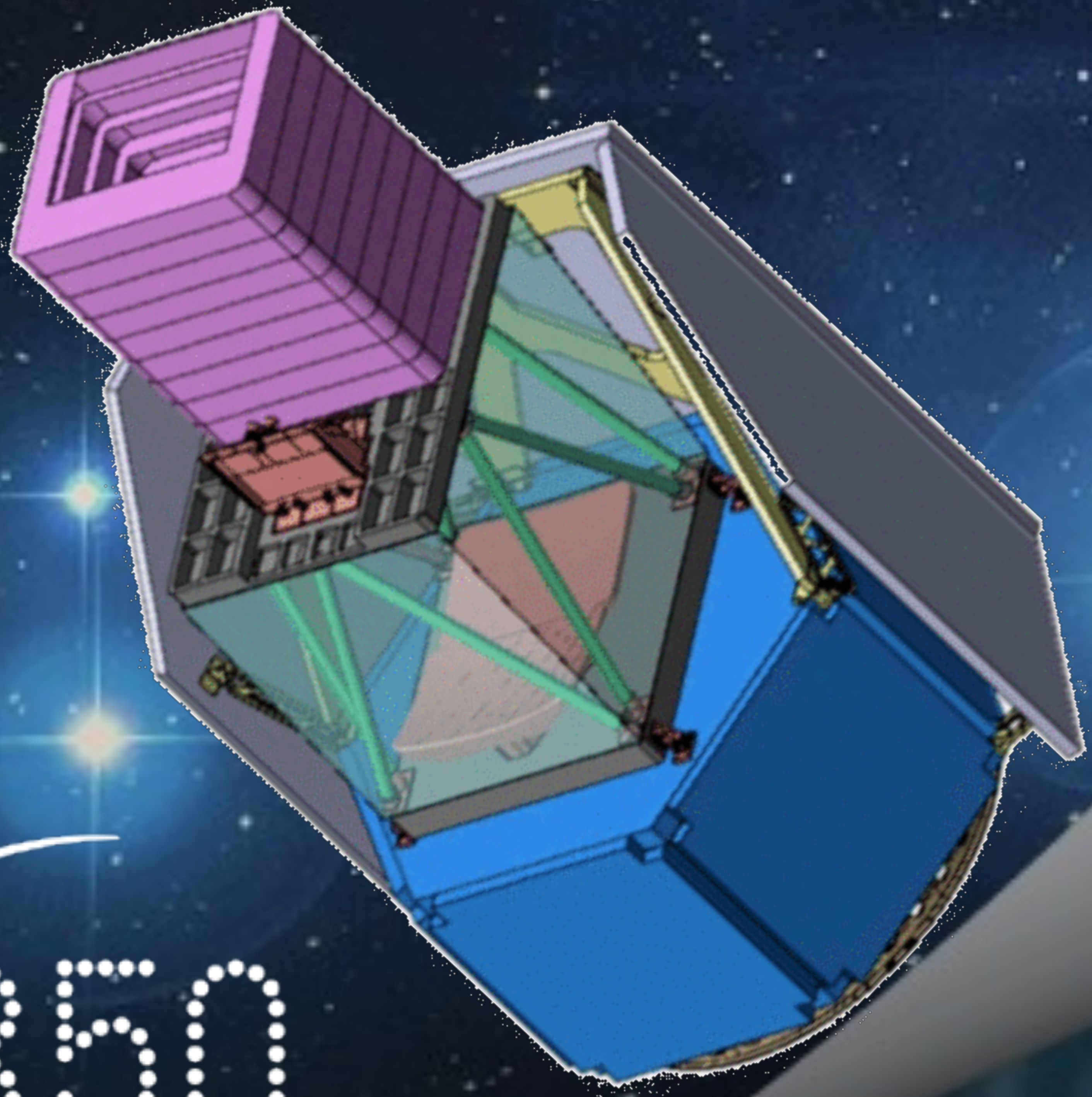
Darkness revealed

The ultra-low surface brightness universe

(including optical /UV transients)

THE MESSIER SURVEYOR



David Valls-Gabaud

CNRS - Observatoire de Paris
Churchill College, University of Cambridge

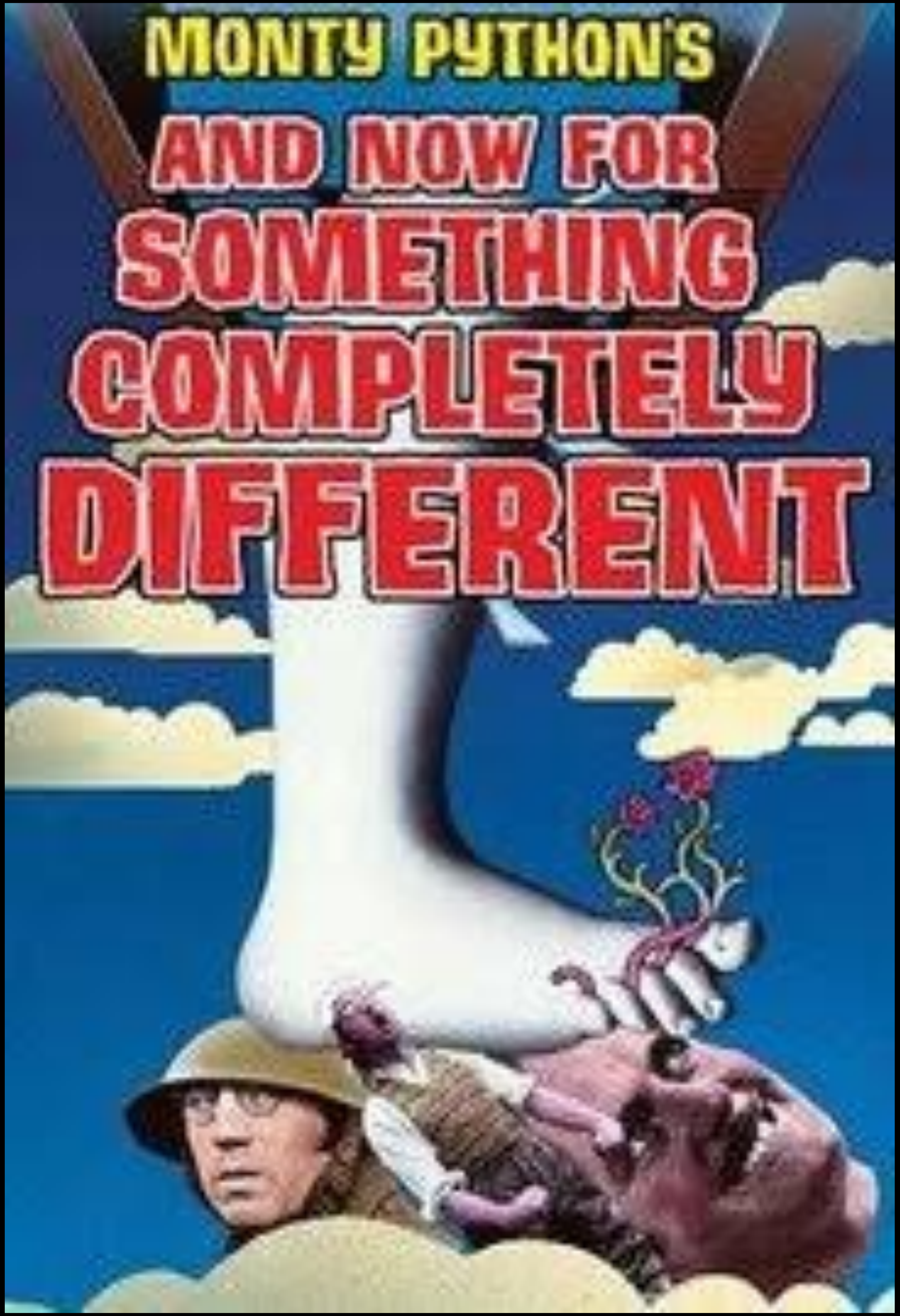
350 ans 1667-2017

l'Observatoire de Paris

CHURCHILL COLLEGE CAMBRIDGE

cnrs

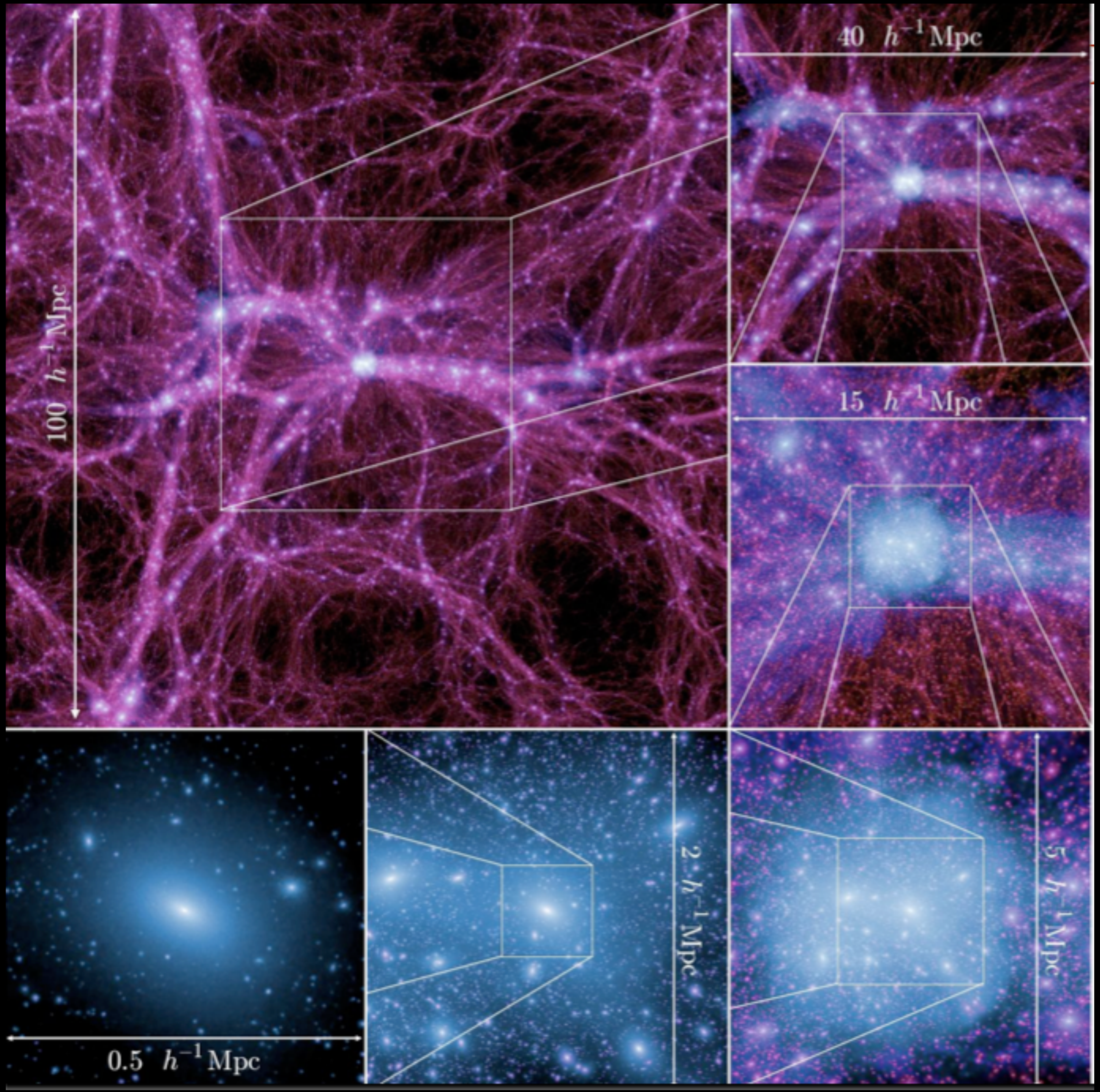
First Meeting of LIA ERIDANUS


MONTY PYTHON'S
AND NOW FOR
SOMETHING
COMPLETELY
DIFFERENT

Current ΛCDM paradigm of cosmological structure formation

linear
&
weakly nonlinear
scales

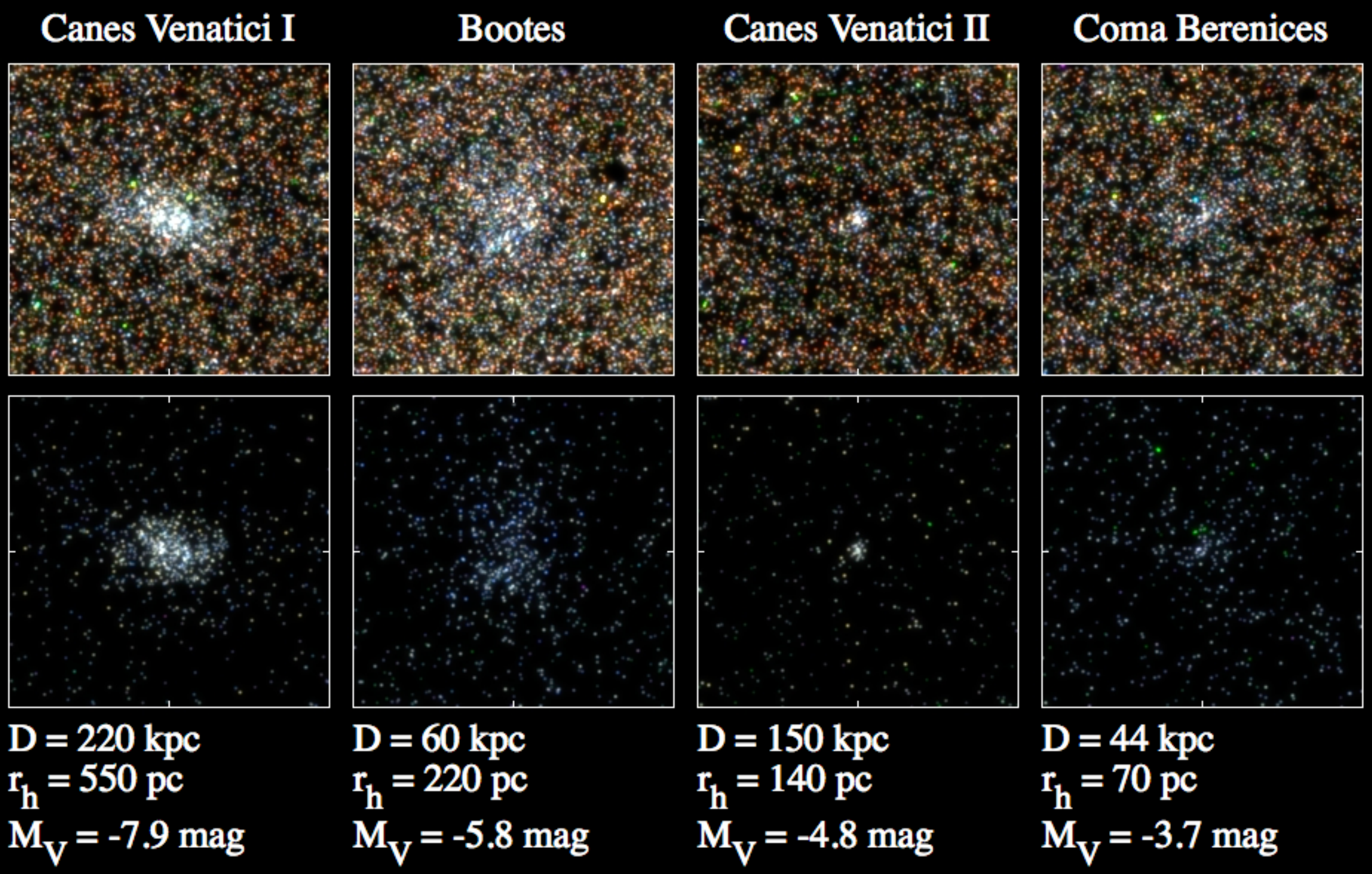
highly
nonlinear



Boylan-Kolchin *et al.* (2009)

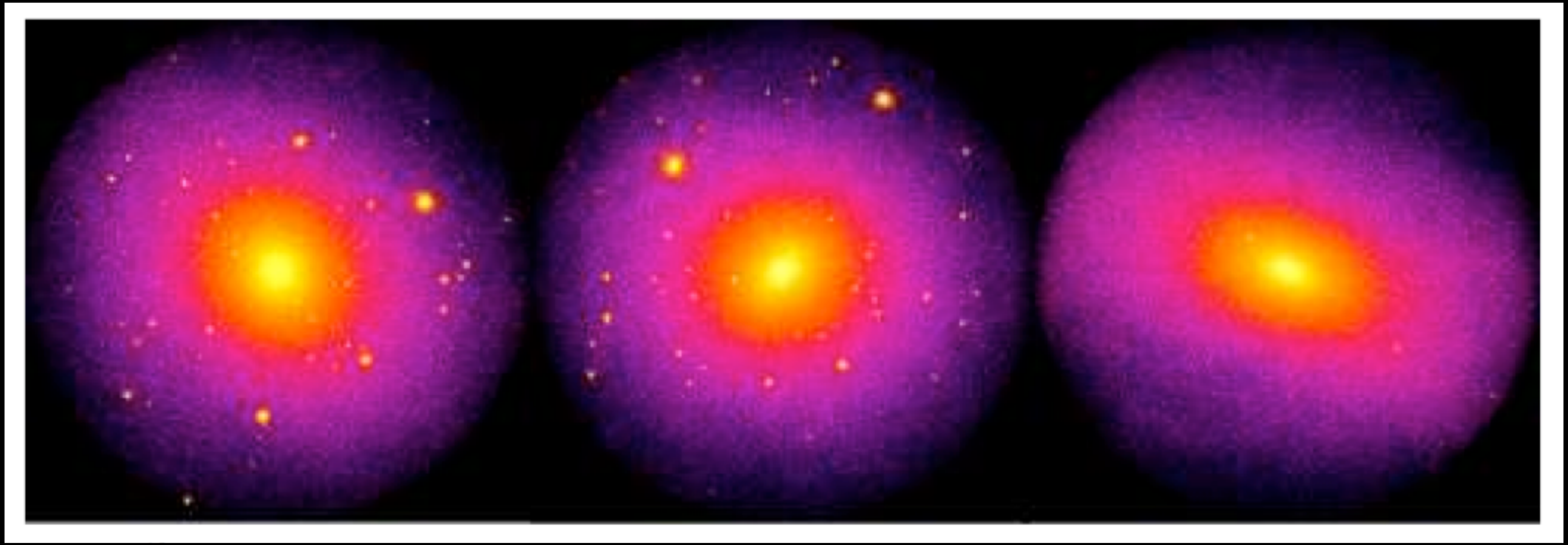
Driving science case #1

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



Belokurov *et al.* (2008)

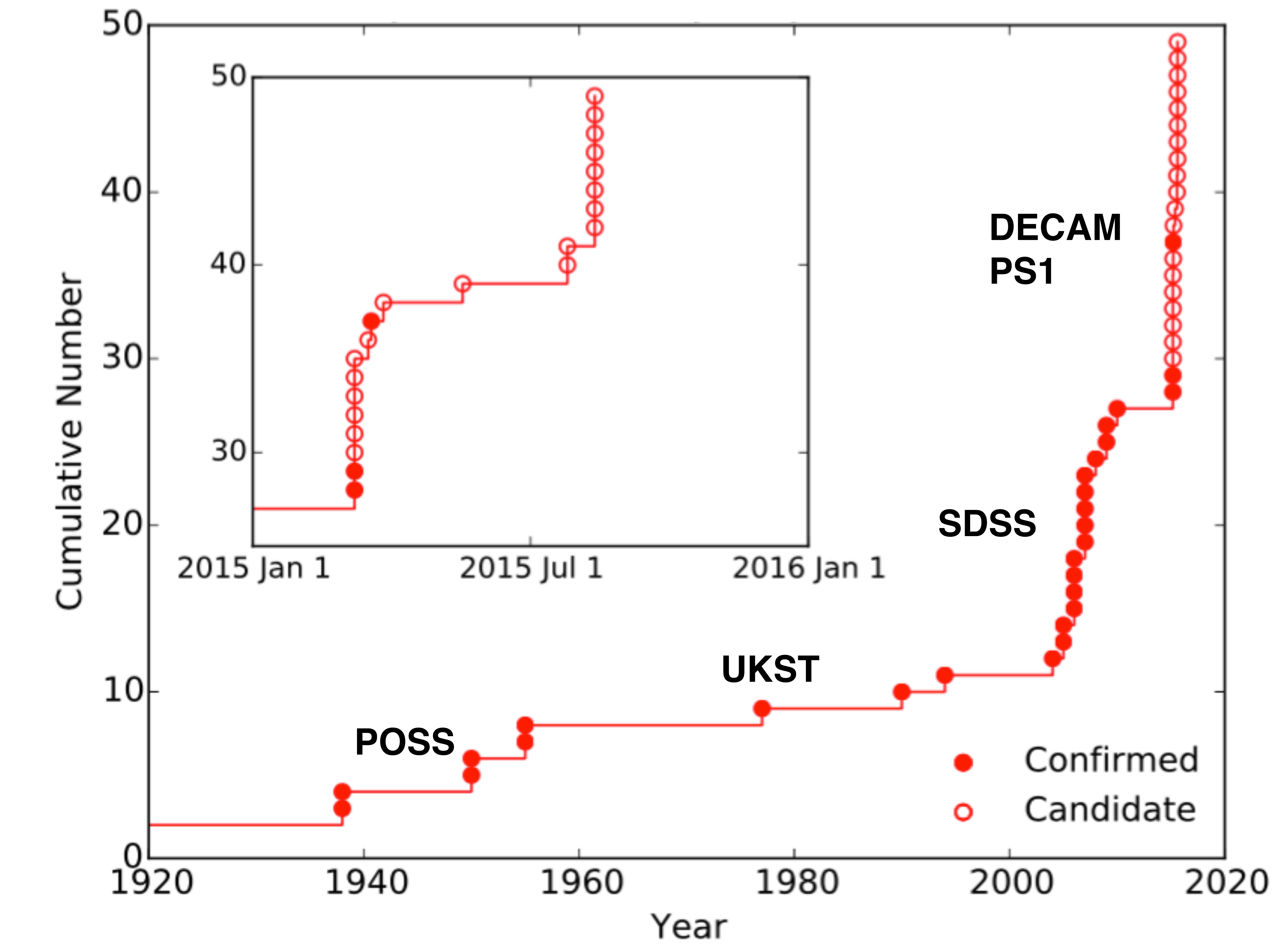
Tension in the CDM paradigm ?



