Prospects for studies of the distant Universe in the warm era

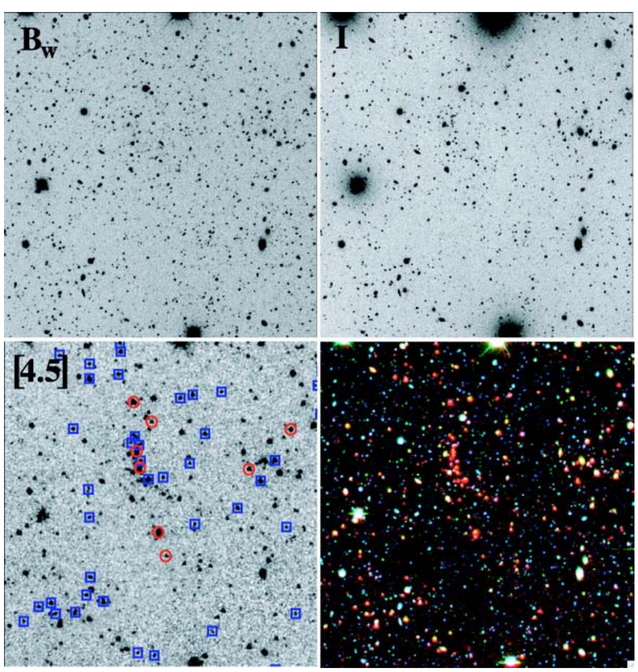
Pieter van Dokkum, Asantha Cooray, Ivo Labbe, Casey Papovich, Daniel Stern

Role of IRAC at z>1

- Unique wavelength regime:
  - At fixed redshift, can study longer rest-frame wavelengths
  - At fixed rest-frame wavelength, can study galaxies to higher redshifts
- Sensitivity
  - SEDs of normal galaxies peak at ~1.6 micron in rest-frame
  - Low background compared to ground-based NIR

Examples of IRAC results

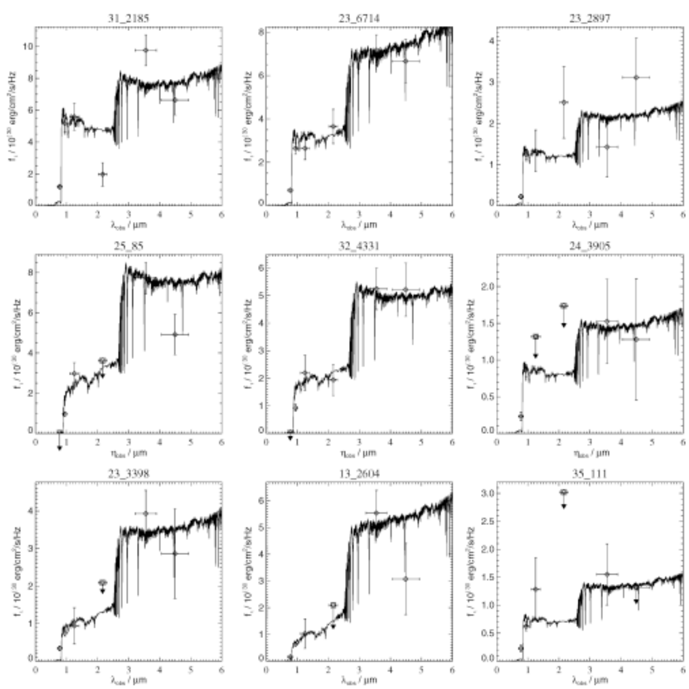
- **Abundance of obscured quasars**
  (Lacy et al. 2004, Stern et al. 2005, Cool et al. 2006)
- **Identification of galaxy clusters at 1<z<2**
  (Stanford et al. 2005, Brodwin et al. 2006)
- **Identification of "red and dead" galaxies at z>2**
  (Yan et al. 2004, Labbe et al. 2005)
- **Stellar masses and ages of galaxies out to z~6**
  (Eyles et al. 2005, Yan et al. 2005, Stark et al. 2007)
- **Confirmation and characterization of galaxies at z~7.5**
  (Egami et al. 2005, Labbe et al. 2006)
- **Possibly fluctuations induced by 1st light objects**
  (Kashlinsky et al. 2005)



