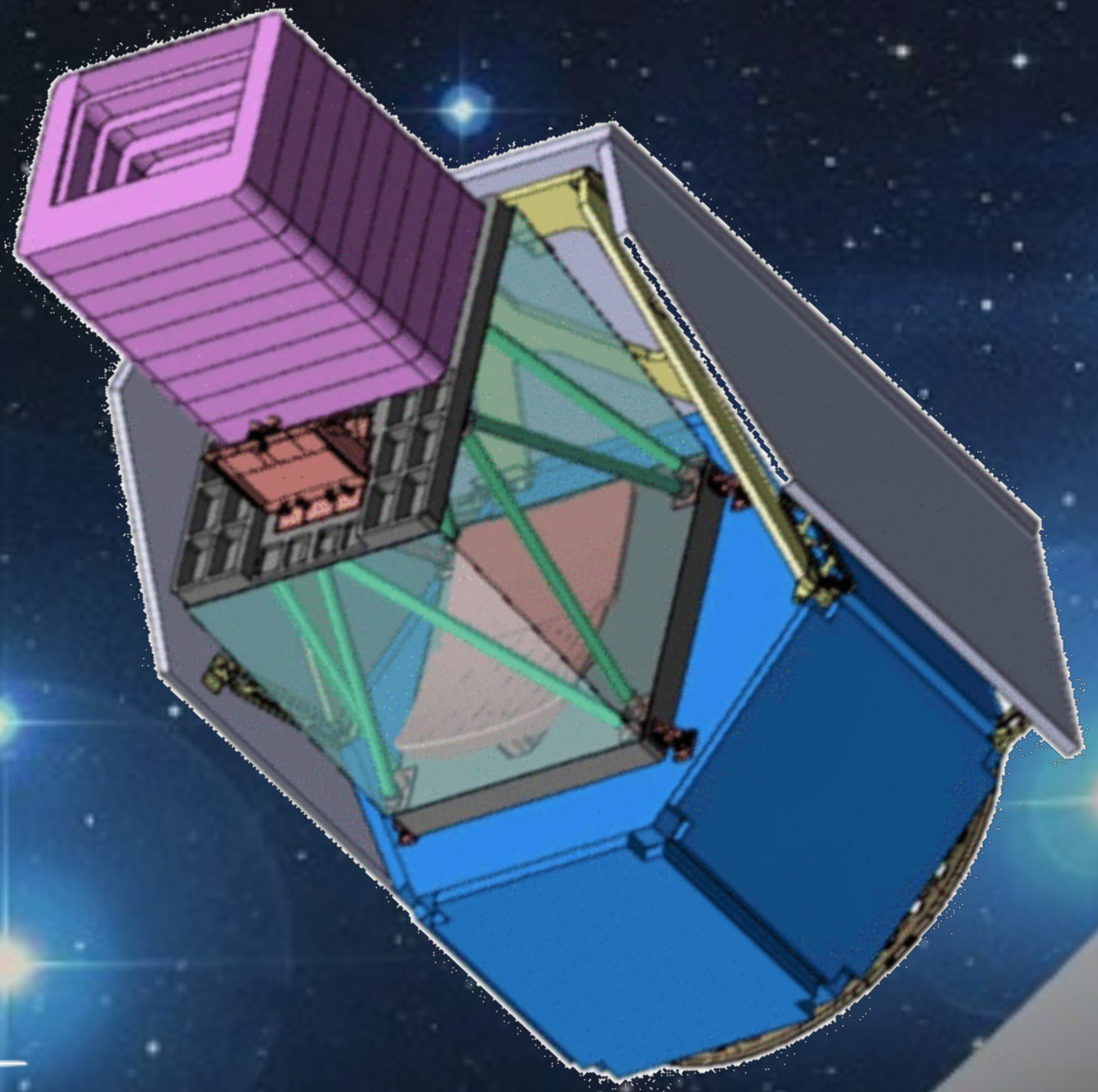
Darkness revealed

The ultra-low surface brightness universe



THE MESSIER SURVEYOR

David Valls-Gabaud

CNRS - Observatoire de Paris

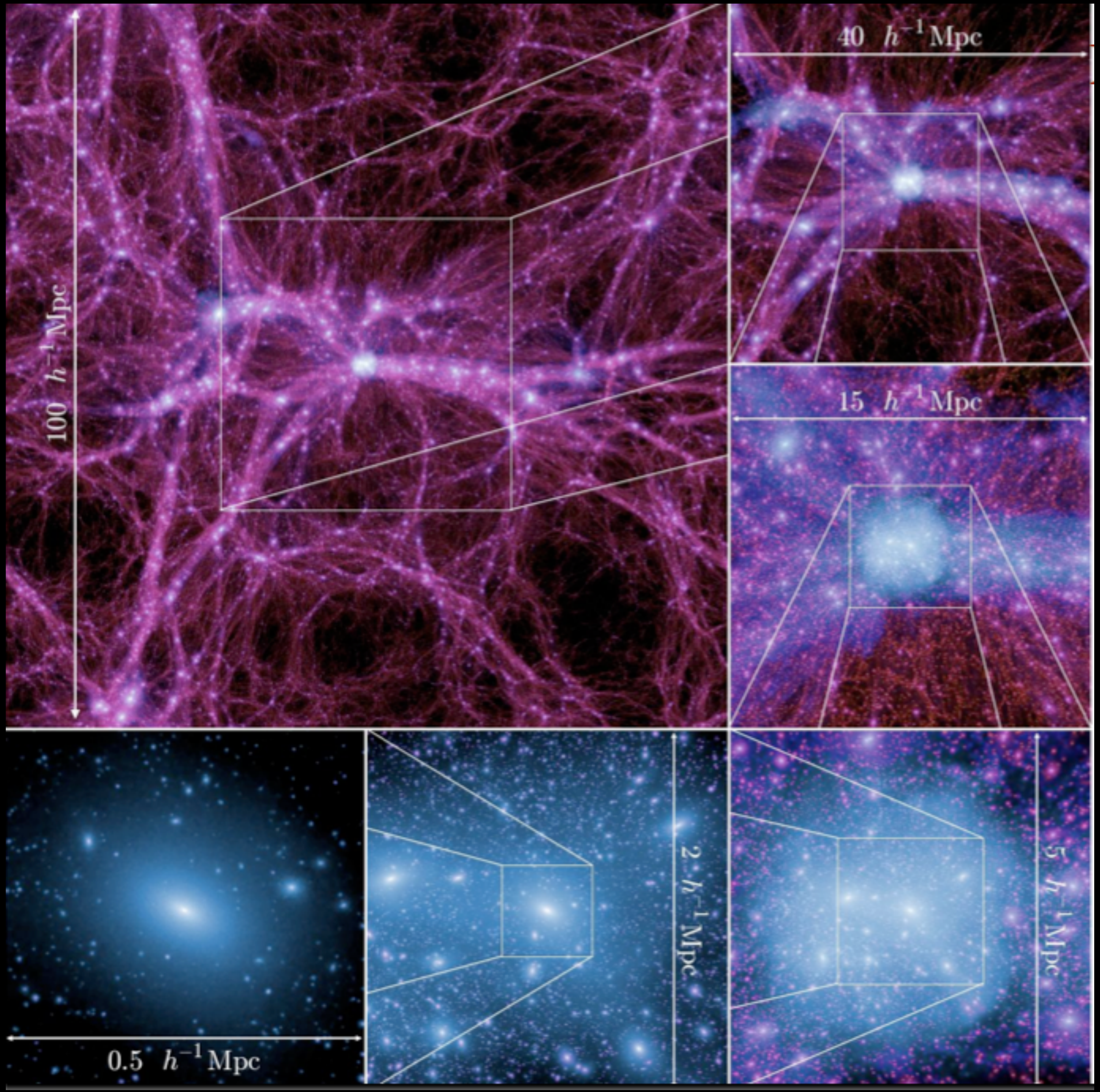
Journées SF2A — Nice

2019 May 15

Current ΛCDM paradigm of cosmological structure formation

linear
&
weakly nonlinear

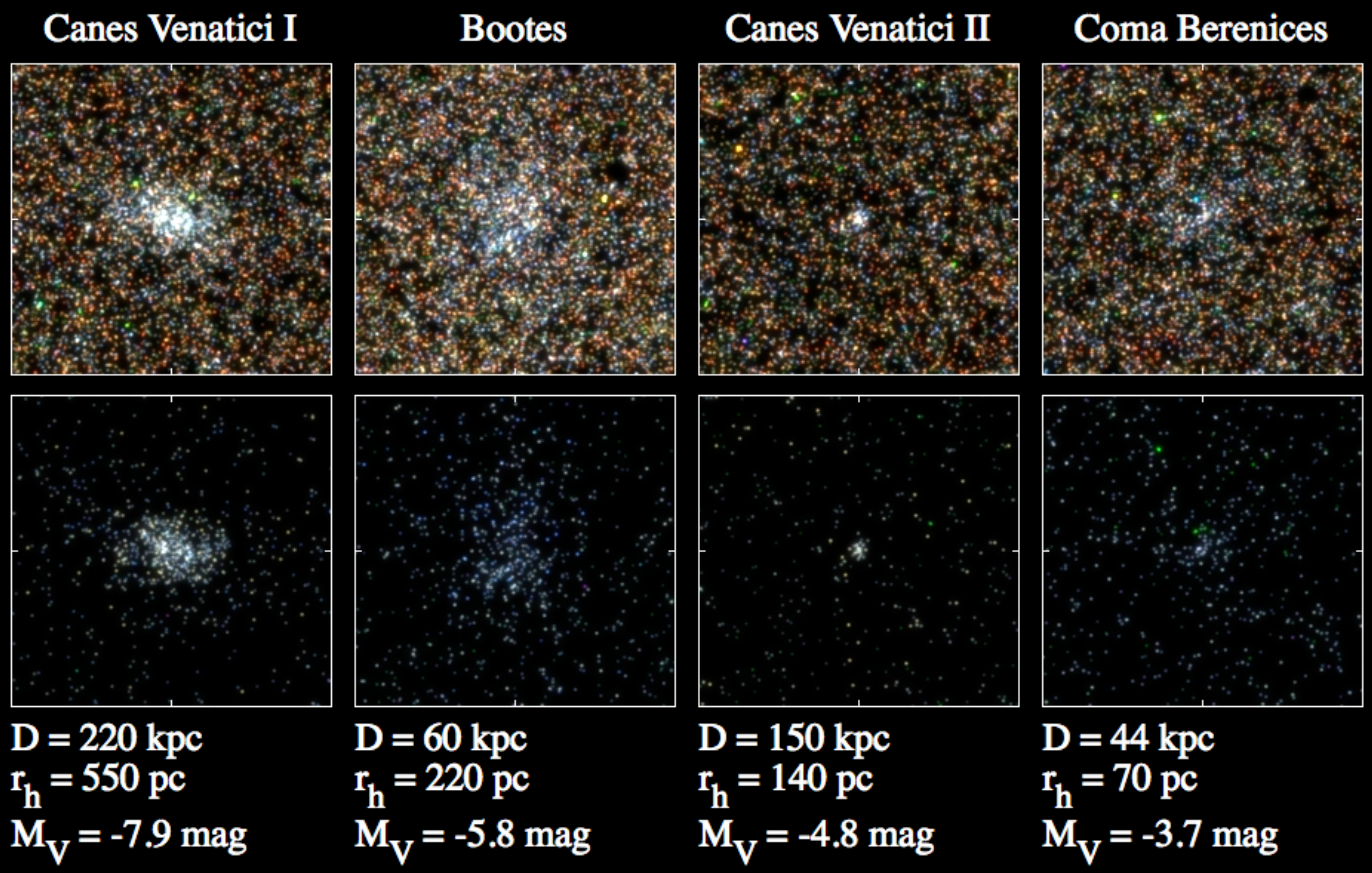
highly
nonlinear



Boylan-Kolchin *et al.* (2009)

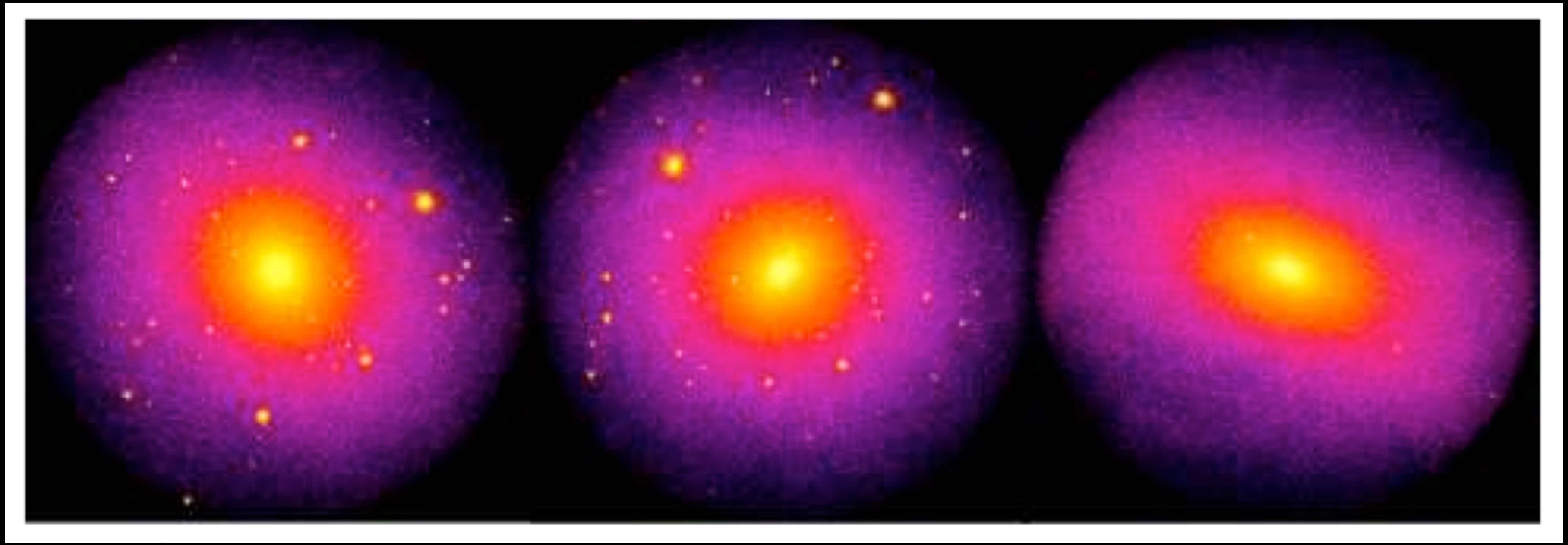
Driving science case #1

Key prediction of the ΛCDM paradigm : The over abundance of dwarf satellites



Belokurov *et al.* (2008)

Tension in the CDM paradigm ?



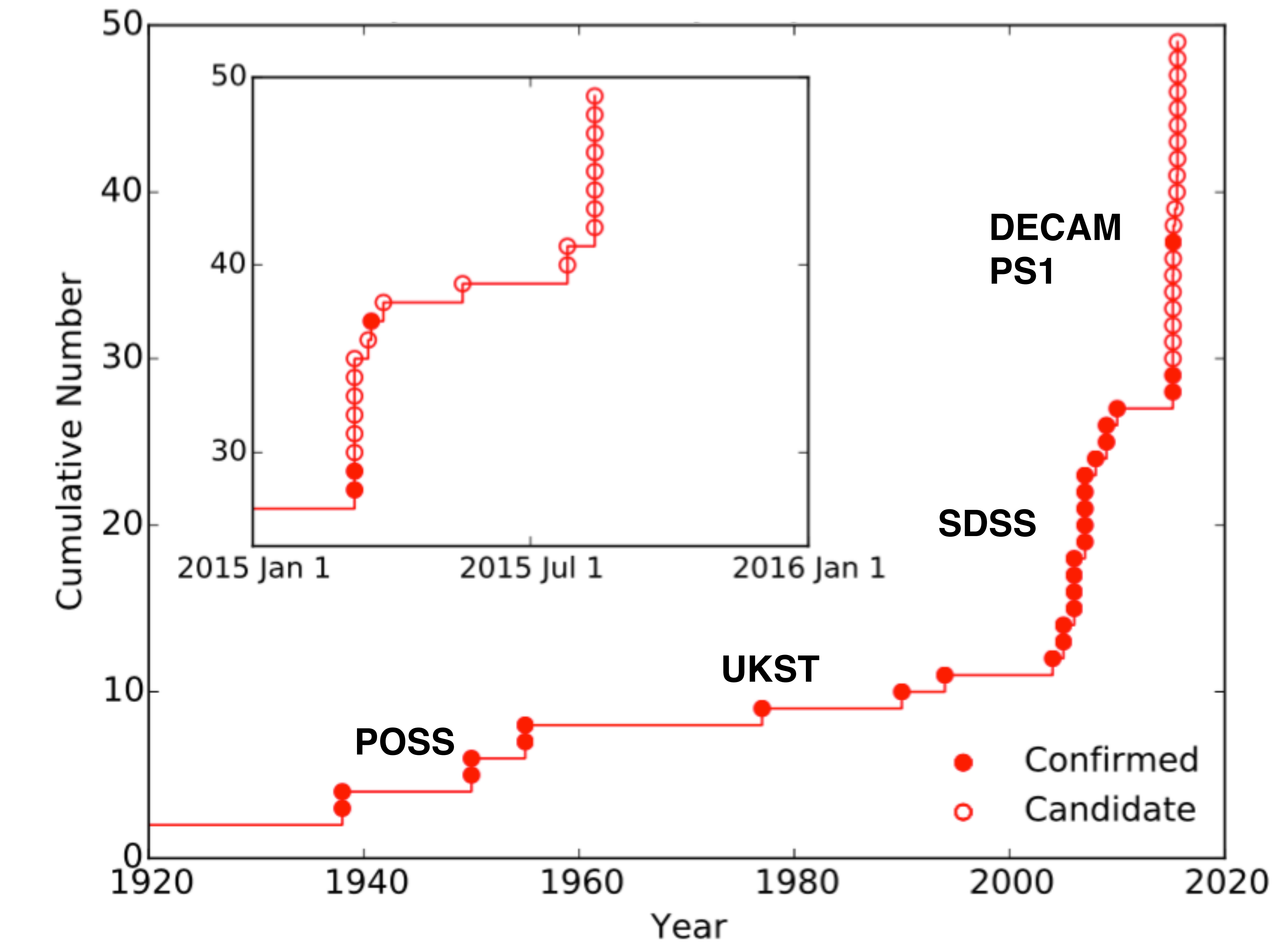
Brooks *et al.* (2014)

