Current Searches for Obscured AGN at High Redshifts

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CDFS/GOODS-AGN (Alexander, Brandt, Bergeron, Conselice, Chary, Cristiani, Daddi, Dickinson, Elbaz, Grogin, Mainieri, Schreier, Treister, Urry, ...)

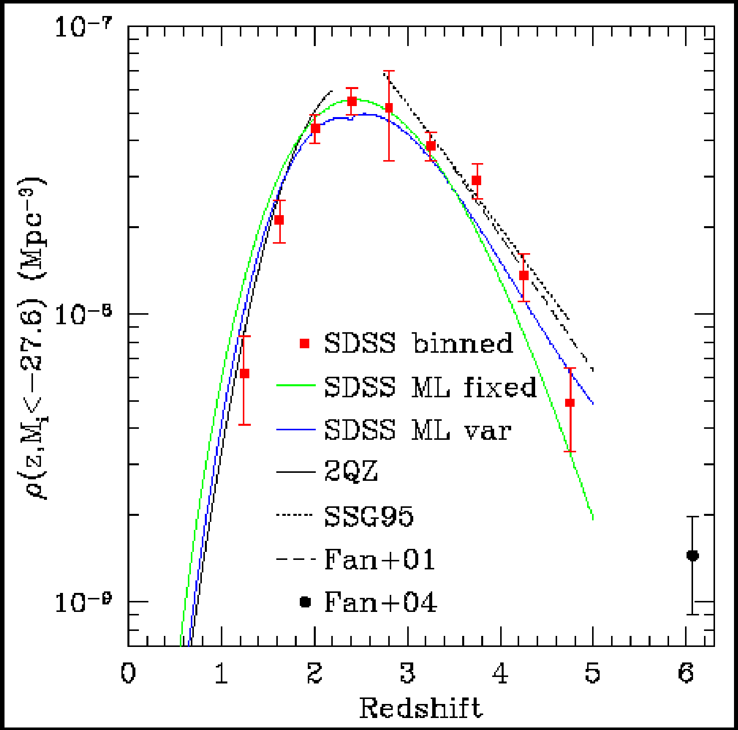
+COSMOS-AGN (Brusa, Carilli, Comastri, Elvis, Fiore, Gilli, Hasinger, Salvato, Sasaki, Scoville, Schinnerer, Taniguchi, Trump, Urry, Zamorani, ...)

Black holes in context:

- May trace hierarchical dark matter halos
- Provide harder ionizing continuum than stars
- May regulate galaxy growth / SFR via feedback
- M-σ relation suggests intimate connection between BH/galaxy formation and growth

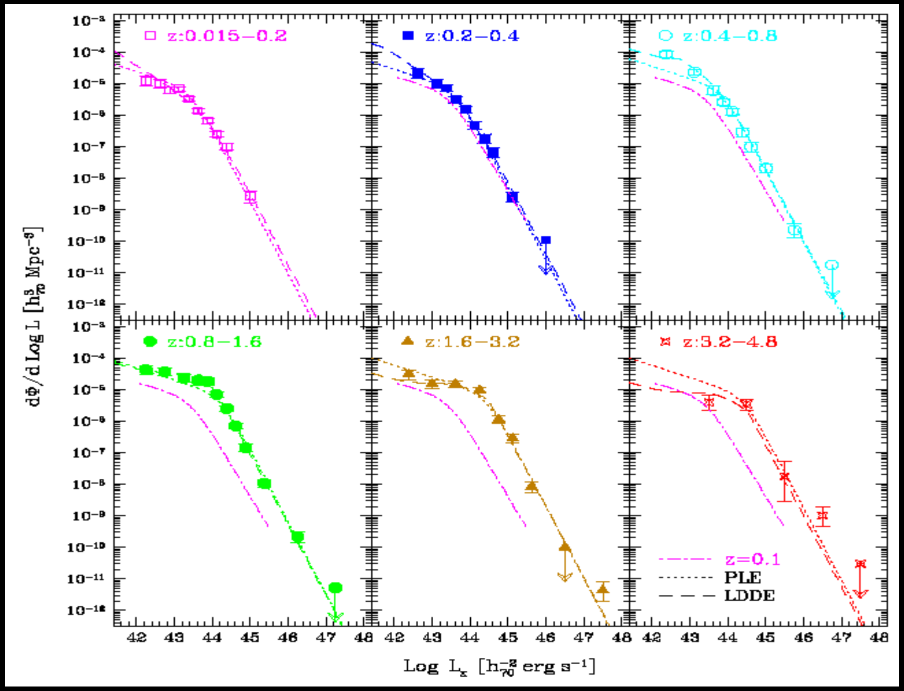
to date:

- At z ~ 6 - 6.5, already have supermassive BHs up to at least M ~ 10^9 M_o (Fan et al 2001-06; Willott et al. 2003; Vestergaard et al. 2004)
- High-luminosity end of AGN LF evolves strongly from z~6 to z~2; PLE is ruled out (Fan et al. 2001+; Richards et al. 2006)

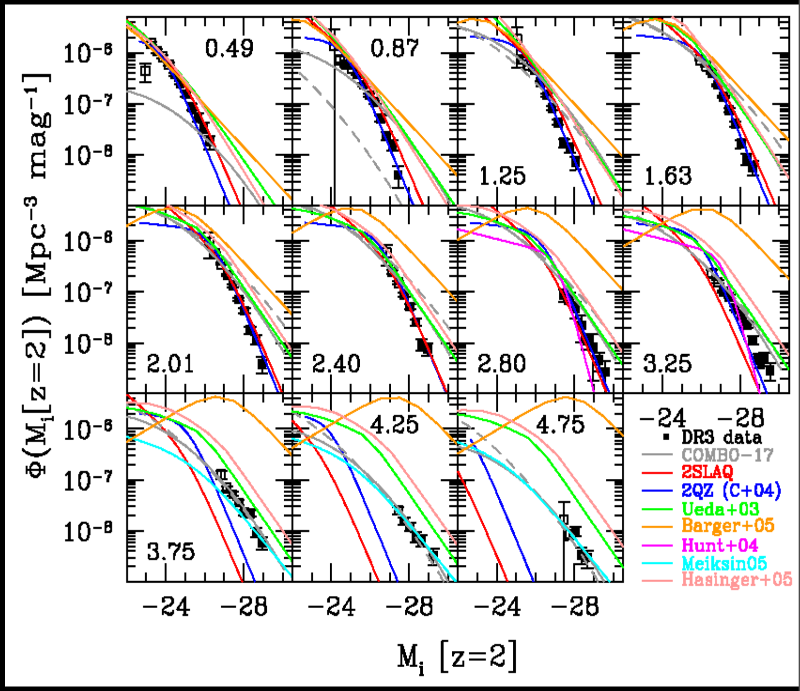


- Instead of PLE, AGN appear to follow "anti-hierarchical evol" -- luminosity-dependent density evolution "LDDE" at least for XLF (Ueda et al. 2003, Hasinger et al. 2005; Gilli, Comastri, Hasinger 2006), QSO LF (Richards et al. 2006); also Merloni et al. (2004):
  - luminous AGN peak earlier (z~2-3)
  - fainter AGN peak more recently (z~1)

(XLF; Hasinger et al. 2005)



(QSO LF, Richards et al. 2006)



Questions:

- How do the most massive BHs form within < 1 Gyr?
- How does BH growth influence the M-σ relation?
- What is the ionizing budget of AGN integrated over the LF beyond z ~ 6, and its contribution to reionization?
- (How) does obscured/unobsc. AGN ratio evolve at z > 6?

Our knowledge has been limited by the following:

- only the top of the AGN LF has been studied at z ~ 6
- no AGN previously confirmed at z > 7

Approach:

- Set out to quantify the faint end of AGN LF at z ~ 6
- Search for more luminous AGN at z > 6 - 7

Require Wide+Deep X-ray / Optical / IR Surveys:

- Depth probes faint/moderate-lum AGN to high z
- Area probes high-lum AGN at high z
- (Hard) X-rays penetrate obscuring torus, IR probes rest-frame optical emission from AGN + host galaxy

New part of parameter space:

- Combined optical + X-ray depth allows wider exploration of F_X/F_{Opt}:

