

Deconstructing Galaxies

Why we need surveys of galactic components

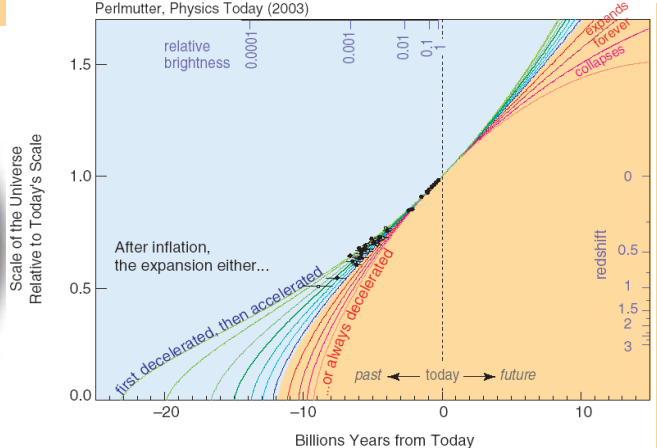
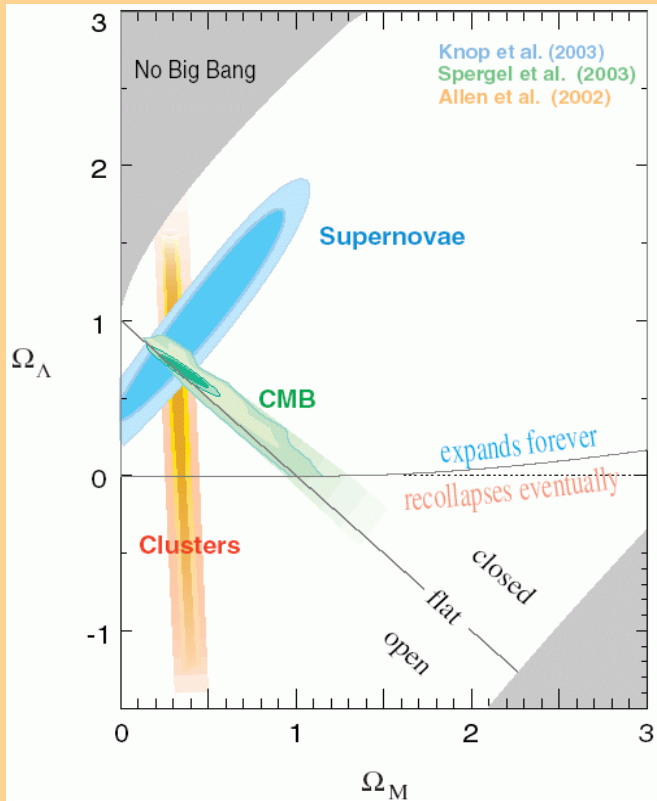
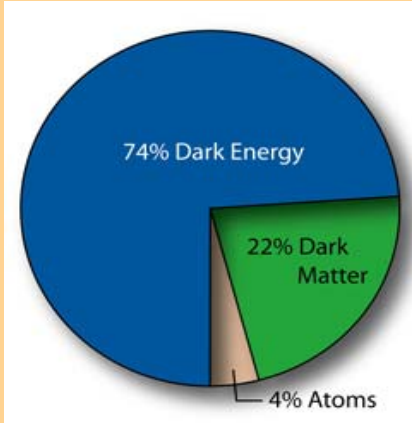
Jochen Liske



The cosmological framework

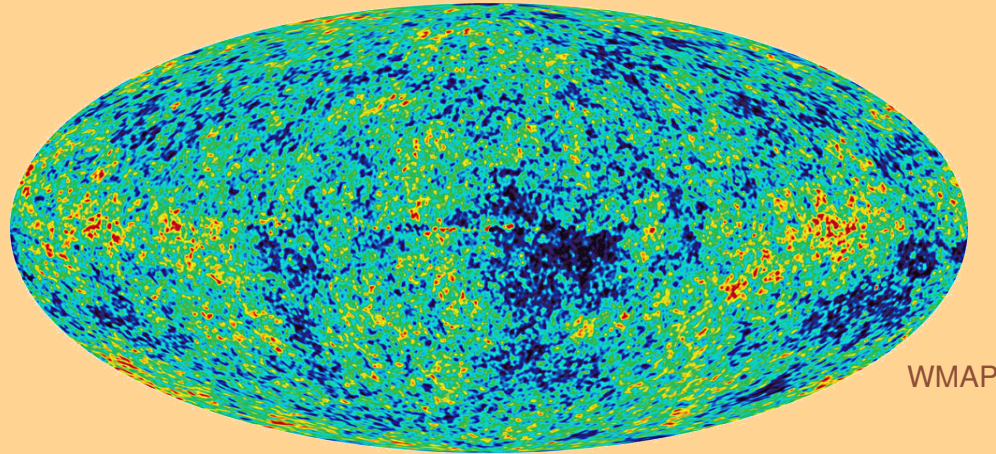
- Observations of the CMB, SNIa, large scale structure, weak lensing, D/H, BAO, abundance of clusters, etc, are all found to be consistent (to the level of accuracy so far probed) with one another and with Λ CDM.
- ➔ The cosmological background model is now known ($\pm 10\%$)!
- Although the model is 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.**

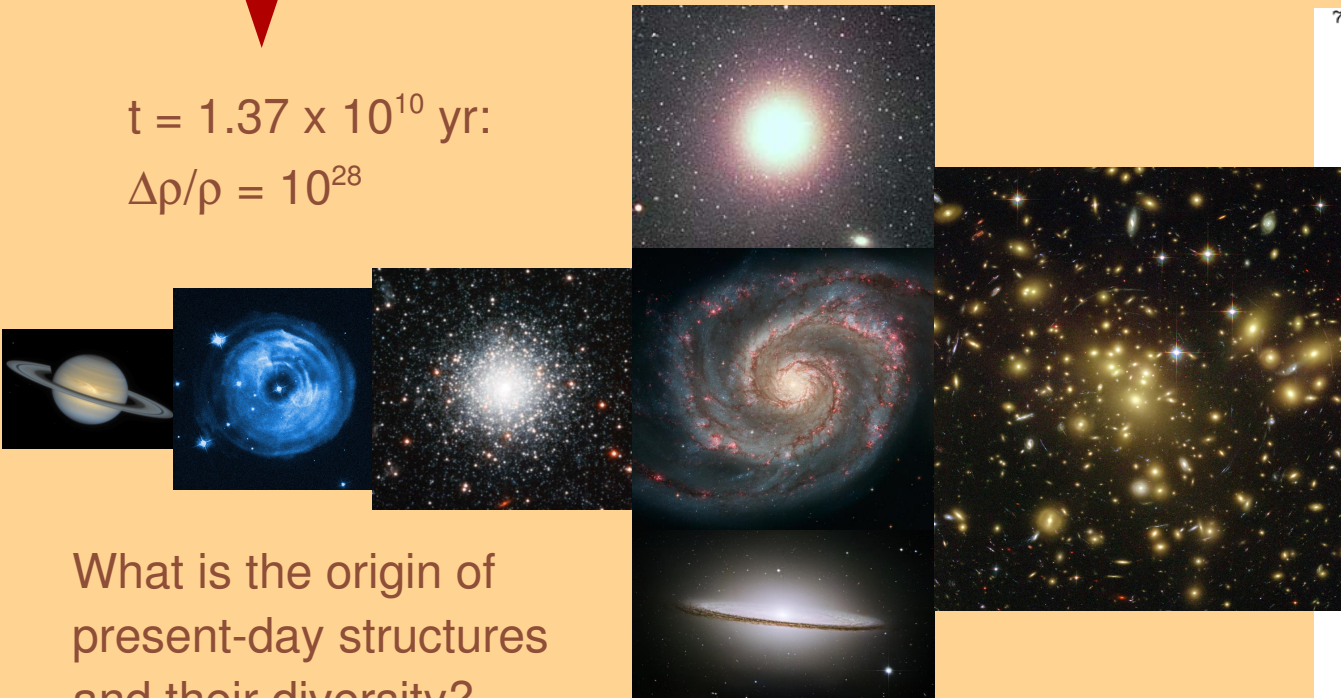


Structure formation

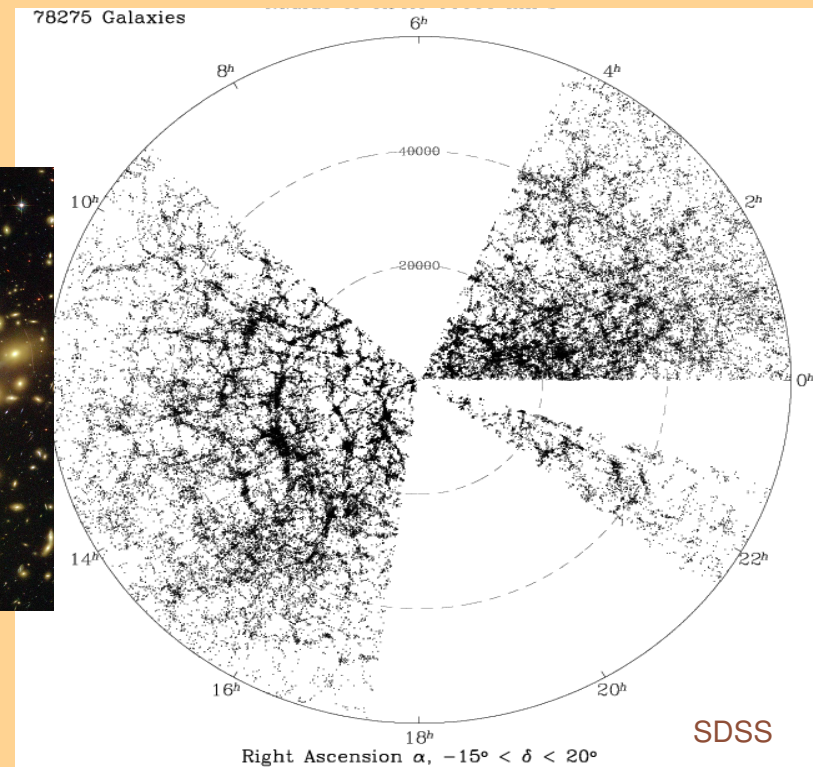
$t = 4 \times 10^5 \text{ yr:}$
 $\Delta\rho/\rho = 10^{-5}$



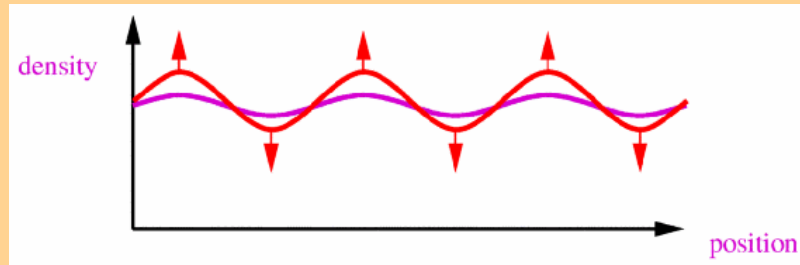
$t = 1.37 \times 10^{10} \text{ yr:}$
 $\Delta\rho/\rho = 10^{28}$