Brooks *et al.* (2014)

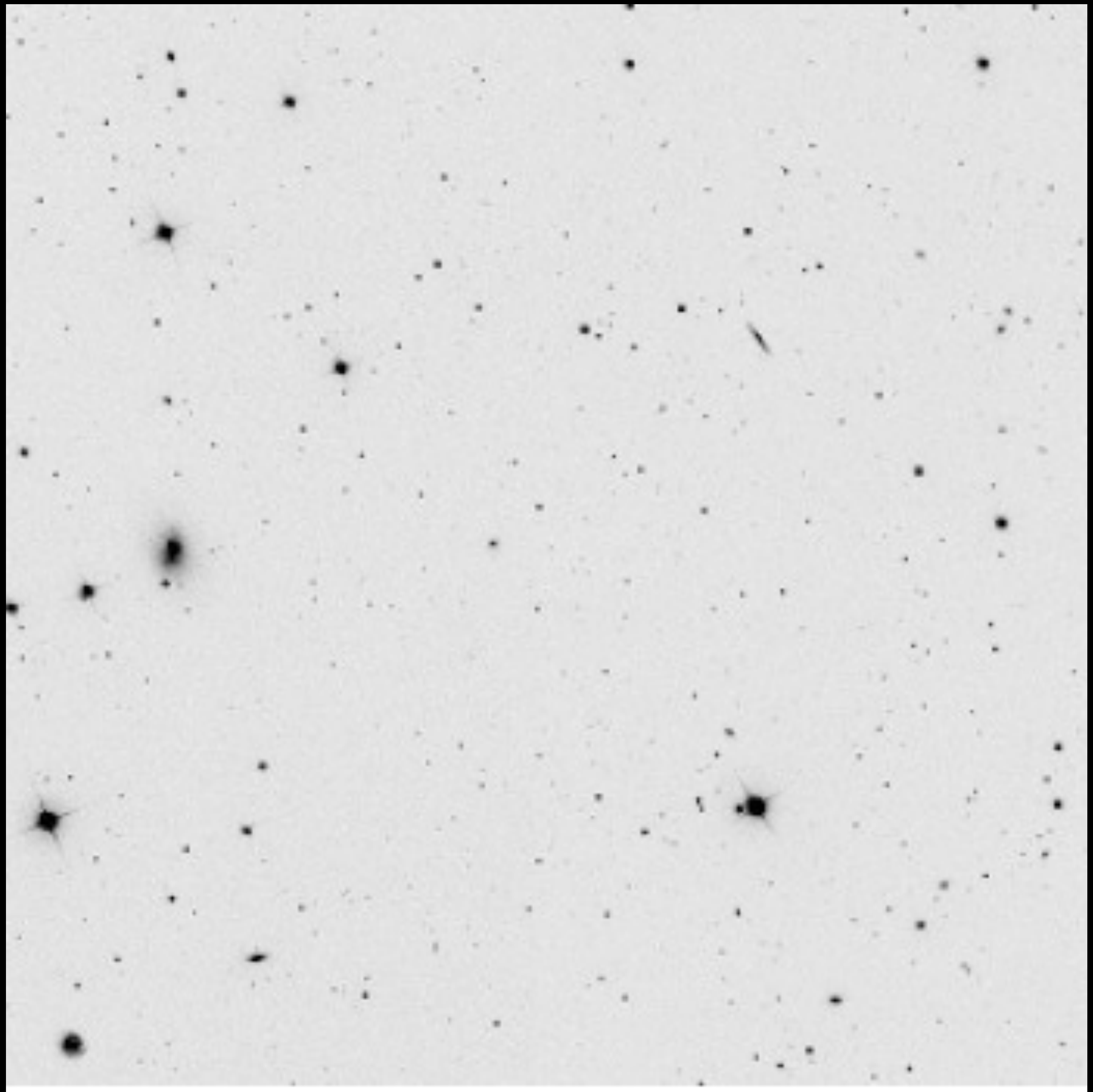
Self-Interacting dark matter | Cold dark matter | Warm dark matter

Discovery rate of Milky Way satellites



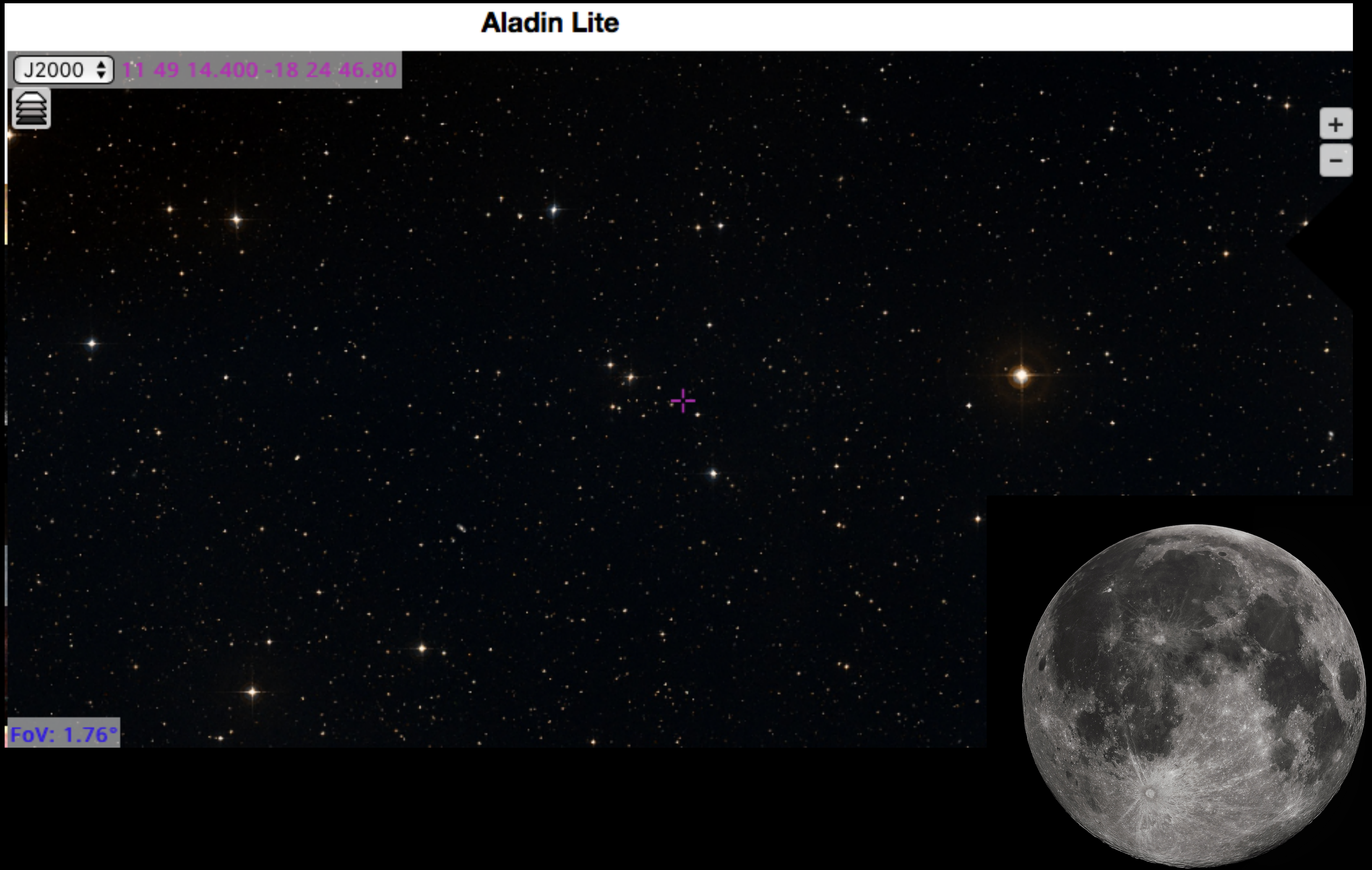
K. Bechtol (2015)

The case of Segue I



Belokurov *et al.* (2007)

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



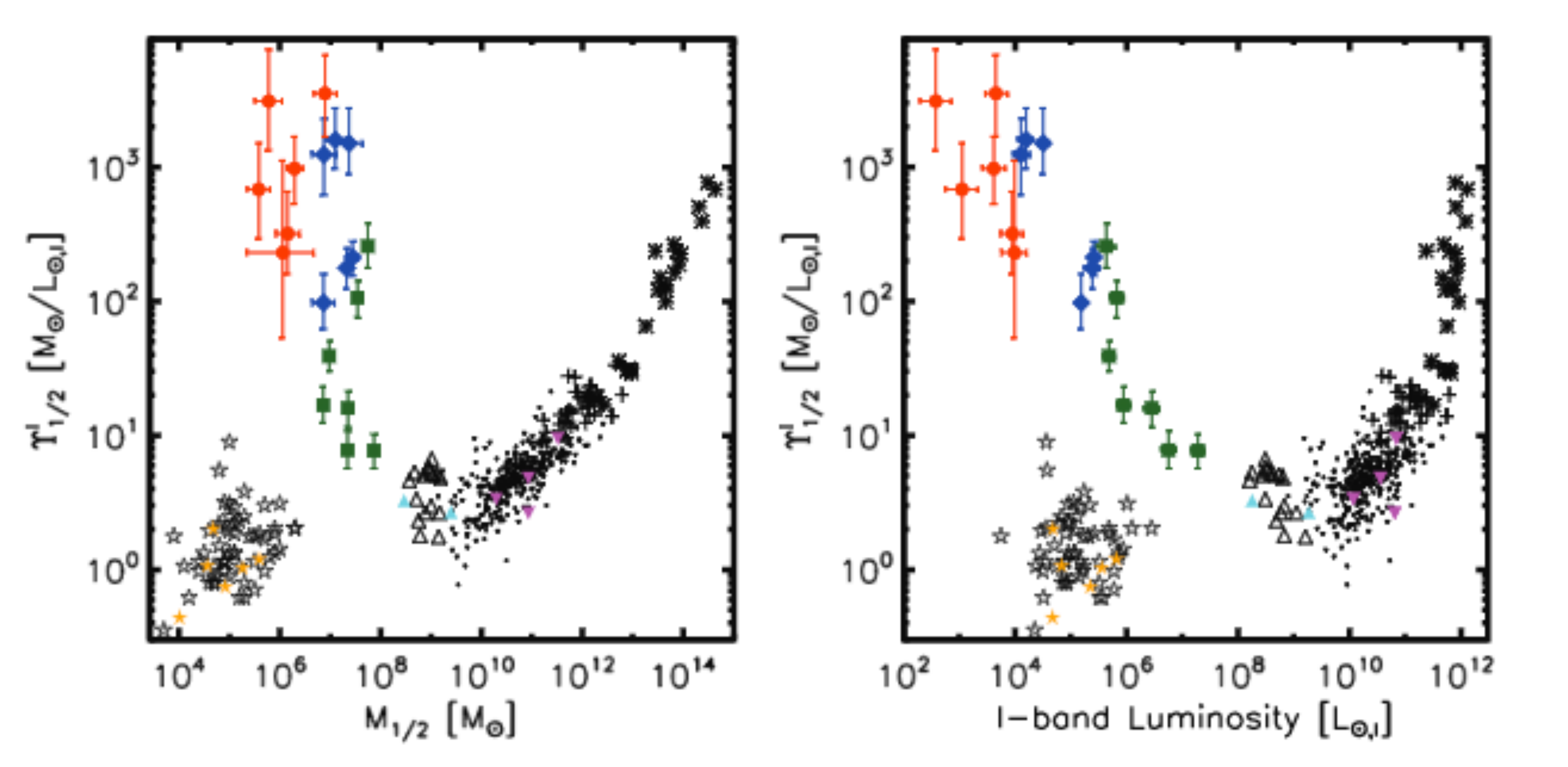
Crater II :   The 5th largest satellite of the Milky Way

d = 120 kpc

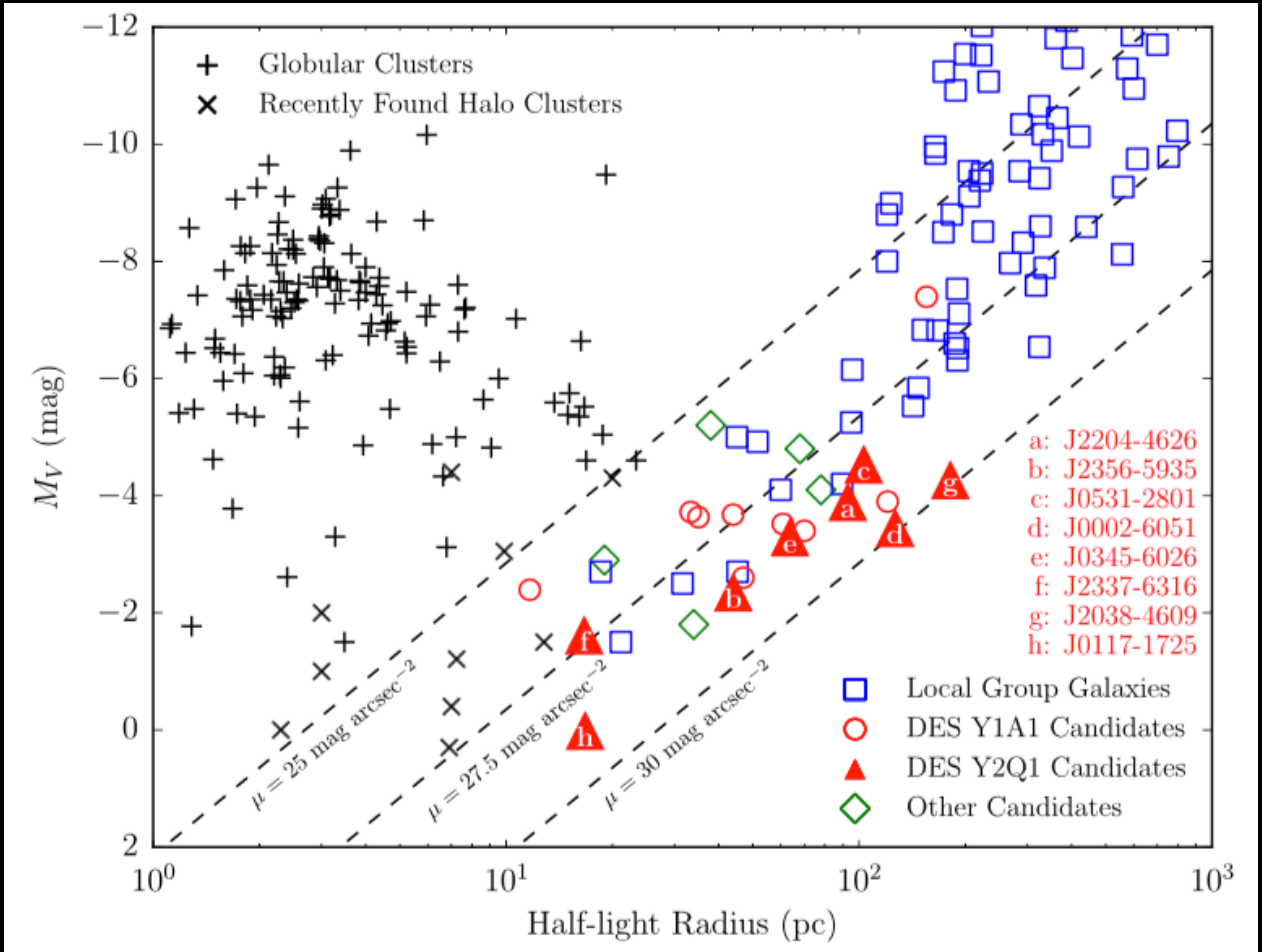
r_h = 1.06 kpc (31′)

$\mu_V(r_h)$ = 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:

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

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

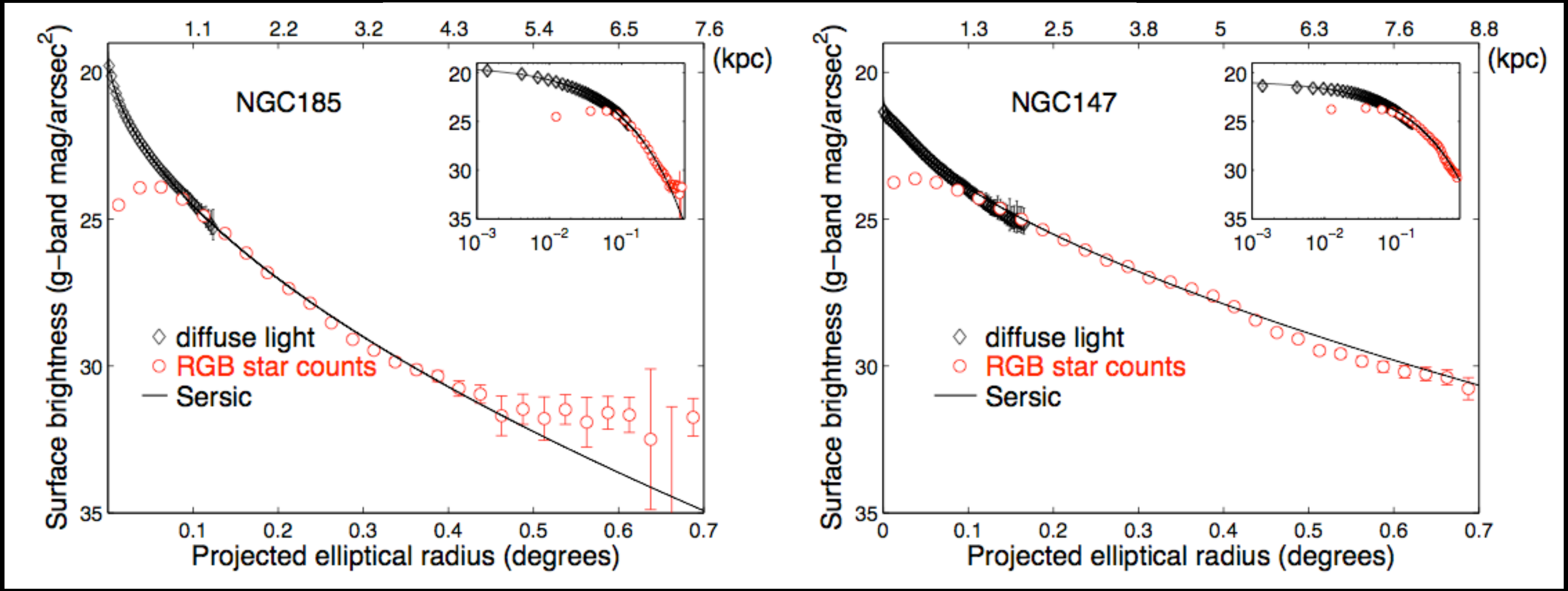
Surface brightness received from an *extended* source:

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

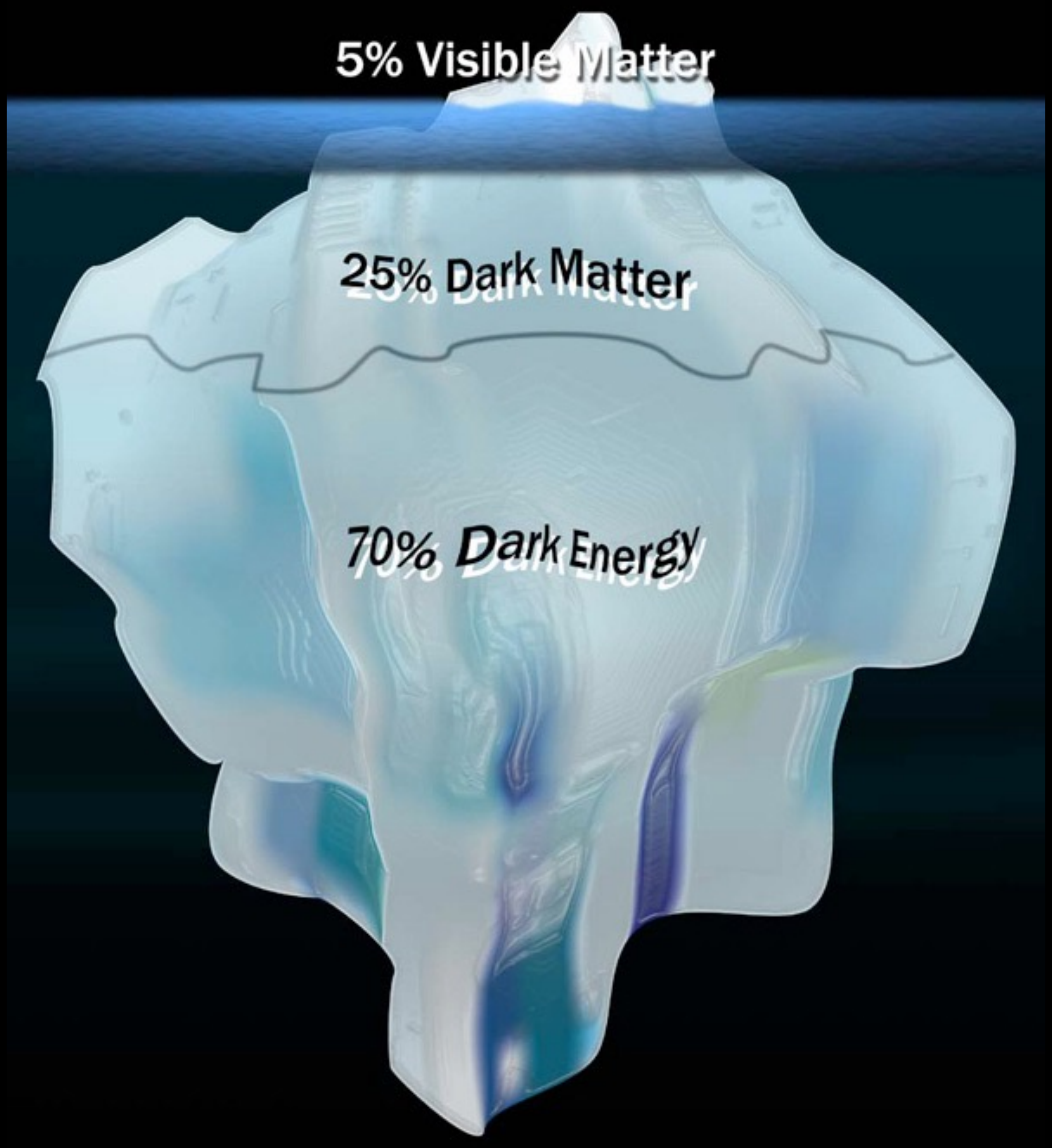
→ requires *fast* optics with *minimal* (*f*/*D*) ratio


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

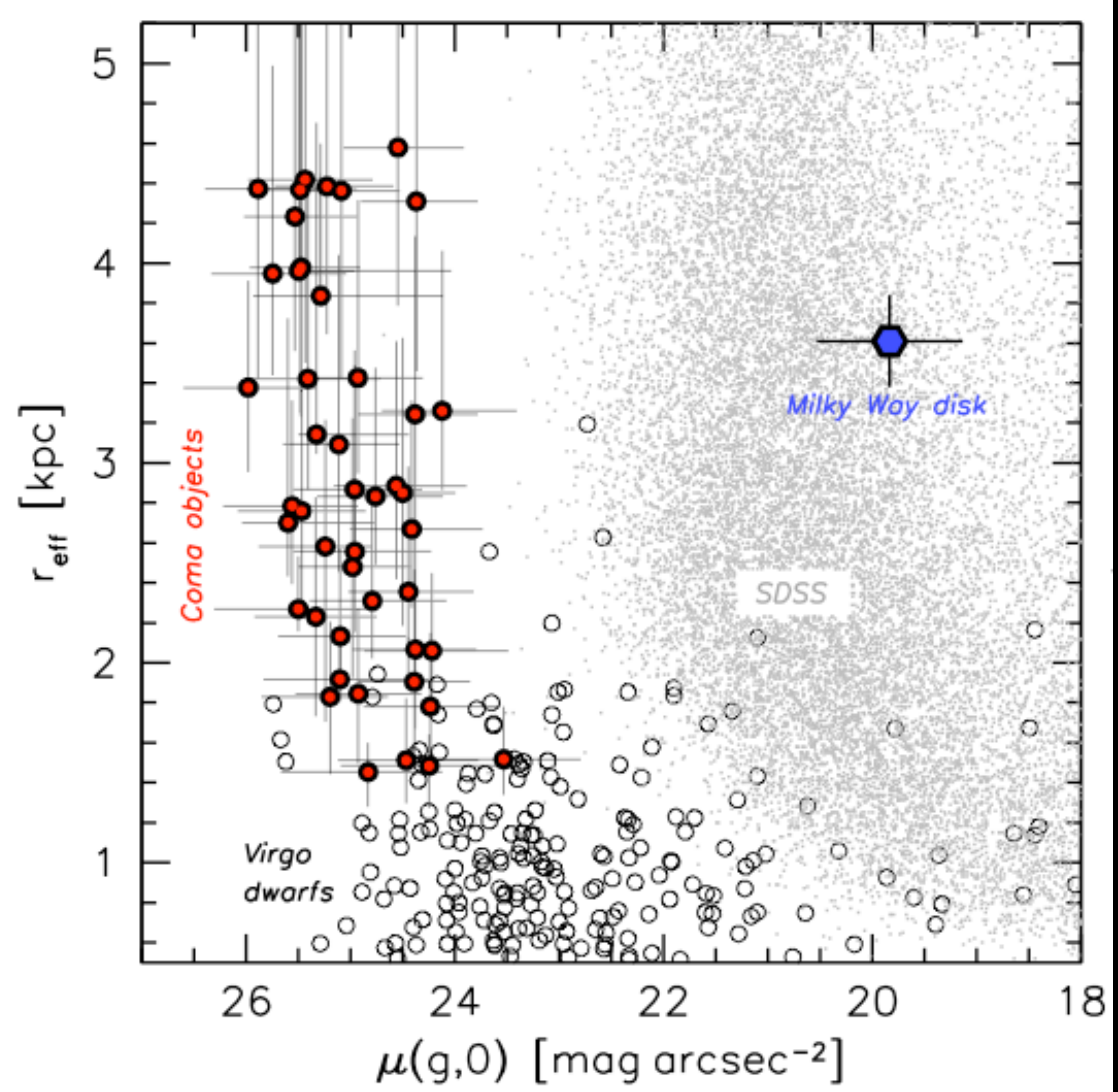
Abraham & Van Dokkum (2014)

