Old Galaxies and New Instruments

Facing the Future: A Festival for Frank Bash

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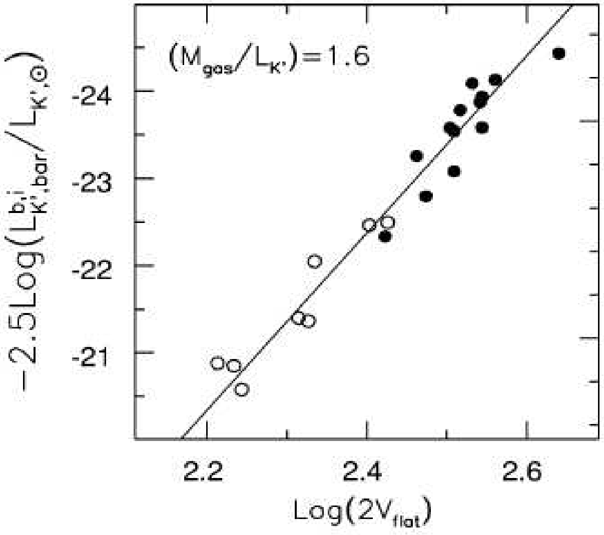
(1) scaling relations at $z = 0$
(2) observing key baryonic processes
  –growth of stellar masses
  –growth of galaxy masses
  –growth of black hole masses
(3) challenges of new instrumentation

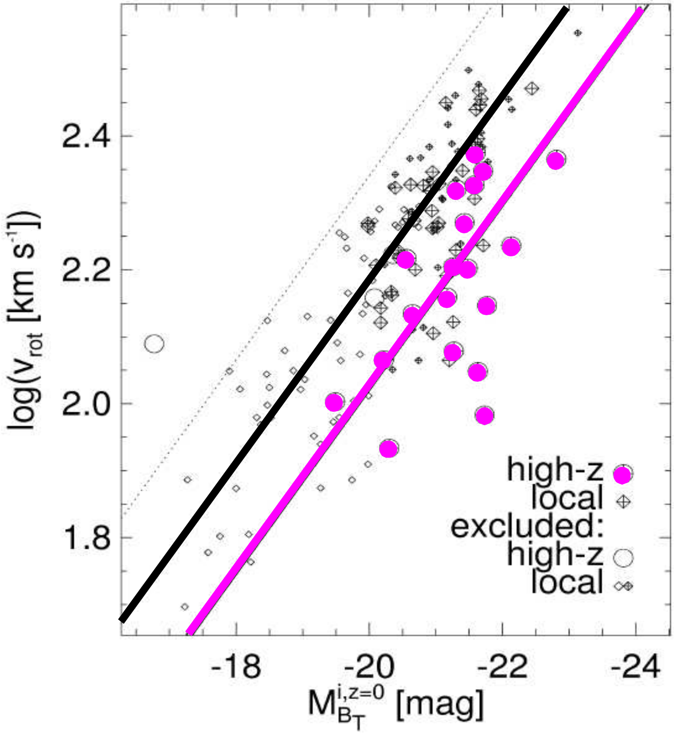
Disk galaxies: the Tully-Fisher relation

Luminosity scales with rotation velocity.



Verheijen (2001)

$$\boxed{L_K \propto v^{4}}$$



Barden et al. (2003)

Questions related to galaxy formation:

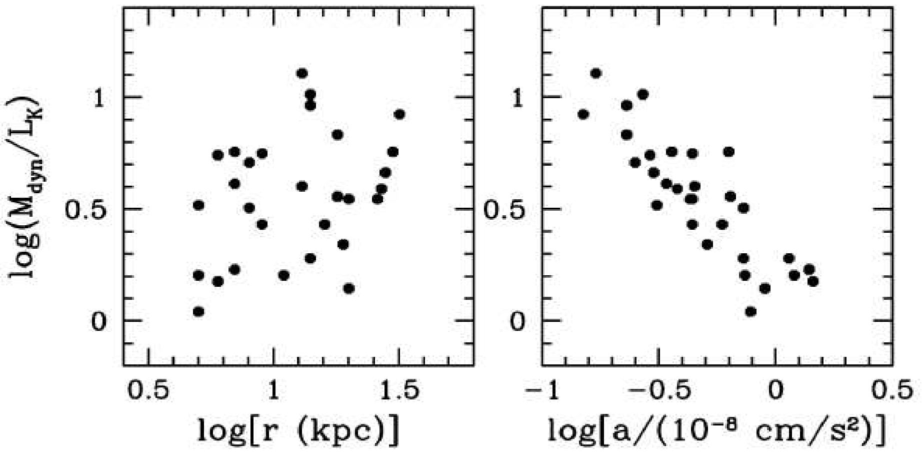
- **How does T-F depend on star formation history (Kannappan et al. 2002)?**
- **Does T-F evolve at *z* ~ 1 (Barden et al. 2003) or not (Vogt et al. 2001)?**
- **Can a single galaxy evolution model reproduce both T-F *and* the local luminosity function (e.g., Somerville & Primack 1999)?**

Disk galaxies: Milgrom’s law

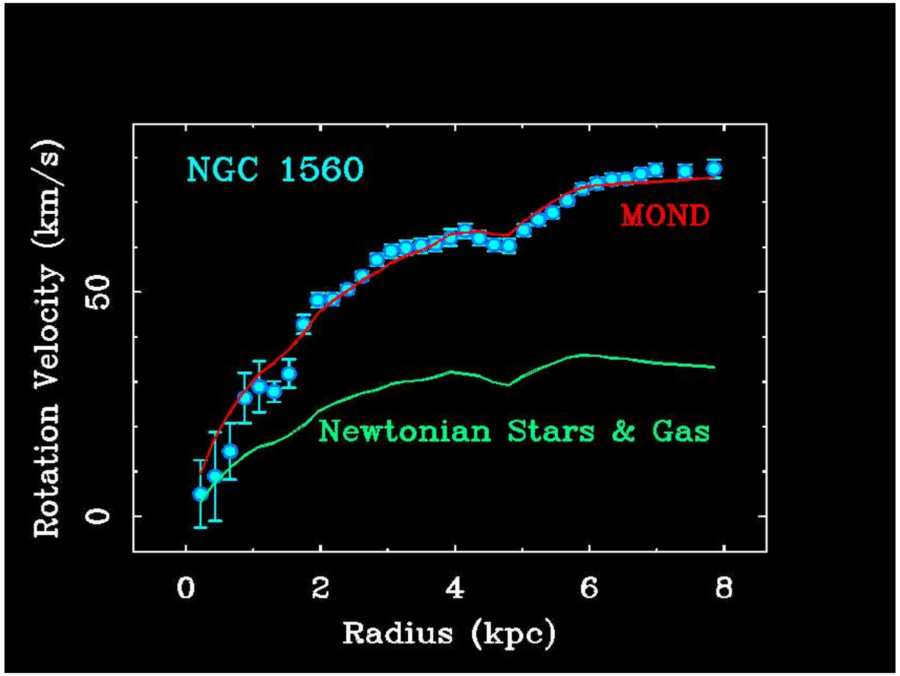
Mass/light ratio scales with acceleration.

$$M_{\mathrm{dyn}}/L_K \propto a^{-1}$$

(for $a < a_0 \simeq 1.2 \times 10^{-8}$ cm s^{-2})



Sanders & McGaugh (2002)



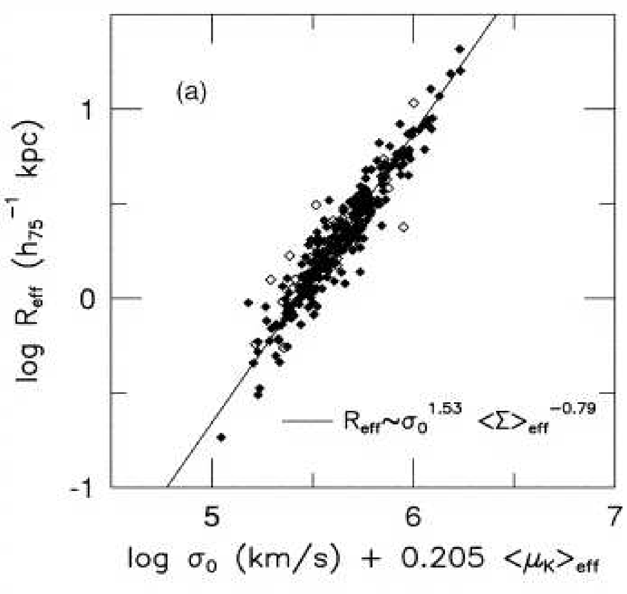
MOdified Newtonian Dynamics (MOND):
first proposed by Milgrom (1983).

Fails (?) for ellipticals (Gerhard et al. 2001) and clusters (Aguirre et al. 2001).

