Nick Scoville, Caltech   Nov 13, 2007

Nature and distribution of low z SF

GMCs
H_2 vs HI
OB and ULIRG SF -- self-regulation
dynamically triggered

High z --

shift to high L galaxies
environmental dependence
merging rate evolution

H2 Gas :

Fueling :

gradual -- smooth accretion inflow + HI clouds <== 1 Msun/yr

dynamically driven -- radial w/i disk : spiral arms + bars

interactions and mergers <== 100 Msun/yr

Properties :

SF gas -- essentially all GMCs but w/ much small structure

starburst disks -- continuous dist. -- e.g. Arp 220

SB dynamically triggered

GMCs :

1) **self - gravitating**

2) **effective internal turbulent pressure ~ 100 P_{ISM}**

3) $\tau_{dyn} = D / V_{turb} \sim 3\text{-}10 \times 10^6$ **yrs**

4) **SFR per τ_{dyn} low !! ==> < 1% efficiency**

GMCs cont'd :

lifetime very long

- **a) mass continuity w/ other phases**
- **b) don't see clouds in disruption**
- **c) what disperses them ?**

abscense of stars w/ age >> 10^7 yrs
but young stars and gas separate on 10^7 yr timescale

typical H_2 molecule lasts $\sim 10^{8-9}$ yrs
clouds may 'rearrange'

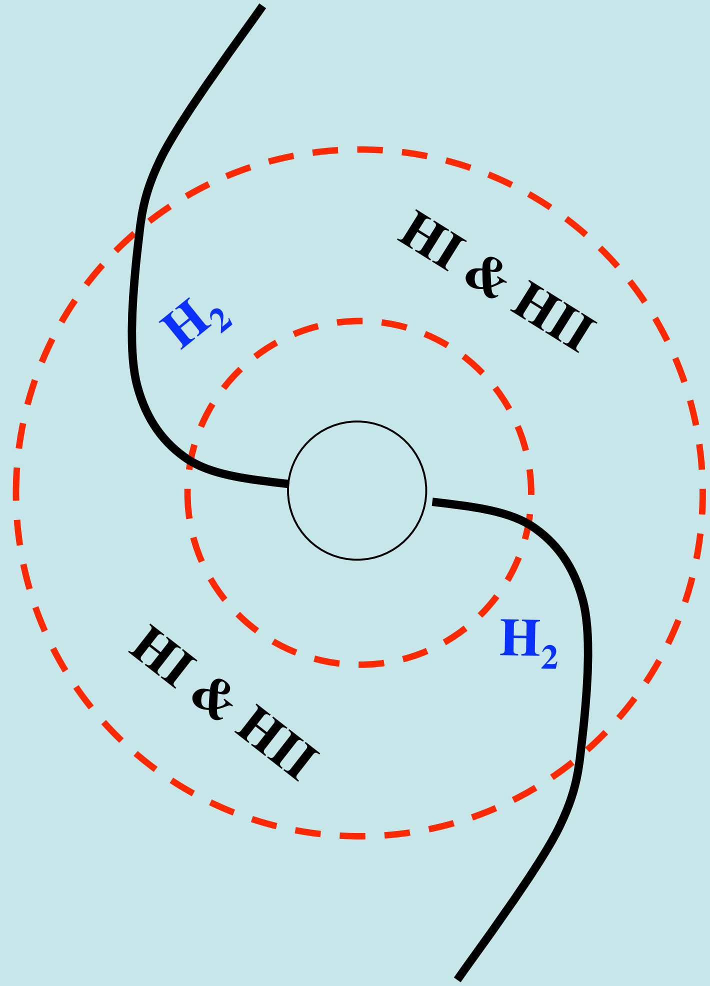
continuity (mass cons.) =>

$M_{H2} / \tau_{H2} = (M_{HI} + M_{HII}) / \tau_{HI\text{-}HII}$

in inner disks of galaxies,

$M_{H2} >> M_{HI} + M_{HII}$

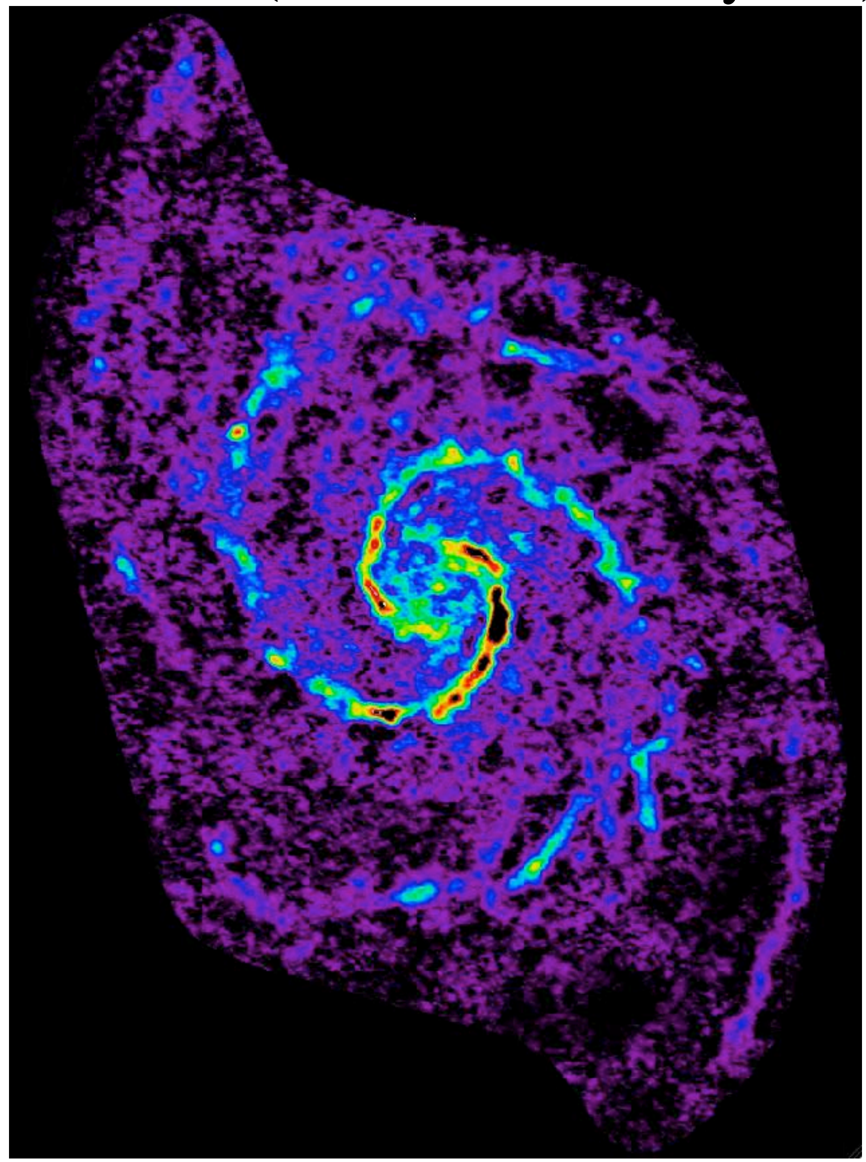
$=> \tau_{H2} >> \tau_{HI\text{-}HII} \geq 3 \times 10^7$ yrs



⇒typical H_2 lifetime ≥ 10^8 yrs !! (could be forever)
(lifetime of H_2, not necessarily GMC)

