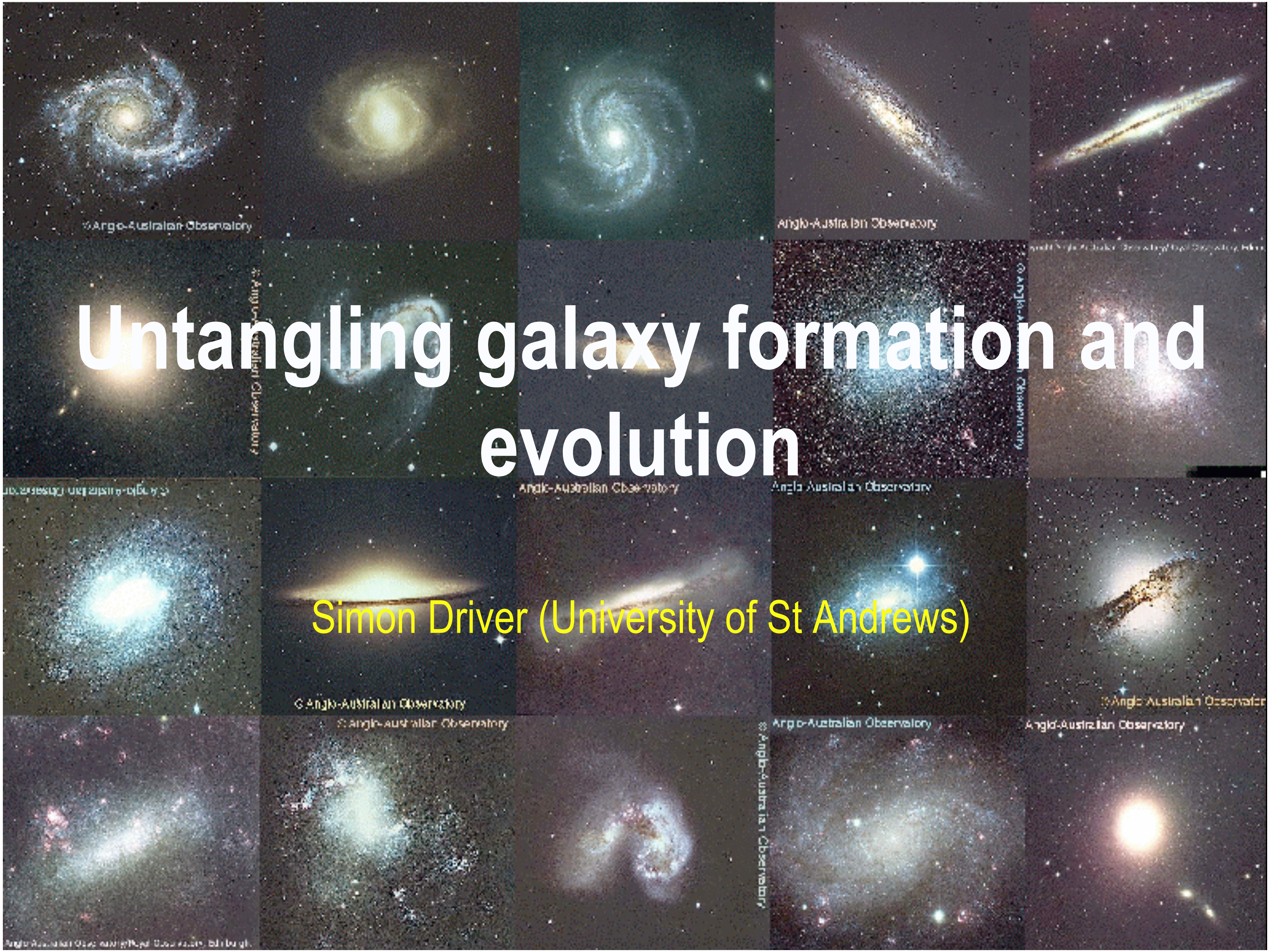
Untangling galaxy formation and evolution

Simon Driver (University of St Andrews)



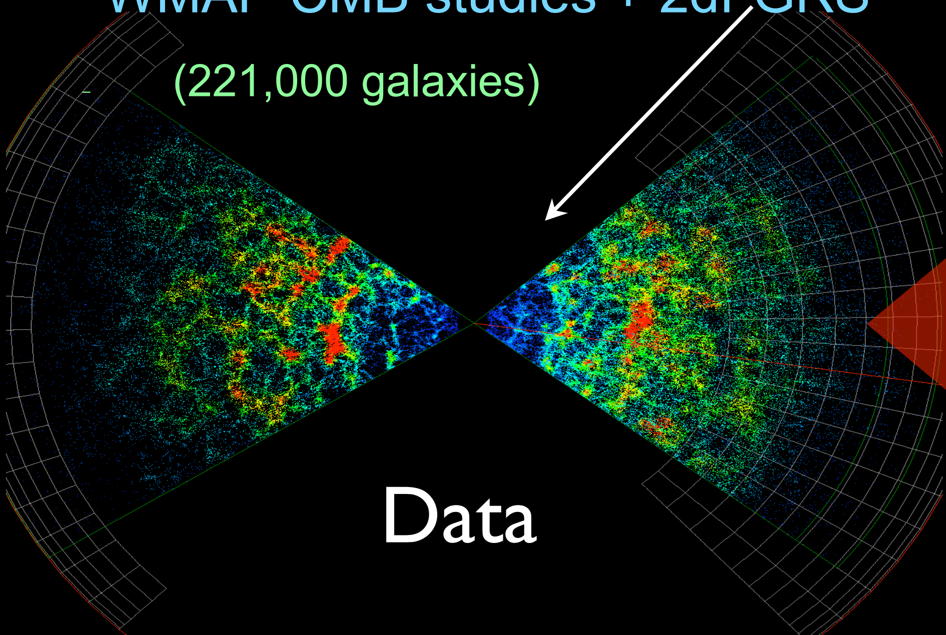
- Premise: "To understand the evolution of the baryons (i.e., galaxy evolution) demands the study of the distinct structural components of galaxies at all epochs --- the construction and deconstruction of the extra-galactic fossil record"
- Perspective: Concordance Cosmology
- Motivation: Omega baryon (Ωb,) physics, galaxies and galaxy evolution
- Approach: The Millennium Galaxy Catalogue
- Progress: The galaxy luminosity function via 2D SWML
- Progress: Galaxy Bimodality: two components not two colours
- Progress: Component LFs and the problem of dust attenuation
- Progress: SMBHs and the SMBH mass function
- Results: The Cosmic Baryon Inventory
- Future Plans: GAMA (Structure on 1kpc-1Mpc), MGC-IR (SN feedback)
- Summary

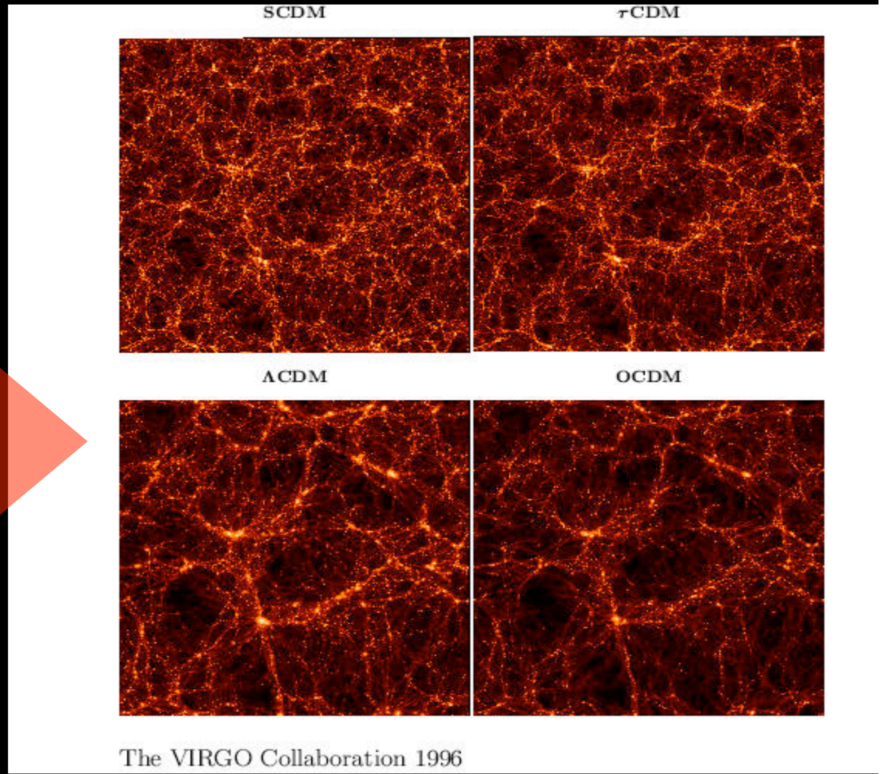
Concordance Cosmology

Simulations

- WMAP CMB studies + 2dFGRS

  (221,000 galaxies)





- Universe comprises, Cole et al (2005):
  - 73% Dark energy, ΩΛ - intrinsic property of space-time
  - 23% Dark matter, ΩM - invisible cold dark matter
  - 4% Baryonic matter, Ωb - visible matter
  - Total Density ~ Critical Density = Flat space-time
- So What Next for Cosmology ?

Ω_Λ Ω_M Ω_b

Dark Energy:

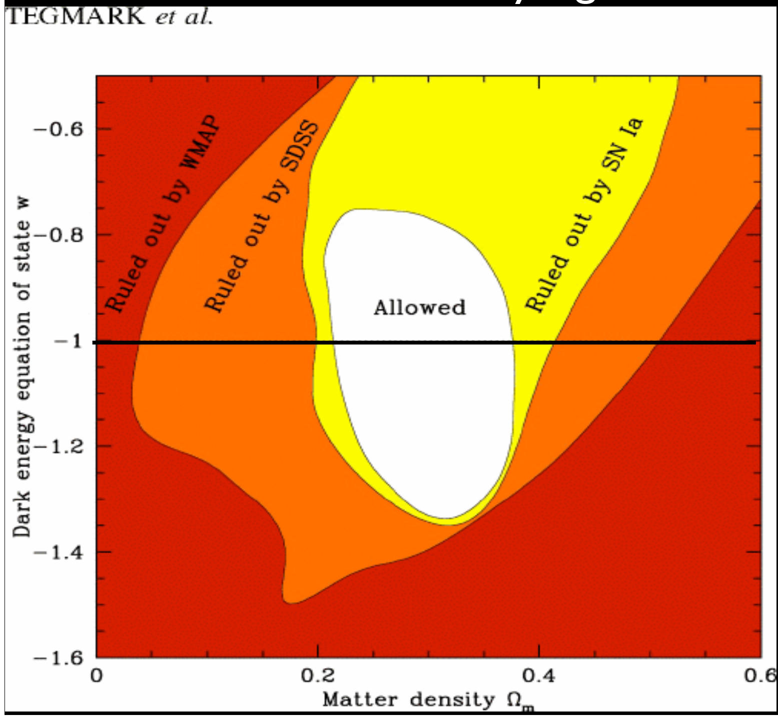
Measure equation of state:

$$dE = -pdV, \rho = wp, if \rho = const, w = -1?$$

ESSENCE, SNAP, PLANCK, WFMOS

Observationally straightforward

Current constraint already significant:



Dark Matter:

Direct detection needed ~30 proposed candidates (e.g., WIMPS)

Main breakthrough will come from particle physics experiments (CERN).

Main advancements from astronomy angle will come from detailed comparison of numerical simulations of dark matter haloes v galaxy population studies although baryon physics critical.

Baryonic Matter:

Dissecting Ωb:

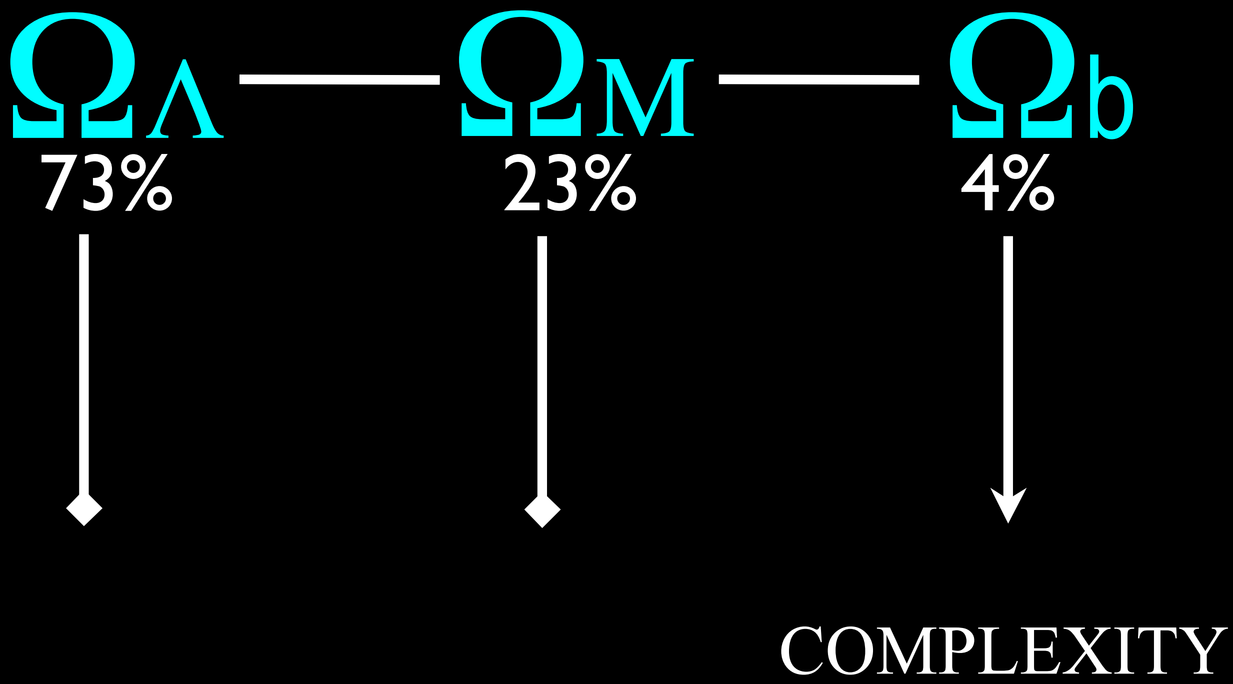
Baryons = known physics

Baryons --> complexity (metals, planets, life)

Where are the baryons today (in what form) ?

How did they get from the smooth primordial CMB distribution to today's lumpy distribution ?

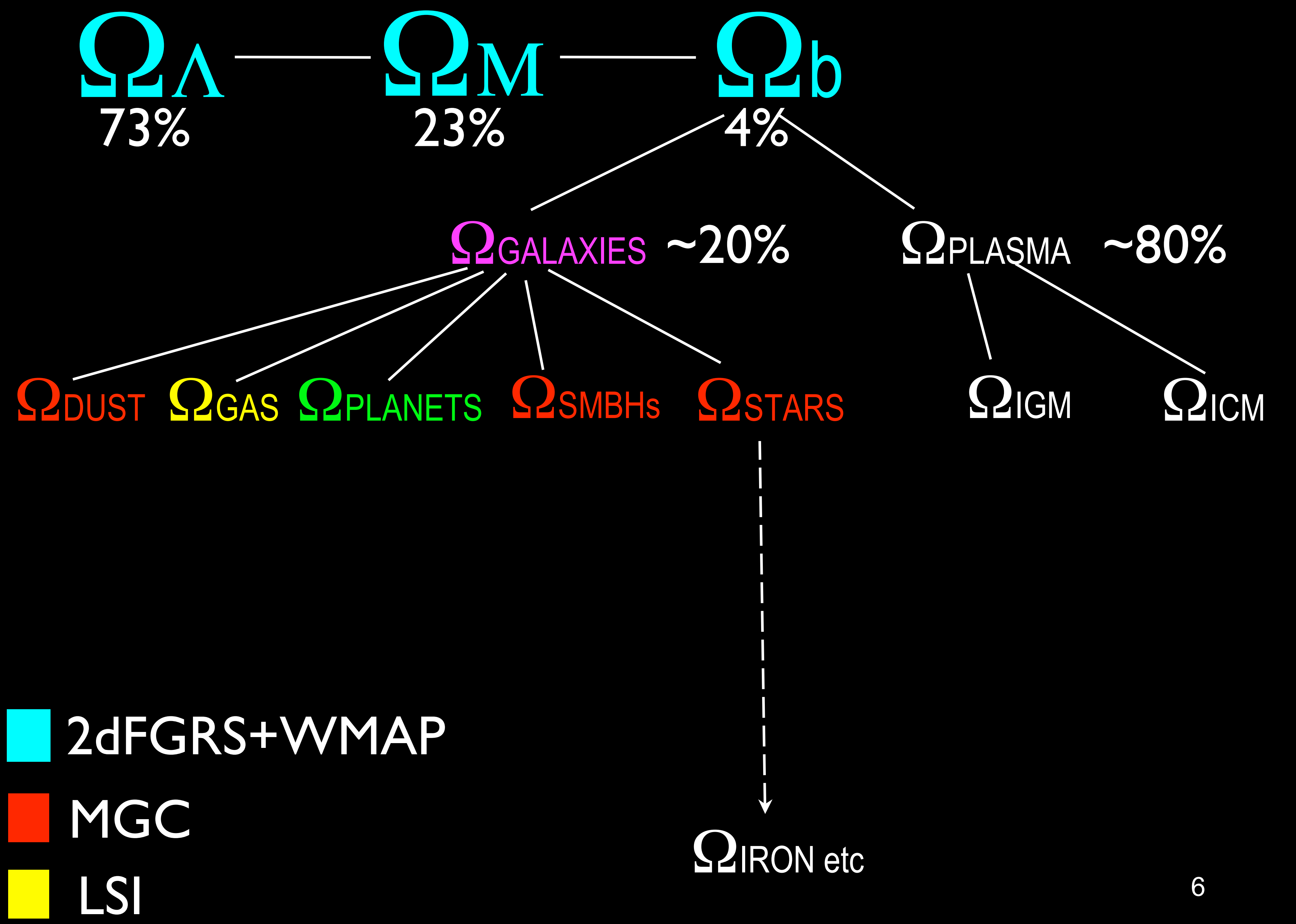
= GALAXY FORMATION & EVOLUTION



2dFGRS+WMAP

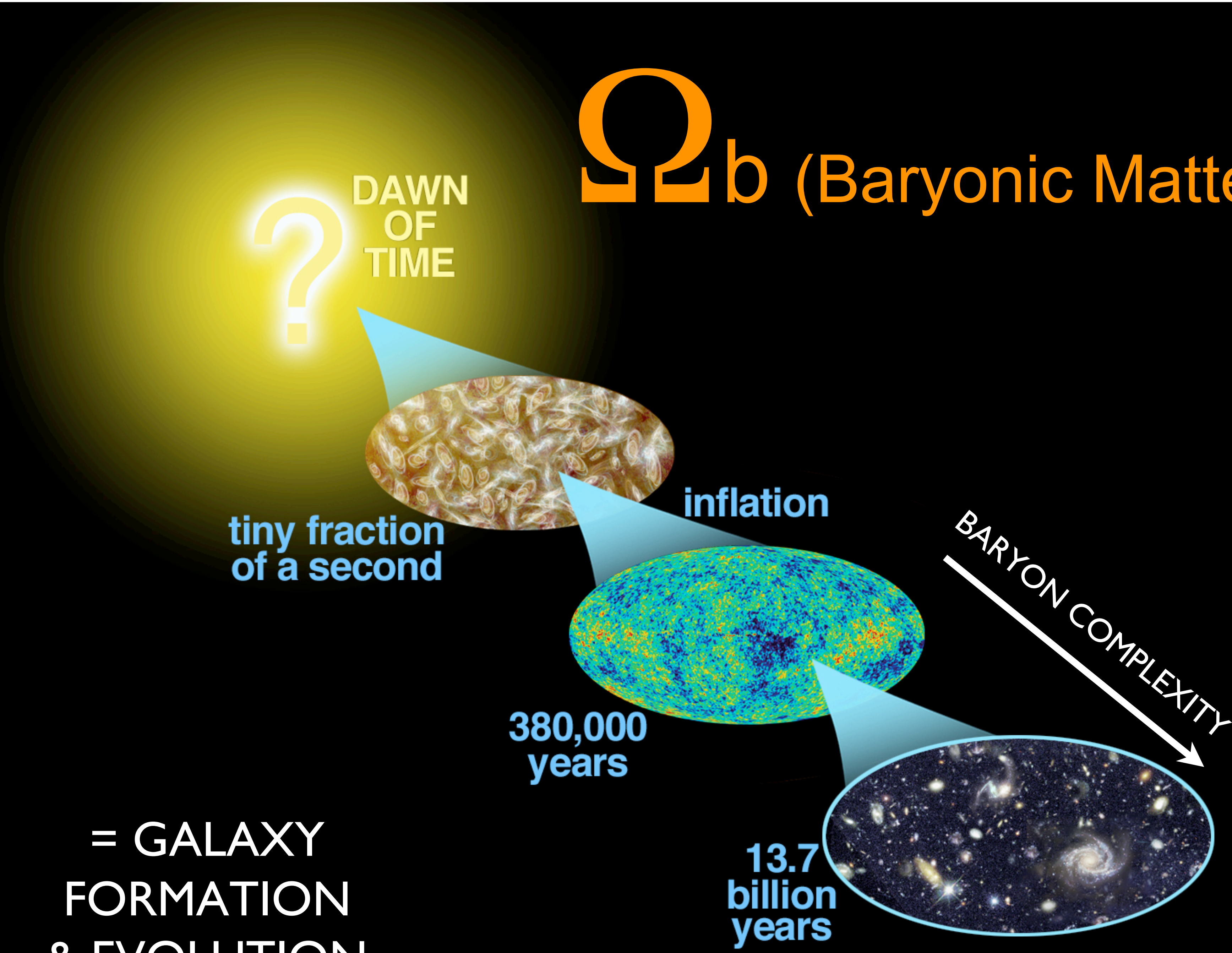
MGC

LSI



ΩΛ
73%
ΩM
23%
Ωb
4%
ΩGALAXIES ~20%
ΩPLASMA ~80%
ΩDUST
ΩGAS
ΩPLANETS
ΩSMBHs
ΩSTARS
ΩIGM
ΩICM
ΩIRON etc
2dFGRS+WMAP
MGC
LSI

Ωb (Baryonic Matter)



= GALAXY FORMATION & EVOLUTION

Galaxy formation (theories)

- Global formation/evolutionary processes:
  - Monolithic collapse (ELS1962)
  - Satellite accretion (Searle & Zinn 1972)
  - Hierarchical merging (Fall & Efstathiou 1985)
  - Major mergers (Toomre 1977)
  - Secular evolution (Kormendy & Kennicutt 2004)
- Environmentally dependent evolutionary processes:
  - Stretching (Barnes & Hernquist 1992)
  - Harassment (Moore et al 1998)
  - Stripping (Gunn & Gott 1972)
  - Strangulation (Balogh & Morris 2002)
  - Squelching (Tully et al 2002)
  - Threshing (Bekki et al 2001)
  - Splashback (Fukugita & Peebles 2005)
  - Cannibalism (Ostriker & Hausman1977)

!

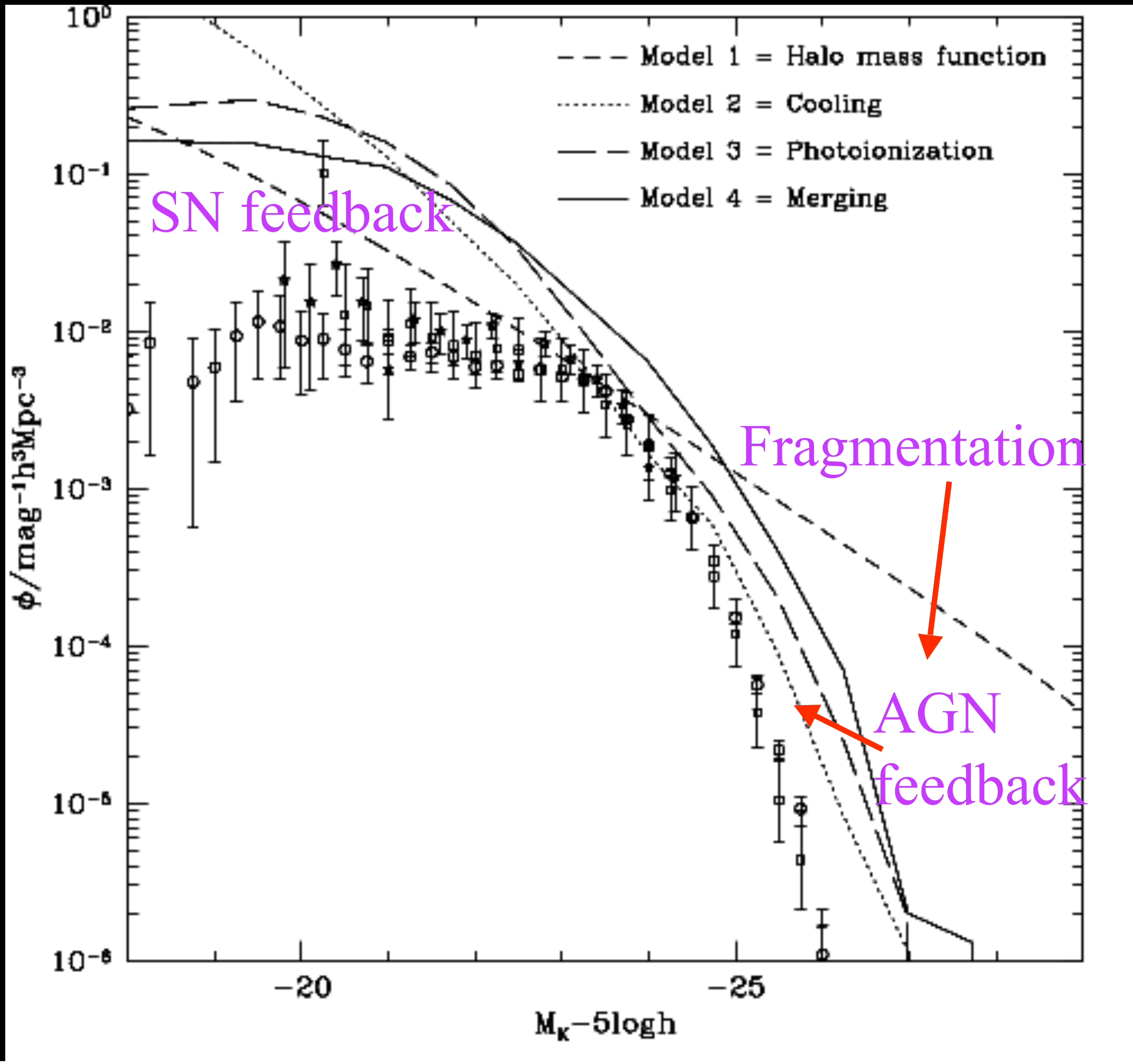
Galaxy formation (sims)

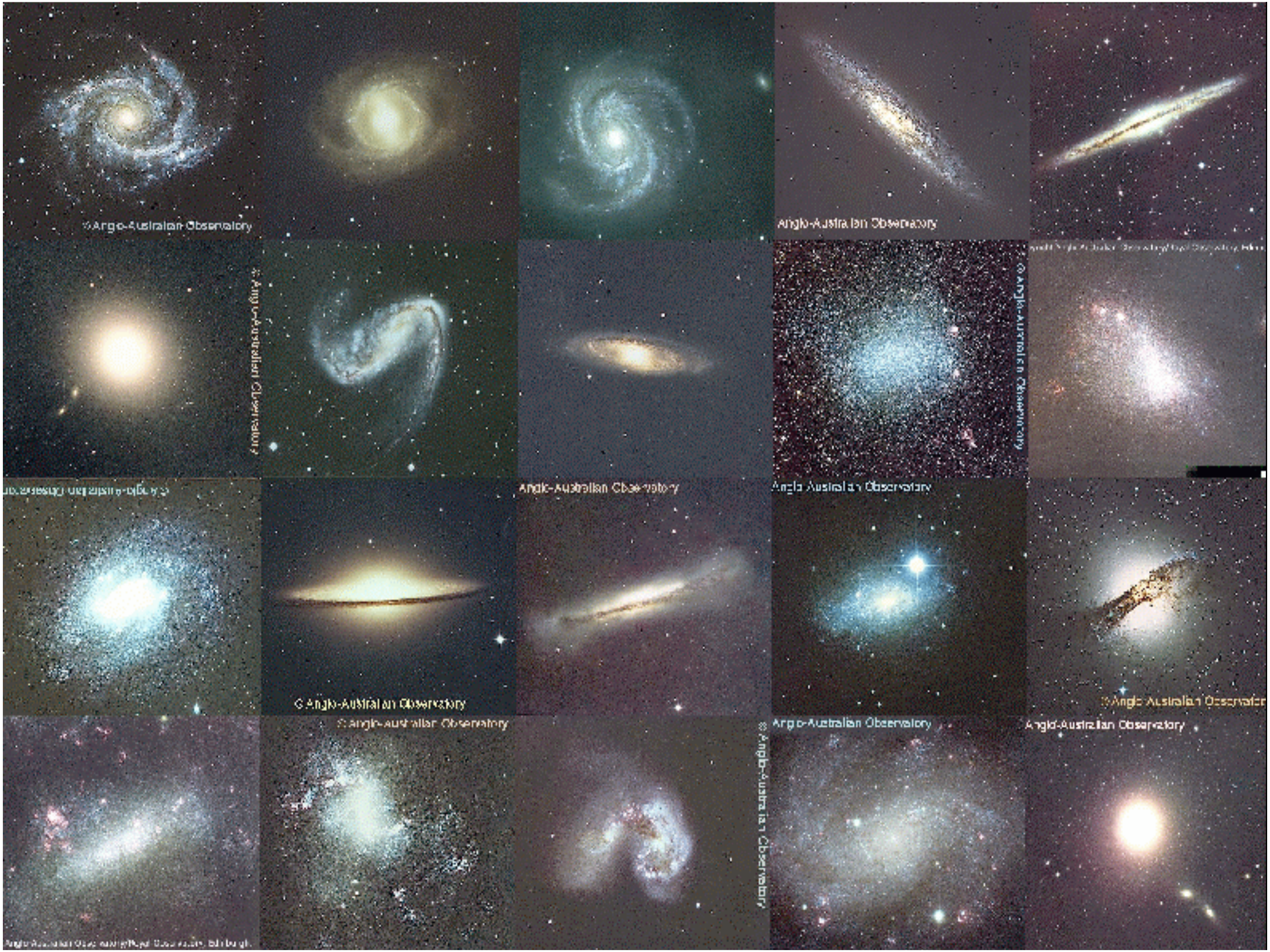
- Numerical codes (e.g., Millennium Simulation):
  - Model dark matter only (i.e., cold dark matter)
  - Re-simulate sub-regions at higher resolution incorporating gas
  - Reproduces observed large scale structure extremely well
  - But no baryons, therefore no galaxies

- Semi-analytic (e.g., Cole et al 2000; Baugh et al 2006):
  - Allocate galaxy properties to DM haloes according to rules
  - Encode key physics (stellar evolution, SN etc)
  - Calibrate to known empirical relationships
  - Attempt to recover other known empirical relationships
  - Fails to reproduce basic relations (e.g., galaxy LF)
  - Predicts a hierarchical build-up of large objects from small

Galaxy formation (sims)

- E.g., the galaxy luminosity function (Benson et al 2003)




© Anglo-Australian Observatory
Anglo-Australian Observatory
© Anglo-Australian Observatory
Anglo-Australian Observatory
Anglo-Australian Observatory
© Anglo-Australian Observatory
© Anglo-Australian Observatory
© Anglo-Australian Observatory
Anglo-Australian Observatory
Anglo-Australian Observatory

Galaxy formation (obs.)

- Great diversity in galaxy properties
- High mass galaxies with high metallicity at high z
- High mass galaxies old (recent dry mergers rare)
- Low mass galaxies young (late formers)
- SMBH-AGN-bulge connection
- No of SMBH coallescences in E's ~<0-2
- Colour & structure bimodality
- Distinct kinematic structures and consistuents
- Multitude of dwarfs (dE(N), dI, BCD, UCD, dS, dSph)
- Low low-z merger rate
- Significant drop in recent star-formation history
- Tully Fischer and Fundamental Plane
- Anti-hierarchical evolution ==> downsizing !

Galaxy formation (obs.)

SACDM

- x • Great diversity in galaxy properties
- x • High mass galaxies with high metallicity at high z
- x • High mass galaxies old (recent dry mergers rare)
- x • Low mass galaxies young
- x • SMBH-AGN-bulge connection
- x • No of SMBH coallescences in E's ~<0-2
- x • Colour bimodality
- x • Distinct kinematic structures and constituents
- x • Multitude of dwarfs (dE(N), dI, BCD, UCD, dS, dSph)
- x • Low low-z merger rate
- x • Significant drop in recent star-formation history
- x • Tully Fischer and Fundamental Plane
- x ‣ Anti-hierarchical evolution ==> downsizing !

Galaxy formation (obs.)

SACDM

- x • Great diversity in galaxy properties
- x • High mass galaxies with high metallicity at high z
- x • High mass galaxies old (recent dry mergers rare)
- x • Low mass galaxi
- OK • SMBH-AGN-bulg
- OK • No of SMBH coa)-2
- OK • Colour bimodality
- x • Distinct kinemati stituents
- x • Multitude of dwa UCD, dS, dSph)
- OK • Low low-z merger rate
- OK • Significant drop in recent star-formation history
- x • Tully Fischer and Fundamental Plane
- OK • Anti-hierarchical evolution ==> downsizing !

Key point: Empirical Observations are leading the way

MGC

Millennium Galaxy Catalogue

The Core MGC Team

MGC Collaborators

Simon Driver (St Andrews)
(Proposals/Vision/
Galaxy Populations & Evolution)

Alister Graham (Swin.)
(Interpretation/
Galaxy Structure/
SMBHs)

Jochen Liske (ESO)
(Image and Spectral Analysis/
QSOs, Cosmology)

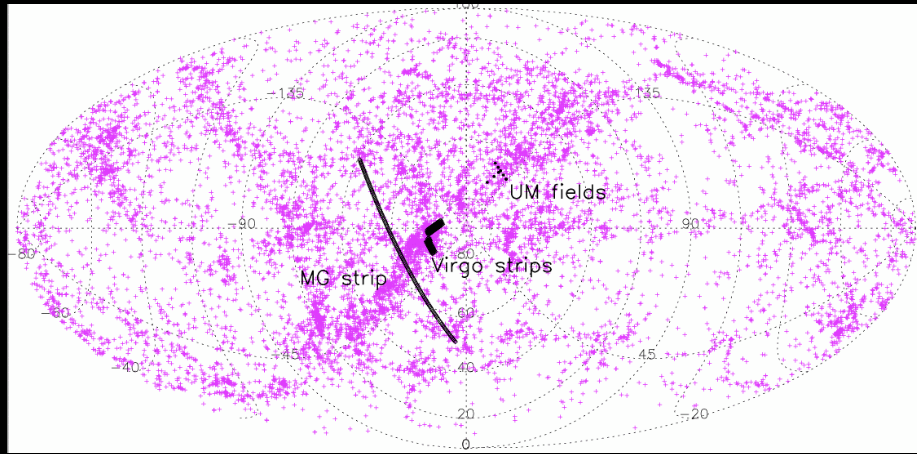
Paul Allen (HO)
(Automated Structural Analaysis, GIM2D)

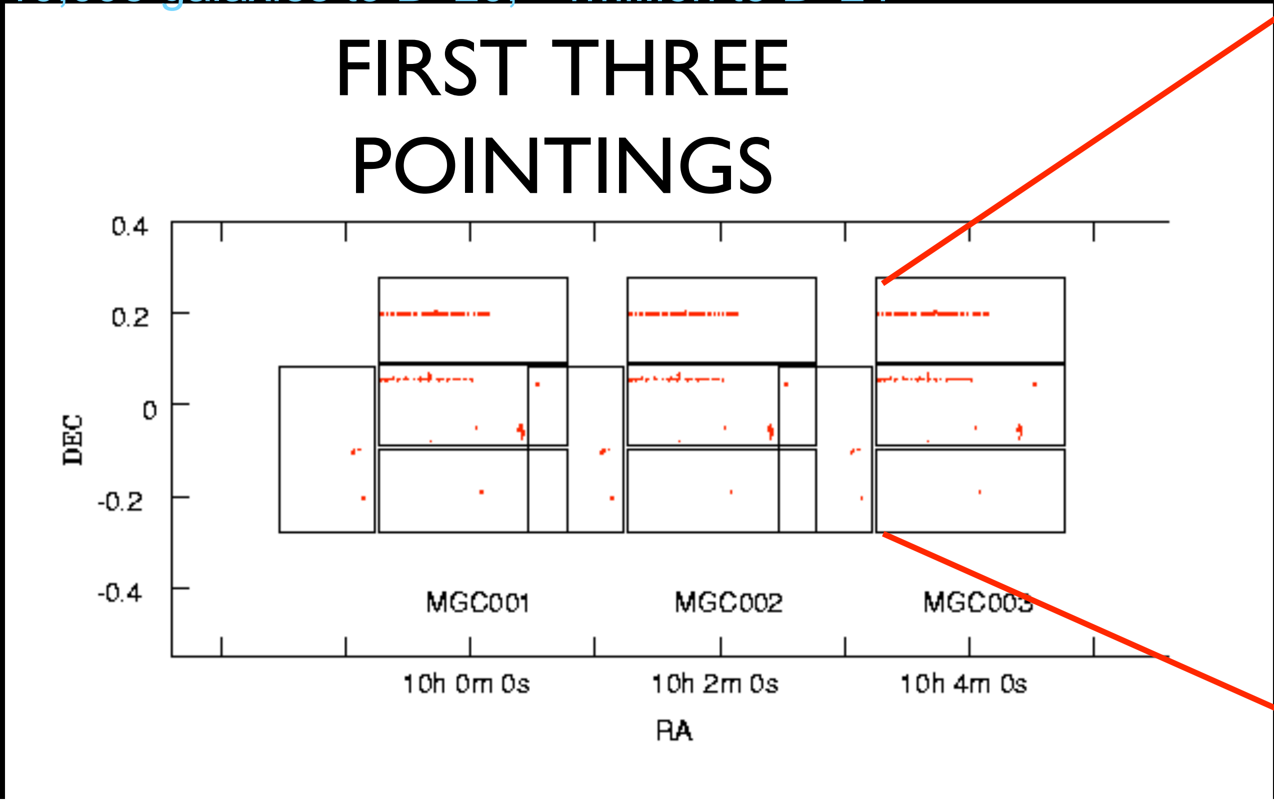
Ewan Cameron (St Andrews)
(PhD Training)

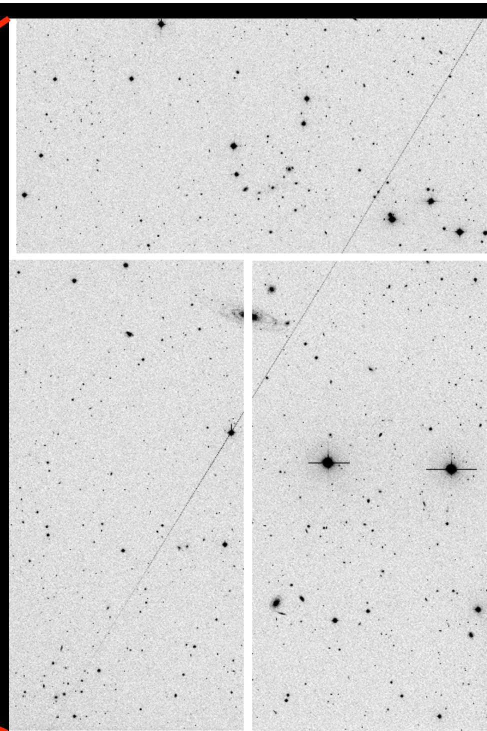
Richard Tuffs
Cristina Popescu
Nicholas Cross
Roberto De Propris
Simon Ellis
Steve Phillipps
Chris Conselice
Dave Patton
Warrick Couch
John Peacock

