The Formation of Disk Galaxies: The Bulge Perspective

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OUTLINE

0. DISK GALAXIES: THE PARADIGM

0.5 (GALAXIES &) BULGES: REALITY CHECK

1. NEWS on DATA

2. NEWS on SIMULATIONS (WITH & WITHOUT GAS)

3. IMPLICATIONS

THEORETICAL "PARADIGM" FOR DISK-GALAXY FORMATION

1) **Baryons & Dark Matter within virialised systems have identical initial angular momentum distributions**
(Fall & Efstathiou 80)

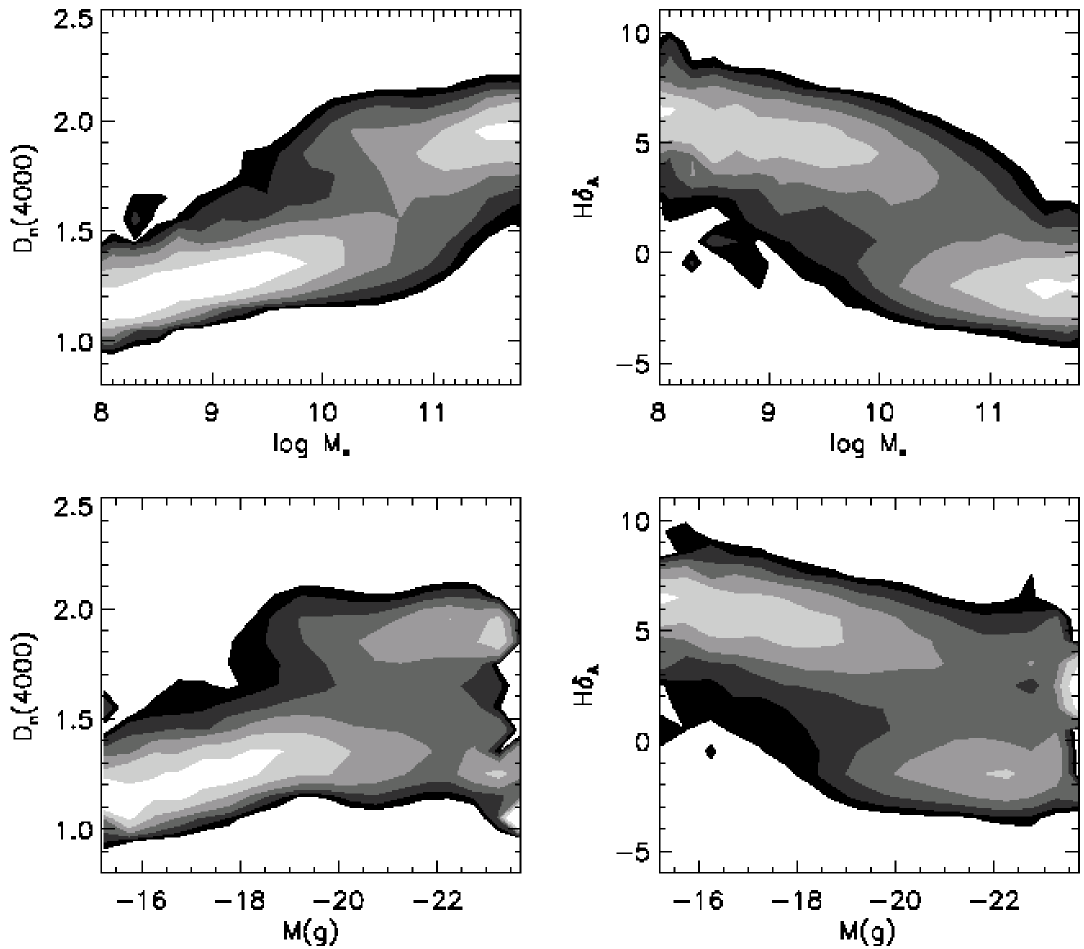
2) **Baryons conserve the angular momentum when cooling**
(Mestel 63)

→ EXPONENTIAL BARYONIC DISKS

3) **BULGES originate from mergers of halos → LIKE ELLIPTICALS**

4) **Disks "grow" around spheroids → Disk Galaxy Population**

VISUALLY: SMOOTH “HUBBLE SEQUENCE”
→ SMOOTH B/D sequence



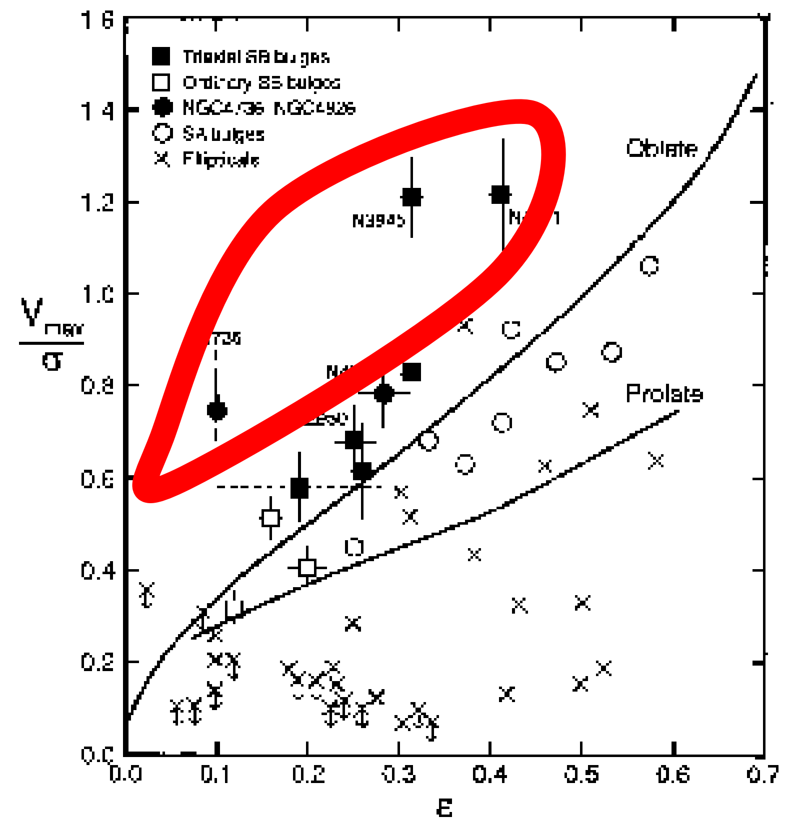
“PHYSICALLY” : “SHARP” DICHOTOMY

kauffmann et al 2003

OBSERVATIONS. 1. KINEMATICS

Disk-like, cold kinematics
(from V/σ measurements)

(Kormendy 93; Kormendy et al 01)

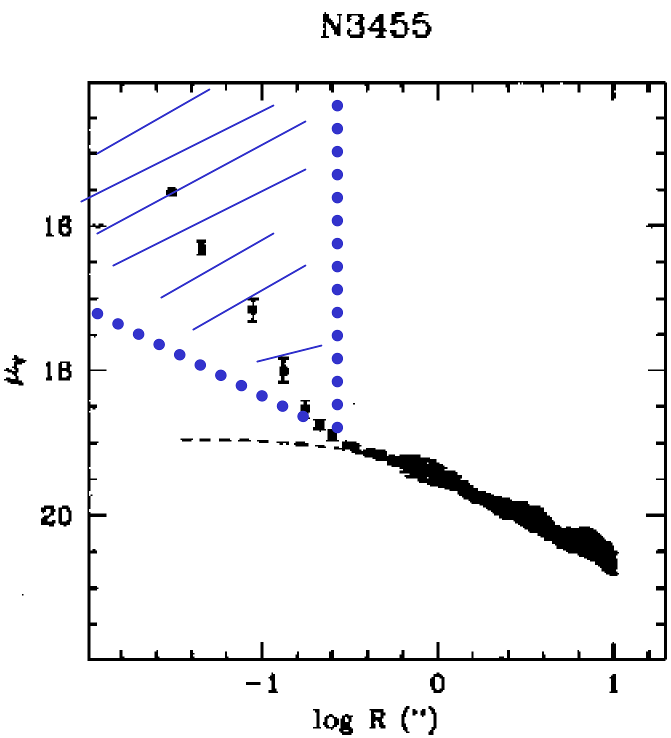


OBSERVATIONS. 2. STRUCTURE

BULGES AT FAINT-END (Sb and later types),
NOT "deVaucouleurs", R $^{1/4}$ STELLAR DENSITY PROFILES

→(ALMOST) EXPONENTIAL "SERSIC" PROFILES with n~1-2

$$\Sigma = \Sigma_0 \exp(-(R/R_d)^{1/n})$$



*(e.g., Andredakis & Sanders 94; de Jong 95; Courteau at al 96; **Carollo et al 98**; Graham 2001; MacArthur et al 03)*

(n=4: deVaucouleurs;
n=1: EXPONENTIAL
i.e., AS IN DISKS)

OBSERVATIONS. 2. STRUCTURE

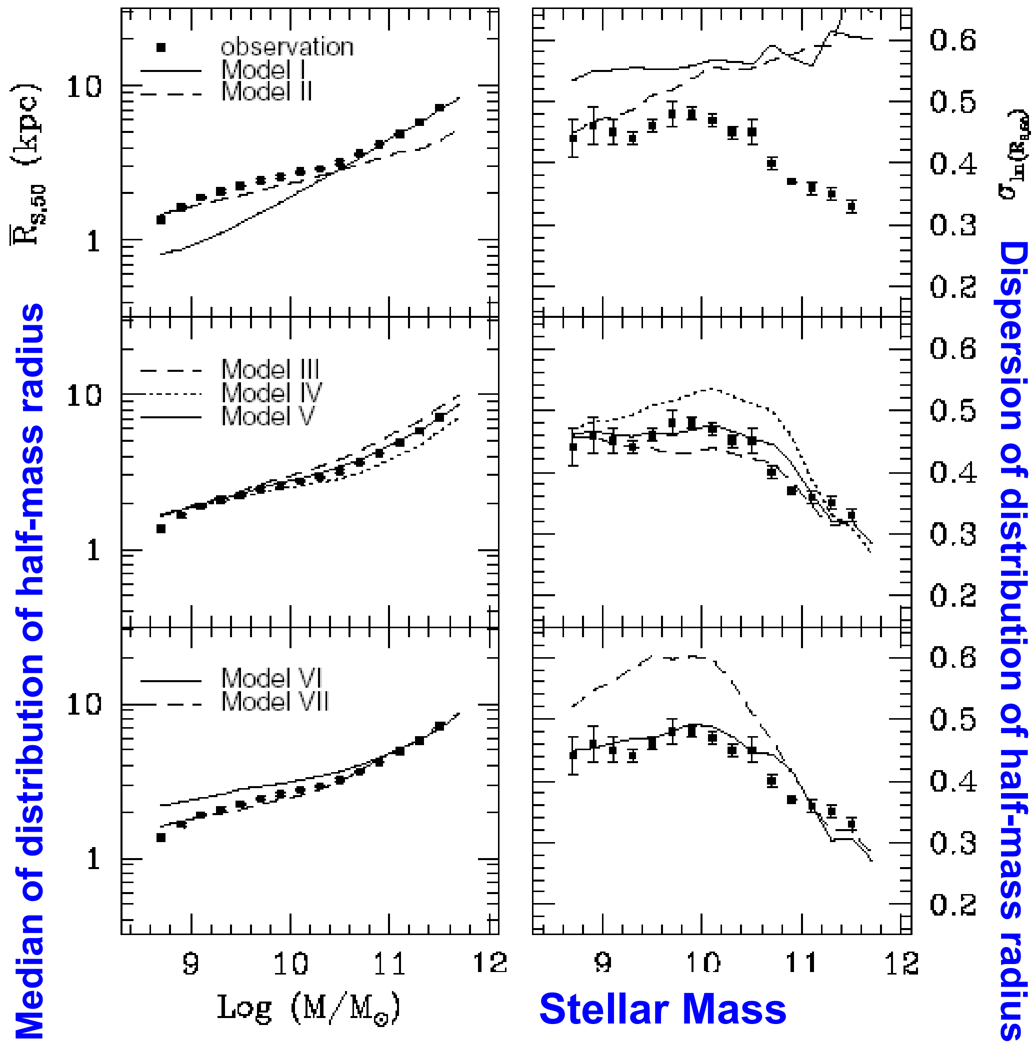
Shen, Mo, White et al 2003

Late-type = c<2.86 and n<2.5

SLOAN
~100000 late-type galaxies

Disks: as in Mo, Mao & White 98;
Bulges: instability criterion or merger recipe

Four key ingredients:
-feedback (→ gas mass fraction)
- bulge/disk ratio (uniform or instab. crit.)
- ang. mom. transfer bulge→ disk
- size-mass relation of bulges



Best fit:
→ Bulges generated by disk instability

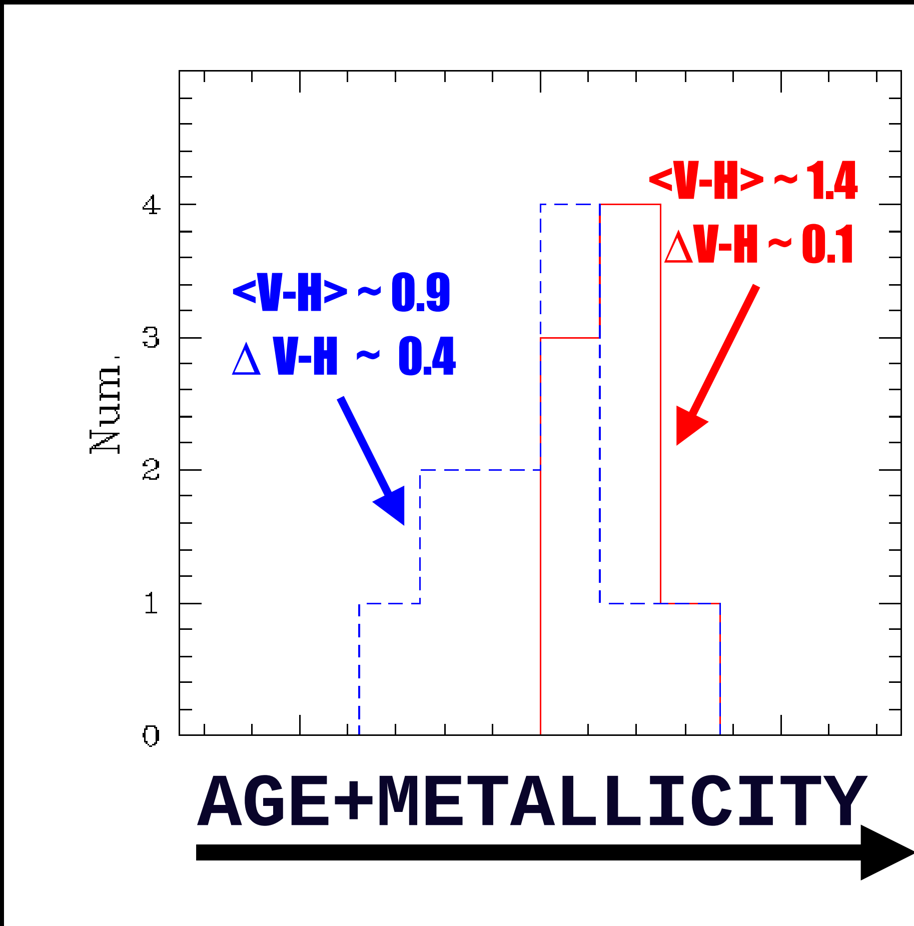
OBSERVATIONS. 3. POPULATIONS at z=0

MASSIVE BULGES (S0-Sab):
$Z > 0.5\ Z_{solar}$

Mean <AGE>: >8-10 Gyrs
ΔAge ~ 2 Gyrs

SMALL BULGES (Sb-Sc):
If $Z=0.4\ Z_{solar}$
→MEAN <AGE> ~ 2-to-5 Gyrs
→BROADER ΔAge

(Carollo, Stiavelli et al 2001, 2002; Carollo 1999)



MANY SMALL BULGES:
→ YOUNGER than MASSIVE SPHEROIDS?
→SIMILAR AGES OF SURROUNDING DISKS?

