The MESSIER orbiter
A European-Chinese mission for unveiling galaxy formation

David Valls-Gabaud
Observatoire de Paris

Wang Xin
SITP

on behalf of the MESSIER consortium

ESA-CAS workshop for a joint mission
Copenhagen 2014 September 23

Europe PI : David Valls-Gabaud
China PI : Jing Yipeng (SJTU, science)
+ Wei Jianyan (NAOC, technology)

Core team

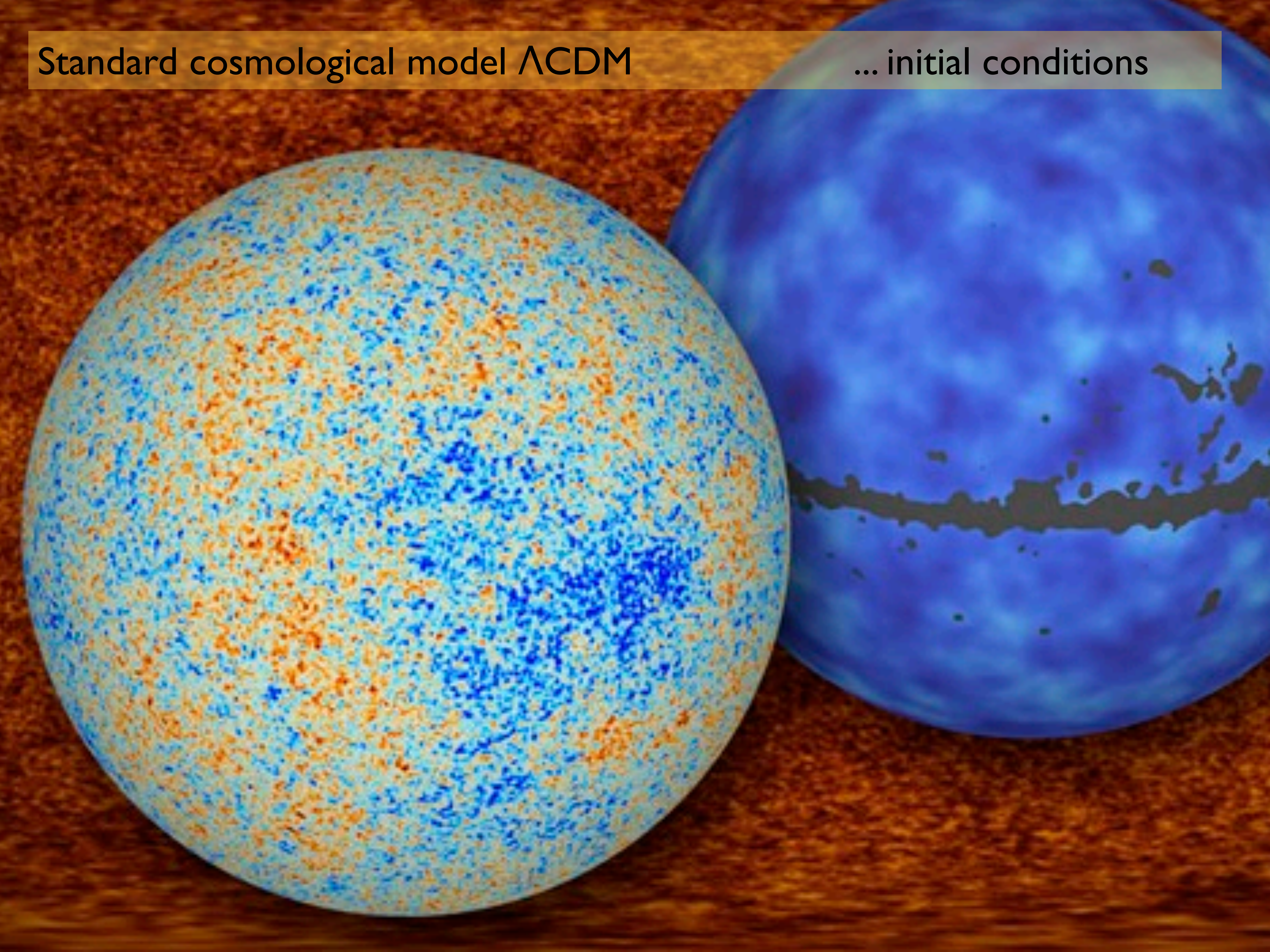
Paris Saclay Strasbourg Marseille
Heidelberg Munich Stockholm Geneva ETHZ
Cambridge UCL Durham IAC
Caltech Arizona JHU Columbia

IHEP NAOC SITP KIAA/PKU Jiaotong SHAO
PMO Tsinghua (TBC)

Interested parties: >190 researchers over 30 institutes

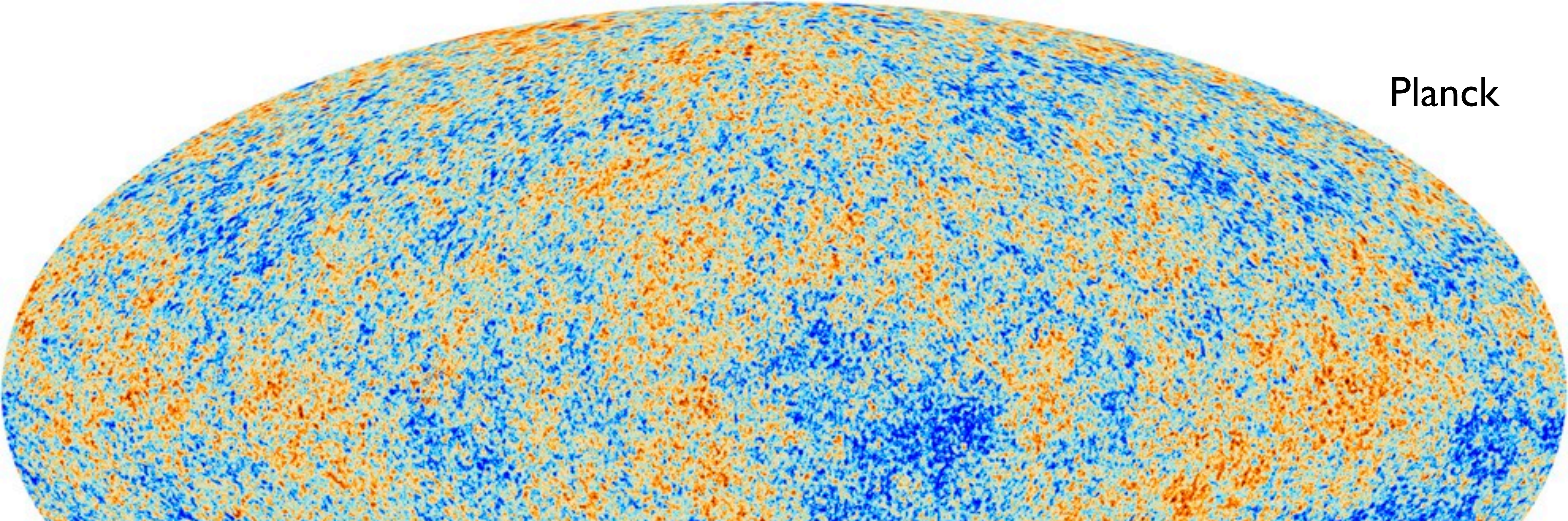
Standard cosmological model ΛCDM

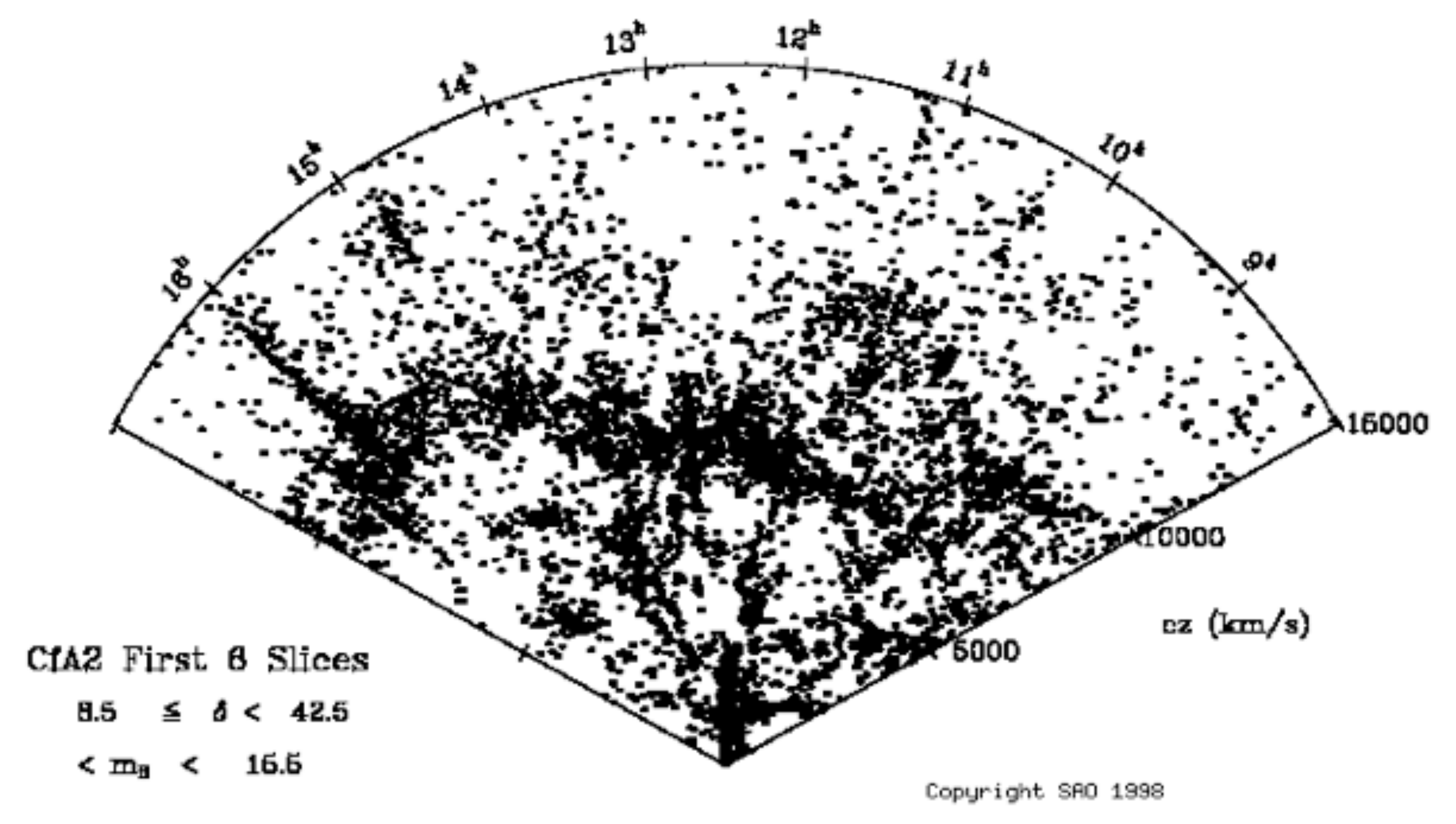
… initial conditions



Standard cosmological model ΛCDM

... from initial conditions

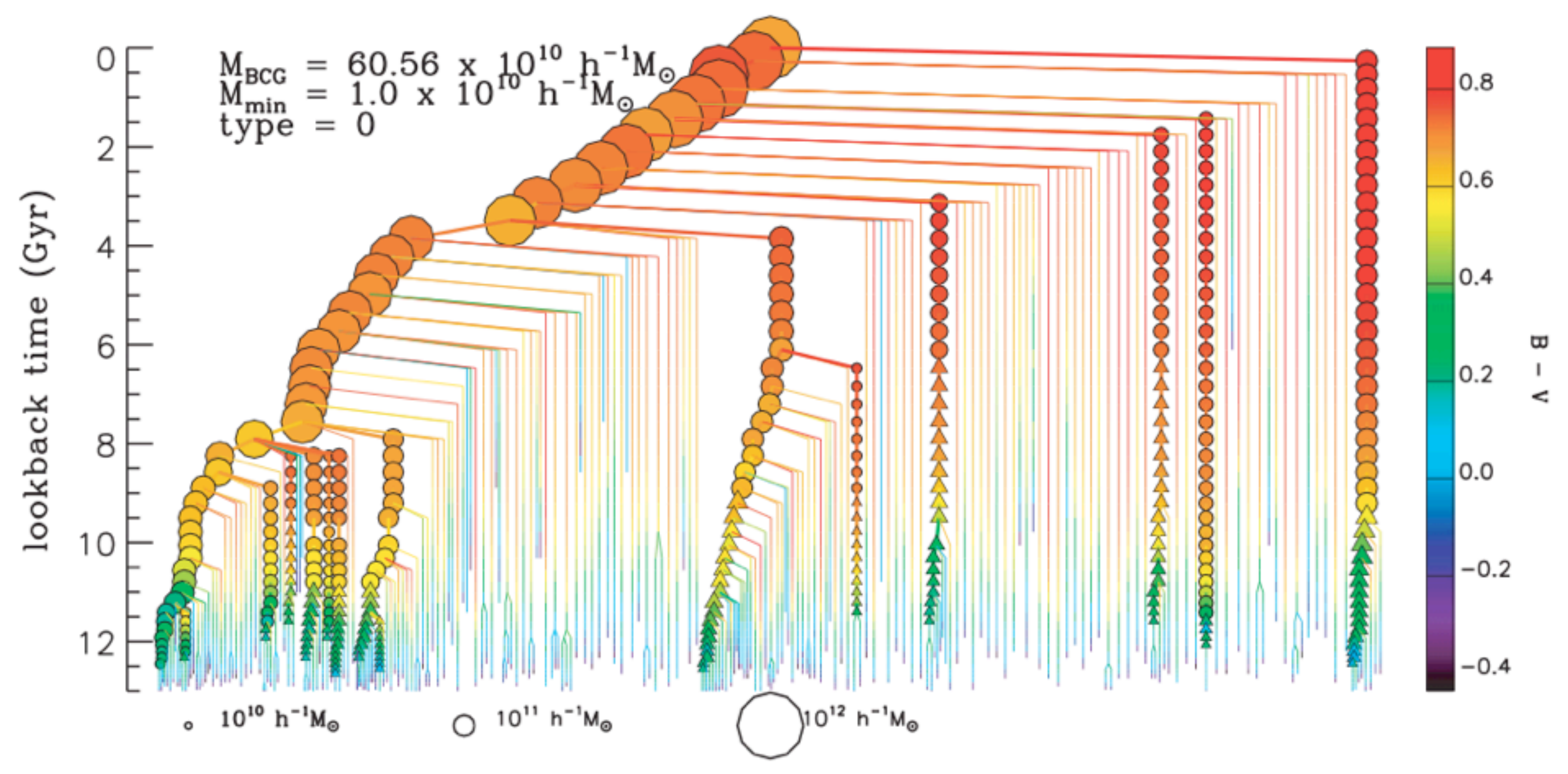




…. to non-linear structures:
filaments, clusters, galaxies

ELVIS

Hierarchical bottom-up process of accretion/merging of cold dark matter (sub)haloes



De Lucia & Blaizot (2007) *MNRAS* 375, 2

Simulations *vs* Observations

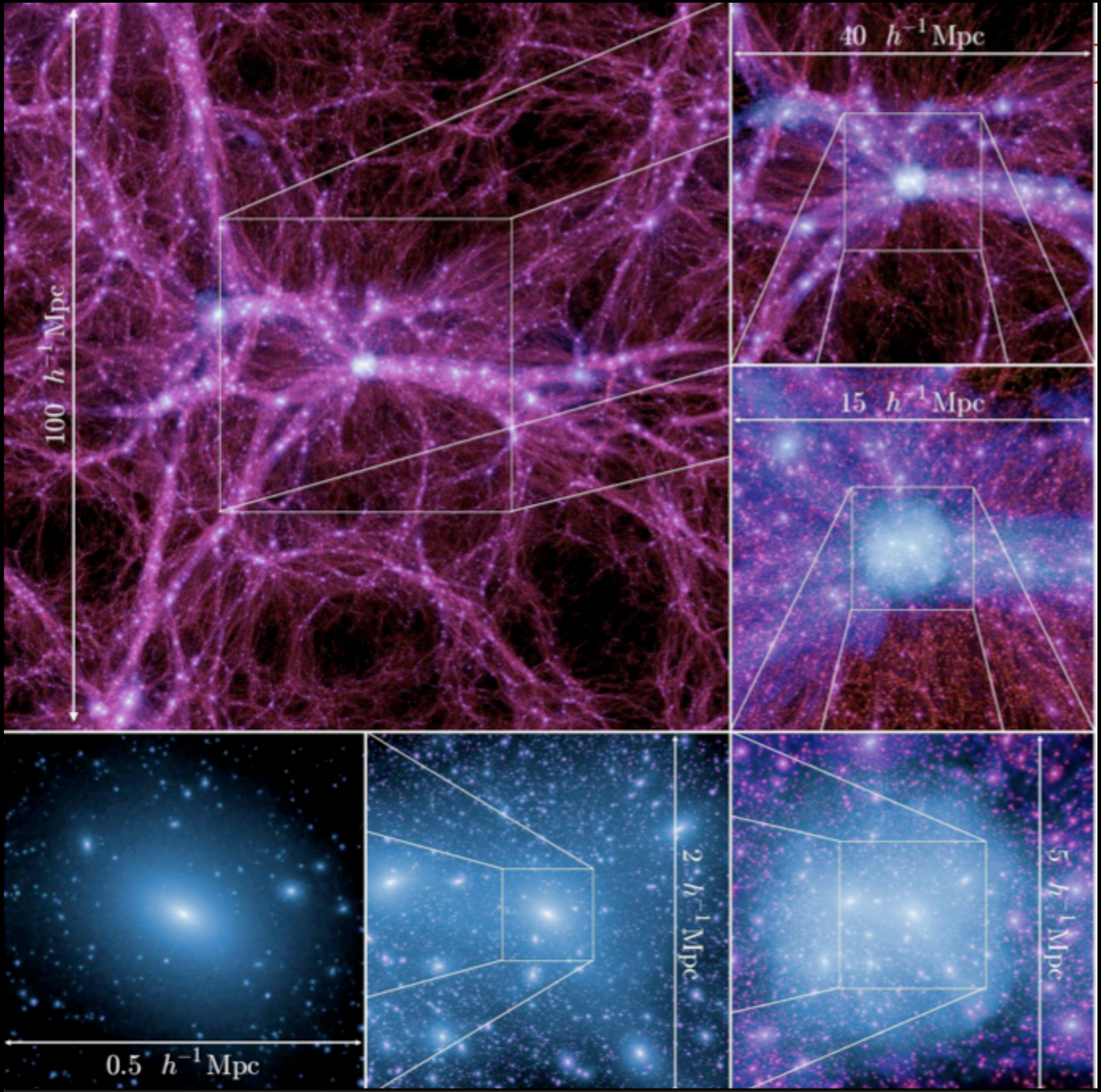
Image credit: The Millennium Run Observatory (R.Overzier, G.Lemson, et al. 2012)

linear

and

mildly nonlinear

highly
nonlinear



Boylan-Kolchin et al. (2009) *MNRAS* 398, 1150

MESSIER's two driving science cases

To critically test the ΛCDM paradigm on *mildy-* and *non-linear* scales

- How do galaxies form by accretion?

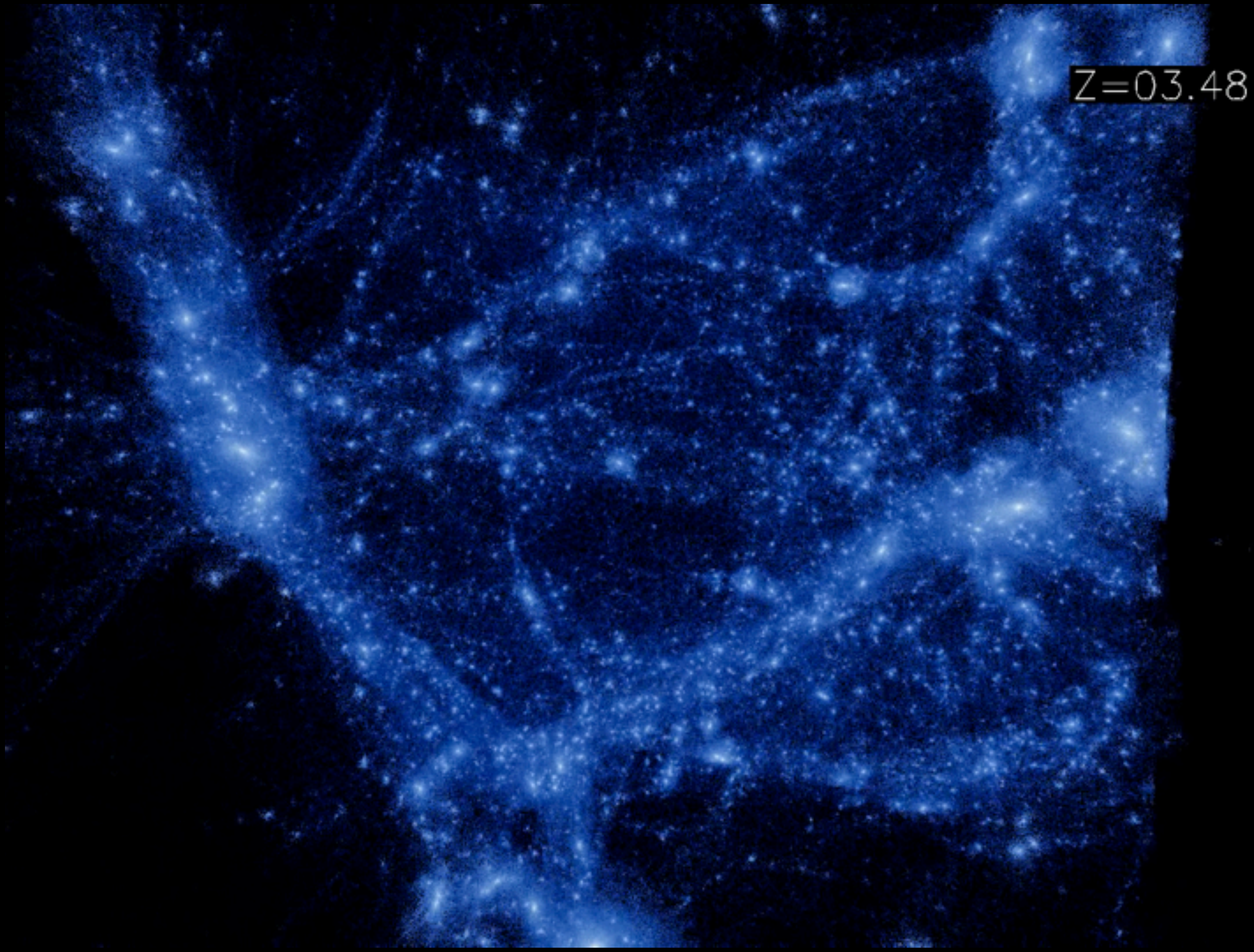
  Anisotropic accretion from filaments? Mergers?
  Discs of satellites? Missing satellites ? Halo profiles?

- What are the properties of the cosmic web ?

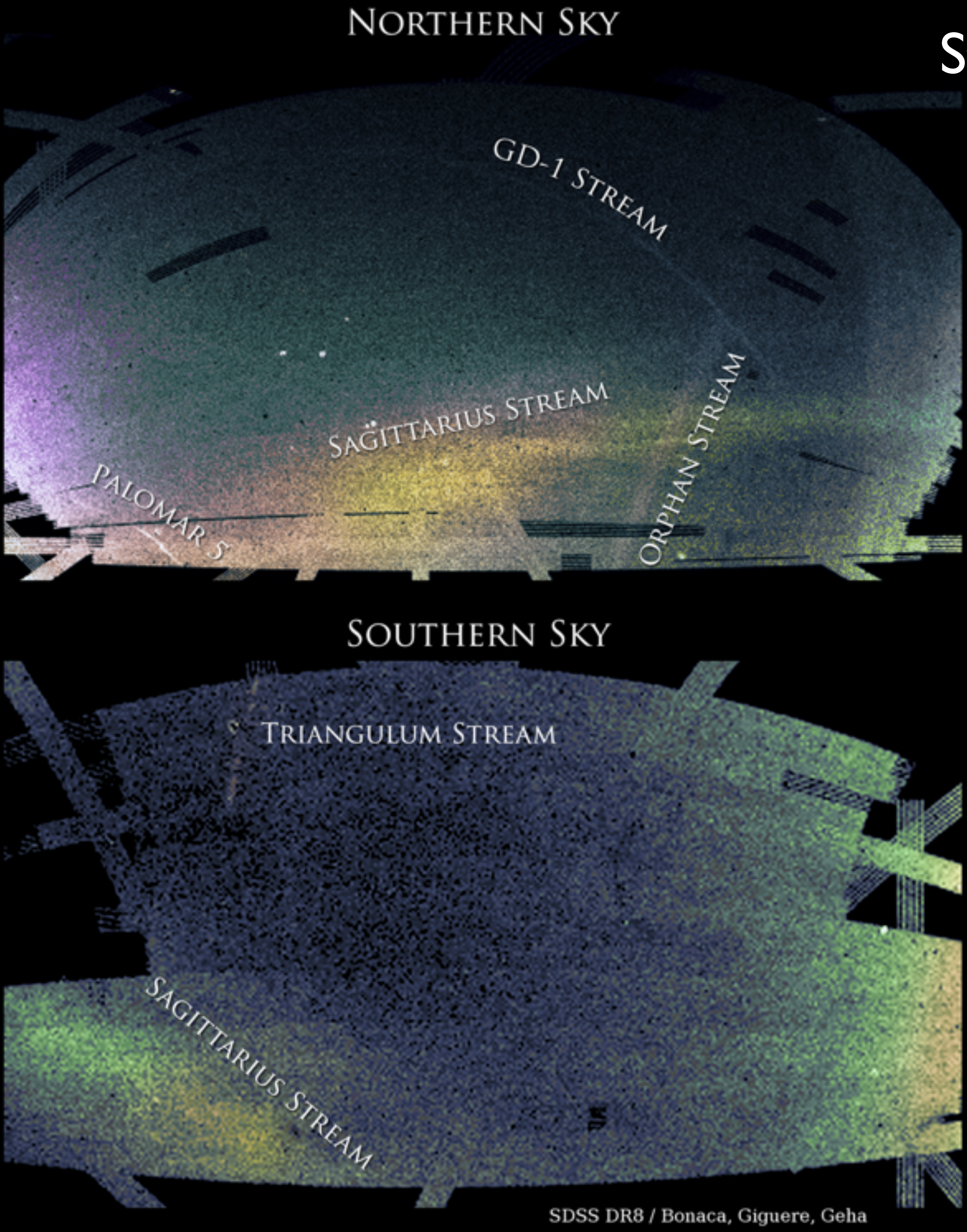
  Does it exist at all?   Do baryons follow dark matter?
  Reservoir of missing baryons? Shock heated? Ionisation?

ESA *Cosmic Vision*:	4.2 The universe taking shape
NSF *Decadal Survey*:	How do cosmic structures form and evolve ?
Europe ASTRONET:	3.2 Cosmic web 3.4 How were galaxies assembled?

Hierarchical formation process through accretion and merging of dark matter haloes



Streams in the Galactic halo

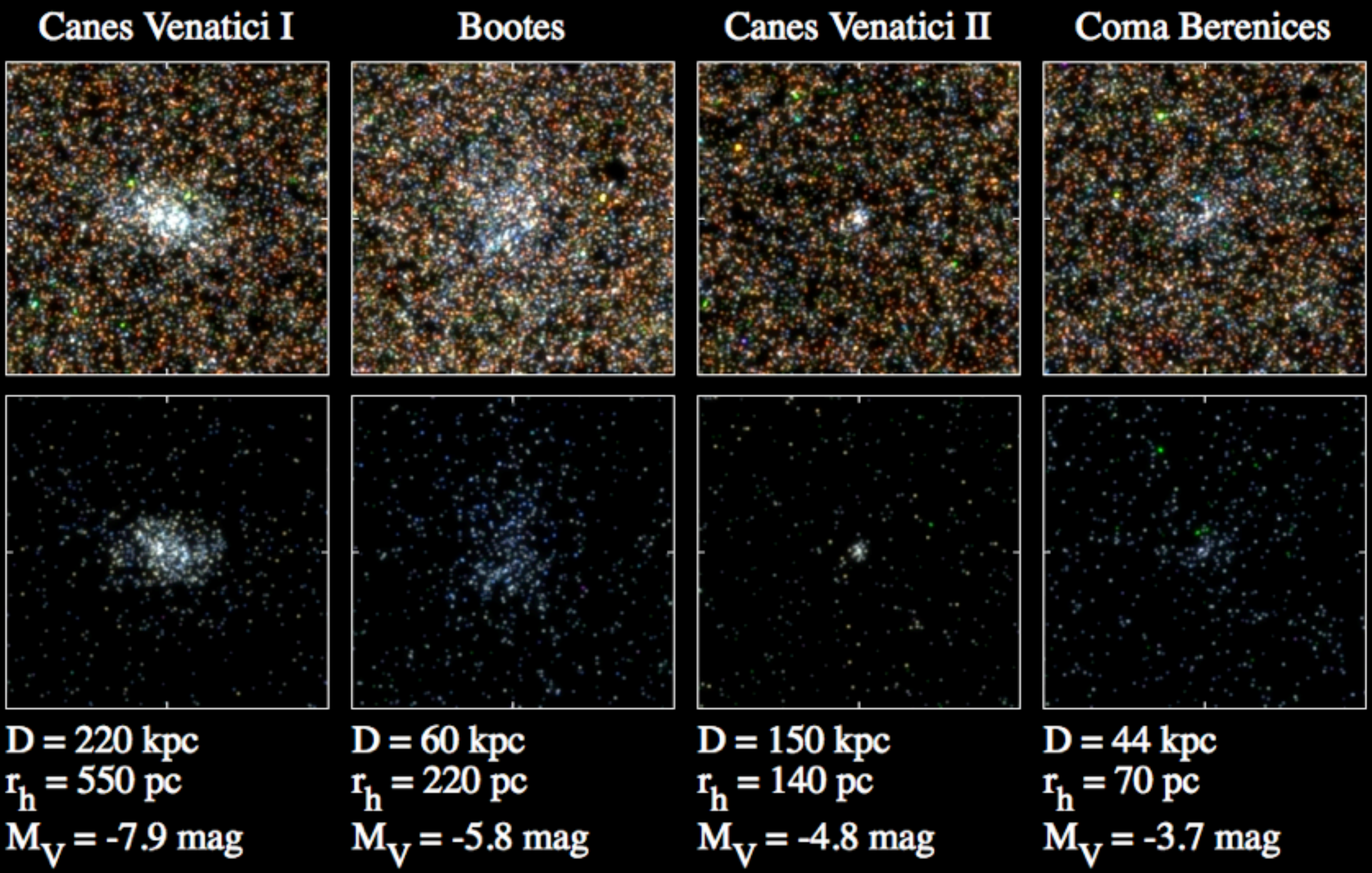


SDSS DR8 / Bonaca, Giguere, Geha

Can we detect the fossil record of past accretion events beyond our Galaxy ?

Driving science case #1

Key prediction of the ΛCDM paradigm the (over?) abundance of dwarf satellites



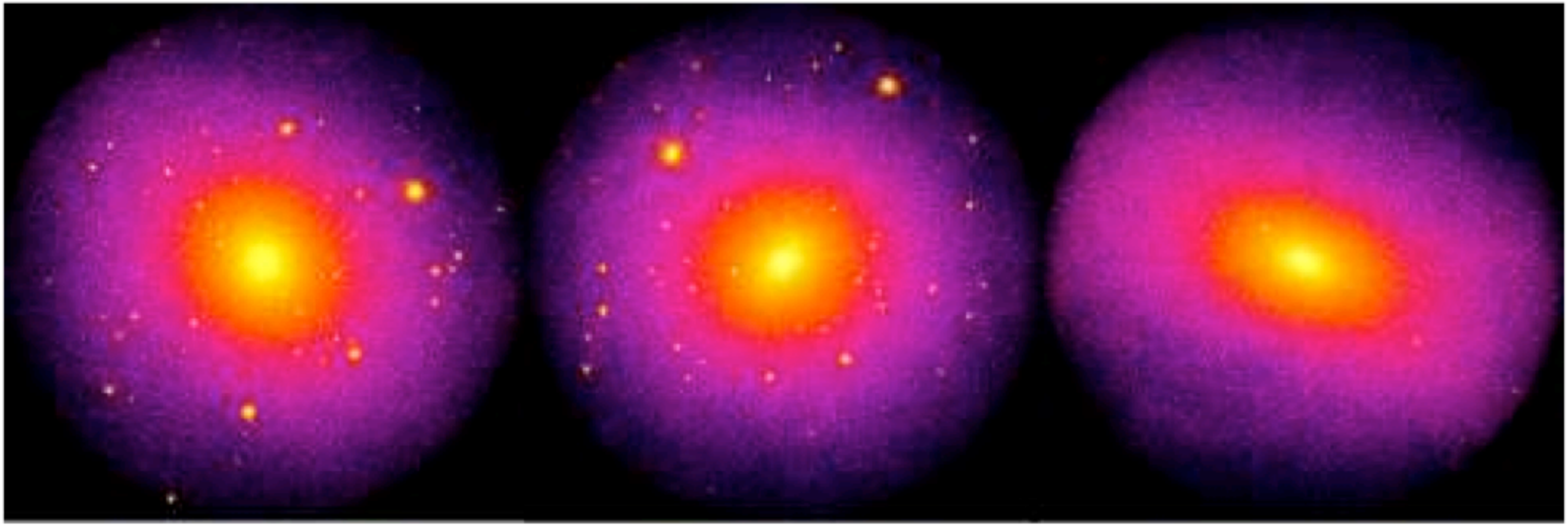
Belokurov et al. (2008)

Tension in the CDM paradigm ?

Self-Interacting Dark Matter

Cold Dark Matter

Warm Dark Matter



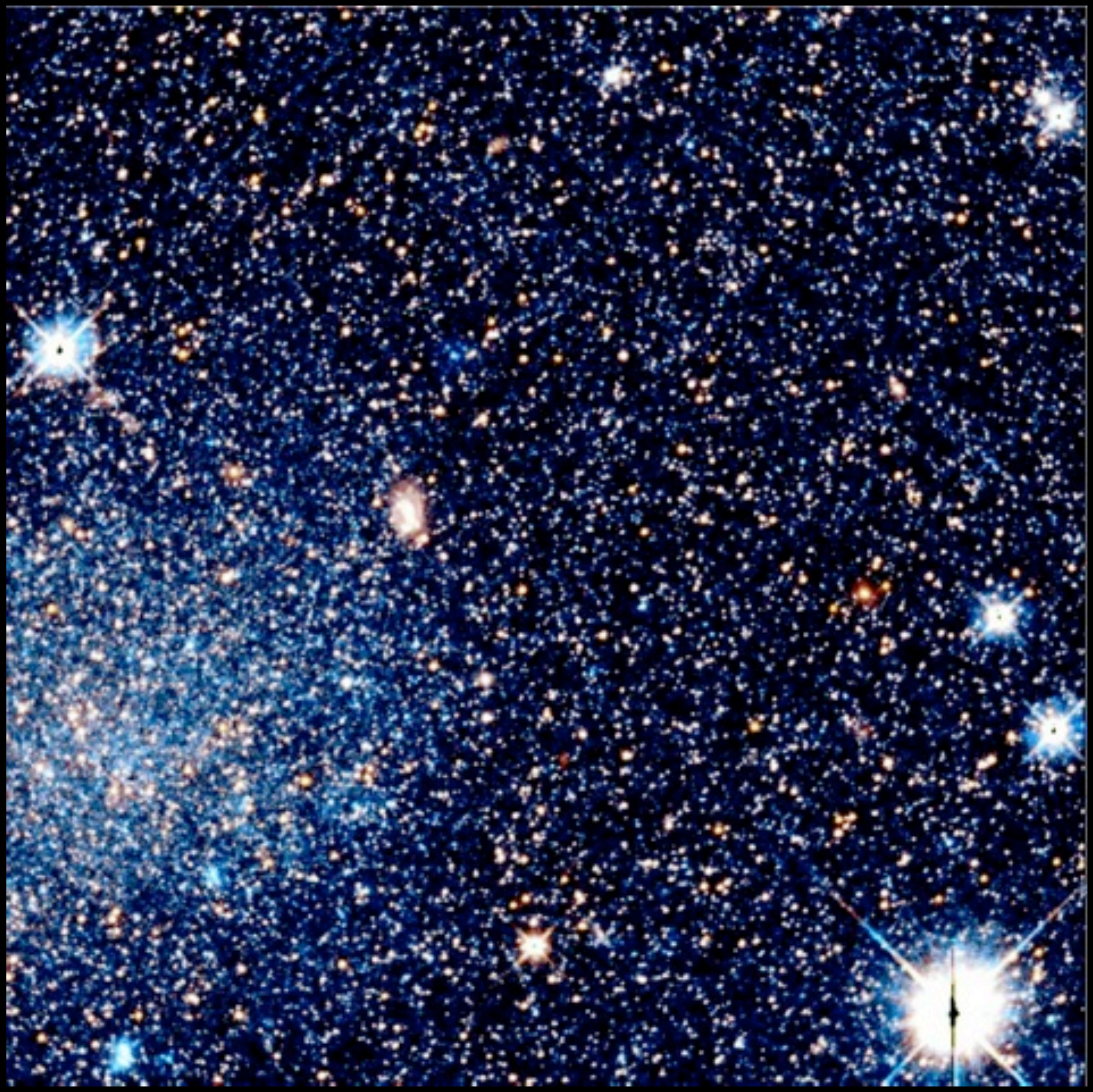
Brooks *et al.* (2014)

All newly-discovered satellites of the Galaxy and Andromeda are at the limit of surface brightness reachable by counting (resolved) stars

Leo T

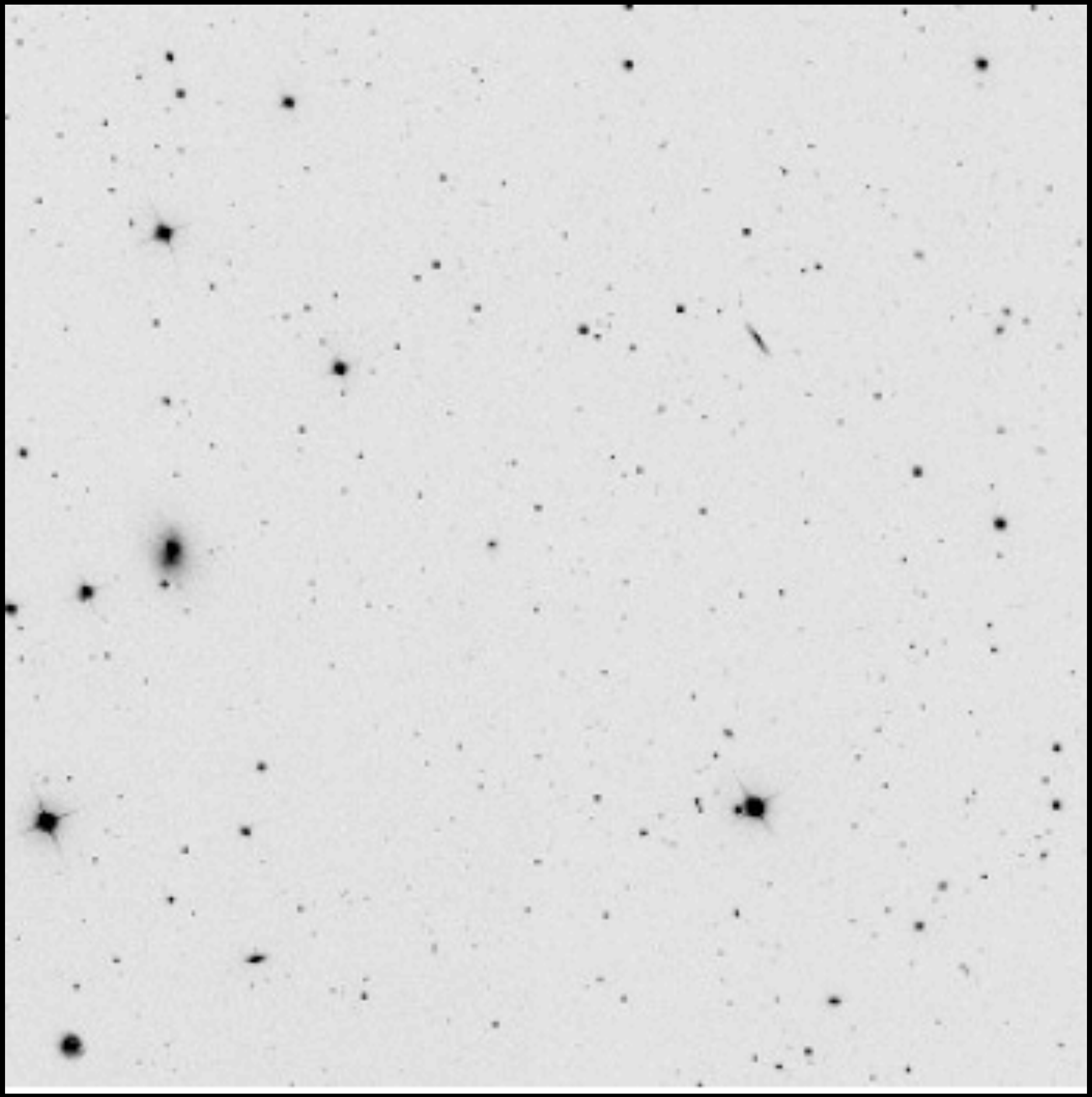
Ground-based

And IV

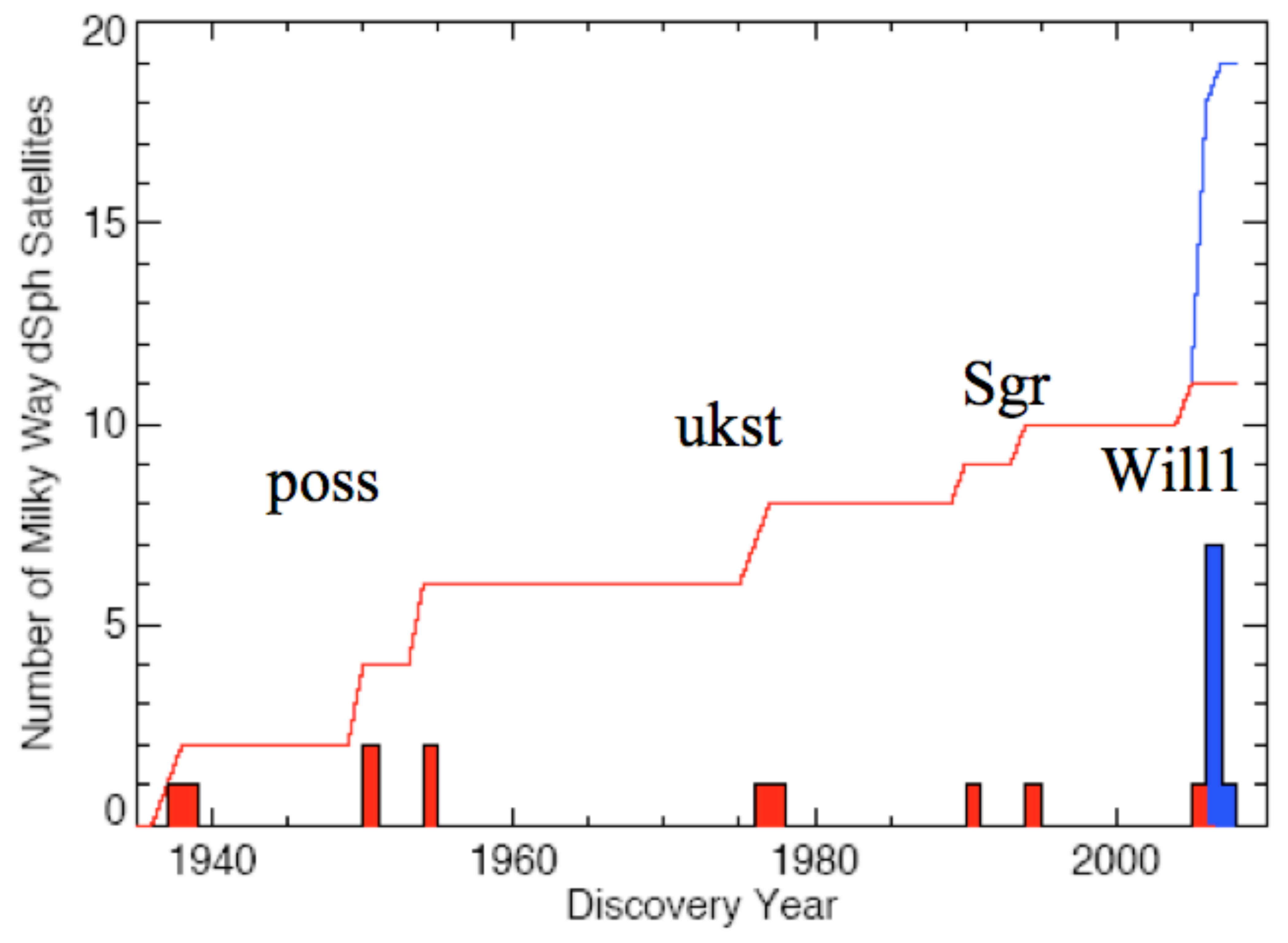


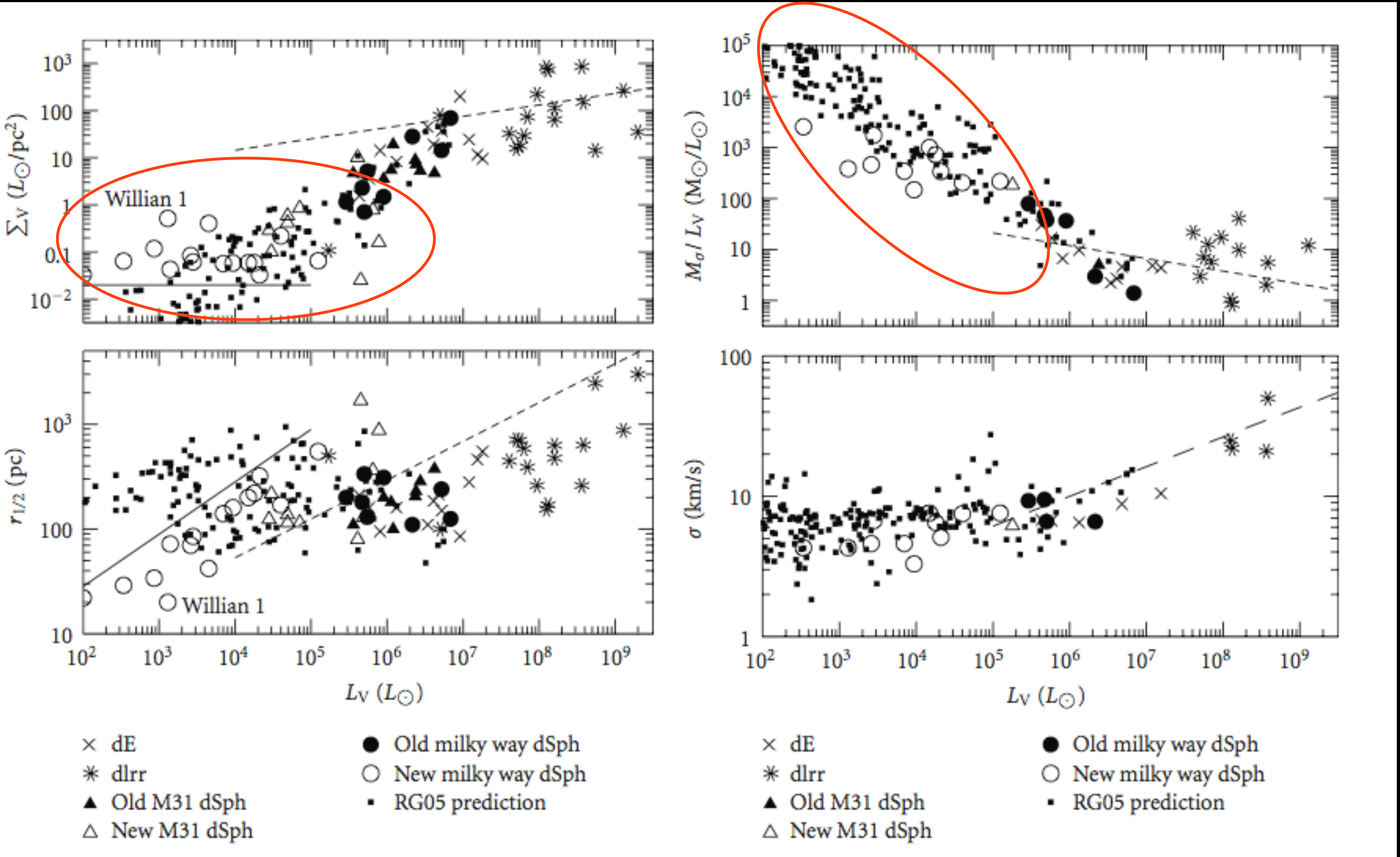
HST

The case of Segue I

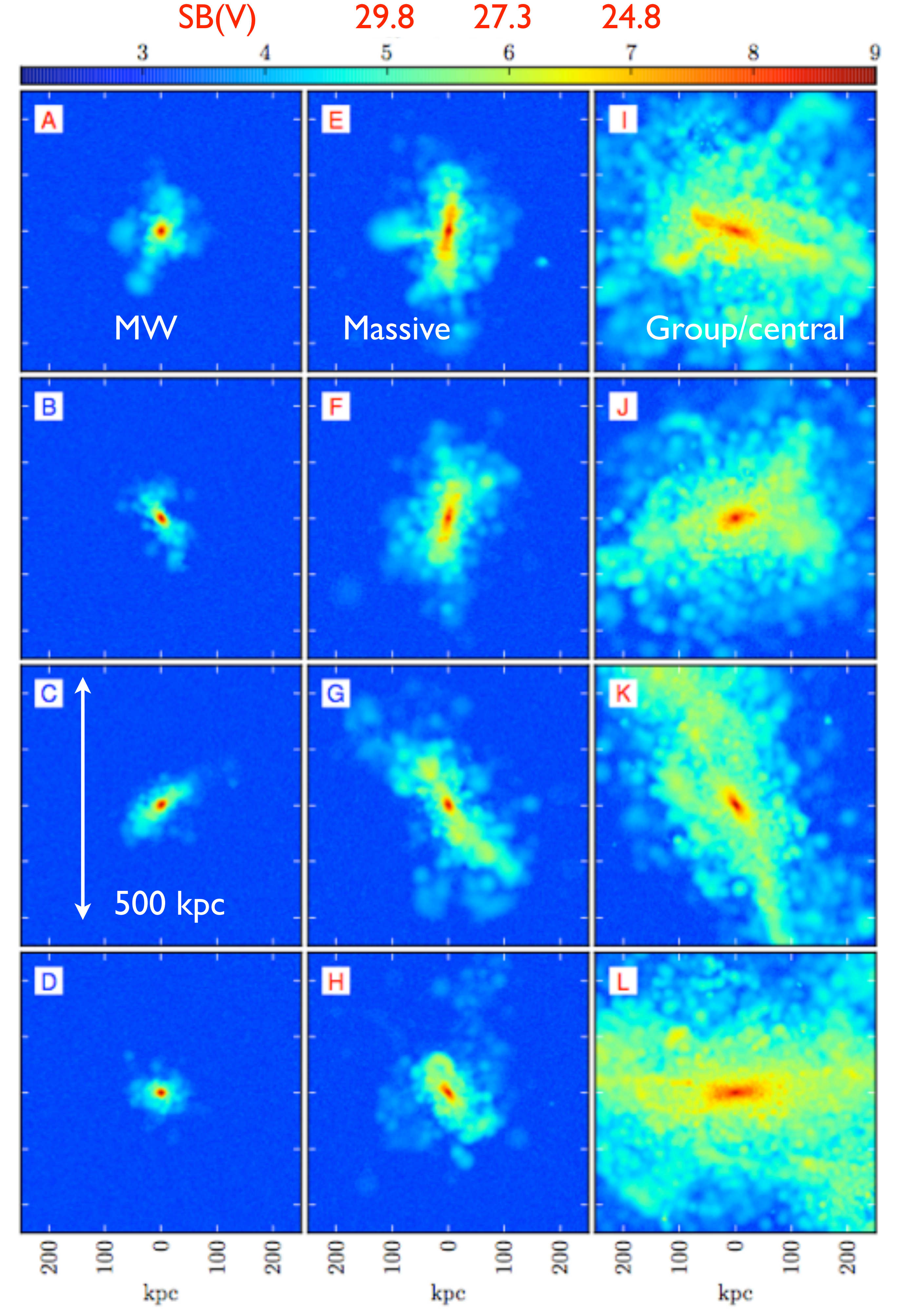


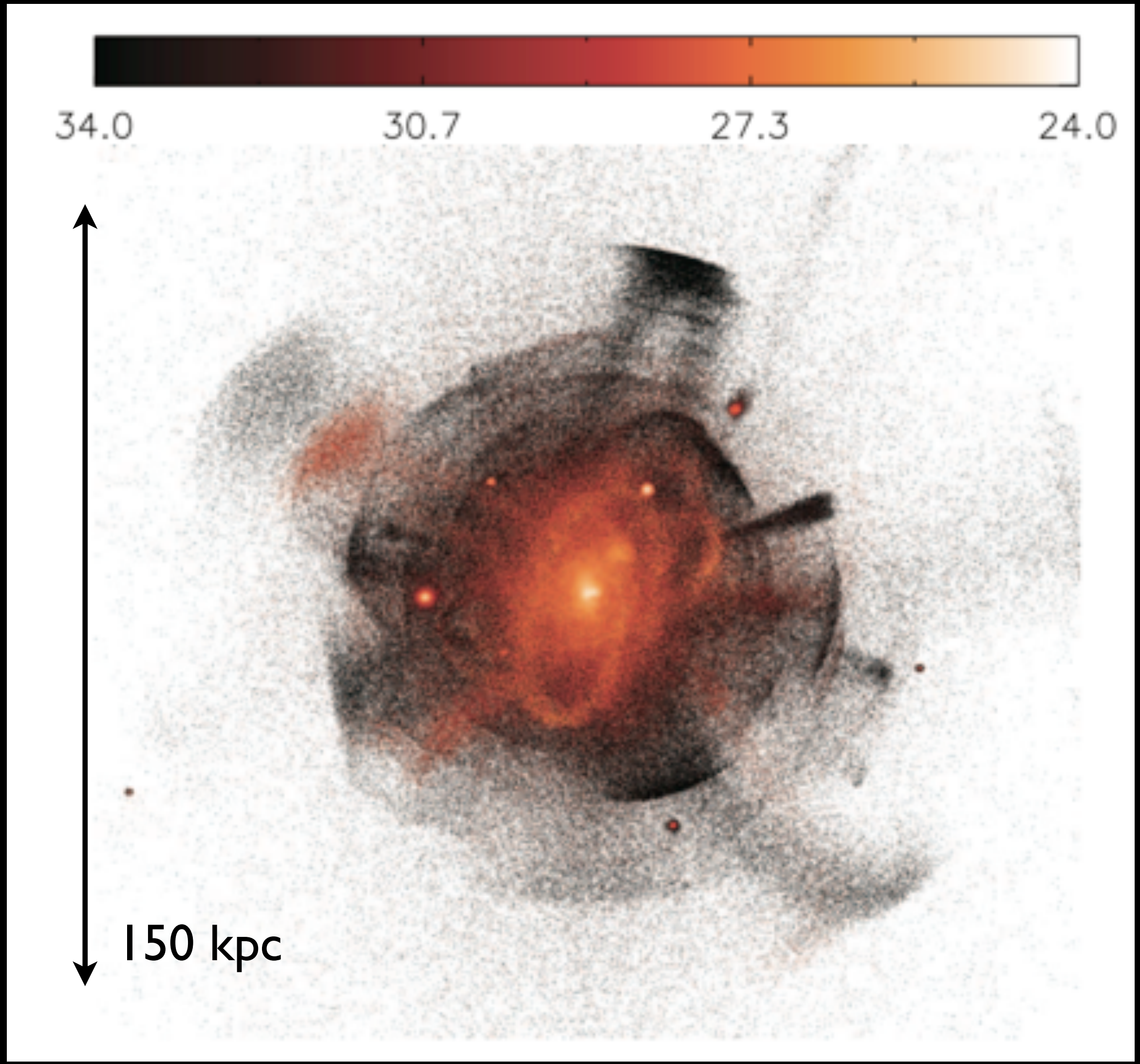
Discovery rate of Milky Way satellites





Ricotti (2011)