47 new Milky Way-sized galaxies in the Coma cluster

26 hours

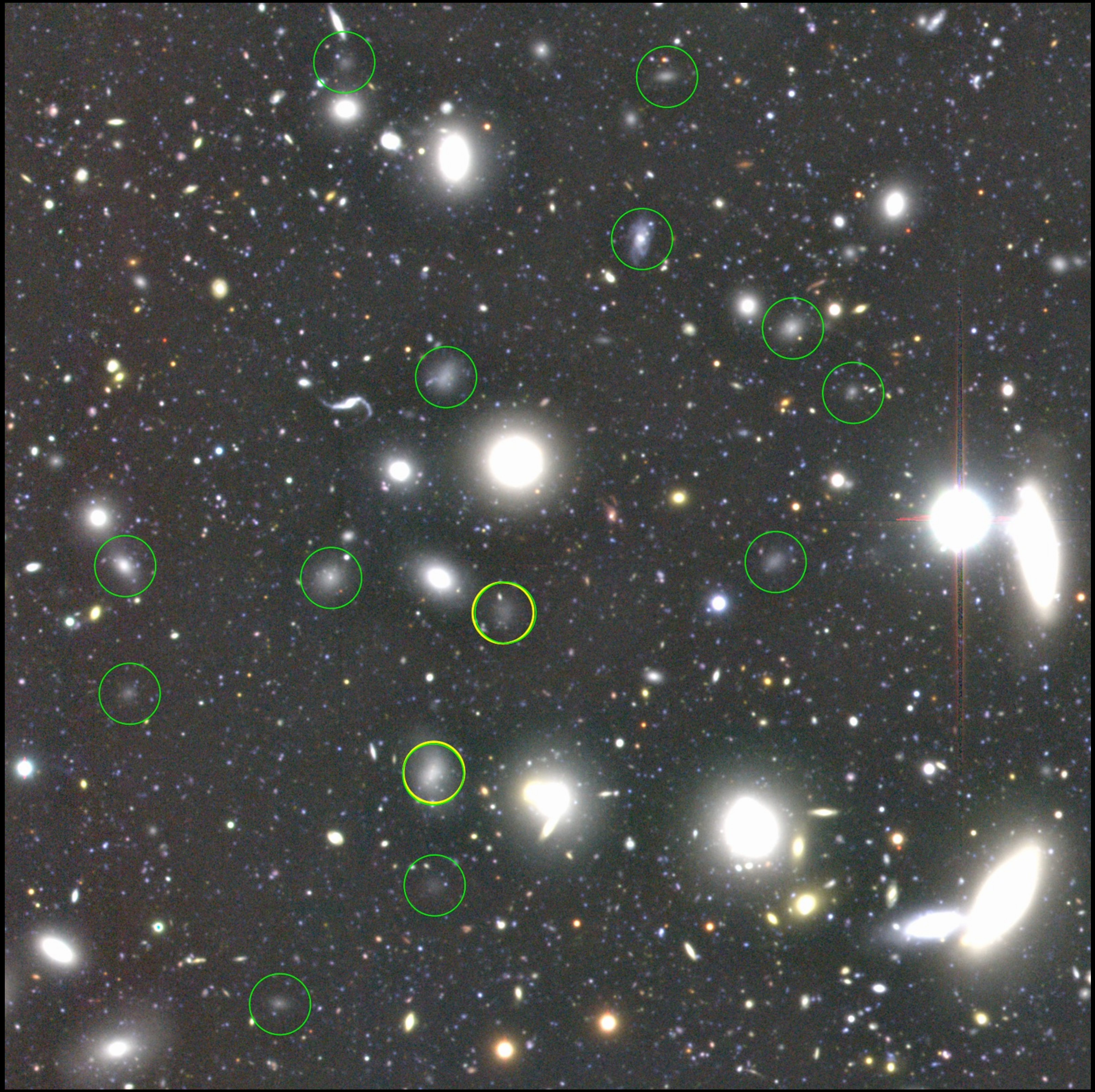
6″ FWHM

SB(g) ~ 29.3 mag arcsec^{-2} @ 10″



Van Dokkum *et al.* (2015)

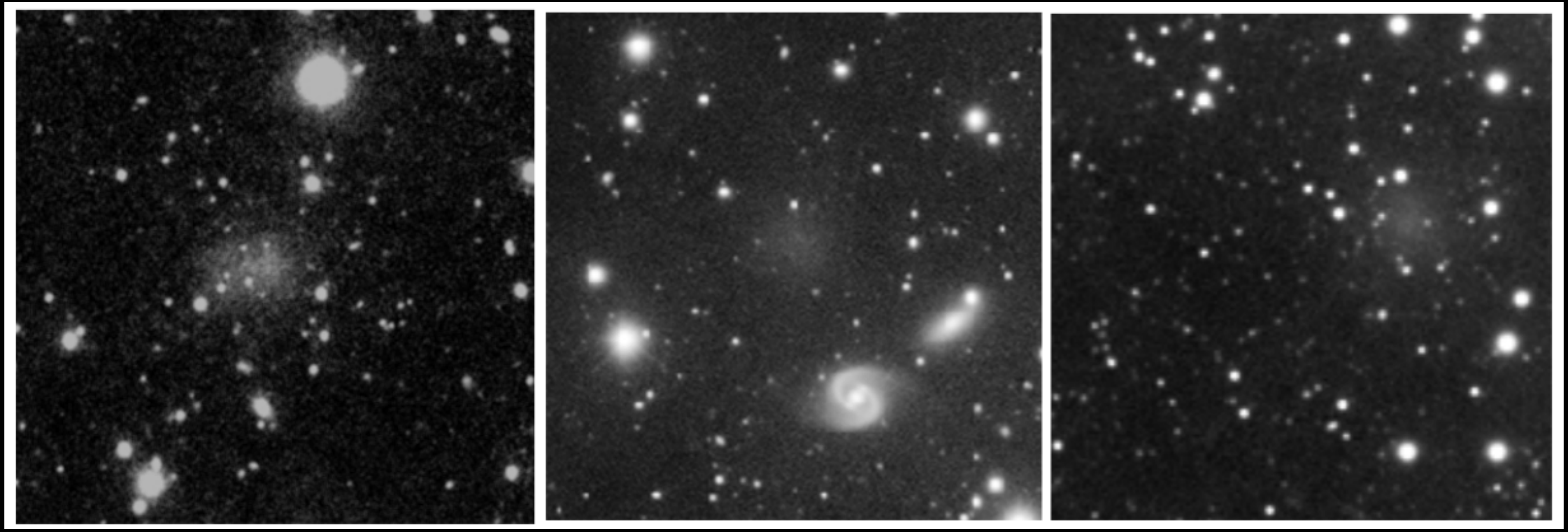
Discovery of ~1000 new galaxies in the Coma cluster



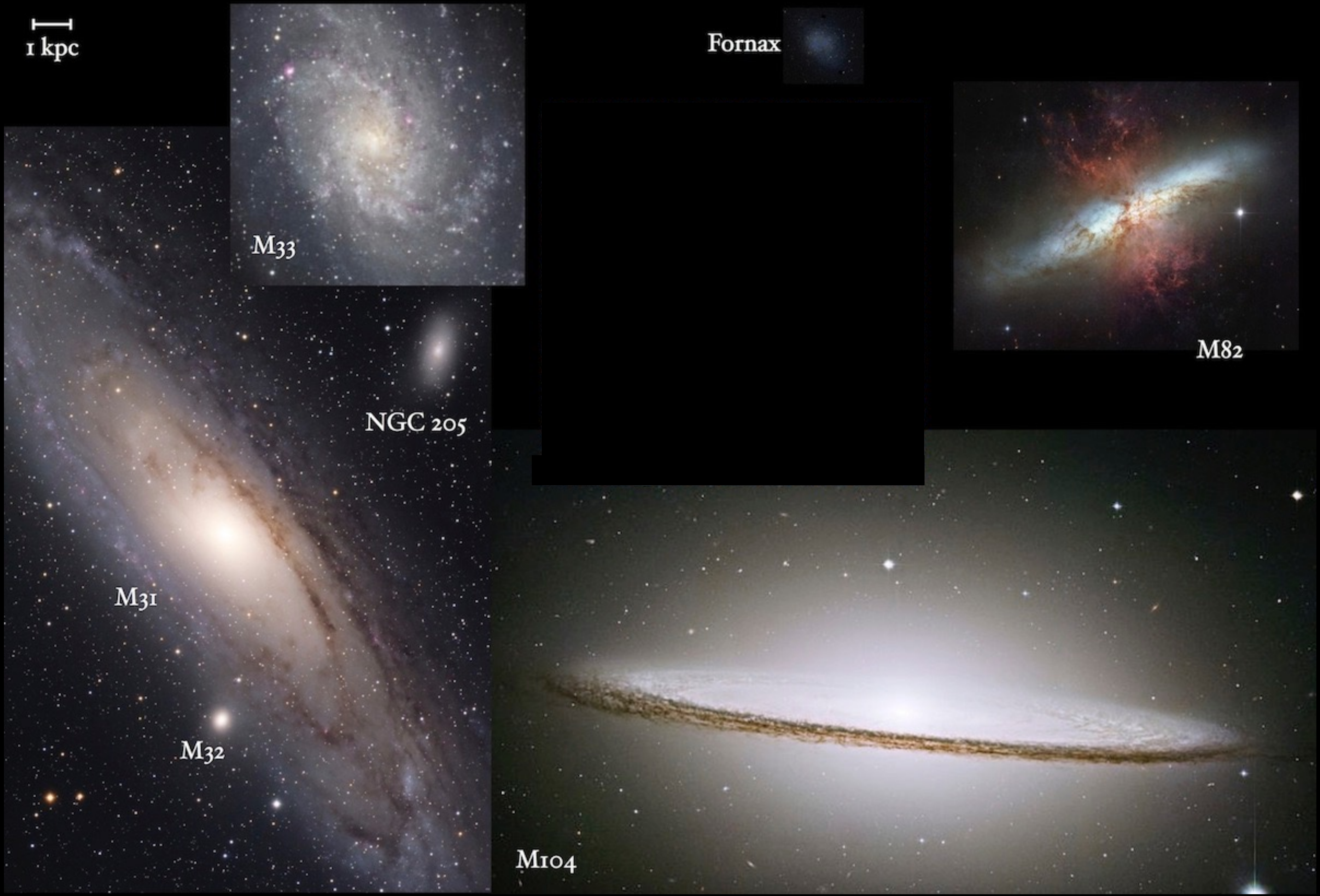
Koda *et al.* (2015)

A new population of hitherto unknown galaxies
ultra-diffuse galaxies

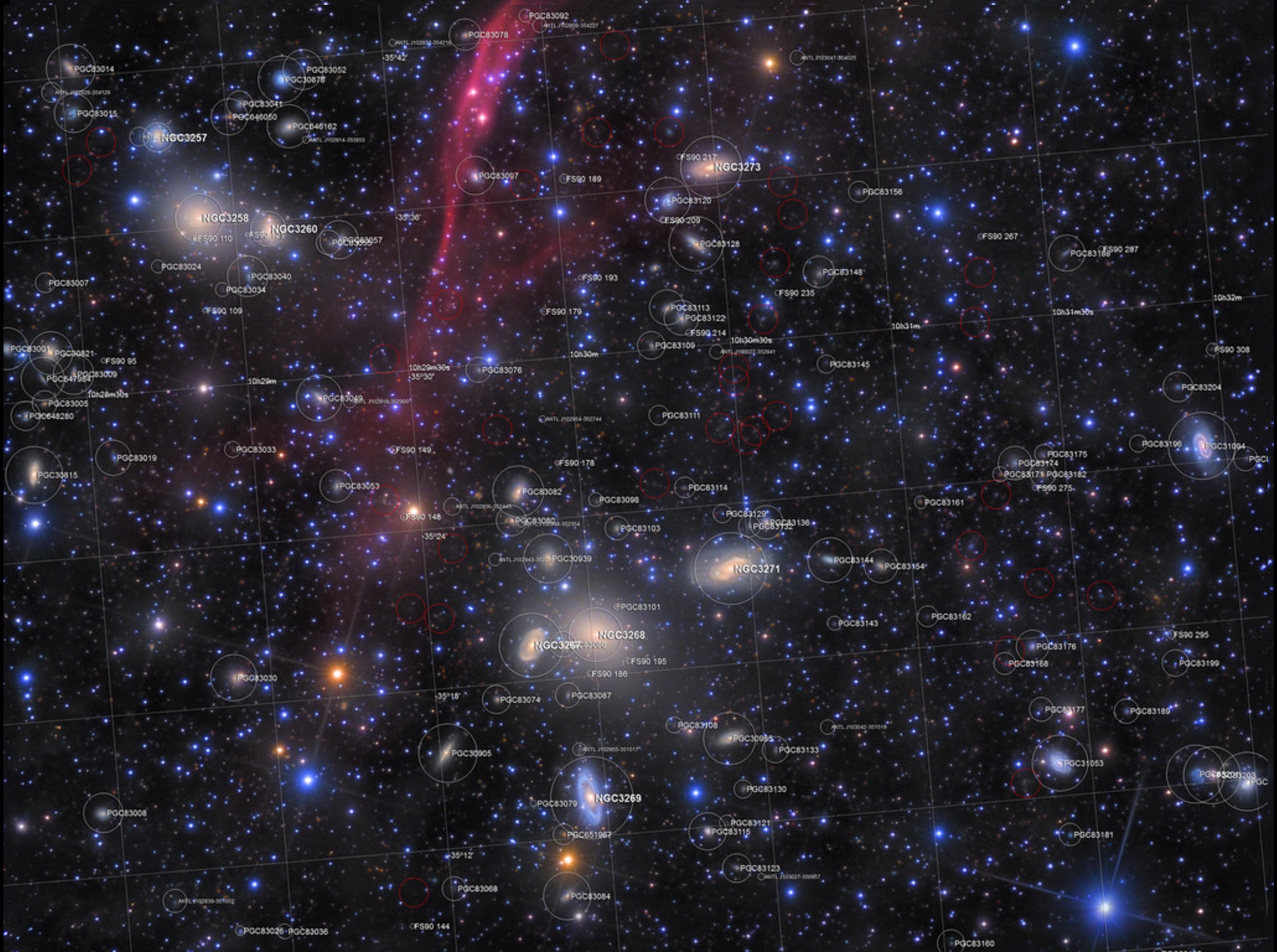
Virgo cluster　　　　　　Perseus-Pisces filament



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

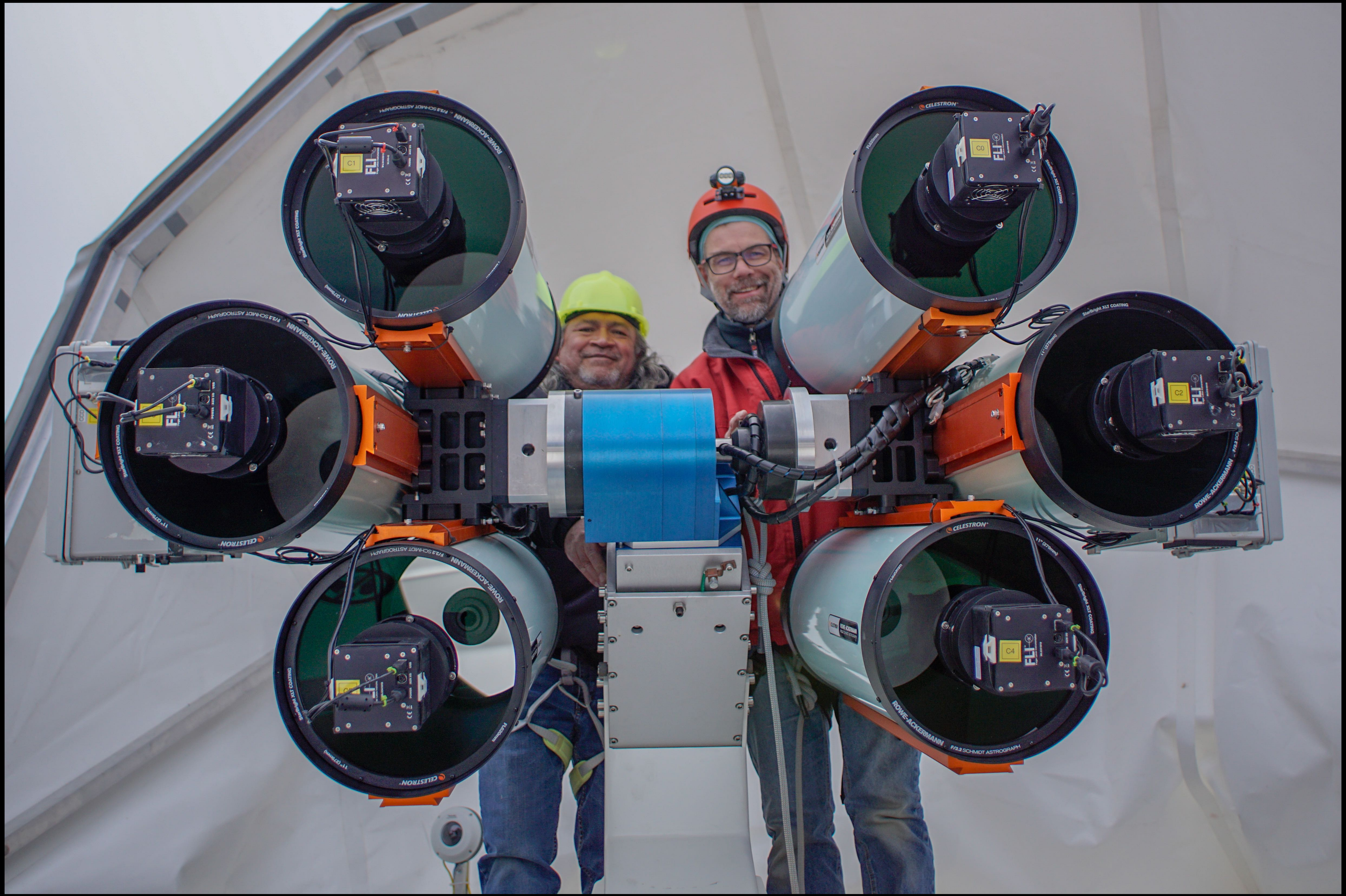


S. Danieli



NGC3257
NGC3258
NGC3260
NGC3273
NGC3271
NGC3268
NGC3267
NGC3269
PGC83014
PGC83015
PGC83052
PGC83041
PGC83078
PGC83092
PGC83097
PGC83120
PGC83128
PGC83156
PGC83148
PGC83024
PGC83007
PGC83040
PGC83034
PGC83113
PGC83122
PGC83109
PGC83145
PGC83076
PGC83001
PGC83005
PGC648280
PGC83111
PGC83204
PGC83033
PGC83019
PGC30815
PGC83053
PGC83082
PGC83114
PGC83098
PGC83103
PGC83161
PGC83175
PGC31094
PGC30939
PGC83144
PGC83154
PGC83101
PGC83143
PGC83162
PGC83176
PGC83199
PGC83168
PGC83030
PGC83074
PGC83087
PGC83177
PGC83189
PGC83108
PGC83133
PGC30905
PGC31053
PGC83130
PGC83008
PGC83079
PGC651967
PGC83121
PGC83115
PGC83181
PGC83123
PGC83068
PGC83084
PGC83036
PGC83160
FS90 217
FS90 189
FS90 209
FS90 110
FS90 267
FS90 287
FS90 193
FS90 235
FS90 109
FS90 179
FS90 214
FS90 95
FS90 308
FS90 149
FS90 178
FS90 275
FS90 148
FS90 295
FS90 195
FS90 186
FS90 144
10h32m
10h31m30s
10h31m
10h30m30s
10h30m
10h29m30s
10h29m
10h28m30s
-35°42'
-35°36'
-35°30'
-35°24'
-35°18'
-35°12'

DDOTI as a low-surface-brightntess discovery machine ?



Driving science case #2

The Cosmic Web

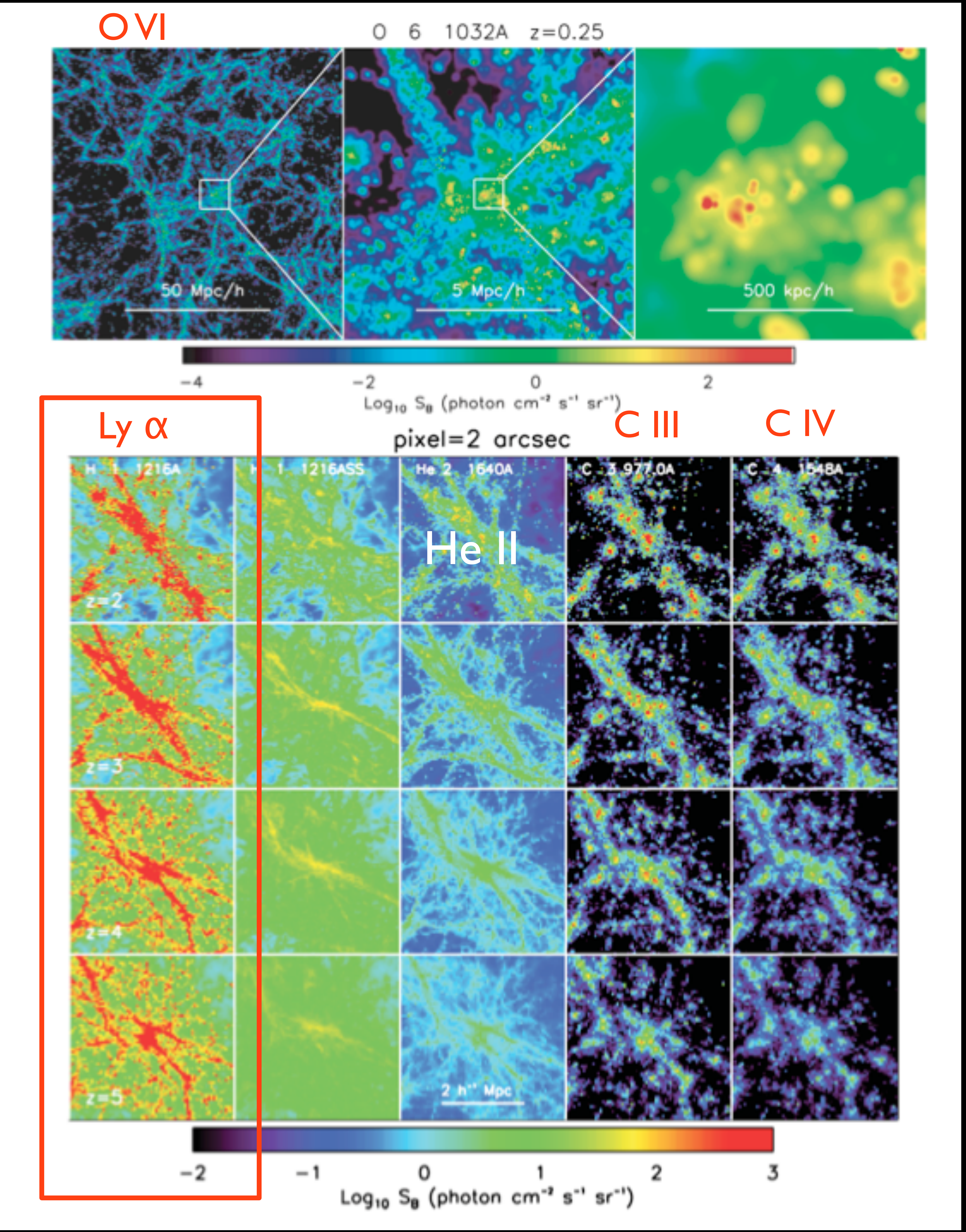
Strongest in Lyman α by >1000 x

The case for low z observations :

(i) stronger filaments

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

(iii) efficient UV detectors



Bertone + Schaye (2012)

