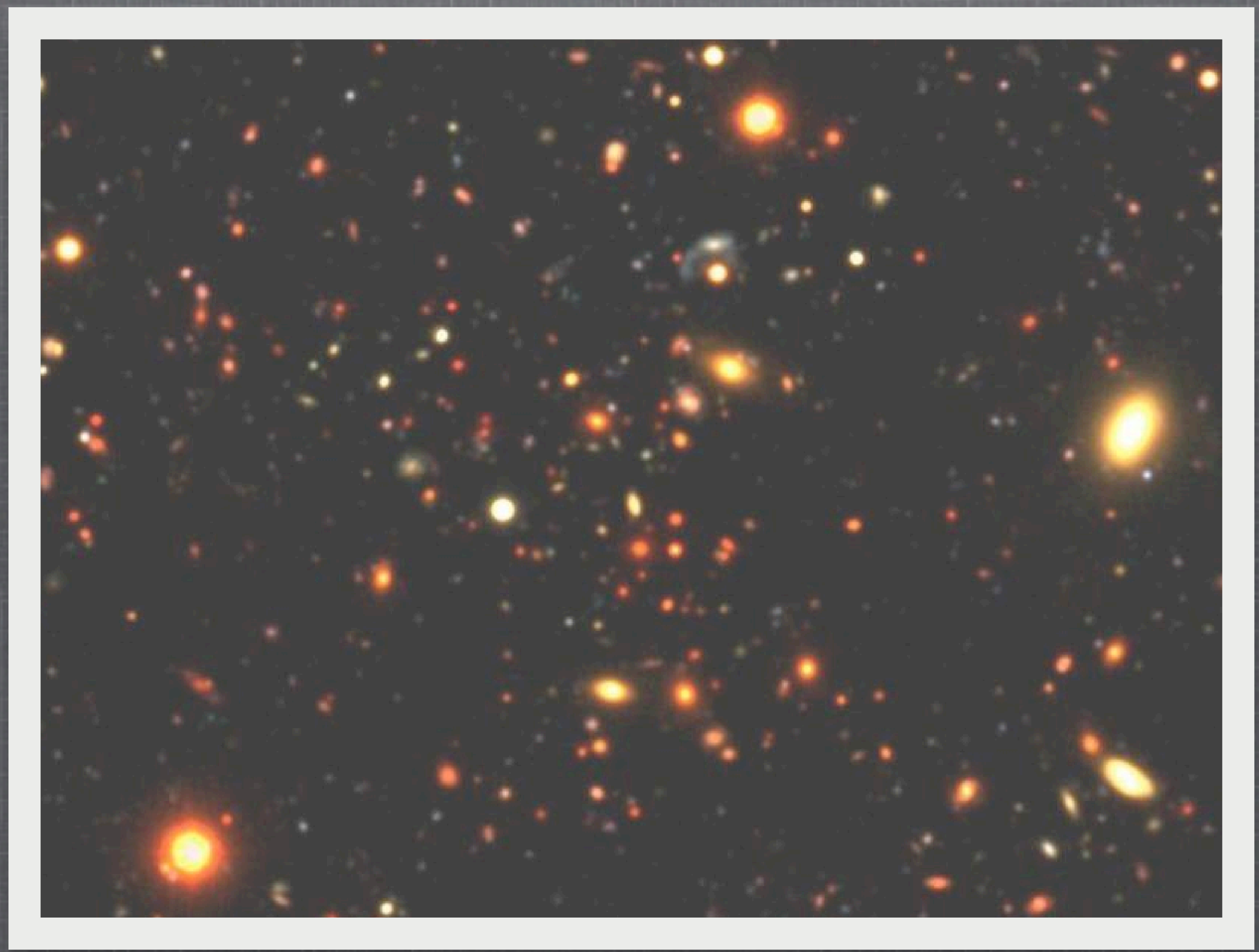
# DEEP EXTRA-GALACTIC IMAGING

Jarle Brinchmann (Leiden)



# Overview

- Brief summary of existing deep-imaging surveys and what we have got out of them.
- A quick look at a couple of surveys and the logic of doing them.
- What part of parameter space is missing?
- Suggestions for future deep wide-field imaging facilities on the E-ELT.

# General considerations

- We are aiming for the post-JWST era.
  - Some areas will have exceptionally deep MIR imaging.
  - Will the **most** distant galaxies still be a main driver for science?
  - We will not know where all the interesting sources are before JWST retires!
- Are there areas of parameter space that have not been covered **and that we wish to cover**?
- What wavelength range do we need?
  - NIR is currently a main limiting factor. Will this still be the case in 10-15 years?
  - Is blue optical sensitivity important?
- What resolution & area coverage do we need?
  - Do we need diffraction limit? What will be possible in 10-15-20 years?
  - Is there a trade-off between resolution & area?
- There will almost certainly be some sort of imaging capability on the E-ELT (pre-imaging, commissioning etc).

# Some existing surveys

- The FIRES survey
  - Deep pointed NIR survey of 2 small patches of sky with deep HST data. Inspiration to the UKIDSS UDS and UltraVISTA surveys.
- The COSMOS survey
  - Deep & wide survey based around an exceptional HST mosaic. Aims to have ~homogeneous multi-wavelength coverage & large enough area to beat (somewhat) cosmic variance.
- The AEGIS survey
  - Multi-wavelength survey with different origins but centered around a large strip with HST data.
- The CDF-S
  - Popular field with plenty of multi-wavelength coverage and a number of "surveys" on top, contains the HUDF.

# SOME EXISTING SURVEYS

- The FIRES survey
  - HST
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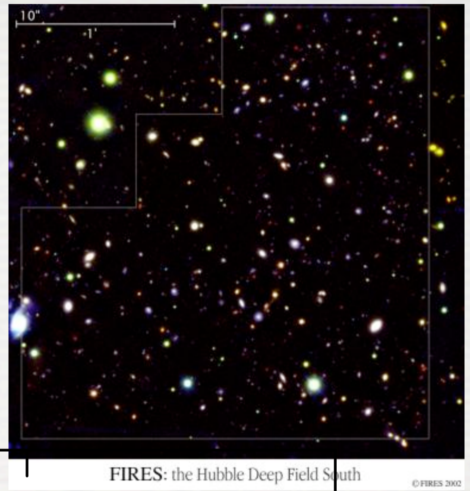
- Th
  - number of "surveys" on top, contains the HUDF.

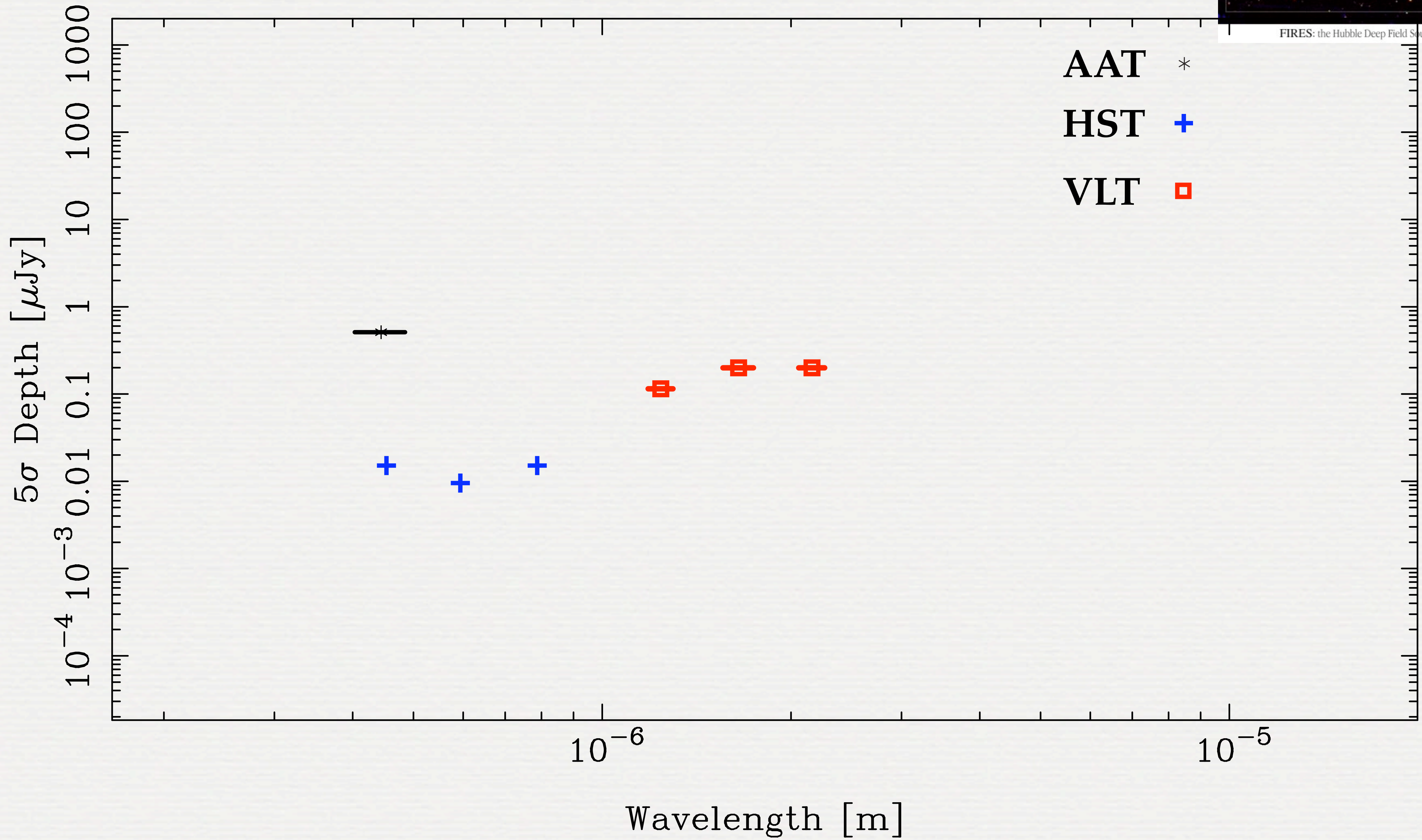
An immediate conclusion:

Successful extra-galactic fields often have deep, high-resolution imaging as a backbone.

This is not always HST, especially if other unique data are available (e.g. SXDS with XMM & SCUBA & Spitzer data and Subaru imaging), but it is often the case.

# FIRES


FIRES: the Hubble Deep Field South


AAT
HST
VLT
5σ Depth [μJy]
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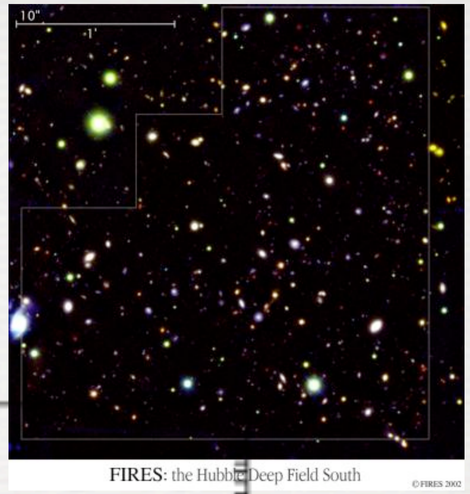
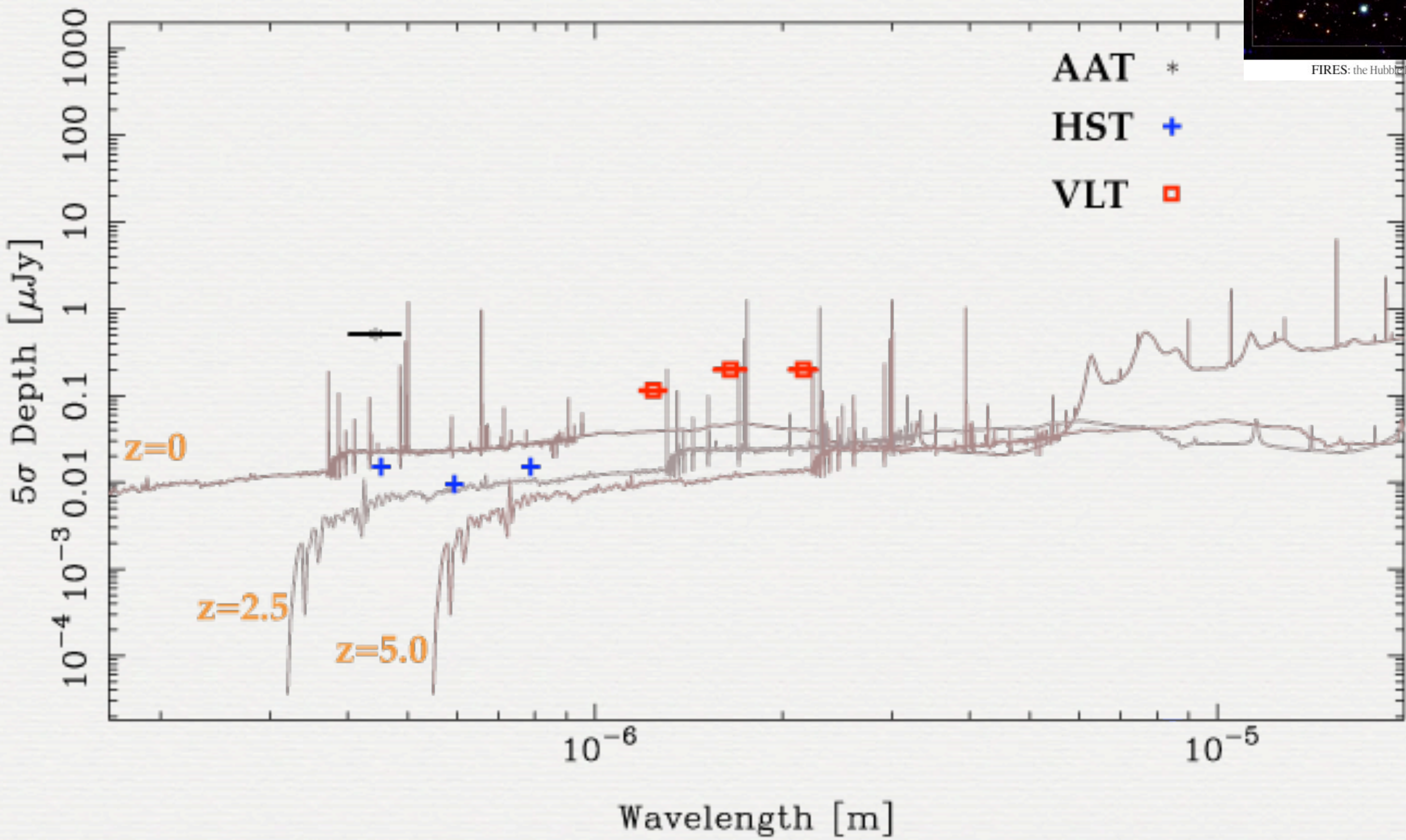
Wavelength [m]