Self-Interacting
dark matter

Cold
dark matter

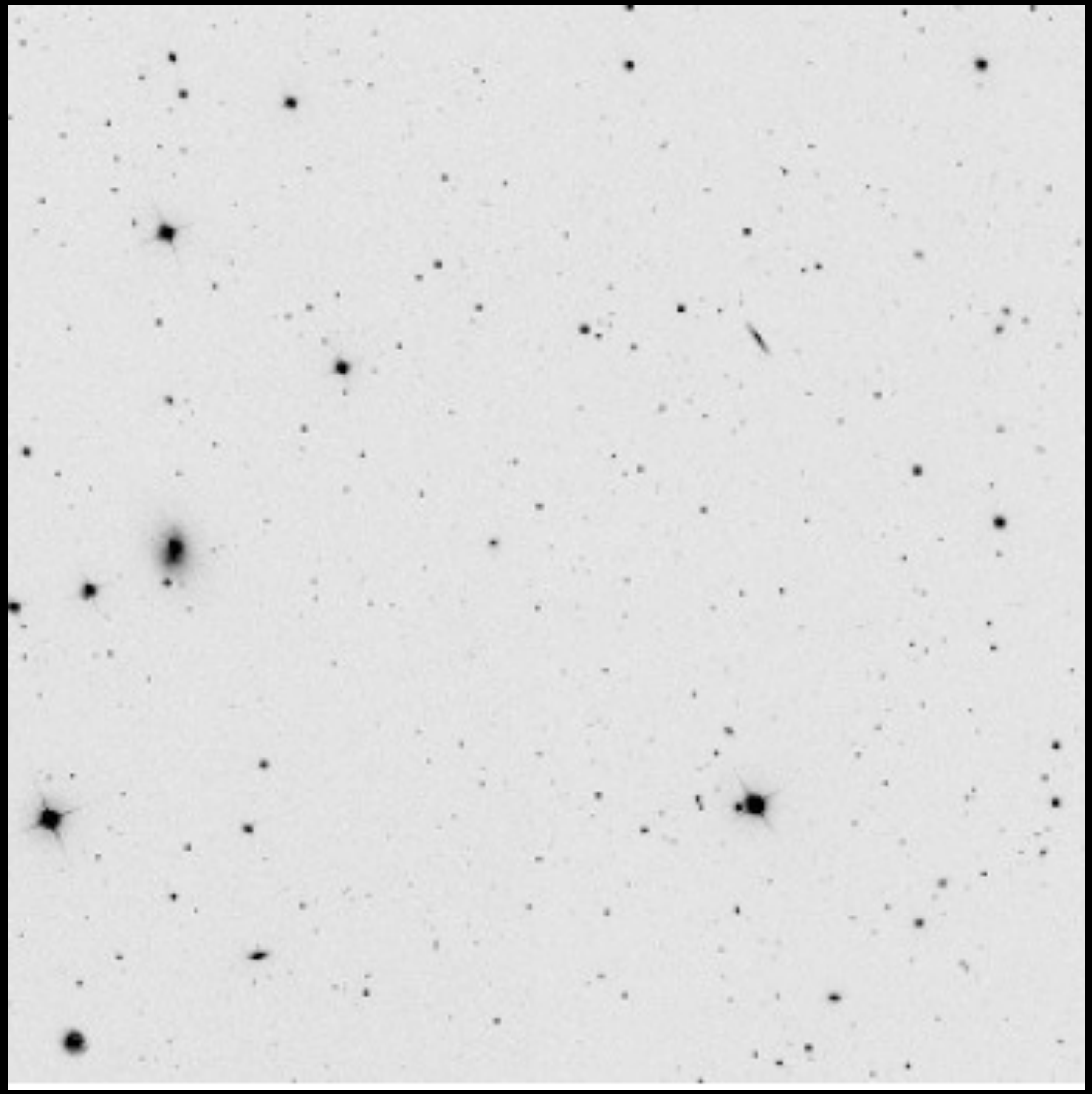
Warm
dark matter

Discovery rate of Milky Way satellites



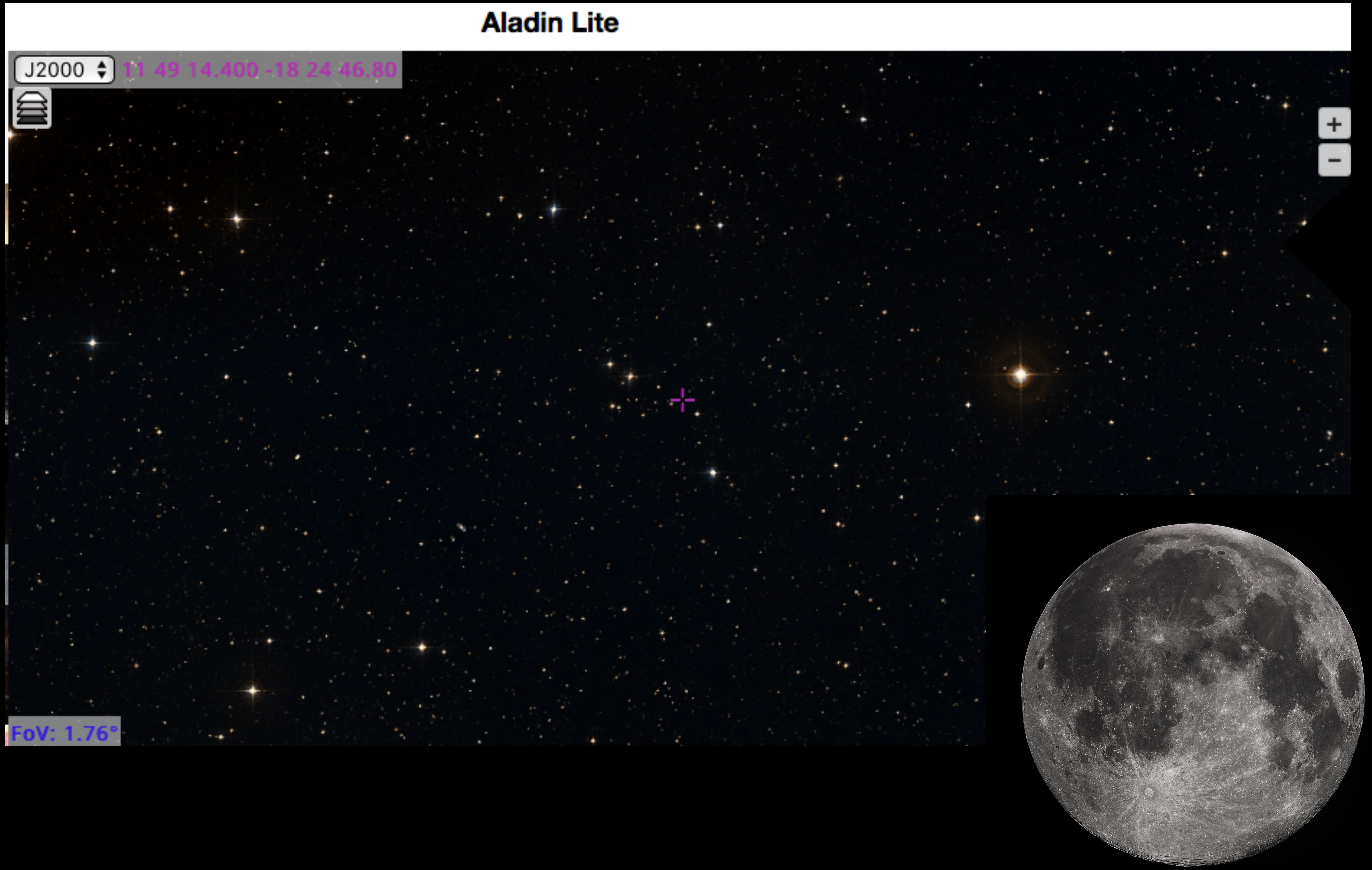
K. Bechtol (2015)

The case of Segue I



Belokurov *et al.* (2007)

Crater II :   The 5th largest satellite of the Milky Way



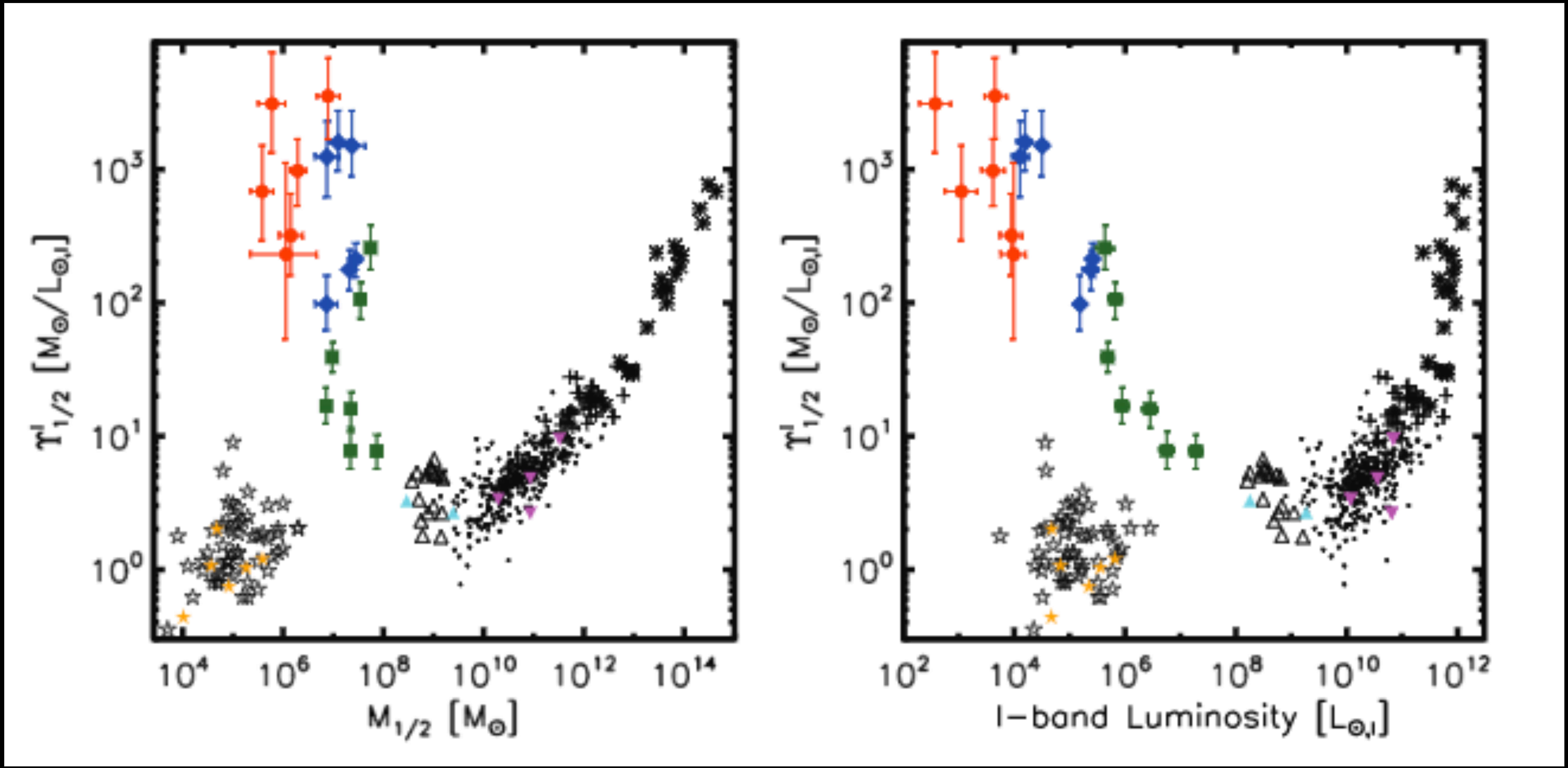
Crater II :   The 5th largest satellite of the Milky Way

d = 120 kpc

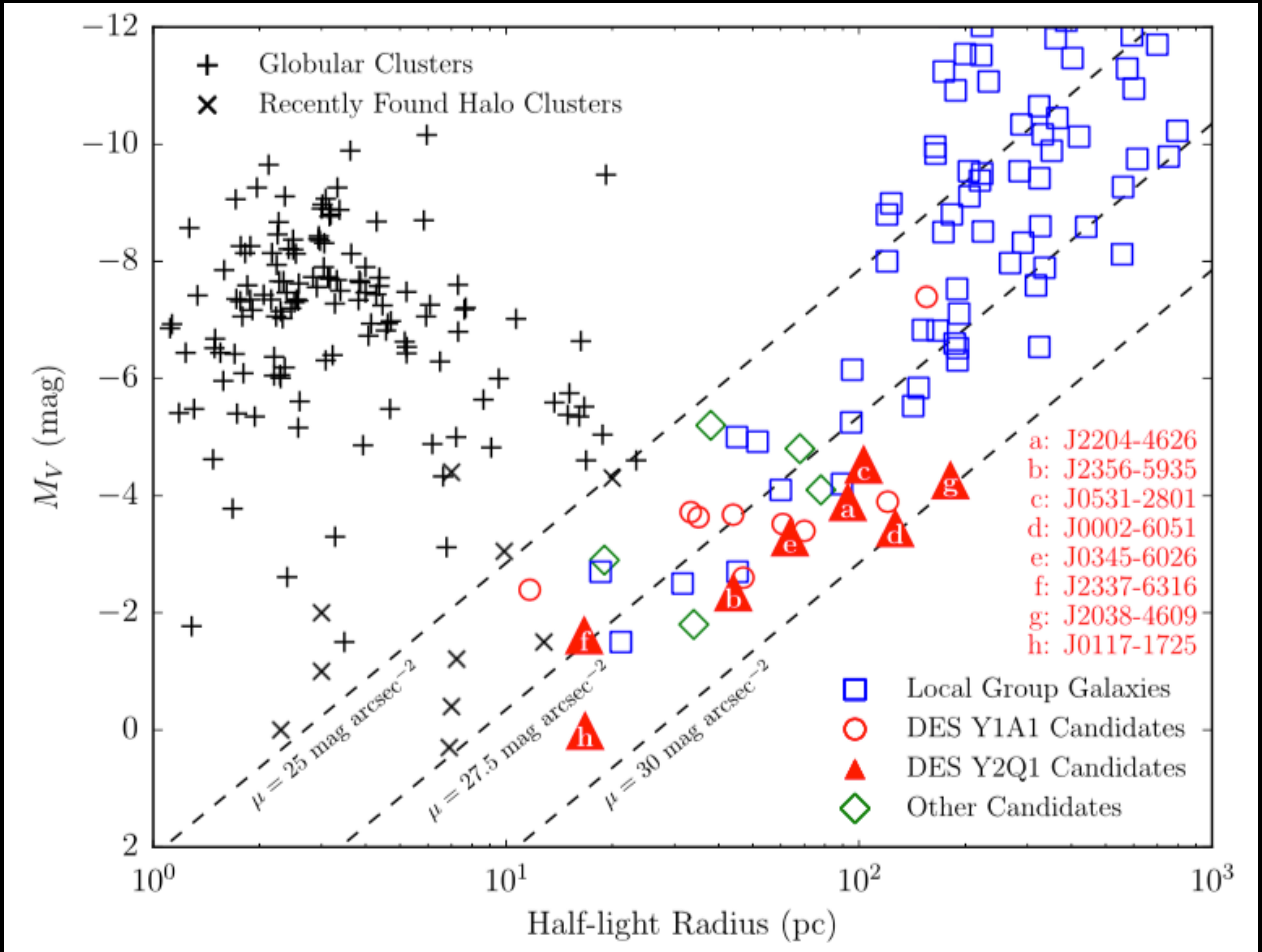
r_h = 1.06 kpc (31′)

$\mu_V(r_h)$ = 30.9 mag arcsec^{-2}

Torrealba *et al.* (2016)



Wolf *et al.* (2011)



Drlica-Wagner *et al.* (2015)

Current instrumentation is *not* adequate for LSB observations

Flux received from a *point* source:

$$F_{\text{point}} = \epsilon\, \pi \left(\frac{D}{2}\right)^2 t_{exp}\, 10^{-0.4\, m}$$

→ drives telescopes with *large* diameters and *large* focal lengths

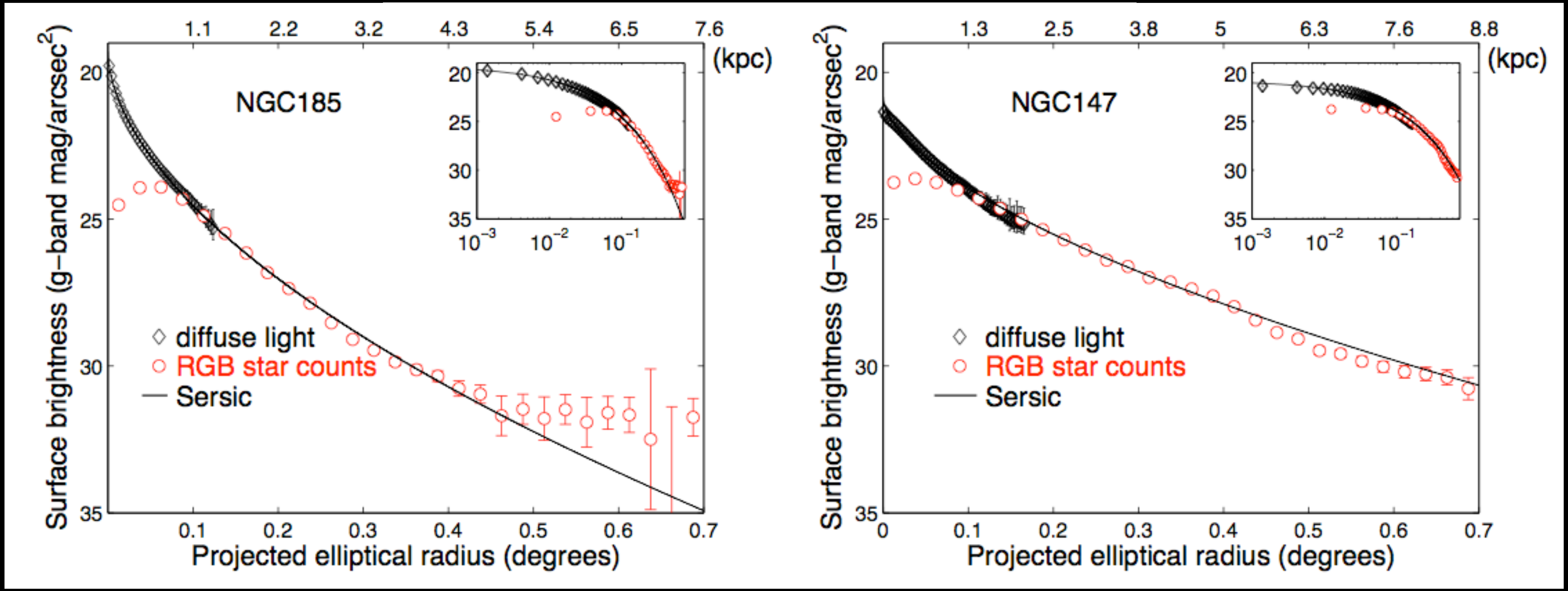
Surface brightness received from an *extended* source:

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

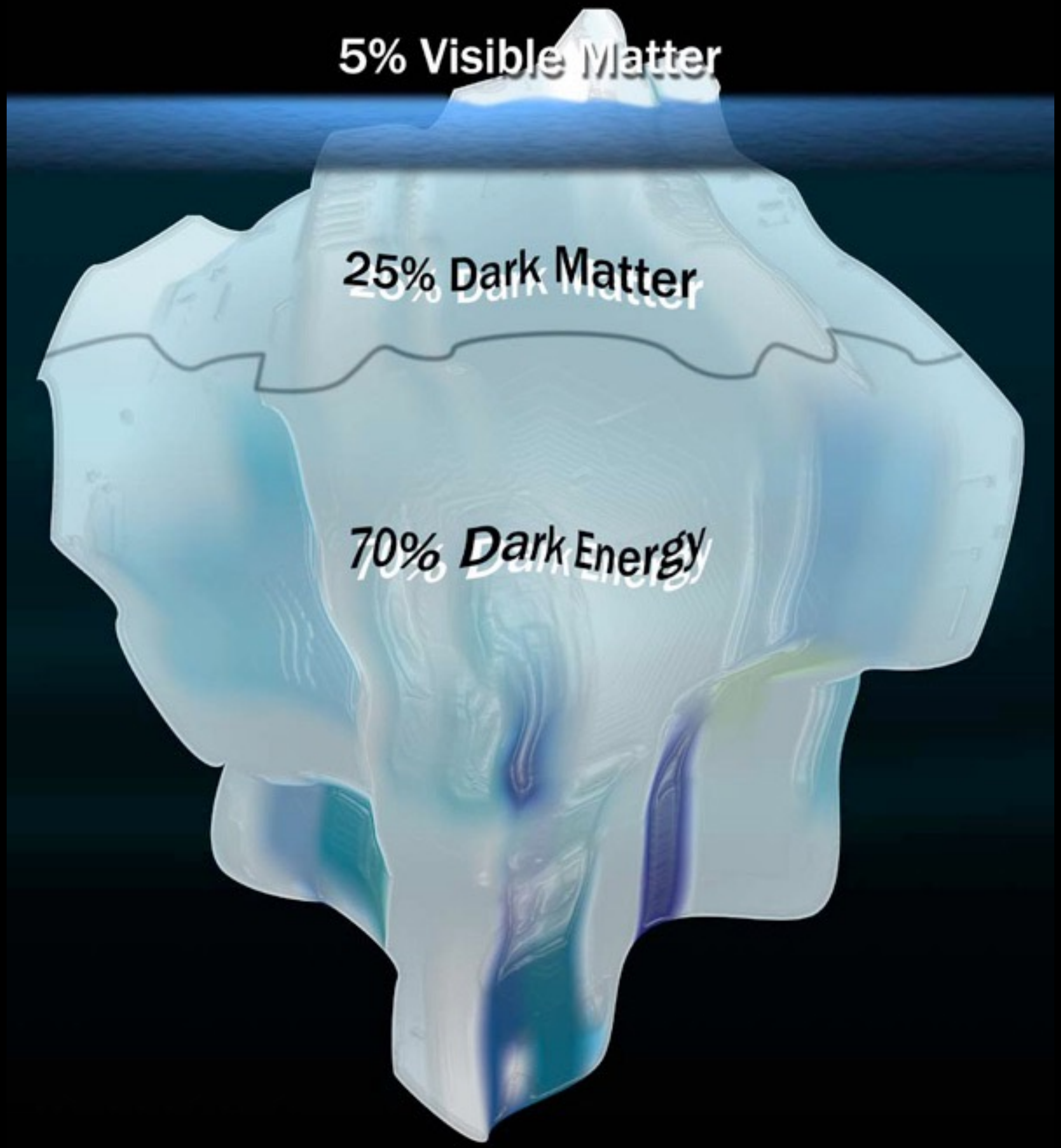
→ requires *fast* optics with *minimal* (*f*/*D*) ratio


Duc *et al.* (2014)

Resolved star counts *vs* diffuse light



Crnojević *et al.* (2015)



