The MESSIER orbiter

A space mission to unveil galaxy formation

David Valls-Gabaud

LERMA - Observatoire de Paris

on behalf of the *MESSIER* consortium

LPNHE

UPMC 2015 January 8

Background and timeline

- 2009 Proposal submitted to CNES
- 2013 Ranked as priority by CNES
- 2014 Budget limitations prevent phase 0 study
- 2014 Submitted to joint ESA-China S-class mission
- 2014 Selected in first (Chengdu) and second round (Copenhagen)

Europe PI : David Valls-Gabaud
China PI : Jing Yipeng + Wei Jianyan

Core science team

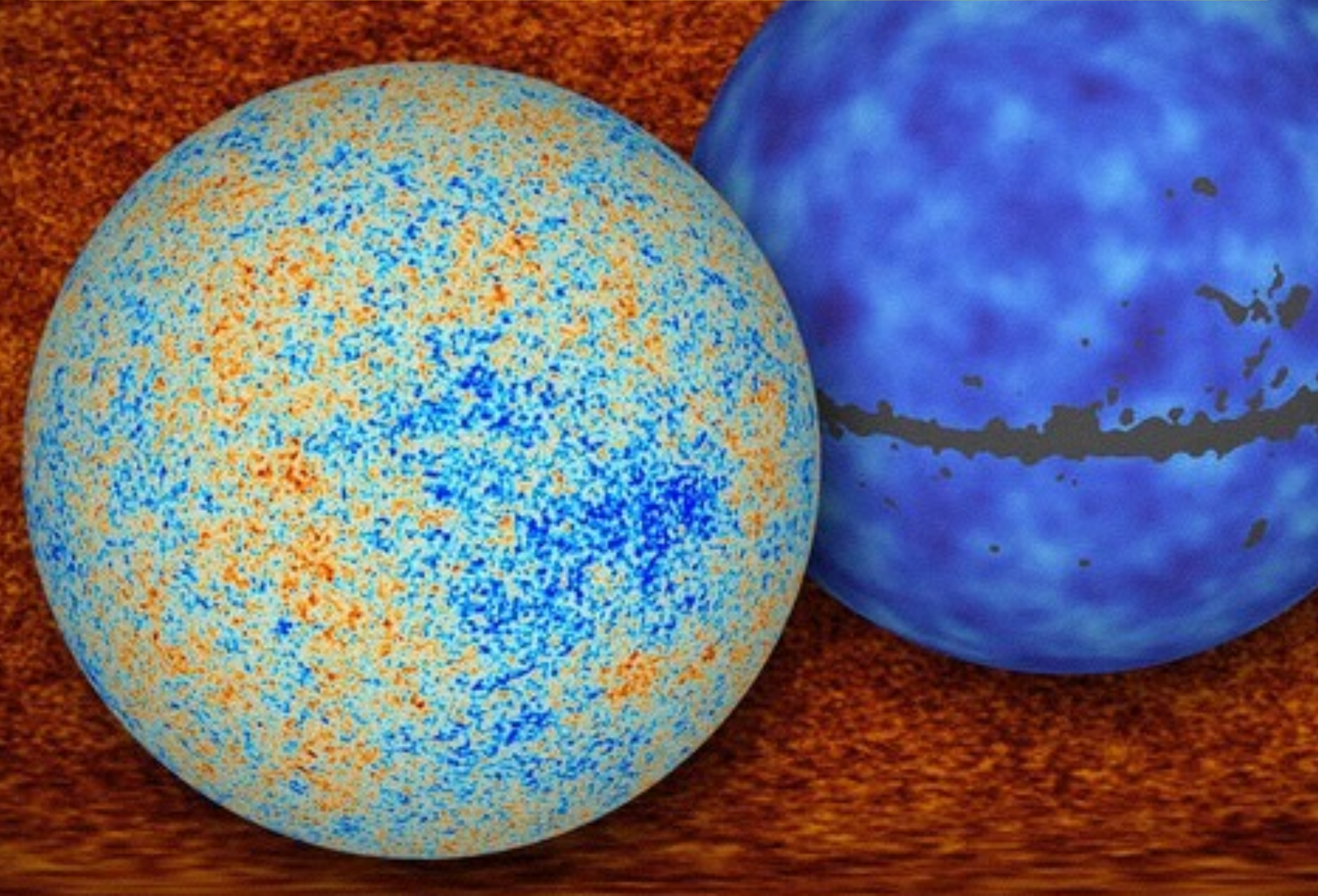
OBSPM IAP Saclay Strasbourg Marseille
Heidelberg Munich Stockholm Geneva ETHZ
Cambridge Durham UCL Cardiff Barcelona
Caltech Arizona JHU Columbia (TBC)
IHEP NAOC SITP KIAA/PKU Jiaotong SHAO
PMO Tsinghua (TBC)

Core instrumentation team

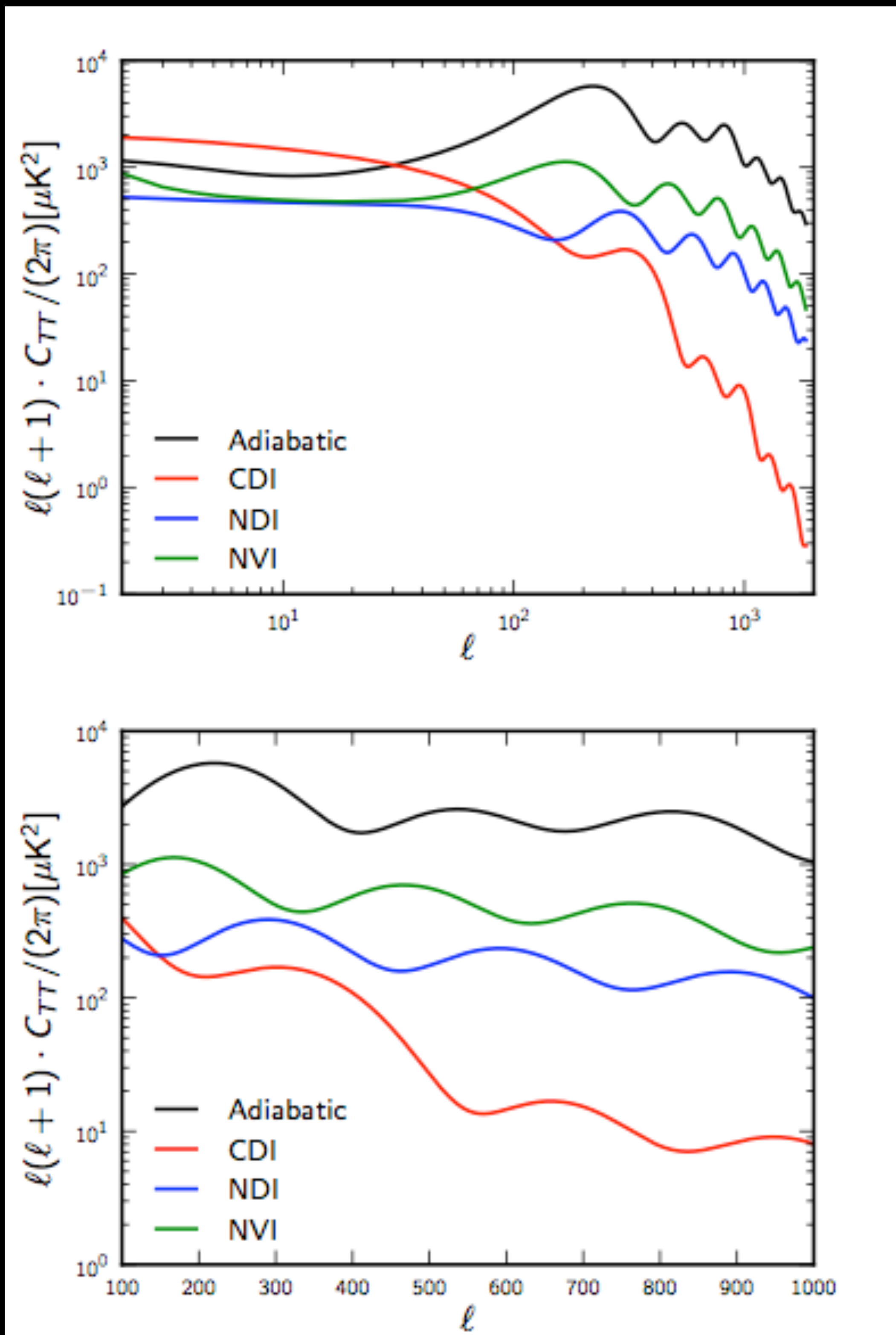
Paris Marseille NAOC SITP

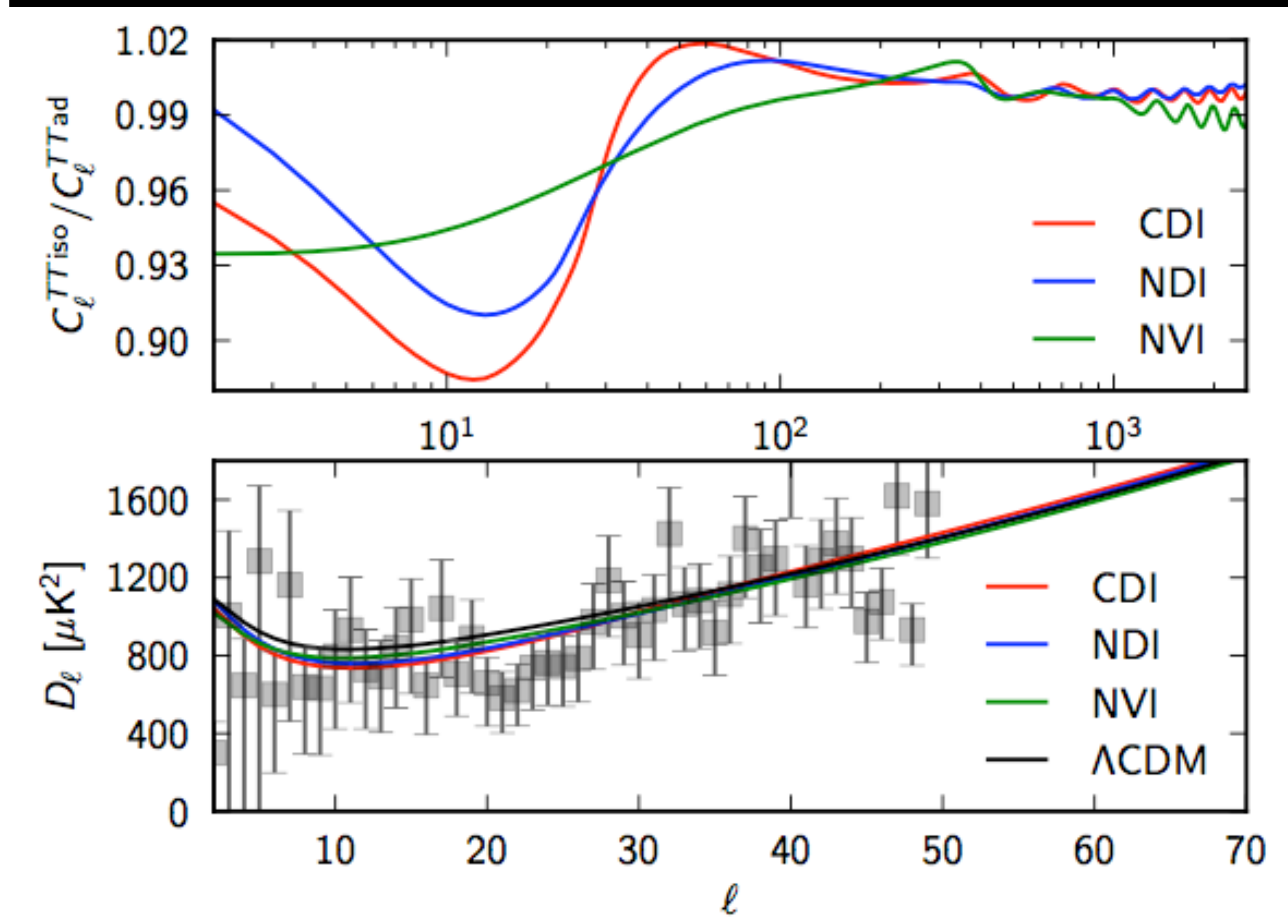
Interested parties: >190 researchers over 30 institutes

Standard cosmological model ΛCDM ... initial conditions



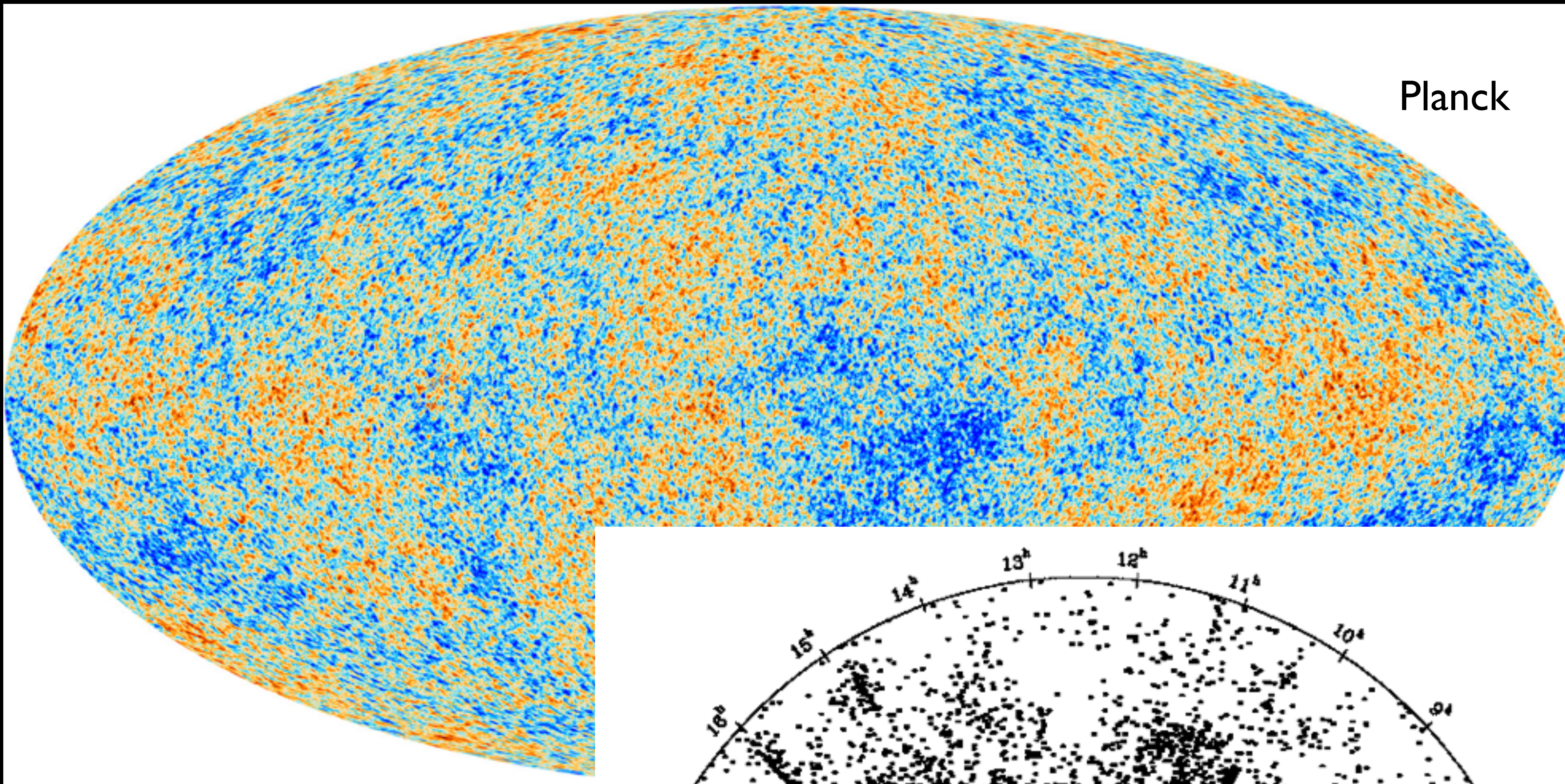
No evidence for strong isocurvature modes
⇒ fluctuations are adiabatic at 95% CL

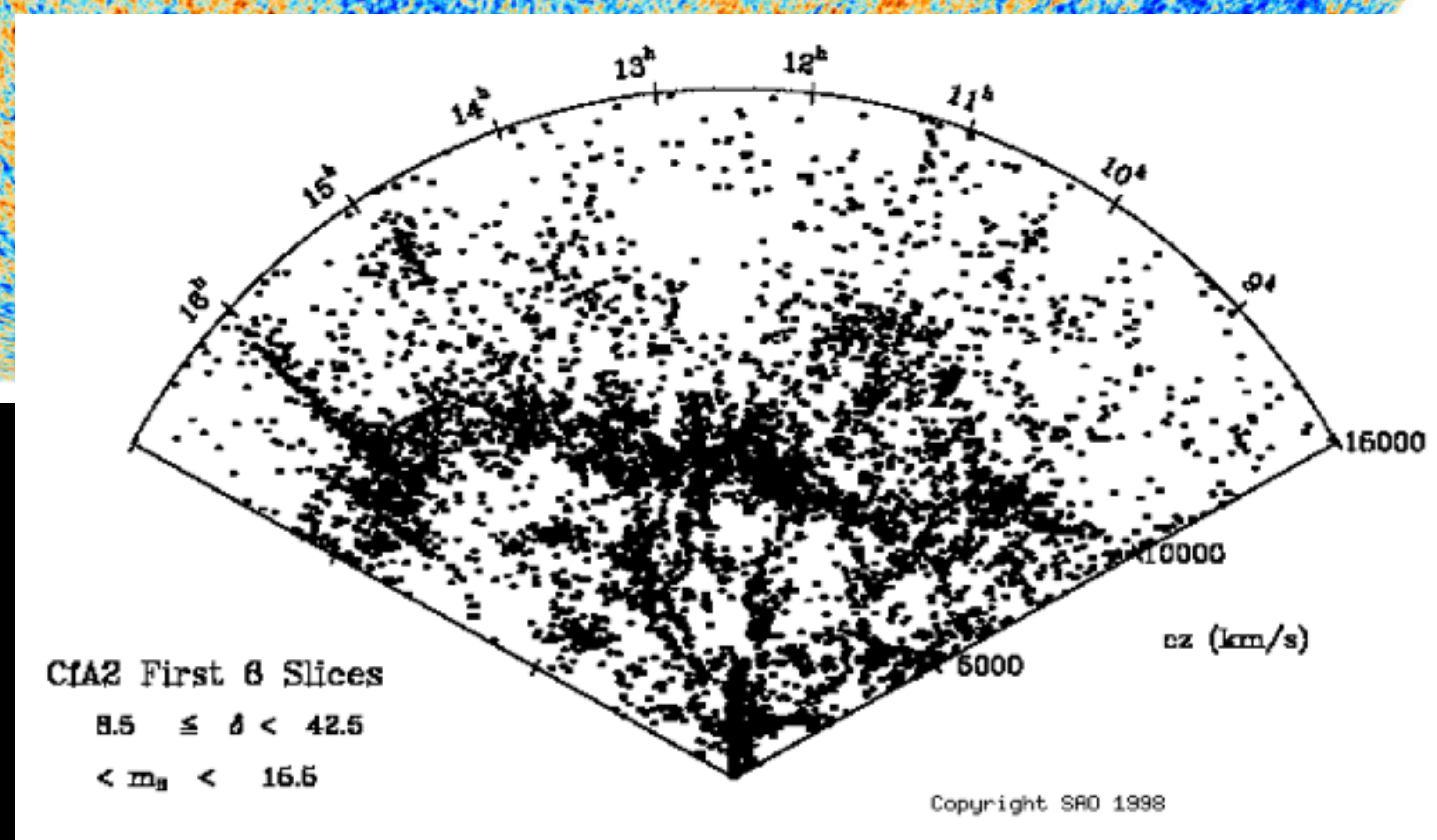




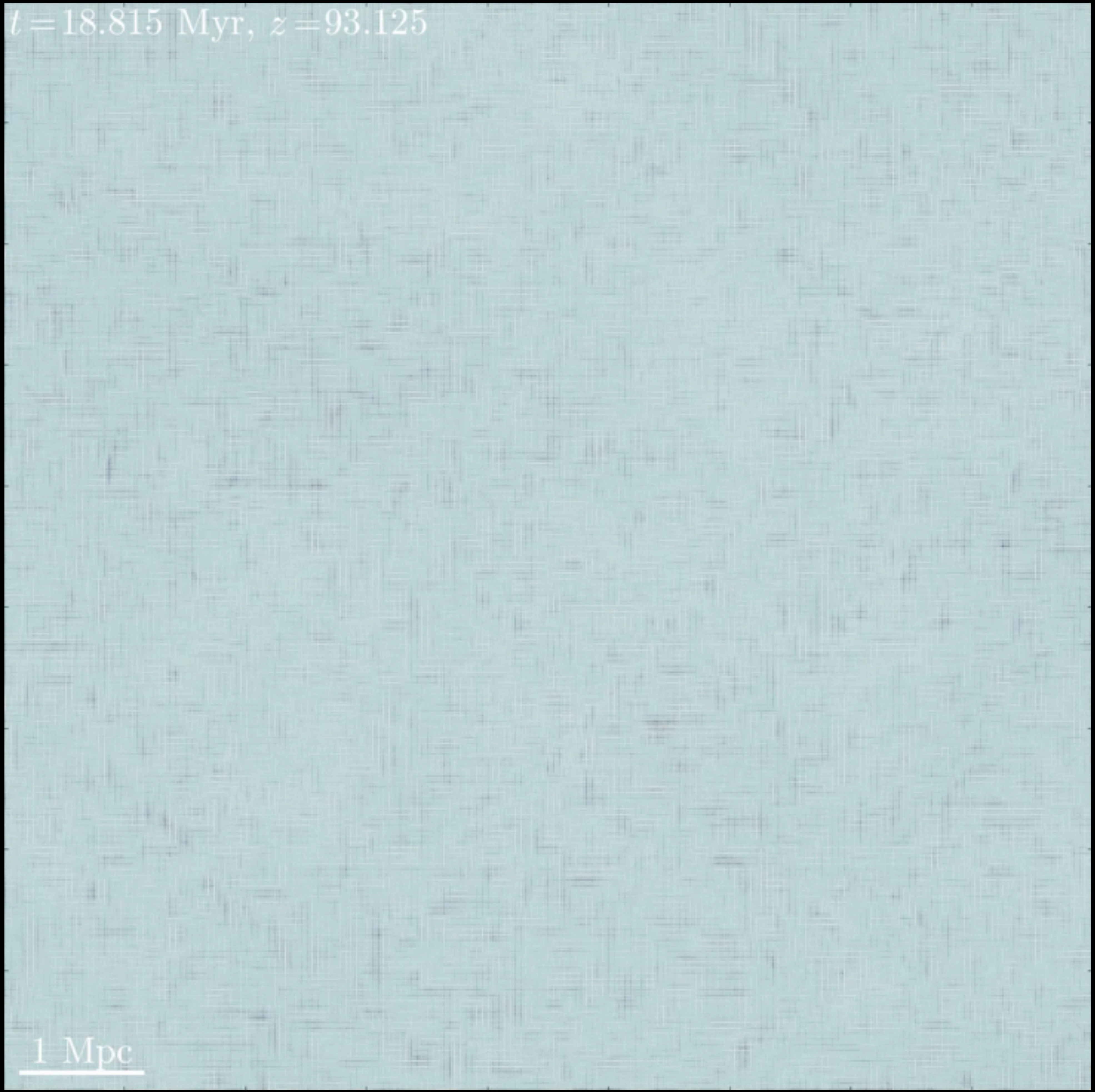
Planck XXII

Standard cosmological model ΛCDM … from adiabatic initial conditions



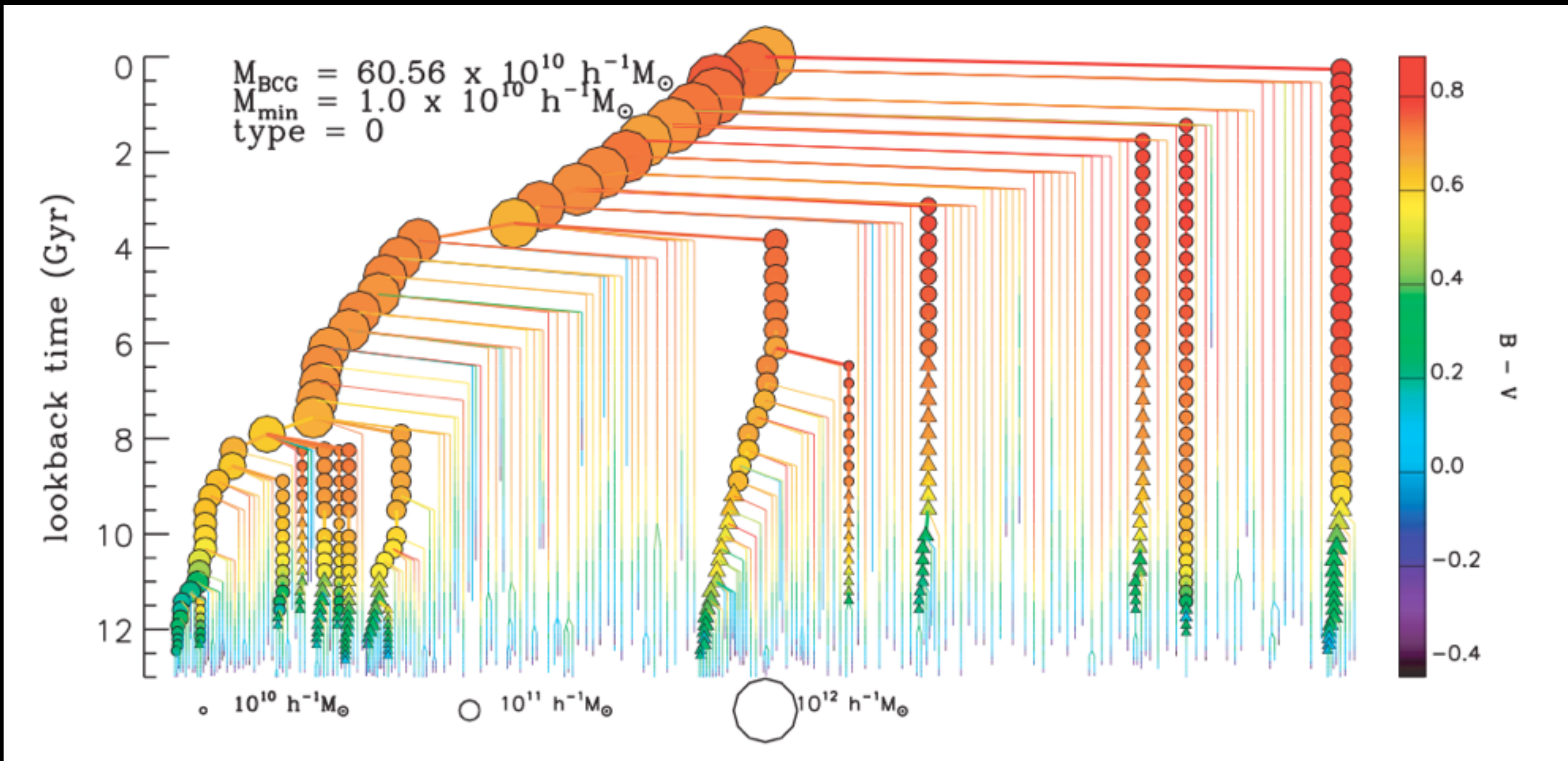


…. to non-linear structures:
filaments, clusters, galaxies



ELVIS

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



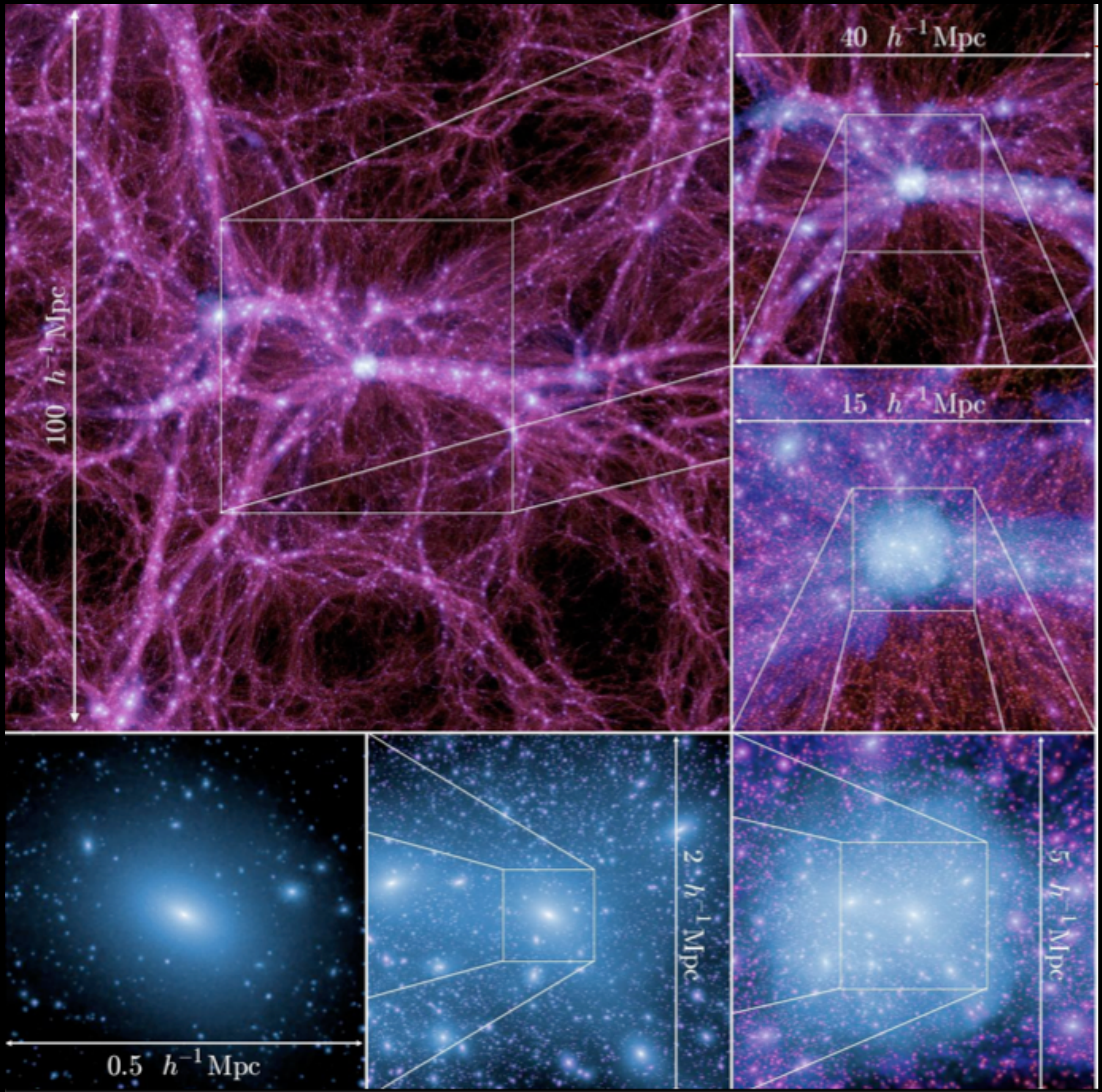
De Lucia & Blaizot (2007) *MNRAS* 375, 2

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

linear

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?

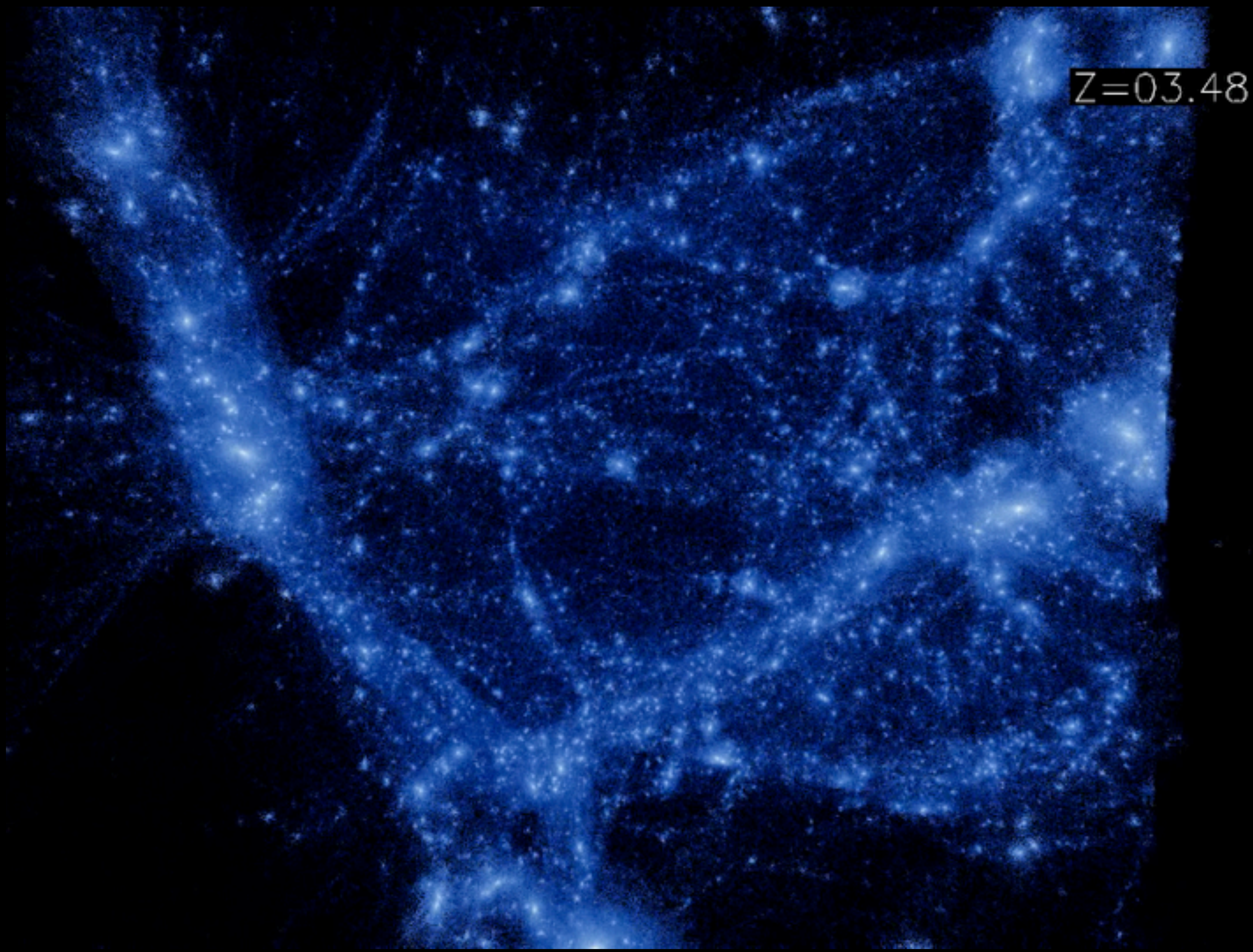
  Reservoir of missing baryons? Shock heated? Ionisation?

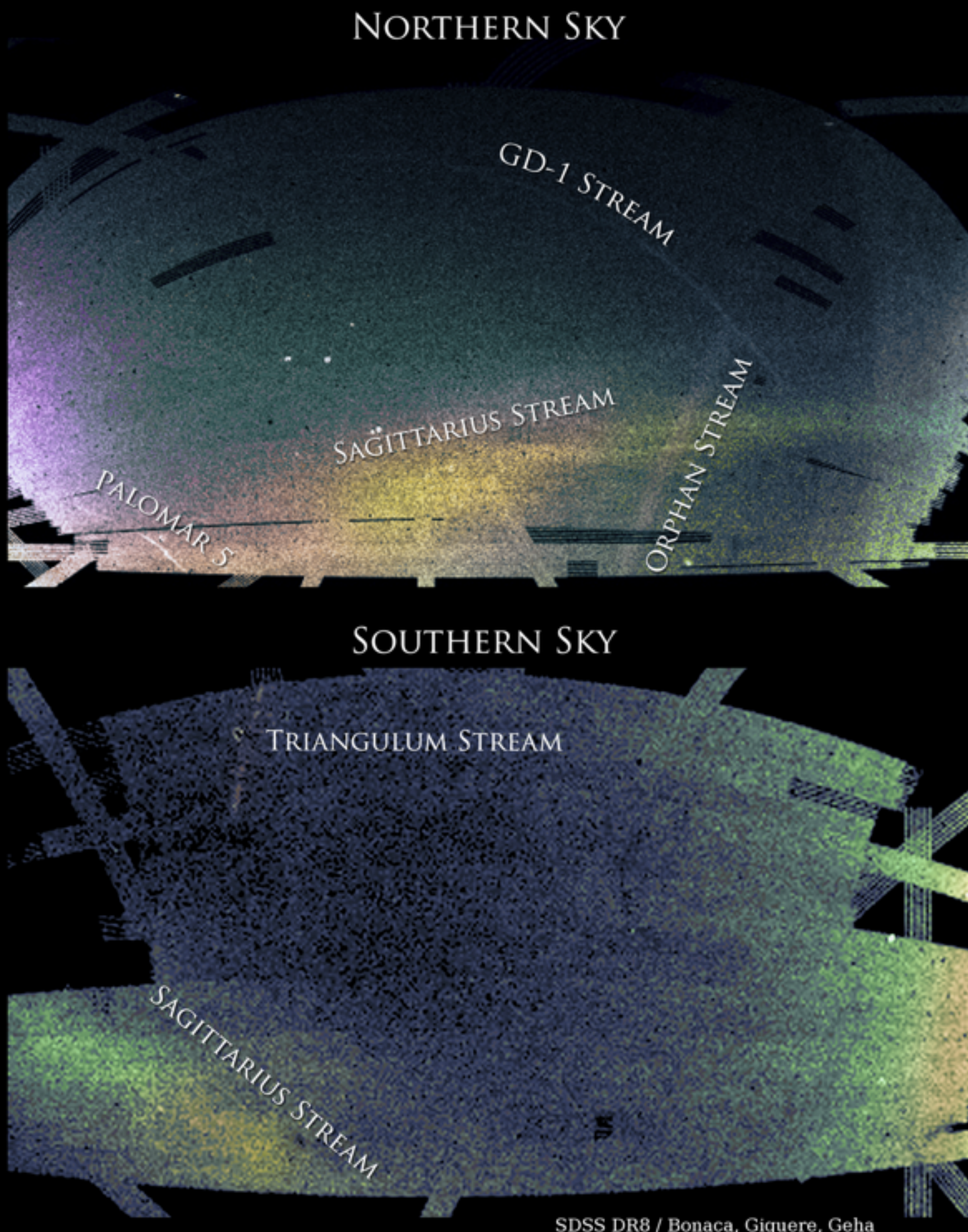
ESA *Cosmic Vision*: 4.2 The universe taking shape

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



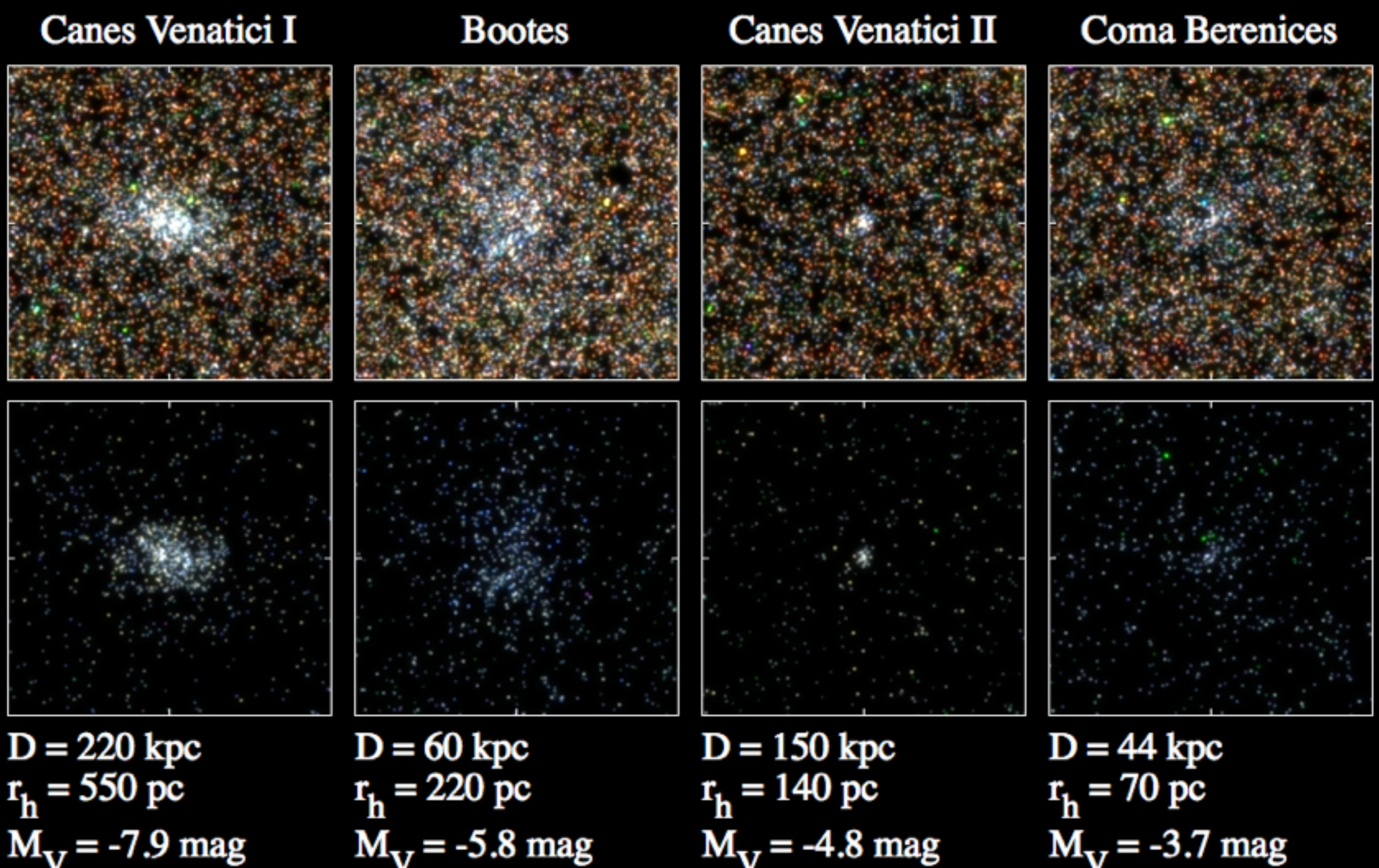


Tidal streams
in the Galactic halo

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

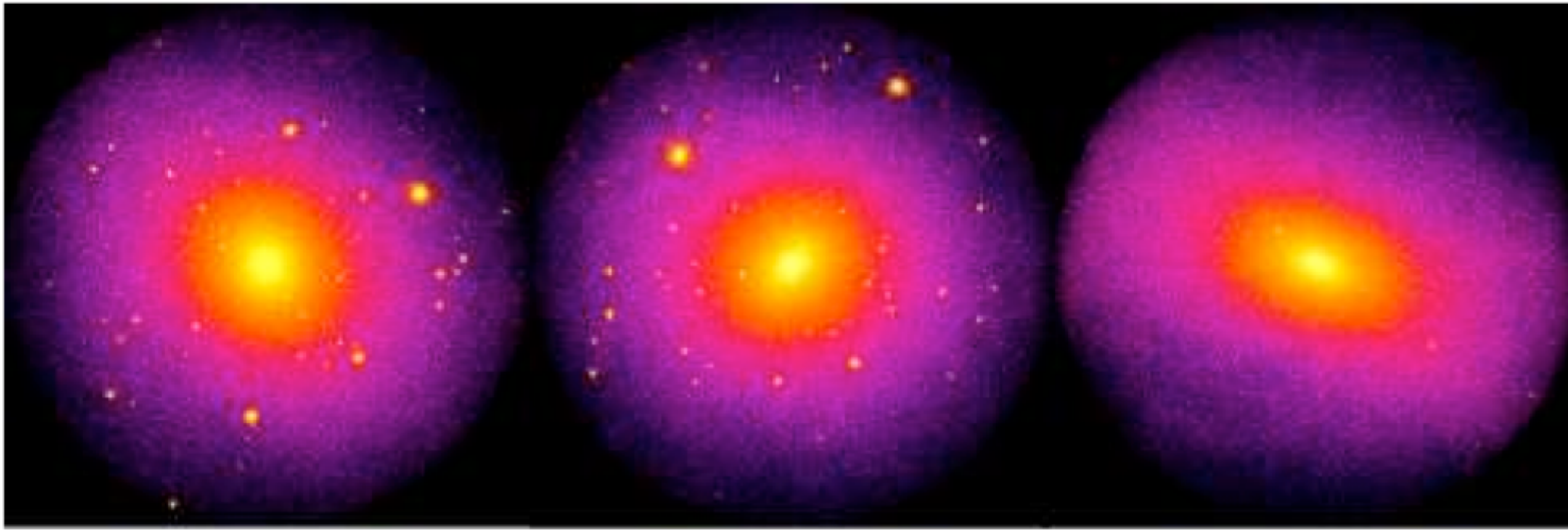
Driving science case #1

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



Belokurov *et al.* (2008)

Tension in the CDM paradigm ?

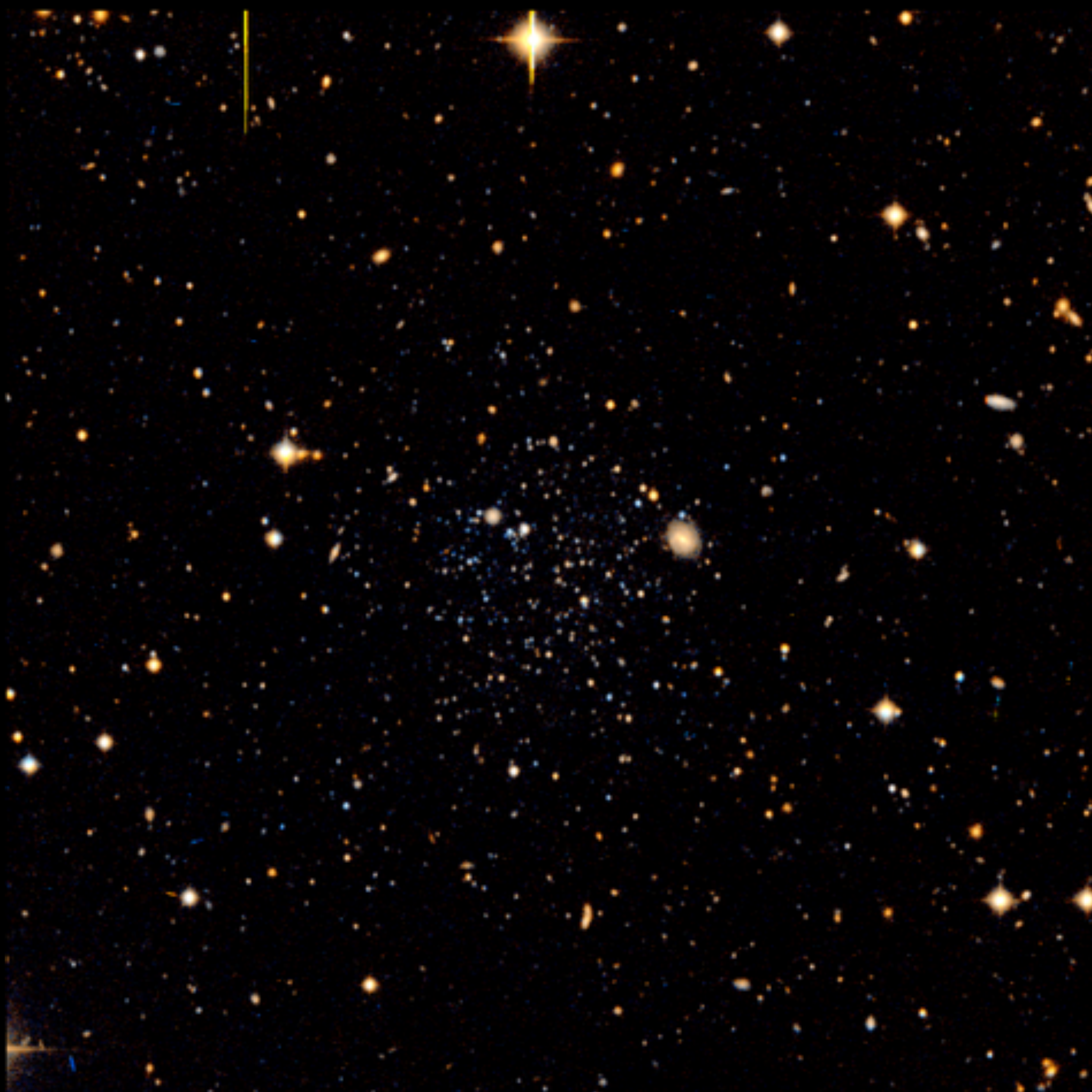


Brooks *et al.* (2014)

Self-Interacting Cold Warm

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

Leo T

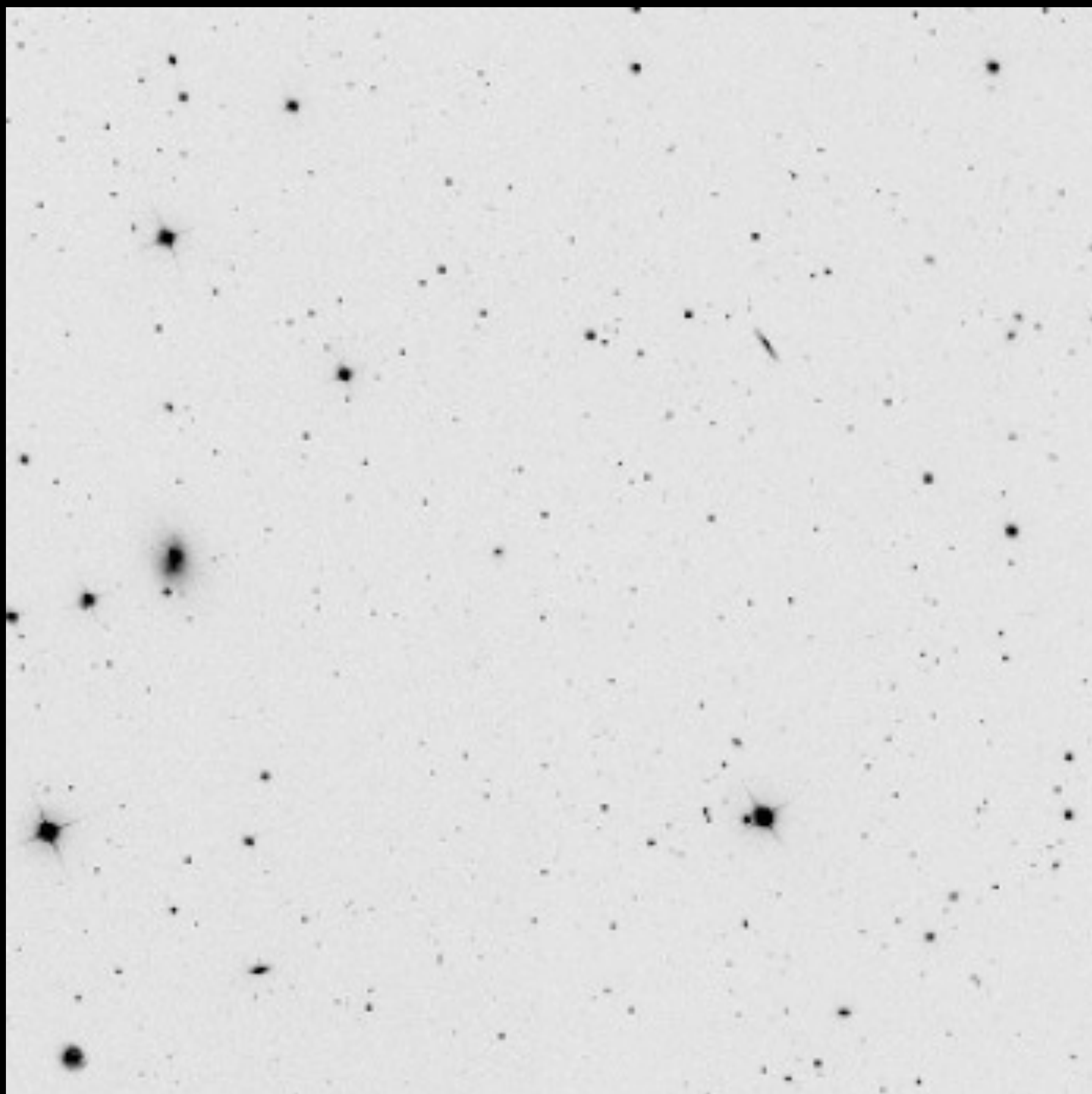


Ground-based

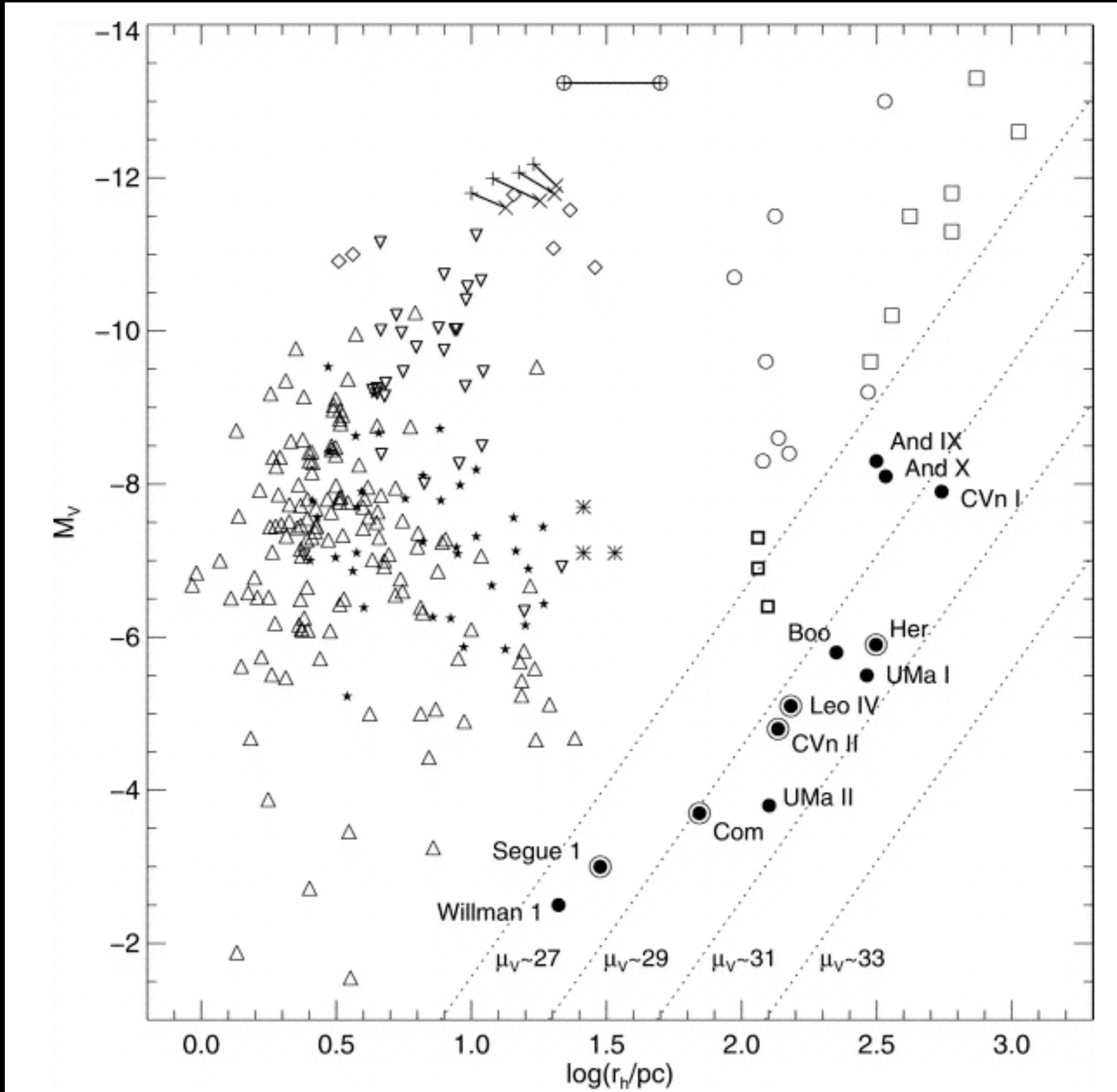
And IV

HST

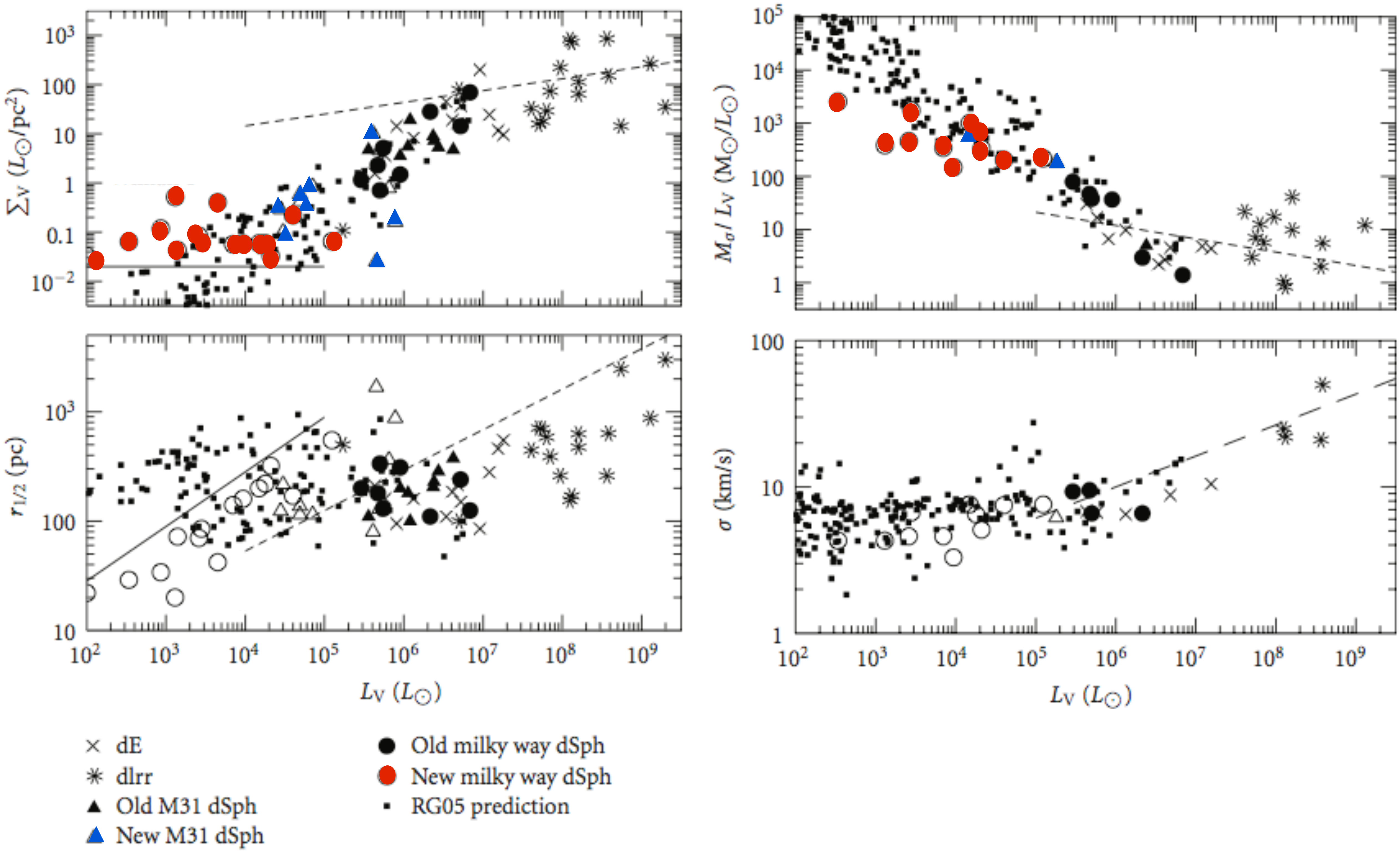
The case of Segue I



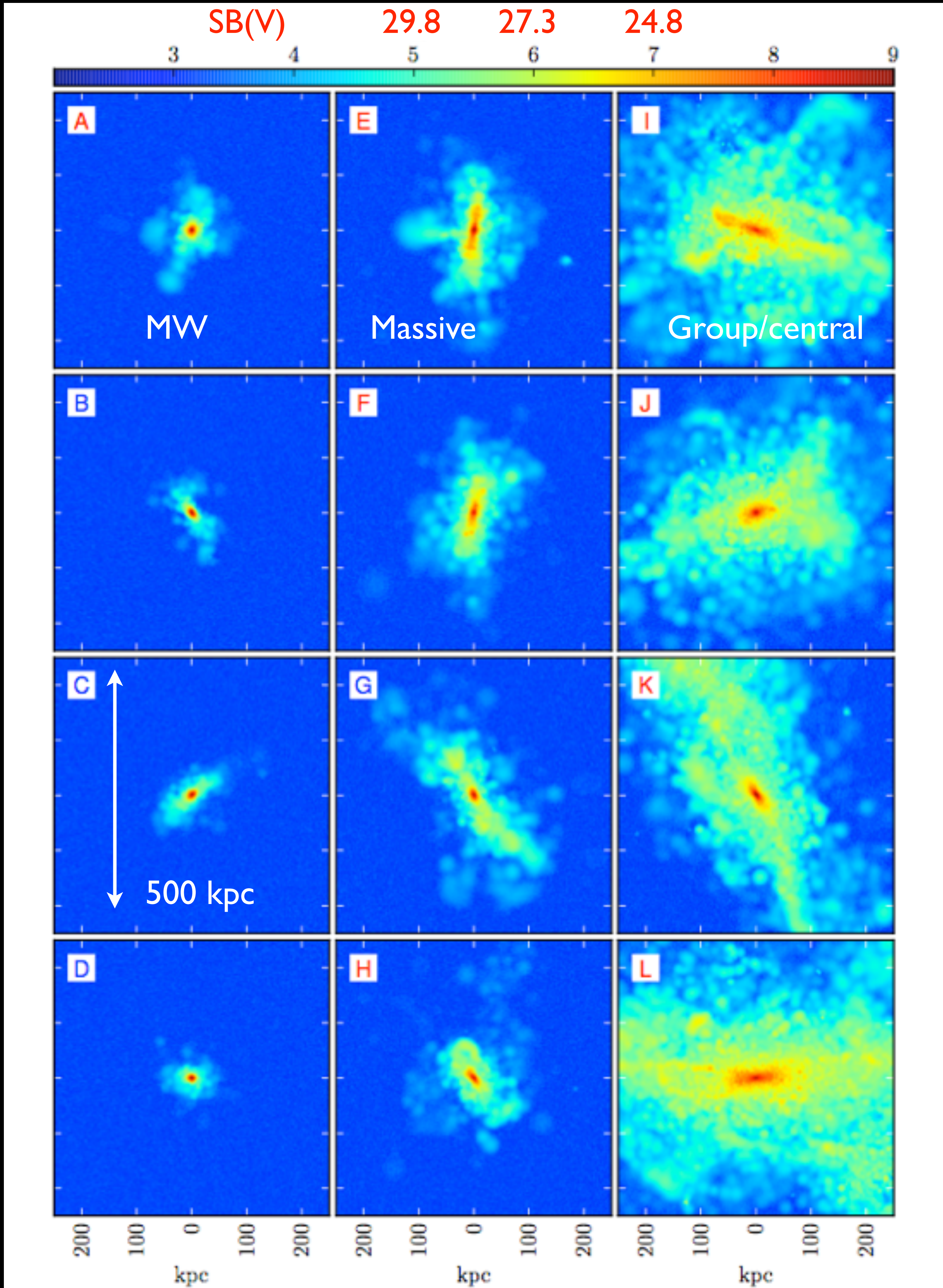
Belokurov *et al.* (2007)

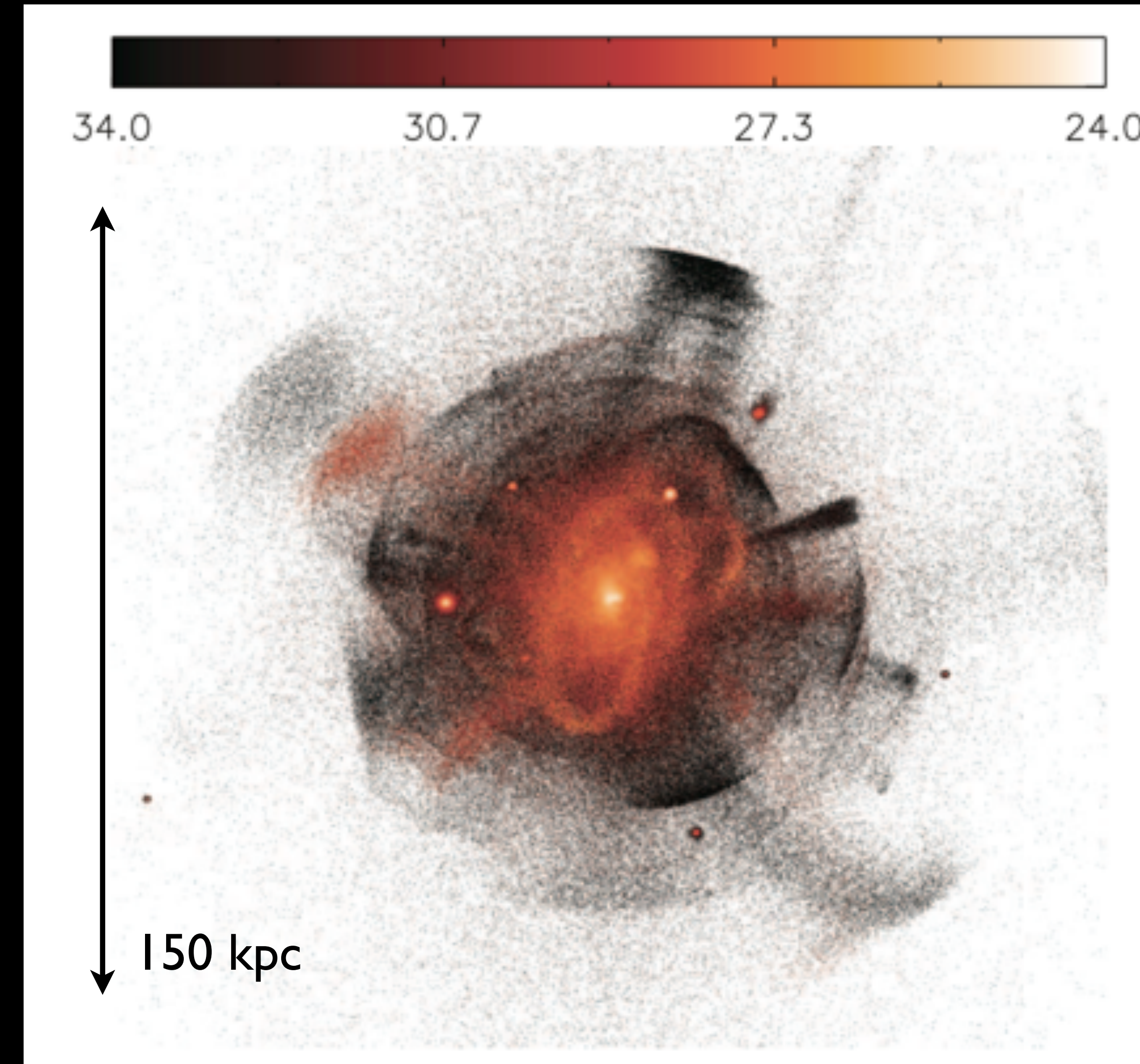


Belokurov *et al.* (2007)



Ricotti (2010)



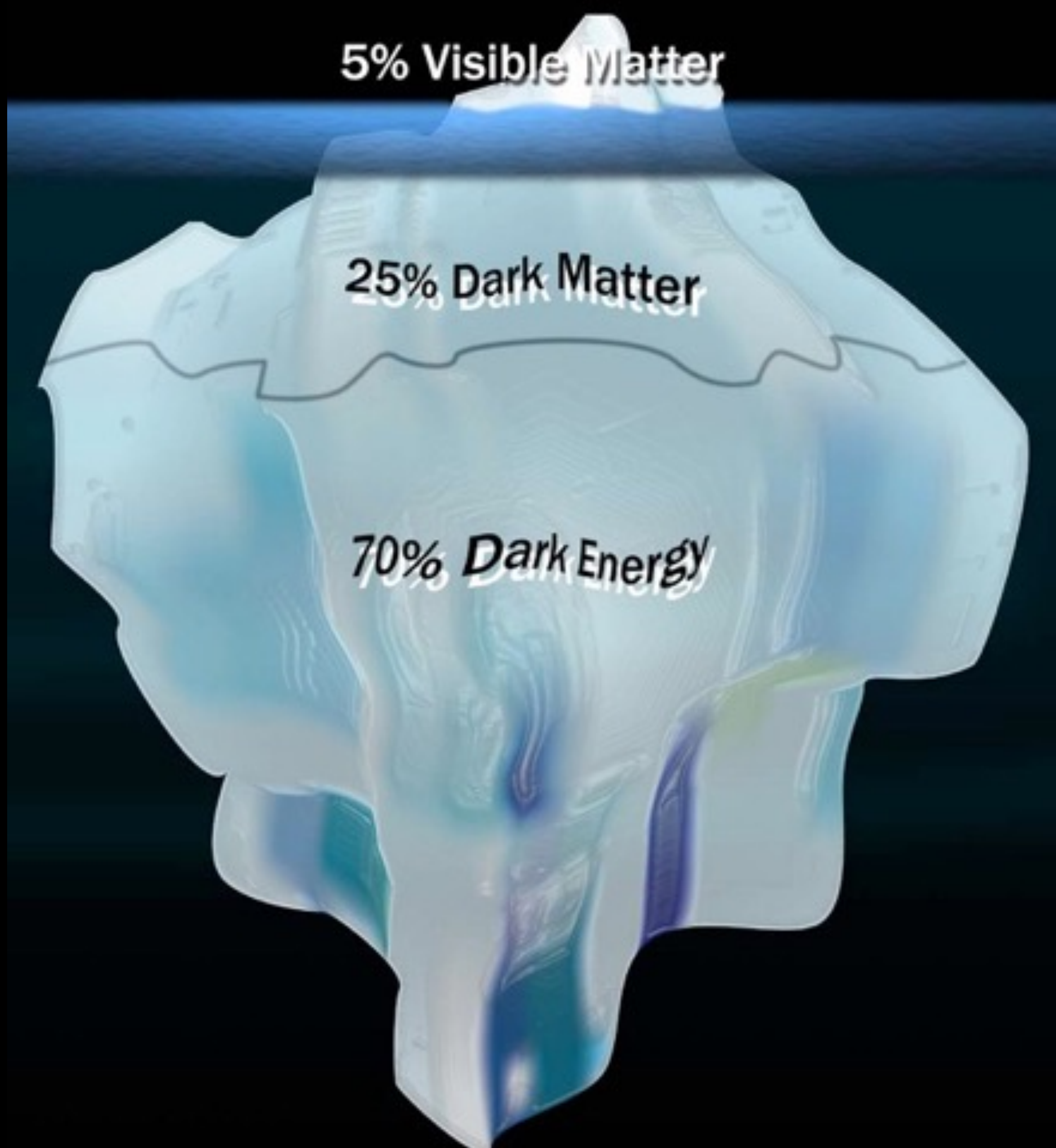


Font *et al.* (2008)

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

Unreachable from the ground

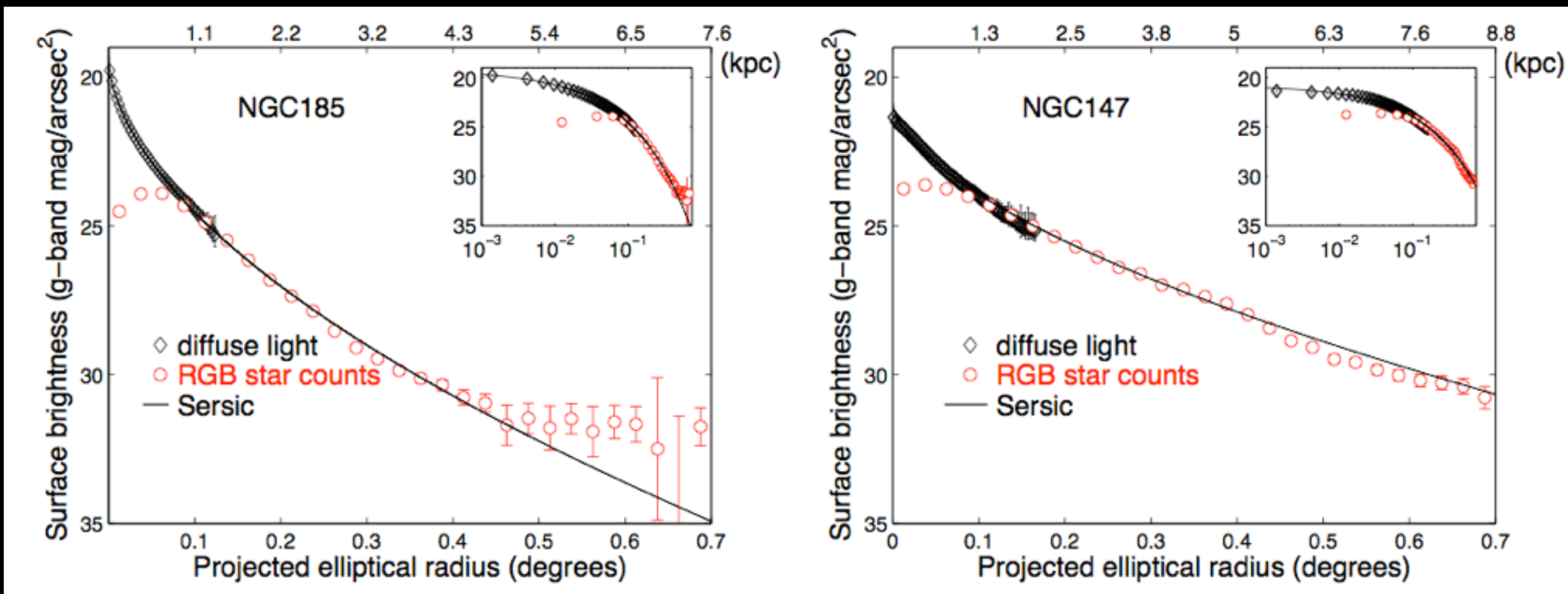
Cooper *et al.* (2013)



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

Michael Disney (1976)