Works for all (?) disk rotation curves: won / lost / tied = 84 / 0 / 11 (S. McGaugh).

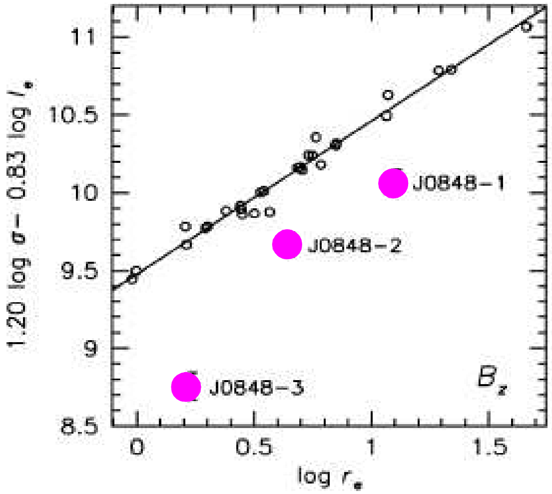
Spheroids: the Fundamental Plane

Velocity dispersion scales with effective radius and mean surface brightness.



$$R_{\mathrm{eff},K} \propto \sigma^{1.5} \langle\Sigma_K\rangle_{\mathrm{eff}}^{-0.8}$$

Pahre et al. (1998a)



van Dokkum & Stanford (2003)

Questions related to galaxy formation:

- **Exactly why isn't the dependence virial ($\propto \sigma^2 \langle\Sigma_K\rangle^{-1}$):**
  - **stellar *M/L* only (Mobasher et al. 1999; Gerhard et al. 2001)?**
  - **dynamical homology breaking (Pahre et al. 1998b)?**
- **Where on the FP do mergers evolve (Naab et al. 1999; Tacconi et al. 2002)?**

Spheroids: the "Photometric Plane"

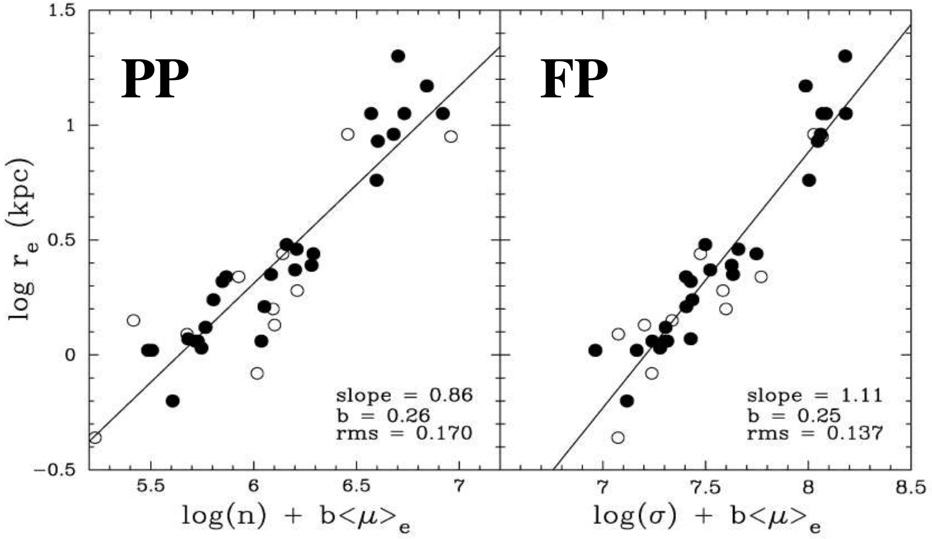
Not all spheroids follow a de Vaucouleurs (1948) $r^{1/4}$ law in intensity: many follow a generalized Sersic (1968) $r^{1/n}$ law (with $n \neq 4$).

Sersic index scales with effective radius and mean surface brightness:

$$\boxed{R_{\mathrm{eff},K} \propto n_K^{5.8} \langle\Sigma_K\rangle_{\mathrm{eff}}^{-1.0}}$$

(Khosroshahi et al. 2000)

Empirically: a "poor man's FP".

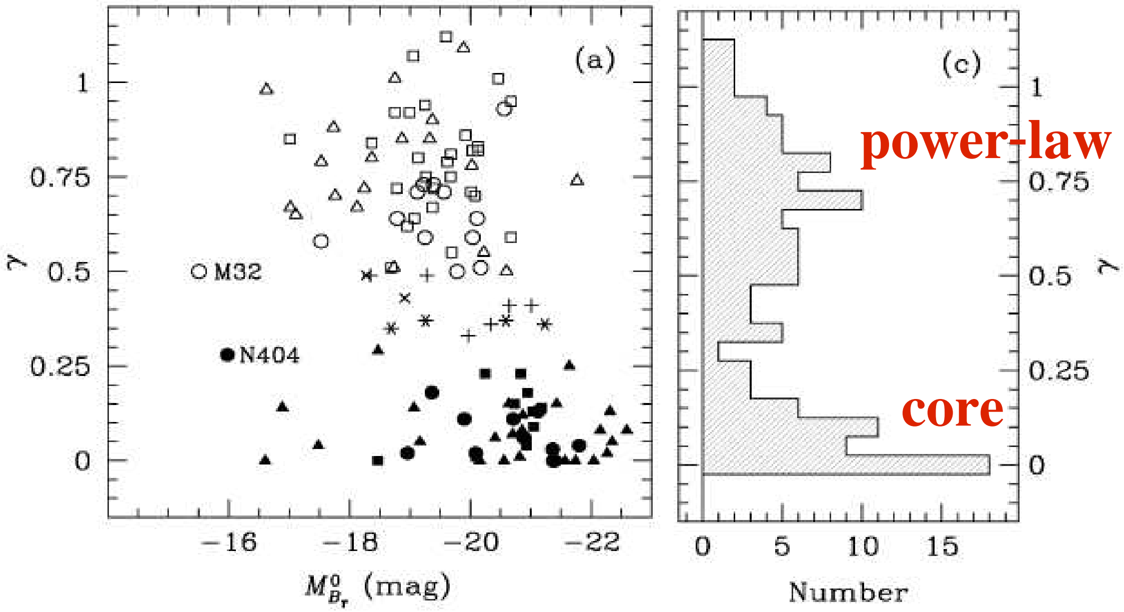


Graham (2001)

Nuclei: inner slope vs. global parameters

For ellipticals: Nuker law inner slope γ defined by $I(r) \propto r^{-\gamma}$ at small r.

$\gamma \geqslant 0.5 \Leftrightarrow$ disky, low L
$\gamma \leqslant 0.3 \Leftrightarrow$ boxy, high L



power-law

core

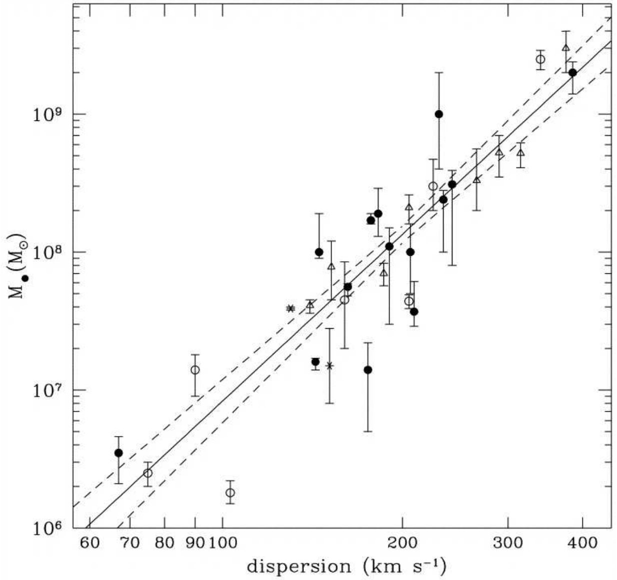
Ravindranath et al. (2001)
(Faber et al. 1997; Rest et al. 2001)

Questions related to galaxy forma

- **–Is the distribution of γ bimodal?**
- **–What drives the trend:**
    - **–adiabatic BH growth (van der Marel 1999)?**
    - **–binary BH scouring (Milosavljevic & Merritt 2001; Ravindranath et al. 2002)?**

Nuclei: black hole mass vs. σ and *n*

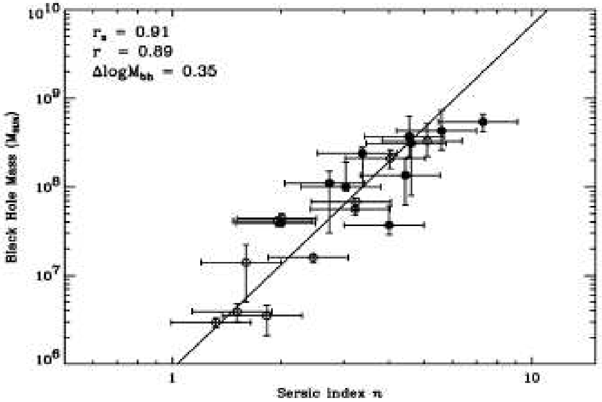
Black hole mass scales with velocity dispersion...



