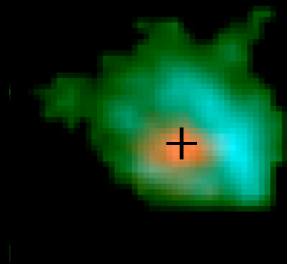
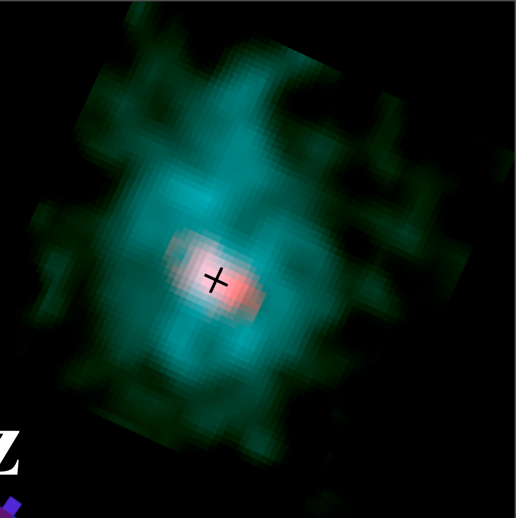
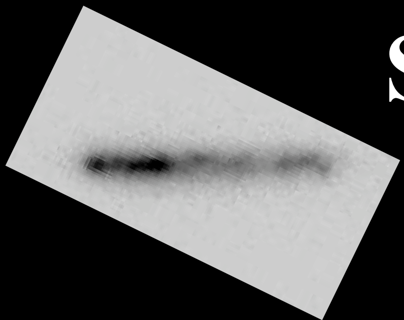


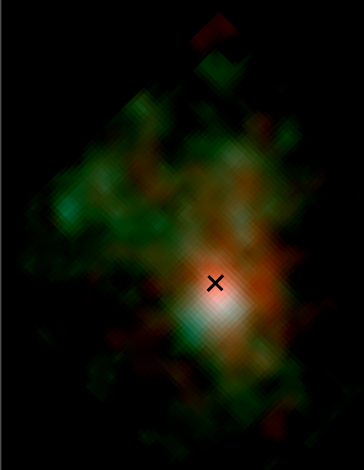


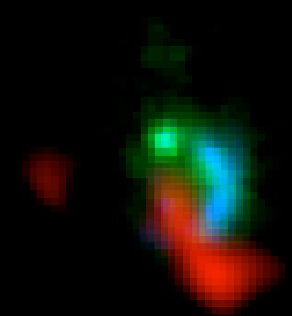


Star Formation at high-z

global properties

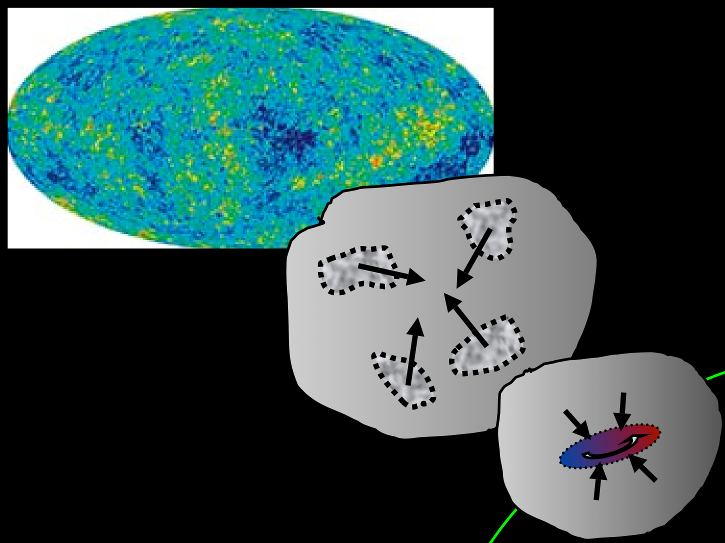
a look at the 'standard' picture
submillimeter galaxies & maximum starbursts
major mergers & disks
implications for galaxy evolution
comments on high-z IMF

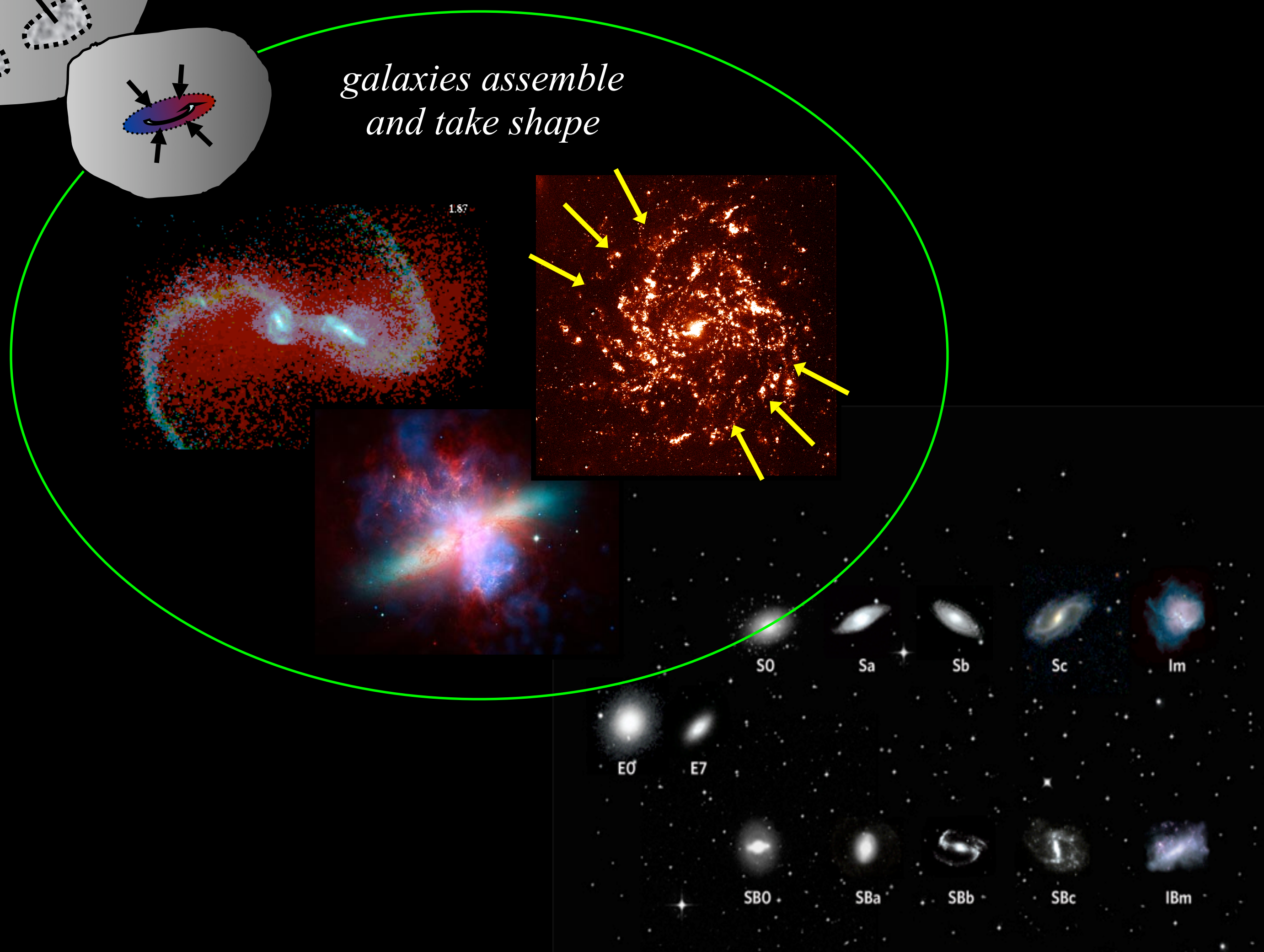


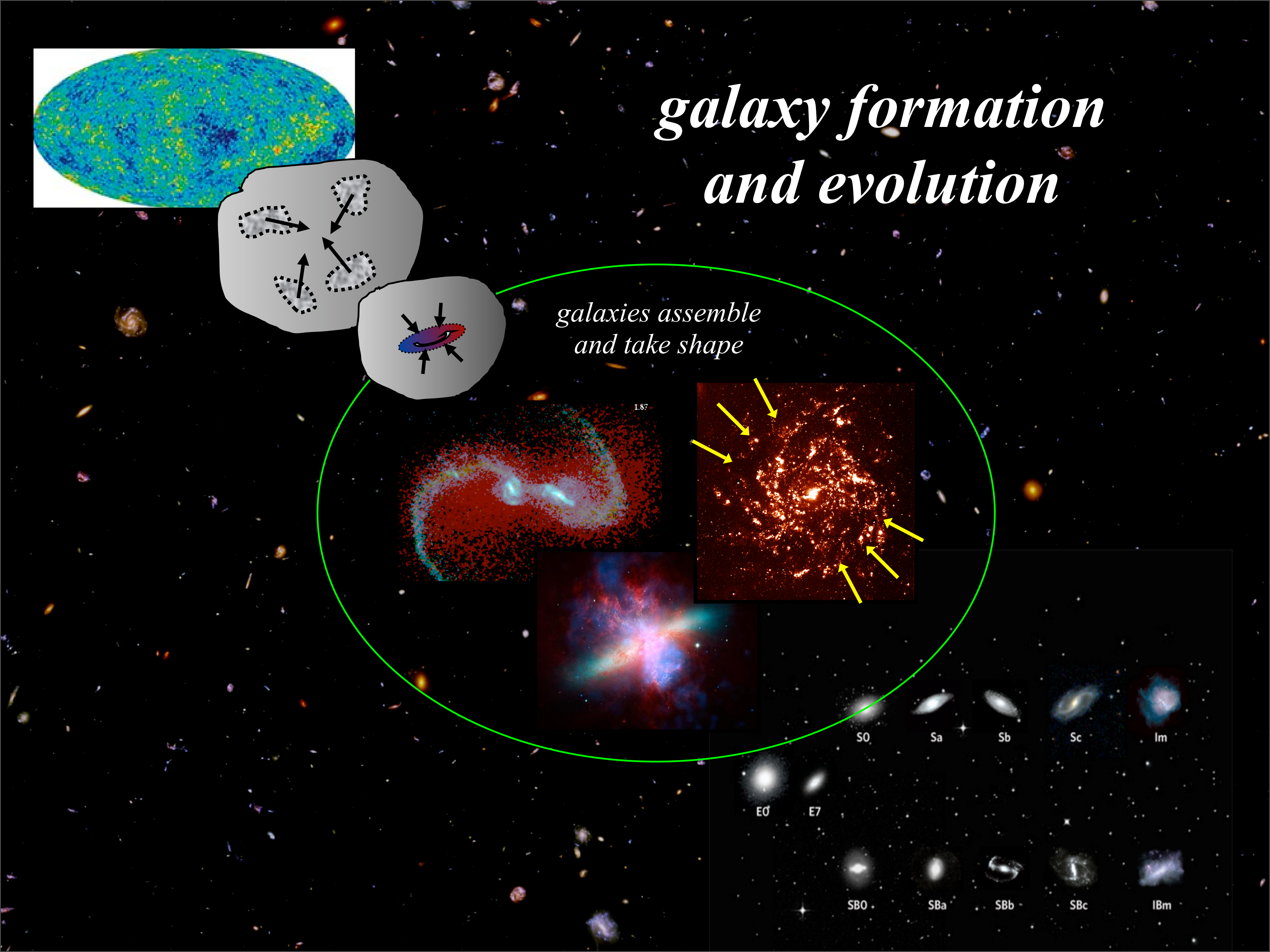


apologies: this talk is based on <10% of the scientific literature in this very active field over the past few years. As such, it is incomplete & probably unbalanced !

galaxy formation and evolution






galaxy formation
and evolution
galaxies assemble
and take shape
1.87
S0
Sa
Sb
Sc
Im
E0
E7
SB0
SBa
SBb
SBc
IBm

predictions from semi-analytic models: evolution of massive (M_*) spheroids

Millemium simulation merger trees + new Munich SAMs, with AGN feedback

de Lucia et al.
2006

Kauffmann et al. 1993, 1999, Primack & Somverville 1999, Baugh et al. 2000

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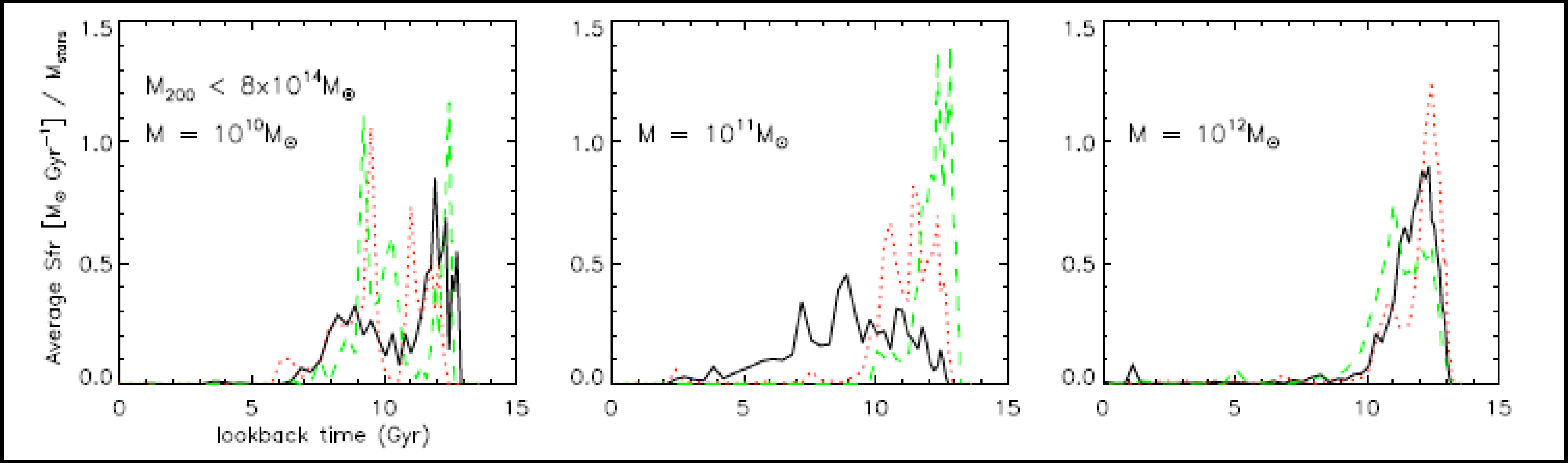

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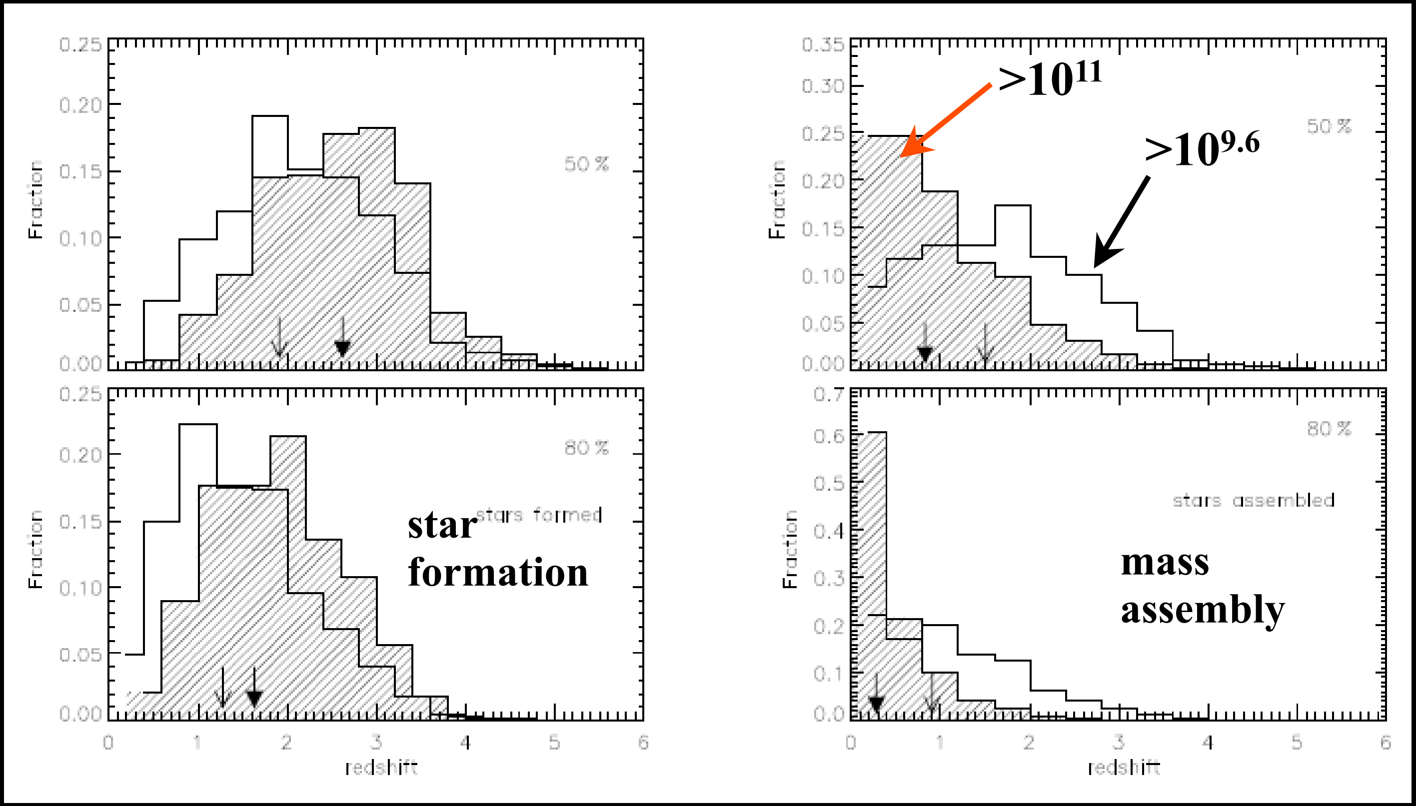
Kauffmann et al. 1993, 1999, Primack & Somverville 1999, Baugh et al. 2000