The WFC Footprint

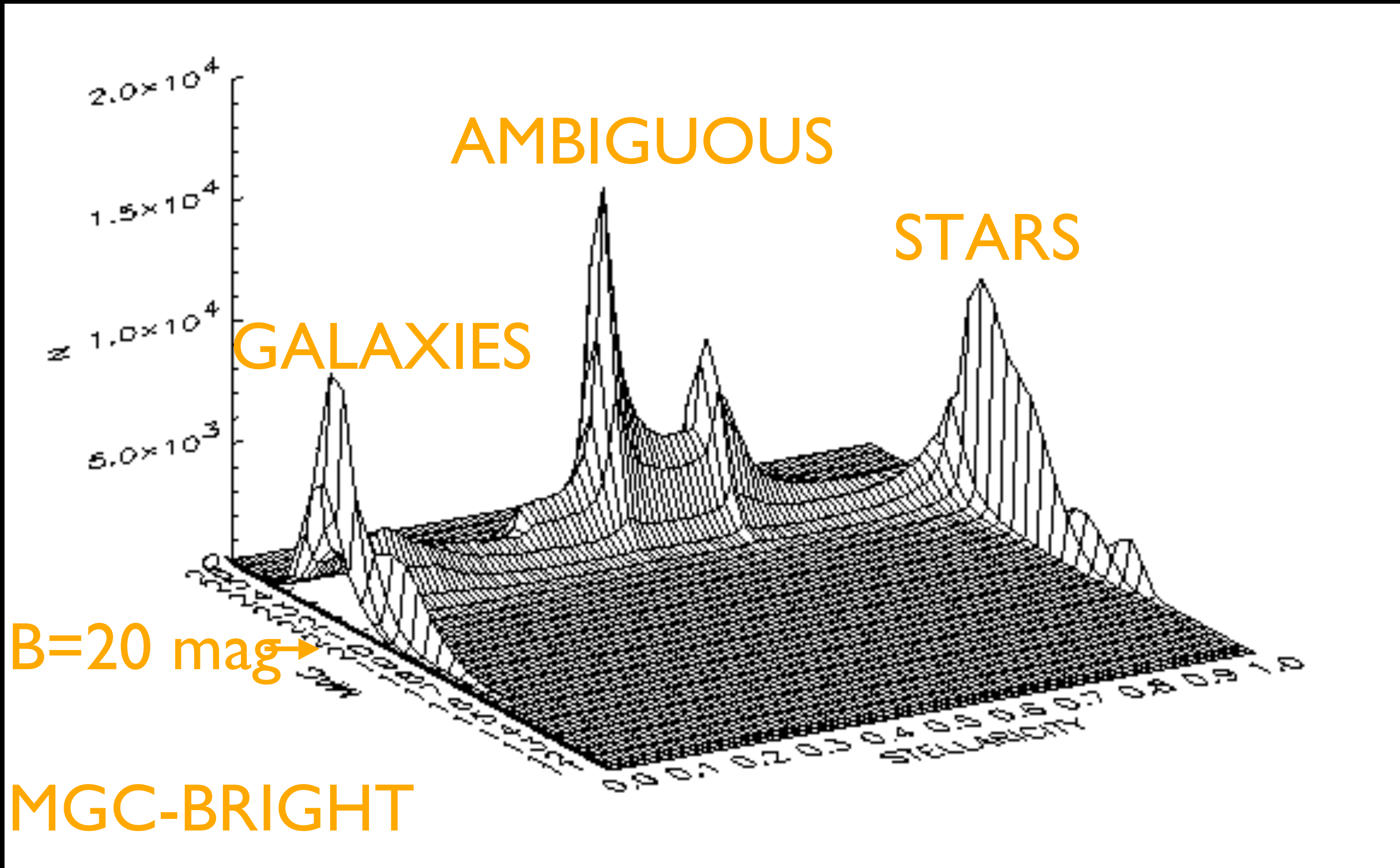
- 144 pointings at δ=0 (10h00m-14h50min)
- 37 sq degrees to B=26 mag/sq arcsec
- 576 individual 2048x4100 CCD images
- 0.33'' pixels, FWHM ~ 1.2'', each 750 sec
- B-band only (u,g,r,i,z from SDSS-EDR)
- High Galactic Latitude
- 10,095 galaxies to B=20, ~1million to B=24







Star/galaxy separation



Viable to B ~ 21 mags,

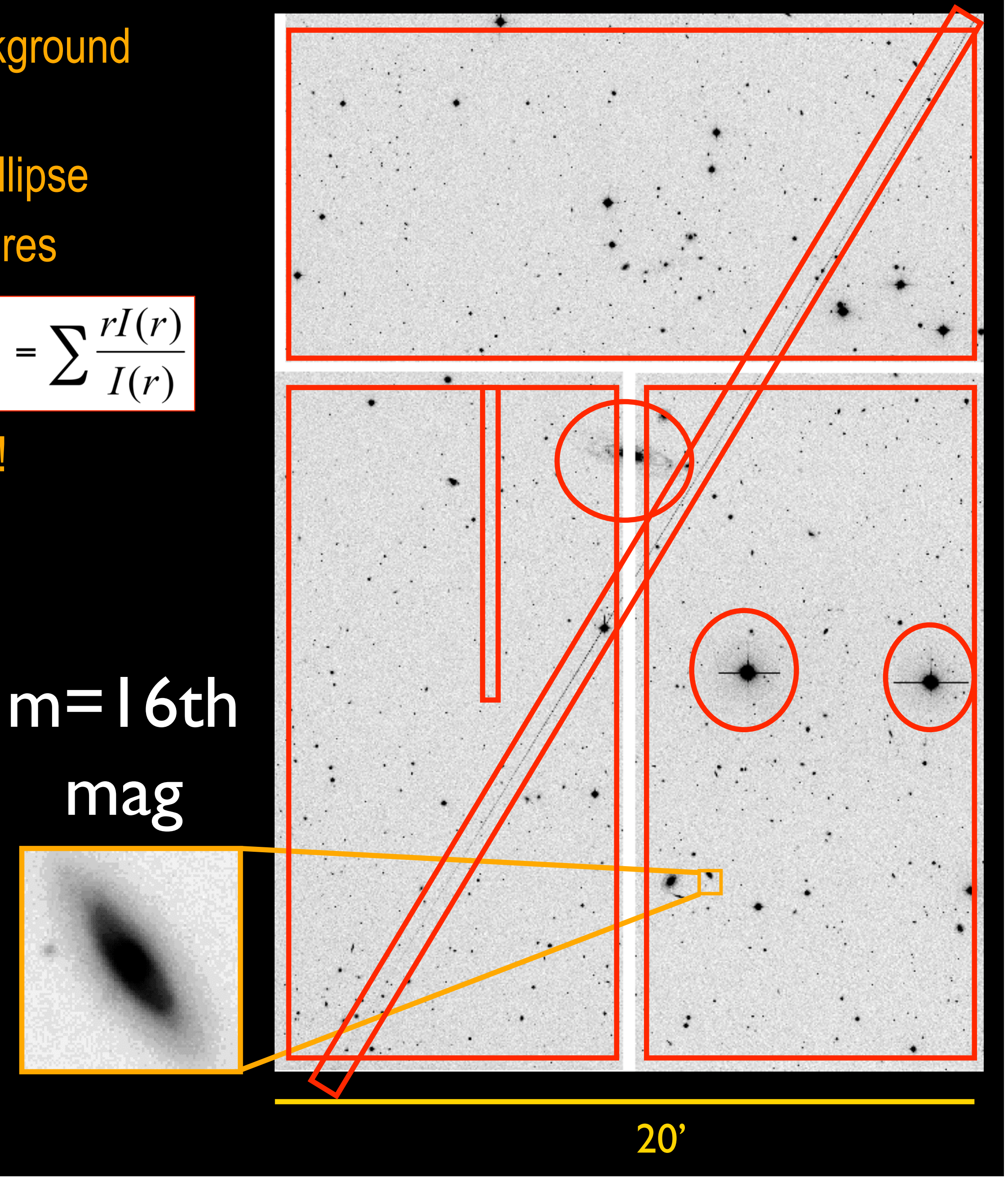
For B > 21 mags use statistical method

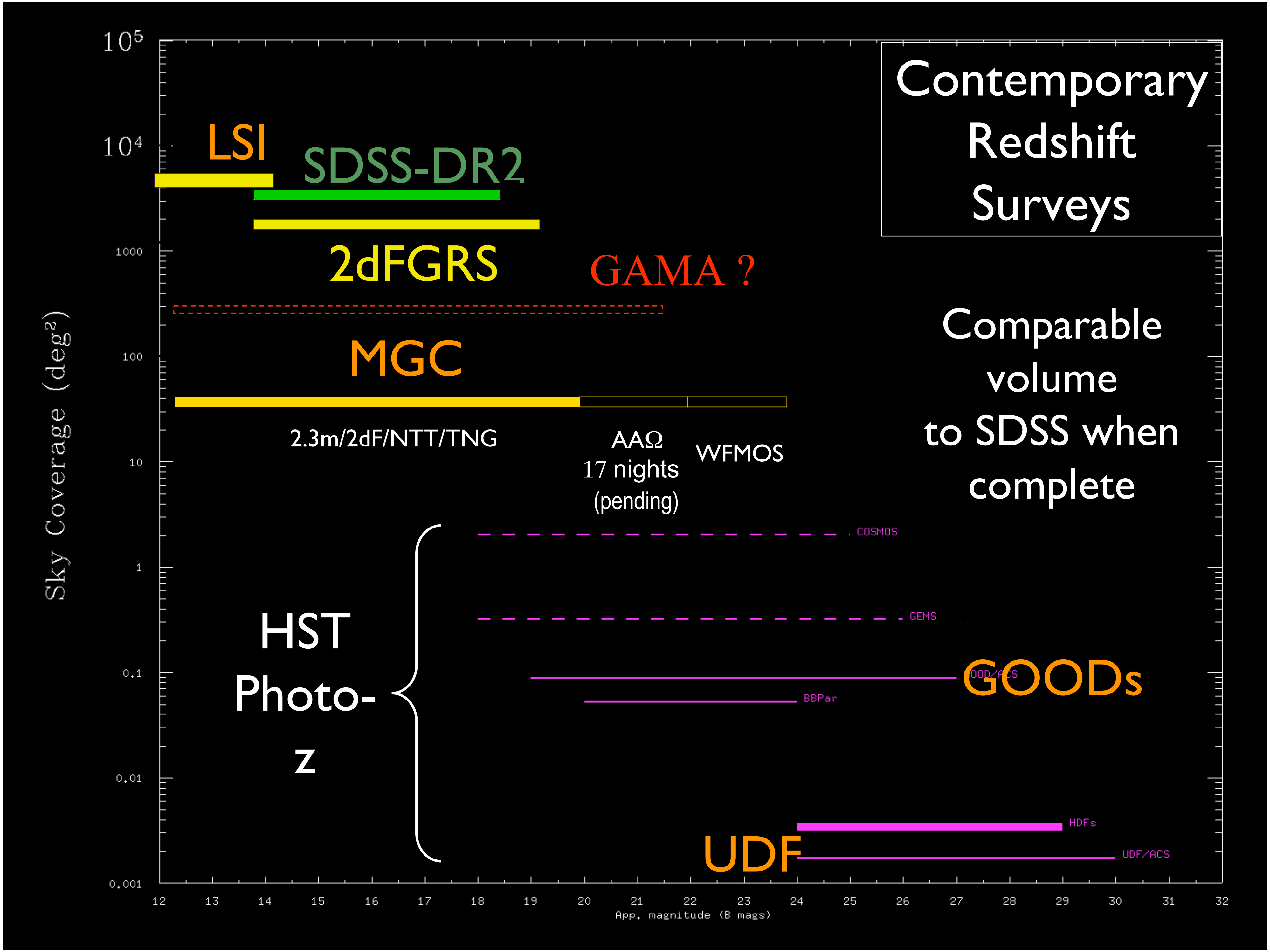
Image Detection and Analysis

- Model sky: Median filtering onto coarse mesh
- Search for connected pixels above background threshold: 26 mags/sq arcsec
- Reanalyse each peak to get isophotal ellipse
- Kron magnitudes within elliptical apertures
- 144 fields or 576 CCDs
- Over 2 million detections
- All B < 20 mag objects checked by eye !
  - Galaxies (12374)
  - Stars (51284)
  - Cosmic Rays (113)
  - Diffraction Spikes (263, 2%)
  - Satellites (162,1%)
  - Dead Pixels (3027)
  - Noise/Artifacts (2023, 16%)
  - Asteroids (145, 1%)
  - Deblends (140, 1%)

$$2.5R_{Kron} = \sum \frac{rI(r)}{I(r)}$$

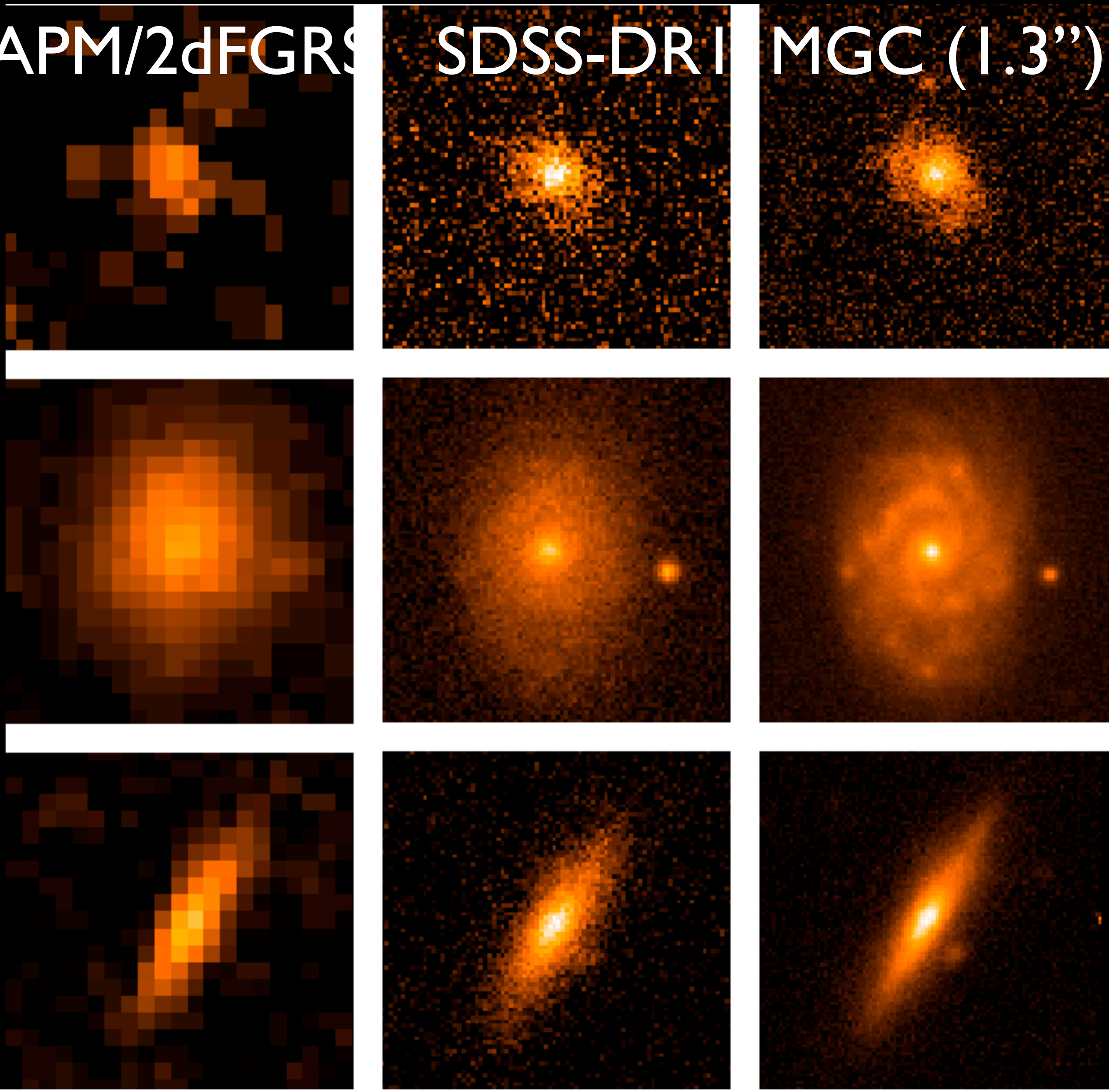
I.e., 20% contamination !





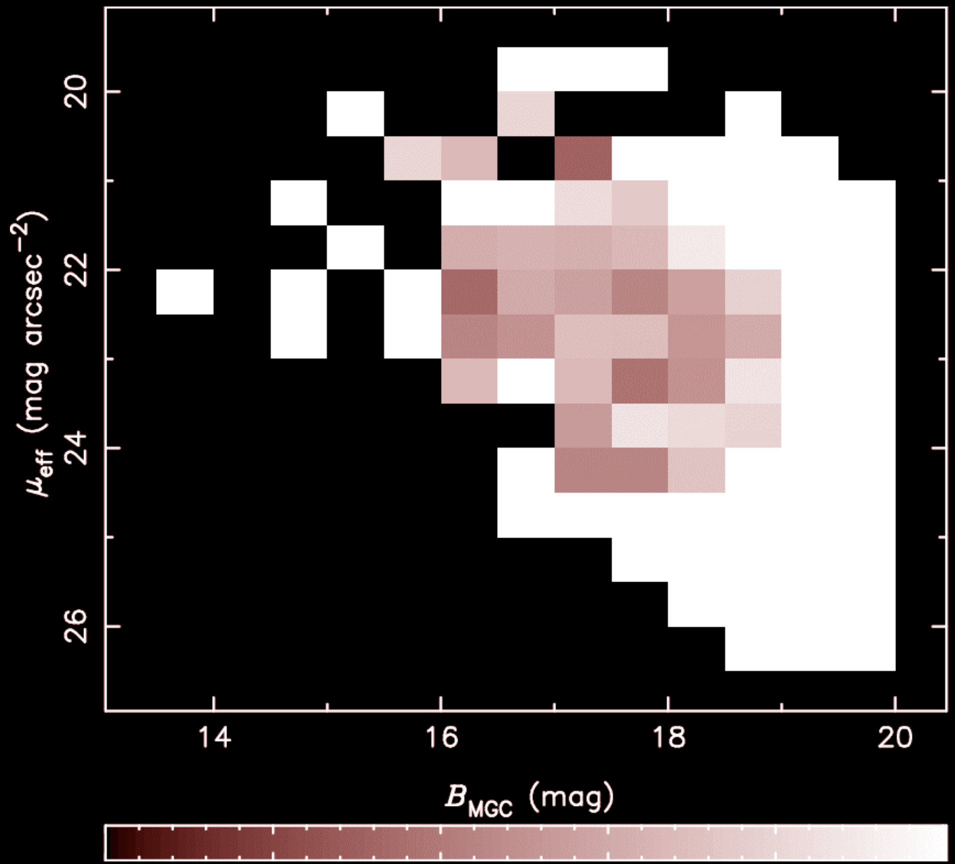
Contemporary Redshift Surveys
LSI
SDSS-DR2
2dFGRS
GAMA ?
MGC
2.3m/2dF/NTT/TNG
AAΩ
17 nights
(pending)
WFMOS
Comparable volume to SDSS when complete
COSMOS
GEMS
GOODs
BBPar
HST Photo-z
HDFs
UDF
UDF/ACS
Sky Coverage (deg²)
App. magnitude (B mags)

MGC data quality v APM & SDSS



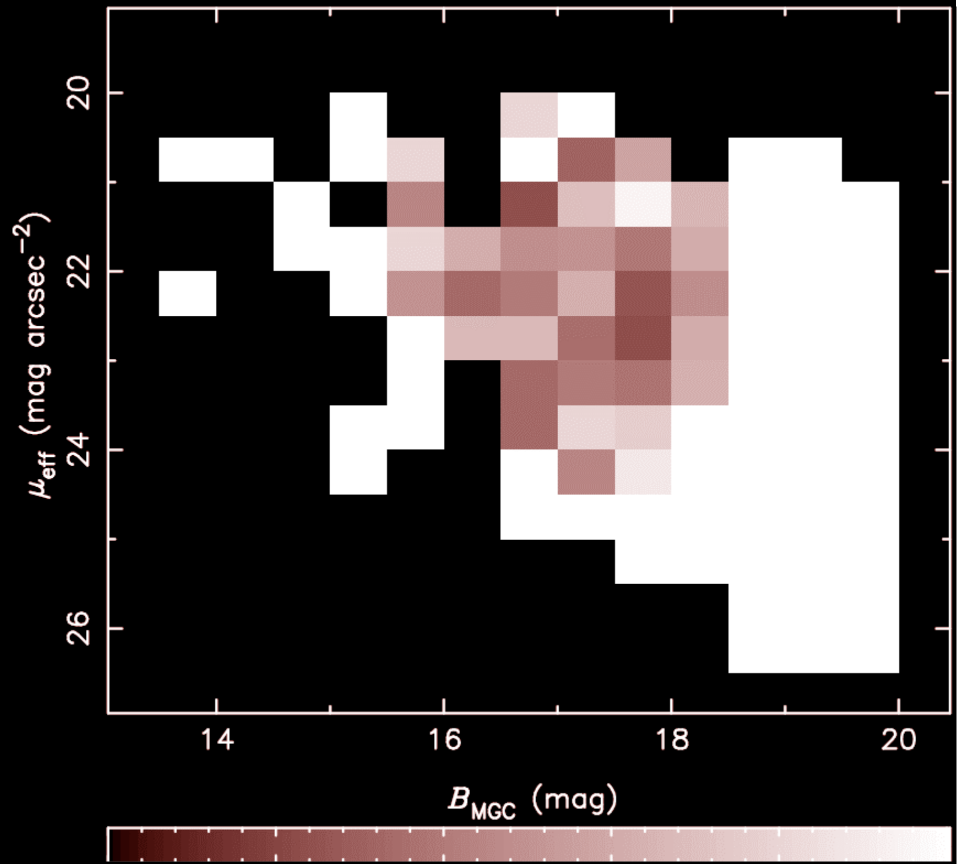
Spectroscopic Incompleteness

2dFGRS



Incompleteness (%)

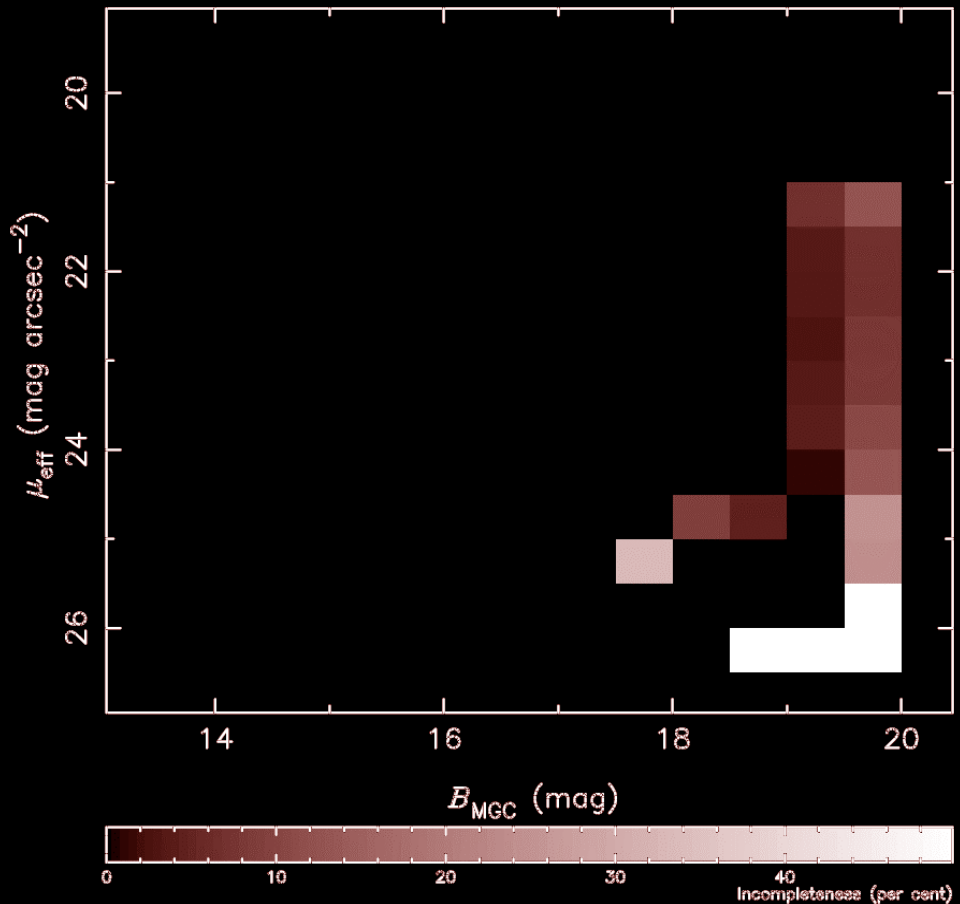
SDSS



Incompleteness (%)

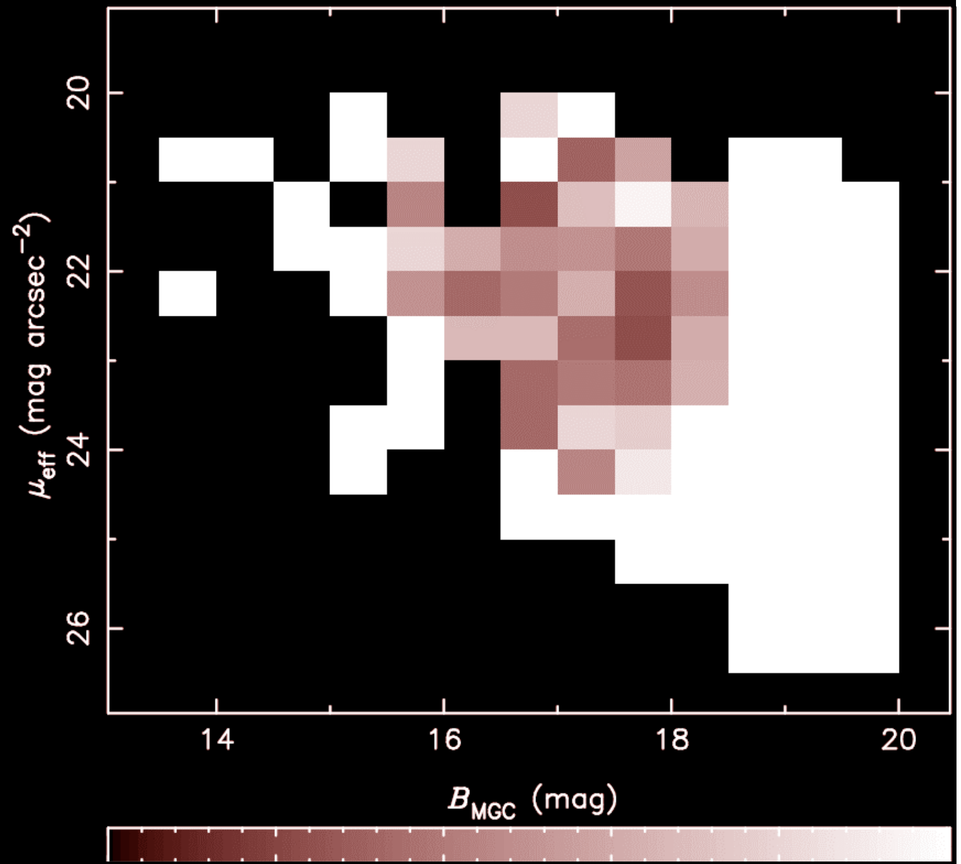
Spectroscopic Incompleteness

MGC



Incompleteness (%)

SDSS



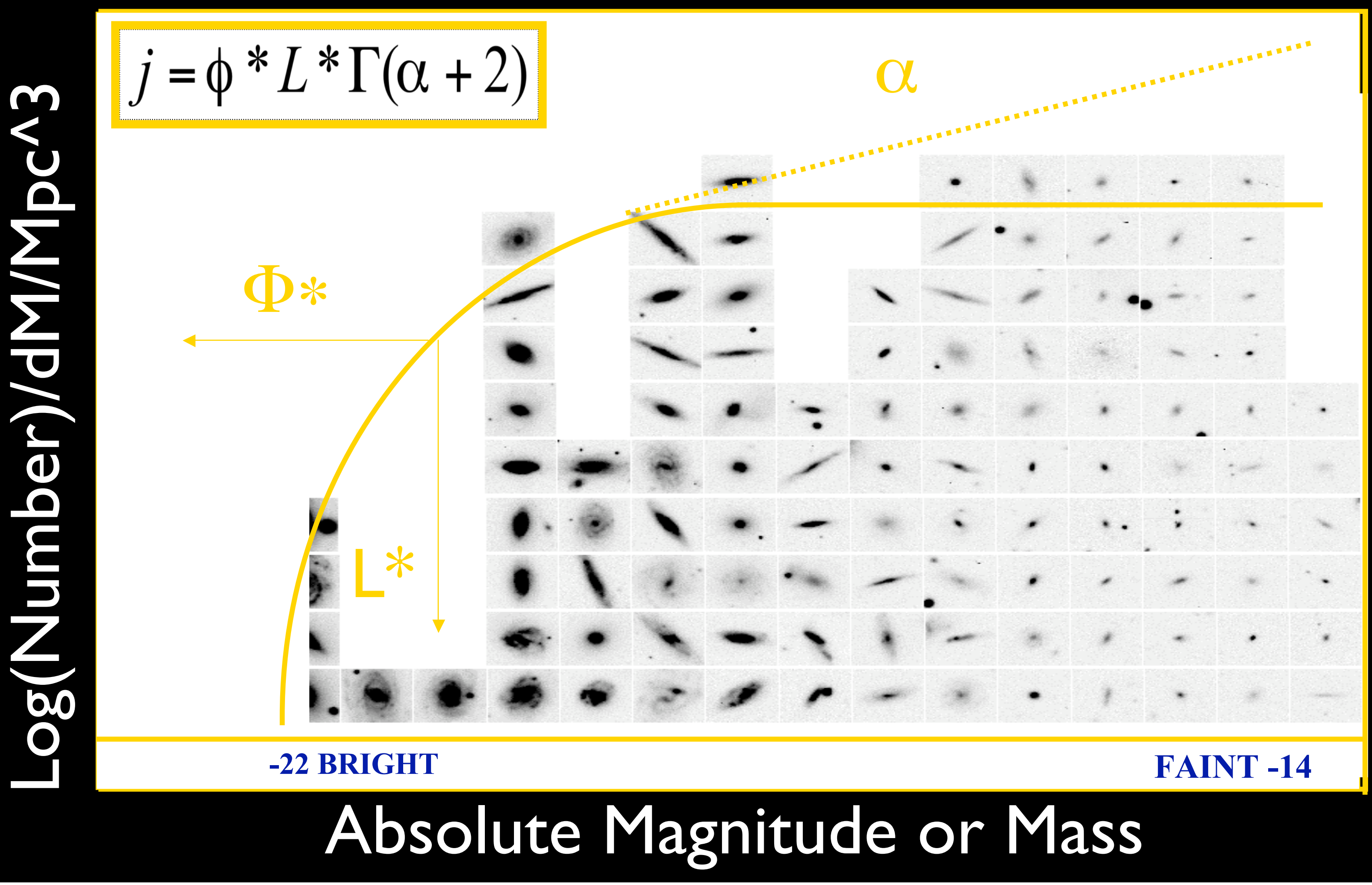
Incompleteness (%)

MGC Publications (9 in press, 4 submitted) [progress is limited by team size..]

- Faint Galaxy Number-Counts, Liske et al (2003), MNRAS
- Star-Counts and the Galactic Halo, Lemon et al (2004), MNRAS
- Photometric accuracy/completeness of APM and SDSS, Cross et al (2004), MNRAS
- ➔ Luminosity and Size distributions, Driver et al (2005), MNRAS
- Galaxy merger rate, De Propris et al (2005), AJ
- PCA analysis of galaxy diversity, Ellis et al (2005), MNRAS
- ➔ Galaxy bimodality, Driver et al (2006), MNRAS
- Space density of Compact Galaxies, Liske et al (2005), MNRAS
- ➔ Structural analysis of galaxies, Allen et al (2005), MNRAS
- ➔ Super Massive Black Hole Mass function, Graham et al (2006),MNRAS, submitted
- Assymetry and the merger rate, De Propris et al (2006), ApJ, submitted
- ➔ Luminosity functions of bulges and disk, Liske et al (2006), ApJL, submitted
- ➔ Dust and galaxy inclination, Driver et al (2006), MNRAS, submitted
- Extreme low surface brightness galaxies, Driver et al (2007), MNRAS, in prep
- The very faint-end of the galaxy LF, Liske et al (2007), MNRAS, in prep
- The luminosity and size distributions of bulges and disks, Liske et al (2007), in prep
- Blue spheriods, Ellis et al (2007), MNRAS, in prep
- PCA II analysis of MGC structural catalogue, Ellis et al (2007), MNRAS, in prep
- UKIRT-MGC galaxy mass function, Cross et al (2007)
- Dust II dependency of structural params. Driver et al (2007)
- SMBH II via M-L relation. Graham et al (2007)

Luminosity Functions and Ω's

- Schechter fn (1976) developed from Press Schechter theory
- Essentially a Gamma function (power law + exponential)
- Directly yields luminosity and mass density (i.e., Omegas)



The Galaxy Luminosity Function

- No consensus
  - x2 uncertainty at M*
  - M > -16 unknown
- SDSS & 2dFGRS:
  - SDSS1 resolved
  - SDSS2 puzzling
- ESP & 2dFGRS OK
- LG best insight ? (~50 galaxies)
- MGC (see later)

