mm observations of strongly lensed z>6 galaxies: a preview to ALMA and E-ELT science on the first galaxies

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Main collaborators: Frédéric Boone, Françoise Combes (Paris),
Roser Pelló (OMP)

- Overview, motivation: dust in SF galaxies at z>4-6
- Case study of a strongly lensed z=6.56 galaxy
- Next targets for mm
- IRAC/Herschel/… Lensing Cluster Survey before ALMA, E-ELT, JWST
- Tracing cosmic reionisation with OPTIMOS-EVE @ E-ELT

- Boone, Schaerer et al. (2007, A&A 460, 397)
- Schaerer & de Barros (2009, A&A, submitted)

Main questions

- Searches for and characterisation of the most distant, primeval galaxies -- z>6
- Identification of the sources of cosmic reionisation
- Trace the history of SF and cosmic reionisation during first Gyr after Big Bang

- **Study evolution of the dust content in the early Universe**
- **Are there dusty/hidden galaxies at z>4-6?**
- **Global picture of the different populations of high-z galaxies and their evolution**

Are there dusty/hidden galaxies at z>4-6?

- SCUBA gals --- generally found at z<~2.5
- Few exceptional cases:
  - z=4.547 SMG (Capak et al. 2008)
  - LABOCA ECDFS z=4.76 object (Coppin et al. 2009)
  - GOODS 850-5: z~4-6 ? (Wang et al. 2009)

BUT:

- All high-z QSO --> large dust masses / high SFR
- What about « normal » high-z galaxies?
- General: LBG blue at z>3 --> little dust
  (e.g. Bouwens et al. 2008: UV attenuation ~1.5 @z~6; cf. Reddy et al. 2009)

→ Now: case study using gravitational lensing!

→ Soon: Spitzer/Herschel/sub-mm lensing cluster survey

→ Soon+Later: ALMA, E-ELT, JWST

Known z>6 galaxies

Found thanks to lensing:

EL selected:

* **z=6.56 galaxy behind A370**: Hu et al. (2002)
* 5 z~8.7-10.2 candidates: Stark et al. (2007)

LBG (z, J dropout):

* z~7 galaxy (HST + Spitzer): Kneib et al. (2004), Egami et al. (2005)
* survey of 2 clusters (VLT+): Richard et al. (2006) - ~10 candidates
* Richard et al. (2008): 6 clusters with ACS+NICMOS --> ~10 candidates
* **« Bright » z~7.6 galaxy in A1689:** Bradley et al. (2008)
* TODAY: 3 new « bright » z~6-6.5 galaxies: Zheng, Bradley et al. (2009)

Found in blank fields:

LAE: found with SUBARU - z=6.56, 6.96 (Iye et al. 2008, Ota et al. 2008)

LBGs: Bouwens et al. (2007, 2009), Labbé et al. (2006): 2-4 z~7 galaxies
Henry et al. (2008 - but refuted in 2009)

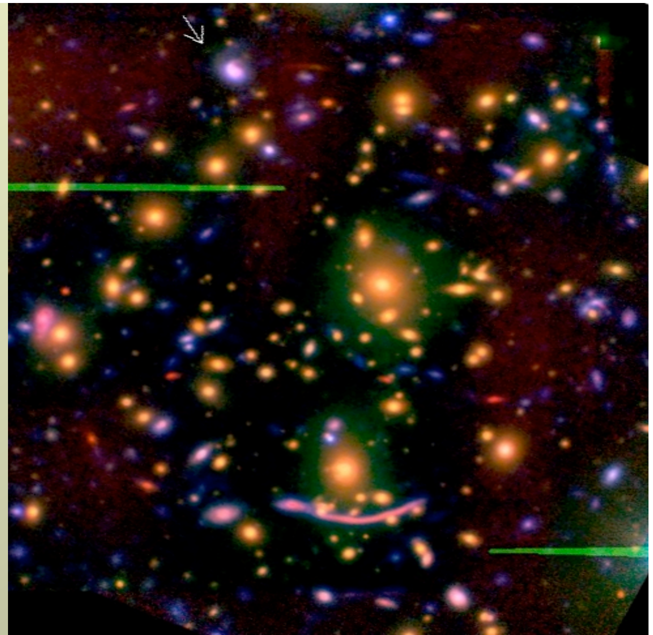
PROBLEM: faint (SFR<~10-20 or less) -- **too faint for IR-mm followup, except if strongly lensed!**

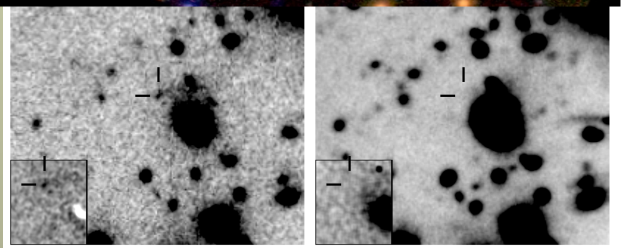
A lensed LAE at z=6.56: multi-wavelength approach

Observations of Abell 370 HCM6A: Hu et al. (2002)

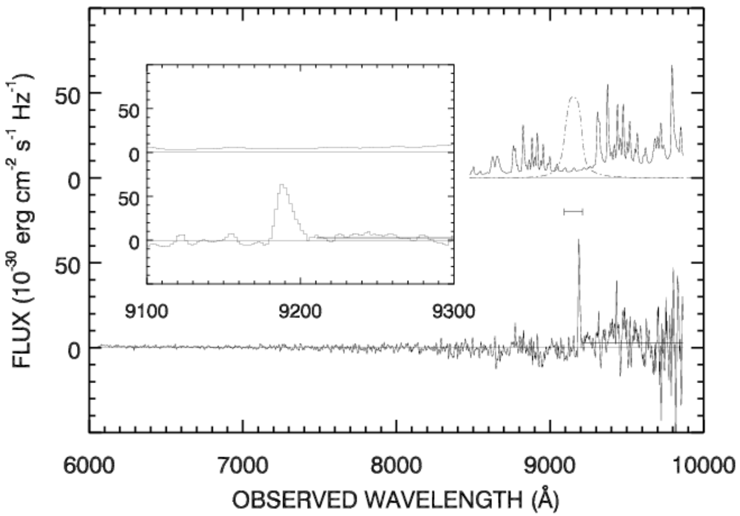
- BVRIZJHK (Keck, SUBARU)
- Lyα emission
- magnification μ~4.5
- also detected at 3.6 and 4.5 micron (IRAC/Spitzer)