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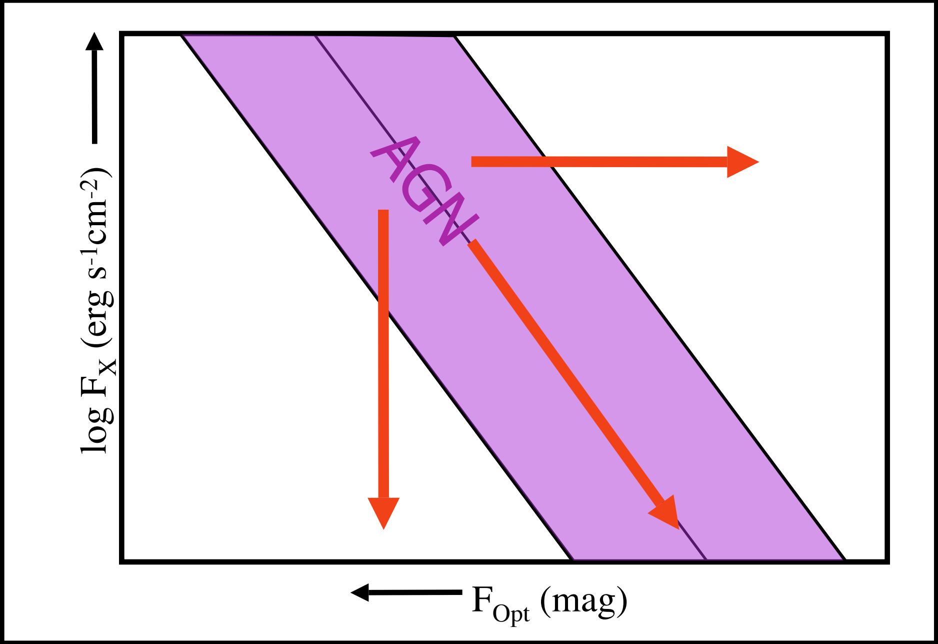


Advantages of X-ray selection:

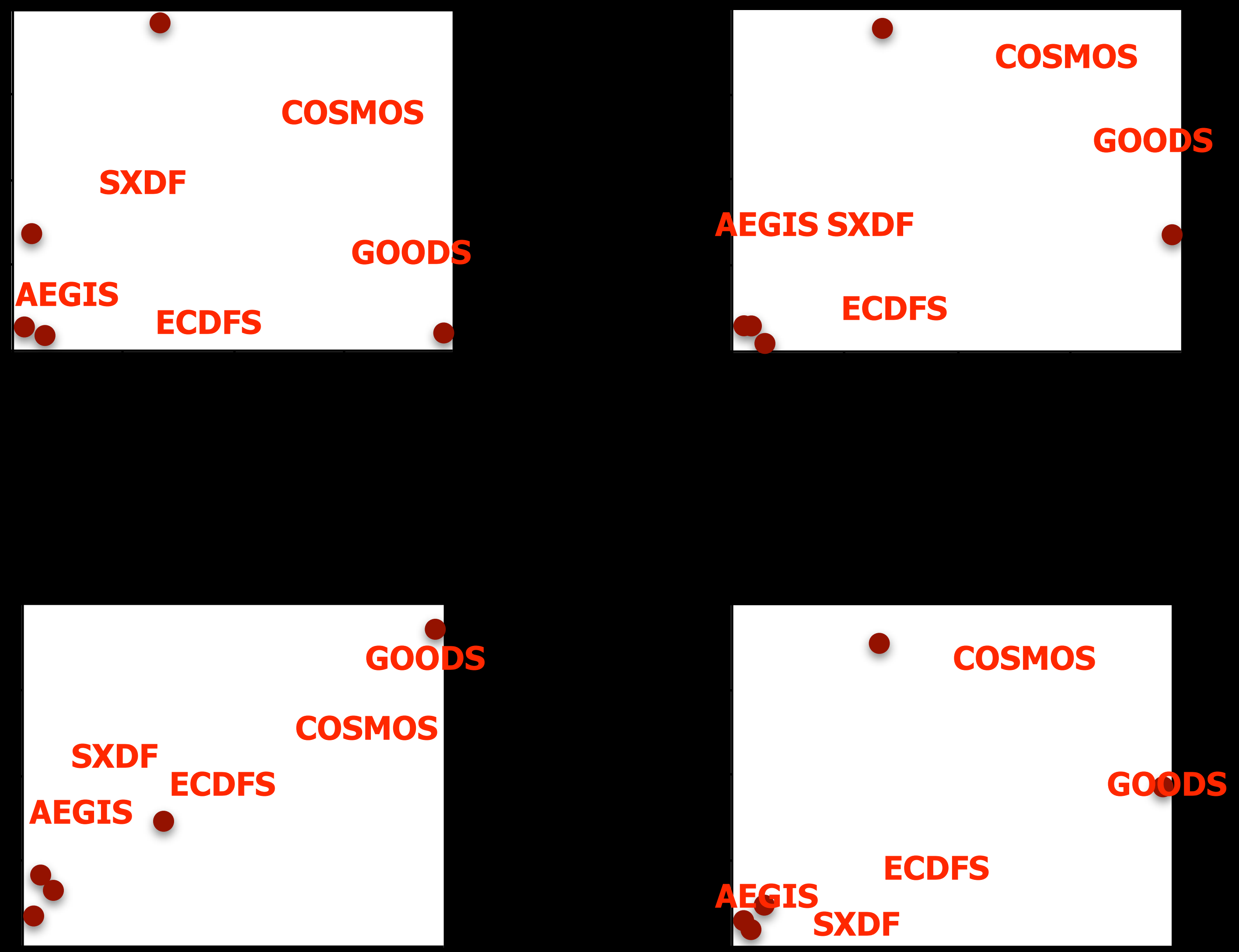
- avoid obscuration effects in optical/IR
- at $z > 2$-3, hard X-rays are redshifted into soft observed X-ray bandpass, allows a more complete selection of obscured AGN (except for Compton thick sources)
- allows selection of more AGN than radio selection.

Other wavelengths needed:

- deep optical to ensure good identification of dropouts:
  - at least R,I, preferably also z
- deep near-IR to provide detections relative to optical:
  - at least K, preferably also J,H
- Spitzer data to allow SED fitting:
  - at least IRAC 3.6 - 8 micron, preferably also MIPS 24 micron

Some current relevant surveys

	Area	Fx (cgs)	R(AB)	I(AB)	z(AB)	J(AB)	K(AB)	f (3.6)
X-Bootes	9.3	4.0e-15	25.5	24.9	-	21.0	20.6	5.0
COSMOS	2	7.0e-16	26.8	26.2	25.2	-	21.6	0.9
HELLAS2XMM	0.9	7.5e-15	25.0	-	-	-	19.1	15.0
XMM/SWIRE/ELAIS-S1	0.6	1.0e-13	24.5	24.5	-	21.0	20.0	3.7
SXDF/UKIDSS-UDS	0.5	1.3e-15	27.2	-	24.0	22.6	22.5	3.7
ECDFS/MUSYC	0.25	3.9e-16	25.8	24.7	23.6	23.5	23.0	0.8
AEGIS	0.2	8.2e-16	26.5	26.0	25.0	24.0	22.6	1.0
GOODS	0.2	2.4e-17	26.2	27.1	26.6	25.5	25.1	0.17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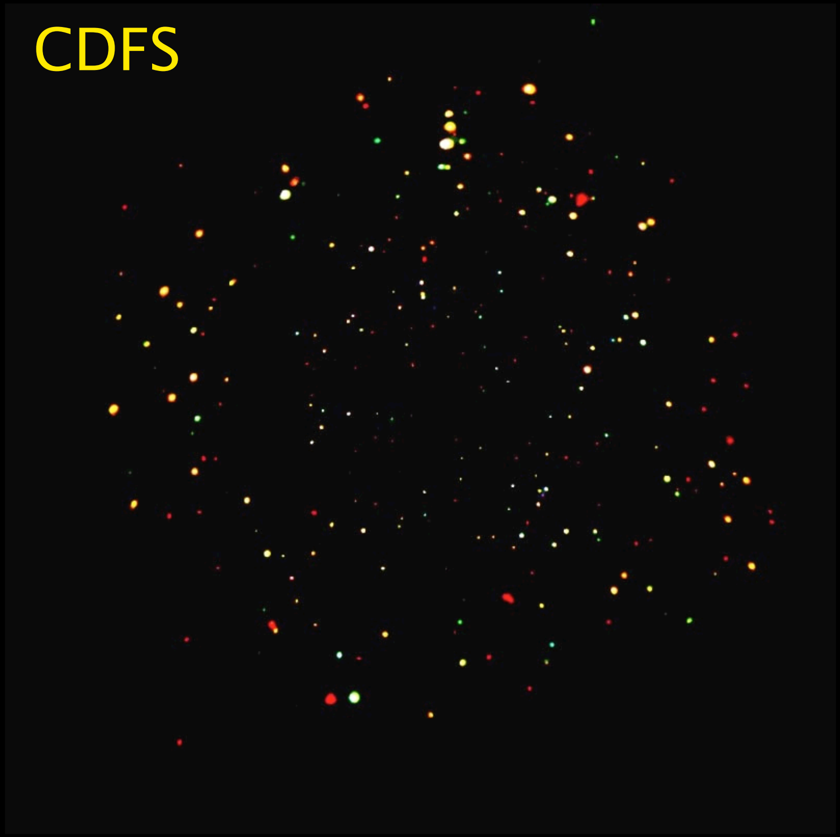
SXDF