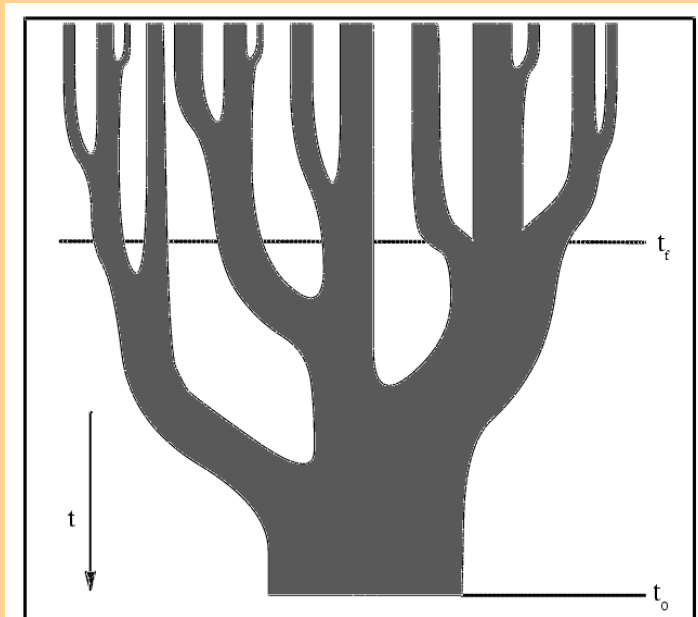
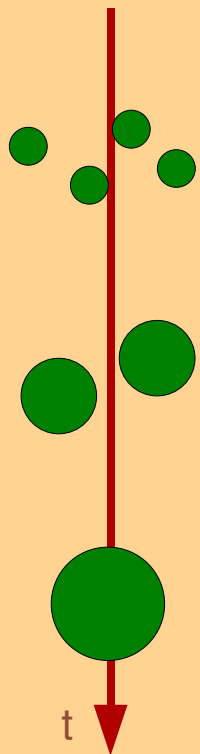
What is the origin of present-day structures and their diversity?



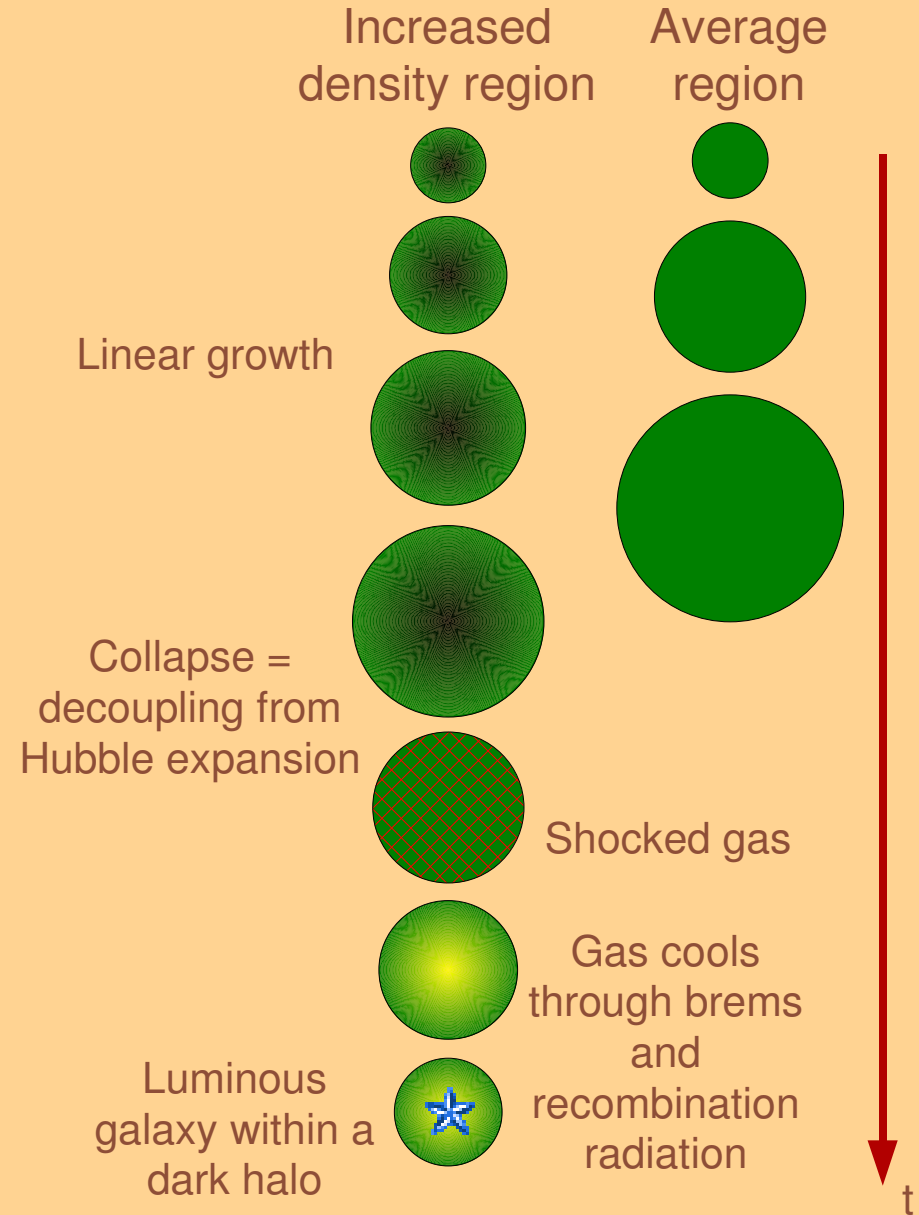
Gravitational instability and hierarchichal build-up



Initial density perturbations grow through gravitational attraction.



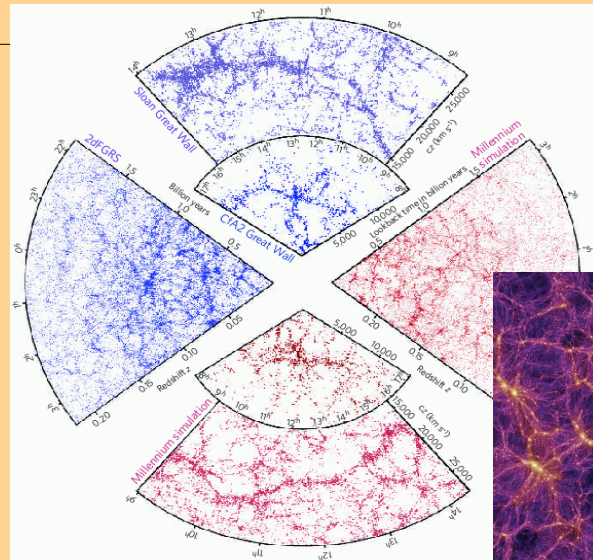
Hierarchical merging of smaller structures to form larger ones.



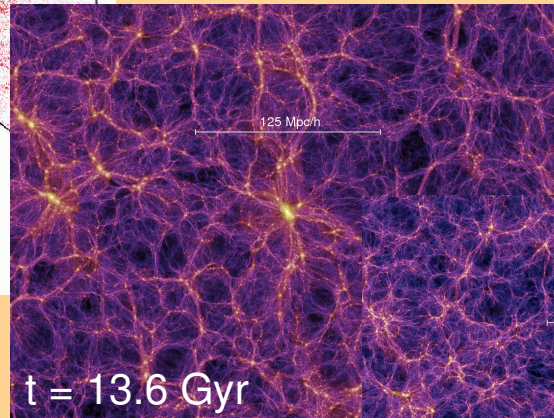
Structure formation

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

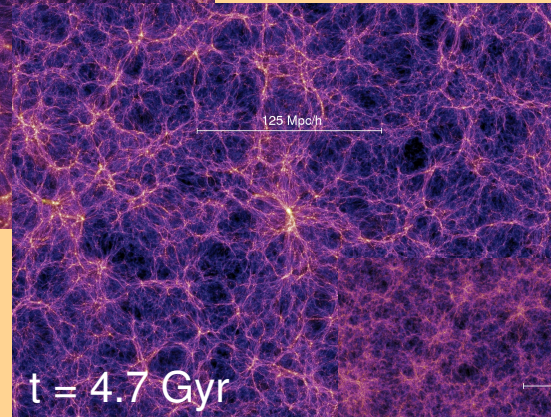
Hydrodynamics of baryons: can be included approximately → excellent reproduction of IGM properties. Problem: gas collapses to very high densities resulting in short timescales → cosmological simulations that resolve collapsed objects require an enormous dynamic range.



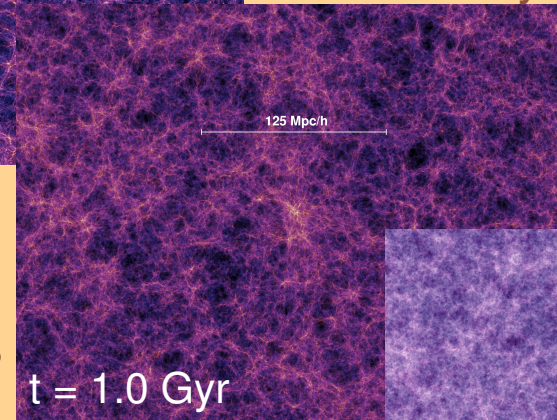
Springel et al. (2006)