Resolved star counts *vs* diffuse light



Crnojević *et al.* 2014 arXiv:1409.7065

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

NGC 4013 *d*=18 Mpc

NGC 5907 *d*=14 Mpc

51 cm Richtey-Chrétien

CCD SBIG 27’ 0.45”/pixel

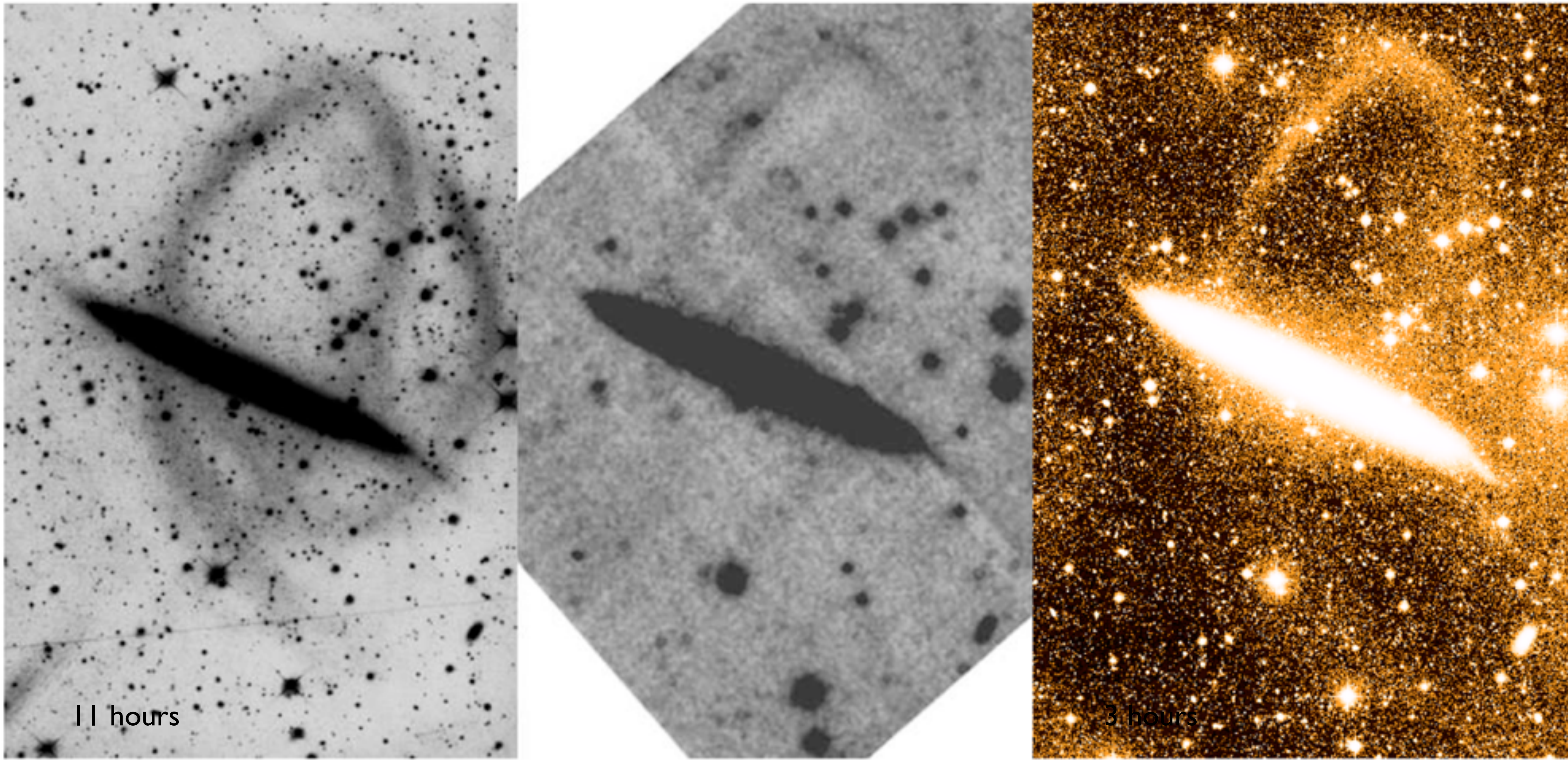
Exposure time: 11 hours

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

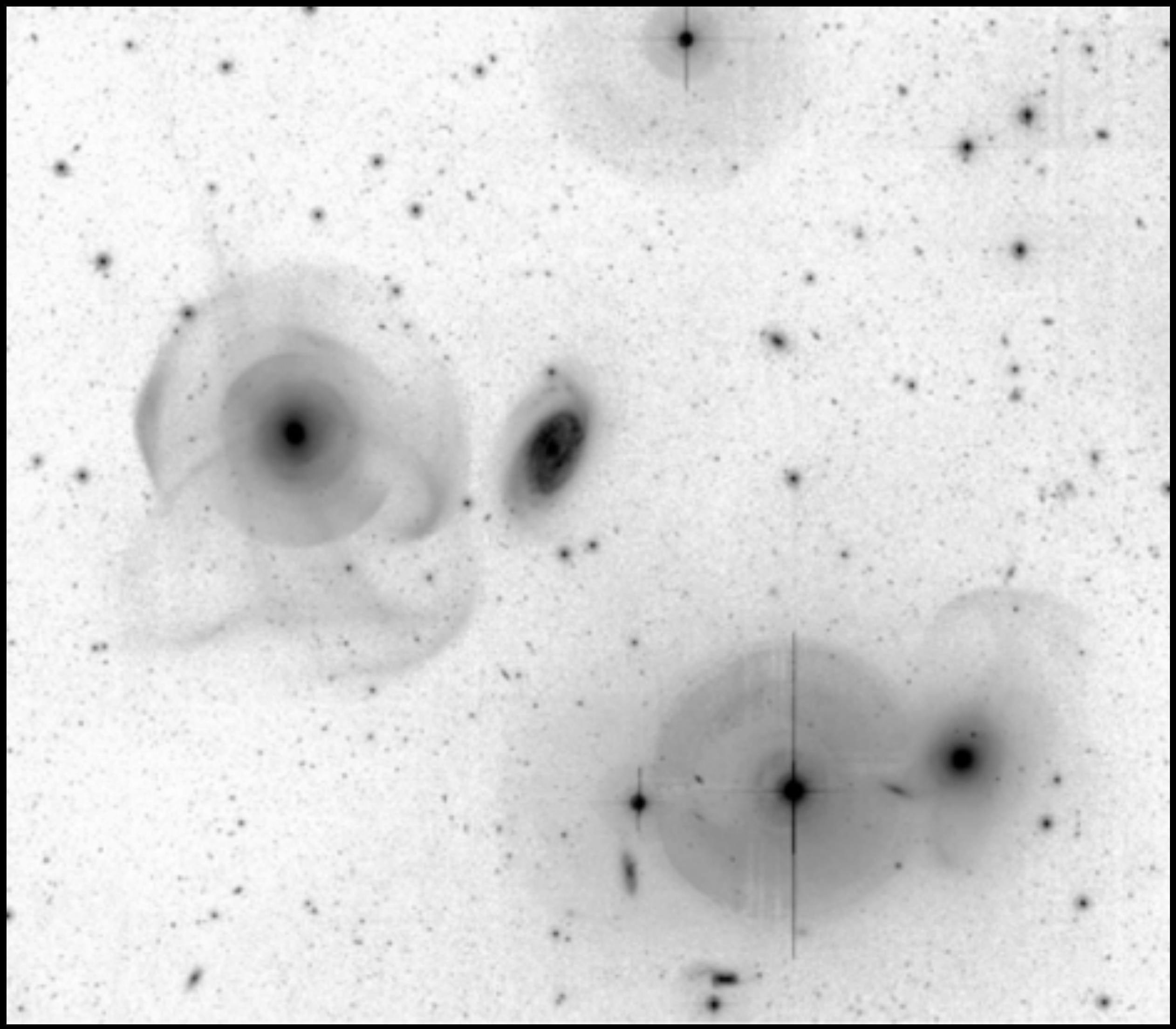
SDSS
Miskolczi et al. 2011

CFHT
Ibata et al. 2011

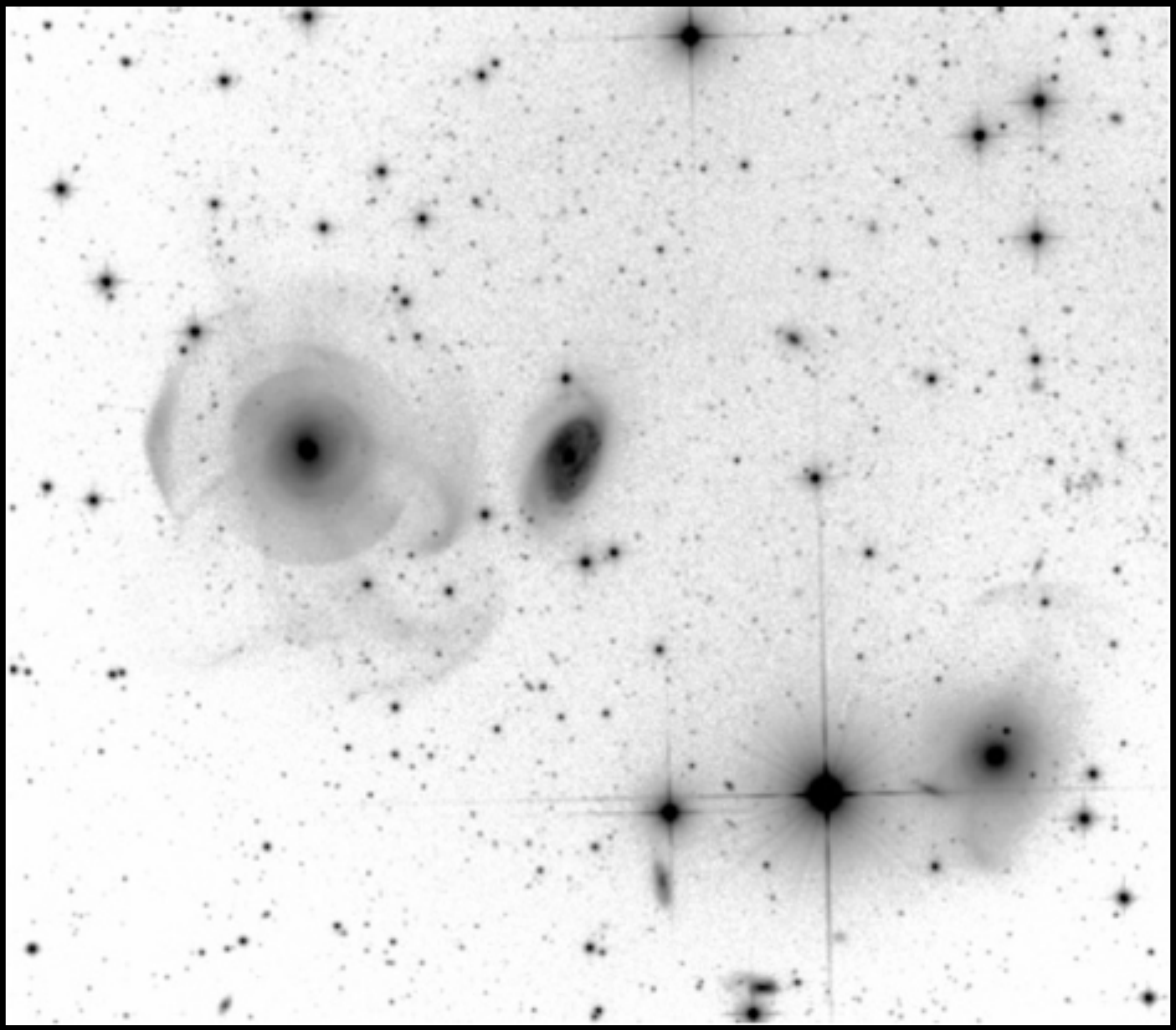
Key points: SB $\propto$ D^2 / F^2 $\propto$ $(D/F)^2$ f/2 is 100x faster than f/20

PSF wings

NGC 474 and NGC 467



CFHT *g*-band 0.7 h



Bulgarian amateur L 21.5 hours

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

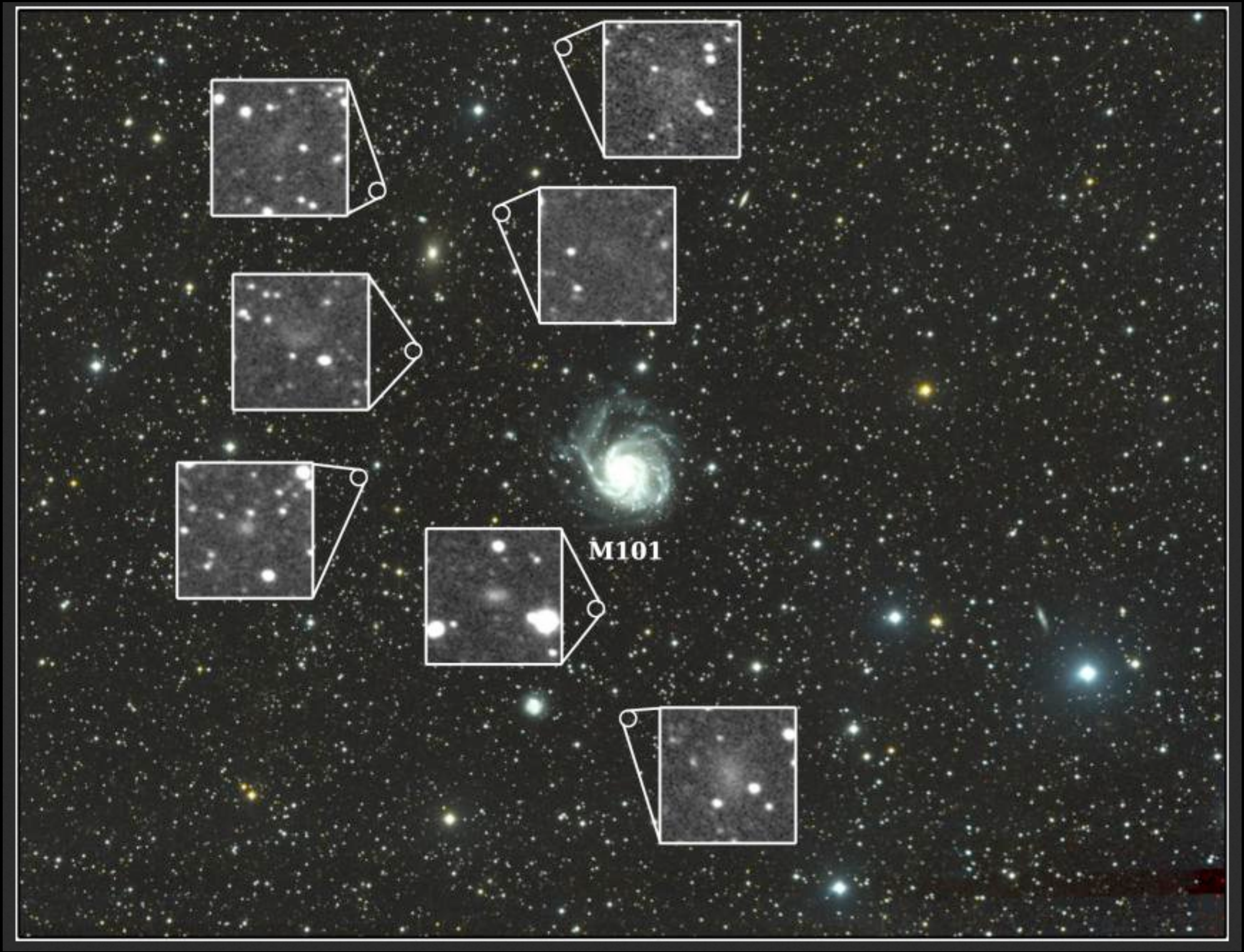
Surface brightness received by a *extended* source:

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

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

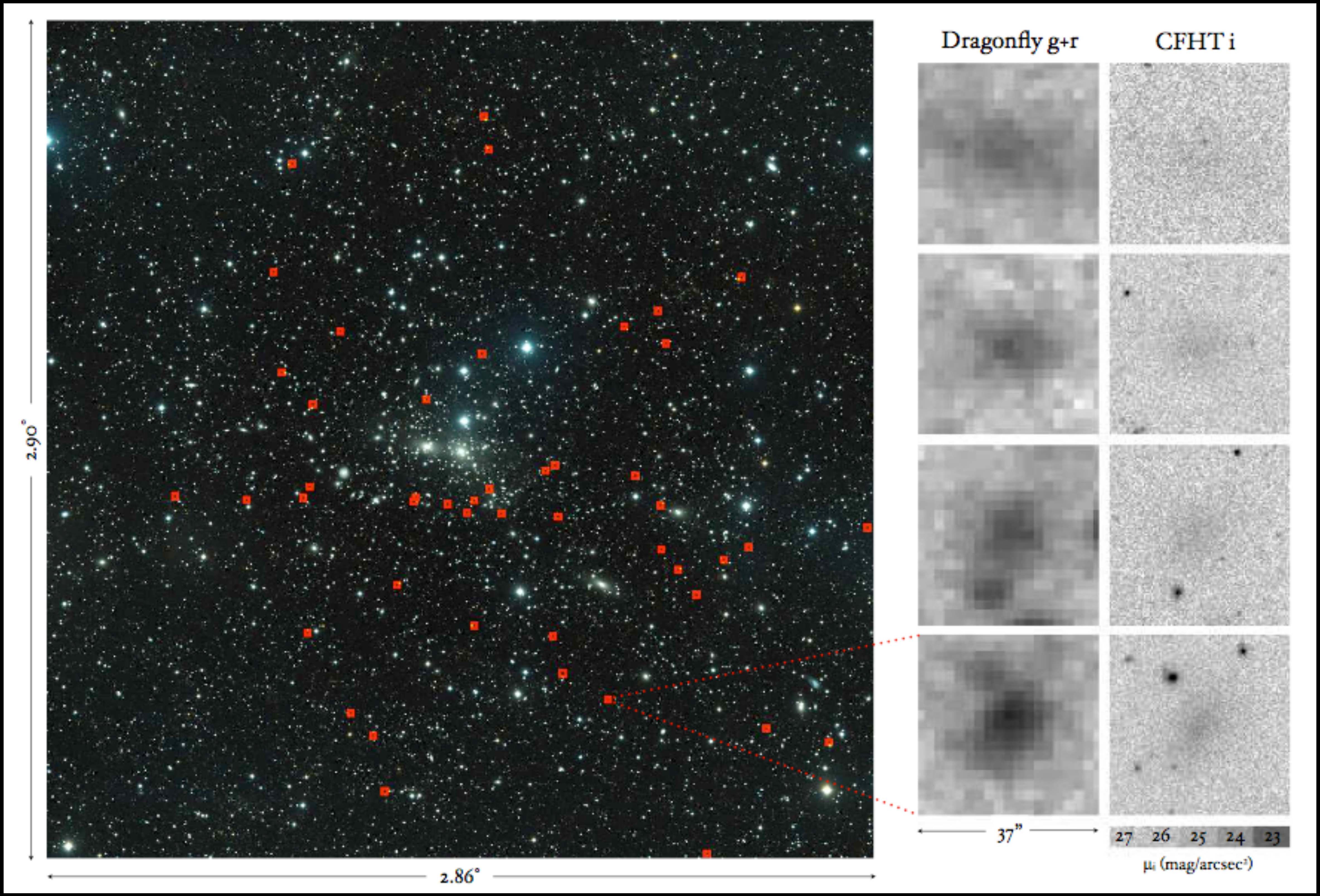
→ drives *small D* telescopes

The Dragonfly camera



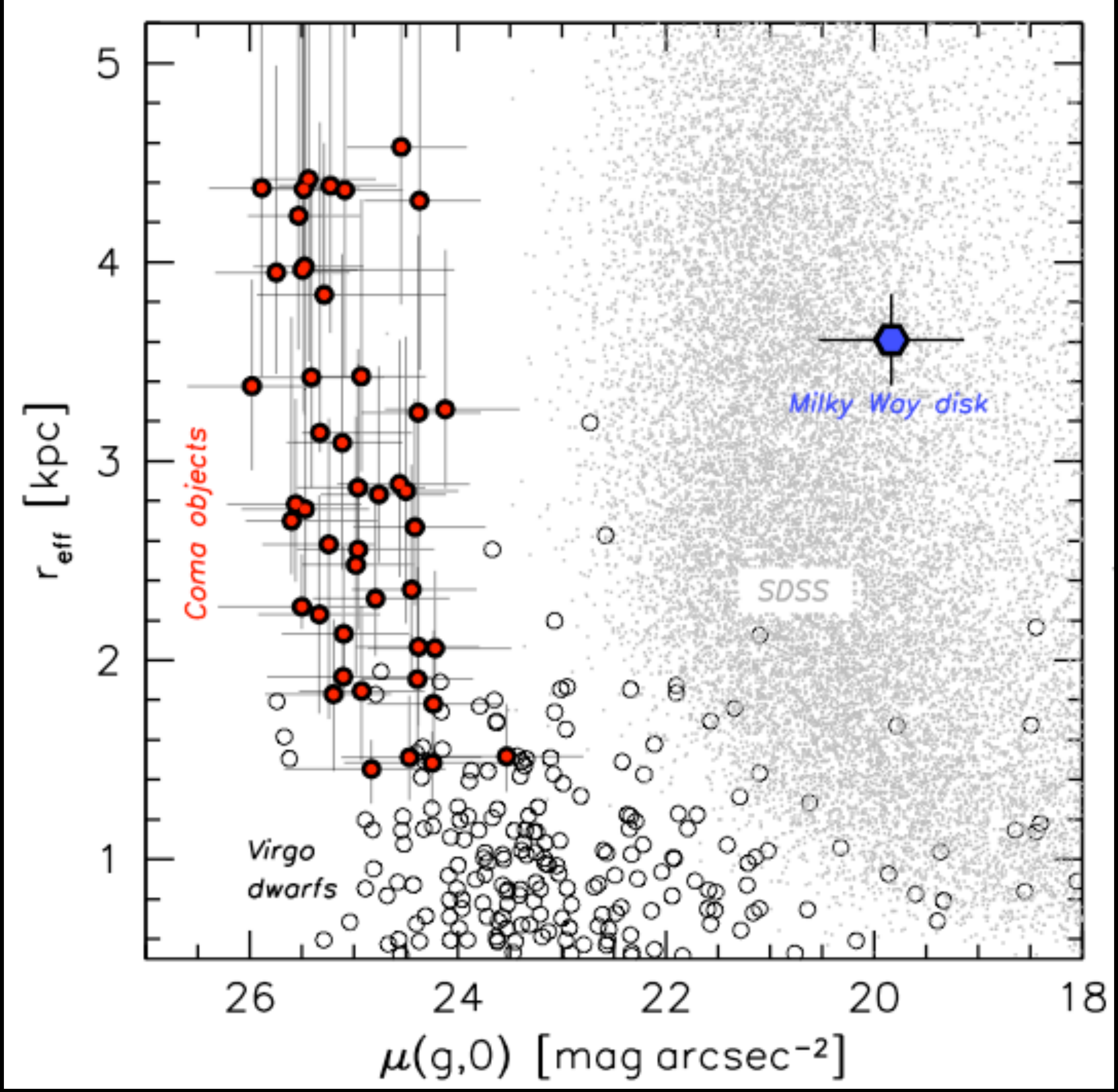
Van Dokkum & Abraham (2014)

47 new Milky Way-sized galaxies in the Coma cluster

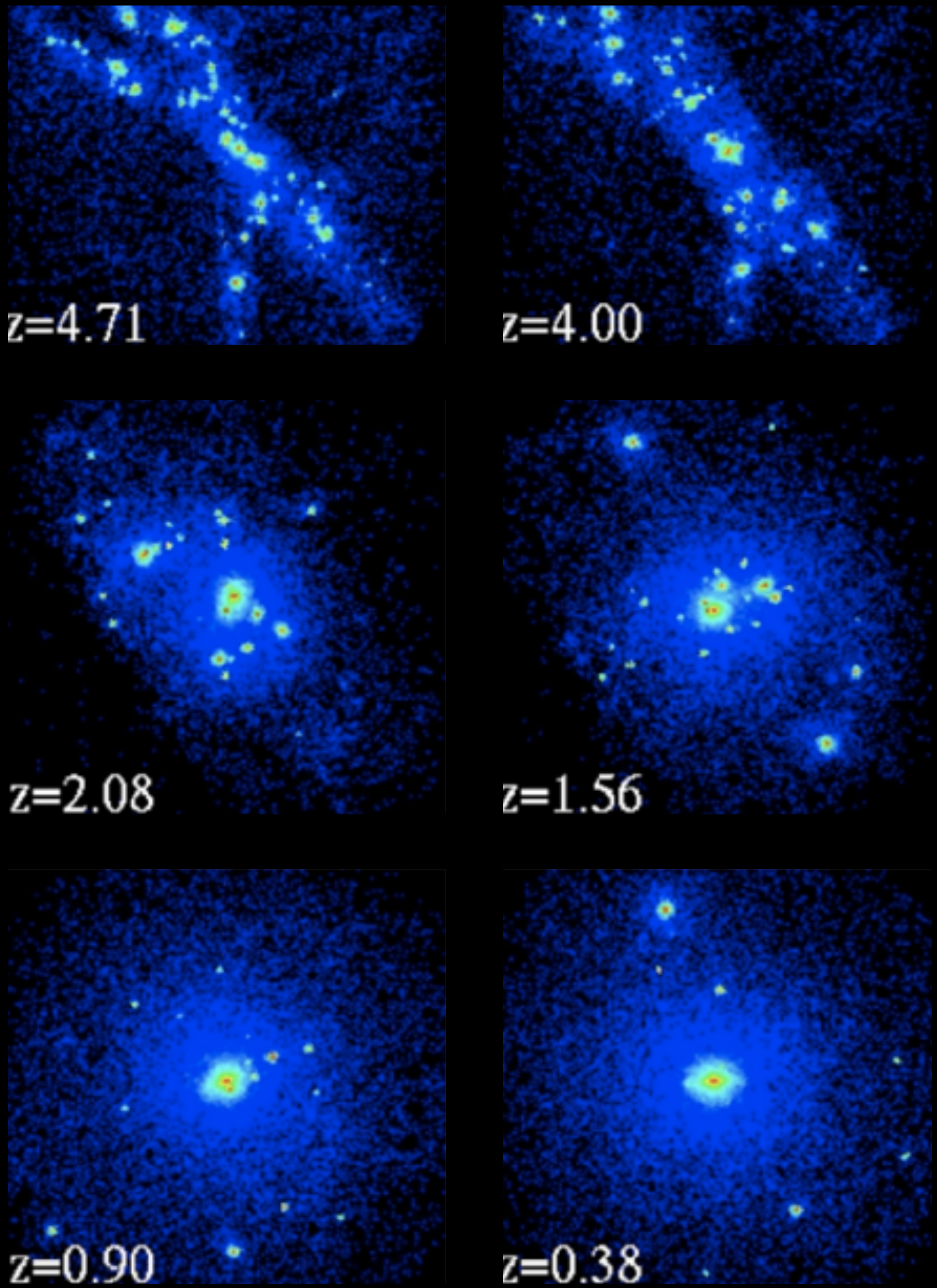


26 hours 6″ FWHM

Van Dokkum *et al.* (2014) *arXiv:*1410.8141

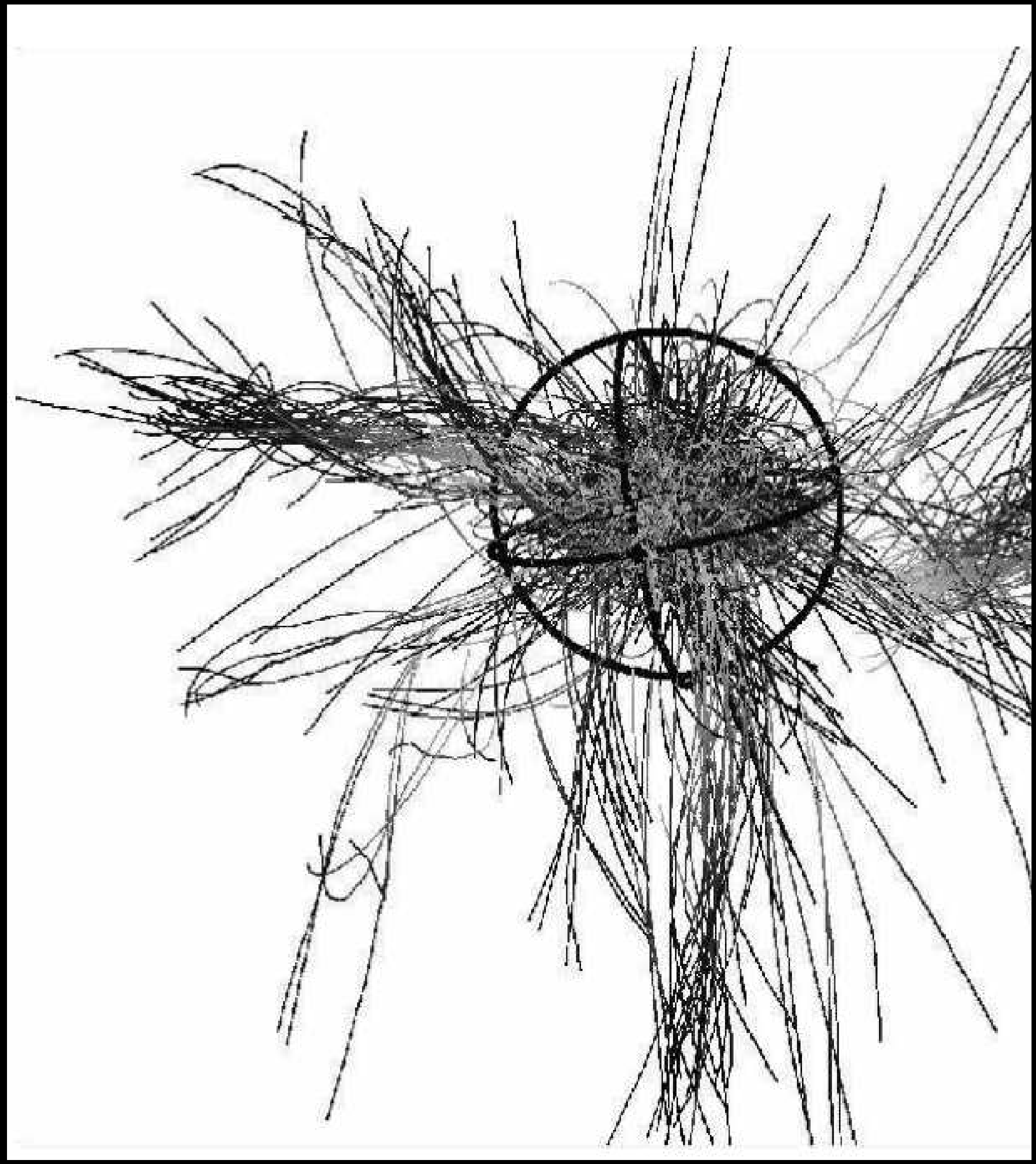


Van Dokkum *et al.* (2014) *arXiv:*1410.8141



Formation histories
of galactic haloes

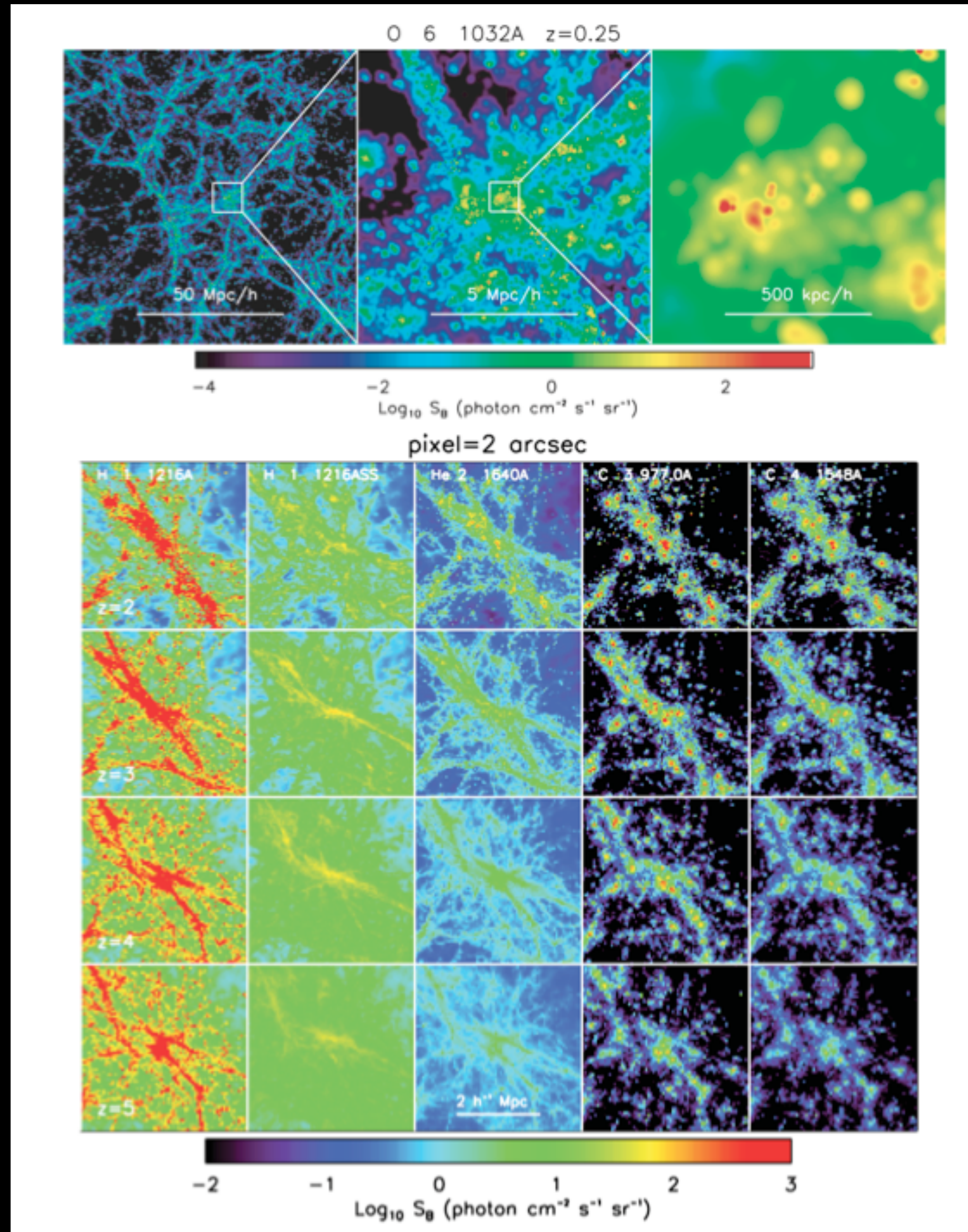
anisotropic accretion
from filaments



Driving science case #2

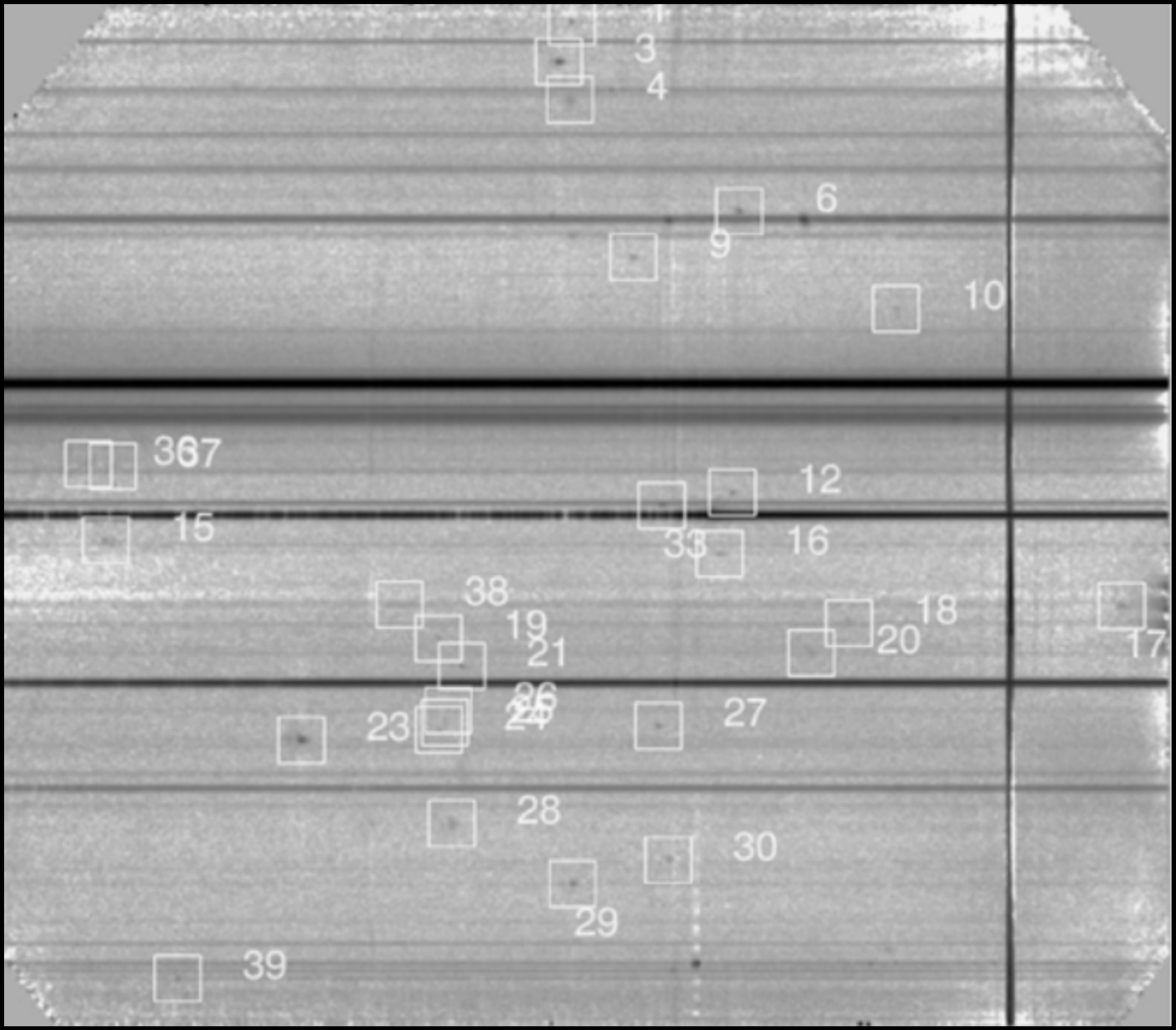
The Cosmic Web

Strongest in Lyman α by ~1000 x



Bertone + Schaye (2012)

Low surface brightness Lyman-α emitters

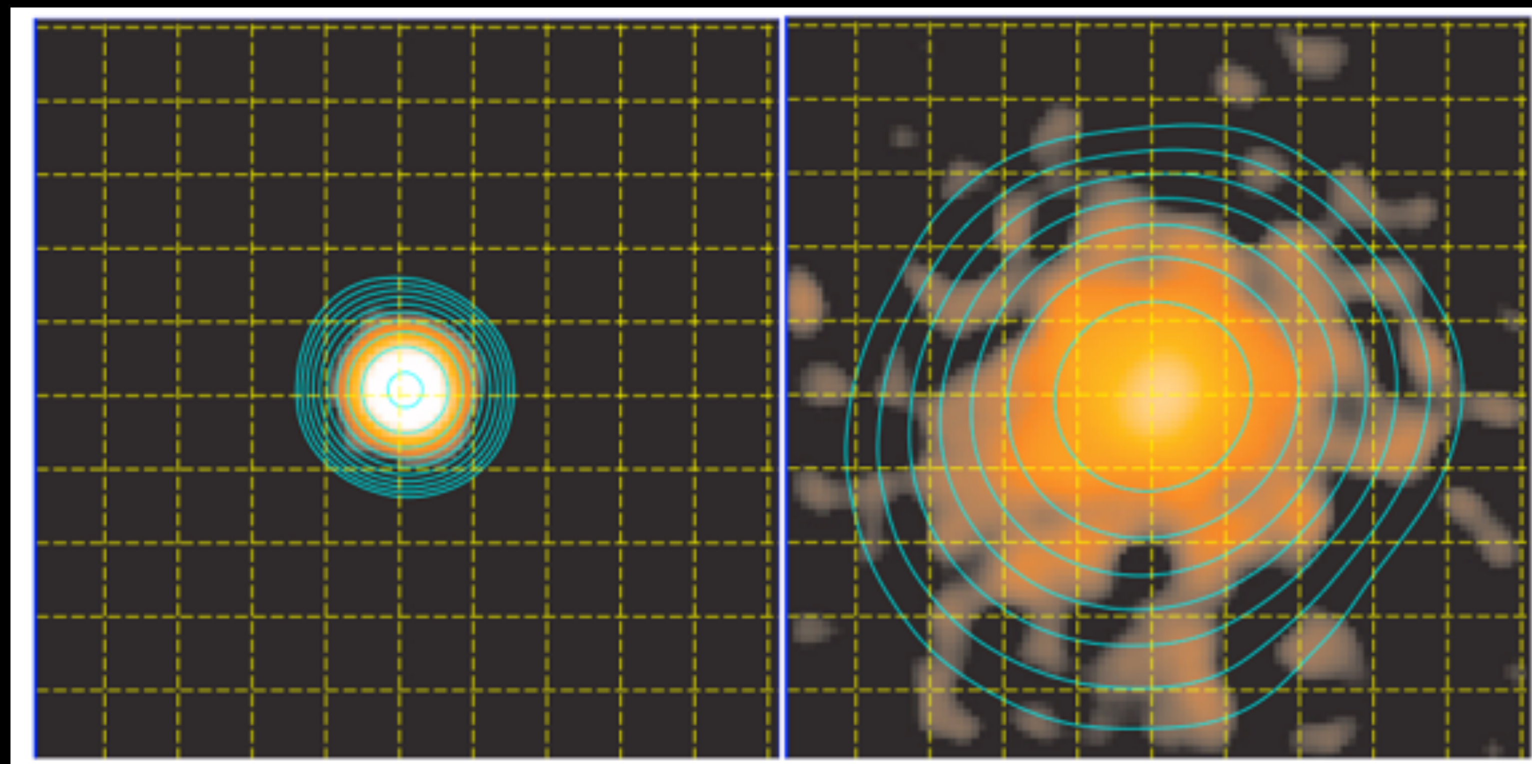


VLT
92 hours exposure

Rauch et al. (2010)

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

UV continuum



Lyman-α

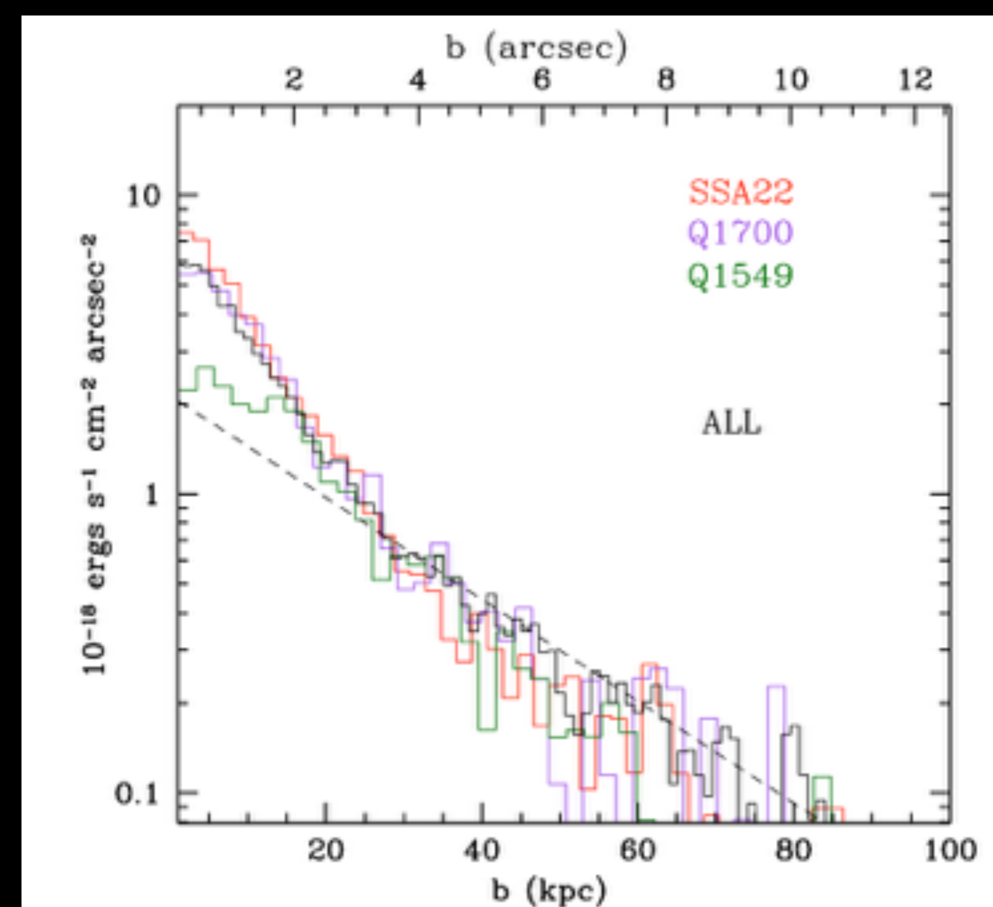
92 UV-selected galaxies with <z>=2.65

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

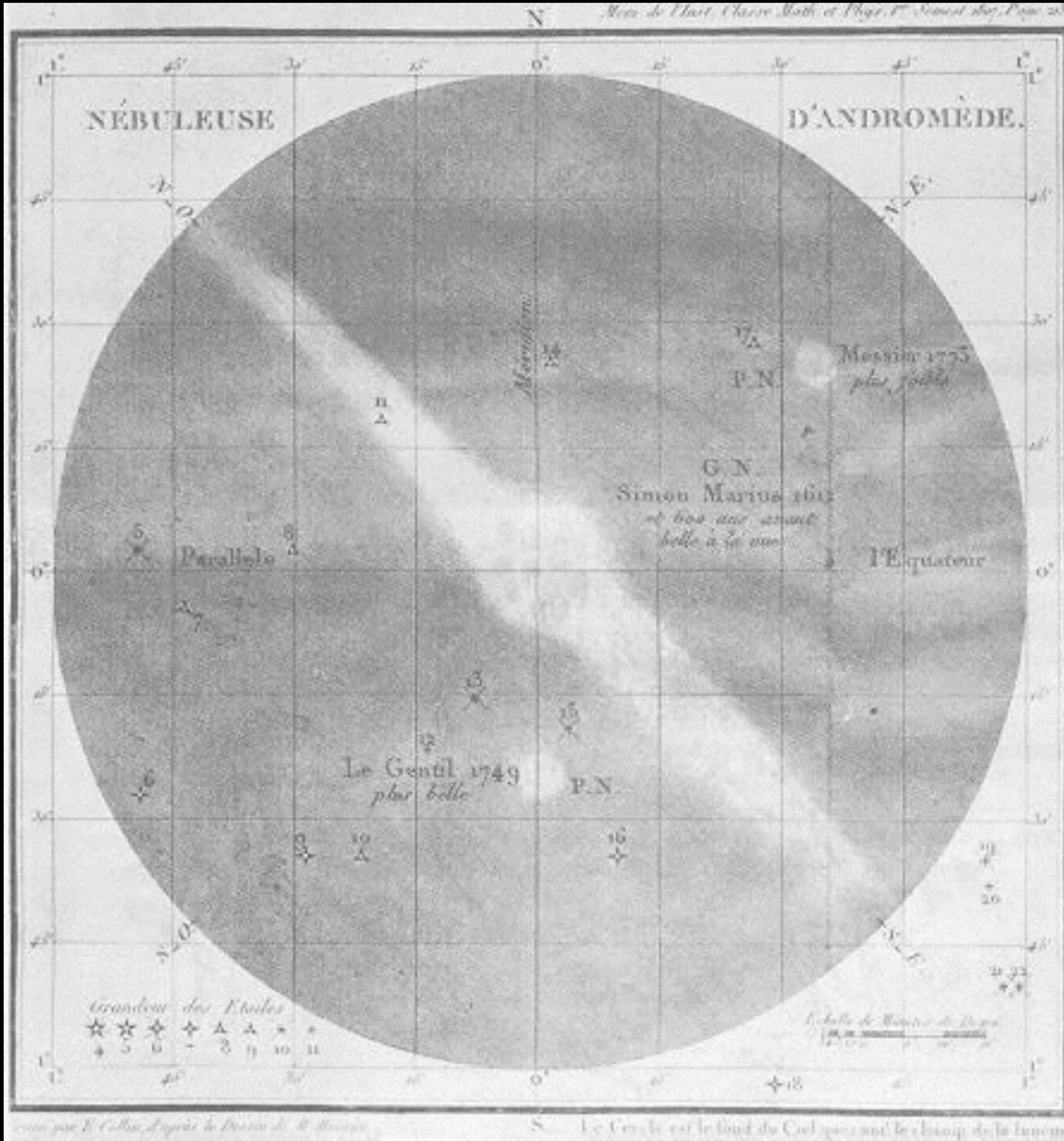
- Lyman-α cooling?
- Fluorescence by ionising radiation?
- Scattering from circumgalactic gas?



Steidel et al. (2011)

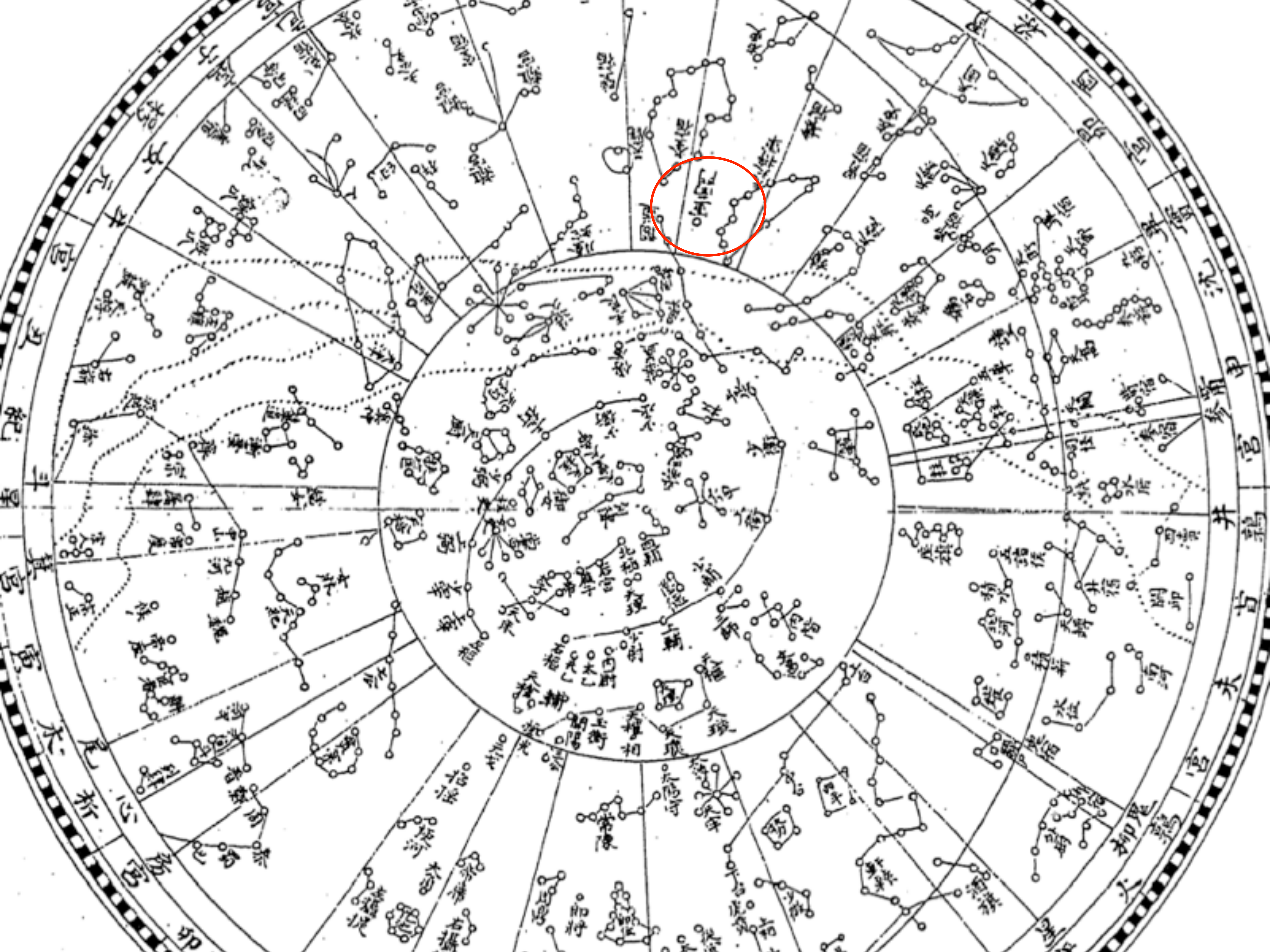
The MESSIER satellite

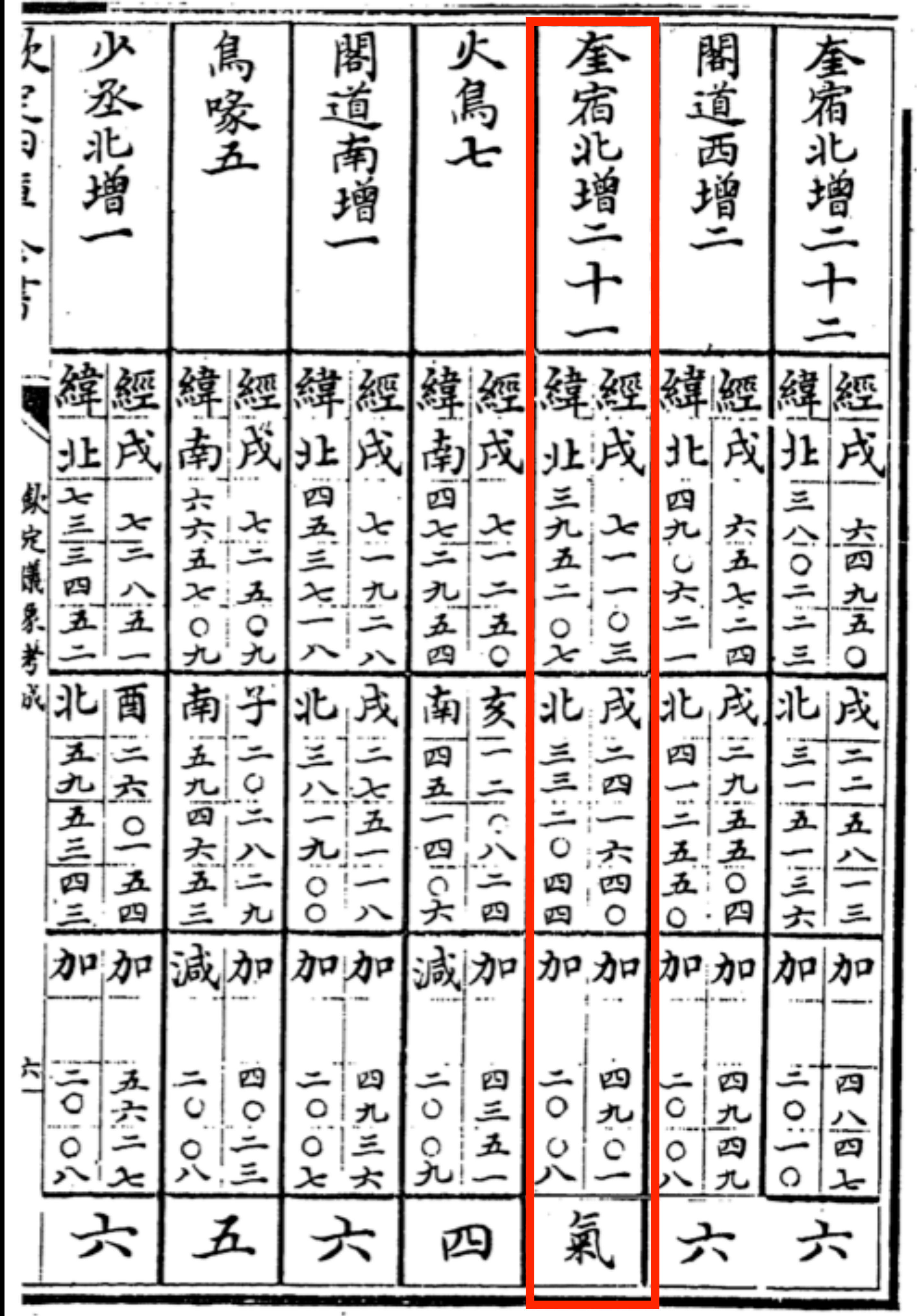
Scientific and technical challenges



First catalogue of diffuse objects

Messier (1771)
Mem. Acad. Sci. Paris





欽定儀象考成

	經	緯					
奎宿北增二十二	戌六四九五〇	北三八〇二二三	戌二二五八一三	北三一五一三六	加四八四七	加二〇一〇	六
閣道西增二	戌六五七二四	北四九〇六二一	戌二九五五〇四	北四一二五五〇	加四九四九	加二〇〇八	六
奎宿北增二十一	戌七一一〇三	北三九五二〇七	戌二四一六四〇	北三三二〇四四	加四九〇一	加二〇〇八	氣
火鳥七	戌七一二五〇	南四七二九五四	亥二二〇八二四	南四五一四〇六	加四三五一	減二〇〇九	四
閣道南增一	戌七一九二八	北四五三七一八	戌二七五一一八	北三八一九〇〇	加四九三六	加二〇〇七	六
鳥喙五	戌七二五〇九	南六六五七〇九	子二〇二八二九	南五九四六五三	加四〇二三	減二〇〇八	五
少丞北增一	戌七三八五一	北七三三四五二	酉二六〇一五四	北五九五三四三	加五六二七	加二〇〇八	六

六

The Yixiangkaocheng catalogue

Ignaz Kögler, SJ

1756 (publ. 1774)

3083 objects
2848 stars
13 nebulosities

Ahn (2012) *MNRAS*, 422, 913

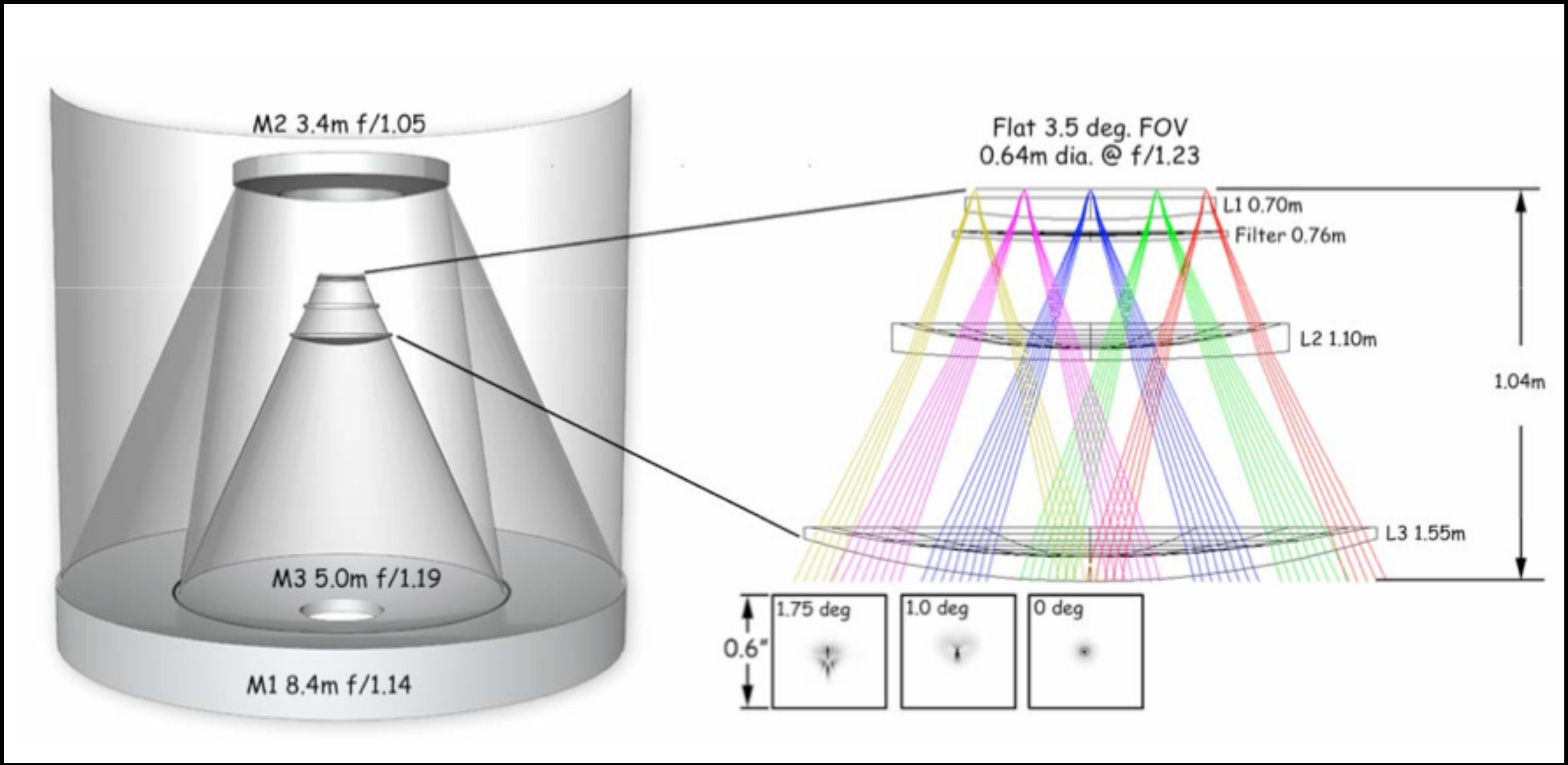
Top-level design requirements

• 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*)
• Survey	all sky	(*unique*)

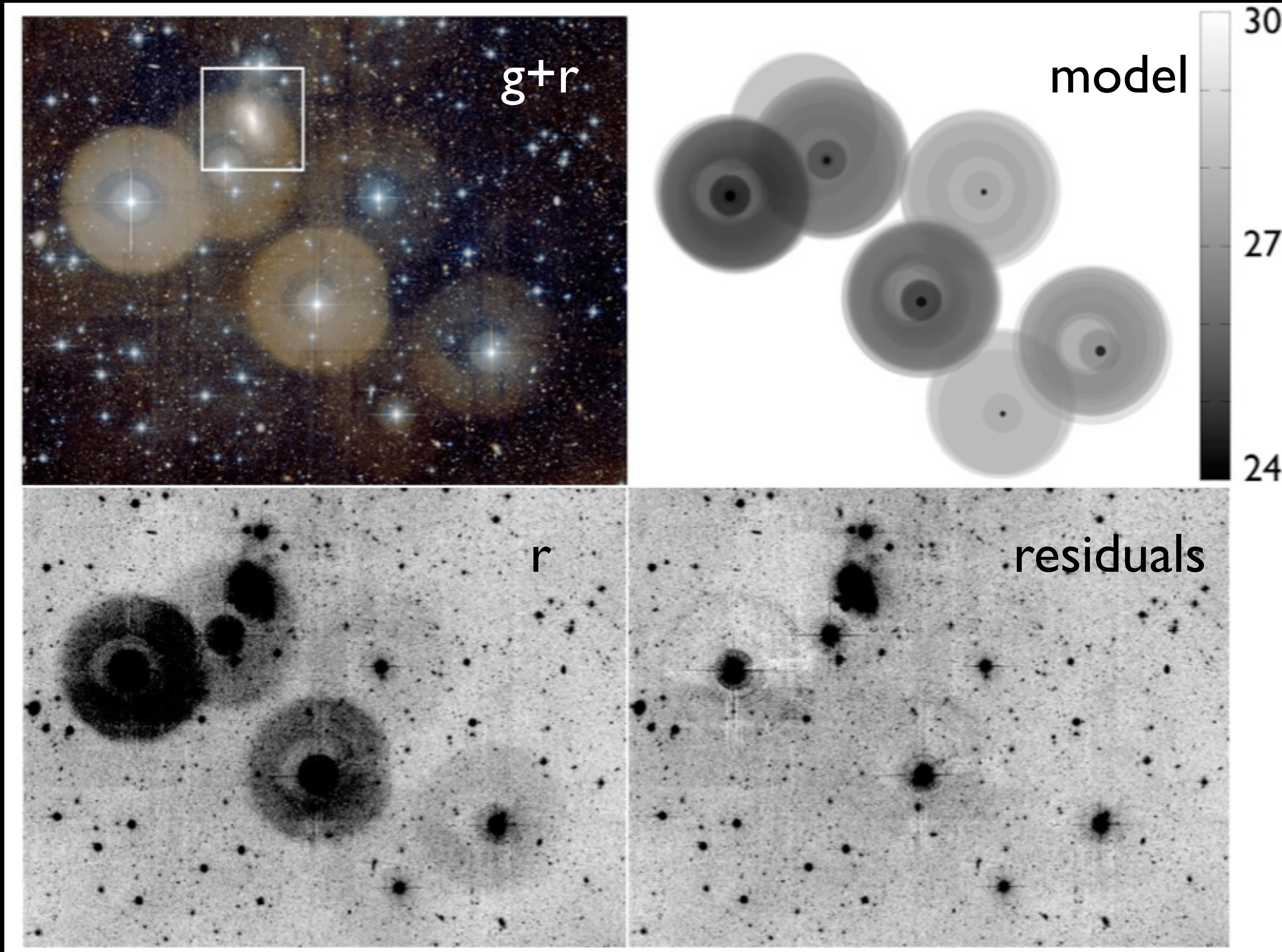
Comparison of current very wide field telescopes

	Design	N_{opt}	D	f ratio	FOV
SDSS	RC + doublet corrector	6	2.4	f/5	2.0x1.5
VST	RC + doublet corrector	6	2.6	f/5	1.0x1.0
CFHT	Paraboloid + triplet corrector	7	3.6	f/4	1.0x1.0
MMT	RC + corrector	6	6.5	f/5	0.5x0.5
LSST	Mersenne + triplet	9	8.4	f/1.2	3.0x3.0
MiniTrust	Rumsey	2	0.45	f/5	1.5x1.5

LSST optical design

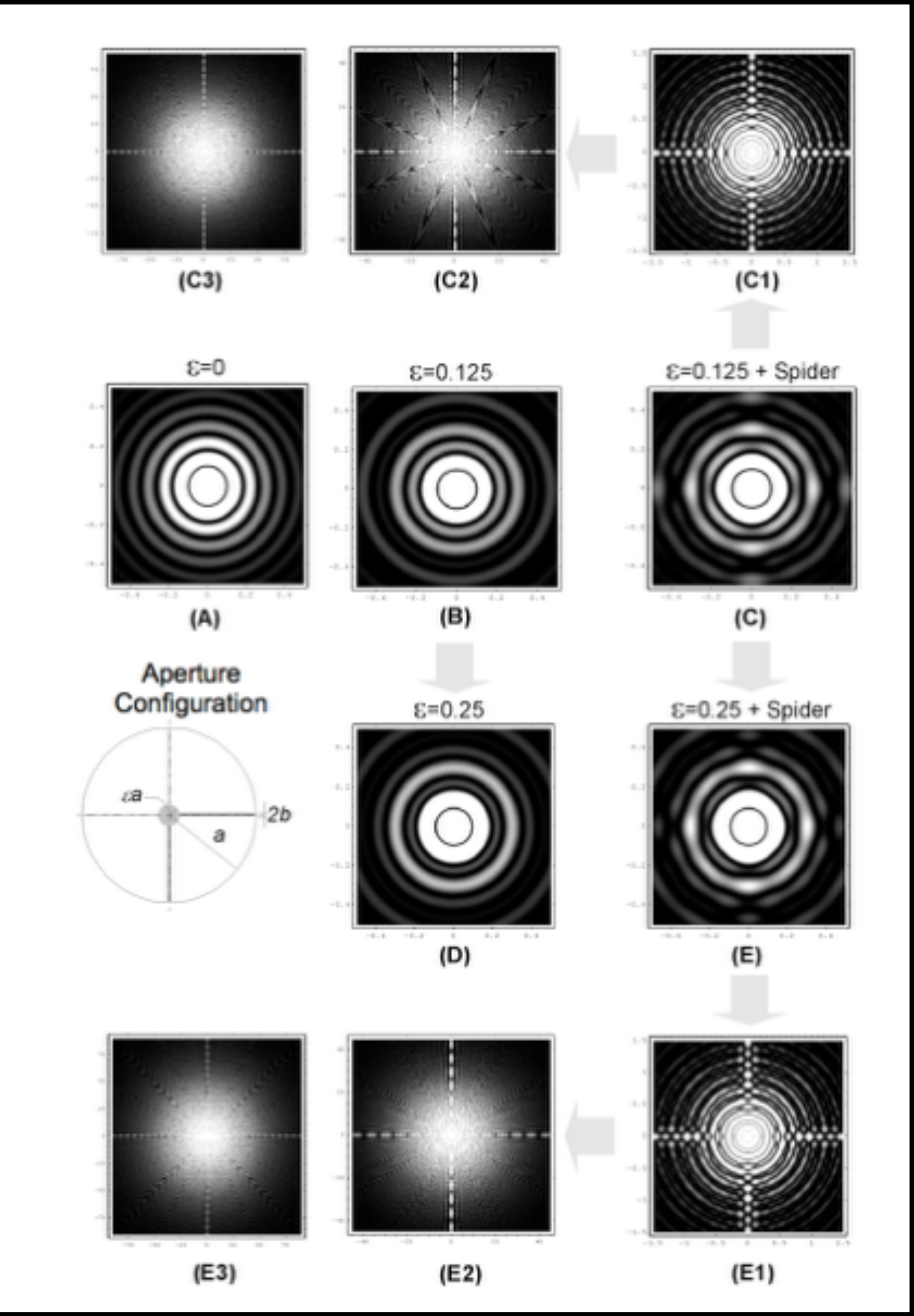


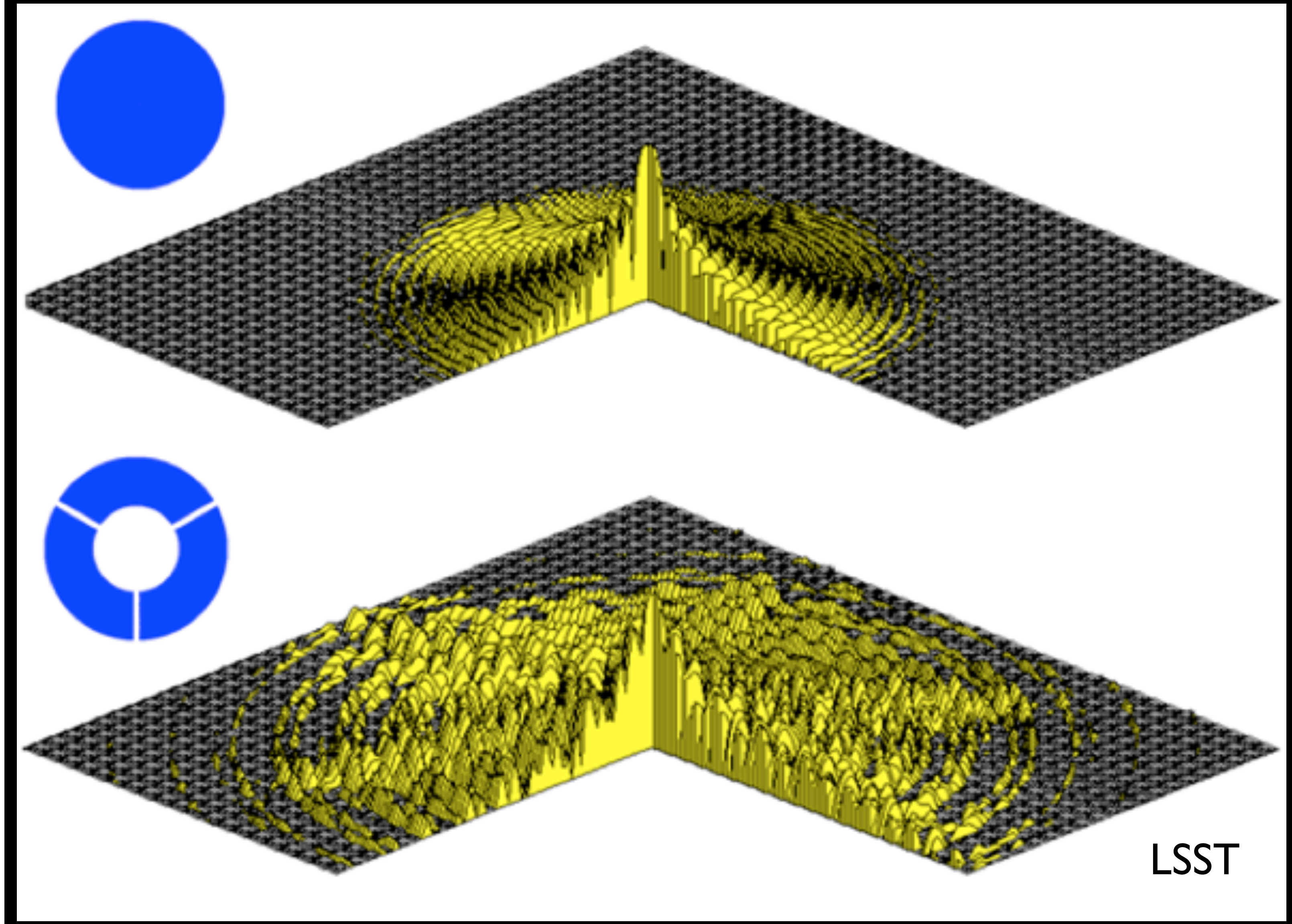

Credit: J.C. Guillandre



Duc *et al.* (2014)

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



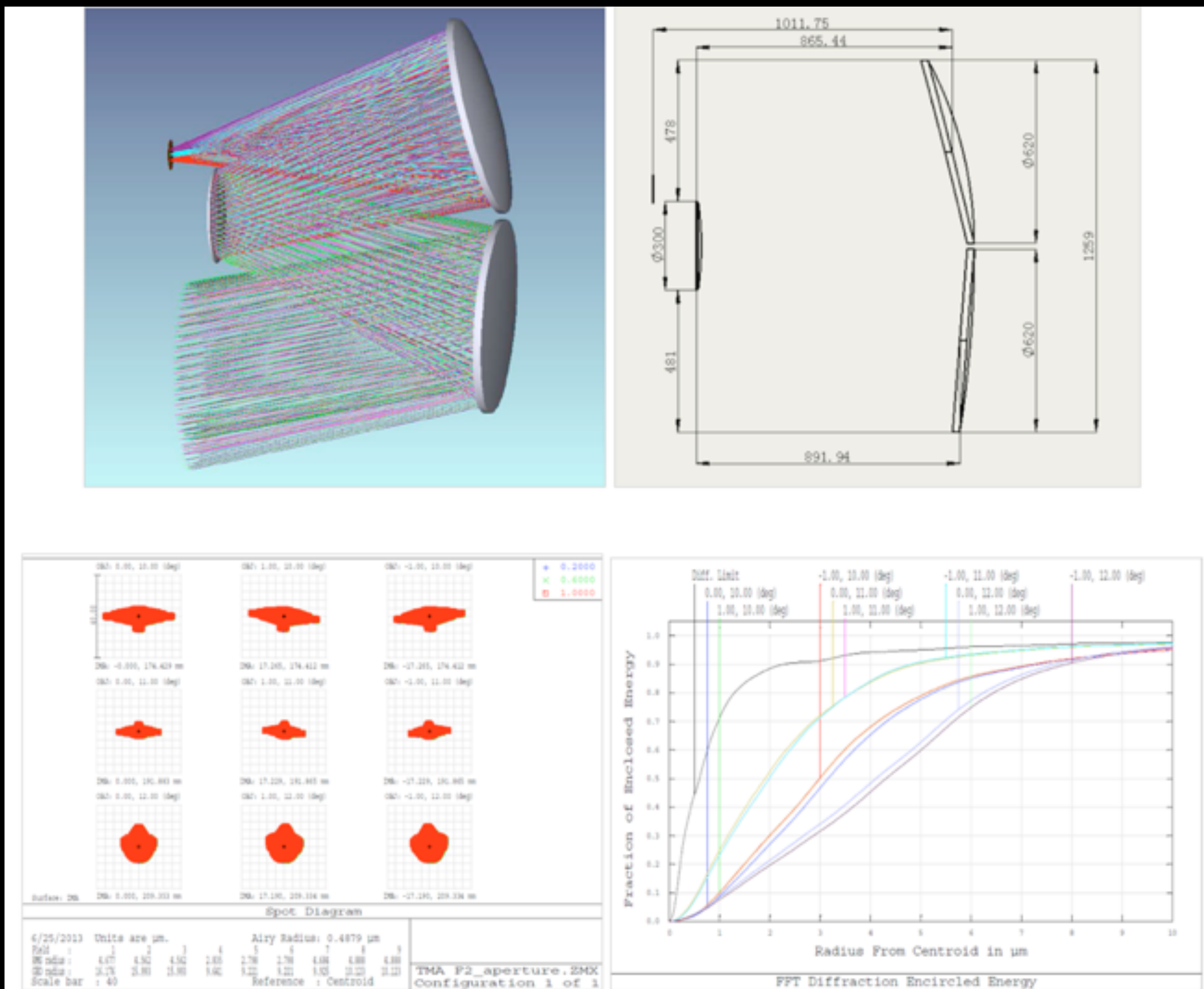


⇒ zero obstruction is required

for ultimate LSB photometry

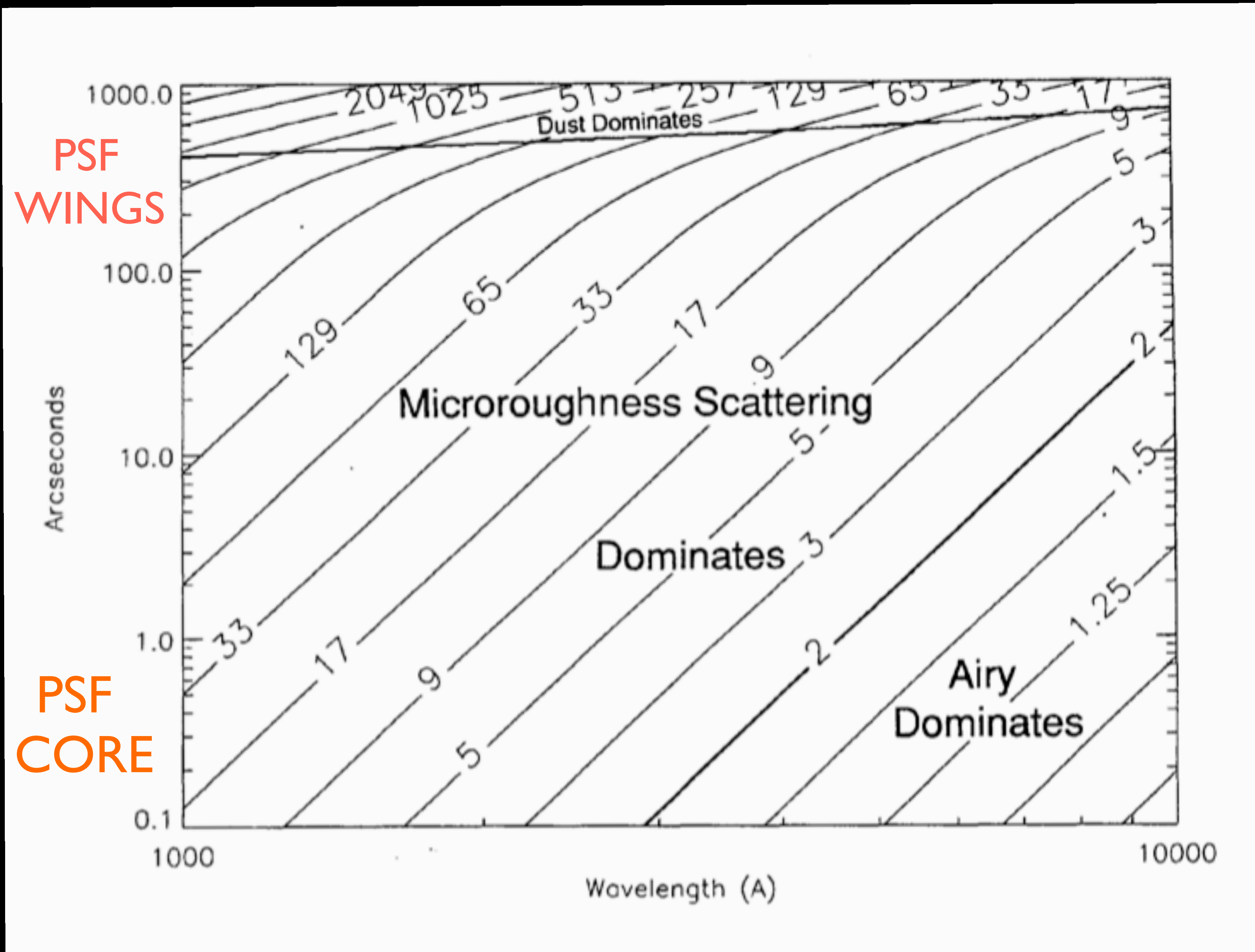
Key additional requirements for MESSIER :

