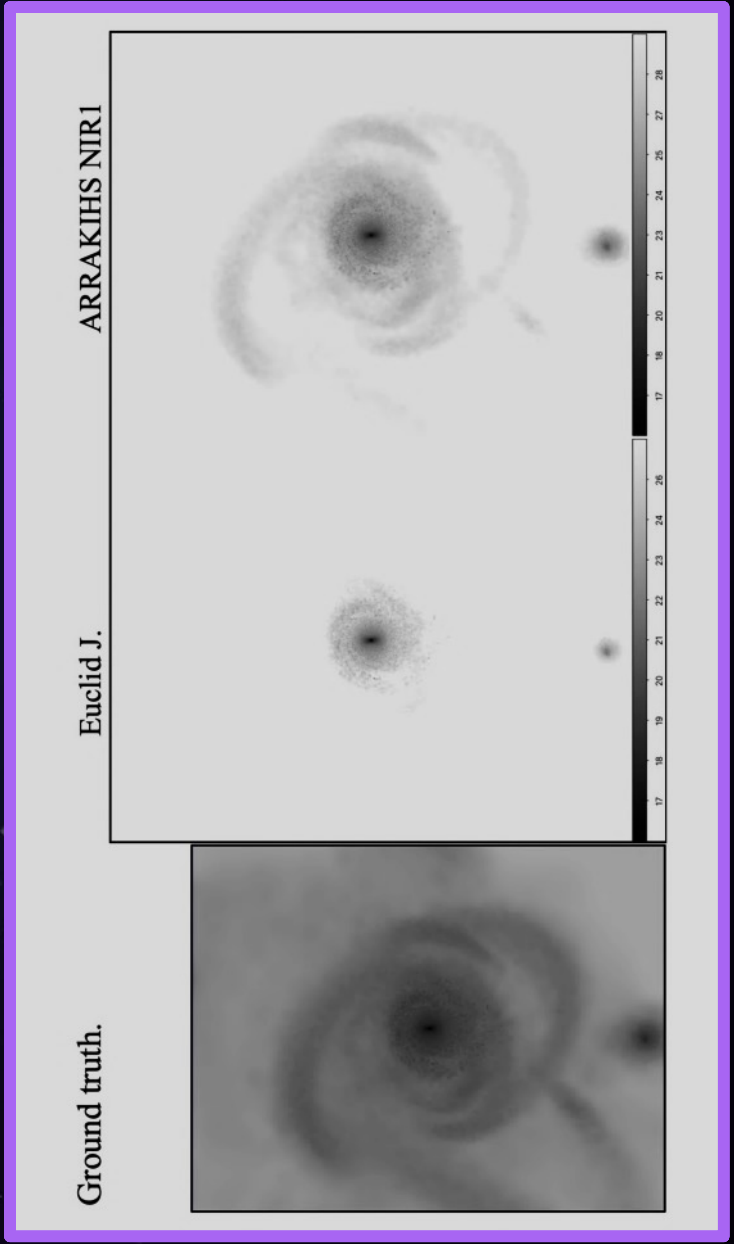

Jablonka + AMC (2024)

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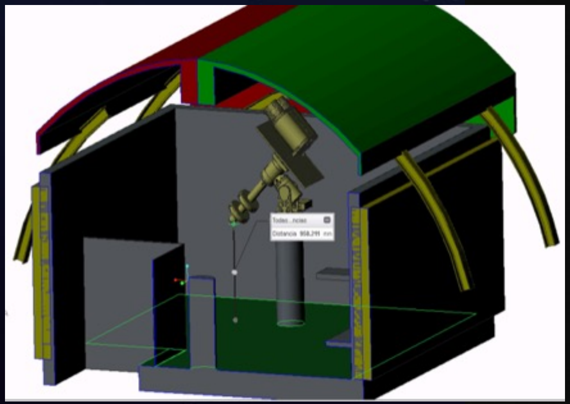
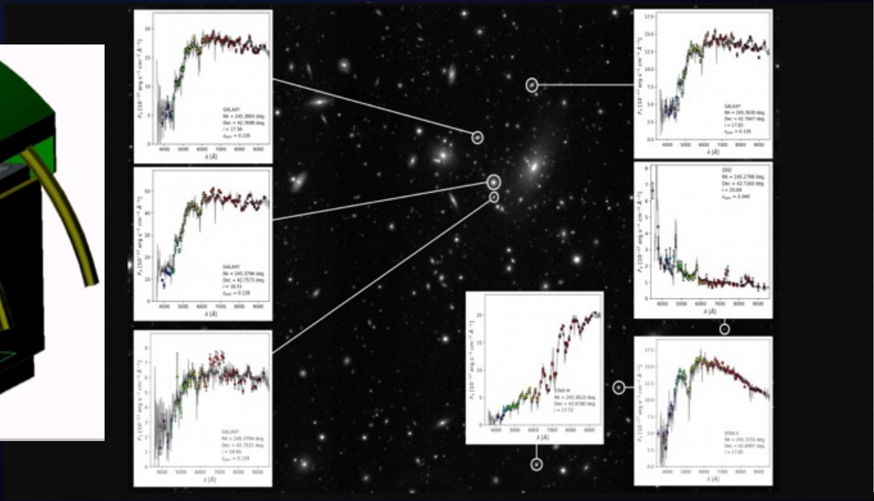
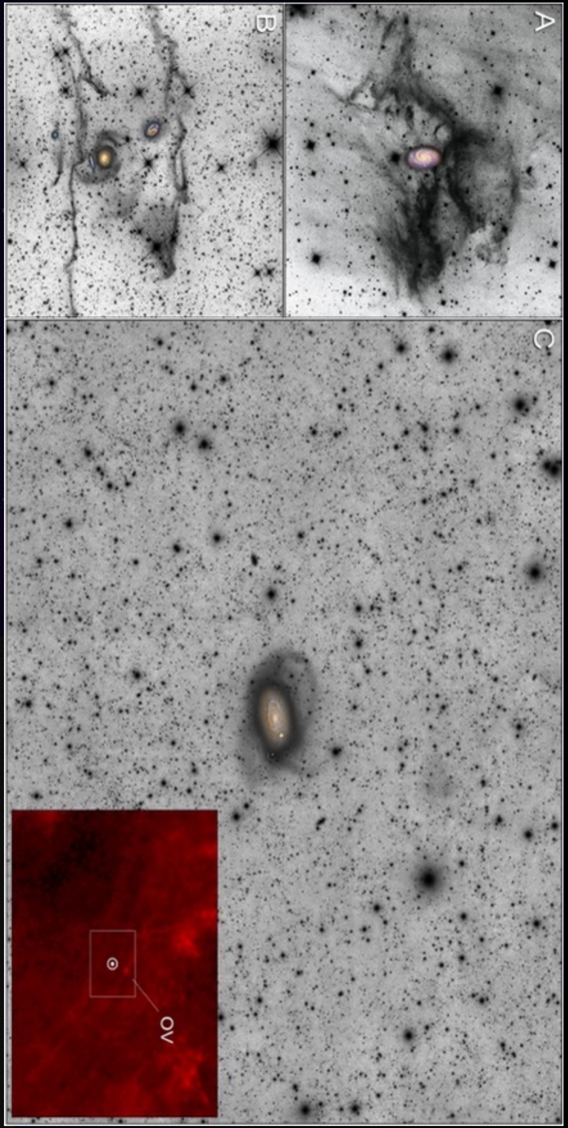
Javalambre Observatory







D. Martínez-Delgado (2023)

ARRAKIHS

Thanks!