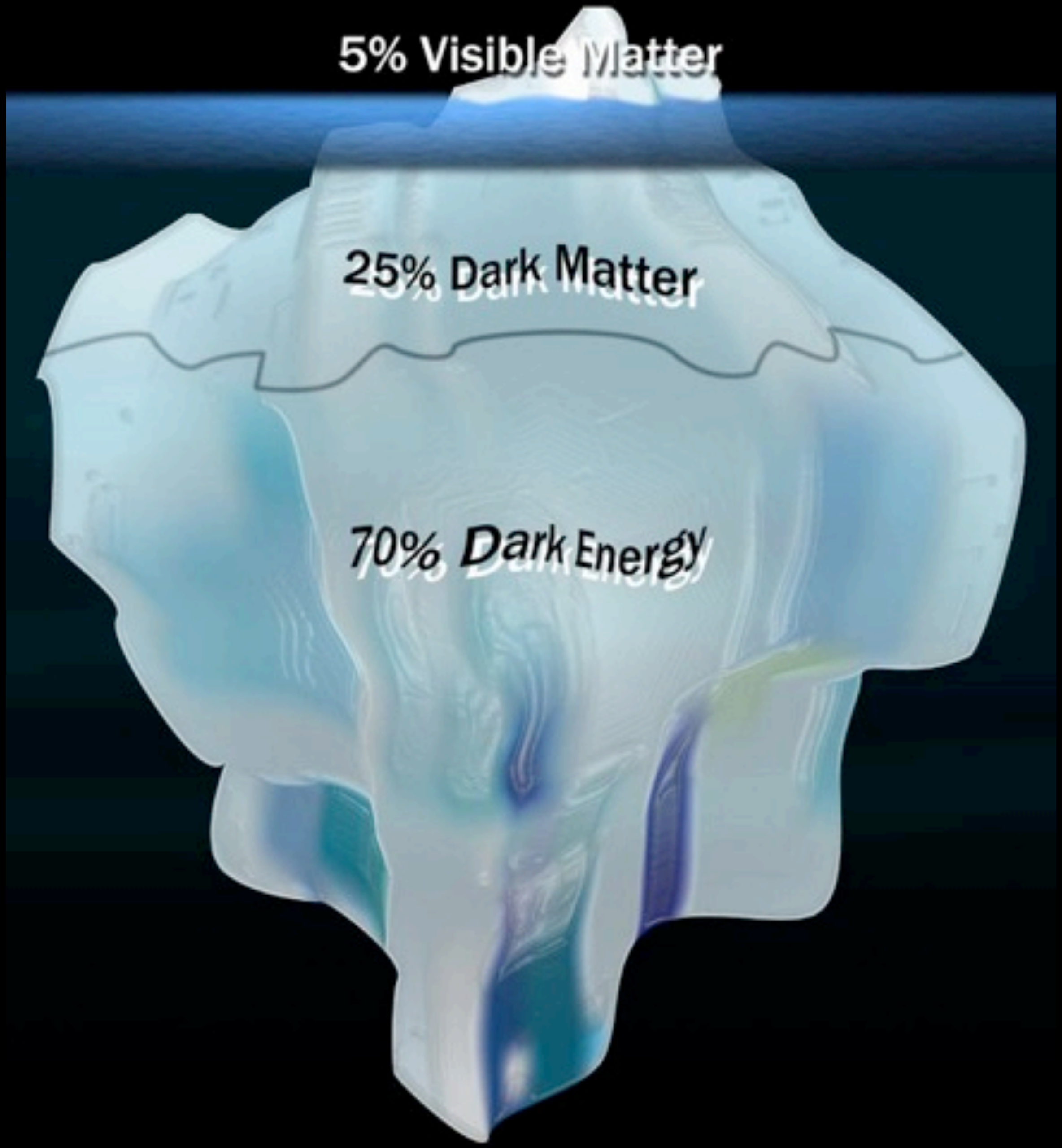


Font *et al.* (2008)

Most predicted structures lie at surface brigtness levels below 30 mag arcsec^{-2}

Unreachable from the ground

Cooper *et al.* (2013)



[...] *galaxies are like icebergs and what is seen above the sky background may be no reliable measure of what lies underneath.*

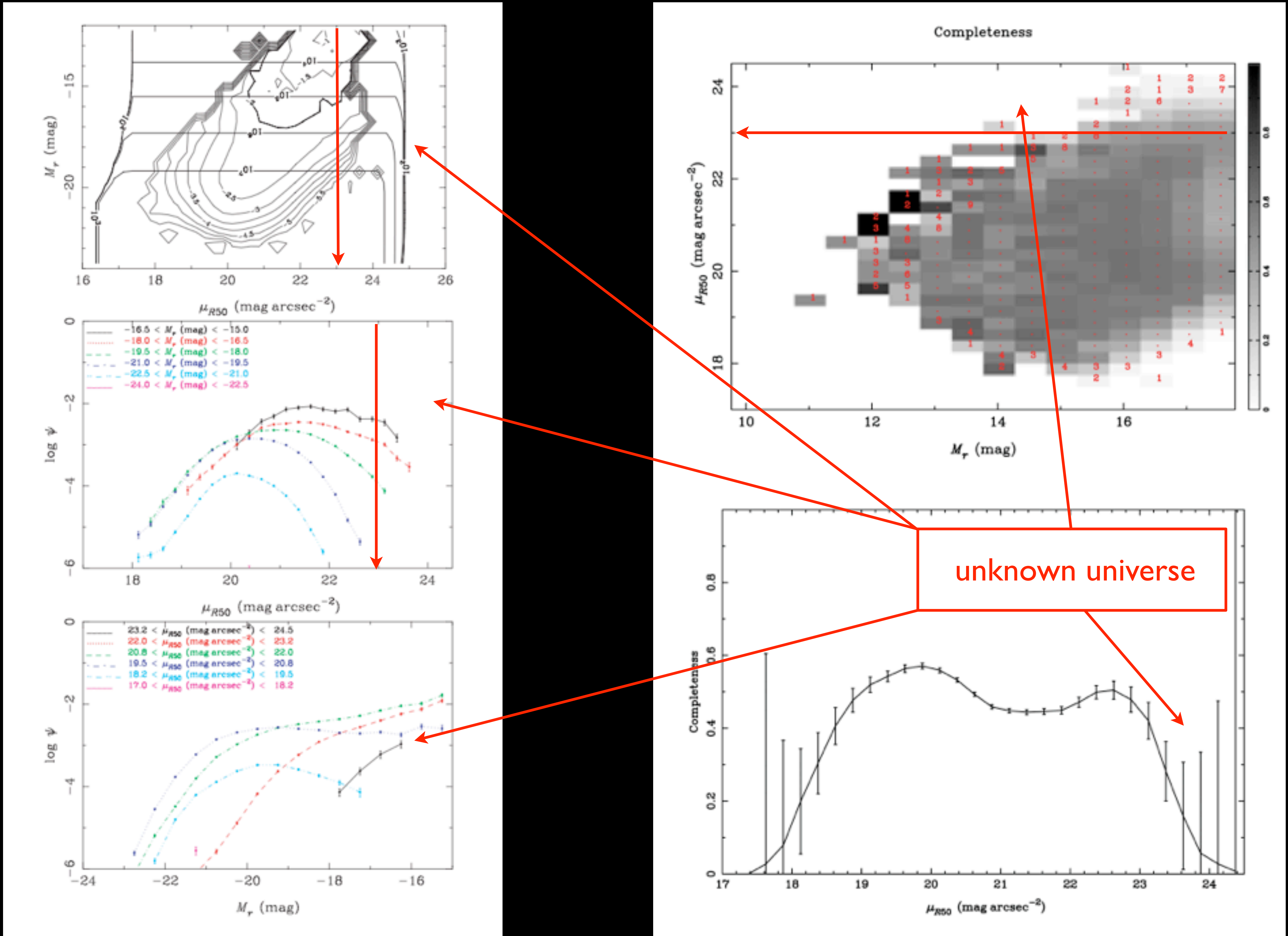
Michael Disney (1976)

The unprobed realm of the low surface brightness universe

Mihos et al. (2005)

Limited by systematics
- sky variability
- straylight
- flat field accuracy
- extended PSF wings

Surface brightness completeness issues



unknown universe

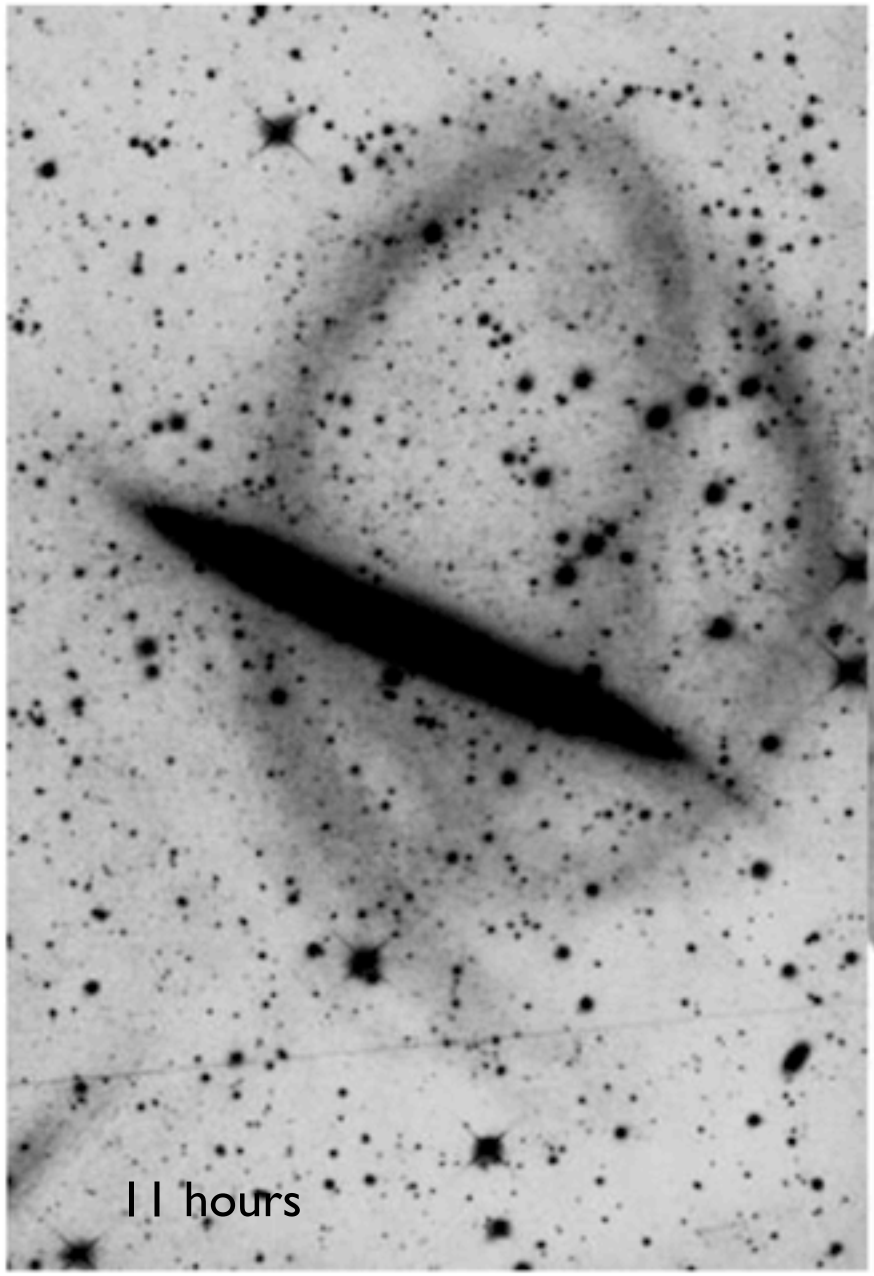
NGC 4013 *d*=18 Mpc

NGC 5907 *d*=14 Mpc

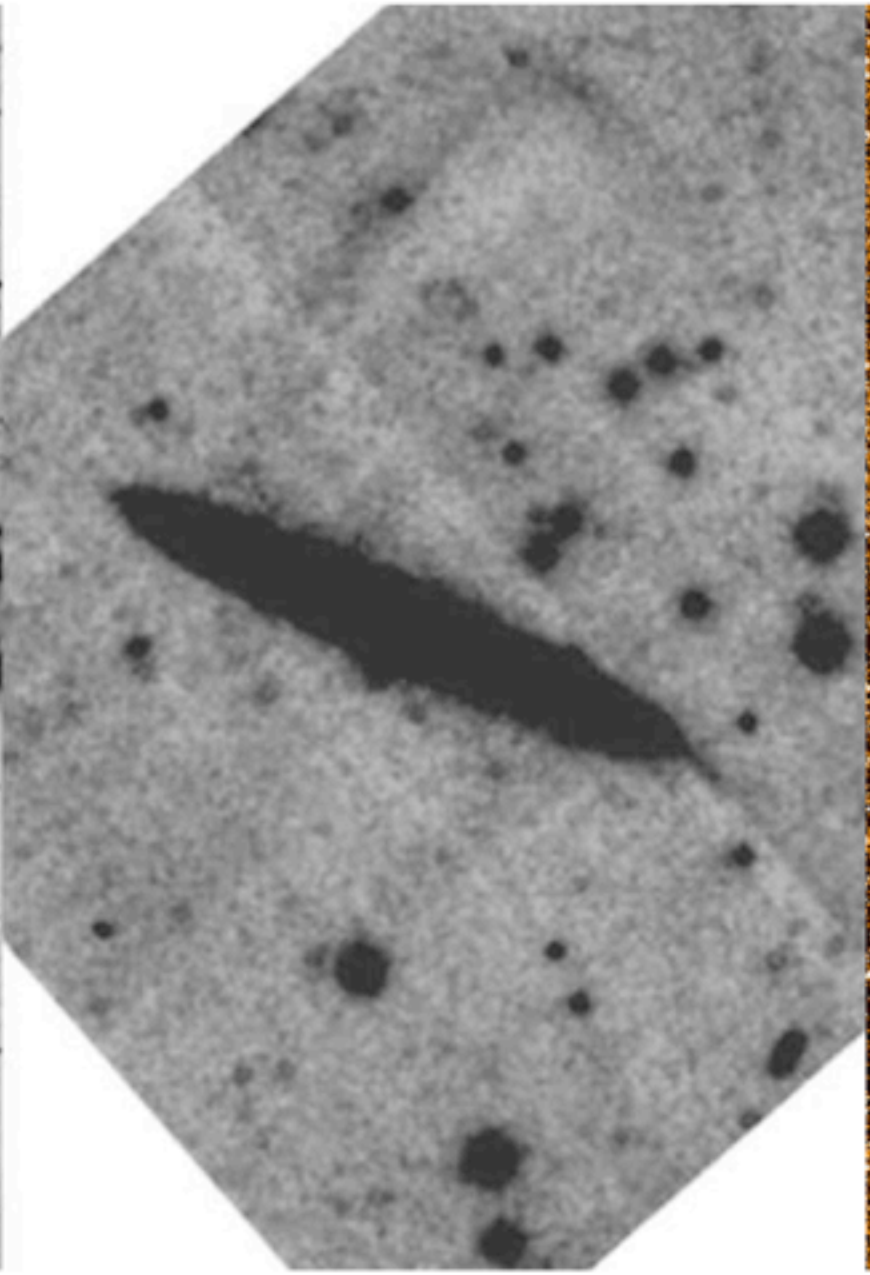
51 cm Richtey-Chrétien
CCD SBIG 27’ 0.45”/pixel
Exposure time: 11 hours
SB ≈29 mag arcsec^{-2}
Amateurs with scopes f/D=8-10

Martinez Delgado *et al.* (2008-2010)

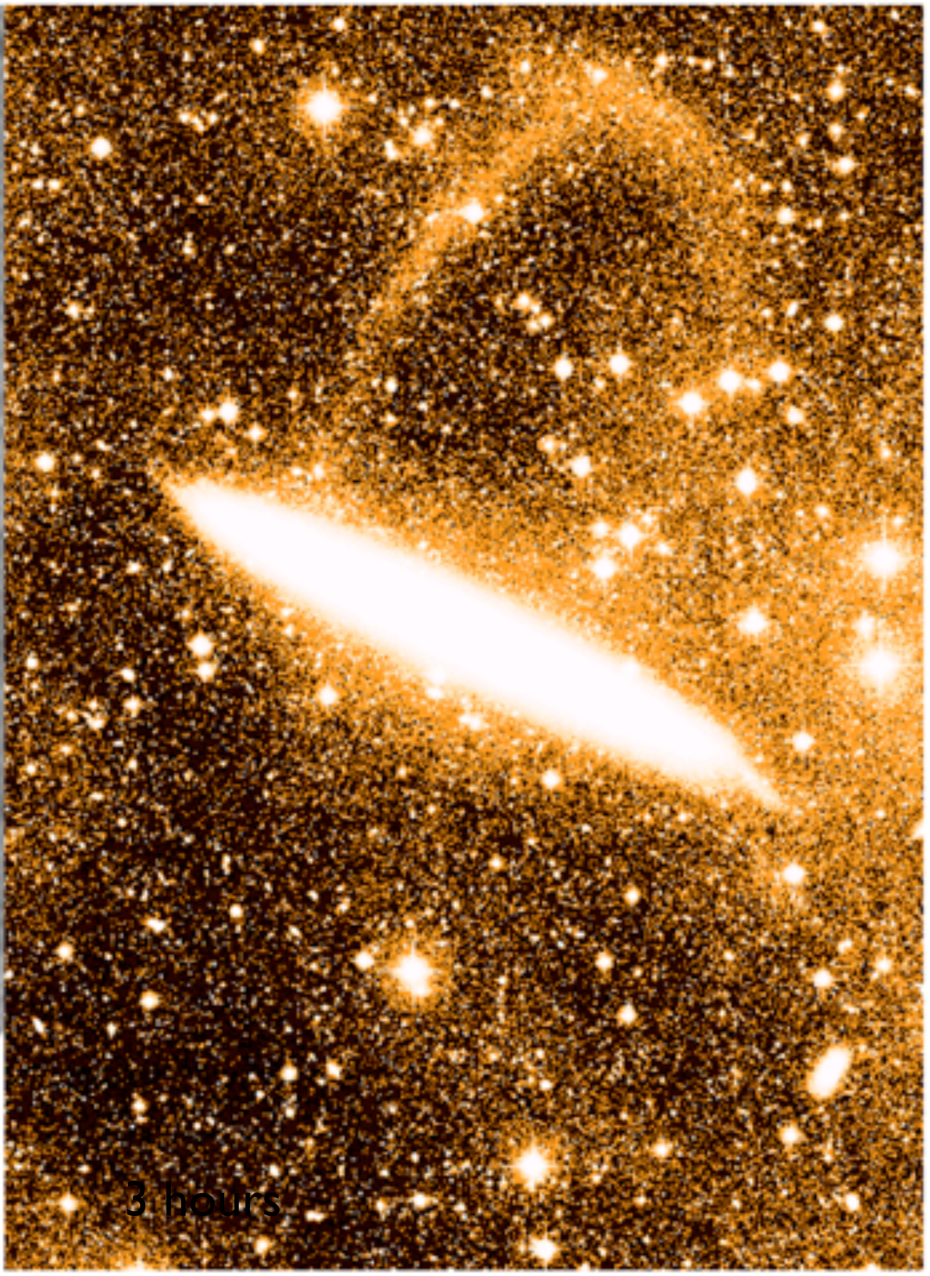
The paradigmatic case of NGC 5907



0.5m f/8.1
Martinez Delgado et al. 2008



SDSS
Miskolczi et al. 2011



CFHT
Ibata et al. 2011

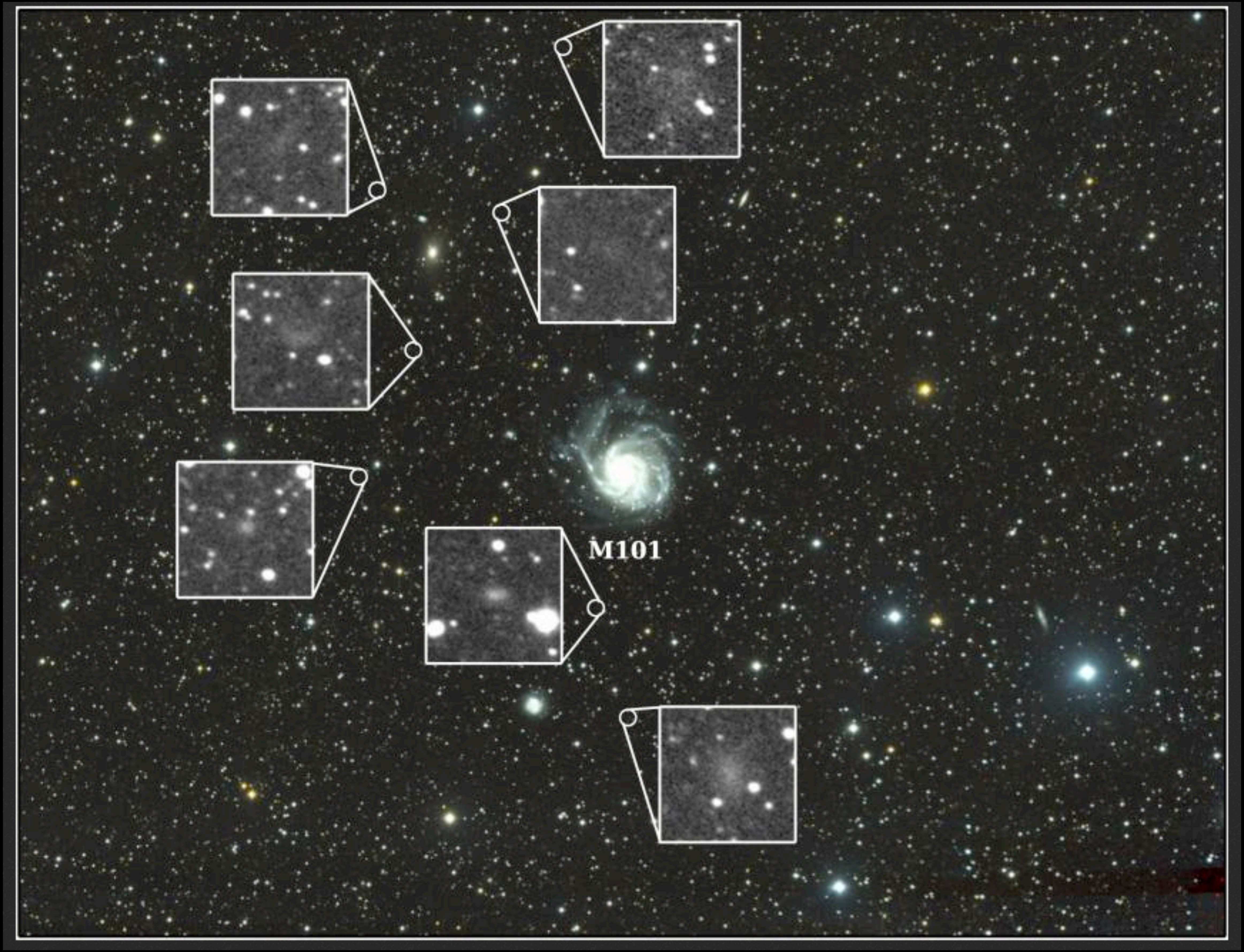
Key points: $SB \propto D^2 / F^2 \propto (D/F)^2$ f/2 is 100x faster than f/20

PSF wings

ATLAS-3D Elliptical galaxies CFHT LSB-Elixir

Credit: P.A. Duc

The Dragonfly camera



Van Dokkum & Abraham (2014)

Current instrumentation is *not* adequate

Signal received by an *unresolved* source:

$$F_{\rm point} \;\propto\; A\,\epsilon\,t_{exp}\,10^{-0.4\,m_{tot}}$$

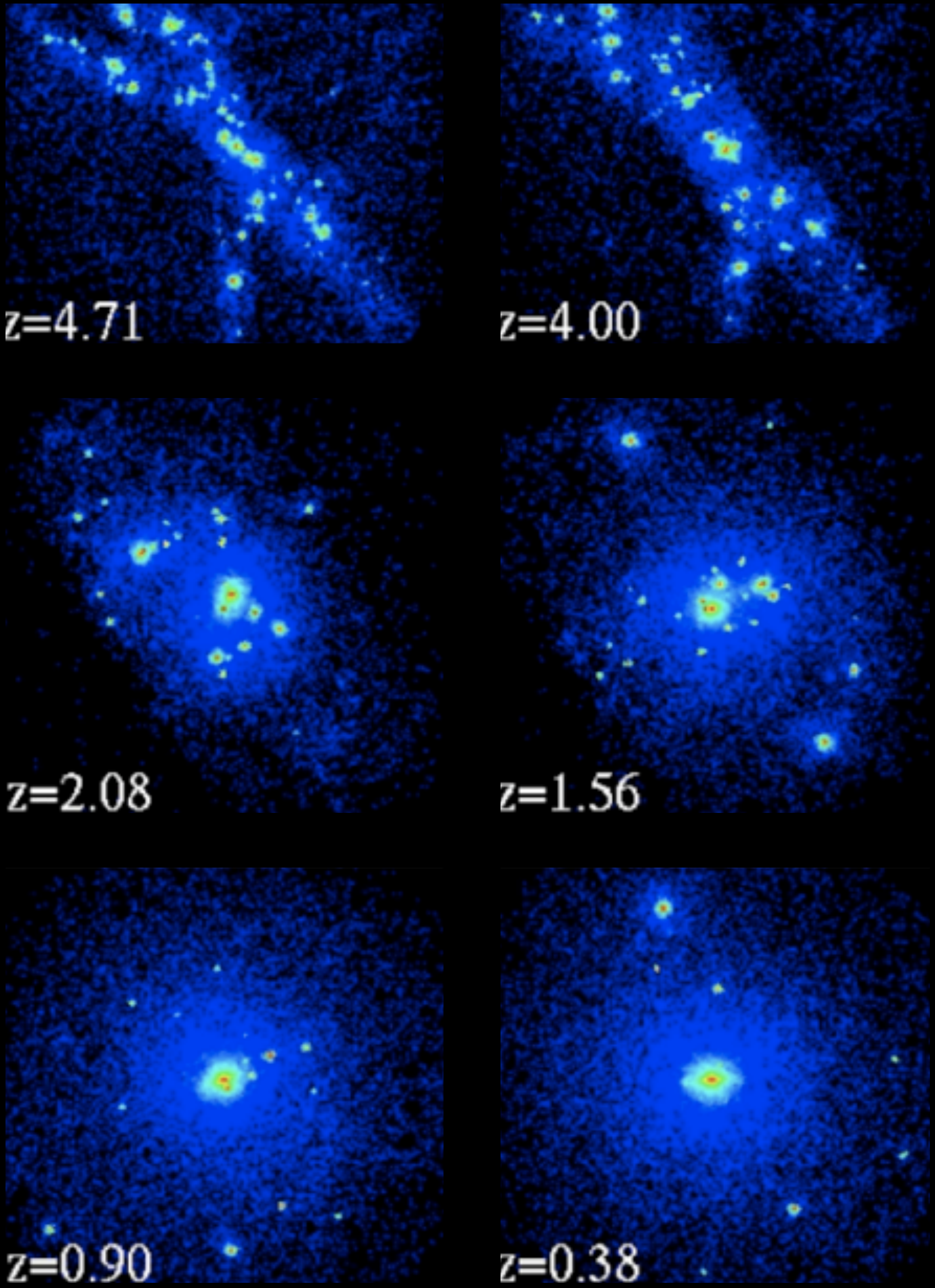
→ drives telescopes with large diameters and large focal lengths

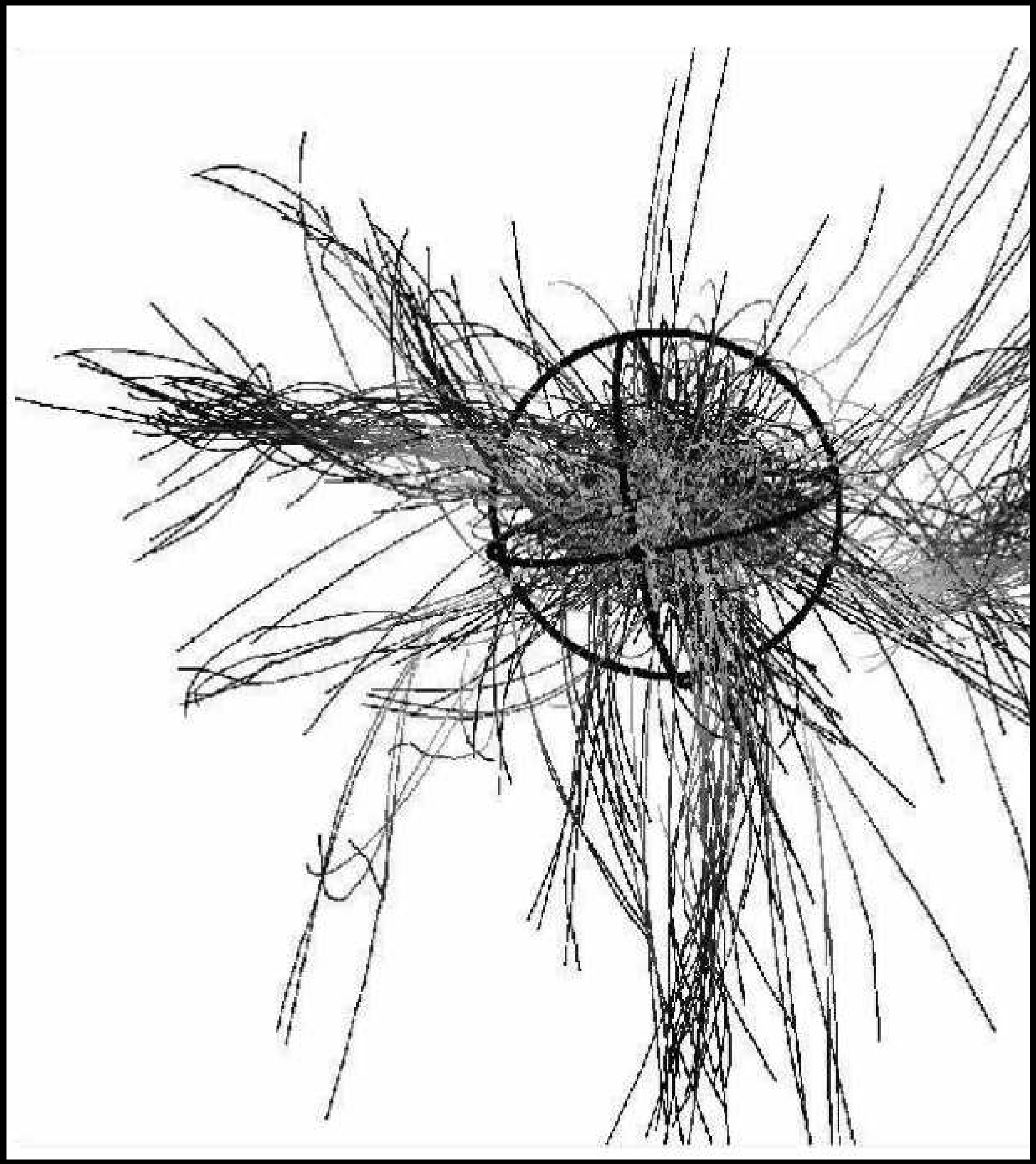
Surface brightness received by a *extended* source:

$$SB_{\rm extended} \;\propto\; \left(\frac{D}{f}\right)^2 \epsilon\,t_{exp}\,s^2_{pix}\,N_{pix}\,10^{-0.4\,\mu}$$

→ requires fast optics with *minimal* (*f*/*D*) ratio
→ drives *small D* telescopes

Formation history of galactic haloes



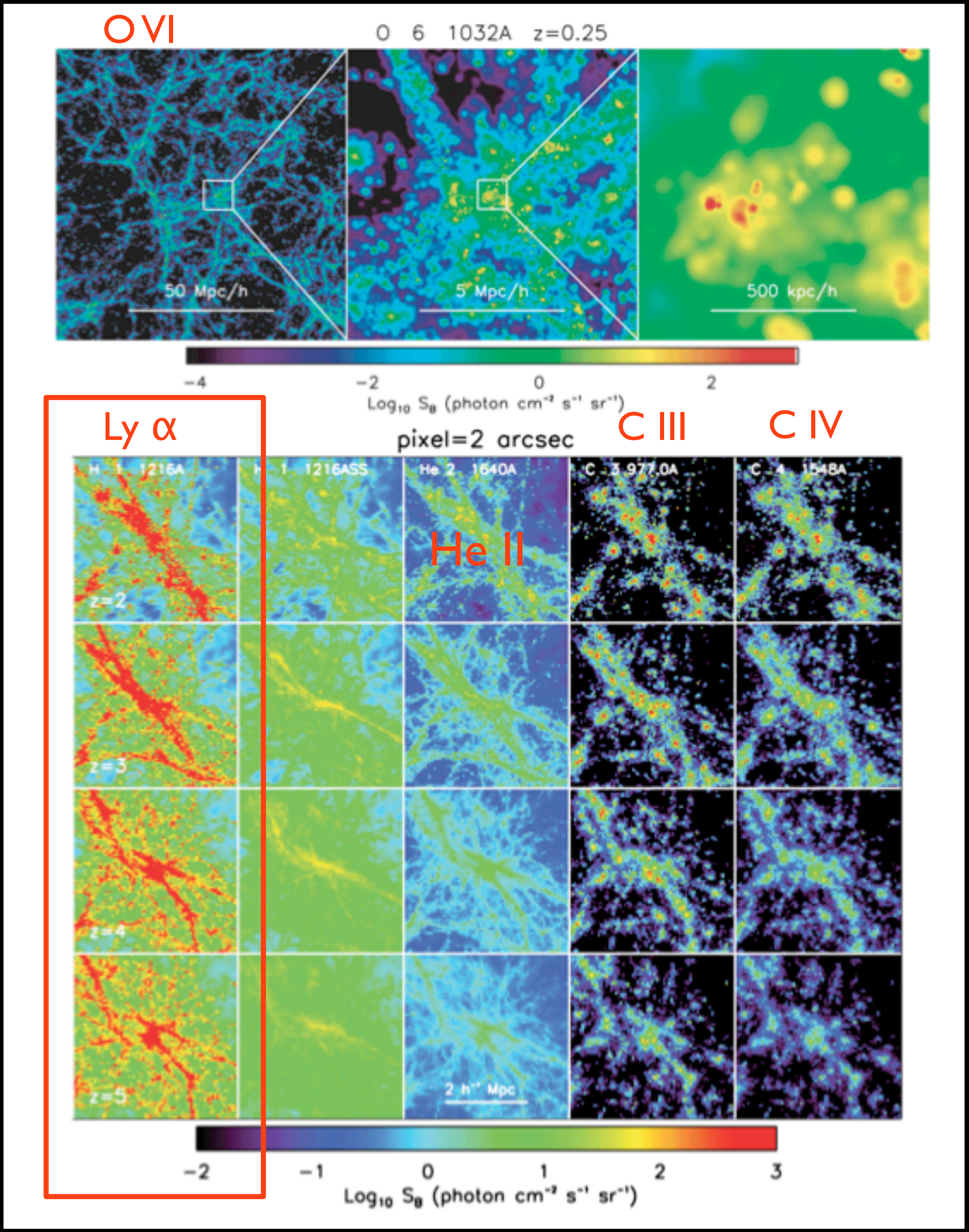


Is there any evidence for accretion by filaments ?

