# The UKIRT Infrared Deep Sky Survey

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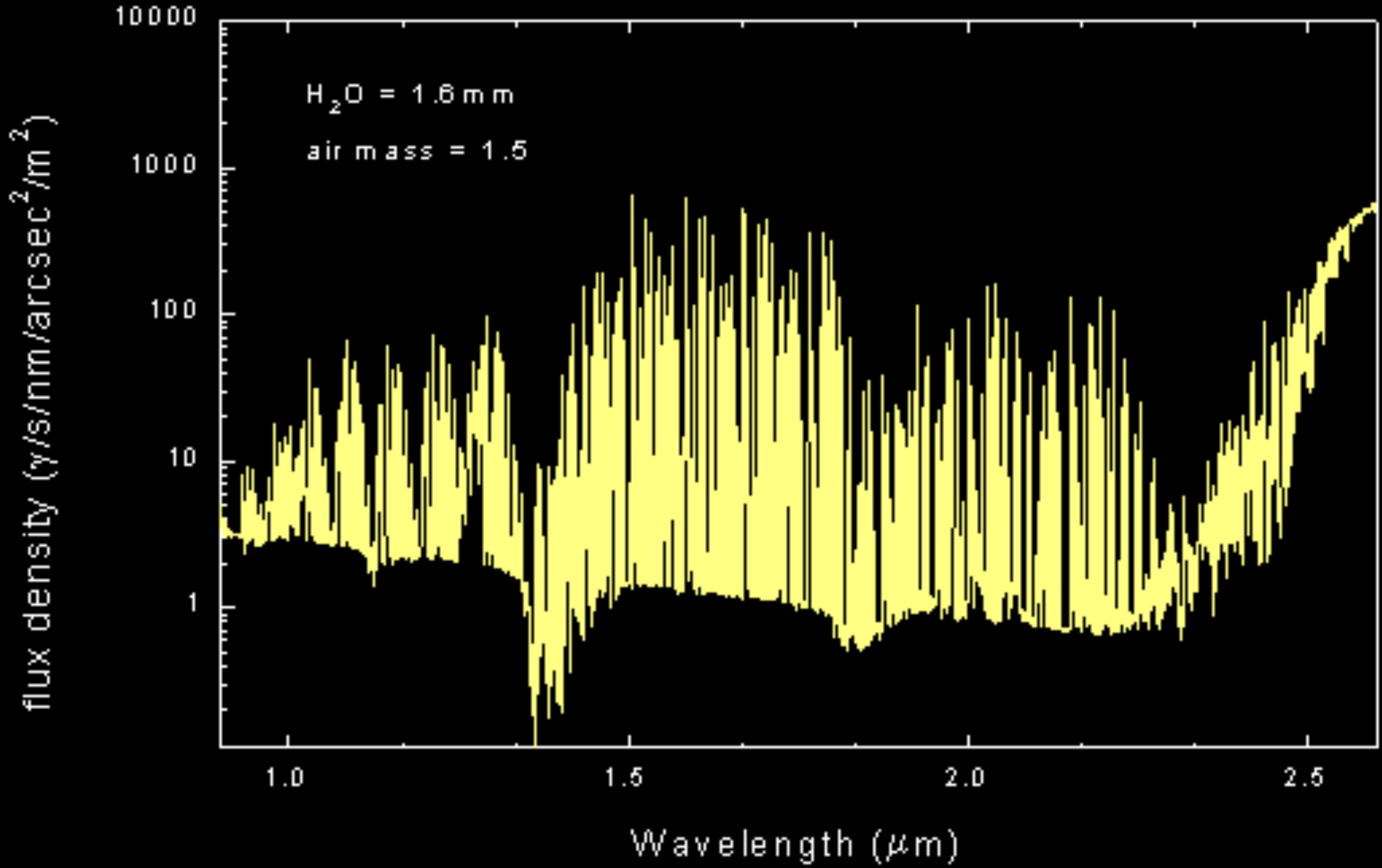
UKIDSS Survey Scientist

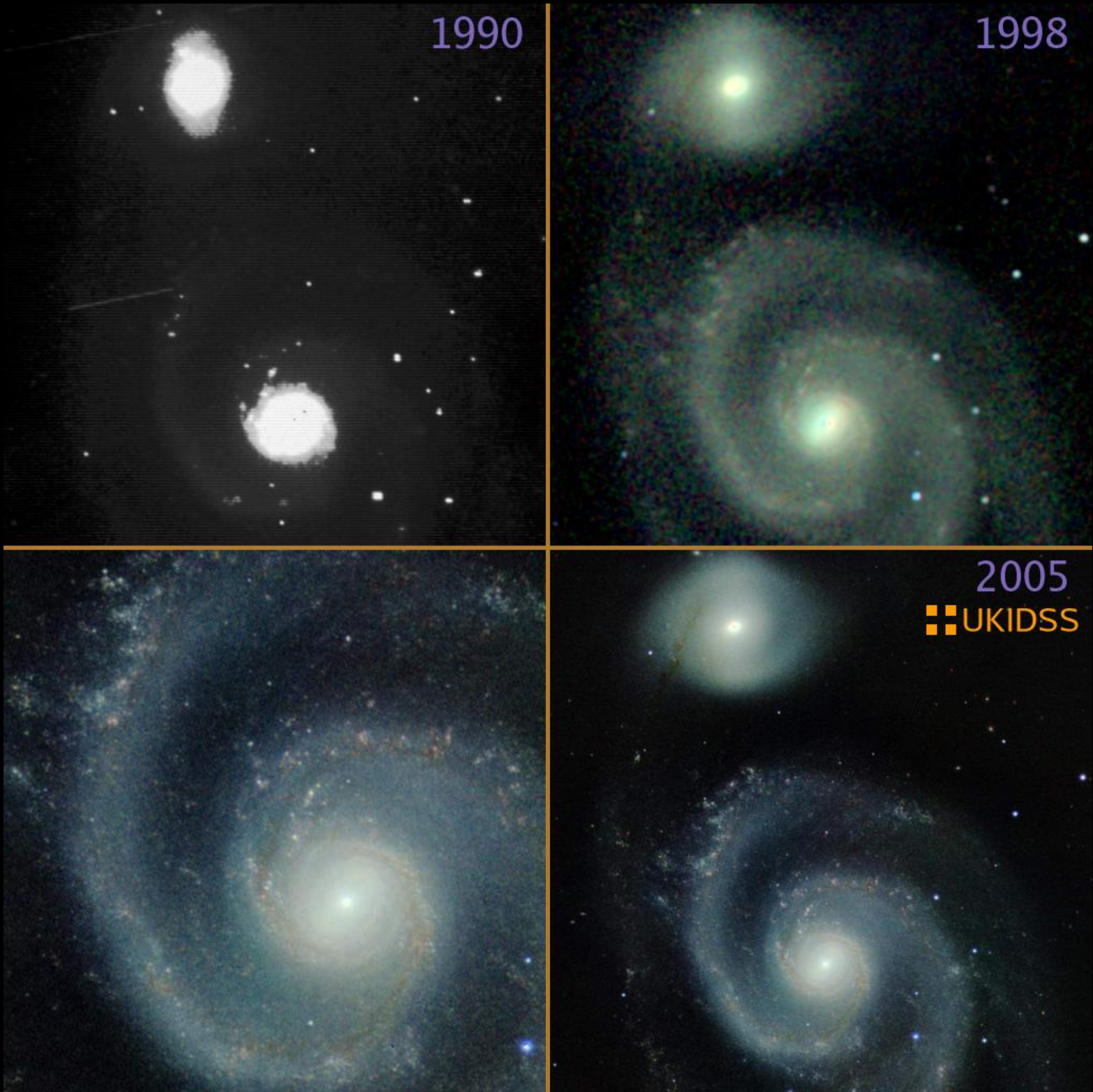
1. Context
2. Why the near-infrared is useful
3. UKIDSS
4. Science highlights
5. Search for high-redshift $5.8<z<7.2$ quasars in UKIDSS
   with Daniel Mortlock, Mitesh Patel, Bram Venemans, Paul Hewett, Richard McMahon, Chris Simpson

# Astronomers' near-infrared is 1-2.5 micron



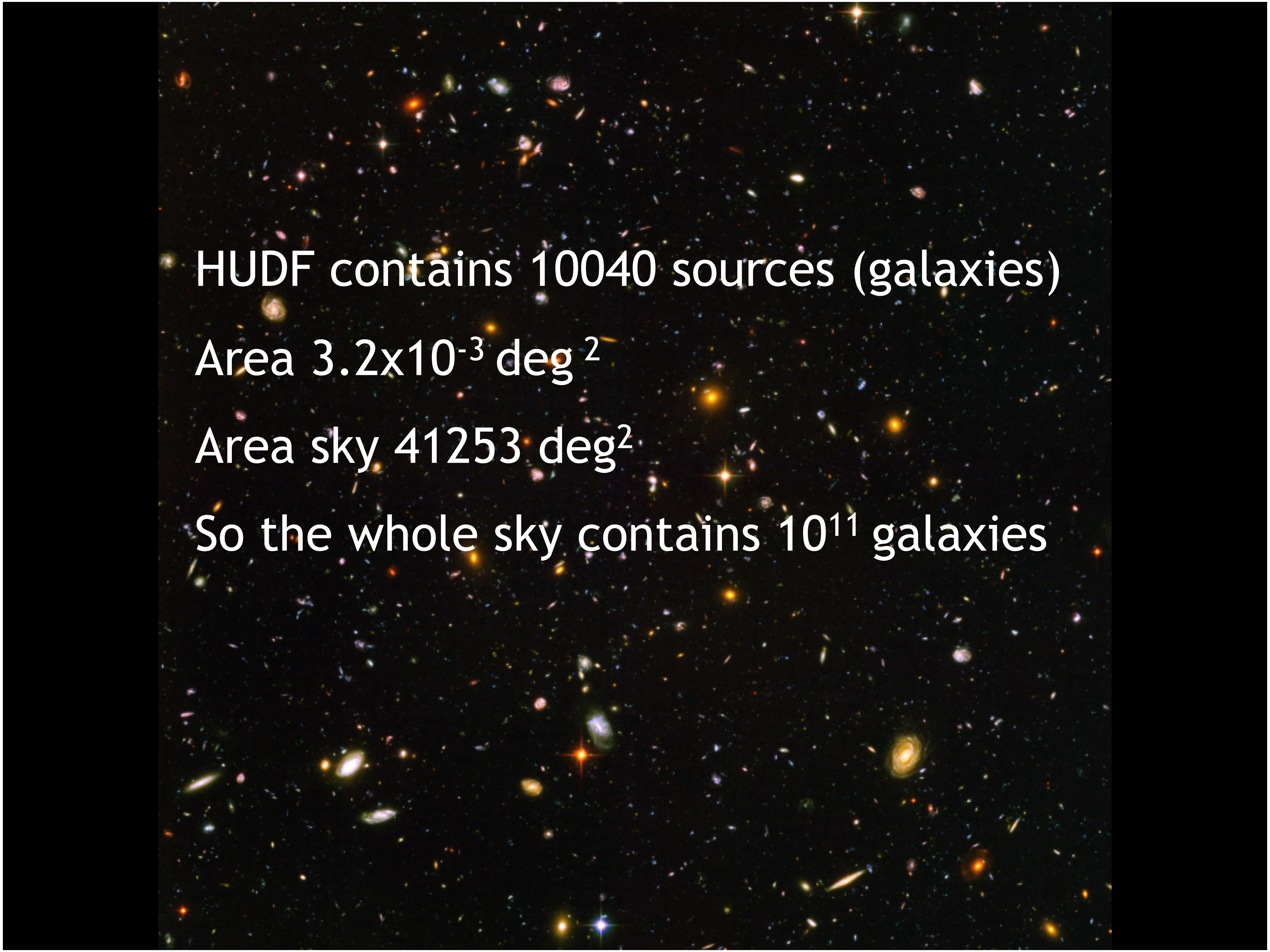
# Landmarks in near-ir surveys

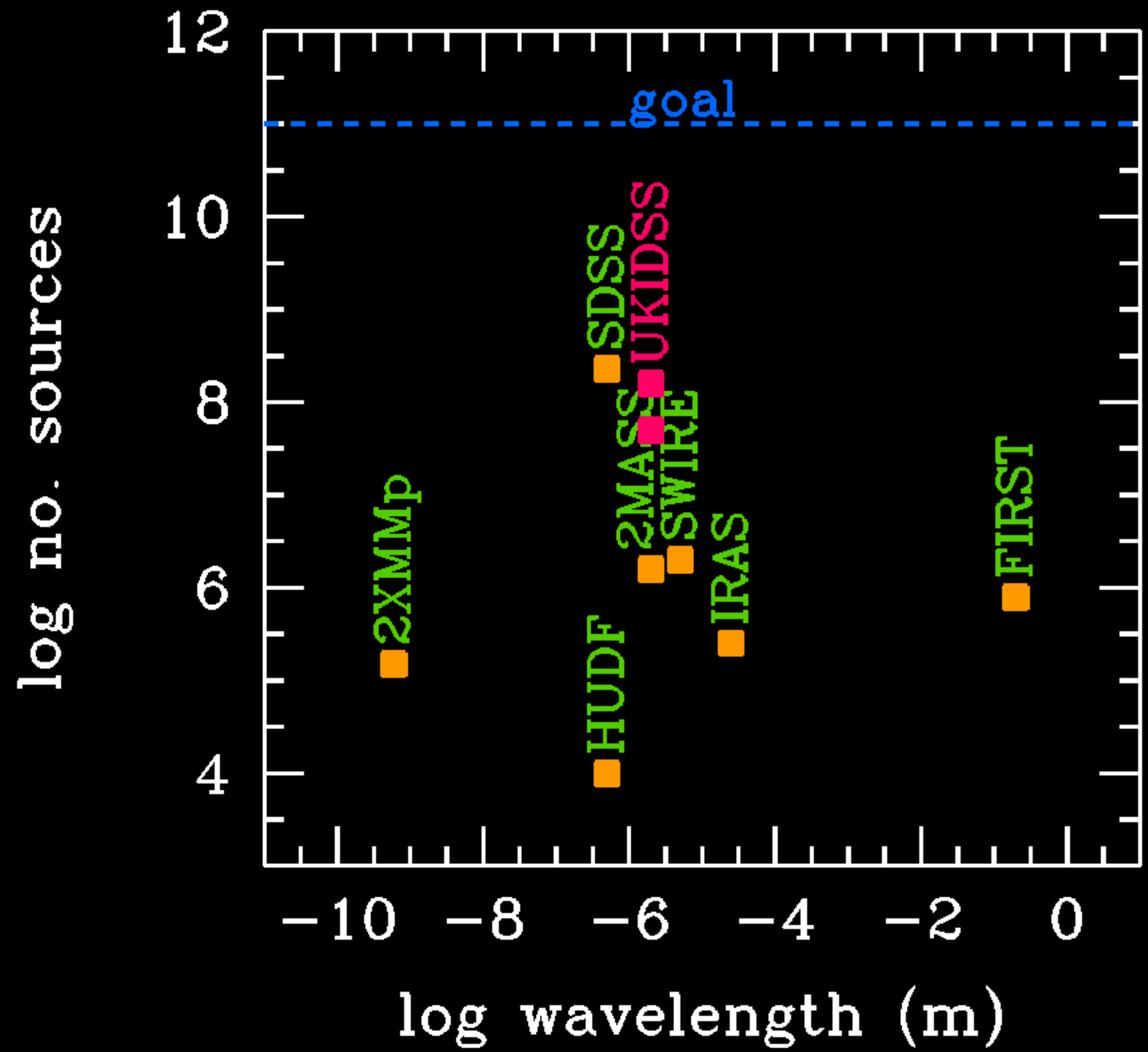
| Survey | Dates | Pix size | No. sources |
|---|---|---|---|
| TMSS | -1969 | 4 arcmin | 5612 |
| 2MASS | 1997-2001 | 2 arcsec | $4.7 \times 10^8$ |
| UKIDSS | 2005-2012 | 0.4 arcsec | $1.8 \times 10^9$+ |


1990
1998
2005
UKIDSS

Sandage (telescope proposal):

"Not all astronomical sources have been observed at all wavelengths. We propose to remedy this."


HUDF contains 10040 sources (galaxies)
Area 3.2x10^-3 deg^2
Area sky 41253 deg^2
So the whole sky contains 10^11 galaxies



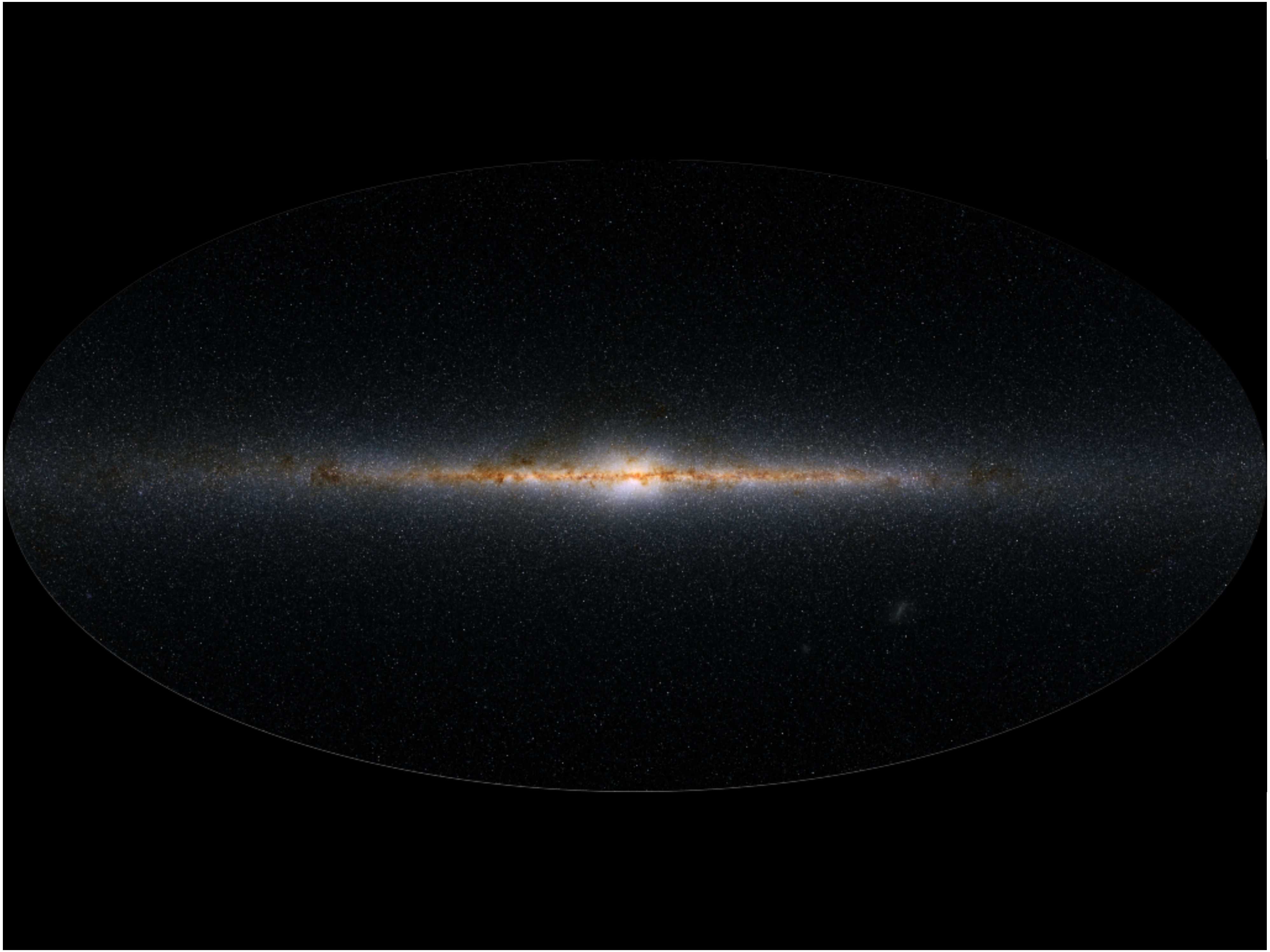
goal
SDSS
UKIDSS
2MASS
SWIRE
2XMMp
HUDF
IRAS
FIRST
log no. sources
log wavelength (m)
12
10
8
6
4
−10
−8
−6
−4
−2
0

