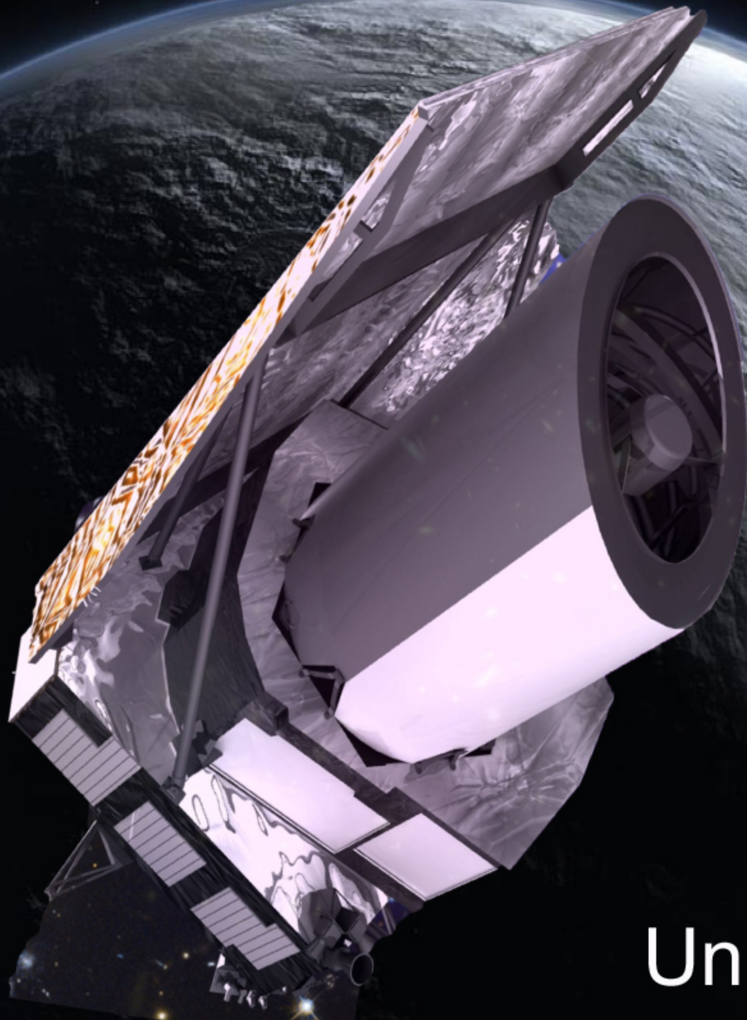
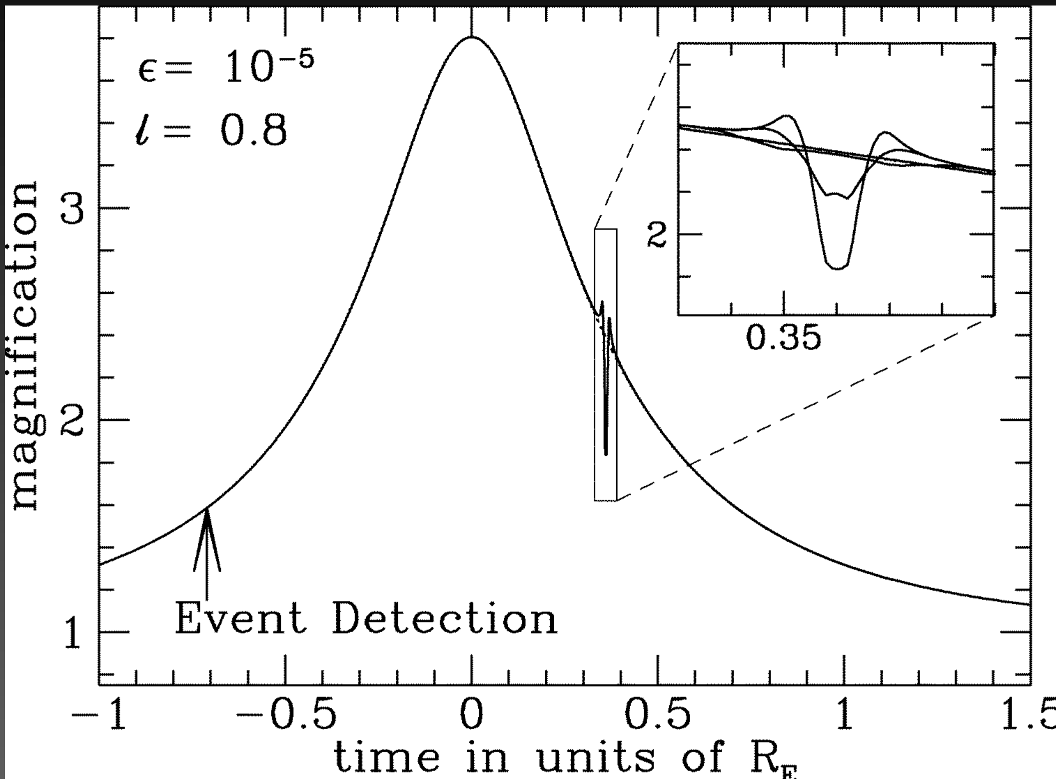
Euclid



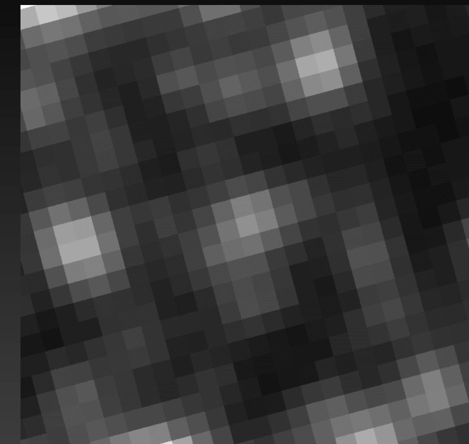
Jean-Philippe Beaulieu

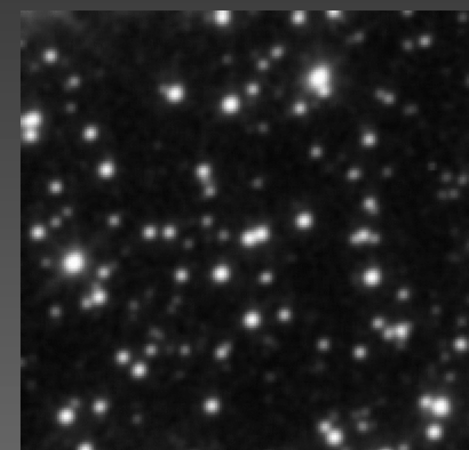
University of Tasmania, Hobart
Institut d'Astrophysique de Paris

To get small planet, you need small sources and higher angular resolution



Bennett & Rhie 1996





High Resolution + large field + 24hr duty cycle

Dark Energy & microlensing

- 2002 Bennett & Rhie space based microlensing
- 2004-2005 : Cosmic shear and microlensing from Dome C ?
  (Mellier/ Beaulieu -> after all, not a good idea, so no papers about it)
- Bennett, Gaudi et al. advocating for space based microlensing

- 2007 DUNE proposal (3 months of microlensing)

« Everything that is good for cosmic shear is good for microlensing »

Beaulieu, Kerins, Mao, Bennett, Dieters, Gaudi, Gould, Batista et al., 2008, « Towards A Census of Earth-mass Exo-planets with Gravitational Microlensing", arXiv:0808.0005

- Microlensing program on board EUCLID (proposed 4 months)
- 2010 Decadal survey with WFIRST

- Thesis of Matthew Penny: simulations for EUCLID & WFIRST.

Euclid Top Level Science Requirements

Sector	Euclid Targets
Dark Energy	• Measure the cosmic expansion history to better than 10% in redshift bins $0.7 < z < 2$. • Look for deviations from $w = -1$, indicating a dynamical dark energy. • Euclid *alone* to give $FoM_{DE} \geq 400$ (1-sigma errors on w_p, & w_a of 0.02 and 0.1 respectively)
Test Gravity	• Measure the growth index, γ, with a precision better than 0.02 • Measure the growth rate to better than 0.05 in redshift bins between $0.5 < z < 2$. • Separately constrain the two relativistic potentials Ψ, Φ. • Test the cosmological principle
Dark Matter	• Detect dark matter halos on a mass scale between 10^8 and $>10^{15}$ M_{Sun} • Measure the dark matter mass profiles on cluster and galactic scales • Measure the sum of neutrino masses, the number of neutrino species and the neutrino hierarchy with an accuracy of a few hundredths of an eV
Initial Conditions	• Measure the matter power spectrum on a large range of scales in order to extract values for the parameters σ_8 and n to a 1-sigma accuracy of 0.01. • For extended models, improve constraints on n and α wrt to Planck alone by a factor 2. • Measure a non-Gaussianity parameter : f_{NL} for local-type models with an error < +/-2.

- DE equation of state: $P/\rho = w$, and $w(a) = w_p + w_a(a_p - a)$
- Growth rate of structure formation: $f \sim \Omega^{\gamma}$;
- FoM=$1/(\Delta w_a \times \Delta w_p) > 400$ → ~1% precision on w's.

Euclid consortium

Euclid cosmological probes

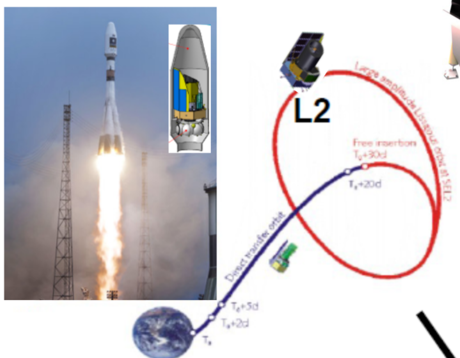
Observational Input	Probe	Description
Weak Lensing Survey	Weak Lensing (WL)	Measures the expansion history and the growth factor of structure
Galaxy Redshift Survey: Analysis of *P(k)*	Baryonic Acoustic Oscillations (BAO)	Measure the expansion history through D(z) and H(z) using the "wiggles-only".
	Redshift-Space distortions	Determine the growth *rate* of cosmic structures from the redshift distortions due to peculiar motions
	Galaxy Clustering	Measures the expansion history and the growth factor using all available information in the amplitude and shape of P(k)
Weak Lensing plus Galaxy redshift survey combined with cluster mass surveys	Number density of clusters	Measures a combination of growth factor (from number of clusters) and expansion history (from volume evolution).
Weak lensing survey plus galaxy redshift survey combined with CMB surveys	Integrated Sachs Wolfe (ISW) effect	Measures the expansion history and the growth
Weak lensing survey plus galaxy redshift survey combined with CMB surveys	Weak lensing on CMB anisotropies	Measures the high redshift expansion regime and growth of structures

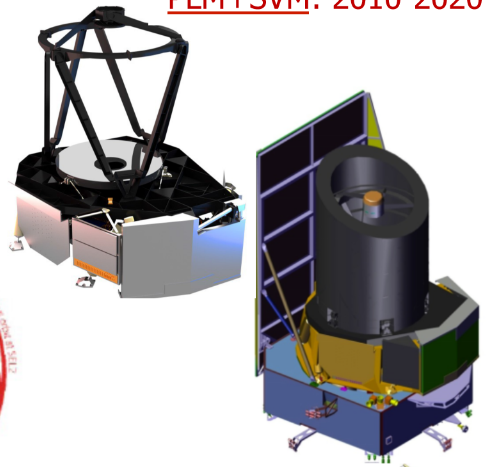
The ESA Euclid space mission

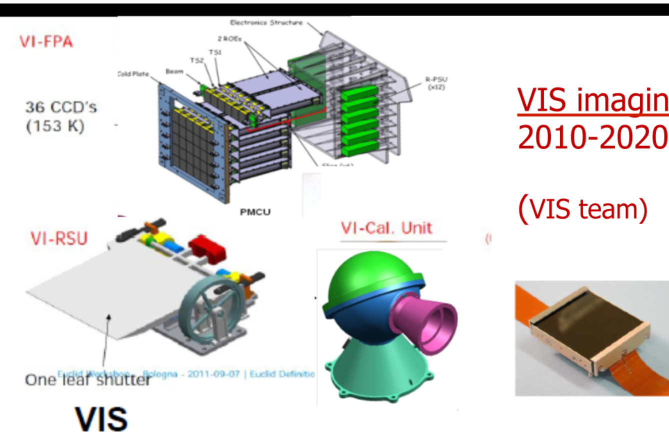
PLM+SVM: 2010-2020

Soyuz@Kourou

Launch date: Dec 2020

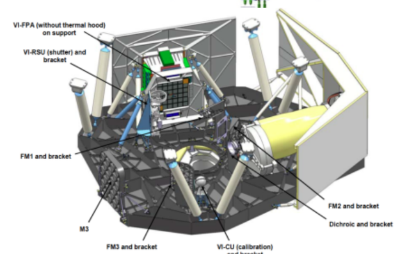






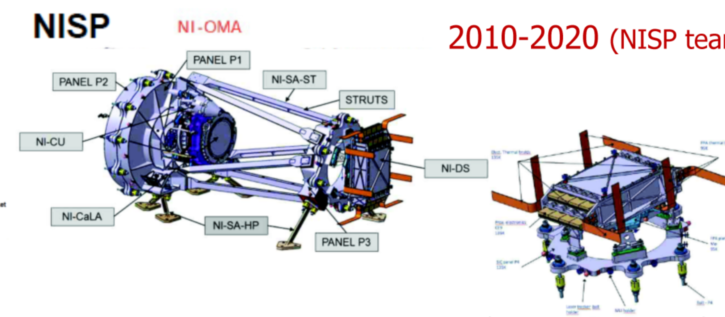
VIS imaging: 2010-2020

(VIS team)

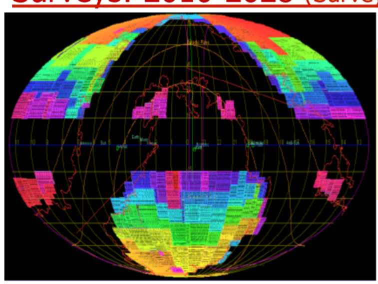


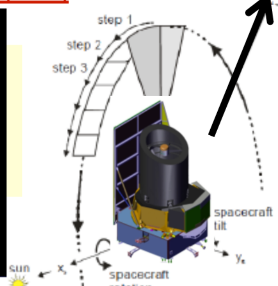
NIR spectro-imaging

2010-2020 (NISP team)



Surveys: 2010-2028 (Survey WG)





Survey duration: 6 yrs

15,000 deg²

Commisionning – SV

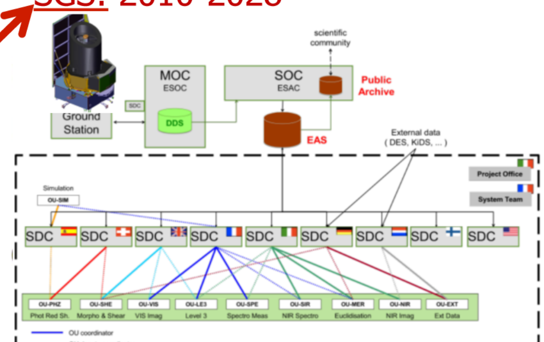
Euclid opération:

5.5 yrs:Euclid Wide+Deep

+: SNIa, mu-lens, MW?