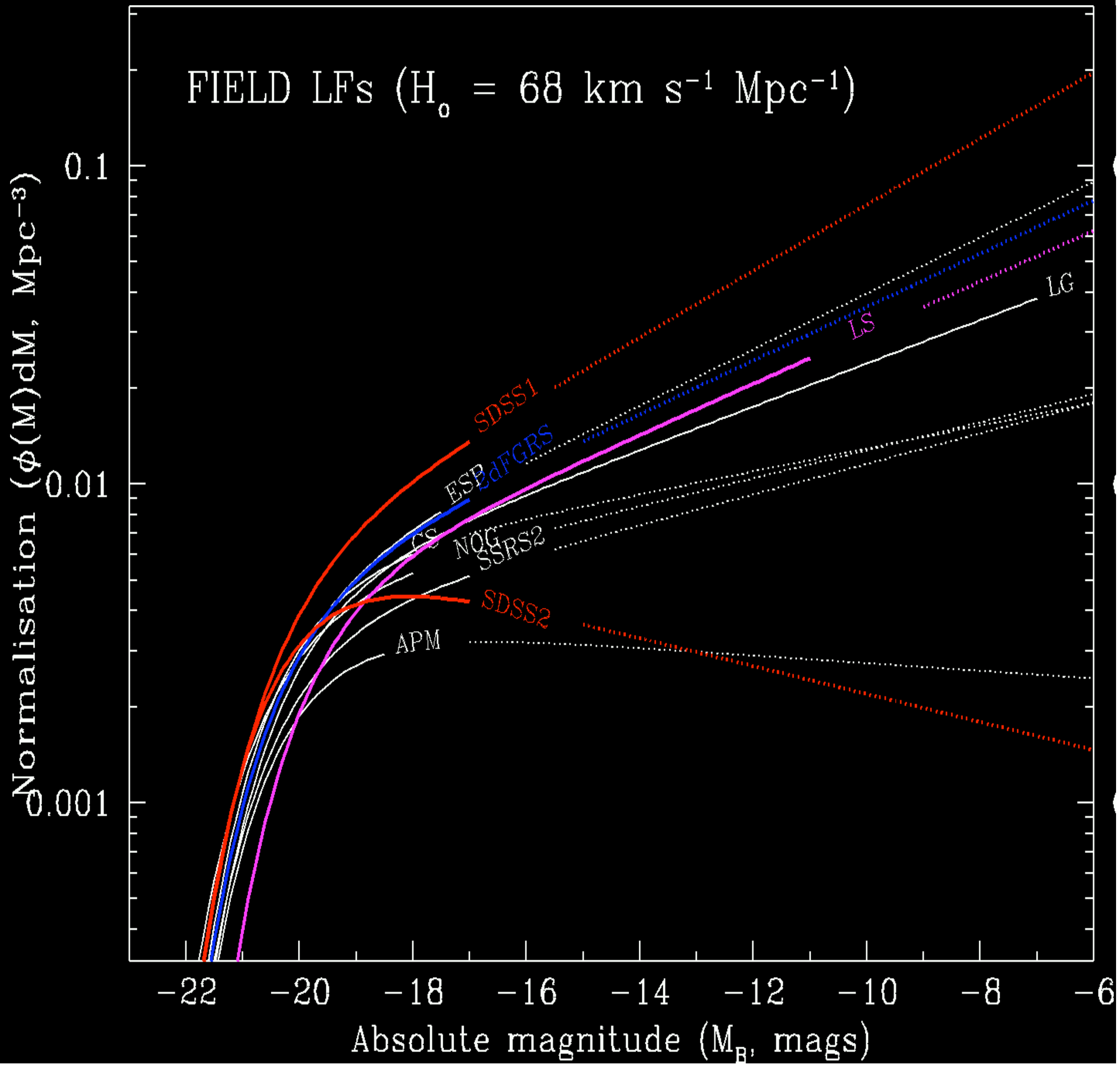


Illustration: Galaxies with B=16

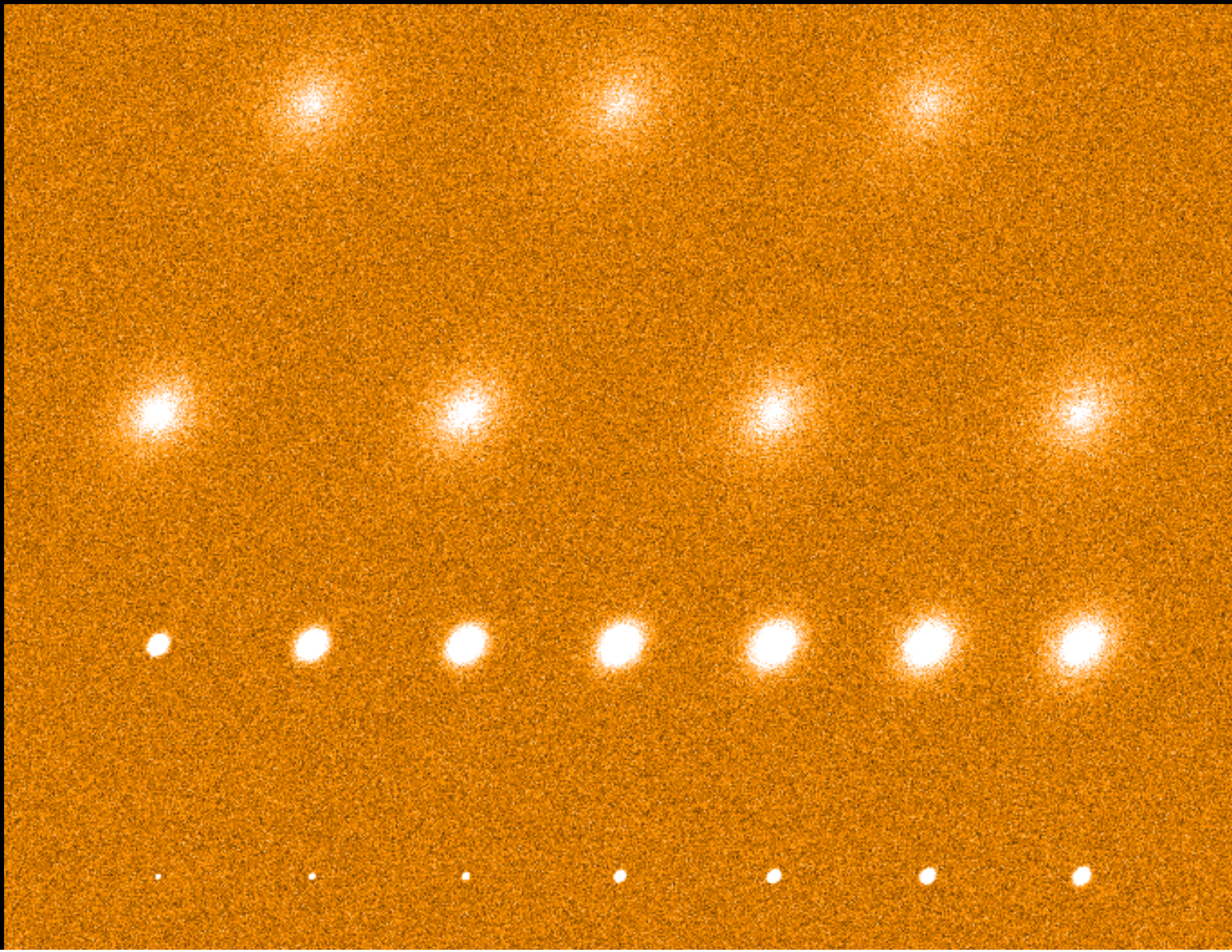
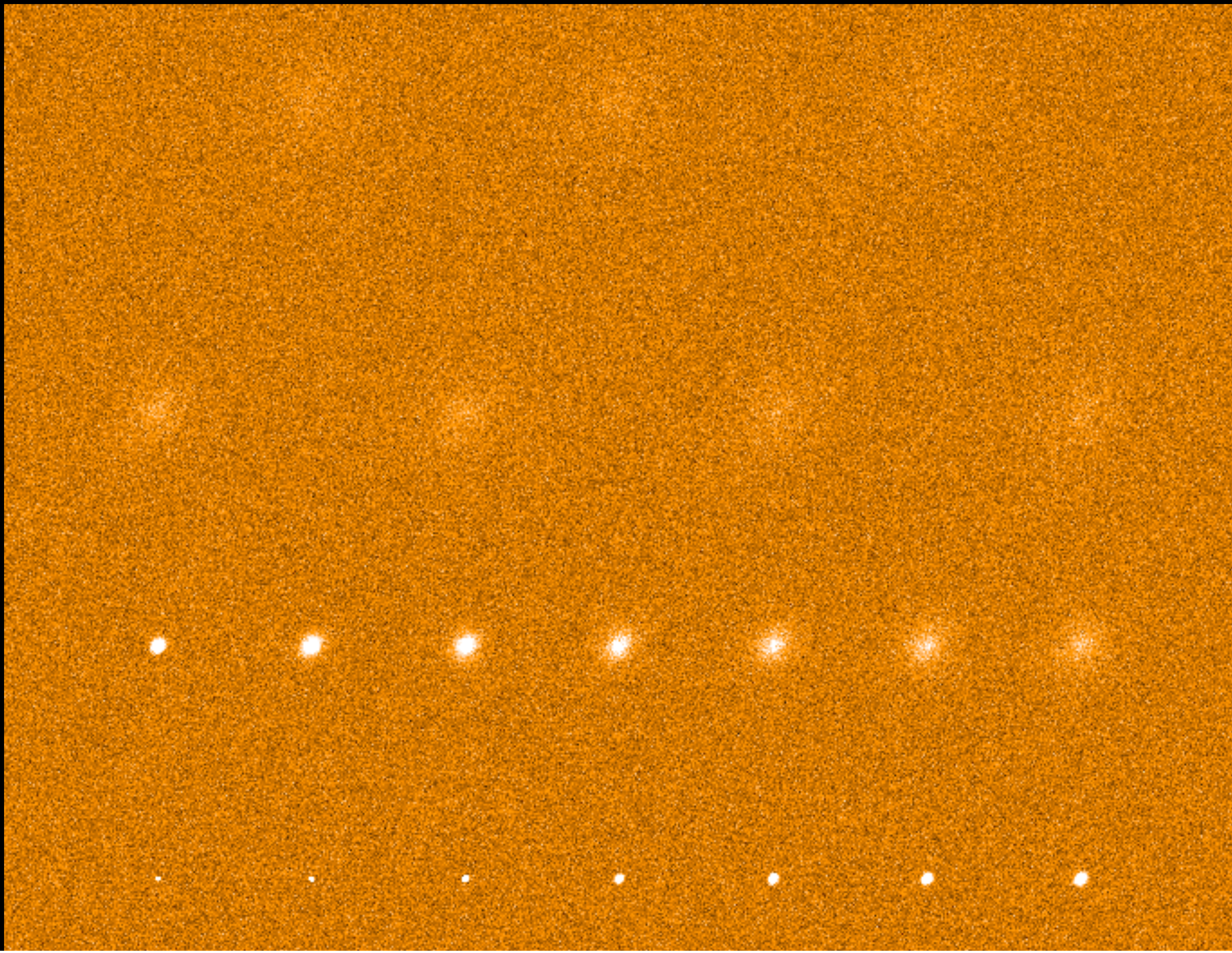
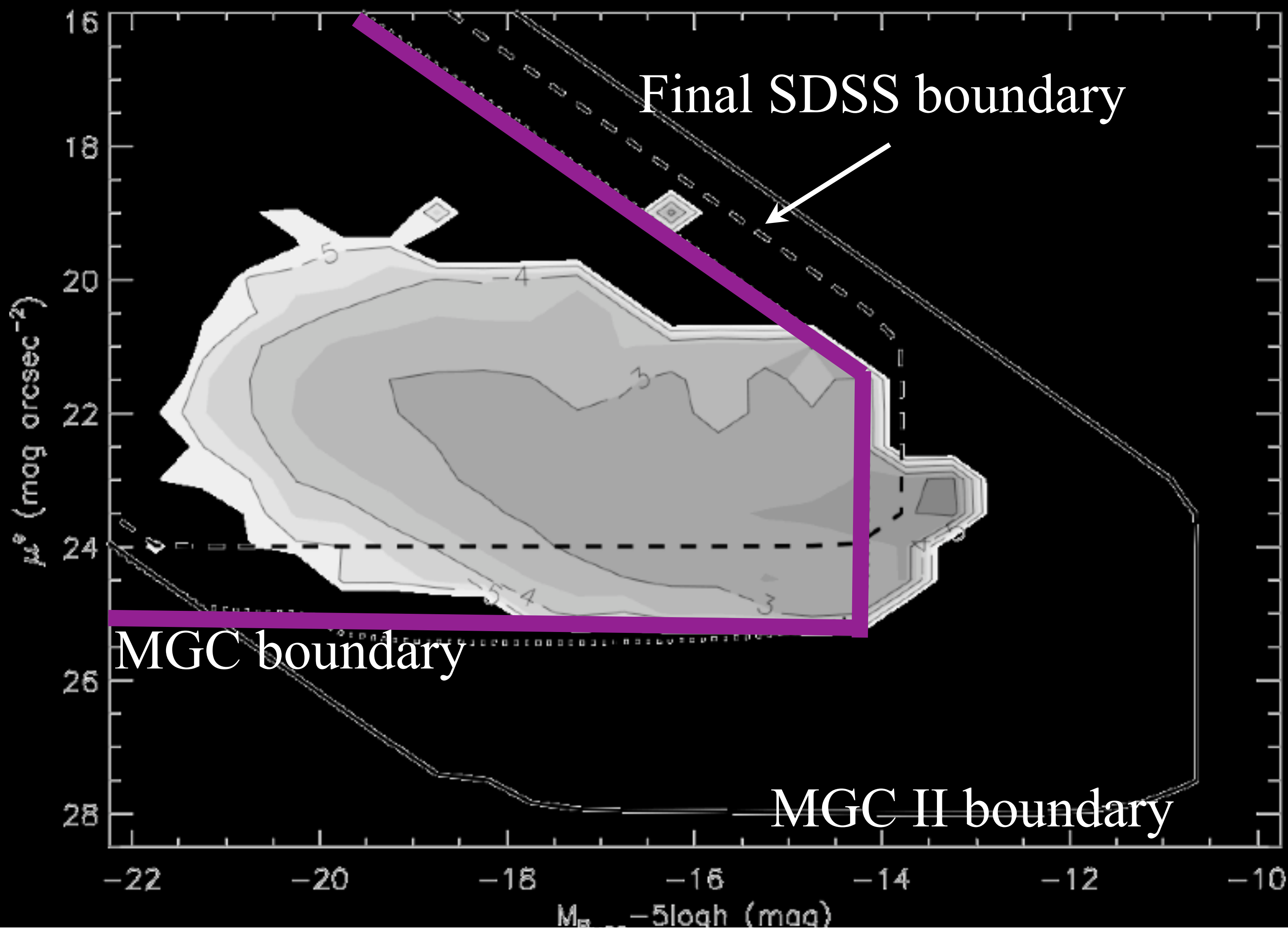
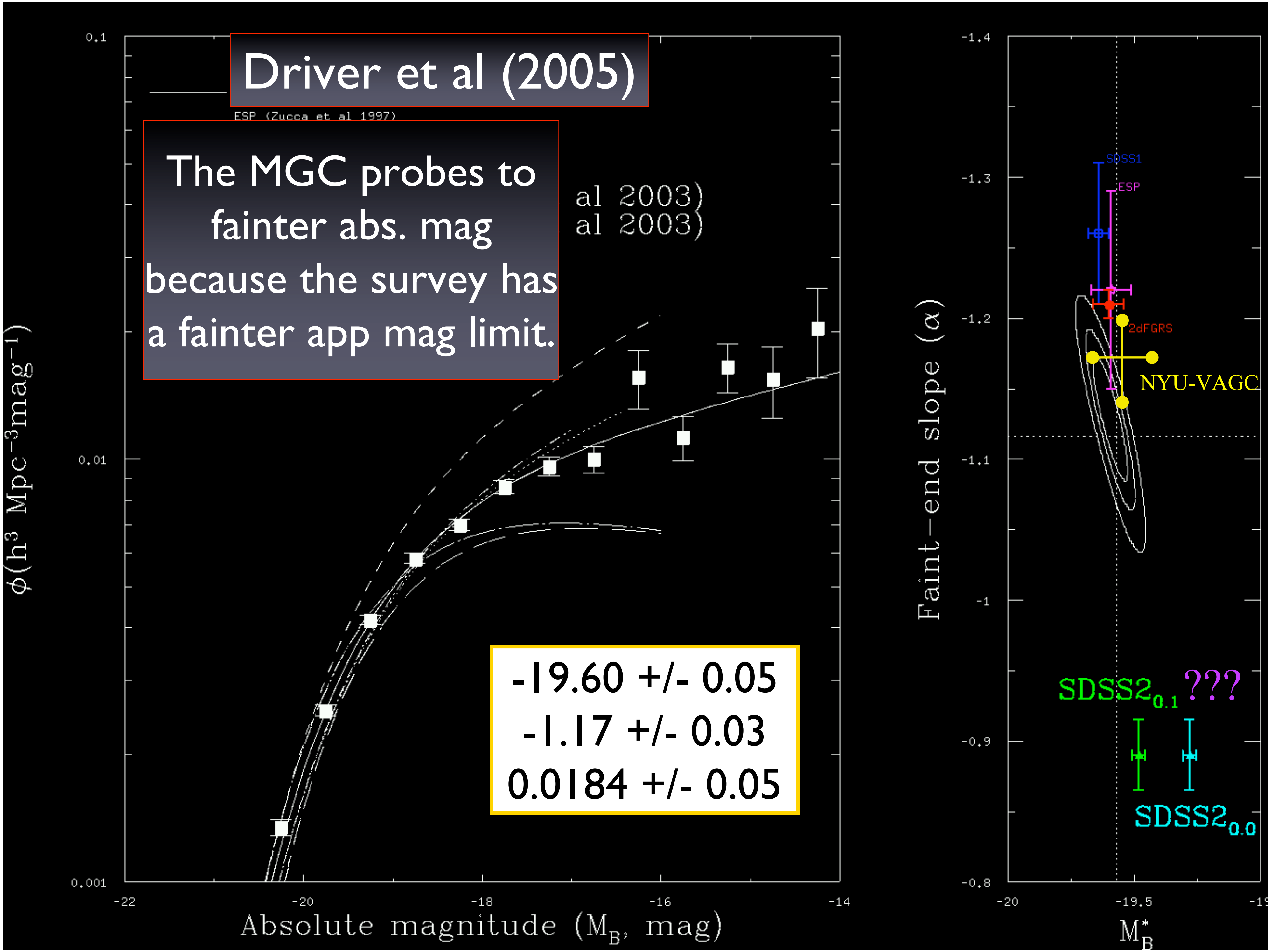


Illustration: Galaxies with B=18



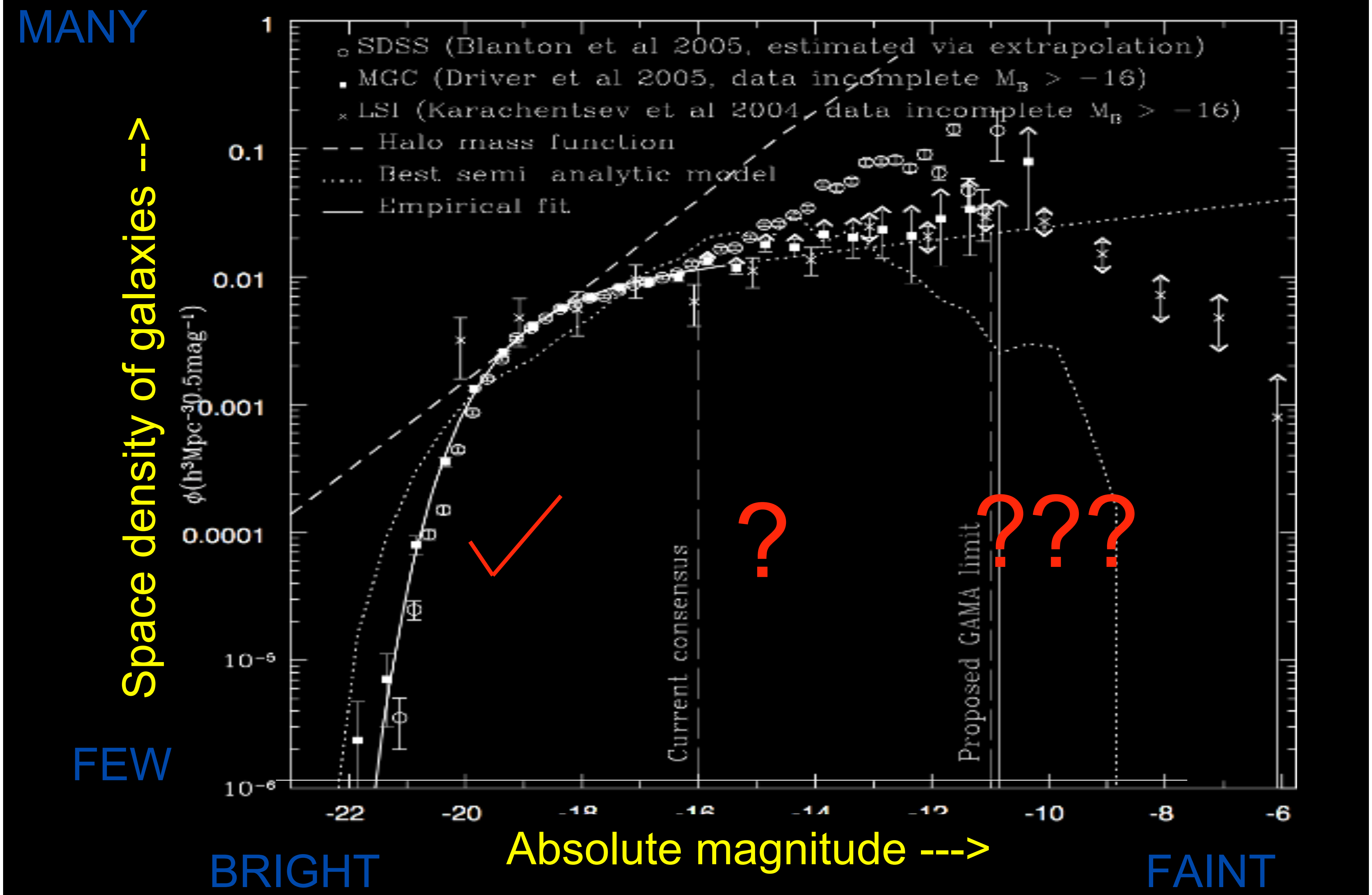
MGC Observations of the Luminosity-Surface Brightness plane (Driver et al 2005)





Driver et al (2005)
ESP (Zucca et al 1997)
The MGC probes to fainter abs. mag because the survey has a fainter app mag limit.
al 2003)
al 2003)
-19.60 +/- 0.05
-1.17 +/- 0.03
0.0184 +/- 0.05
φ(h³ Mpc⁻³mag⁻¹)
0.1
0.01
0.001
-22
-20
-18
-16
-14
Absolute magnitude (M_B, mag)
Faint-end slope (α)
-1.4
-1.3
-1.2
-1.1
-1
-0.9
-0.8
SDSS1
ESP
2dFGRS
NYU-VAGC
SDSS2_0.1 ???
SDSS2_0.0
-20
-19.5
M*_B

BUT…still a long way to go at z=0



The advent of structural analysis (MGC) and the limitations of SDSS & 2MASS !

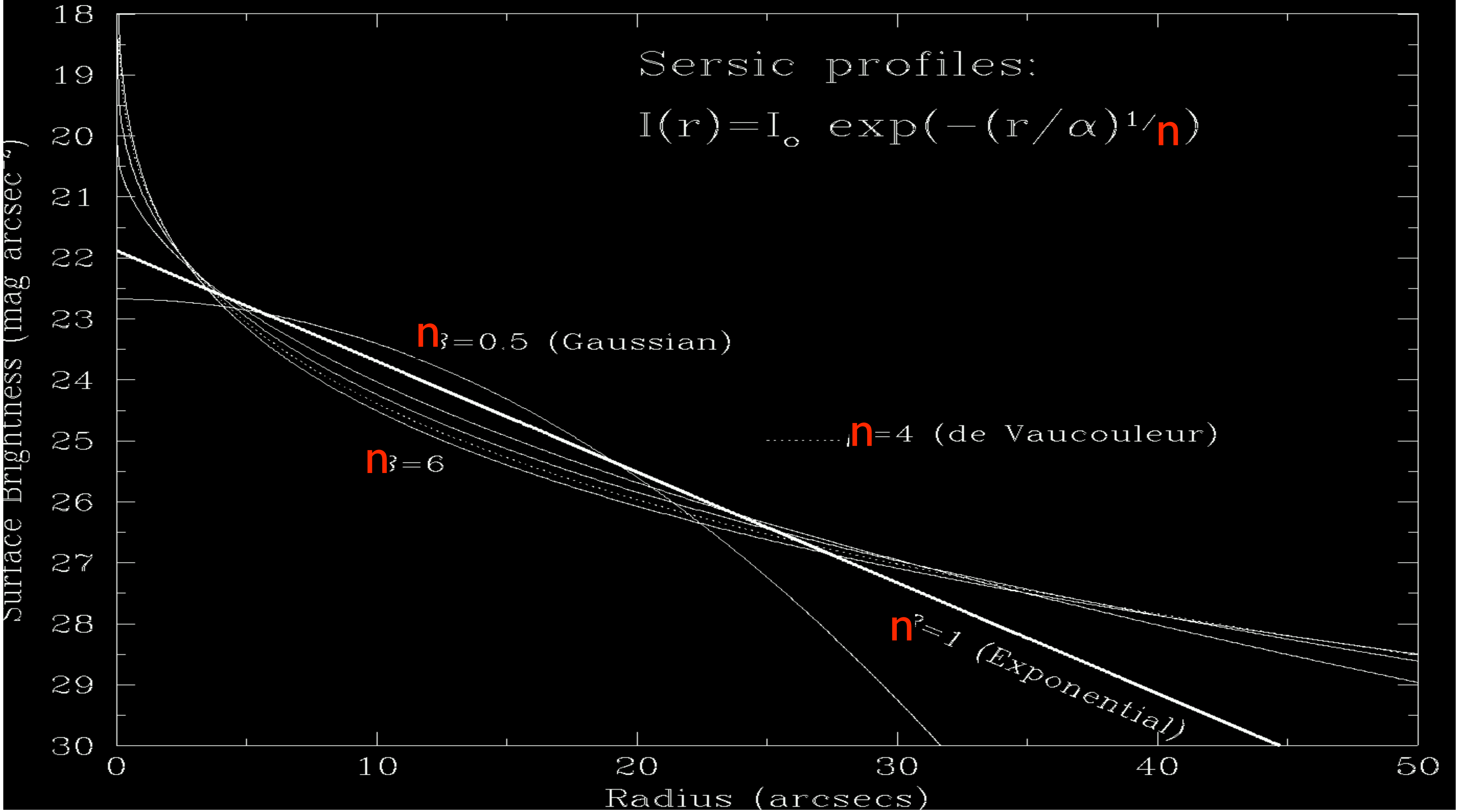
- Issues:
  - Shallow imaging => missing galaxies and missing flux ?
  - Low spatial resolution => unresolved/poorly resolved ?
  - Circular photometry => muddles inclination & structural information
  - Low redshift completeness (60-80 %) => biased ?

- Why is structure important ?
  - Galaxies are fundamentally multiple component systems (bulge+disc)
  - Easy to change a galaxy's colour but hard to modify 1 billion orbits
  - Galaxy structure <=> formation history ? (e.g., Bulge-SMBH relation)
  - Numerical simulations starting to produce galaxy size distributions

- MGC represents the first large-scale structural galaxy resource since the RC3 and the first CCD based resource

The Sersic index (n)

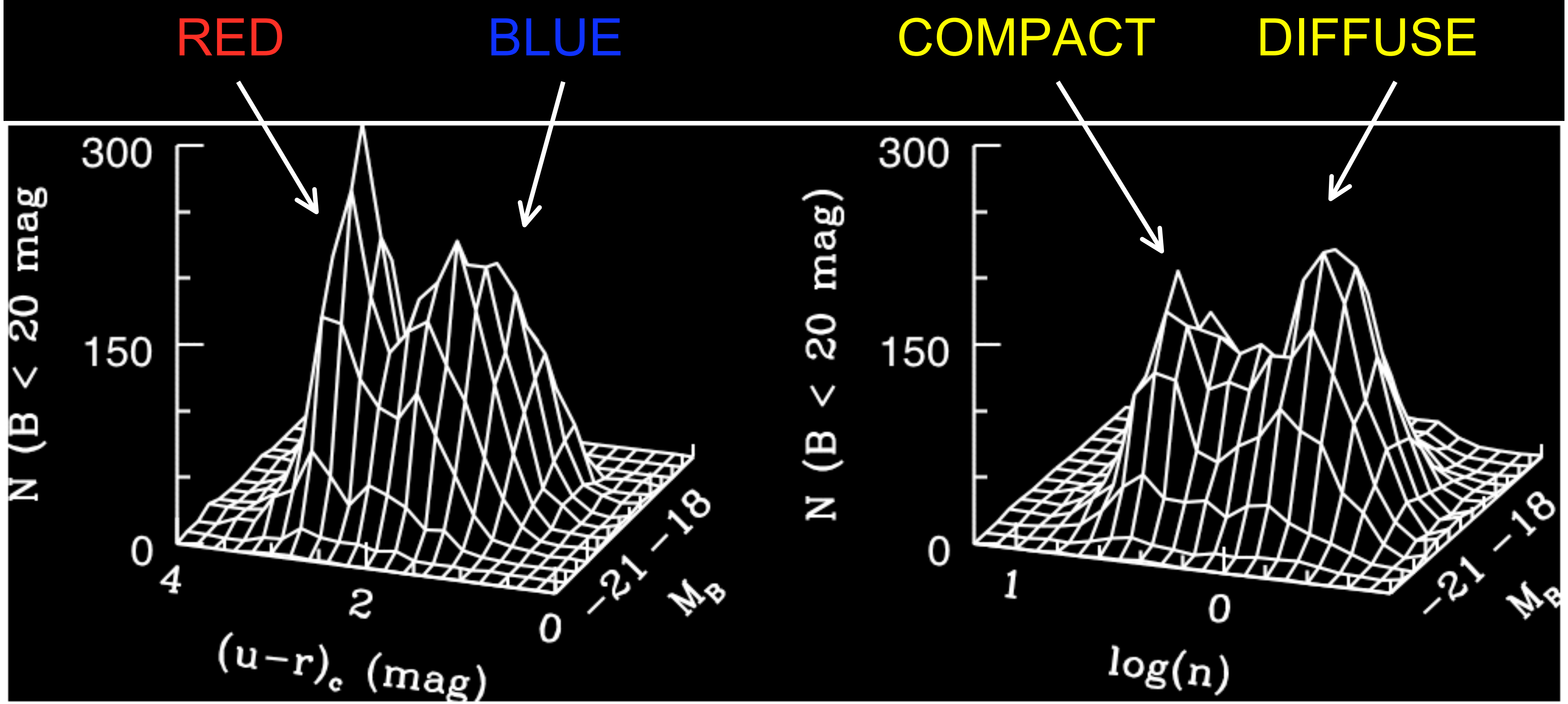
The Sersic index (Sersic 1963, 1968; Graham & Driver 2005) describes the projected light distribution of Spheriods and Bulges.



Galaxy Bimodality

Observe strong colour *(u-r)* and structural (log*n*) bimodalities (Strateva et al 2001; Baldry et al 2004; Driver et al 2006)

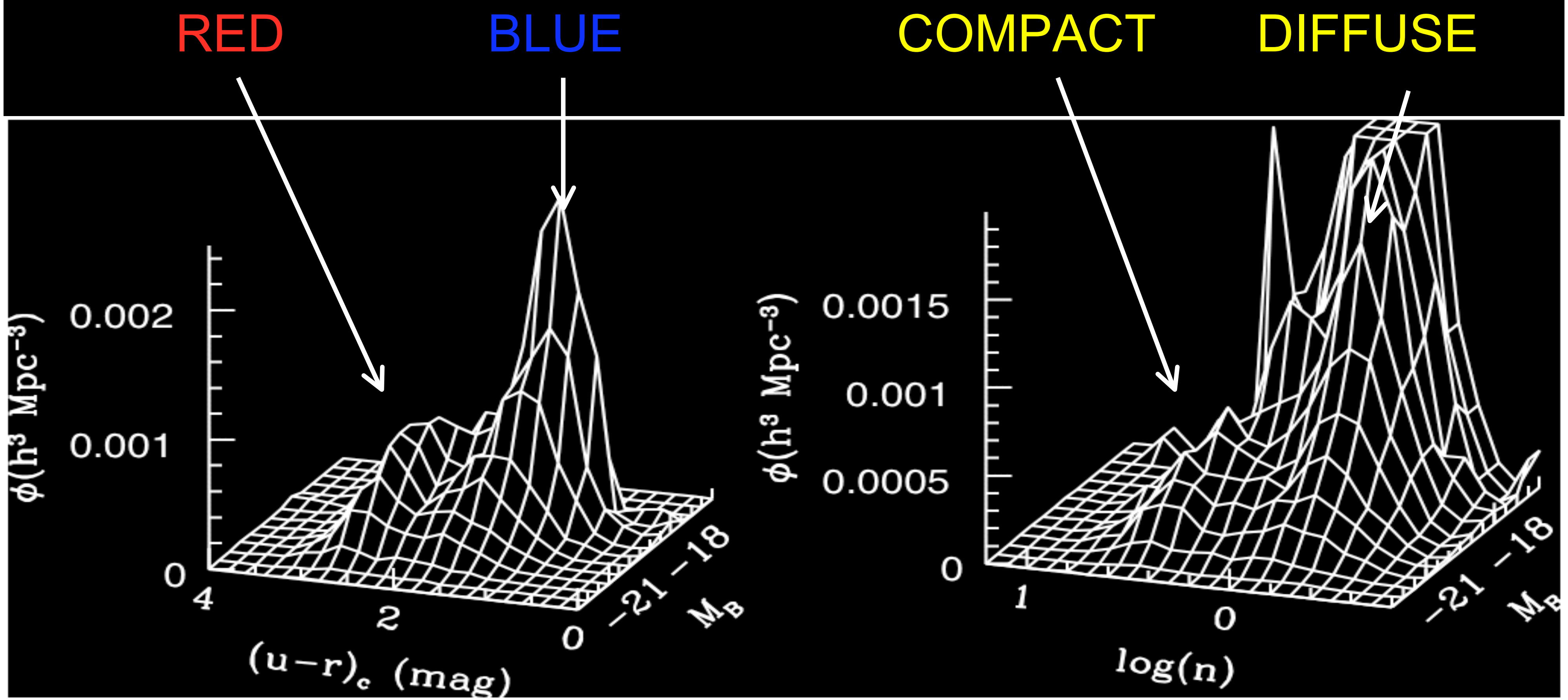
OBSERVED DISTRIBUTIONS ($M_B < -16$)



Galaxy Bimodality

Observe strong colour *(u-r)* and structural (log*n*) bimodalities (Strateva et al 2001; Baldry et al 2004; Driver et al 2006)

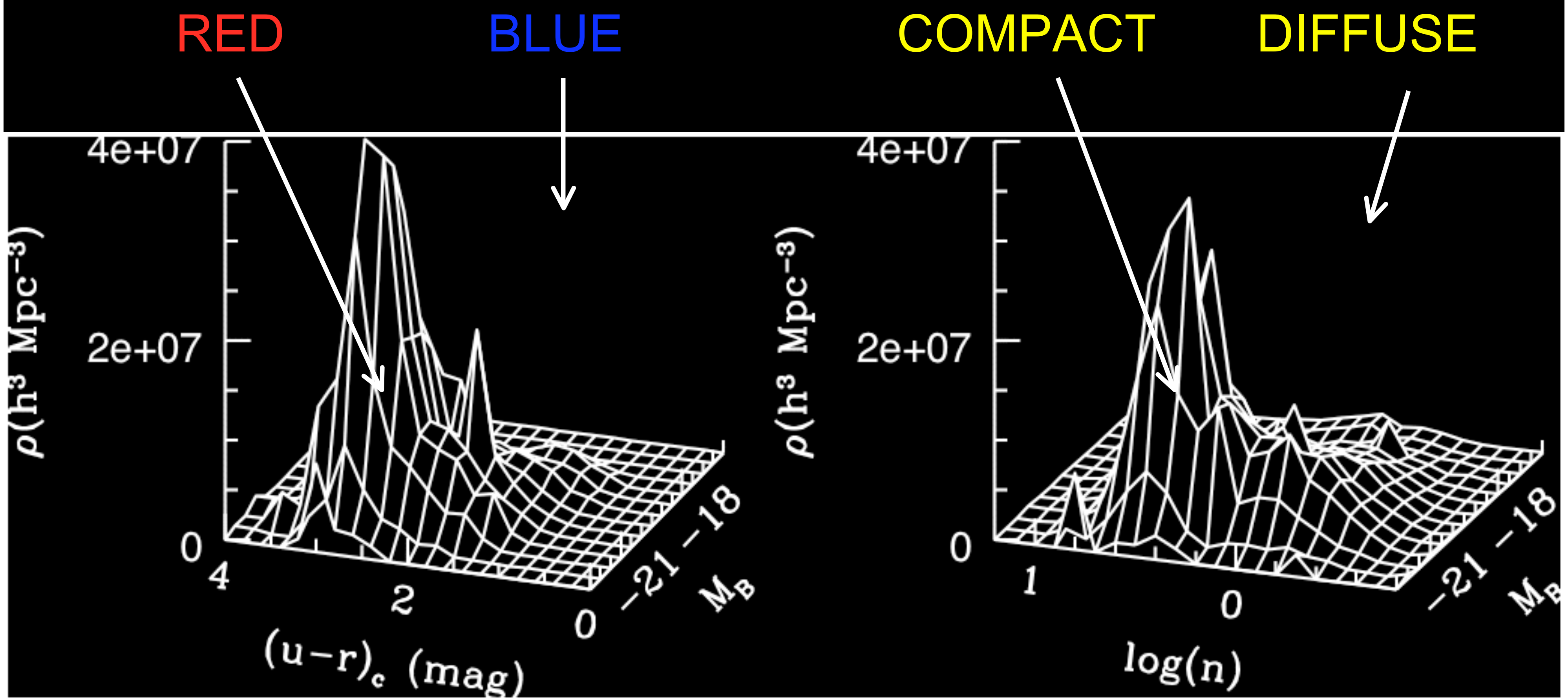
VOLUME CORRECTED (NUMBER DENSITY)



Galaxy Bimodality

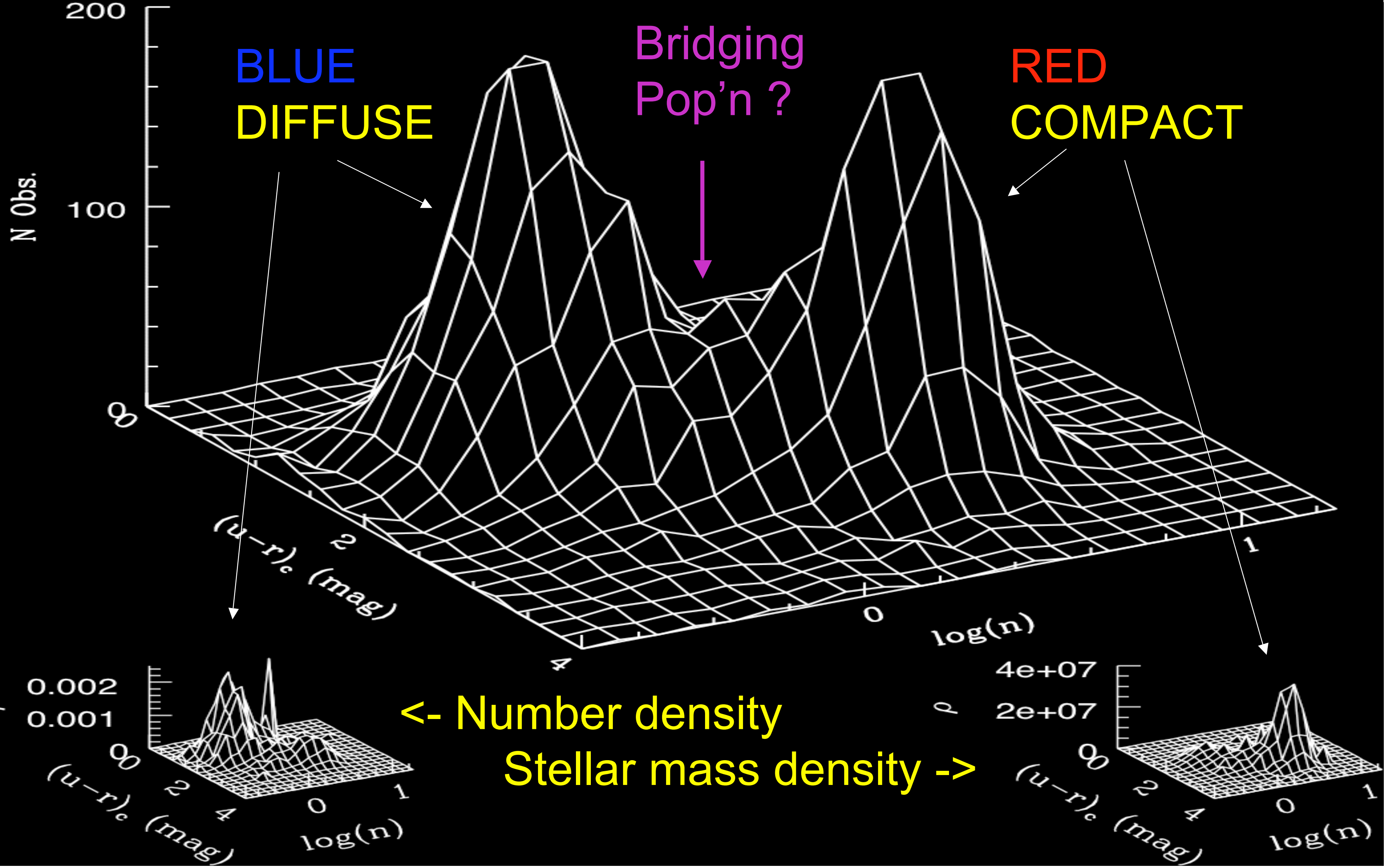
Observe strong colour *(u-r)* and structural (log*n*) bimodalities (Strateva et al 2001; Baldry et al 2004; Driver et al 2006)

VOLUME CORRECTED (MASS DENSITY)



Bimodality in (u-r)-log(n)

Driver et al, 2006, MNRAS, astro-ph/0602240



Two populations or two components ?

E/S0s

Bulge systen

El(Old)

Sabc

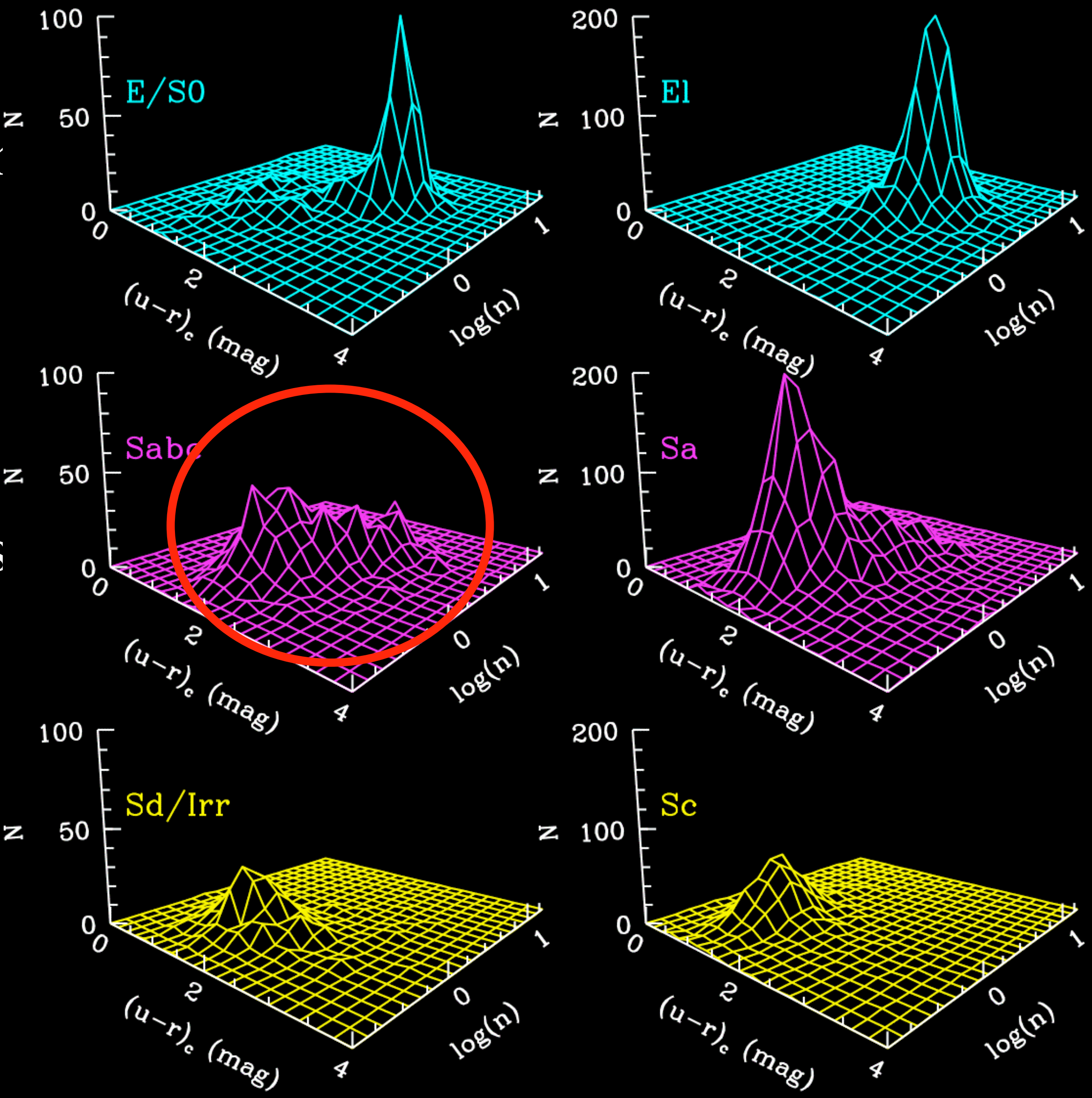
Bulge+Disks

Sa(Interm.)