Brodwin et al 2006

Examples of IRAC results

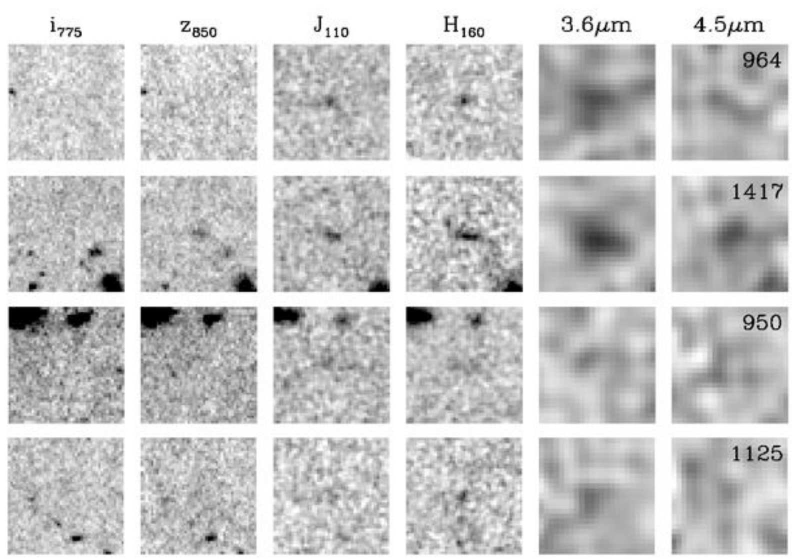
- Abundance of obscured quasars
  (Lacy et al. 2004, Stern et al. 2005, Cool et al. 2006)
- Identification of galaxy clusters at 1<z<2
  (Stanford et al. 2005, Brodwin et al. 2006)
- **Identification of "red and dead" galaxies at z>2**
  (Yan et al. 2004, Labbe et al. 2005)
- **Stellar masses and ages of galaxies out to z~6**
  (Eyles et al. 2005, Yan et al. 2005, Stark et al. 2007)
- **Confirmation and characterization of galaxies at z~7.5**
  (Egami et al. 2005, Labbe et al. 2006)
- **Possibly fluctuations induced by 1[st] light objects**
  (Kashlinsky et al. 2005)



Eyles et al 2005

Examples of IRAC results

- Abundance of obscured quasars
  (Lacy et al. 2004, Stern et al. 2005, Cool et al. 2006)
- Identification of galaxy clusters at 1<z<2
  (Stanford et al. 2005, Brodwin et al. 2006)
- Identification of “red and dead” galaxies at z>2
  (Yan et al. 2004, Labbe et al. 2005)
- Stellar masses and ages of galaxies out to z~6
  (Eyles et al. 2005, Yan et al. 2005, Stark et al. 2007)
- **Confirmation and characterization of galaxies at z~7.5**
  (Egami et al. 2005, Labbe et al. 2006)
- **Possibly fluctuations induced by 1st light objects**
  (Kashlinsky et al. 2005)



Galaxies at z=7-8 in Hubble UDF (Labbe et al 2006)

Objects responsible for reionizing the Universe

Examples of IRAC results

- Abundance of obscured quasars
  (Lacy et al. 2004, Stern et al. 2005, Cool et al. 2006)
- Identification of galaxy clusters at 1<z<2
  (Stanford et al. 2005, Brodwin et al. 2006)
- Identification of "red and dead" galaxies at z>2
  (Yan et al. 2004, Labbe et al. 2005)
- Stellar masses and ages of galaxies out to z~6
  (Eyles et al. 2005, Yan et al. 2005, Stark et al. 2007)
- Confirmation and characterization of galaxies at z~7.5
  (Egami et al. 2005, Labbe et al. 2006)
- **Possibly fluctuations induced by 1st light objects**
  (Kashlinsky et al. 2005)

Prospects in the warm era

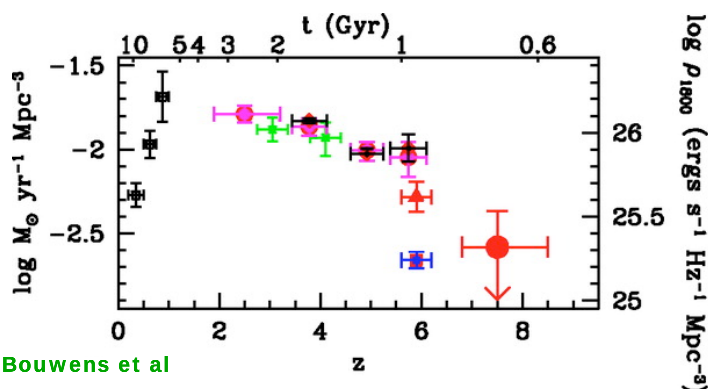
- **Nearly all results driven by channels 1 and 2, mostly from GOODS and SWIRE**
- **Limited by depth, area, or both**
  - **Only ~10 objects at z~6, and 2 at z~7.5, with firm IRAC detections**
  - **Insufficient area for clustering and for study of rare objects**

Prospects in the warm era

- Three pronged approach for studying high z universe
  - 1. Ultradeep: 250 hr depth, 0.04 sq deg (z=6-10)
  - 2. Deep: 20 hr depth, 2 sq deg (z=2-6)
  - 3. Wide: 120 s depth, 500 sq deg (clusters at z=1-2, high z quasars)
- All extend current datasets by at least an order of magnitude and enable qualitatively new science
- Together, programs characterize the build-up of stars and black holes from z~10 to z~1

1. An IRAC Ultradeep Field

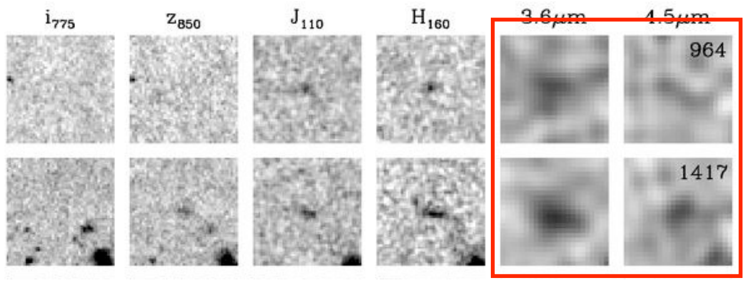
- Strawman survey: 150 sq arcmin area with 250 hr depth (size of 1 GOODS field, >10x deeper)
- Total cost (including overheads) ~ 2500 hrs
- Main science goal is exploration of z>6 Universe