predictions from semi-analytic models: evolution of massive (M_*) spheroids

Millemium simulation merger trees + new Munich SAMs, with AGN feedback

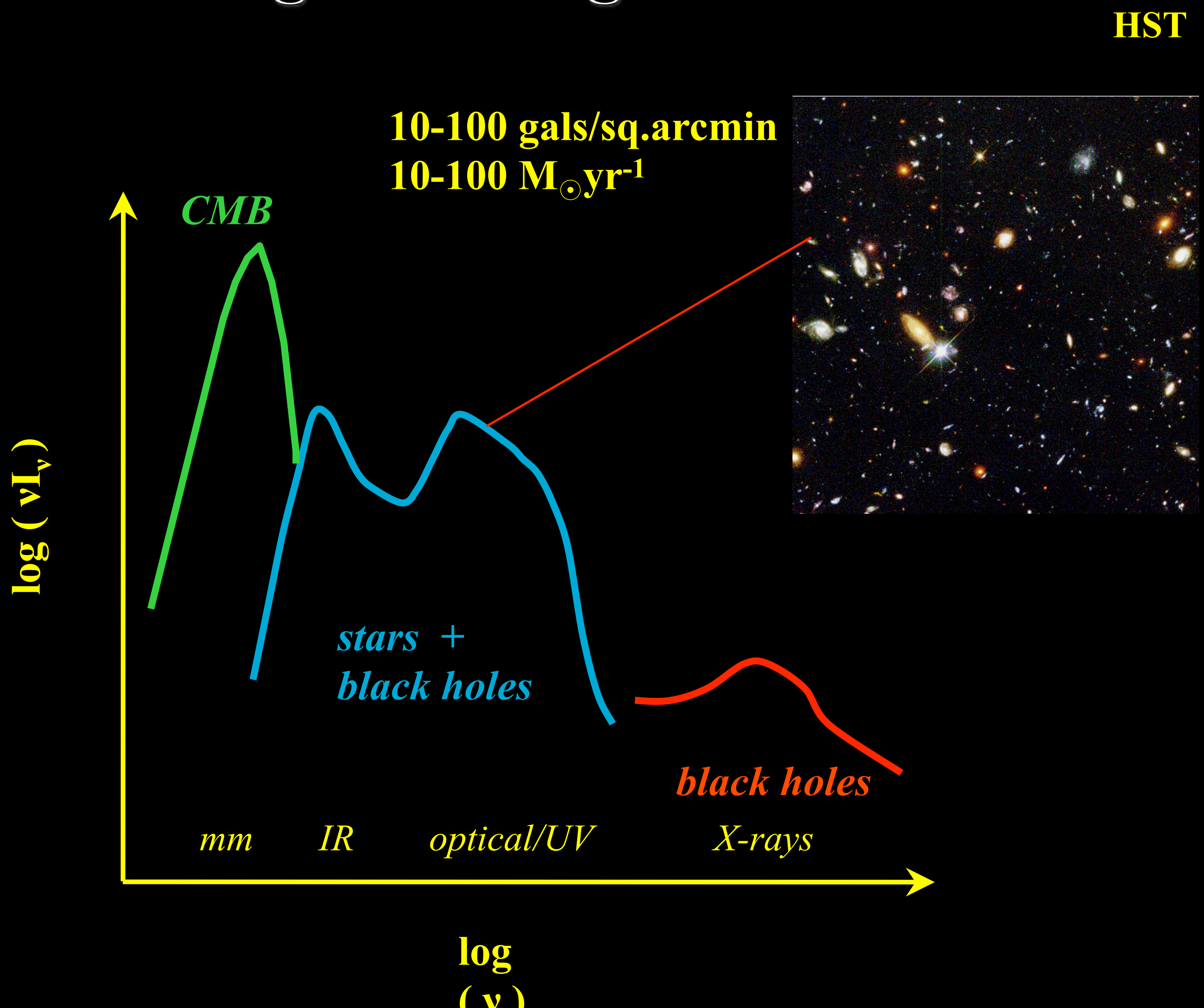
$t_{assembly}$ ~ 10 Gyrs >>$t_{star\ form}$ ~ 2-4 Gyr



de Lucia et al. 2006

Kauffmann et al. 1993, 1999, Primack & Somverville 1999, Baugh et al. 2000

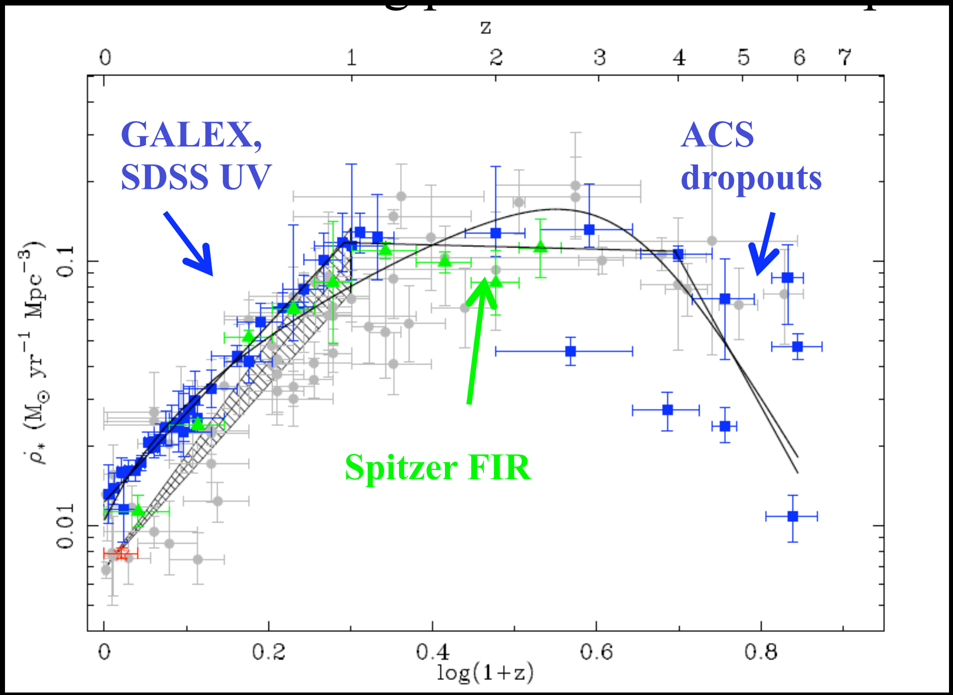
extragalactic backgrounds



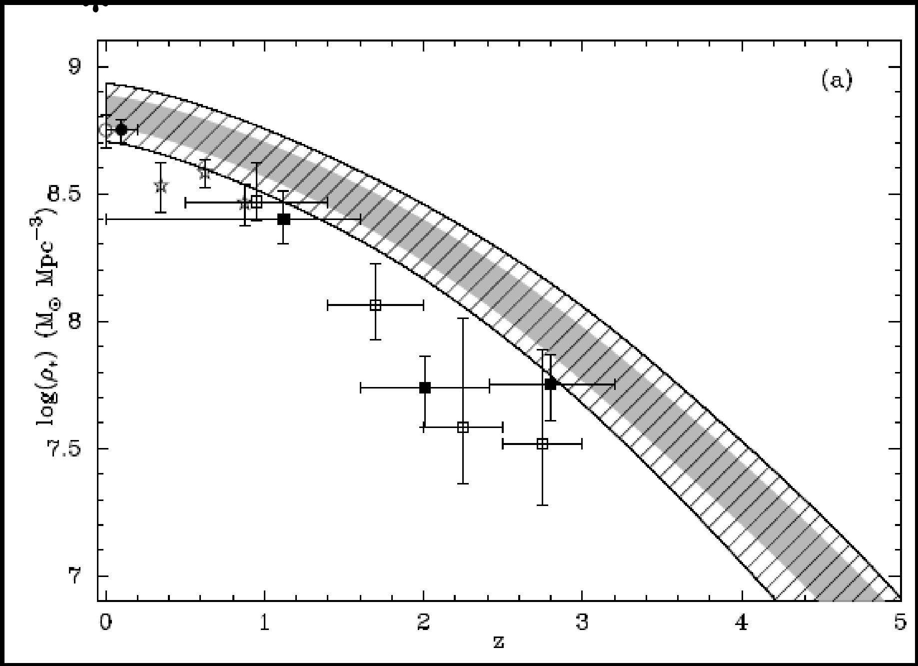
Aussel, Barger, Blain, Cowie, Cesarsky, Elbaz, Giacconi, Hasinger, Hughes, Ivison, Madau, Mushotzky, Pettini, Steidel, Williams, Beckwith, et al. 1996-2006

The cosmic star formation history

star formation history



mass assembly history

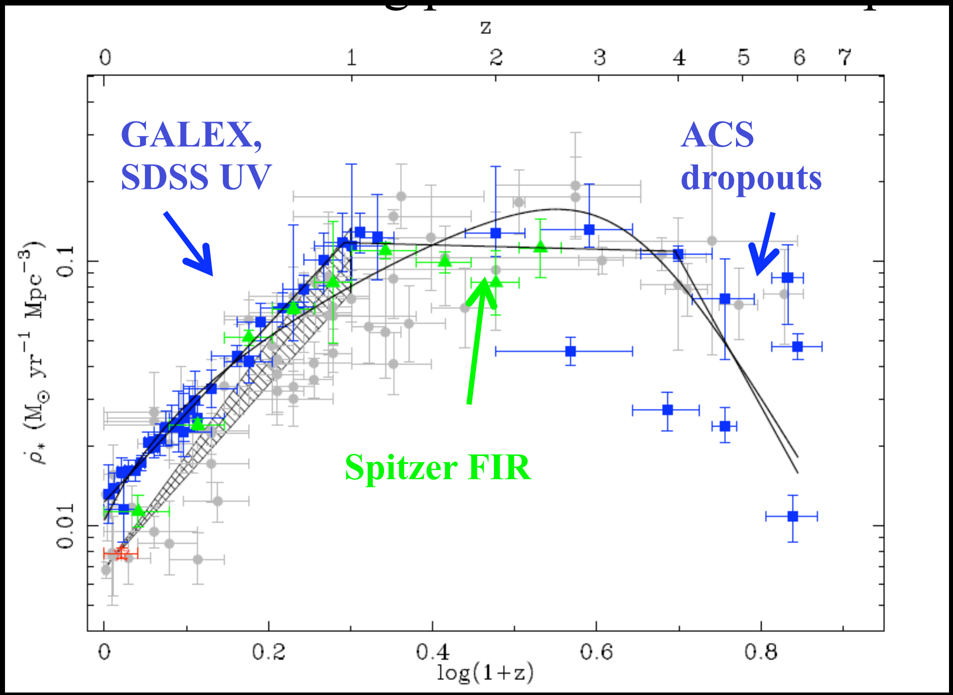


taken
from Hopkins 2006

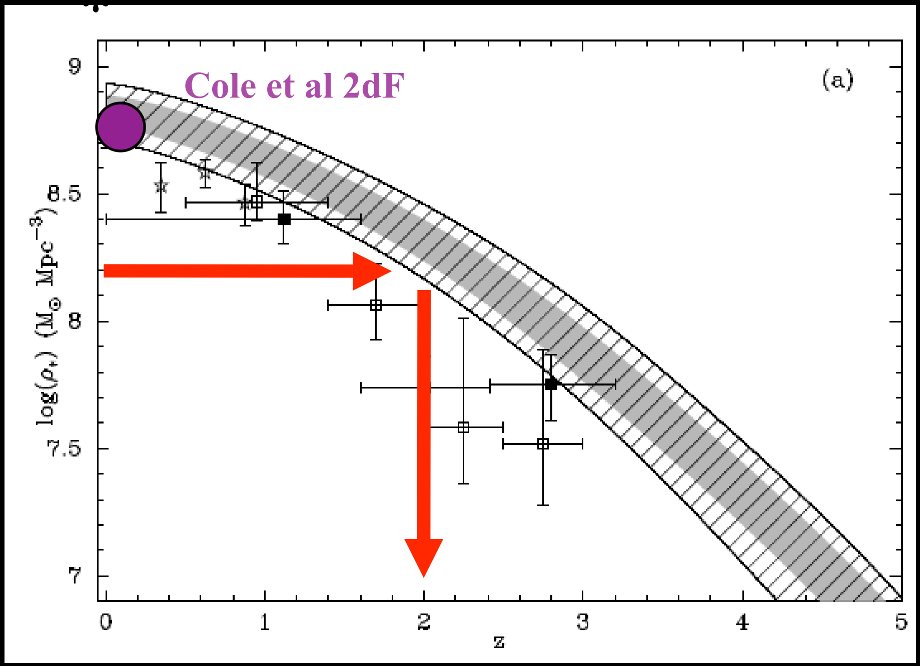
Steidel, Madau, Dickinson, Taniguchi, Cowie, Blain, Lilly et al. 1996….., Hopkins & Beacom 2006

The cosmic star formation history

star formation history



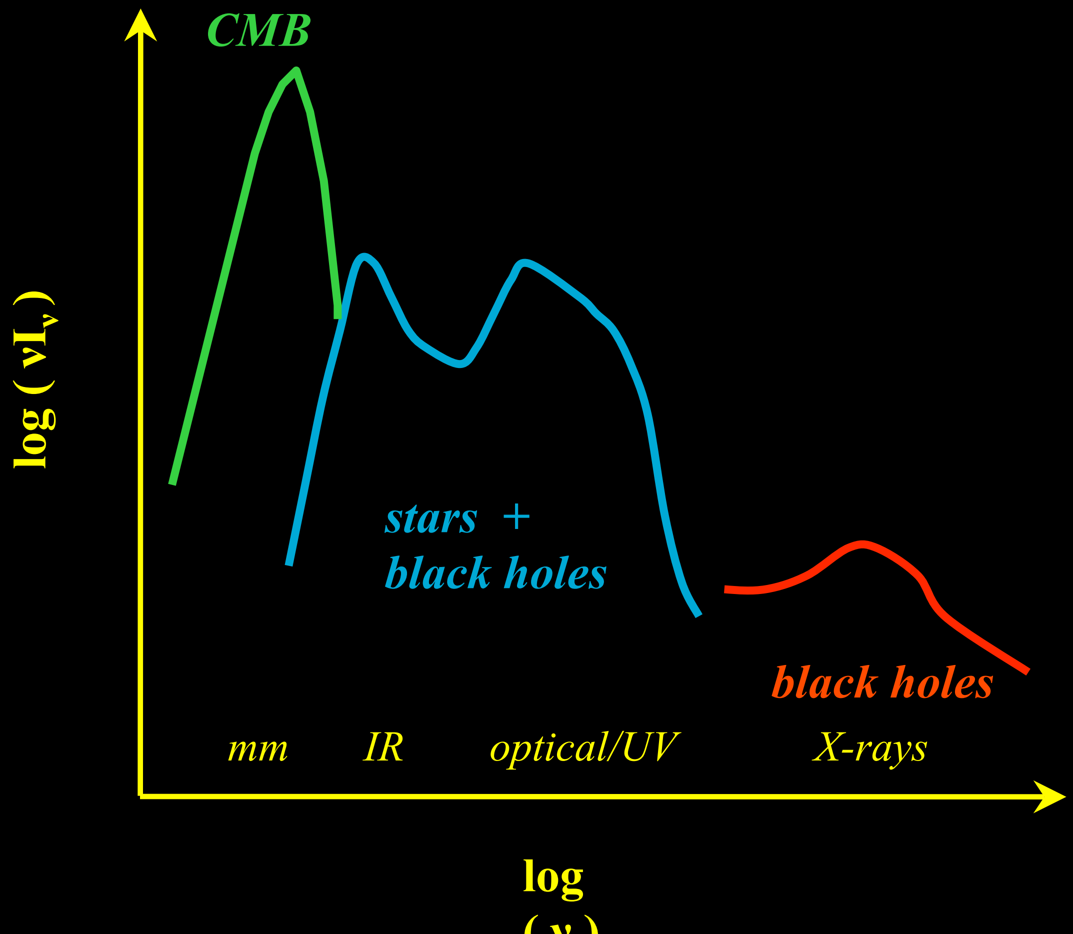
mass assembly history



- satisfactory agreement with local 2dF/2MASS mass density
- data suggests half the local mass in stars is in place at z~2 ± 0.2
- major uncertainties are IMF and luminosity-dependent extinction

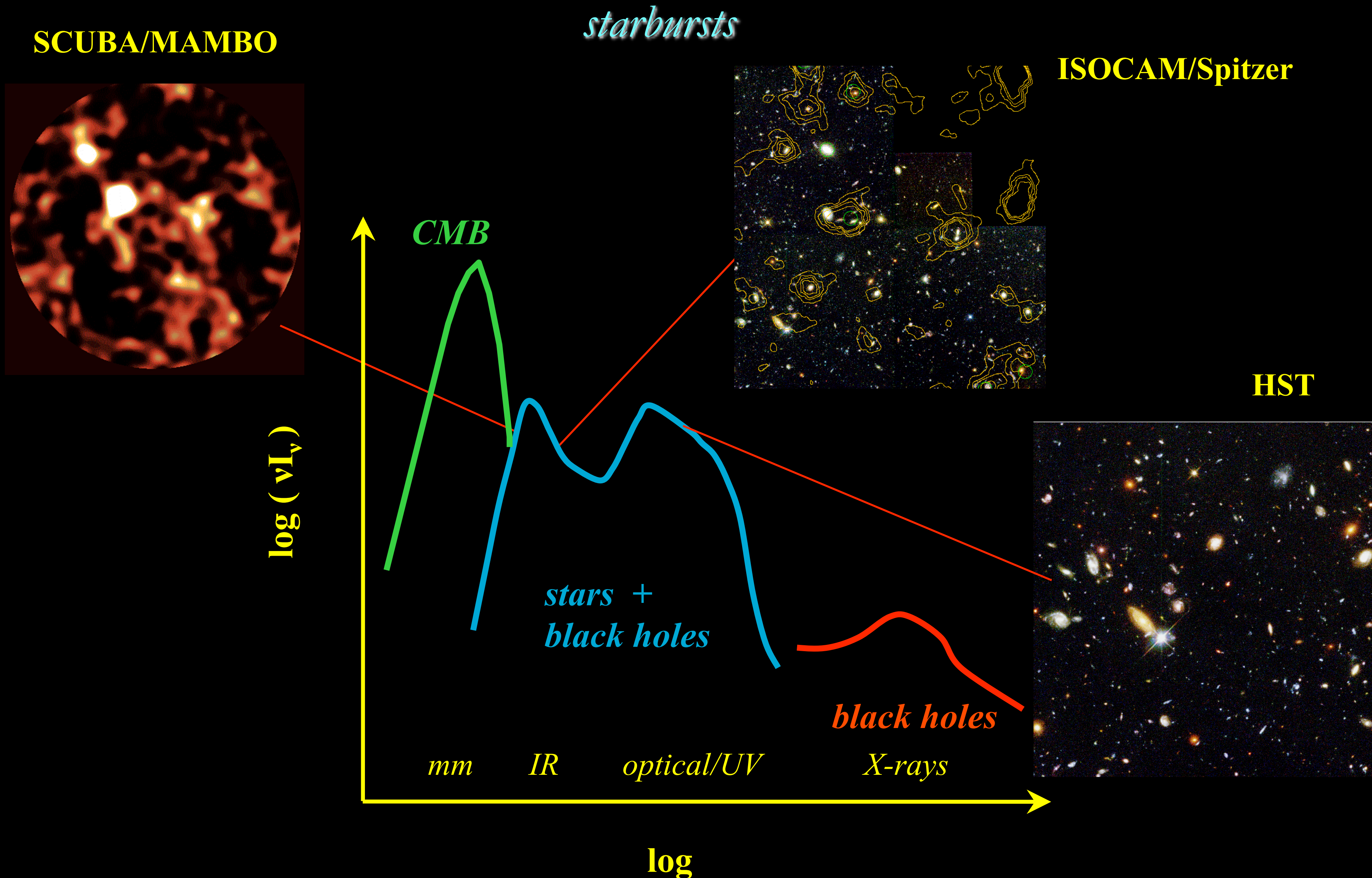
taken
from Hopkins 2006

Steidel, Madau, Dickinson, Taniguchi, Cowie, Blain, Lilly et al. 1996….., Hopkins & Beacom 2006 *extragalactic backgrounds:* *luminous dusty starbursts*



Aussel, Barger, Blain, Chapman, Cimatti,Cowie, Cesarsky, Elbaz, Franx, Giacconi, Hasinger, Hughes, Ivison, Lilly, Madau, Papovich, Pettini, Smail, Steidel, Williams, Beckwith, et al. 1996-2006

extragalactic backgrounds:

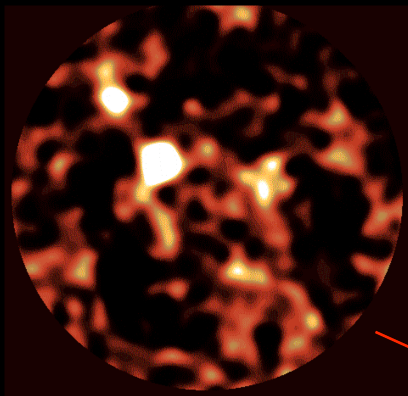


Aussel, Barger, Blain, Chapman, Cimatti,Cowie, Cesarsky, Elbaz, Franx, Giacconi, Hasinger, Hughes, Ivison, Lilly, Madau, Papovich, Pettini, Smail, Steidel, Williams, Beckwith, et al. 1996-2006

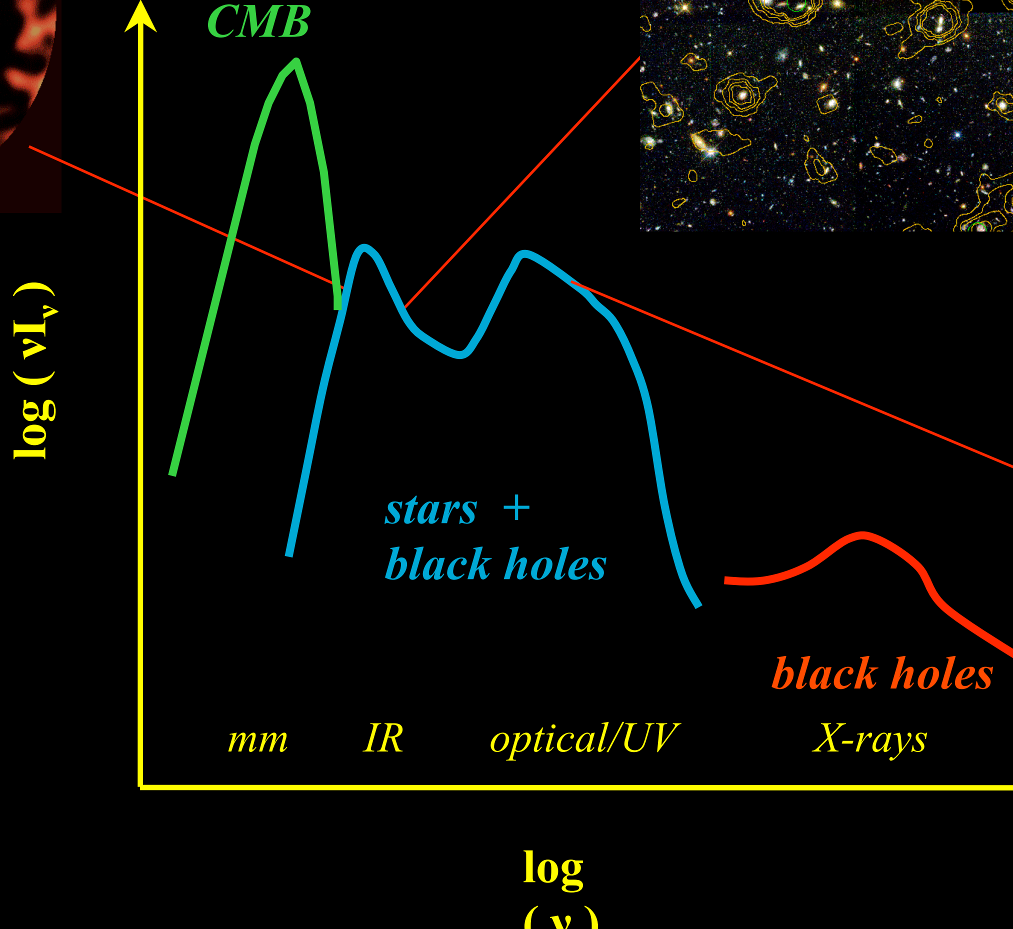
extragalactic backgrounds:

luminous dusty starbursts

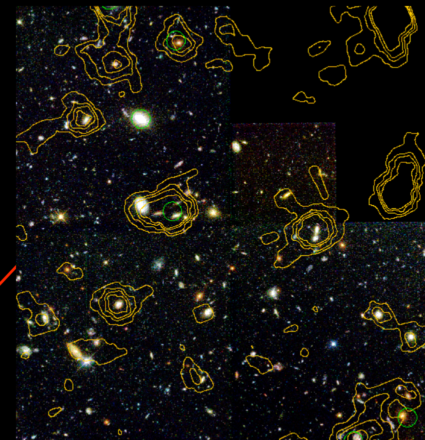
SCUBA/MAMBO



IR/submm samples:
~$10^{2.5}$ gals
z~1.4-5
SFR~$10^{2...3}$ $M_{\odot}yr^{-1}$

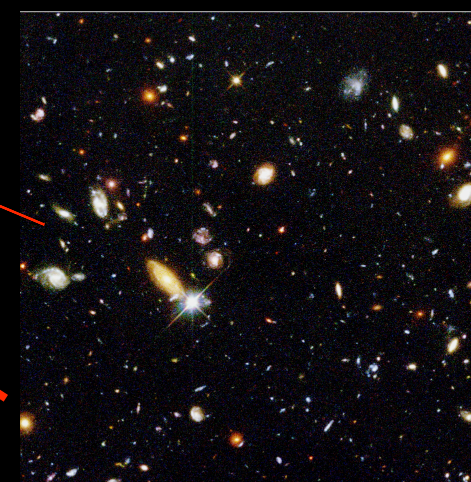


ISOCAM/Spitzer



UV/optical samples:
~$10^{3.6}$ gals
z~1.4-7
~10^4 z<1.4

HST



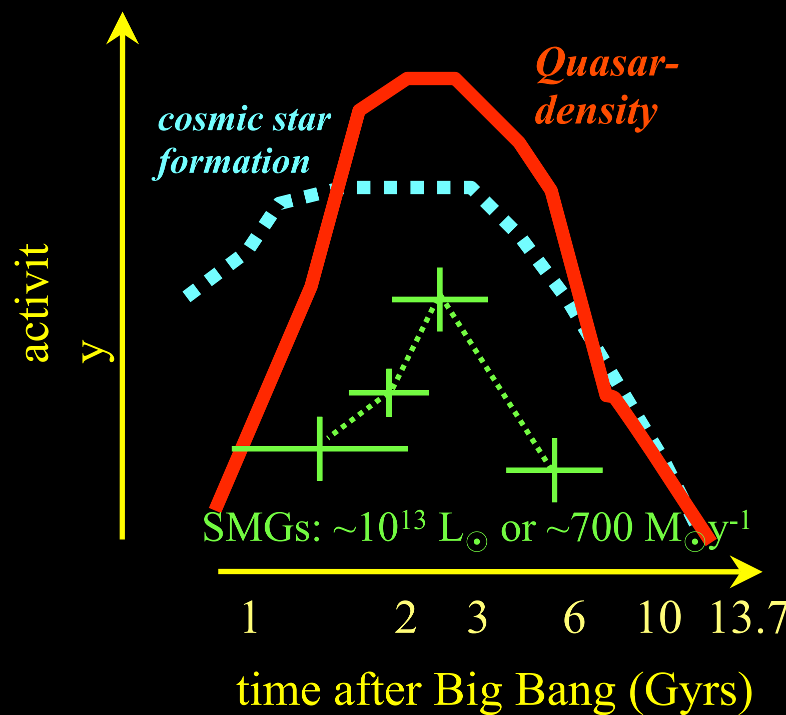
Aussel, Barger, Blain, Chapman, Cimatti, Cowie, Cesarsky, Elbaz, Franx, Giacconi, Hasinger, Hughes, Ivison, Lilly, Madau, Papovich, Pettini, Smail, Steidel, Williams, Beckwith, et al. 1996-2006

massive ($\geq 10^{11}\ M_{\odot}$) galaxy assembly & QSO co-evolution

major mergers?

Boyle et al. 2000, Fan et al. 2001, Hasinger et al. 2002, Chapman et al. 2003, 2005, Hopkins et al. 2006

massive (≥10^{11} $M_\odot$) galaxy assembly & QSO co-evolution



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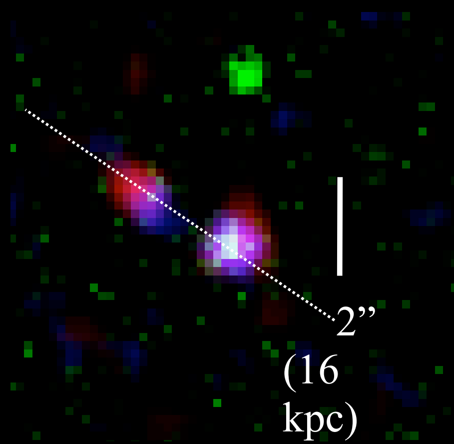
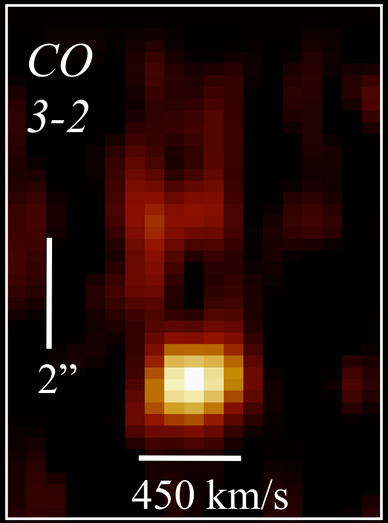
Spatially resolved dynamics of high-z galaxies: mm-interferometry with IRAM

major mergers

SMMJ123707+6214 (HDF 242) z=2.49



CO (red), 1,4GHz (blue), K-band (green)



resolution 0.3-0.5”

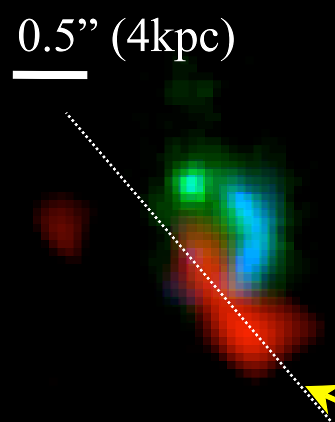
M_{dyn}~10^{11} $M_{\odot}$, f_{gas}~0.4, SFR~900 $M_{\odot}yr^{-1}$

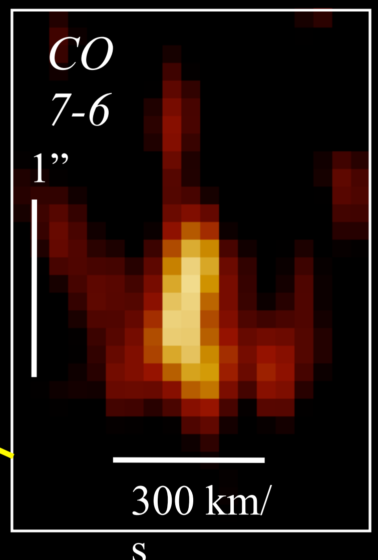
Tacconi et al. 2006, 2007

Spatially resolved dynamics of high-z galaxies: mm-interferometry with IRAM

major mergers

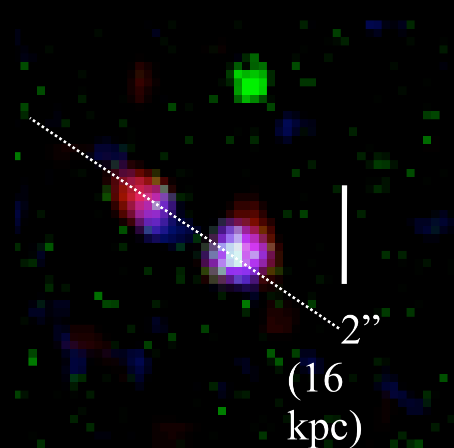
SMMJ163650+4057 (N2 850.4) z=2.39

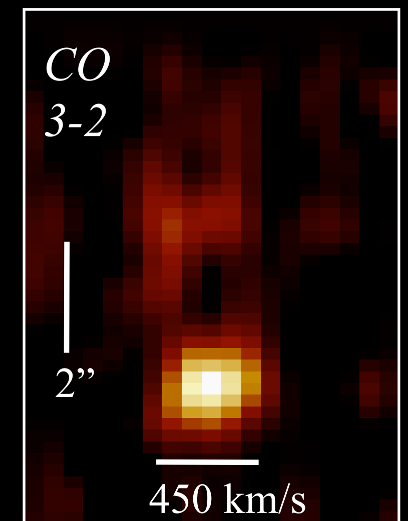




CO 7-6 (red) on ACS (blue) & NICMOS (green)

SMMJ123707+6214 (HDF 242) z=2.49





CO (red), 1,4GHz (blue), K-band (green)

resolution 0.3-0.5"

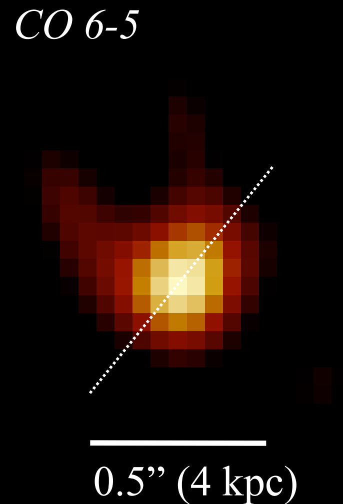
M_{dyn}~10^{11} $M_{\odot}$, f_{gas}~0.4, SFR~900 $M_{\odot}yr^{-1}$

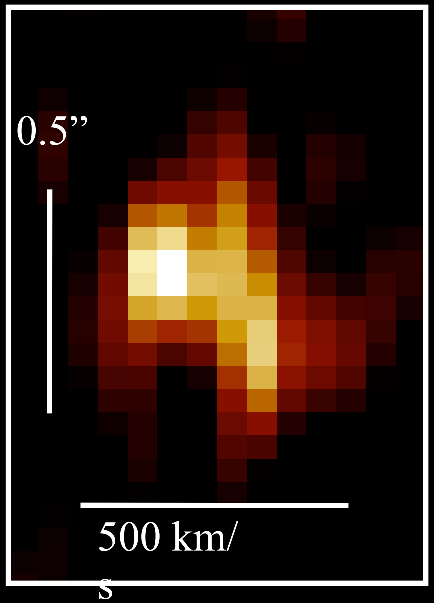
Tacconi et al. 2006, 2007

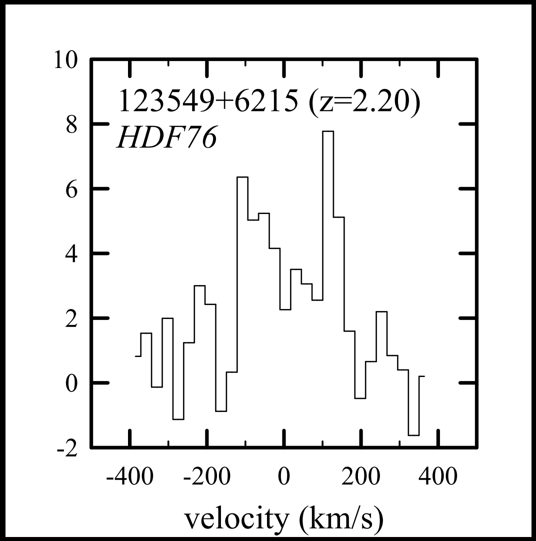
Spatially resolved dynamics of high-z galaxies: mm-interferometry with IRAM PdBI

compact merger remnants

SMMJ123549+6215 (HDF76) z=2.20







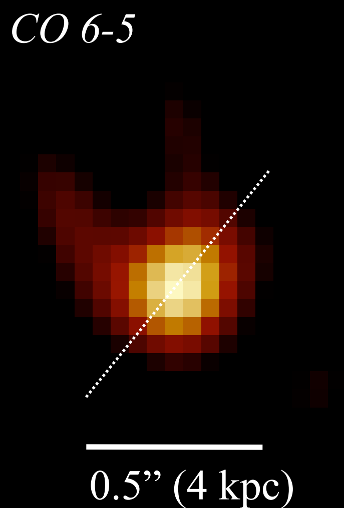
resolution 0.3-0.5"

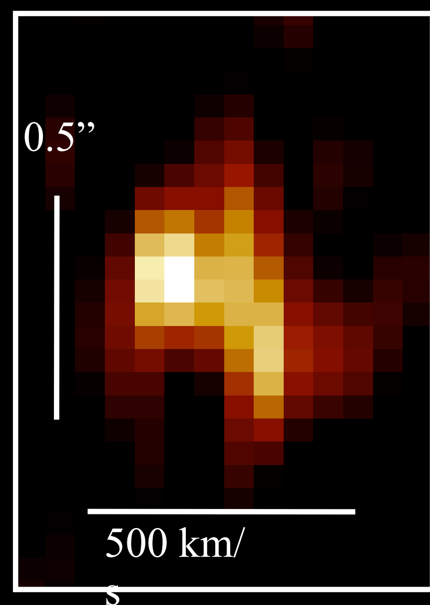
Tacconi et al. 2006, 2007

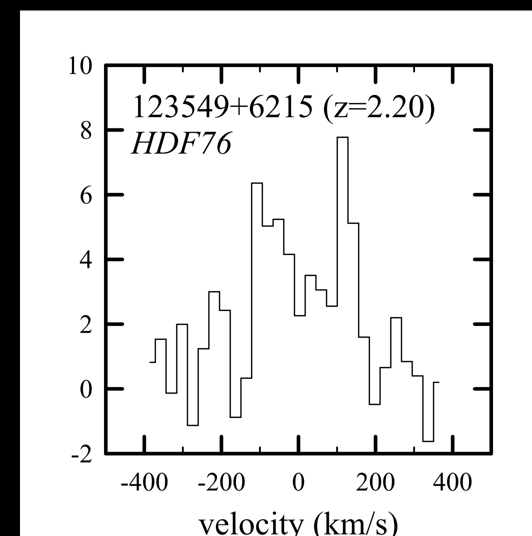
Spatially resolved dynamics of high-z galaxies: mm-interferometry with IRAM PdBI

compact merger remnants

SMMJ123549+6215 (HDF76) z=2.20







resolution 0.3-0.5”