[...] *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 ultra-low surface brightness universe

$\mu(V) < 21.5$ mag arcsec^{-2}

Mihos *et al.* (2005)

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

The Dragonfly array telescope

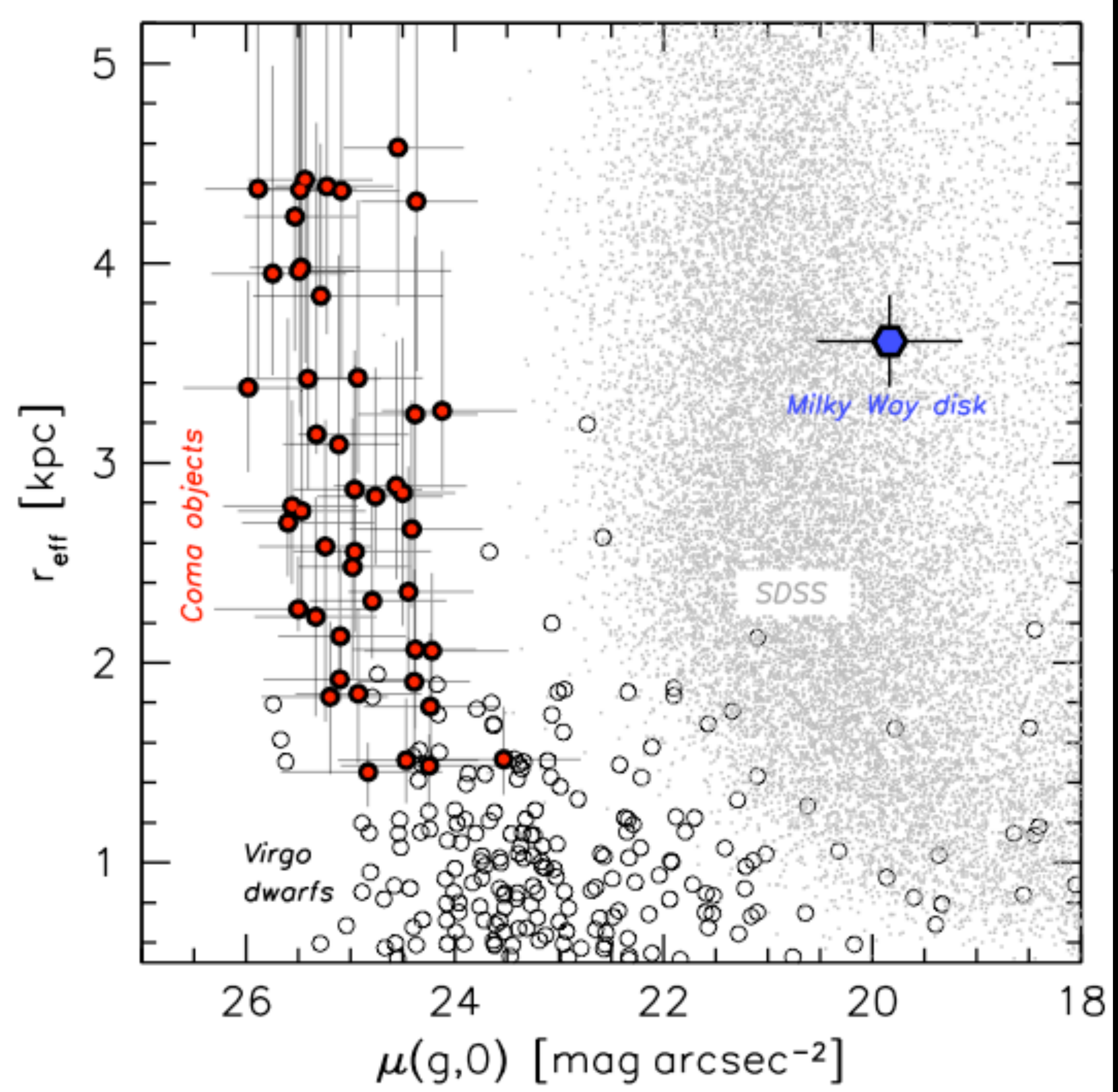
Abraham & Van Dokkum (2014)

47 new Milky Way-sized galaxies in the Coma cluster

26 hours

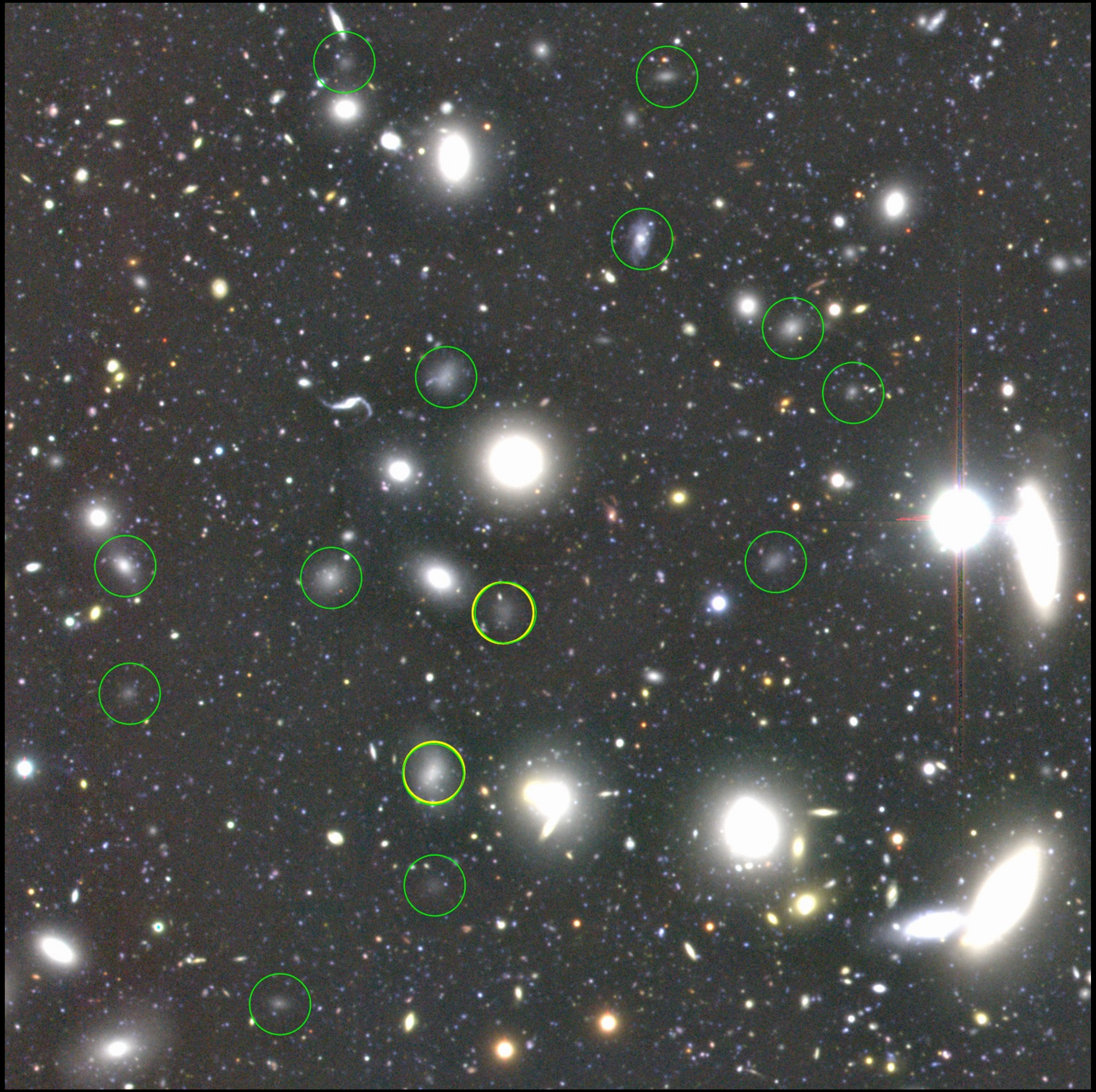
6″ FWHM

SB(g) ~ 29.3 mag arcsec^{-2} @ 10″



Van Dokkum *et al.* (2015)

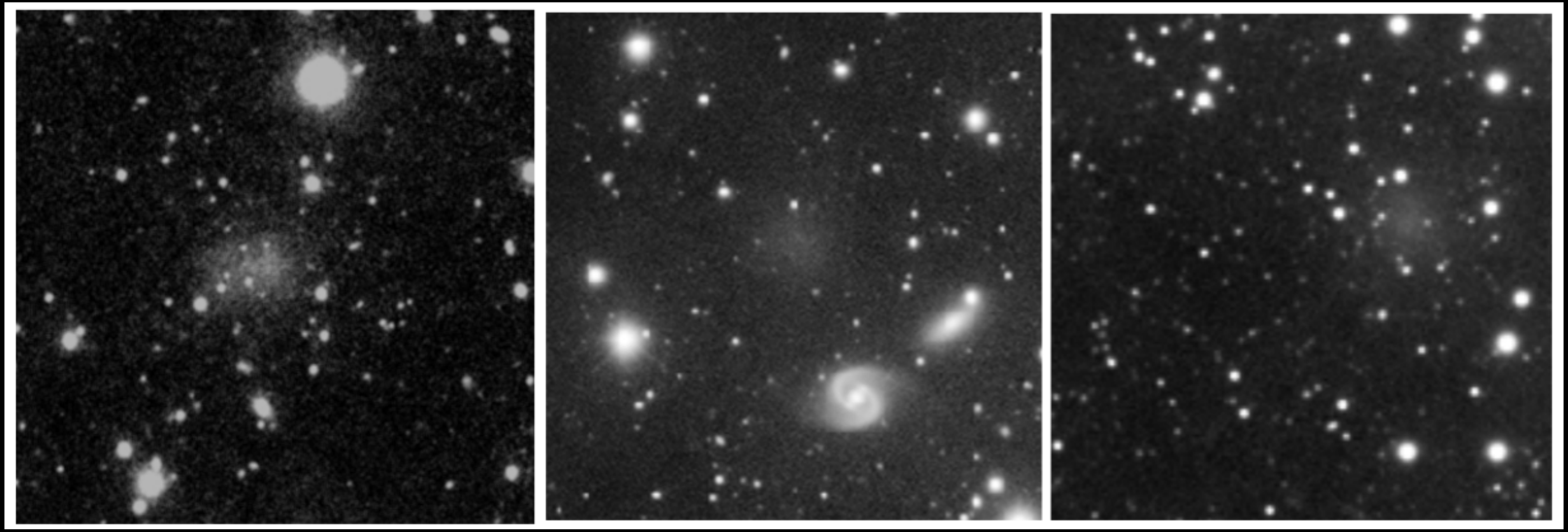
Discovery of ~1000 new galaxies in the Coma cluster



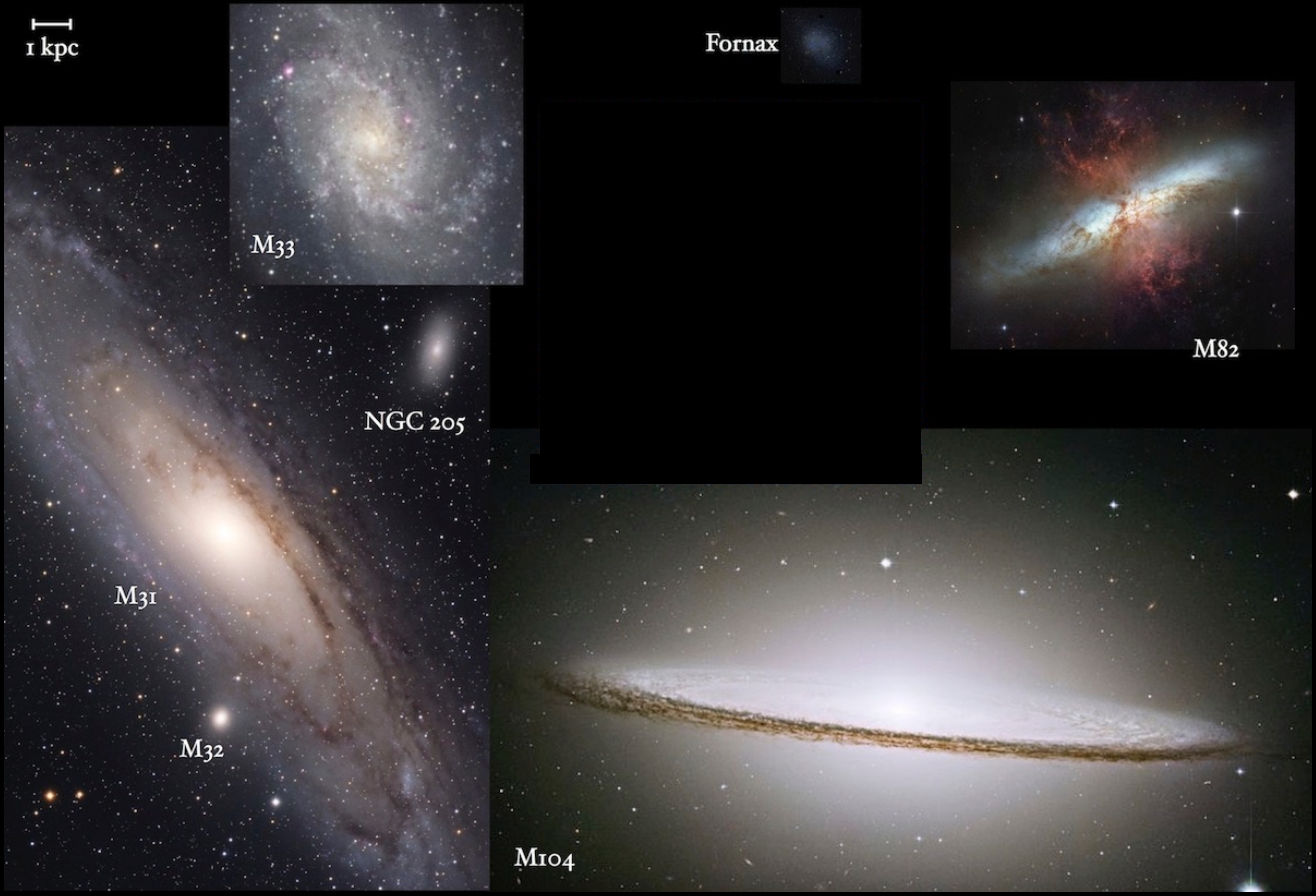
Koda *et al.* (2015)

A new population of hitherto unknown galaxies
ultra-diffuse galaxies

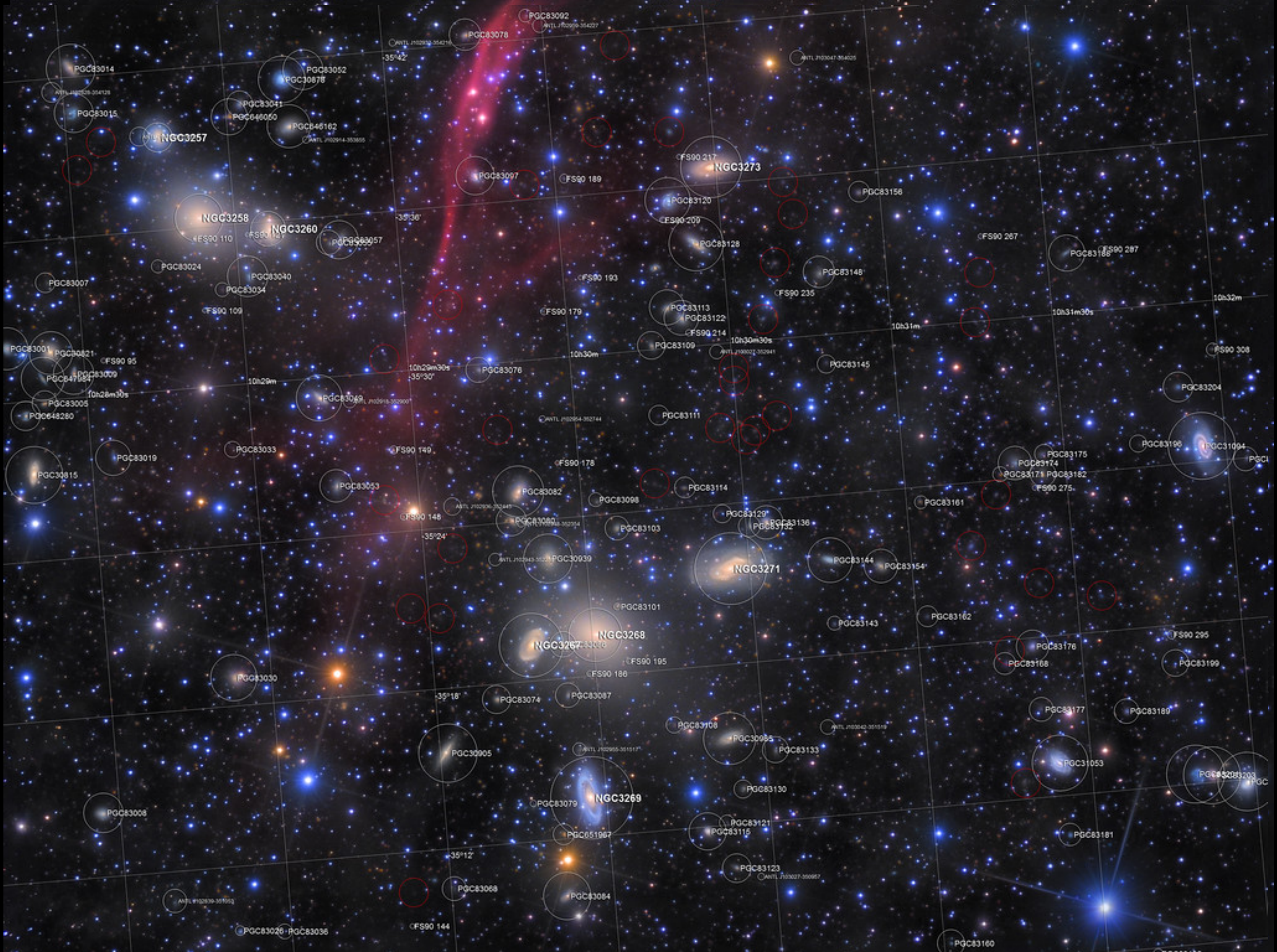
Virgo cluster | Perseus-Pisces filament



Merritt *et al.* (2014) | Martinez Delgado *et al.* (2016)