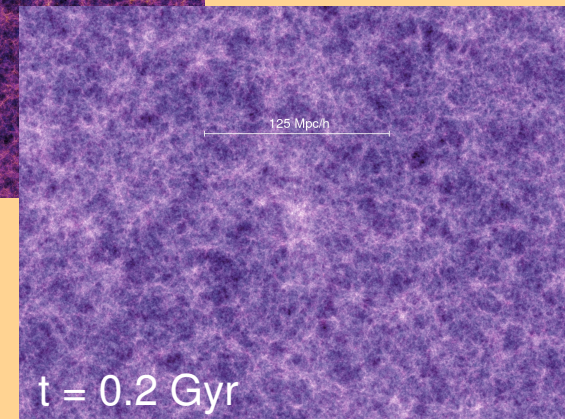
t = 13.6 Gyr



t = 4.7 Gyr

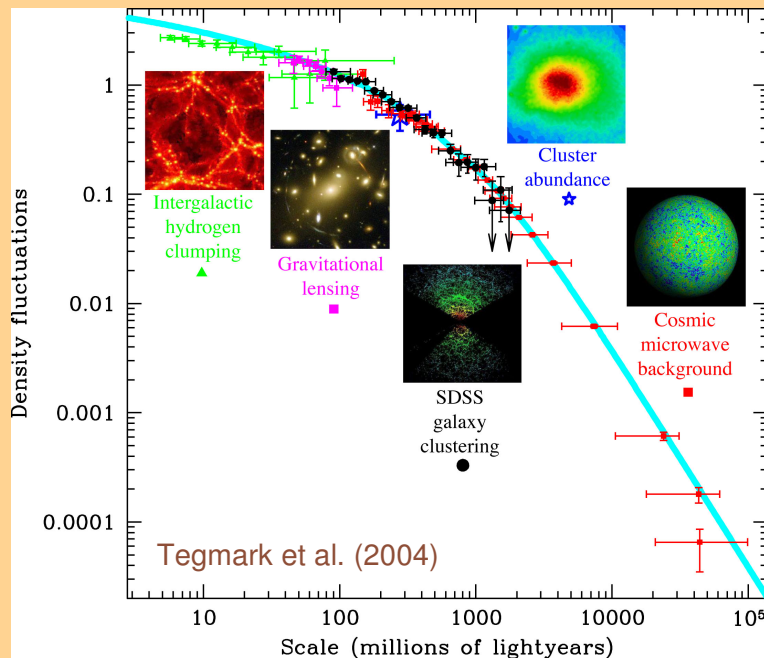


t = 1.0 Gyr



t = 0.2 Gyr

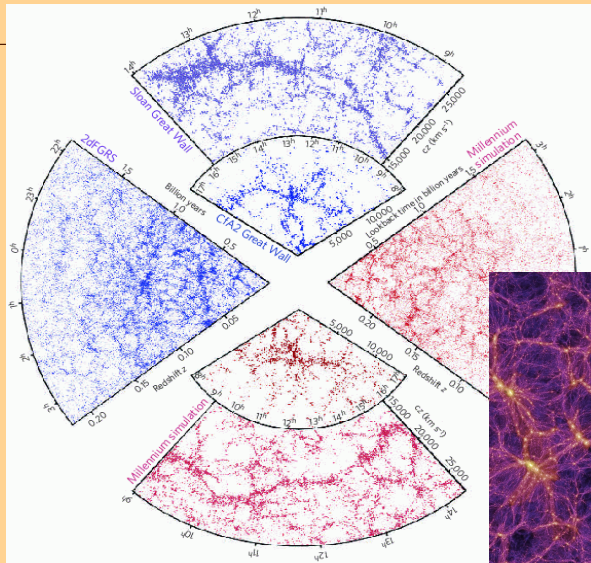
Makeshift solution: semi-analytical models = combination of the hierarchical structure formation process of CDM halos from simulations with analytical 'recipes' describing the physics of the baryons.



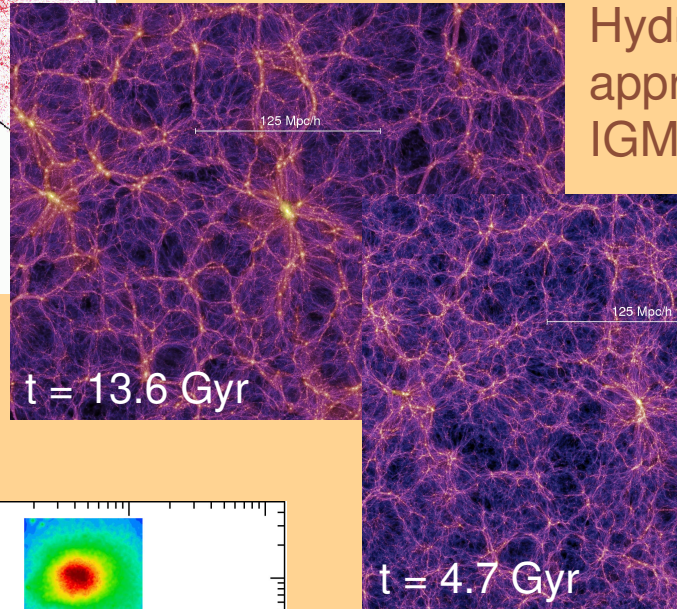
Tegmark et al. (2004)

Structure formation

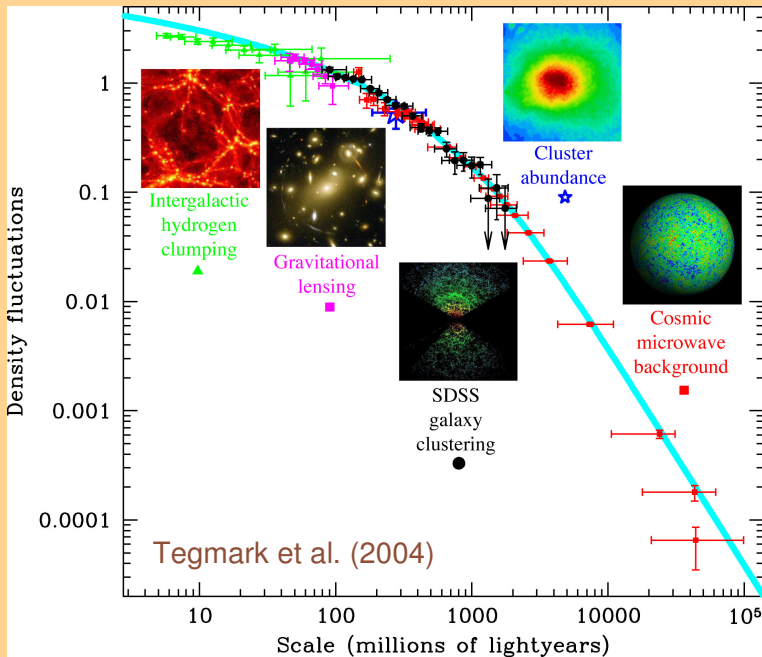
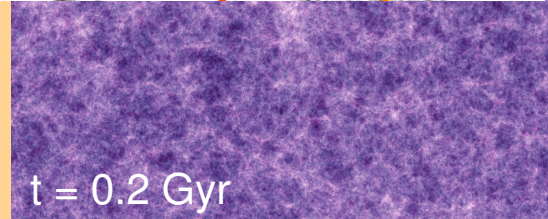
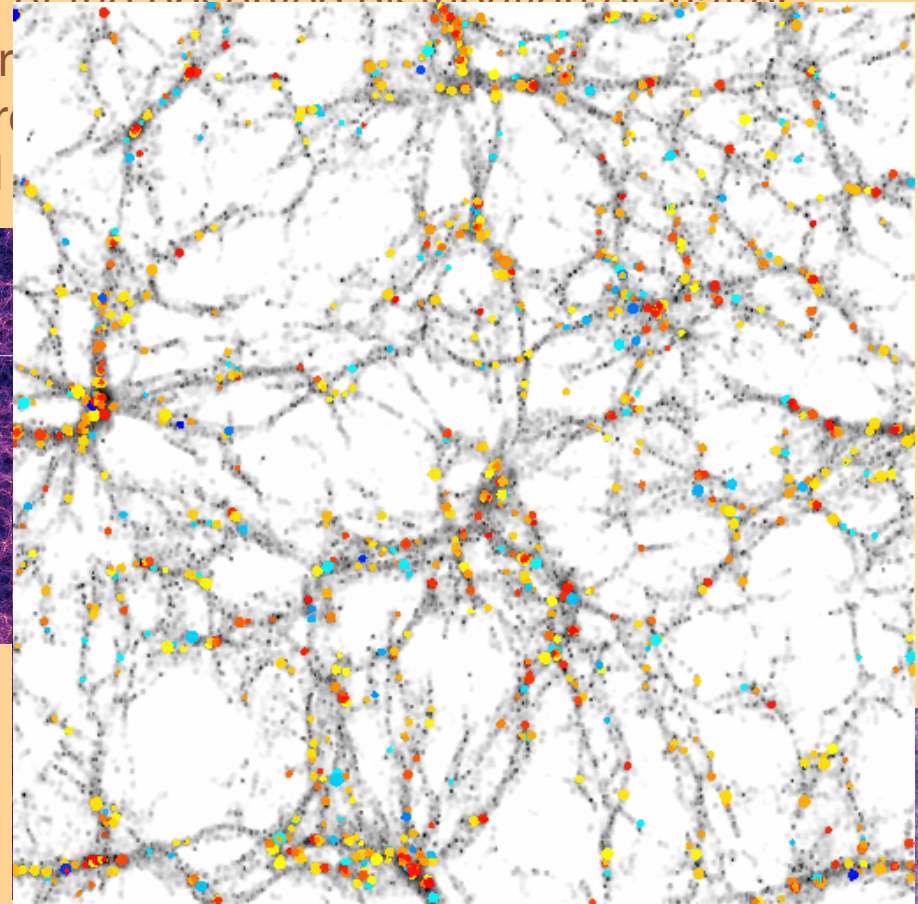
CDM simulations: numerical solution of the coupled Boltzmann and Poisson equations through discretization as N-body system
 → excellent reproduction of the observed distribution of matter



Springel et al. (2006)

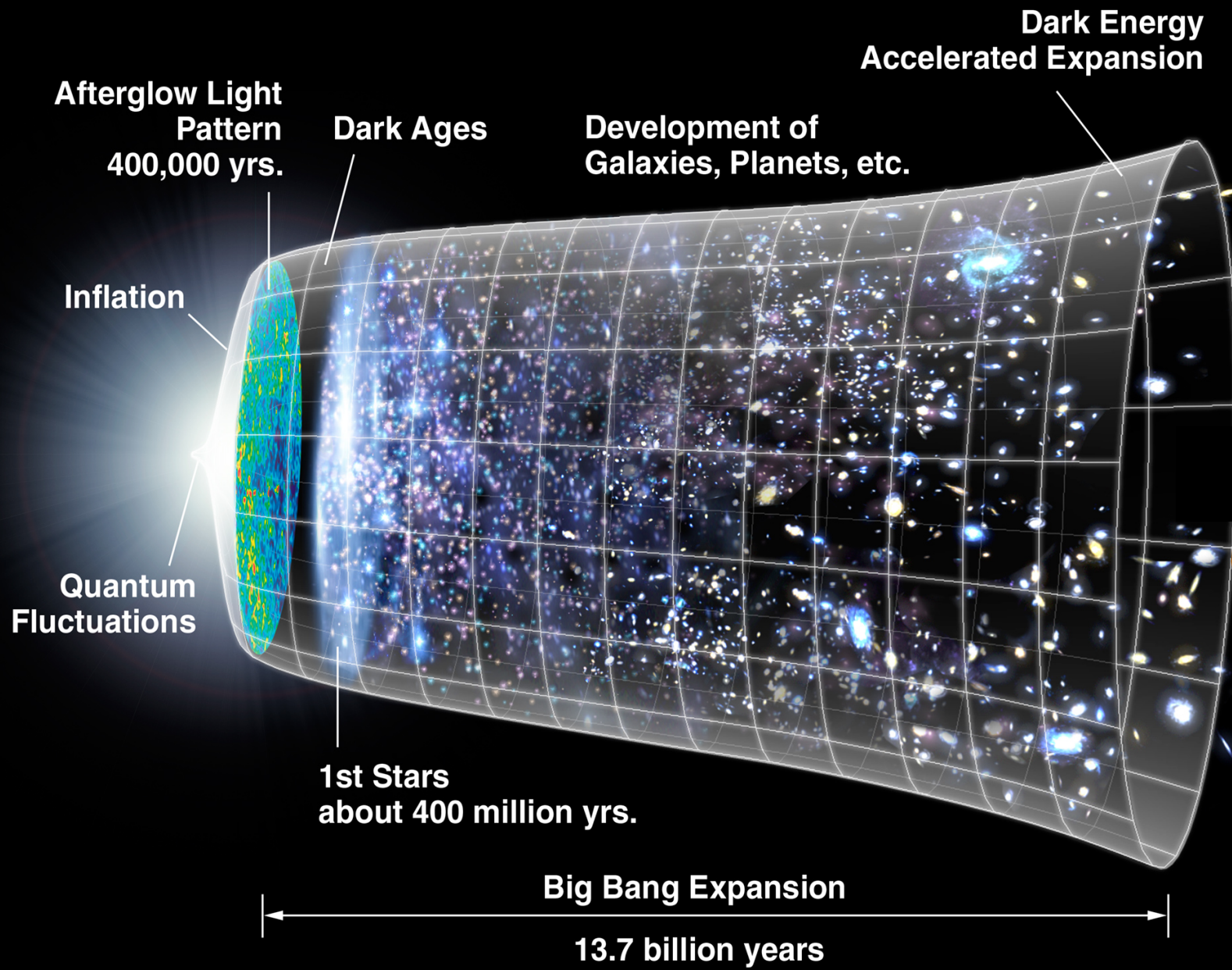


Hydro approximation
IGM



Tegmark et al. (2004)

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.