Driving science case #2

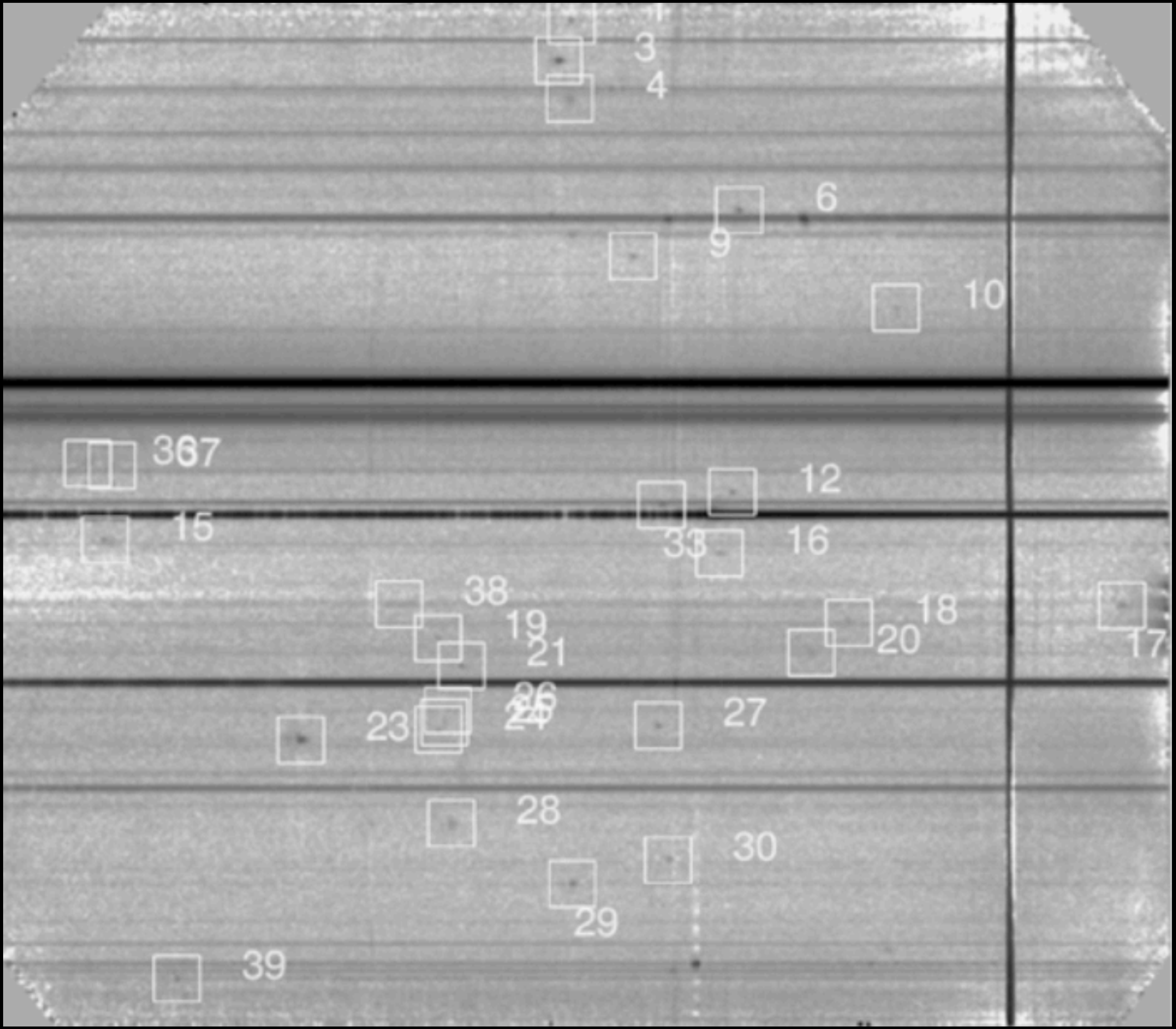
The Cosmic Web

Strongest in Lyman α by ~1000 x



Bertone + Schaye (2012) *MNRAS* 419, 780

Low surface brightness Lyman-α emitters

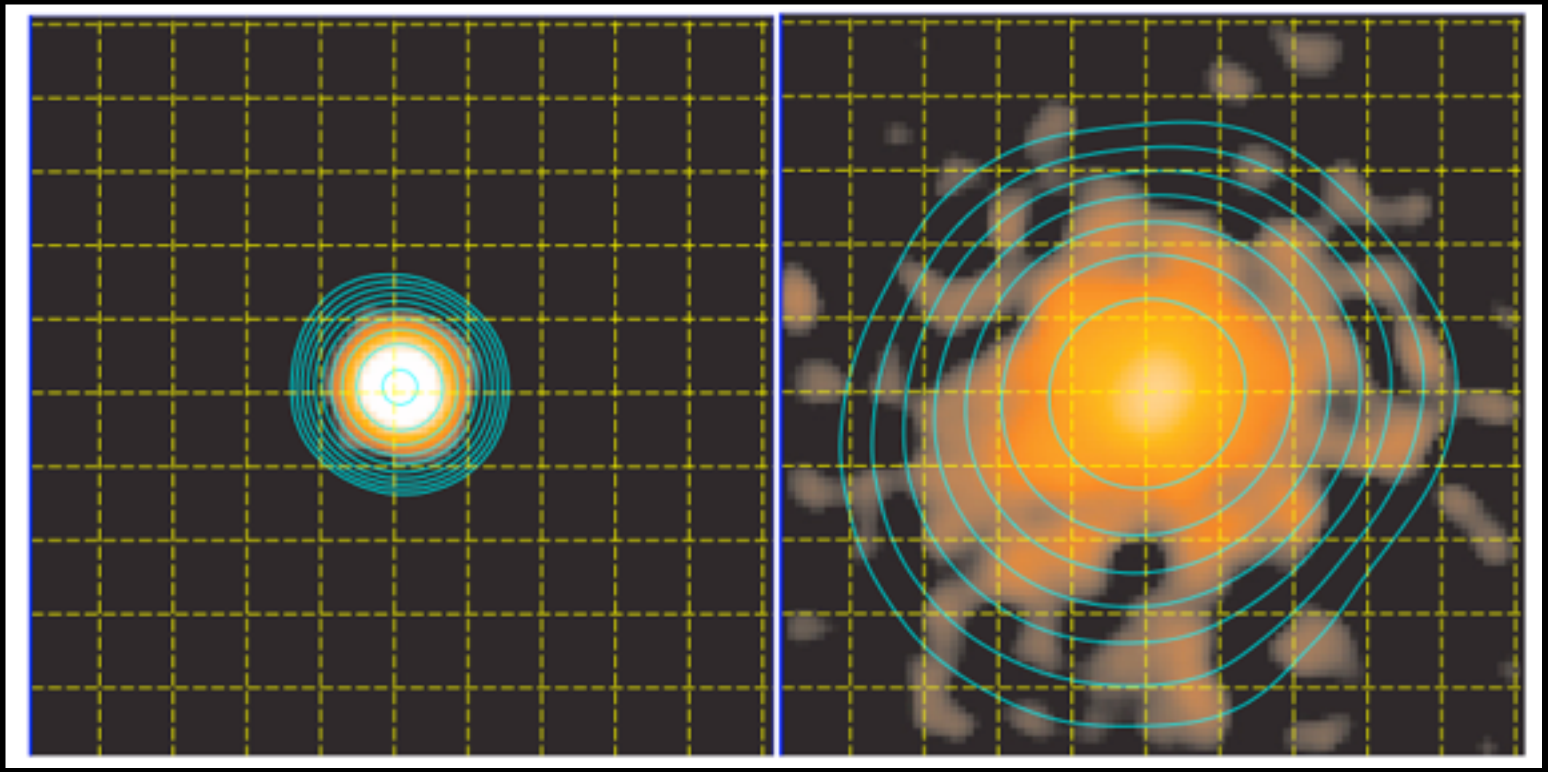


VLT
92 hours exposure

Rauch *et al.* (2008)
ApJ 681, 856

Extended Lyman-α emission from z = 2.65 star-forming galaxies

UV continuum



Lyman-α

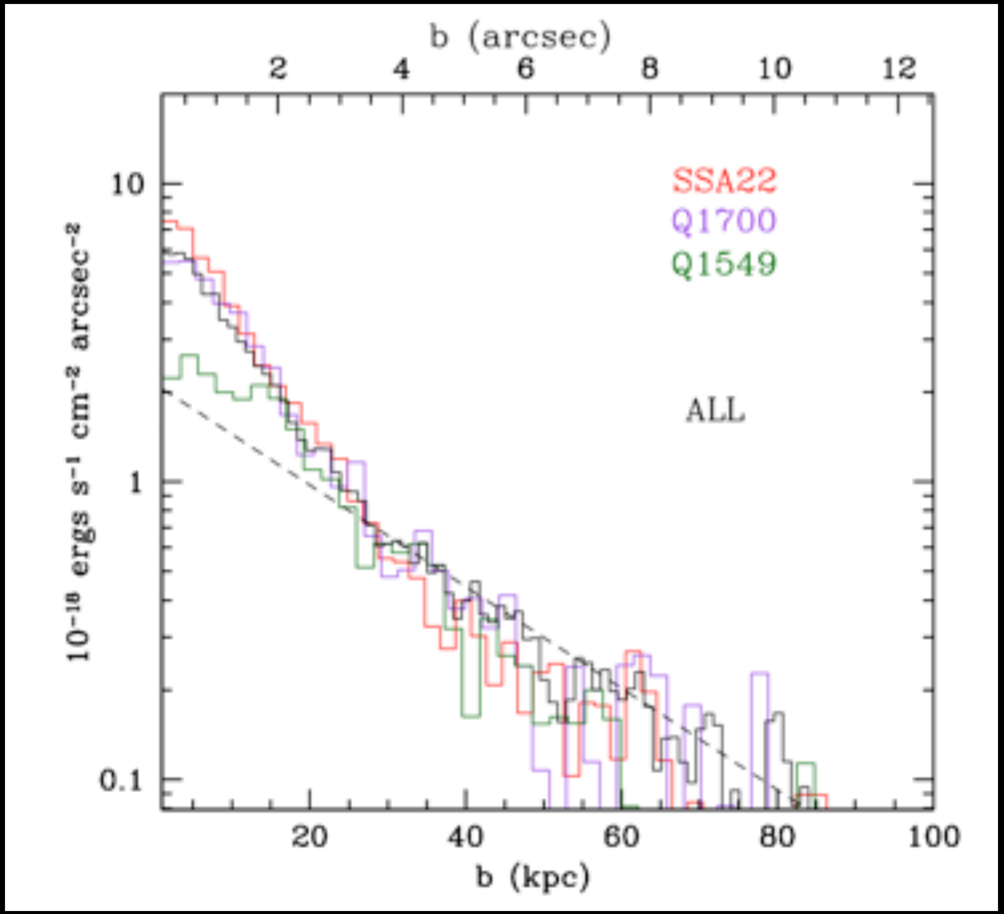
92 UV-selected galaxies with <z>=2.65

Extended haloes to ~ 80 kpc (when stacked)

SB ~ 10^{-19} erg s^{-1} cm^{-2} $arcsec^{-2}$

900 hours integration at 8-10m class telescopes

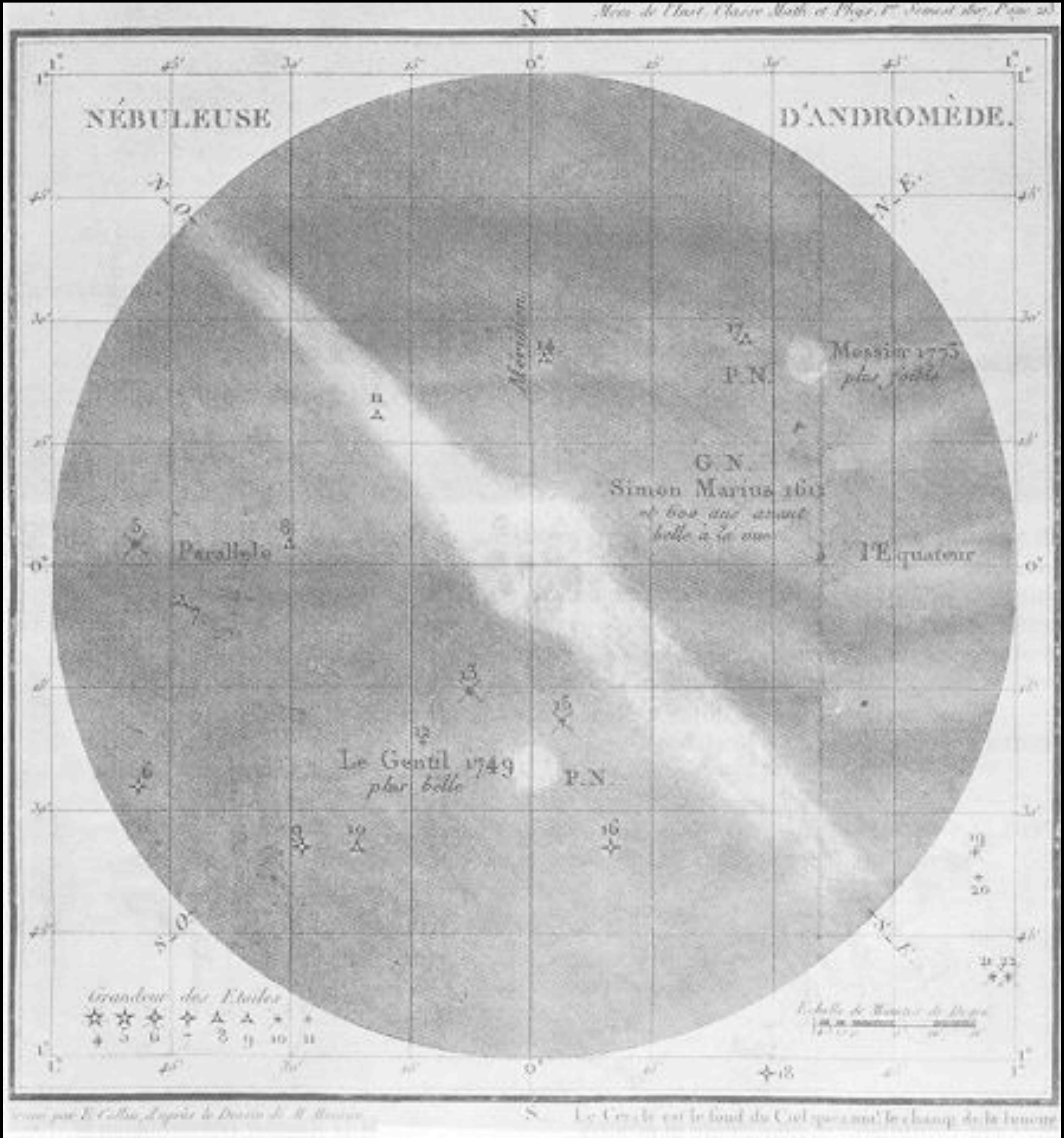
Lyman-α cooling?
Fluorescence by ionising radiation?
Scattering from circumgalactic gas?



Steidel *et al.* (2011) ApJ 736, 760

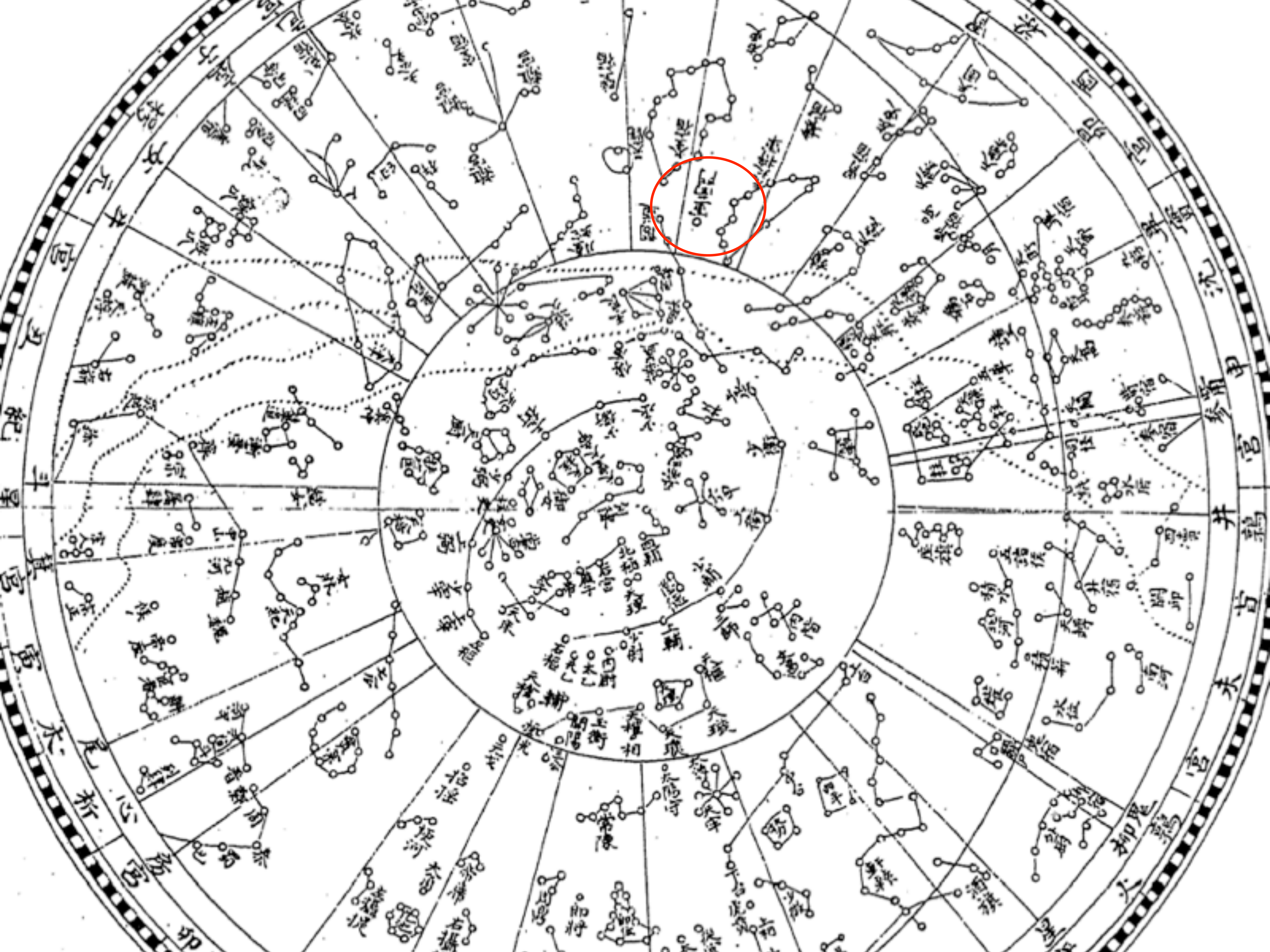
The MESSIER satellite

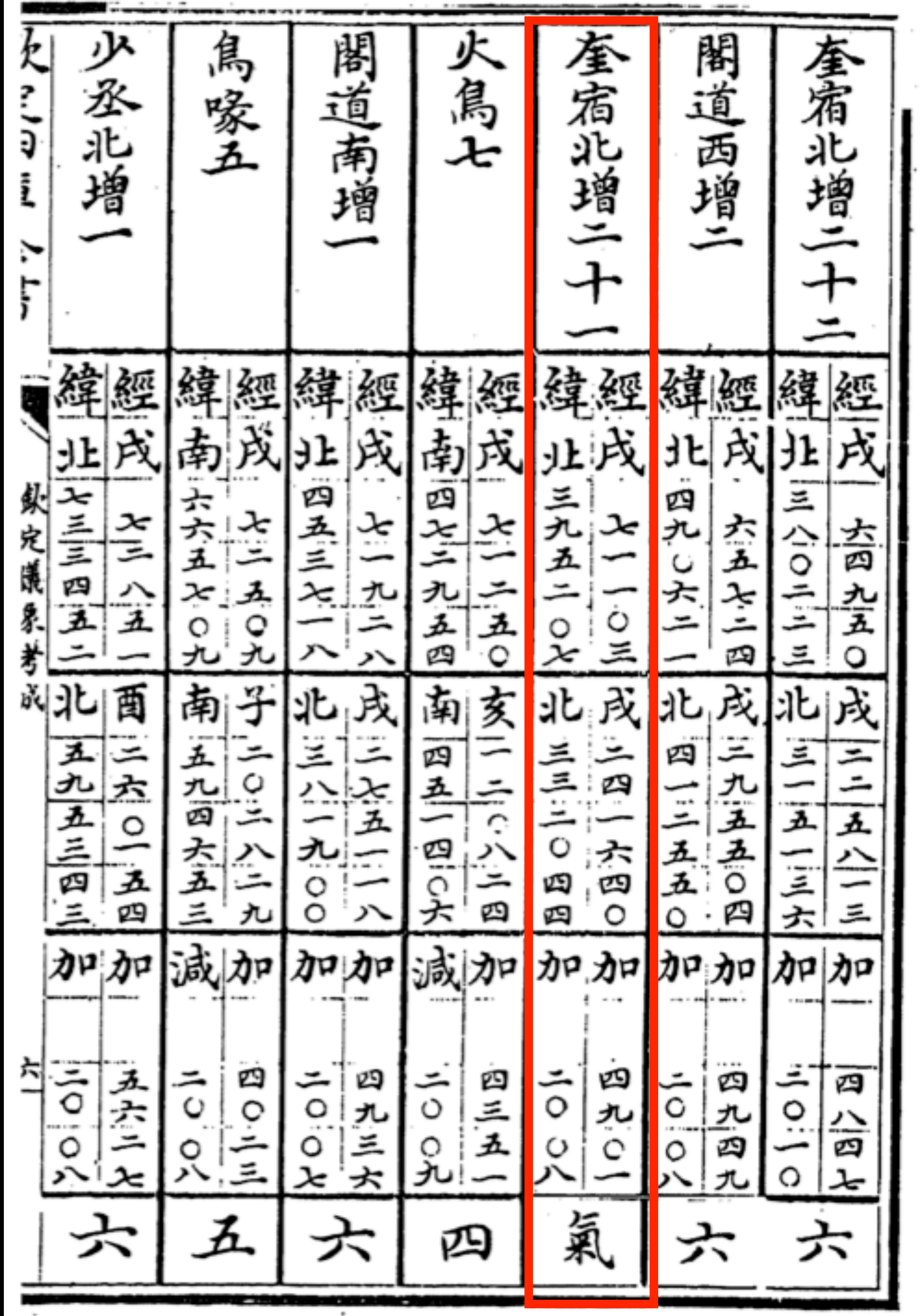
1. Science rationale
2. Technical design



First catalogue
of
diffuse objects

Messier (1771)
Mem. Acad. Sci. Paris





奎宿北增二十二	閣道西增二	奎宿北增二十一	火鳥七	閣道南增一	鳥喙五	少丞北增一
經 戌 六四九五〇	經 戌 六五七二四	經 戌 七一一〇三	經 戌 七一二五〇	經 戌 七一九二八	經 戌 七二五〇九	經 戌 七三八五一
緯 北 三八〇二二三	緯 北 四九〇六二一	緯 北 三九五二〇七	緯 南 四七二九五四	緯 北 四五三七一八	緯 南 六六五七〇九	緯 北 七三三四五二
戌 二二五八一三	戌 二九五五〇四	戌 二四一六四〇	亥 二二〇八二四	戌 二七五一一八	子 二〇二八二九	酉 二六〇一五四
北 三一五一三六	北 四一二五五〇	北 三三二〇四四	南 四五一四〇六	北 三八一九〇〇	南 五九四六五三	北 五九五三四三
加 四八四七	加 四九四九	加 四九〇一	加 四三五一	加 四九三六	加 四〇二三	加 五六二七
加 二〇一〇	加 二〇〇八	加 二〇〇八	減 二〇〇九	加 二〇〇七	減 二〇〇八	加 二〇〇八
六	六	氣	四	六	五	六

欽定儀象考成

六

The Yixiangkaocheng catalogue

Ignaz Kögler, SJ

1756 (publ. 1774)

3083 objects
2848 stars
13 nebulosities

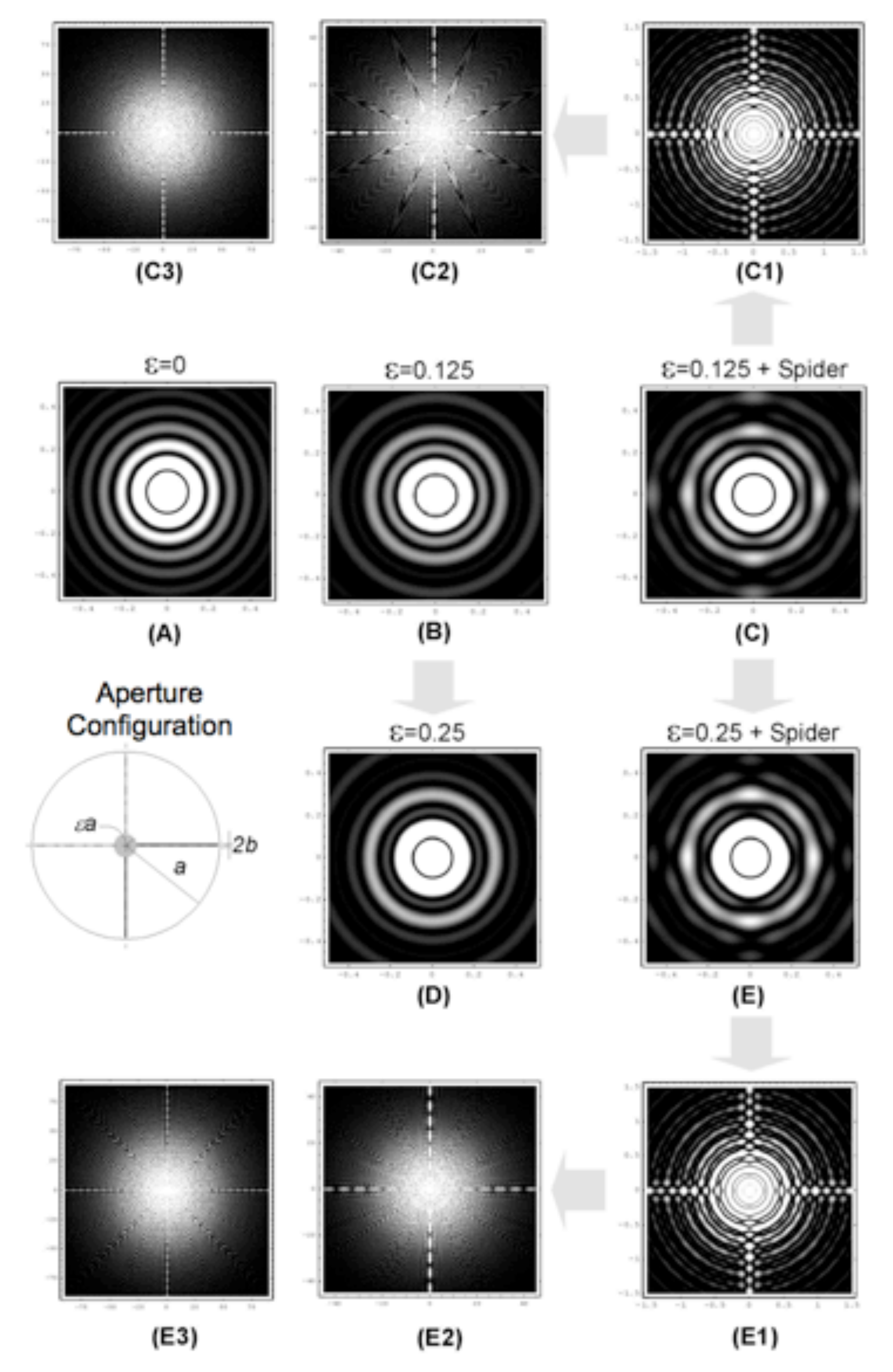
Ahn (2012) *MNRAS*, 422, 913

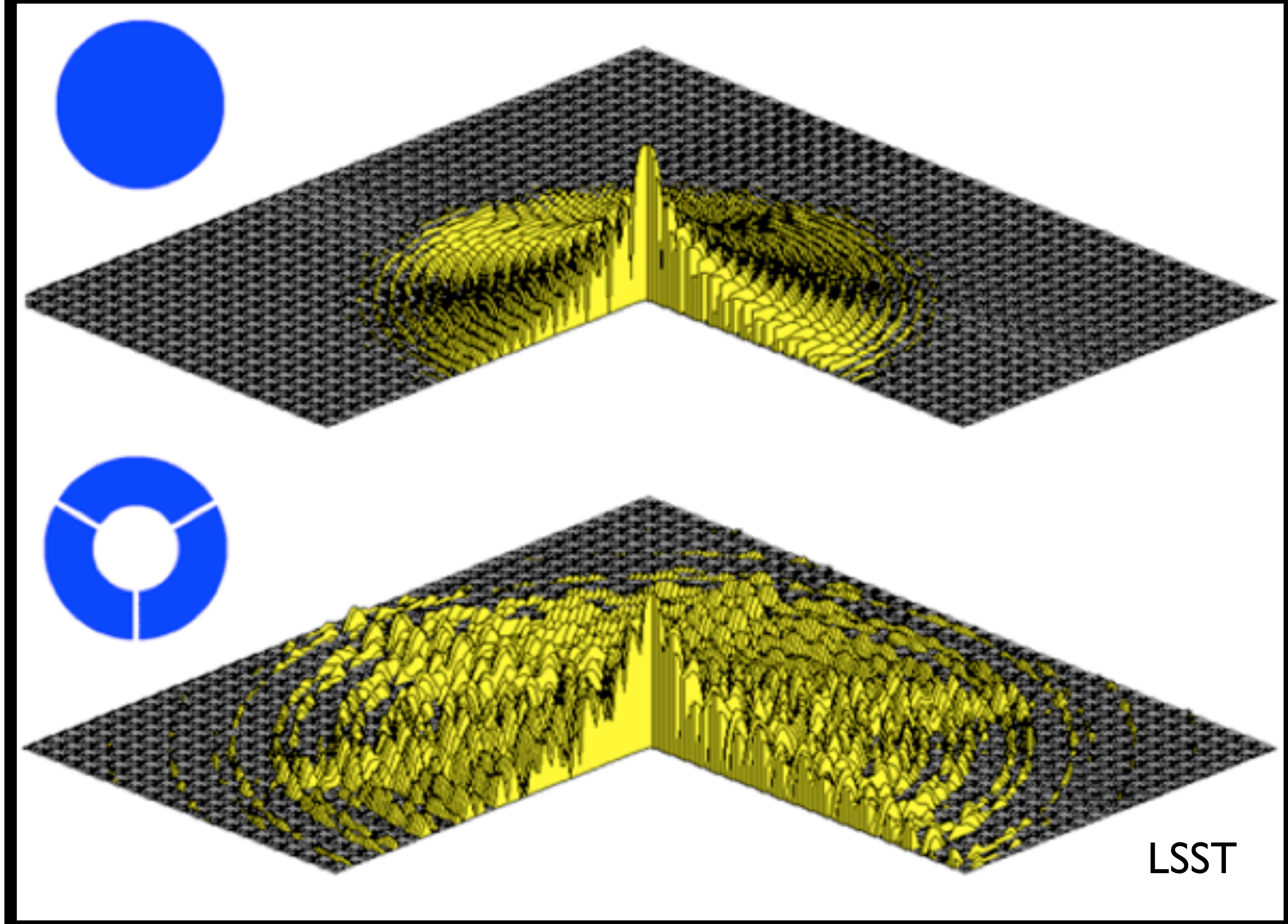
Top-level design requirements

FOV	2°x4°	(*lifetime of satellite*)
Focal ratio	f/2	(*200x better than HST*)
Central obscuration	none	(*minimal PSF wings*)
Spatial resolution	1″ per pixel	(*matches ground*)
Roughness	< 0.5 nm	(*UV to optical*)
Flat field rms	< 0.0025%	(*TDI / drift scan*)
Distortion	< 0.5% in one direction	
Diameter	50 cm	(*set by platform*)

Credit: J.C. Cuillandre

Obstruction by secondary mirrors yields very *extended* and *anisotropic* PSFs



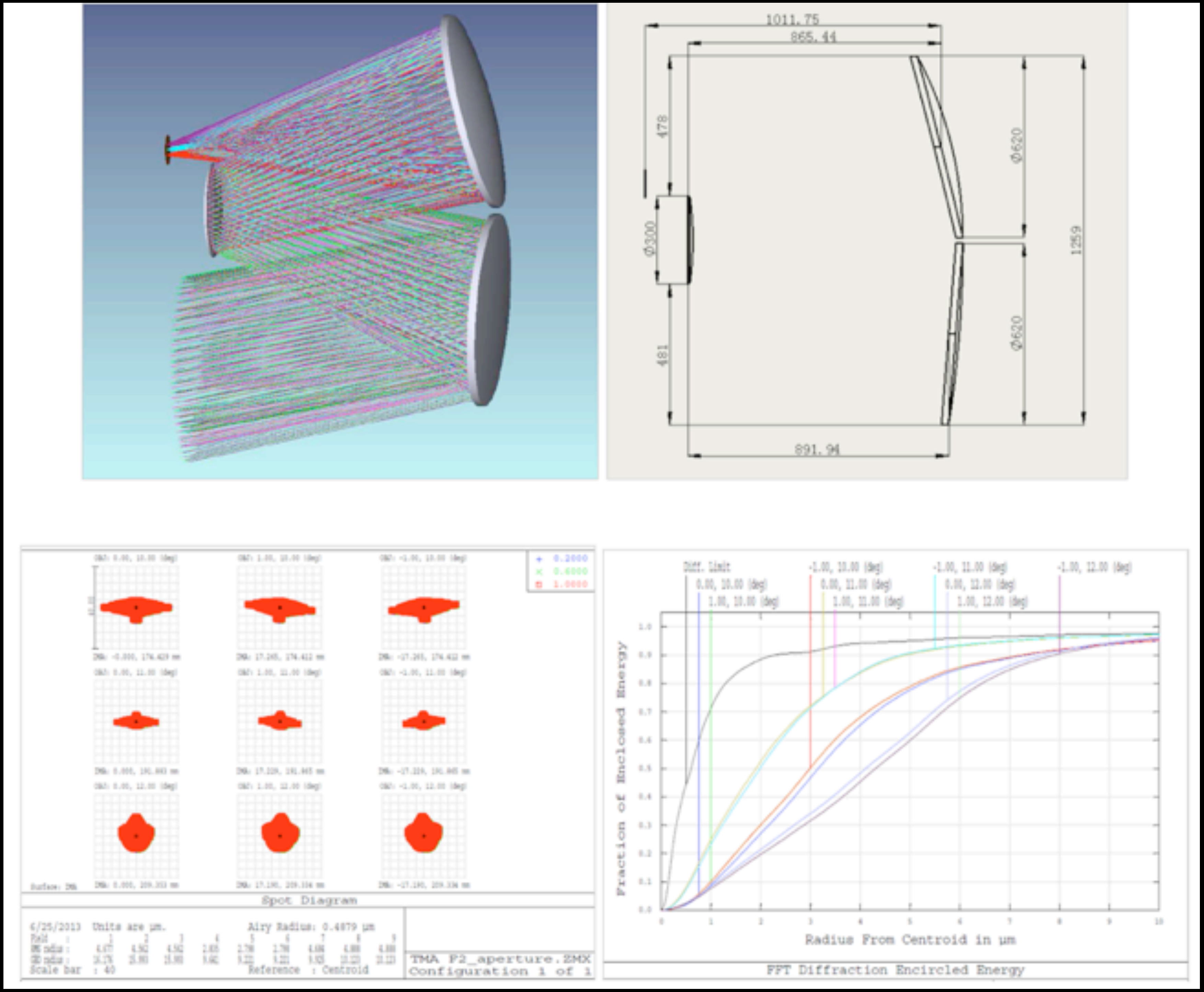


⇒ zero obstruction is required

for proper LSB photometry

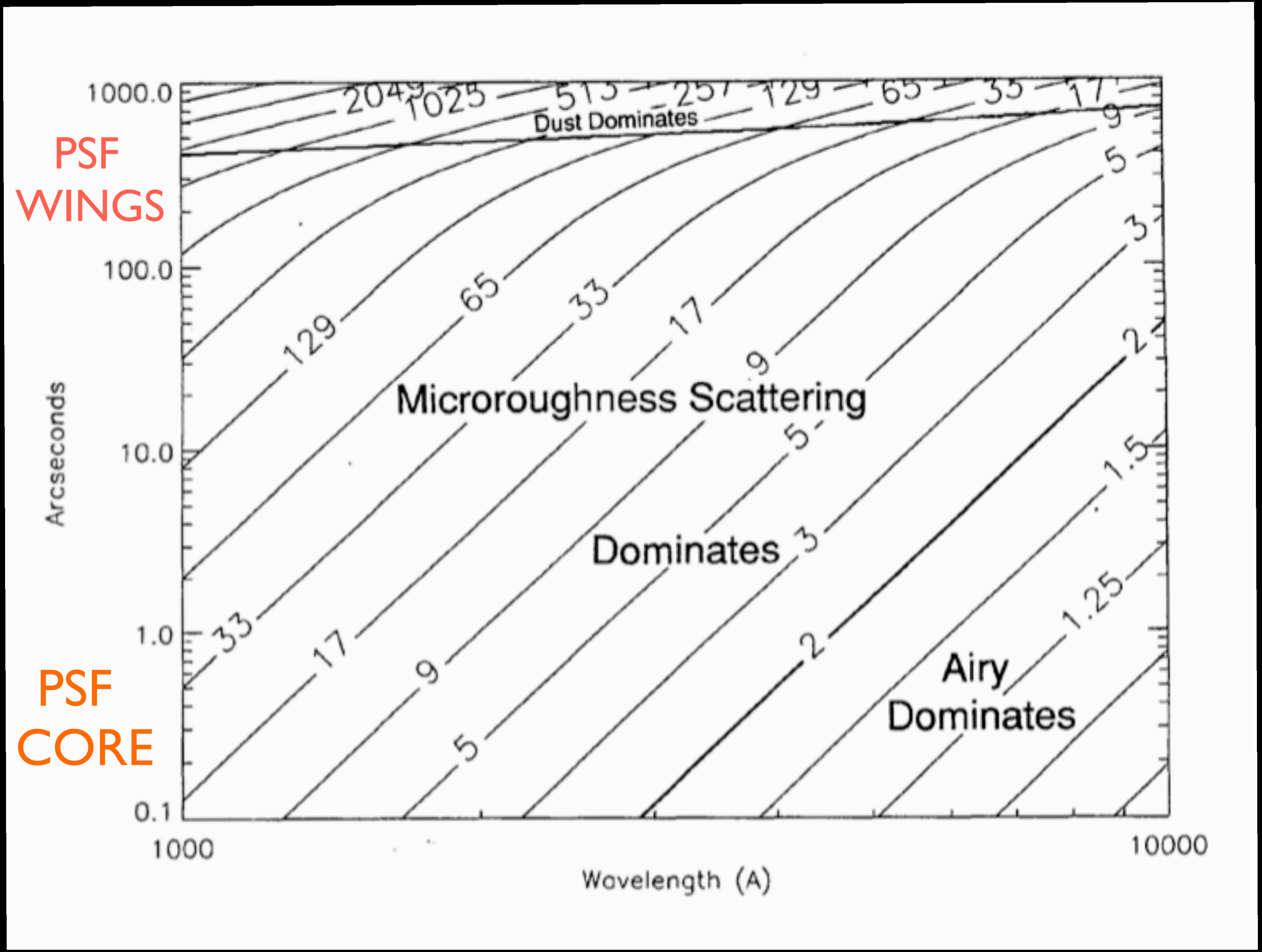
Key additional requirements for MESSIER :

— flat(ish) focal plane (Gaia-like?)
— no lenses (avoid Čerenkov radiation)



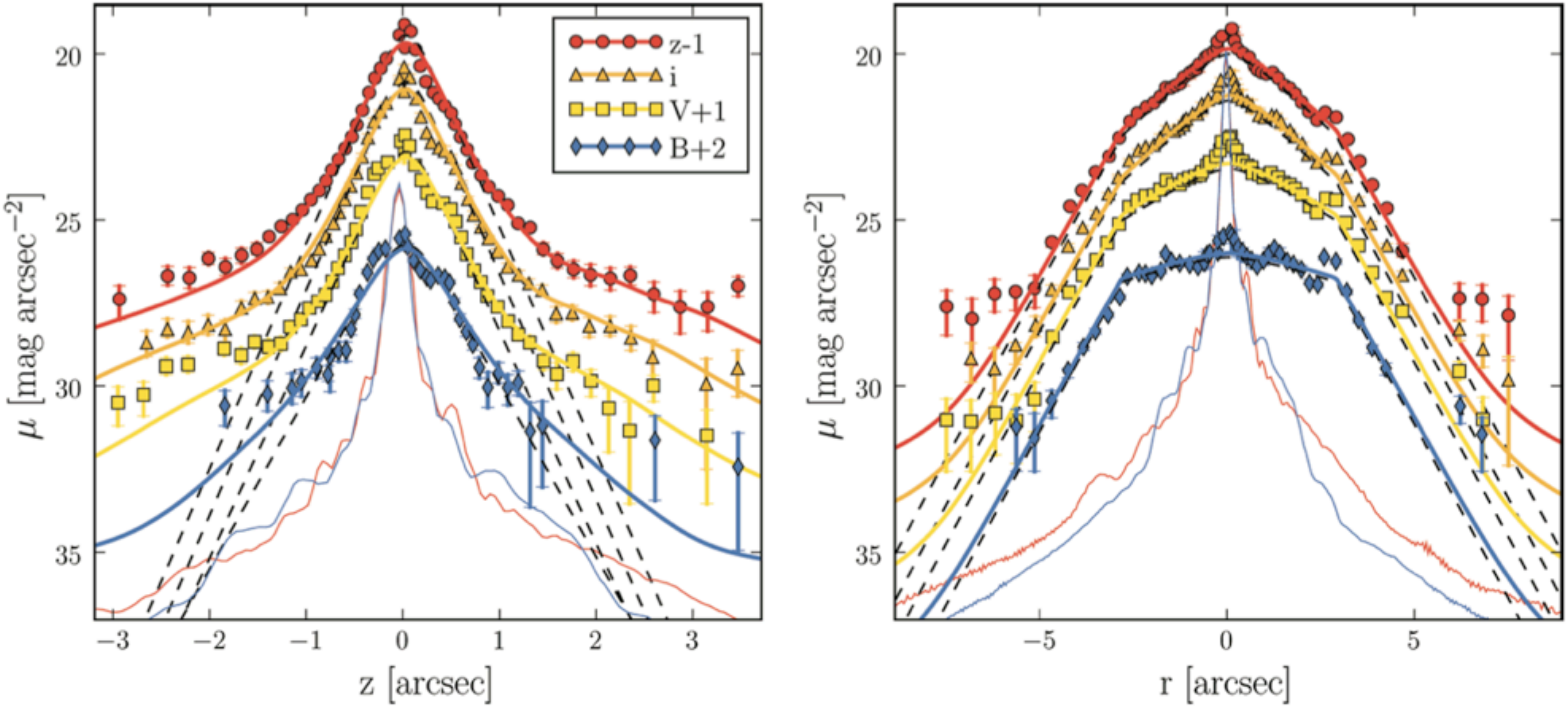
Current solution

TMA
unobscured, off-axis
easy baffling
flat focal plane
f/2
4° x 2°
TRL 9 (optics/FP)



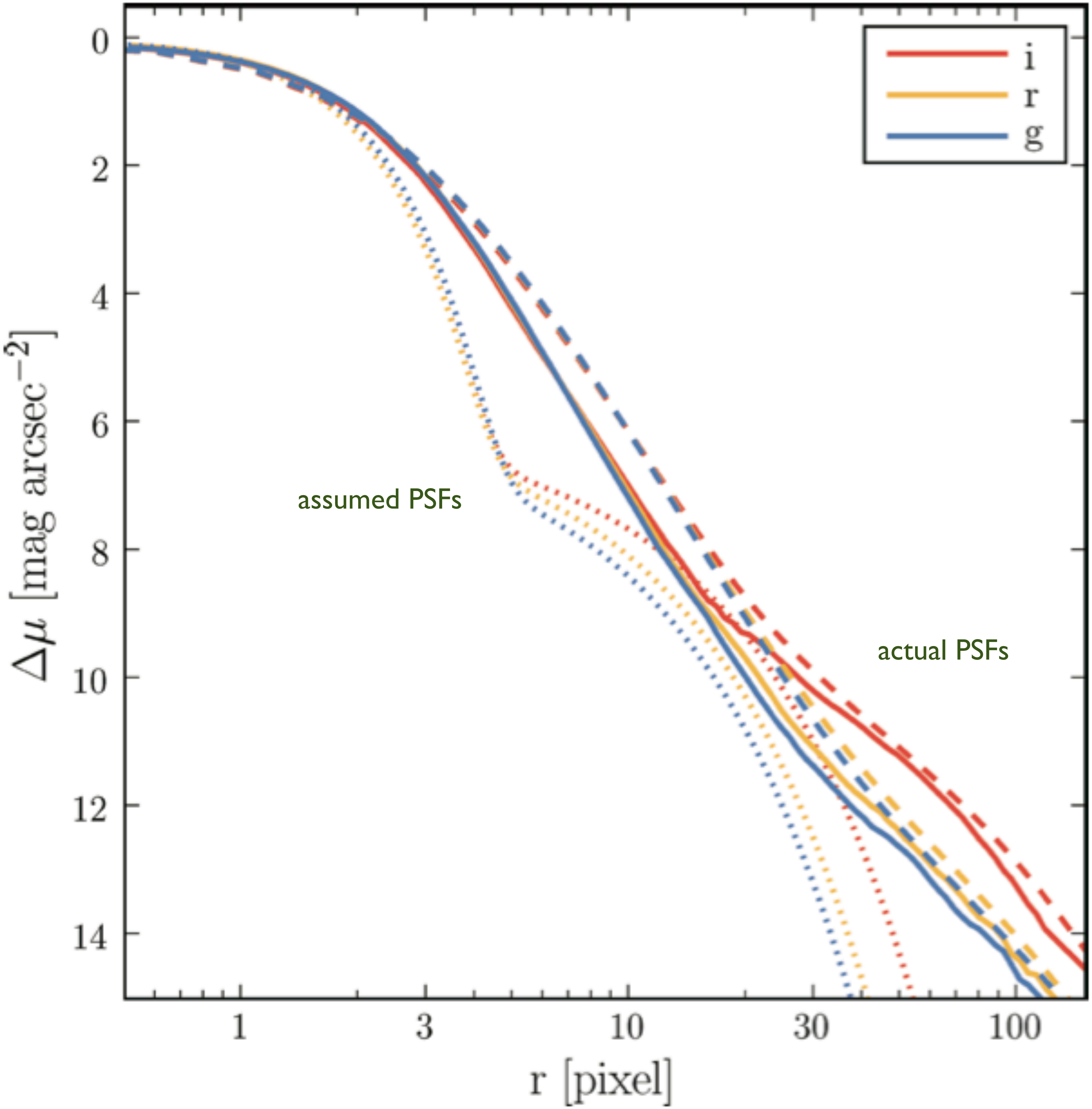
Stringent quality control of the 3 mirrors, from 200 nm to 900 nm
UV coatings reach 80% reflexivity

Importance of the stability and of the wings of the PSF



Extended galactic red haloes ??

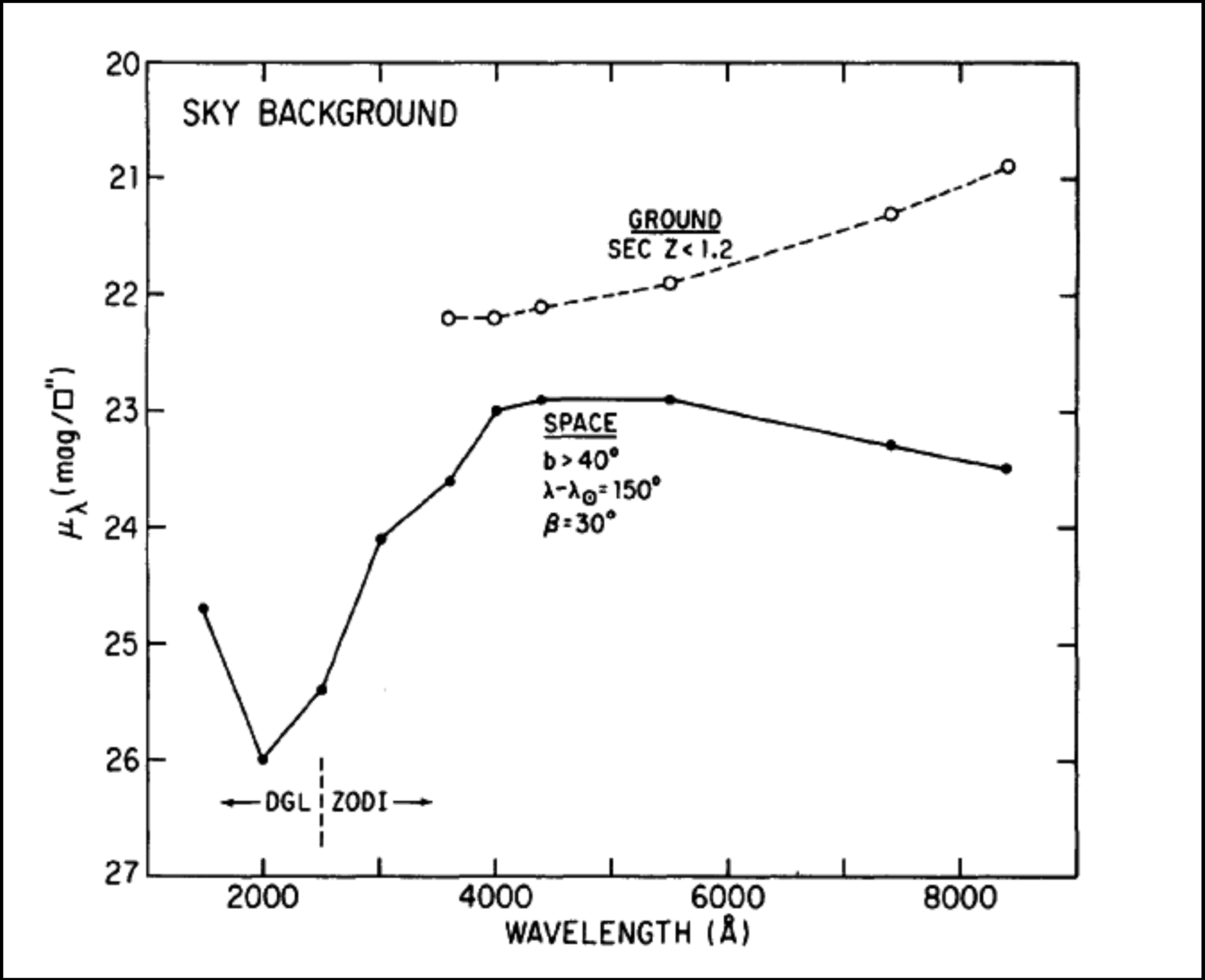
Zibetti, White + Brinkmann (2004)

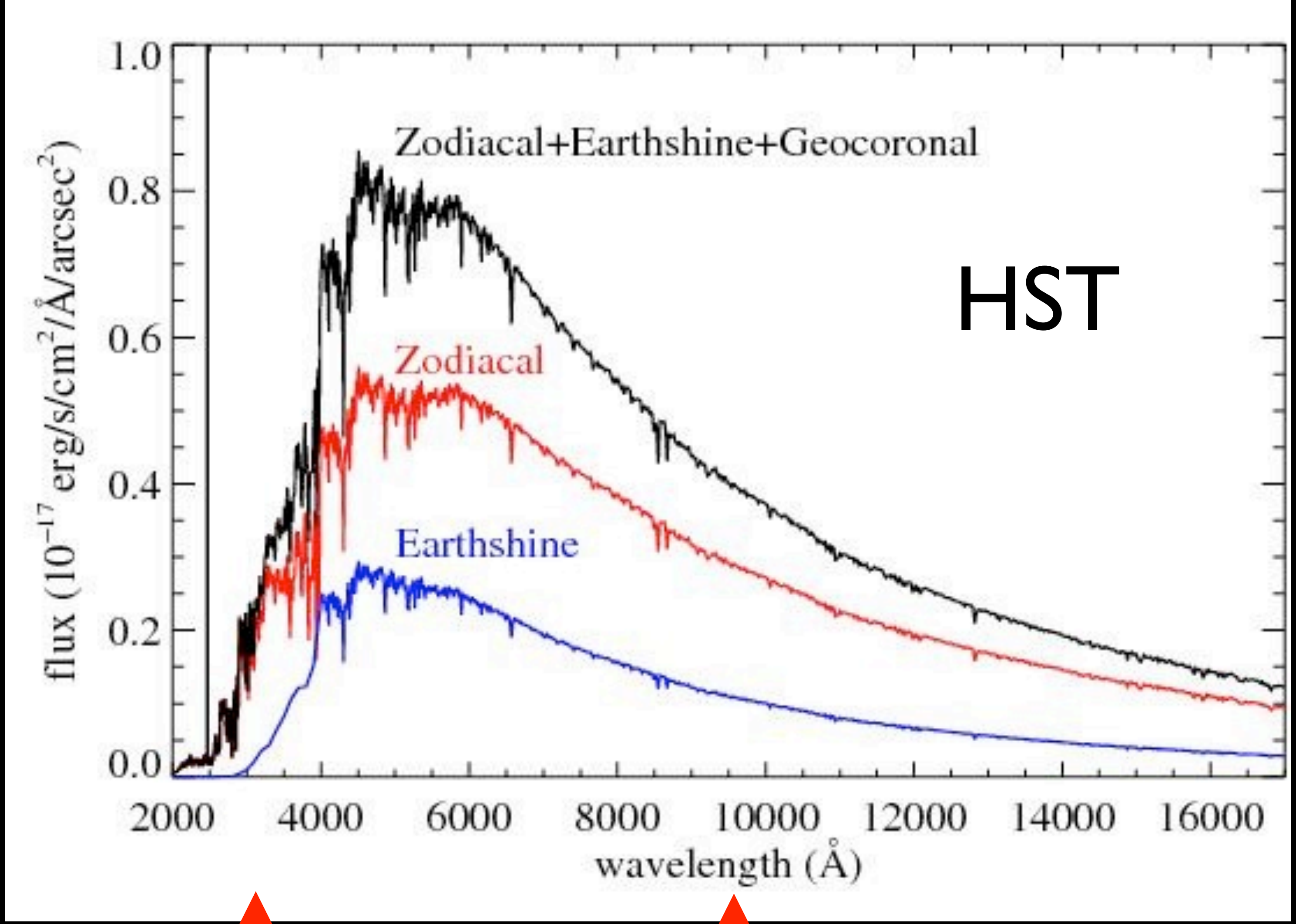


assumed PSFs

actual PSFs

Going into space: issues and challenges

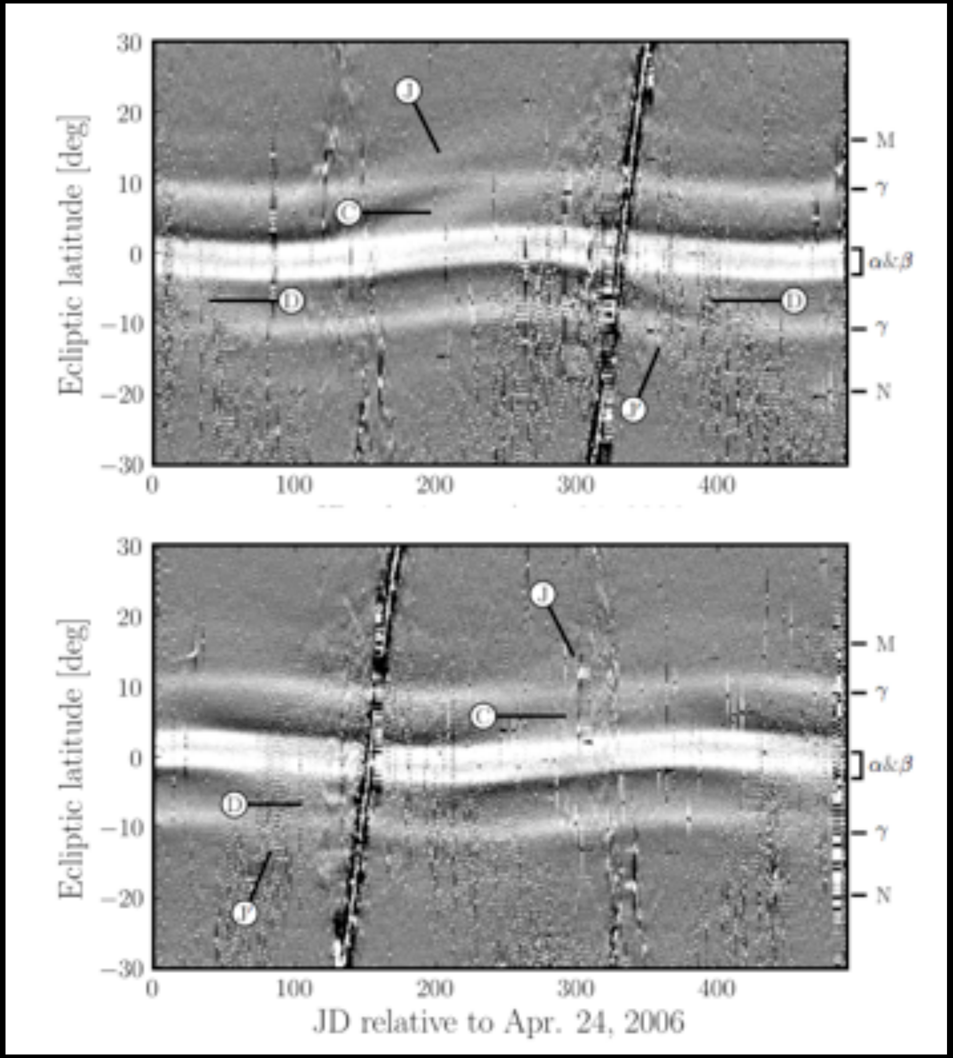




No sky variability but many foregrounds:

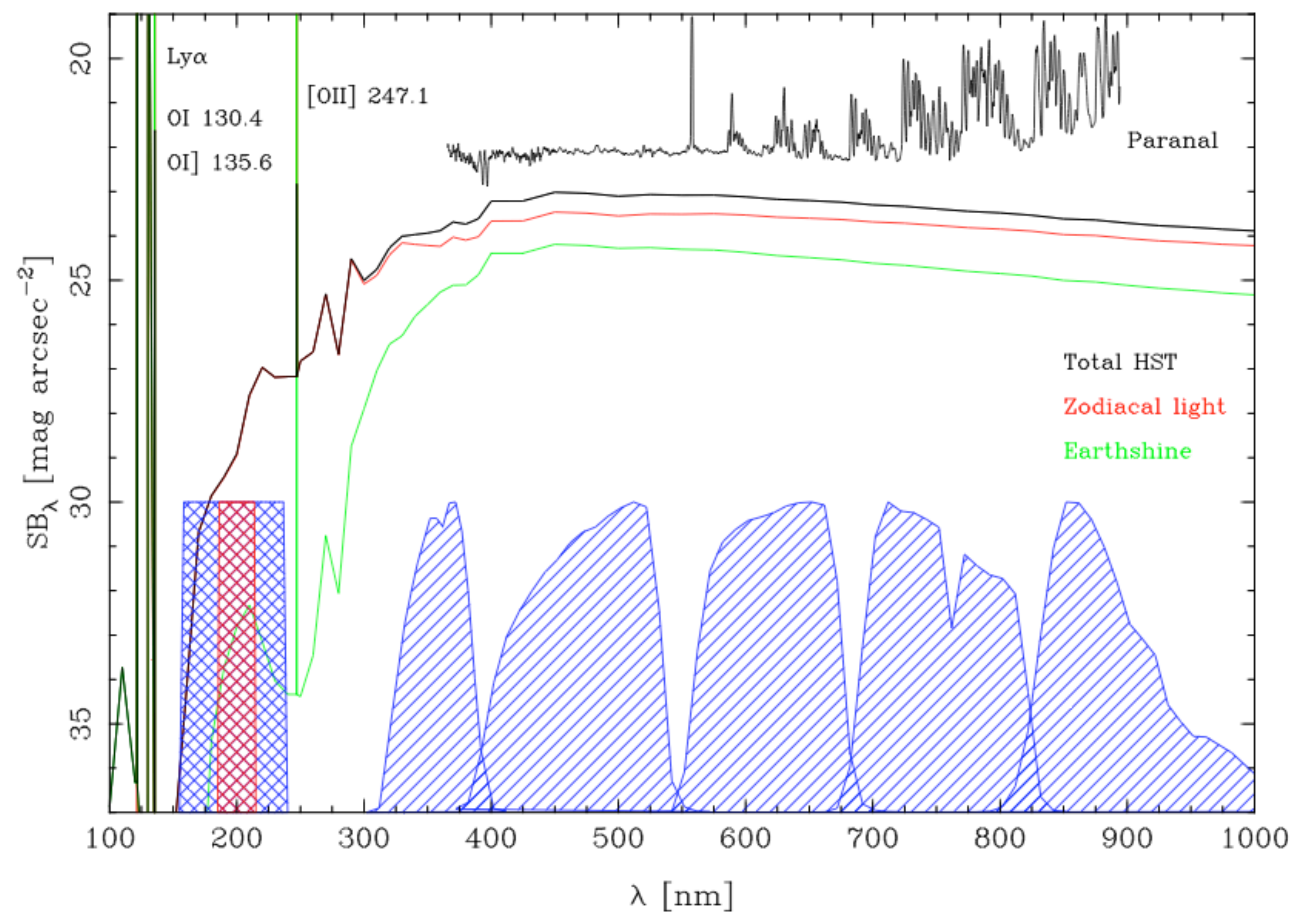
- zodiacal light (variable)
- stray light contamination
- geocoronal/airglow emission
- optical/UV emission from Galactic dust (cirrus)

Zodiacal light variability as observed by AKARI



Minimise zodiacal contamination while keeping key information on stellar populations

Requirement for filters

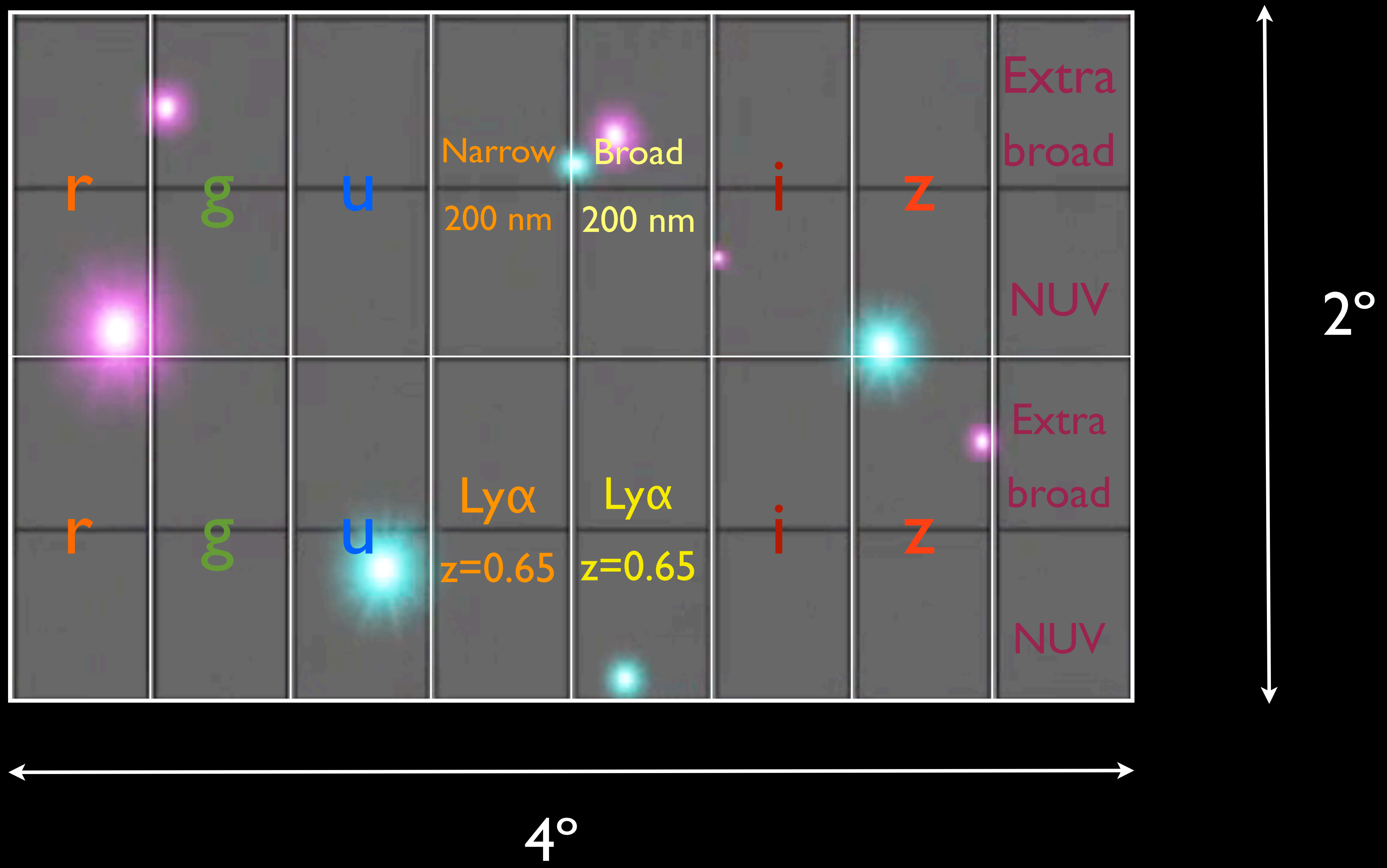


Focal plane configuration

8 x 2 independent CCD controllers in drift-scan mode

QE of each detector optimised for each filter (>85%)

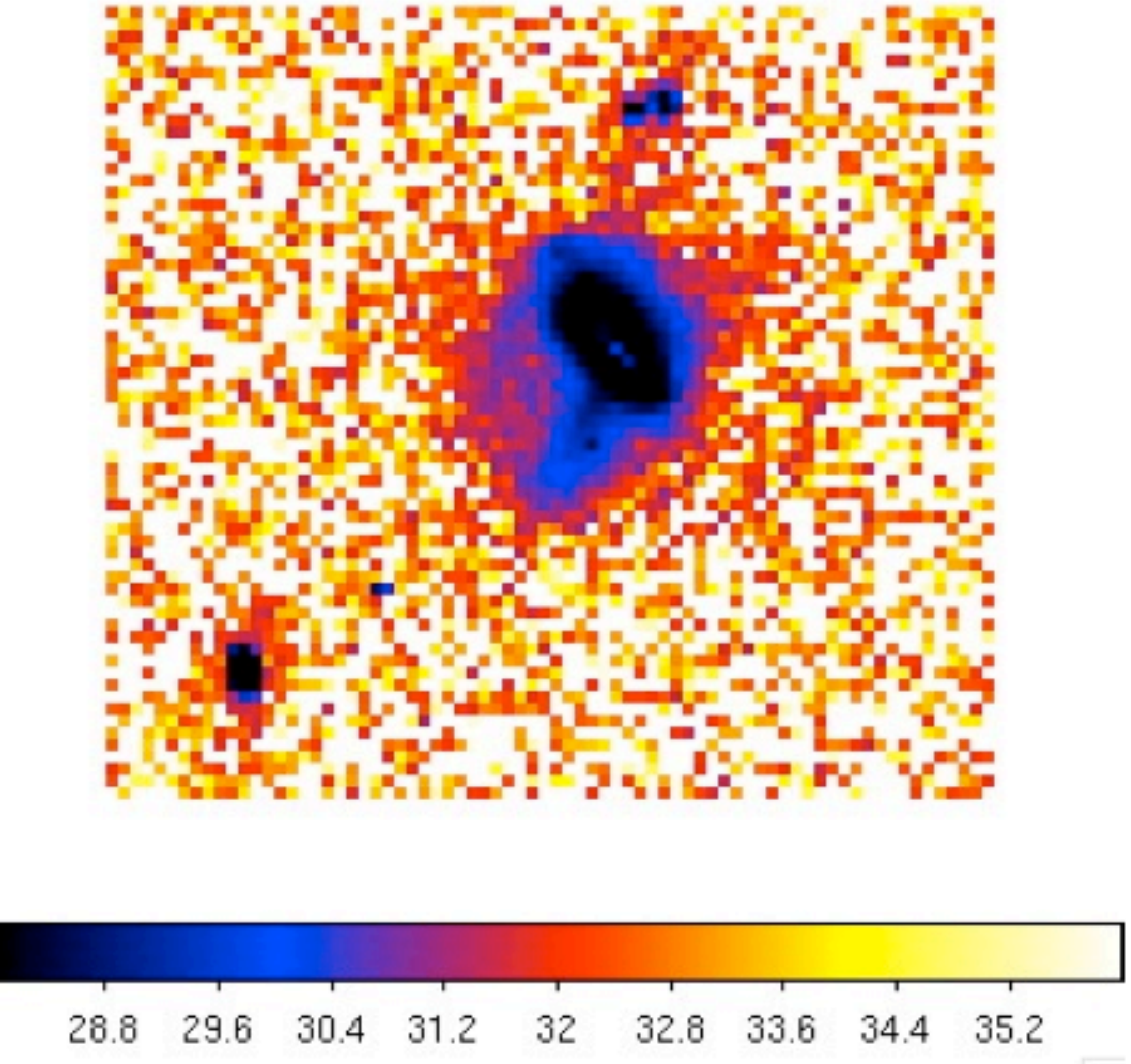
Highly efficient: no moving parts, passive cooling

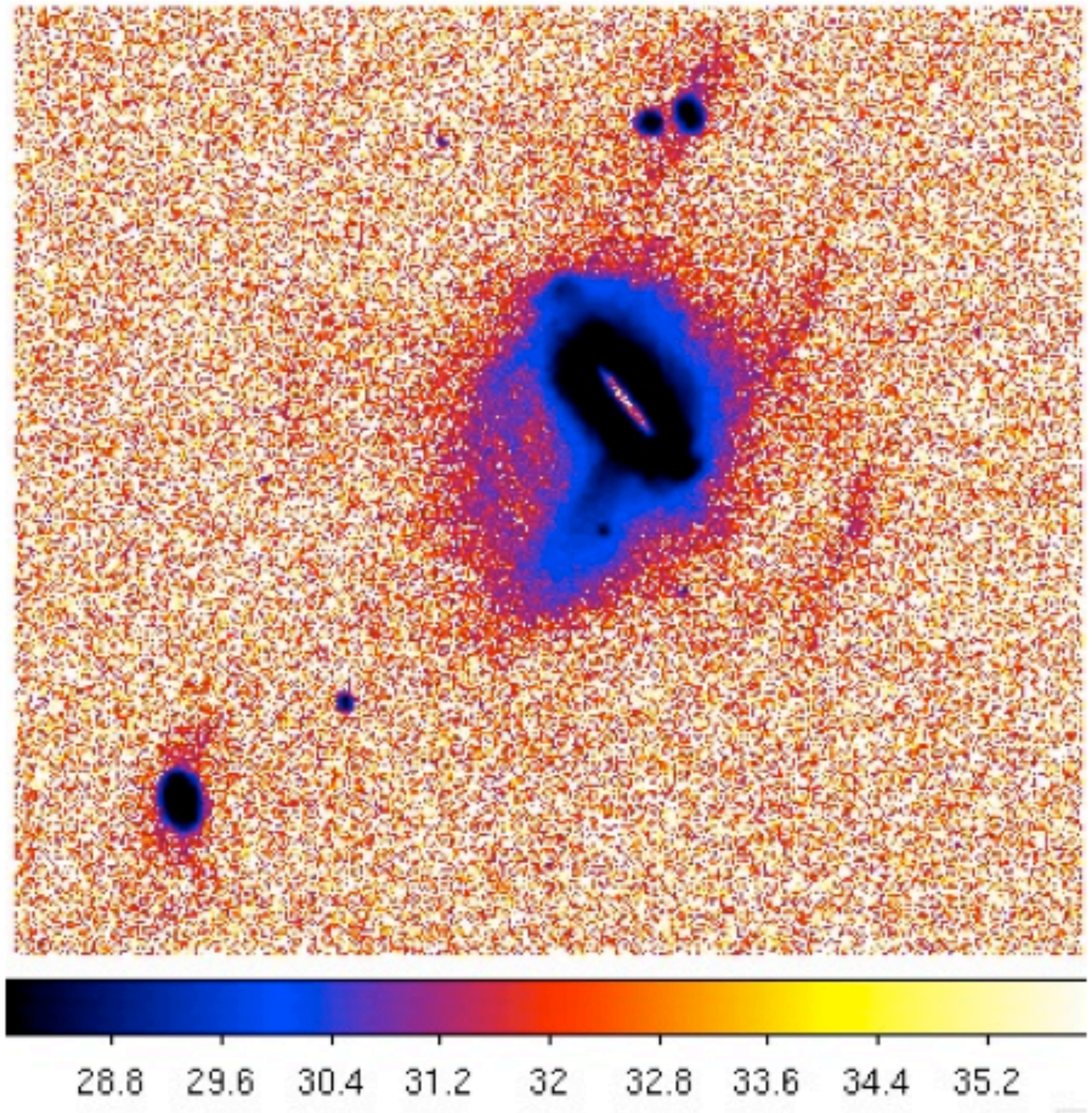


r	g	u	Narrow 200 nm	Broad 200 nm	i	z	Extra broad NUV
r	g	u	Lyα z=0.65	Lyα z=0.65	i	z	Extra broad NUV

Expected performances - I   Optical bands

Simulated MESSIER images of a galaxy (M31) at 15 Mpc





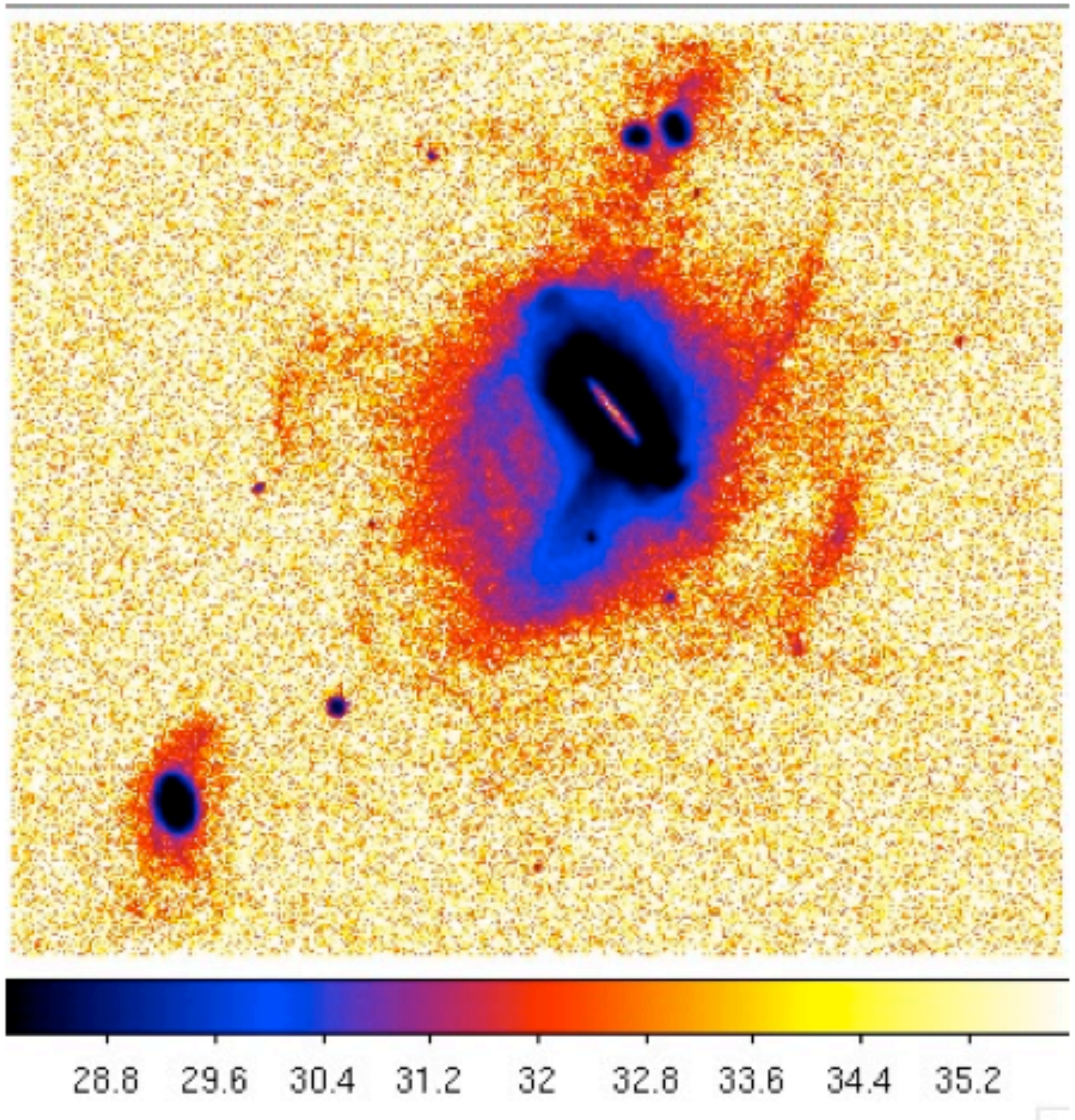
R. Ibata

10 ksec
5 kpc × 5 kpc

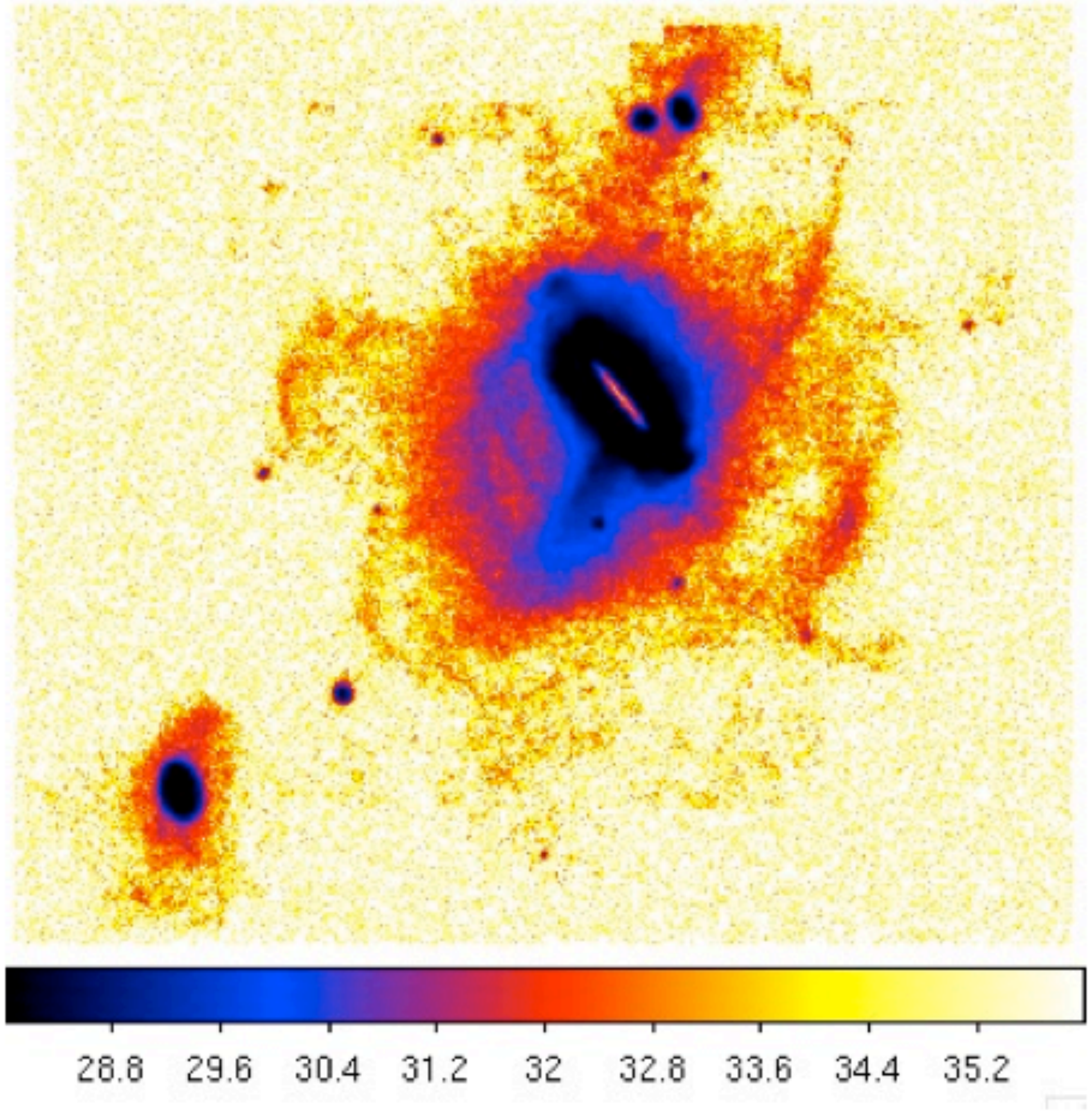
100 ksec
1 kpc × 1 kpc   (14″ × 14″)

Expected performances - 1   Optical bands

Simulated MESSIER images of a galaxy (M31) at 15 Mpc



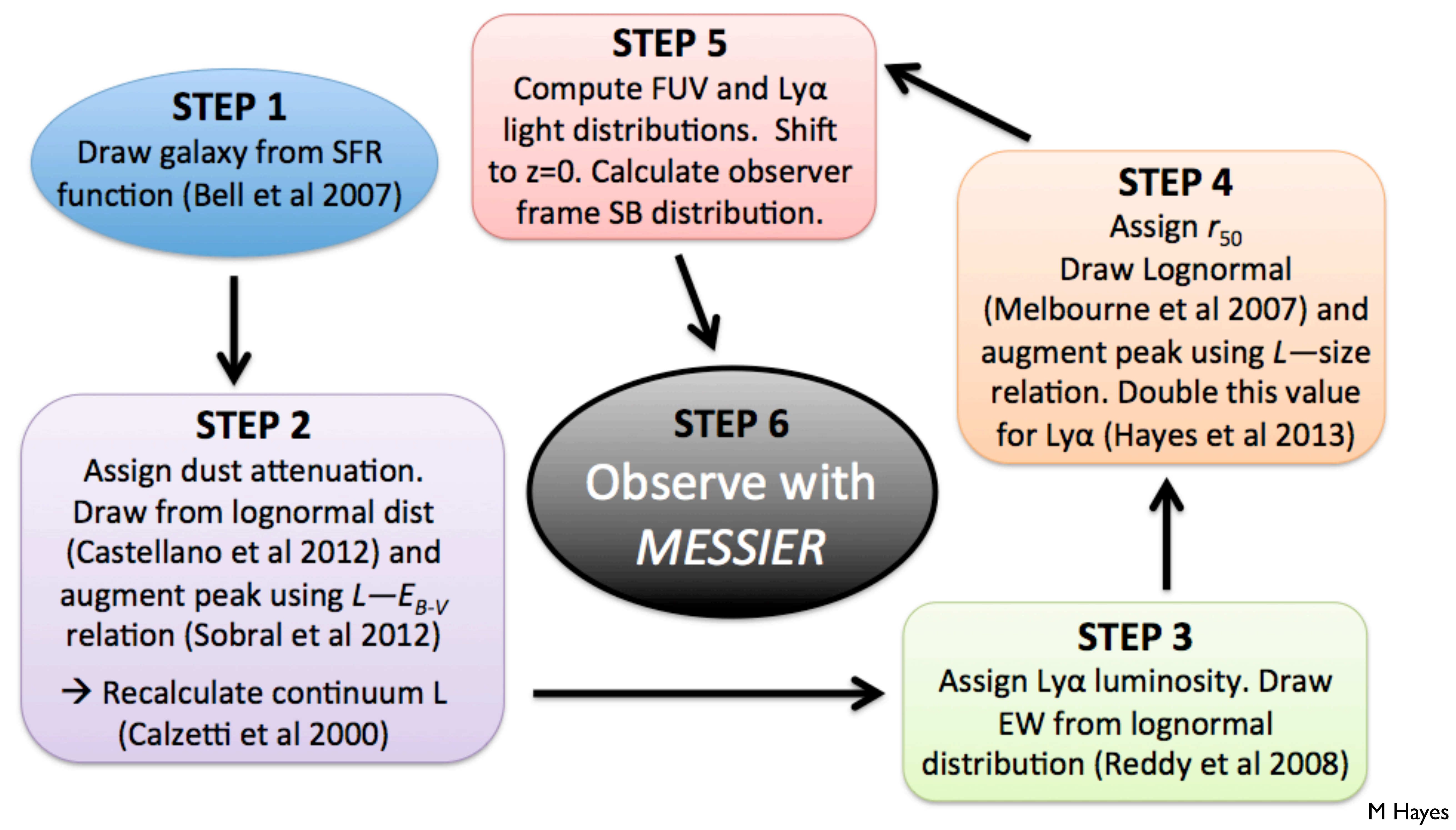
1 Msec
1 kpc × 1 kpc



R. Ibata

10 Msec
1 kpc × 1 kpc

Expected performances - II UV bands



STEP 1
Draw galaxy from SFR function (Bell et al 2007)

STEP 2
Assign dust attenuation. Draw from lognormal dist (Castellano et al 2012) and augment peak using L—$E_{B\text{-}V}$ relation (Sobral et al 2012)

→ Recalculate continuum L (Calzetti et al 2000)

STEP 3
Assign Lyα luminosity. Draw EW from lognormal distribution (Reddy et al 2008)

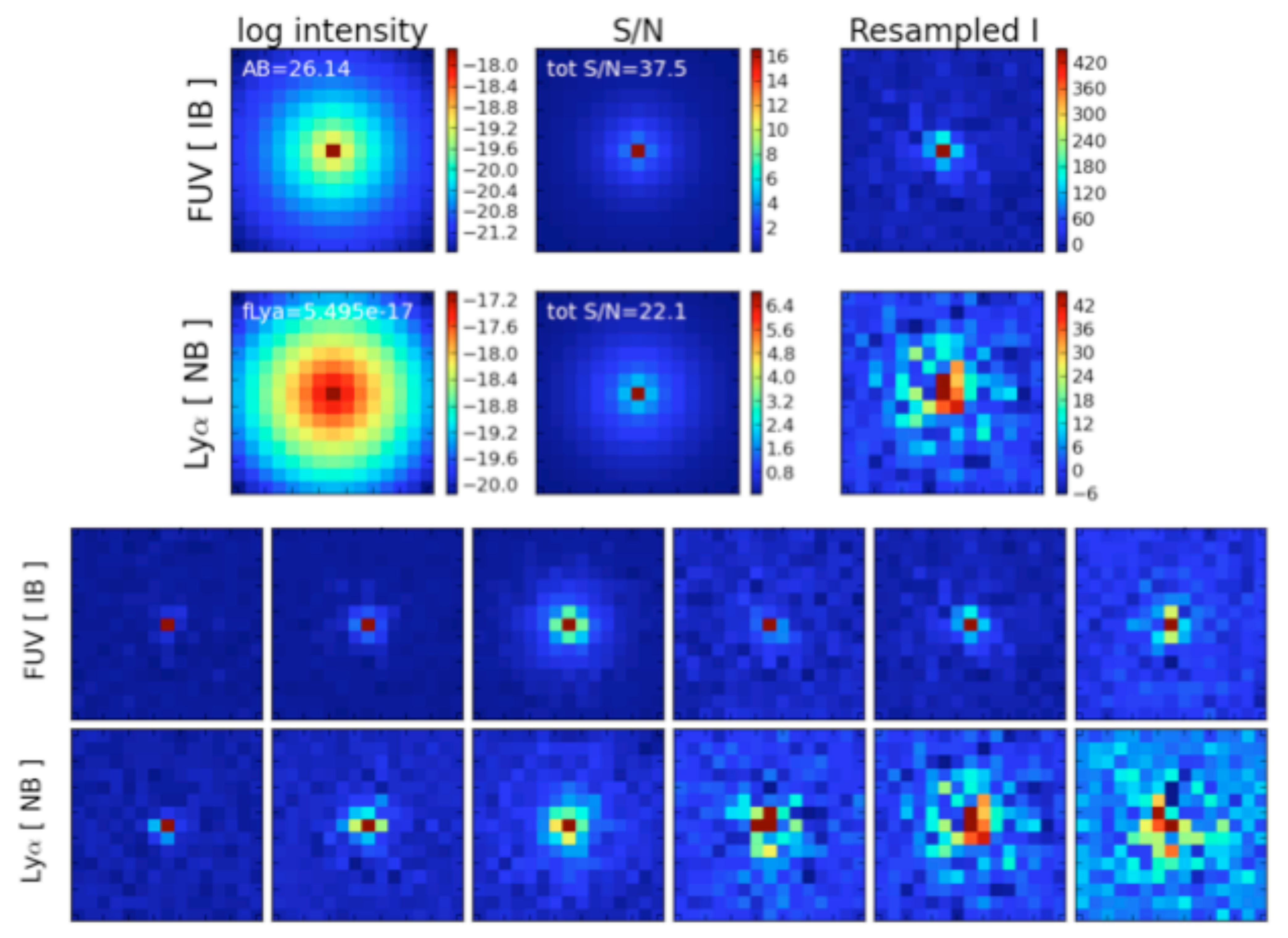
STEP 4
Assign r_{50}
Draw Lognormal (Melbourne et al 2007) and augment peak using L—size relation. Double this value for Lyα (Hayes et al 2013)

STEP 5
Compute FUV and Lyα light distributions. Shift to z=0. Calculate observer frame SB distribution.

STEP 6
Observe with *MESSIER*

M Hayes

Expected performances - II   UV bands



Over 3 ×10^6 galaxies at z=0.65 detected in Lyα with S/N>30

What is the nature of Lyα blobs ?

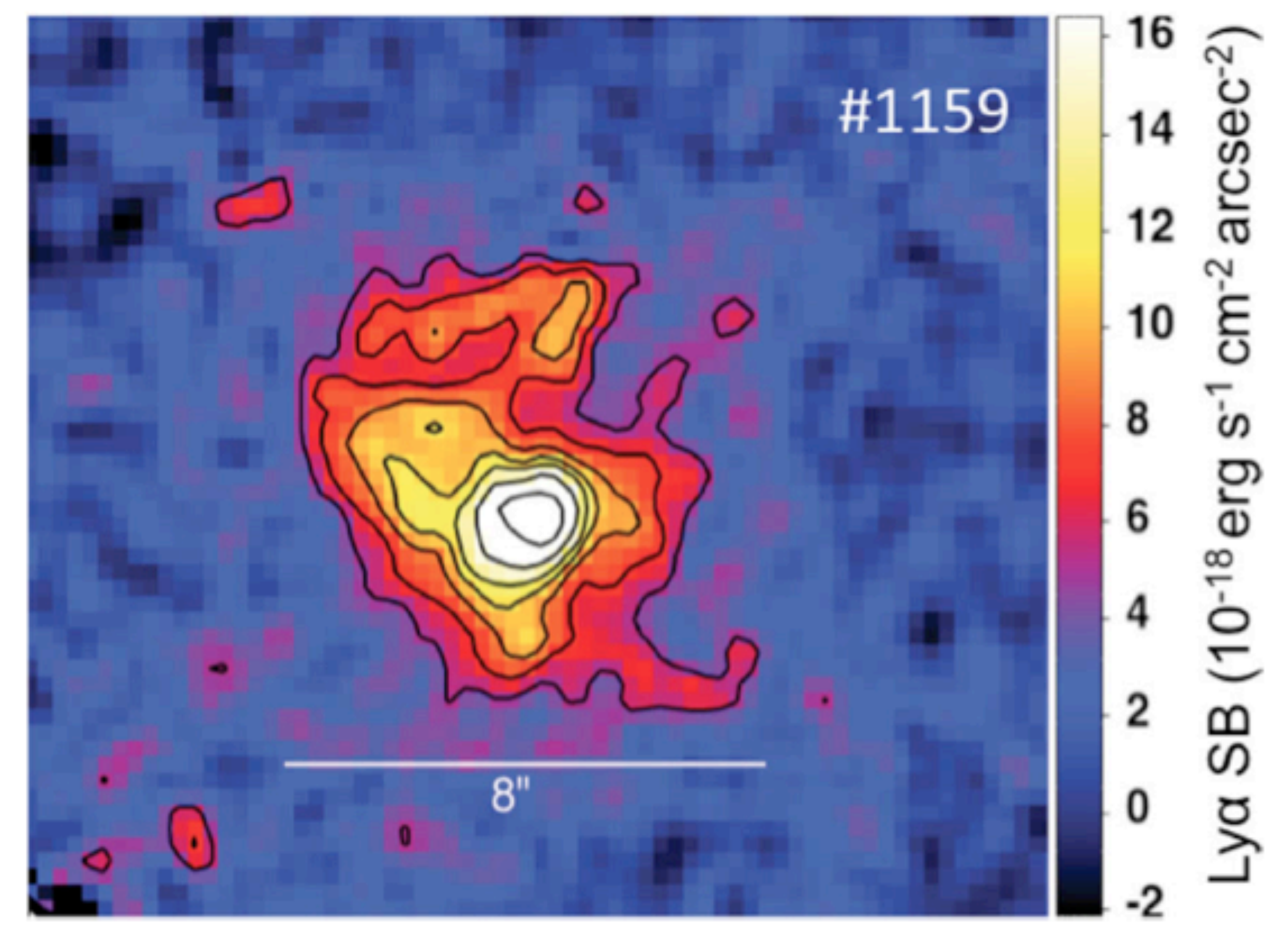
Photoionisation by a central AGN

Cooling radiation

Shocks by galactic outflows

Resonant scattering from sources

27 hours
at VLT

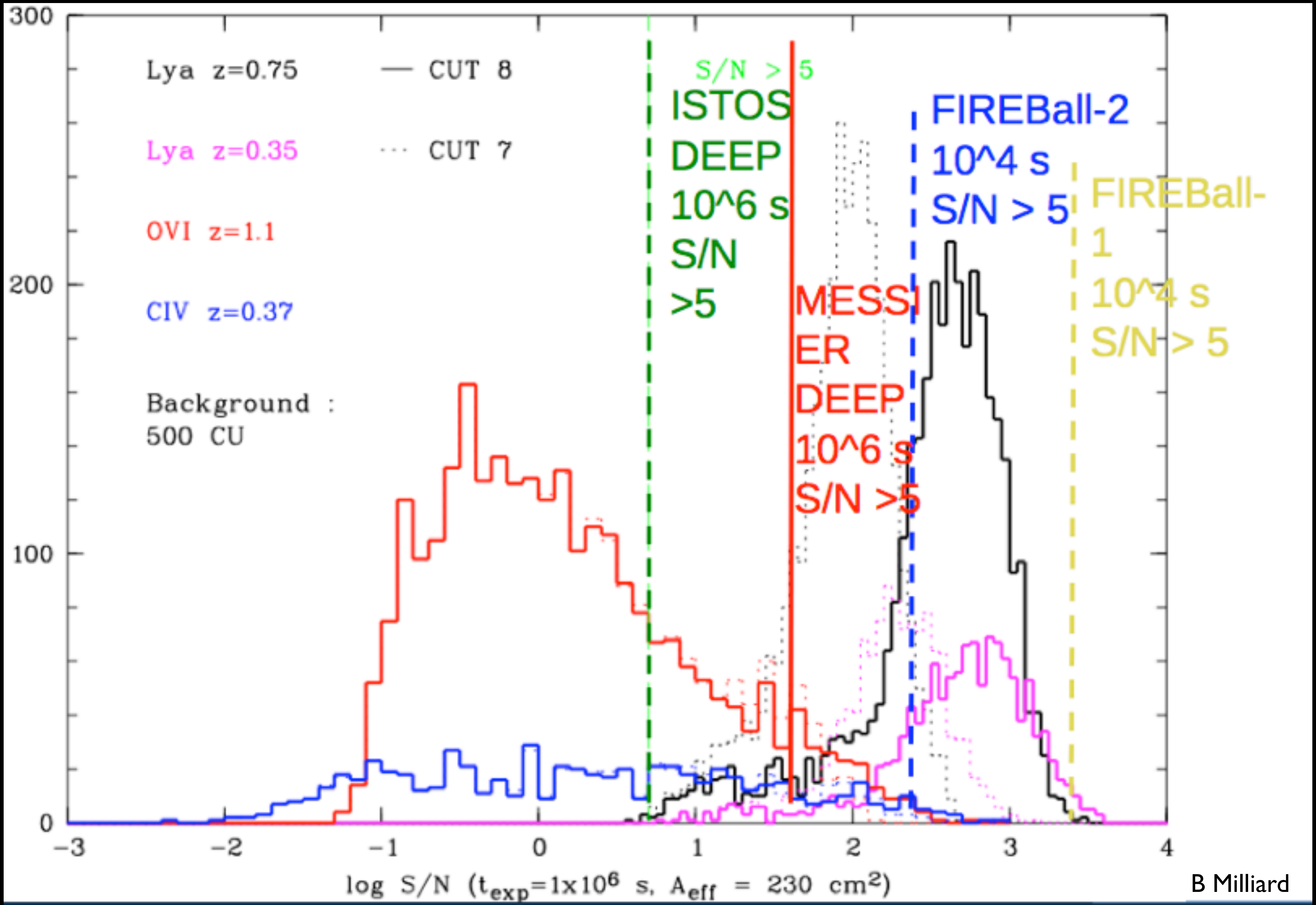


Cantalupo, Lilly & Haehnelt (2012)

Fluorescent Lyα emission of the circum-galactic medium around a QSO at *z*=2.4

Expected performances - II UV bands

Signal / Noise for simulated MESSIER images of the cosmic web

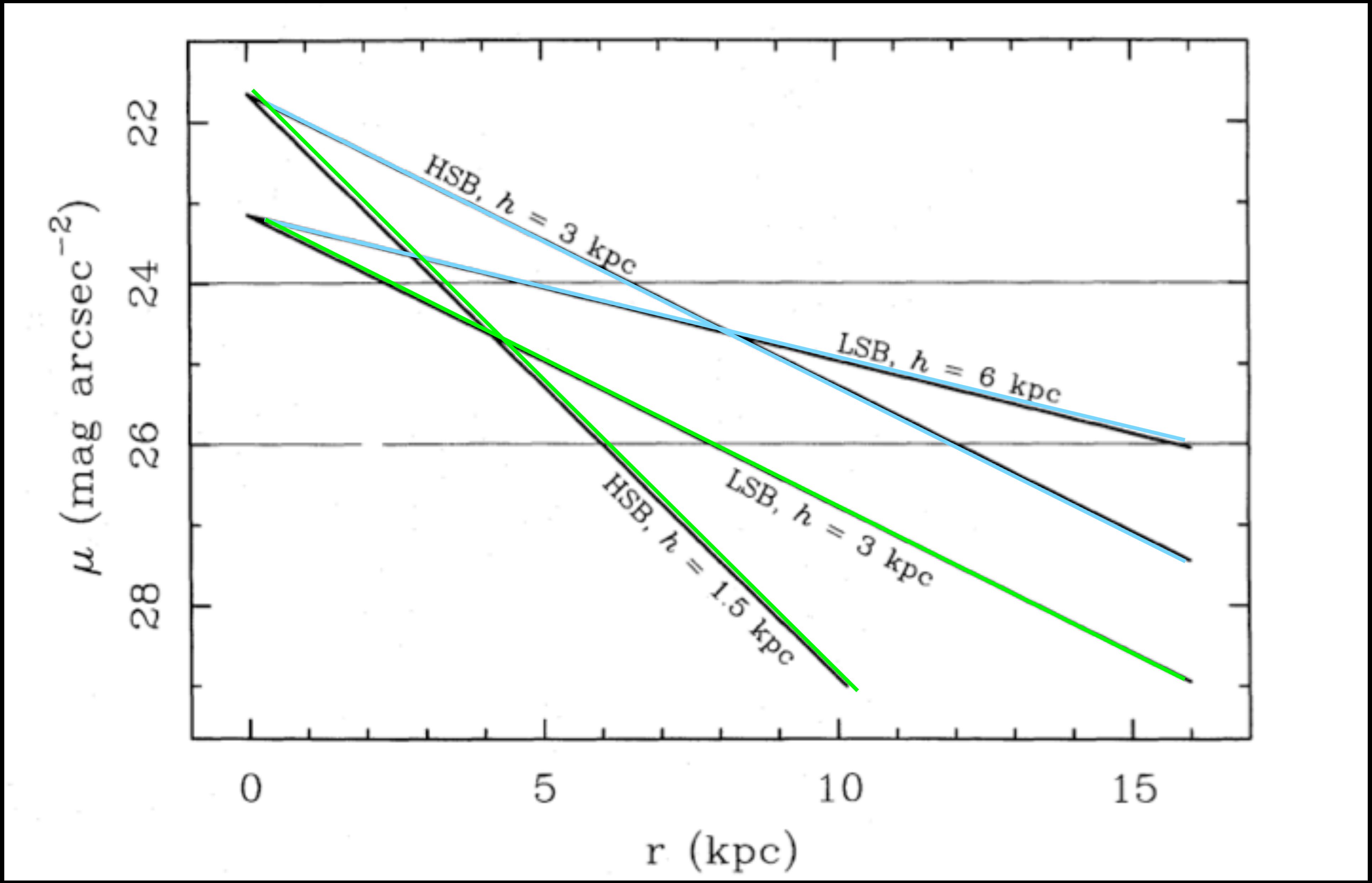


B Milliard

Key science issues (free by-products)

- KS1 What is the luminosity function of galaxies ?
- KS2 What is the optical / UV cosmological background radiation ?
- KS3 What is the molecular content of galaxies in the low-z universe ?
- KS4 What is the role of intracluster light and the accretion history in galaxy clusters ?
- KS5 What is the extent of mass loss in giant stars ?
- KS6 Calibration of the cosmological distance ladder with SB fluctuations
- KS7 Time domain astronomy: multi-λ stellar/AGN/black hole variability
- KS8 Zodiacal dust, comet tails, properties of dust grains …
- KS9 Synergies with LAMOST, MSE, Gaia and EUCLID

KSI What is the luminosity function of galaxies ?