SFR(UV) ~ 5.6 $M_\odot$/yr
SFR(Lya) ~ factor >~5 lower

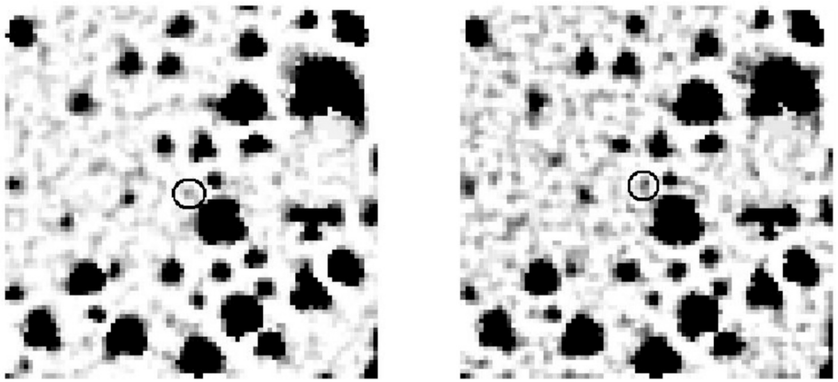




Hu et al. (2002)

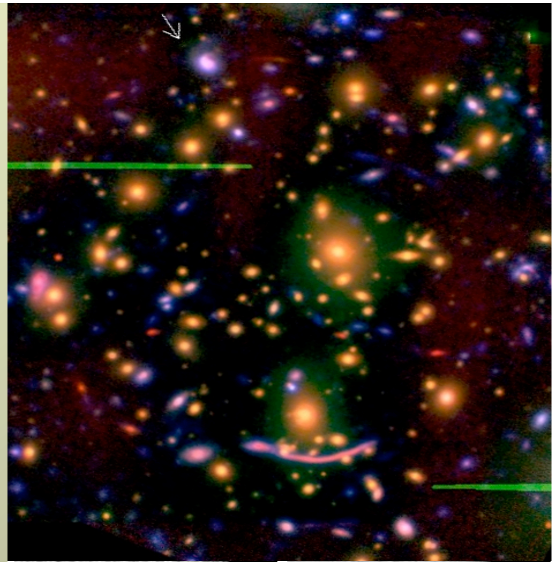


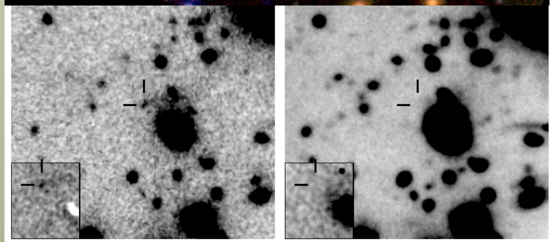
Chary et al. (2005), Lai et al. (2009)



A lensed LAE at z=6.56: multi-wavelength approach

Observations of Abell 370 HCM6A: BVRIZJHK (Keck, SUBARU), Lyα emission ,magnification μ~4.5 (Hu et al. 2002)

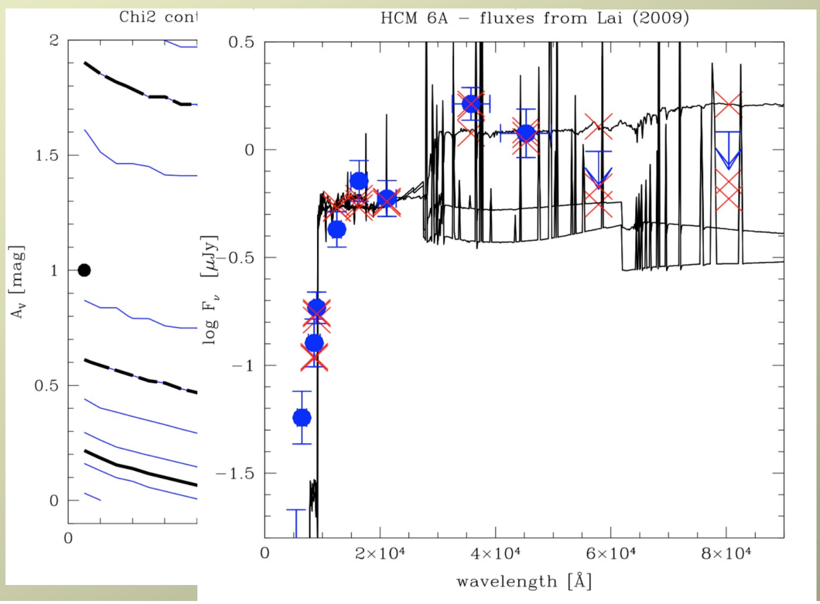




Spectral fitting: to reconcile SED + Lyα emission --> short bursts excluded

→SFR=const + non-negligible extinction (A_V~1)

→a dusty z=6.56 galaxy !?



