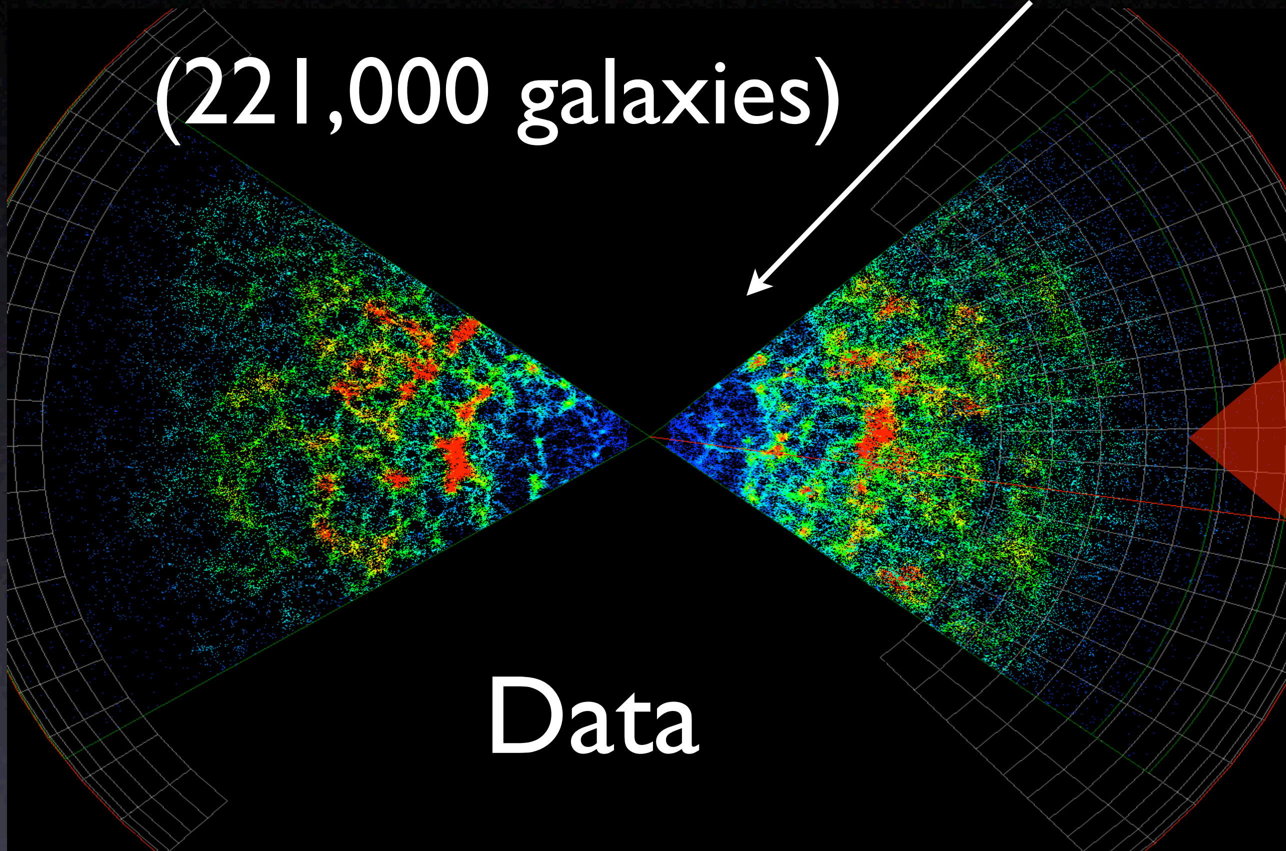
Untangling galaxy formation and evolution

Simon Driver (RSAA)

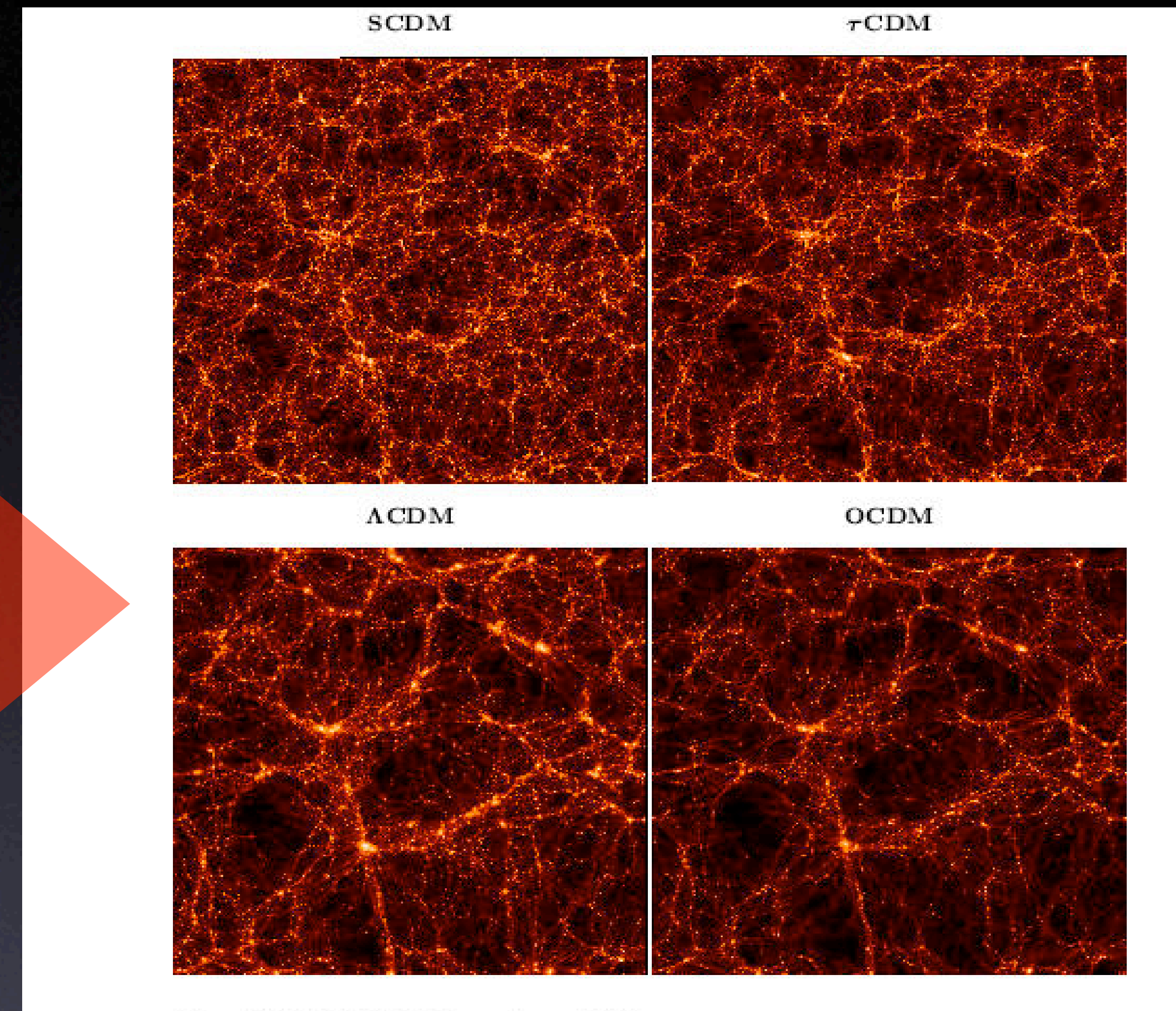
- Premise: ”To understand the evolution of the baryons (i.e., galaxy evolution) demands the study of the distinct structural properties of galaxies at all epochs --- the construction and deconstruction of the extra-galactic fossil record”
- Perspective: Concordance Cosmology
- Motivation: Omega baryon (Ωb,) physics, galaxies and galaxy evolution
- Approach: The Millennium Galaxy Catalogue
- [Progress: LF, BBD, merger rate, SMBH mass fn, galaxy opacity, bulge-disk decomp’]
- Progress: Bimodalityies blue spheriods, bulges, pseudo-bulges, disks and dwarfs
- Progress: 6dfGS and climbing the dwarf galaxy mountain
- Future Plans: MGC II (AAOmega+VST+VISTA+ARECIBO+GMOS+SUBARU)
- Summary

Concordance Cosmology

- WMAP CMB studies + 2dFGRS (221,000 galaxies)



Simulations



- Universe comprises, Cole [Driver] et al (2005):
  - 73% Dark energy, Ω_Λ - intrinsic property of space-time
  - 23% Dark matter, Ω_M - invisible cold dark matter
  - 4% Baryonic matter, Ω_b - 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:

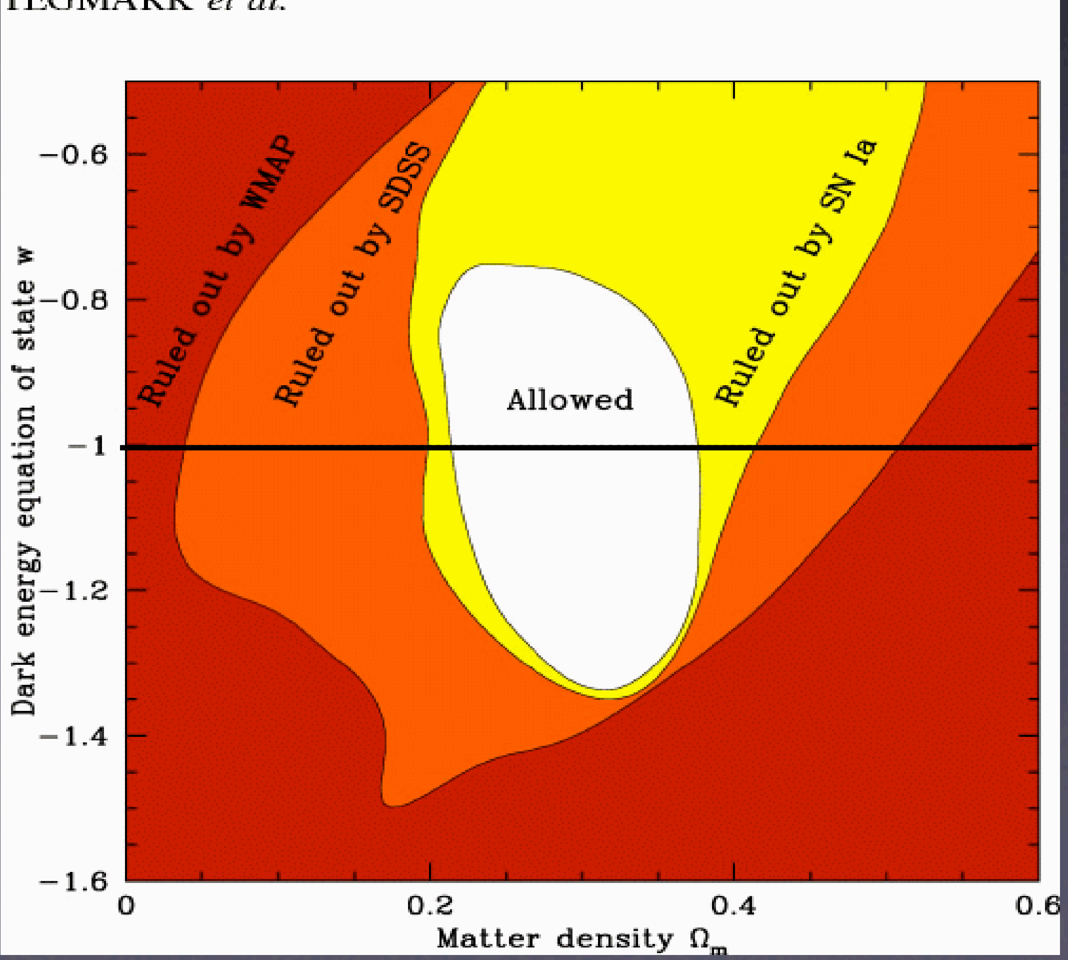
$$dE = -pdV, \rho = wp, if \rho = const, w = -1?$$

ESSENCE, SNAP, PLANCK, WFMOS

Observationally straightforward

Current constraint already significant:

TEGMARK *et al.*



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 = physics

Baryons --> complexity

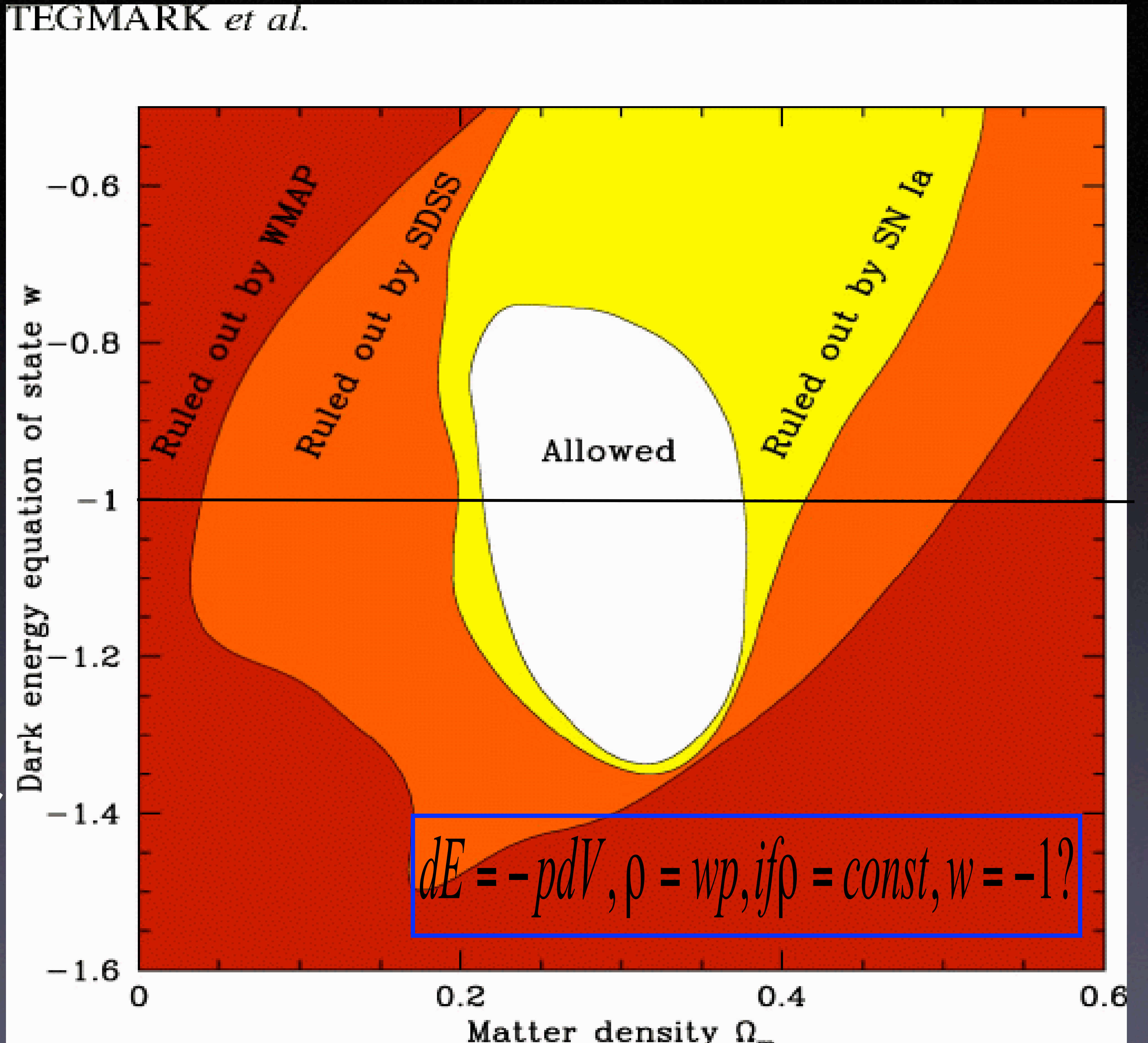
(metals, planets, life)

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

If w is essentially measured (?) and Dark Matter is awaiting a CERN detection what next for Cosmology ?



Ω_Λ — Ω_M — Ω_b

73% 23% 4%

COMPLEXITY

- 2dFGRS+WMAP
- MGC
- LSI

Cosmology: Energy to Iron

EARLY UNIVERSE

- Hot Big Bang (GR+QM+PP+TD) --> production of matter and energy
- Inflation --> rapid exponential expansion = flat universe
- Quark Soup --> all possible particles and photons in thermal equilibrium
- Symmetry breaking by Higgs Boson --> excess of matter & photons
- Baryosynthesis/Quark-Hadron phase transition --> mesons and baryons
- Nucleosynthesis --> H, D, He and Li production
- Decoupling of radiation & matter --> The Cosmic Microwave Background

---

BARYONIC MATTER IN A NEUTRAL SMOOTH GAS OF LIGHT ELEMENTS

OBSERVATIONAL REGIME

- Gravitational instabilities --> galaxy formation
- AGN/SMBH formation + First stars --> Re-ionisation & Nucleosynthesis
- Violent galaxy evolution --> galaxy mergers, SMBH coalescence etc
- Second phase of inflation --> Cosmological constant/Dark Energy
- Secular galaxy evolution --> pseudo-bulges, bars, cool disks
- Stardust --> Planets --> Life

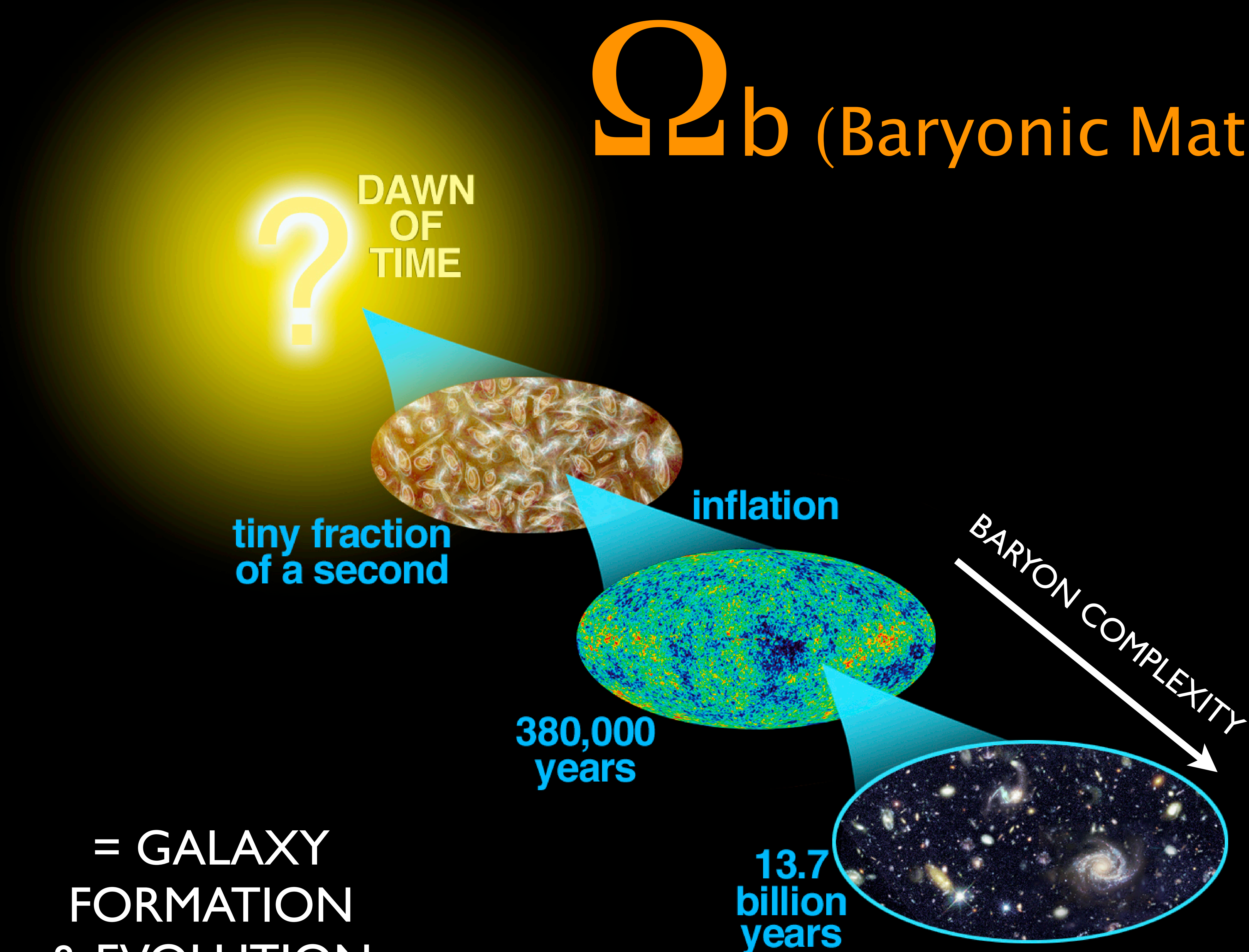
HOW IS THE MATTER DISTRIBUTED TODAY ?

➡ Cold isolated metal-rich super-galaxies awash with low energy photons ?

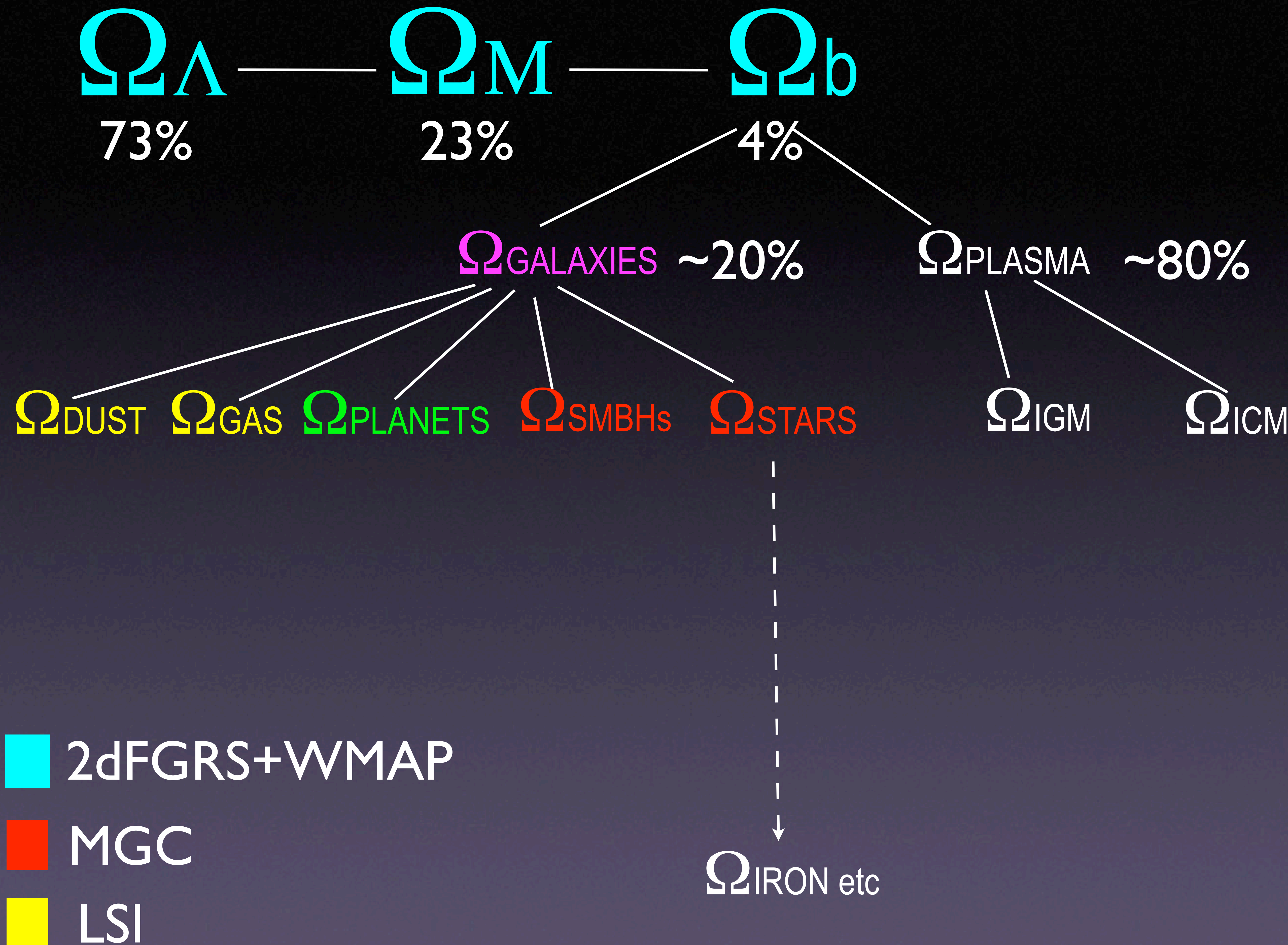
ADIABATIC EXPANSION

TIME
ENTROPY
SIZE
METALS
7 Param's.

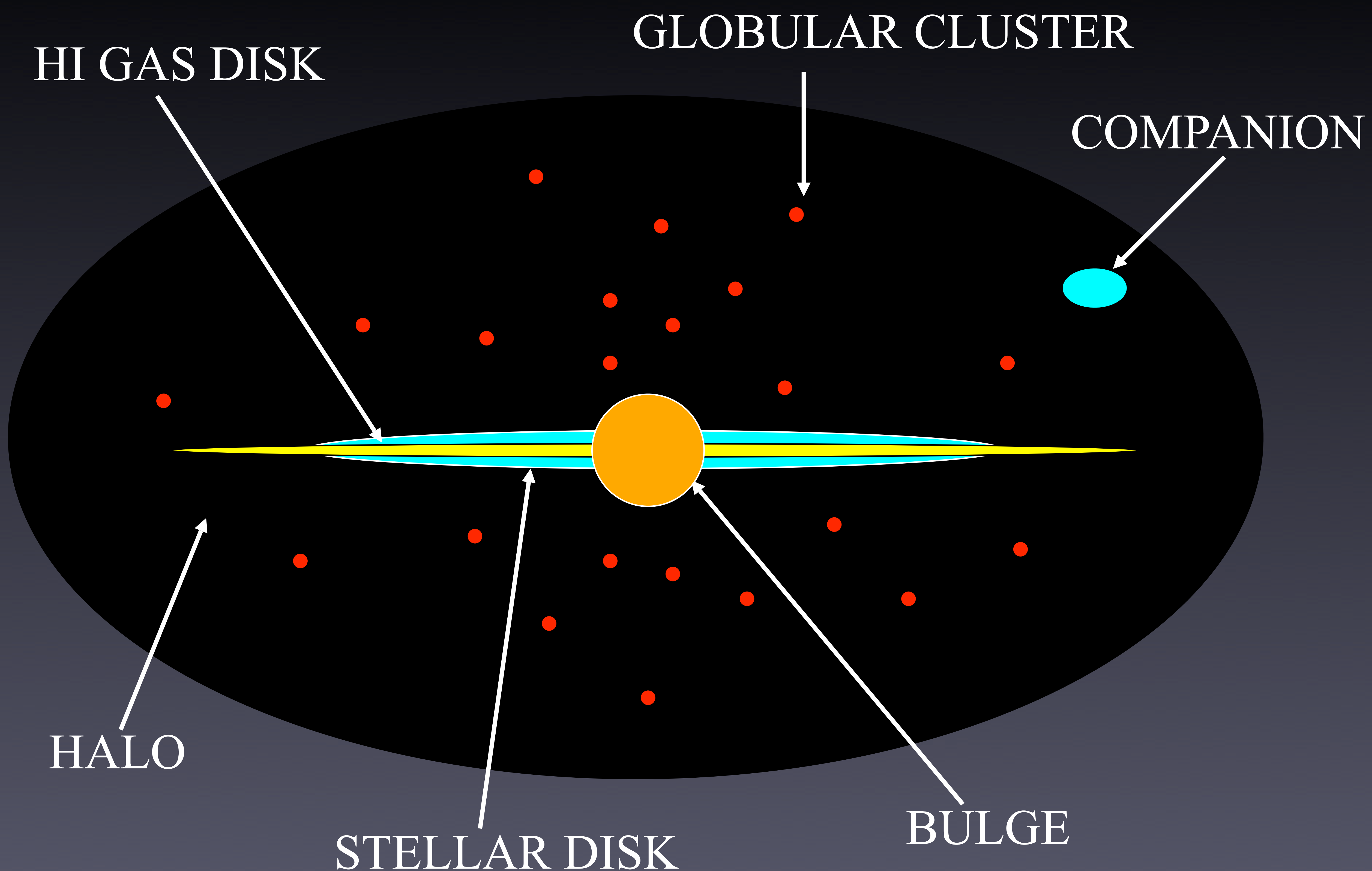
Ωb (Baryonic Matter)



= GALAXY FORMATION & EVOLUTION

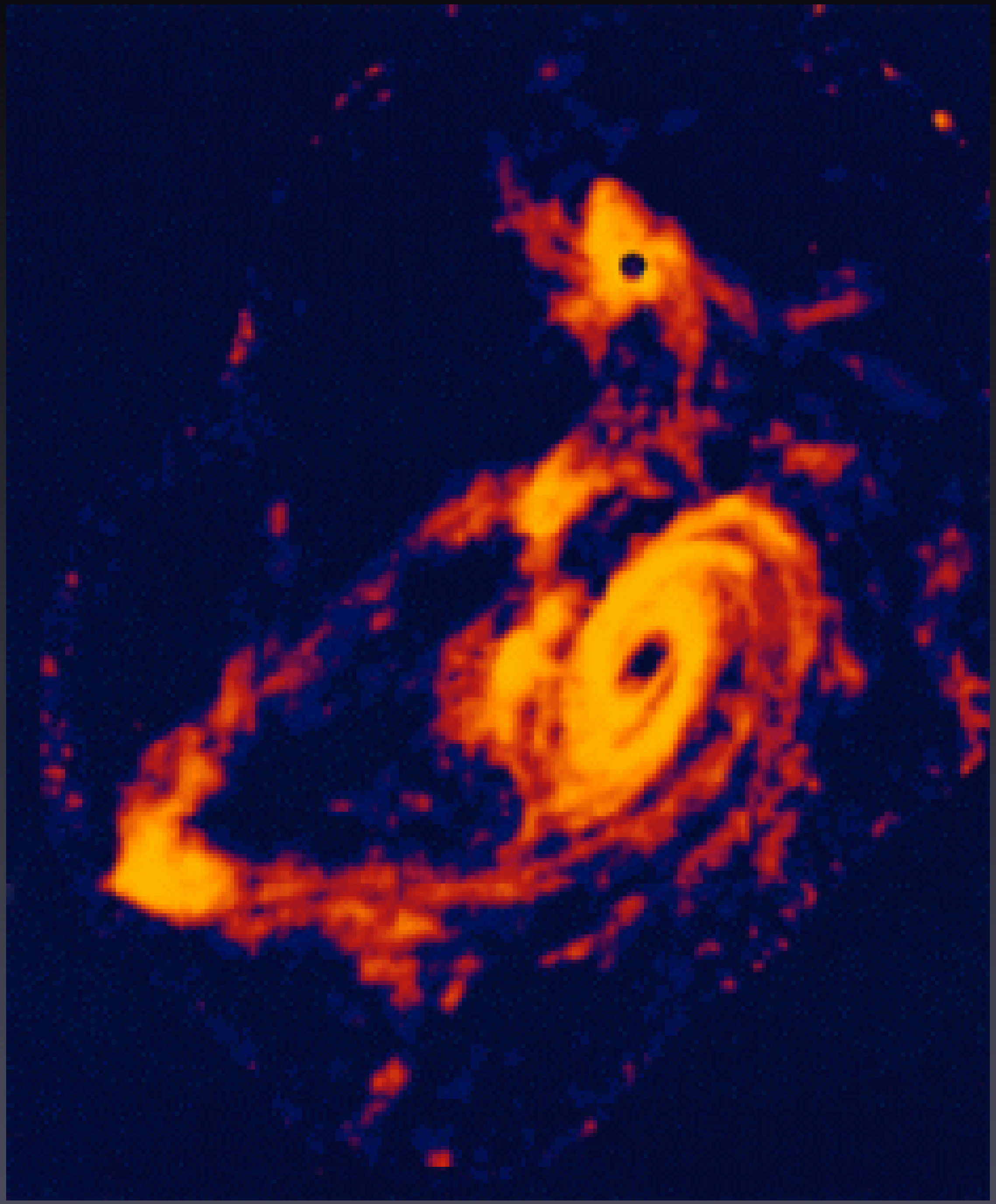

Ω_Λ
73%
Ω_M
23%
Ω_b
4%
$\Omega_{GALAXIES}$ ~20%
Ω_{PLASMA} ~80%
Ω_{DUST}
Ω_{GAS}
$\Omega_{PLANETS}$
Ω_{SMBHs}
Ω_{STARS}
Ω_{IGM}
Ω_{ICM}
$\Omega_{IRON\ etc}$
2dFGRS+WMAP
MGC
LSI