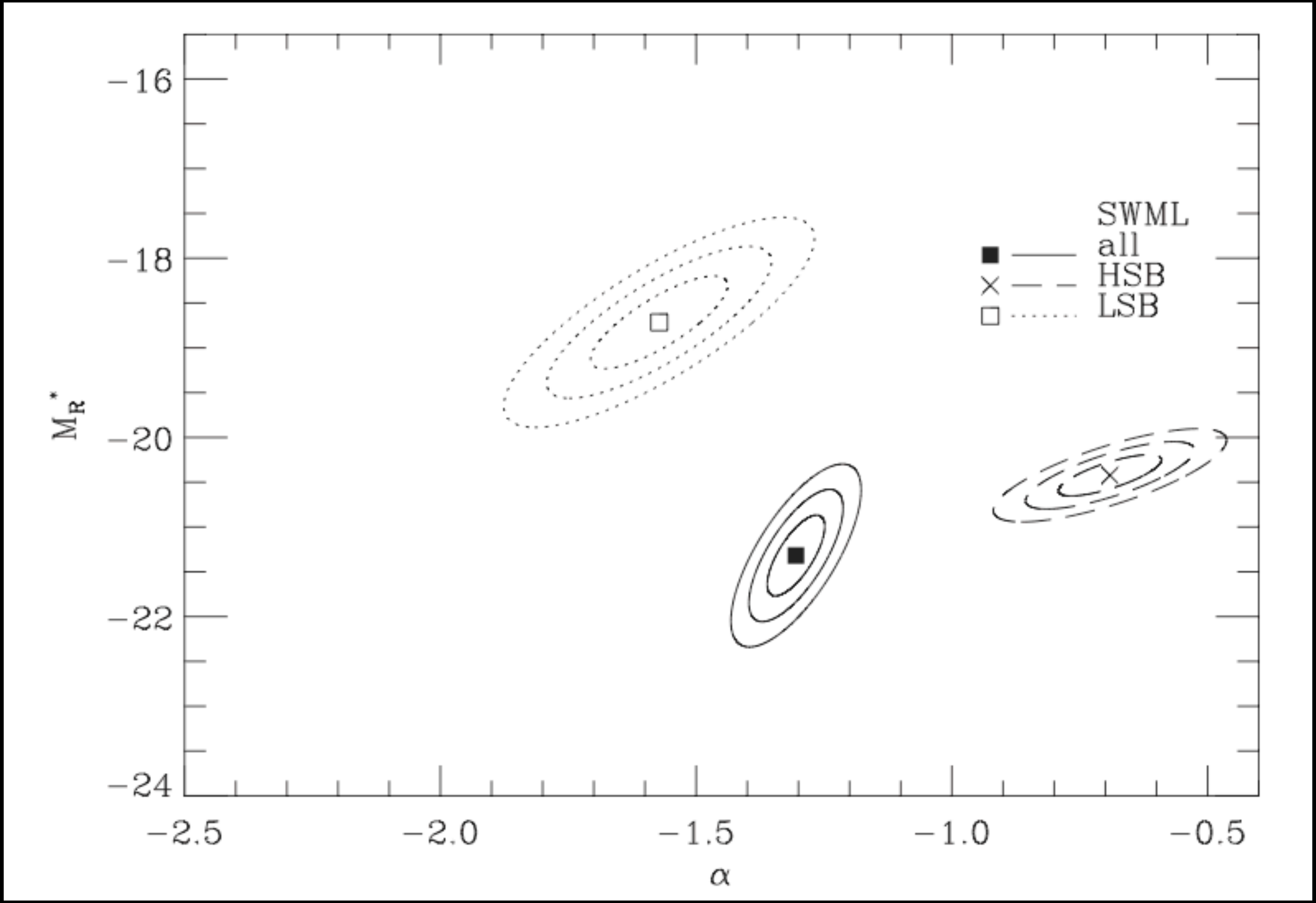


McGaugh (1996)

LSB galaxies appear fainter than HSB of the same luminosity

LSB galaxies appear smaller than HSB of the same size

4 deg^2
R<20.6
553 galaxies
0.02<z<0.1
SB$_{50R}$>22.5



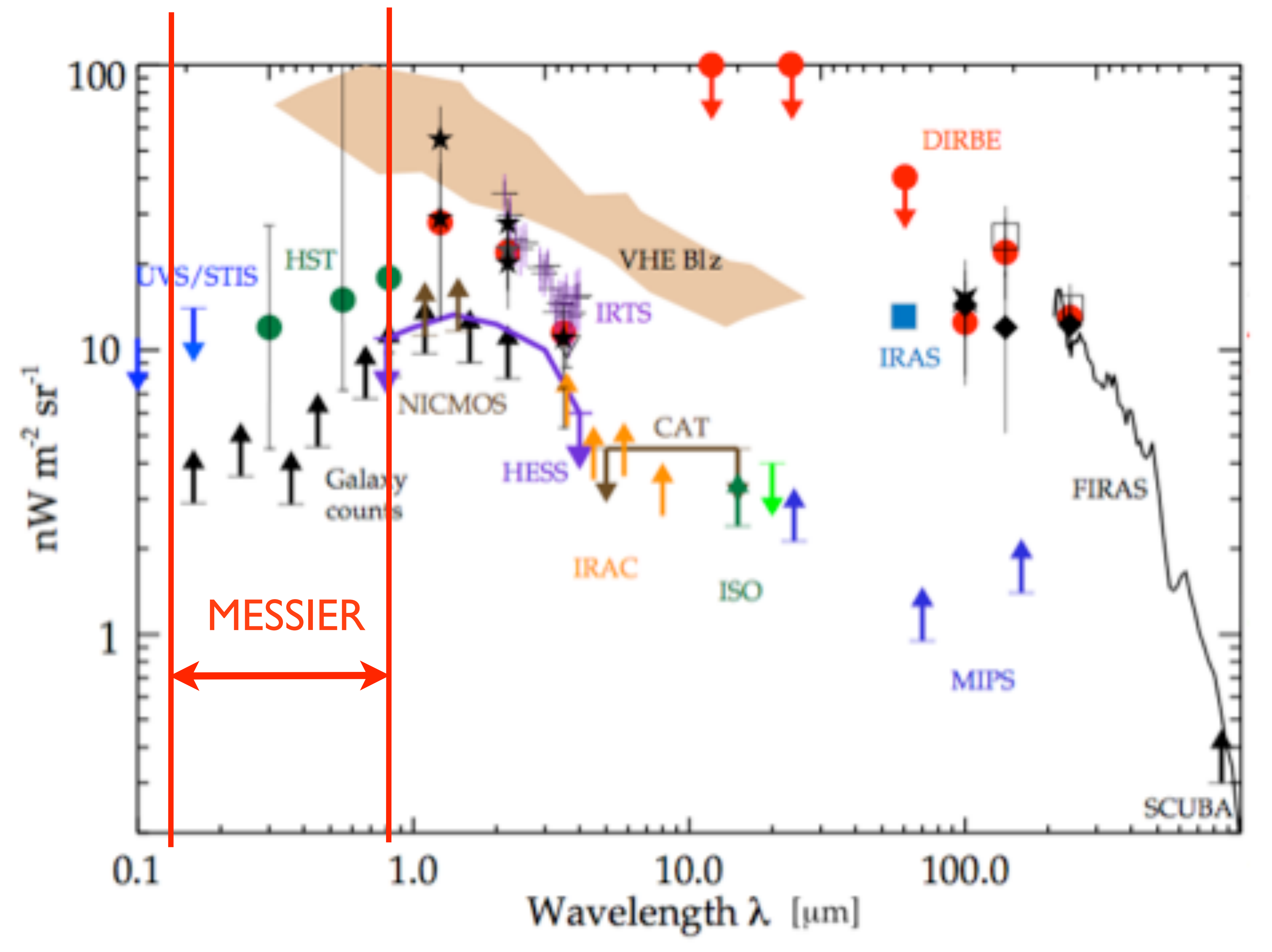
Measuring the slope of the faint end of the galaxy luminosity function, α*, remains an unresolved observational challenge.*

[…] incompleteness at the faint end is a frustrating and serious issue.

Geller *et al.* (2012) AJ 143, 102

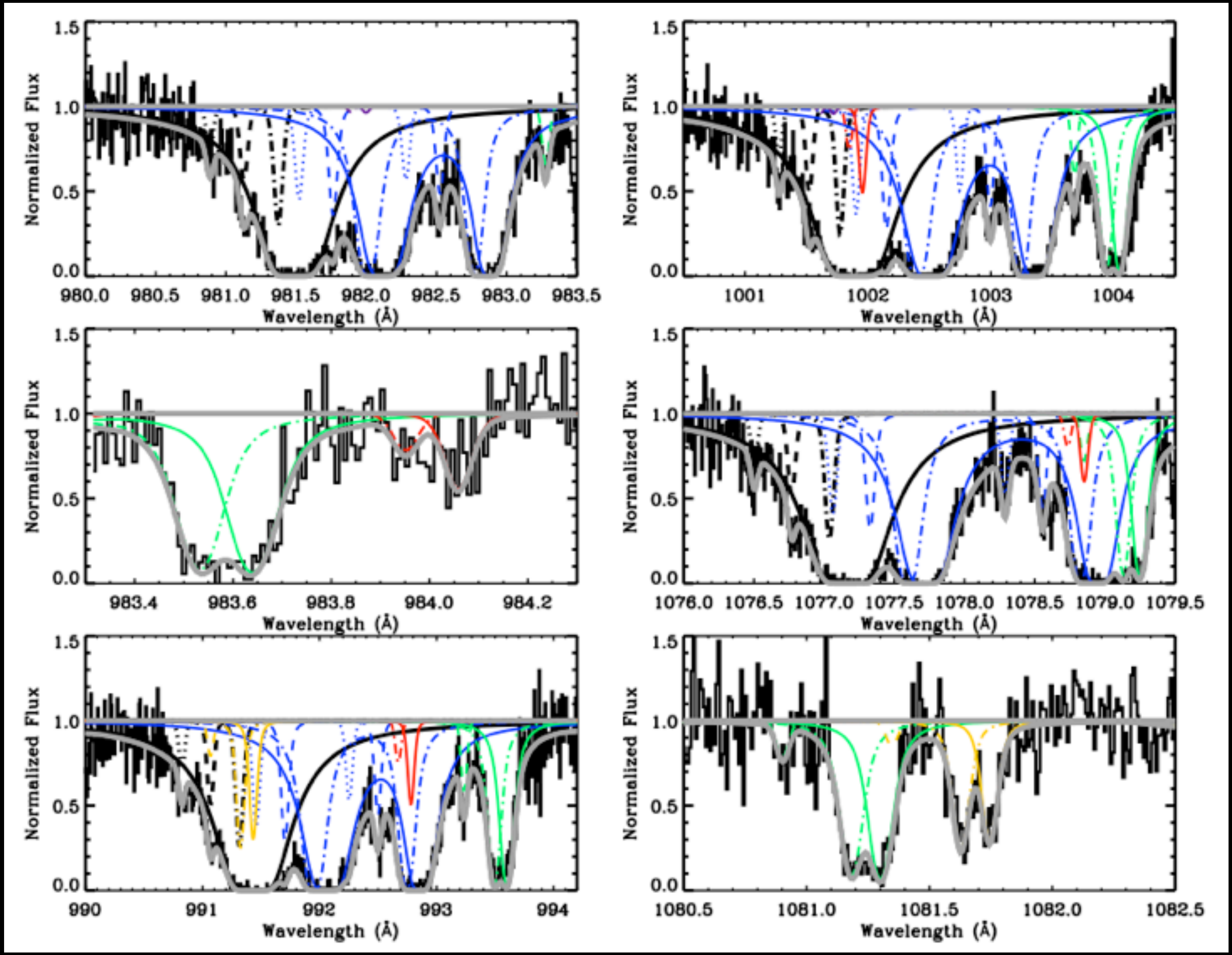
KS2 The optical / UV cosmological background radiation

$$I_\nu(\lambda_0, z_0) = \frac{1}{4\pi} \int_{z_0}^{\infty} \mathcal{L}_\nu(\lambda, z) \left| \frac{c\,dt}{dz} \right| dz$$



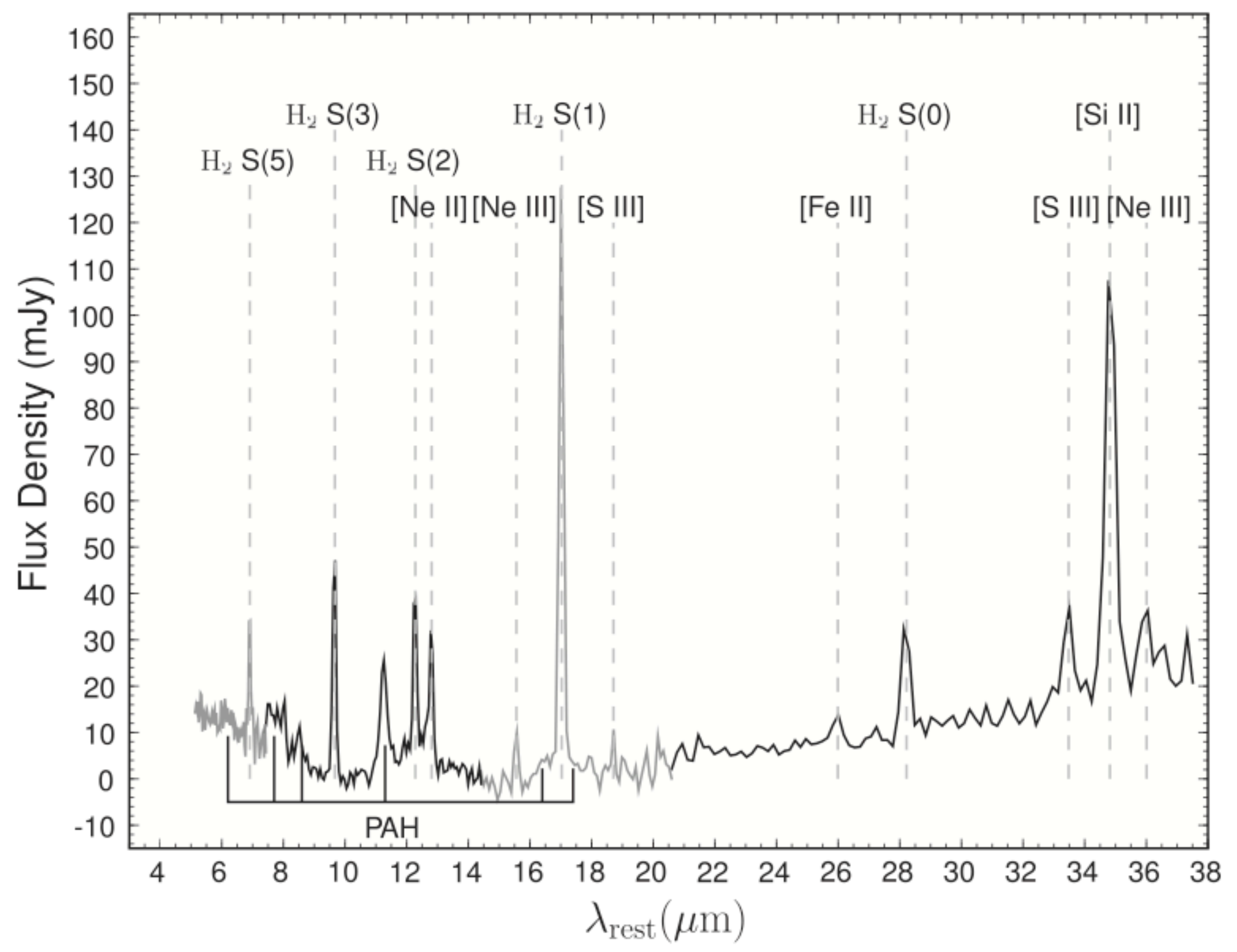
Cooray *et al.* (2009)

KS3 What is the molecular content of galaxies ?
The prevalence of cold/warm molecular H_2



DLA
$z = 0.185$

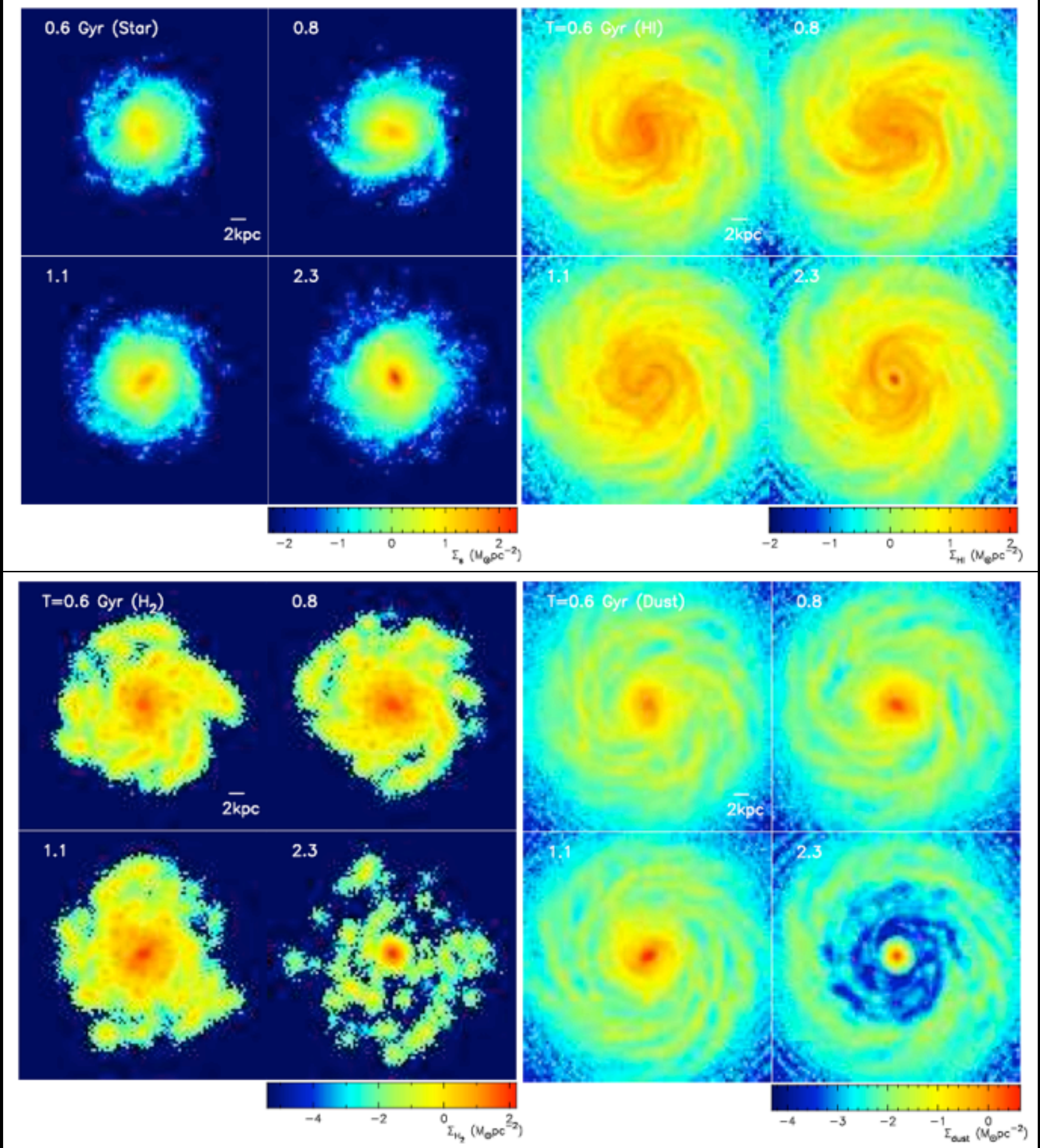
Oliveira et al. (2014)



Cluver *et al.* (2012)

stars

HI

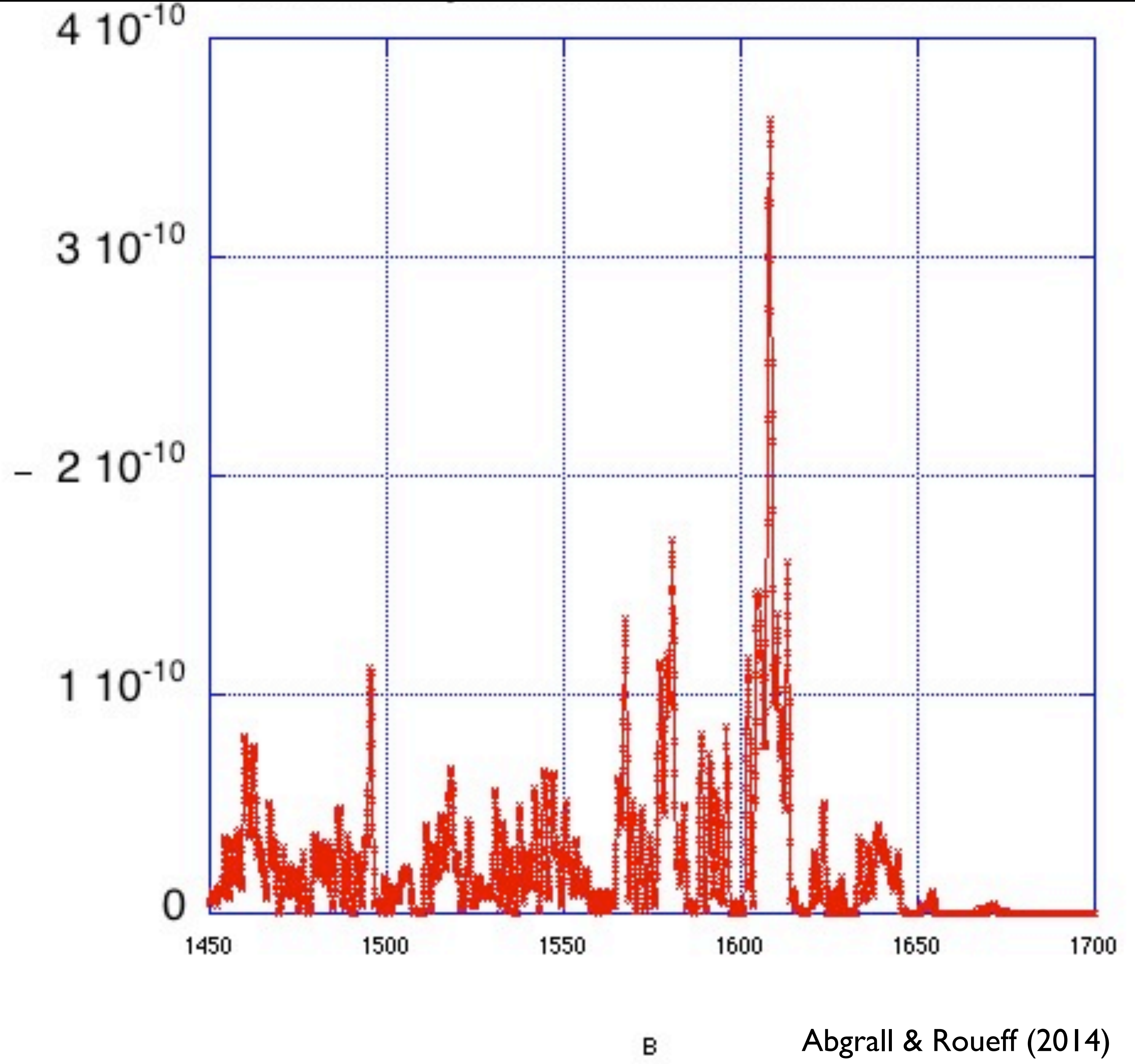


H_2

dust

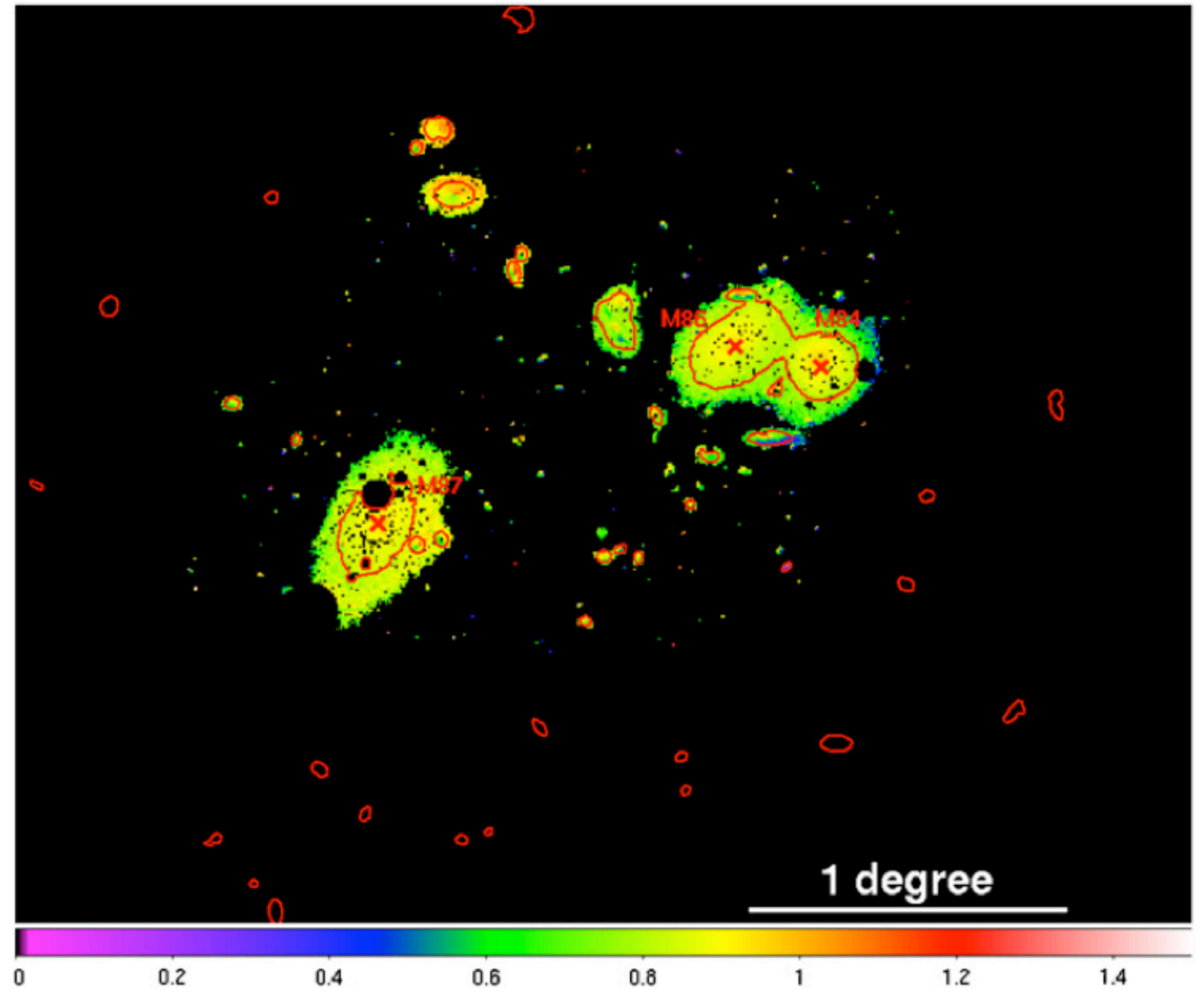
Bekki (2014)

Predicted spectrum for Stephan’s quintet in the Lyman-Werner bands



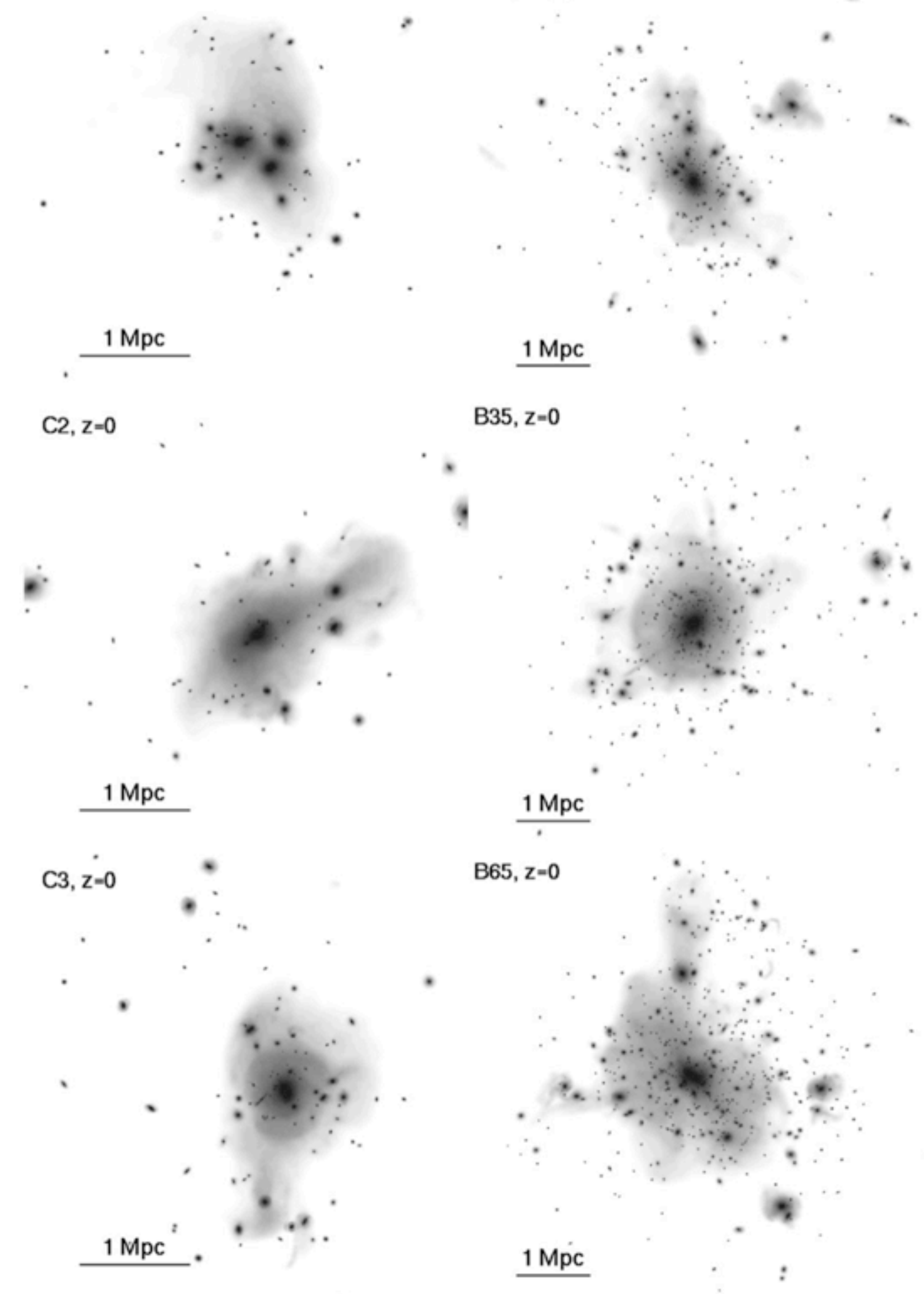
Abgrall & Roueff (2014)

KS4 What is the role of intracluster light in the evolution of galaxies and clusters?

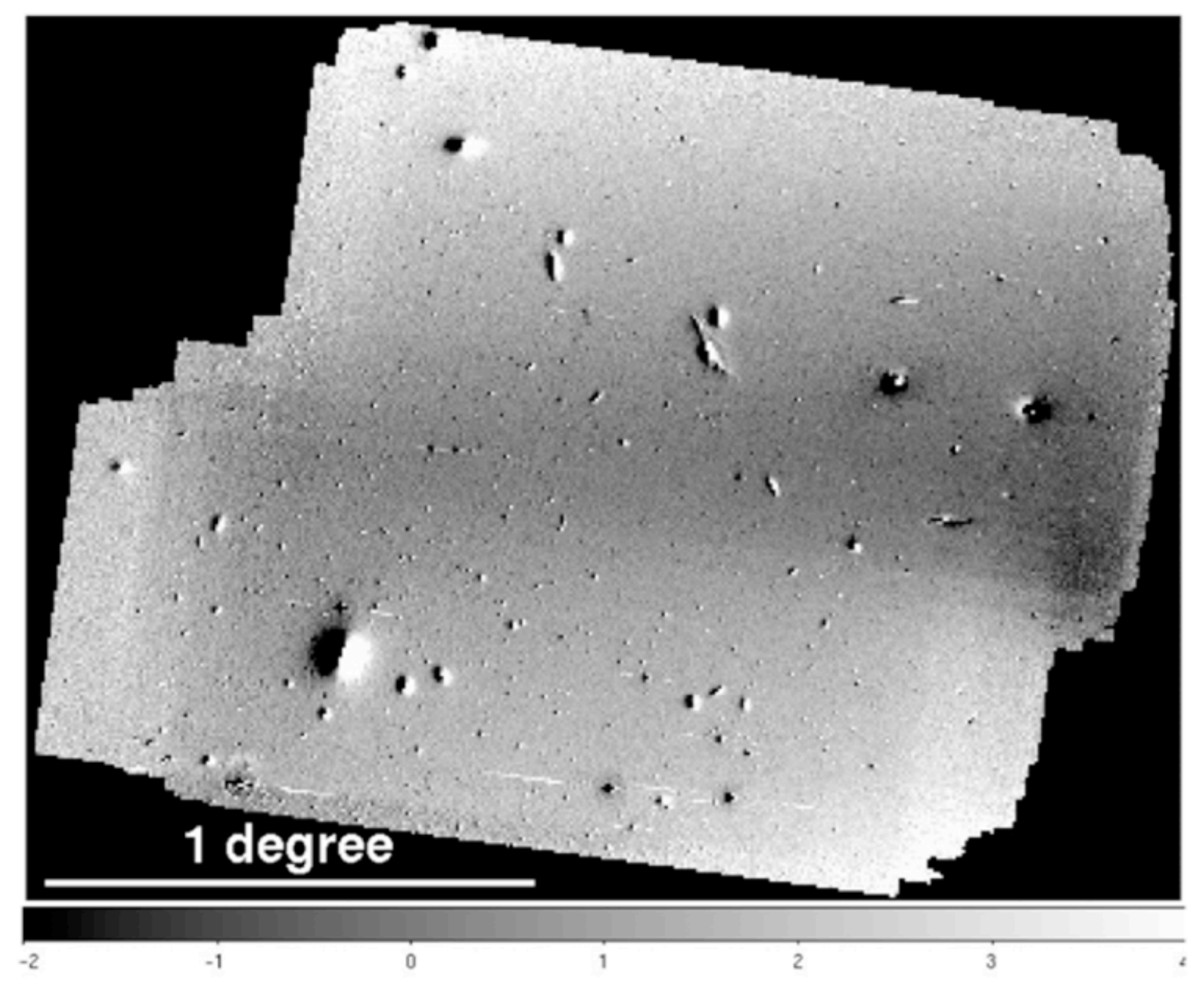


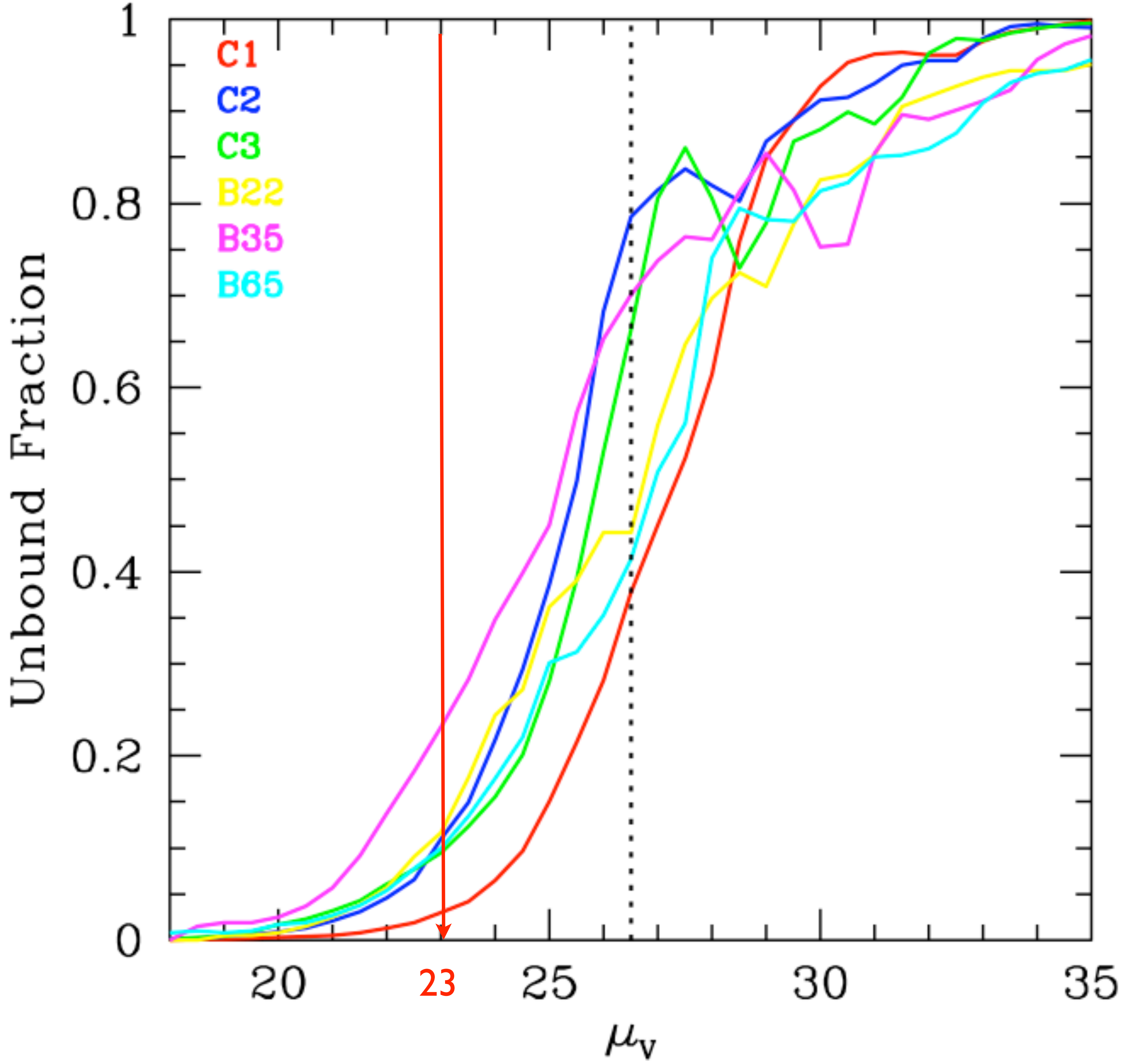
Predicted diffuse light in galaxy clusters

gas + star stripping in N-body simulations

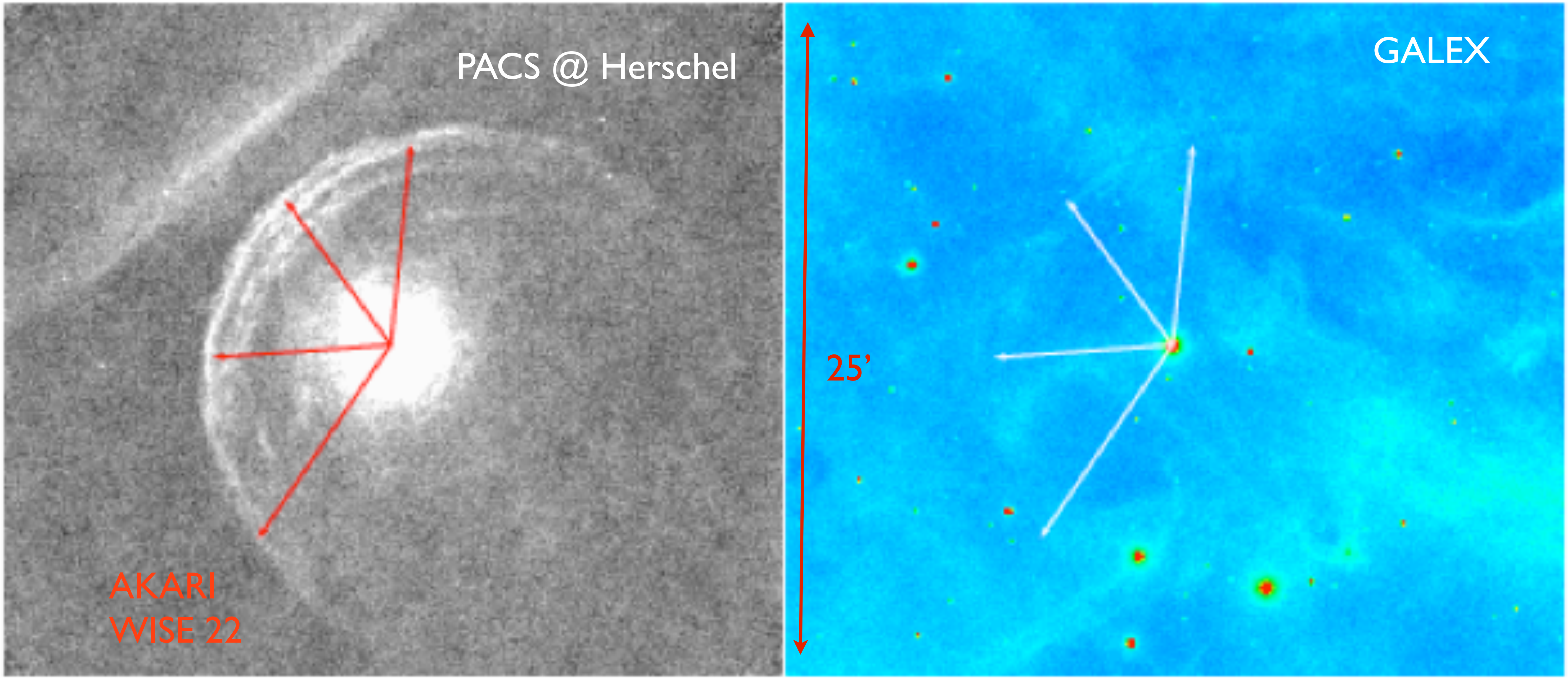


Artifacts produced by flat field residuals ?




C1
C2
C3
B22
B35
B65
Unbound Fraction
1
0.8
0.6
0.4
0.2
0
20
23
25
30
35
μ_V

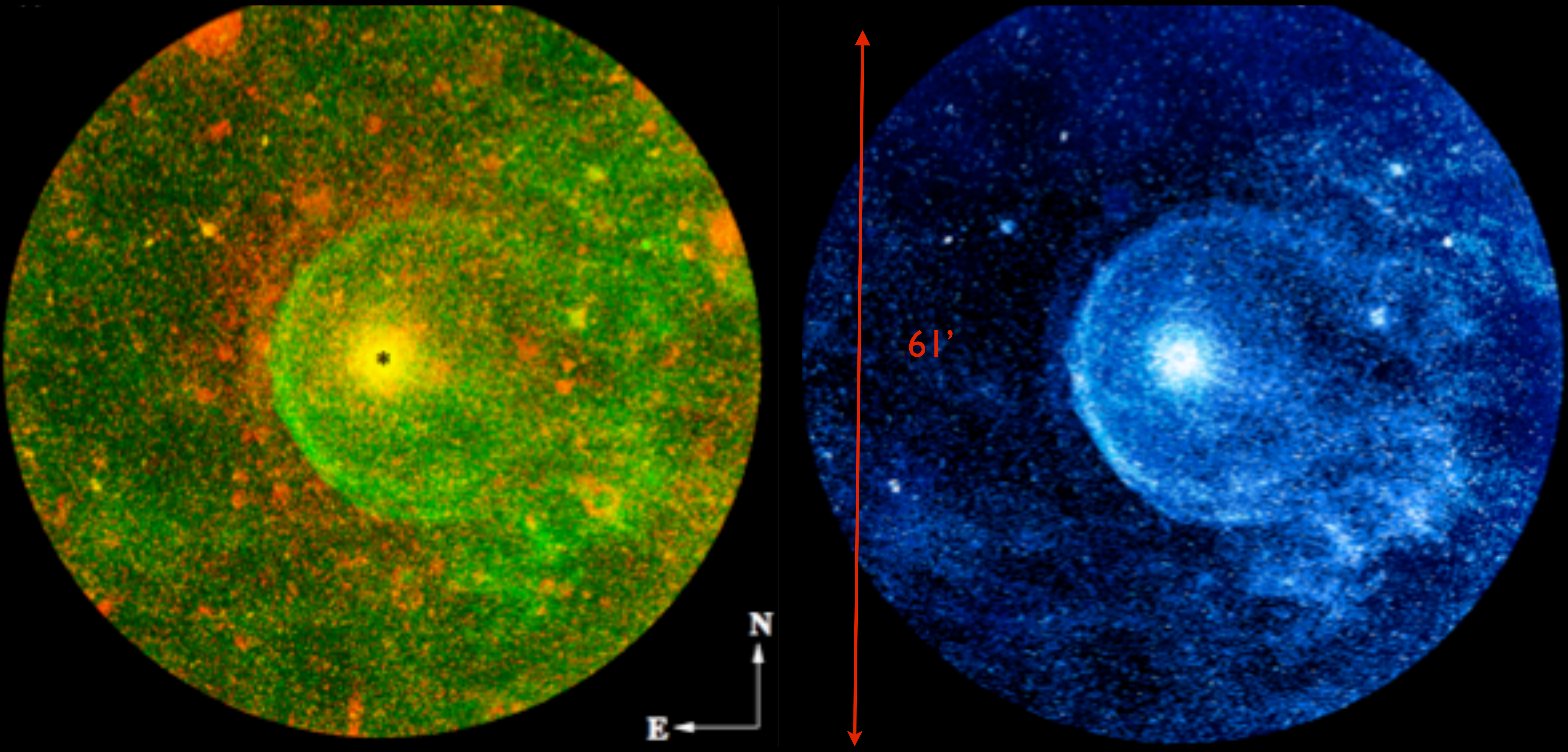
KS5 Mass loss from stars and the chemical evolution of galaxies



Betelgeuse

Decin *et al.* (2012)

AGB IRC+10216



FUV+NUV @ GALEX

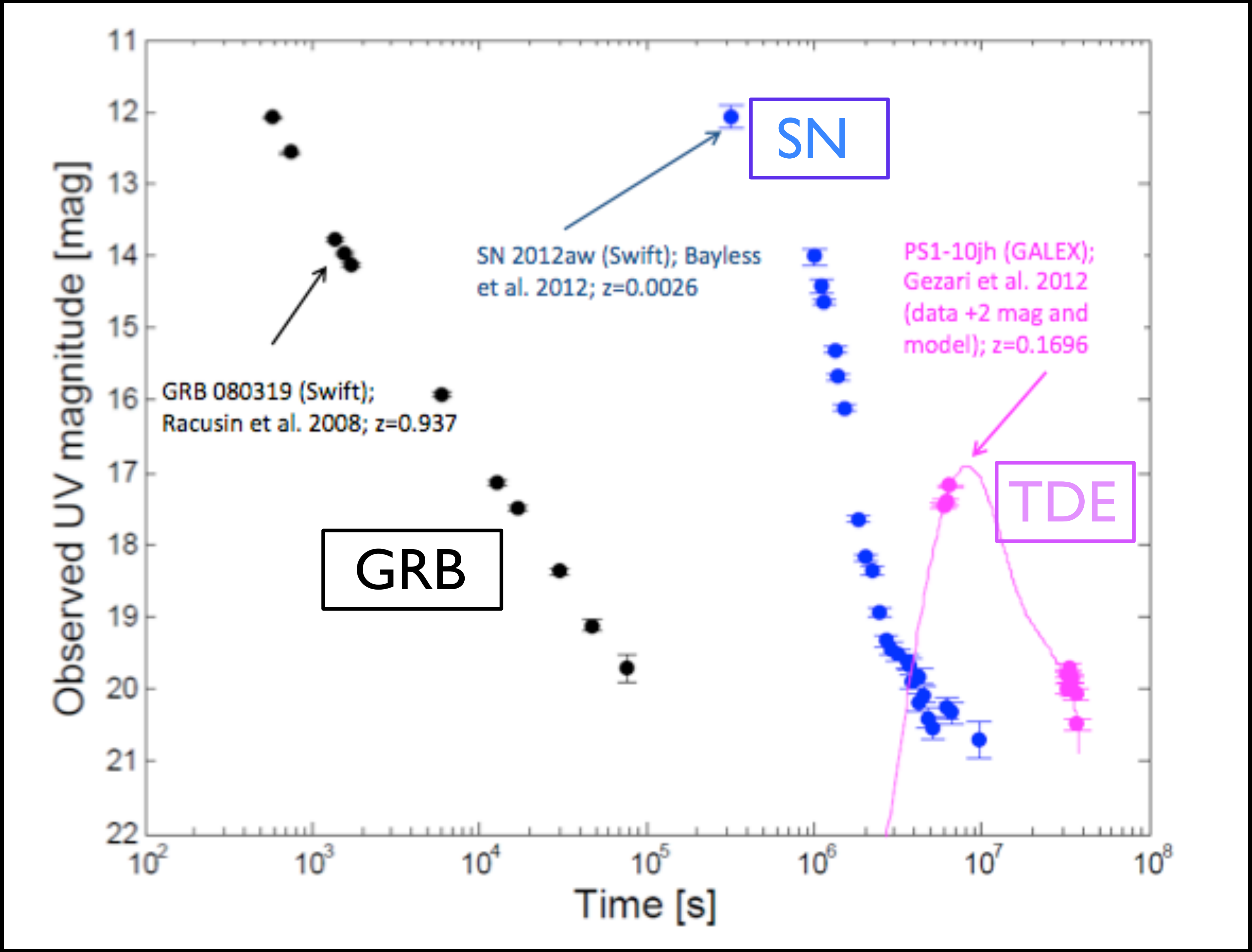
FUV @ GALEX

Sahai & Chronopoulos (2010)

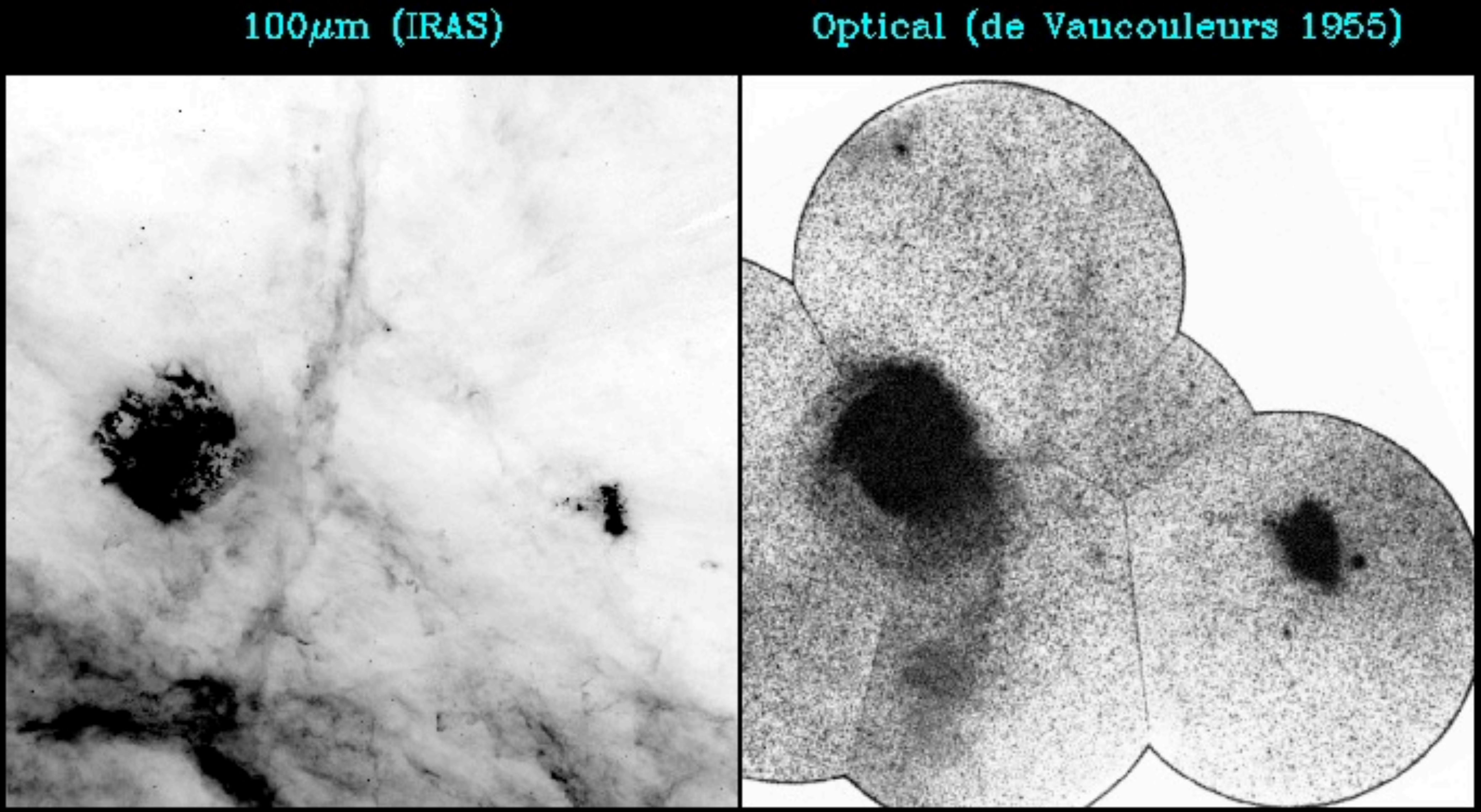
~350 RGB/AGB within the MESSIER reach

Unique tool for the reclying of stellar matter in the interstellar medium

KS7 Time-domain astronomy :
variability and transients from the UV to the optical