M51

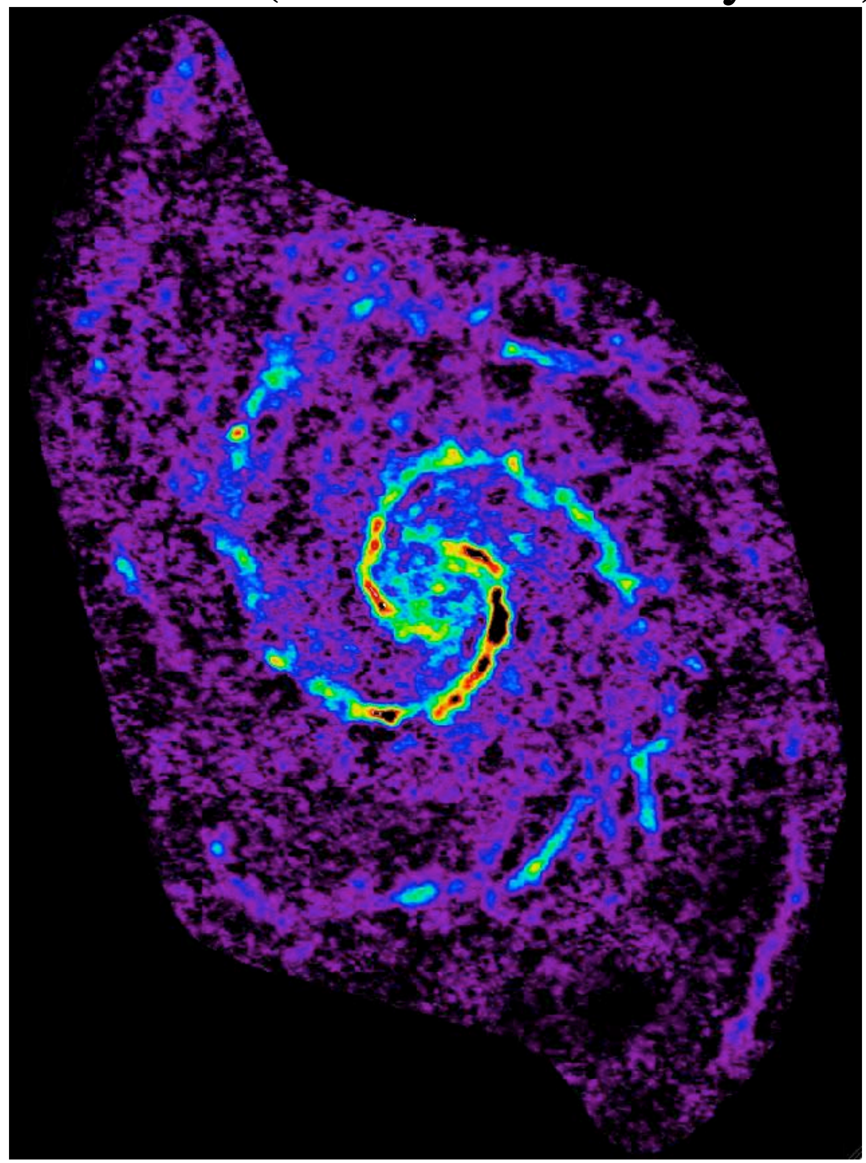
CO (CARMA + Nobeyama)



Koda etal

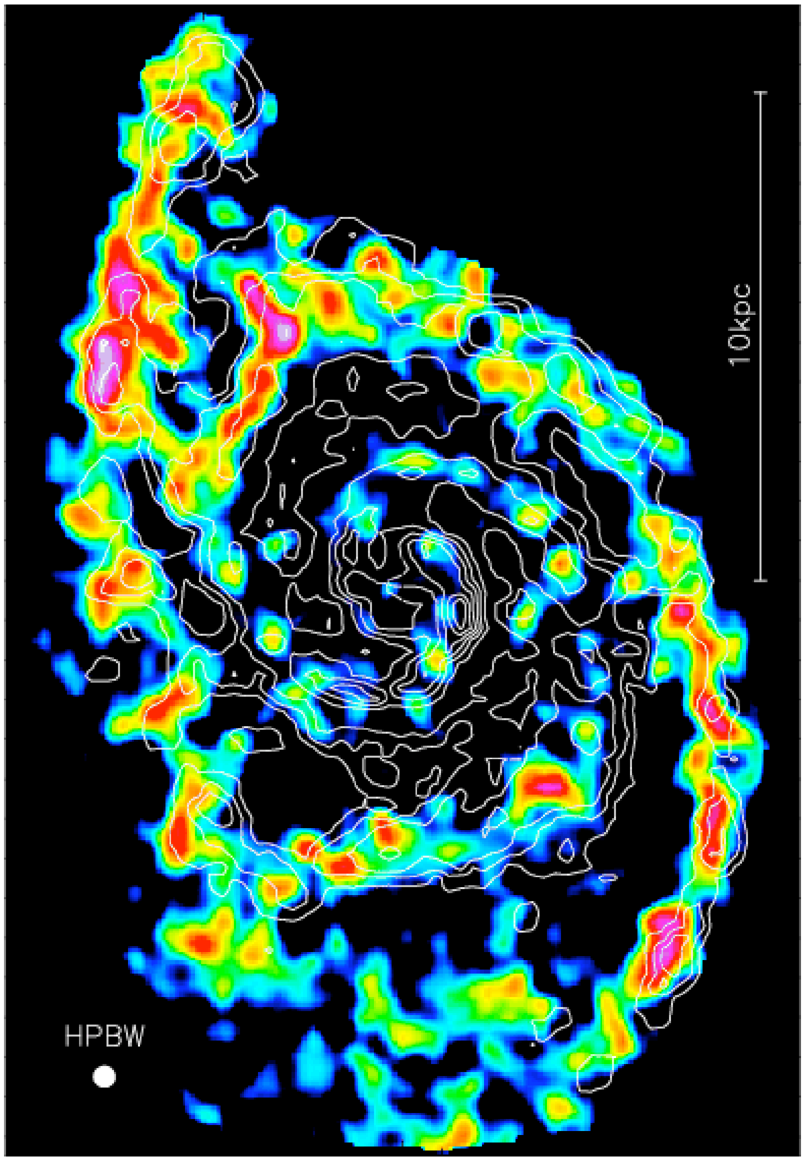
8 micron SINGS

CO (CARMA + Nobeyama)

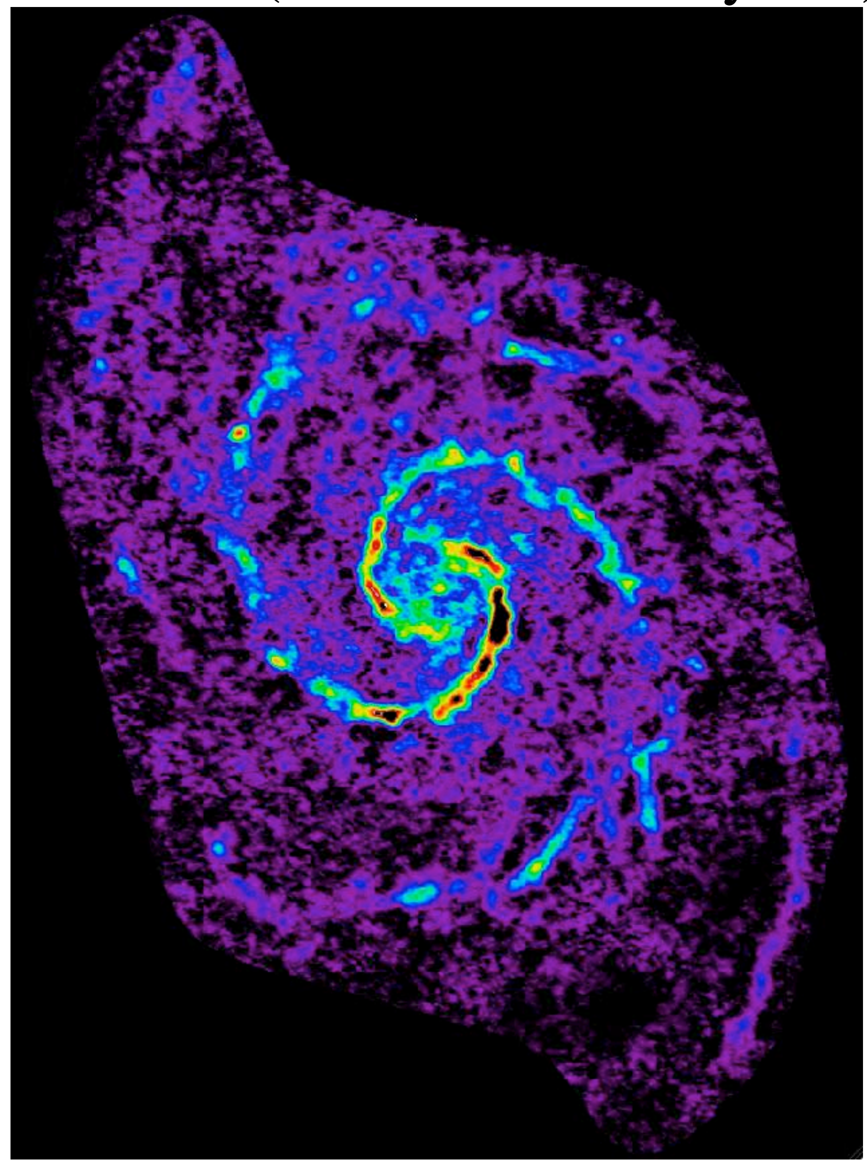


Koda etal

HI VLA



CO (CARMA + Nobeyama)