Dark Energy Accelerated Expansion

Structure of the MVV pricing system?

Für eine einzelne Fahrt: Die Einzelfahrkarten

Für eine Person und eine Fahrt in Richtung auf das Fahrzeug Umsteigen und Fahrzeugbrüche erlaubt, Rück- und Rundfahrten nicht erlaubt. Höchstfahrzeiten: Kursstrecke 1 Stunde, 1 Zone 3 Stunden, ab 2 Zonen 4 Stunden; Einzelfahrkarte für Kinder ebenfalls 4 Stunden

Mitnahme von Handgepäck, Kinderwagen und 1 Hund kostenlos

Für Ihre Fahrkarte erforderliche Preisstufe: siehe Tarifplan oder Fahrzeilverzeichnis an den Automaten, übrige Felder:

Preis:	Kursstrecke	1 Zone	2 Zonen	3 Zonen	ab 4 Zonen
Erwachsene Barzahlung	1,10	2,20	4,40	6,60	8,80
Erwachsene mit Cashless	1,05	2,10	4,20	6,30	8,40
Kinder (6-14 Jahre) Barzahlung	entsprechend 1/2				
Kinder (6-14 Jahre) mit Cashless	entsprechend 1/2				

Kaufmöglichkeiten: MVV-Verkaufsstellen und Automaten
Zahlungsmittel: siehe Anzeige am Automaten
Fahrkarte vor Fahrtantritt erwarten, ausgenommen aus Bus- und Tramfahrplänen

Für mehrere Fahrten: Die Streifenkarten

Für mehrere Fahrten einer oder mehrerer Personen in Richtung auf ein Fahrzeug Umsteigen und Fahrzeugbrüche erlaubt, Rück- und Rundfahrten nicht erlaubt. Höchstfahrzeiten: Kursstrecke 1 Stunde, 1 Zone 3 Stunden, ab 2 Zonen 4 Stunden; Streifenkarte für Kinder ebenfalls 4 Stunden

Mitnahme von Handgepäck, Kinderwagen und 1 Hund kostenlos

Für Ihre jeweiligen Fahrkarte eine Person zu entwerdende Streifenzahl:

Erwachsene: siehe Tarifplan oder Fahrzeilverzeichnis an Automaten, übrige Felder: Jugendliche (15-20 Jahre): Kursstrecke 1 Streifen, sonst 1/2 Streifen; Erwachsene (21-25 Jahre): Kursstrecke 1 Streifen, sonst 1/2 Streifen; Kinder (6-14 Jahre): Kursstrecke 1 Streifen

Streifenzahl	Kursstrecke	1 Zone	2 Zonen	3 Zonen	ab 4 Zonen
10er-Streifenkarte für Kinder (6-14 Jahre)	10,50 €	1 Streifen	2 Streifen	4 Streifen	8 Streifen
10er-Streifenkarte für Kinder (6-14 Jahre)	5,20 €	entsprechend 1/2			

Kaufmöglichkeiten: MVV-Verkaufsstellen und Automaten
Zahlungsmittel: siehe Anzeige am Automaten
Fahrkarte vor Fahrtantritt erwarten

Für beliebig viele Fahrten: Die Tageskarten

Single-Tageskarte für 1 Erwachsene, Tageskarte für Kinder (6-14 Jahre) oder Partner-Tagekarte für bis zu 5 Erwachsene oder 10 Kinder (6-14 Jahre, bei Schulfahrten Kinder bis 9. Klasse bei beliebig vielen Fahrten im geschlossenen Geltungsbereich, gültig vom Zeitpunkt der Entwertung bis zum Ende des Tages einschließlich spätester 24 Stunden) (siehe Tarifplan)

Mitnahme von Handgepäck, Kinderwagen und 1 Hund kostenlos

Für Ihre Fahrkarte erforderliche Geltungsbereich: siehe Tarifplan oder Fahrzeilverzeichnis an den Automaten, übrige Felder:

Preise	Innen- oder Außenbereich	München XXL	Gesamtnetz	3 Tage Innenraum
Single-Tageskarte	5,00	6,70	10,00	12,30
Partner-Tageskarte	9,00	11,80	18,00	21,00
Kinder-Tageskarte (6-14 Jahre)	-	-	2,40	-

Kaufmöglichkeiten: MVV-Verkaufsstellen und Automaten
Zahlungsmittel: siehe Anzeige am Automaten
Fahrkarte vor Fahrtantritt erwarten, ausgenommen aus Bus- und Tramfahrplänen

Für beliebig viele Fahrten: Die IsarCard

Für beliebig viele Fahrten während einer Kalenderwoche oder einem Kalendermonat in den gewählten Ringen

Mitnahme von Handgepäck, Kinderwagen und 1 Hund kostenlos. Mitnahme von max. drei Kindern (6-14 Jahre, zur Familie gehörende Kinder, Einzelkinder in unbeschränkter Anzahl) an Sa., So. und Feiertagen gratis, Mo. Fr. ab 9:00 Uhr kostenlos. Für Ihre Fahrkarte erforderliche Ringe: siehe Tarifplan

Preise:

Kosten	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Wochen	11,00	13,00	15,00	18,00	20,00	23,00	25,00	28,00	30,00	33,00	35,00	38,00	40,00	43,00	45,00	48,00
Monat	40,10	45,00	50,00	55,00	60,00	65,00	70,00	75,00	80,00	85,00	90,00	95,00	100,00	105,00	110,00	115,00

Kaufmöglichkeiten: MVV-Verkaufsstellen und Automaten an Haltestellen, auch über den Internet-Shop (10 Monate bezahlen, 12 Monate fahren) oder jährlich
Zahlungsmittel: siehe Anzeige am Automaten
Keine Entwertung erforderlich

Gesamtnetz

Tarifplan

So erhalten Sie die richtige Preisstufe:

Einzelfahrkarten und Streifenkarten

Erwachsene: Anzahl der bezahlten Zonen von Start bis Zielhaltestelle (siehe Tarifplan). Zonen, die nach dem Zielhaltestellenbereich befahren werden, sind erneut zu zahlen (insgesamt 4 Zonen)

Kinder (6-14 Jahre): Jede Fahrt bis zur 4. Haltestelle nach dem Ziel, danach über höchstens 2 Haltestellen mit 3 oder 10 bis 8 h.h. Umsteigen erlaubt. Im Regionalverkehr: jeder halbe München zählt als Bus oder als Kurstrecke.

Tageskarten

Geltungsbereich auswählen (siehe Tarifplan):
Innenraum (weiße Zone)
München XXL (weiße und grüne Zone)
Außenraum (grün, gelb und rote Zone)
Gesamtnetz (alle 4 Zonen)

So erhalten Sie die richtige Preisstufe:

Zielkarten

Geltungsbereich (Ringe 1-16) auswählen (siehe Tarifplan, Haltestellenverzeichnis im Fahrplänbuch oder im Internet)

Zonen und Ringe:

- Innenraum
- München XXL
- Außenraum

Ringeneinteilung (1-16) gilt nur für Zielkarten

Legende:
— S-Bahn
— U-Bahn
— MVV Regionalbus
— DB-Züge

Realis- oder Privatbus MVV-Fahrten werden anerkannt

IsarCard: Ihre Card Uhr: IsarCard ab 12 Uhr: Je mehr Fahrpläne, desto mehr Geld! IsarCard ab 12 Uhr: Je mehr Fahrpläne, desto mehr Geld! IsarCard ab 12 Uhr: Je mehr Fahrpläne, desto mehr Geld!

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Big Bang Expansion
13.7 billion years

Dark Energy Accelerated Expansion

Structure of the MVV pricing system?

Evidence for non-intelligent design?

Für eine einzelne Fahrt: Die Einzelfahrkarten

Für eine Person und eine Fahrt in Richtung auf das Fahrzeug. Umsteigen und Fahrzeugübertragung erlaubt; Rück- und Rundfahrten nicht erlaubt. Höchstfahrzeiten: Kursstrecke 1 Stunde, 1 Zone 3 Stunden, ab 2 Zonen 4 Stunden; Einzelfahrkarte für Kinder ebenfalls 4 Stunden.

Mitnahme von Handgepäck, Kinderwagen und 1 Hund kostenlos. Für Ihre Fahrkarte erforderliche Preisstufe: siehe Tarifplan oder Fahrzeilverzeichnis an den Automaten, sonstige Felder:

Preise:	Kursstrecke	1 Zone	2 Zonen	3 Zonen	ab 4 Zonen
Erwachsene Barzahlung	1,10	2,20	4,40	6,60	8,80
Erwachsene mit Cashless	1,05	2,10	4,20	6,30	8,40
Kinder (6-14 Jahre) Barzahlung	einheitlich 1,10				
Kinder (6-14 Jahre) mit Cashless	einheitlich 1,04				

Kaufmöglichkeiten: MVV-Verkaufsstellen und Automaten
Zahlungsmittel: siehe Anzeige am Automaten
Fahrkarte vor Fahrtantritt erwarten, ausgenommen aus Bus- und Tramfahrplänen

Für mehrere Fahrten: Die Streifenkarten

Für mehrere Fahrten einer oder mehrerer Personen in Richtung auf ein Fahrzeug. Umsteigen und Fahrzeugübertragung erlaubt; Rück- und Rundfahrten nicht erlaubt. Höchstfahrzeiten: Kursstrecke 1 Stunde, 1 Zone 3 Stunden, ab 2 Zonen 4 Stunden; Streifenkarte für Kinder ebenfalls 4 Stunden.

Mitnahme von Handgepäck, Kinderwagen und 1 Hund kostenlos. Für Ihre jeweiligen Fahrkarte zum Person zu entwerdende Streifenzahl: Erwachsene: siehe Tarifplan oder Fahrzeilverzeichnis an Automaten, blauer Felder Jugendliche (15-20 Jahre): Kursstrecke 1 Streifen, sonst 1/2 Streifen; Erwachsene Kinder (6-14 Jahre): einheitlich 1 Streifen.

