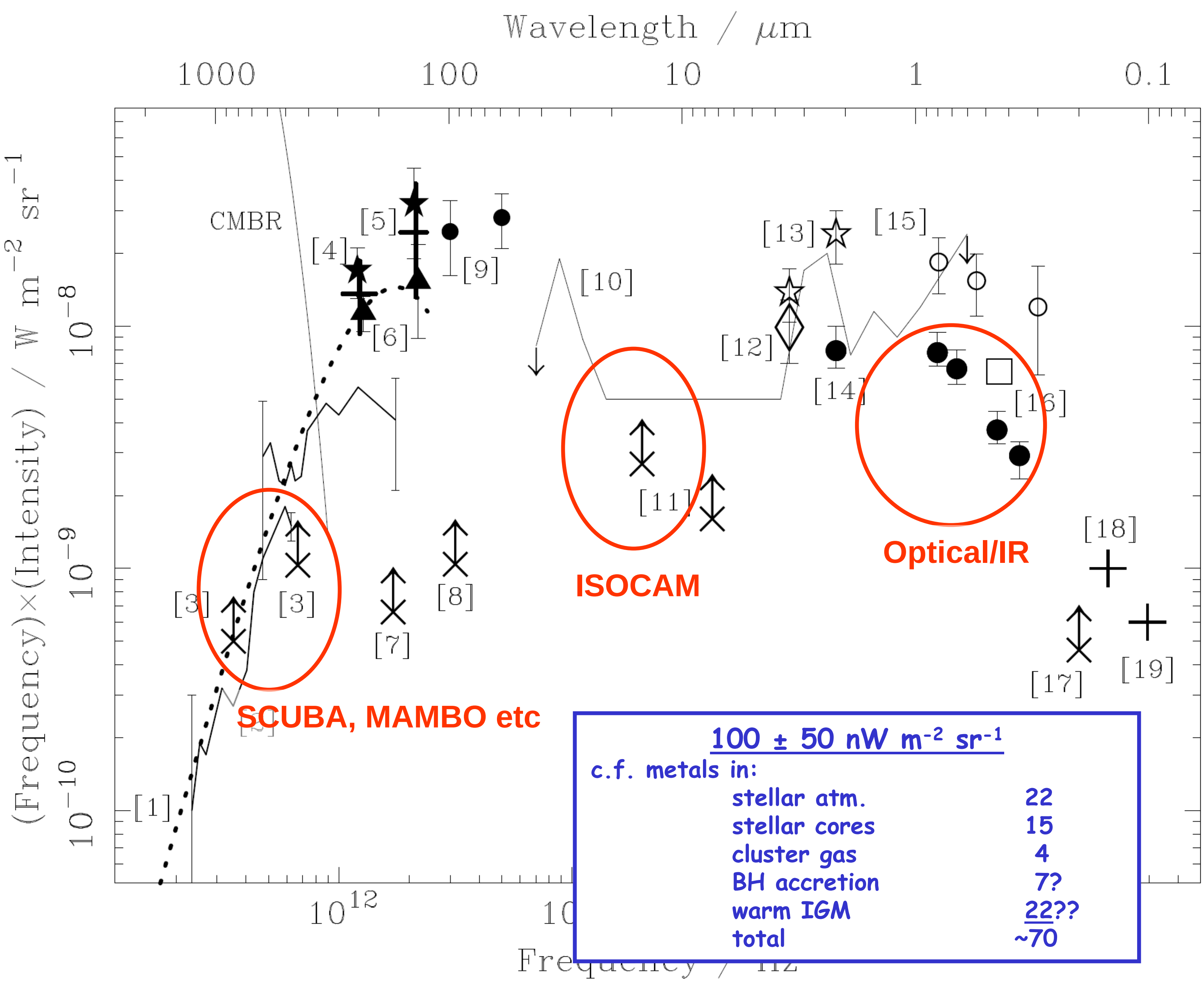
The high redshift Universe and the formation and evolution of galaxies

Simon Lilly

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich


Wavelength / μm
1000
100
10
1
0.1
(Frequency)×(Intensity) / W m⁻² sr⁻¹
10⁻⁸
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Frequency / Hz
CMBR
[1]
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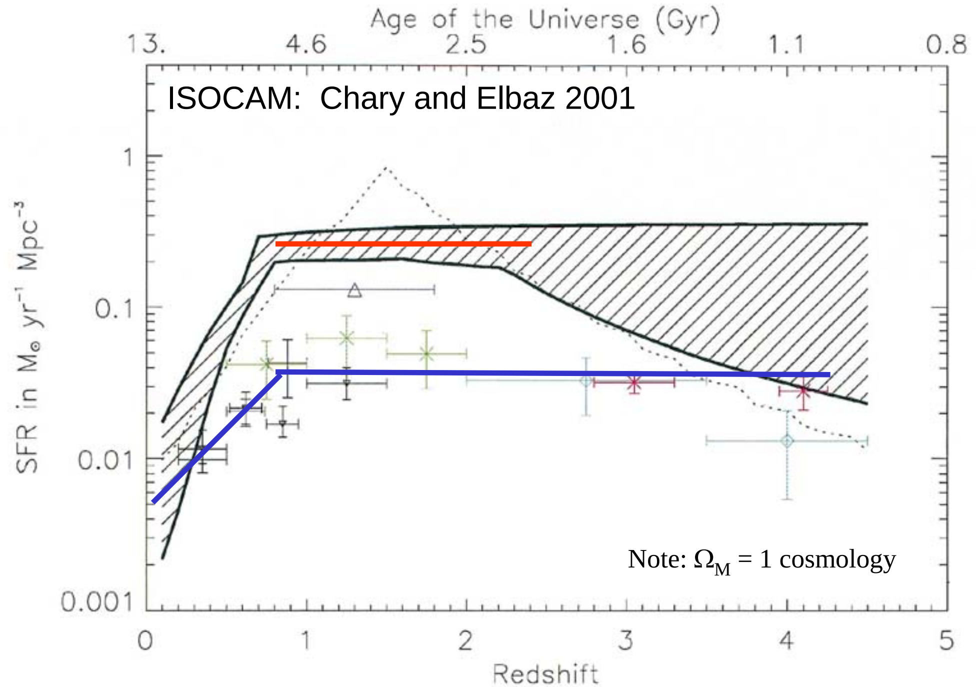
SCUBA, MAMBO etc
ISOCAM
Optical/IR
100 ± 50 nW m⁻² sr⁻¹
c.f. metals in:
stellar atm. 22
stellar cores 15
cluster gas 4
BH accretion 7?
warm IGM 22??
total ~70

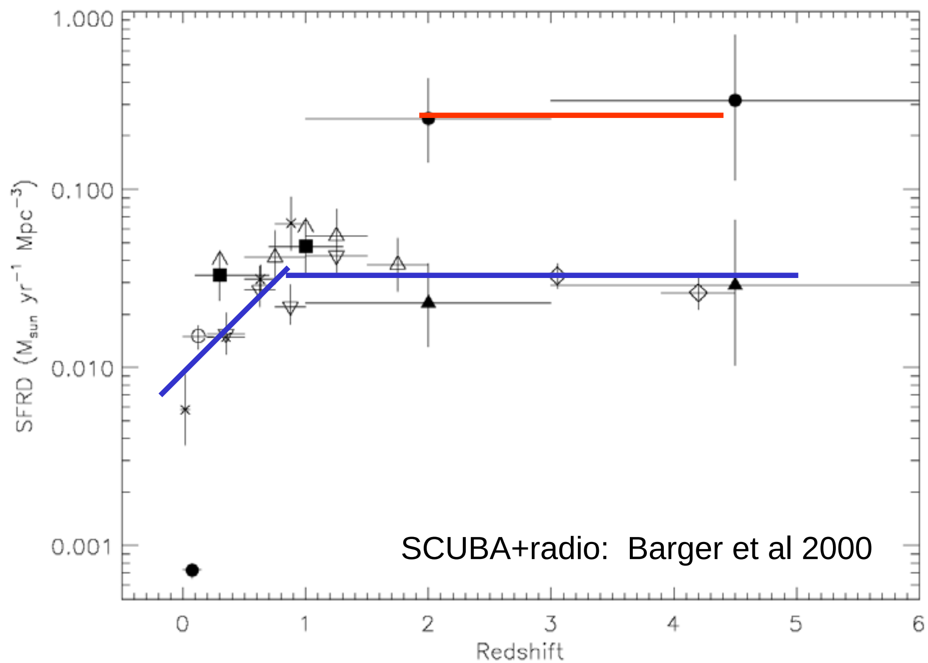
80-90% of star-formation at 1 > z > 4 is obscured by dust

Mildly up to heavily extinguished as luminosity increases (as locally)

Very luminous ULIRGs 2 x 10^{12} $L_\odot$ (400 $M_\odot yr^{-1}$) produce 10-15% of Universe luminosity at z ~ 2, c.f. 0.3% locally

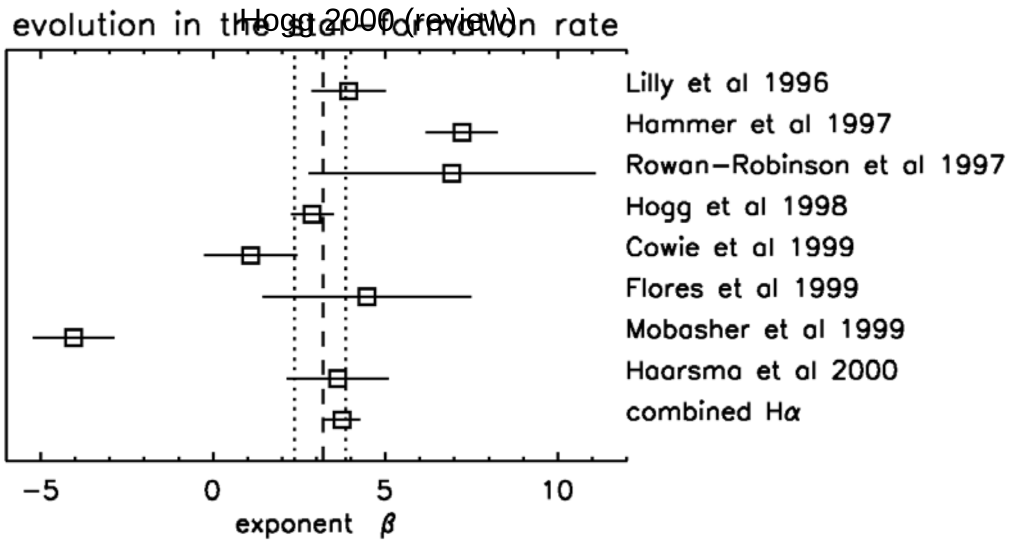
- c.f. known LBG about 20%





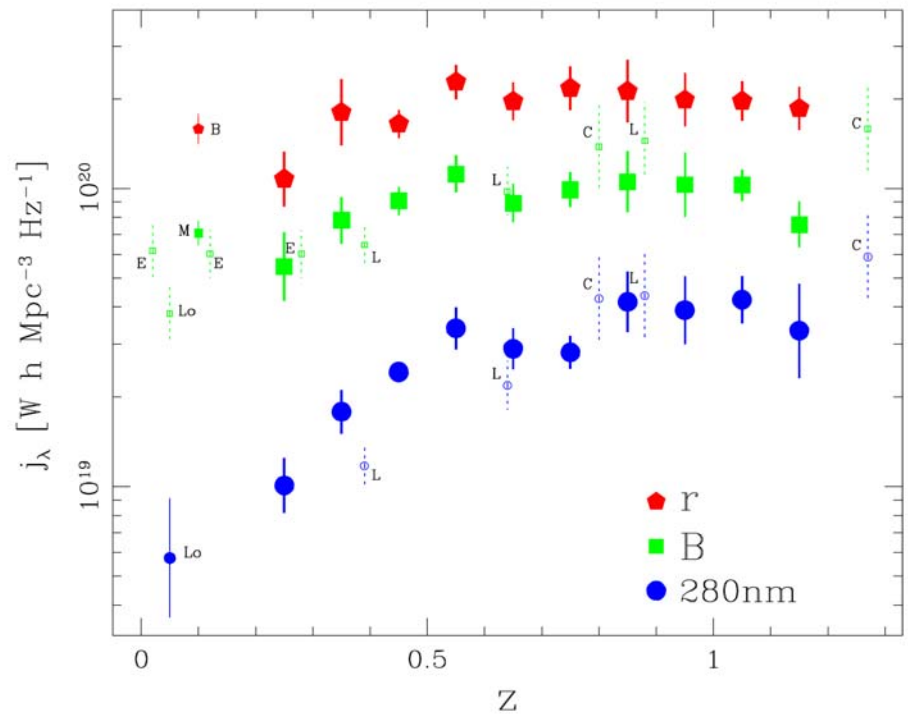
Cosmic star-formation rate

Hogg 2000 (review)



rest-frame UV
[OII] 3727
far-IR
[OII] 3727
rest-frame UV
far-IR (ISO)
radio continuum
radio continuum
Hα

COMBO-17 Wolf et al 2003

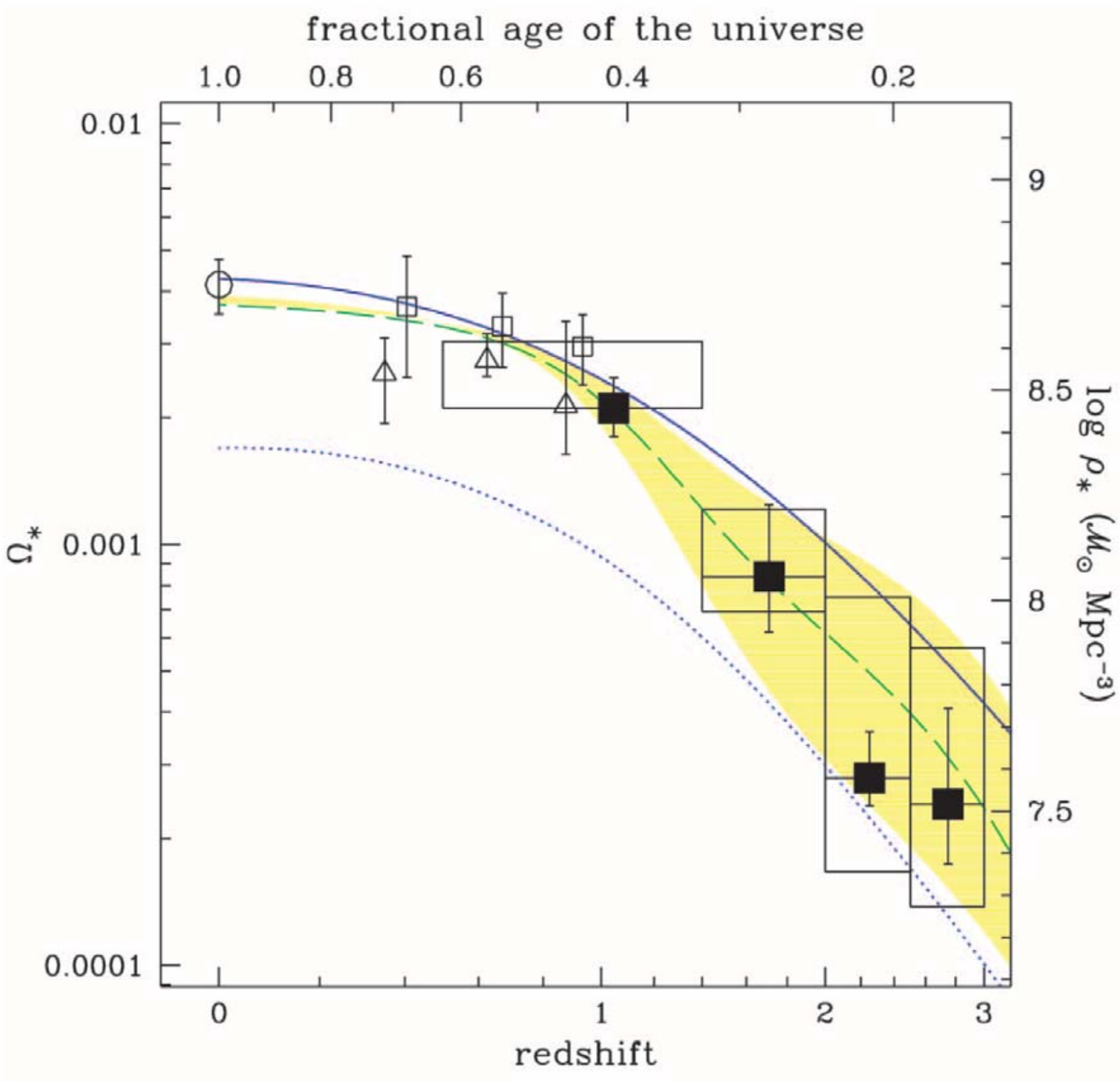


Increase in global star-formation rate to z ~ 1

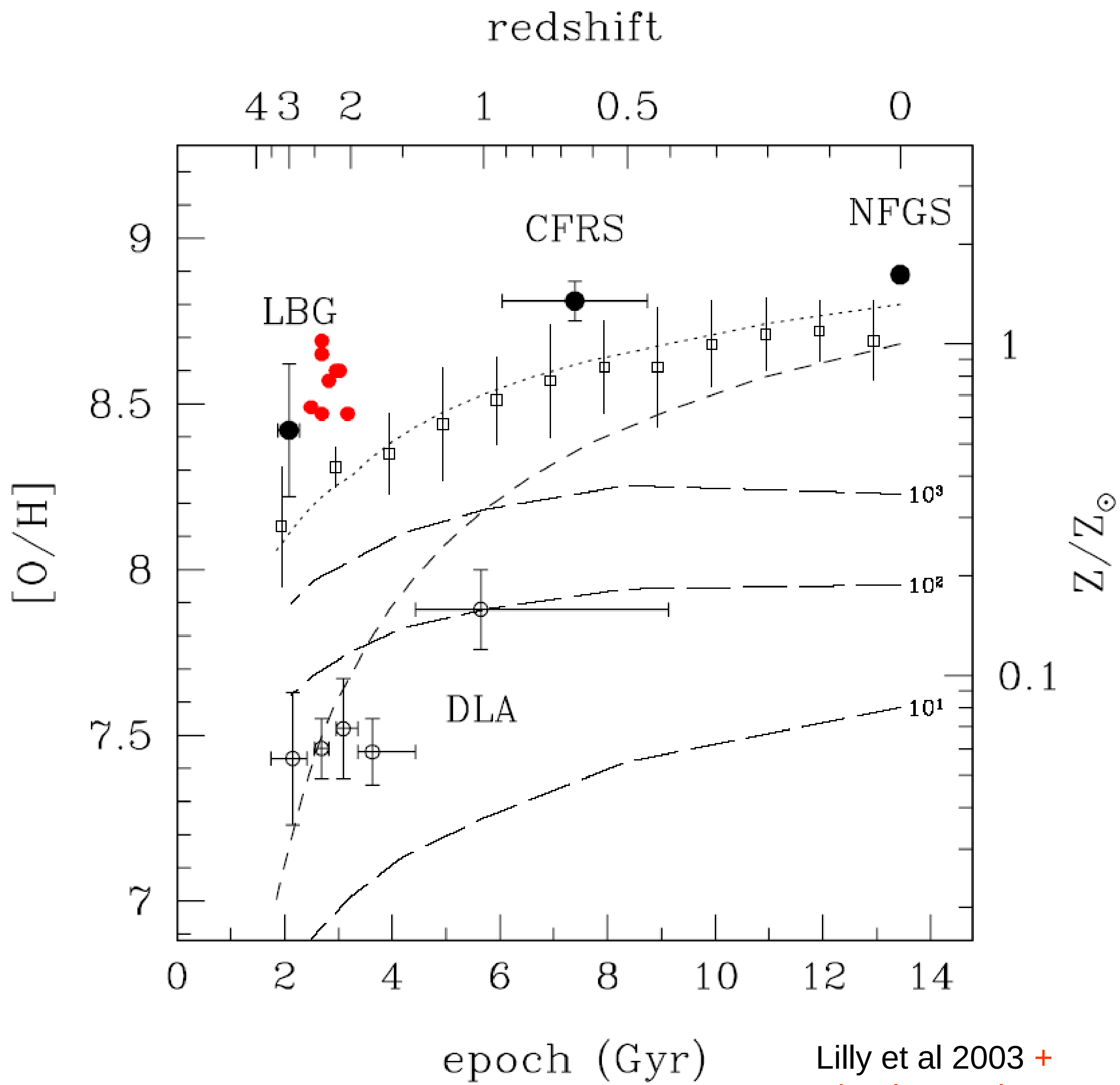
Increase in luminosity density in (short-lived) star-formation indicators (i.e. uv continuum, far-IR, Hα or [OII], radio continuum

$\beta \sim 3.0 \pm 0.8$ "old" $\Omega = 1$
$\beta \sim 2.2 \pm 0.8$ $\Lambda = 0.3$