Our Working Galaxy Model

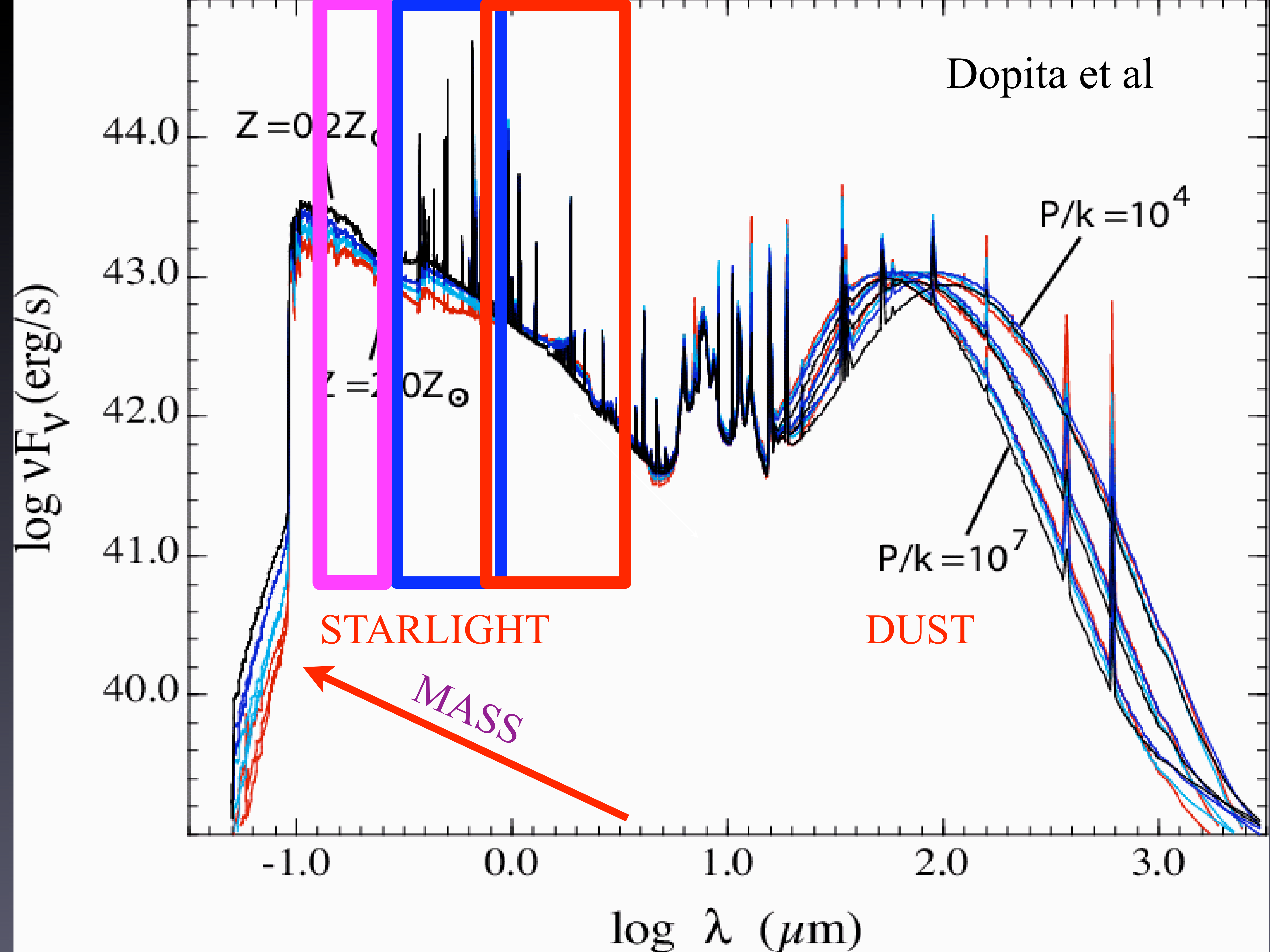


Distribution of Gas and Stars

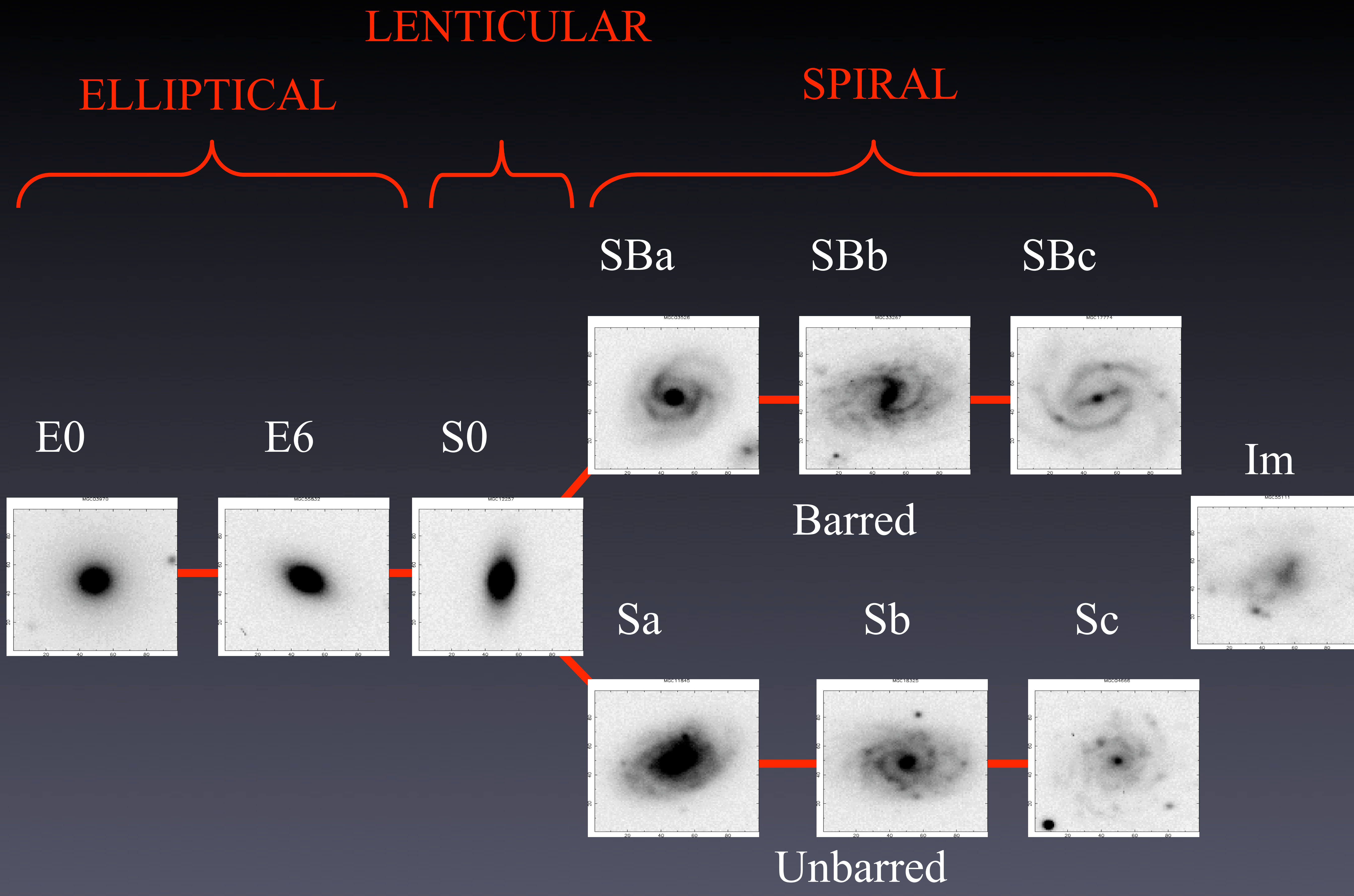
STARLIGHT



GAS (HI)



Dopita et al
Z = 0.2Z⊙
Z = 2.0Z⊙
P/k = 10^4
P/k = 10^7
STARLIGHT
DUST
MASS
log νFν (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



LENTICULAR
ELLIPTICAL
SPIRAL
SBa
SBb
SBc
E0
E6
S0
Im
Barred
Sa
Sb
Sc
Unbarred

Galaxy formation (theory)

- 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)

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 & Hausman1977)

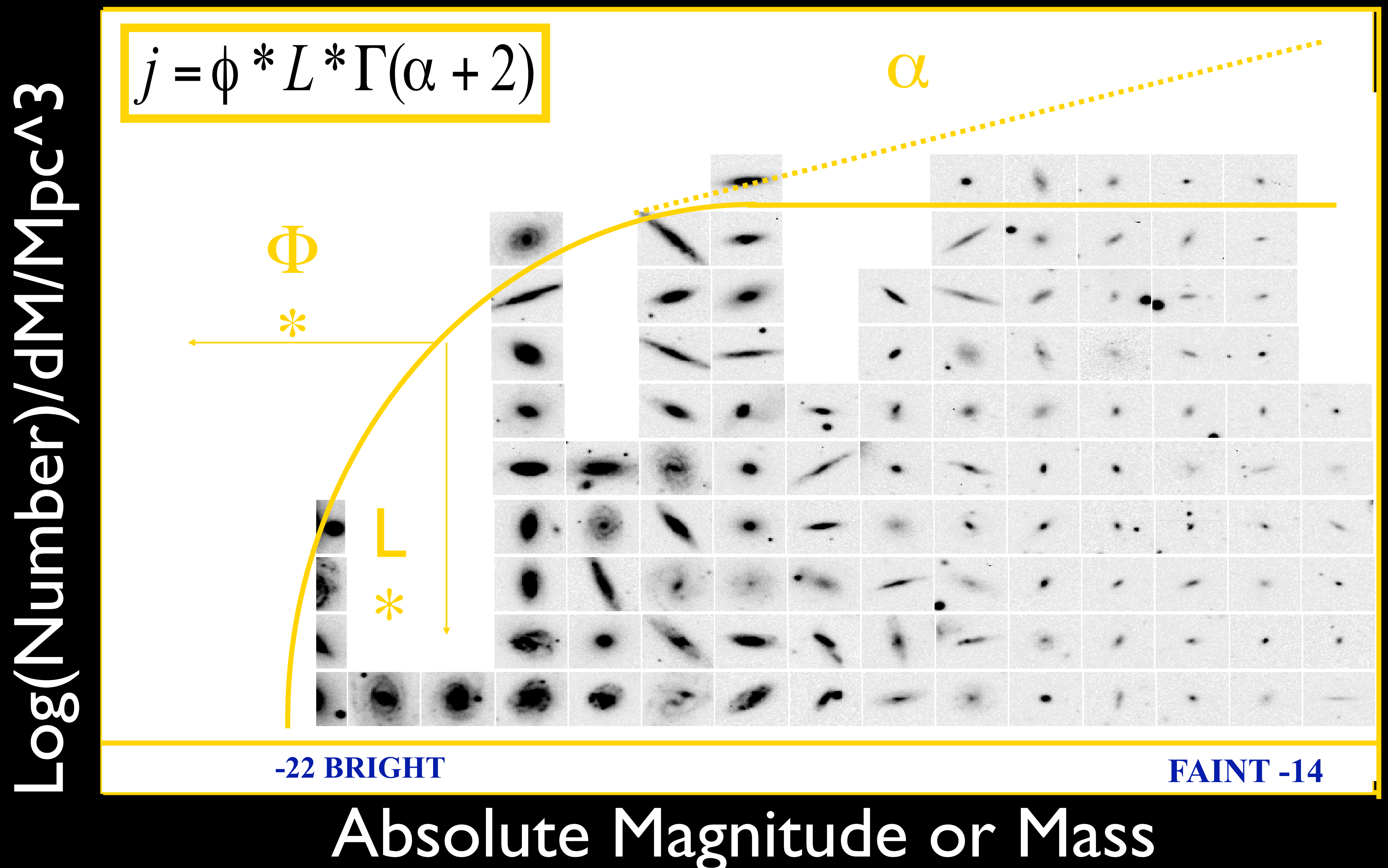
!

Galaxy formation (sims)

- Numerical:
  - 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 2005):
  - 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

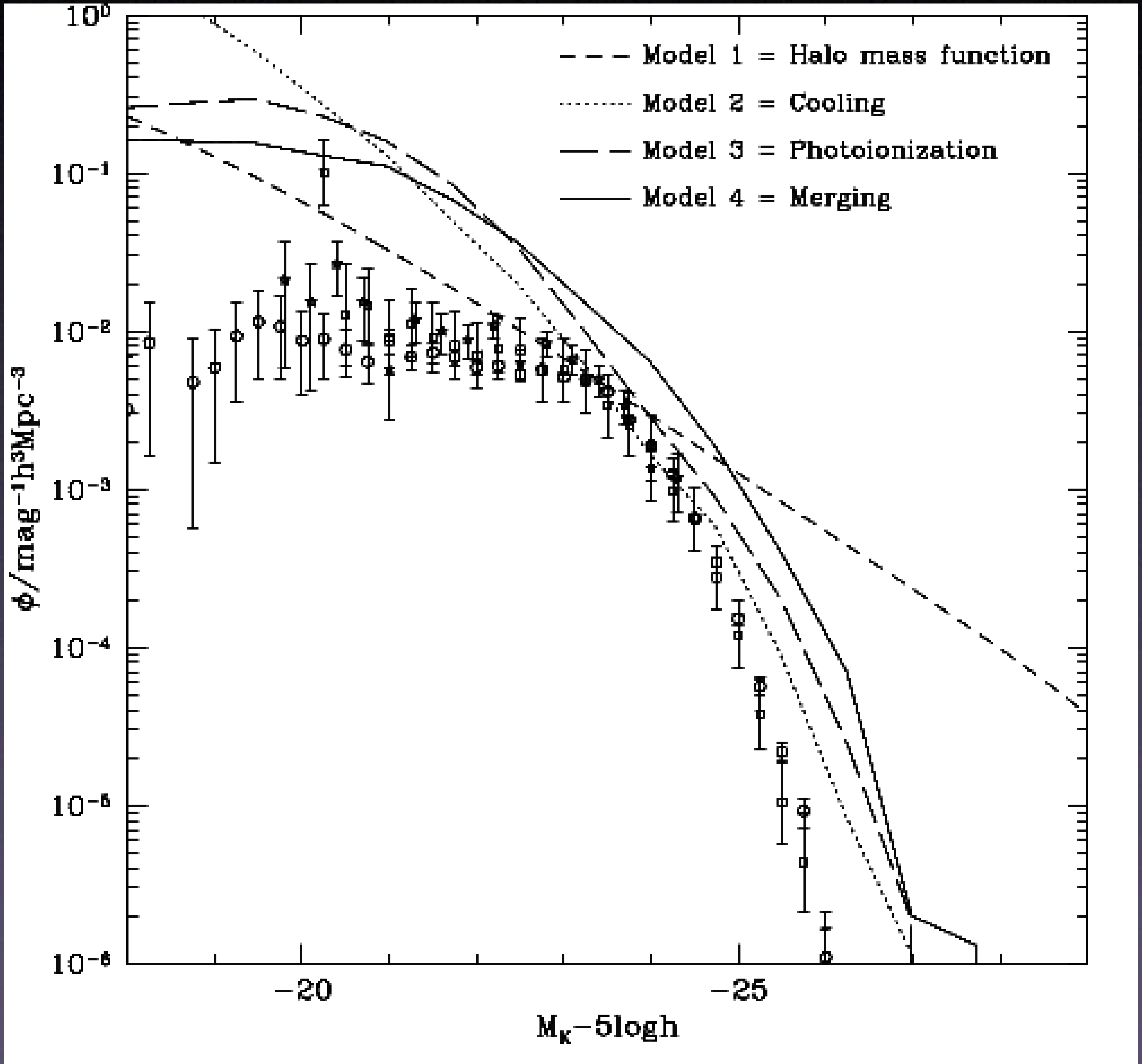
Luminosity Functions and Ω's

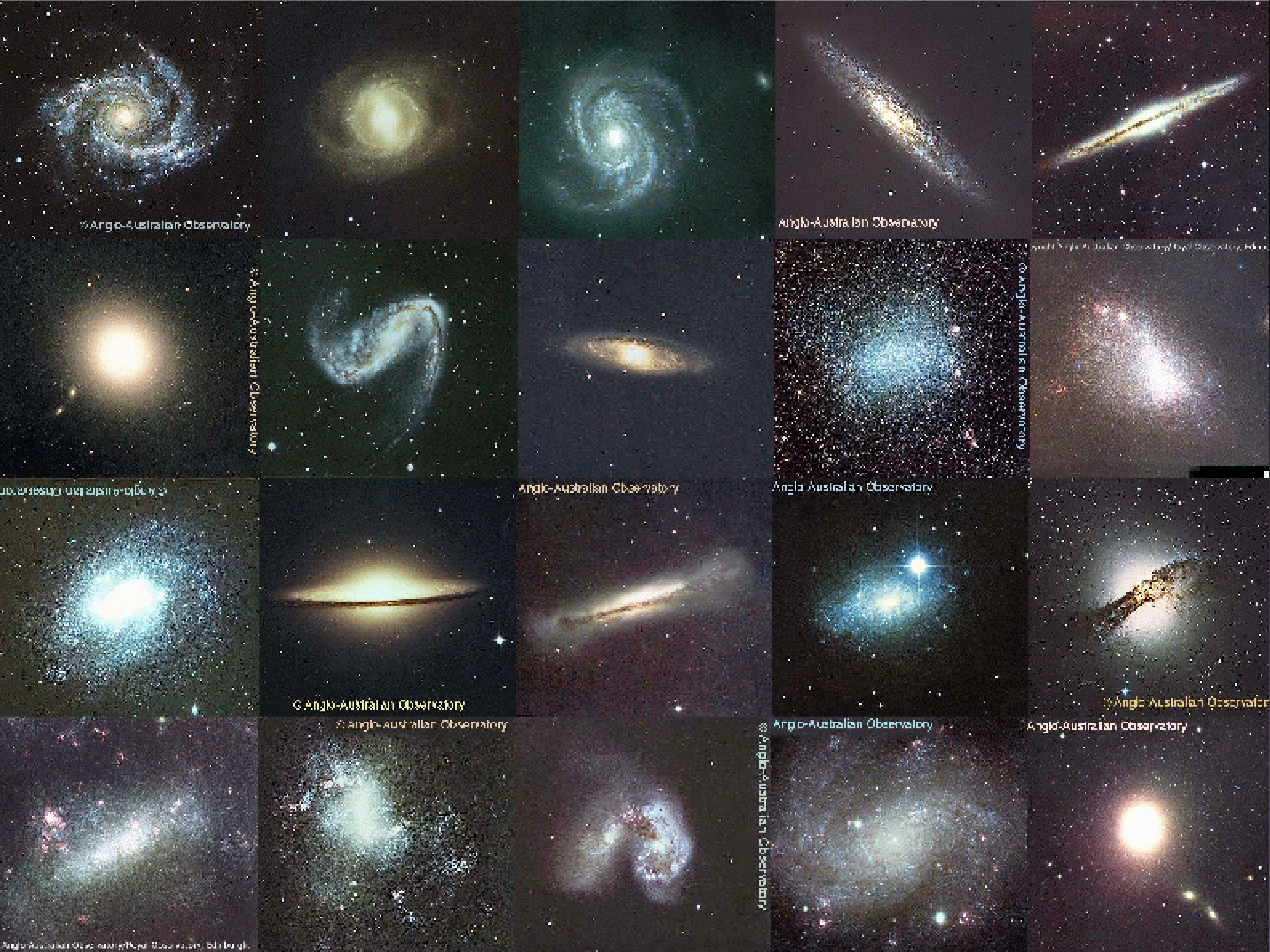
- Schechter fn (1976) developed from Press Schechter theory
- Essentially a Gamma function (power law + exponential)
- Directly yields luminosity and mass density (i.e., Omegas)
- A foundation measurement vital for all of extragalactic astronomy



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 Observator
© 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
- SMBH-AGN-bulge connection
- No of SMBH coallescences in E's ~<0-2
- Colour 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

▸ Anti-hierarchical evolution ==> downsizing !

37 sq degrees to B=24 mag

The Core MGC Team

Simon Driver (RSAA)
(Proposals/Vision/
Galaxy Populations & Evolution)

Alister Graham (RSAA)
(Interpretation/
Galaxy Structure/
SMBHs)

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

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

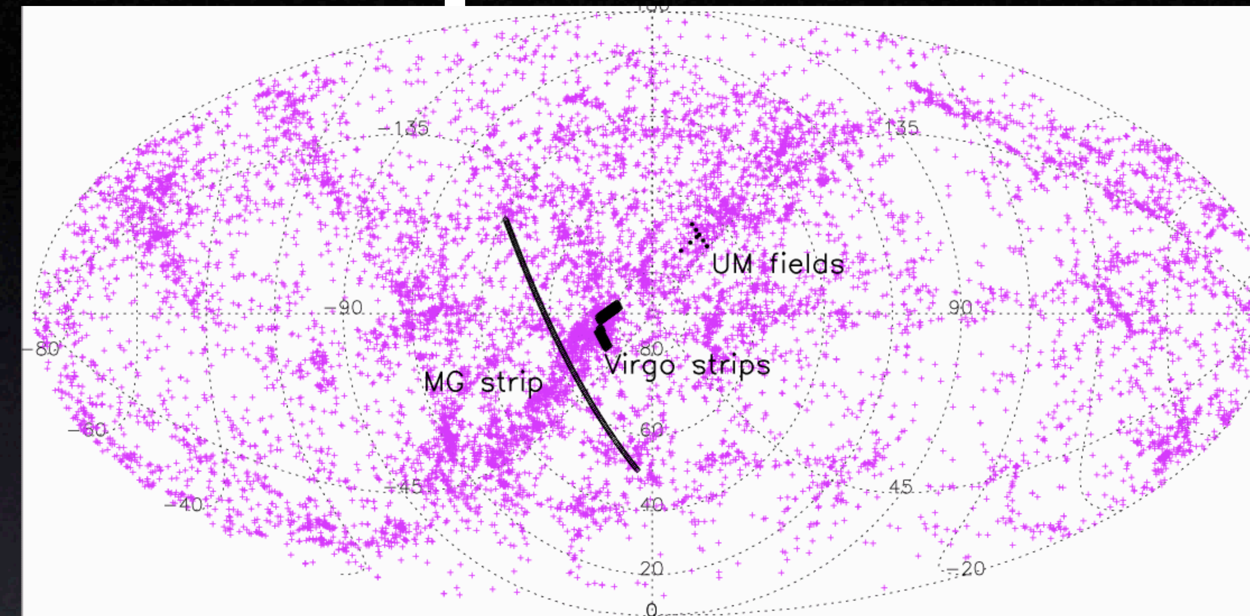
Ewan Cameron (RSAA)
(PhD Training)

MGC Collaborators

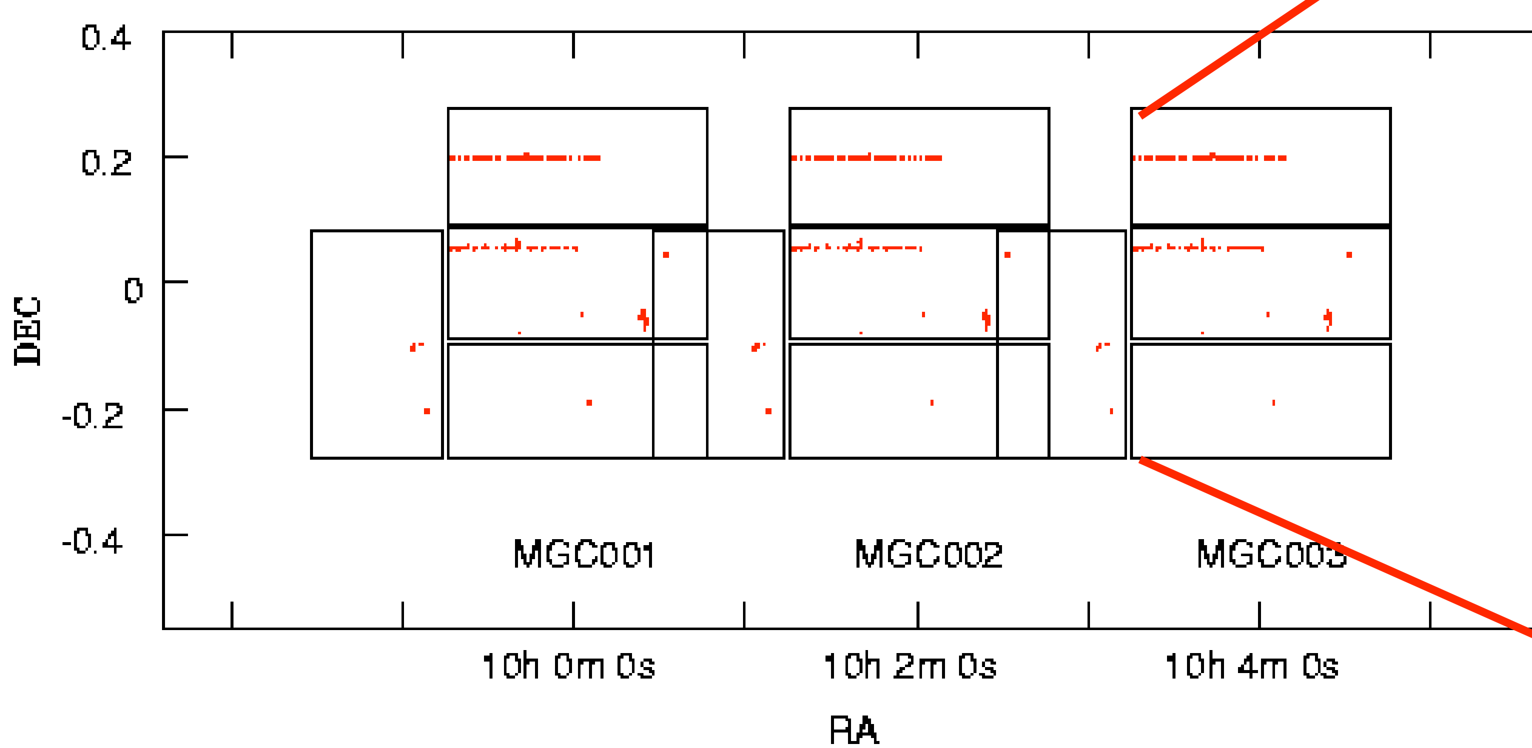
Nicholas Cross
Roberto De Propris
Simon Ellis
Steve Phillipps
Chris Conselice
Warrick Couch
John Peacock