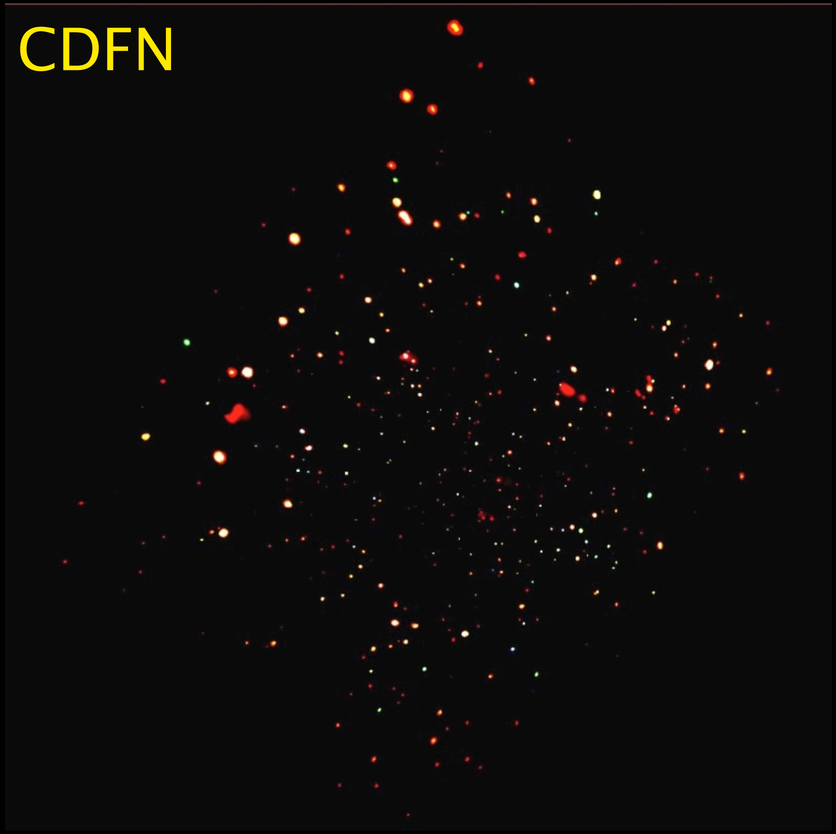
CDFS/GOODS-S+N survey:

- powerful combination of wide area and depth, opt/Xray: CDFS + CDFN have 1 & 2 Msec Chandra depth respectively
  - X-ray depth sufficient for AGN LF faint end ($L_X \sim 10^{43-44}$ erg s^{-1}) up to $z \geq 6 - 7$
  - area sufficient (0.1 sq deg) to provide number statistics on AGN LF at these redshifts
- More than 800 AGN from Chandra in GOODS-N & S (> 600 covered by HST/ACS and Spitzer)
- Extensive optical spectroscopic coverage
- Deep multi-band optical/NIR/Spitzer coverage:
  - JHK + Spitzer/IRAC 3.6 – 8 μm observations trace host stellar mass for z > 1-2
  - Spitzer/MIPS 24 μm data helps constrain thermal dust emission

X-ray data:

- CDFS (Giacconi, Hasinger et al. 2001+):
  - 940 ksec divided over 11 intervals, one orientation

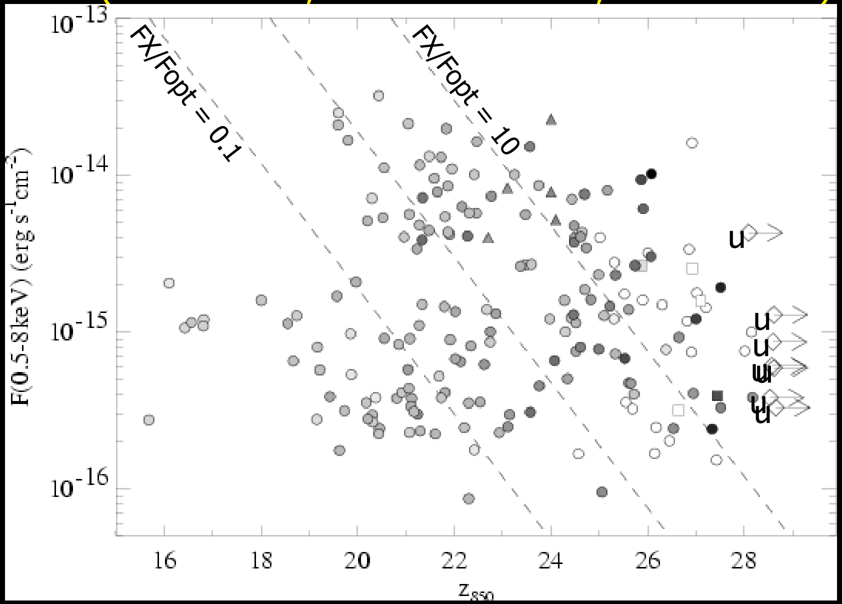




Selection criteria:

- Based on SED change with z:
  - Drop-outs in z_{850lp} (>27)
  - Anomalous Fx/Fopt (>100)
  - Red z_{850lp} - K (>4)
- Expect mostly obscured sources, but unobscured AGN are not excluded

CDFS (Brandt et al, Koekemoer et al, 2001 - 2005)



Highest F_X/F_{Opt}:

- found in several studies so far (Koekemoer et al 2002; Tozzi et al 2002; Brusa et al. 2004; Koekemoer et al 2004, 2006)
- EXO's - Extreme X-ray / Optical sources
  - Only revealed by extending optical depth below ~27
  - Optically faint sources with anomalously high F_X/F_{Opt} >100
  - Typically have extremely red z-K > 4-6
  - Appear to have no comparable analogs in the local universe

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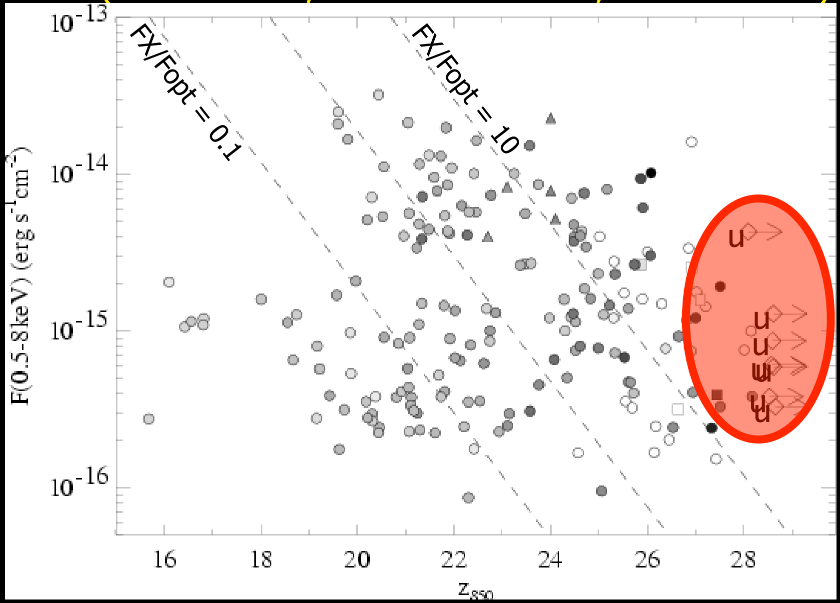

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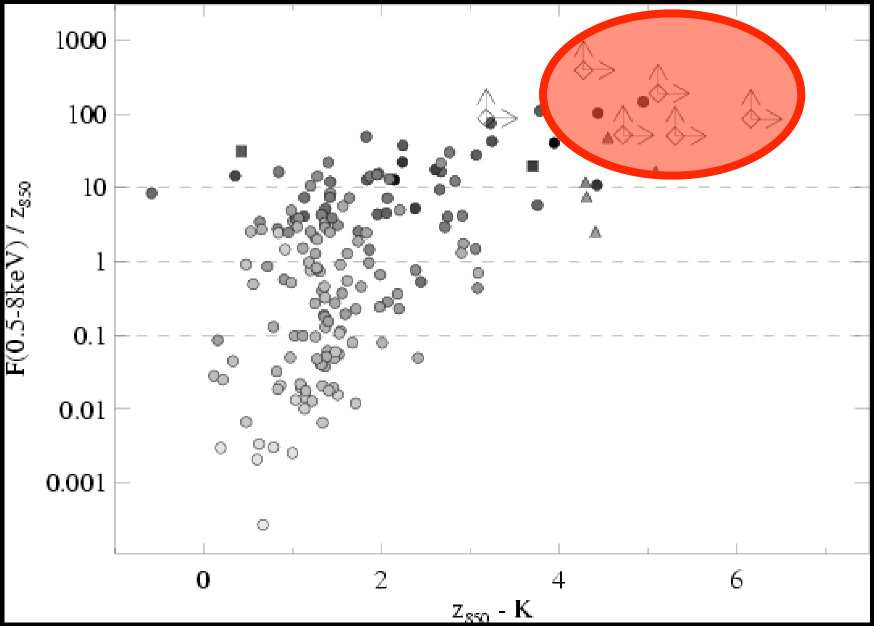
Candidate high-z AGN:



