Deconstructing Galaxies

Why we need surveys of galactic components

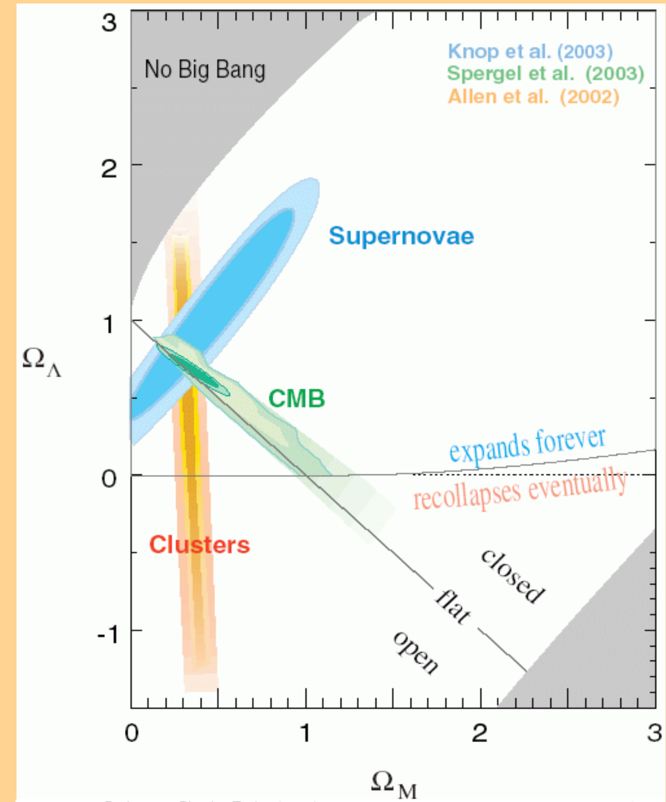
Jochen Liske

The cosmological framework

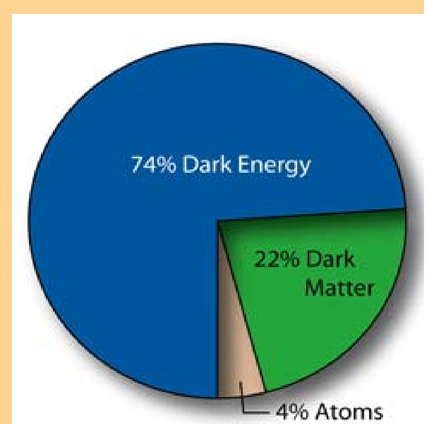
- Observations of the CMB, SNIa, large scale structure, weak lensing, D/H, BAO, abundance of clusters, etc, are all found to be consistent (to the level of accuracy so far probed) with one another and with ΛCDM.

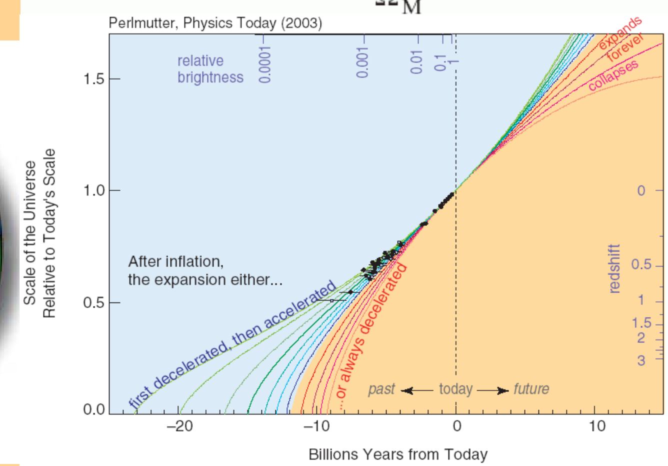
➔ The cosmological background model is now known (±10%)!

- Although the model is incomplete (nature of DM, DE, quantum-gravity?) any changes/additions are unlikely to *significantly* affect our understanding of galaxy formation and evolution.

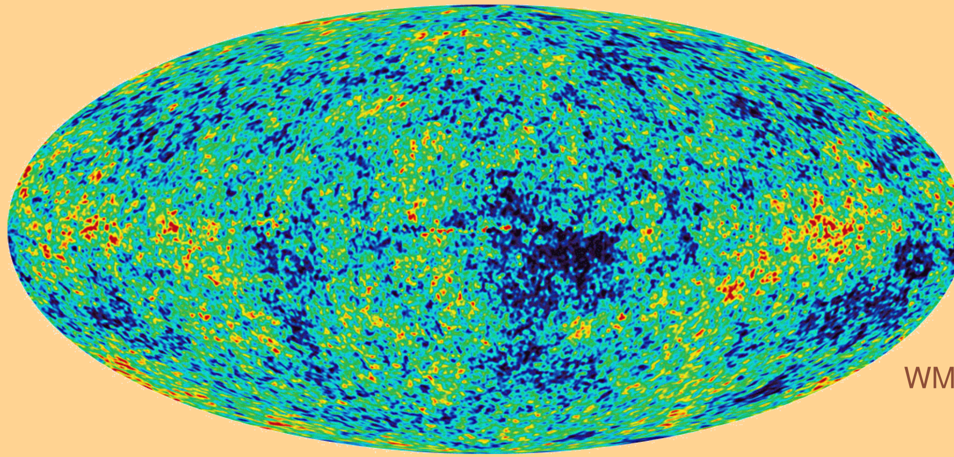


⇒ From the point of view of galaxy evolution **cosmology is solved.**





Structure formation



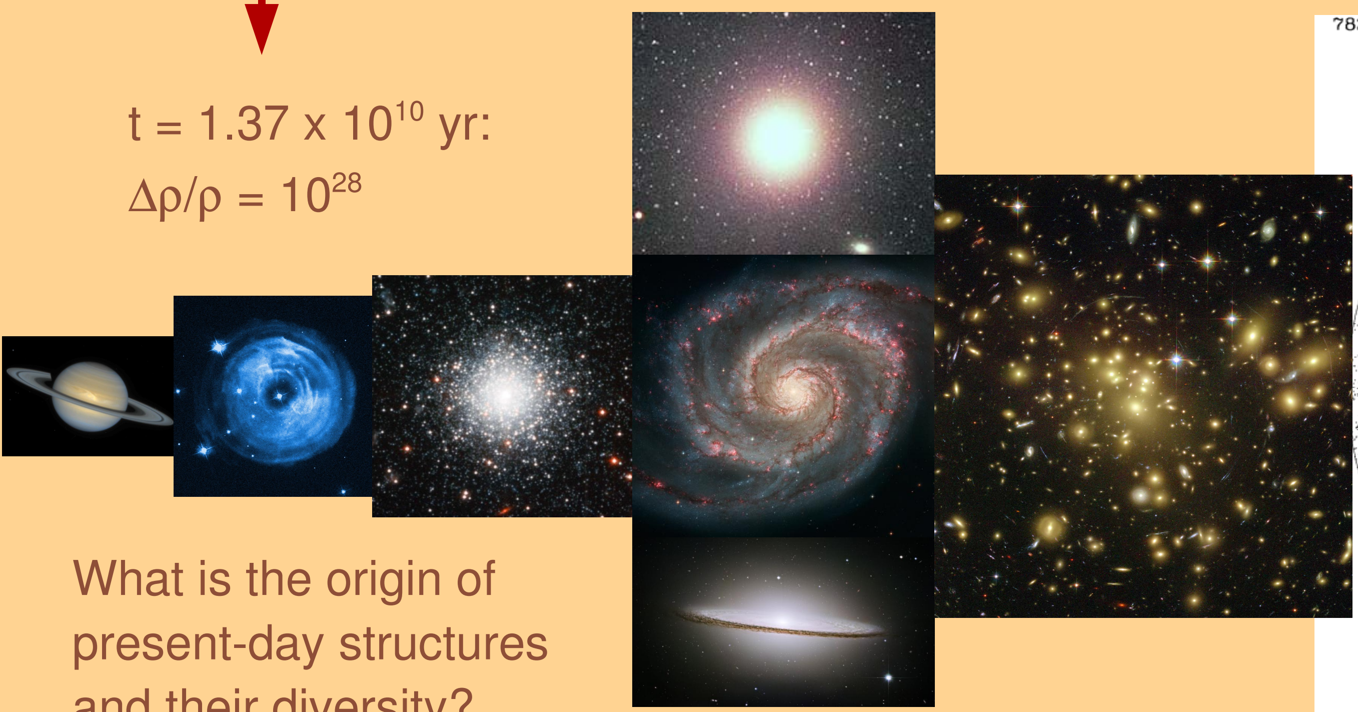
WMAP

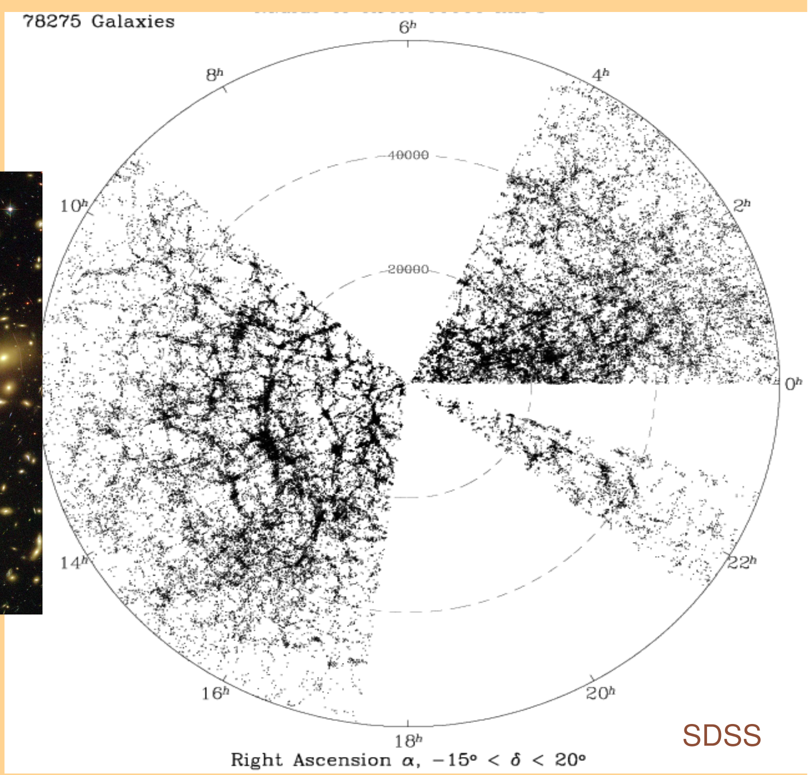
t = 4 x 10^5 yr:

$\Delta\rho/\rho = 10^{-5}$

t = 1.37 x 10^{10} yr:

$\Delta\rho/\rho = 10^{28}$

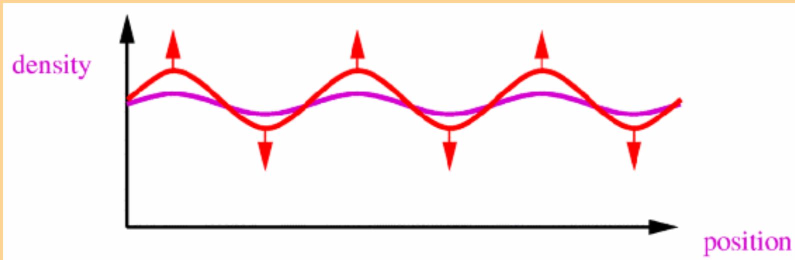




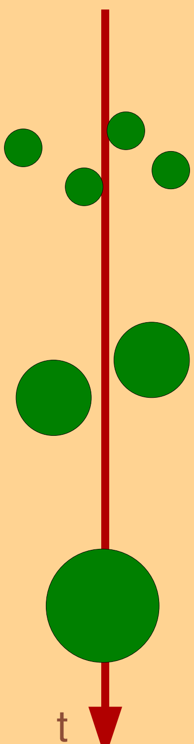
SDSS

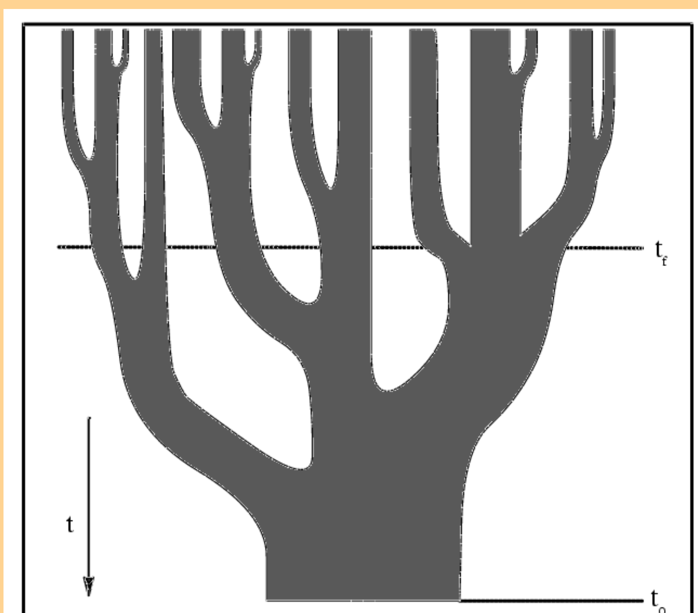
What is the origin of present-day structures and their diversity?

Gravitational instability and hierarchichal build-up

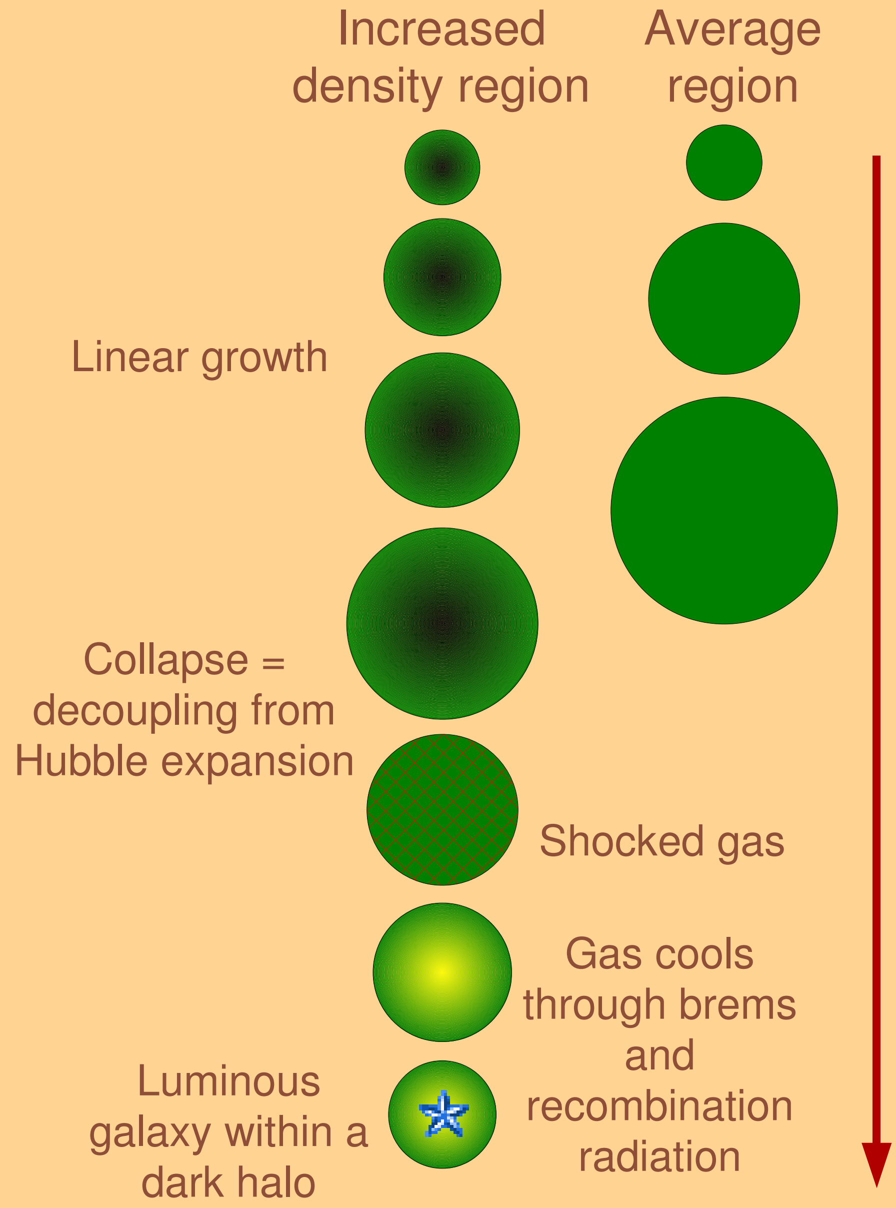


Initial density perturbations grow through gravitational attraction.





Hierarchical merging of smaller structures to form larger ones.



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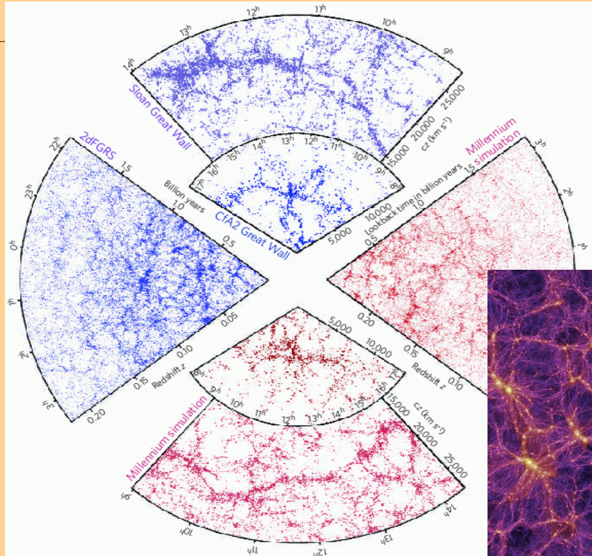
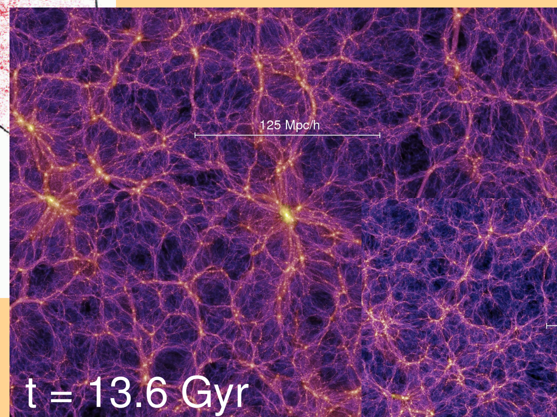
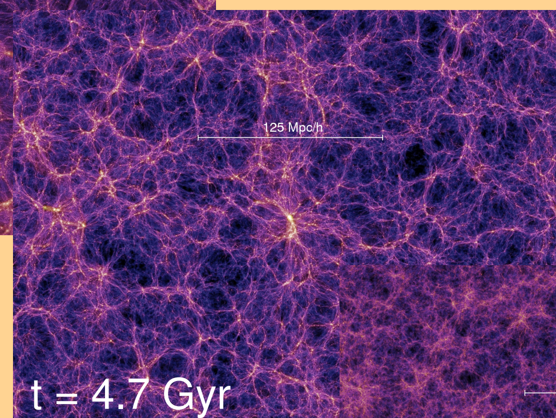


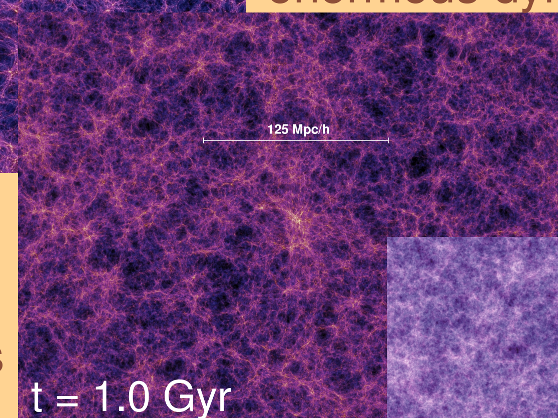
Springel et al. (2006)

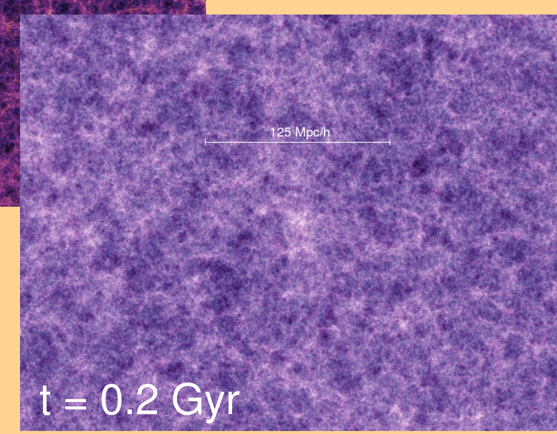
CDM simulations: numerical solution of the coupled Boltzmann and Poisson equations through discretization as N-body system $\rightarrow$ excellent reproduction of the observed distribution of matter.

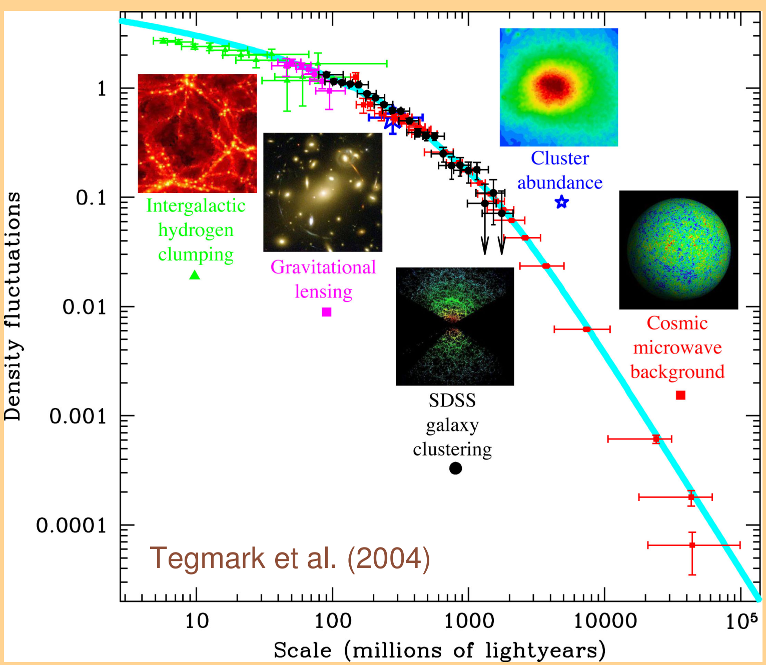


Hydrodynamics of baryons: can be included approximately $\rightarrow$ excellent reproduction of IGM properties. Problem: gas collapses to very high densities resulting in short timescales $\rightarrow$ cosmological simulations that resolve collapsed objects require an enormous dynamic range.



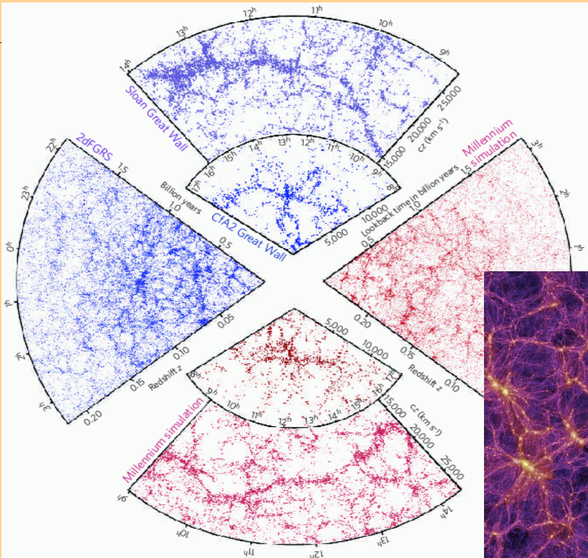






Makeshift solution: semi-analytical models = combination of the hierarchical structure formation process of CDM halos from simulations with analytical 'recipes' describing the physics of the baryons.

Structure formation



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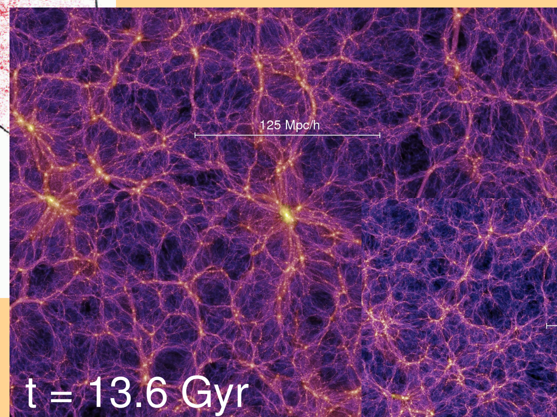
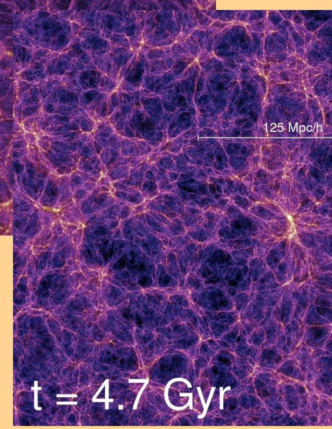
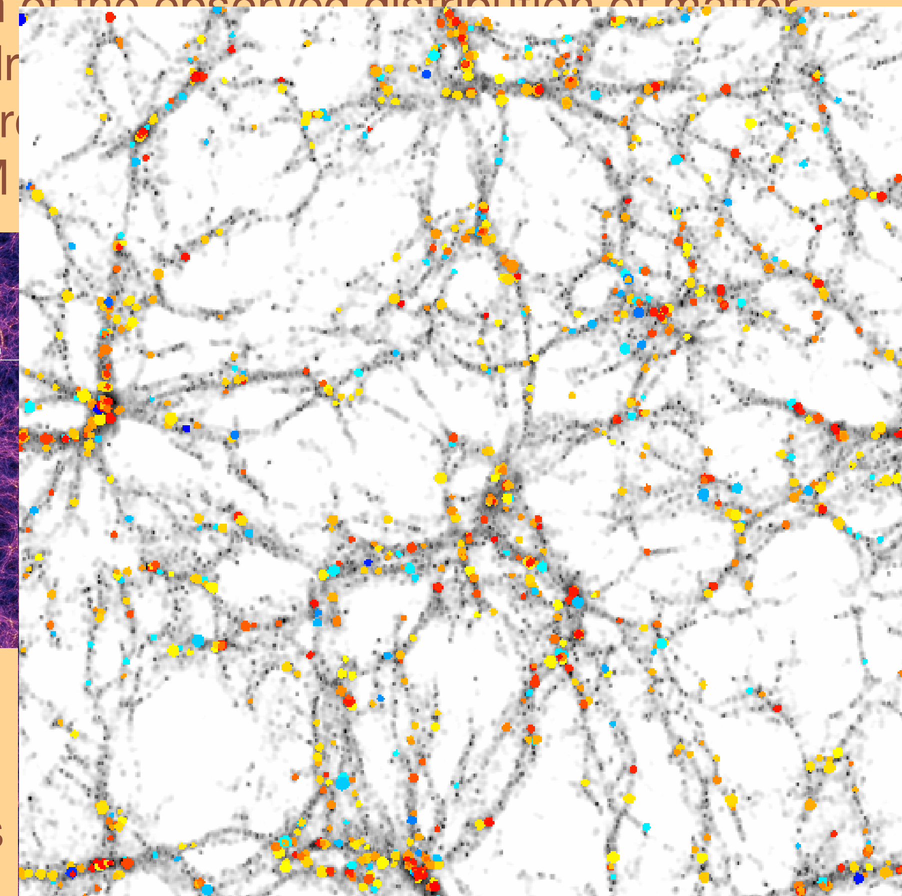
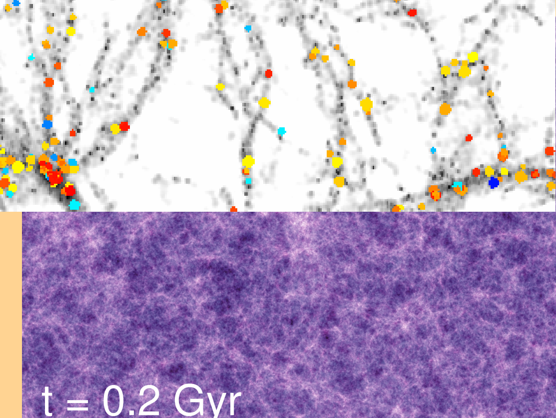
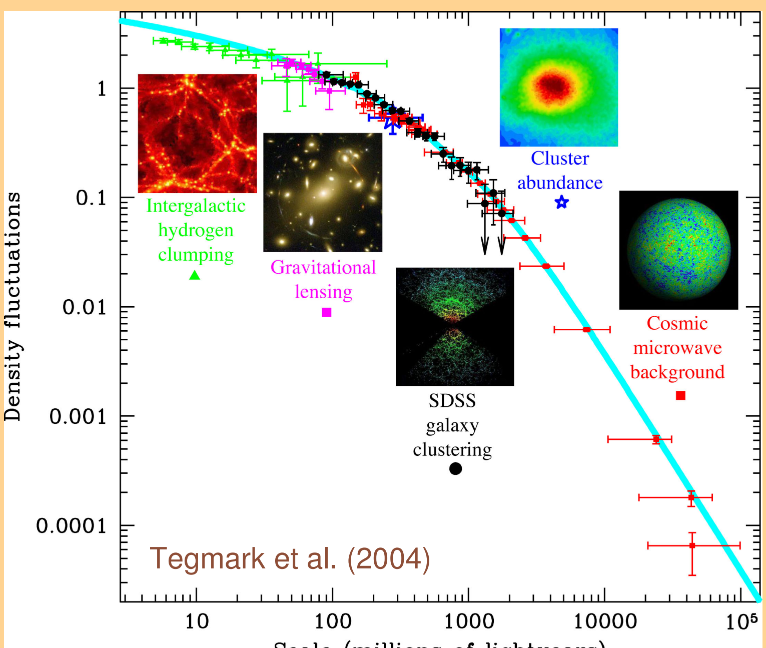
Hydr
appr
IGM











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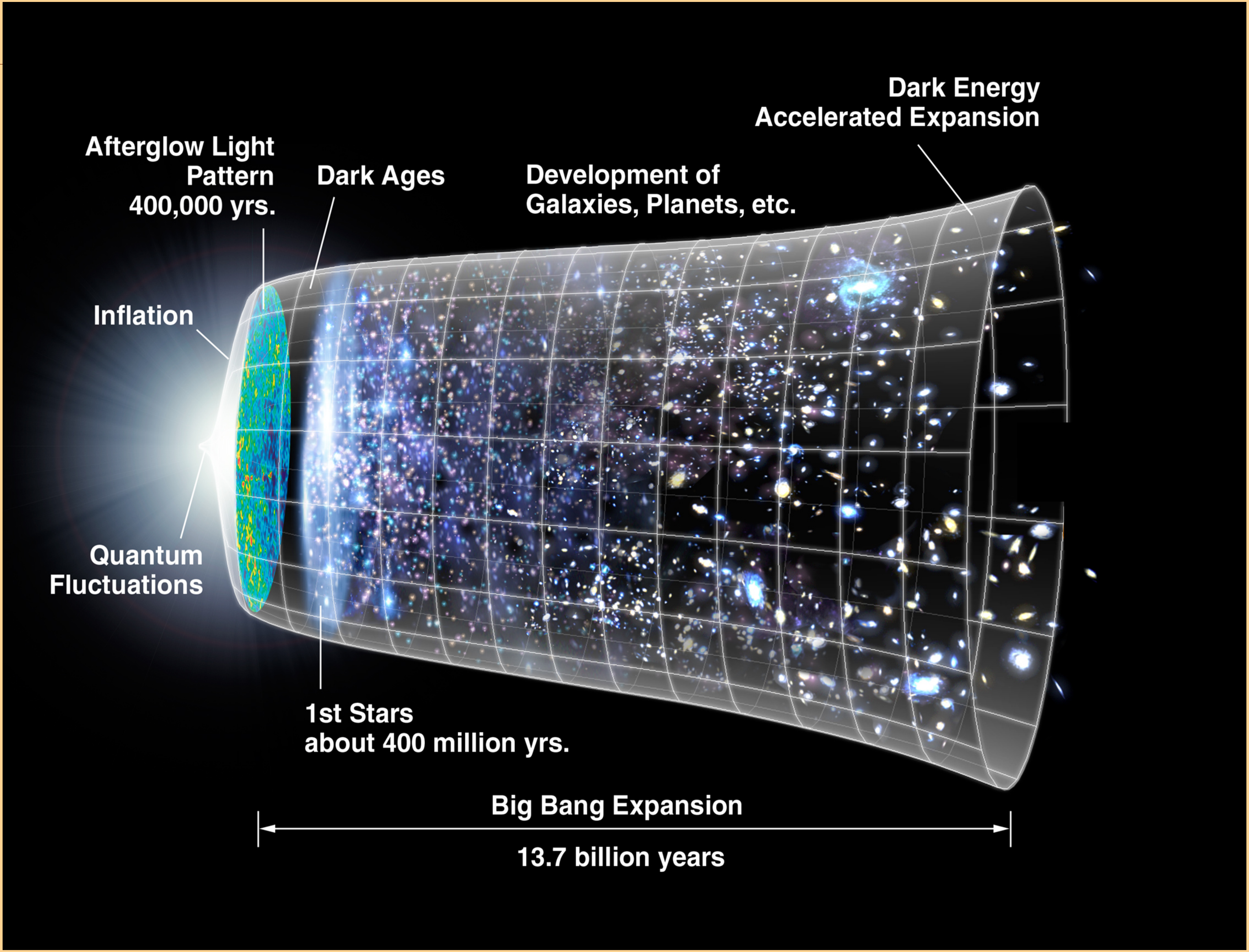
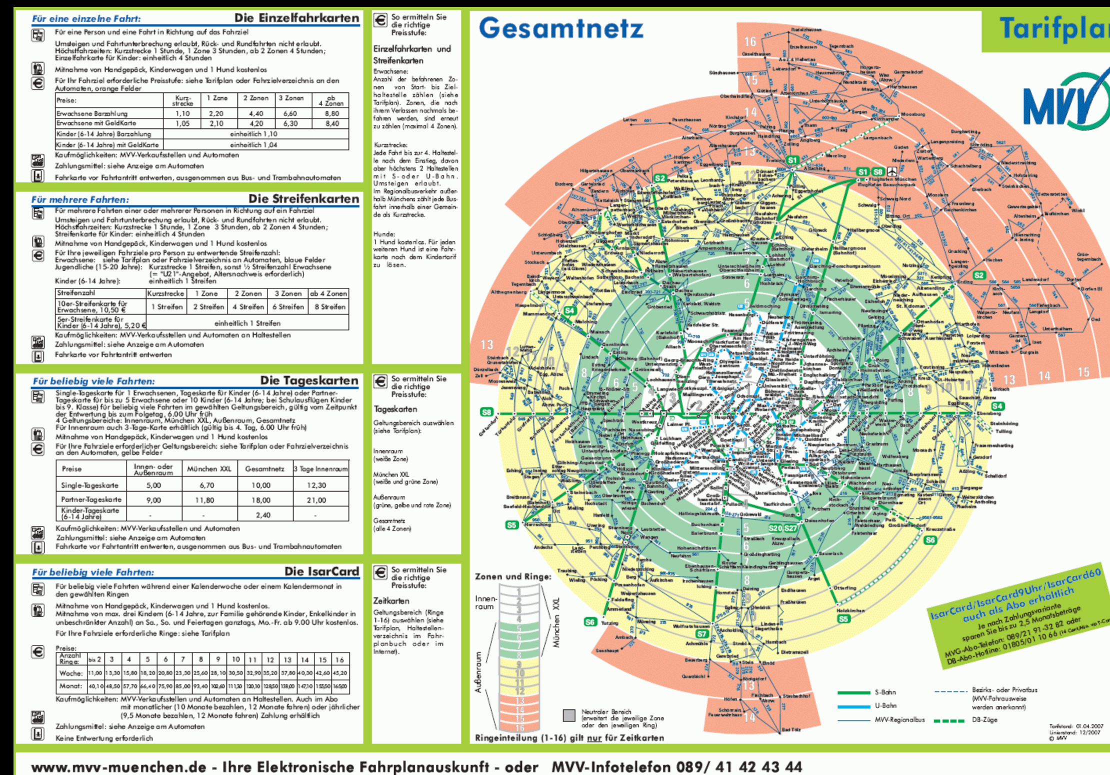


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Dark Energy
Accelerated Expansion

Structure of the MVV pricing system?



Big Bang Expansion

13.7 billion years

Dark Energy
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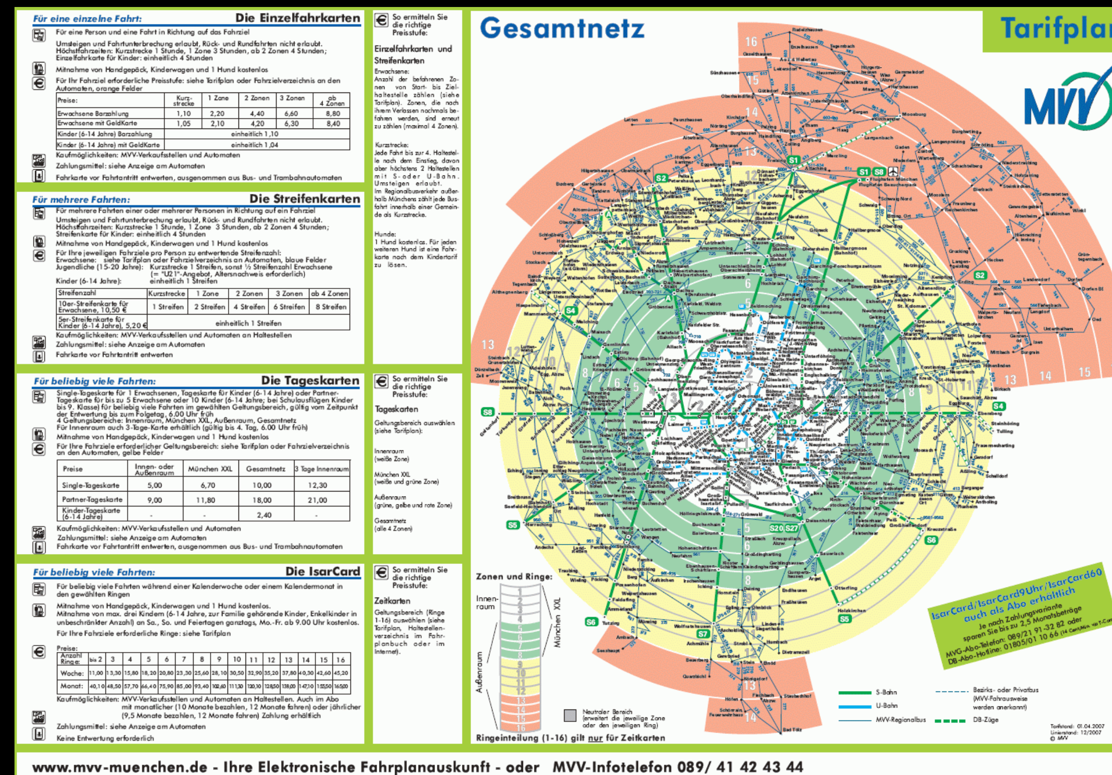
Structure of the MVV pricing system?