# FIRES



FIRES: the Hubble Deep Field South

AAT
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z=0
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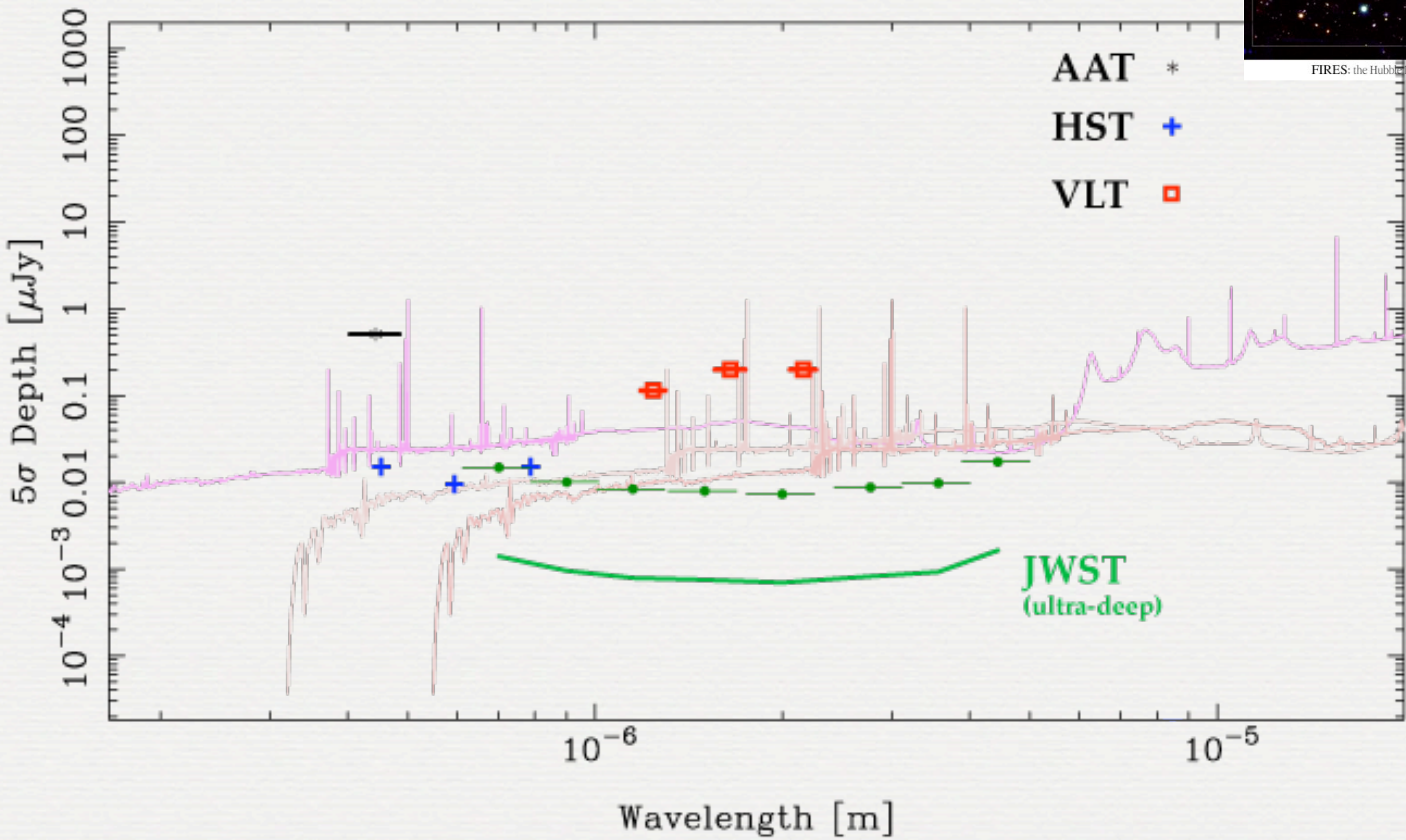
Wavelength [m]

# FIRES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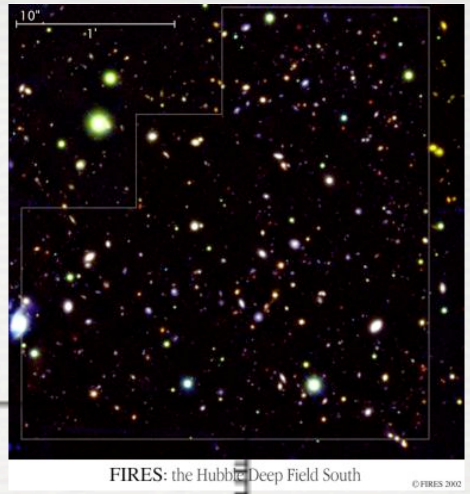
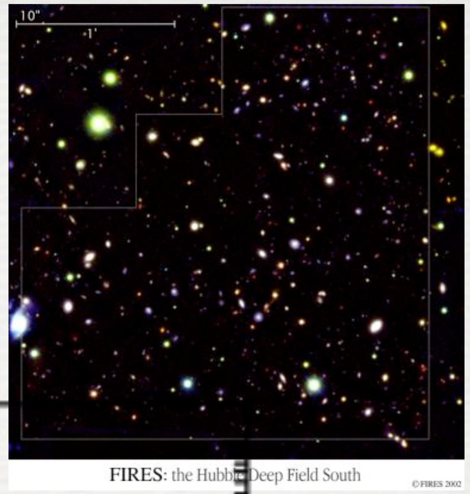
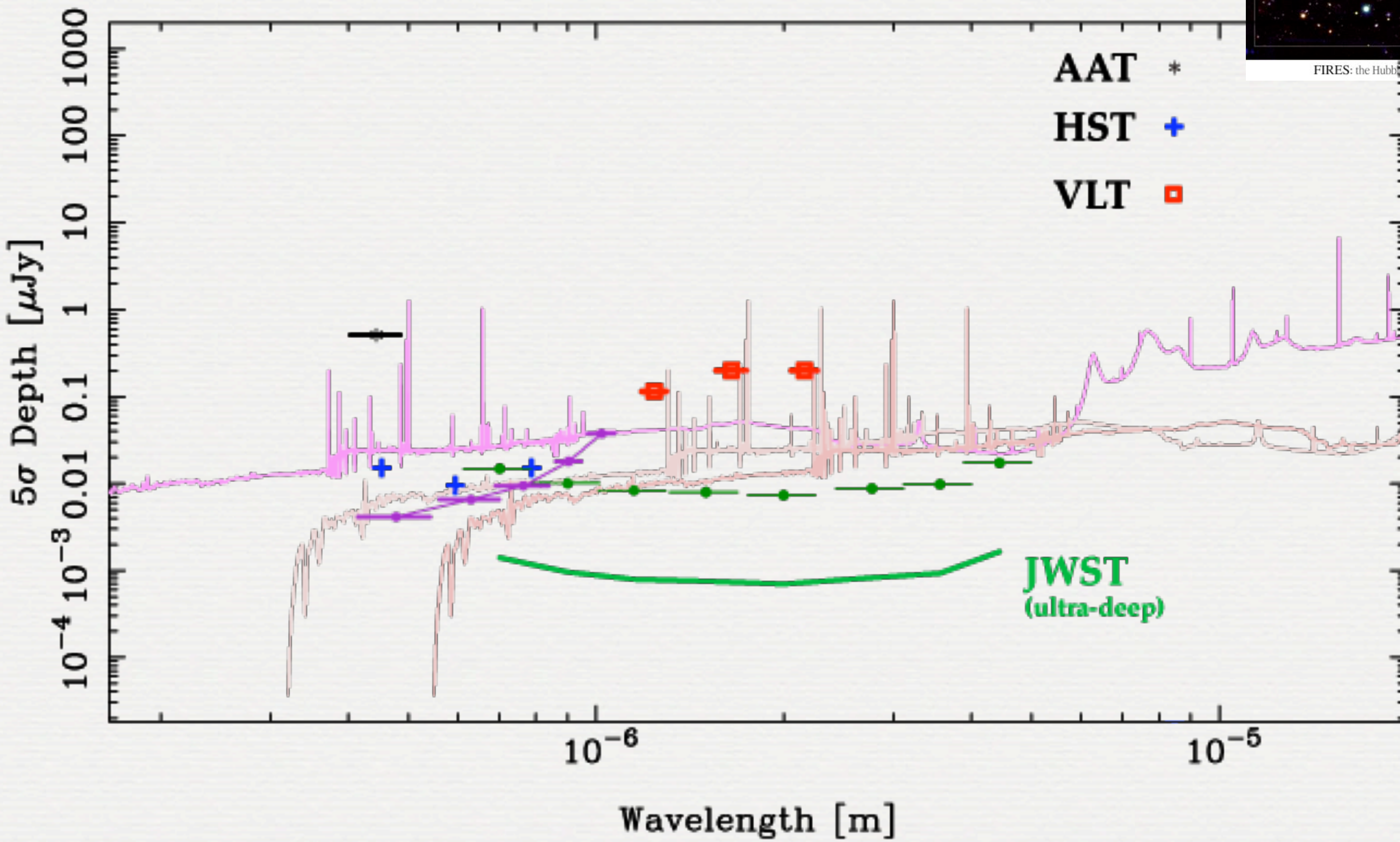
$10^{-5}$
Wavelength [m]