Ground data

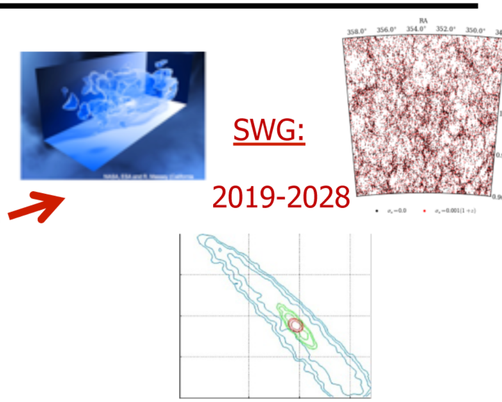
SGS: 2010-2028



~100 PB data processing (EC-SGS team)

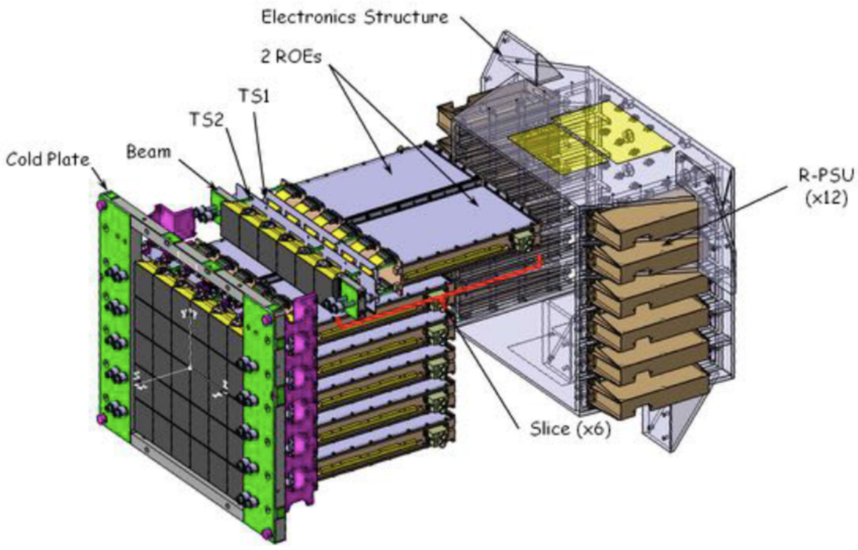
SWG:

2019-2028



Science analyses

VIS

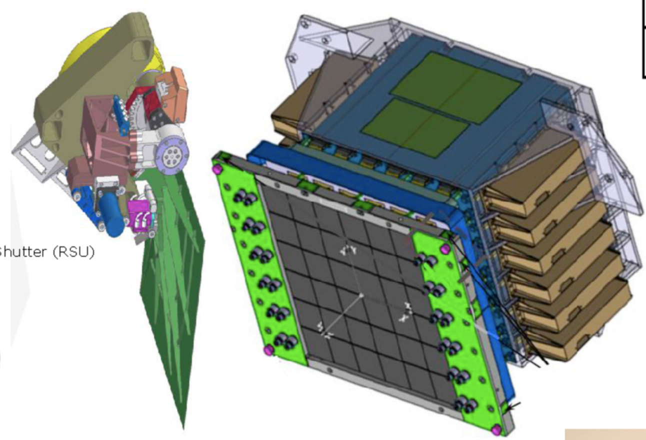


Courtesy: S. Pottinger, M. Cropper and the VIS team

Table 1: VIS and weak lensing channel characteristics

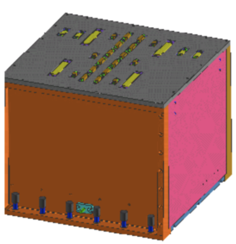
Spectral Band	550 – 900 nm
System Point Spread Function size	≤0.18 arcsec full width half maximum at 800 nm
System PSF ellipticity	≤15% using a quadrupole definition
Field of View	>0.5 deg^2
CCD pixel sampling	0.1 arcsec
Detector cosmetics including cosmic rays	≤3% of bad pixels per exposure
Linearity post calibration	≤0.01%
Distortion post calibration	≤0.005% on a scale of 4 arcmin
Sensitivity	$m_{AB} \geq 24.5$ at 10σ in 3 exposures for galaxy size 0.3 arcsec
Straylight	≤20% of the Zodiacal light background at Ecliptic Poles
Survey area	15000 deg^2 over a nominal mission with 85% efficiency
Mission duration	6 years including commissioning
Shear systematic bias allocation	additive $\sigma_{sys} \leq 2 \times 10^{-4}$; multiplicative $\leq 2 \times 10^{-3}$

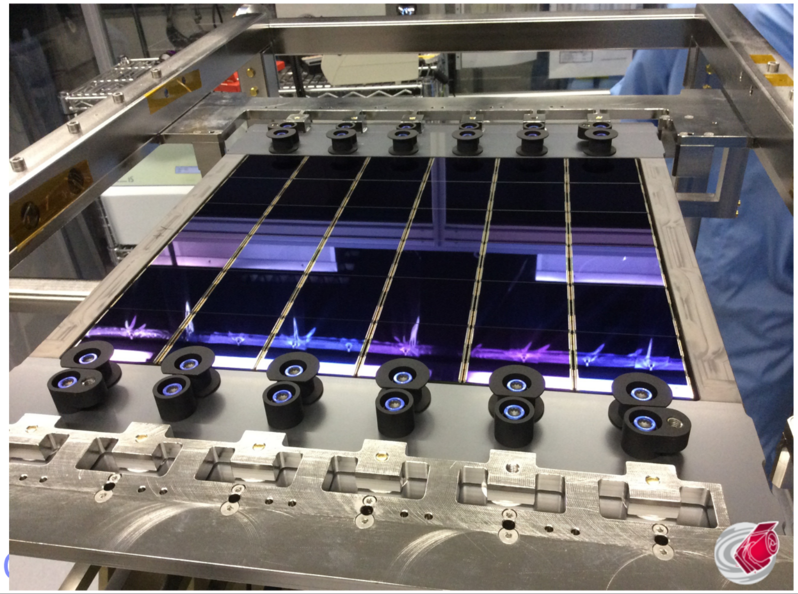
Cropper et al 2016.SPIE



Warm Units in Service Module

Payload and Mechanism Control Unit (PMCU)

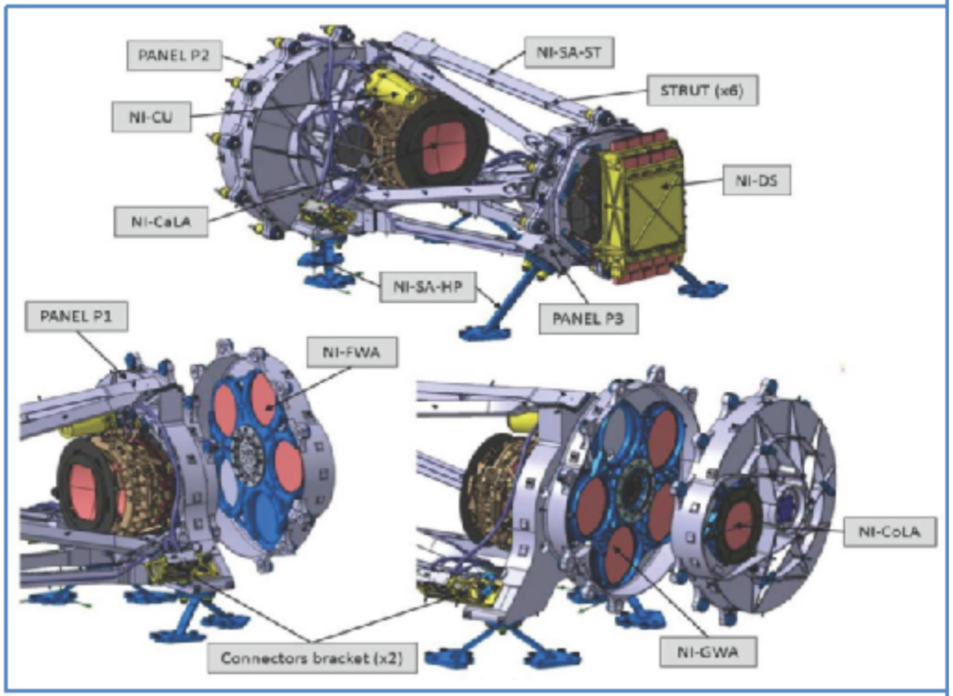


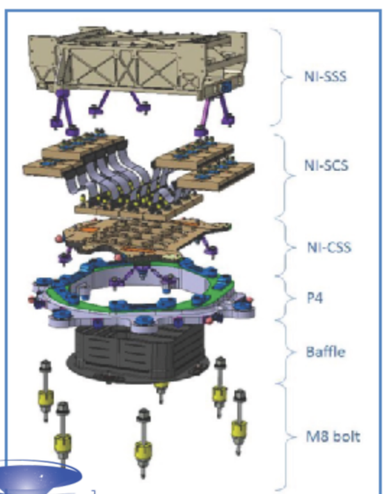


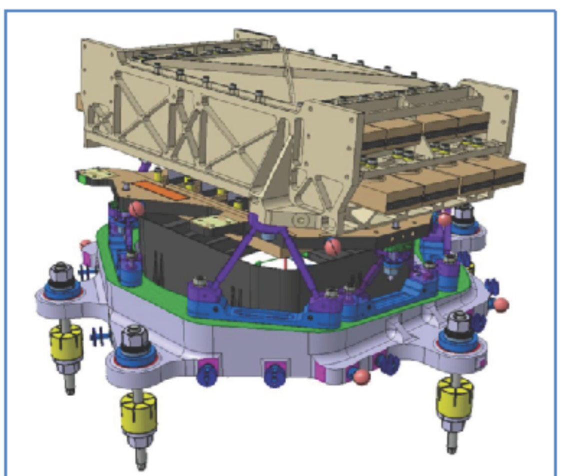
Euclid C

NISP

Courtesy: T. Maciaszek and the NISP team



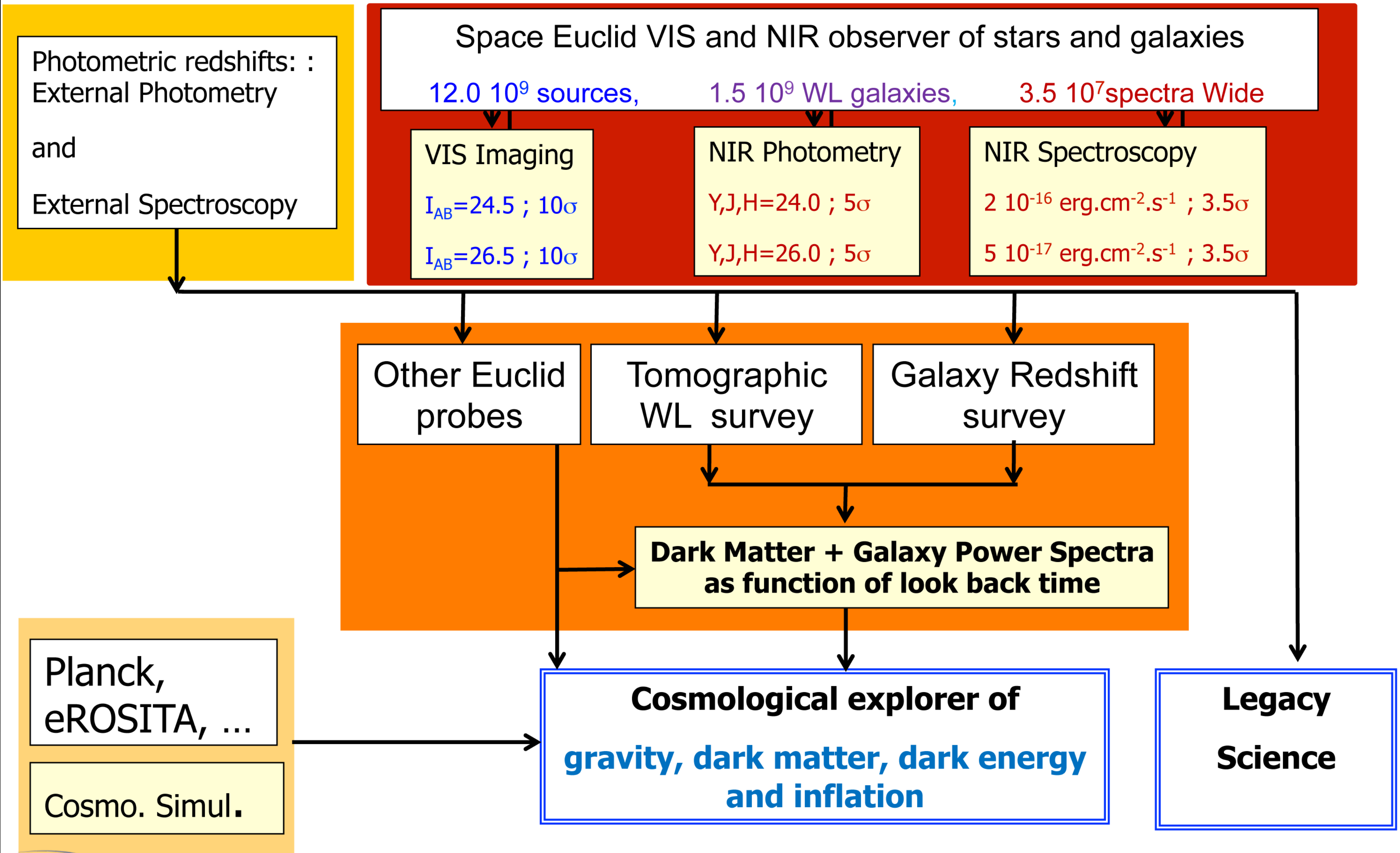




- FoV: 0.55 deg^2
- Mass : 159 kg
- Telemetry: < 290 Gbt/day
- Size: 1m x 0.5 m x 0.5 m
- 16 2kx2K H2GR detectors
- 0.3 arcsec pixel on sky
- Limiting mag, wide survey AB : 24 (5 σ)
- **3 Filters**:
- Y (950-1192nm)
- J (1192, 1544nm)
- H (1544, 2000nm)
- **4 grisms**:
- 1B (920 – 1300) , 1 orientation 0°
- 3R (1250 – 1850), 3 orientations 0°, 90°, 180°

Maciaszek et al 2016:SPIE

Euclid Survey Machine:15,000 deg^2 + 40 deg^2 deep



ESA Mission PDR October 2015 successful:

Technical Performance Measure		Requirement	CBE
Image Quality			
VIS Channel	FWHM (@ 800nm)	180 mas	163 mas
	ellipticity	15.0%	5.9%
	R2 (@ 800 nm)	0.0576	0.0530
	ellipticity stability σ(εi)	2.00E-04	2.00E-04
	R2 stability σ(R2)/<R2>	1.00E-03	1.00E-03
	Plate scale	0.10 "	0.10 "
	Out-of-band avg red side	1.00E-03	1.13E-05
	Out-of-band avg blue side	1.00E-03	2.12E-04
	Slope red side	35 nm	15 nm
	Slope blue side	25 nm	8 nm
NISP Channel	rEE50 (@1486nm)	400 mas	217 mas
	rEE80 (@1486nm)	700 mas	583 mas
	Plate scale	0.30 "	0.30 "
Sensitivity			
VIS SNR (for mAB = 24.5 sources)		10	17.1
NISP-S SNR (@ 1.6um for 2xe-16 erg cm-2 s-1 source)		3.5	4.87
NISP- P SNR (for mAB = 24 sources)	Y-band	5	5.78
	J-band	5	6.69
	H-band	5	5.35
NISP-S Performance			
Purity		80%	72%
Completeness		45%	0.52
Survey			
Wide Survey Coverage		15,000 deg2	15,000
Survey length [years]		5.5	5.4

Euclid performances meet the scientific and survey requirements

- Image quality of the system fully in line with needs.
- Ellipticity, R^2 stability and Non-convolutive errors performance dictated mainly by ground processing
- *Purity* not compliant with current data processing methods but expected to be recovered with Euclid specific algorithms (not yet installed at this stage).

Need Wide+Deep Surveys: photom+spectro

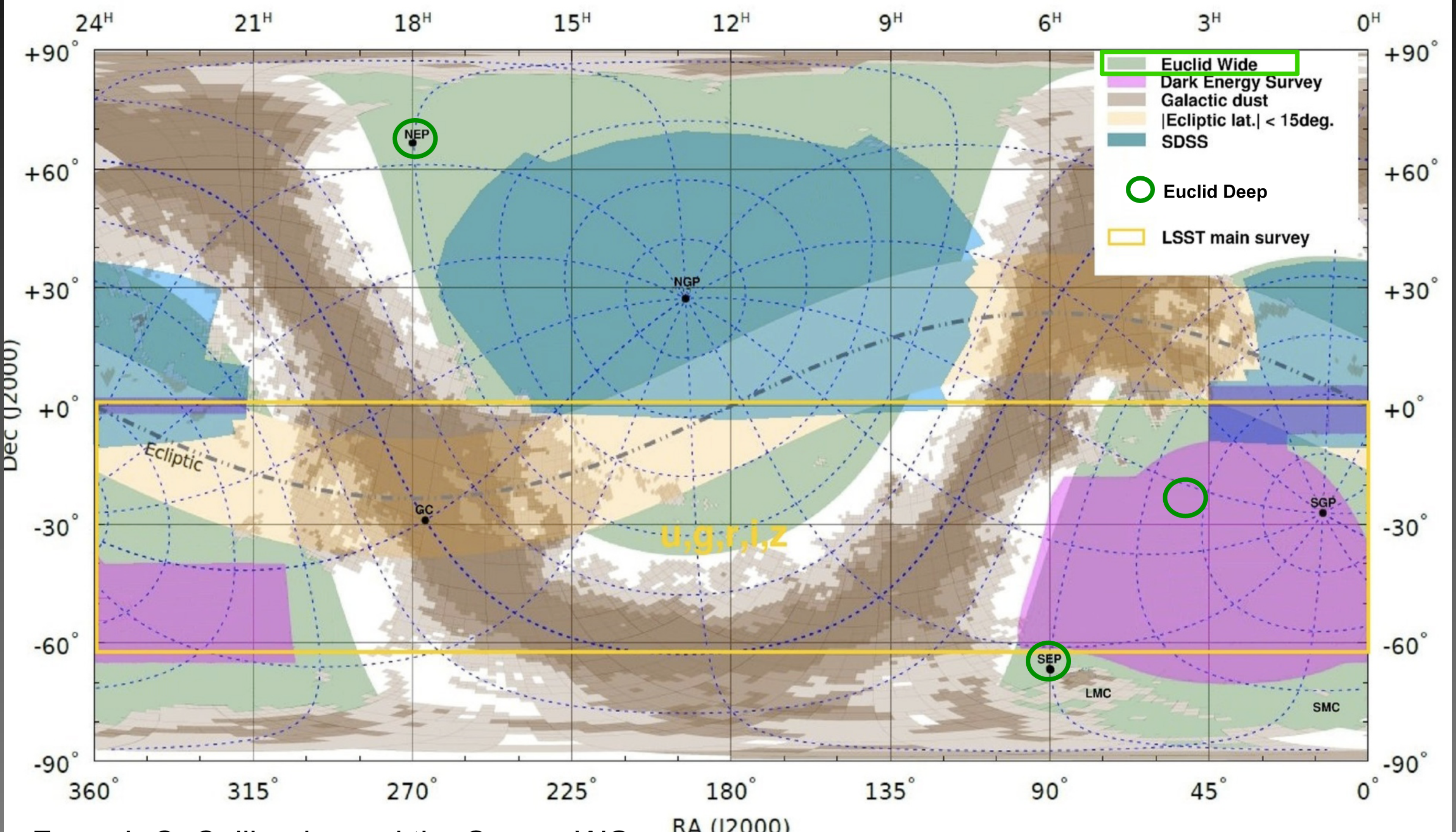
- **Euclid Wide:**
  - 15000 deg^2 outside the galactic and ecliptic planes
  - 12 billion sources (3-σ)
  - 1.5 billion galaxies with
    - Very accurate morphometric information (WL)
    - Visible photometry: (u), g, r, i, z , (R+I+Z) AB=24.5, 10.0 σ +
    - NIR photometry : Y, J, H AB = 24.0, 5.0σ
    - Photometric redshifts with 0.05(1+z) accuracy
  - 35 million spectroscopic redshifts of emission line galaxies with
    - 0.001 accuracy
    - Halpha galaxies within $0.7 < z < 1.85$
    - Flux line: 2 . 10^{-16} erg.cm^{-2}.s^{-1} ; 3.5σ