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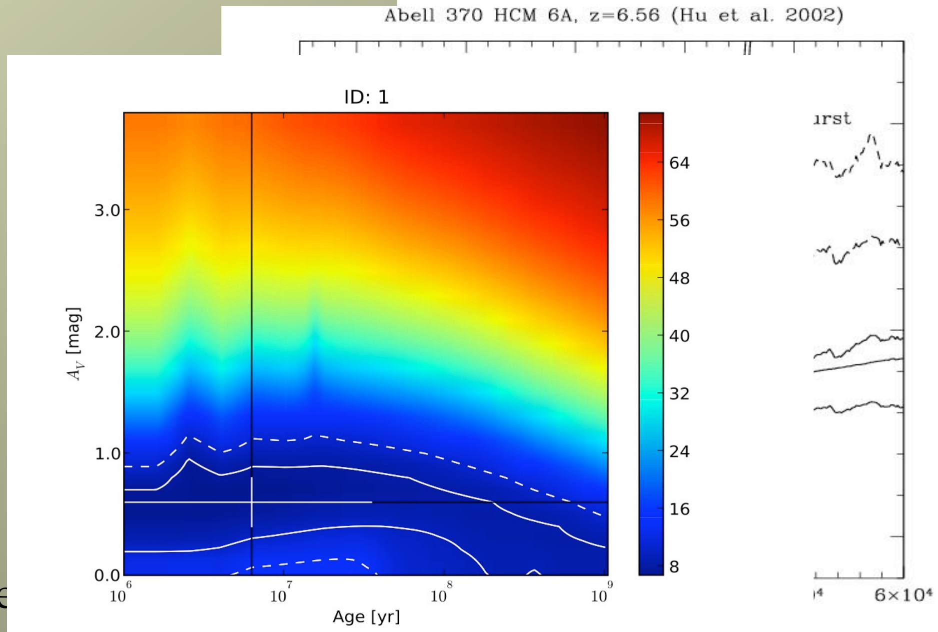
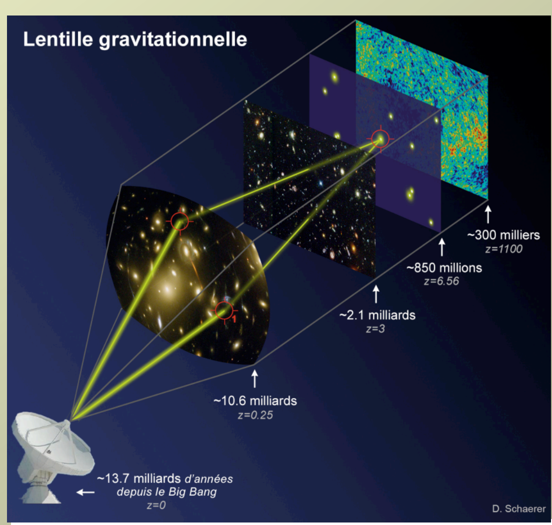


LAE at z=6.56: multi-wavelength approach

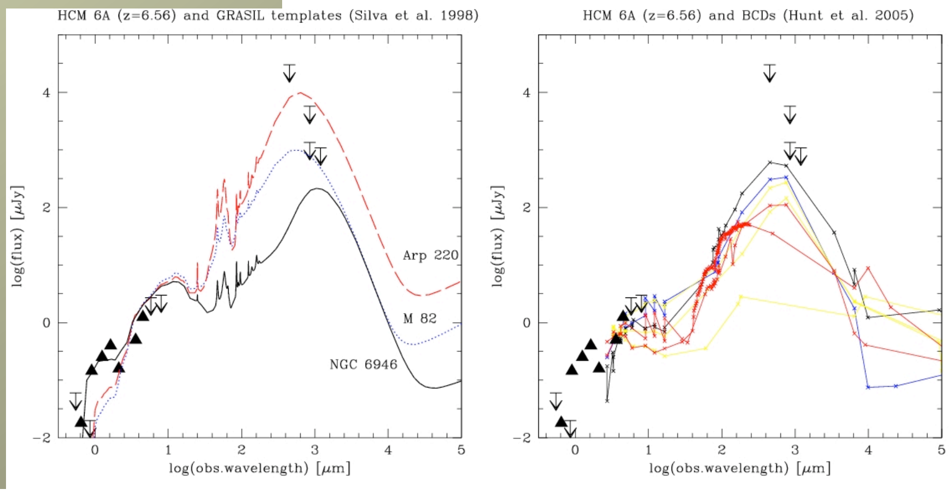
Deep 1.2mm observations of HCM6A (30m IRAM): non-detection <1.08 mJy (3σ)



- Dust mass < 5.3 10^7 $M_\odot$. No strong constraint on production from SNII.
- SFR(IR) <~35 $M_\odot$/yr just compatible with SFR(UV) and SFR(Lya)
- SED: ULIRG type excluded, ressembles likely SED of normal or dwarf galaxies

	$T_d = 18$	$T_d = 36$	$T_d = 54$
Dust mass	$< 7.0 \times 10^8$	$< 5.3 \times 10^7$	$< 1.5 \times 10^7$
L_{FIR}	$< 6.4 \times 10^{10}$	$< 2.1 \times 10^{11}$	$< 5.4 \times 10^{11}$
SFR(IR)	< 11	< 35	< 87
L_{bol}		$(1-4) \times 10^{11}$	
$SFR_{UV}(A_v = 1)$		11–41	
$SFR_{Ly\alpha}(A_v = 1)$		7–12	
$SFR_{UV}(A_v = 0)$		5.6	
$SFR_{Ly\alpha}(A_v = 0)$		0.4–0.8	

Gravitational lensing + deep observations ==> Upper limits on (M_d, SFR, L_{FIR}) for LAE at z=5.7..6.5 improved by factor 8-20!
(cf. Webb et al. 2007, Carilli et al. 2007)



Boone, Schaerer et al. (2007)

LAE at z=6.56: multi-wavelength approach

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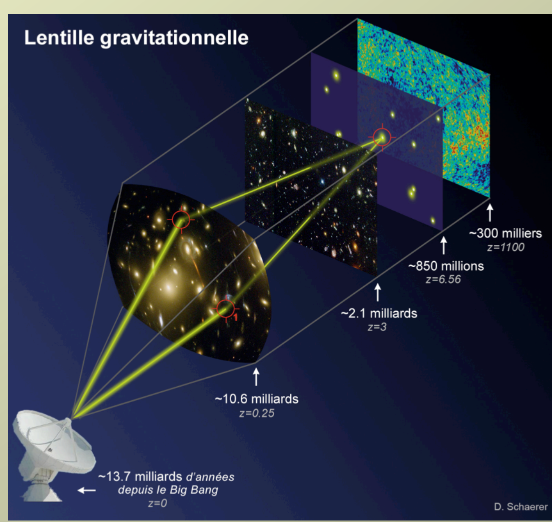
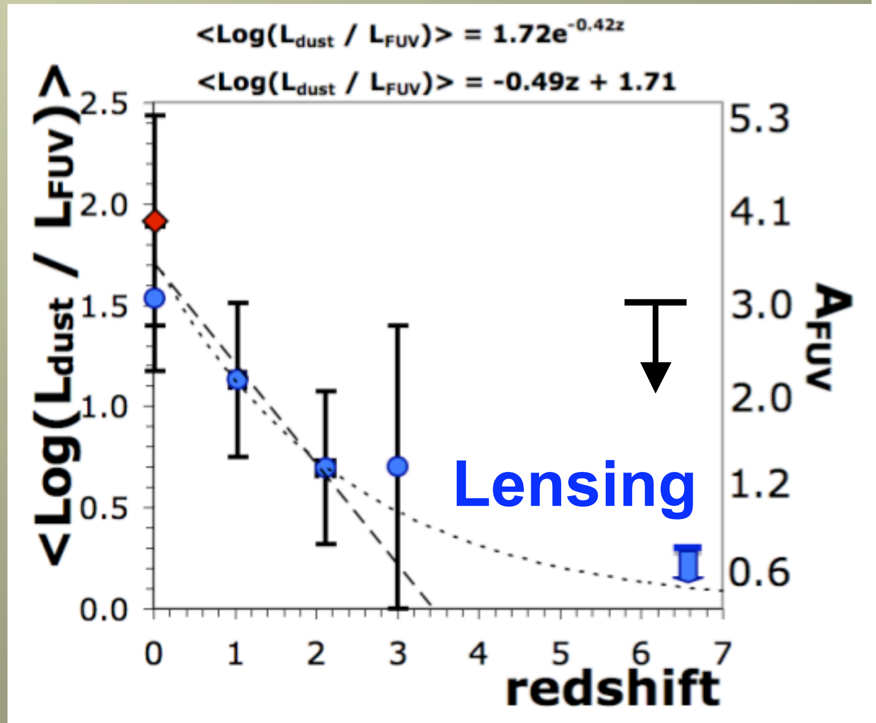