Star-formation rates to z ~ 1

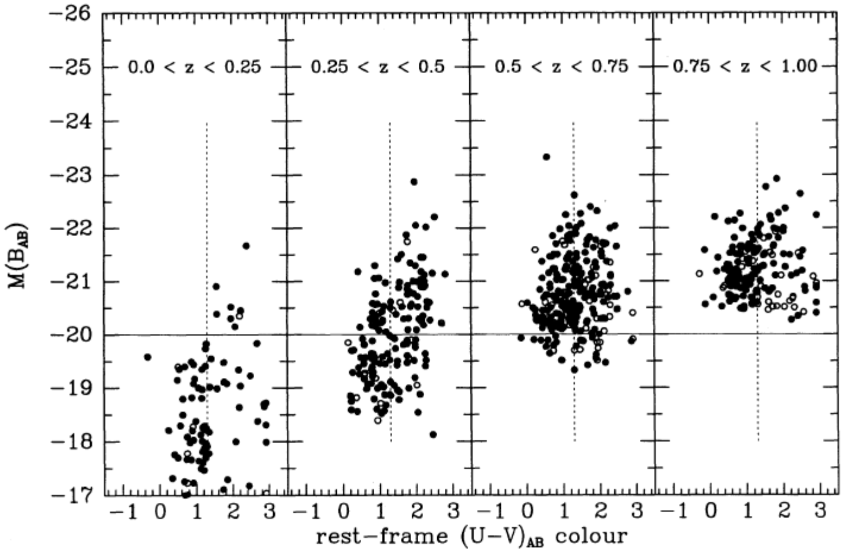


Expect (and observe) only about 10% of present-day stellar mass to be formed at z > 3



Lilly et al 2003 + Shapley et al 2004

CFRS: Lilly et al 1995

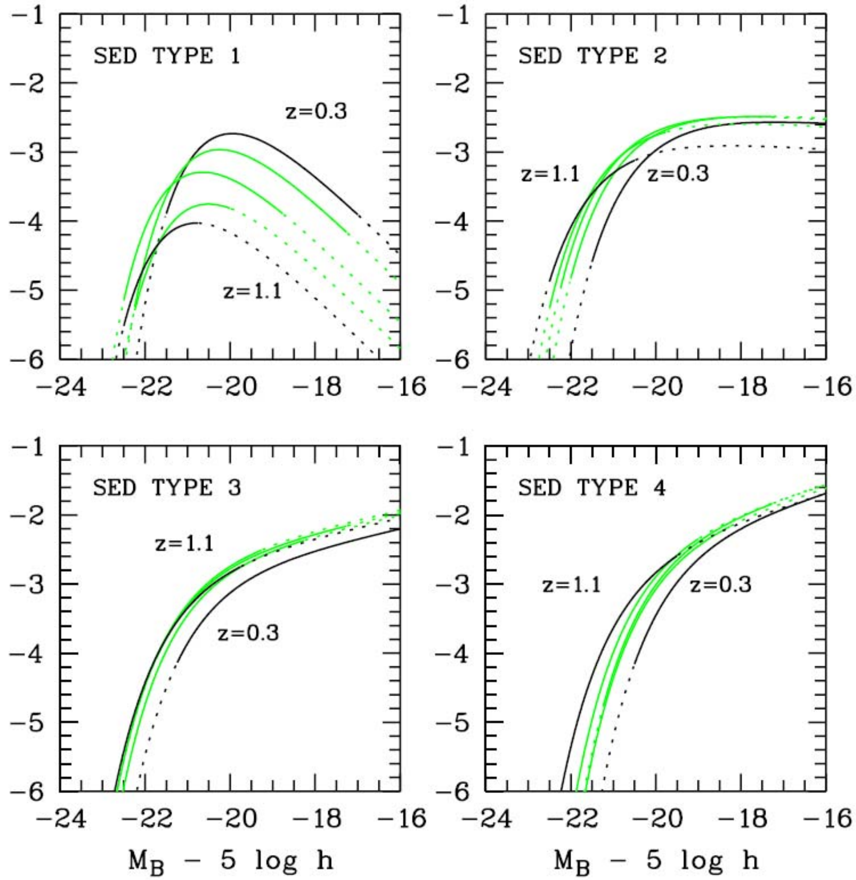


Down-sizing

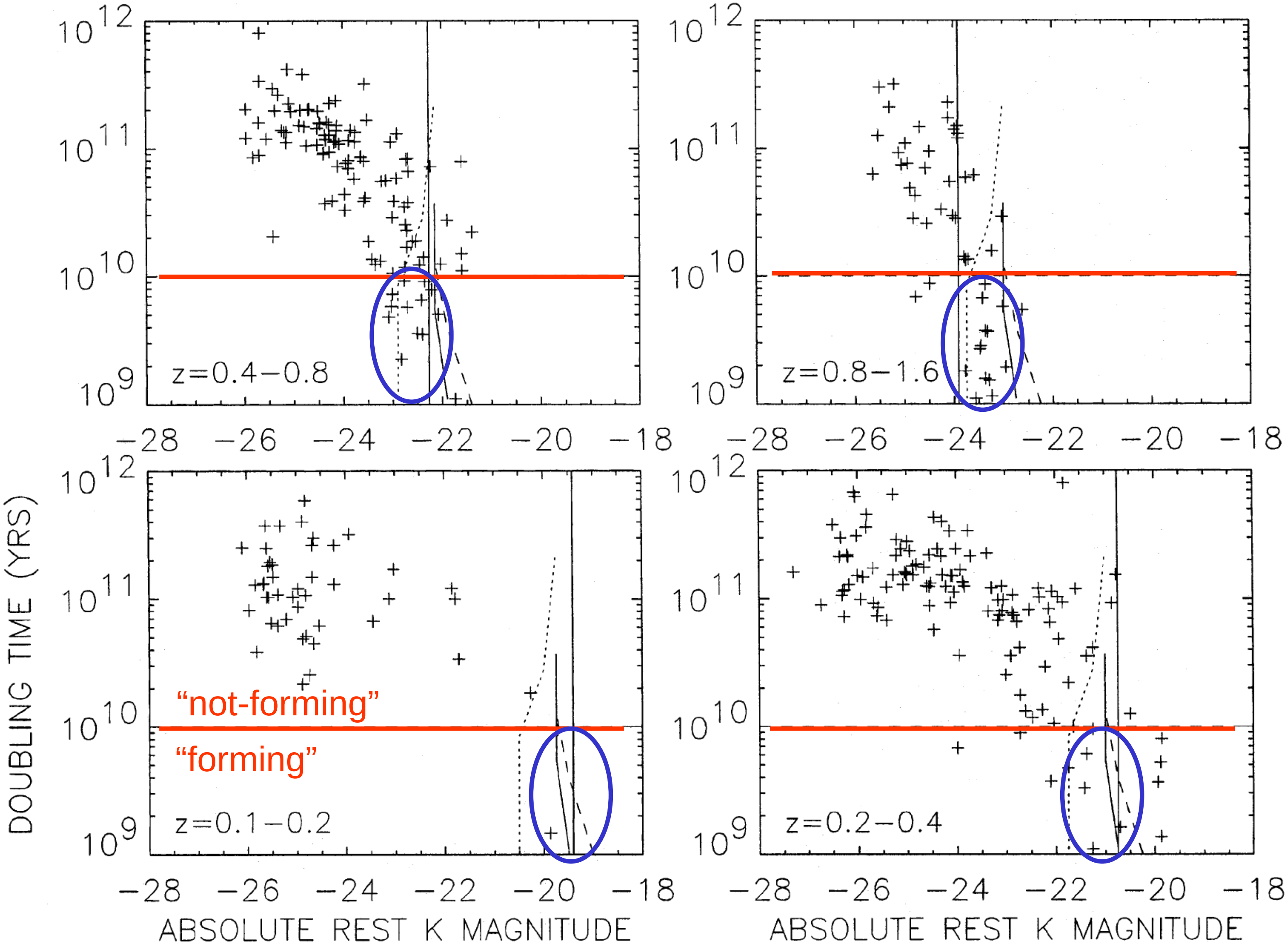
Signatures of youth seen in more luminous and presumably more massive objects at earlier times:

$$\frac{\dot{M}}{M}$$ (uv-optical) colours, emission line W_0, irregular morphologies

COMBO-17 Wolf et al 2004



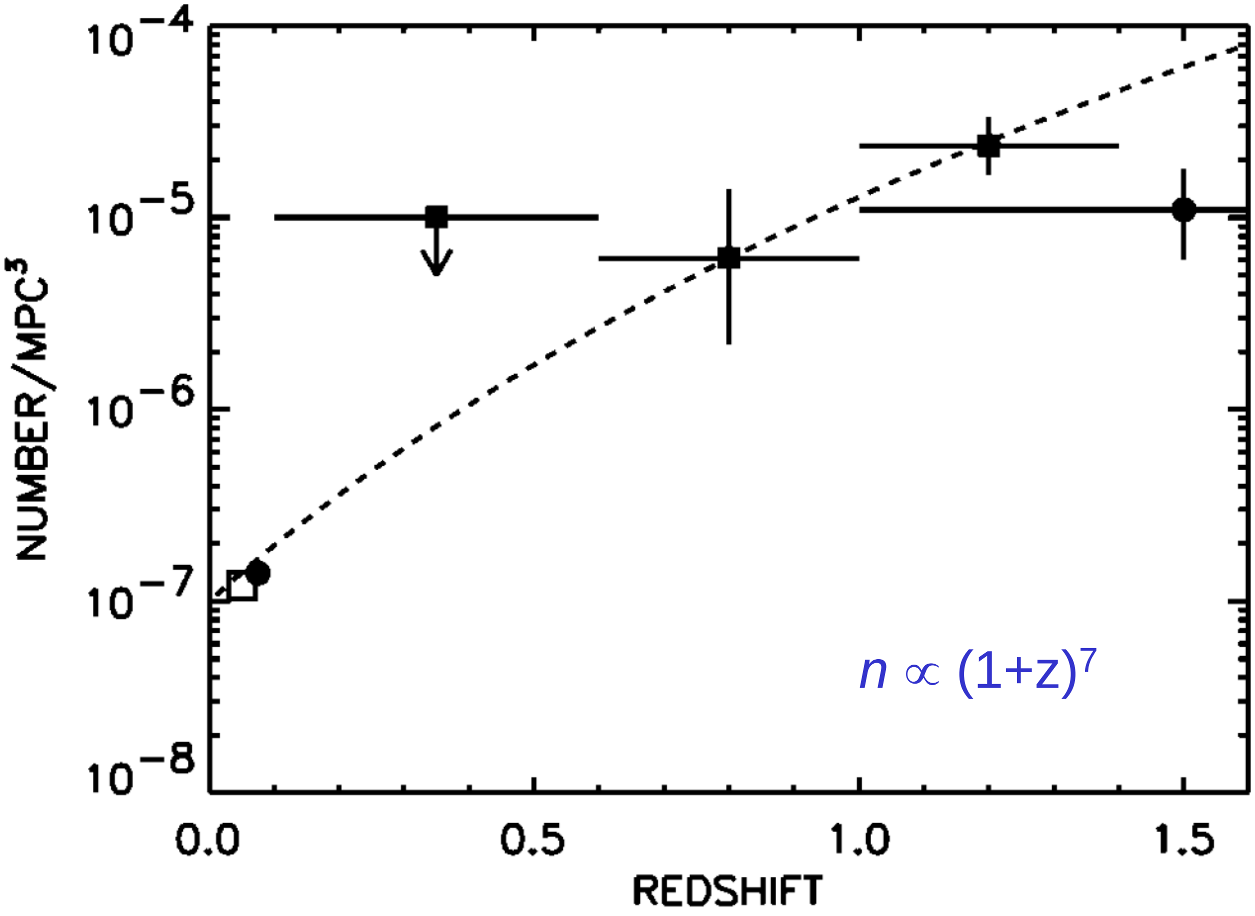
Cowie et al 1996



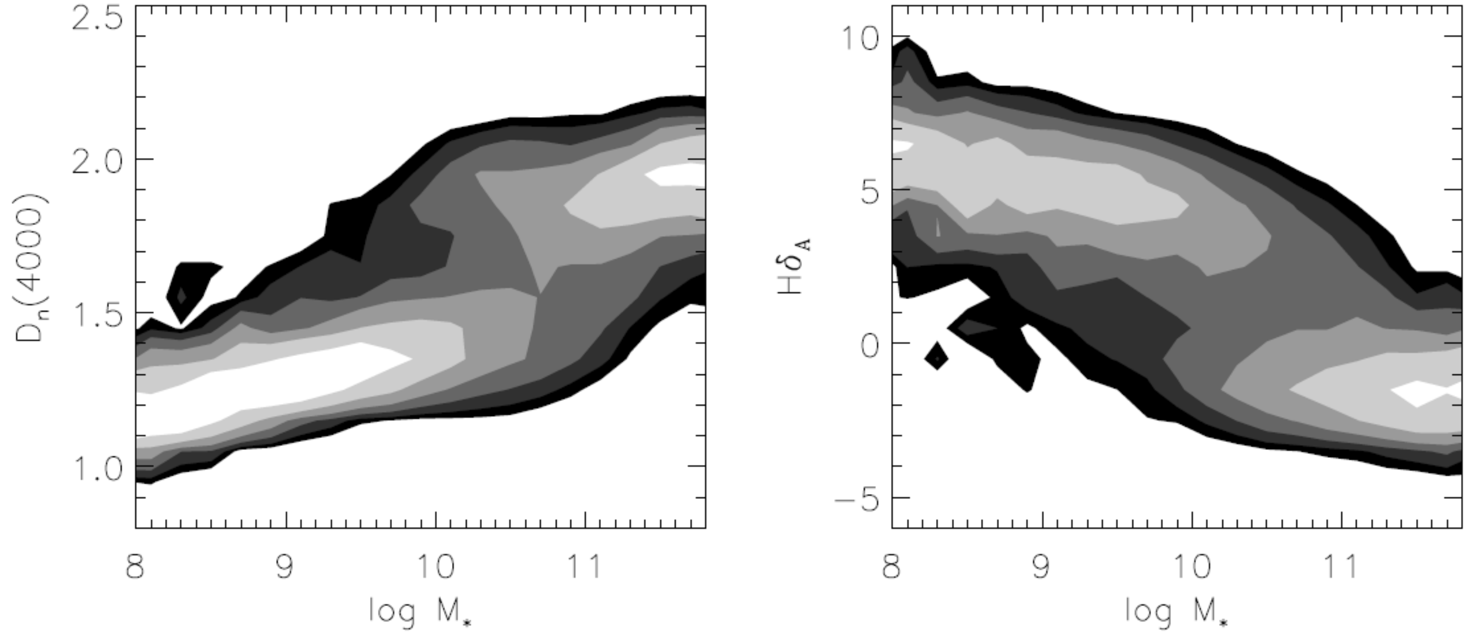
Down-sizing

Strong number density evolution of most luminous sources: e.g. radio sources with implied $L_{FIR} > 10^{12}\ L_{\odot}$ (Cowie et al):

$n \propto (1+z)^7$

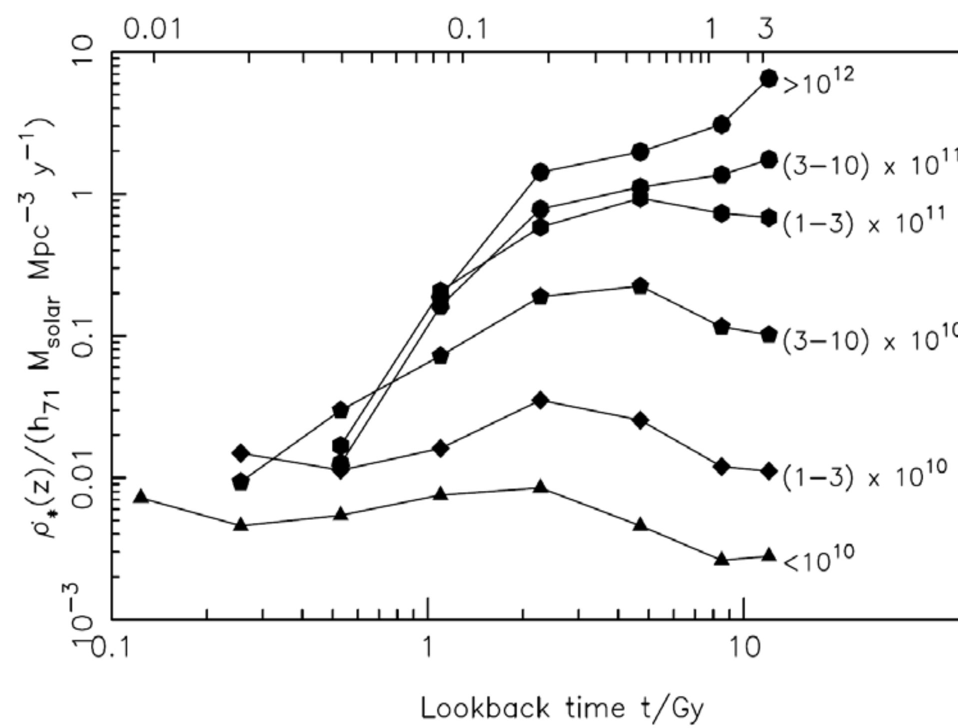


SDSS – Kauffmann et al 2003



Local galaxy properties: massive galaxies have older stellar populations

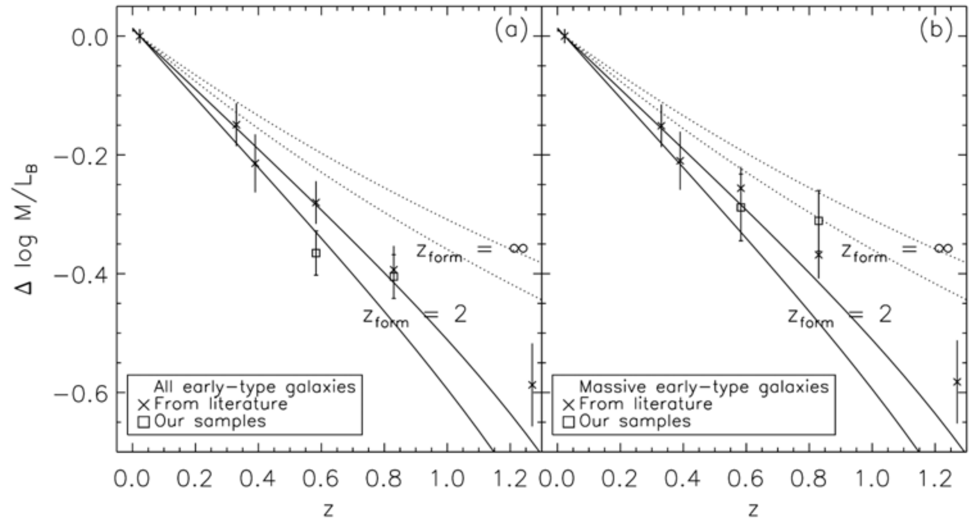
SDSS – Heavens et al 2004



Consistency with local trends

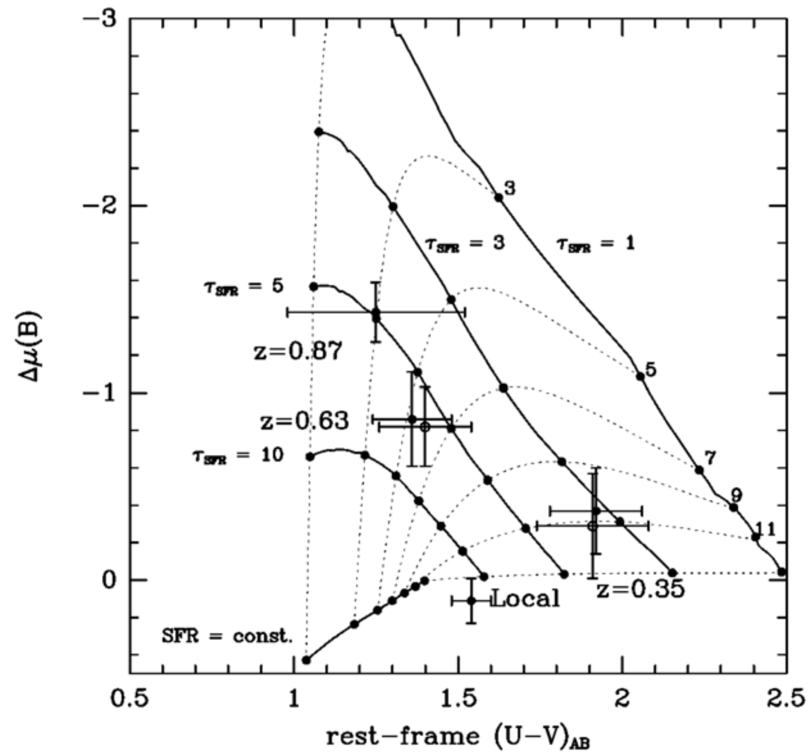
M/L of early type galaxies:

Evolves as expected for $z_F \sim 2$ or greater



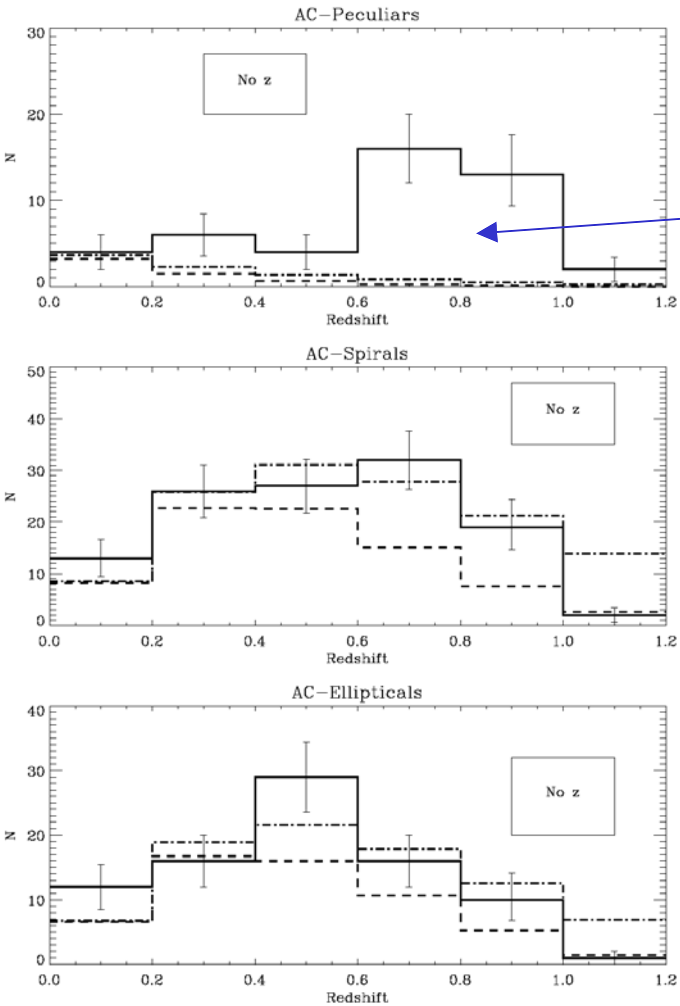
Disk surface brightnesses –

Declining SFR $\tau \sim 5$ Gyr



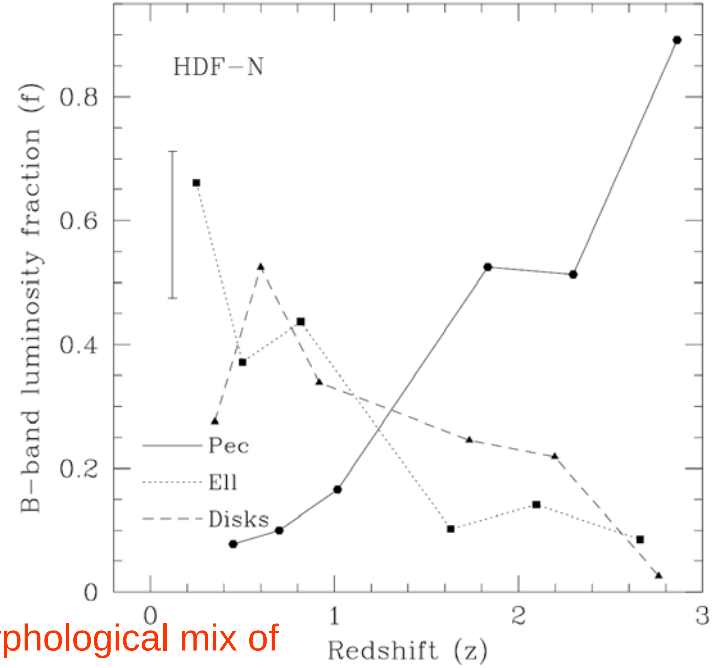
Morphological evolution of galaxy population

Not simply λ effect (but beware of SB effects)

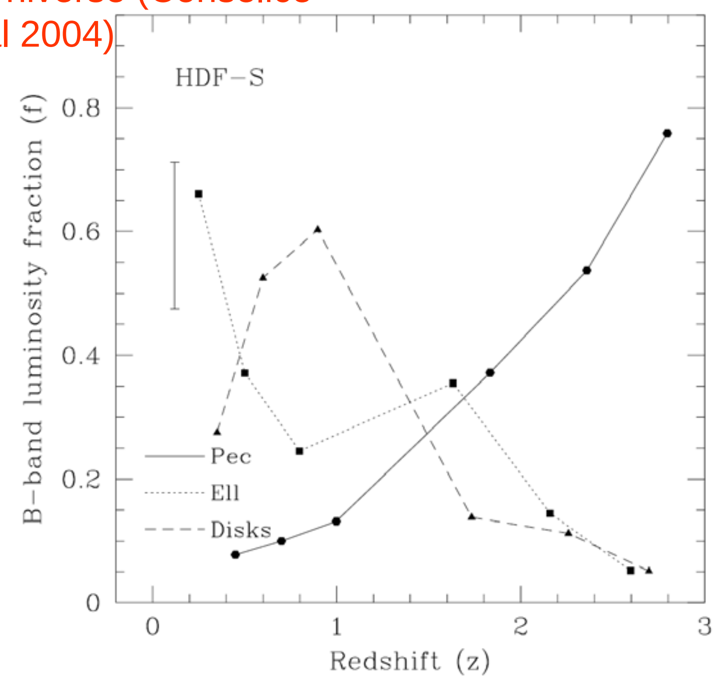


Excess of bright Irr at z ~ 1

Numbers of E and Sp consistent with modest luminositye volution



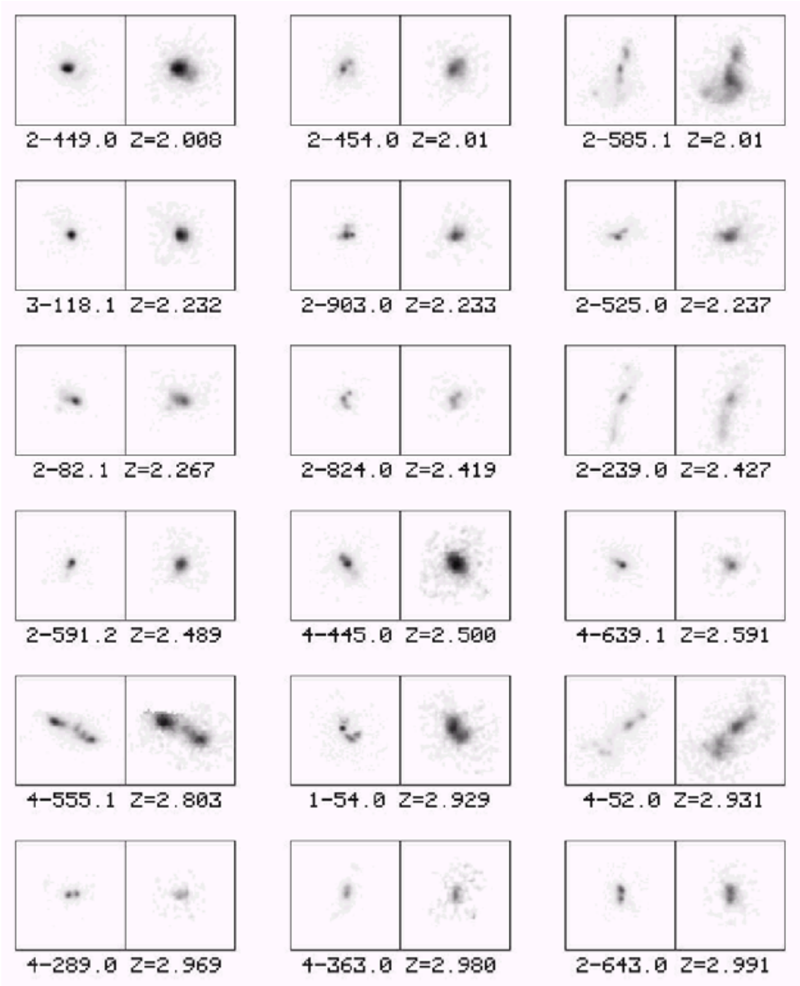
Morphological mix of rest-frame B luminosity in Universe (Conselice et al 2004)



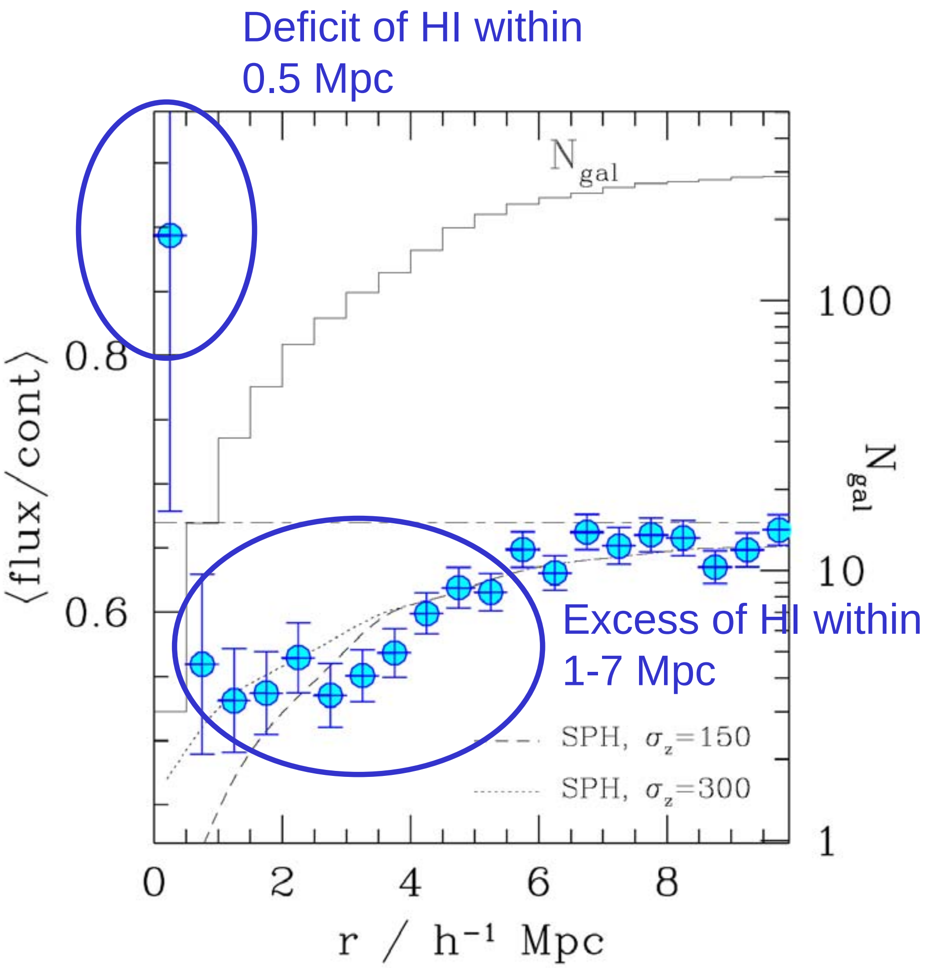
Changes in morphology

z ~ 3 “Forming galaxies” in the optical:

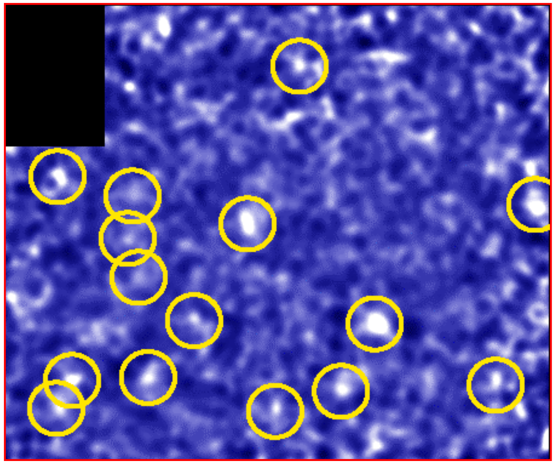
Highly irregular morphologies…

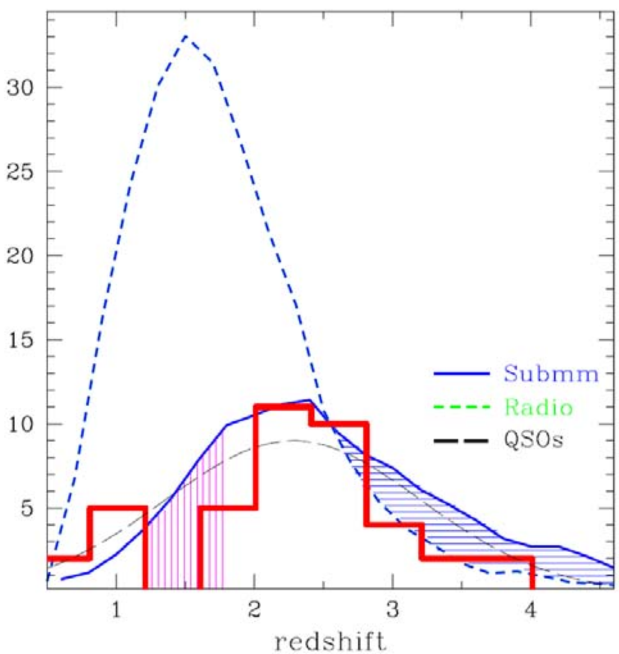


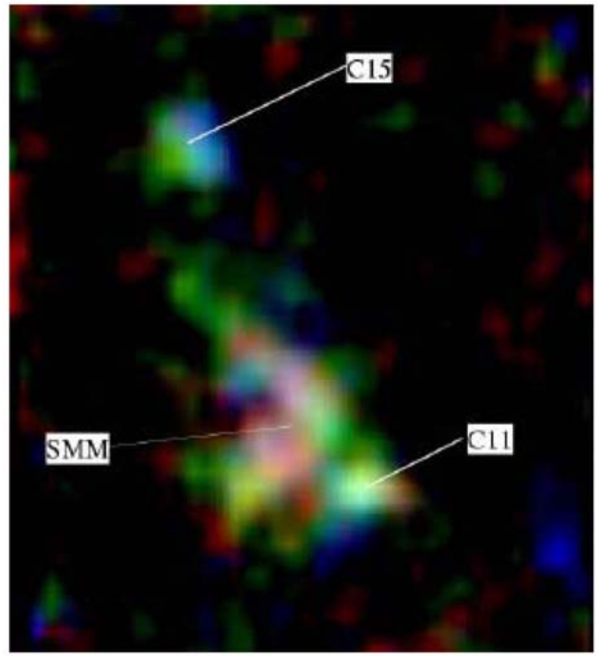
Enriched superwinds …



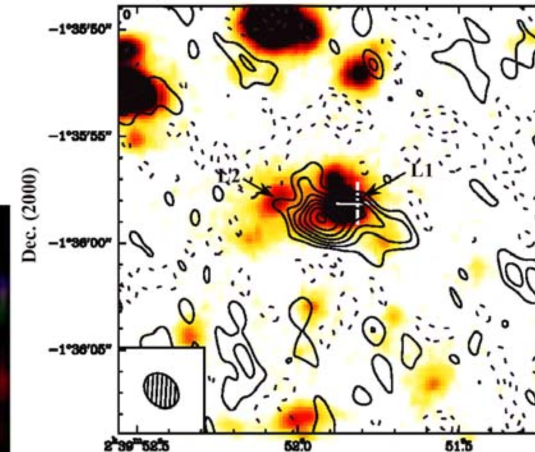
z ~ 3 “Forming galaxies” in the submm:

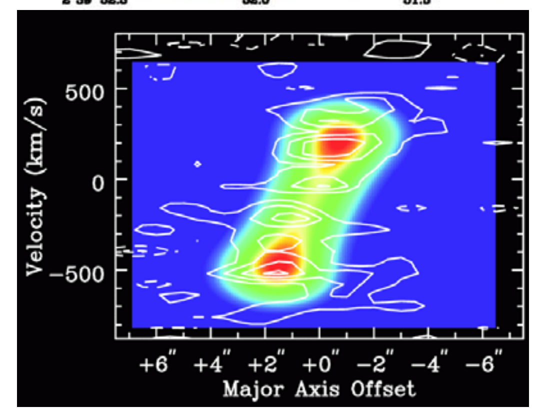






Sauron Data Lya data-cube on z = 3.1 sub-mm source/LAB





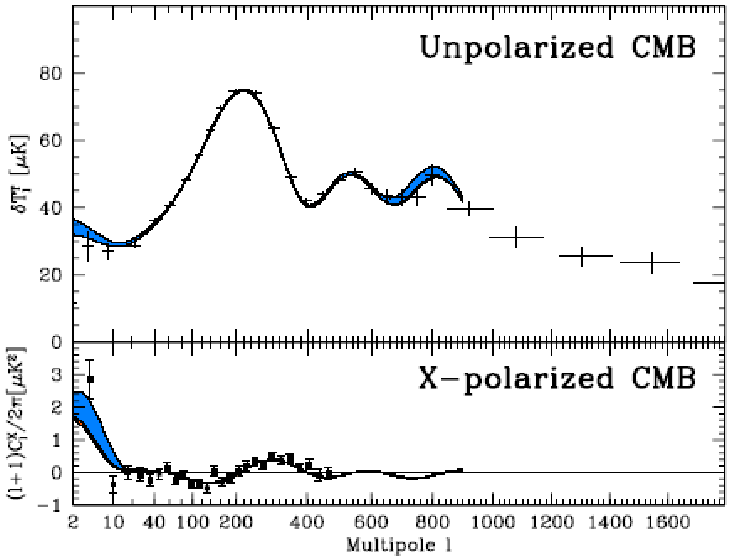
SMM J020399-0136 (Genzel et al 2002)
z=2.80 M > 3 x 10^{11} $M_{\odot}$ within 8 kpc?

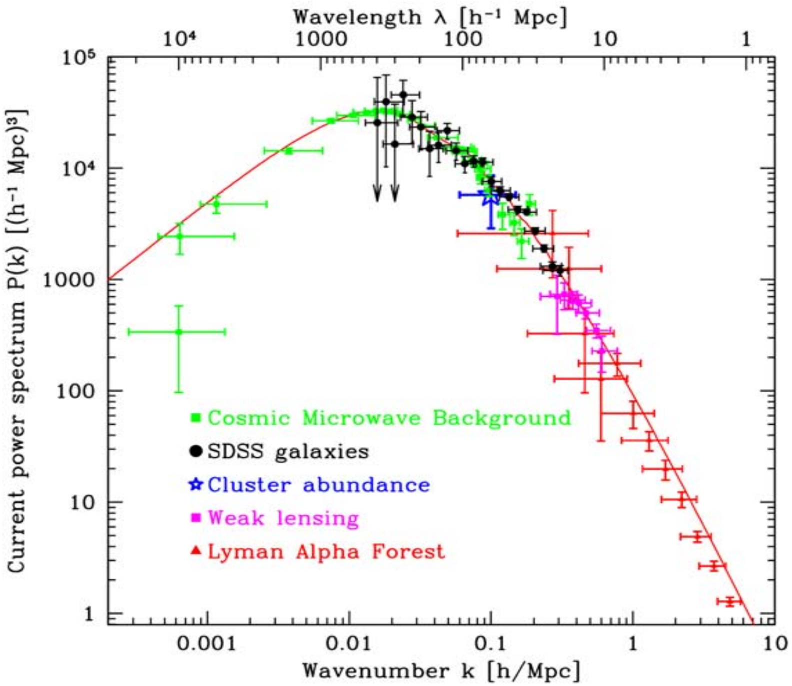
The theoretical paradigm: Λ-CDM

$\Omega_m \sim 0.3$, $\Omega_b \sim 0.04$, $\Omega_L \sim 0.7$, $h \sim 0.7$, plus random phase $n_p = 1$ fluctuation spectrum

Great successes

- CMB fluctuations
- Self-consistent estimates for P(k) over 4.5 dex in scale

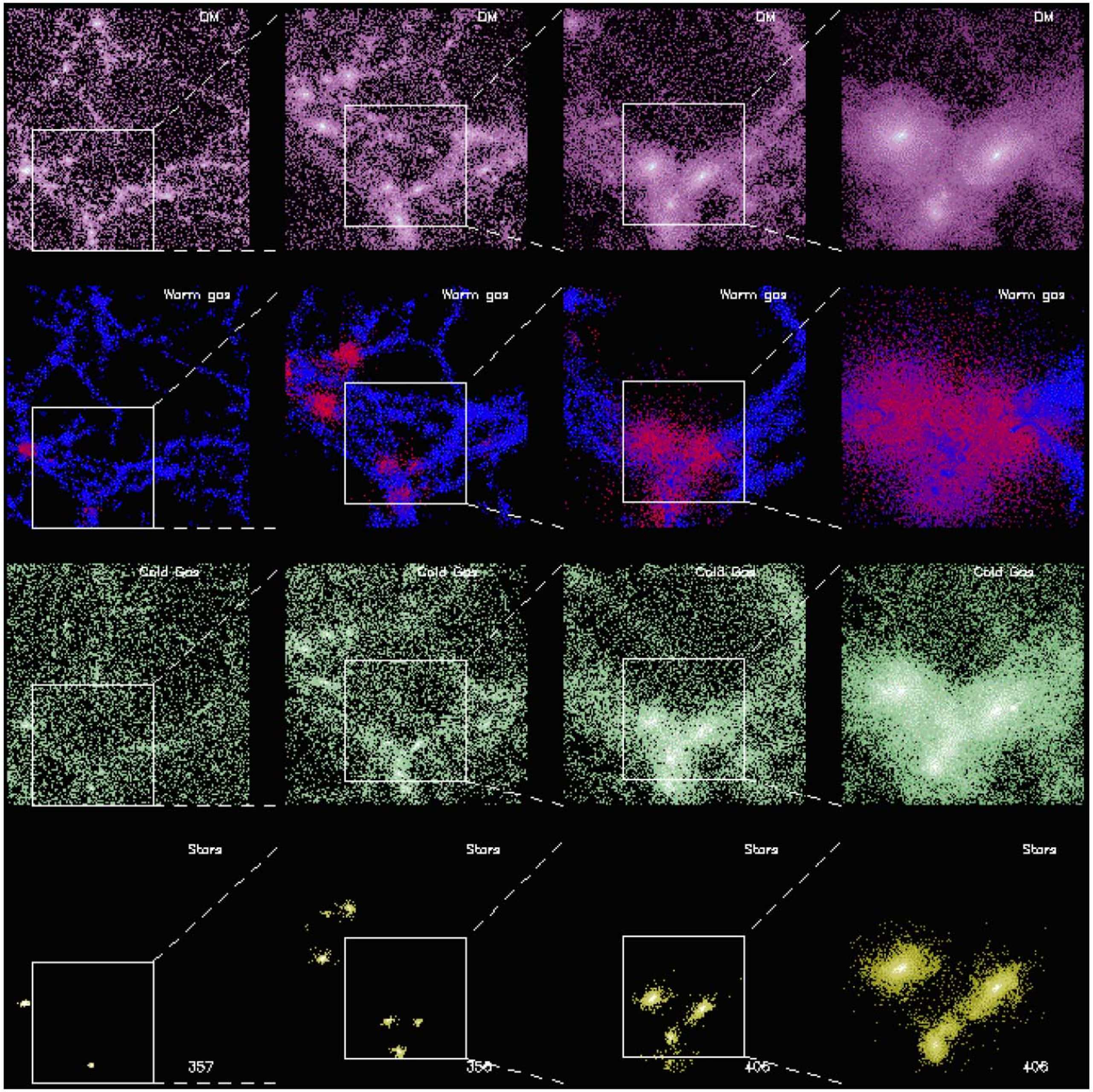




Precision cosmology!