The 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

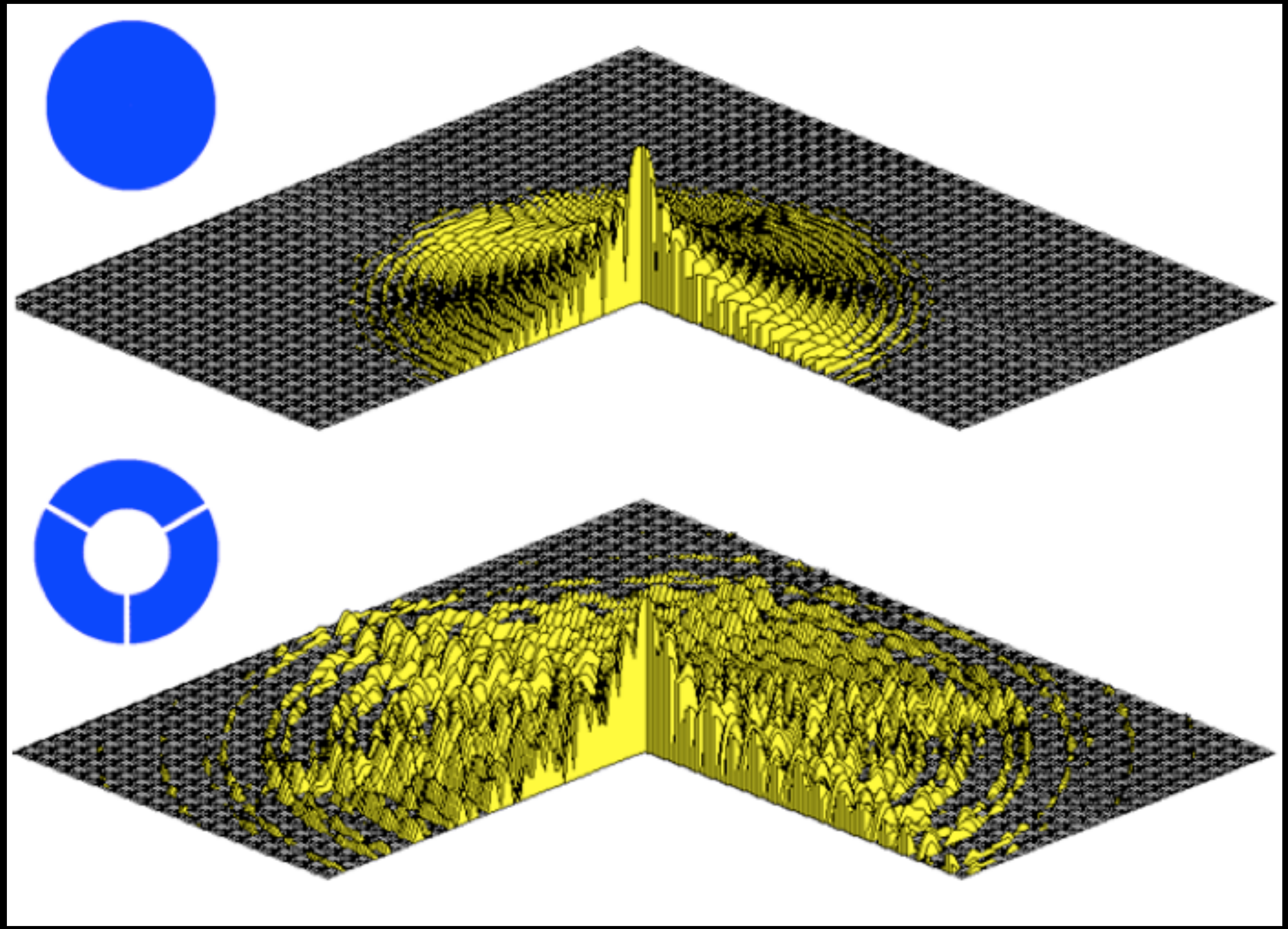
The (obvious) solution:

a space observatory with a purpose-built telescope

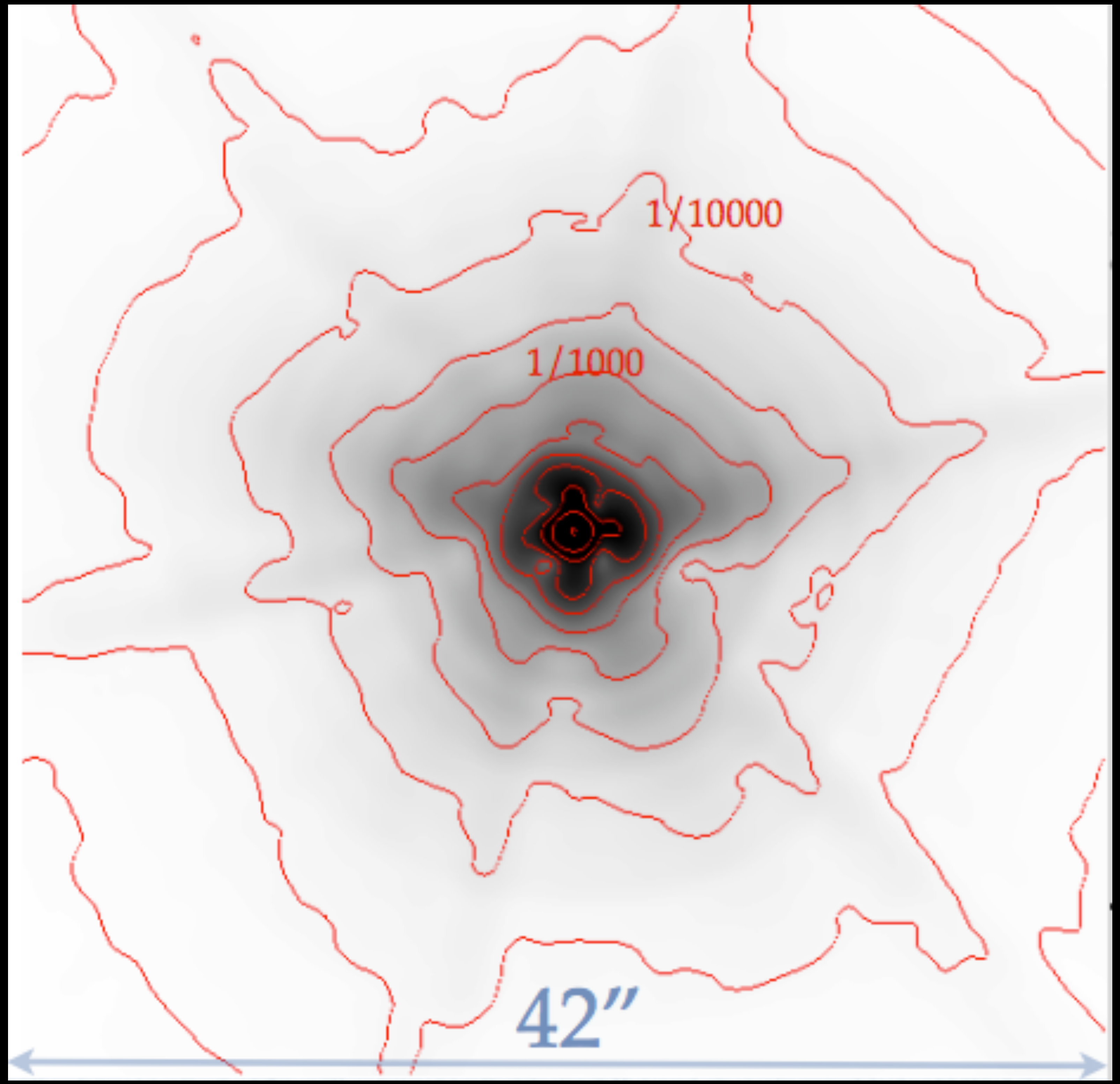
Top-level design requirements

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

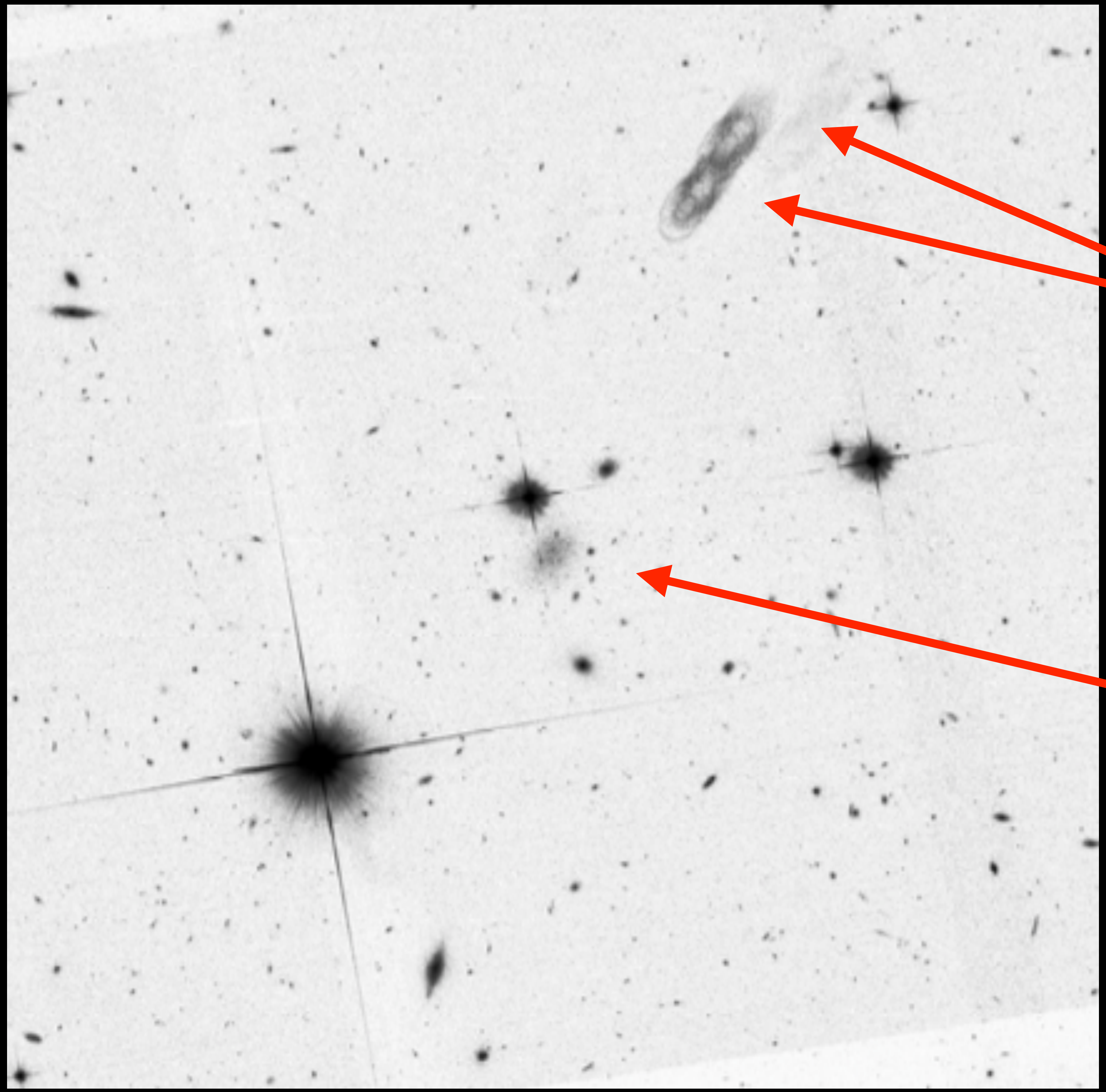


EUCLID

NO LENSES ALLOWED

(1) multiple internal scattering

(2) Čerenkov emission



GHOSTS produced by ACS/HST

New ultra-diffuse galaxy (2019)

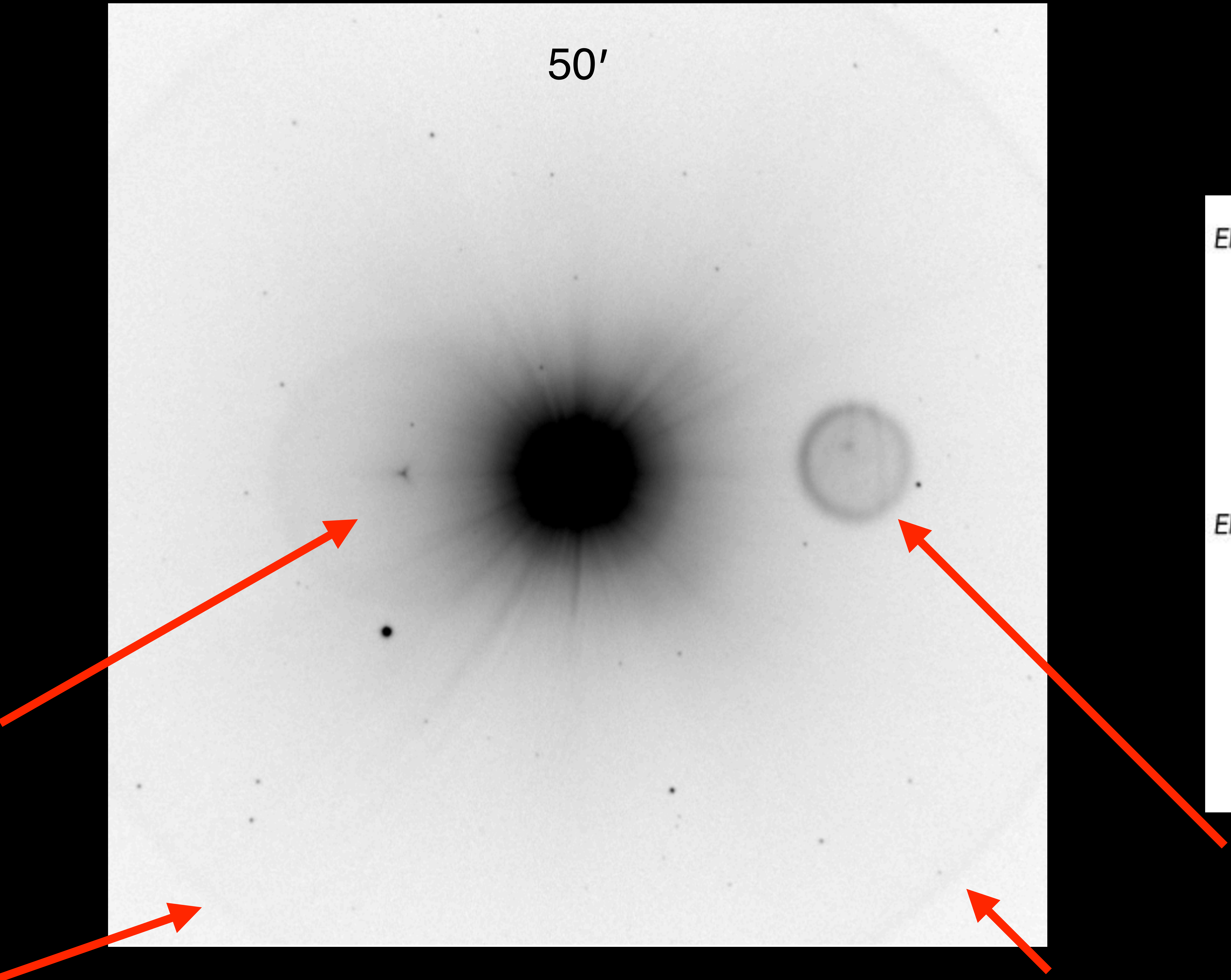
师冬冬 & 郑宪忠老师

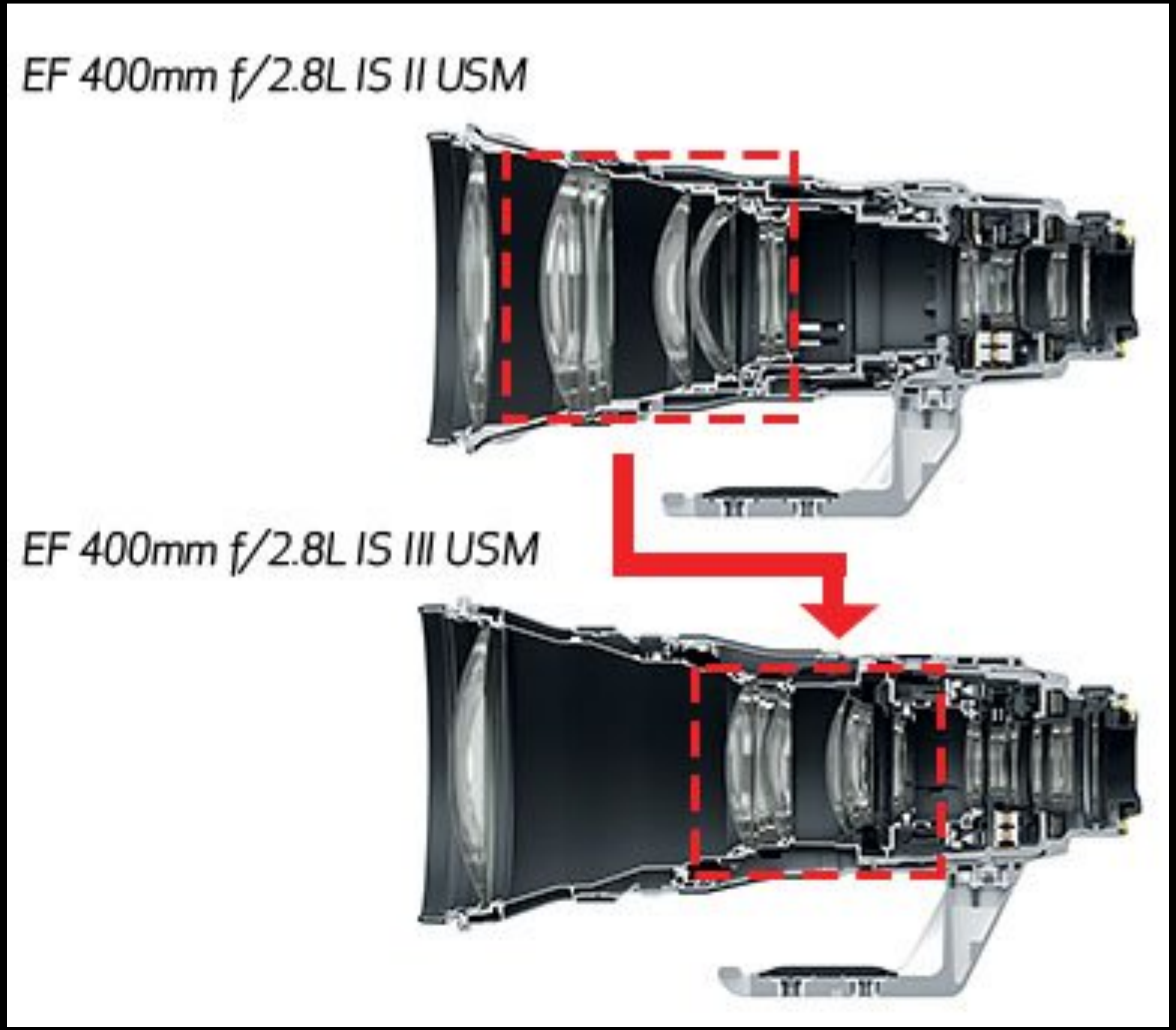
Shi Dongdong & Zheng Xiangzhong

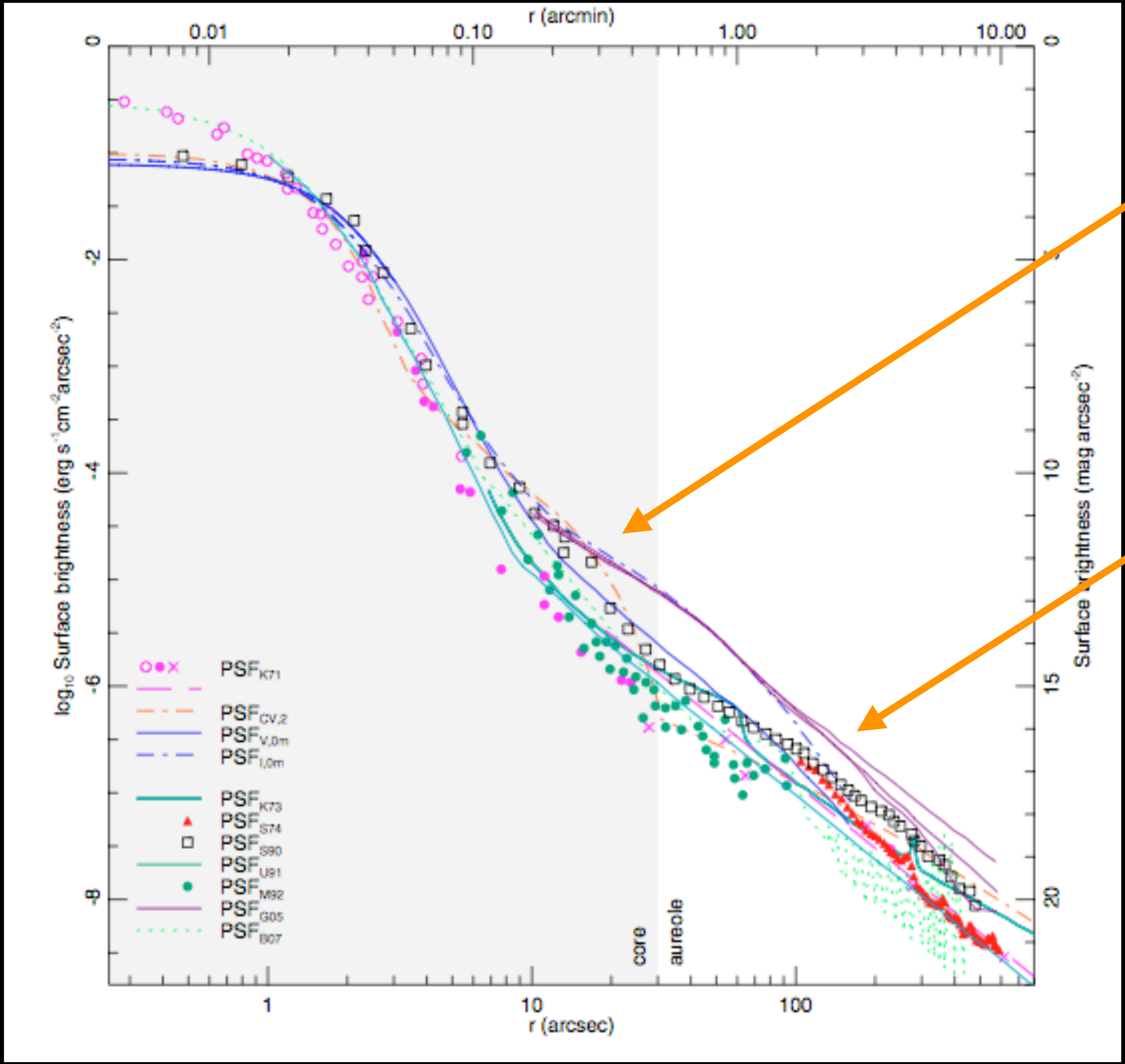
ACS

Dragonfly ghosts

17 optical elements in 13 groups







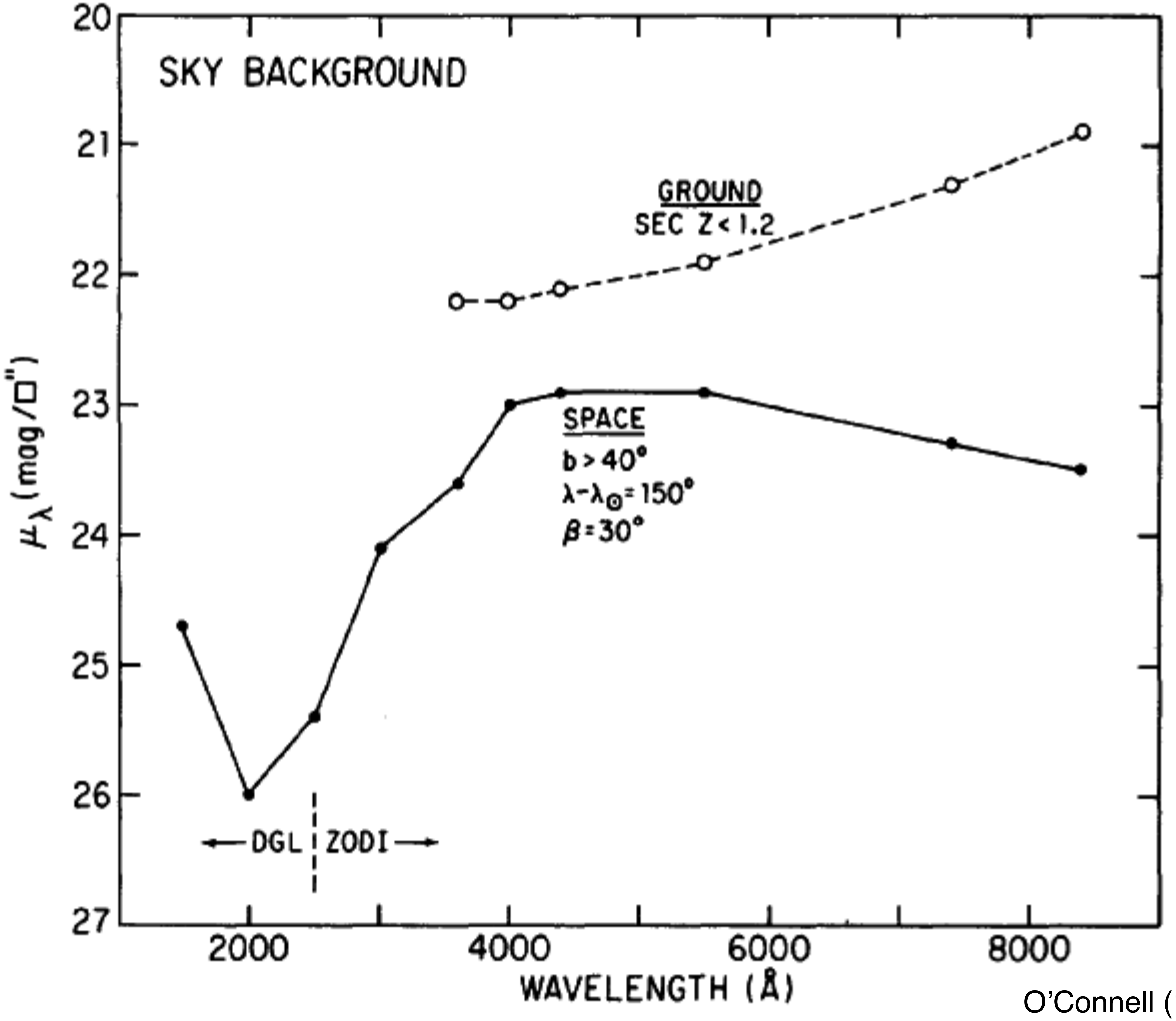
Internal scattering in optics
(prime focus corrector, filters)