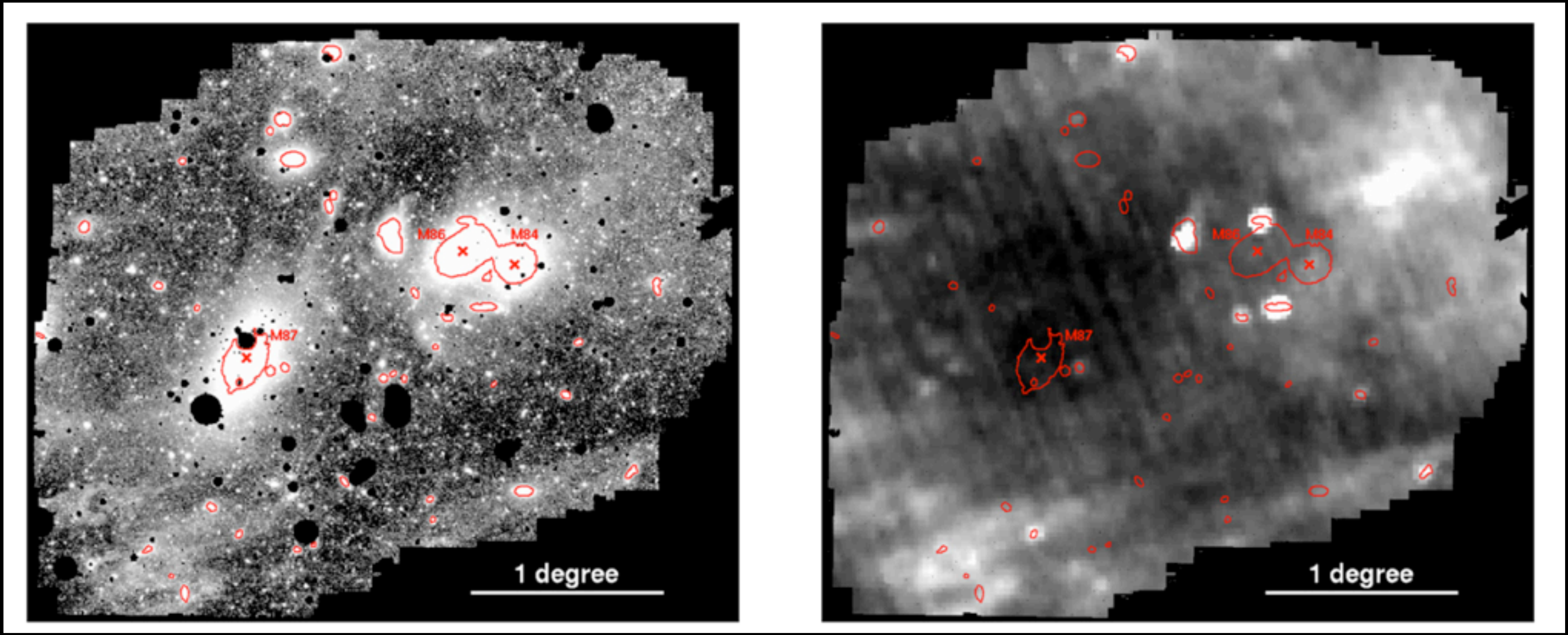
The main challenge for MESSIER
The foreground contamination at ultra-low SB



Magellanic Clouds

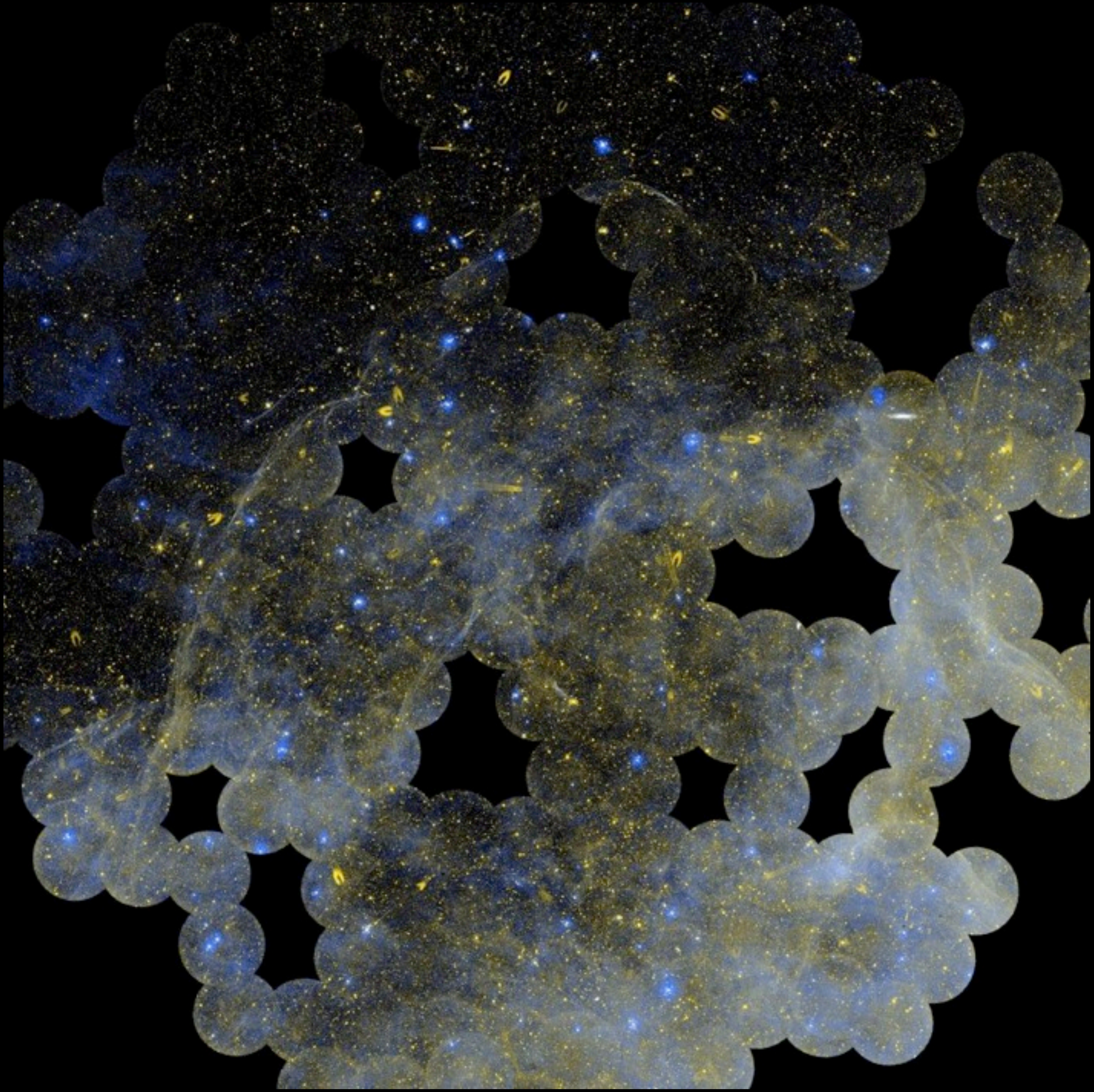
Optical emission

IRAS 100 µm



Mihos et al. (2009)

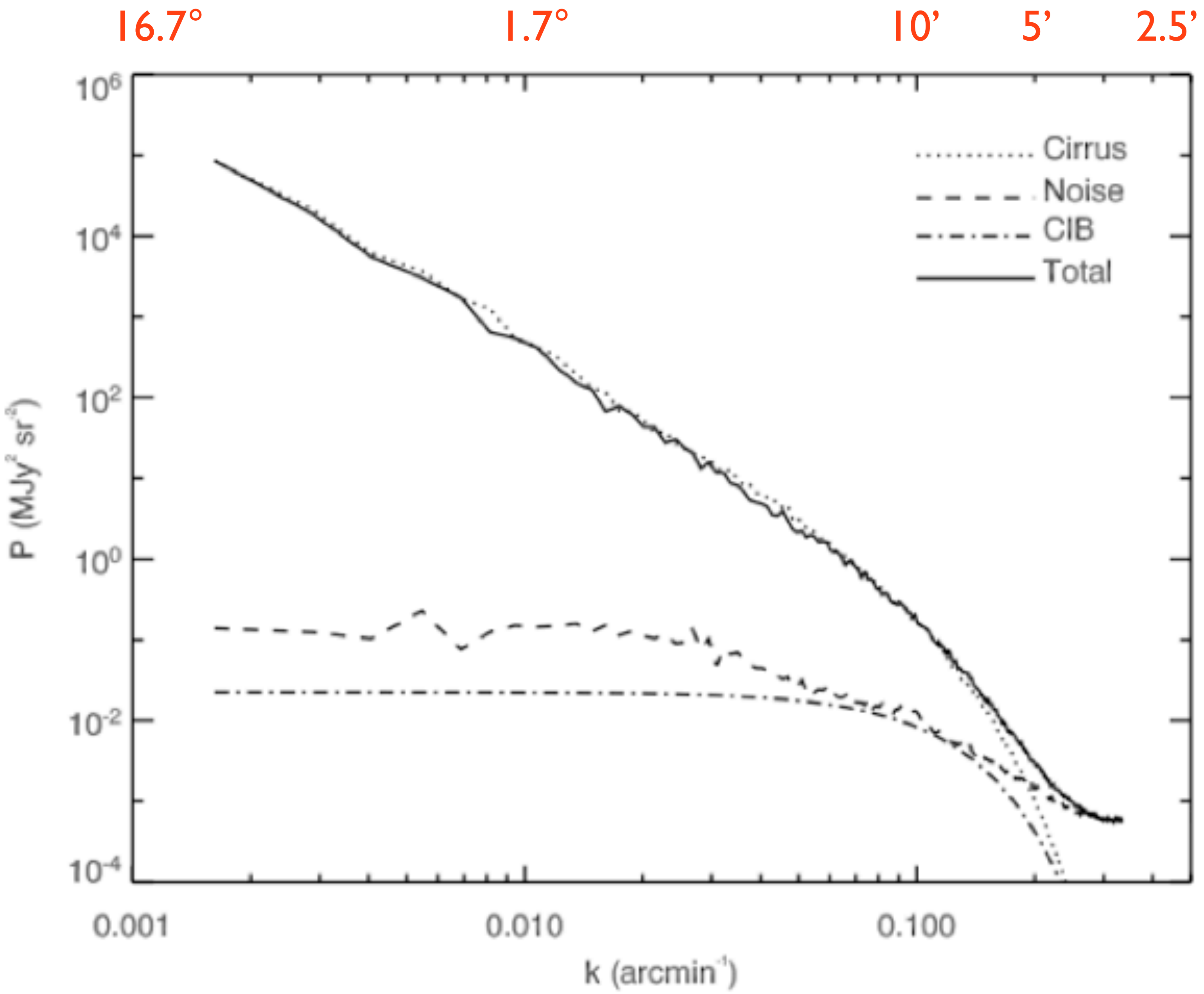
Virgo cluster field



GALEX

Angular power spectrum of IR cirri

angular distribution



the smaller
the scale,
the smaller
the fluctuations

IRAS 100um
Miville-Deschênes et al., 2007

PLANCK 857 GHz
Dole et al., 2013

Synergies

- GAIA

  MESSIER provides extension of star counts to fainter levels than *G*=20
  Use GAIA astrometry as prior for MESSIER detections
  Problem: pixel size to separate dwarf galaxies from stars down to *g*~25
  Solution: use EUCLID astrometry as prior

- EUCLID

  Requires multi-band follow-up for photometric redshifts
  Use EUCLID astrometry as prior for MESSIER detections

- LAMOST + MES

  MESSIER will provide unique targets for kinematics

- Time-domain astronomy

  Transients, transits, TDE, GRB, SN, QSO/AGN variability
  Complements UV-based projects (Ultrasat) on longer timescales

- Unique legacy value

  The reference catalogue of multi-band space-based photometry

The MESSIER satellite

1. Science rationale
2. Technical design

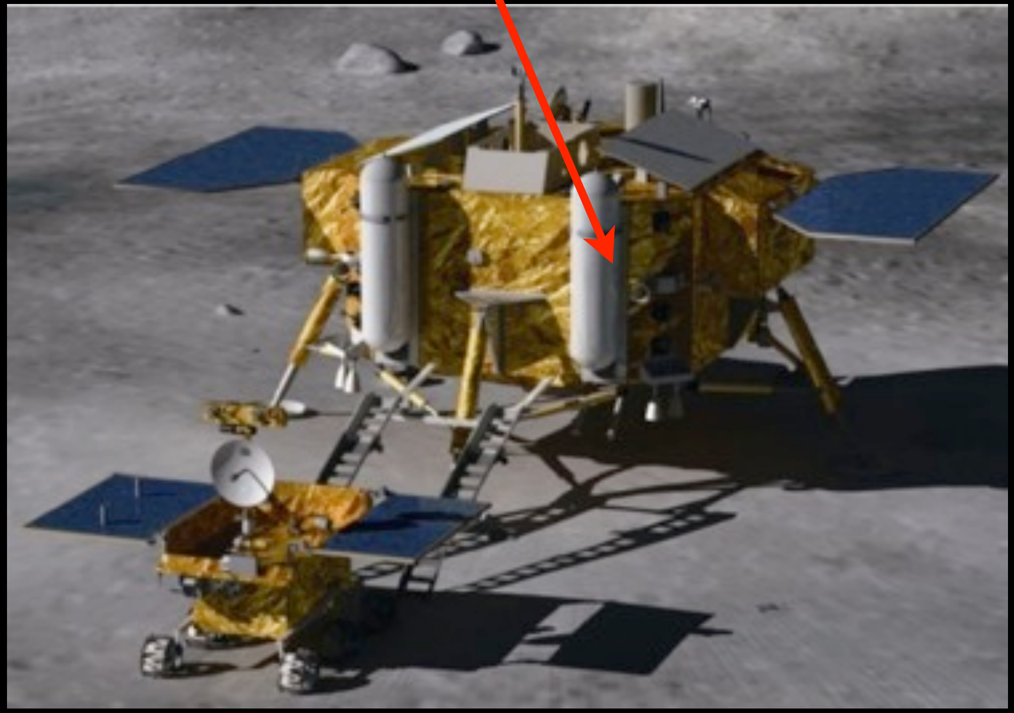
National Astronomical Observatory of China (NAOC)
Chinese Academy of Sciences (CAS)

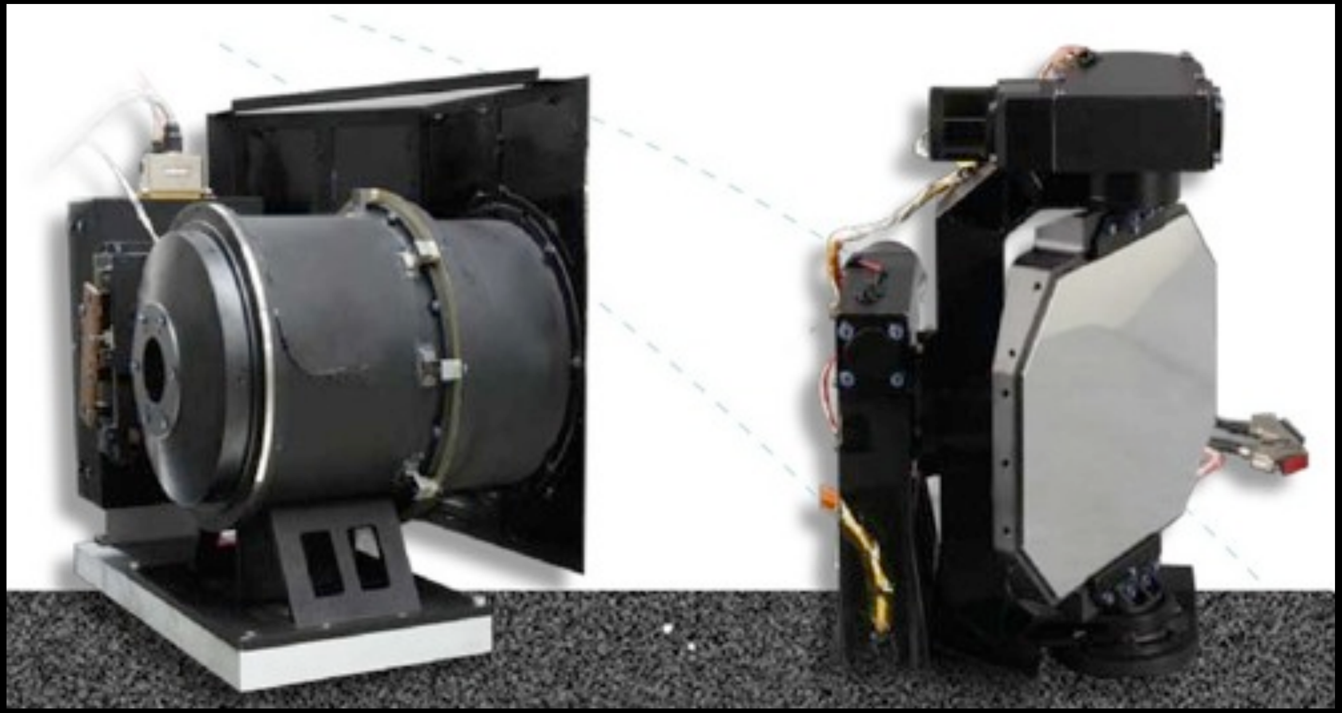
✔ Heritage Expertise in UV space instrumentation

Lunar-based UV Telescope

LUT @ Chang’e 3

D=150 mm Ritchey-Chrétien
λλ 245−340 nm

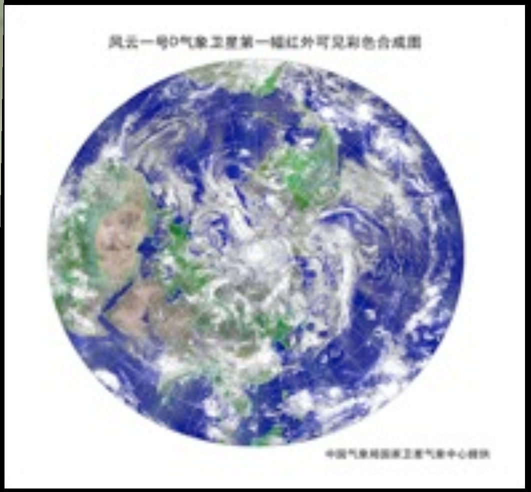


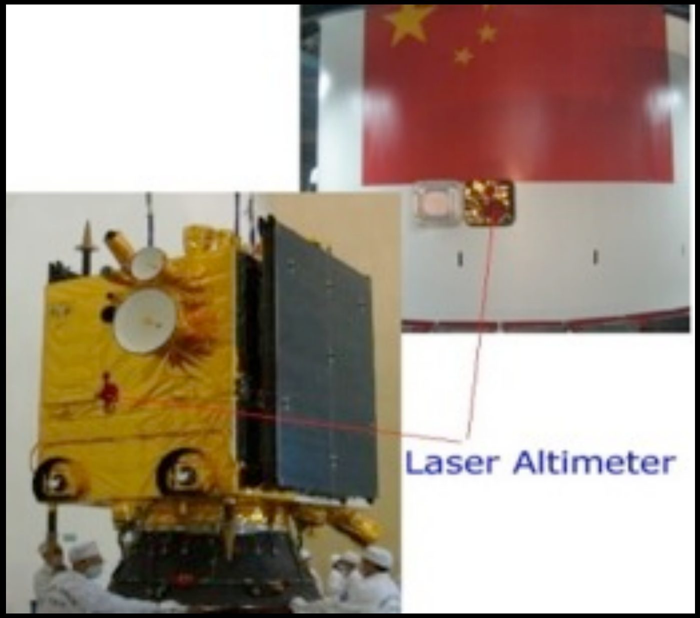


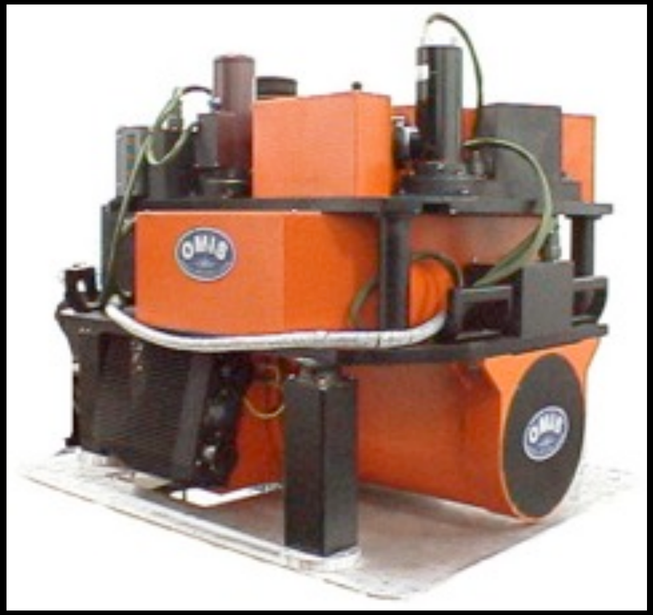
Shanghai Institute of Technical Physics (SITP)
Chinese Academy of Sciences (CAS)

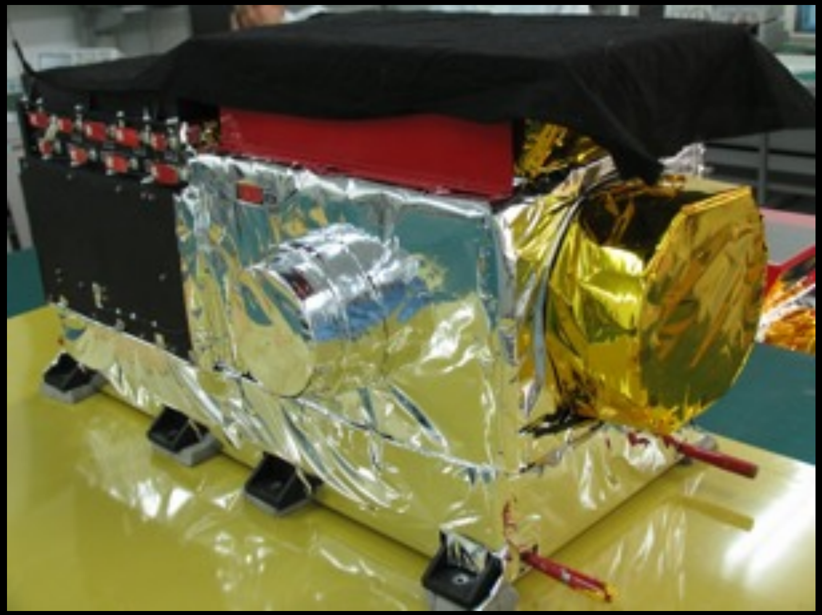
1958 - Co-founded by Fudan University and CAS
1962 - Independent CAS Institute

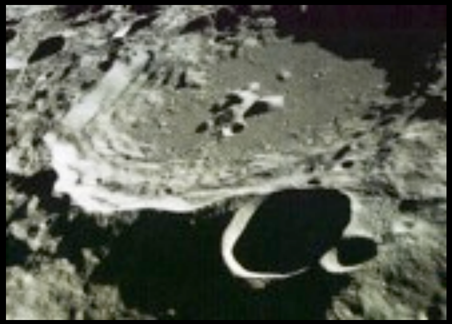
- ✓ Space and aerial remote sensing
- ✓ Optoelectronic information processes
- ✓ Miniature cooling techniques for space applications
- ✓ Optical coatings
- ✓ Infrared detectors











Mission concept

- Platform

  ESA's PROBA-V (160 kg, 120 W peak)
  with VESPA dual-payload adapter @ Vega rocket

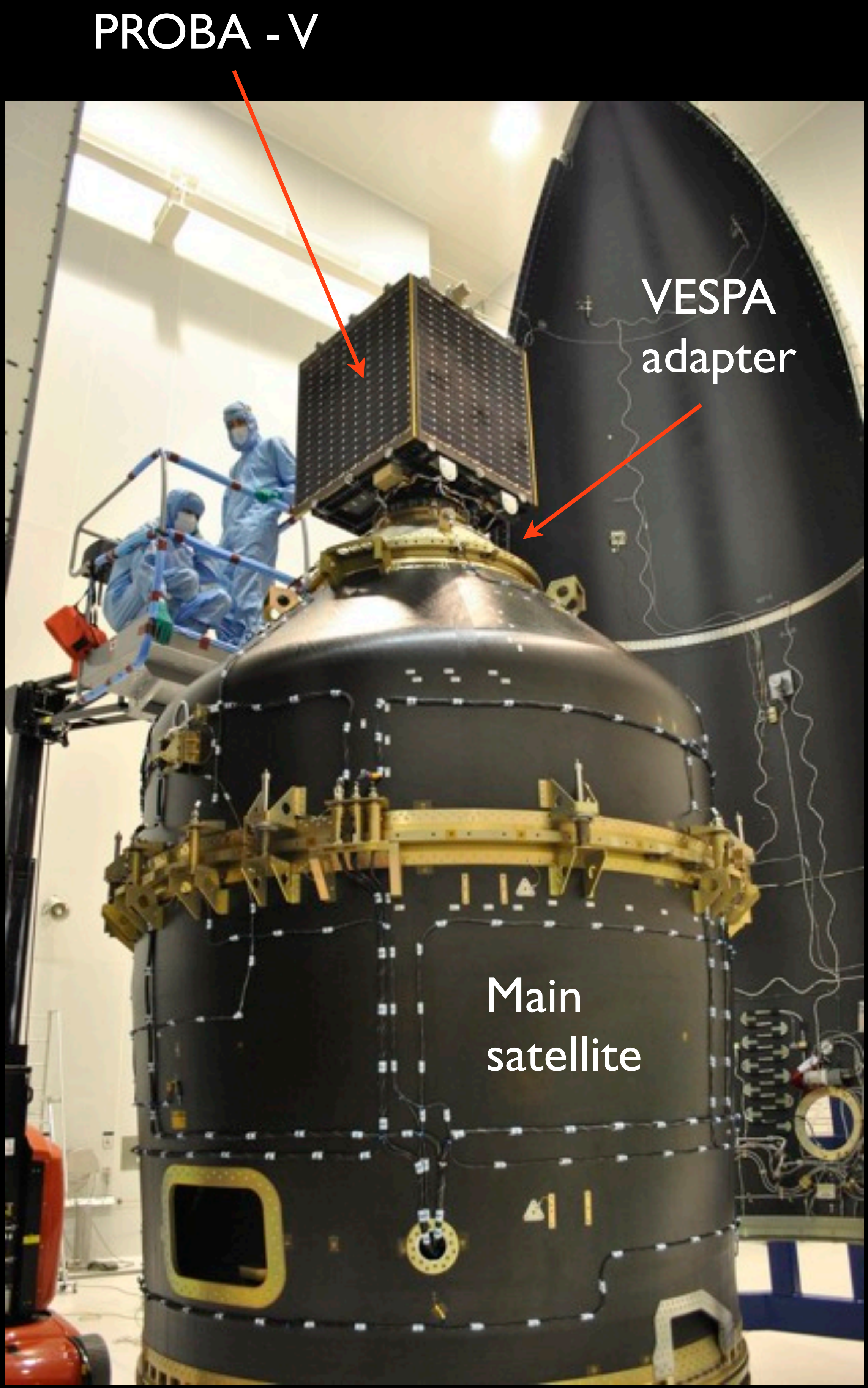
Subsystem	Equipment	Heritage
Avionics	ADPMS, memory	Proba2+ProbaV
Electric power	GaAs cells	Herschel
Bus structure	Al	Proba V
AOCS	Magnetotorquer	Proba2
Onboard SW	RealTimeExecPr	Proba2
Thermal	Passive	ProbaV
RF	S and X bands	Proba V
Design life	3-5 years	Proba2+ProbaV

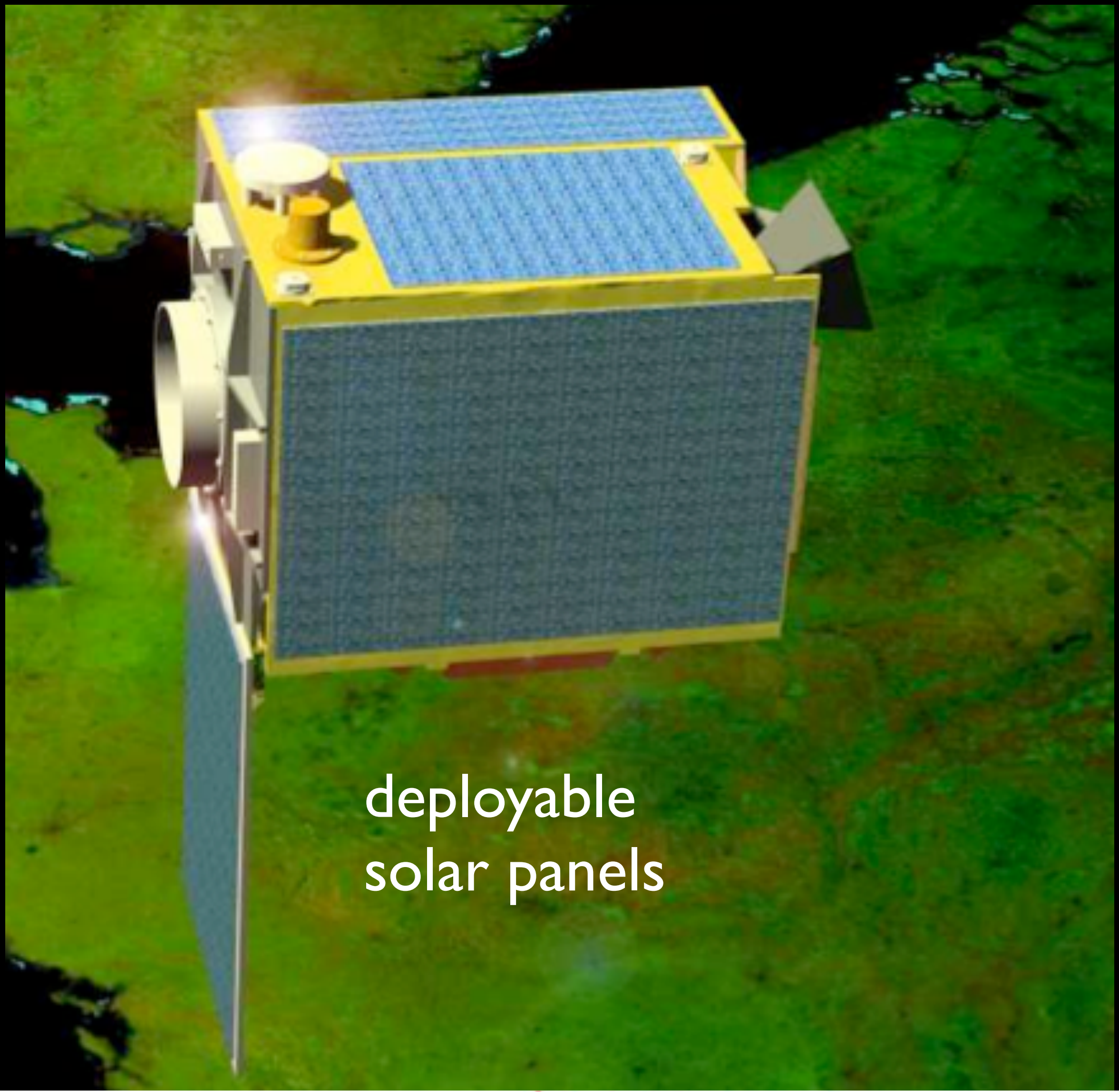
ESA PLATFORM

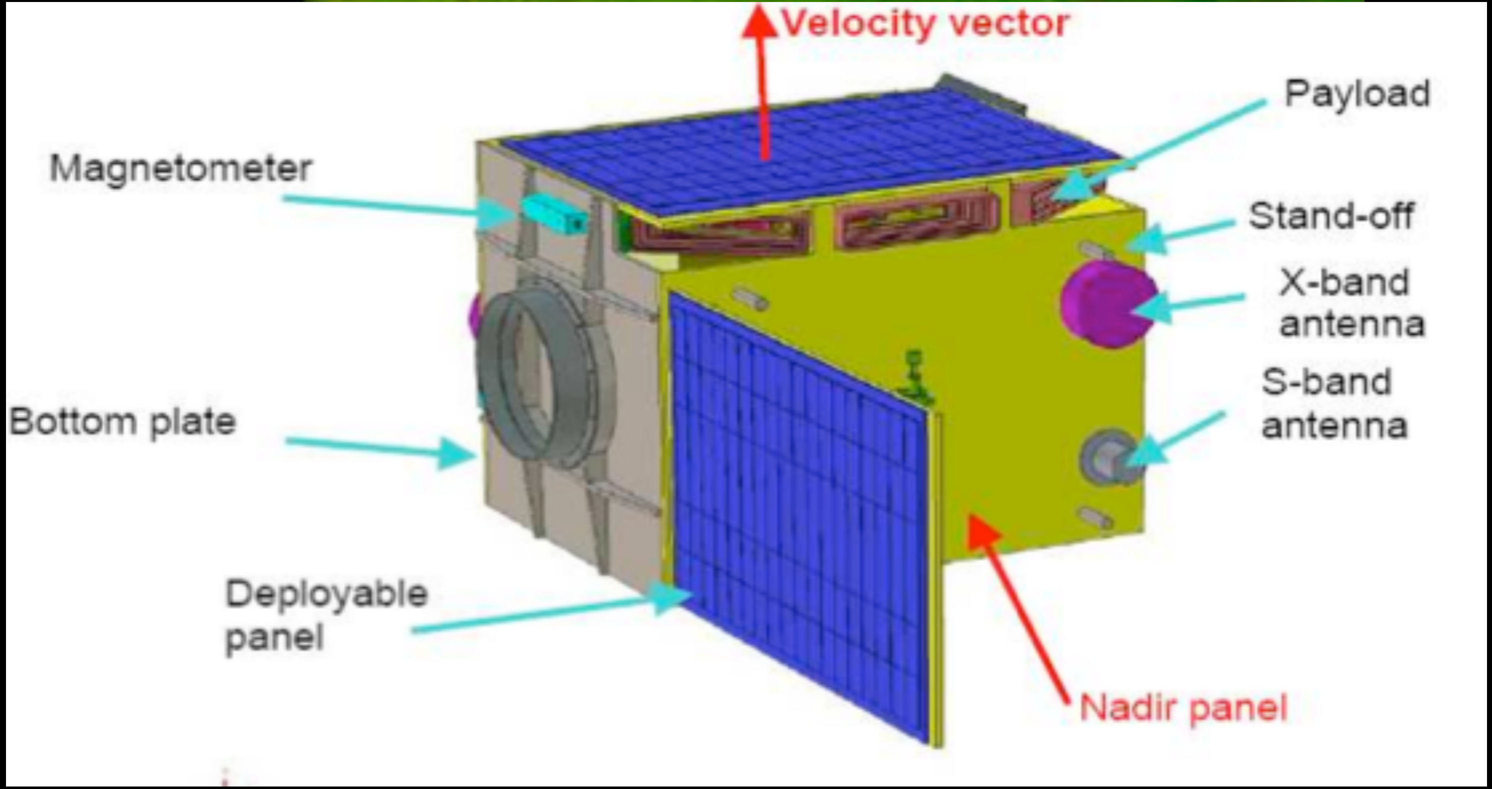
PROBA - V : PRojet for On-Board Autonomy - Vegetation

- Mass: 160 kg
- Dimensions: 765 x 730 x 840 mm
- Three axis-stabilised RPE < 1.5″
- Body mounted Solar Array
- Payload downlink
  3 X-band transmitters

Consortium: CNES France BelSPO/VITO Belgium SNSB Sweden building on PROBA-2 heritage


PROBA - V
VESPA adapter
Main satellite


deployable solar panels


Velocity vector
Payload
Magnetometer
Stand-off
X-band antenna
S-band antenna
Bottom plate
Deployable panel
Nadir panel

Mission concept

- Platform

  ESA's PROBA-V with VESTA dual-payload adapter @ Vega

- Payload

  Off-axis TMA f/2 telescope, 340 mm × 210 mm pupil

  flat focal plane, FOV : 4 × 2 square degrees

  ultra-stable PSF with ultra-low wings

  no lenses (to avoid Čerenkov radiation)

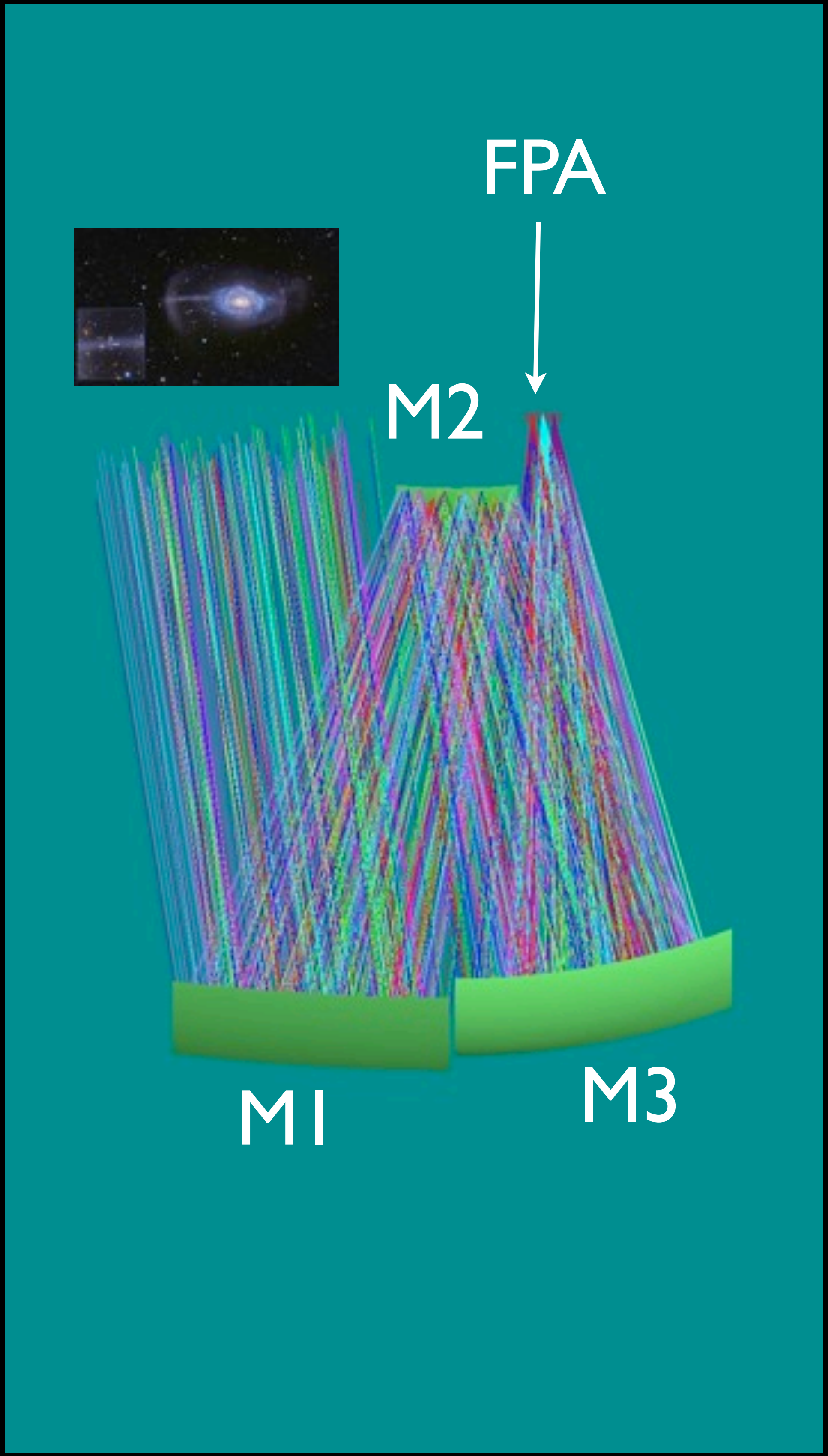
  extreme baffling to limit straylight contaminations

  8 UV / optical filters

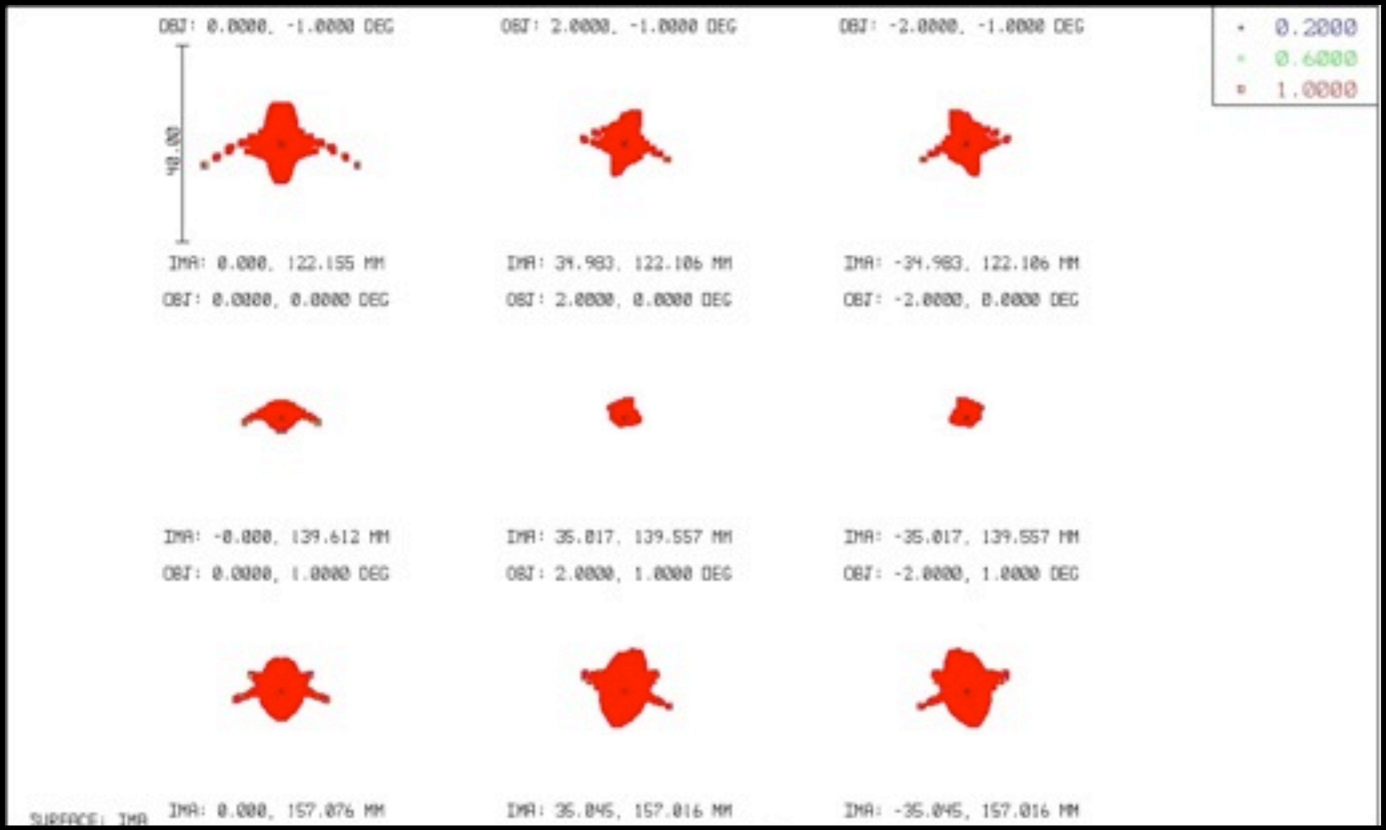
  no moving parts, passive cooling, low power

  TRL 9

Optical design



- Off-axis TMA f/2 telescope
  - free-form rectangular mirrors
  - 340 mm × 210 mm pupil
  - flat focal plane
  - FOV : 4° × 2°
  - ultra-stable PSF with ultra-low wings
  - no lenses (to avoid Čerenkov radiation)



Re-focusing through M2 (TRL9)

out-of-focus (1 mm)