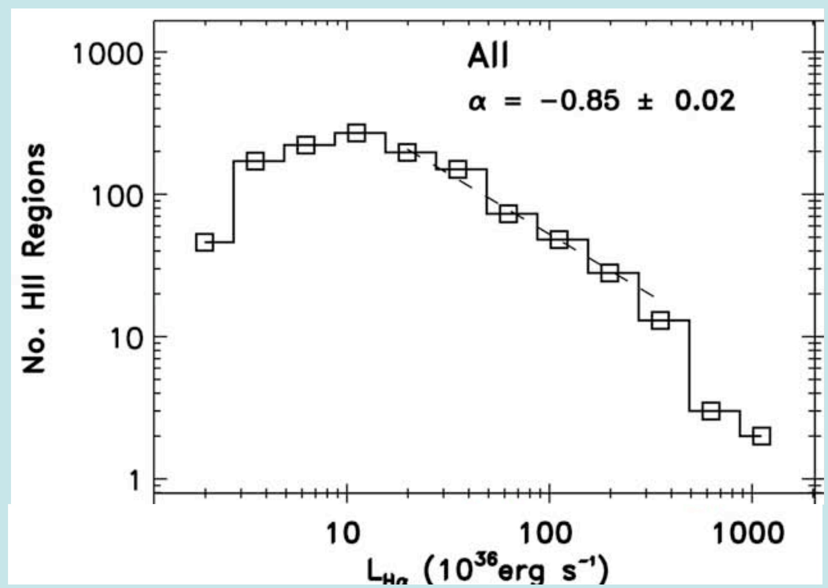
Koda etal

GMCs in interarm (not just arms) !

==> large cloud associations separate into GMCs

(due to gal. shear coming out of arms)

upper limit to HII LF. , corresponds to few 10^3 M_{sun}



Why are OB * clusters on arms ??

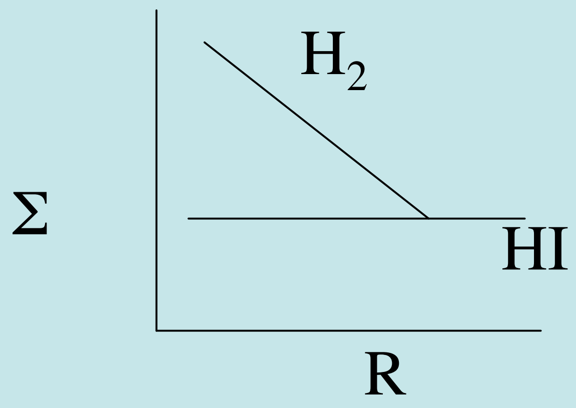
(if GMCs widespread)

Kennicutt star formation law :

SF requires a min. gas surface density

& SF ~ $\Sigma_{gas}^{1.6}$ above threshold

is SF correl. w/ HI due to dissoc.

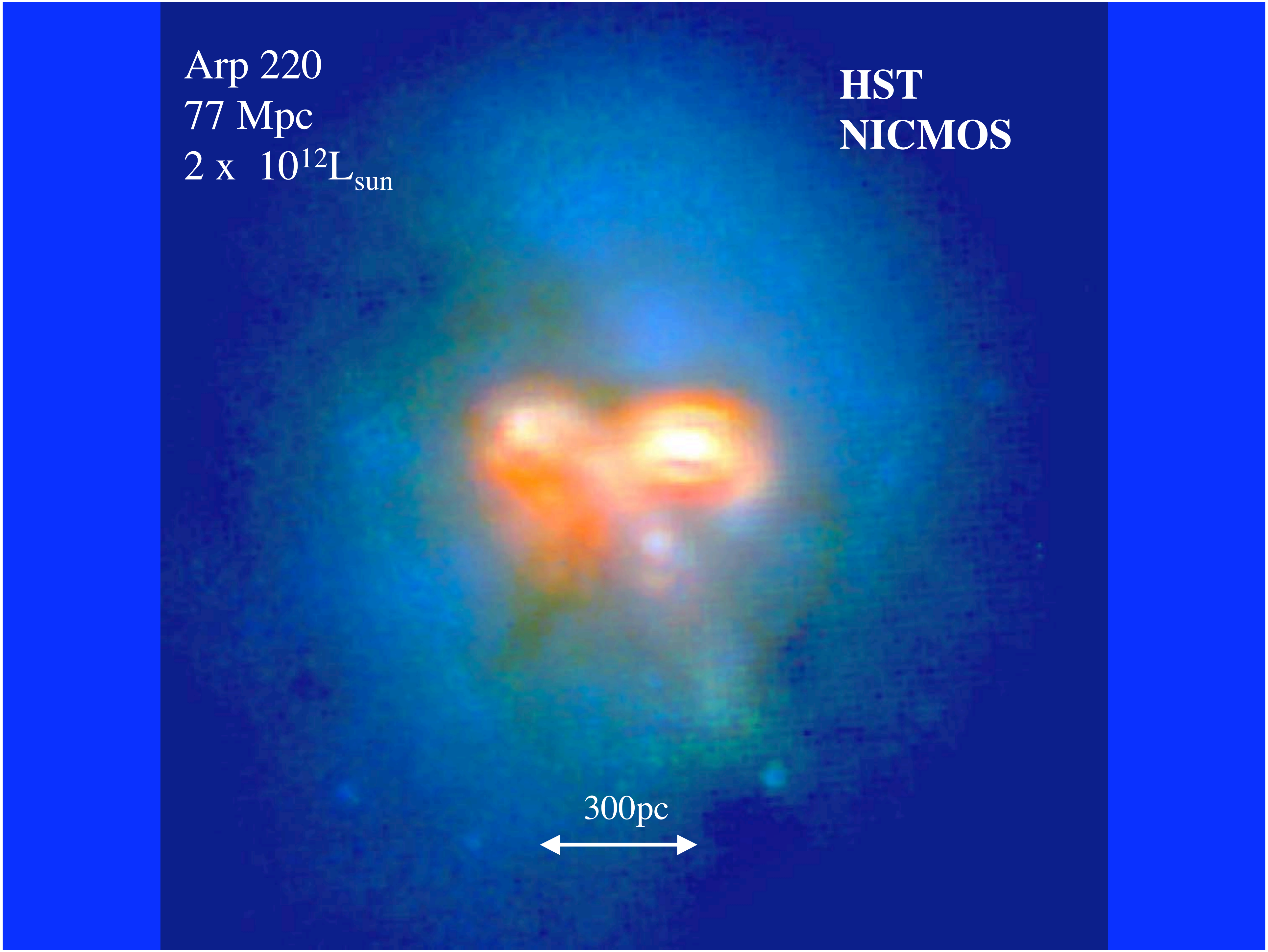


If SF GMCs self-gravitating and long lived , above criterion is really for cloud formation, not SF