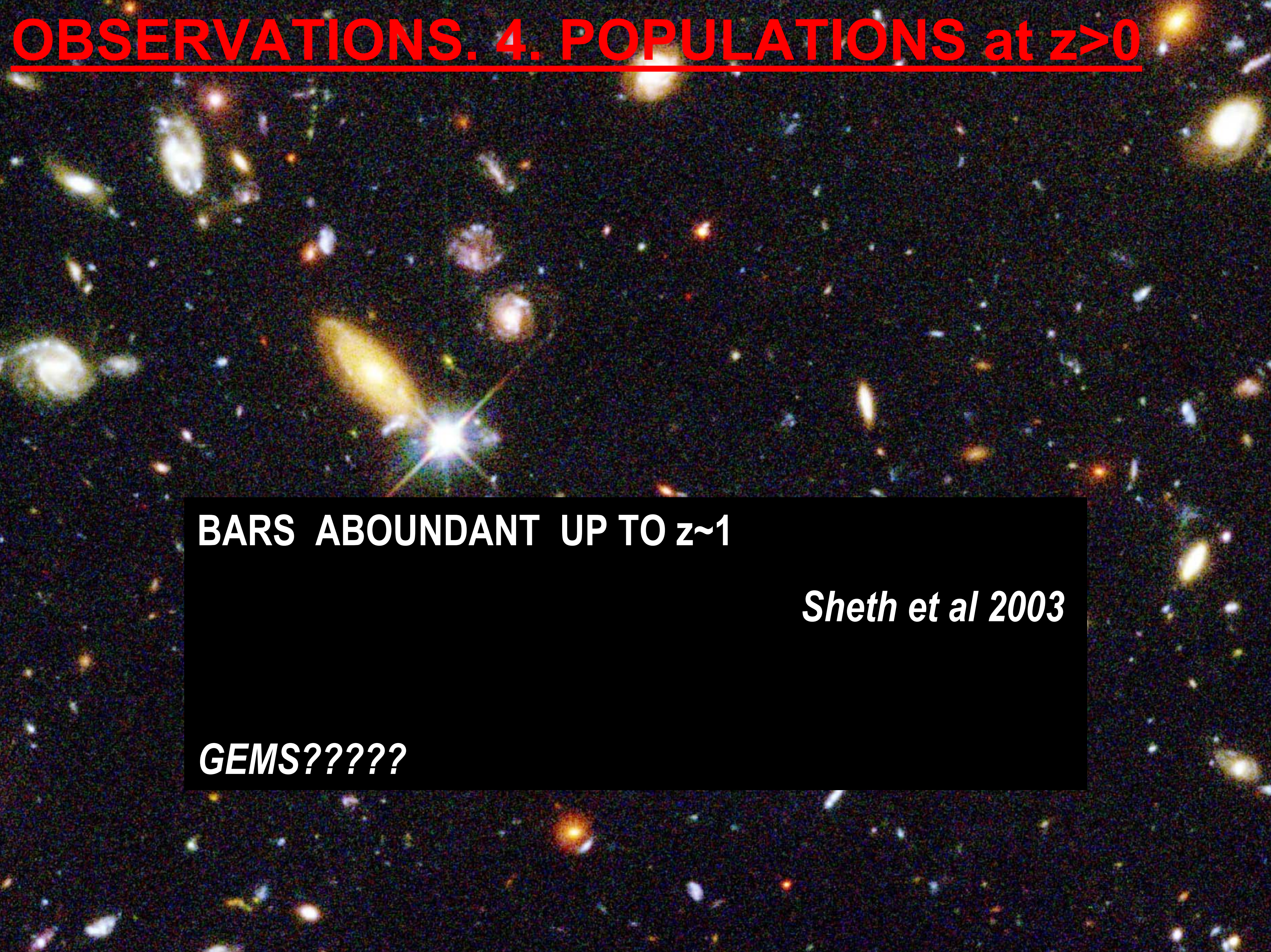
OBSERVATIONS. 4. POPULATIONS at z>0

- z~1 regime: **“Normal Disk galaxies”:**

  → Disk scale-lengths not much evolved since (*Lilly et al. 1998; Ravindranath et al. 2004; GEMS? HWR’s talk?*)

  → Disks + BULGES : Already in place

OBSERVATIONS. 4. POPULATIONS at z>0



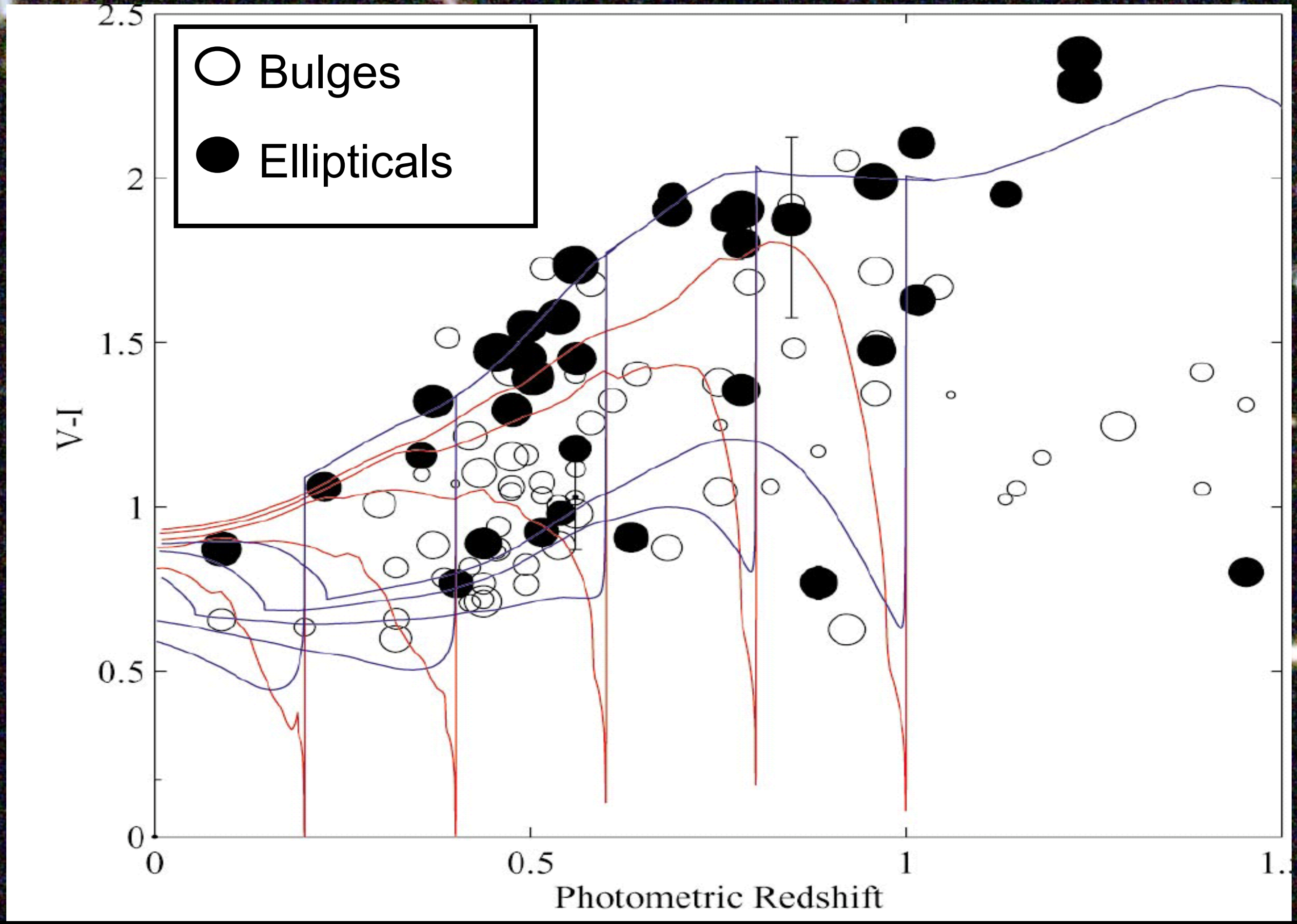
BARS ABOUNDANT UP TO z~1

Sheth et al 2003

GEMS?????

OBSERVATIONS. 4. POPULATIONS at z>0

(Ellis et al 2001)



Colors of Bulges at z > 0.5: Bluer than ellipticals at similar z

COSMIC VARIANCE? AGE/METALLICITY ?

1. BULGES: OBSERVATIONS

NEARBY BULGES: STELLAR POPULATIONS

HST ACS FOLLOW UP (+ U, B, I)

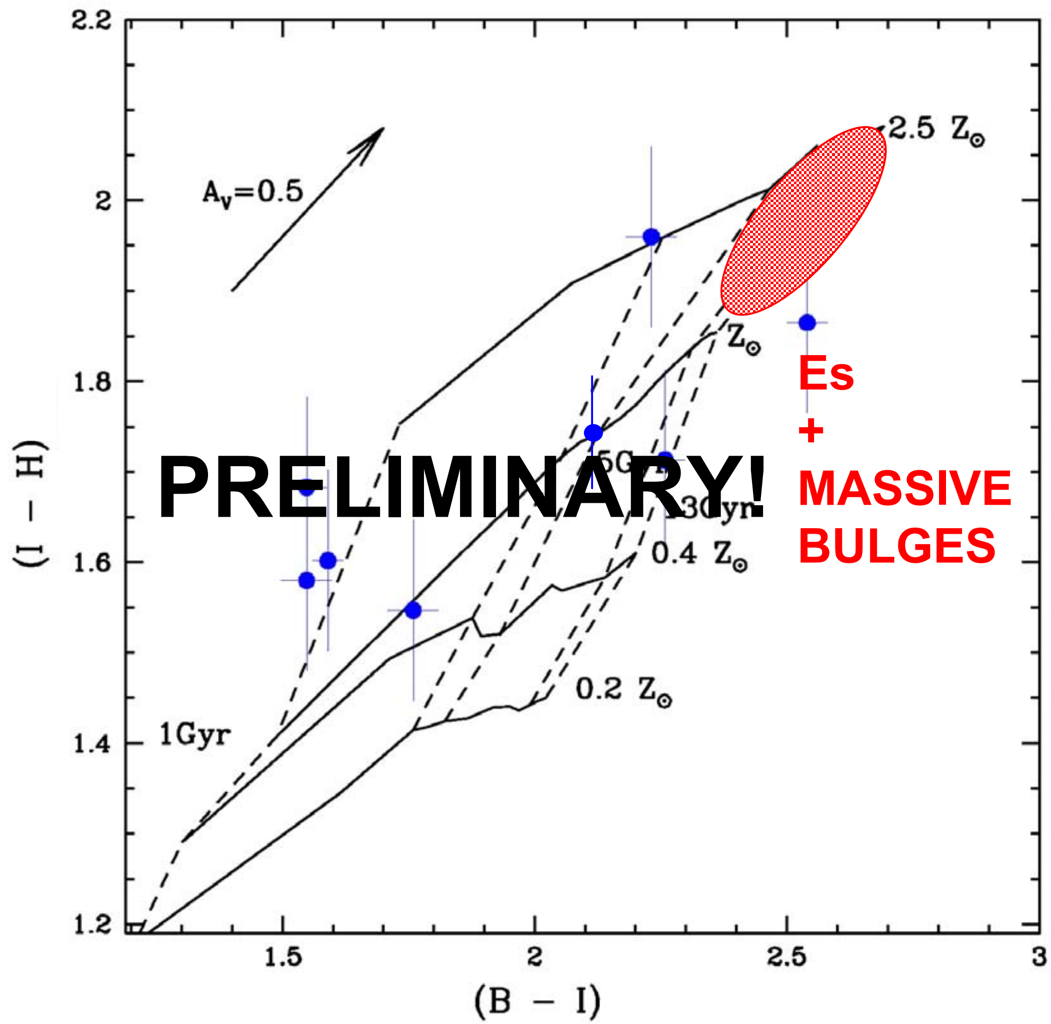
Scarlata, Carollo, Stiavelli & Wyse 2004
to be submitted (soon)

NEARBY BULGES: STELLAR POPULATIONS

SIGNIFICANT % of Sb-Sc BULGES
are on average
"YOUNG"
AND
METAL-RICH
stellar structures

COLORS of "UNDERLYING" POPULATIONS OF SMALL BULGES*

(Scarlata, Carollo et al. 2004)



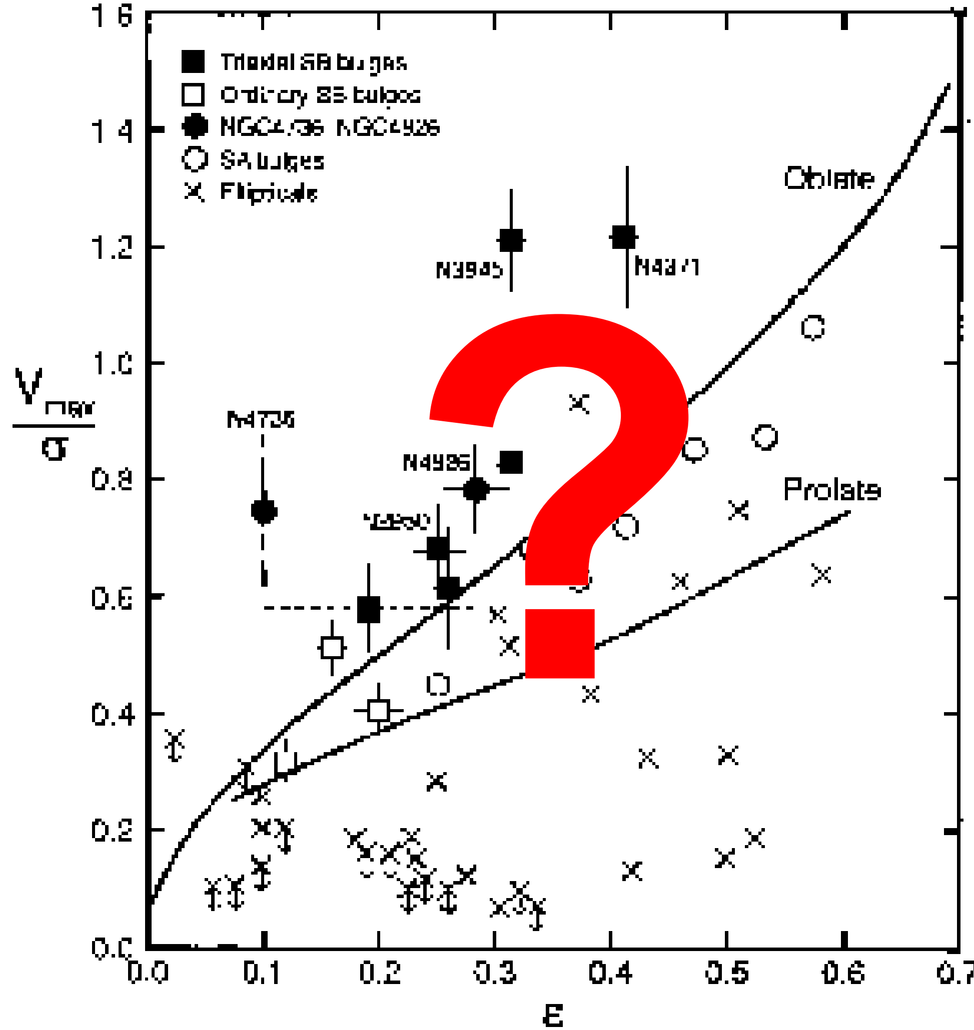
*EXCLUDING
CENTRAL DISTINCT NUCLEI

WHT 2-D SAURON SPECTRA

(Carollo + SAURON Team)