Evidence for non-intelligent design?



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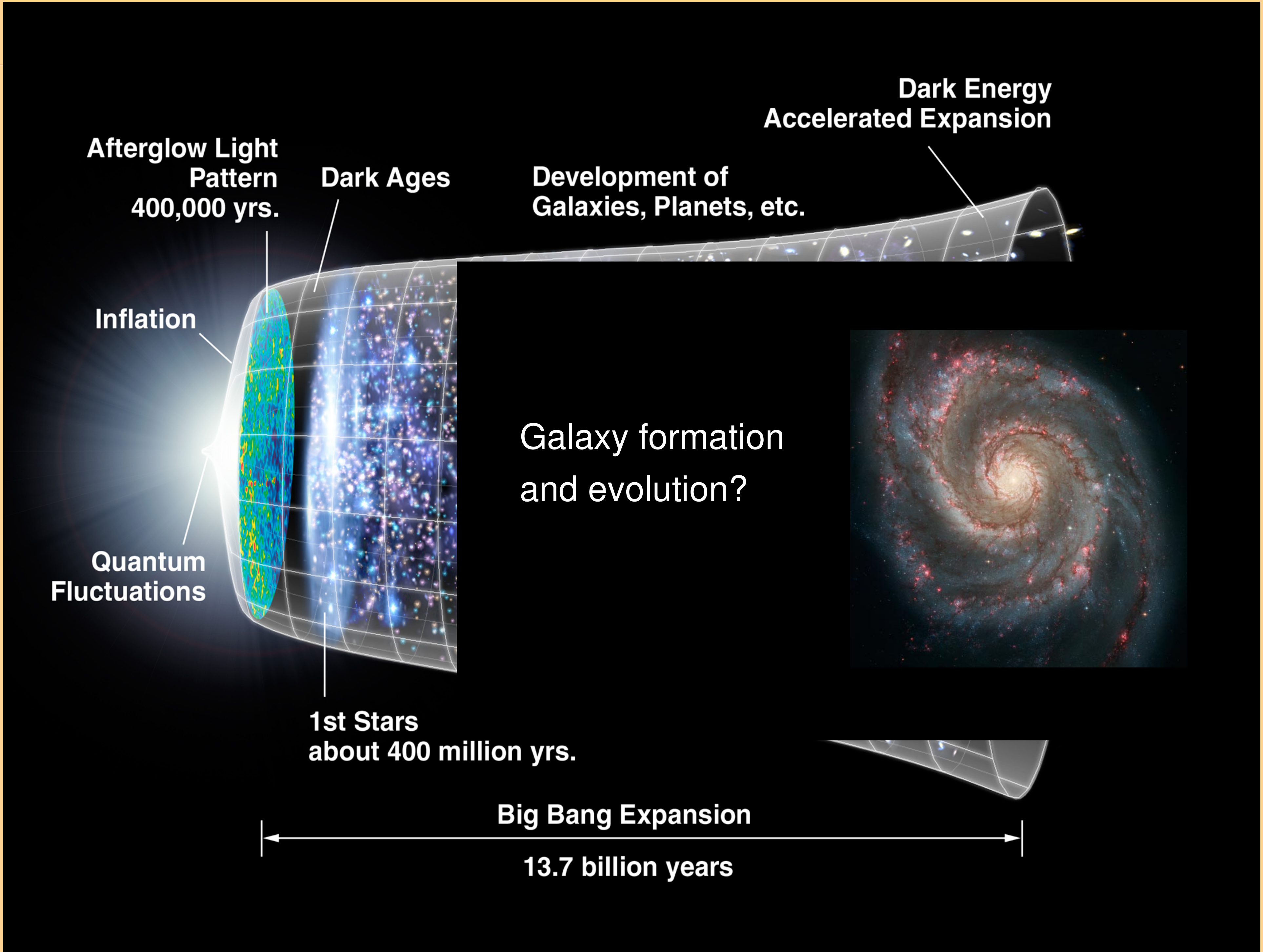
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How to approach galaxy formation and evolution?

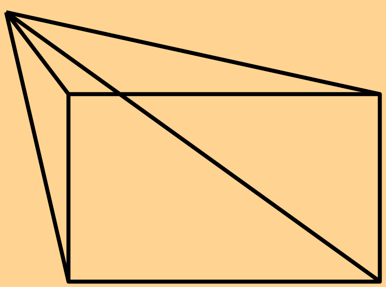
Observations

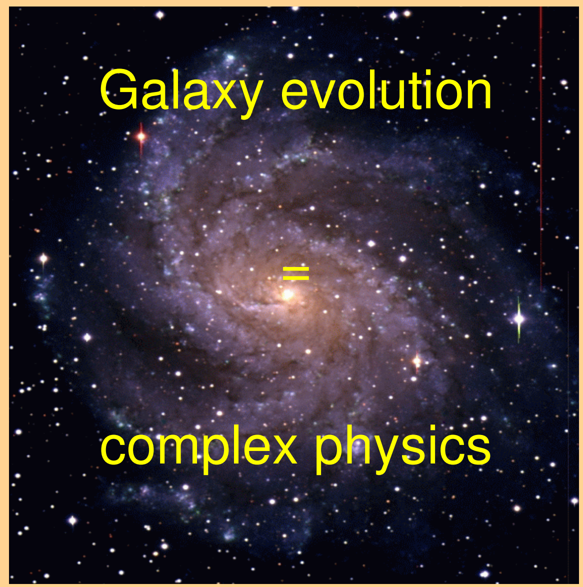
Large surveys of galaxy population(s)

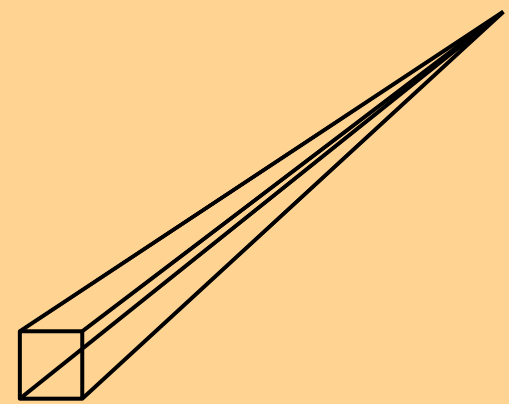
Level of detail

Statistical power, completeness

Detailed investigations of individual galaxies







Theory

(analytic, semi-analytic, numerical)

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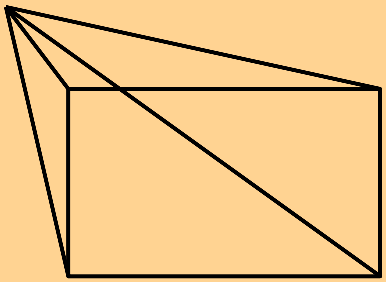

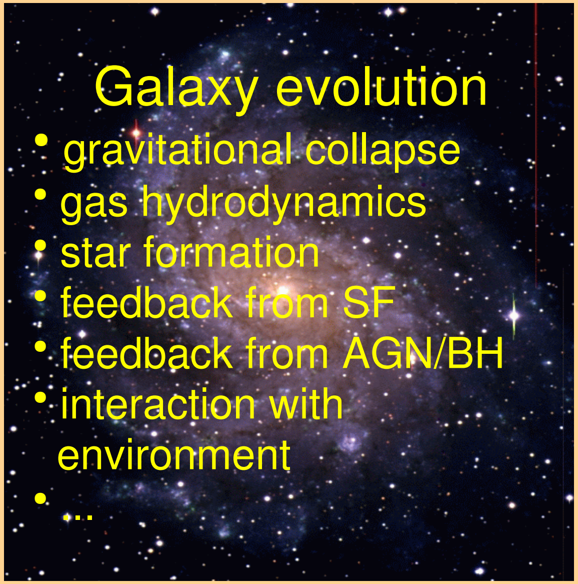

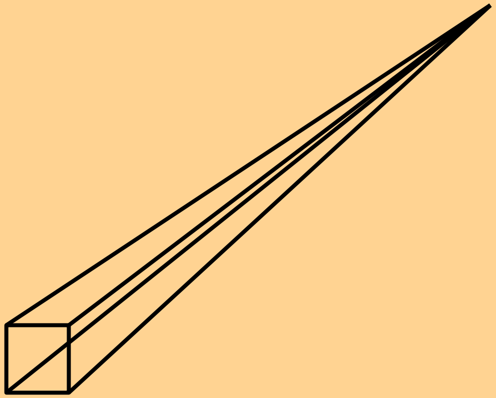

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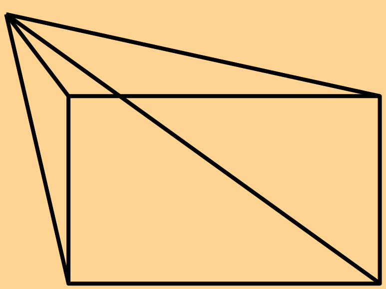

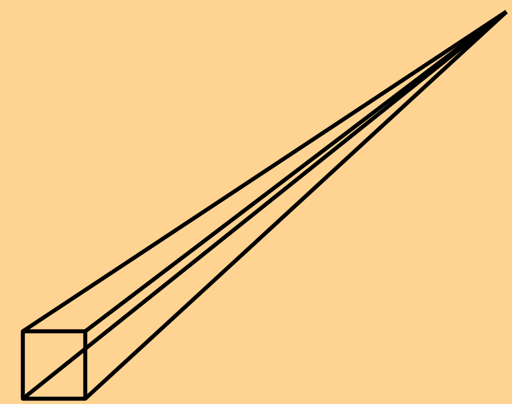

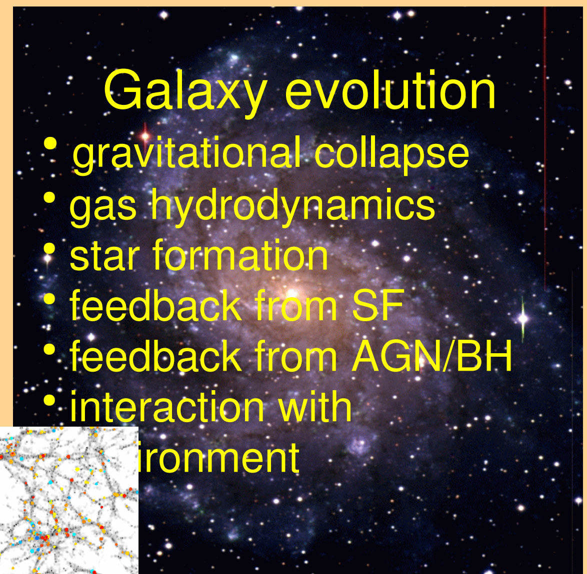

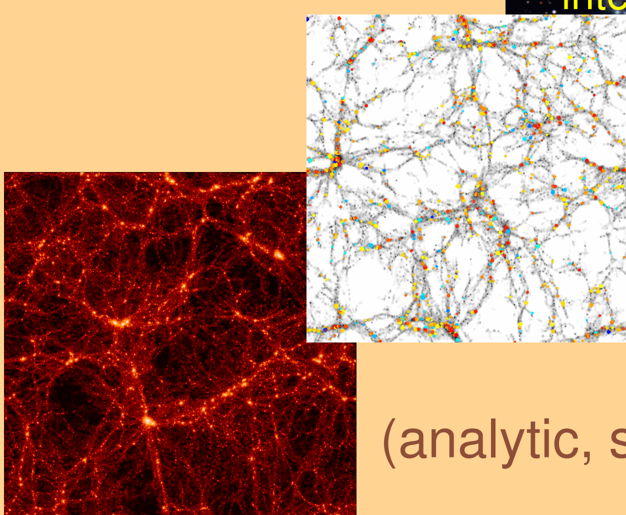

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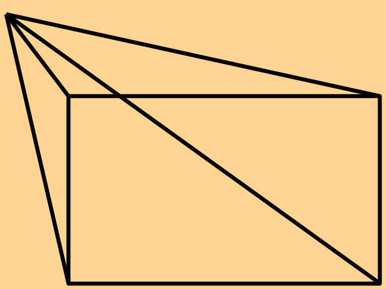

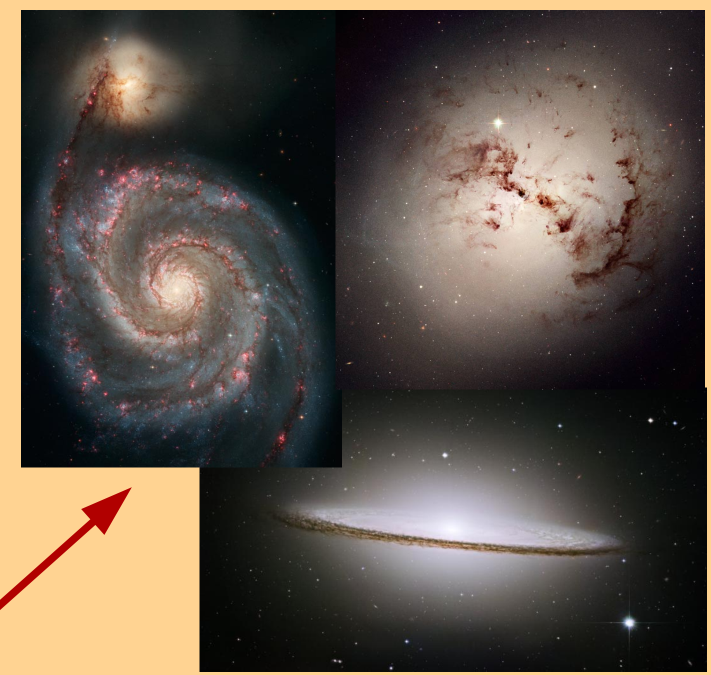

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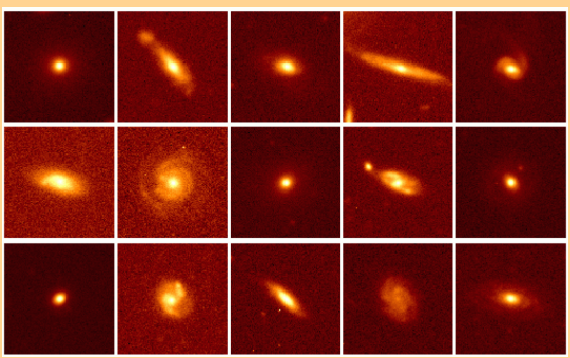

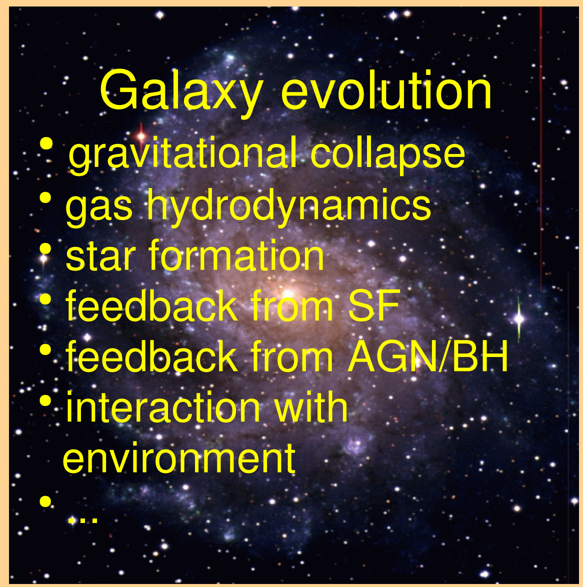

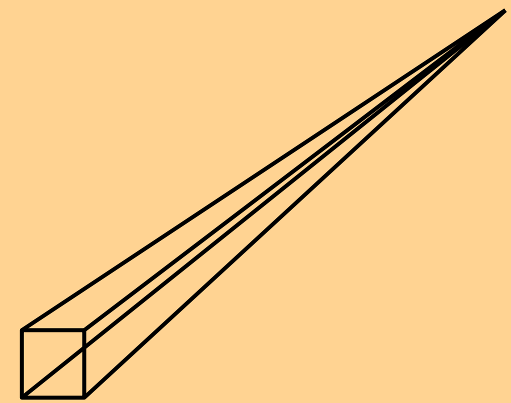

Theory

(analytic, semi-analytic, numerical)

How to approach galaxy formation and evolution?

Most of today's stellar mass is in luminous giant galaxies. Their properties show significant diversity, which presumably reflects a corresponding diversity of formation and/or evolutionary mechanisms.

- Luminosity / Mass — giant ↔ dwarf
- Morphology
  - Hubble type — E1-7 ↔ S(B)abc ↔ Sd/Irr
  - Concentration/Asymmetry/Clumpiness
- Stellar population
  - Colour — blue ↔ red
  - Continuum type — young ↔ old, metal rich ↔ poor
  - PCA — SF ↔ non-SF
- Structure
  - Size
  - Surface brightness
  - Surface brightness profile type — exponential ↔ deVauc.
- Dynamics — rotating ↔ dynamically hot

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blue ↔ red
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exponential ↔ deVauc.
rotating ↔ dynamically hot

?

Different evolutionary processes/paths/modes:

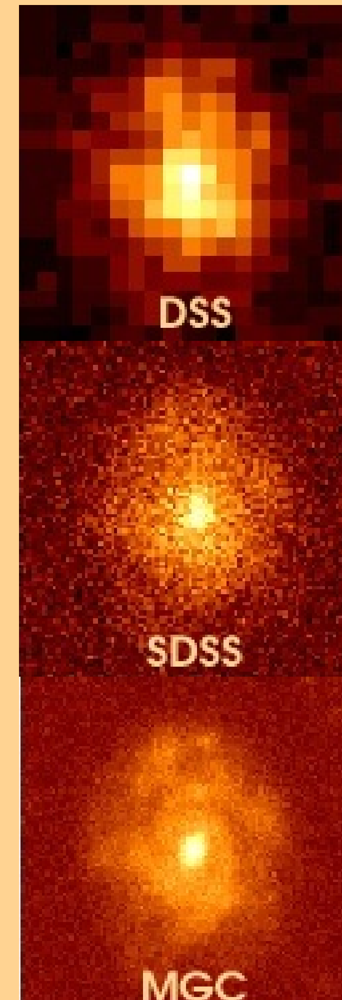
- Gas accretion
- Major mergers
- Minor mergers
- 'Monolithic' collapse
- Secular evolution
- Harassment
- ...

Observationally, what is the best way to isolate, identify and investigate the various formation/evolutionary mechanisms?

The Millennium Galaxy Catalogue (MGC)

www.eso.org/~jliske/mgc

- Deep, wide-field B-band imaging survey using WFC/INT
- Area = 37.5 deg^2
- Median seeing = 1.3 arcsec, pixel size = 0.33 arcsec
- B_{lim} = 24 mag μ_{lim} = 26 mag $arcsec^{-2}$
  internal photometric accuracy = 0.03 mag
- B + ugriz (SDSS) photometry
- Main sample: B < 20 mag (10,095 galaxies):
  - structural parameters, morphological classification
  - MGCz = redshift survey (96% completeness)
- A z=0 reference point.



The Millennium Galaxy Catalogue

MGC Core Team

Simon Driver (St Andrews)

Joe Liske (ESO)

Alister Graham (Swinburne)

Ewan Cameron (St Andrews)

David Hill (St Andrews)

(Paul Allen)

Collaborators

Chris Conselice (Nottingham)

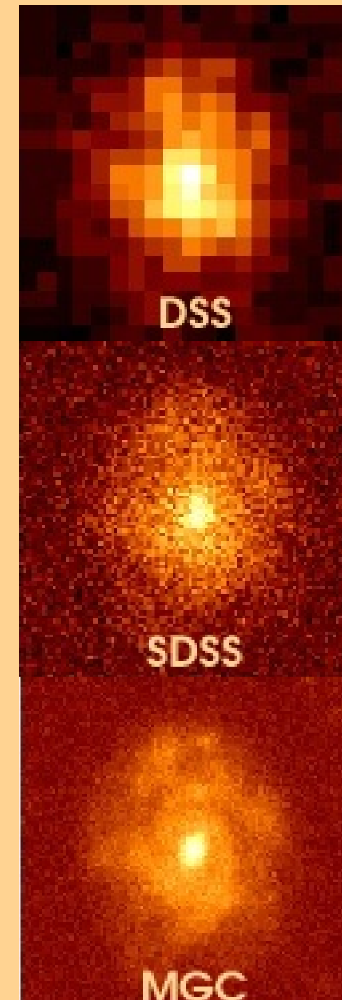
Roberto de Propris (CTIO)

Nick Cross (Edinburgh)

Simon Ellis (AAO)

Richard Tuffs (MPIfK)

Cristina Popescu (UCLAN)

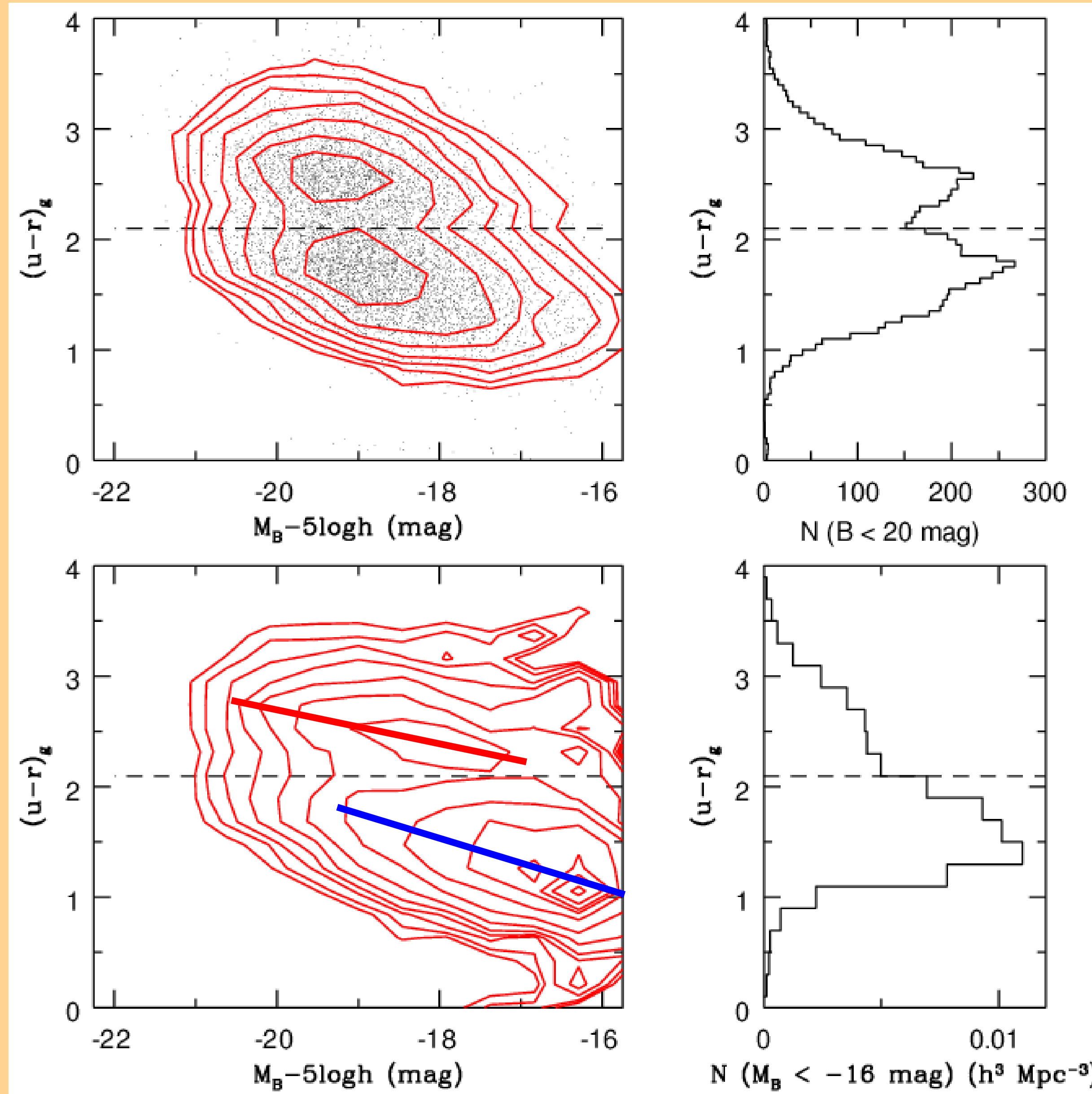


Bimodality of the galaxy population

Observed number

Bivariate colour-luminosity distribution

Volume corrected

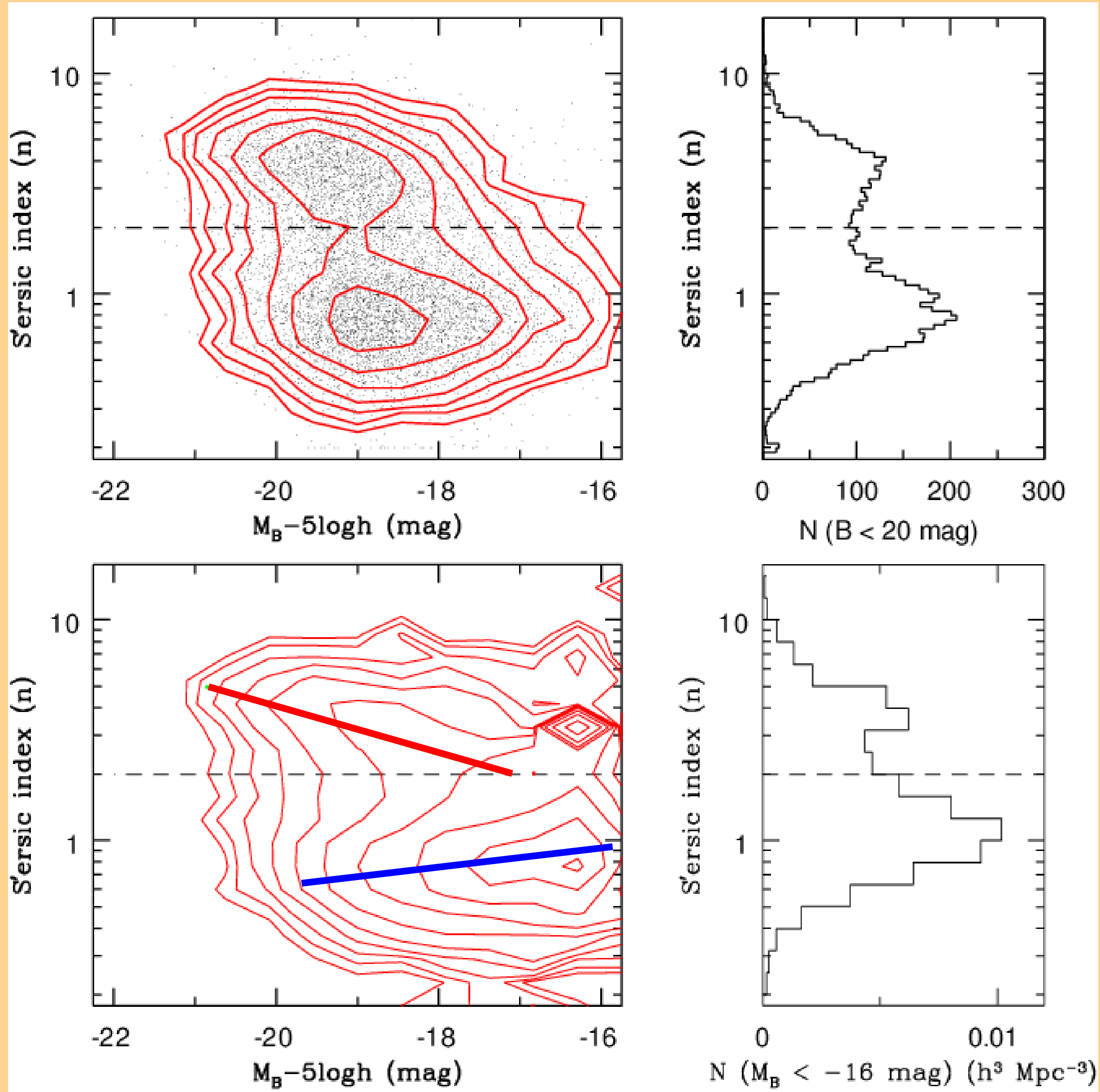


Bimodality of the galaxy population

Observed number

Bivariate Sersic index-luminosity distribution

Volume corrected

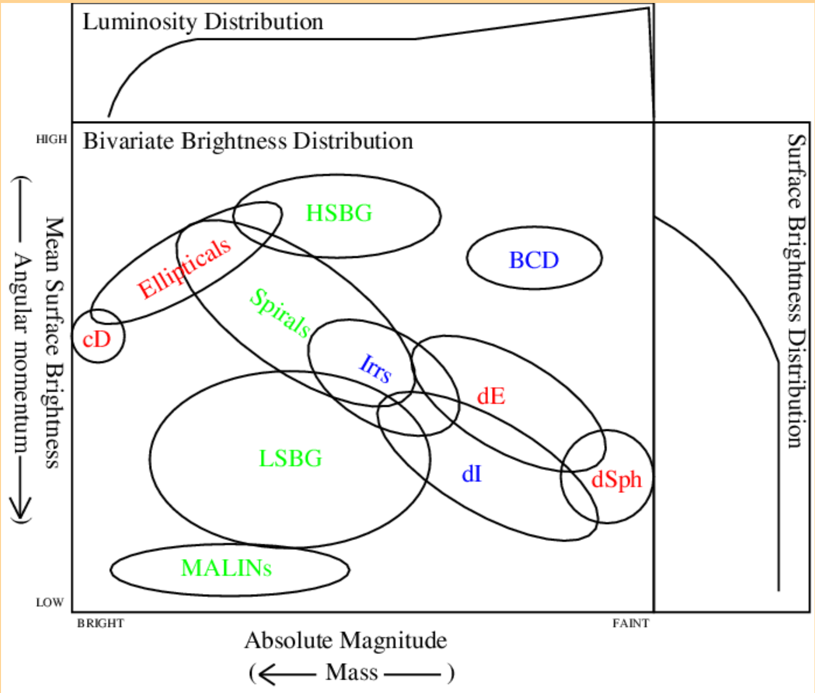


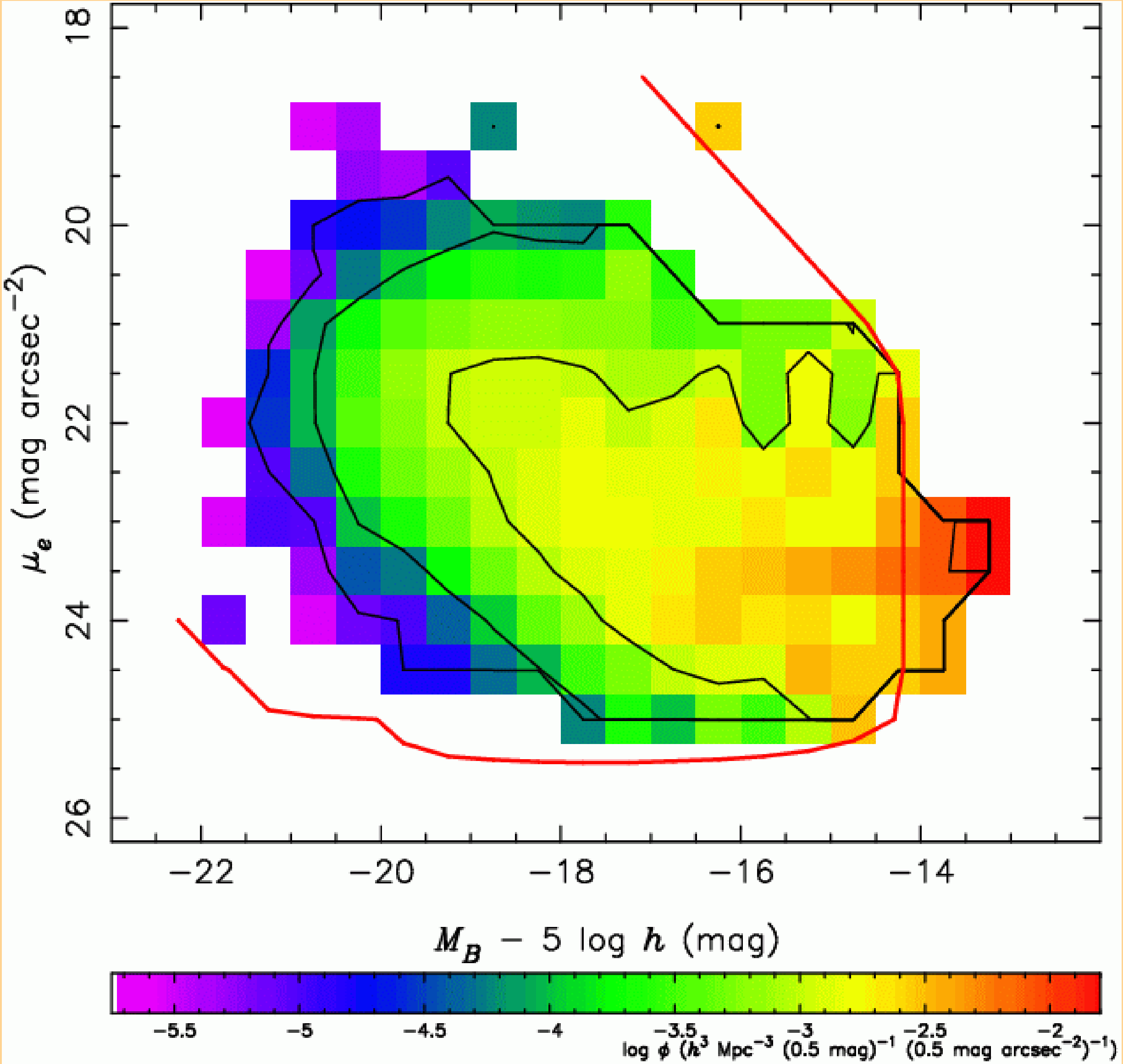
Bimodality of the galaxy population

Bimodality is not everywhere!

Here: Surface brightness-luminosity distribution (BBD)

Although there is structure, there is no clear separation into two peaks.