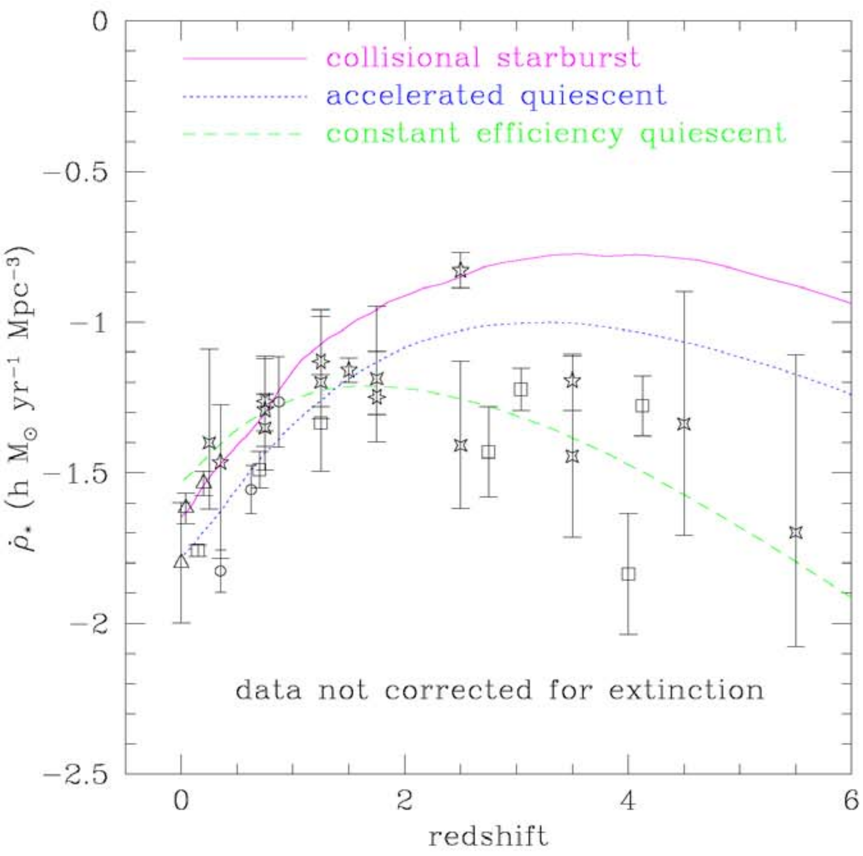
We have a quantitatively precise (in principle) "theoretical paradigm" for structure formation and we know how to translate our observations

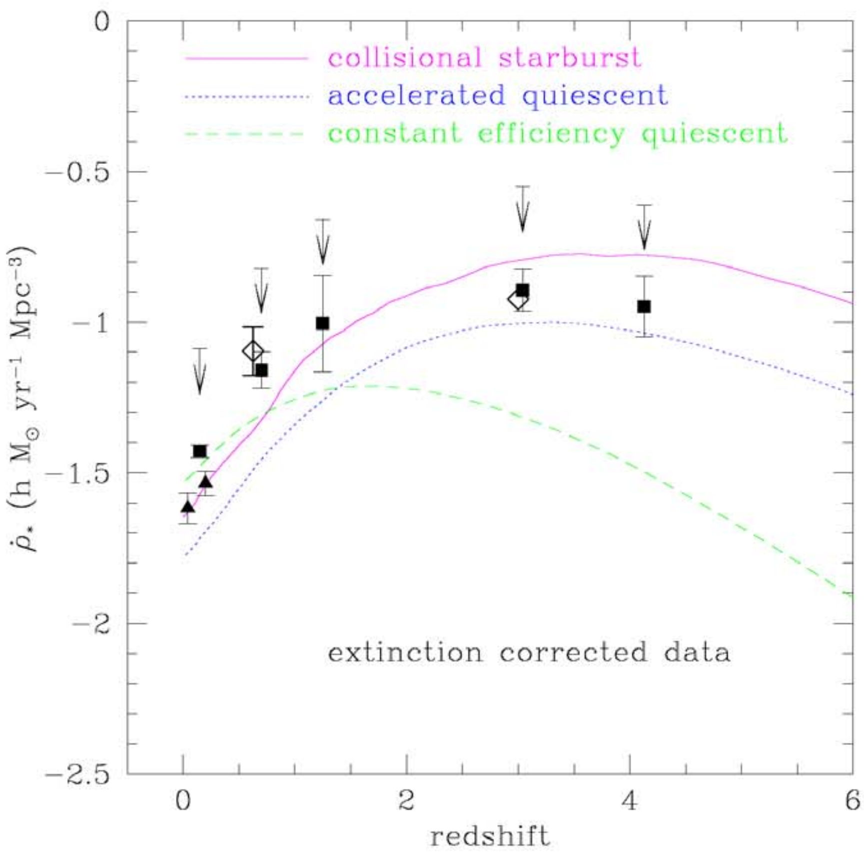
- → Hierarchical collapse of dark matter haloes
- → Cooling baryons leads to star-formation and galaxy formation



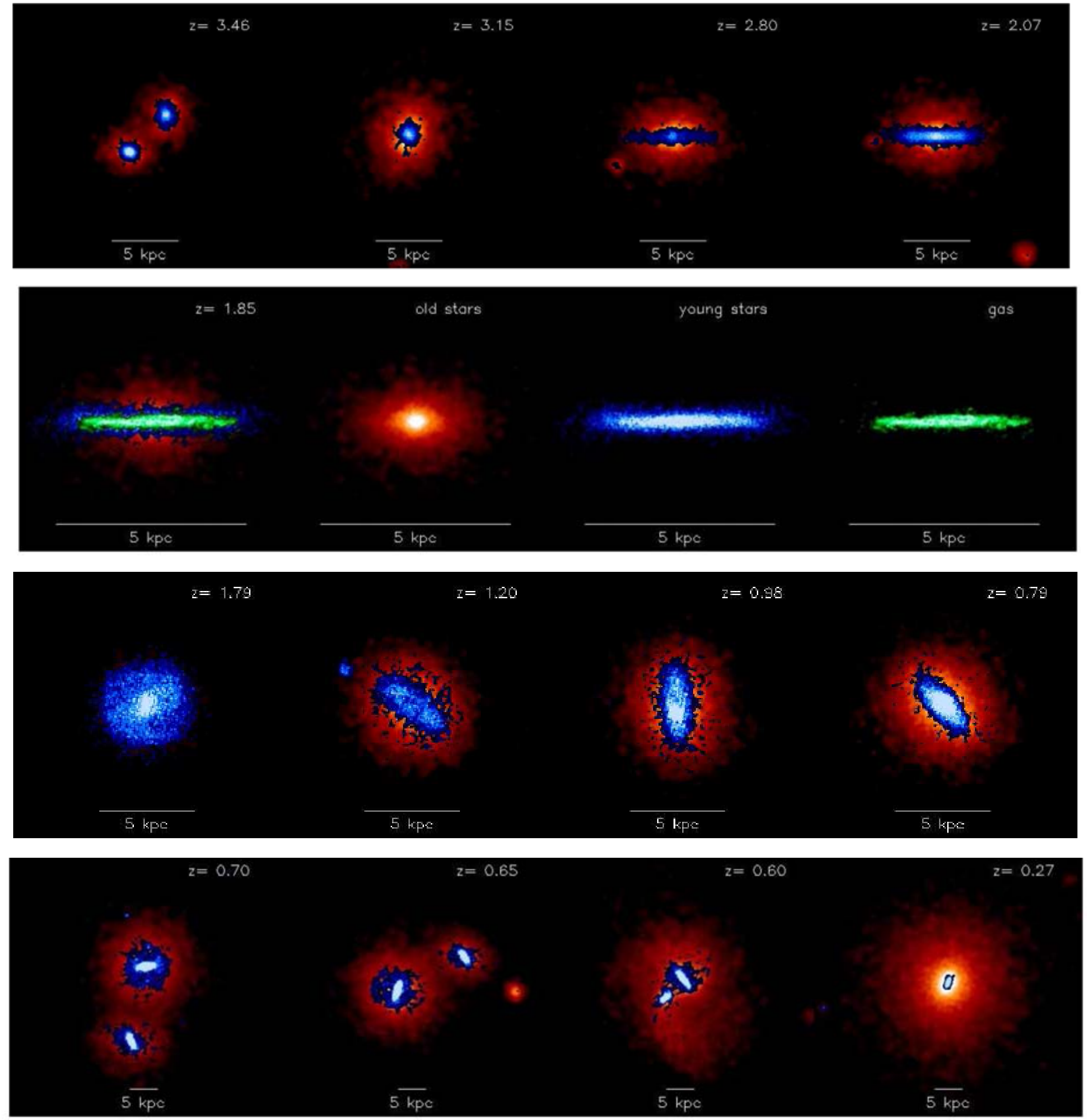
Semelin & Coombes 2003

Semi-analytic models: Merger tree, plus prescriptions for gas and stars during merger, cooling rates, SFR and feedback etc.





Hydrodynamical models:

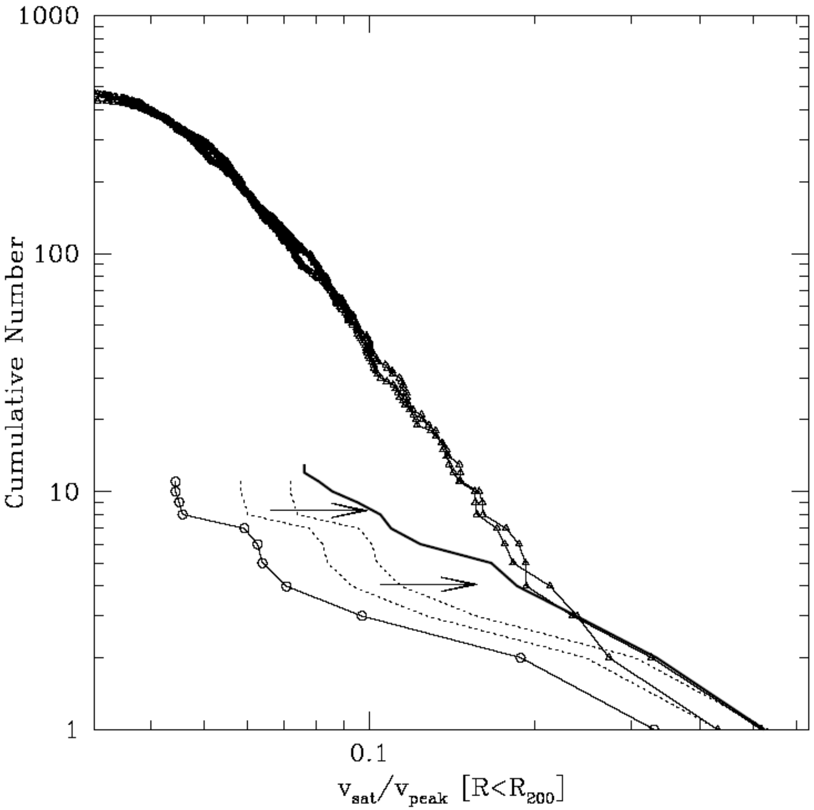


Steinmetz and Navarro

Possible problems?

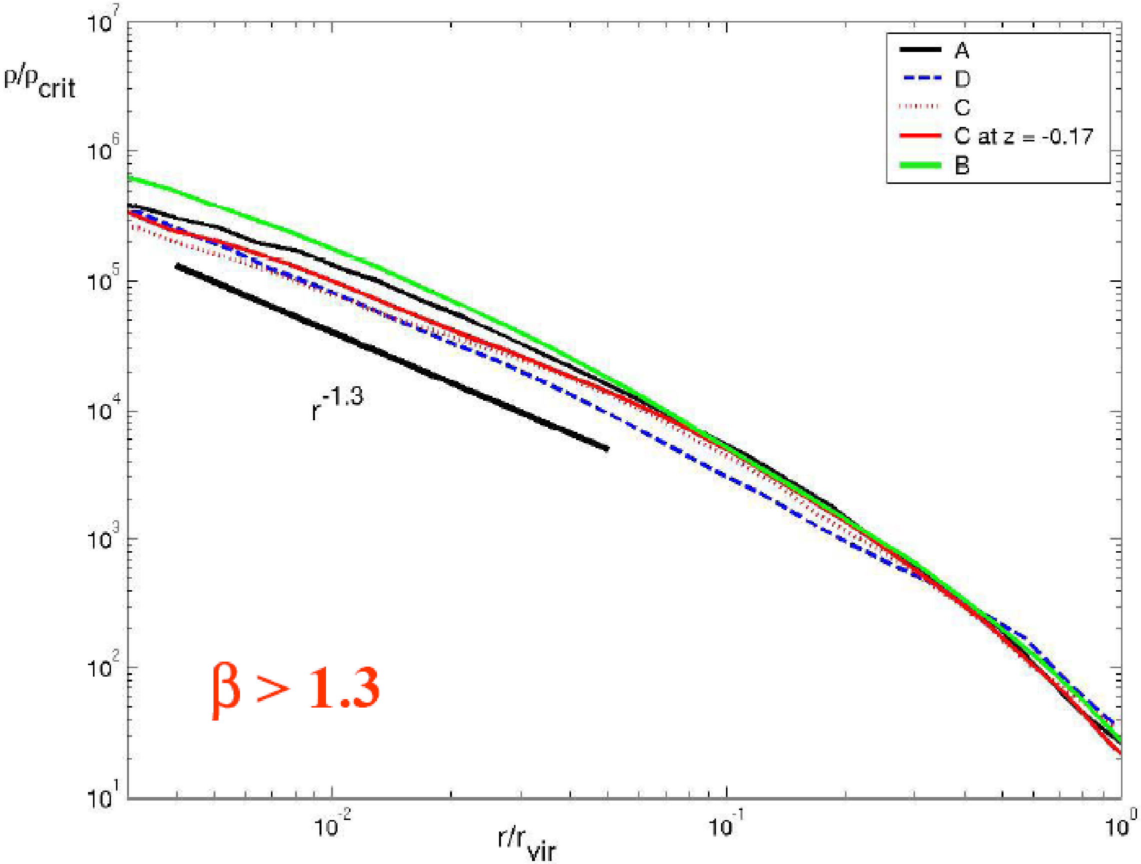
- Too many small haloes predicted (and which survive in larger haloes)

Re-ionization prevents cooling into late-forming haloes?



Possible problems?

- Two many small haloes predicted
- DM haloes are predicted to be too cuspy

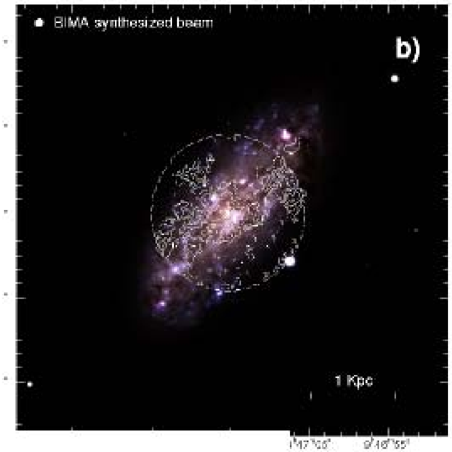


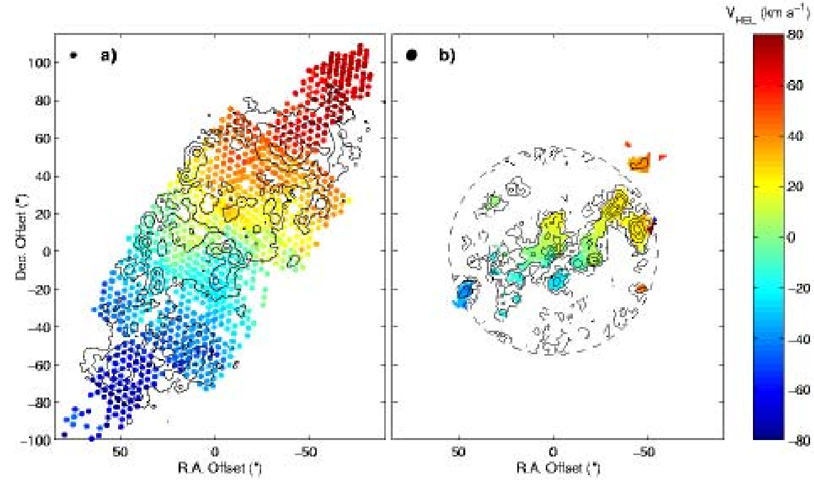
$\rho \propto r^{\beta}$: $\beta \sim 1$ NFW

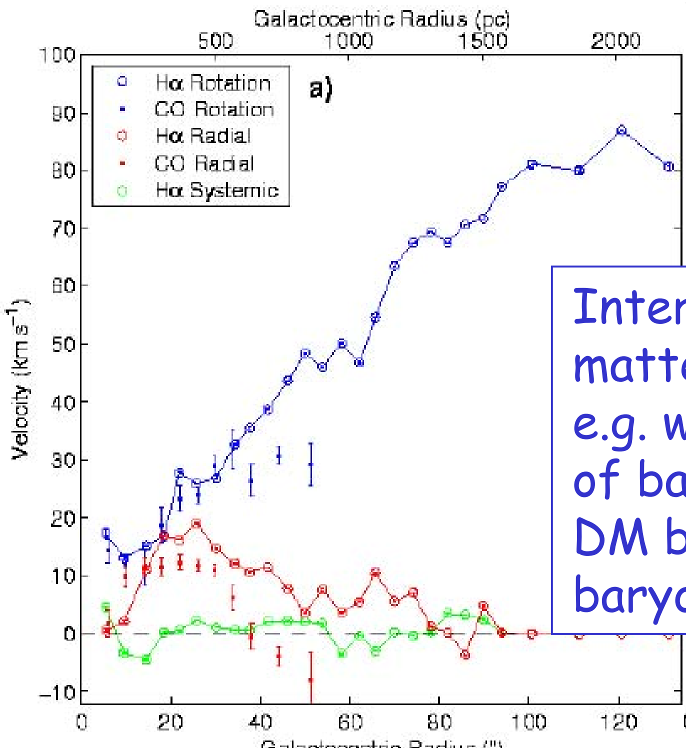
$\beta \sim 1.5$ Moore

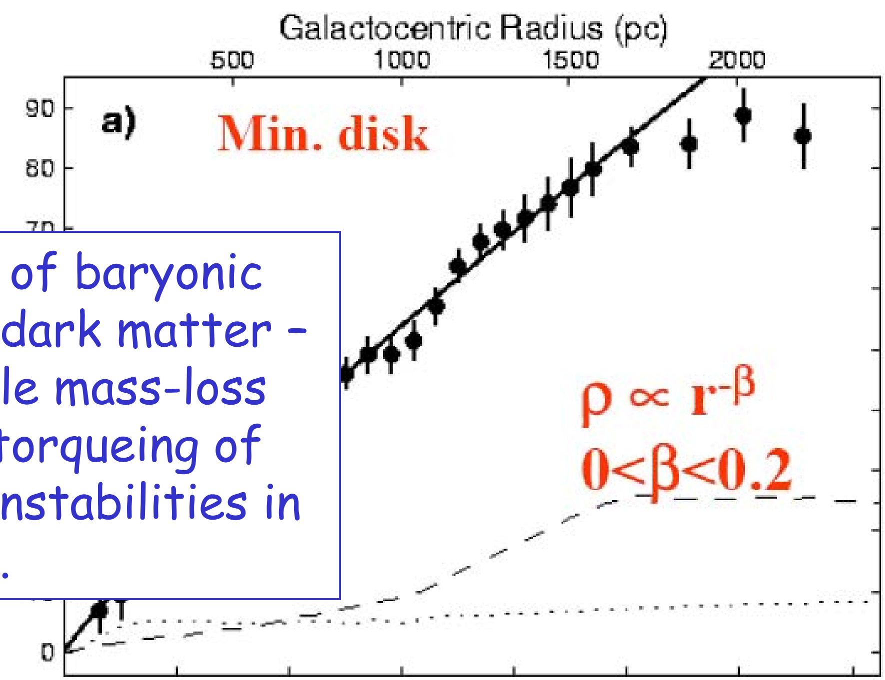
NGC 2976 Simon et al (astro-ph/0307154)

2-D CO and Hα dynamics at 75 pc resolution









Min. disk

$\rho \propto r^{-\beta}$

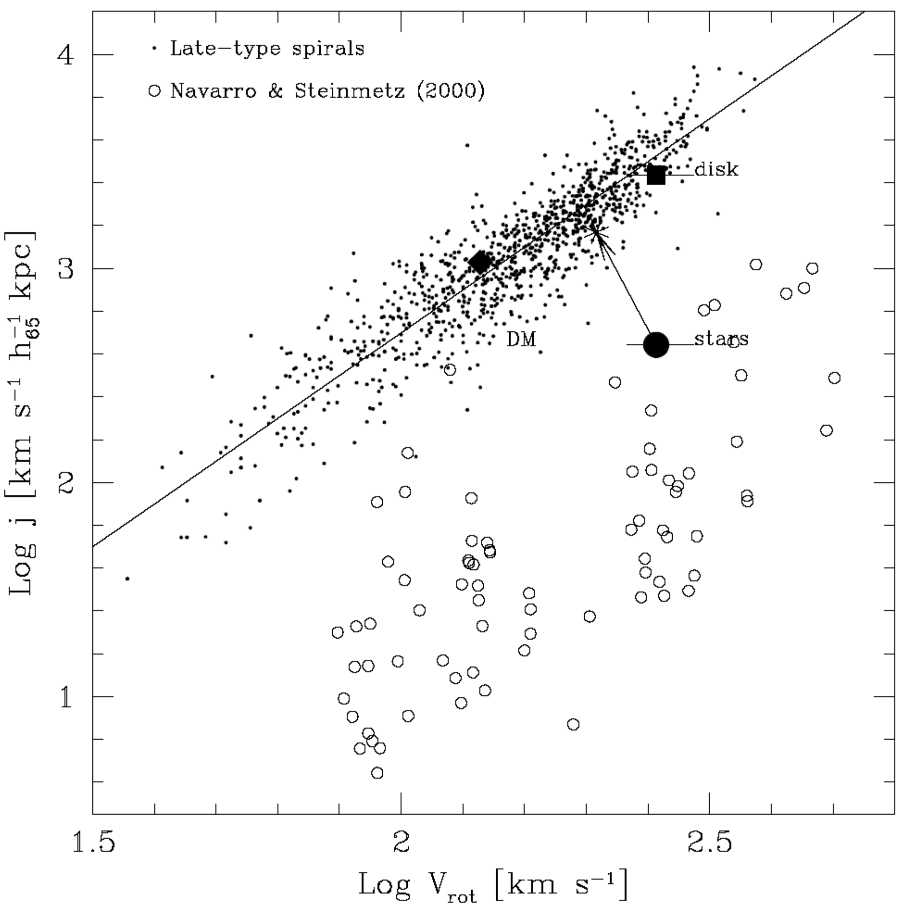
$0<\beta<0.2$

Interaction of baryonic matter and dark matter – e.g. wholesale mass-loss of baryons,torqueing of DM by bar instabilities in baryons etc.