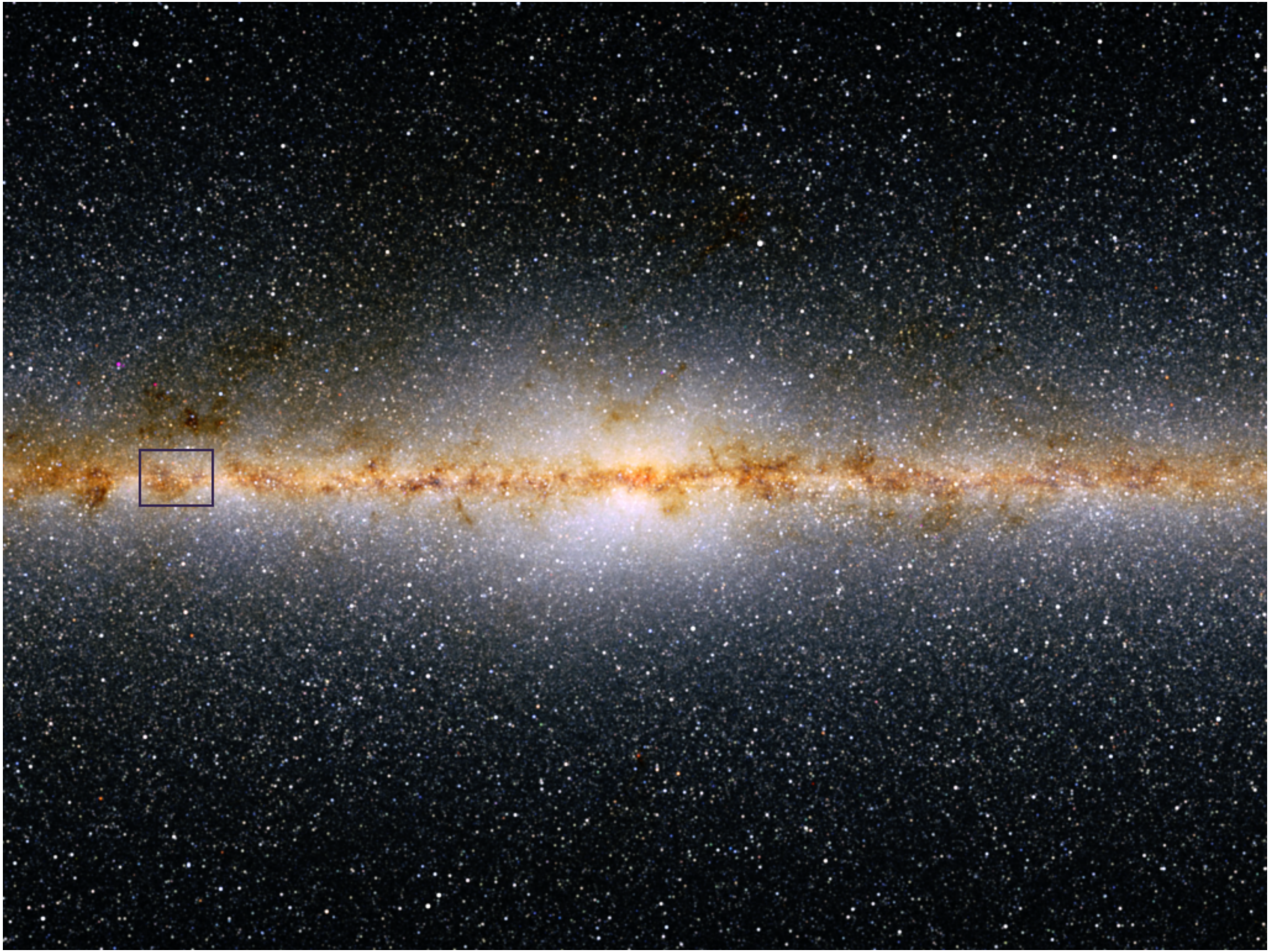
## 2. Why the near-infrared is useful

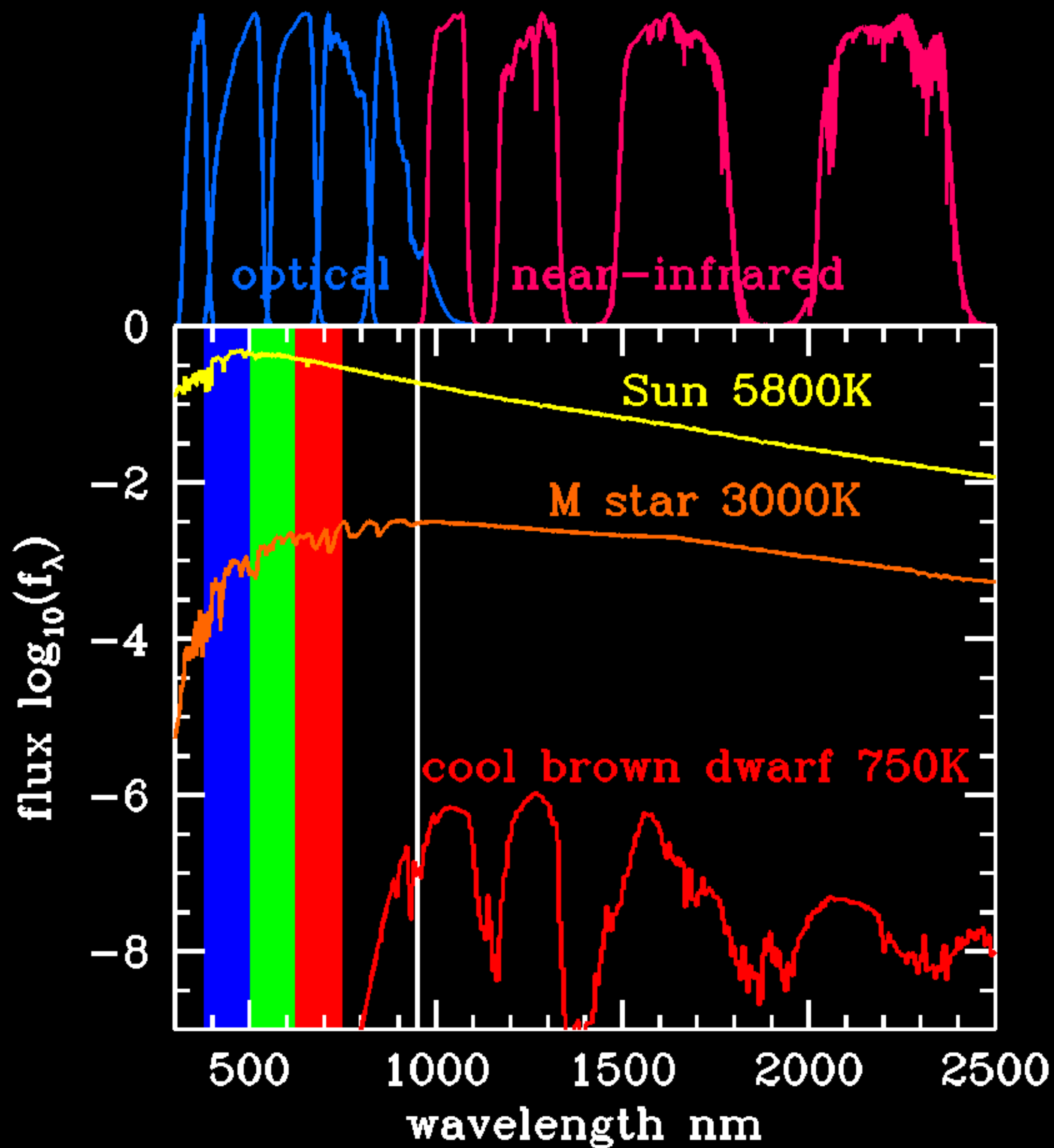
Detecting obscured objects

Detecting cool objects

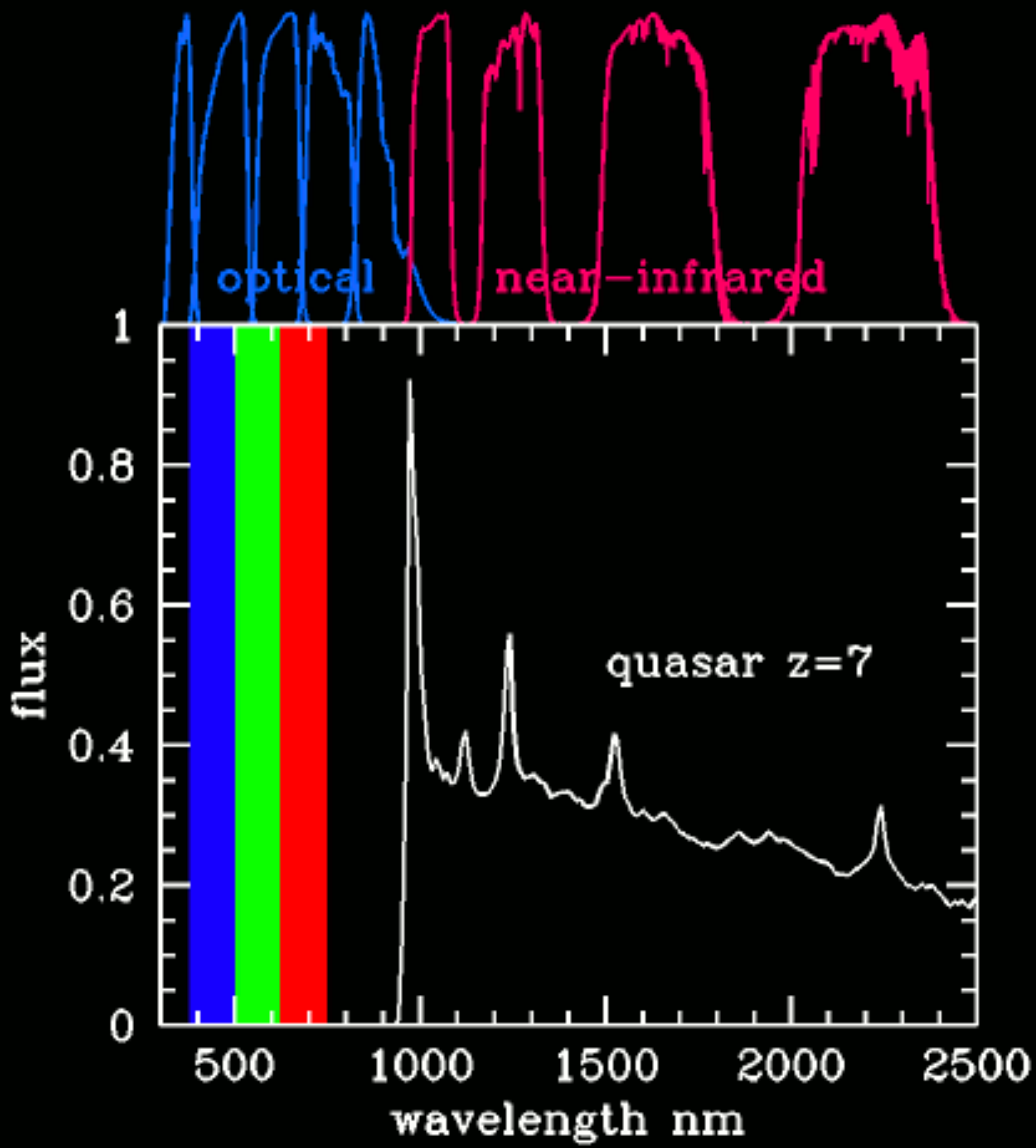
Detecting high-redshift objects





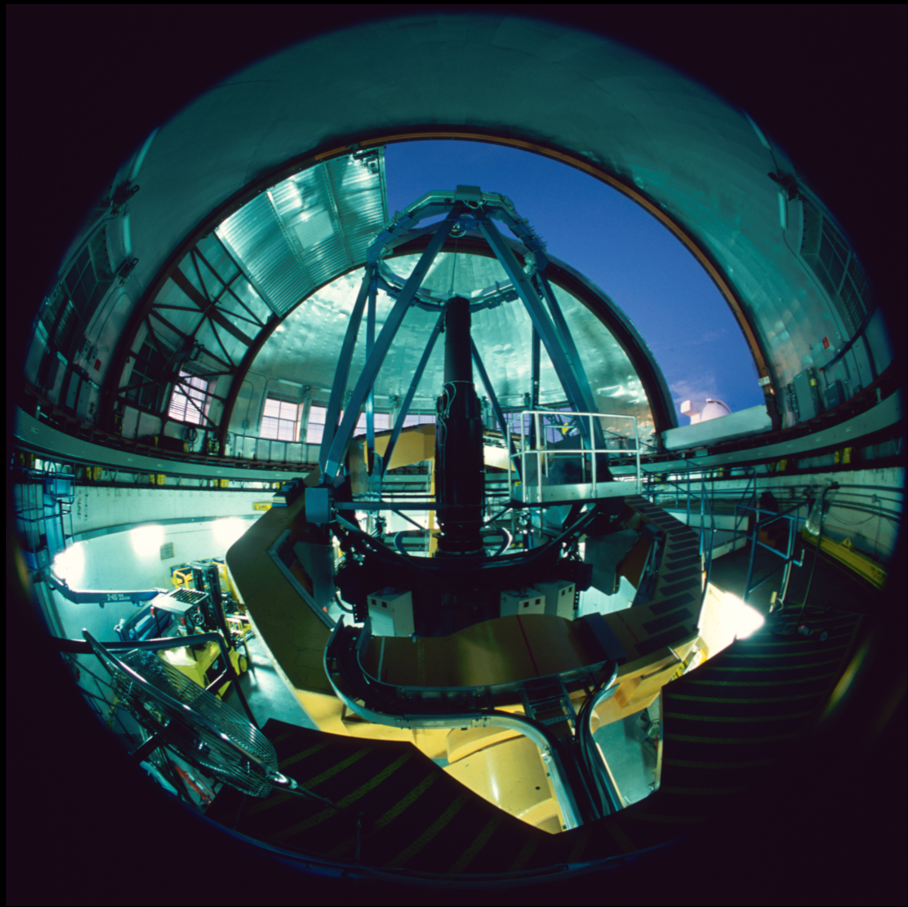


optical
near-infrared
Sun 5800K
M star 3000K
cool brown dwarf 750K
flux $\log_{10}(f_\lambda)$
0
−2
−4
−6
−8
500
1000
1500
2000
2500
wavelength nm


optical
near-infrared
1
0.8
0.6
0.4
0.2
0
flux
quasar z=7
500
1000
1500
2000
2500
wavelength nm

# 3. The UKIRT Infrared Deep Sky Survey

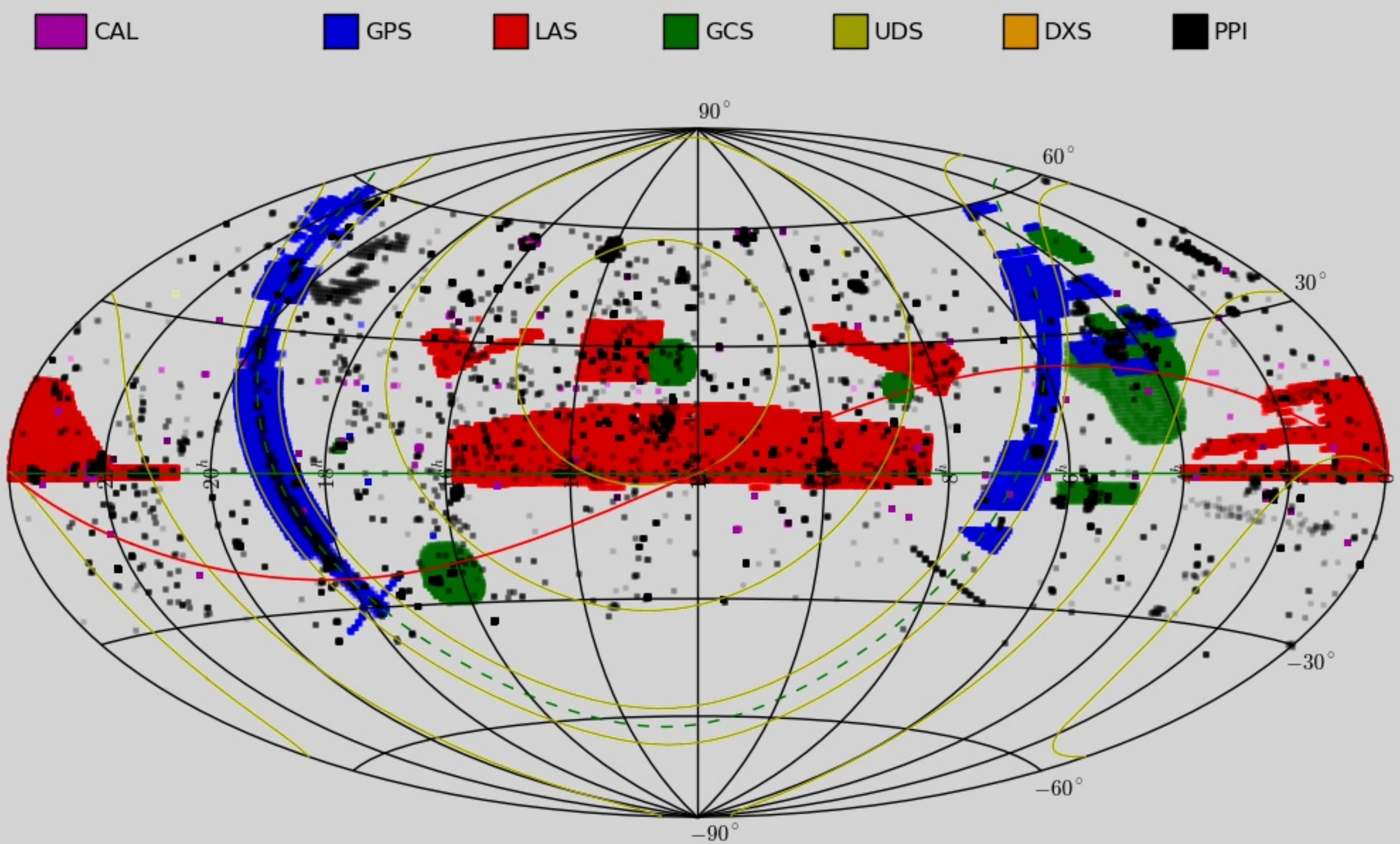
- UKIDSS will run 2005-2012
- UKIDSS comprises 5 surveys of different depth/area combinations
- UKIDSS surveys in 5 bands at 1-2micron, ZYJHK
- UKIDSS will survey 20x the volume of 2MASS and detect 100x as many photons



# DR8: UKIDSS is 60% released, 75% observed

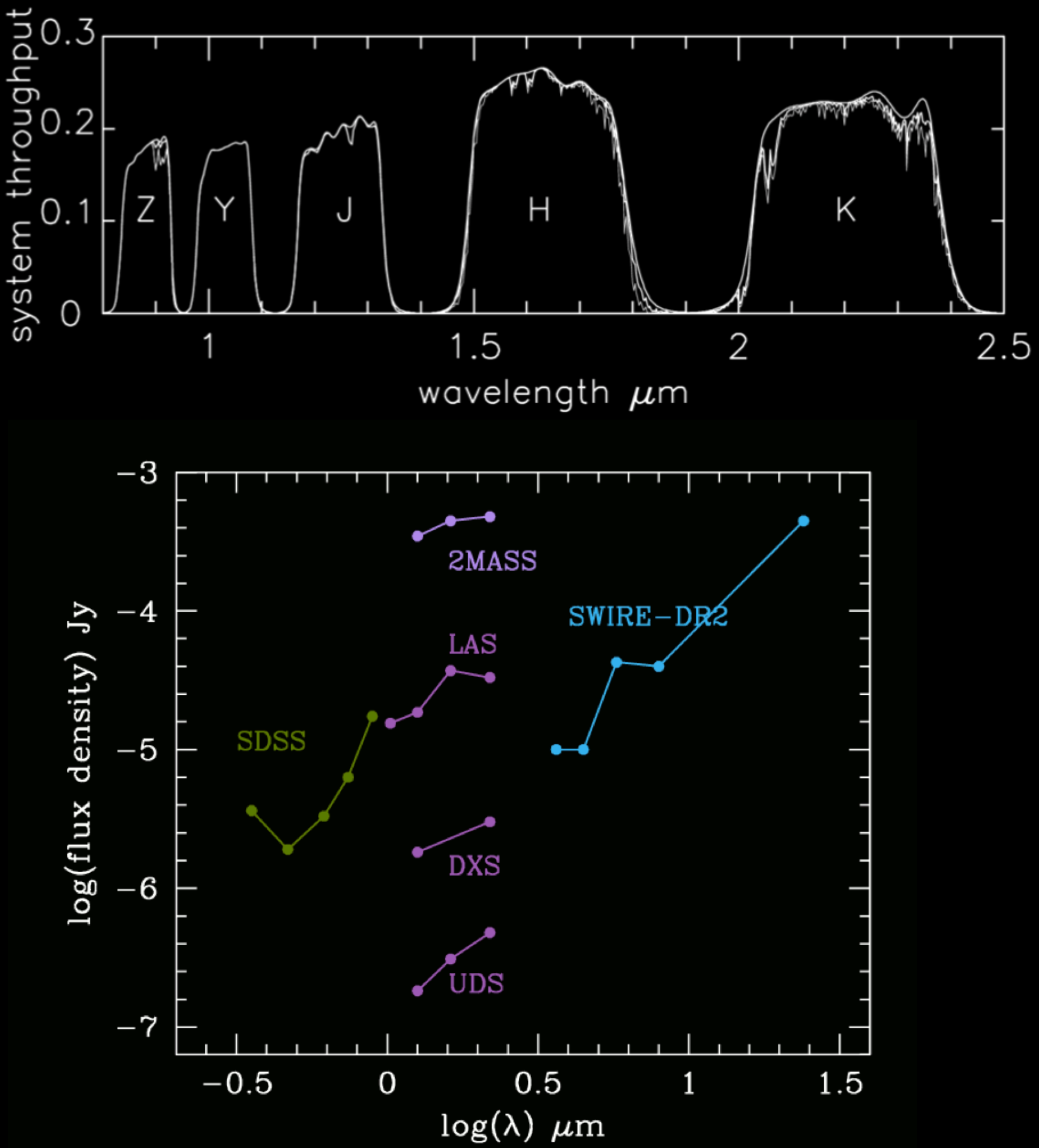
| | | | | | | |
|---|---|---|---|---|---|---|
| Large Area Survey | LAS | YJHK | 18.2K | 3792 s.d. | 262n | ExGal |
| Deep Extragalactic Survey | DXS | JK | 20.8 | 31 | 118 | ExGal |
| Ultra Deep Survey | UDS | JHK | 22.8 | 0.77 | 296 | ExGal |
| Galactic Plane Survey | GPS | JHK | 18.8 | 1851 | 186 | Gal |
| Galactic Clusters Survey | GCS | ZYJHK | 18.5 | 1069 | 84 | Gal |

| | |
|---|---|
| Large Area Survey | SDSS near-ir photom, Y dwarfs, z=7 quasars |
| Deep Extragalactic Survey | Multiwavelength fields, the Universe at 1<z<1.5 |
| Ultra Deep Survey | Multiwavelength field SXDS, the Universe at z=3 |
| Galactic Plane Survey | Galactic-plane atlas -5<b<+5 |
| Galactic Clusters Survey | Universality of the stellar IMF |