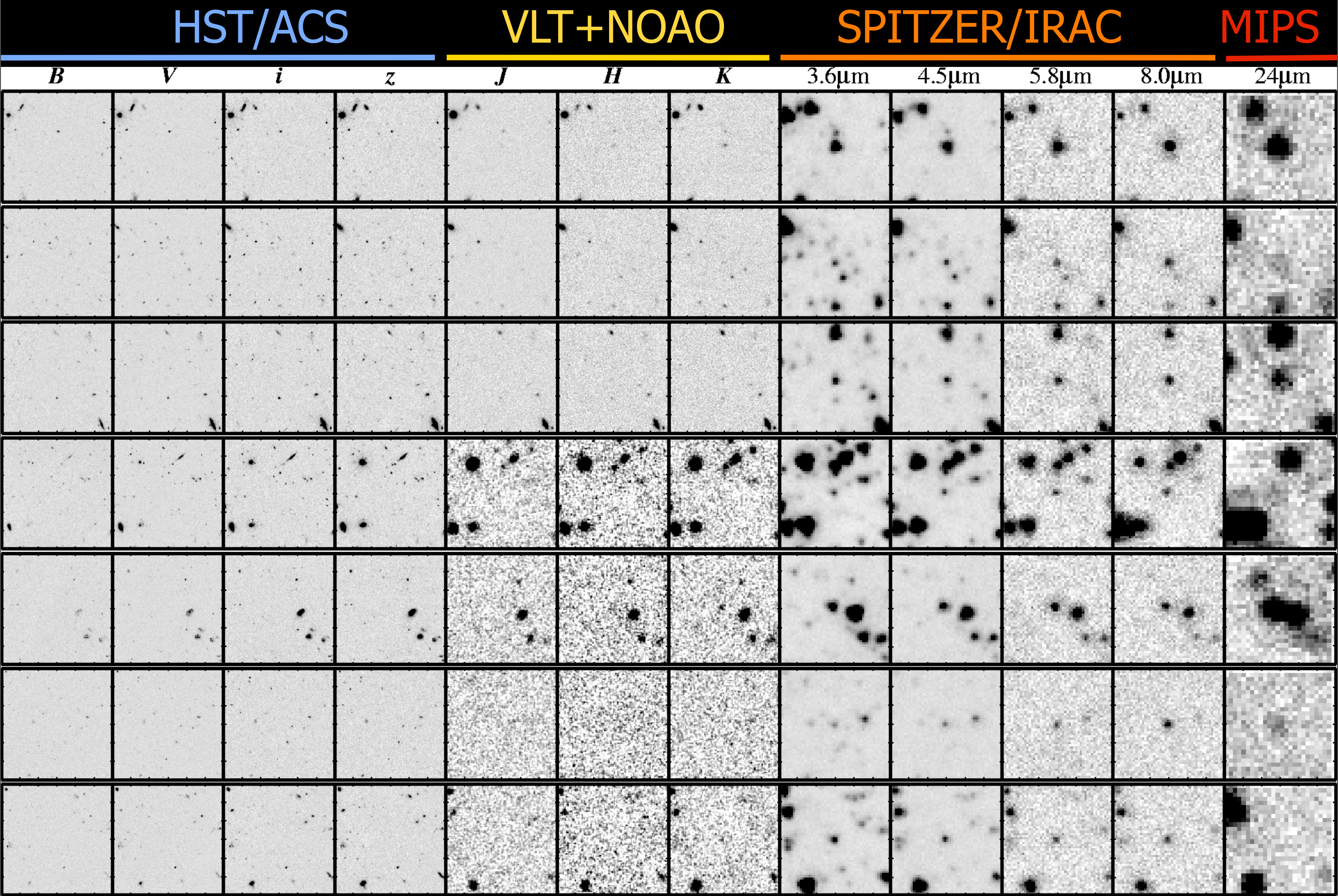
X-ray properties:

- Well-detected by Chandra ($\sim 10^{-16}$-10^{-15} erg $s^{-1}cm^{-2}$)
- F_X/F_{Opt} is a lower limit, and is > ~100x above the average for AGN
- Similar number in CDFN
- Generally have soft and hard X-ray emission (excludes z<2 obscured AGN)

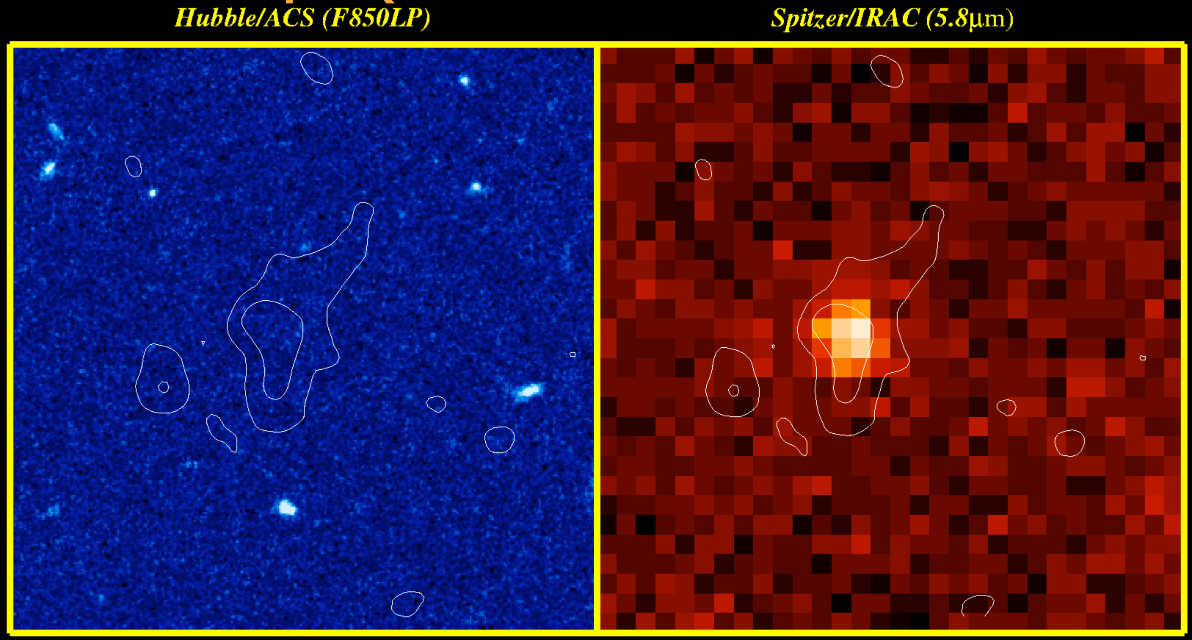
Redder z-K colour:

- most AGN with F_X/F_{Opt} ~ 0.1 - 10 have fairly tight z-K ~1-2, with some slight scatter:
  - z-K ~ -1 to 2 for quasars/Seyferts
  - z-K ~ 2 to 4 for ERO's
- However, the EXO high-z candidates generally have z-K >4

EXO/high-z candidates from GOODS N+S



EXO Close-up (contours = Chandra 0.5-8 keV)



Anton Koekemoer and the GOODS Team (2004)