+

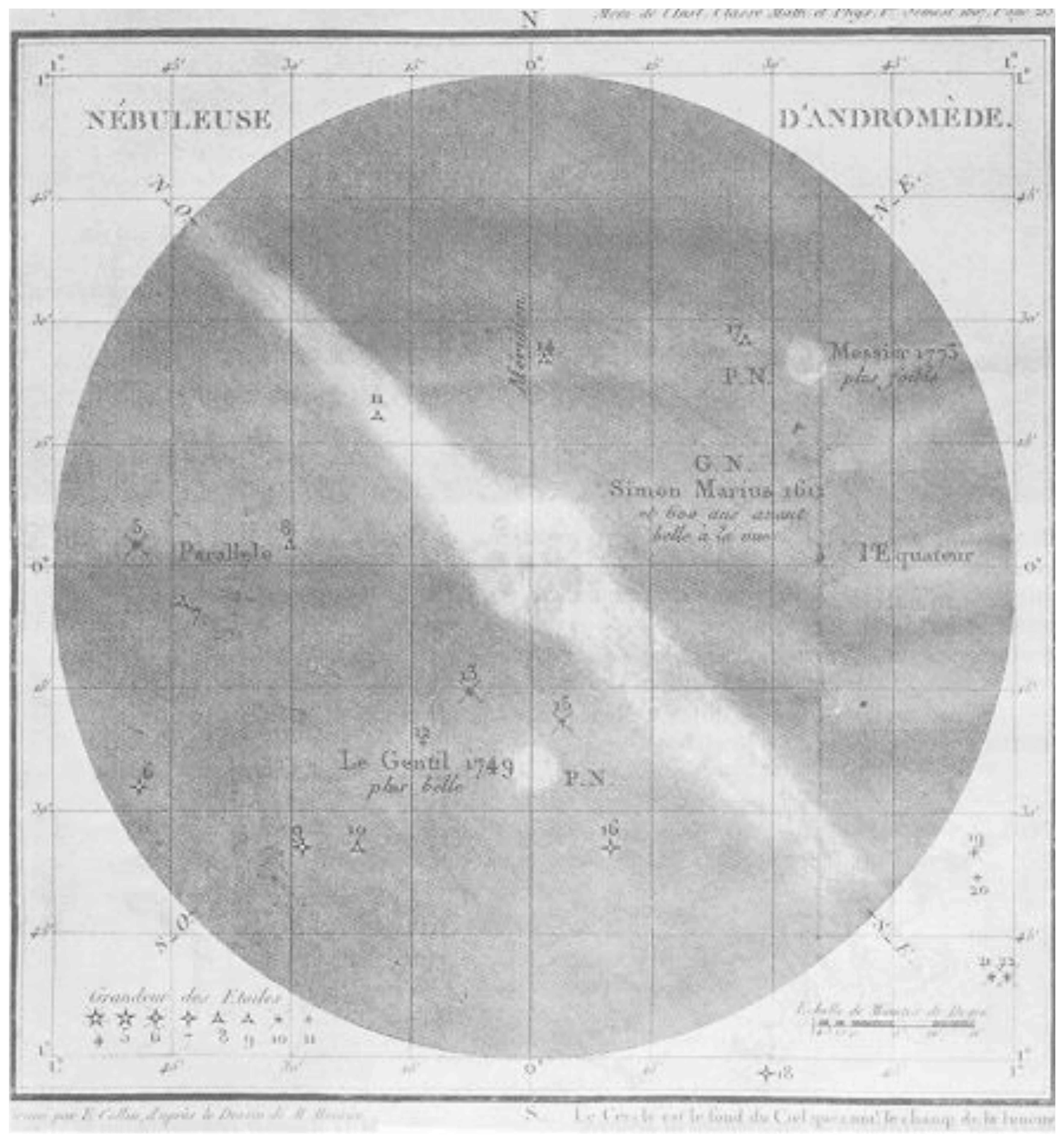
Scattering by
atmospheric molecules

Major limitations
for ground-based detections

Sandin (2015)



O’Connell (1986)

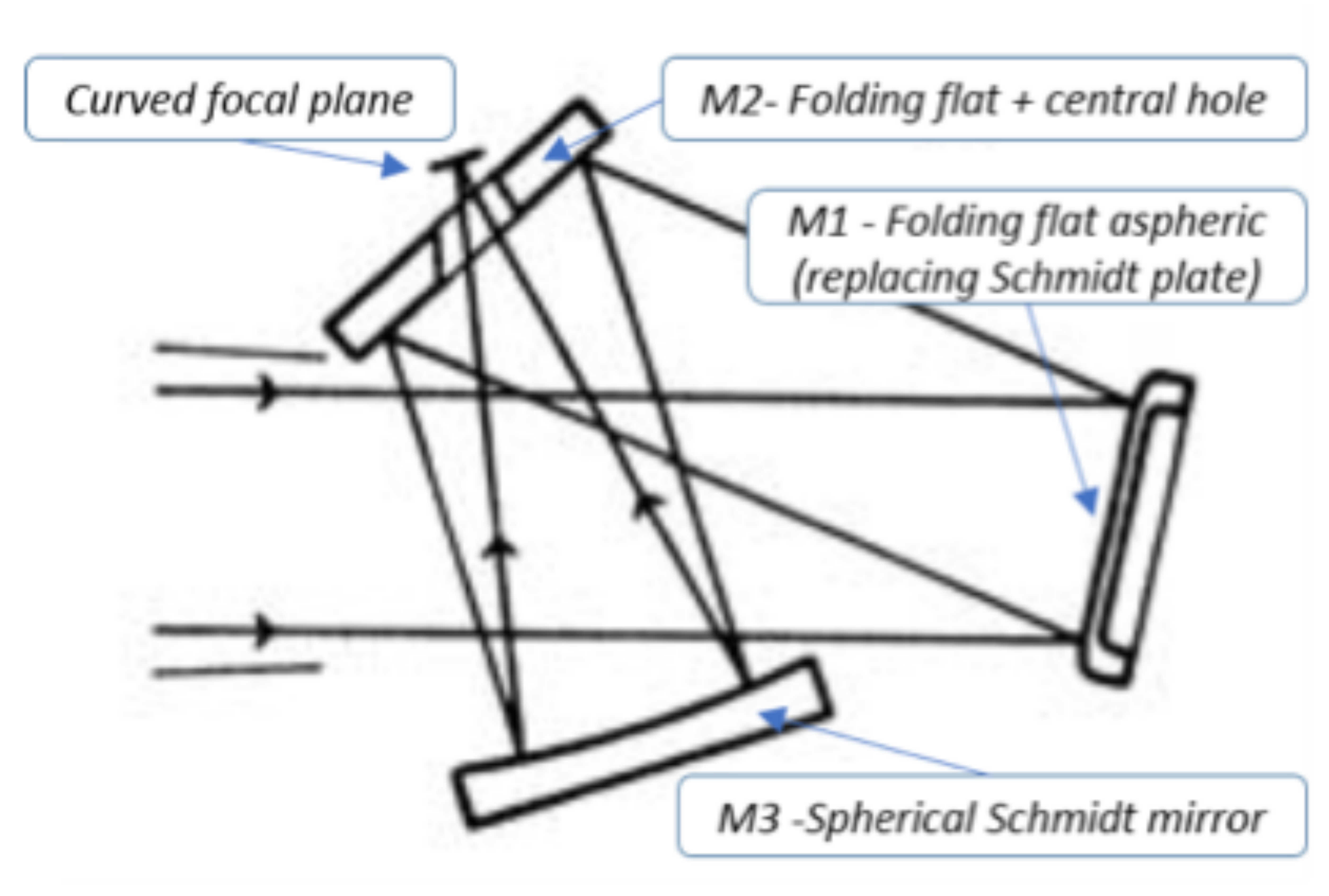


Messier (1771) *Mem. Acad. Sci. Paris*
Messier (1780) *Conn. Temps*

Key additional requirement for MESSIER :

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

— ~~flat focal plane~~



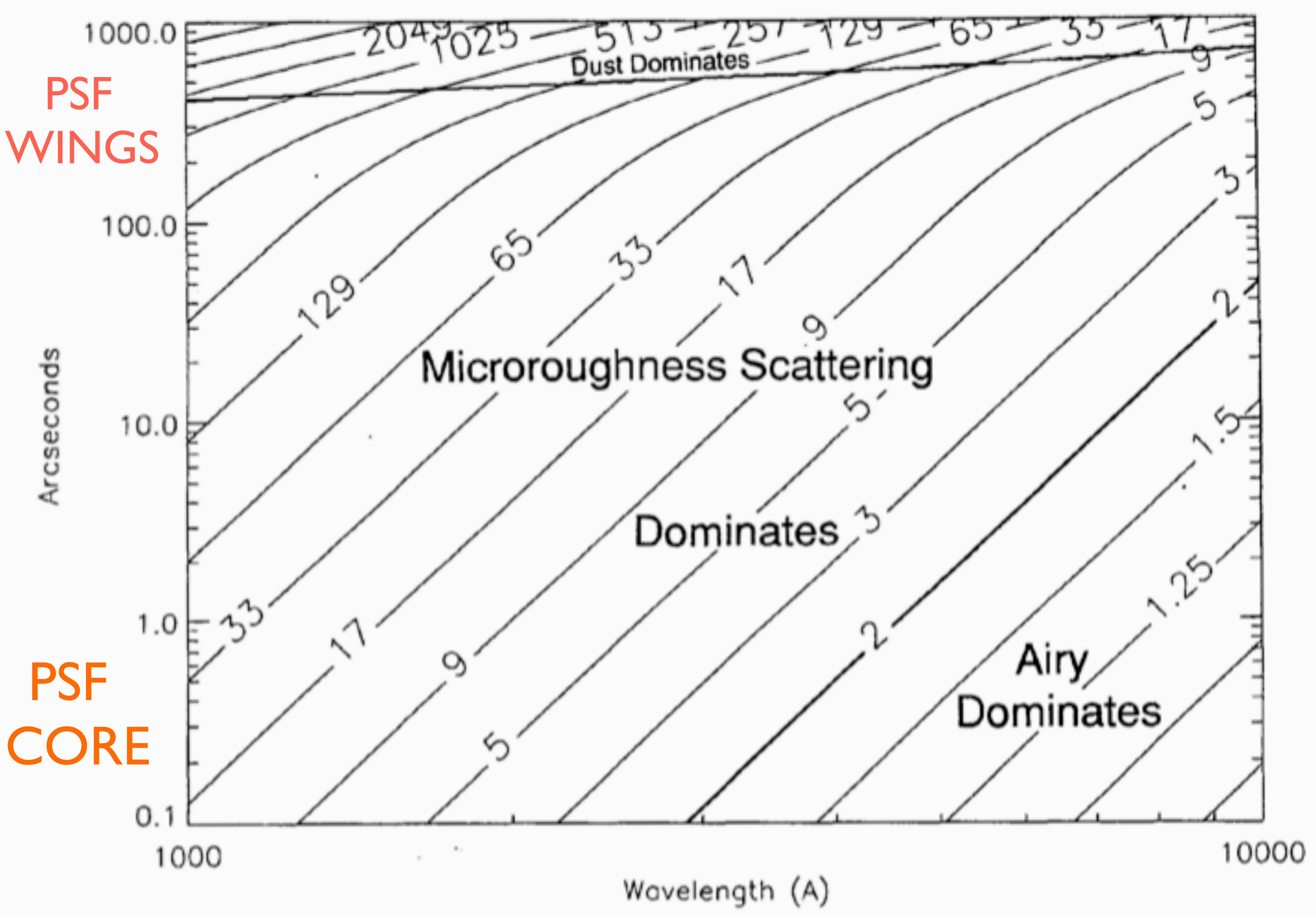
Optimal off-axis
mirror-only solution

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)

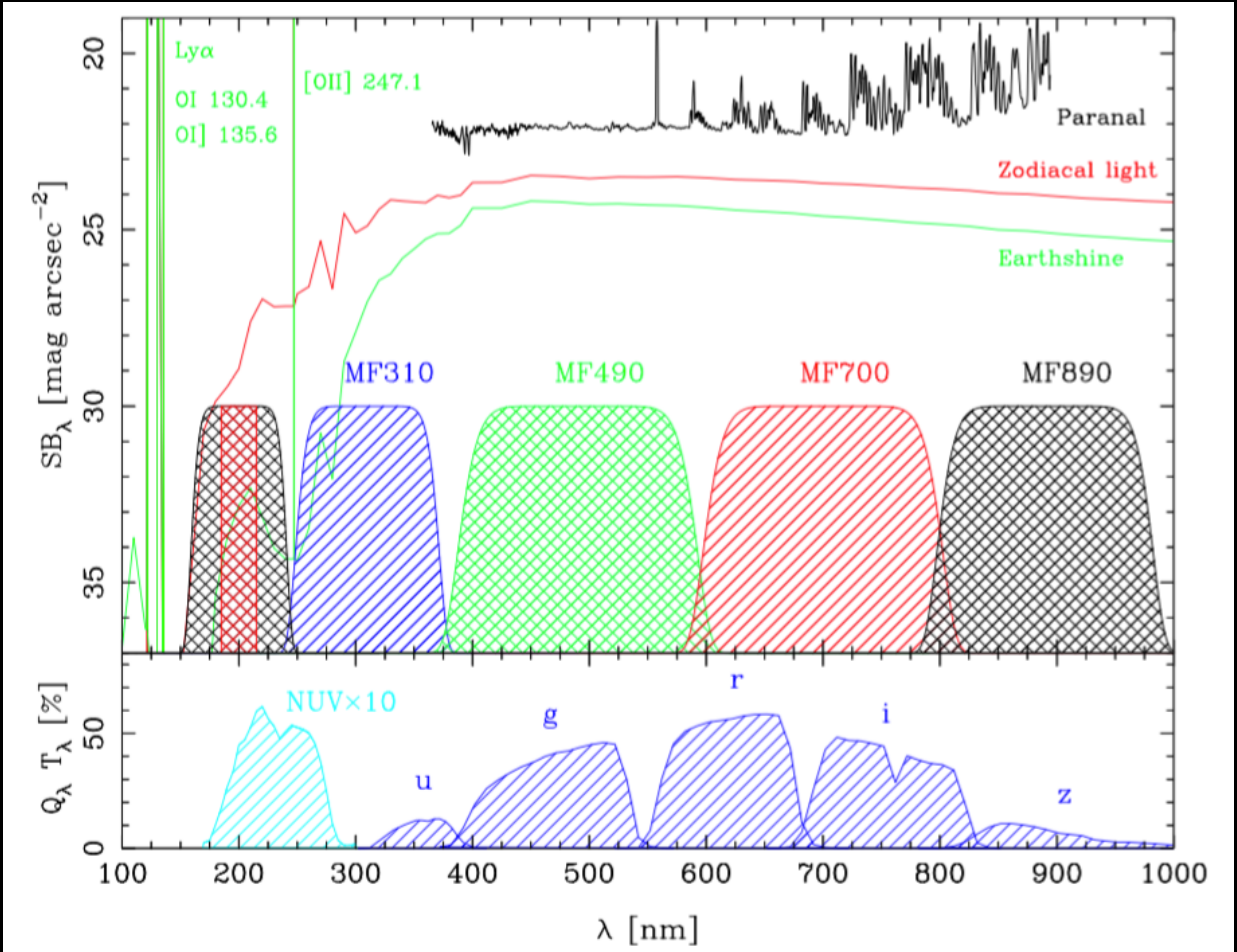
TWO DISRUPTIVE BREAKTHROUGHS : Off-axis purely reflective Schmidt
Curved CCDs


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

Requirements for filters

Broad filters :
  characterise SEDs of stellar populations

Narrow + broad filters :
  Lyman-α intensity mapping

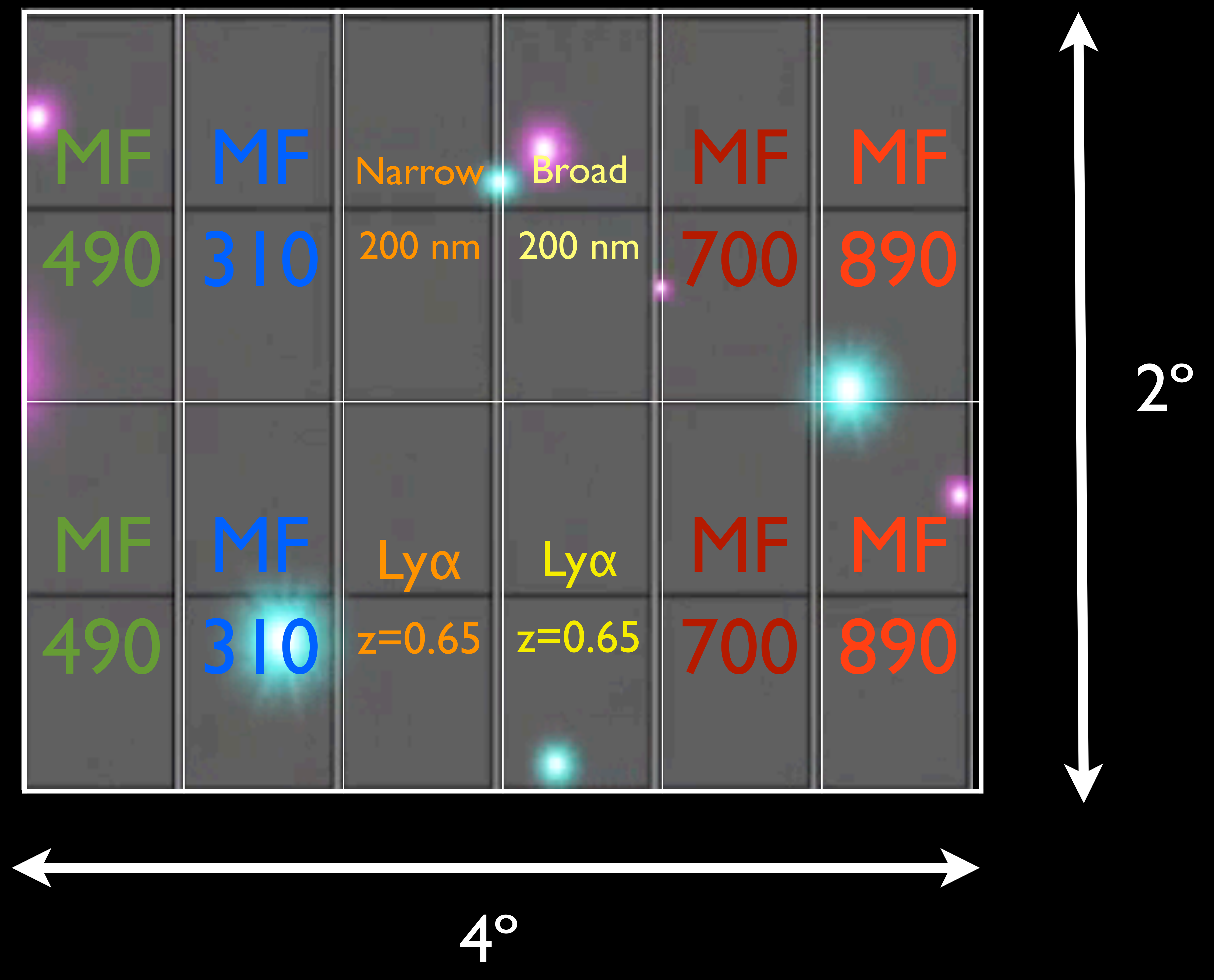


Curved focal surface configuration

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

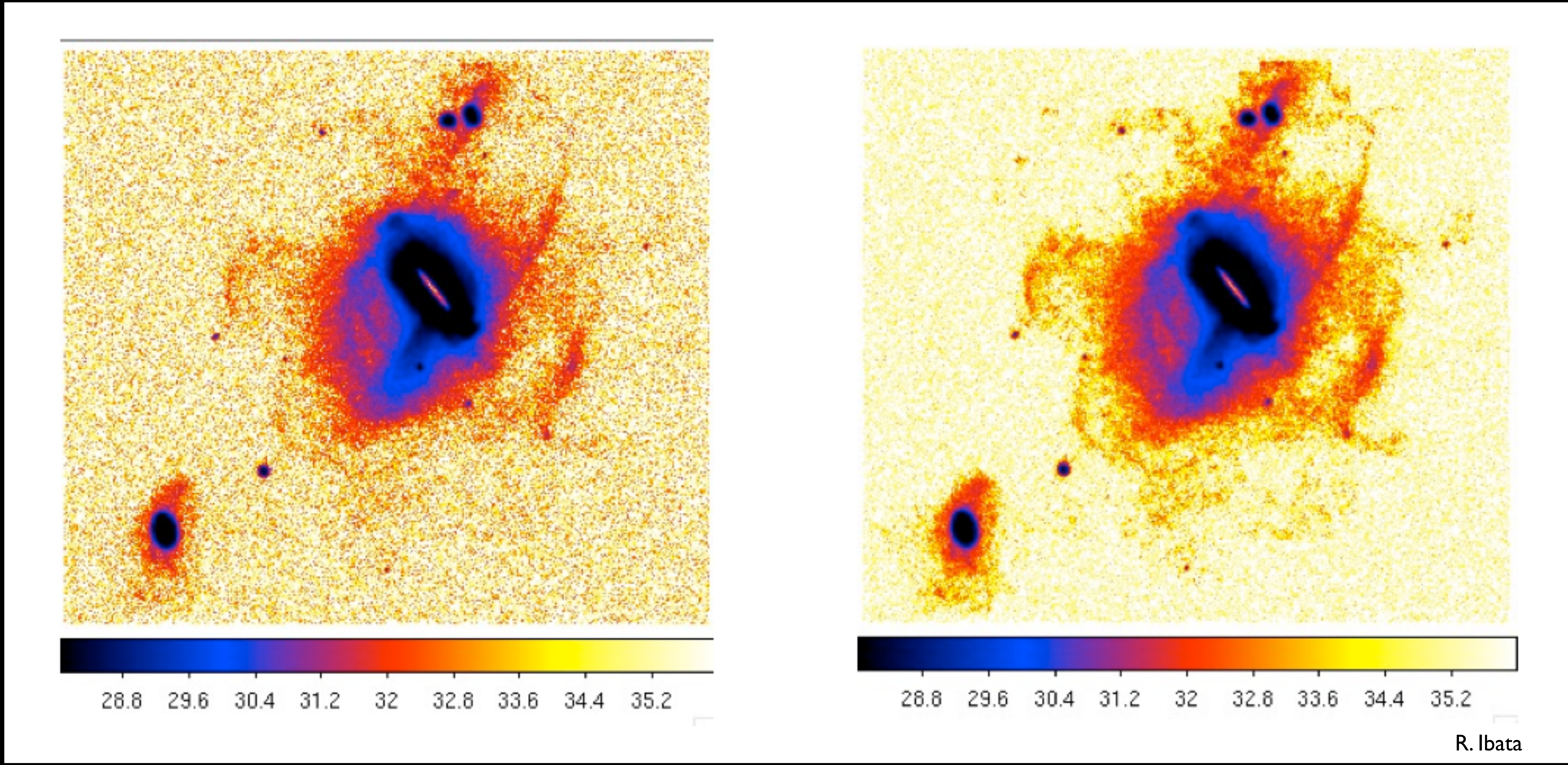
QE of each curved CCD optimised for each filter (TQ>85%)