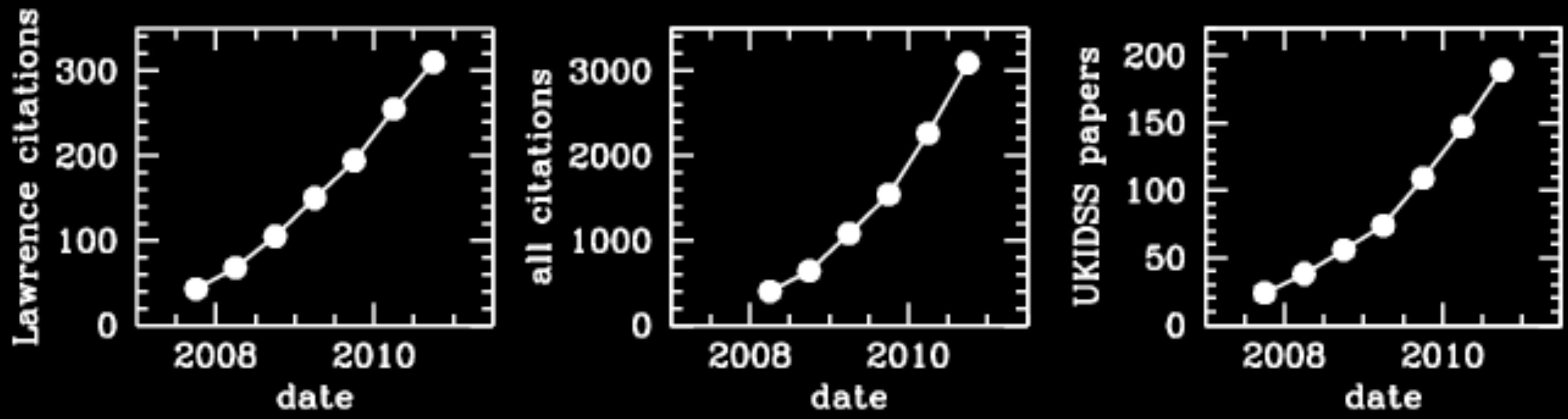

Date Range: 20050401 - 20100913

Last Updated: 20100920



system throughput
0.3
0.2
0.1
0
Z
Y
J
H
K
1
1.5
2
2.5
wavelength μm
−3
−4
−5
−6
−7
log(flux density) Jy
2MASS
SWIRE−DR2
LAS
SDSS
DXS
UDS
−0.5
0
0.5
1
1.5
log(λ) μm

summary Sept 2010



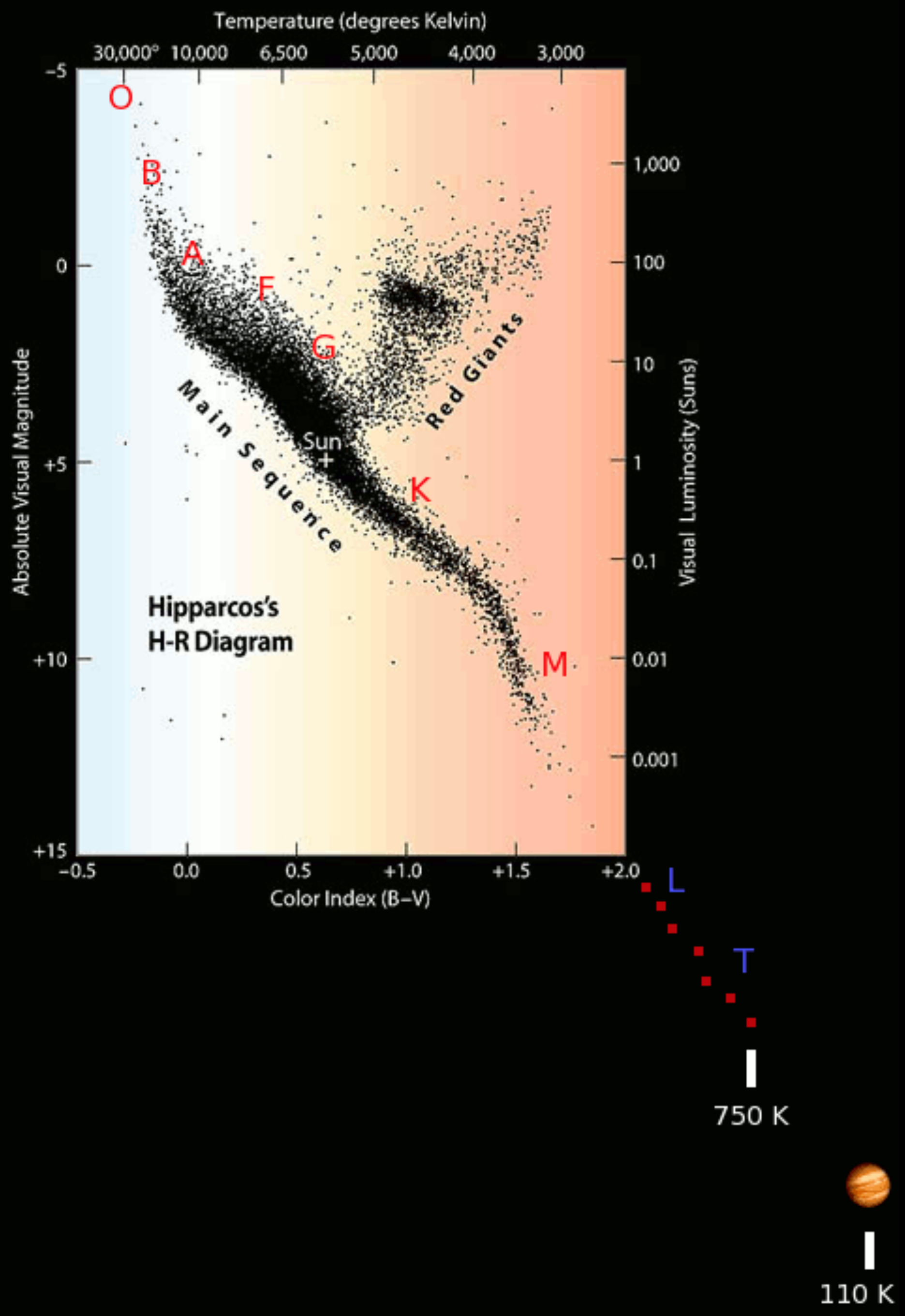
## 4. Science highlights

i. The coolest brown dwarfs (LAS, GPS)

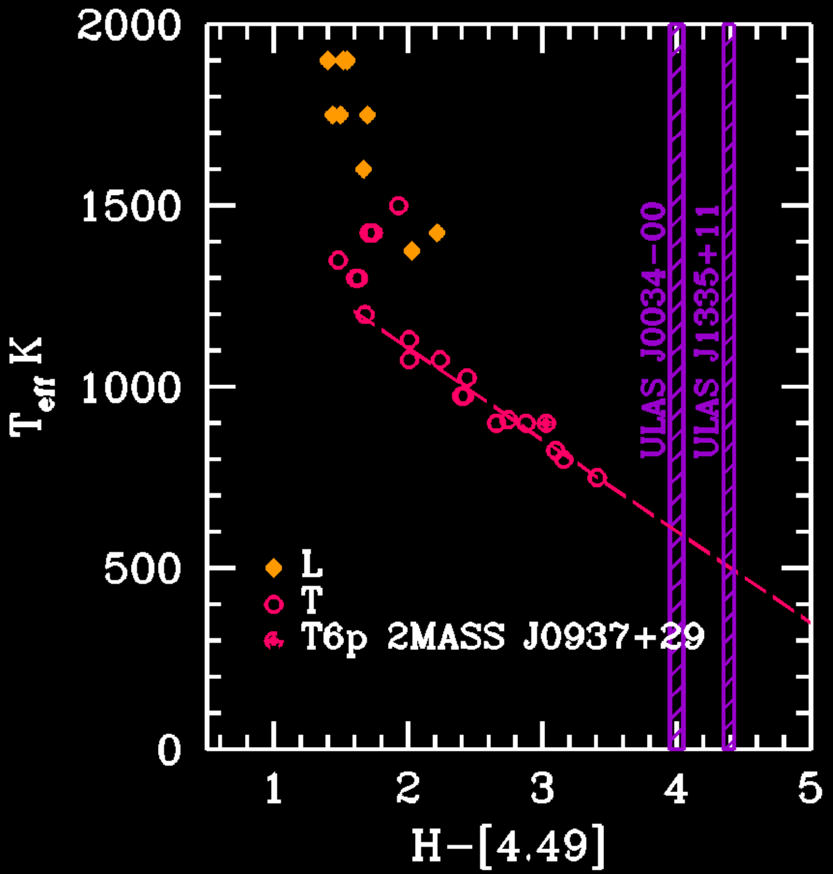
ii. The low-mass end of the stellar IMF (GCS)

iii. Bimodal galaxy colours $0<z<2.5$ (UDS)

iv. The galaxy luminosity function $5<z<6$ (UDS)

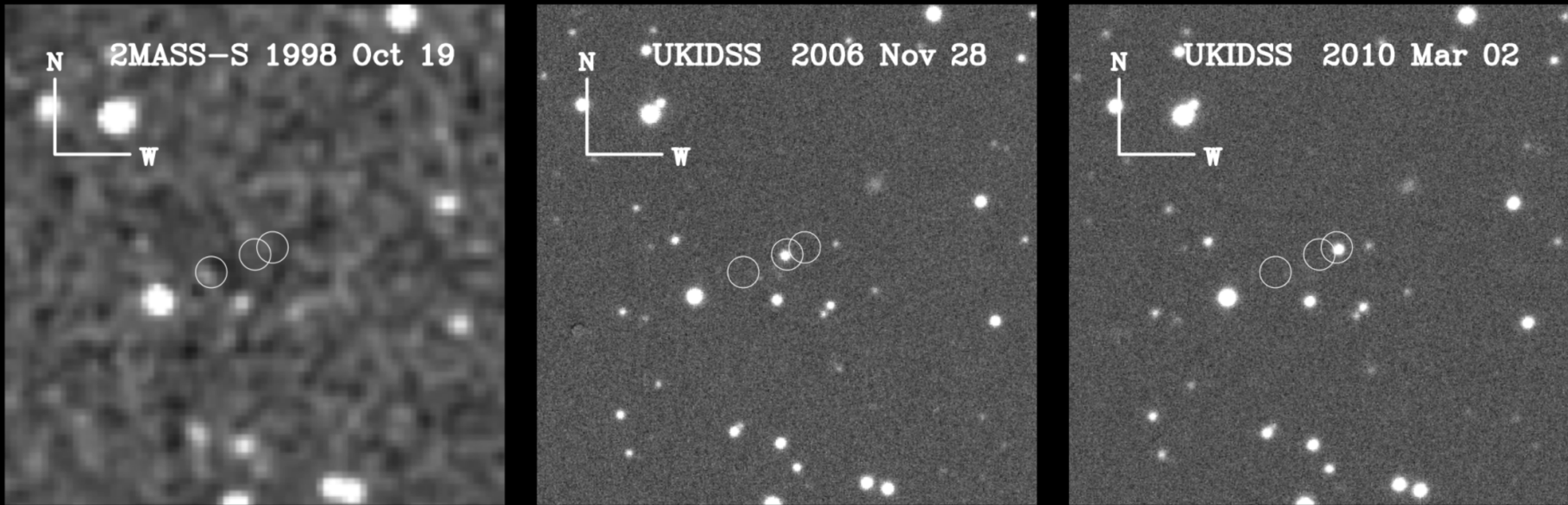


Temperature (degrees Kelvin)
30,000° 10,000 6,500 5,000 4,000 3,000
-5 0 +5 +10 +15
Absolute Visual Magnitude
1,000 100 10 1 0.1 0.01 0.001
Visual Luminosity (Suns)
−0.5 0.0 0.5 +1.0 +1.5 +2.0
Color Index (B−V)
O
B
A
F
G
K
M
L
T
Sun
Main Sequence
Red Giants
Hipparcos's
H-R Diagram
750 K
110 K



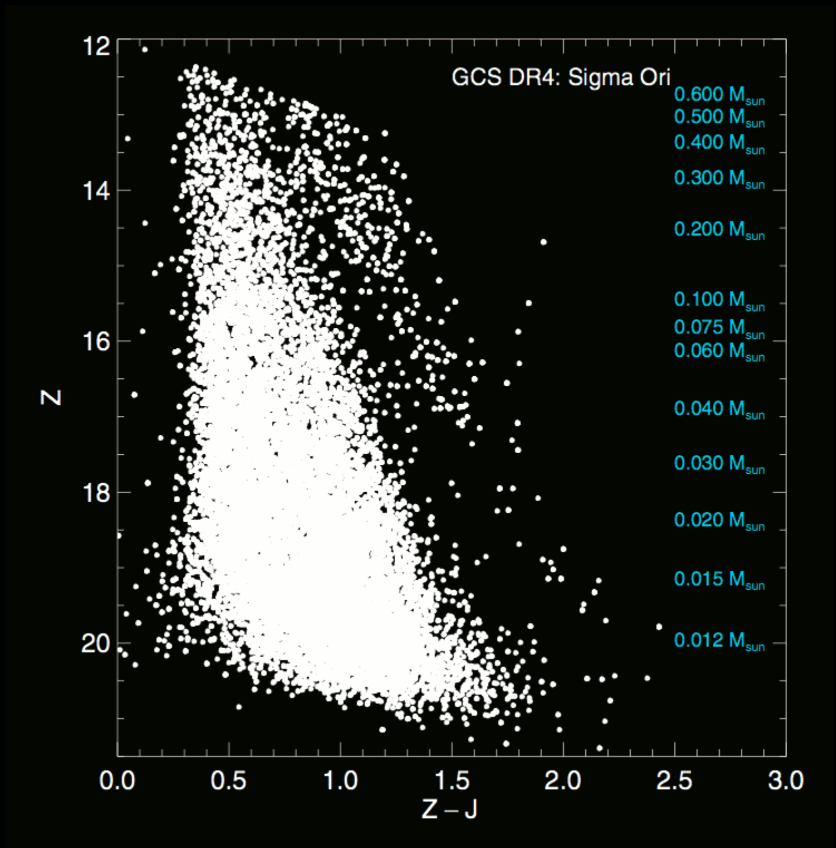
2000
1500
1000
500
0
1
2
3
4
5
T_eff K
H−[4.49]
ULAS J0034−00
ULAS J1335+11
L
T
T6p 2MASS J0937+29

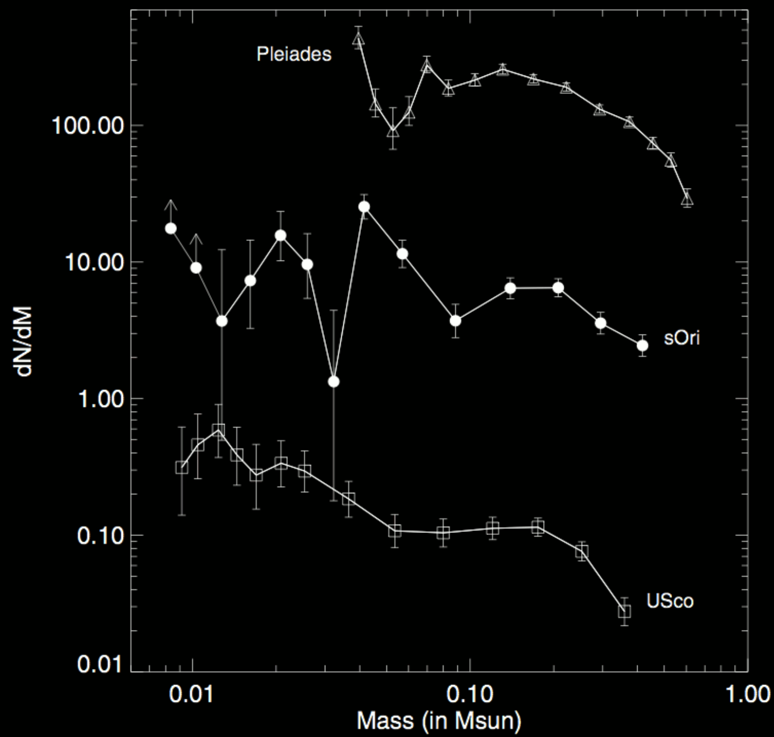
# The coolest brown dwarf UGPS 0722



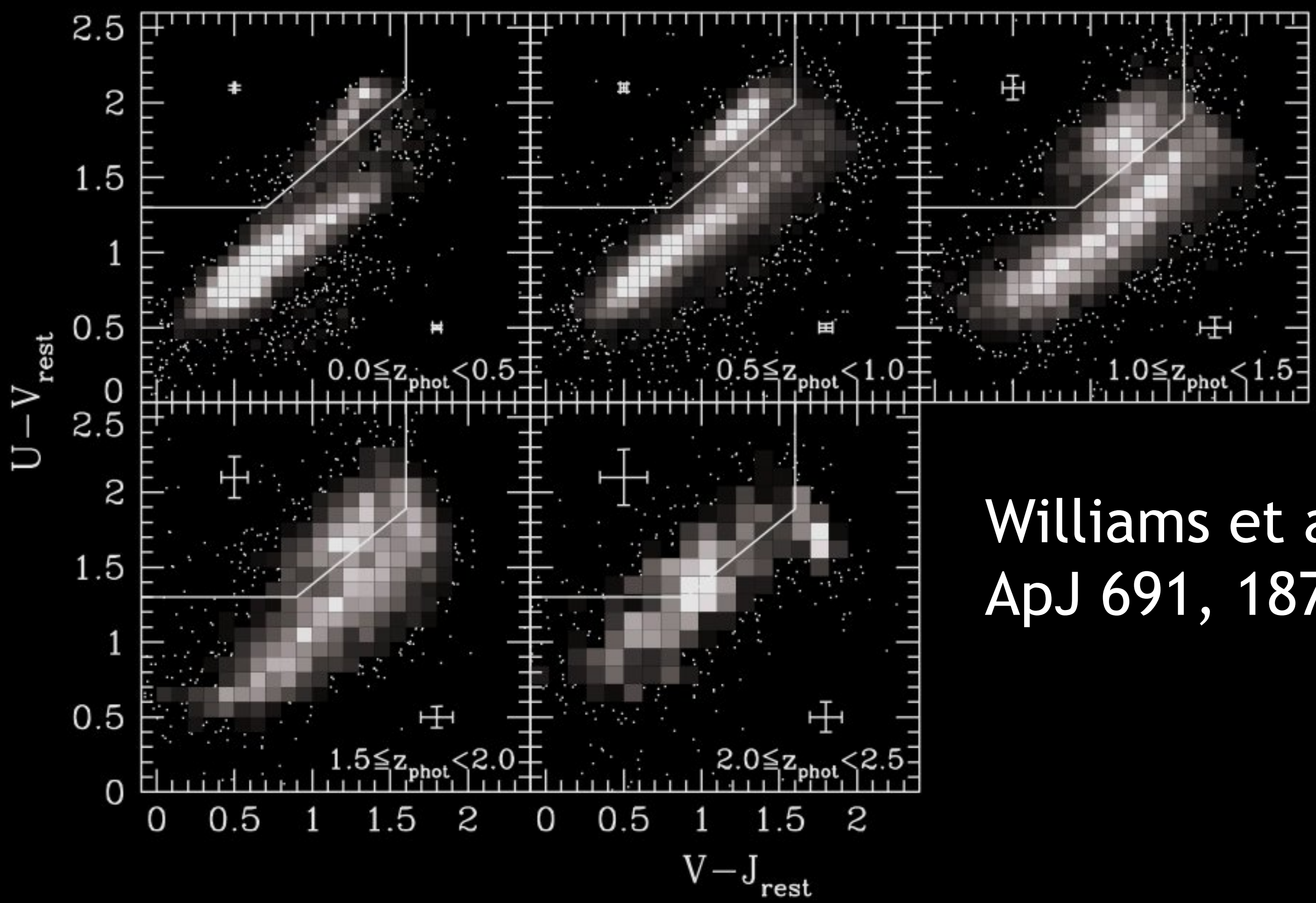

Distance 4pc, 480K<$T_{eff}$<560K

# ii. The low mass end of the stellar IMF



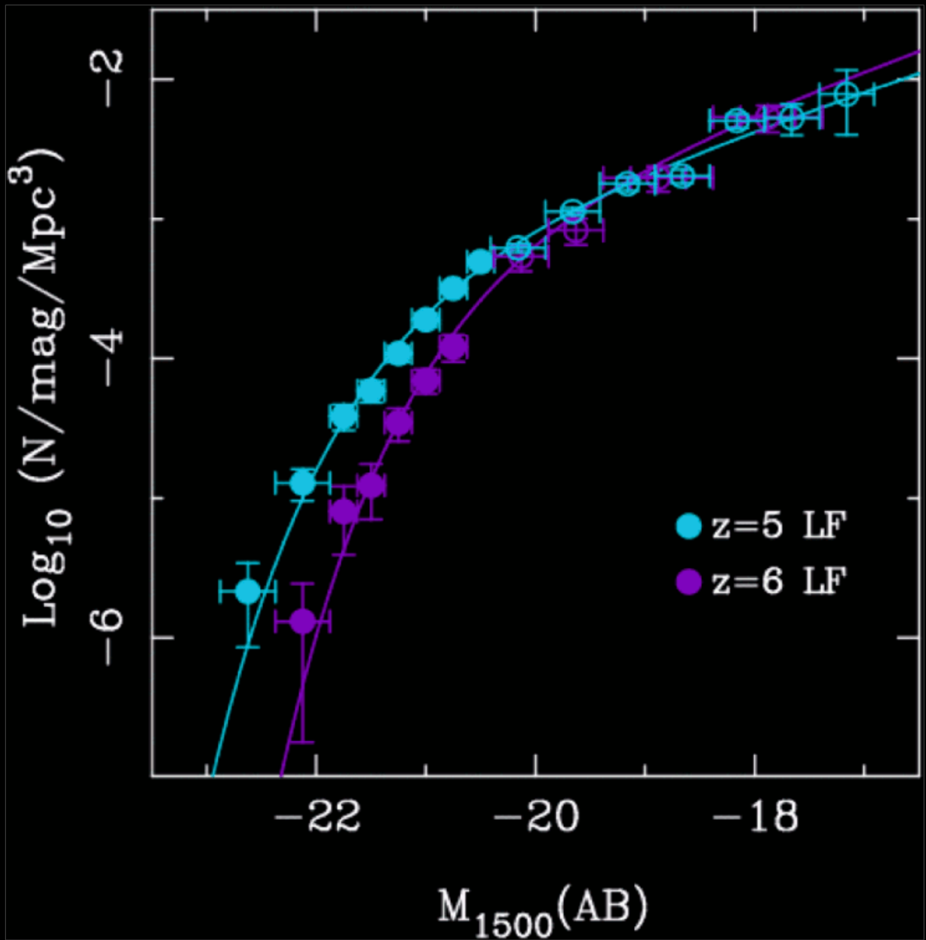



# iii. Bimodal galaxy colours 0<z<2.5




Williams et al. 2009
ApJ 691, 1879

# iv. The galaxy luminosity function 5<z<6




McLure et al. 2009 bright end of the high-reshift galaxy LF, from the UDS K=22.7 over 0.8 deg$^2$

## 5. Search for high-redshift $5.8<z<7.2$ quasars in UKIDSS

Motivation

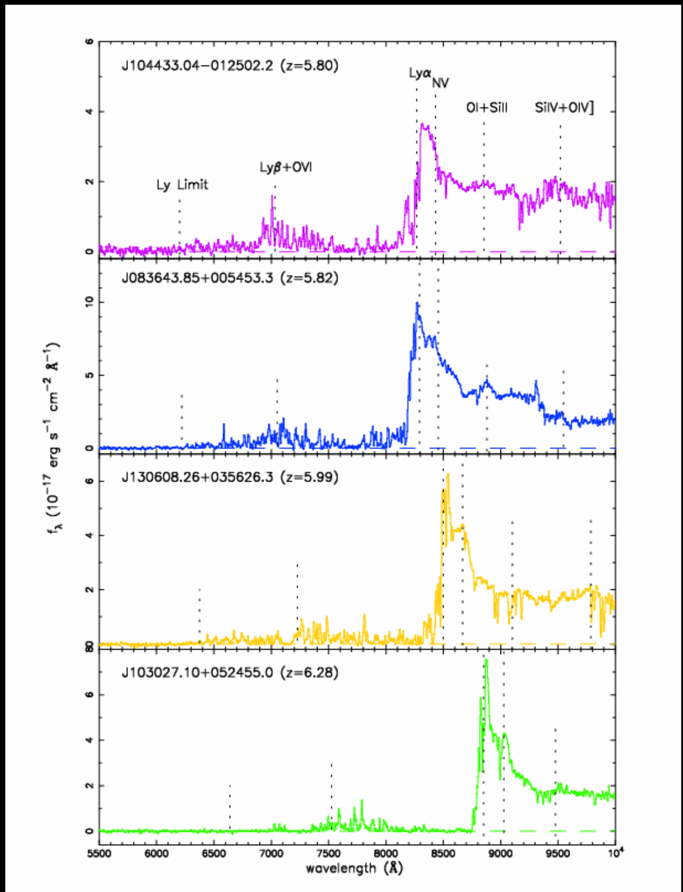
- reionisation
- decline in space density