- **Euclid Deep:**
  - 1x10 deg^2 at North Ecliptic pole + 1x20 deg^2 at South Ecliptic pole

    + 1x10 deg^2 South close to Equatorial area
  - 10 million sources (3-σ)
  - 1.5 million galaxies with
    - Very accurate morphometric information (WL)
    - Visible photometry: (u), g, r, i, z , (R+I+Z) AB=26.5, 10.0 σ +
    - NIR photometry : Y, J, H AB = 26.0, 5.0σ
    - Photometric redshifts with 0.05(1+z) accuracy
  - 150 000 spectroscopic redshifts of emission line galaxies with
    - 0.001 accuracy
    - Halpha galaxies within $0.7 < z < 1.85$
    - Flux line: 5 . 10^{-17} erg.cm^{-2}.s^{-1} ; 3.5σ

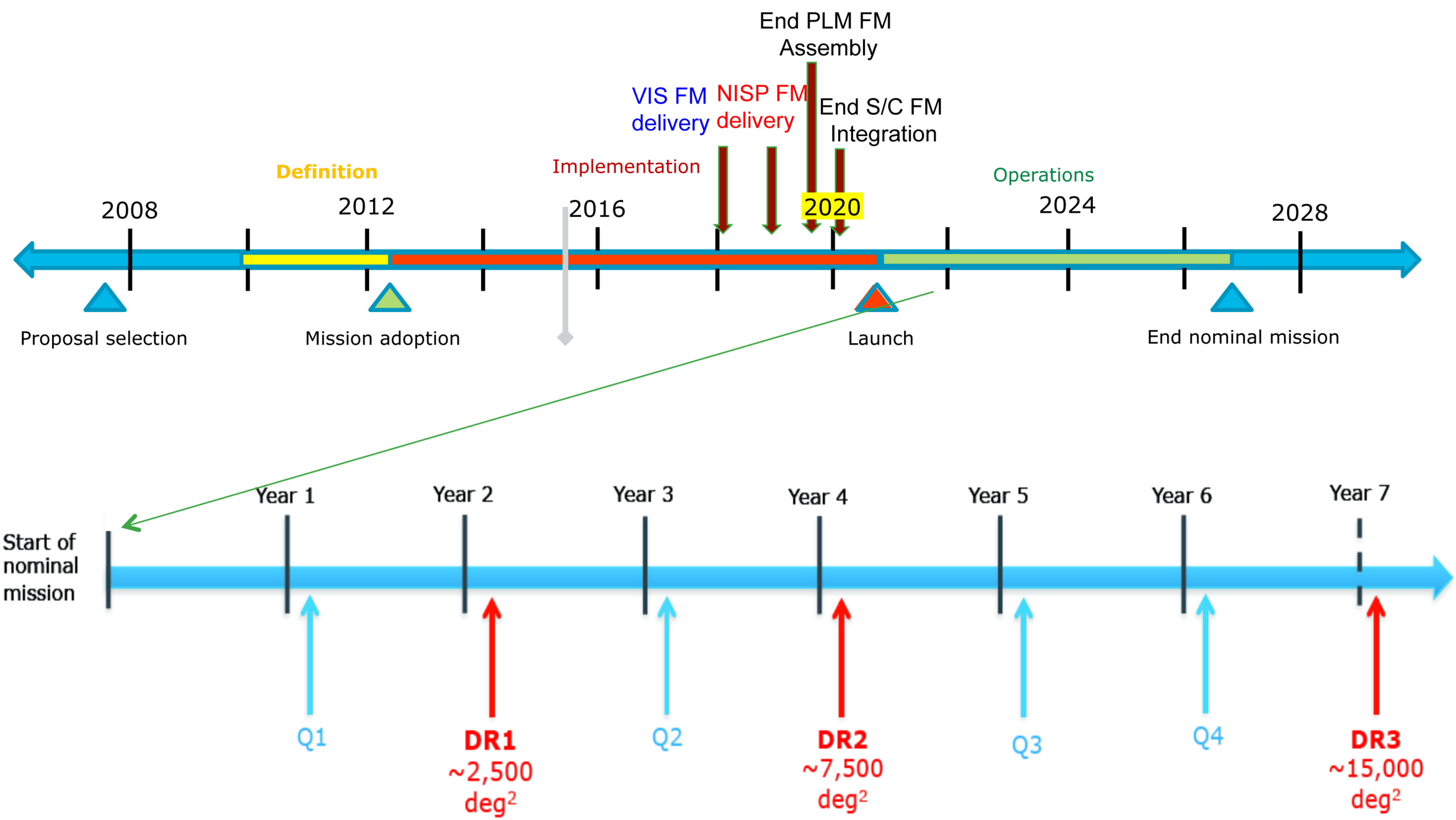
Euclid consortium

Euclid Wide and Deep Surveys



From J.-C. Cuillandre and the Survey WG

Overview mission timeline



Science with Euclid will start in 2022 with Q1 and in 2023 with DR1

Sun Avoidance Angle

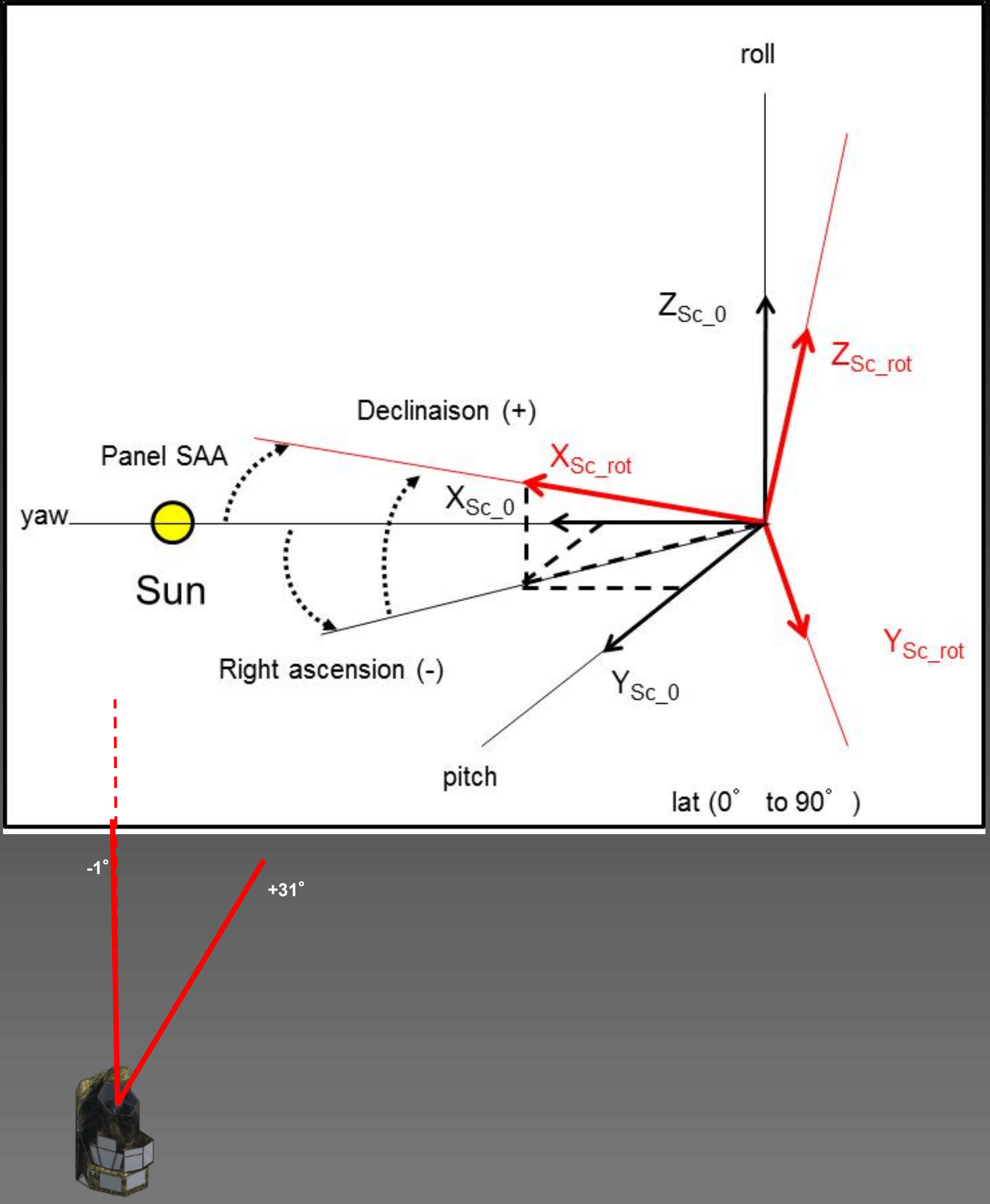
Pointing constraints

The S/C can be operated for a certain range of SAA orientations that limit depointing of the S/C:

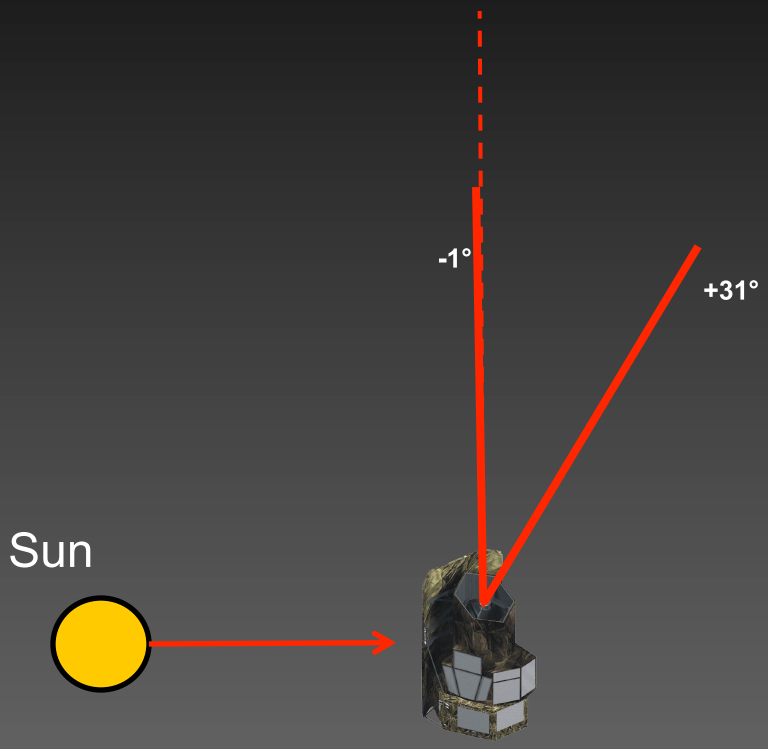
MRD R-440-8: The EUCLID spacecraft shall be able to implement the Deep and the Wide Extragalactic Survey with a variable solar aspect angle included between 89 degrees and 121 degrees.

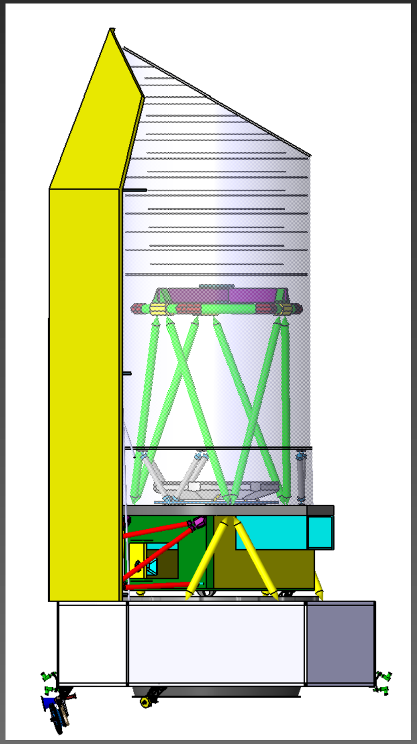
PSF stability requirements can be ensured for a given range of SAA variation around a reference pointing direction:

MOCD R-SYS-OP-MS-030: The EUCLID spacecraft shall be able to implement the Deep and the Wide Extragalactic Survey with a variable solar aspect angle included between 90 degrees and 95 degrees.

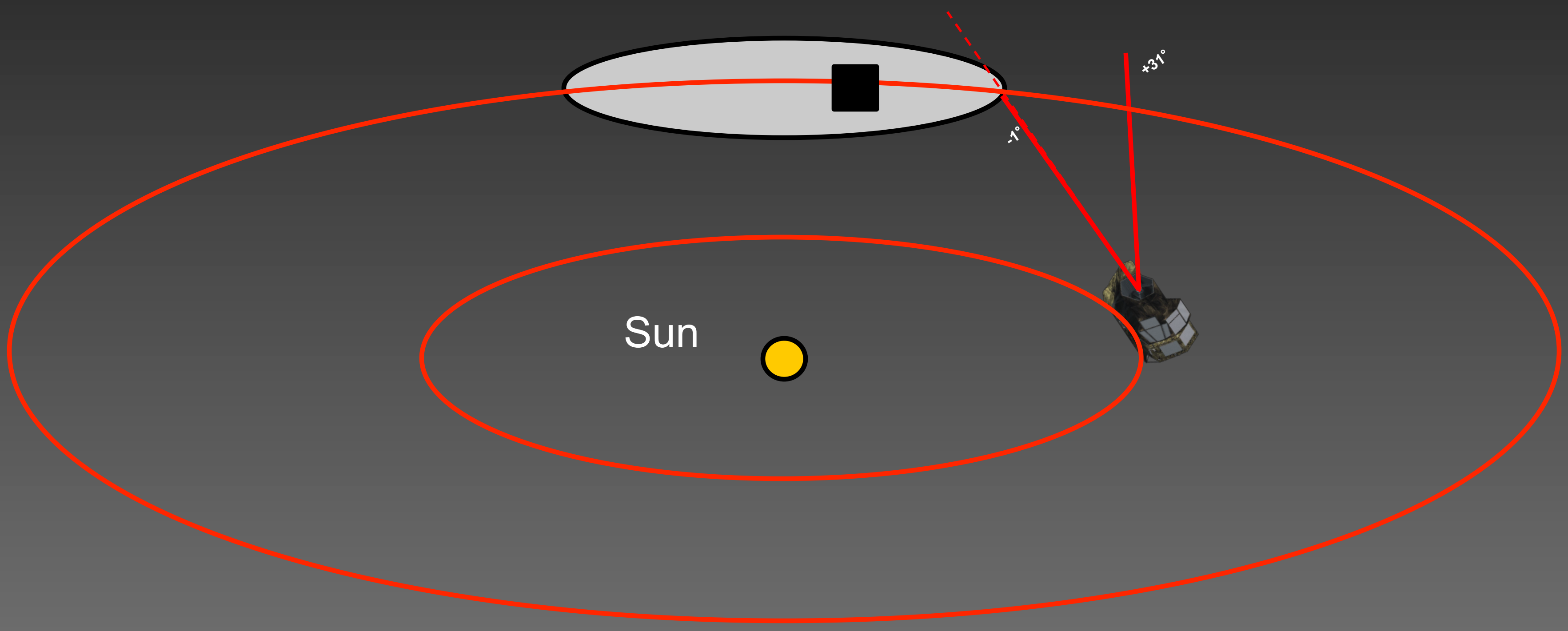


Work Flow for Survey Optimisation





Work Flow for Survey Optimisation



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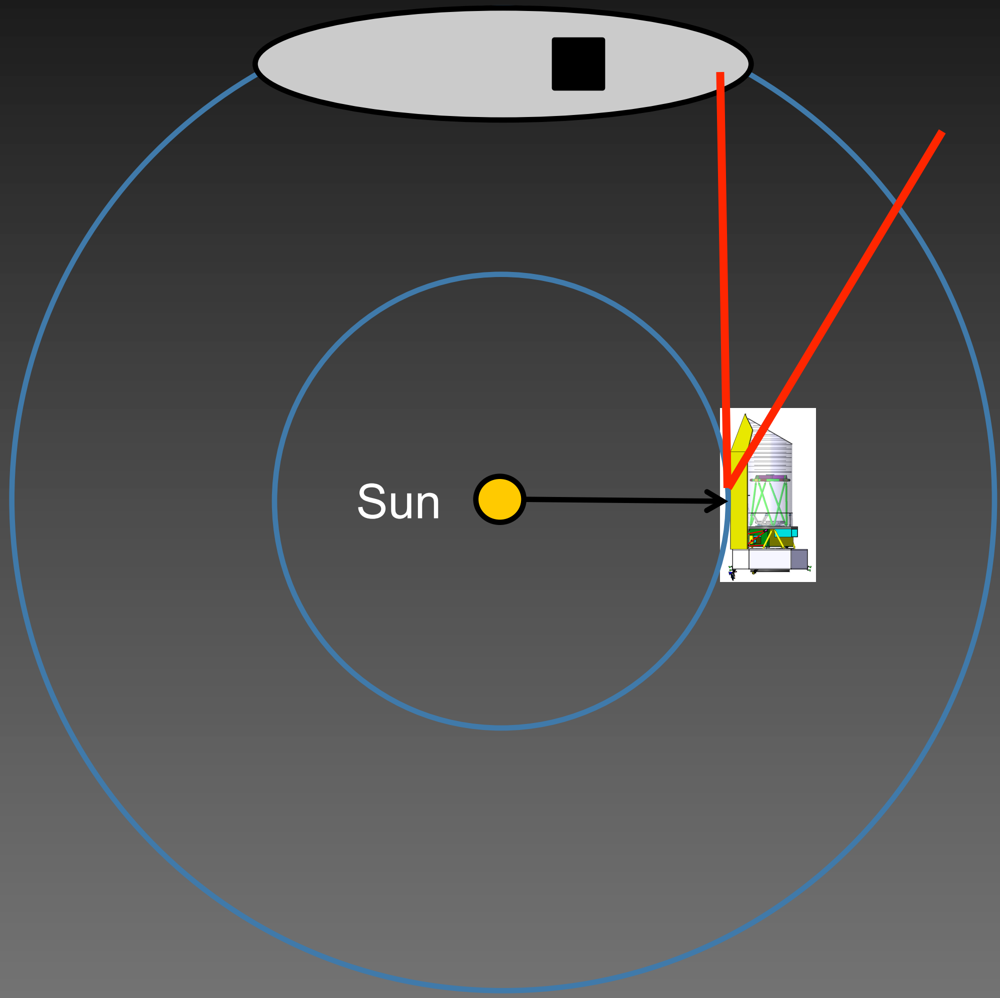