Streifenzahl	Kursstrecke	1 Zone	2 Zonen	3 Zonen	ab 4 Zonen
10er-Streifenkarte für Kinder (6-14 Jahre)	10,50 €	1 Streifen	2 Streifen	4 Streifen	8 Streifen
10er-Streifenkarte für Kinder (6-14 Jahre)	einheitlich 5,20 €				

Kaufmöglichkeiten: MVV-Verkaufsstellen und Automaten
Zahlungsmittel: siehe Anzeige am Automaten
Fahrkarte vor Fahrtantritt erwarten

Für beliebig viele Fahrten: Die Tageskarten

Single-Tageskarte für 1 Erwachsene, Tageskarte für Kinder (6-14 Jahre) oder Partner-Tagekarte für bis zu 5 Erwachsene oder 10 Kinder (6-14 Jahre, bei Schulpflichtigen Kinder bis 9. Klasse bei beliebig vielen Fahrten im geschlossenen Geltungsbereich, gültig vom Zeitpunkt der Geltungsbereich: Innenstadt, München XXL, Außenraum, Gesamtnetz. Für Innenraum auch 2 Tage gültig bis 8. Tag, 6:00 Uhr bis 1:00 Uhr.)
Mitnahme von Handgepäck, Kinderwagen und 1 Hund kostenlos.
Für Ihre Fahrkarte erforderliche Geltungsbereich: siehe Tarifplan oder Fahrzeilverzeichnis an den Automaten, sonstige Felder:

Preise	Innen- oder Außenbereich	München XXL	Gesamtnetz	3 Tage Innenraum
Single-Tageskarte	5,00	6,70	10,00	12,30
Partner-Tageskarte	9,00	11,80	18,00	21,00
Kindertageskarte (6-14 Jahre)	-	-	2,40	-

Kaufmöglichkeiten: MVV-Verkaufsstellen und Automaten
Zahlungsmittel: siehe Anzeige am Automaten
Fahrkarte vor Fahrtantritt erwarten, ausgenommen aus Bus- und Tramfahrplänen

Für beliebig viele Fahrten: Die IsarCard

Für beliebig viele Fahrten während einer Kalenderwoche oder einem Kalendermonat in den gewählten Ringen.

Mitnahme von Handgepäck, Kinderwagen und 1 Hund kostenlos. Mitnahme von max. drei Kindern (6-14 Jahre, zur Familie gehörende Kinder, Einzelkinder in unbeschränkter Anzahl) an Sa., So. und Feiertagen gratis, Mo. Fr. ab 9:00 Uhr kostenlos. Für Ihre Fahrkarte erforderliche Ringe: siehe Tarifplan.

Preise:

Ring	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Wochen	11,00	13,00	15,00	18,00	21,00	23,00	25,00	27,00	29,00	31,00	33,00	35,00	37,00	39,00	41,00	43,00
Monat	40,10	45,00	49,90	54,80	59,70	64,60	69,50	74,40	79,30	84,20	89,10	94,00	98,90	103,80	108,70	113,60

Kaufmöglichkeiten: MVV-Verkaufsstellen und Automaten an Haltestellen, auch vorüber mit monatlicher (10 Monate bezahlen), 12 Monate fahren) oder jährlich (2,5 Monate bezahlen, 12 Monate fahren) Zahlung erhältlich.
Zahlungsmittel: siehe Anzeige am Automaten
Keine Entwertung erforderlich.

Gesamtnetz

Tarifplan

So erhalten Sie die richtige Preisstufe:
Einzelfahrkarten und Streifenkarten
Erwachsene: Anzahl der bezahlten Zonen von Stadt bis Zielhaltestelle nachrechnen (siehe Tarifplan). Zonen, die nach Zielhaltestelle nachrechnen müssen, sind ab 2 Zonen (ab 2 Zonen).
Kinder (6-14 Jahre): einheitlich 1,10.
Erwachsene: Jede Fahrt bis zur 4. Haltestelle nach dem Einstieg, danach über höchstens 2 Haltestellen mit 3 oder 10 bis 8 h.h. Umsteigen erlaubt.
Im Regionalverkehr: außerhalb München gilt die Buslinie ebenfalls einer Gemahne als Kursstrecke.
Runde: 1 Hund kostenlos. Für jeden weiteren Hund ist eine Fahrkarte nach dem Kinderort zu lösen.

So erhalten Sie die richtige Preisstufe:
Tageskarten
Geltungsbereich auswählen (siehe Tarifplan):
Innenraum (weiße Zone)
München XXL (weiße und grüne Zone)
Außenraum (grün, gelb und rote Zone)
Gesamtnetz (alle 4 Zonen)

So erhalten Sie die richtige Preisstufe:
Zielkarten
Geltungsbereich (Ringe 1-16) auswählen (siehe Tarifplan, Haltestellenverzeichnis im Fahrplänbuch oder im Internet):
Innenraum
München XXL
Außenraum
Gesamtnetz

Zonen und Ringe:
Innenraum
München XXL
Außenraum

Ringeneinteilung (1-16) gilt nur für Zeitkarten

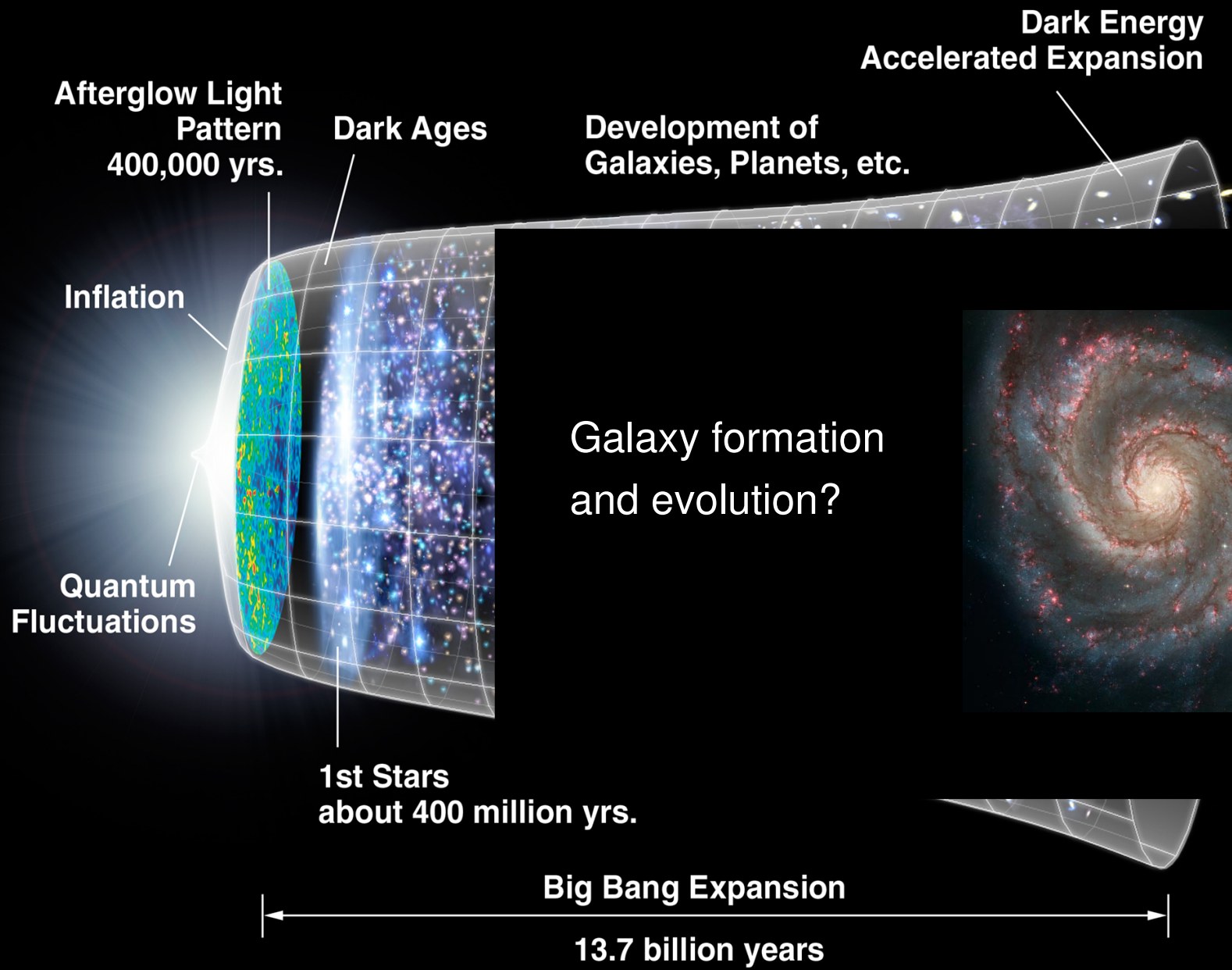
Legende:
S-Bahn
U-Bahn
MVV Regionalbus
Regionalbus
DB-Züge

IsarCard: Ihre Card gilt nur für Zeitkarten
Je mehr Fahrpläne Sie haben, desto mehr Fahrpläne können Sie mit Ihrer IsarCard nutzen.
MVV-Info-Service: 089 71 11 32 82 oder 08 90 11 10 86 (kostenlos, 24h)

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Big Bang Expansion
13.7 billion years



How to approach galaxy formation and evolution?

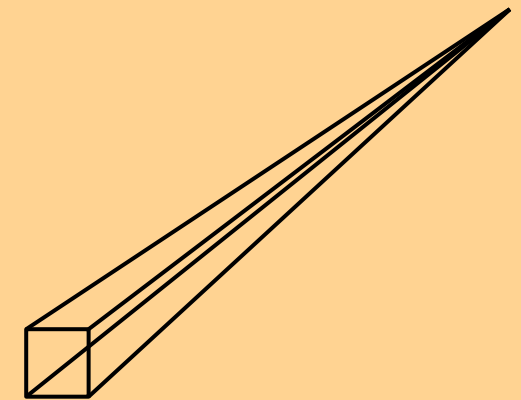
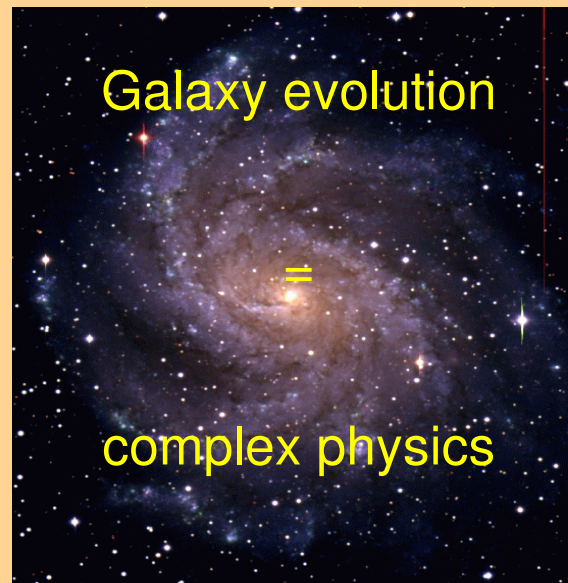
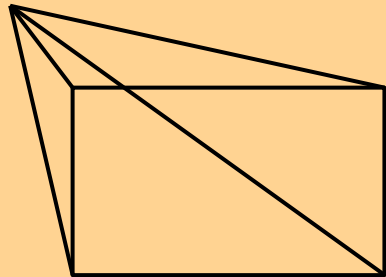
Observations

Large surveys of
galaxy population(s)

Level of detail

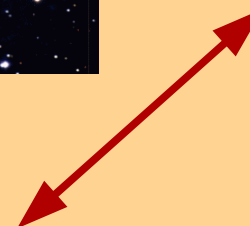
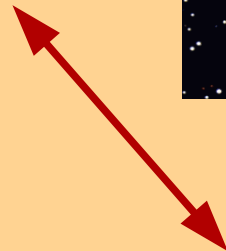
Statistical power, completeness

Detailed
investigations of
individual galaxies



Theory

(analytic, semi-analytic, numerical)



How to approach galaxy formation and evolution?