Timescale for using up gas : M_{gas}/SFR ~ 10^9 yrs

Requires replenishment -- infall appears insufficient

Extreme Starbursts -- ULIRGs -- dynamically driven


Arp 220
77 Mpc
2 x $10^{12} L_{sun}$
HST
NICMOS
300pc

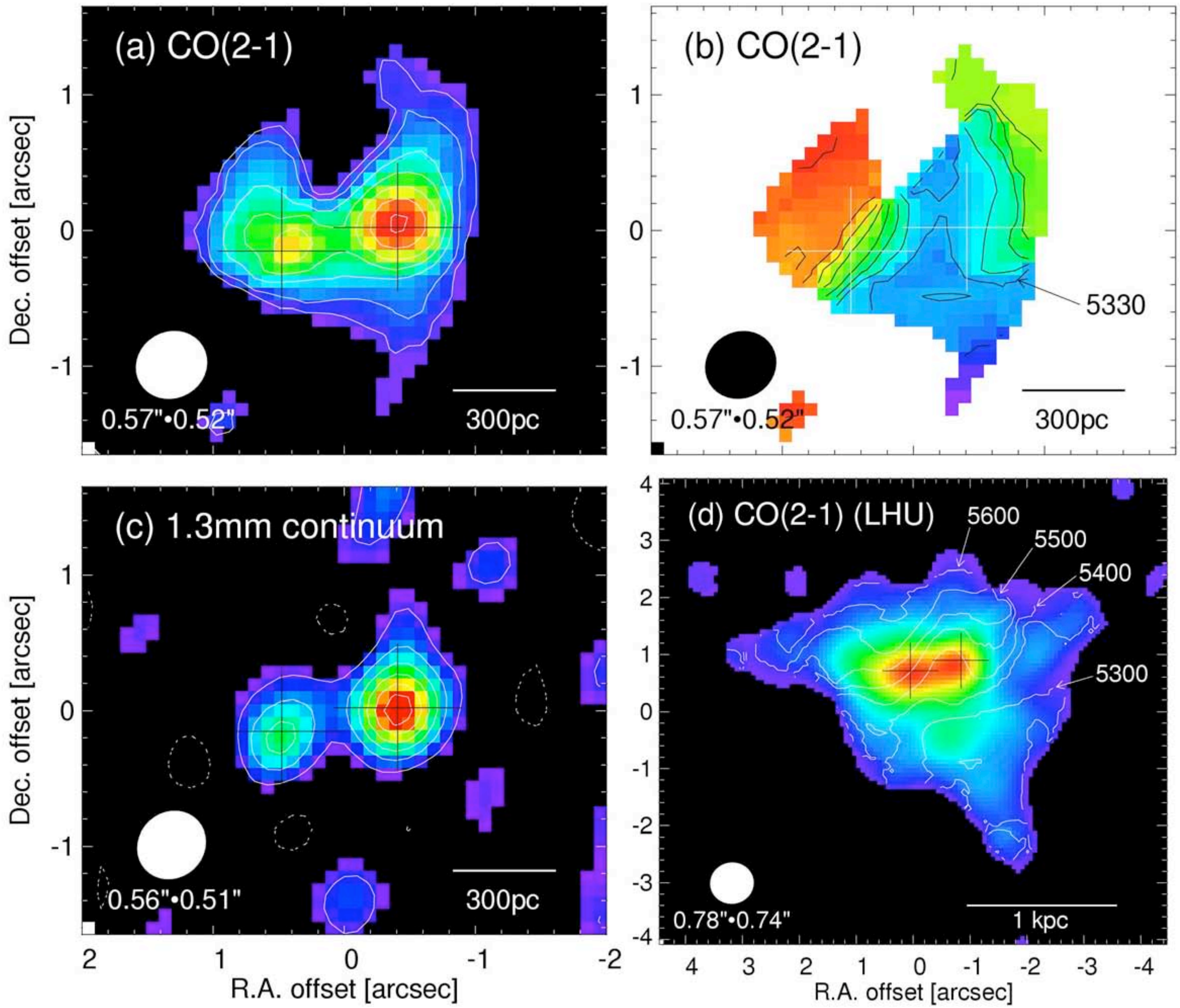


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TABLE 1

PARAMETERS OF ARP 220

Parameter	unit	Arp 220 E	Arp 220 W	Total
position $(\Delta\alpha, \Delta\delta)^a$	$('')$	(0.89, −0.18)	(0, 0)	...
$S_{1.3\mathrm{mm}}$	(mJy)	66	142	208^b
deconvolved size at 1.3 mm	(pc)	unresolved	120 × 70 (p.a. 170°)	...
$\Delta T_{\mathrm{equiv,1.3mm}}$	$(K)^c$	29	51	...
$S_{3.0\mathrm{mm}}$	$(\mathrm{mJy})^d$	(9.5)	(19)	34
$S_{\mathrm{CO}(2-1)}$ (OVRO U-array)	(Jy km s^{-1})	120	187	307^e
$\Delta T^{\mathrm{peak}}_{\mathrm{b,CO}(2-1)}$	$(K)^f$	38	37	...
V_{mean}	$(\mathrm{km\ s^{-1}})^g$	5523	5350	...
P.A. of velocity gradient	$(^\circ)^h$	52	263	25
$\Delta V(r \leq 0''.3)$	$(\mathrm{km\ s^{-1}})^i$	540	> 480	...
$M_{\mathrm{dyn}} \sin^2 i$	$(M_\odot)^j$	1.9×10^9	$> 1.5 \times 10^9$	5.4×10^9
M_{gas}	$(M_\odot)^k$	$\sim 10^9$	$\sim 10^9$	...

high gas mass fraction

high area filling

strong HCN inevitable

disks are counter-rotating ! => merger

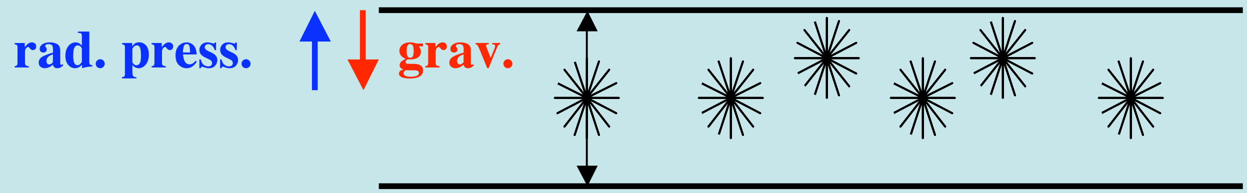
$A_V \sim 5000$ mag perp. to disk

Sakamoto etal

Nuclear Starburst Structure

- ISM disipative => disk / ring
- mm-obs => uniform (not cloudy) distribution

obs. σ_v => h = 20 -- 50 pc



Self-regulating :

SFR $\nearrow$ => σ_v $\nearrow$, P_{rad} $\nearrow$ => h $\nearrow$ => SFR $\searrow$

$\Sigma \propto M / R^2$

$P_{rad} \propto L / R^2$

} max L/M ~ 200-500 L_{sun}/M_{sun}

$$\frac{f_{rad}}{g_z} = \frac{(\kappa / c)\, \Sigma_L}{(-4\pi\, G)\, \Sigma_M} \qquad \kappa = 300\, \lambda_V / \lambda_L$$

$$\Rightarrow f_{rad} / g_z > 1 \quad , \quad \underline{\Sigma_L / \Sigma_M > 300 - 500\ L_{sun} / M_{sun}}$$

Predict :

max L/M for ULIRG starburst disks ~ 500 L_{sun}/M_{sun}

limited by radiation pressure swelling disk

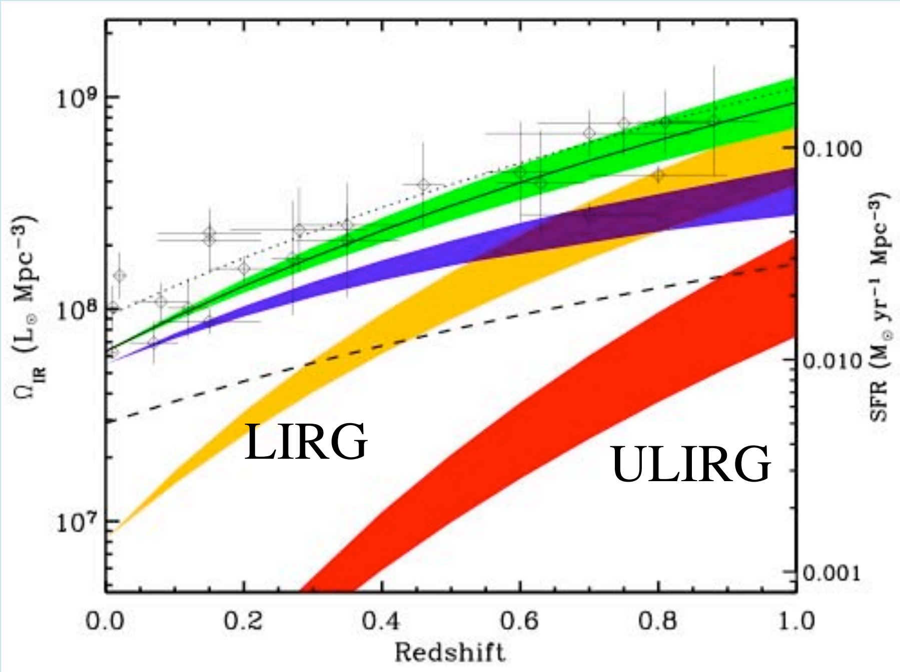
Low z SF :

GMCs normally 'quiescent' and long-lived

natural maximum star formation efficiency (SFE)
==> maximum max for normal clusters ~few x $10^3 M_{sun}$
==> maximum for starburst activity ~ 400 L_{sun}/M_{sun}