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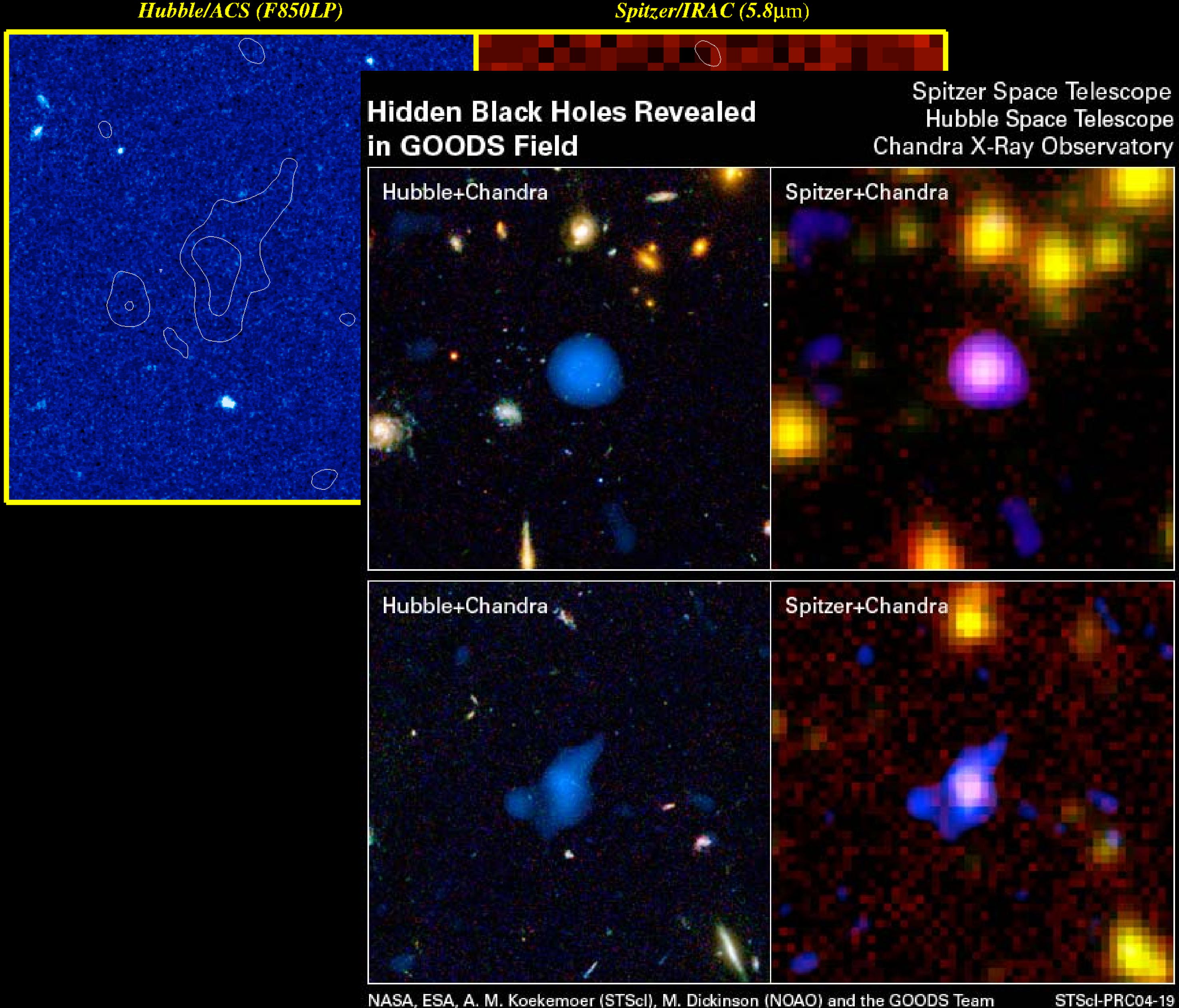
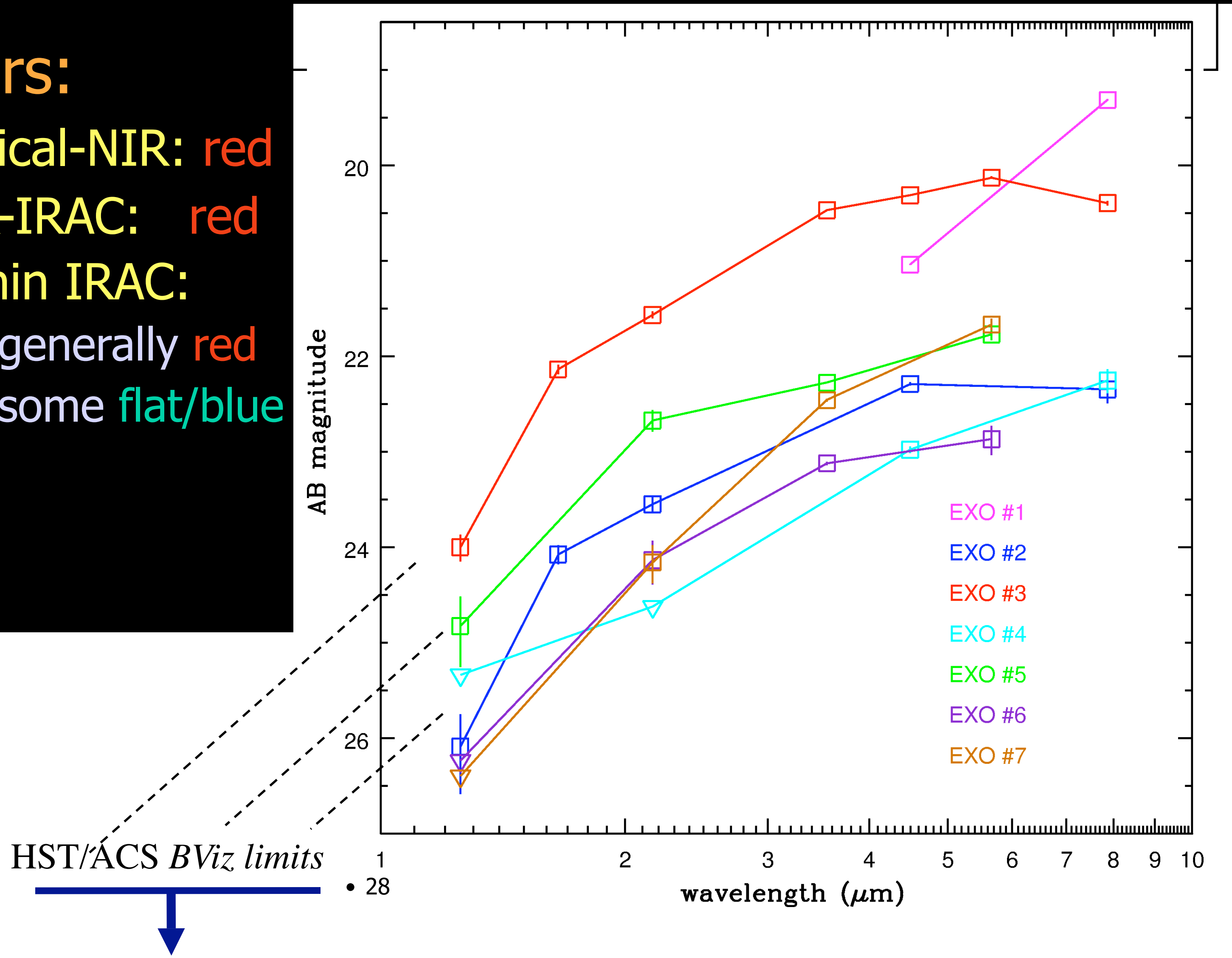


SEDs: NIR+Spitzer

Colours:

- Optical-NIR: red
- NIR-IRAC: red
- within IRAC:
  - generally red
  - some flat/blue



High-z Candidate SED Constraints

Two fundamental observational constraints:

- NIR/IRAC colours - generally red for EXO's:
  - typically K - IRAC1 (or IRAC2) ~ 2 mag(AB)
  - some of the sources have K - IRAC ~ 3 mag
- IRAC colours:
  - Some have red IRAC1-IRAC3 (or IRAC2-IRAC4)
  - Others have flat or blue IRAC colours

SED fitting:

- Explore a full grid of parameters to differentiate high-z from lower-z (eg z~2-3 "red and dead" DRGs, etc):
  - use Charlot & Bruzual (2003), also Maraston (2005-2006)
  - combine SSP + CSP
  - reddening laws (Calzetti, LMC, SMC, galactic)

SED Fitting

Parameterization:

- redshift
- Mass
- η - stellar mass formed as SSP / CSP
- τ - reddening (Fall & Charlot; Calzetti; SMC; LMC)

Fits driven by two observational features:

- red opt/NIR - IRAC colours
- colours within IRAC

General results:

- a number of the $z_{850lp}>27$ source sources are fit by z~2-3 old populations with little or no dust
- younger models requiring more dust
- host galaxies typically underluminous (c.f. AGN locally)

some examples (from GOODS):

- some EXOs are fit by z~2-3 evolved or dusty SEDs
- others have higher-z fits
- host galaxies typically underluminous (c.f. AGN locally)
- Mainieri et al 2005 (JHK), Koekemoer et al 2007 (Spitzer); also Treister et al (2006)

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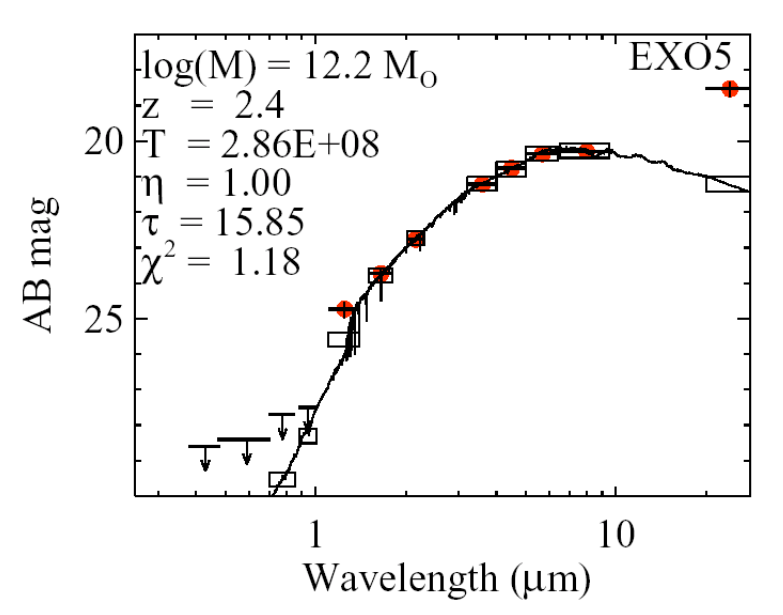