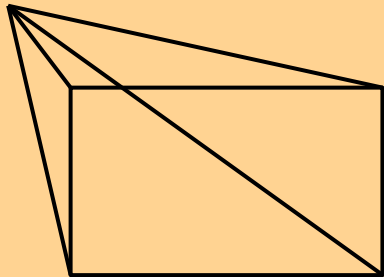
Observations

Large surveys of
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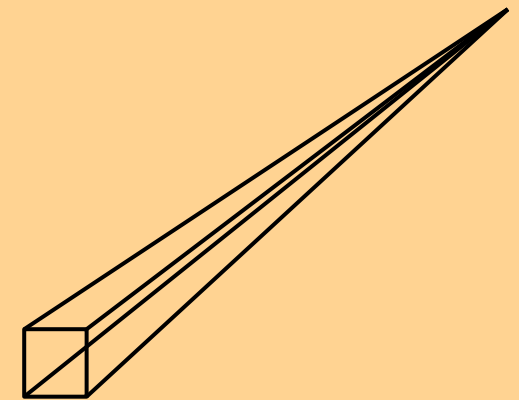
Statistical power, completeness

Detailed
investigations of
individual galaxies



Galaxy evolution

- gravitational collapse
- gas hydrodynamics
- star formation
- feedback from SF
- feedback from AGN/BH
- interaction with environment
- ...



Theory

(analytic, semi-analytic, numerical)



How to approach galaxy formation and evolution?

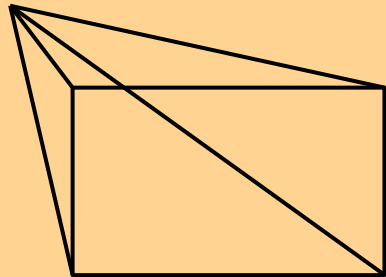
Observations

Large surveys of galaxy population(s)

Level of detail

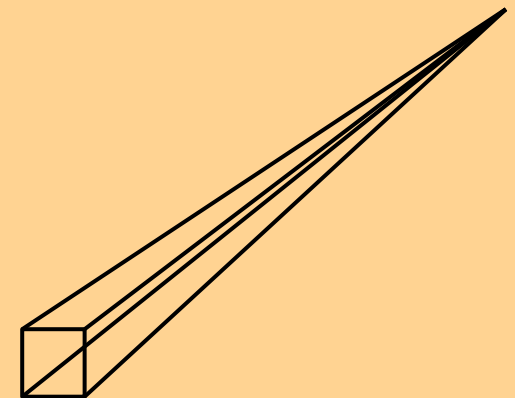
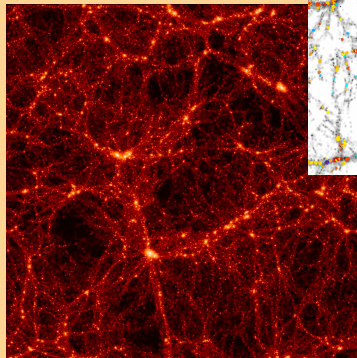
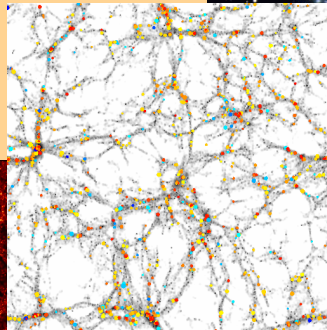
Statistical power, completeness

Detailed investigations of individual galaxies



Galaxy evolution

- gravitational collapse
- gas hydrodynamics
- star formation
- feedback from SF
- feedback from AGN/BH
- interaction with environment



Theory

(analytic, semi-analytic, numerical)

How to approach galaxy formation and evolution?

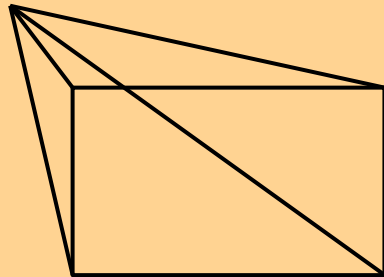
Observations

Large surveys of
galaxy population(s)

Level of detail

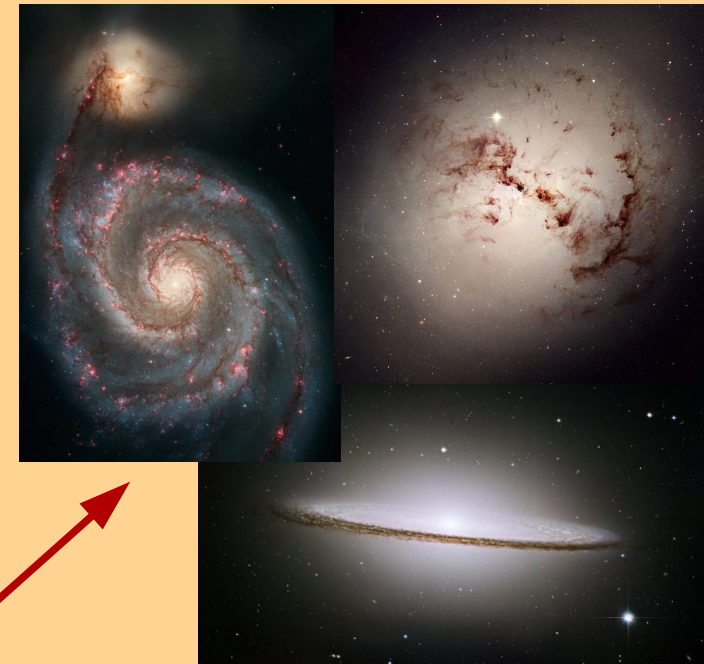
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Galaxy evolution

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- ...

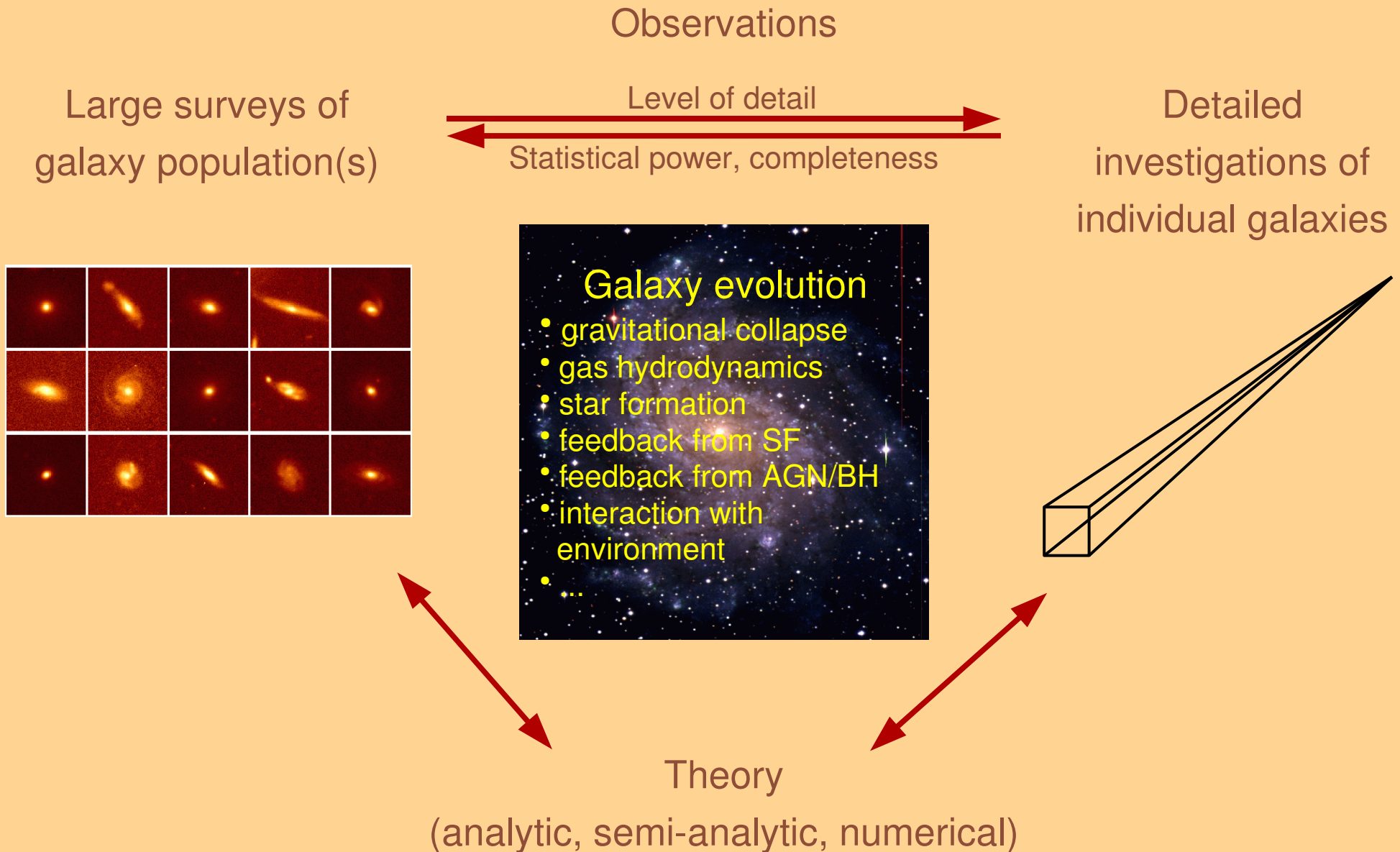


Theory

(analytic, semi-analytic, numerical)



How to approach galaxy formation and evolution?