Sd/Irr

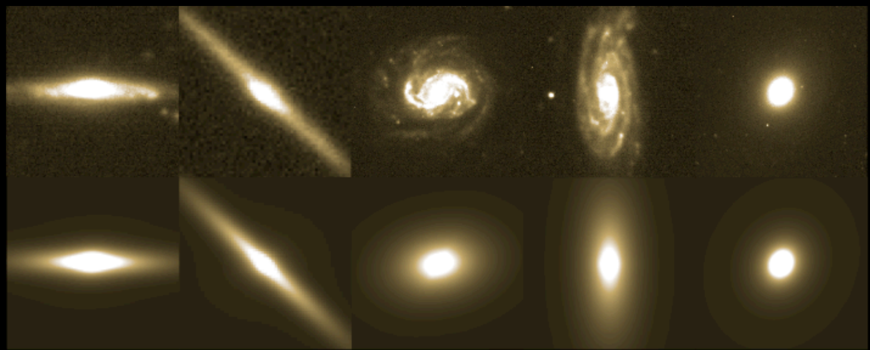
Disk systems

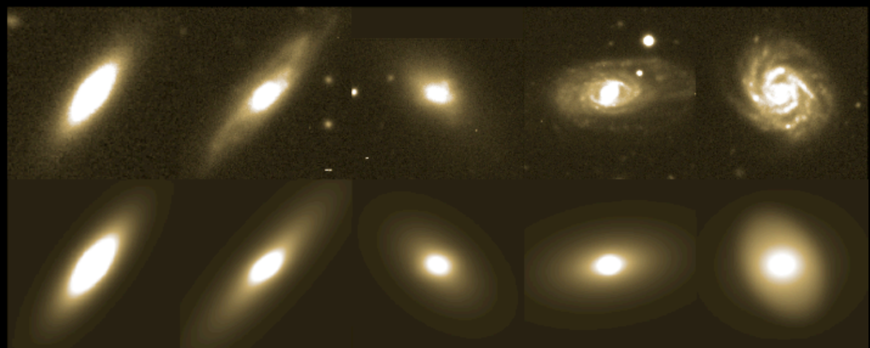
Sc(Young)

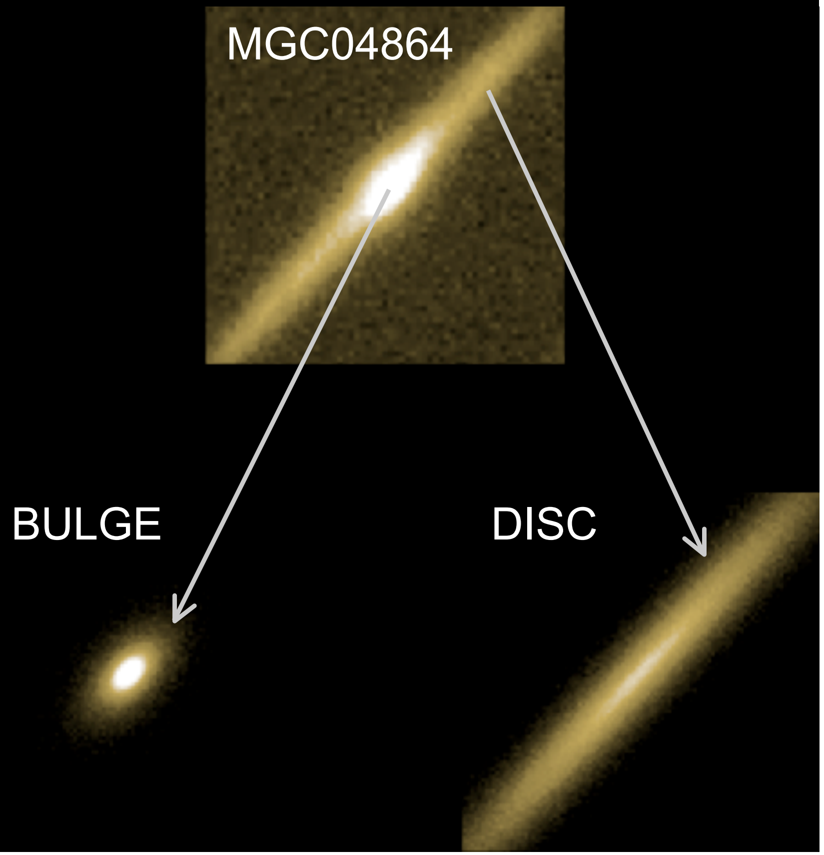


MGC bulge/disc decomposition

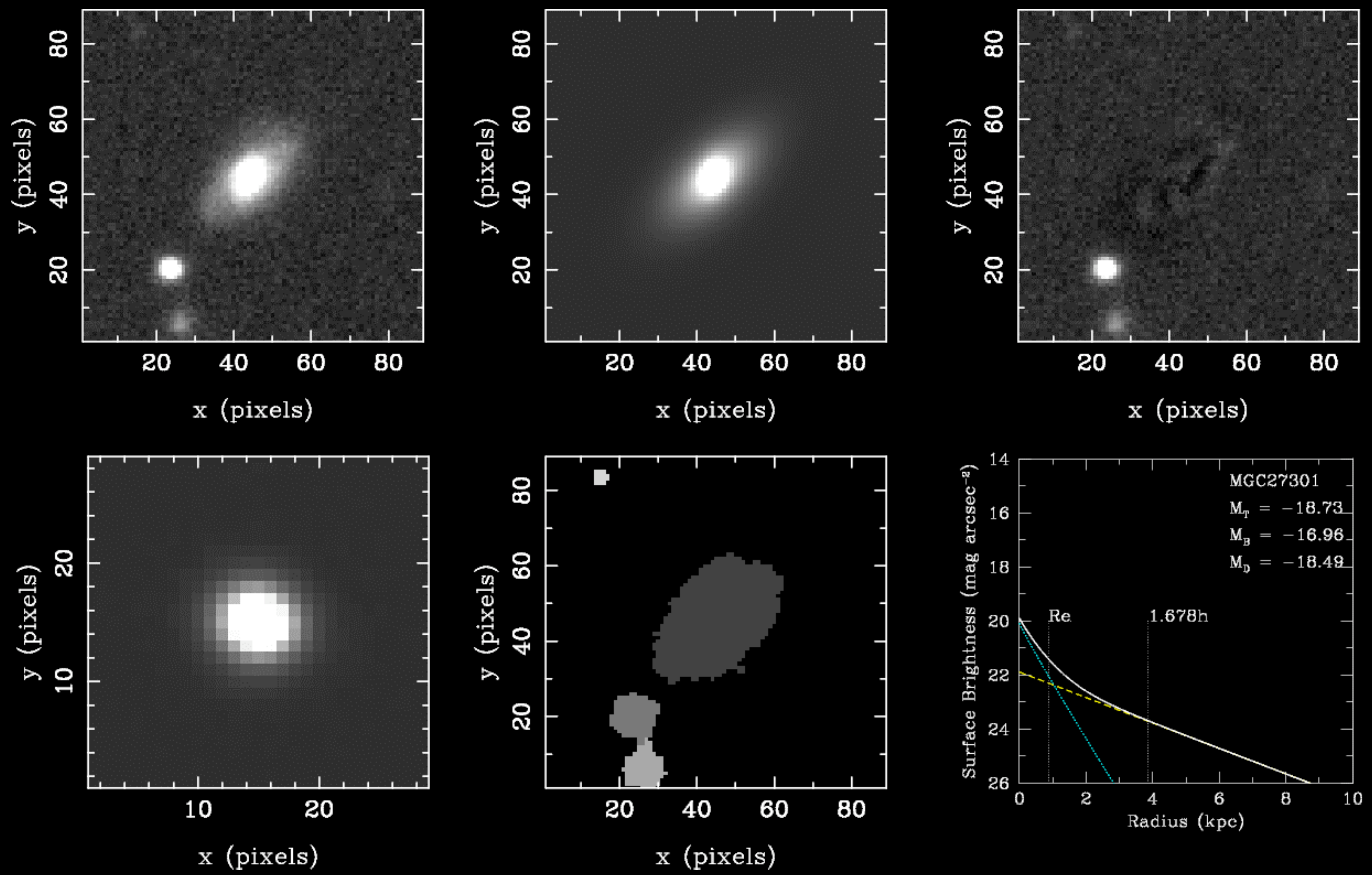
- Sersic+exponential profiles+PSF convolution via GIM2D, Simard et al (1998)
- 10,095 gals = largest available sample, Allen et al (2006)
- 96% redshift completeness (AAT/GEMINI) to B=20.0 mag, Driver et al (2005)
- B(INT) + ugriz(SDSS) + YJHK(UKIRT) imaging now 50% complete.
- All data available online: http://www.eso.org/~jliske/mgc/



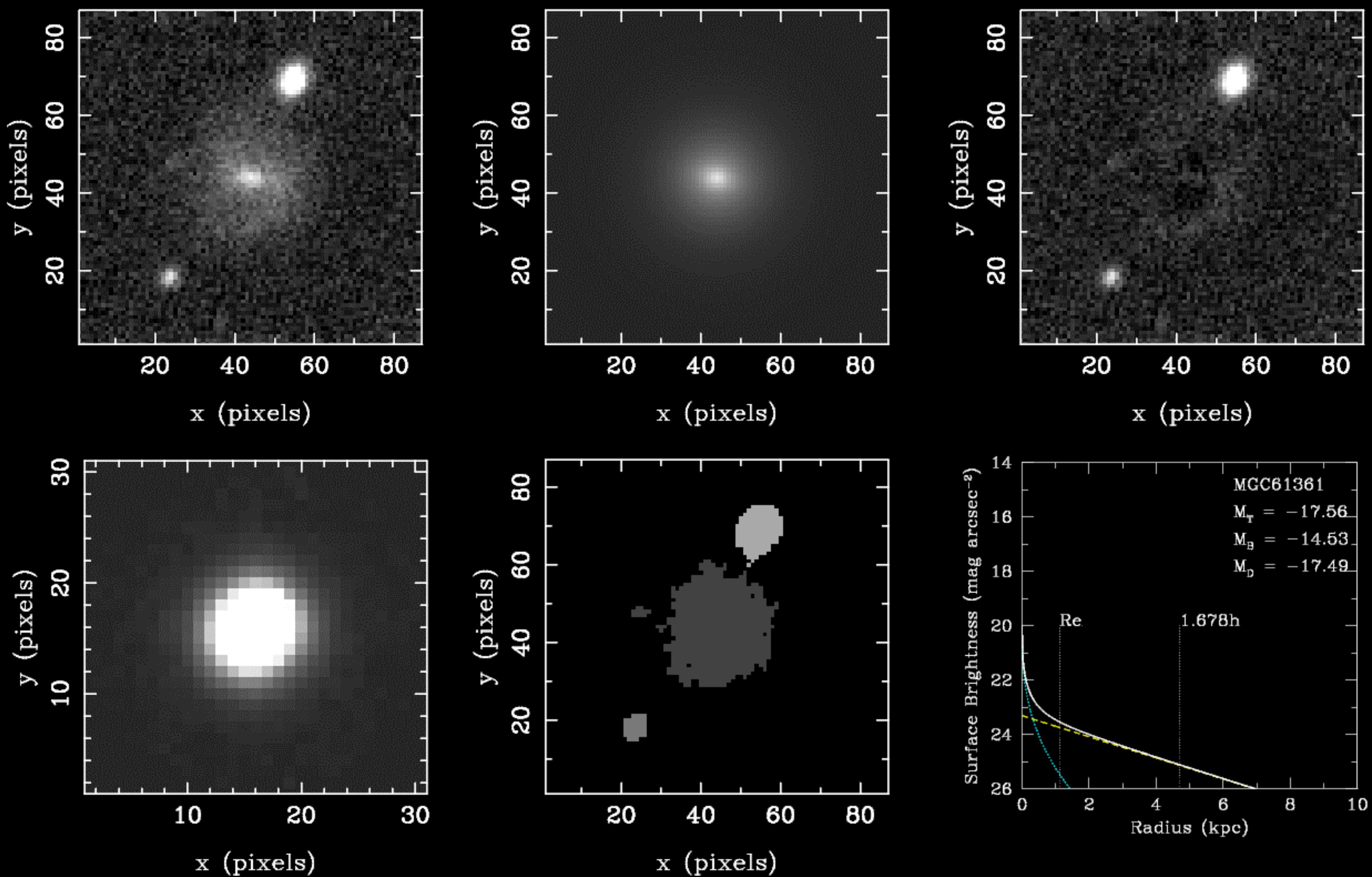




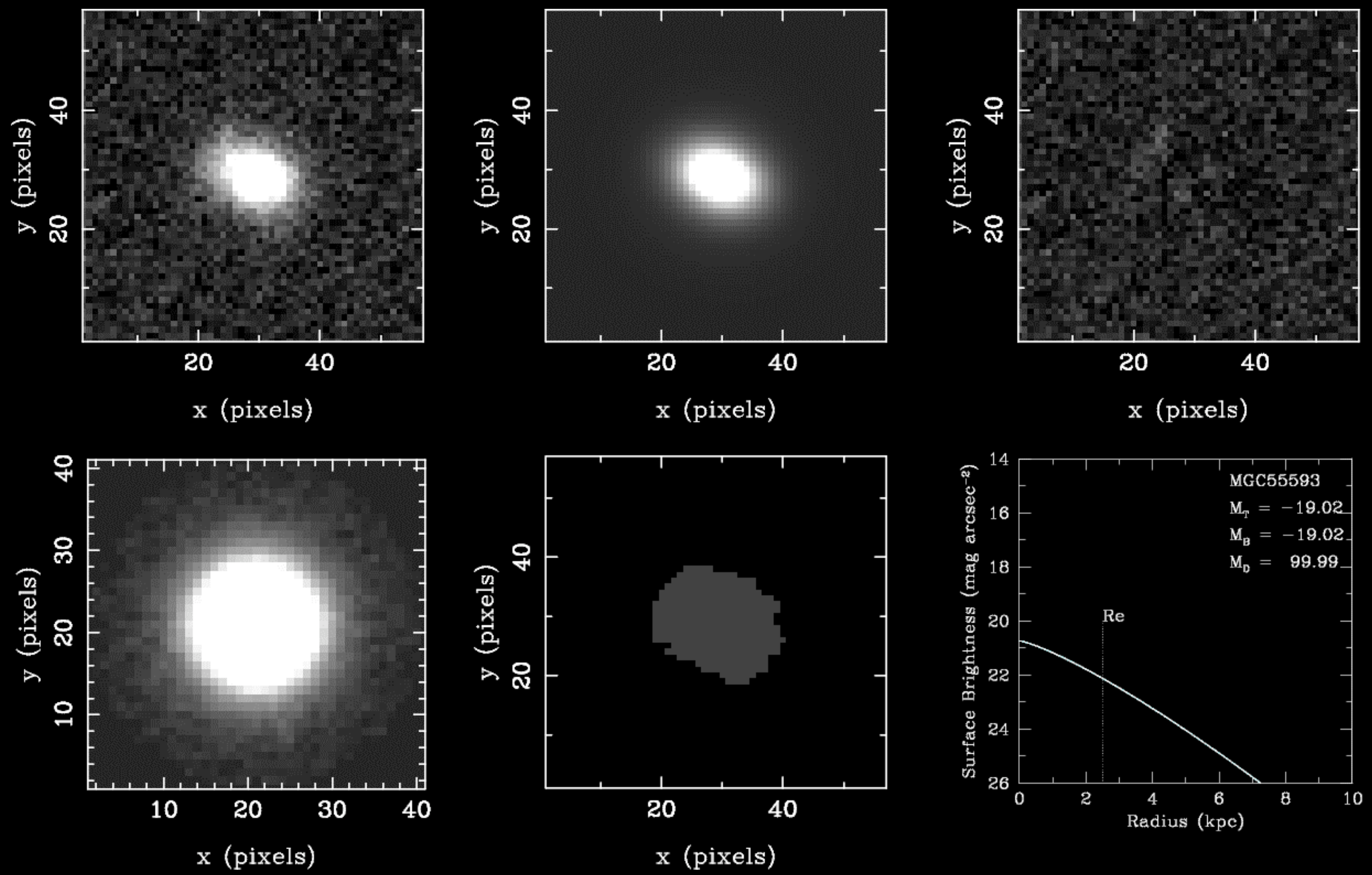
Example 1: MGC27301



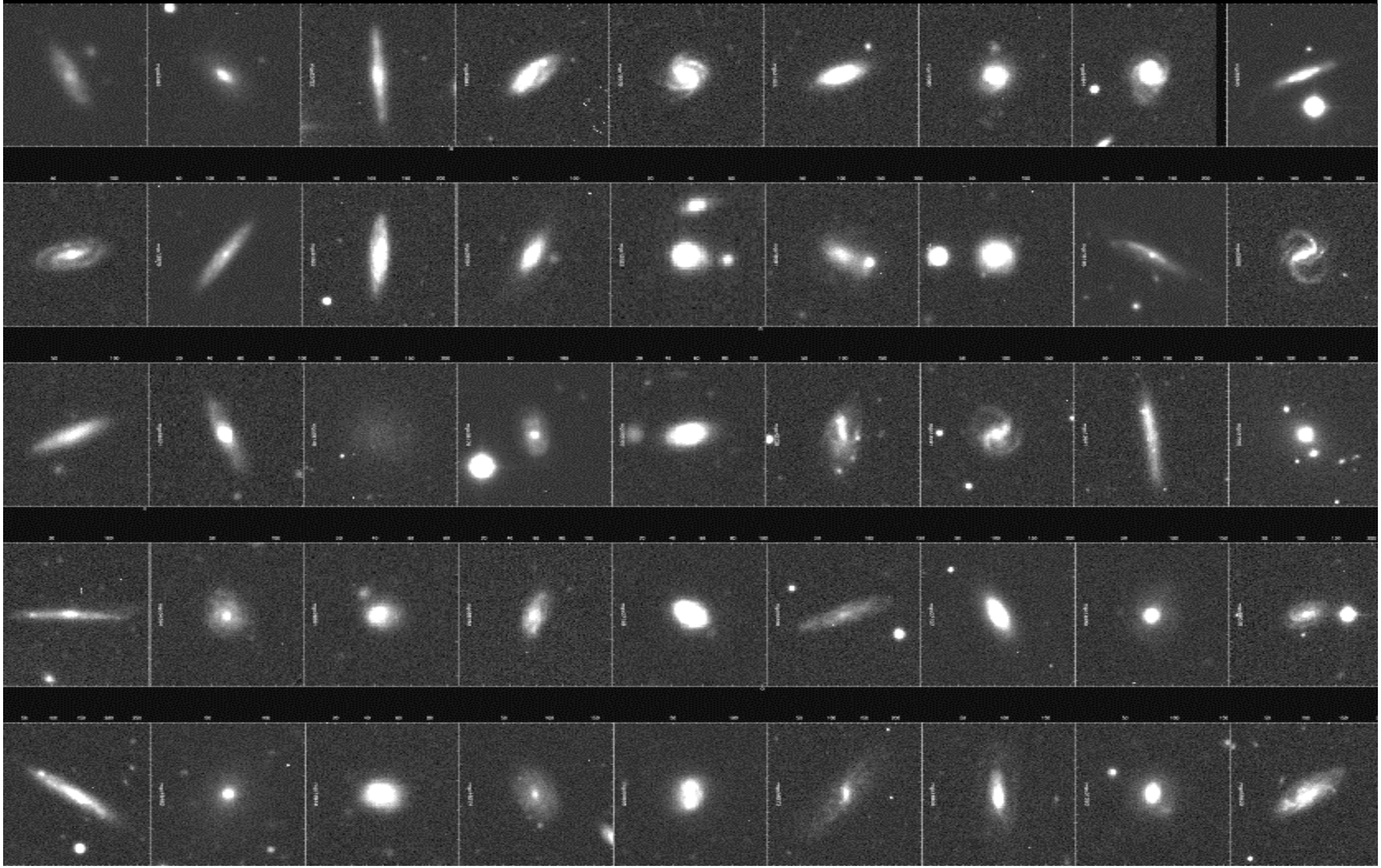
Example 2: MGC61361



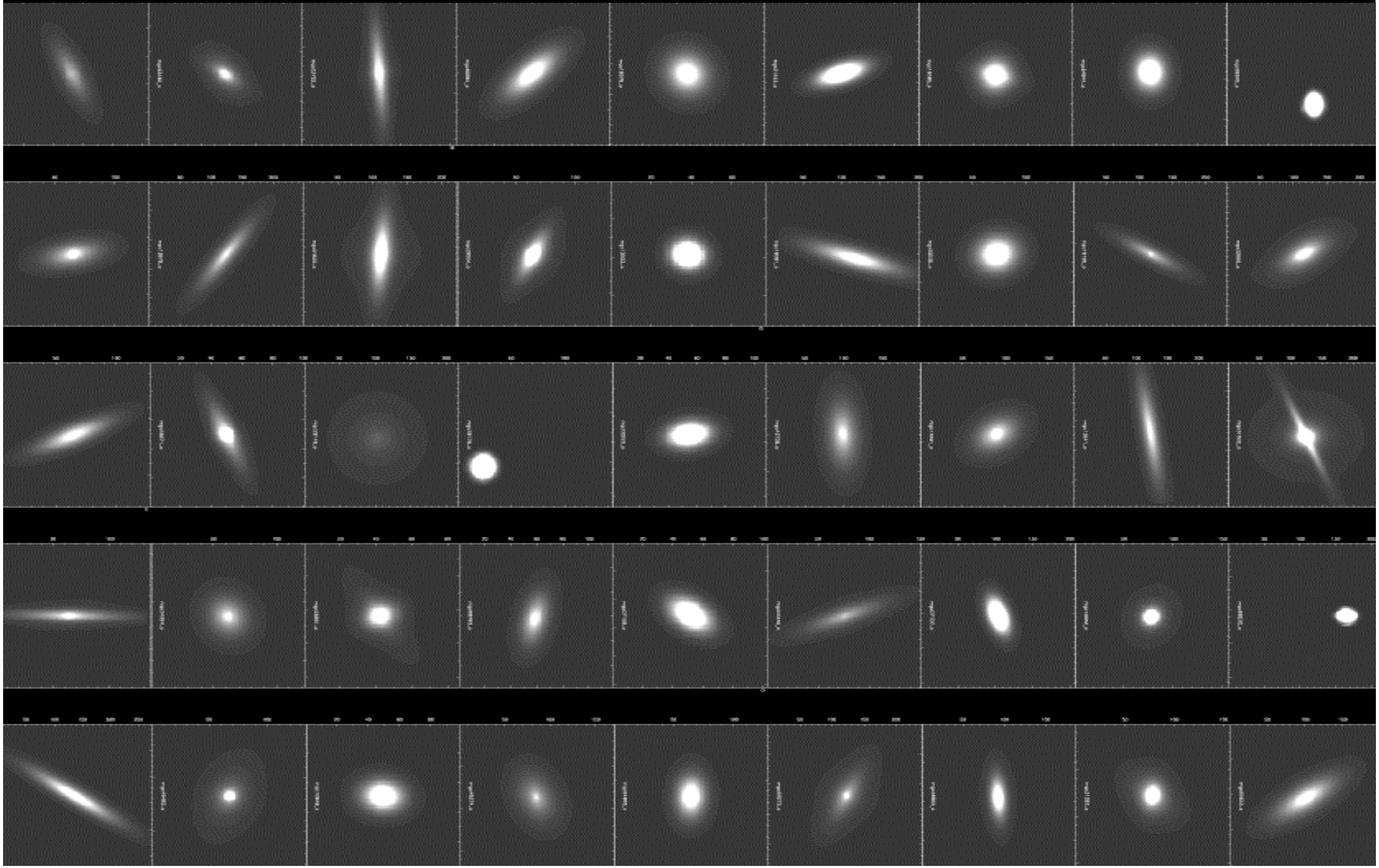
Example 3: MGC55593



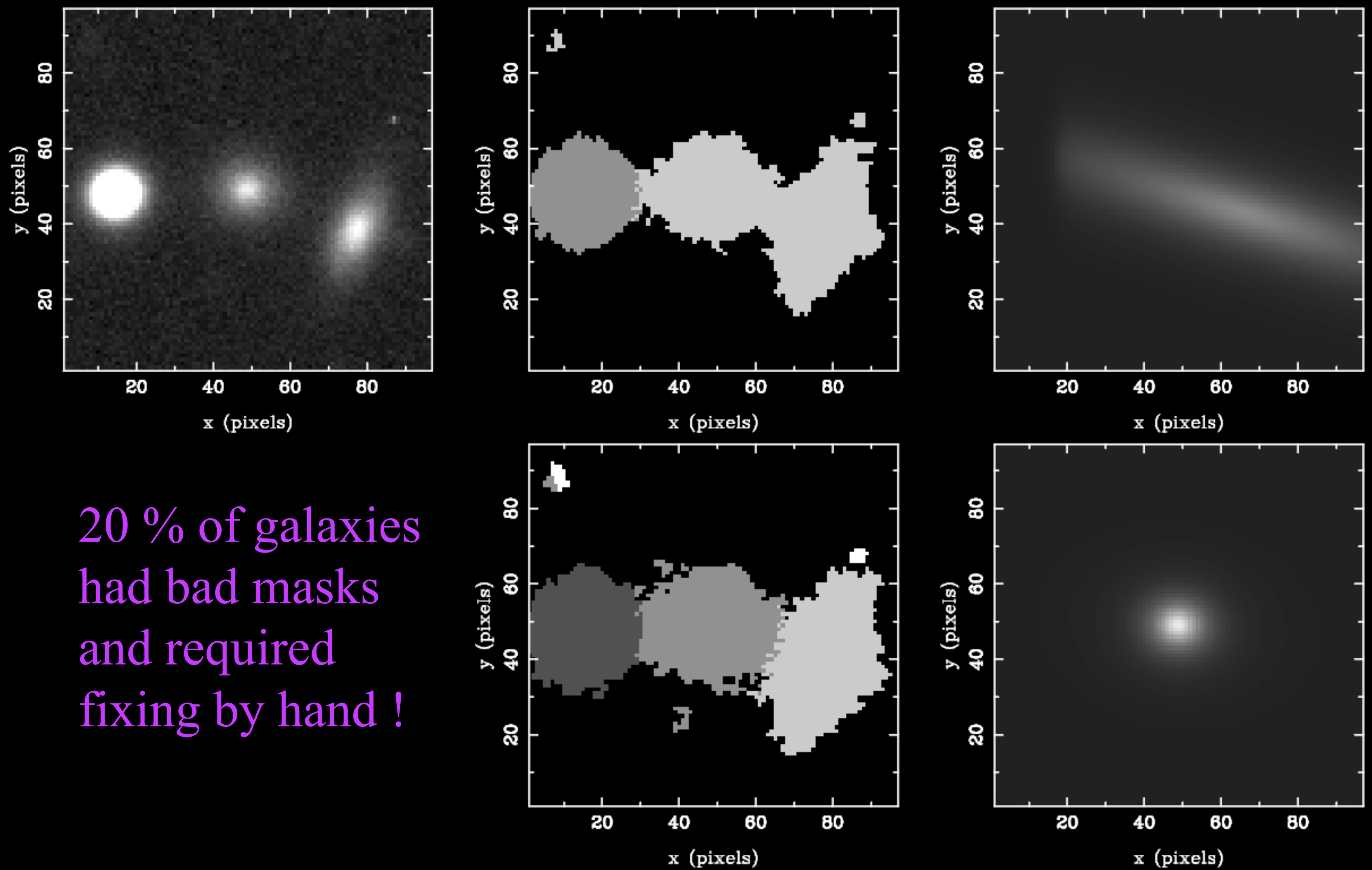
MGC: Bulge Disk Decomposition, originals



MGC: Bulge Disk Decomposition, models

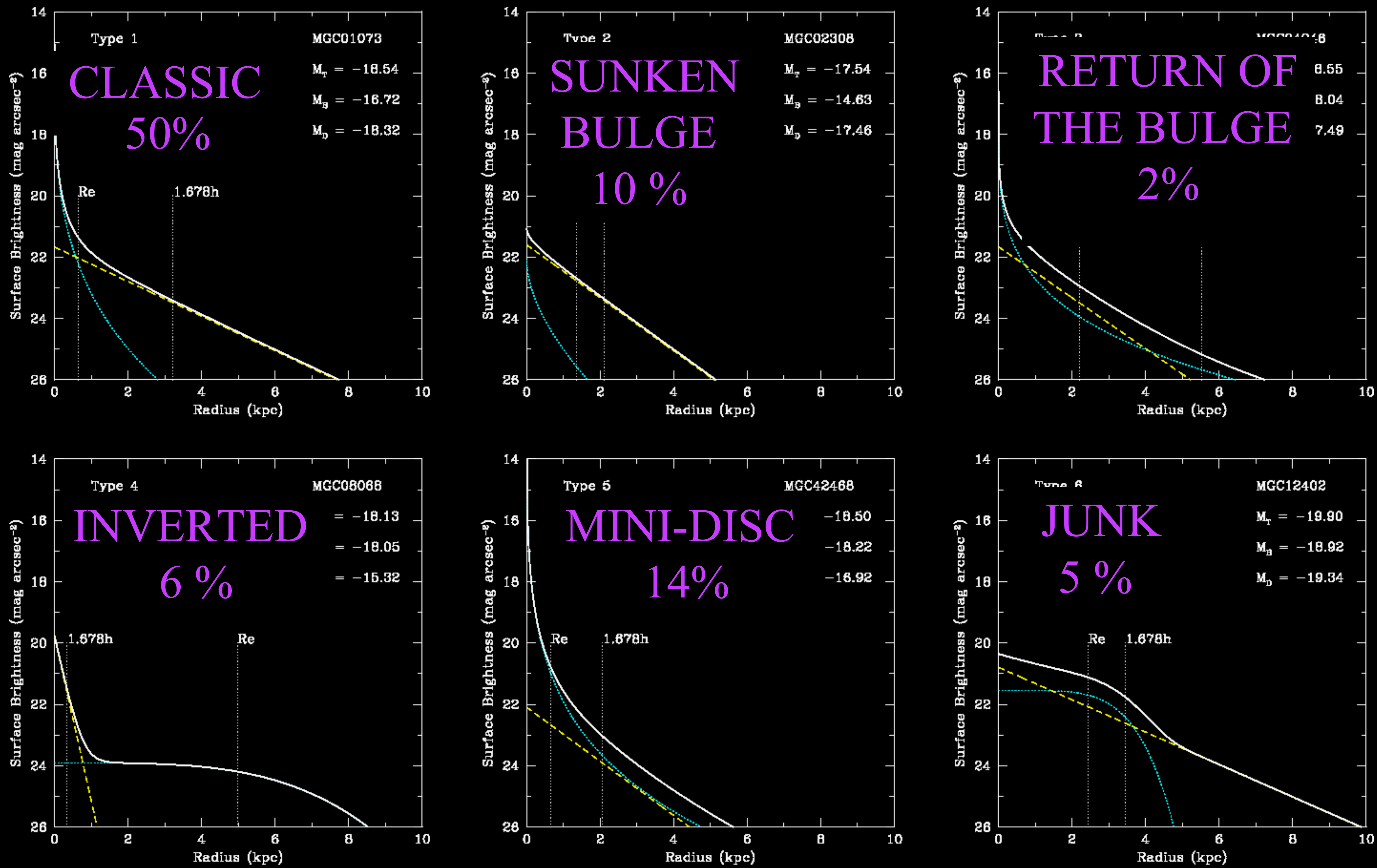


Example: Bad mask



20 % of galaxies had bad masks and required fixing by hand !

Identify 8 profile types.



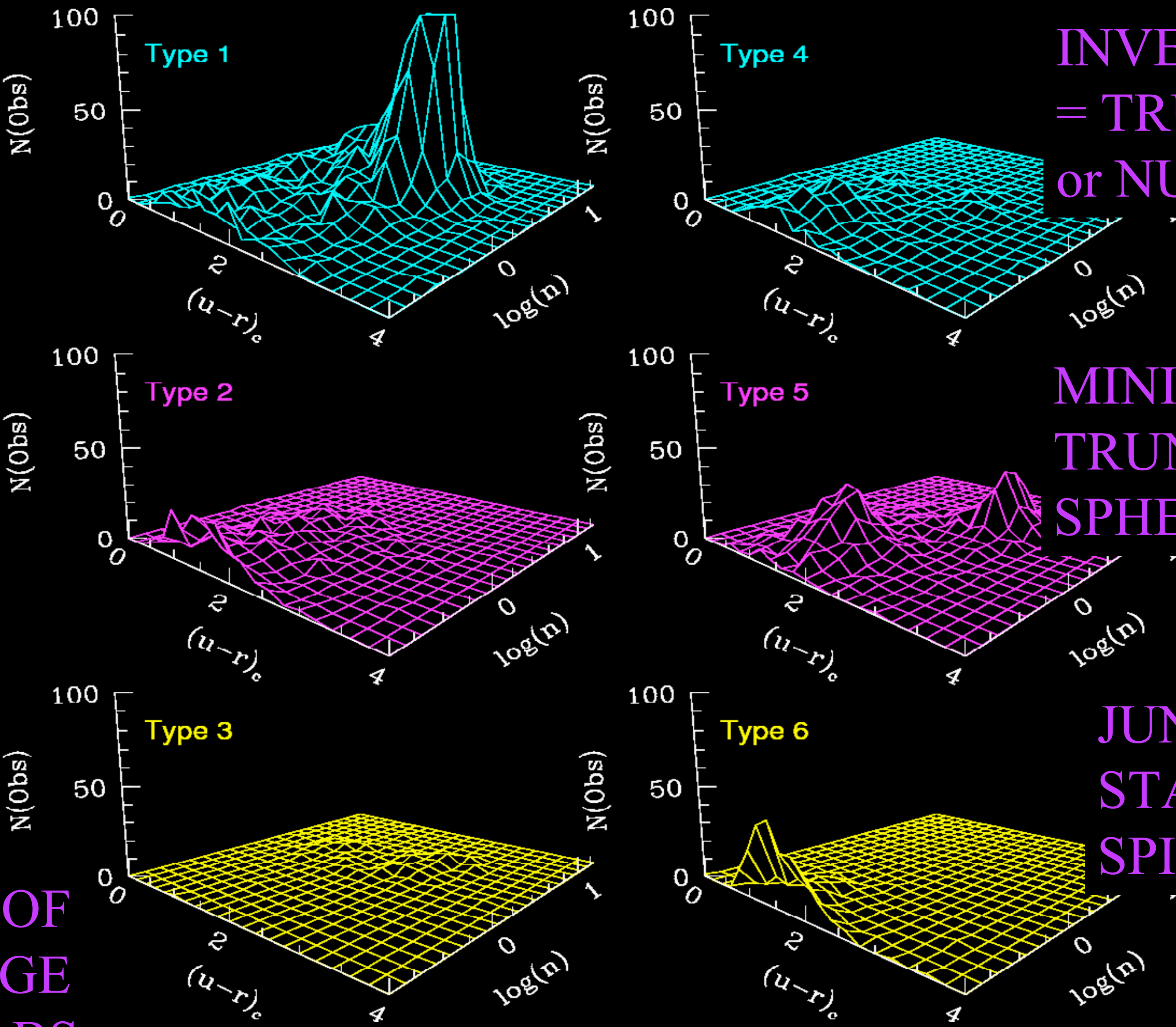
Types 7 & 8: 13 % Sersic only fits

Bulge distribution in (u-r)-n

CLASSIC = OK

SUNKEN BULGE = pBULGE or BARS

RETURN OF THE BULGE = E/S0s & BSs

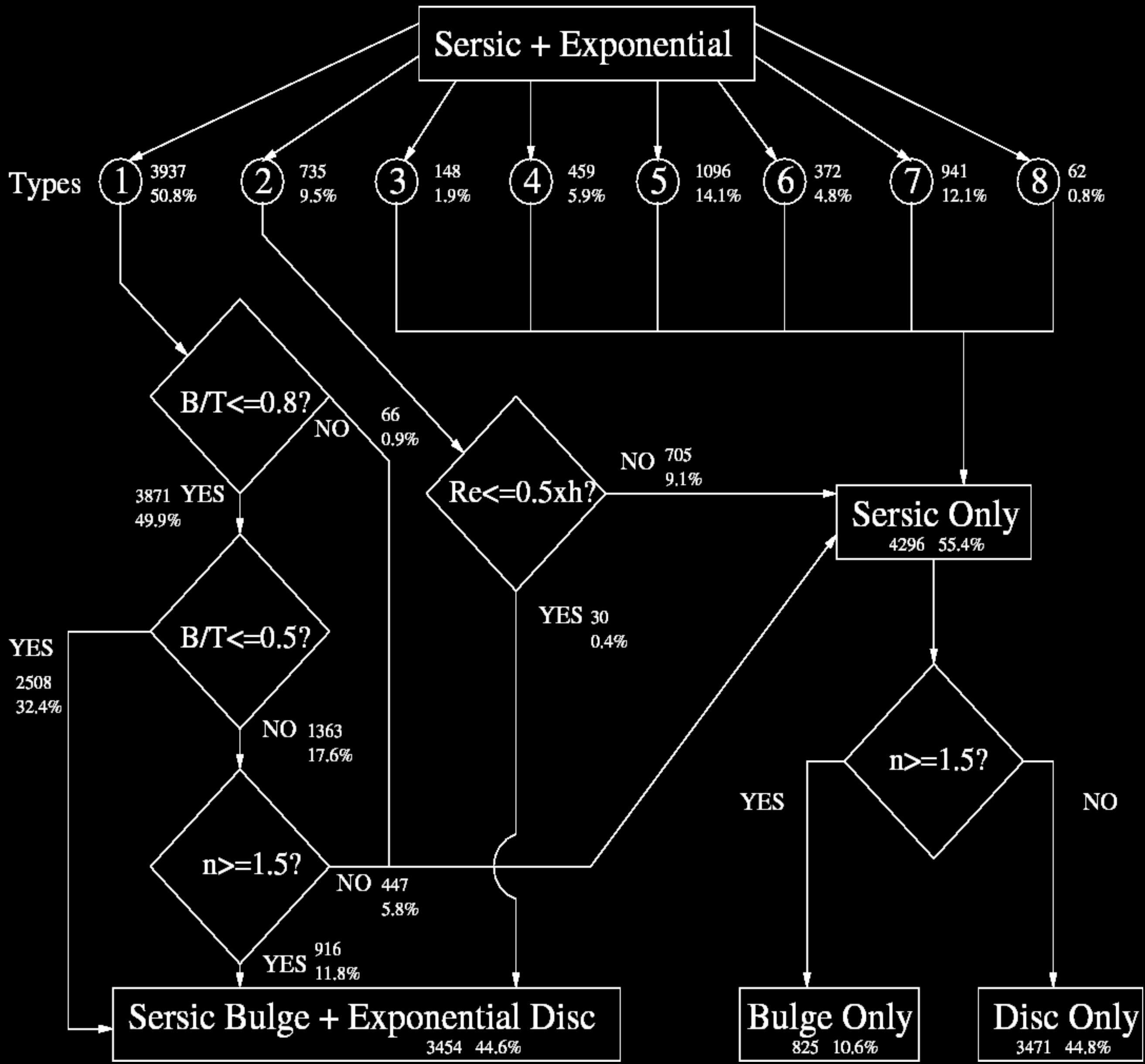


INVERTED = TRUNCATED or NUCLEATED

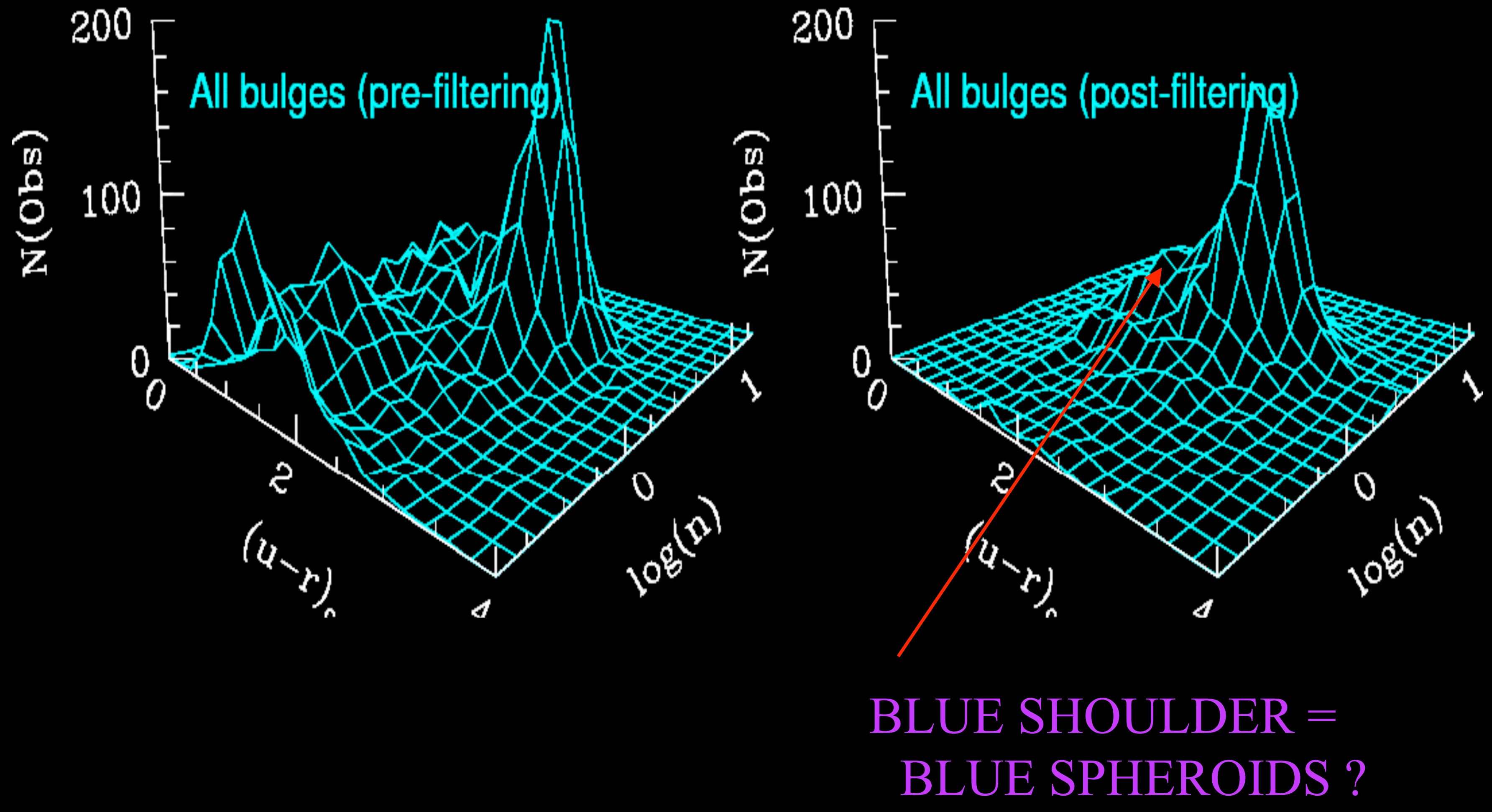
MINI-DISC = TRUNCATED or SPHEROIDAL

JUNK = STARBURSTS SPIRAL ARMS

The Logic Filter !

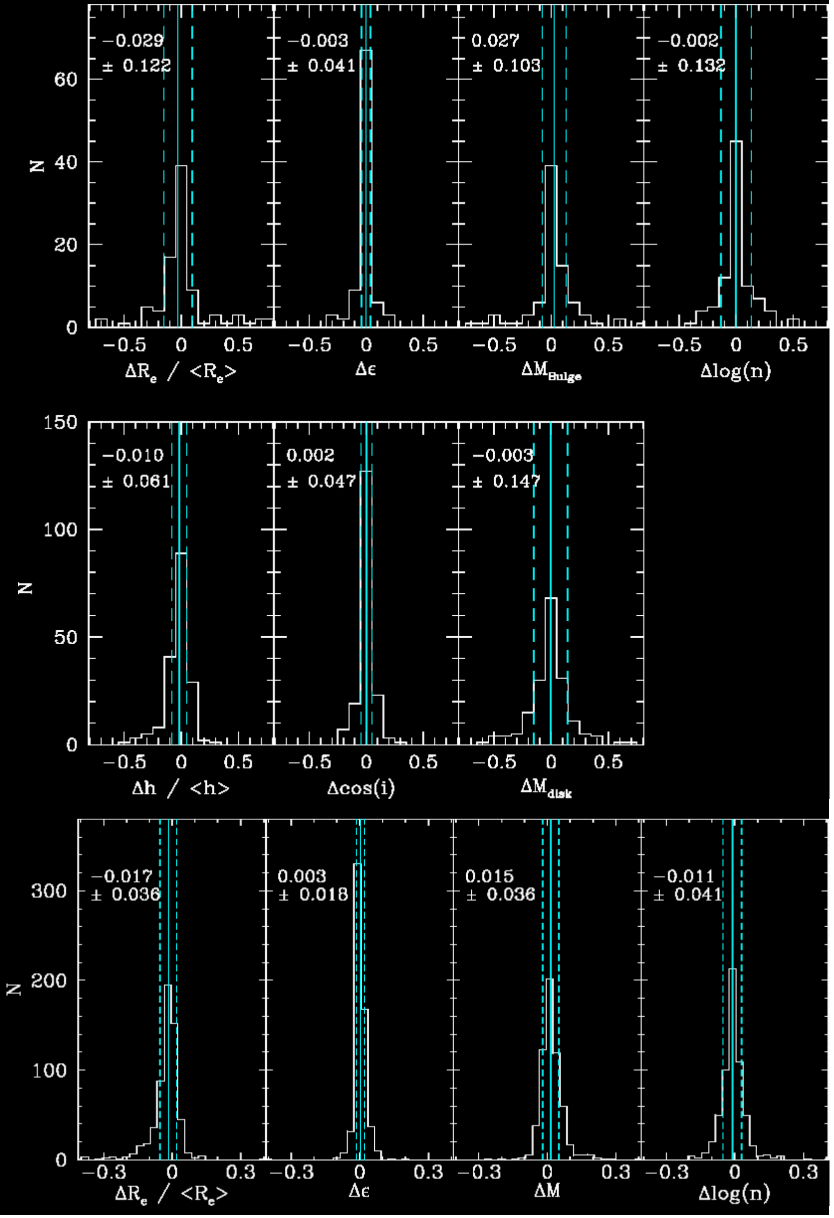


Pre and post filtered bulge dist'n



Sanity check via repeat obs.