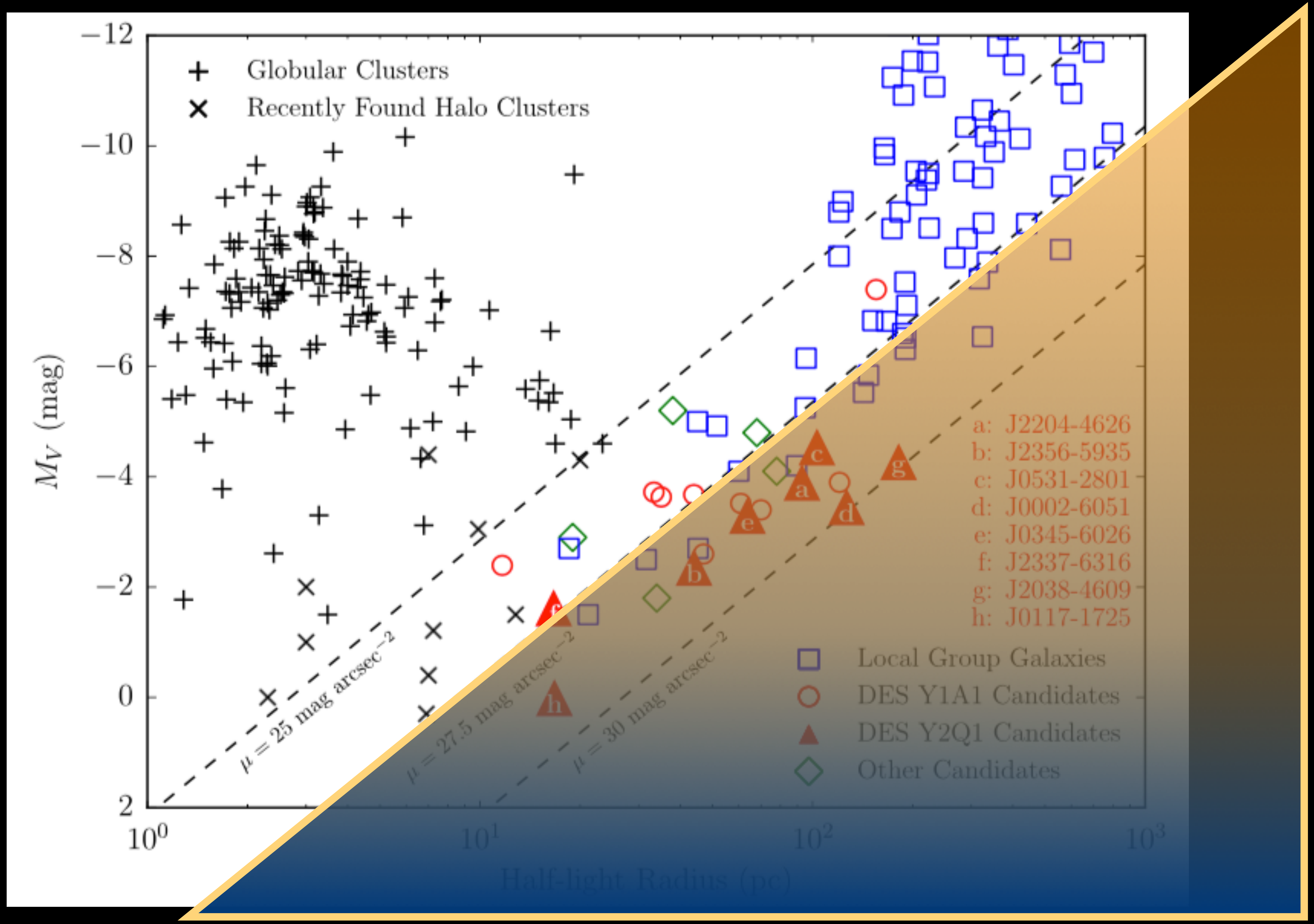


S. Danieli

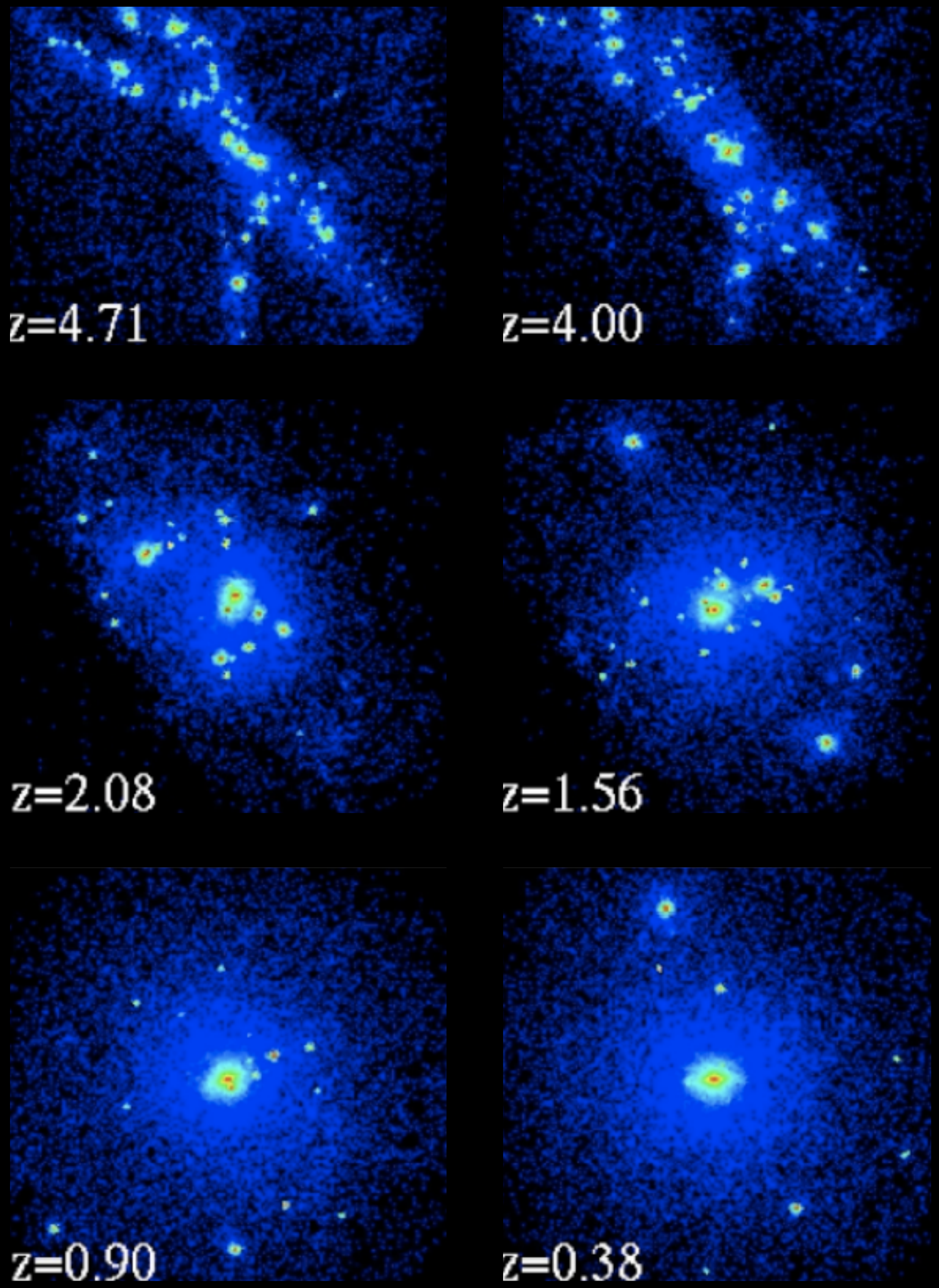


PGC83092
PGC83078
-35°42'
PGC83014
PGC83052
PGC30878
PGC83041
PGC646050
PGC83015
PGC646162
NGC3257
FS90 217
NGC3273
PGC83097
FS90 189
PGC83120
PGC83156
NGC3258
NGC3260
-35°36'
FS90 110
FS90 209
PGC83057
PGC83128
FS90 267
FS90 287
PGC83024
PGC83040
FS90 193
PGC83148
PGC83007
PGC83034
FS90 235
FS90 109
FS90 179
PGC83113
PGC83122
10h32m
10h31m
10h31m30s
FS90 214
10h30m30s
PGC83109
10h30m
PGC83001
PGC30821
FS90 95
10h29m30s
PGC83076
PGC83145
FS90 308
-35°30'
PGC83009
10h29m
10h28m30s
PGC83005
PGC83049
PGC83204
PGC648280
PGC83111
PGC83033
FS90 149
PGC83019
PGC83196
PGC83175
PGC31094
FS90 178
PGC83174
PGC30815
PGC83171
PGC83182
PGC83053
PGC83082
PGC83114
FS90 275
PGC83098
PGC83161
FS90 148
PGC83129
PGC83136
PGC83103
-35°24'
PGC30939
NGC3271
PGC83144
PGC83154
PGC83101
PGC83143
PGC83162
NGC3268
NGC3267
FS90 296
PGC83176
FS90 195
PGC83168
PGC83199
PGC83030
FS90 186
-35°18'
PGC83074
PGC83087
PGC83177
PGC83189
PGC83108
PGC30905
PGC83133
PGC31053
PGC83130
PGC83008
PGC83079
NGC3269
PGC83121
PGC651967
PGC83115
PGC83181
-35°12'
PGC83123
PGC83068
PGC83084
FS90 144
PGC83026
PGC83036
PGC83160

Driving science case #1
The complete inventory of galaxies (without surface brightness bias)

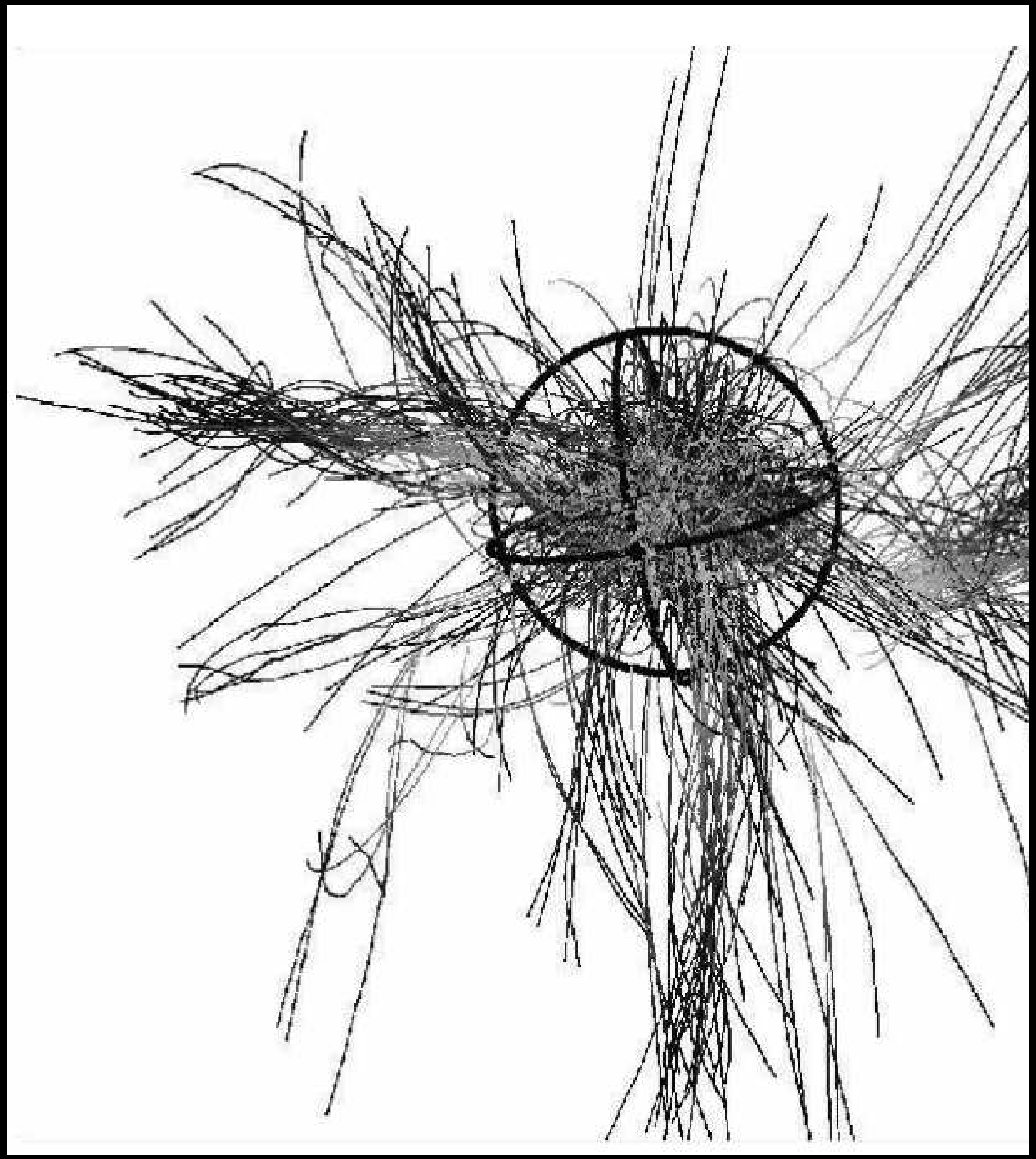


Drlica-Wagner *et al.* (2015)



Formation histories of galactic haloes

Anisotropic accretion from filaments



Driving science case #2

The Cosmic Web

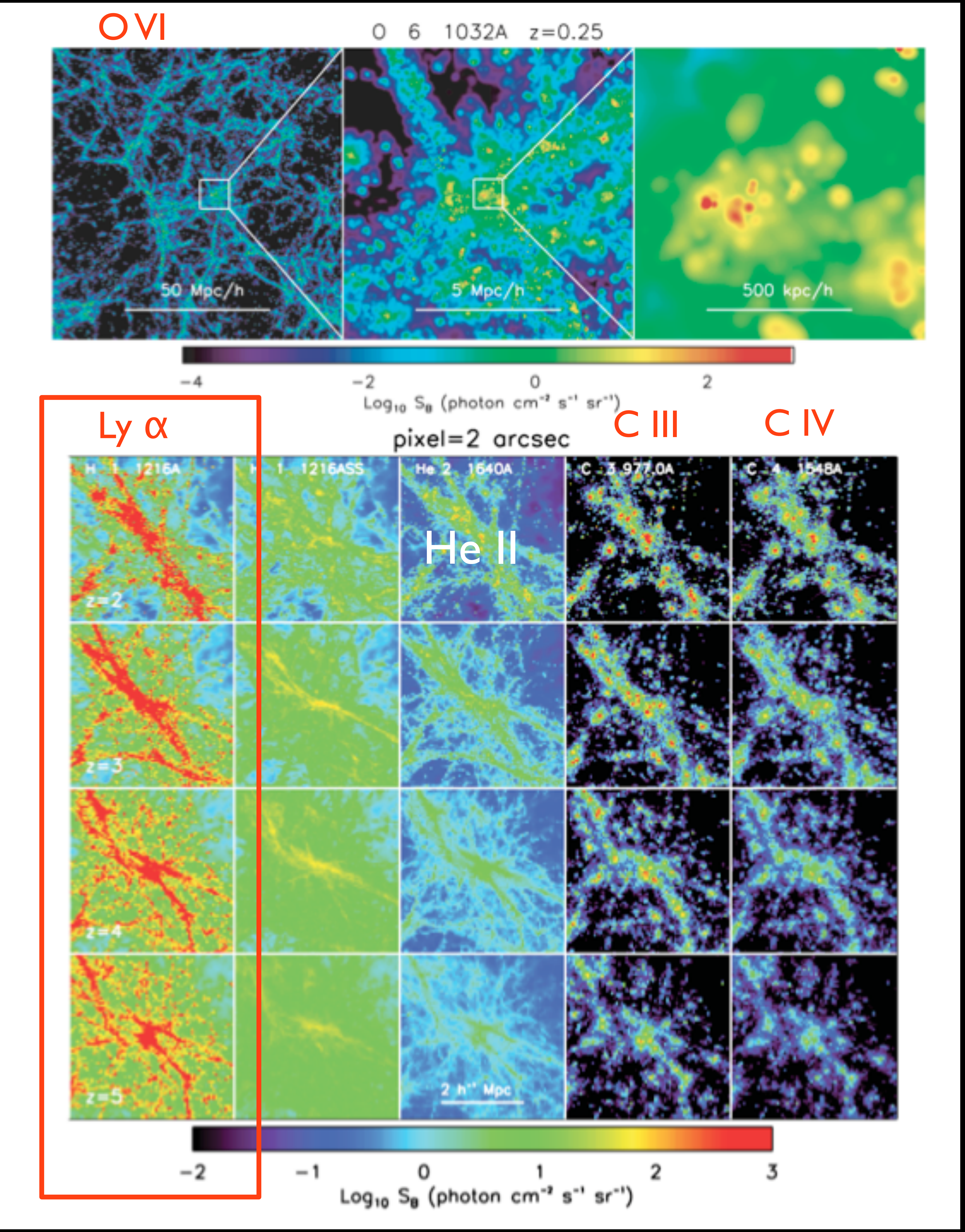
Strongest in Lyman α by >1000 x

The case for low z observations :

(i) stronger filaments

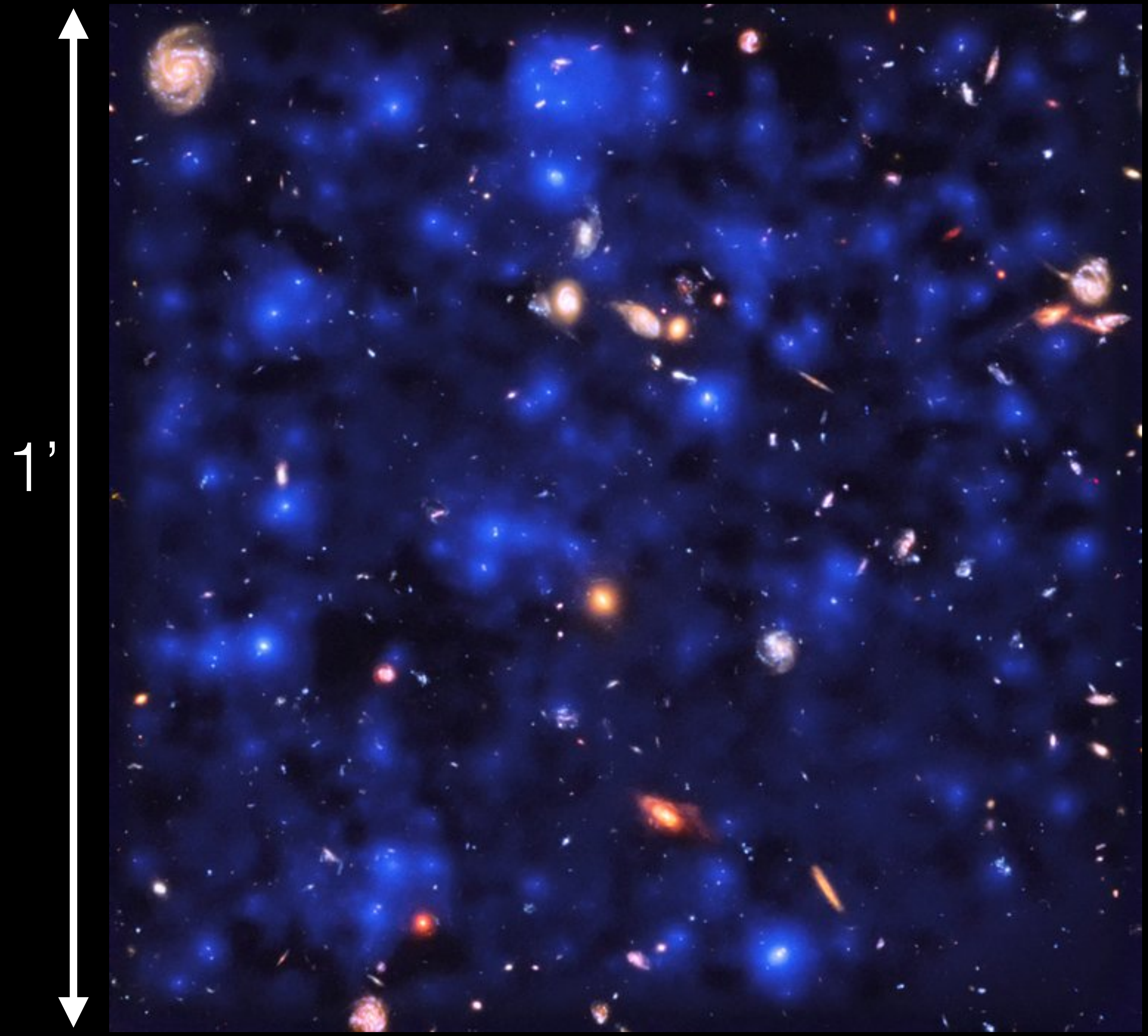
(ii) minimise cosmological dimming ~ $(1+z)^4$

(iii) efficient UV detectors



Bertone + Schaye (2012)

The MUSE Hubble Deep Field



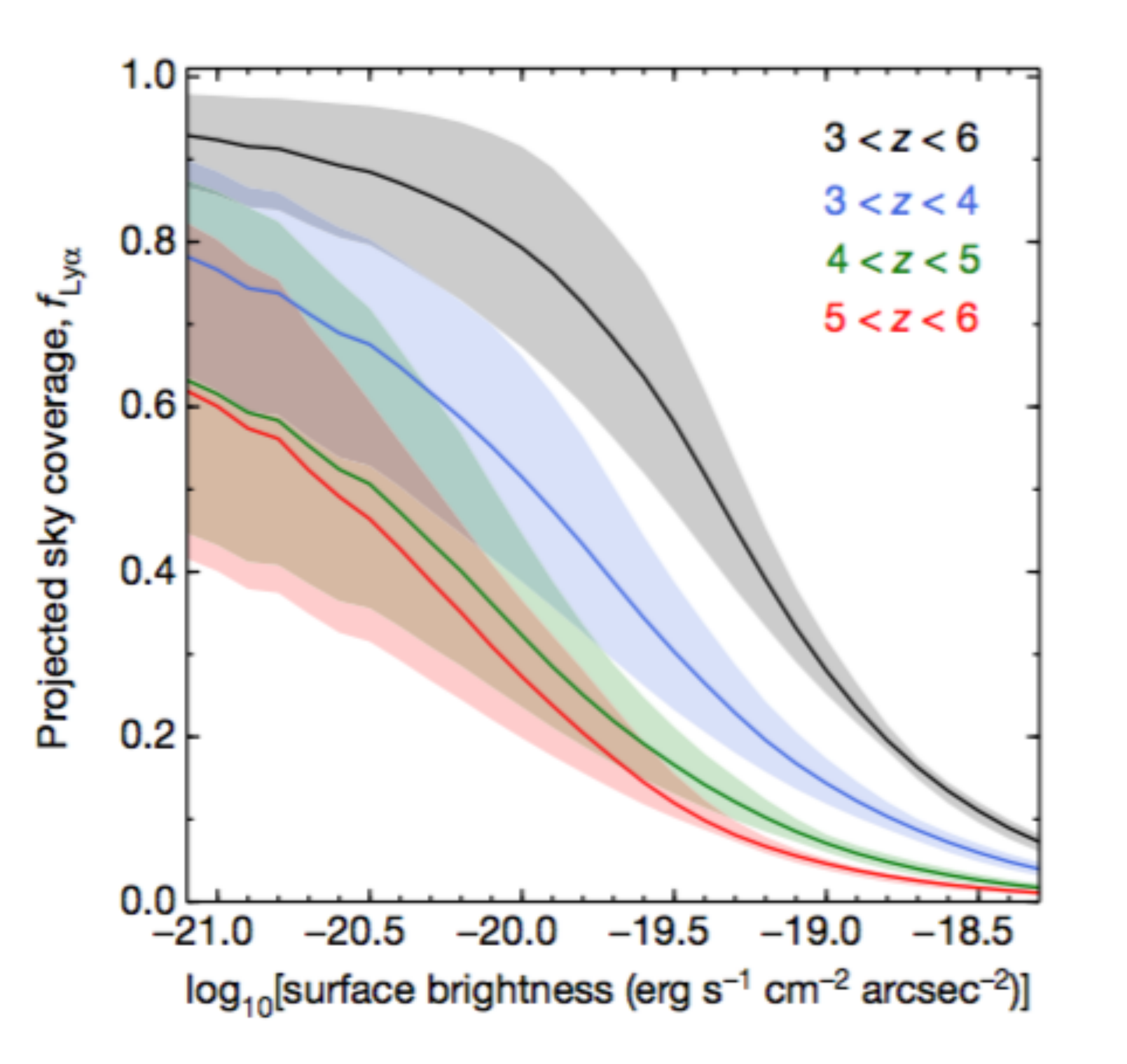
$S(\mathrm{Ly}\alpha) > 10^{-19}$ erg s^{-1} cm^{-2} arcsec^{-2}