Tremaine et al. (2002)

$$M_{\mathrm{BH}} \propto \sigma^{4.0}$$

...and with Sersic index.



Erwin et al. (2003)

$$M_{\mathrm{BH}} \propto n_R^{?}$$

What form of coevolution drives this correlation?

- **–SF regulated by AGN feedback (Silk & Rees 1998; Wyithe & Loeb 2003)?**
- **–BH growth regulated by SF competition (Burkert & Silk 2001)?**
- **–BH mass set by angular momentum of proto-bulge (Adams et al. 2003)?**

Galaxy evolution: follow the baryons!

Three processes to keep track of:

- gas → stars
- stars → galaxies
- baryons → black holes

Two ways to track each process as a function of redshift:

- measure a rate
- measure a formed/assembled/accreted mass

$$\frac{d^2 M_i(z)}{dV\,dt} \qquad \frac{dM_i(z)}{dV}$$

(M_i denotes a mass *bin*, because we are interested in distributions)

Gas → stars: rest-UV selected galaxies

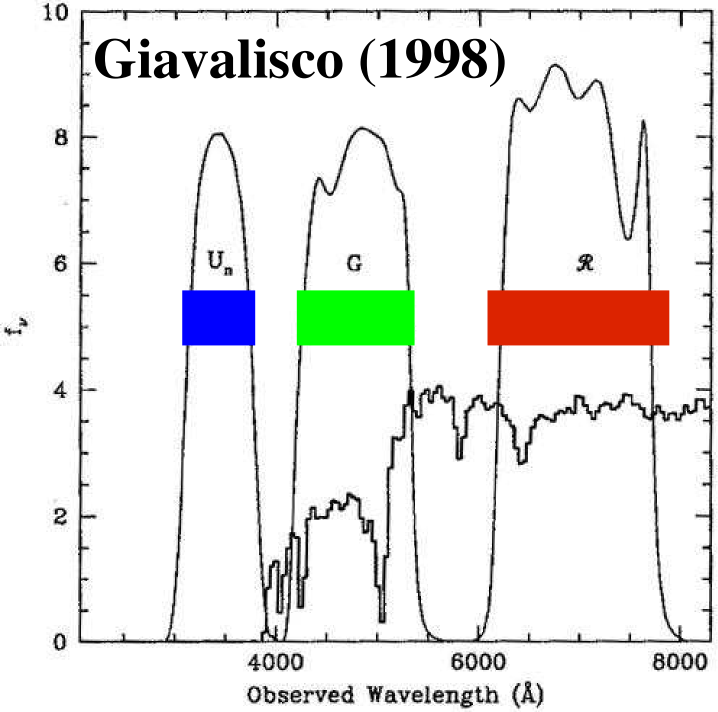
Lyman break technique works at

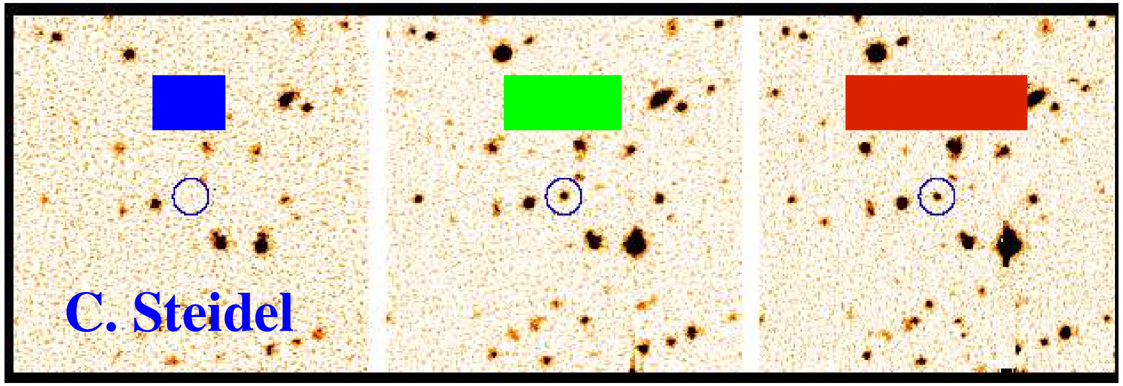
$z \sim 1$: GALEX

$z \sim 3$: Steidel et al. (1996)

$z \sim 4$: Steidel et al. (1999)

$z \sim 5$: Lehnert & Bremer (2003)





$z \sim 3$ Lyman break galaxies = *U*-band dropouts

Stellar masses: mid-infrared photometry (e.g., SIRTF/MIPS: 3.8-8 μm) is key.

Star formation rates: correction for dust obscuration is key.

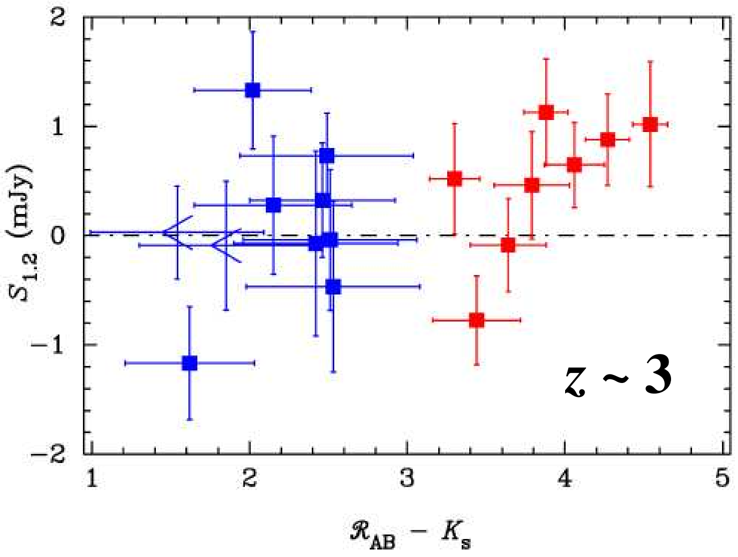
Faint sources ⇒ new bolometer arrays

Pushing the limits of current bolometer arrays (SCUBA and MAMBO):

Lyman break galaxies contribute 10-30% of the FIR background

(Peacock et al. 2000; Chapman et al. 2000; Webb et al. 2002)

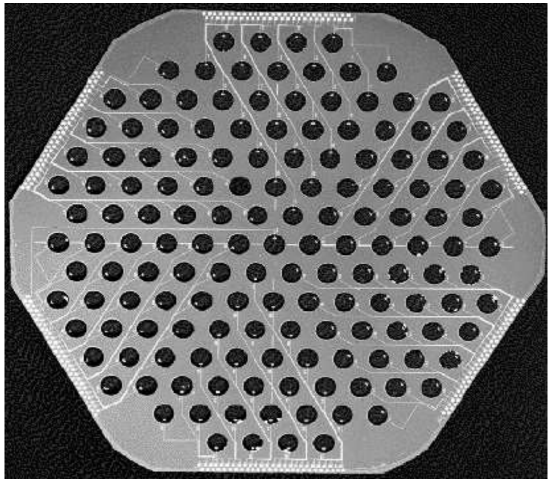
MAMBO at the IRAM 30m:



Baker et al. (2004)

BOLOCAM at the LMT/GTM 50m:

- **larger diameter**
- **active optics**
- **better site**

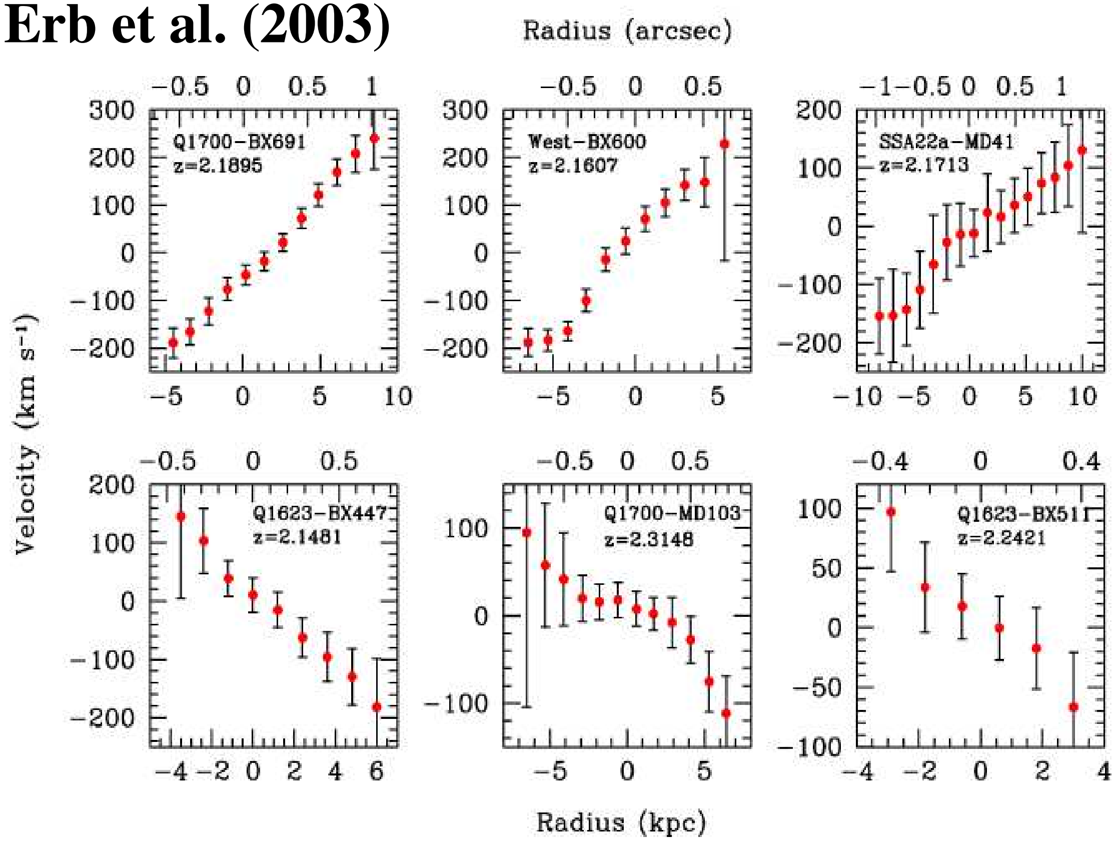


J. Glenn

Compact disks ⇒ AO and/or JWST

Resolved velocity gradients more common at *z* ~ 2 than at *z* ~ 3.

Erb et al. (2003)



z ~ 2 Lyman break galaxies

Hα observed with Keck/NIRSPEC

To watch the development of the Tully-Fisher relation at the epoch of disk formation:

- **–high spatial resolution**
- **–good tracers of SF and galaxy dynamics**

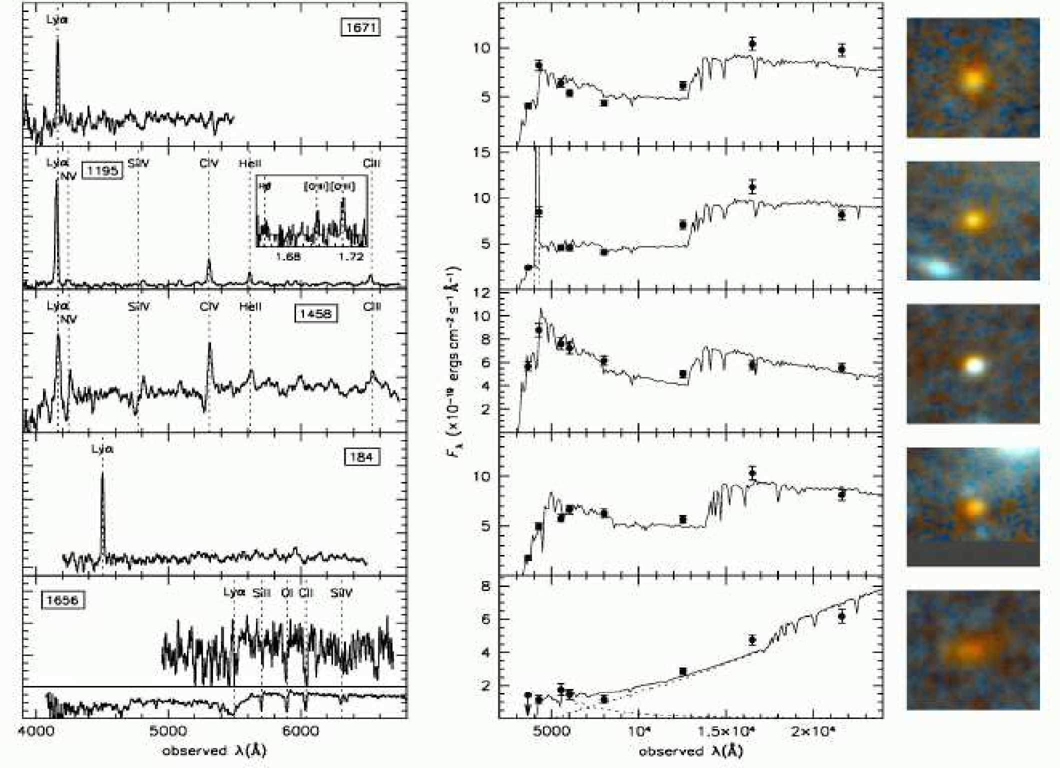
⇒ nebular emission lines in the near-IR (e.g., AO + JWST/NIRCam)

Gas → stars: rest-optical selected galaxies

FIRES galaxies selected with $J_s - K_s > 2.3$ (Franx et al. 2003):

- **–$< z >$ ~ 2.7; stellar populations > 300 Myr old**
- **–volume density ~ half volume density of LBGs**
- **–stellar mass density ~ stellar mass density of LBGs**

van Dokkum et al. (2003)



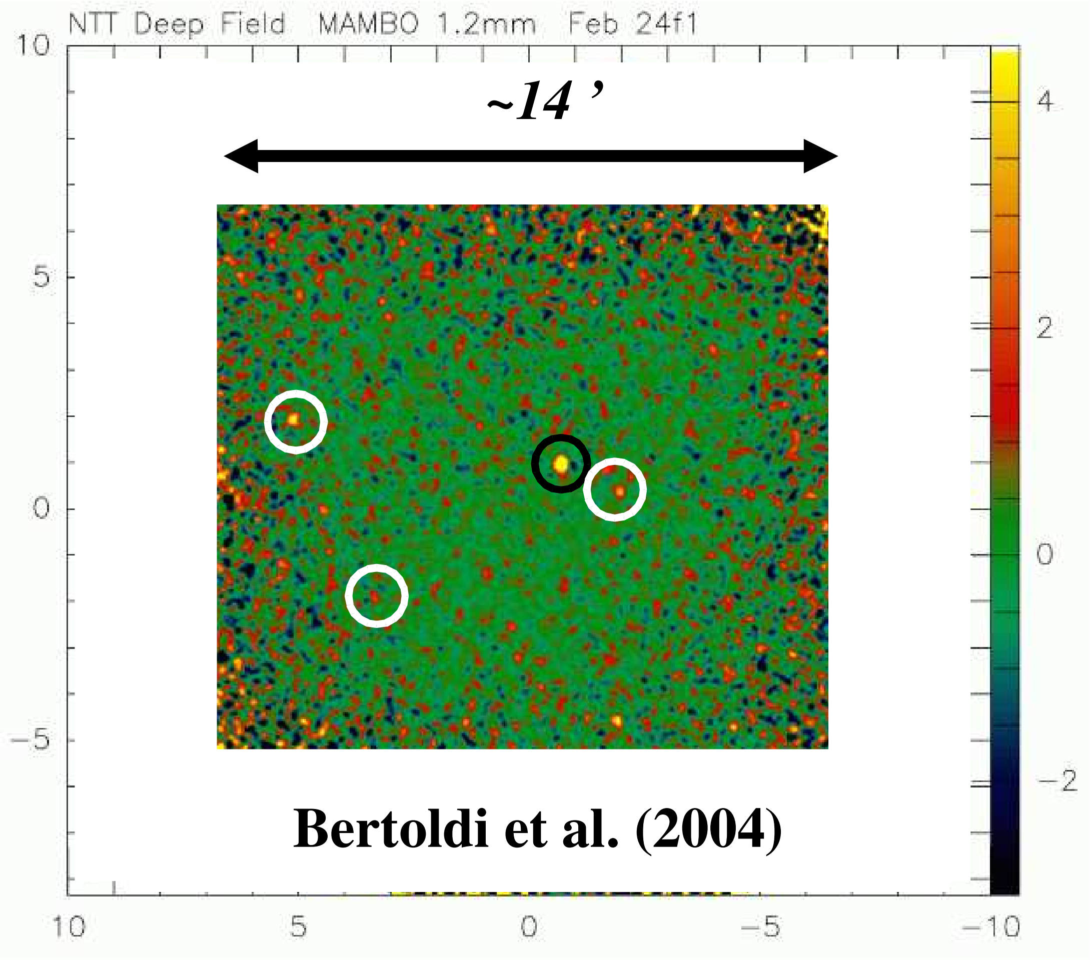
rest-UV spectra (Keck/LRIS)

rest-UV/optical SEDs (VLT)