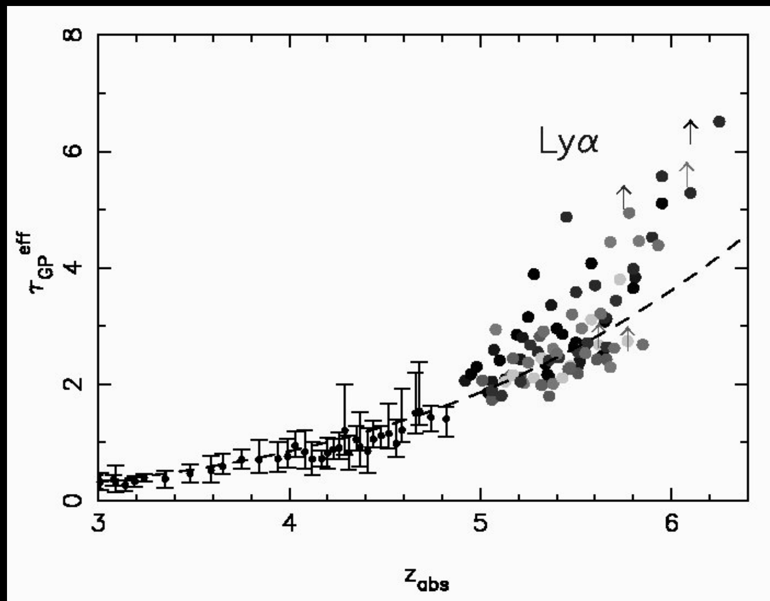
Methods

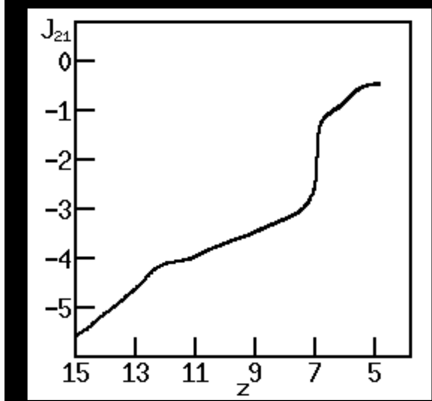
Results

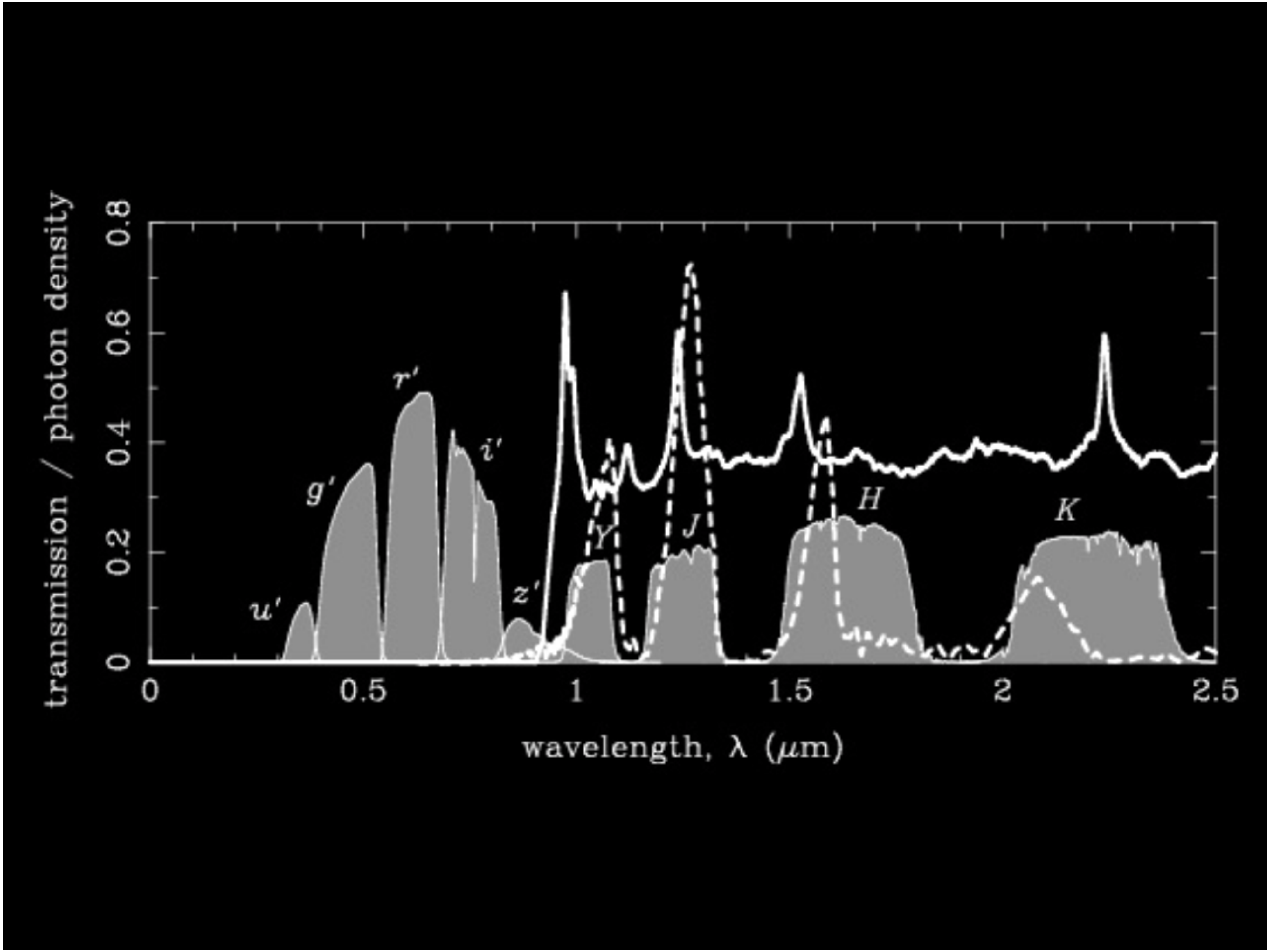
# Motivation: reionisation

From SDSS z=6 is threshold of epoch of reionisation (?)
Reionisation supposed to be rapid (?)
WMAP suggests z(reion)=11+/-1.4
z=6.4 is SDSS limit



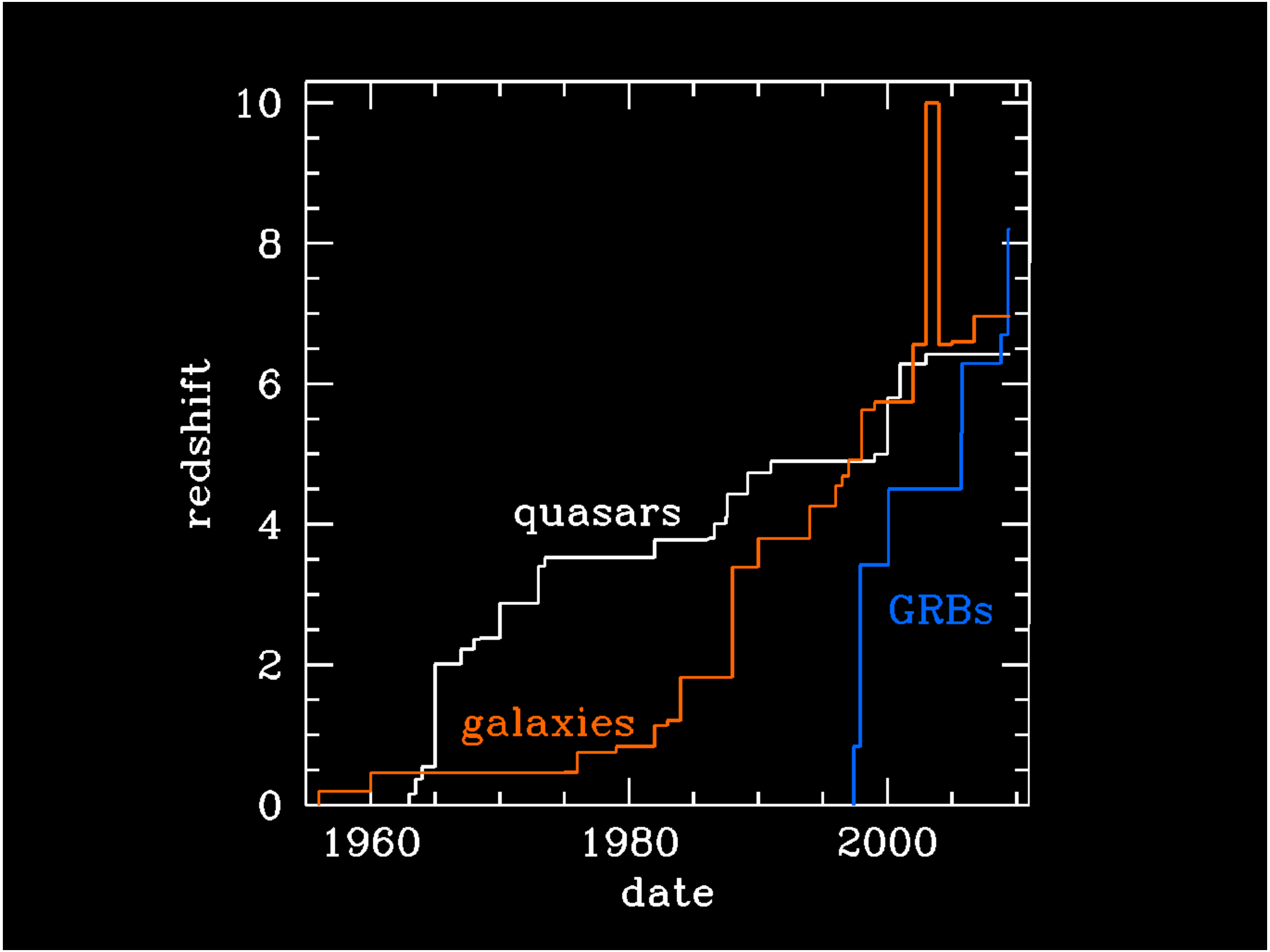



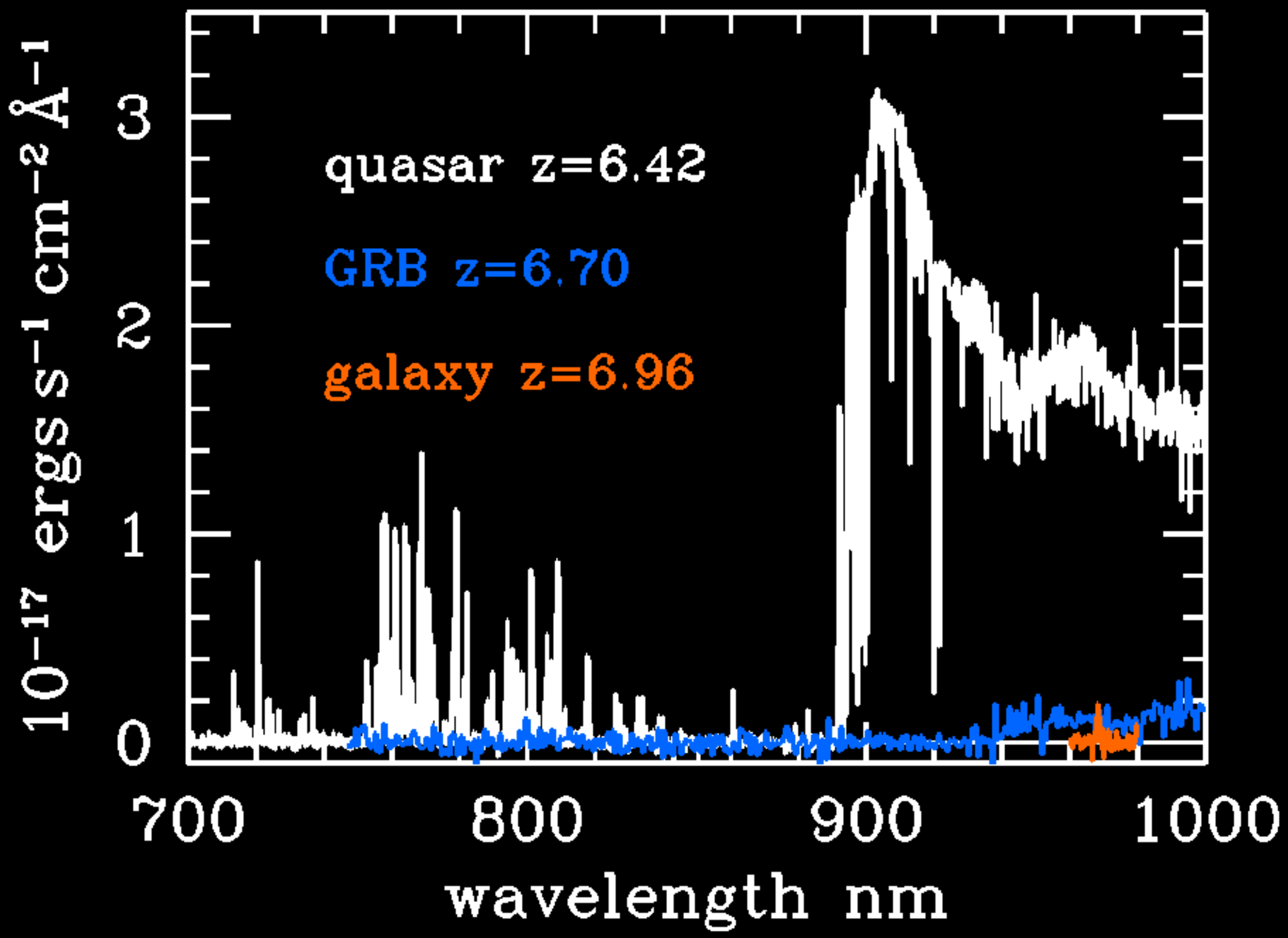


transmission / photon density
0
0.2
0.4
0.6
0.8
0
0.5
1
1.5
2
2.5
wavelength, λ (μm)
u′
g′
r′
i′
z′
Y
J
H
K

# Motivation: reionisation

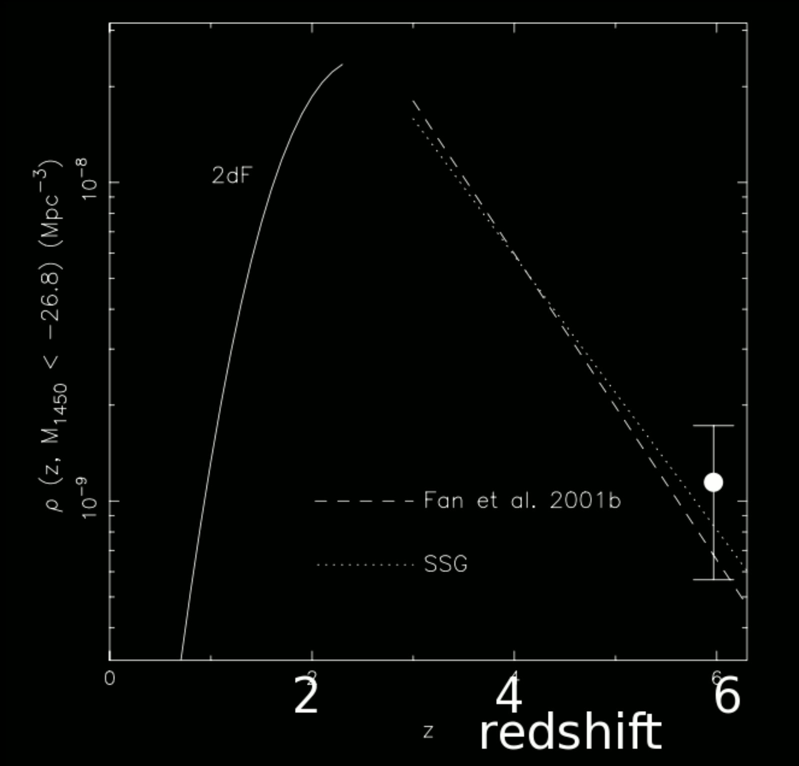
- eROSITA
- IXO
- Pan-STARRS
- Skymapper
- LSST
- VISTA Hemisphere Survey
- VIKING
- VIDEO
- JANUS
- EUCLID
- LOFAR
- MeerKAT
- SKA


10
8
6
4
2
0
redshift
quasars
galaxies
GRBs
1960
1980
2000
date



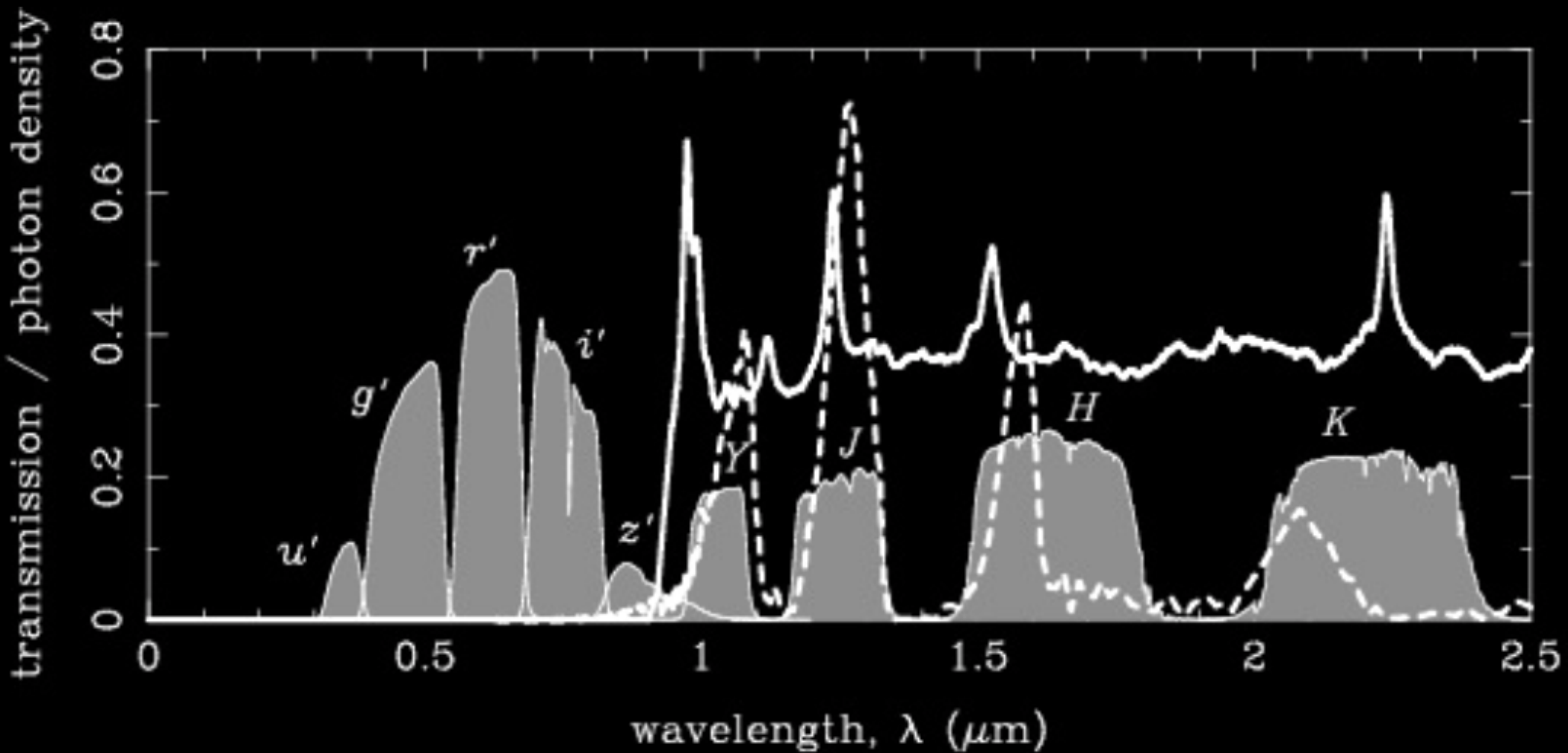
quasar z=6.42
GRB z=6.70
galaxy z=6.96
3
2
1
0
700
800
900
1000
wavelength nm
10⁻¹⁷ ergs s⁻¹ cm⁻² Å⁻¹

# Motivation: decline in space density



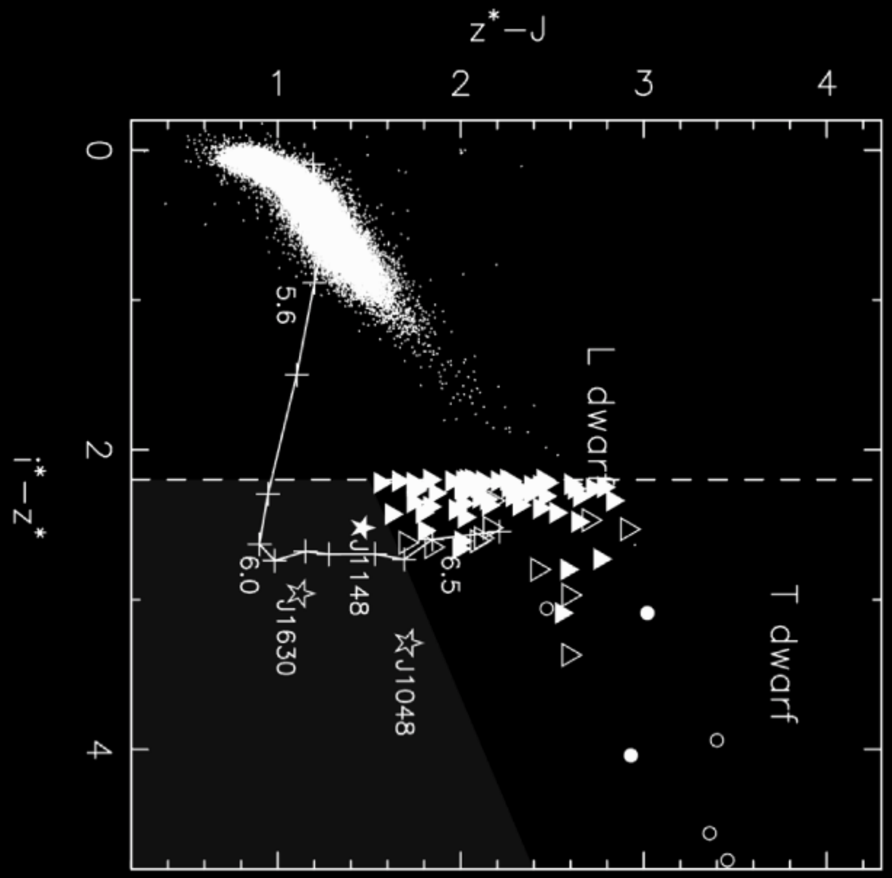

Space density at z=6, is consistent with the extrapolation of the measured rate of decline in space density over the redshift interval 3<z<5 by Fan et al. 2001.