Bouwens et al

1. An IRAC Ultradeep Field

- Strawman survey: 150 sq arcmin area with 250 hr depth (size of 1 GOODS field, >10x deeper)
- Total cost (including overheads) ~ 2500 hrs
- Main science goal is exploration of z>6 Universe



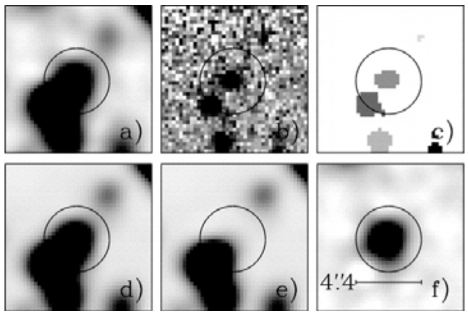
49 hr depth in UDF yielded only 2 galaxies at z=7-8

1. An IRAC Ultradeep Field

- Strawman survey: 150 sq arcmin area with 250 hr depth (size of 1 GOODS field, >10x deeper)
- Total cost (including overheads) ~ 2500 hrs
- Main science goal is exploration of z>6 Universe
- Expected number of galaxies at >5_:
  - ~ 100 at 6.5<z<7.5
  - ~ 5 at 9<z<11
  - perhaps 1 or 2 at 12<z<14

1. An IRAC Ultradeep Field

- Drawbacks / limitations:
  - Confusion: not a hard limit, but leads to reduced efficiency as effective field gets smaller

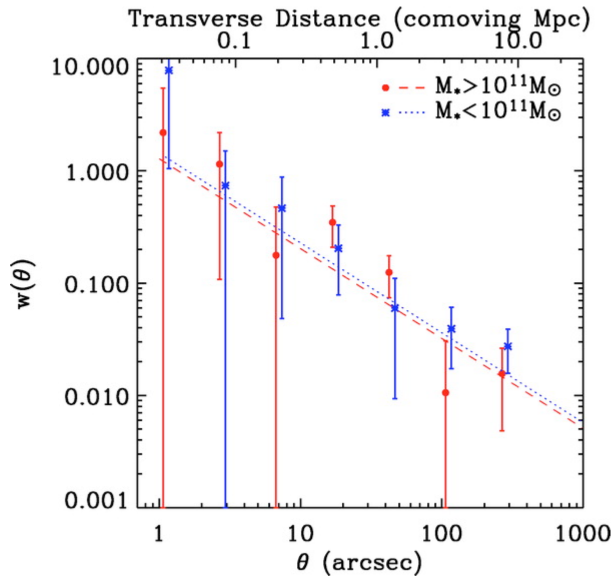


Example of deblending

  - JWST/NIRCAM factor of ~100 faster for galaxy surveys

2. GOODS depth over 2 sq deg

- GOODS fields are 2 x 10' x 15'; covered with Chandra, HST/ACS, and Spitzer/IRAC+MIPS
- Despite success of GOODS, limited by area:
  - Cosmic variance very significant over ~10' fields
  - Too small for finding brightest galaxies at high z; e.g. only ~5 $L>3L_*$ galaxies expected at $5.5<z<6.5$
  - Too small for clustering studies



Clustering by mass; using three 10’x10’ fields
(Quadri et al. 2007)

2. GOODS depth over 2 sq deg

- GOODS fields are 2 x 10’ x 15’; covered with Chandra, HST / ACS, and Spitzer / IRAC+MIPS
- Despite success of GOODS, limited by area:
  - Cosmic variance very significant over ~10’ fields
  - Too small for finding brightest galaxies at high z; e.g. only ~5 $L>3L_*$ galaxies expected at $5.5<z<6.5$
  - Too small for clustering studies
- **In last few years, fields of 0.25 – 2 sq degrees have been surveyed with HST, Chandra, Spitzer**

2. GOODS depth over 2 sq deg

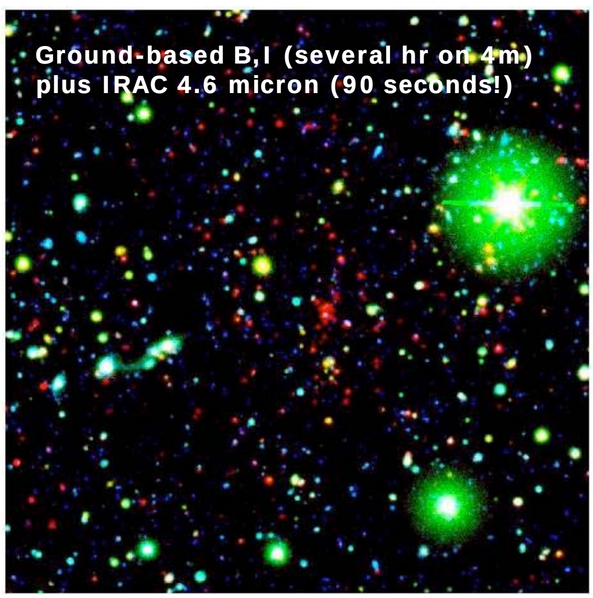
- Image multiple >0.25 sq deg area fields to GOODS depth of 20 hrs
- Most plausible fields:
  - UltraVISTA part of COSMOS (0.8 sq deg)
  - UKIDSS Ultra Deep Survey (0.7 sq deg)
  - EGS / AEGIS Strip (0.25 sq deg)
  - Extended CDFS (aka GEMS) (0.25 sq deg)
- Four fields have different and complementary legacy value; cost of doing all is ~7,500 hrs