— flat focal plane (but curved Gaia-like FPA TBD)
— no lenses (to avoid Čerenkov radiation)

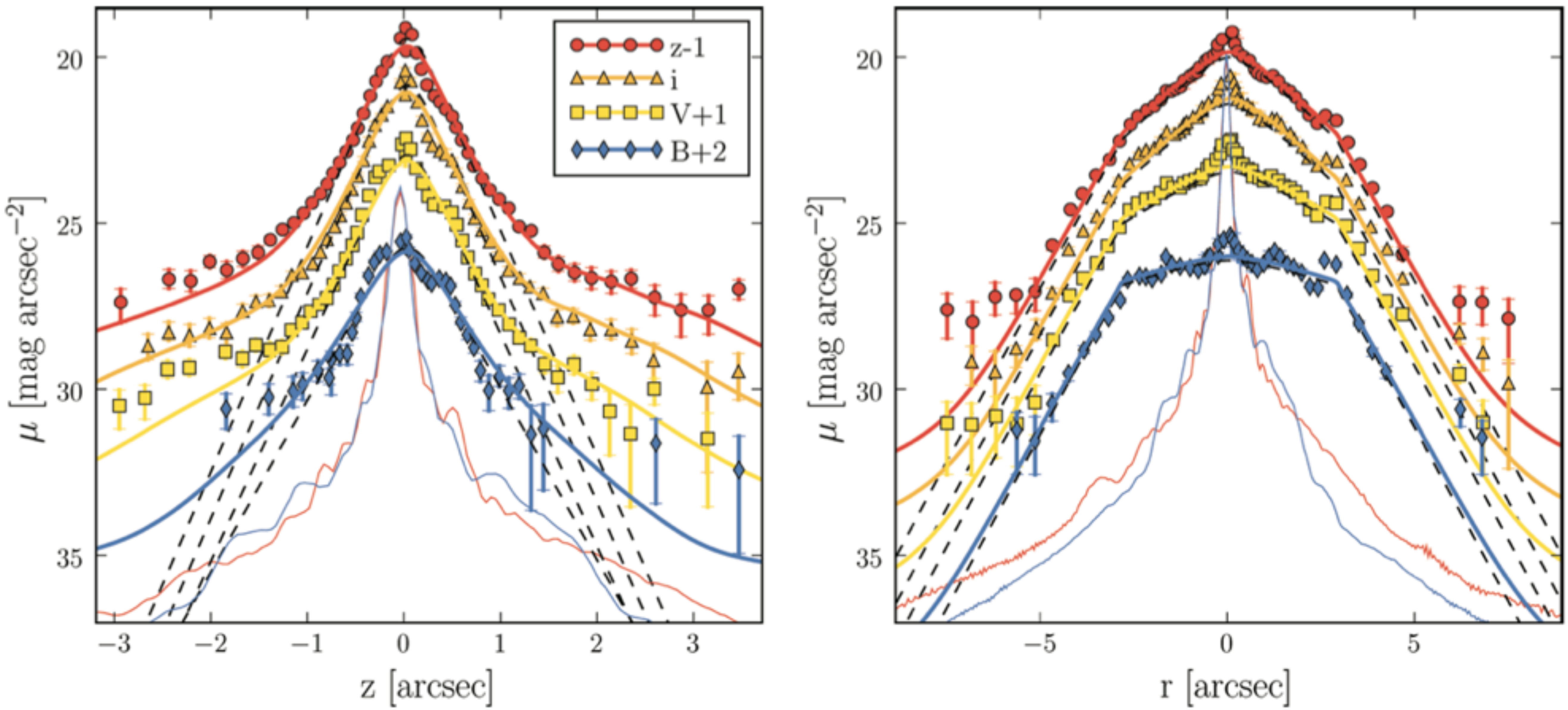


Current solution

TMA
free-form mirrors
unobscured, off-axis
easy baffling
flat focal plane
f/2
4° x 2°
TRL 9 (optics/FP)
alignment issues TBD

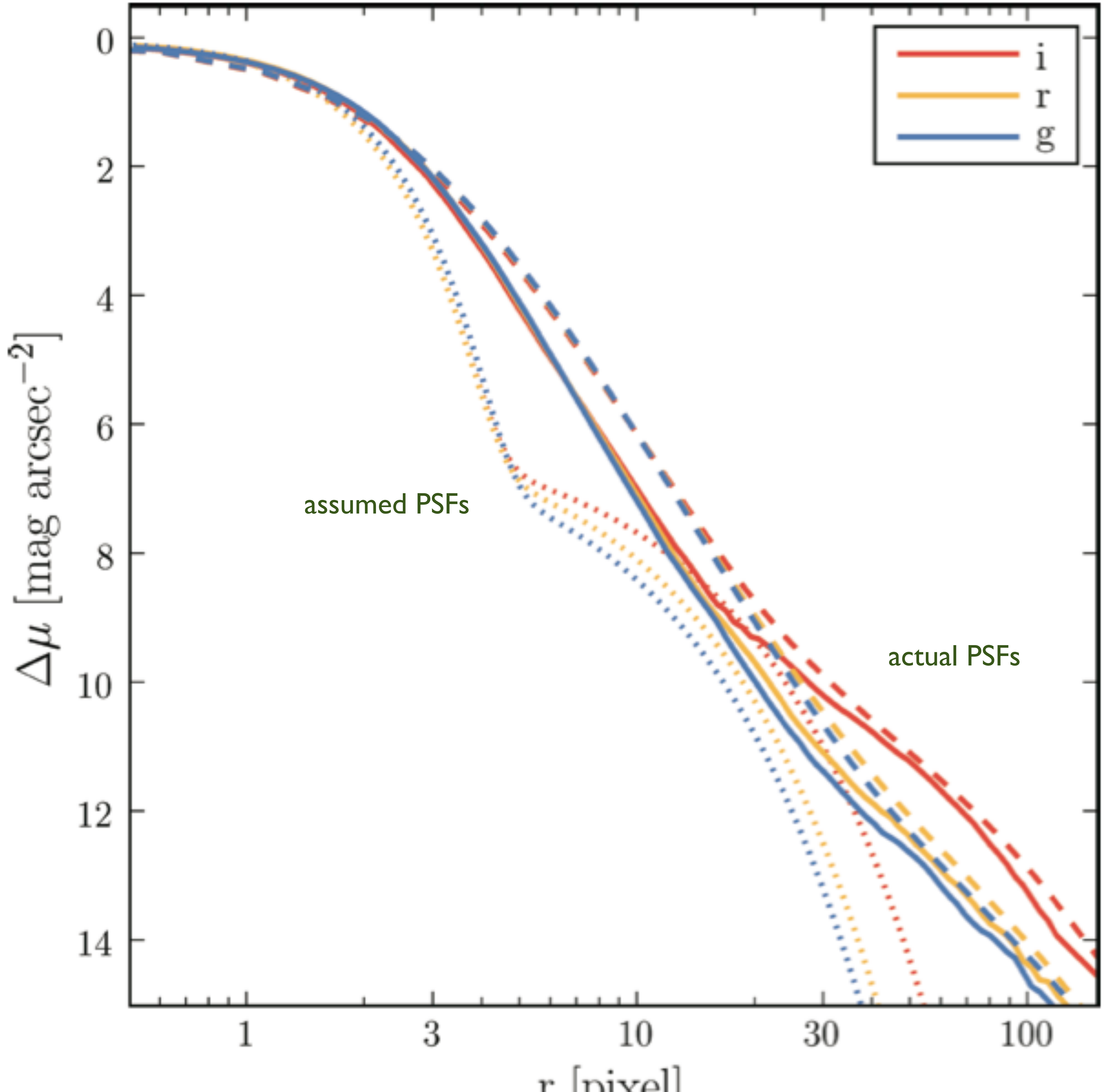

PSF
WINGS
PSF
CORE
Dust Dominates
Microroughness Scattering
Dominates
Airy
Dominates
Arcseconds
Wavelength (A)
1000.0
100.0
10.0
1.0
0.1
1000
10000
2049
1025
513
257
129
65
33
17
9
5
3
2
1.5
1.25

Importance of the stability and of the wings of the PSF



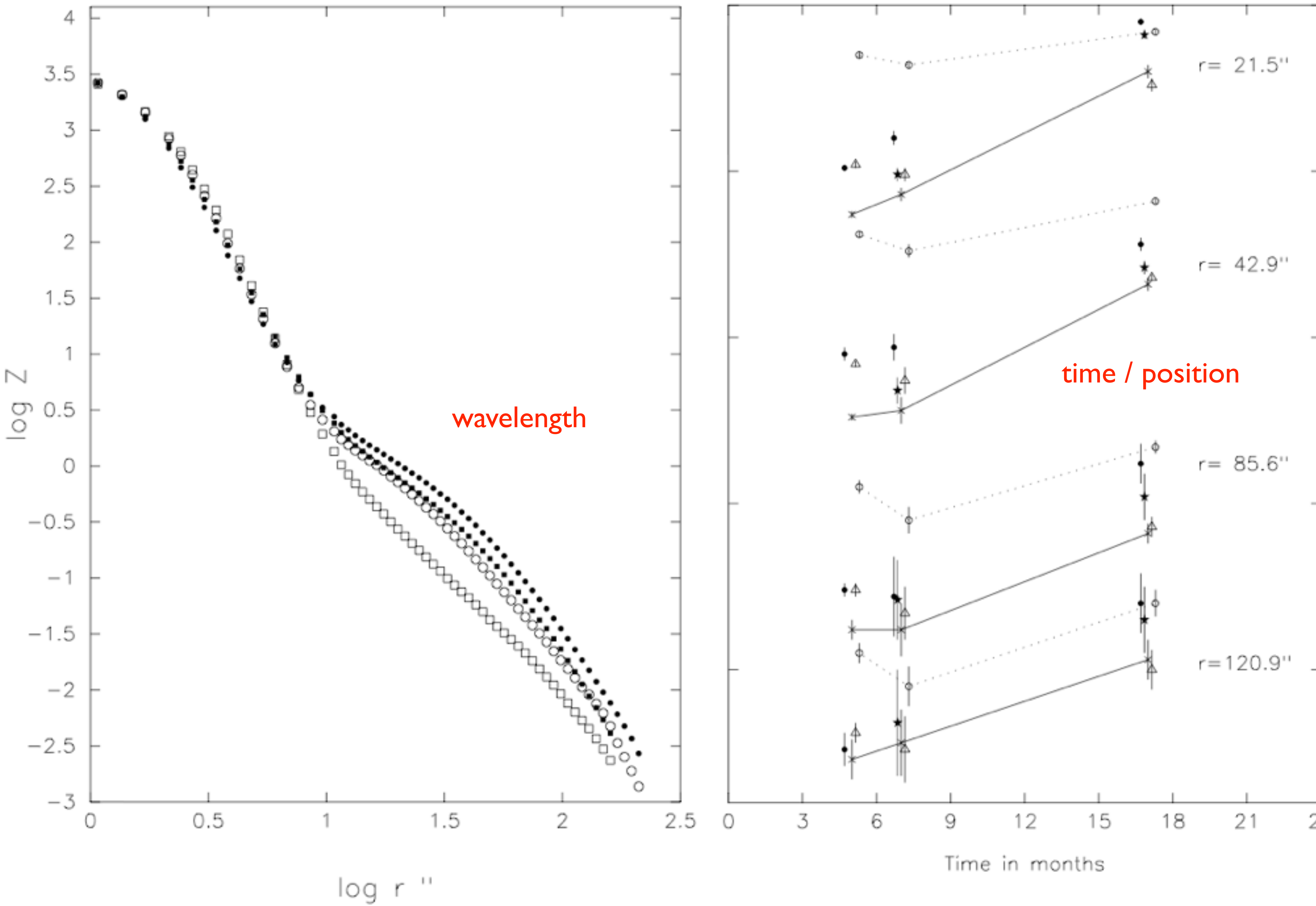
Extended galactic ultra red haloes ??

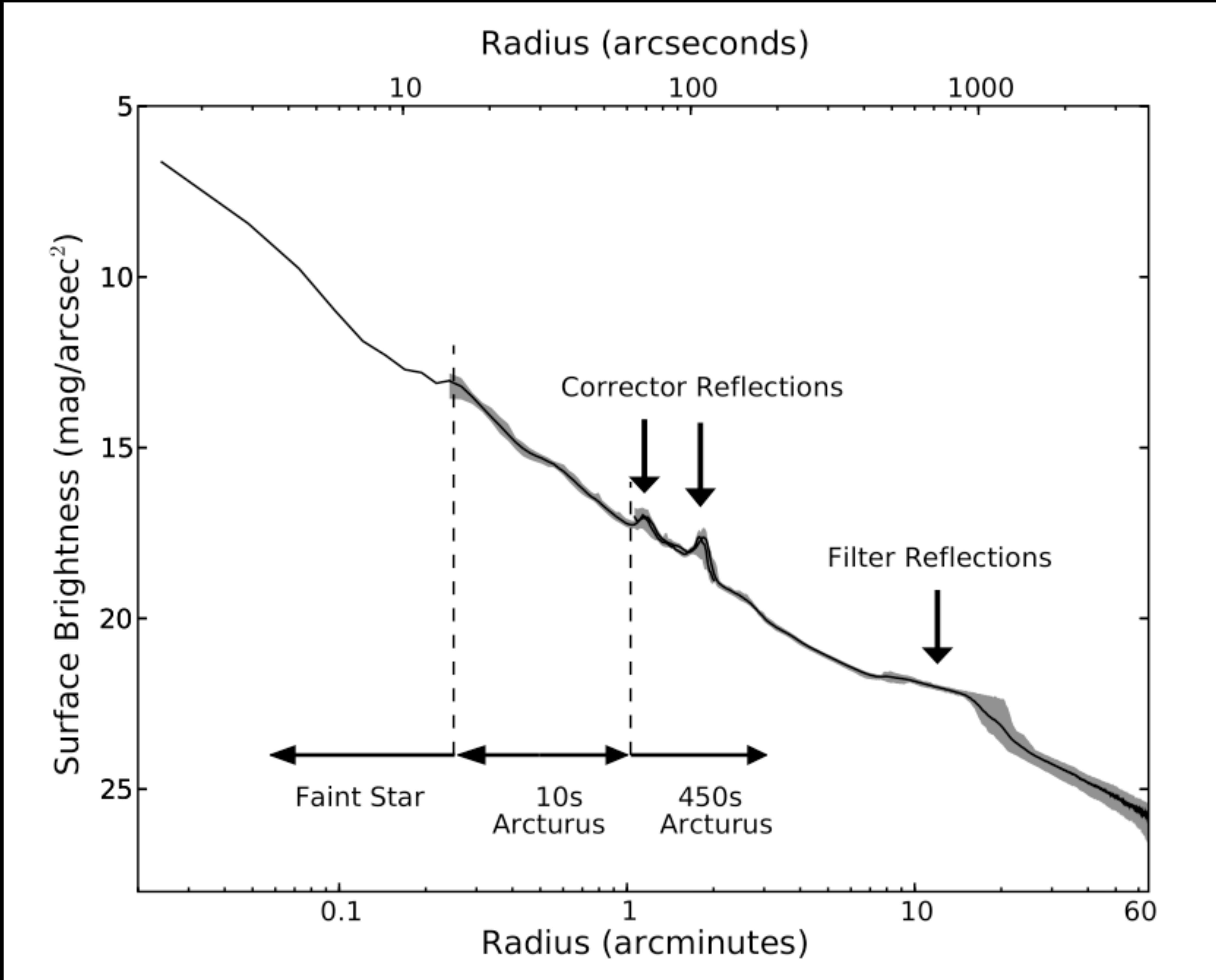
Zibetti, White & Brinkmann (2004)



i
r
g
assumed PSFs
actual PSFs
0
2
4
6
8
10
12
14
1
3
10
30
100
$\Delta\mu$ [mag arcsec^{-2}]
r [pixel]

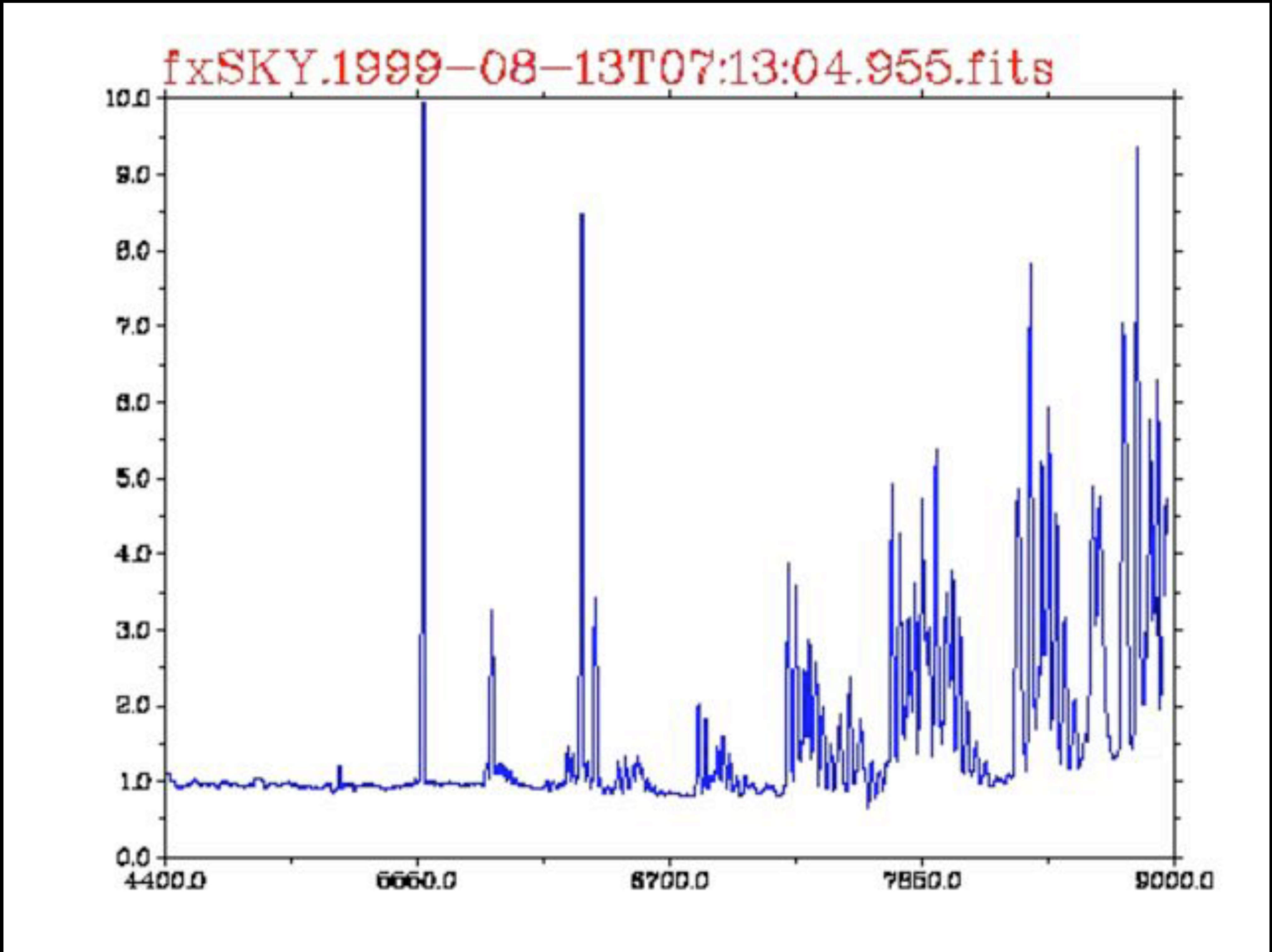
Variations in the PSF (Michard 2002)





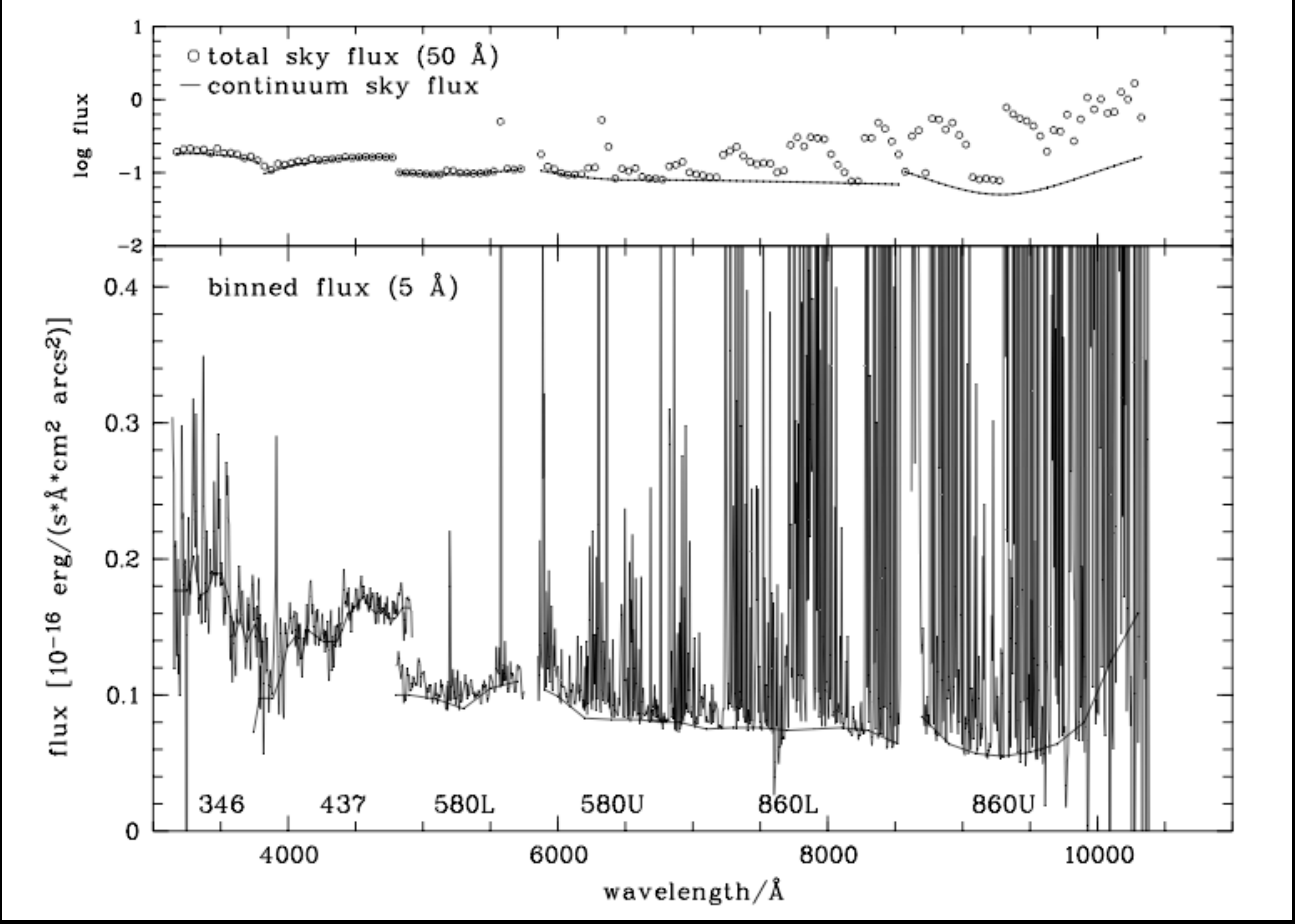
Radius (arcseconds)
10
100
1000
5
10
15
20
25
Surface Brightness (mag/arcsec^2)
Corrector Reflections
Filter Reflections
Faint Star
10s
Arcturus
450s
Arcturus
0.1
1
10
60
Radius (arcminutes)

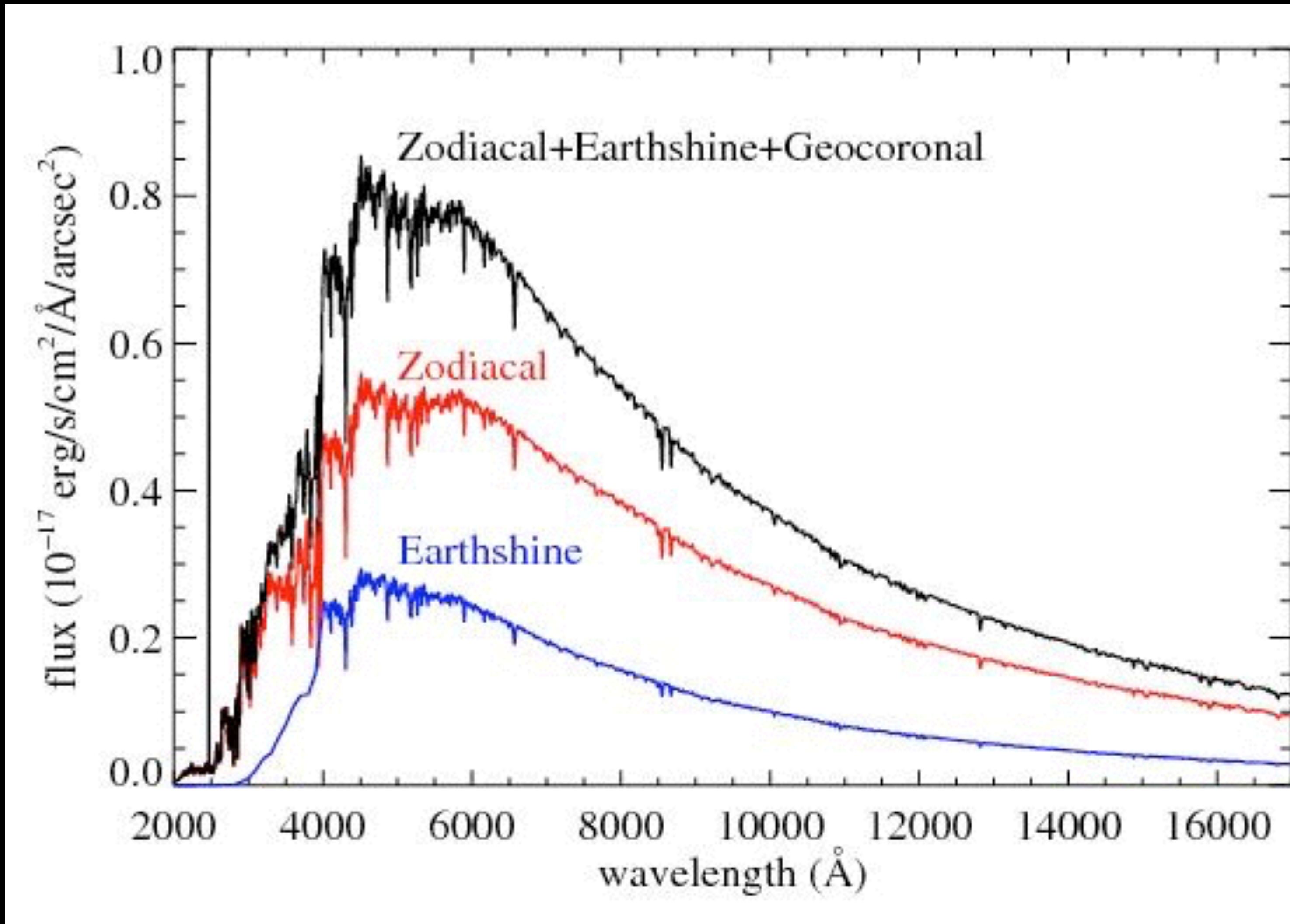
Fighting against the variable sky background



F. Patat (Paranal)

Going into space: issues and challenges



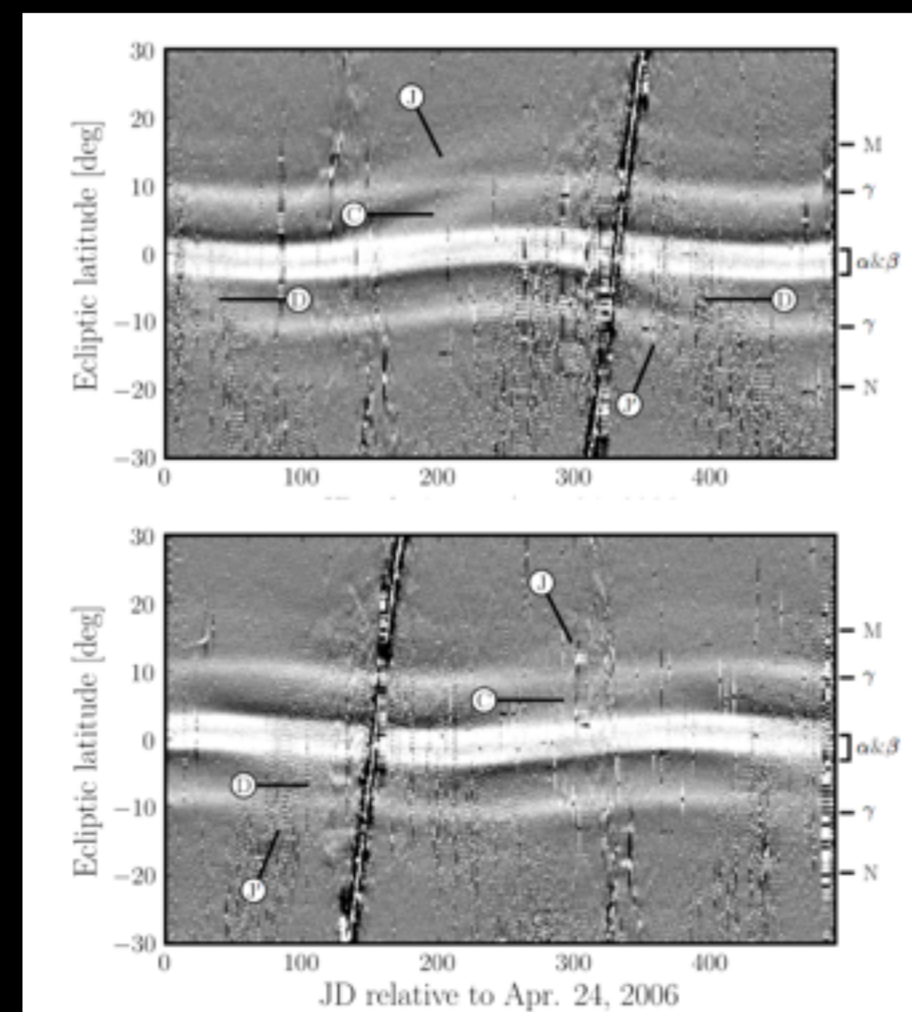


No sky variability but three foregrounds:

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

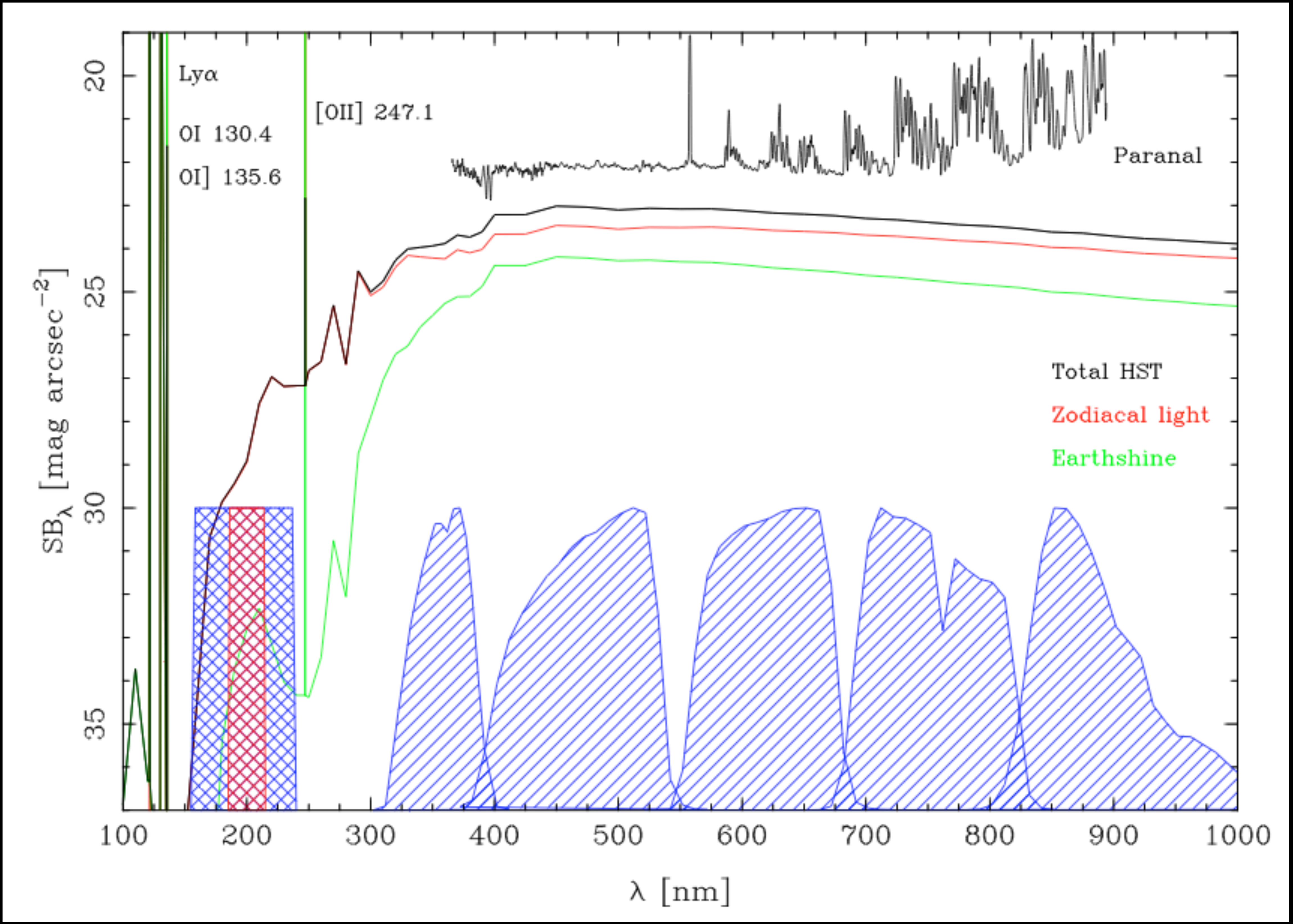
➔ Minimise zodiacal contamination
orbit to oversample ecliptic poles

➔ Minimise airglow/geocorona
orbit >> 300 km (HST)

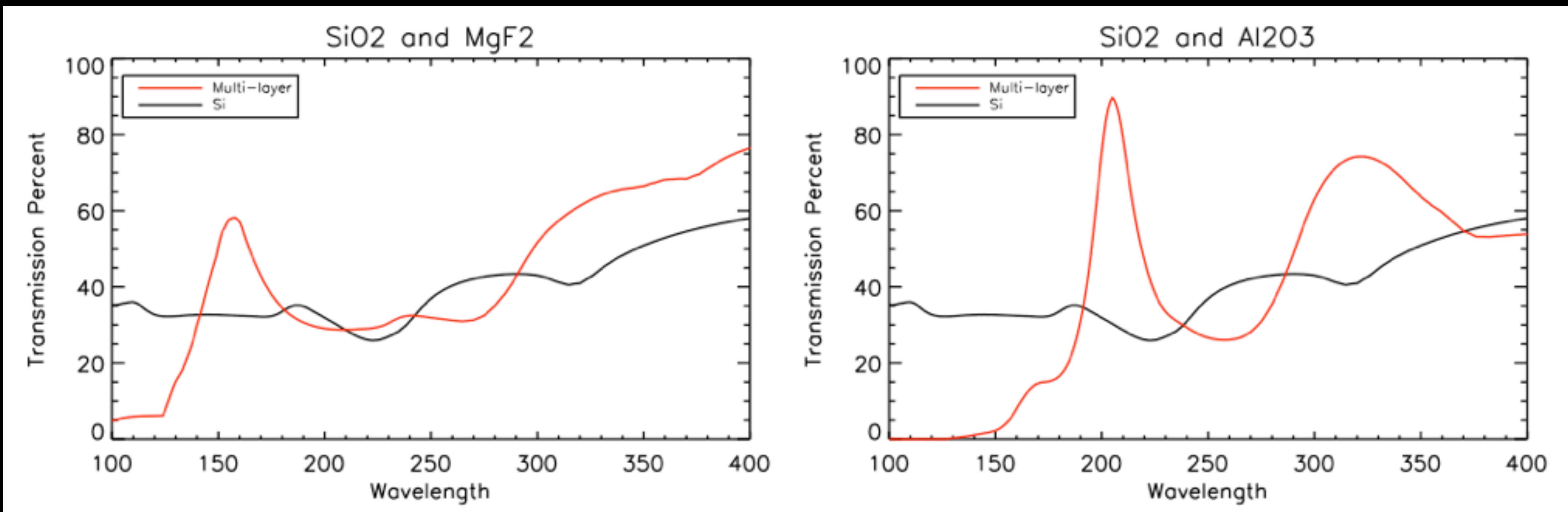


Zodiacal light variability as observed by AKARI

Requirement for filters



New generation of UV detectors



JPL/Columbia

Delta doping Atomic Layer Deposition (multi-layer)
+ AR coatings are reaching a quantum efficiency of 80-90%

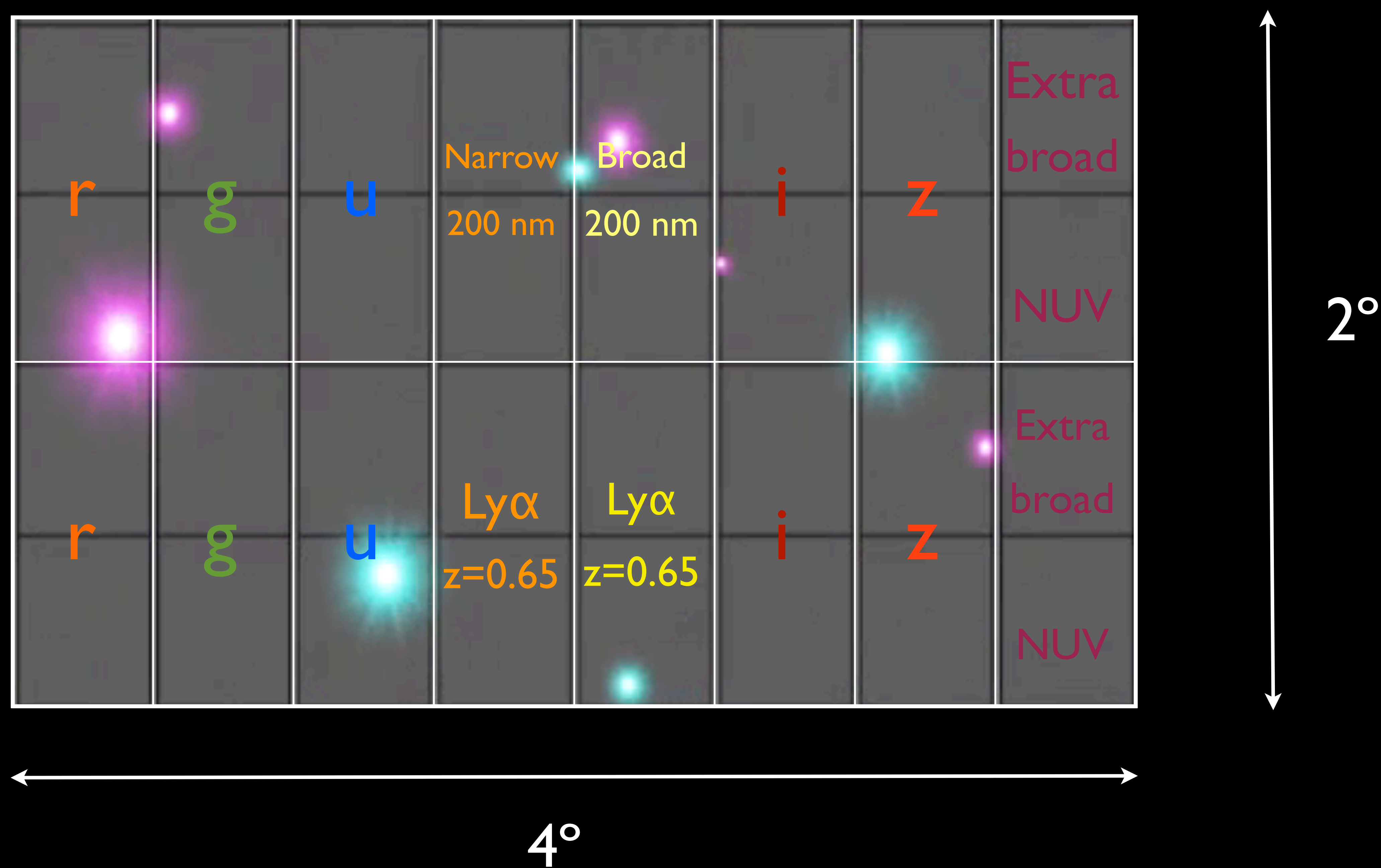
ITAR free (in principle, TBC)

Focal plane configuration

8 x 2 independent controllers in drift-scan mode

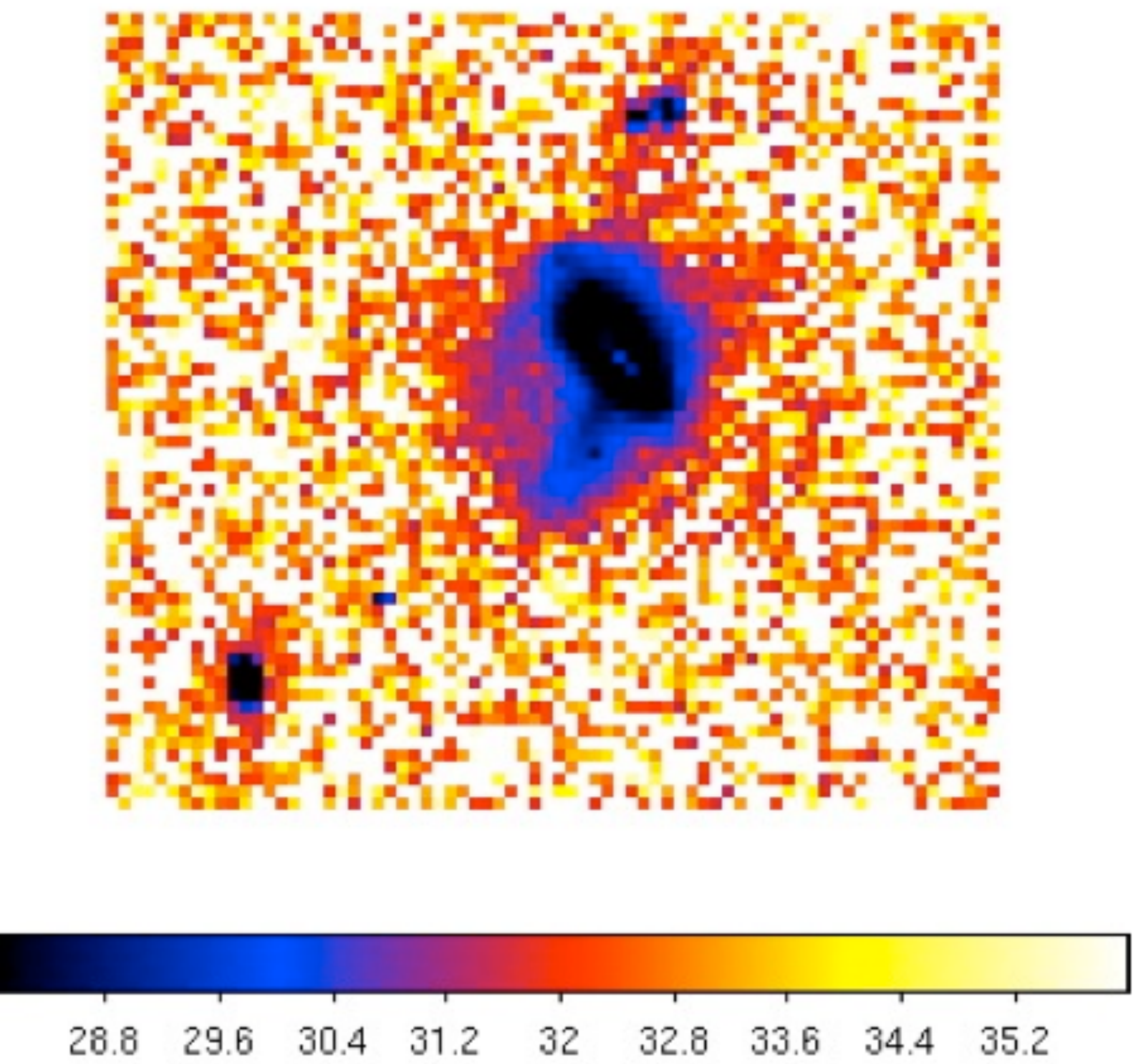
QE of each EMCCD optimised for each filter (>85%)

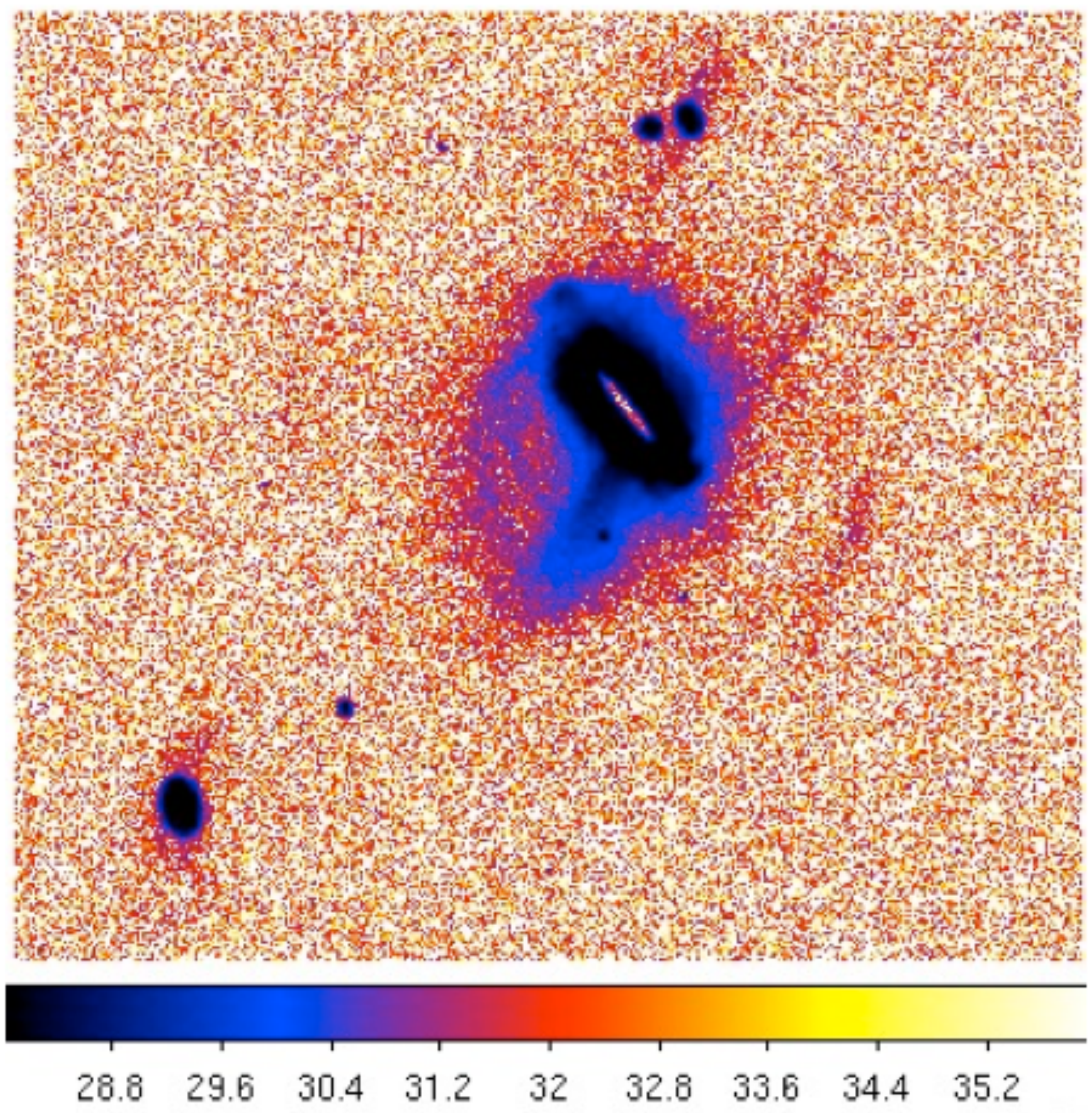
Highly efficient: no moving parts, passive cooling



Expected performances - I   Optical bands

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





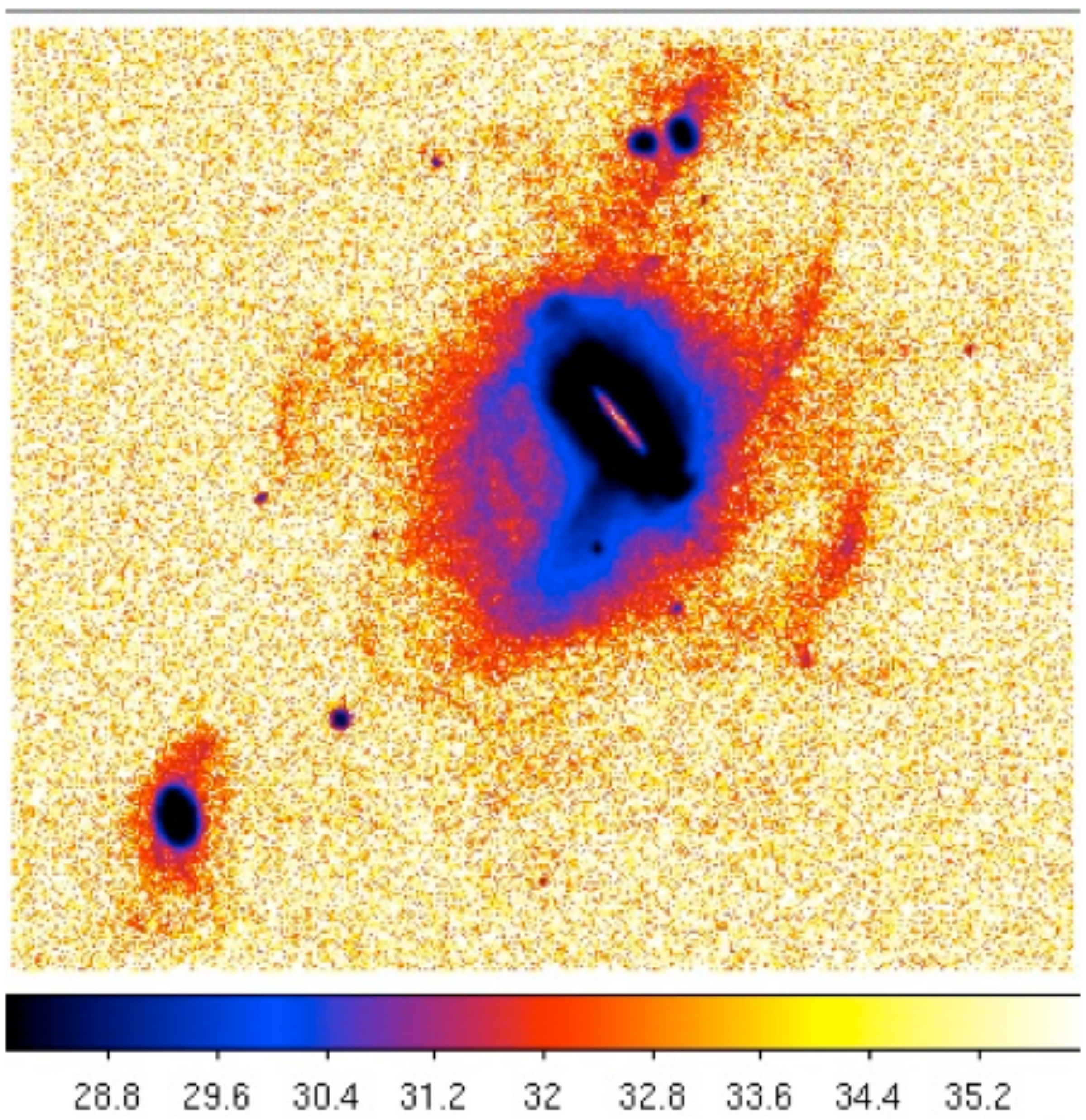
R. Ibata

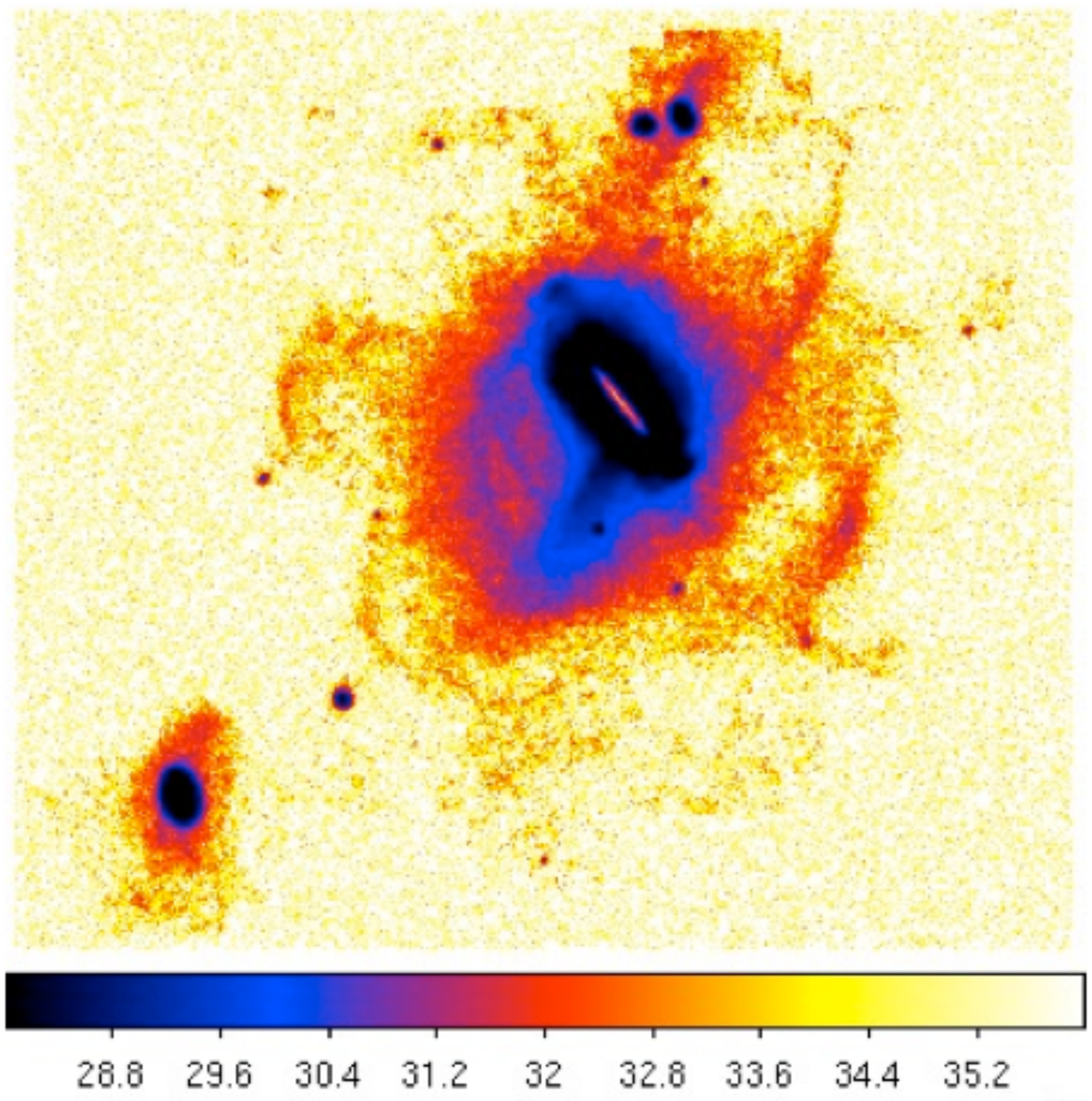
10 ksec
5 kpc × 5 kpc

100 ksec
1 kpc × 1 kpc (14″ × 14″)

Expected performances - 1   Optical bands

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





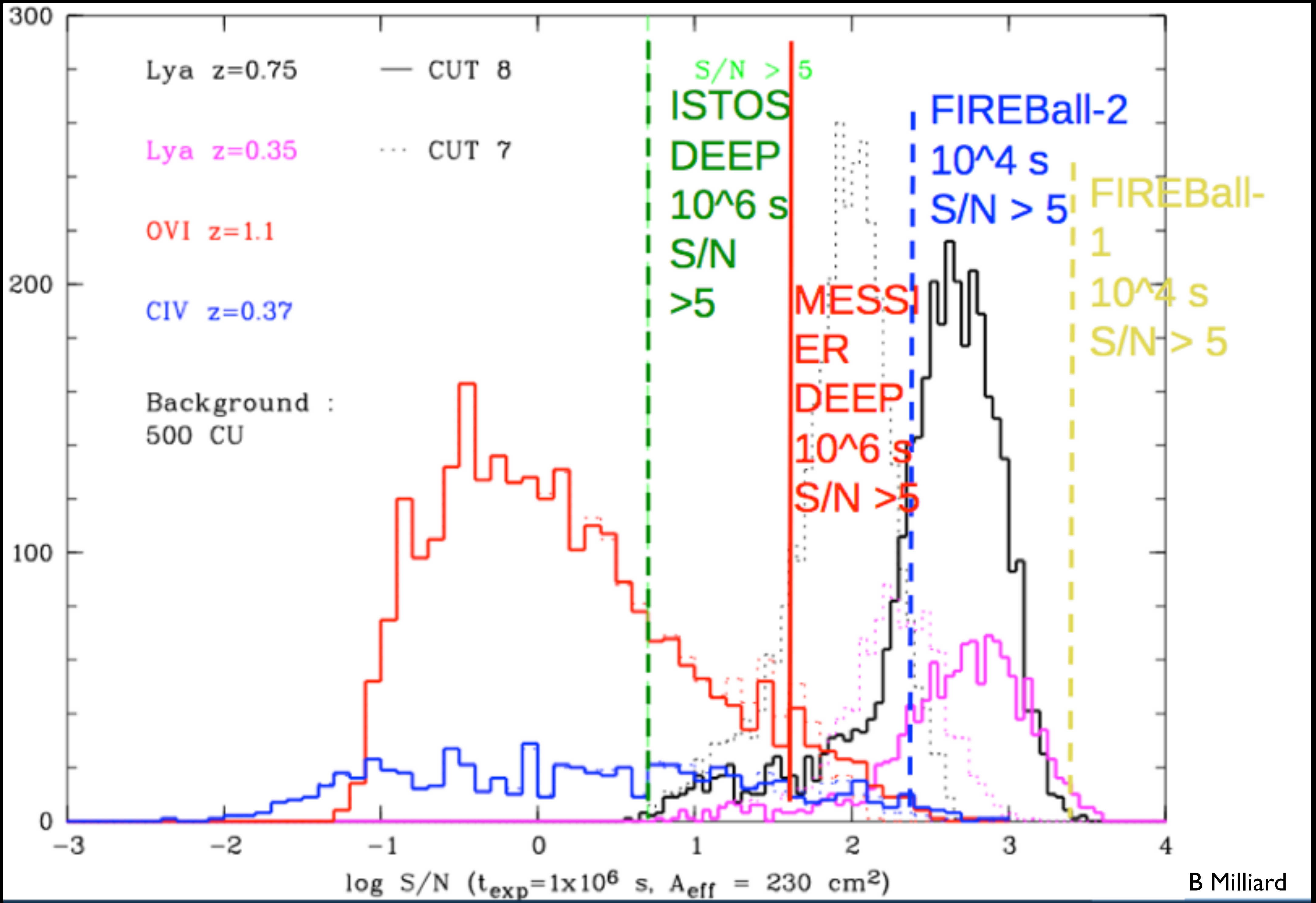
R. Ibata

1 Msec
1 kpc × 1 kpc

10 Msec
1 kpc × 1 kpc

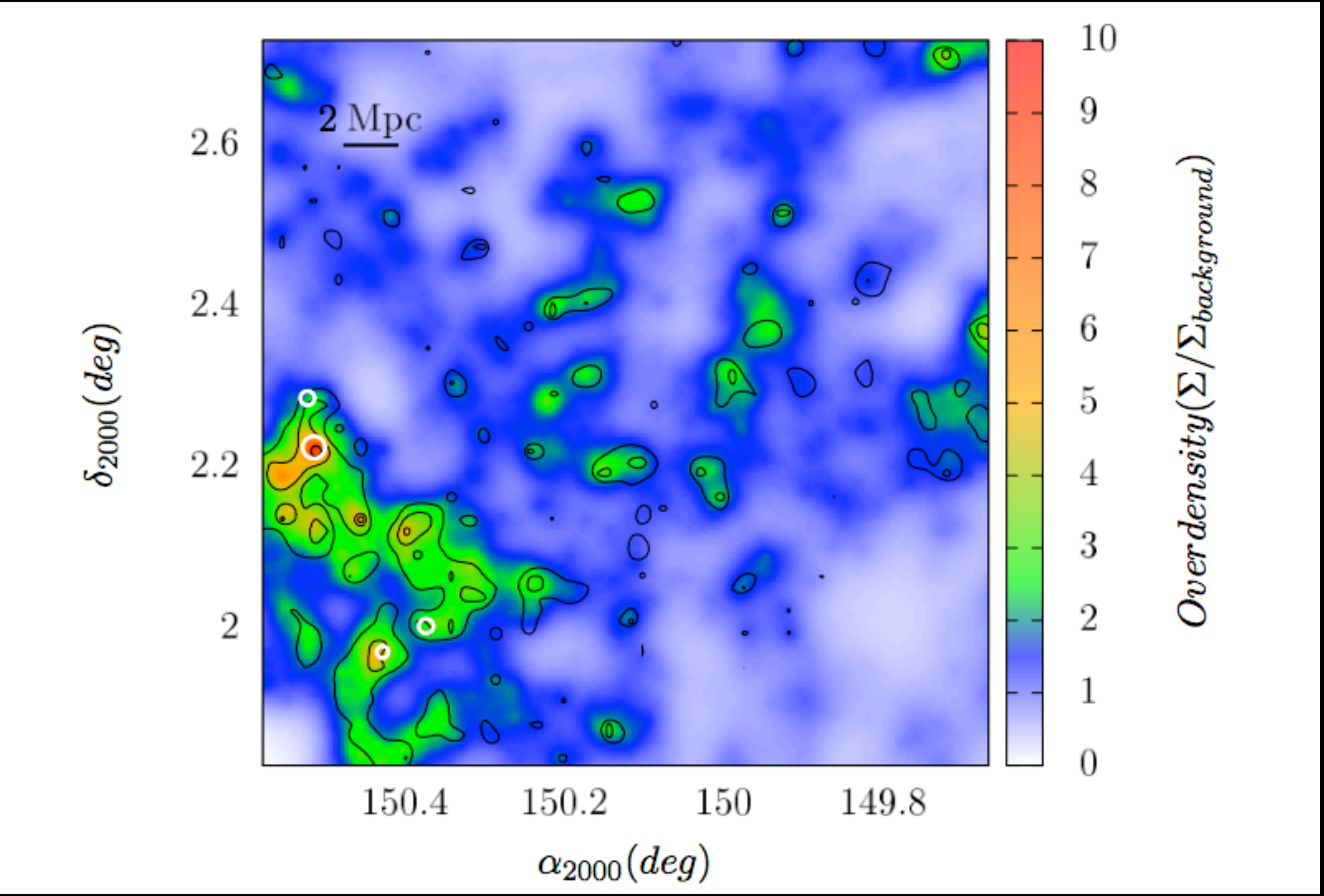
Expected performances - II   UV bands

Signal / Noise for simulated MESSIER images of the cosmic web



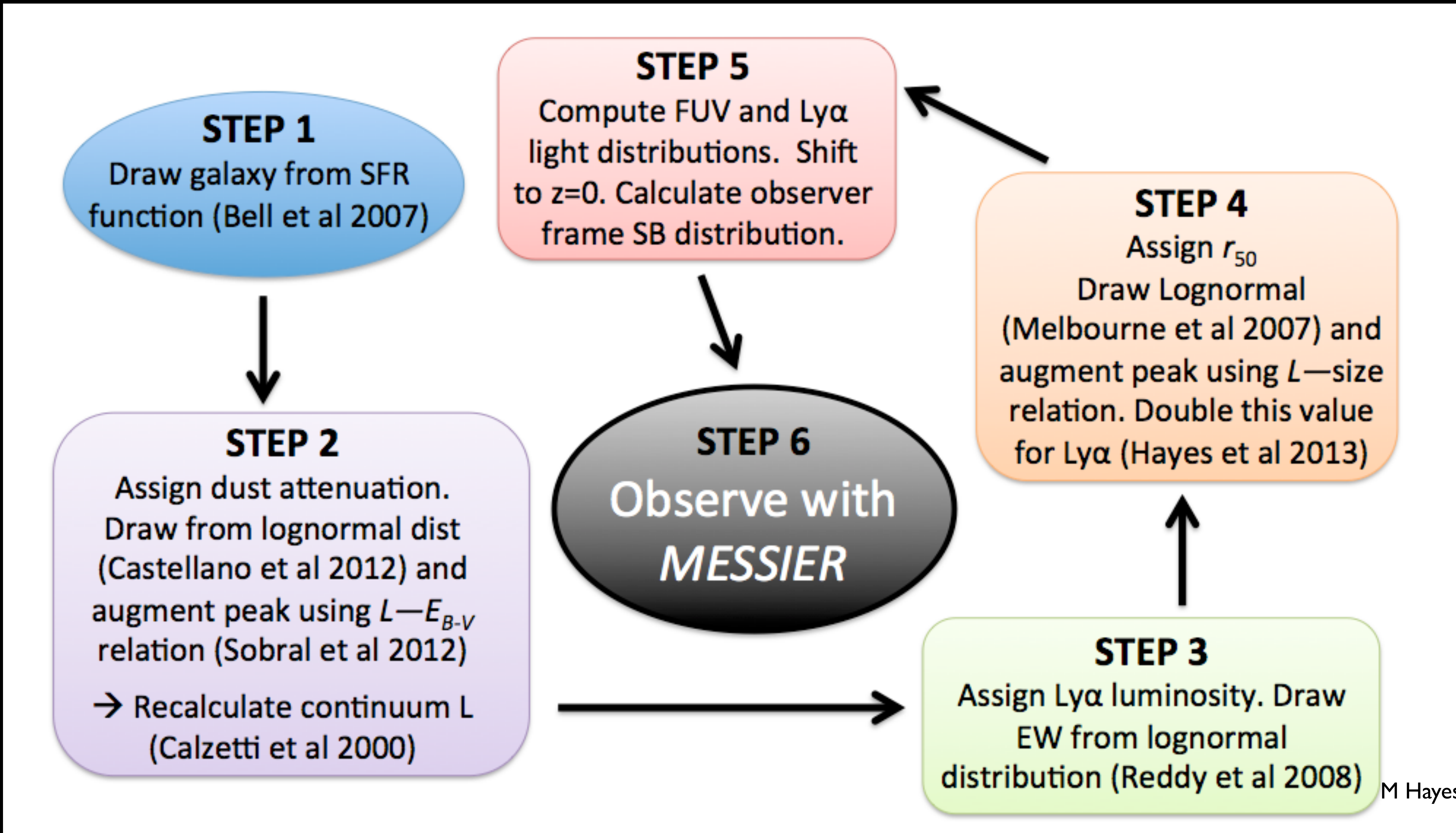
B Milliard

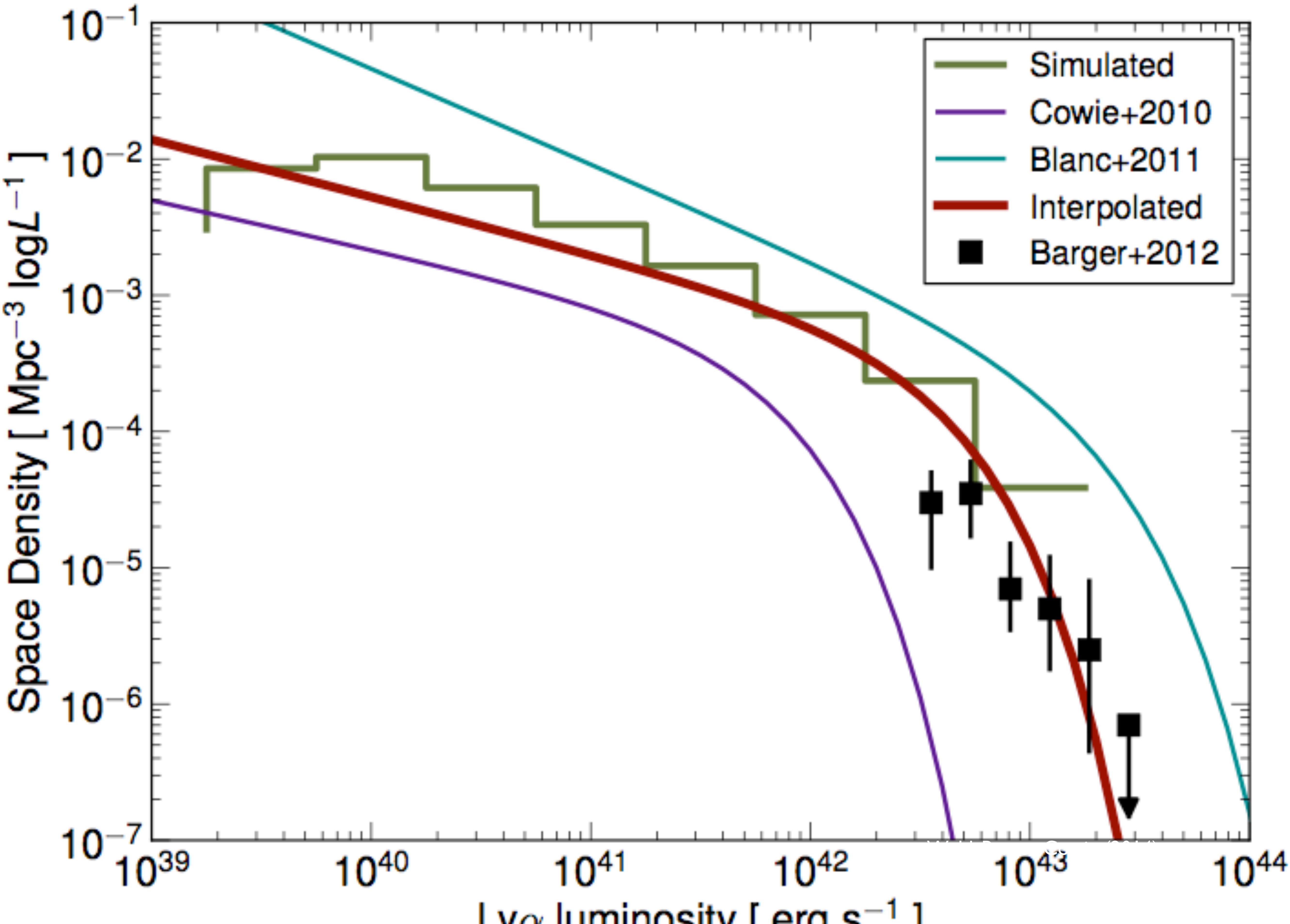
K_s-selected filaments at $0.83 < z < 0.86$ (HiZELS area within COSMOS)



Darvish *et al.* (2014) arXiv:1409:7695

Expected performances - II UV bands

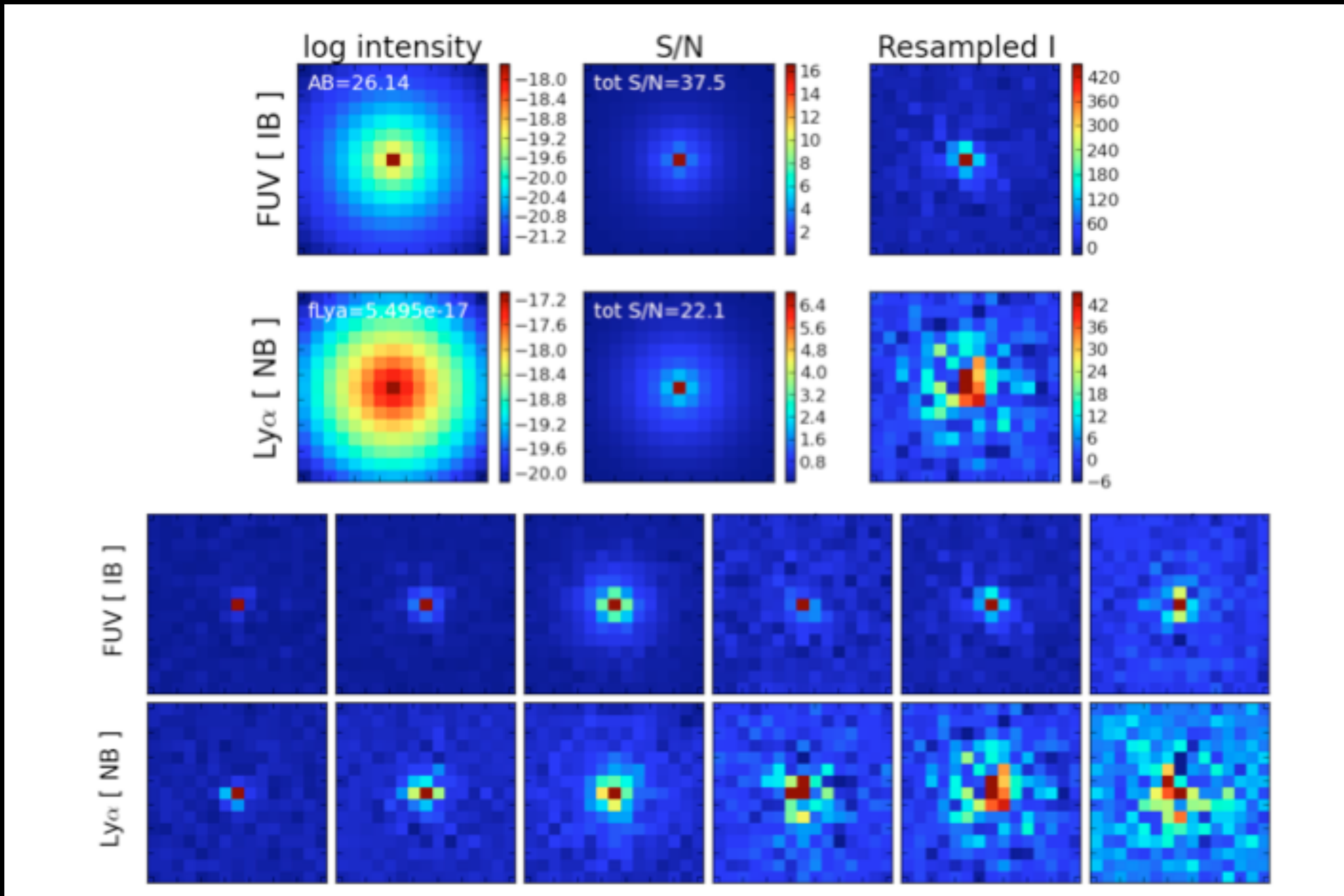




Simulated
Cowie+2010
Blanc+2011
Interpolated
Barger+2012
Space Density [Mpc^{-3} logL^{-1}]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{39}
10^{40}
10^{41}
10^{42}
10^{43}
10^{44}
Lyα luminosity [erg s^{-1}]

M Hayes

Expected performances - II   UV bands

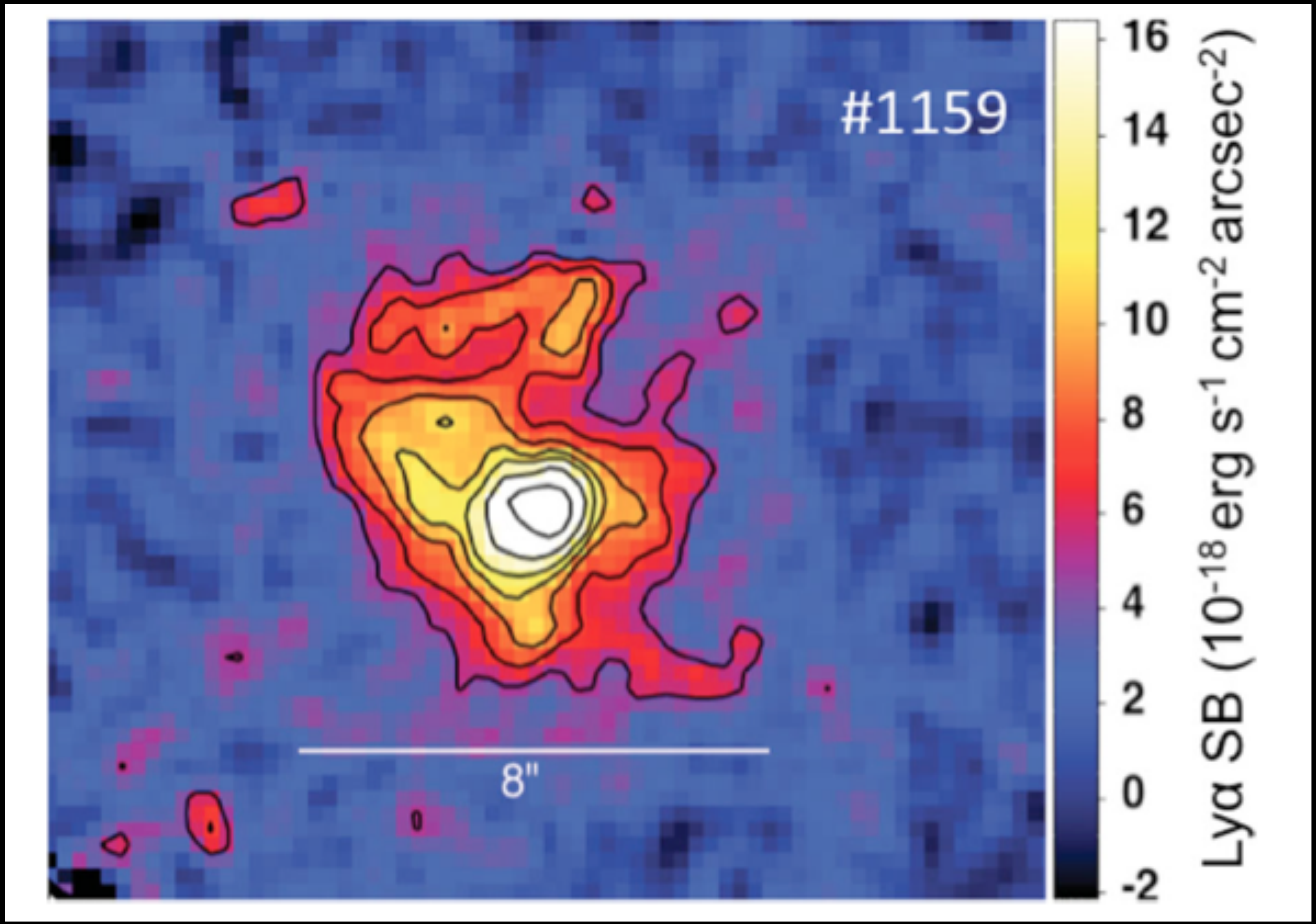


Over 3 $\times 10^6$ galaxies at $z=0.65$ detected in Lyα with S/N>30

What is the nature of Lyα blobs ?