Possible problems?

- Two many small haloes predicted
- DM haloes are predicted to be too cuspy
- Galaxies are predicted to be too small at a given v_{rot} (angular momentum problem)

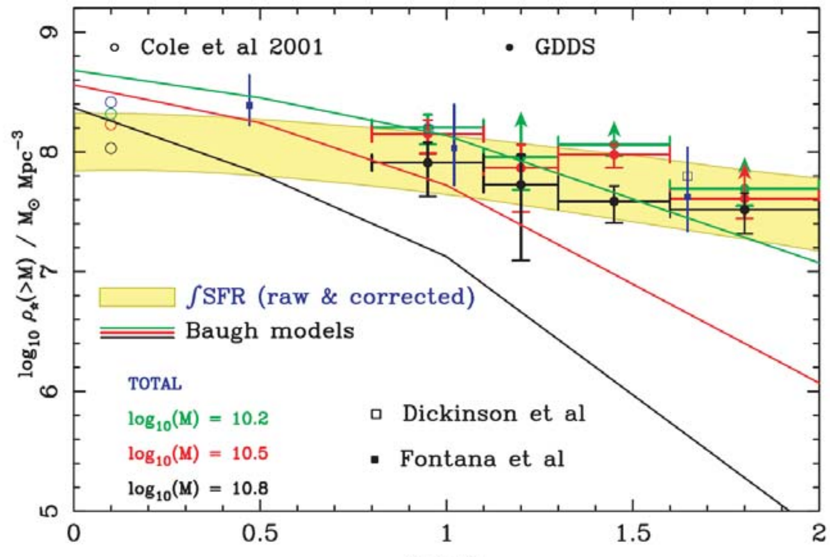
Due to angular momentum exchange between DM and baryons during cooling

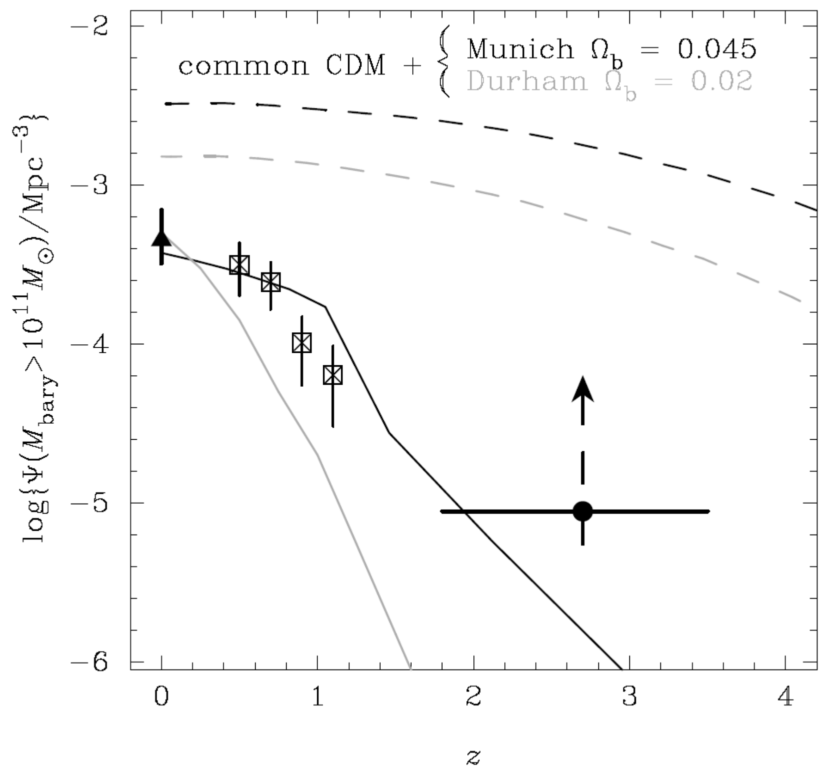


Possible problems?

- Two many small haloes predicted
- DM haloes are predicted to be too cuspy
- Galaxies are predicted to be too small (angular momentum problem)
- Massive galaxies appear to have formed rather early

Haloes with this amount of baryons predicted - something wrong with star-formation, cooling etc.





- Dark matter physics, cosmology(?)
- Interaction of the baryons with the dark matter
- Interaction of the baryons with themselves: esp. <u>the great unknown of galaxy formation</u>: STAR-FORMATION (also, cooling and shock heating outside of galaxies, AGN interactions inside)

We do not have theory for local star-formation, have only rather sketchy ideas about what regulates disk SFR, and virtually none about "spheroid star-formation", and anyway conditions in the early Universe will differ….

- Star-formation rate and efficiency
- Initial mass function (light and mass)
- Supernova heating – feedback, outflows
- Chemical evolution (also cooling etc)

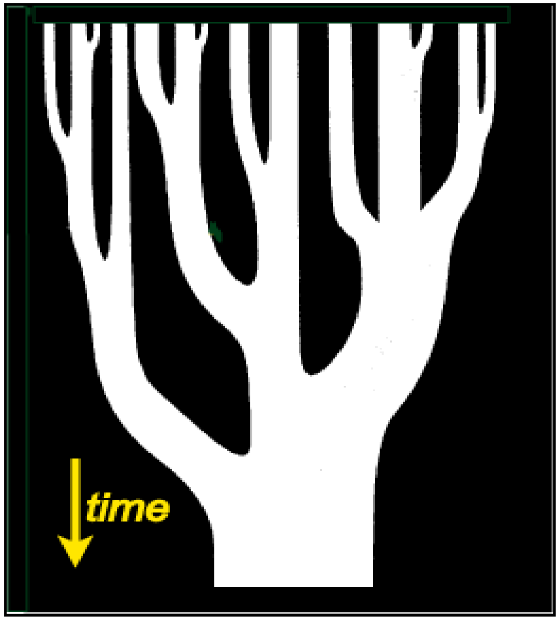
Uncertain feedback loops via photo-, chemical- and mechanical interaction with medium

Galaxy masses at high redshift are uncertain

Table 5. Comparison of Dynamical and Stellar Masses

Galaxy	σ[a] (km s^{-1})	M_{dyn}[b] ($10^{11} M_\odot$)	τ_{min}[c] (Gyr)	$M_{star}(\tau_{min})$[d] ($10^{11} M_\odot$)	τ_{max}[e] (Gyr)	$M_{star}(\tau_{max})$[f] ($10^{11} M_\odot$)
Q1623-BX274	121	0.28	0.20	1.27 (0.70)	5.00	2.76 (1.52)
Q1623-MD66	120	0.28	0.05	0.49 (0.27)	∞	1.19 (0.65)
Q1623-BX344	92	0.16	0.20	1.06 (0.58)	2.00	2.18 (1.20)
Q1623-BX453	61	0.07	0.01	0.49 (0.27)	∞	0.92 (0.51)
Q1623-BX528	142	0.58	0.20	1.09 (0.60)	2.00	2.47 (1.36)
Q1623-BX599	162	0.50	0.20	0.83 (0.46)	5.00	1.69 (0.93)
Q1623-BX663	132	0.45	0.20	1.06 (0.58)	1.00	2.35 (1.29)

Shapley et al, astro-ph last week

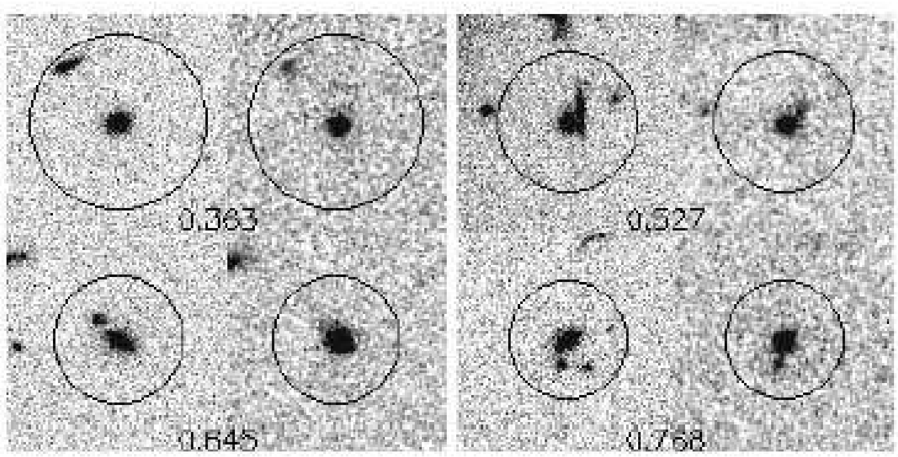


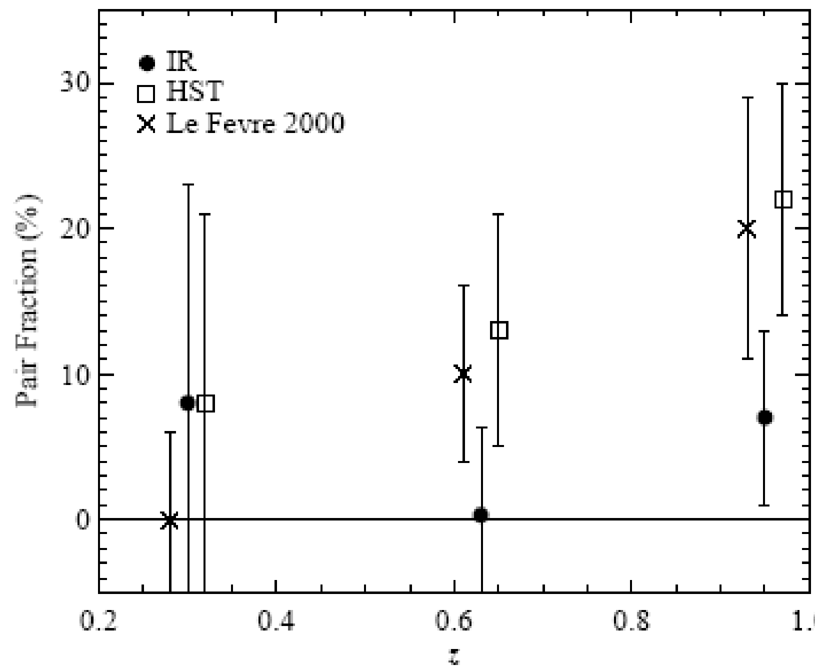
Galaxy dm/dt at high redshift are uncertain

The merger rate:

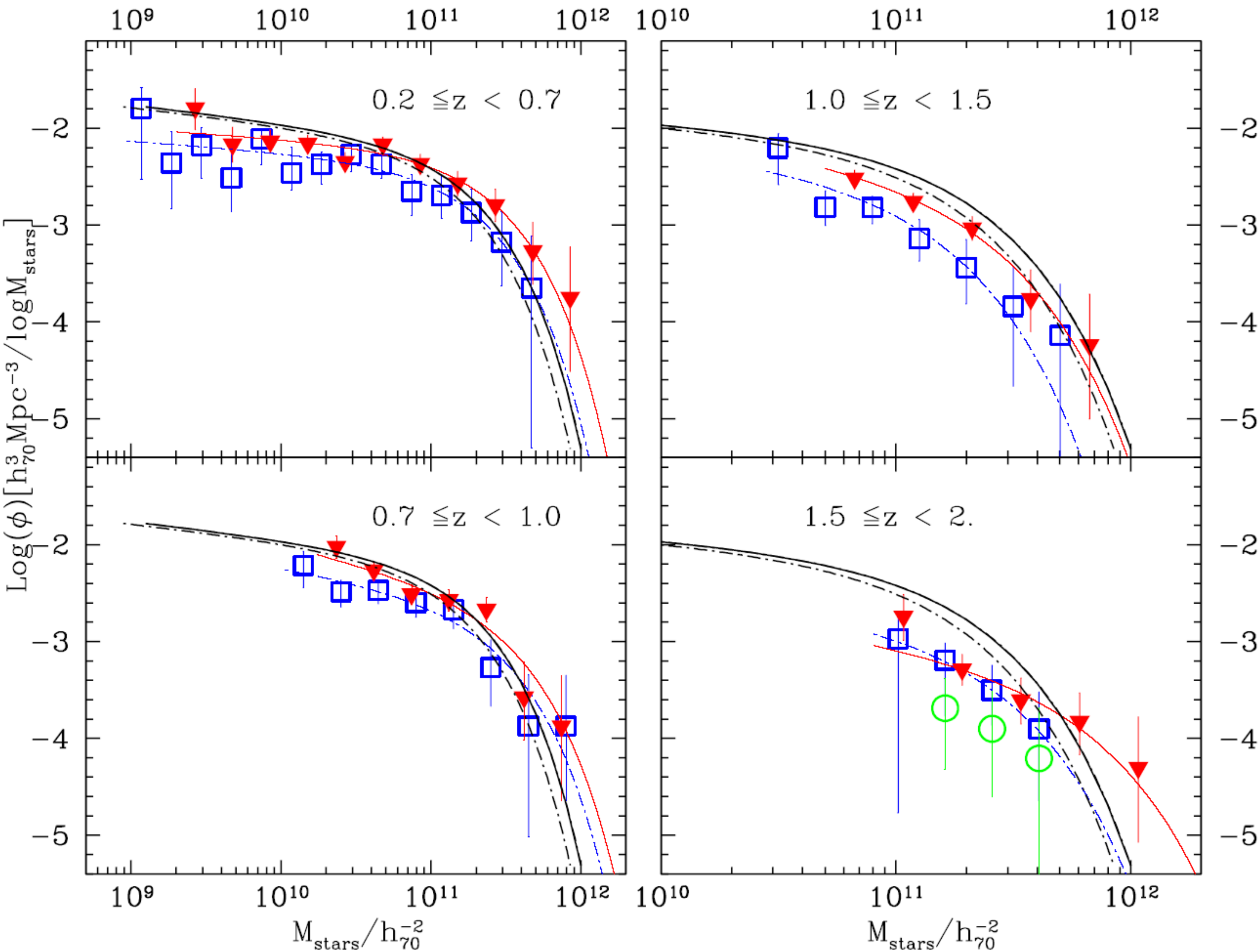
For a typical galaxy what is

- Δm from continuously forming stars
- Δm from addition of existing stars
- Δm from star-burst in addition of gas





Accumulation of mass



0.2 ≦z < 0.7
1.0 ≦z < 1.5
0.7 ≦z < 1.0
1.5 ≦z < 2.
$\mathrm{Log}(\phi)[h_{70}^{3}\mathrm{Mpc}^{-3}/\log M_{stars}]$
M_{stars}/h_{70}^{-2}
M_{stars}/h_{70}^{-2}

What is needed (1): More comprehensive phenomenology of galaxies at high redshift

Spitzer:	Galaxy stellar masses, obscured star-formation
ALMA:	Molecular gas and dust content of normal galaxies Gas kinematics Obscured star-formation Nature of highly luminous star-bursts
JWST:	Galaxy populations (e.g. LMC at rest–V at z = 5) Gas/stellar kinematics, metallicities, reddening etc Galaxy morphologies (bars etc.)
ELT:	More of the same (already at limits of 8-10m telescopes), especially complementarity with ALMA and JWST.

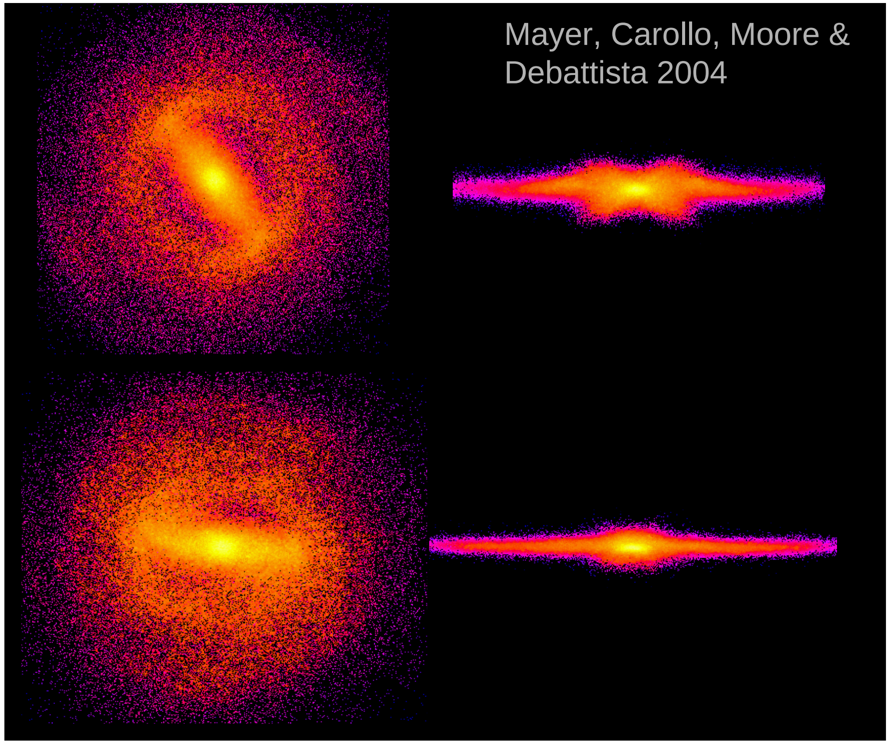
Key questions: stellar mass assembly via star-formation, mergers or star-bursts? Physical processes in high z ULIRGs? Role of environment? Chemical evolution of IGM?

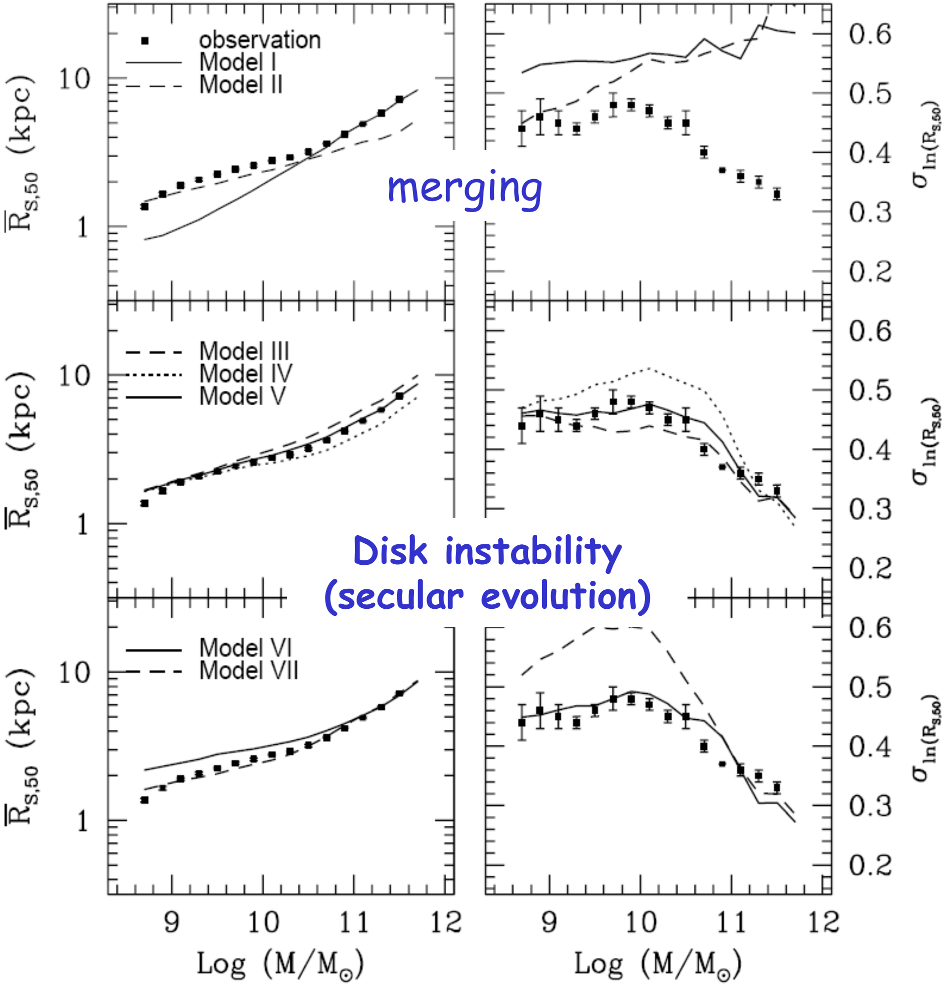
What is needed (2) Studies of galaxies today – e.g. secular evolution of disks

Most small bulges (later than Sbc) made from disk instabilities?

e.g. SDSS size distribution (Shen et al 2003)

How to make merger-less disks in hierarchical models?