High z : larger fraction of SF in SB :

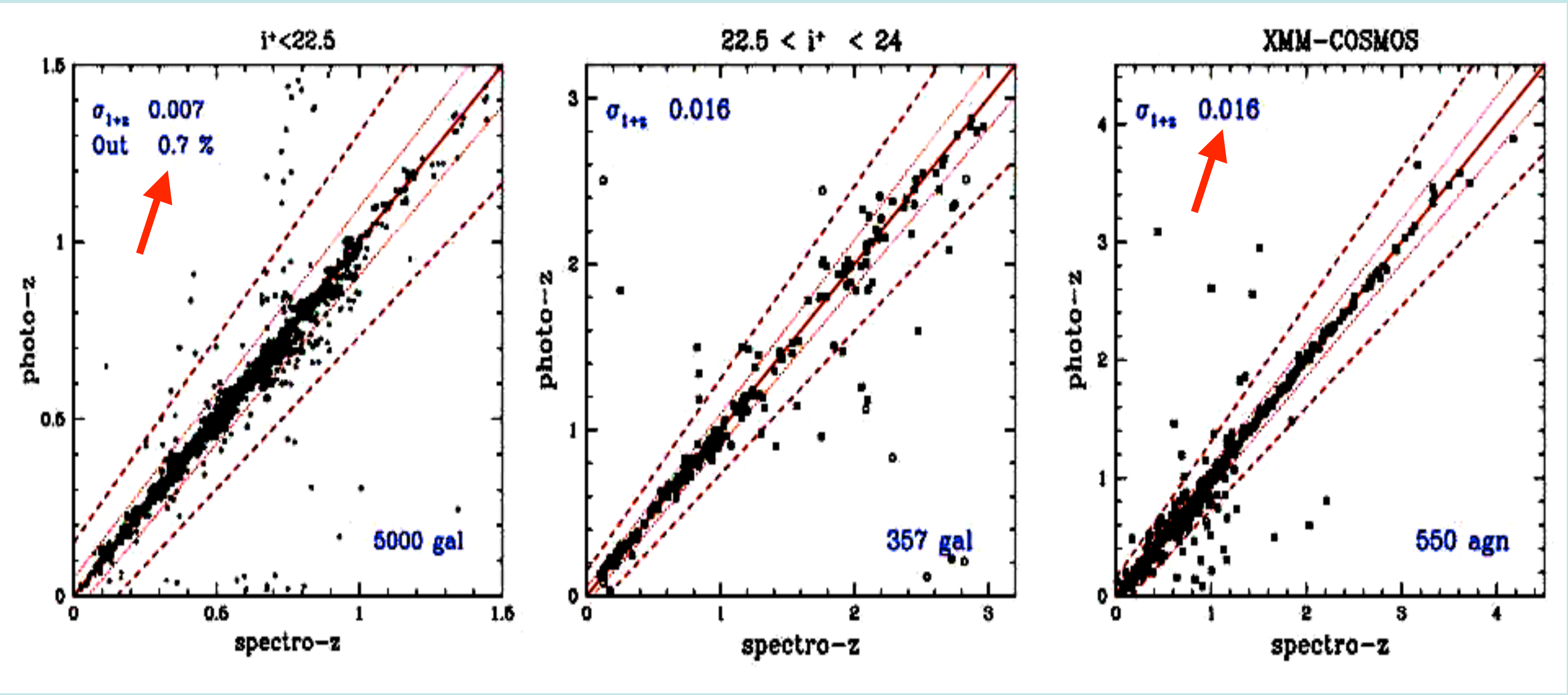
dynamically triggered



LeFloc'h etal 05

COSMOS 2 deg^2 survey --
envir. dep. of gal/AGN evolution

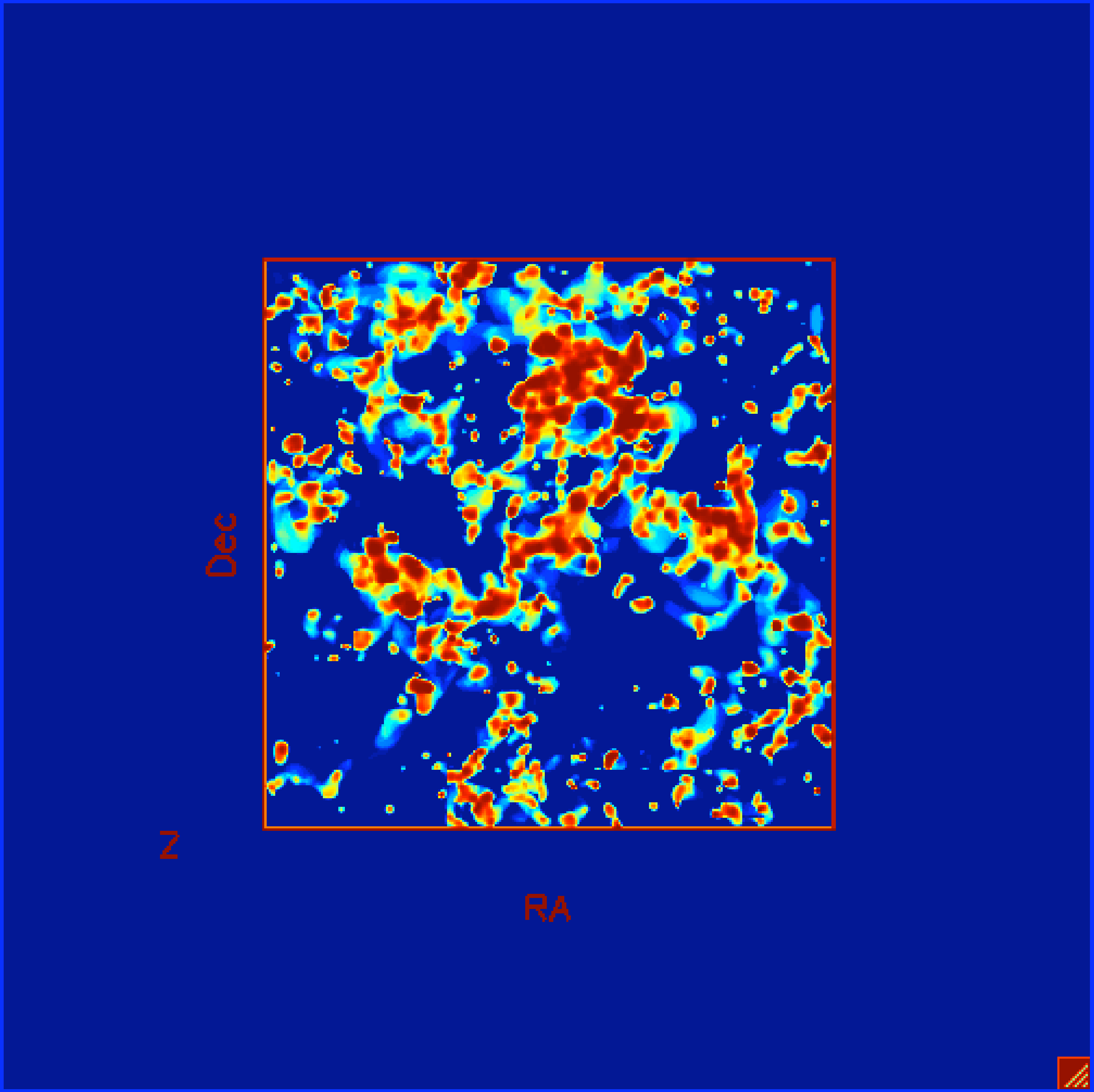
photometric redshifts for line of sight separation (34 opt/ir bands)