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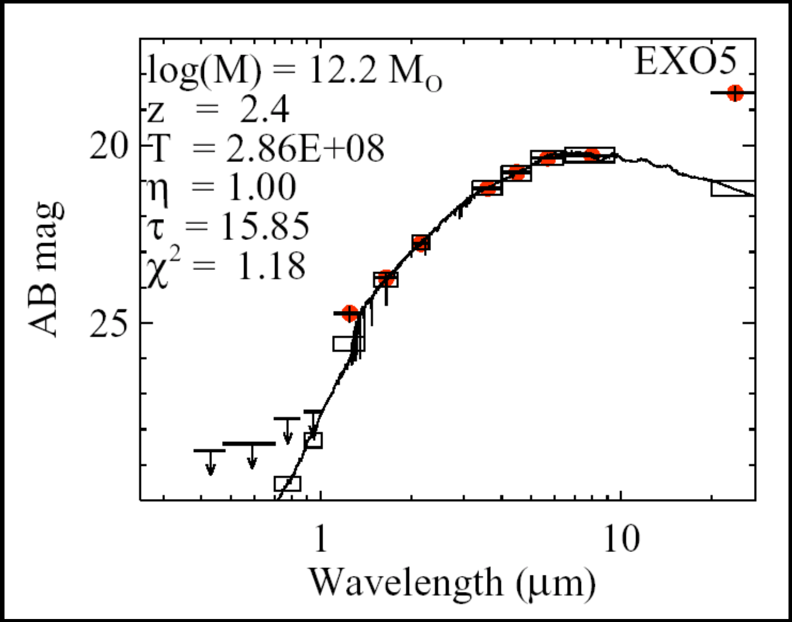
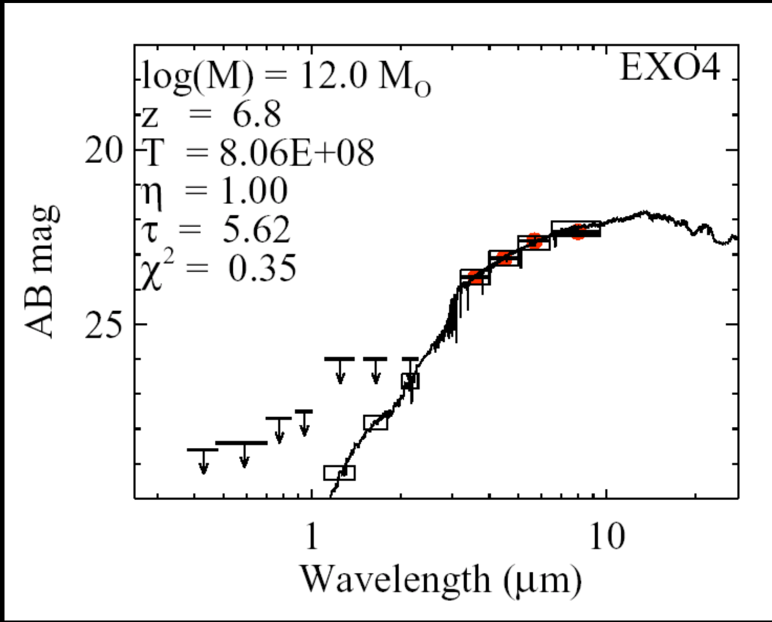
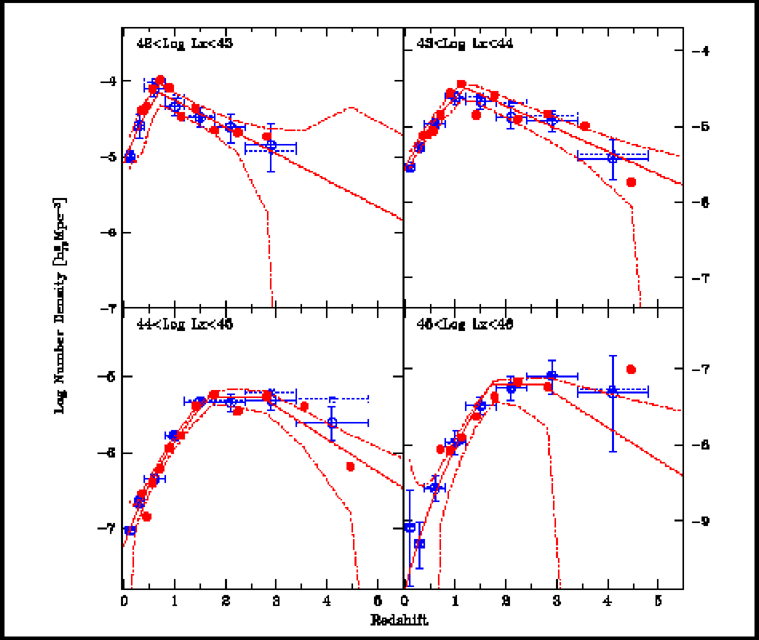


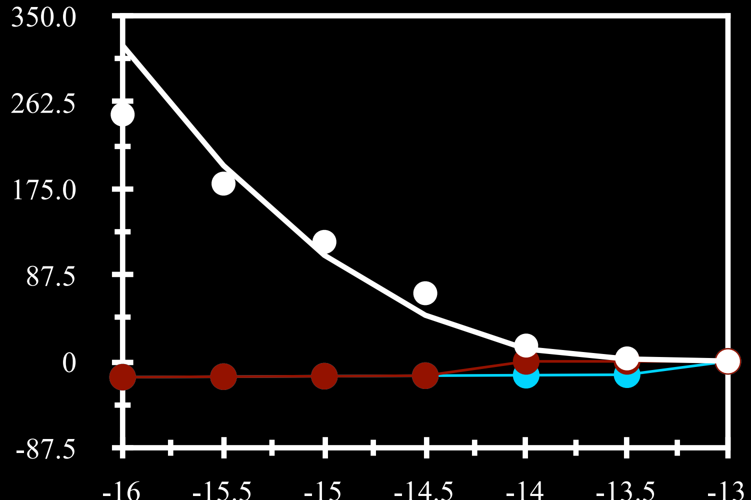


Constraining high-z AGN LF:

- Use Ueda / Hasinger / Gilli hard X-ray XLF to estimate expected number of optically unidentified sources as a function of redshift:
  - Most of the optically unidentified AGN are evolved interlopers at intermediate z > 2
- Compare with observed number of undetected sources:
  - use existing X-ray detection limits
  - apply optical detection cut-off (z(AB) ~ 27.5 for ACS)
- Integrate over X-ray luminosities at each redshift bin:
  - Use the difference to calculate cumulative number N(>6)
  - Compare with N(>6) from XLF



- Number of optically unID'd sources N(z) based on z(AB)=27.5 limit, for current Chandra catalogs, using:
  - X-ray sensitivity
  - Optical flux limits
  - Spitzer flux limits
- LDDE predicts total of ~3 AGN at z>7 in GOODS (out of all the X-ray sources with ACS coverage):



- After removing low-z interlopers, currently have 1 likely z~7 candidate in GOODS

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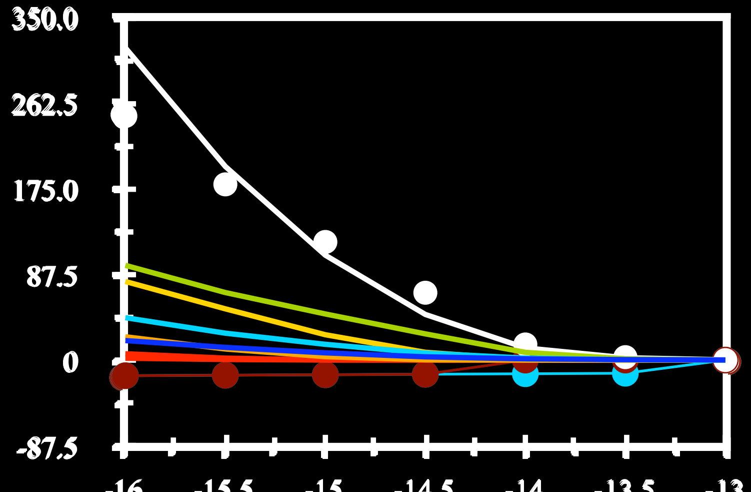