Highly efficient: *no moving parts, passive cooling*



Expected performances - I   Optical bands

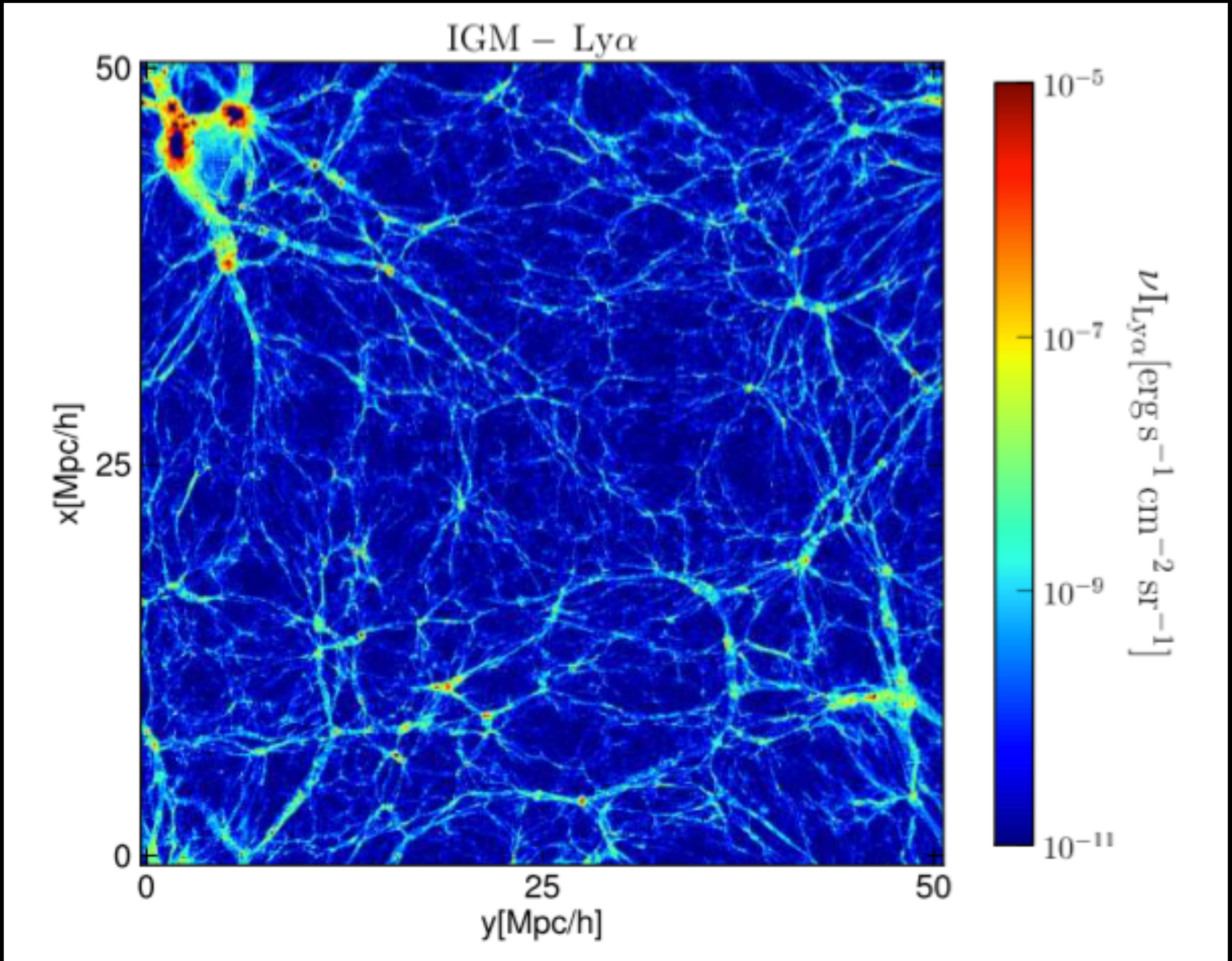
Simulated MESSIER images of a real galaxy (M31) seen at 150 Mpc



1 Msec

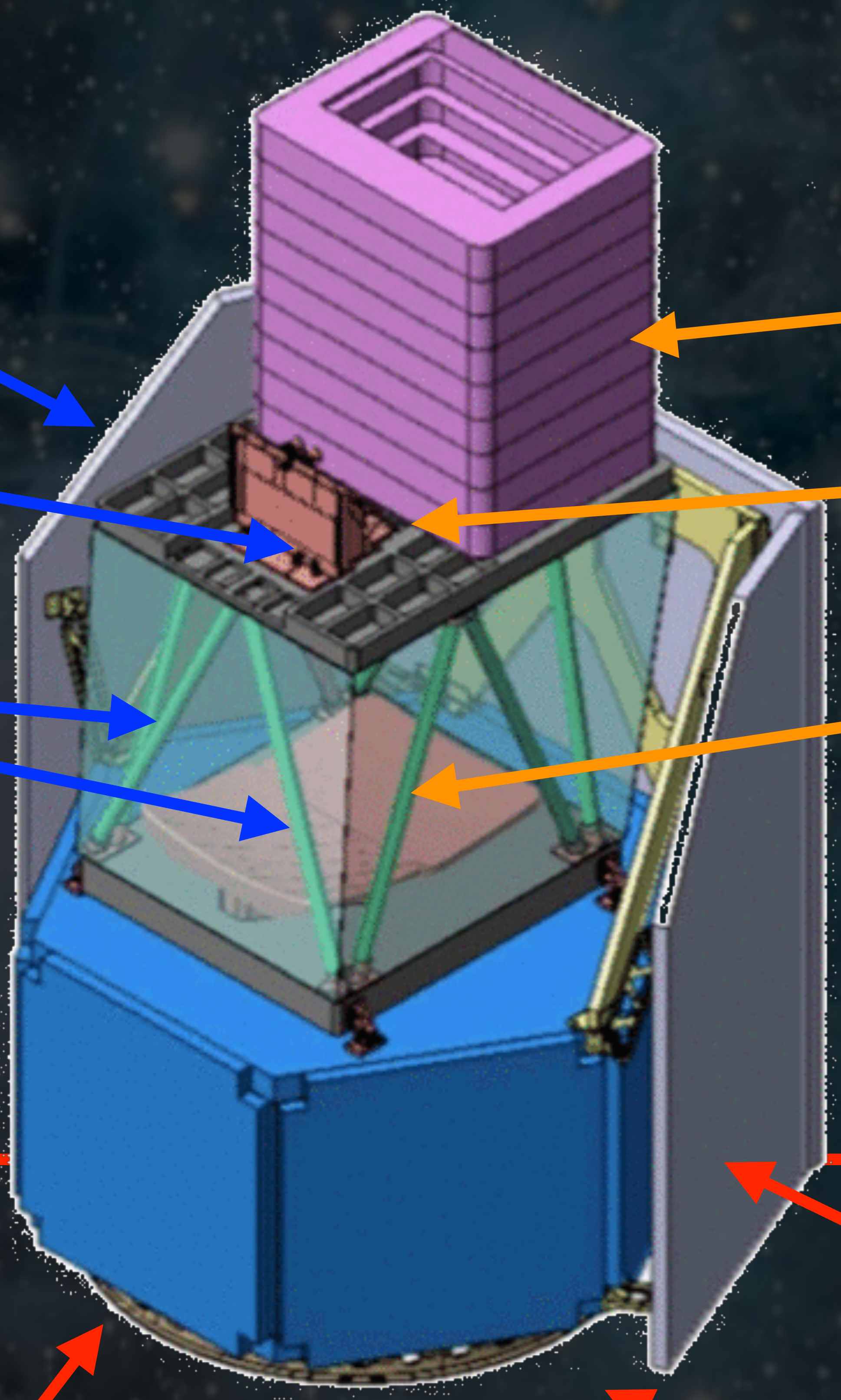
10 Msec

Expected performances - II UV bands

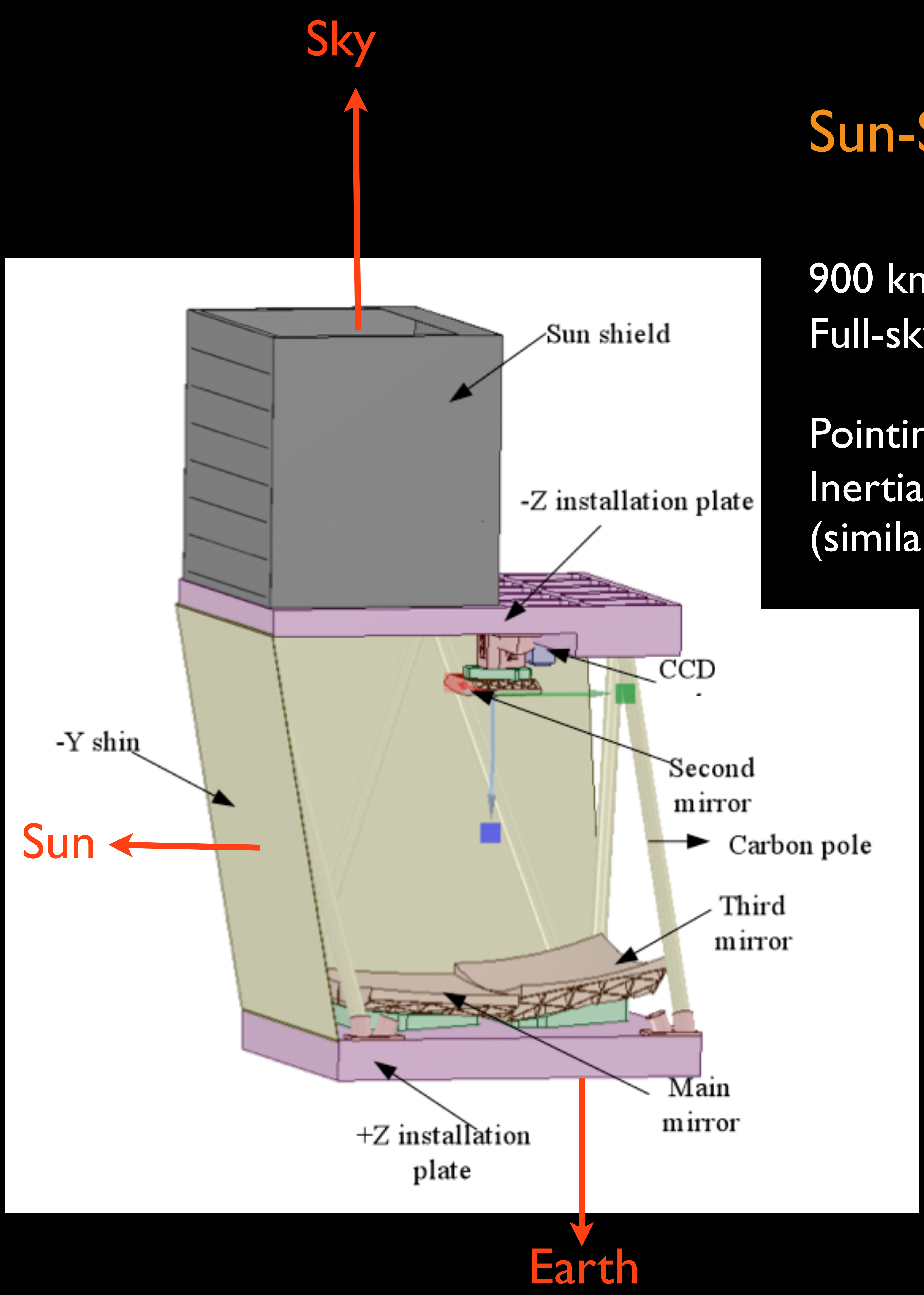


Credit: J. Fonseca & M. Silva / F. van de Voort & J Schaye

MESSIER Overview of Subsystems

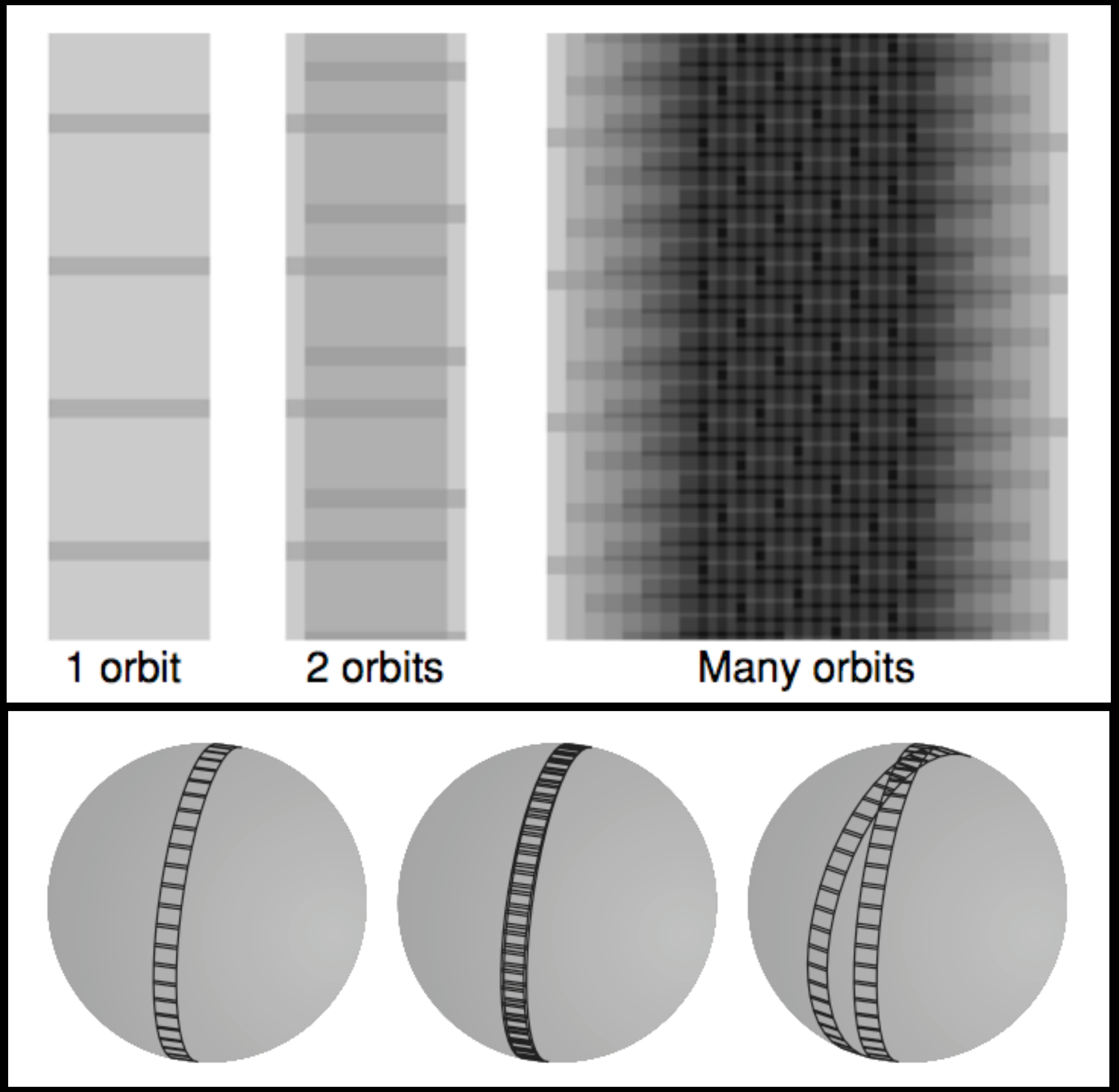


Sun-Synchronous Orbit



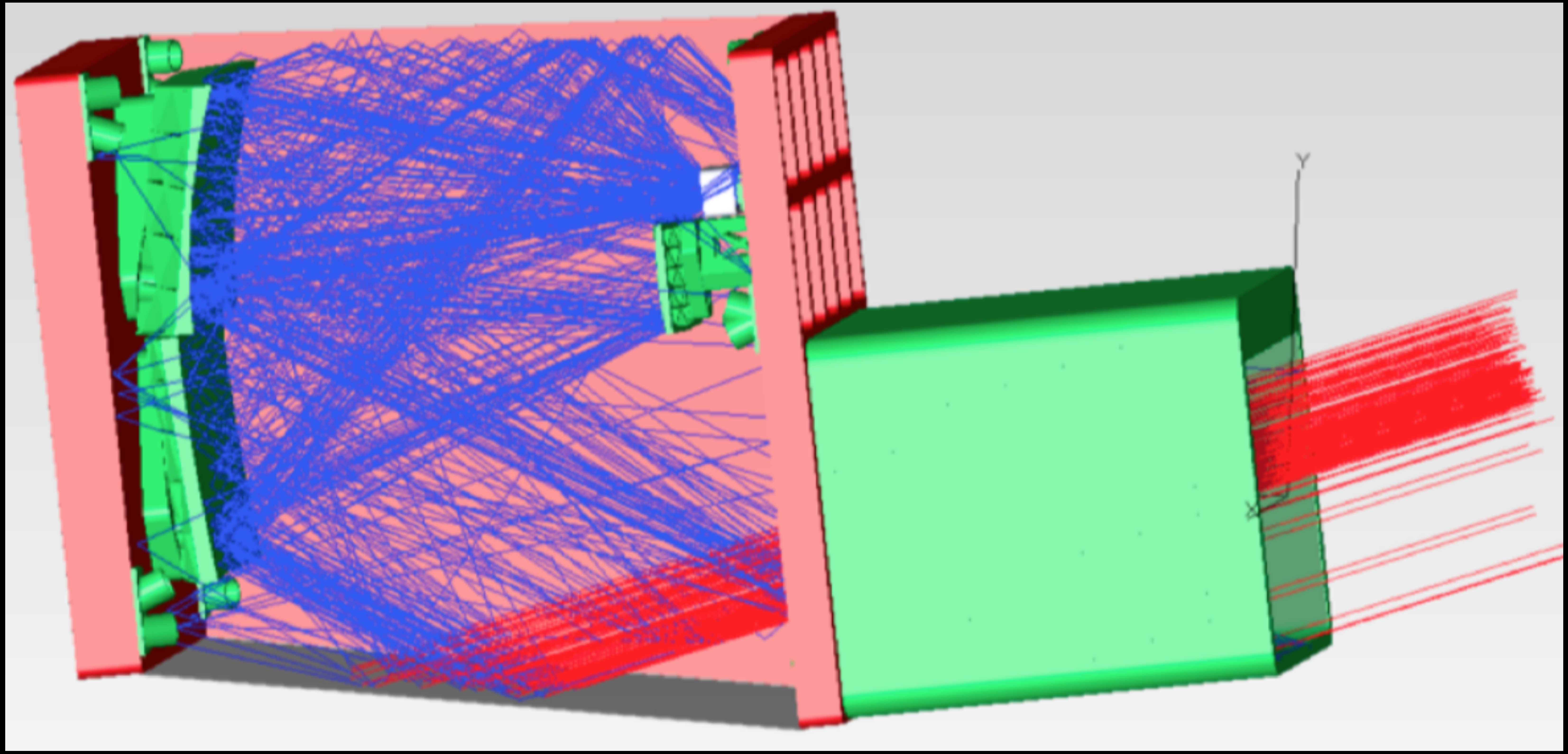
900 km, 98° inclination, LTAN 6h
Full-sky survey in 6 months

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

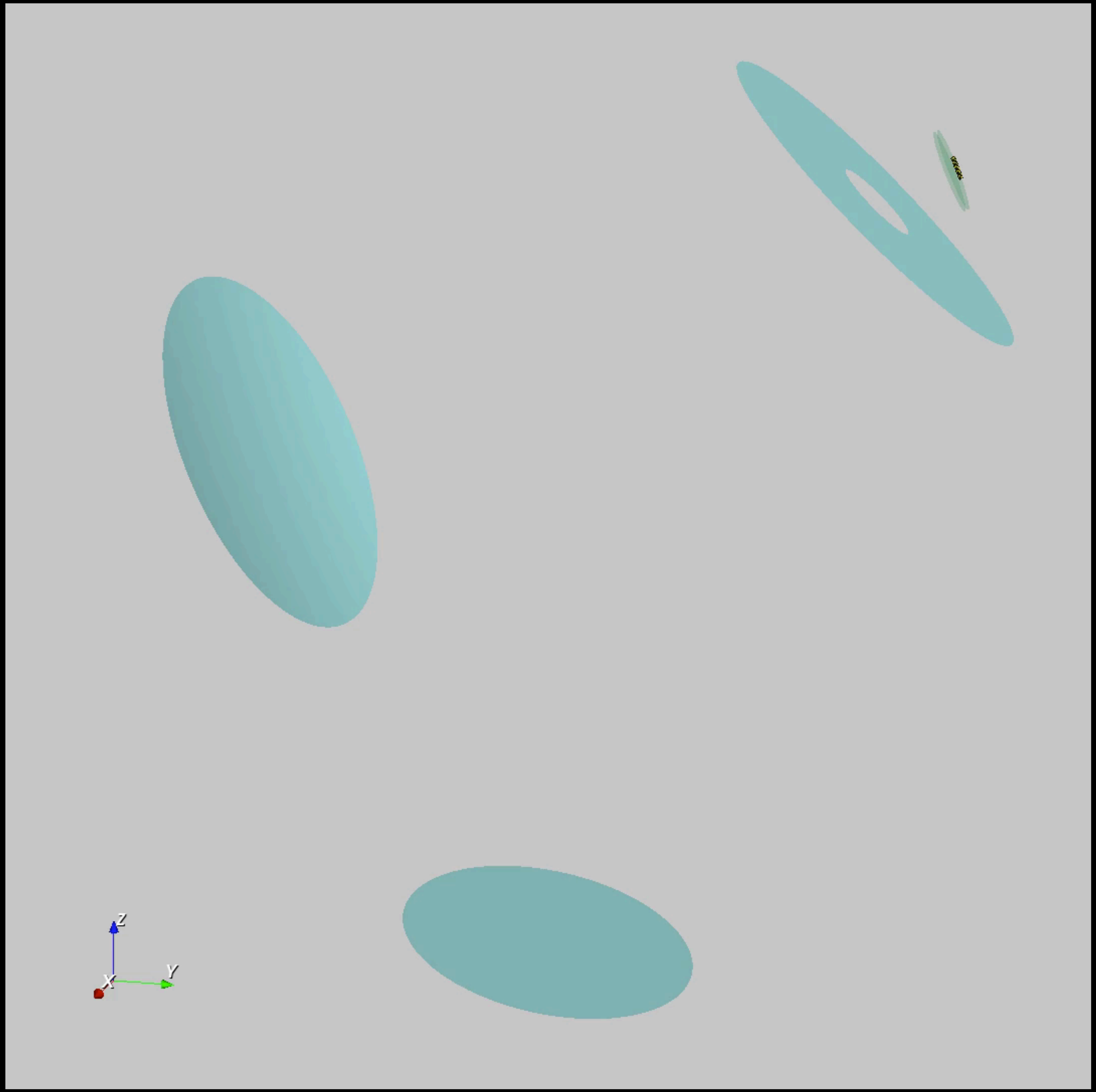


Photon Monte Carlo Simulations

Allows for the detailed modelling of *all* the physical processes involved

End-to-end simulation

Quantifies the variability of the wings of the PSF across FOV



Lombardo *et al.* (2019)

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

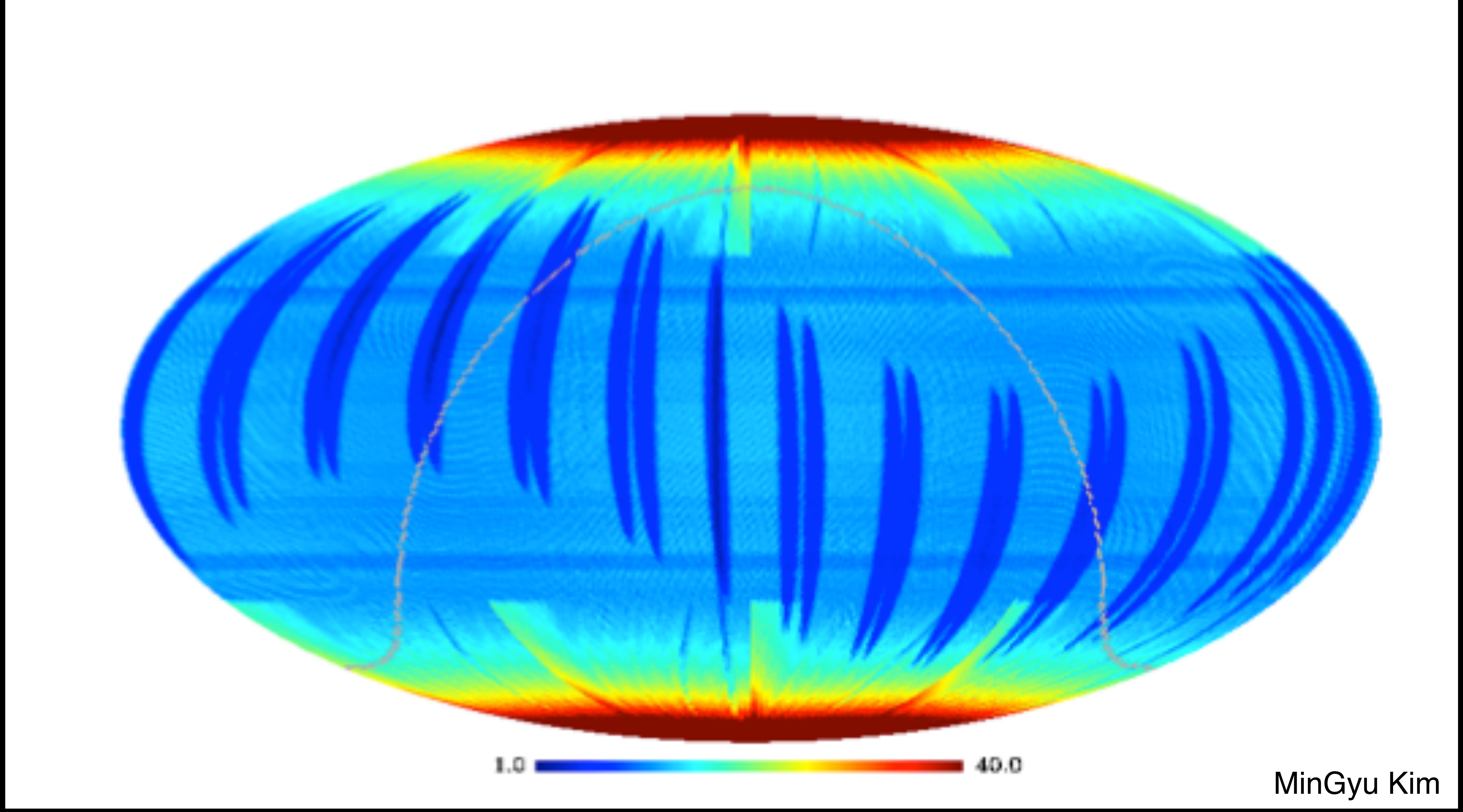
- What is the true luminosity function of galaxies ?
- What is the warm molecular content of galaxies in the low-z universe ?
- What is the role of intracluster light and the accretion history in clusters ?