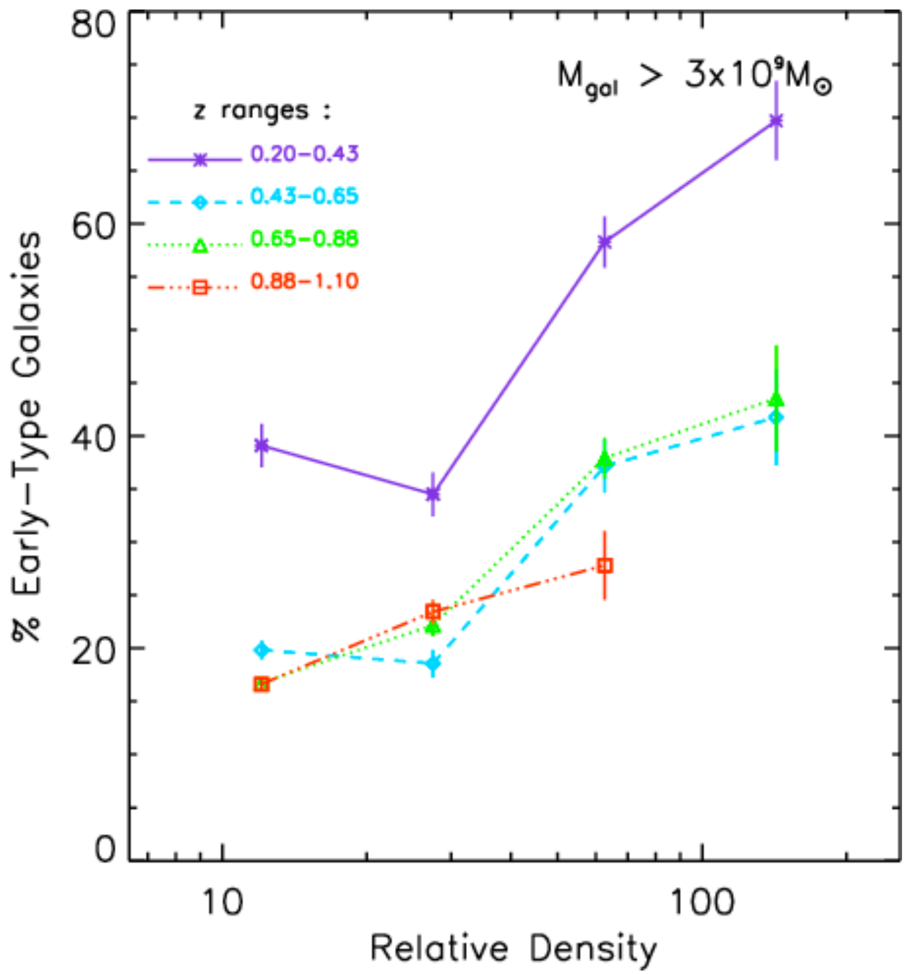


σ_z / (1+z) = 0.7% -- 1.6% !!! to z = 1.5

Ilbert etal 07, Salvato etal 07

LSS in 3-d
Galaxy overdensities
z = 0.1 to 1.5

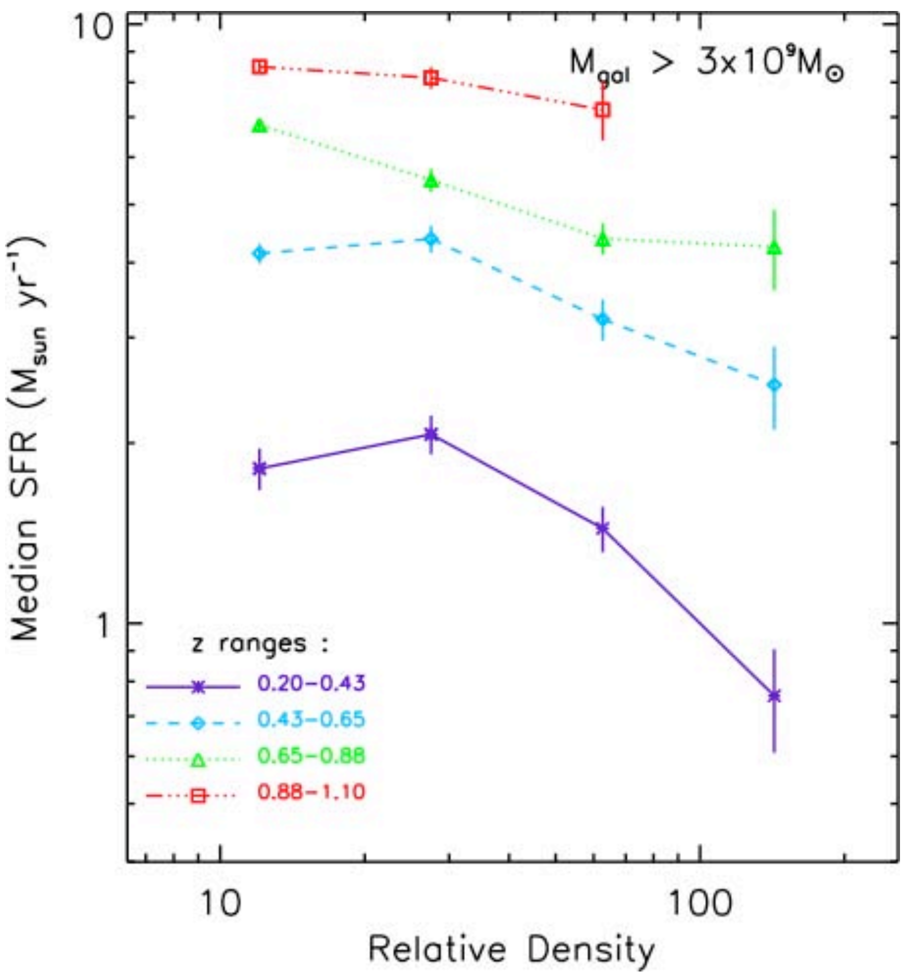


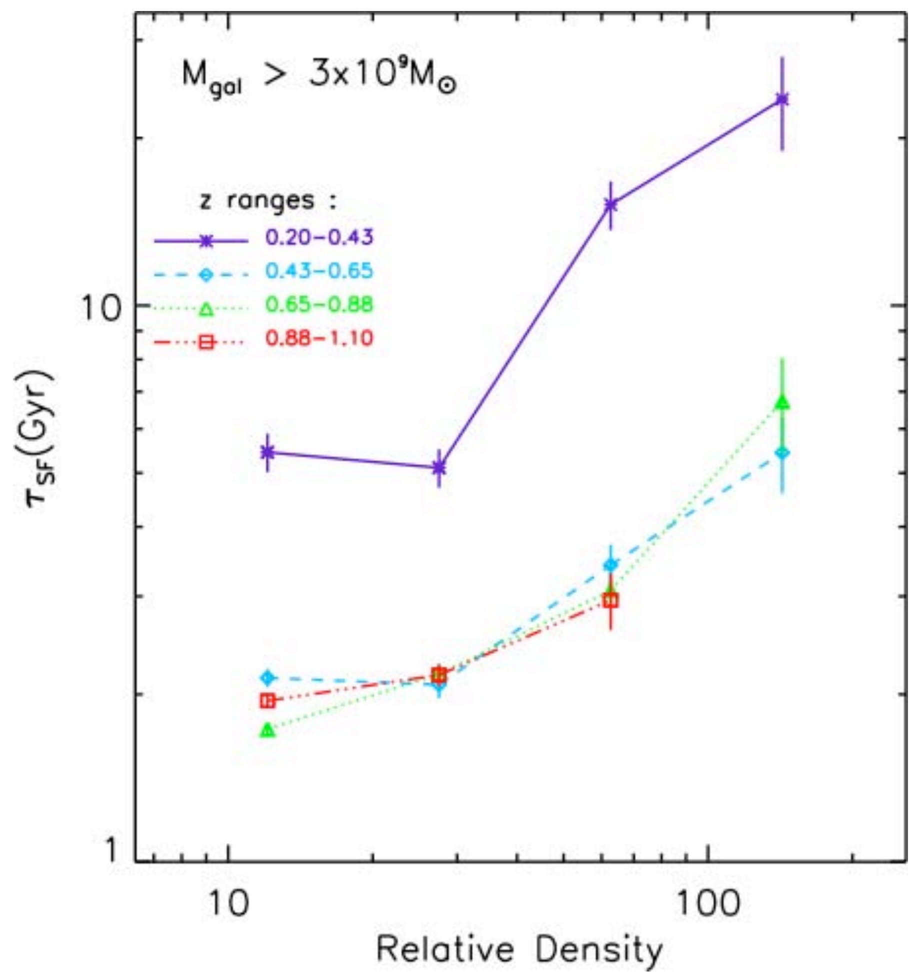


==> early-type fraction increases w/ time and density

SFR

$\tau_{SF} = M_* / SFR$