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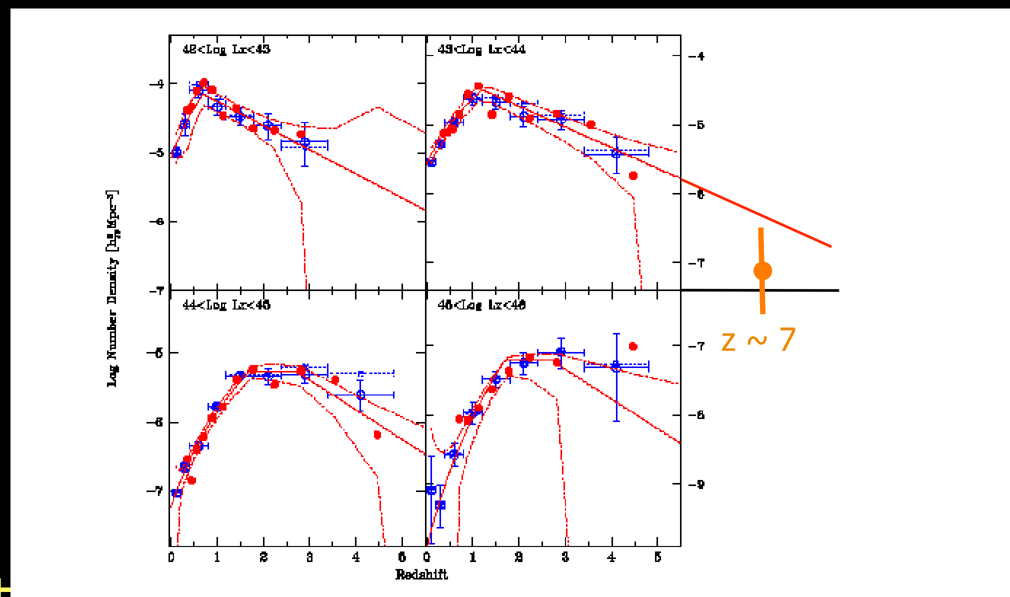
Constraints on z~7 AGN LF:

- at z~7, sensitive to Lx ~ 10^{44} erg s^{-1} cm^{-2}
  - Expected ~3 sources, found 1 candidate so far
  - other sources are ruled out as lower-z interlopers
- Convert this to a limit on the LDDE XLF:

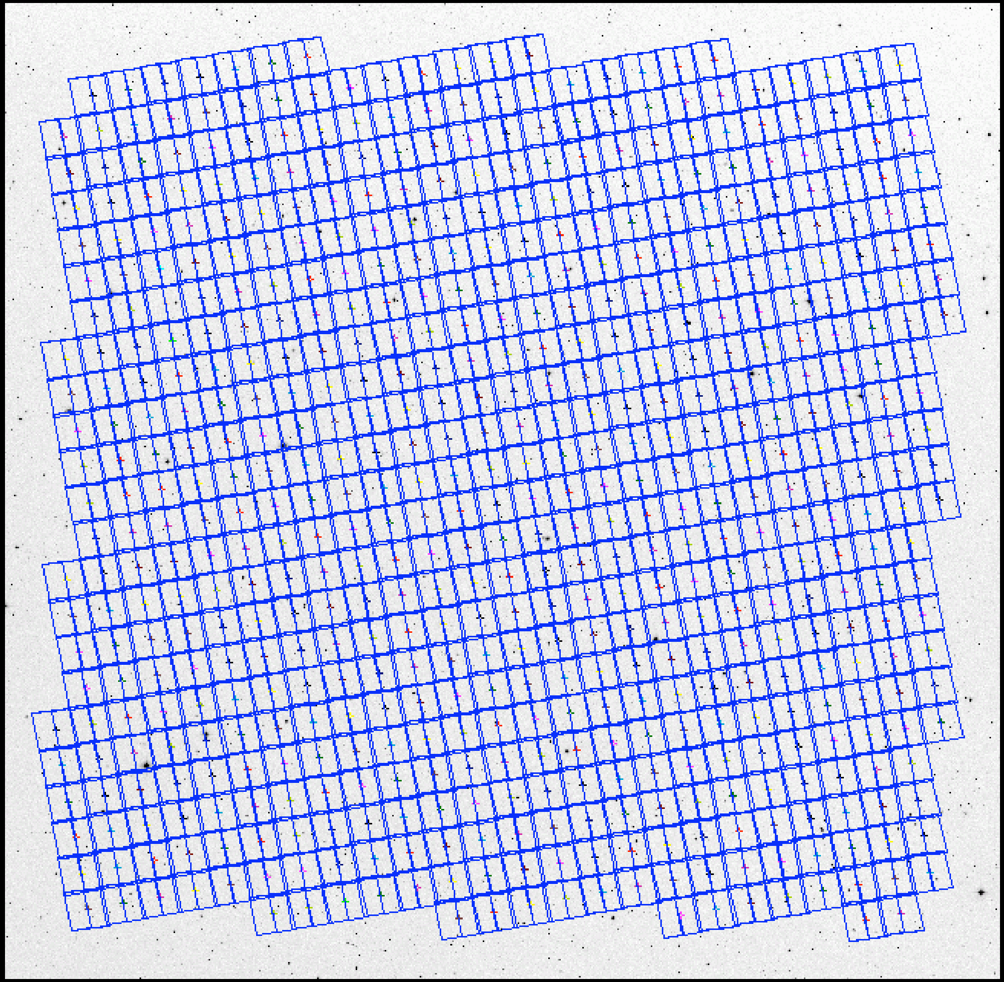


- Consistent with low end of AGN LF at z>7
  - Supports continued "anti-hierarchical" evol, ie very few low-lum AGN at high-z

Next: Expand the EXO sample - COSMOS

- 600 orbits of HST/ACS, i-band, 27th mag
- total ~2 million galaxies, ~1300 AGN (XMM: Hasinger et al, Brusa et al 2006) + radio (Schinnerer et al)