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

Complete sky coverage every 6 months



Includes Moon avoidance angle (35 degrees) and South Atlantic Anomaly

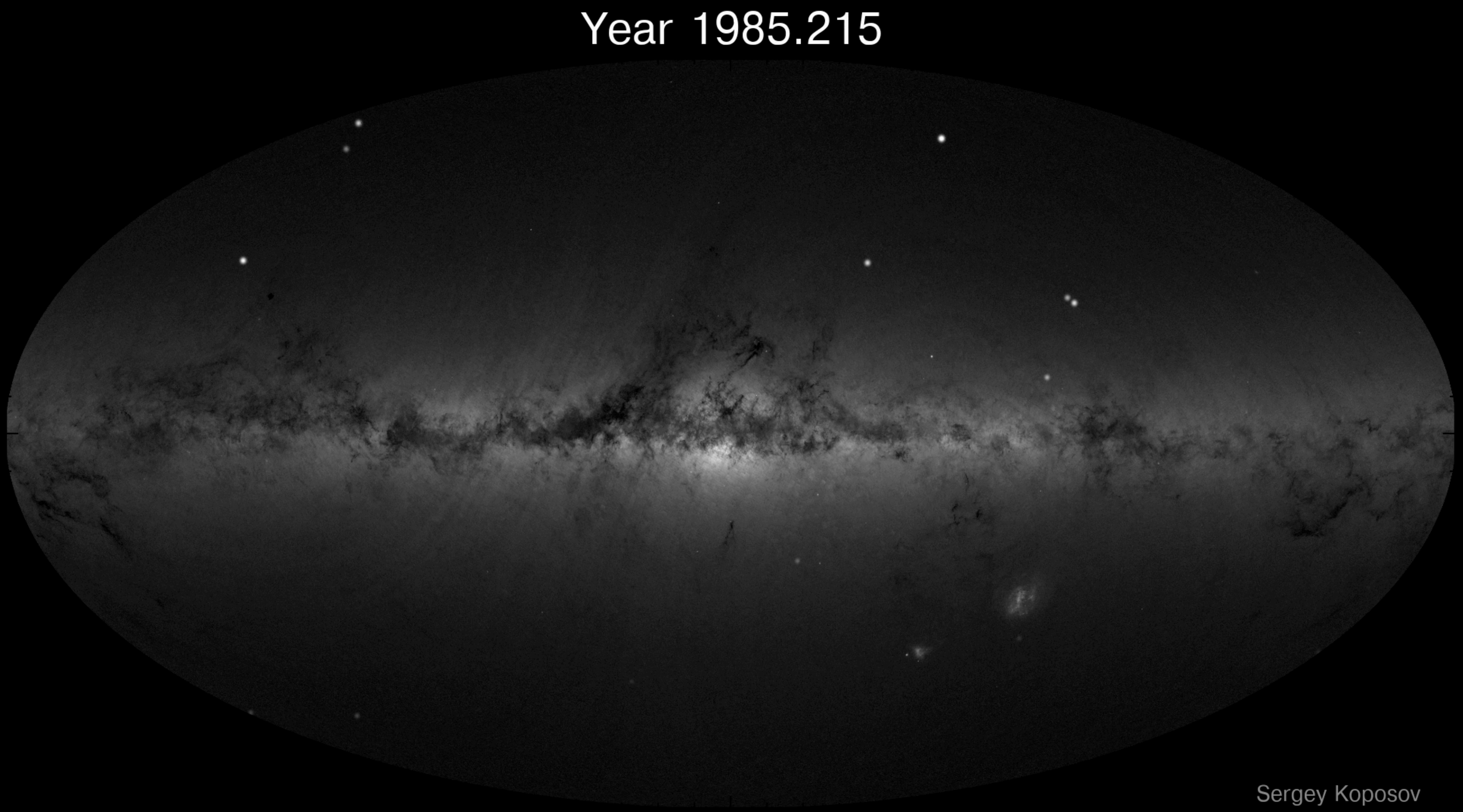
Time sampling

One UV-optical measure per pixel every 90 minutes for 2 days at $\beta = 0$

One UV-optical measure per pixel every 90 minutes at $|\beta| \geqq 80$ <u>at all times</u>

CSC 9 Time-domain astronomy

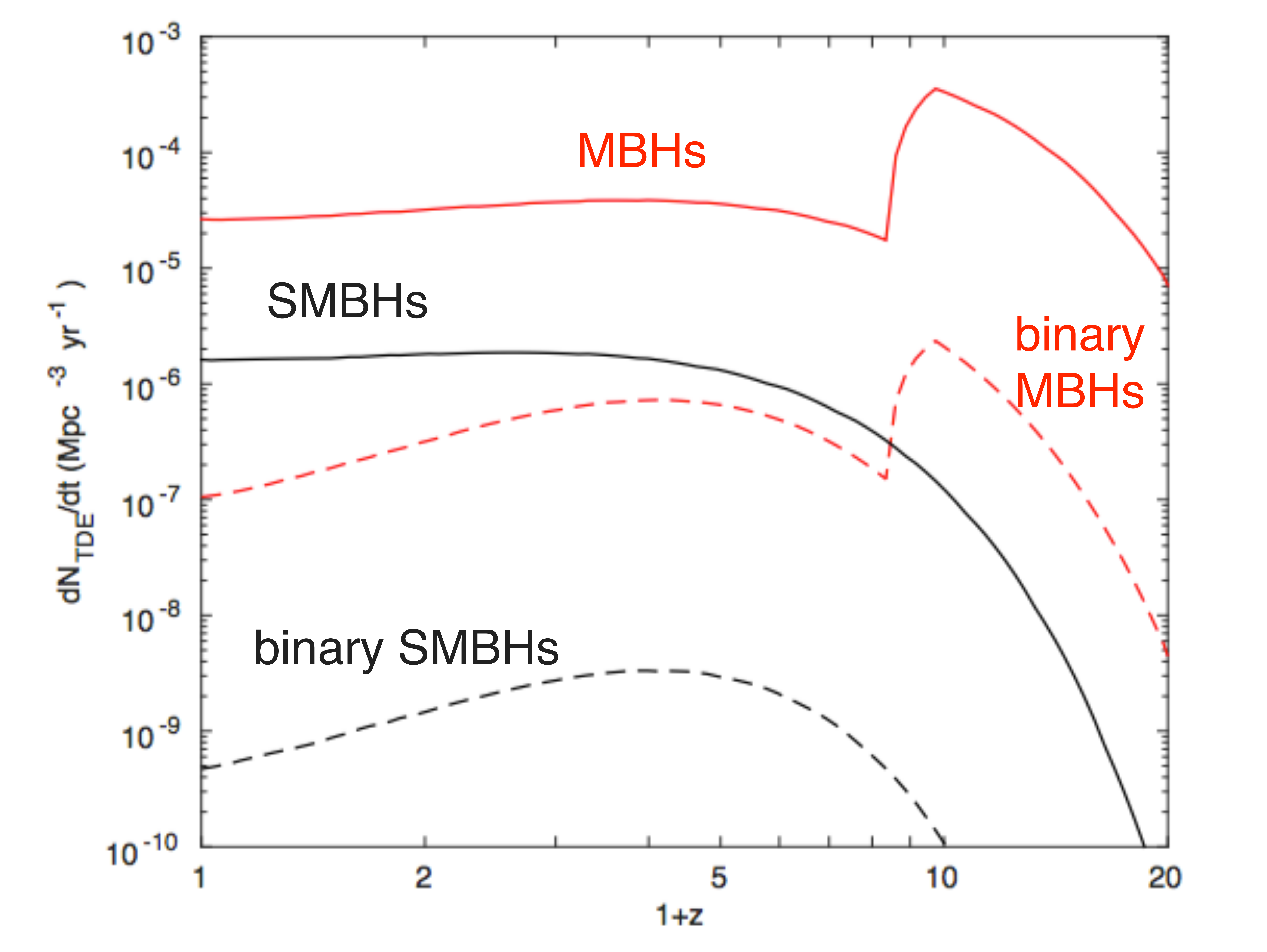
Variability and transients *simultaneously* from the UV to the optical



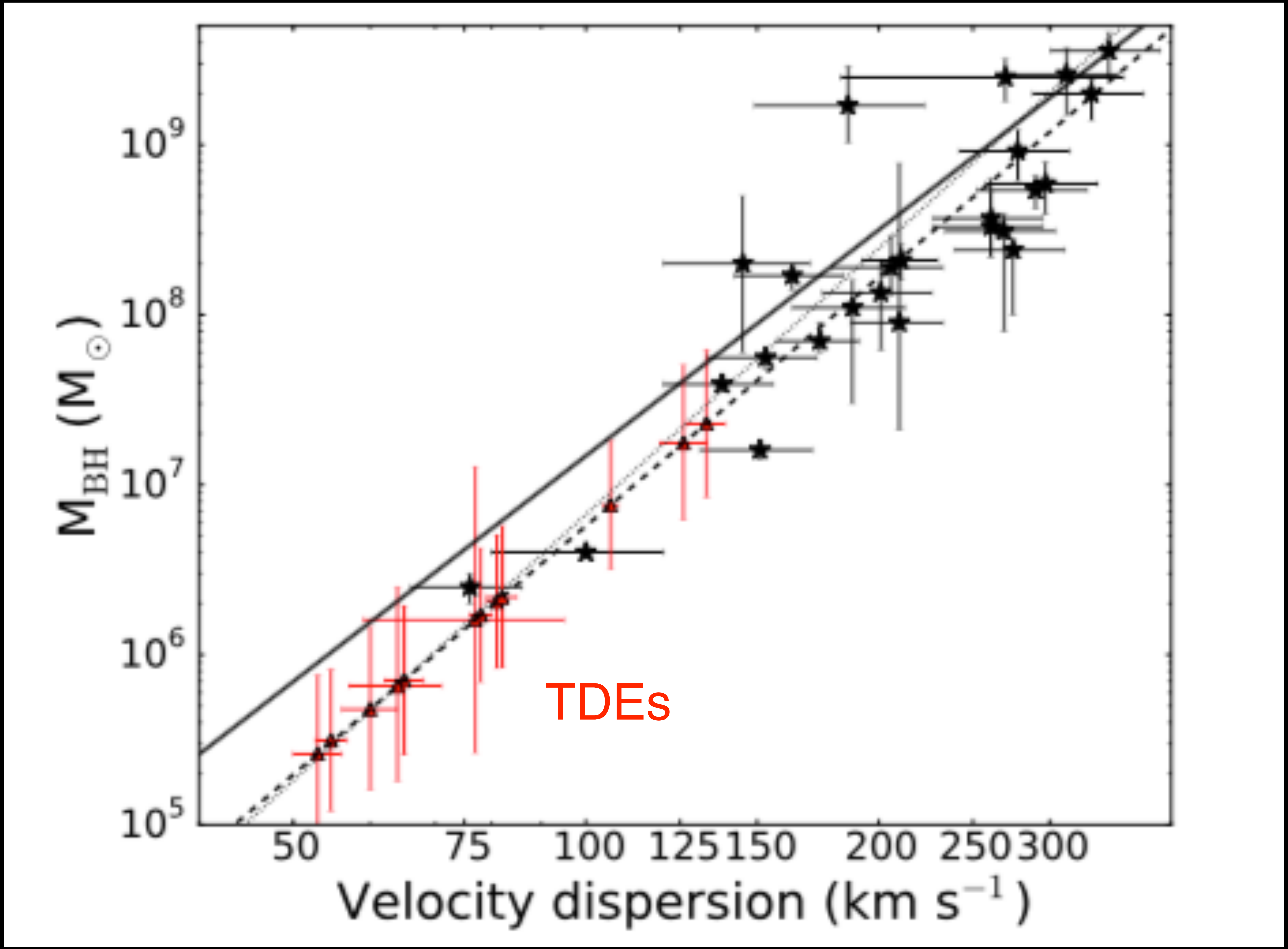
(i) rest-frame UV light curves for SNIa

(ii) Tidal Disruption Events

Rate per comoving volume

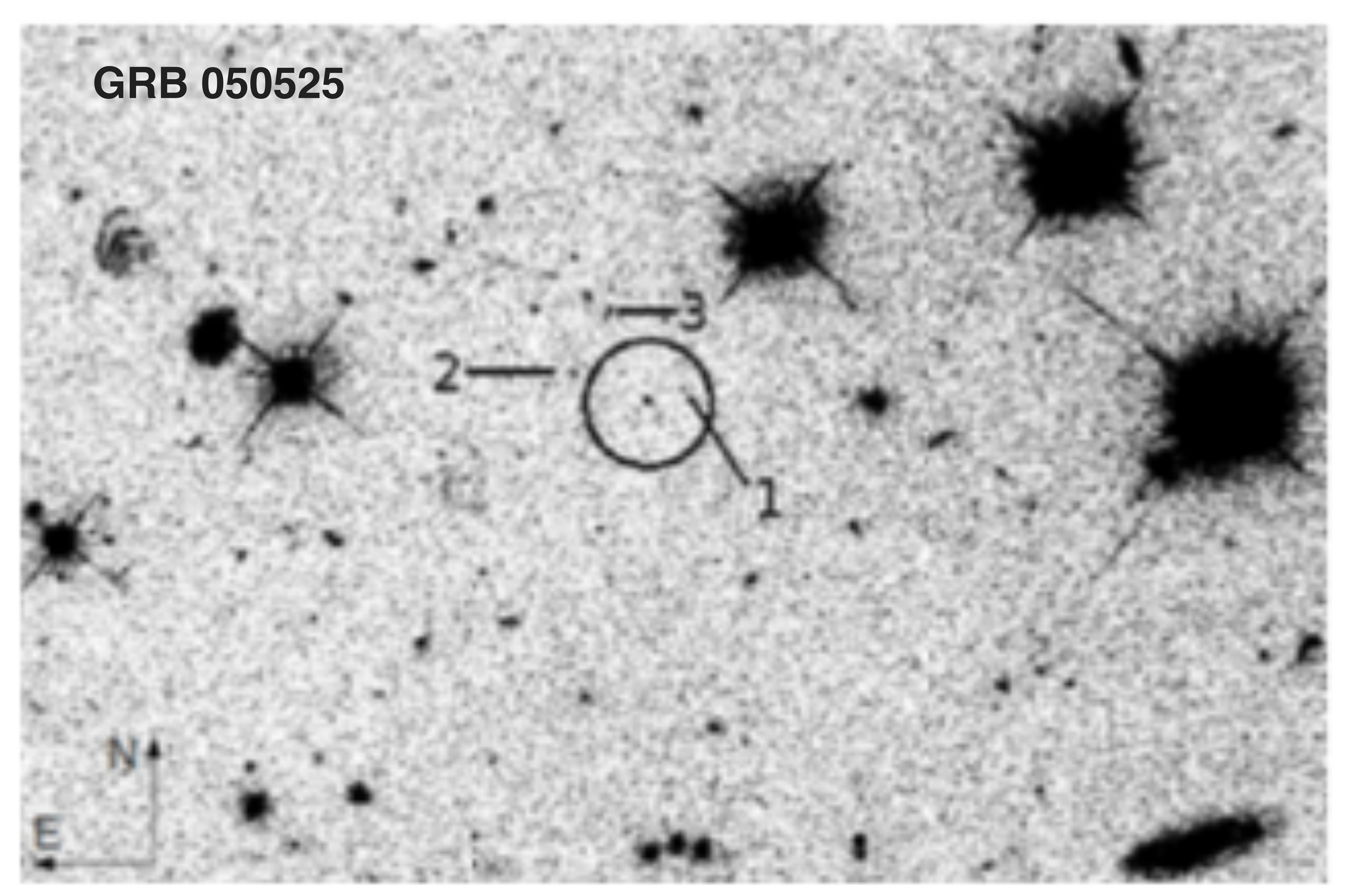


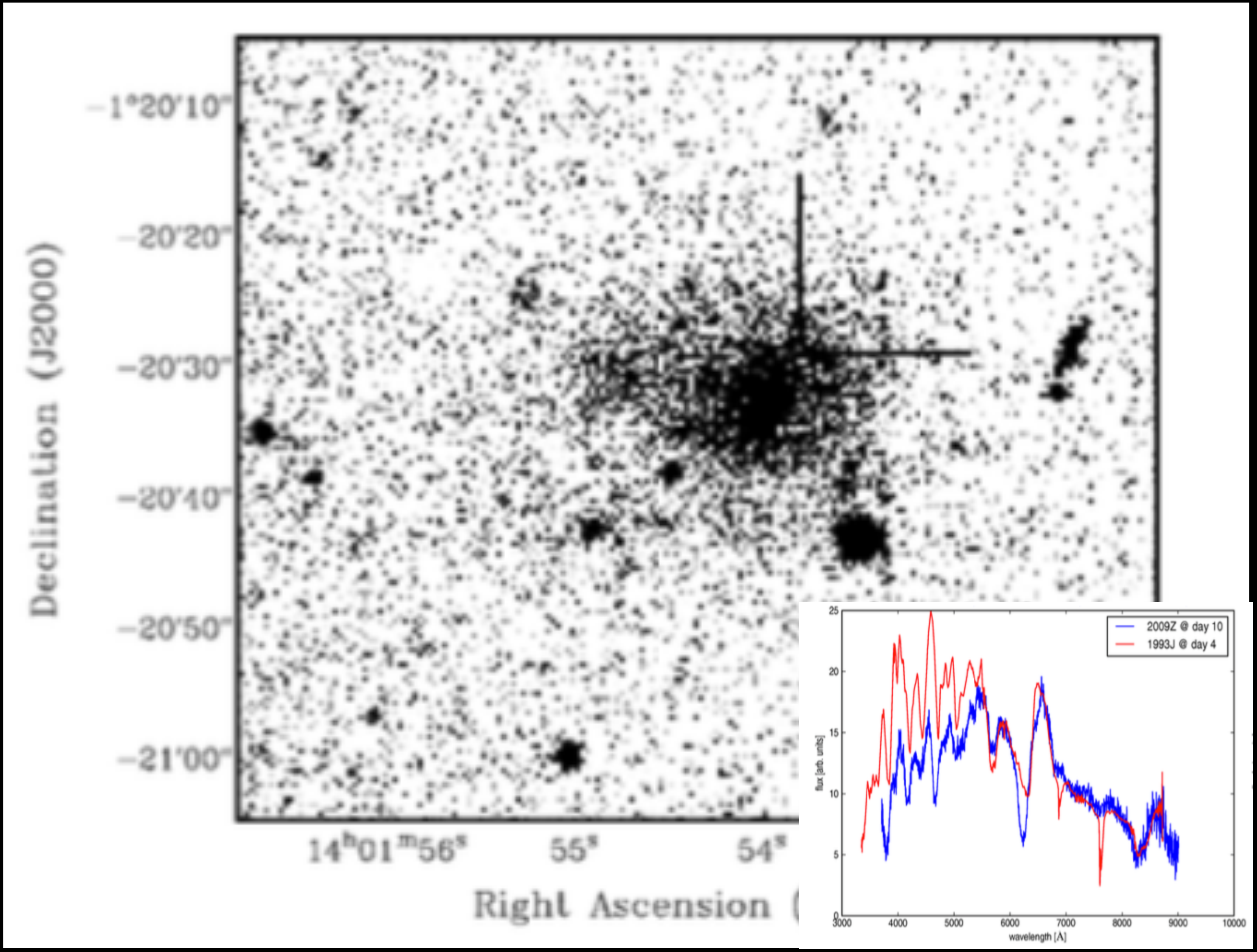
Fialkov & Loeb (2017)



Wevers *et al.* (2017)