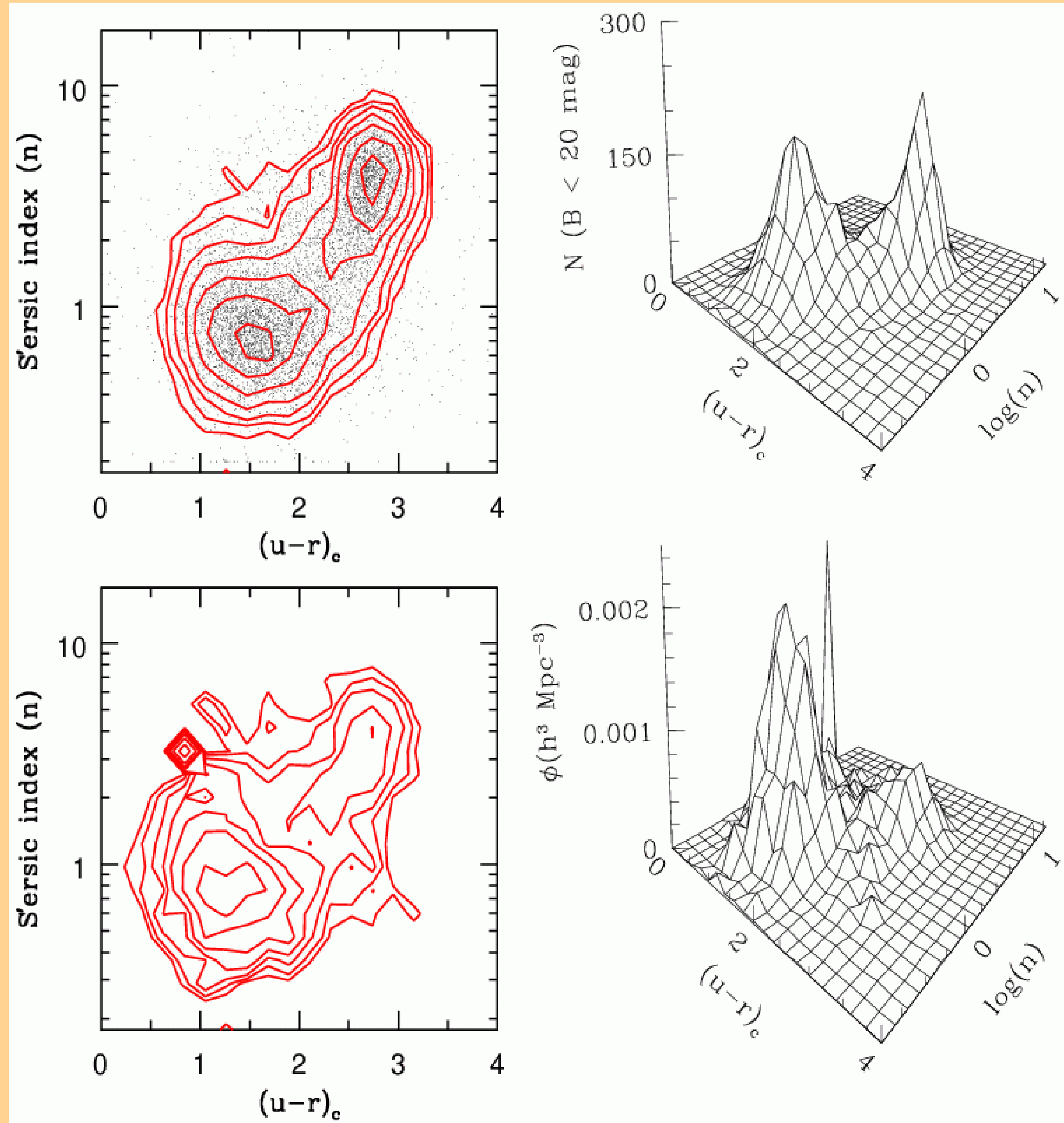


Bimodality of the galaxy population

Observed number

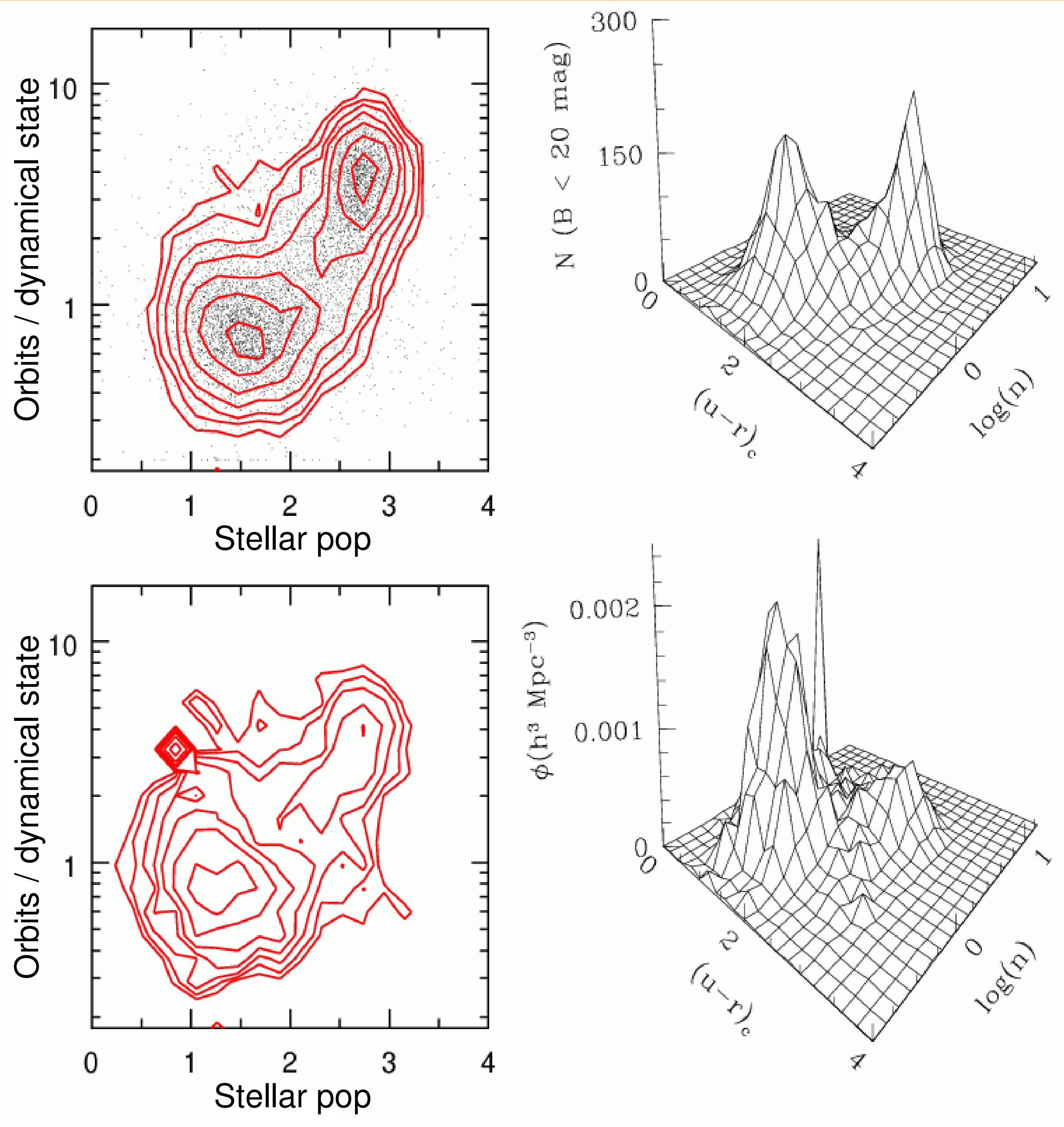
Bivariate Sersic index-colour distribution

Volume corrected



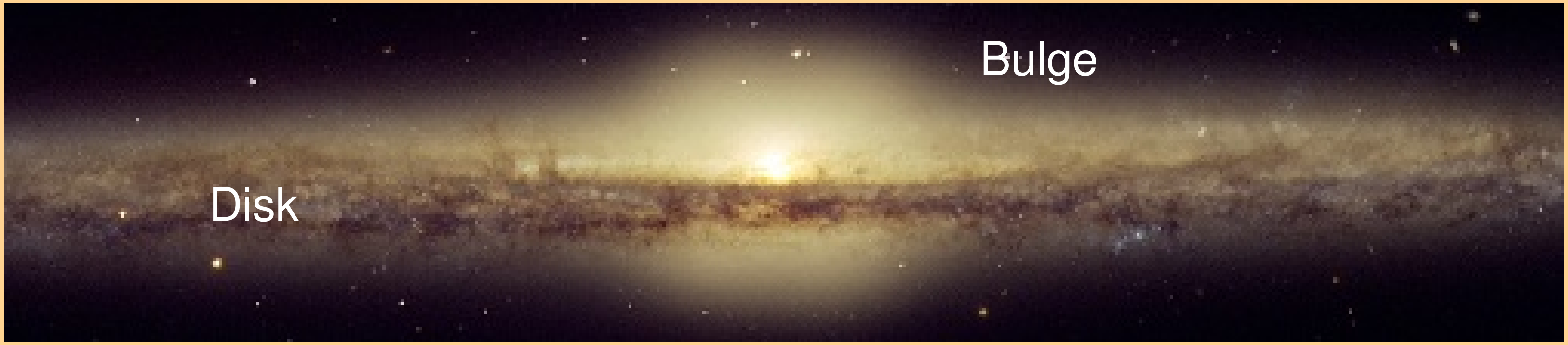
Bimodality of the galaxy population

- Multivariate analyses involving luminosity, surface brightness, size, light concentration, asymmetry, Hubble classifications, colour, spectral classifications and star-formation indicators consistently indicate the existence of two, and only two, sub-groups.
- These are best separated in the colour-Sersic index plane.



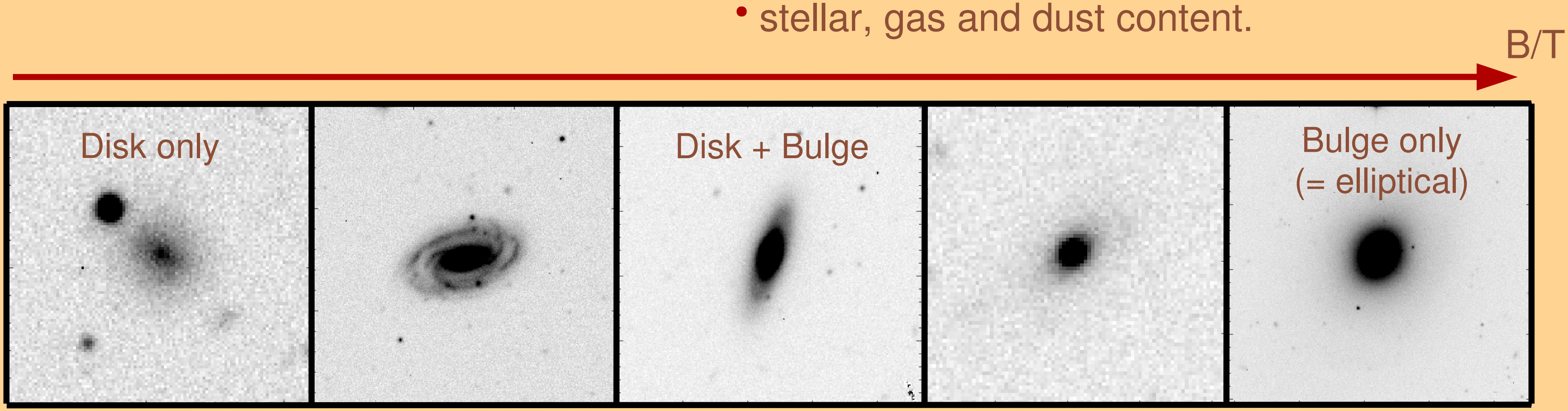
The two-component nature of galaxies

Today's giant galaxies consist of two distinct components which contain almost all of their stellar mass:



Bulges and disks differ in terms of:

- photometric structure
- dynamics
- stellar, gas and dust content.



Bimodality ↔ 2-component nature?

B/T

⇑

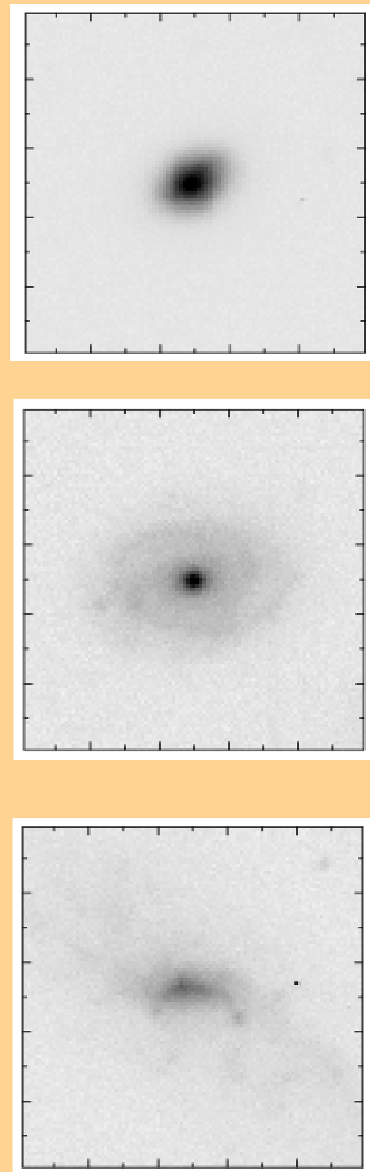
Hubble type

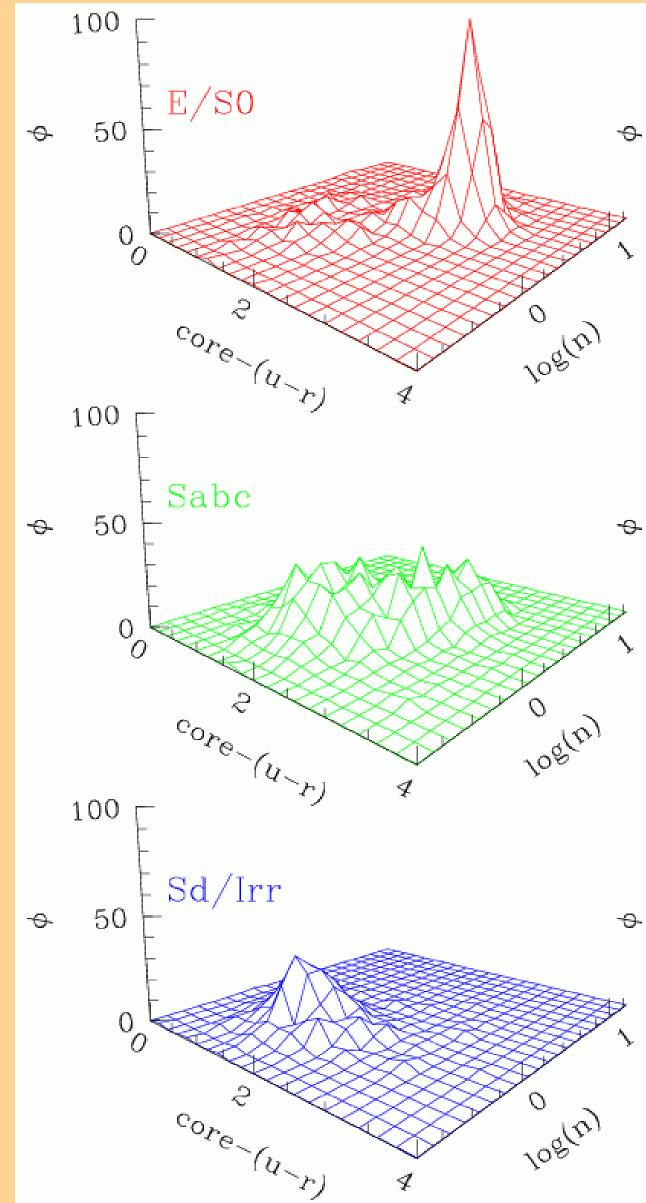
⇓

location in colour log(n) plot

→ Good evidence that the bimodality is caused by the two-component nature of galaxies, i.e. by disks and spheroids.

B/T





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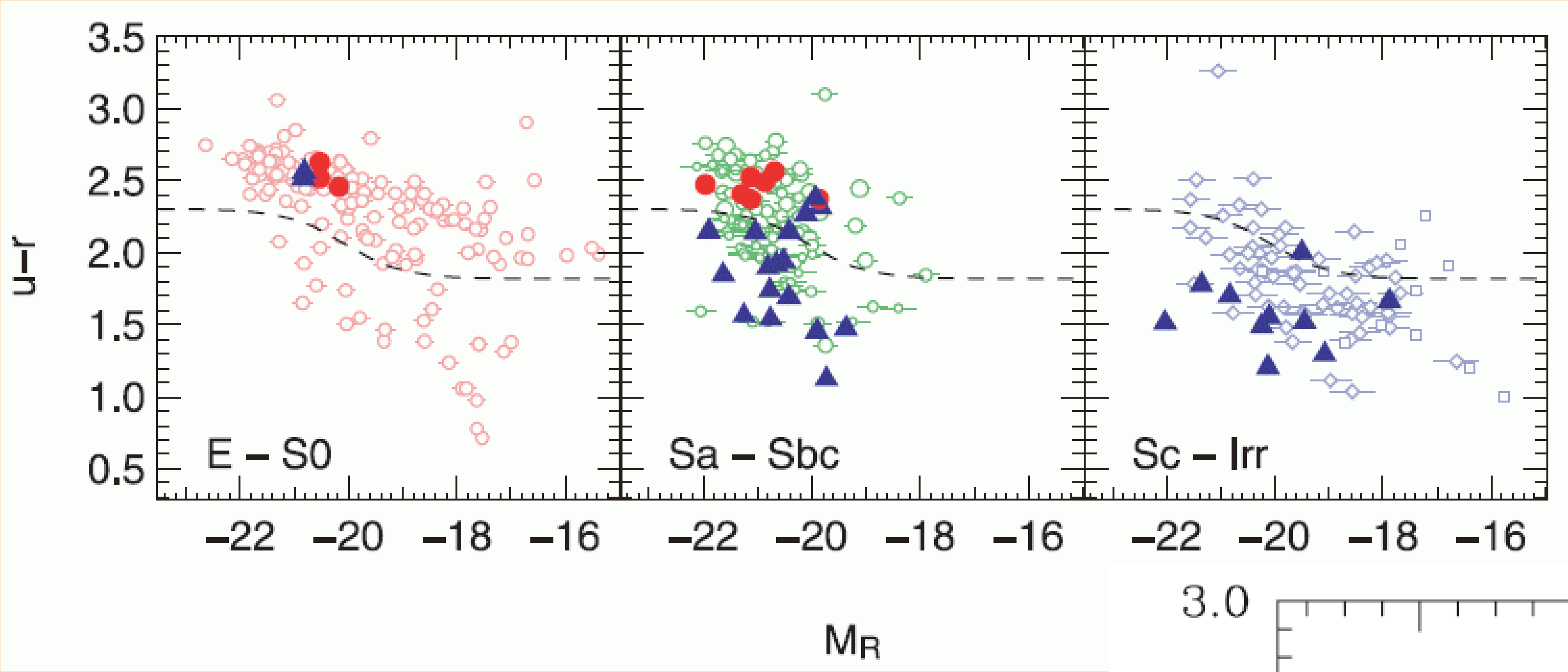
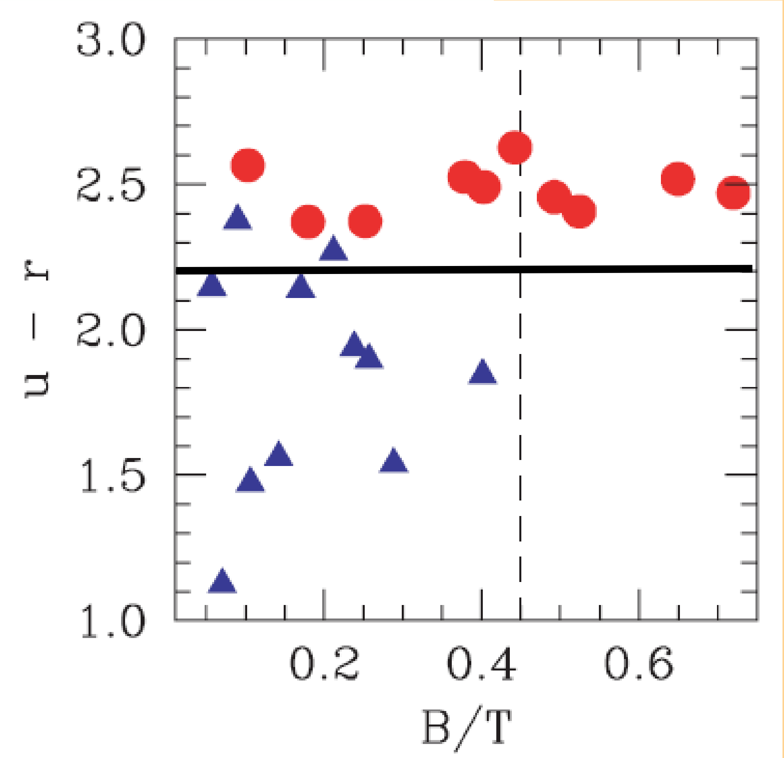


Drory & Fisher (2007)



It's not that simple:

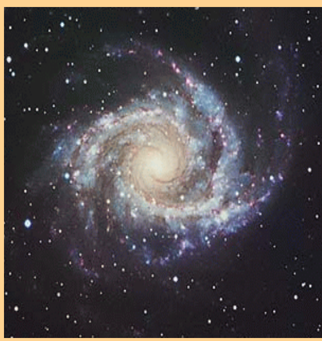
1. There are two types of bulges ('classical' and 'pseudo') and one of them is like a disk.

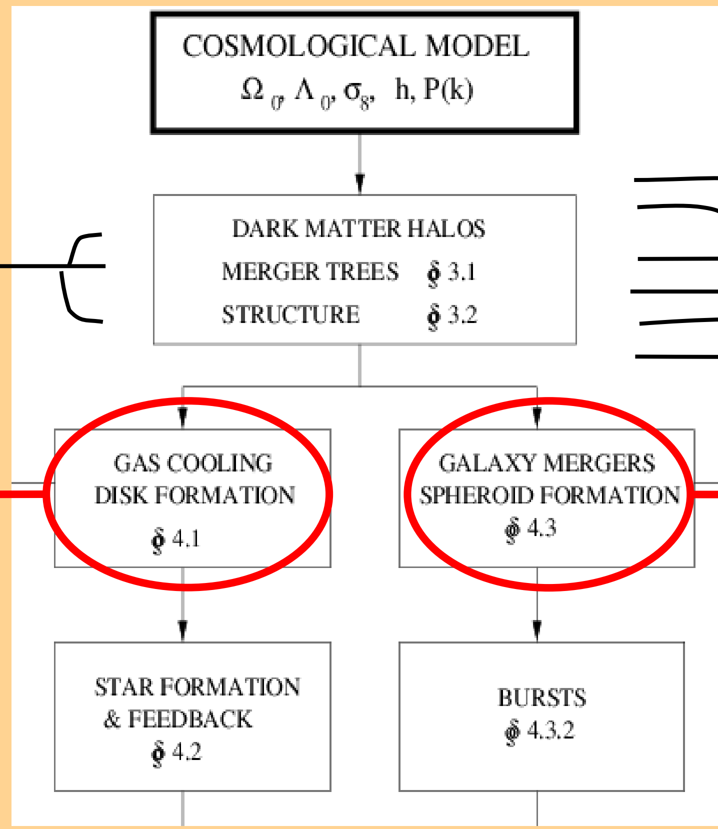
2. Disk properties correlate with type of bulge so that type of bulge predicts total galaxy properties.

→ Galaxy ≠ random bulge + random disk

Hierarchical galaxy formation

“Galaxies are assumed to form inside dark matter halos, and their subsequent evolution is controlled by the merging histories of the halos containing them.”





Cole et al. (2000)

“We assume that disks form by cooling of gas initially in the halo.”

“In our model, the primary route by which bright elliptical galaxies and the bulge components of spiral galaxies form is through galaxy mergers.”

Implications

- There are clear observational and theoretical motivations to consider:

  Galaxy types or classes

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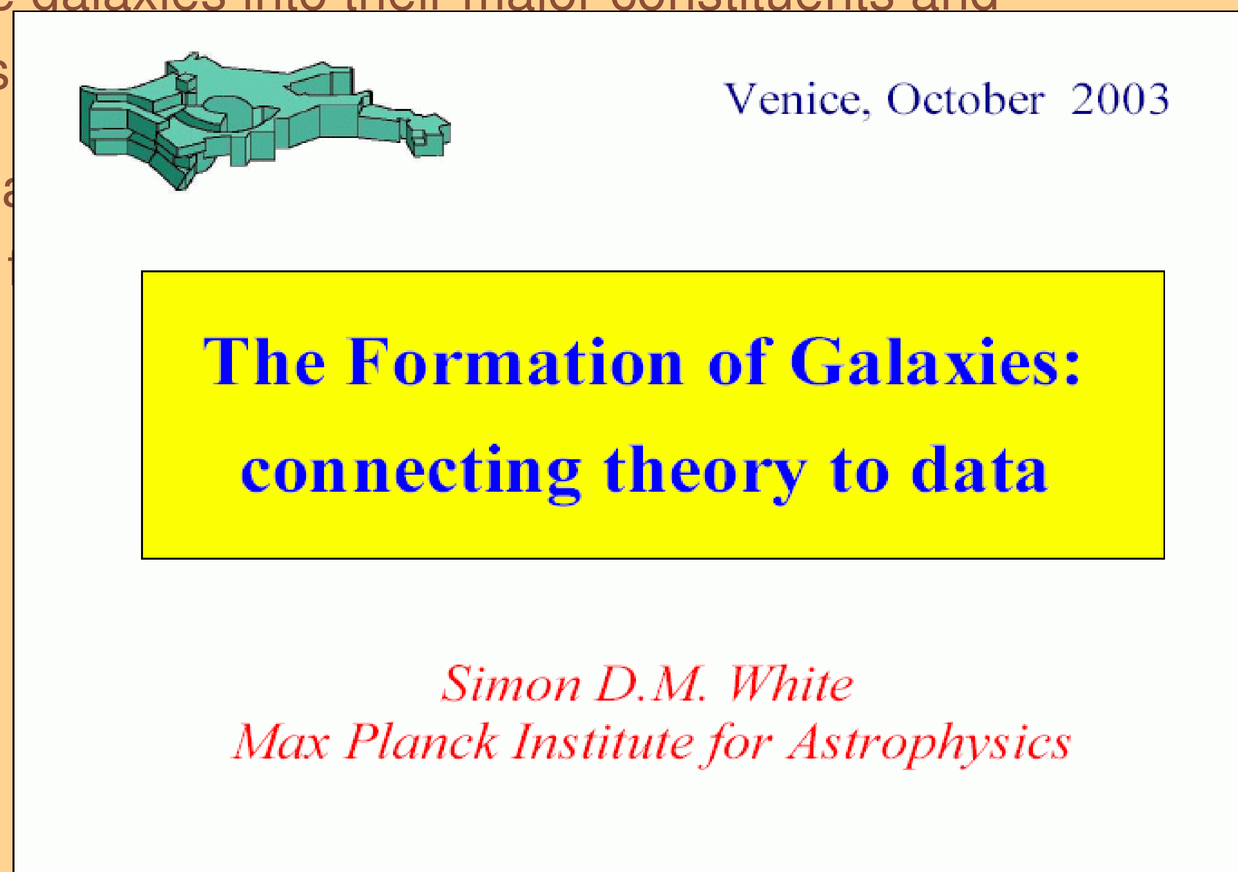
- The disk-bulge view of gala
confront models of galaxy f



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Critical issues for galaxy formation

- Origin of the bright and faint cutoffs in the luminosity function
- Relative prevalence of disks/spheroids -- violent/quiescent modes
- Sizes of disks and spheroids -- *J* evolution, merging
- Efficiency/IMF of star formation -- understanding down-sizing
- Efficiency of feedback -- heating/enrichment of galaxies/IGM
- Relation of SMBH growth to galaxy formation -- QSOs/starbursts

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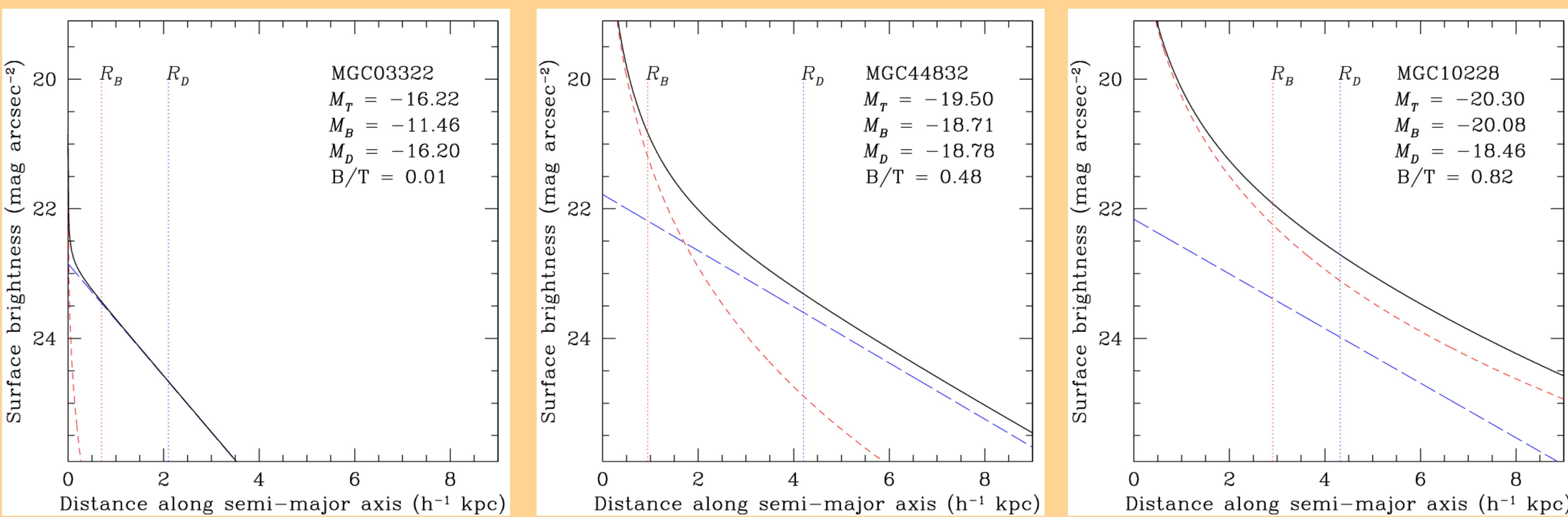
- The disk-bulge view of galaxies is the most 'natural' language in which to confront models of galaxy formation and evolution with observations.
- To probe disk/bulge evolution requires high-quality data at both low and high z:
  - Deep
  - High resolution
  - Wide area

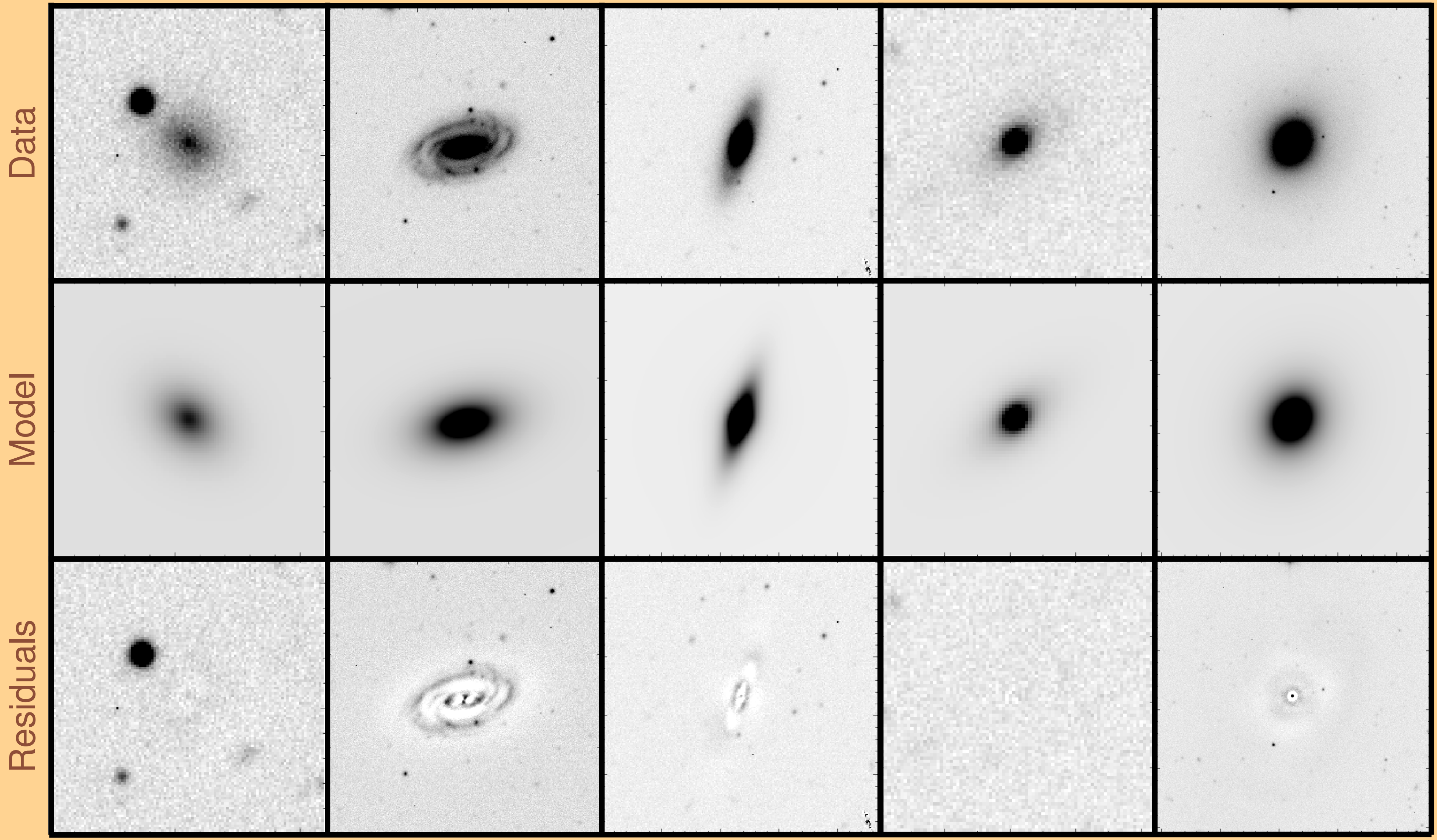
➔ The MGC is an excellent place to start.

MGC bulge-disk decomposition

- Model: Sersic bulge + exponential disk → 12 parameters
- Careful PSF modelling → convolve model profile with seeing
- Used GIM2D (Simard et al. 2002)
- Applied to all 10,095 MGC galaxies with B < 20 mag ← largest available sample



MGC bulge-disk decomposition



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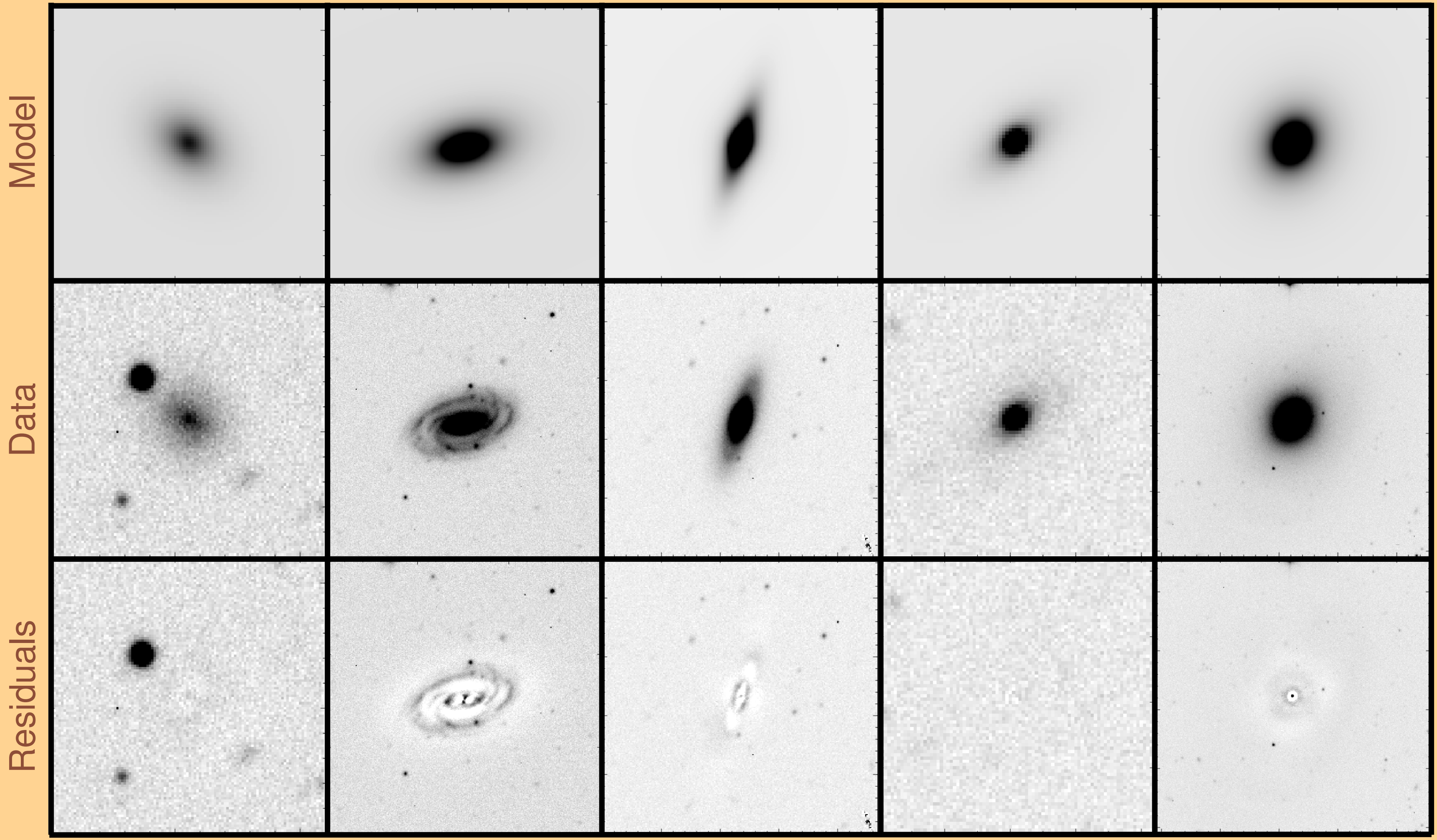
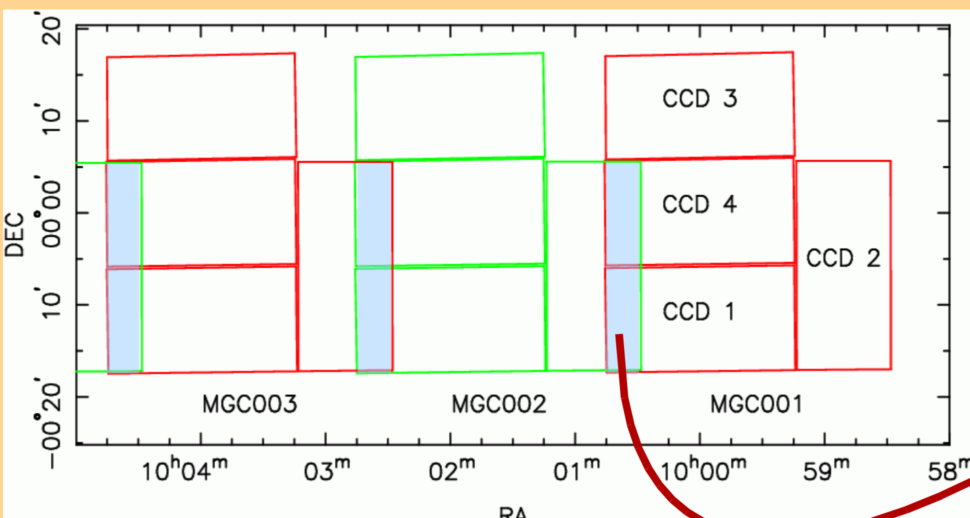
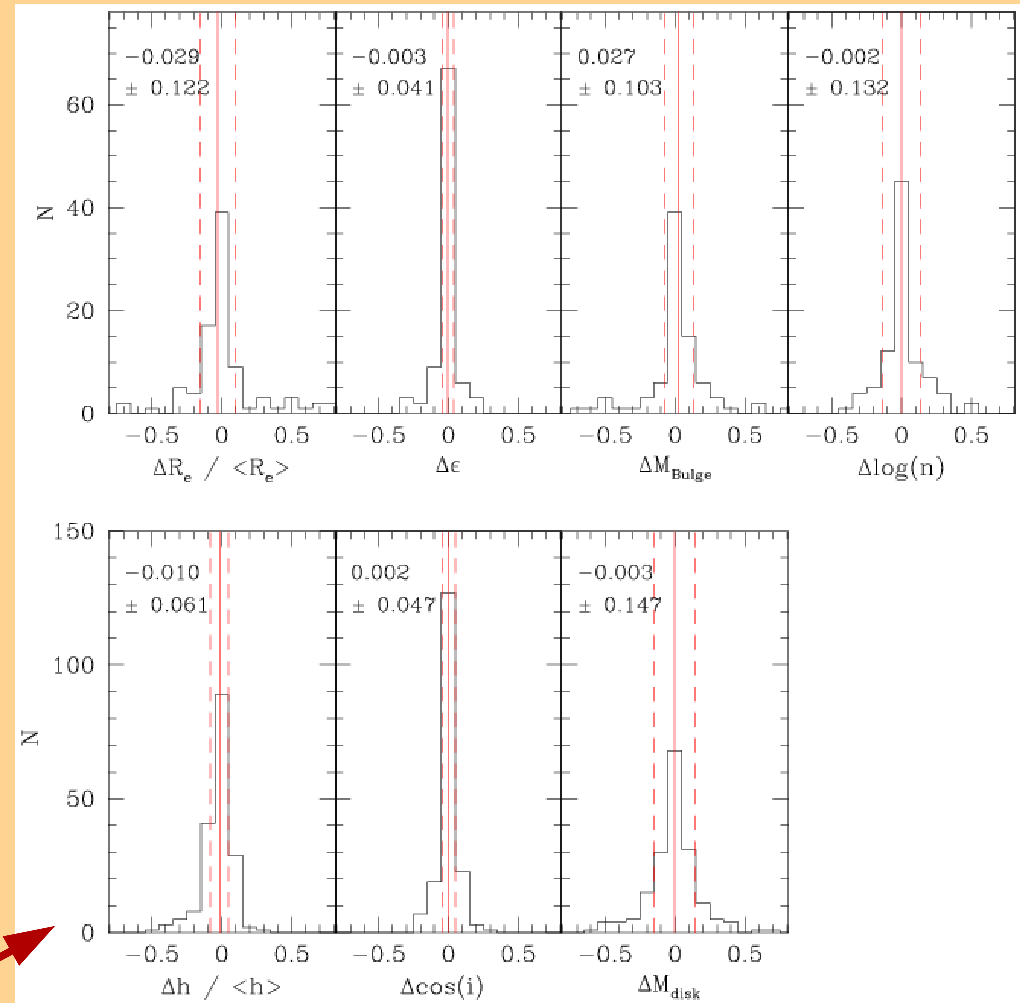


MGC bulge-disk decomposition

Reproducability: comparison of parameters independently derived from duplicate observations of 702 galaxies in overlap regions between individual MGC fields.