- From 700 repeat obsevations we can test the structural reliability after logical filtering.
- For final catalogue we find:
  - +/- 0.103 mag
  - +/- 0.132 in log(n)
  - +/- 0.047 in cos(I)
  - +/- 0.122 in R(HLR)
- For Sersic only cat we find:
  - +/- 0.036 mag
  - +/- 0.041 in log(n)
  - +/- 0.036 in R(HLR)



Two populations or two components ?

E/S0s

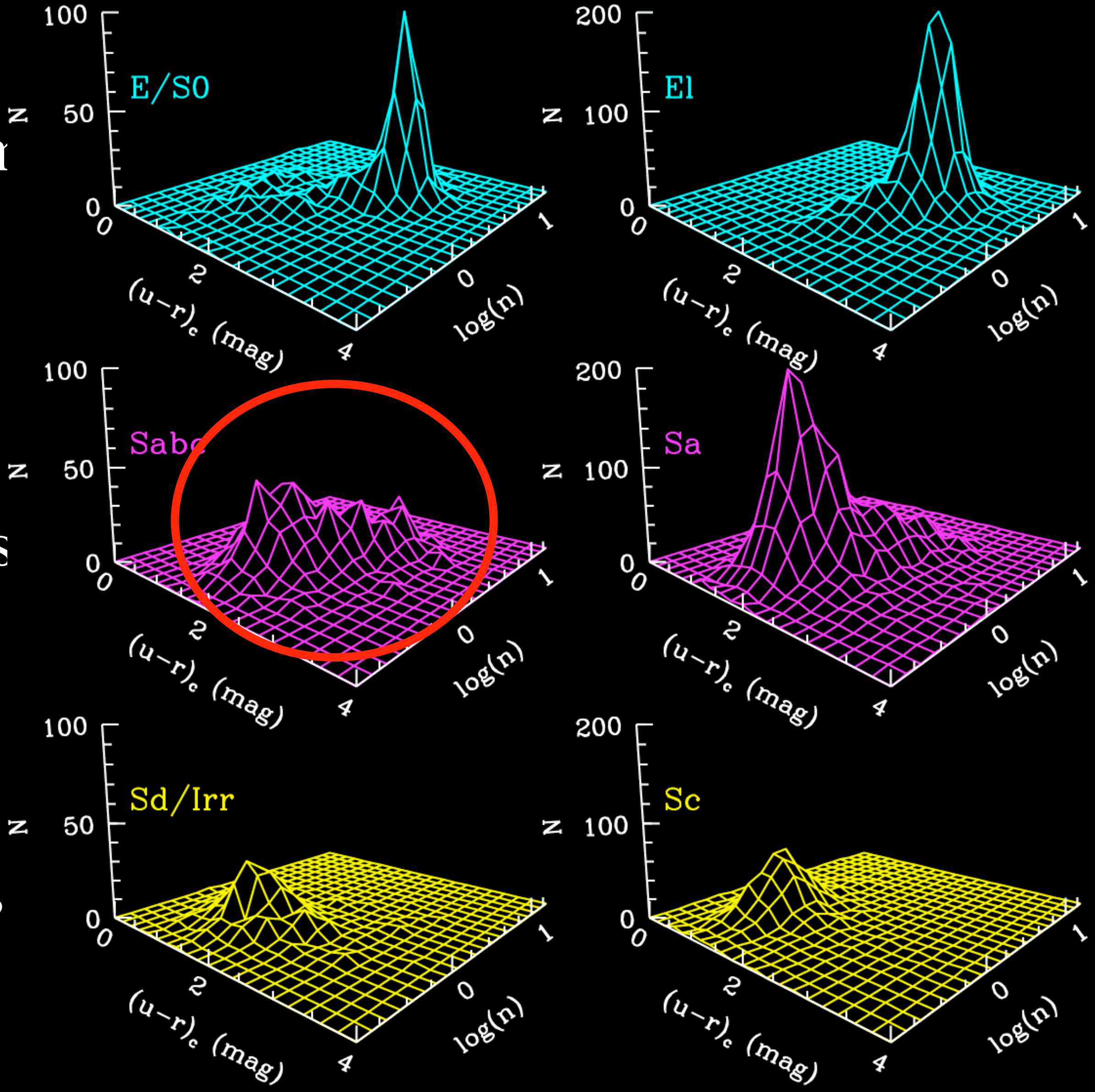
Bulge systen

Sabc

Bulge+Disks

Sd/Irr

Disk systems



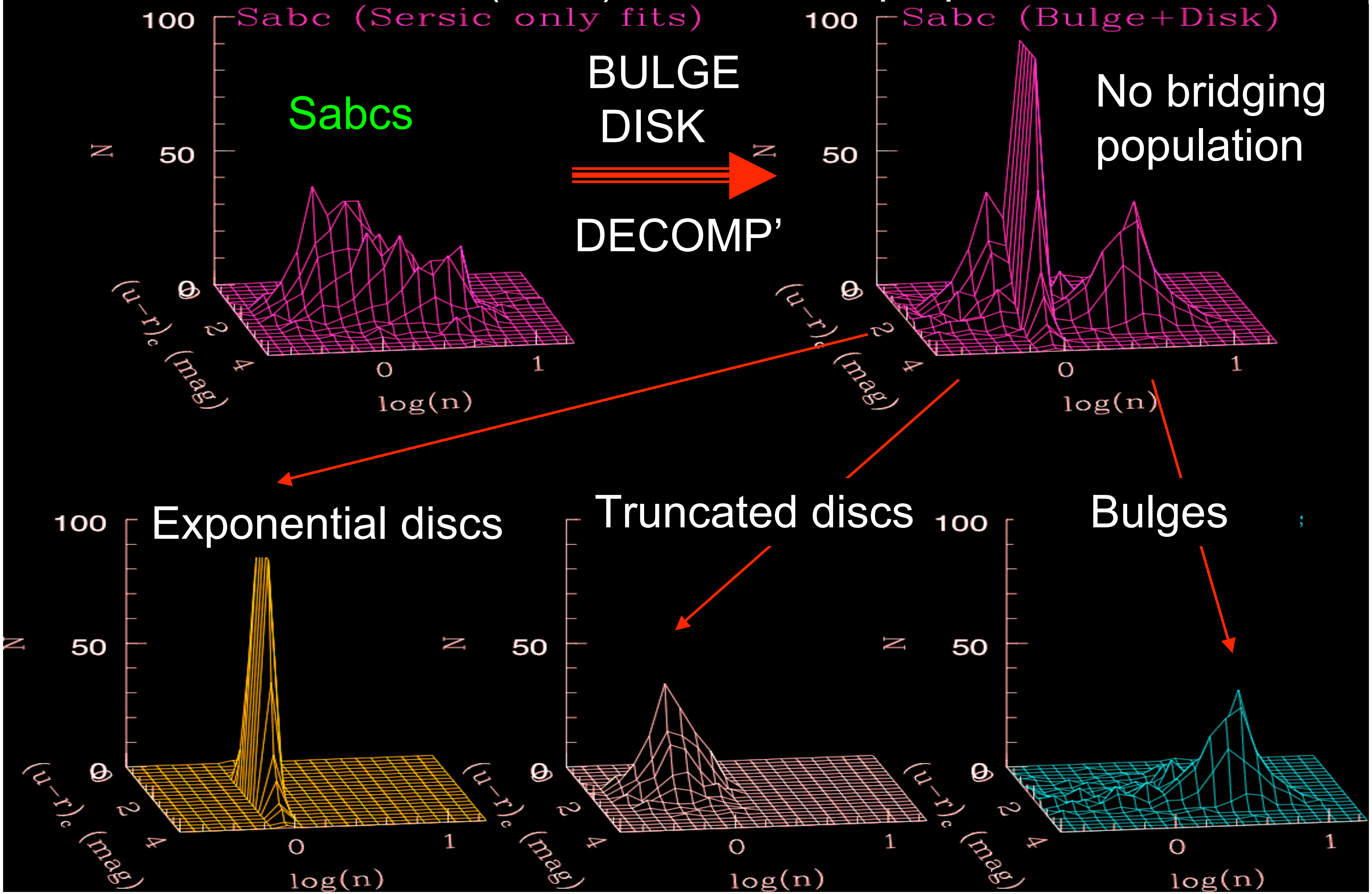
El(Old)

Sa(Interm.)

Sc(Young)

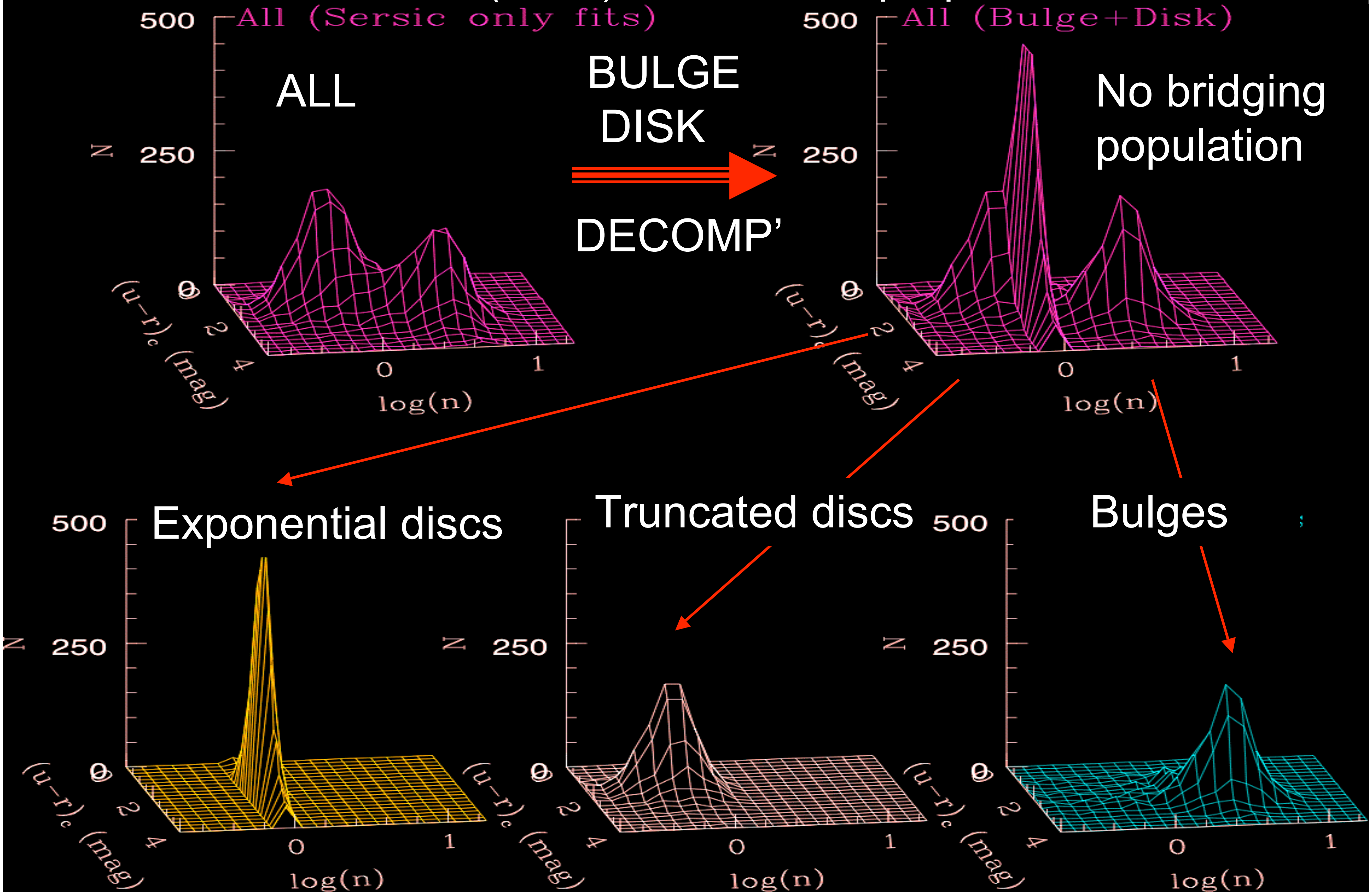
Two populations or two components ?

Driver et al (2006), MNRAS, in preparation

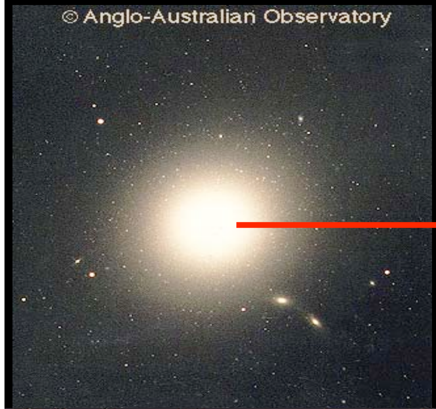


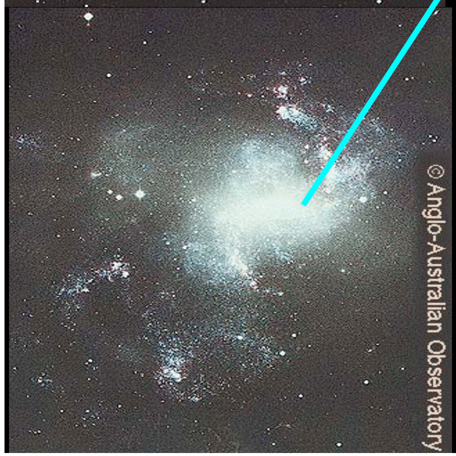
Two populations or two components ?

Driver et al (2006), MNRAS, in preparation



Galaxy types v components ?



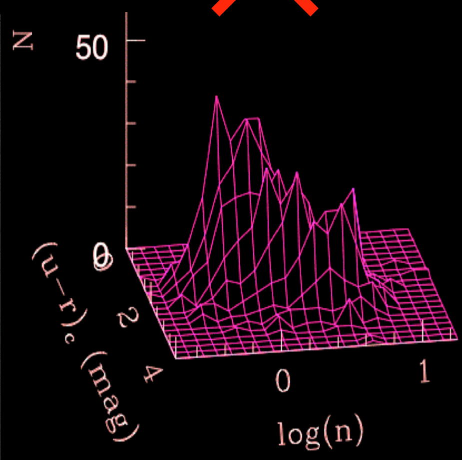


(z > 0.1)

E/S0s(red)

Sabc
(red&blue)

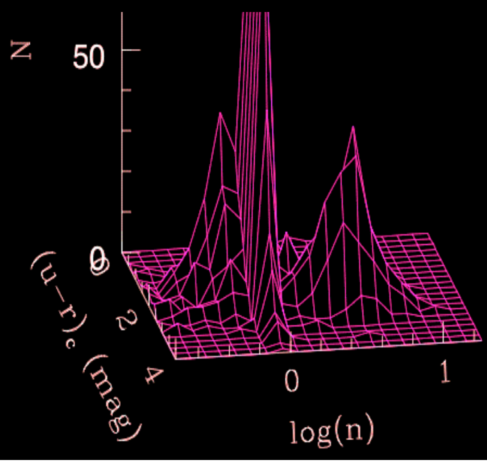
Sd/Irrs(blue)

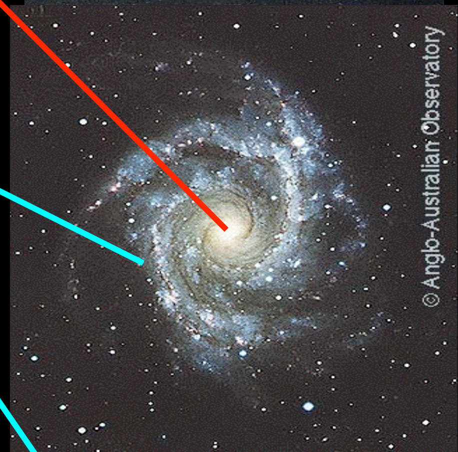


(z < 0.1)

Spheroids
& Bulges

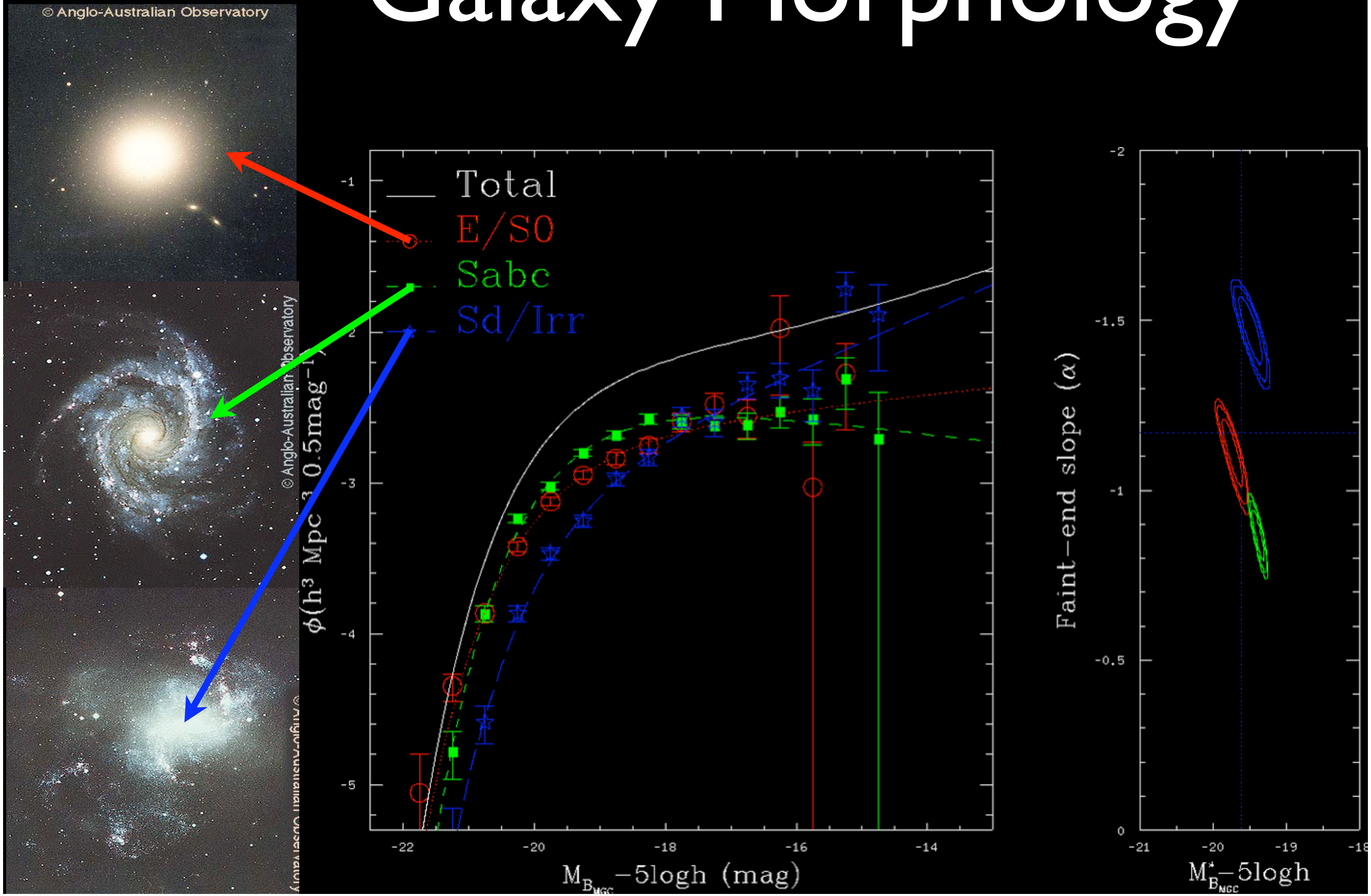
Discs



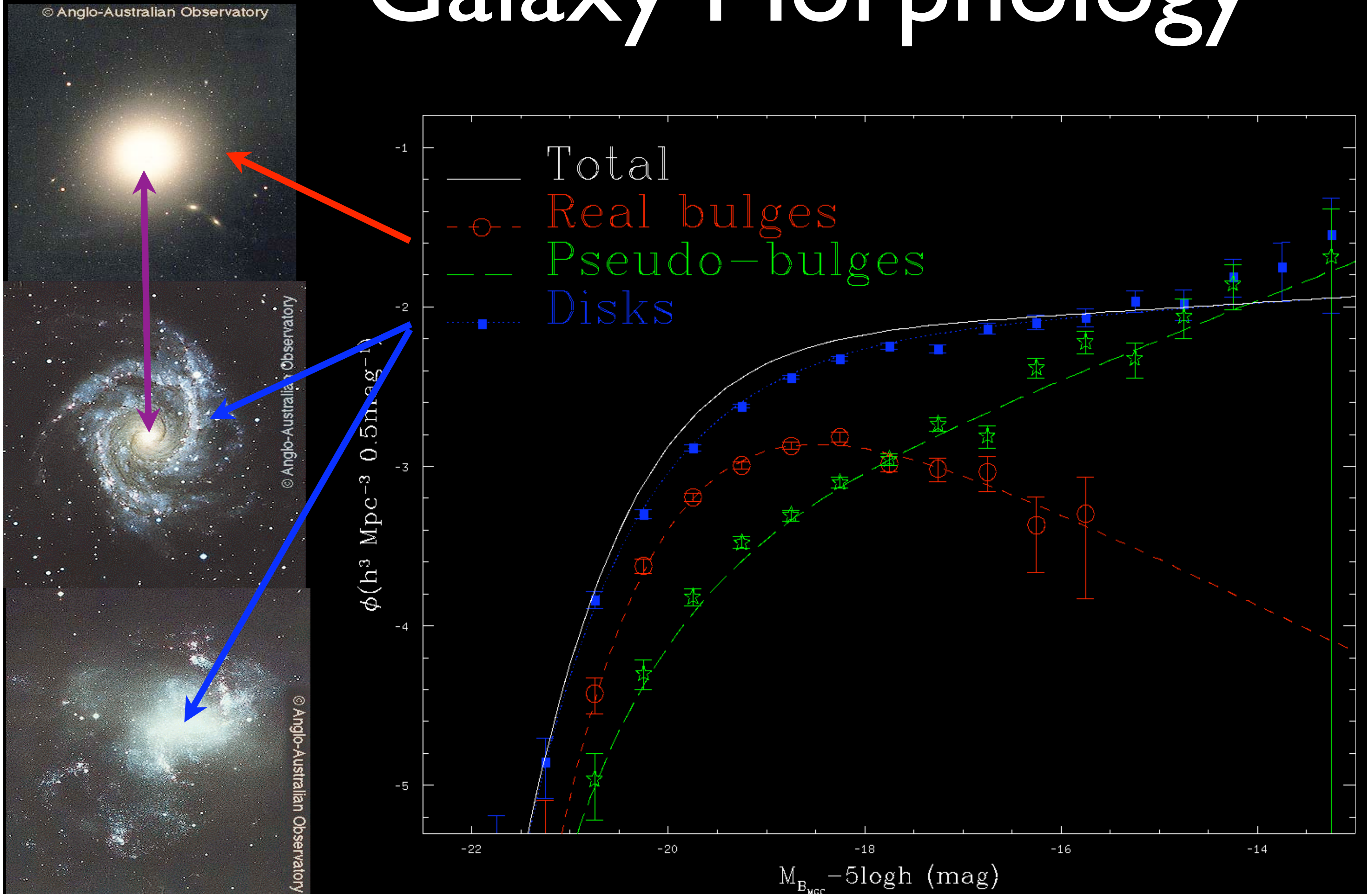


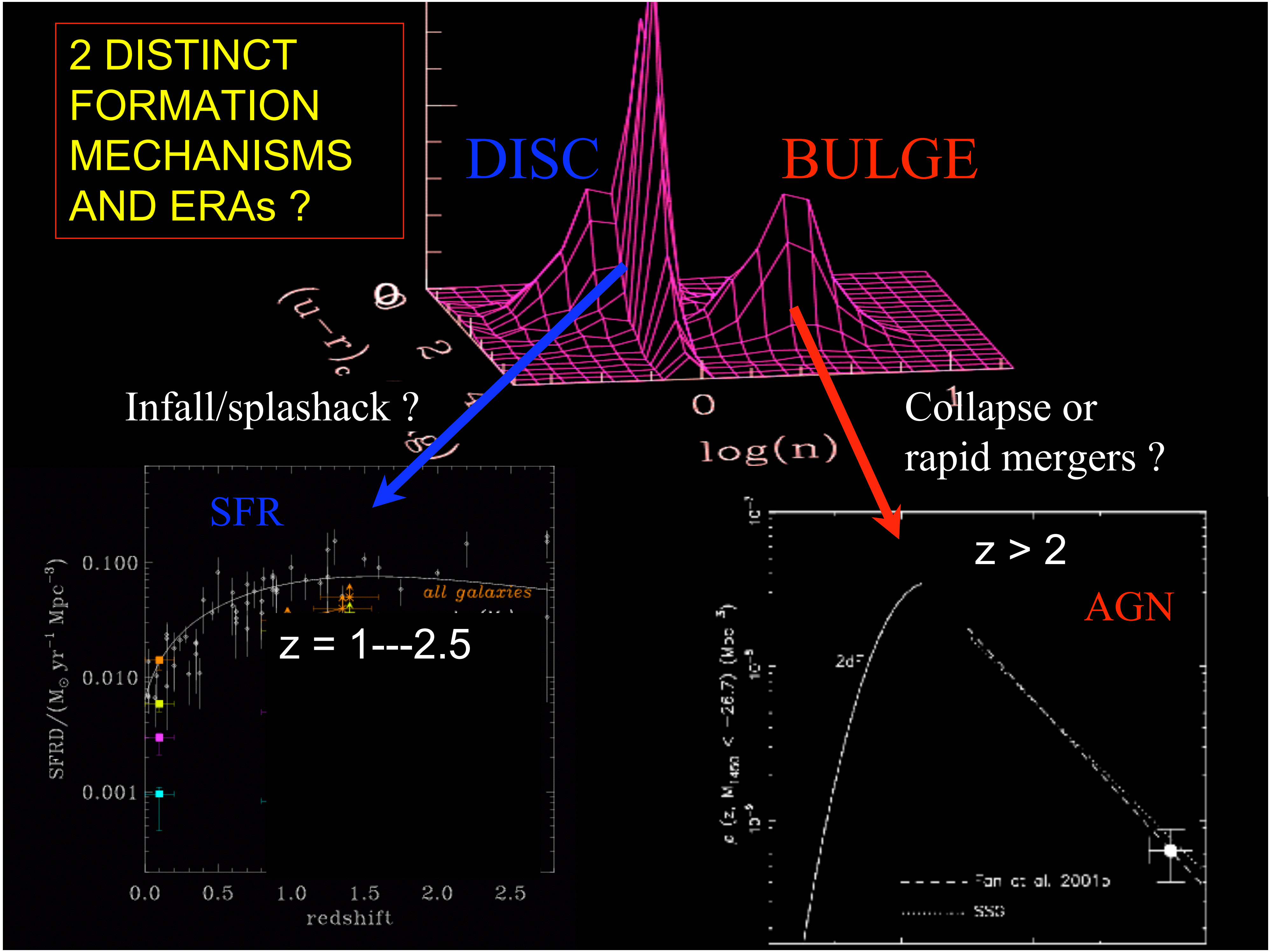
Galaxy Morphology

Text



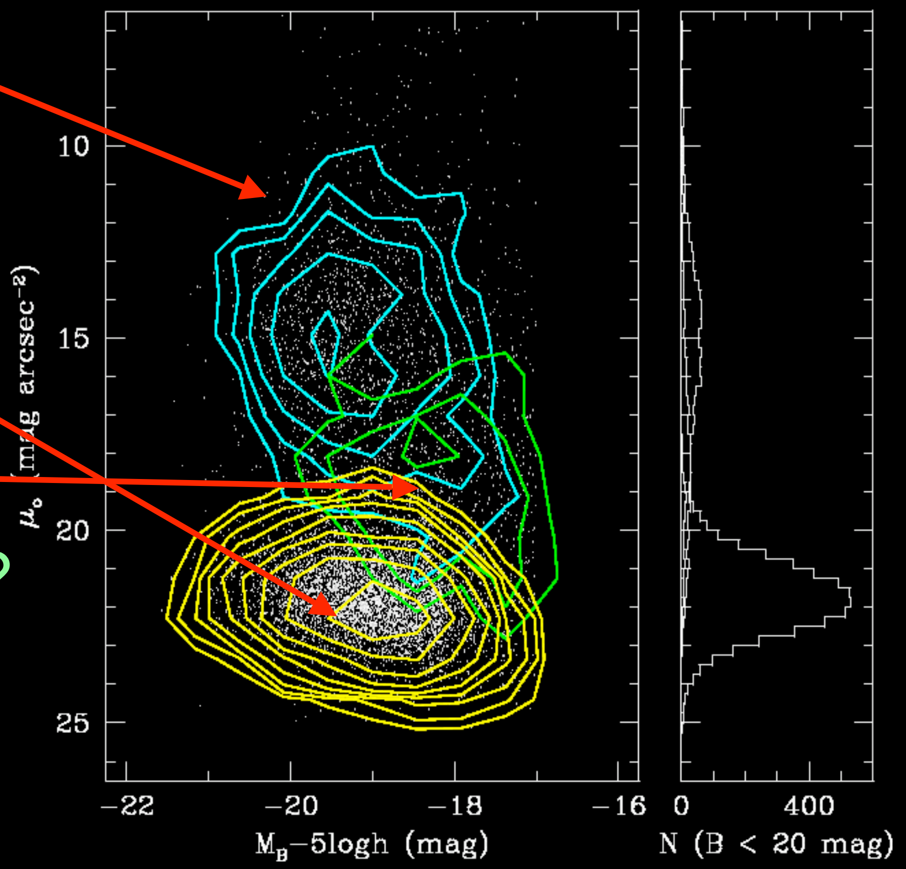
Galaxy Morphology




2 DISTINCT FORMATION MECHANISMS AND ERAs ?
DISC
BULGE
(u−r)c
log(n)
Infall/splashack ?
Collapse or rapid mergers ?
SFR
all galaxies
z = 1---2.5
SFRD/(M⊙ yr⁻¹ Mpc⁻³)
0.100
0.010
0.001
0.0
0.5
1.0
1.5
2.0
2.5
redshift
z > 2
AGN
Fan et al. 2001b
SSG

4 distinct structural types

- Classical Bulges
- Discs
  - Exponential discs
  - Truncated discs
- Pseudo-bulges
  - Real or failed discs ?
- Blue Spheroids
  - Real or resolution ?



Galaxy formation/evolution

- Global formation/evolutionary processes:
  - Monolithic collapse (ELS1962) ---> Bulges, SMBHs, AGN ?
  - Satellite accretion (Searle & Zinn 1972) --> Halo growth
  - Hierarchical merging (Fall & Efstathiou 1985) --> Disk growth
  - Major mergers (Toomre 1977) --> Spheriods
  - Secular (Kormendy & Kennicutt 2004) --> Pseudo-bulges

+INFALL

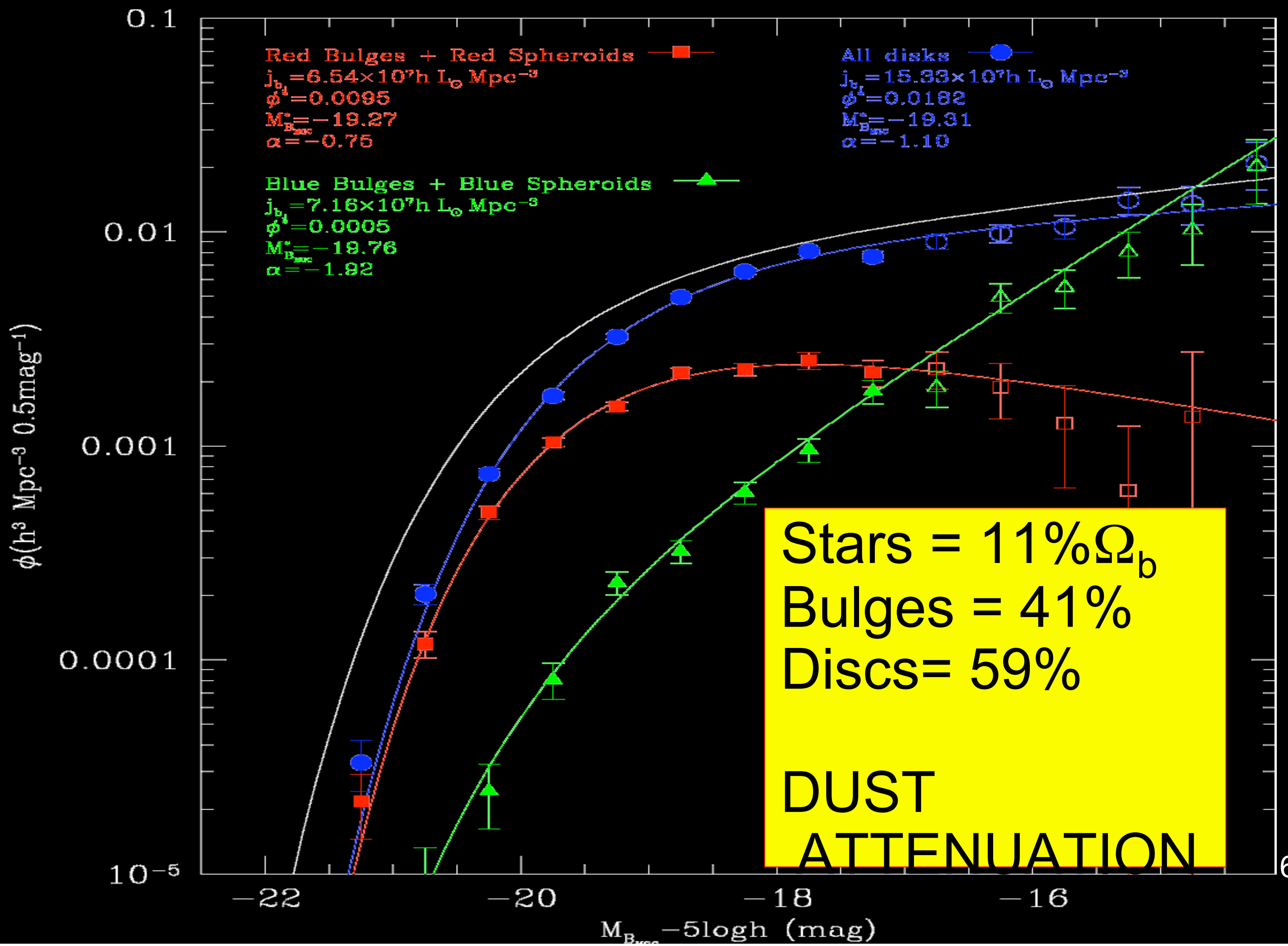
Text

- Environmentally dependent evolutionary processes:
  - Stretching (Barnes & Hernquist 1992)
  - Harassment (Moore et al 1998)
  - Stripping (Gunn & Gott 1972)
  - Strangulation (Balogh & Morris 2002)
  - Squelching (Tully et al 2002)
  - Threshing (Bekki et al 2001)
  - Splashback (Fukugita & Peebles 2005)
  - Cannibalism (Ostriker & Hausman 1977)

DWARFS !

The Component Luminosity Functions

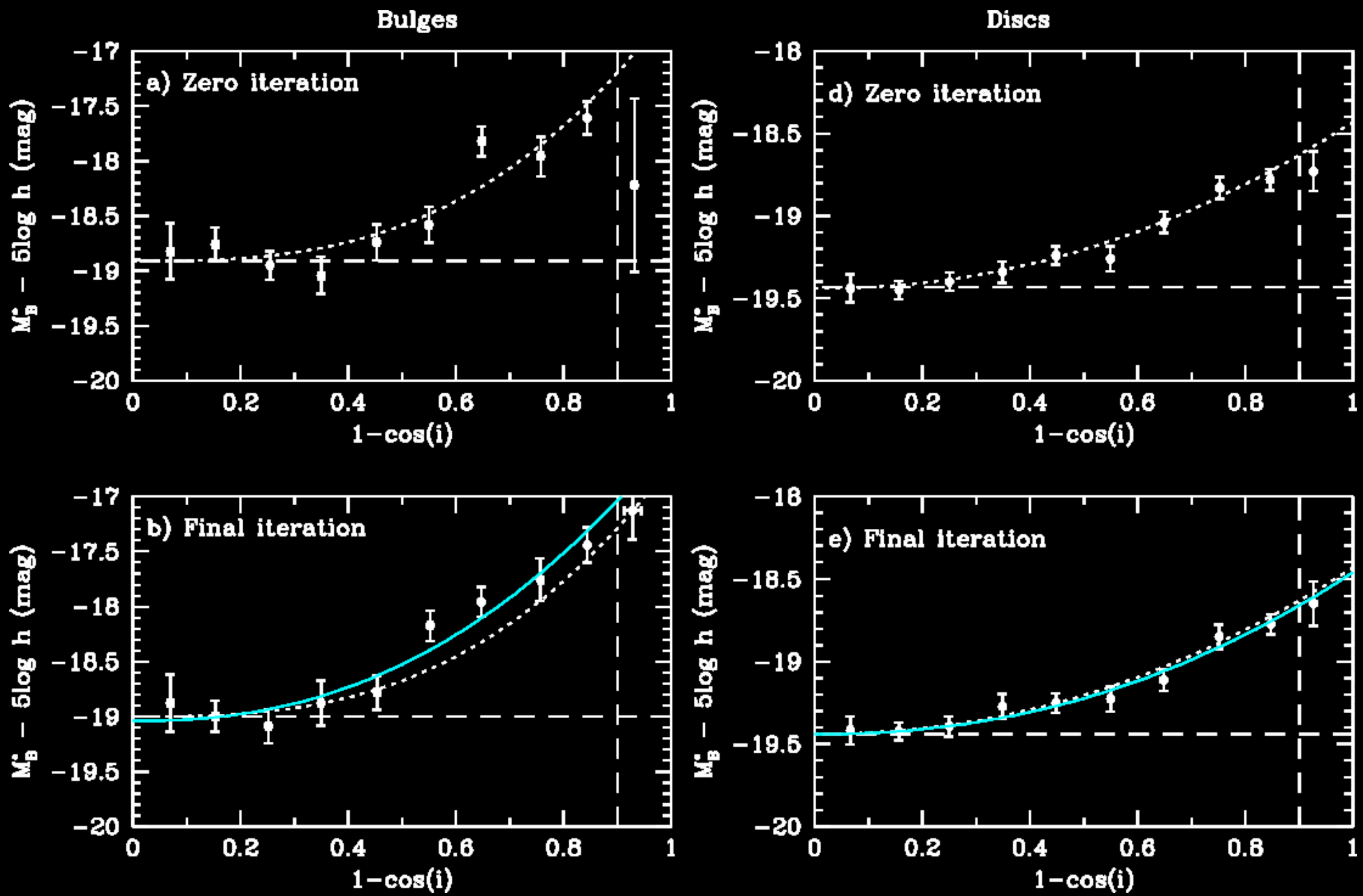
Liske et al (2006), ApJL, submitted

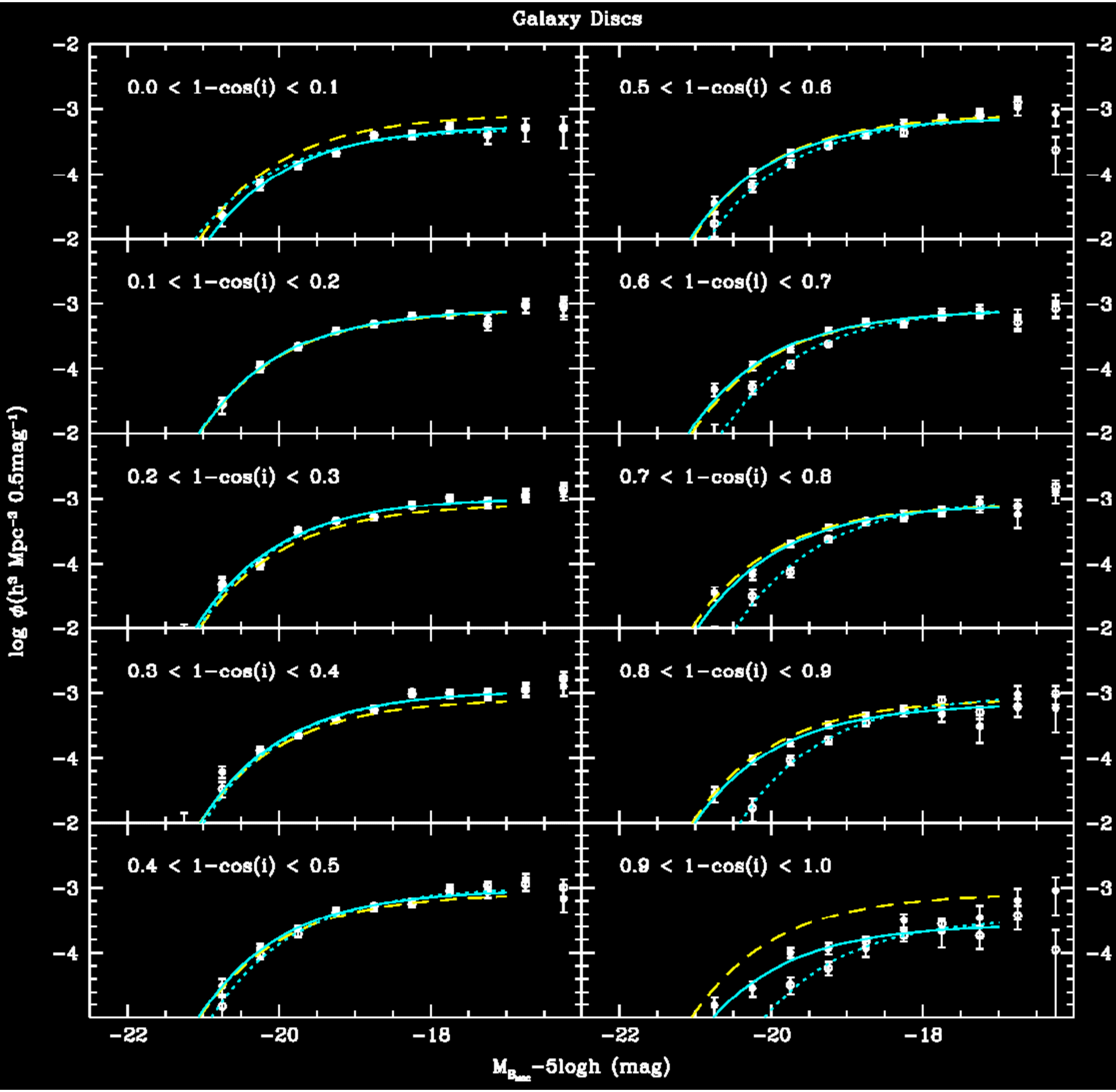


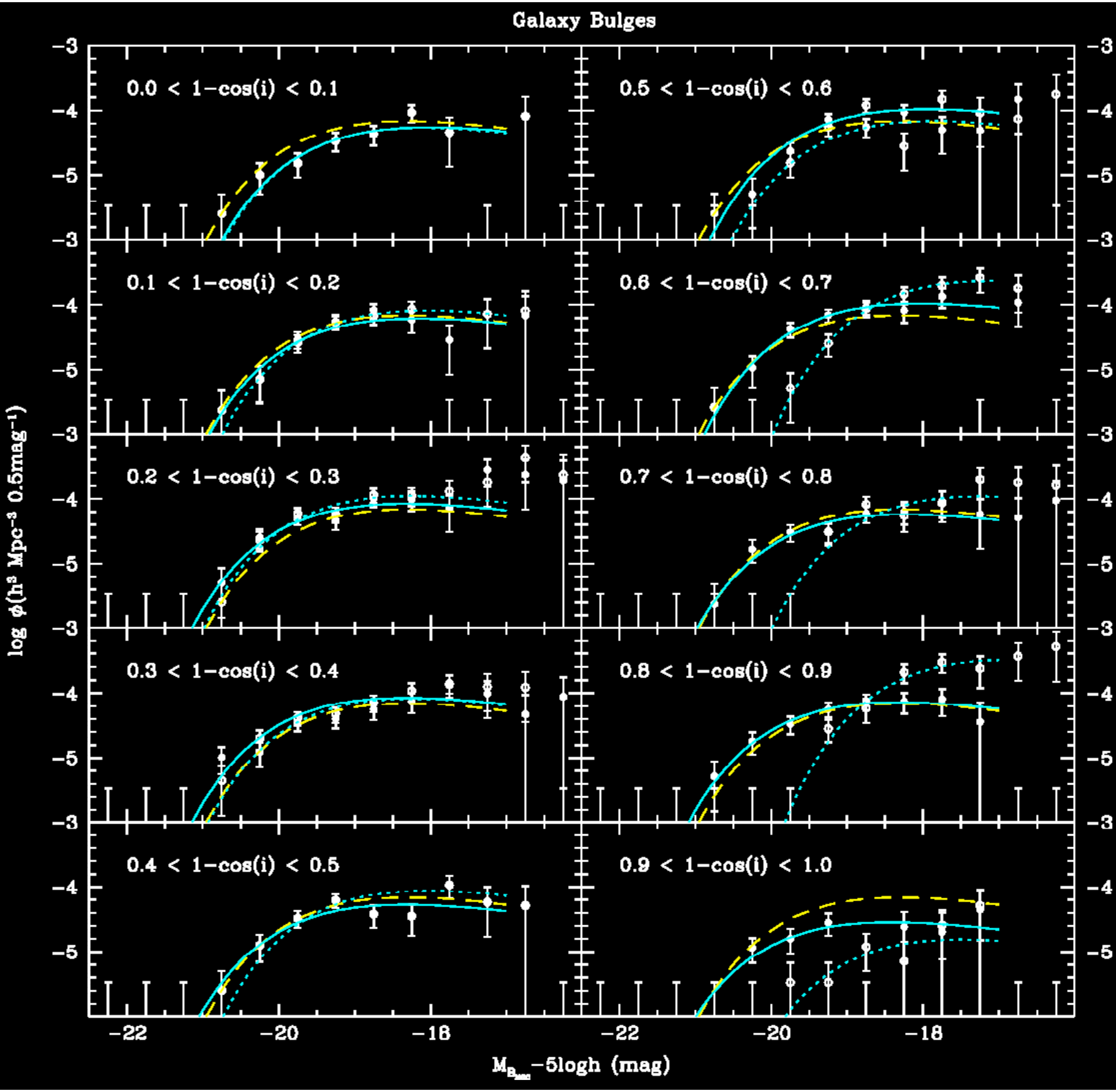
Science: Dust

1. Bulge and disc dust attenuation in B (Driver et al 2006)
   - How much is the B band LF affected by dust ?
   - By using inclination information we can derive mean disc opacity
   - Derive M* in 1-cos(i) intervals
   - Plot M* v 1-cos(i)
   - Fit attenuation-inclination with a dust model ==> OPACITY
   - Dust mass to light ratio + luminosity density ==> DUST DENSITY