2. GOODS depth over 2 sq deg

- Survey would enable broad range of science, and serve large part of community:
  - Detect 1000s of galaxies at $5<z<8$, tens of 1000s at $2<z<5$, and 1000s of AGNs
  - Accurate measurement of evolution of mass function and luminosity function
  - Relation between galaxy properties and the emerging large scale structure over $2<z<6$
  - Bright $z>6$ galaxies: follow-up with existing and future telescopes, and JWST
  - Robust measurement of clustering signal in background fluctuations

3. SWIRE depth over 500 sq deg

- **Rare objects such as clusters of galaxies and luminous quasars require very large areas**
- **SWIRE depth of 120 s sufficient to detect clusters** (Brodwin et al 2006; Eisenhardt cluster program; also SPARCS survey by Wilson & Muzzin) **and QSOs** (e.g. Stern et al 2005)



Cluster at z=1.41, from Stanford et al 2005

3. SWIRE depth over 500 sq deg

- **Rare objects such as clusters of galaxies and luminous quasars require very large areas**
- **SWIRE depth of 120 s sufficient to detect clusters** (Brodwin et al 2006; Eisenhardt cluster program; also SPARCS survey by Wilson & Muzzin) **and QSOs** (e.g. Stern et al 2005)
- **SWIRE covered 50 sq deg (in ~ 10 sq deg patches)**

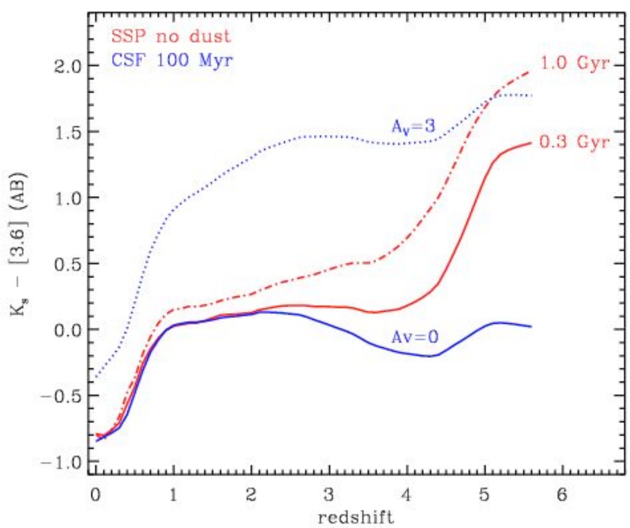
3. SWIRE depth over 500 sq deg

- **Strawman survey: 500 sq deg to 120 s per pix depth**
- **Total cost ~ 4000 hrs**
- **Among the science returns:**
  - **~ 1500 clusters at $1<z<2$ with masses $>10^{14}$ M_{sun}, for studying galaxy evolution and constraining cosmological parameters**
  - **High redshift quasars for studying reionization**
  - **Clustering of high redshift quasars will provide masses of their halos**
  - **May also be very good way to find Y dwarfs**

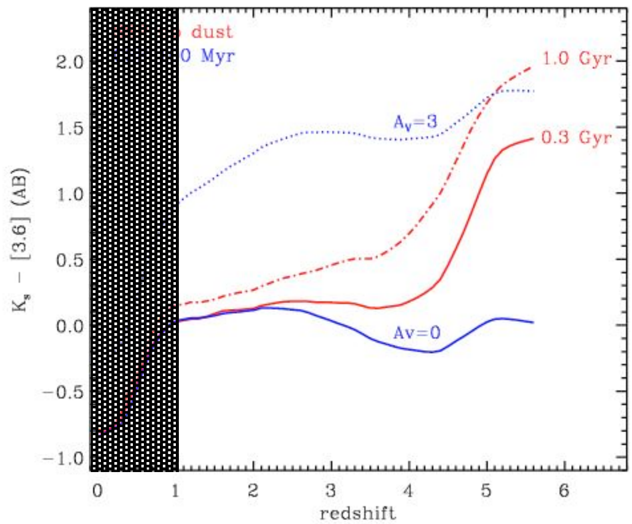
Importance of near-IR data

- For all three surveys, the IRAC data in isolation have very little value
- Near-IR data particularly important:
  - Photometric redshift determination
  - Measure Balmer and Lyman break
  - Deblending and accurate flux measurements of IRAC sources