FIRES: the Hubble Deep Field South

# FIRES



FIRES: the Hubble Deep Field South

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(ultra-deep)
5σ Depth [μJy]
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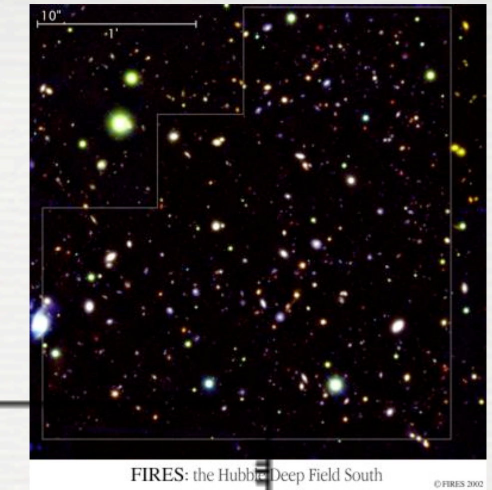
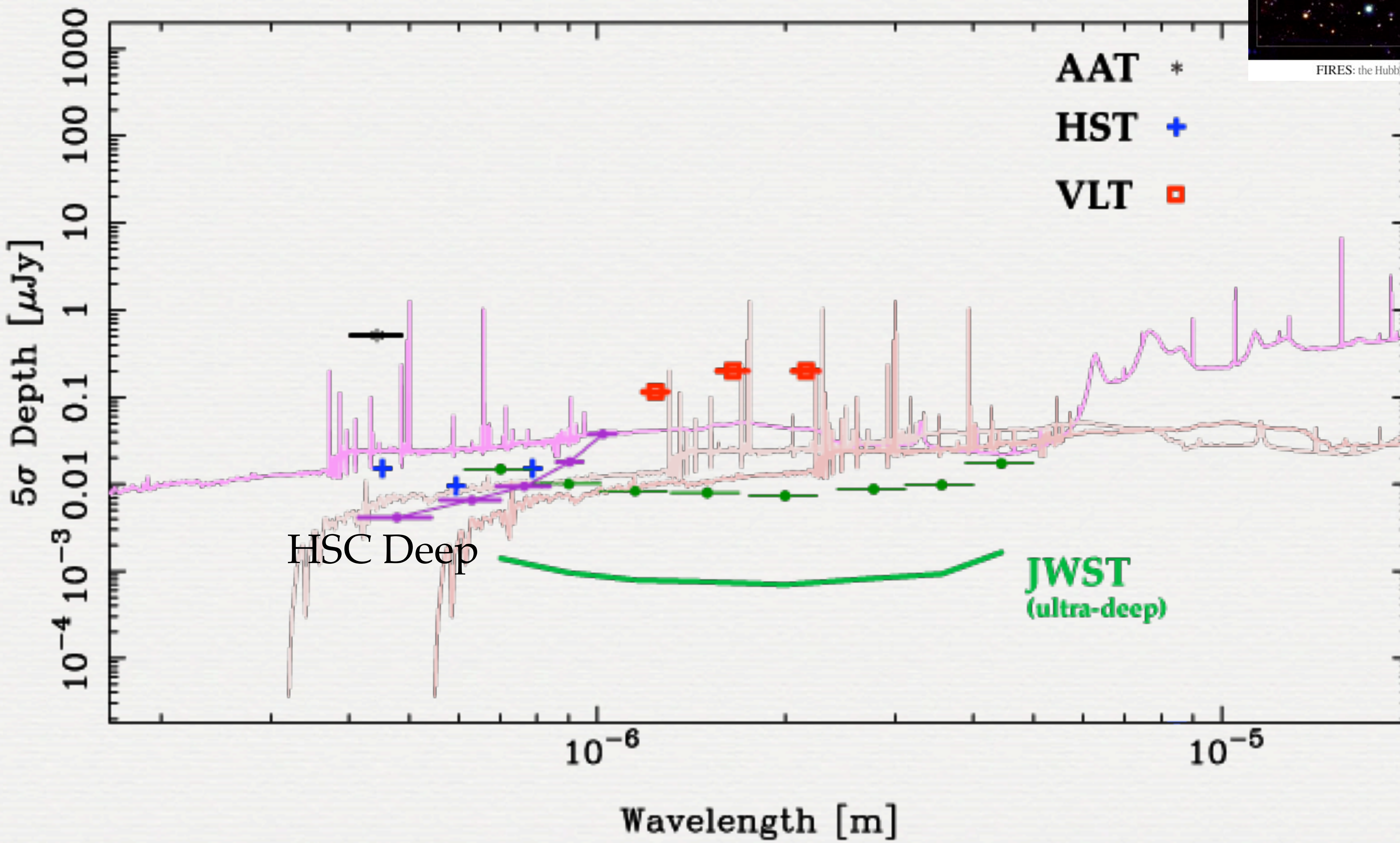
Wavelength [m]

# FIRES


FIRES: the Hubble Deep Field South


AAT
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5σ Depth [μJy]
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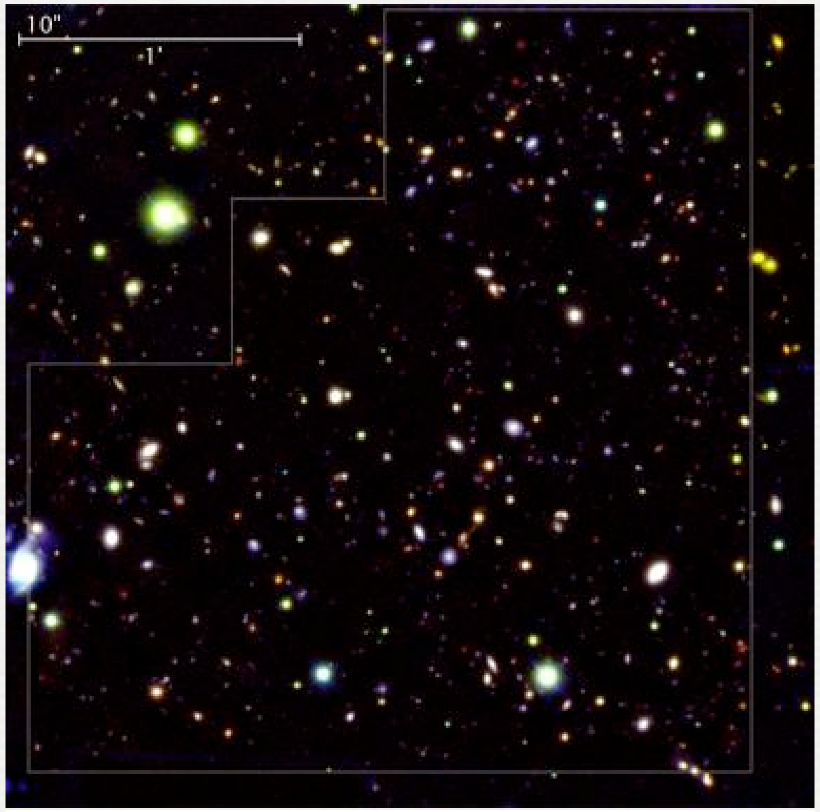
# FIRES



FIRES: the Hubble Deep Field South ©FIRES 2002

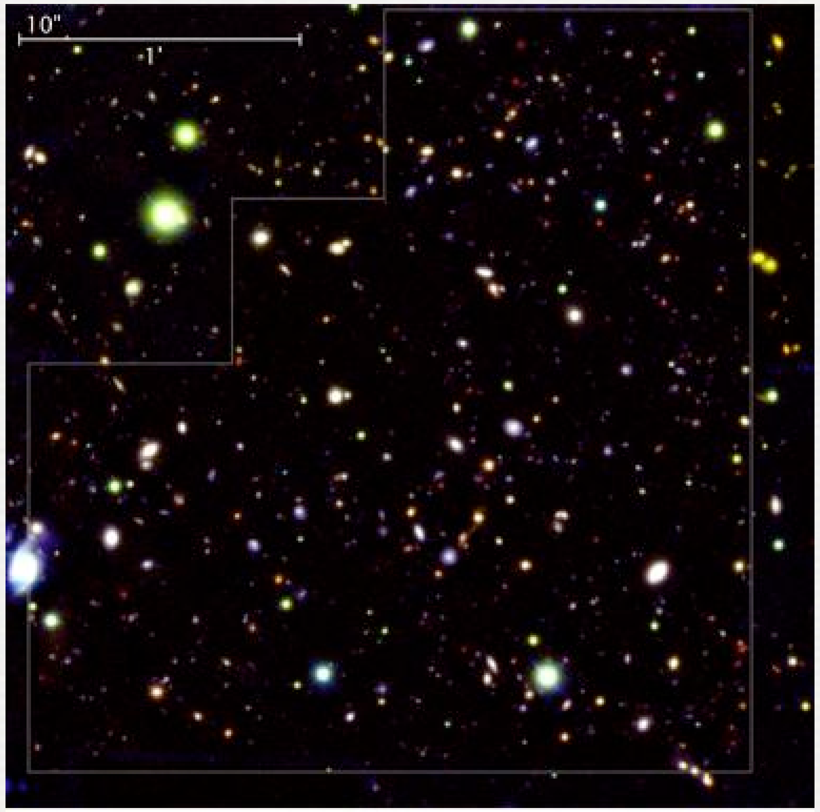
Set the standard for deep field NIR imaging using ISAAC. Reaches AB~26. in J,H,K

The depth and the red bands allowed the detection of massive, old galaxies at z~2. Helped give a broader view of the z~2 galaxy population.

A key result (e.g. van Dokkum et al 2006) is that most of the stars in the Universe at z~2 are in massive, old galaxies.

Problem for FIRES: Massive galaxies are clustered so a large areas is required to get a fair sample.

# FIRES

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Pr

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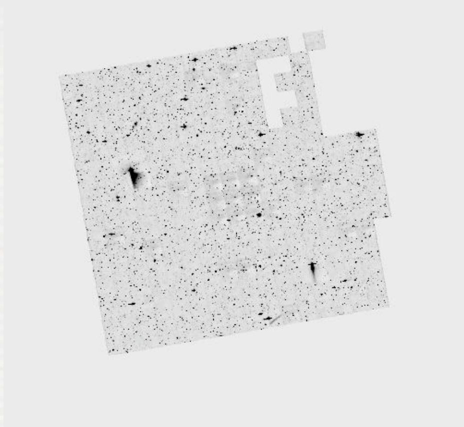
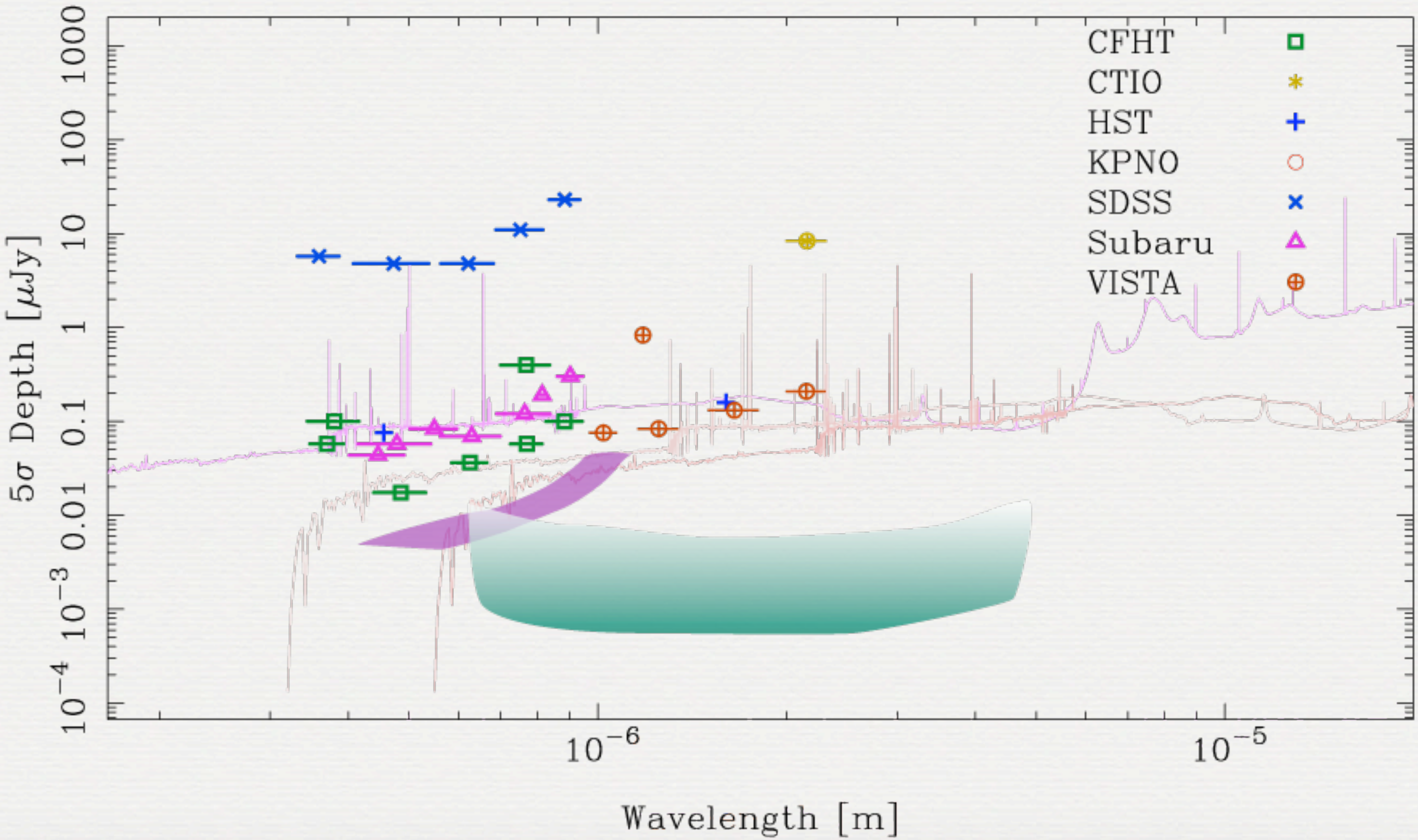
Since 100 Mpc (comoving) corresponds to:

3$^{o}$ at z~0.5 and 1$^{o}$.5 at z~2

you really would like to sample that scale at least.