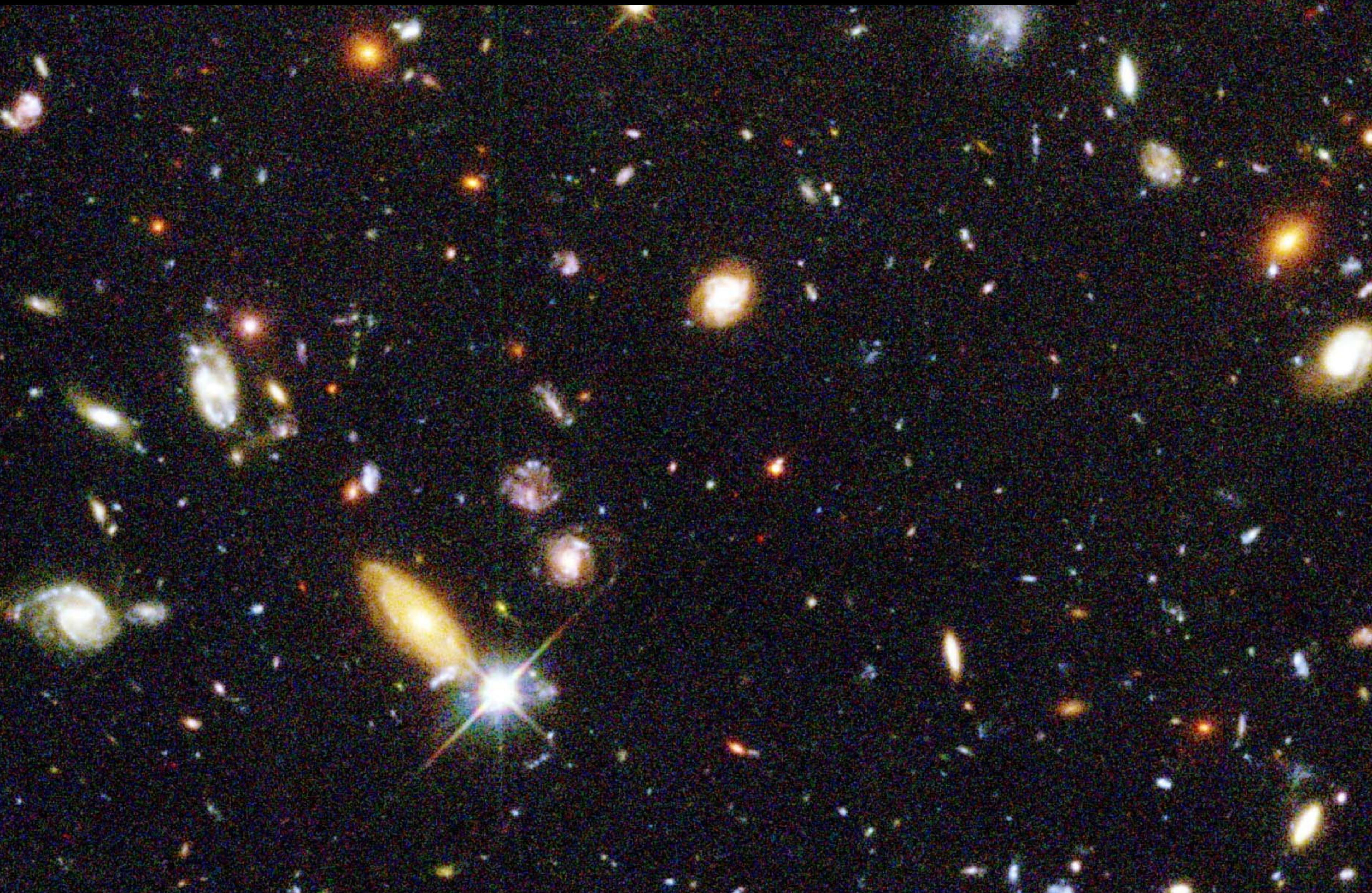
CYCLE 13 HST STIS SPECTRA

(Carollo et al)



→ **As a function of age/Z & mass, down to smallest bulges**

BULGES AT INTERMEDIATE-z ?



BULGES AT INTERMEDIATE-z ?

→ANALYSIS OF STELLAR POPULATIONS of DISK GALAXIES in GOODS/CDFS ACS

+ ***Ferreras,*** *Lilly, Lisker, Mobasher*

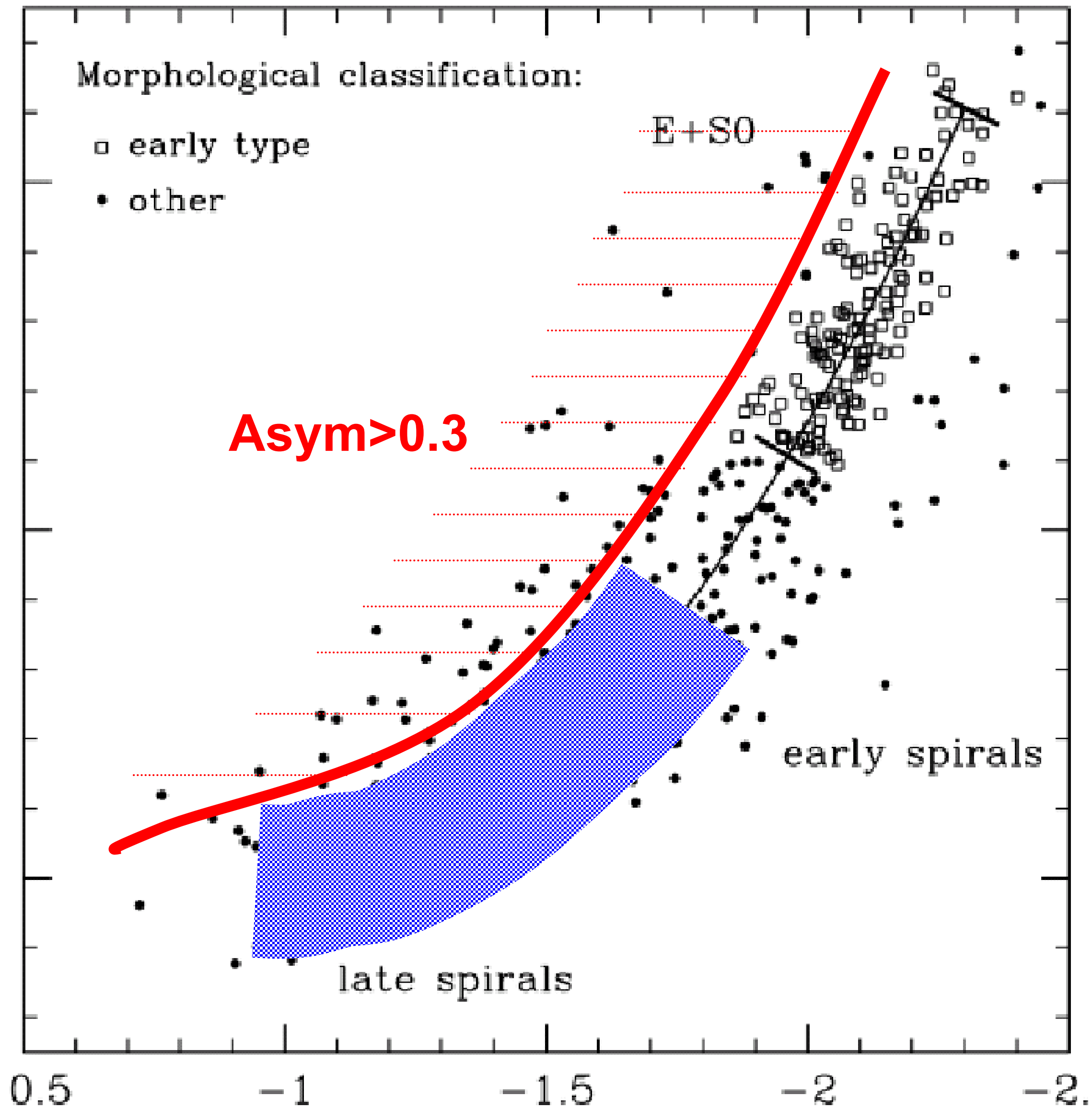
→ ***BULGES @ 0.5 < z < 1***

z's: phot-z by Mobasher et al 2004 + ESO/FORS & VIRMOS DFs

$I_{AB} < 23.5$ $\langle z \rangle \sim 0.7$

SAMPLE SELECTION. 1. SED CLASSIFICATION

GOODS: MORPHOLOGICAL SELECTION



$$C = 5\log 10\left(\frac{r_{80}}{r_{20}}\right)$$

+

i < 30°

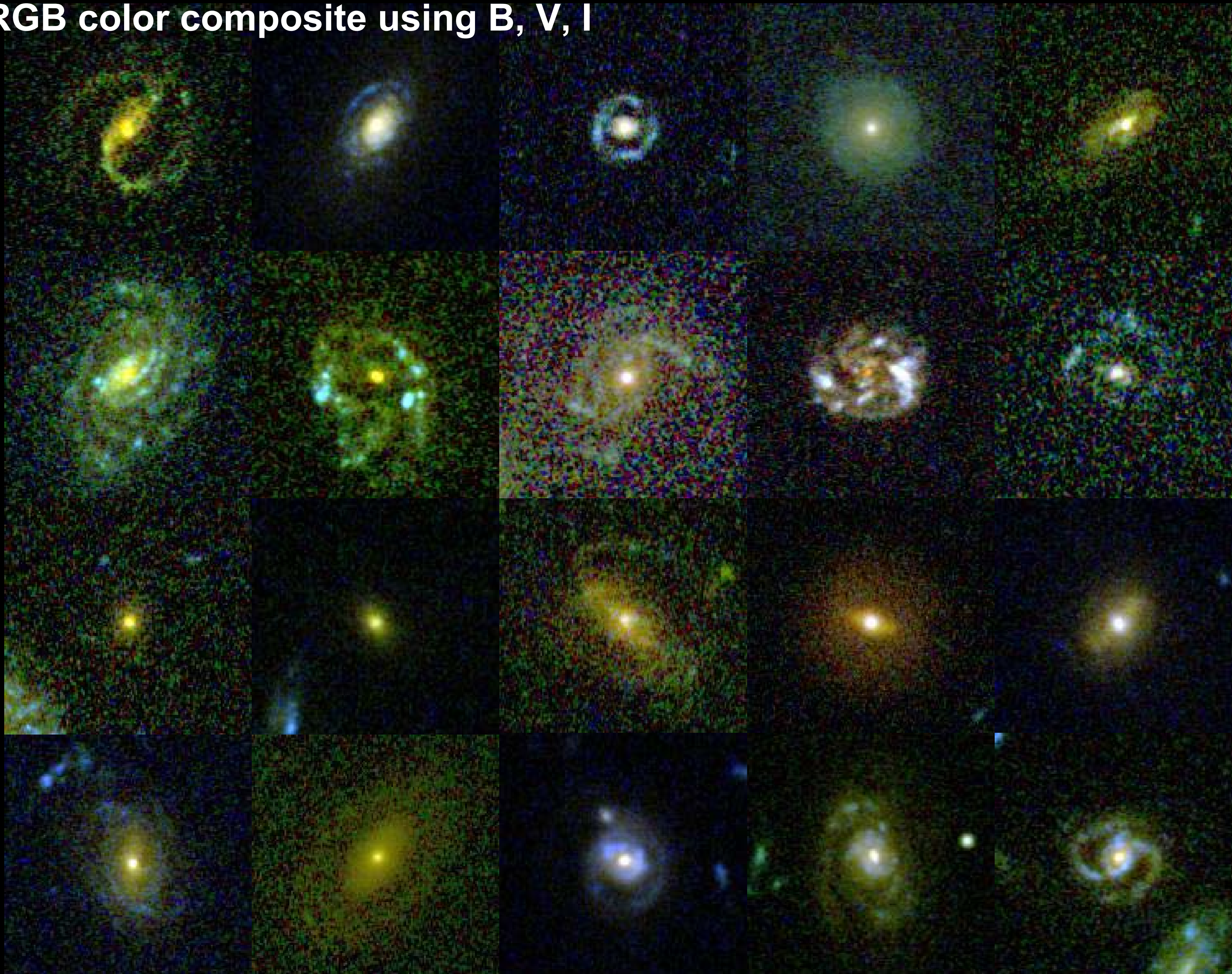
+

Visual Inspection..

M_{20} = 2nd-order mom of brightest 20% of galaxy flux

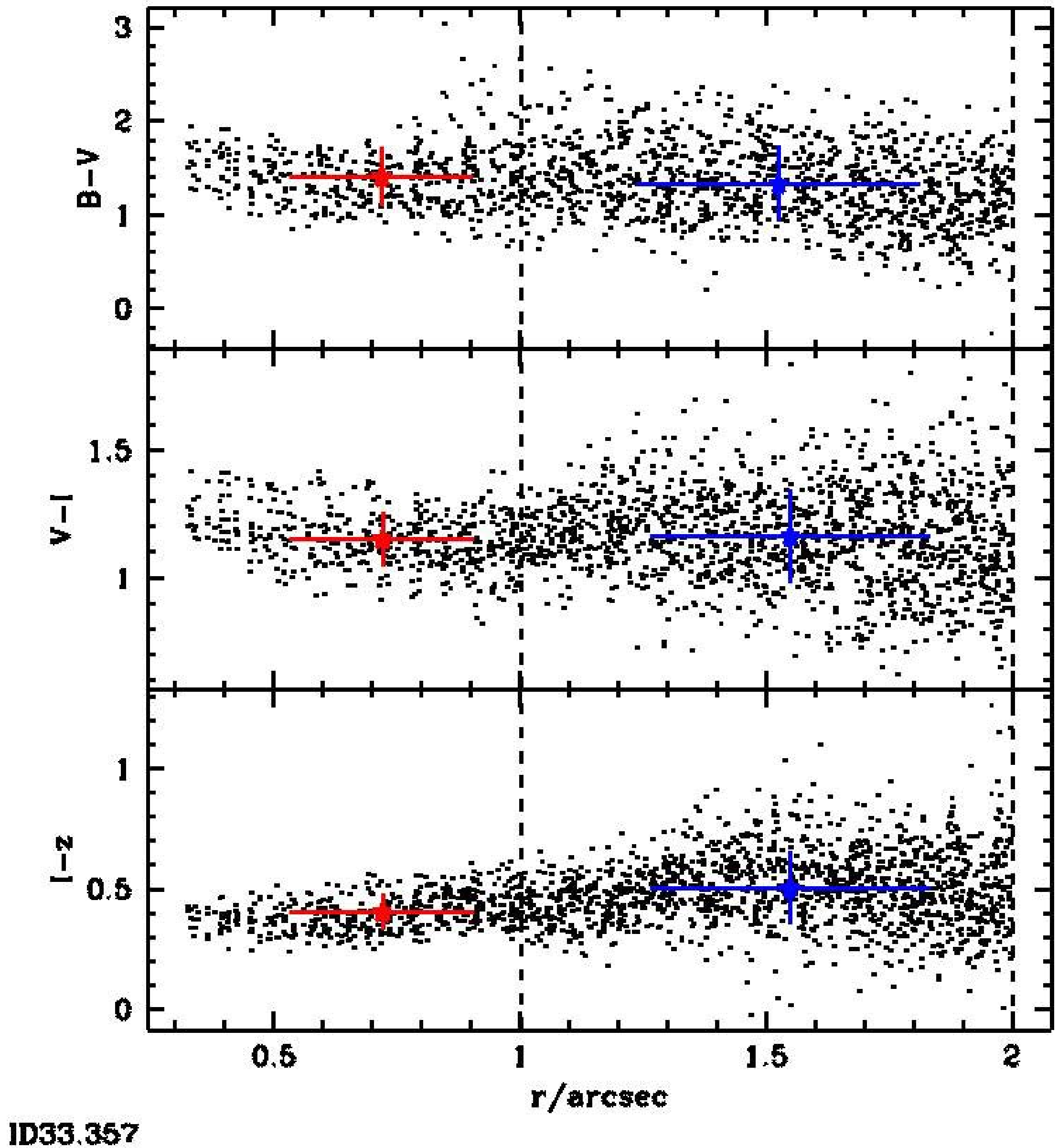
Lisker, Lilly, Ferreras & Carollo 2004

RGB color composite using B, V, I



I-z V-I B-V COLOR PROFILES

pix-to-pix on drizzled images (0.03")
$S/N_{pix}>0.5$



Measured:
Average & variance

Compared with SSPs:

B&C 2003

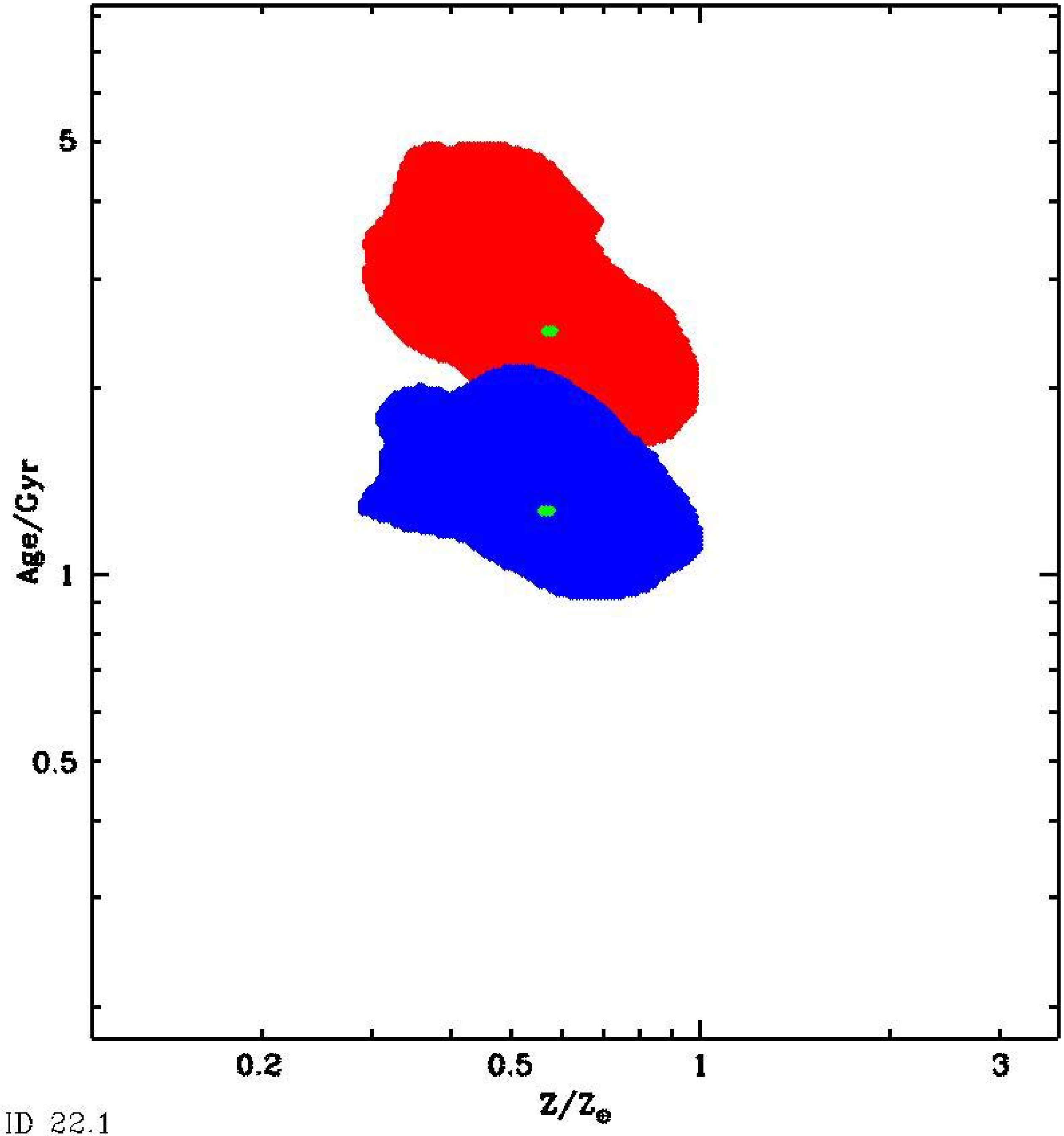
- **Standard Padova tracks**
- **IMF Salpeter 0.1-100M_{sun}**

Age vs Z

RED=BULGE
BLUE=DISK

Plotted: 1-σ confidence levels

GREEN: χ^2 MIN



“STATISTICAL” INTERPRETATION

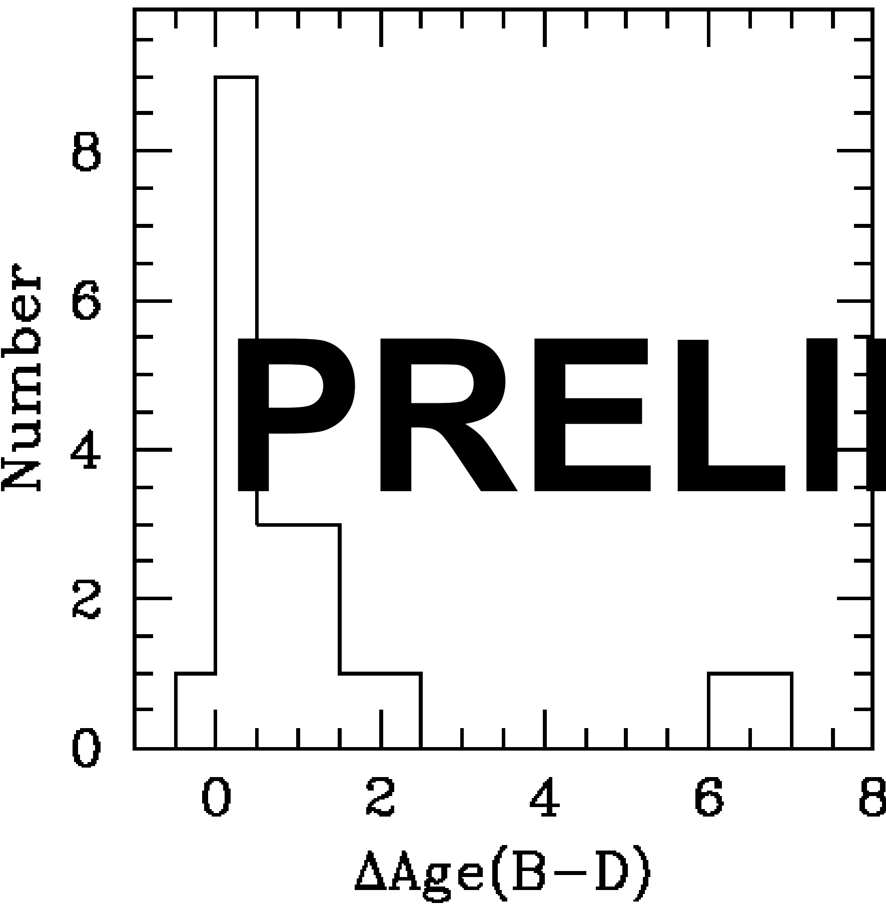
NEEDS:

→ **SIMULATIONS TO UNDERSTAND WHETHER/HOW BULGE COLORS ARE CONTAMINATED BY DISK LIGHT AS A FUNCTION OF z**

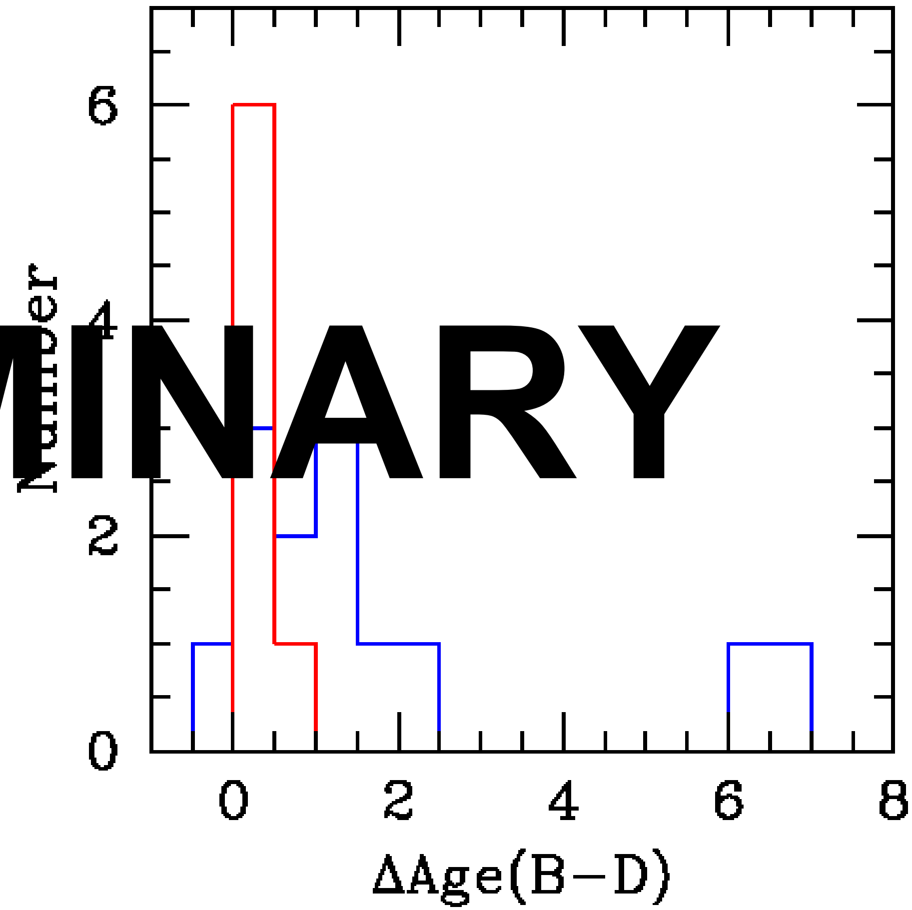
→ **UNDERSTAND SAMPLE SELECTION BIASES (e.g., different S/N in different passbands; C, M_{20} depend on passband, etc etc)**

→ IN PROGRESS

DISTRIBUTION of $\Delta Age = Age_{BULGE} - Age_{Disk}$



PRELIMINARY



AT 0.5 < z < 1:

➔**MANY BULGES in INTERMEDIATE→LATE-TYPE DISKS HAVE AVERAGE AGES COMPARABLE TO AGES OF SURROUNDING DISKS**

SUMMARY. 1. OBSERVATIONS

1. LOCAL Sb→LATER-TYPE BULGES:

STRUCTURE, KINEMATICS

and STELLAR POPULATIONS of DISKS

2. INTERMEDIATE-z "INTERMEDIATE-SIZE" BULGES:

YOUNGER THAN Es

and STELLAR POPULATIONS SIMILAR TO HOST DISKS

→ CONSISTENT WITH "LATE" BULGE FORMATION

→ Sb+ BULGES:

PRODUCTS OF INTERNAL DISK EVOLUTION?

2. BULGES: SIMULATIONS

OUR SIMULATION SURVEY. 1

(Debattista, Carollo, Mayer & Moore 2004 ApJL 604, 93
Debattista, Mayer, Carollo & Moore 2004, to be submitted soon)

1. Live Disk inside Dark Matter Halo FROZEN SPHERICAL POTENTIAL

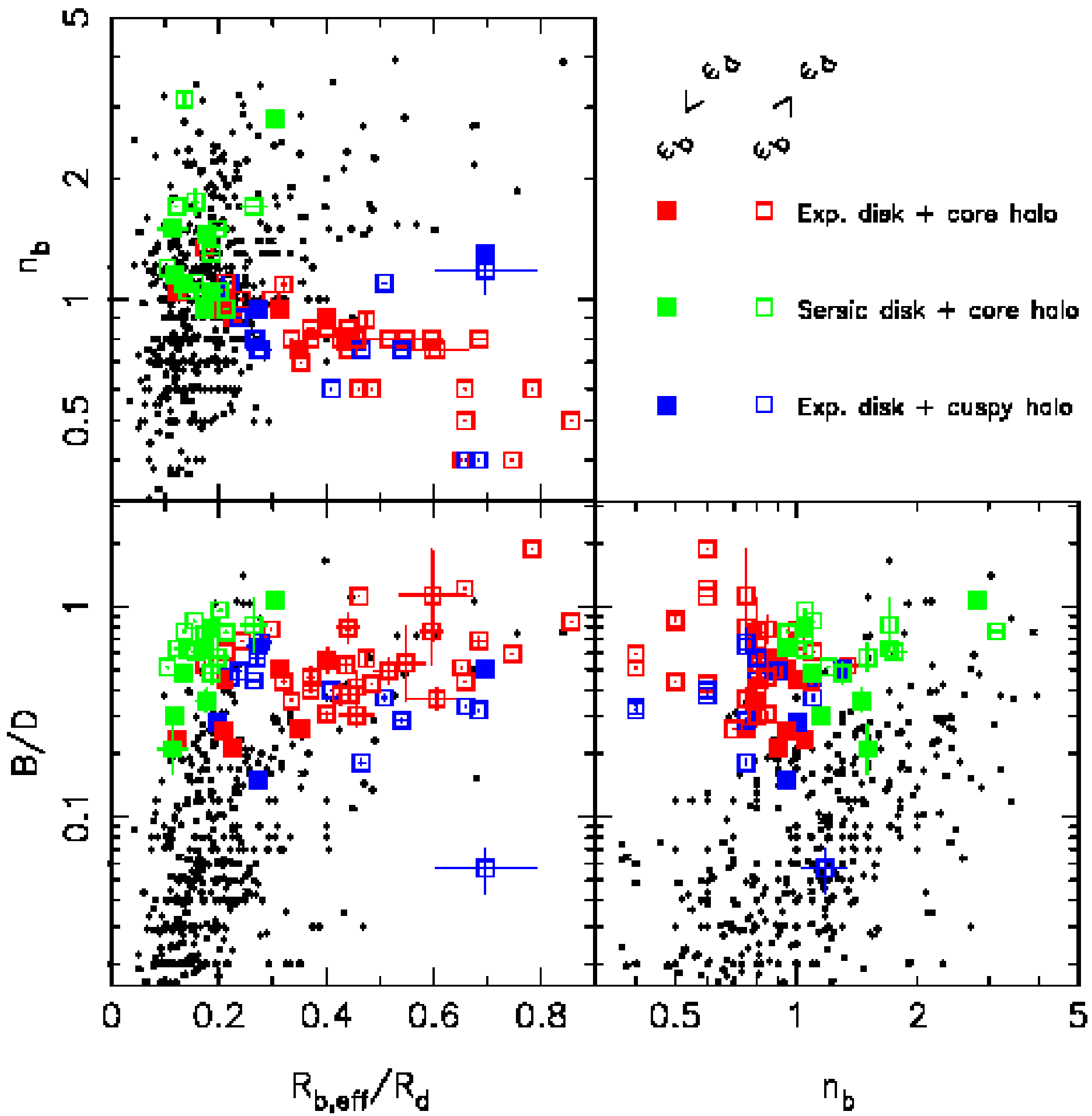
High resolution polar grid code

(Sellwood & Valluri 1997; Debattista & Sellwood 1998)