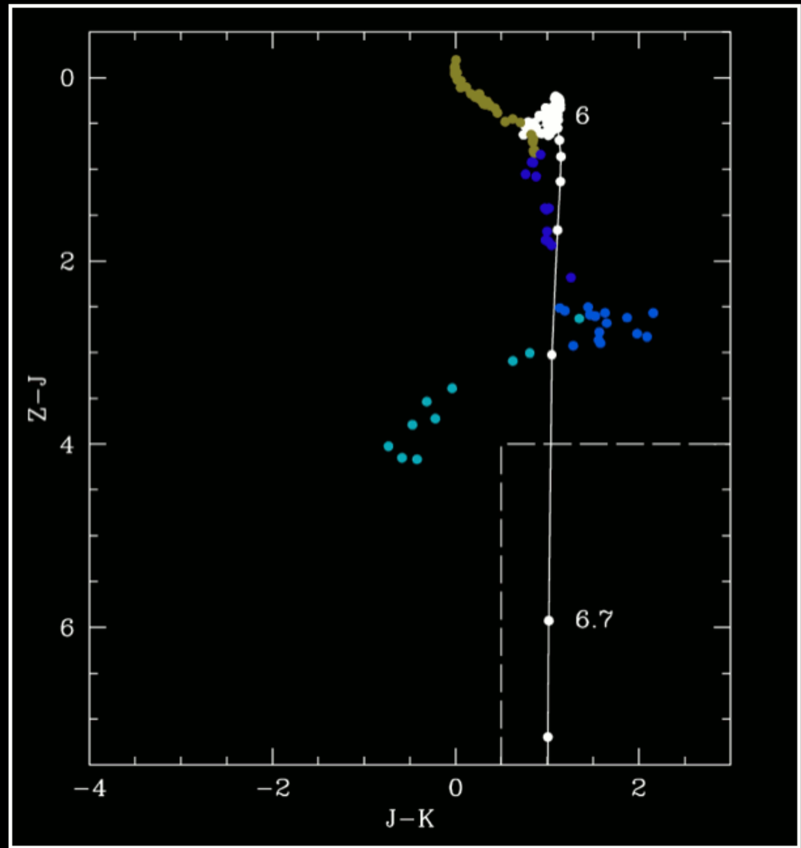
# Methods



transmission / photon density
0
0.2
0.4
0.6
0.8
0
0.5
1
1.5
2
2.5
wavelength, λ (μm)
u′
g′
r′
i′
z′
Y
J
H
K

# The search for z>6.4 quasars




zJH zJK do not work because quasars are red in J-H, J-K

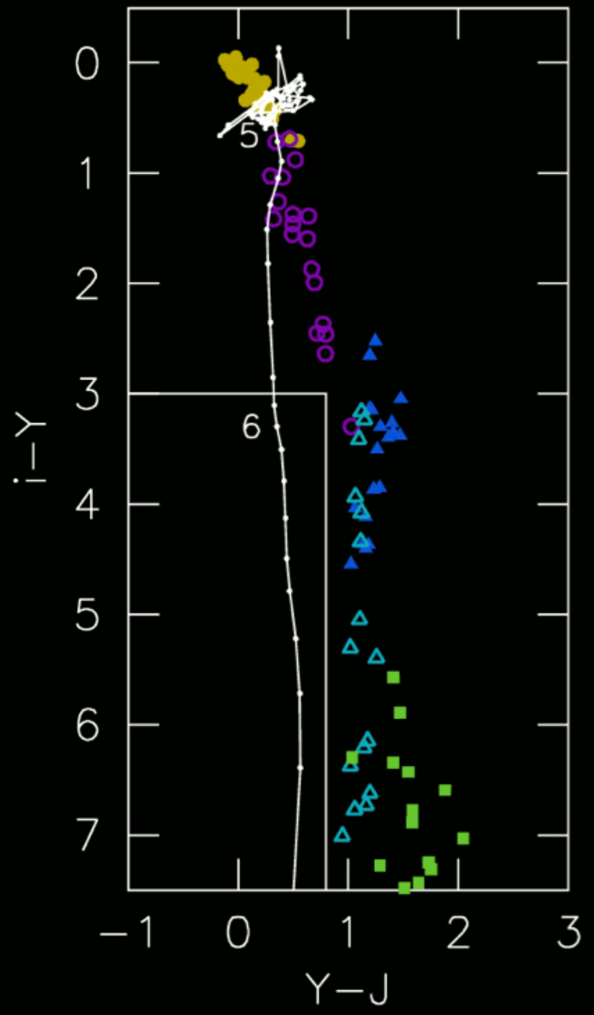
# The search for z>6.4 quasars

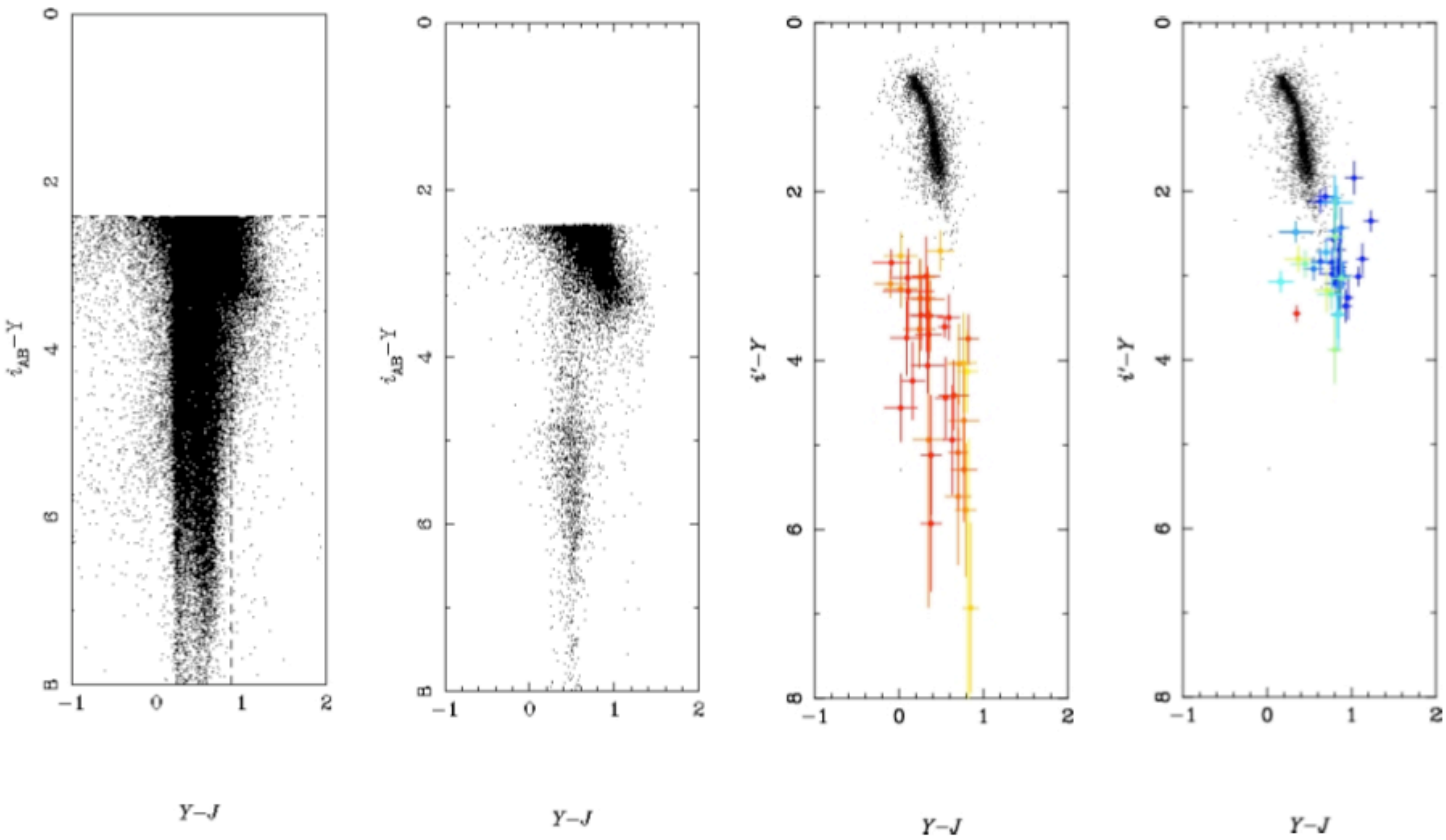
iYJ works above z=6
zYJ works above z=6.4

Work with izYJ

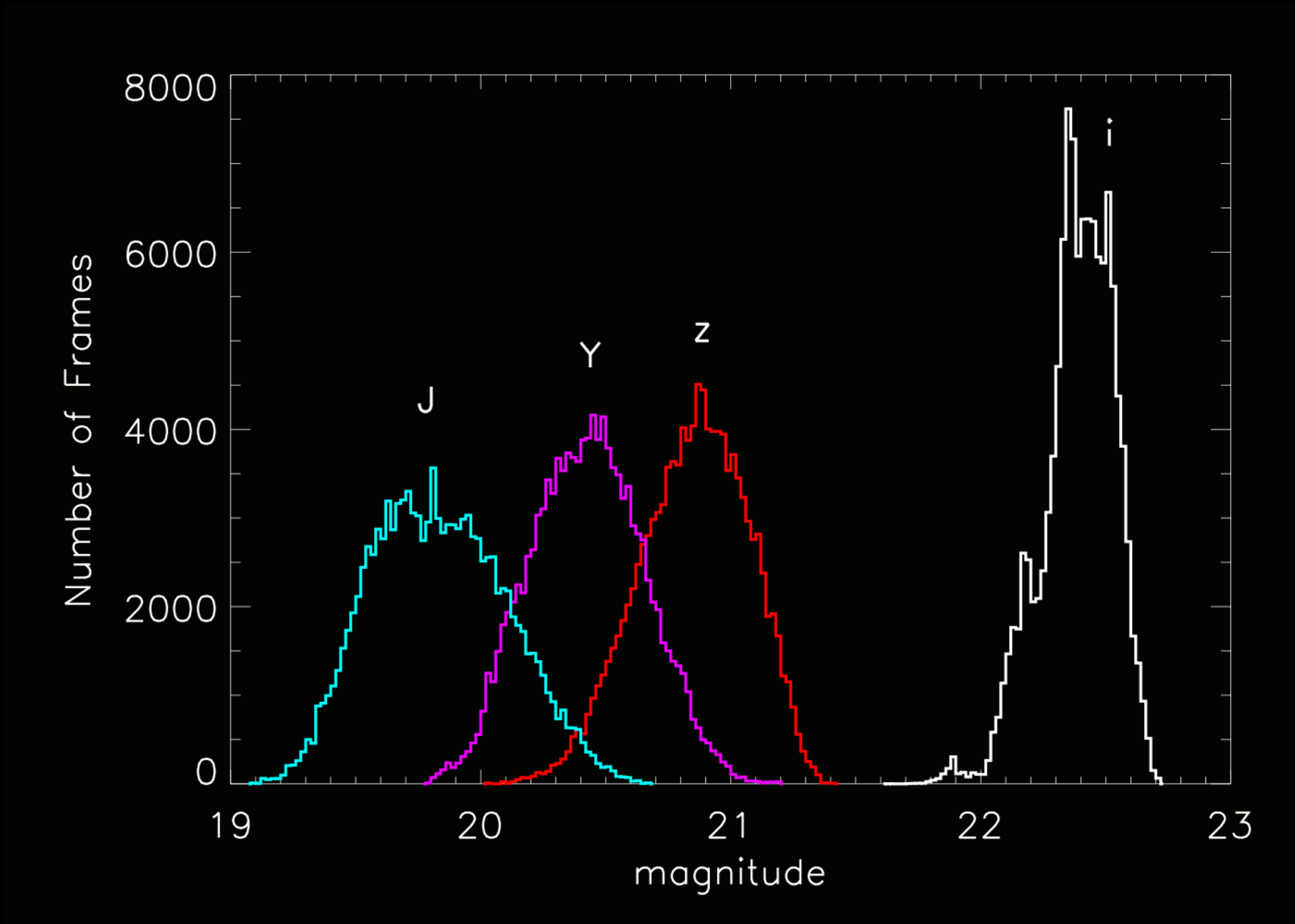
Starting with YJ, obtain iz from SDSS, or for non-detections remeasure flux (even if –ve), and flux error

At z~6 quasars have z-Y~0.8 i.e. Y=19.88 equiv 0.5 mag deeper than z=20.2



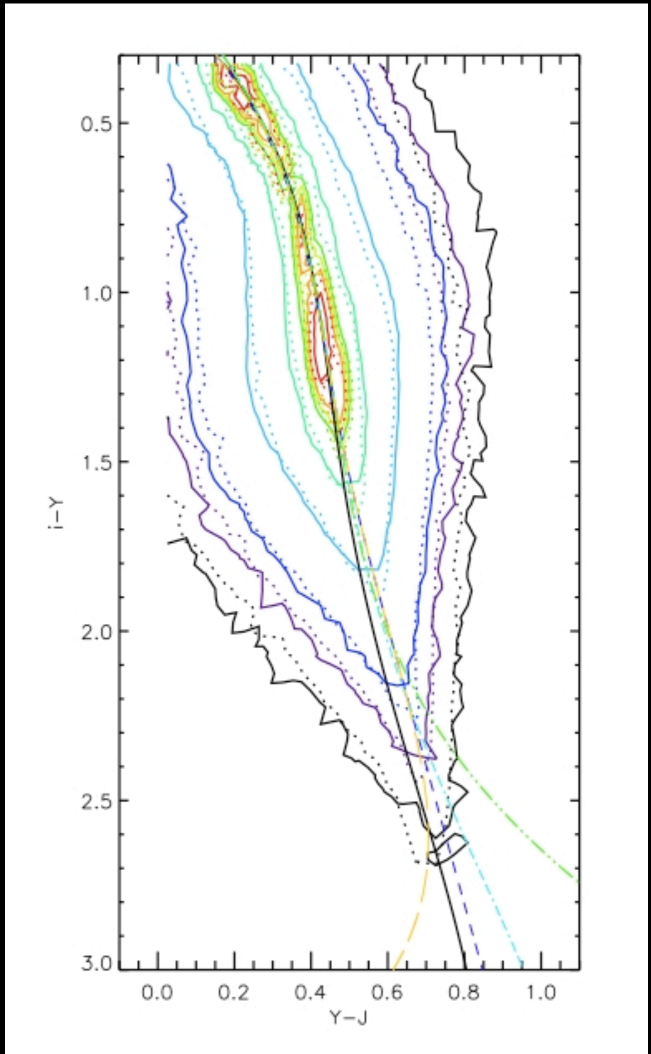

$i_{AB}-Y$
Y−J
$i_{AB}-Y$
Y−J
i′−Y
Y−J
i′−Y
Y−J

# Completeness calculation



# Bayesian model selection: p(quasar)

Mortlock et al. 2011

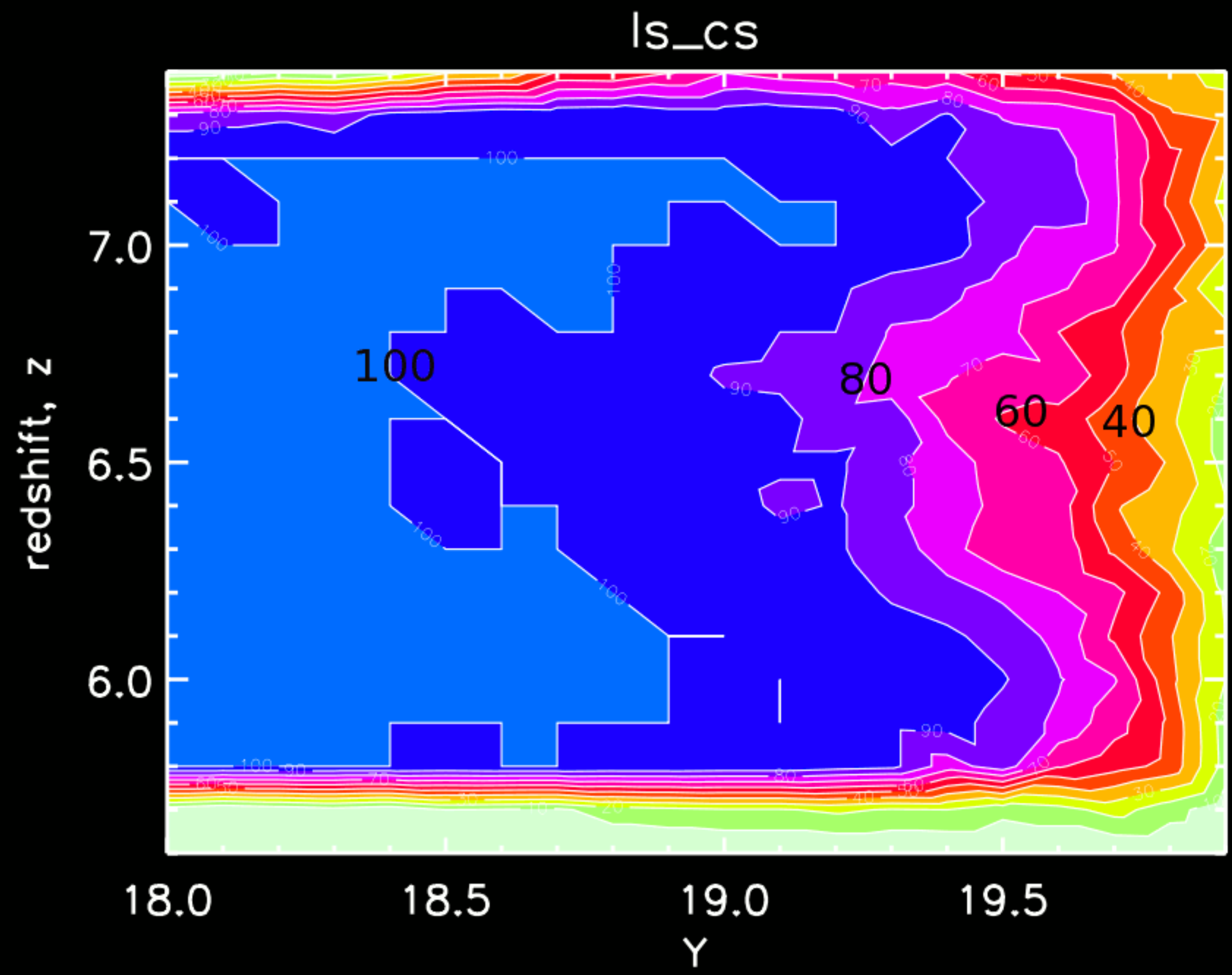



$$P_{\rm q}(\boldsymbol{d}, M_{\rm q}, M_{\rm s}) = \frac{\pi_{\rm q}(M_{\rm q}) E_{\rm q}(\boldsymbol{d}, M_{\rm q})}{\pi_{\rm q}(M_{\rm q}) E_{\rm q}(\boldsymbol{d}, M_{\rm q}) + \pi_{\rm s}(M_{\rm s}) E_{\rm s}(\boldsymbol{d}, M_{\rm s})}$$

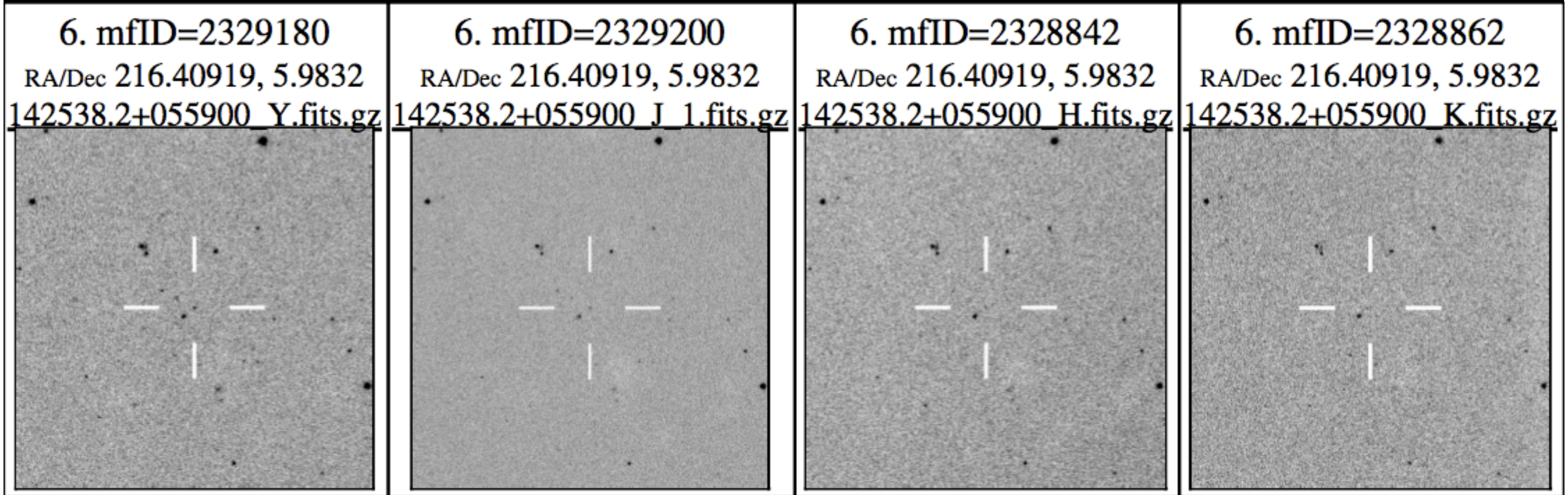
$$W_p(\boldsymbol{d}, M_p) = \int \rho_p(\boldsymbol{m}_p M_p) L_p(\boldsymbol{d}|\boldsymbol{m}_p)\, {\rm d}m_1\, {\rm d}m_2\, \ldots\, {\rm d}m_{N_{\rm p}}$$

$$P_{\rm q}(\boldsymbol{d}, M_{\rm q}, M_{\rm s}) = \frac{W_{\rm q}(\boldsymbol{d}, M_{\rm q})}{W_{\rm q}(\boldsymbol{d}, M_{\rm q}) + W_{\rm s}(\boldsymbol{d}, M_{\rm s})}$$

# Completeness calculation



# Difficult cases





Cross talk, SDSS funnies, asteroids, variables

# Results from 2250 $deg^2$

| Source | redshift | Y(Vega) | Data release |
|---|---|---|---|
| SDSS J0836+0054 | 5.82 | 18.3 | SDSS |
| SDSS 0841+2905 | 5.96 | 19.7 | SDSS |
| SDSS 1030+0524 | 6.31 | 19.3 | SDSS |
| SDSS 1044-0125 | 5.74 | 18.9 | SDSS |
| SDSS J1411+1217 | 5.93 | 19.5 | SDSS |
| SDSS J1623+3112 | 6.22 | 19.7 | SDSS |
| ULAS J0148+0600 | 5.92 | 18.9 | DR6 |
| ULAS J0203+0012 | 5.72 BAL | 19.8 | DR1 |
| ULAS J0828+2633 | 6.1 | 19.6 | DR7 |
| ULAS J1207+0630 | 6.04 | 19.5 | DR5 |
| ULAS J1319+0950 | 6.13 | 19.2 | DR3 |
| ULAS J1609+3041 | 6.08 | 20.0 | DR7 |