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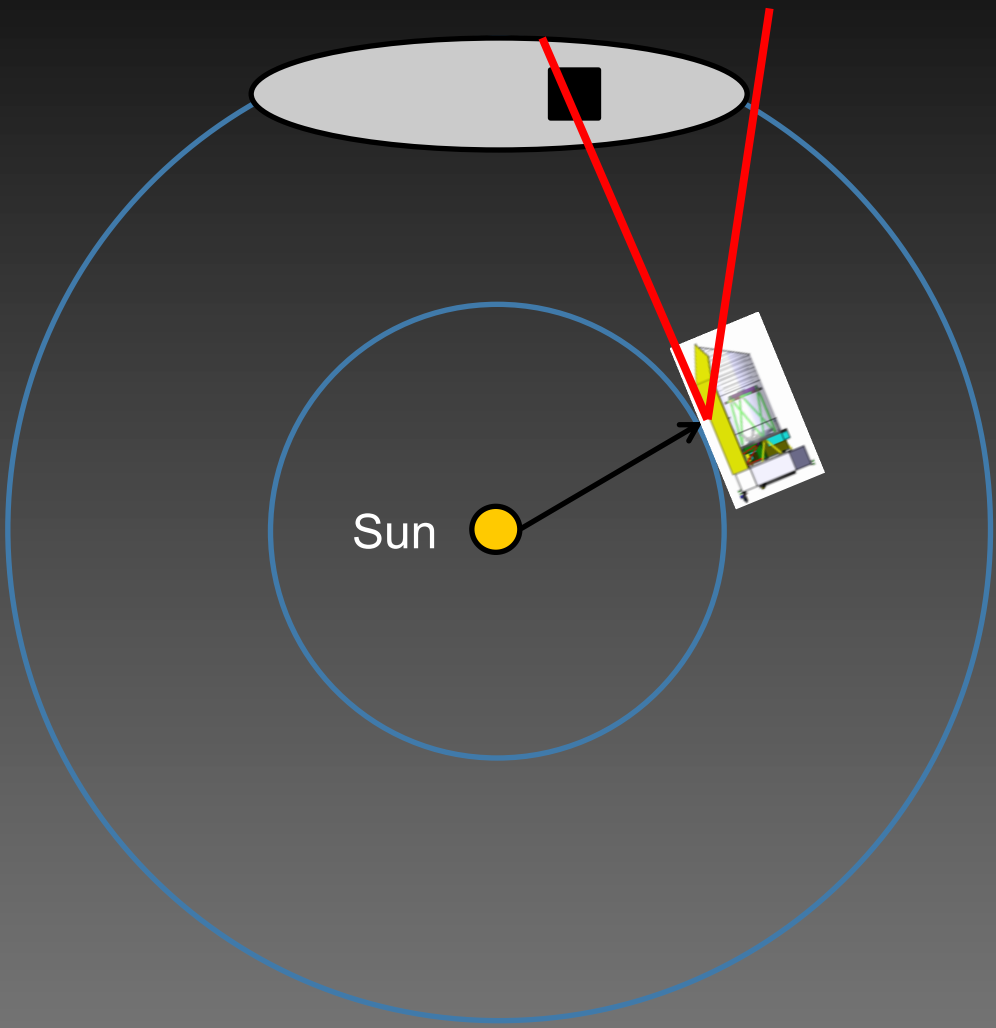
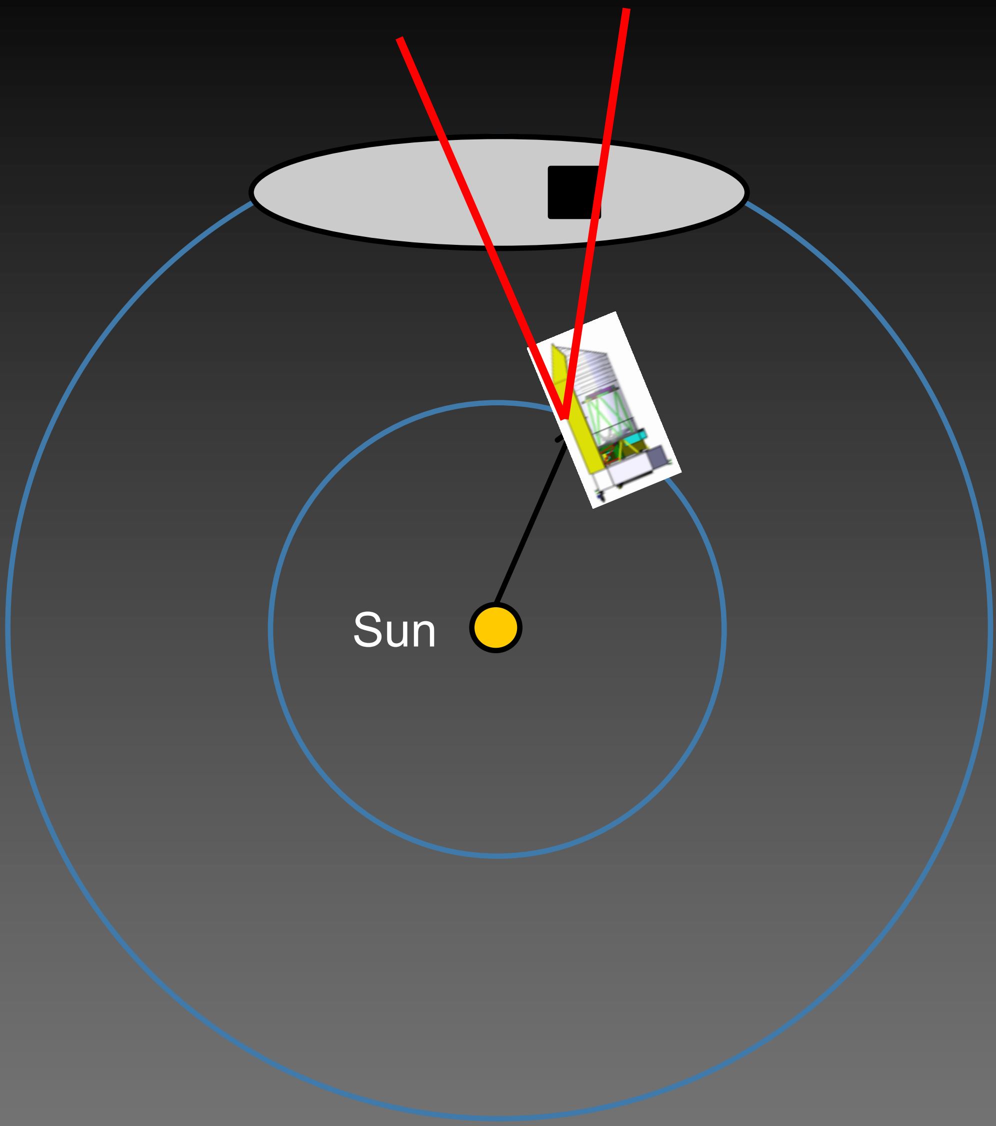
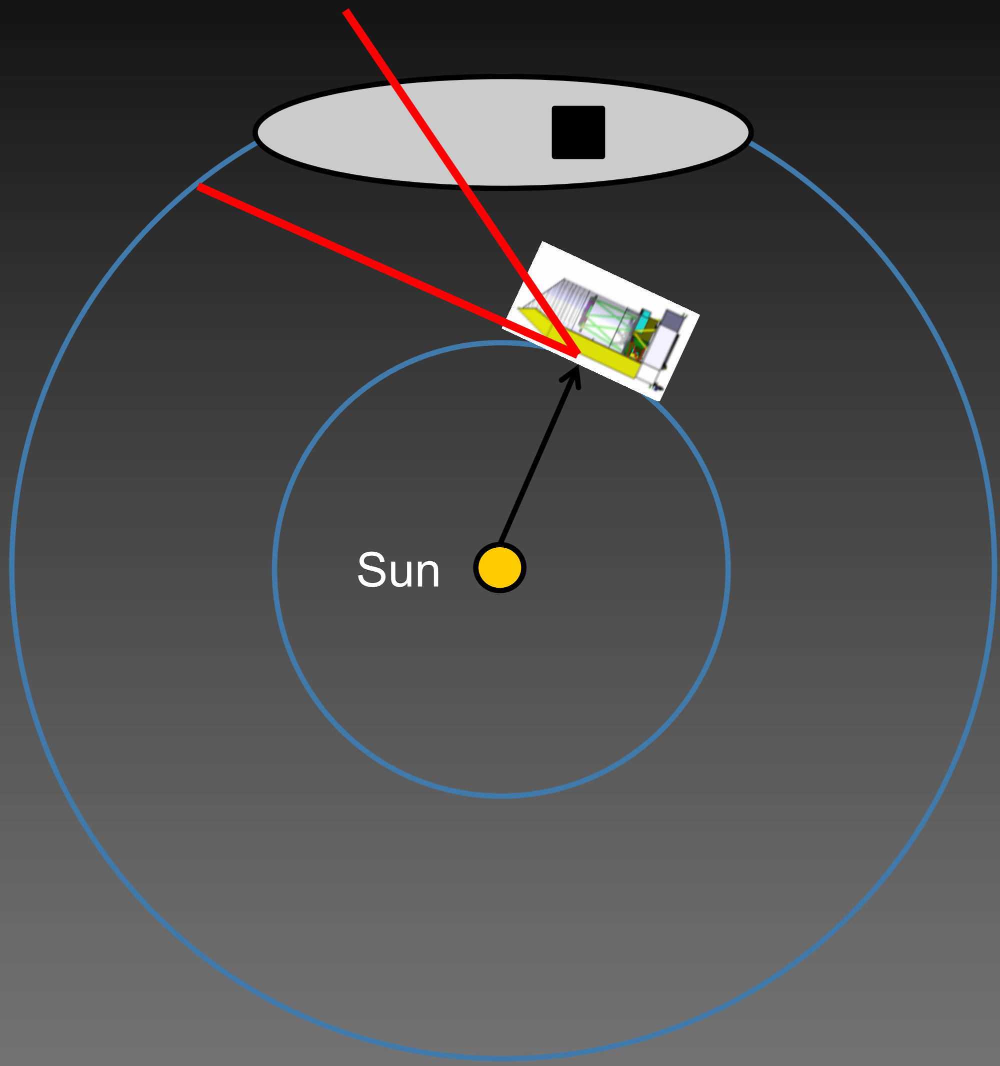