# COSMOS





CFHT
CTIO
HST
KPNO
SDSS
Subaru
VISTA
5σ Depth [μJy]
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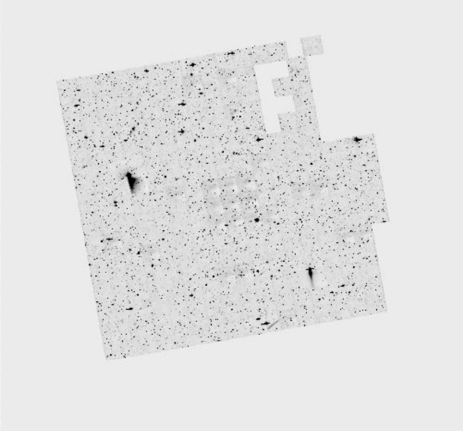
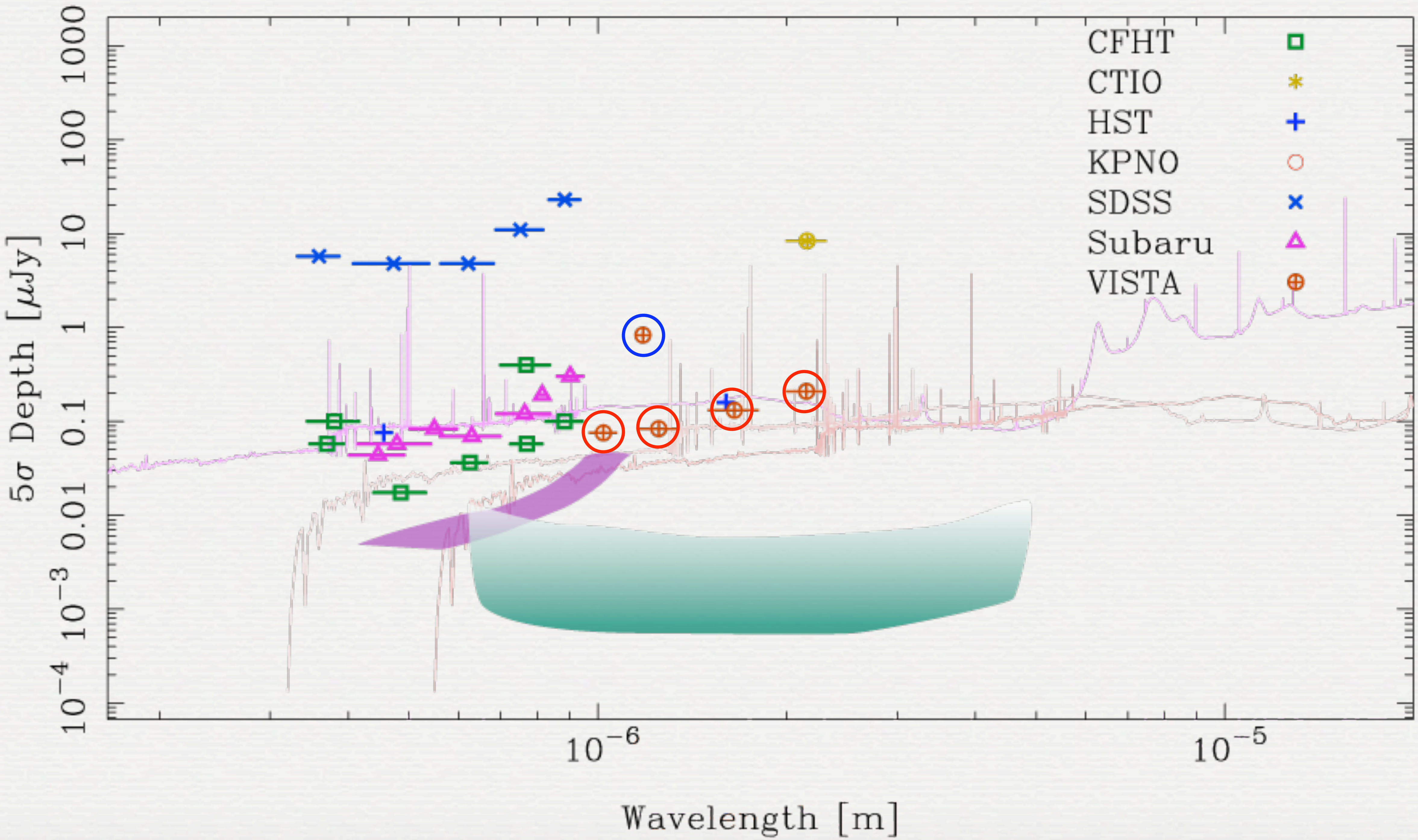
10^-5
Wavelength [m]

# COSMOS




CFHT
CTIO
HST
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5σ Depth [μJy]
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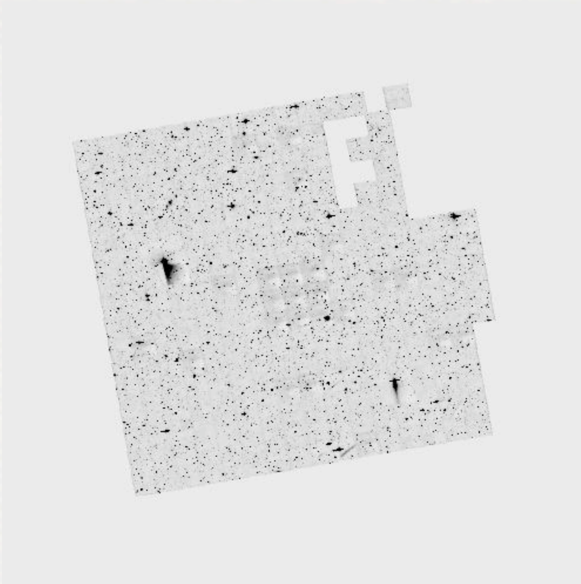
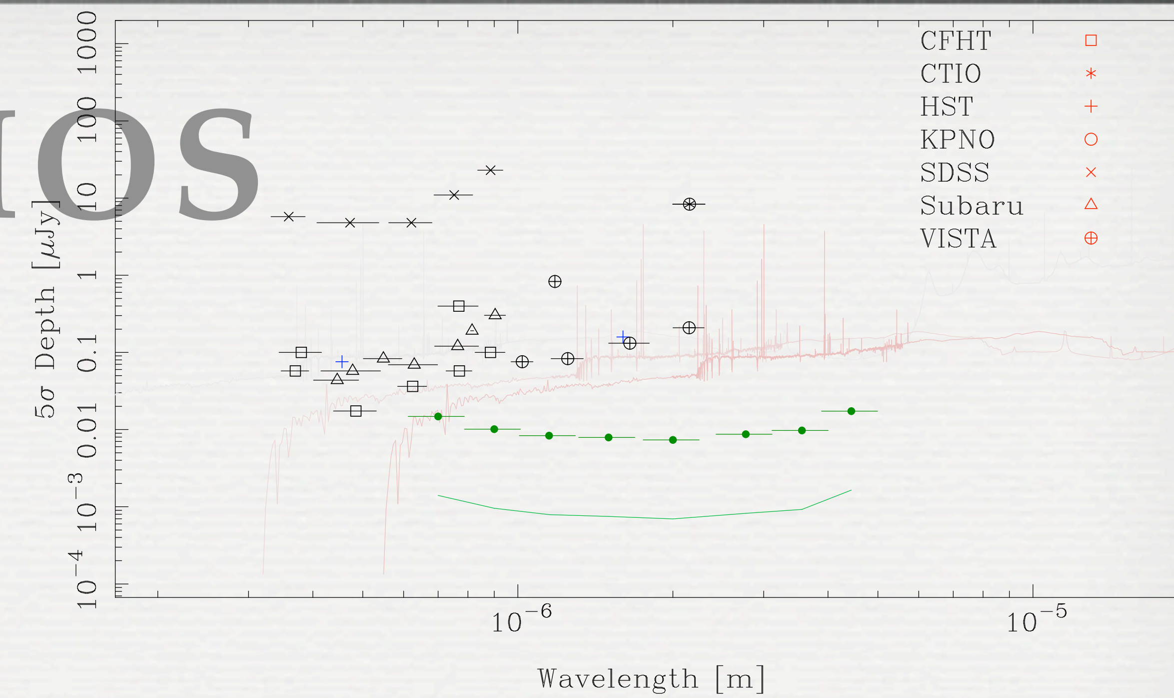
Wavelength [m]

# COSMOS






2 square degree HST mosaic.

Science: Active Galactic Nuclei, Star formation, Galaxy evolution, LFs, Galaxy mergers, multi-wavelength properties of galaxies, **Large Scale Structure** etc.

NIR data will be greatly improved with Ultravista. Spectroscopic follow-up ongoing and probably essential to fully achieve all scientific goals.

# THE POPULAR GUYS

| Name | Nobs | Ra | Dec | Area-range | X | UV | U,B | V,R | I,z | NIR |
|---|---|---|---|---|---|---|---|---|---|---|
| CDF-S | 79 | +03:32:30.40 | -28:07:56.59 | 32.9"x32.9" - 2.2°x2.2° | 4 | 2 | 14 | 15 | 16 | 13 |
| MUSYC Field 1 | 68 | +03:32:33.55 | -28:10:11.34 | 32.9"x32.9" - 0.7°x0.7° | 4 | 2 | 13 | 14 | 14 | 11 |
| GEMS | 67 | +03:32:33.70 | -28:10:10.24 | 32.9"x32.9" - 0.5°x0.5° | 4 | 2 | 14 | 15 | 16 | 9 |
| GOODS-S | 65 | +03:32:33.83 | -28:10:10.15 | 32.9"x32.9" - 0.7°x0.7° | 4 | 2 | 11 | 13 | 14 | 11 |
| GOODS Field 1 | 65 | +03:32:33.83 | -28:10:10.15 | 32.9"x32.9" - 0.7°x0.7° | 4 | 2 | 11 | 13 | 14 | 11 |
| HUDF | 61 | +03:32:34.08 | -28:10:04.26 | 32.9"x32.9" - 0.7°x0.7° | 4 | 2 | 10 | 12 | 12 | 11 |
| HDF-S | 44 | +22:33:00.54 | -61:22:59.46 | 2.3'x2.3' - 0.7°x0.7° | | 1 | 11 | 8 | 6 | 14 |
| E-CDF-S | 44 | +03:32:33.18 | -28:11:16.89 | 32.9"x32.9" - 0.5°x0.5° | 2 | | 12 | 11 | 10 | 5 |
| AKARI-DF Field 1 | 37 | +17:57:00.97 | +66:36:59.68 | 1.4'x1.4' - 2.5°x2.5° | | | 2 | 3 | 4 | 8 |
| AKARI-DF-NEP | 37 | +17:57:00.97 | +66:36:59.68 | 1.4'x1.4' - 2.5°x2.5° | | | 2 | 3 | 4 | 8 |
| SXDS | 32 | +02:20:04.83 | -05:11:55.09 | 1.1'x1.1' - 3.0°x3.0° | 1 | | 1 | 2 | 2 | 13 |
| COSMOS | 31 | +10:00:28.45 | +02:12:22.45 | 0.3°x0.3° - 1.4°x1.4° | 4 | 2 | 8 | 4 | 8 | 3 |
| AEGIS | 26 | +14:17:28.46 | +52:32:03.27 | 6.8'x6.8' - 2.3°x2.3° | 2 | 2 | 3 | 3 | 4 | 6 |
| HDF-N | 23 | +12:36:50.13 | +62:13:16.37 | 58.8"x58.8" - 0.7°x0.7° | 2 | 1 | 4 | 4 | 5 | 1 |
| GOODS Field 2 | 23 | +12:36:50.13 | +62:13:16.37 | 58.8"x58.8" - 0.7°x0.7° | 2 | 1 | 4 | 4 | 5 | 1 |