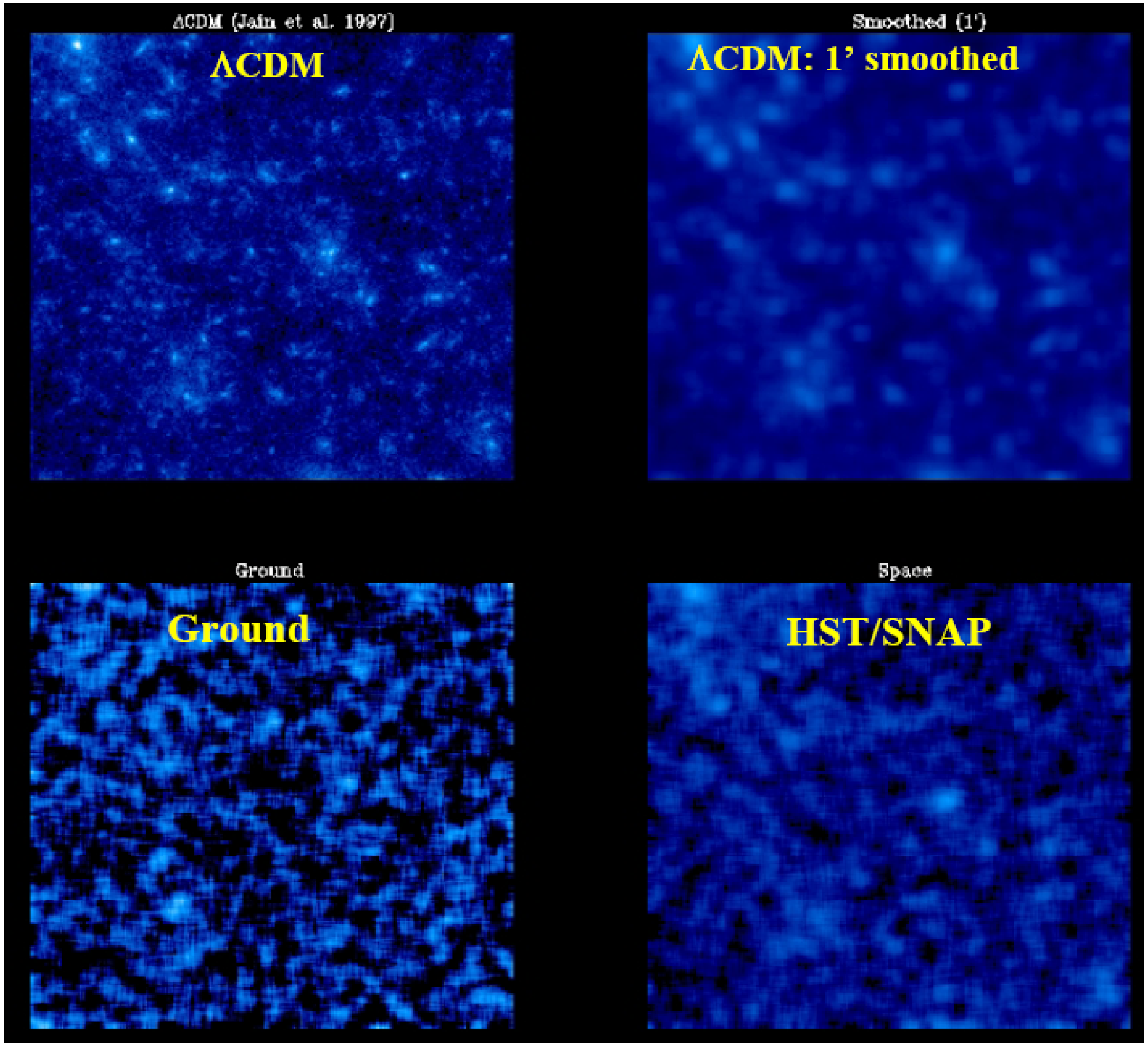




SDSS: Shen et al 2004

What is needed (3): Extension to the other components in Universe

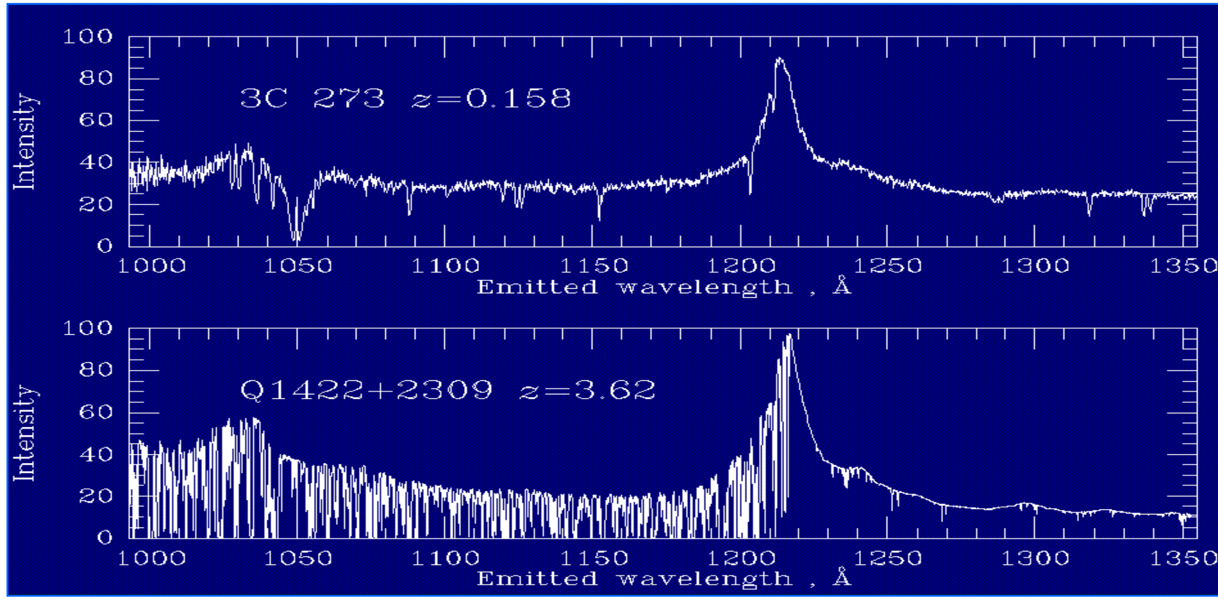
e.g. dark matter



What is needed (3): Extension to the other components e.g. gas

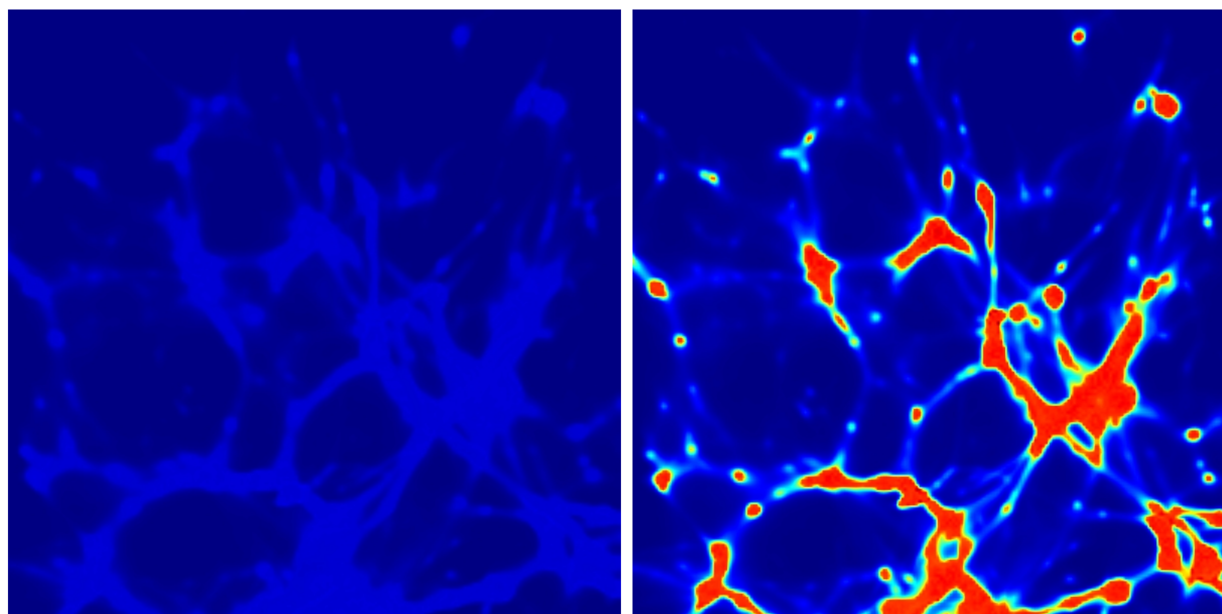
Galaxy formation is only ~10% efficient.

At z ~ 3, the neutral gas alone > the stellar mass



Flourescence of ionizing radiation for $N_{HI} > 10^{18}$ cm^{-2}

NB: DLA ($N_{HI} > 10^{22}$ cm^{-2}) systems avoid galaxies



Fluorescent Lyα in 6x6x6 Mpc^3
Cantalupo et al, 2004

What is needed (4):   Extremely large samples of galaxies

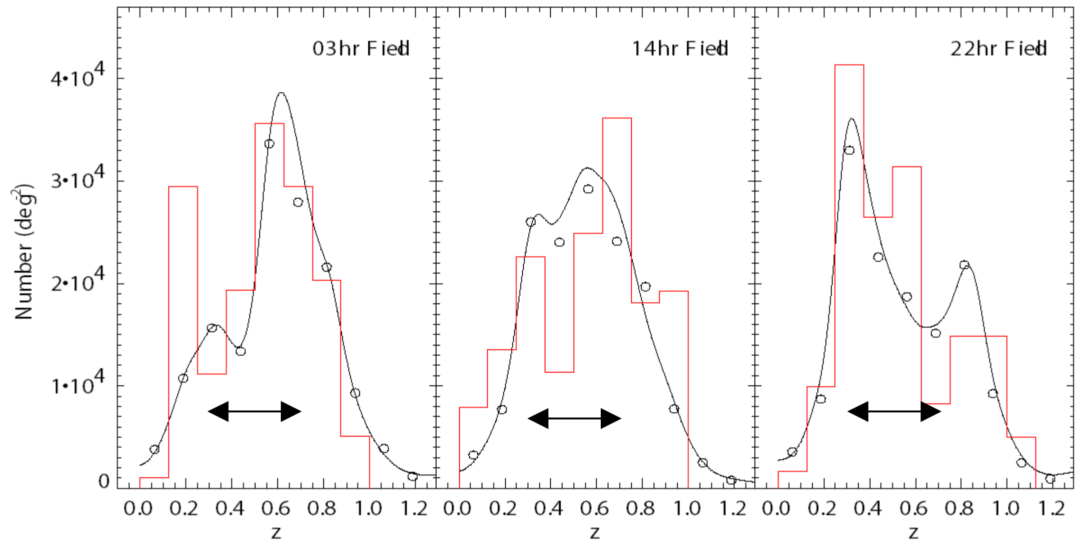
1 (a) Evolution must depend on mass, environment (directly and through epoch of collapse), stochastic processes….

(b) Want to use homegeneity of Universe to relate populations at different epochs.

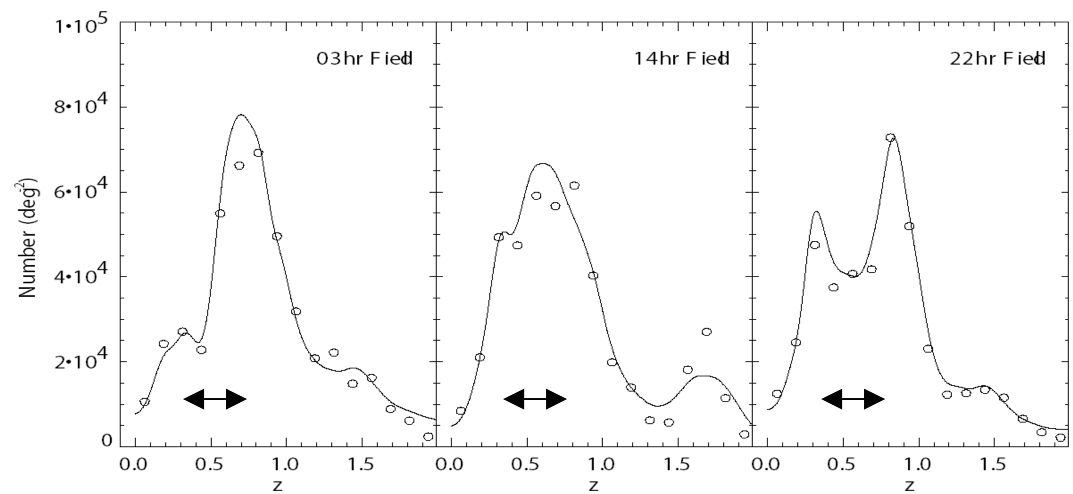
2. Cosmic variance – a cautionary example

9x9 arcmin^2 CFRS fields (~ 150 gals each)

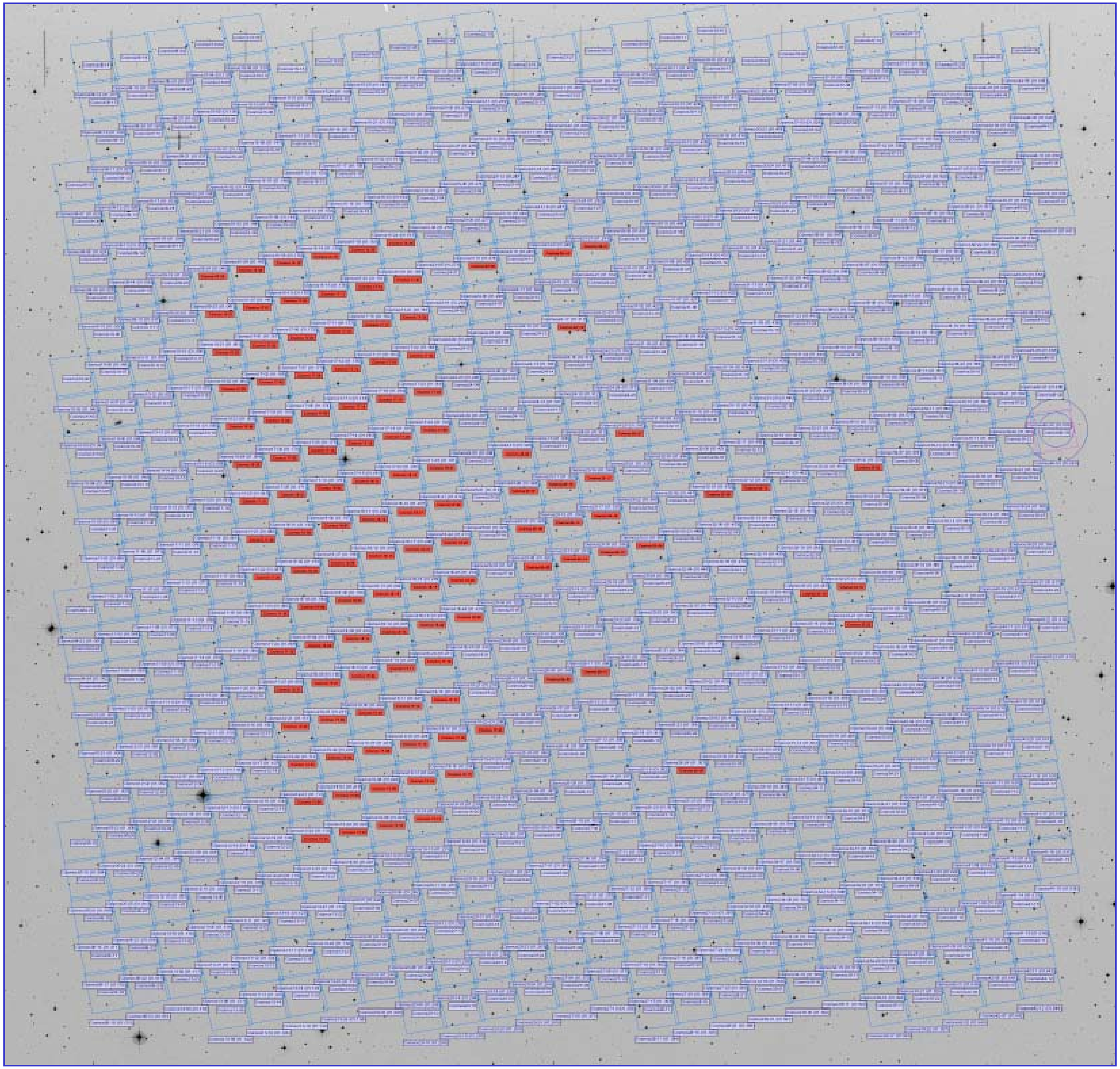
30x30 arcmin^2 CFRS fields (~ 2500 gals each) – Brodwin et al 2004 photo-z



Down to IAB ~ 24 (10,000 galaxies each)



Equivalent surveys	30' at z = 0.7 (23 Mpc)	Δz = 0.4 at z = 0.7 (1200 Mpc)
At *z* ~ 1.5	15 arcmin	Δz = 0.8
At *z* ~ 3	10 arcmin	Δz = 1.6
At *z* ~ 6	8 arcmin	Δz = 3.5



COSMOS (Scoville et al)

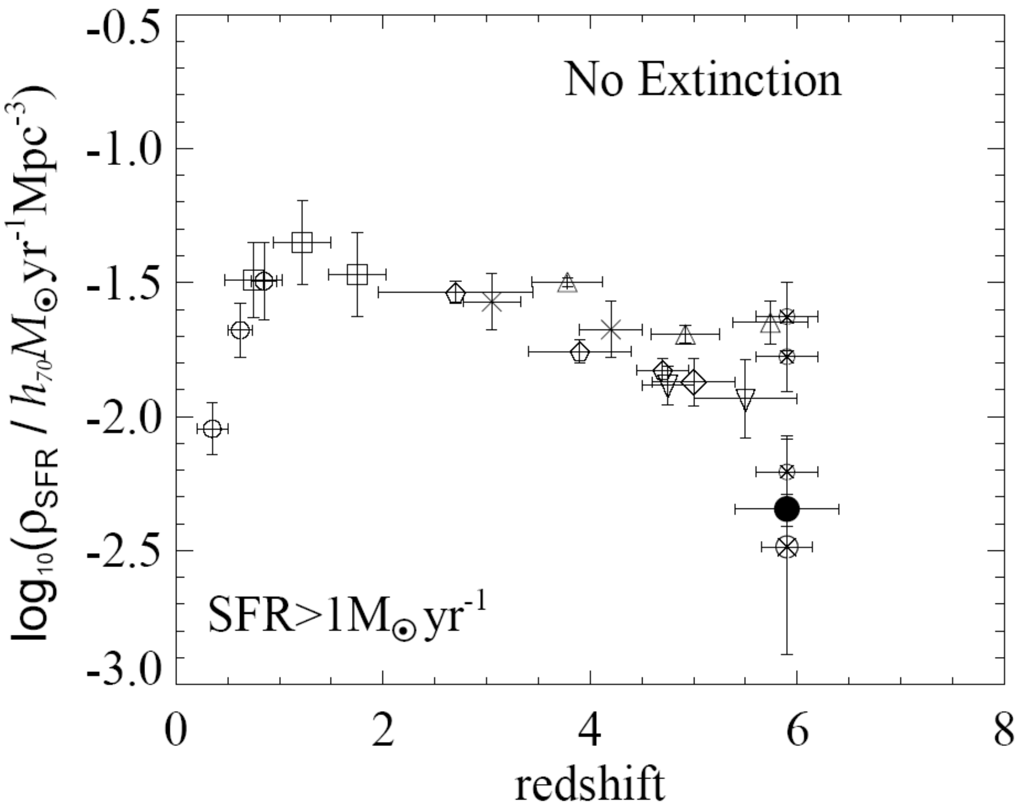
1.4×1.4 deg^2 ~$100+ \times 100+$ Mpc^2

- 600 HST/ACS pointings (F814W)
- Subaru/CFHT UBVRIZ @ 26-27 mag
- CSO 1.1mm @ 2 mJy
- Galex near-UV @ AB=26
- XMM @ 800ksec
- ~90,000 redshifts VIMOS
- Spitzer 3-160 mm - 2mJy – 40 mJy
- VLA S1.4 ~ 7.5/17 μJy