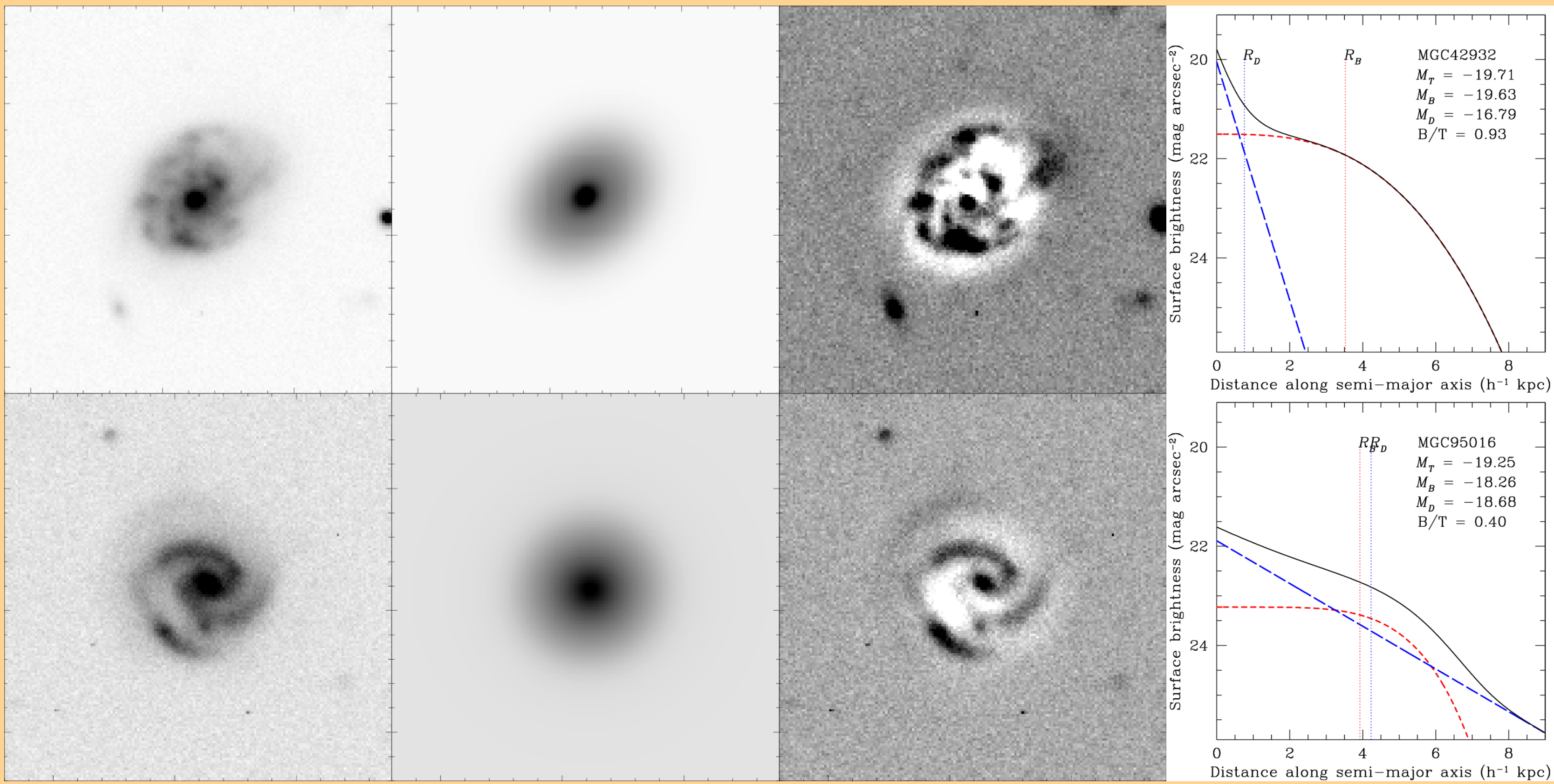




MGC B-D decomposition: problems

'Inverted' profile

'Double-crossing' profile



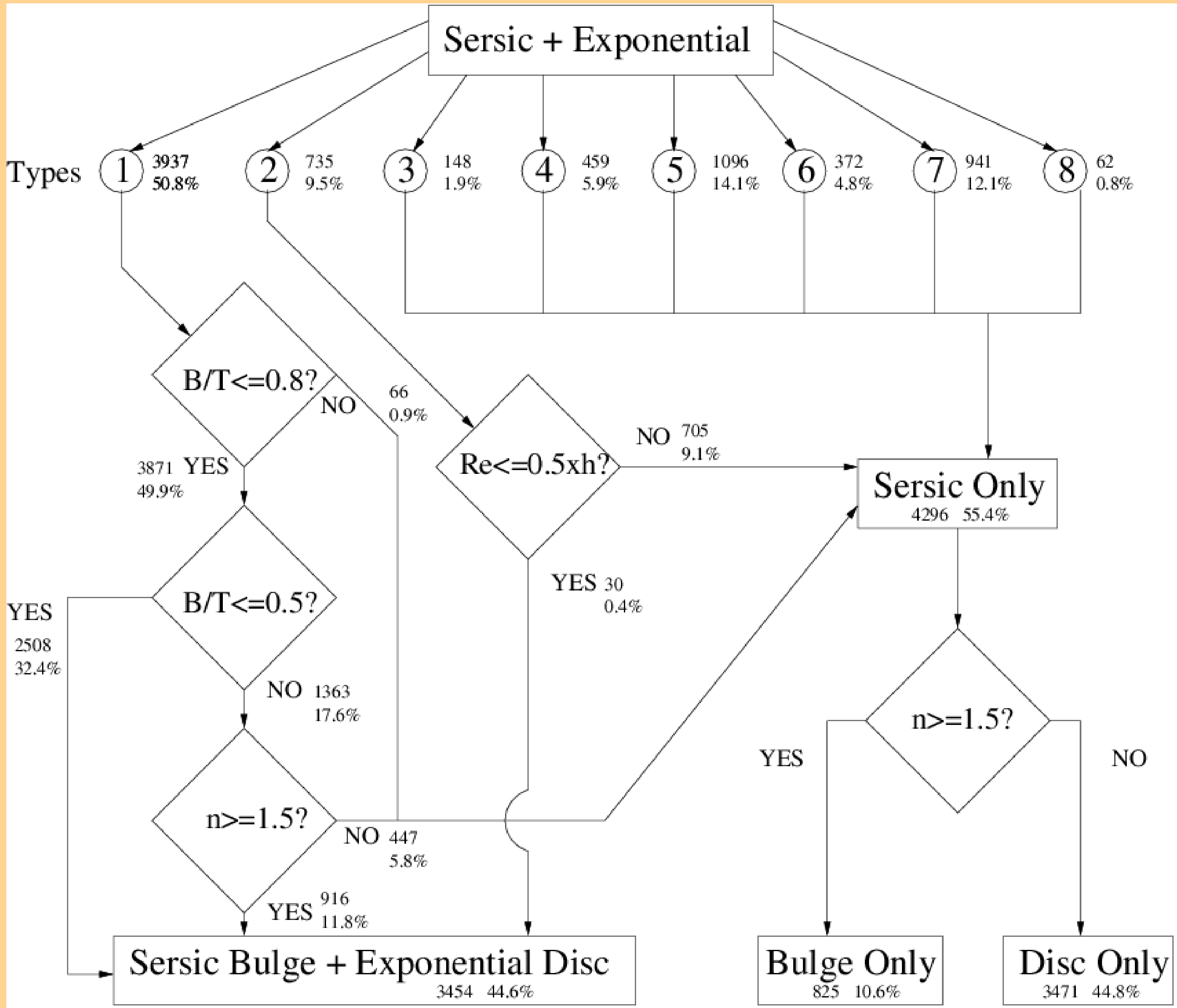
The presence of 'second order' features can result in (apparently?) unphysical models: Spiral arms, irregular morphology, dust, SF regions, truncated disks, bars, rings, inner disks, unresolved central components (AGN, nuclear starburst), twisted isophotes, perturbed background, ...

MGC B-D decomposition: problems

Current 'solution':
Replace 'unphysical' fits with Sersic-only fits.

Better solutions needed:

- Faster algorithms to be able to explore a range of models.
- Longer wavelengths where irregularities are less pronounced.



Motivation for a new B-D decomp code

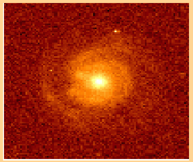
Fundamental problem: Speed ⟷ Robustness

Difficult to achieve both at the same time and yet both are crucial for automated analysis of large samples (~10^5 galaxies).

Existing (public) codes: GALFIT (C. Peng) — fast, flexible, not robust; GIM2D (L. Simard) — slow, unflexible, robust

Solution: data compression and fitting of model to the compressed data:
MOPED (Heavens et al. 2000)
Data compression with respect to a given model:

Original data vector = 100 x 100 pixel



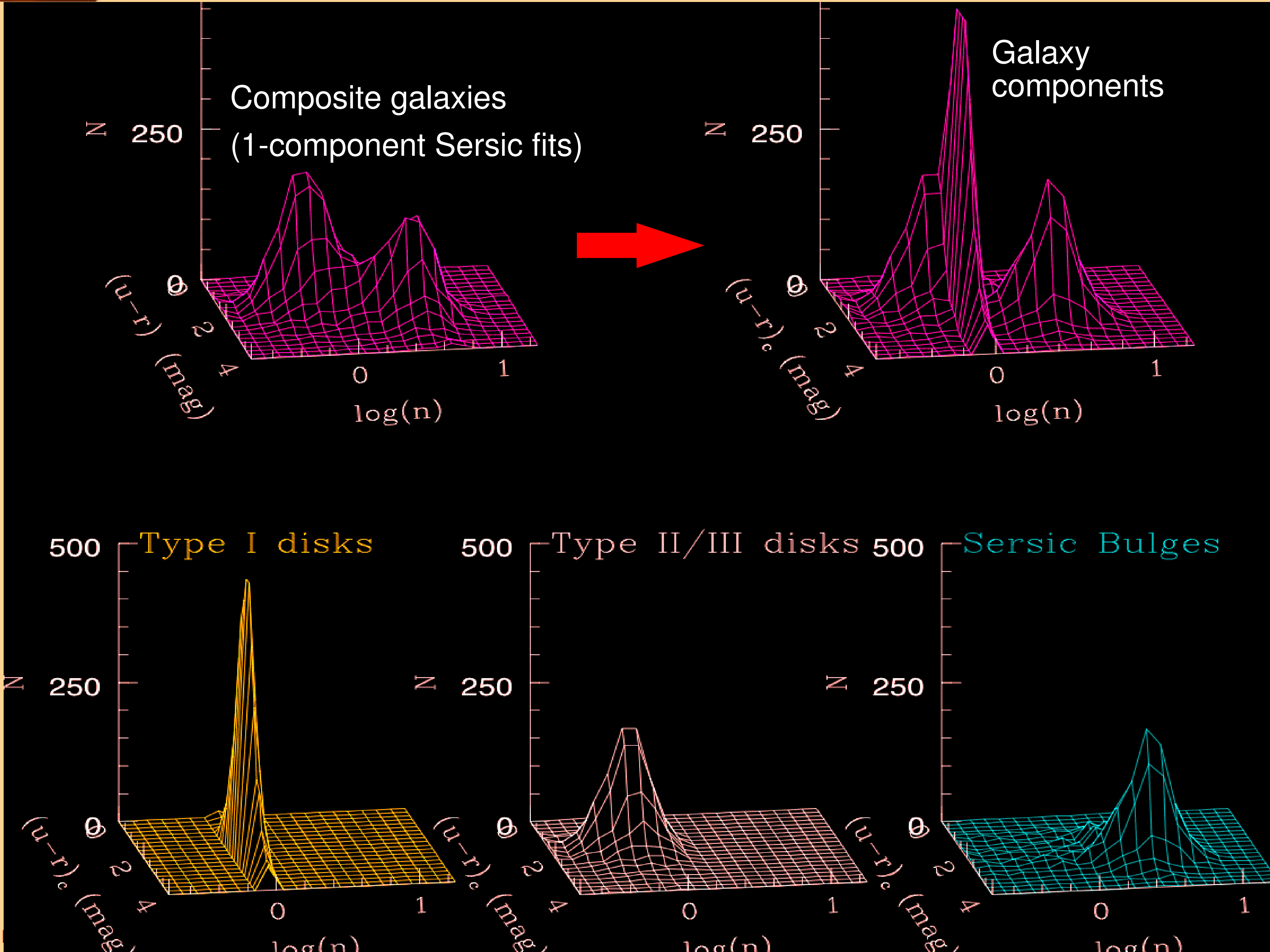
Compression →

Length of new data vector = # of model parameters

With respect to the model the compression is lossless.

→ Massive speed-up of the exploration of the likelihood surface by x 10-1000.

Component bimodality



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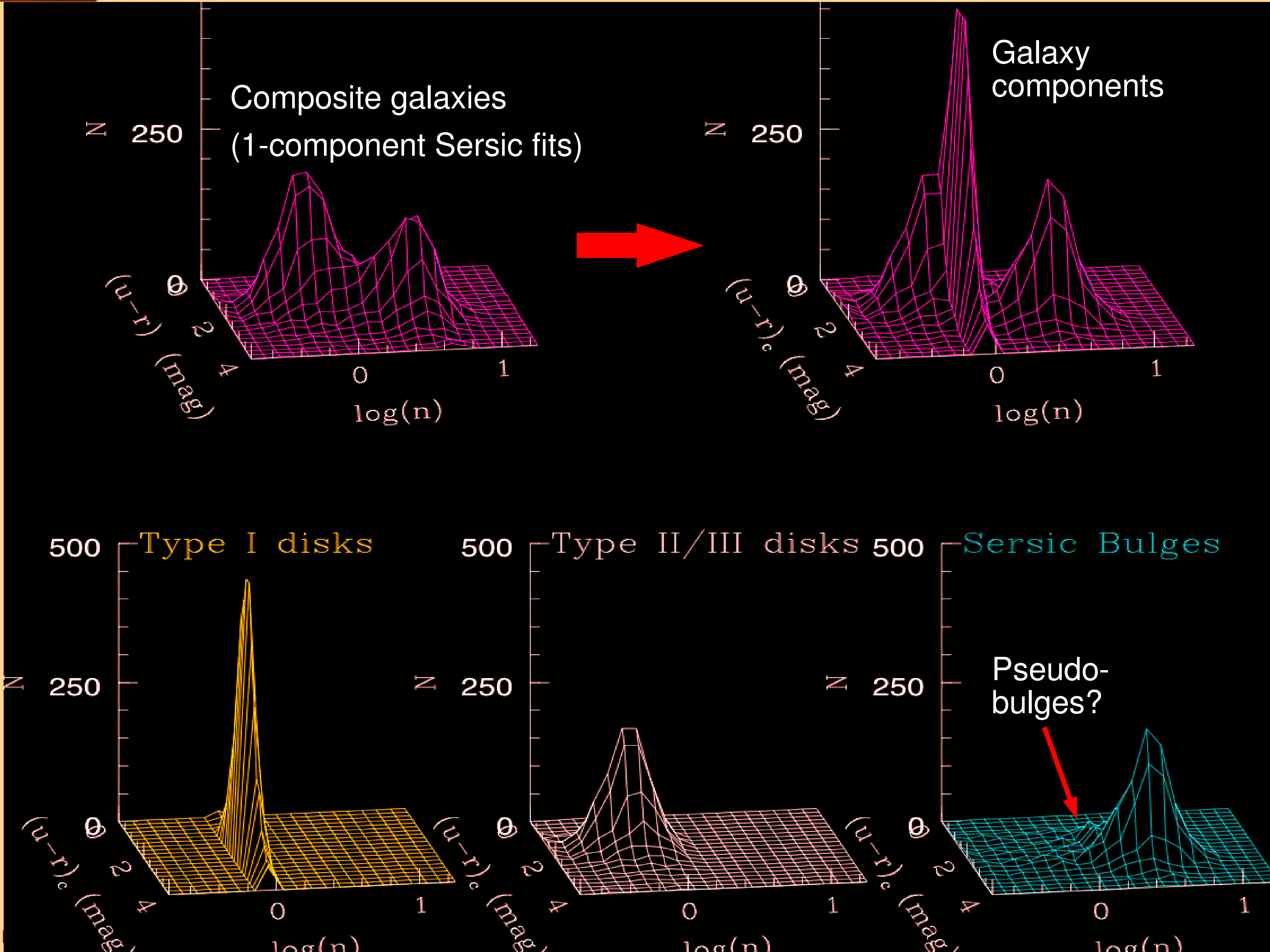
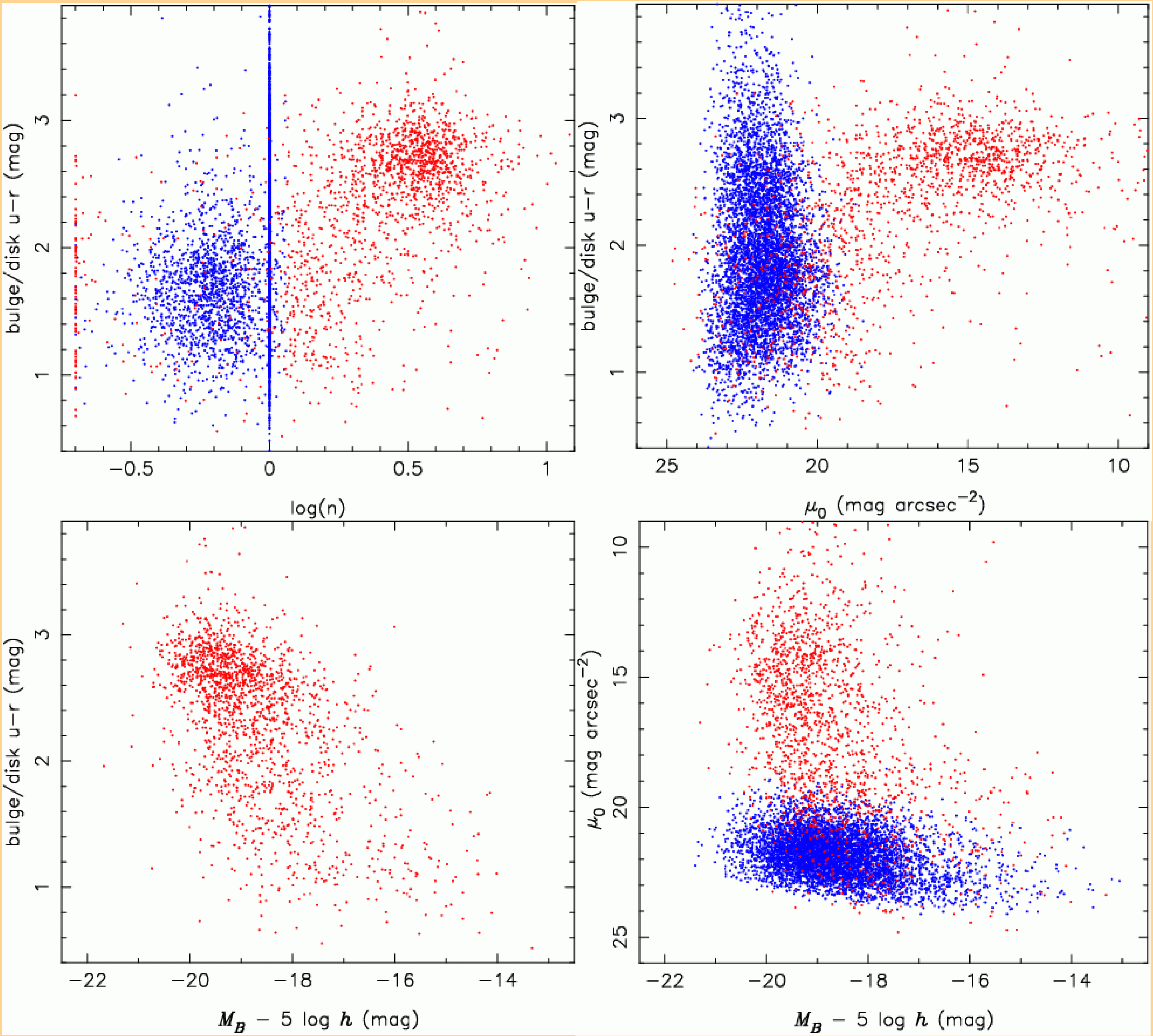


Two types of bulges?

Disks

Bulges



Two types of bulges?

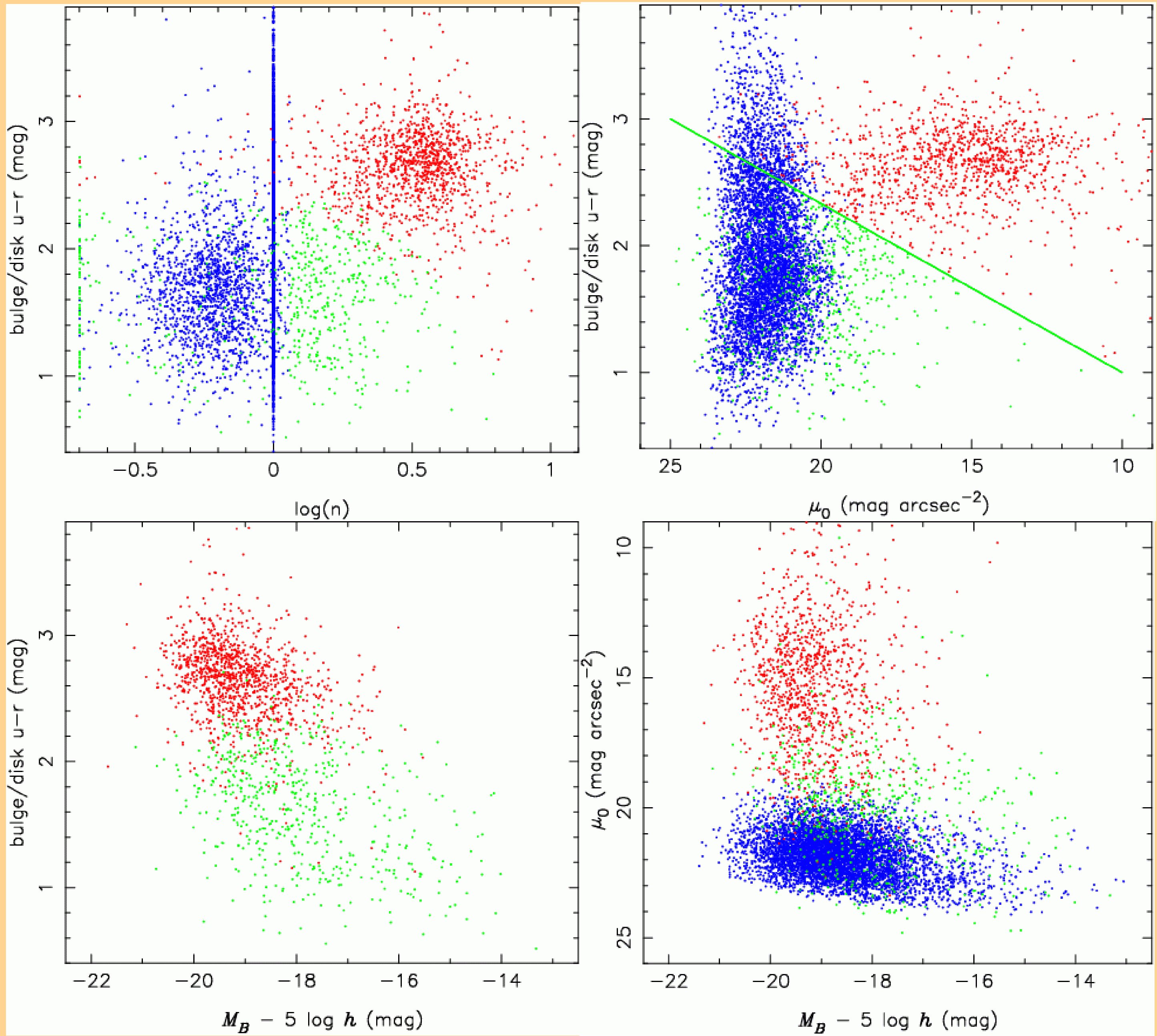
Disks

Bulges

'classical' bulges

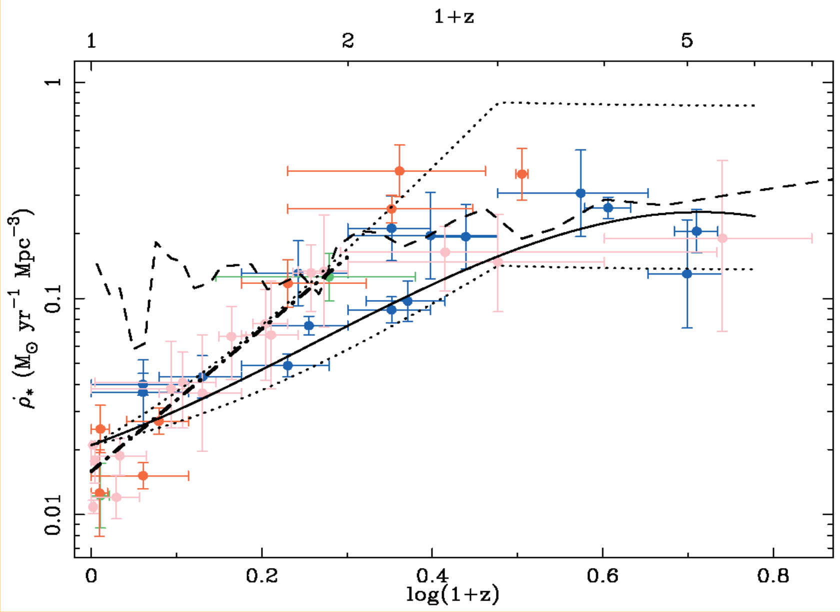
'pseudo' bulges

Probably a catch-all class!



Component luminosity functions

Global SFH tells us WHEN the bulk of present-day stars were formed. What structures did they assemble into? What is the relative importance of the formation mechanisms associated with these structures?



Hopkins (2004)

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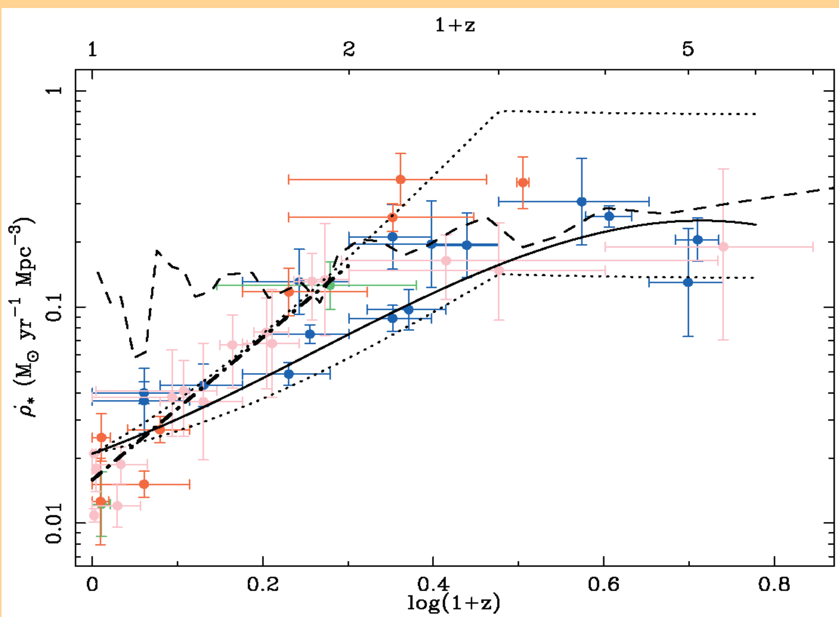
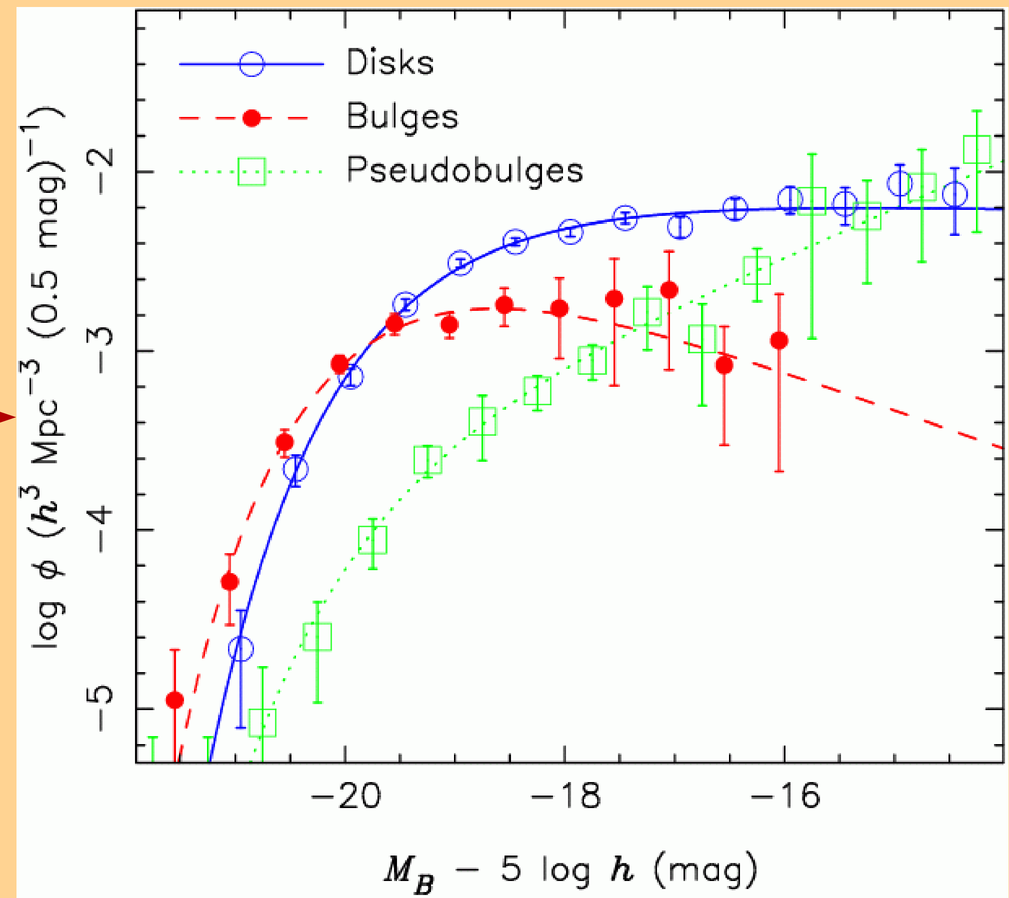


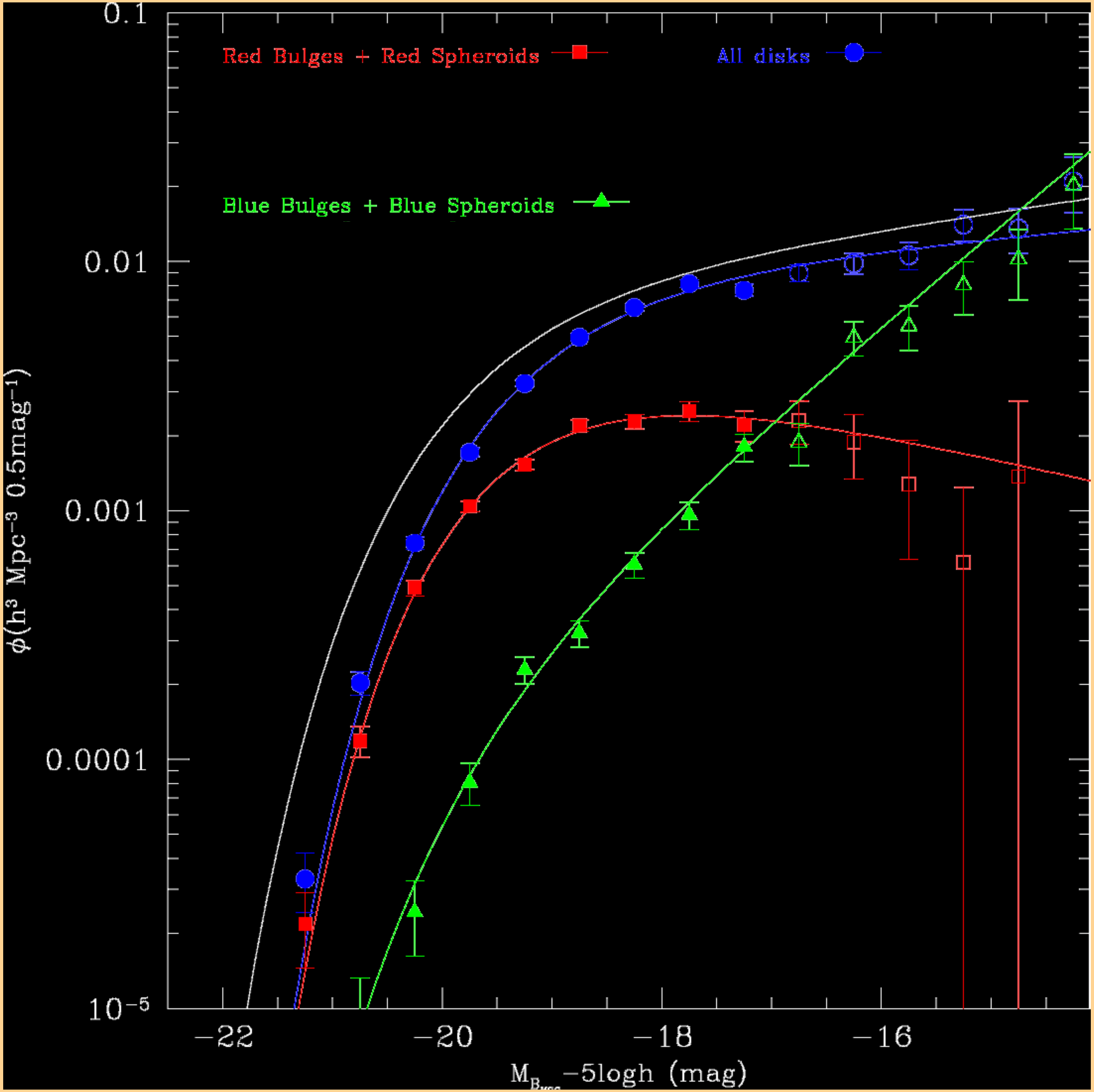
Hopkins (2004)



Component luminosity functions

Luminosity density:

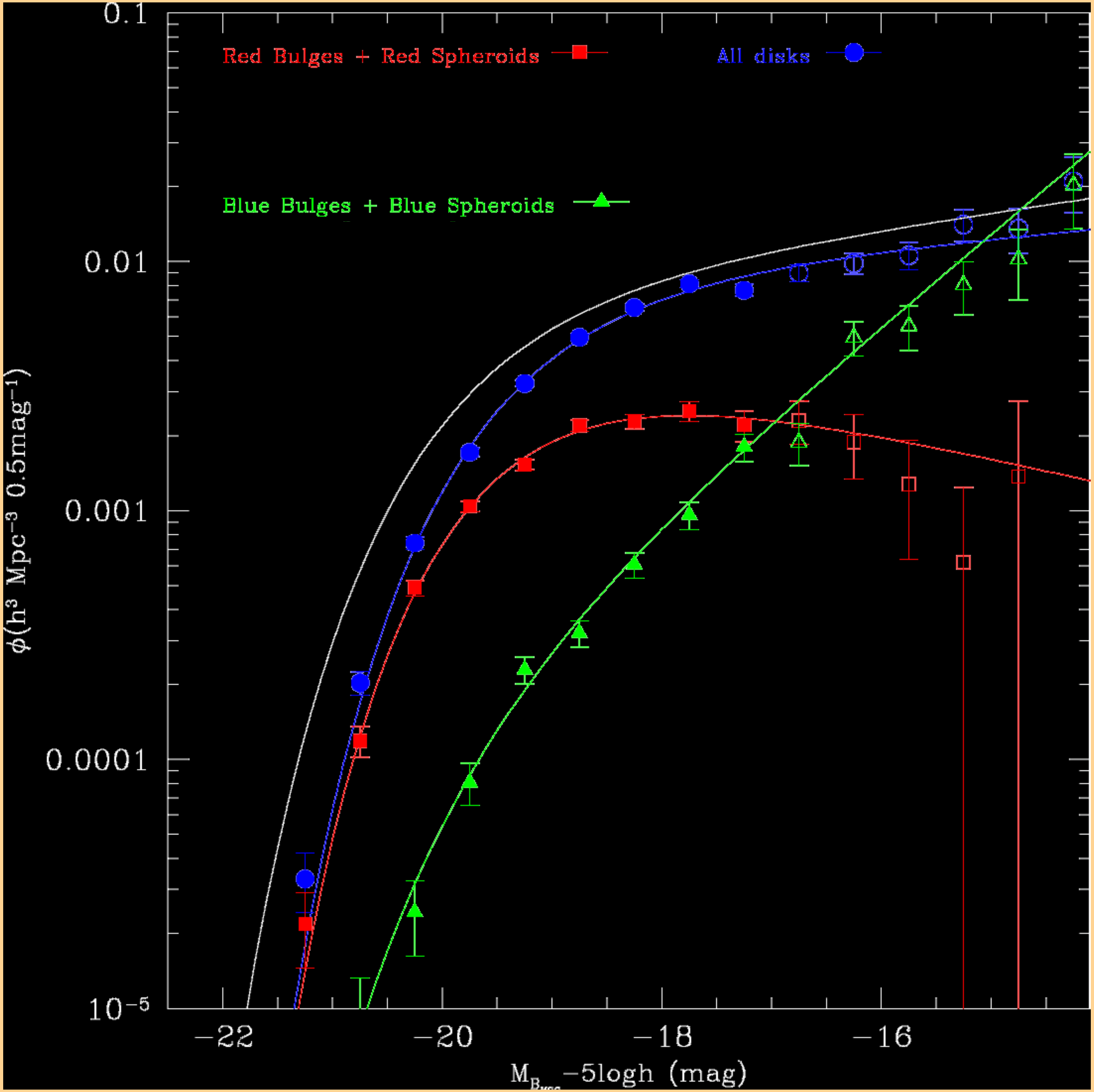
Disks	68%
Spheroids	32%
Bulges	19%
Ellipticals	13%
Red bulges	16%
Blue bulges	3%
Red ellipticals	10%
Blue ellipticals	3%
Red spheroids	26%
Blue spheroids	6%



Component luminosity functions

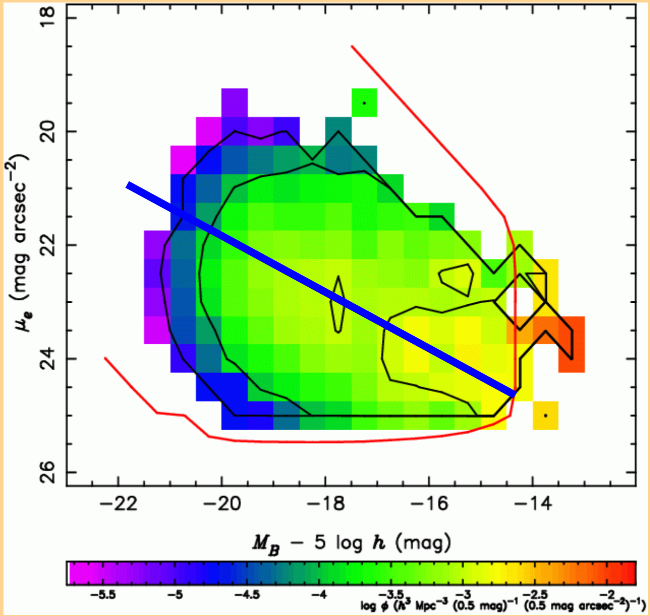
Stellar mass density:

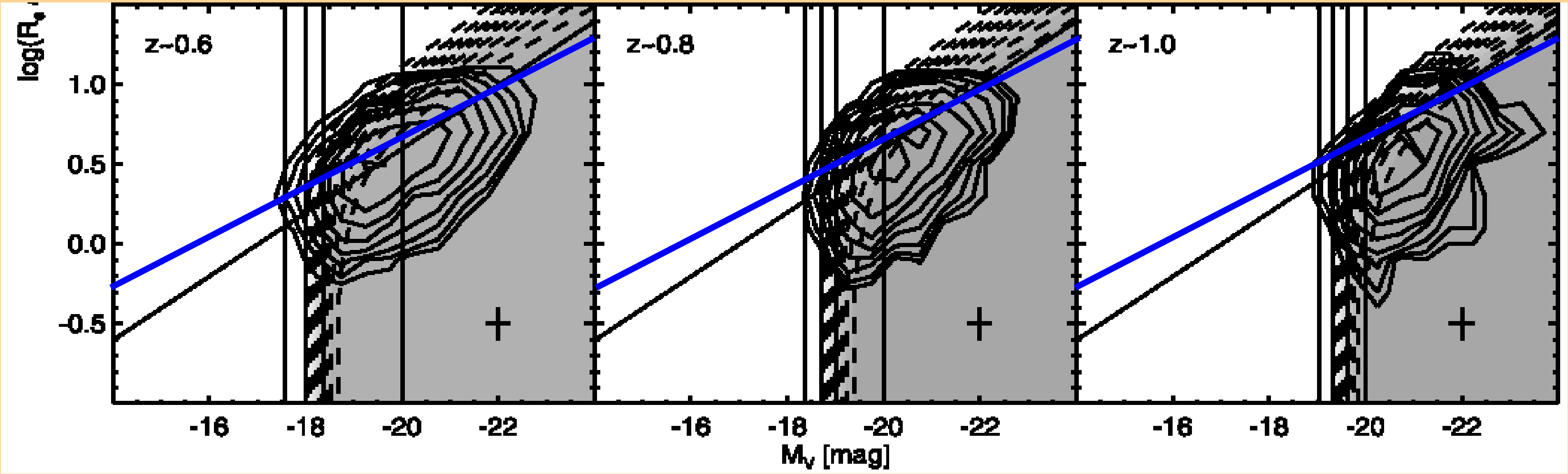
Disks	58%
Spheroids	42%
Bulges	27%
Ellipticals	15%
Red bulges	26%
Blue bulges	1%
Red ellipticals	13%
Blue ellipticals	2%
Red spheroids	39%
Blue spheroids	3%



The luminosity-size relation of disks

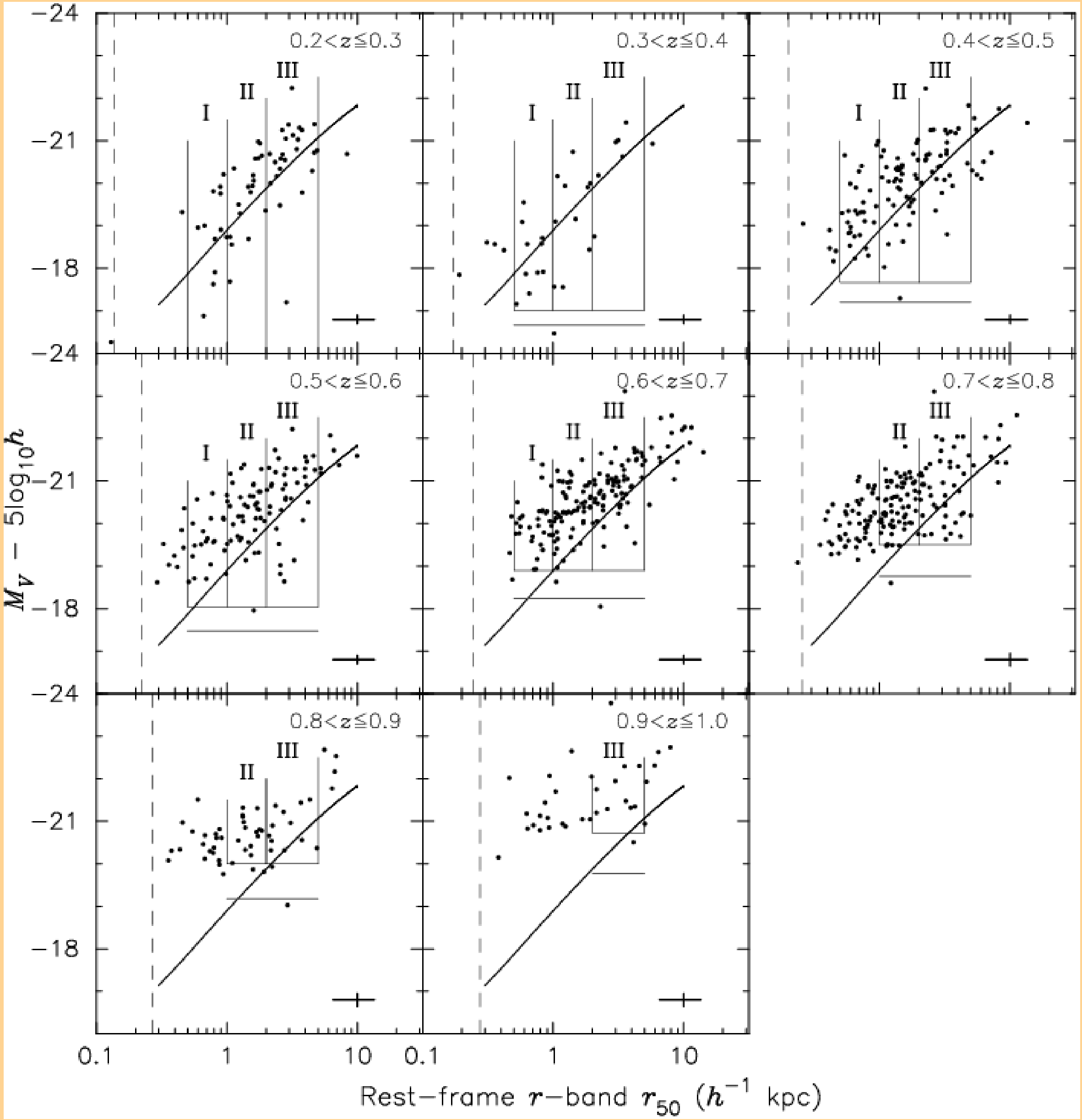
- In hierarchical CDM models the angular momentum of disks is tightly coupled to the angular momentum of their halos → strong dependence of disk size on z.
- The angular momentum distribution of halos is a robust prediction of CDM models.
- (Problem: hydrodynamical sims produce disks that are far too small.)
- Barden et al. (2005) measure the L-R relation from GEMS/COMBO-17 data out z ~ 1.
- Comparing the local MGC relation with GEMS reveals an evolution ~1 mag arcsec^{-2} out to z ~ 1.
- This appears to be consistent with hierarchical models. BUT: need to convert to stellar mass.





The luminosity-size relation of spheroids

- Monolithic collapse models: size evolution due to passive evolution of old stellar population.
- Hierarchical models: depends on details of merger statistics, i.e. frequency and properties of product of each type of merger.
- MGC/GEMS comparison:
  - L-R evolution consistent with passive evolution
  - Newly formed spheroids follow same L-R relation as older spheroids.

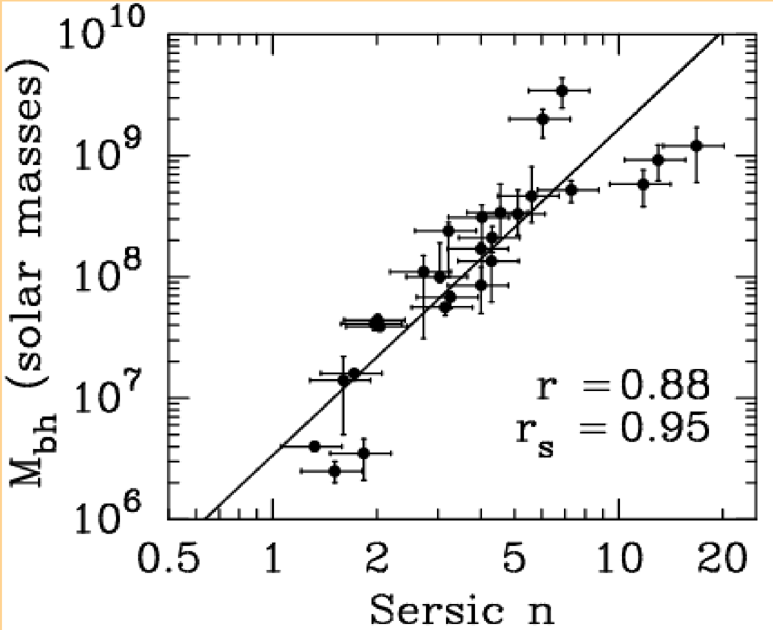


McIntosh et al. (2005)

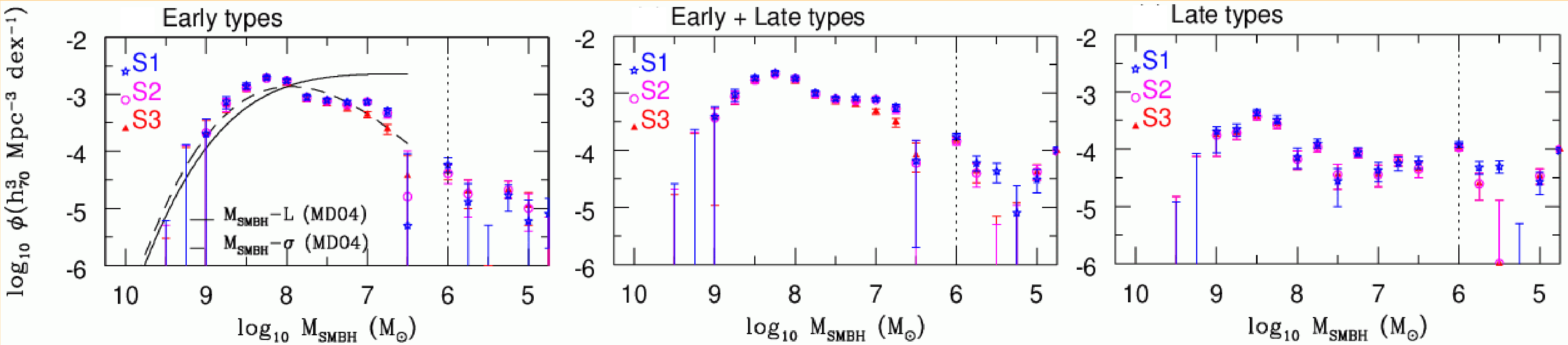
The mass function of SMBH

- Feedback from SMBH is currently the favoured process to curtail SF in massive galaxies.
- The present-day mass function of SMBH tells how much material has been accreted in the past.
- Combined with the luminosity function of QSOs one can estimate their average efficiency.
- M_{SMBH} not only correlates with σ and L_{bulge} but also with Sersic index.
- Use n-distribution to obtain mass function of SMBHs.

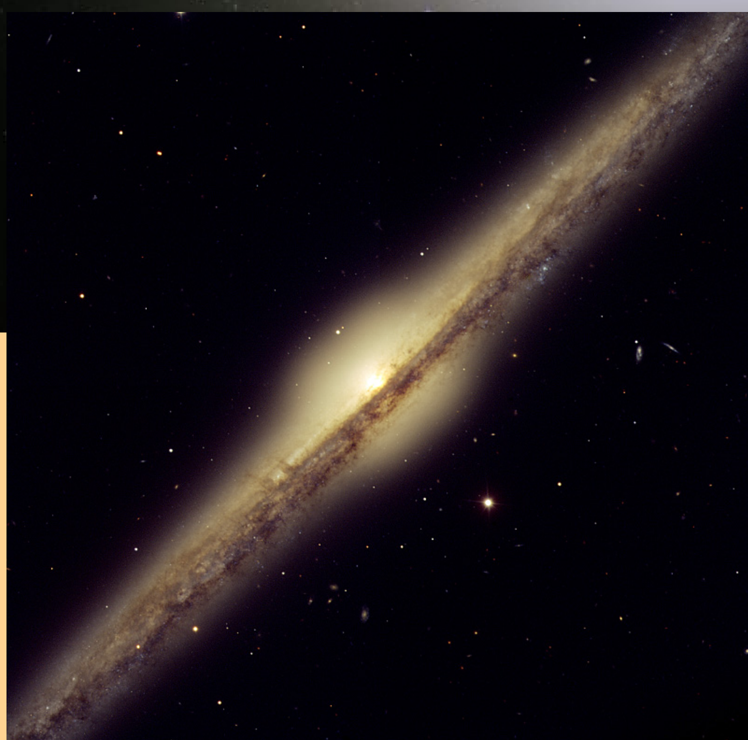
➔ $\Omega_{SMBH} = (3.8 \pm 1.3) \times 10^{-6}$ h

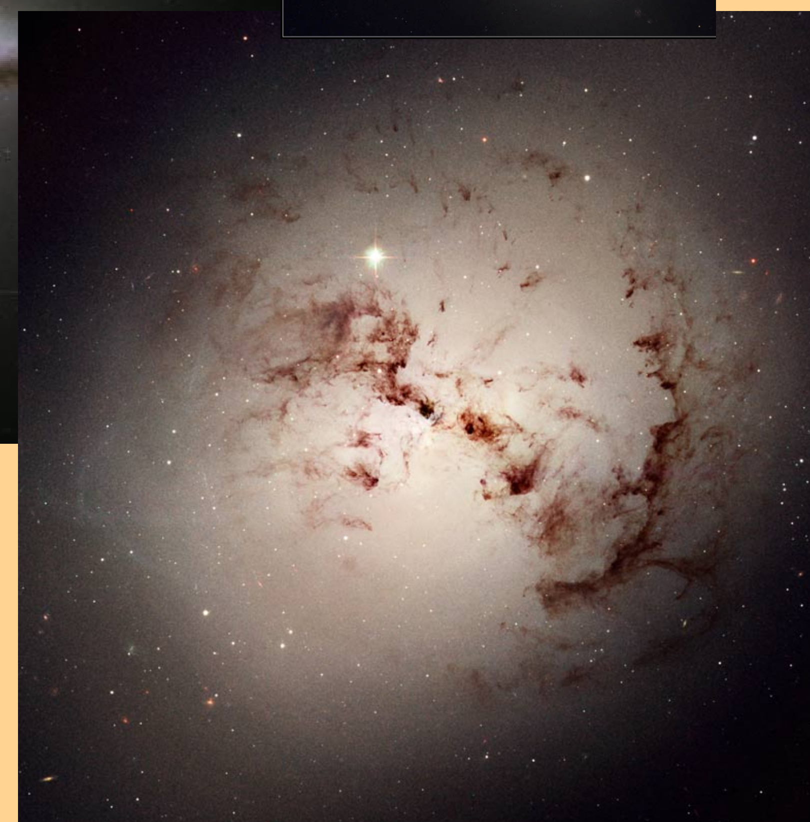


Graham et al. (2006)



What about dust?





MGC Millennium Galaxy Catalogue

What about dust?

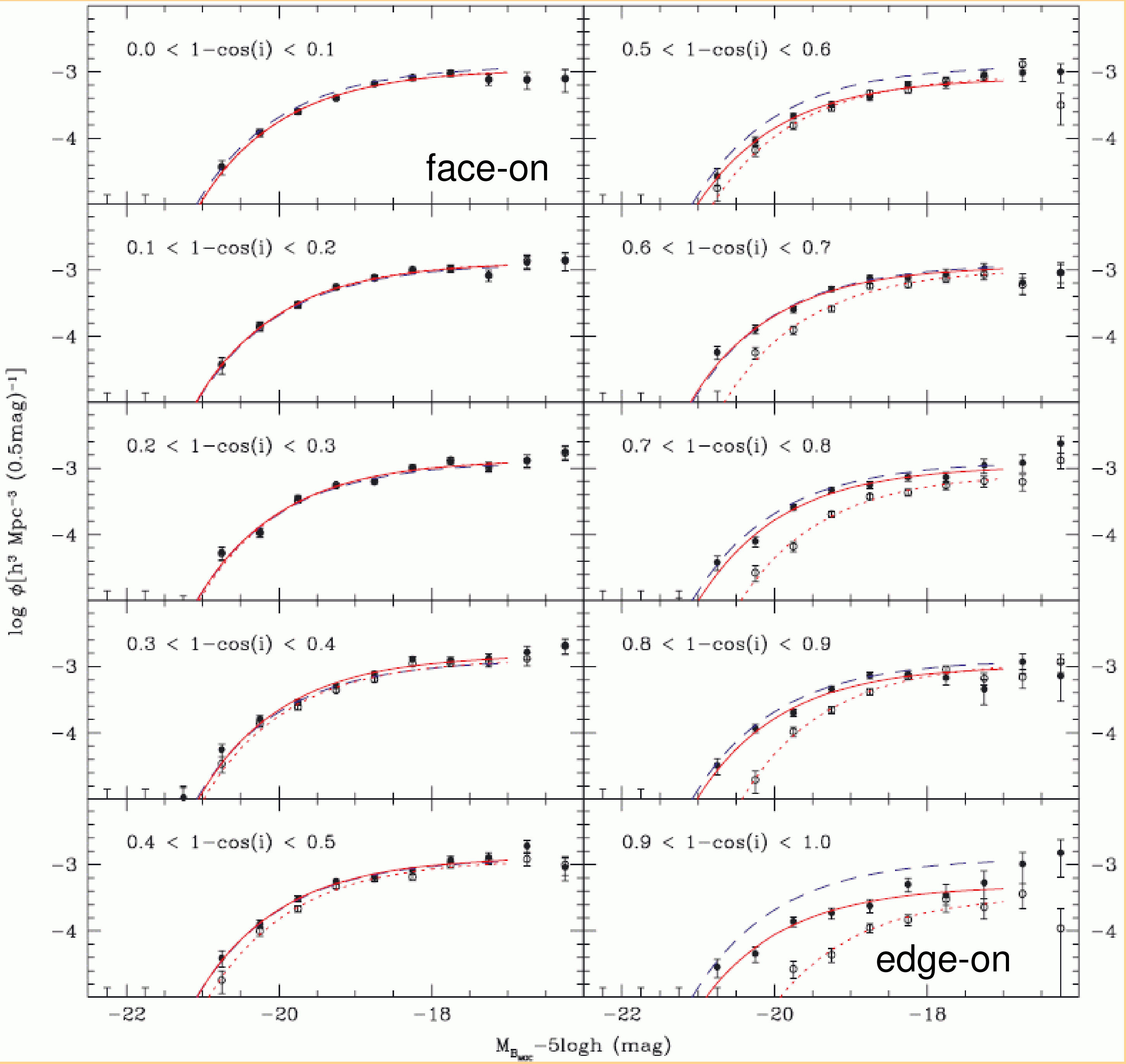
- Dust in the disks of galaxies may severely affect all photometric measurements (mags, colours), stellar mass, size, morphology, SB profile...
- (Spheroids are assumed to be dust-free.)
- **To what extent does dust distort our view of galaxies?**
- The Holmberg test: disk galaxy properties as a function of inclination. Here: luminosity.
- Advantages of bulge-disk composition:
  - Enables the selection of pure disks, without any bulge components.
  - Improves estimation of inclination.
  - Enables the study of the effect of the dust in the disk on the bulge.
- Recent realisation in the survey community that this might be a problem: Shao et al. (2007), Driver et al. (2007), Choi et al. (2007), Unterborn & Ryden (2008), Driver et al. (2008), Padilla & Strauss (2008), Maller et al. (2008)

Disk LF versus inclination

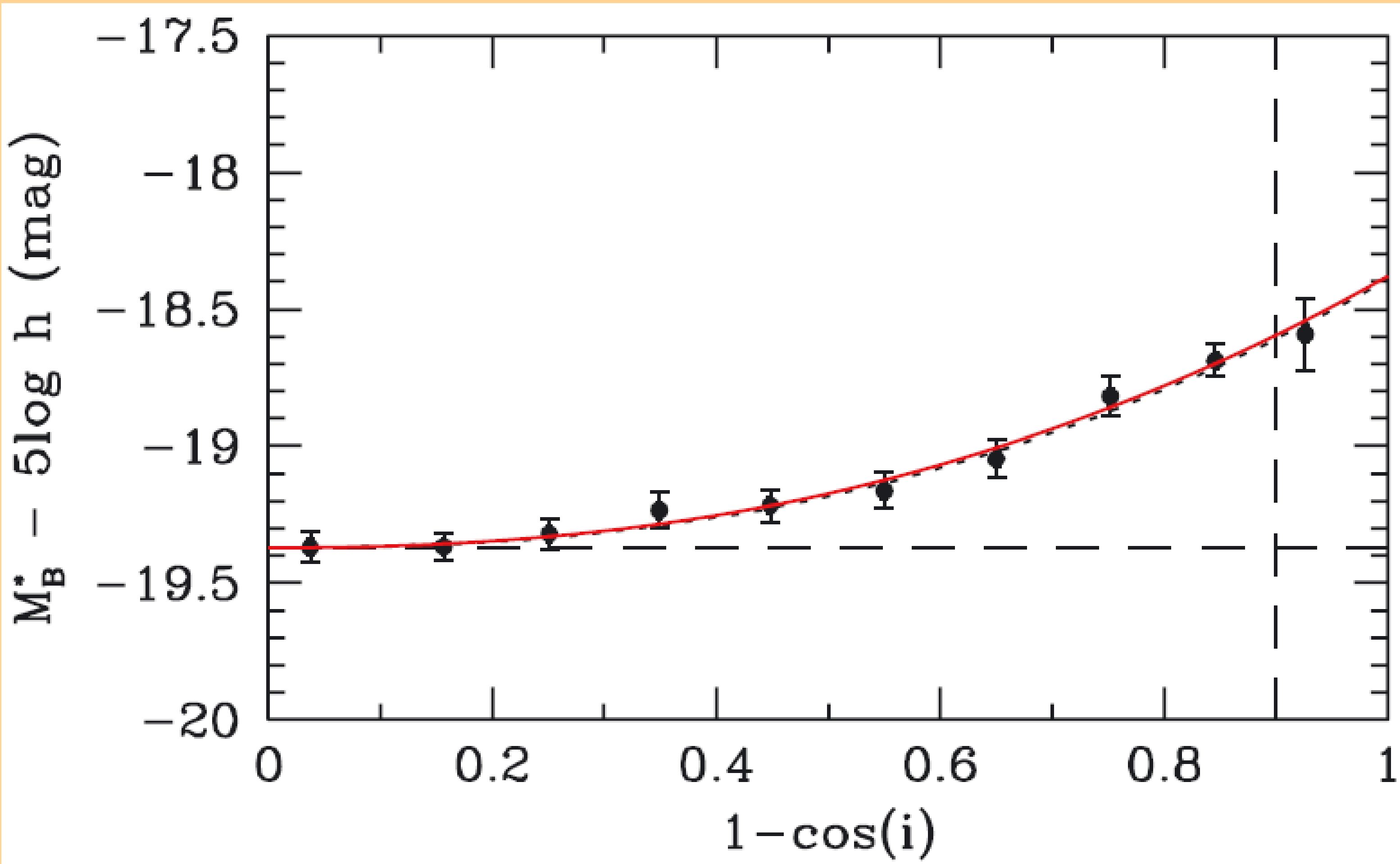
Red dotted line: measured LF

Red solid line: corrected LF

Blue dashed line: face-on sample



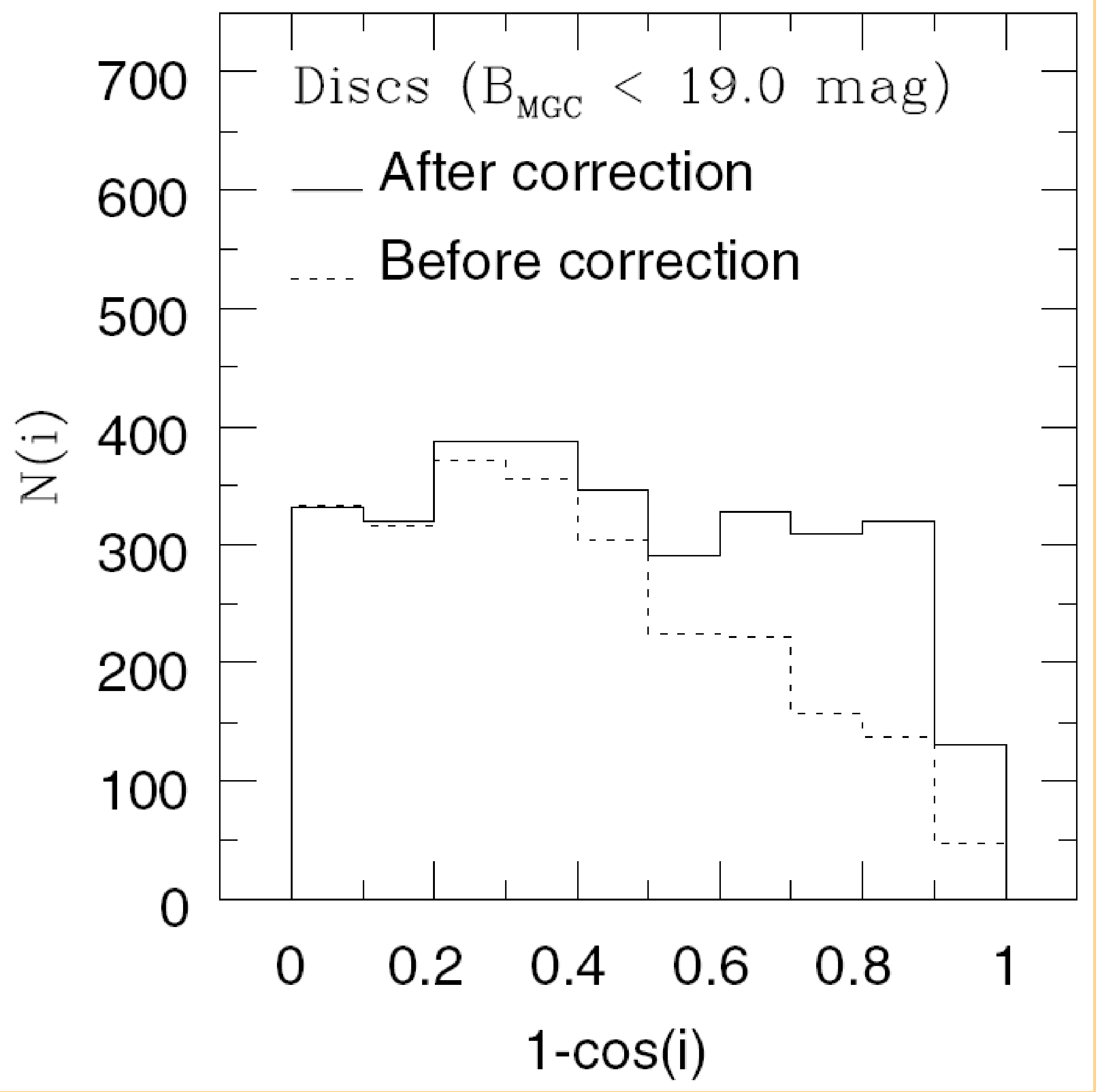
Disk attenuation-inclination relation



0.8 mag!

Sanity check

- For randomly orientated disks (and no dust) the cos(i) distribution should be flat. Initially it's not!
- The empirical attenuation-inclination correction also successfully corrects the inclination distribution.
- Some residual incompleteness in the highest inclination bin remains.



Modeling the dust

Popescu et al. (2000)
Tuffs et al. (2004)

Old stellar bulge:

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

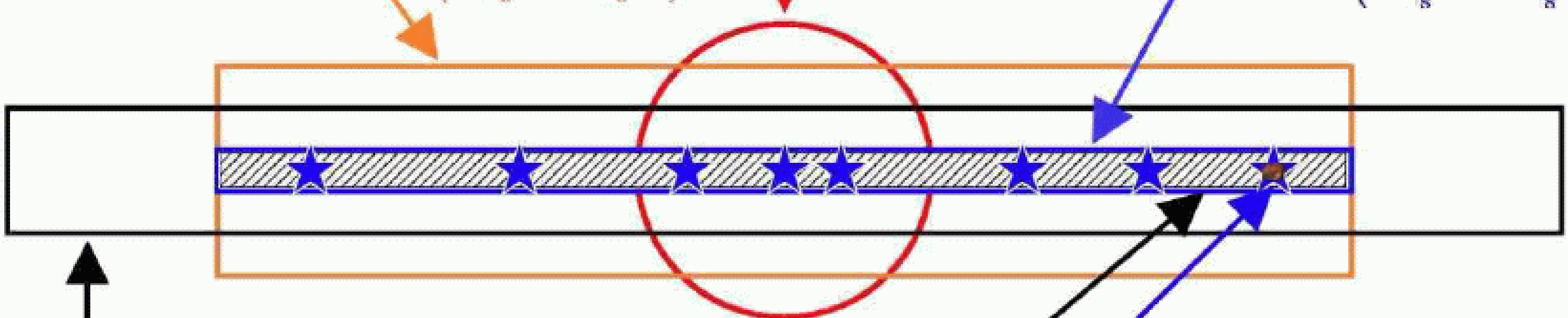
$$B = \frac{\sqrt{R^2 + z^2\,(a/b)^2}}{R_e}$$

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:

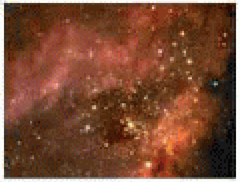
$$\eta^{\rm tdisk}(\lambda, R, z) = \eta^{\rm tdisk}(\lambda, 0, 0)\exp\left(-\frac{R}{h_{\rm s}^{\rm tdisk}} - \frac{|z|}{z_{\rm s}^{\rm tdisk}}\right)$$



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



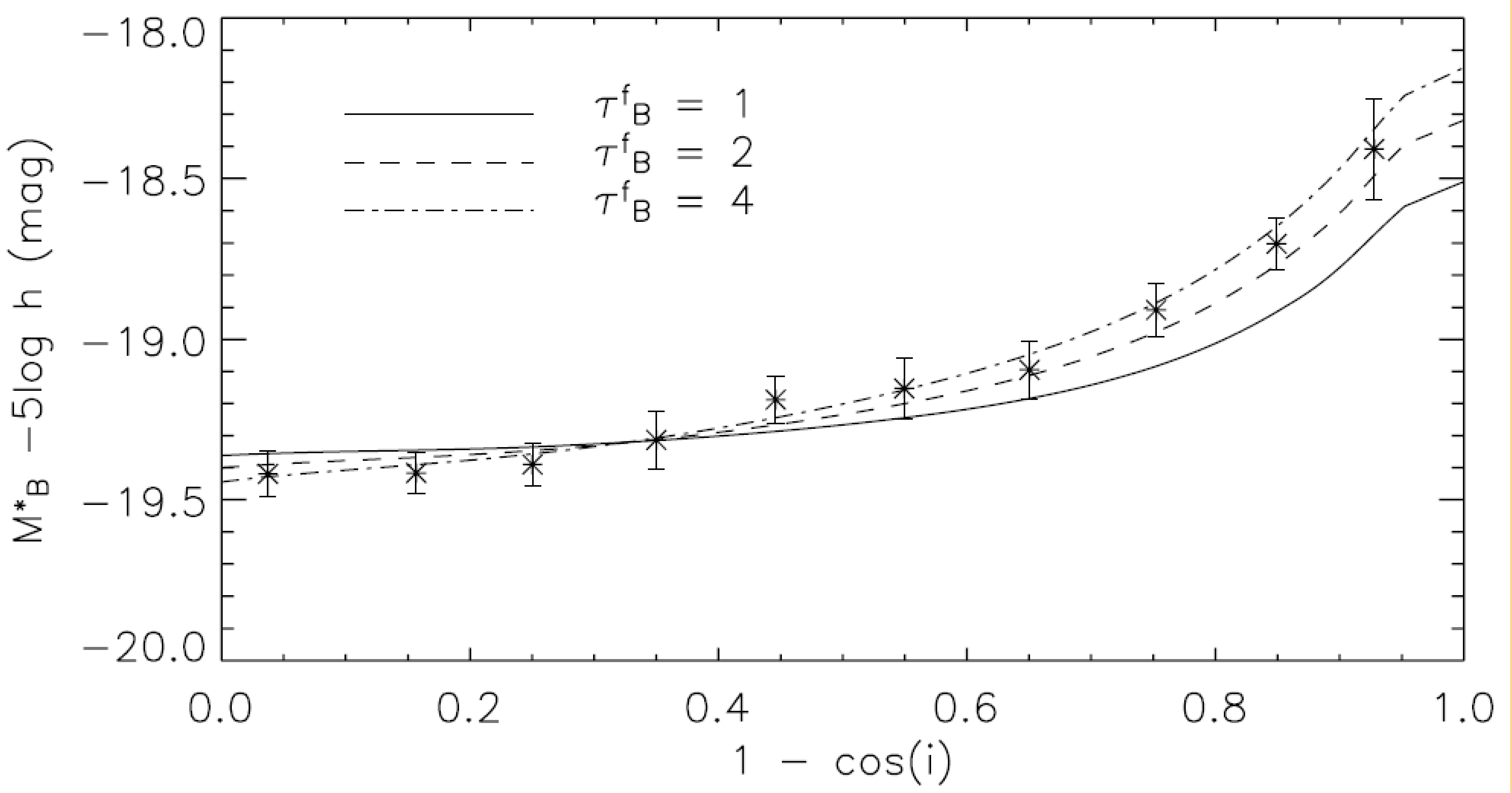
Dust disk associated with the young stellar disk:

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

Based on UV+optical+NIR +Spitzer data of 6 very nearby galaxies.

Modeling the dust

- The Popescu & Tuffs model has only one free parameter: the central face-on B-band optical depth.
- Best-fit τ^{f}_{B} = 3.8 ± 0.7
- Note: popular τ = 1, one dust-disk models fail miserably!