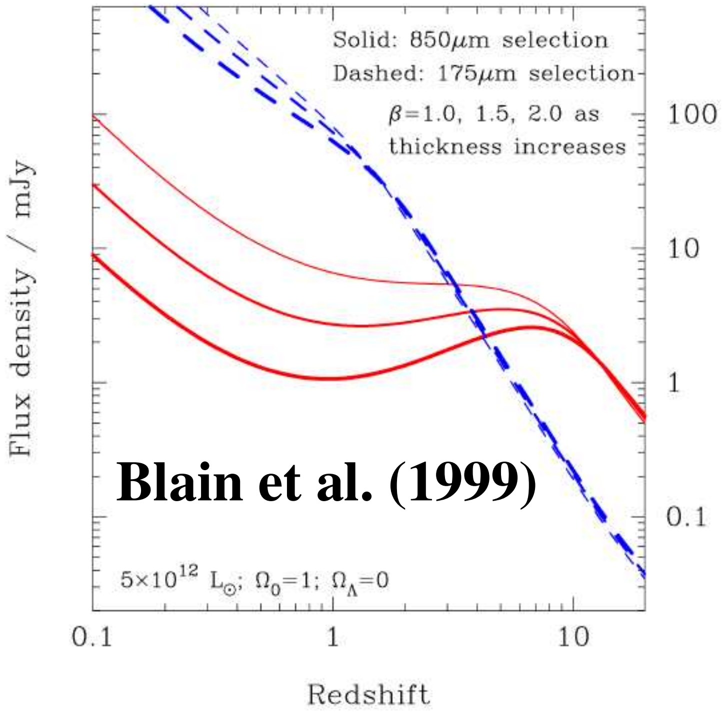
R_{AB} + K_s images

Gas → stars: rest-FIR selected galaxies

Submillimeter galaxies: rare but luminous starbursts (and AGN?).



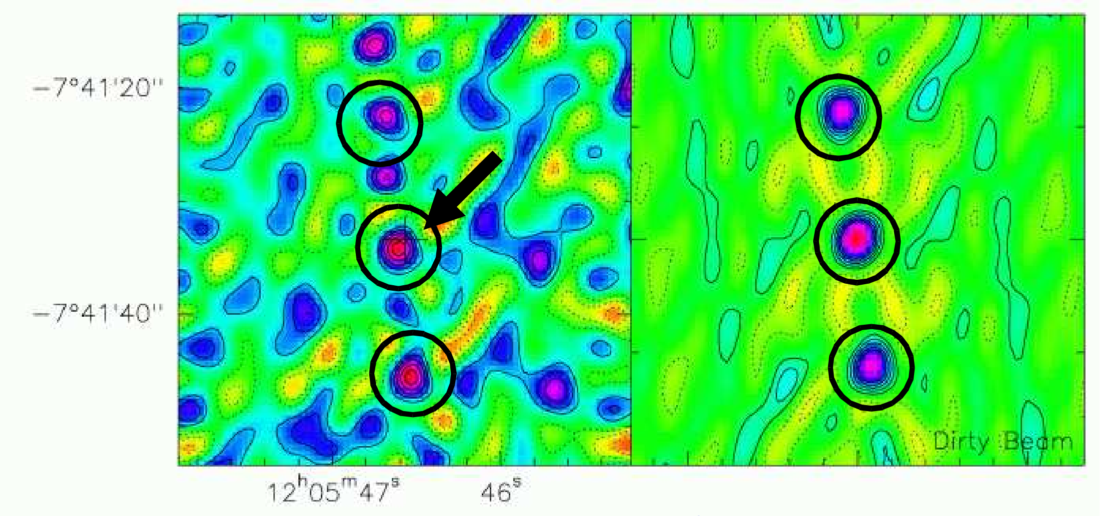
Bertoldi et al. (2004)

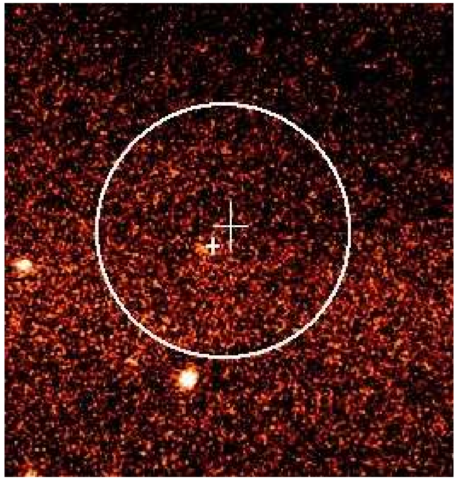


Blain et al. (1999)

Generally poor constraints on position and redshift.

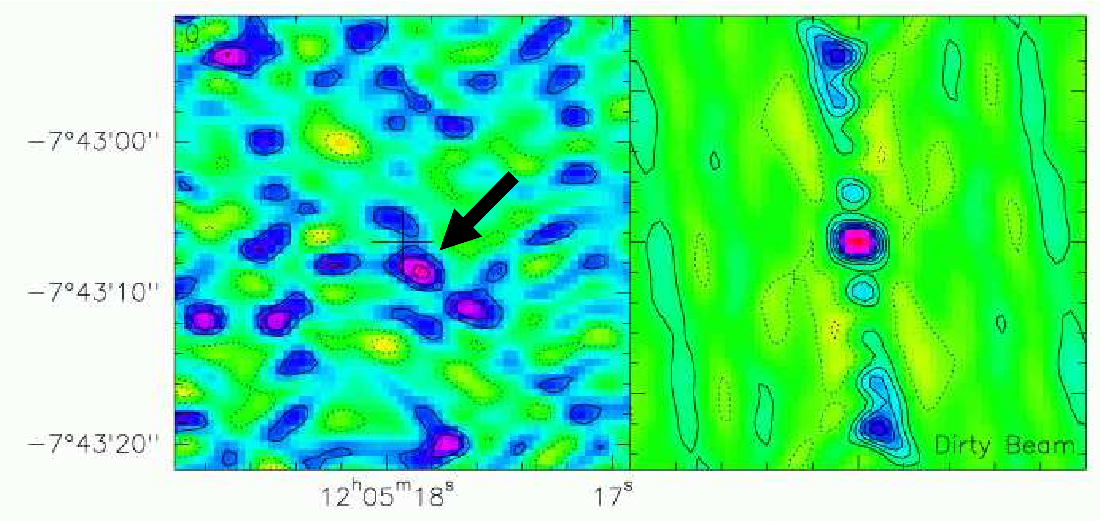
Optical/radio counterparts are faint!