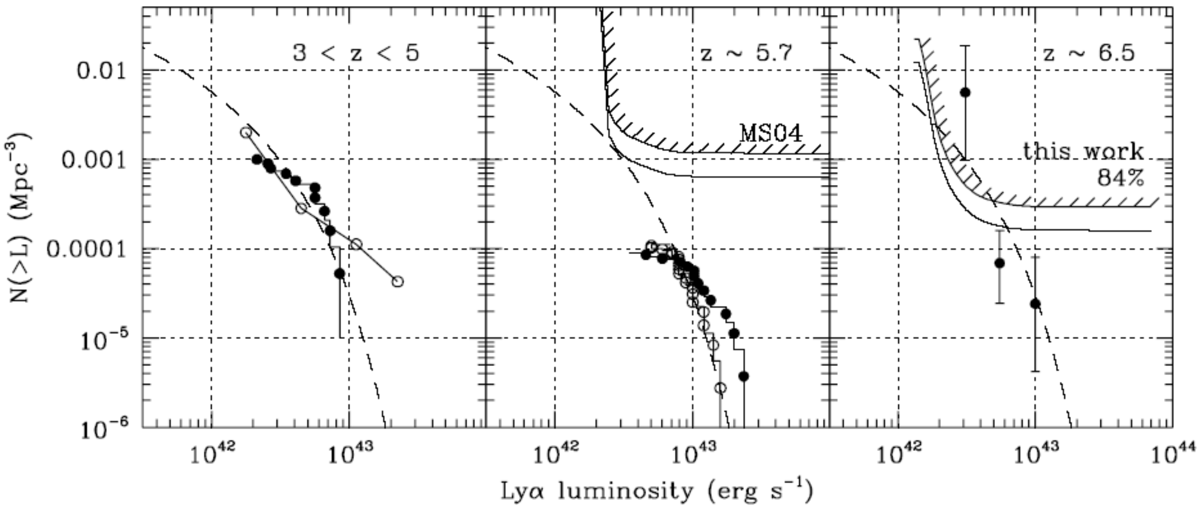
300,000 $I_{AB} < 25$ objects, of which

- 160,000 $z > 0.7$ galaxies
- 50,000 $z > 1.5$ galaxies
- 15,000 $0.7 < z < 2$ ERO ellipticals
- 20,000 $1.8 < z < 3.5$ LBG
- 5000 $2 < z < 3.5$ “red galaxies”
- 40000 XMM AGN
- 3000 SCUBA ULIRGs
- 120 X-ray clusters

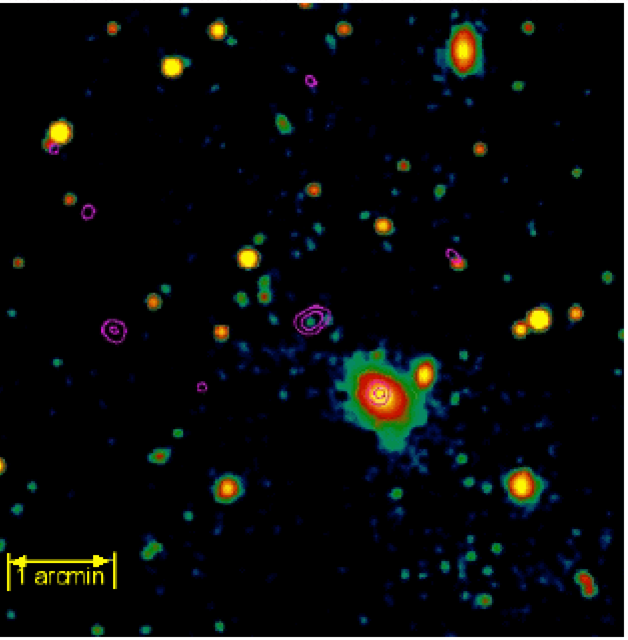
Towards Reionization…



Lyman break galaxies in the HDF, GOODS, UDF etc



Lyman α emitting galaxies



SDSS J1148

MAMBO 1.2 mm (contour)

S/N on SLOAN z' image.

Dust at z=6.42!

$7\times10^8\ M_{sun}$ in <700 Myr

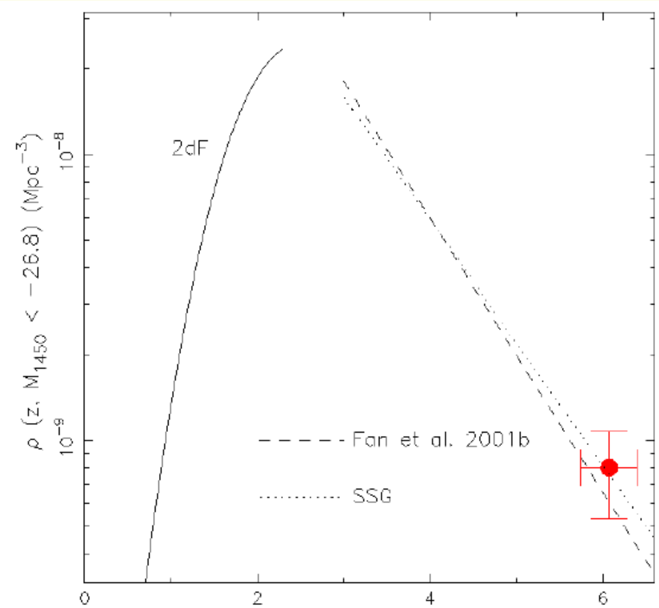
Bertoldi et al. 2003

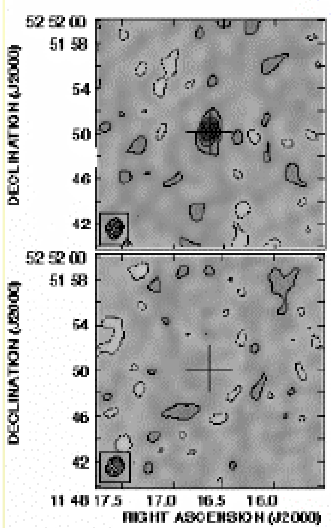
Submm and CO detection in the highest-redshift quasar:

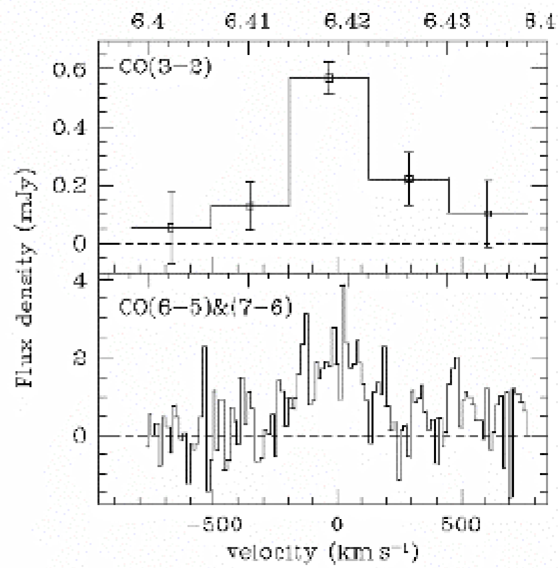
- Dust mass: 10^8 – 10^9
- H2 mass: 10^10
- Star forming rate: 10^3/yr

→ *co-formation of SBH and young galaxies*

CO 3-2 (VLA), 6-5, 7-6 (PdBI)



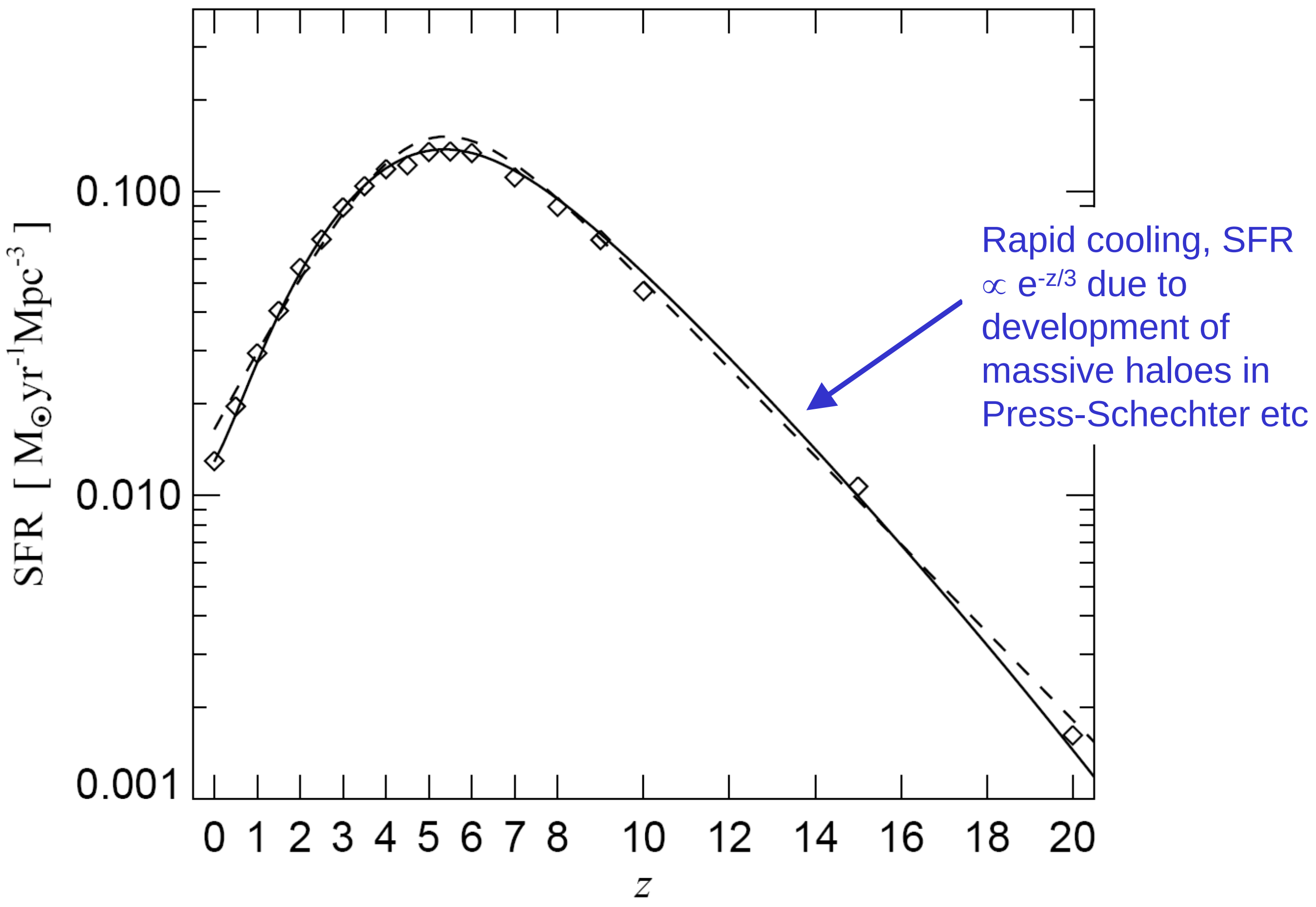




Walter, Bertoldi, Carilli et al. 2003, Nature

Bertoldi, Cox, Neri et al. 2003, A&ALet

Generic prediction: Hernquist & Springel analytic modelling of numerical hydro simulation gives exponential decline at high redshifts

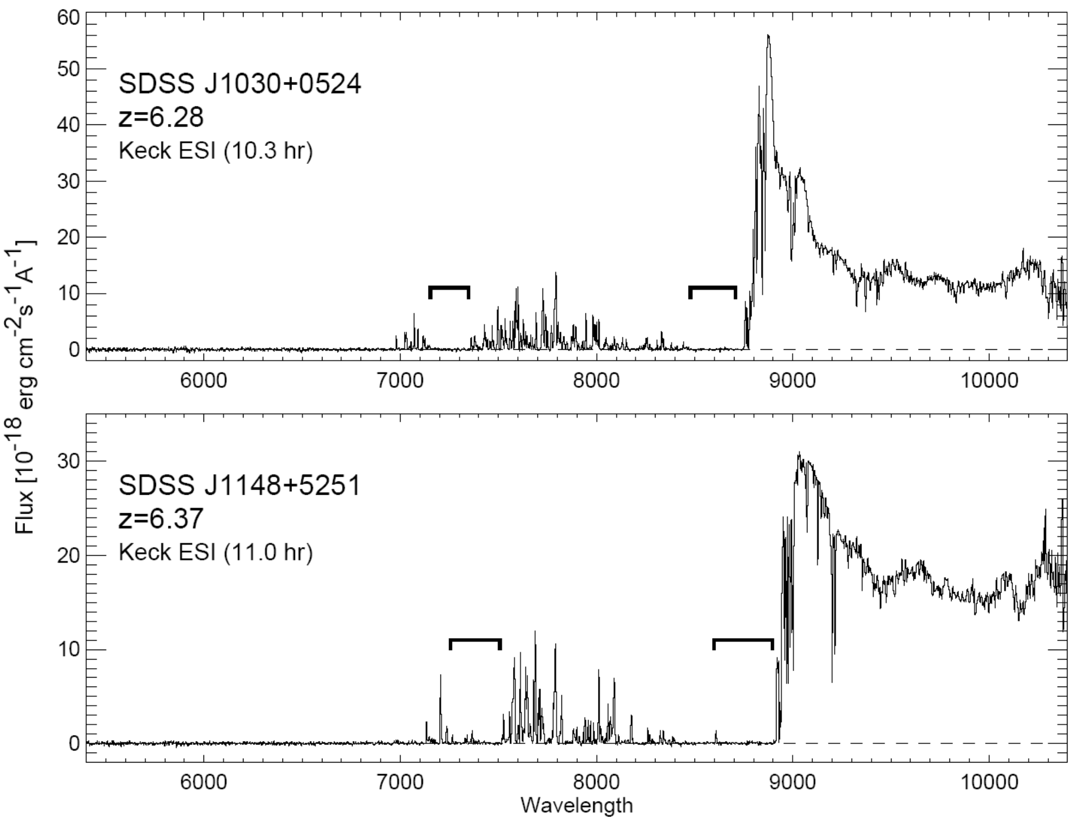


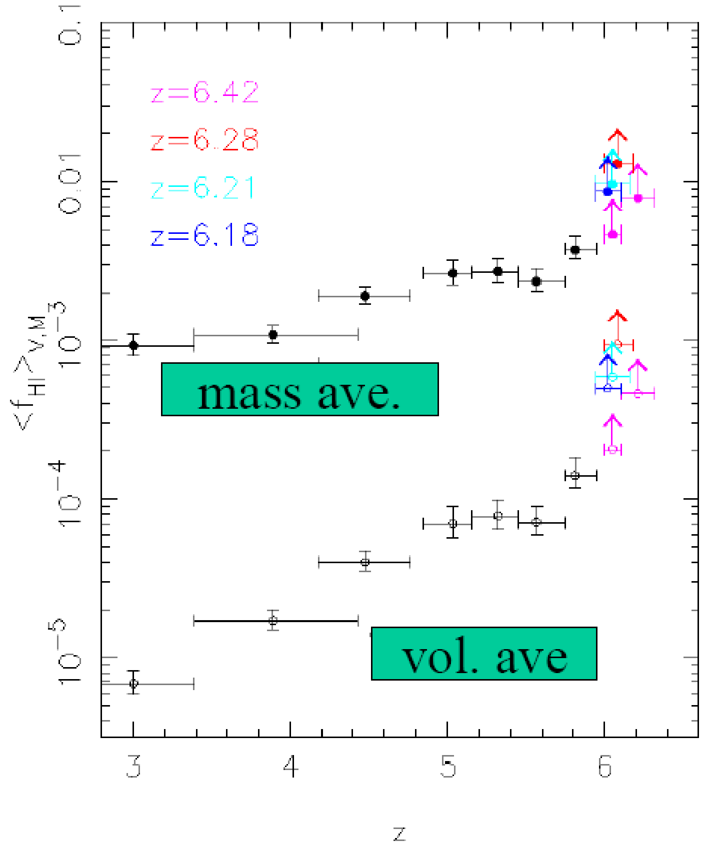
The “frontier” (I): Reionization

SDSS QSO Gunn-Peterson trough $\tau_{HI} > 20 \rightarrow$

$x_{HI} > 10^{-2}$ mass-weighted
$x_{HI} > 10^{-3}$ volume-weighted

$\times$10-100 from $z \sim 3$ – smooth trend with z or sharp rise? **$z_{reion} > 6$**



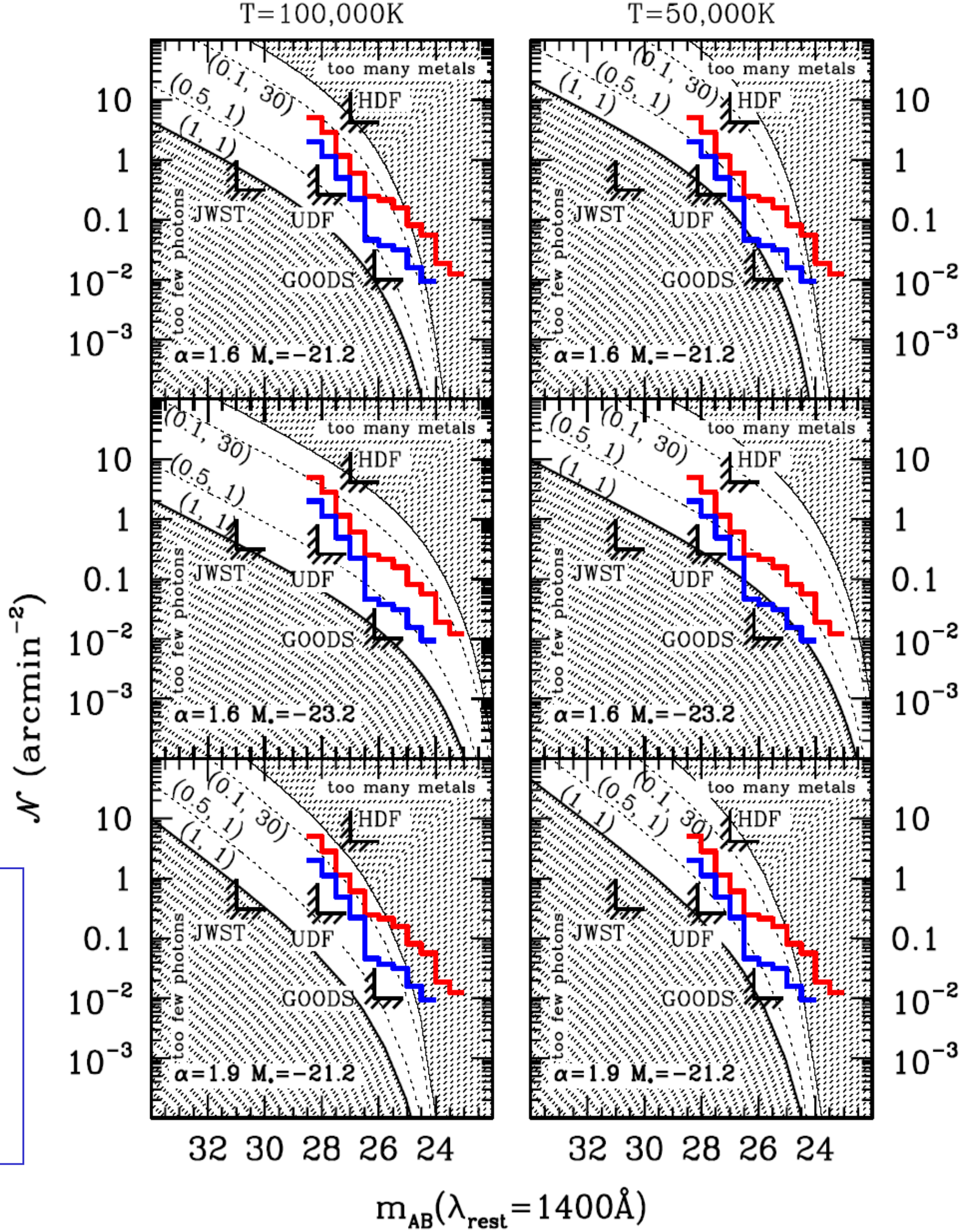


WMAP $\tau \sim 0.17$(?)
$z_{reion} < 17$(?)

What did it?