# Results

## Total candidates from 2250 $deg^2$ and status of photometric follow-up

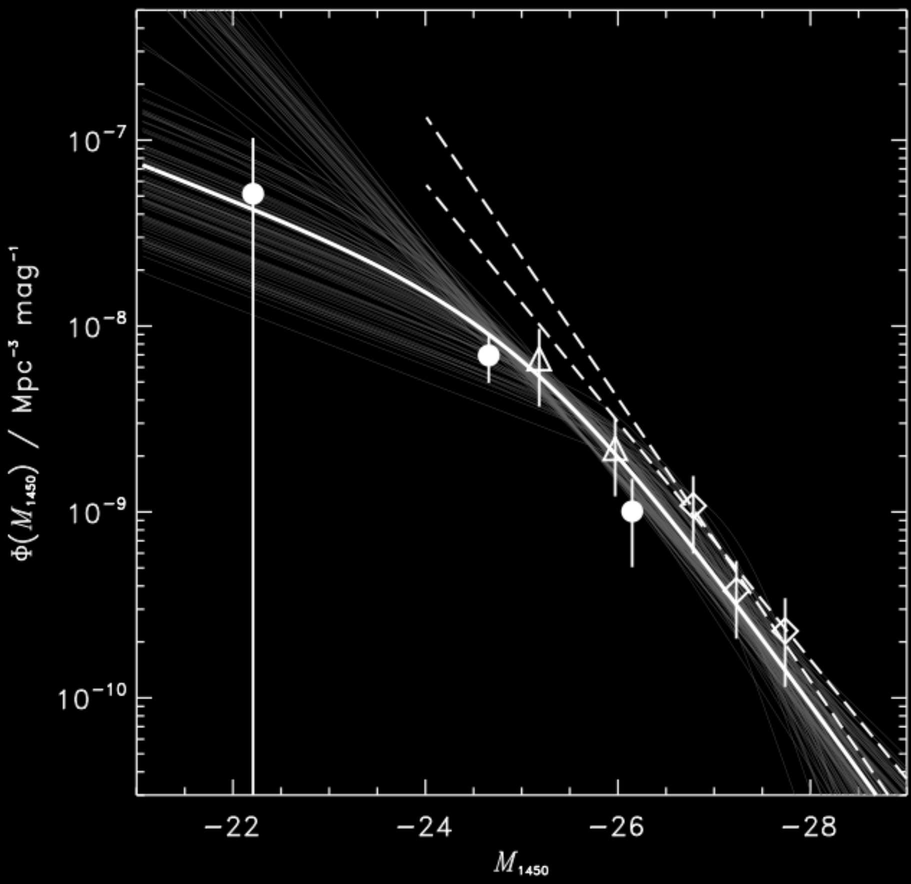
| | N cand | N obs | N quasars |
|---|---|---|---|
| $0.5<p<1.0$ | 37 | 32 (5 left) | 9 |
| $0.15<p<0.5$ | 43 | 33 (10 left) | 1 |
| all | 80 | 65 (15 left) | 10 |

# Predicted numbers for DR8

For Willott et al (2010) LF at z=6, Y<19.8, 2250deg[2]

Fan et al (2001) decline extrapolated to z>6

5.8<z<6.4 predict 12.3 quasars, compared to 10+ found

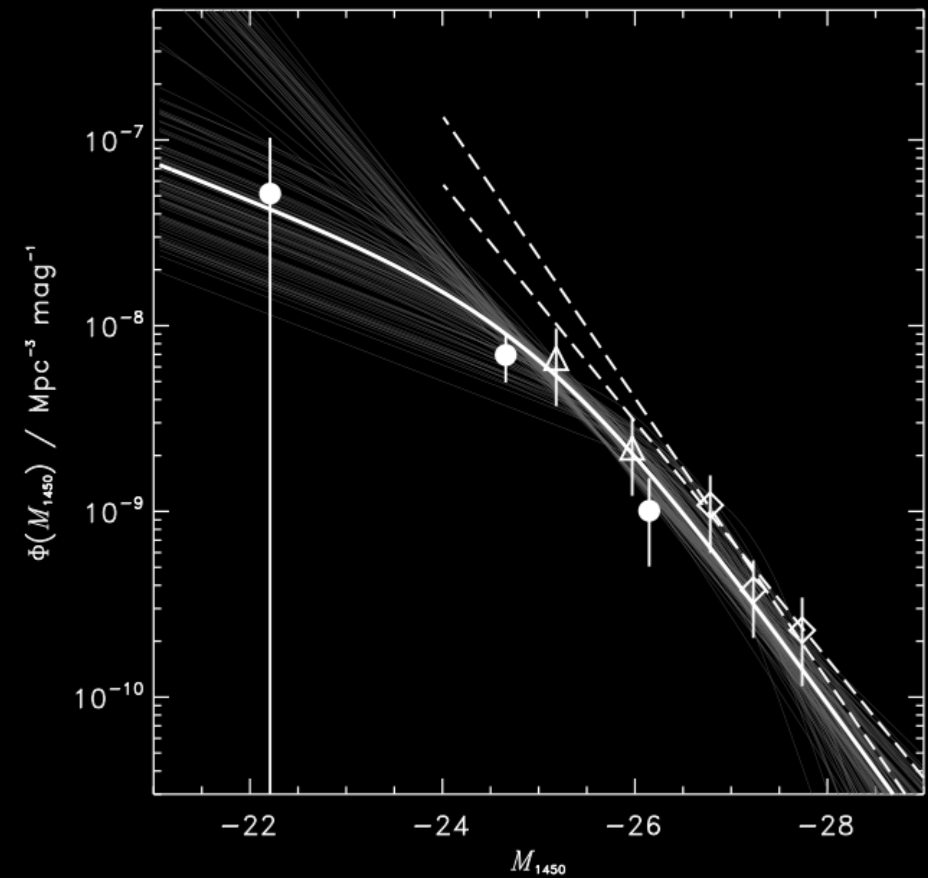


# Predicted numbers for DR8

$6.4<z<7.2$ predict 3.3 quasars compared to 0+ found.

Null detection at $z>6.4$ is inconsistent with prediction at 96% confidence.

If instead 1 is found amongst remaining candidates, probability changes to 84%, and not significant.



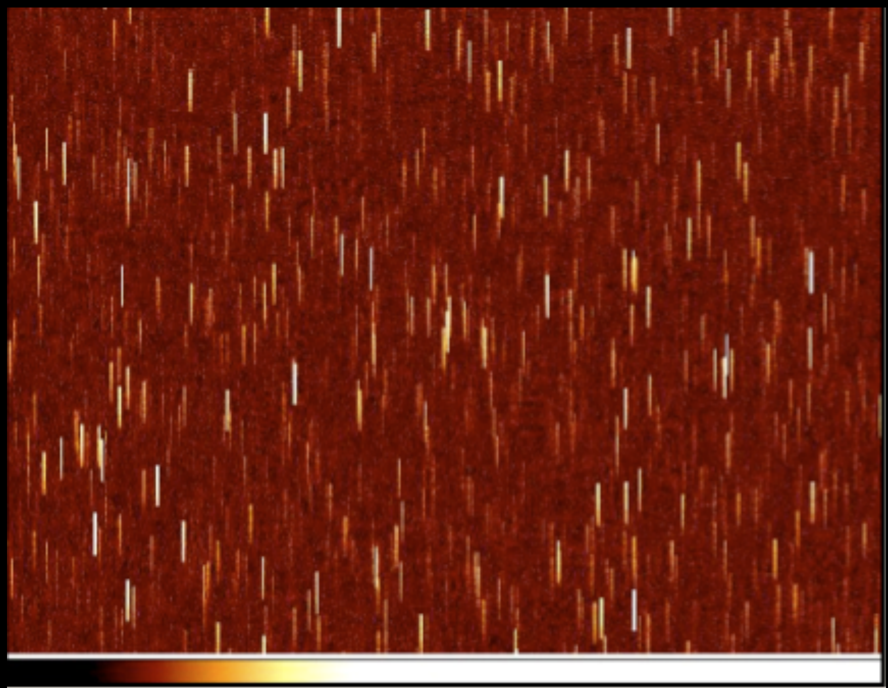
# Predictions for future surveys

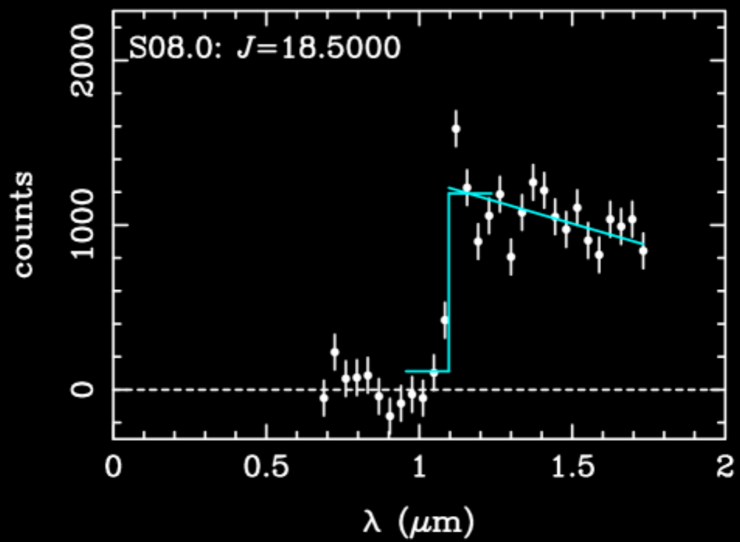
| Survey | Area | Depth Y (Vega) | Number | complete |
|---|---|---|---|---|
| UKIDSS | 3800 | 19.6 | 6 | 2012 |
| VIKING | 1000 | 20.8 | 9 | 2015 |
| PanSTARRS 10 sigma | 20000 | 19.6 | 33 | 2015 |

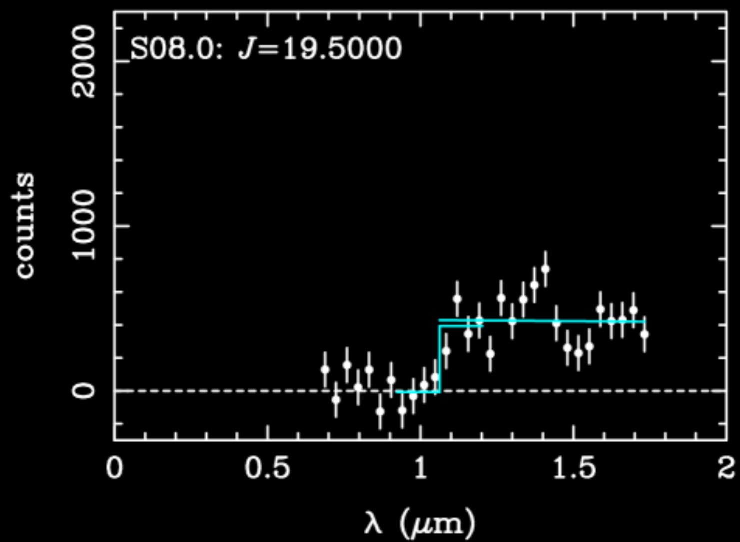
# The best future quasar survey JANUS 20000 deg$^2$

**NIRT: R=14 objective prism spectroscopy, 0.7-1.7um, over 0.36 deg$^2$**

J=19.9, 4sigma per pix, 480s





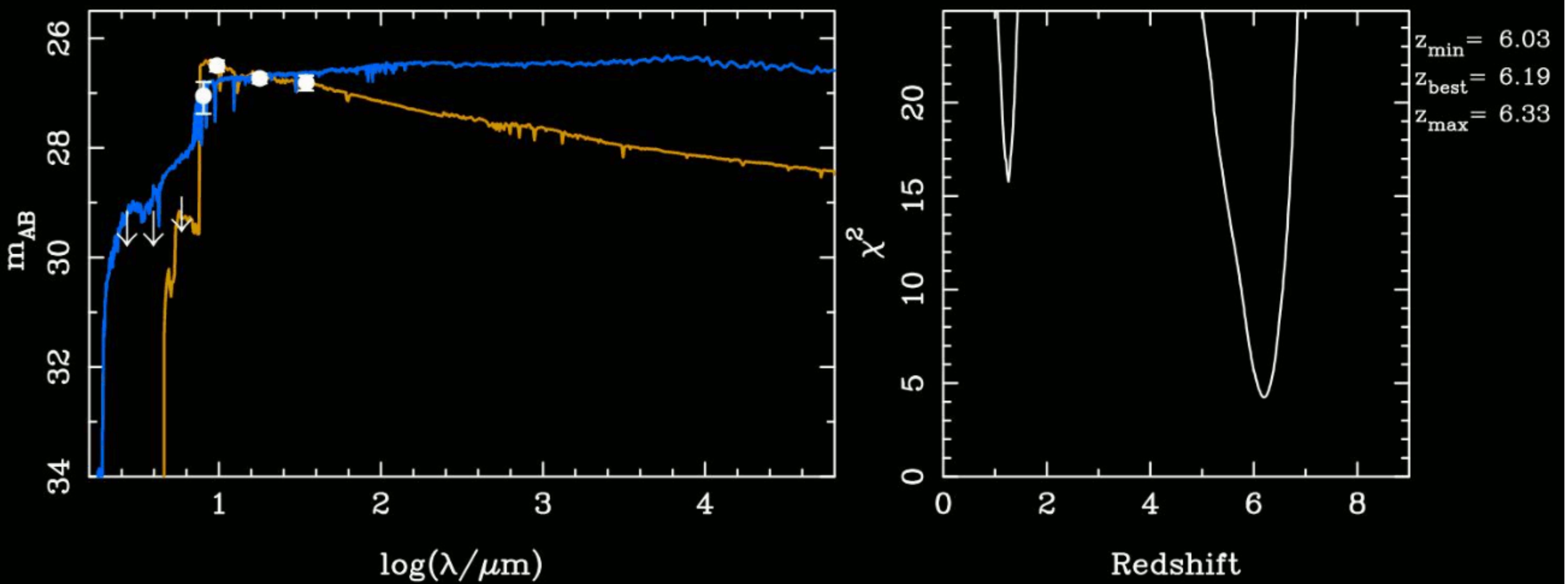
# Conclusions

- Evidence that the decline in quasar space density accelerates beyond z=6
- UKIDSS and PanSTARRS offer the best chance of finding z>6.4 quasars over next 2-3 years
- The most promising mission in the medium term 5-10 years is JANUS

# Life after SDSS, CFHQS
# >40 optical quasars $5.7<z<6.4$

1. Current status and next few years at
   - X ray
   - Mid-ir
   - Radio (radio quasars, radio galaxies)
2. Current status of UKIDSS (near-ir)
3. Prospects with JANUS

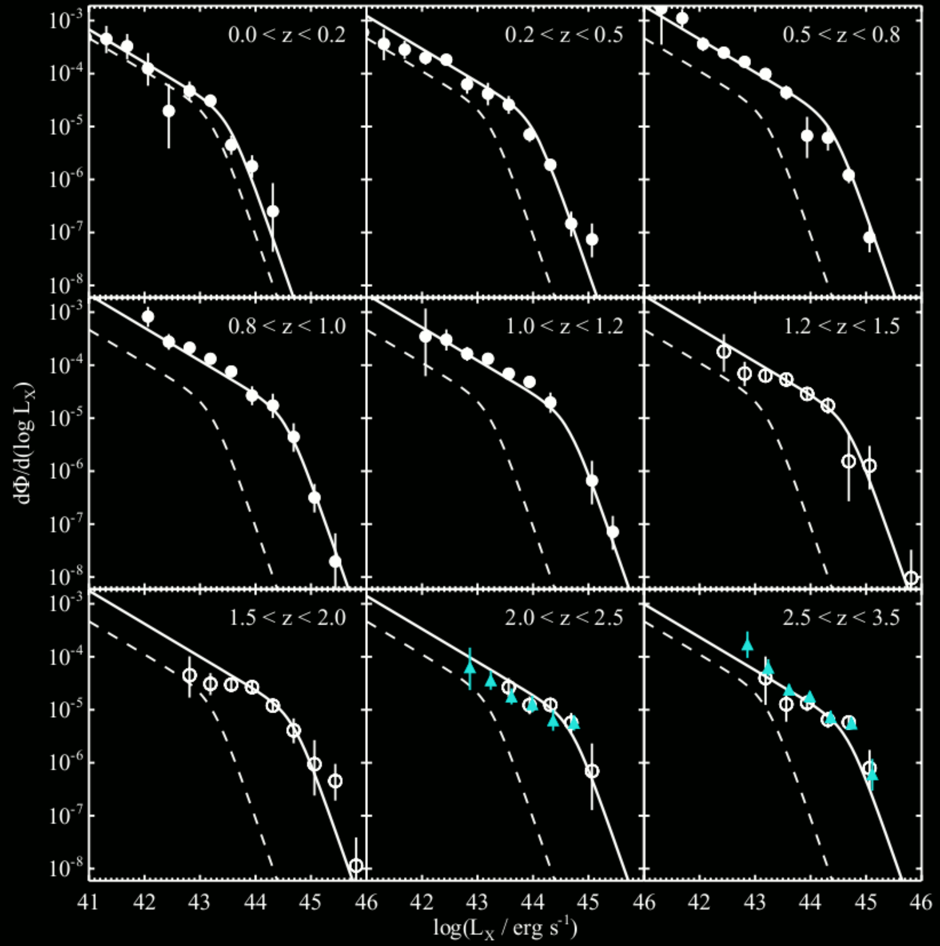
# X rays: current status



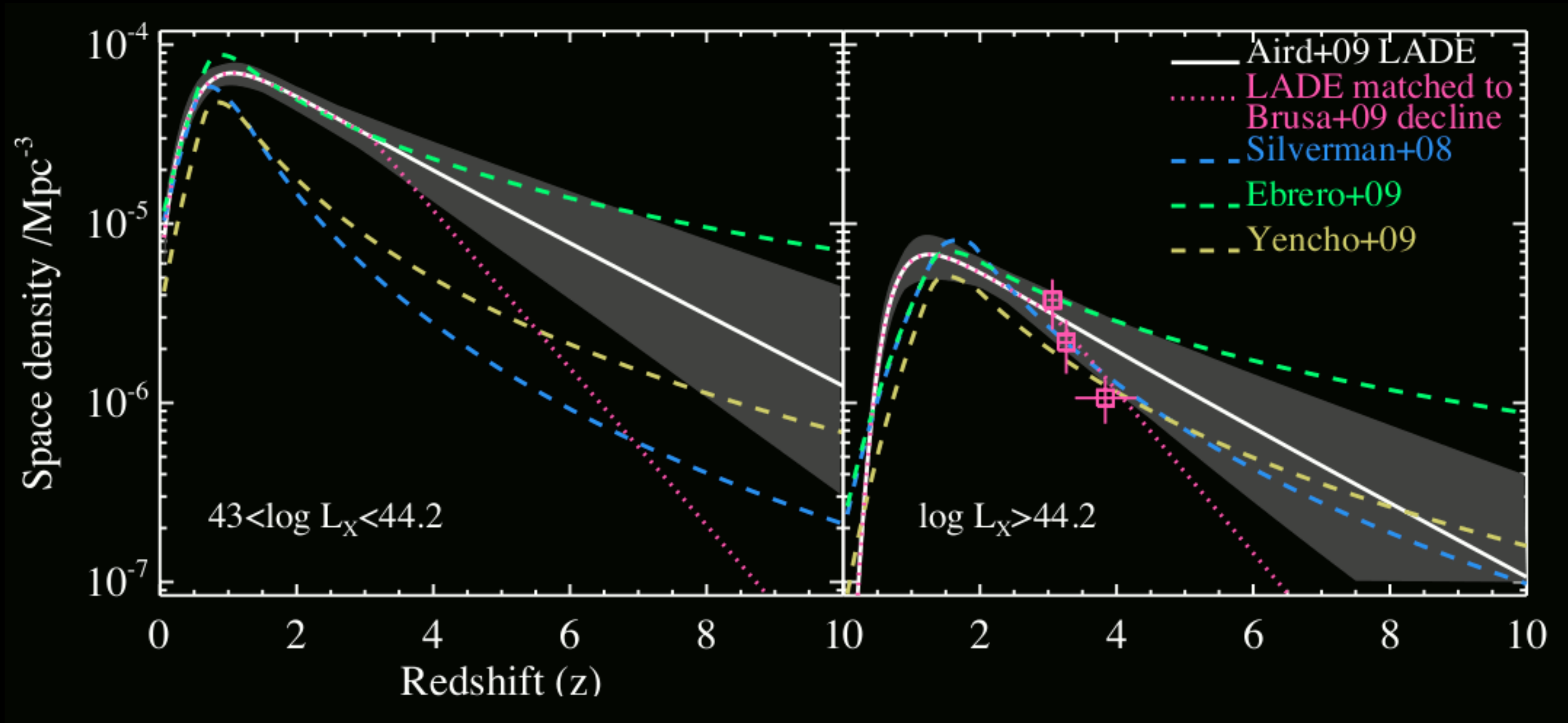

- z=6.19 candidate CDFS

# X rays: the near future

Predictions using the hard X-ray luminosity function of Aird et al. (2010)



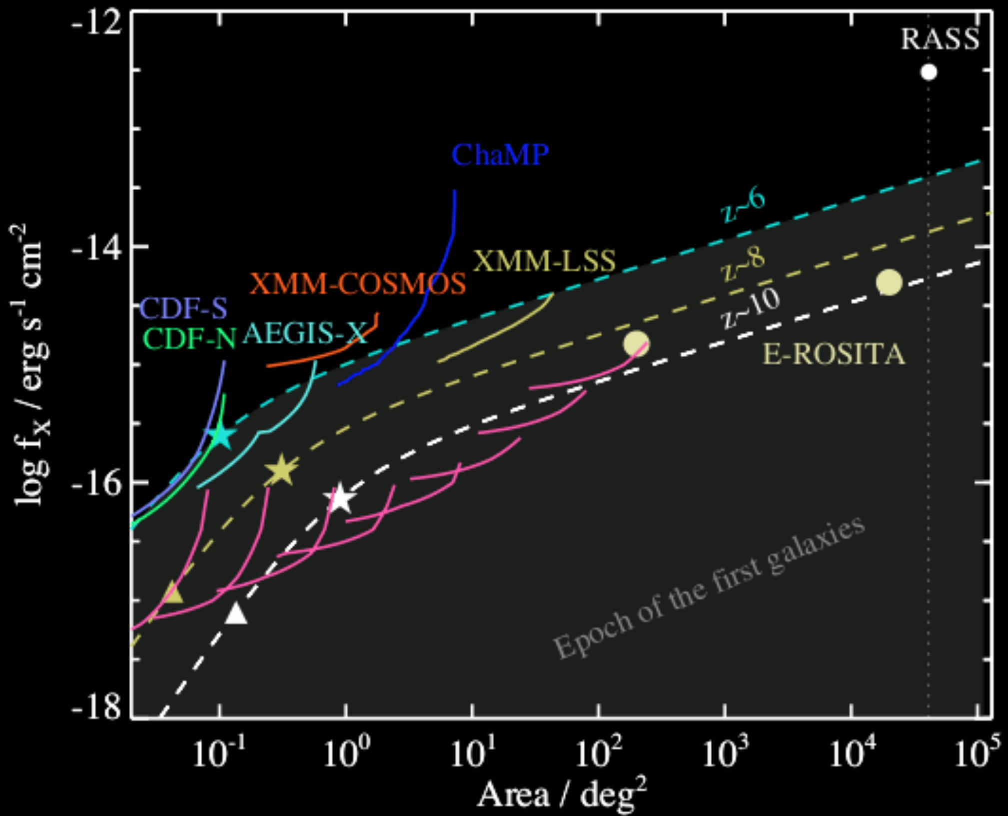
# X rays: the near future



# X rays: the near future

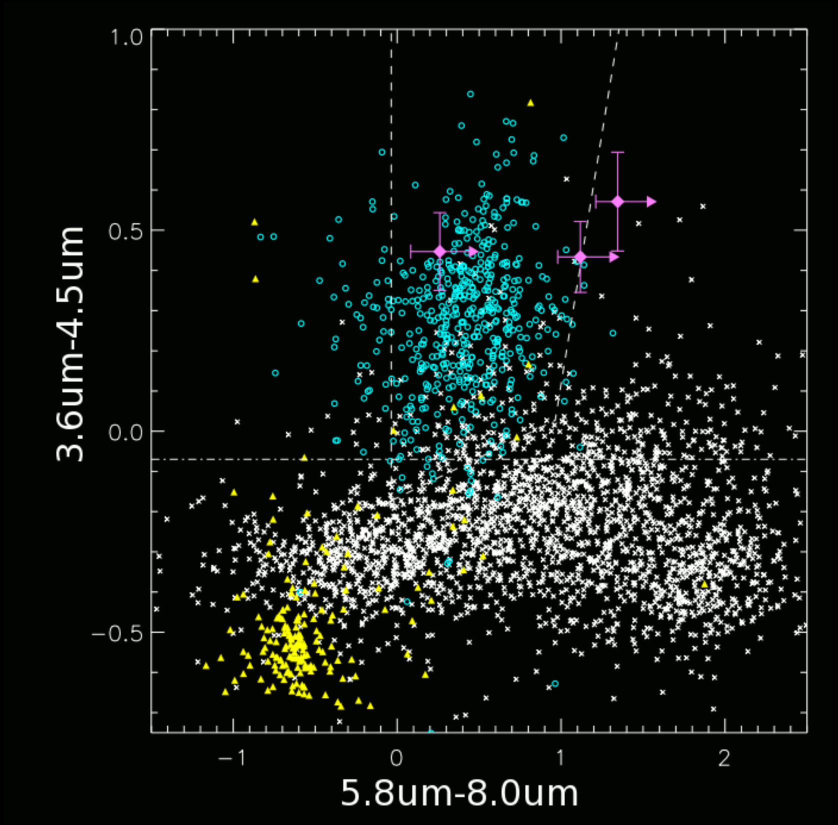
eROSITA all-sky survey (launch 2012) could find a number of z>6 AGN, but