Photoionisation by a central AGN
Cooling radiation
Shocks by galactic outflows
Resonant scattering from sources

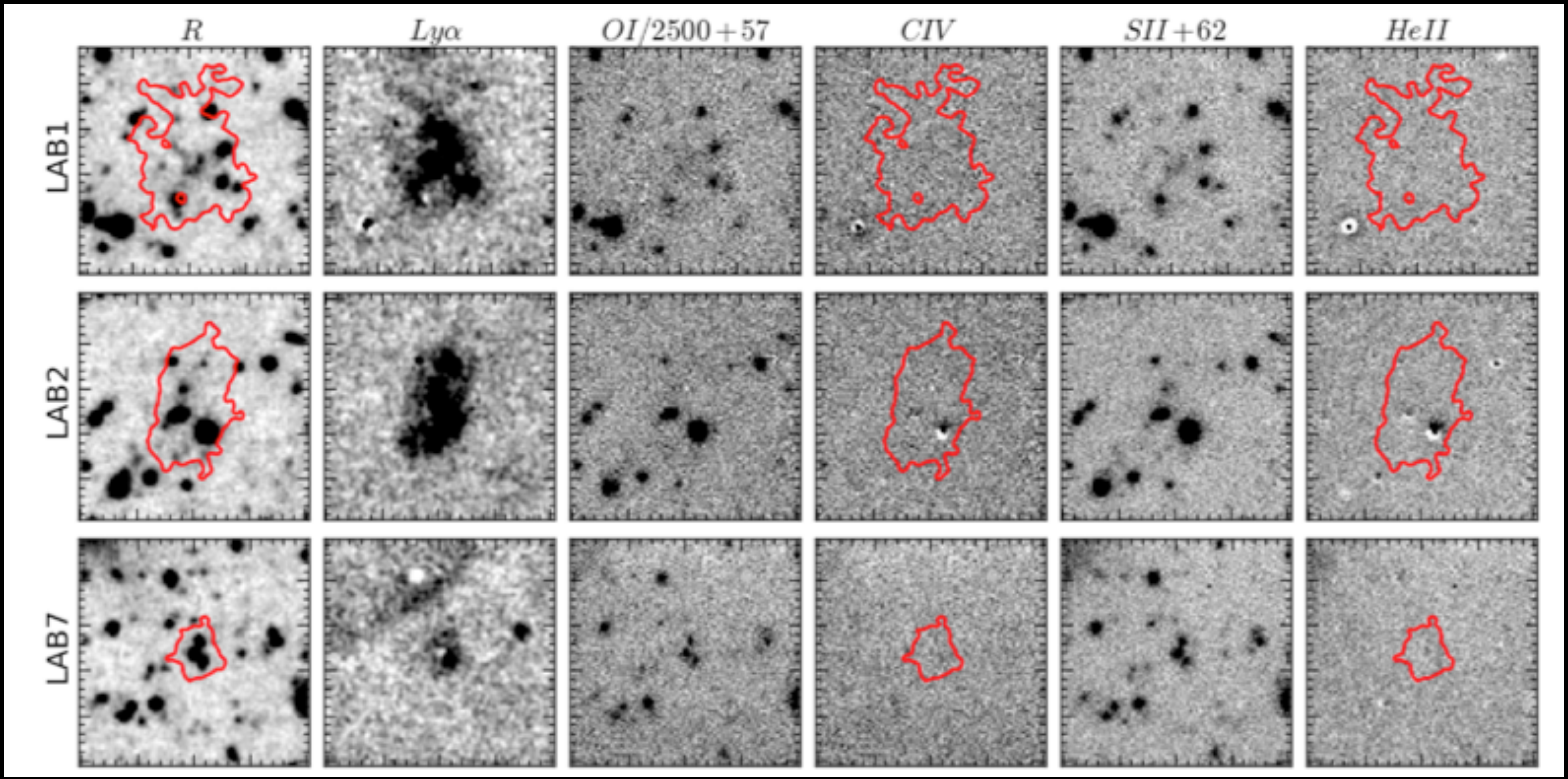
27 hours at VLT



Cantalupo, Lilly & Haehnelt (2012)

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

Searching for possible He II and C IV emission lines at z=3.1



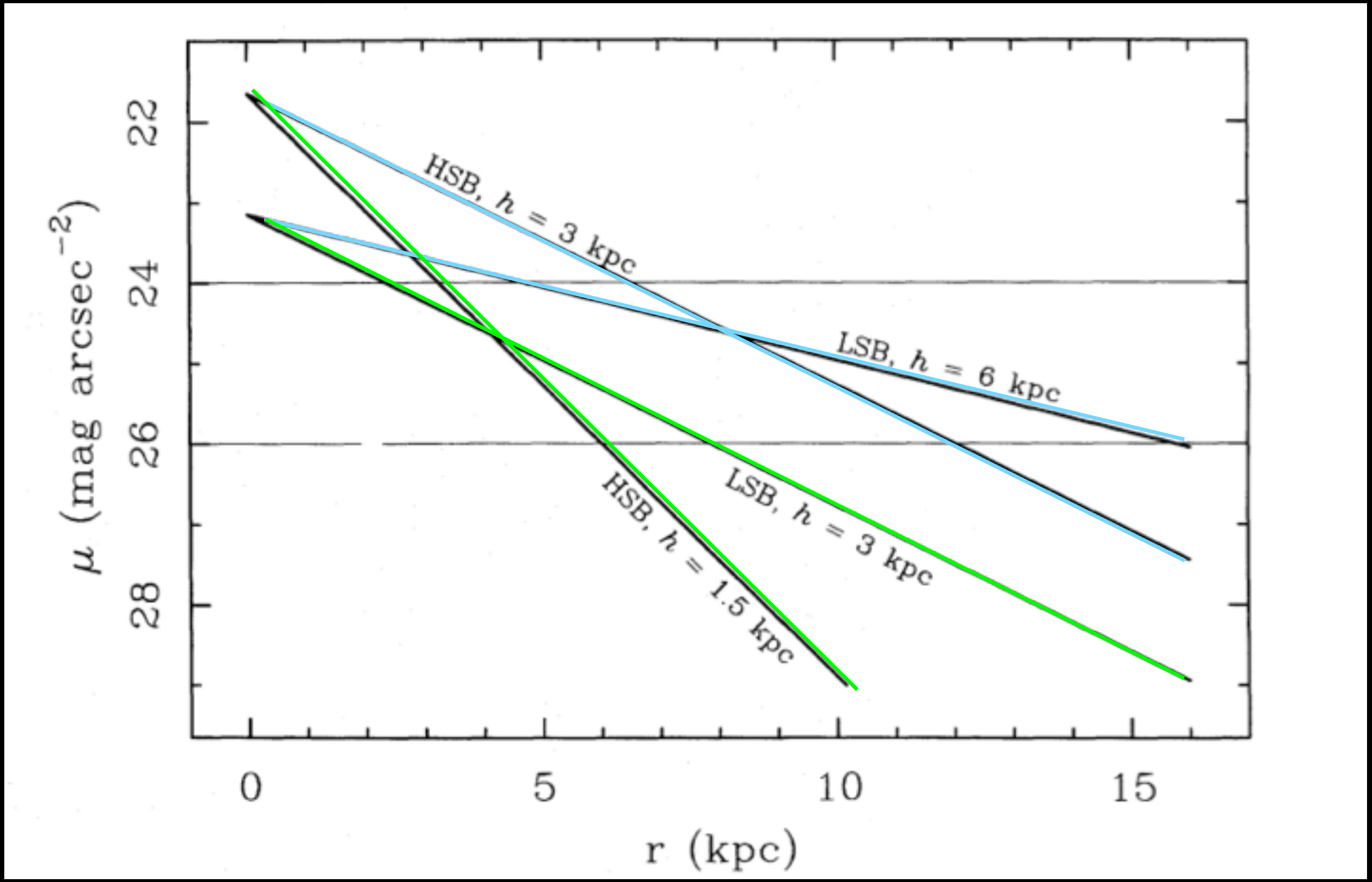
Exposure time: 45 hours at VLT+Subaru

Arrigoni Battaia *et al.* (2014)

Key science issues (free by-products)

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

SC1 What is the luminosity function of galaxies ?

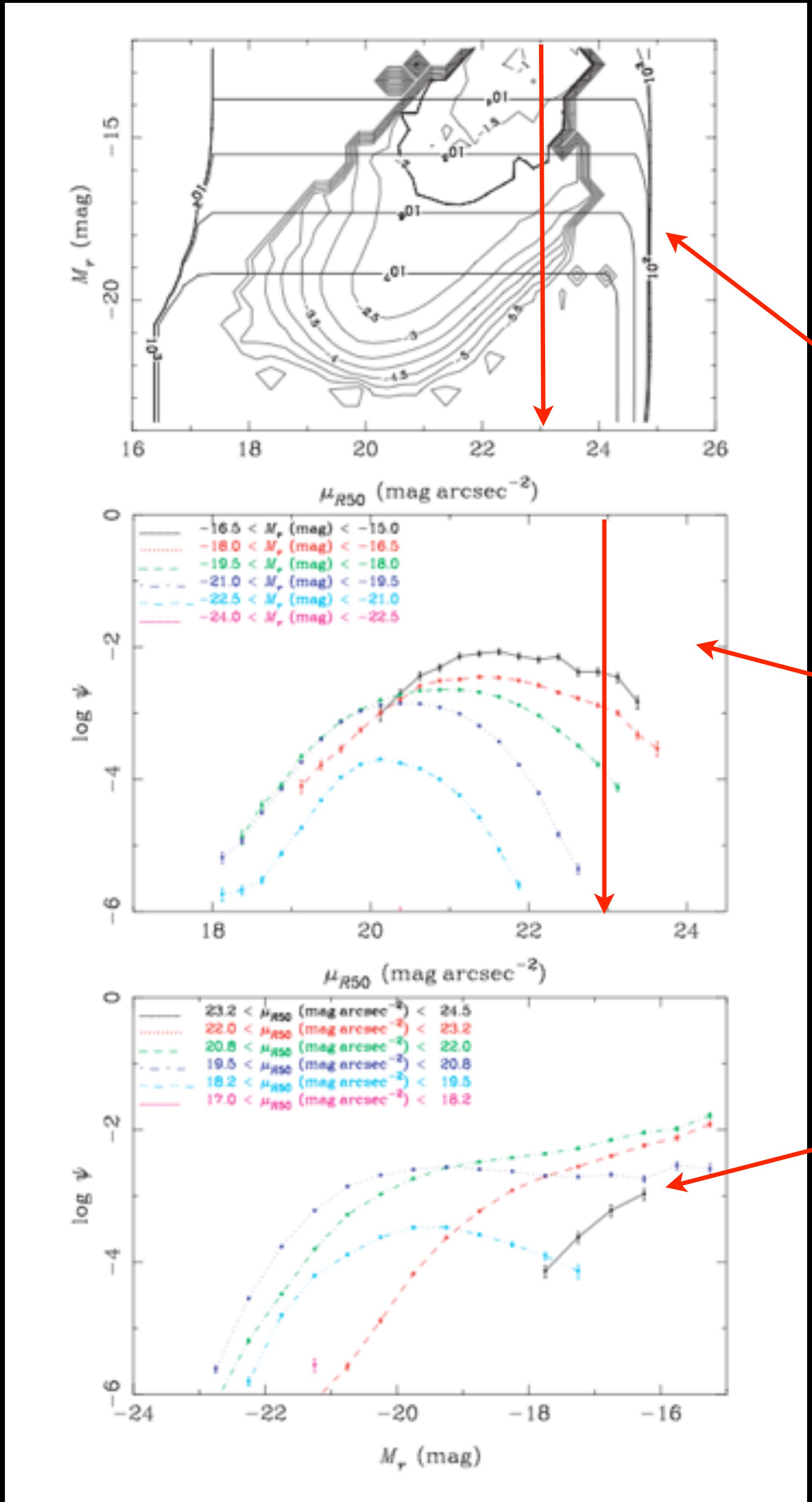


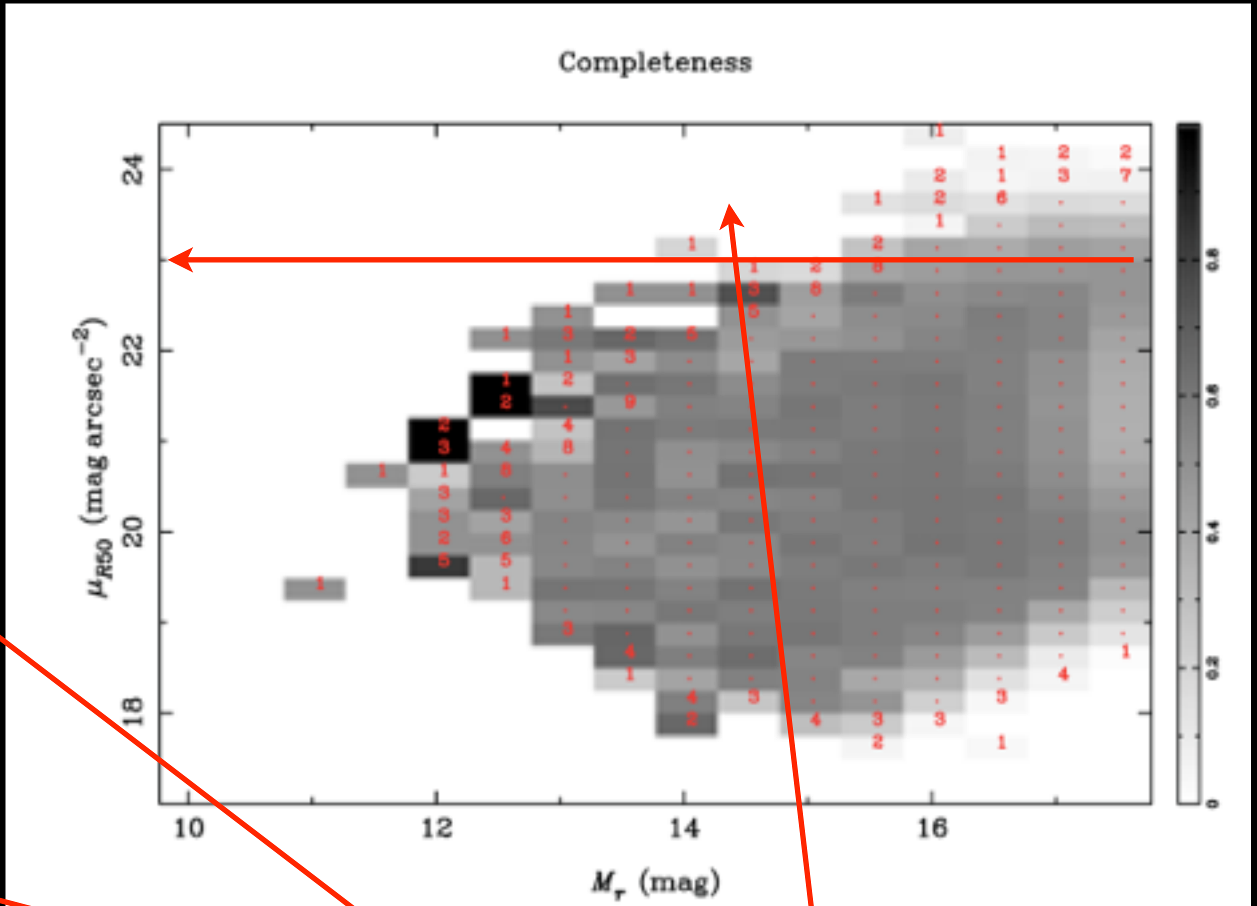
McGaugh (1996)

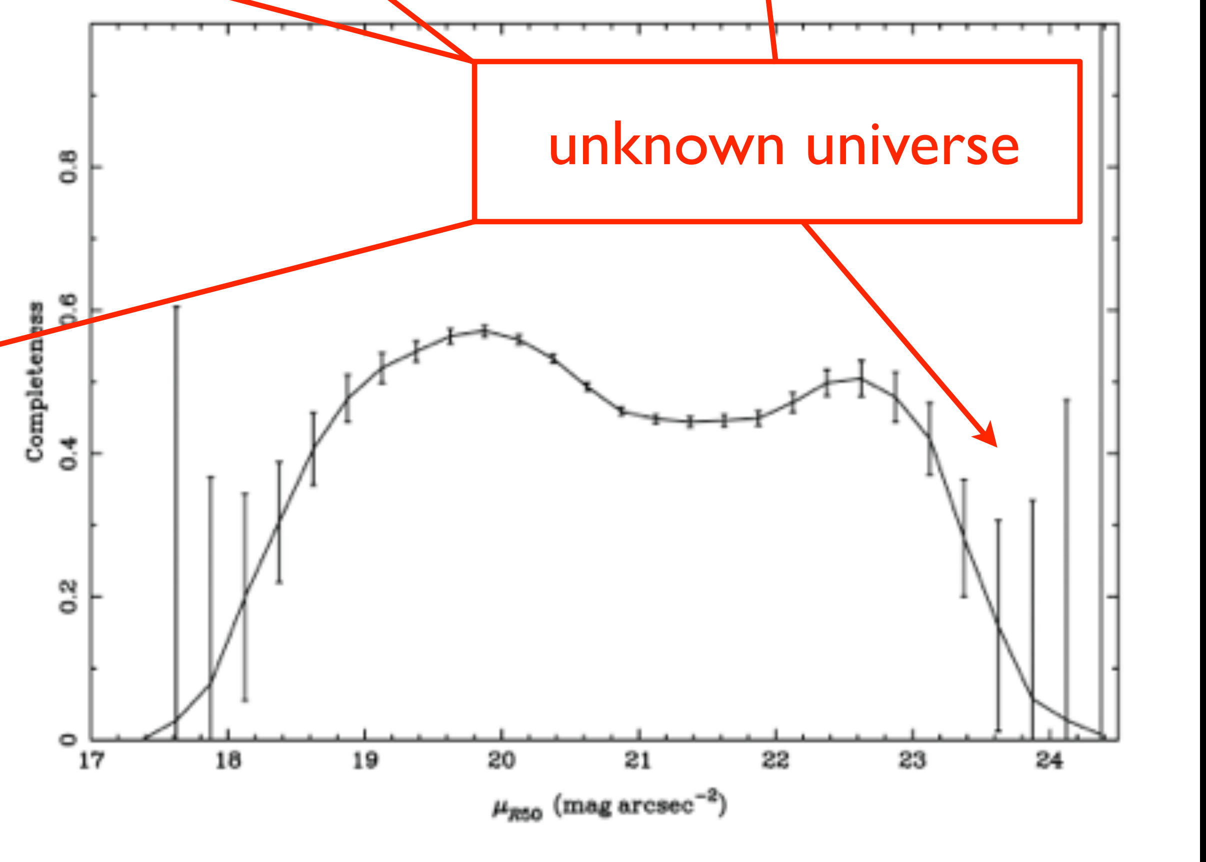
LSB galaxies appear fainter than HSB of the same luminosity

LSB galaxies appear smaller than HSB of the same size

Surface brightness completeness issues: the SDSS case

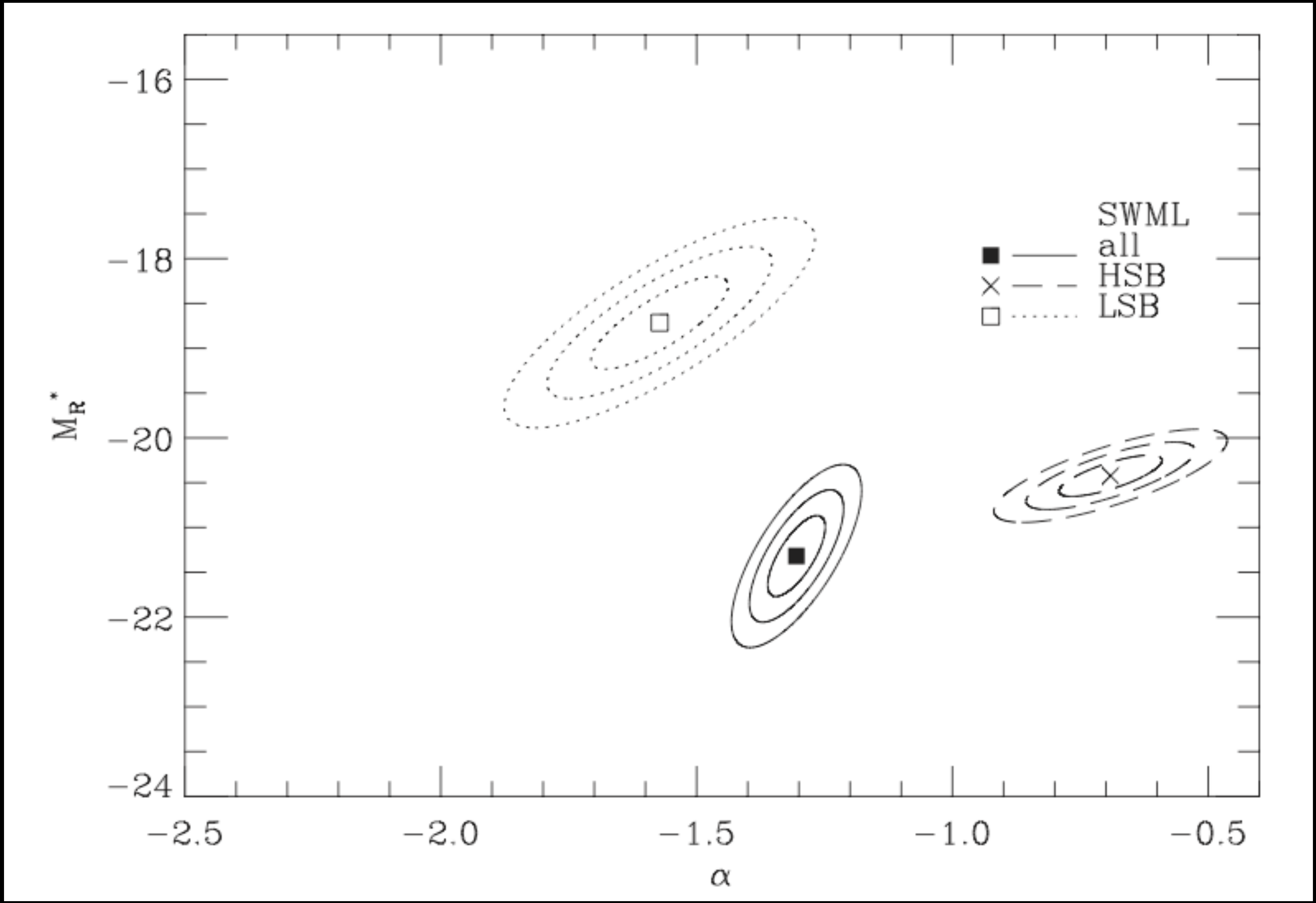






unknown universe

4 deg^2
R<20.6
553 galaxies
0.02<z<0.1
SB_{50R}< 22.5



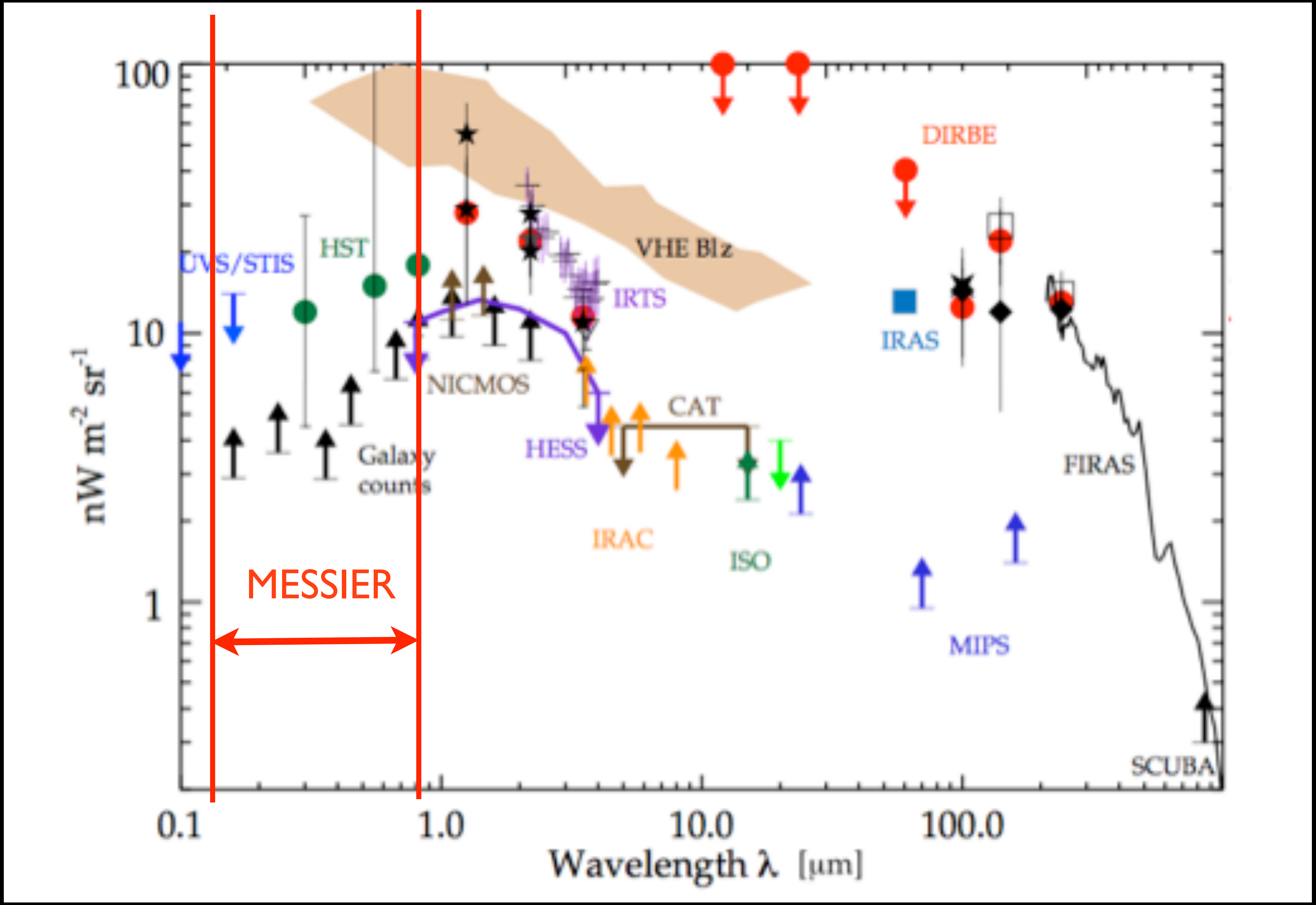
Measuring the slope of the faint end of the galaxy luminosity function, α, remains an unresolved observational challenge.

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

Geller *et al.* (2012)

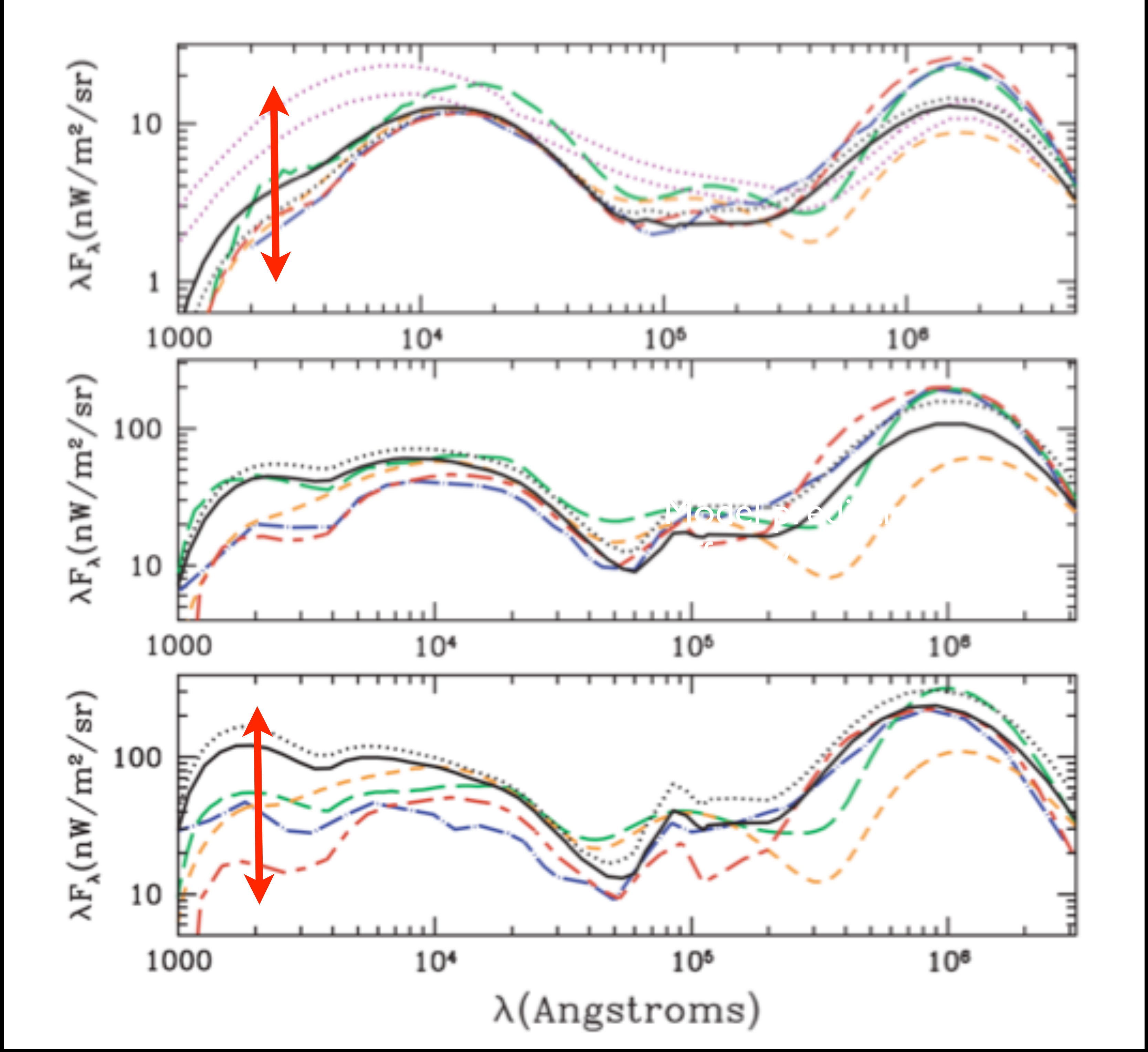
SC2 The optical / UV cosmological background radiation

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



Cooray *et al.* (2009)

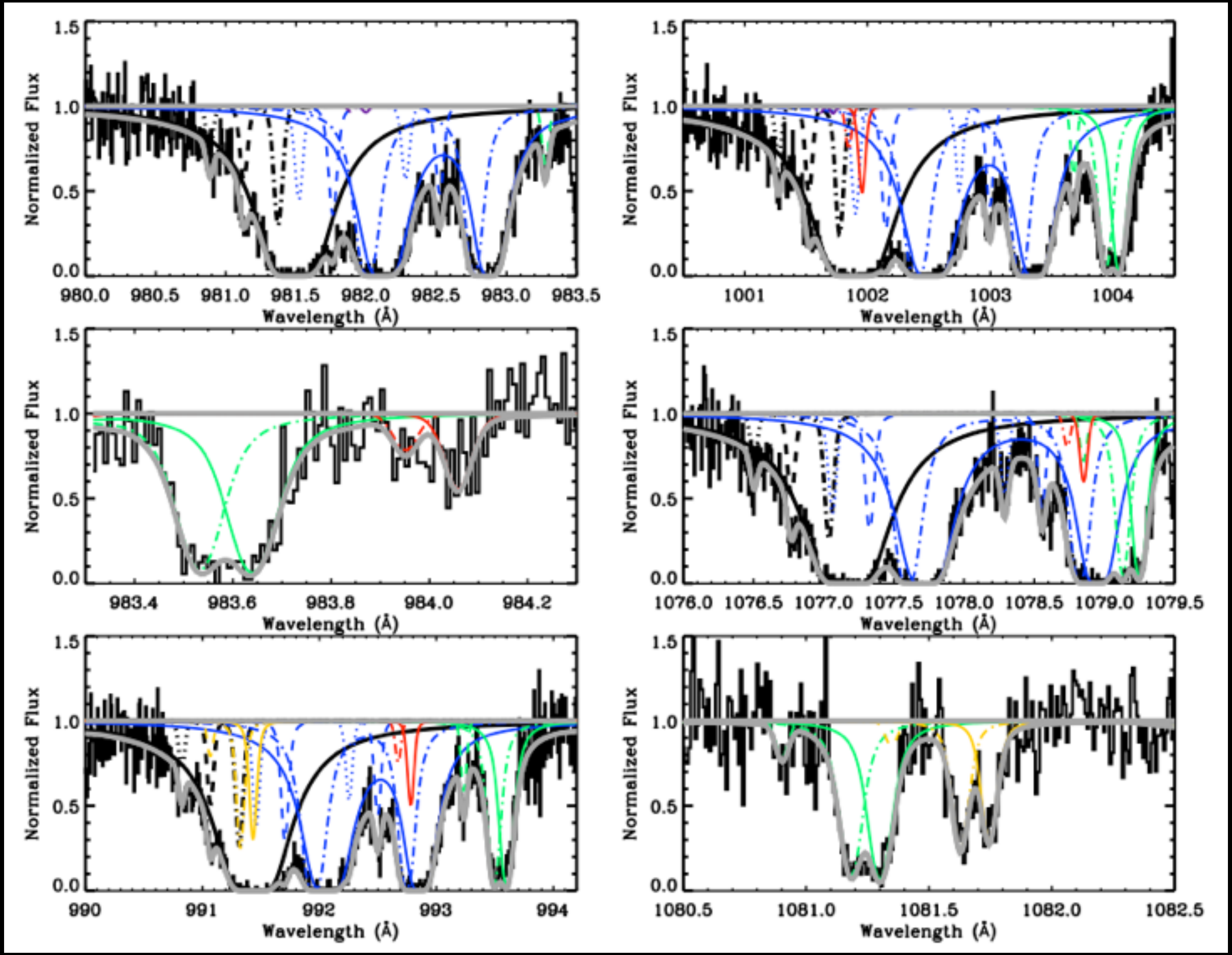
Models of the optical / UV cosmological background radiation



Model predictions differ by over one order of magnitude

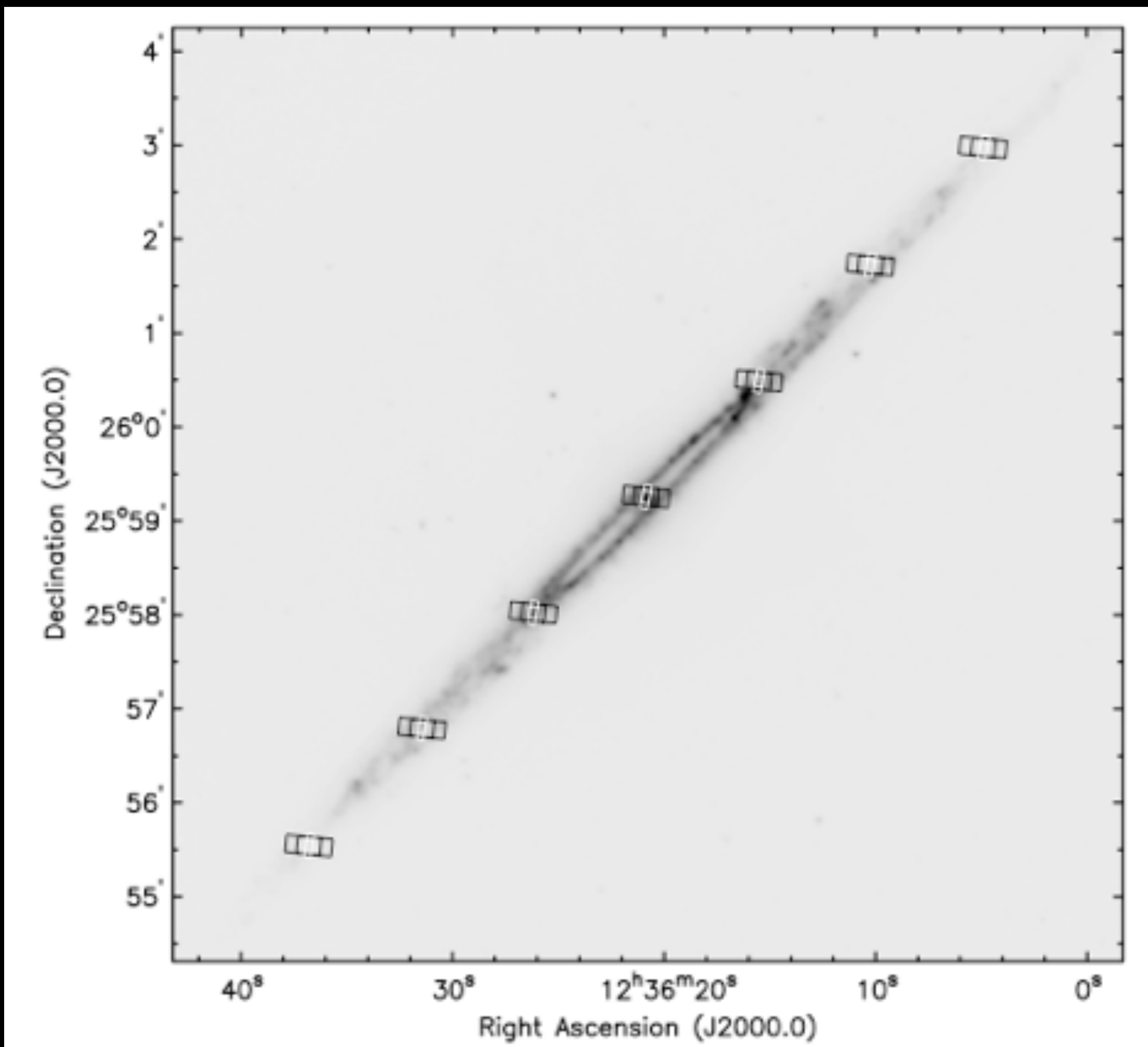
Gilmore *et al.* (2012)

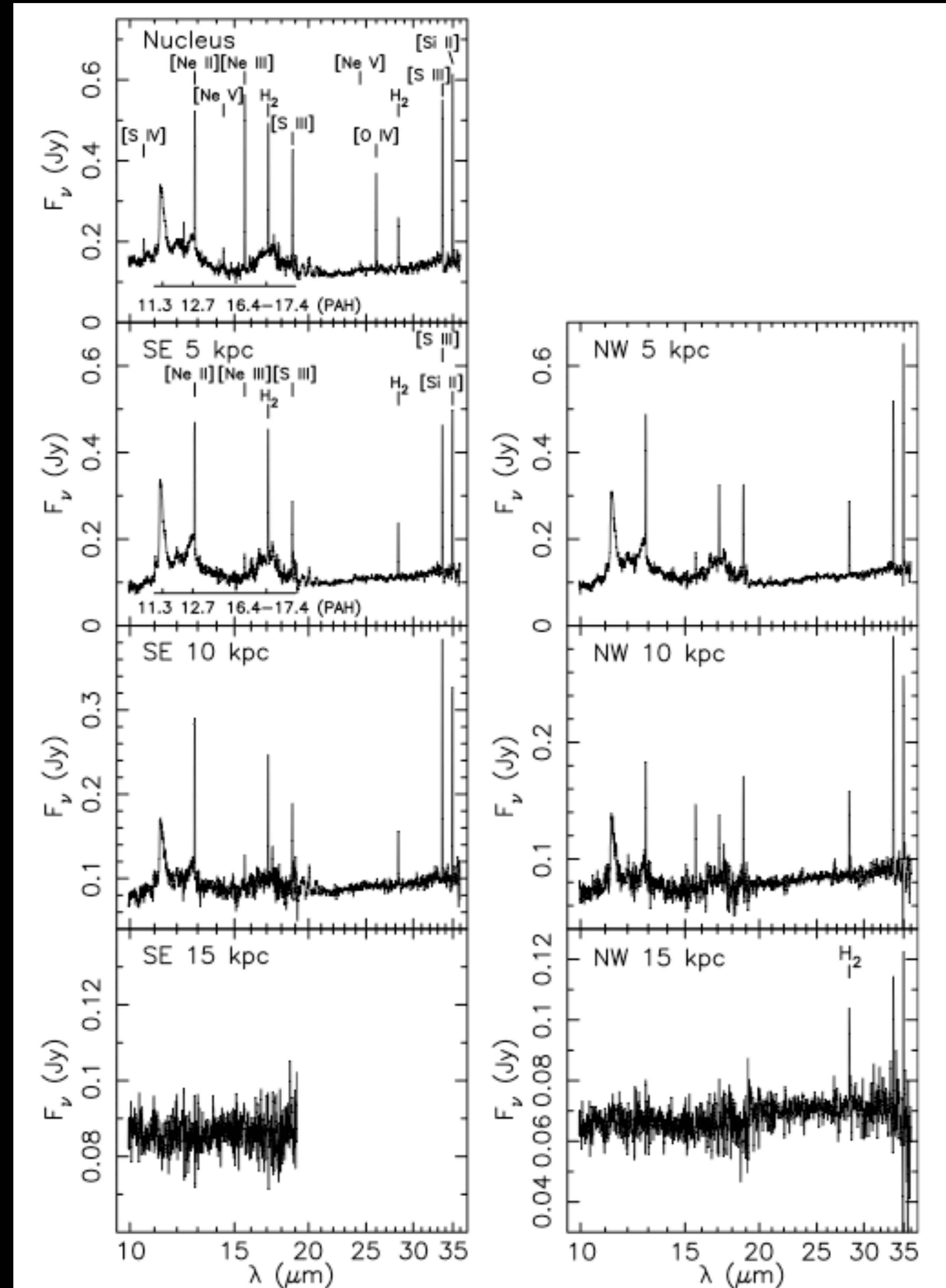
SC3 What is the molecular content of galaxies ?
The prevalence of warm molecular H_2



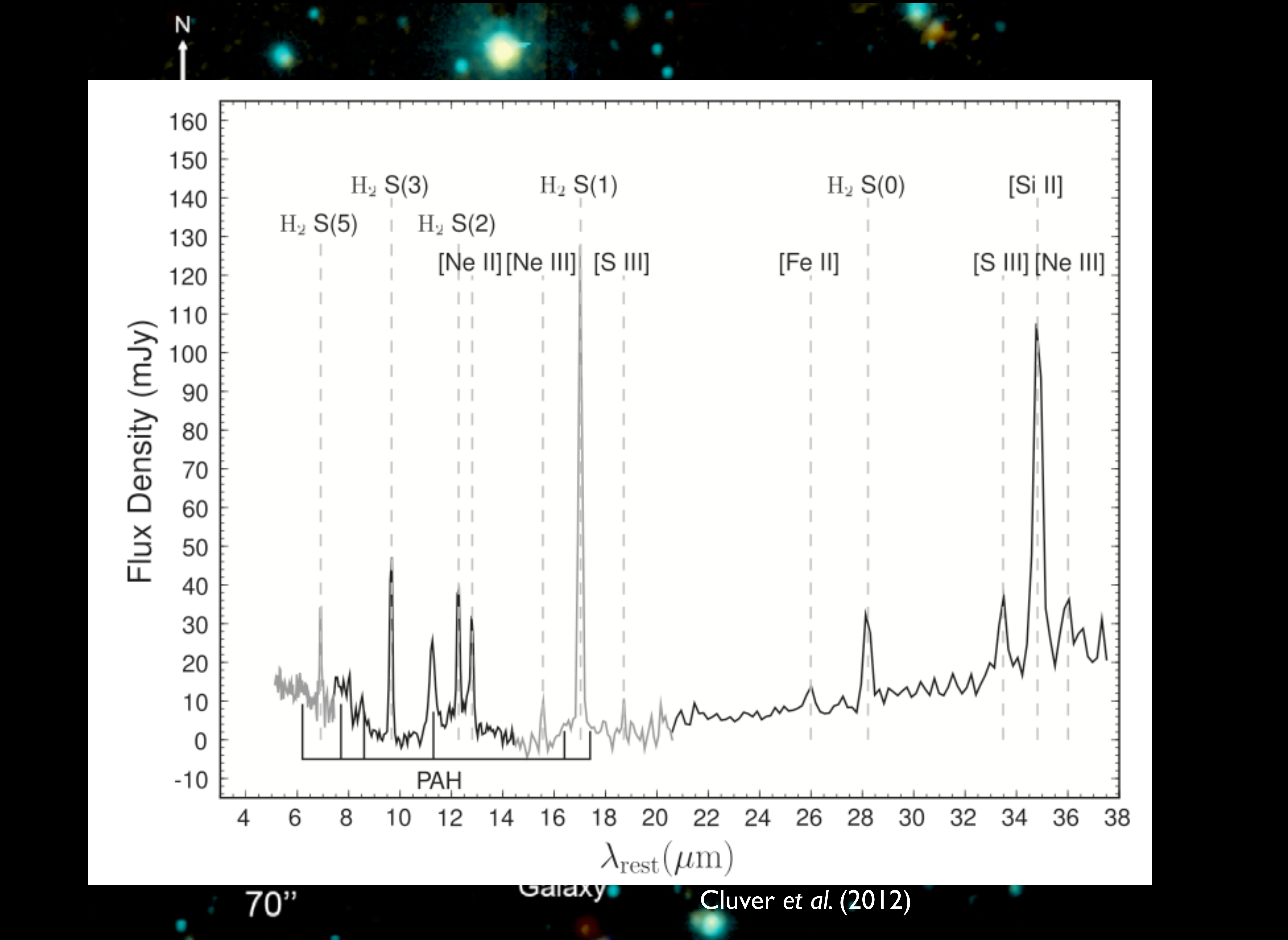
DLA
z = 0.185

Oliveira *et al.* (2014)



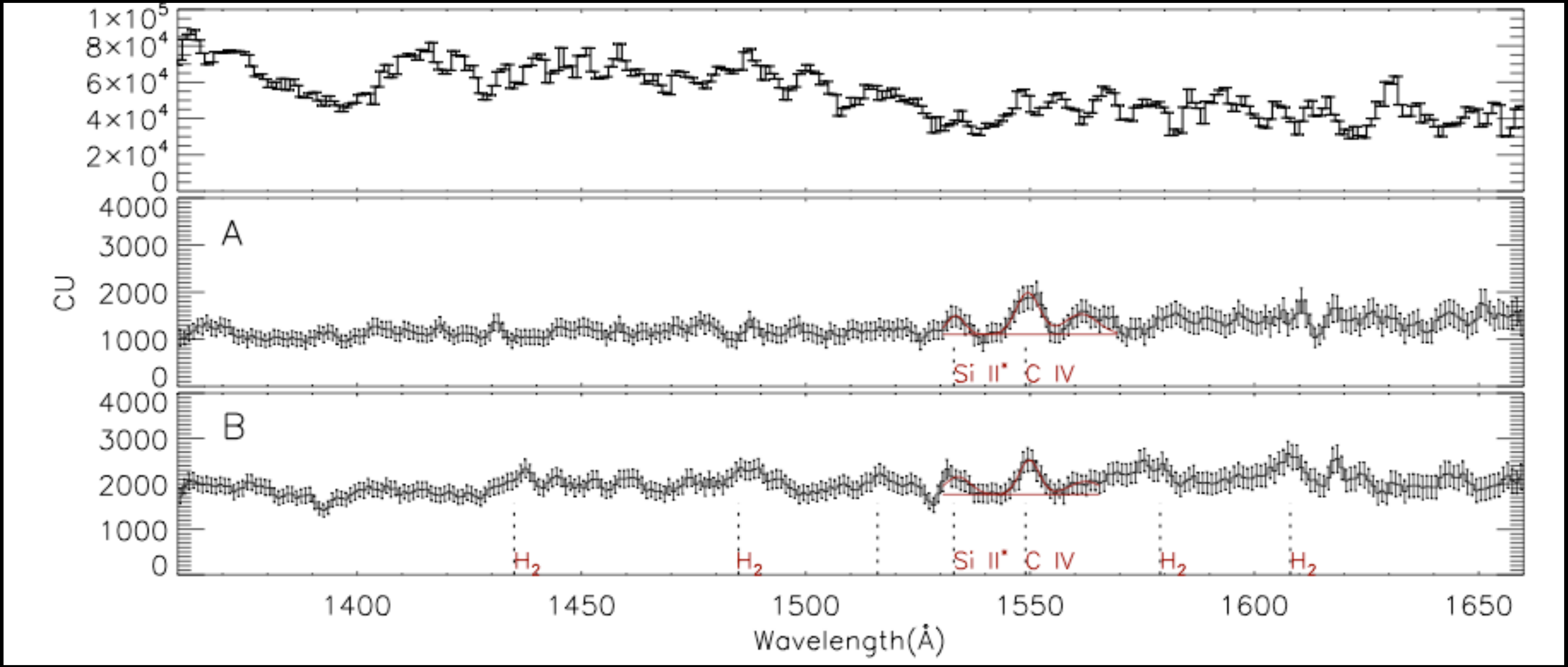


Laine *et al* (2012)

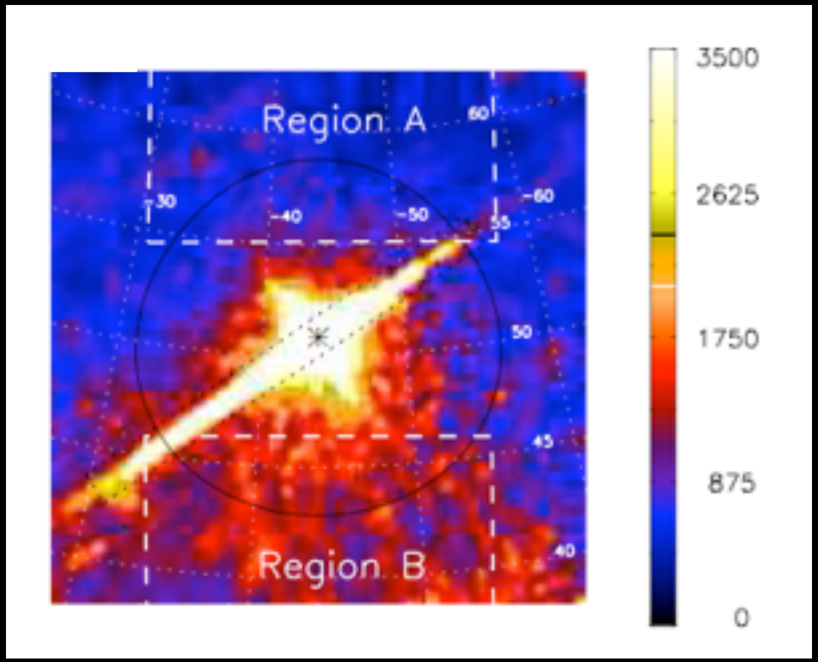


Cluver *et al.* (2012)

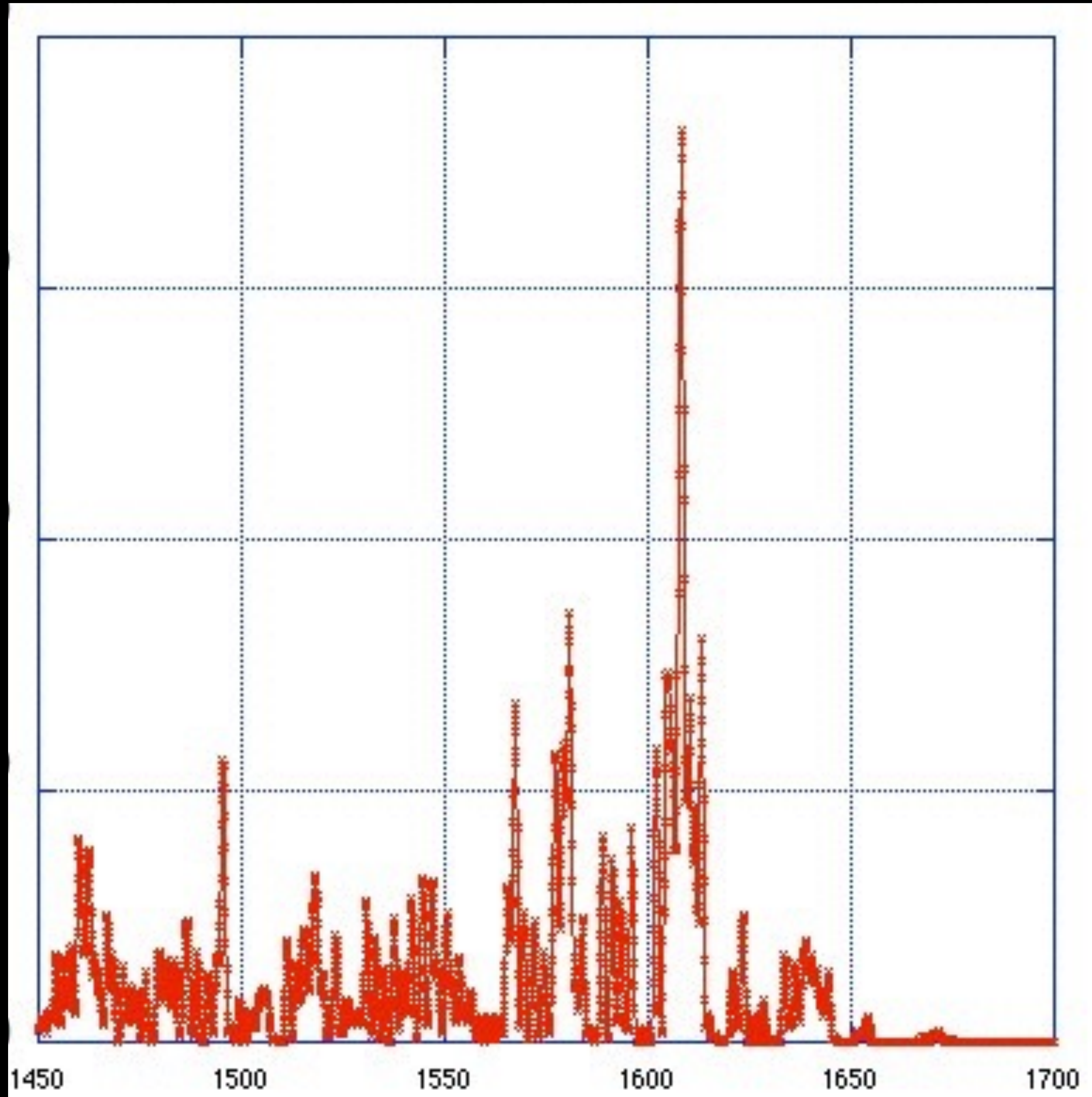
Detection of H_2 in the Lyman-Werner bands



Choi *et al.* (2013)



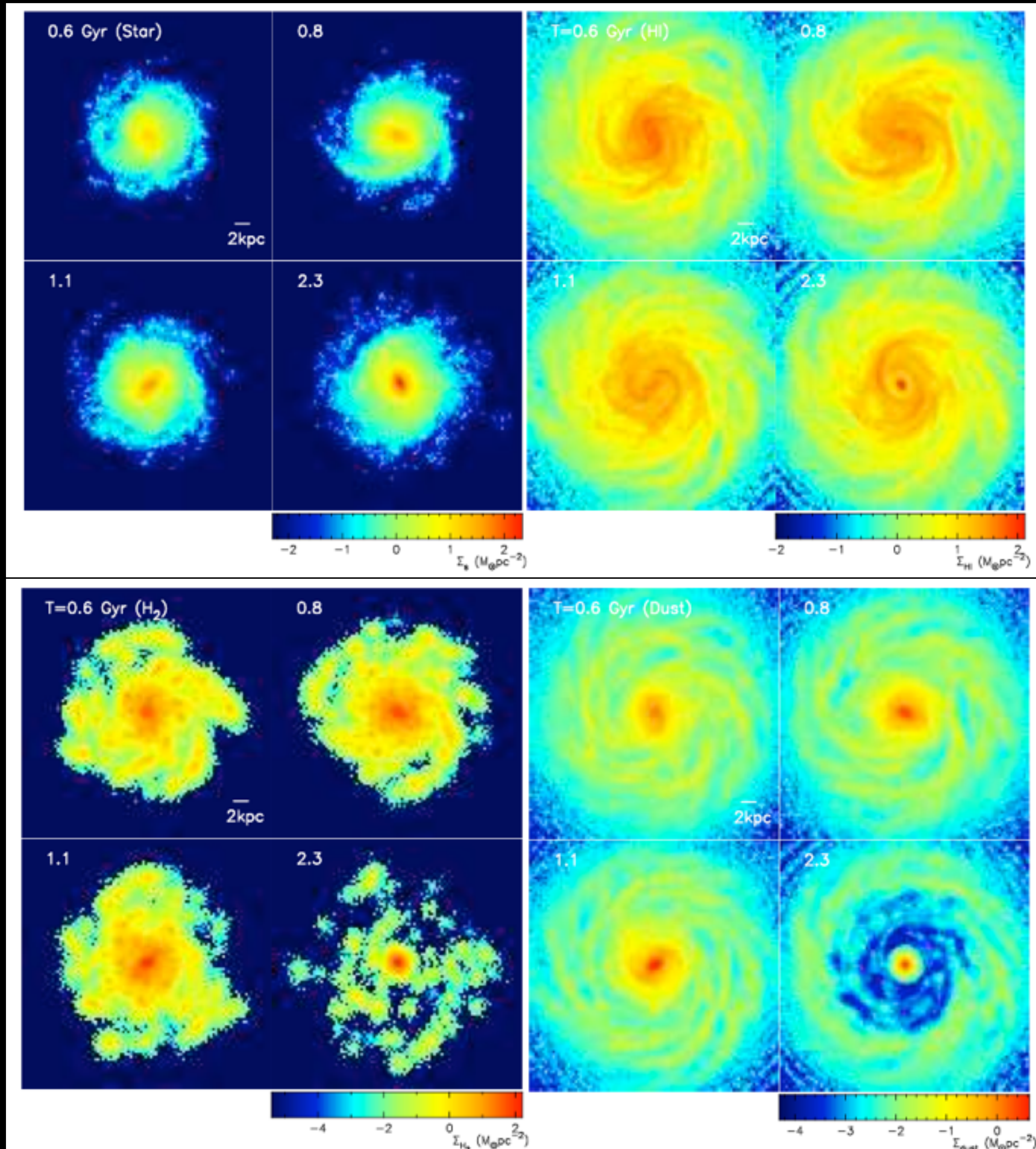
Predicted H_2 spectrum for Stephan's quintet in the Lyman-Werner bands



Abgrall & Roueff (2014)

stars

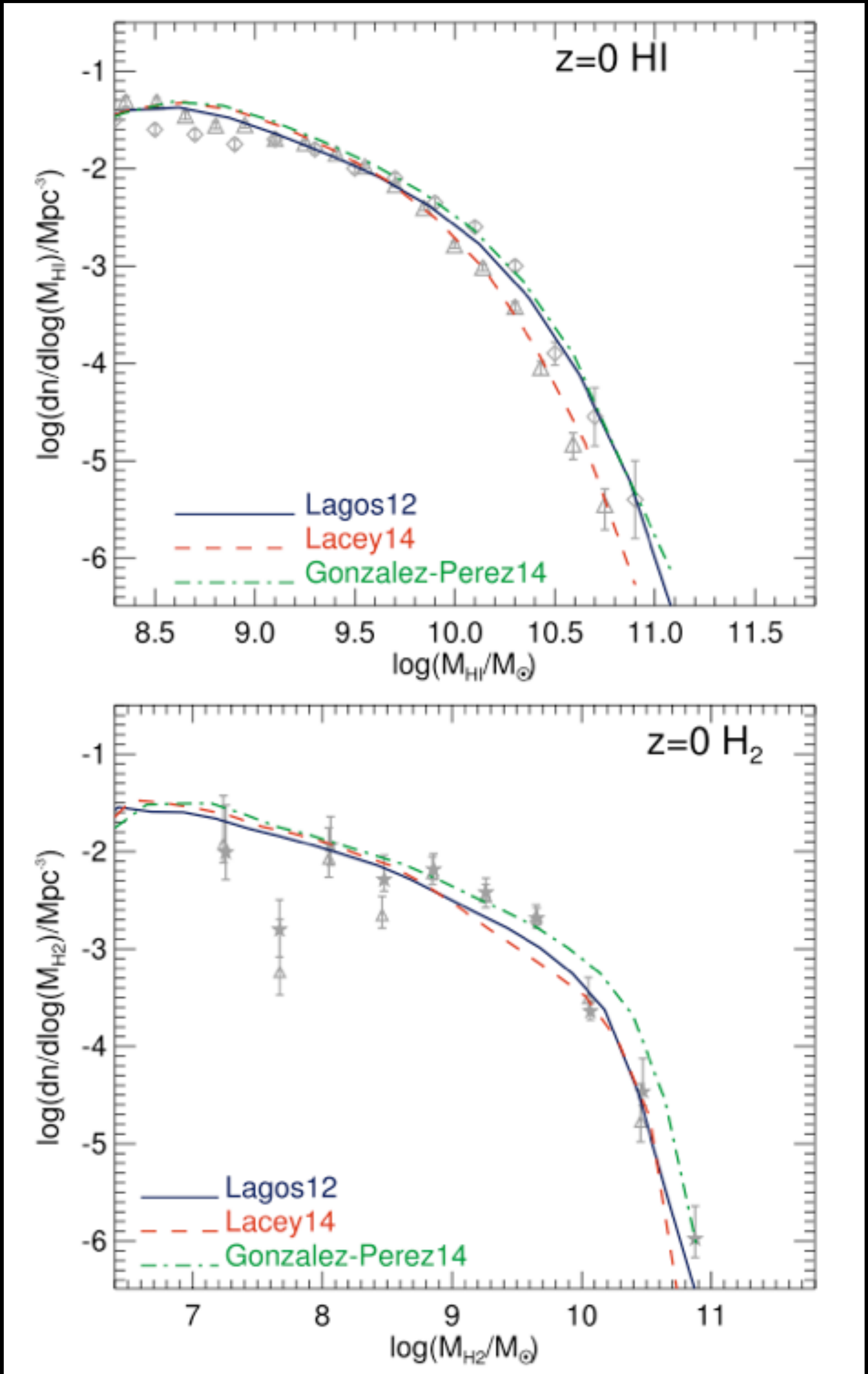
HI



H_2

dust

Bekki (2014)

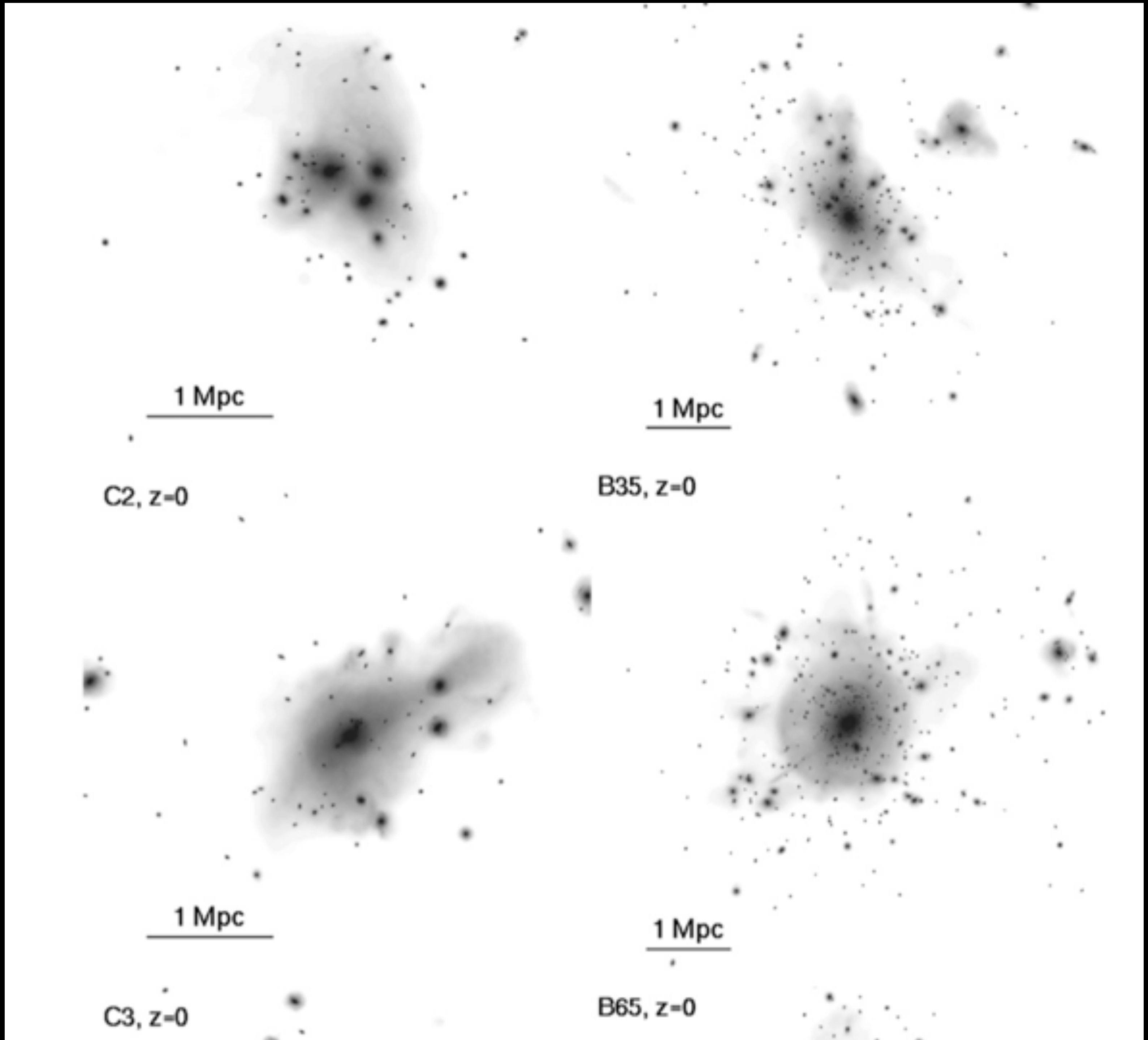


Lagos *et al.* (2014)

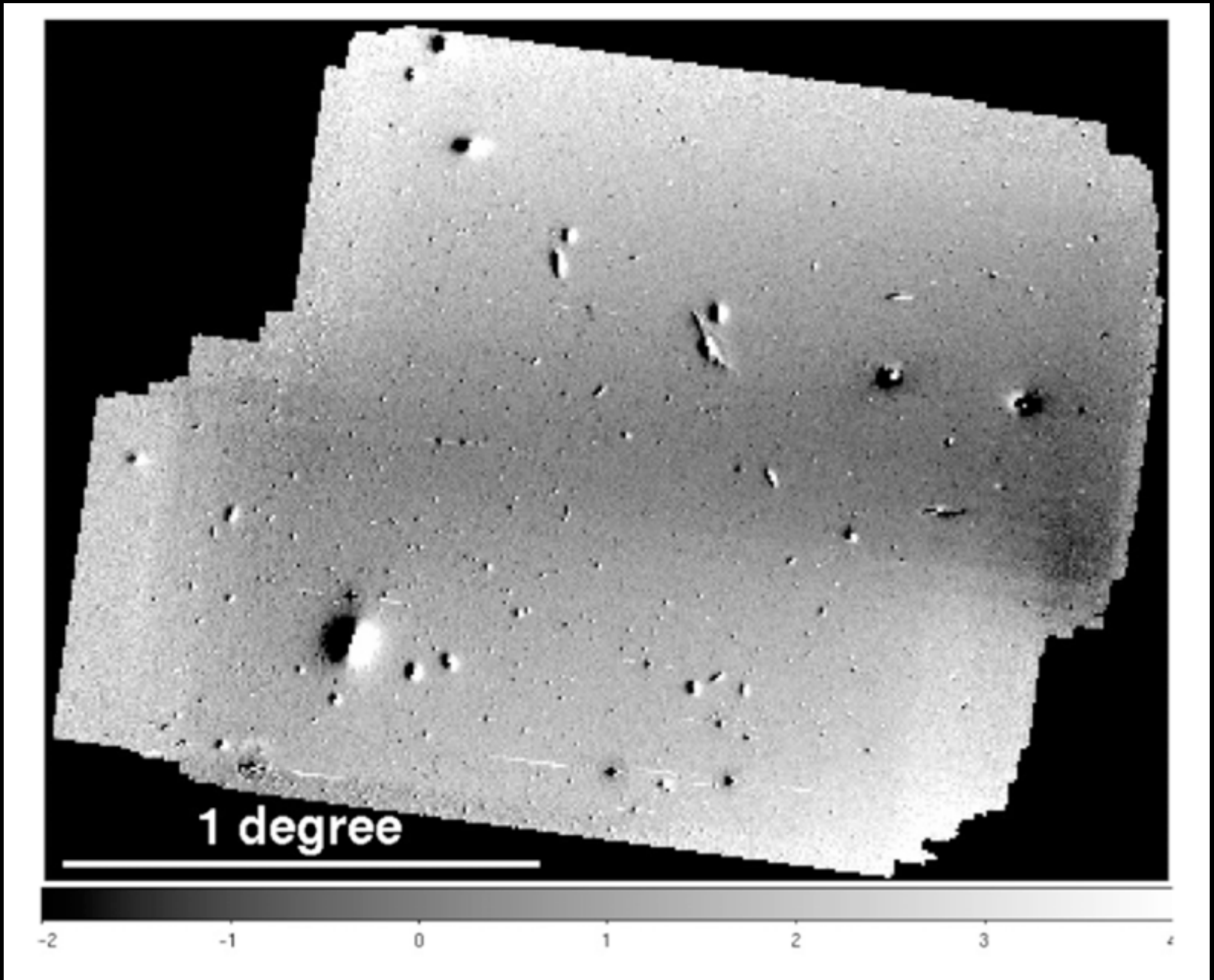
SC4 What is the role of intracluster light in the evolution of galaxies and clusters?