http://www.strw.leidenuniv.nl/~jarle/Surveys/DeepFields

# The Popular Guys

| Name | Nobs | Ra | Dec | Area-range | X | UV | U,B | V,R | I,z | NIR |
|---|---|---|---|---|---|---|---|---|---|---|
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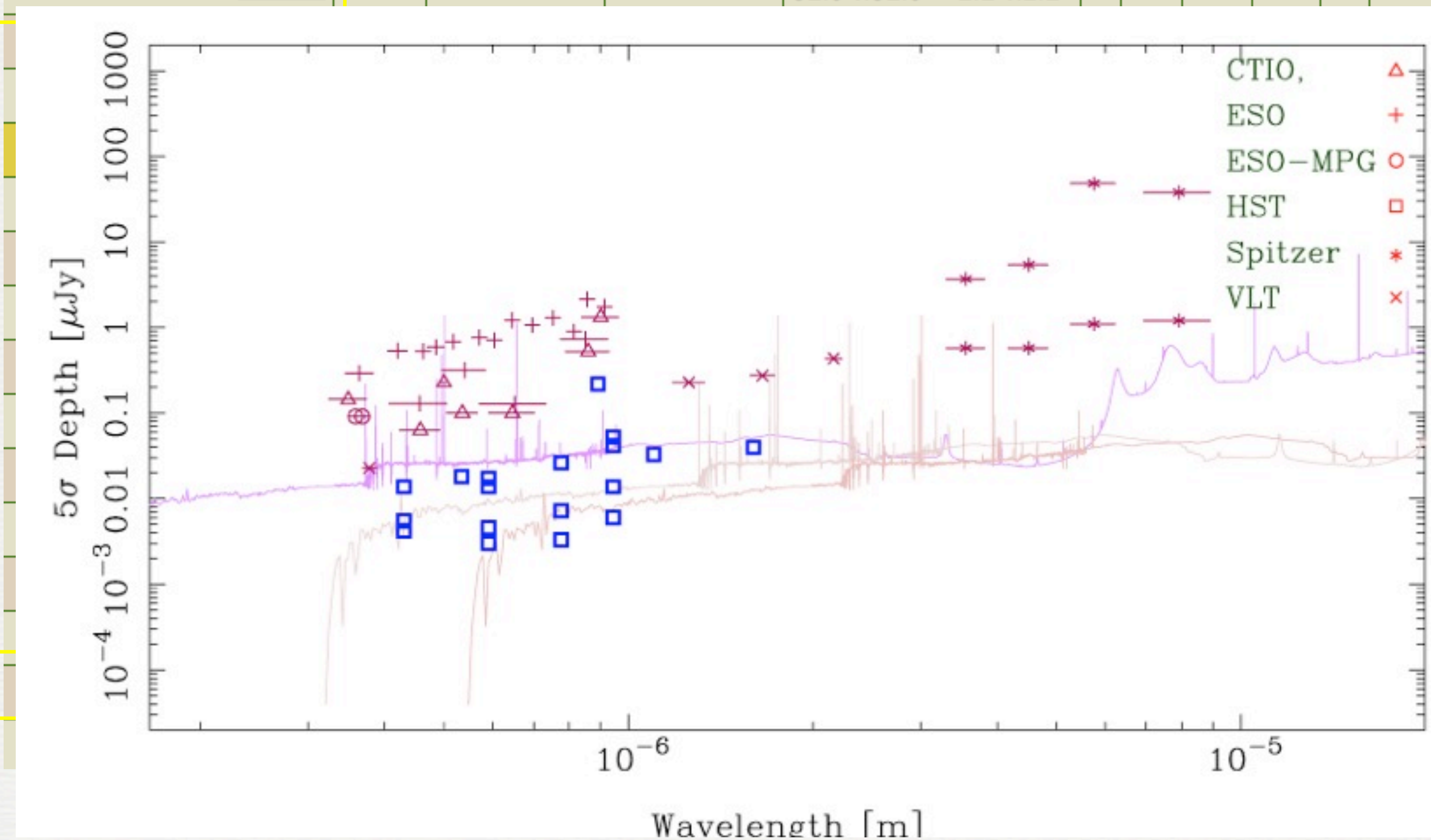
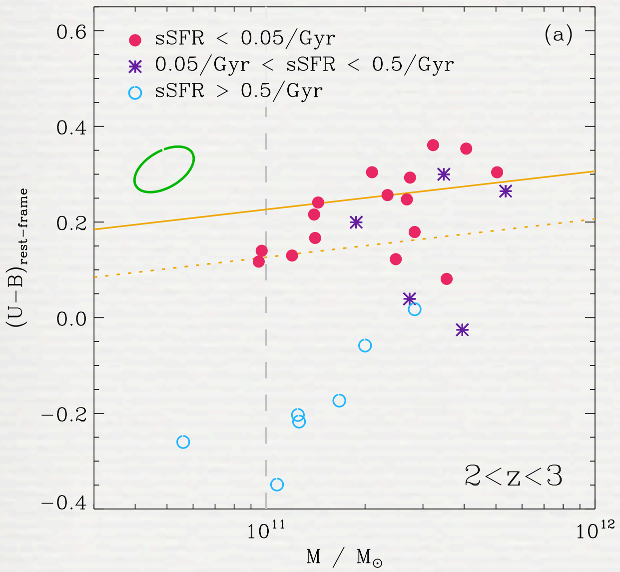
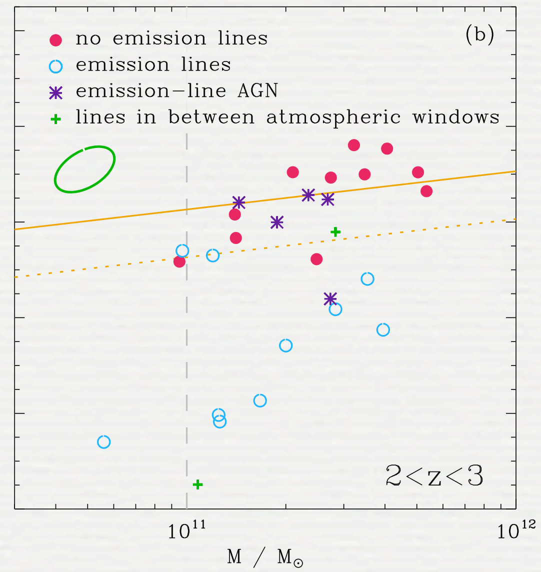



http://www.strw.leidenuniv.nl/~jarle/Surveys/DeepFields

# Scientific Areas

## Selection of interesting classes of objects

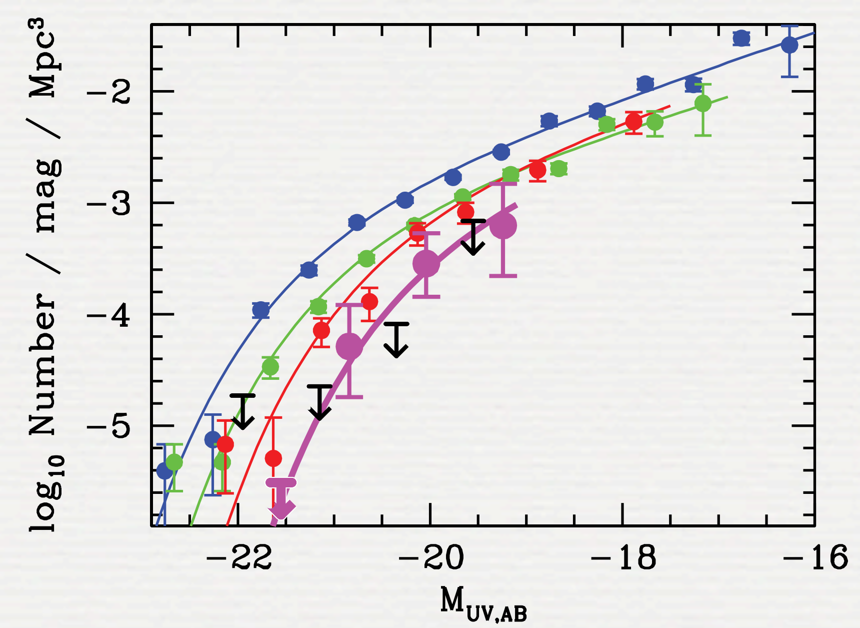


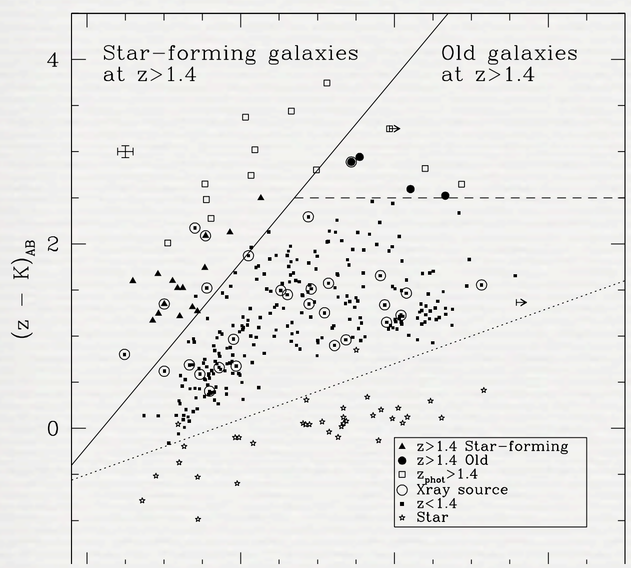




**Old and dead red.**
E.g. Kriek et al (2008), CDF-S etc. Depth and field of view allows the selection of old red galaxies at z~2.3. Spectroscopic follow-up allows the detection of a red sequence at z~2.3

**NIR & area**

Bouwens et al 2008



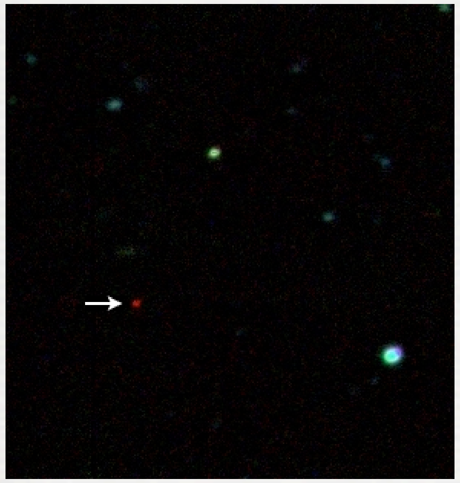




Daddi et al 2004

**Mixed bags & distant star-forming**
Both BzK and drop-out searches allow the construction of huge samples of distant galaxies of all kinds. Drop-out techniques are ideal for studying star-forming systems but need large area for the bright end of the LF and depth for the faint end.

**Multi-wavelength, NIR, Resolution, Depth**

# Scientific Areas

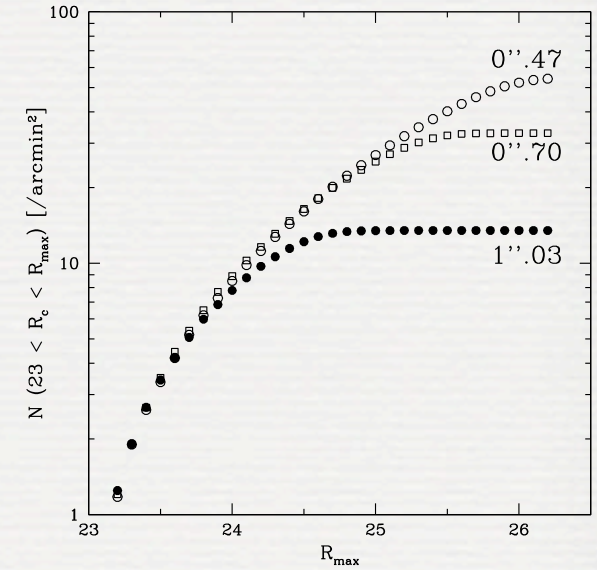


**Finding rare objects**

e.g. the CFHT QSO survey, finding L/T dwarfs.

**Area, multi-wavelength, Depth**

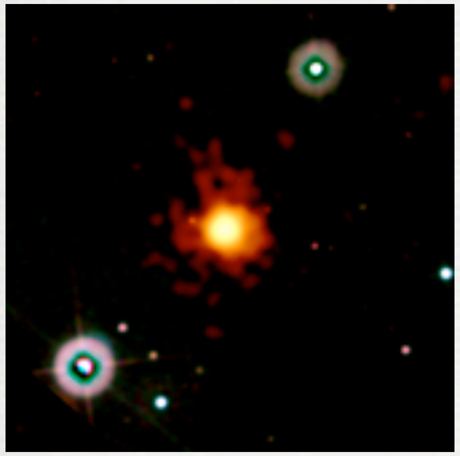
Miyazaki et al (2007)




**Weak gravitational lensing**

To do lensing studies from the ground you need a lot of background galaxies - but you can provide very interesting constraints on cosmology