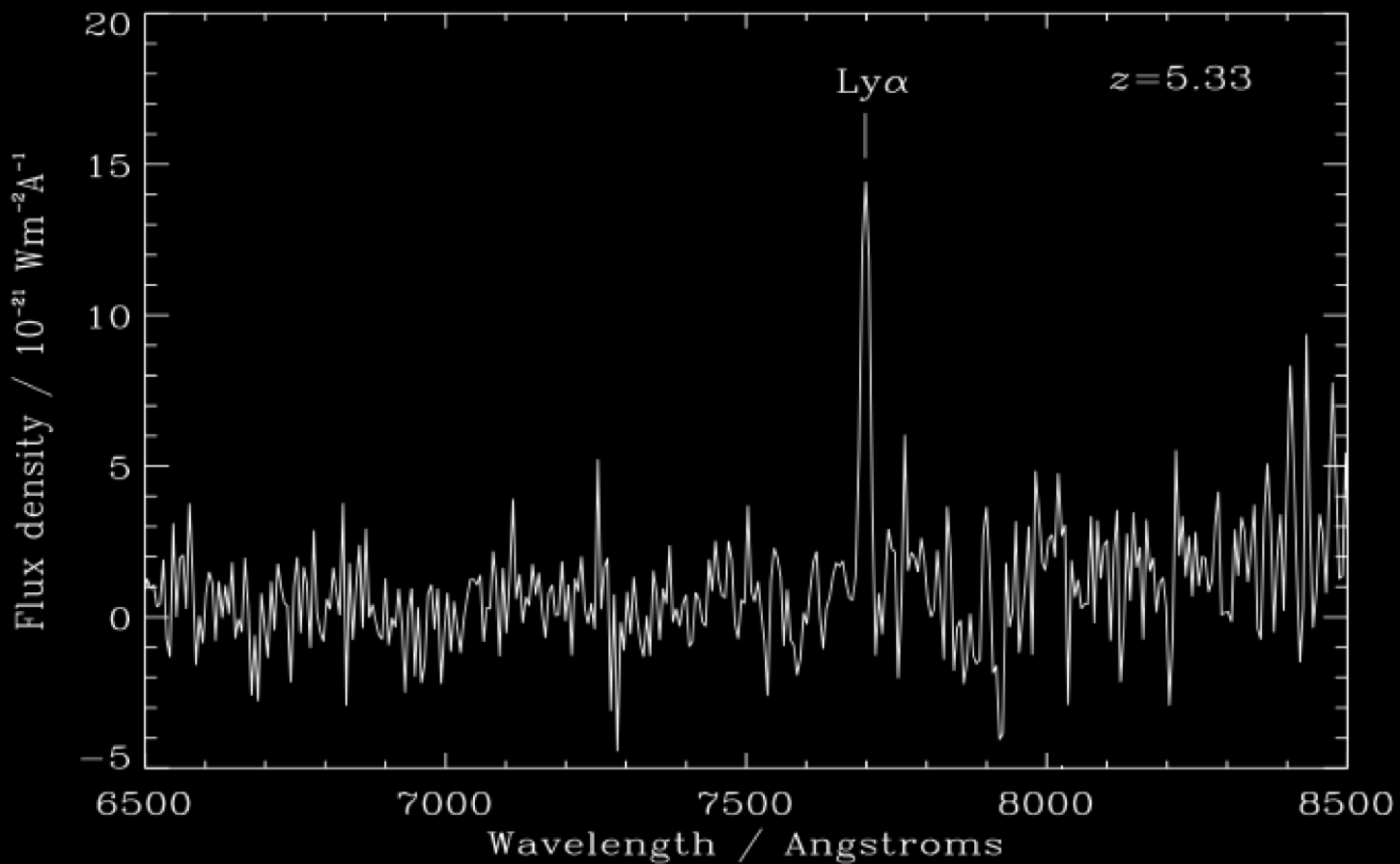
- numbers uncertain
- very substantial follow-up required




# Mid-ir: current status

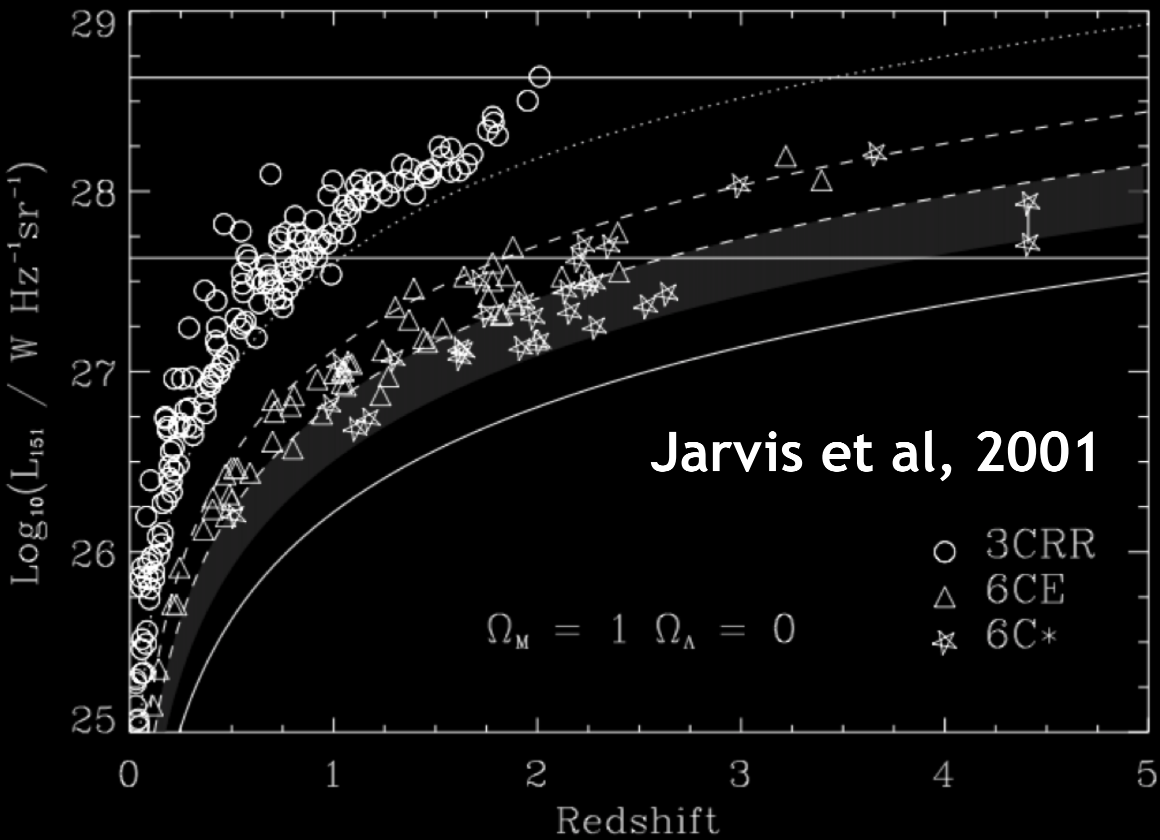
- Motivation
  - Avoiding selection biases
- Results
  - z=5.39, 5.53, 5.85 (Cool et al 2006)
  - z=6.12 (Stern et al 2007)
- Drawback z>6.4
  - Near-ir data needed
  - Brown dwarf contamination
  - WISE not deep enough





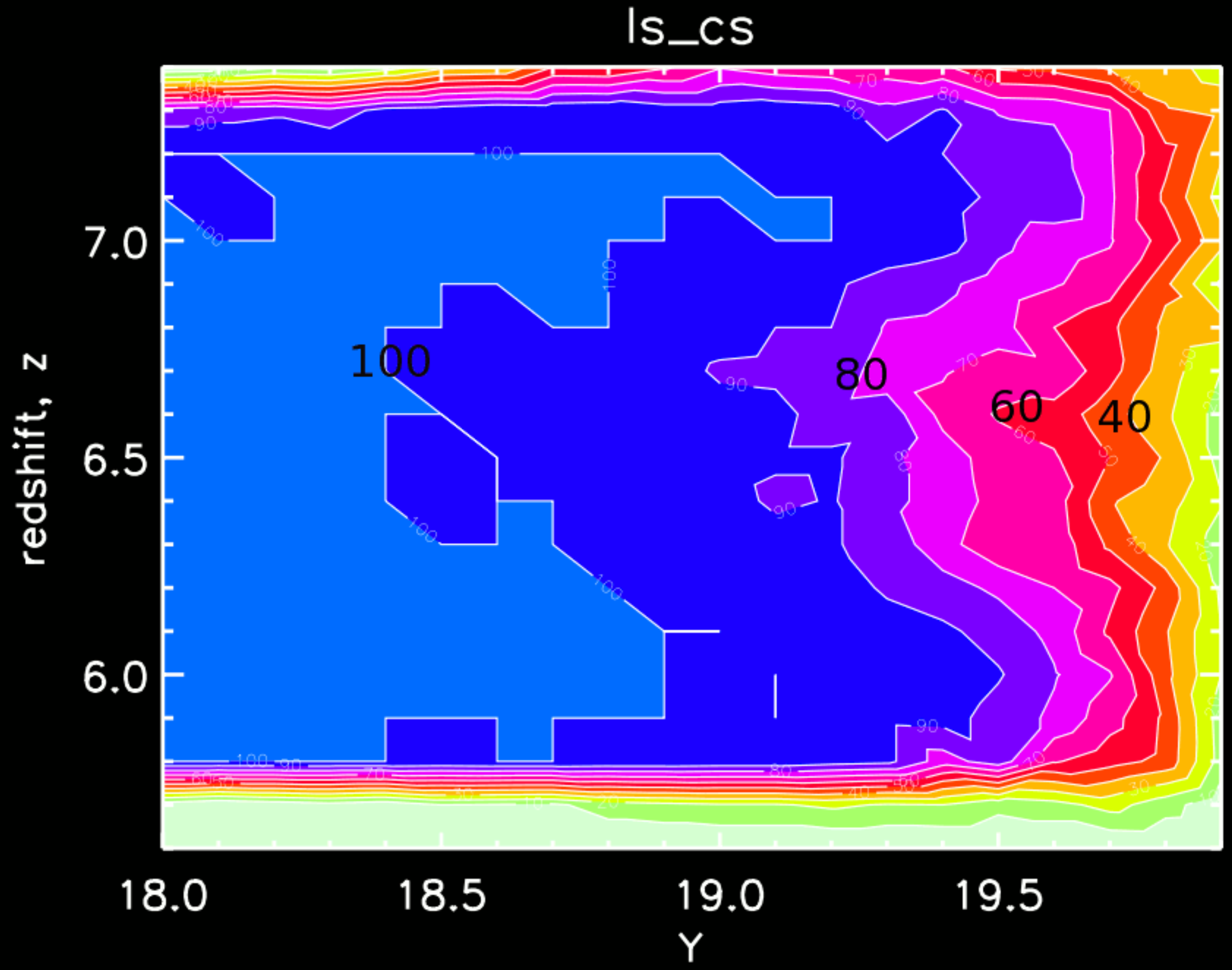

1999)

- z=5.33 (Teimourian et al 2010)




- ht
- an
- Radio galaxies-PanSTARRS, WISE blank, very faint in K
  - Predicted numbers very uncertain
  - Very extensive follow-up needed

# Completeness calculation

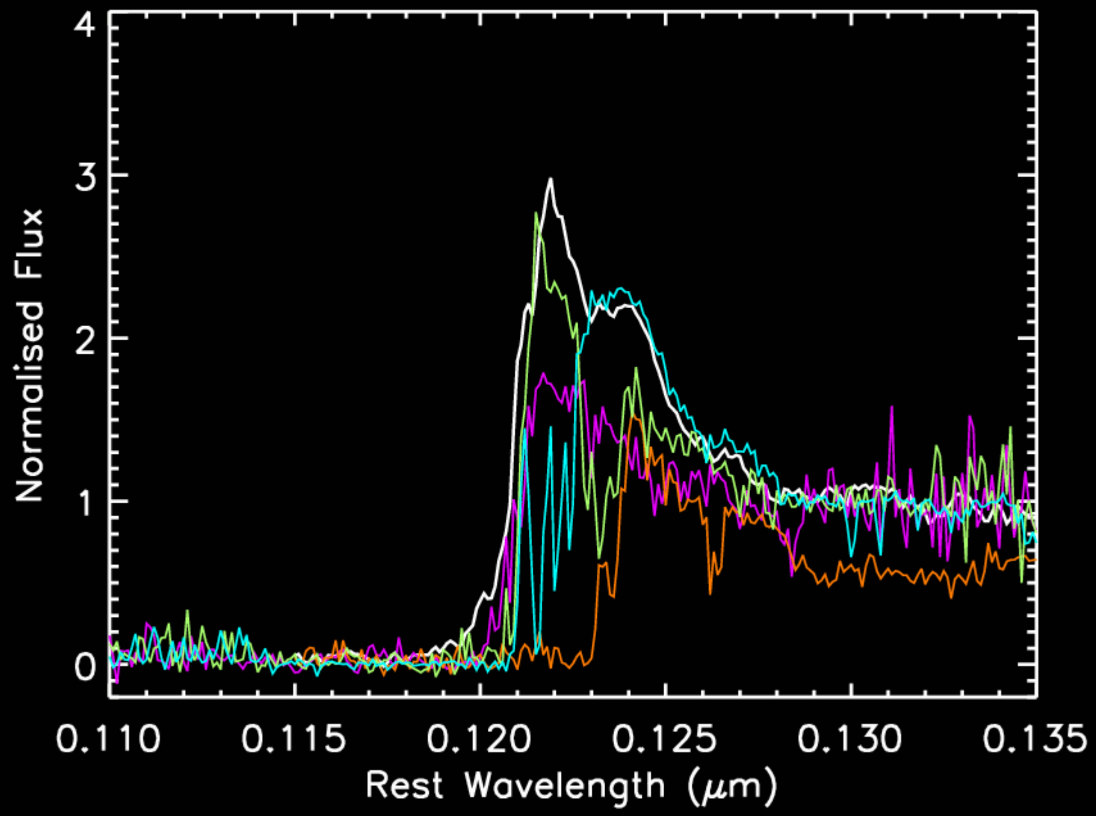


# Detected high-z quasars UKIDSS DR7

| Source | redshift | Y(Vega) | Data release |
|---|---|---|---|
| SDSS J0836+0054 | 5.82 | 18.3 | SDSS |
| SDSS J1411+1217 | 5.93 | 19.5 | SDSS |
| SDSS J1623+3112 | 6.22 | 19.7 | SDSS |
| ULAS J0148+0600 | 5.92 | 18.9 | DR6 |
| ULAS J0203+0012 | 5.72 BAL | 19.8 | DR1 |
| ULAS J1207+0630 | 6.04 | 19.5 | DR5 |
| ULAS J1319+0950 | 6.13 | 19.2 | DR3 |
| ULAS J1609+3041 | 6.08 | 20.0 | DR7 |

# Spectral comparison

UKIDSS quasars have on average smaller Lya EW than SDSS quasars, because selected in Y rather than z.

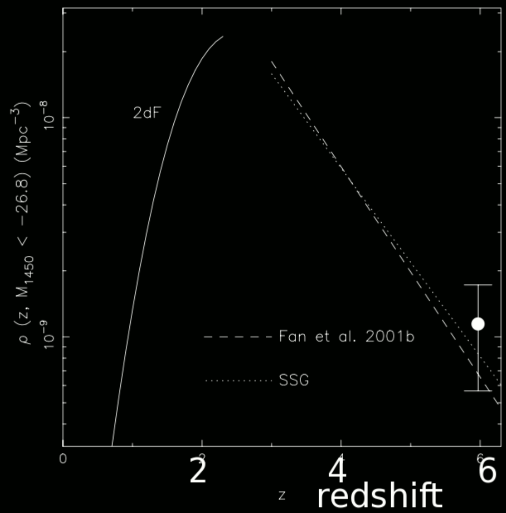


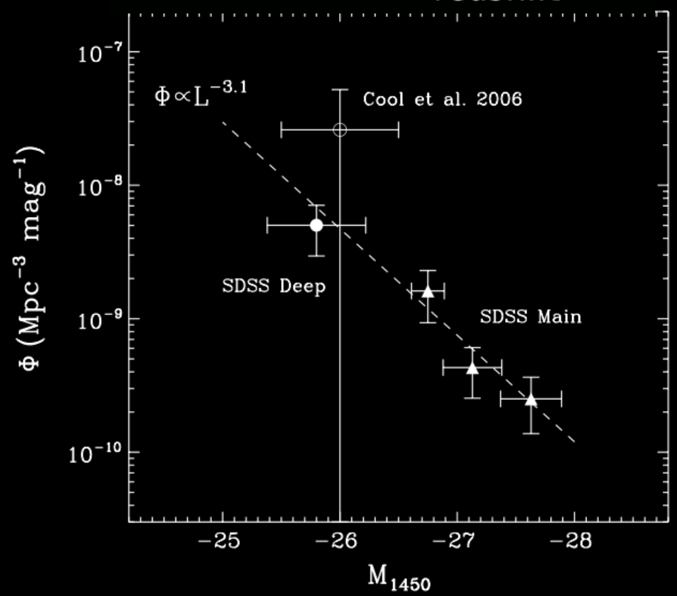
# Predicted numbers

For Jiang et al (2008) LF and Fan et al. (2001) evolution (B=0.47) Y<19.8, 1900deg$^2$

5.8-6.4 predict 14.6 compared to 6 found

6.4-7.2 predict 4.7 compared to 0 found



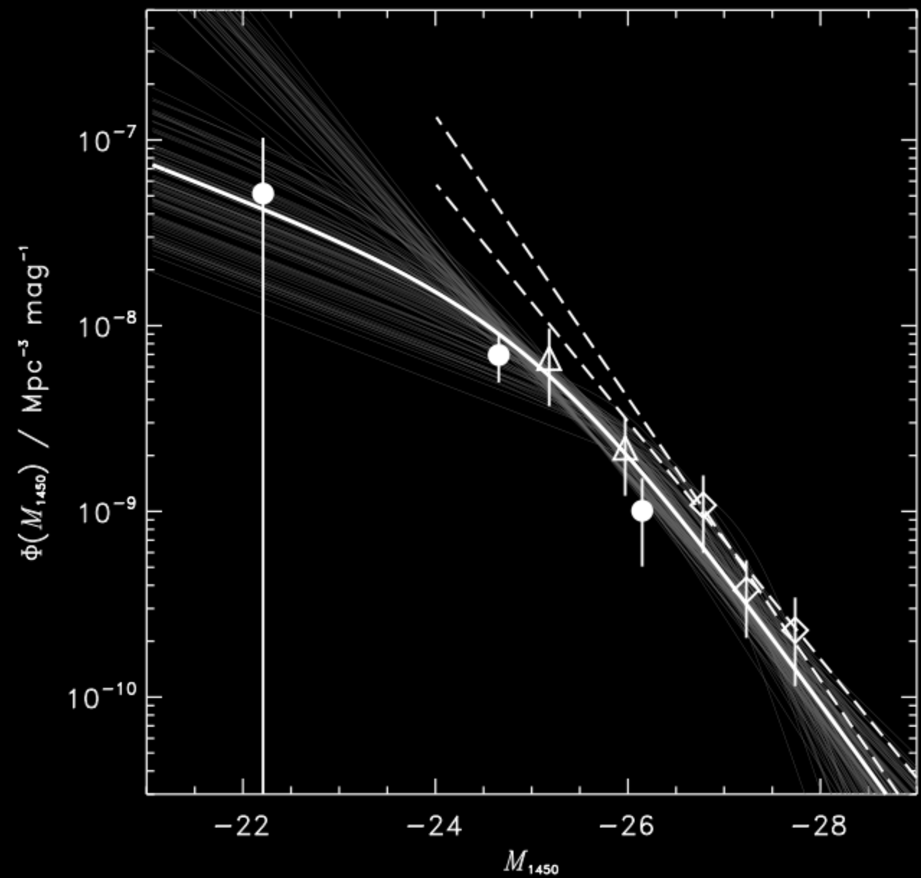
# Predicted numbers

For Willott et al (2009) LF
Y<19.8, 1900deg$^2$

5.8-6.4 predict 10.4
compared to 6 found

6.4-7.2 predict 2.8
compared to 0 found

Null detection at z>6.4 is
inconsistent with prediction
at 94% confidence



# Summary

Null detection in UKIDSS DR7 1900deg$^2$ is inconsistent with expectation at 94% confidence. Decline at high z is accelerating.