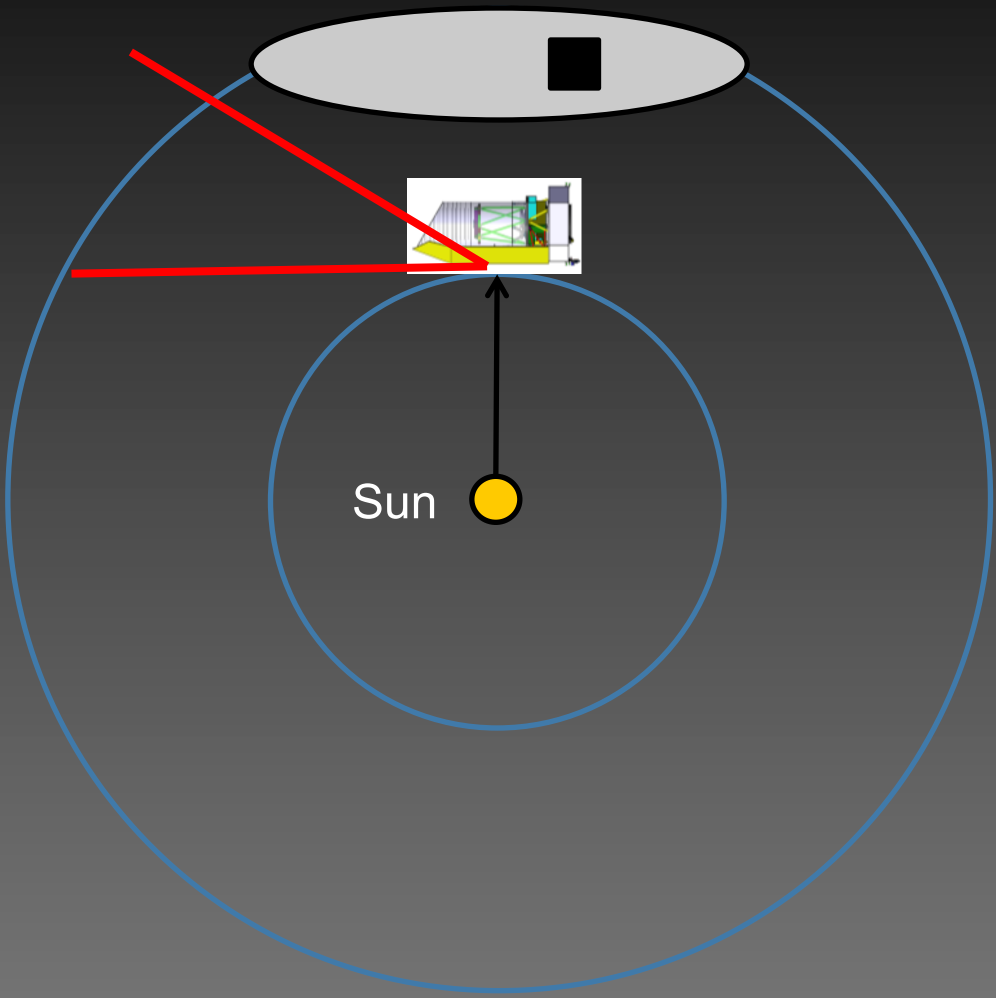
Work Flow for Survey Optimisation



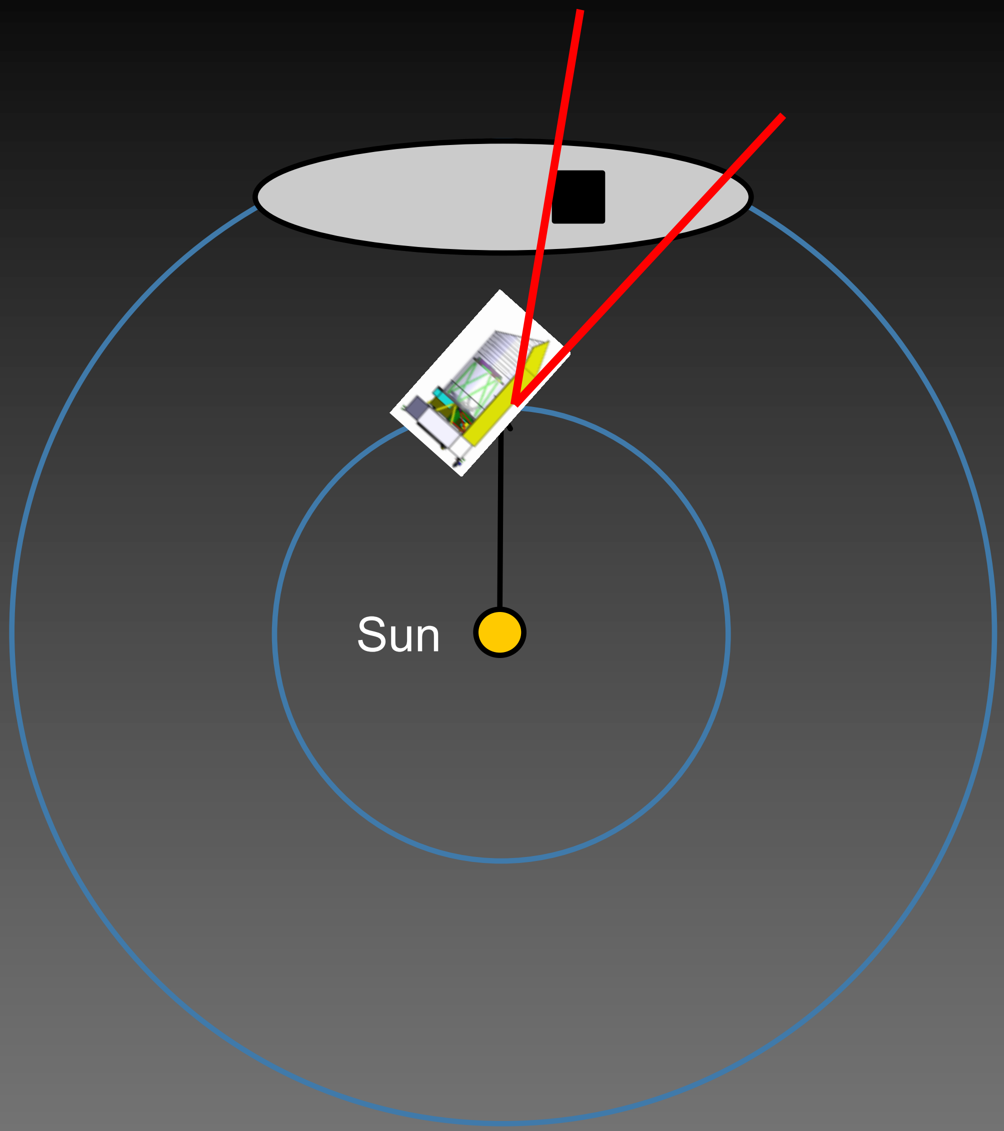
Work Flow for Survey Optimisation



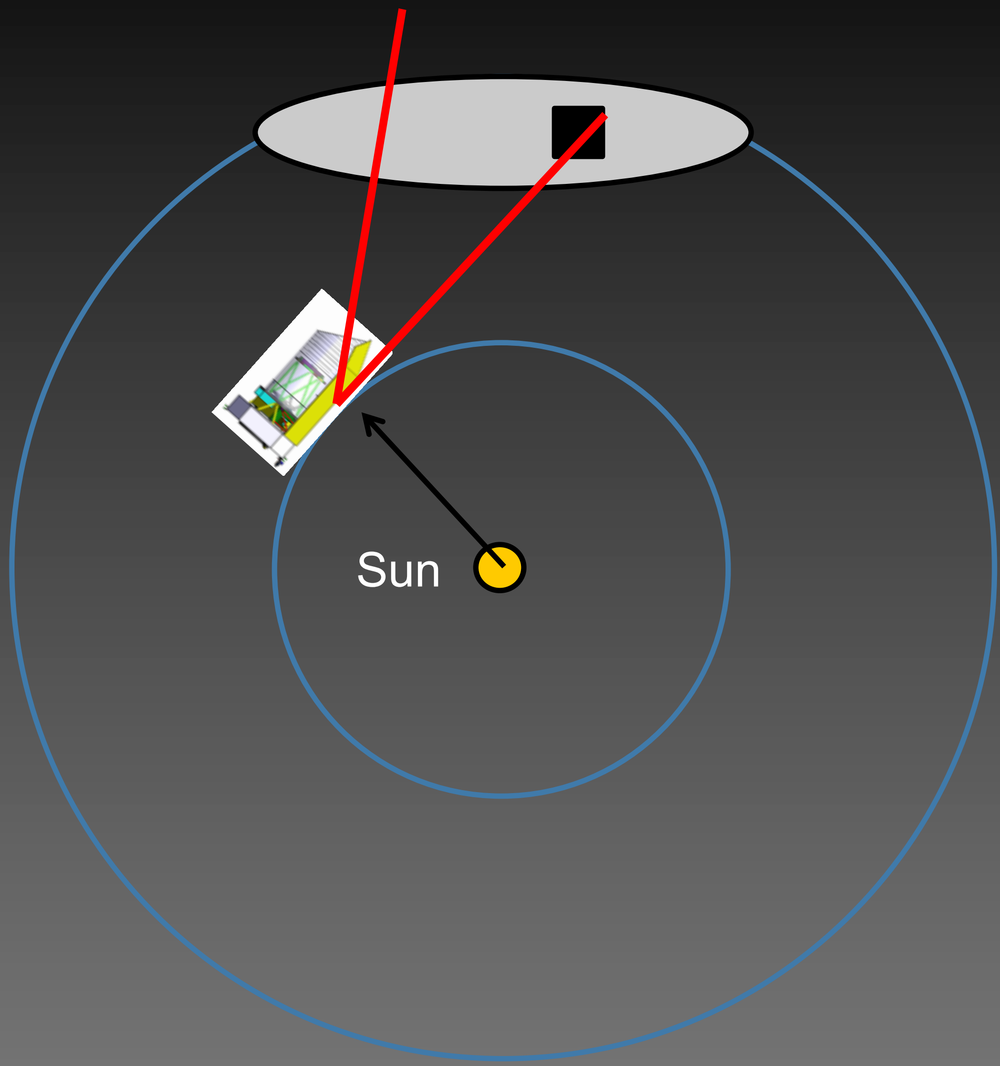
Work Flow for Survey Optimisation



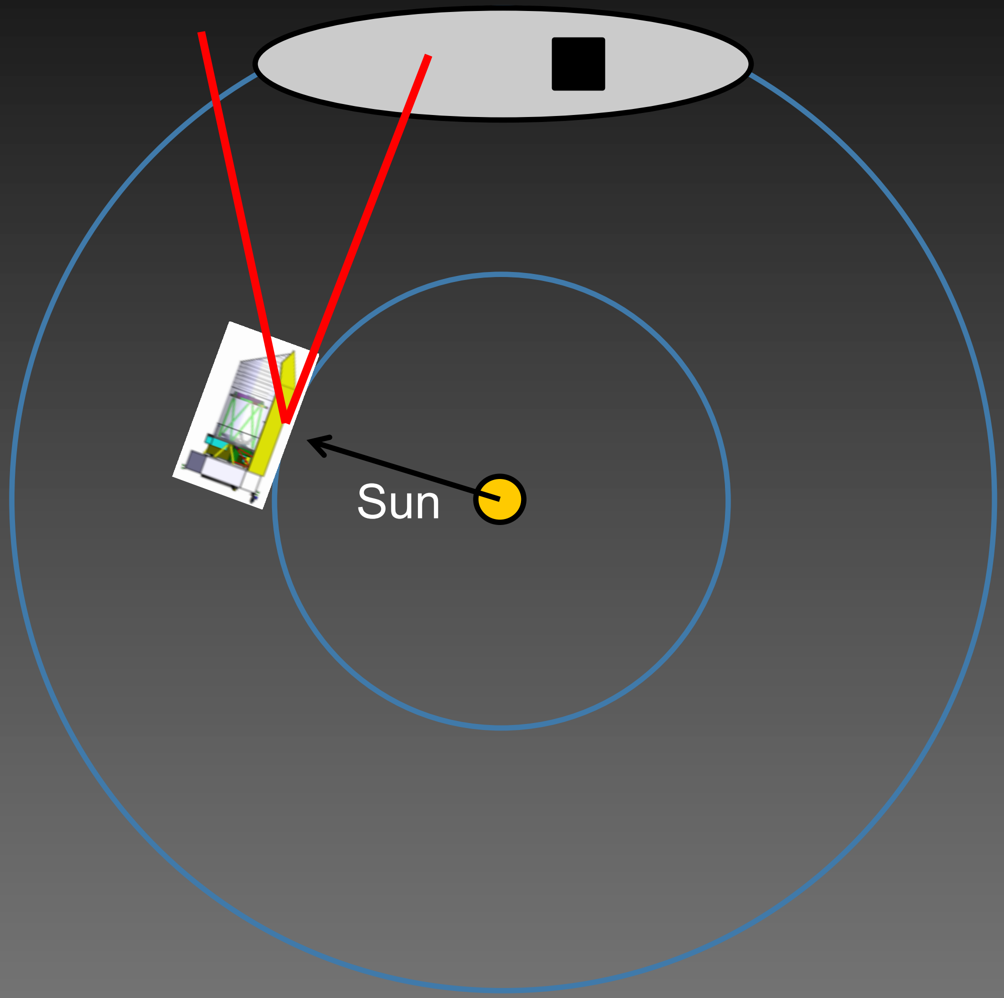
Work Flow for Survey Optimisation



Work Flow for Survey Optimisation



Work Flow for Survey Optimisation



Operation angle from -1 deg to +31 deg.

We can observe for about a month, twice a year.

EUCLID has no contigency for weight : we cannot extend the shielding.

→ Maximum observation : 2 months/year

MaBμLS simulator

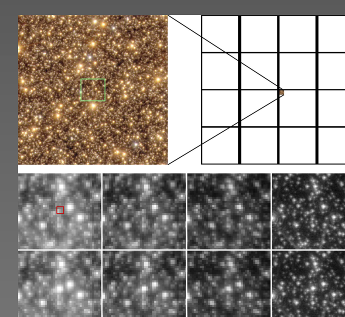
Diameter (m)	1.2
Central blockage (m)	0.4
Slew + settle time (s)	85(285)

Detector parameters

Instrument	VIS		NISP	
Filter	*RIZ*	*Y*	*J*	*H*
Size (pixels)	24k × 24k		8k × 8k	
Pixel scale (arcsec)	0.1		0.3	
PSF FWHM (arcsec)	0.18	0.3*	0.36*	0.45*
Bias level (e^-)	380†		380†	
Full well depth (e^-)	2^{16}		2^{16}	
Zero-point (ABmag)	25.58⋆	24.25⋆⋆	24.29⋆⋆	24.92⋆⋆
Readout noise (e^-)	4.5	7.5*	7.5*	9.1*
Thermal background (e^- s^{-1})	0	0.26	0.02	0.02
Dark current (e^- s^{-1})	0.00056◇		0.1*	
Systematic error	0.001†		0.001†	
Diffuse background (ABmag $arcsec^{-2}$)	21.5‡	21.3‡	21.3‡	21.4‡
Exposure time (s)	540(270)	90	90	54
Images per stack	1	3(1)	3(1)	5(2)
Readout time (s)	< 85		5†	

\+ Besançon model

Microlensing simulator
3 fields, 270 sec per pointing,
5x2 months observing



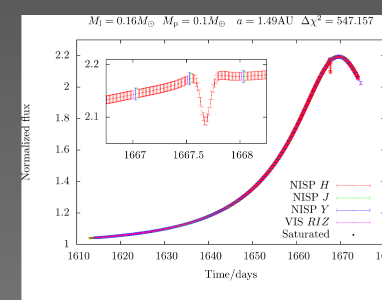
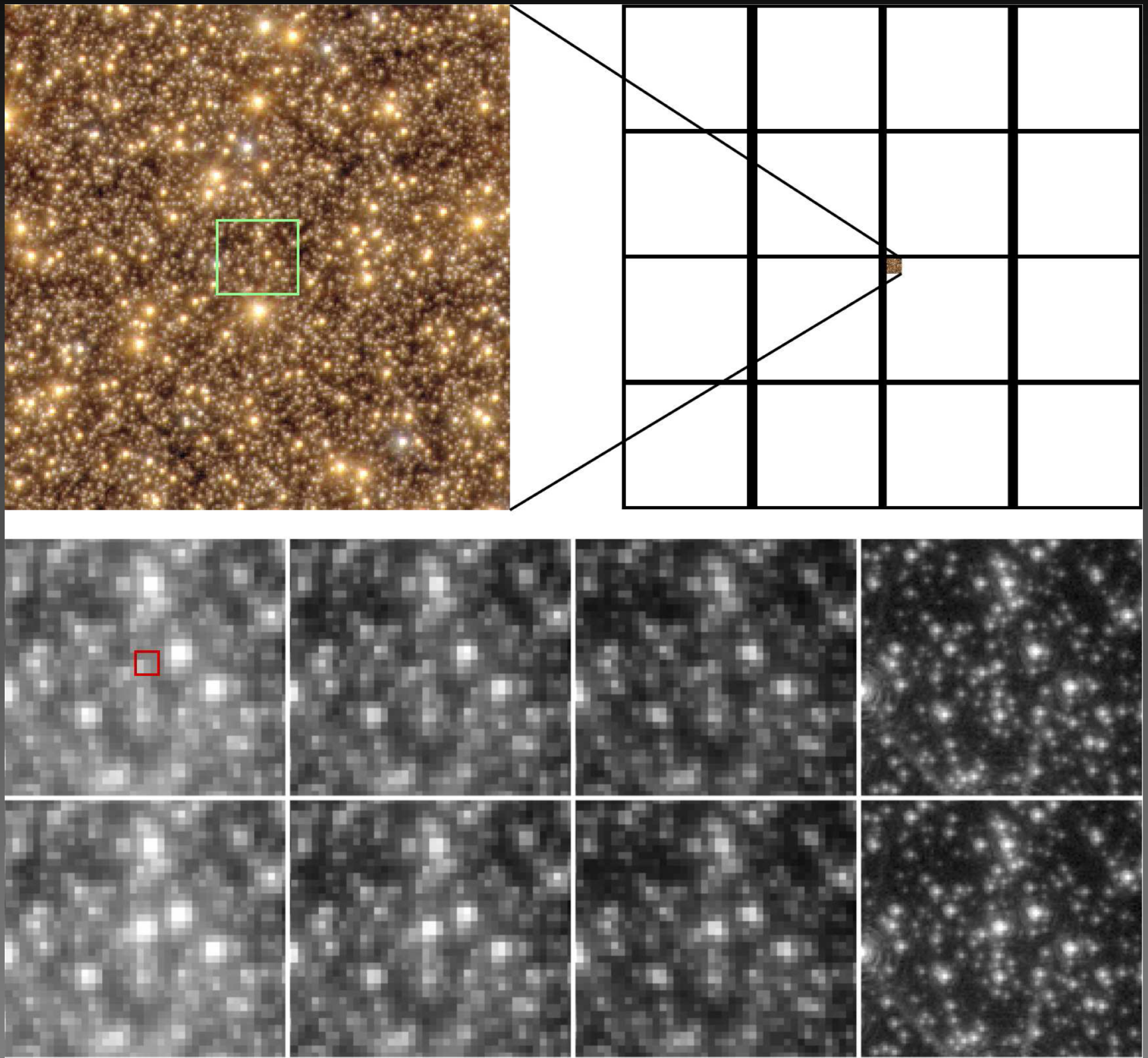


Figure 3. Example lightcurves

Penny, Kerins, Rattenbury, Beaulieu, Robin, 2013, MNRAS
PhD Matthew Penny

Simulated images of galactic Bulge



EUCLID Microlensing survey

Beaulieu, Kerins, et al.

Simulation work done during Matthew Penny's thesis

3 fields observed every 17 min in H, every 12 hours in VIS, J, Y.

Mini-survey during commissionning (24h), then 4 x 1 months survey

- Measuring cold Earth abundance and mass function

  ~35 planets / month (5 Earth / month, 15 Neptune / month)