~1.4°



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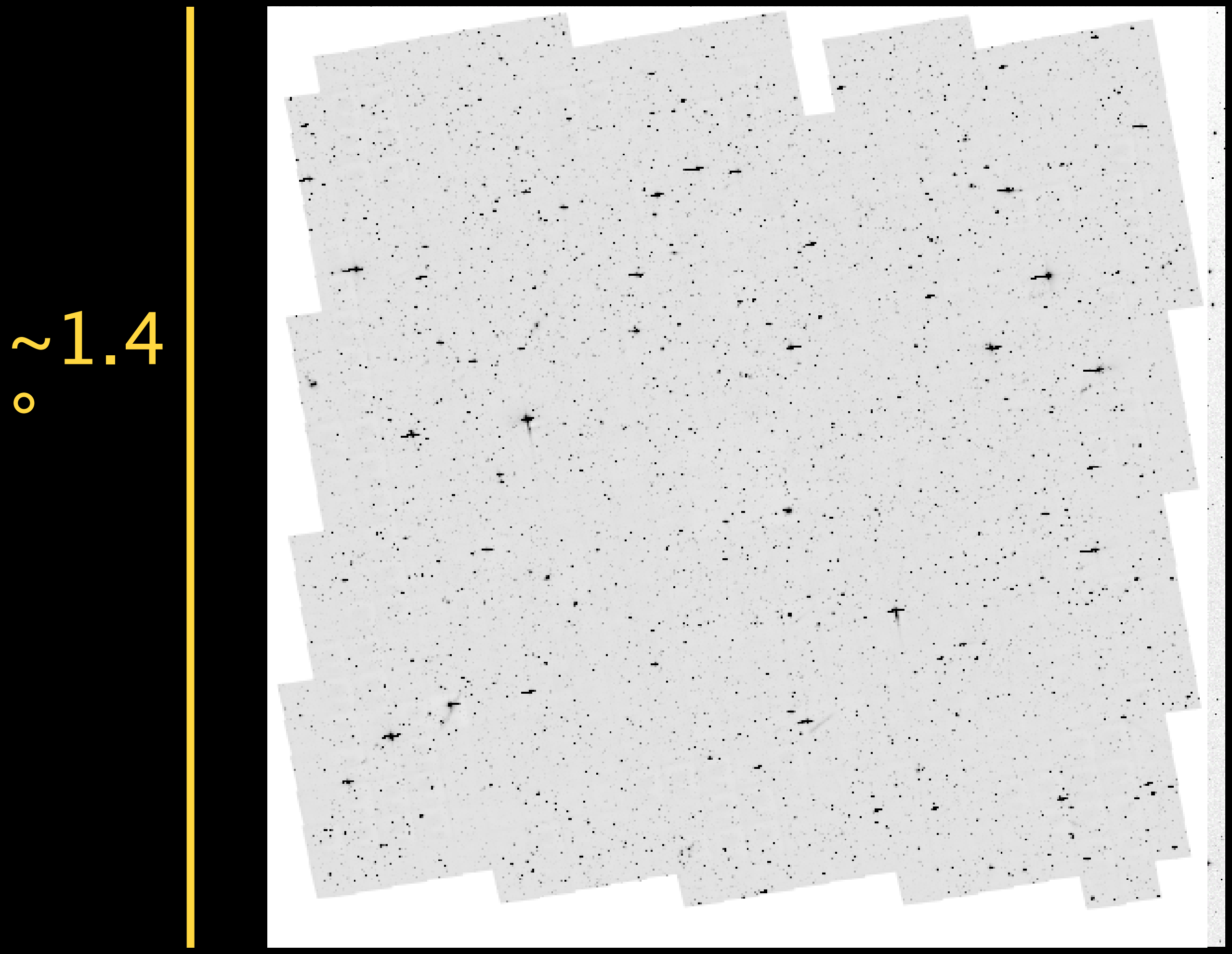
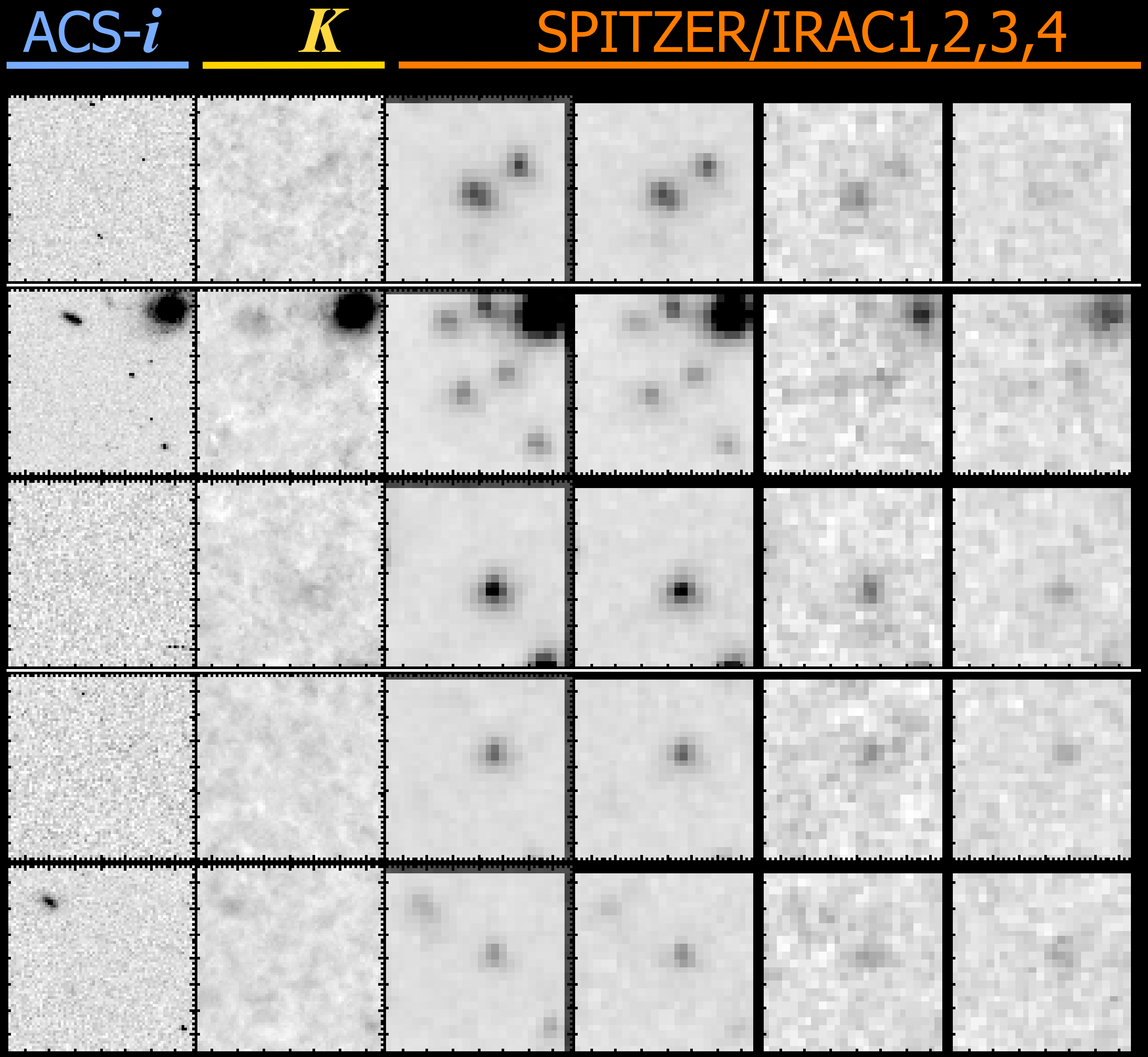


EXO/high-z candidates from COSMOS



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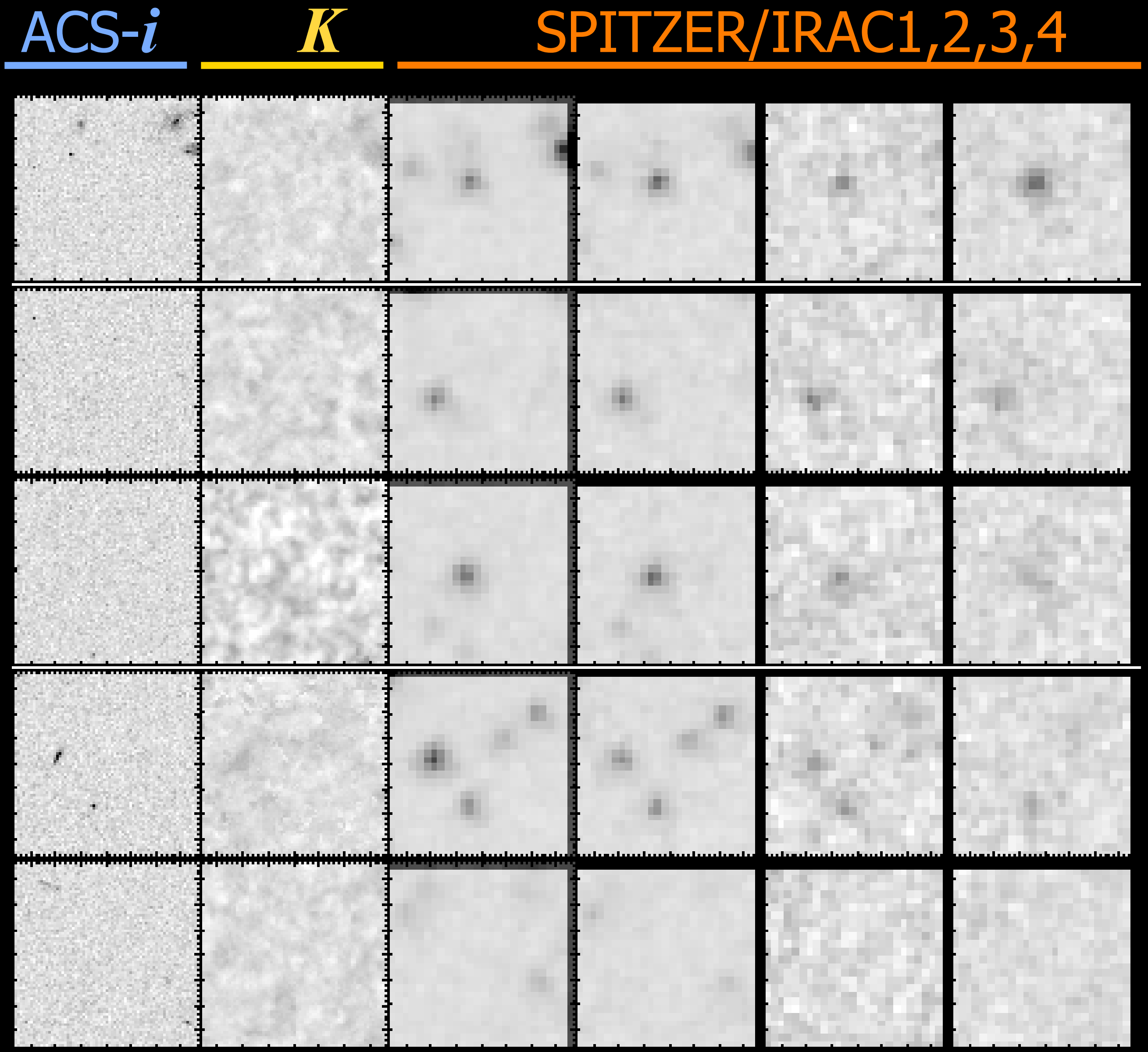

Conclusions:

- Overall number of AGN found in GOODS agrees with that expected based on LDDE:
  - Intermediate-z interlopers successfully accounted for
  - Found 1 plausible candidate z ~ 7 AGN in GOODS; compared with ~3 expected from extending LDDE to z ~ 7
- LDDE/anti-hierarchical evol appears to extend up to at least z~7 (some possible decrease in faint end of AGN LF)
- Would suggests that AGN growth/accretion mechanisms continue to track galaxy growth into reionization:
  - AGN feedback regulating star formation up to early epochs
  - black holes tracing dark matter halos since at least z ~ 7
- Next steps:
  - need larger/deeper area coverage in multiple bands (esp JHK) to improve the sample statistics
  - need more deep red optical + IR spectroscopy!