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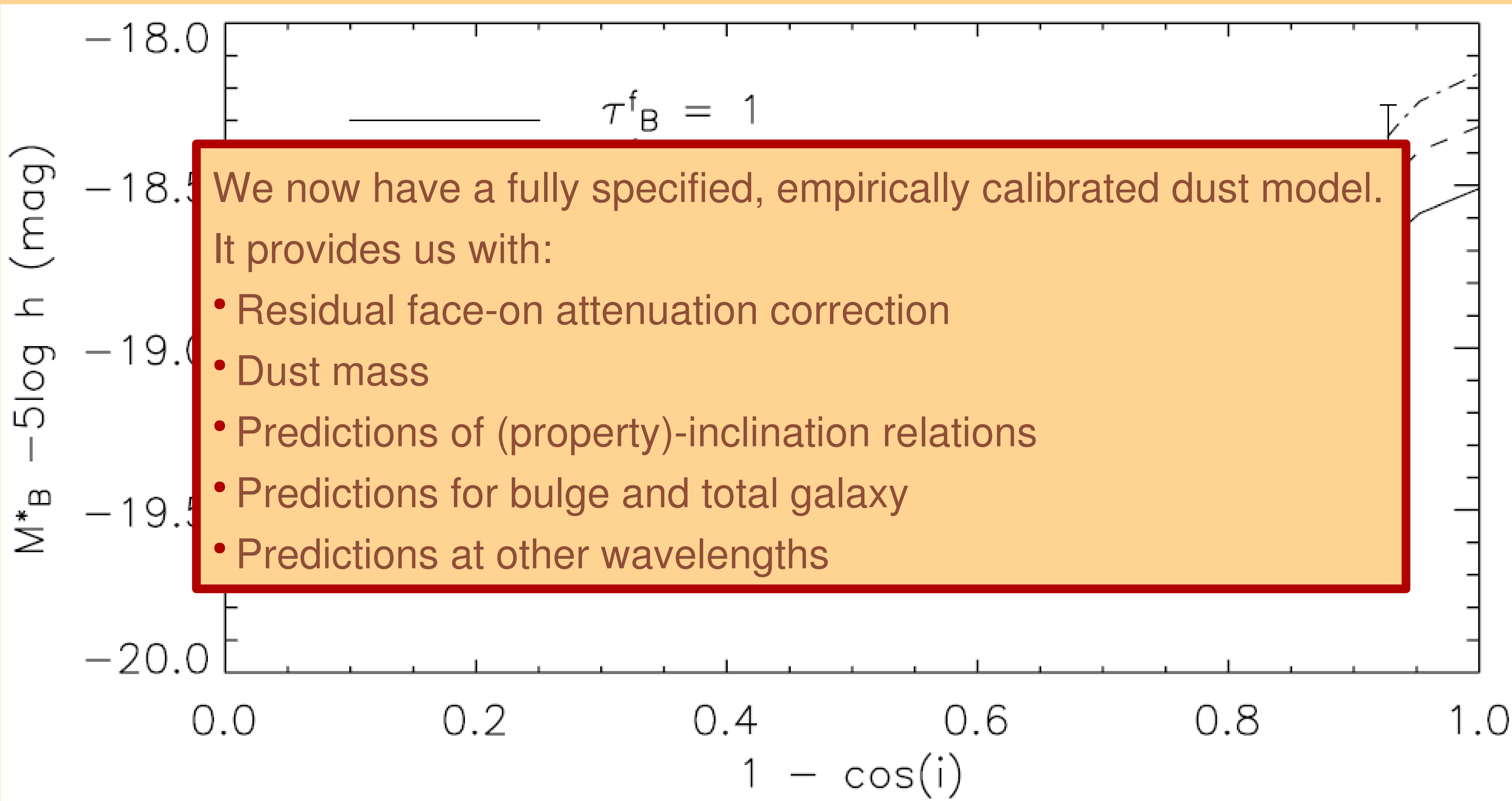
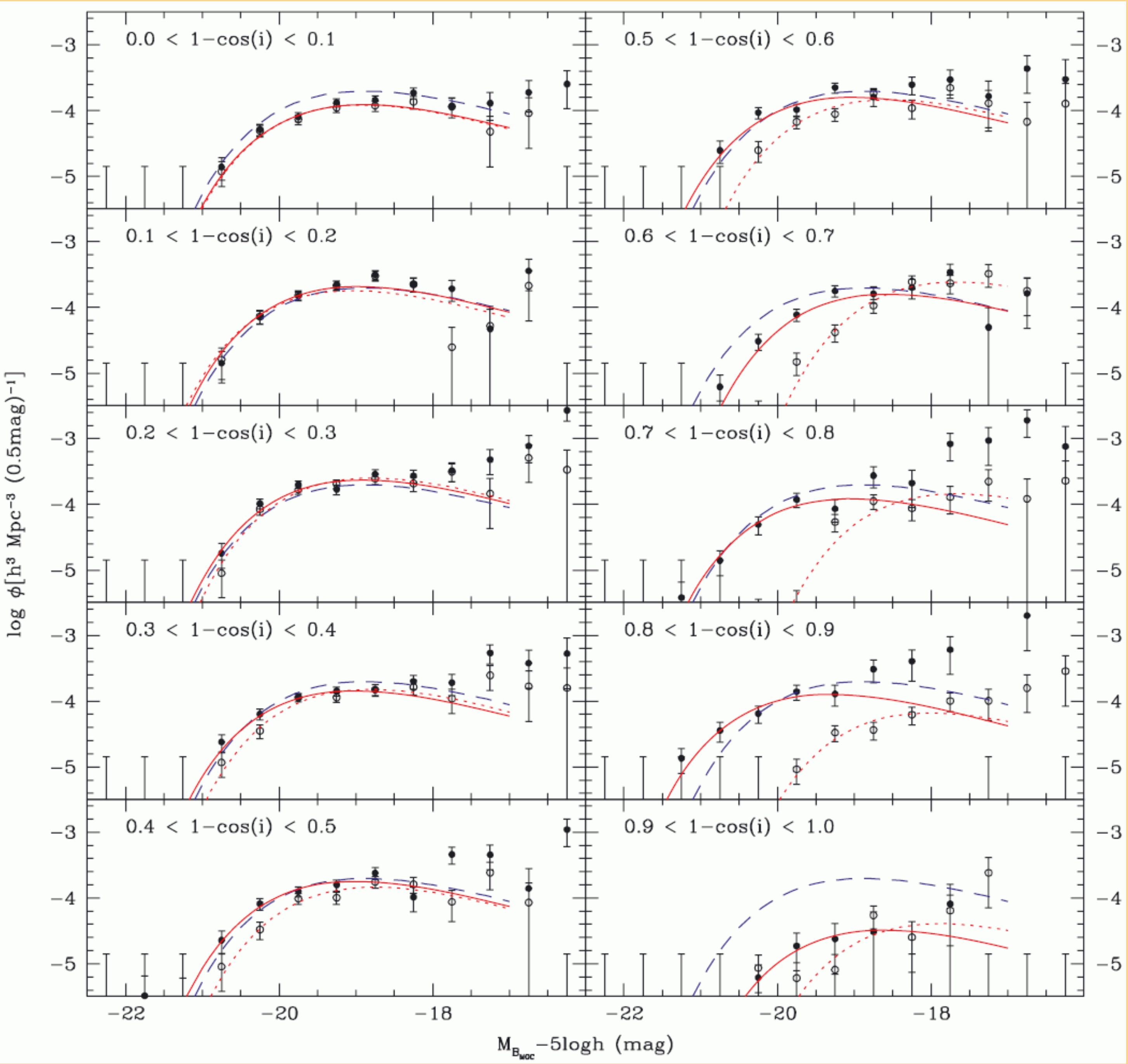


We now have a fully specified, empirically calibrated dust model.

It provides us with:

- Residual face-on attenuation correction
- Dust mass
- Predictions of (property)-inclination relations
- Predictions for bulge and total galaxy
- Predictions at other wavelengths

Bulge LF versus inclination

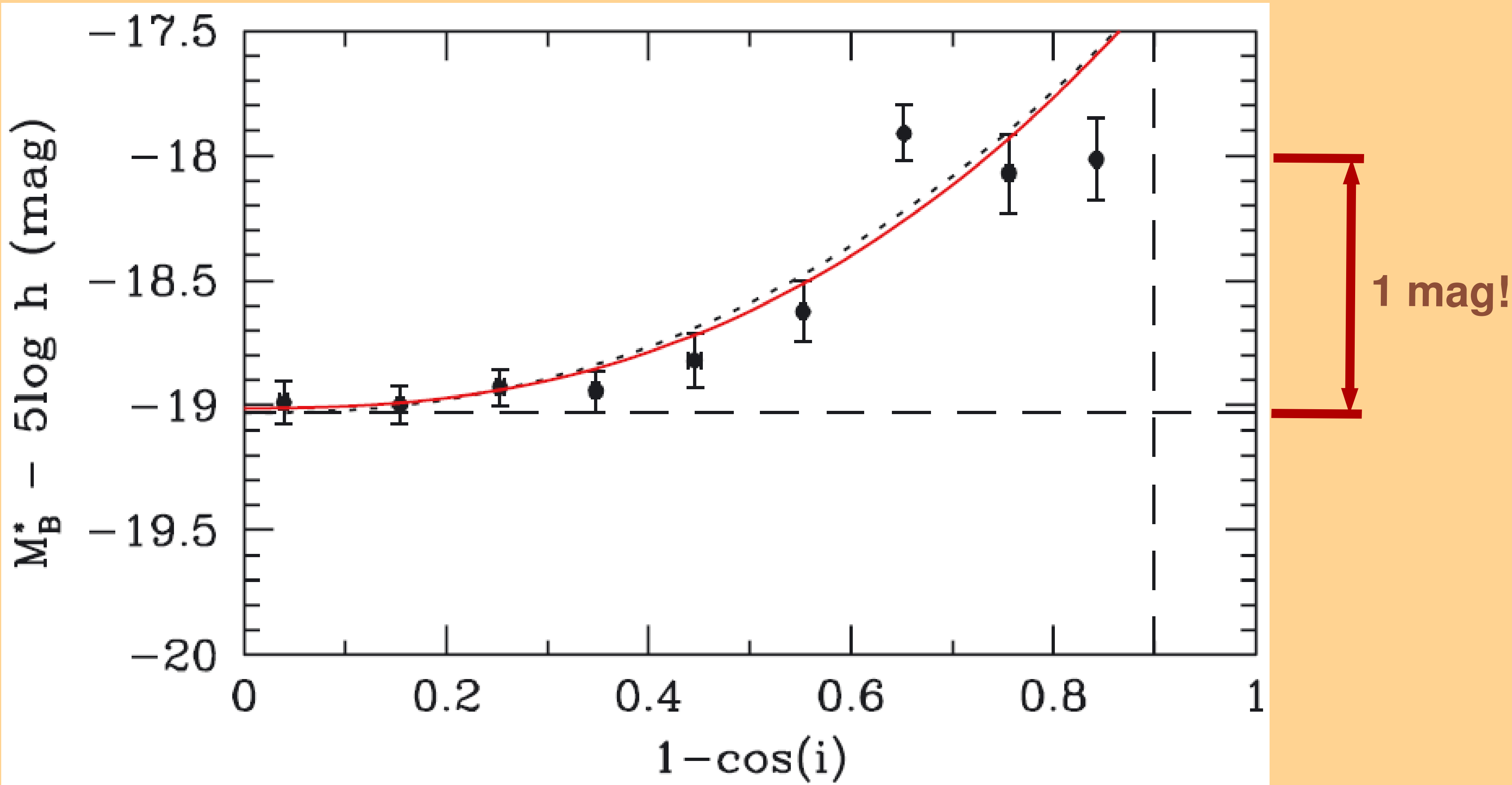


Red dotted line: measured LF

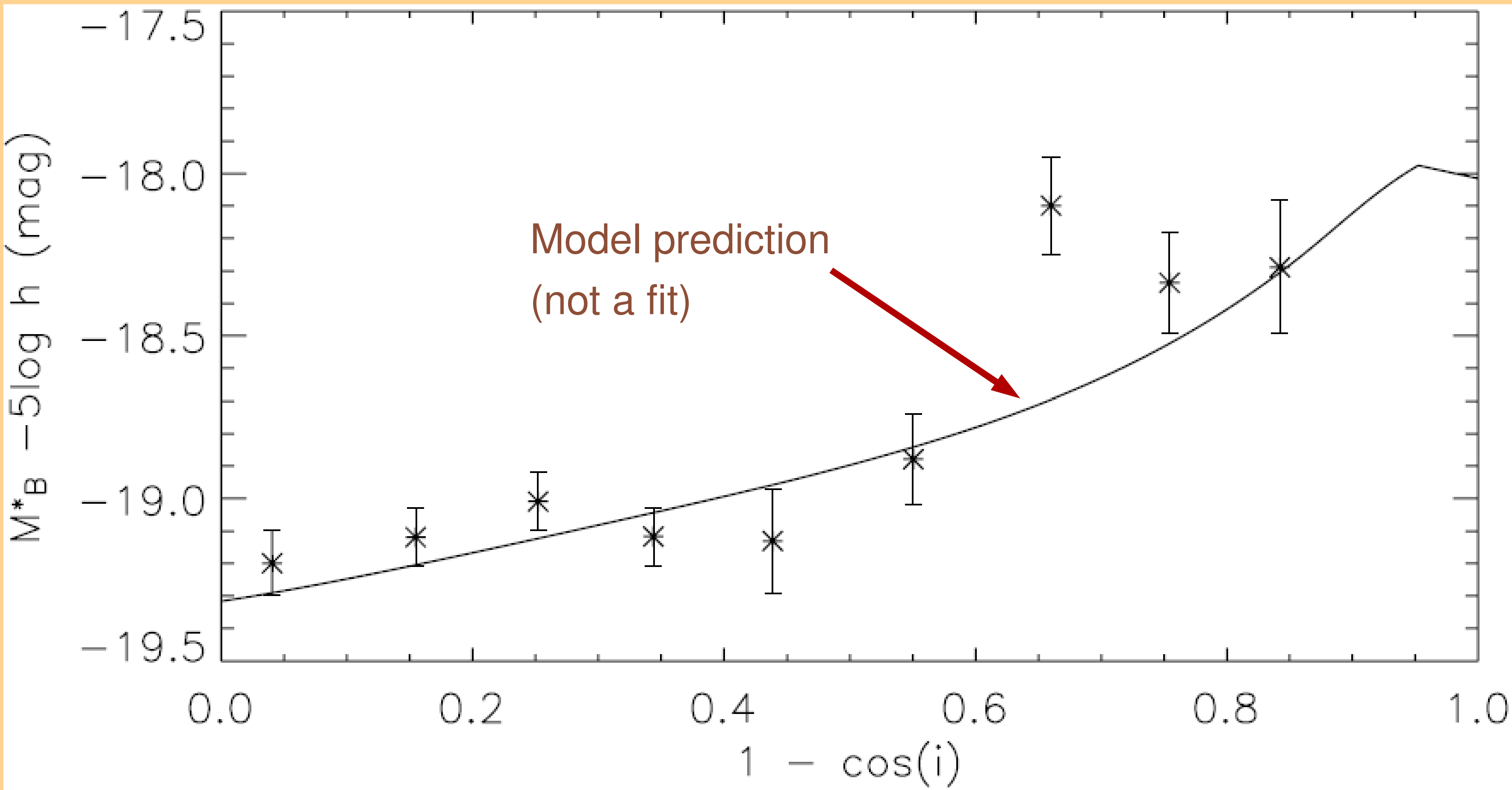
Red solid line: corrected LF

Blue dashed line: face-on sample

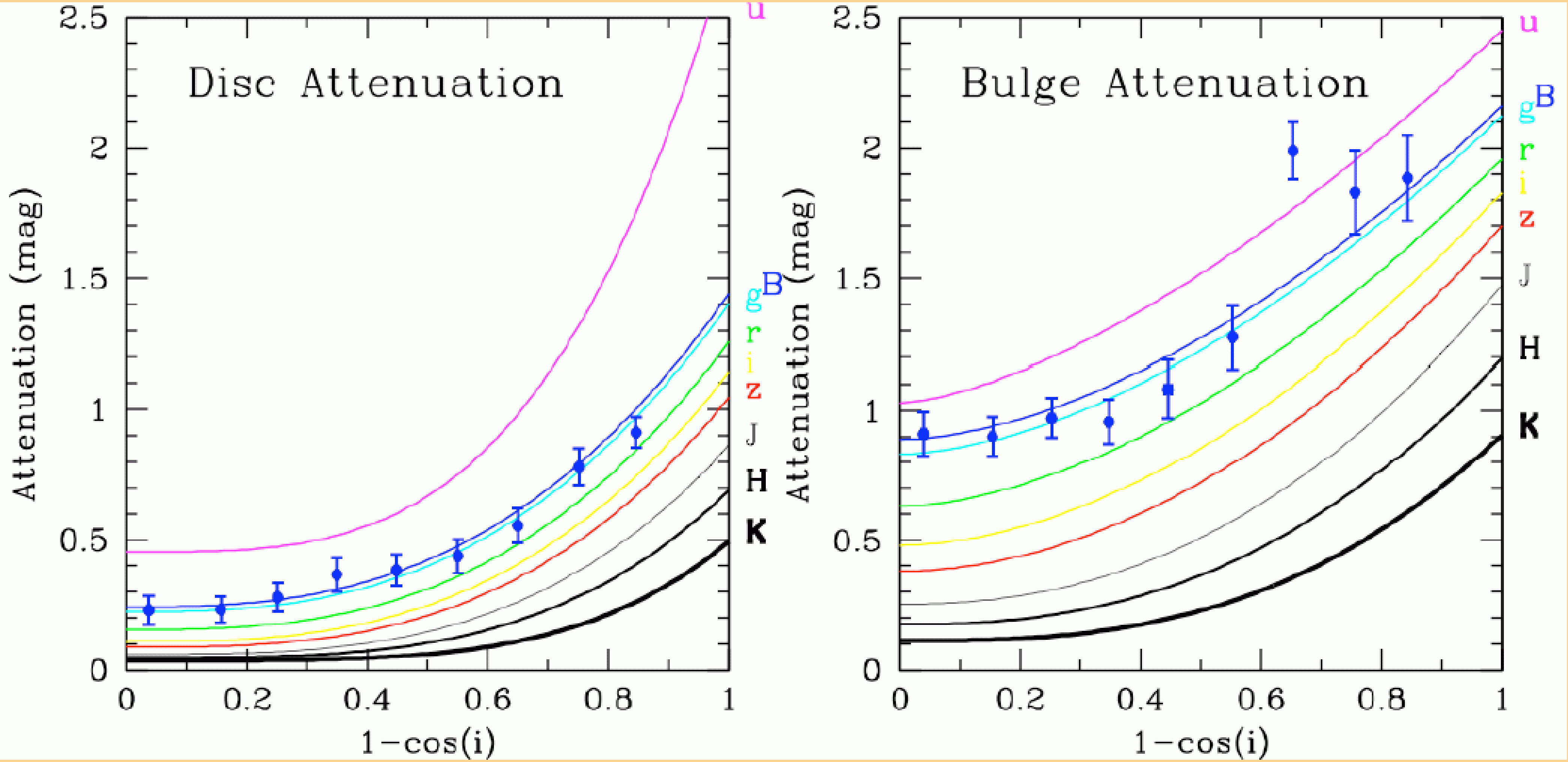
Bulge attenuation-inclination relation



Bulge attenuation-inclination relation



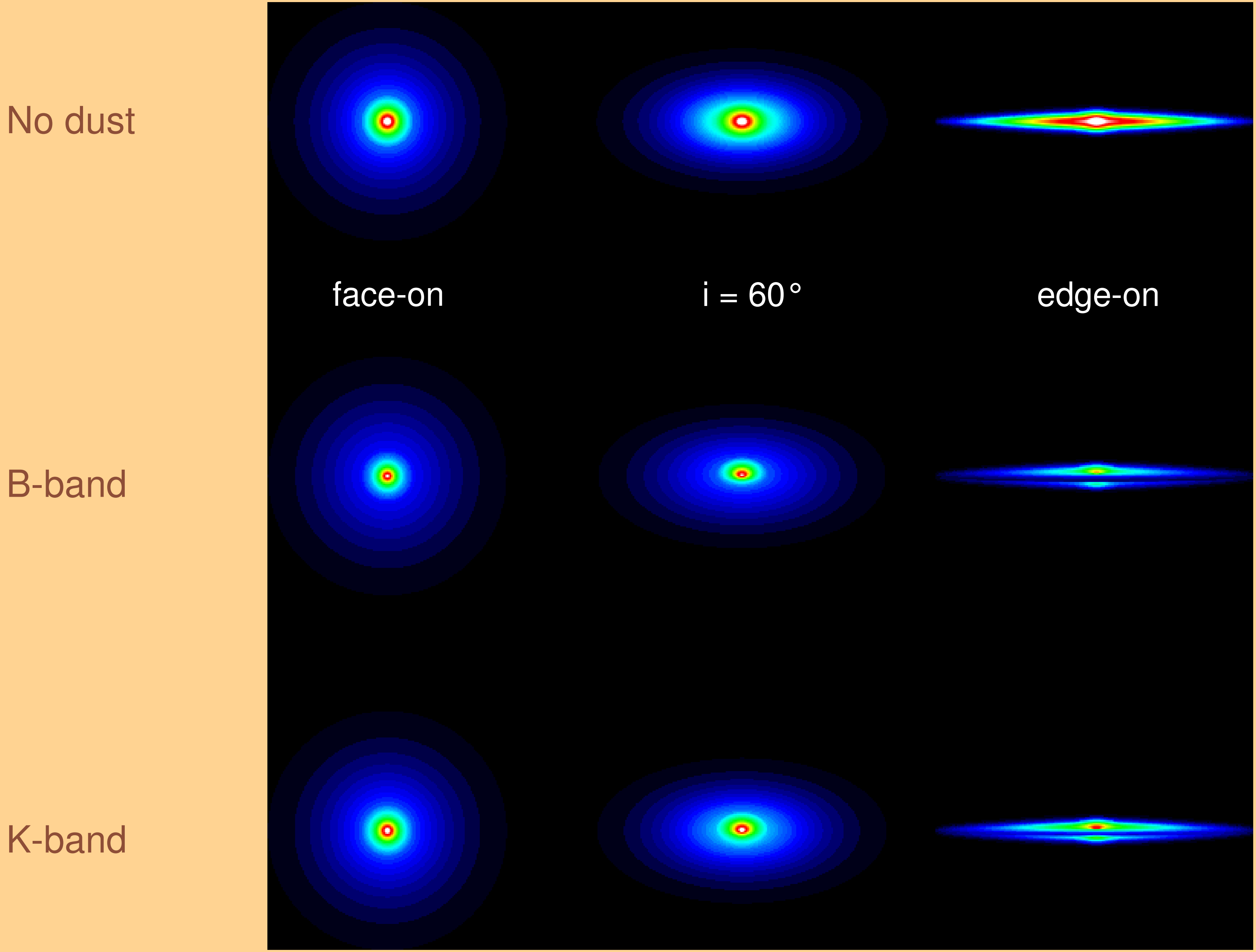
Total attenuation



Face-on B-band disk attenuation = 0.2 mag

Face-on B-band bulge attenuation = 0.88 mag (!)

A model galaxy



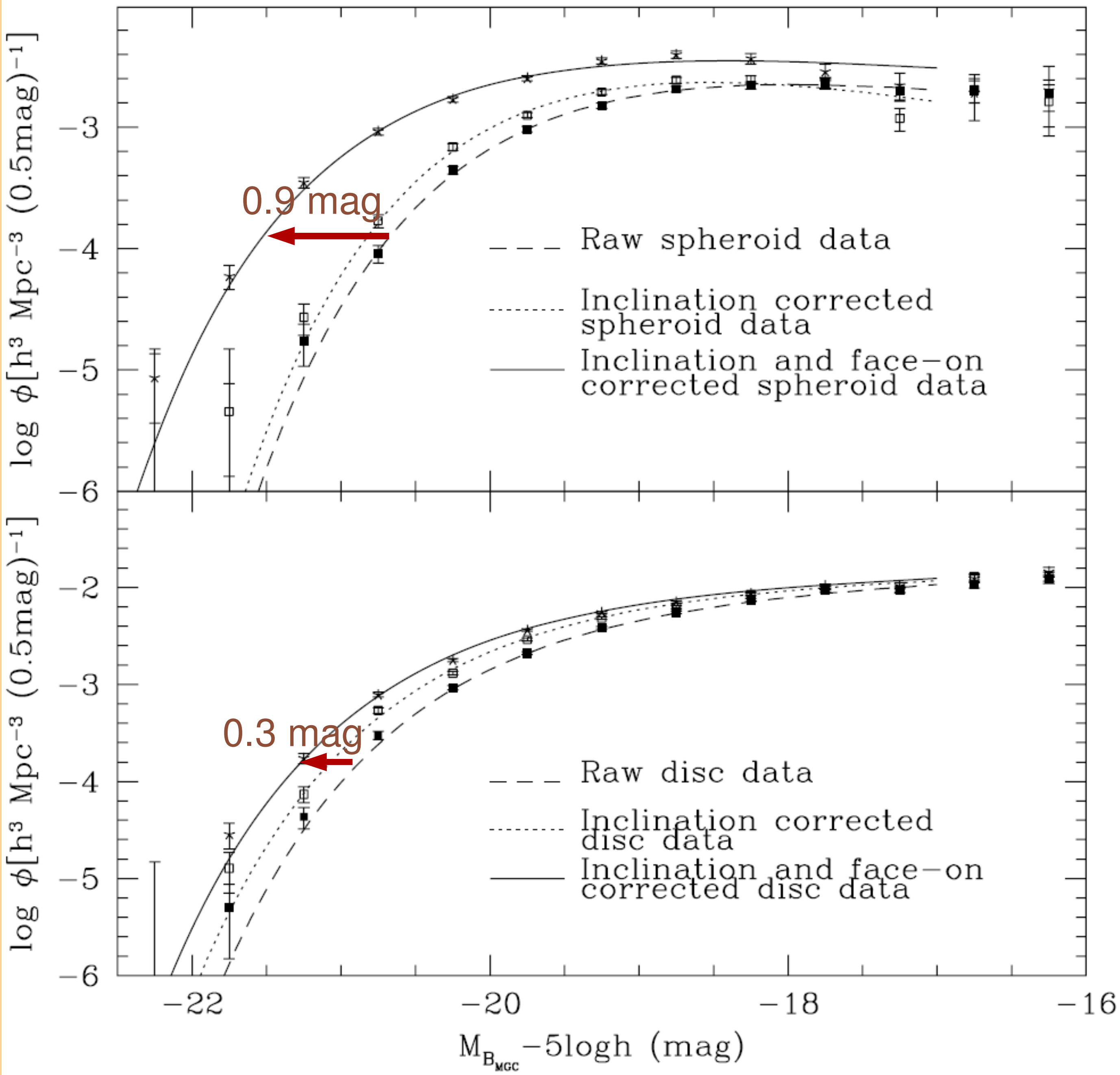
Corrected component LFs

Luminosity density:

Disks: up by 59%

Bulges: up by 230%!

Ellipticals: no change



Corrected component LFs

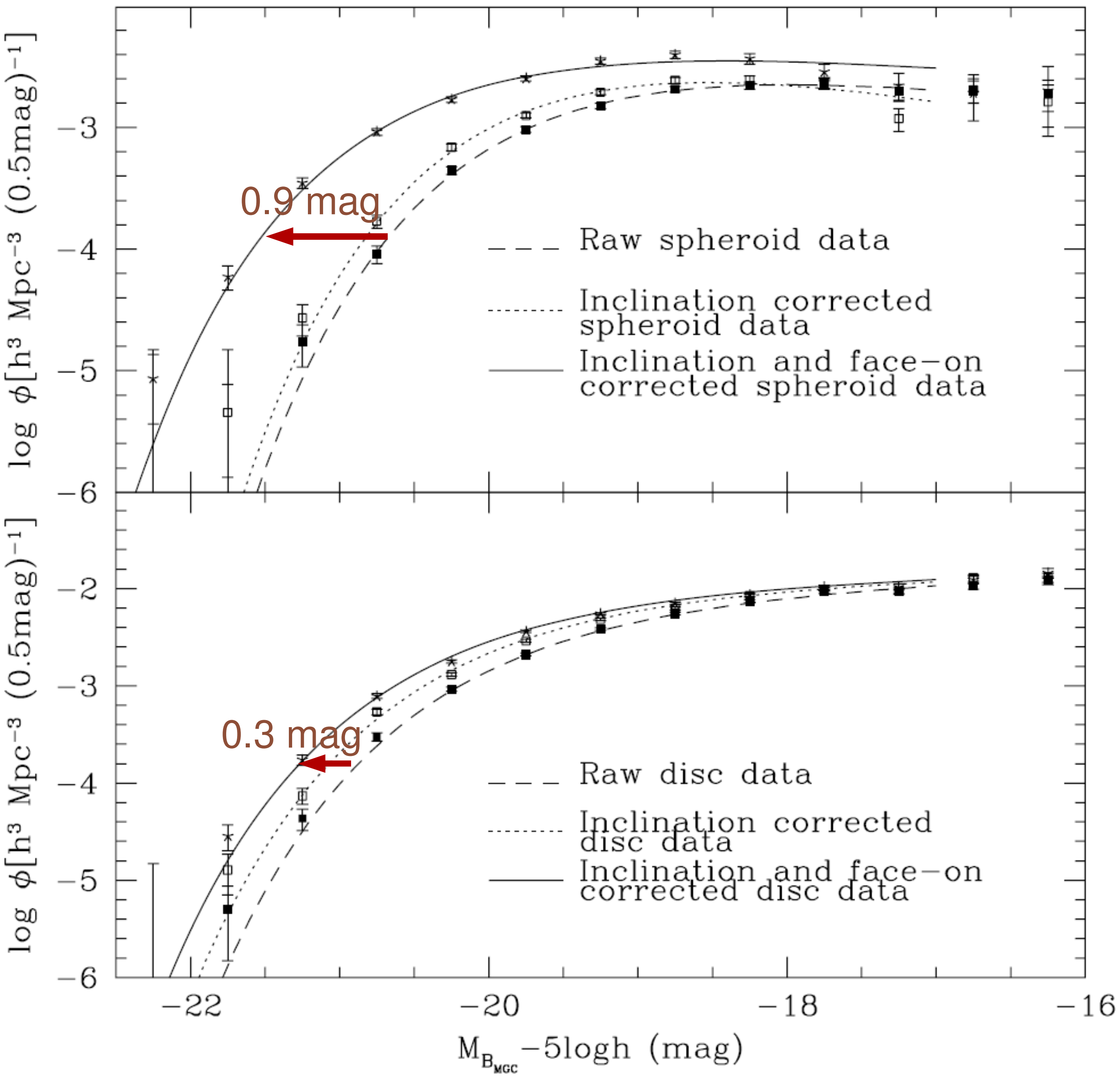
Stellar mass density:

Disks: up by 16%

Bulges: up by 38%

Ellipticals: no change

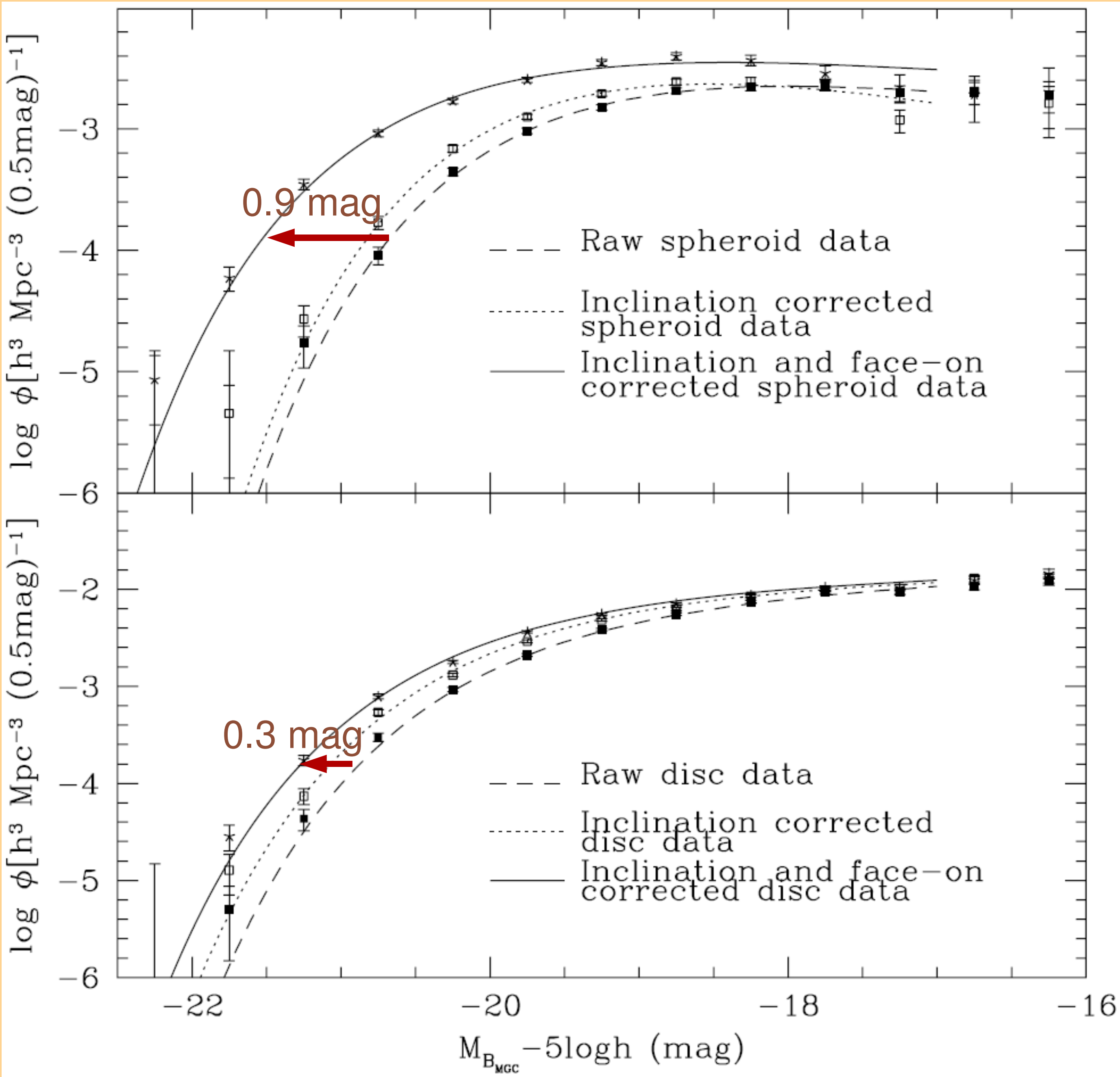
Total: up by 19%



Corrected component LFs

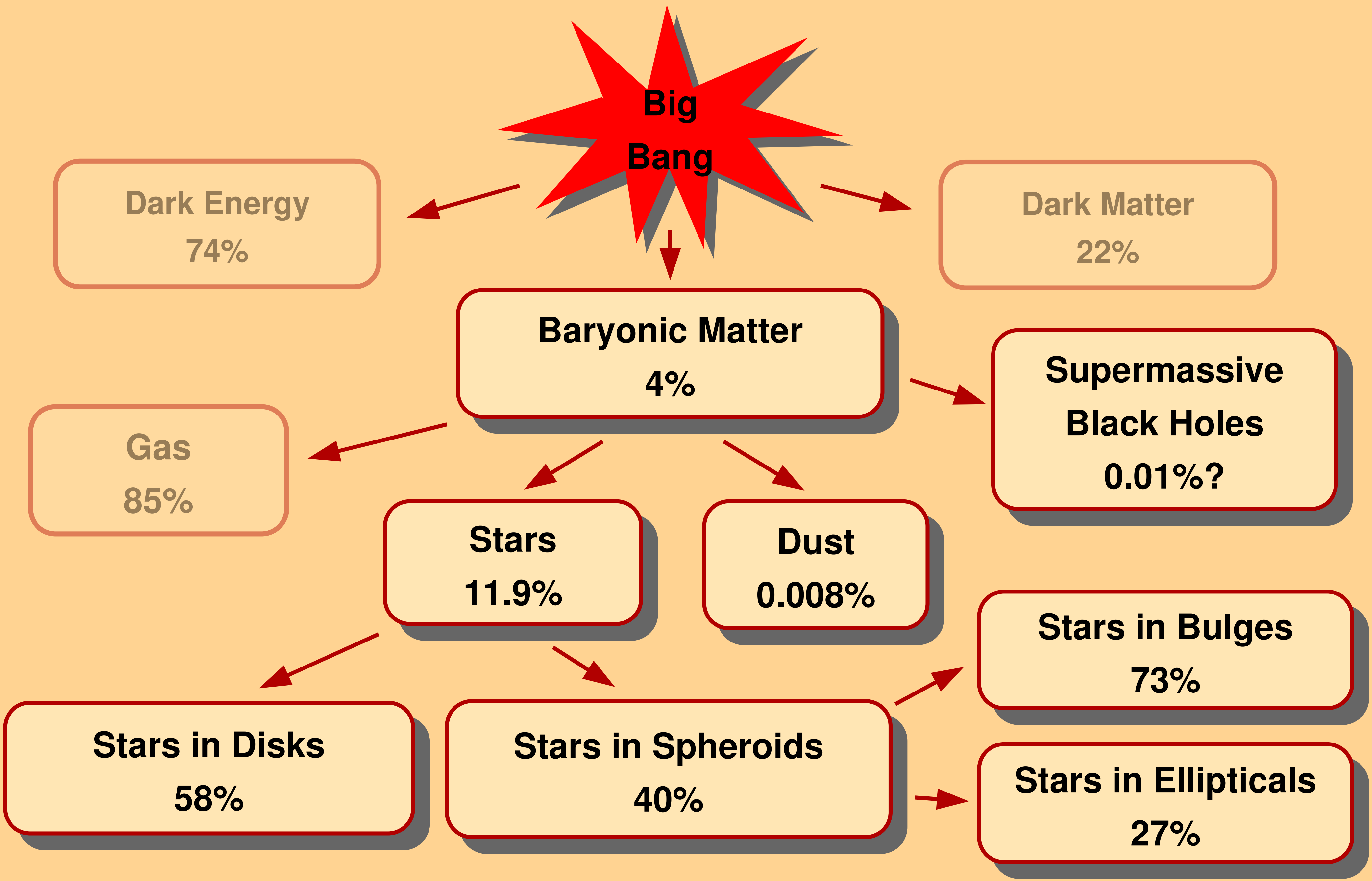
Stellar mass density split:

Disks:	58 → 58%
Bulges:	26 → 29%
Ellipticals:	13 → 10.5%
Blue spheroids:	3 → 2.5%

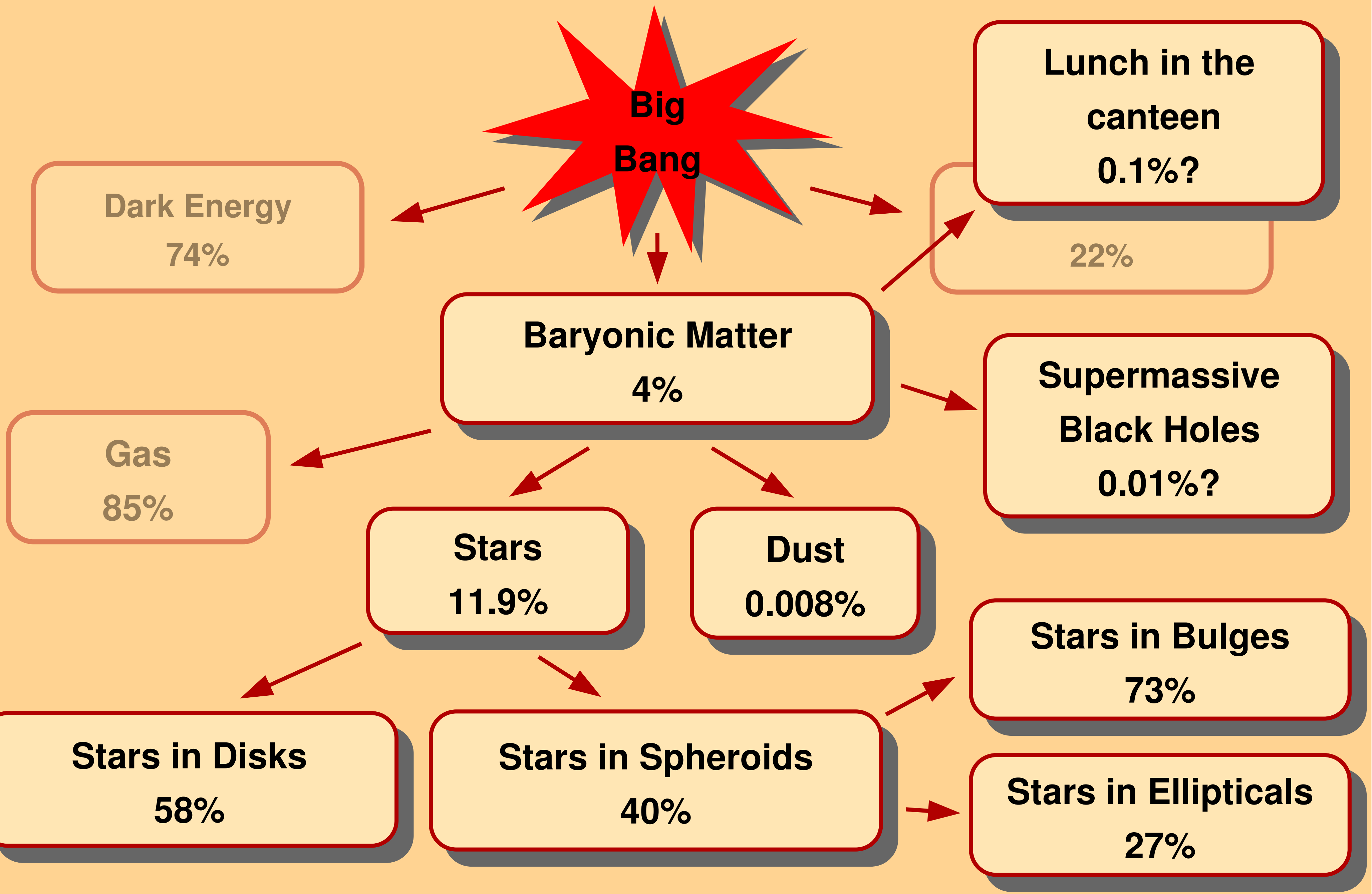


MGC Millennium Galaxy Catalogue

The cosmic mass budget



The cosmic mass budget



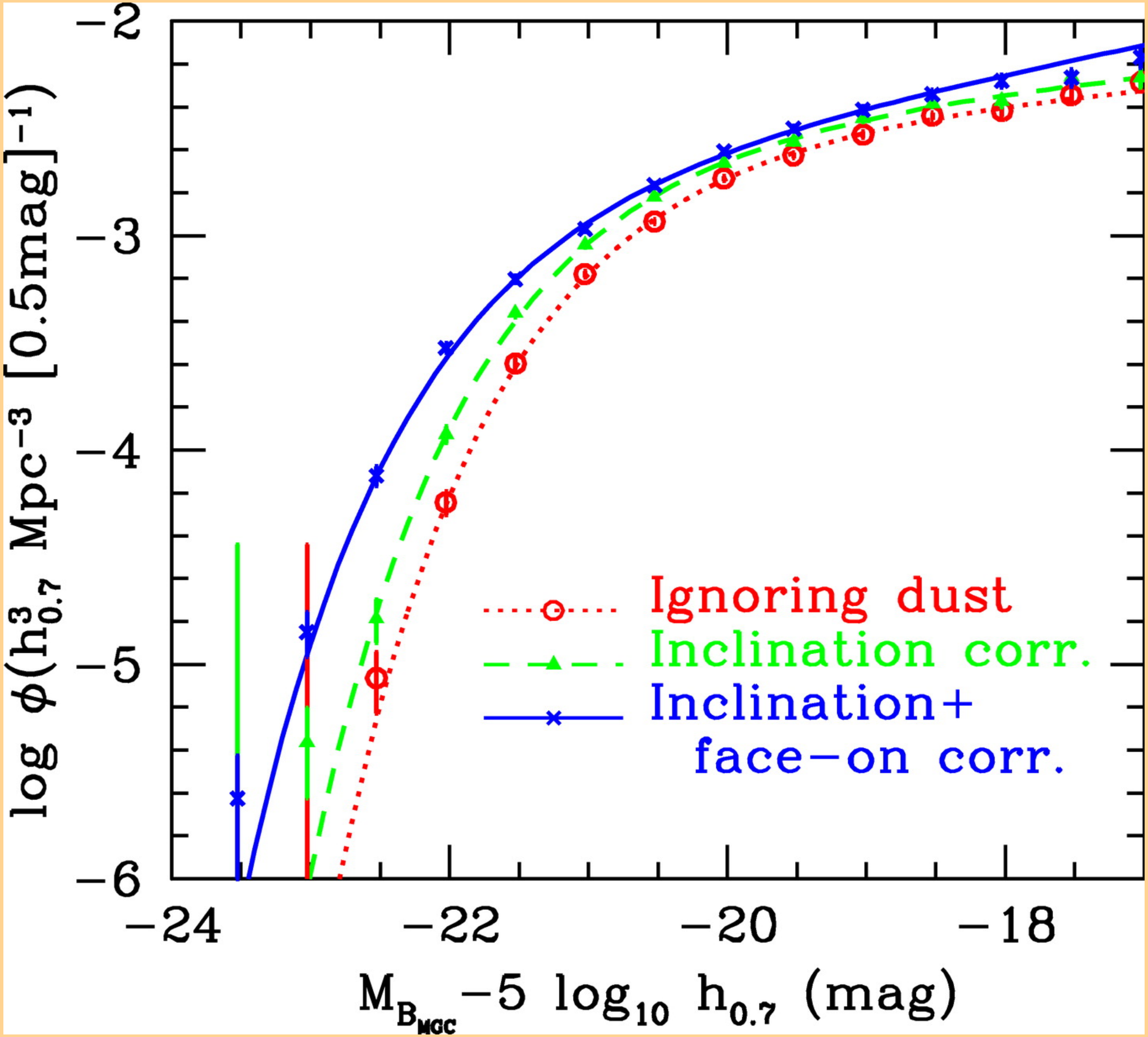
Corrected total galaxy LF

Full dust correction increases the total luminosity density increases by 63%.

In other words:
Only 61% of B-band photons that are produced by stars actually escape into the IGM.

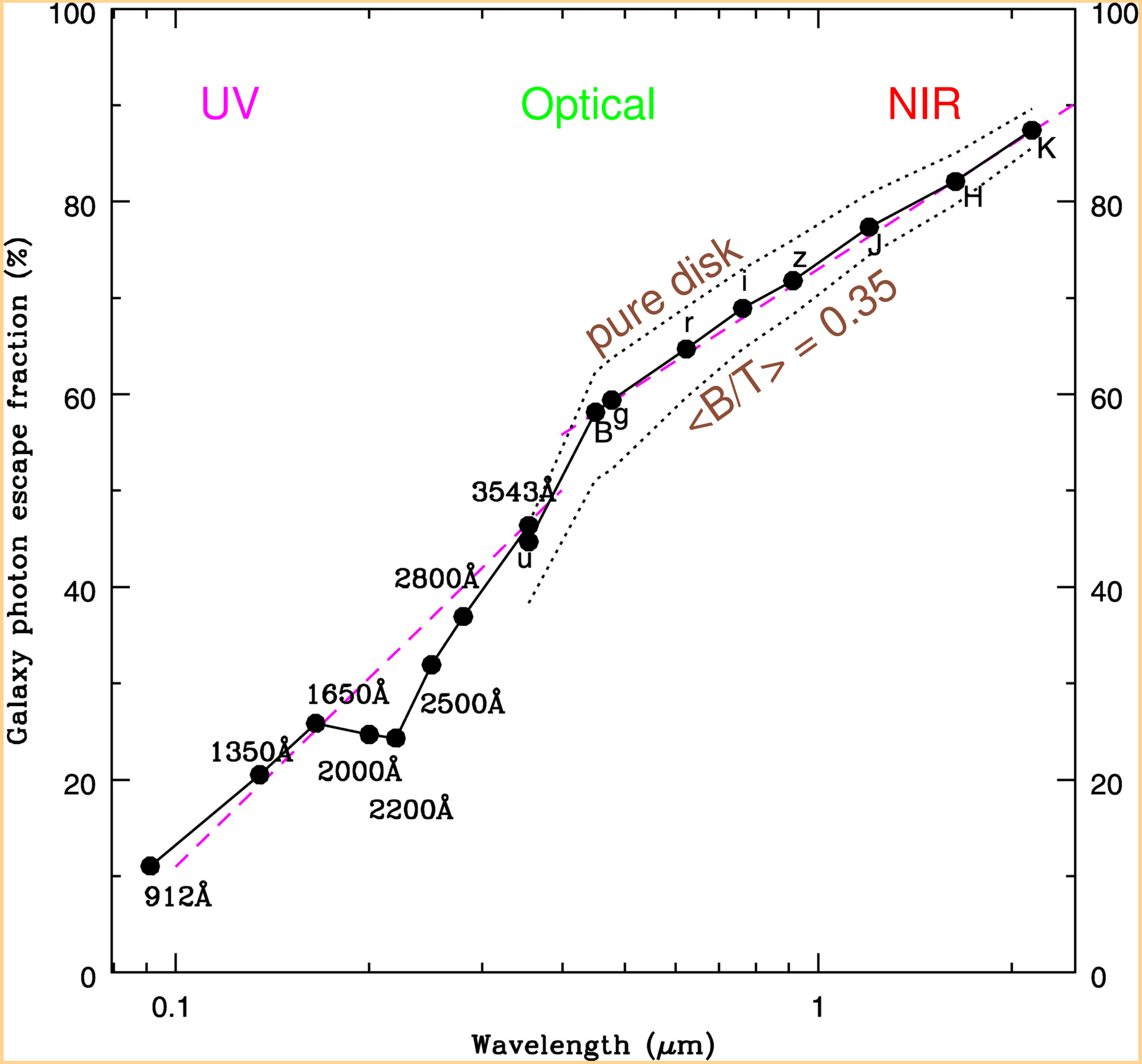
What about other wave-lengths?

And what happens to the energy absorbed by the dust in the UV-optical?

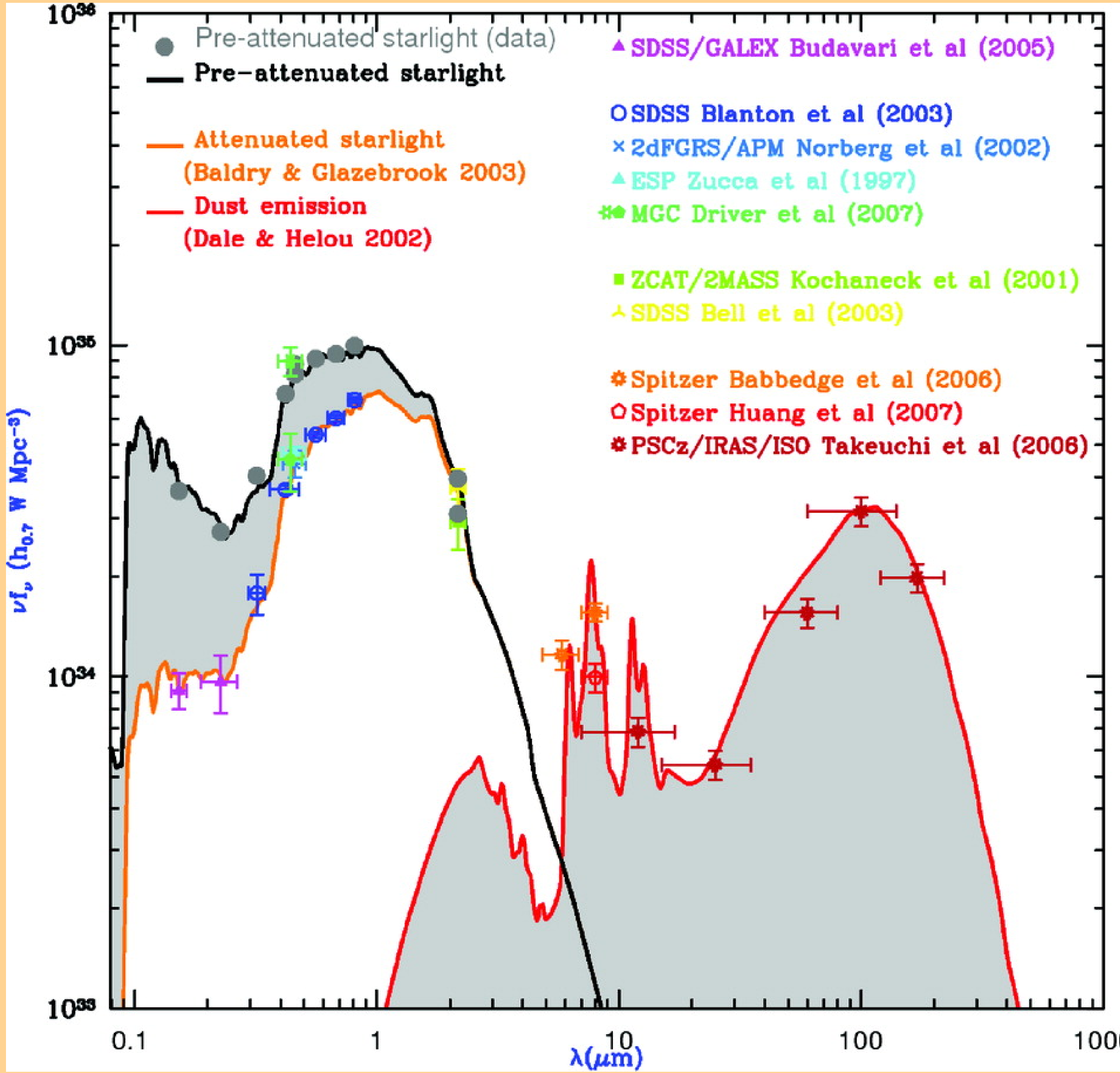


Photon escape fractions

- Use dust model to calculate photon escape fraction averaged over all cos(i) as a function of B/T.
- Pick B/T that corresponds to observed B-band escape fraction.
- Transform this B/T to other wavelengths using mean bulge and disk colours.
- Using the dust model transform the B/T to a corresponding photon escape fraction at each wavelength.



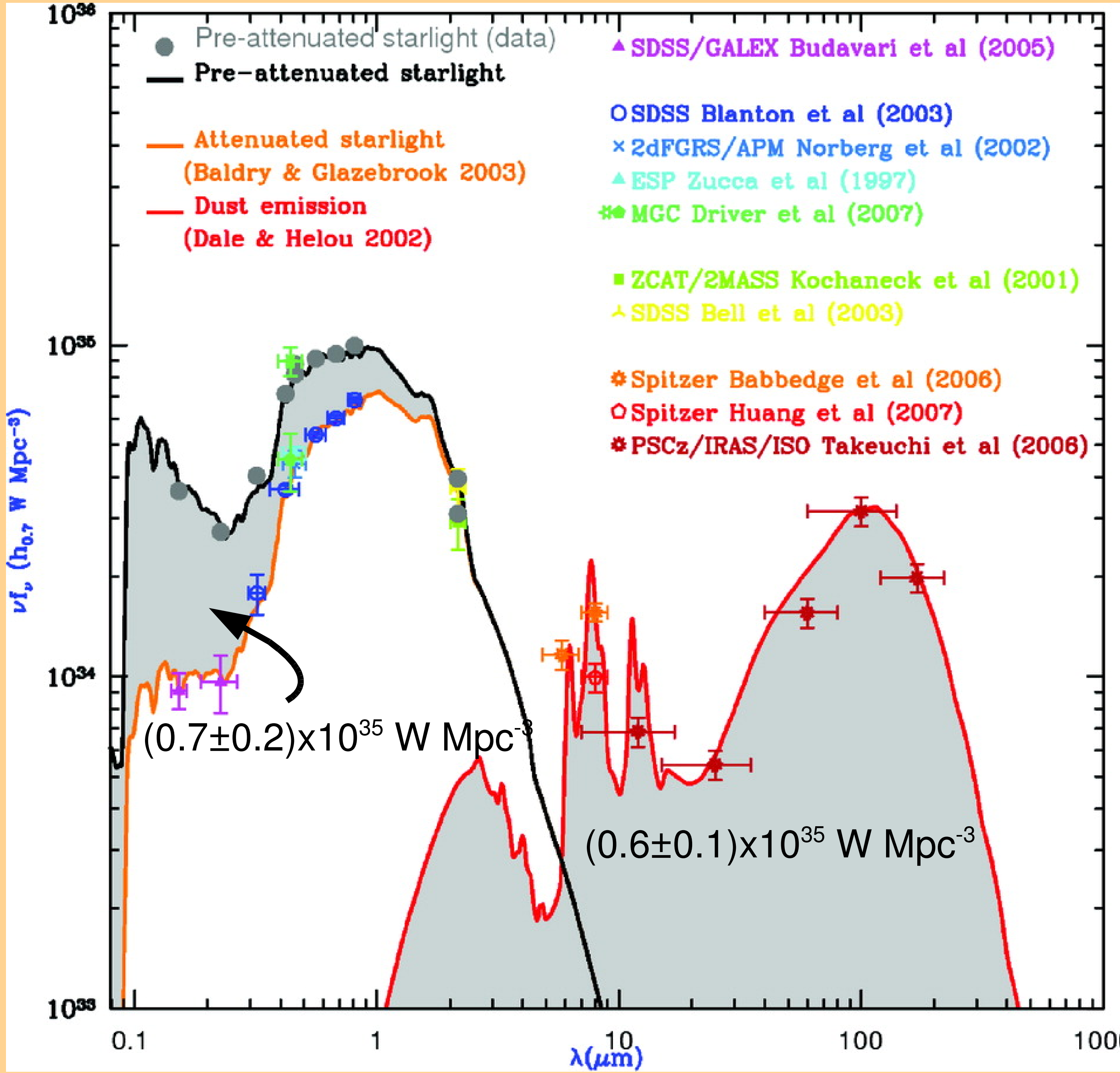
The cosmic SED



The cosmic SED

Energy of starlight absorbed by dust
=
Energy of FIR emission by dust

➔ No room for dust heating by AGN!



The (immediate) future

The next generation of wide-field survey instruments + HST/ACS will provide datasets with an unprecedented combination of size, depth and resolution:

Low z:

- KIDS – VST ugri imaging survey over ~1000 deg^2 (approved ESO Public Survey)
  Compared to MGC: 2 x resolution, 1.5 mag deeper, 30 x area, 4 bands
- VIKING – KIDS NIR extension with VISTA (co-I, approved EPS)
- GAMA – Deep redshift survey with AAOmega over ~250 deg^2 (co-PI)

High z:

- COSMOS – 2 deg^2 ACS survey (largest HST survey ever, complete)
- zCOSMOS – VLT/VIMOS redshift survey for COSMOS (in progress)

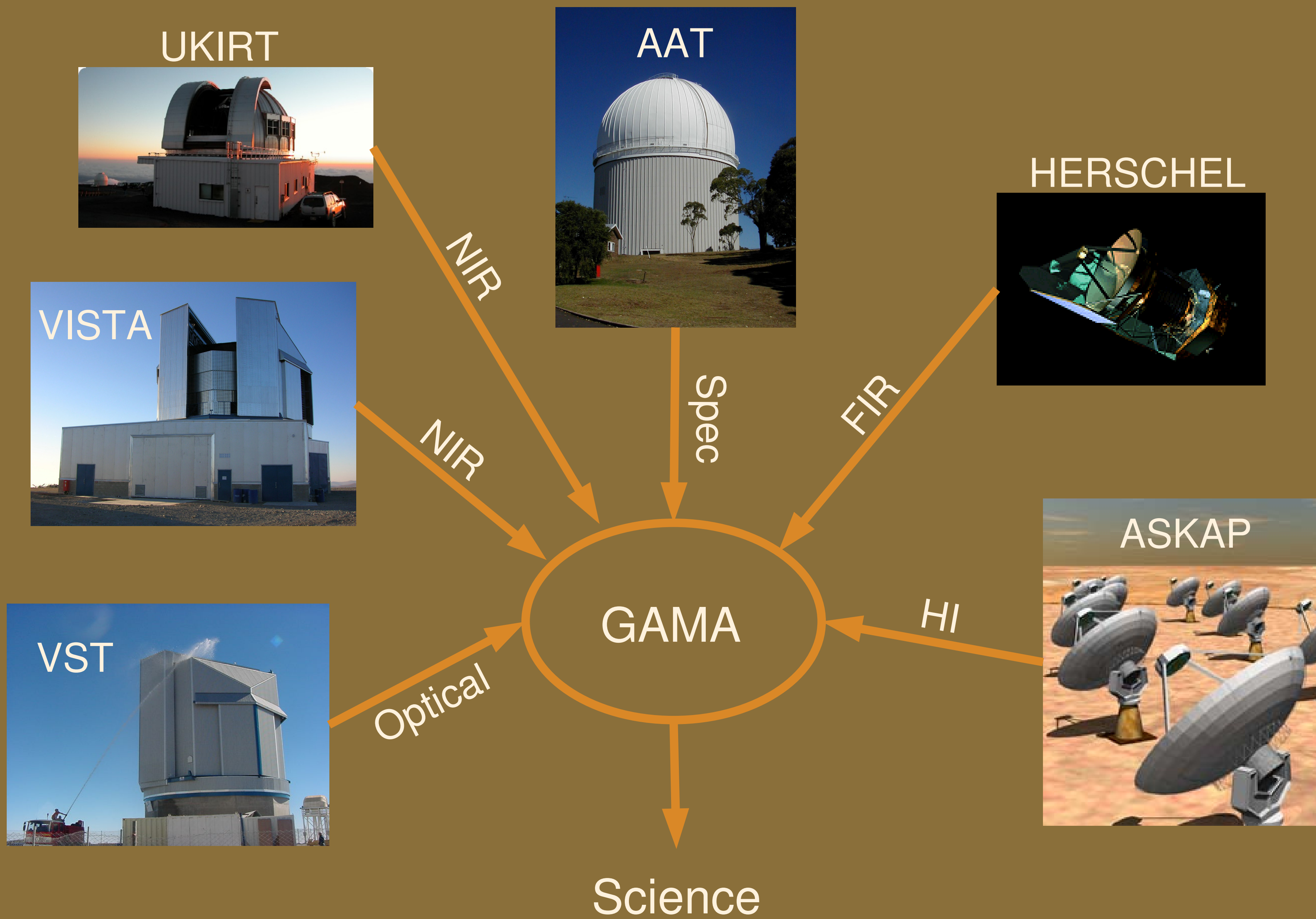
→ Bulge/disk decomposition of ~2 x 10^5 galaxies with 0 < z < 1 from UV to NIR.

Galaxy And Mass Assembly (GAMA)

www.eso.org/~jliske/gama

- Spectroscopic component of a comprehensive, multi-wavelength, state-of-the-art survey of the local Universe, bringing together data from the latest generation of survey facilities.
- Spectroscopy from AAT/AAOmega
- 5 regions, ~250 deg^2, ~250K galaxies to r < 19.8 mag + K-band selection
- Science goal: study of structure on 1 kpc – 1 Mpc scales
  - CDM halo mass function of groups and clusters from group velocity dispersion
  - Galaxy stellar mass function to Magellanic Cloud masses
  - Merger rate as a function of mass and mass ratio
  - Properties of galaxy components

GAMA facilities



GAMA team and structure

WORKING GROUPS AND HEADS

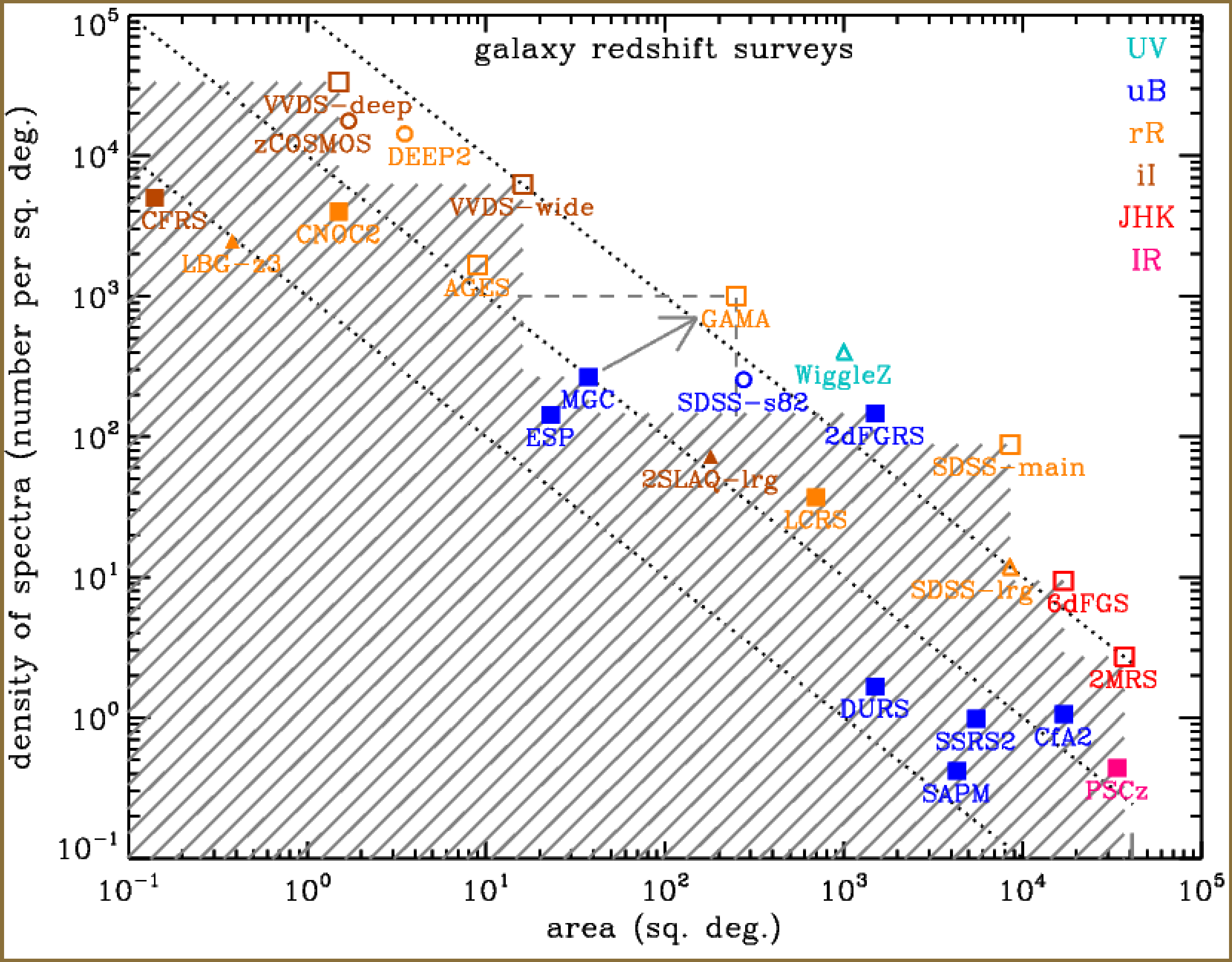
SCIENCE	CATS	DATABASE	OBS	MOCKS	RADIO	SPEC. PIPE.	IMAGE. PIPE.
Peacock	Baldry	Liske	Driver	Norberg	Hopkins	Loveday	Bamford
(ROE)	(LJMU)	(ESO)	(St And)	(ROE)	(USyd)	(Sussex)	(Portsmouth)

TEAM MEMBERS

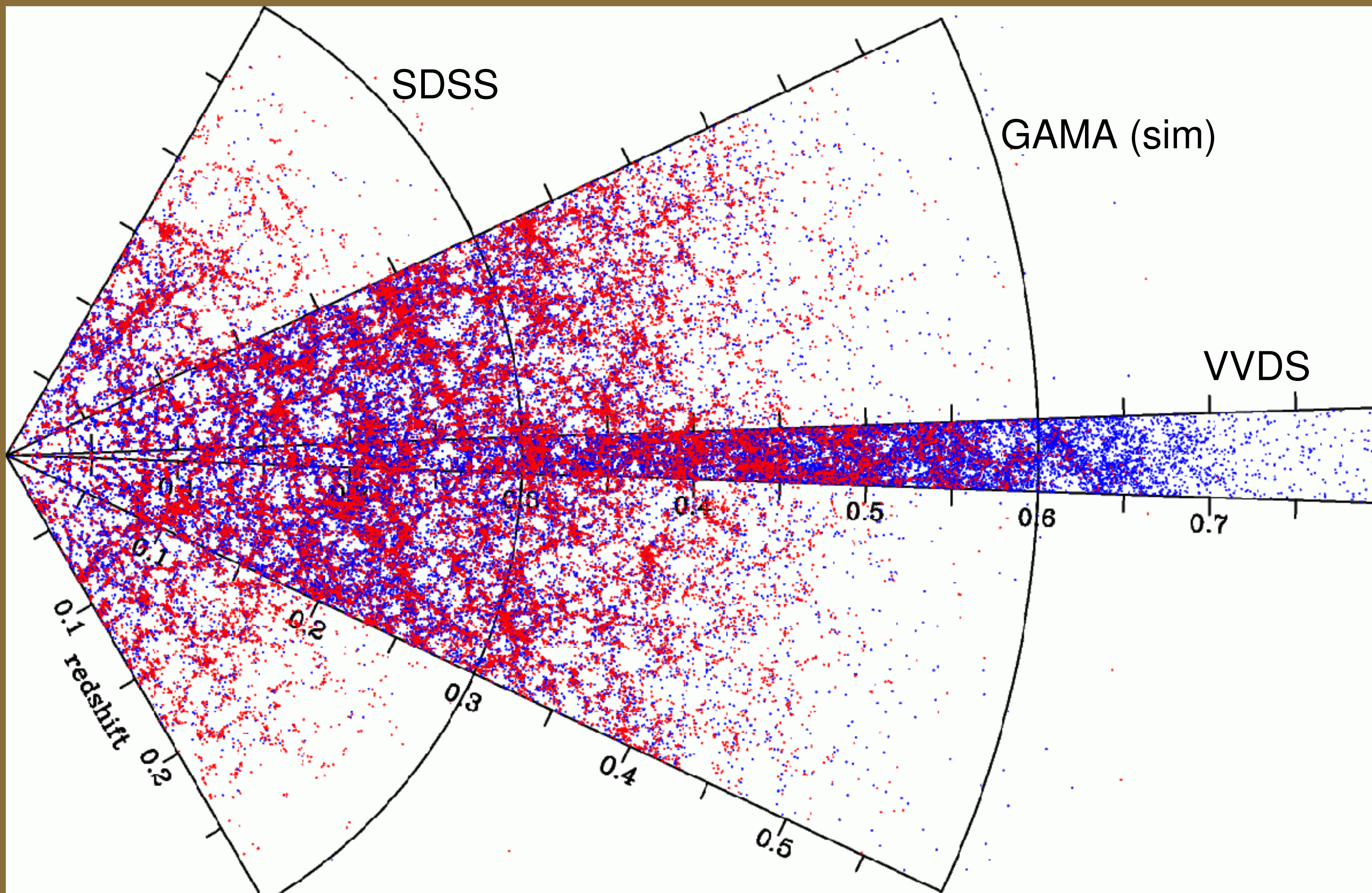
Bland-Hawthorn (USyd)	Cameron (St Andrews)	Conselice (Nottingham)
Couch (Swinburne)	Croom (U.Syd)	Cross (ROE)
Eales (Cardiff)	Edmondson (Portsmouth)	Ellis (AAO)
Frenk (Durham)	Graham (Swinburne)	Hill (St Andrews)
Jones (AAO)	van Kampen (Salzburg)	Kuijken (Leiden)
Lahav (UCL)	Nichol (Portsmouth)	Oliver (Sussex)
Parkinson (ROE)	Phillipps (Bristol)	Popescu (UCLan)
Prescott (LJMU)	Proctor (Swinburne)	Sharp (AAO)
Staveley-Smith (UWA)	Sutherland (Camb.)	Tuffs (MPIA)
Quinn (UWA)	Warren (Imperial)	3 PDRAs pending