LETTER

https://doi.org/10.1038/s41586-018-0564-6

Nearly all the sky is covered by Lyman-α emission around high-redshift galaxies

L. Wisotzki[1]*, R. Bacon[2], J. Brinchmann[3,4], S. Cantalupo[5], P. Richter[6], J. Schaye[3], K. B. Schmidt[1], T. Urrutia[1], P. M. Weilbacher[1], M. Akhlaghi[3], N. Bouché[7], T. Contini[7], B. Guiderdoni[2], E. C. Herenz[8], H. Inami[2], J. Kerutt[1], F. Leclercq[2], R. A. Marino[5], M. Maseda[3], A. Monreal-Ibero[9,10], T. Nanayakkara[3], J. Richard[2], R. Saust[1], M. Steinmetz[1] & M. Wendt[1,6]



Wisotski *et al.* (2018)

The future of ultra-low surface brightness imaging

Large telescopes (LSST, GMT, TMT, ELT)

- ✗ not optimal *f/D* + lens correctors
- ✗ complex, extended, anisotropic PSF
- ✗ high pressure (TAC)

Small telescopes (Super Dragonfly, Huntsm

- ✔ massive array of telephoto lenses
- ✗ low efficiency (Moon, weather)

Fundamental limits

- ✗ the sky is (very) bright and highly varia
- ✗ high PSF wings due to scattering by atr
- ✗ straylight contamination amplifies surfa
- ✗ limits to the flat-field accuracy

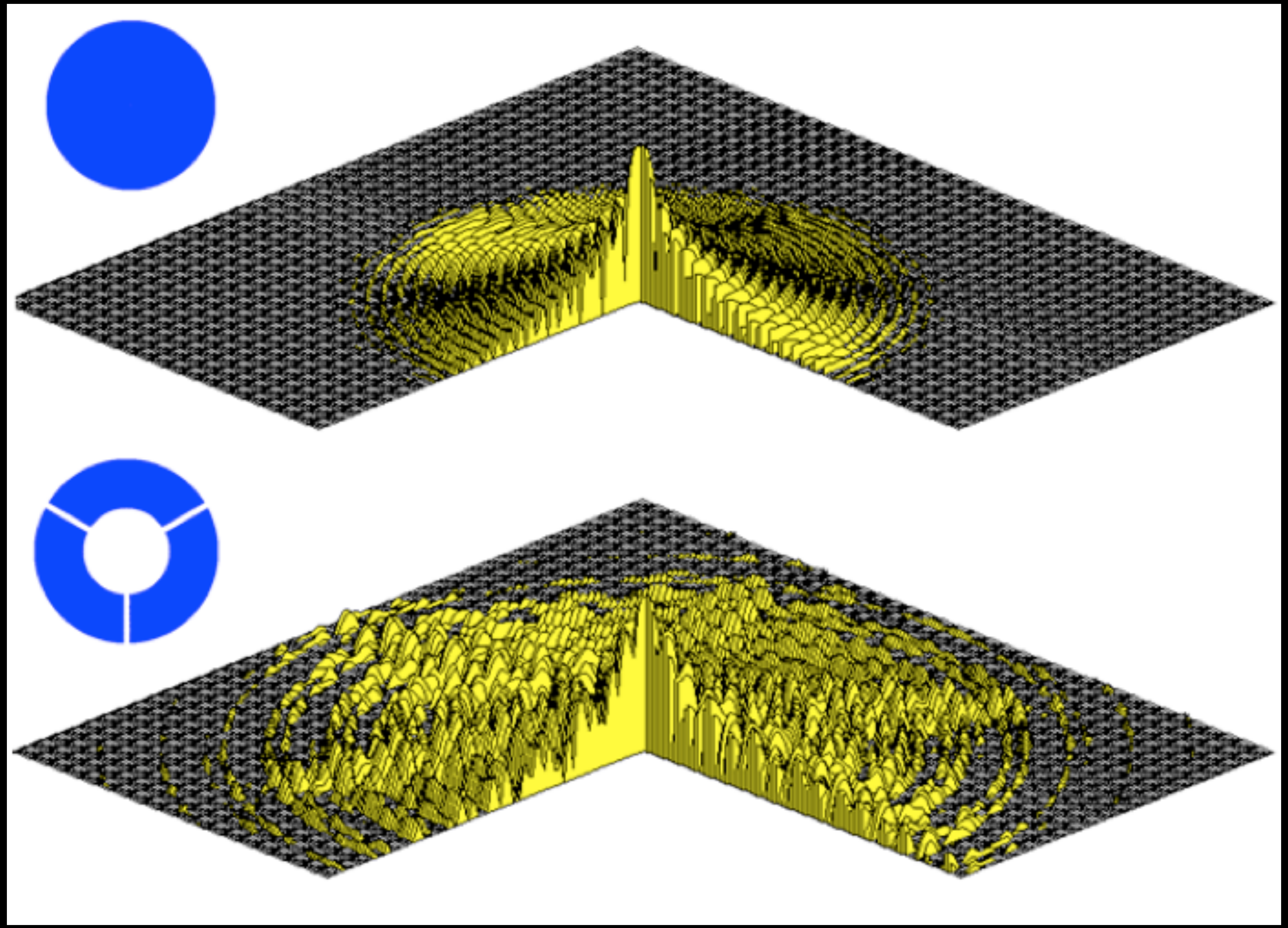
The (obvious) solution:

a space observatory with a purpose-built telescope

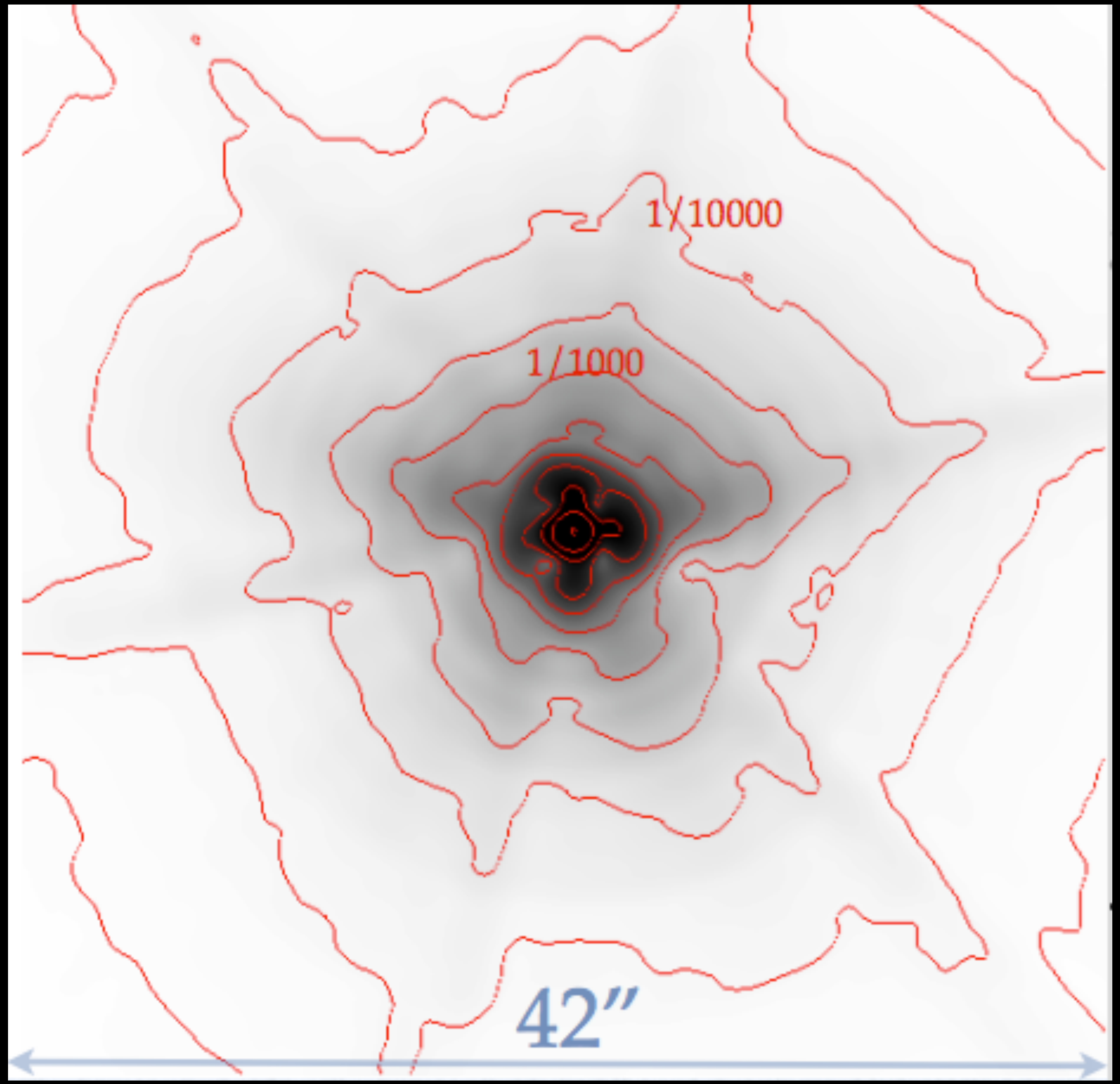
Top-level design requirements

• FOV	2° x 4°	*(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 to 150 cm	*(set by platform)*
• Survey	all sky	*(unique)*

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



LSST

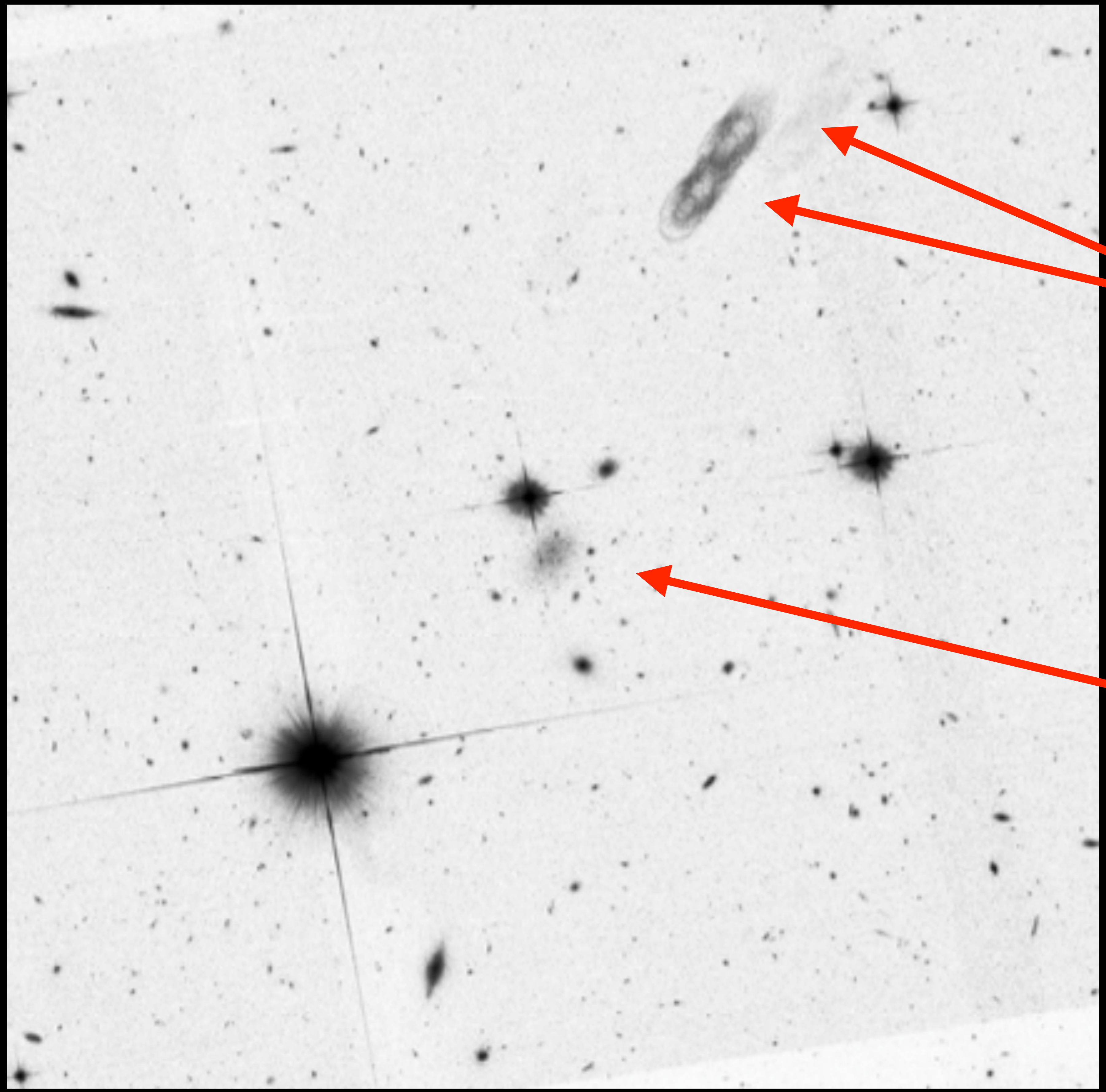


EUCLID

NO LENSES ALLOWED

(1) multiple internal scattering

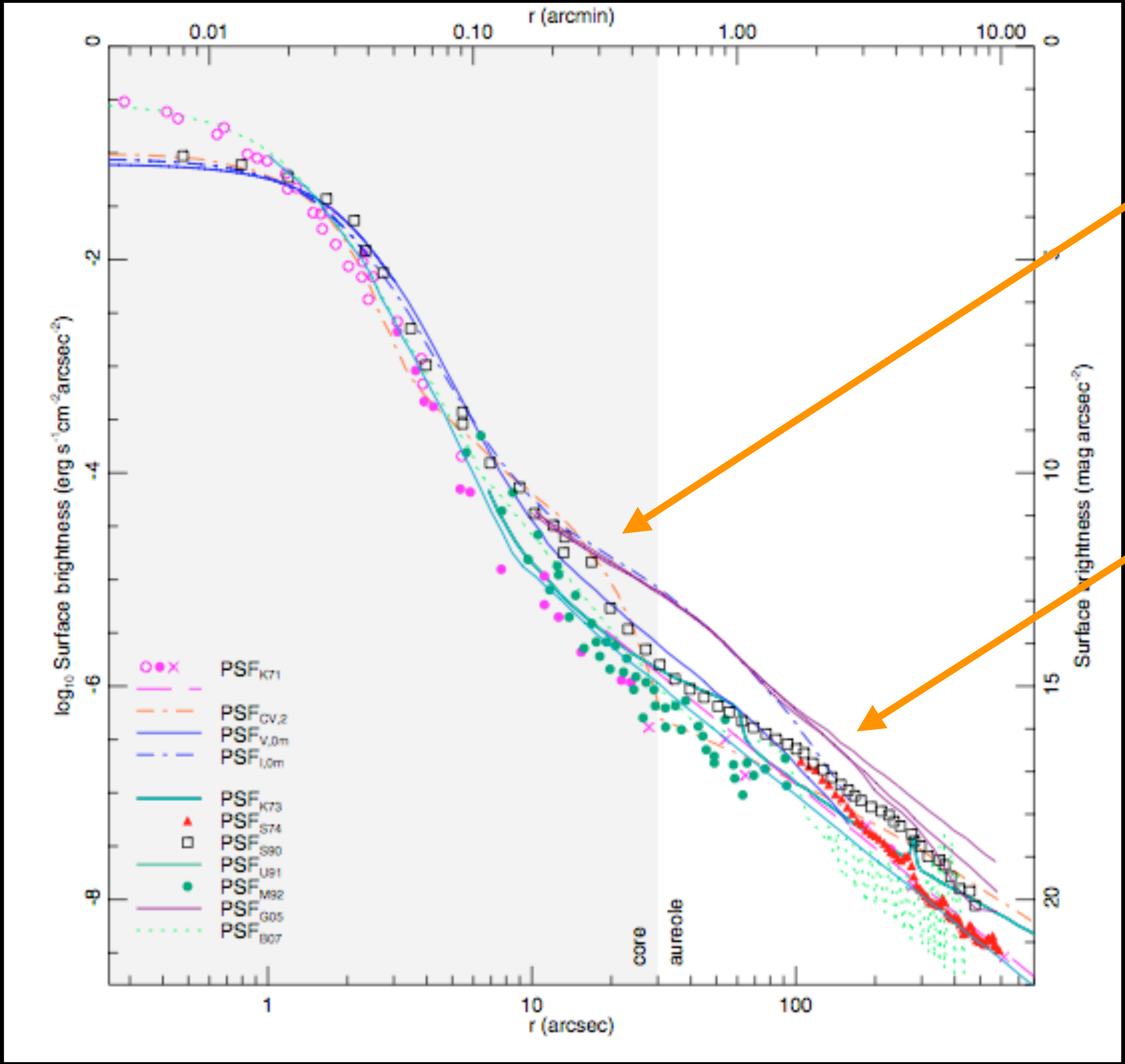
(2) Čerenkov emission



GHOSTS produced by ACS/HST

New ultra-diffuse galaxy (2019)
师冬冬 & 郑宪忠老师
Shi Dongdong & Zheng Xiangzhong

ACS



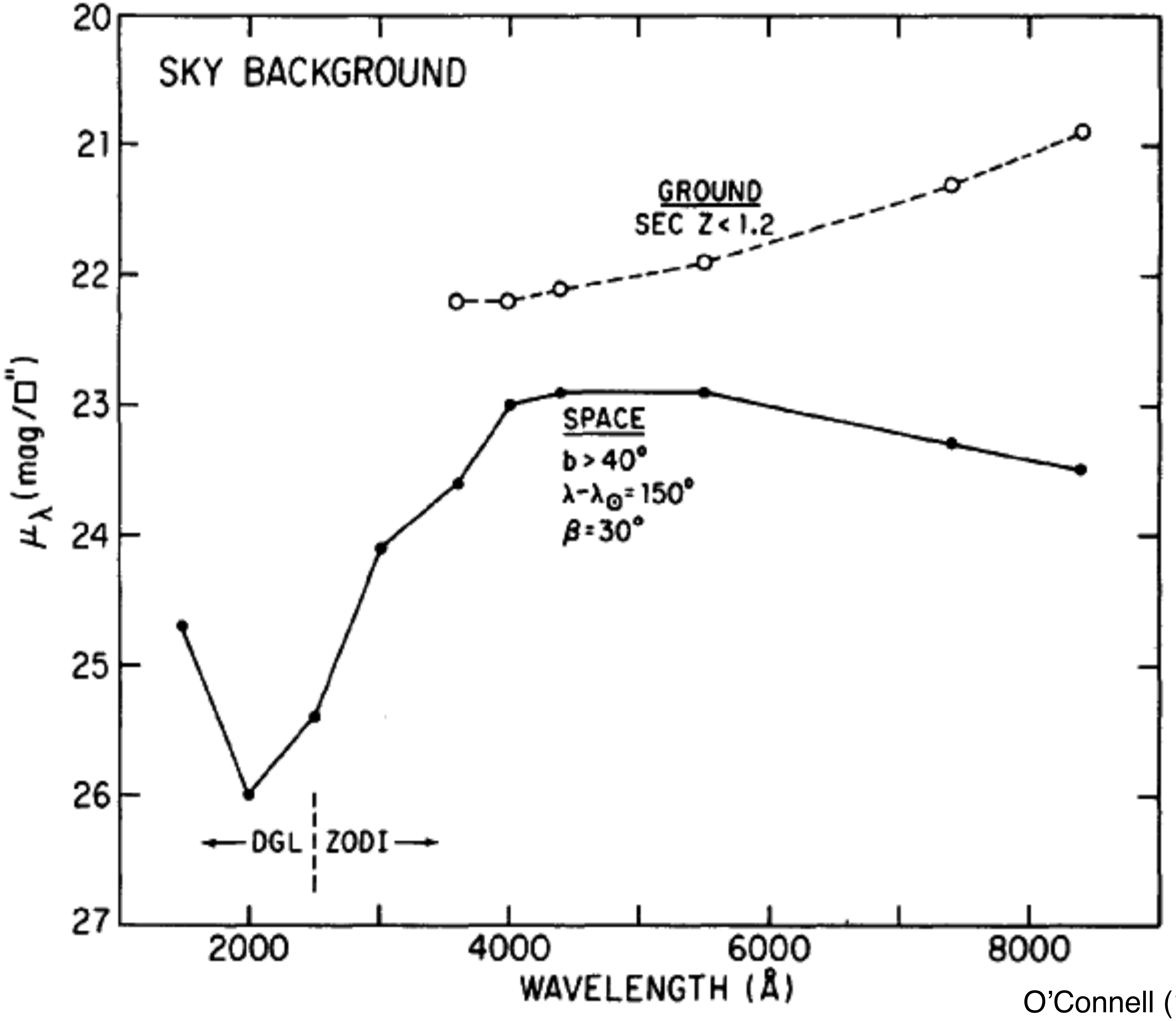
Internal scattering in optics
(prime focus corrector, filters)