IRAC versus ground-based K

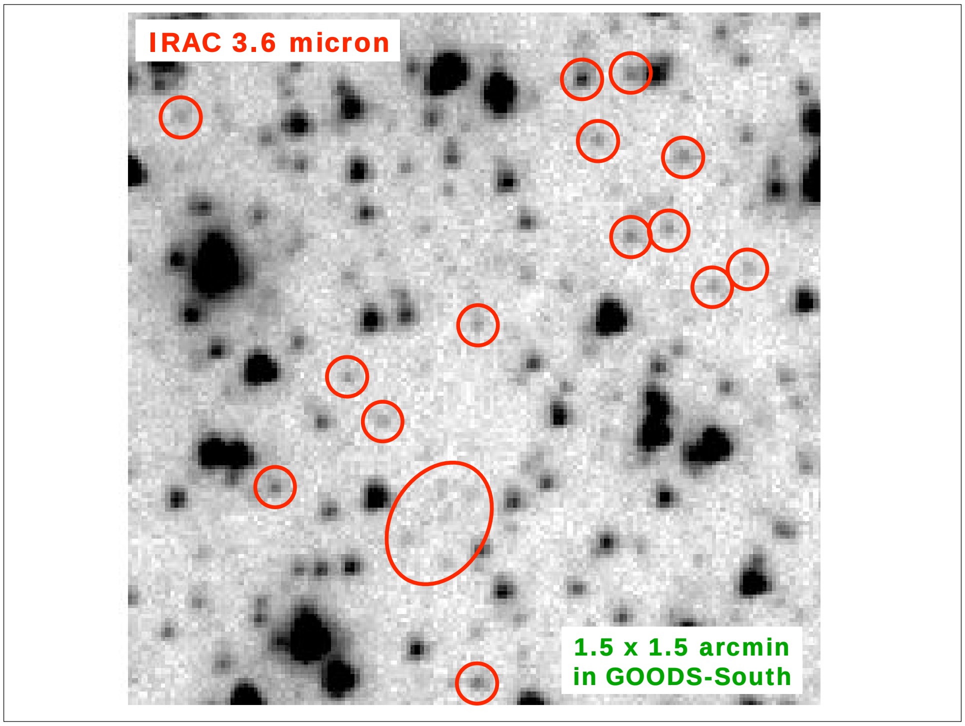


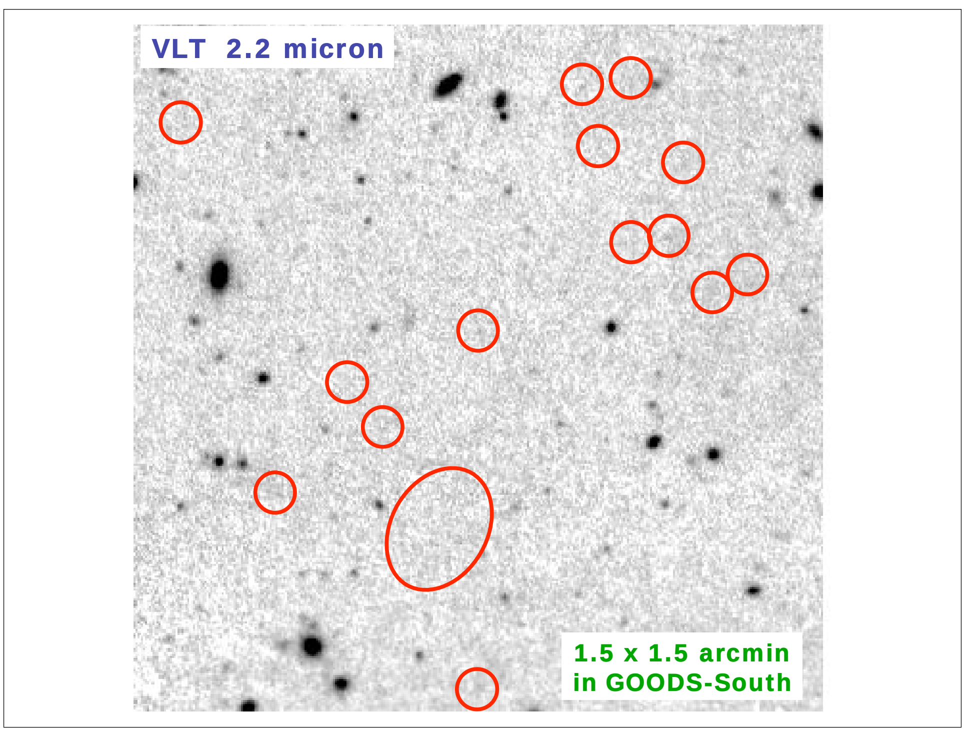
IRAC versus ground-based K

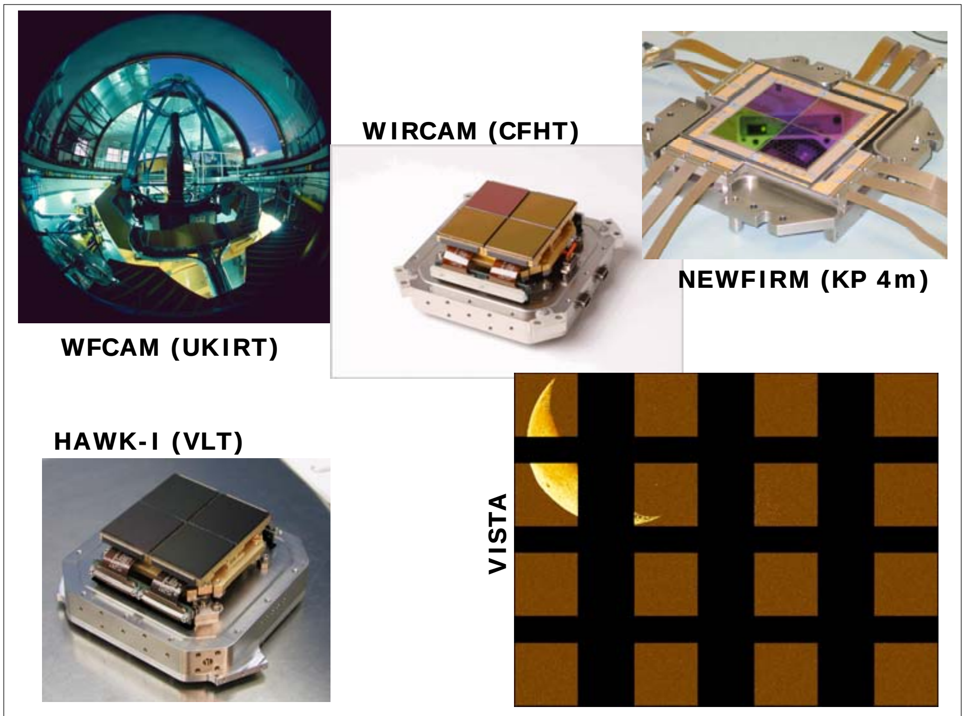


IRAC versus ground-based K

- Galaxies at z>1 have K-[3.6] ≥ 0 in AB units
  - To match (e.g.) K_{AB} = 25, IRAC does not need to go fainter than [3.6] = 25
  - However, to match [3.6] = 25, one needs to go ***at least*** to K_{AB} = 25
- For typical NIR cameras on 4m telescopes, it takes ~ 20 x longer to reach same per-pixel AB depth as IRAC