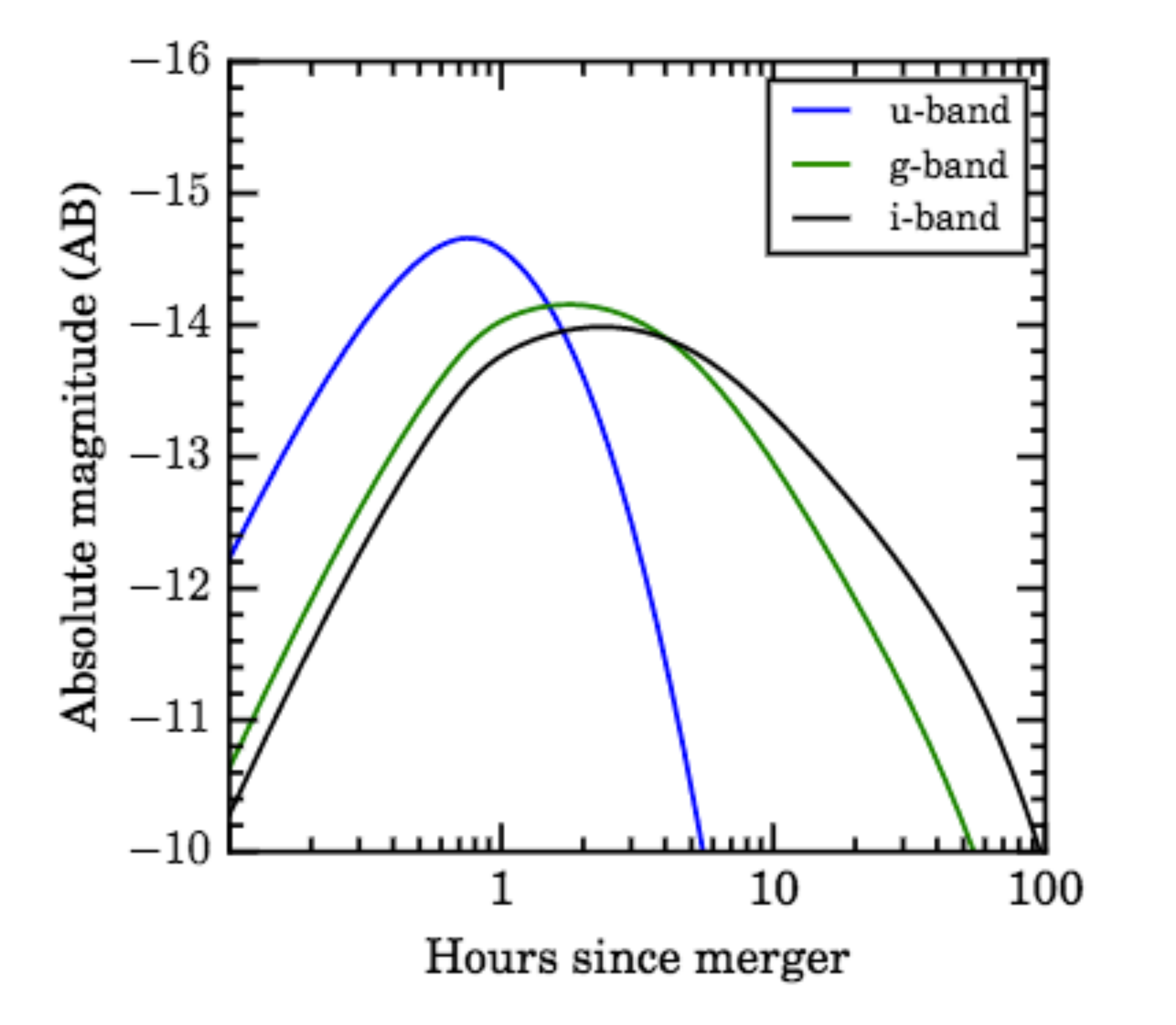
(iii) Orphan SN and GRB



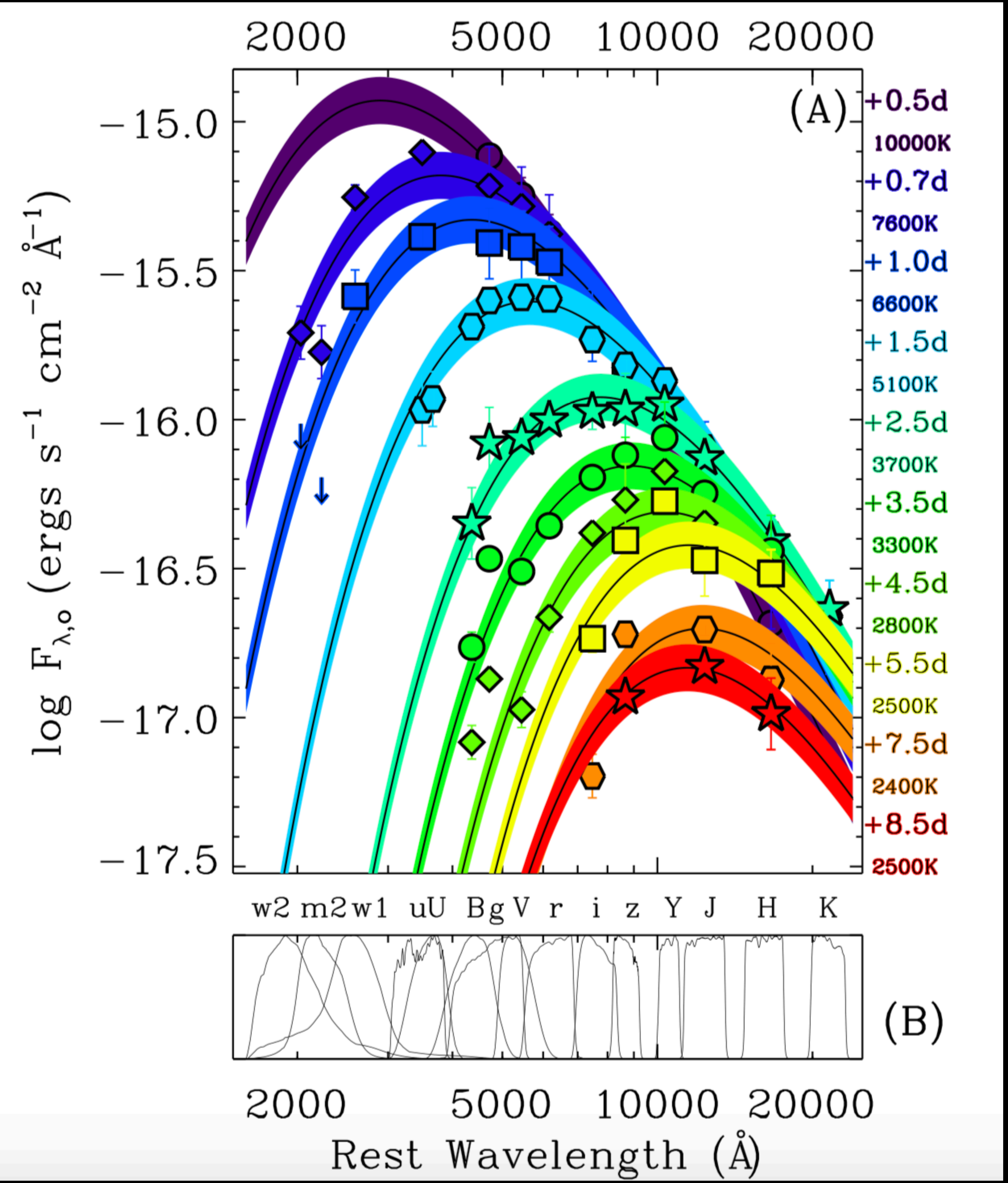


Zinn *et al.* (2012)

(iv) UV counterparts of gravitational wave events

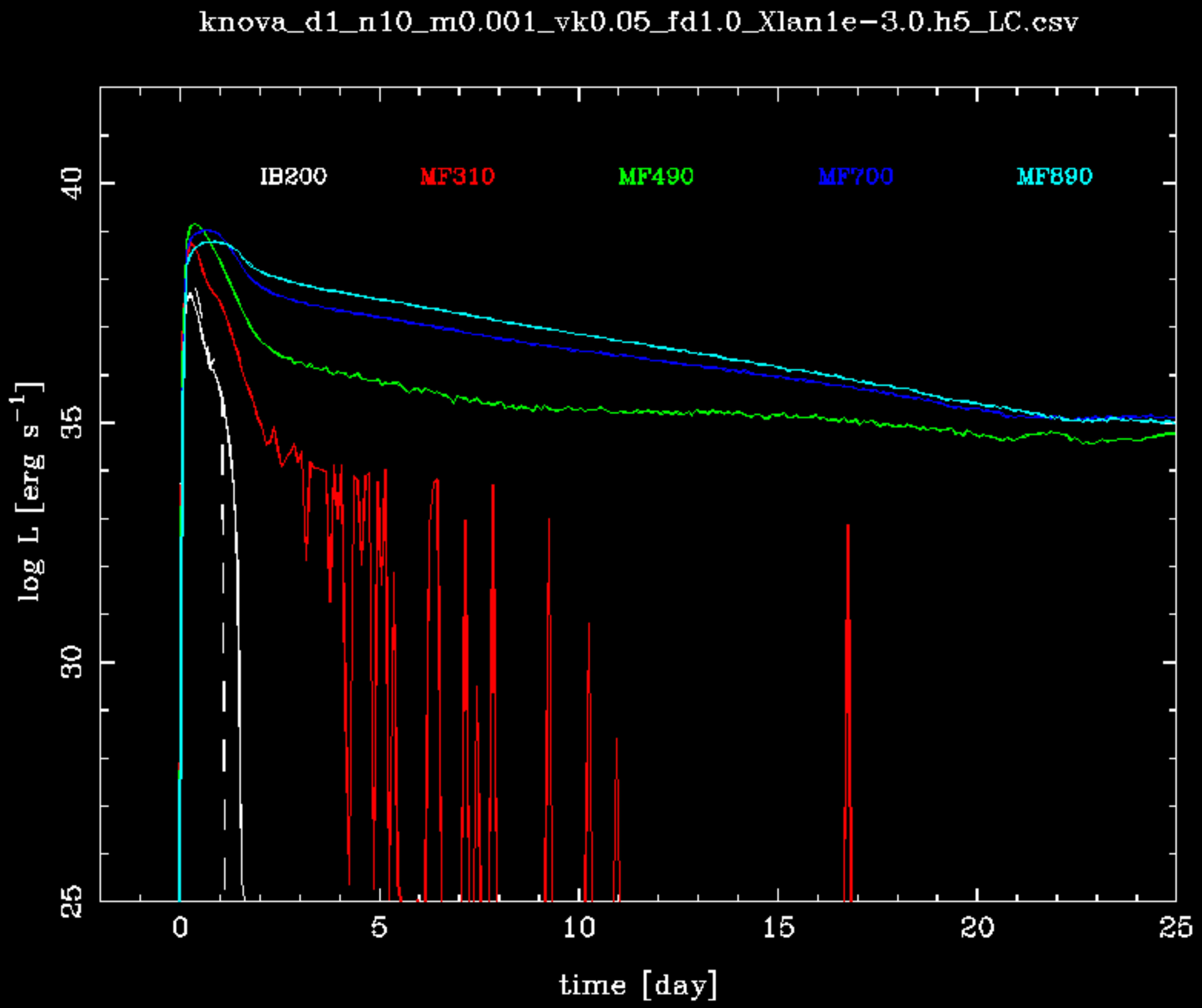


Ridden-Harper *et al.* (2017)



Drout *et al.* (2017)

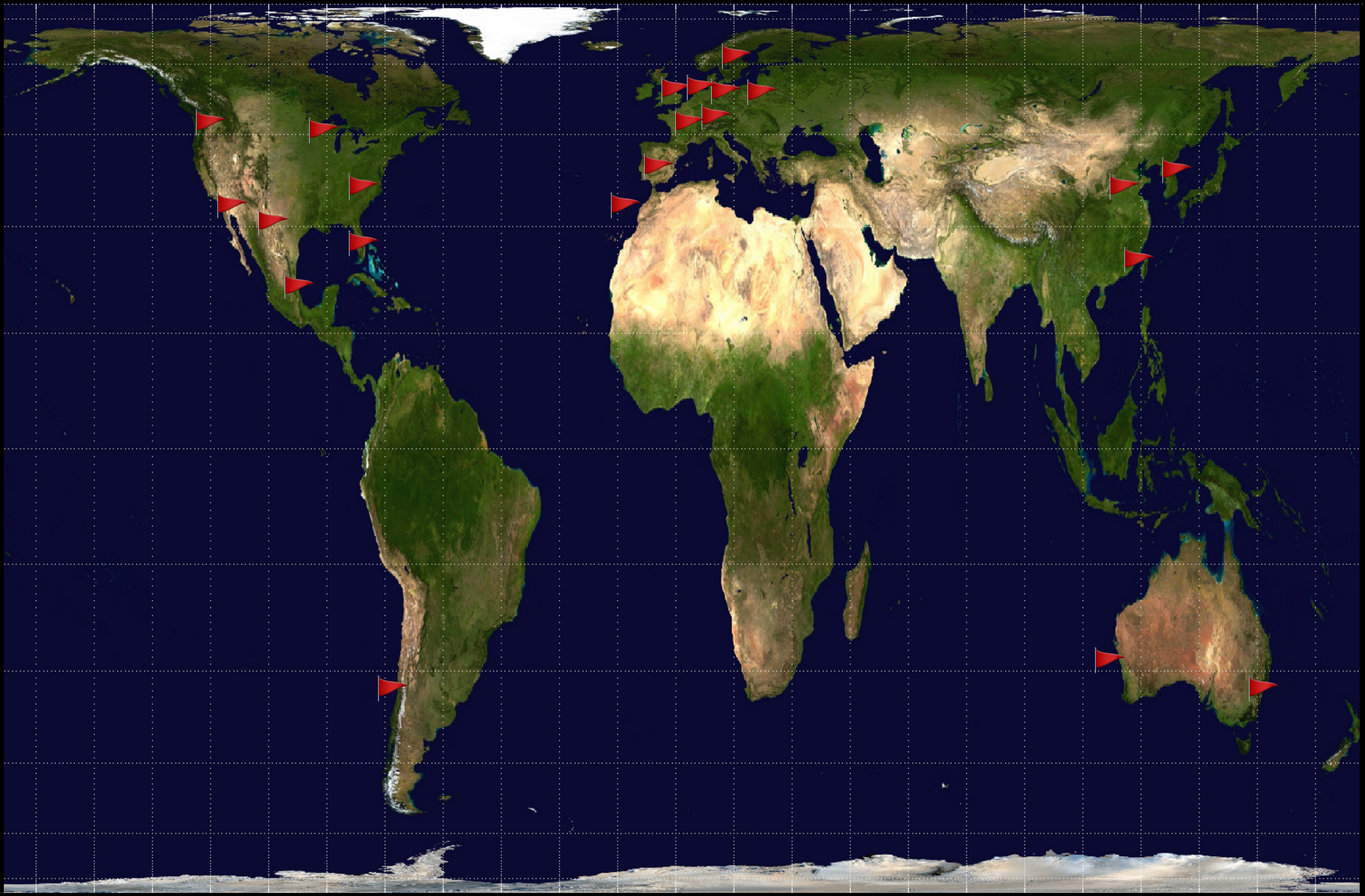
Multiband lightcurves of EM counterparts of gravitational wave events



Kilonovae
observed with MESSIER

Models
by Kasen *et al.* (2017)

The MESSIER collaboration



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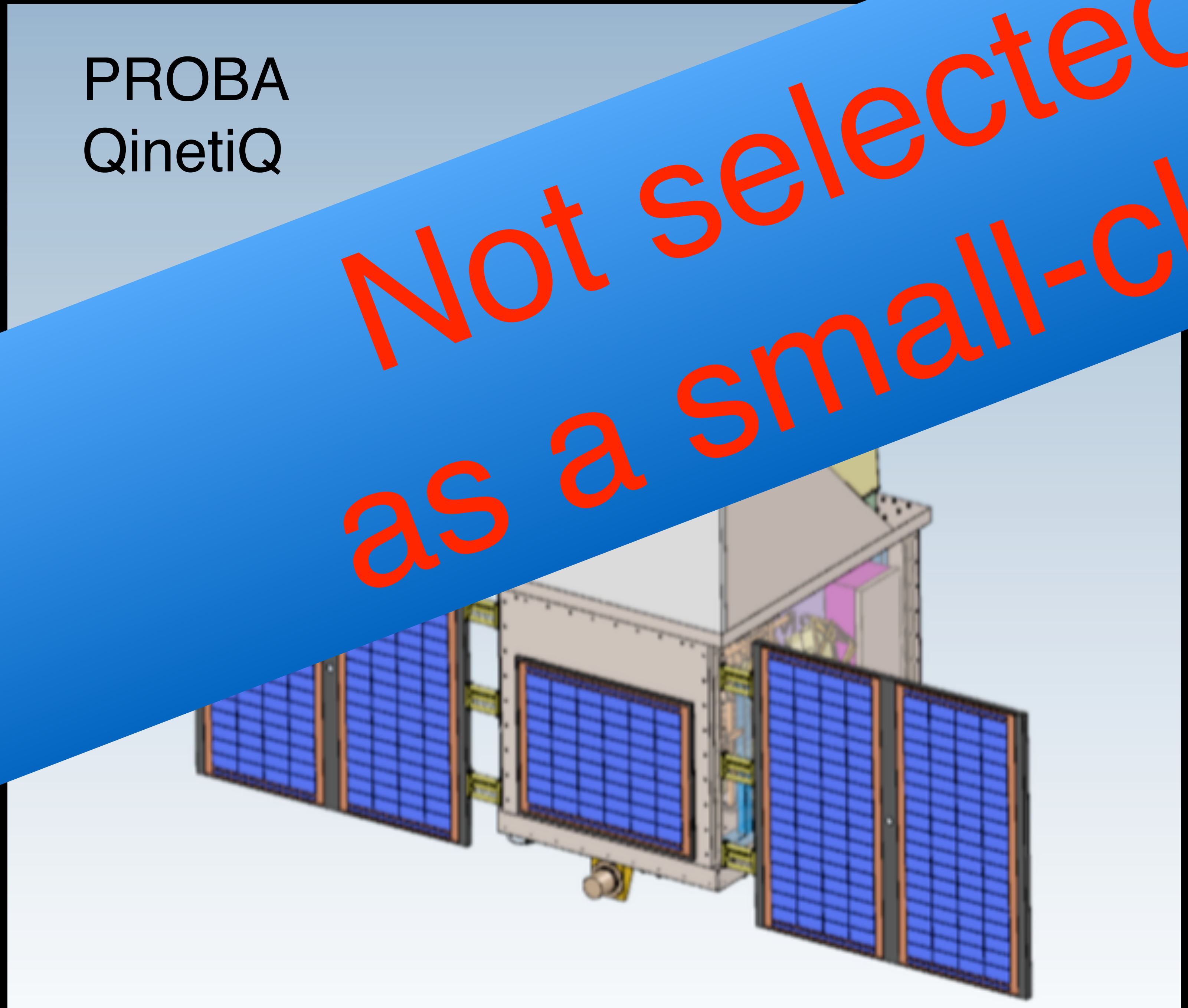
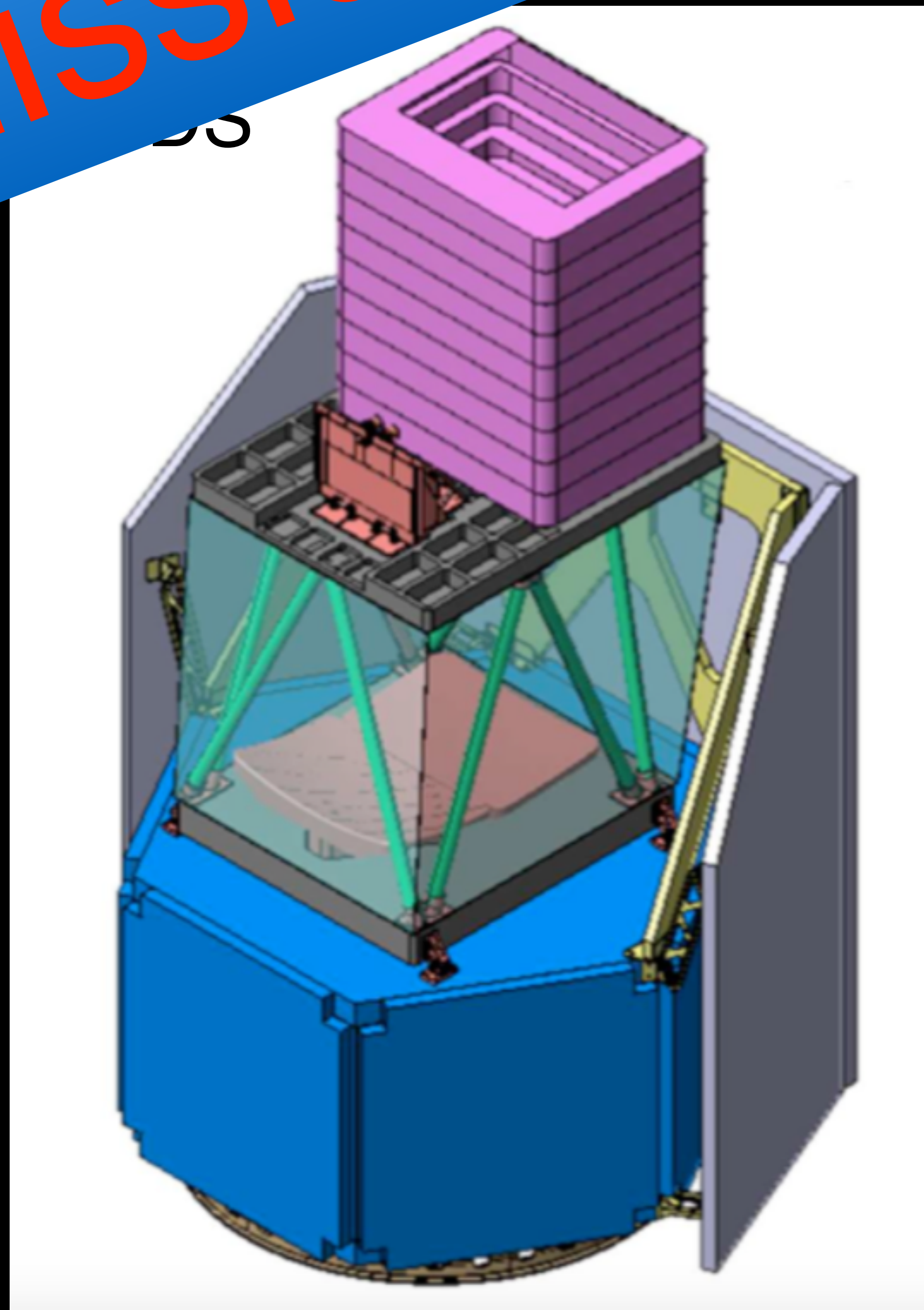
Designs by two competing industrial contractors (EADS/CASA & QinetiQ)

- 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





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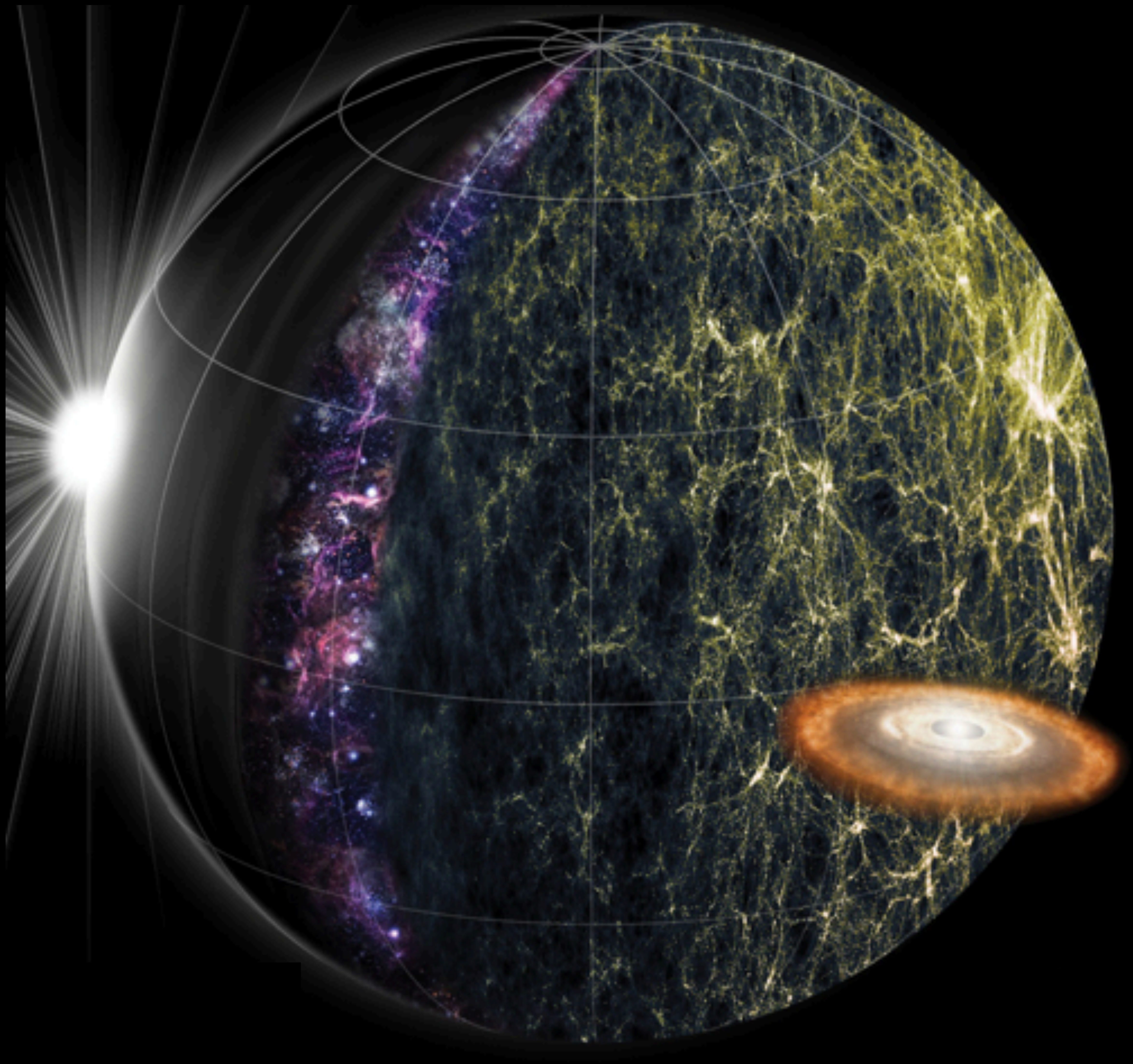

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- From the Zodiacal Light to the Cosmological Optical/UV backgrounds
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