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
- Morphology
 - Hubble type
 - Concentration/Asymmetry/C
- Stellar population
 - Colour
 - Continuum type
 - PCA
- Structure
 - Size
 - Surface brightness
 - Surface brightness profile ty
- Dynamics

giant ↔ dwarf

E1-7 ↔ S(B)abc ↔ Sd/Irr

blue ↔ red

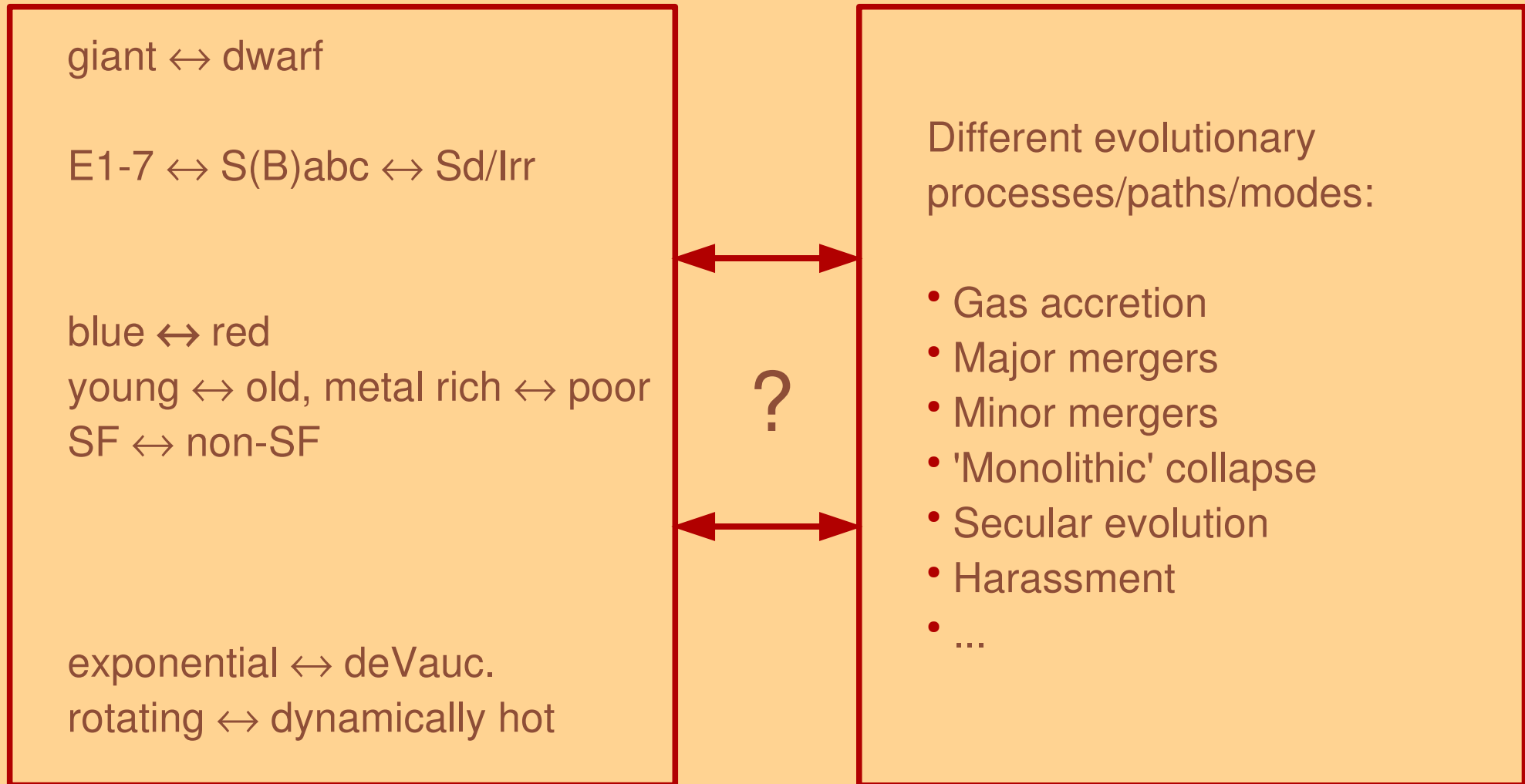
young ↔ old, metal rich ↔ poor

SF ↔ non-SF

exponential ↔ deVauc.

rotating ↔ dynamically hot

How to approach galaxy formation and evolution?

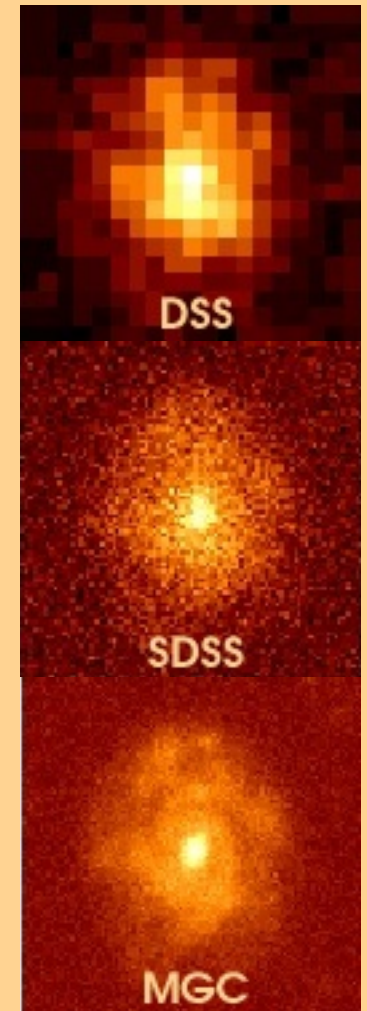


Observationally, what is the best way to isolate, identify and investigate the various formation/evolutionary mechanisms?

The Millennium Galaxy Catalogue (MGC)

www.eso.org/~jliske/mgc

- Deep, wide-field B-band imaging survey using WFC/INT
- Area = 37.5 deg²
- Median seeing = 1.3 arcsec, pixel size = 0.33 arcsec
- $B_{\text{lim}} = 24 \text{ mag}$ $\mu_{\text{lim}} = 26 \text{ mag arcsec}^{-2}$
internal photometric accuracy = 0.03 mag
- B + ugriz (SDSS) photometry
- Main sample: $B < 20 \text{ mag}$ (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)

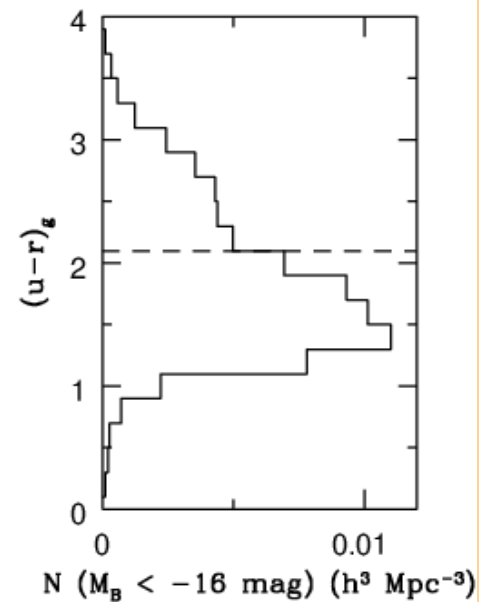
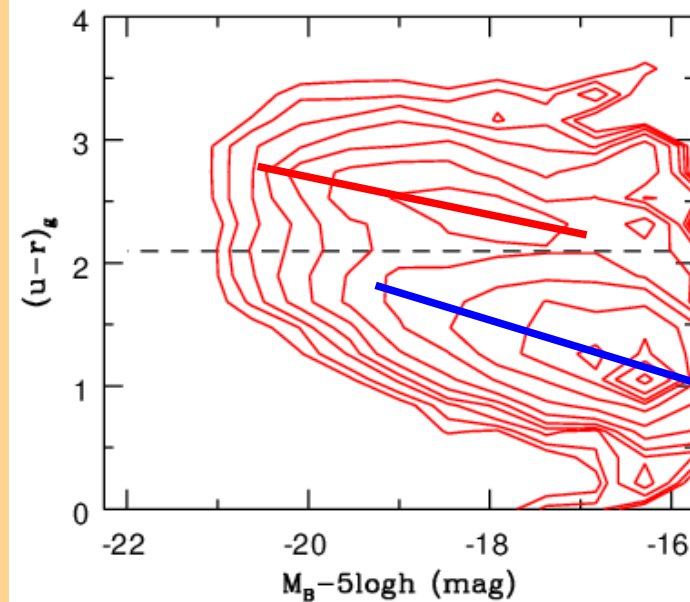
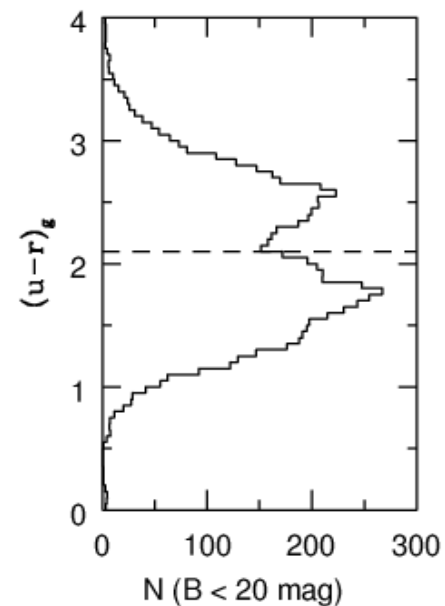
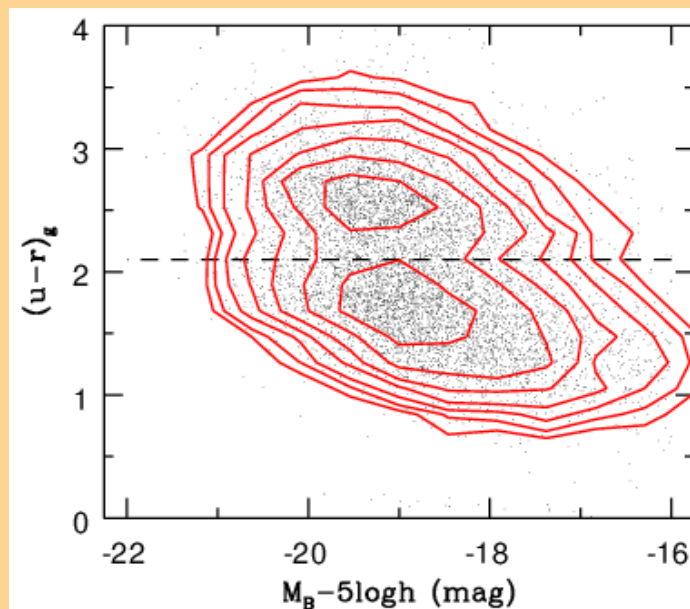