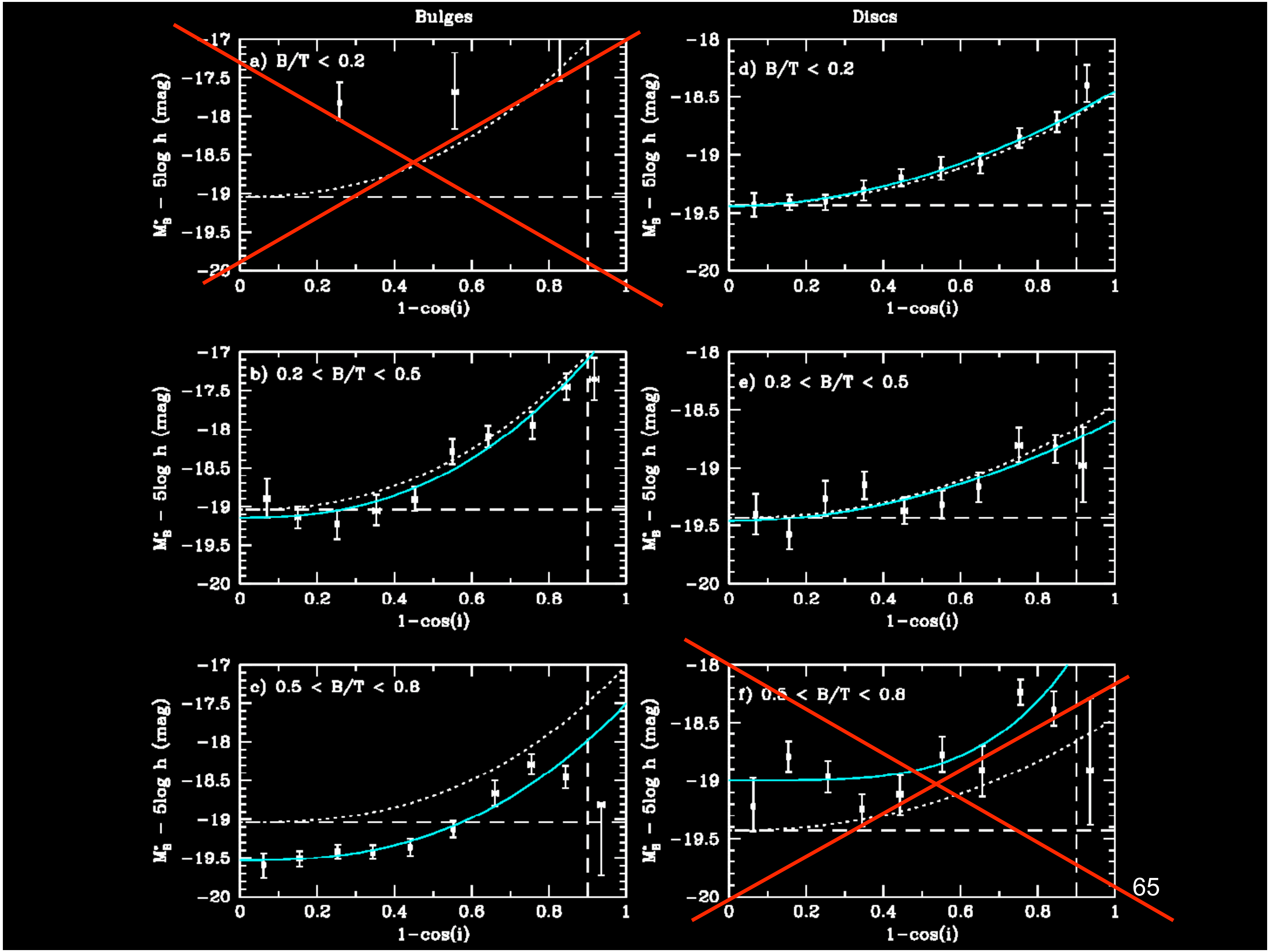
Purely empirical result




Galaxy Discs
0.0 < 1−cos(i) < 0.1
0.1 < 1−cos(i) < 0.2
0.2 < 1−cos(i) < 0.3
0.3 < 1−cos(i) < 0.4
0.4 < 1−cos(i) < 0.5
0.5 < 1−cos(i) < 0.6
0.6 < 1−cos(i) < 0.7
0.7 < 1−cos(i) < 0.8
0.8 < 1−cos(i) < 0.9
0.9 < 1−cos(i) < 1.0
log φ(h³ Mpc⁻³ 0.5mag⁻¹)
M_B −5logh (mag)

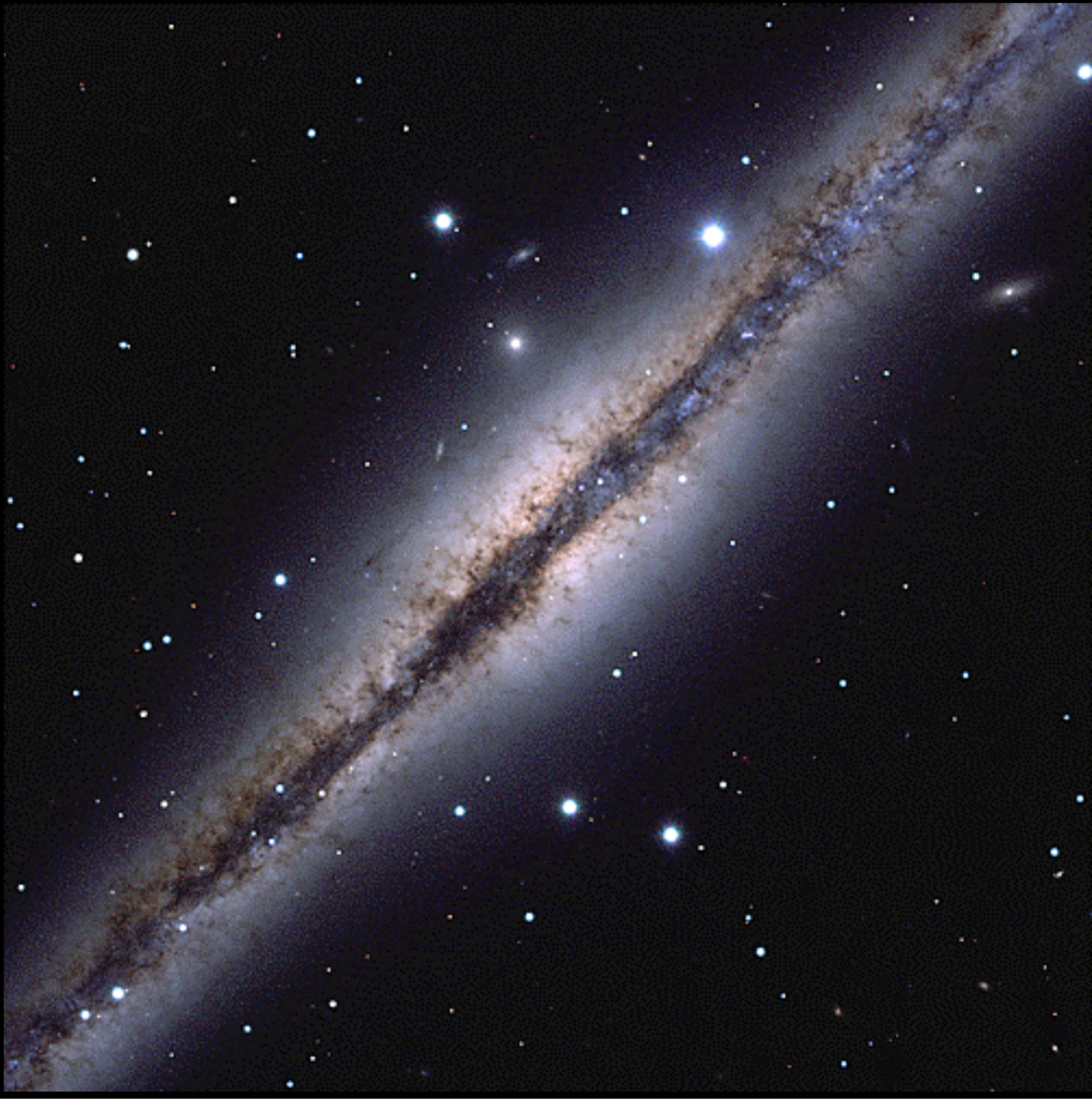


Galaxy Bulges
0.0 < 1−cos(i) < 0.1
0.1 < 1−cos(i) < 0.2
0.2 < 1−cos(i) < 0.3
0.3 < 1−cos(i) < 0.4
0.4 < 1−cos(i) < 0.5
0.5 < 1−cos(i) < 0.6
0.6 < 1−cos(i) < 0.7
0.7 < 1−cos(i) < 0.8
0.8 < 1−cos(i) < 0.9
0.9 < 1−cos(i) < 1.0
log φ(h³ Mpc⁻³ 0.5mag⁻¹)
$M_{B_{MGC}}$ −5logh (mag)



Bulges
Discs
a) B/T < 0.2
b) 0.2 < B/T < 0.5
c) 0.5 < B/T < 0.8
d) B/T < 0.2
e) 0.2 < B/T < 0.5
f) 0.5 < B/T < 0.8
M°B − 5log h (mag)
1−cos(i)

NGC891



Modelling the UV/optical-FIR/submm SED of star-forming galaxies

The model (Popescu et al. 2000):

- full radiative transfer calculation
  - anisotropic scattering
- realistic geometries
  - finite disks, bulges
  - clumpy component
- realistic dust emission models
  - stochastic heating of grains

898 E.M. Xilouris et al.: Optical and

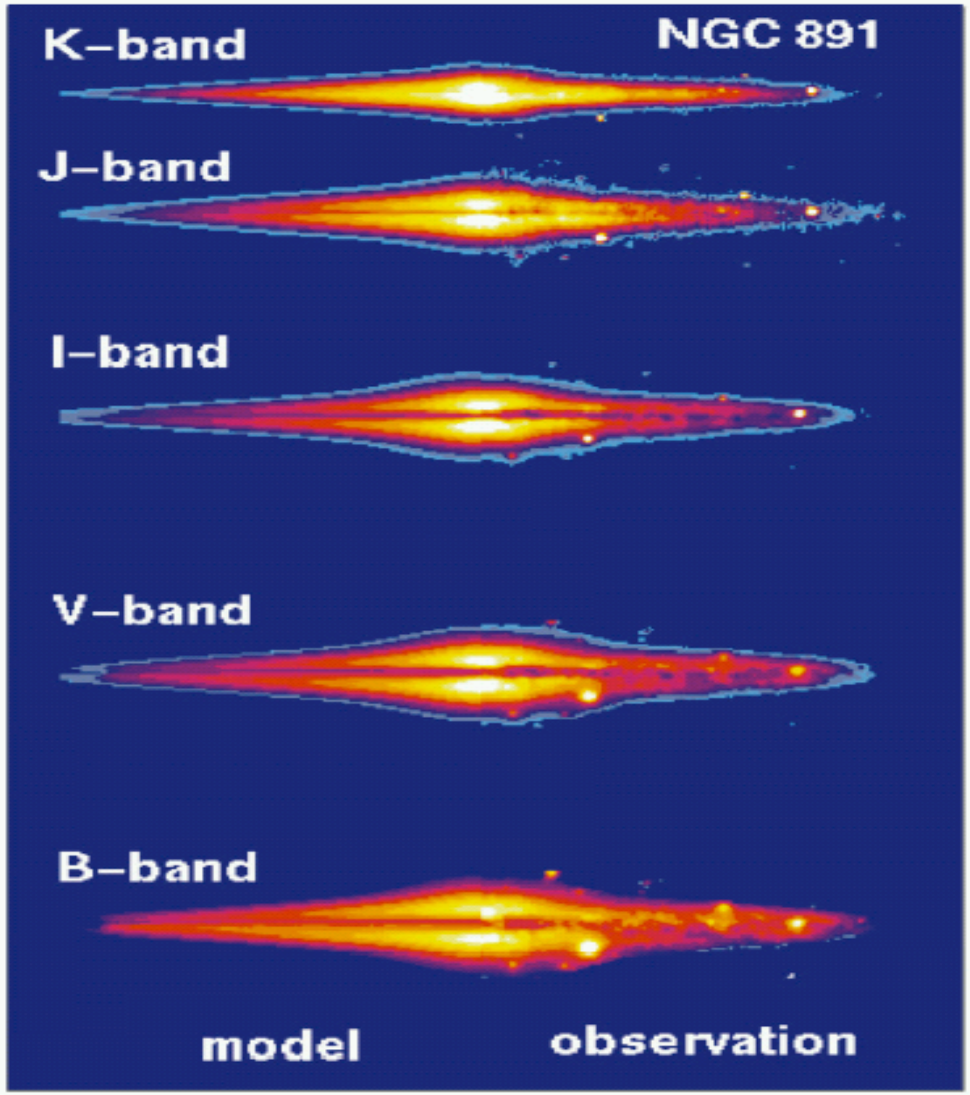


Fig. 3. Images of NGC 891 in K, J, I, V, B bands (top to bottom). The left half in each panel is the model image and the right half is the real galaxy image (folded).

- constrains geometries for stars and dust by fitting optical/NIR images
- only three free parameters: SFR, Mdust, F (clumpiness factor)

Old stellar bulge:

$$\eta(\lambda, R, z) = \eta^{\rm bulge}(\lambda, 0, 0)\exp(-7.67\,B^{1/4})\,B^{-7/8},$$

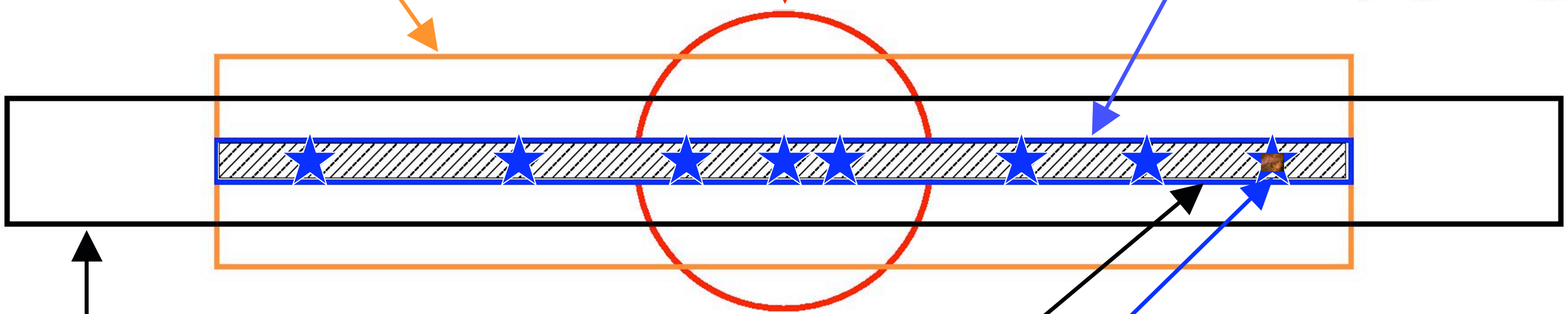
$$B = \frac{\sqrt{R^2 + z^2\,(a/b)^2}}{R_e}$$

Old stellar disk:

$$\eta(\lambda, R, z) = \eta^{\rm disk}(\lambda, 0, 0)\exp\left(-\frac{R}{h_{\rm s}^{\rm disk}} - \frac{|z|}{z_{\rm s}^{\rm disk}}\right)$$

Young stellar disk:

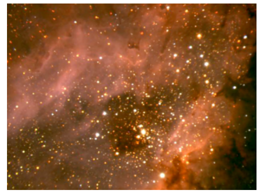
$$\eta^{\rm tdisk}(\lambda, R, z) = \eta^{\rm tdisk}(\lambda, 0, 0)\exp\left(-\frac{R}{h_{\rm s}^{\rm tdisk}} - \frac{|z|}{z_{\rm s}^{\rm tdisk}}\right)$$



Dust disk associated with the old stellar disk:

$$\kappa_{\rm ext}^{\rm disk}(\lambda, R, z) = \kappa_{ext}^{\rm disk}(\lambda, 0, 0)\,\exp\left(-\frac{R}{h_{\rm d}^{\rm disk}} - \frac{|z|}{z_{\rm d}^{\rm disk}}\right)$$

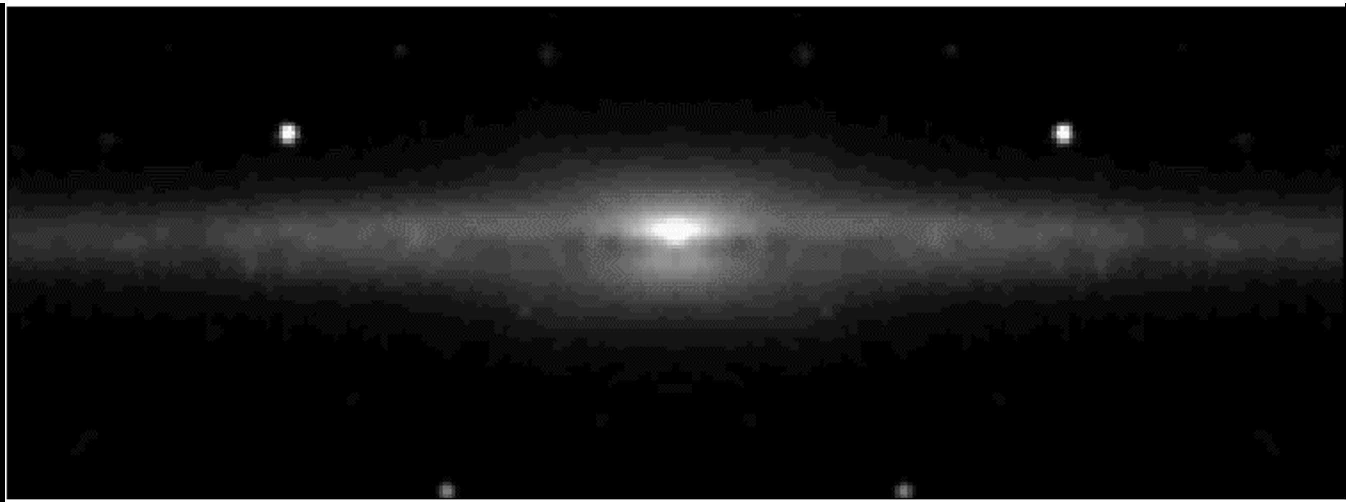
Clumpy component



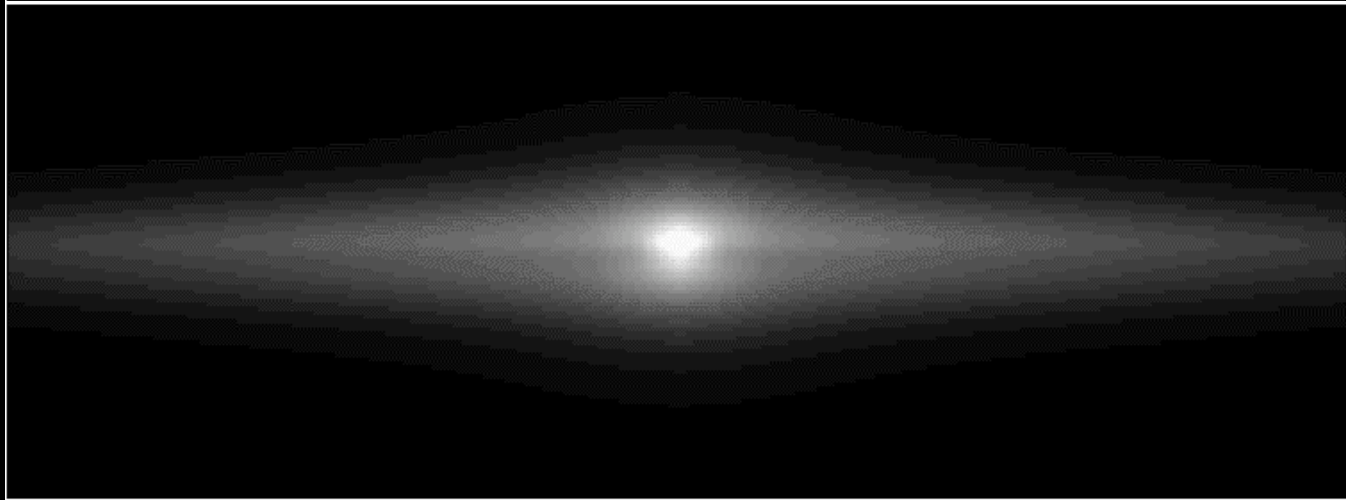
Dust disk associated with the young stellar disk:

$$\kappa_{ext}^{\rm tdisk}(\lambda, R, z) = \kappa_{ext}^{\rm tdisk}(\lambda, 0, 0)\,\exp\left(-\frac{R}{h_{\rm d}^{\rm tdisk}} - \frac{|z|}{z_{\rm d}^{\rm tdisk}}\right)$$

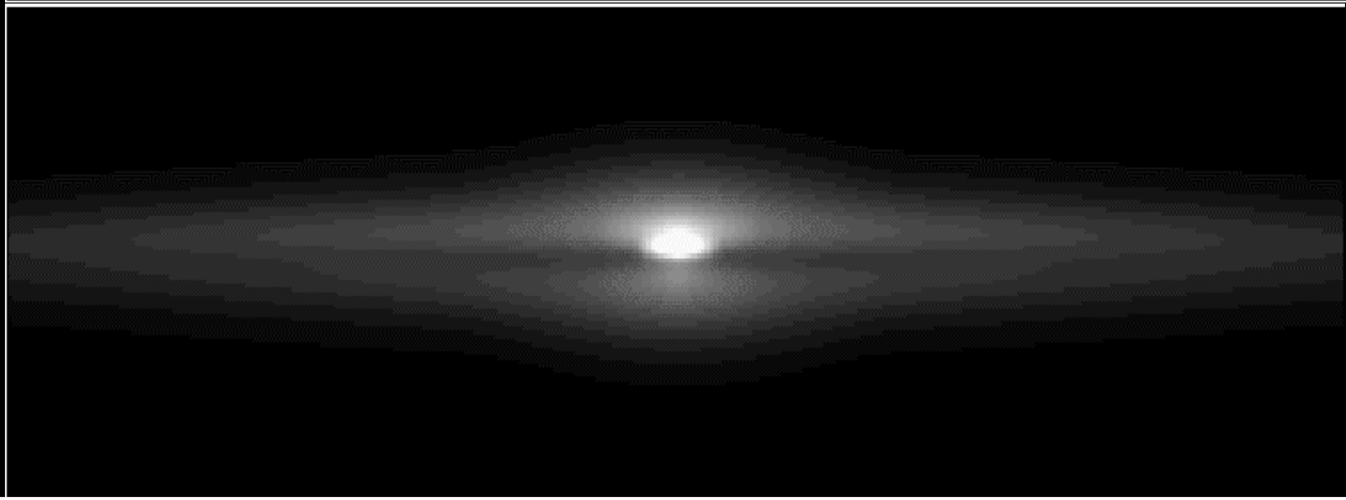
2MASS image

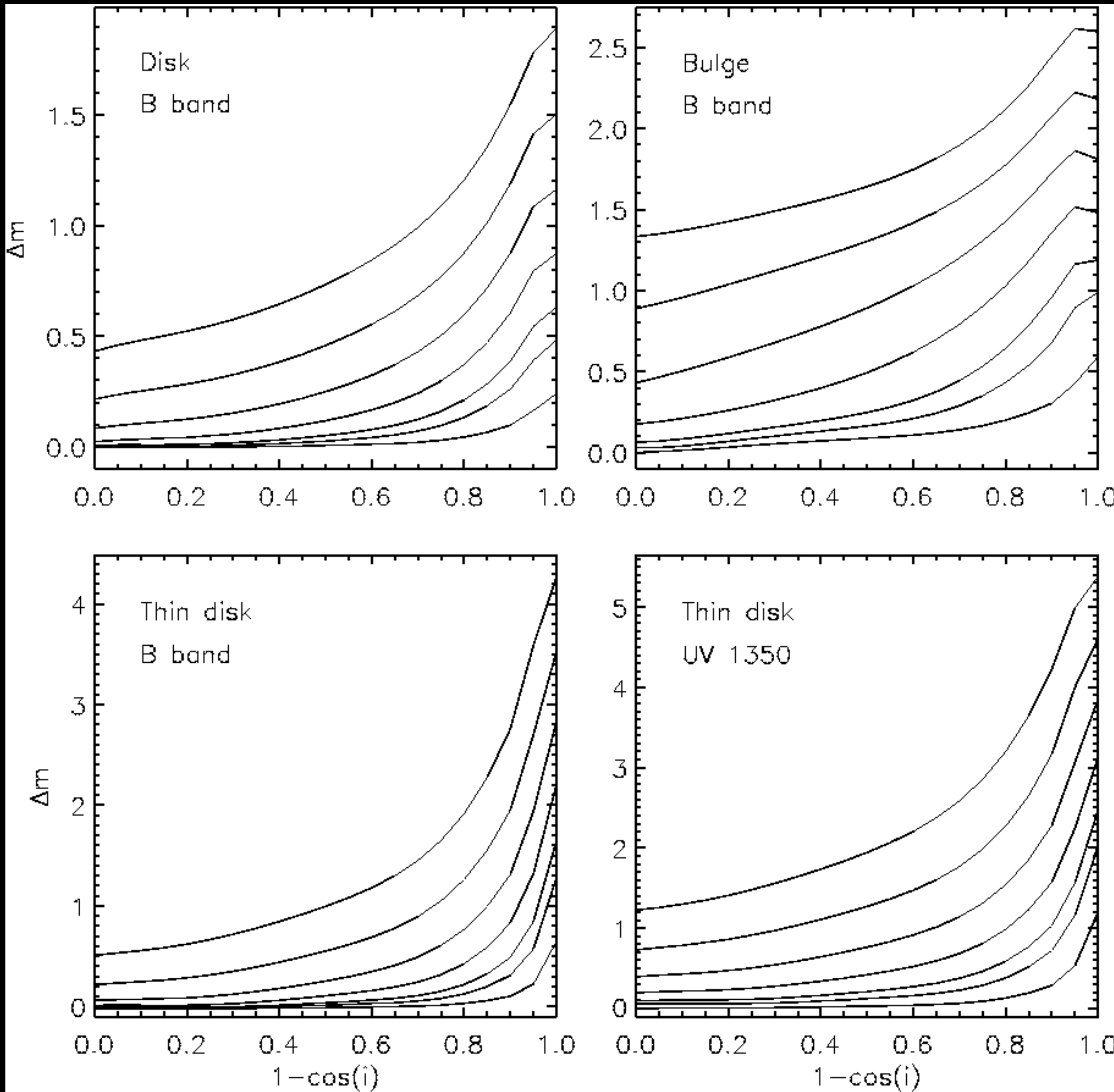


one dust disk model



two dust disk model

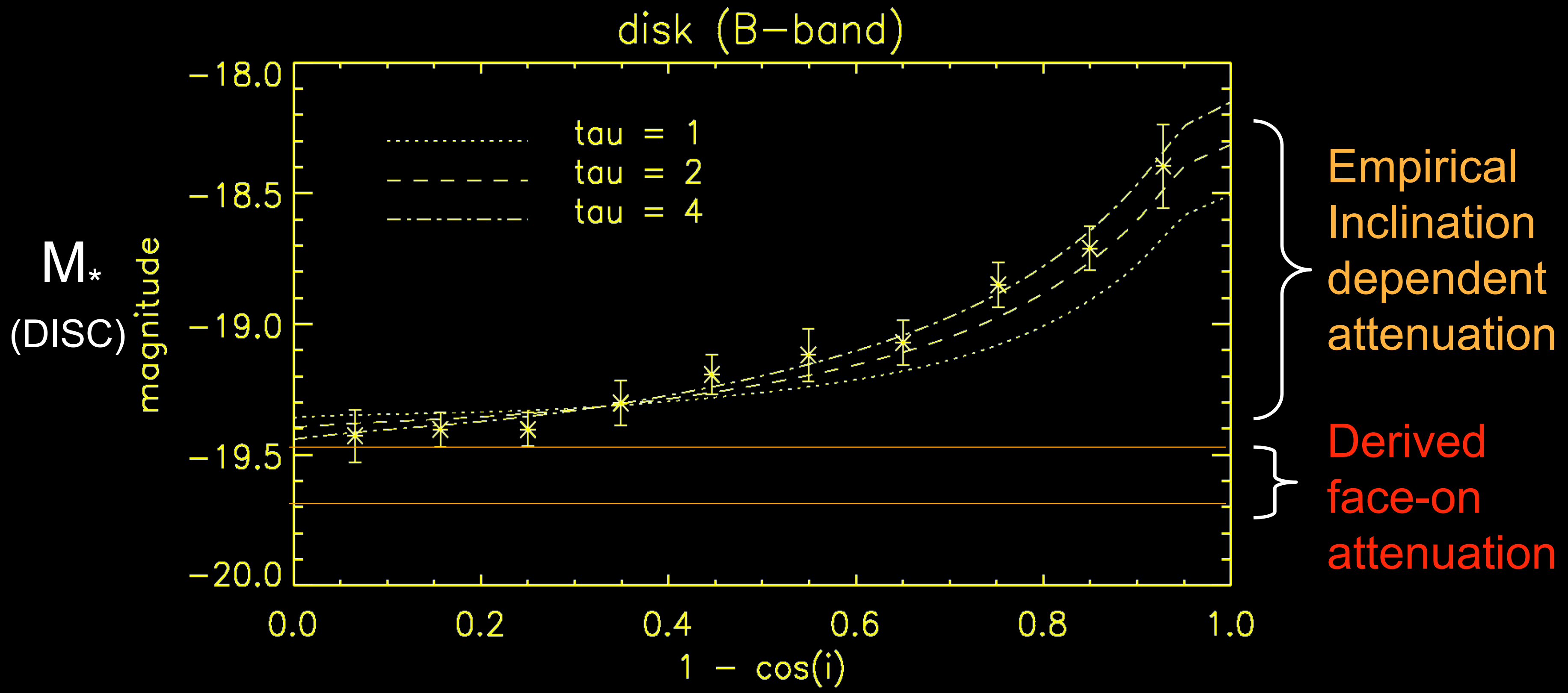




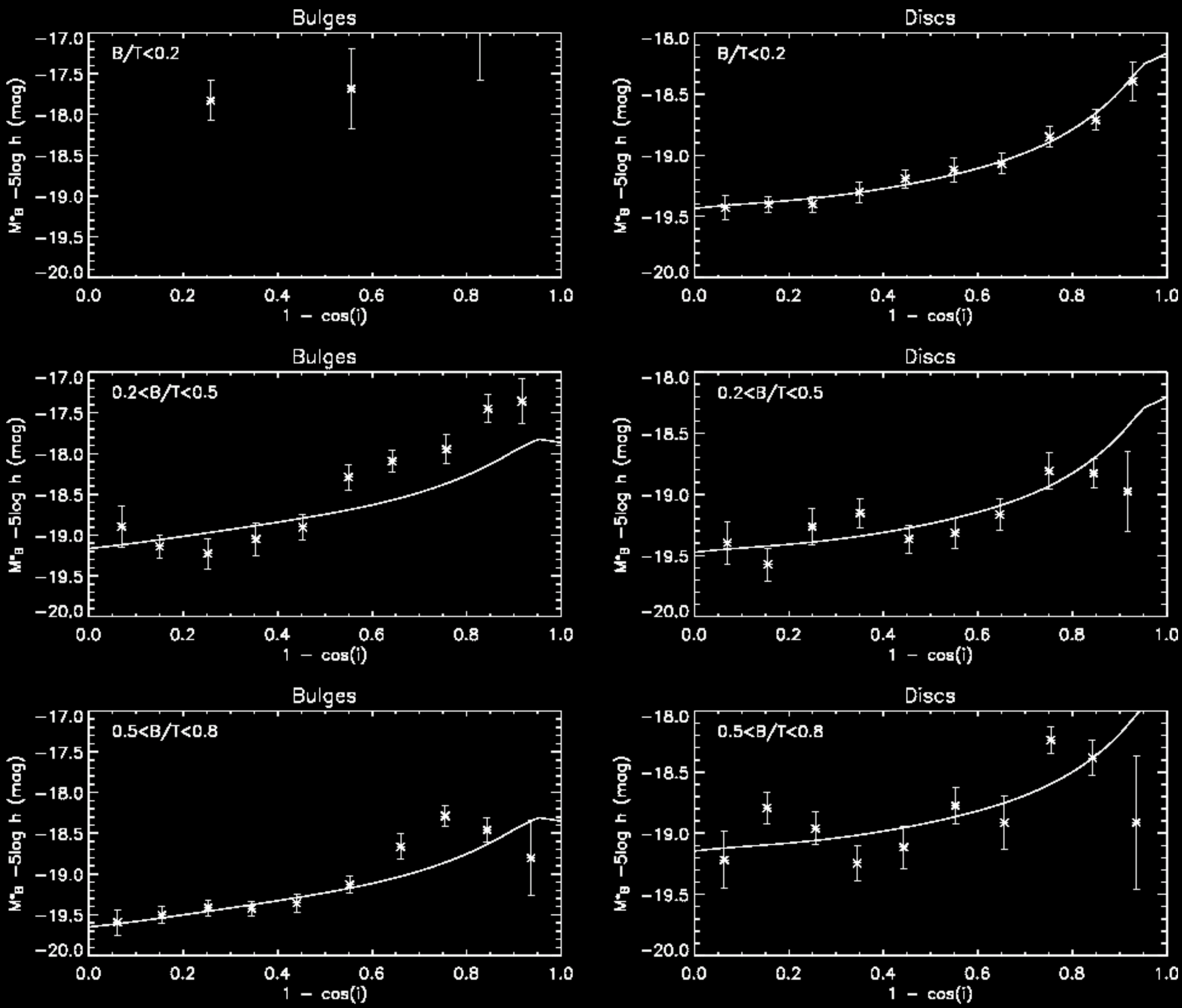
Tuffs et al. 2004 (all data available in electronic form)

Dust modelling

- We fit the Tuffs and Popescu dust model and derive: τ_B = 3.8 +/- 0.7
  (Popescu et al 2000; Tuffs et al 2004; Popescu et al 2005; Mollenhoff et a 2006)
- Model based on UV+ugrizJHK+Spitzer data of 6 nearby galaxies
- One free parameter = core dust density

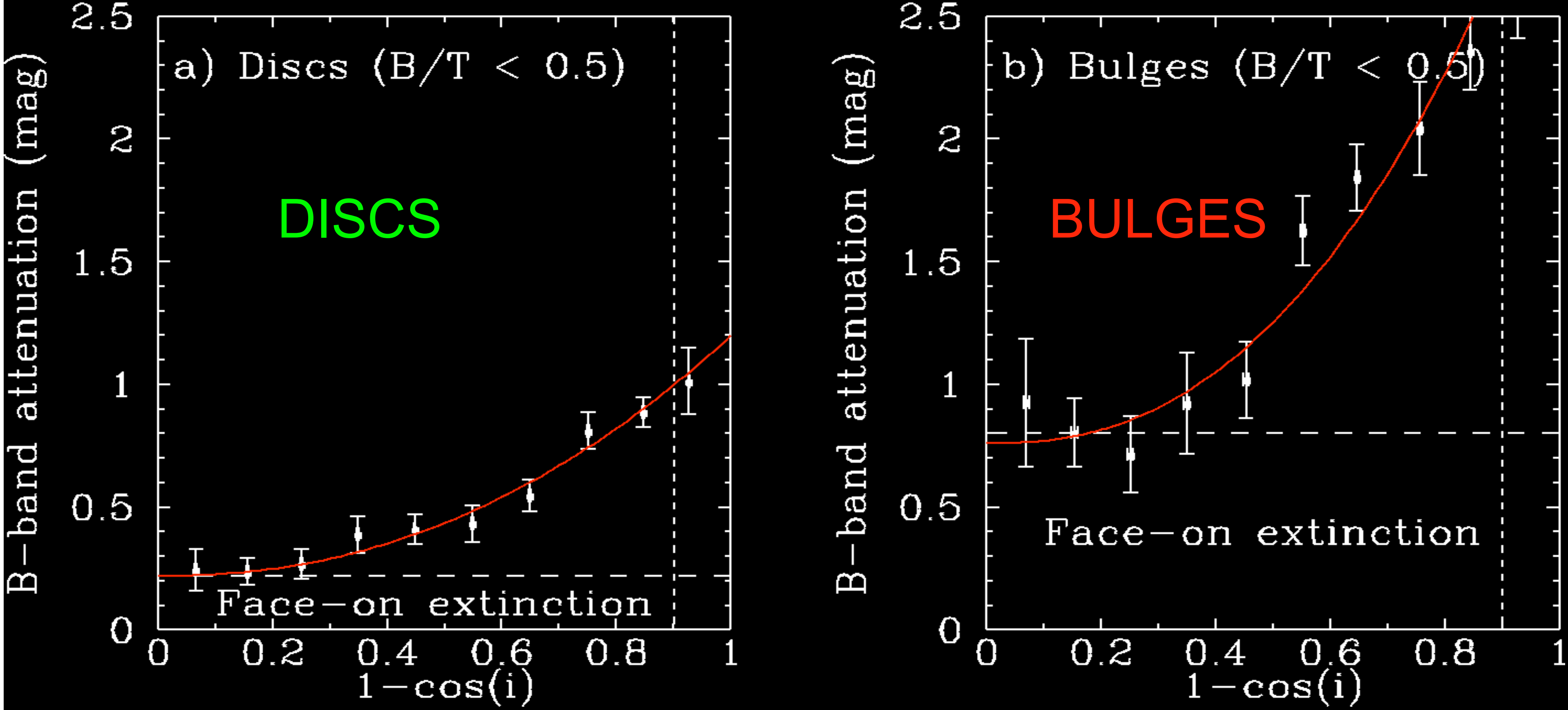


- Face-on attenuation correction in B: Discs = 0.20 mag; Bulges = 0.84 mag
- Total attenuation in B: **Discs = 0.2 - 1.1 mag; Bulges = 0.8 -3.4 mag !!!**



Bulges
Discs
B/T<0.2
0.2<B/T<0.5
0.5<B/T<0.8
M*B −5log h (mag)
1 − cos(i)

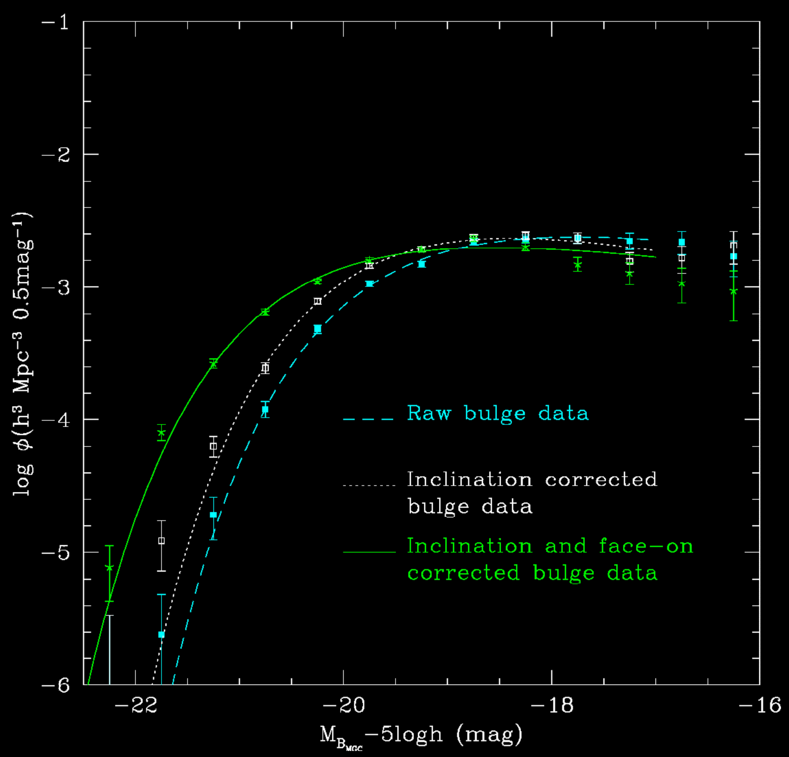
Empirical dust attenuation in B

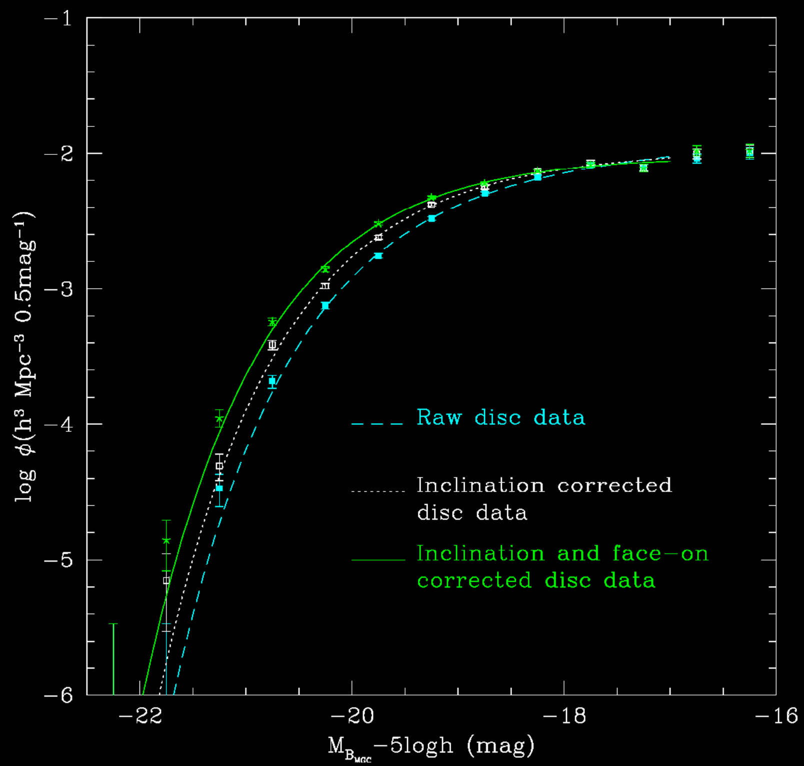


- Models provide face-on attenuation (Tuffs & Popescu):
  => Bulges = 0.8 mag, discs = 0.2 mag !
- Total: Bulges = 0.8-3.4 mag, discs =0.2 -1.1 mag !!!