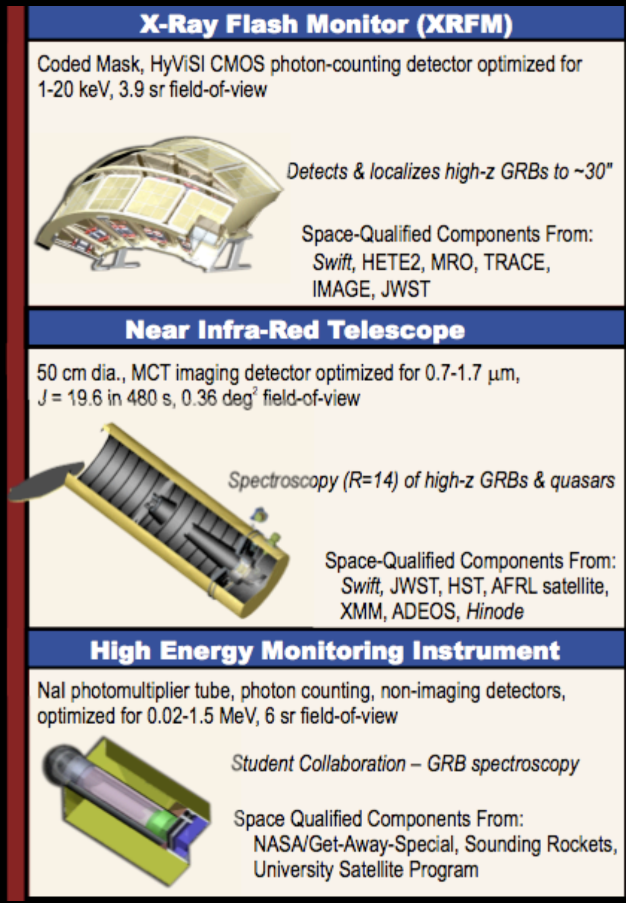
Future:

UKIDSS will grow
1900deg$^2$ -> 2900deg$^2$ (2011) -> 3800deg$^2$ (2012)

Main competitor over next 2 years is PanSTARRS (just started)

# JANUS instruments

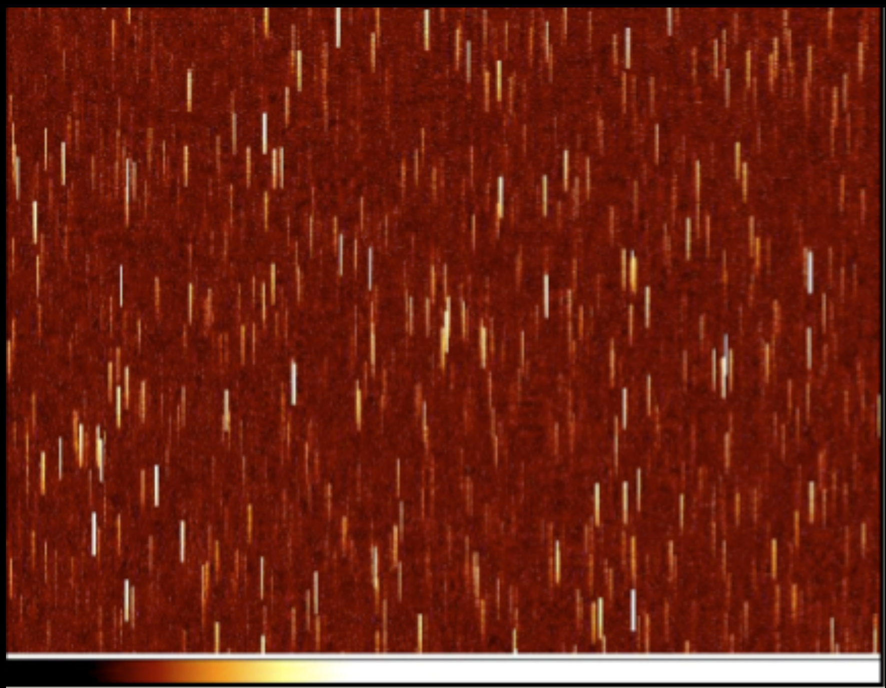
- XRFM 1-20 keV: detects GRBs
- NIRT 0.5m dia., 0.7-1.7um, 0.36deg$^2$, R=14 objective prism spectra: locates GRB, measures redshift. Meanwhile undertakes 20,000deg$^2$ survey
- HEMI 0.02-1.5 MeV: SEDs of GRBs

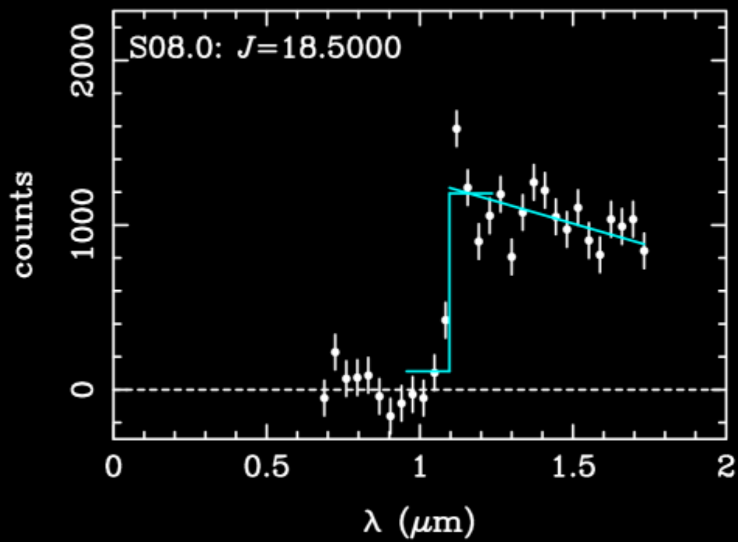


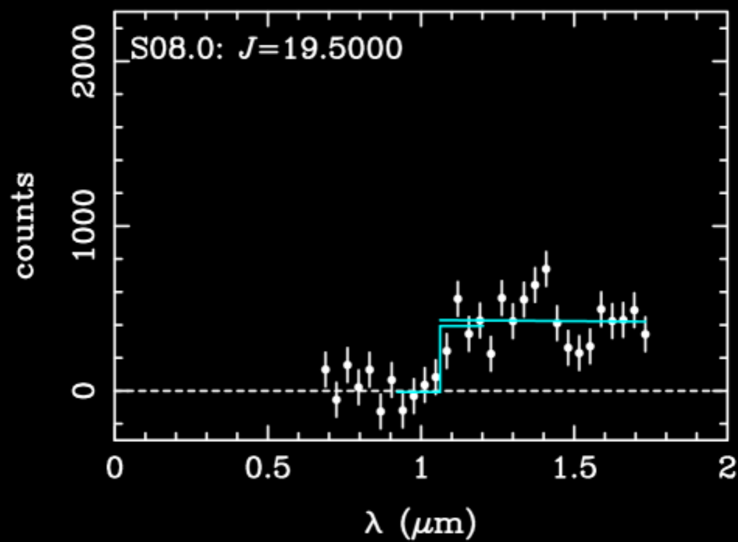
# The best future quasar survey JANUS 20000 deg$^2$

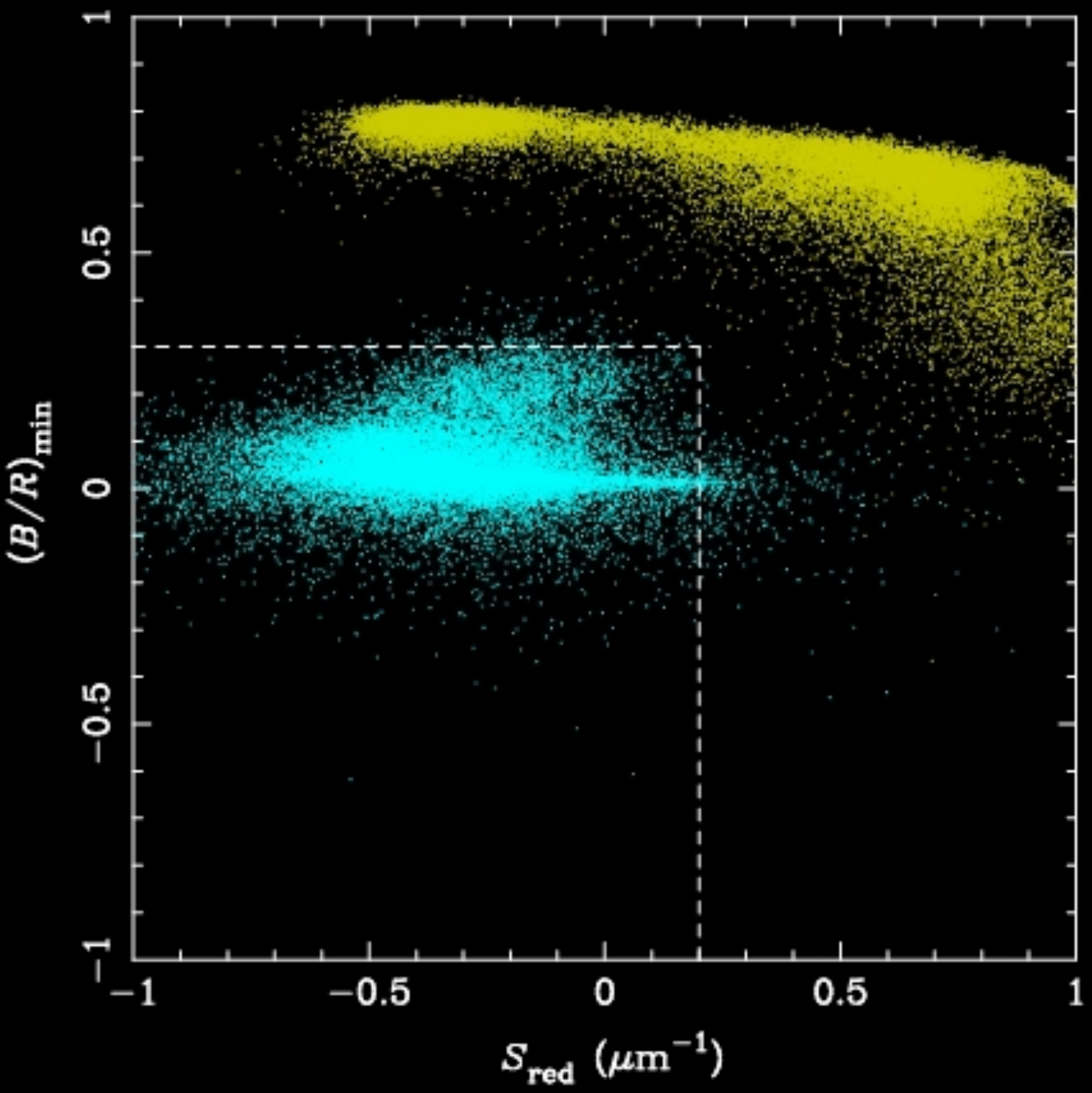
**NIRT: R=14 objective prism spectroscopy, 0.7-1.7um, over 0.36 deg$^2$**

J=19.6, 4sigma per pix, 480s



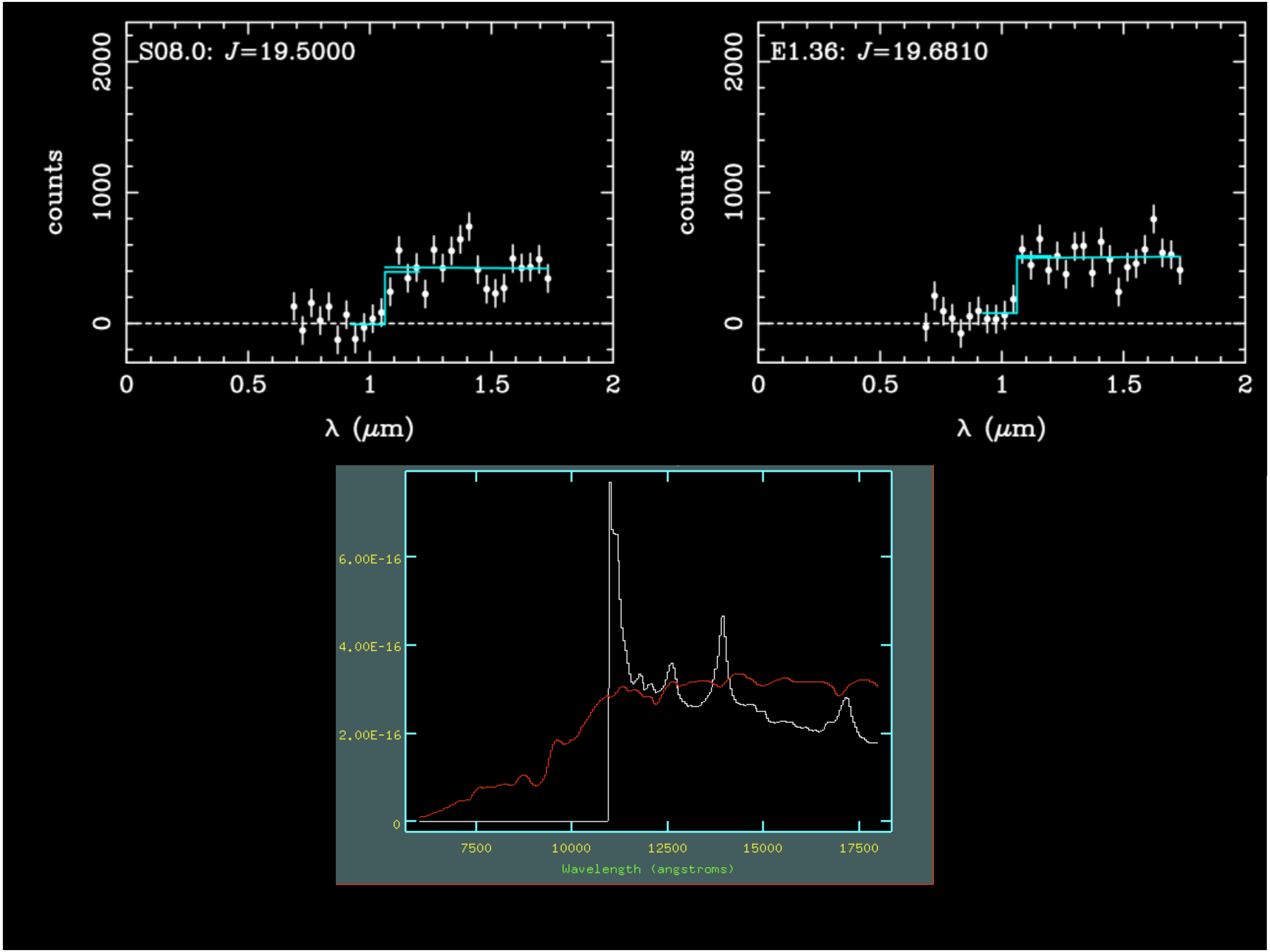


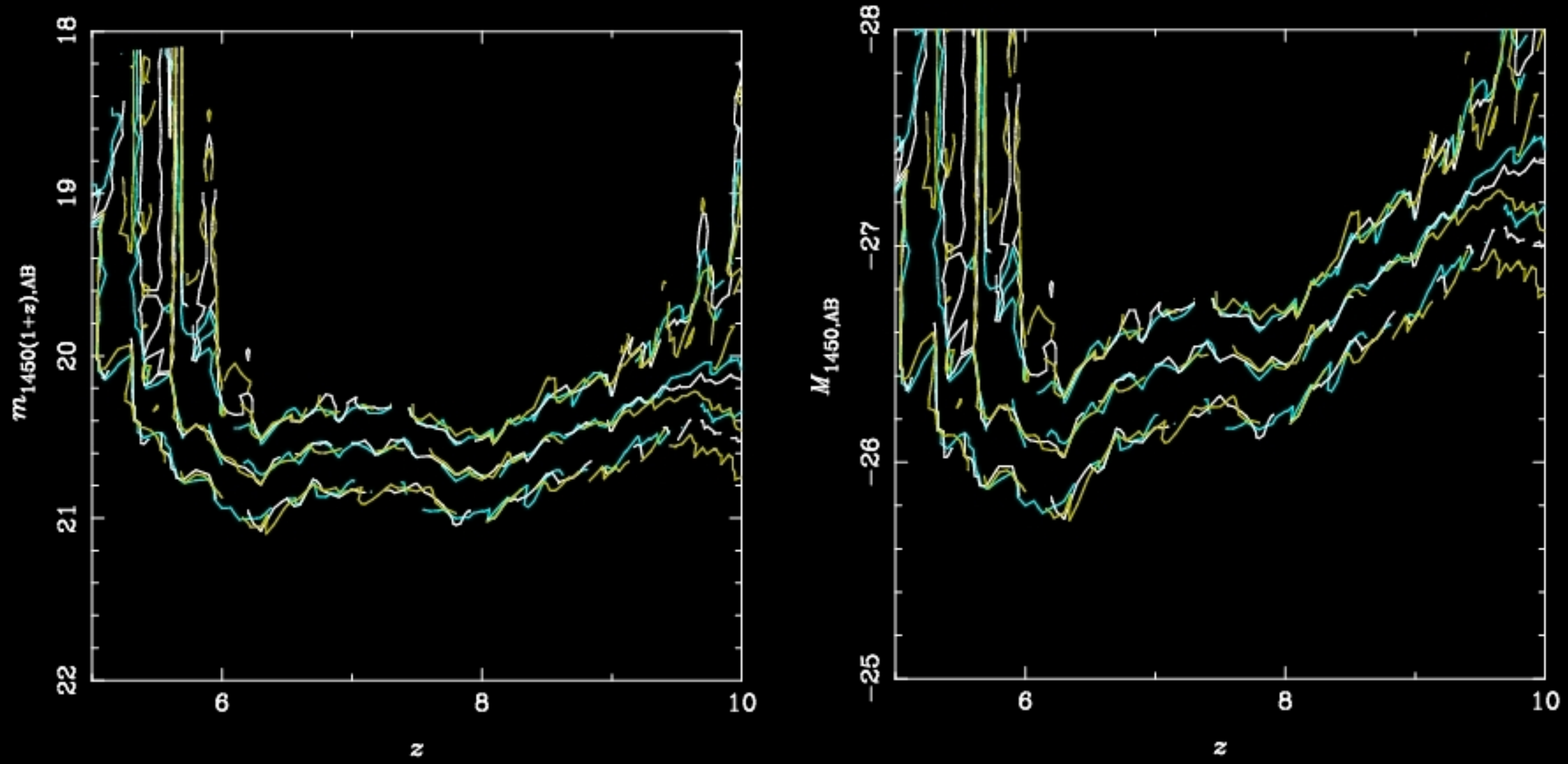






For predicted quasar numbers, contamination ratio ellip:quasar is 5:1

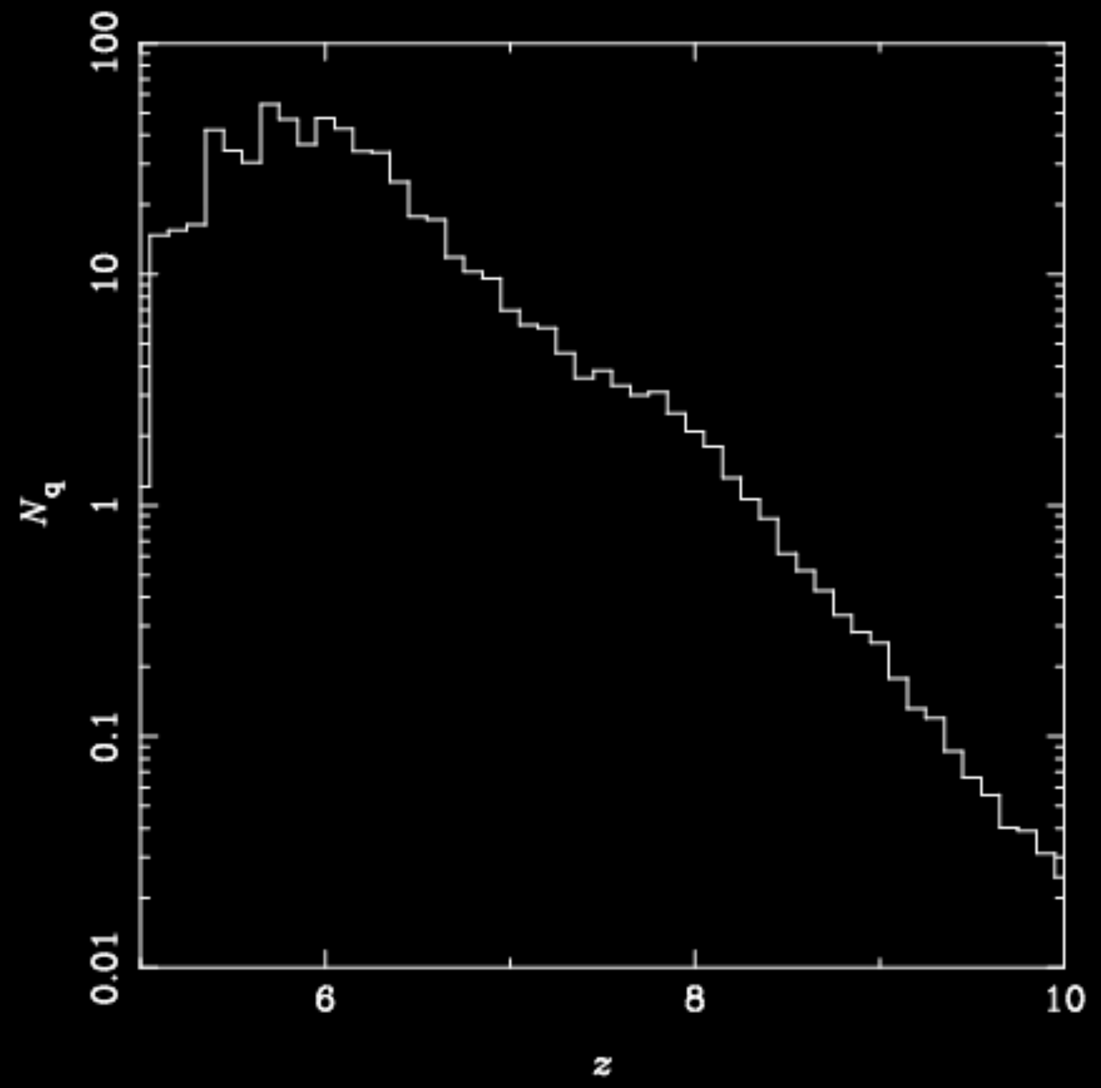
All stars, brown dwarfs, irregulars eliminated


S08.0: $J$=19.5000
counts
0
1000
2000
0
0.5
1
1.5
2
λ (μm)
E1.36: $J$=19.6810
counts
0
1000
2000
0
0.5
1
1.5
2
λ (μm)
6.00E-16
4.00E-16
2.00E-16
0
7500
10000
12500
15000
17500
Wavelength (angstroms)




Completeness is insensitive to line strength

# Predicted numbers of high-z quasars




| | |
|---|---|
| 168 | 6.0<z<6.5 |
| 61 | 6.5<z<7.0 |
| 25 | 7.0<z<7.5 |
| 15 | 7.5<z<8.0 |
| 6 | 8.0<z<8.5 |
| 2 | 8.5<z<9.0 |
| 1 | z>9.0 |

total 278 z>6

# JANUS summary

- JANUS NIRT should find 50 quasars z>7 and will be an order of magnitude better than existing surveys in 2016
- On balance the uncertainties in the assumptions made suggest this number is realistic
- Contamination will be very manageable

# Conclusions

- Decline in quasar space density accelerates beyond z=6
- UKIDSS and PanSTARRS offer the best chance of finding z=7 quasars over next 2-3 years
- The most promising mission in the medium term 5-10 years is JANUS