$\rho_{dyn} \sim 10^{3 \ldots 4}$ cm^{-3}

$\Sigma_{dyn} \sim 10^4\ M_\odot\ pc^{-2}$

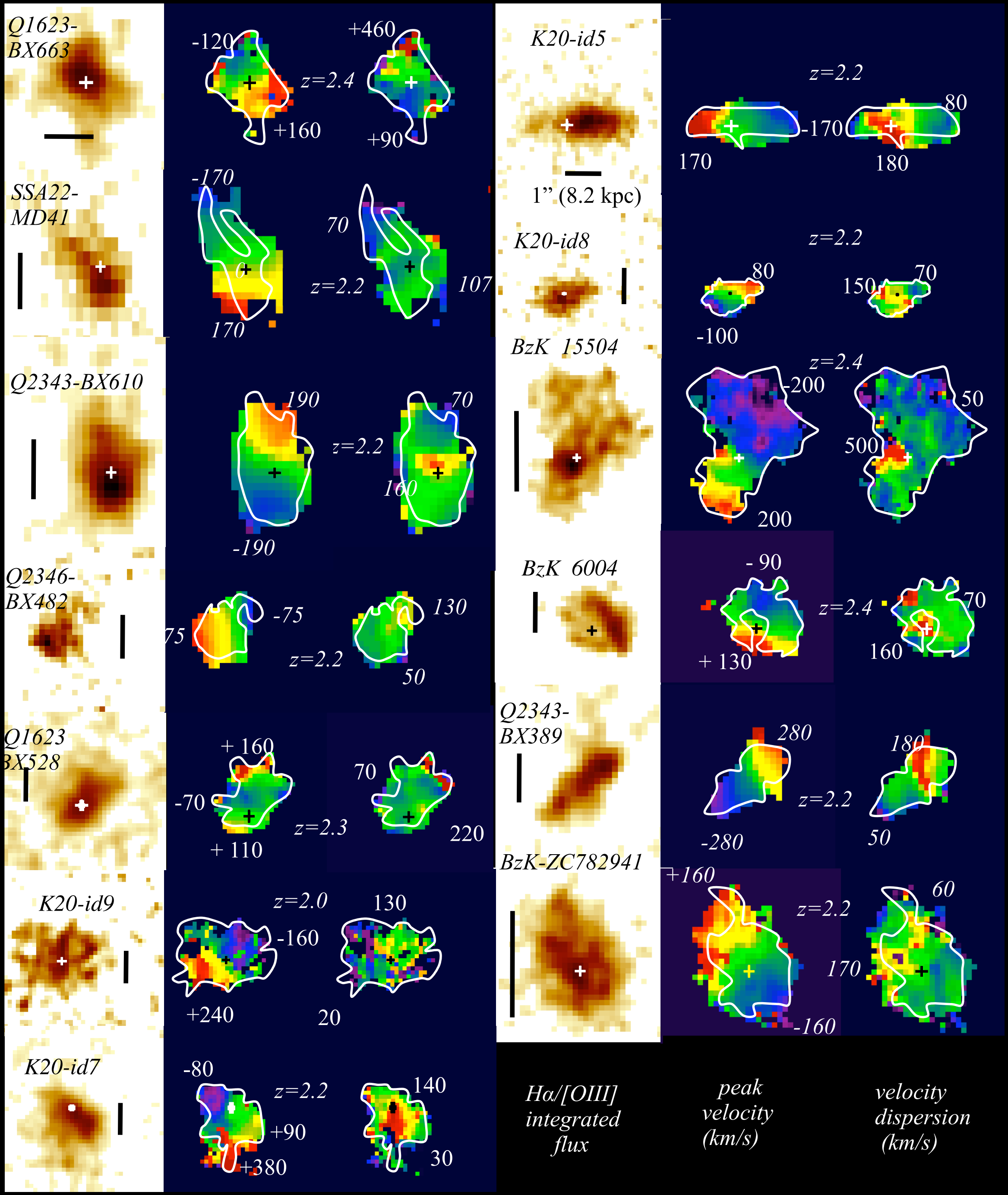
Tacconi et al. 2006, 2007

SINS survey of dynamics of ~45 UV-/ optically selected, z~1.5-2.5 star forming galaxies

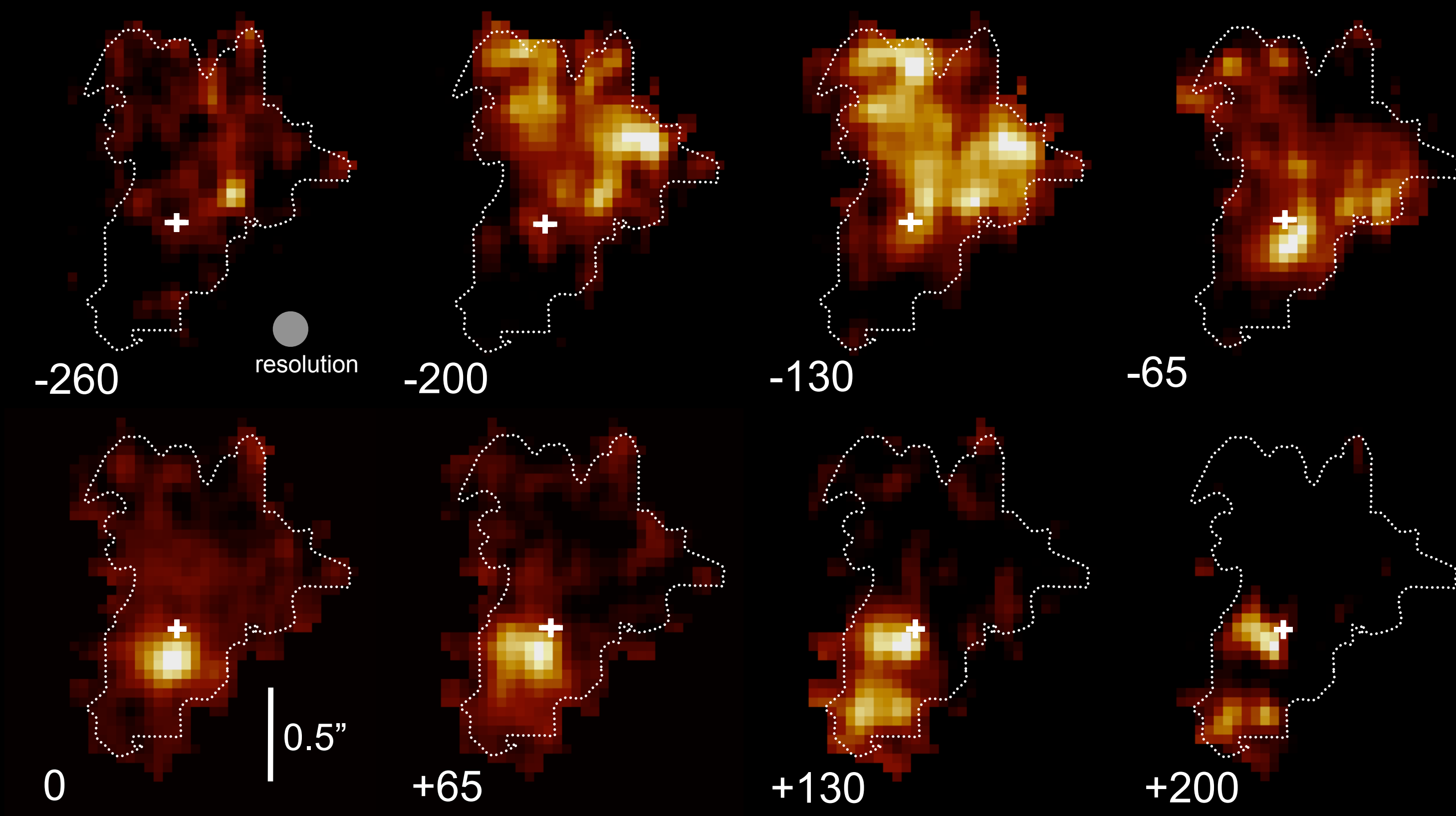
resolution 0.15”-0.5”
(1.2-4 kpc)

majority exhibit coherent large scale motion

Förster Schreiber et al. 2006, Genzel et al. 2006, Bouche et al. 2007, Cresci et al. 2007, Shapiro et al. 2007, see also Wright et al. 2007, Law et al. 2007



globally unstable disk with large star forming 'clumps'

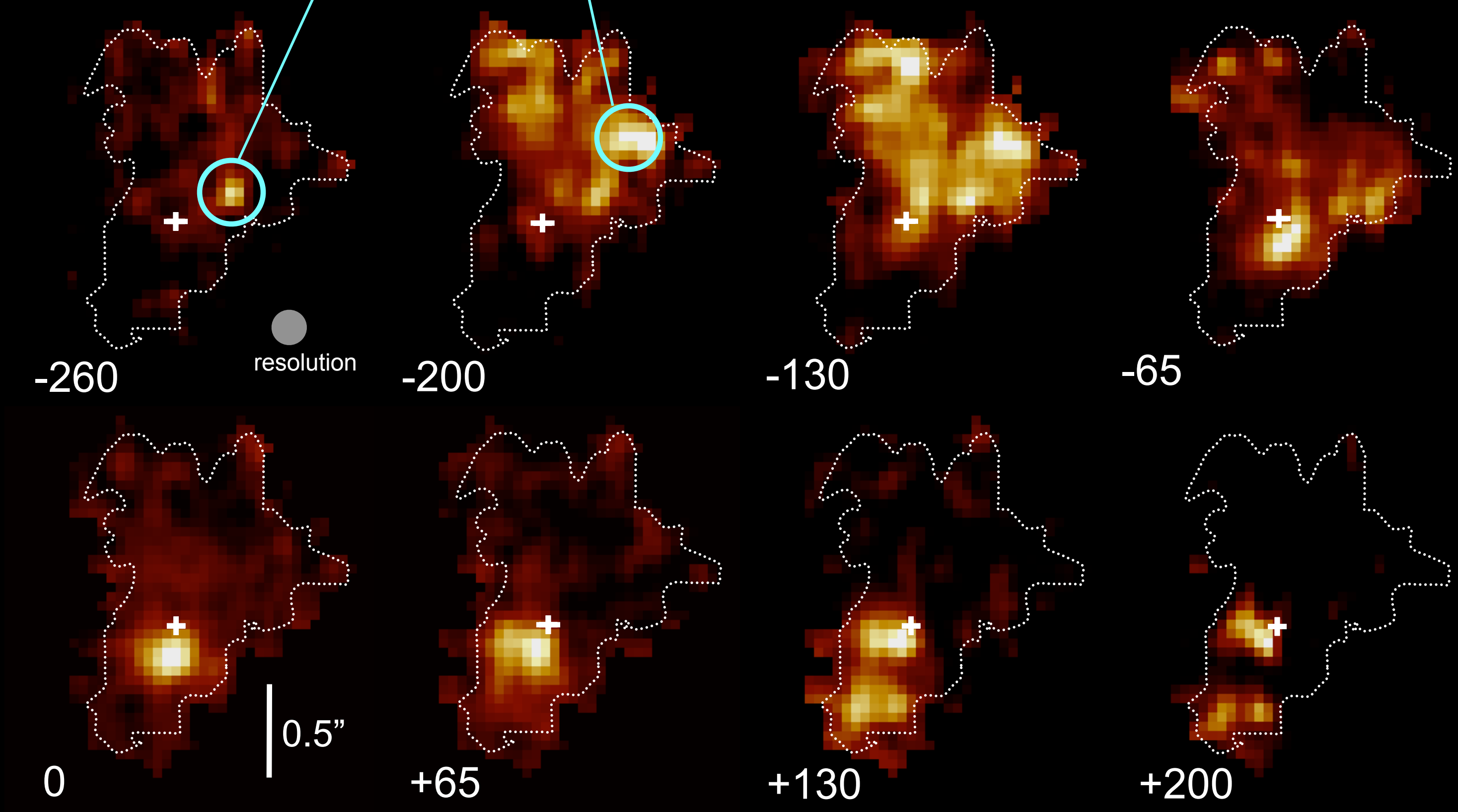


see Bruce Elmegreen's talk

Genzel et al. 2006, see also Elmegreen + 2003-07

globally unstable disk with large star forming 'clumps'

star forming complexes: ~$10^{8.5...9}$ $M_\odot$



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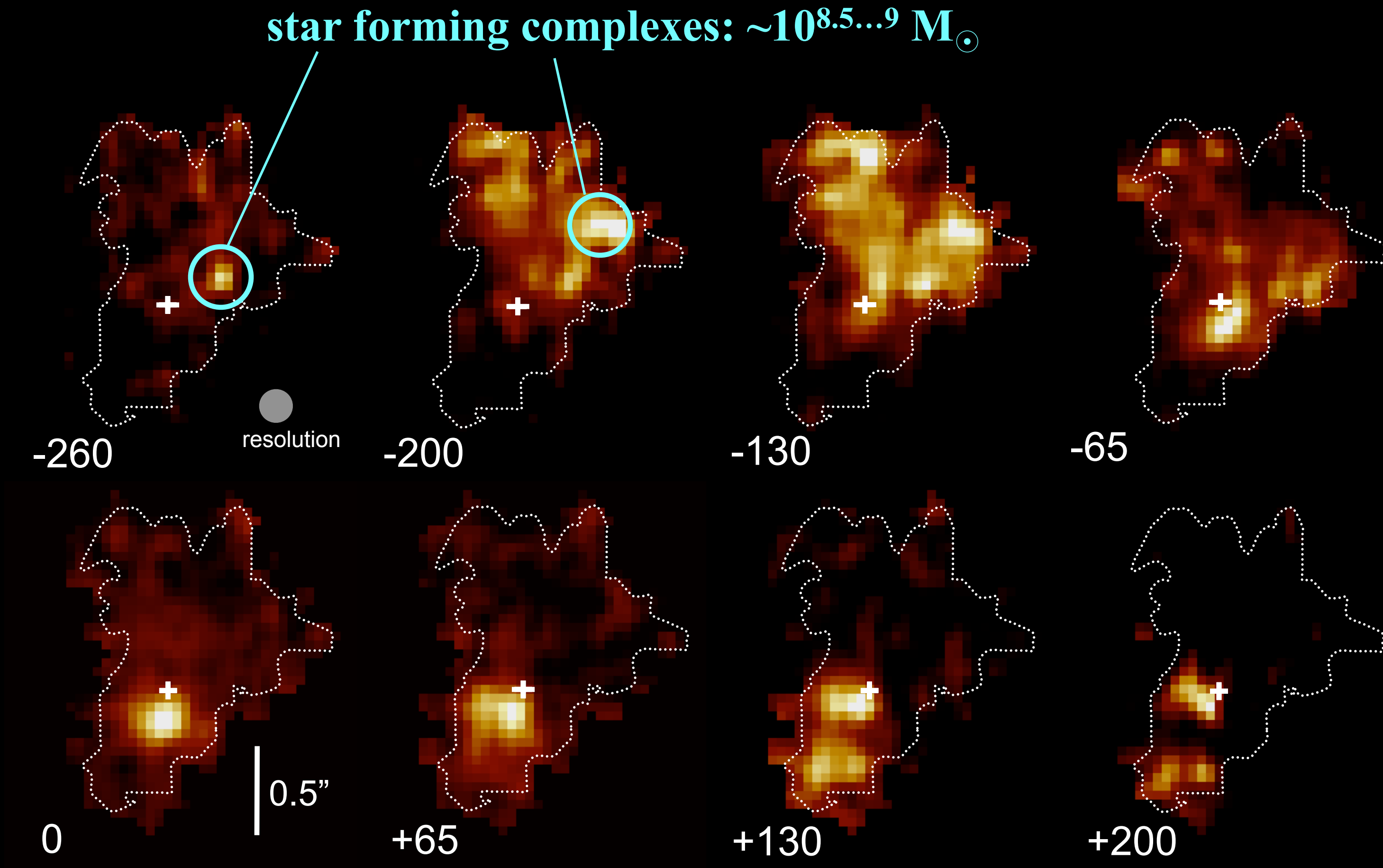
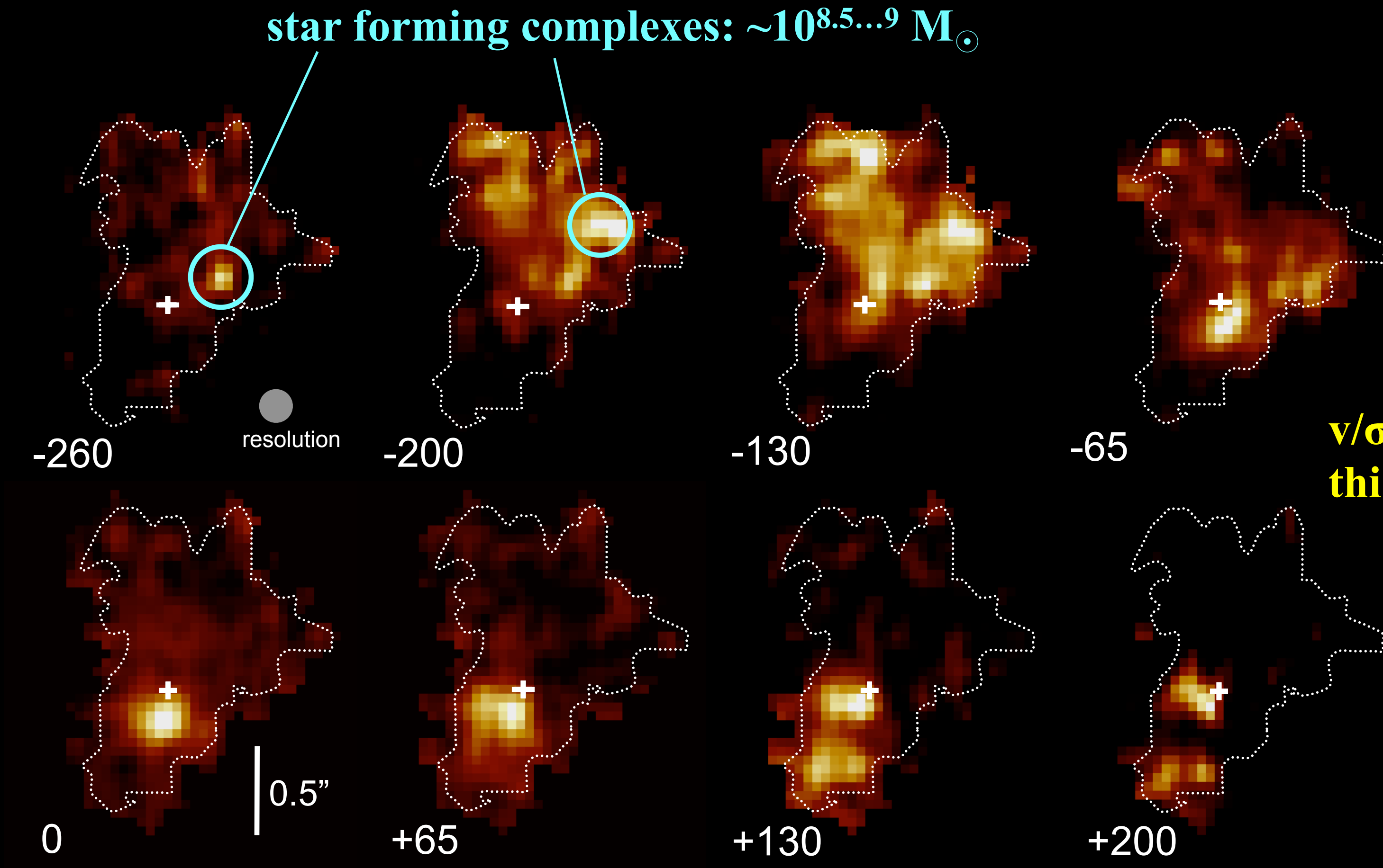


$\Sigma \sim 10^{3.5}\ M_{\odot}\ pc^{-2}$, $\sigma \sim 30\text{-}60$ km/s, $Q \sim 1$

see Bruce Elmegreen's talk

Genzel et al. 2006, see also Elmegreen + 2003-07

globally unstable disk with large star forming 'clumps'



v/σ~4-5:
thick disks!