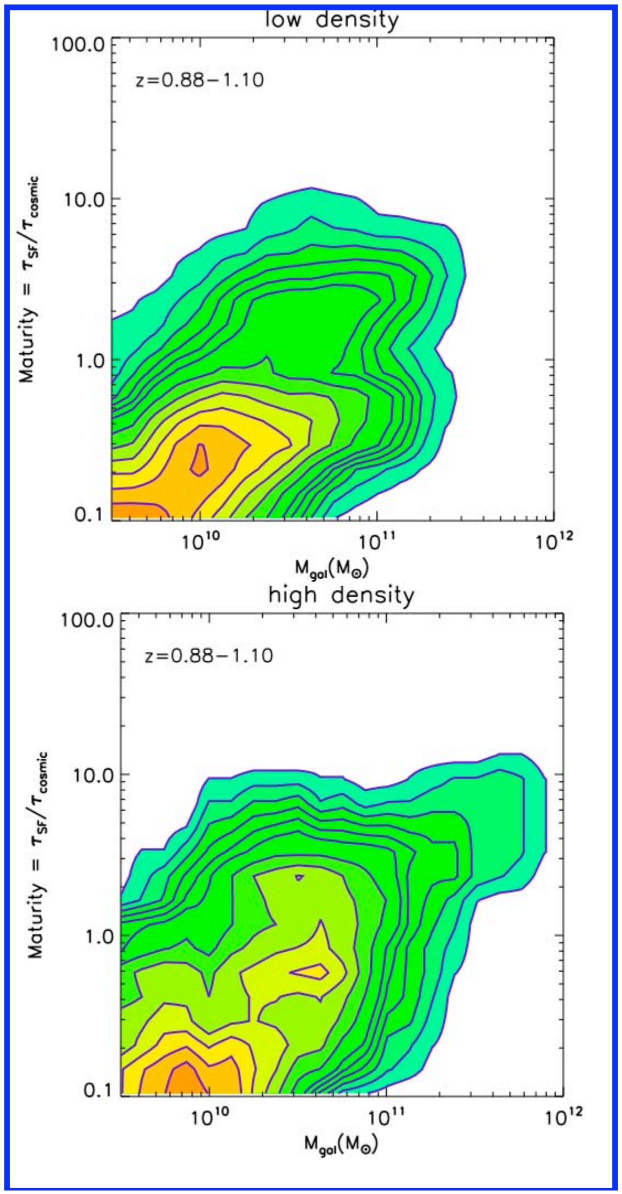


==> SFR decreases at later epoch and at high density
higher mass gal. have higher SFR
SFR / mass ~ constant , down to last 4 Gyr

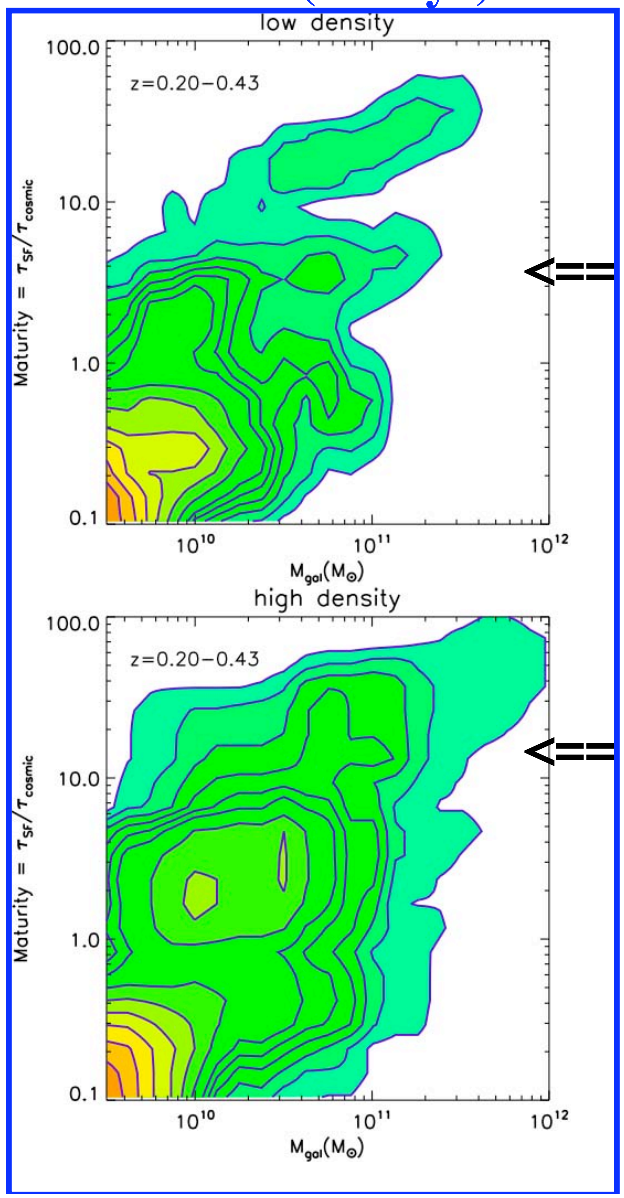
normalize SFR to Hubble time

==> $\tau_{SF} / \tau_{cosmic}$ call this -- the Maturity (μ)

z = 1.0 (5 Gyr)



z = 0.3 (10 Gyr)