• several x 10^6 particles

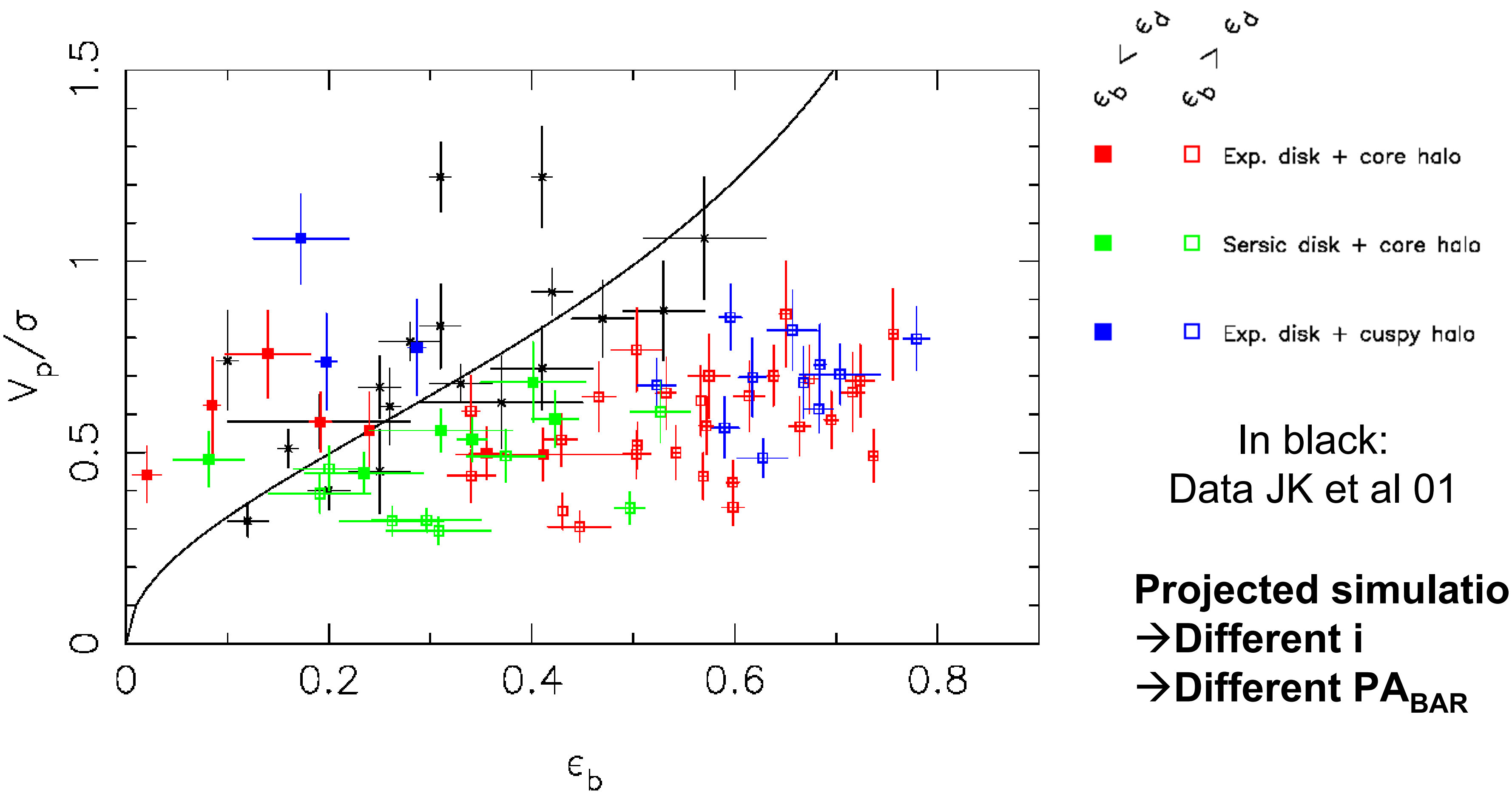
PHOTOMETRIC/STRUCTURAL COMPARISON

Black Dots:
Data from
MacArthur et al 02



Projected simulations:
→Different i
→Different PA_{BAR}

(GLOBAL) KINEMATIC COMPARISON



In black:
Data JK et al 01

Projected simulations:
→Different i
→Different PA_{BAR}

→(BUCKLED) BARS CAN MIMICK <u>BOTH</u>
JK's PSEUDO-BULGES & "ISO-OBLATE-LIKE" KINEMATICS

(see John&Rob's review)

OUR SIMULATION SURVEY. 2

(in collaboration with: ***L. Mayer,*** *B. Moore & V. Debattista)*

2. Live Disk inside LIVE, SPHERICAL Dark Matter Halo

PKDGRAV *(Stadel 2001)*

3. SPH+NBODY

GASOLINE *(Wadsley, Stadel & Quinn 2004)*

LIVE HALO: N-BODY

ADOPTED MODEL: Λ-CDM of MILKY WAY (e.g., Klypin et al 2002)

HALO: NFW with c=11 (cnf: cosmological simulations)
→ adiabatic-contraction-recipe of Mo, Mao & White 98

$V_{virial\text{-}radius}$ = 140 km/s (Peak: ~200 km/s)

Spin Parameter = 0.0465 (~ mean value in cosmological runs)

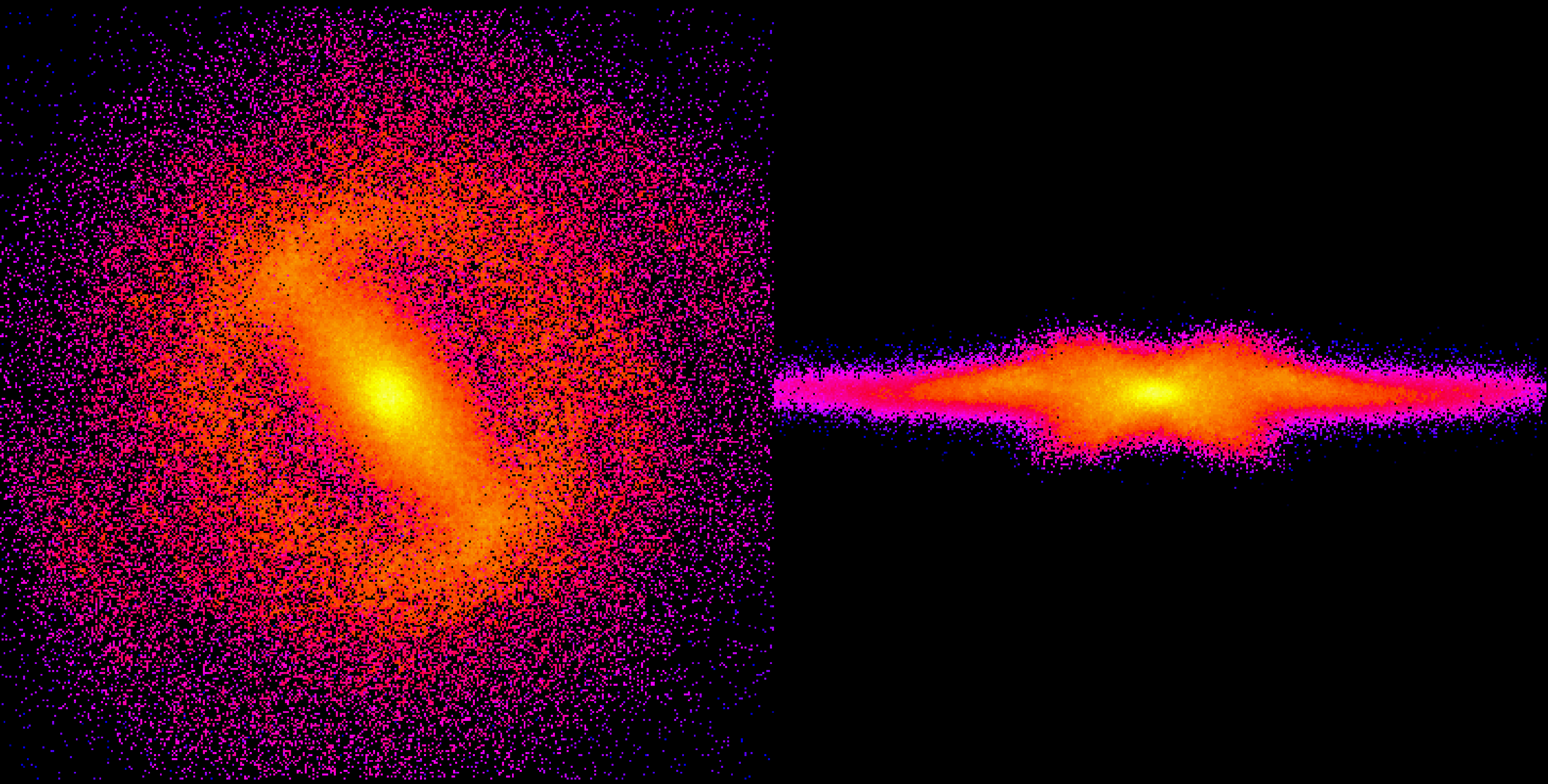
Disk/Halo Mass = 0.06 (→ Scale-length: ~3 kpc)

Disk Height = 0.05 x Disk Scale-length

Softening: 300pc

$10^6 \rightarrow 10^7$ DM particles

COLLISIONLESS



SPH SIMS

10^6 DM particles **+ $2\text{x}10^5$ stars; 10^5 gas**

(same softening)

THE GAS

IDEAL with **$P = (\gamma-1)\rho u$**

γ = ratio of specific heats = 5/3
(gaseous disk represents atomic hydrogen component)

→Solved internal energy equation which includes artificial viscosity term to model irreversible heating from shocks
→Adopted standard Monaghan artificial viscosity and Balsara (1995) criterion to reduce unwanted shear viscosity

→ Adiabatic runs: Thermal energy can rise (compressional & shock heating) or drop (decompressions)
→ Radiative cooling: Energy can be released also through radiation; Standard complete cooling function with primordial H+He (sharp drop at 10^4 K)

GASEOUS DISK

→ T = 10000K (consistent with observed gas velocity dispersions; *Martin & Kennicutt 2001*)

→ Expo surface density profile with same scale-length of stellar disk

→ Thickness determined by local hydrostatic equilibrium

GLOBAL STABILITY: COMBINED STABILITY of gas+stars

For chosen T → $Q_{GAS,\,MIN} \leq Q_{STARS,MIN}$ (Jog & Solomon 91)

→IF THE DISK REMAINS COLD, GRAVITATIONAL INSTABILITIES WILL BE MORE VIGOROUS IN THE GASEOUS DISK AND AFFECT THE DEVELOPMENT OF NON-AXISYMMETRY EVEN IN THE STELLAR DISK *(e.g., Rafikov 2001)*

→ STABILITY OF COMPONENTS NOT SIMPLY "ADDITIVE"

STAR FORMATION à la Katz 1992

1) gas particles turn gradually into star particles

→i.e., they remain "hybrid" for some time, and each gas particle can "make" more than one star particle as its mass decreases

2) To turn into stars gas particles must be:

→ in a collapsing region (convergent flow, i.e. DIVv <0 around target particle in a volume containing 32 SPH neighbours)

→Jeans unstable (because either t_{dyn} or t_{cool} < t_{sound}, the timescale for pressure waves to propagate

→ above density threshold (=1 atom/cm^3) → $d \ln\rho_g /dt = -c_*/t_g$

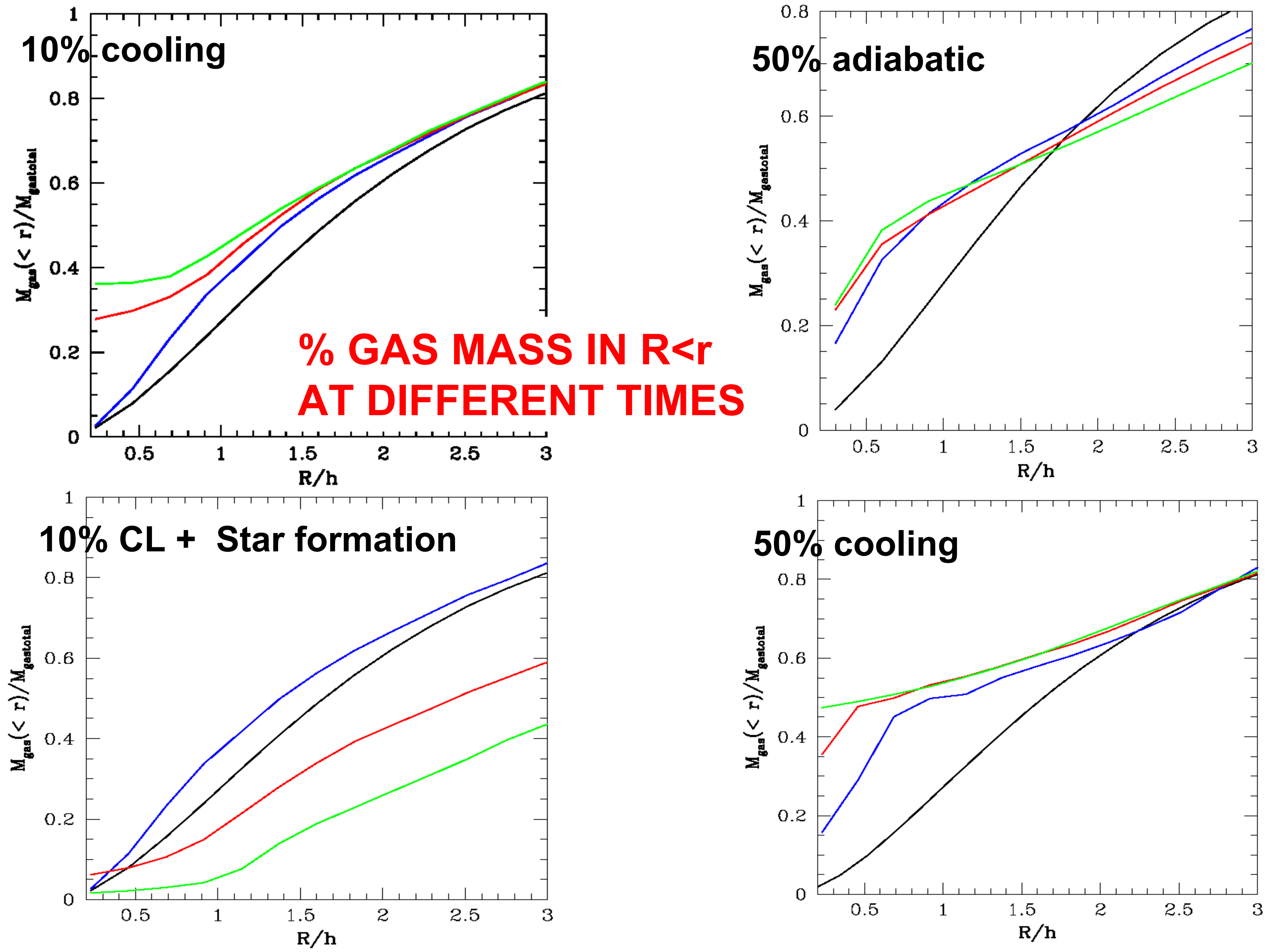
[t_g = max between local t_{gasdyn} & local $t_{cooling}$]

→reproduces Kennicutt's law

3) Efficiency parameter (set to give SFR of local spirals)

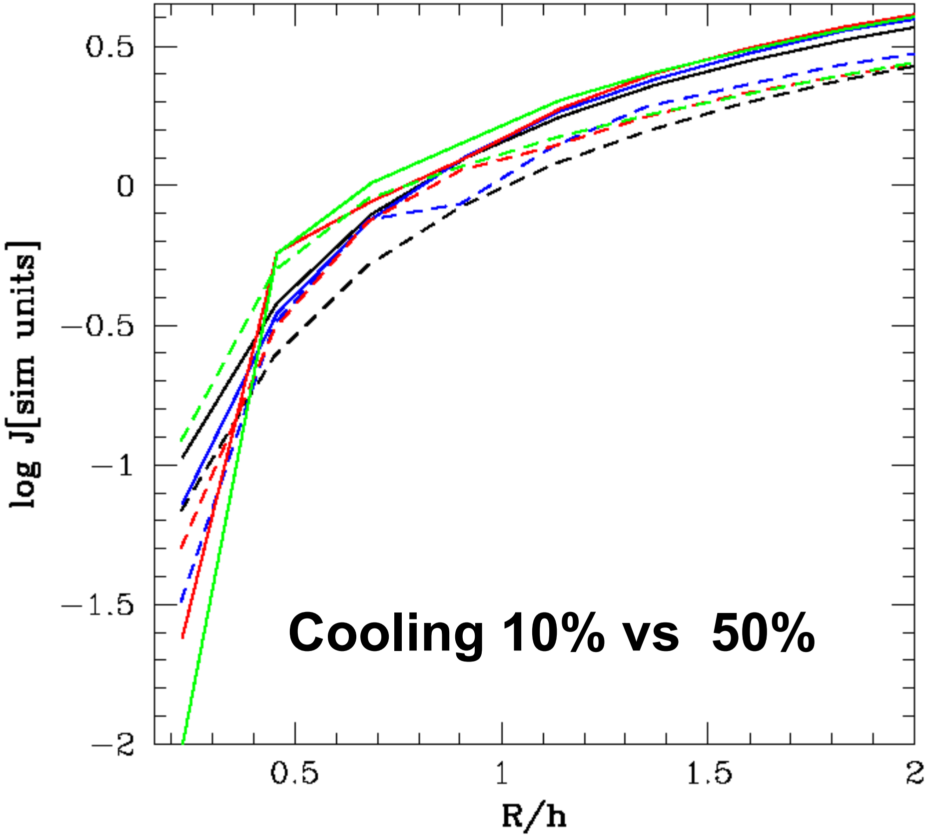
4) Stars form with Miller-Scale IMF

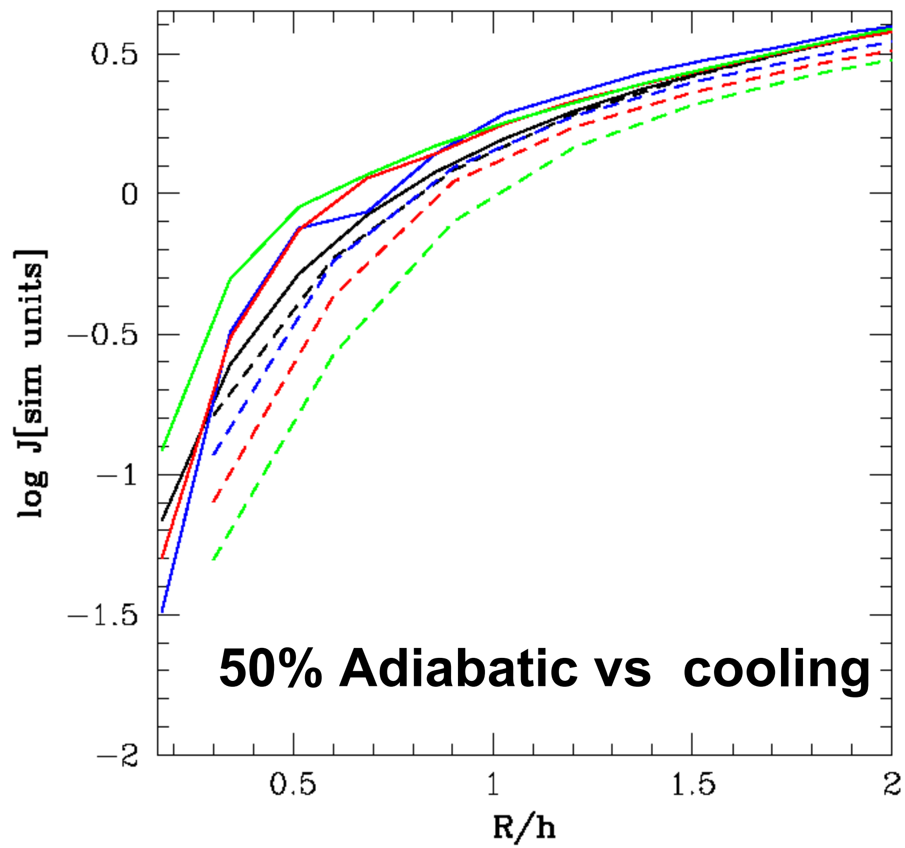
(used for SNI&II rates→ NOT today!)