- Getting constraints on free floating planets

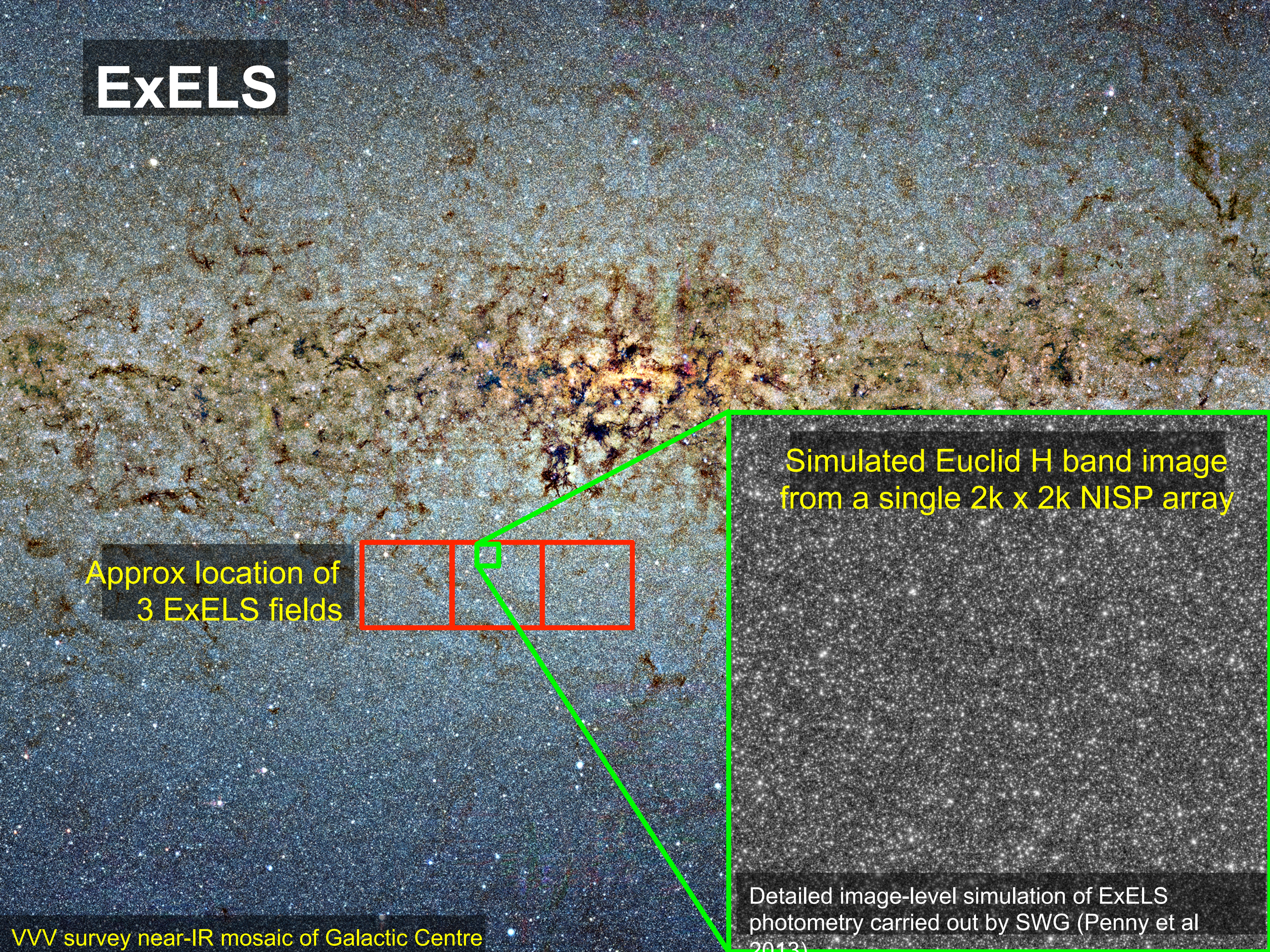
  ~15 free-floating planets / month

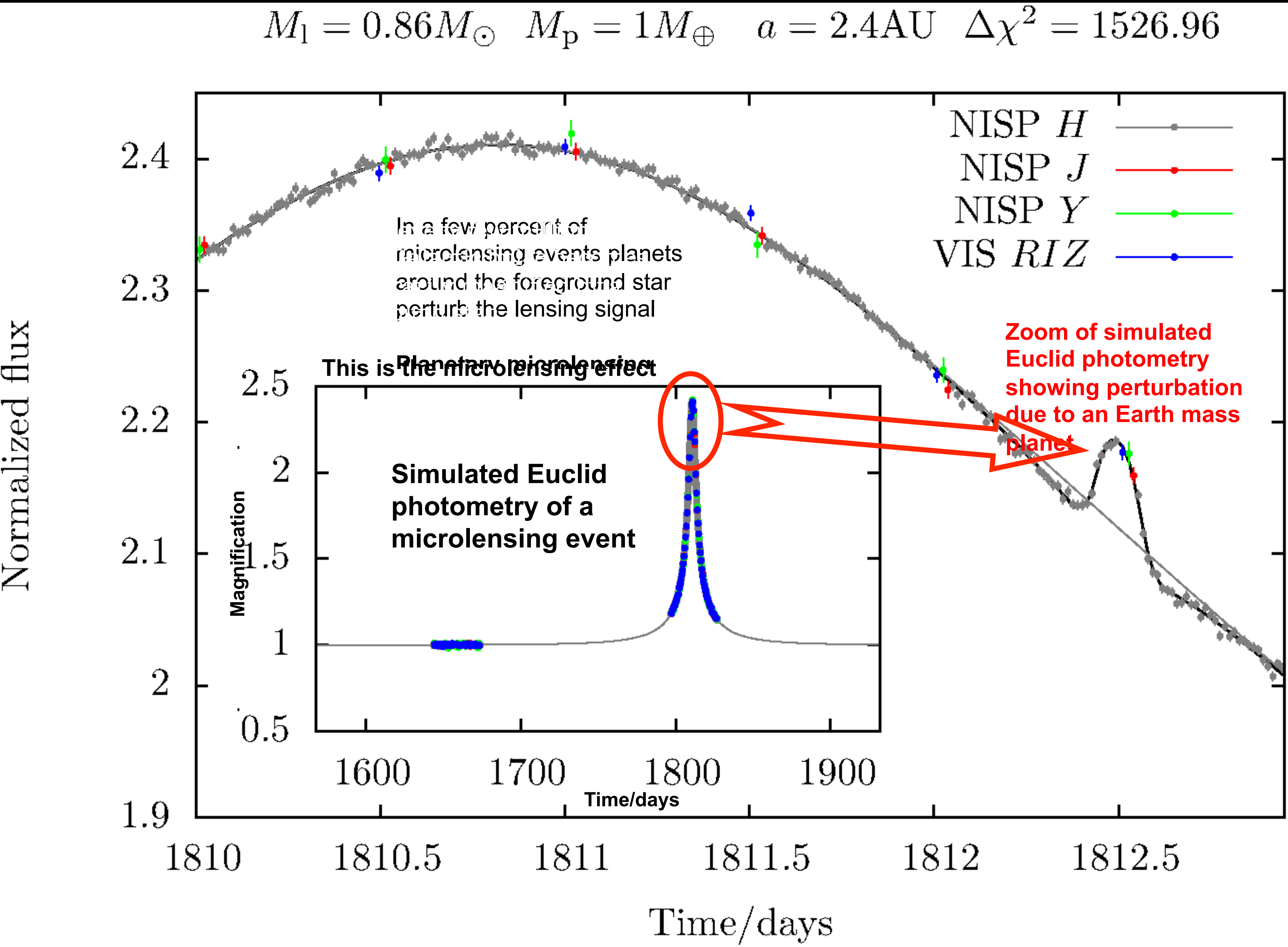
- EUCLID/ML complements parameter space probed by RV and KEPLER

Measuring the cold planet mass function below 1 Earth mass.

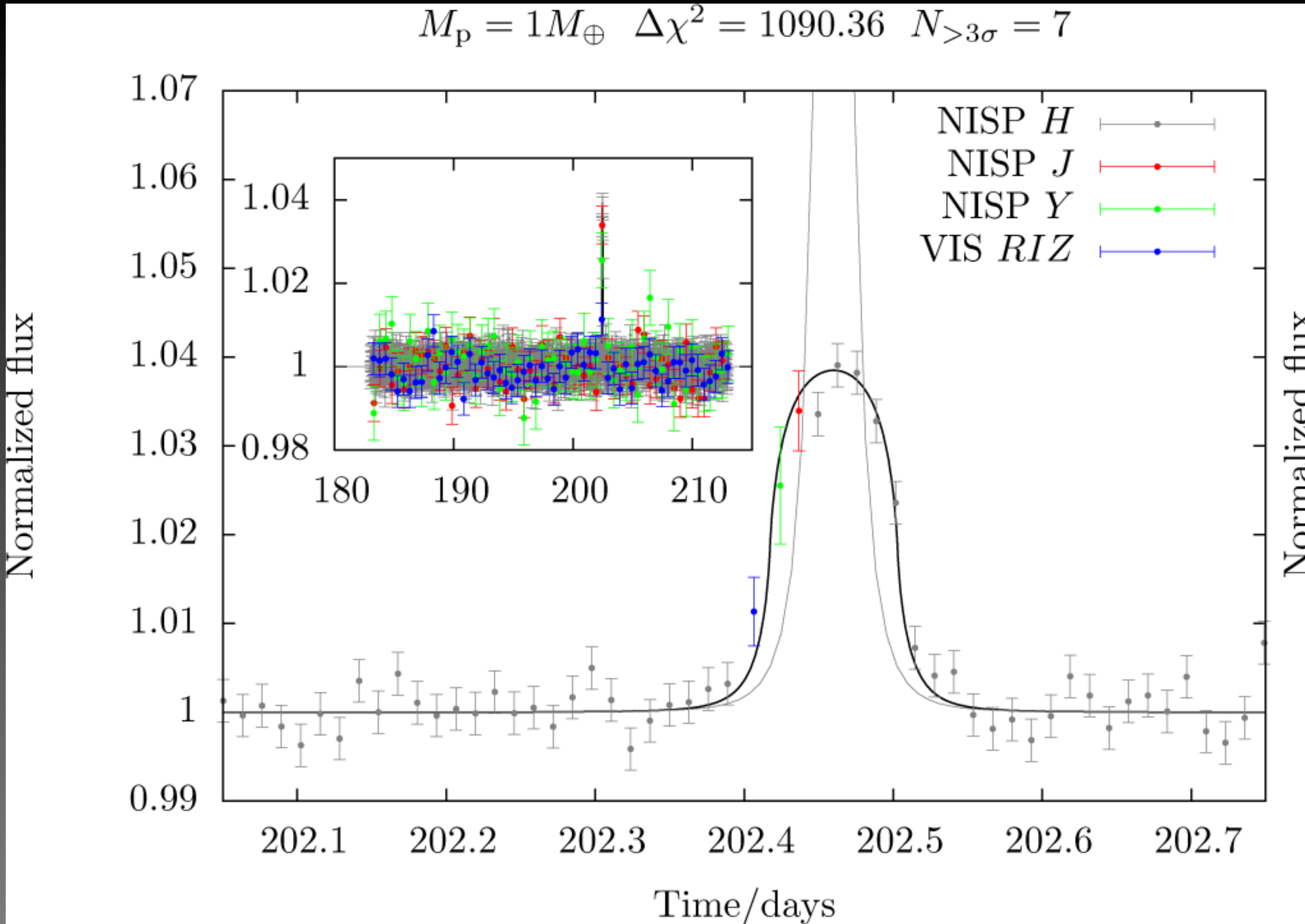
- Possibility of simultaneous EUCLID-WFIRST in the extended mission 2026+ (parallax between EUCLID and WFIRST to measure masses of Earth mass free floaters)

Penny et al., 2013 MNRAS 434, 2


ExELS
Simulated Euclid H band image from a single 2k x 2k NISP array
Approx location of 3 ExELS fields
Detailed image-level simulation of ExELS photometry carried out by SWG (Penny et al 2013)
VVV survey near-IR mosaic of Galactic Centre



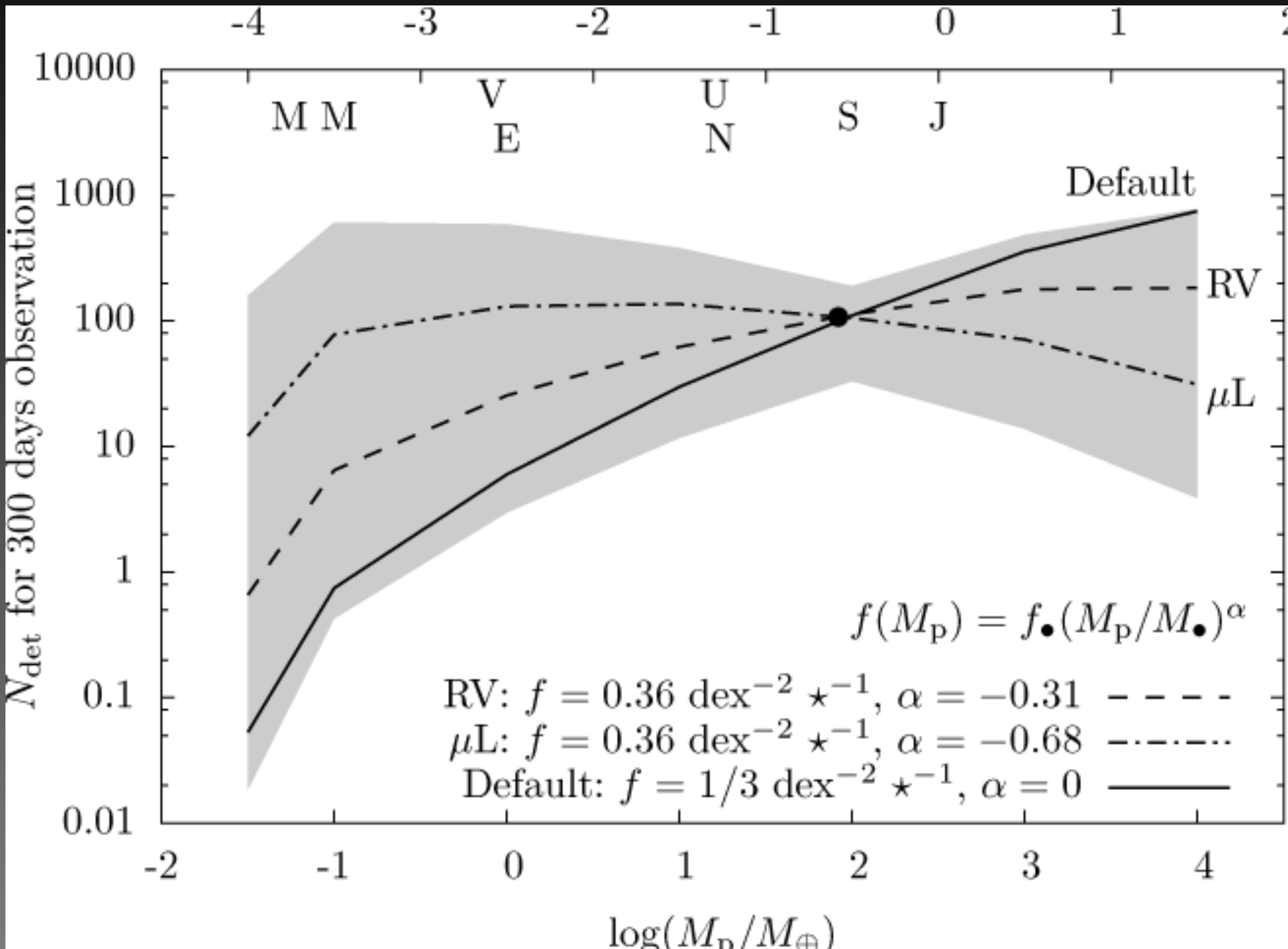
$M_l = 0.86 M_\odot$ $M_p = 1 M_\oplus$ $a = 2.4$AU $\Delta\chi^2 = 1526.96$
NISP H
NISP J
NISP Y
VIS RIZ
Normalized flux
Time/days
In a few percent of microlensing events planets around the foreground star perturb the lensing signal
Planetary microlensing
This is the microlensing effect
Simulated Euclid photometry of a microlensing event
Magnification
Time/days
Zoom of simulated Euclid photometry showing perturbation due to an Earth mass planet



$M_p = 1M_\oplus$ $\Delta\chi^2 = 1090.36$ $N_{>3\sigma} = 7$
NISP H
NISP J
NISP Y
VIS RIZ
Normalized flux
Time/days
1.07
1.06
1.05
1.04
1.03
1.02
1.01
1
0.99
202.1
202.2
202.3
202.4
202.5
202.6
202.7
1.04
1.02
1
0.98
180
190
200
210

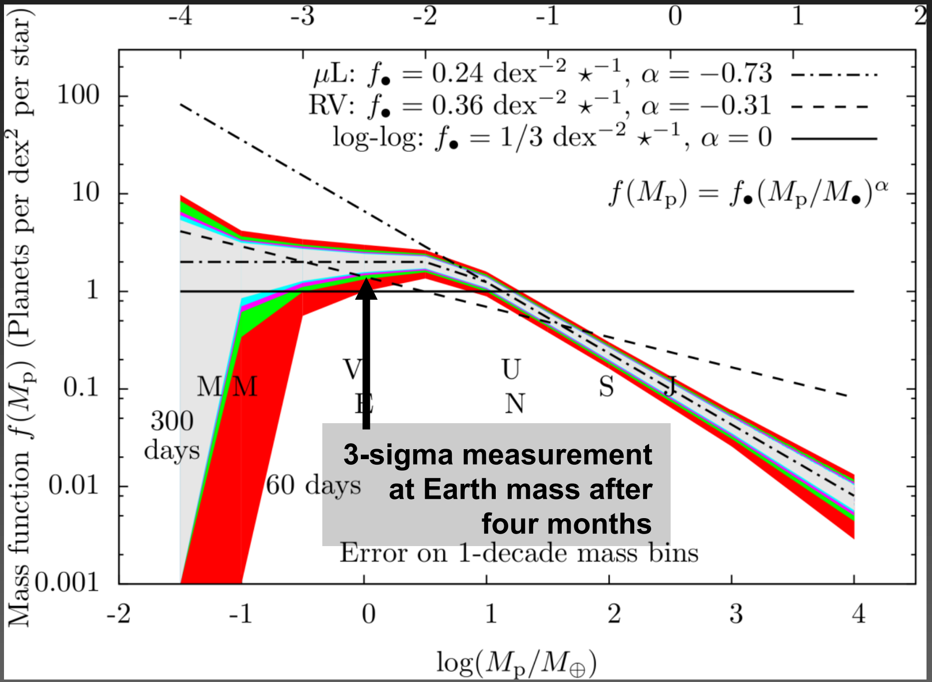
(c)

Measuring the planet mass function



Survey constraints

- Observability of the Gal Centre limited by design of Sun shield and the constraint on Solar aspect angle. This fixes the times when the bulge is observable with Euclid. ExELS could get squeezed if these times are used up for primary science calibration or other surveys.
- Current simulations based on Red Book Euclid design indicates that ExELS requires 4 months of observing time in order to achieve the primary science objective of measuring the abundance of cold Earth mass planets with at least 3-sigma precision.



Abundance measurement sensitivity versus planet mass for different extrapolations of measured exoplanet mass functions and survey lifetimes

Microlensing program on board the EUCLID Dark Universe Probe

- Measuring cold Earth abundance and mass function with 4 months of survey
- Getting free floating planets down to the mass of Earth
- Mass measurement of free floaters (ground-space parallax)
- EUCLID complements parameter space probed by RV and KEPLER
- Entering the habitable Earth around G stars would require larger survey (300+ days)
- EUCLID will launch in 2020, WFIRST in 2025+

Penny et al., 2013, MNRAS, « ExELS: an exoplanet legacy science proposal for the ESA Euclid mission I. Cold exoplanets, arXiv:1206.5296

Beaulieu et al., 2010, "EUCLID : Dark Universe Probe and Microlensing planet Hunter", arXiv:1001.3349

Conclusion

- Statistics of planets beyond the snow line.
- Sensitivty to low mass planets, and free floating planets

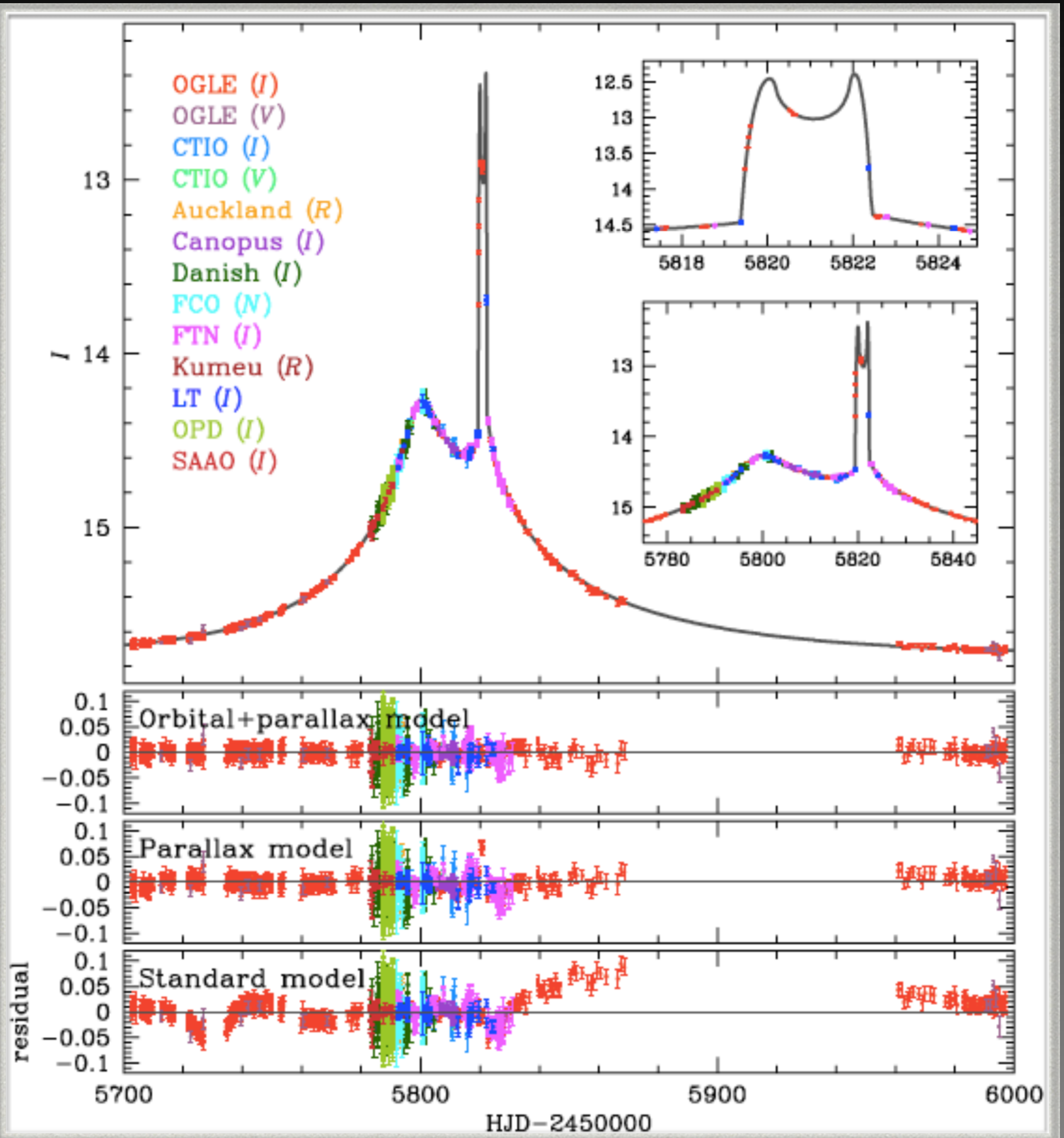
EUCLID microlensing

- EU thought of DE & Microlensing in 2007 already
- Proposed 4 Months (decision in 2018?)
- Mass function of cold planets, first results on free-floaters (if any) ?