$\Sigma \sim 10^{3.5}$ $M_\odot$ pc^{-2}, σ~30-60 km/s, Q~1

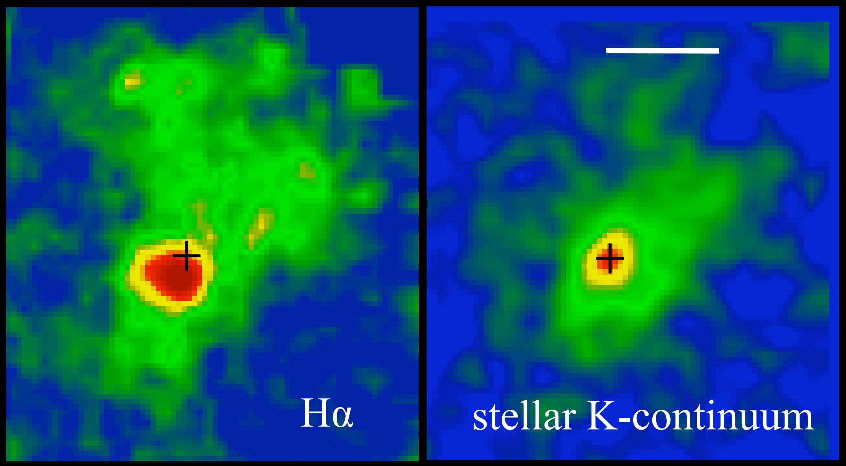
see Bruce Elmegreen's talk

Genzel et al. 2006, see also Elmegreen + 2003-07

physical properties of BzK15504 (2)

BzK15504 z=2.38

0.5”
(4kpc)



SINFONI & AO *NACO+LGSF AO*

resolution ~0.15” (1.2 kpc)

Genzel et al. 2006

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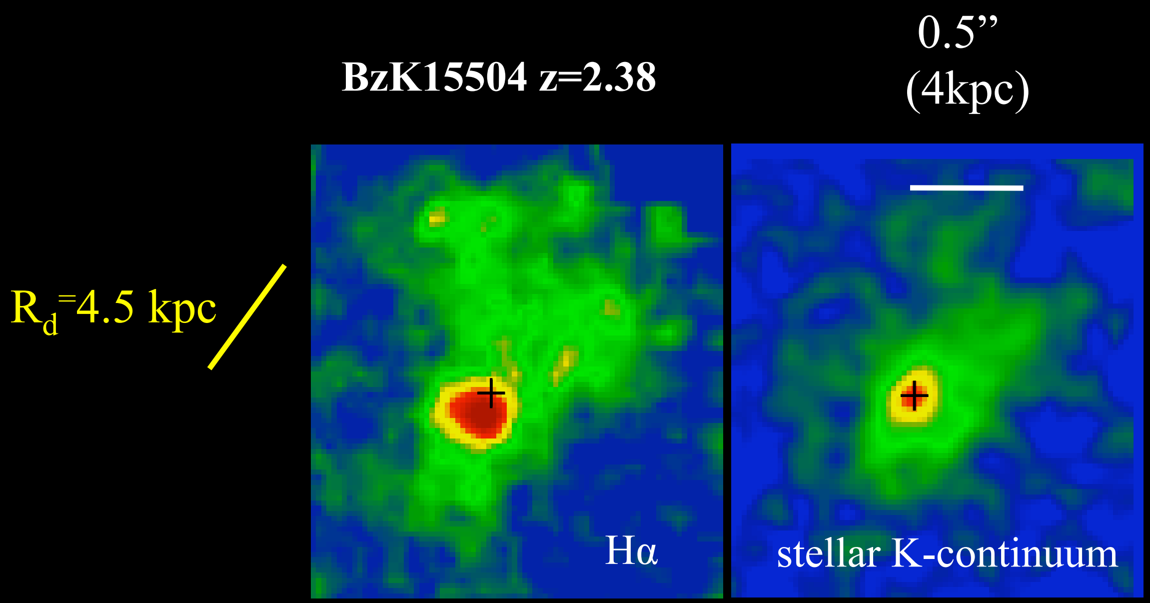

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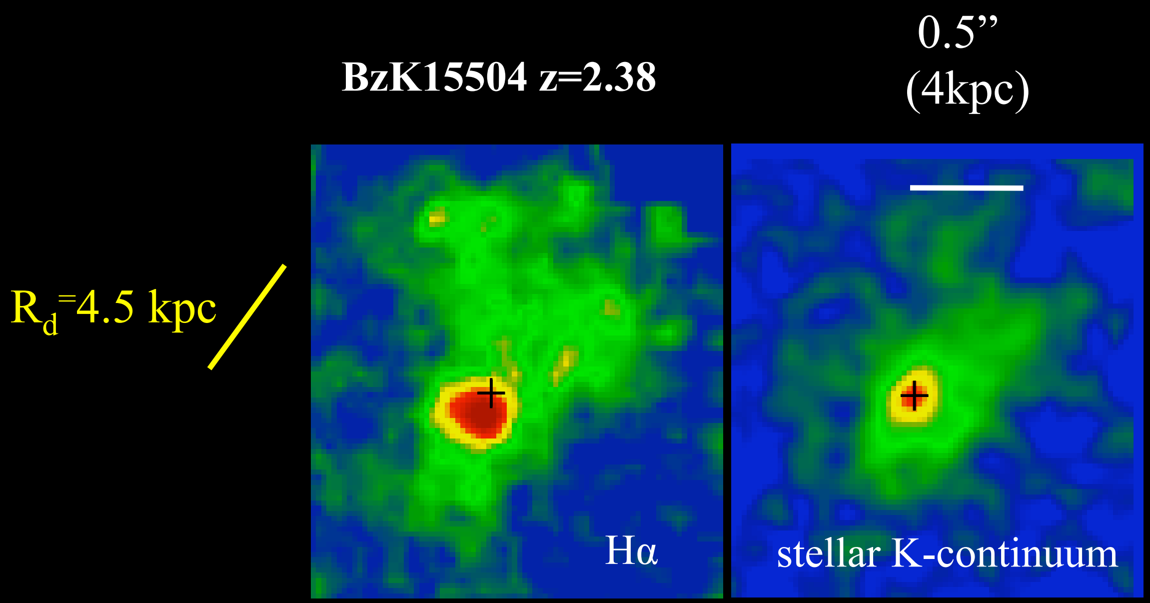

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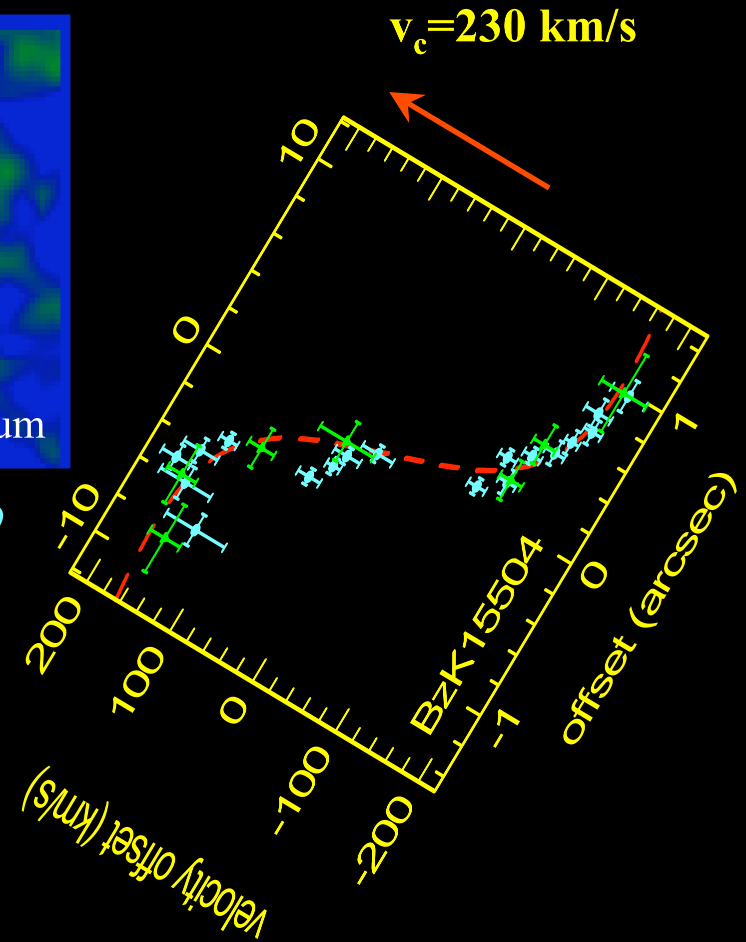


Genzel et al. 2006

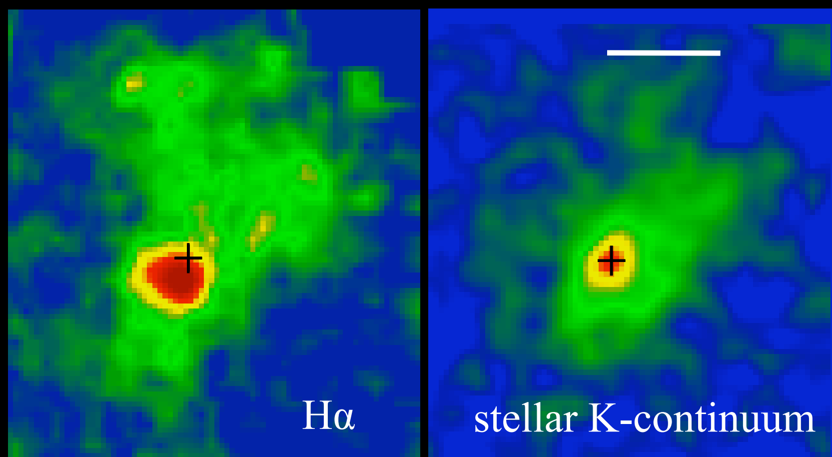
physical properties of BzK15504 (2)

$M_{dyn}(r \leq 10kpc) = 1.1\ 10^{11}\ M_{\odot} \sim M_{*}\,(0.8\ 10^{11}) + M_{gas}\,(0.4\ 10^{11})$

BzK15504 z=2.38

0.5”
(4kpc)

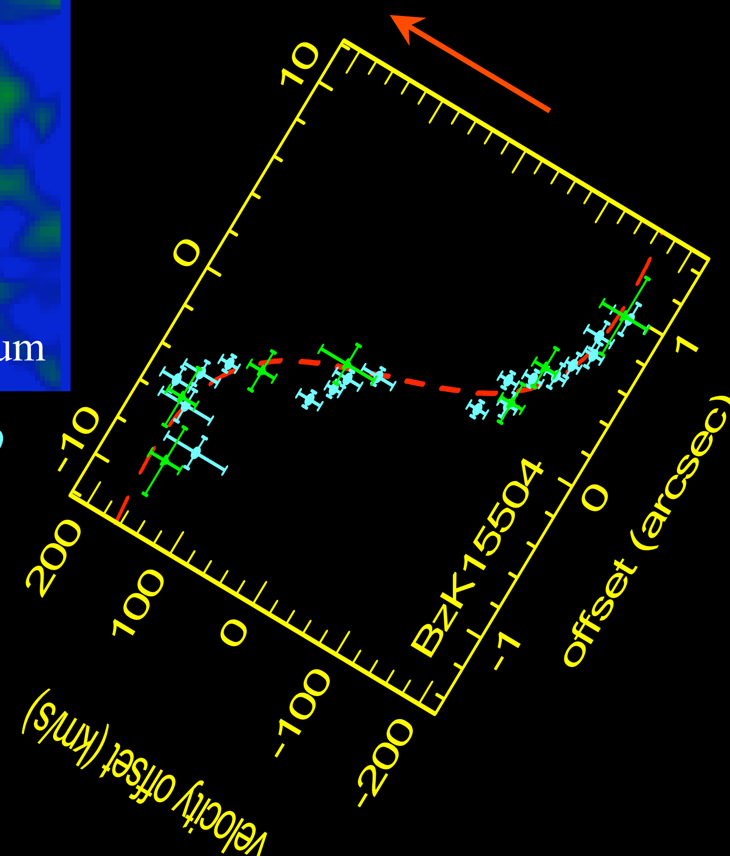
R_d=4.5 kpc



SINFONI & AO *NACO+LGSF AO*

resolution ~0.15” (1.2 kpc)

v_c=230 km/s



Genzel et al. 2006

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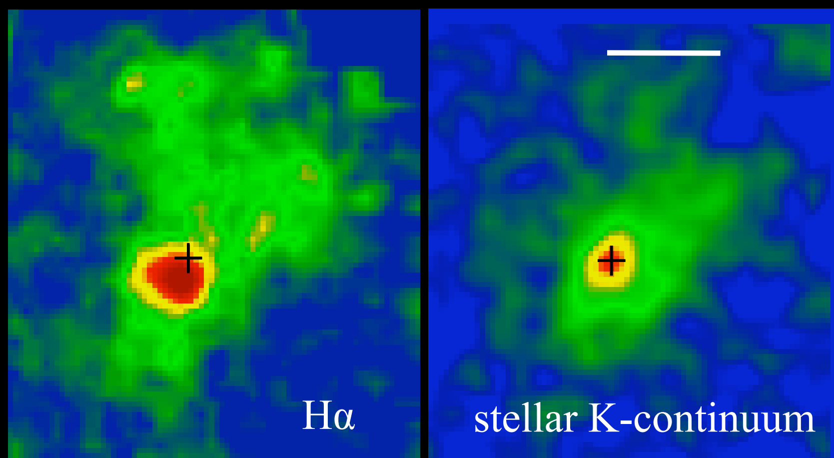
0.5”
(4kpc)

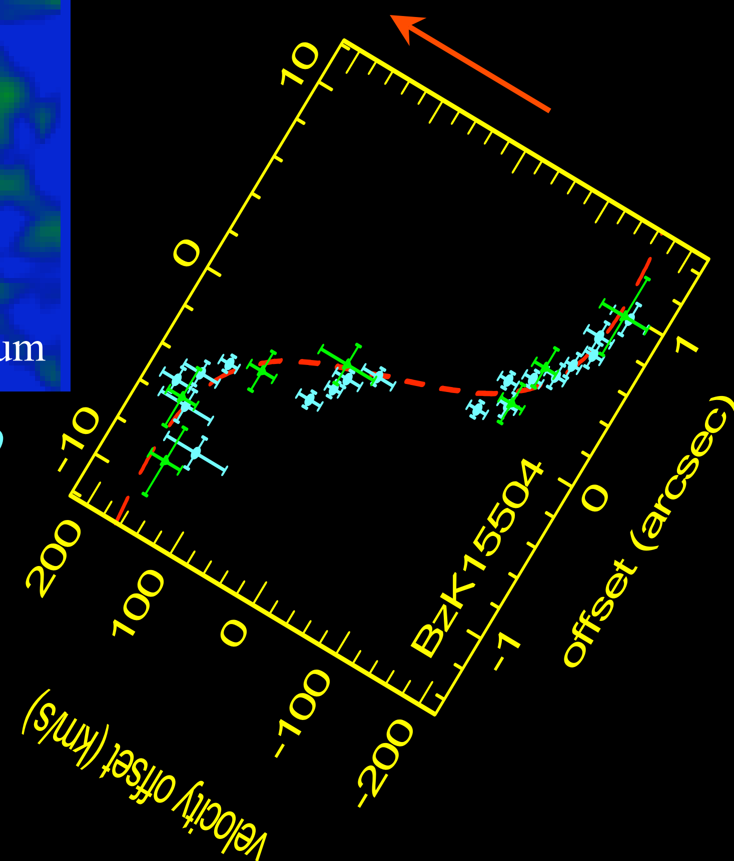
R_d=4.5 kpc



SINFONI & AO   *NACO+LGSF AO*

resolution ~0.15” (1.2 kpc)

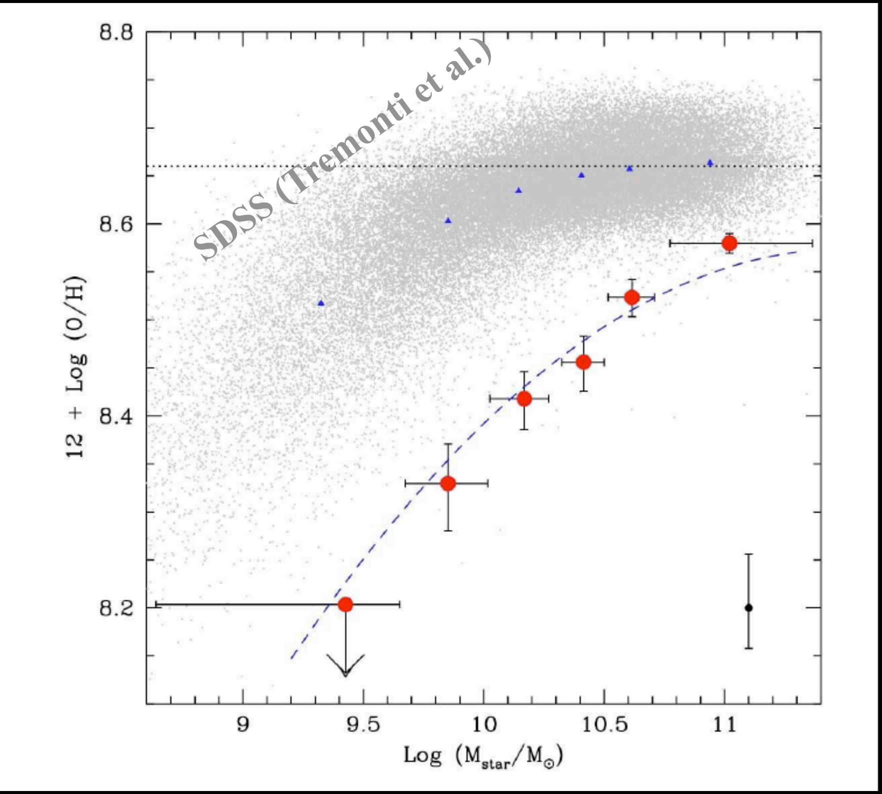
v_c=230 km/s



SFR~150 $M_{\odot}yr^{-1}$, t_{*}~t_{gas}~500 Myrs

Genzel et al. 2006

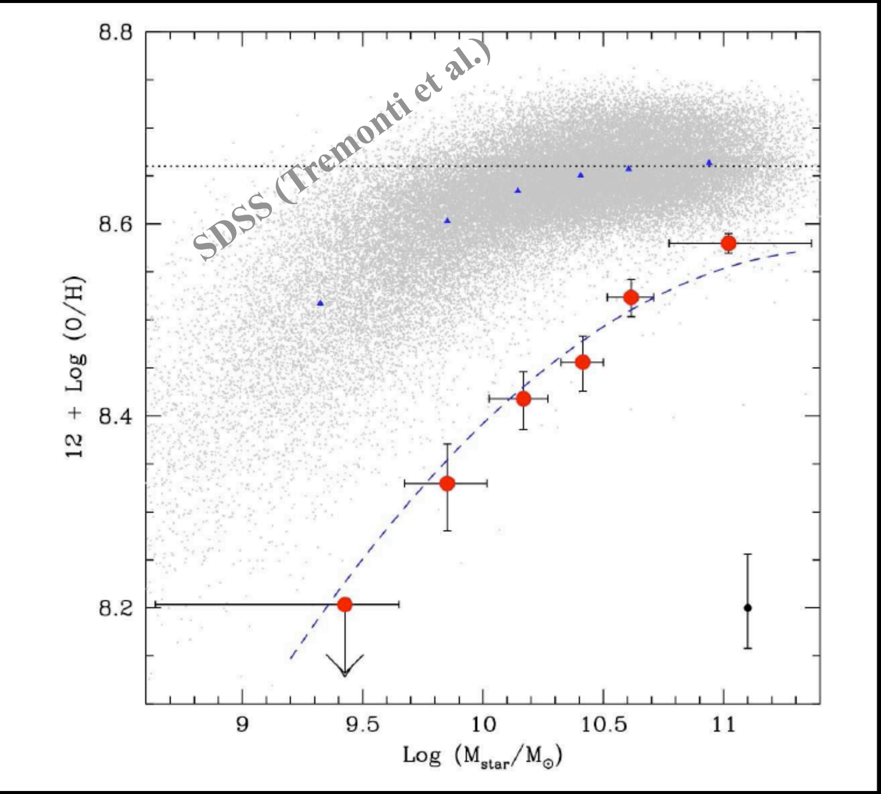
rapid build-up of mass-metallicity relation at z~2