10% cooling
50% adiabatic
% GAS MASS IN R<r
AT DIFFERENT TIMES
10% CL + Star formation
50% cooling
M_gas(< r)/M_gastotal
R/h

RADIAL PROFILE of J GAS AT DIFFERENT TIMES

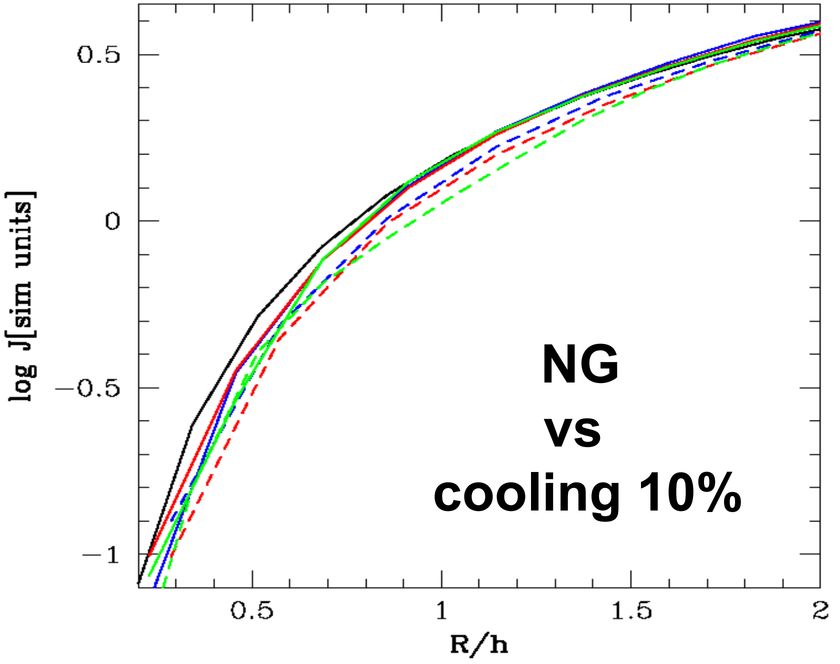


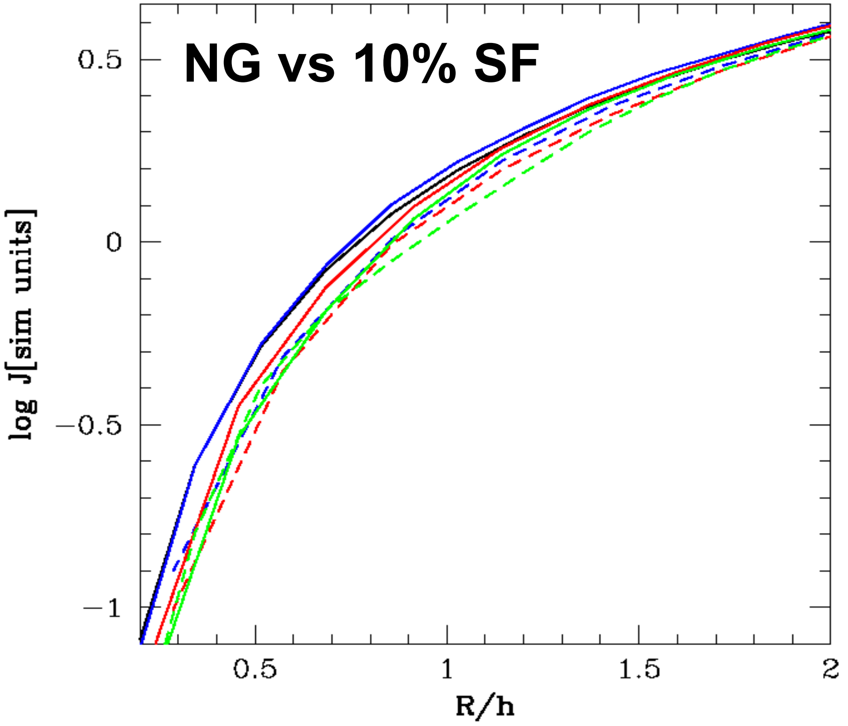


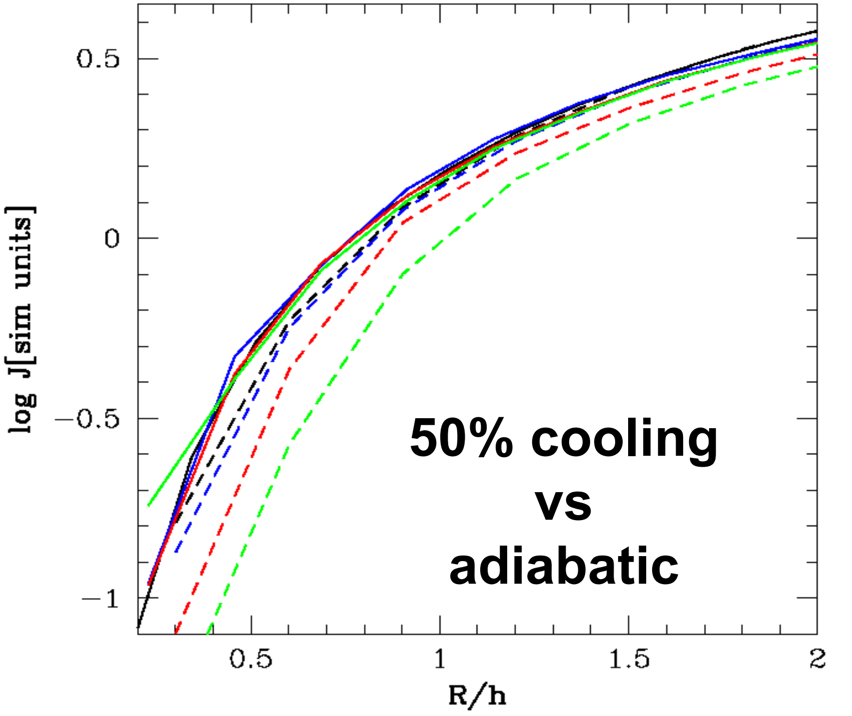
10%: huge loss inside;
note “inversion” at R/h~0.5

50% cooling: initial loss & final gain

RADIAL PROFILE of J STARS AT DIFFERENT TIMES







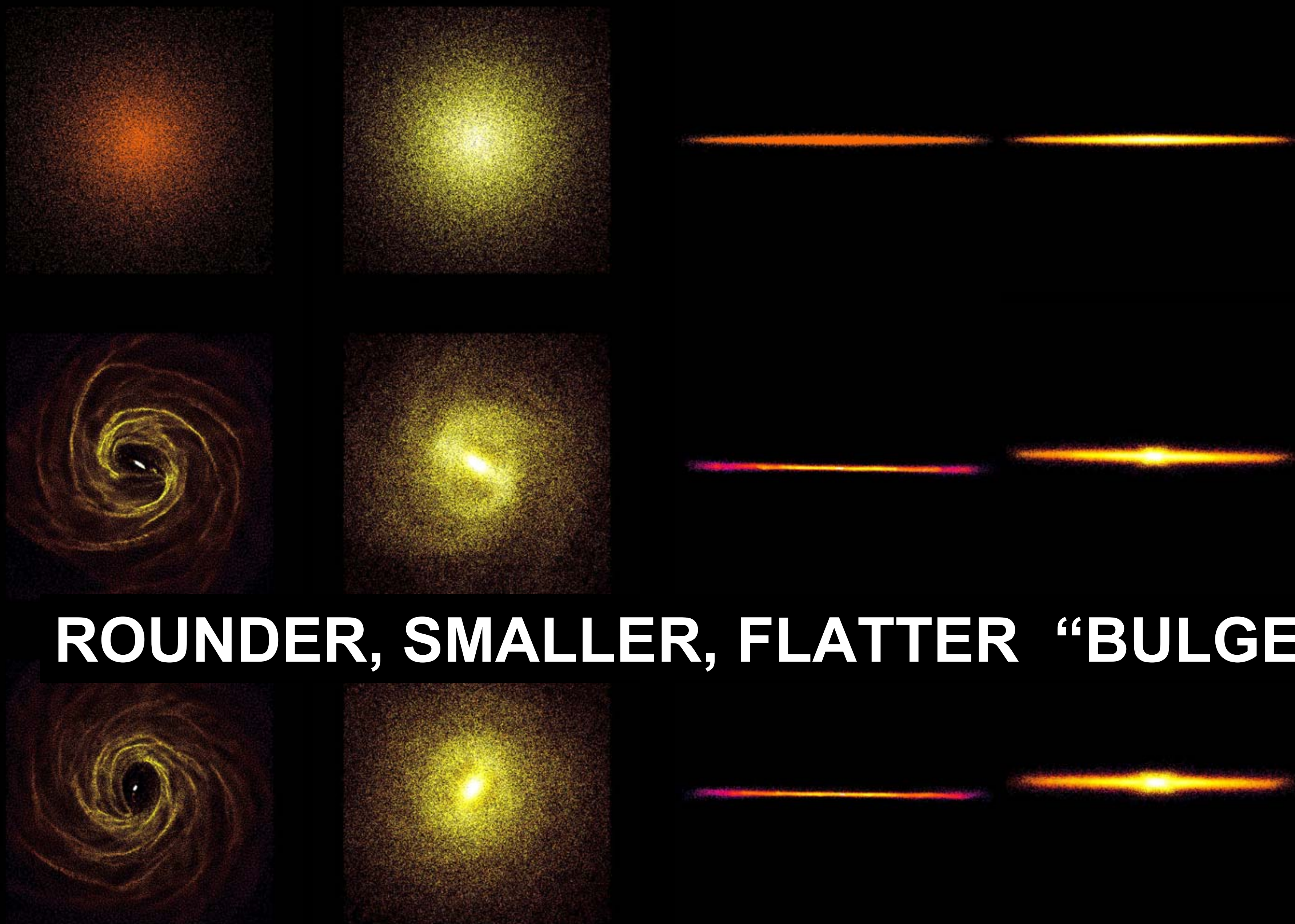
TOTAL $J_{final}/J_{initial}$ for Stars, Gas & DM

	Stars	Gas	DM
collisionless	0.89		1.004
Cooling 10%	0.99	0.83	1.001
Cooling 50%	1.055	0.77	1.001
Ad. 50%	0.98	0.89	1.006
SF (10%)	0.94	1.35 (?)	1.001

DM: LEAST "RESPONSIVE" (DOMINATES MASS)

HOWEVER: 3-WAY EXCHANGE, ALL COMPONENTS INVOLVED

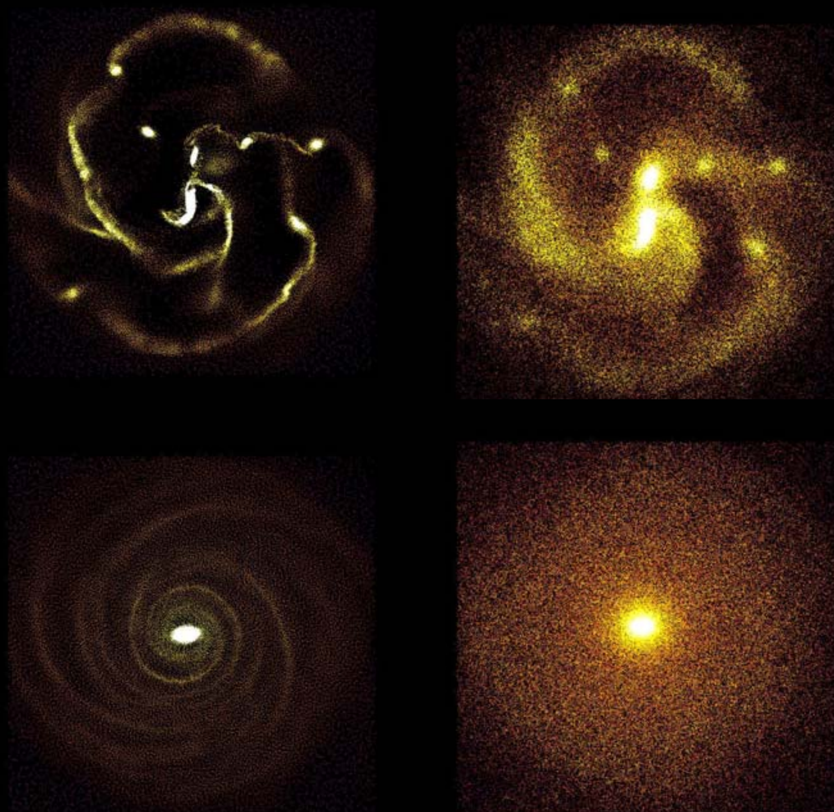
10% mass in gas (with RADIATIVE COOLING)

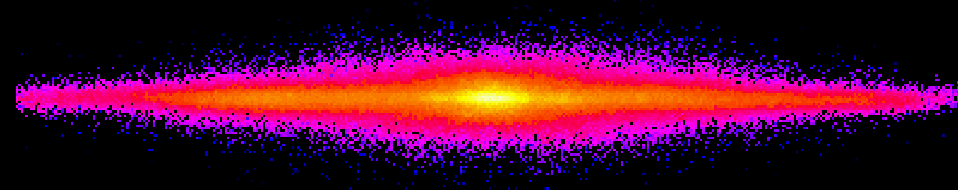


ROUNDER, SMALLER, FLATTER “BULGE”

50% mass in gas (with RADIATIVE COOLING)

DOMINANT CAUSE OF TRANSFER OF ANGULAR MOMENTUM:
SPIRAL INSTABILITIES & CLUMPS @ EARLY TIMES (NOT BAR!)
→→→ very round structures
→see models by *Noguchi 2000*
→→ DIFFERENT “REGIME” WHEN DISK
IS GASEOUS & HIGHLY TOOMRLY UNSTABLE