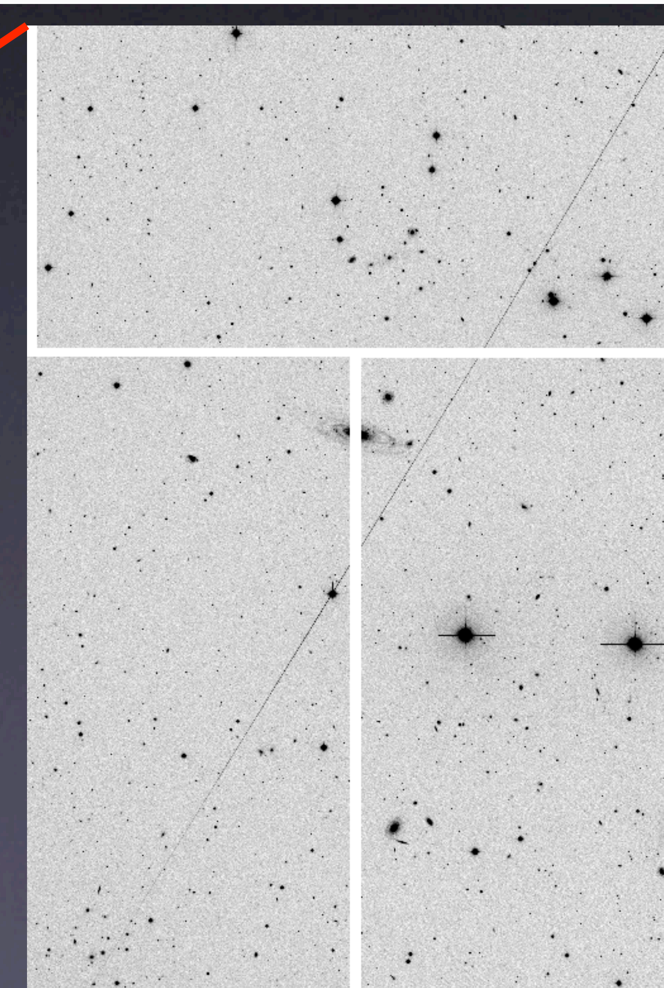
The WFC Footprint

- 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, ~1M to B=24

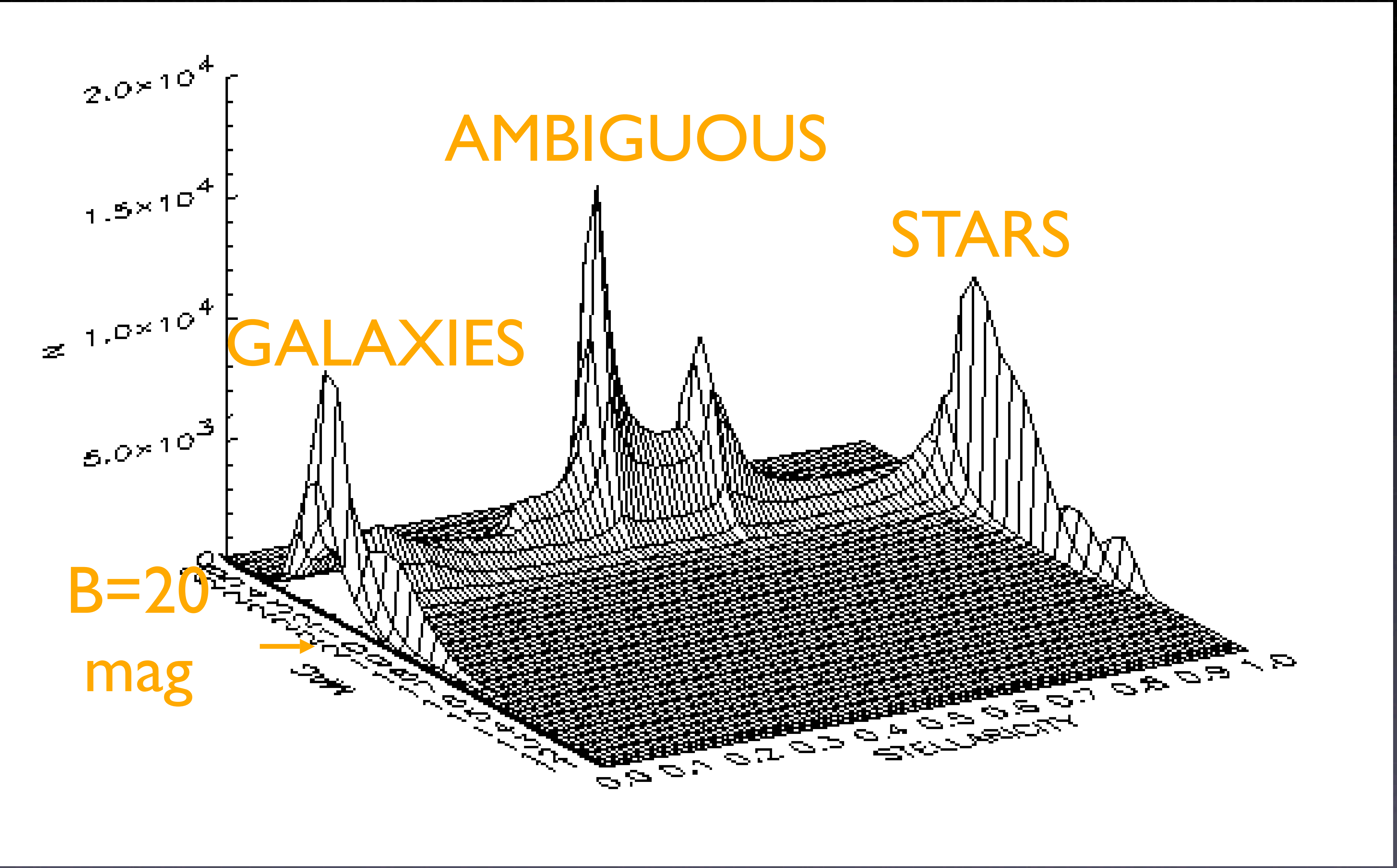


FIRST THREE POINTINGS





Star/galaxy separation



Viable to B ~ 21 mags,

For B > 21 mags use statistical method

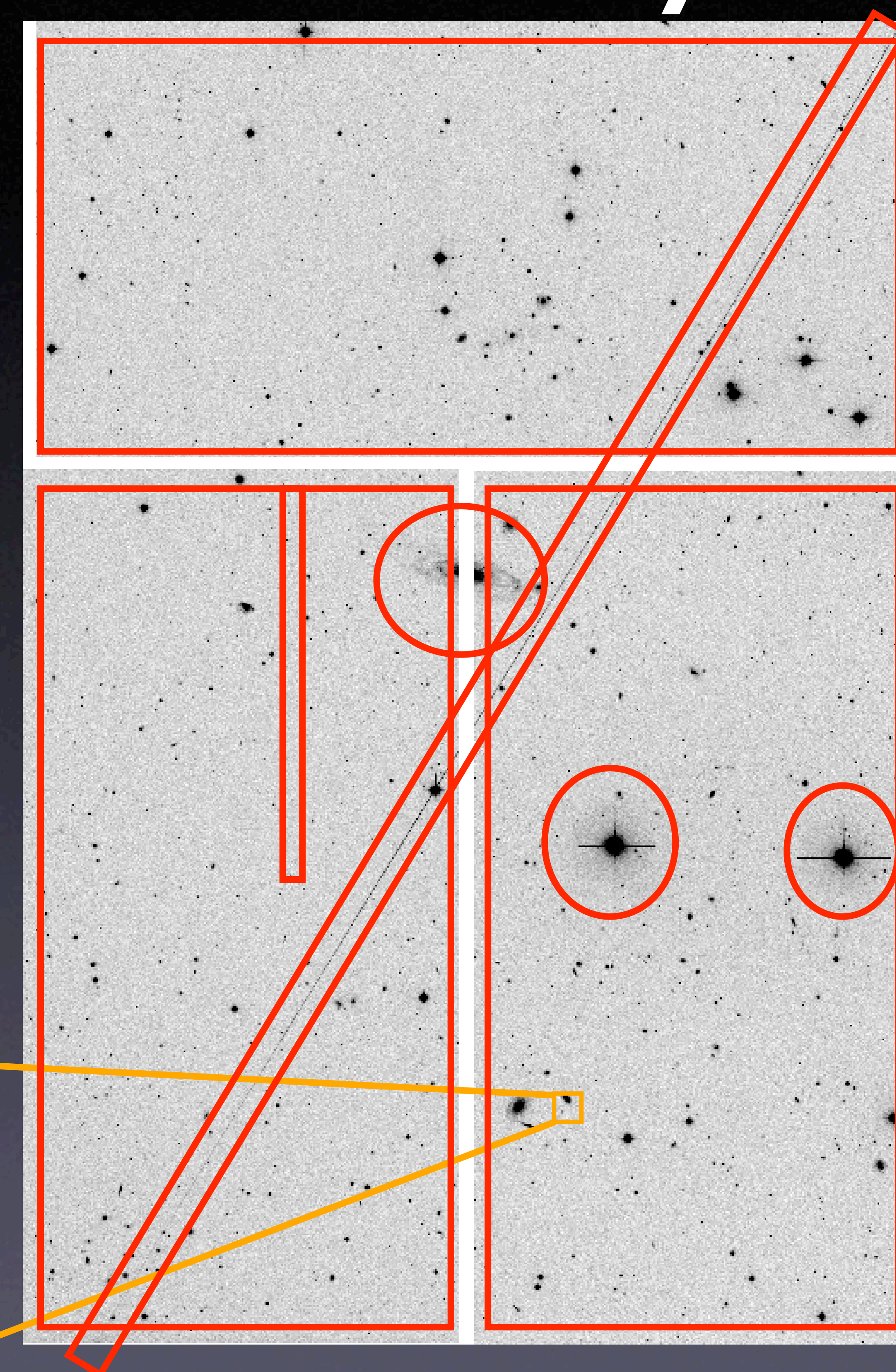
Image Detection and Analysis

- 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 < 20mag 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%)

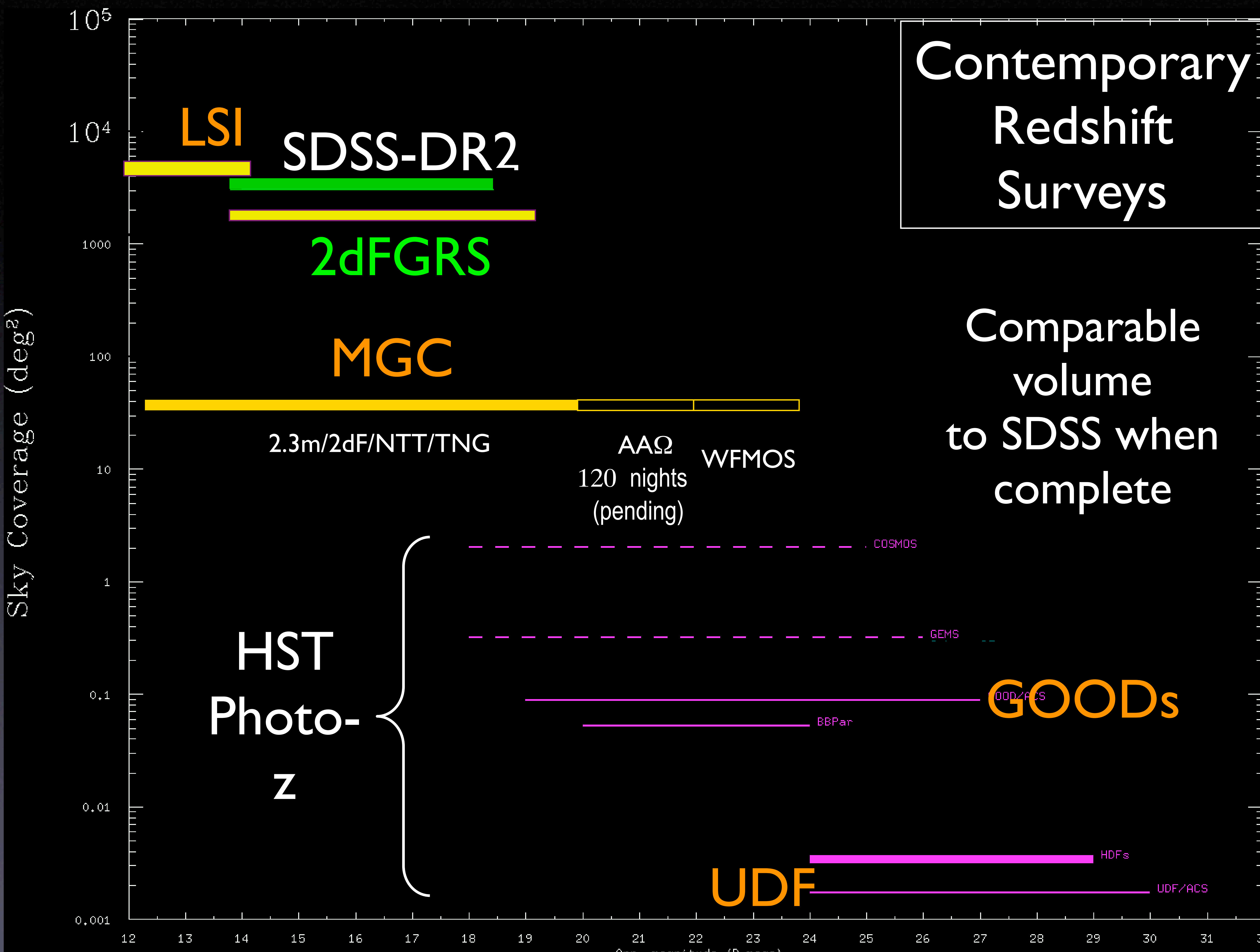
  I.e., 20% contamination !

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

m=16th mag

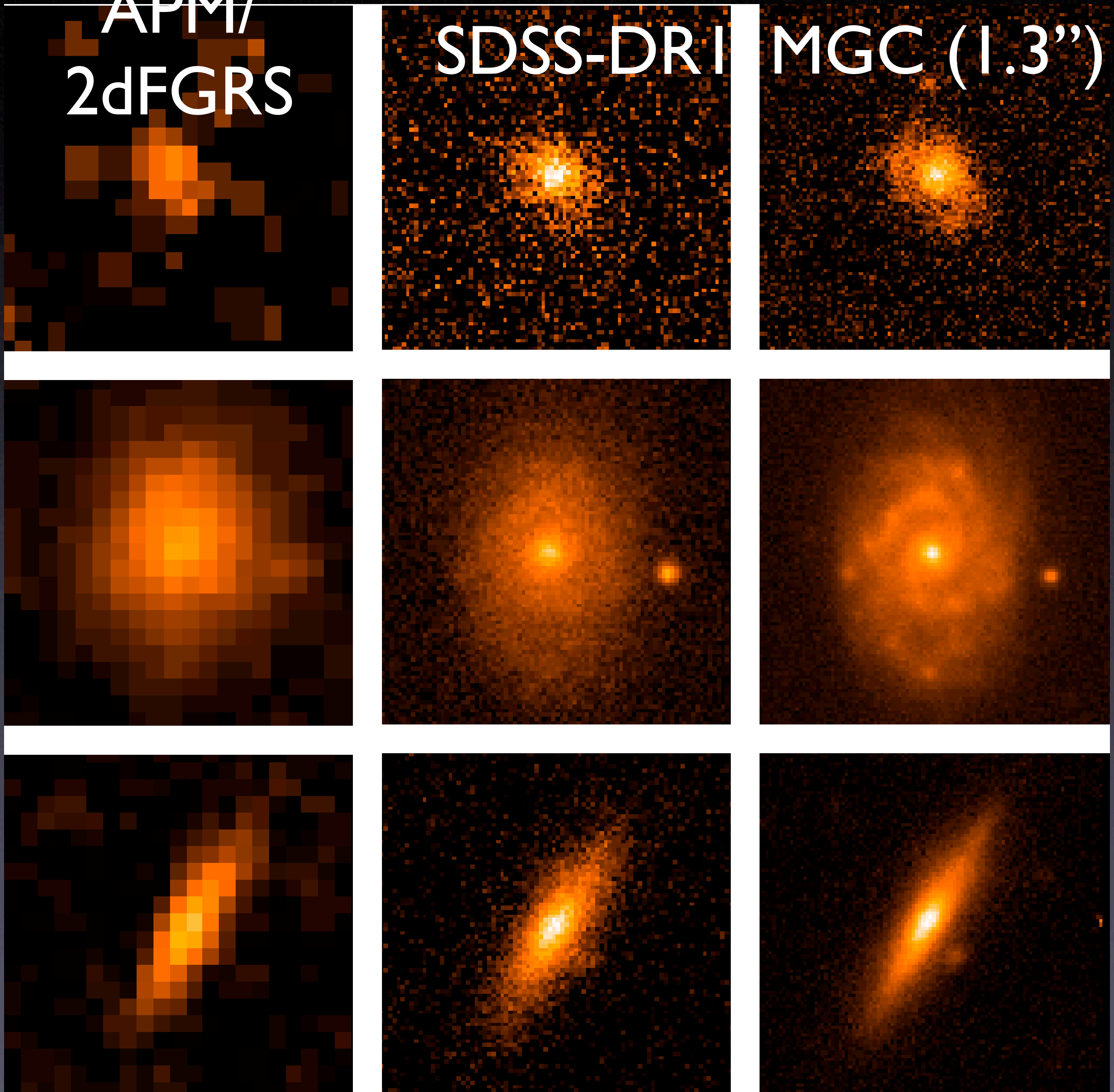


20’

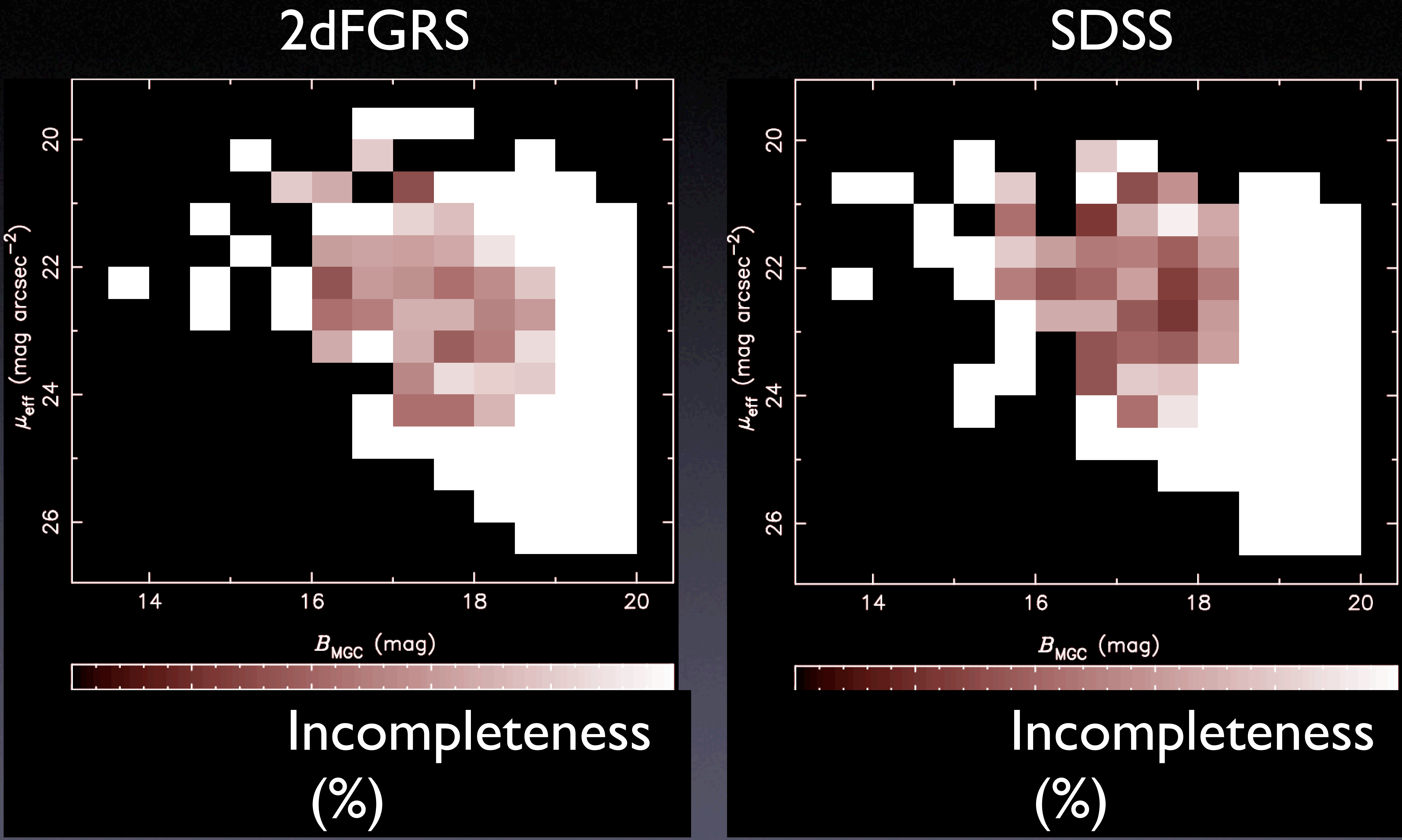


Contemporary Redshift Surveys
LSI
SDSS-DR2
2dFGRS
MGC
2.3m/2dF/NTT/TNG
AAΩ
120 nights (pending)
WFMOS
Comparable volume to SDSS when complete
HST Photo-z
COSMOS
GEMS
GOODs
BBPar
HDFs
UDF
UDF/ACS
Sky Coverage (deg²)
App. magnitude (B mags)
10⁵
10⁴
1000
100
10
1
0.1
0.01
0.001
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32

MGC data quality v APM & SDSS

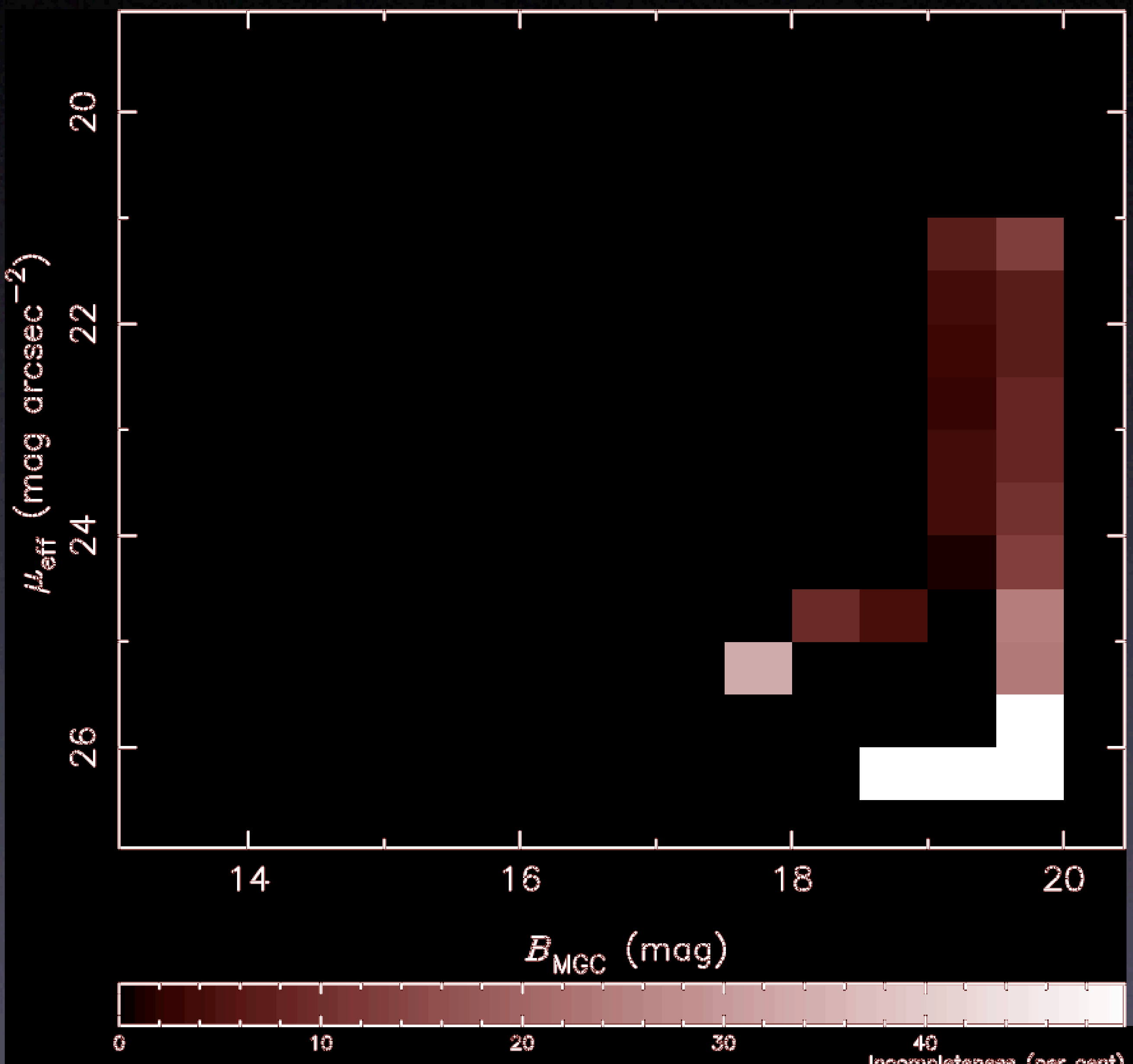


Spectroscopic Incompleteness



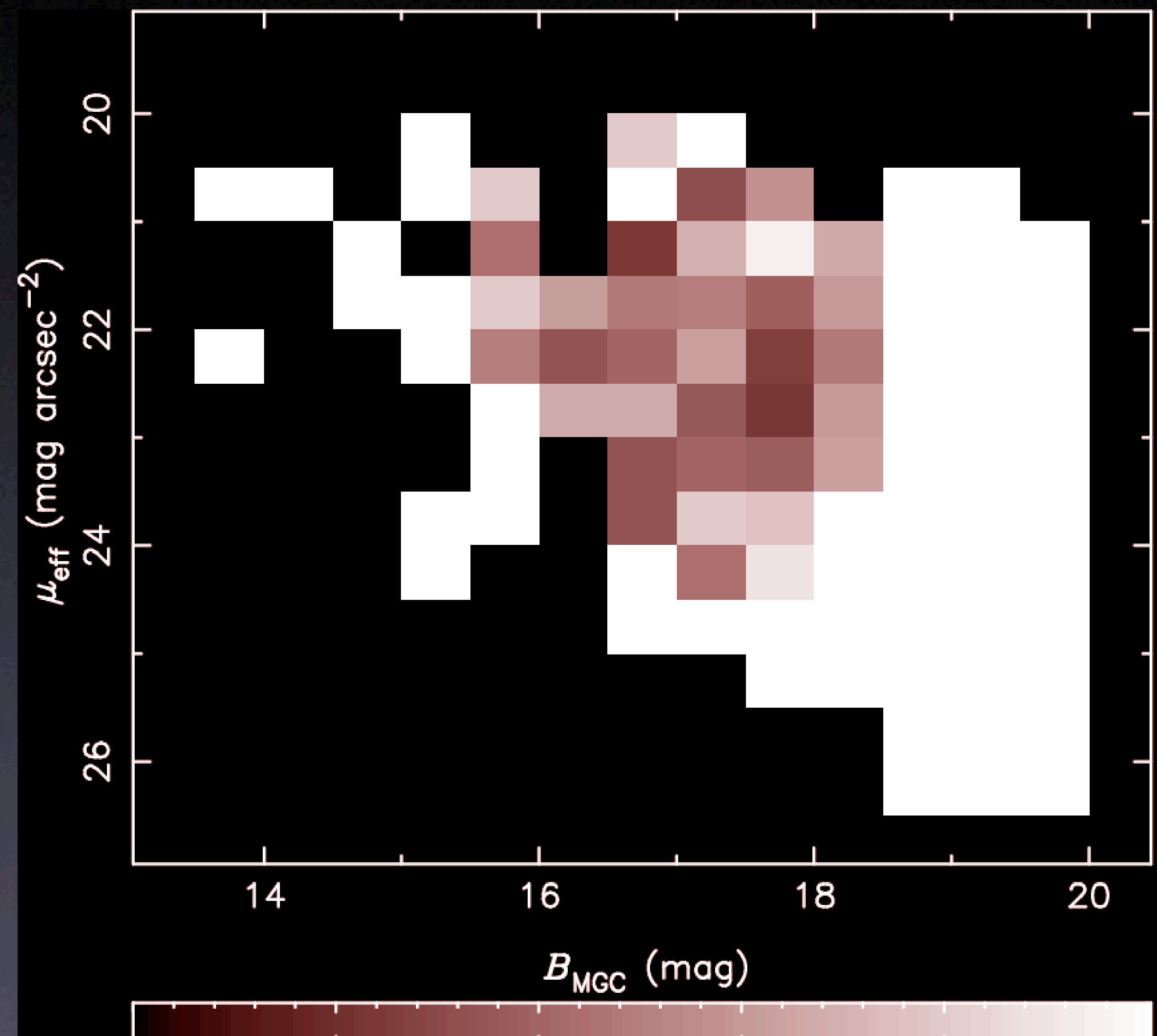
Spectroscopic Incompleteness

MGC



Incompleteness (%)

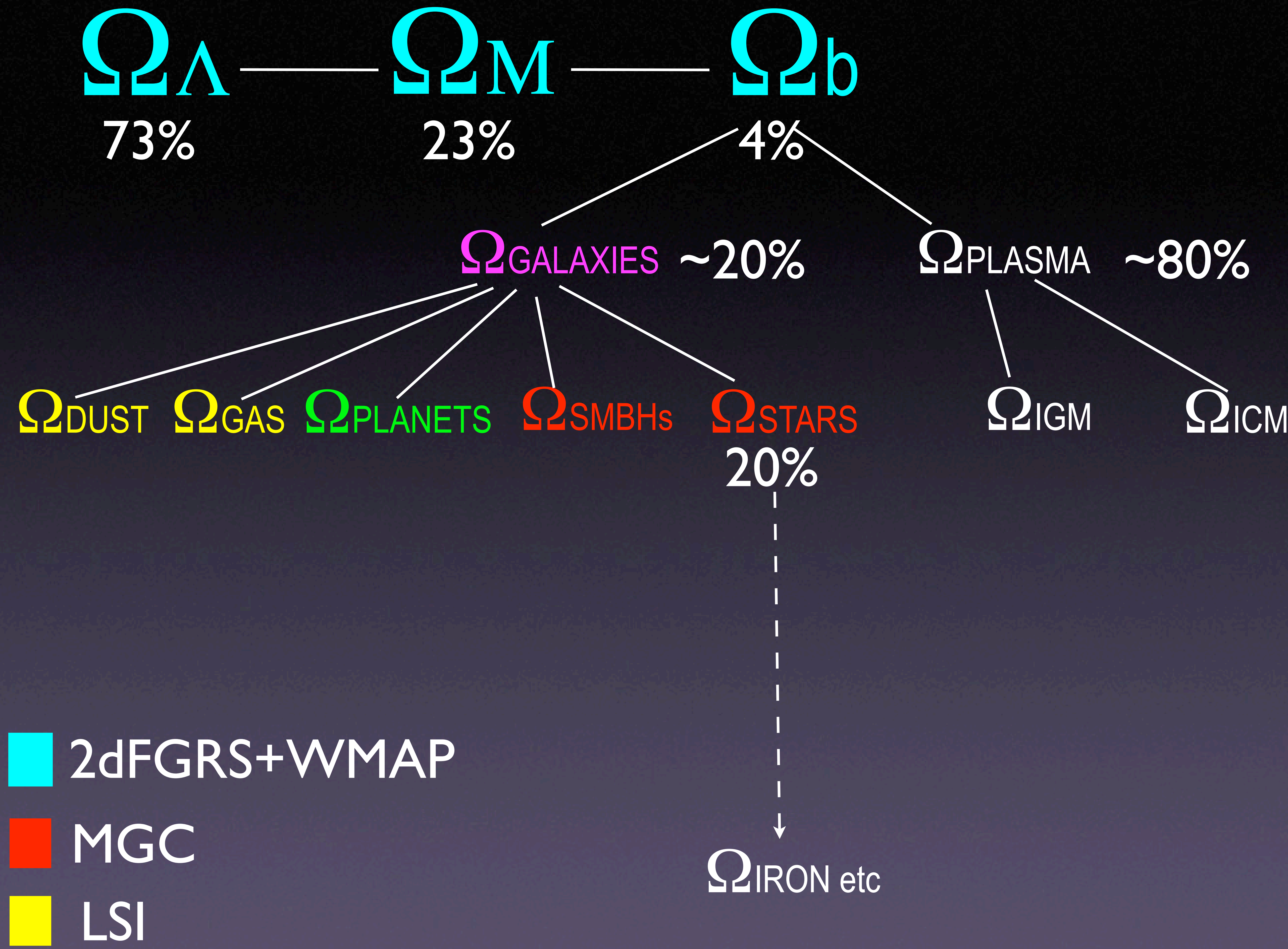
SDSS



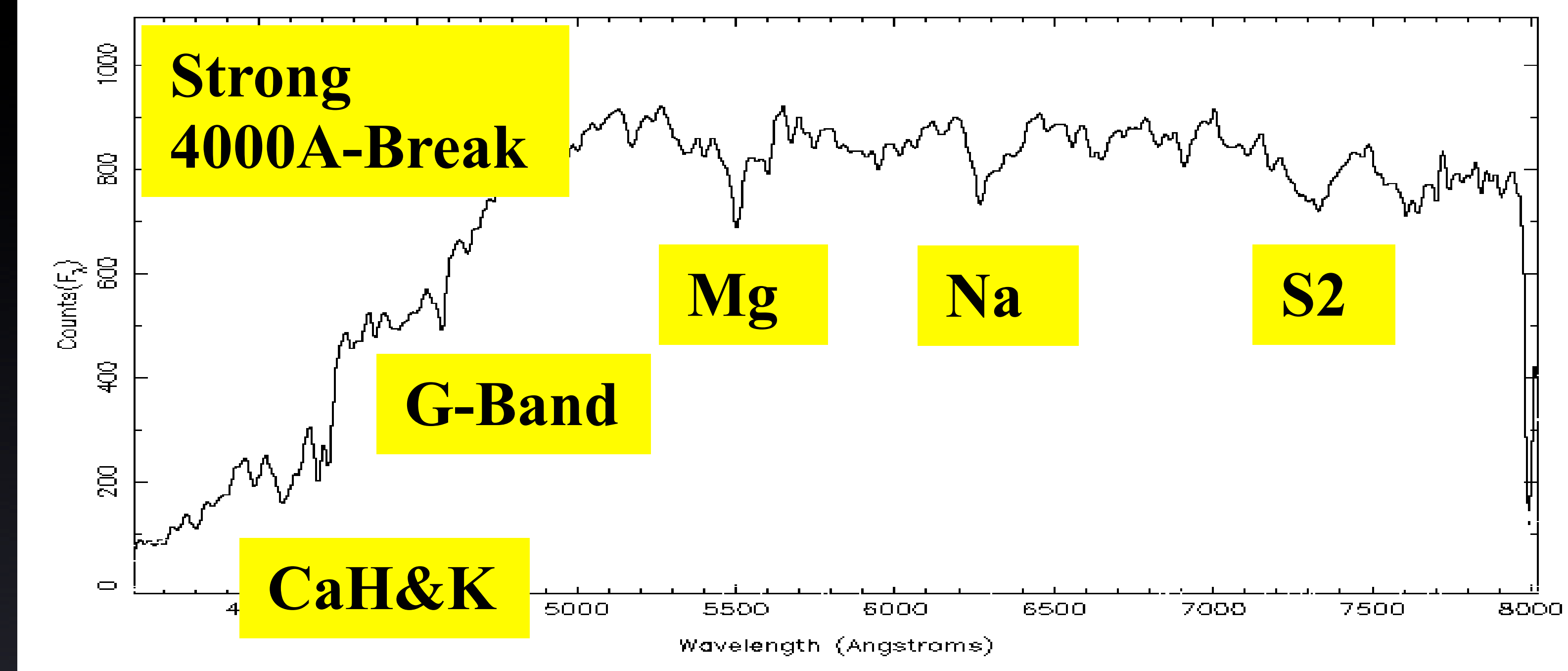
Incompleteness (%)