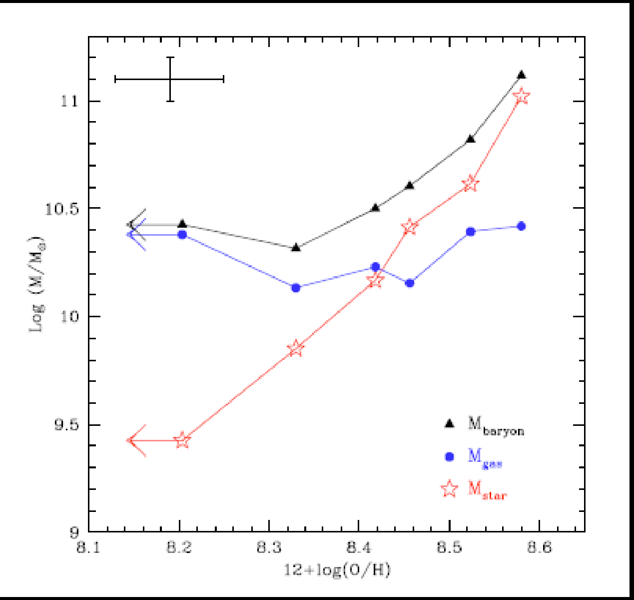


NIRSPEC Hα/[NII] spectroscopy of ~80 <z>=2.2 BX/BM galaxies

Erb et al. 2006a-c

rapid build-up of mass-metallicity relation at z~2



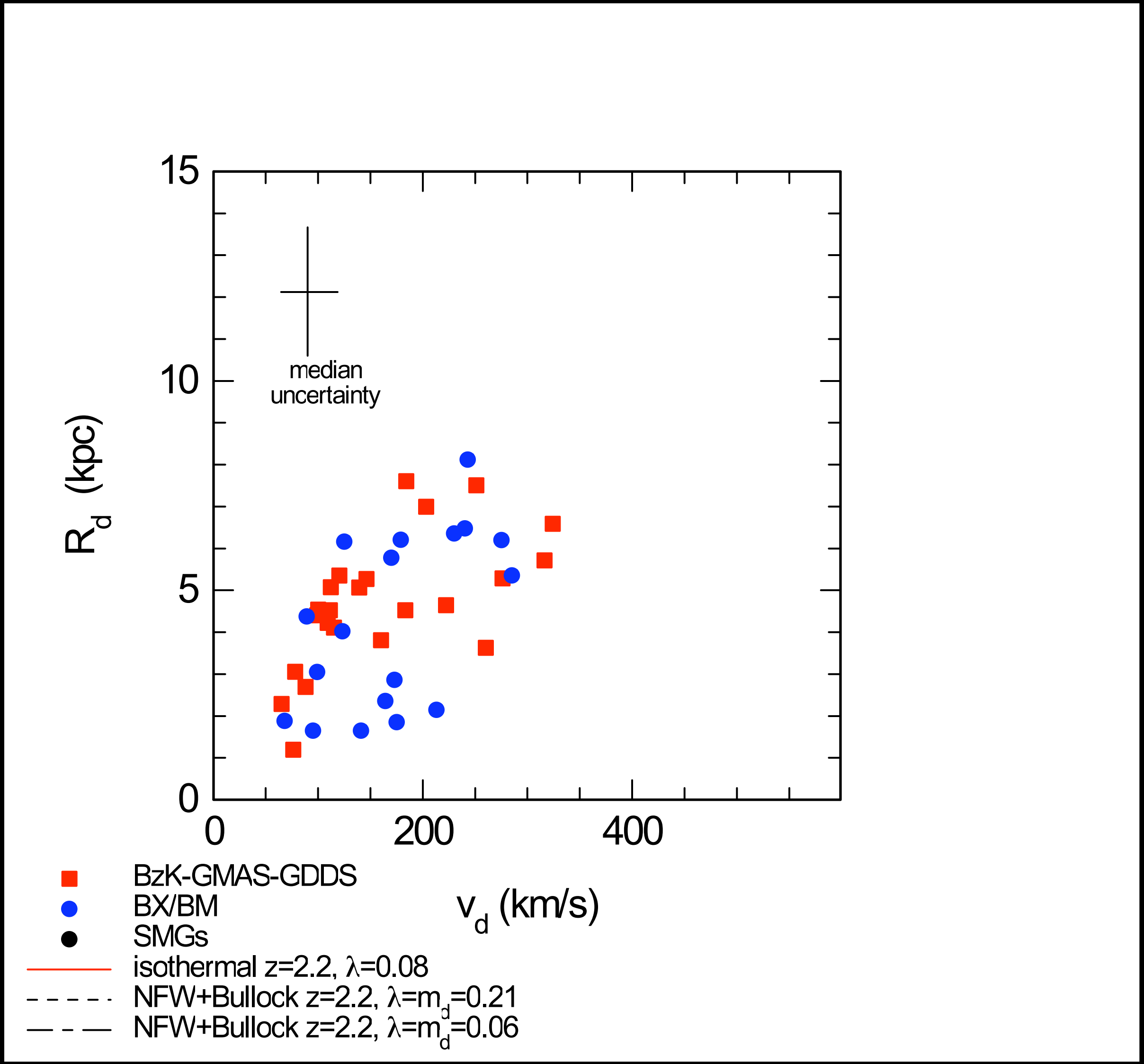


mass-met. relation driven by exhaustion of gas! best fits to yields as a function of inferred gas fraction: $f_{ejection}$~4 !

NIRSPEC Hα/[NII] spectroscopy of ~80 <z>=2.2 BX/BM galaxies

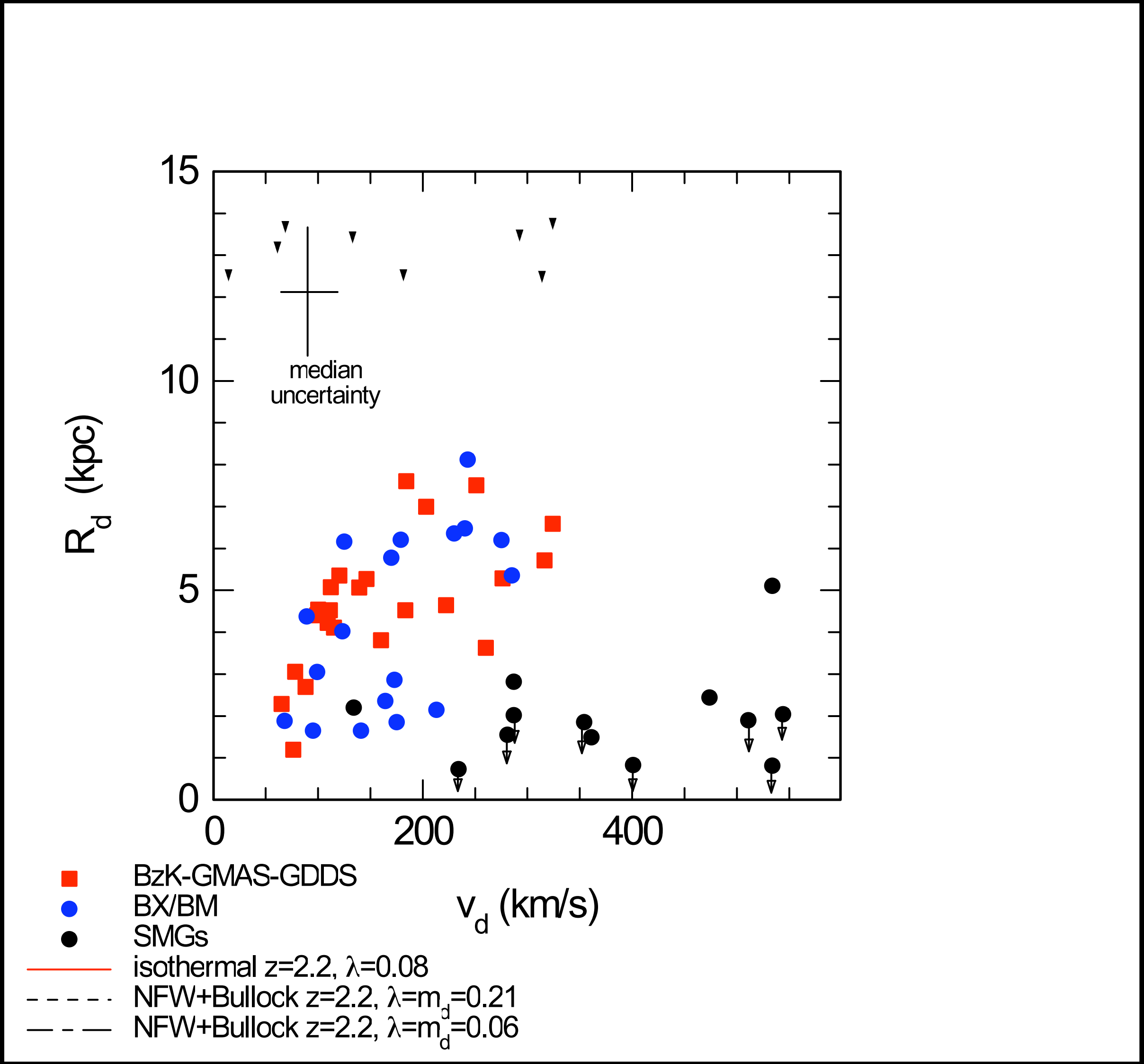
Erb et al. 2006a-c

velocity-size distribution of z~2 galaxies are remarkably close to z~0 disks



Bouché et al. 07,
Bullock et al. 01,
Courteau 1997

velocity-size distribution of z~2 galaxies are remarkably close to z~0 disks



Bouché et al. 07,
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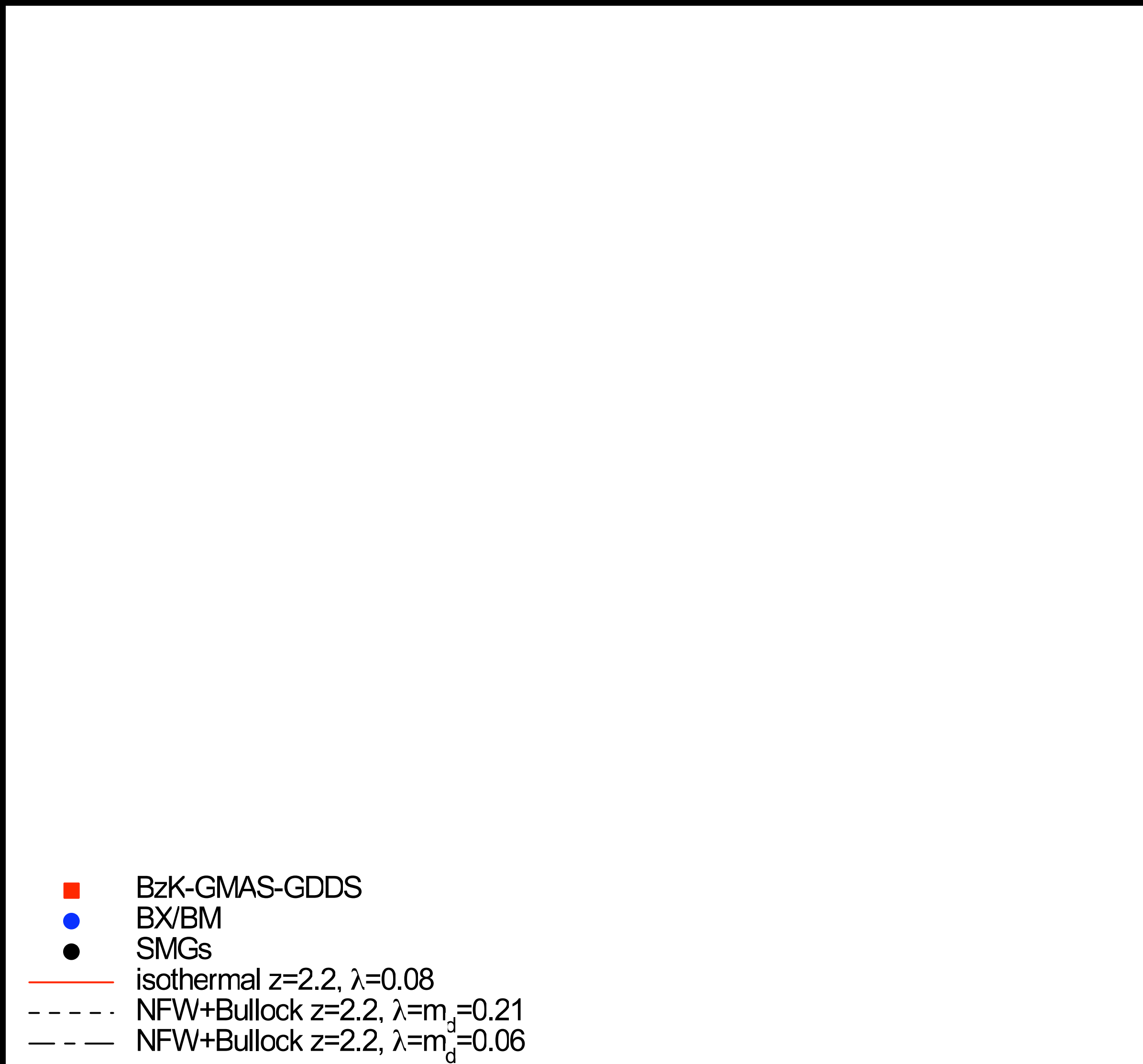
Courteau 1997

velocity-size distribution of z~2 galaxies are remarkably close to z~0 disks



Bouché et al. 07,
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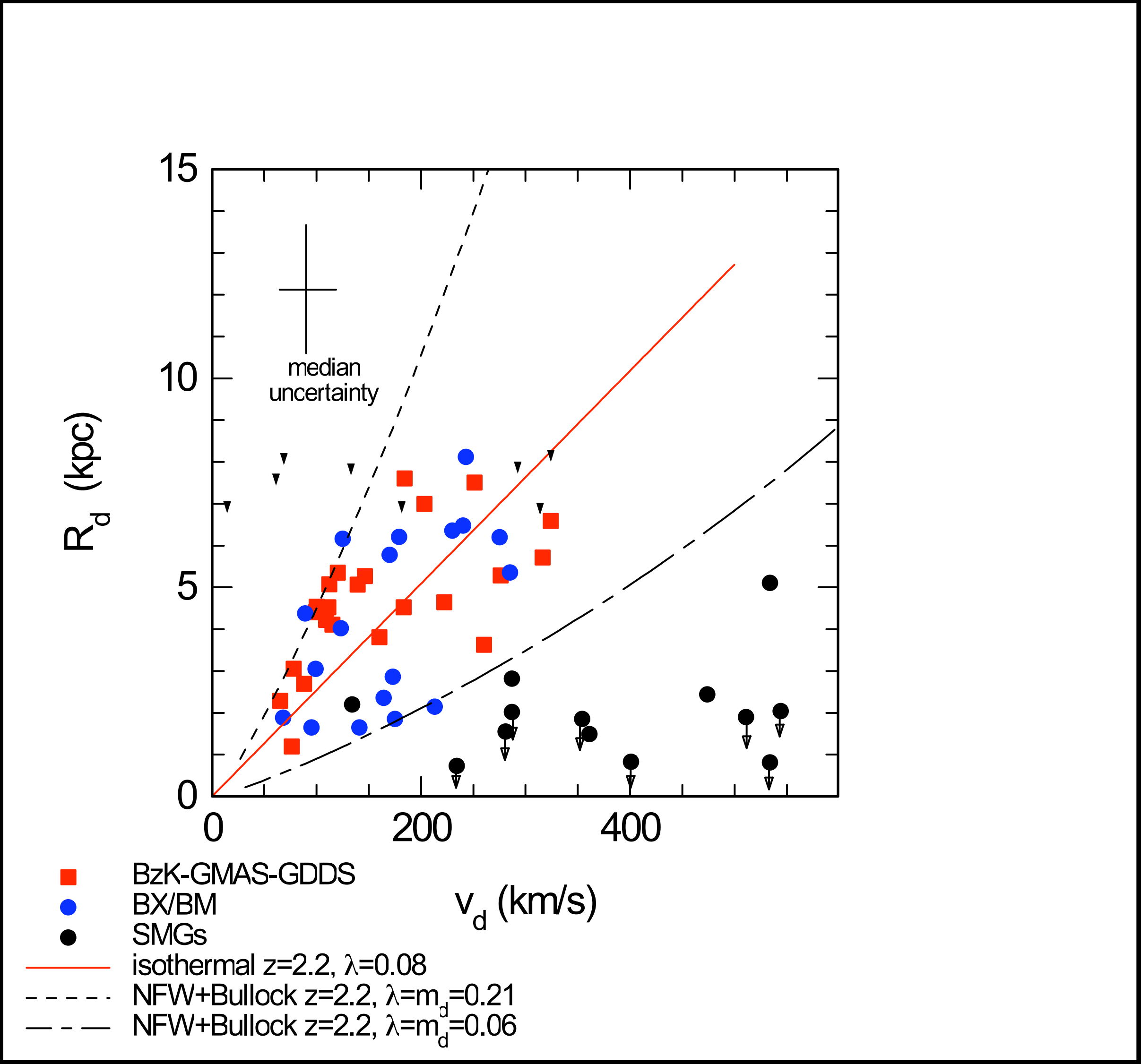