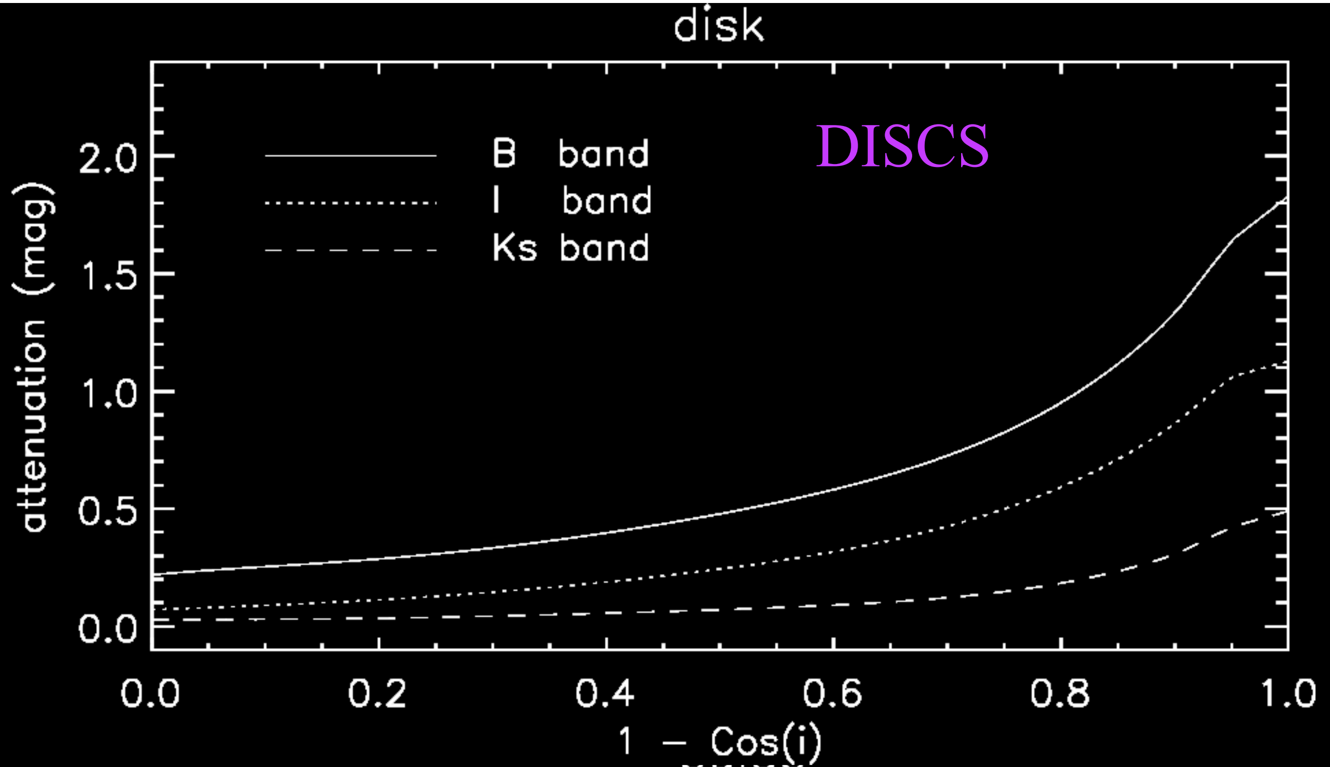
Dust corrected LFs !

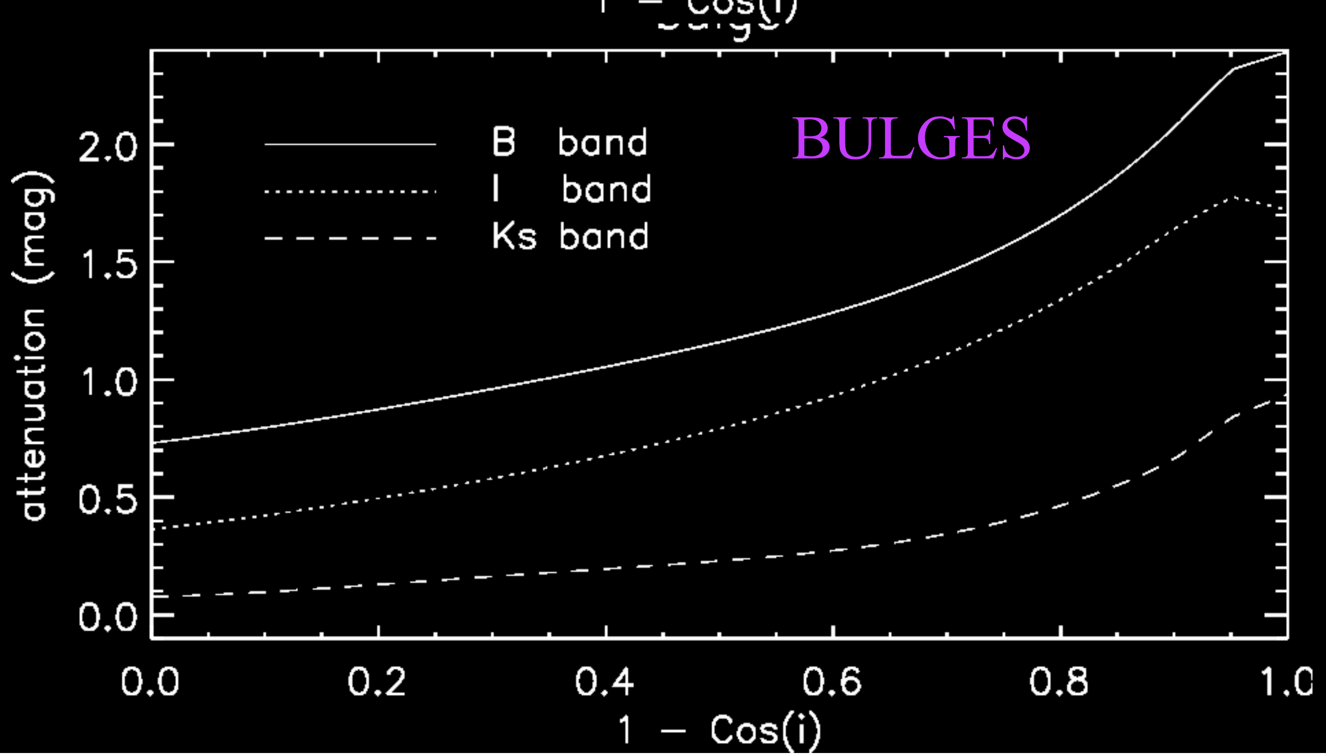
- Bulge LD up 100%; Disc LD up 20%
- Bulge mass up 400%; Disc mass up 20%
- Similar results derived from scaling up face-on LFs + offsets

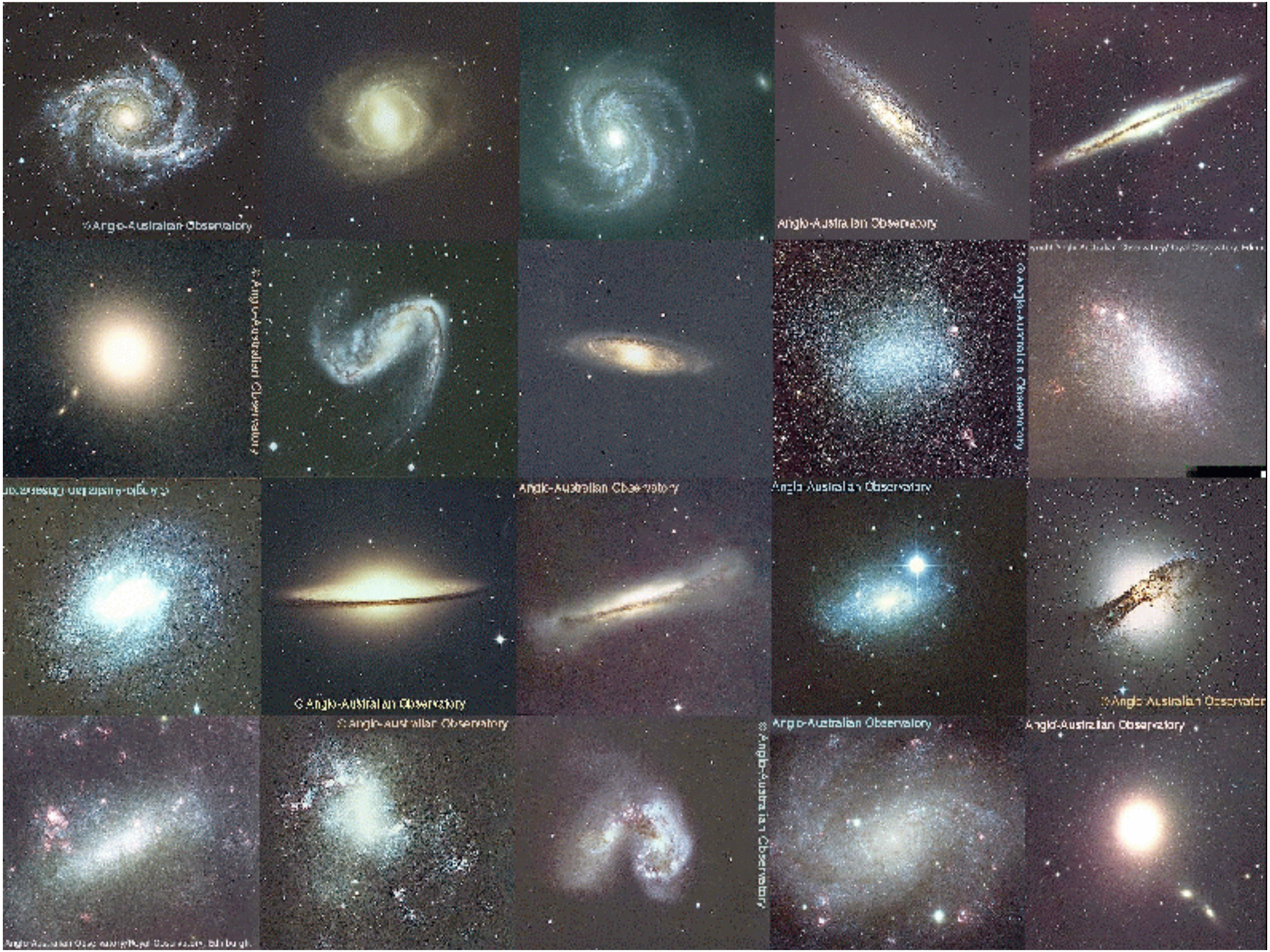




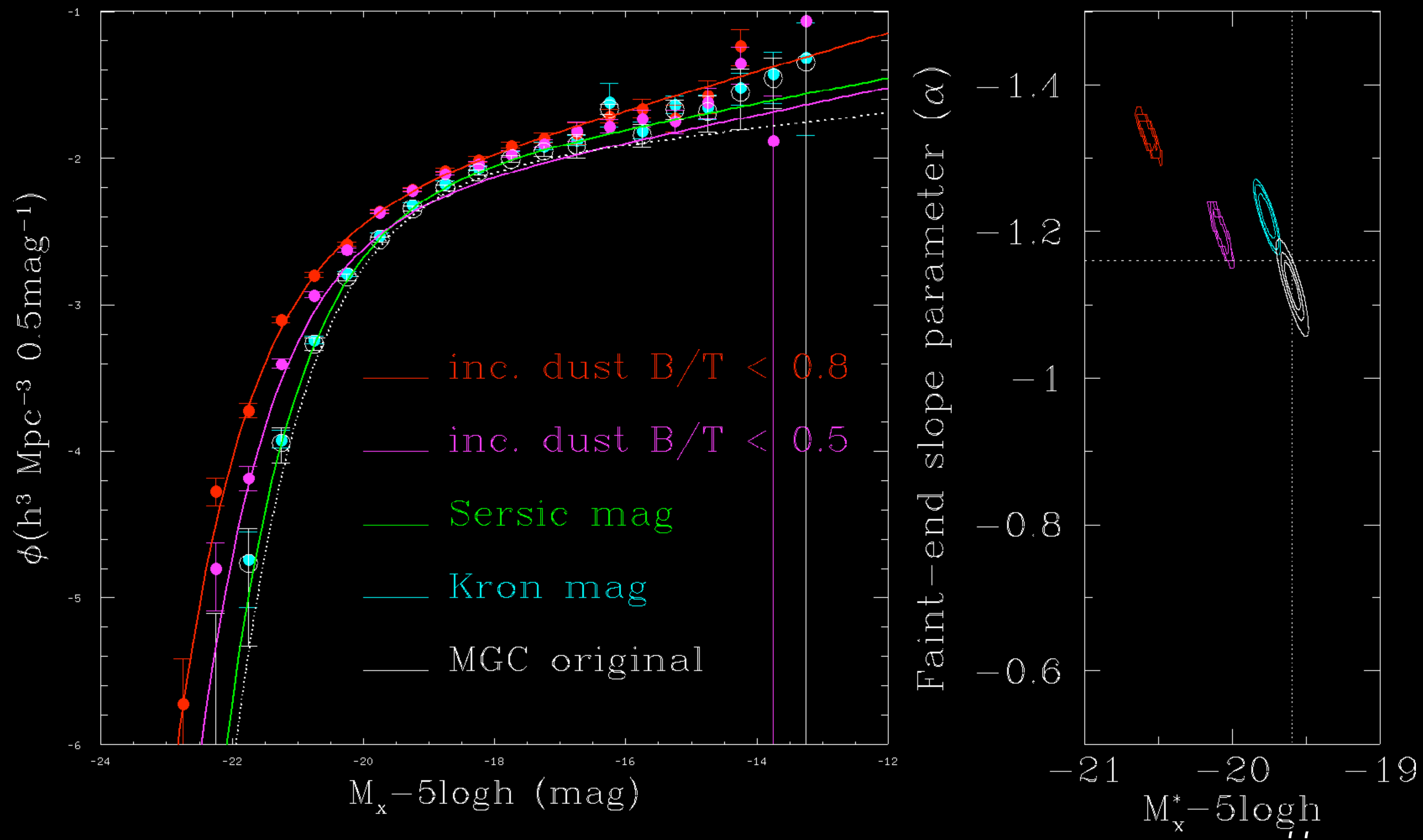
- Can now derive the cosmic dust and stellar mass densities.


disk
DISCS
B band
I band
Ks band
attenuation (mag)
0.0
0.5
1.0
1.5
2.0
0.0
0.2
0.4
0.6
0.8
1.0
1 – Cos(i)


BULGES
B band
I band
Ks band
attenuation (mag)
0.0
0.5
1.0
1.5
2.0
0.0
0.2
0.4
0.6
0.8
1.0
1 – Cos(i)


© Anglo-Australian Observatory
Anglo-Australian Observatory
© Anglo-Australian Observatory
© Anglo-Australian Observatory
Anglo-Australian Observatory
Anglo-Australian Observatory
© Anglo-Australian Observatory
© Anglo-Australian Observator
© Anglo-Australian Observatory
© Anglo-Australian Observatory
Anglo-Australian Observatory
Anglo-Australian Observatory

Impact of dust on global LF



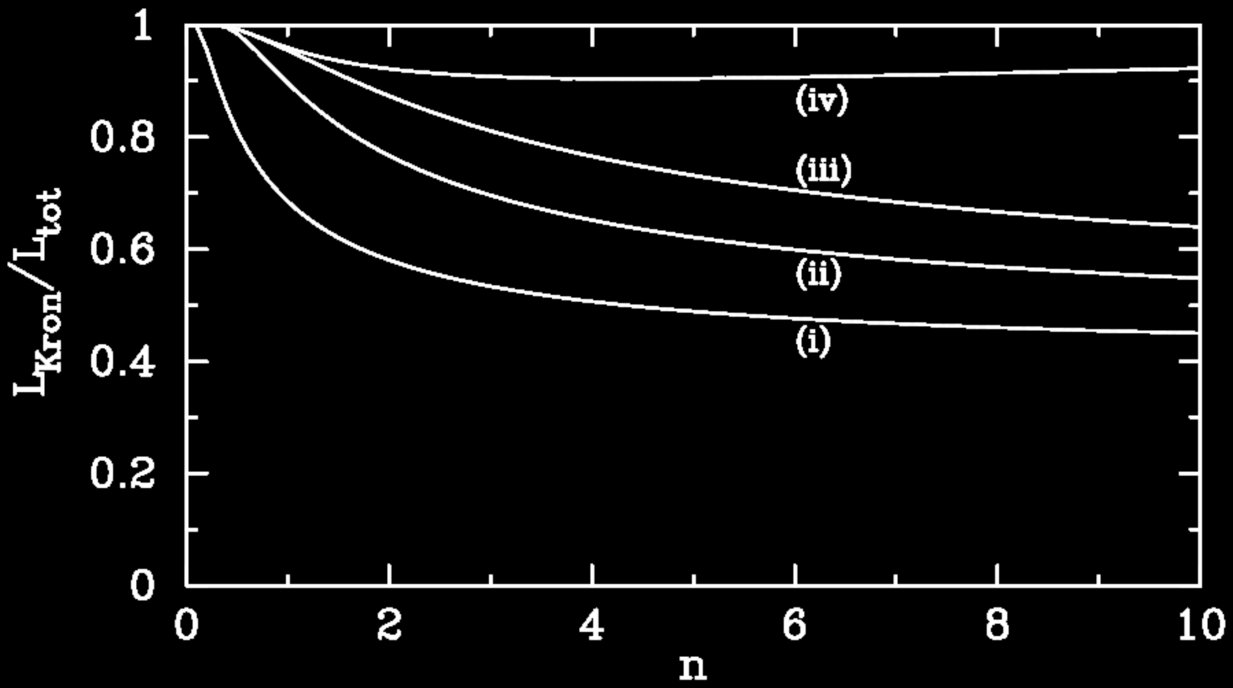


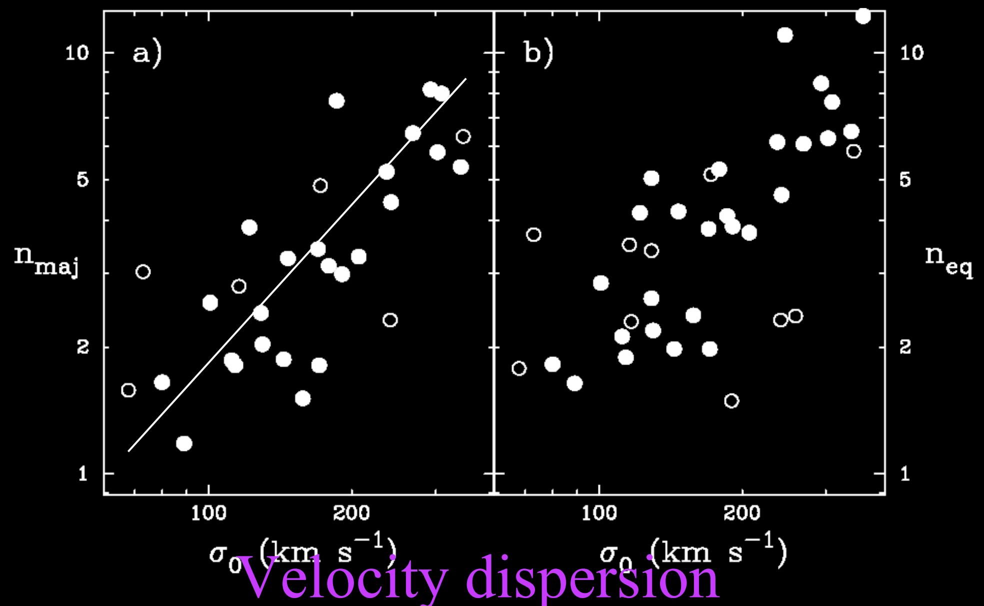
Figure 10: Kron luminosity within $2.5R_1$, normalised against the total luminosity, as a function of the underlying light–profile shape n. The different curves arise from the different values of $R1$ obtained by integrating Equation (31) to (i) $1R_e$, (ii) $2R_e$, (iii) $4R_e$, and (iv) infinity.

Science: SMBHs

1. SMBH Mass Function (Graham et al 2006)
   - Use bulge Sersic index Black Hole mass relation (Graham & Driver 2006)
   - Derive early and late-type SMBH mass function
   - Integrate to get ==> BLACK HOLE MASS DENSITY

Sersic

index



Graham et al 2002

Figure 1. a) Major-axis and b) equivalent-axis Sérsic index n plotted against the central galaxy velocity dispersion. Elliptical galaxies are marked with filled circles, while S0 galaxies are denoted by open circles.

Novak, Faber & Dekel (2005) Review all Known BH Relations ==>

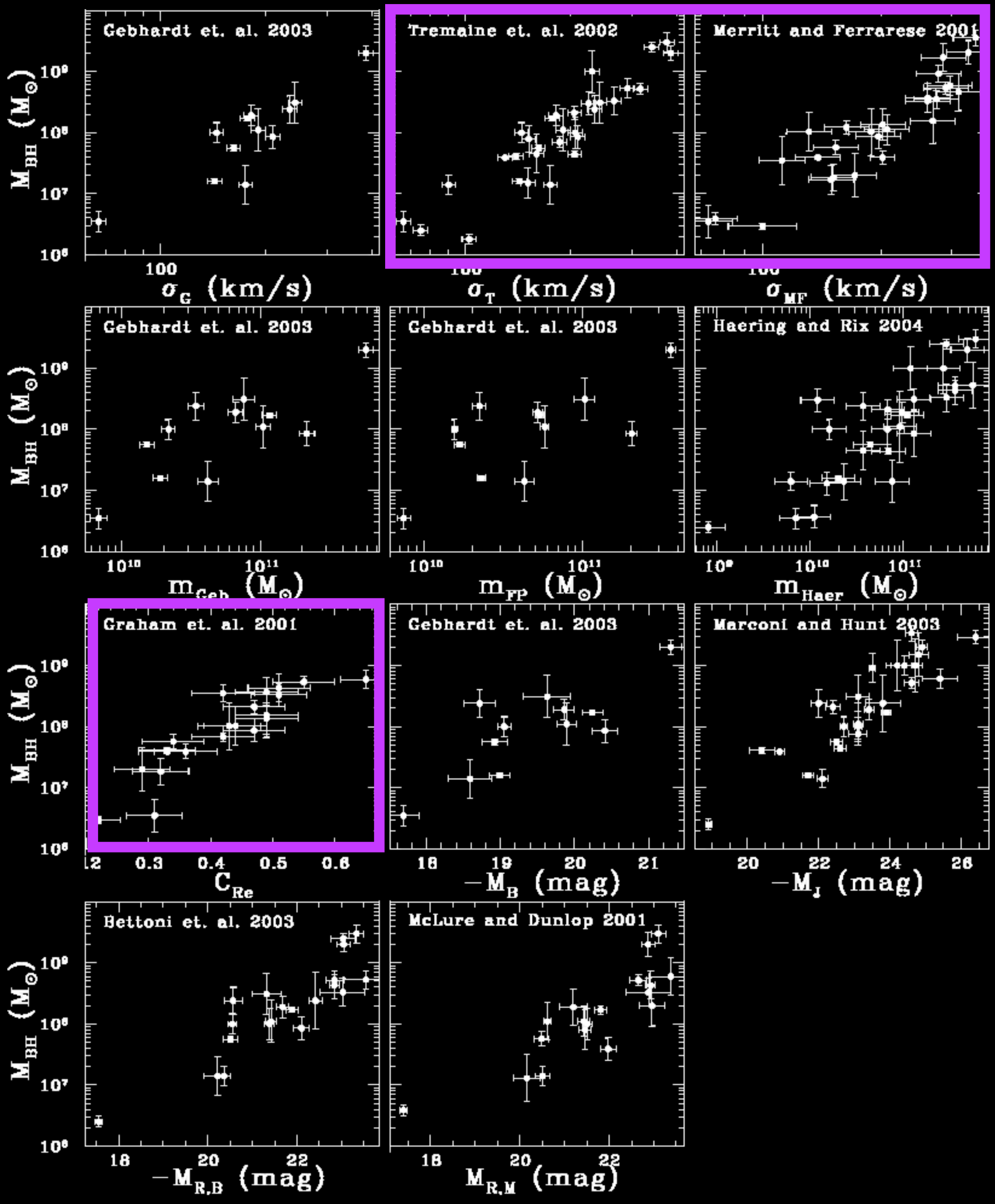
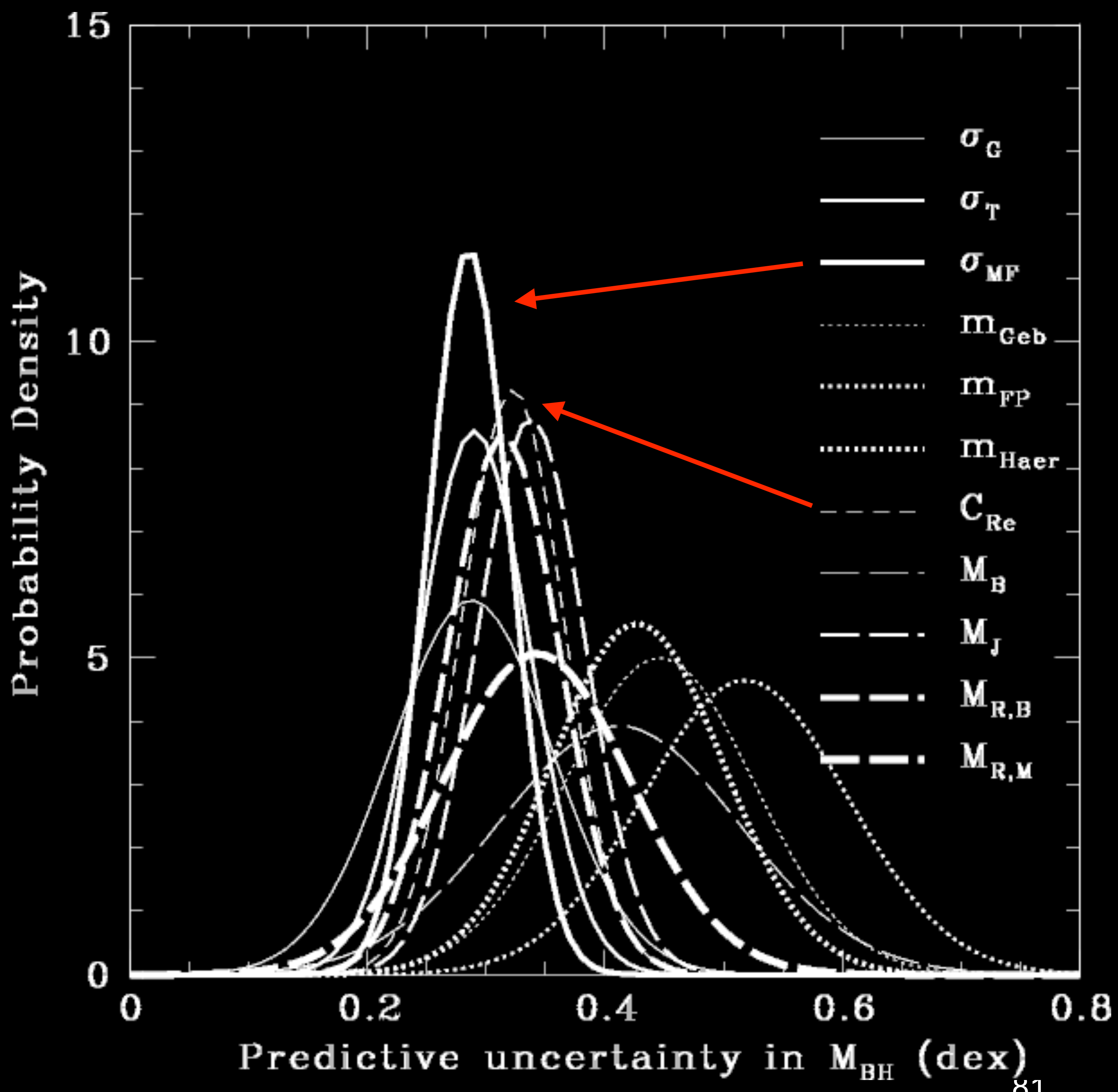


Fig. 1.— BH mass plotted against different predictor variables. See §3 for details.

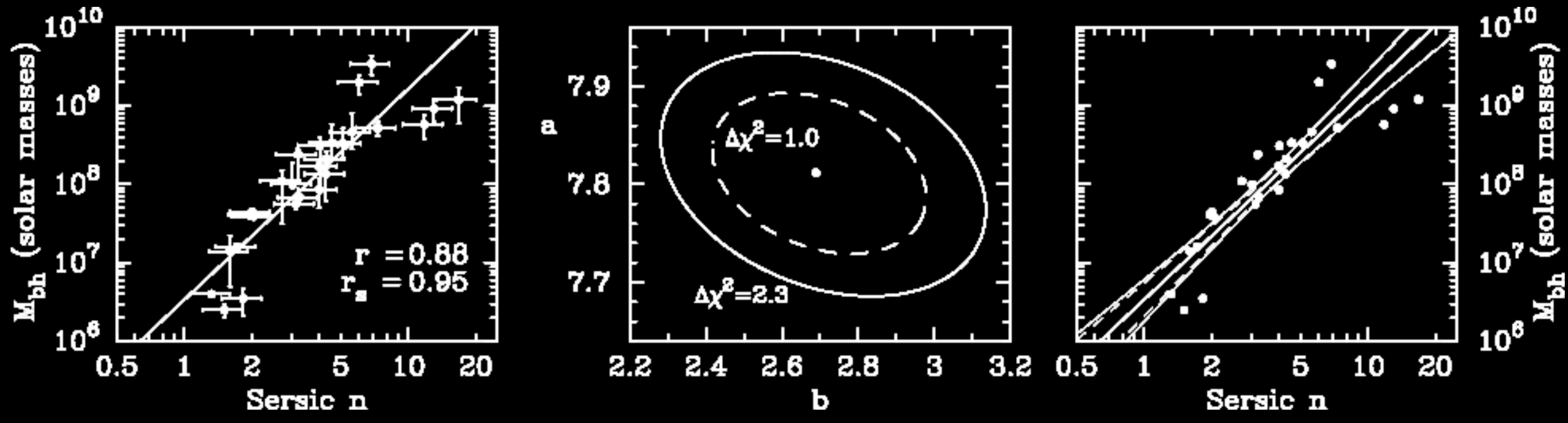
They identify velocity disperision and concentration (Sersic index) as being equally good at predicting BH masses.

c.f. Novak, Faber & Dekel (2005)

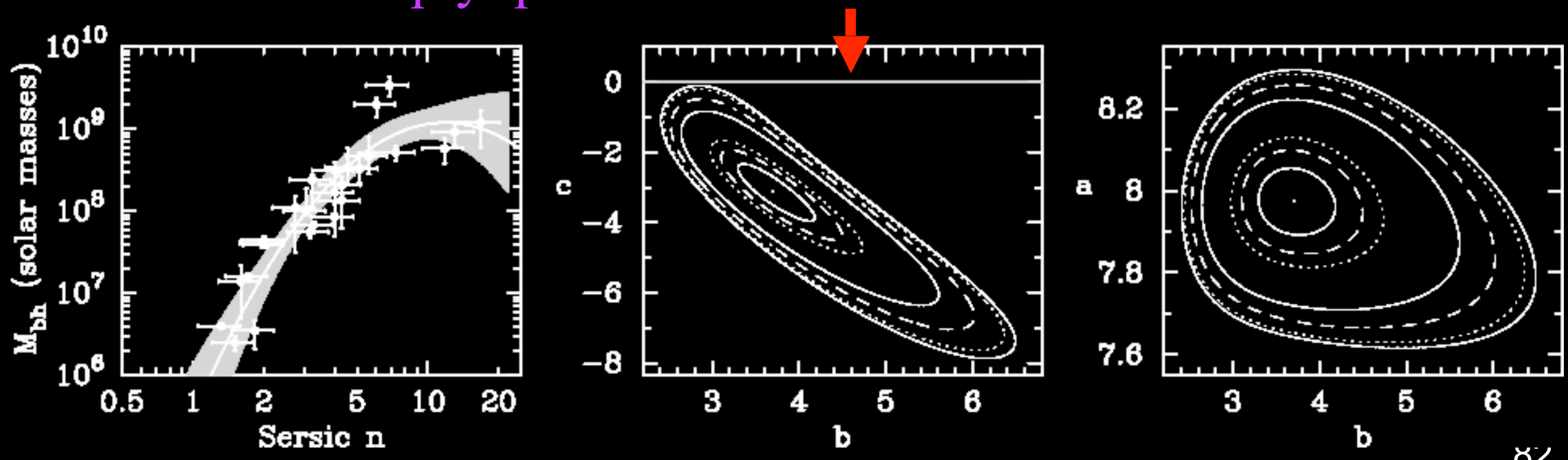


Linear or quadratic ?