MGC Publications

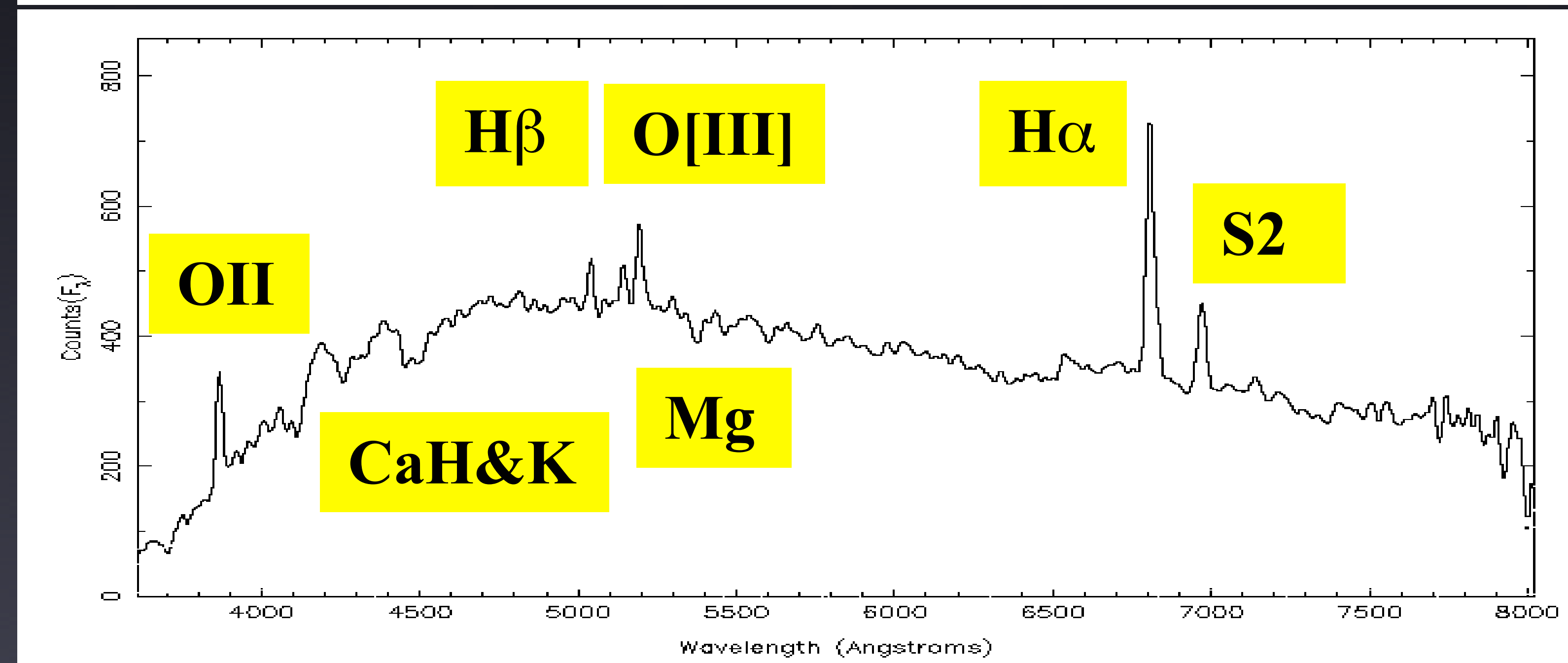
- Faint Galaxy Number-Counts, Liske et al (2003), MNRAS
- Star-Counts and the Galactic Halo, Lemon et al (2004), MNRAS
- Photometric accuracy/completeness of APM and SDSS, Cross et al (2004), MNRAS
- Luminosity and Size distributions, Driver et al (2005), MNRAS
- Galaxy merger rate, De Propris et al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


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

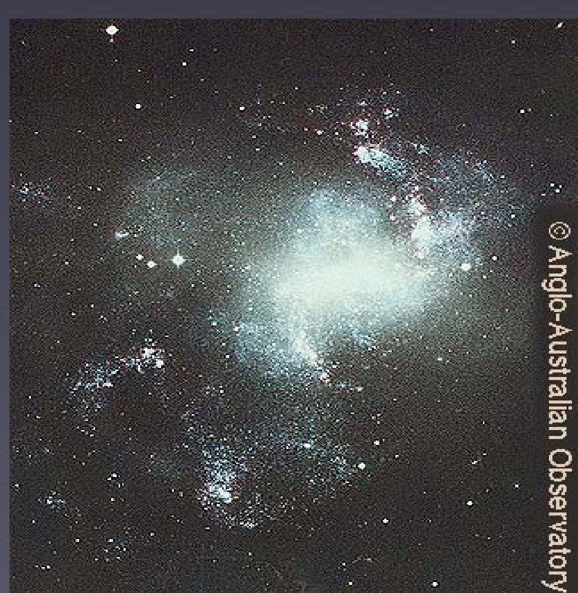
Elliptical
(E/S0)

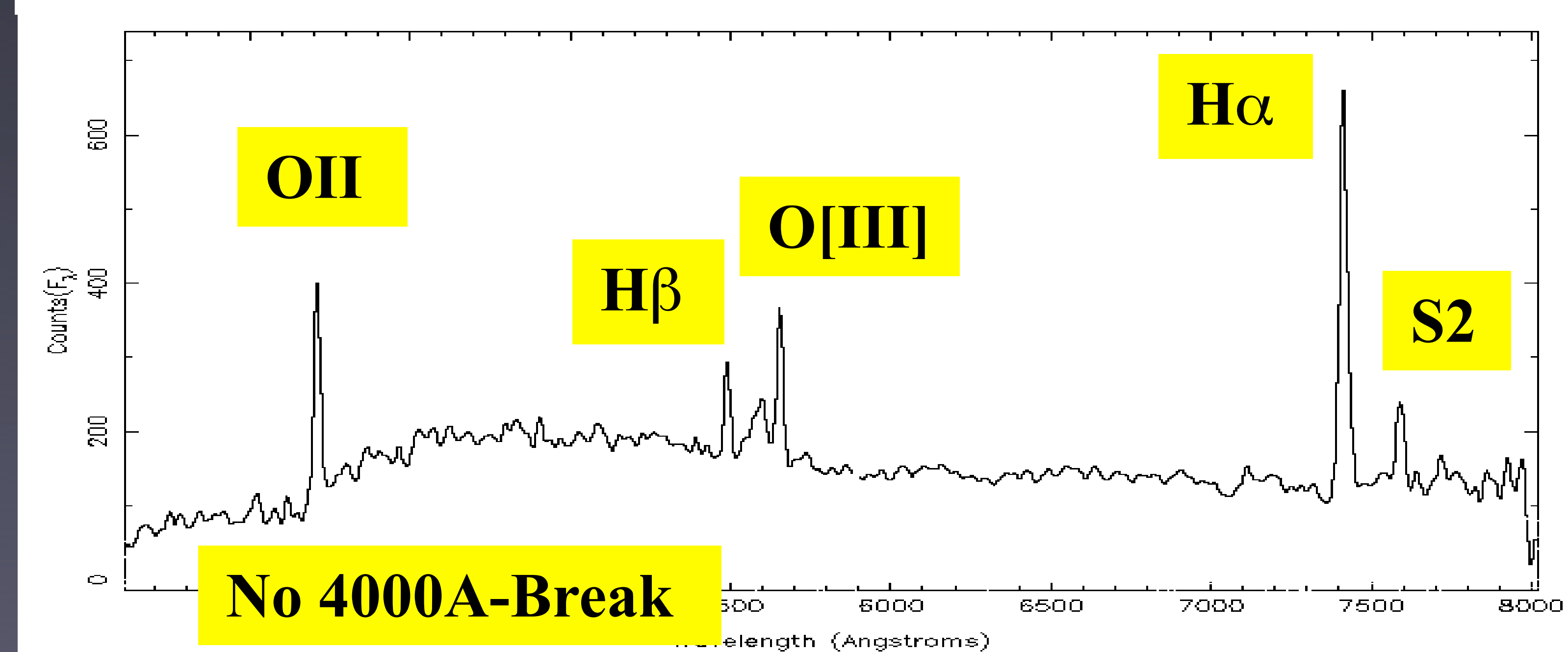


Spiral
(Sabc)



Irregular
(Sd/Irr)



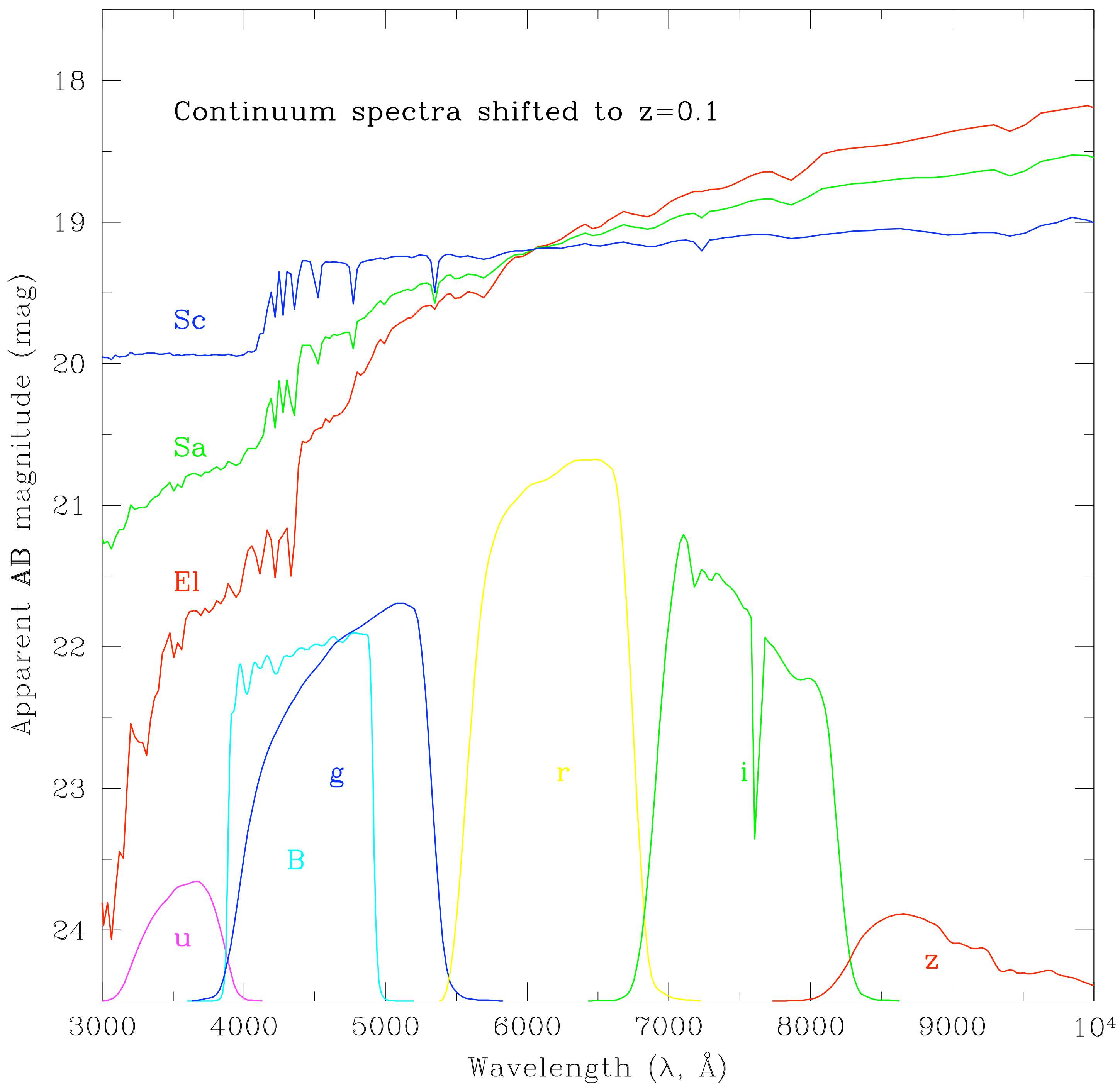


Continuum Type

Young Sc

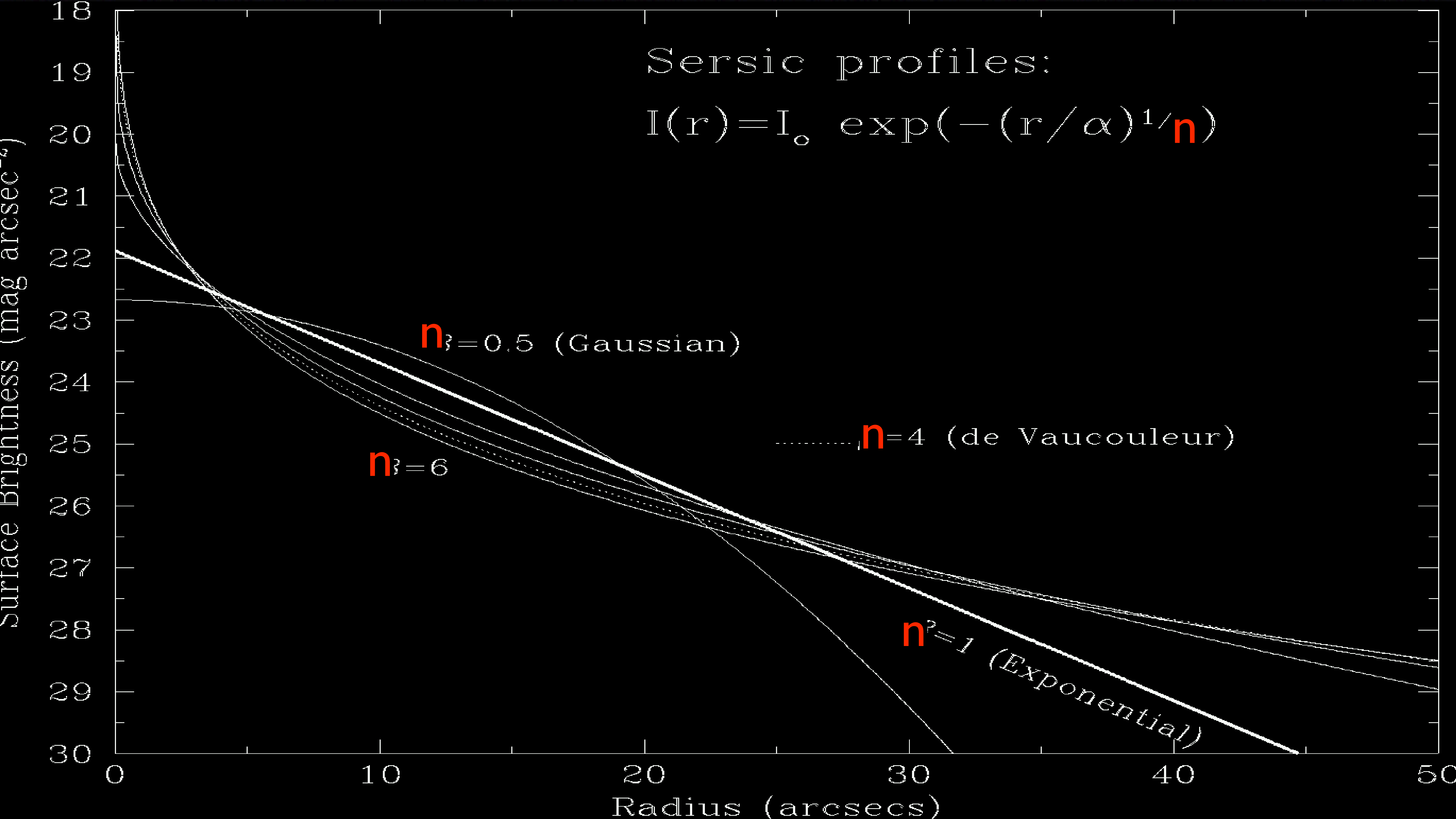
Intermediate Sa

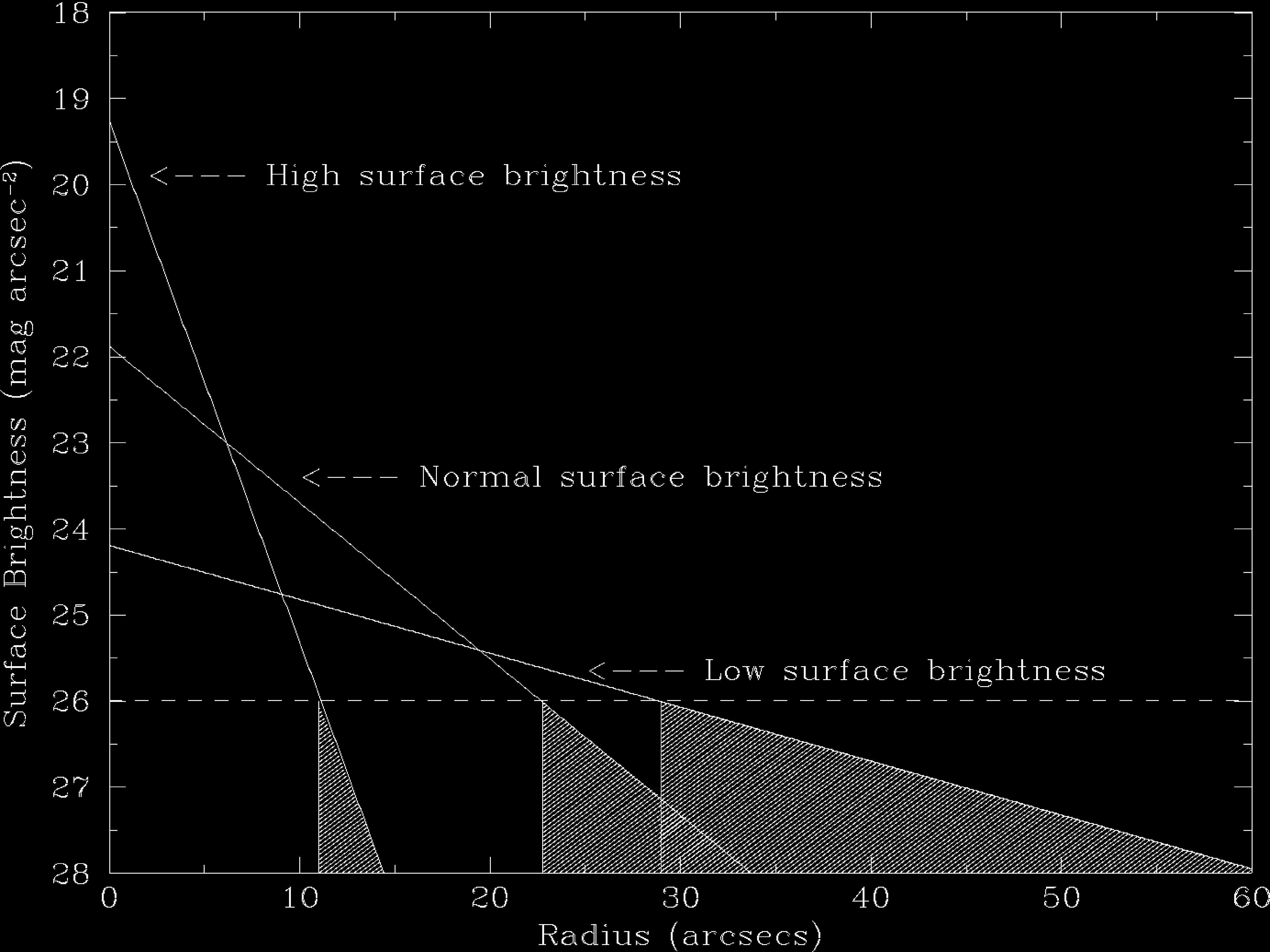
Old El



The Sersic index (n)

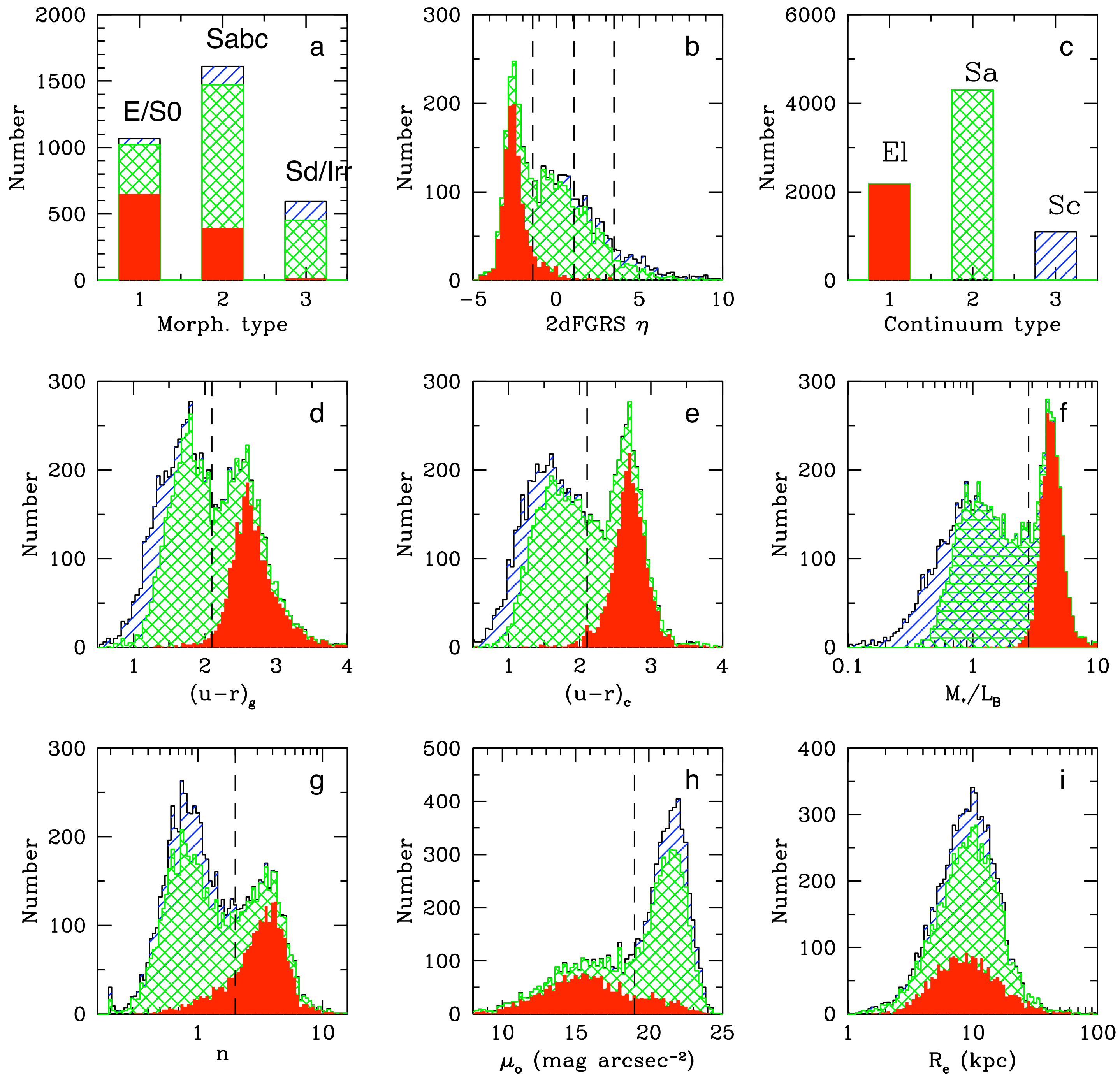
The Sersic index (Sersic 1963, 1968; Graham & Driver 2005) describes the projected light distribution of Spheriods and Bulges.



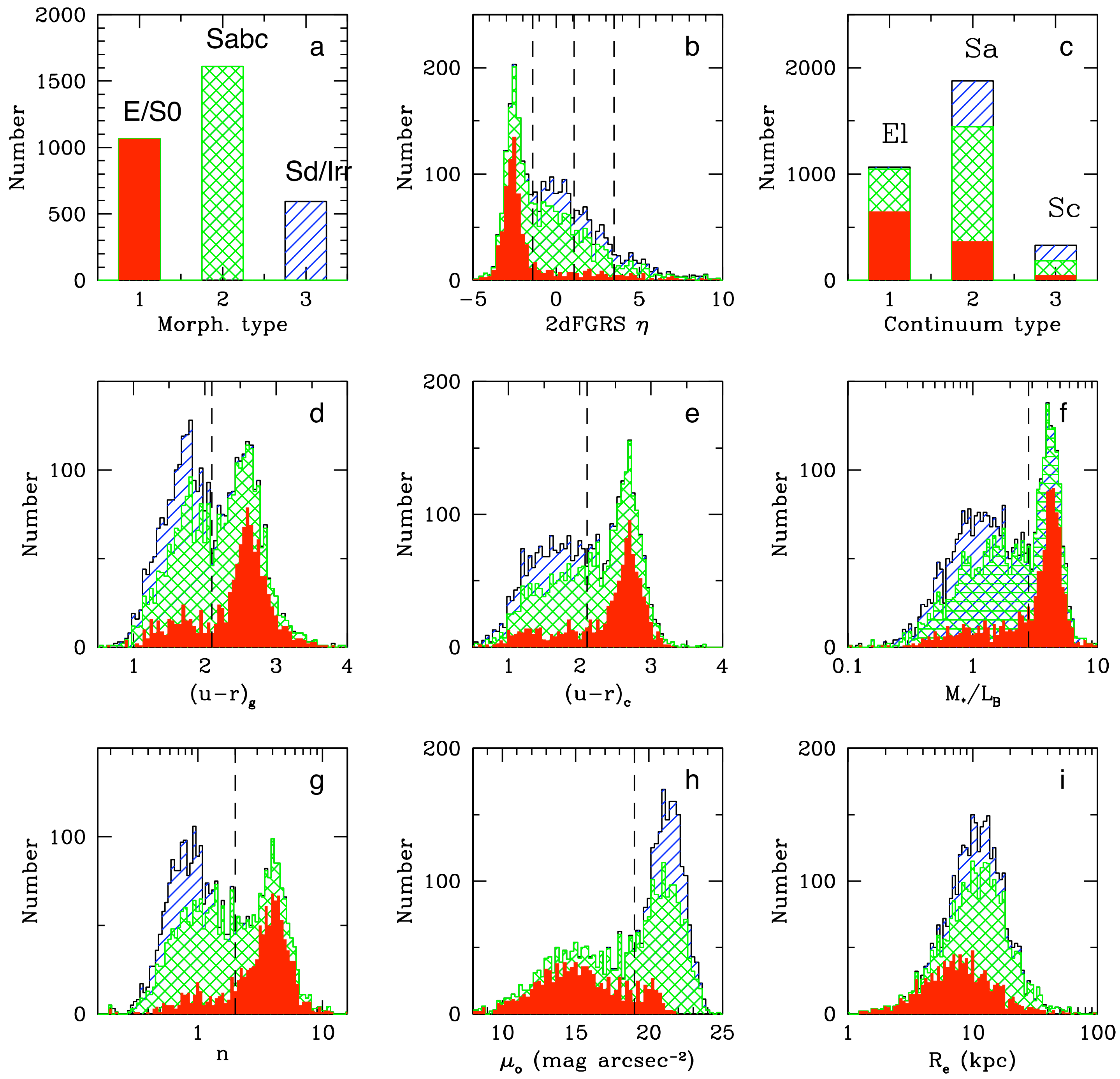


<--- High surface brightness
<--- Normal surface brightness
<--- Low surface brightness
Surface Brightness (mag arcsec^{-2})
Radius (arcsecs)
18
19
20
21
22
23
24
25
26
27
28
0
10
20
30
40
50
60

Observed properties

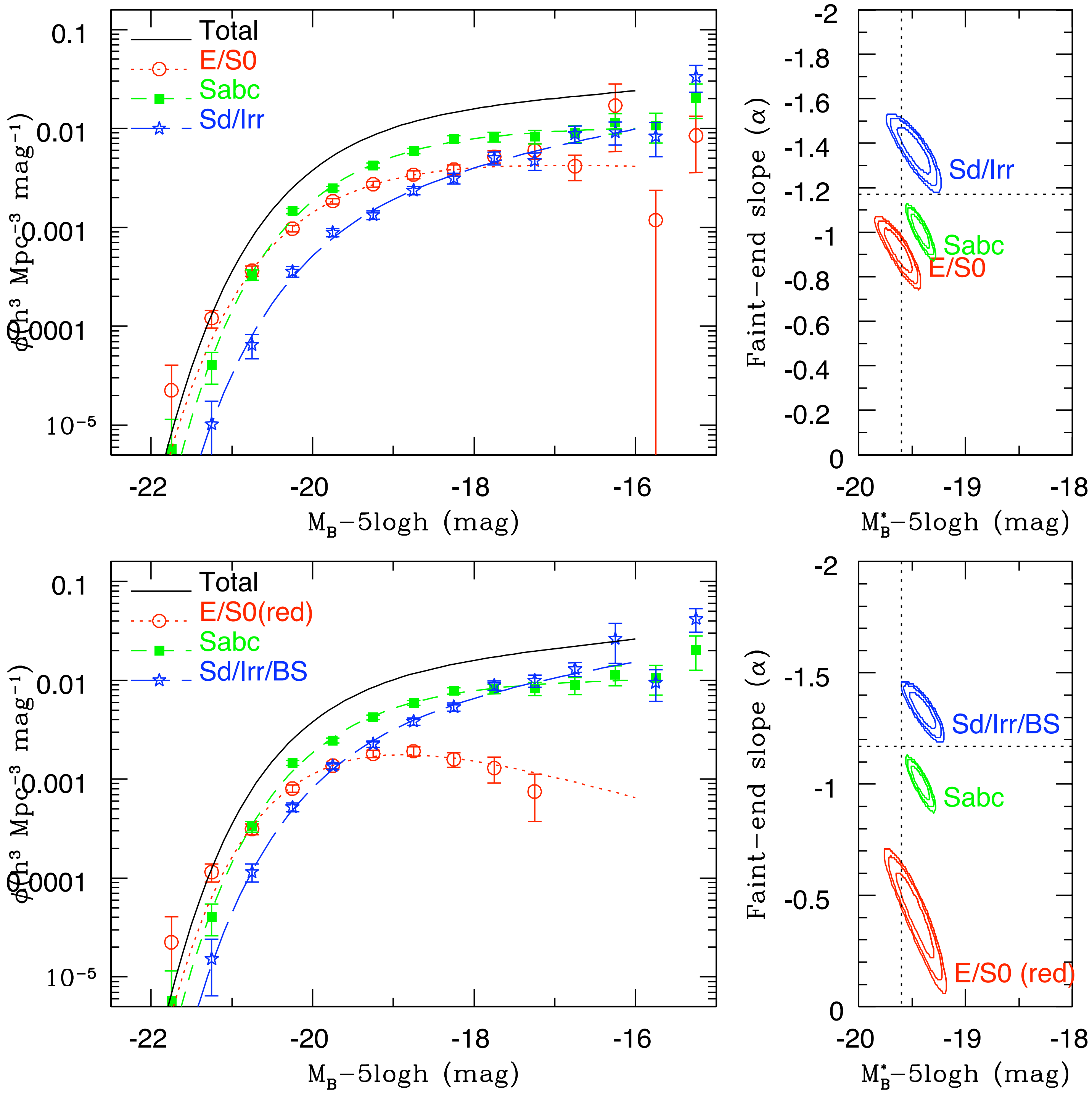


Observed properties



Luminosity functions by type

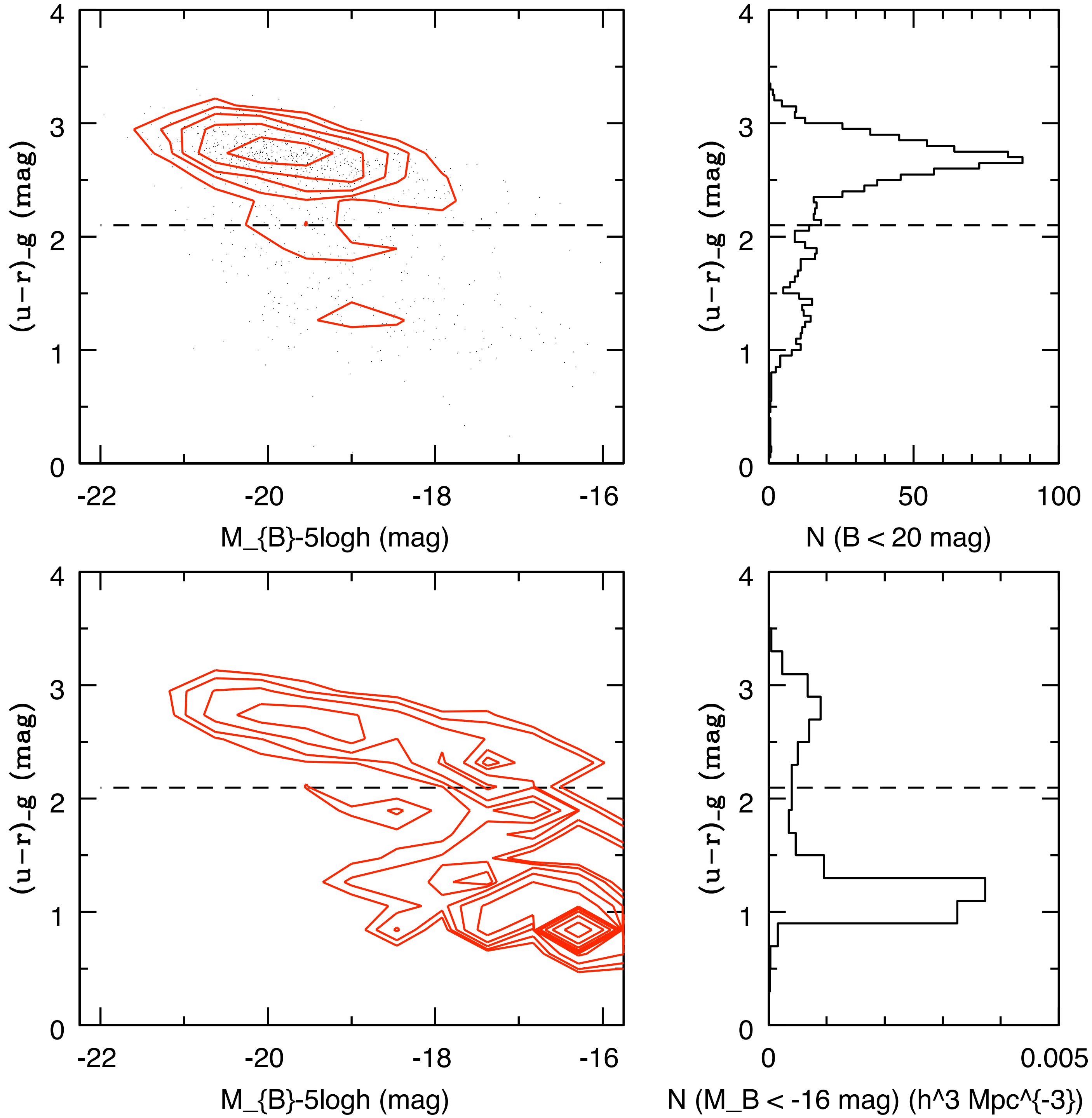
Eyeball
Morph.