- L(FIR)/L(UV)<~ 2

cf. earlier limits: 2 LAE at z~6.5 observed with SCUBA --> L(FIR)/L(UV)<35 (Webb et al. 2007)

- --> First constraint on evolution of dust content in UV selected SF galaxies with redshift



Burgarella et al. (2007, 2009)

Boone, Schaerer et al. (2007)

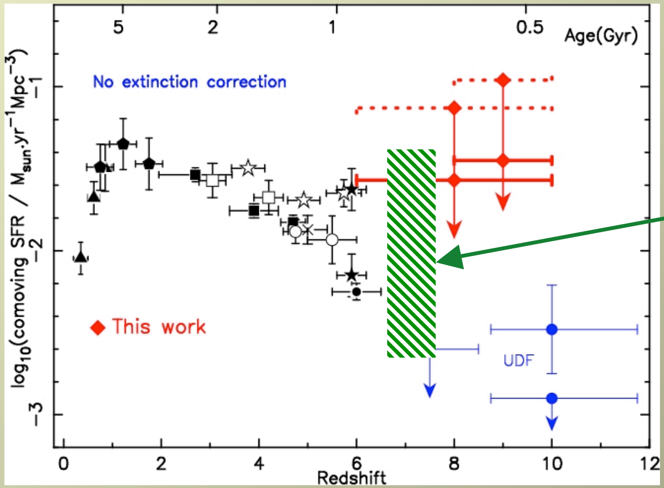
LAE at z=6.56: multi-wavelength approach

- HCM6A: L(Lyα)=2. 10^{42} erg/s corresponds to faintest/most numerous LAE known at z~6.6
- SFR(IR) and number density N(>L)~7.10^{-4} Mpc^{-3}

→Estimate of the obscured SFR density (SFRD) of LAE at z=6.6 (upper limit)

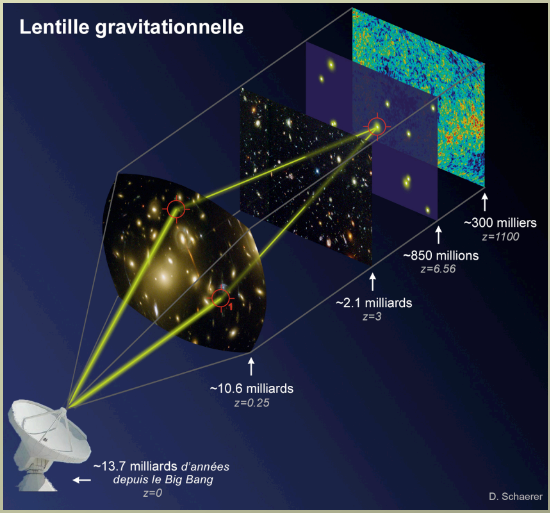
→With LF(Lyα) --> lower limit for SFRD

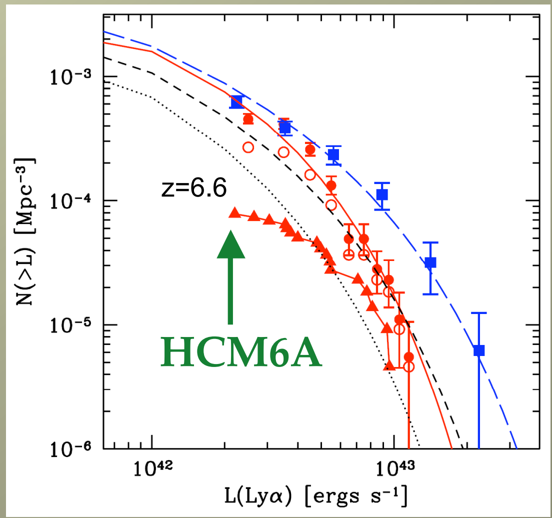
⇒Intense star formation at z >~6.6 !?



Allowed SFRD range (from LAE at z~6.6)