- Hard to reach ! Example: 288 hrs of VLT time in GOODS-South (twice the IRAC investment)


IRAC 3.6 micron
1.5 x 1.5 arcmin
in GOODS-South


VLT 2.2 micron
1.5 x 1.5 arcmin
in GOODS-South



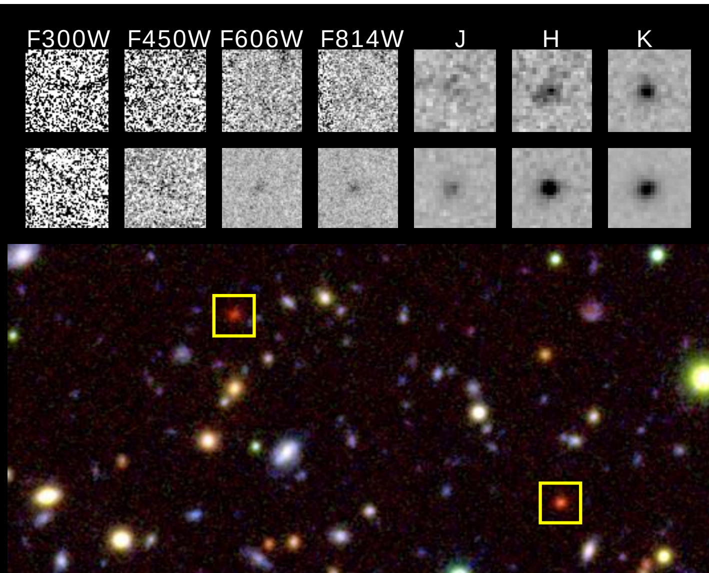
Implications for surveys

- **Ultra-deep IRAC survey** cannot be matched by ground-based NIR imaging – need ~700 orbits of HST/WFC3
- **2 degree survey** depth can only be matched by 1000s of hrs of 4m time; already planned for part of COSMOS (UltraVISTA) and UKIDSS/UDS
- **500 degree survey** depth also requires large investment of 4m time; e.g. VISTA Kilo Degree Survey