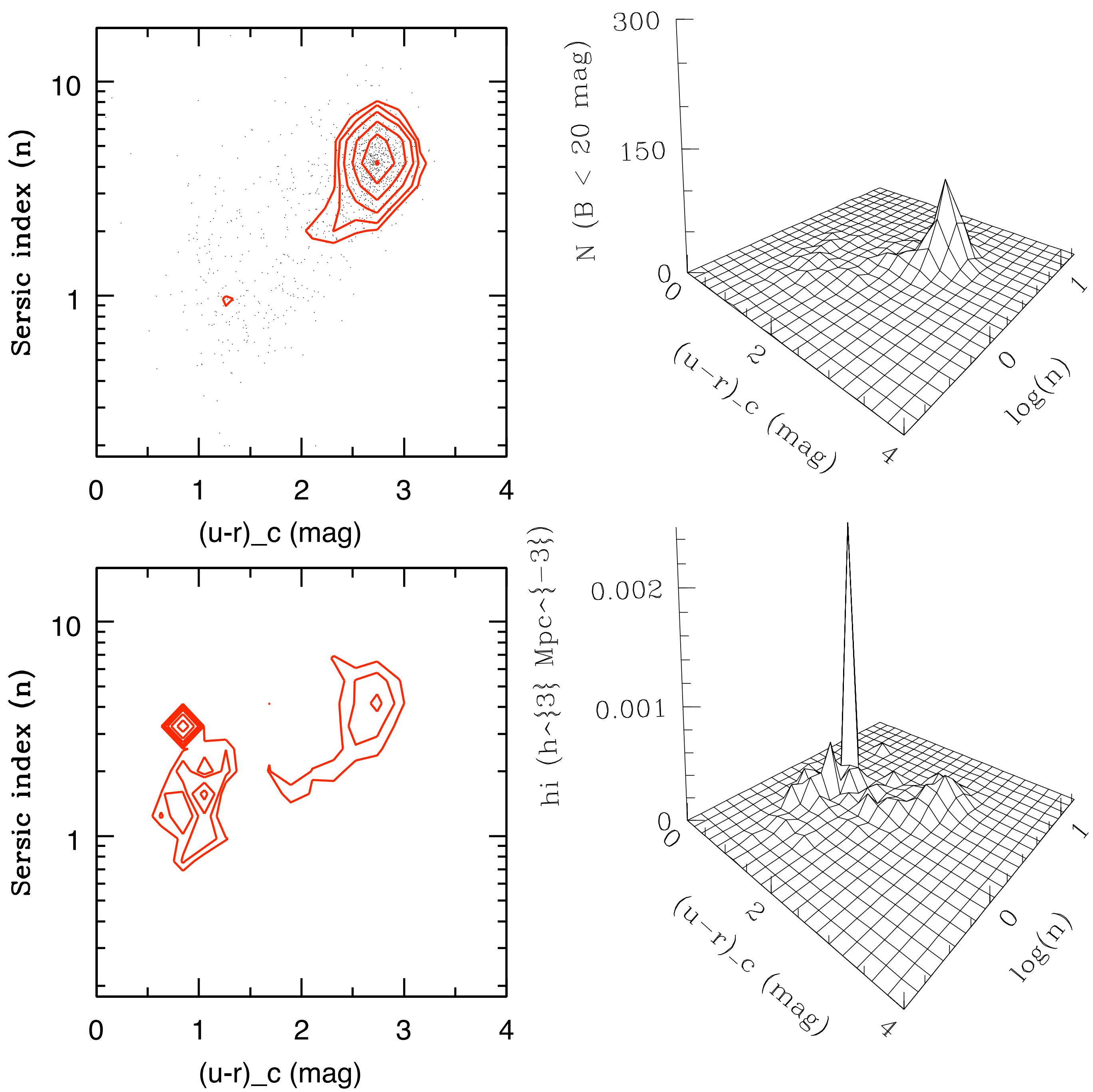
Eyeball
Morph.

Abs. mag

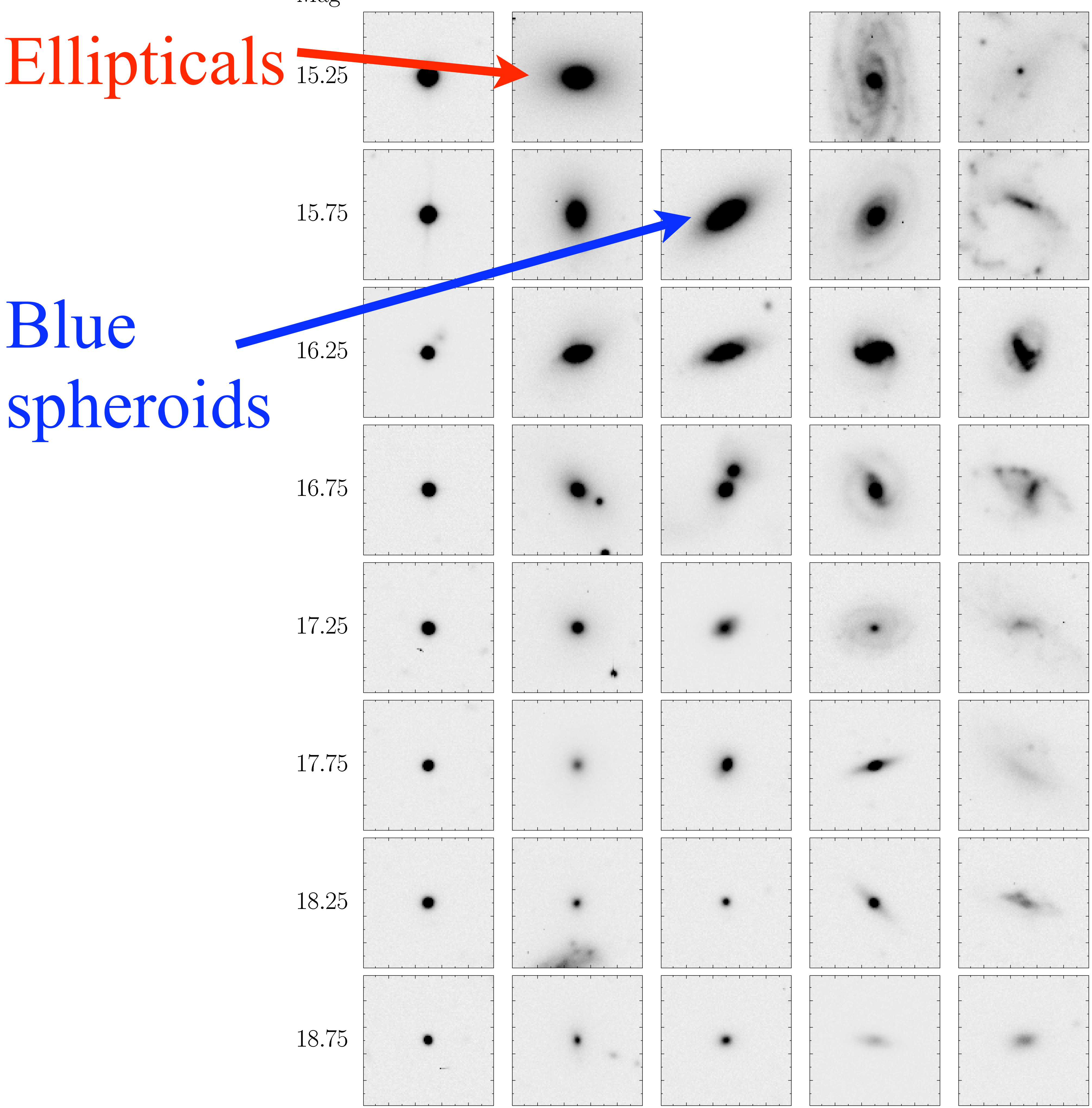
Blue spheroids ?



Blue spheroids ?



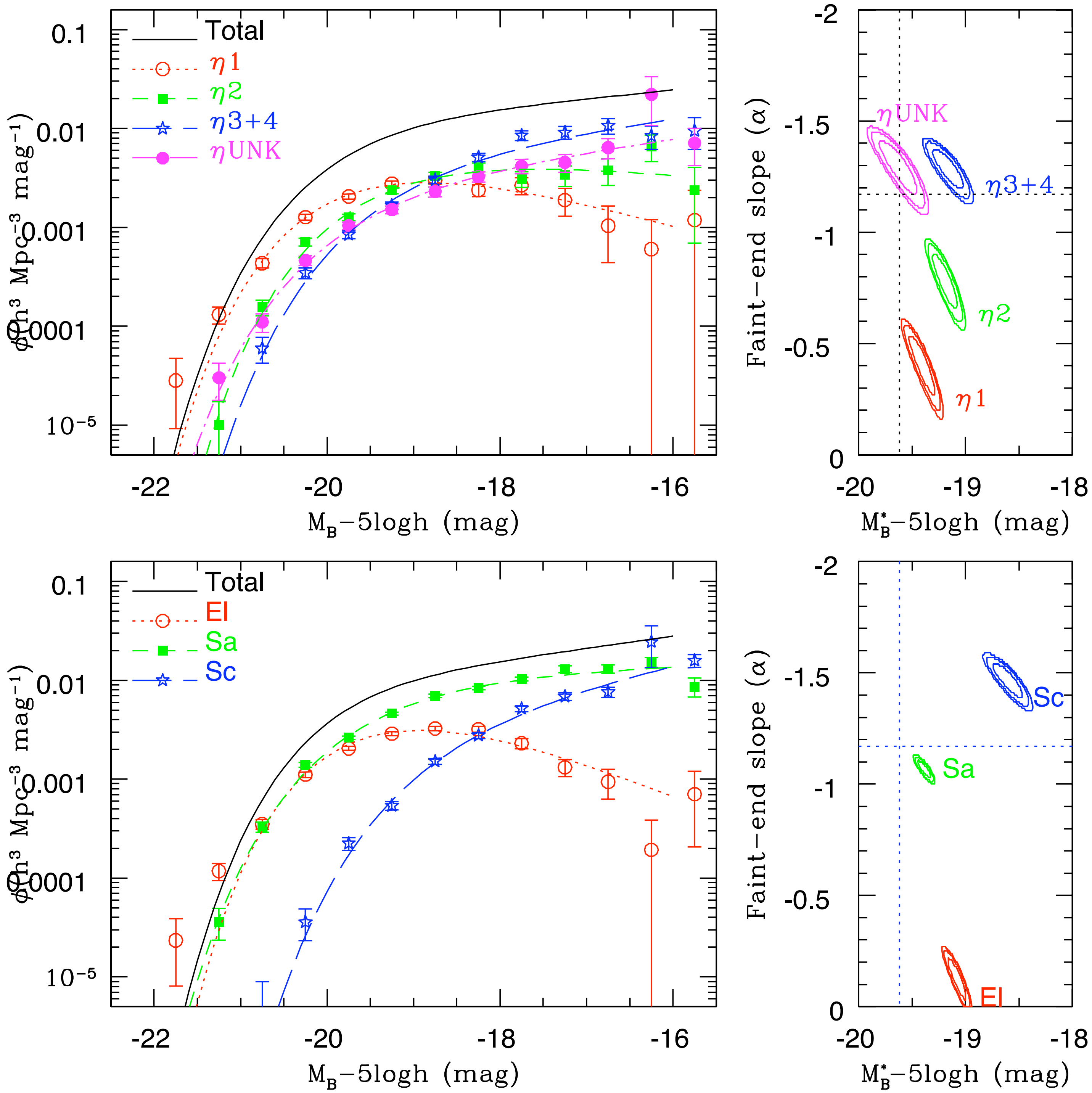
Spheroid downsizing in action ?