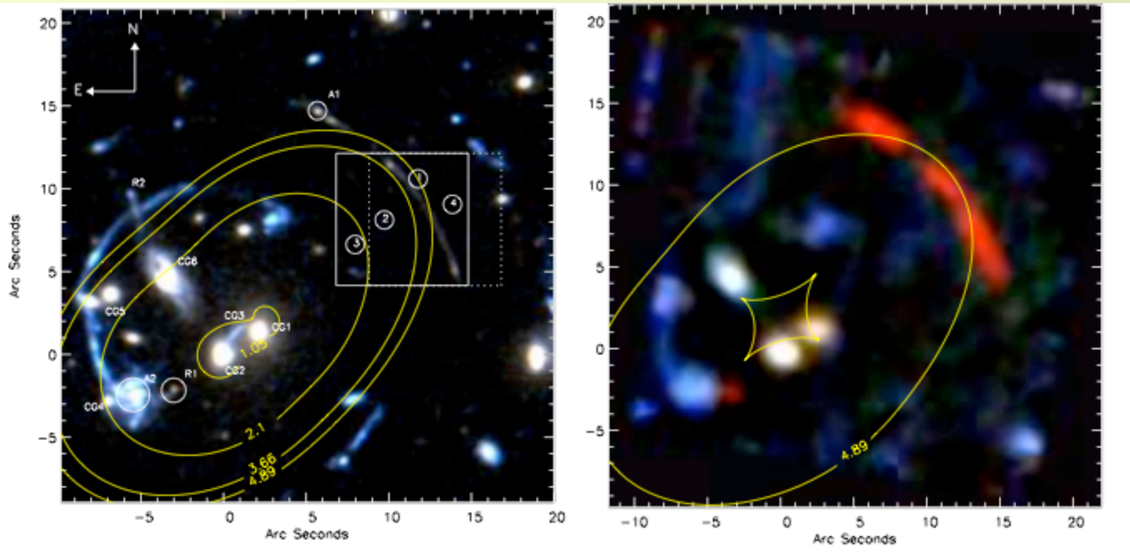
Boone, Schaerer et al. (2007)





Kashikawa et al. (2006)

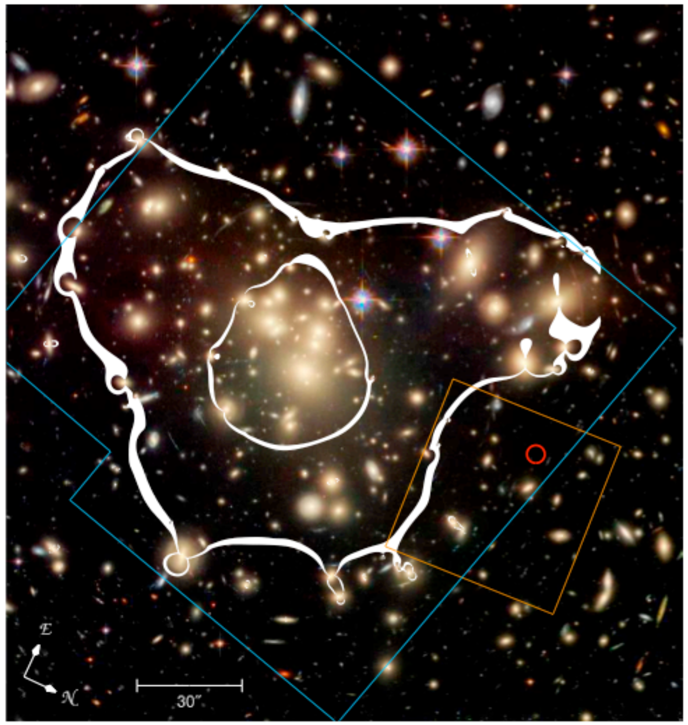
Other currently feasible lensed candidates

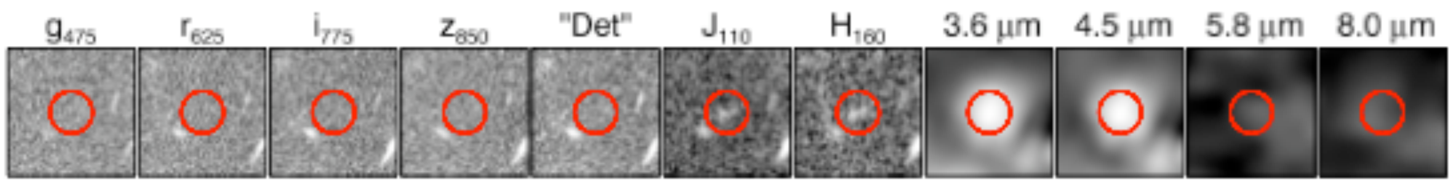


• z~5 galaxy in RCS0224-002 (Swinbank et al. 2007): SFR*μ~192

• z~7.6 galaxy in Abell 1689 (Bradley et al. 2008: brightest observed, highly reliable z>7 galaxy candidate found today) SFR* μ ~65

• 4 strongly lensed z>~6 candidates (Richard et al. 2008, Bouwens et al. 2009)



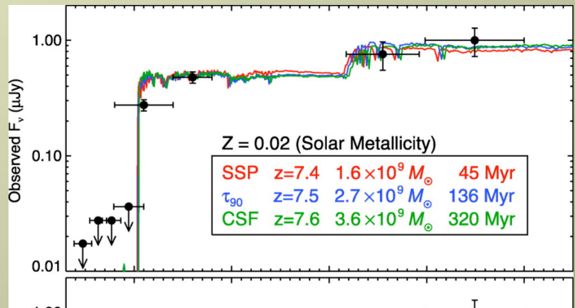


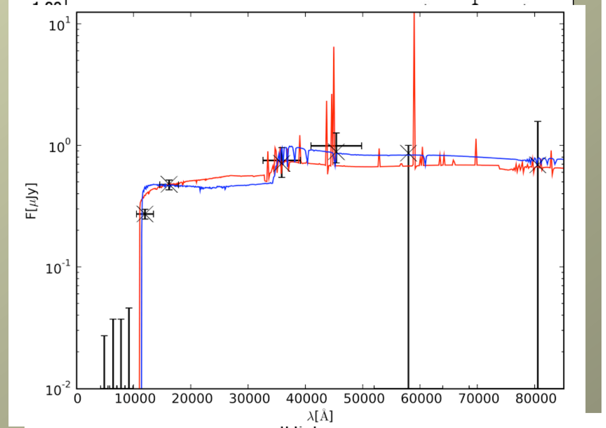
Other currently feasible lensed candidates

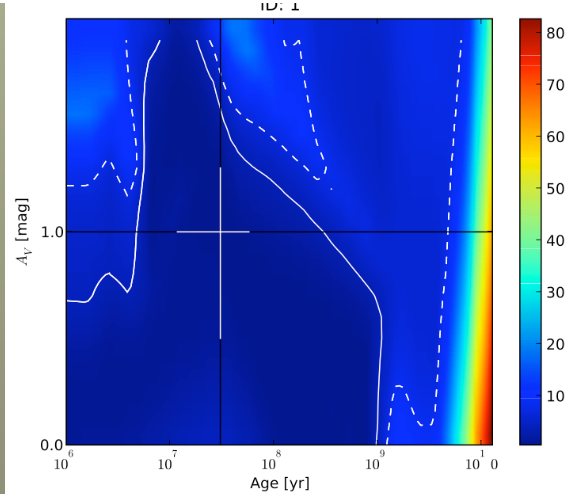
- Possible evidence for dust from SED fits