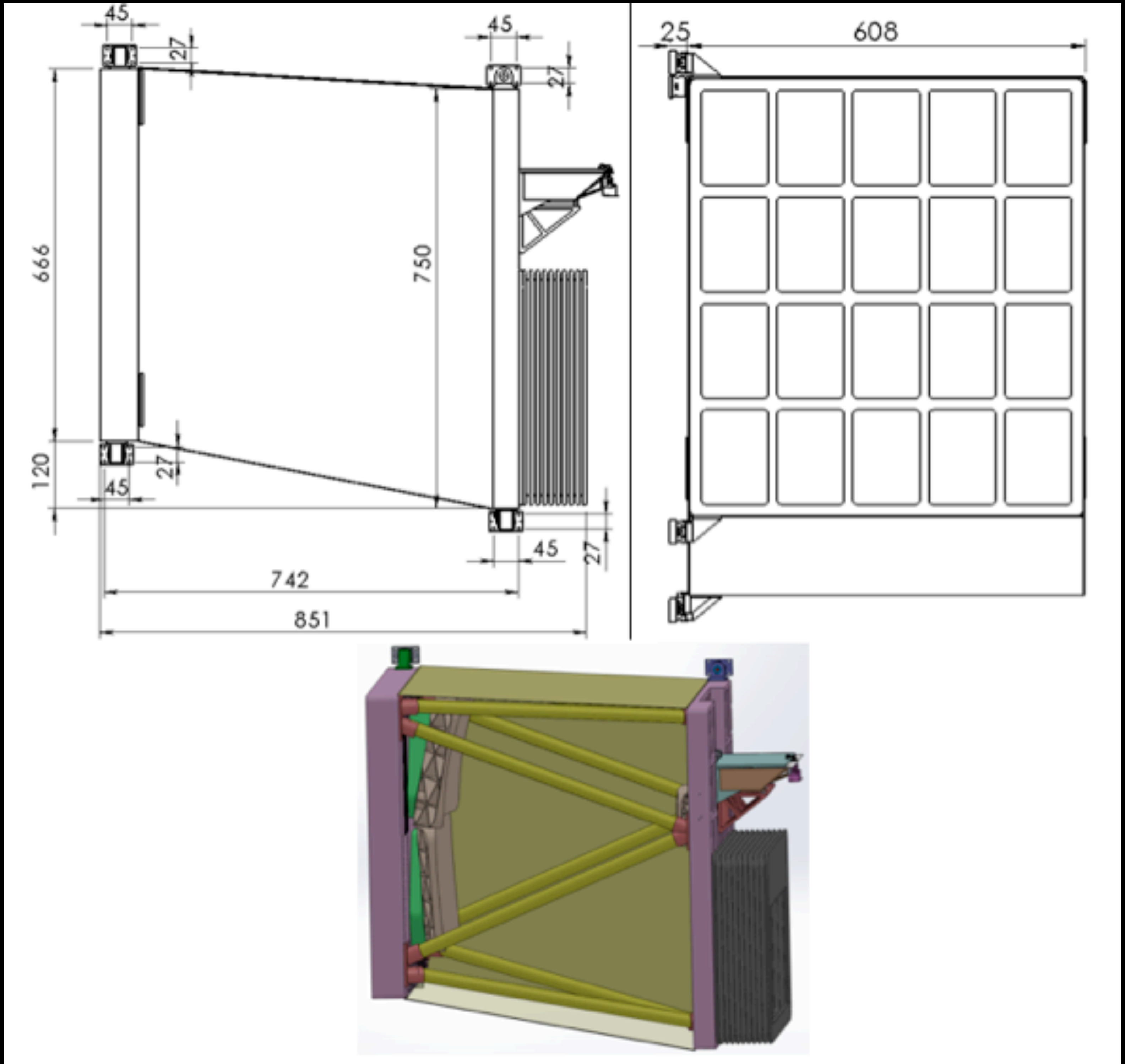
```
SURFACE: IMA   IMA: 0.000, 157.076 MM   IMA: 35.045, 157.016 MM   IMA: -35.045, 15
                                SPOT DIAGRAM
TUE AUG 12 2014  UNITS ARE µm.
FIELD      :      1      2      3      4      5      6      7      8      9
RMS RADIUS :  4.760  3.887  3.887  1.892  1.573  1.573  3.581  4.655  4.655
GEO RADIUS : 16.119 13.456 13.456  7.456  5.244  5.244  9.382 13.374 13.374
AIRY DIAM  :  0.6302                     REFERENCE  : CENTROID
```

successful re-focus

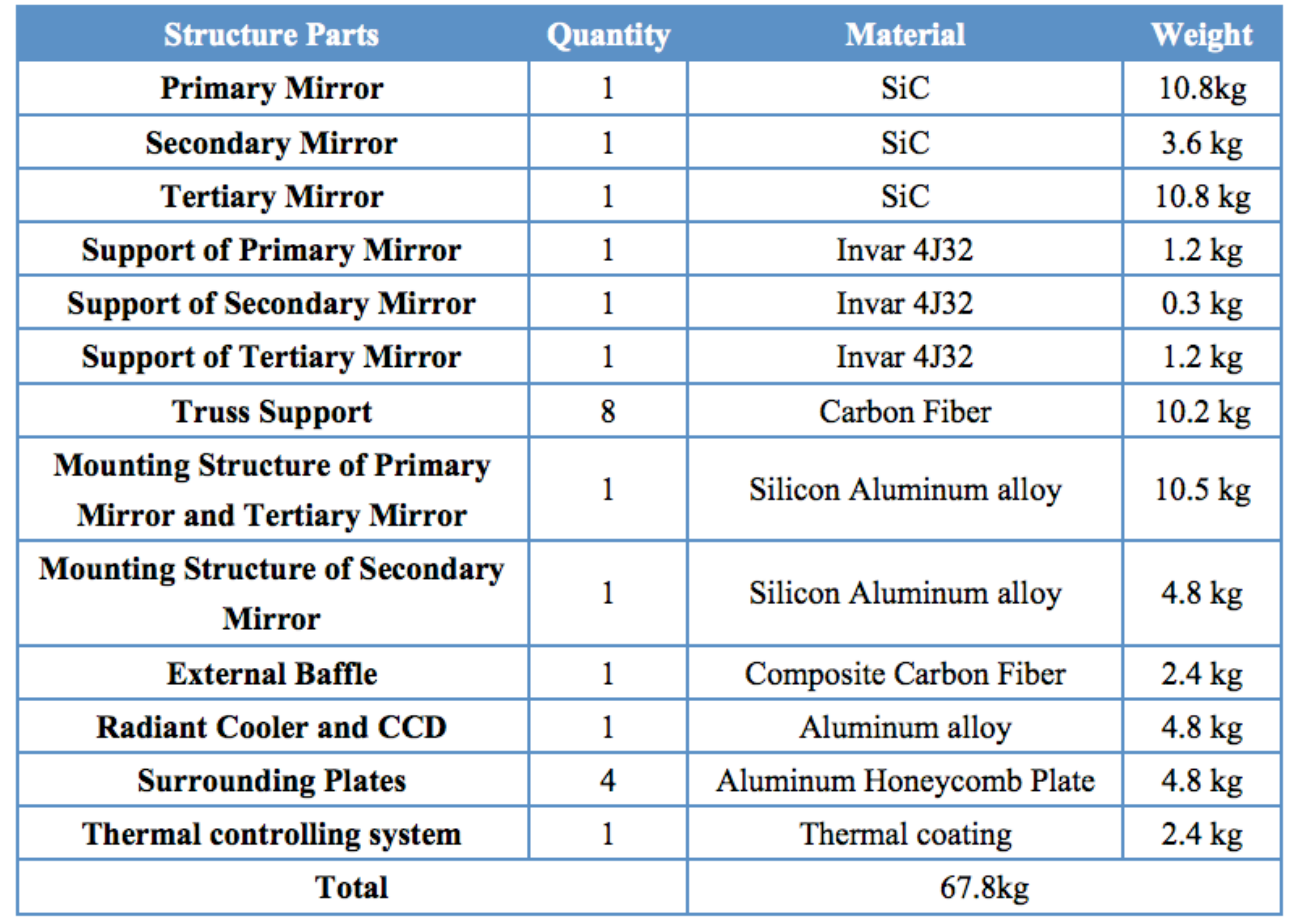
```
SURFACE: IMA   IMA: 0.000, 157.030 MM   IMA: 36.036, 156.970 MM   IMA: -35.036, 156.970 MM
                                SPOT DIAGRAM
TUE AUG 12 2014  UNITS ARE µm.
FIELD      :      1      2      3      4      5      6      7      8      9
RMS RADIUS :  7.039  6.512  6.512  4.952  4.864  4.864  4.871  5.808  5.808
GEO RADIUS : 20.163 18.979 18.979 13.316 13.814 13.814 14.938 21.104 21.104
AIRY DIAM  :  0.6307                     REFERENCE  : CENTROID
TMA WITH STOP AT SECONDARY MIRROR_F2_RECTANGLE_RESULT.ZMX
CONFIGURATION 1 OF 1
```

Mechanical design

Overall dimensions within PROBA platform

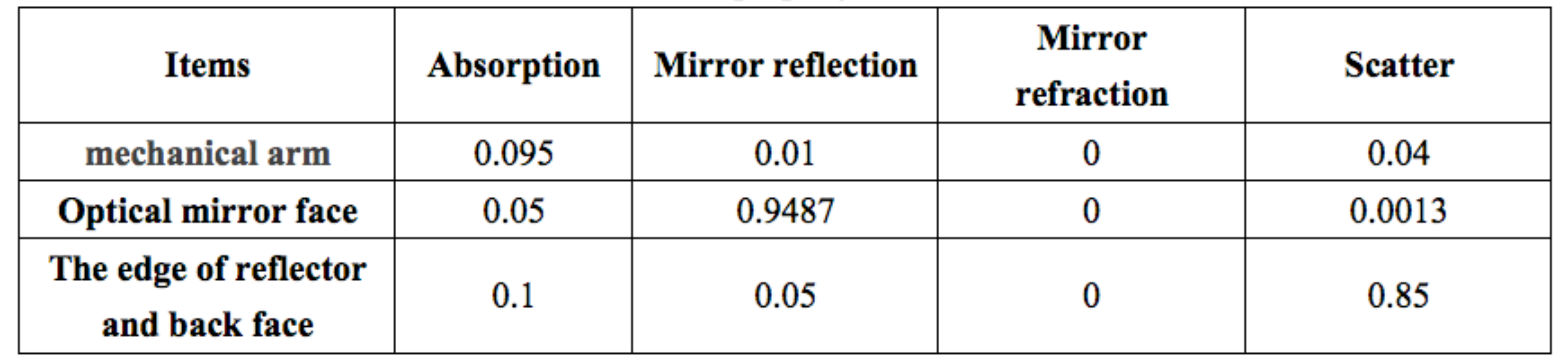


Mass budget

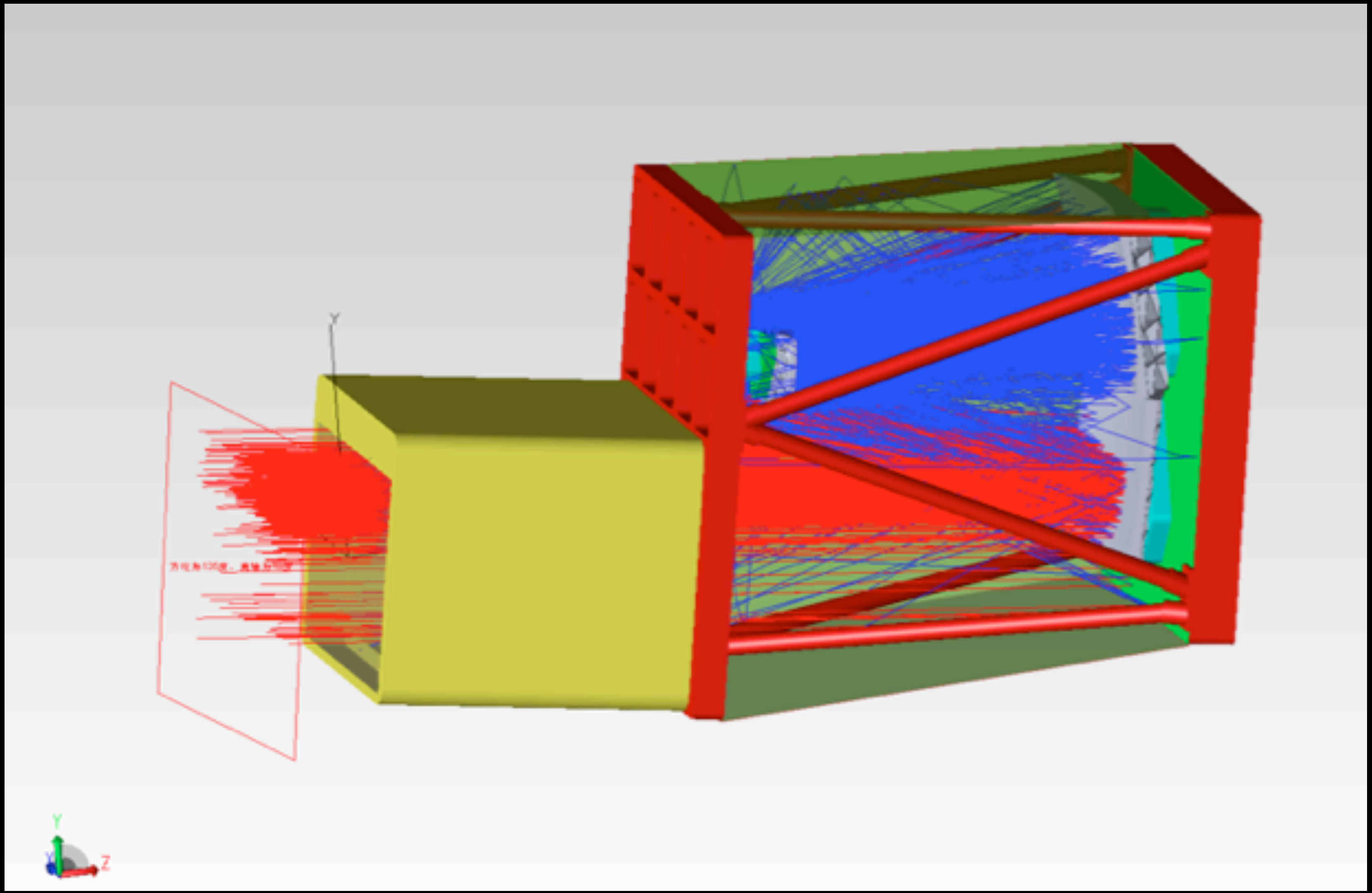


Structure Parts	Quantity	Material	Weight
Primary Mirror	1	SiC	10.8kg
Secondary Mirror	1	SiC	3.6 kg
Tertiary Mirror	1	SiC	10.8 kg
Support of Primary Mirror	1	Invar 4J32	1.2 kg
Support of Secondary Mirror	1	Invar 4J32	0.3 kg
Support of Tertiary Mirror	1	Invar 4J32	1.2 kg
Truss Support	8	Carbon Fiber	10.2 kg
Mounting Structure of Primary Mirror and Tertiary Mirror	1	Silicon Aluminum alloy	10.5 kg
Mounting Structure of Secondary Mirror	1	Silicon Aluminum alloy	4.8 kg
External Baffle	1	Composite Carbon Fiber	2.4 kg
Radiant Cooler and CCD	1	Aluminum alloy	4.8 kg
Surrounding Plates	4	Aluminum Honeycomb Plate	4.8 kg
Thermal controlling system	1	Thermal coating	2.4 kg
Total		67.8kg	

Straylight analysis

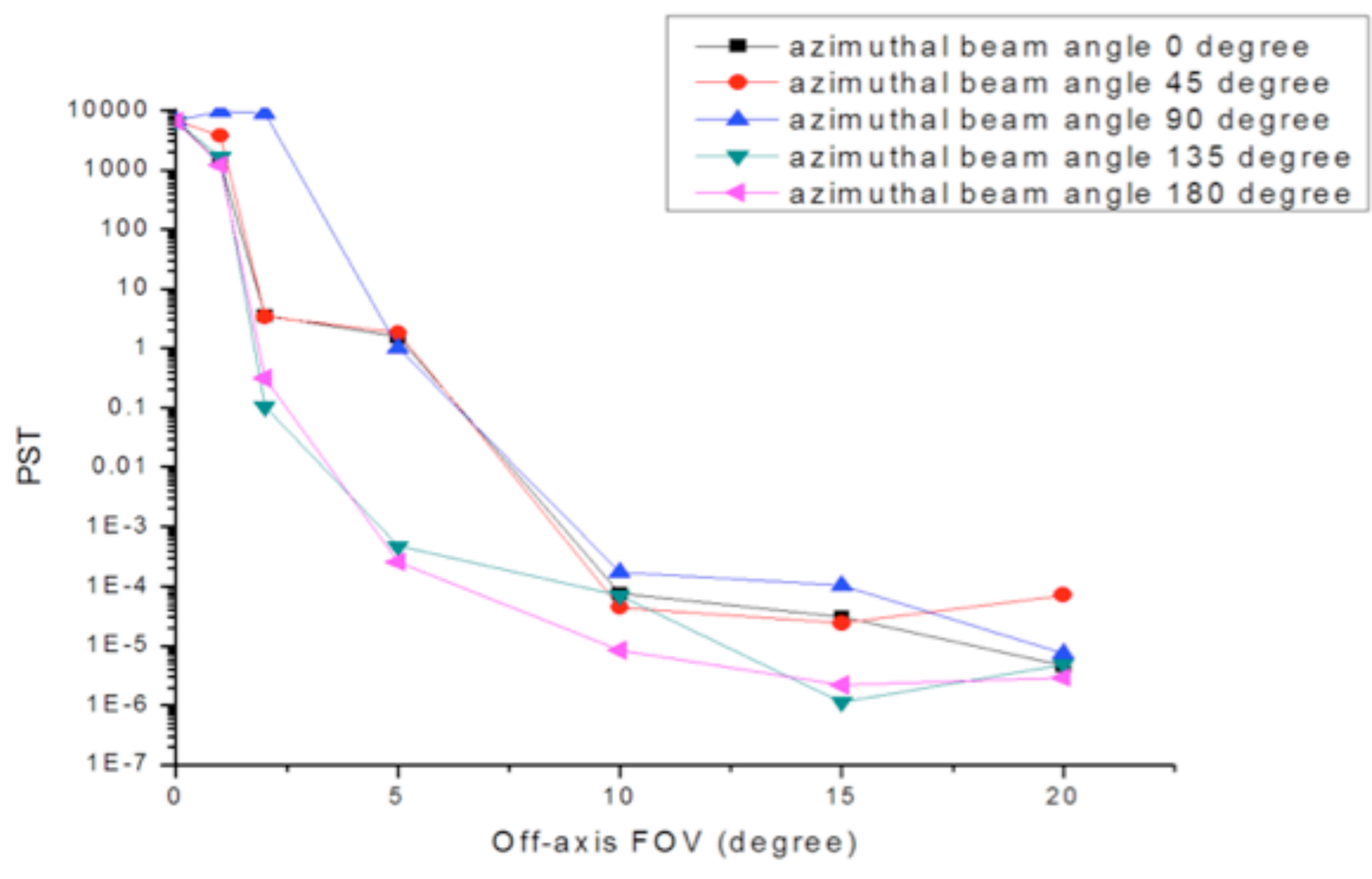


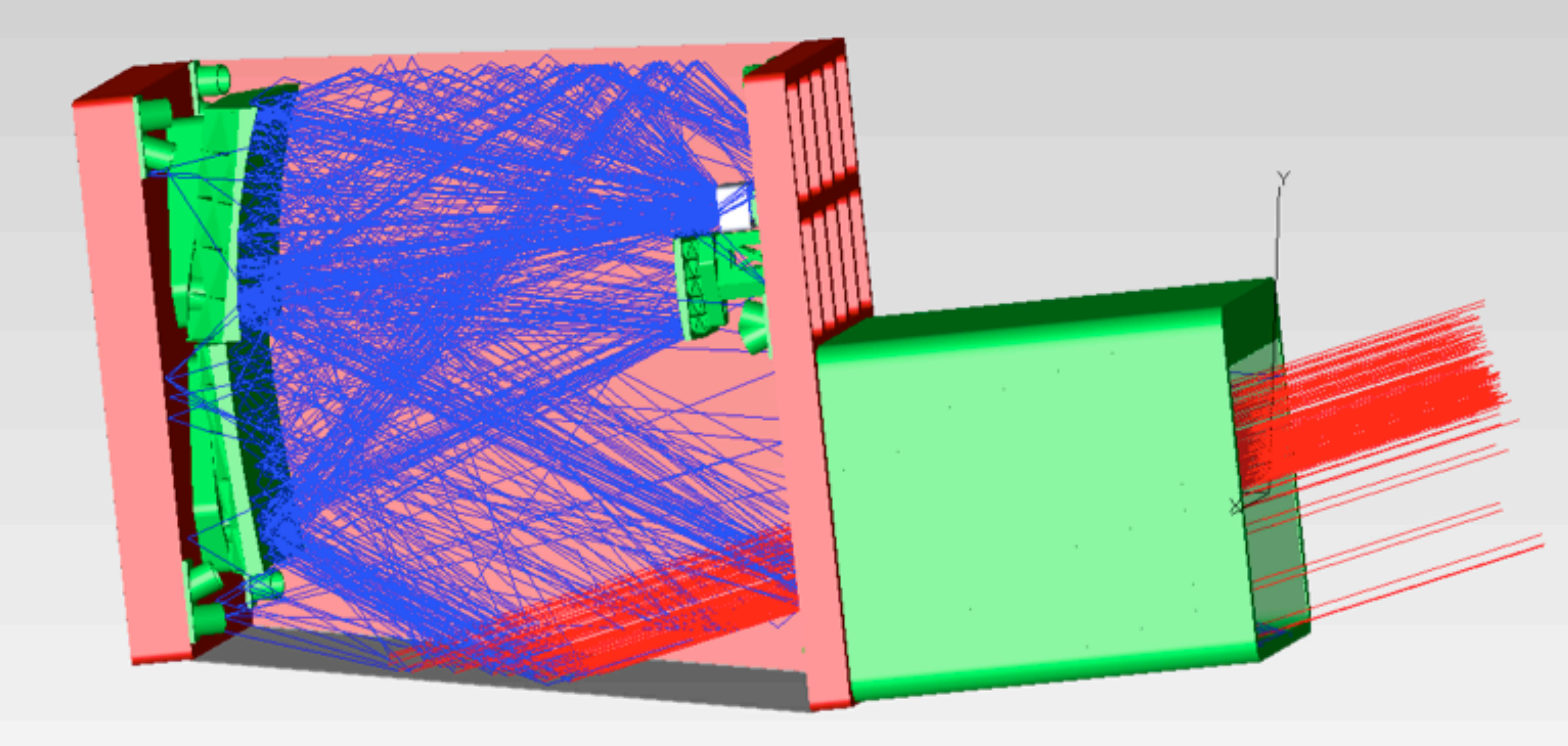
Items	Absorption	Mirror reflection	Mirror refraction	Scatter
mechanical arm	0.095	0.01	0	0.04
Optical mirror face	0.05	0.9487	0	0.0013
The edge of reflector and back face	0.1	0.05	0	0.85



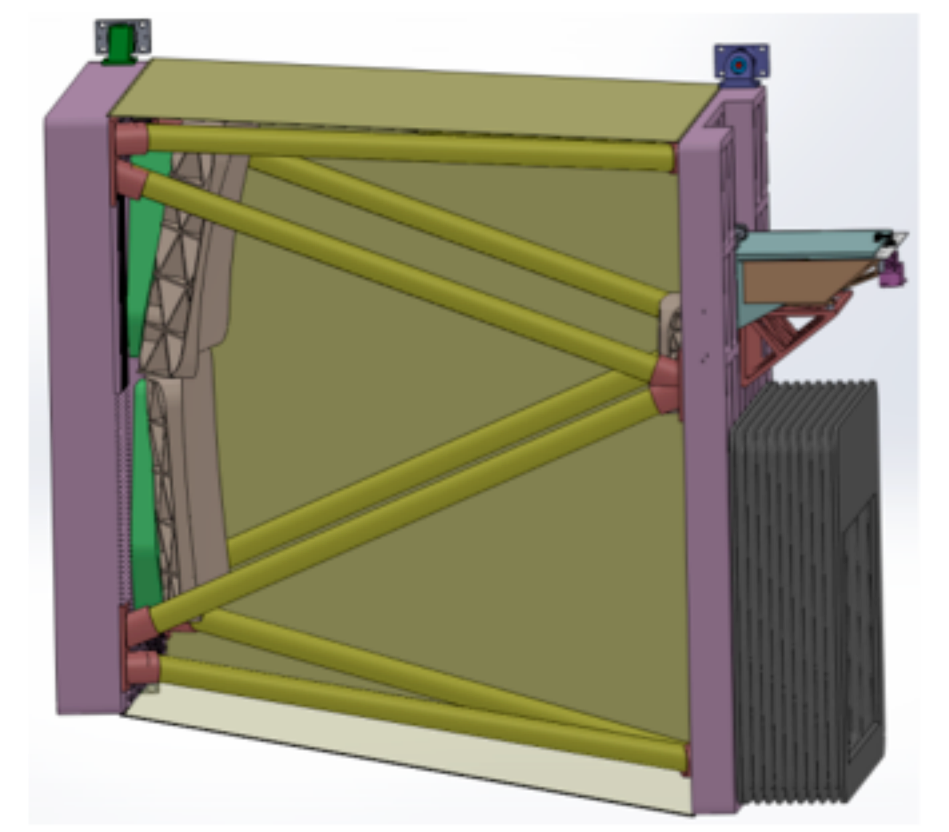
Stringent limit to straylight within 20°

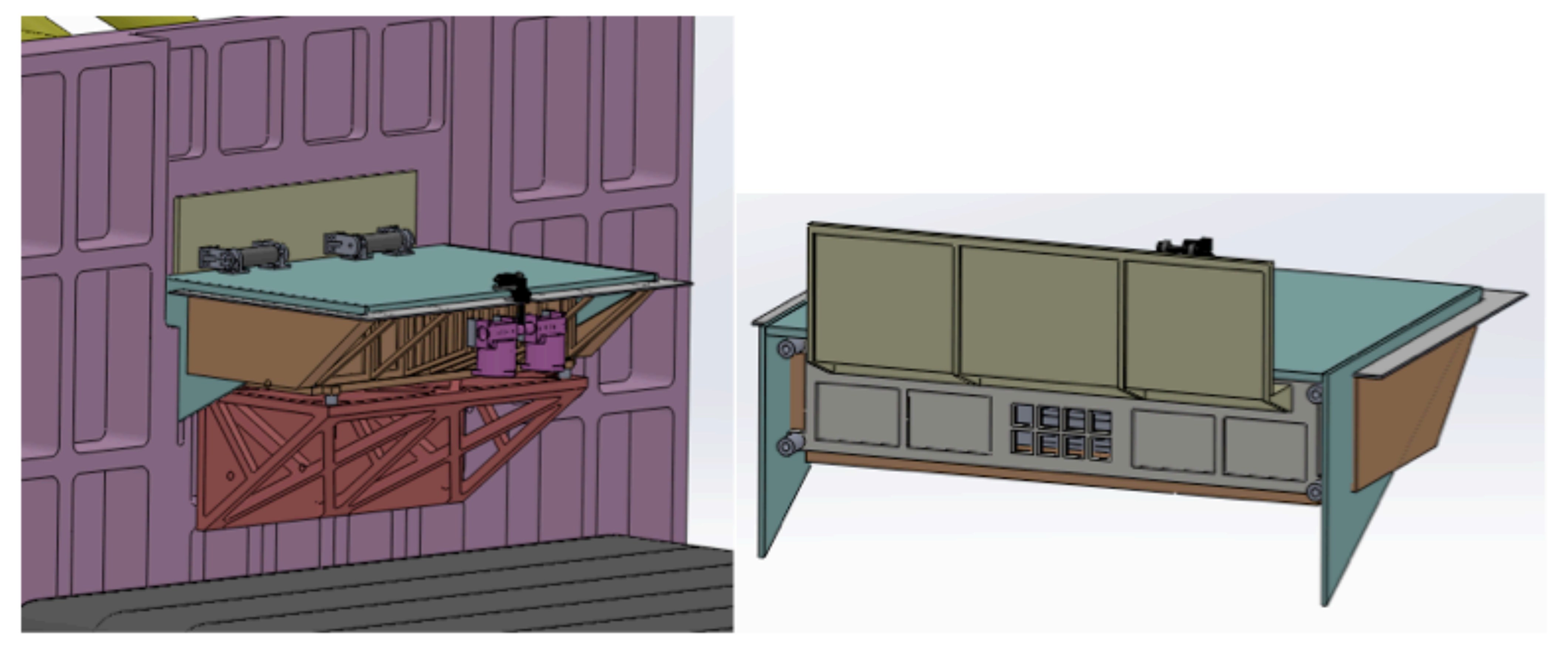
⇒ External pyramidal pop-up extendable baffle



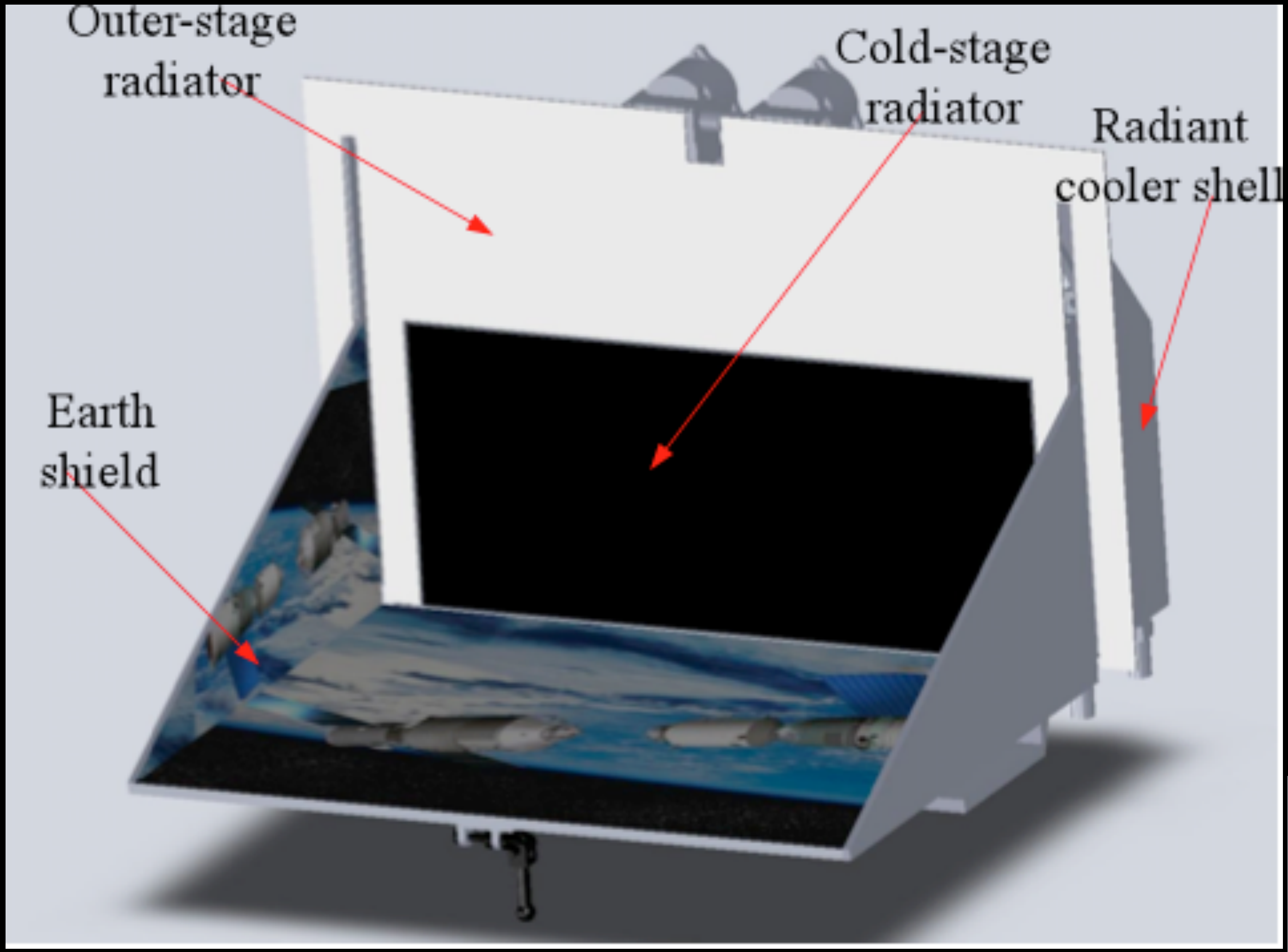


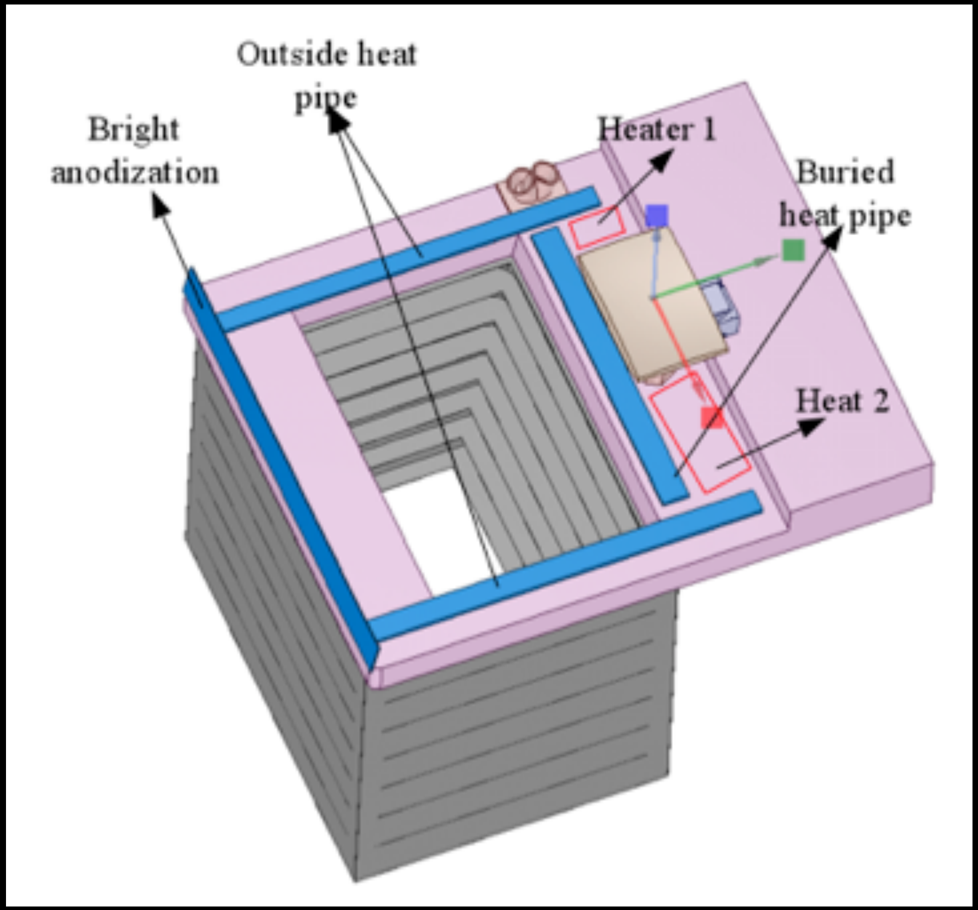
Passive cooling of the FPA

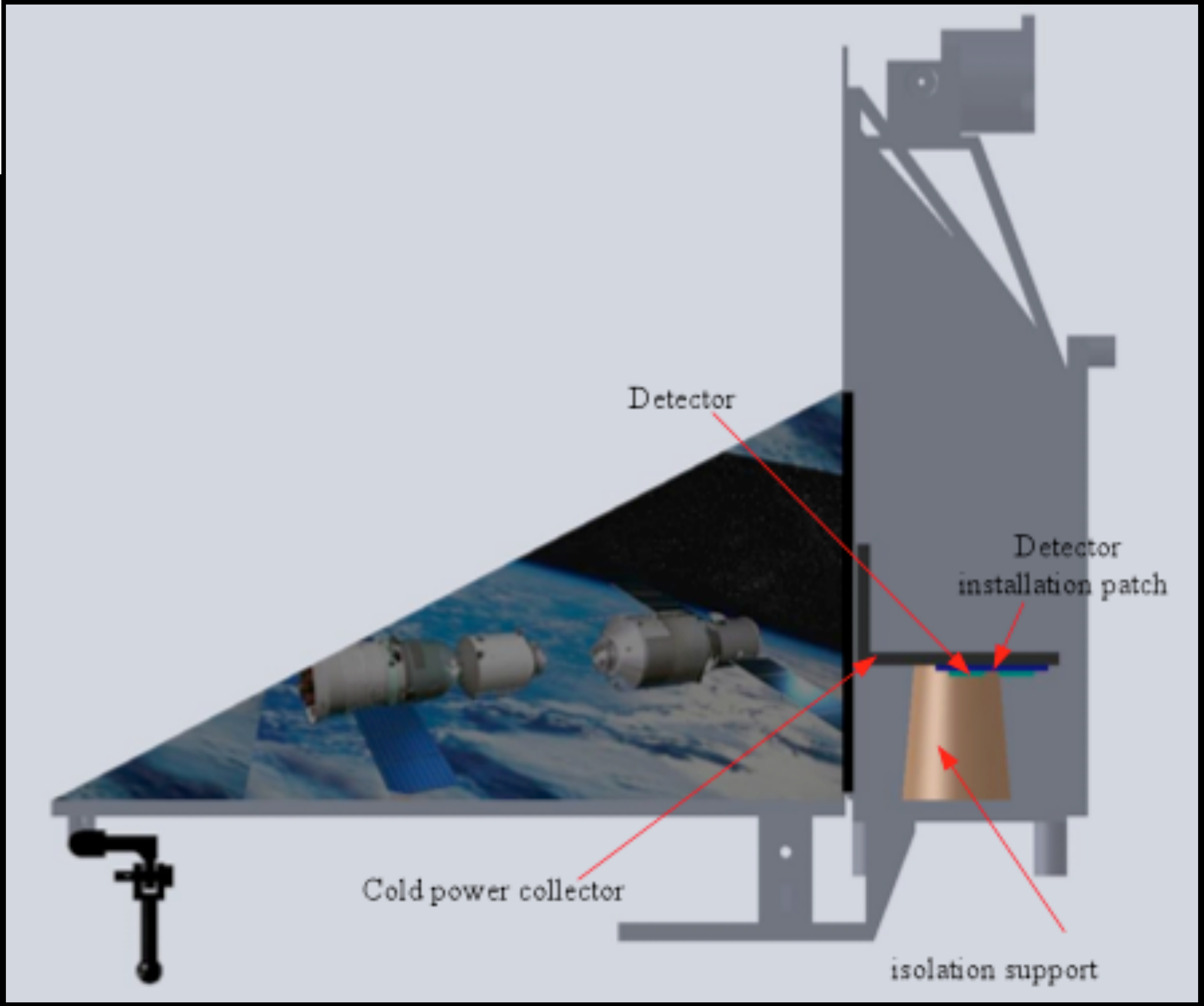




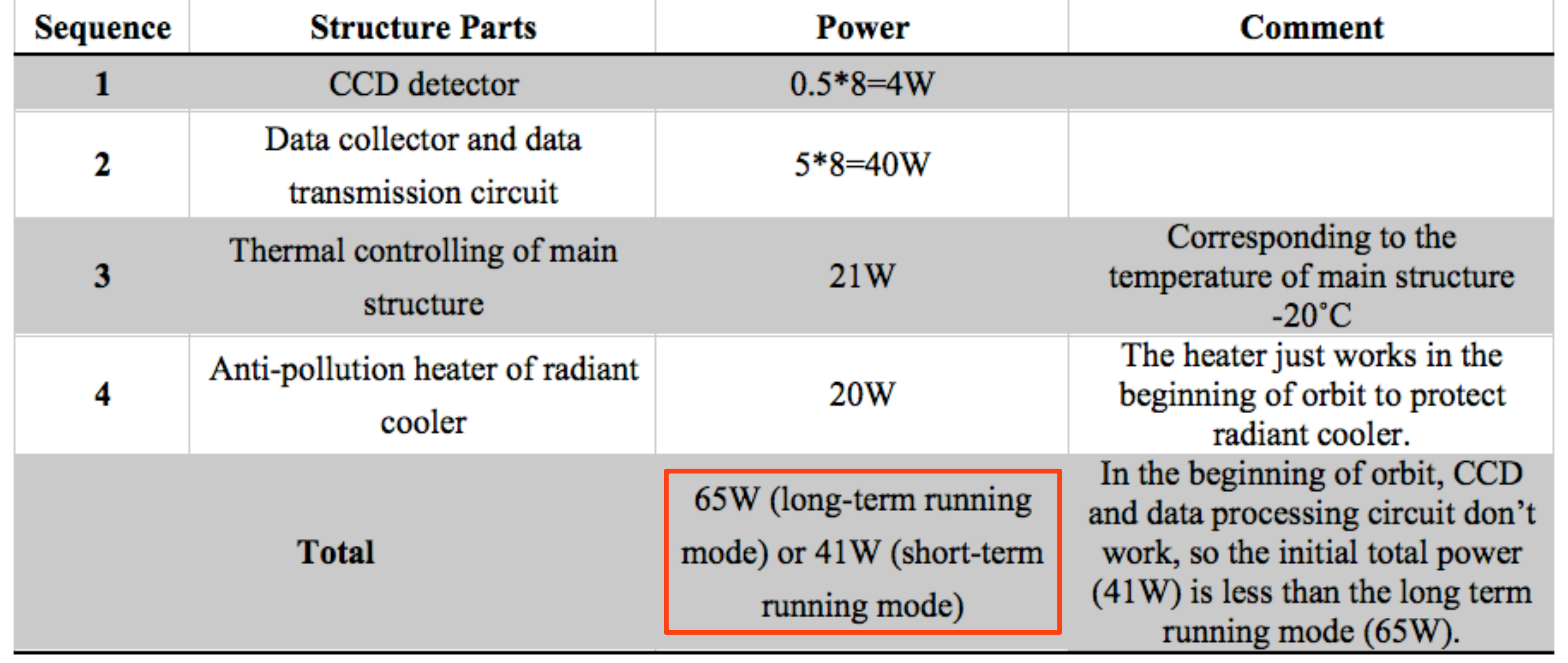
Passive cooling of the FPA (TRL9)







Power consumption budget



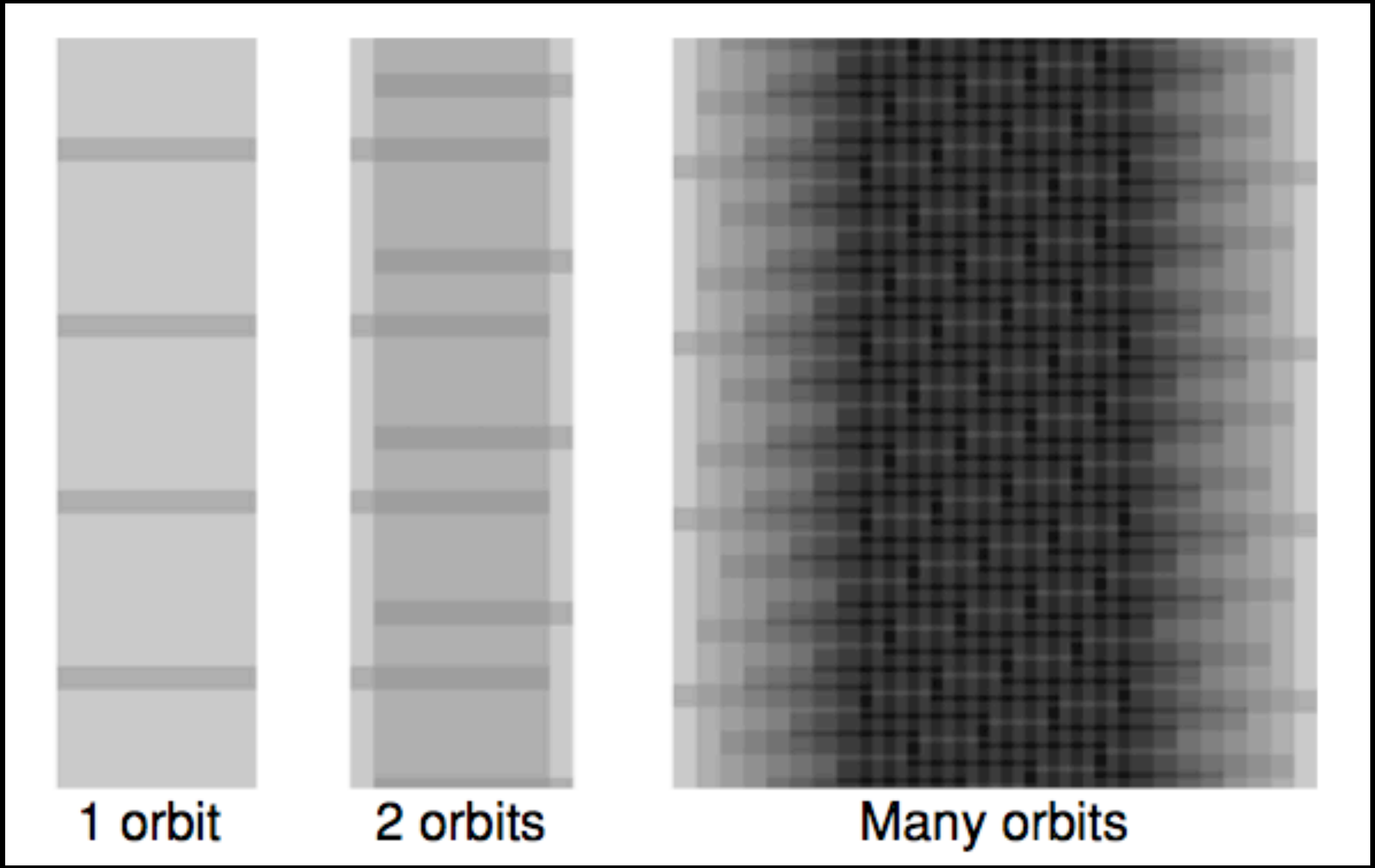
Sequence	**Structure Parts**	**Power**	**Comment**
1	CCD detector	0.5*8=4W	
2	Data collector and data transmission circuit	5*8=40W	
3	Thermal controlling of main structure	21W	Corresponding to the temperature of main structure -20°C
4	Anti-pollution heater of radiant cooler	20W	The heater just works in the beginning of orbit to protect radiant cooler.
Total		65W (long-term running mode) or 41W (short-term running mode)	In the beginning of orbit, CCD and data processing circuit don't work, so the initial total power (41W) is less than the long term running mode (65W).