Ellipticals
Blue spheroids
15.25
15.75
16.25
16.75
17.25
17.75
18.25
18.75

Luminosity functions by spectral type

2dFGRS
eta type



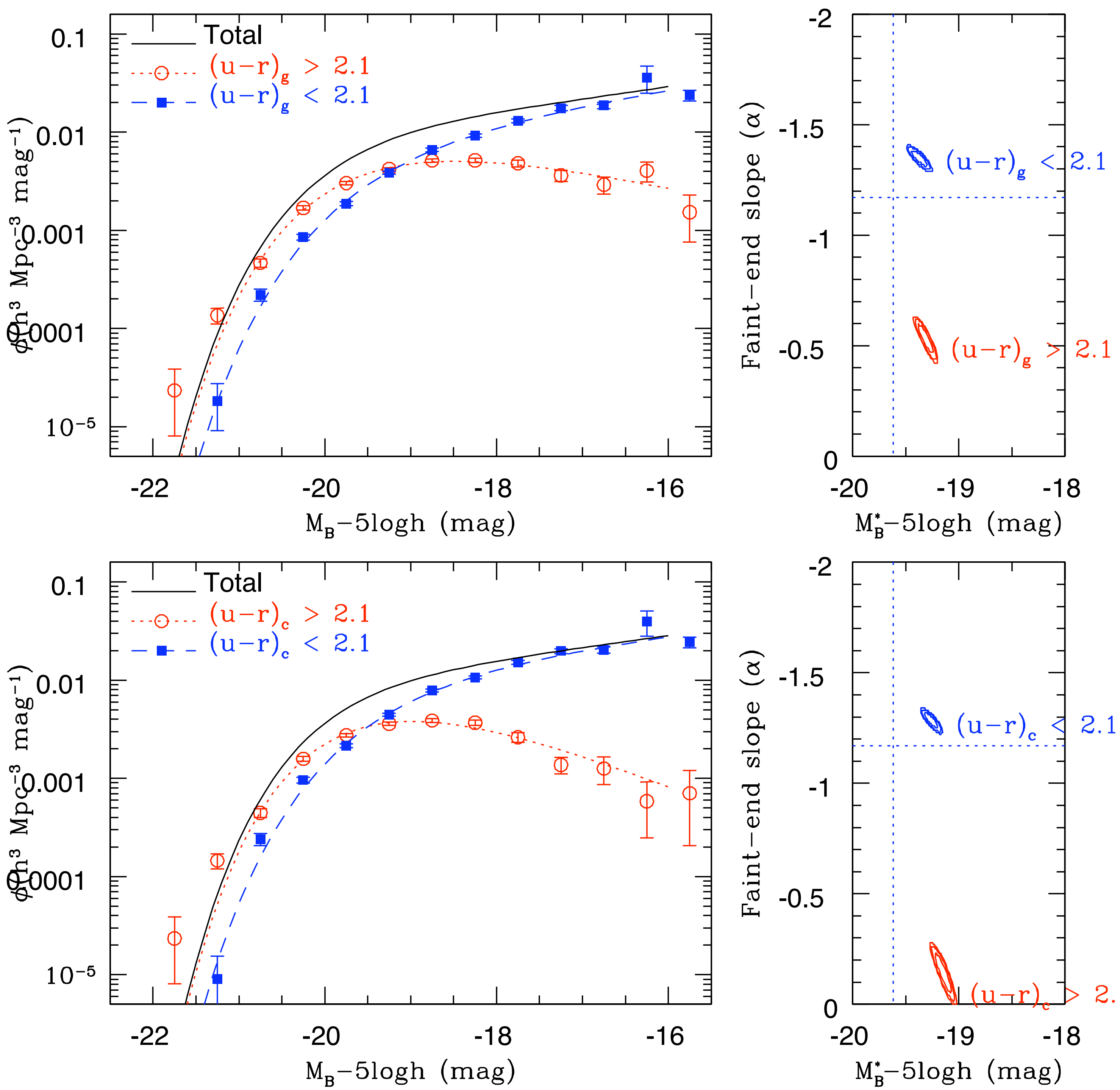
Spectral
Type

Abs. mag

Luminosity functions by colour

Global
colour
(u-r)_g

Core
Colour
(u-r)_c

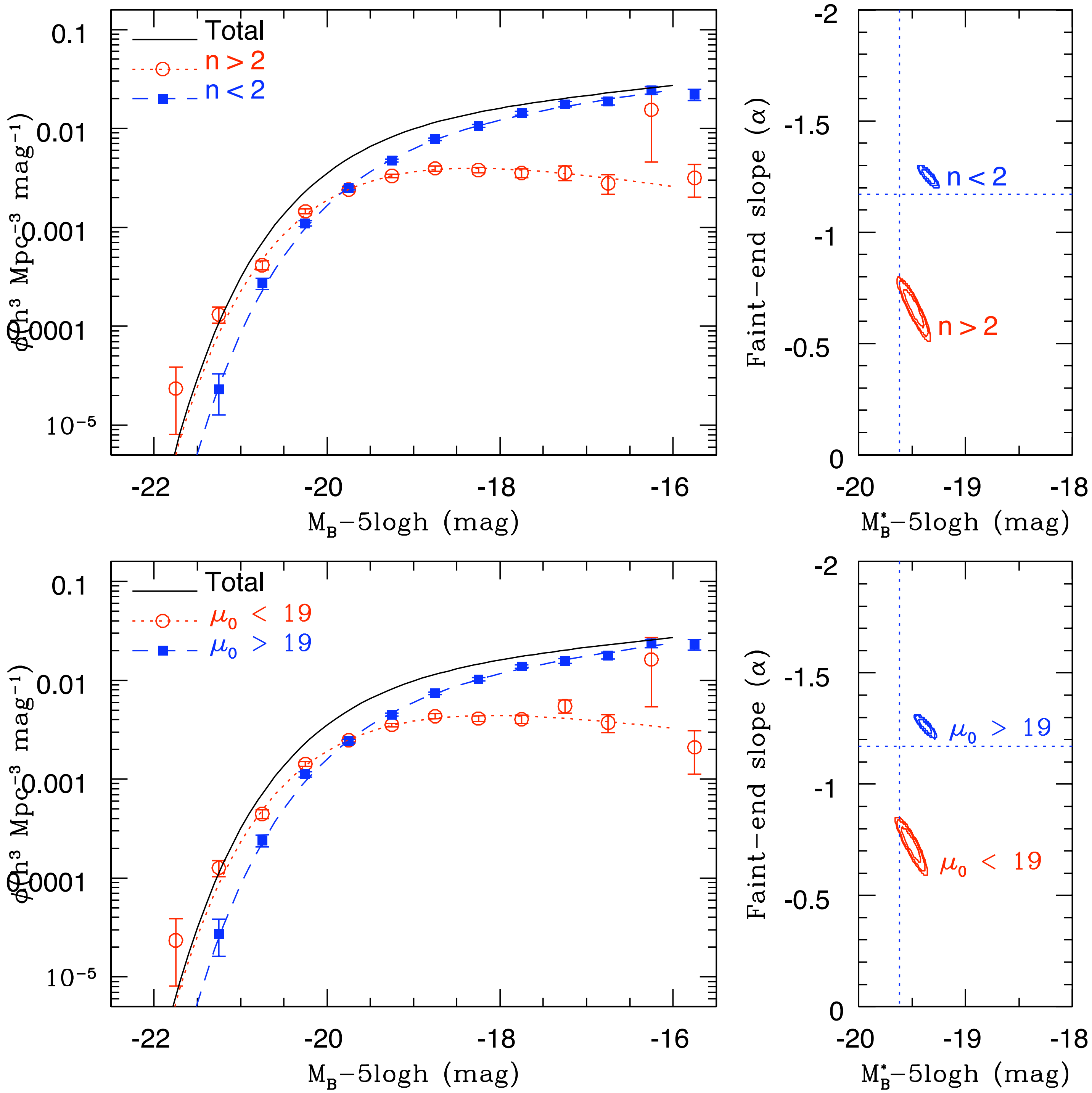


Abs. mag

Luminosity functions by structure

Sersic index

Eff. SB inside Re

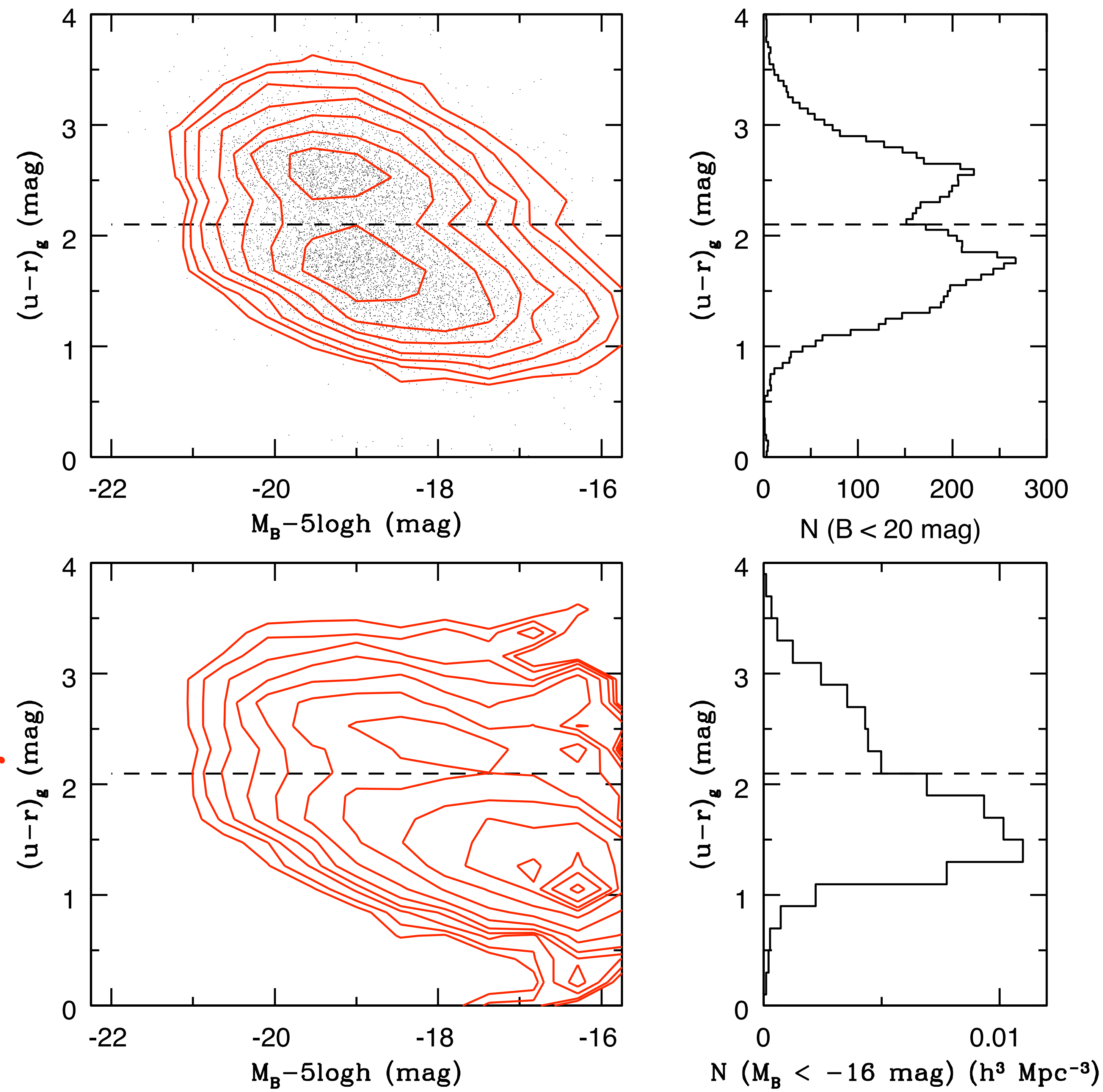


Abs. mag

Bivariate colour luminosity distributions

Observed
Global colour

Volume corr.
Global colour

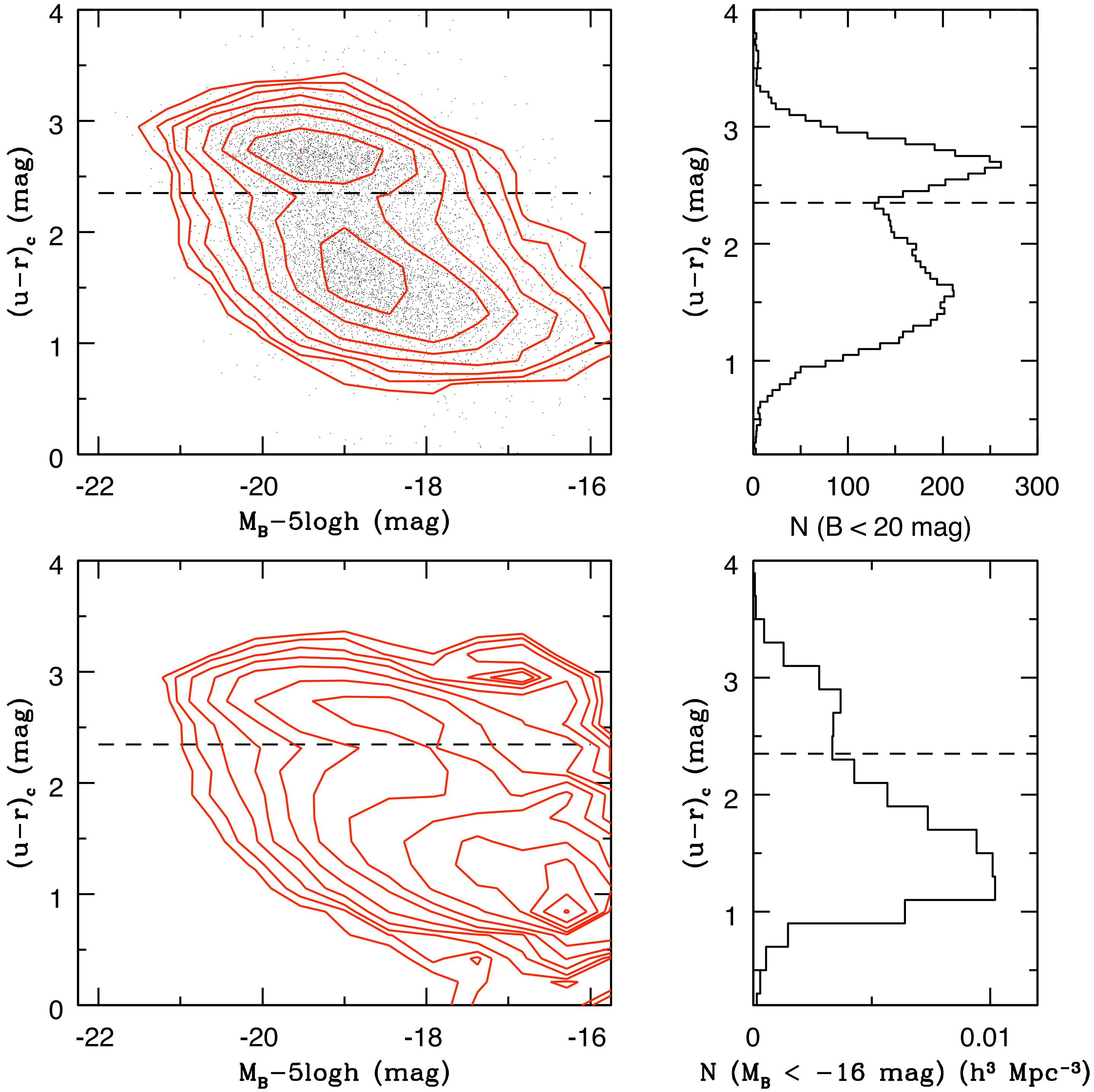


Abs. mag

Bivariate colour luminosity distributions

Observed
Core colour

Volume corr.
Core colour

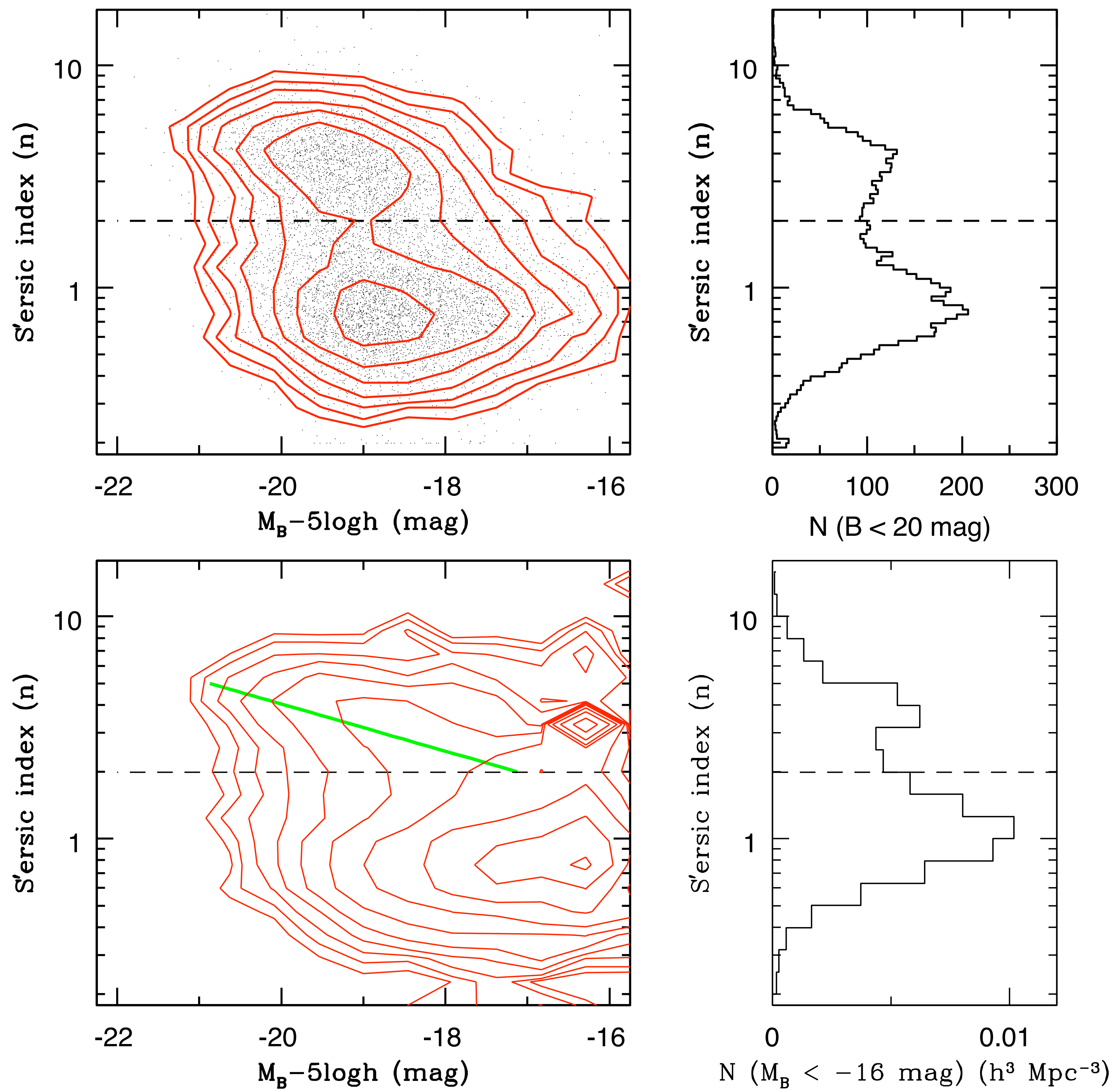


Abs. mag

Bivariate Sersic index luminosity distributions

Observed Sersic index

Volume corr. Sersic index

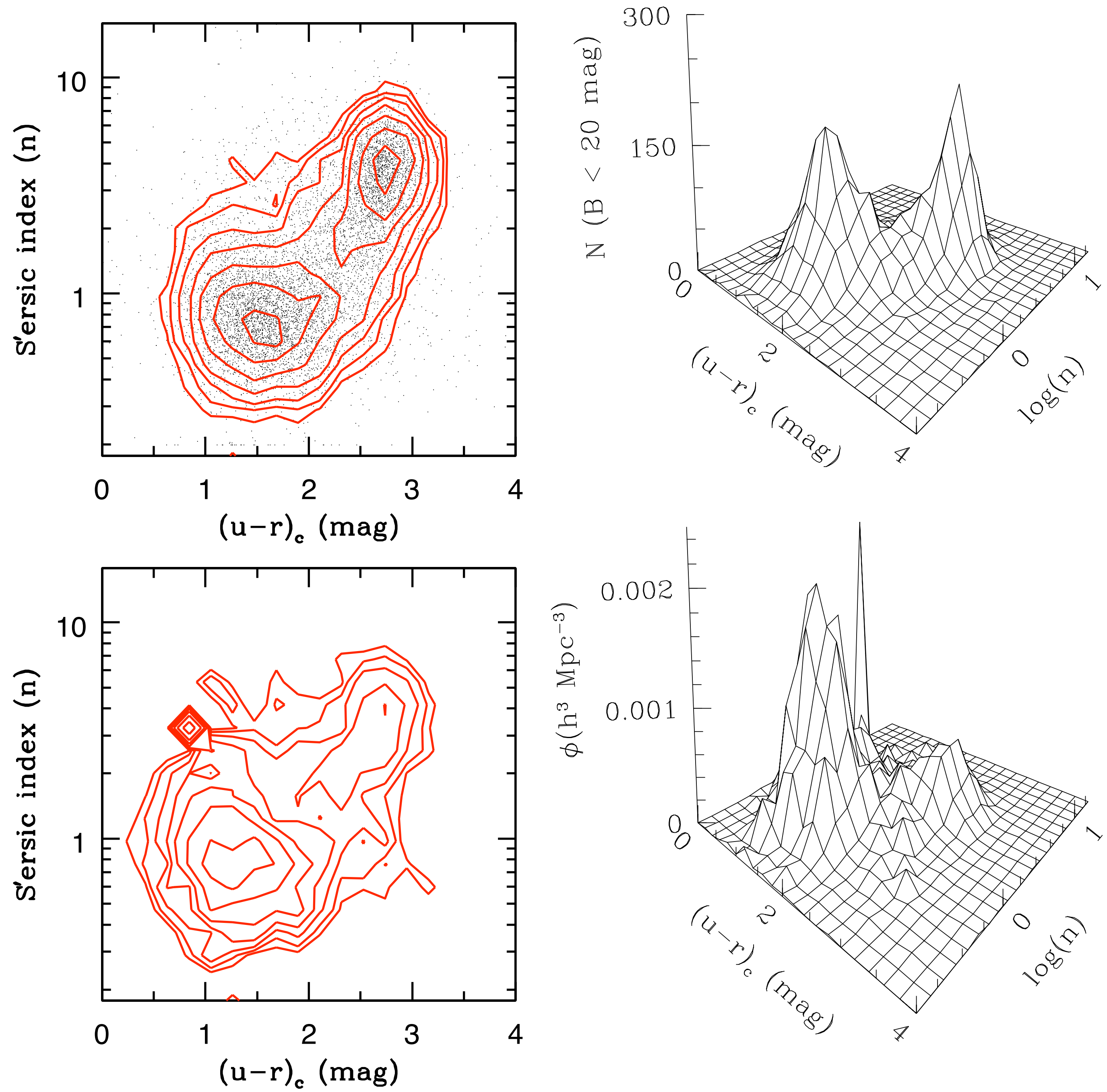


Abs. mag

Bivariate colour Sersic index distributions

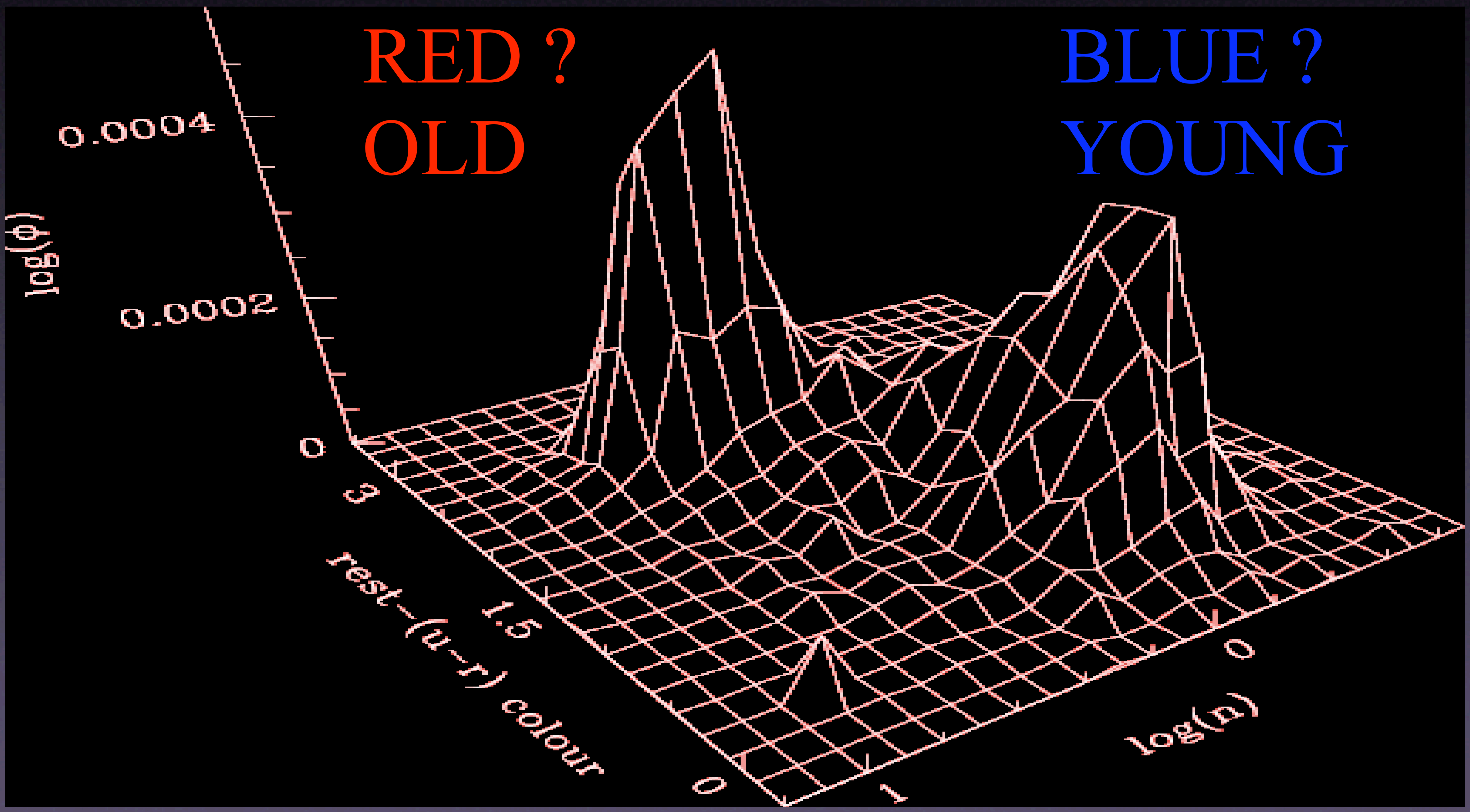
Observed
n v (u-r)_c

Volume corr.
n v (u-r)_c



Galaxy bimodality

- Bimodality now seen in the Colour Sersic-index plane (Driver et al 2005)



Bimodality ?

E/S0s

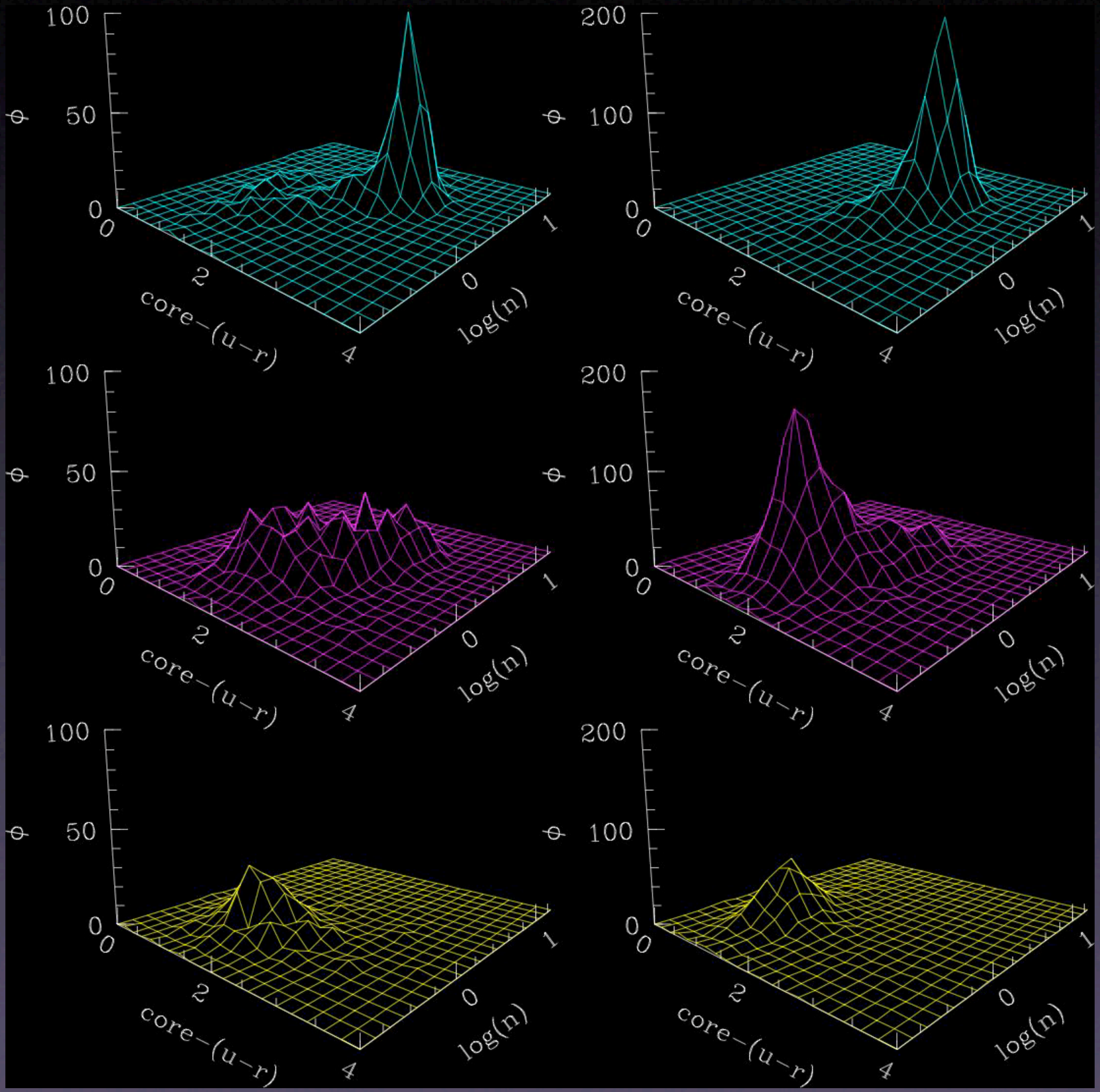
Bulge systems

Sabc

Bulge+Disks

Sd/Irr

Disk systems



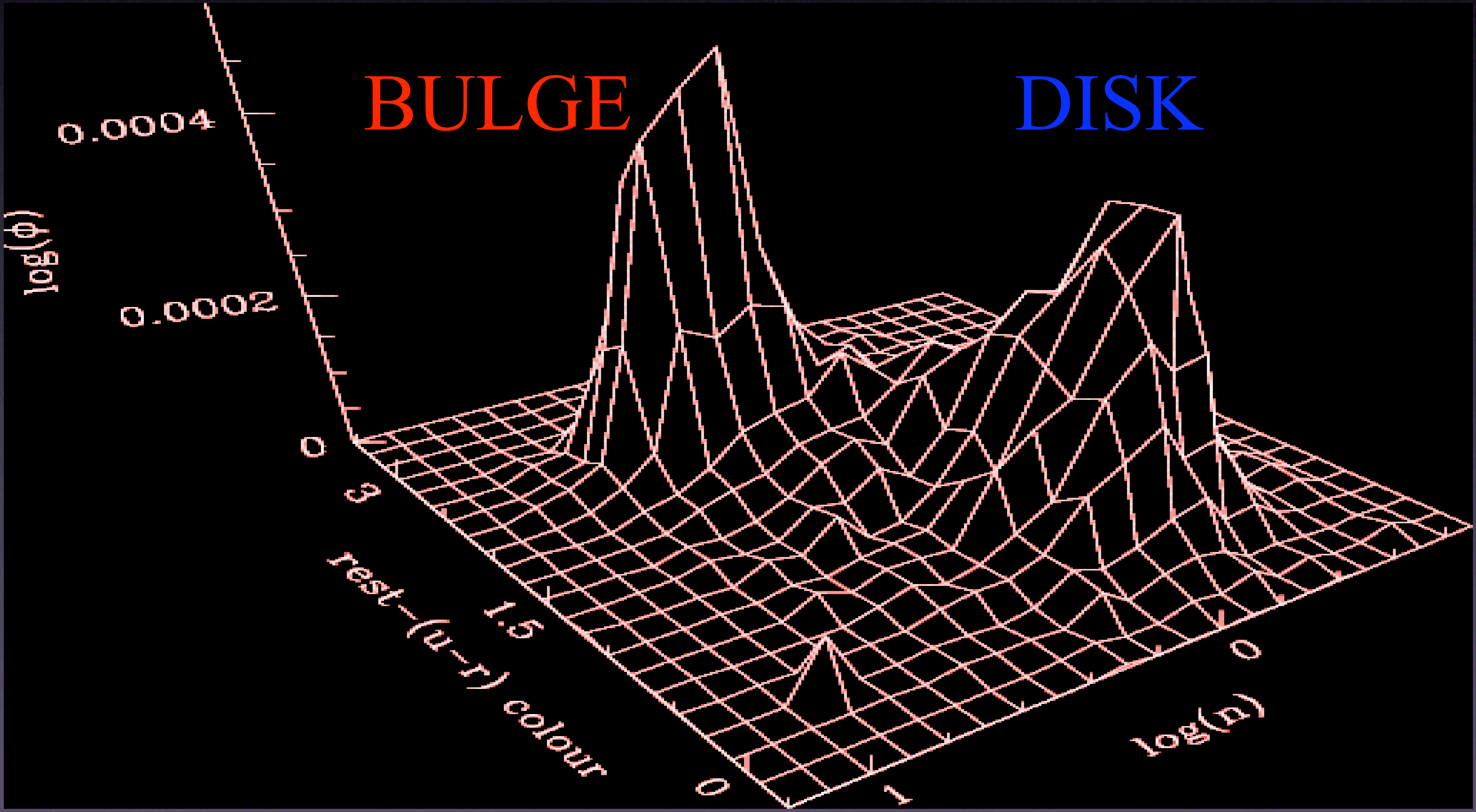
El

Sa

Sc

Galaxy bimodality

- Bimodality now seen in the Colour Sersic-index plane (Driver et al 2005)



Galaxy formation/evolution

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

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 !

Numercial Simulations: The Evolution of Spin

- Peirani et al (2004)
  - Mergers increase λ –> Building Bulges ?
  - Accretion decreases λ –> Building Disks ?
  - Bulge dominated and disk dominated systems should have distinct size (SB) distributions ?

AGN/SMBH	⟷	NUCLEUS
MERGERS	⟷	BULGE
SECULAR	⟷	P-BULGE
→ COLLAPSE	⟷	DISK
ACCRETION	⟷	HALO

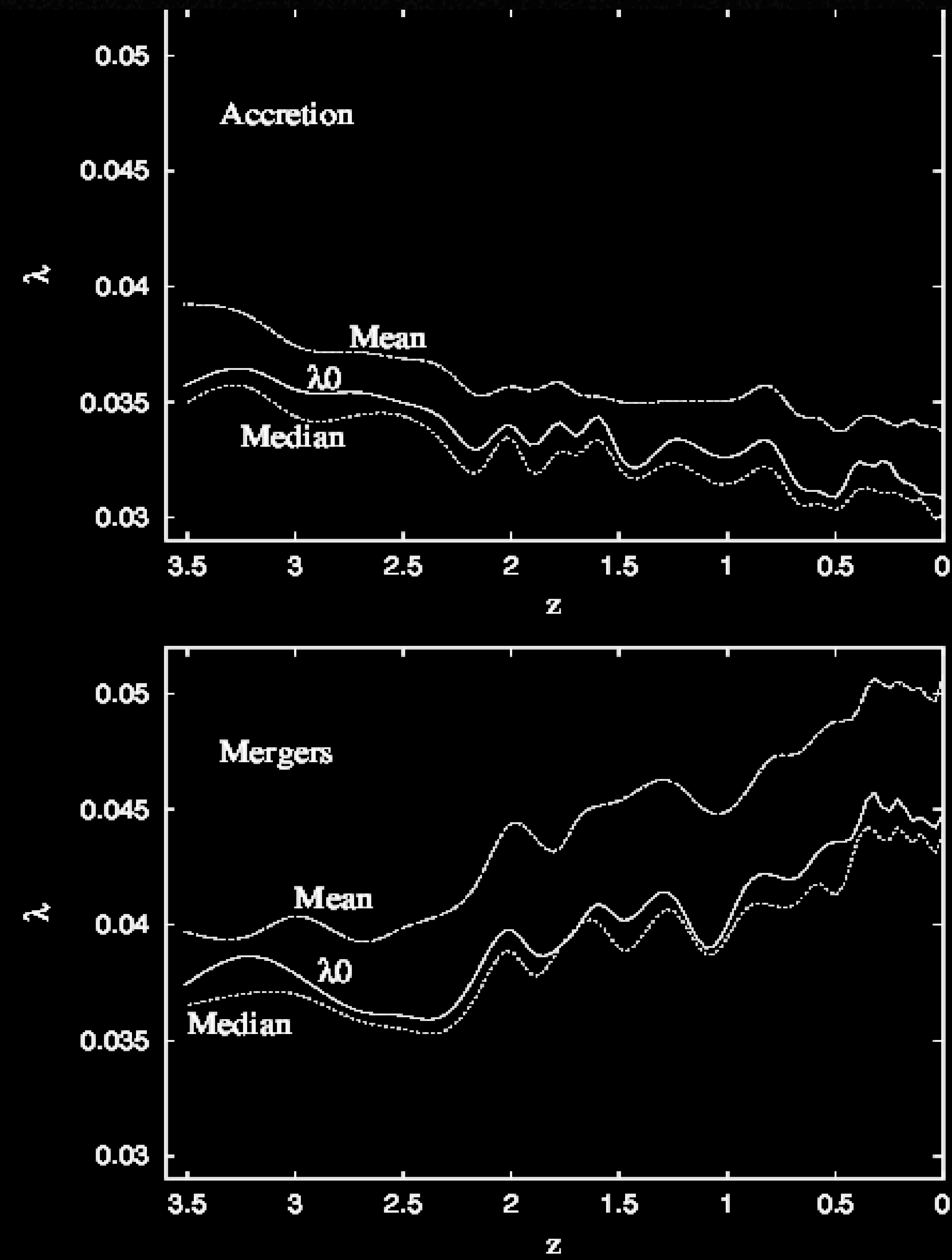
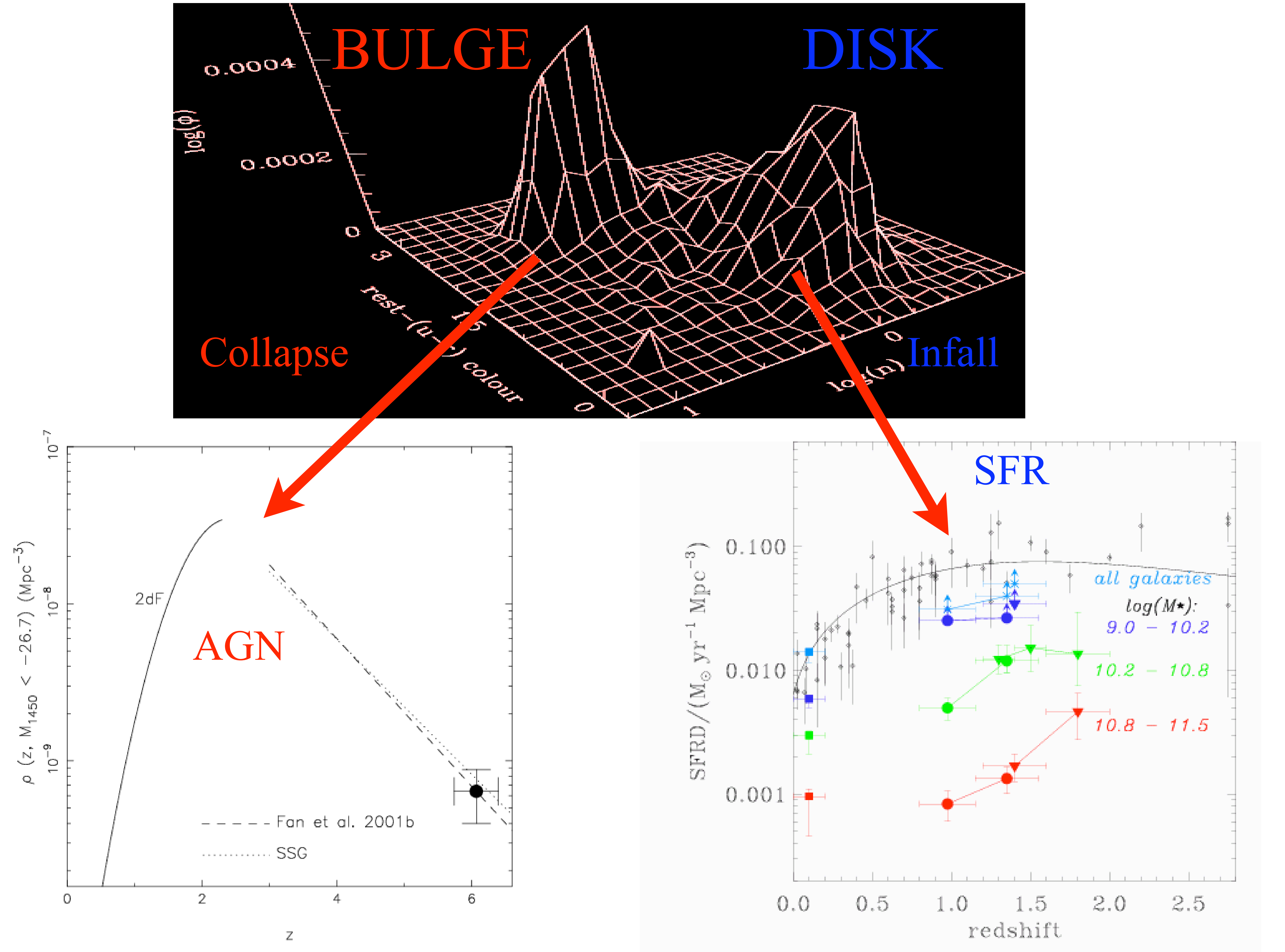
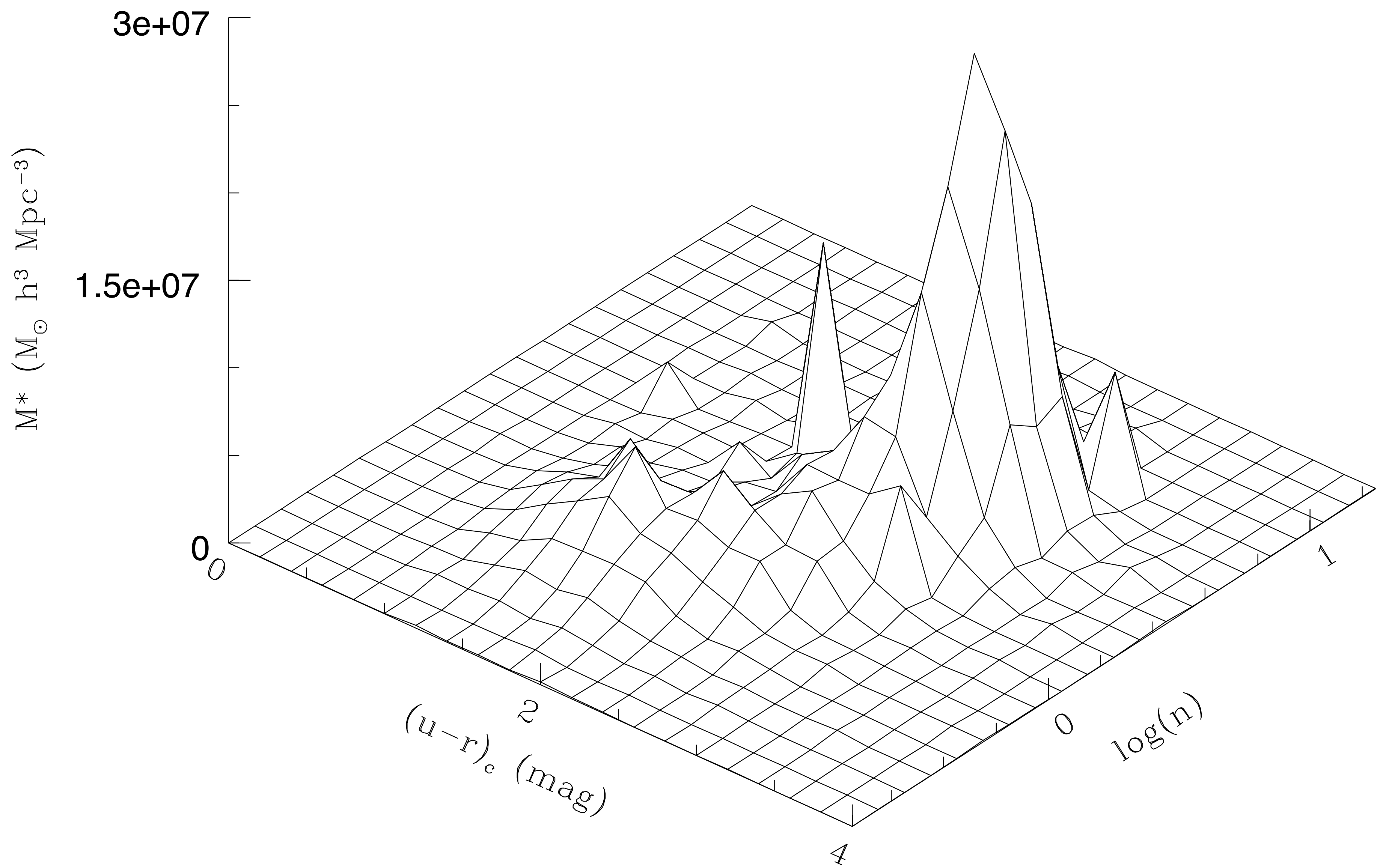


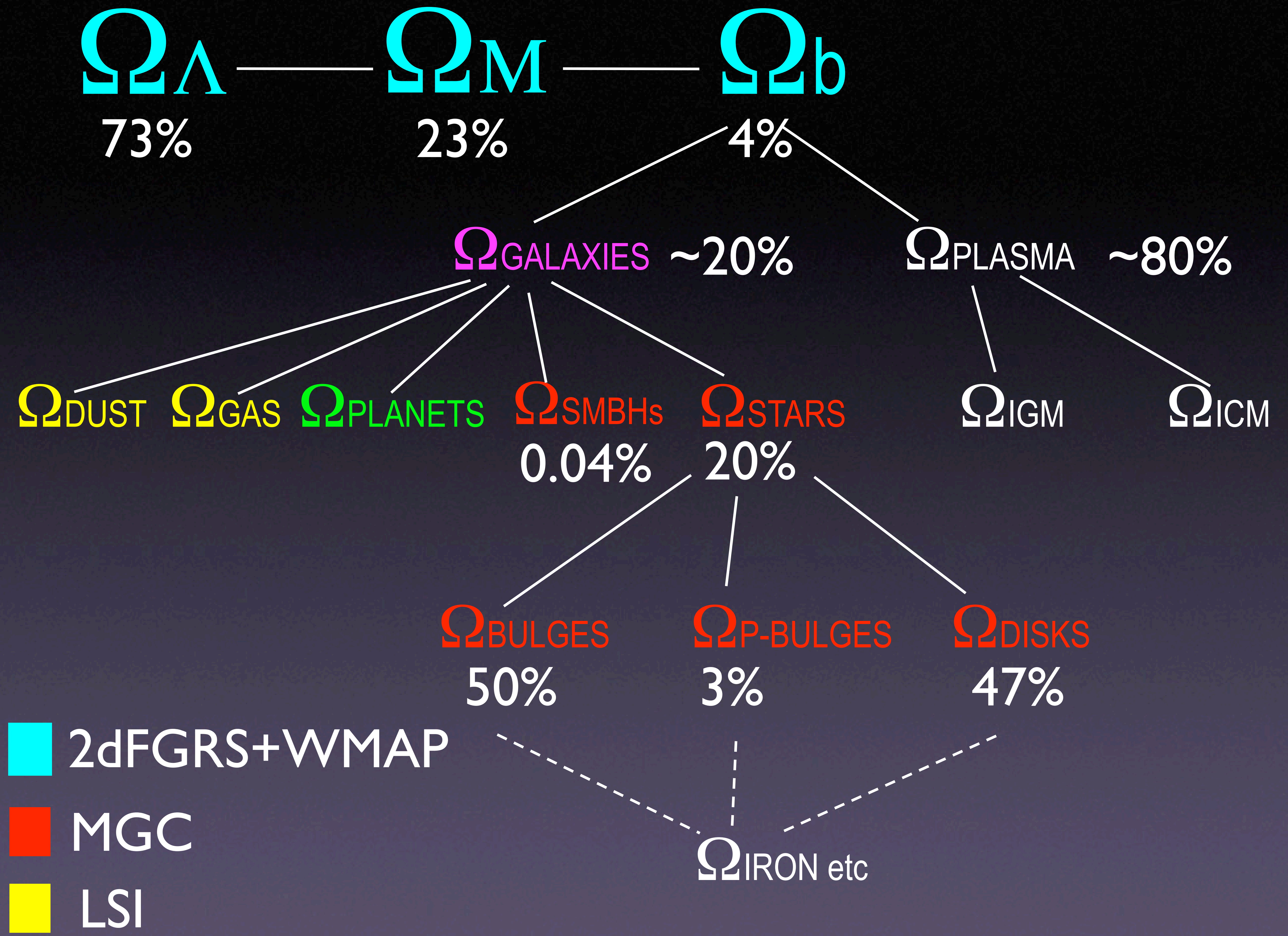
Figure 8. Panels from up to down: a) evolution of the spin parameter for all the halos (accretion + merger). Three statistical parameters are shown: the median, the mean and λ_0; evolution of the same parameters but for halos of the accreting catalog only (b) and for halos of the merger catalog (c).