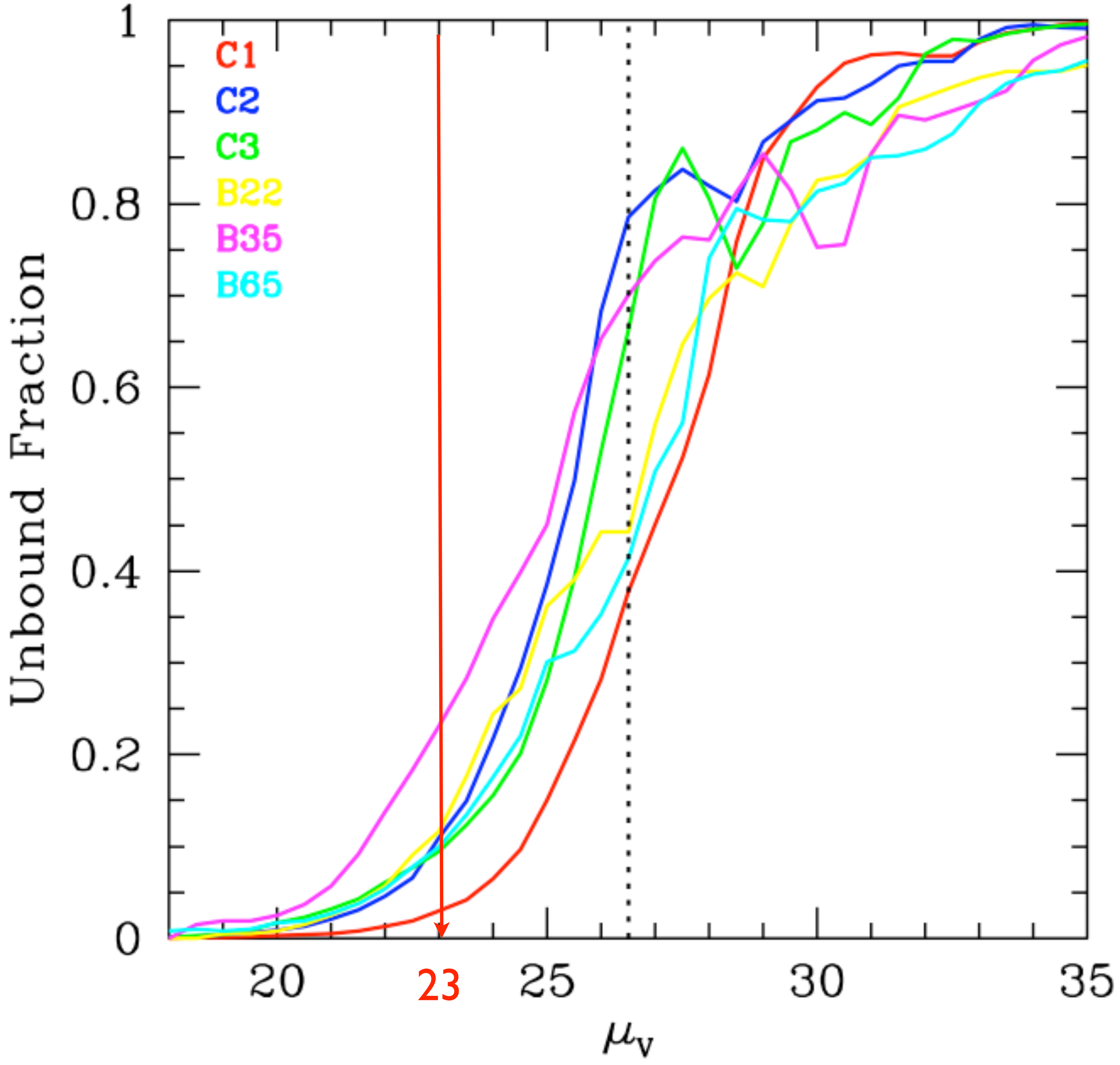
Predicted diffuse light in galaxy clusters

gas + star stripping in N-body simulations



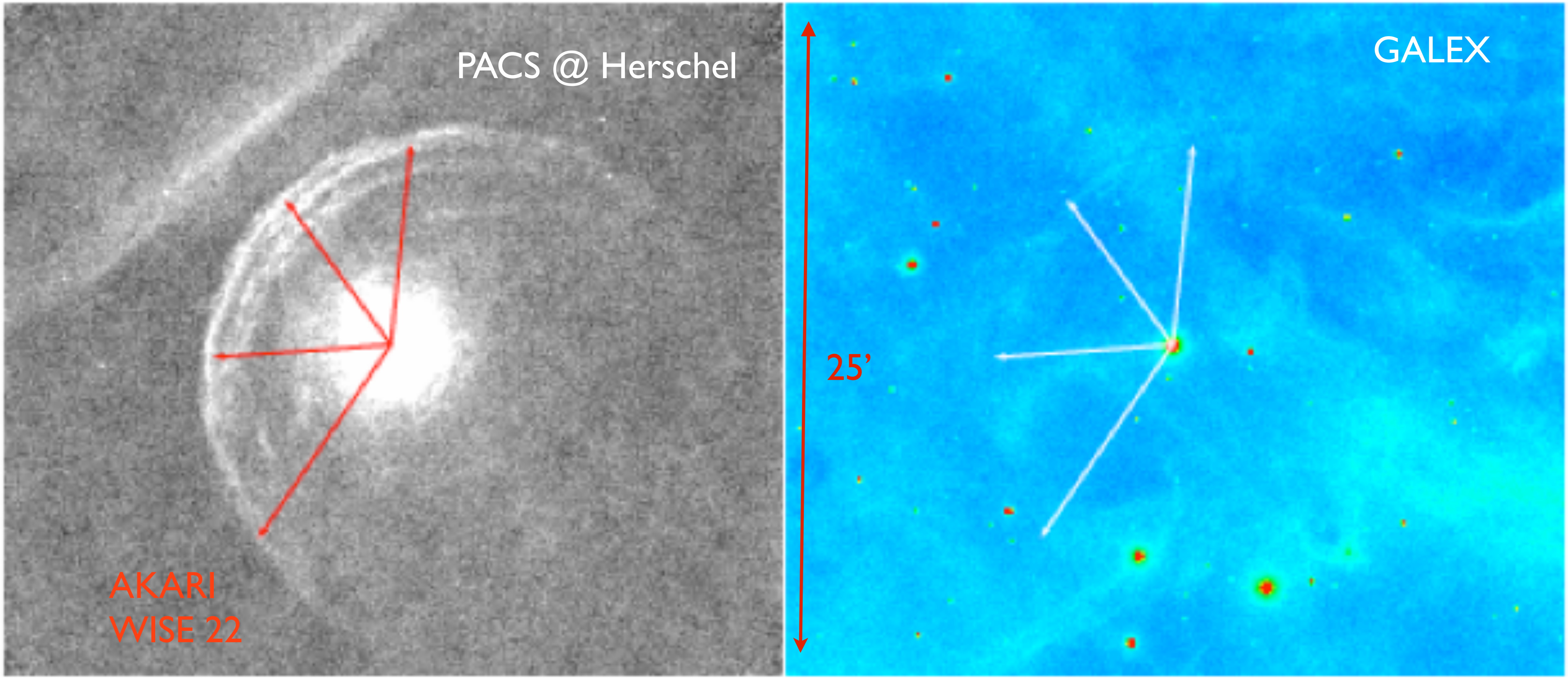
Artifacts produced by low-level flat field residuals ?





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

SC5 Mass loss from stars and the chemical evolution of galaxies

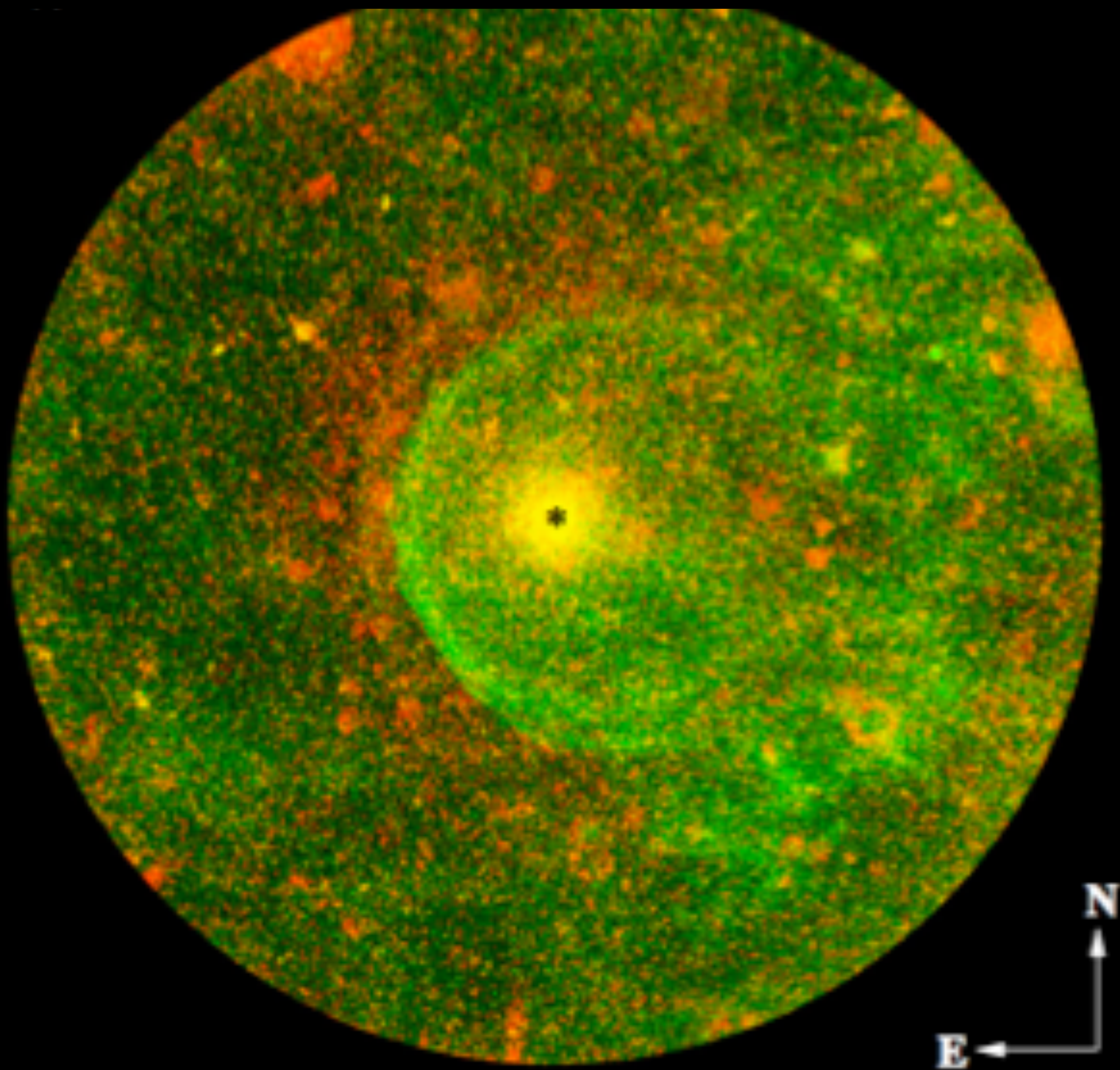


Betelgeuse

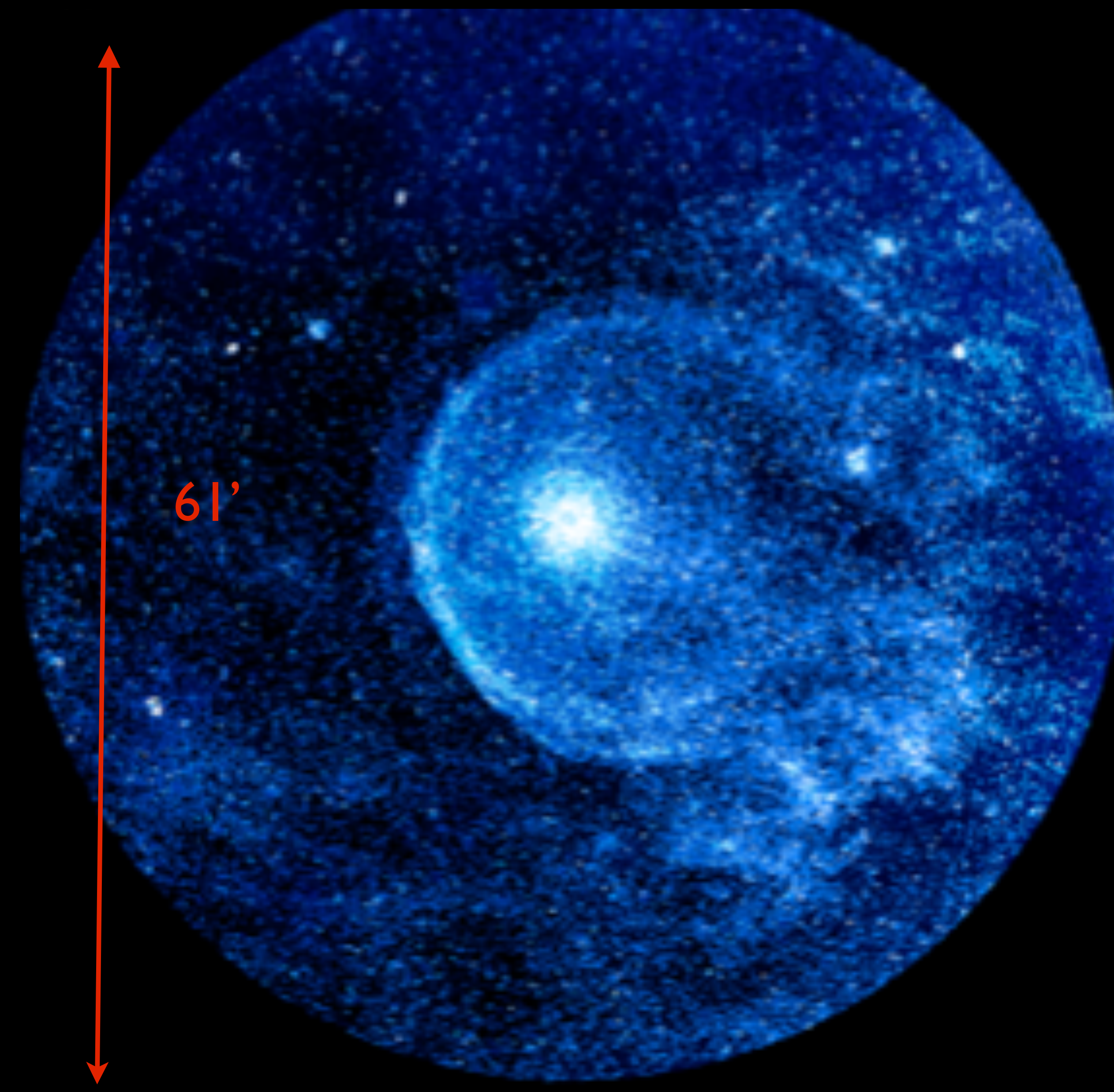
Decin *et al.* (2012)

AGB IRC+10216

FUV+NUV @ GALEX



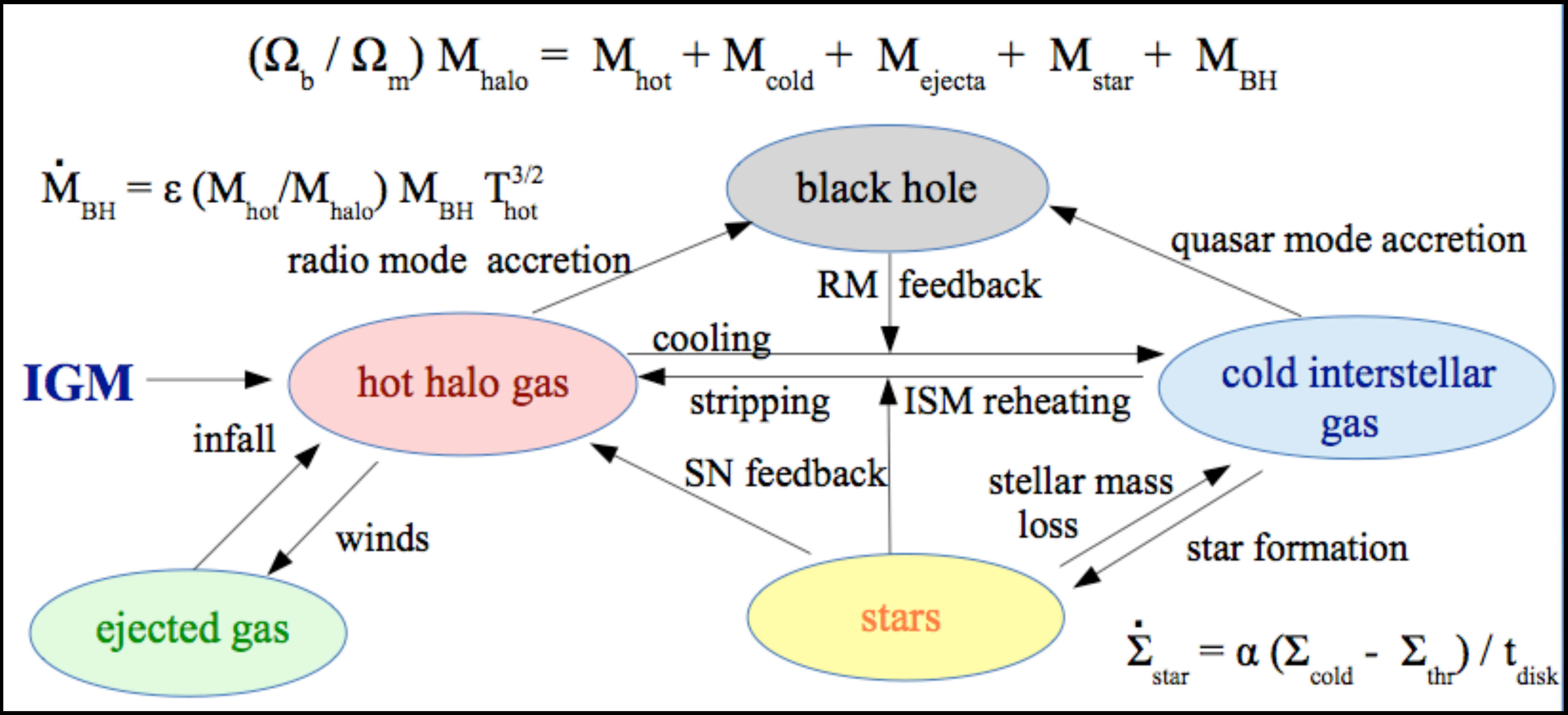
FUV @ GALEX



Sahai & Chronopoulos (2010)

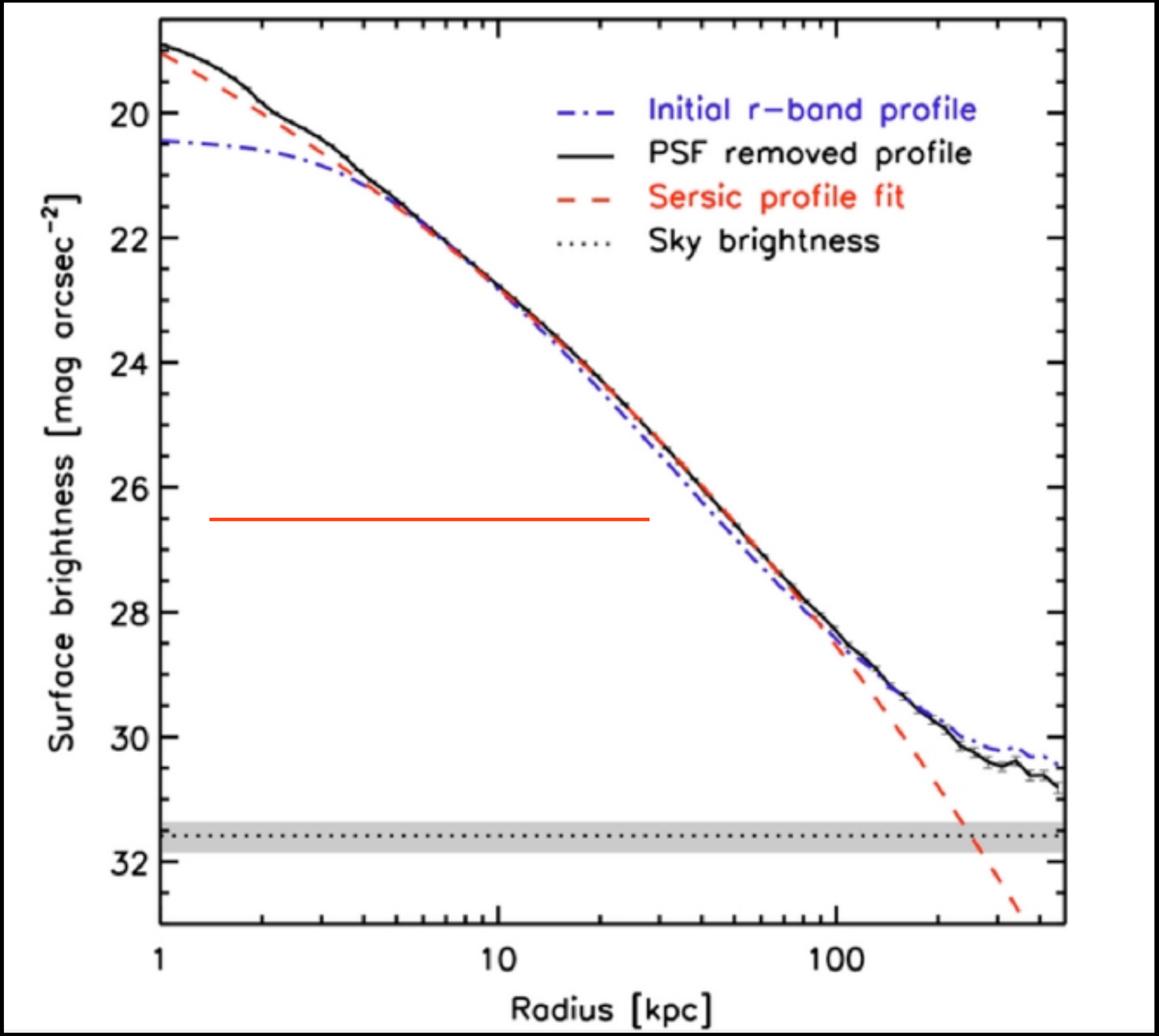
SC 8 What is the actual extent and profile of galaxies ?

Baryonic + radiative processes within dark matter haloes



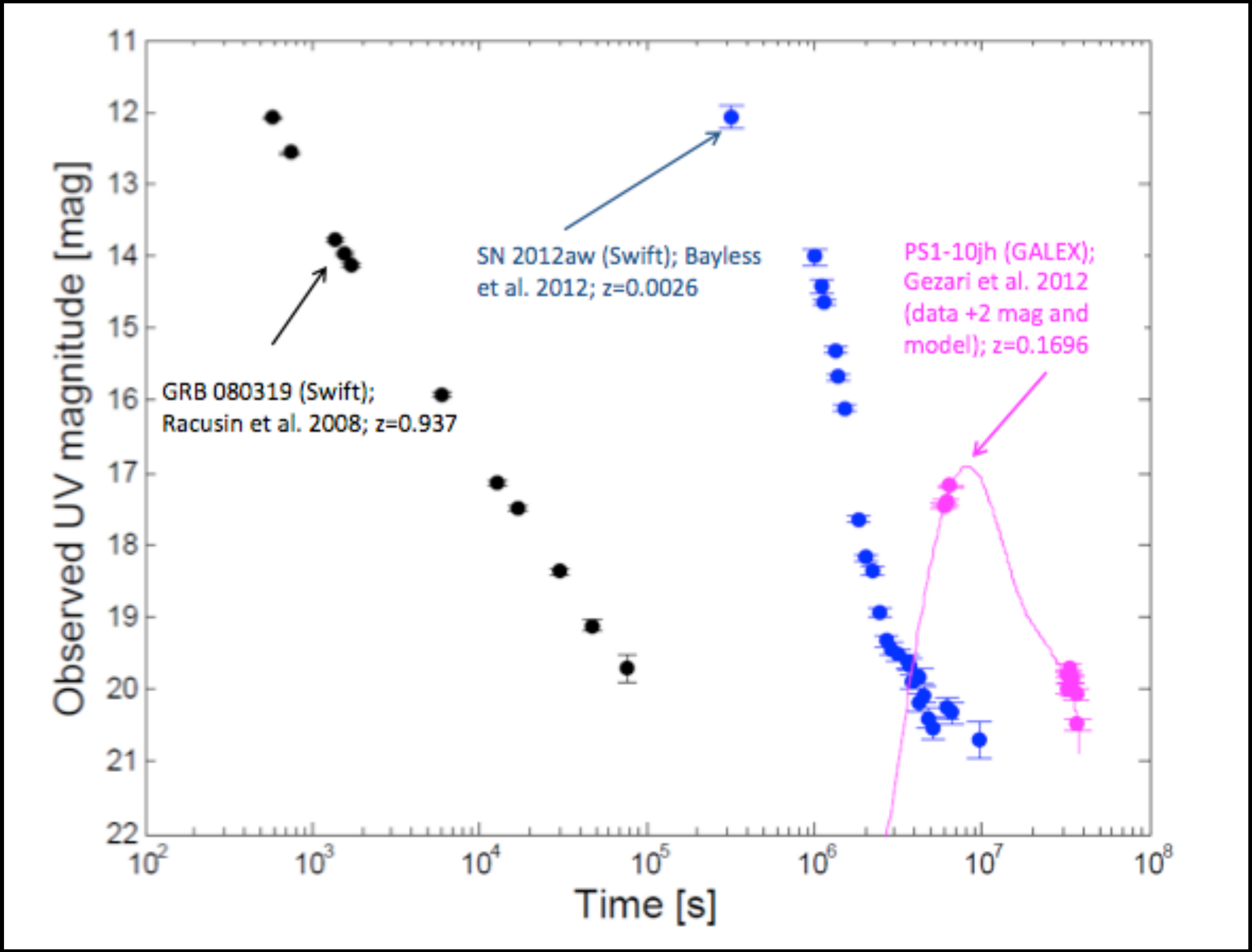
S. White (2013)

Stacking of 42,000 SDSS Luminous Red Galaxies

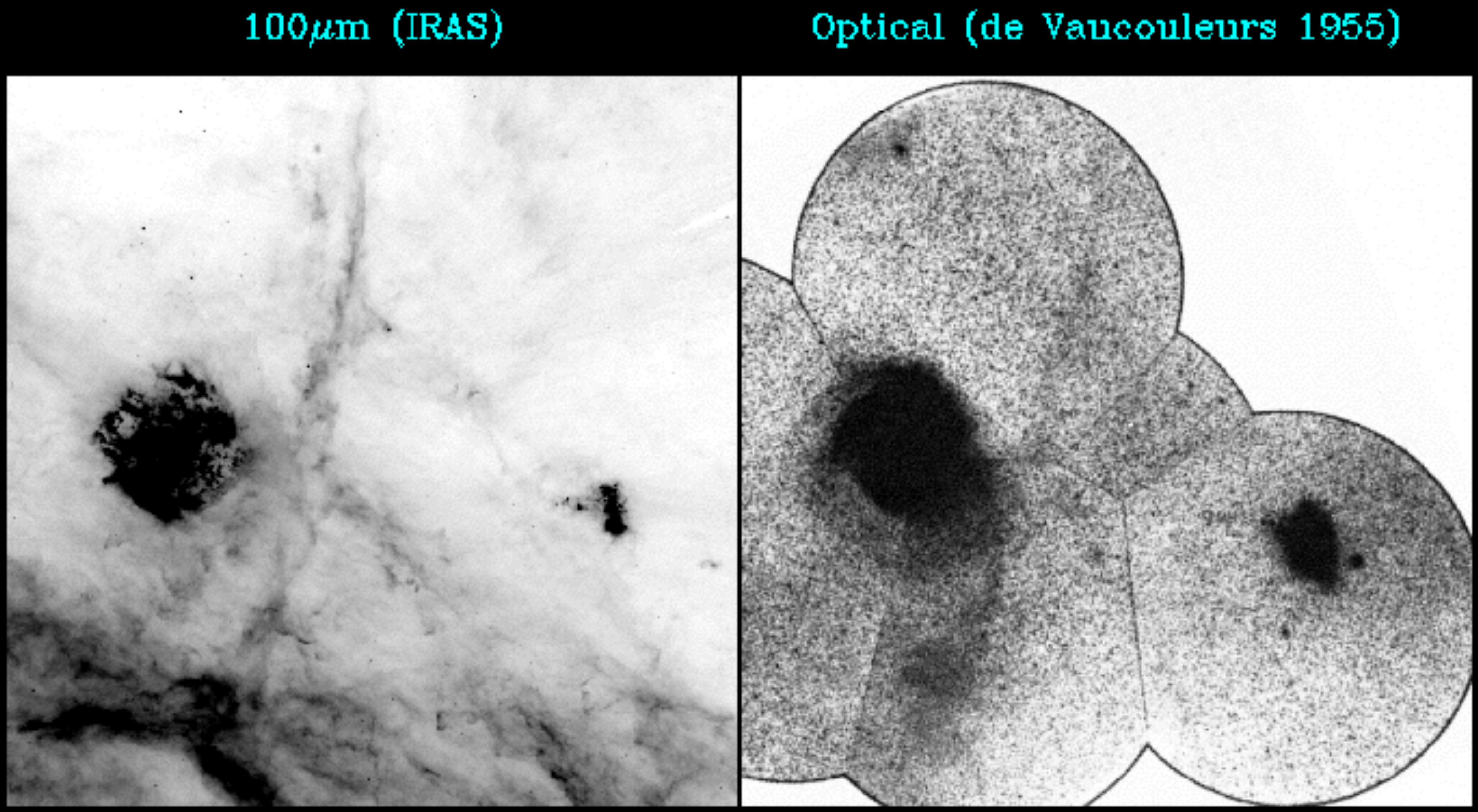


Tal & Van Dokkum (2012)

SC 9 Time-domain astronomy
Variability and transients from the UV to the optical



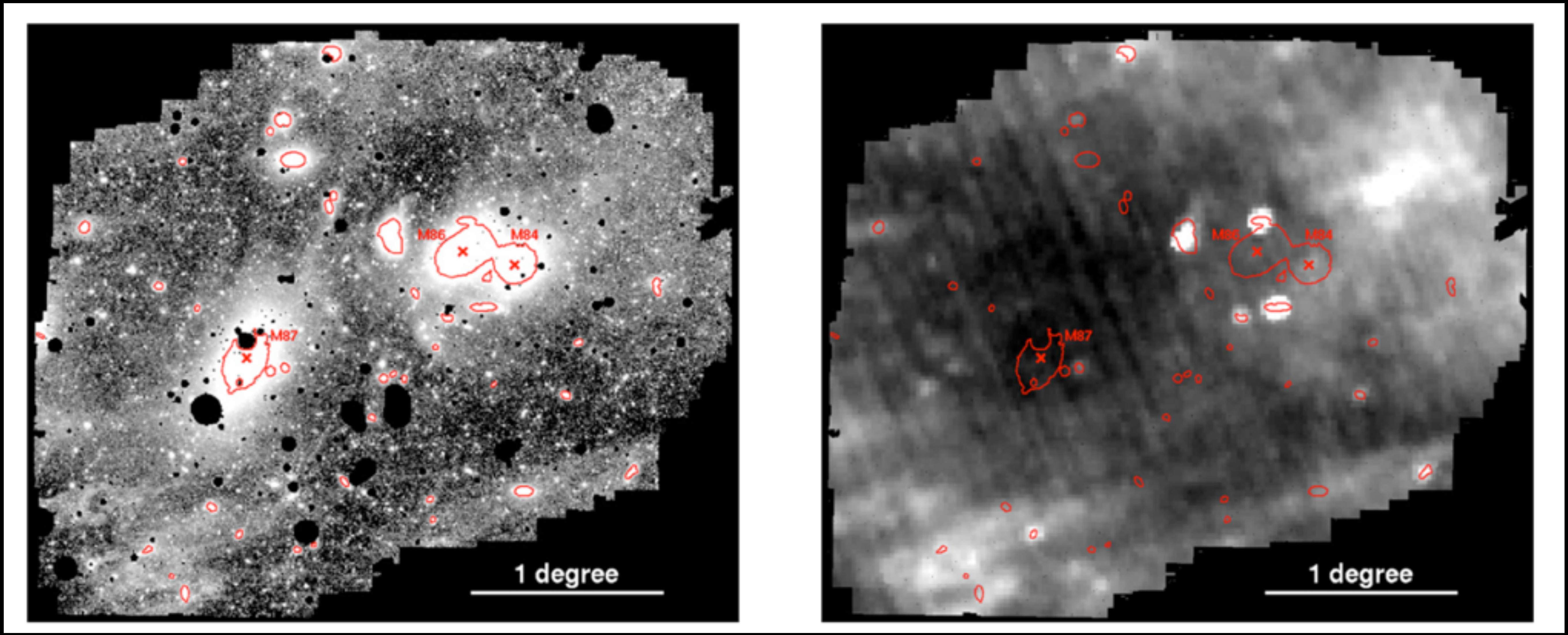
The main challenge for MESSIER
The foreground contamination at ultra-low SB levels



Magellanic Clouds

Optical emission

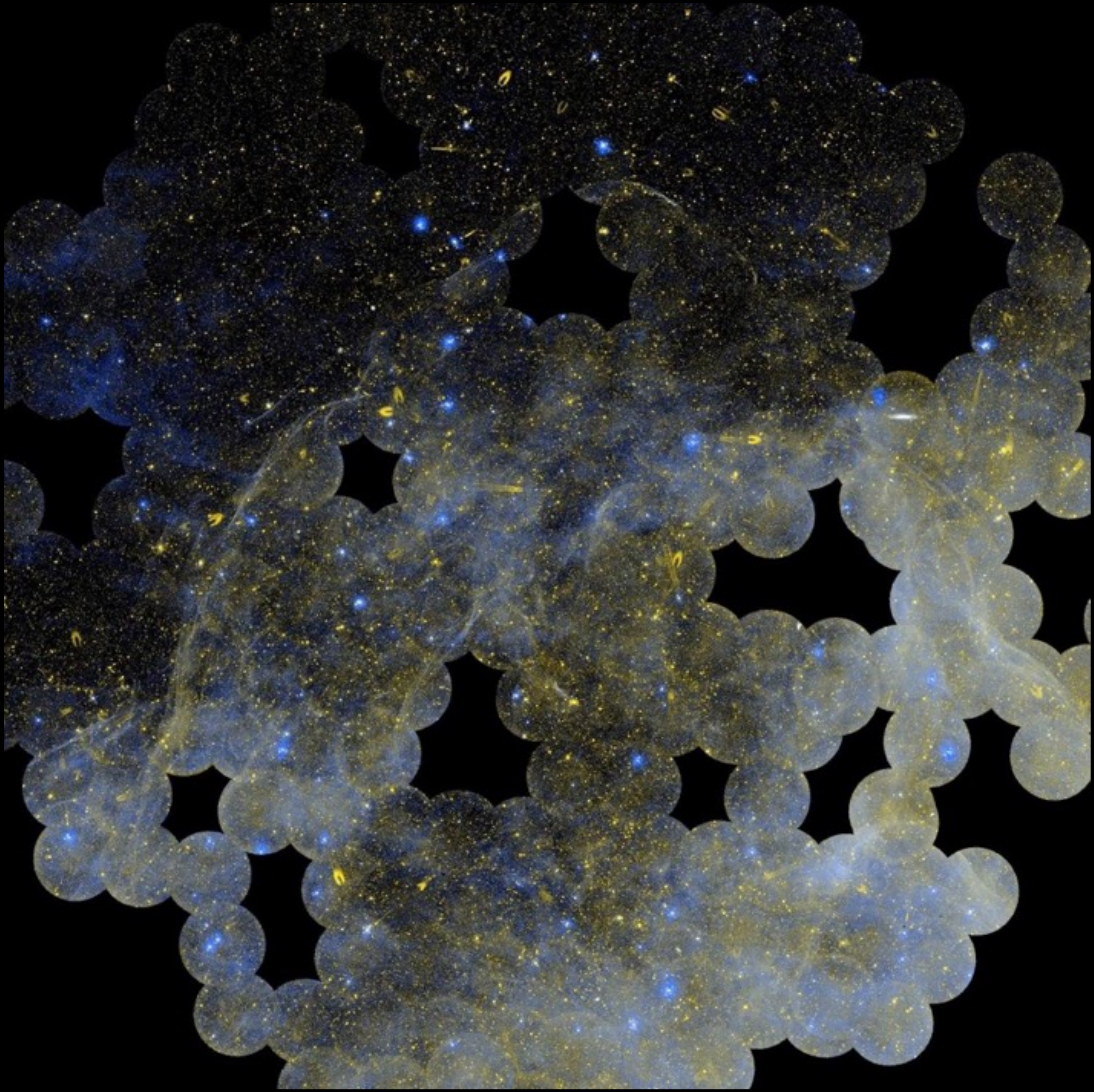
IRAS 100 μm



Mihos *et al.* (2009)

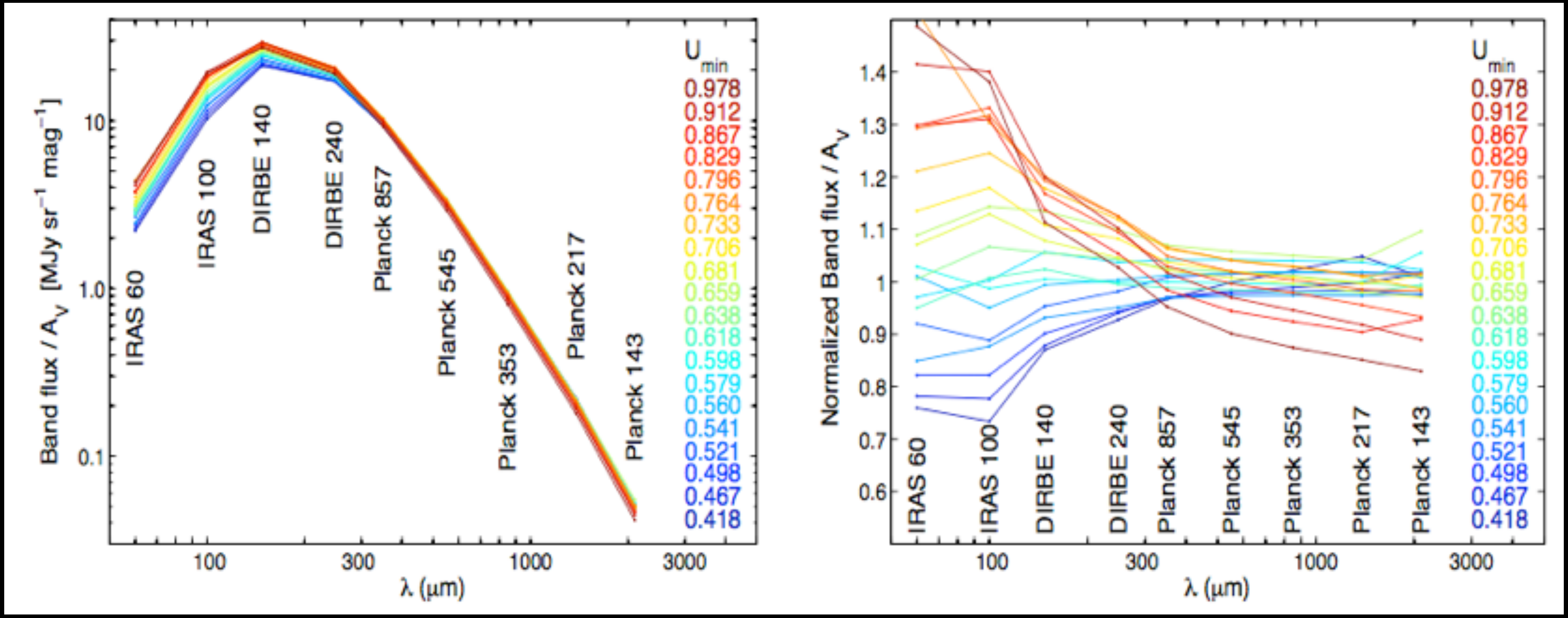
Virgo cluster field


(c)David La



GALEX

MESSIER foreground removal
Independent Component Analysis à la EoR-LOFAR @21cm

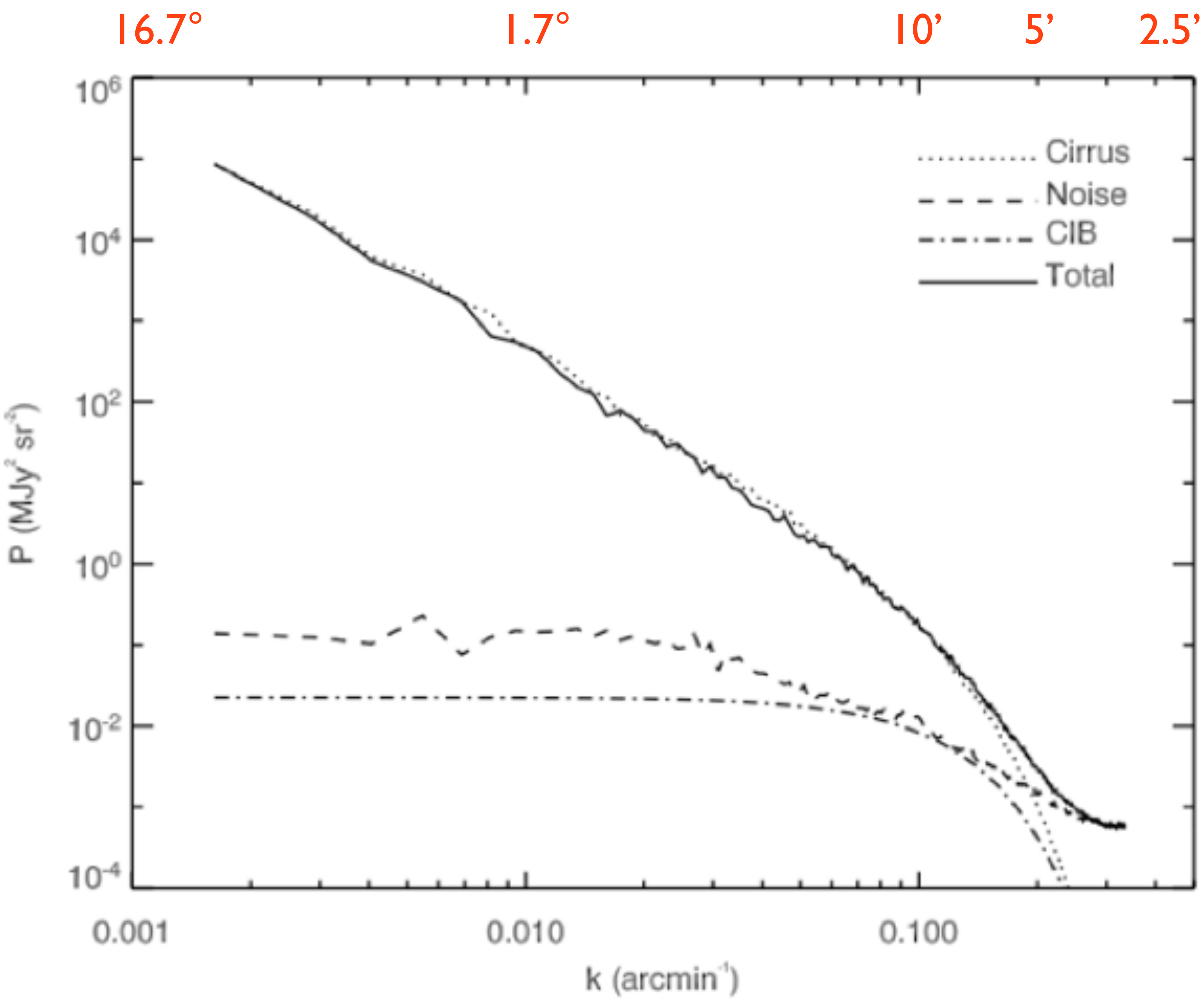


Planck XXIX
arXiv:1409.2495

No prior knowledge of the background signal (unlike CMB)
Assumes SEDs are contrained (from 200 nm to 350 µm)
Non-parametric solutions
Assumes that components are statistically independent
Remains to be tested within the MESSIER context

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

- Massive multiplex spectroscopy

  MESSIER will provide unique targets for kinematics/dynamics

- Time-domain astronomy

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

- Unique legacy value

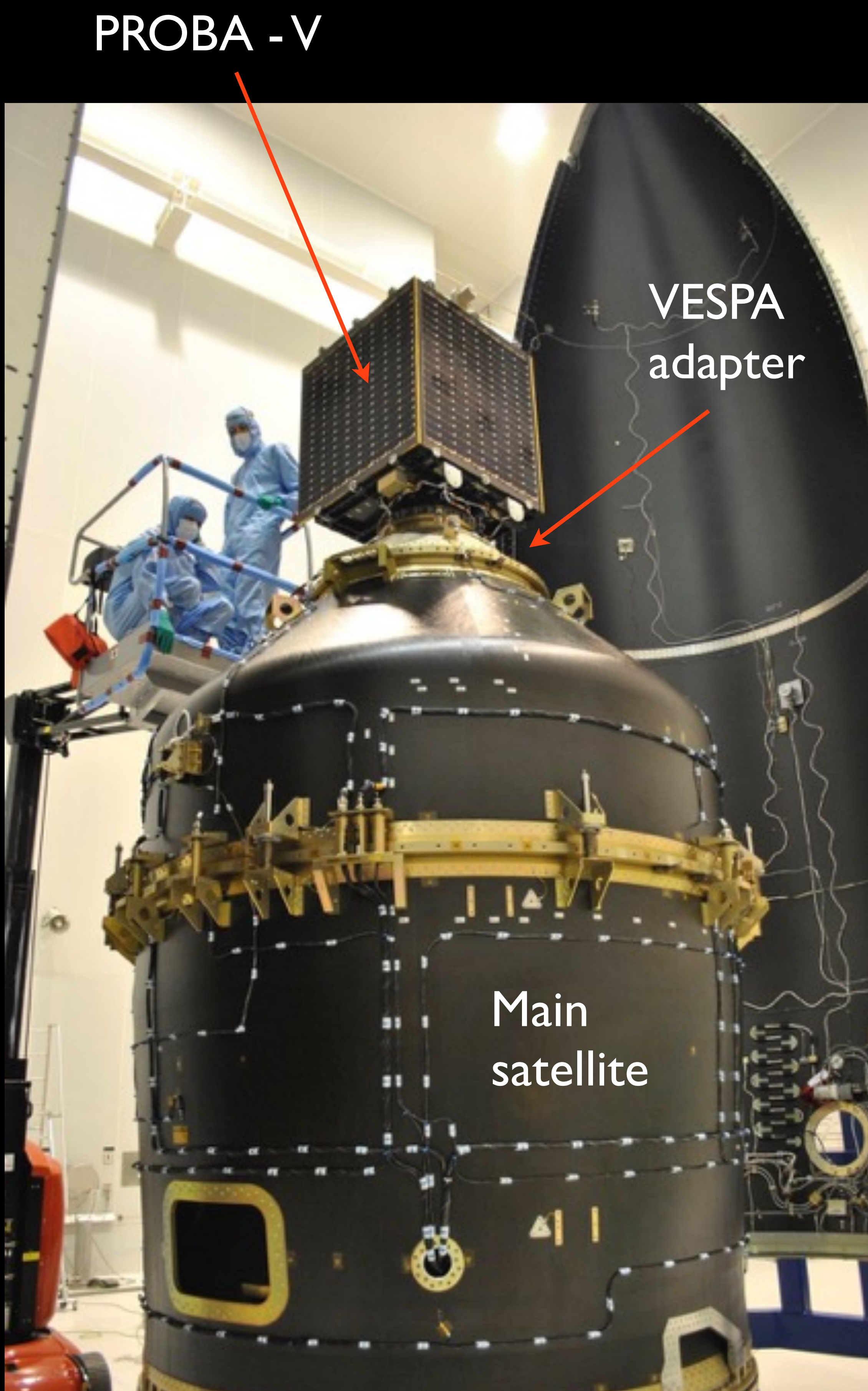
  The reference catalogue of multi-band space-based photometry

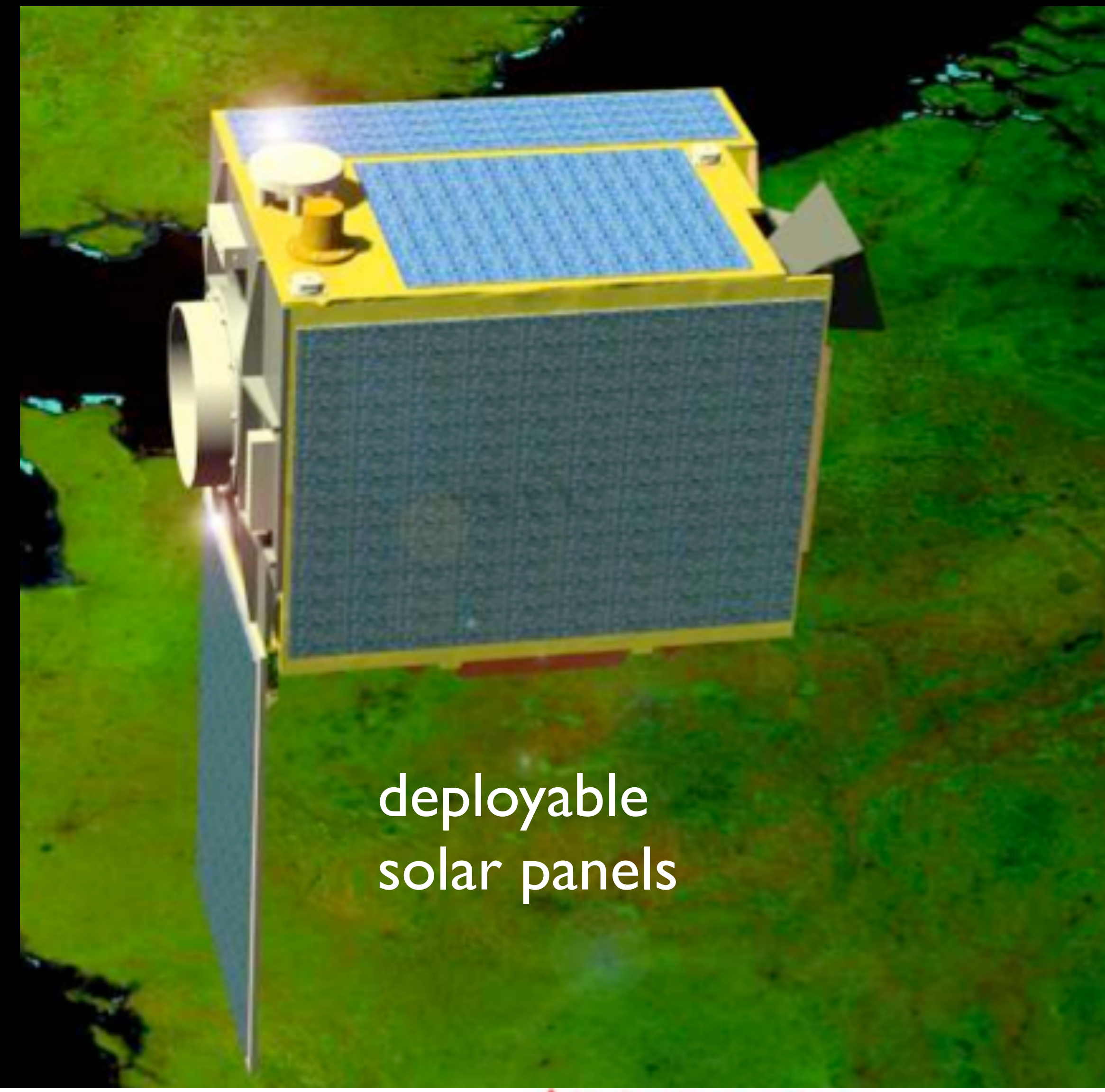
Mission concept / Feasibility study

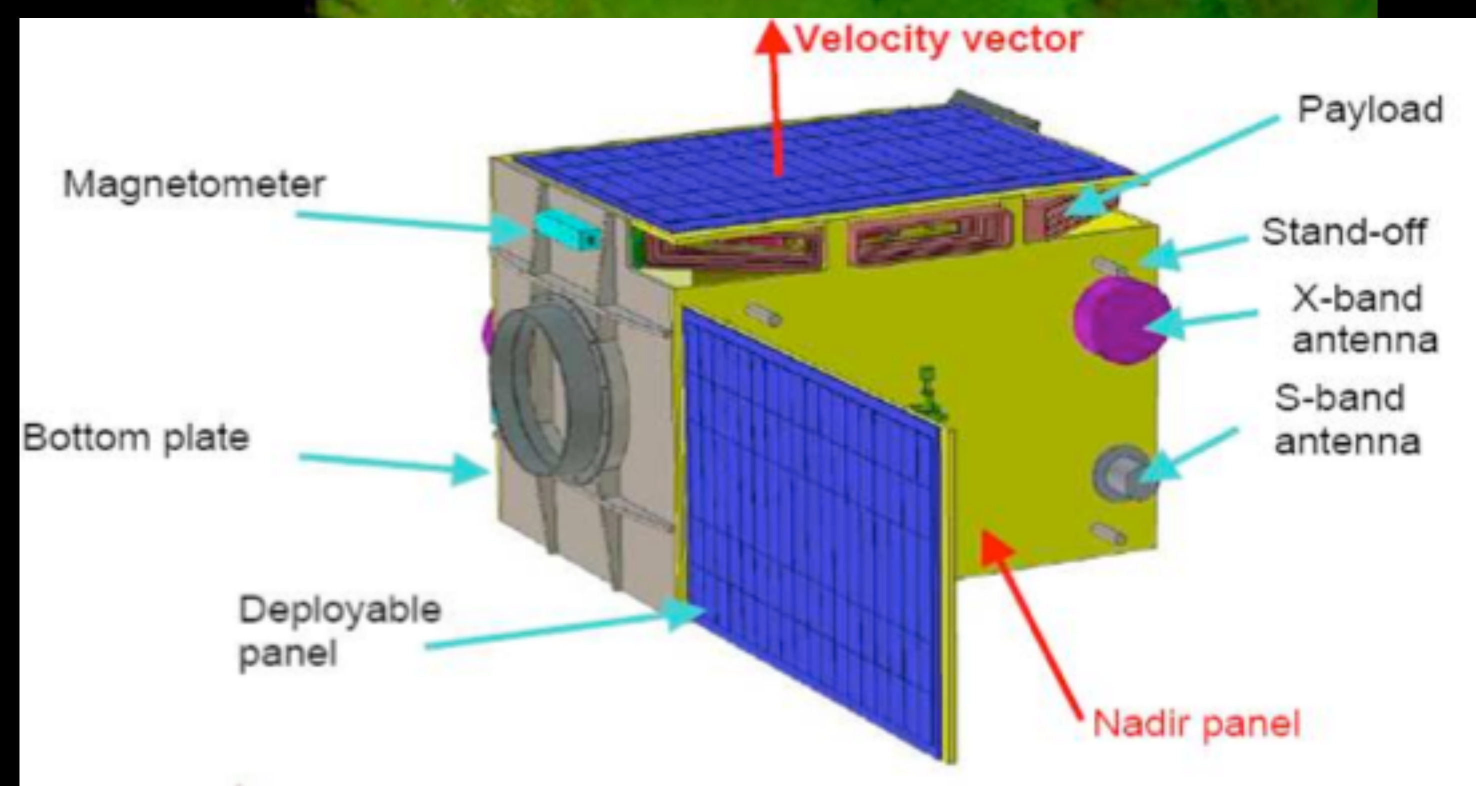
- Platform

  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


PROBA - V
VESPA adapter
Main satellite

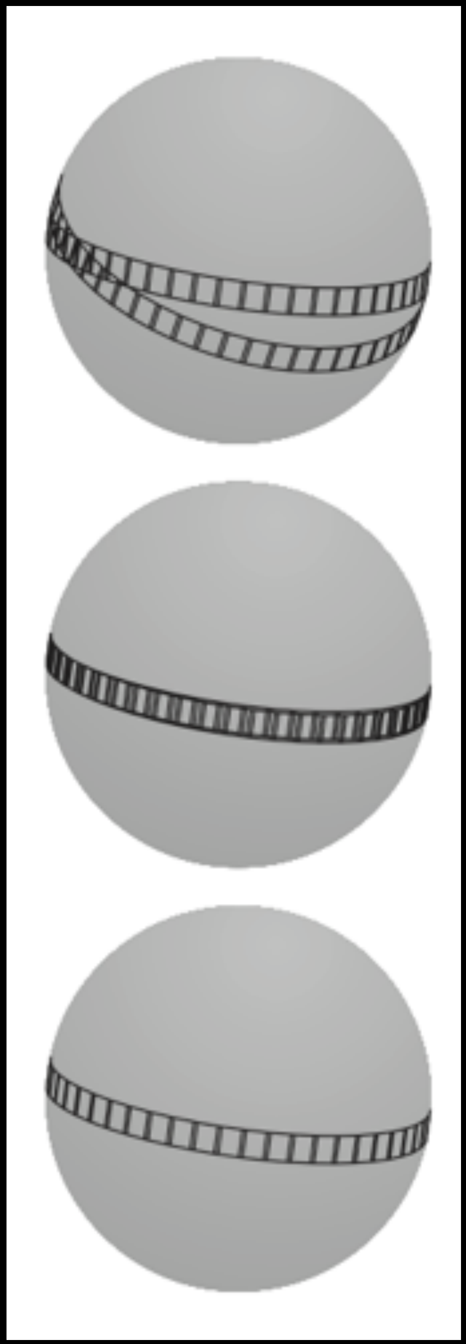

deployable solar panels

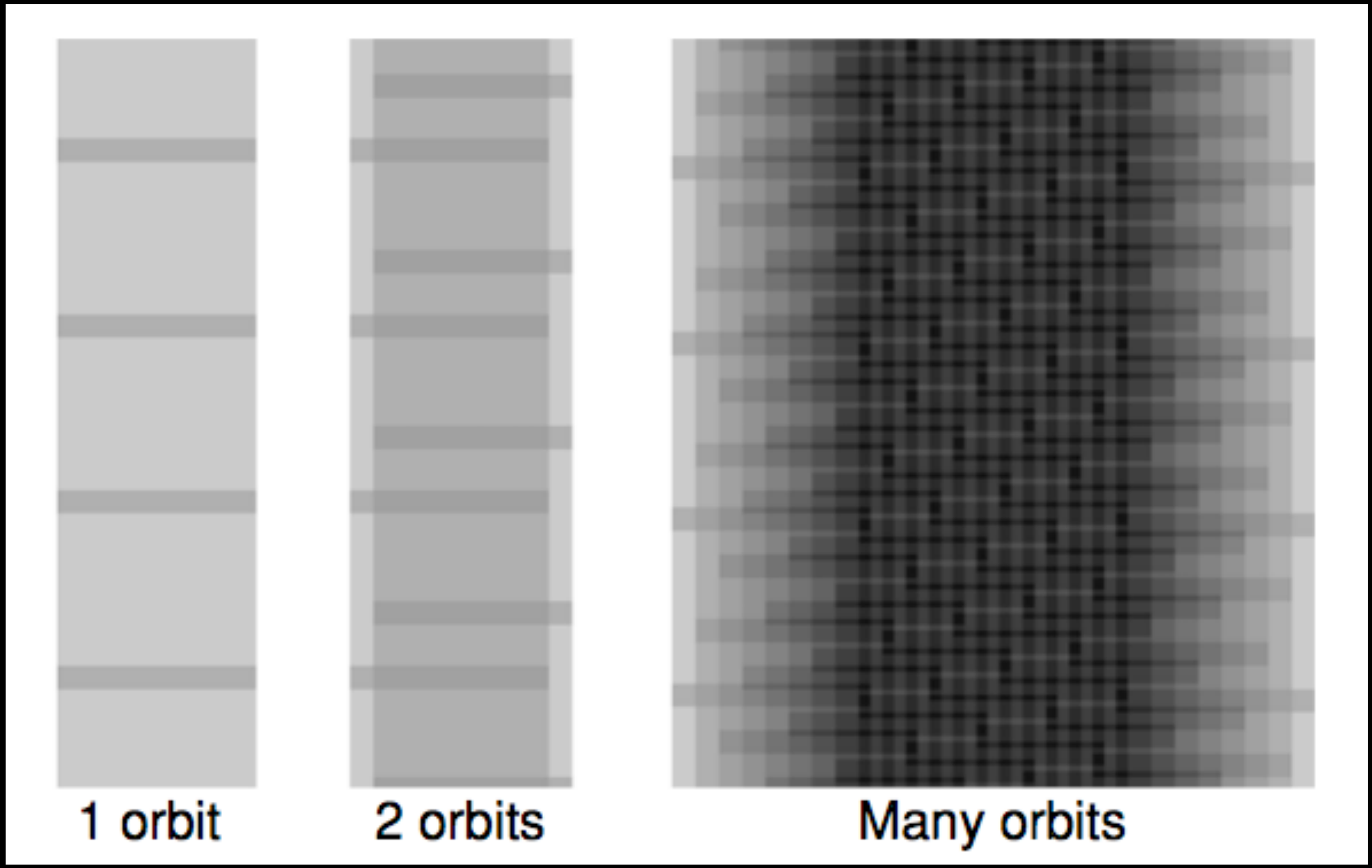

Velocity vector
Payload
Magnetometer
Stand-off
X-band antenna
S-band antenna
Bottom plate
Deployable panel
Nadir panel

Orbit

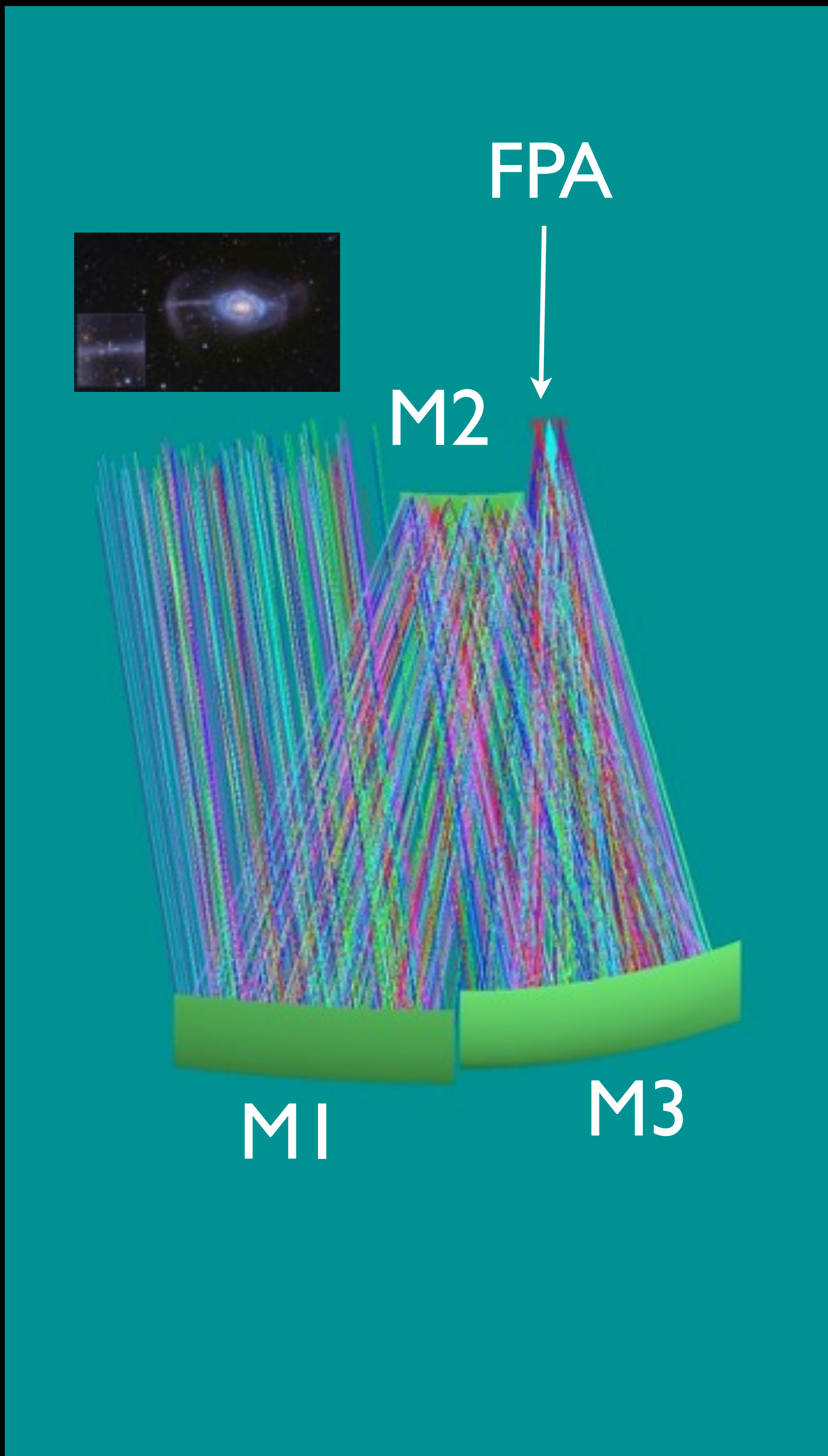
Sun-Synchronous Orbit

900 km, 98° inclination, LTAN 6h, full-sky survey
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)



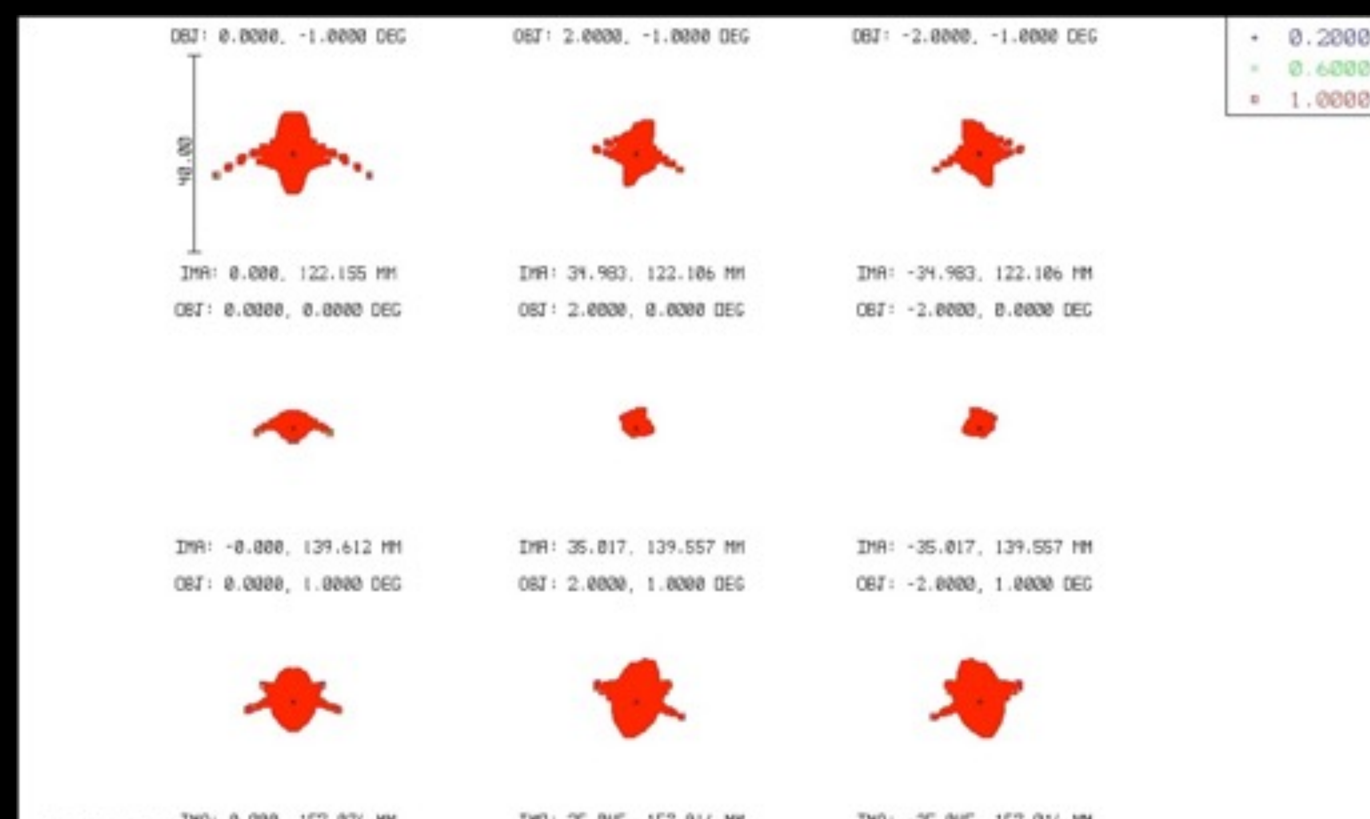


Payload: optical design

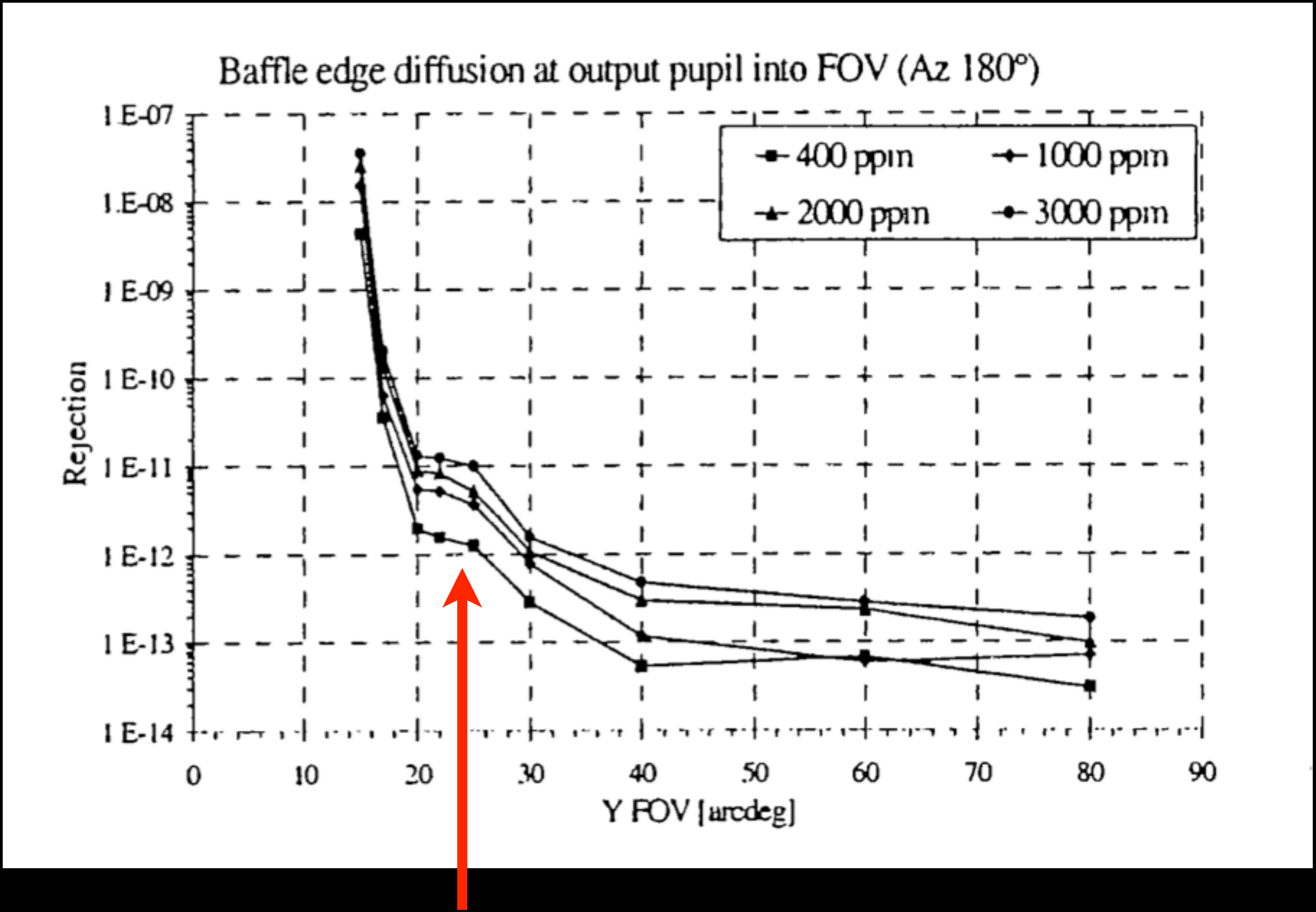


Off-axis TMA f/2 telescope

- 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)