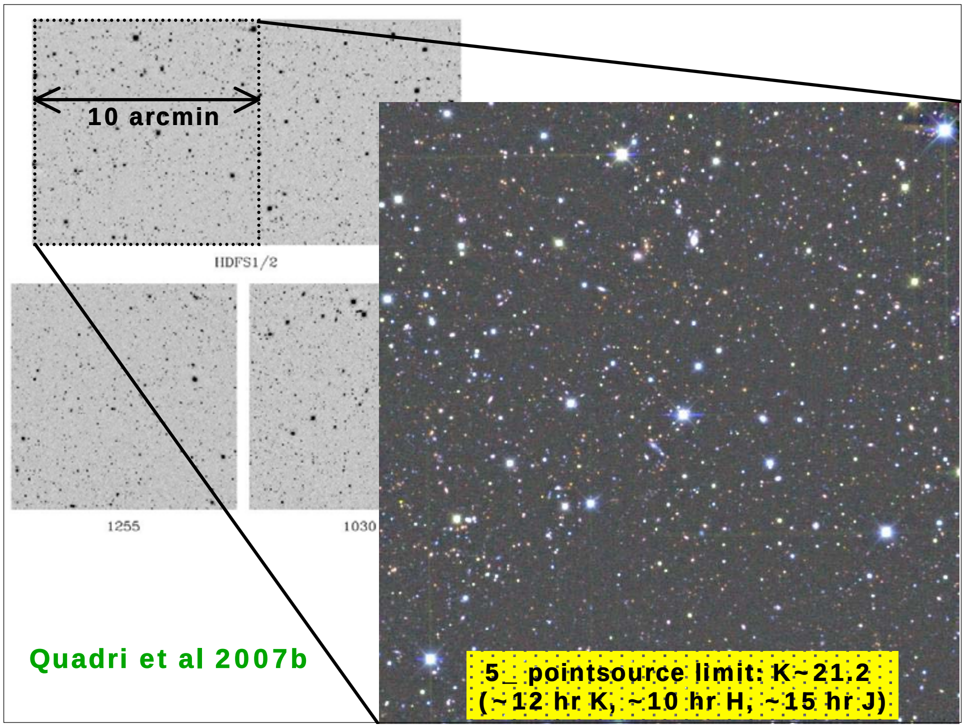
*Given the large investment of Spitzer time, supporting data products **MUST** be public*