BULGE
DISK
0.0004
0.0002
log(φ)
0
rest-(u-r) colour
log(n)
Collapse
Infall
AGN
2dF
Fan et al. 2001b
SSG
z
0
2
4
6
SFR
0.100
0.010
0.001
SFRD/(M$_\odot$ yr^{-1} Mpc^{-3})
all galaxies
log(M⋆):
9.0 – 10.2
10.2 – 10.8
10.8 – 11.5
0.0
0.5
1.0
1.5
2.0
2.5
redshift

Stellar Mass distribution

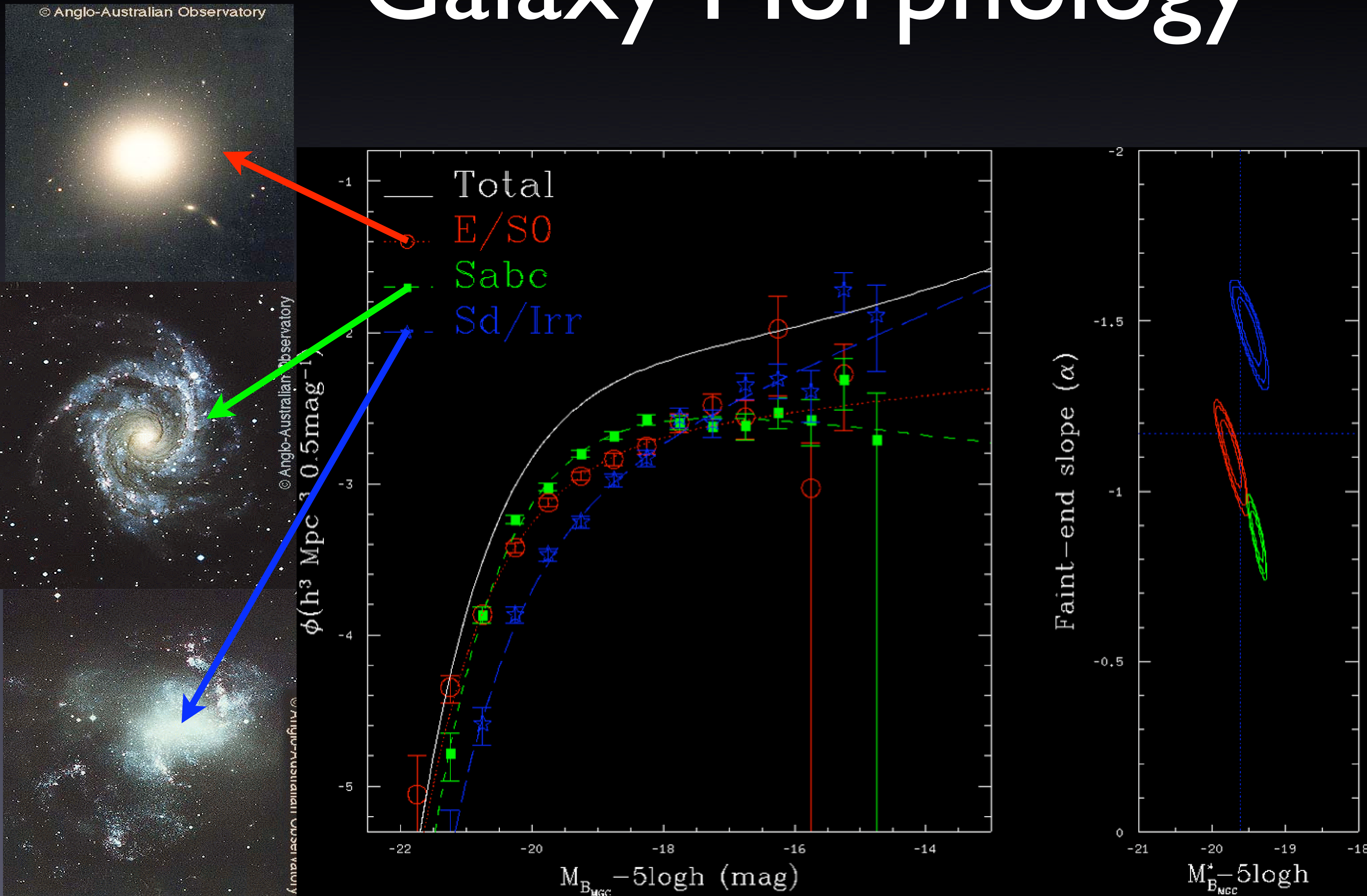
Spheroids: 35+/- 2%
Bulges: 18+/-7%
Bulge disks: 18+/-7%
Disk only: 29+/-7%





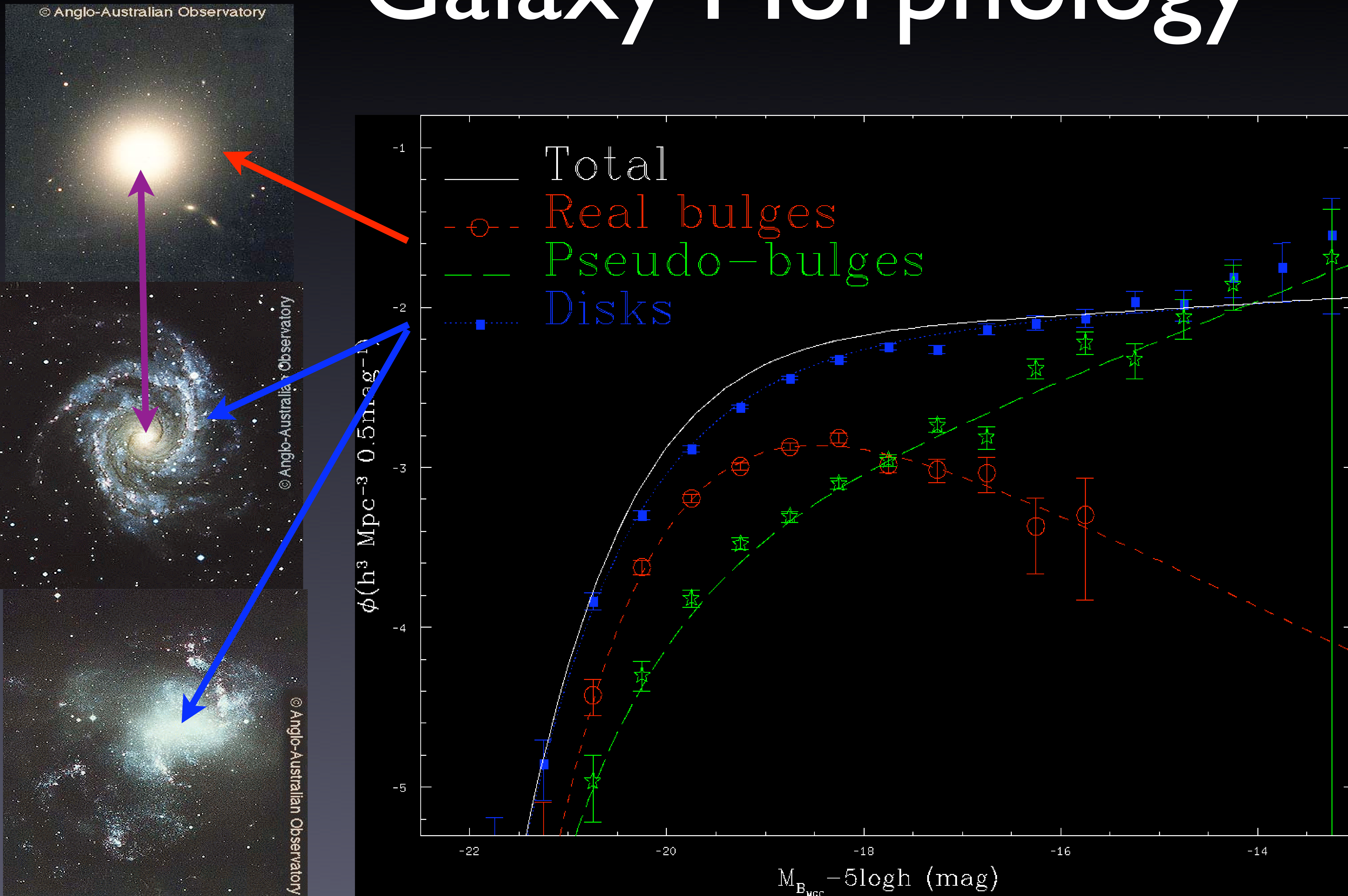
ΩΛ
73%
ΩM
23%
Ωb
4%
ΩGALAXIES ~20%
ΩPLASMA ~80%
ΩDUST
ΩGAS
ΩPLANETS
ΩSMBHs
0.04%
ΩSTARS
20%
ΩIGM
ΩICM
ΩBULGES
50%
ΩP-BULGES
3%
ΩDISKS
47%
ΩIRON etc
2dFGRS+WMAP
MGC
LSI

Galaxy Morphology



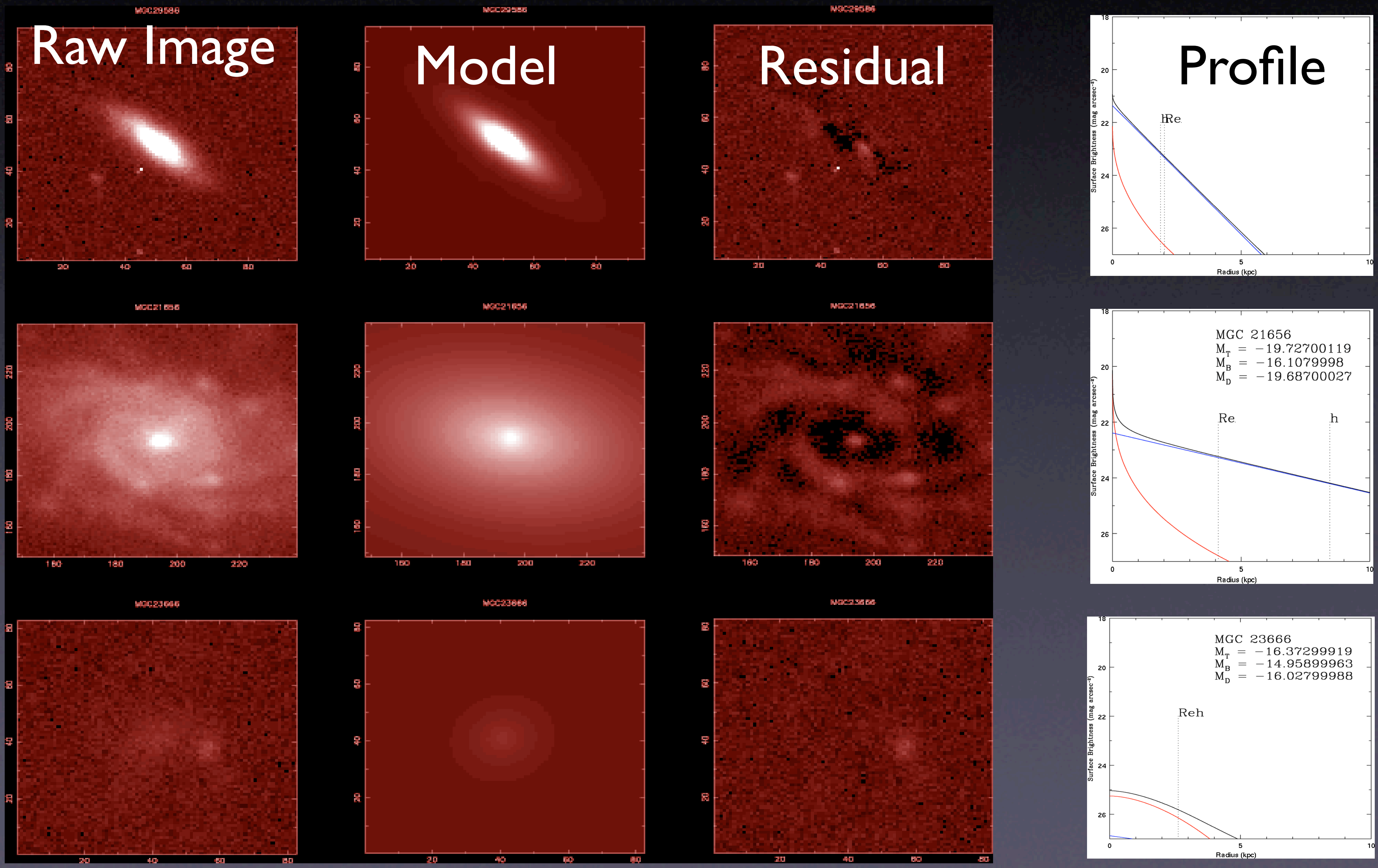
Galaxy Morphology

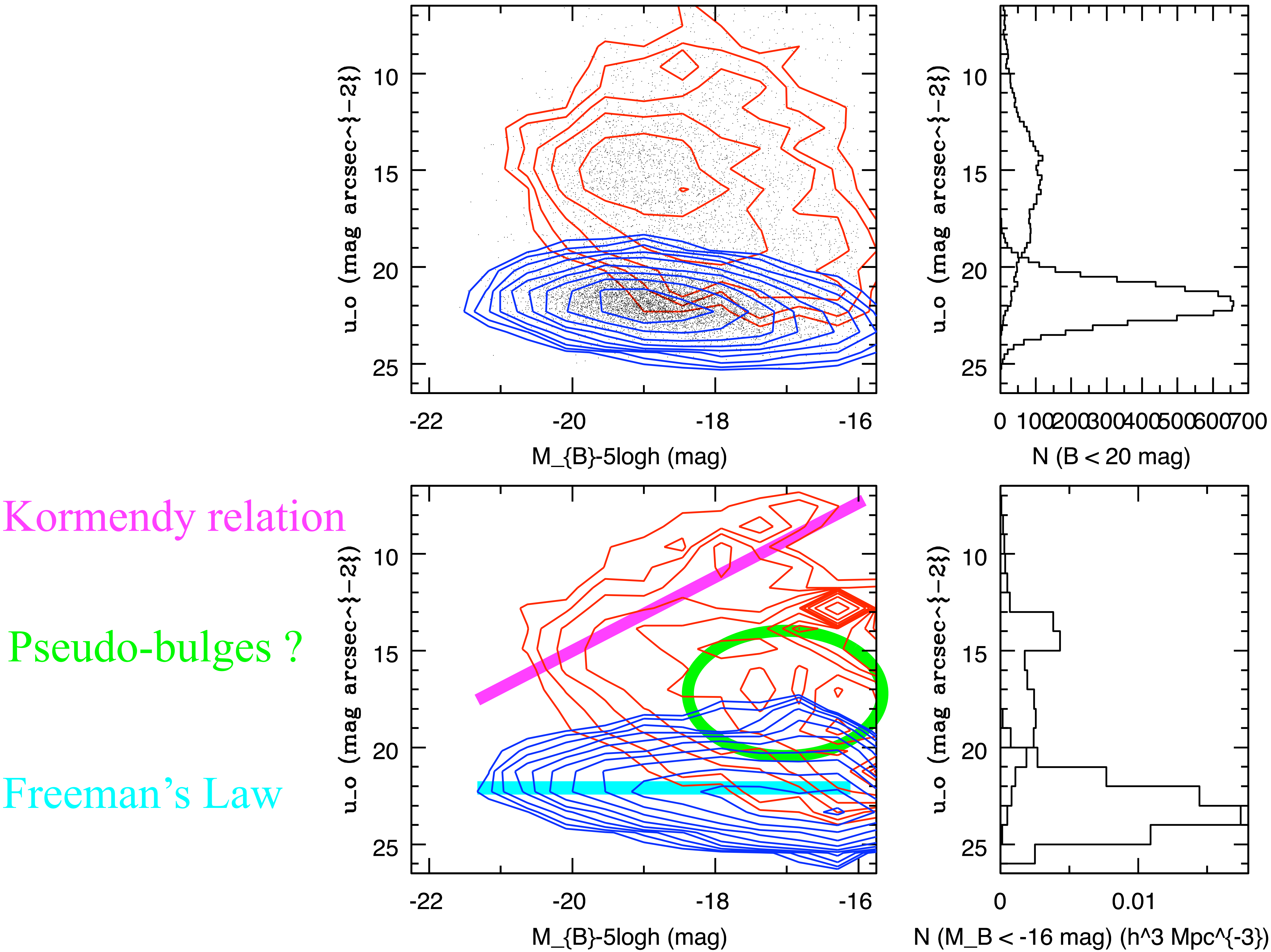
Text



Structural Analysis (GIM2D)

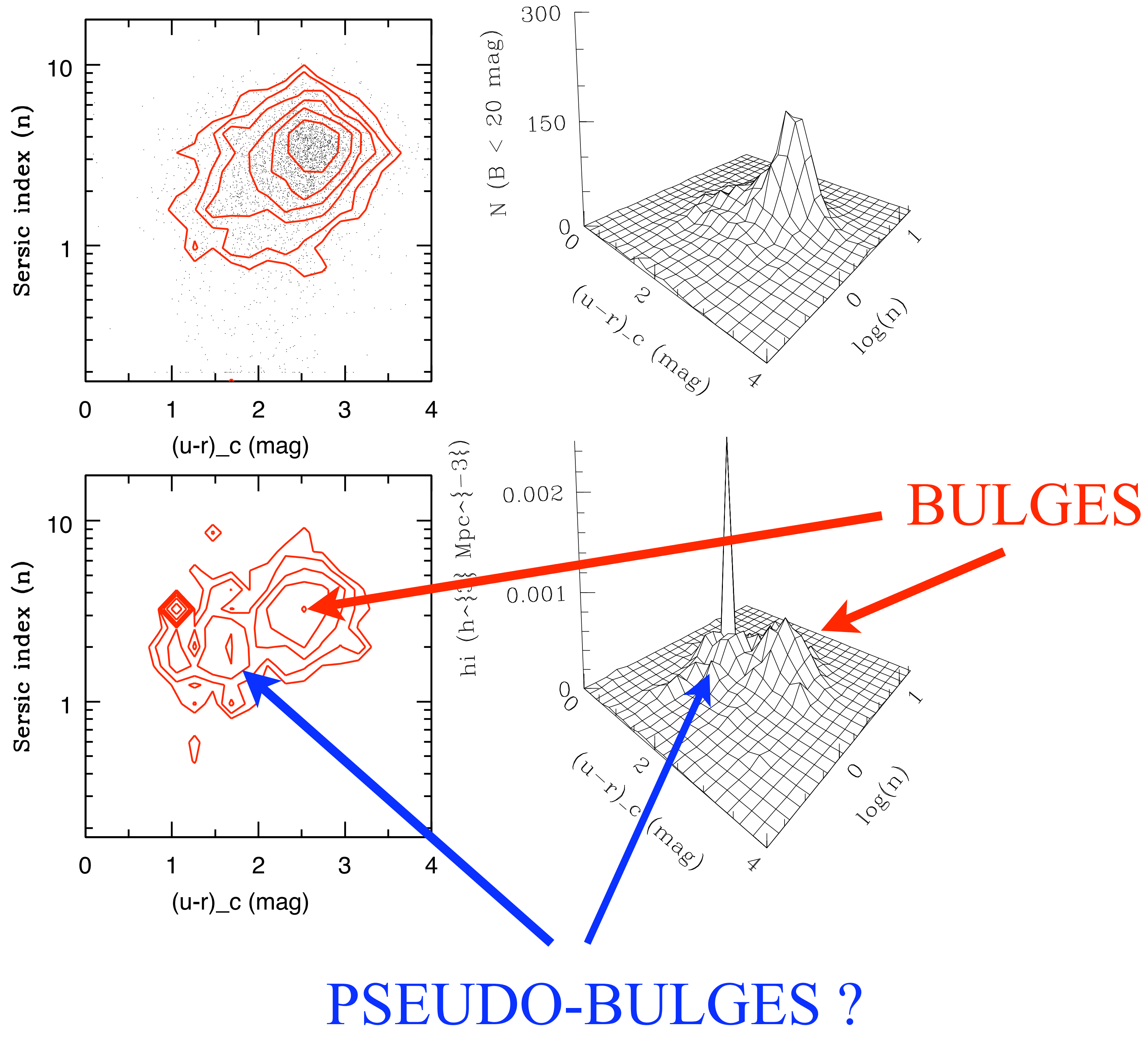
- 12 Dimensional minimisation (Sersic+exponential profiles+PSF convolution)
- 10,095 galaxies now completed, largest available sample, Allen,[Driver] et al (2005)





Kormendy relation
Pseudo-bulges ?
Freeman's Law
u_o (mag arcsec^{-2})
M_{B}-5logh (mag)
N (B < 20 mag)
N (M_B < -16 mag) (h^3 Mpc^{-3})
10
15
20
25
-22
-20
-18
-16
0 100 200 300 400 500 600 700
0
0.01

MGC Bulges



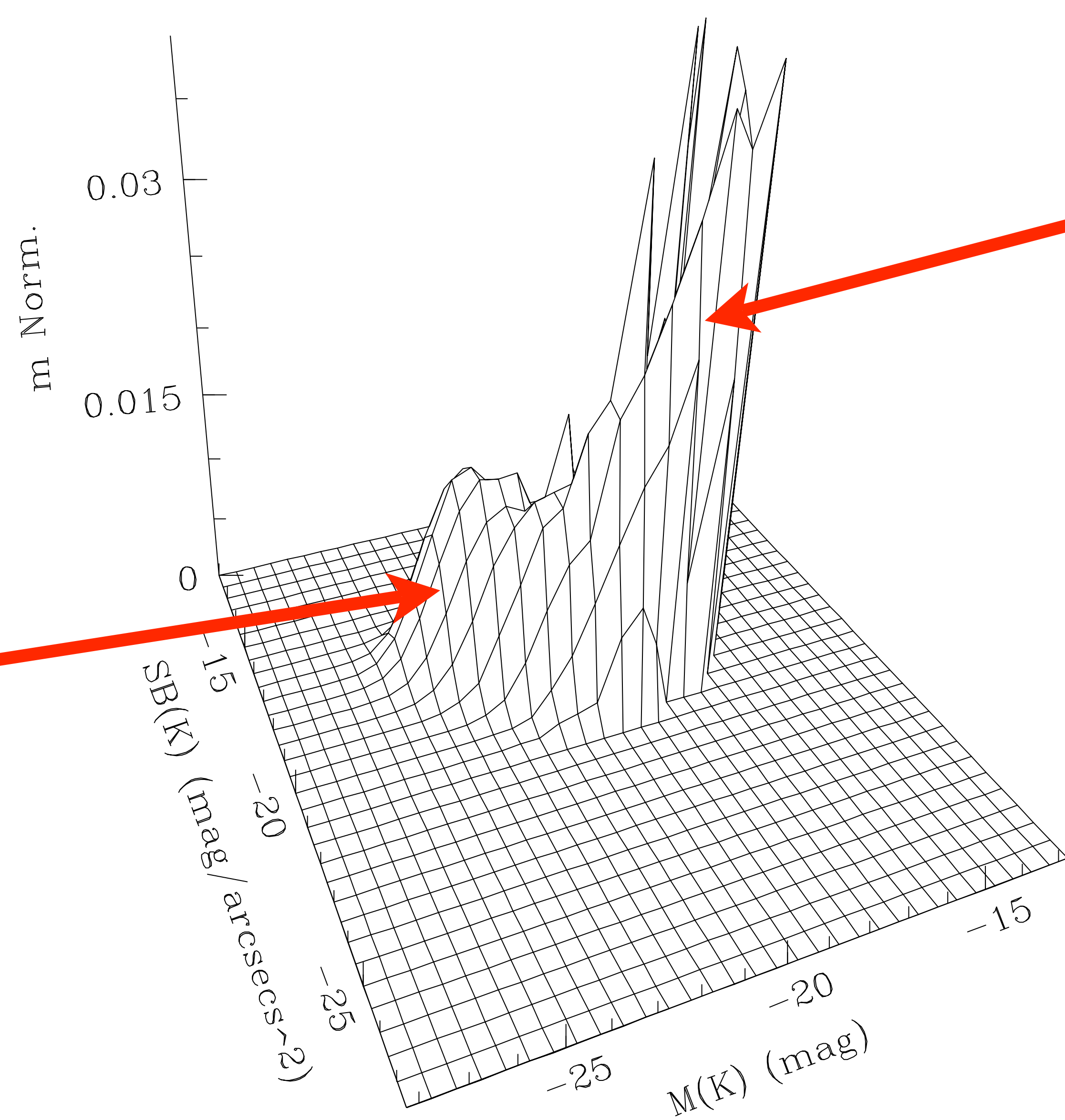
Sersic index (n)
10
1
0
1
2
3
4
(u-r)_c (mag)
300
150
0
N (B < 20 mag)
0
2
4
(u-r)_c (mag)
0
1
log(n)
Sersic index (n)
10
1
0
1
2
3
4
(u-r)_c (mag)
0.002
0.001
0
hi (h~{3} Mpc^{-3})
0
2
4
(u-r)_c (mag)
0
1
log(n)
BULGES
PSEUDO-BULGES ?