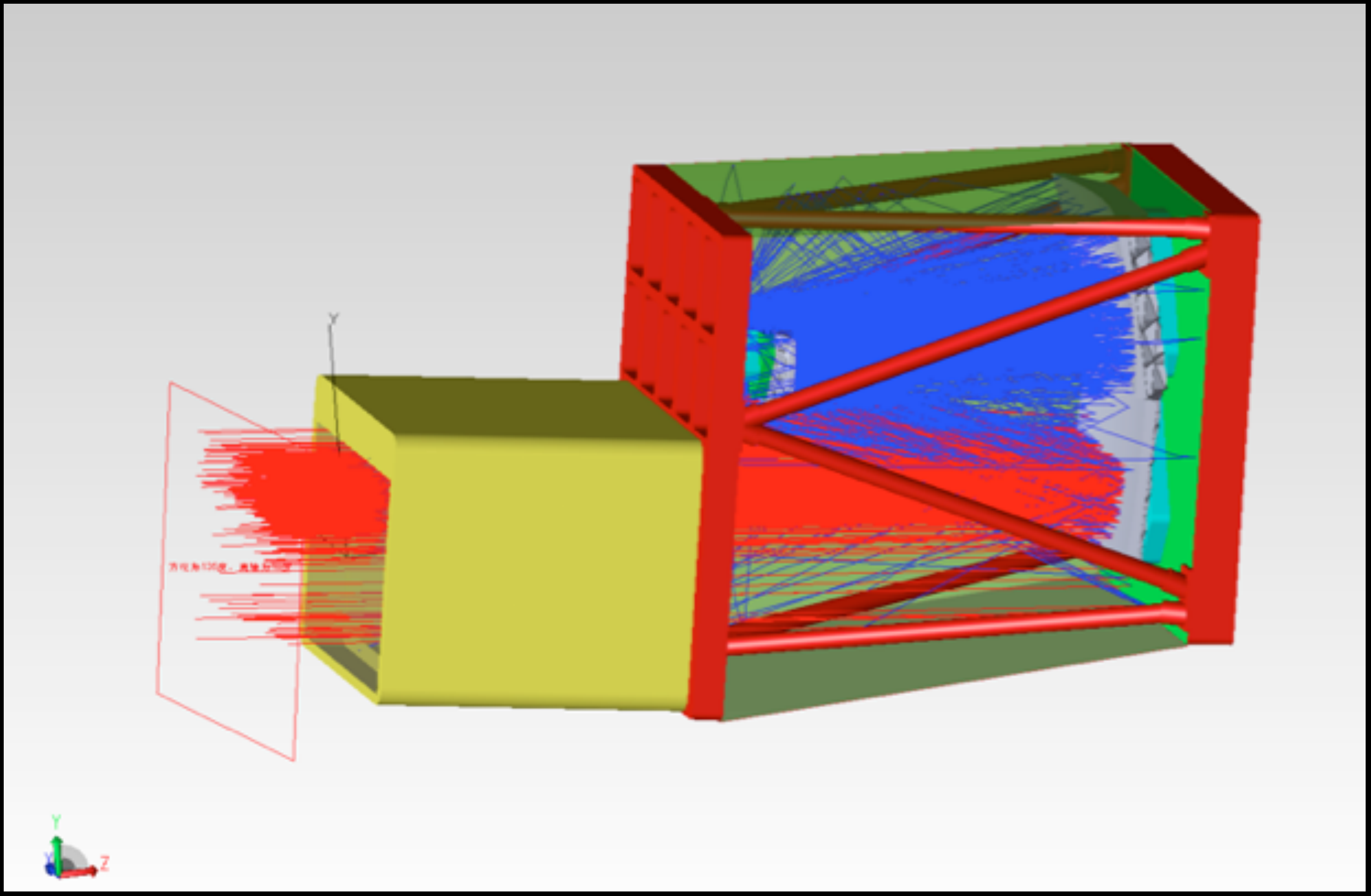


Stray light contamination: the CoRoT case

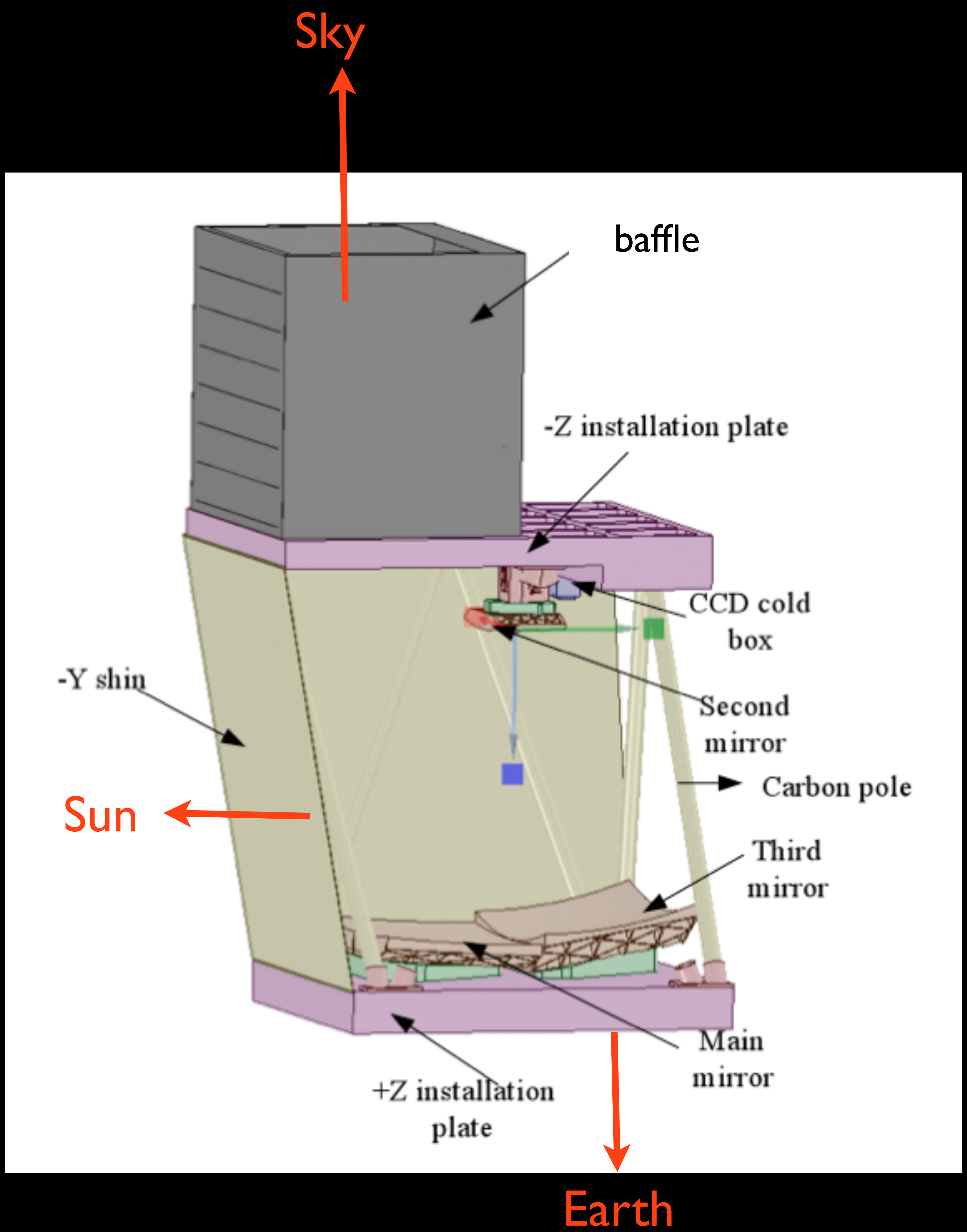


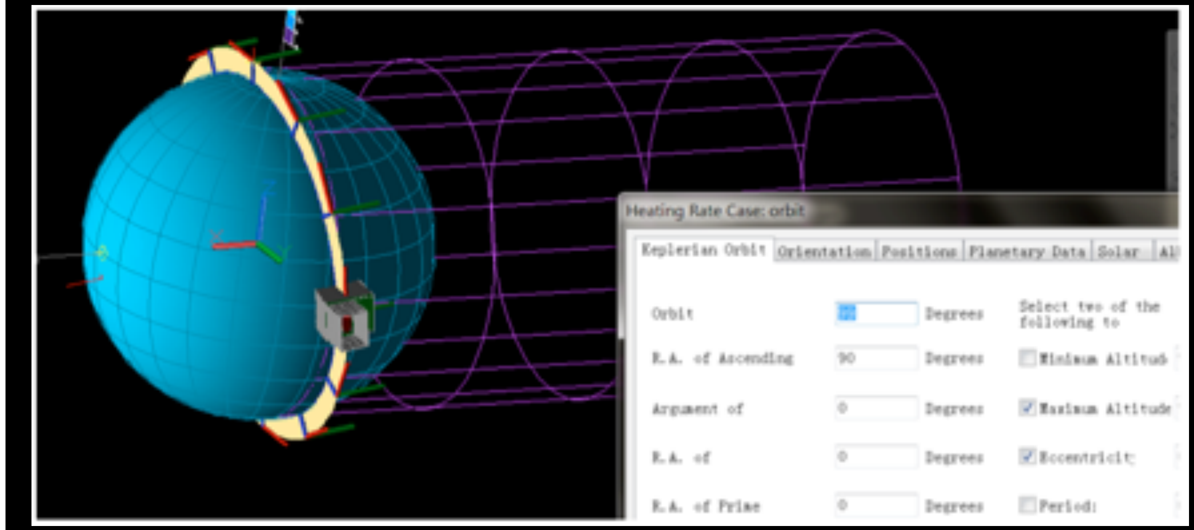
Straylight analysis

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

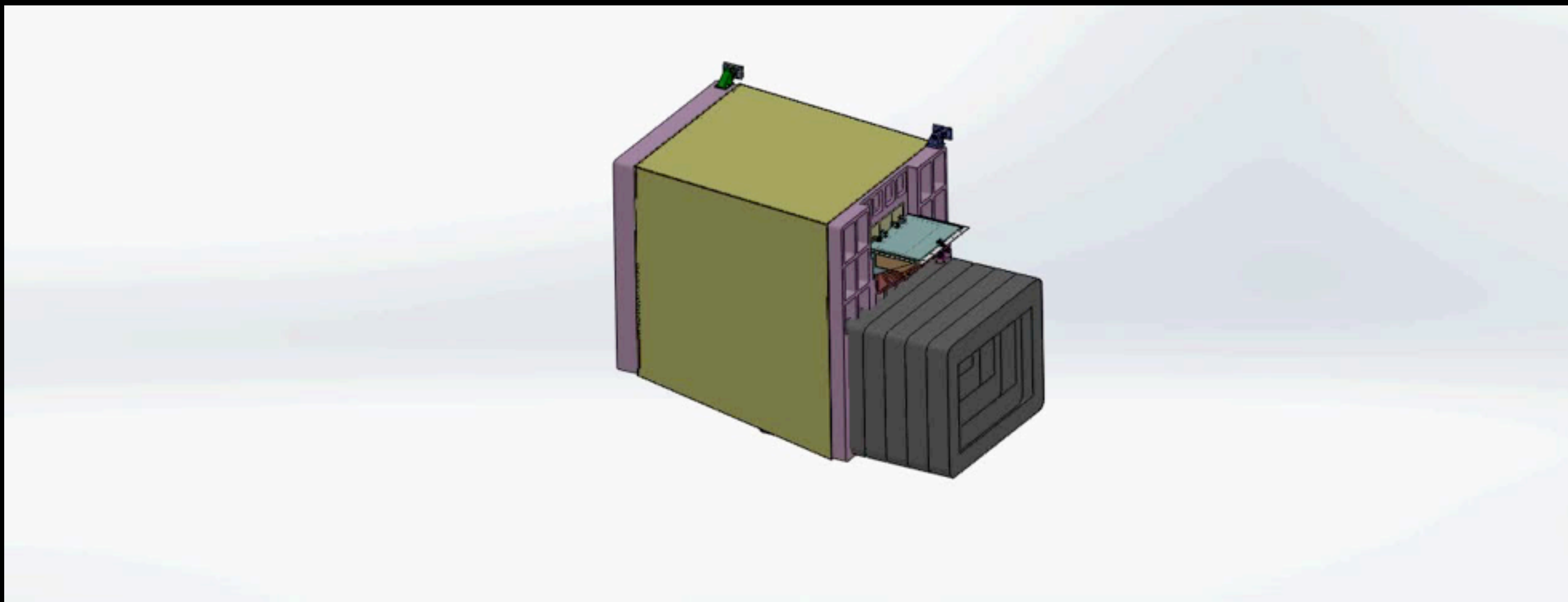


Thermal analysis





Current design of MESSIER within the PROBA-V platform



Mass budget : 60 kg within ESA-CAS
Power budget : 65 W boundary conditions

R&D: deployable external baffle

MESSIER
a piggyback trip to 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 parameter space

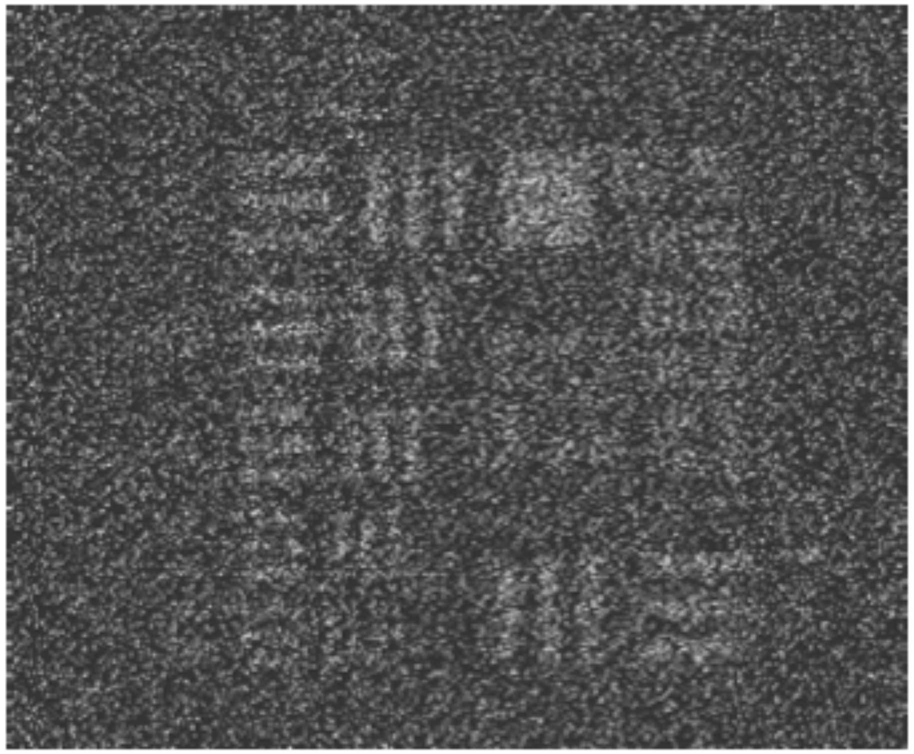
Unique scientific returns in
cosmology, galaxy evolution, stellar physics

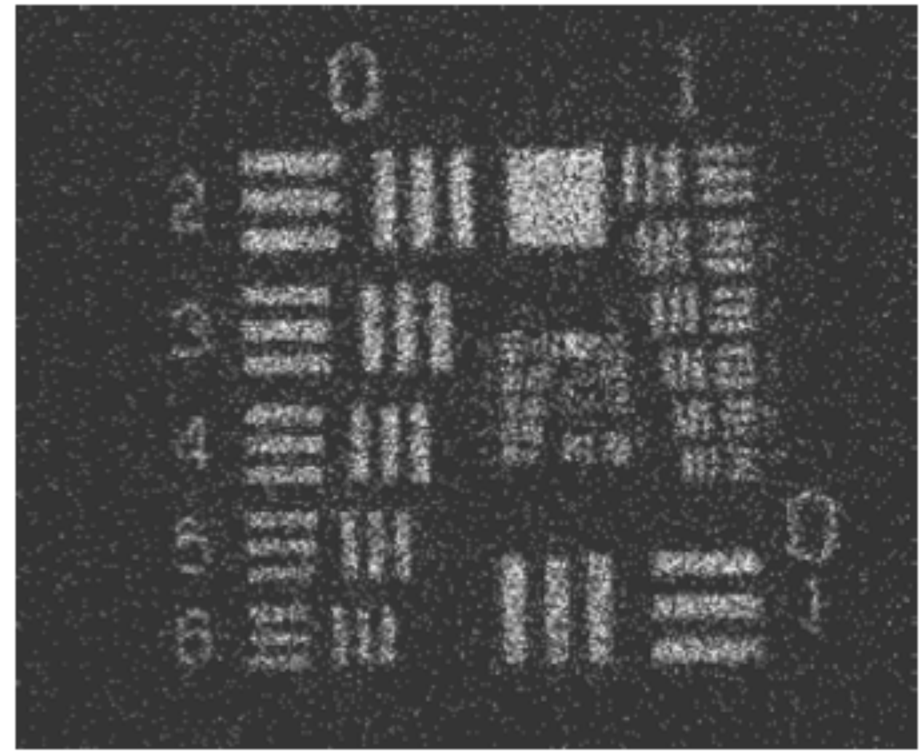
Legacy value: reference catalogue
for multi-band optical/UV photometry

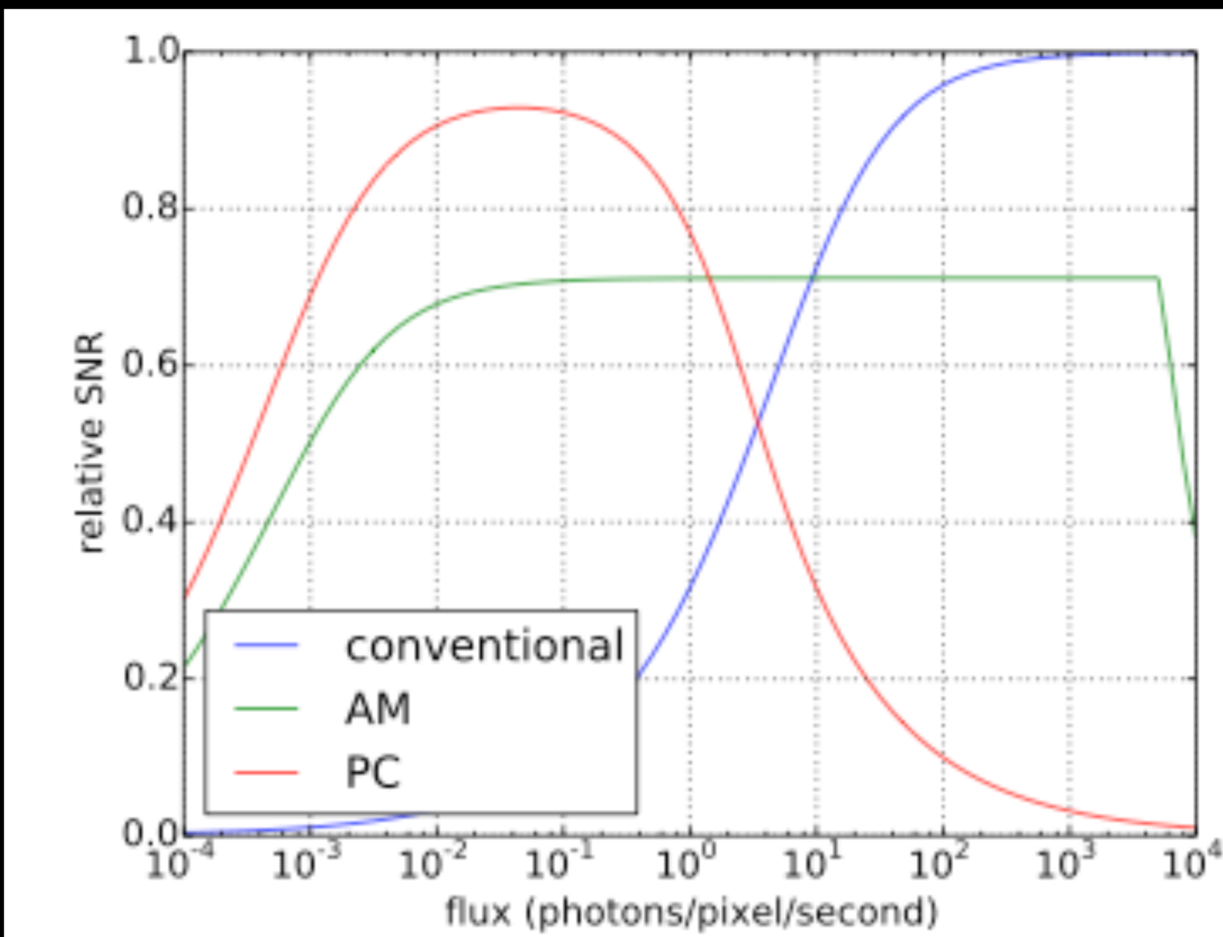
Further partners most welcome !

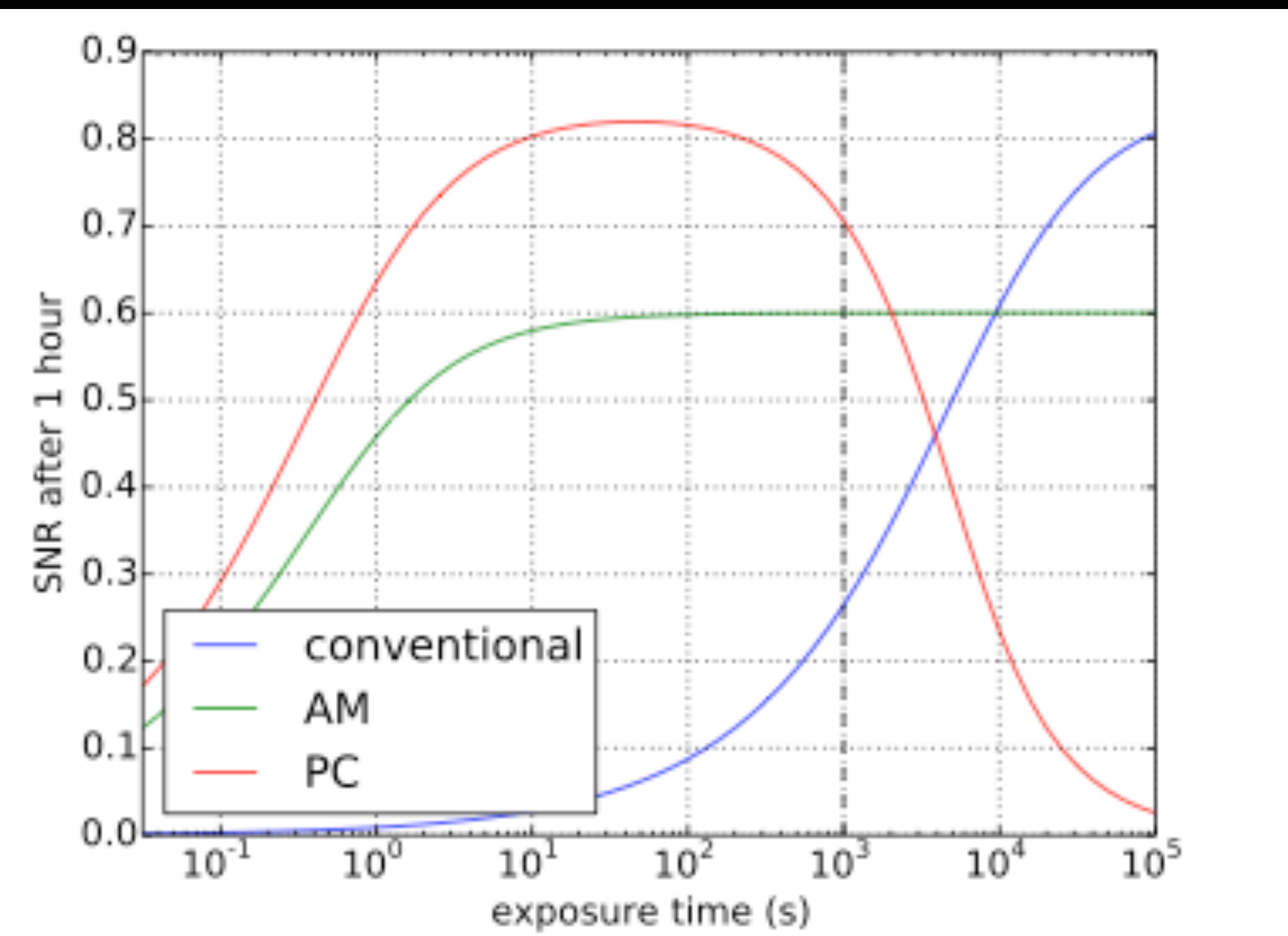
CCD

EMCCD

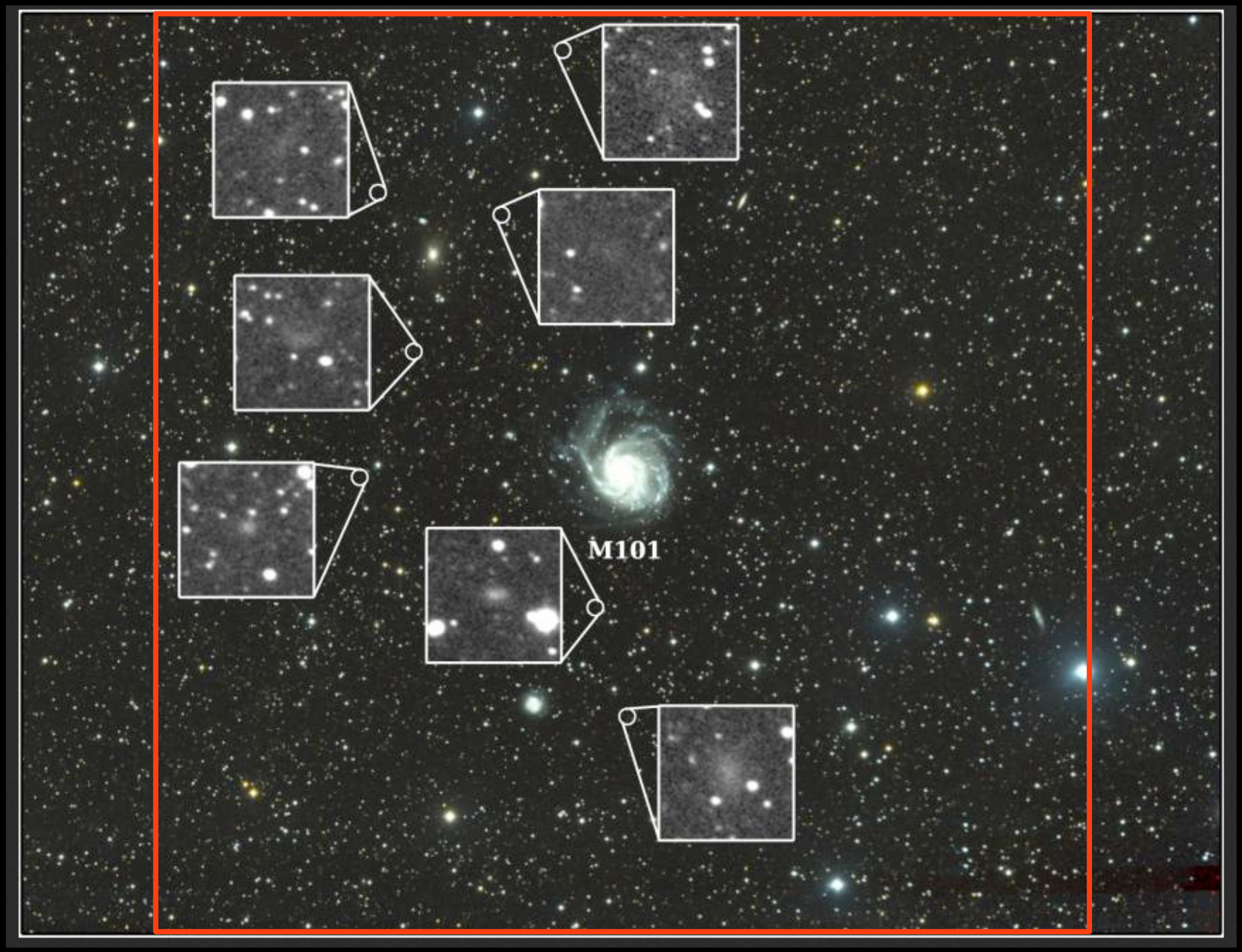




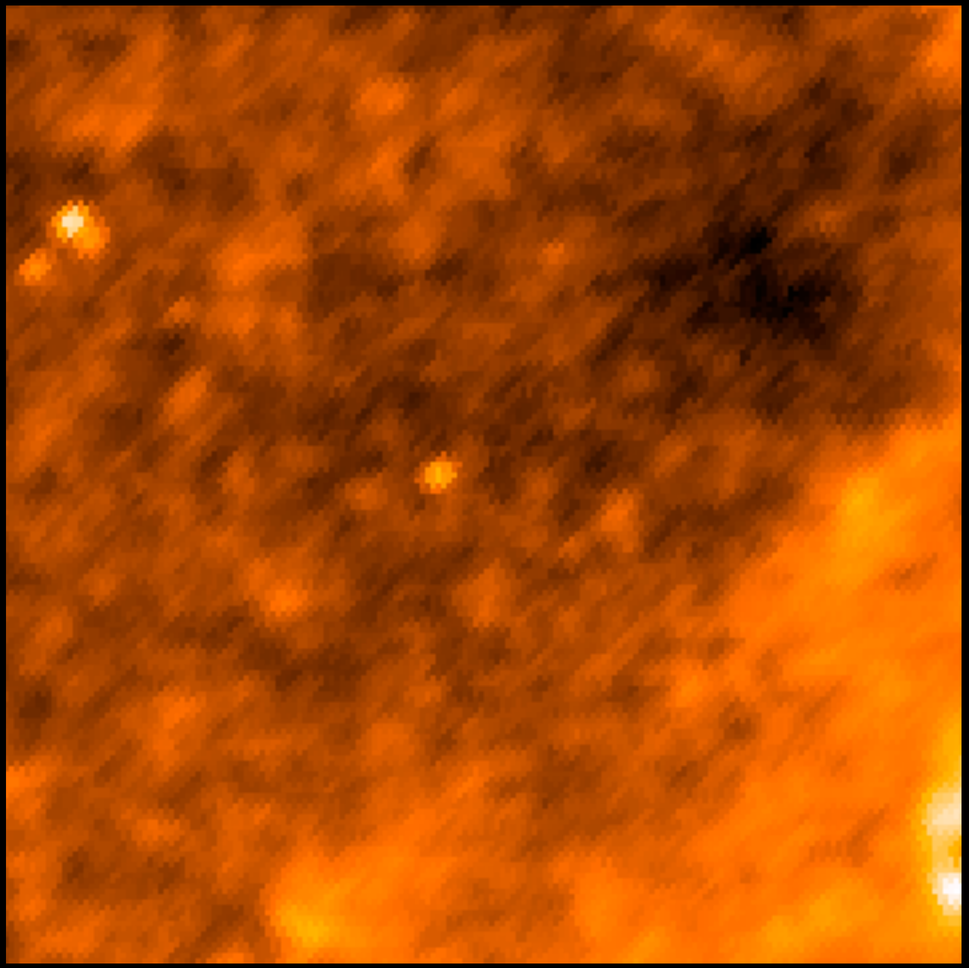

relative SNR
flux (photons/pixel/second)
conventional
AM
PC


SNR after 1 hour
exposure time (s)
conventional
AM
PC

Non detection of optical emission from IR cirri in M101 ?

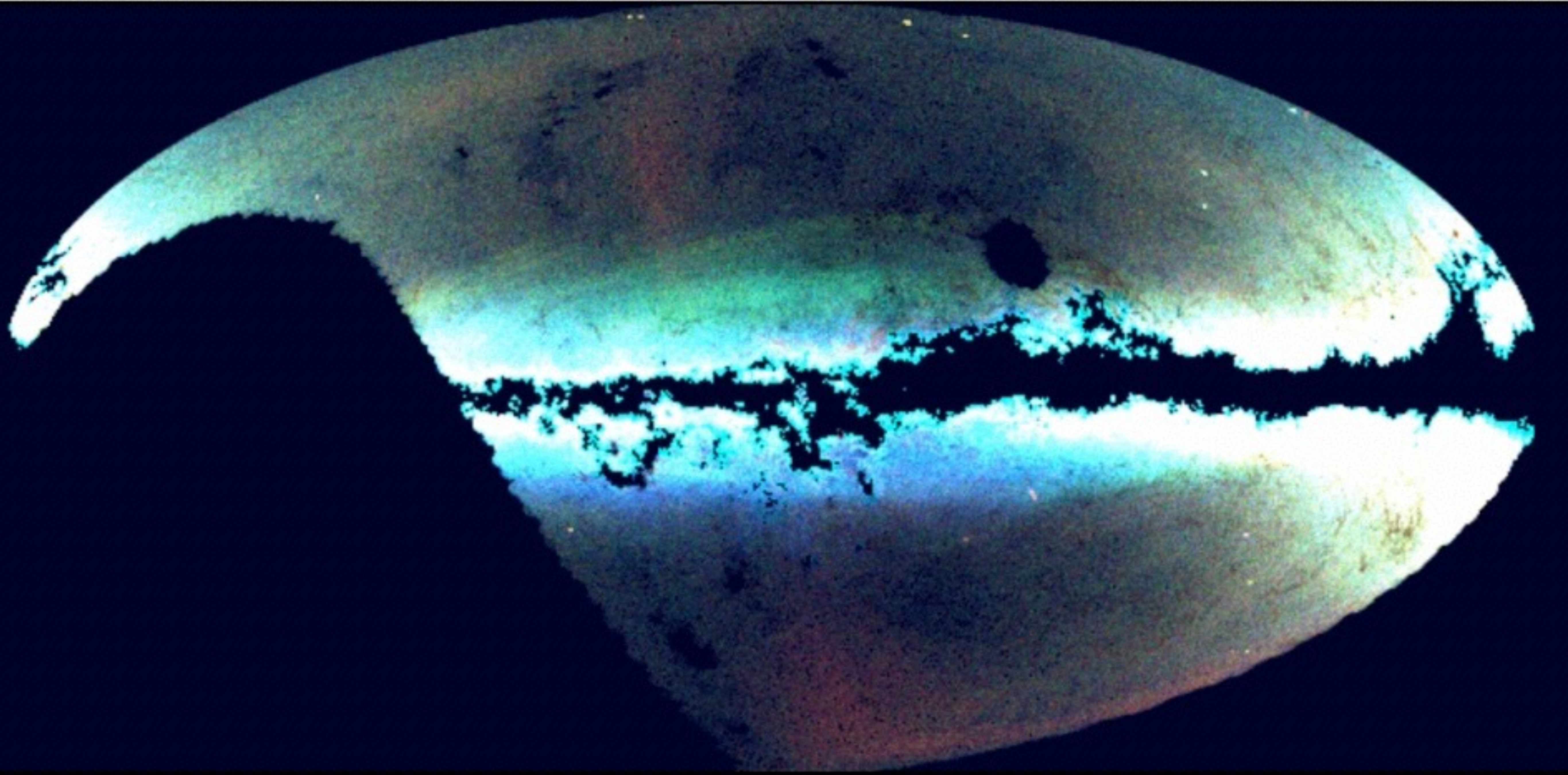


Dragonfly (37 hours)



Planck 857 GHz

The Galactic anti-centre as seen by PanSTARRS1



7.6 Background

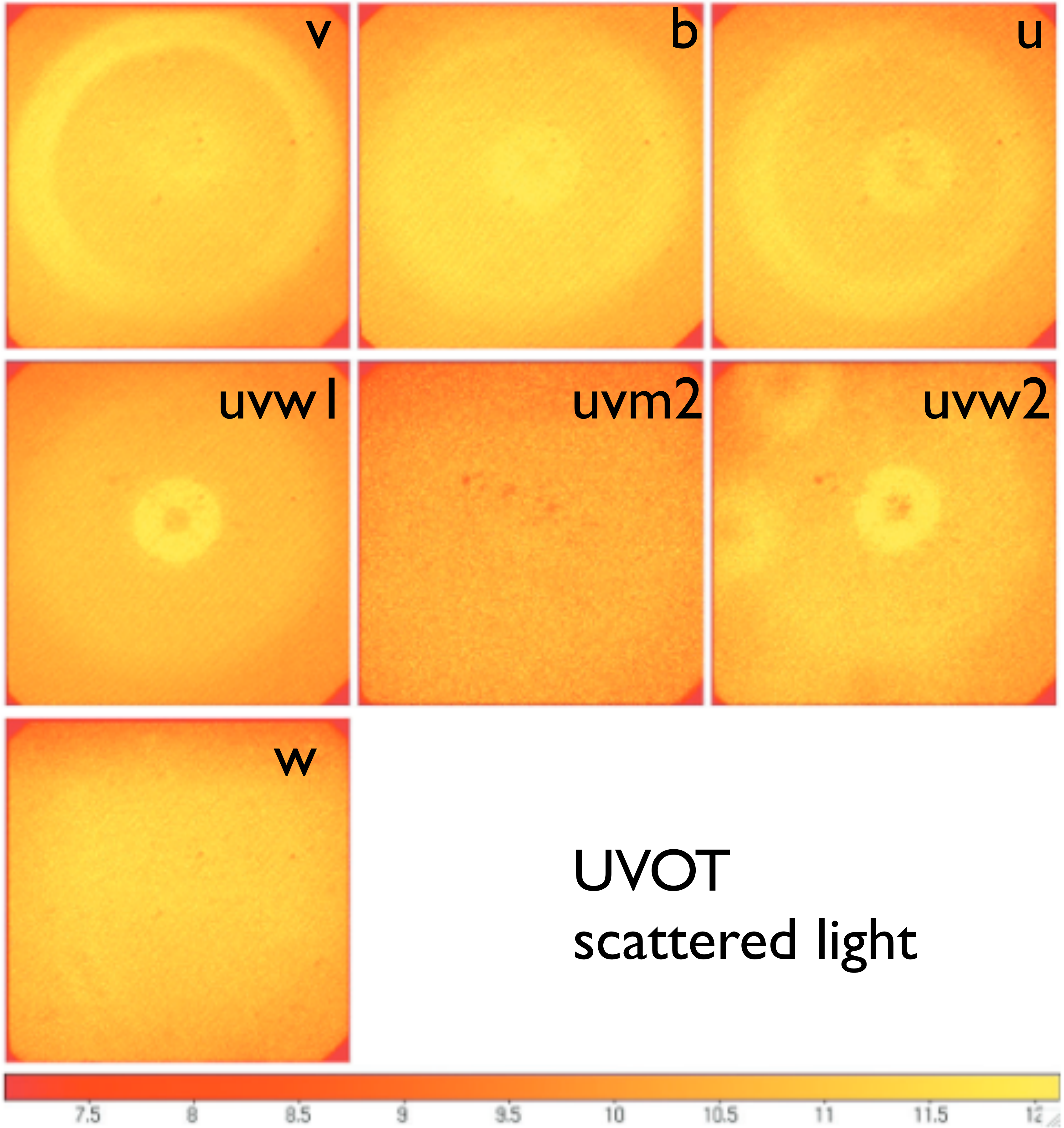
[Top] [Prev] [Next]

The FOC suffers from various types of background, the most important of which are thermal electrons, Cerenkov radiation from high energy particles, geocoronal emission lines, zodiacal light, and light scattered within HST from the bright Earth or Moon. Because the particle-induced background levels are essentially unpredictable, the FOC pipeline does not attempt to remove the background from a geometrically corrected and flatfielded image. In practice, most astronomical data analysis procedures derive the background locally as needed, so pipeline background removal is unnecessary.

The levels, spatial distribution, and time variation of the principal sources of background are discussed below to help you decide whether the background on your images might be astronomically interesting or is merely an instrumental effect. For a more thorough discussion, see the *FOC Instrument Handbook*.

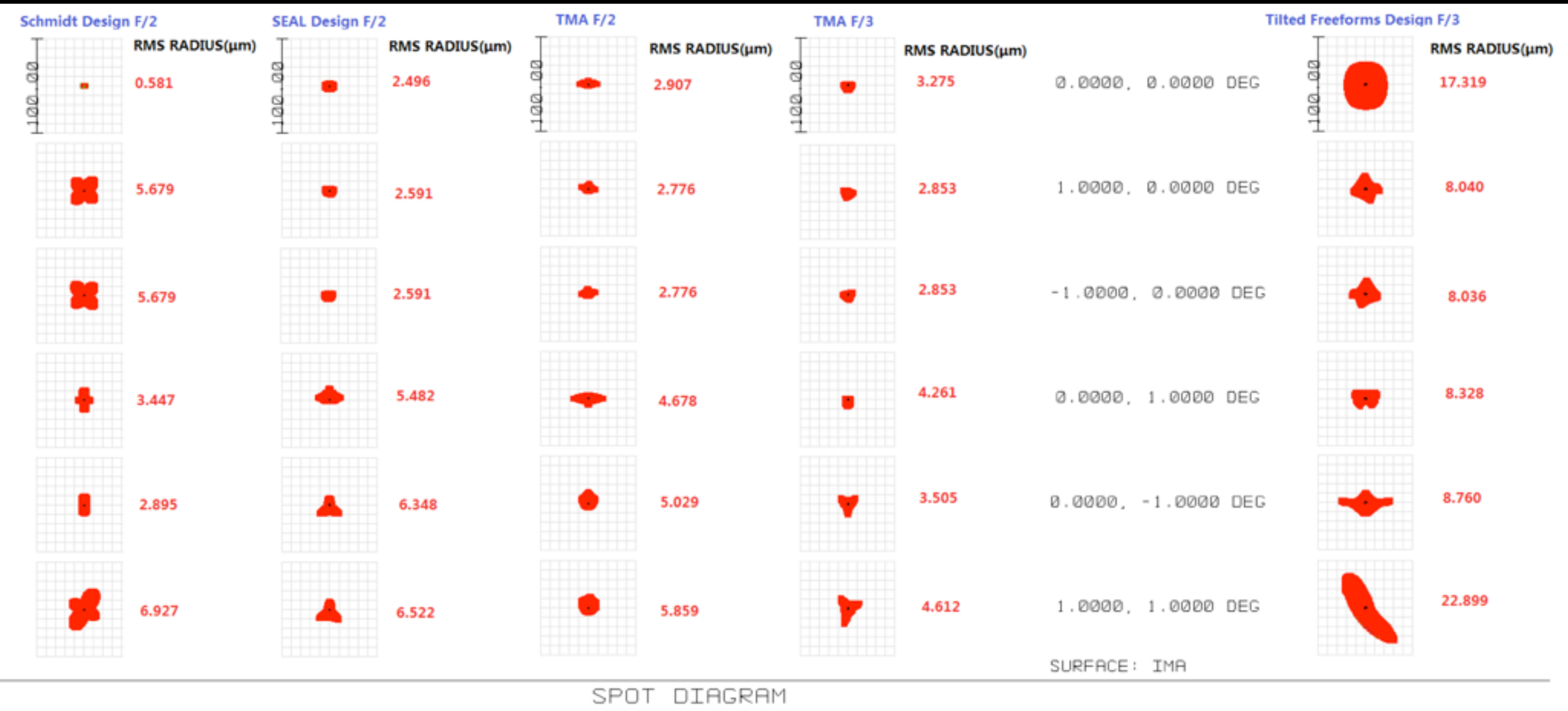
7.6.1 Detector Background

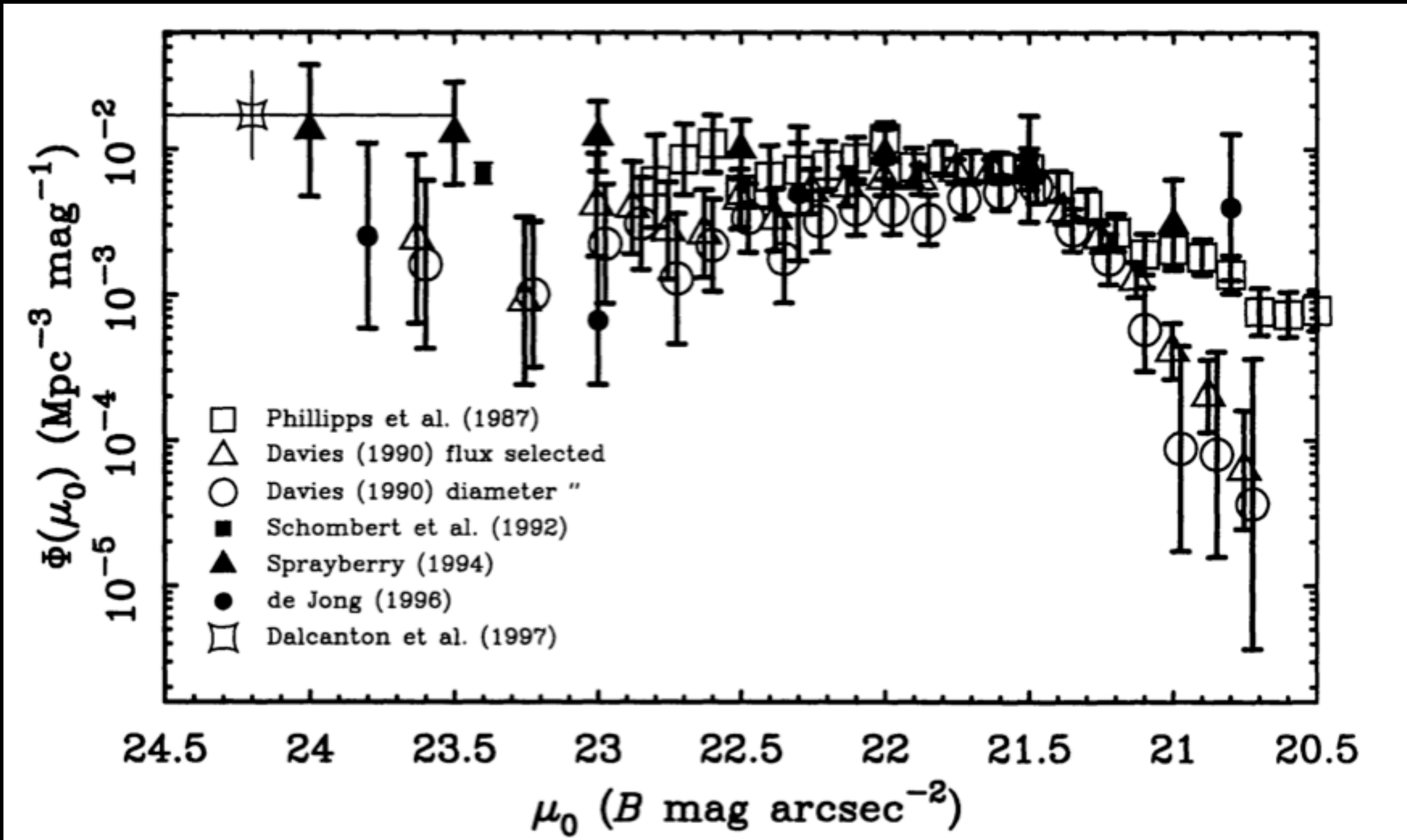
The detector background arises primarily from thermal electrons at the first photocathode and high energy particles. The dark current due to thermal electrons is rather lower than the particle-induced background, at approximately 2 x 10^{-4} counts/sec/pixel. This background source is likely uniform over the field and temporally stable and does not show the Reseau marks as dark holes. The particle-induced background is caused by high-energy electrons and protons which generate intense flashes of Cerenkov radiation as they pass through the photocathode window. The FOC's video processing unit (VPU) cannot distinguish the photons from these flashes from celestial photons, and so they appear as a background. The flux of these particles rises strongly over the South Atlantic Anomaly (SAA), but even well away from the SAA, they are the principal contributor to the background of most FOC images. For most of the useful orbit of HST, the particle-induced background is of the order of 7 x 10^{-4} counts sec-1 pixel-1 on the *f*/96 side, and 1-3 x 10^{-3} on the *f*/48 channel. Upward fluctuations of these values are sometimes recorded. Because the particle-induced background generates photons, its spatial distribution looks like a flatfield, except the shadows at the edges of the field caused by obstructions in the FOC beam between the aperture plate and the photocathode are not present. The Reseau marks are between the photocathode faceplate where the Cerenkov radiation originates and the photocathode, so they will show up in exposures dominated by such backgrounds.



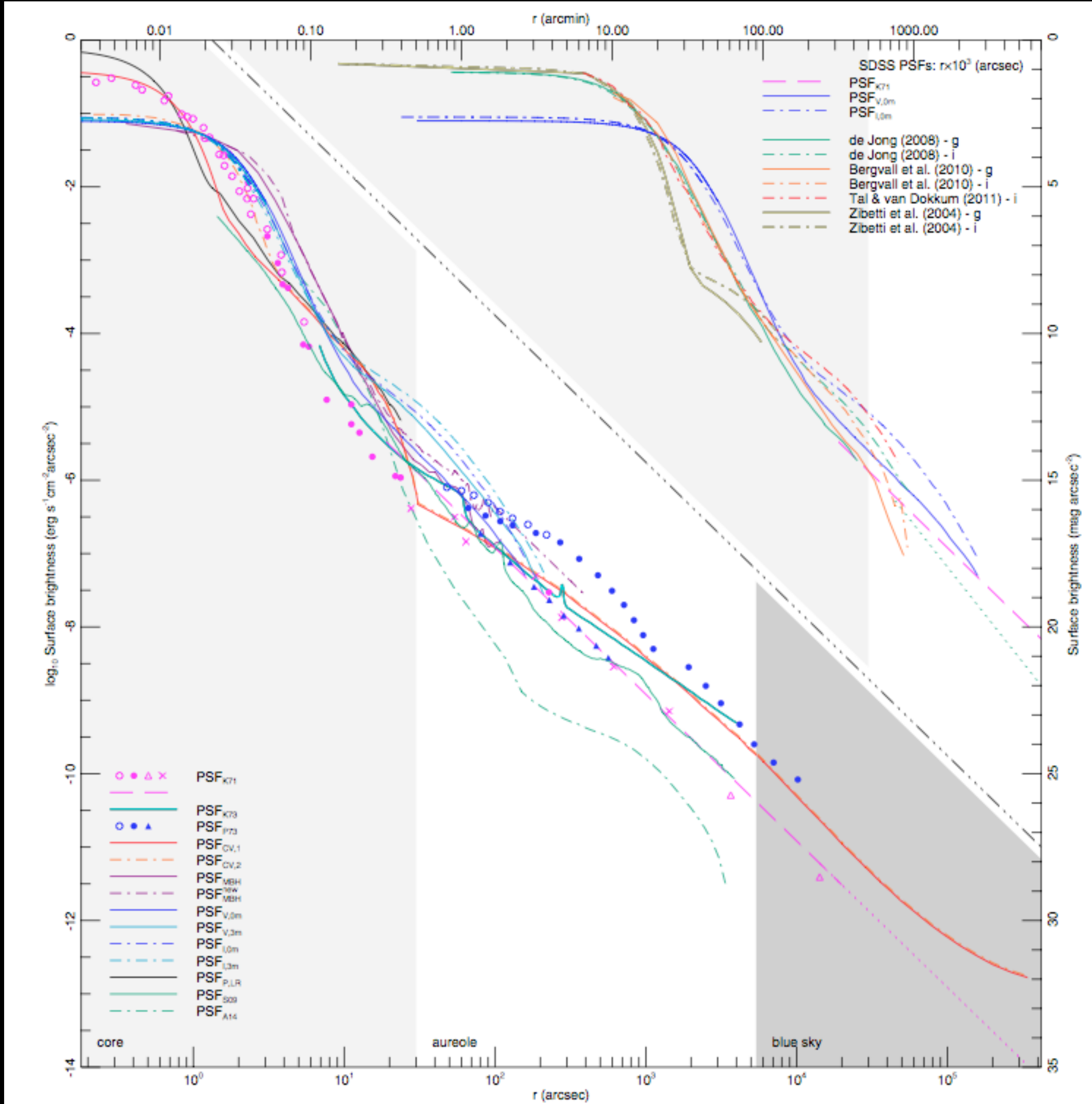
UVOT
scattered light

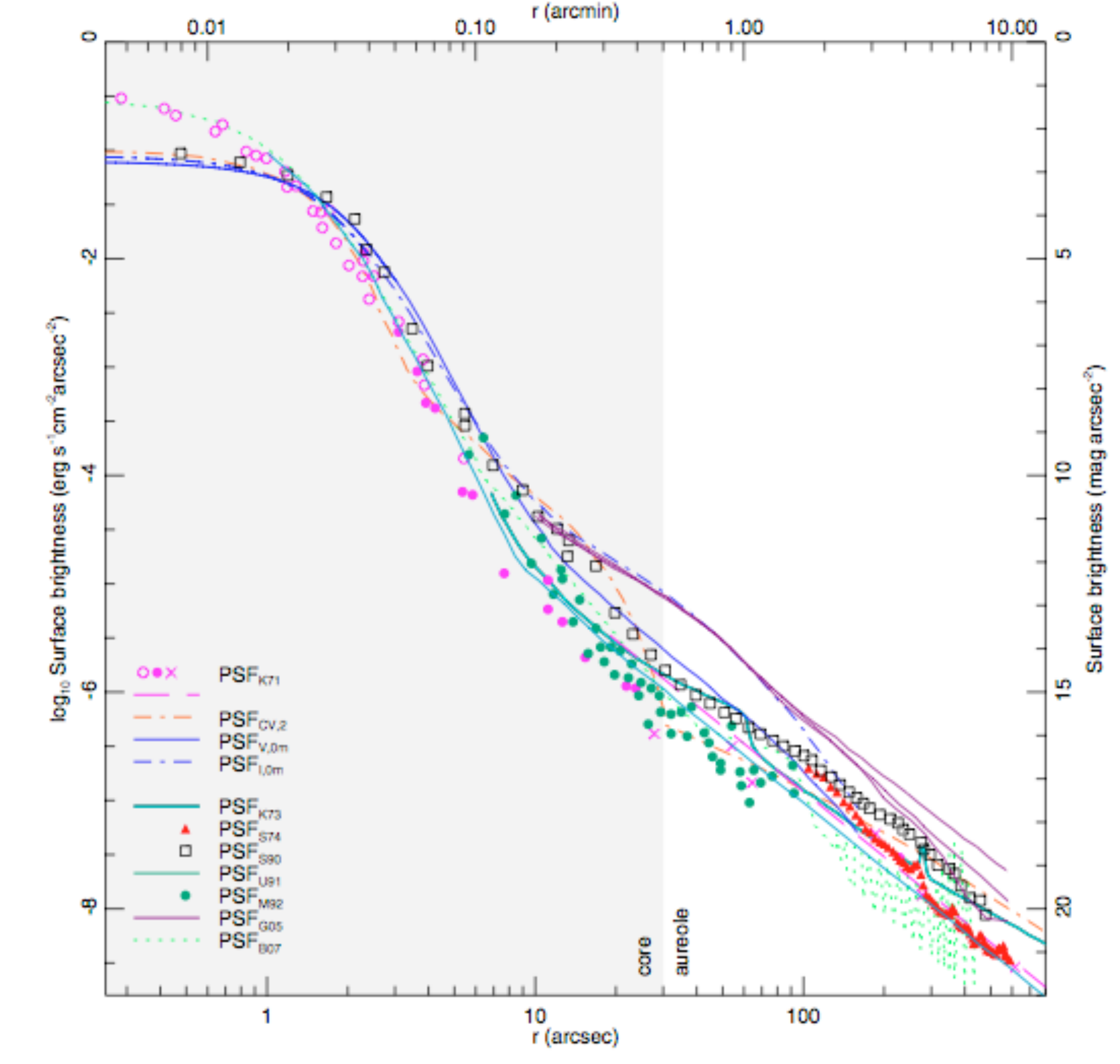
Comparison of optical designs



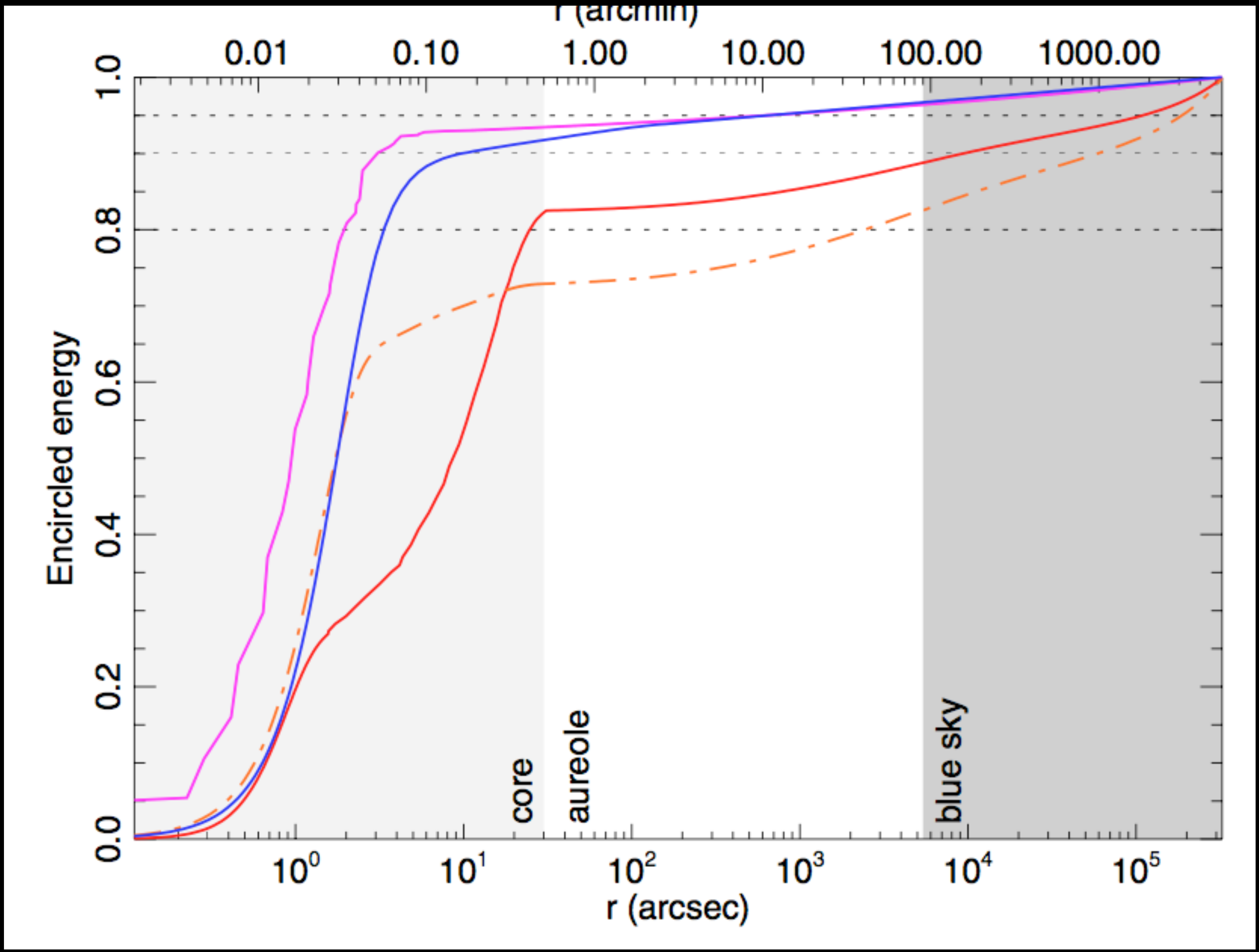


McGaugh (1999)


r (arcmin)
0.01
0.10
1.00
10.00
100.00
1000.00
SDSS PSFs: r×10³ (arcsec)
PSF K71
PSF V,0m
PSF I,0m
de Jong (2008) - g
de Jong (2008) - i
Bergvall et al. (2010) - g
Bergvall et al. (2010) - i
Tal & van Dokkum (2011) - i
Zibetti et al. (2004) - g
Zibetti et al. (2004) - i
log10 Surface brightness (erg s⁻¹ cm⁻² arcsec⁻²)
Surface brightness (mag arcsec⁻²)
PSF K71
PSF K73
PSF P73
PSF CV,1
PSF CV,2
PSF MBH
PSF new MBH
PSF V,0m
PSF V,3m
PSF I,0m
PSF I,3m
PSF P,LR
PSF S09
PSF A14
core
aureole
blue sky
r (arcsec)



r (arcmin)
0.01
0.10
1.00
10.00
0
-2
-4
-6
-8
5
10
15
20
log₁₀ Surface brightness (erg s⁻¹cm⁻²arcsec⁻²)
Surface brightness (mag arcsec⁻²)
PSF_K71
PSF_CV,2
PSF_V,0m
PSF_I,0m
PSF_K73
PSF_S74
PSF_S90
PSF_U91
PSF_M92
PSF_G05
PSF_B07
core
aureole
1
10
100
r (arcsec)



r (arcmin)
0.01
0.10
1.00
10.00
100.00
1000.00
Encircled energy
0.0
0.2
0.4
0.6
0.8
1.0
core
aureole
blue sky
10^0
10^1
10^2
10^3
10^4
10^5
r (arcsec)

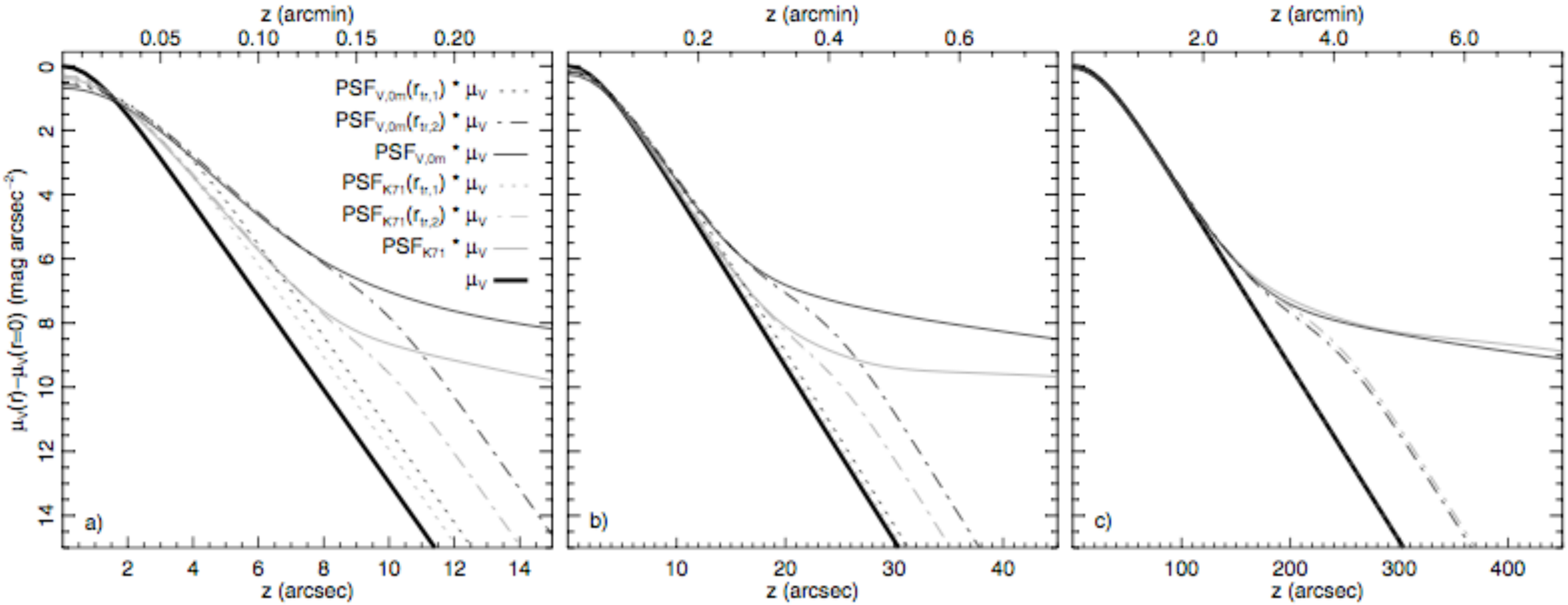


Fig. 5. Vertical-axis surface-brightness profiles that illustrate effects of radial truncation of PSF_{K71} and $PSF_{V,0m}$ in example models. The three panels show: **a**) a small edge-on galaxy, **b**) an edge-on galaxy of intermediate size, and **c**) a large edge-on galaxy. In each panel, the disc-galaxy model profile is drawn with a thick solid black line, and model profiles that were convolved with $PSF_{V,0m}$ (PSF_{K71}) are drawn with thin black (grey) lines. The profile of the model that is convolved with the complete PSF is drawn with a thin solid line. Profiles are also shown where each PSF was truncated at $r_{tr,1}$ ($r_{tr,2}$) with a dotted line (dash-dotted line) in each panel; **a**) $r_{tr,1} = 4''$ and $r_{tr,2} = 10''$; **b**) $r_{tr,1} = 10''$ and $r_{tr,2} = 25''$; **c**) $r_{tr,1} = 10''$ (lines fall on top of the model line and are not visible) and $r_{tr,2} = 250''$ (Table 3).

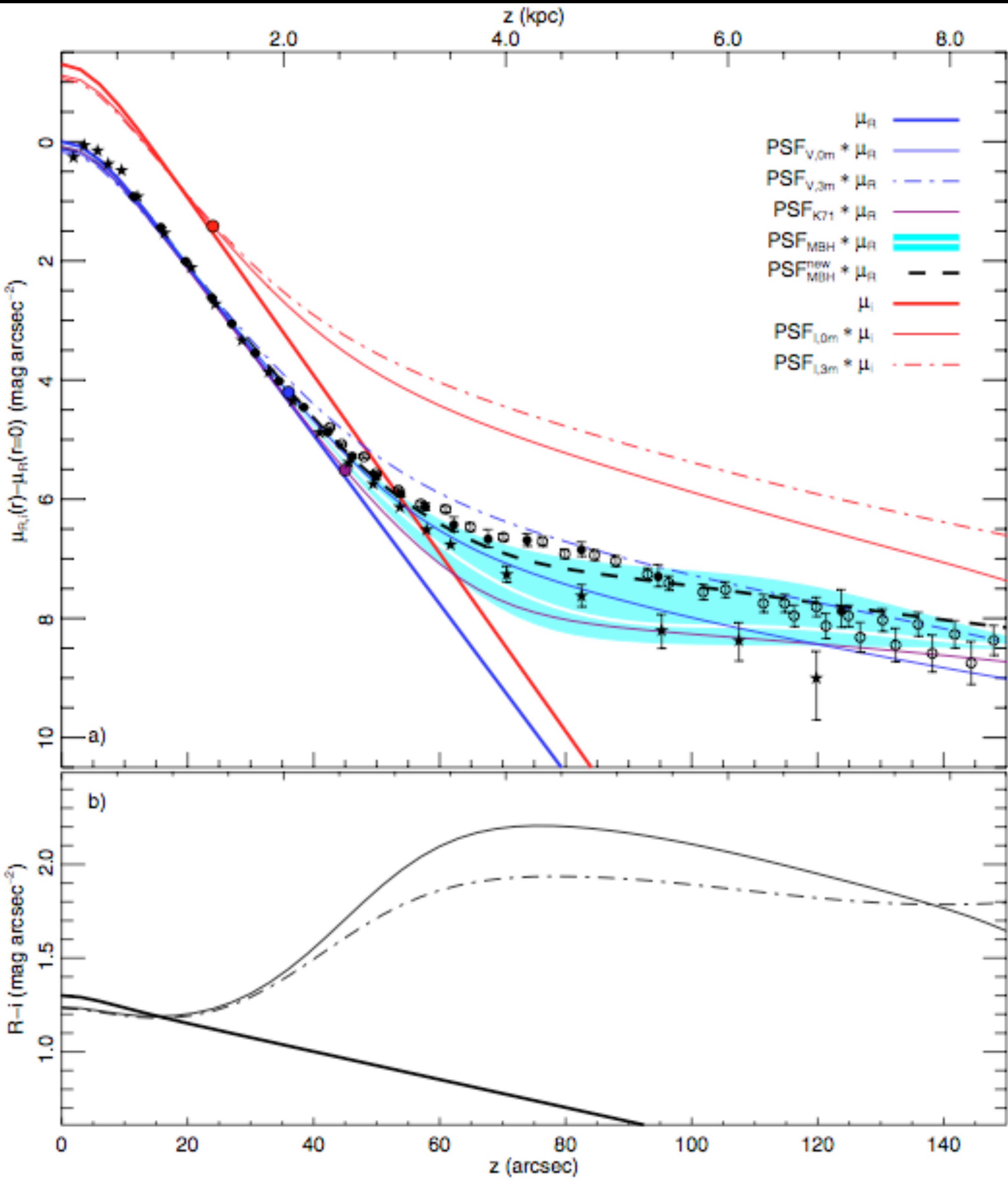
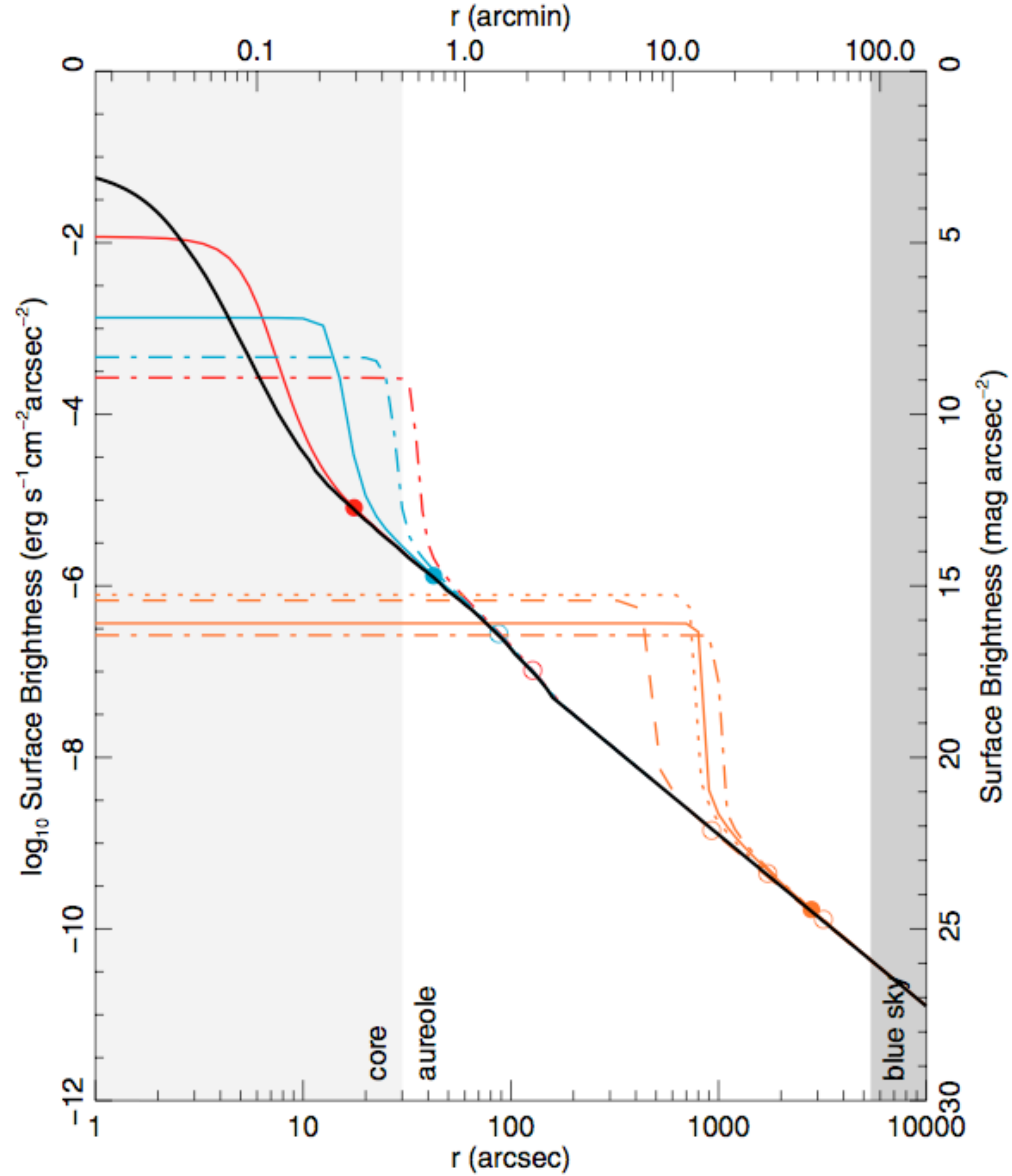
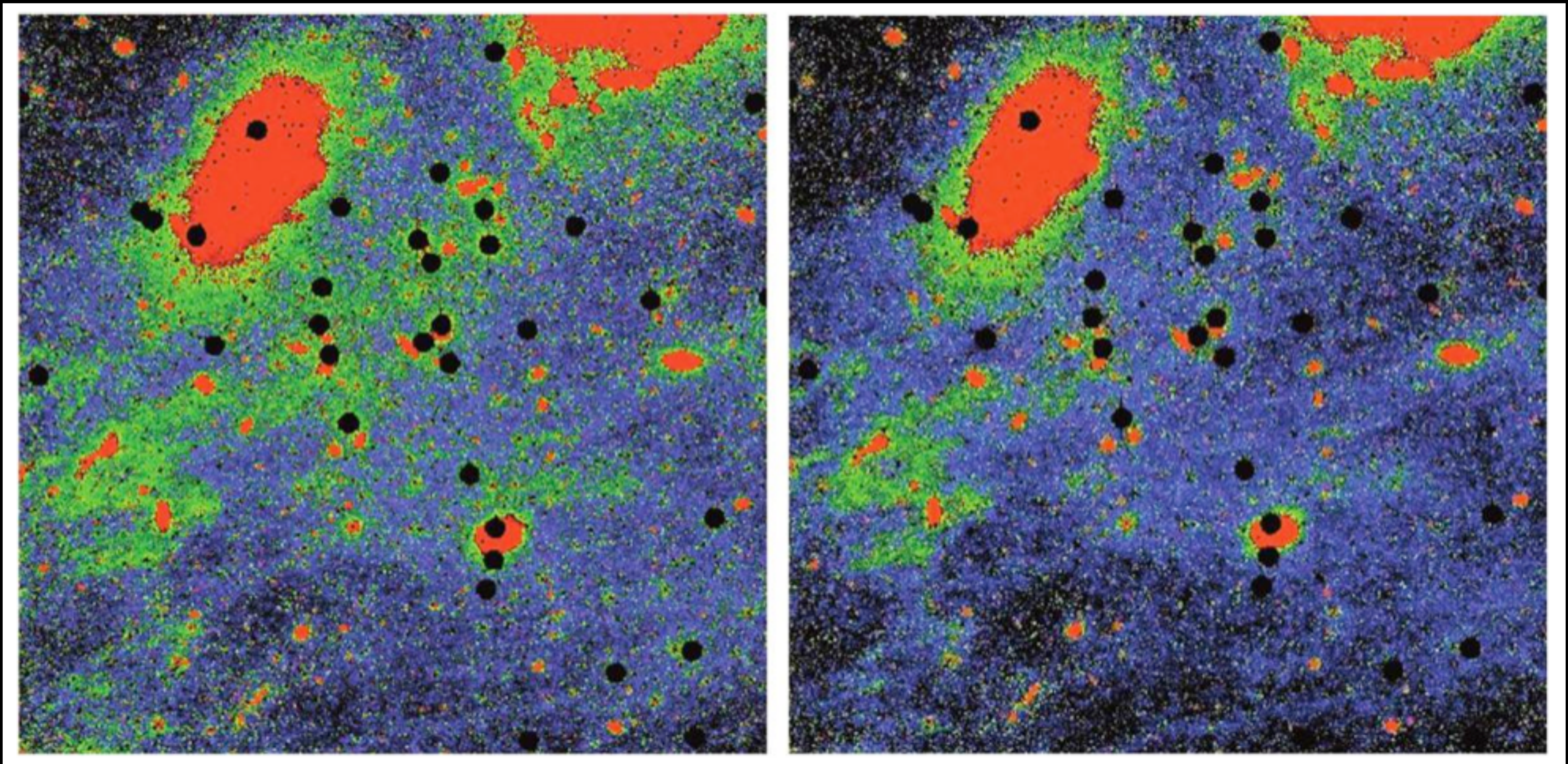
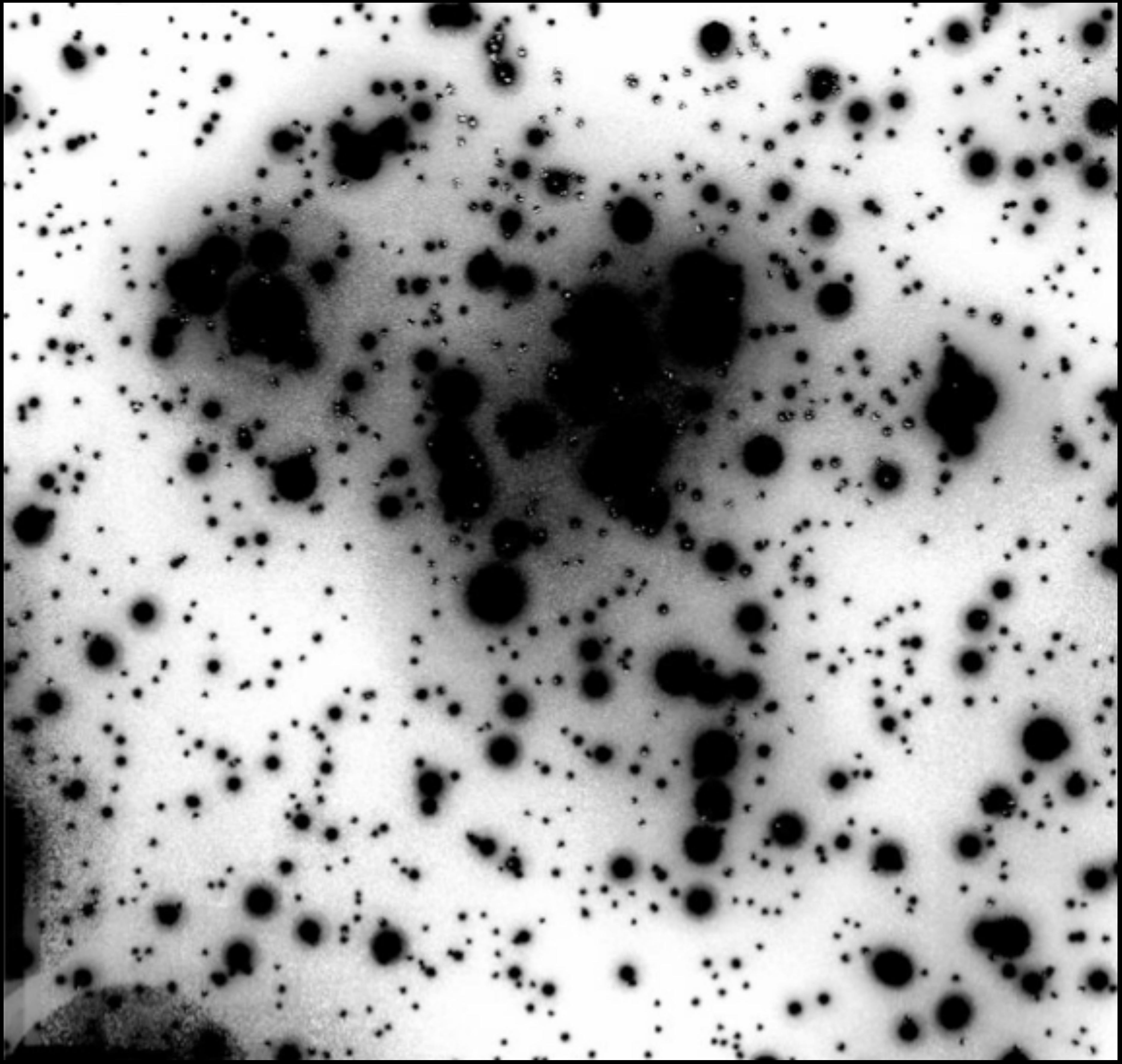


Fig. 6. Vertical-axis R-band and i-band surface-brightness profiles versus the vertical distance z of models and measurements of the edge-on galaxy NGC 5907. **a)** Blue and purple lines show R-band profiles, and red lines i-band profiles. Model profiles are drawn with thick solid lines. Solid (dash-dotted) lines are profiles of convolved models using $PSF_{V,0m}$ and $PSF_{i,0m}$ ($PSF_{V,3m}$ and $PSF_{i,3m}$), the purple line used PSF_{K71}. Three different symbols and error bars show measured values: • R band (Sackett et al. 1994; MBH94), ★ V band (LFD96), and from profiles on both sides of the disc ∘ 6660 Å band (ZSS99). The R-band model was convolved with the measured PSF_{MBH} (including lower and upper errors) to produce the white line (cyan-coloured region). The lower limiting radius r_{110} – where the convolved models using $PSF_{V,0m}$, $PSF_{i,0m}$, and PSF_{K71} lie ≥ 10 per cent above the input model – is marked with a coloured bullet with a black border. **b)** Three colour profiles $R-i$ are shown for: the model (thick solid line), the convolved model using $PSF_{V,0m}$ and $PSF_{i,0m}$ (solid line), and the convolved model using $PSF_{V,3m}$ and $PSF_{i,3m}$ (dash-dotted line).



r (arcmin)
0.1
1.0
10.0
100.0
log10 Surface Brightness (erg s-1cm-2arcsec-2)
Surface Brightness (mag arcsec-2)
0
-2
-4
-6
-8
-10
-12
0
5
10
15
20
25
30
core
aureole
blue sky
1
10
100
1000
10000
r (arcsec)