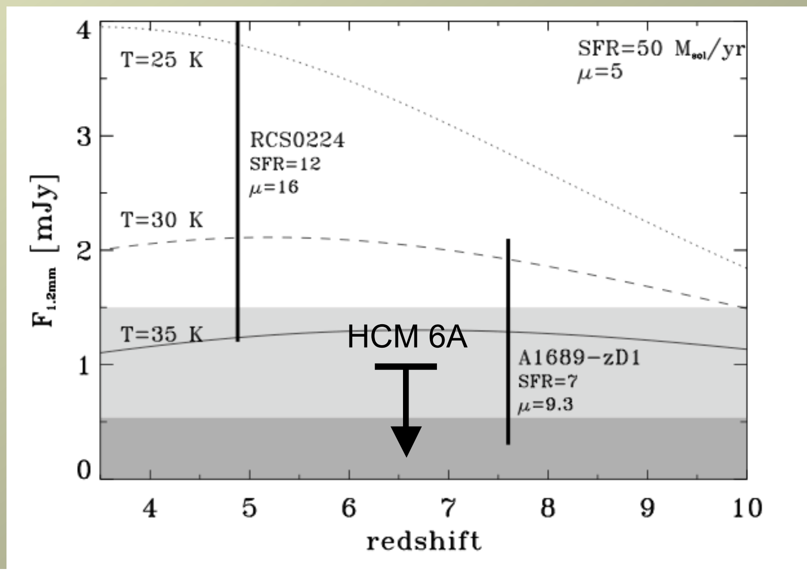
- Negative k-correction: detection at mm wavelength possible (IRAM, LABOCA)

- 0.5 mJy RMS reachable in 6 hours ON/OFF









The multi-wavelength Lensing Survey

Team: Egami, Kneib, Altieri, Blain, Boone, Combes, Dessauges, Ivison, Lutz, Omont, Pelló, Richard, Rieke, Schaerer, Smail, Smith, van der Werf, Werner, …

- **Systematic near-IR, IR, mm/radio observations of ~50 strong lensing clusters with deep visible observations, good mass models, 24 micron imaging… (+observable with ALMA)**

Approved:

✓ New **HST WFC3** imaging

✓ **Herschel Lensing Survey** (OT Key Programme, ~300h): deep PACS/SPIRE imaging

✓ **IRAC Lensing Survey** (~500 h, warm mission): deep 3.6, 4.5 micron imaging

TBD:

- SCUBA2 + LABOCA: (sub)-mm observations
- eMerlin
- Other follow-up…

The multi-wavelength Lensing Survey

Main objectives:

- ✓ Identify and charactise z>6 galaxies
- ✓ Resolve a large fraction of the far-infrared/submillimeter background in the PACS/SPIRE bands
- ✓ Map out full SED of high-z galaxies from mid-infrared to submillimeter (24 micron selected)
- ✓ Probe high-z galaxy population not sampled by 24 micron observations
- ✓ Search for z>6 supernovae
- ✓ …

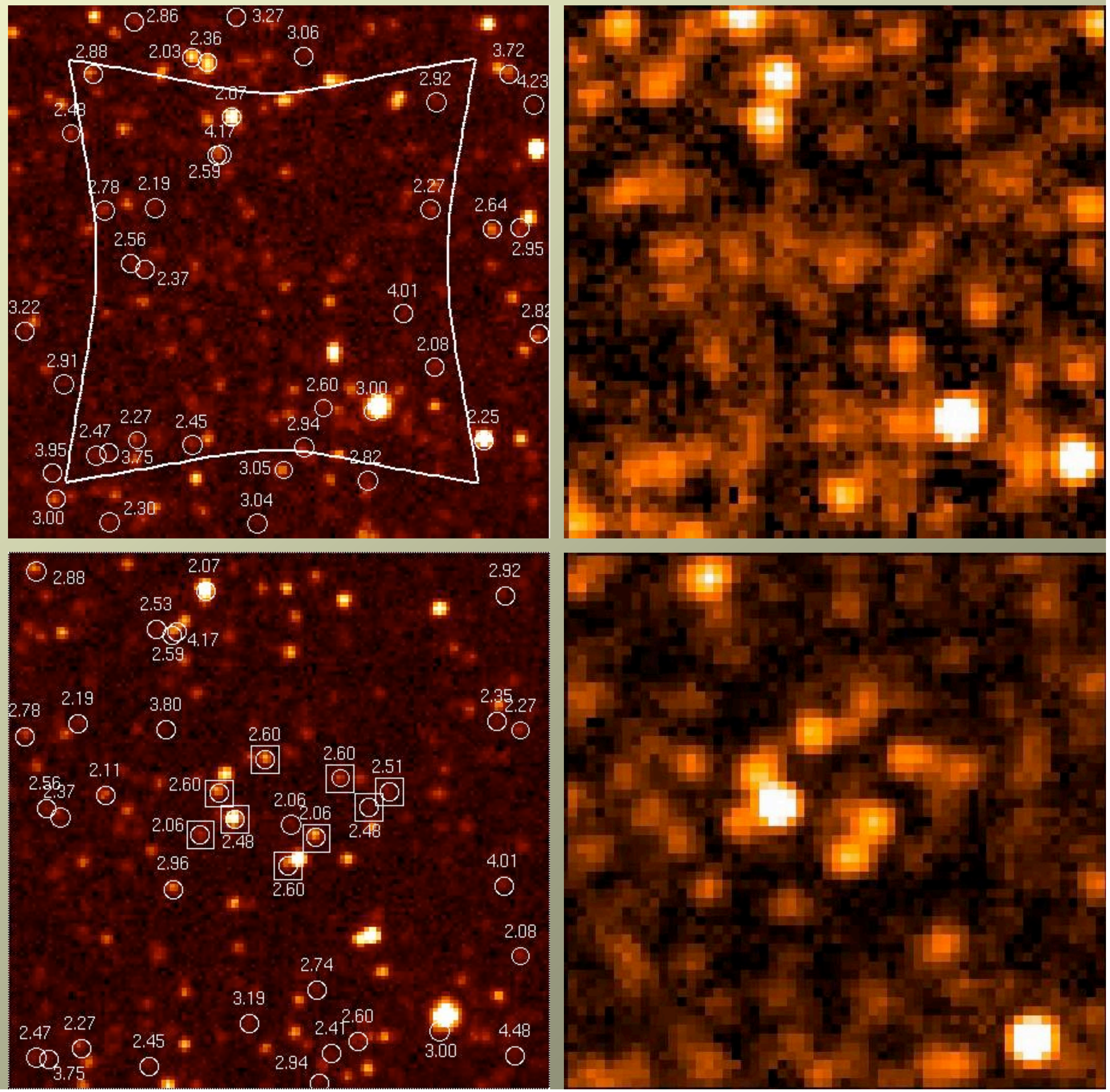
Also: provide deep legacy fields for ALMA, ground-based near-IR MOS follow-ups, JWST