**Area, Resolution, Multi-band**

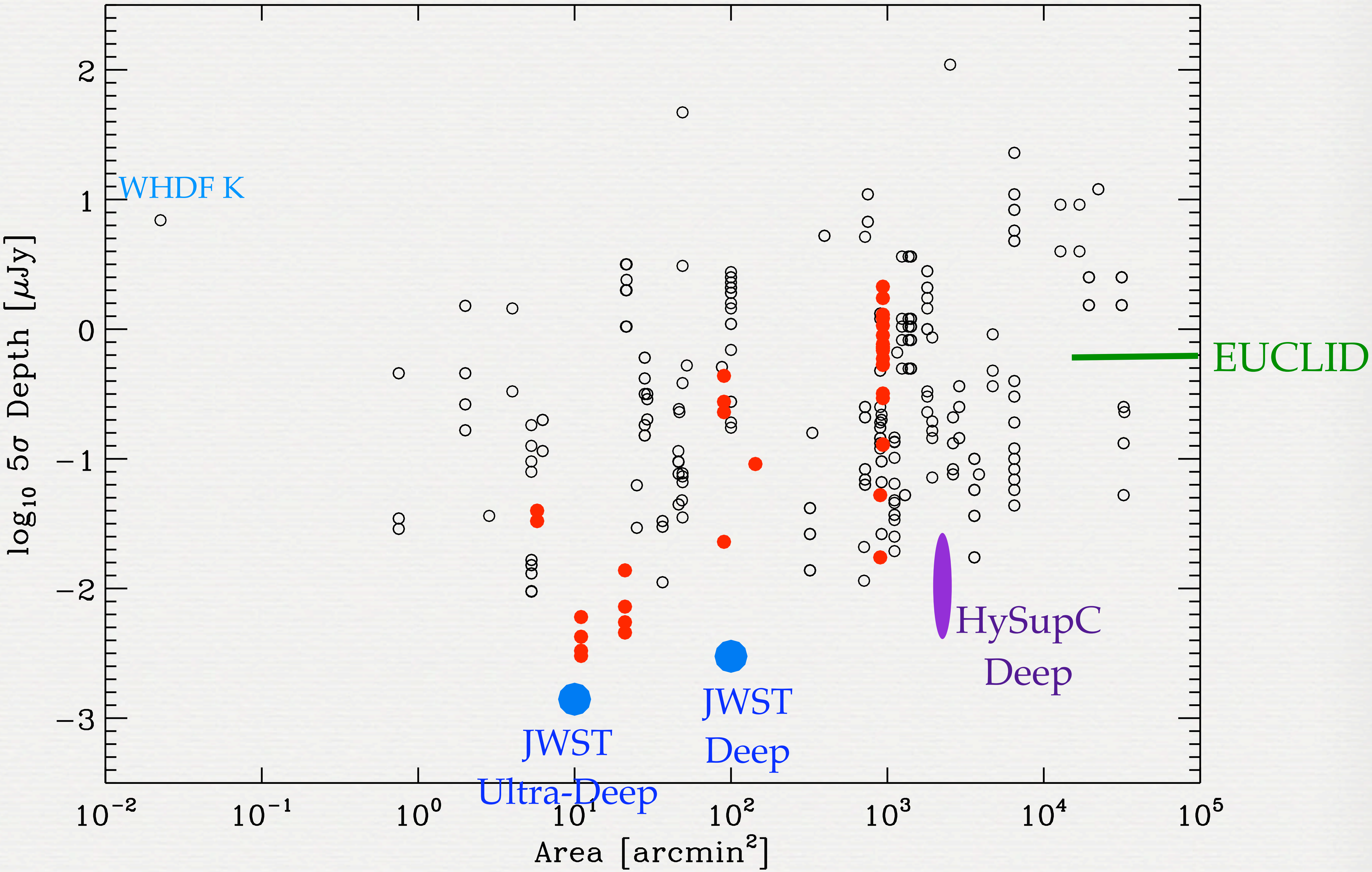


**Temporal events/variability**

Faint gamma-ray bursts, SNe (Pop III?), XXX, LSST will open up this area and it is likely to be of considerable interest in the future.