Graham & Driver (2006)

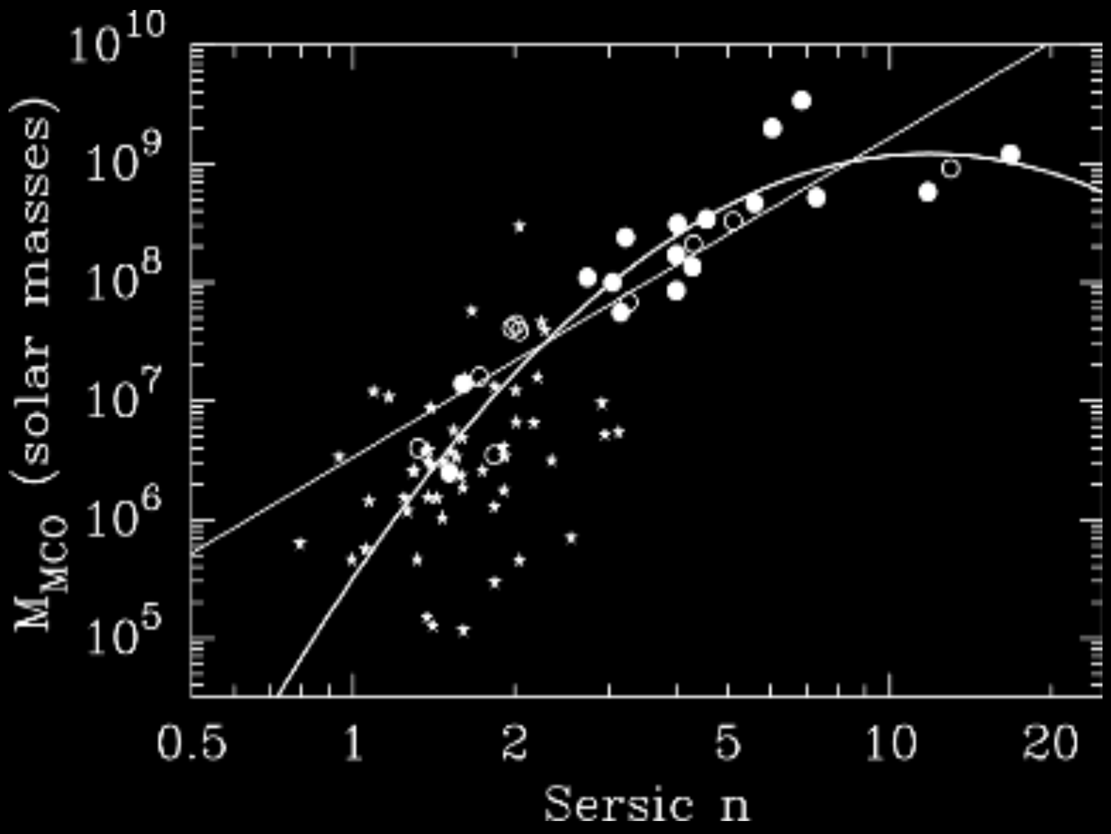


Contours imply quadratic is better fit at 99% confidence



SMBHs

- BH mass Sersic index relation is as strongly correlated as BH-sigma relation (see Novak et al 2005)
- Recently recalibrated with a quadratic (Graham & Driver 2006)

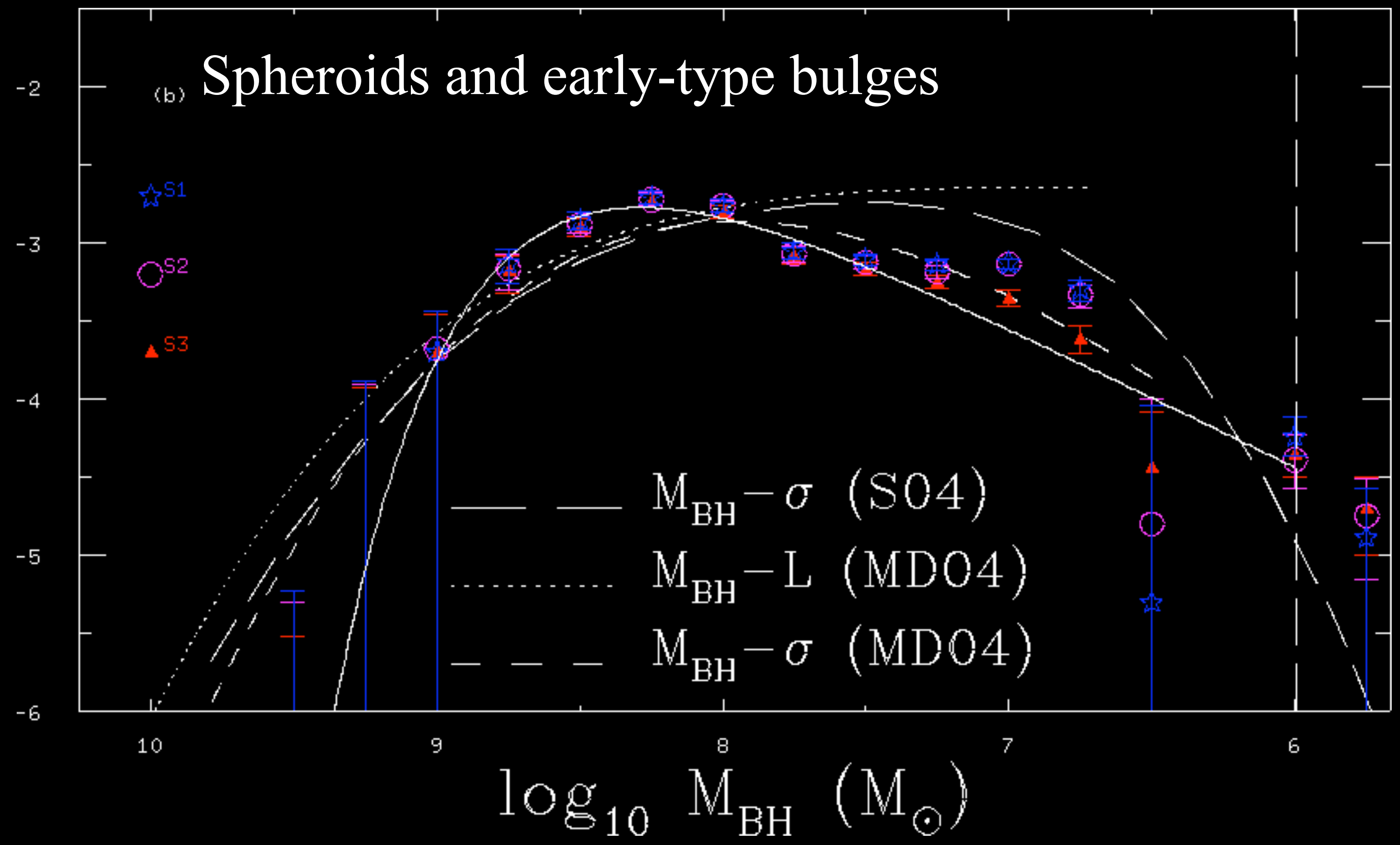


- Can now use Spheroid and bulge Sersic indices to predict BH masses and derive mass functions for early and late type bulges ==>

SMBH Mass functions

<-- Log(Mbh)

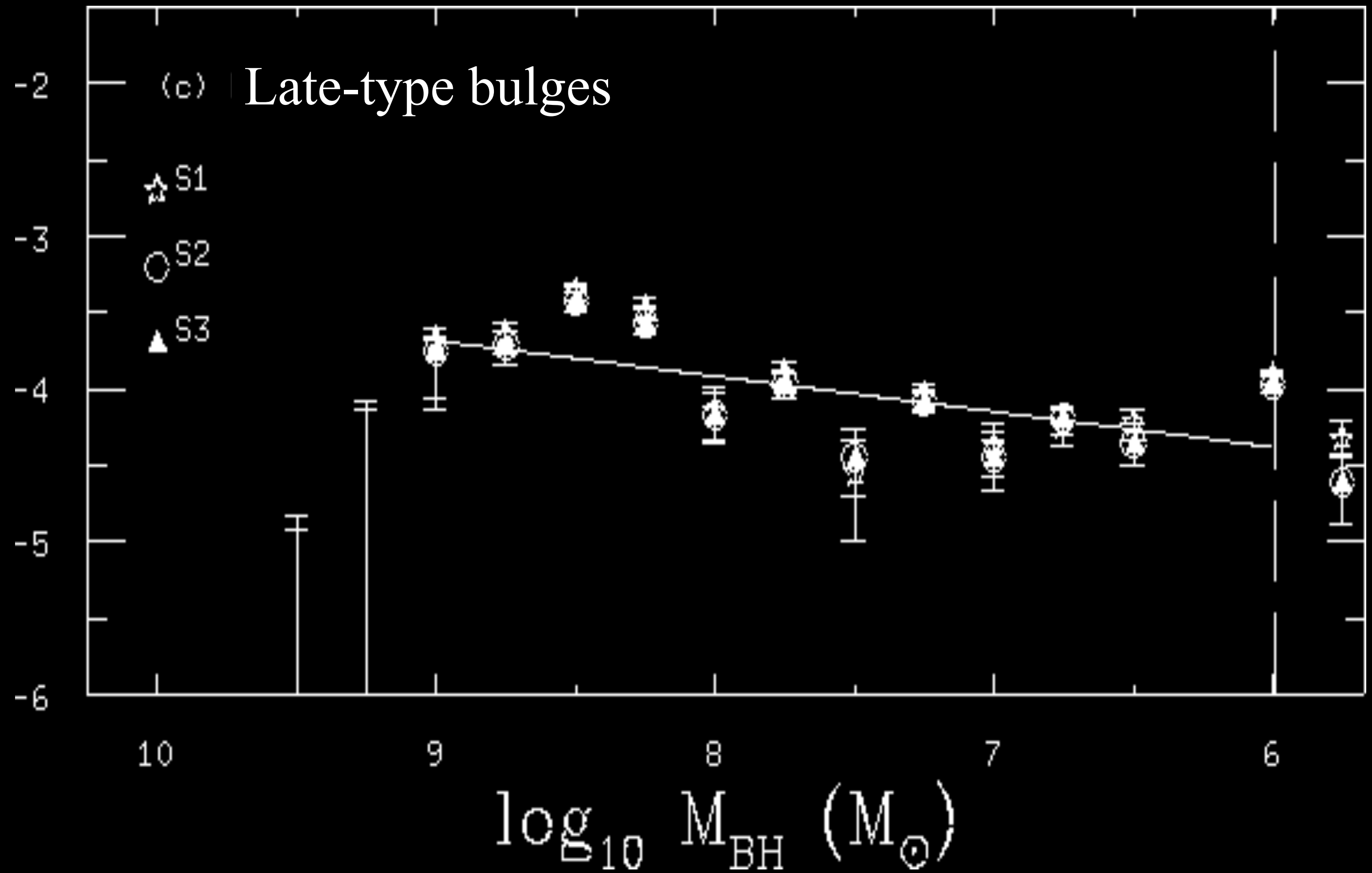
Log(Number density) -->



SMBH Mass functions

<-- Log(Mbh)

Log(Number density) -->



SMBH Mass functions

Previous estimates assumed bulge LF = spiral LF & 0.33' B/T !

<-- Log(Mbh)

Log(Number density) -->

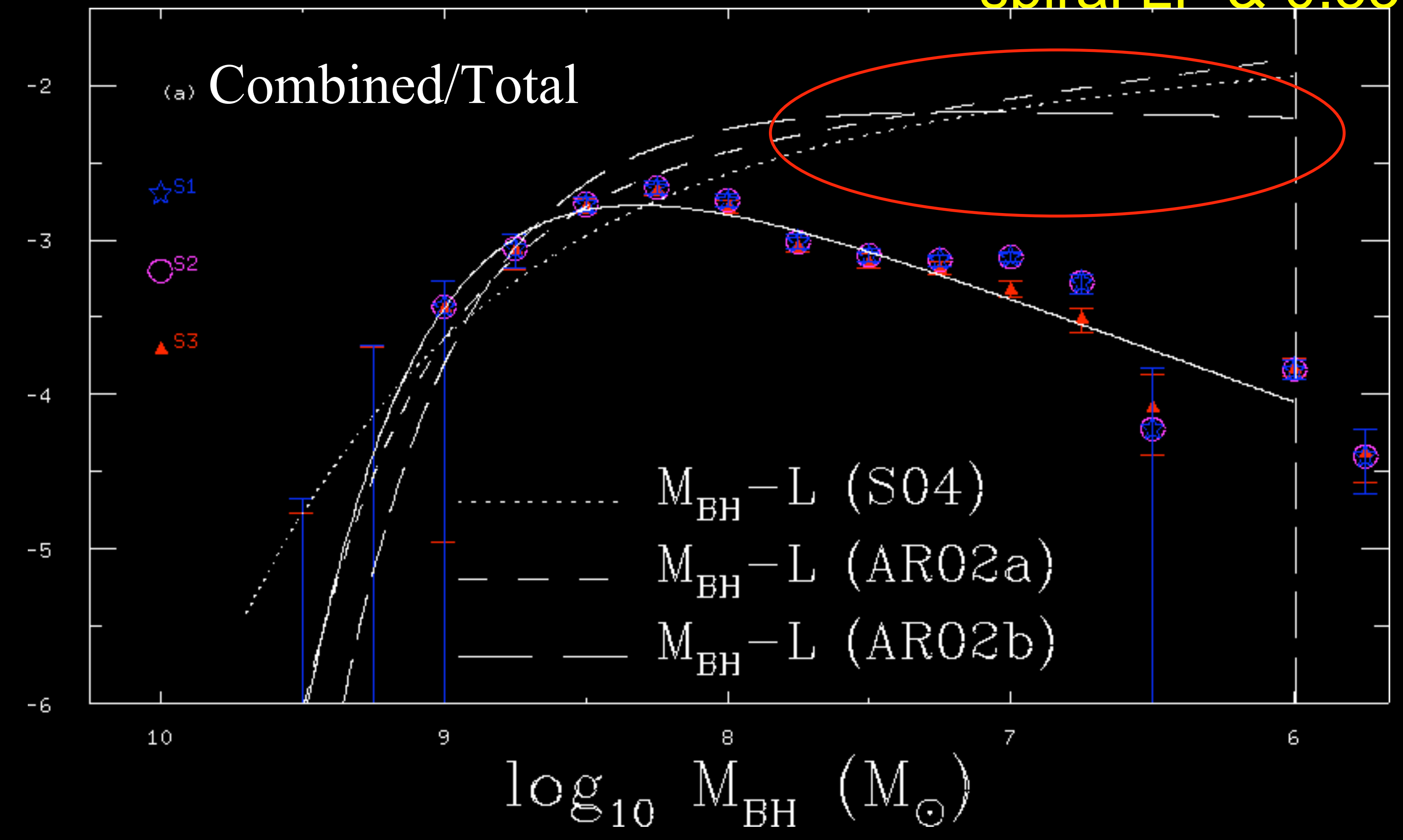


Table of SMBH density estimates

Study	$\rho_{\rm bh,0}$ (E/S0) $h_{70}^2\,10^5 M_\odot$ Mpc^{-3}	$\rho_{\rm bh,0}$ (Sp) $h_{70}^2\,10^5 M_\odot$ Mpc^{-3}	$\rho_{\rm bh,0}$ (total) $h_{70}^2\,10^5 M_\odot$ Mpc^{-3}
This study (Sample 1)	$(3.9 \pm 1.2)h_{70}$	$(1.2 \pm 0.6)h_{70}$	$(5.1 \pm 1.8)h_{70}$
This study (Sample 3)	$(3.7 \pm 1.1)h_{70}$	$(1.0 \pm 0.5)h_{70}$	$(4.7 \pm 1.6)h_{70}$
Wyithe (2006)	...	...	2.28 ± 0.44
Fukugita & Peebles (2004)[a]	$(3.4^{+3.4}_{-1.7})h_{70}^{-1}$	$(1.7^{+1.7}_{-0.8})h_{70}^{-1}$	$(5.1^{+3.8}_{-1.9})h_{70}^{-1}$
Marconi et al. (2004)	3.3	1.3	$4.6^{+1.9}_{-1.4}$
Shankar et al. (2004)[b]	$3.1^{+0.9}_{-0.8}$	$1.1^{+0.5}_{-0.5}$	$4.2^{+1.1}_{-1.1}$
McLure & Dunlop (2004)	2.8 ± 0.4	...	...
Wyithe & Loeb (2003)	...	...	$2.2^{+3.9}_{-1.4}$
Aller & Richstone (2002)[c]	1.8 ± 0.6	0.6 ± 0.5	2.4 ± 0.8
Yu & Tremaine (2002)[d]	2.0 ± 0.2	0.9 ± 0.2	2.9 ± 0.4
Merritt & Ferrarese (2001)[e]	...	...	$4.6h_{70}^{-1}$
Salucci et al. (1999)	6.2	2.0	8.2

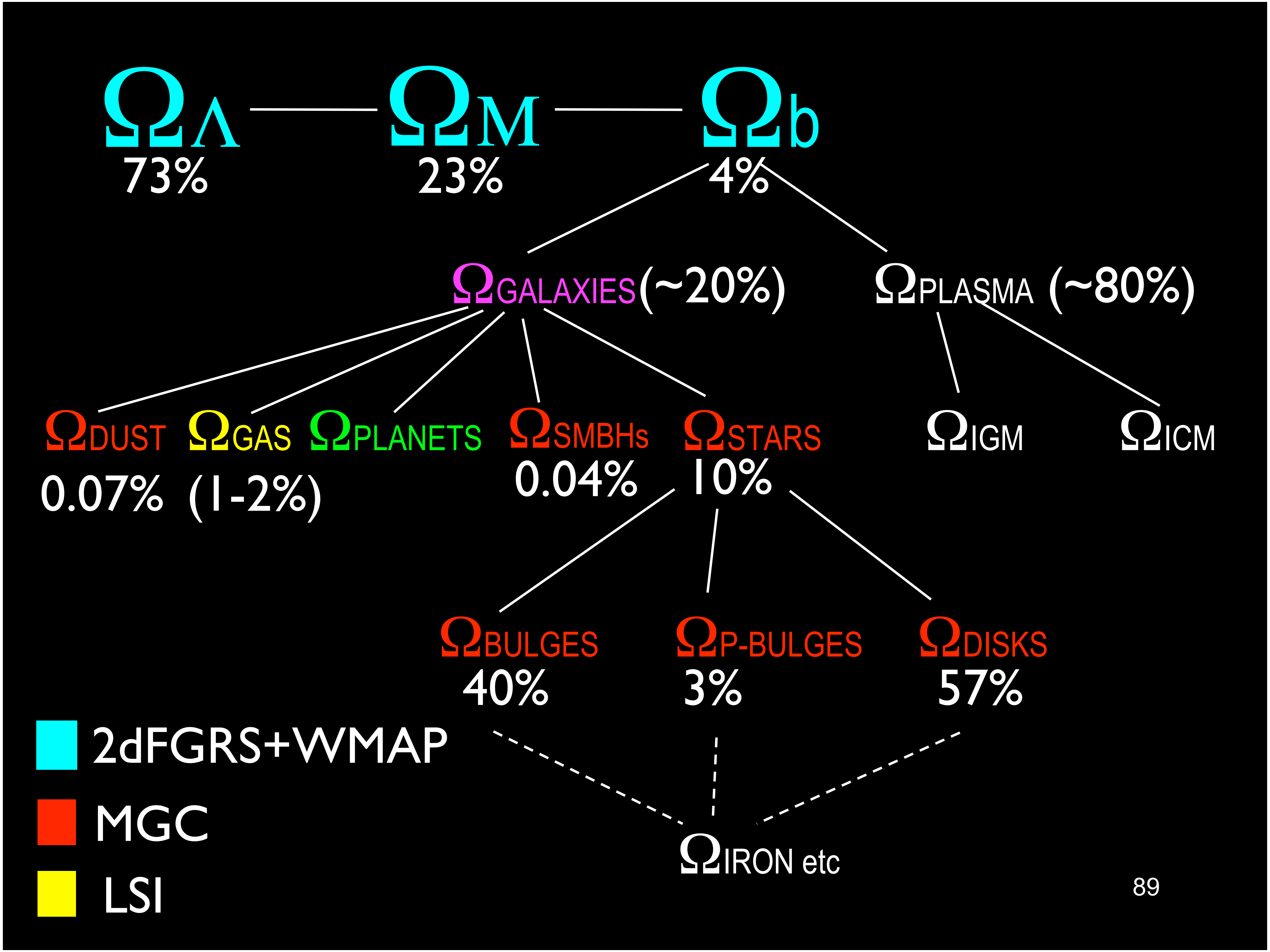
A lot of scatter partly caused by incomplete h corrections

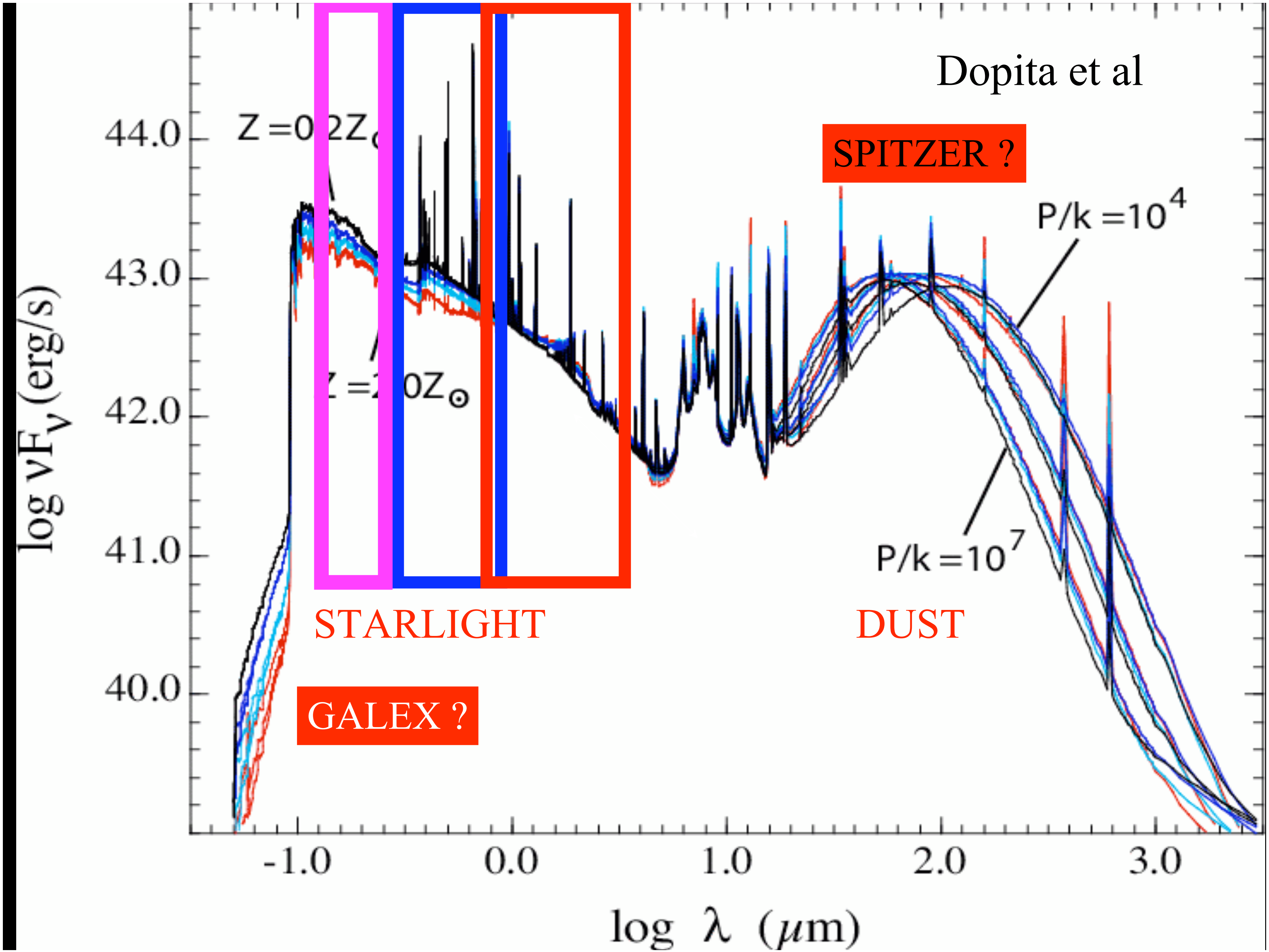
Table of SMBH density estimates

Study	$\rho_{\rm bh,0}$ (E/S0) $10^5 M_\odot$ Mpc^{-3}	$\rho_{\rm bh,0}$ (Sp) $10^5 M_\odot$ Mpc^{-3}	$\rho_{\rm bh,0}$ (total) $10^5 M_\odot$ Mpc^{-3}
This study (Sample 1)	$(3.9 \pm 1.2)h_{70}^3$	$(1.2 \pm 0.6)h_{70}^3$	$(5.1 \pm 1.8)h_{70}^3$
This study (Sample 3)	$(3.7 \pm 1.1)h_{70}^3$	$(1.0 \pm 0.5)h_{70}^3$	$(4.7 \pm 1.6)h_{70}^3$
Wyithe (2006)	...	...	$(1.98 \pm 0.38)h_{70}^3$
Fukugita & Peebles (2004)[a]	$(3.4^{+3.4}_{-1.7})h_{70}$	$(1.7^{+1.7}_{-0.8})h_{70}$	$(5.1^{+3.8}_{-1.9})h_{70}$
Marconi et al. (2004)	$3.3h_{70}^{0.74} f(h)$	$1.3h_{70}^{0.74} f(h)$	$(4.6^{+1.9}_{-1.4})h_{70}^{0.74} f(h)$
Shankar et al. (2004)[b]	$(4.4^{+1.3}_{-1.1})h_{70}^{0.5} f(h)$	$(1.6^{+0.7}_{-0.7})h_{70}^{0.5} f(h)$	$(5.9^{+1.6}_{-1.6})h_{70}^{0.5} f(h)$
McLure & Dunlop (2004)	$(4.8 \pm 0.7)h_{70}^{0.5} f(h)$	...	...
Wyithe & Loeb (2003)	...	...	$(2.1^{+3.4}_{-1.3})h_{70}^3$
Aller & Richstone (2002)[c]	$(4.5 \pm 1.5)h_{70}^{0.39} f(h)$	$(1.4 \pm 1.3)h_{70}^{0.39} f(h)$	$(5.9 \pm 2.0)h_{70}^{0.39} f(h)$
Yu & Tremaine (2002)[d]	$(2.0 \pm 0.2)h_{70}^3$	$(0.9 \pm 0.2)h_{70}^3$	$(2.9 \pm 0.4)h_{70}^3$
Merritt & Ferrarese (2001)	...	...	$4.6h_{70}$
Salucci et al. (1999)	$6.2h_{70}^{1.5}$	$2.0h_{70}^{1.5}$	$8.2h_{70}^{1.5}$

With proper h corrections

see Graham et al (2006)


ΩΛ
73%
ΩM
23%
Ωb
4%
ΩGALAXIES(~20%)
ΩPLASMA (~80%)
ΩDUST
0.07%
ΩGAS
(1-2%)
ΩPLANETS
ΩSMBHs
0.04%
ΩSTARS
10%
ΩIGM
ΩICM
ΩBULGES
40%
ΩP-BULGES
3%
ΩDISKS
57%
ΩIRON etc
2dFGRS+WMAP
MGC
LSI



Dopita et al
SPITZER ?
GALEX ?
STARLIGHT
DUST
P/k =10^4
P/k =10^7
log νF_ν (erg/s)
log λ (μm)
44.0
43.0
42.0
41.0
40.0
-1.0
0.0
1.0
2.0
3.0

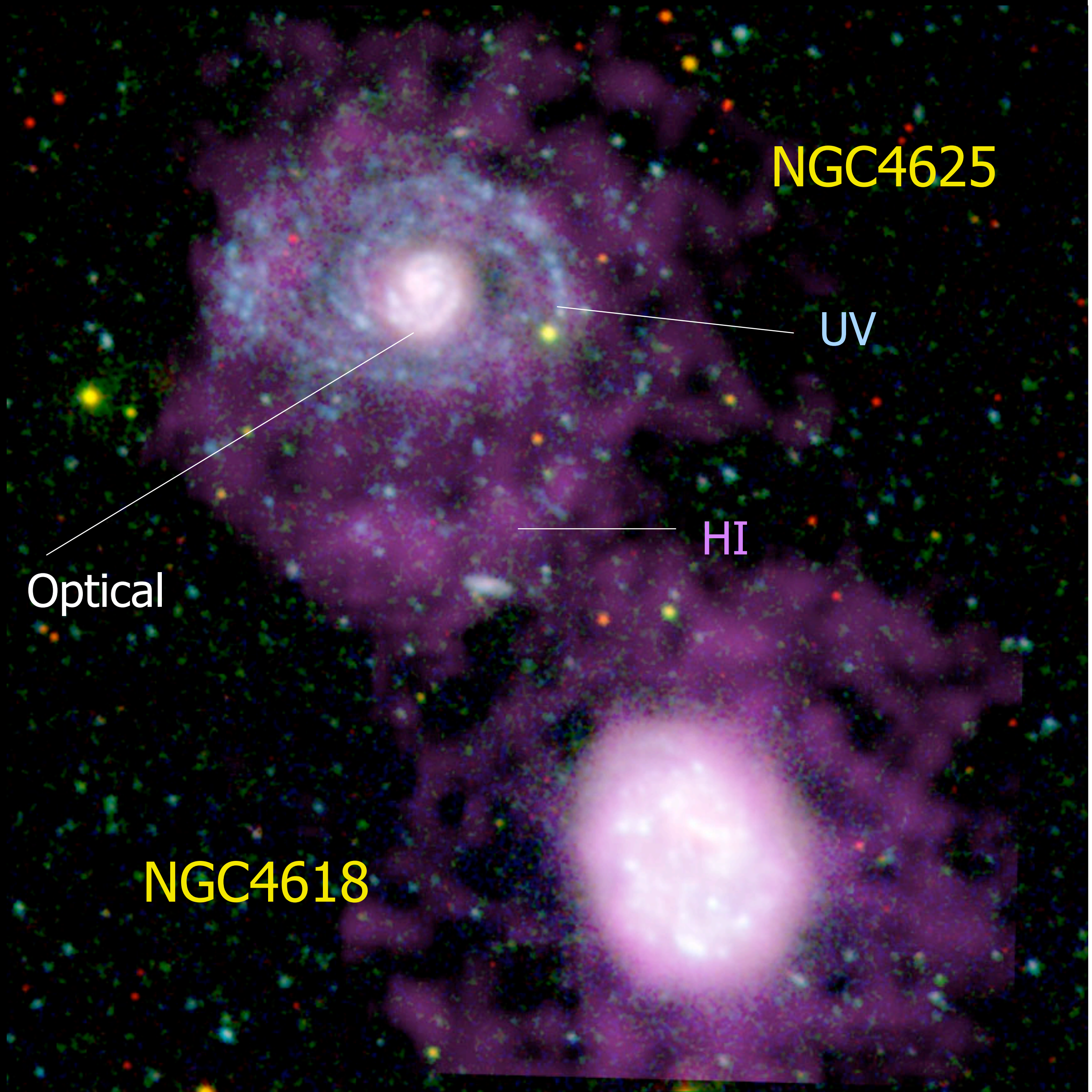
GALEX Imaging of NGC4625

Disk 4 times larger in the UV than in optical

Young stars forming rapidly out of hydrogen cloud

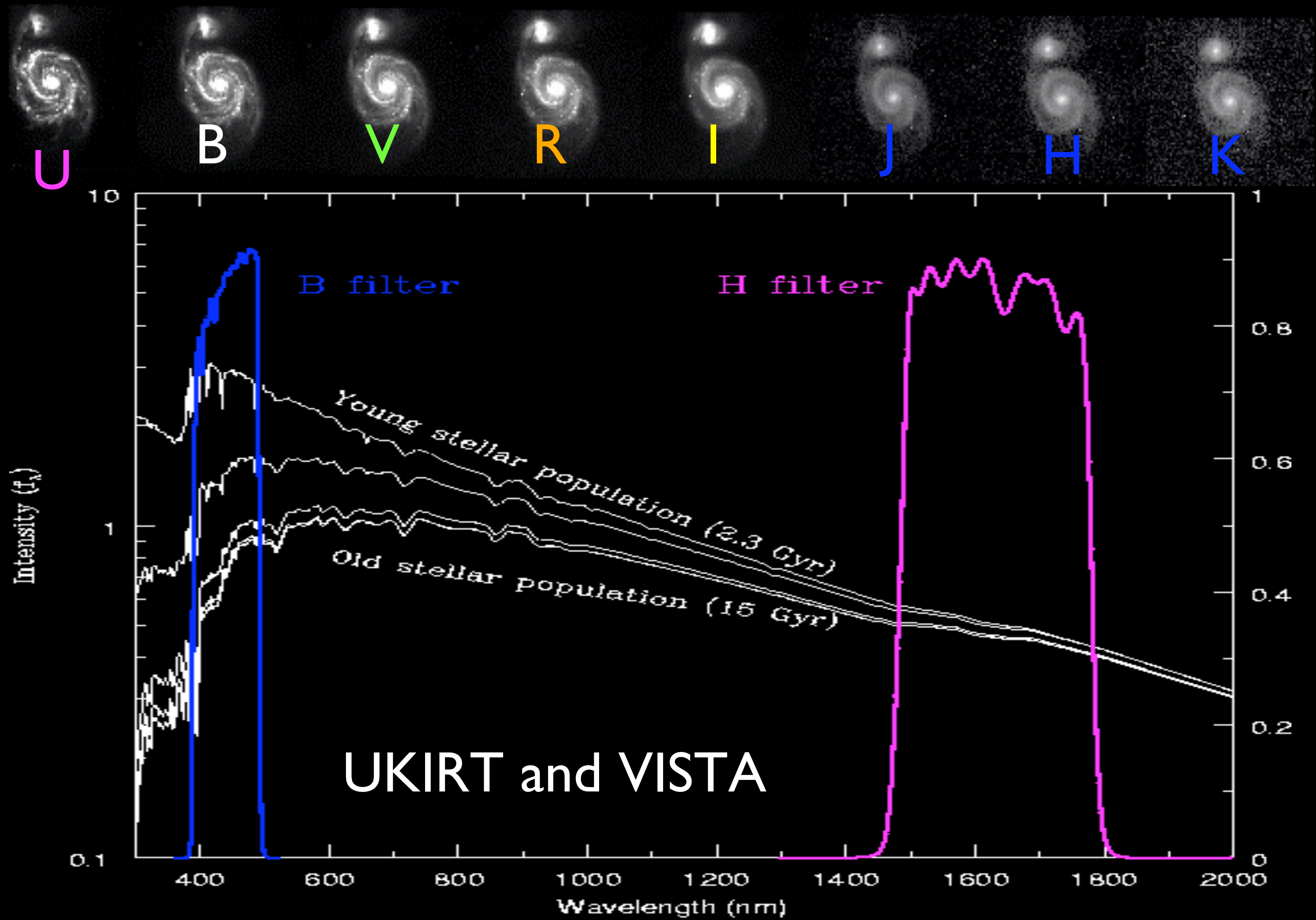
System resembles galaxy formation in the early universe?

Need xNTD to obtain HI measurements for all MGC



Gil de Paz et al. 2005

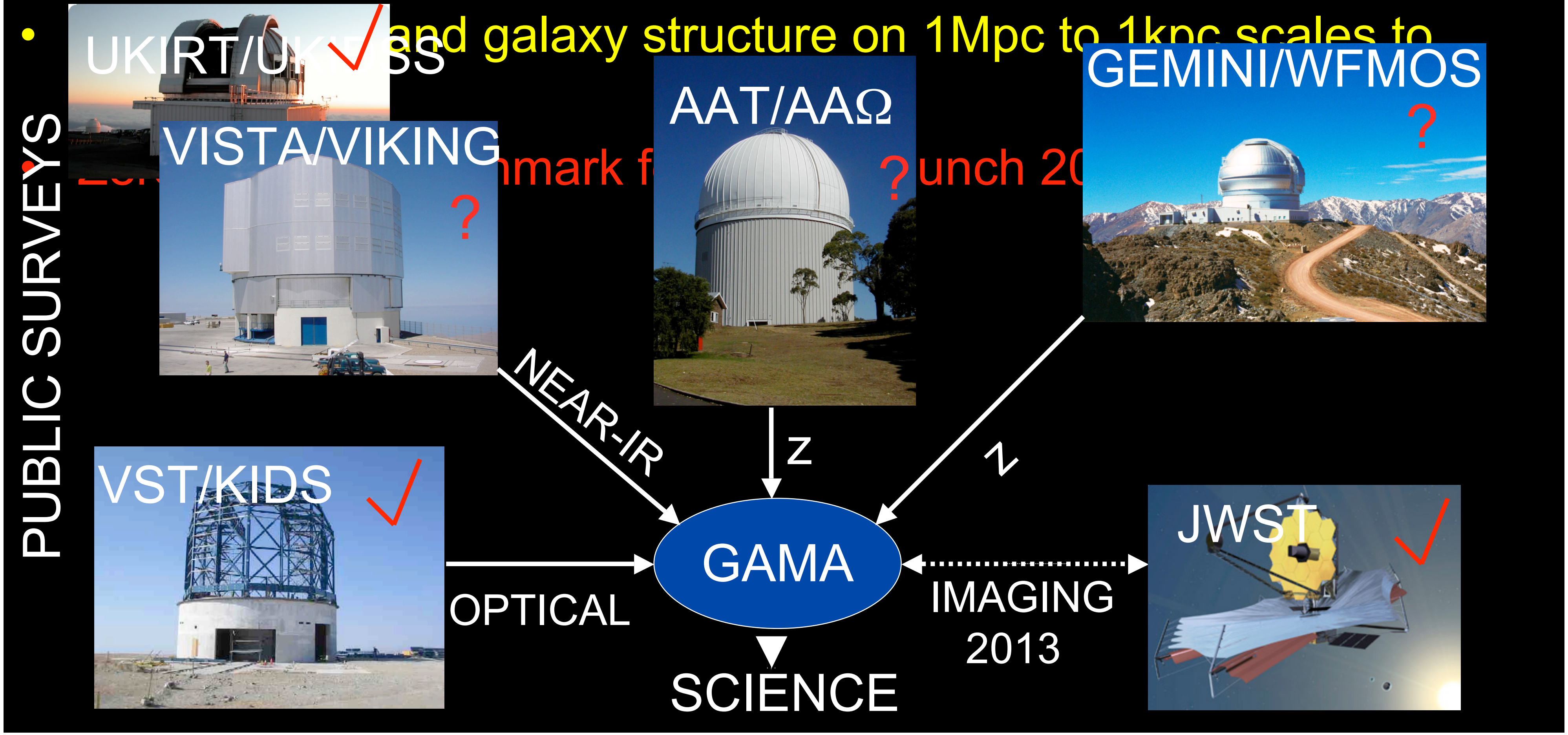
The Near-IR



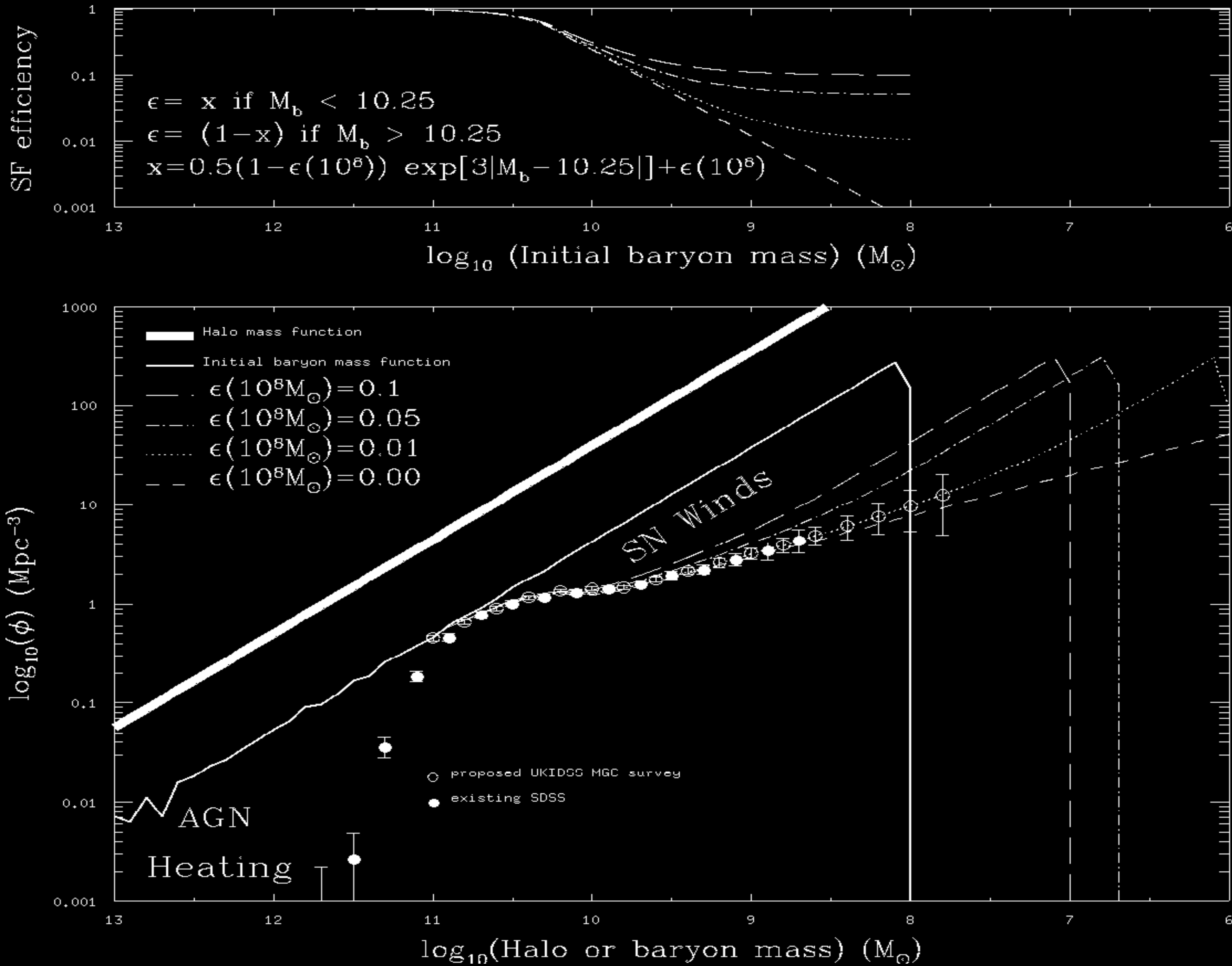
UKIRT and VISTA

Galaxy And Matter Assembly

- **300 sq deg ugrizJHK sub-arcsec** deep imaging and spectroscopic survey
- St Andrews (Driver), Edinburgh (Peacock), LJMU (Baldry), ESO (Liske)
- and galaxy structure on 1Mpc to 1kpc scales to
- mark f unch 20



Constraining SN feedback ?



Summary

- Galaxy luminosity function only known: -21 < M < -16 but galaxies known to M= -3 !
  - Galaxy record woefully incomplete at z=0.0 must try harder by going fainter !
  - Dwarf domain more complex & entirely uncharted (great VST/VISTA op.)
- Galaxy bimodality seen in both colour and Sersic-index
  - Bimodality best explained by Bulges & Disks
  - Bulges bimodal ? (detection of pseudo-bulges ?)
  - Red bulges form early via collapse (coeval with AGN peak ?)
  - Blue spheroid population exists (downsizing pop or classif'n error ?)
  - Disks form later via infall/merging/splashback (coeval with SFR and from inside-out?)
  - Pseudo-bulges via secular evolution (post-Lambda evolution ?)
- Formation mechanisms = evolutionary markers => spatial studies
- The baryons are distributed as follows (~20 % in galaxies), as follows:
  - 10% in stars (60% disc, 30% bulge, 10% spheroids)
  - 1-2 per cent in neutral hydrogen gas,
  - 0.07 per cent in dust,
  - 0.04 per cent in SMBHs
- Dust a major problem in optical must now switch to near-IR (UKIRT & VISTA) and
  - Expand survey to include dwarf population etc (GMOS/AAOmega) PENDING
  - Improve imaging resolution to 1kpc at z=0.1(VST KIDS) YES
  - Add near-IR to penetrate dust (UKIDSS/VIKING) YES/PEND
  - Extend in redshift (HST/JWST, GTO JWST) YES
  - Obtain HI (xNTD and SKA) SUPA II opportunity ?
  - Develop a decent galaxy photometry pipeline (PPARC/WFU ?) ???