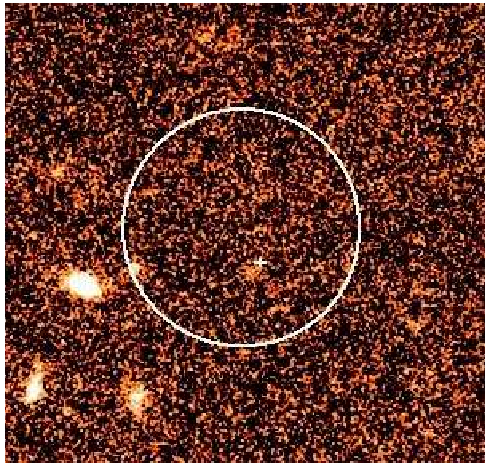




K_s = 21.9

PdBI 1mm data **point source response** **VLT/ISAAC imaging**

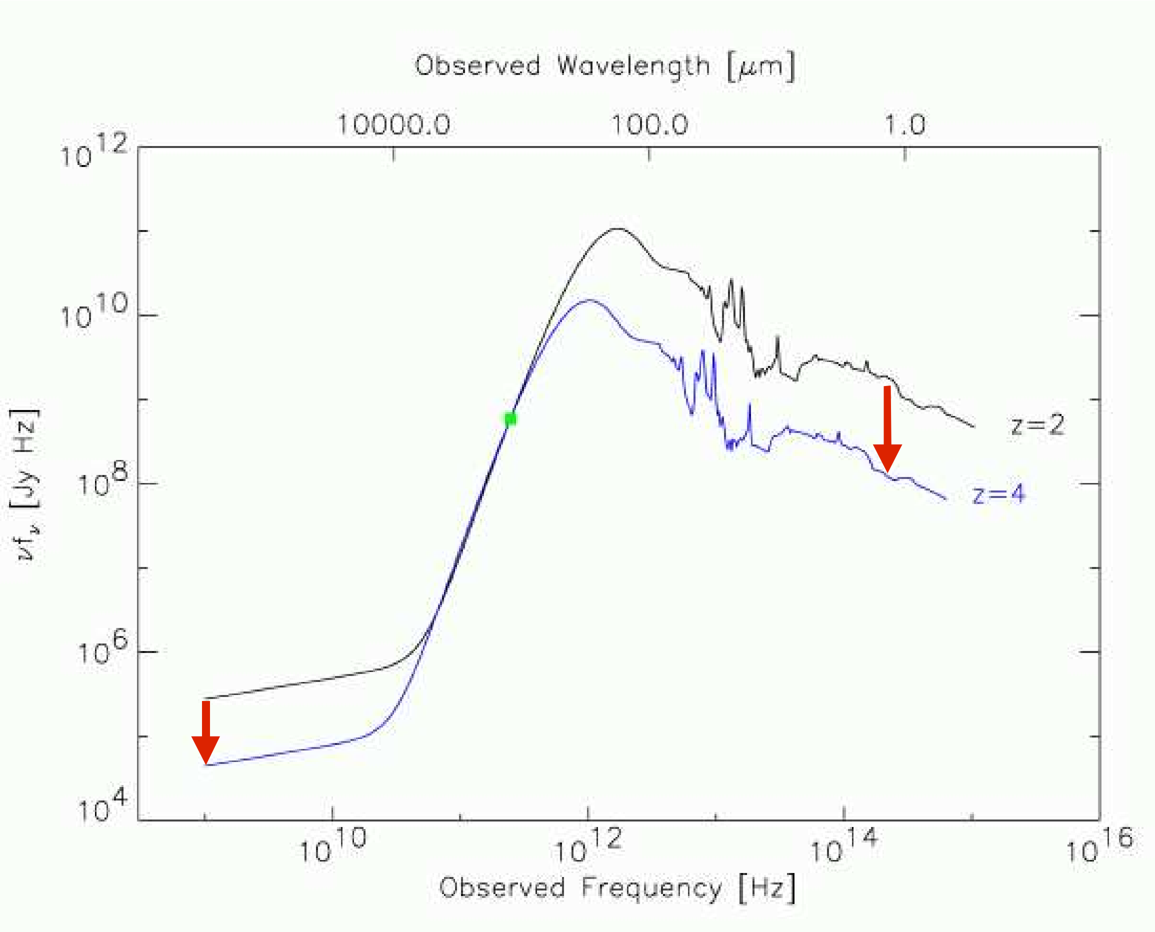




K_s = 22.5

Dannerbauer et al. (2002)

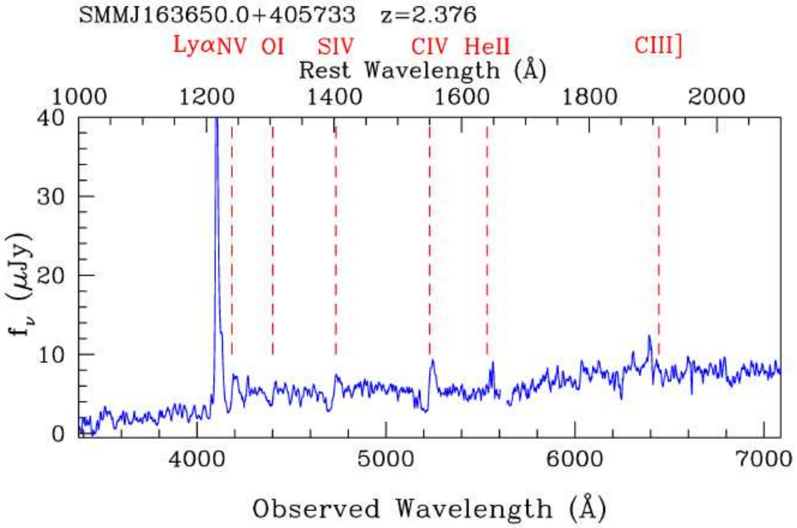
IDs toughest at the highest redshifts



For the same submillimeter flux: higher *z* ⇔ fainter radio and optical.

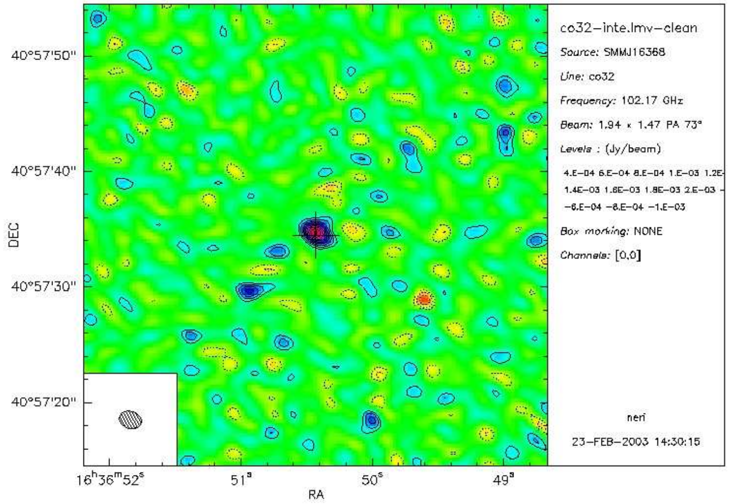
Current state of the art

Keck/LRIS-B redshifts for submillimeter galaxies with VLA positions...



Chapman et al. (2003)

... confirmed by PdBI CO maps.



Neri et al. (2003)

So far: ~6 new submillimeter galaxies have been detected in CO ($<z> \sim 2.4$).

Future state of the art

Rare sources ⇒ map wider fields at more wavelengths.

–today: MAMBO + SCUBA

–future: BLAST (2004) + LABOCA (2004)

+ BOLOCAM (2005) + SCUBA2 (2005) + SPIRE (2007)

Positional uncertainty ⇒ obtain more sensitive interferometry.

–today: VLA + PdBI + OVRO

–future: EVLA Phase I (2006-9) + ALMA (2006-10)

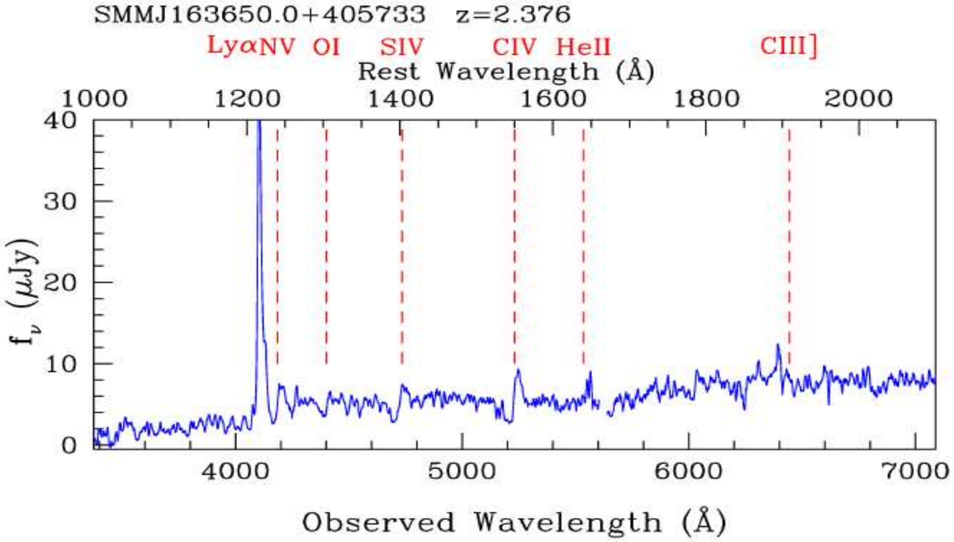
Too obscured for optical redshifts

⇒ build a dedicated CO "*z* machine".

Wanted: high fractional bandwidth

For LRIS-B: Δλ/λ ~ Δz/(1+z) ~ 0.7

For PdBI: Δλ/λ ~ Δz/(1+z) ~ 0.006
(~30Å coverage in optical!)



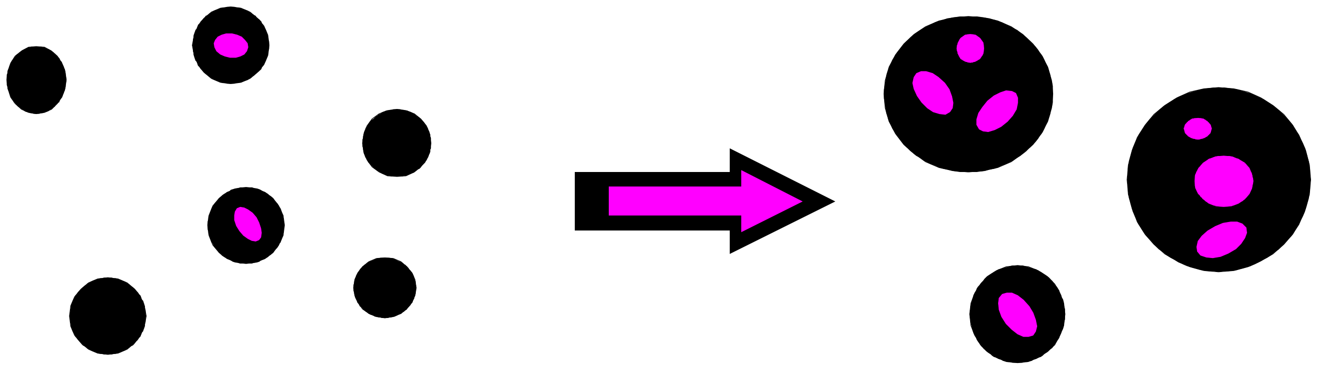
Chapman et al. (2003)

Need to increase instantaneous millimeter Δν from 600 MHz to > 30 GHz;
designs under consideration at LMT and GBT.