- Ionizing spectrum λ < 912Å
- Escape fraction
- Clumpiness and Temperature in IGM

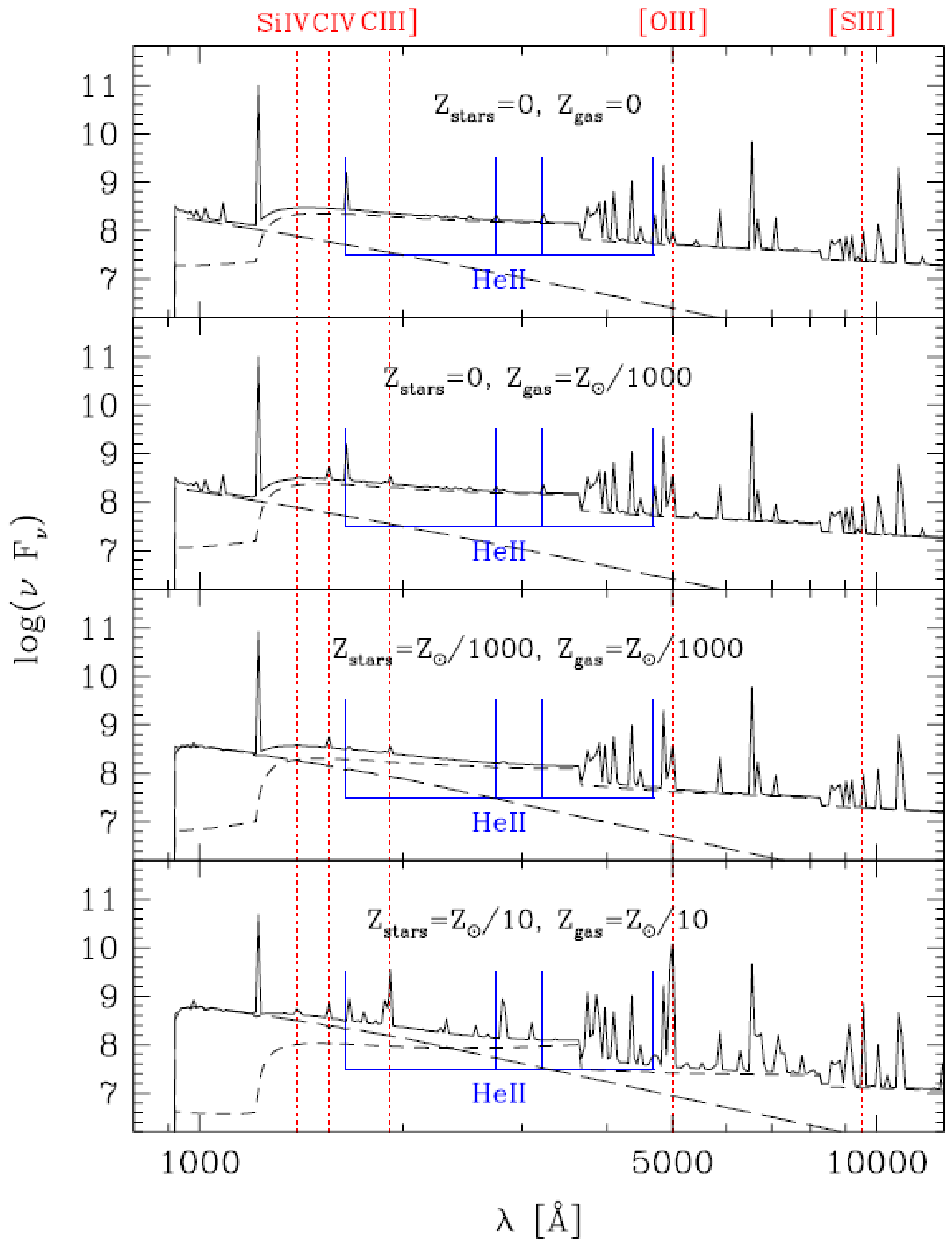
With reasonably optimistic assumptions, known LBG in GOODS + UDF are in fact <u>sufficient</u> to ionize between 6 < z < 7 (Stiavelli et al, c.f. Bunker et al)



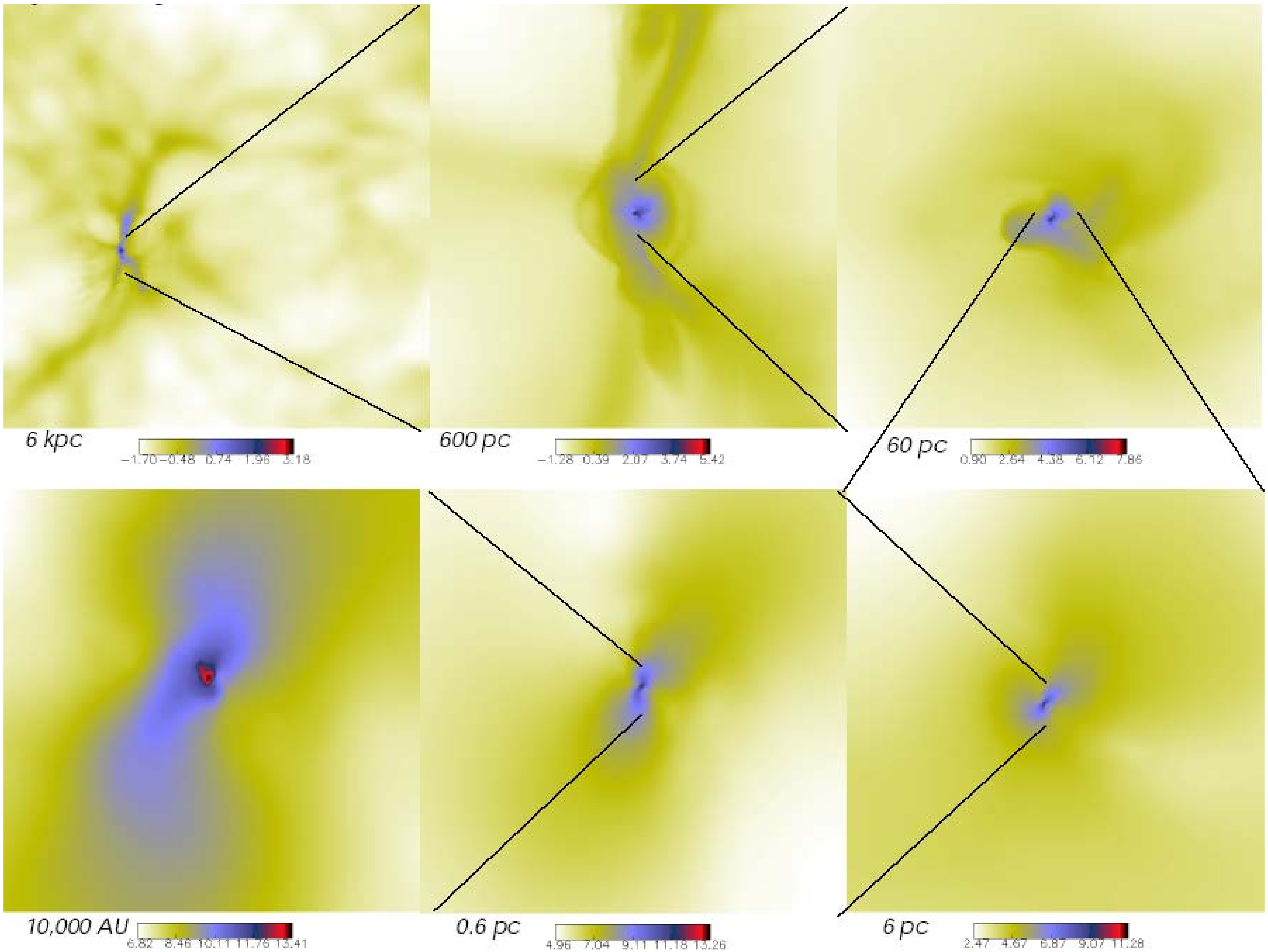
Need better probes of when and how reionizing proceeded

- Metal forest (e.g. OI 1302)
- SKA 21 cm emission etc

Low metallicity signatures – Panagia etc

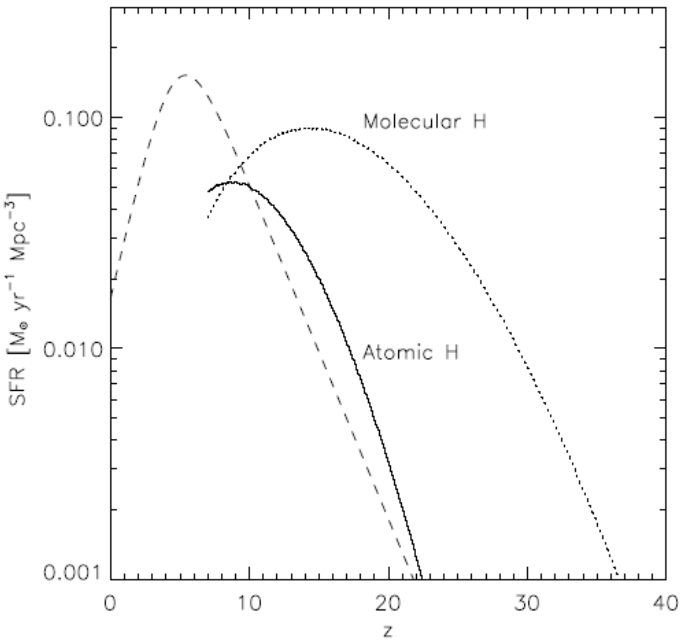


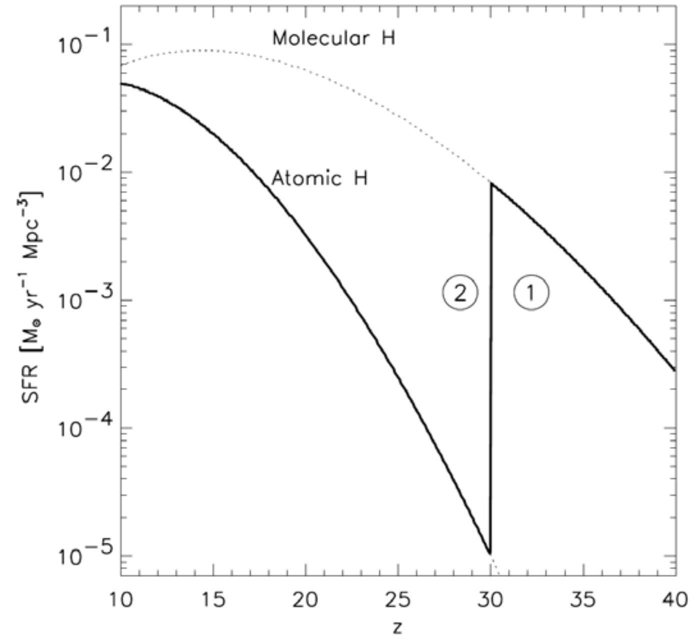
Hydrodynamic simulations of first star formation – single massive stars one per halo?

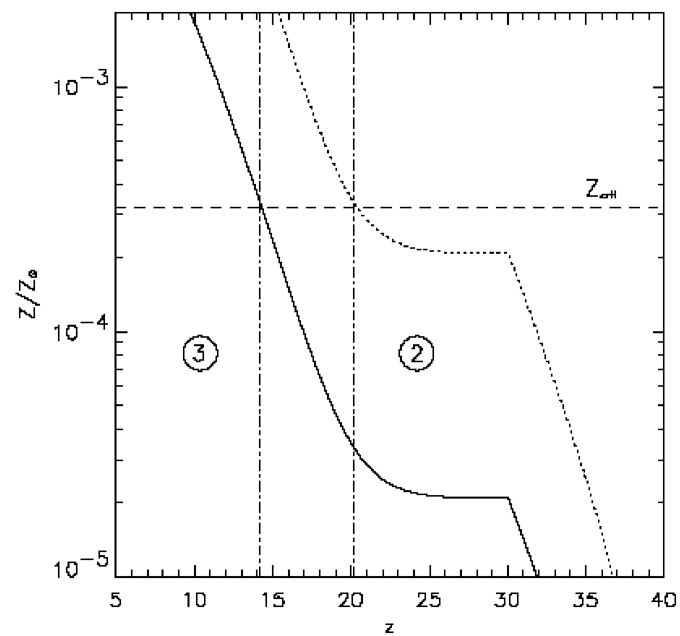


Abel et al 1999

Such single stars would be very hard to observe individually (AB ~ 40)







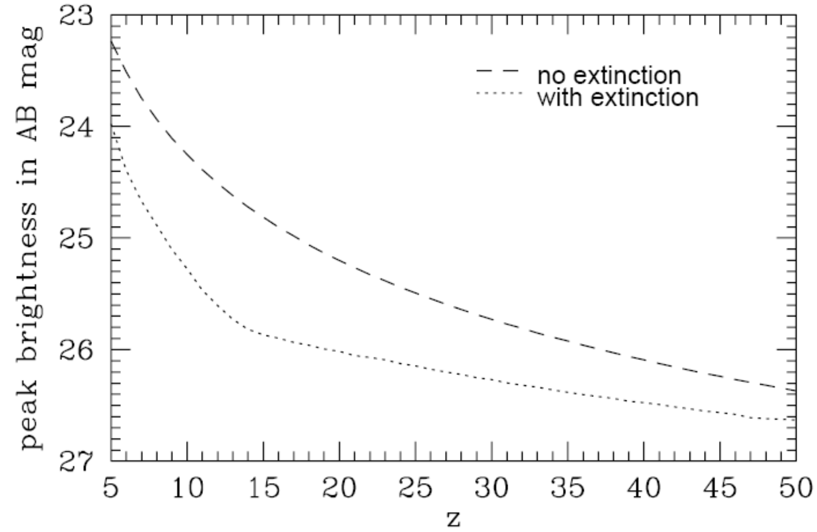
e.g. Mackey, Bromm and Springel (2003):

Phase 1: H_2 cooling in haloes

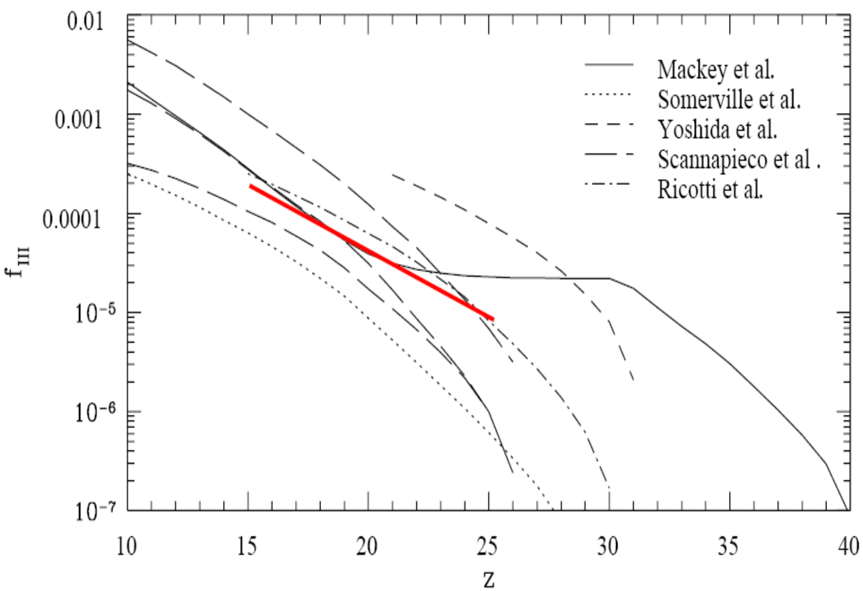
Phase 2: H_2 dissociated but still required for star-formation

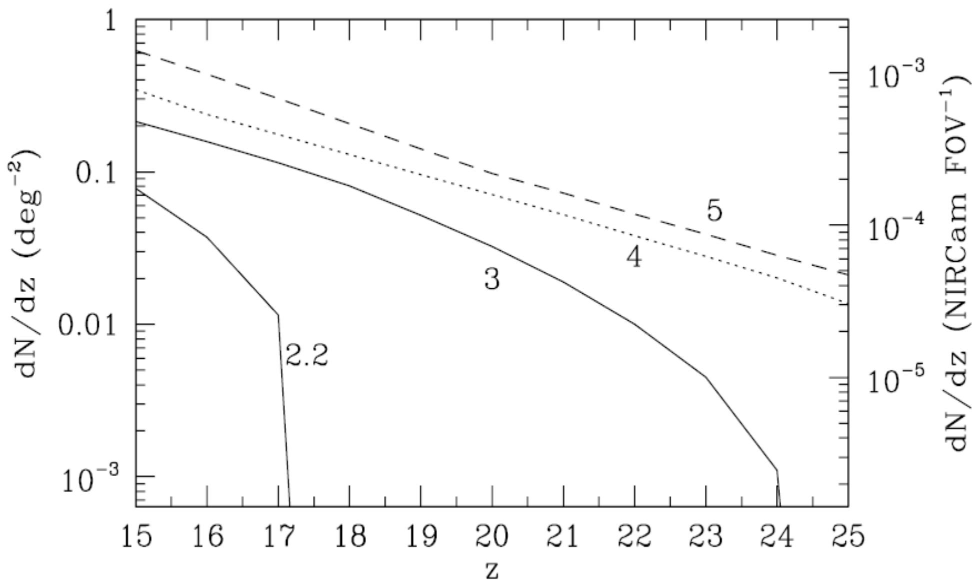
Phase 3: Metal cooling → normal imf?

	redshift	f_{PopIII}	f_{SN}	m_{SN}	Rate yr^{-1} deg^{-2}	Adjusted
Mackey et al	$z>15$	3×10^{-4}	1	250	50	50
Heger et al	$z\sim20$	10^{-6}	1	250	120	0.3
Cen	z>13	10^{-4}	0.25	100	620	43
Wise & Abel	z~10				2500	0.2
	z~15	2×10^{-4}	0.1	225	4	
	z~25	10^{-5}	0.1	225	0.2	

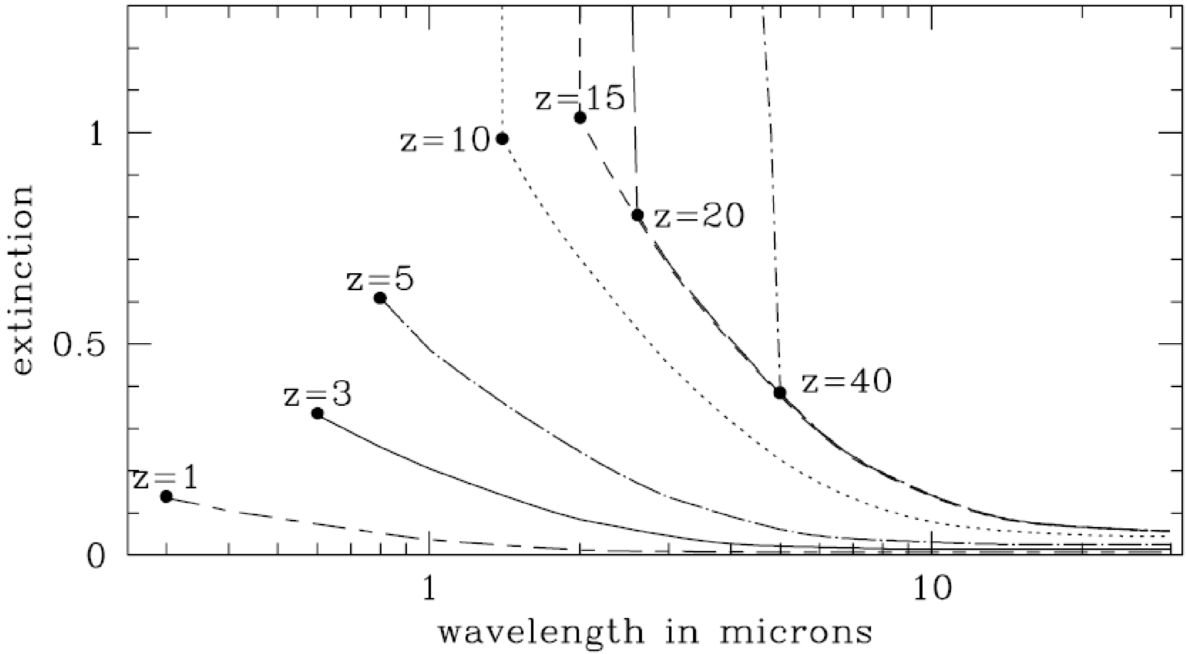


Observability of Pop III PISNe (140-250 $M_\odot$)

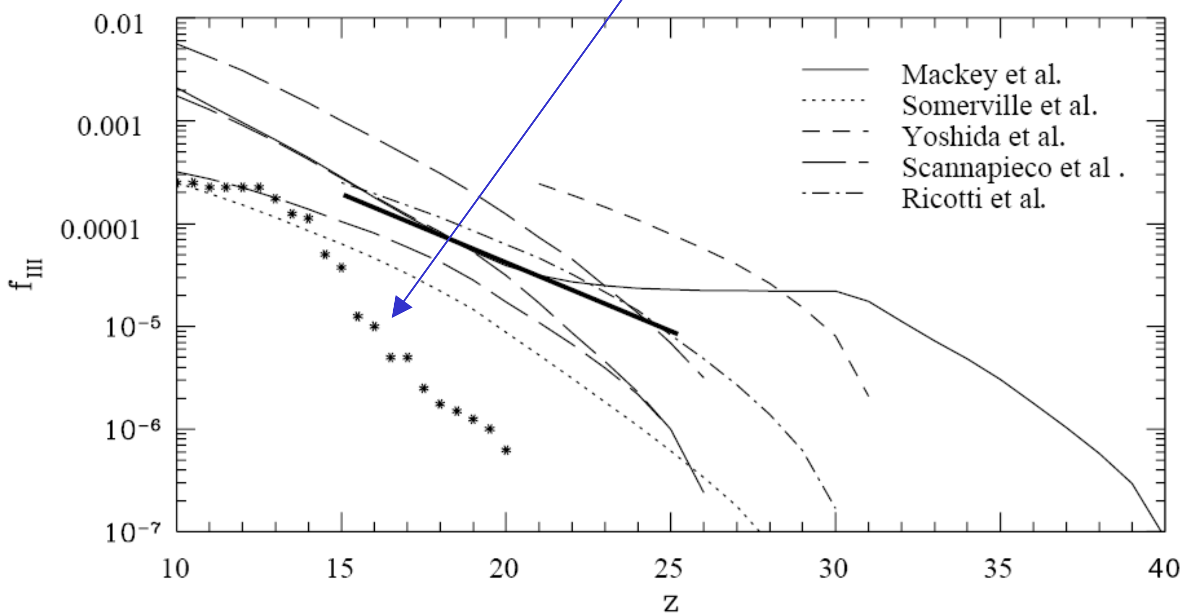




Pop III PISN supernovae



Assumed dust is probably rather high



The dark ages…… LOFAR/SKA!

We have a theoretical paradigm, but the predictions from this are very uncertain due to baryonic physics, especially star-formation.

We know where most of the energy emitted by objects is, and can paint a broadly consistent picture of this out to $z \sim 6$.

Need much better astrophysical analysis of “known objects” – certainly multi-band and multi-facility (Spitzer-JWST, ALMA, ELT, SKA….) – in order to move beyond “consistency”

The earliest phases $z > 6$ are highly uncertain, but probably accessible to observation