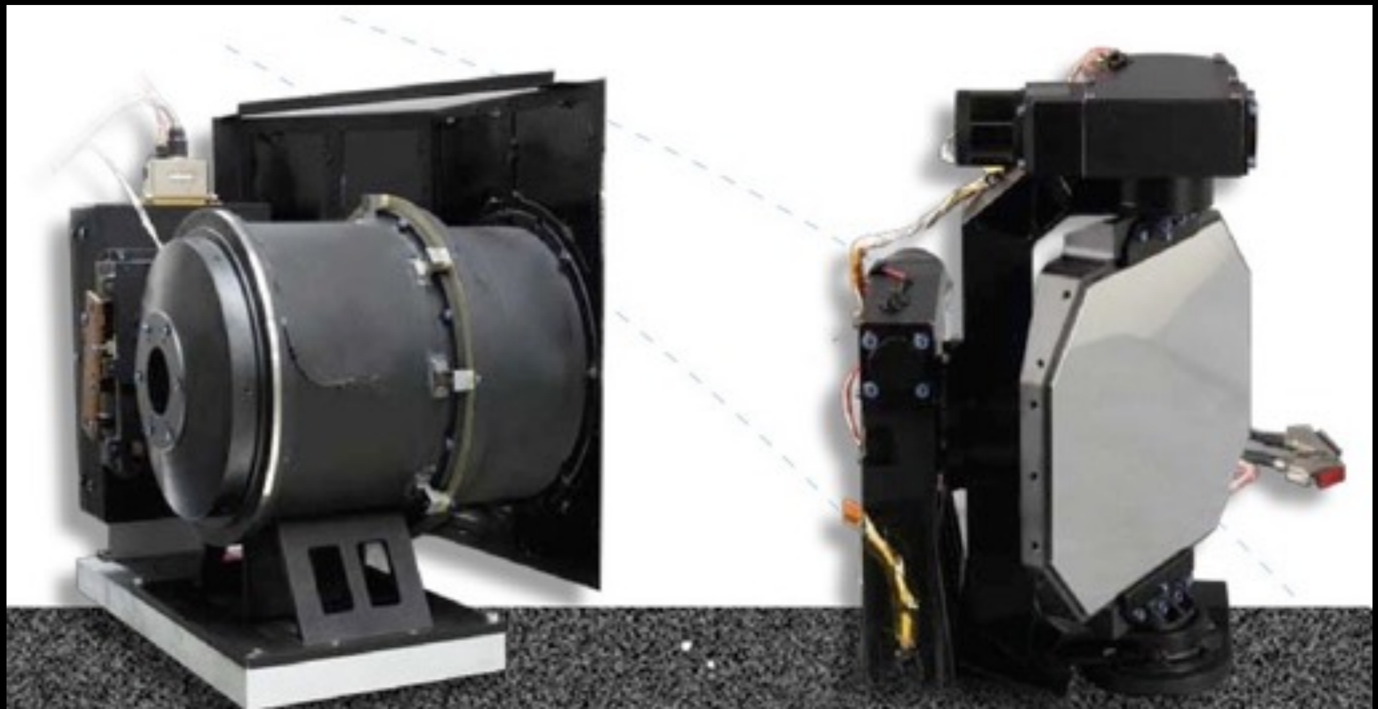


Contributions by China to MESSIER

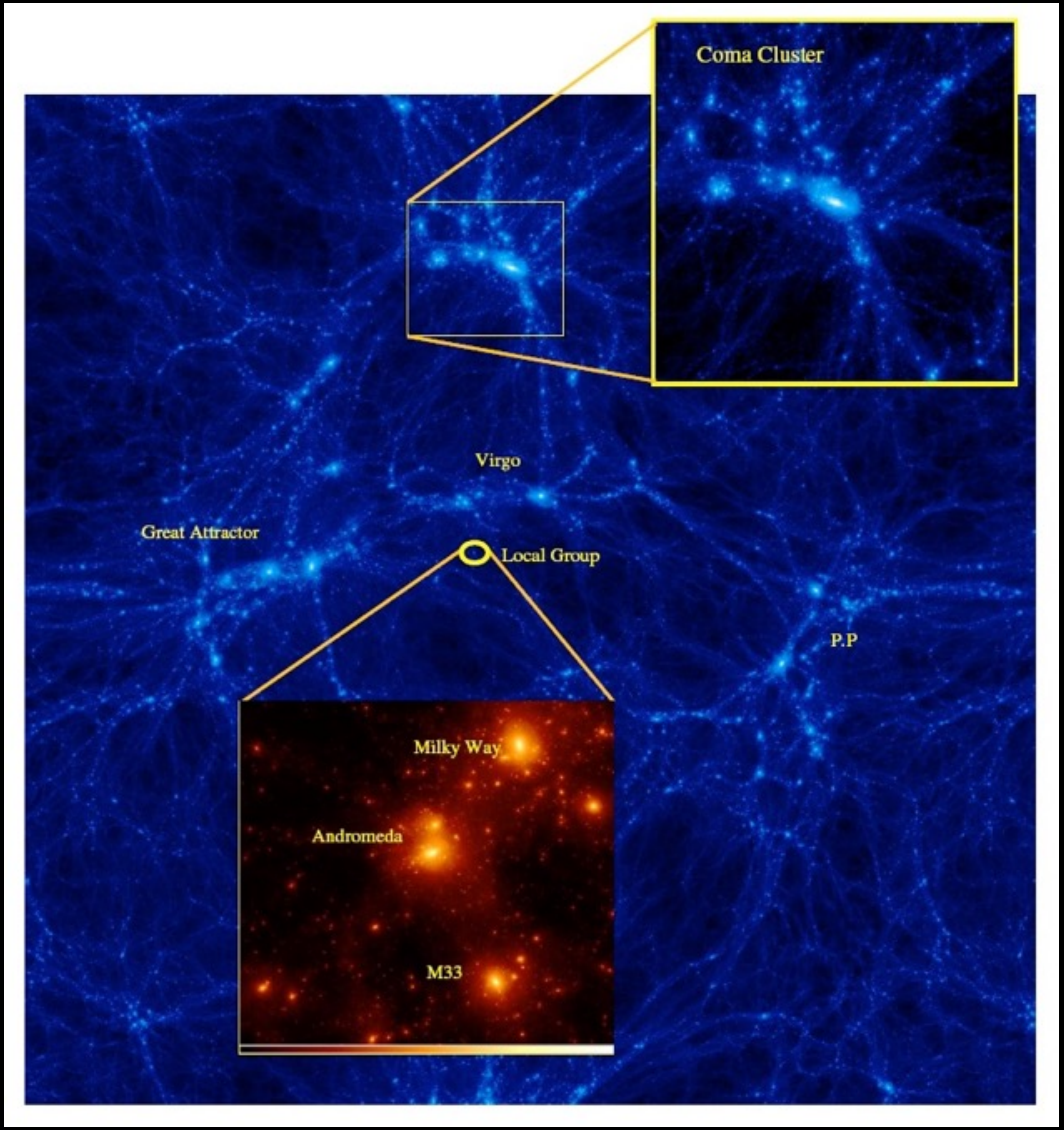
✔ Innovative optical design of the off-axis *f*/2 TMA telescope
Marseille + Shanghai SITP

✔ Large community working in cosmology / galaxy evolution
ample scope for science and technology collaborations

✔ Expertise in UV instrumentation: Lunar-based UV Telescope
NAOC: LUT @ Chang'e 3 150mm RC 245-340 nm



Cosmological simulations: extraction of Local Group candidates



CLUES

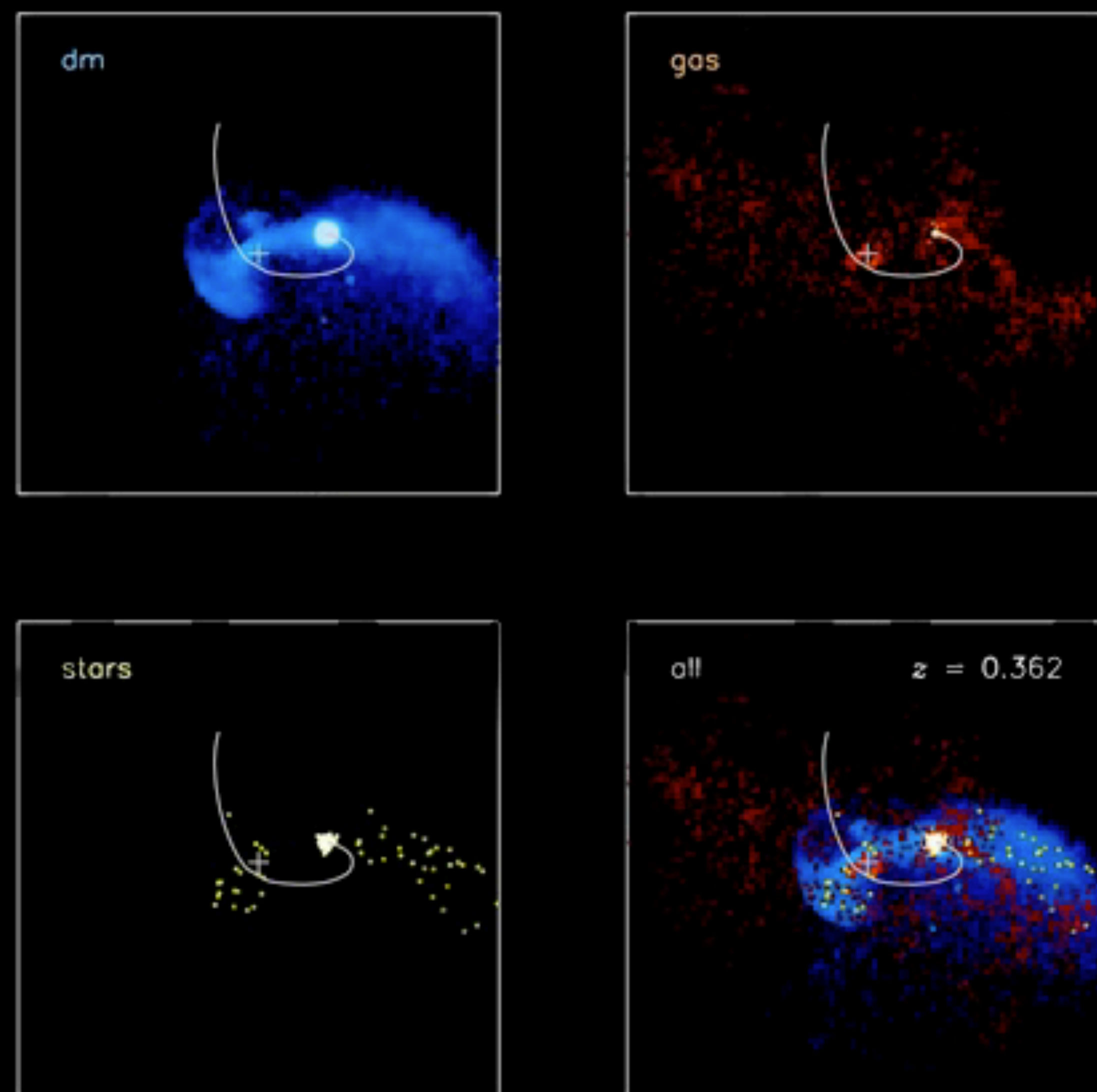
Hierarchical formation through accretion of dark matter haloes

CDM

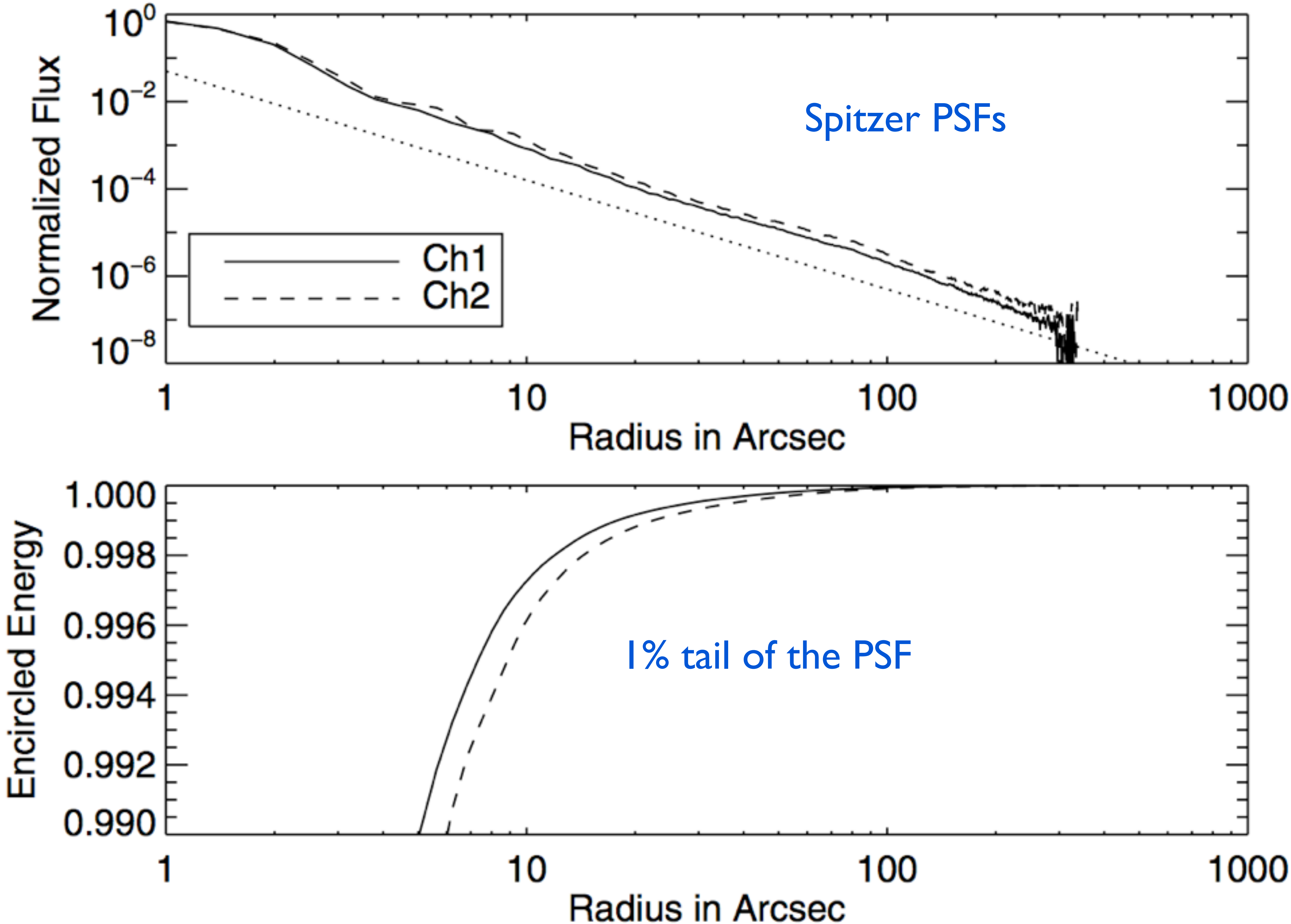
Gas

Stars

CDM+gas+stars



Zoom on M33 in a Local Group constrained simulation 4096^3 WMAP3 CLUES


Normalized Flux
Spitzer PSFs
Ch1
Ch2
Radius in Arcsec
Encircled Energy
1% tail of the PSF
Radius in Arcsec

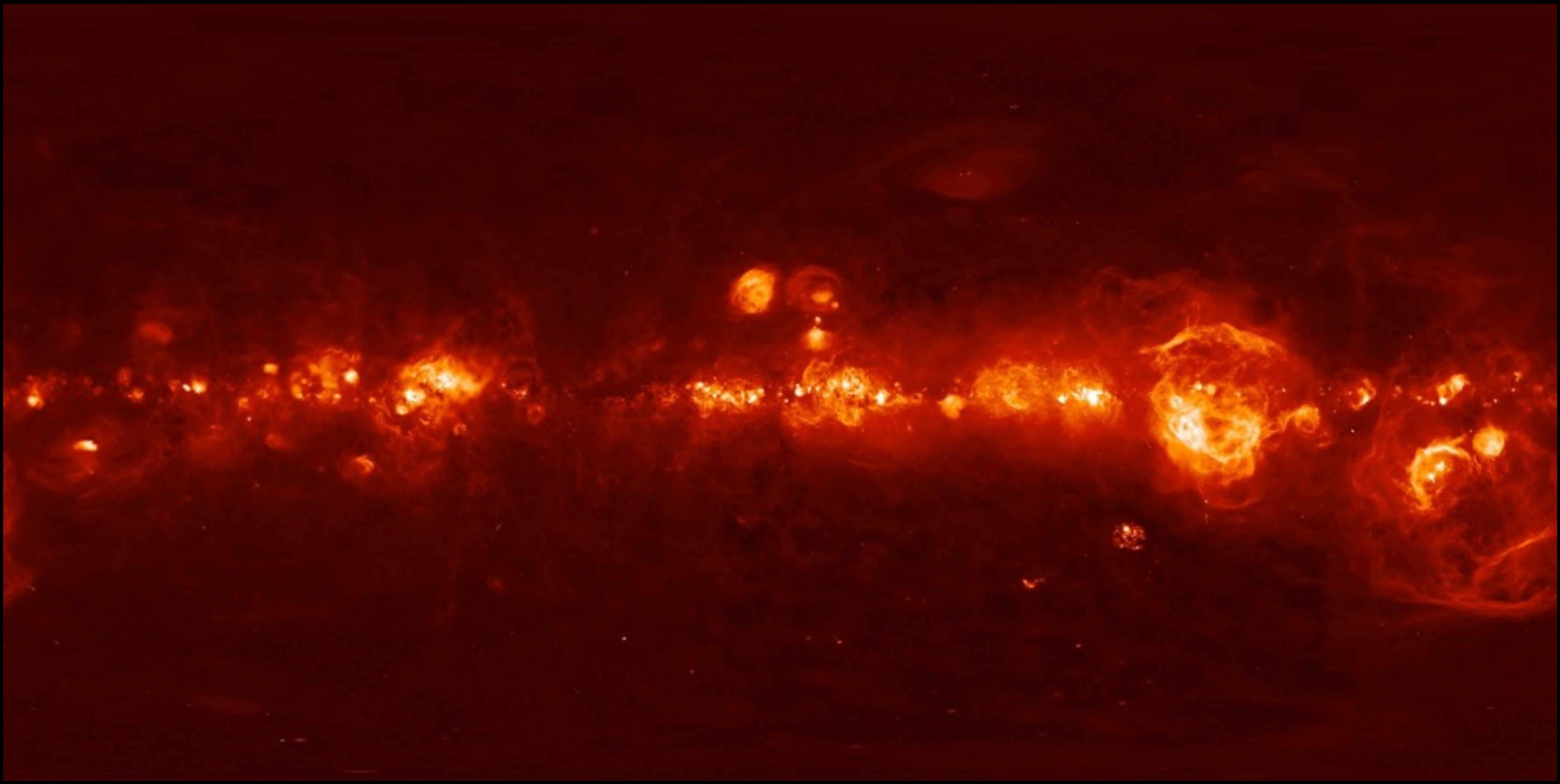
Absolute limits to the surface brightness of galaxies

Scattering of stellar light by dust grains associated with HI

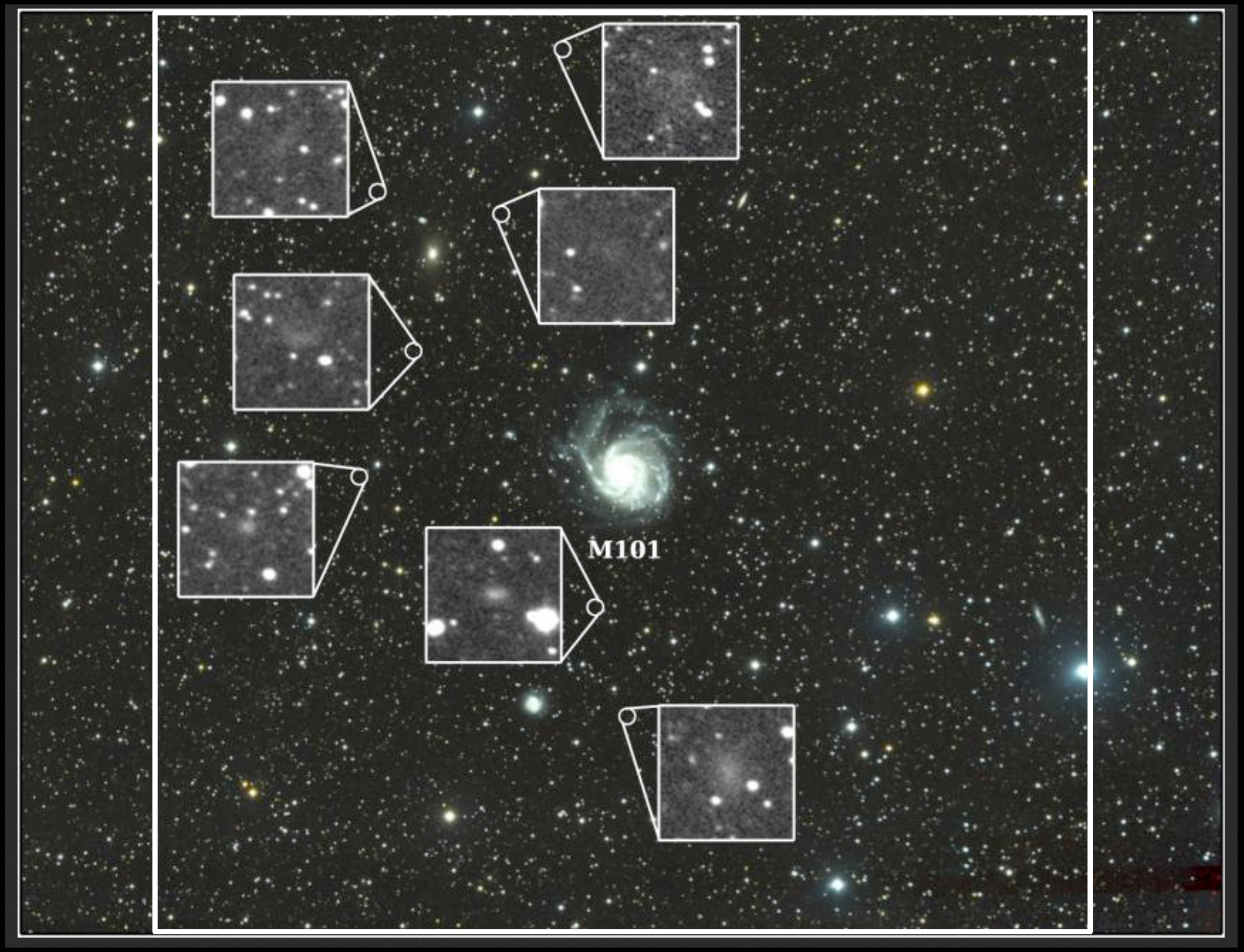
$$I_\nu = \frac{L_\nu}{4\pi r^2} \frac{N_{\rm HI}}{\cos i} \sum_j \frac{n_j}{n_{\rm H}} \left(\frac{d\sigma_\lambda}{d\Omega} \right)_j$$

$$\frac{I_\nu}{29 \text{ mag arcsec}^{-2}} = \frac{1}{\cos i} \left(\frac{r/D}{\rm arcsec} \right)^{-2} \left(\frac{N_{\rm H} I}{10^{18} {\rm cm}^{-2}} \right) \left(\frac{F_X(\lambda, \theta_s)}{10^{-24} {\rm cm}^2 {\rm sr}^{-1}} \right) 10^{0.4(14 - m_{\rm gal})}$$

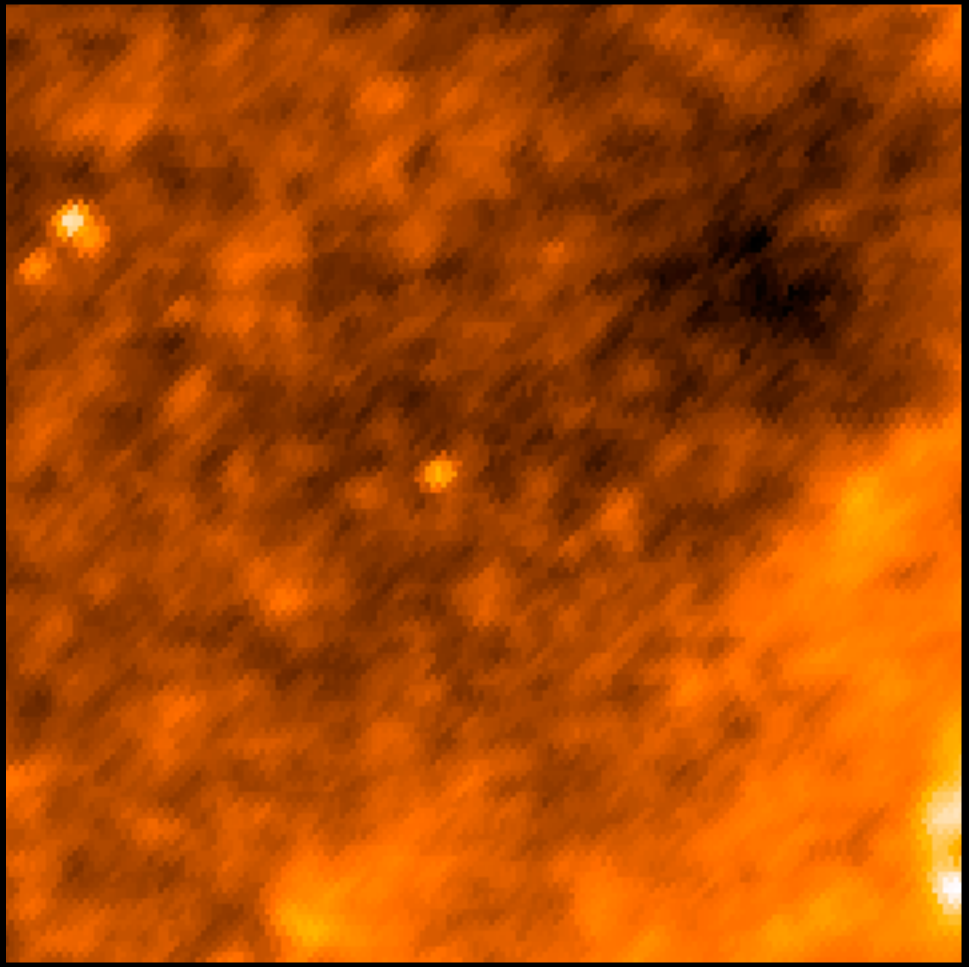
All-sky [local v < 100 km/s] Hα map (for free-free templates)



Non detection of optical emission from IR cirri in M101 ?

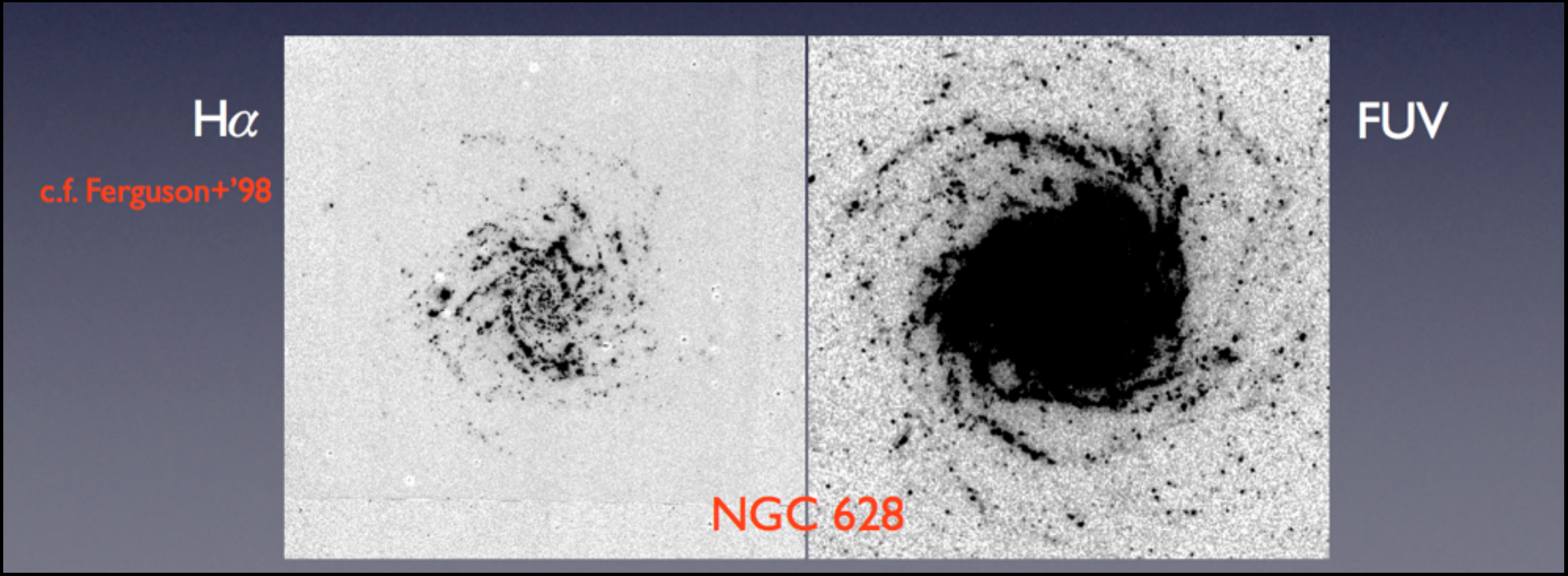


Dragonfly 35 hours



Planck 857 GHz

The importance of UV channels for galaxy evolution

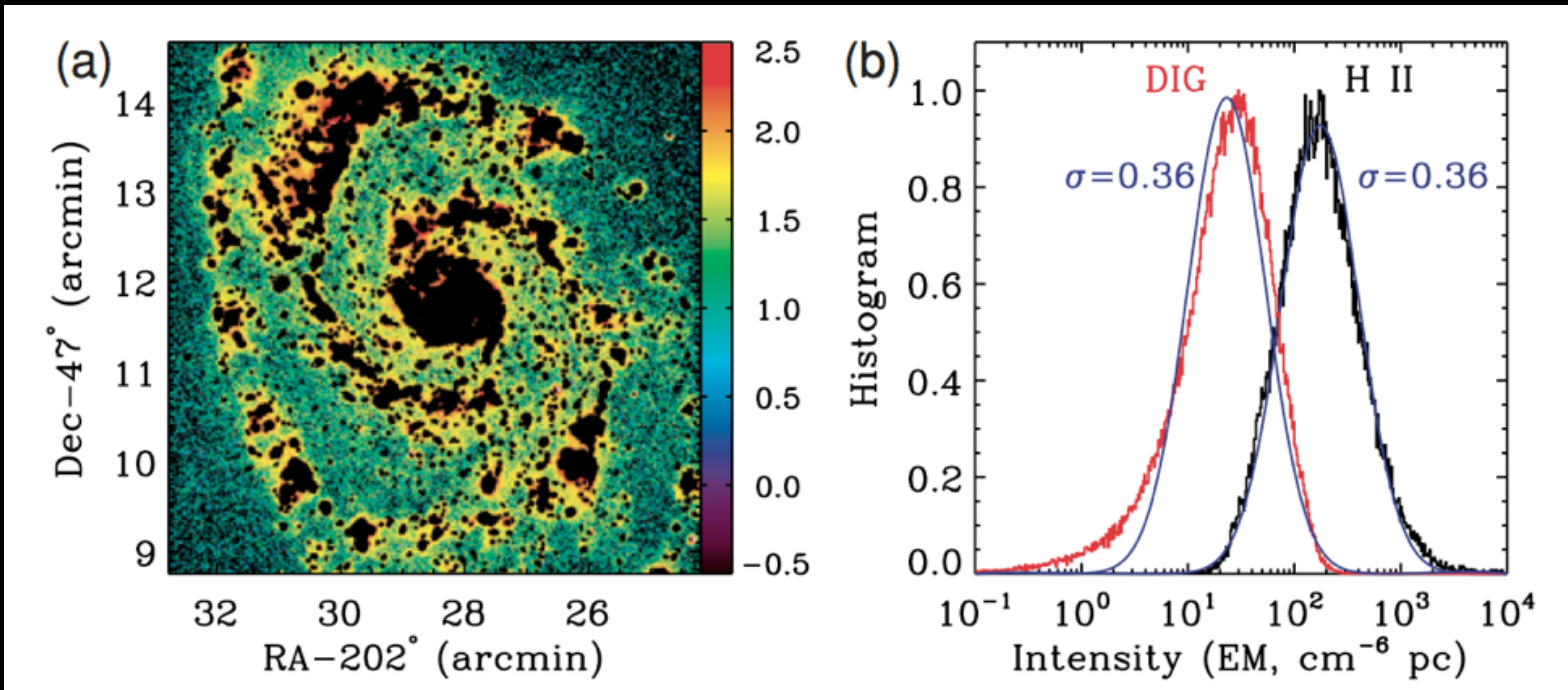


Outer, low-density star formation activity

UV is a better tracer of low-level SF

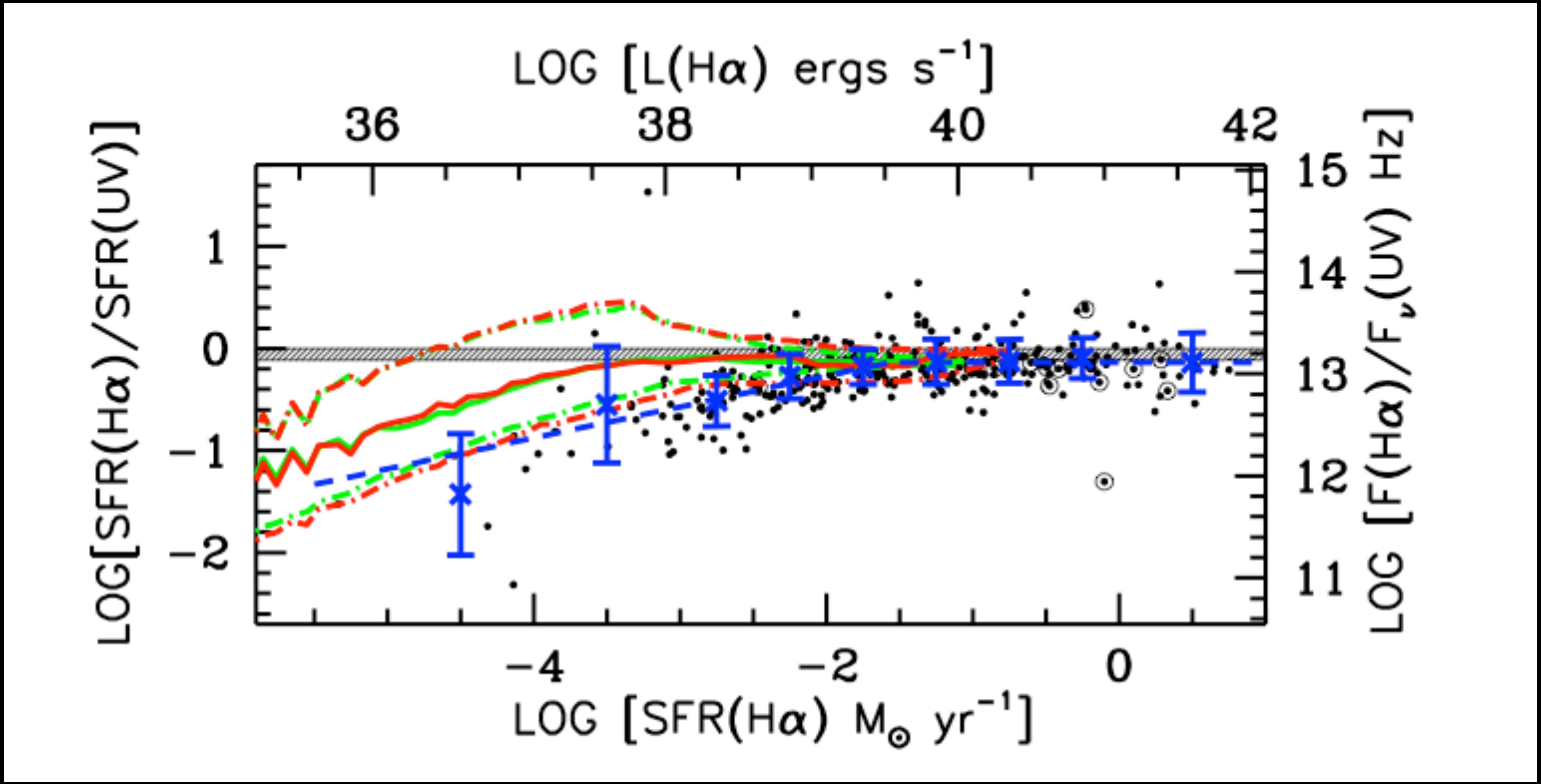
XUV discs: are galaxies still growing today ?

The diffuse interstellar medium of Messier 51



Seon (2009)

Linking (massive) star formation tracers
UV vs Hα



A freeform-based, fast, wide-field and distortion-free camera for ultra low surface brightness surveys

Emmanuel Hugot[a], Xin Wang[a,d], David Valls-Gabaud[b,e,f], Gérard Lemaître[a],
Tibor Agócs[c], Rong Shu[d], Jianyu Wang[a]

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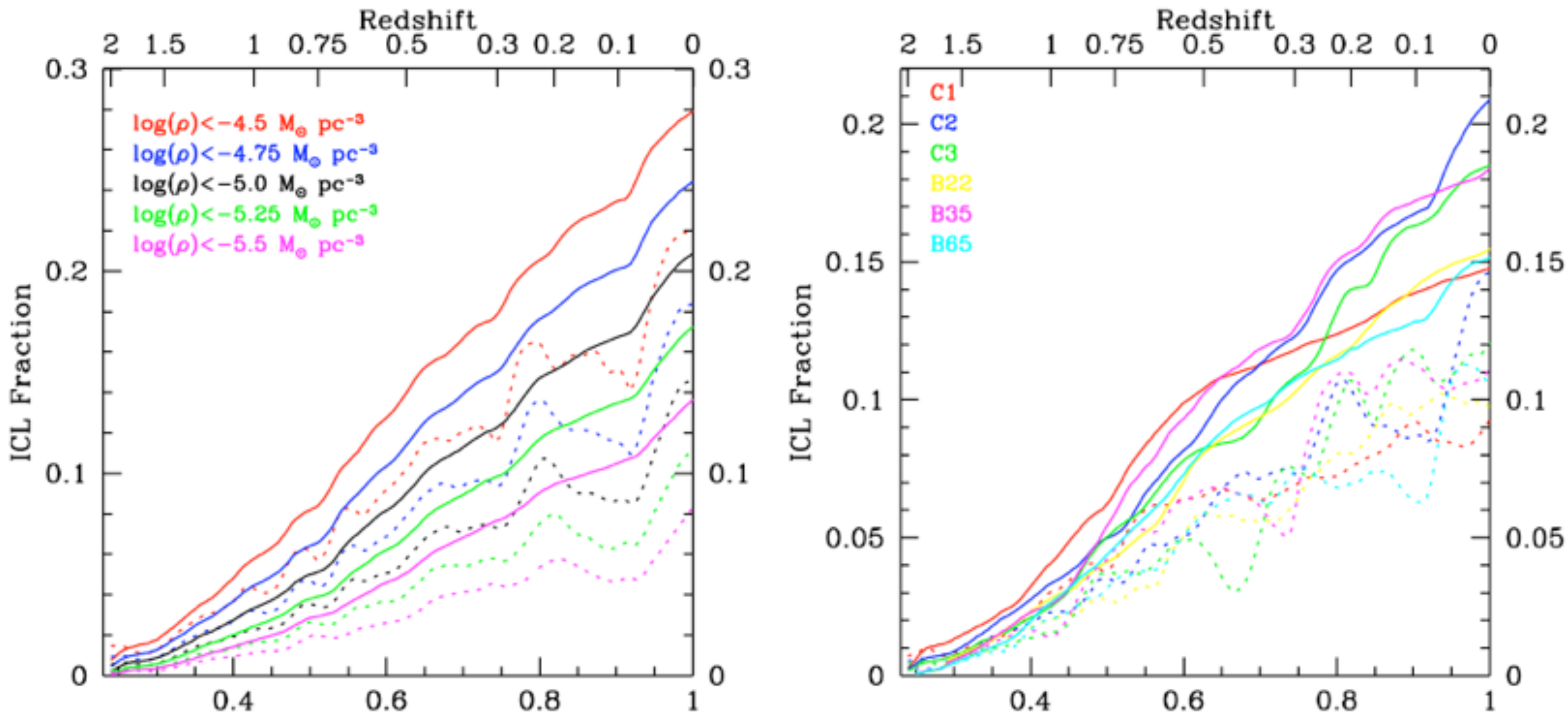
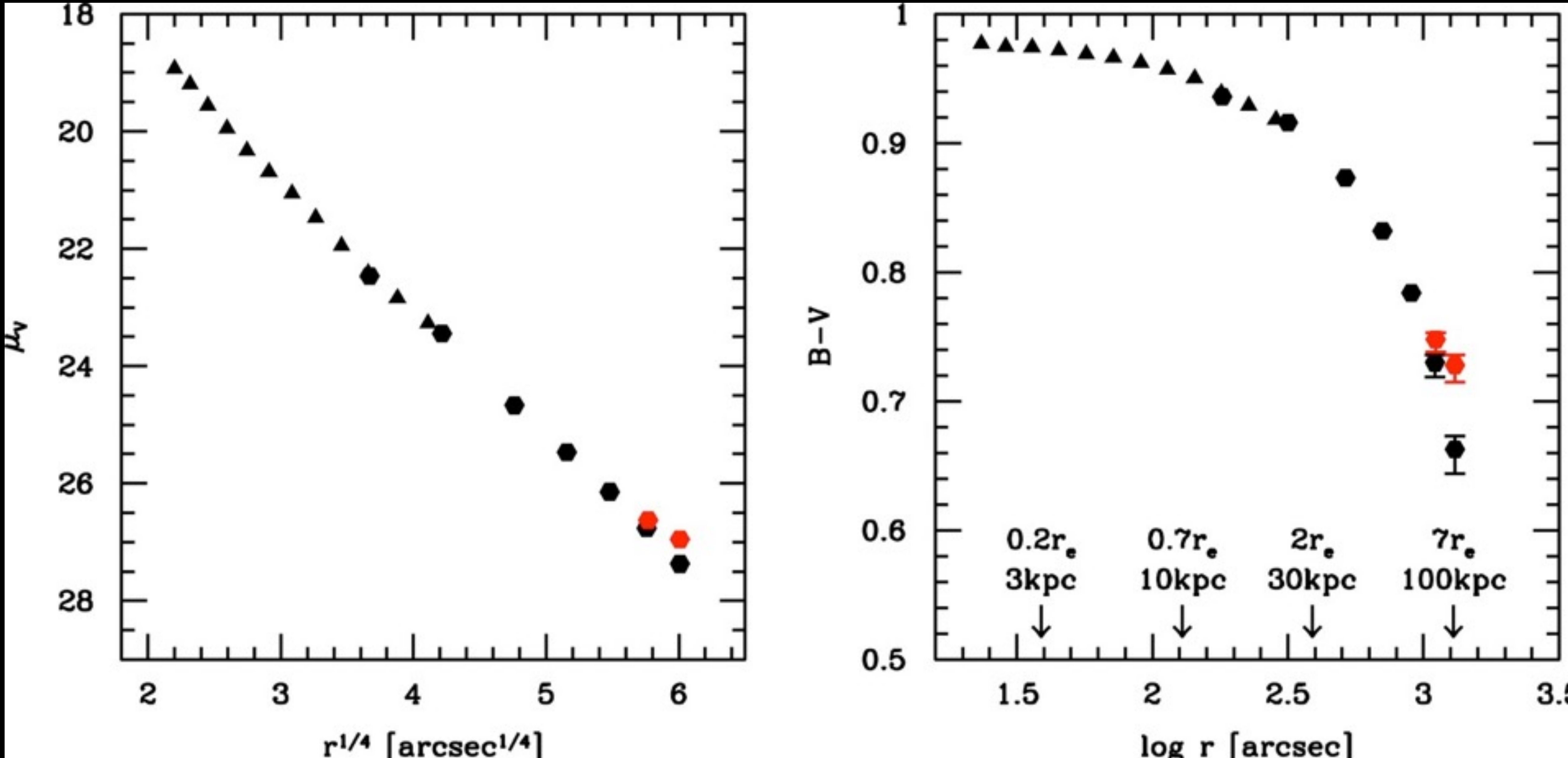
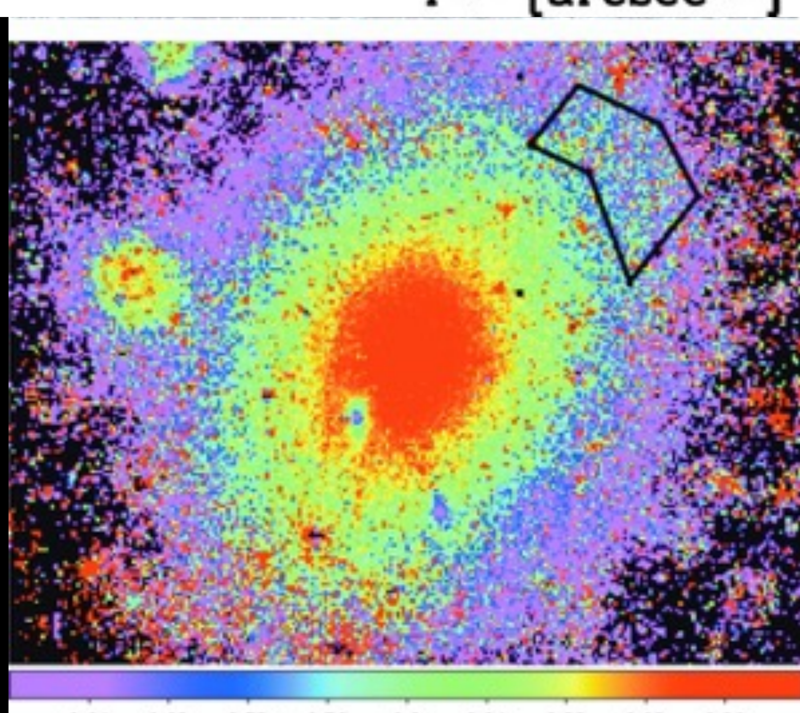
20A Datun Road, Beijing 100020, China
[f] Institute of High Energy Physics, Chinese Academy of Sciences,
19B Yuquan Road, Beijing 100049, China

SPIE *Telescope Instrumentation,* Montréal, June 2014


Redshift
2 1.5 1 0.75 0.5 0.3 0.2 0.1 0
ICL Fraction
log(ρ)<−4.5 M⊙ pc⁻³
log(ρ)<−4.75 M⊙ pc⁻³
log(ρ)<−5.0 M⊙ pc⁻³
log(ρ)<−5.25 M⊙ pc⁻³
log(ρ)<−5.5 M⊙ pc⁻³
0 0.1 0.2 0.3
0.4 0.6 0.8 1
Redshift
2 1.5 1 0.75 0.5 0.3 0.2 0.1 0
ICL Fraction
C1
C2
C3
B22
B35
B65
0 0.05 0.1 0.15 0.2
0.4 0.6 0.8 1

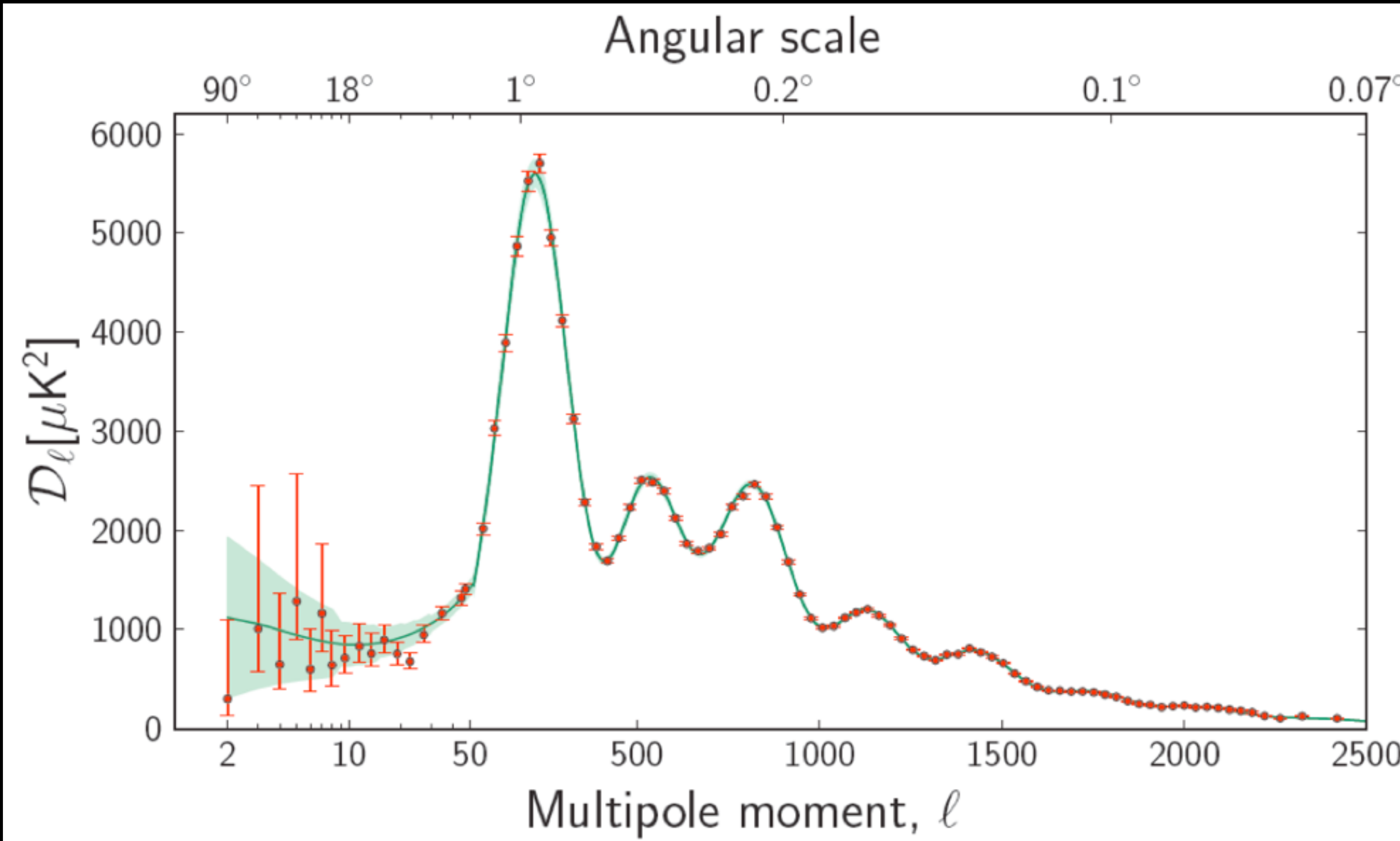




Mihos et al. (2013)

M49 massive elliptical in Virgo

Blue outskirts → blue filters
(old) stellar streams → red filters



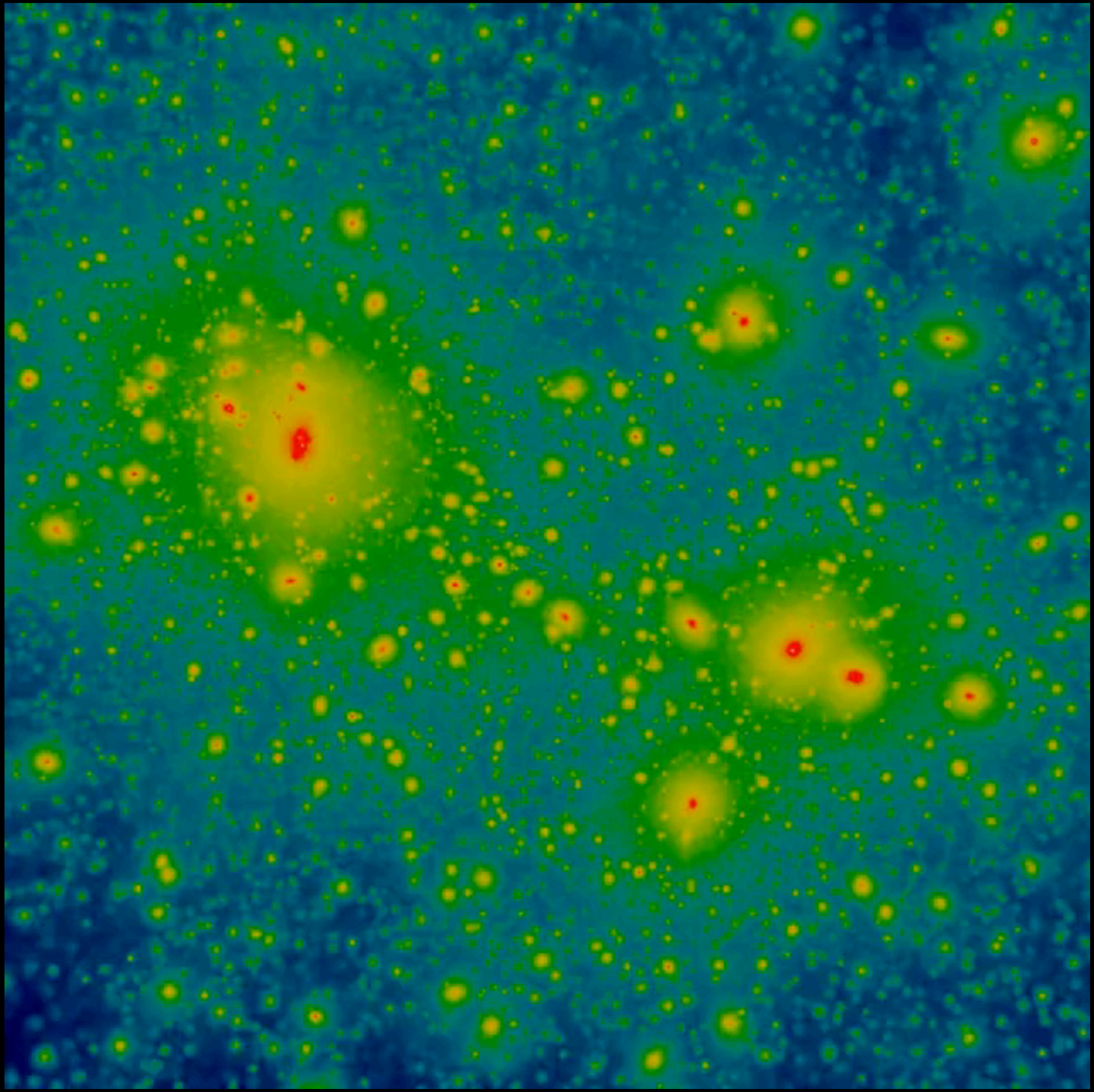
Angular scale
90° 18° 1° 0.2° 0.1° 0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2 10 50 500 1000 1500 2000 2500
Multipole moment, ℓ

Planck XVI

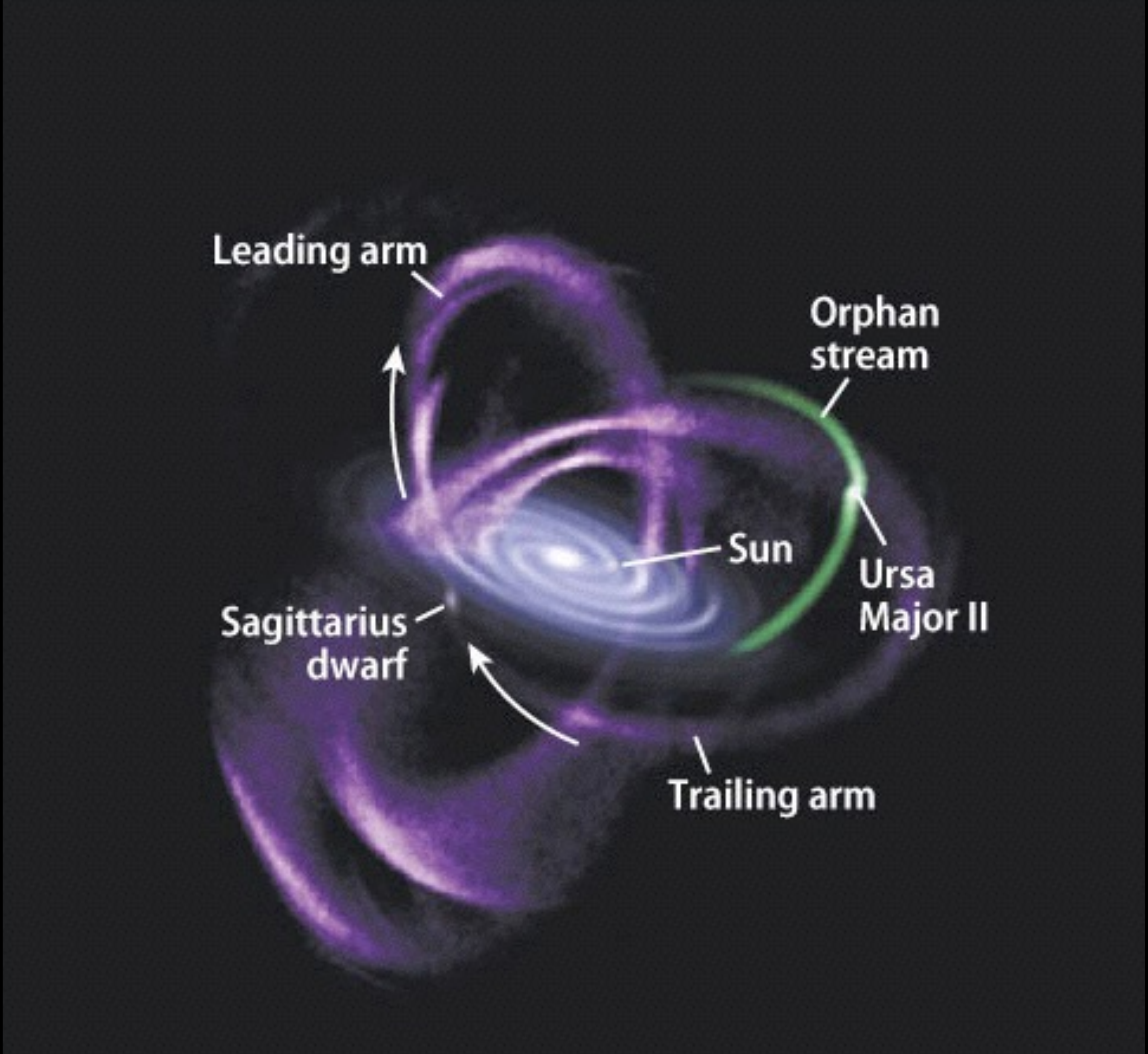
Minimal 6 parameter fit

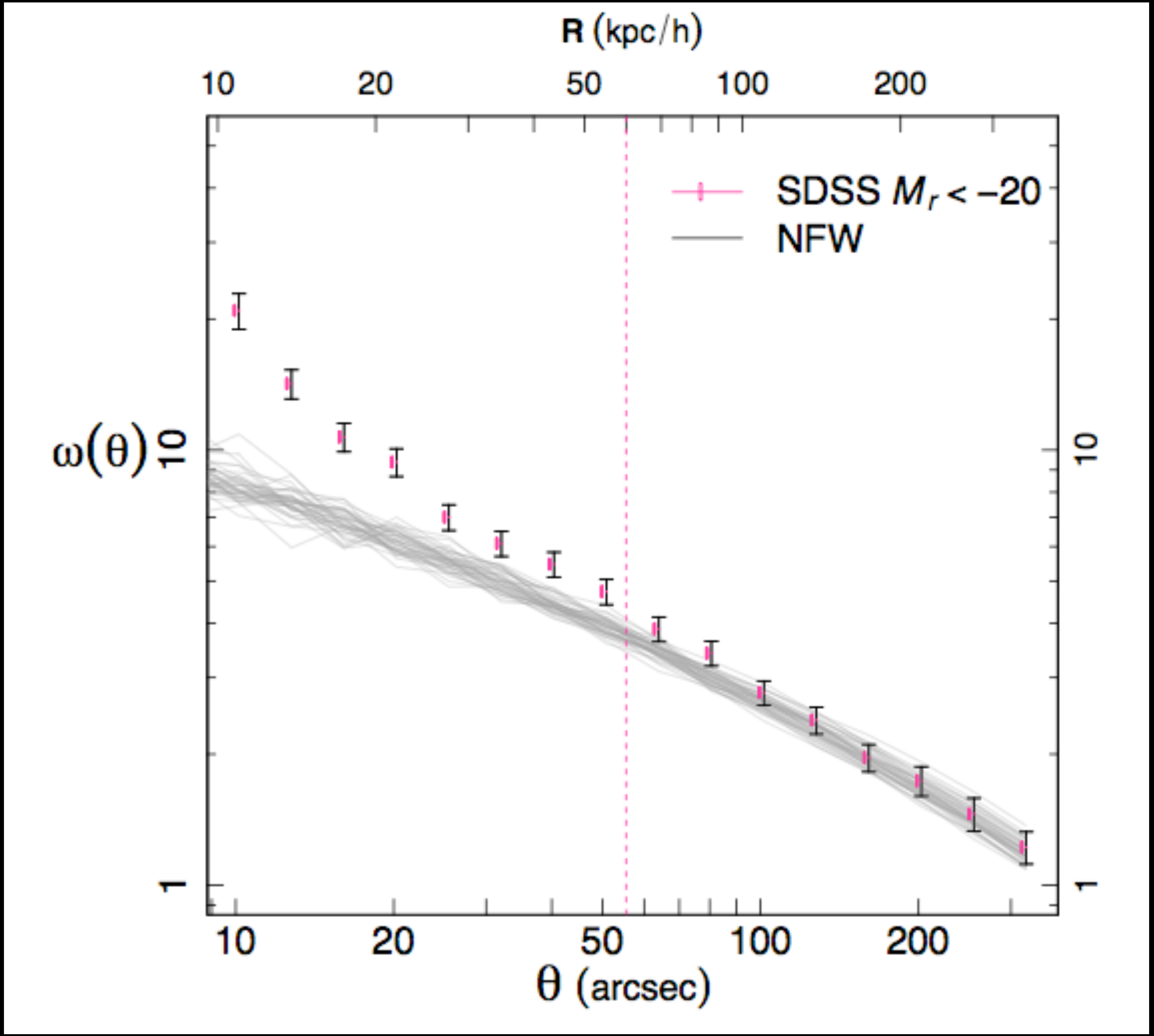
Parameter	*Planck*+WP	
	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

Planck XVI



ELVIS

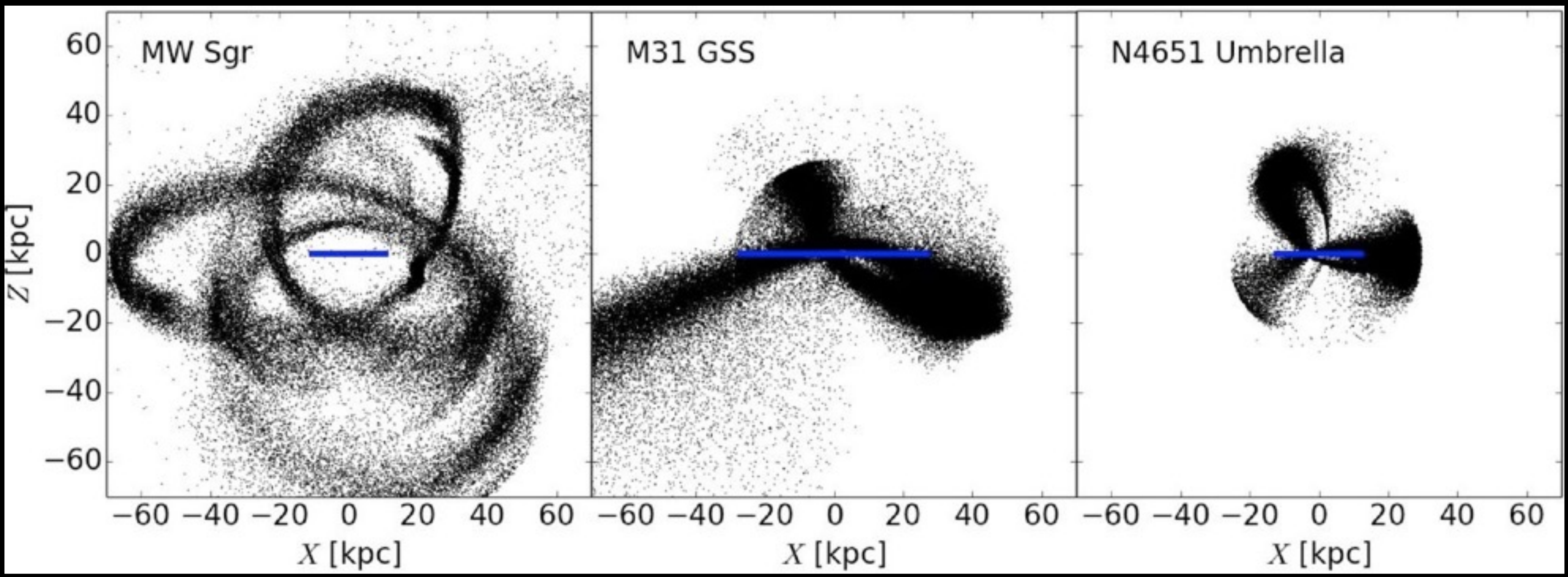

Leading arm
Orphan stream
Sun
Ursa Major II
Sagittarius dwarf
Trailing arm



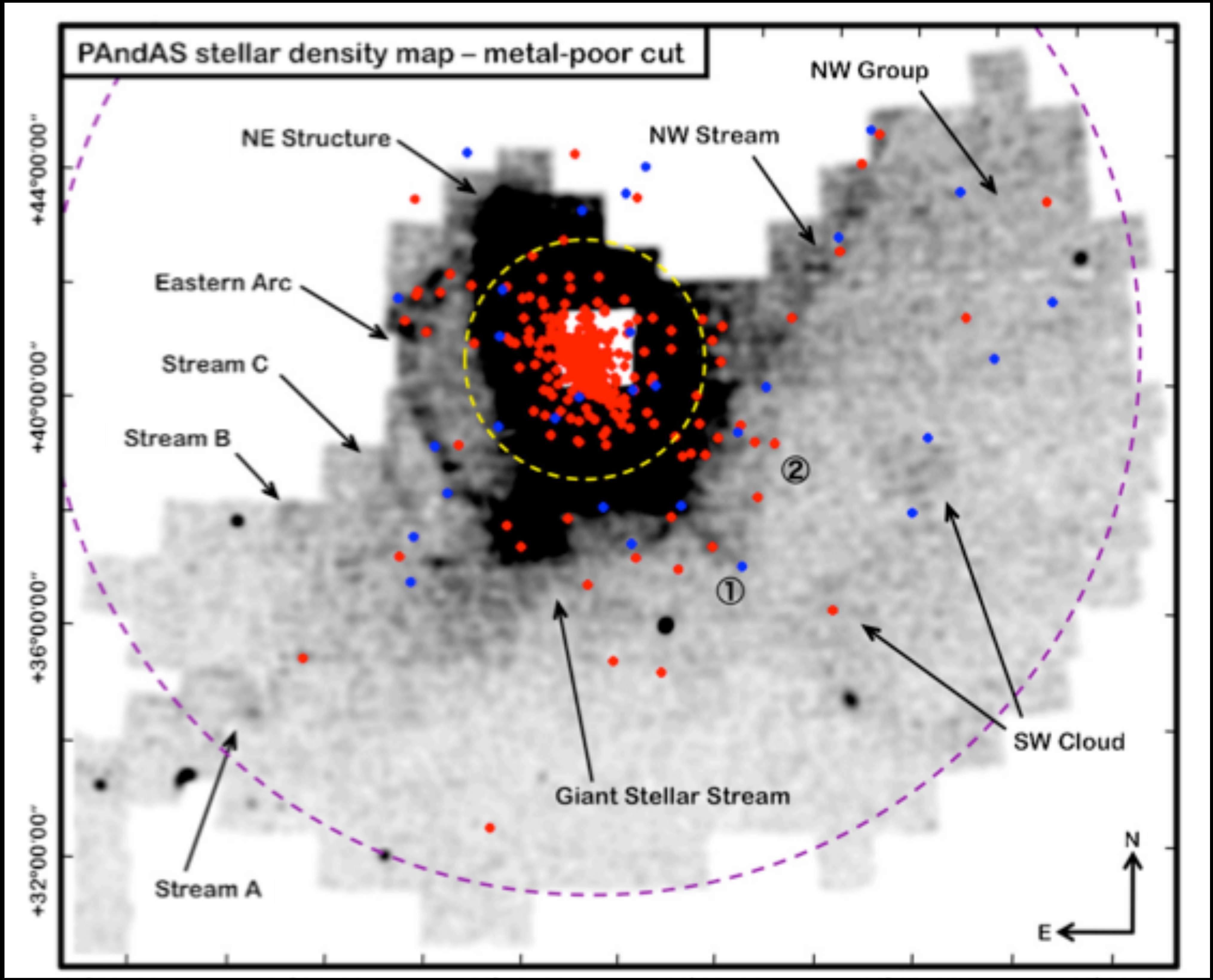
Piscionero *et al.* (2014)

NGC 5907 D=60cm F=494cm f/8 6.5 hours
sec mirror

Observed stream configurations



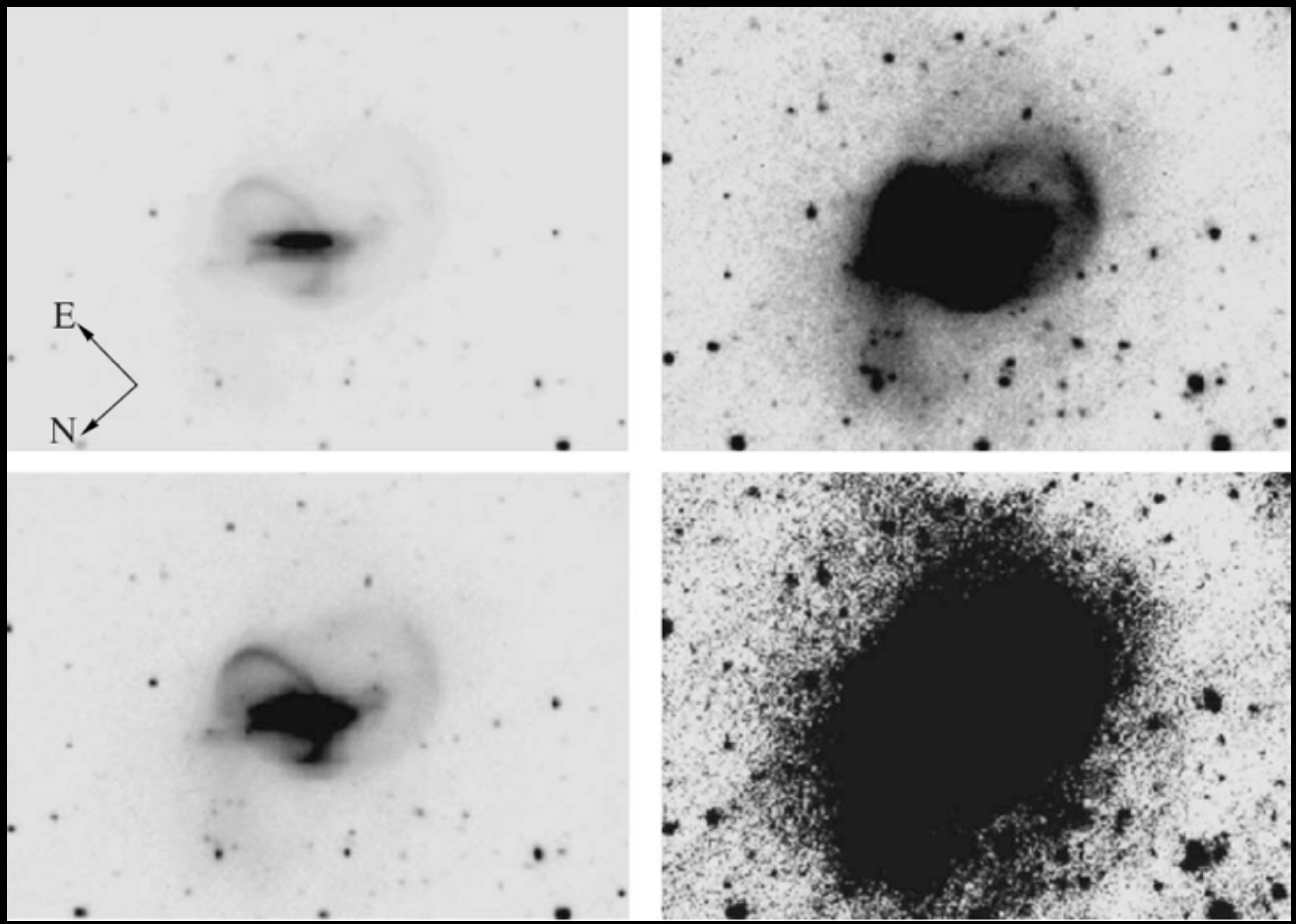
Globular clusters further away than 30 kpc are associated with tidal streams