Stars → galaxies: total baryonic masses

Cold Dark Matter halos collapse and merge.

Baryonic matter collapses to form galaxies within the halos.



M_{bary} observations at high redshift represent a

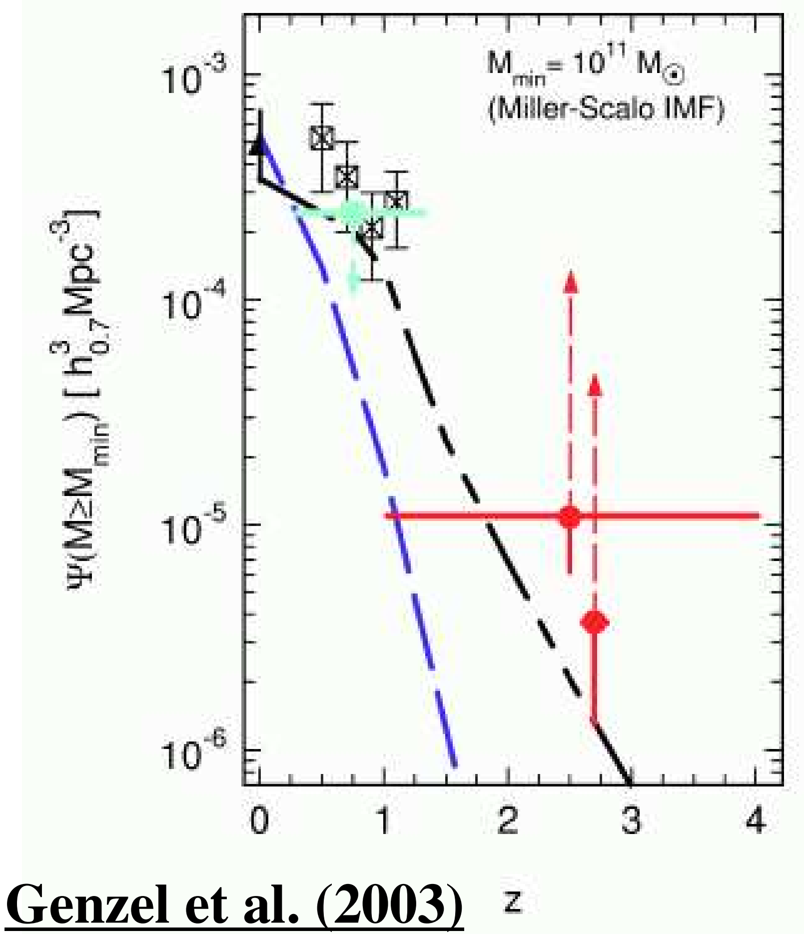
baryonic mass assembly test

for theoretical models of the evolution of Ω_b.

Applied to stellar masses of optical/NIR-selected galaxies:
Cimatti et al. (2002); Daddi et al. (2003); Saracco et al. (2003).

The mass assembly test at $10^{11}\,M_\odot$

Standard ΛCDM parameters for halo evolution; different baryonic physics.



Genzel et al. (2003)

Semi–analytic model predictions:

Baugh et al. (2002)	**"Durham"**
Kauffmann et al. (1999)	**"Munich"**

Observations:

Cole et al. (2001)	**2dF/2MASS**
Drory et al. (2002)	**MUNICS**
Rigopoulou et al. (2002)	***ISO* HDF–S**

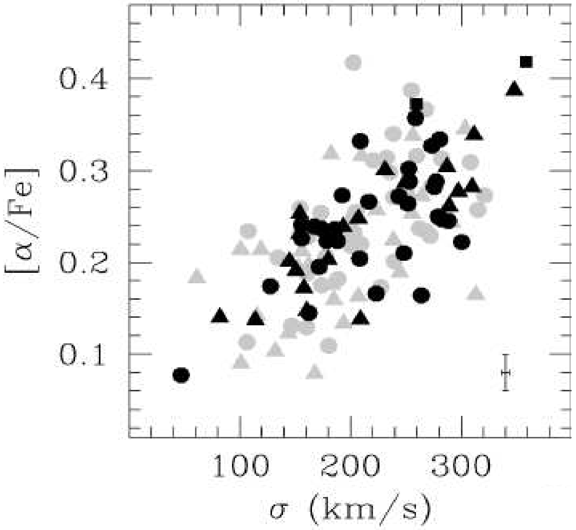
Lower point: two SCUBA galaxies with measured dynamical masses

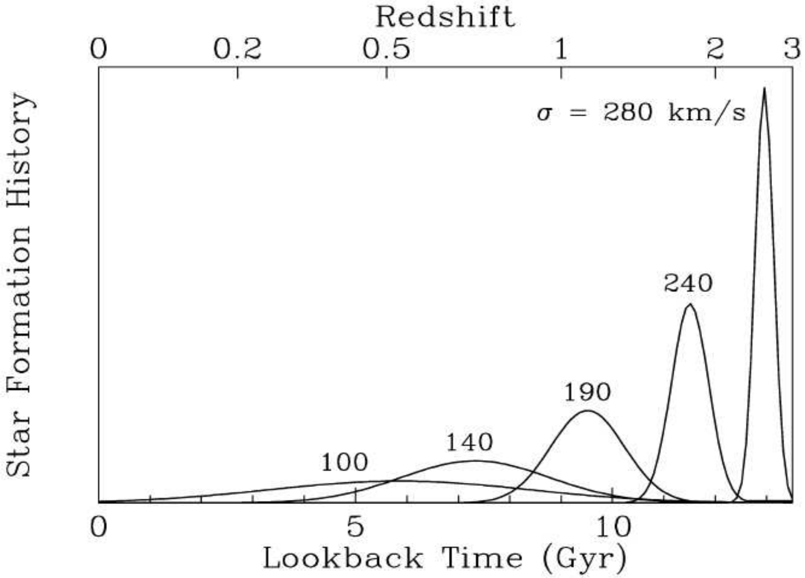
Upper point: all six bright sources from same survey (Ivison et al. 2000)

Stars → galaxies: fossil evidence at *z* ~ 0

Abundance ratios in *z* ~ 0 ellipticals:
[α/Fe] enhancement increases with age and σ.

A flattened IMF has trouble explaining both!





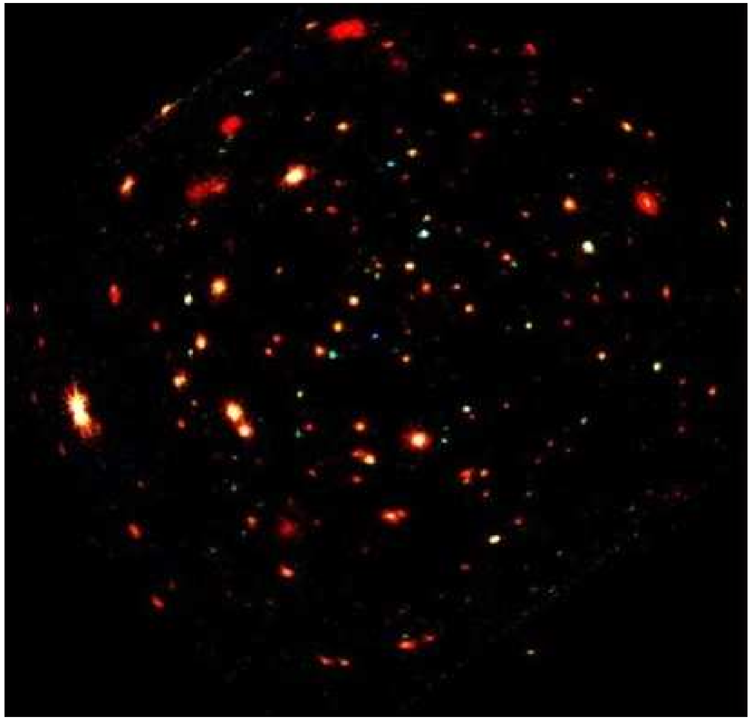
Thomas et al. (2003)

Implication: more massive ellipticals
did not formed more recently, but
formed longer ago in more rapid bursts.

Baryons → black holes: accretion rates

80% of the 0.1-10 keV background is resolved.

However, 50% of the energy flux in the X-ray background emerges at 20-70 keV.