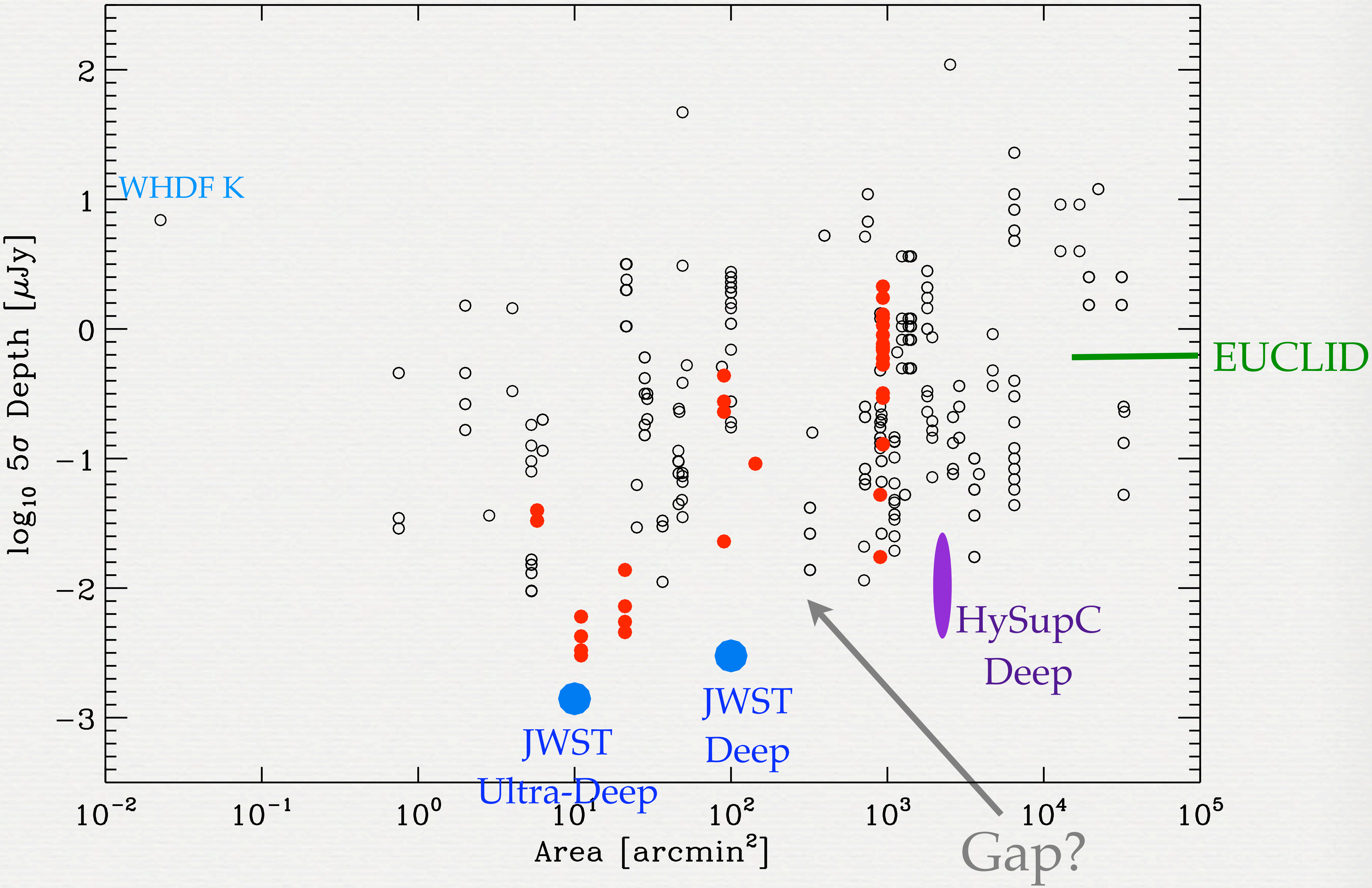
**Area, Resolution**

# AREA - DEPTH



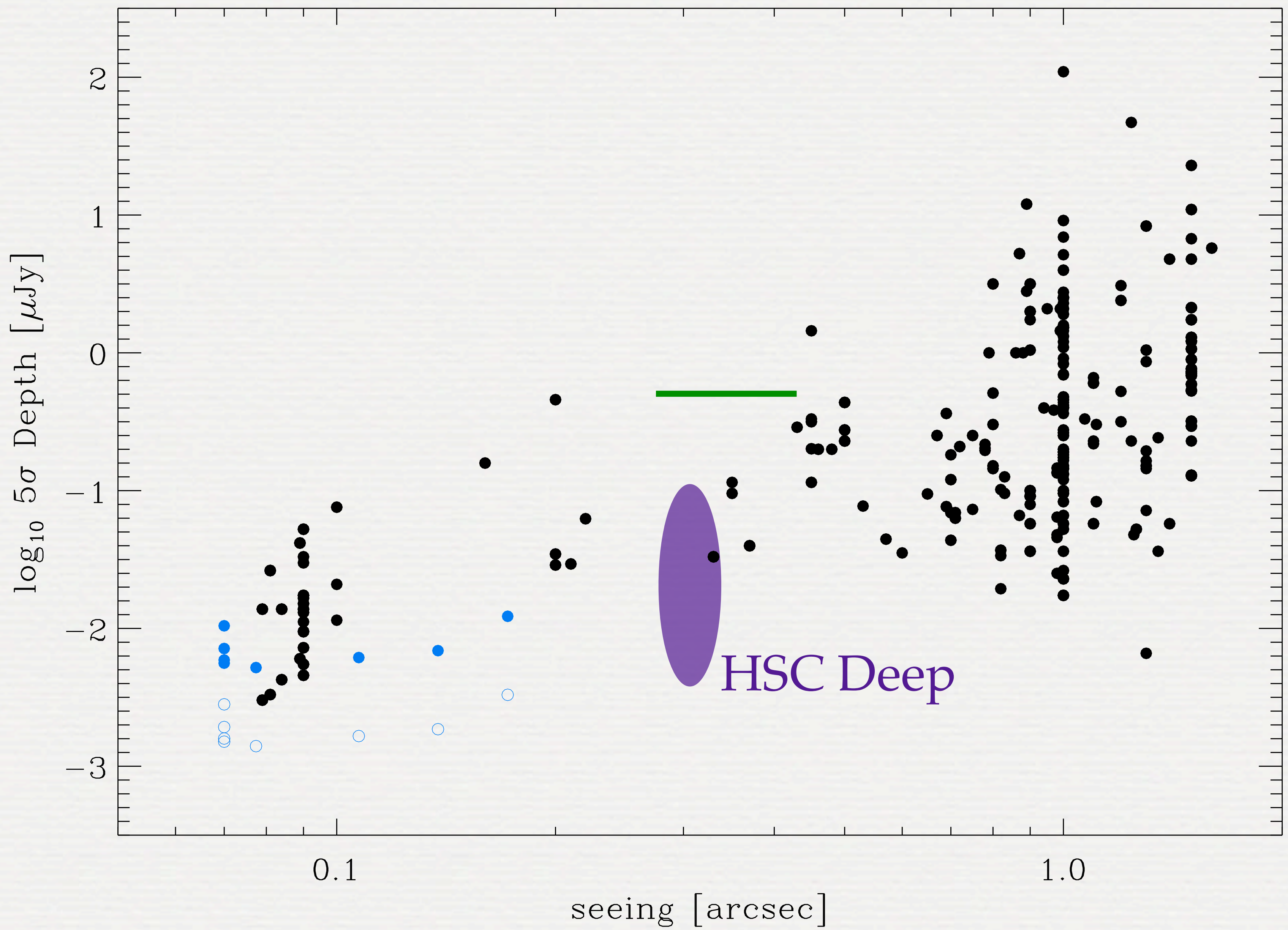

373 deep optical & NIR extra-galactic fields

# AREA - DEPTH

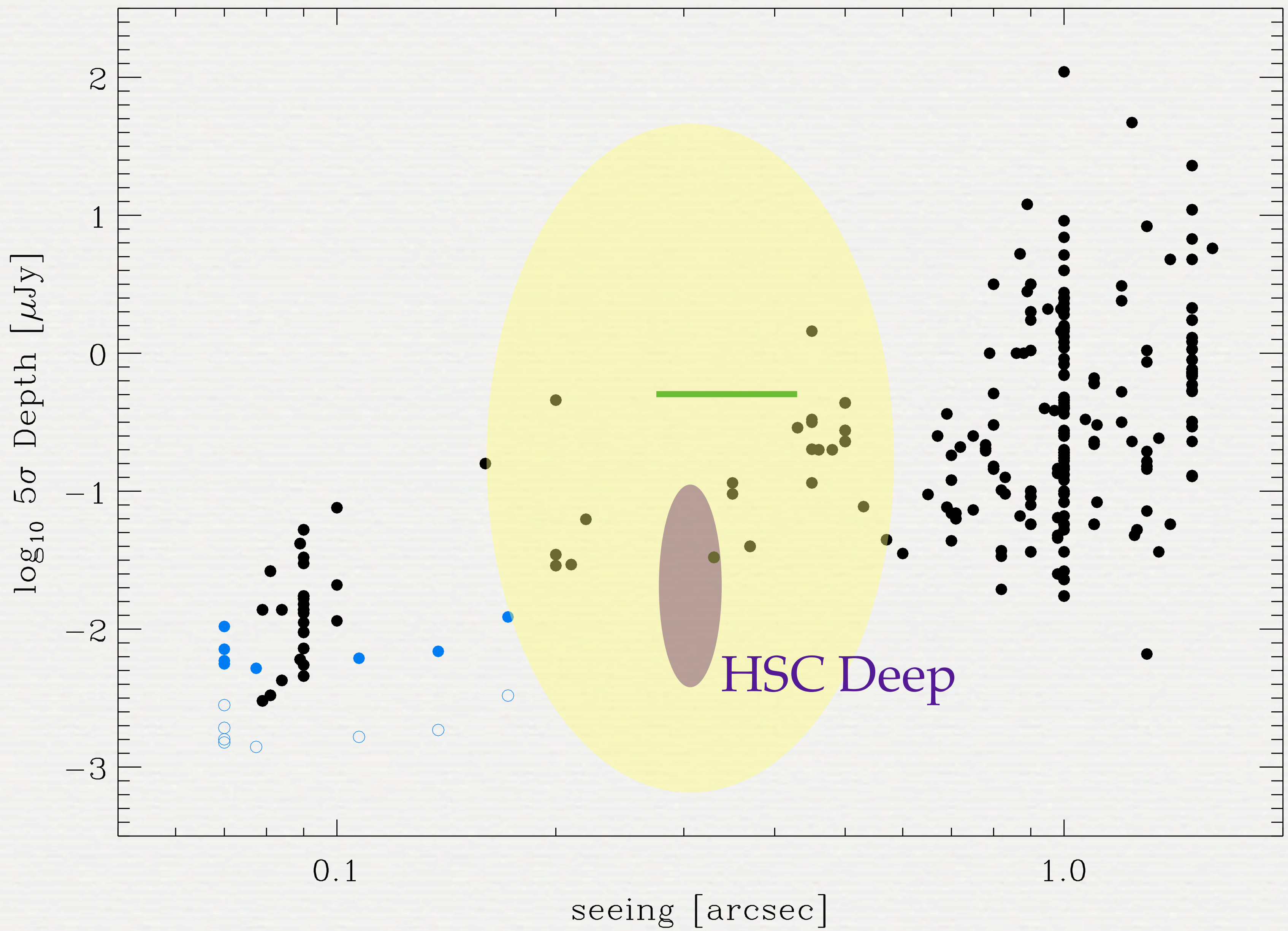



373 deep optical & NIR extra-galactic fields

# Resolution - Depth

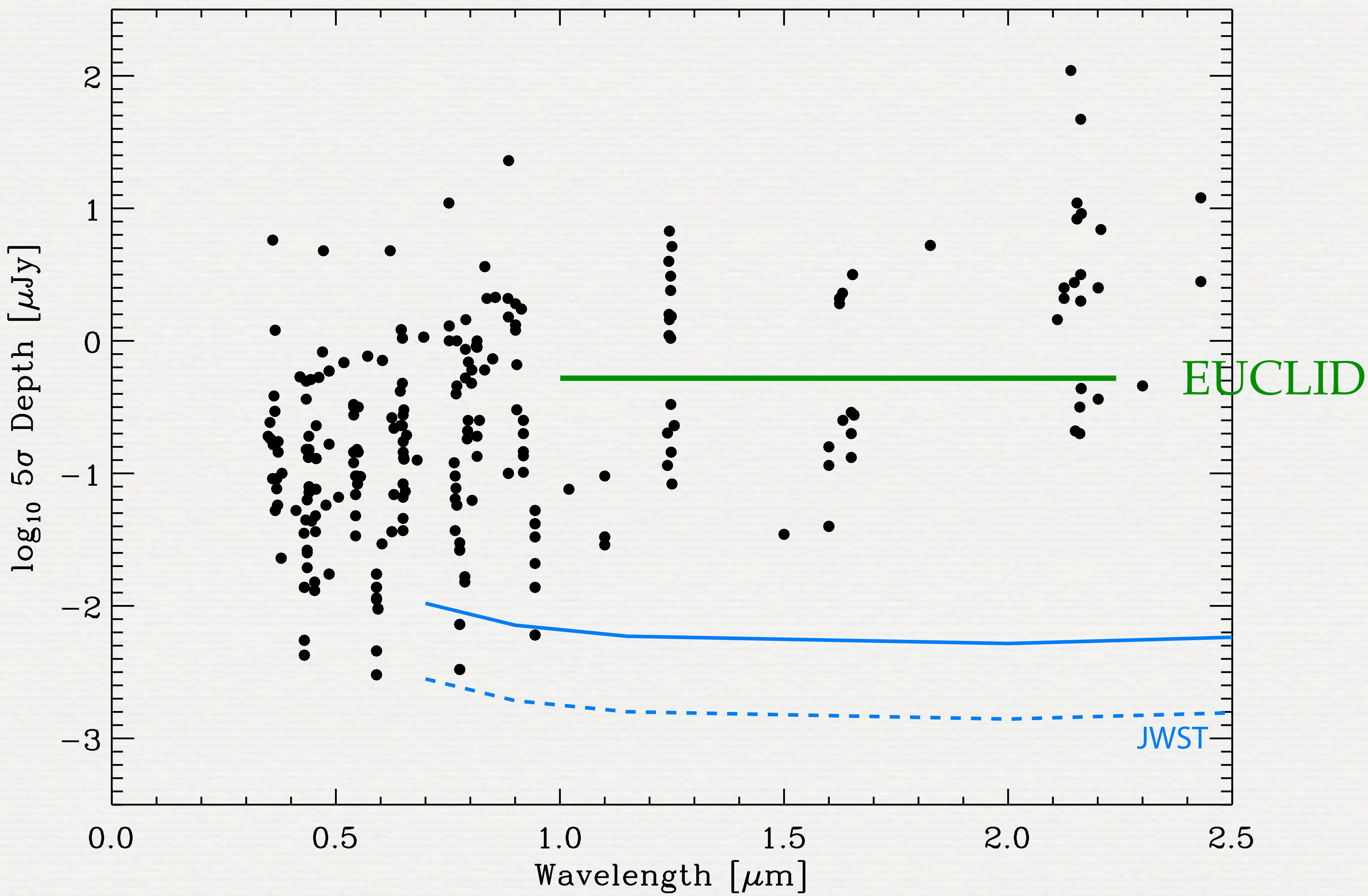


# Resolution - Depth



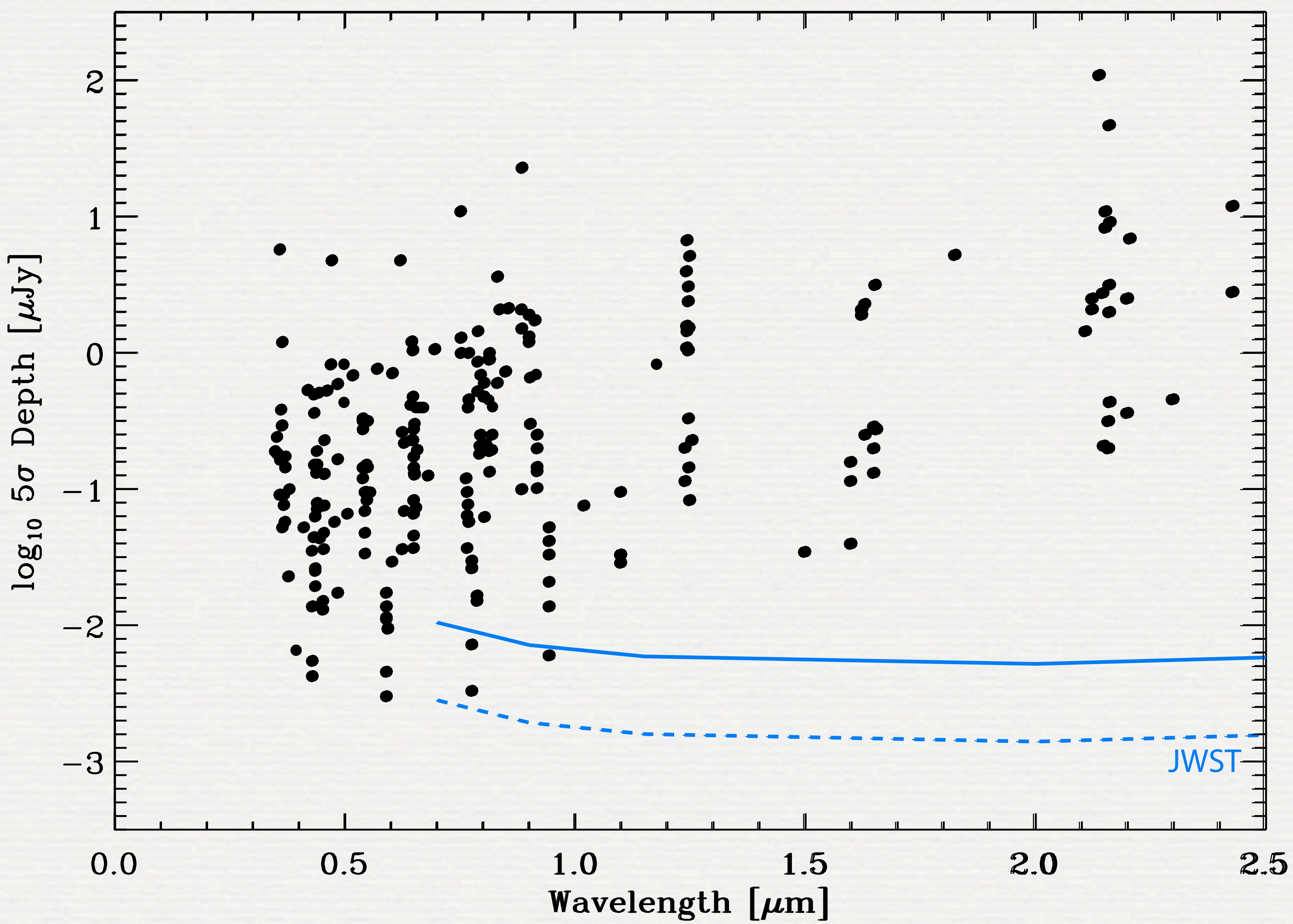

Here there is clearly relatively few intermediately good seeing data, deep, images available. This is furthermore the optimal size-range for high-z galaxies with sizes 0.1-0.3″ - note that this is a prime target for 4-8m class GLAO imagers! This also matches well to ALMA etc. - a resolution of 0.1″ is a good target.

# WAVELENGTH - DEPTH



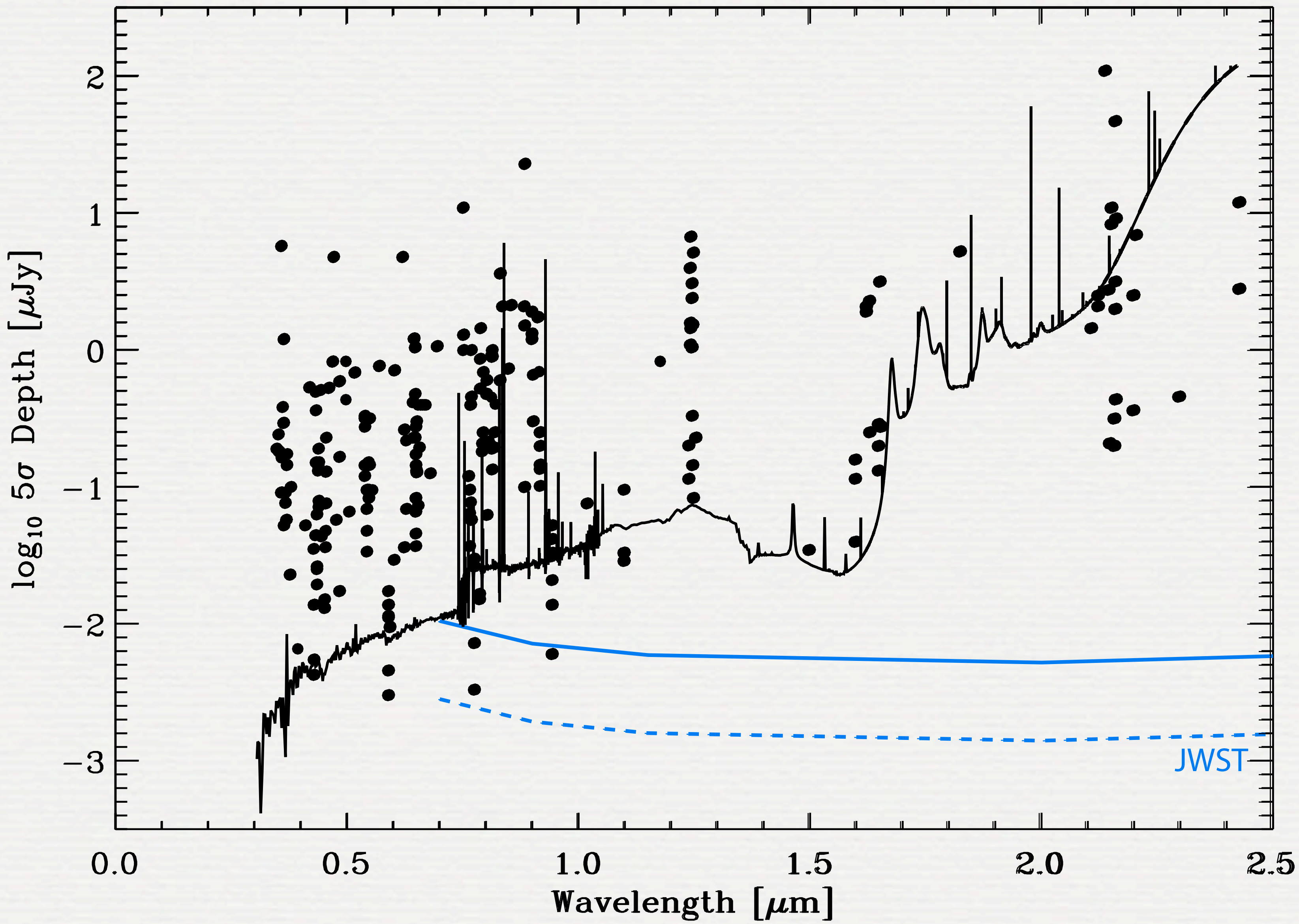

No gap might be apparent...