+

Scattering by
atmospheric molecules

Major limitations
for ground-based detections

Sandin (2015)



O'Connell (1986)

Key additional requirement for MESSIER :

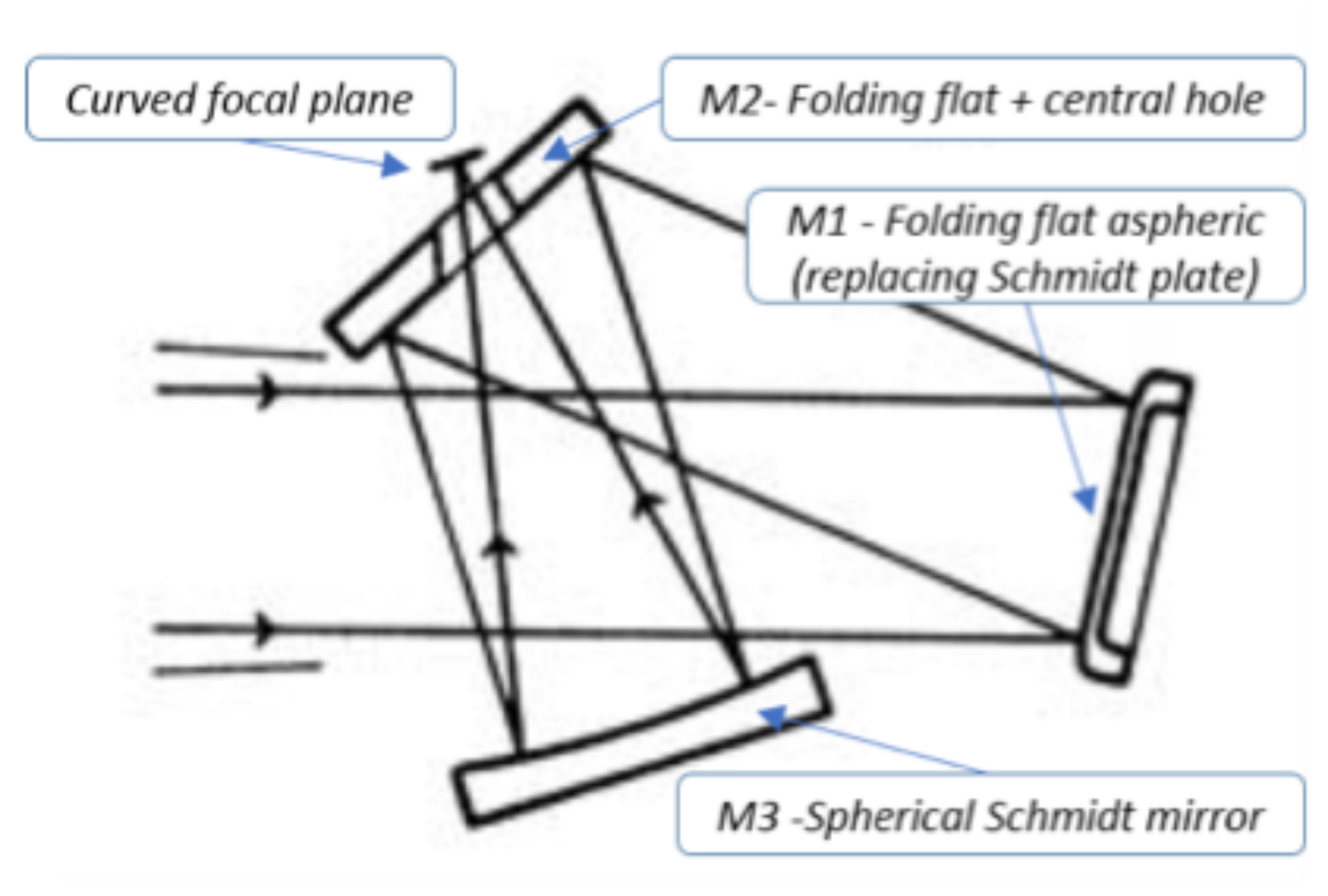
— no lenses (to avoid internal scattering and Čerenkov radiation)

— ~~flat focal plane~~

Optimal off-axis mirror-only solution

curved focal surface
tiled with curved CCDs

Space Surveillance Telescope
by MIT for DARPA ($75M)
(but huge obscuration by M2)



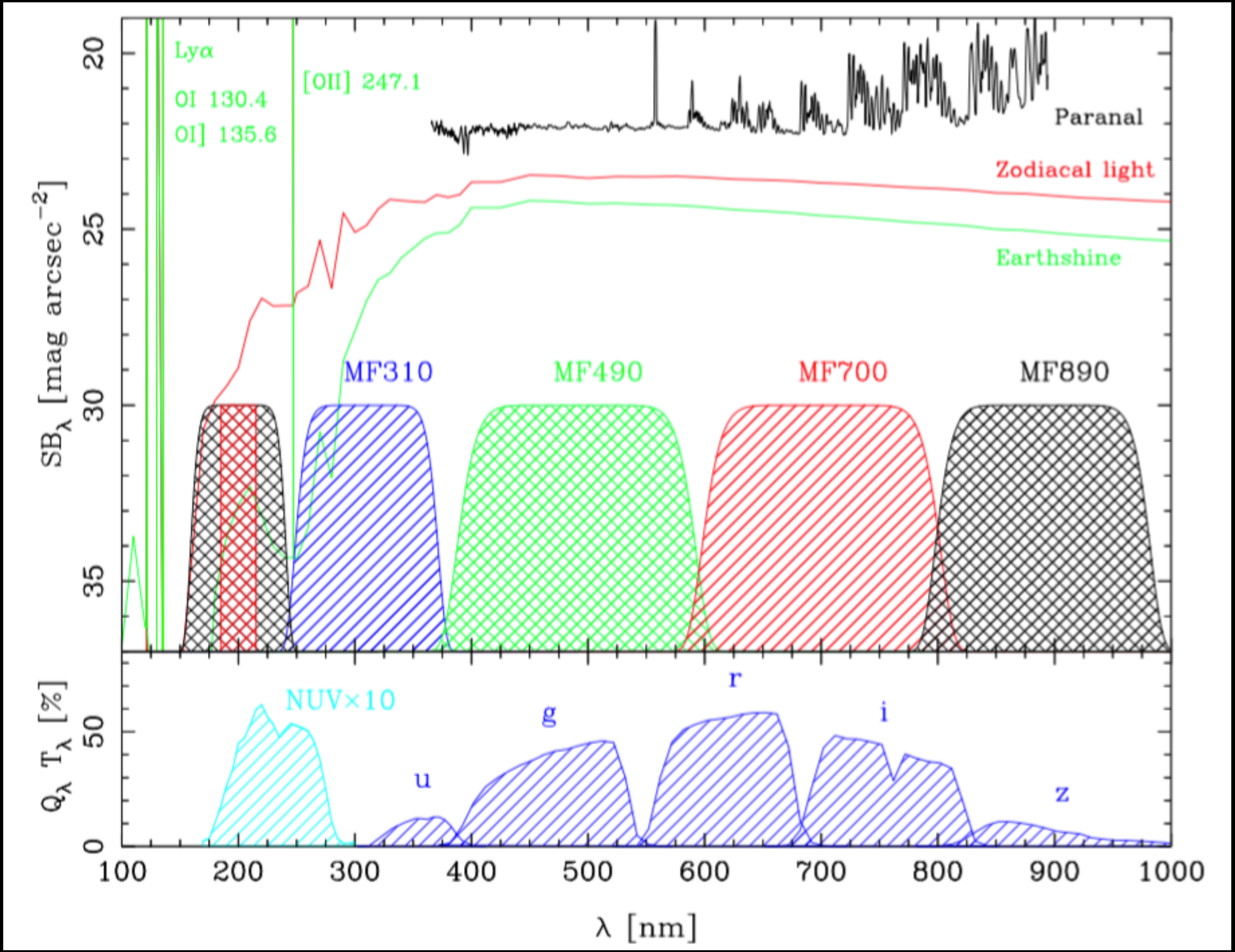
Muslimov, Valls-Gabaud, Lemaître *et al.* (2017)

TWO DISRUPTIVE BREAKTHROUGHS : Off-axis purely reflective Schmidt
Curved CCDs

Requirements for filters

Broad filters :
characterise SEDs of stellar populations

Narrow + broad filters :
Lyman-α intensity mapping

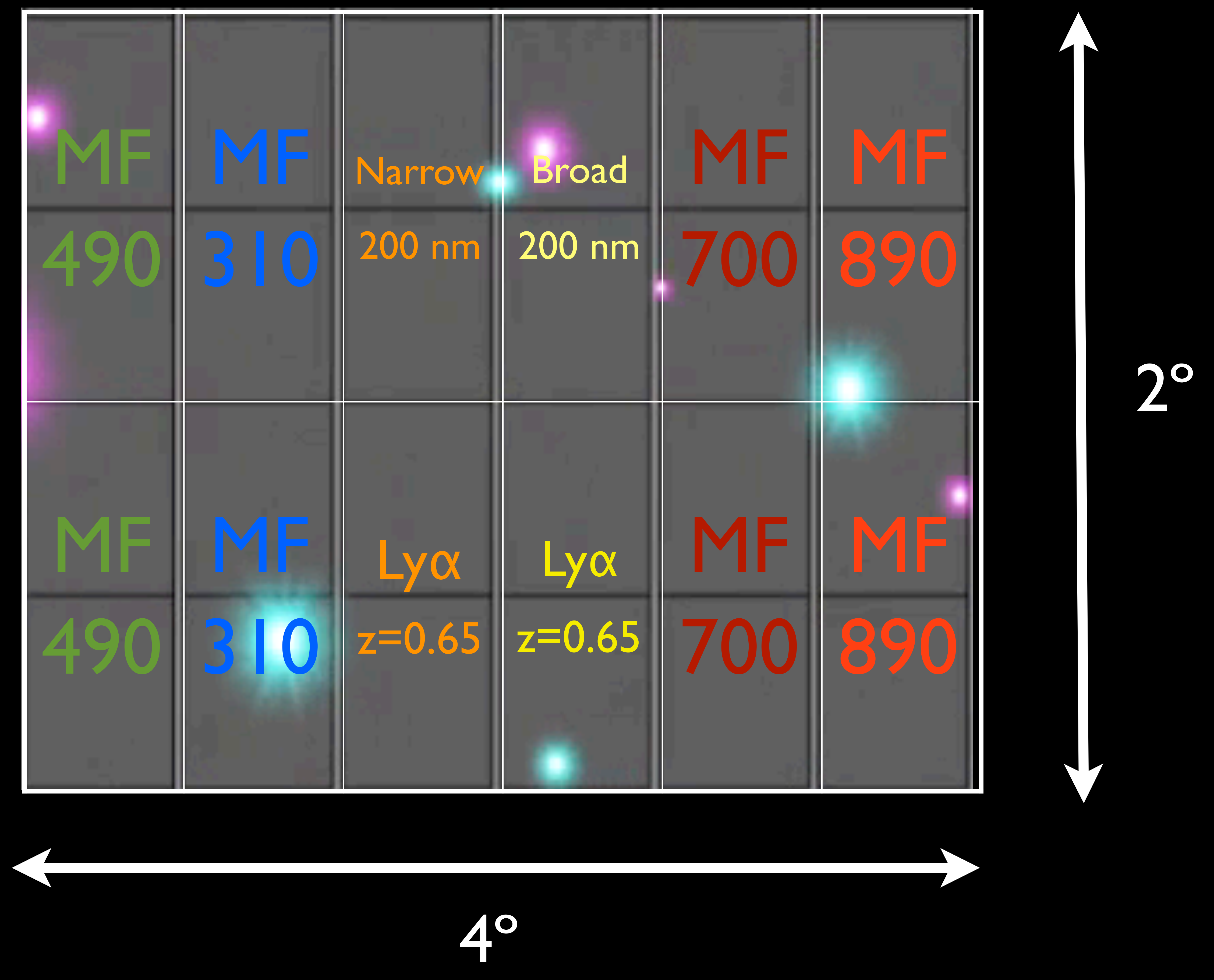


Curved focal surface configuration

6 x 2 independent controllers in drift-scan mode, coatings as filters

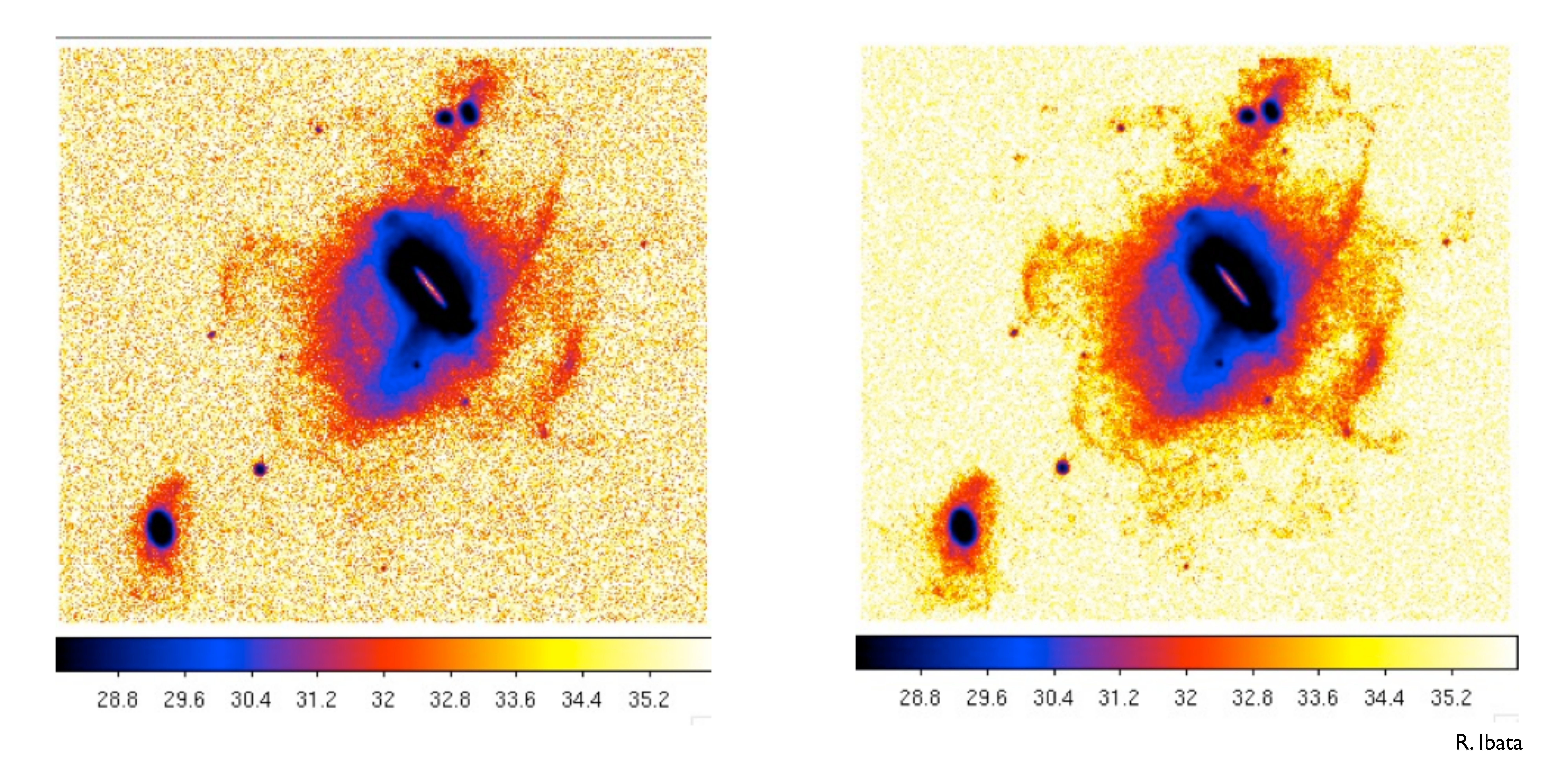
QE of each curved CCD optimised for each filter (TQ>85%)

Highly efficient: *no moving parts, passive cooling*



Expected performances - I Optical bands

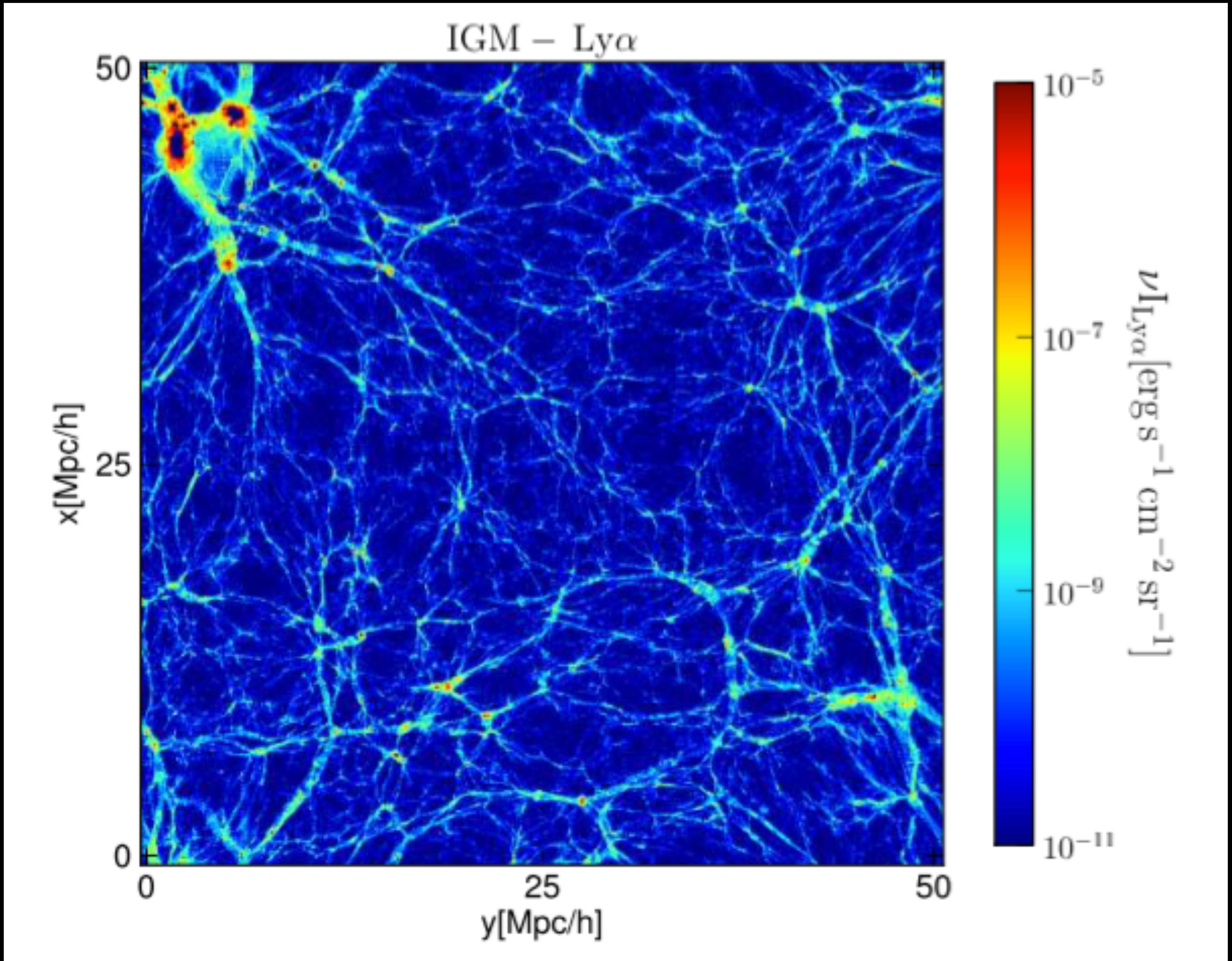
Simulated MESSIER images of a real galaxy (M31) seen at 150 Mpc