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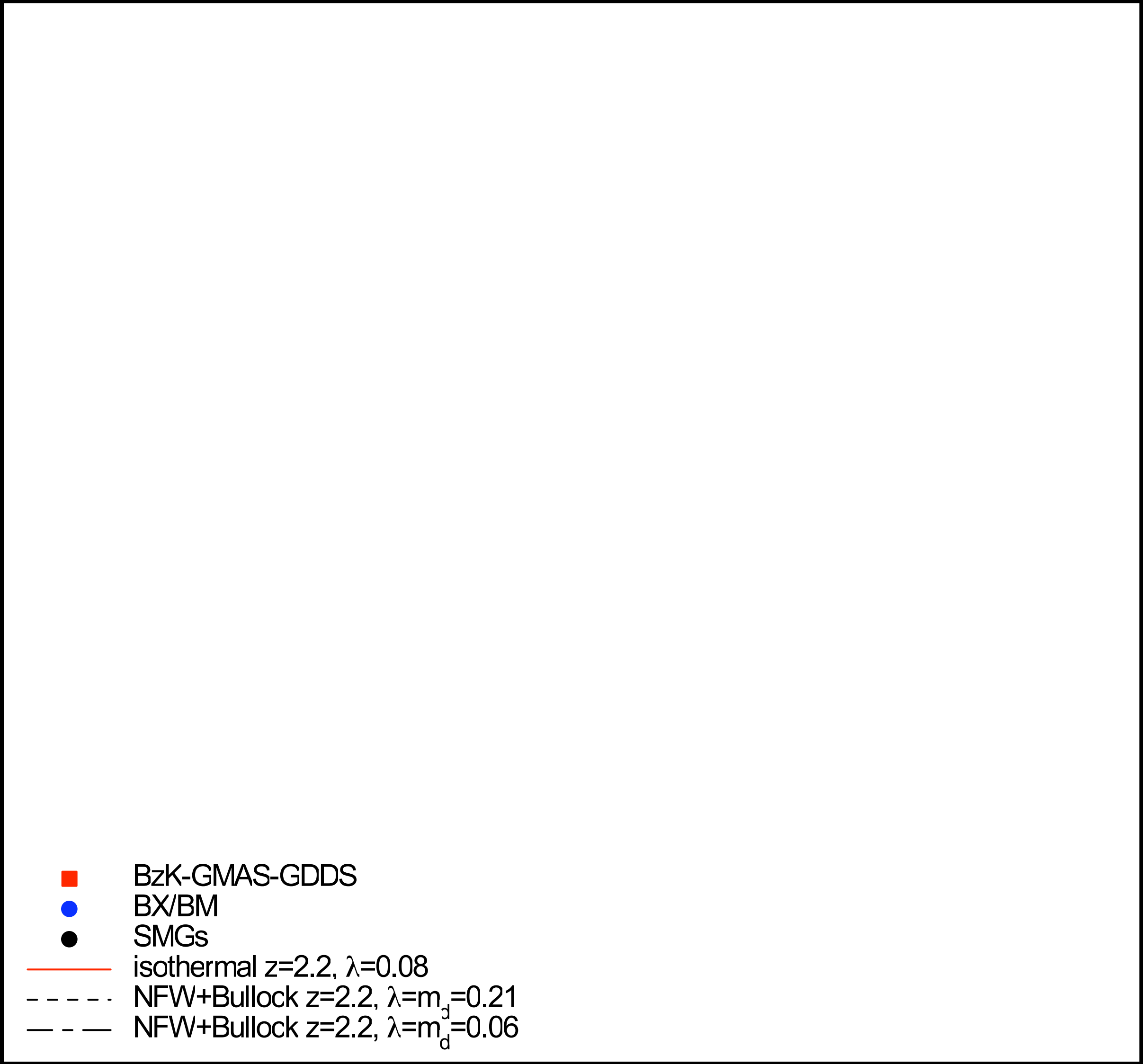

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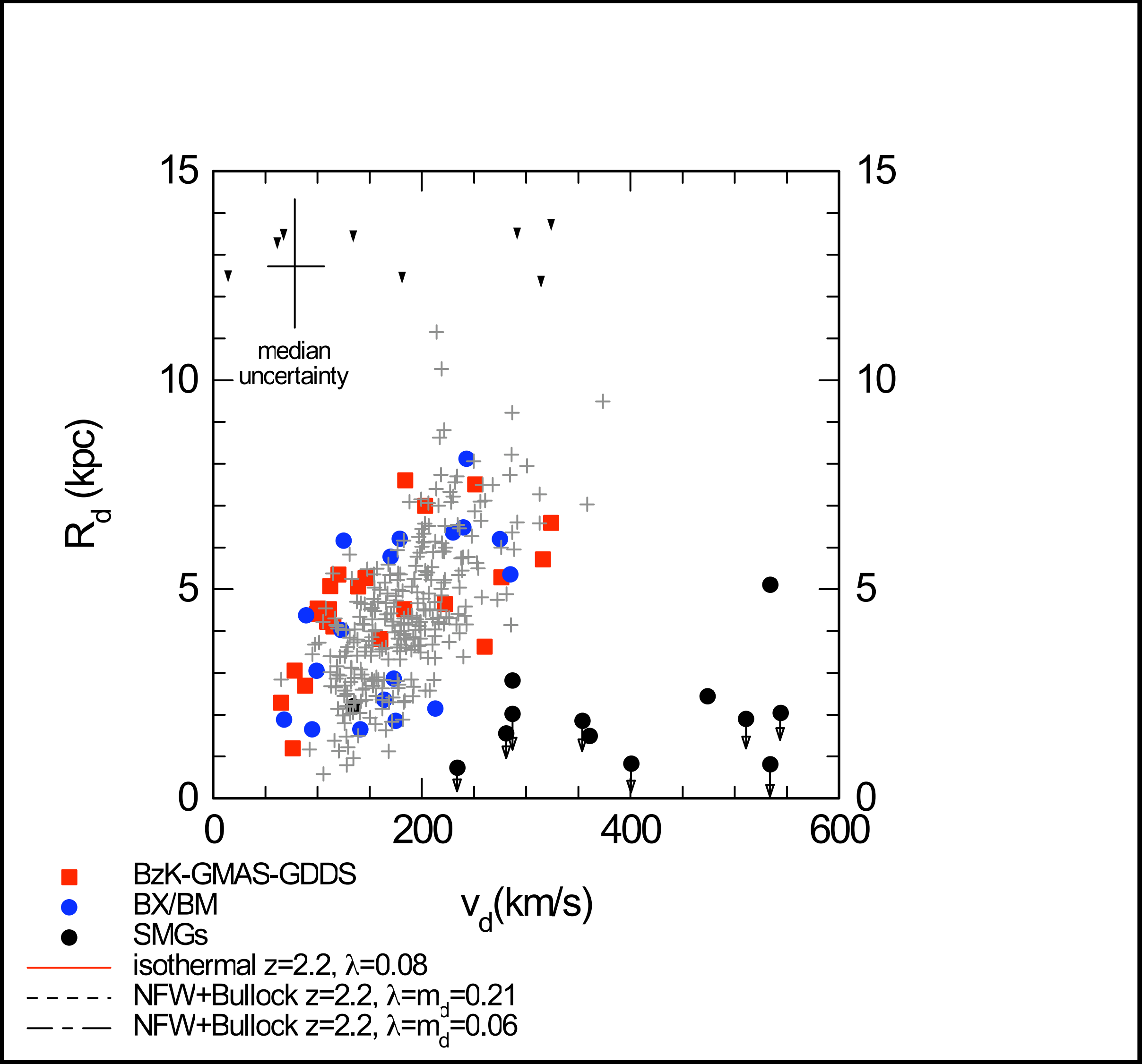

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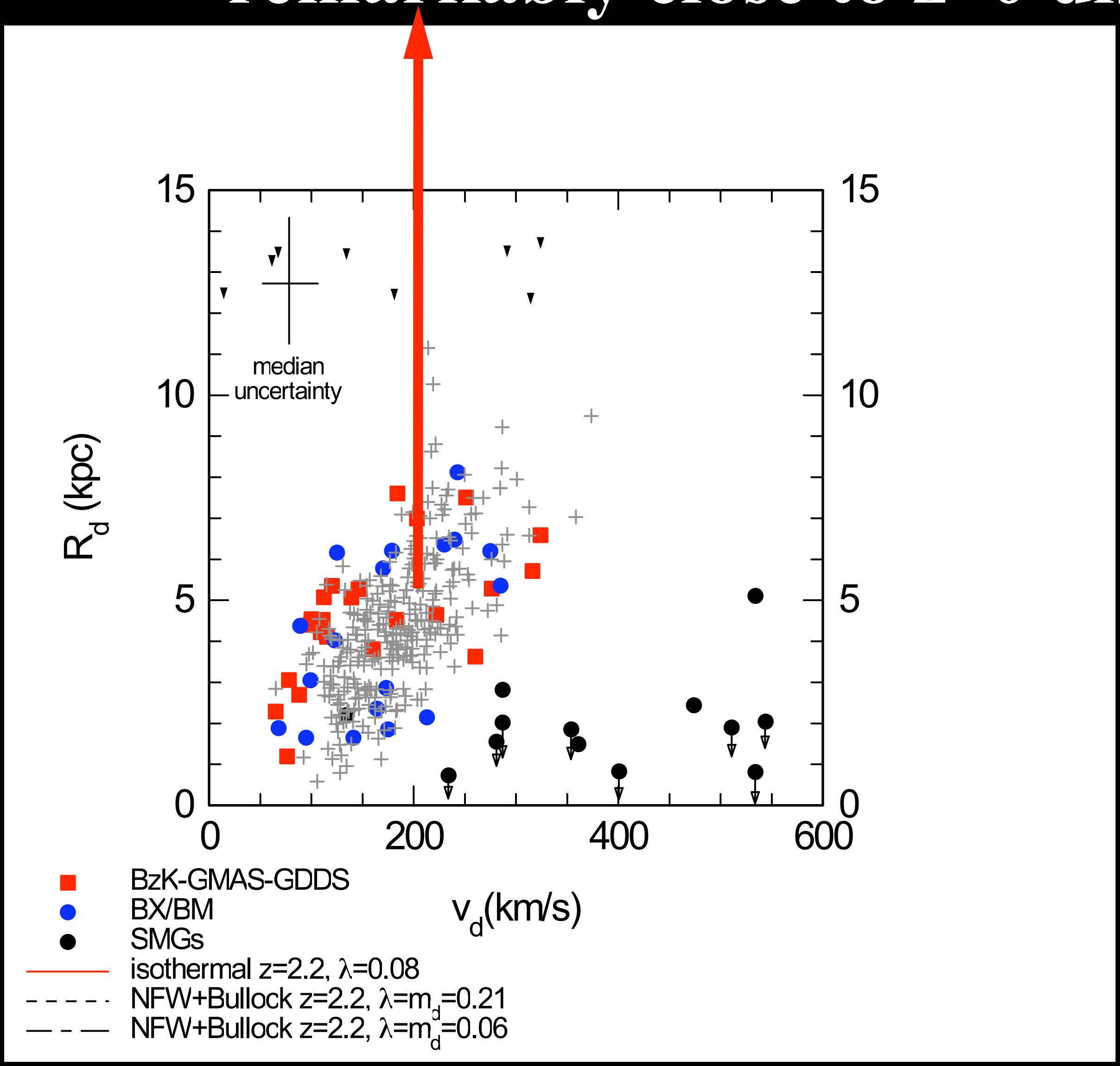

clearly cannot be simple forward evolution as in simple most dissipative accretion model: ~1/H(z)

better with NFW+ c_{halo}(z)

Bouché et al. 07, Bullock et al. 01, Courteau 1997

rapid formation: mergers or rapid collapse?

BzK-15504, SMGs and several other BX/BzK:

$t_{*} \sim t_{gas\ exhaustion} <$ a few 10^2 Myrs $\sim t_{dyn}(R_{virial}) << t_{Hubble}$

'maximum starbursts' (Elmegreen 1999, Tacconi et al. 2006)

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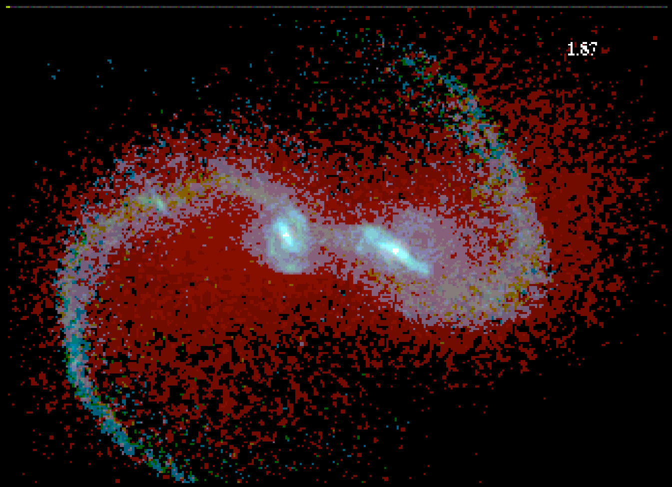

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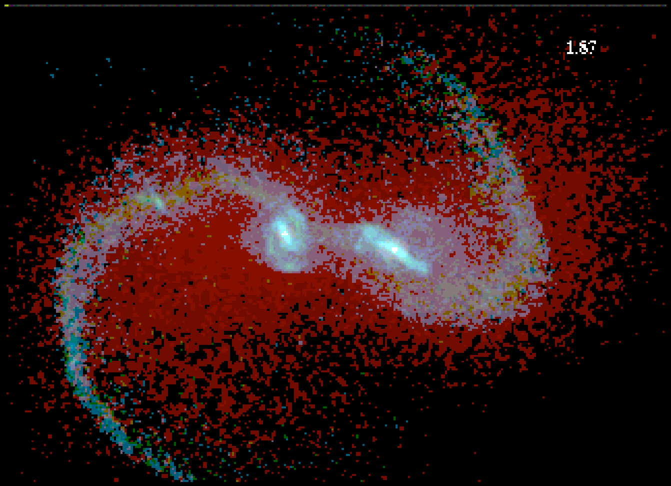

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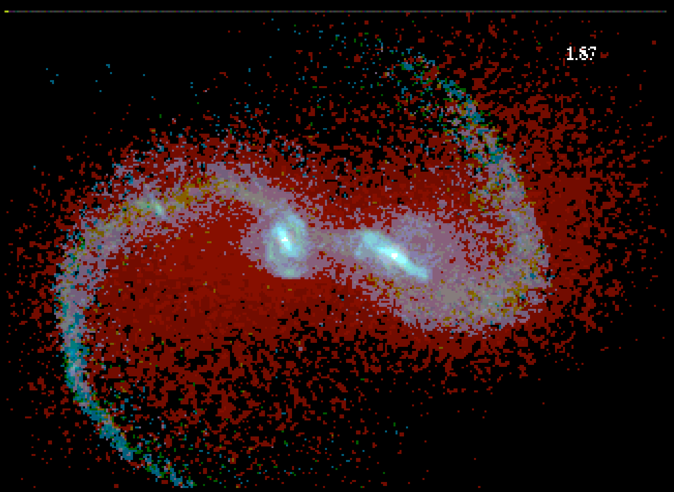

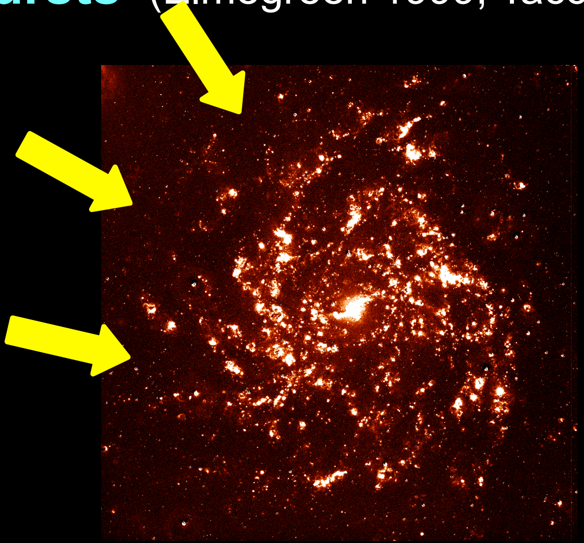

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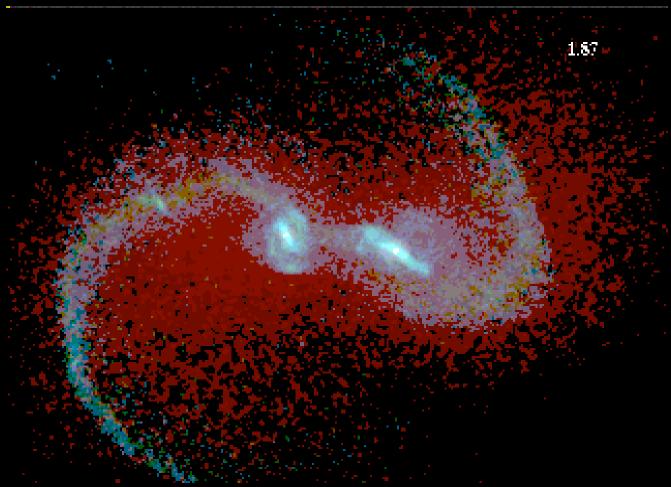

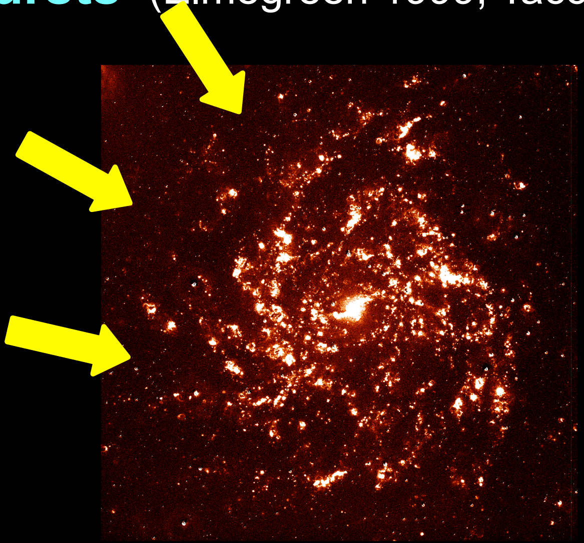

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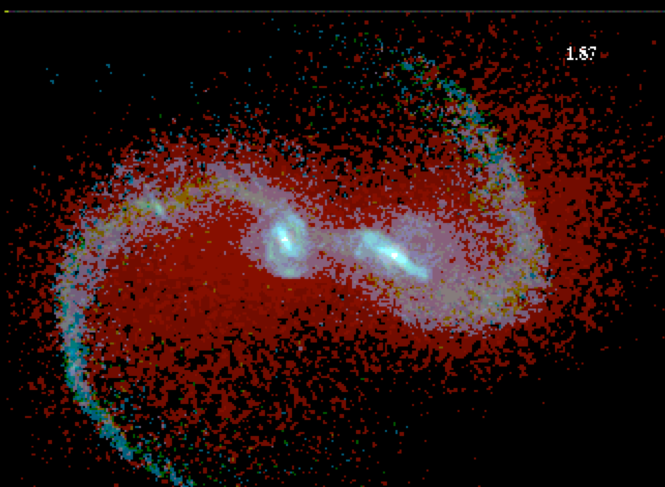

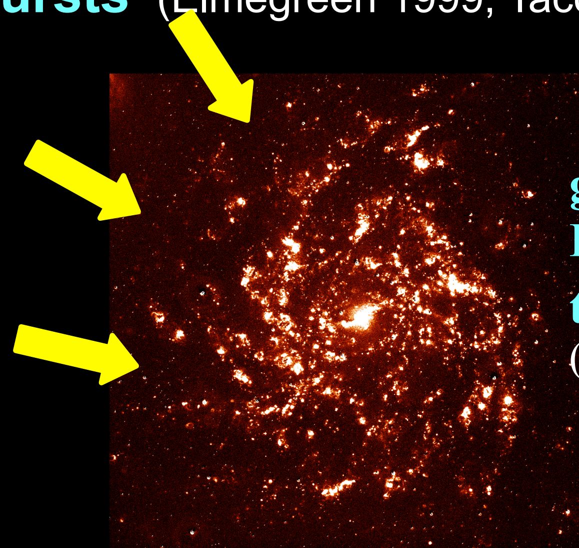

gaseous accretion!
HI/H_2 phase transition
(Blitz & Rosolowsky 06)

major merger scenario:
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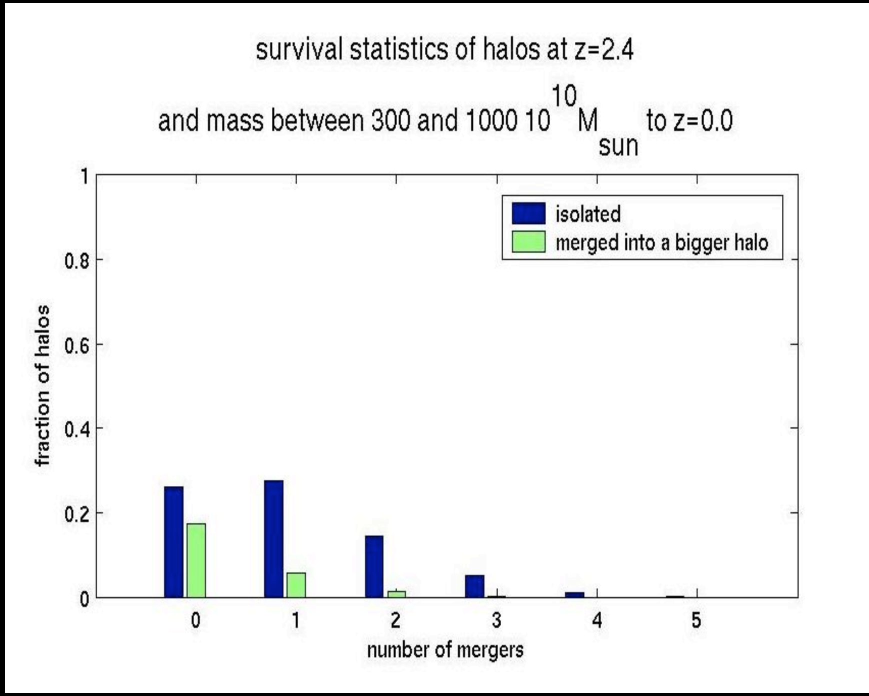
evolution from z=2 to 0 ?