# WAVELENGTH - DEPTH




In fact with the hugely improved performance in the NIR/MIR from JWST we might be lacking in the optical! (At high redshift perhaps less as dust-free young galaxies are closer to AB~constant)

# WAVELENGTH - DEPTH

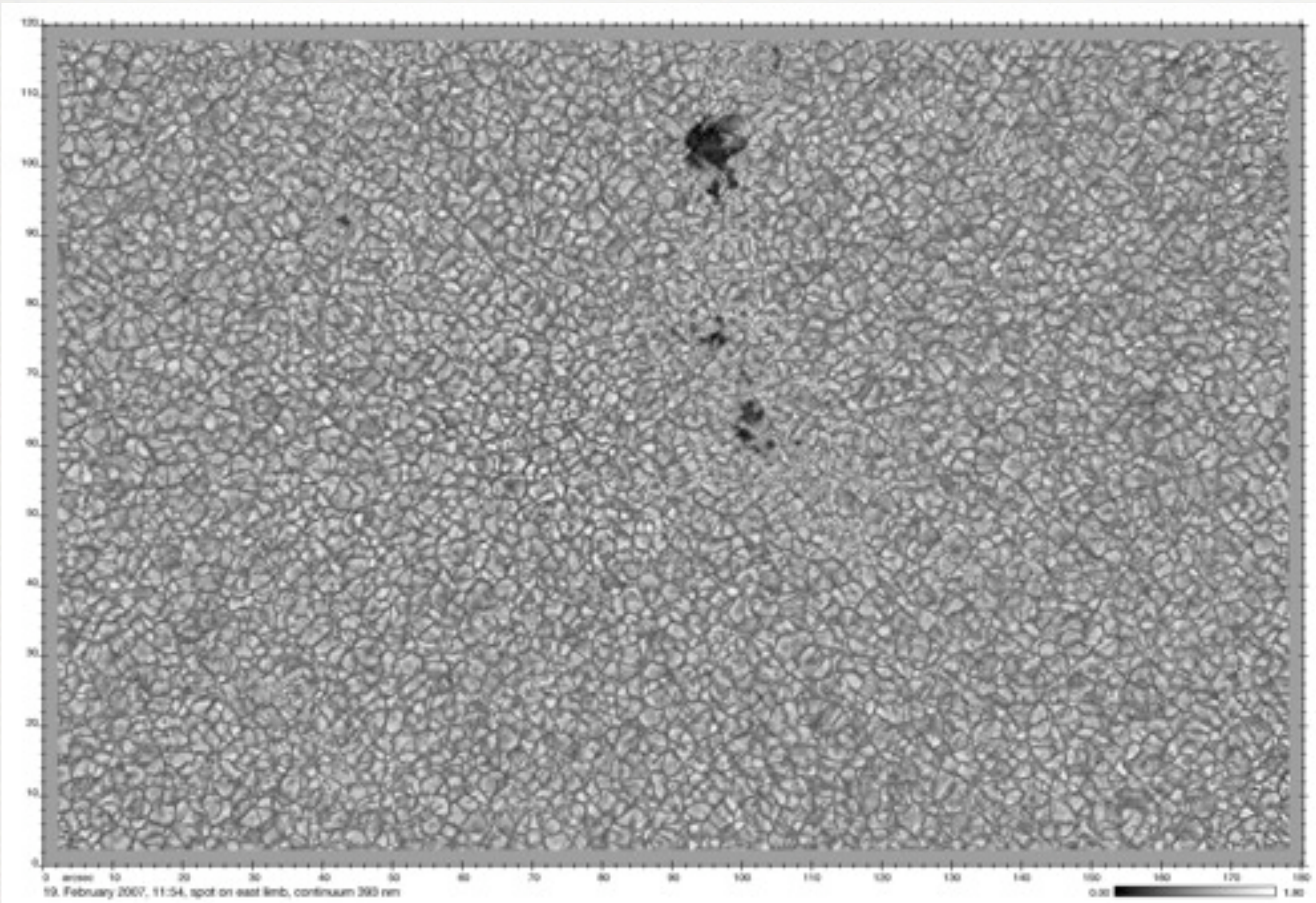



In fact with the hugely improved performance in the NIR/MIR from JWST we might be lacking in the optical! (At high redshift perhaps less as dust-free young galaxies are closer to AB~constant)

# In summary

- Deep imaging surveys have formed the fundament for a large amount of progress in extra-galactic astronomy in the last 10-15 years.
- Multi-wavelength coverage and spectroscopic follow-up has been crucial & HST has been the backbone for much of the work.
- Lack of deep, wide-field images with seeing ~0.3-0.4 arcsec - this will also be very helpful for lensing studies.
- 10-20 $arcmin^2$ deep fields are not very abundant but you really want to cover $>1deg^2$

# WHAT WE REALLY WANT!



2x3 arcmin$^2$ FOV -
diffraction limit, simple AO!

Solar astronomers have shown us that the atmosphere really can be understood well enough, routinely reaching diffraction limit in the optical.

So can we hope for MCAO over ~0.5 deg$^2$ FOV with ~0.1″ seeing @600nm?

A goal to stretch towards!

# So what next? (examples)

- VISTA
  - Deep NIR imaging - great jump forwards in area coverage but some science already doable with UKIDSS data.
- VST
  - Not a major player for the deep-field scene but useful complement.
- Hyper-Suprime Cam
  - 1.5 deg diameter, very deep images. Deep layer survey planned to g=29.8, r=29.3, i=28.9, z=28.2, y=27.4 over 5 $deg^2$ with narrow band coverage as well.
- LSST (not yet? funded)
  - 8m dedicated survey telescope. Not particularly deep imaging but will be very powerful for the time-domain, weak lensing.
- JWST
  - An entirely different ball-game. $\mu$Jy -> nJy. Will be without competition at $\lambda>3\mu$m for most extra-galactic science.

# THE COMPETITORS: JWST

Sky background at 2$\mu$m ~ 1000 times higher on the ground and JWST is a 6.5m telescope so if we look at resolved sources JWST is ~1000/($42^2$/$6.5^2$) ~ 25 times faster than an E-ELT.

NIRCAM is ~2′x2′ so an E-ELT imager with FoV ~10x10 arcmin$^2$ should be competitive with JWST at 2$\mu$m and shorter.

However the time-scales are such that a straight comparison is incorrect. For distant galaxies an imager with <0.3″ PSF over >5 arcmin$^2$ can be an excellent complement to JWST at wavelengths shorter than K even though it might have a somewhat slower mapping speed.

Would really enter a different area if it becomes possible to get <0.1″ PSFs over areas of this order.

# THE COMPETITORS:
# 8M WIDE-FIELD IMAGERS

Comparable sky background (unless we go to Antarctica) so for resolved sources the E-ELT is ~ 25 times faster than an 8m with the same FOV. The issue is with the FOV! (although few 8m-class telescopes have wide-field possibilities...)

Hyper Suprime Cam for instance, will have a FOV ~ 1.75 $deg^2$ so the E-ELT imager would need to have a FOV > 15'x15' (plus, of course, that the HSC would have been on the sky for a long time by the time the E-ELT imager comes along)

**So, is that the end of it?**

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# 8M WIDE-FIELD IMAGERS

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**So, is that the end of it?**

*Not necessarily:*

**Time-domain** does not allow as long integration times (SNe, GRBs, other variable sources).

**Resolution** - esp. in NIR (although techniques will prob. first be implemented on 8m class telescopes).

**Ultra-deep data** - optical complement to JWST.

# What about EUCLID/JDEM?

Deep (~24 AB) NIR imaging across most of the sky.

Deep optical imaging in the same areas (one band?)

Needs ground-based additional data for phot-zs.(?)

Small telescope (~1.2m) so limited resolution & not competitive in *depth* with ground in optical.

Not really a direct competitor but an excellent complement.

Would however do much/most of the lensing work.

# So is there a case for a WFI on the E-ELT from the extra-galactic point of view??

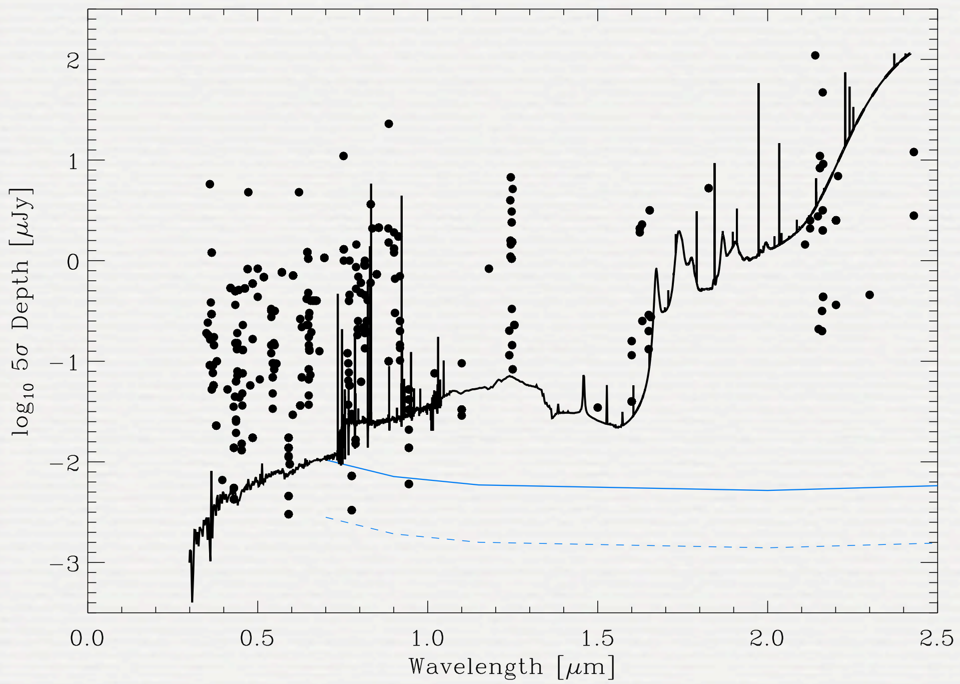
Probably:

**Depth** - needs to beat 8m survey telescopes (4m if no replacement to VISTA appears), so ultra-deep images are of interest. This then would complement JWST - for that need ~100 $arcmin^2$ to match the deep-wide survey.

**Time-variability** - faint SNe, optical (and other) transients.

**Resolution over wide area** - Would need PSF sizes <0.3″ across a wide FOV. More extreme AO would be even better but it is likely that this will first be implemented on smaller telescopes.

# What could it do?




Establish the faint galaxy population out to z~7-8 (LFs, clustering, SFR)

Faint QSOs to very high-z. Poor correlation between halo mass and luminosity means a large luminosity range must be sampled to constrain models.

Weak lensing & hence cosmology, AGNs.

Nearby galaxies, Galactic work (e. g. WD, neutron stars), all PSF dependent to some extent - resolved stellar populations in nearby galaxy halos (e.g. M31) is often limited by star-galaxy separation

Variability of very faint sources (AGNs, μlensing, optical transients), follow-up of faint SNe, GRBs & other outbursts. Particular interest: Pop III SNe (JWST will probably not be very efficient at detecting them)

# Characteristics?

- For extra-galactic work, $\lambda < 3\mu m$ is probably sufficient for much work because JWST would be unbeatable at longer wavelengths. However it will probably also not be working any more!
- The optical regime might be useful for characterising high-z galaxies and complement JWST. As blue as possible but AO gain is important ($\lambda > 0.6\mu m$?). Ultra-deep imaging.
- To be competitive with/beat JWST the FoV must be >10'x10' with <0.3" "PSF". (GLAO/MCAO?), a stable PSF is important for lensing. To beat 8m class telescopes, even larger FoVs > 15'x15' and/or better PSFs ("SuprimeCam"). Aim towards 0.1" PSFs into the optical region ( don't ask me to design/build it!!)
- The time-domain has the potential to be of major interest - here there are no competitors for faint work - but few strong science cases have been worked out thus far probably.
- Equally strong/stronger constraints are likely to come from solar system studies, Galactic science.