Mackey *et al.* (2010) *ApJ* 717, L11

Beyond the Local Group

2.4’
62 kpc

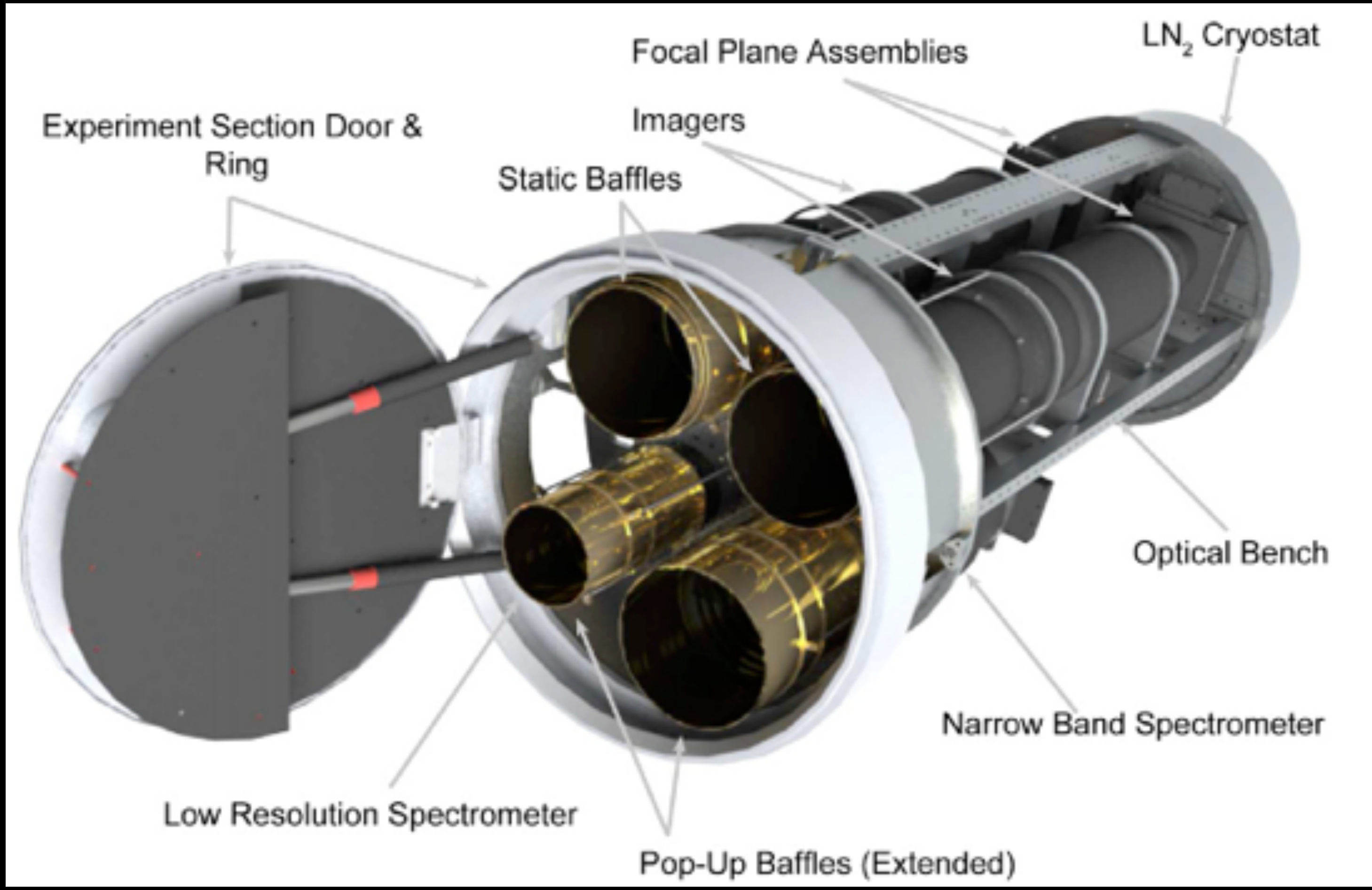


UGC 7388 94 Mpc

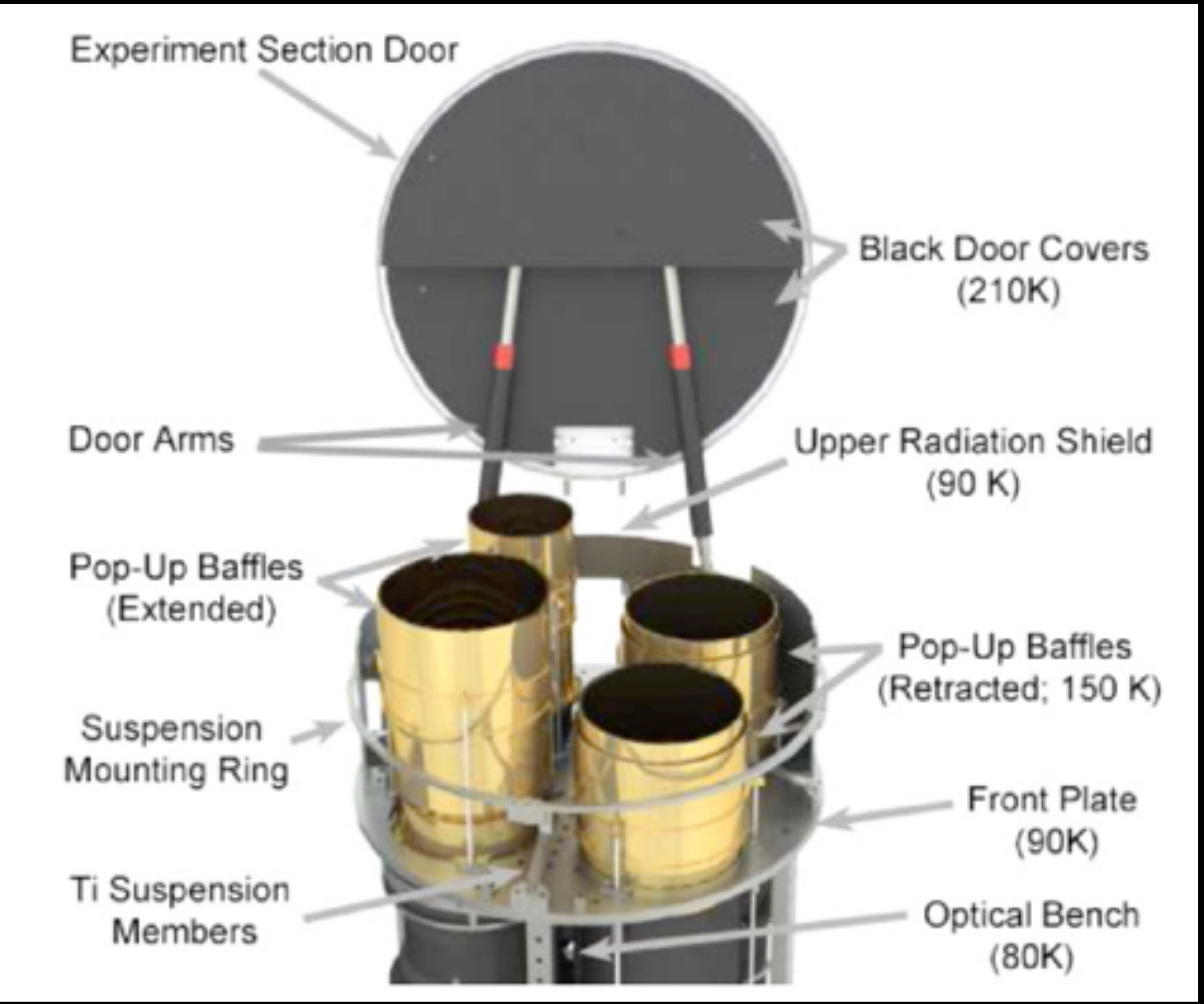
Gemini

Pop-up baffles

Heritage from *CIBER*
Cosmic IR Background
Experiment
sounding rocket



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



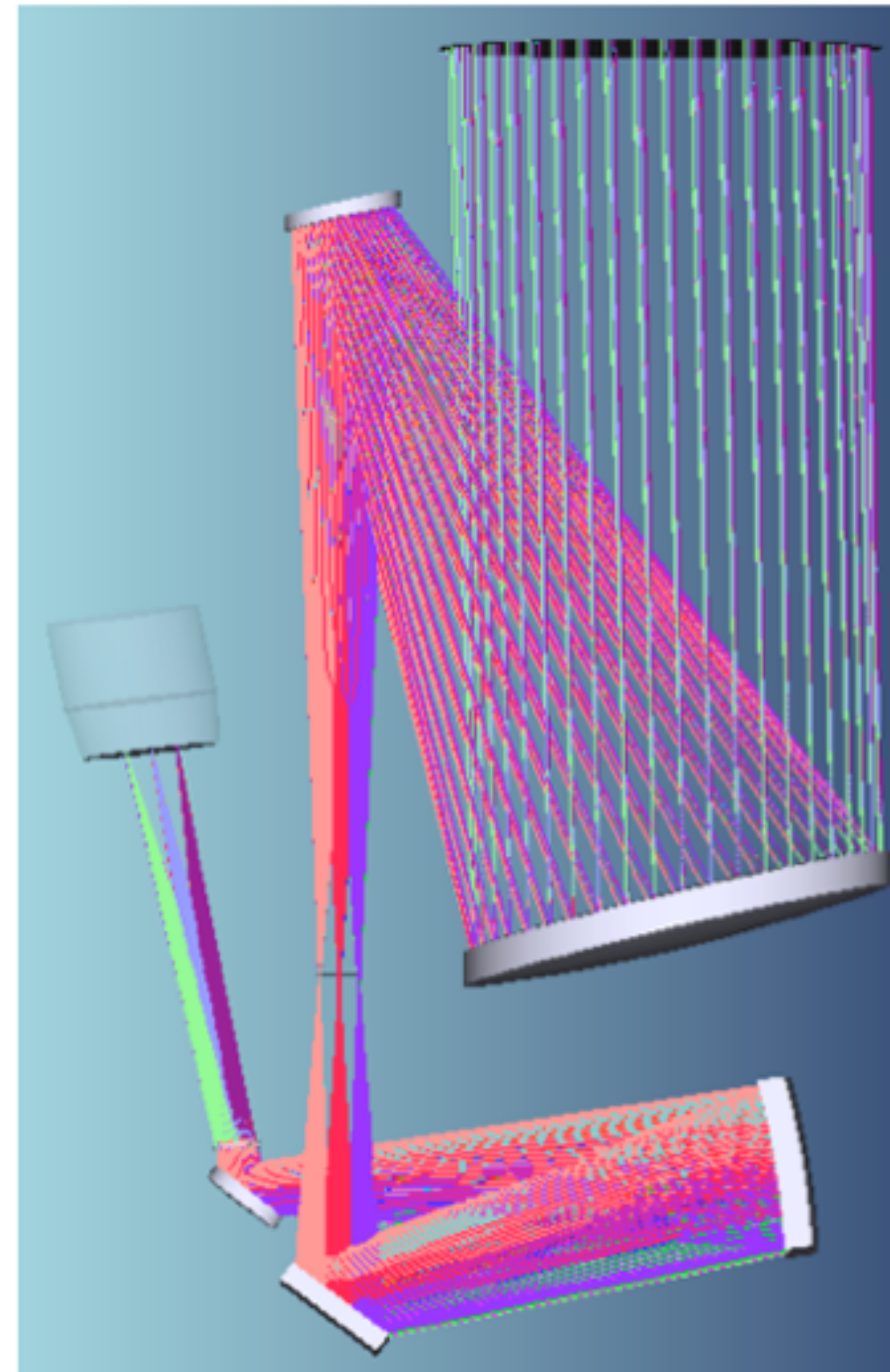
Baffles made with Al6061
Coated with Epner Laser Black
multilayer metallic oxyde
with microdendrites
(<1% reflective)
Spring loaded / tied to door

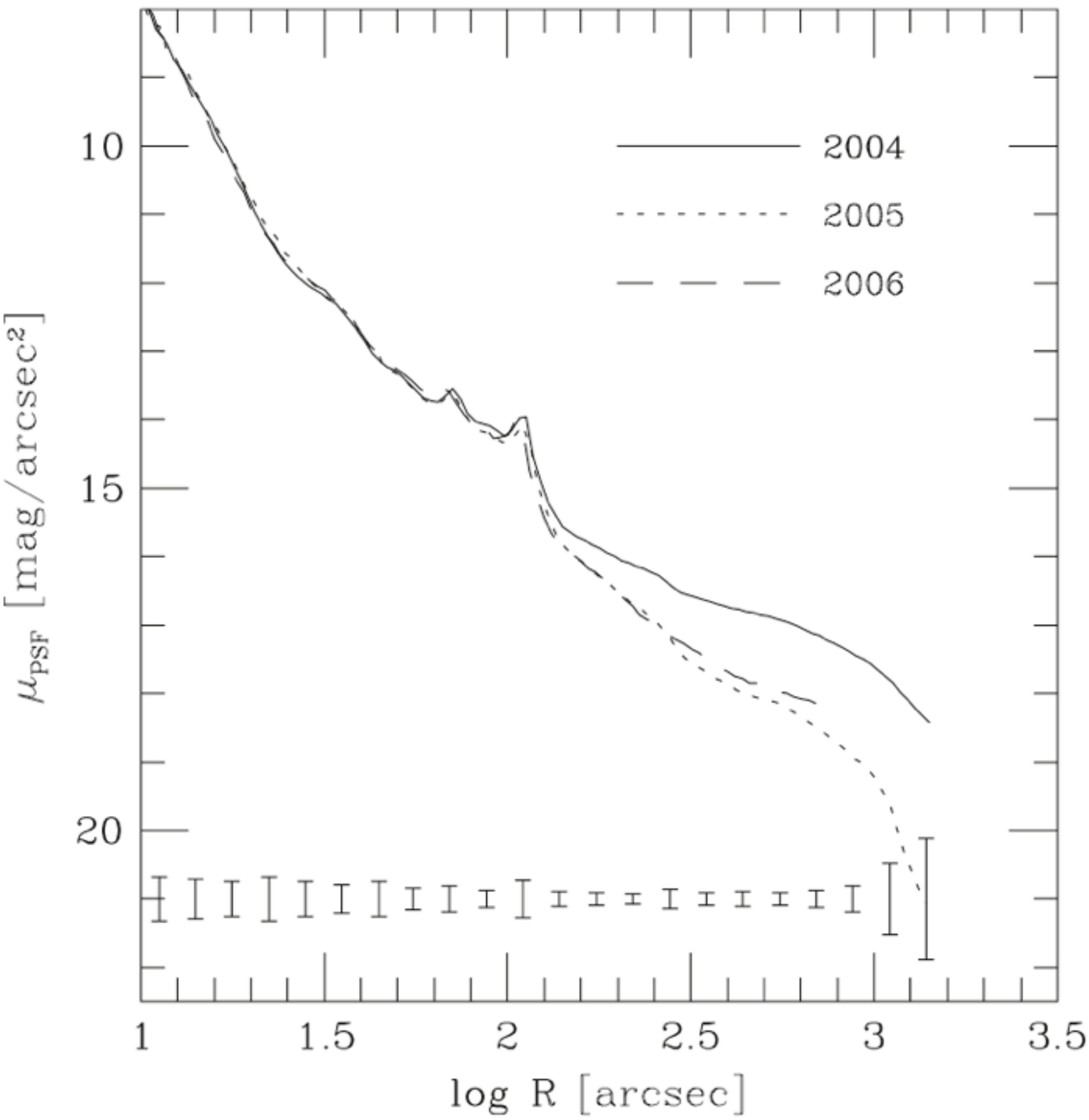
TMA Telescope

- Three Mirror Anastigmatic
- Unobscured (unocculted) design
- Three powered (curved) mirrors
- 9 degrees of freedom from mirrors

  (curvature, conic constant, position for each)
- Allows control of 9 parameters

  (focal length, magnification of each mirror, astigmatism, coma, spherical aberration, field curvature)
- Wider field than Ritchey-Chrétien
- Better image quality than Schmidt




2004
2005
2006
10
15
20
μ_{PSF} [mag/arcsec²]
1
1.5
2
2.5
3
3.5
log R [arcsec]

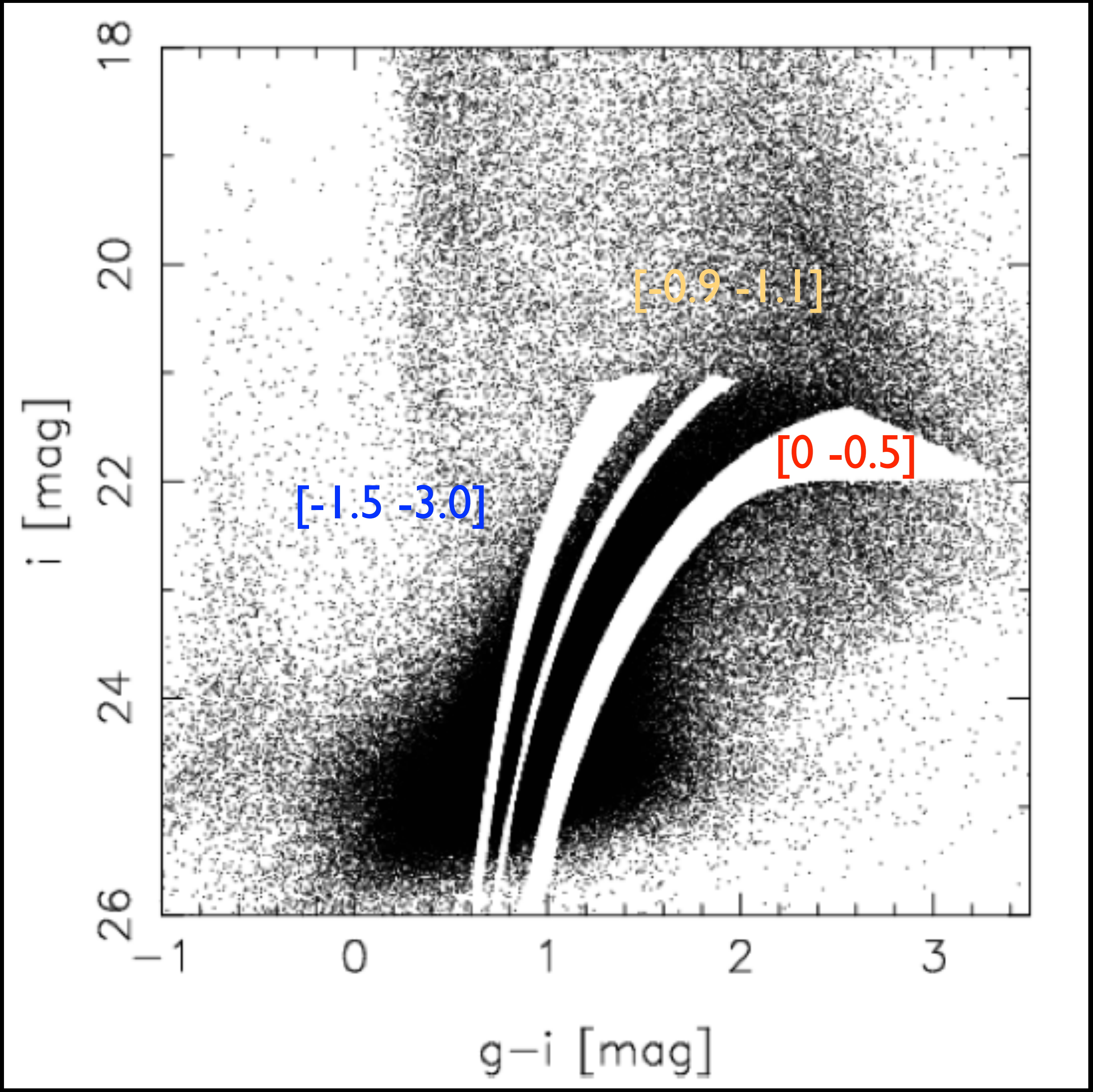
Filters for characterising the underlying stellar populations

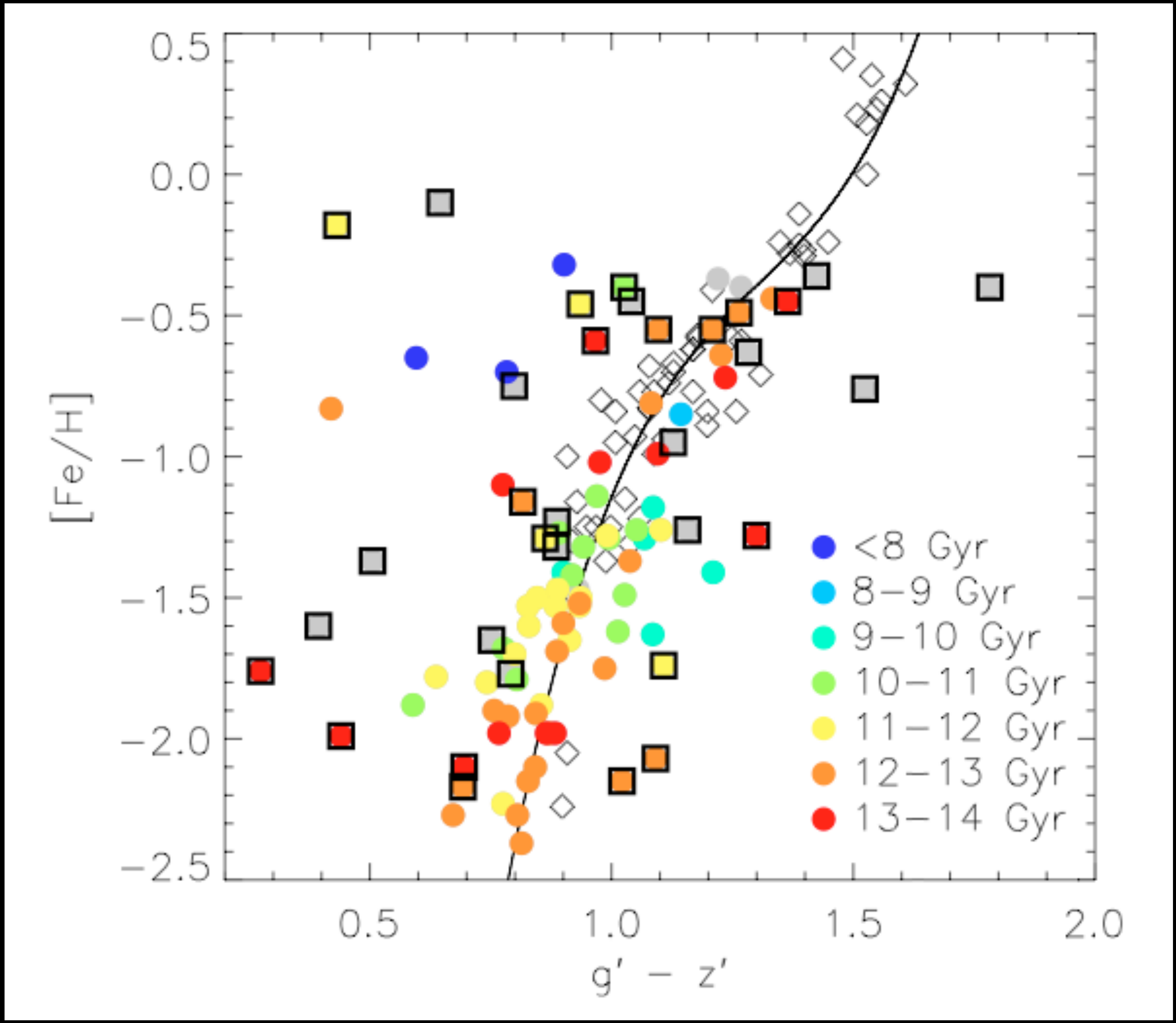
SDSS

Strömgren

Washington

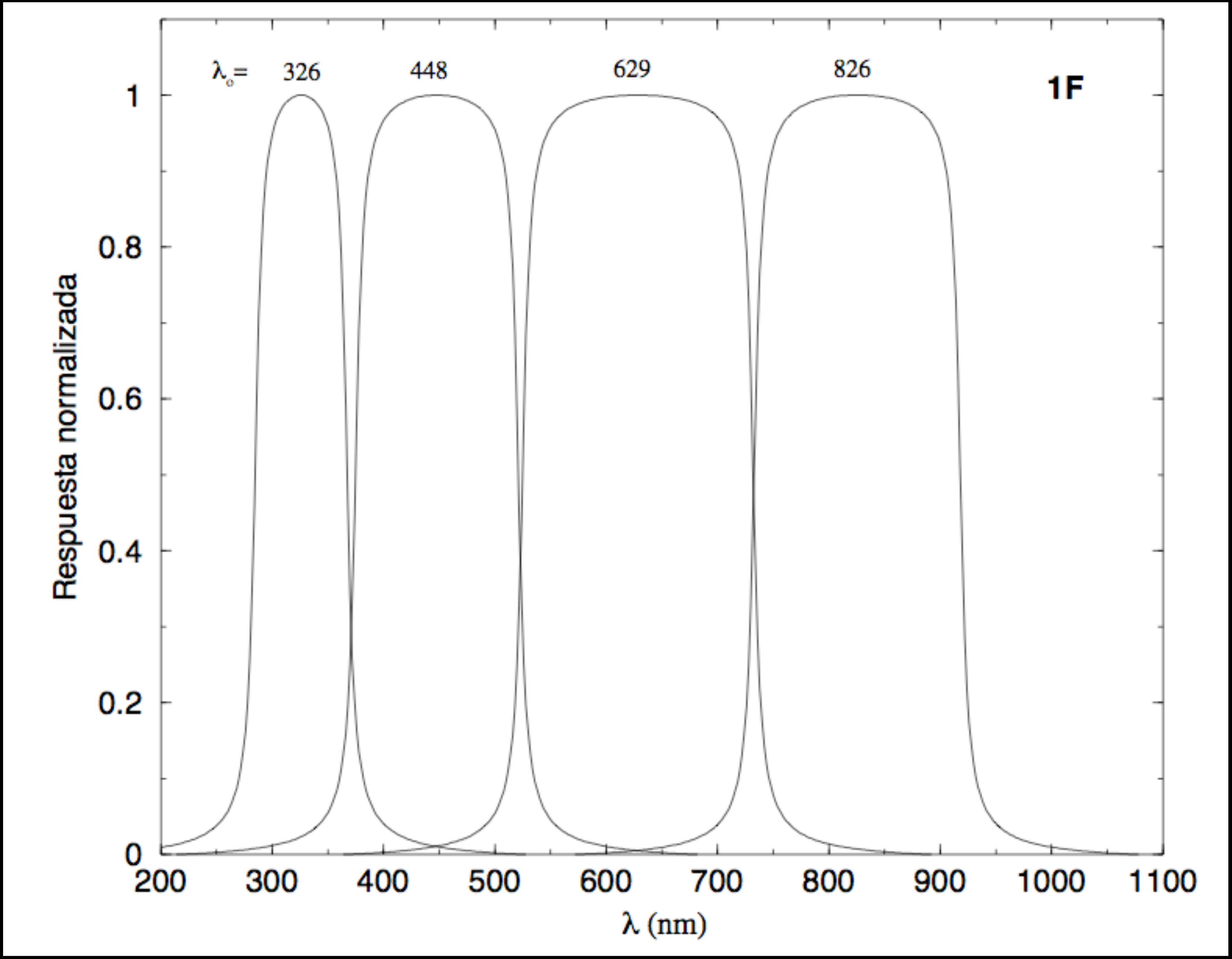
Custom ?





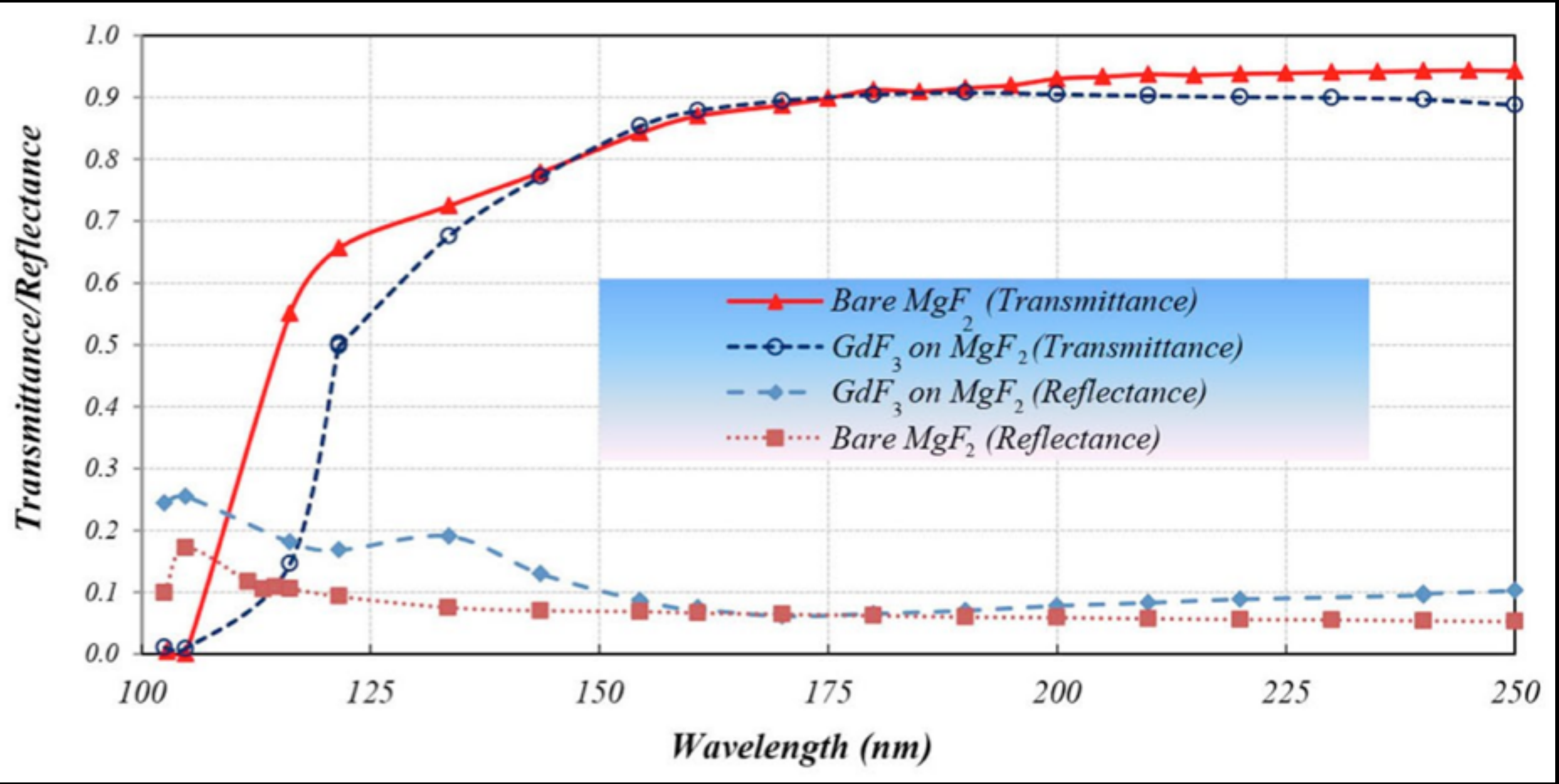
Vanderbeke *et al.* 2014 MNRAS 437, 1734

GAIA broad-band system



Technology Development Title	PI	Institution	Start Year & Duration	Current TRL	Quad Chart & PI Report Locations
Kinetic Inductance Detector Arrays for Far-IR Astrophysics	J. Zmuidzinas	Caltech	FY13; 3 yrs	3, 6	p. 43, p. 52
Cross-Strip Micro-Channel Plate Detector Systems for Spaceflight	J. Vallerga	UC Berkeley	FY12; 3 yrs	4[§]	p. 44, p. 59
High-Efficiency Detectors in Photon-Counting and Large Focal Plane Arrays (FPAs)	S. Nikzad	JPL	FY13; 3 yrs	4	p. 45, p. 70
A Far-Infrared Heterodyne Array Receiver for CII and OI Mapping	I. Mehdi	JPL	FY14; 3 yrs	4	p. 46, p. 77
Advanced UVOIR Mirror Technology Development for Very Large Space Telescopes	P. Stahl	MSFC	FY14; 3 yrs	3 – 5	p. 47, p. 85
Ultraviolet Coatings, Materials, and Processes for Advanced Telescope Optics	K. Balasubramanian	GSFC	FY13; 3 yrs	3	p. 48, p. 92
Enhanced MgF_2 and LiF Over-Coated Al Mirrors for FUV Space Astronomy	M. Quijada	SAO	FY12; 3 yrs	4	p. 49, p. 103
Development of Digital Micro-Mirror Device Arrays for Use in Future Space Missions	Z. Ninkov	RIT	FY14; 2 yrs	3	p. 50, p. 114

Table 2-1. *COR Strategic Technology Development Portfolio as of FY 2014.*



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Transmittance/Reflectance
Bare MgF2 (Transmittance)
GdF3 on MgF2 (Transmittance)
GdF3 on MgF2 (Reflectance)
Bare MgF2 (Reflectance)
100
125
150
175
200
225
250
Wavelength (nm)

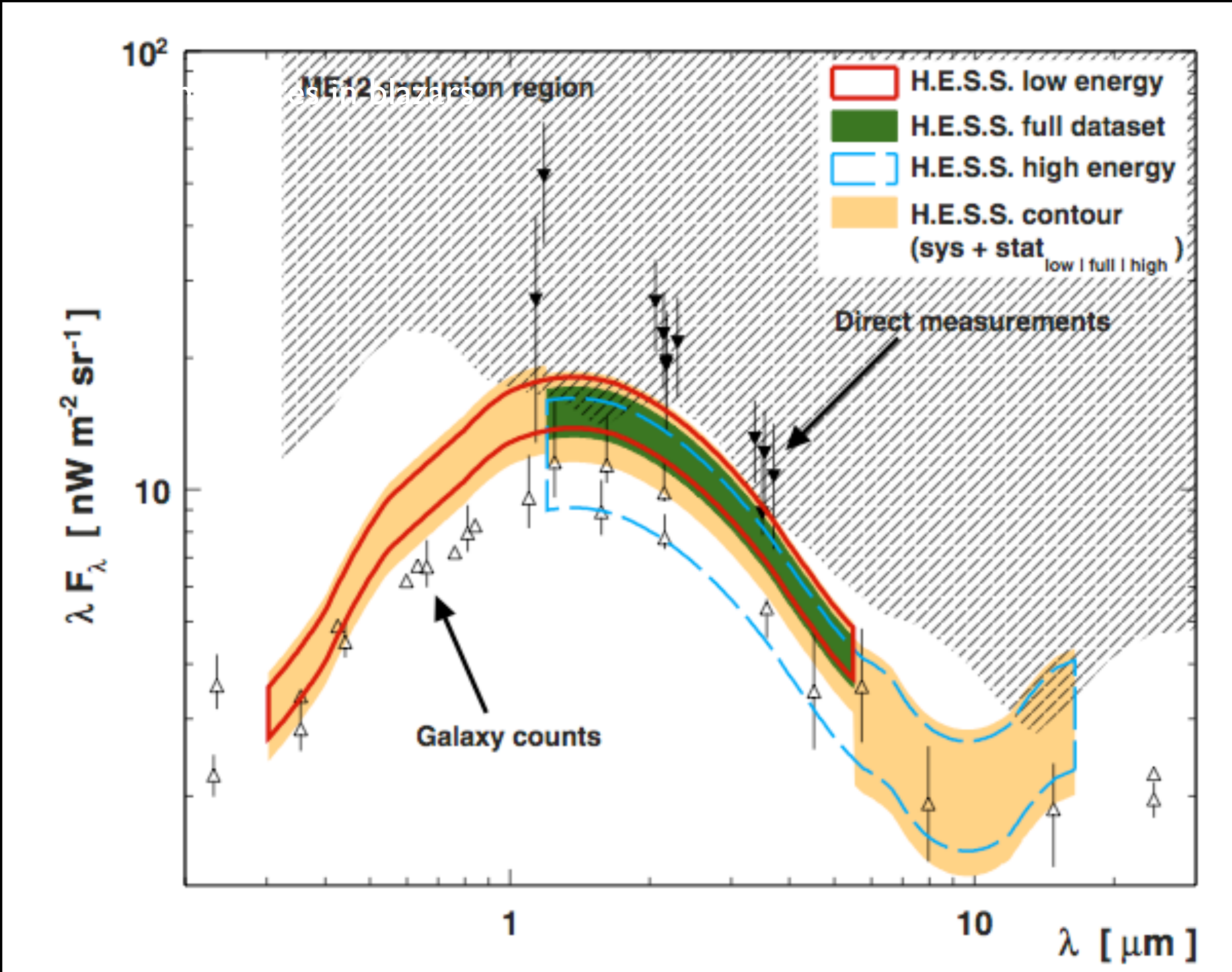
Focal plane configuration

8 x 2 independent CCD controllers in drift-scan mode

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

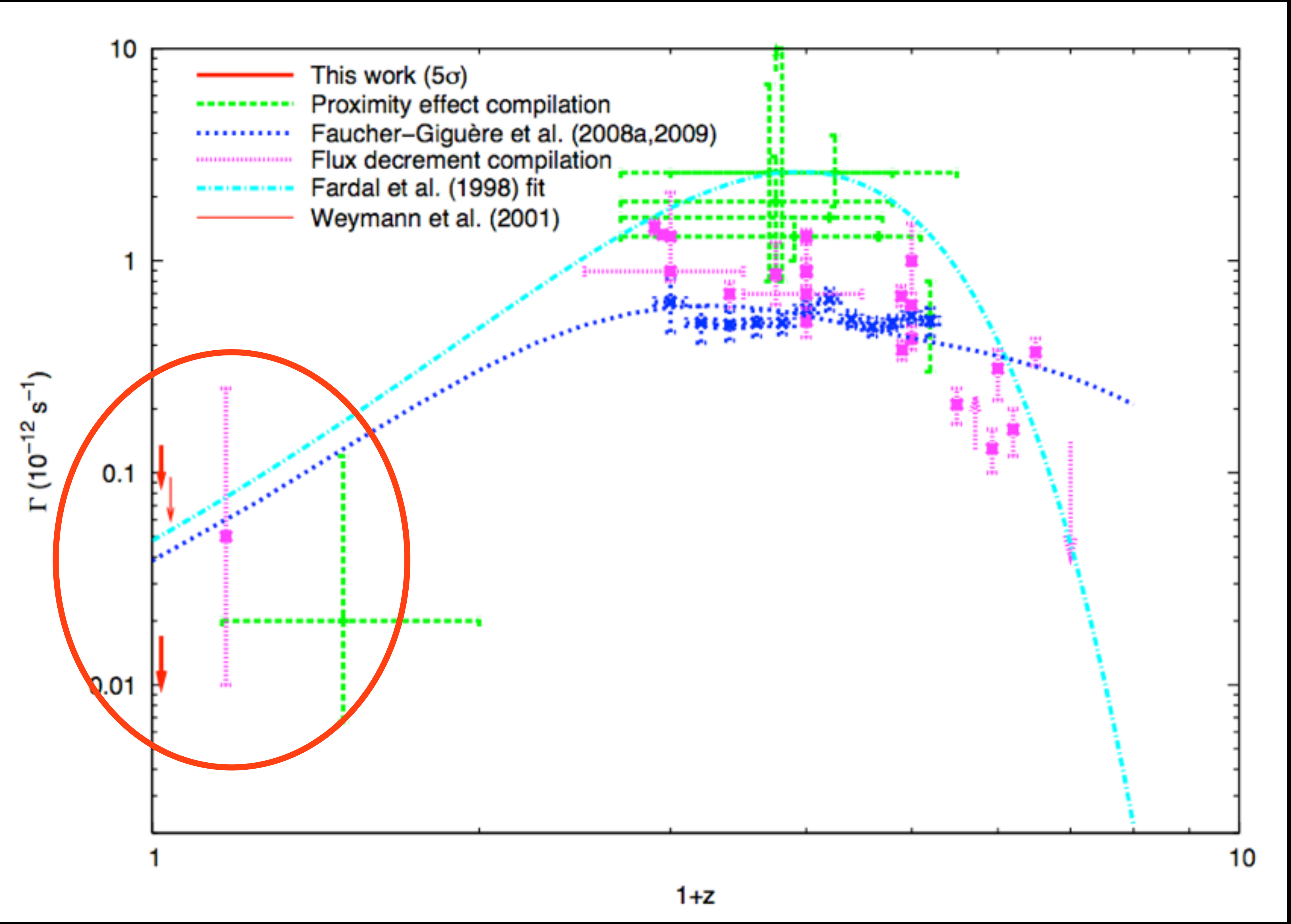
Highly efficient: no moving parts, passive cooling

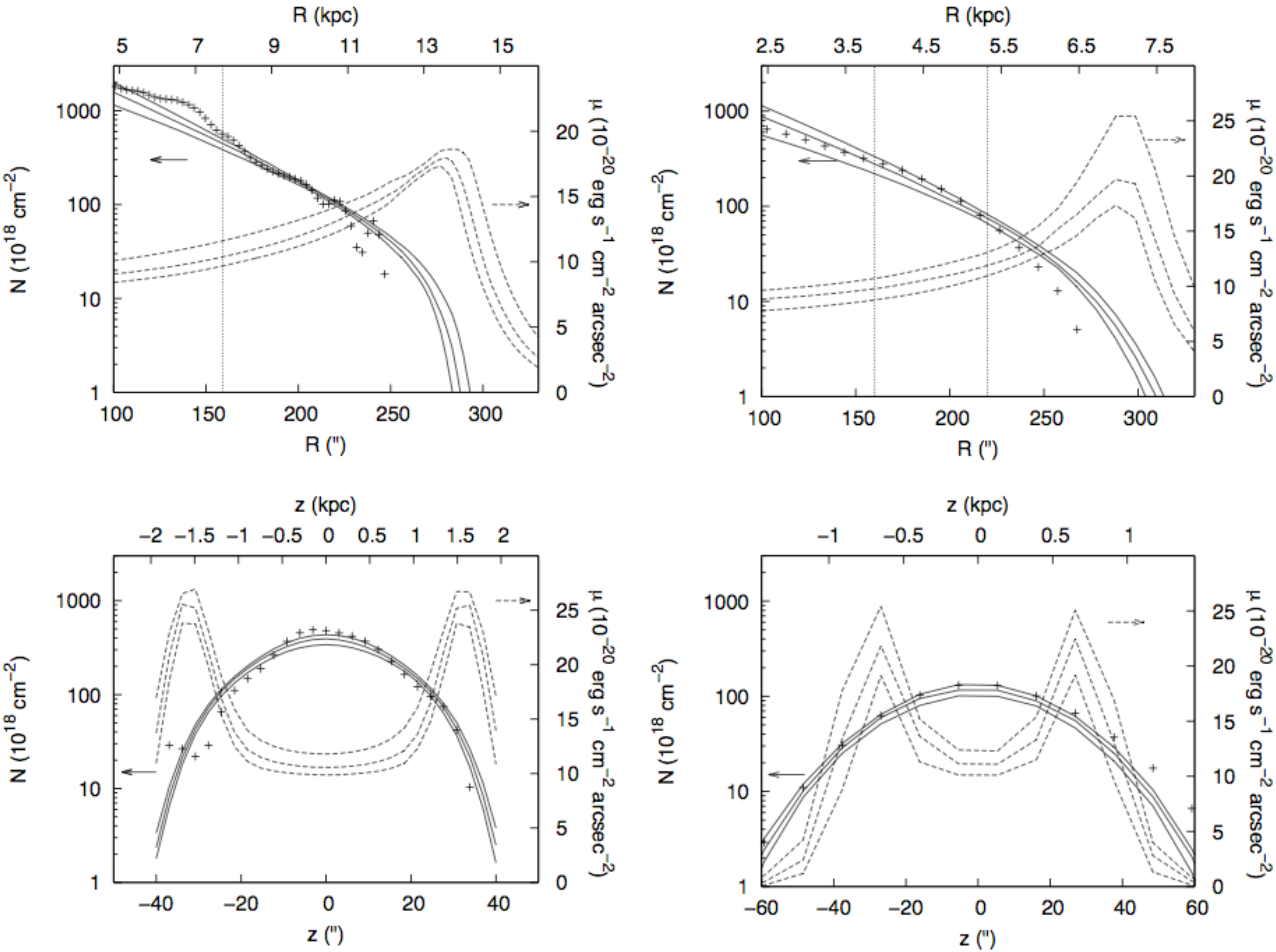
r	g	u	Narrow band 200 nm	Broad-band 200 nm	i	z	Extra broad
r	g	u	Lyα z=0.65	Lyα z=0.65	i	z	Extra broad



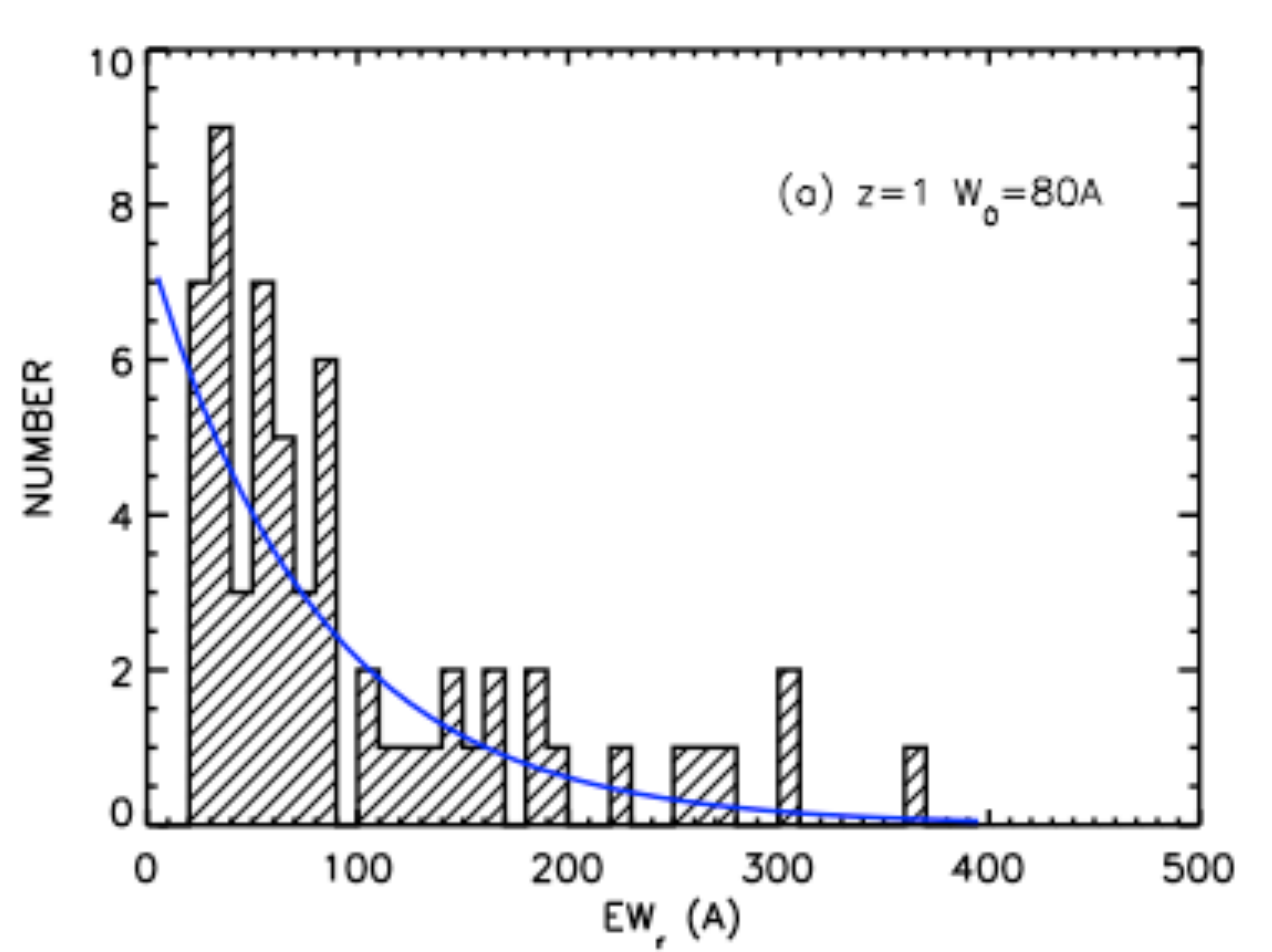
Abramowski et al. (2013)

The ionising background radiation





R (kpc)
5 7 9 11 13 15
N (10^{18} cm^{-2})
1 10 100 1000
μ (10^{-20} erg s^{-1} cm^{-2} arcsec^{-2})
0 5 10 15 20
100 150 200 250 300
R (")
R (kpc)
2.5 3.5 4.5 5.5 6.5 7.5
N (10^{18} cm^{-2})
1 10 100 1000
μ (10^{-20} erg s^{-1} cm^{-2} arcsec^{-2})
0 5 10 15 20 25
100 150 200 250 300
R (")
z (kpc)
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2
N (10^{18} cm^{-2})
1 10 100 1000
μ (10^{-20} erg s^{-1} cm^{-2} arcsec^{-2})
0 5 10 15 20 25
−40 −20 0 20 40
z (")
z (kpc)
−1 −0.5 0 0.5 1
N (10^{18} cm^{-2})
1 10 100 1000
μ (10^{-20} erg s^{-1} cm^{-2} arcsec^{-2})
0 5 10 15 20 25
−60 −40 −20 0 20 40 60
z (")



Wold, Barger & Cowie (2014)

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

Mission concept II

- Spacecraft
  similar to ESA's Proba-V (instrument: 40 kg, 43 W)
  platform: 40×60×80 cm; 95 kg
  comp. MIDEX WISE (40 cm telescope, 200x285x173cm, 660 kg, 300 W, 540 km)
  VESTA dual-payload adapter @ Vega rocket

- Orbit
  SSO 700-900 km, precession 360°/year
  pointing ⊥ Sun-Earth direction avoiding Earthshine
  great circle drift scan with centre at the Sun

- Mission lifetime
  3 to 5 years
  full sky coverage to SB > 32 (optical) - 37 (UV) mag arcsec^{-2}

Mission concept I

- Payload

  Off-axis TMA f/2 telescope, 40 cm diameter

  flat focal plane, FOV : 8 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 (but stability of FP TBD)

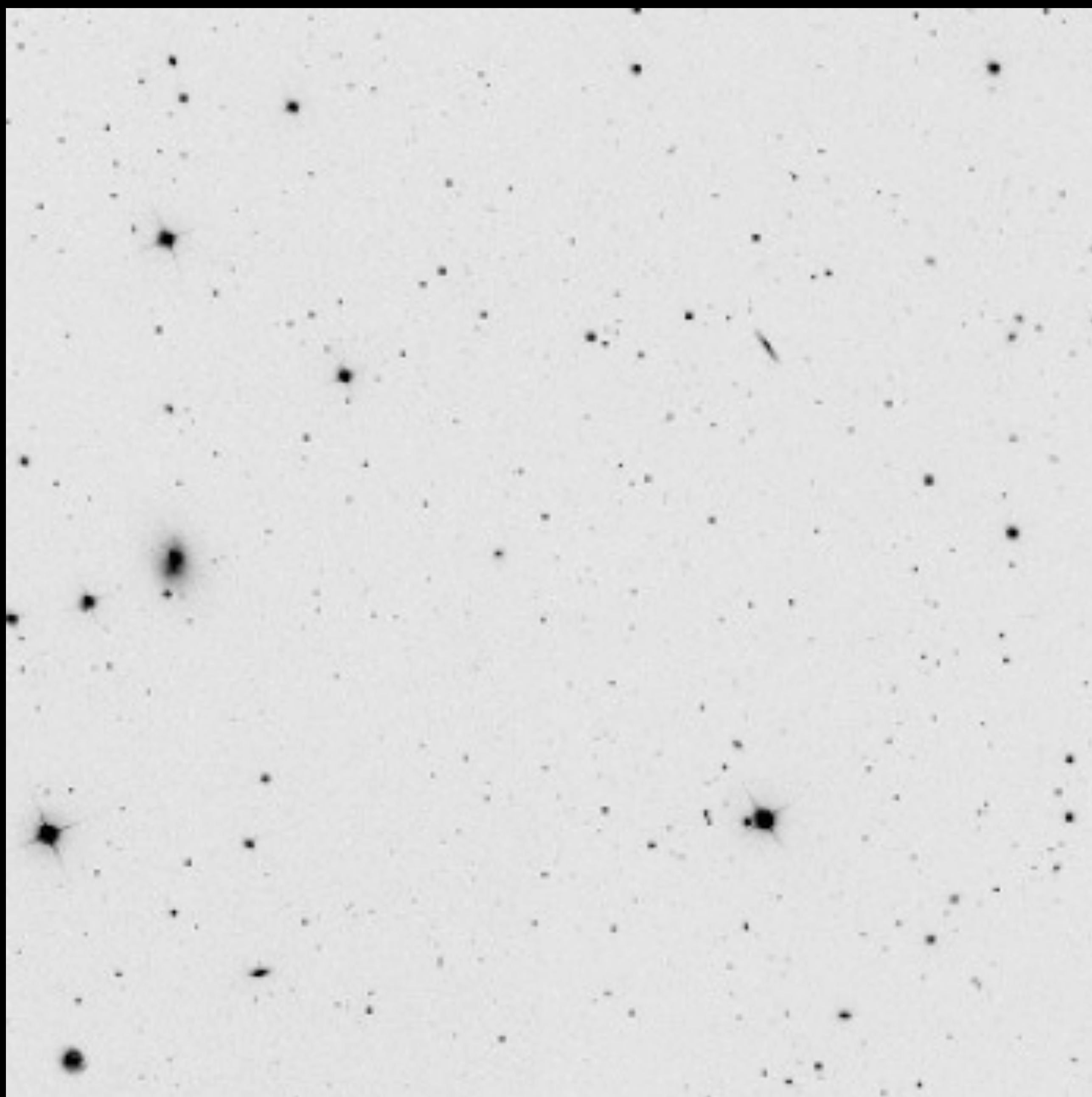
- Detectors

  optimised QE > 80% for each UV/optical band

  ITAR free (TBC)

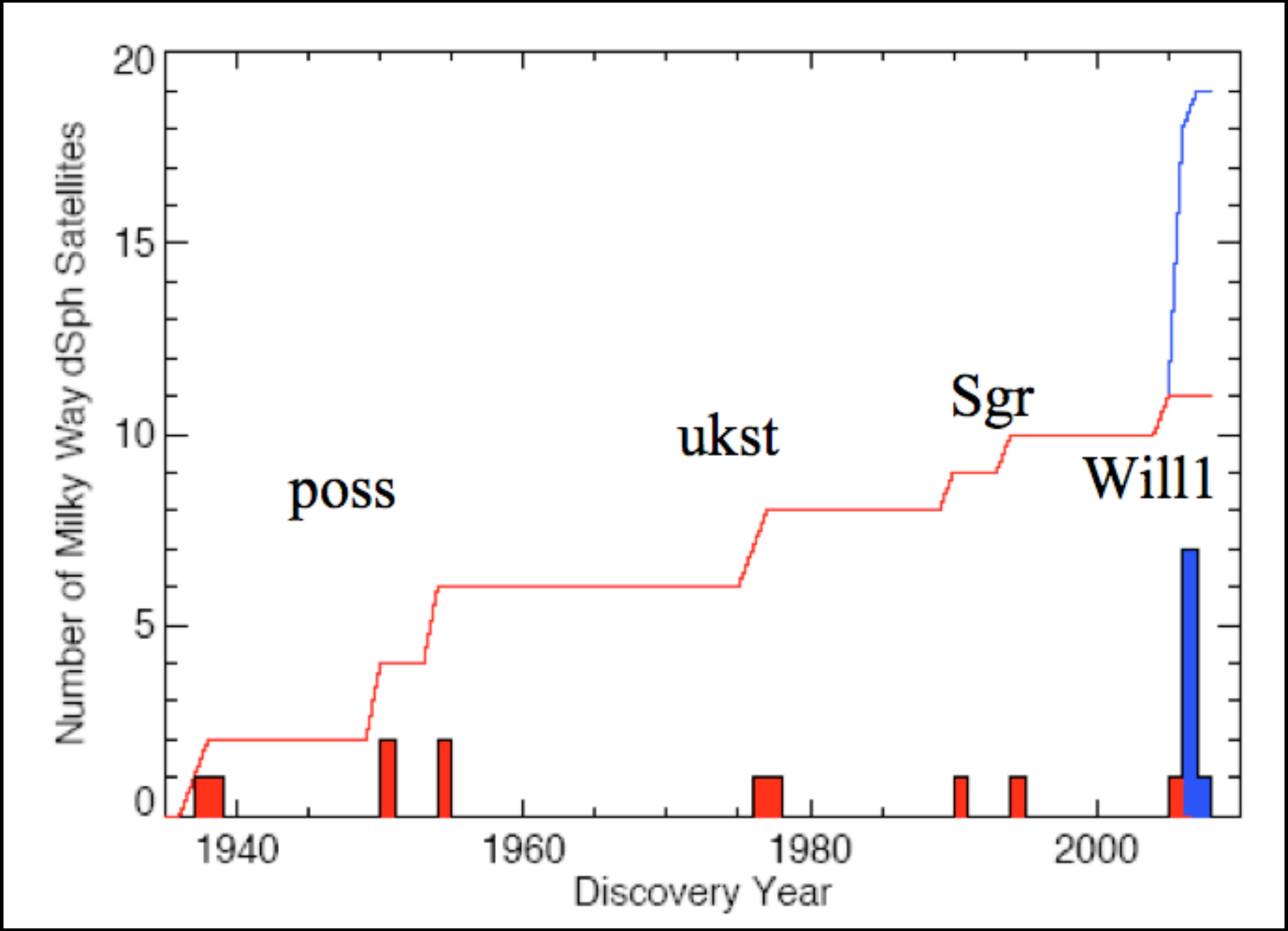
  time delay integration controllers + data flow to ground

The case of Segue I



Belokurov *et al.* (2007)

Discovery rate of Milky Way satellites

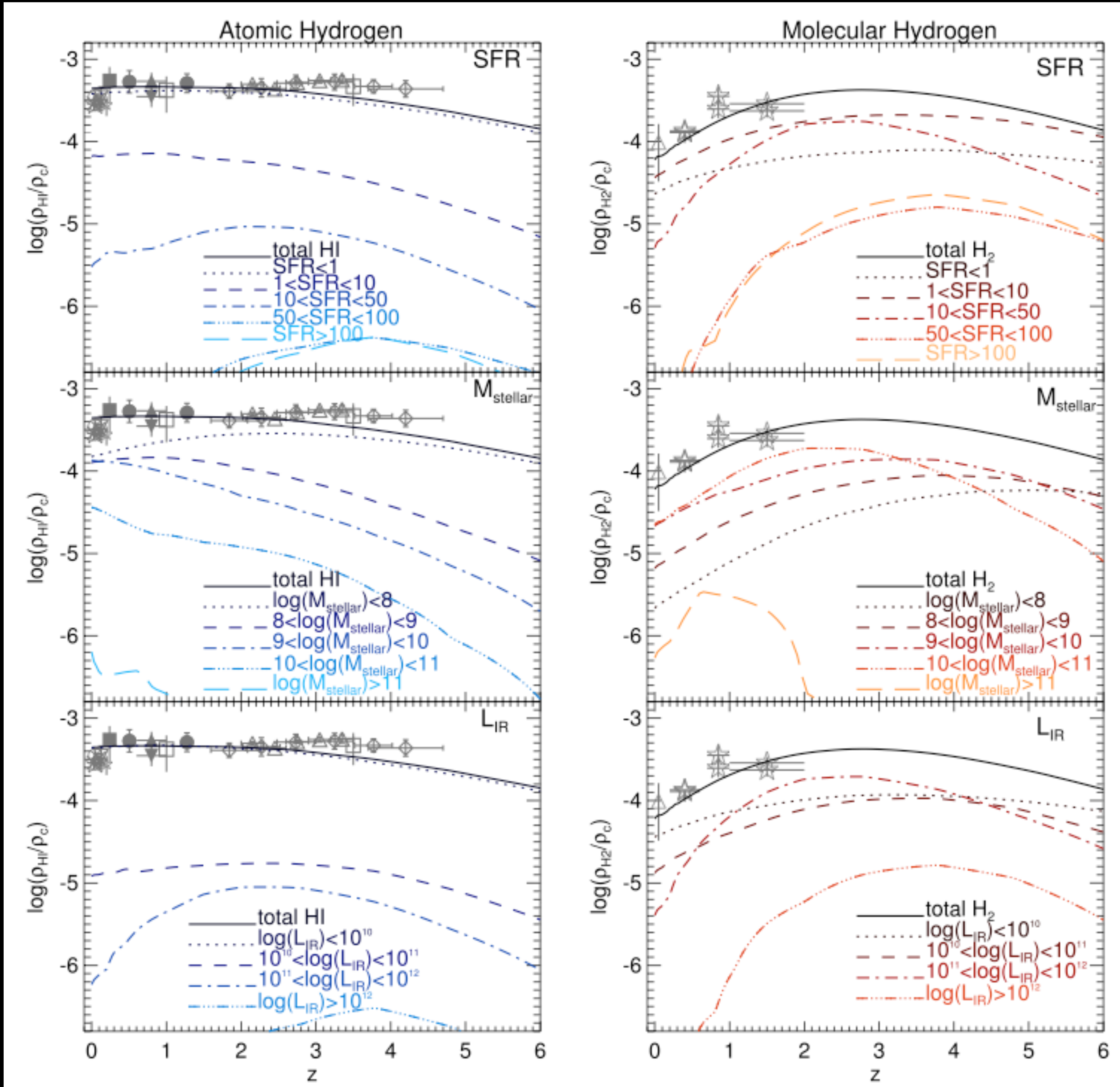


NGC 5907 D=60cm F=180cm f/3
prime focus

4.0 hours integration

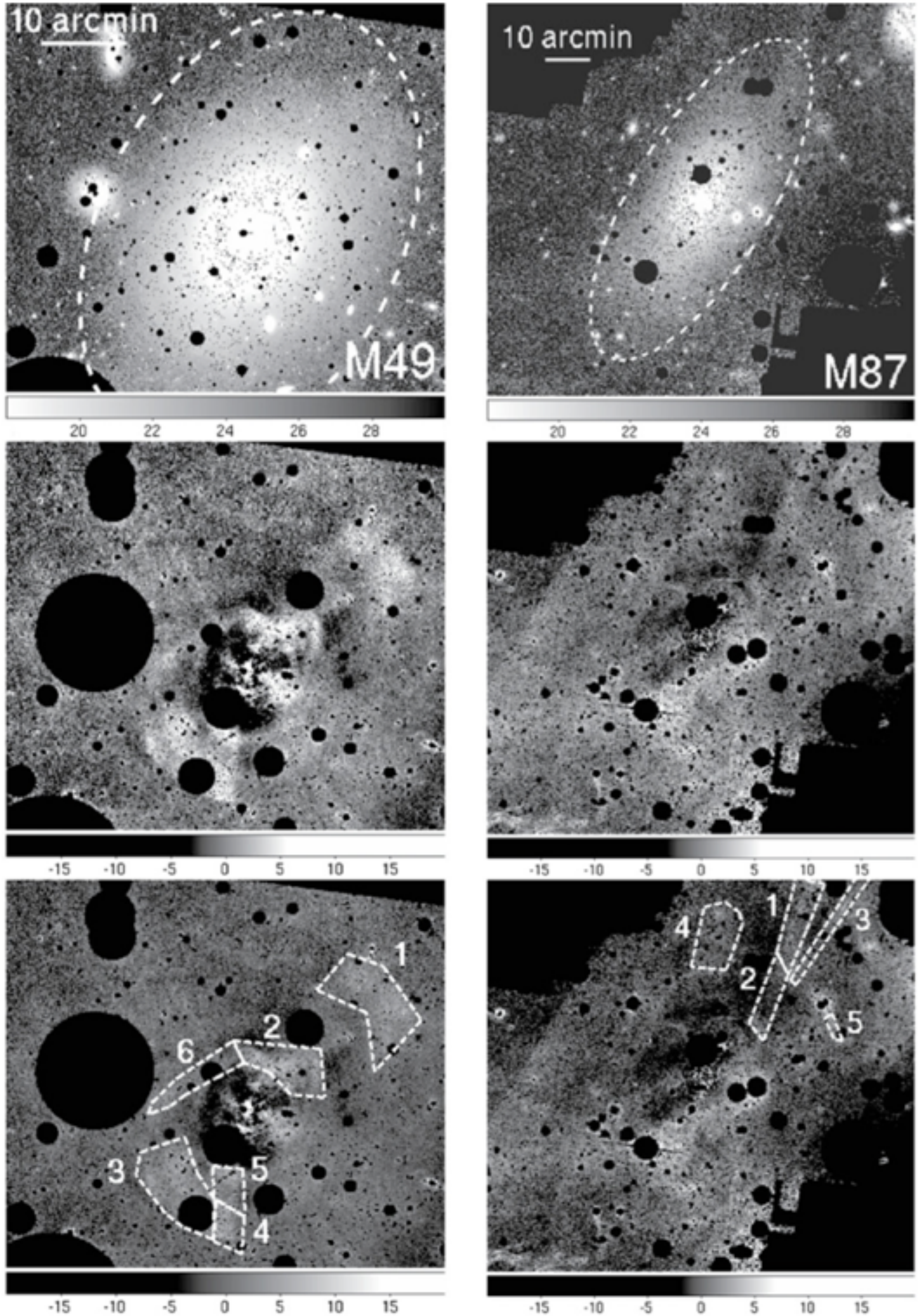
ATLAS-3D   Elliptical galaxies   CFHT LSB-Elixir

Duc *et al.* (2014)

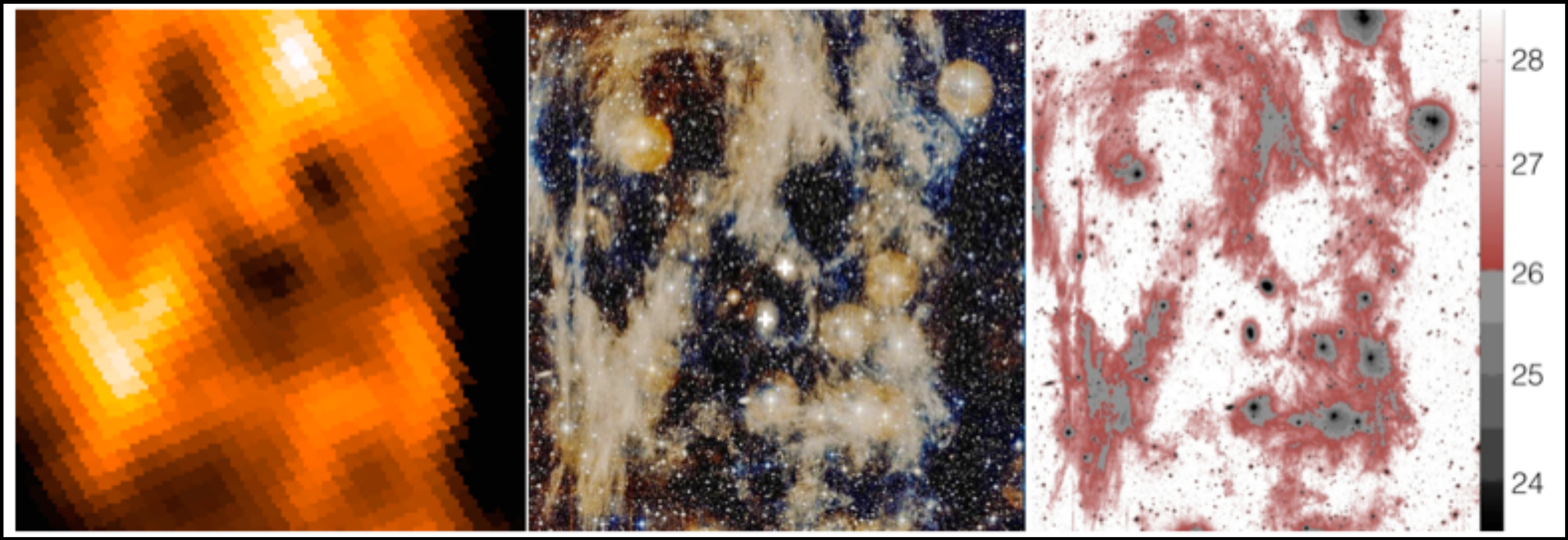


Lagos *et al.* (2014)

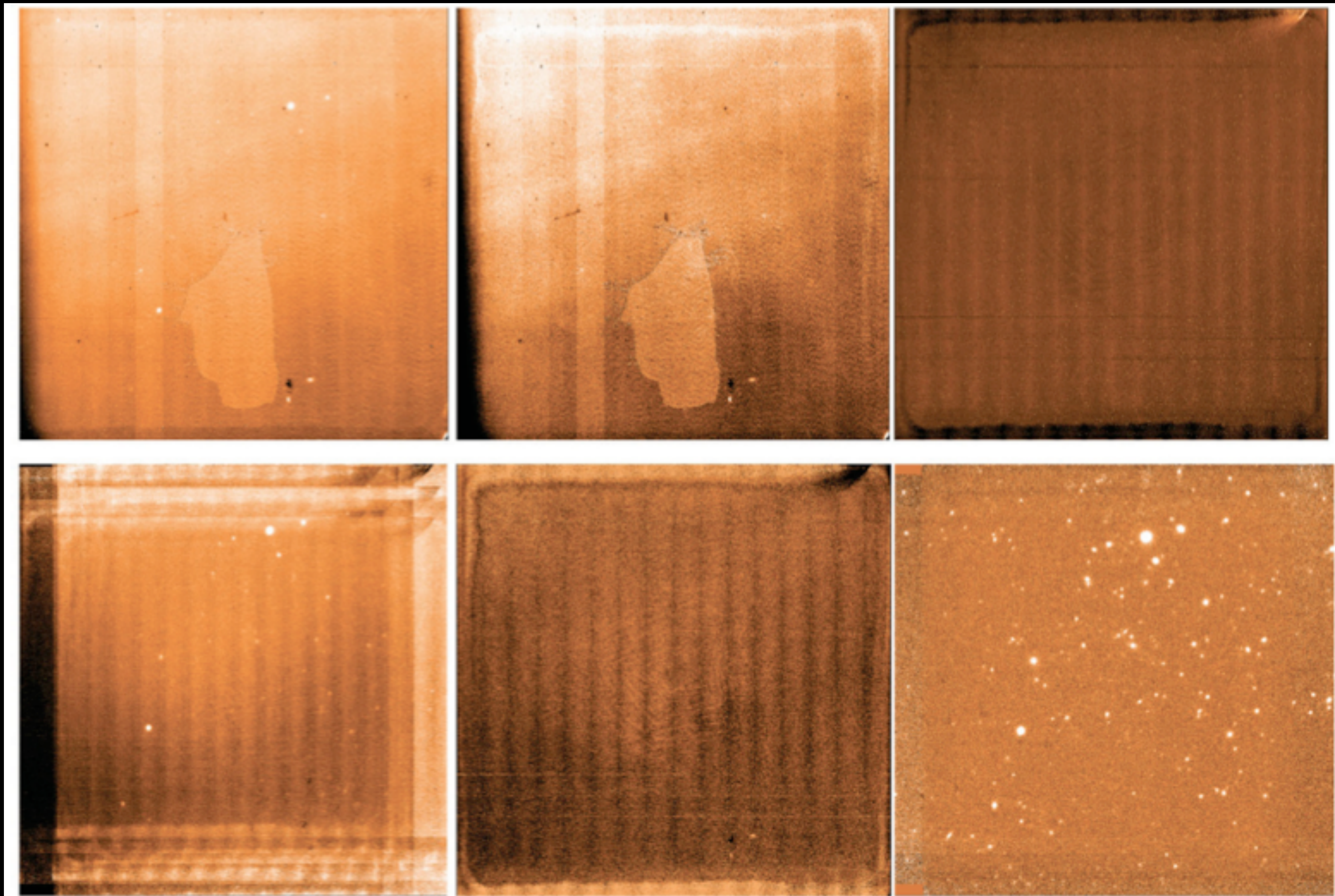
Virgo cluster observations



Mihos *et al.* 2002



Planck 857 GHz 350 µm *r* + *g* *SB levels*

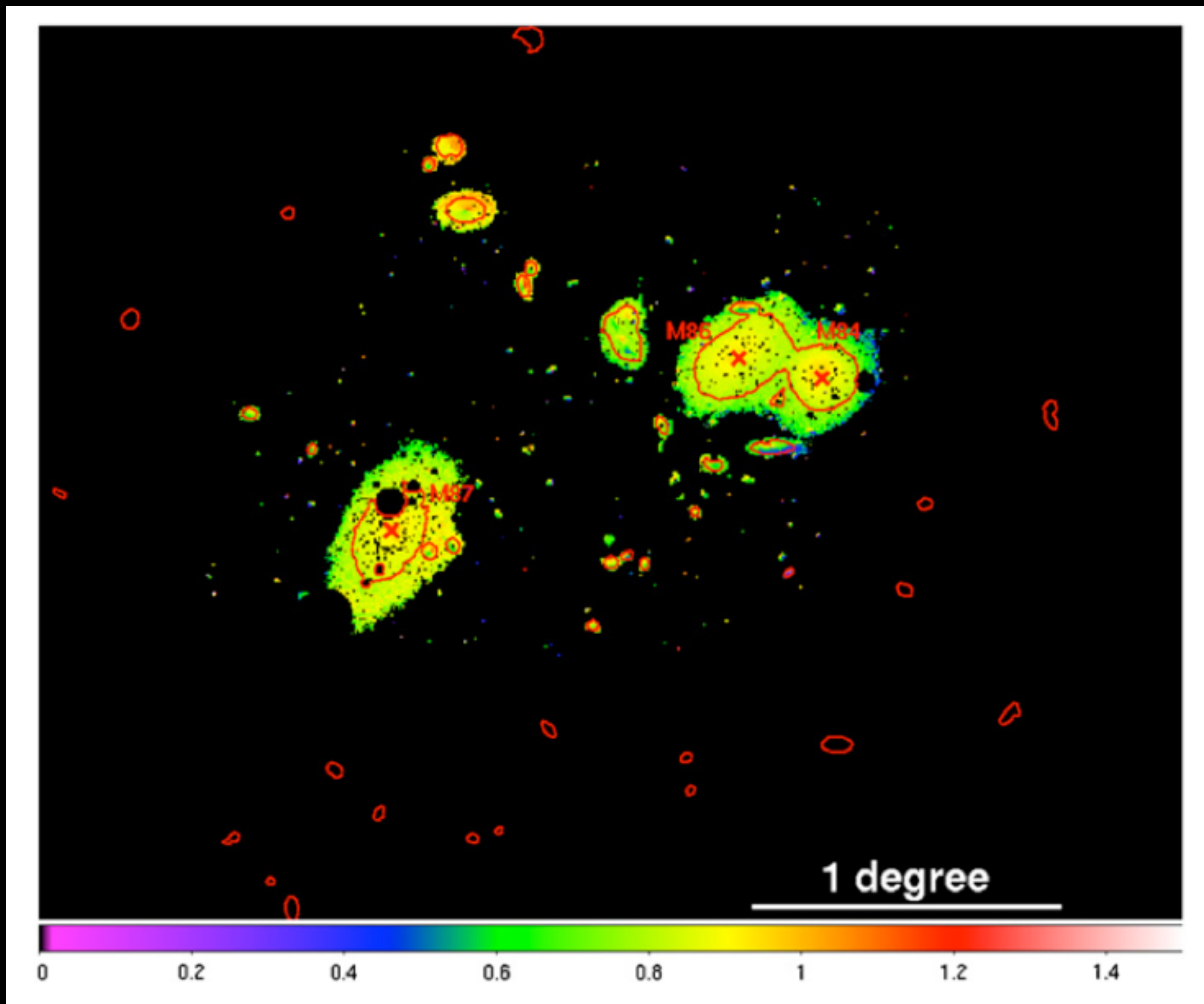


Umbrella galaxy - Subaru

SC4 What is the role of intracluster light in the evolution of galaxies and clusters?

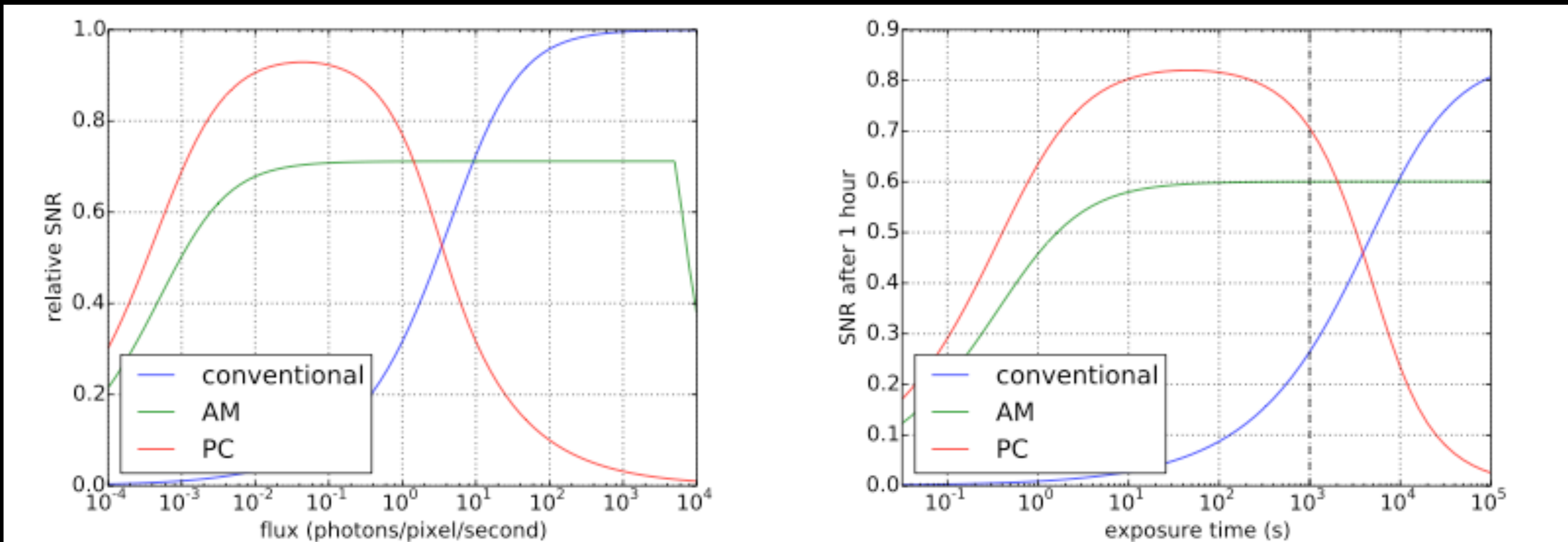
B-V map

Virgo cluster



C. Mihos

Photon counting EMCCDs *vs* conventional CCDs

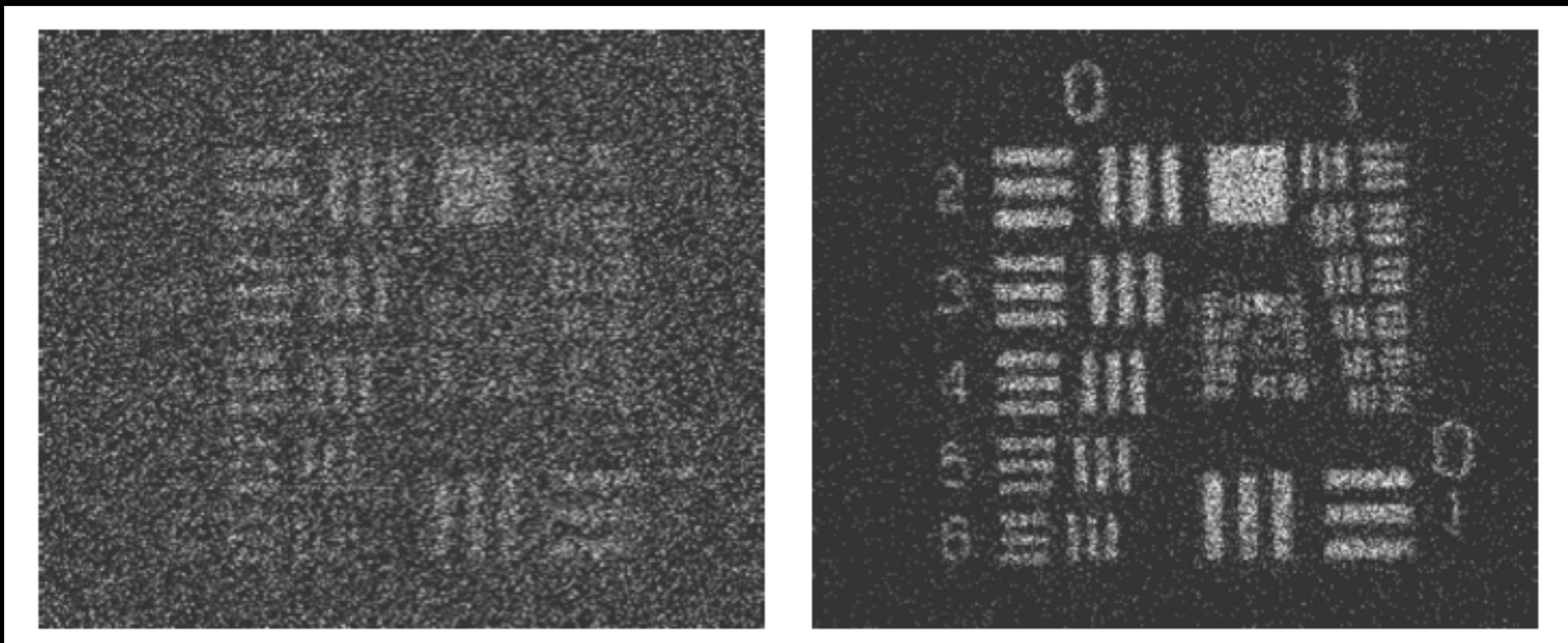


Wilkins *et al.* (2014)

536 EM stage e2v 512×512 pixels Nüvü controller

800,000 e	full well
3 e	read noise
0.0001 e/pixel/s	dark current
0.0007 events/pixel/s	CIC
1 frame/s	operation
1000	gain

Gain in SNR for the same exposure time



337 nm and 777 nm MMIA cameras for ASIM onboard ISS TRL 9