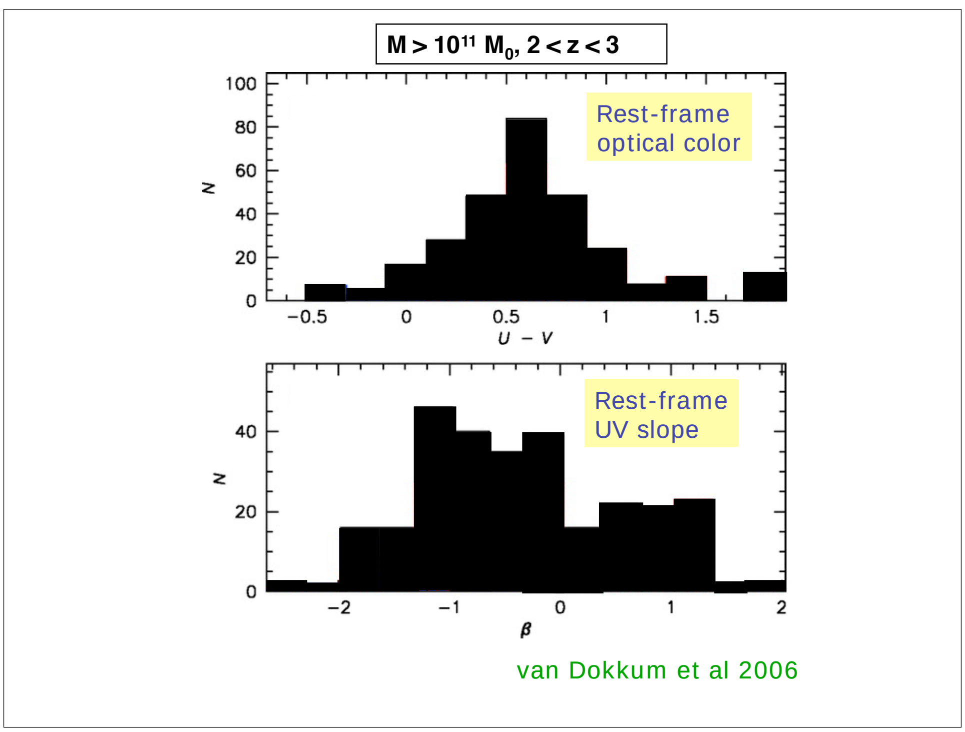
Conclusions

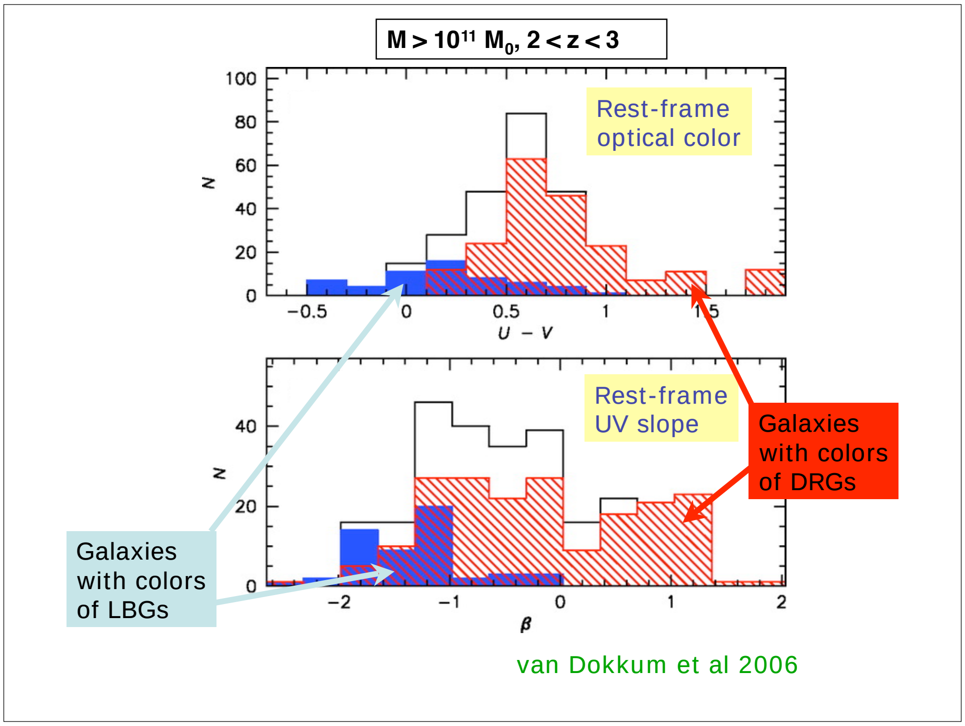
- **Three-pronged survey program would greatly advance study of galaxies at 1<z<10, AGN, and clusters at 1<z<2**
- **Other survey ideas briefly discussed in white paper (e.g., strong lensing, ultra-wide survey)**
- **Some time should remain available for small/medium programs, e.g.**
  - **Massive galaxy cluster at z=4**
  - **Lensed z=10 galaxy**
  - **Very special gamma-ray burst**
- **One or more surveys could be executed by SSC – would allow community to focus on science**

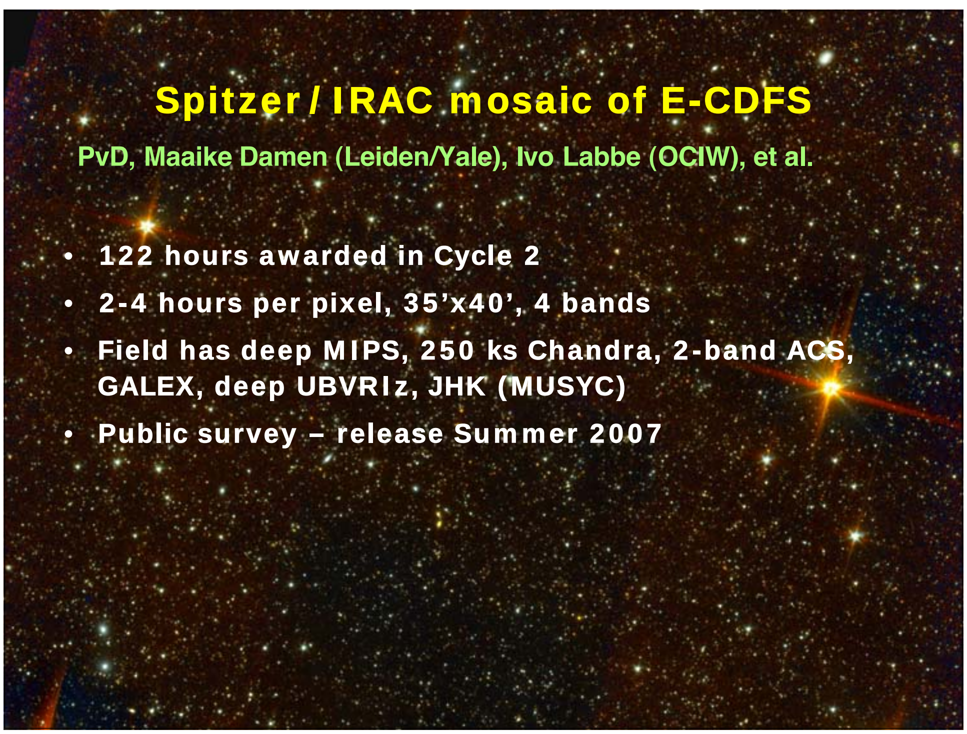


- **Red galaxies at z>2 (Distant Red Galaxies, or DRGs)**
  Franx+ 03, vD+ 03, 04, Daddi+ 04, Forster Schreiber+ 04, Rubin+ 04, Knudsen+ 05, Labbe+ 05, Webb+ 05, Papovich+ 05, Quadri+ 06, ...


10 arcmin
HDFS1/2
1255
1030
Quadri et al 2007b
5_ pointsource limit: K~21.2
(~12 hr K, ~10 hr H, ~15 hr J)


M > 10¹¹ M₀, 2 < z < 3
Rest-frame
optical color
U − V
N
Rest-frame
UV slope
β
van Dokkum et al 2006


M > 10^11 M_0, 2 < z < 3
Rest-frame optical color
U − V
N
Rest-frame UV slope
β
Galaxies with colors of DRGs
Galaxies with colors of LBGs
van Dokkum et al 2006


Spitzer / IRAC mosaic of E-CDFS
PvD, Maaike Damen (Leiden/Yale), Ivo Labbe (OCIW), et al.
• 122 hours awarded in Cycle 2
• 2-4 hours per pixel, 35’x40’, 4 bands
• Field has deep MIPS, 250 ks Chandra, 2-band ACS, GALEX, deep UBVRIz, JHK (MUSYC)
• Public survey – release Summer 2007