1 Msec

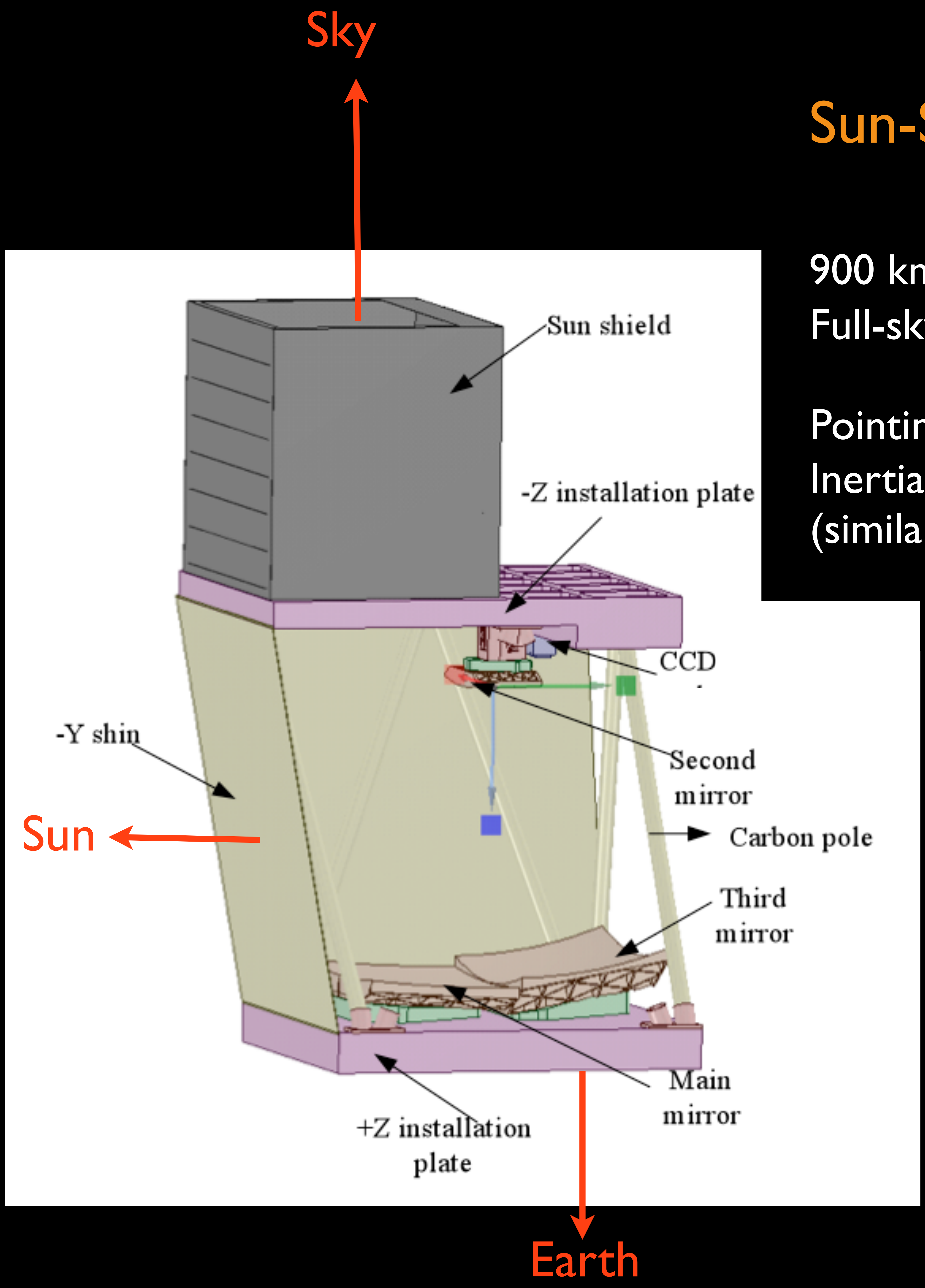
10 Msec

Expected performances - II   UV bands



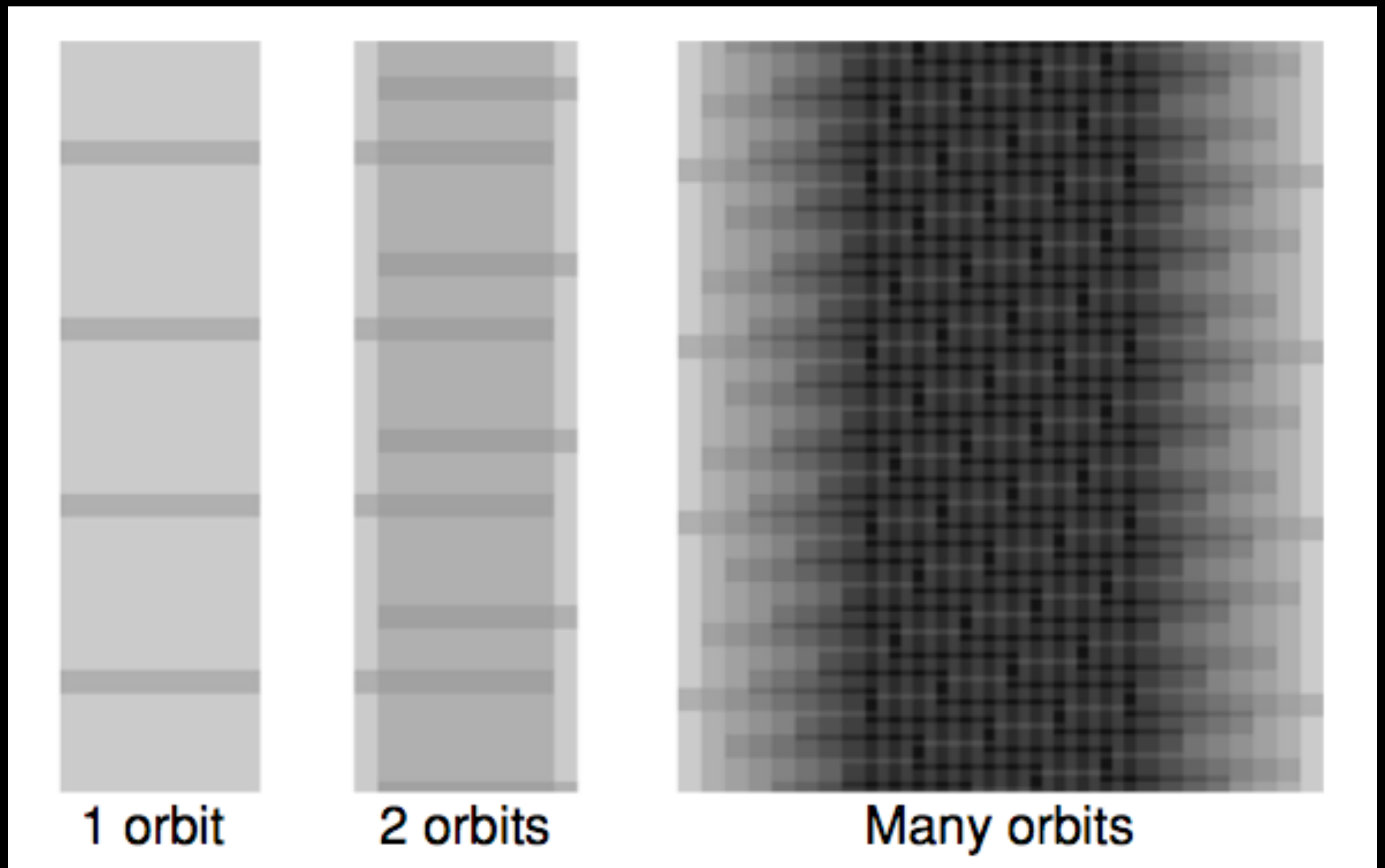
Credit: J. Fonseca & M. Silva / F. van de Voort & J Schaye

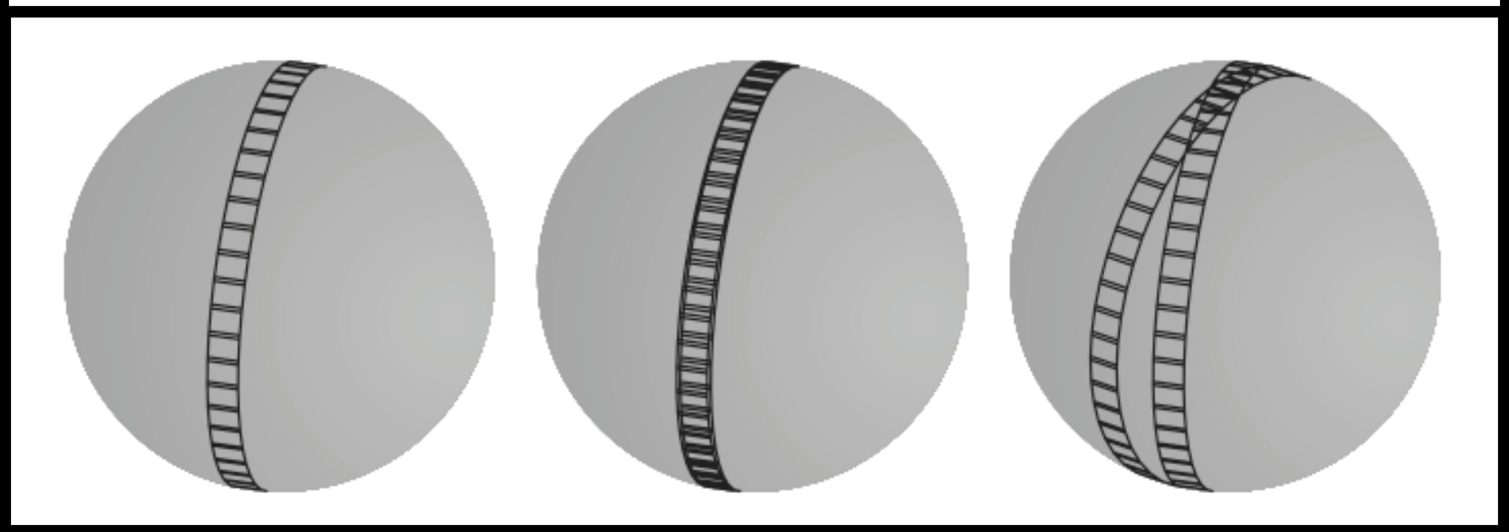
Sun-Synchronous Orbit



900 km, 98° inclination, LTAN 6h
Full-sky survey in 6 months

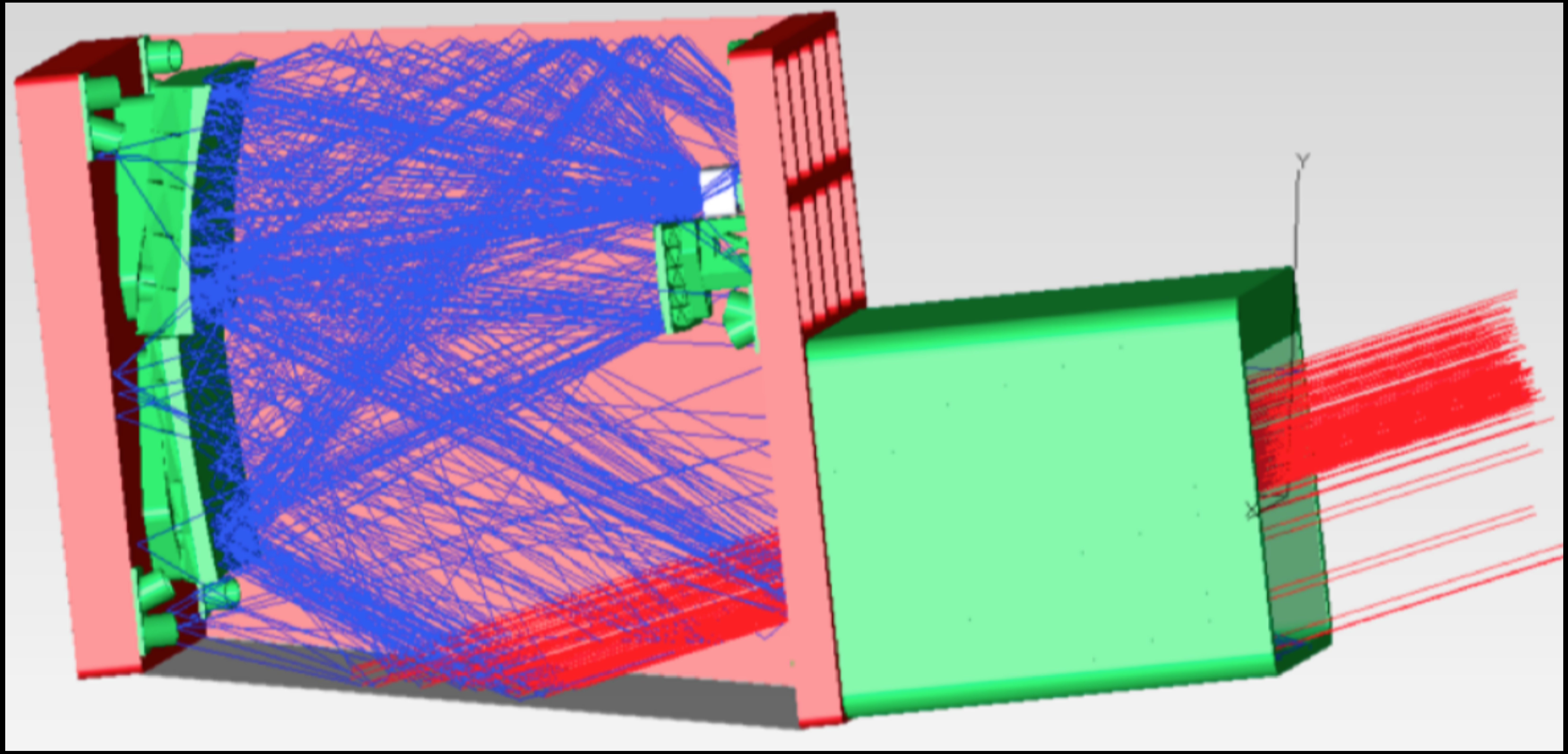
Pointing ⊥ Sun-Earth direction (no Earthshine)
Inertial great-circle drift scan centred at the Sun
(similar to COBE, WISE, PROBA-V)





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



CSC Collateral Science Cases (*free* by-products)

Solar System

- Comet tails, interplanetary and cometary dust grains

Stellar physics

- The extent of mass loss in giant and massive stars
- Debris discs + exozodi (optical/UV scattering by dust grains)
- Nature of orphan SN and GRB
- Time-domain stellar astronomy: simultaneous multi-wavelength variability tidal disruption events, SNIa, GW UV counterparts
- *Legacy*: Ultimate multi-band photometric full-sky survey of point sources

Interstellar medium

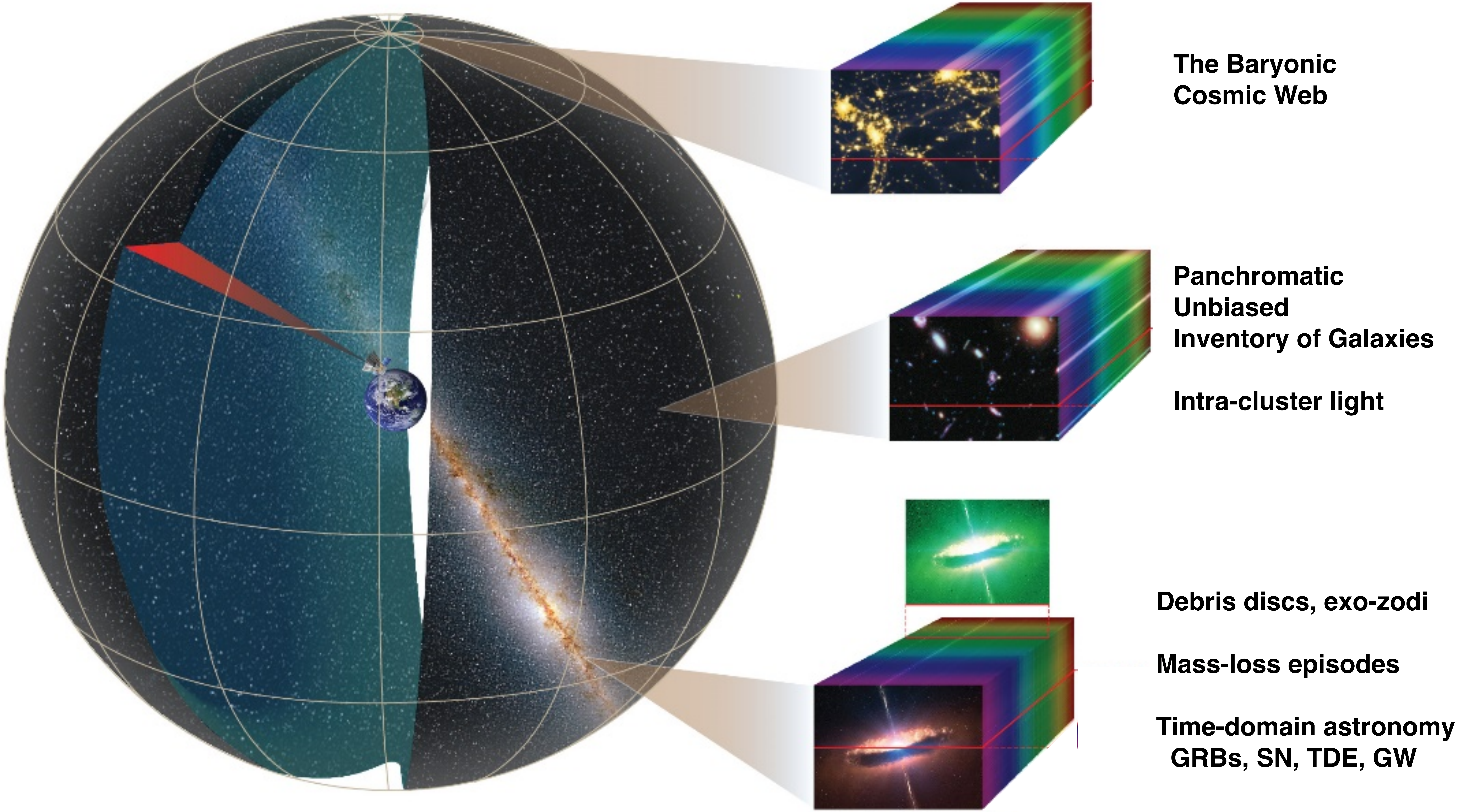
- Properties of interstellar dust grains + Interstellar radiation field

Extragalactic

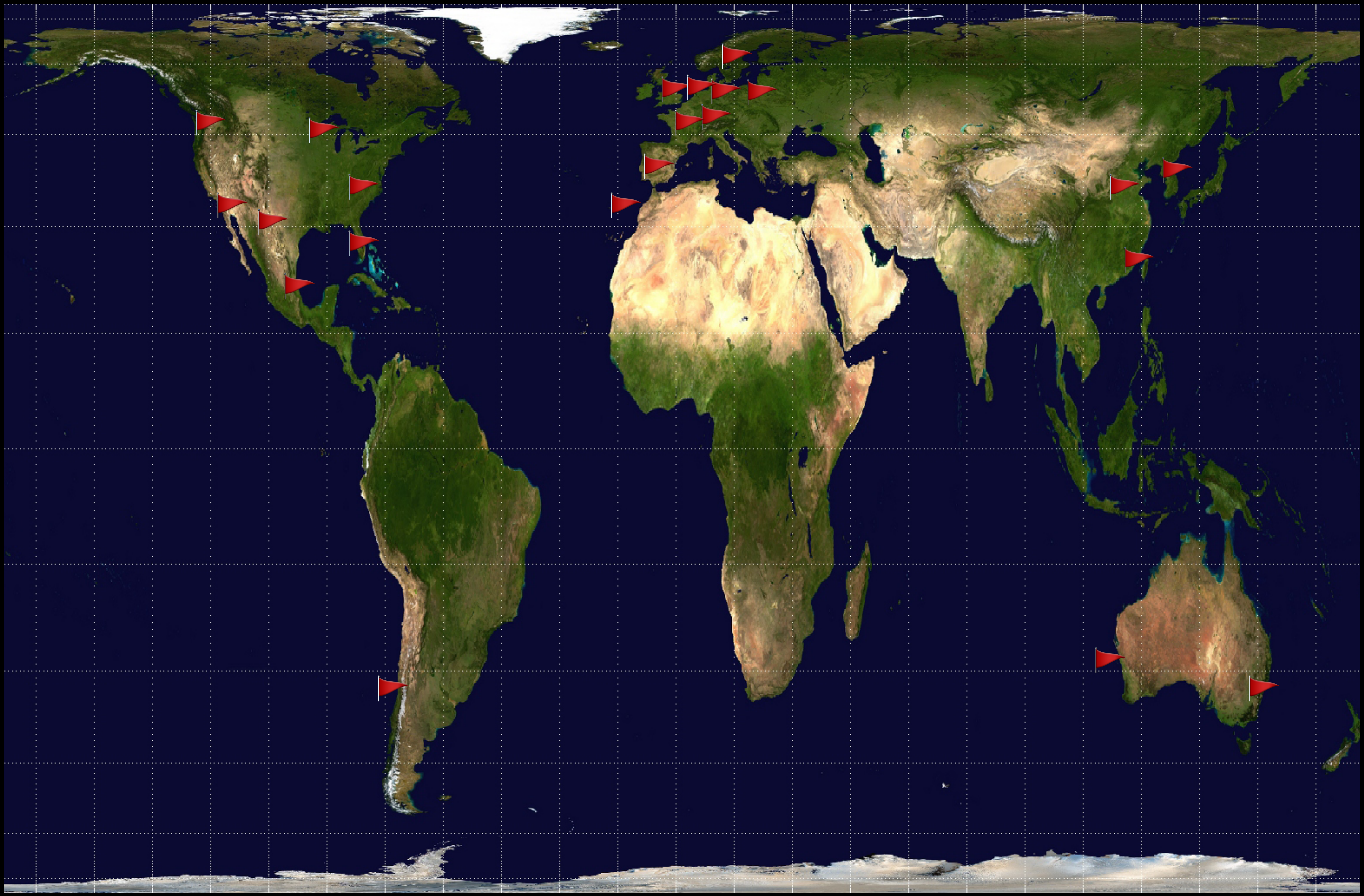
- What is the true luminosity function of galaxies ?
- What is the warm molecular content of galaxies in the low-z universe ?
- What is the role of intracluster light and the accretion history in clusters ?