6dFGS interlude

K-band LF => BBD => stellar and baryonic mass dist'n

~80 000 galaxies with sizes from 2MASS

Local flow corrected

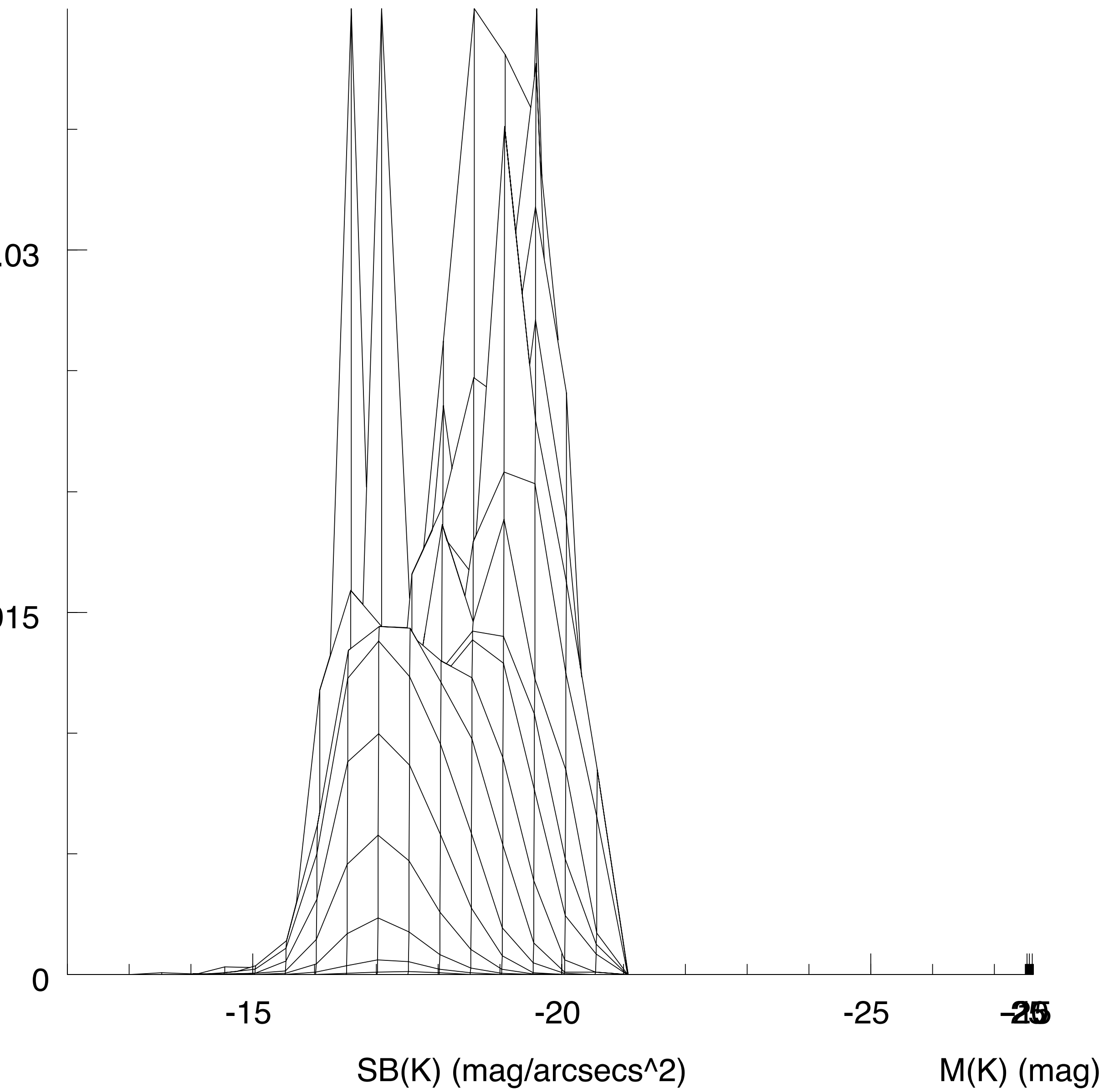


The dwarf "mountain"

The giant "hill"

6dFGS interlude

K-band SB distribution

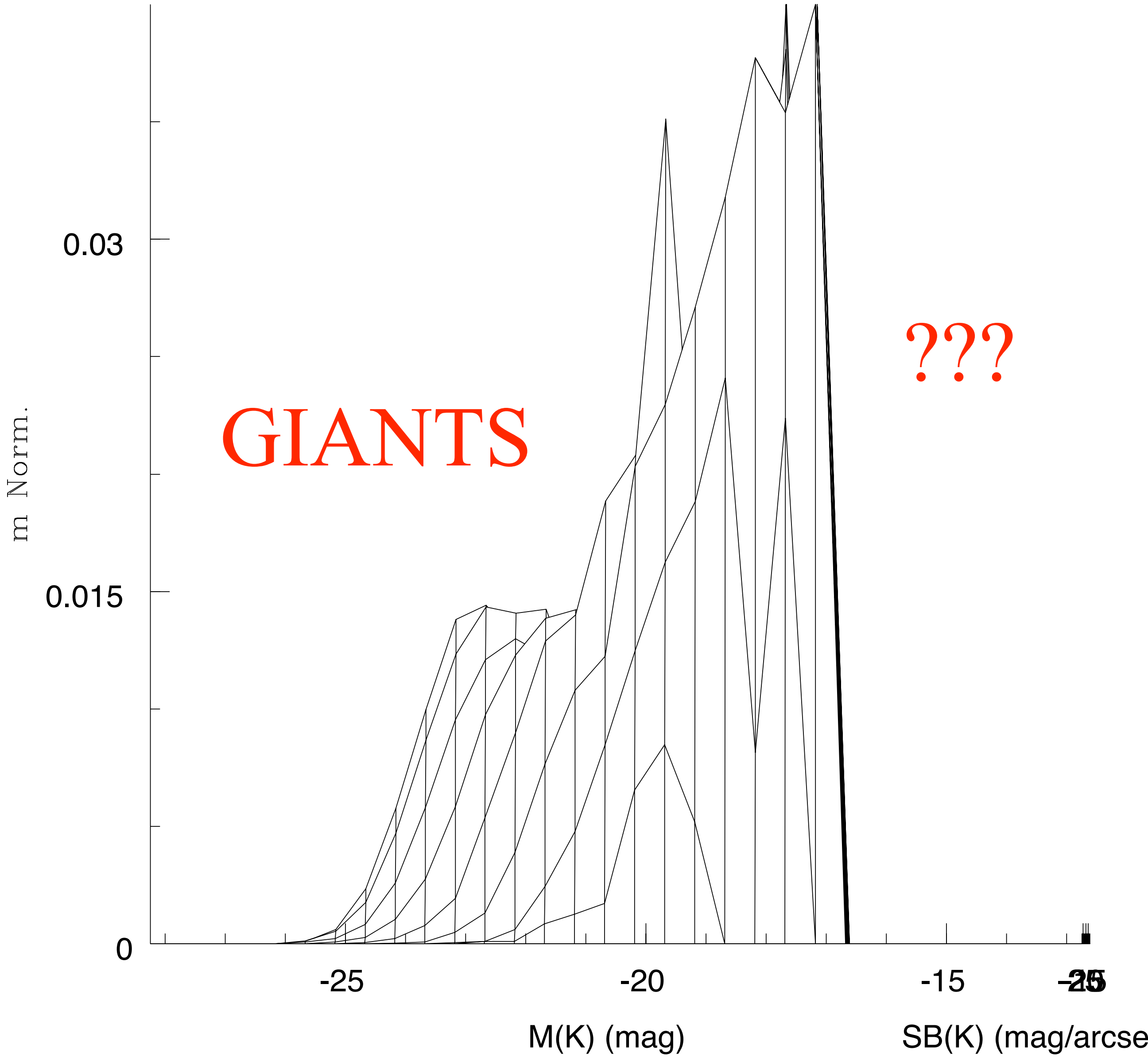


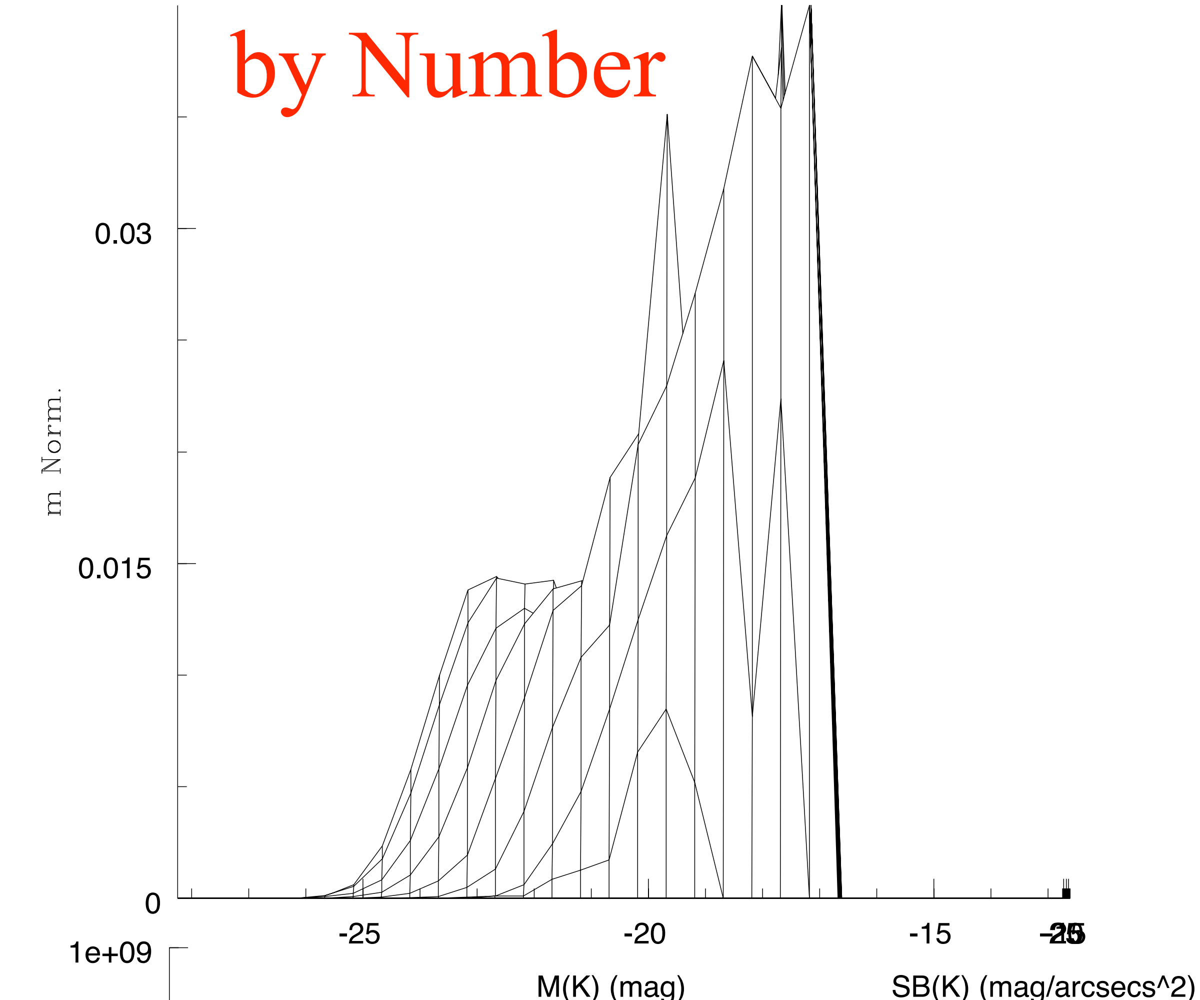
K-band Luminosity fn

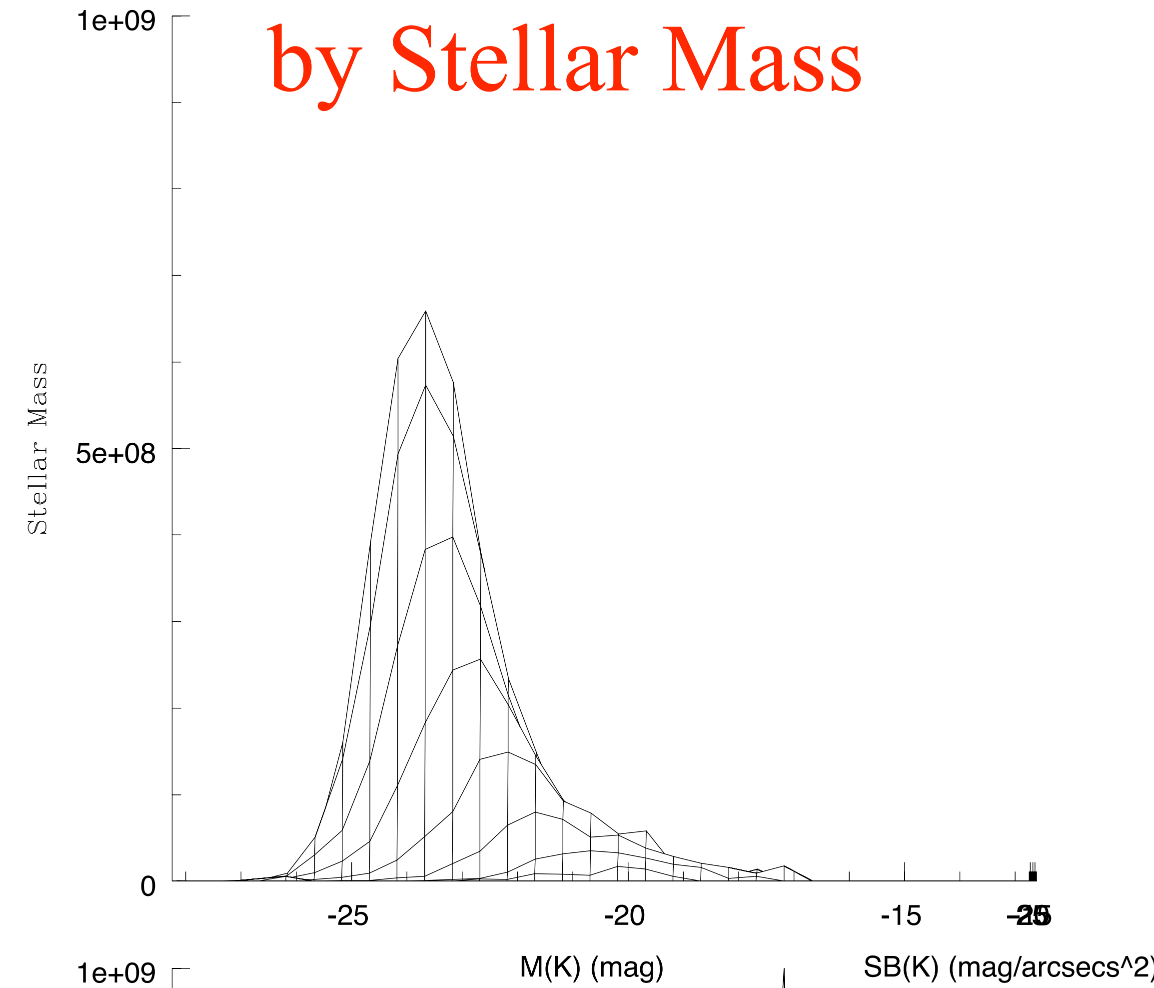
DWARFS !

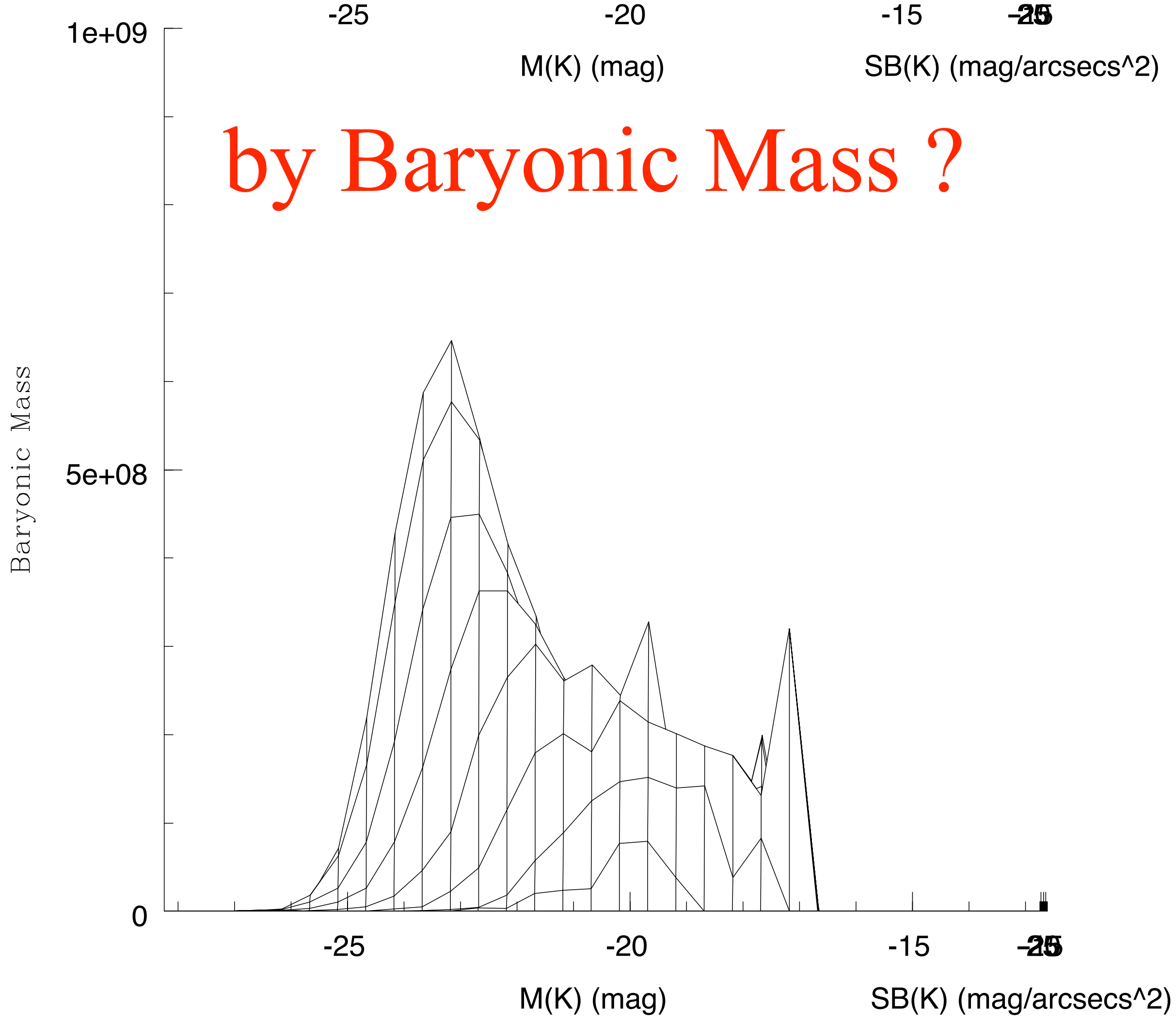
GIANTS

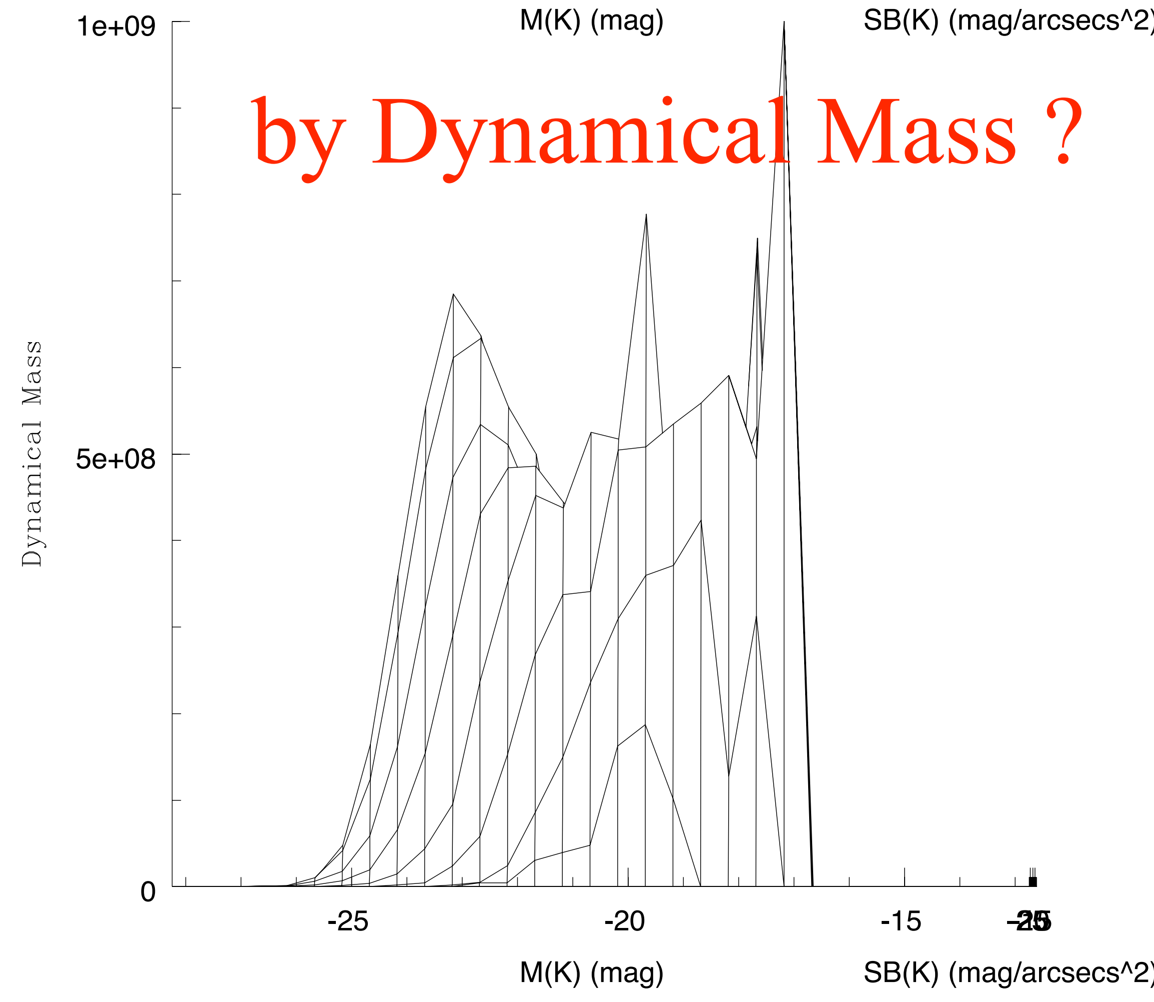
???




by Number
m Norm.
0.03
0.015
0
-25
-20
-15
M(K) (mag)
SB(K) (mag/arcsecs^2)


by Stellar Mass
Stellar Mass
1e+09
5e+08
0
-25
-20
-15
M(K) (mag)
SB(K) (mag/arcsecs^2)

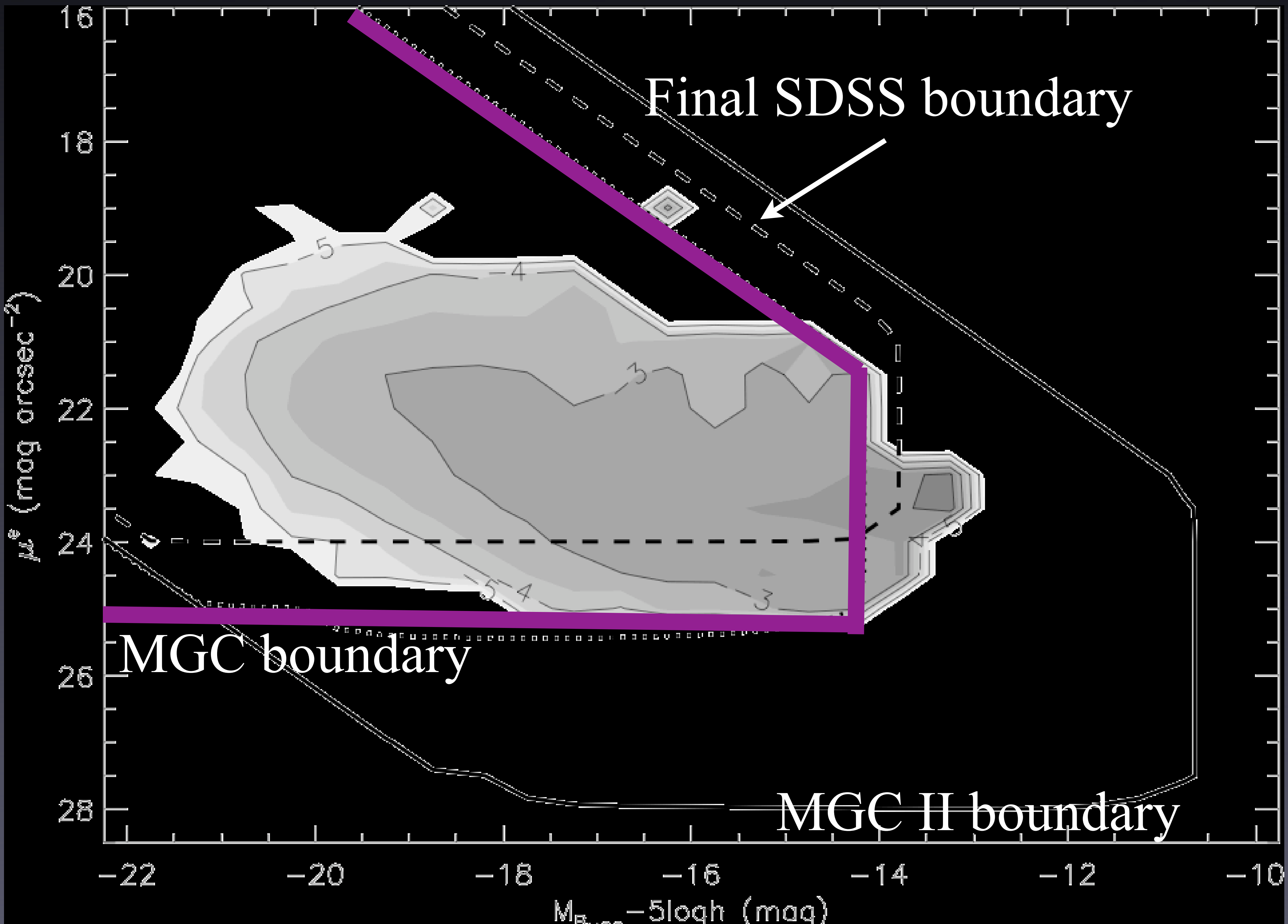

by Baryonic Mass ?
Baryonic Mass
1e+09
5e+08
0
-25
-20
-15
M(K) (mag)
SB(K) (mag/arcsecs^2)


by Dynamical Mass ?
Dynamical Mass
1e+09
5e+08
0
-25
-20
-15
M(K) (mag)
SB(K) (mag/arcsecs^2)

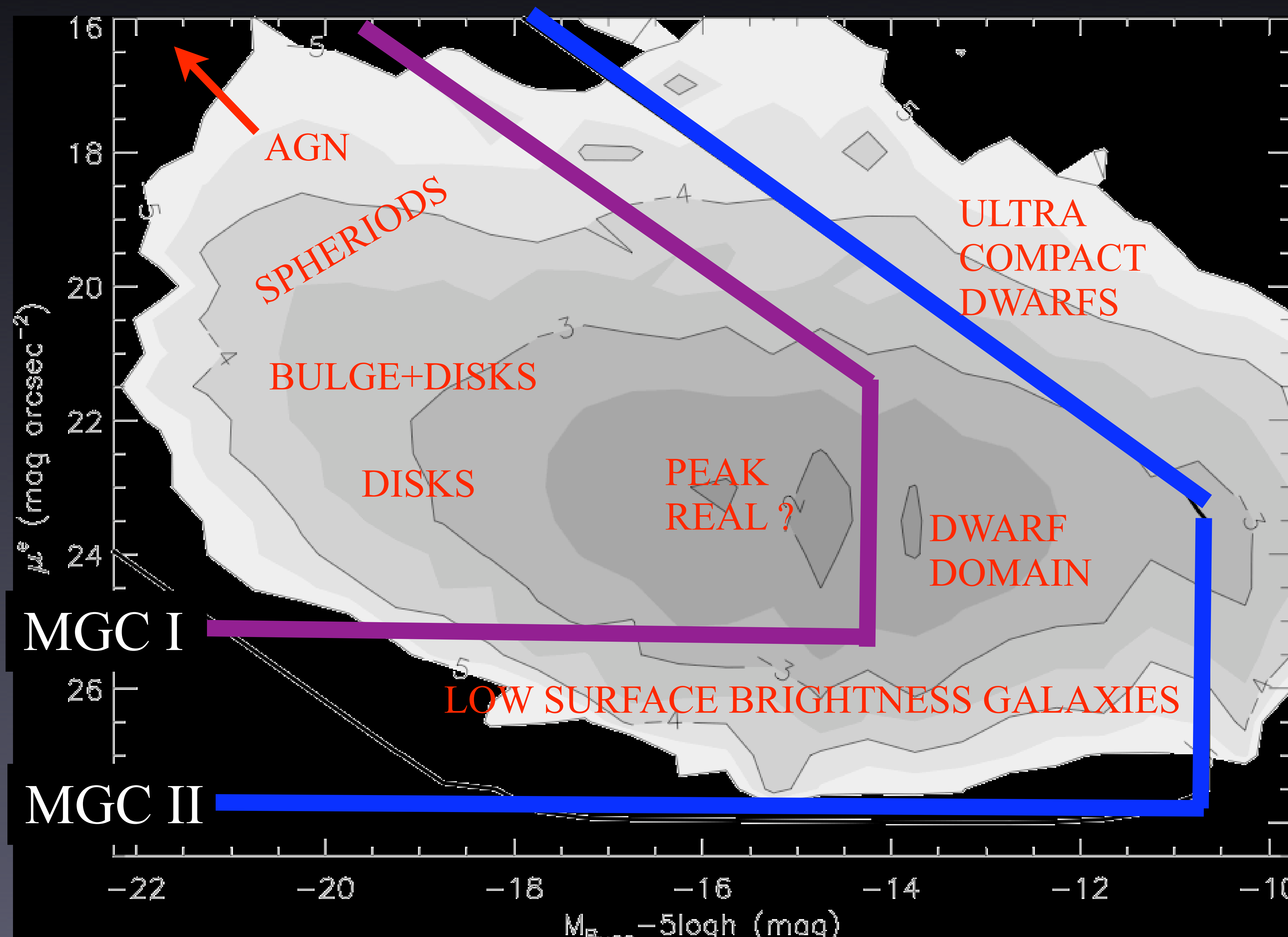
Summary

- Galaxy luminosity function known: -21 < M < -16
- Galaxy luminosity function unknown: -16 < M < -6 !
- 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 mystery (downsizing pop or classif'n error ?)
- Disks form later via infall/merging/splashback (coeval with SFR ?)
- Pseudo-bulges via secular evolution (post-Lambda evolution ?)
- Dwarf domain more complex & entirely uncharted (great VST/VISTA op.)
- Need to summit the dwarf mountain (great AAT op.)
- Exteme-LSBG domain uncharted (does it exist ?)
- Formation mechanisms = evolutionary markers = spatial studies
- Need to:
    - Expand survey to LSBGs, dwarfs etc (GMOS/AAOmega) PEND/NO
    - Improve imaging resolution to 1kpc at z=0.1(VST) YES
    - Add near-IR to penetrate dust (UKIDSS/VISTA) YES/PEND
    - Extend in redshift (HST/JWST, GTO JWST) YES

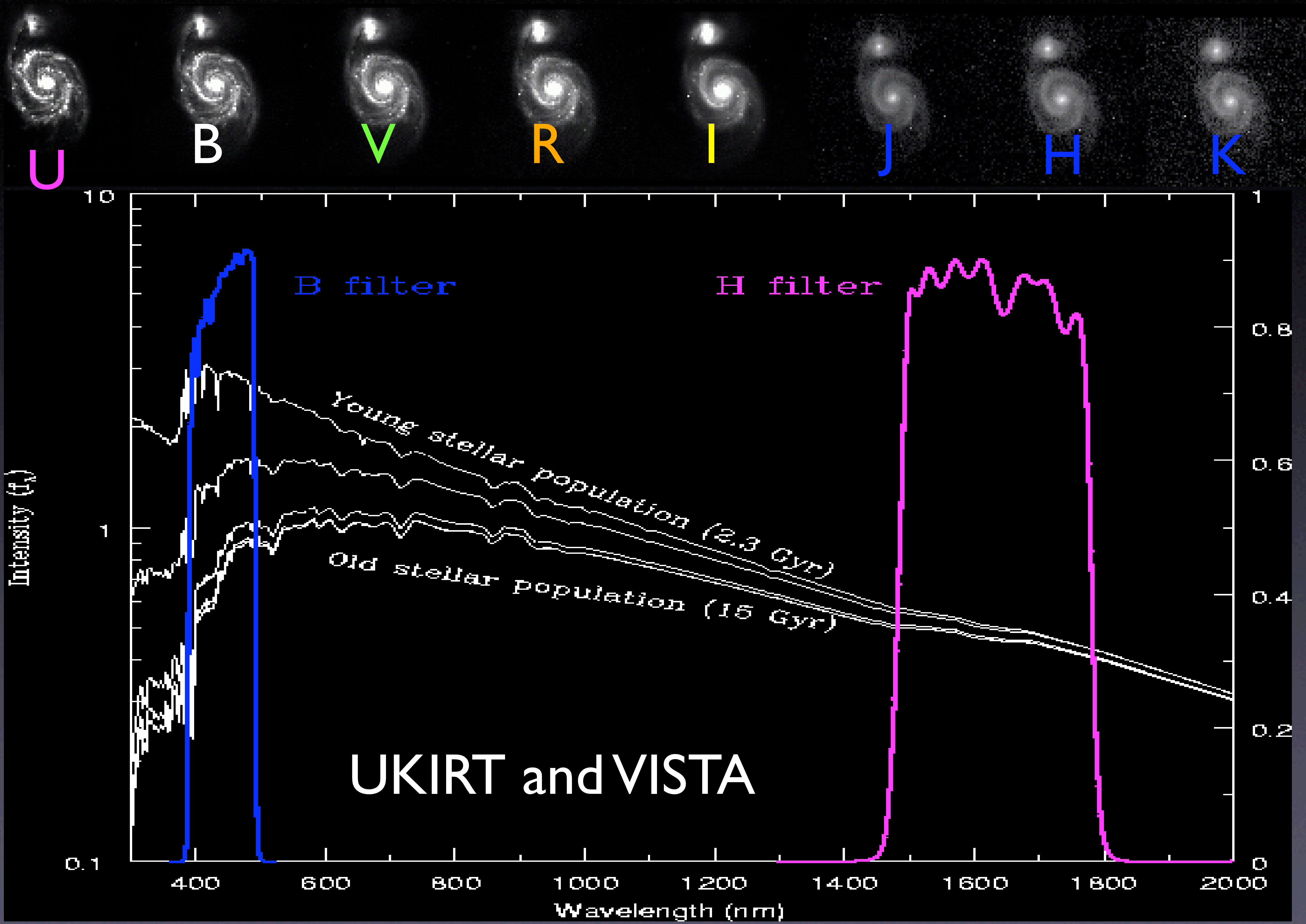
MGC Observations of the Luminosity-Surface Brightness plane (Driver et al 2005)



MGC II: AAOmega + ultra-deep VST and VISTA will survey well into the dwarf domain and trace the giants to z=0.5



The Near-IR


U
B
V
R
I
J
H
K
10
1
0.1
Intensity (f_λ)
B filter
H filter
Young stellar population (2.3 Gyr)
Old stellar population (15 Gyr)
1
0.8
0.6
0.4
0.2
0
400
600
800
1000
1200
1400
1600
1800
2000
Wavelength (nm)
UKIRT and VISTA