EUCLID contributions to WFIRST

- Matthew Penny ! (PhD thesis on EUCLID microlensing, building the reference tools)
- An early survey to serve as position reference for mass-measurements.
- Simultaneous EUCLID/WFIRST observations (extended part of the mission)

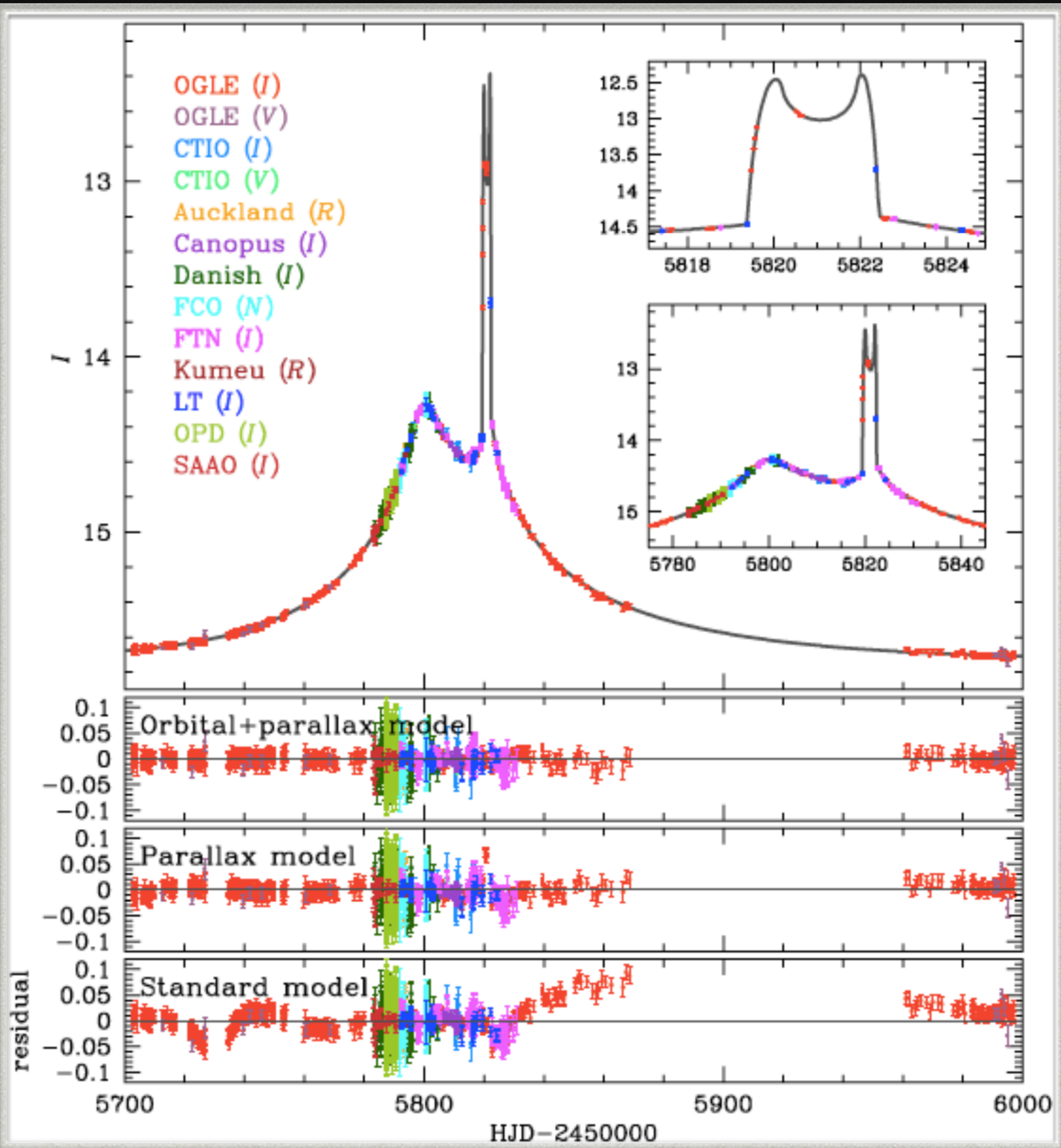
A binary, with very bright lens



Source star:
K3 red giant at 8 kpc
I=16.42, V=19.42

Lens star:
Binary composed of Mdwarfs
I=16.3, V=18.2

A binary, with very bright lens



Source star:
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Binary composed of Mdwarfs
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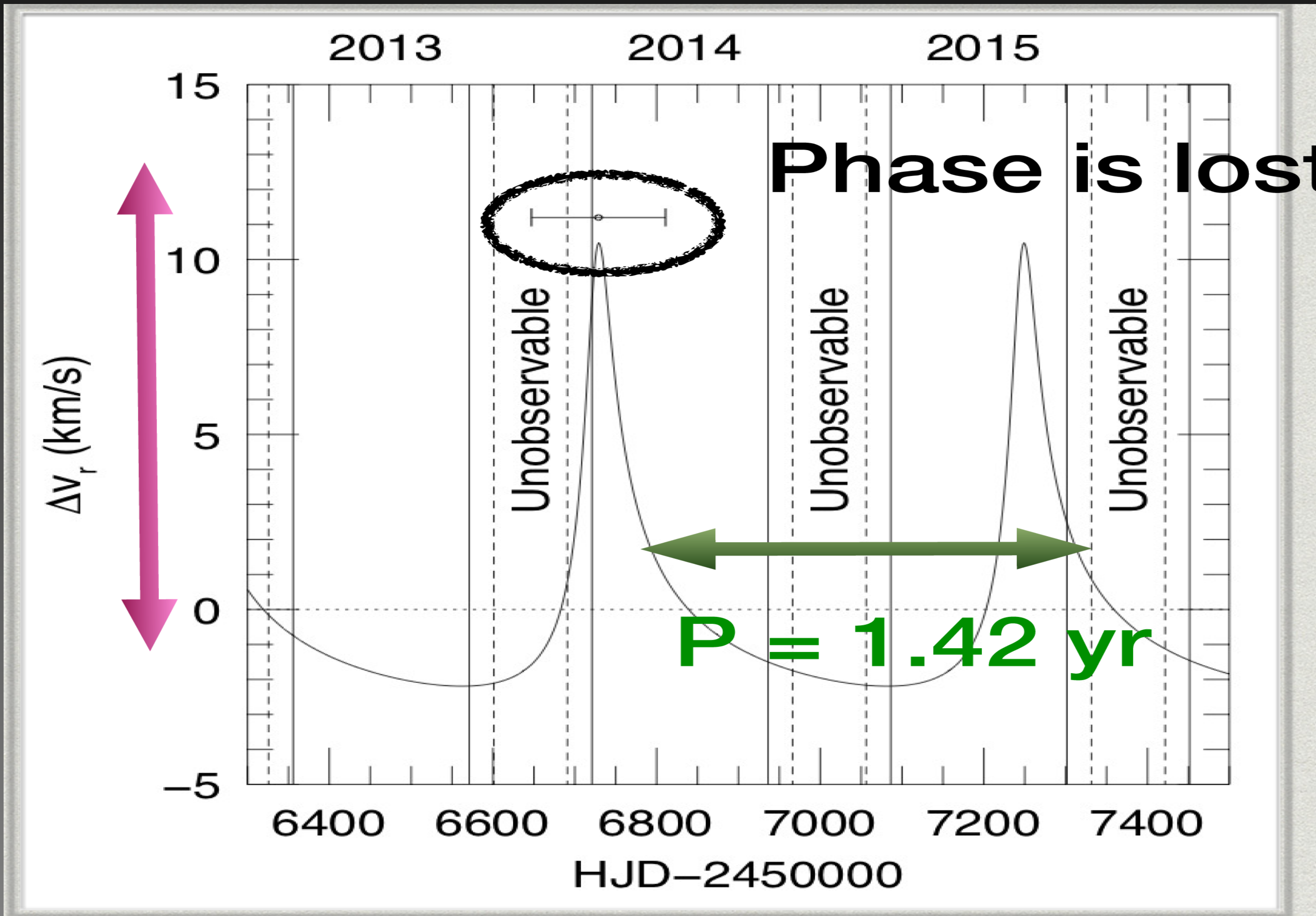
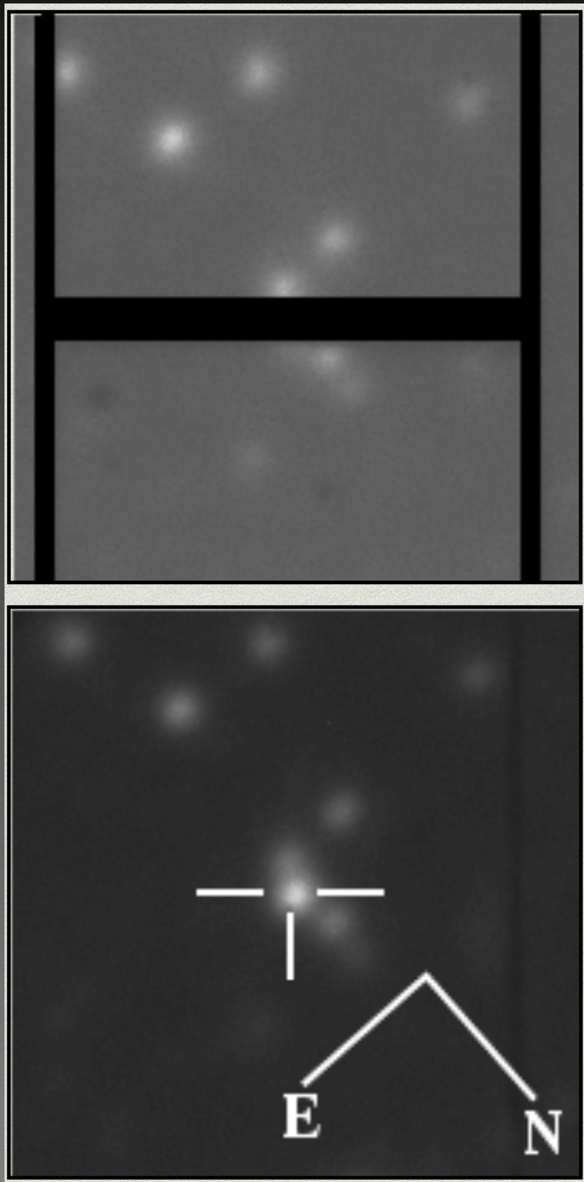
Prediction by Gould et al.



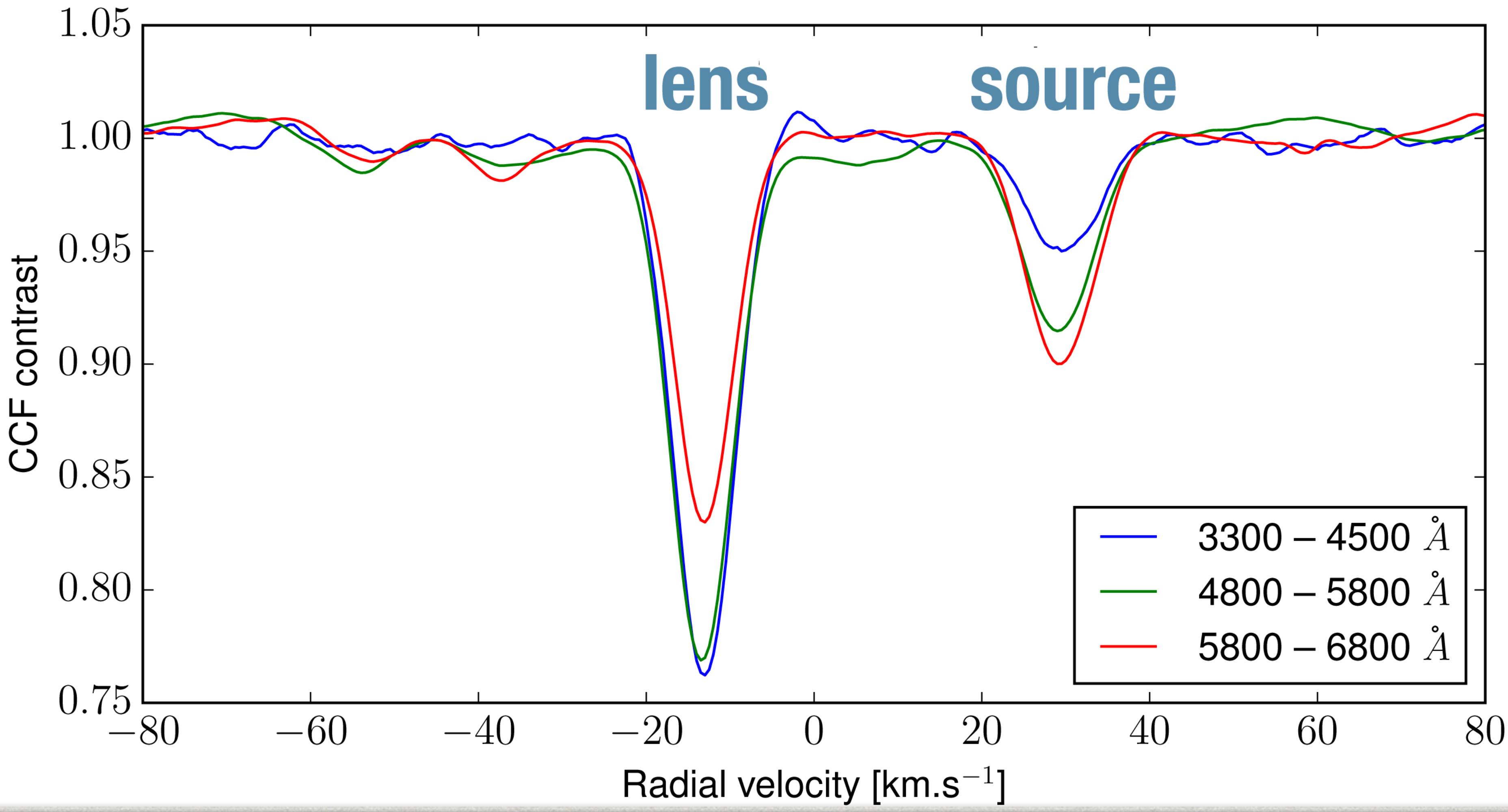
VLT UVES observations

At the initative of I. Boisse and A Santerne (LAM, Marseille) RV People

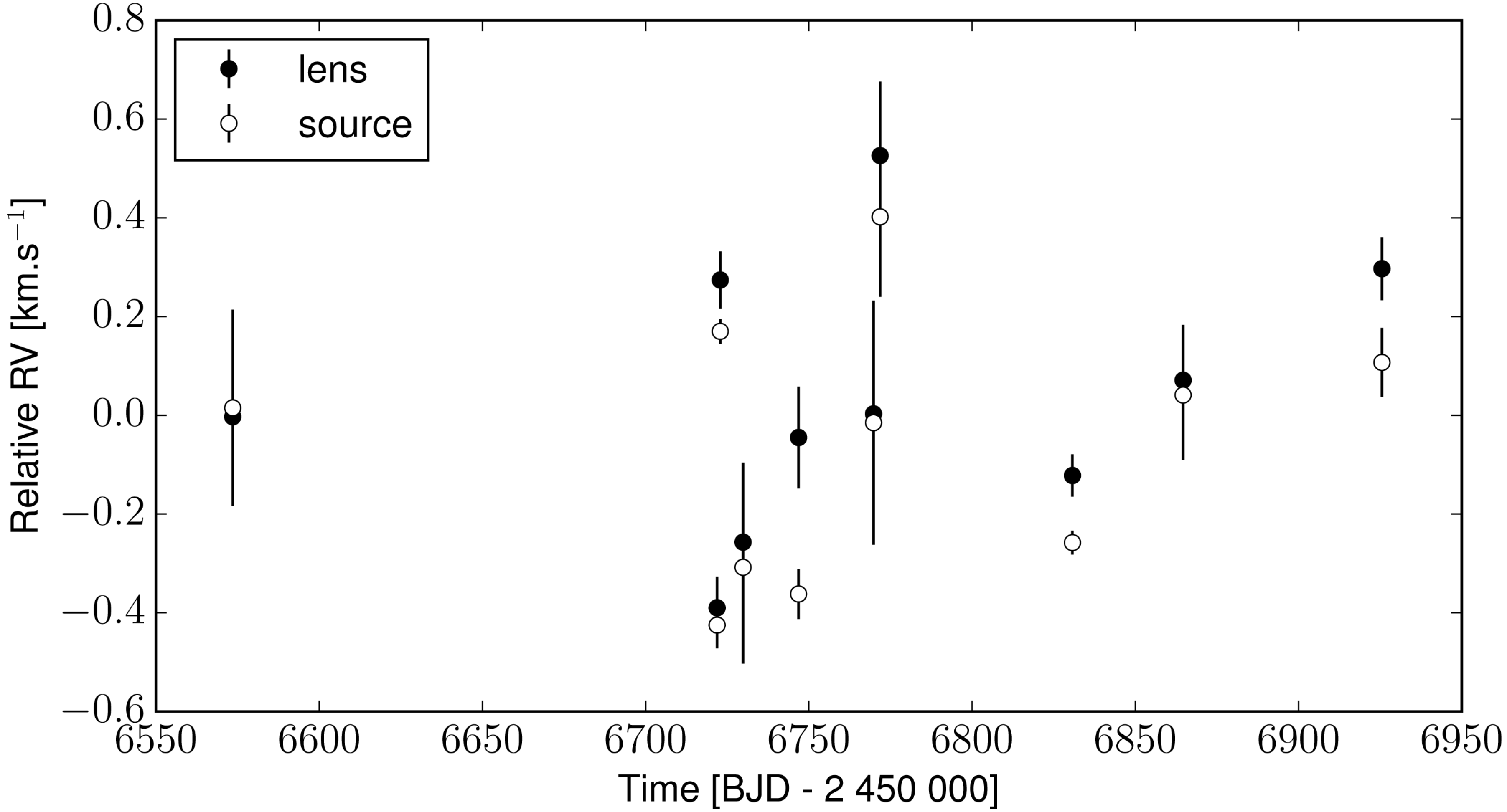
10 spectra, 1h, S/N~20, R~ 40 000
Th-Ar calibrations before and after