- destruction: subsequent major mergers, especially in dense regions
- internal secular evolution by bar- bulge formation
- internal quenching of accretion
- AGN feedback effects



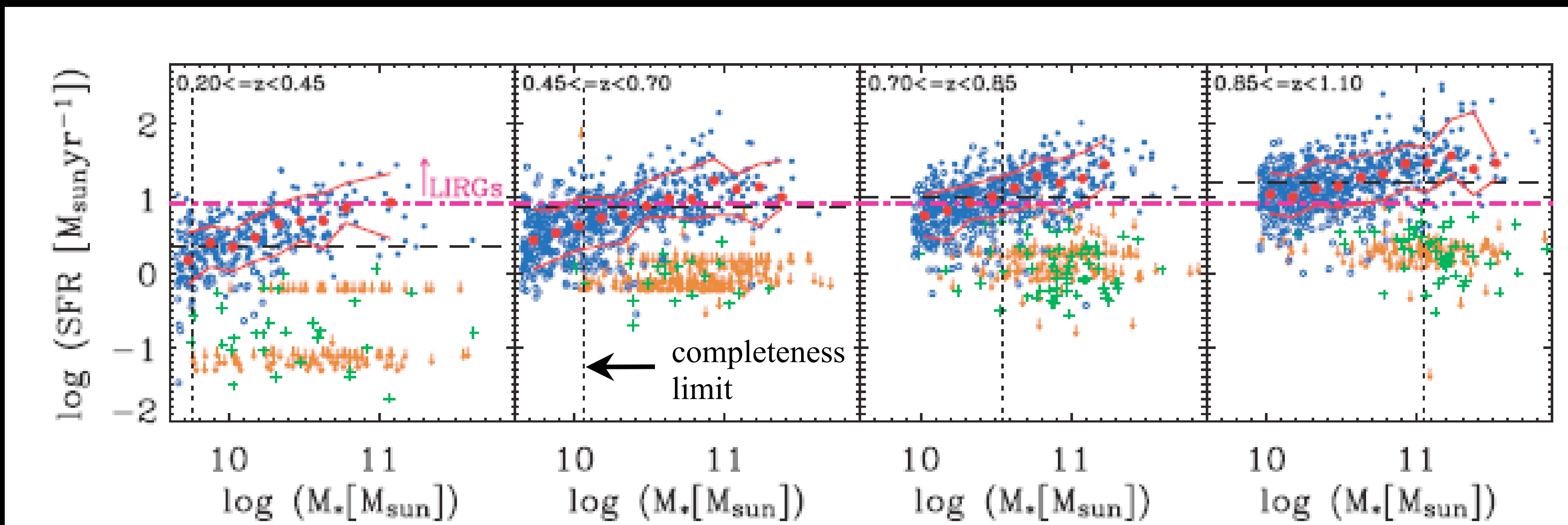
S.Genel 2007
based on Millenium simulation (Springel et al. 2005)

see Bruce Elmegreen's talk

van den Bosch 2002, Immeli et al. 2004, Croton et al. 2005, Burkert & Lin 2006, Governato et al. 2006, Birnboim et al. 2007

star formation in the DEEP2 survey

z<1: evidence for a gradual decline of star formation with low fraction of starbursts



mass limited ($10^{10..11}$ $M_\odot$) survey of $10^{3.5}$ galaxies in DEEP2/AEGIS:
emission line/GALEX/Spitzer SFR:
from small δ(log SFR): 67% (95%) of the time <2 (<4) times <SFR>

Noeske et al. 2007

a 'universal' star

'Kennicutt-Schmidt'-relations

$$\Sigma_{starformation}(M_{\mathbf{e}}\, yr^{-1} kpc^{-2}) = k_1 (f_{gas} \Sigma_{matter} (M_{\mathbf{e}}\, kpc^{-2}))^{\alpha},$$

with $\alpha = 1.4(\pm 0.15)$

$$\Sigma_{starformation} = k_2 \frac{f_{gas}\Sigma_{matter}}{\tau_{dyn}}, \quad \text{with } \tau_{dyn} = R_d / v_c(R_d)$$

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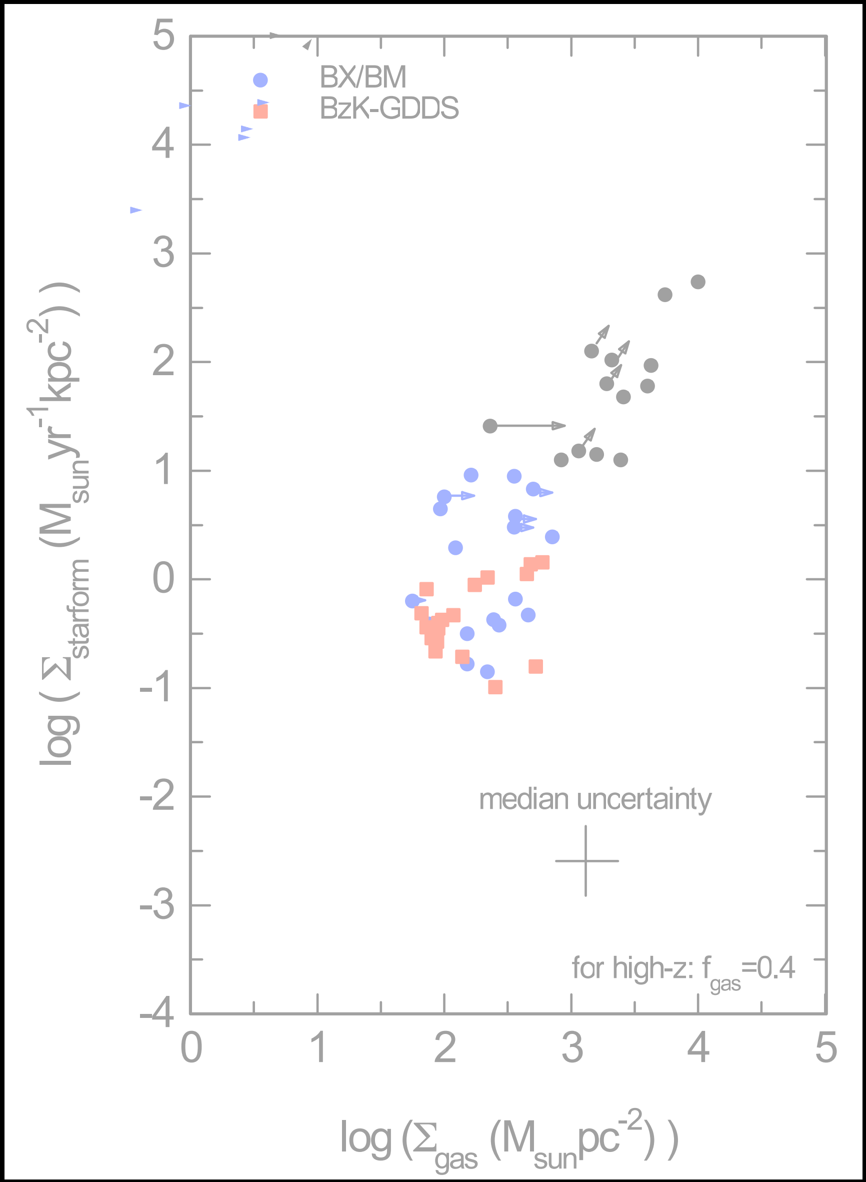

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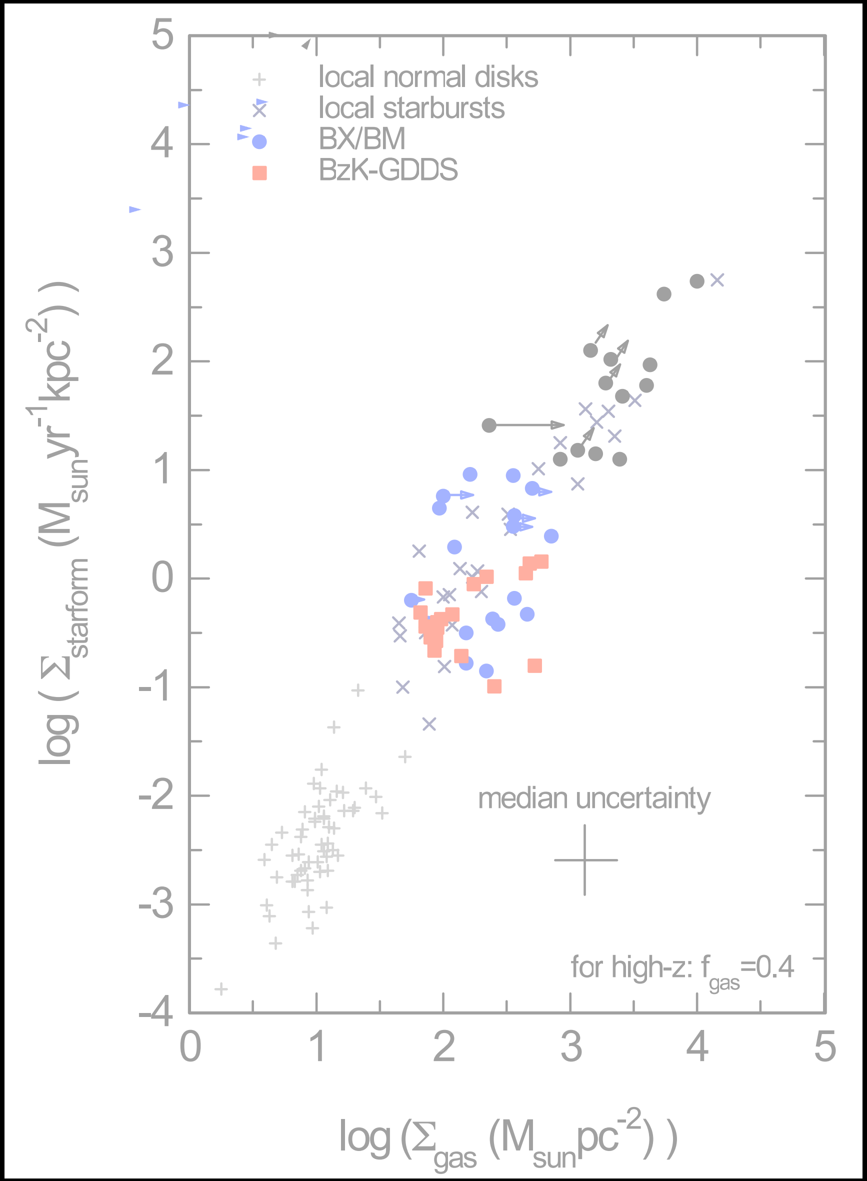

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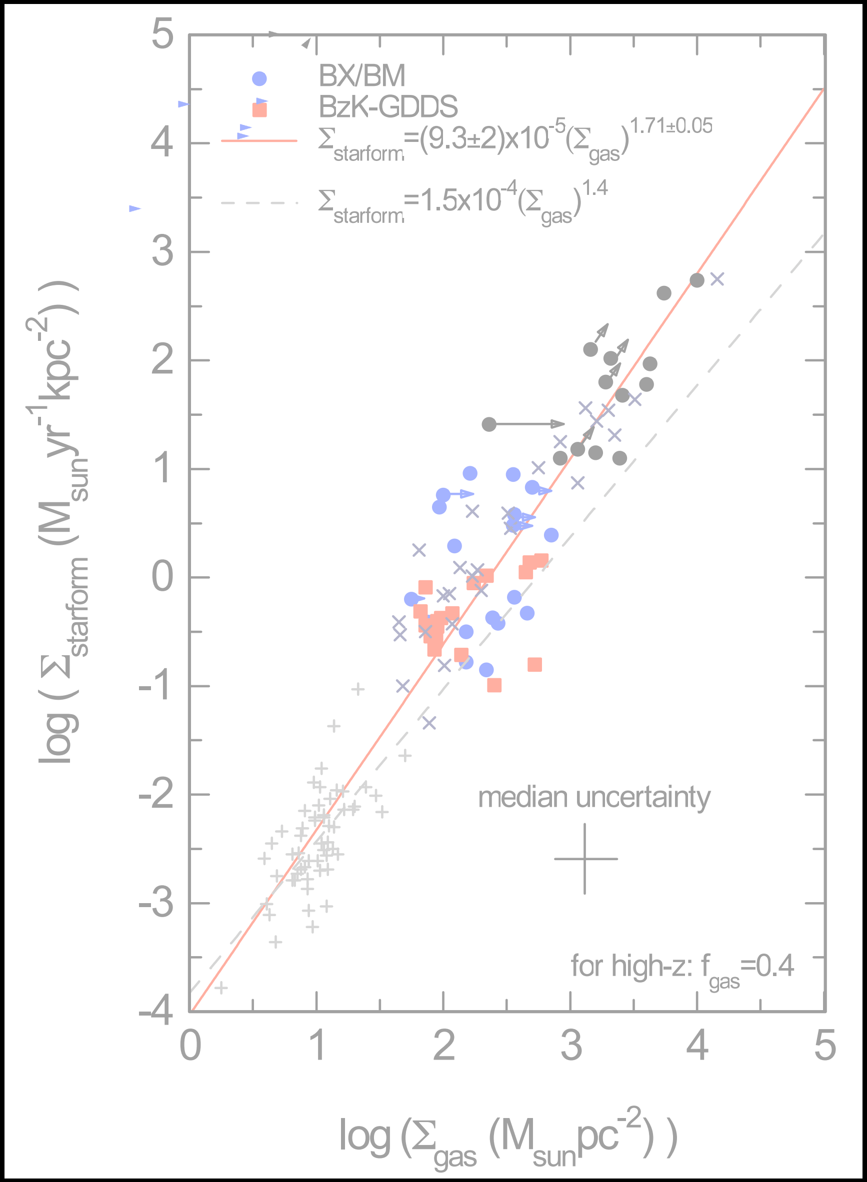

comments on the IMF at high-z

constraints from semi-analytic modeling of SMG luminosity function

Can the faint sub-mm galaxies be explained in the ΛCDM model?

C. M. Baugh[1], C. G. Lacey[1], C. S. Frenk[1], G. L. Granato[2], L. Silva[3], A. Bressan[2], A. J. Benson[4], S. Cole[1].

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[2] *Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio, 5, I-35122 Padova, Italy.*
[3] *Osservatorio Astronomico di Trieste, via Tiepolo 11, I34131 Trieste, Italy.*
[4] *Astrophysics, University of Oxford, Keble Road, Oxford, OX1 3RH, UK.*

proposal: very flat IMF
($dN(m) \sim M^{-1}\,dm$)

Baugh et al. 2004, Lacey et al. 2006

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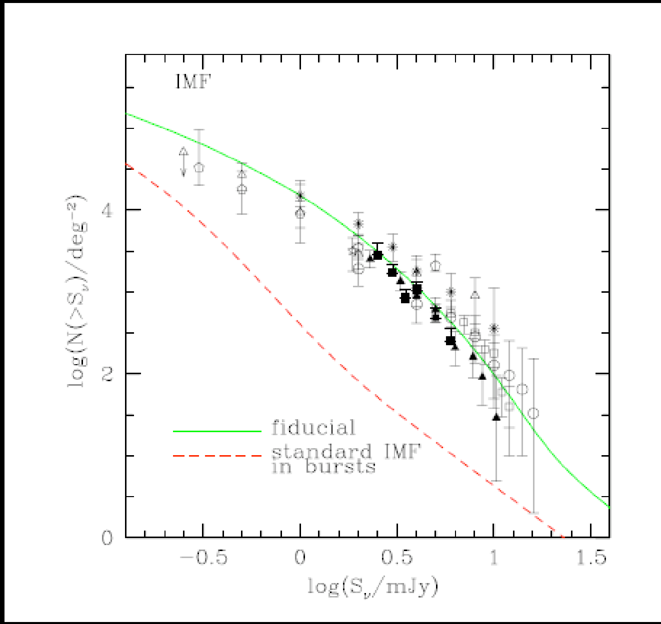

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constraints on high-z IMF

- $z\sim0$ M_*/L_B in ellipticals
- evolution of slope and offset of elliptical fundamental plane from $z\sim0$-1.3
- metal abundance inventory in galaxy clusters
- dynamical constraints in $z\sim2$ galaxies

Renzini 2003, 2004, Erb et al. 2006b, Förster Schreiber et al. 2006, Tacconi et al. 2007

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- data consistent with 'universal' Kroupa/Chabrier IMF
- Salpeter 0.1-100 excluded for $X_{CO} > 0.22\ X_G$, especially if allowance is made for dark matter (<10-20 kpc)
- top heavy IMF with $M_{tot} \leq 0.5\ M_{Kroupa}$ excluded

Renzini 2003, 2004, Erb et al. 2006b, Förster Schreiber et al. 2006, Tacconi et al. 2007

Conclusions

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- luminous star forming galaxies at z~2 convert a significant fraction of their gas mass to stars, and enrich their metallicity on a ≤1 Gyr time scale
- a significant number of UV/optically selected z~2 star forming galaxies are 'protodisks' with an angular momentum similar to large z~0 spirals
- SMGs may be major mergers leading to rapid formation of very compact spheroids; disks may have been created by a less violent process, such as minor mergers or cold flows
- the difference in star formation rates between submillimeter and UV-optically selected galaxies may be largely accounted for by 'universal' Kennicutt-Schmidt law
- a wide range of data presently are consistent with 'universal' IMF to z~2-3