Cosmology

- The fluctuations of the optical / UV cosmological background radiation
- Calibration of the cosmological distance ladder with Surface Brightness fluctuations
- Baryonic acoustic oscillations with 3 10^6 galaxies in a thin shell at z=0.65


The Baryonic
Cosmic Web
Panchromatic
Unbiased
Inventory of Galaxies
Intra-cluster light
Debris discs, exo-zodi
Mass-loss episodes
Time-domain astronomy
GRBs, SN, TDE, GW

The MESSIER collaboration



THE UNIVERSITY OF ARIZONA

CASE WESTERN RESERVE UNIVERSITY EST. 1826

UF UNIVERSITY of FLORIDA

PONTIFICIA UNIVERSIDAD CATÓLICA DE CHILE

UNAM Universidad Nacional Autónoma de México

UAM Universidad Autónoma de Madrid

UNIVERSIDAD COMPLUTENSE MADRID

UNIVERSITAT DE BARCELONA

INSTITUTO DE ASTROFISICA DE CANARIAS IAC

Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences

JAGIELLONIAN UNIVERSITY IN KRAKÓW

KIAS

KASI Korea Astronomy and Space Science Institute

Universiteit Leiden

university of groningen

Stockholm University

AIP

ZAH ZENTRUM FÜR ASTRONOMIE

NAOC

TEL AVIV UNIVERSITY

THE UNIVERSITY OF SYDNEY

UCL

ROYAL OBSERVATORY EDINBURGH

UNIVERSITY OF CAMBRIDGE

CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

UNIVERSITÉ DE GENÈVE

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

LAM LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

irap astrophysique & planétologie

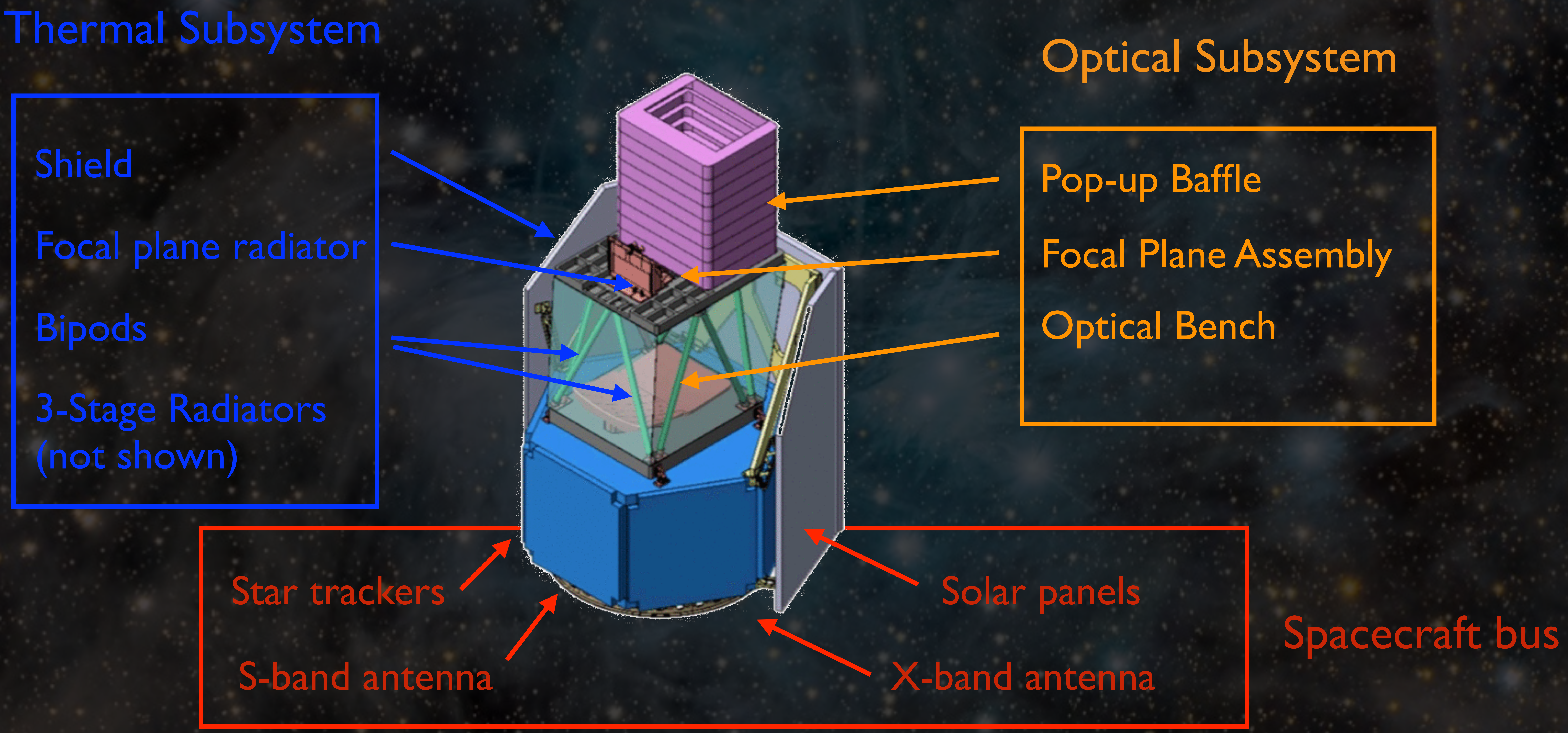
l'Observatoire de Paris

cea SACLAY

IAP

ICRAR

MESSIER Overview of Subsystems



Designs by two competing industrial contractors (EADS/CASA & QinetiQ)

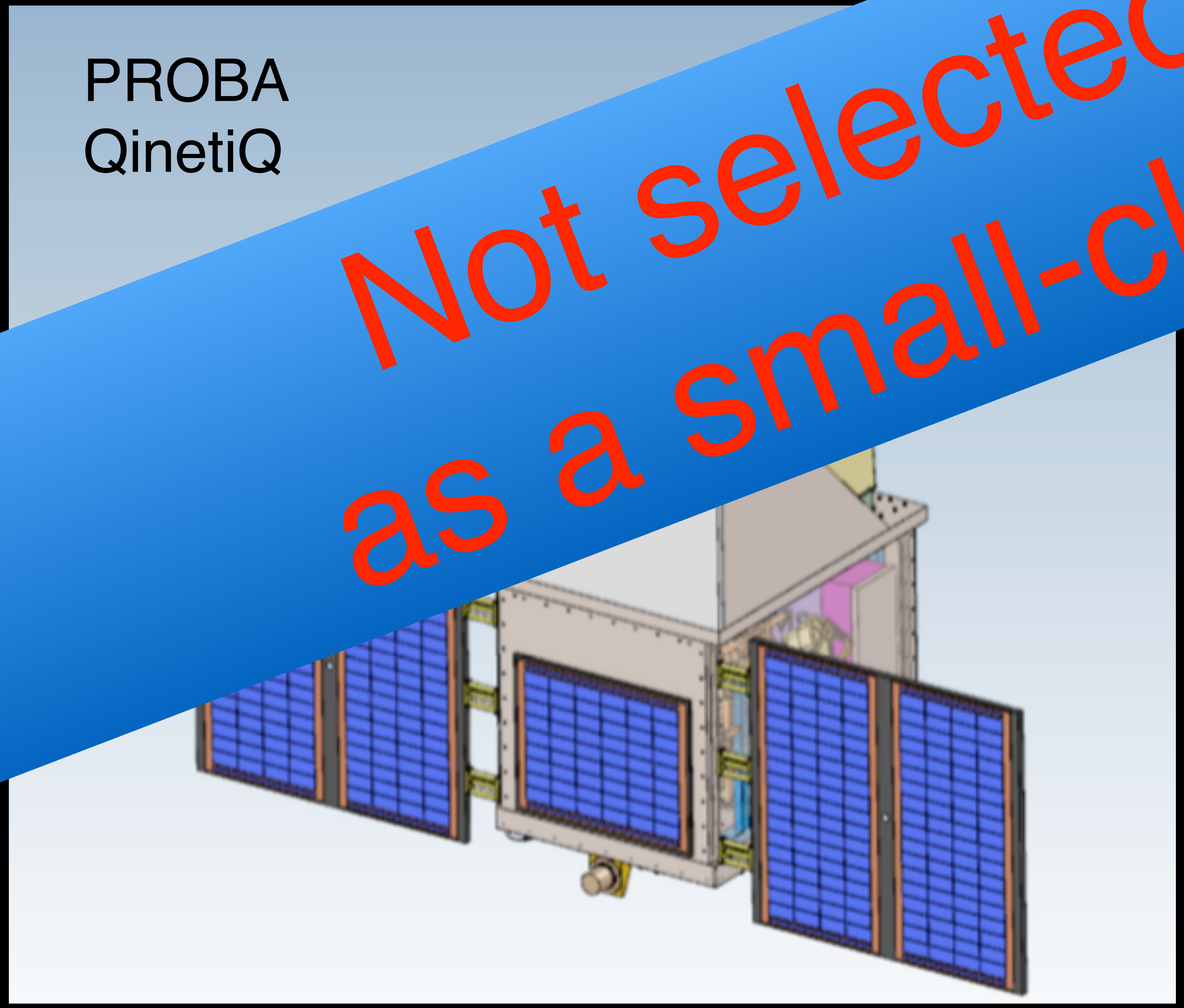
— Platform : heritage from CHEOPS *or* PROBA-V

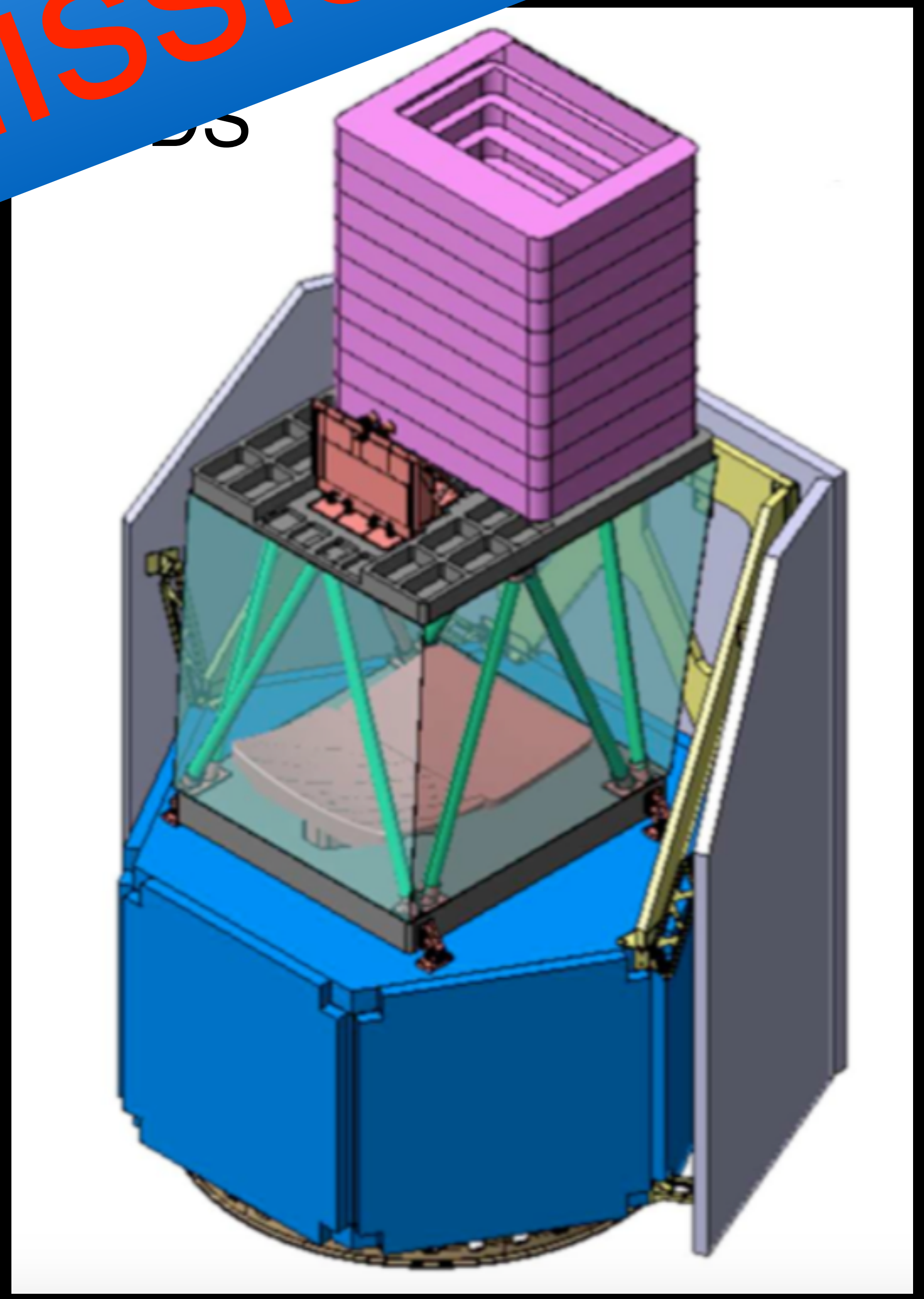
— Payload constraints: 65 kg and 60 W TRL > 6

— Total budget : 120 M€ (cost at completion)

— 150+ scientists in 16 countries

Not selected by ESA as a small-class mission





QinetiQ

AIRBUS DEFENCE & SPACE SENER

Timeline

✔ October 2018 — ESA F(fast) Mission

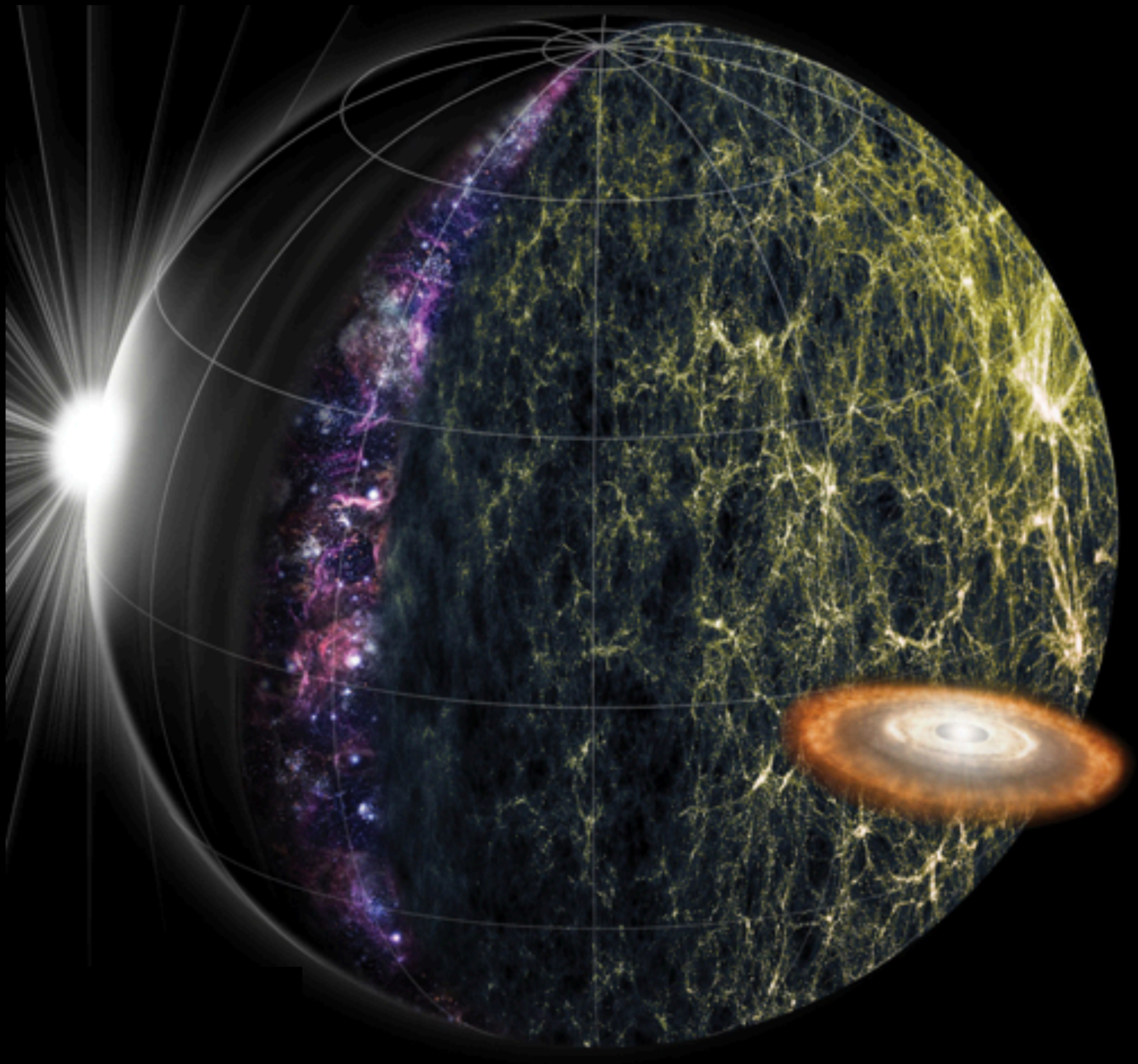
- ESA-led mission
- cost at completion: cap fixed at 150 M€ + free/shared launch
- TRL > 5–6
- contributions by partners (Canada, Korea, China, Australia)
- launch in 2026/28

✔ June 2019 — MESSIER White Book

✔ July 2019 — Astro-2020 Decadal + ESA Voyage 2050

✔ August 2019 — NASA SMEX

MESSIER: An All-Sky Ultra-Low Surface Brightness Survey



Designed for New Science

- The Complete Inventory of Galaxies
- The Baryonic Cosmic Web
- From the Zodiacal Light to the Cosmological Optical/UV backgrounds

The First All-Sky Optical-UV LSB Survey

A Unique Legacy Archive for the Astronomy Community with 100s of Millions of Stars and Galaxies

Low-Risk Implementation

- Single Observing Mode
- No Moving Parts
- Passive Cooling


IAU Symposium 355
The Realm of the Low Surface Brightness Universe
Tenerife
8 –12 July 2019
http://www.iac.es/congreso/iaus355

ESA Voyage 2050 White Paper call

Workshop: 14 June 2019

Observatoire de Paris

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