AFFILIATED CONSORTIA

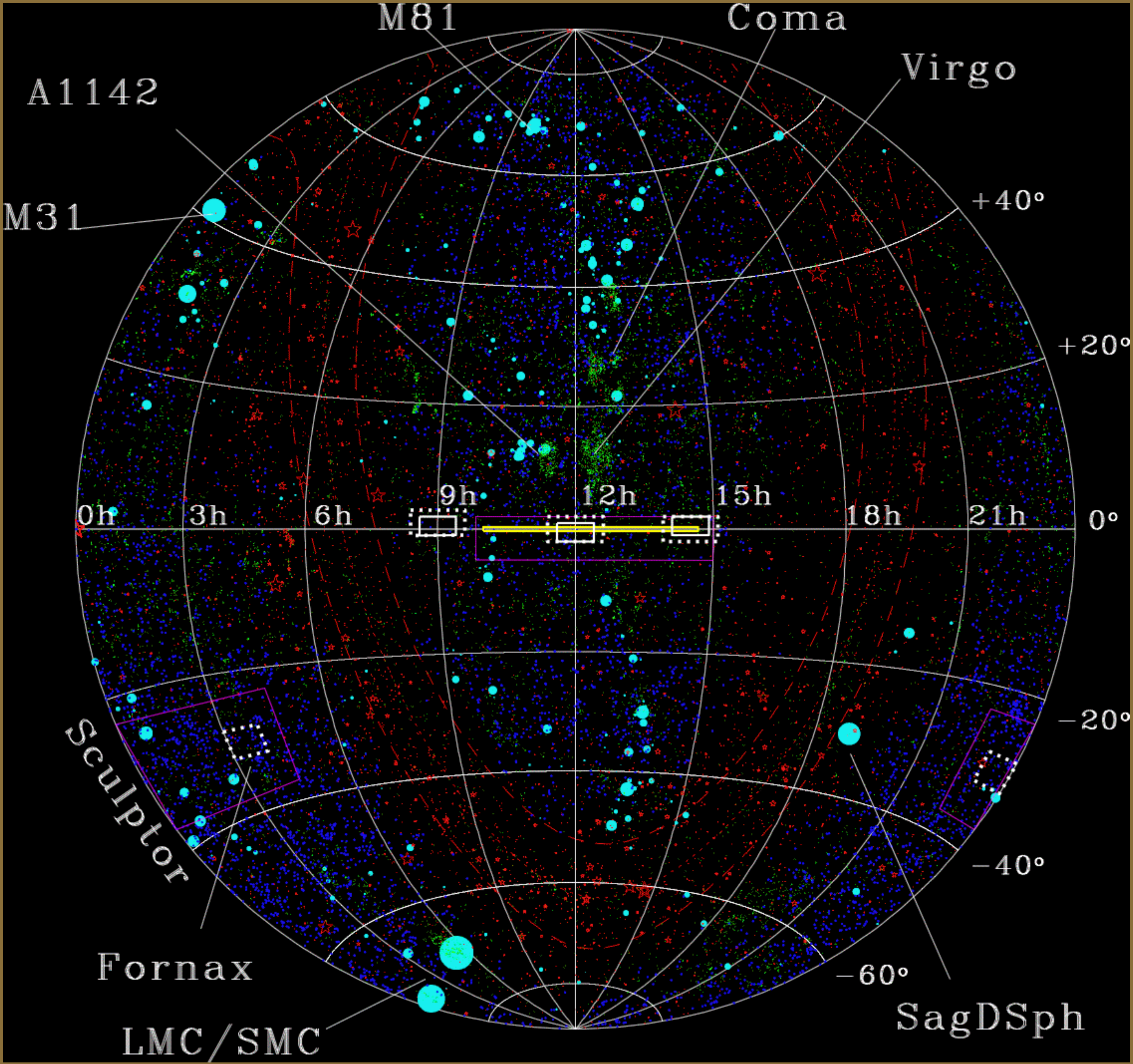
GAMA in comparison



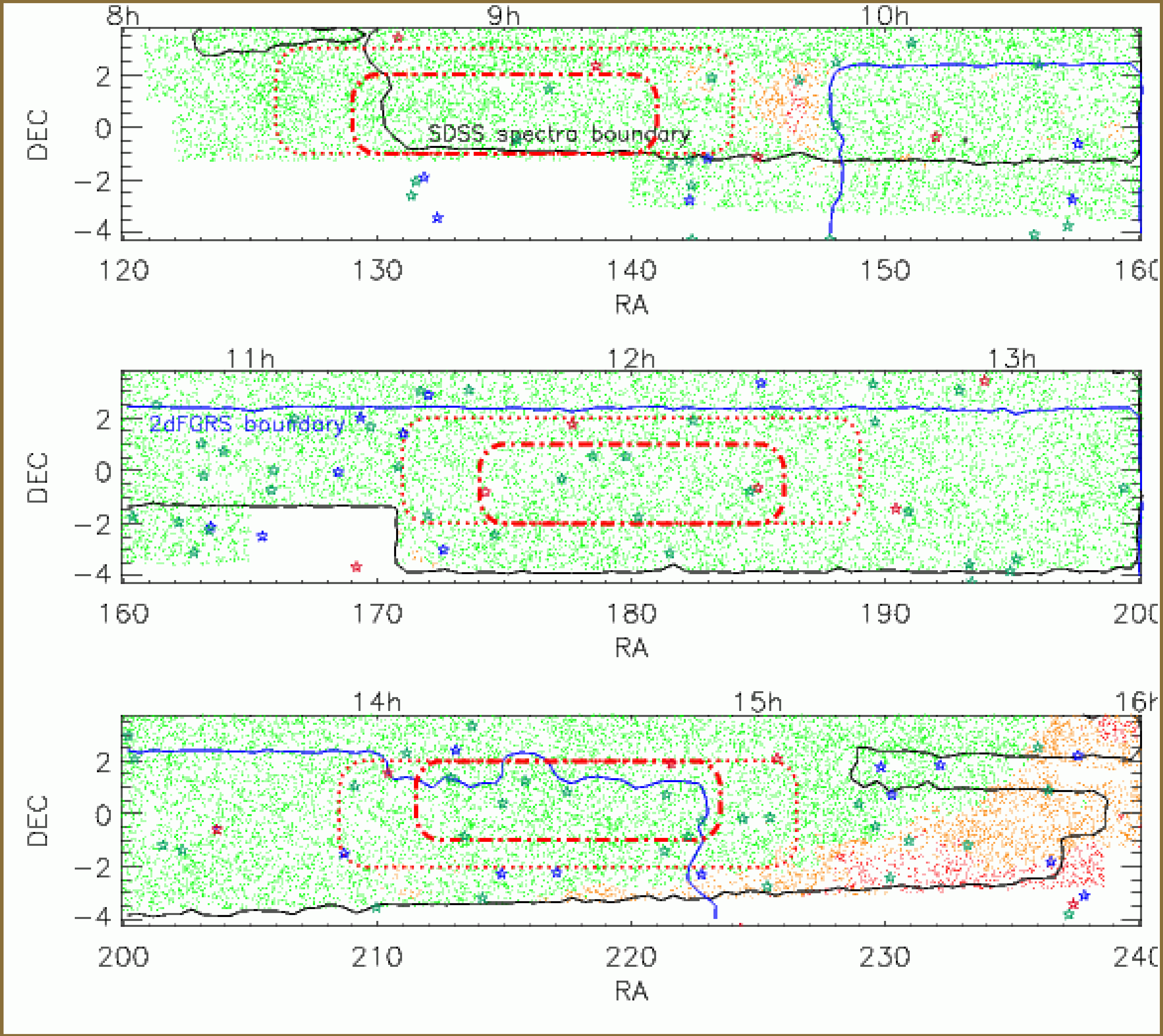
GAMA in comparison



GAMA survey regions



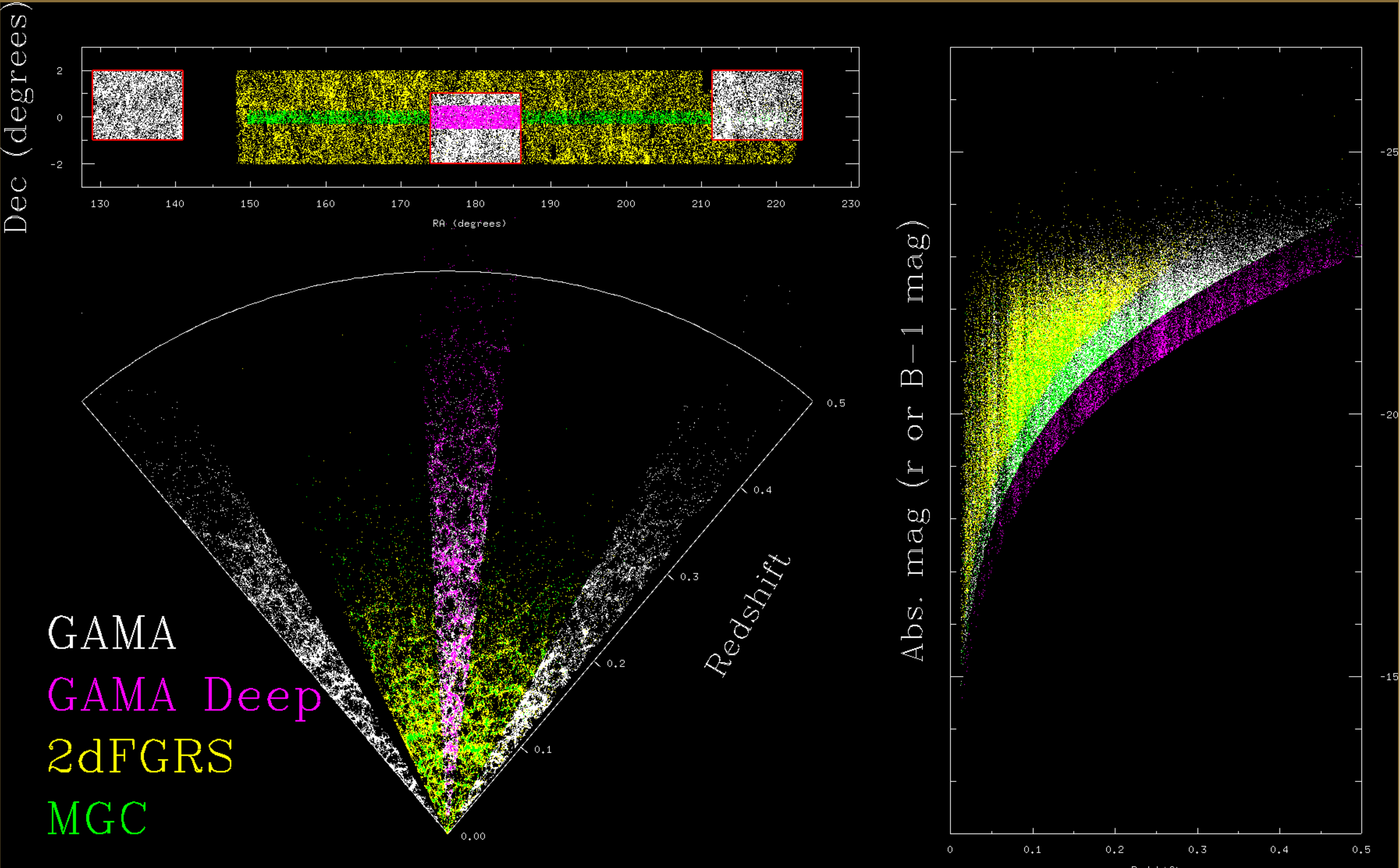
GAMA survey regions



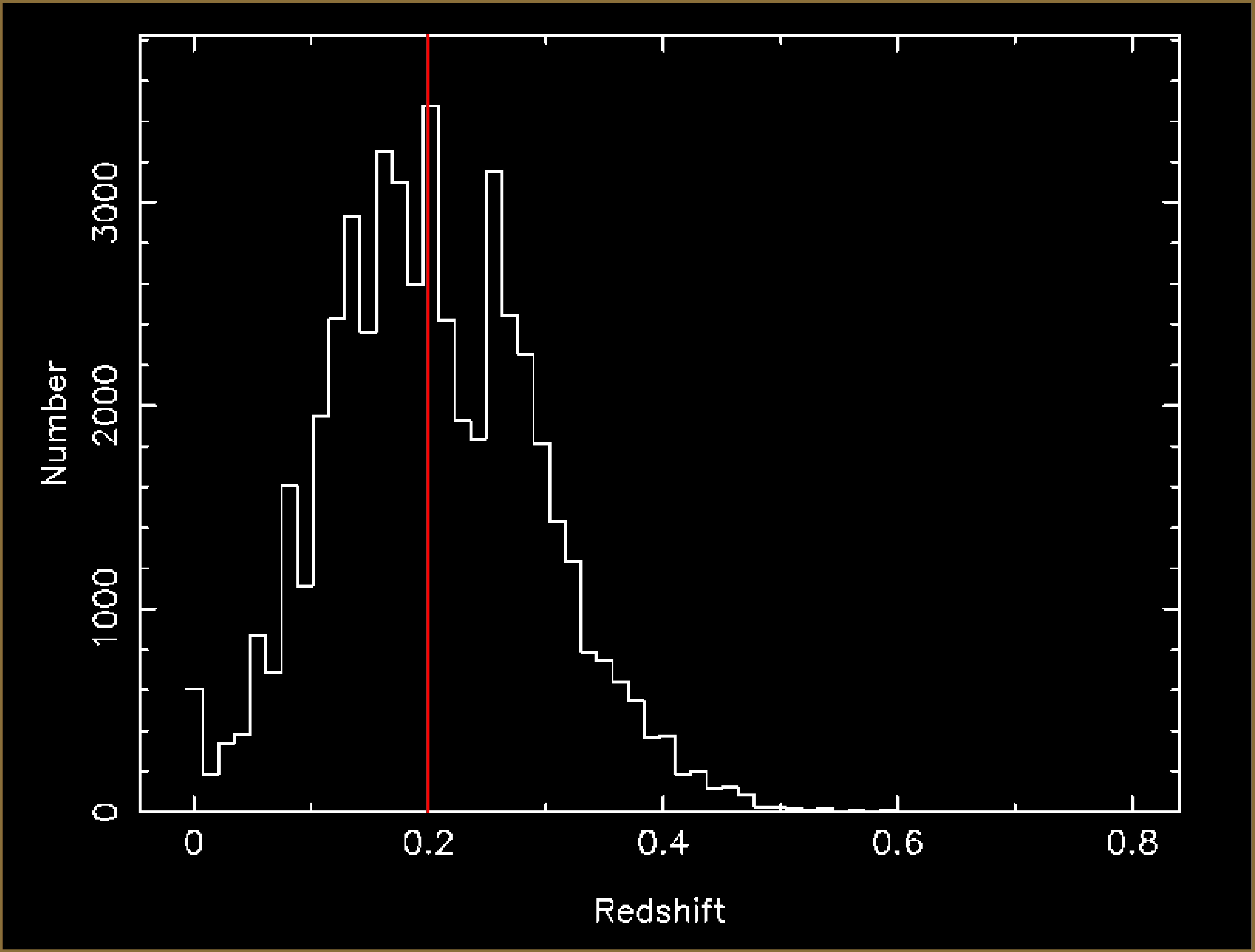
Survey progress

- 66 nights allocated over 3 years (~1/2 of the nights required)
- 21/22 clear nights in March-April 2008
- 50-75 min exposures in dark/grey time
- 159 fields observed → all 3 GAMA I regions covered almost entirely at least once to variable depths (including a deep strip to $r < 19.8$ mag)
- All data reduced and redshifted
- 50,746 good quality redshifts at 96.6% (!) completeness

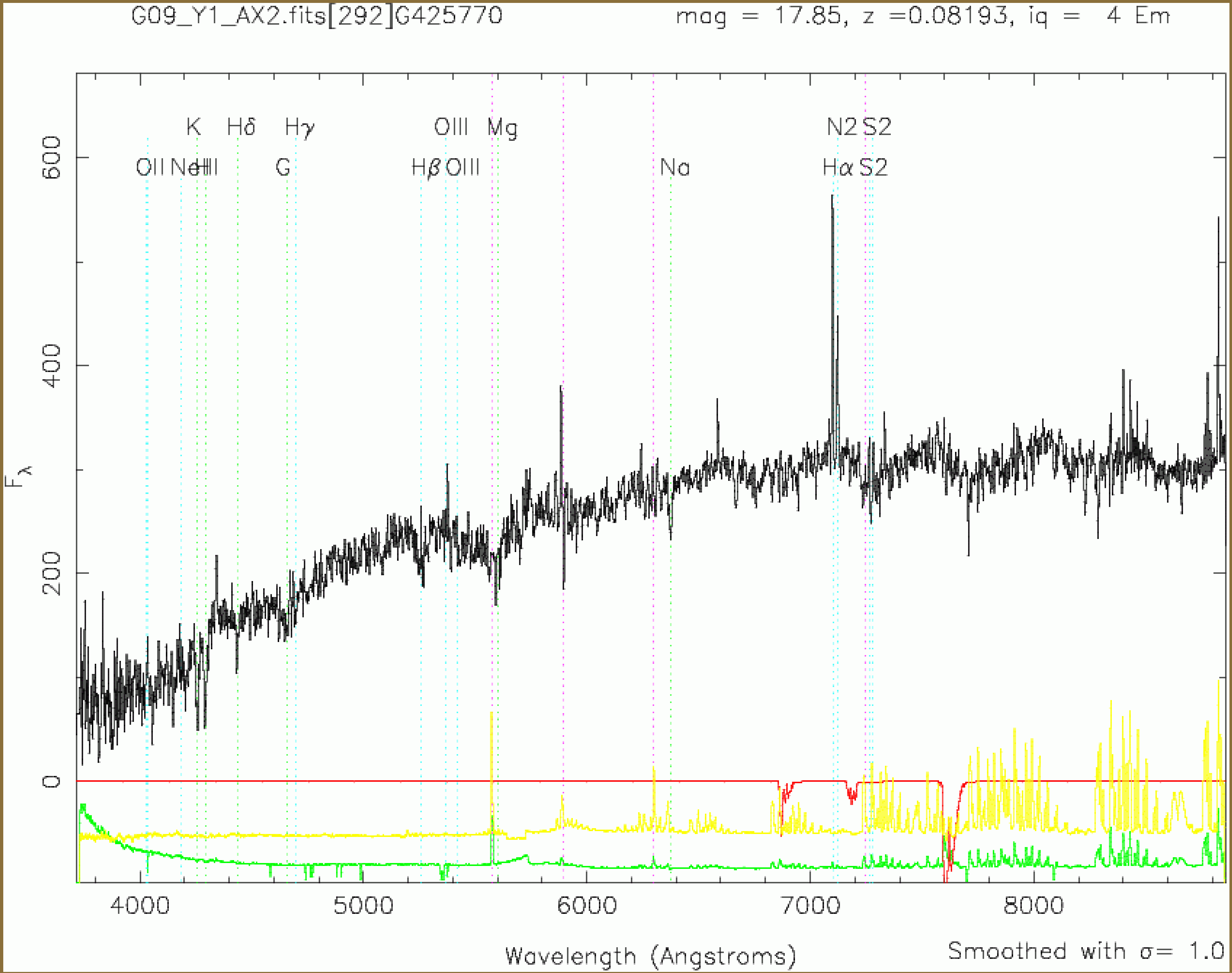
GAMA redshift cone



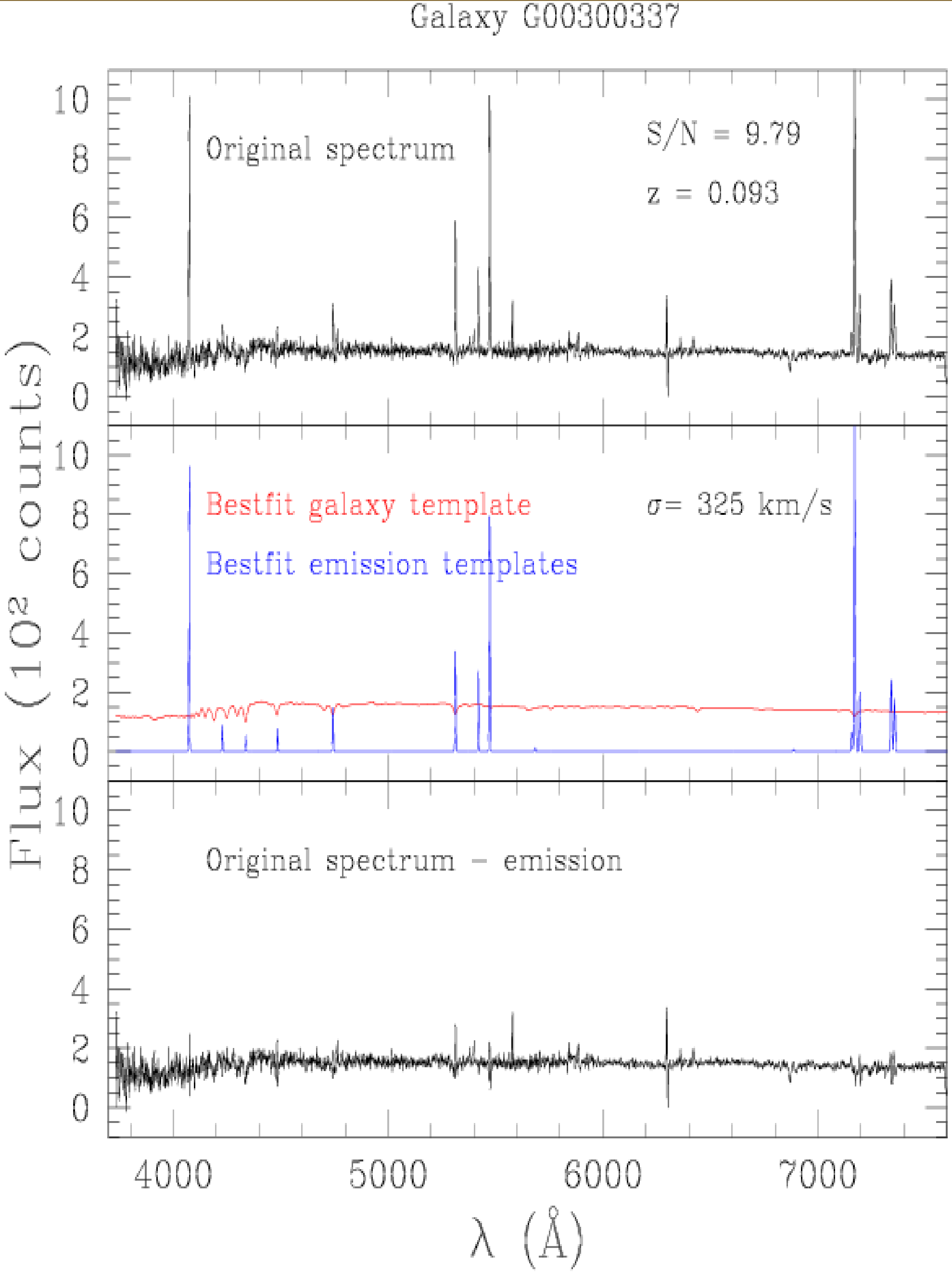
GAMA redshift distribution

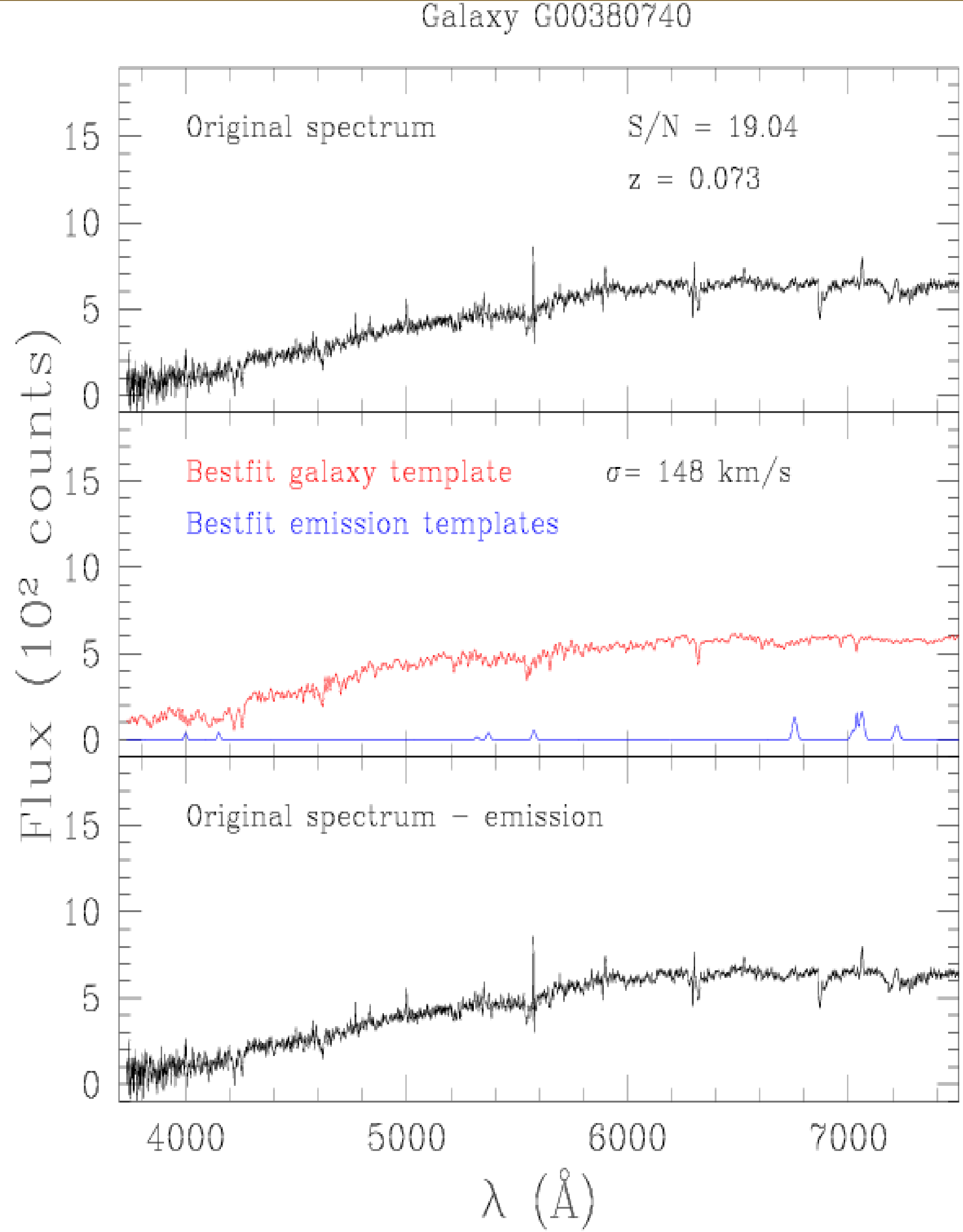


GAMA example spectra

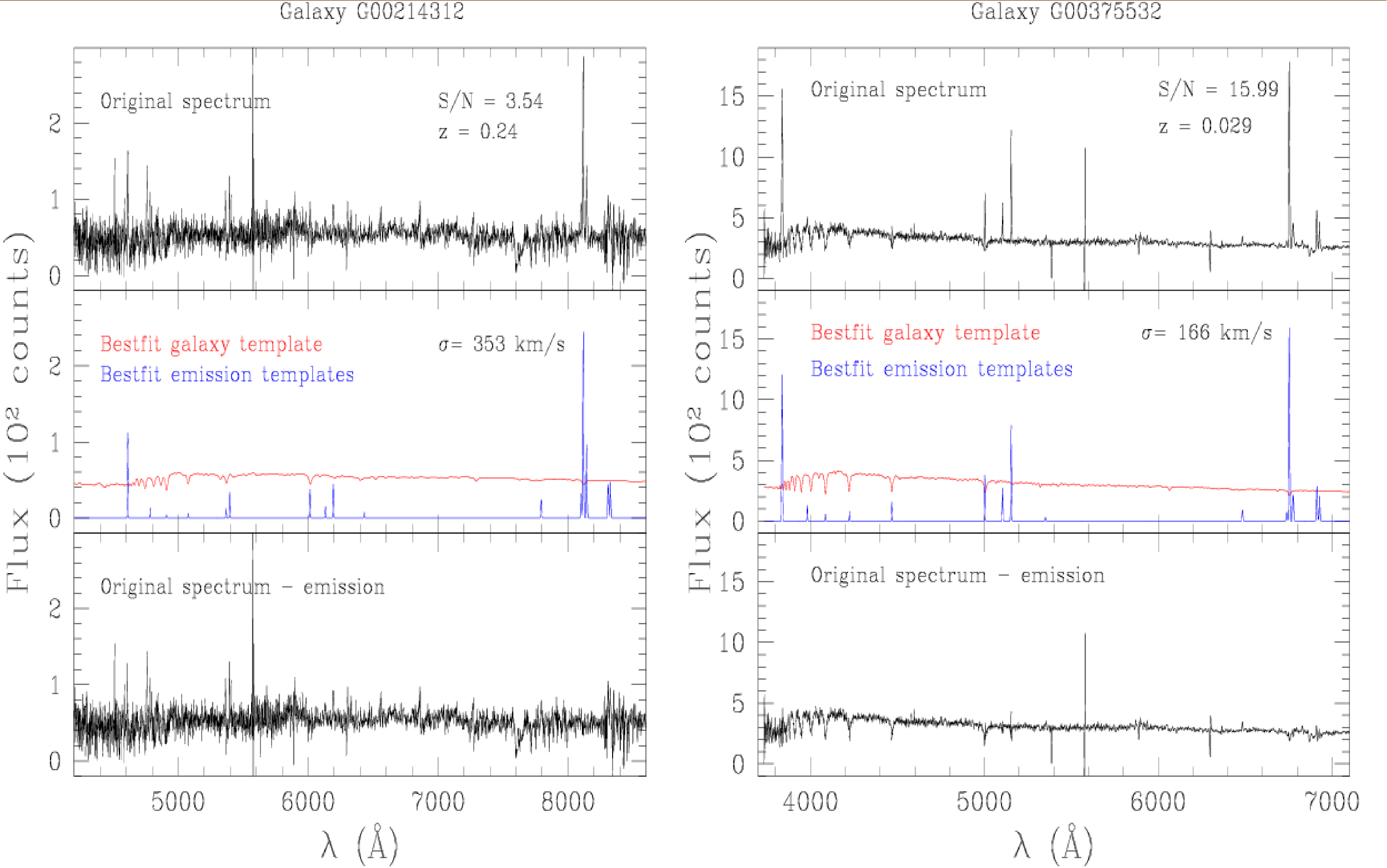


GAMA example spectra

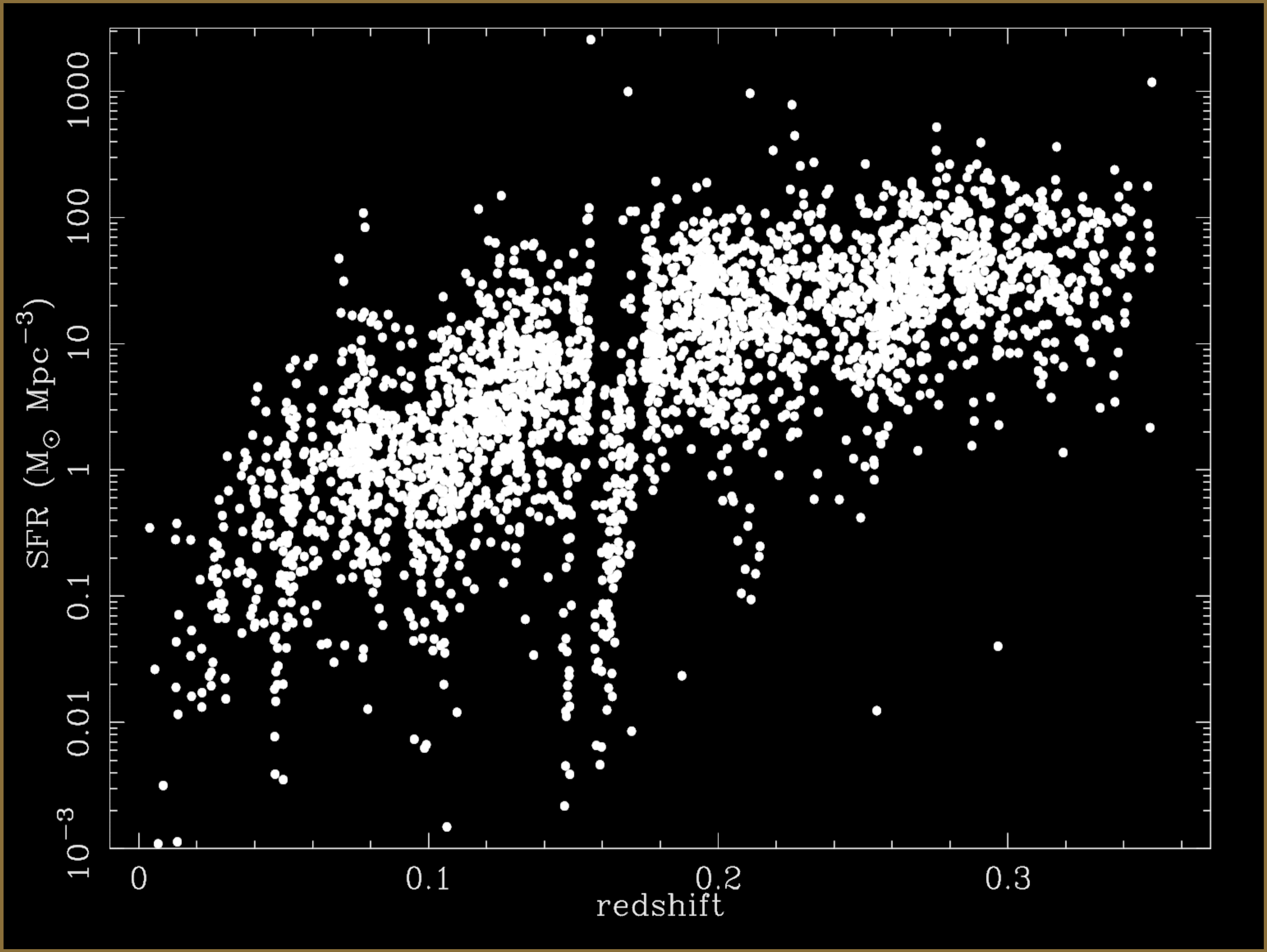




GAMA example spectra

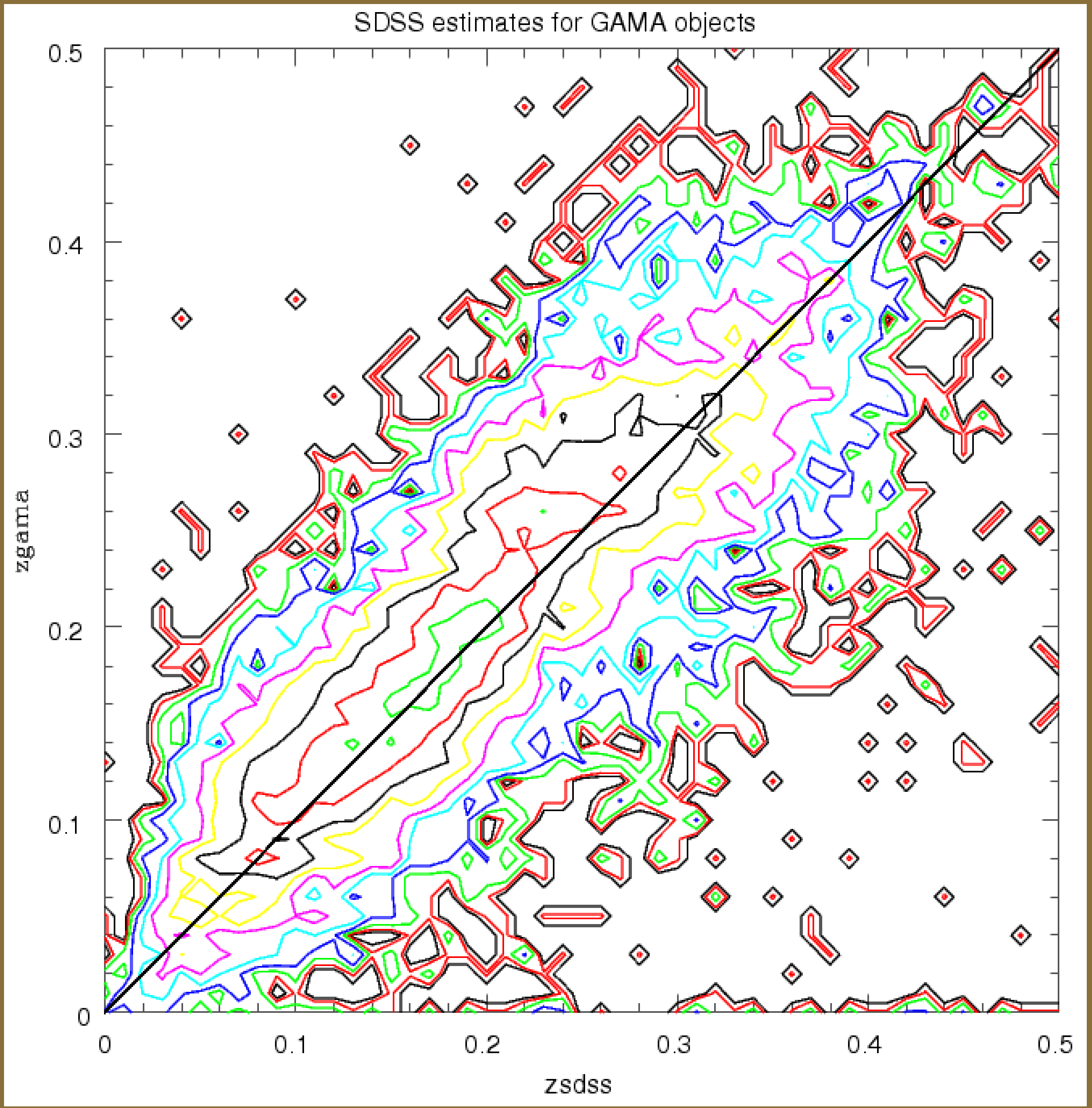


Quick-look science: SFR vs z

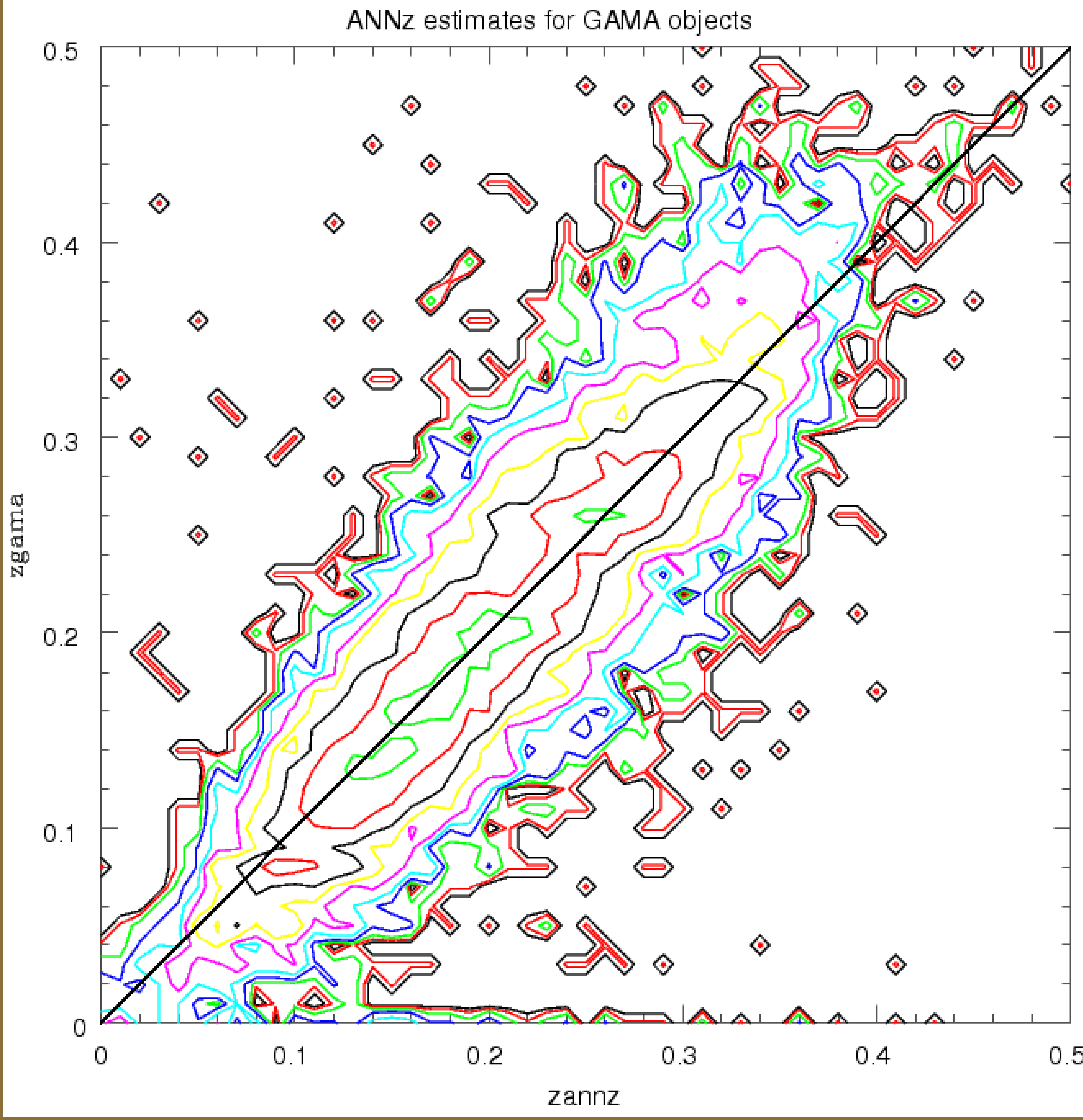


Quick-look science: colour bimodality vs z

Quick-look science: photo-z improvement



Quick-look science: photo-z improvement



Conclusions

- The distinction between galaxy disks and spheroids contains most of the variance of the galaxy population as a whole.
- The decomposition of galaxies from large, complete samples into their main stellar components provides a crucial tool for isolating, identifying and studying different formation and evolutionary mechanisms.
- Studying the evolution of disks and bulges [can | may be necessary to] discriminate between competing formation scenarios.
- Significant progress is imminent: VST, VISTA and HST will provide the data to construct x20 larger, x2 higher resolution, multi-wavelength databases of disk and bulge properties.

→ New technology enabling the birth of a new research area:
Survey-style quantitative morphology and ~~galaxy~~ bulge/disk evolution.