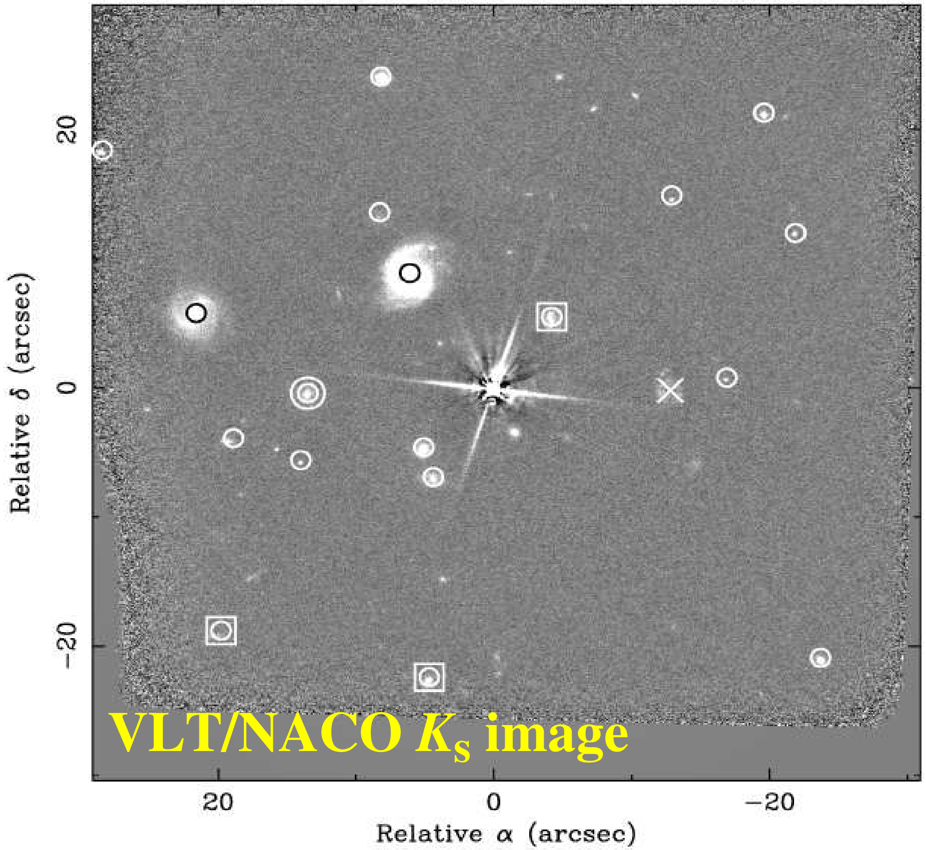
Lockman Hole with XMM-Newton (Hasinger et al. 2001)

To constrain accretion rates in obscured AGN, need high-resolution imaging at harder energies.

SIMBOL-X (20'' resolution, 0.5-70 keV) in 2010?

Baryons → black holes: $\{M_{\mathbf{BH}}\}$ at high z

Principal idea: exploit the local scaling relations using AO.



Viehhauser et al. (2003)

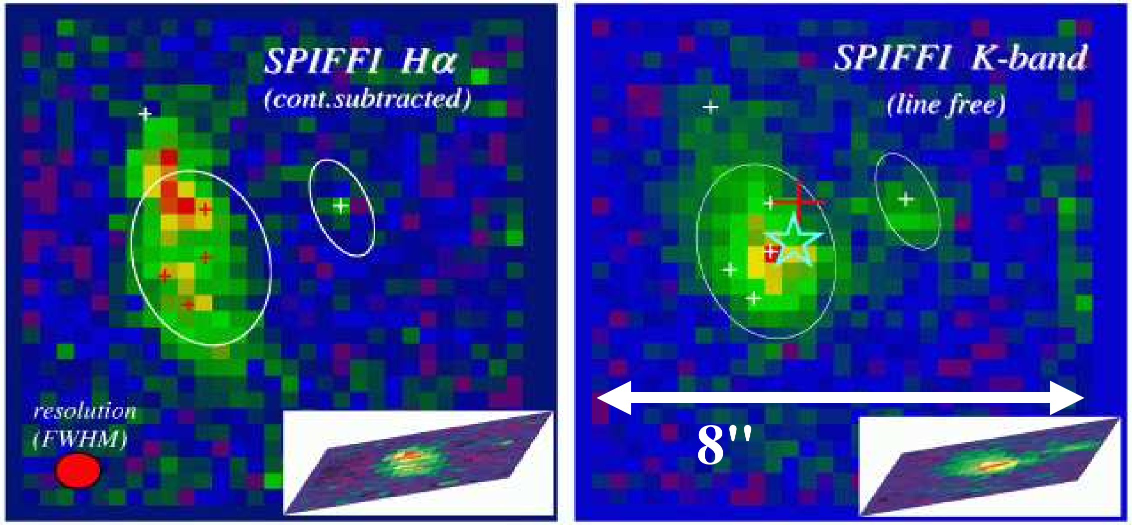
Provided that $M_{BH}-n$ is really as tight as $M_{BH}-\sigma$ ...

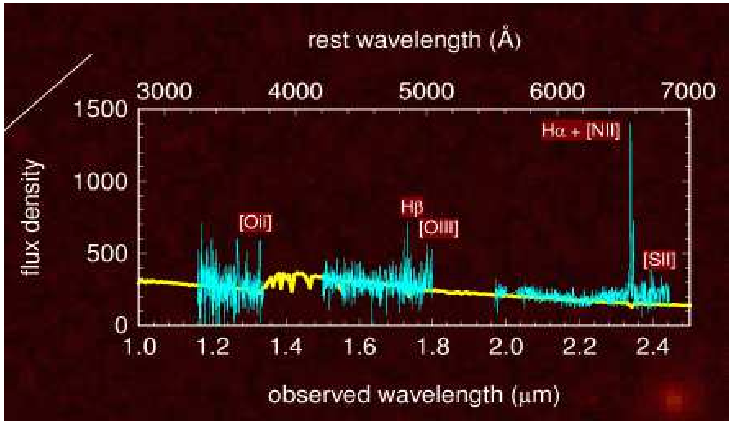
... we can constrain the black hole mass function at a given redshift from the observed distribution of $\{n\}$.

(VLT → ELT will make this easier.)

Challenge #1: 3D datasets

Integral field units on large telescopes (Keck/OSIRIS, VLT/{VIMOS, KMOS, SINFONI}, etc.) are increasingly popular for good reason: they facilitate spatially resolved abundance and dynamics studies.



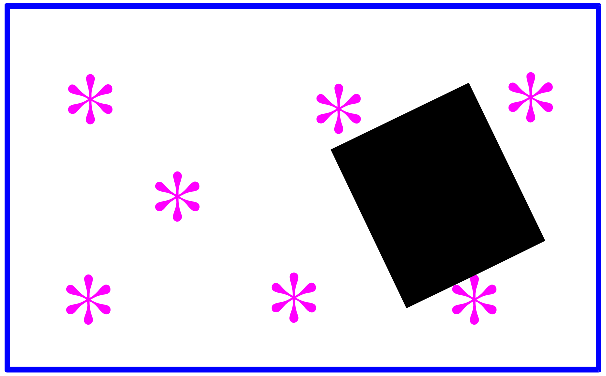


Tecza et al. (2004)

VLT/SPIFFI observations of SMM J14011+0252 ($z = 2.565$)

It can be tough to make full use of all three dimensions (i.e., resist the temptation just to compress 3D data into a 2D paper!).

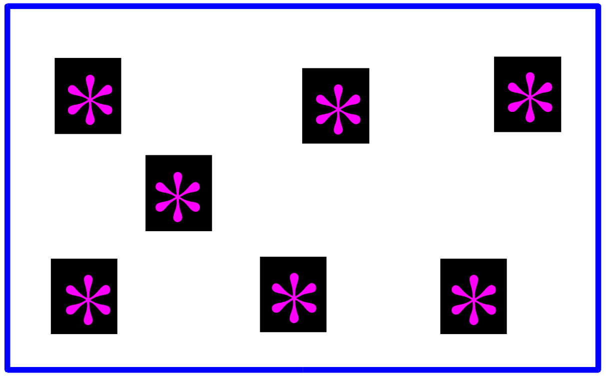
Challenge #2: cosmology with AO



No bright natural guide stars in deep fields.

Hard(ware) solution: construct a laser guide star.

Easy solution: construct a discrete deep field
(Larkin & Glassman 1999; Baker et al. 2003).



PSF varies across the field.

Hardware solution:
build multi-conjugate AO (MCAO) system
(may work without lasers on ELTs).

Software solution:
post-process using wavefront sensor
data or empirical calibration techniques.

Greatest scientific payoff will focus on faint, red, compact [pieces of] objects.

Summary

Galaxy evolution models that do not reproduce the $z = 0$ scaling relations are incomplete or wrong.

New instrumentation will allow us to improve constraints on the rates and results of star formation, galaxy assembly, and accretion as a function of redshift.

New instrumentation comes with new challenges.

(P.S. Frank: please retire again next year!)