The multi-wavelength Lensing Survey

Simulated PACS (100 mu), SPIRE (250 mu) images

7’ x 7’ field

Gravitational lensing --> efficient detection of z>2 sources due to reduced confusion!

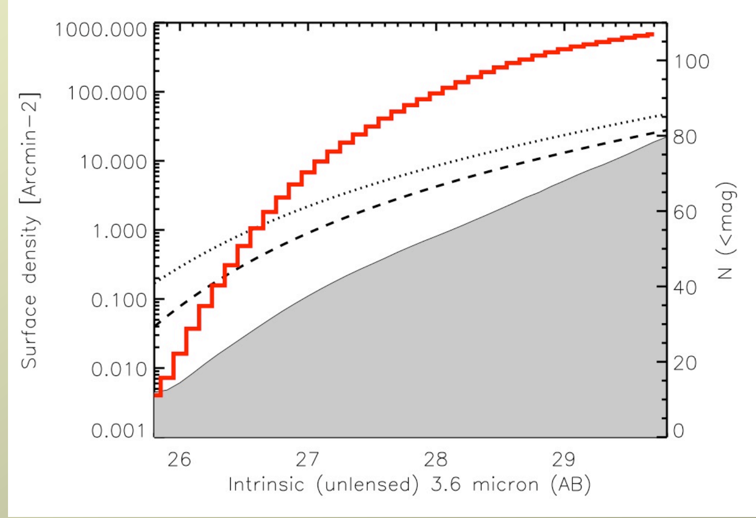


The multi-wavelength Lensing Survey

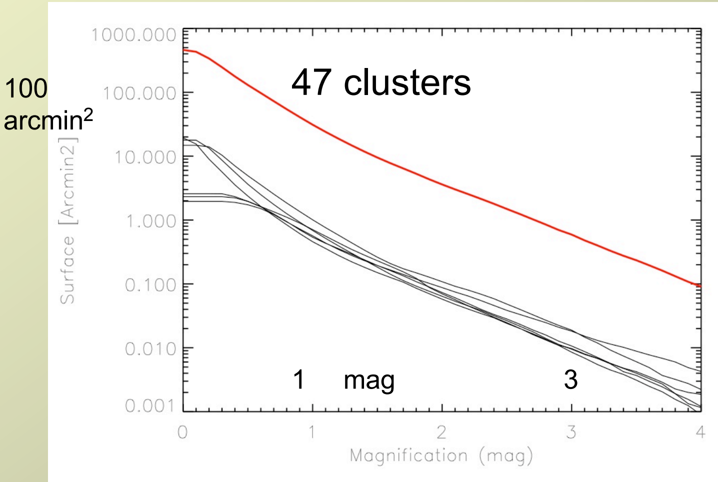
IRAC Lensing Survey: Achieving JWST Depth with Spitzer

[e.g. 10 nJy (3σ) reached at 3.6-4.5 μm for objects with μ~3 mag]

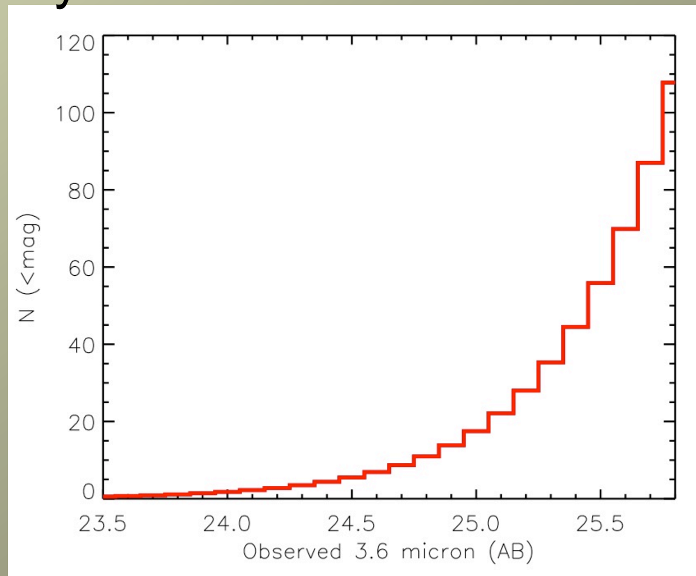
==> **expect detection of >~ 100 galaxies at z~7.5!**



Sensitivity at z~7.5 based on current LFs



Survey area z~6 above given magnification



Cumulative counts vs observed mag at z~7.5

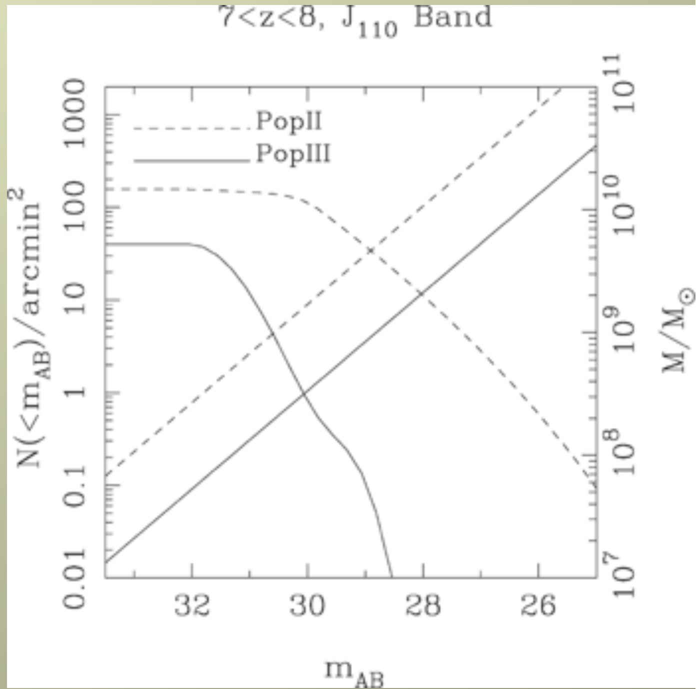
Tracing cosmic reionisation with OPTIMOS-EVE @ E-ELT

Lesson from models + blank fields + lensing:
Expected number density of z>~7 galaxies at faint magnitudes (28..30 AB): high!!