+10% contingency: 72 W (peak)

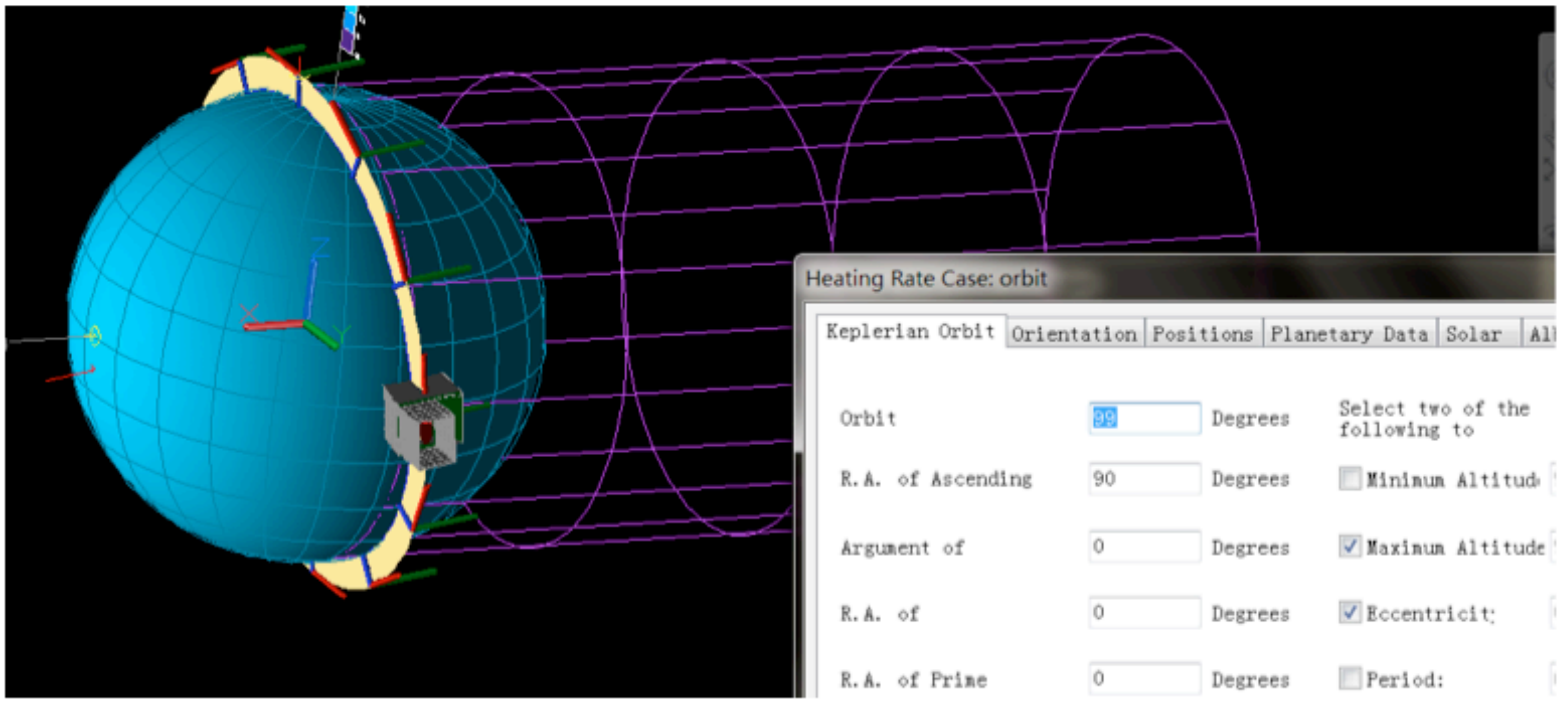
Orbit

Sun-Synchronous Orbit

- 900 km, 98° inclination, LTAN 6h
- precession 360°/year
- pointing ⊥ Sun-Earth direction avoiding Earthshine
- inertial great circle drift scan with centre at the Sun
- (similar to COBE, WISE, PROBA-V)



Thermal analysis



Orbit 99 Degrees

R. A. of Ascending 90 Degrees

Argument of 0 Degrees

R. A. of 0 Degrees

R. A. of Prime 0 Degrees

Select two of the following to

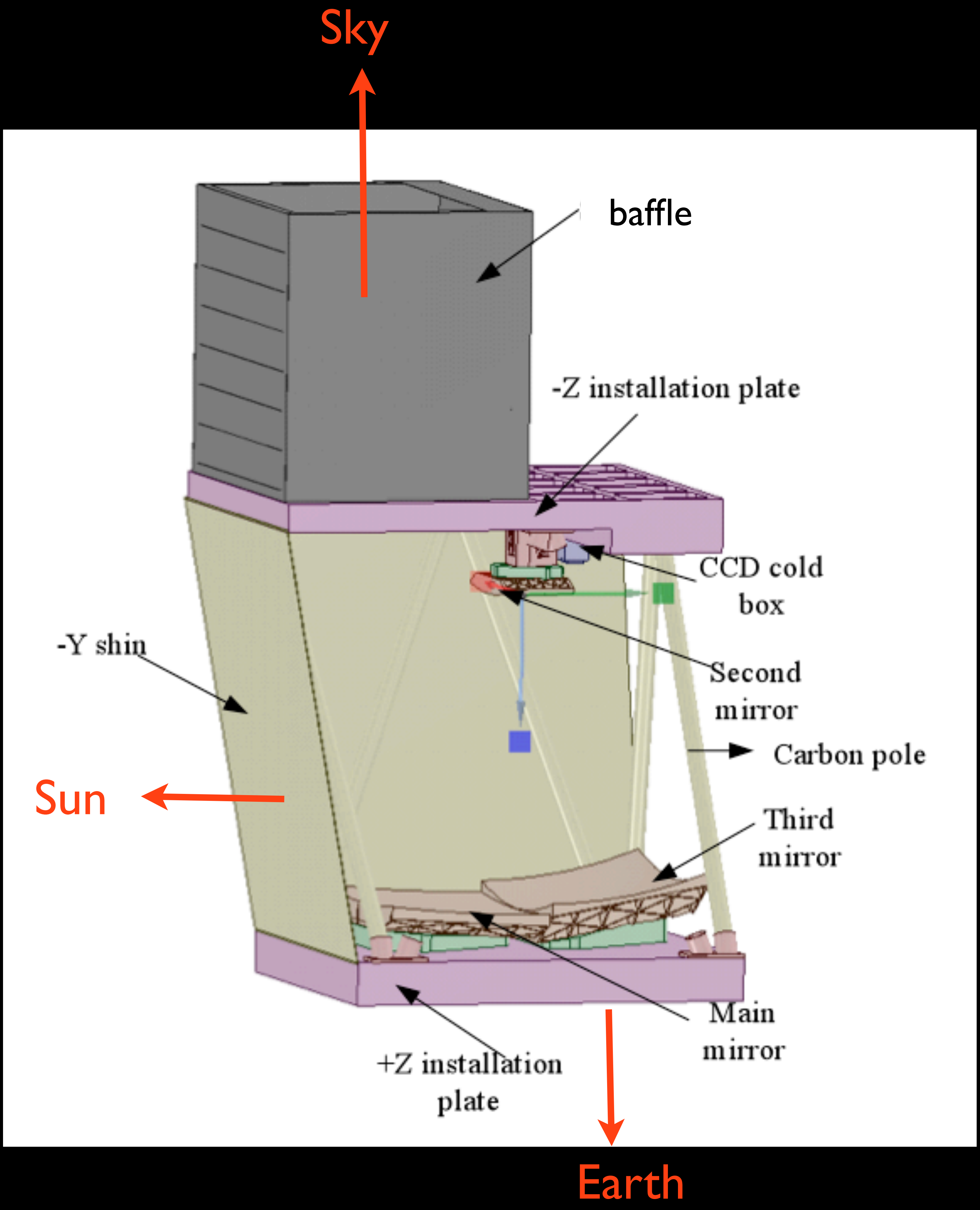
☐ Minimum Altitud

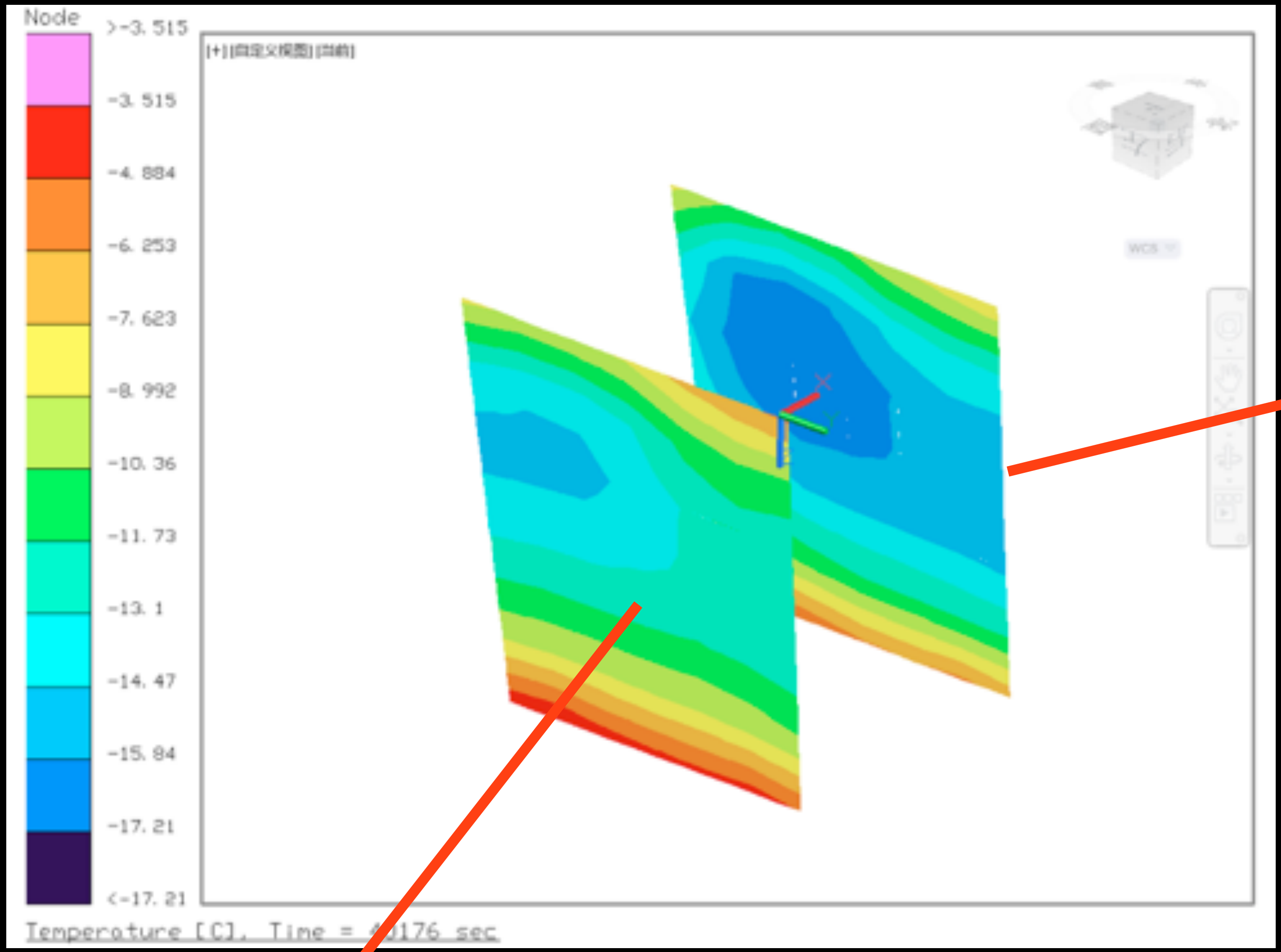
☑ Maximum Altitude

☑ Eccentricit

☐ Period:

Thermal analysis

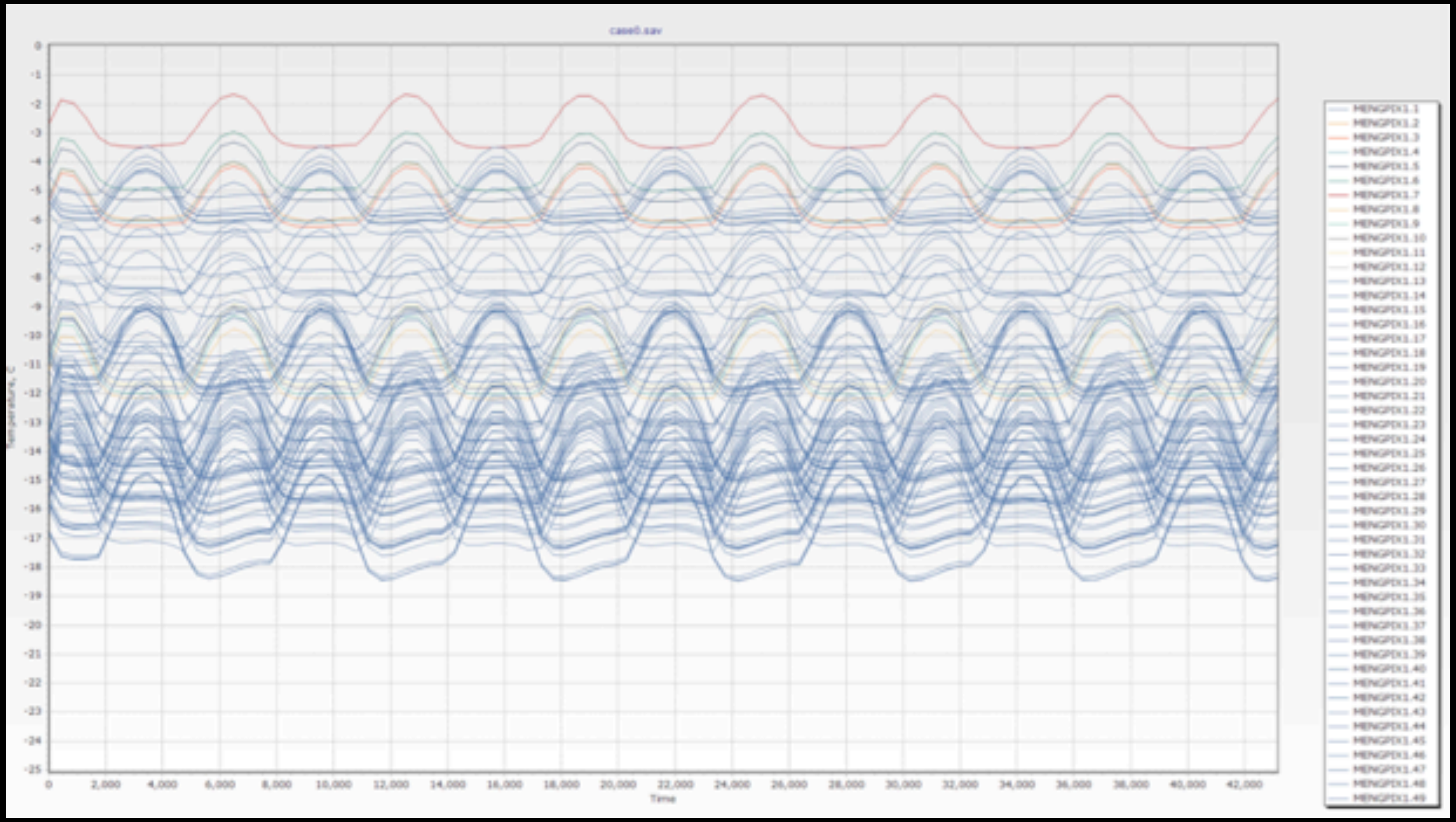


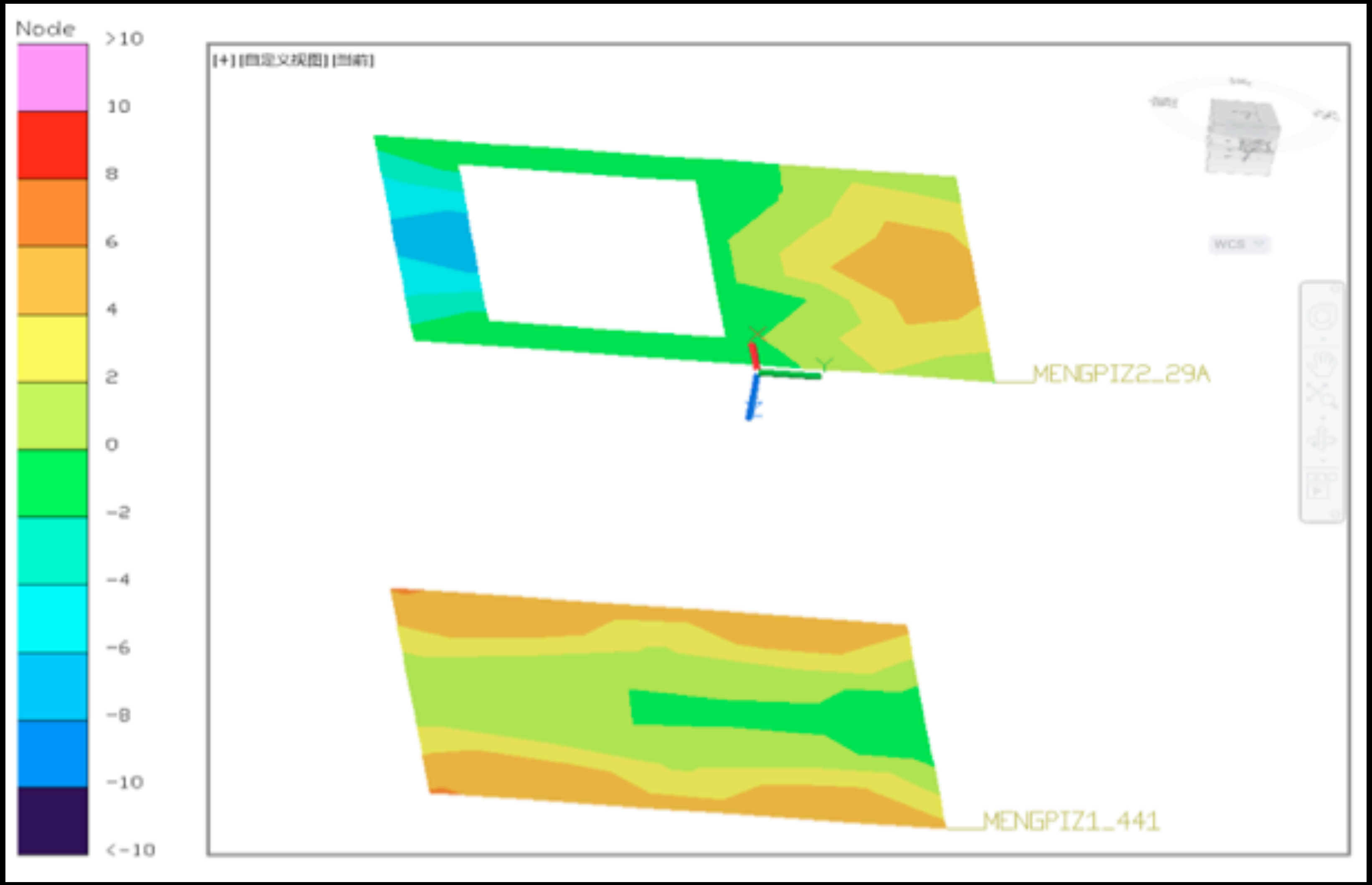


Temperature gradients

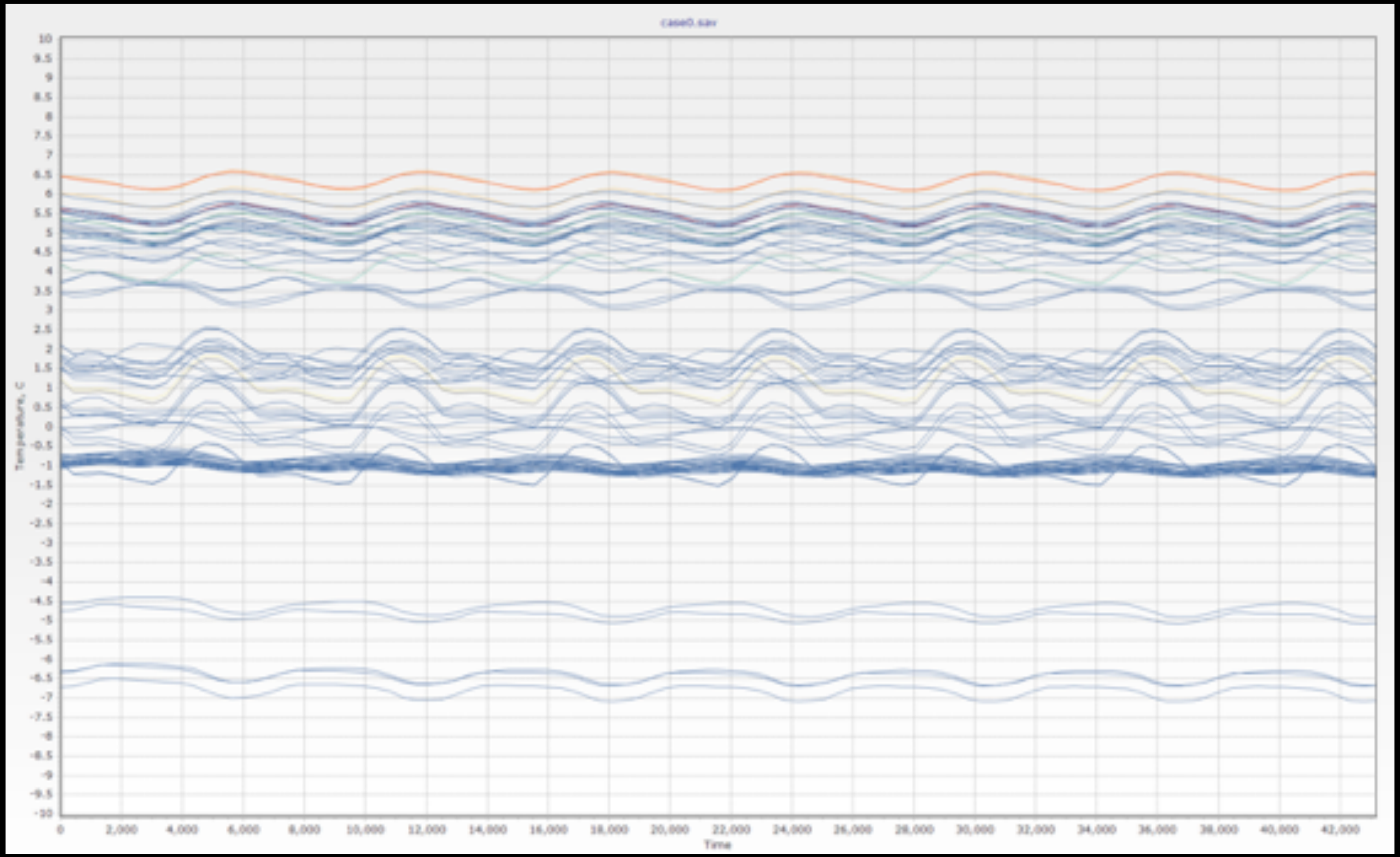
opposite to Sun

face to Sun
−18 °C to −2 °C



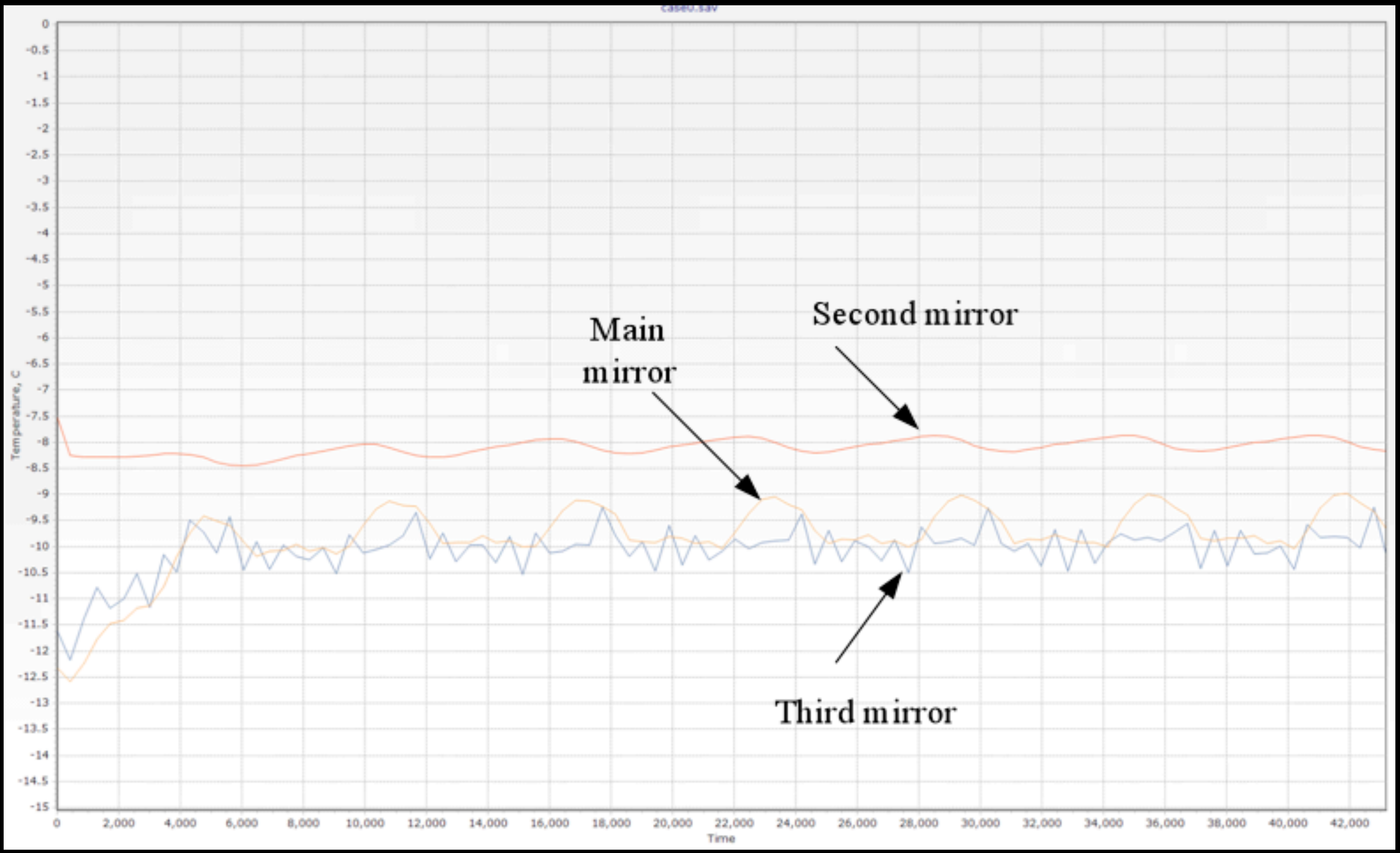


Temperature gradients
in zenith (sky)
and nadir (Earth)
directions
0 °C to +7 °C

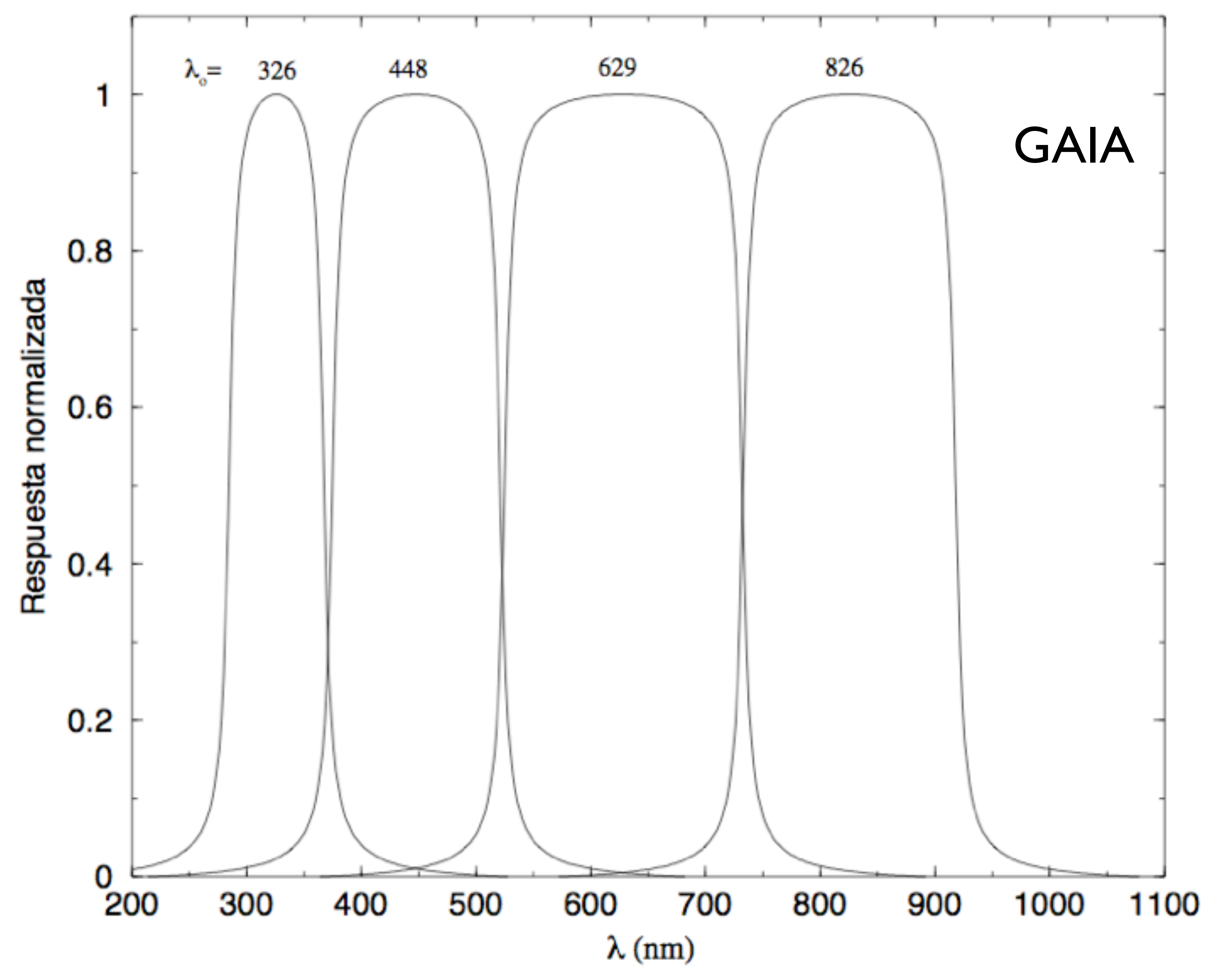


Temperature stability of the mirrors

M1 : 1°C   M2 : 0.5°C   M3 : 1°C
(peak to valley)

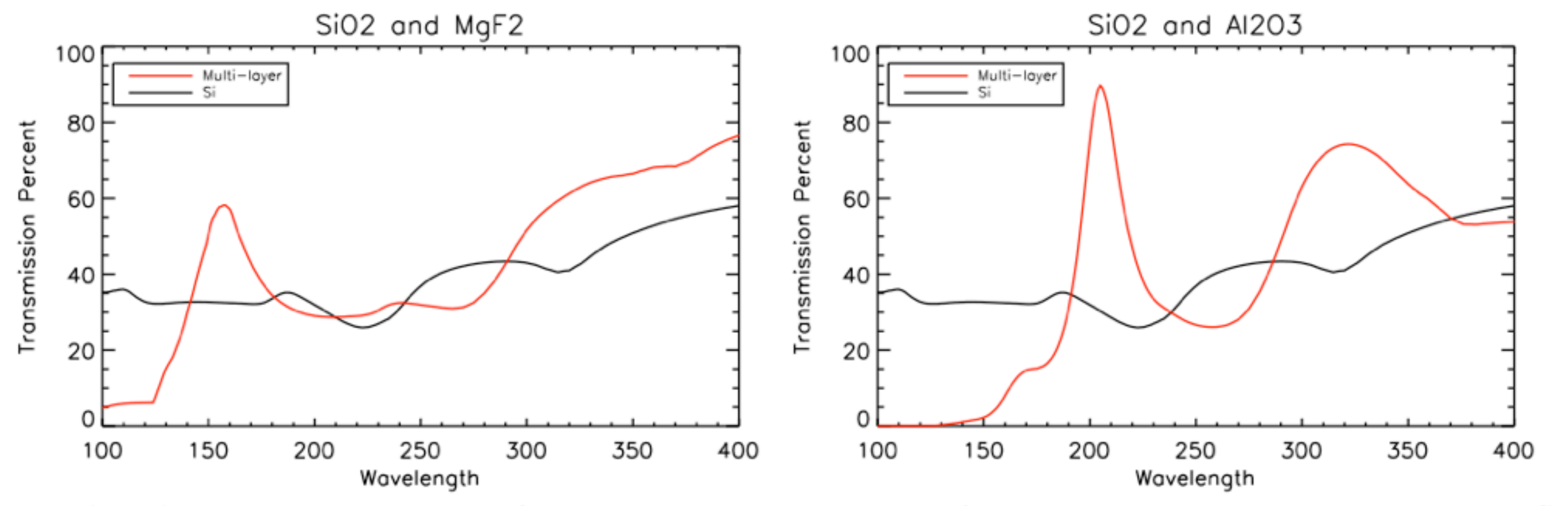


The MESSIER system of filters



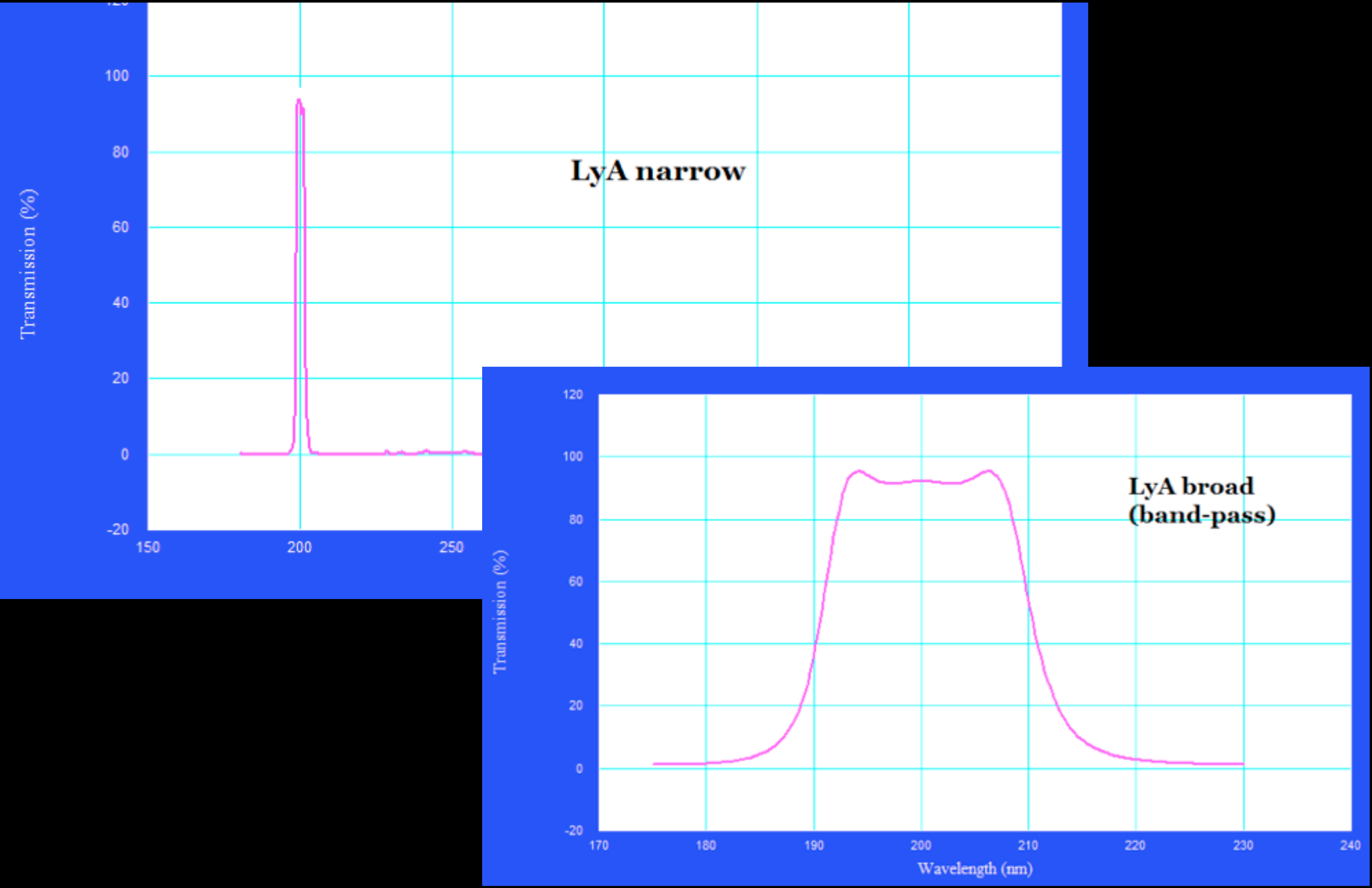
The MESSIER system of filters

New generation of UV detectors

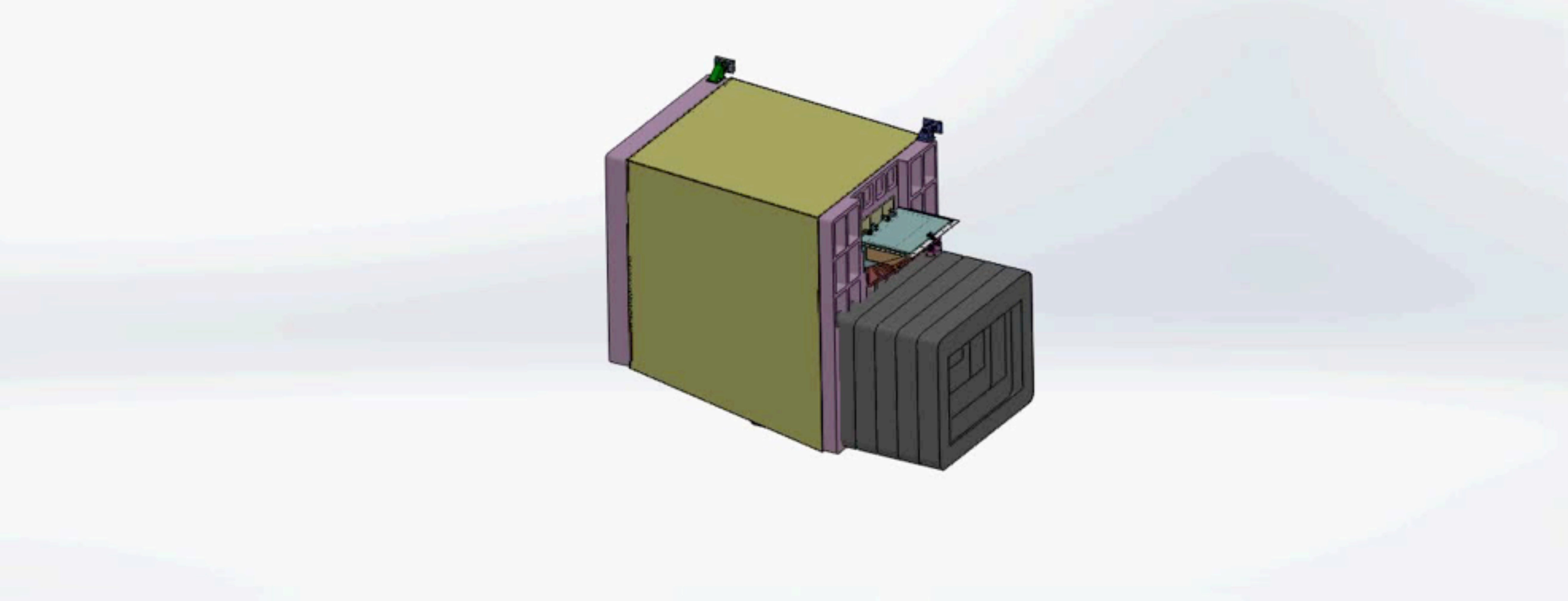


New AR coatings allow to reach a quantum efficiency of 80-90%
Atomic Layer Deposition: multi-layer (JPL/Columbia)
ITAR free
Qualified during the FireBall-2 balloon mission in 2015 (Caltech/Marseille)

The MESSIER system of filters



Current design of MESSIER within the PROBA-V platform



Mass budget : 67.8 kg (+10% contingency)
Power budget : 65 W (+10% contingency)

Mission concept (continued)

- Detectors and filters

  optimised QE > 80% for each UV/optical band (ITAR free)

  time delay integration controllers + data flow to ground

- Orbit

  SSO 700-900 km, precession 360°/year

  pointing ⊥ Sun-Earth direction avoiding Earthshine

  great circle drift scan with centre at the Sun

- Ground segment

  Small antenna network in China and Europe

  Two data analysis centres (Terapix legacy) + LSST pipeline

- Mission lifetime

  3 to 5 years

  full sky coverage to SB > 32 (optical) → 37 (UV) mag arcsec^{-2}

Issues

- Deployable pop-up baffle
  - CIBER legacy TBC

- Charge Transfer Inefficiency degradation
  - Realistic simulations of final photometric quality (WFC3)
  - 2021: solar minimum of activity
  - OMERE simulations

- Ground segment
  - Data flow to the ground (70 Gb/orbit)
  - Flash memory (120 Gb)
  - Onboard lossless compression (Euclid)
  - Open source pipeline (LSST)
  - Proper foreground subtraction (Planck)

MESSIER
Unveiling the ultra-low surface brightness universe

Fruitful European-Chinese collaboration
built upon strong joint heritage
(LUT, Gaia, PROBA)

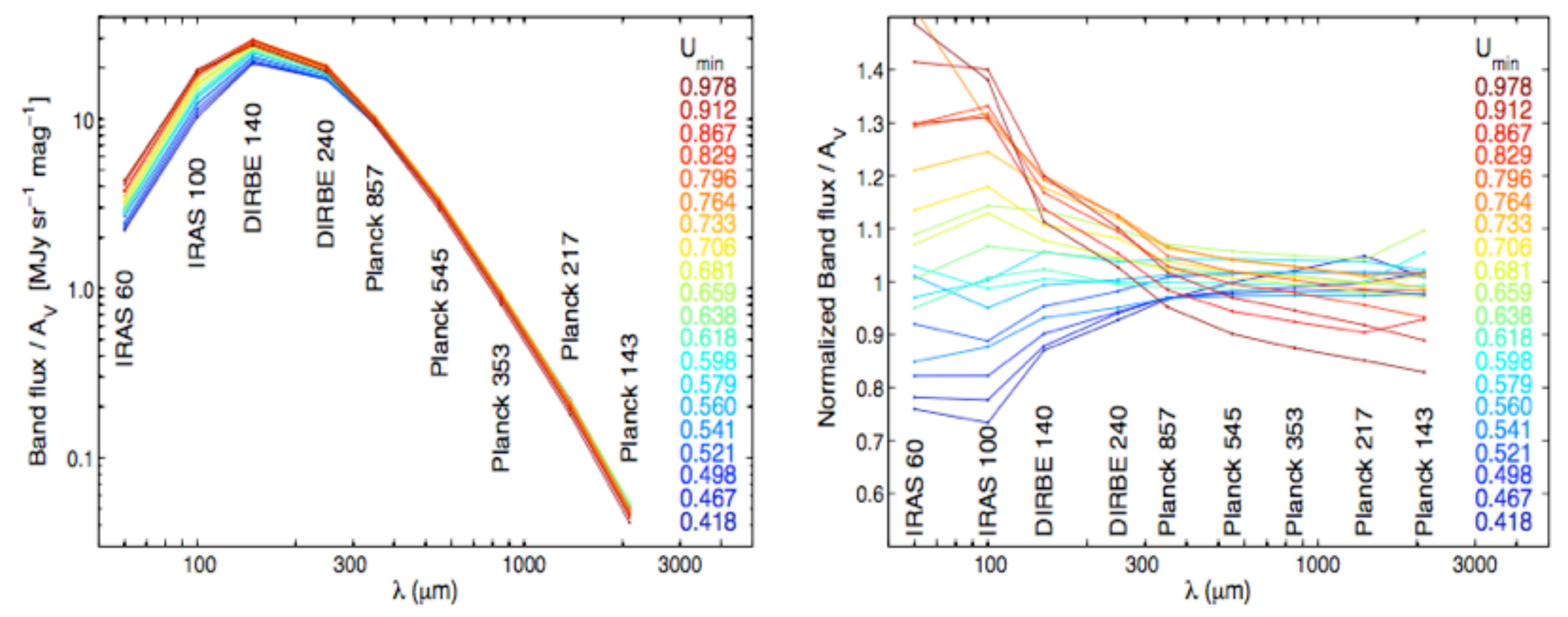
The last unexplored niche
remaining in observational space

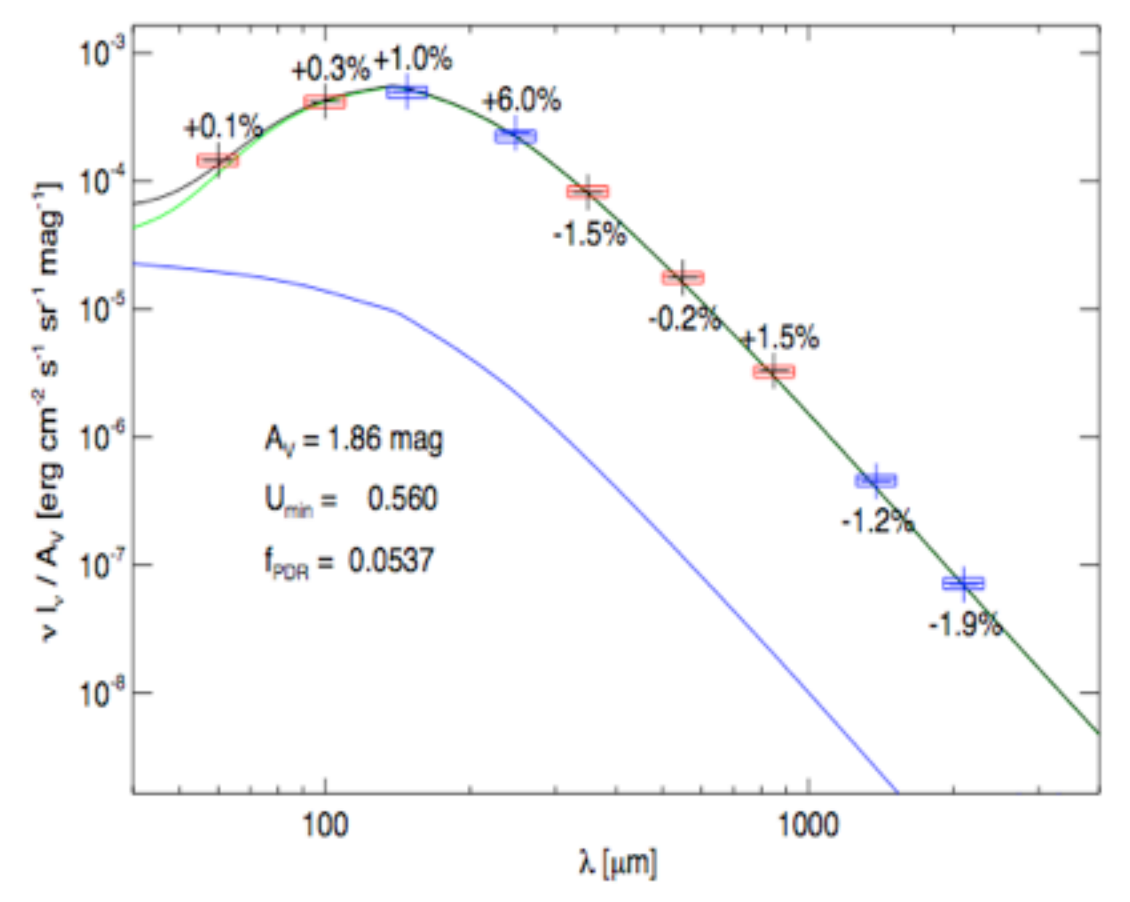
Unique scientific returns in
cosmology, galaxy evolution, stellar physics

Legacy value: reference catalogue
for multi-band optical/UV photometry

EXTRA

Subtraction of the dust foreground



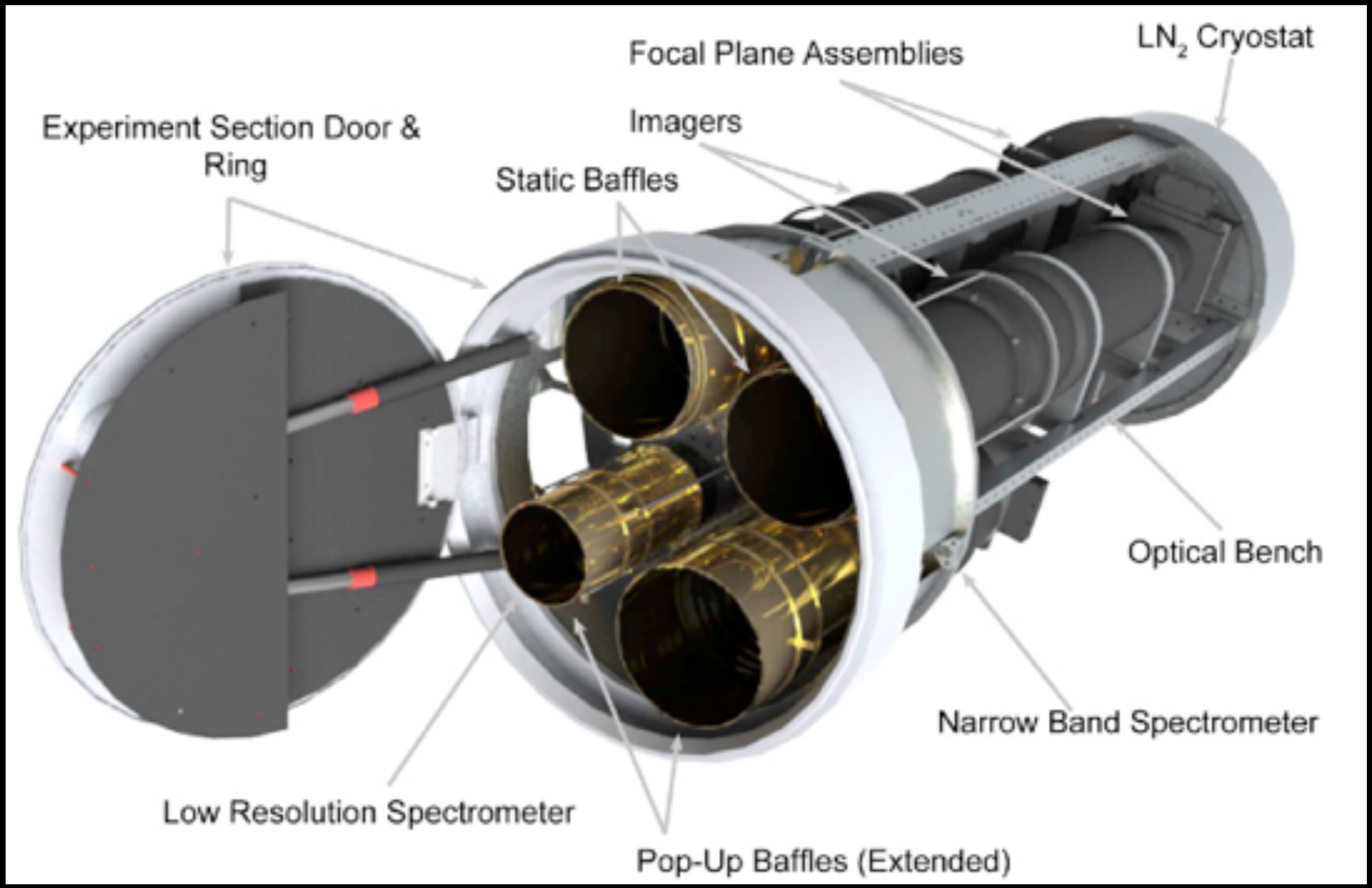


Use Planck+IRAS+WISE+DIRBE + MESSIER UV/VIS constraints on albedo and size distribution of dust grains

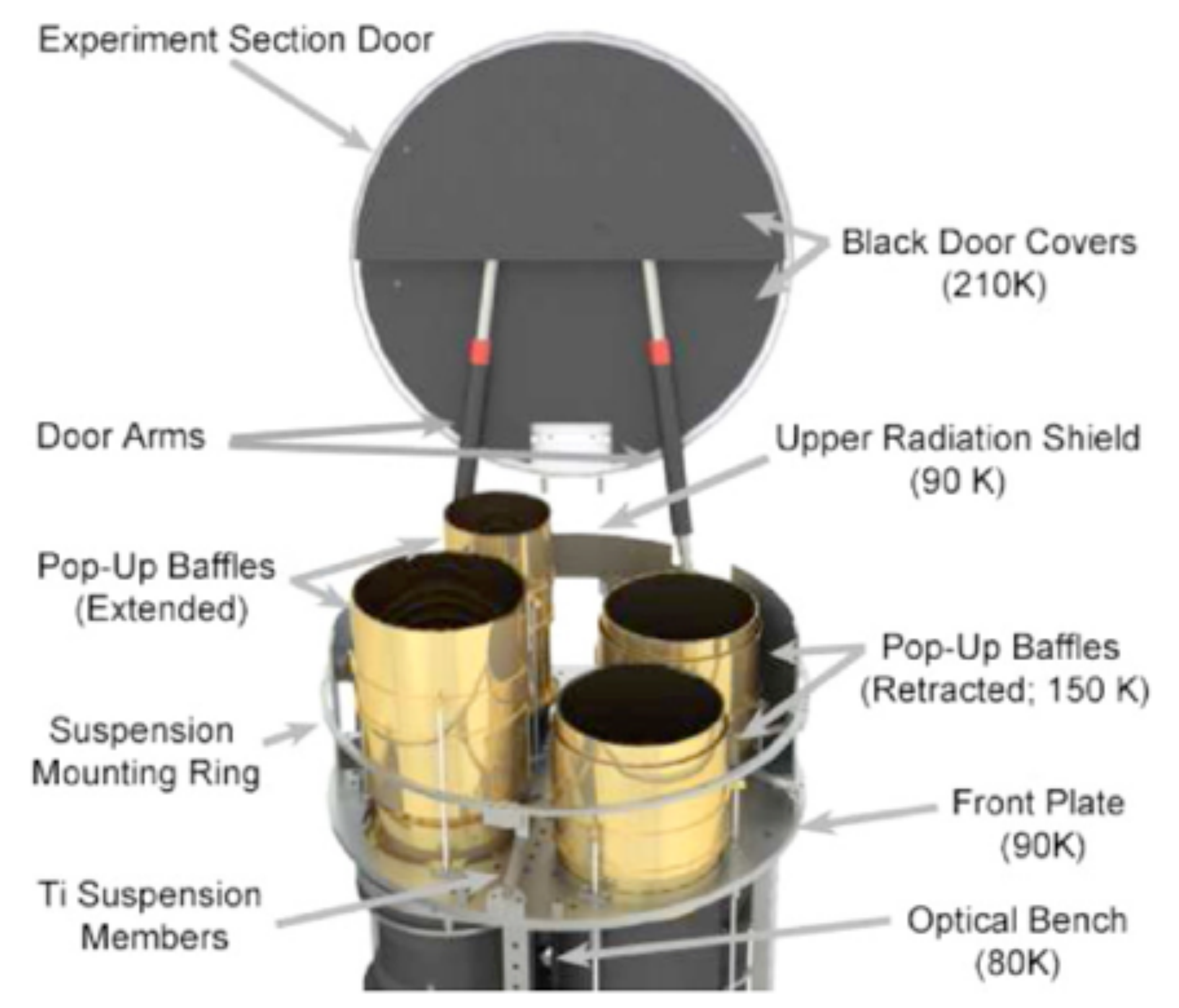
Planck XXIX
arXiv:1409.2495

Pop-up baffles

Heritage from *CIBER*
Cosmic IR Background
Experiment
sounding rocket



Zemcov *et al.* (2013) ApJS 207, 31



Baffles made with Al6061
Coated with Epner Laser Black
multilayer metallic oxyde
with microdendrites
(<1% reflective)
Spring loaded / tied to door