<== low density

<== high density

in dense environments,

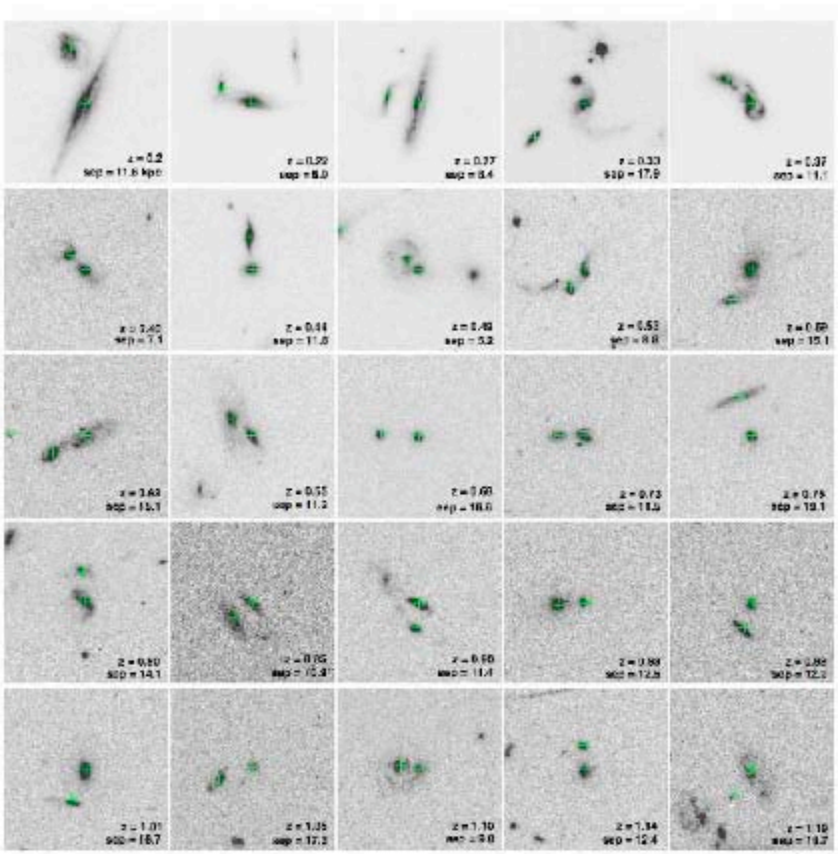
most massive galaxies

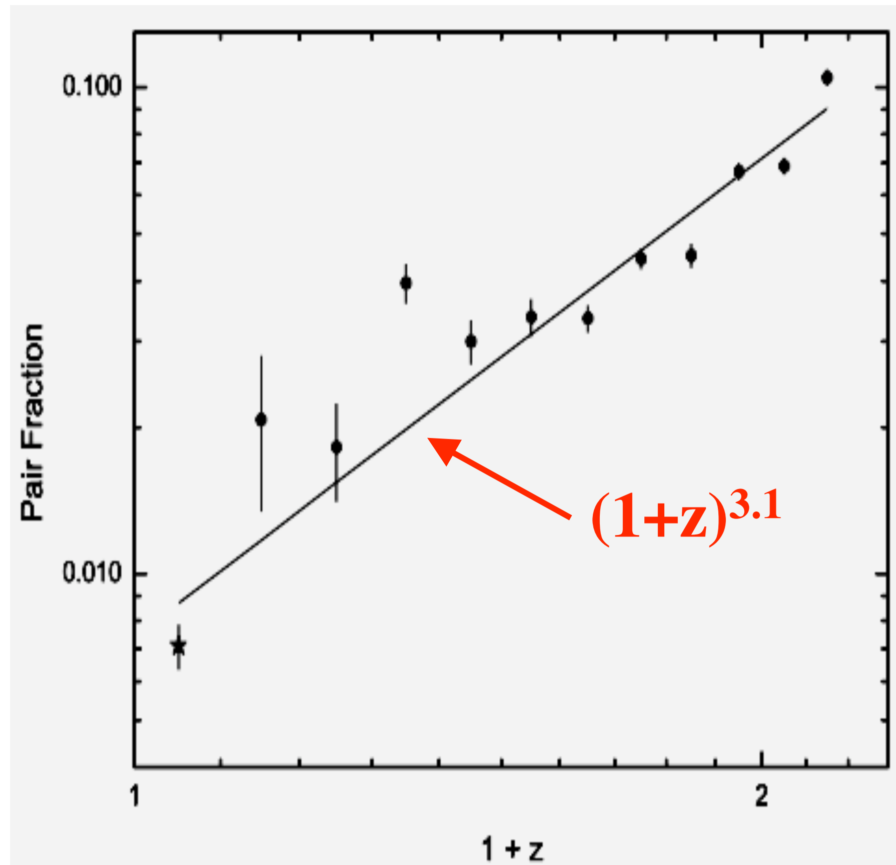
buildup earliest

most rapidly

Pair fraction / merger history :

L_* galaxies w/ L_* companion w/i 5-20 kpc

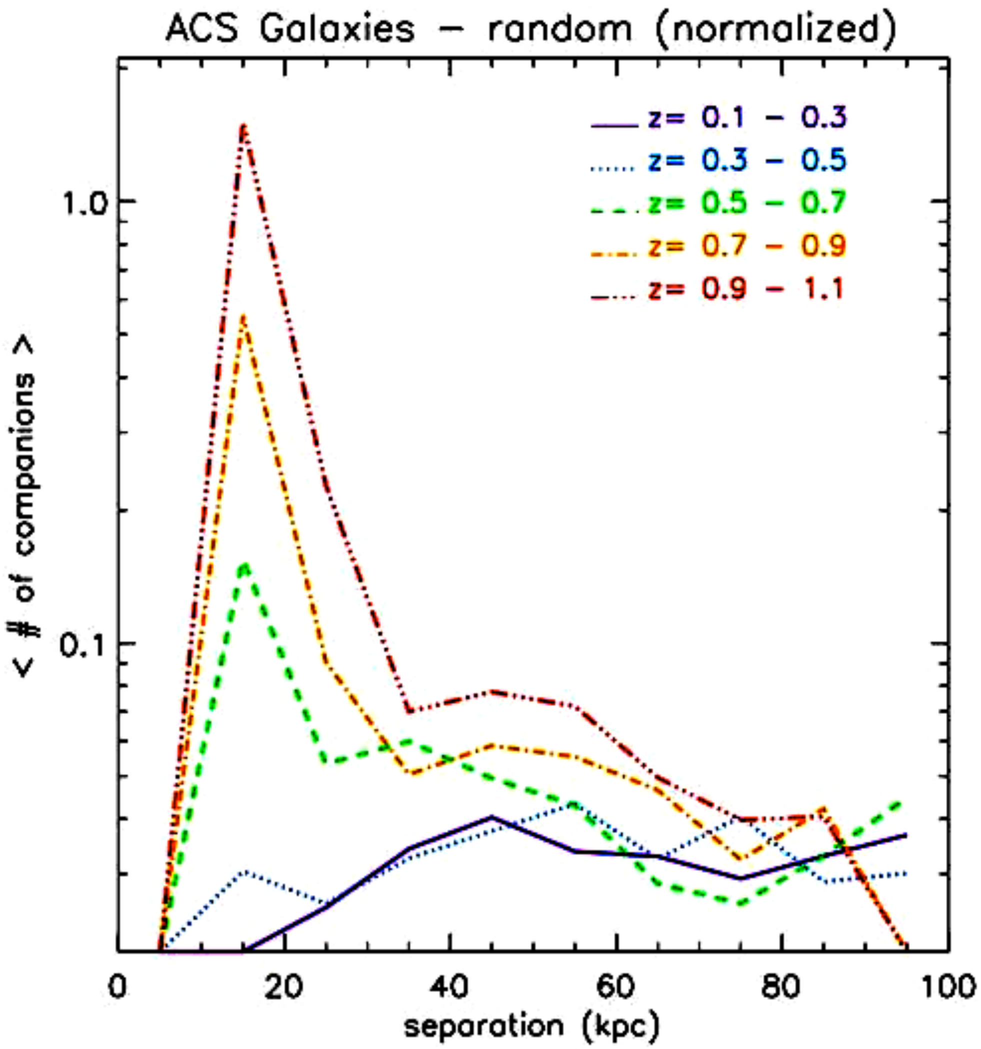


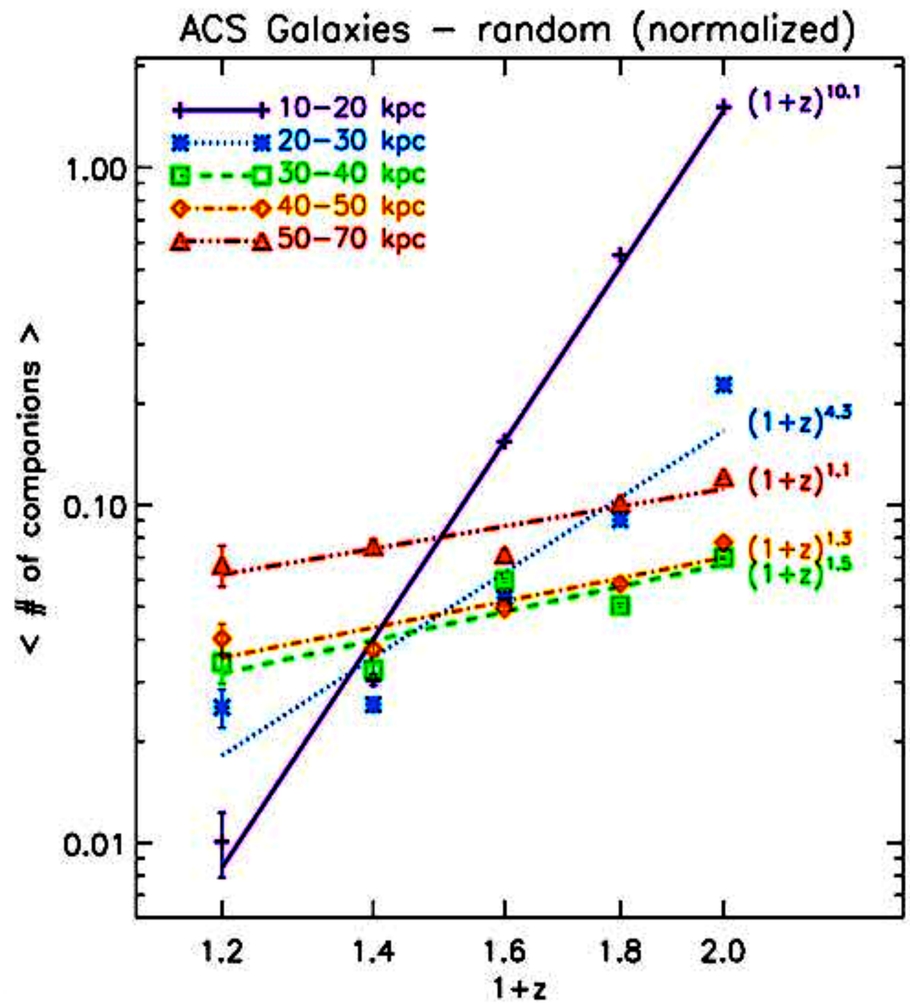


Kartaltepe, Sanders & Scoville 07

merger rate evolution :

for each L_* gal. # of $L_*/10$ gal. companions





==> very strong evol. of merger rate

Scoville etal

Links : SF <==> AGN <==> Gal. Morph.

AGN <==> bulge component ?

- $M_{BH} \sim 0.5\% \ M_{bulge}$
- bulges probably formed during violent merging

  ~ 40% of ULIRGs w/ $R^{1/4}$ law profiles

bulge connection circumstantial rather than direct

Starburst ==> feed AGN

Fuel AGN

Merger

Bulge formation