•3-100 $arcmin^{-2}$ $(\Delta z=1)^{-1}$ for z~7..8 and m_AB=28..30

• 40 times higher for FOV 5arcmin diameter and ($\Delta z=2$)

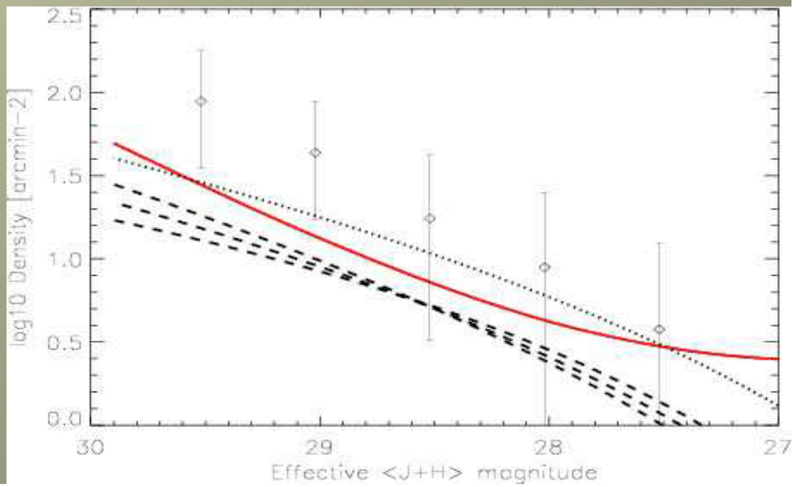
Based on models + observations, cf:
Chodhoury & Ferrara (2007), Stiavelli et al. (2004), Richard et al. (2008), Bouwens et al. (2008)



Will be imaged with JWST

==> **Calls for *very high* multiplex spectrograph at E-ELT including near-IR**

Extreme Visual Explorer

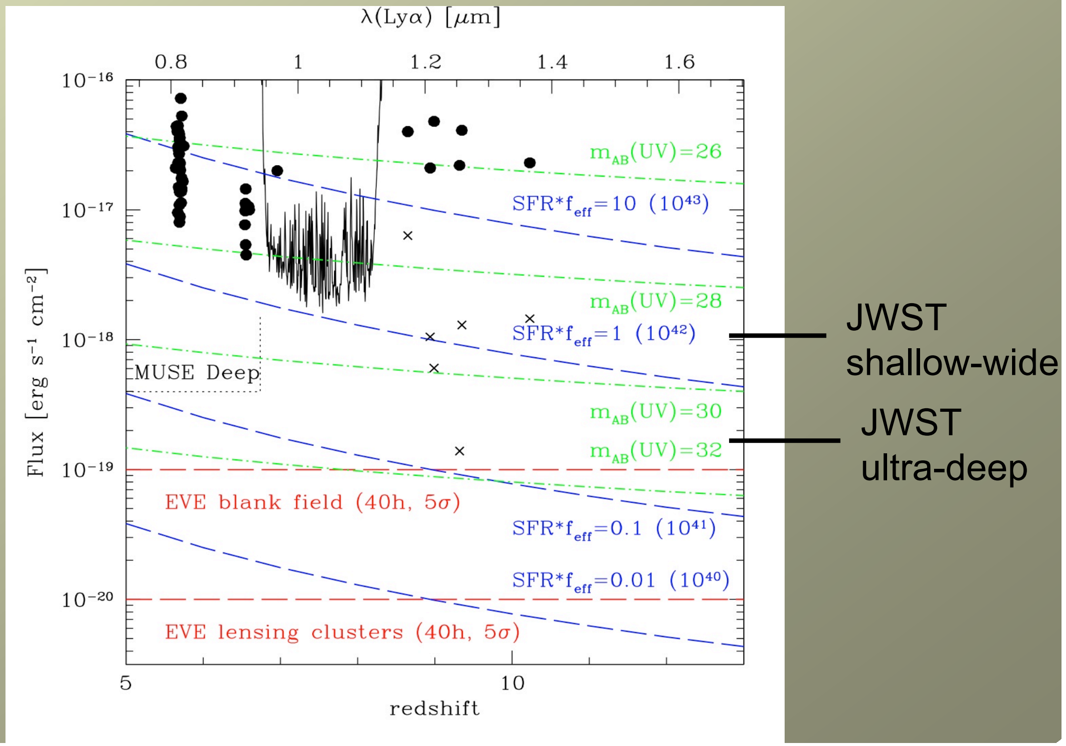


Tracing cosmic reionisation with OPTIMOS-EVE @ E-ELT

OPTIMOS-EVE:

- 0.4 - 1.6 micron
- R~5000-20'000
- FOV: 5 arcmin diameter
- High multiplex: 300-500!

→measure Lya fluxes + profiles of SF galaxies from z~6 to 12
→Trace reionisation history
→Spectroscopic follow-up of faintest galaxies



Summary

- Gravitational lensing offers unique views on faint, z>6 galaxies
- **First interesting limits on dust emission from « normal » z>6 galaxies**
- Several new strongly lensed z~5-8 candidates feasible with current mm facilities (IRAM+)

- New Lensing Survey: ~50 clusters with HST, Spitzer, Herschel, … --> ideal fields for ALMA!
- E-ELT: need for *very* high multiplex spectrograph to follow-up numerous population of faintest galaxies (e.g. OPTIMOS-EVE)

Observatoire Midi-Pyrénées