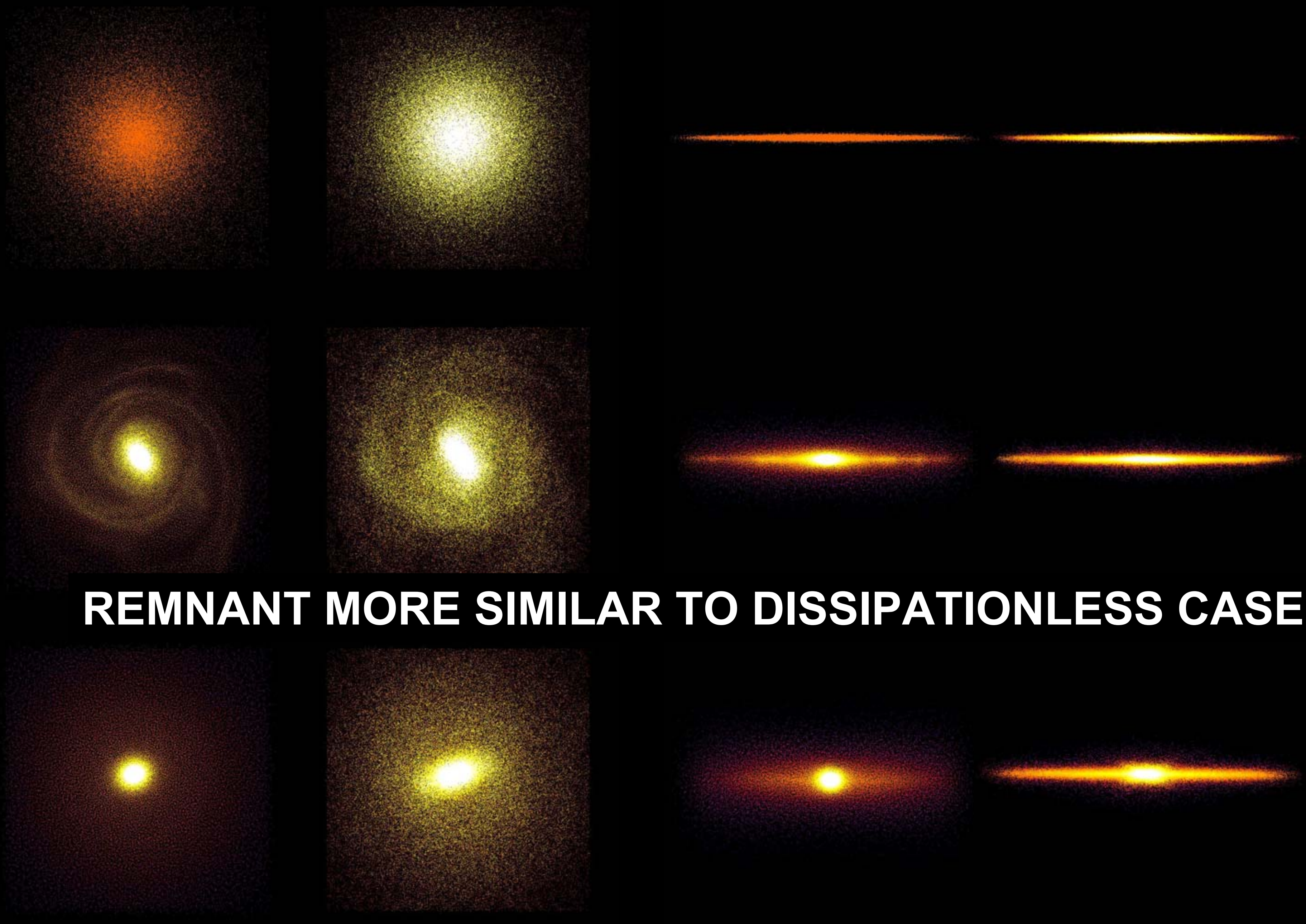




0.87Gyr

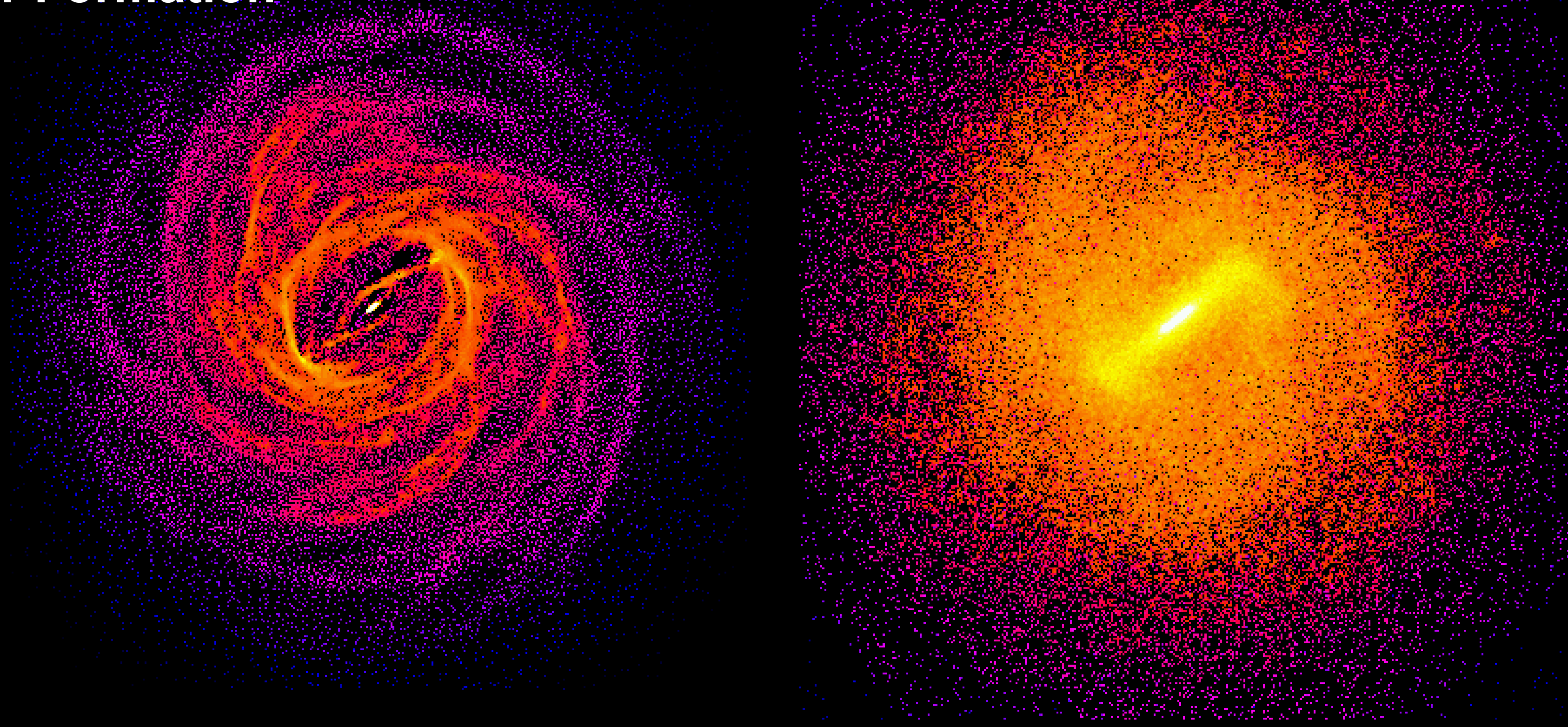
→Can make
“old” remnants !

50% mass in gas (ADIABATIC CASE)

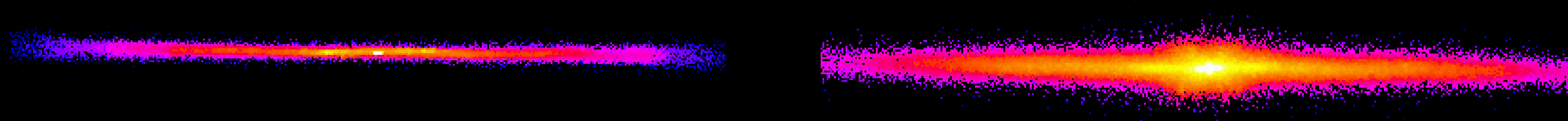


REMNANT MORE SIMILAR TO DISSIPATIONLESS CASE

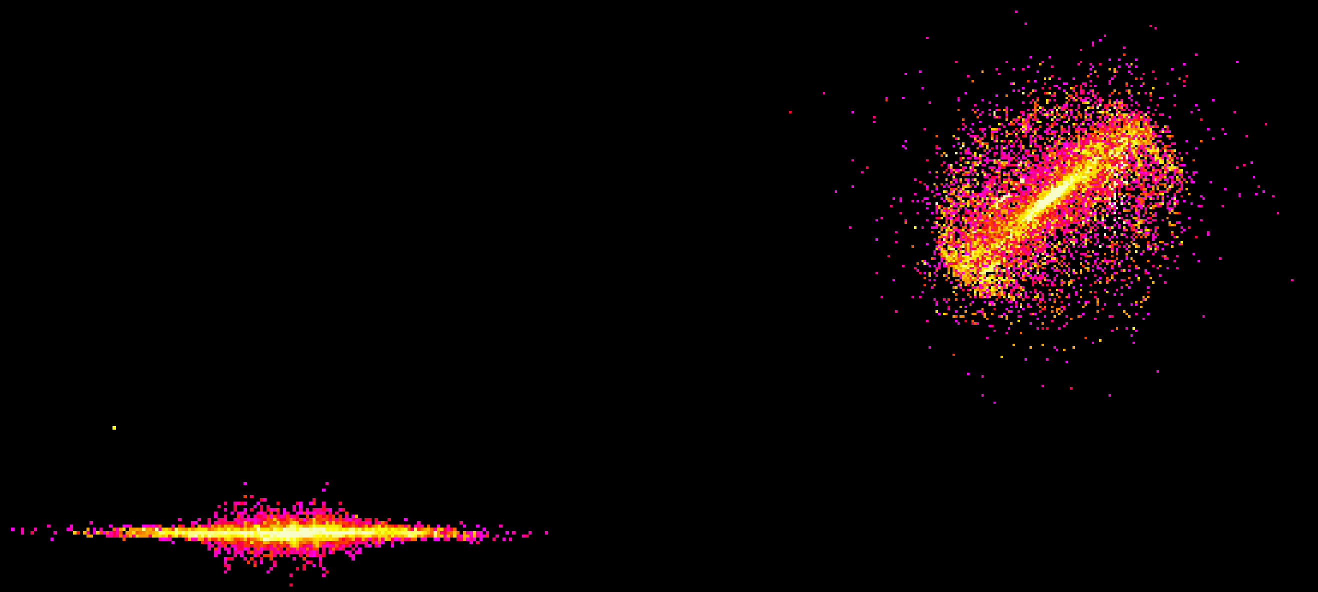
Star Formation

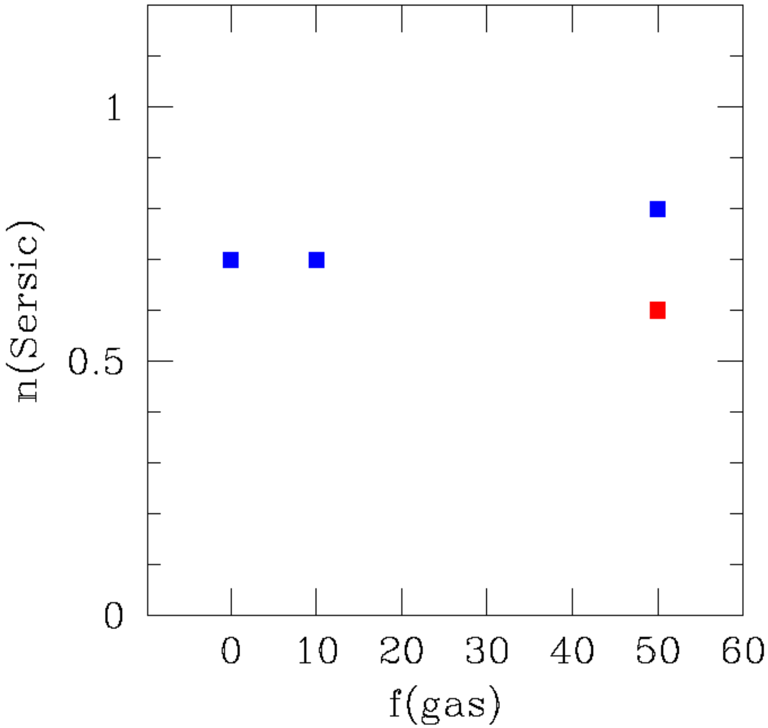


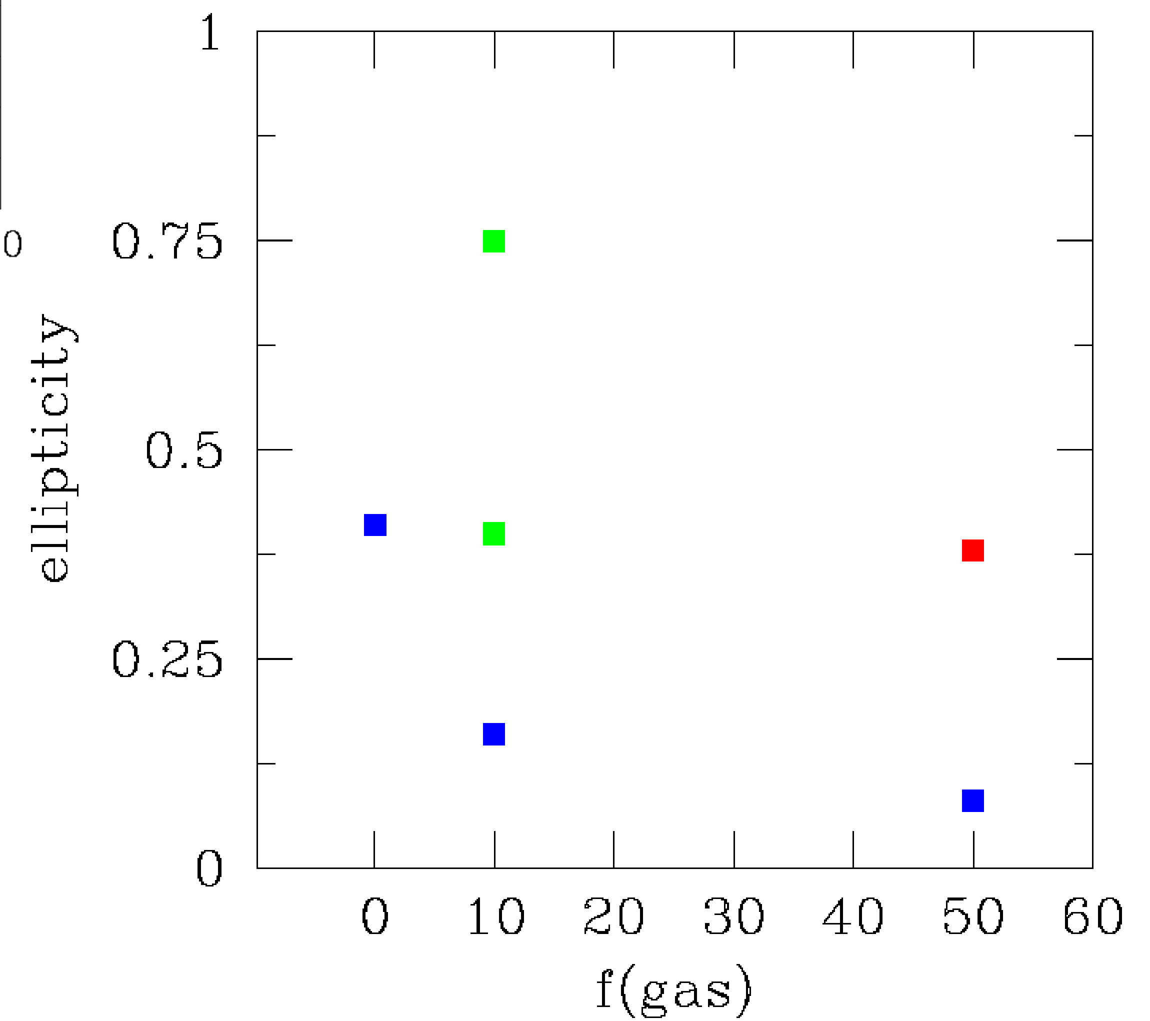
CENTRAL STRUCTURE: SIMILAR THICKNESS OF MATCHED NO-SF RUN, BUT MORE ELONGATED!