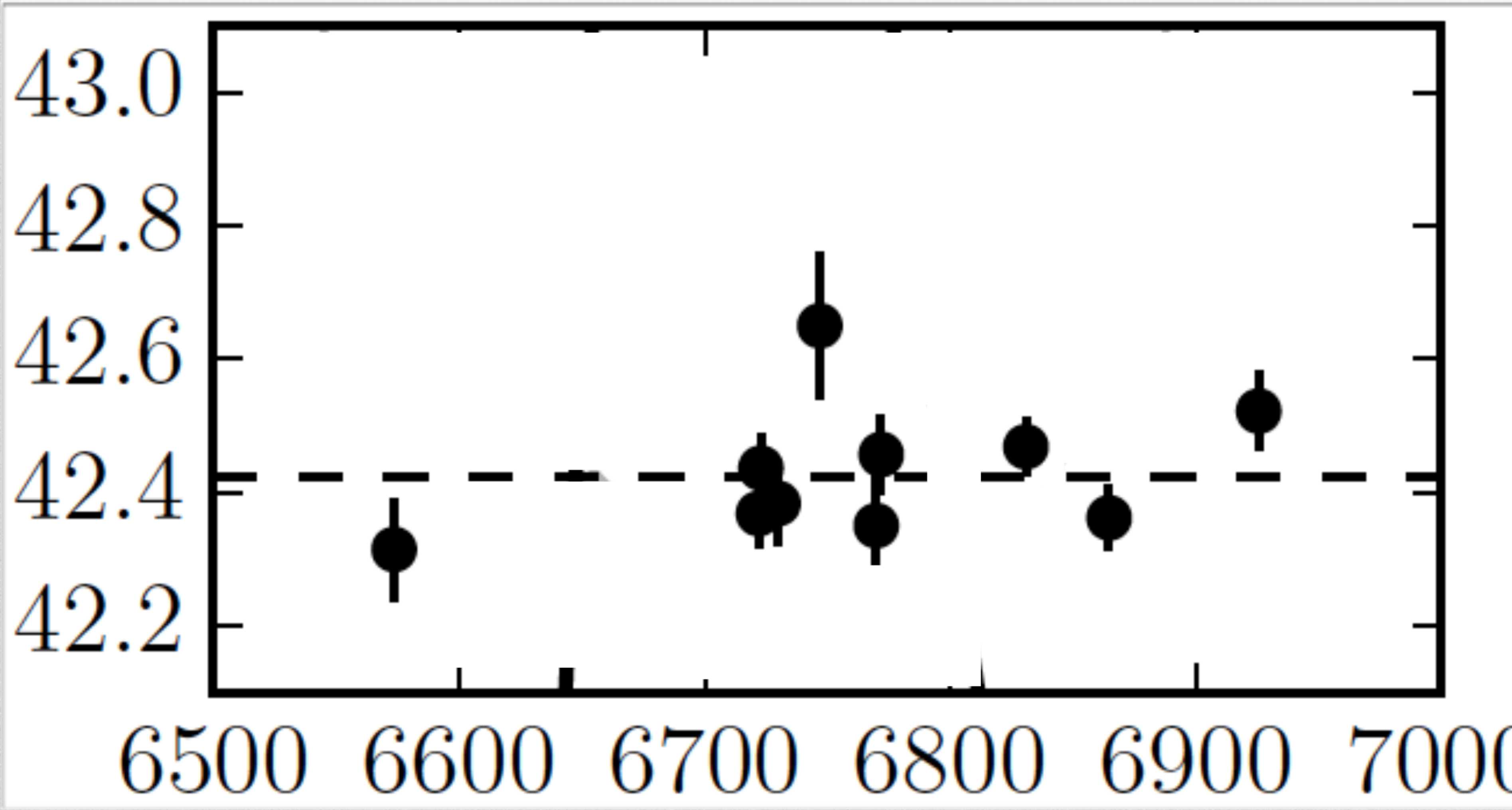
Cross correlation



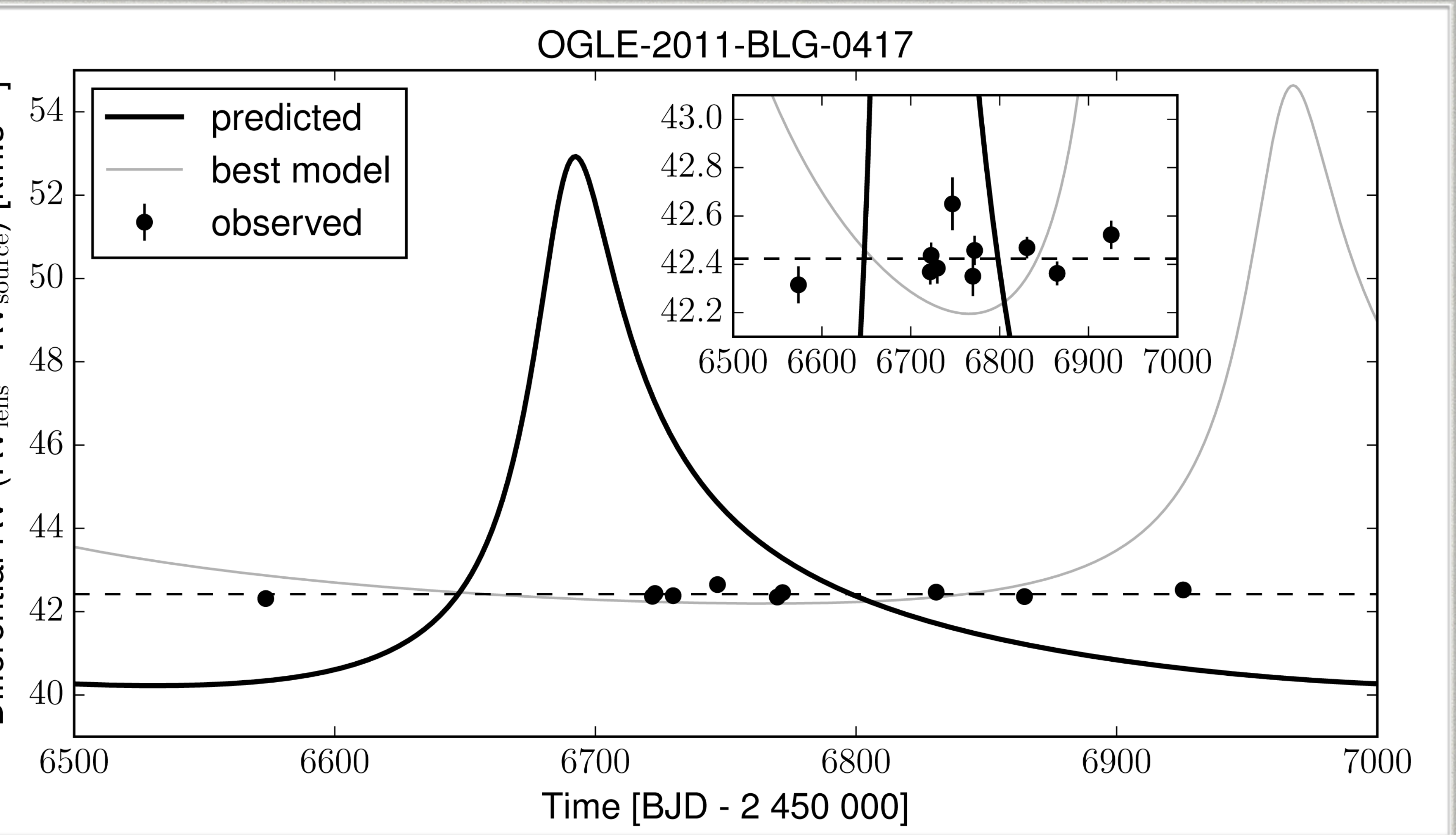
Source and lens RV



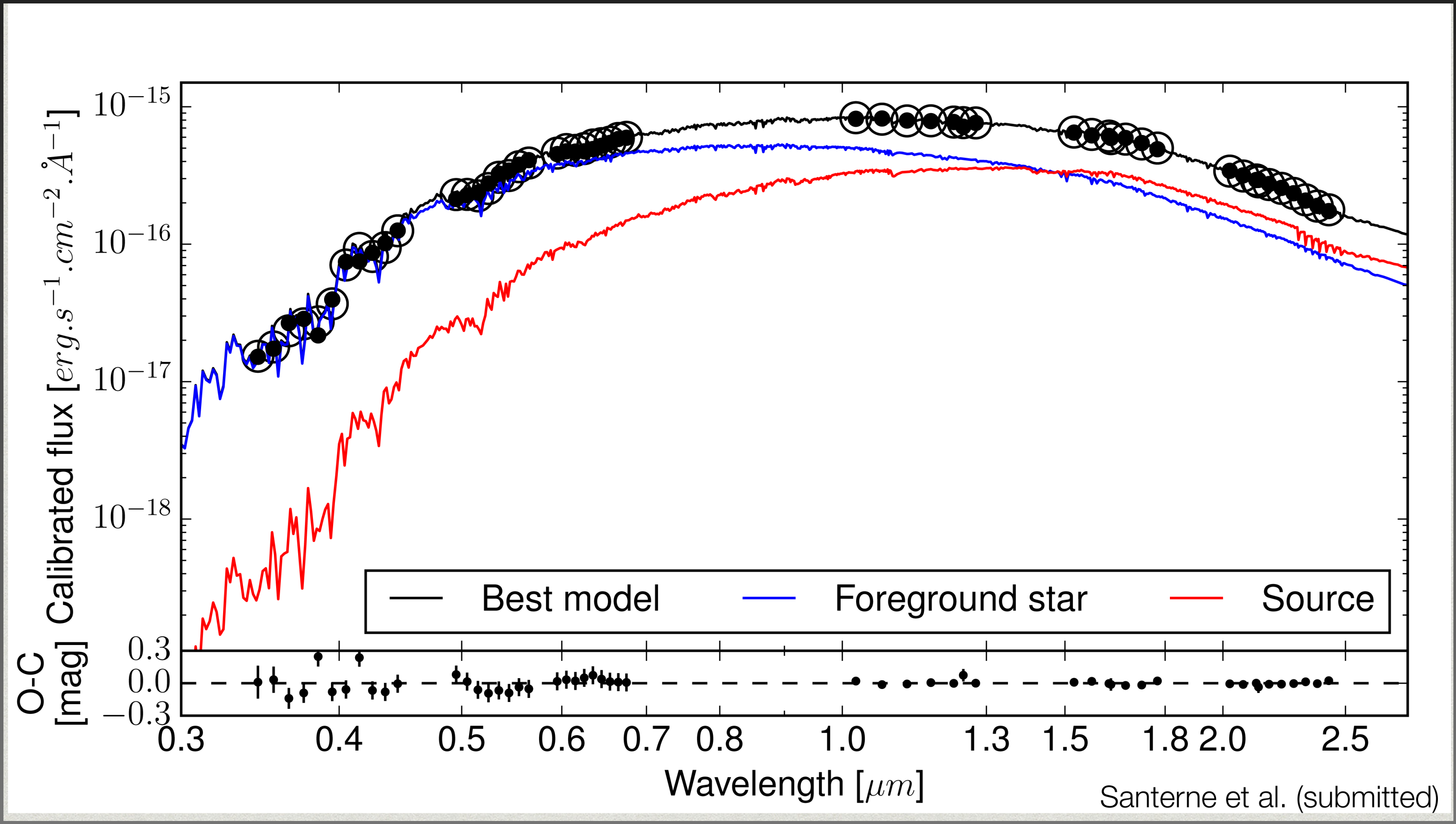
Using the source as RV reference.
94 m/s RMS



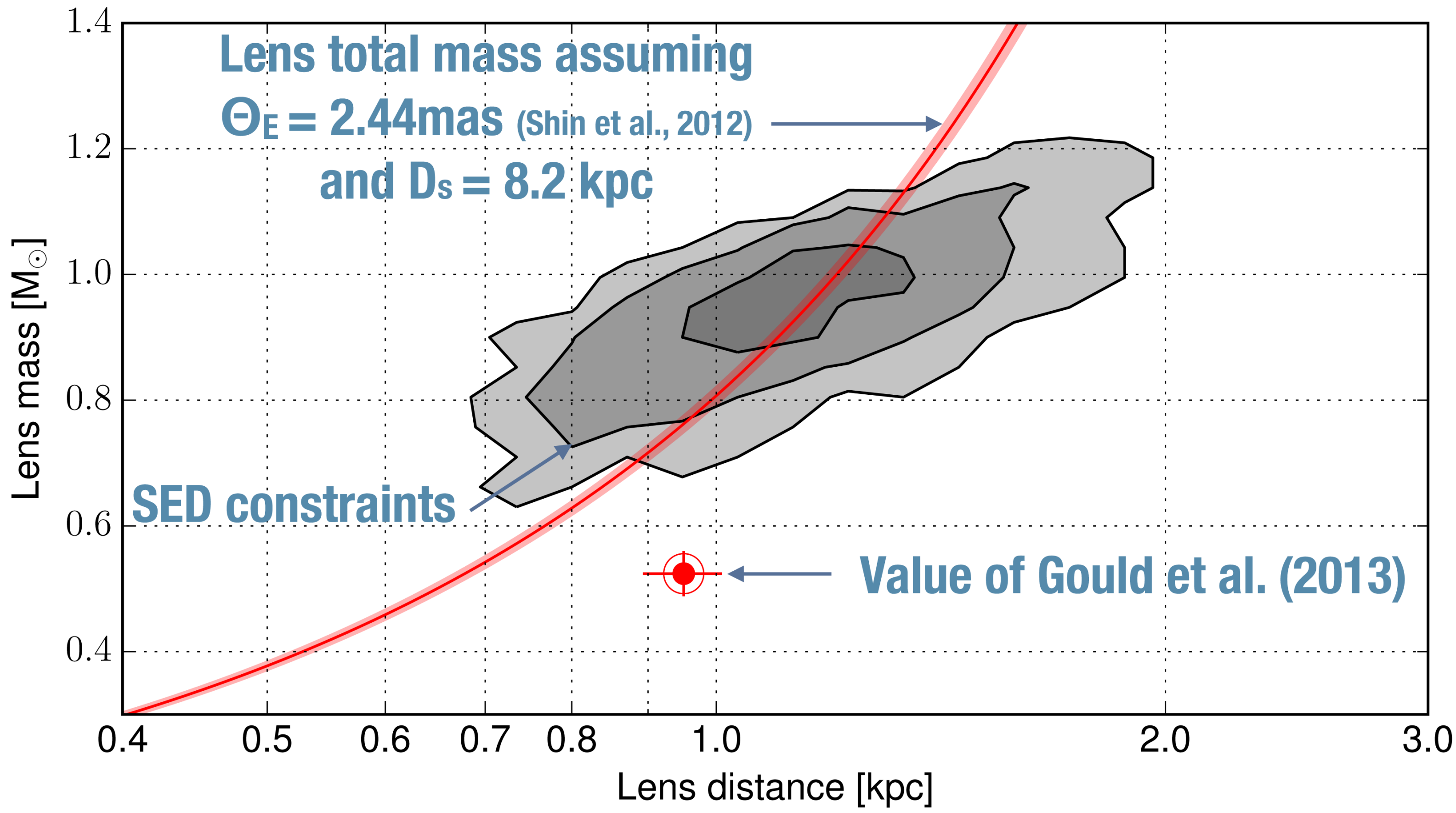
RV model and data



Fitting Source and lens spectra
UVES, OGLE, KECK AO, ARCoIRIS



Giant source, forground G star, 0.95 Mo at 1.1 kpc



Lesson from RV

We can detect binary lens RV modulation.

Here, the initial microlensing model was wrong.

New modeling, using constraint on source and lens needed.

Boisse et al., 2015, The first radial velocity measurements of a microlensing event: no evidence for the predicted binary, A&A

Santerne et al. 2016, Spectroscopic characterisation of microlensing events Towards a new interpretation of OGLE-2011-BLG-0417, astroph

See also another system :
Yee et al., 2016, Two Stars Two Ways: Confirming a Microlensing Binary Lens Solution with a Spectroscopic Measurement of the Orbit