“NEW” STARS:
AGE & SPATIAL DISTRIBUTION

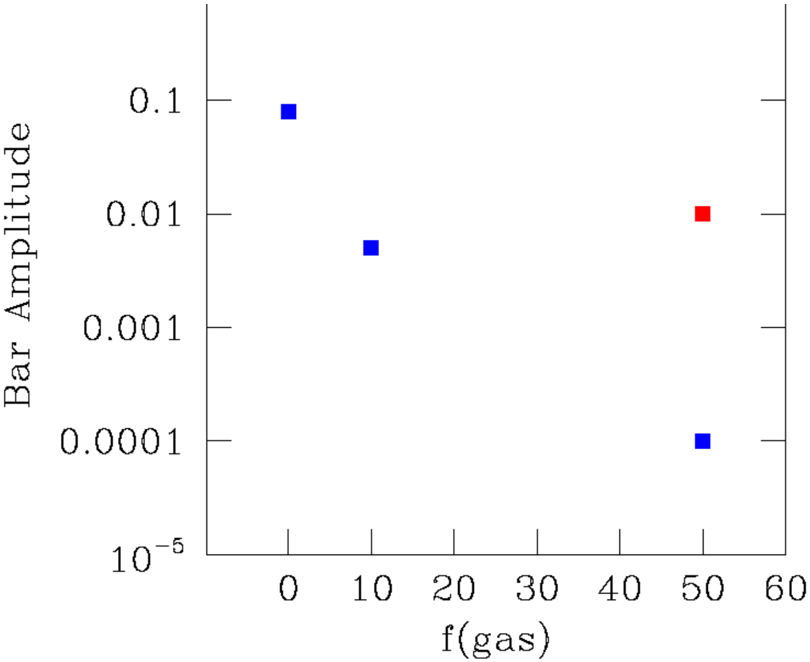


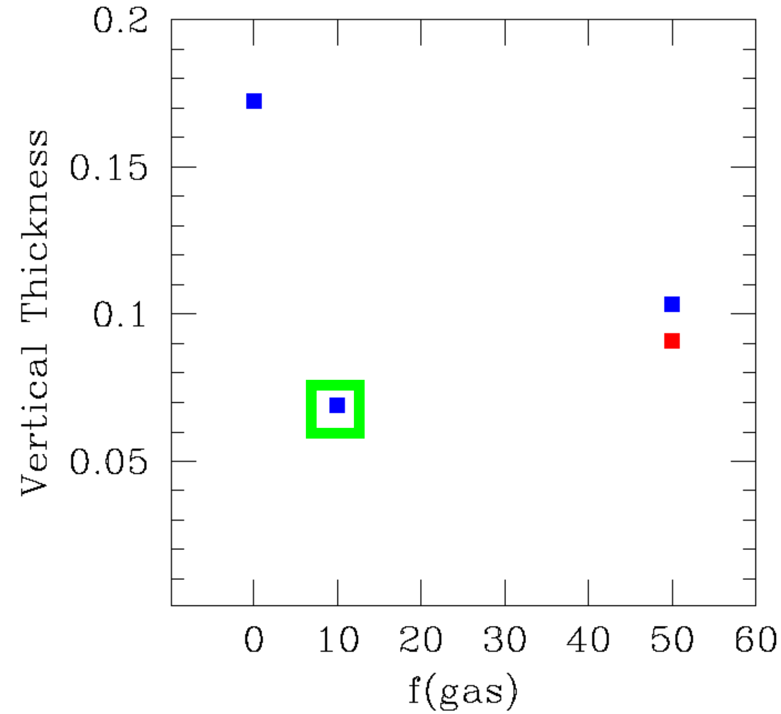


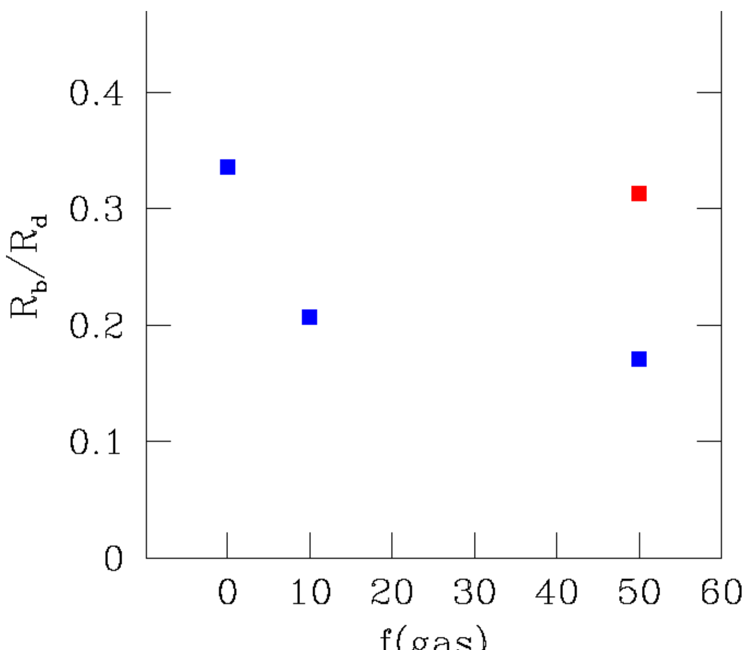


GLOBAL COMPARISON. 1

GLOBAL COMPARISON. 2







GLOBAL COMPARISON. 2

Gas: Qualitative trends as in Berentzen, Heller, Shlosman & Fricke 98

Improvements:

→ non-truncated, non-core "cosmologically-motivated" models with adiabatic contraction, link between spin$_{halo}$ & h$_{disk}$, 30x DM particles

→non-isoT EQ-S (I.e., we model heating in shocks, "complete" radiative cooling >10^4K), 10x gas particles

GLOBAL COMPARISON. 2

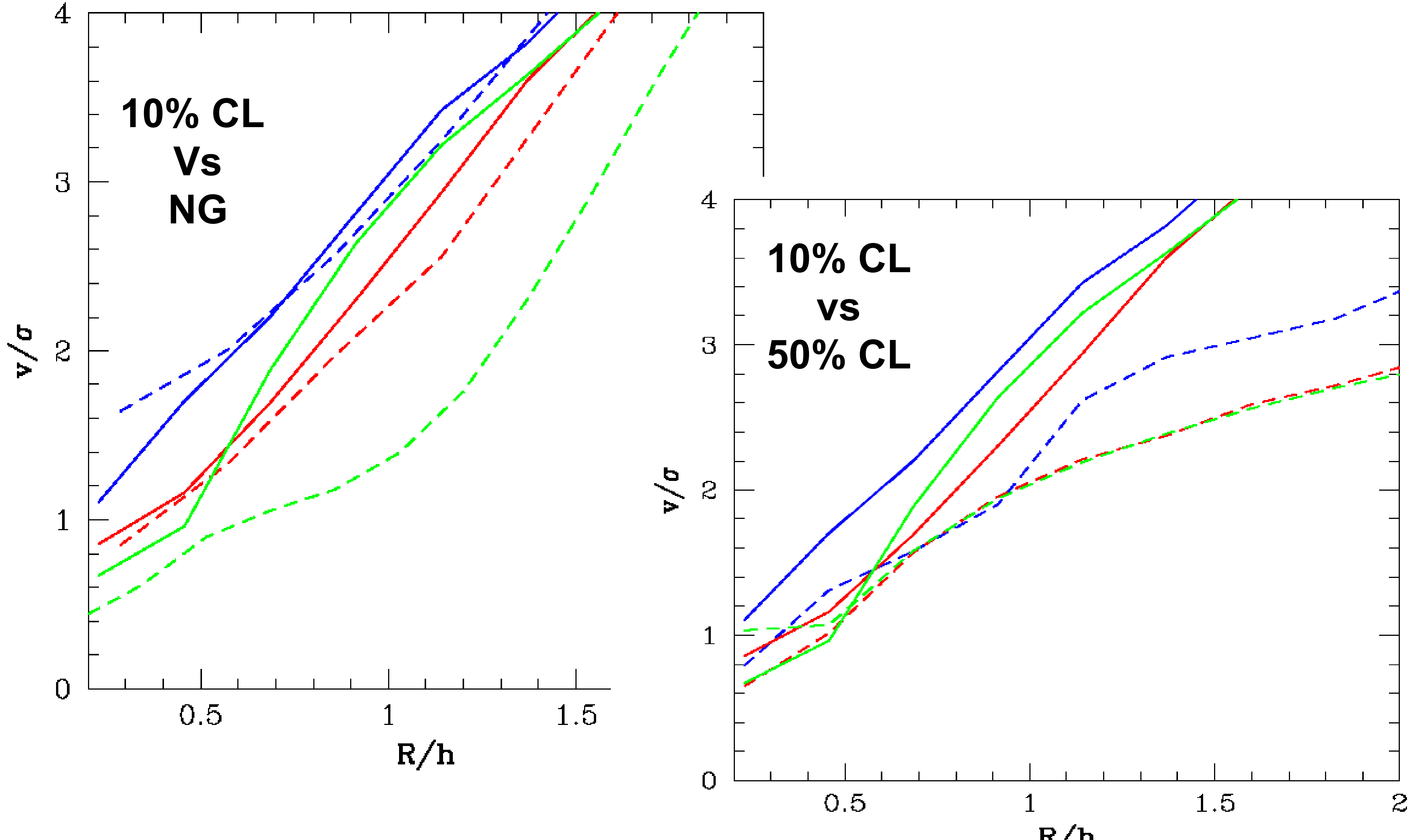
50% COOLING, 50% ADIABATIC & SF   RUNS:

→ "NON-LINEARITY", COMPLEXITY OF TRENDS,

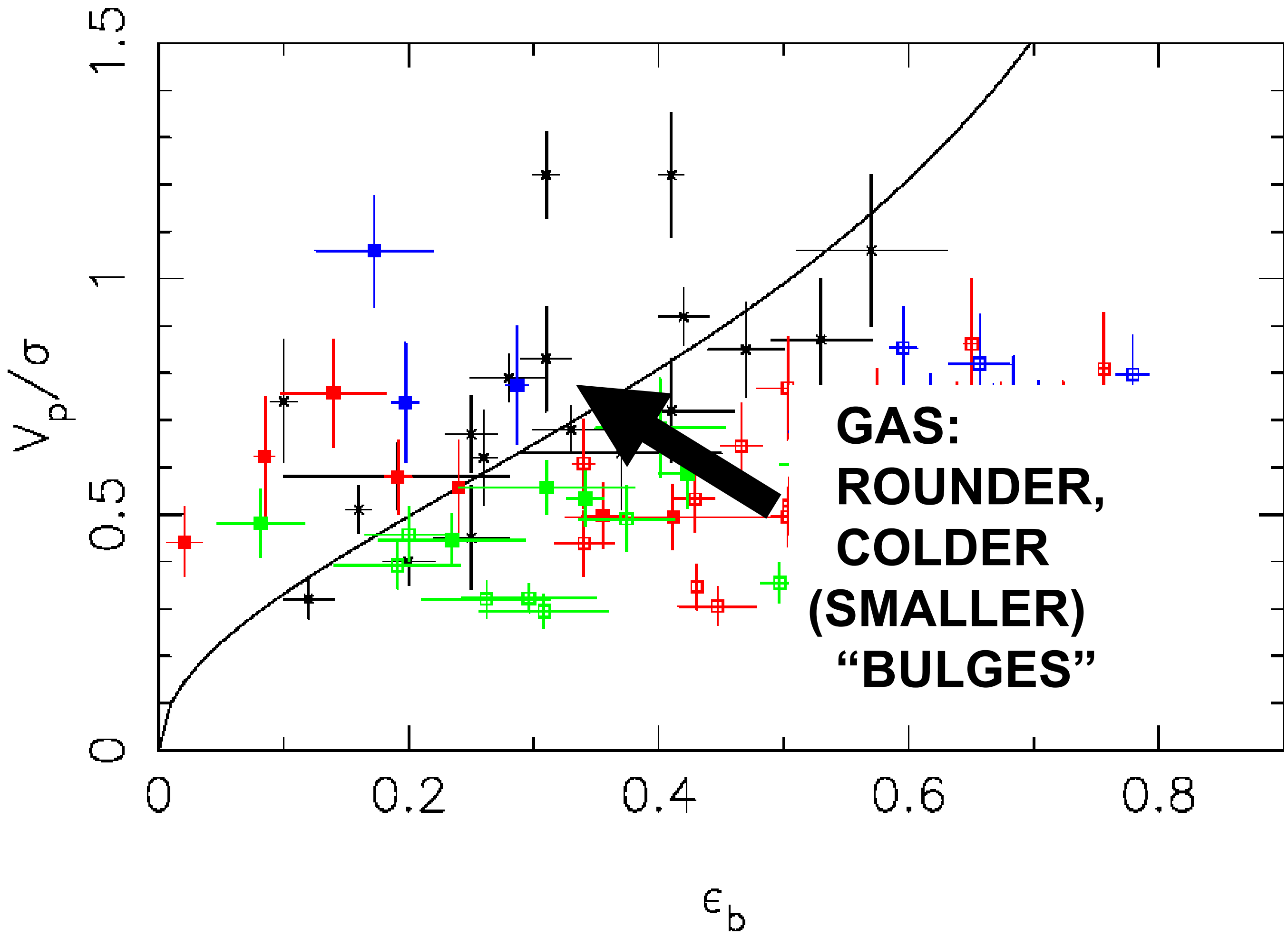
→ STRONGLY DEPENDENT ON "PHYSICS" OF GAS & GAS HYDRODYNAMICS

KINEMATIC COMPARISON:

STELLAR V/s as a function of RADIUS (and TIME)



(GLOBAL) KINEMATIC COMPARISON



(GLOBAL) KINEMATIC COMPARISON

BUT, STRONG DEPENDENCE ON:

→ f_{gas}
→ Cooling properties
→ Star Formation
→ Feedback ?

→→ DIFFERENT "REGIMES"

→→→DISK INTERNAL EVOLUTION WITH z:
CAN BE VERY COMPLEX

SUMMARY. 2. SIMULATIONS

1. DISSIPATIONLESS DISK EVOLUTION (BAR BUCKLING)

→ BUCKLED BARS HAVE THE "OBSERVED" STRUCTURAL AND KINEMATIC PROPERTIES OF BULGES
(FROM DYNAMICALLY-COLD TO -HOT, ISOTROPIC-OBLATE-ROTATOR-LIKE PROPERTIES)

2. DISSIPATIVE DISK EVOLUTION :

A) CAN "ROUND, SHRINK & COOL" THE REMNANT (BUCKLED) BAR
i.e., THE FINAL BULGE-LIKE STRUCTURE

B) BUT: VERY COMPLEX PROCESS
→→ VASTE RANGE OF "BULGE" PROPERTIES OBTAINABLE, INCLUDING THICKNESS, HOT DYNAMICS, "OLD AGES" ETC

→ DISSIPATIVE+DISSIPATIONLESS DISK (SECULAR=SLOW & NON) EVOLUTION CAN REPRODUCE THE ENTIRE PARAMETER SPACE of Sb & LATER-TYPE BULGES

CONCLUSION

1) **Sb & LATER-TYPE BULGES:**
   LIKELY NOT MERGER REMNANTS BUT PRODUCED BY INTERNAL EVOLUTION OF PARENT DISKS

IMPLICATIONS

2) IF Sb→Sc BULGES ARE THE RESULT OF DISK EVOLUTION

→ ***TOTAL STELLAR MASS IN SPHEROIDS ~ 50%***

GALAXY PARAMETERS

Parameter	E	S0	Sab	Sbc	Scd	Irr
Bulge fraction $\kappa(r)$	1	0.75	0.40	0.24	0.10	0
Bulge fraction $\kappa(B)$	1	0.64	0.33	0.16	0.061	0
Morphology fraction $\mu(B)$	0.11	0.21	0.28	0.29	0.045	0.061
H I typical mass ($10^9\ M_\odot$)	0	0.64	2.5	4.0	2.9	1.8
H_2/H I	...	2.5	1.0	0.63	0.25	0.06

(Fukugita etal 98)

→ ***FRACTION IN LATE-TYPE BULGES: NEGLIGIBLE***

IMPLICATIONS

2) IF Sb→Sc BULGES ARE THE RESULT OF DISK EVOLUTION

→ **~30-40% of GALAXIES MUST BE BORN AS "PURE DISKS" (NO INNER "MERGER REMNANT" COMPONENT)**

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→ IMPORTANT CONSTRAINT TO GALAXY FORMATION IN CDM!