Bimodality of the galaxy population

Observed number

Bivariate colour-
luminosity distribution

Volume corrected

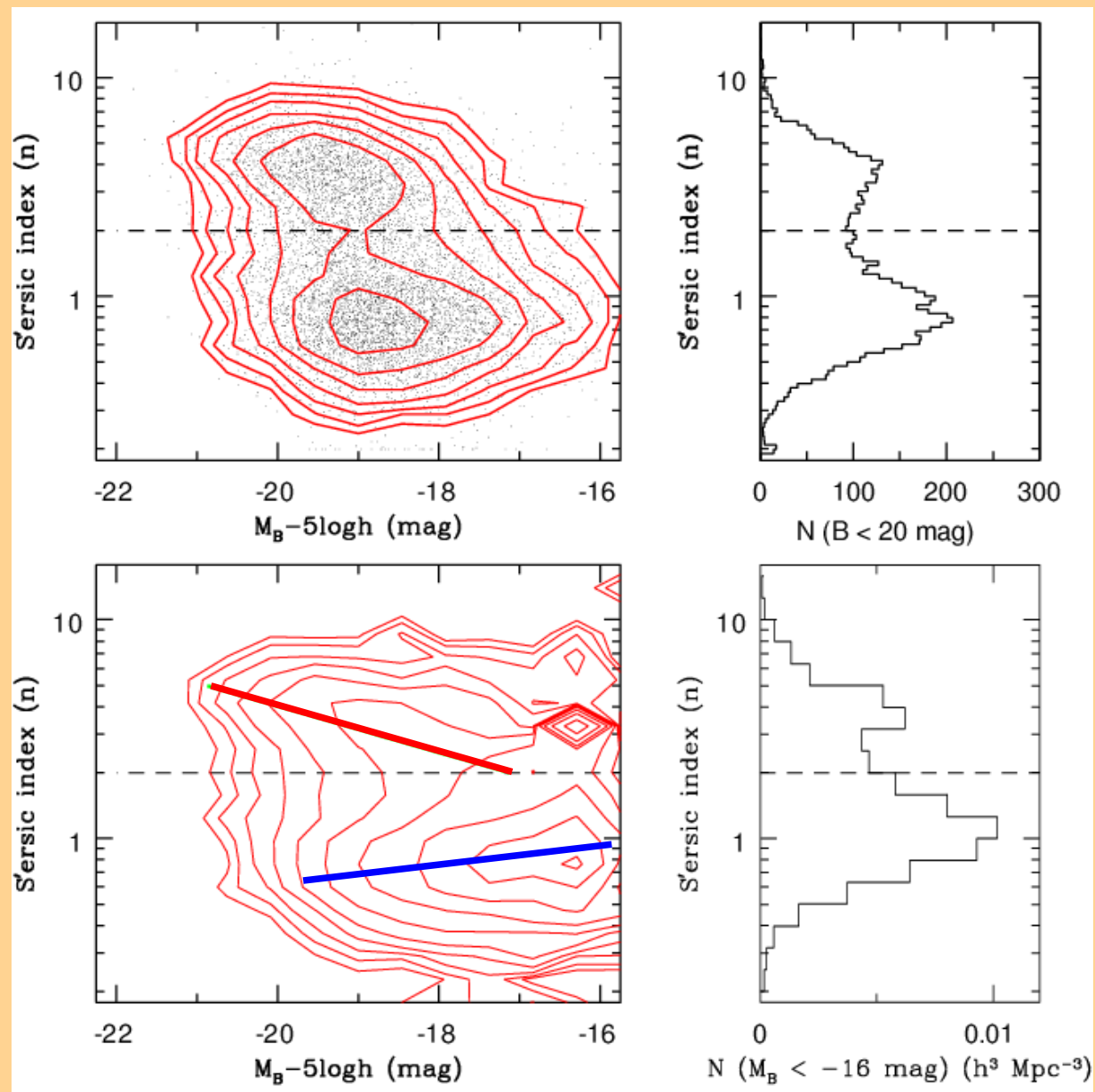


Bimodality of the galaxy population

Observed number

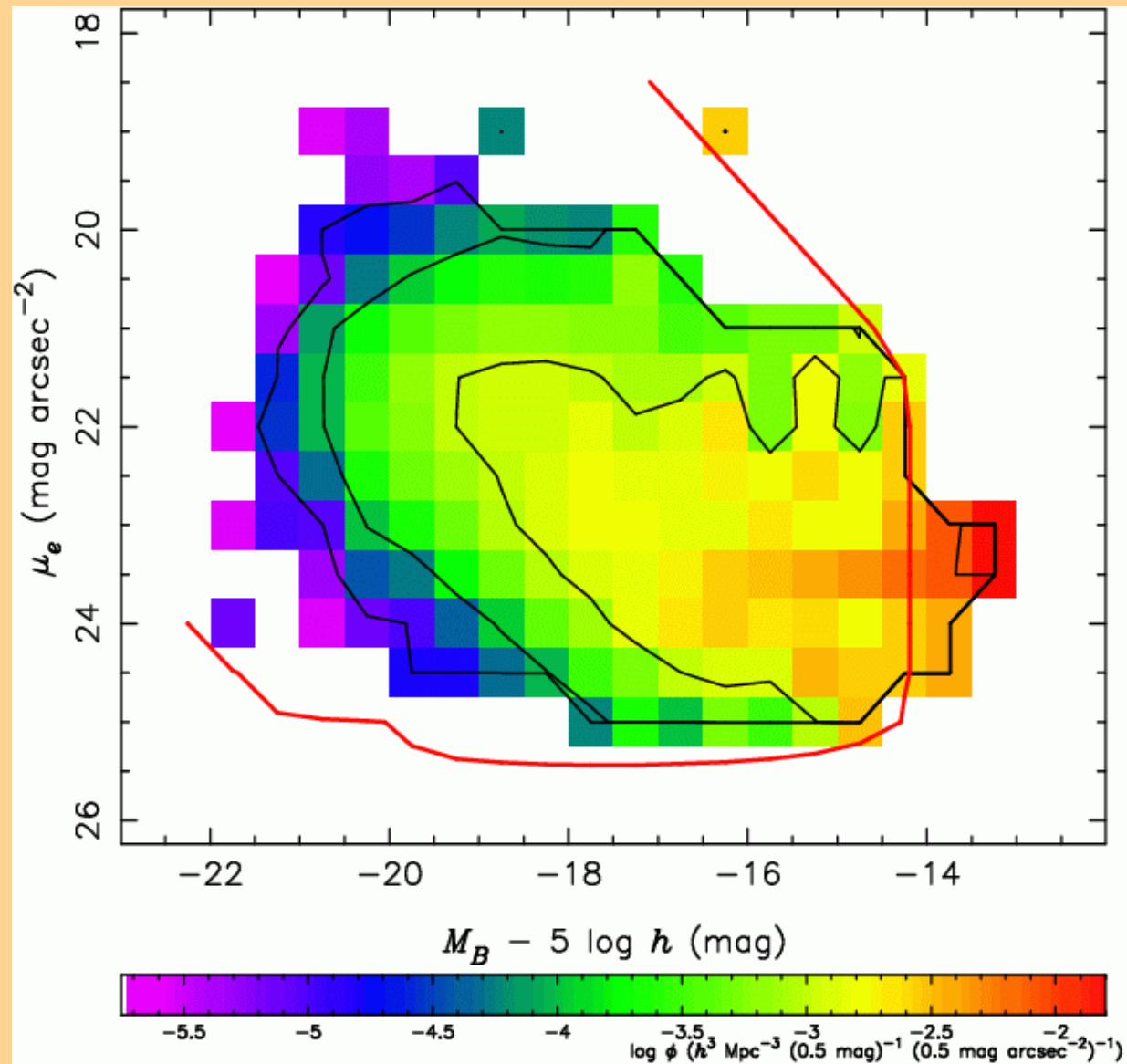
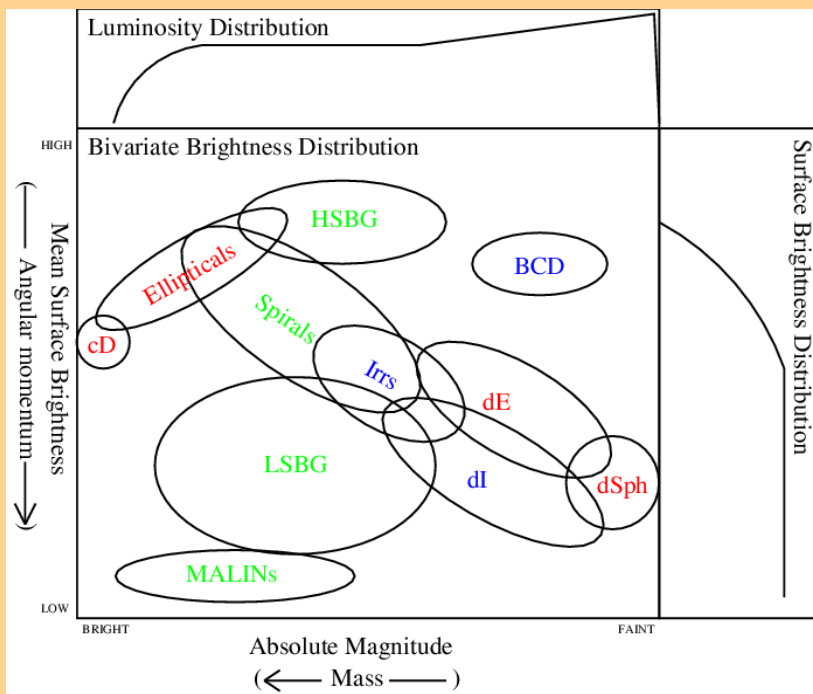
Bivariate Sersic index-
luminosity distribution

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.

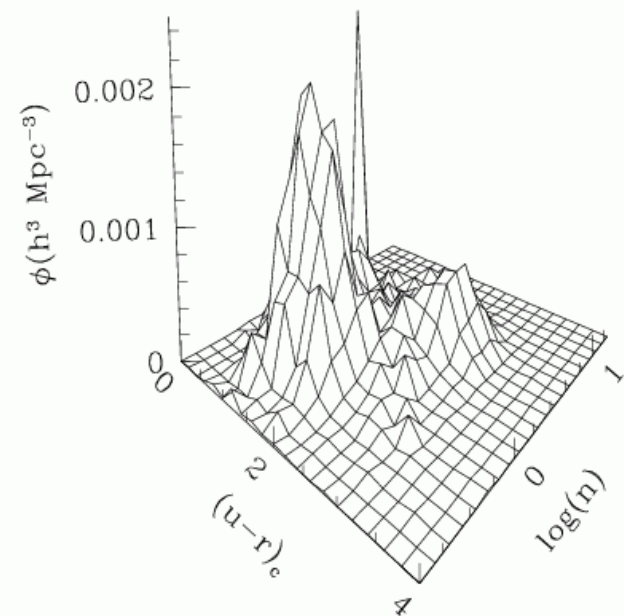
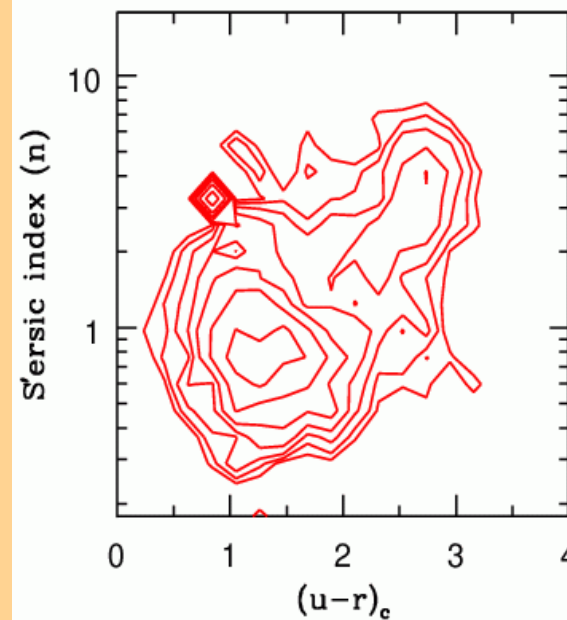
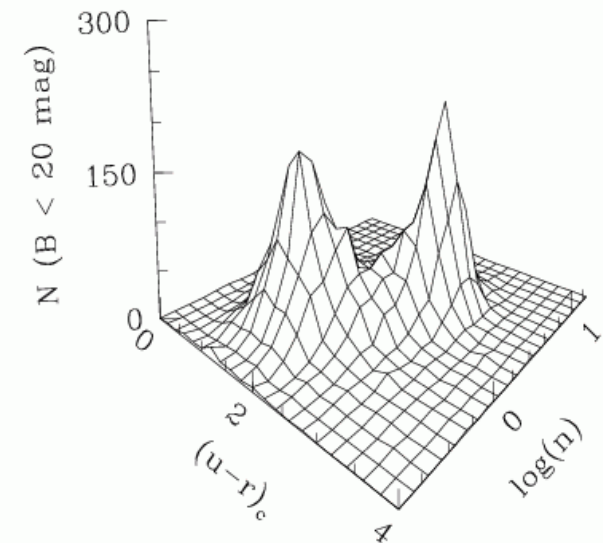
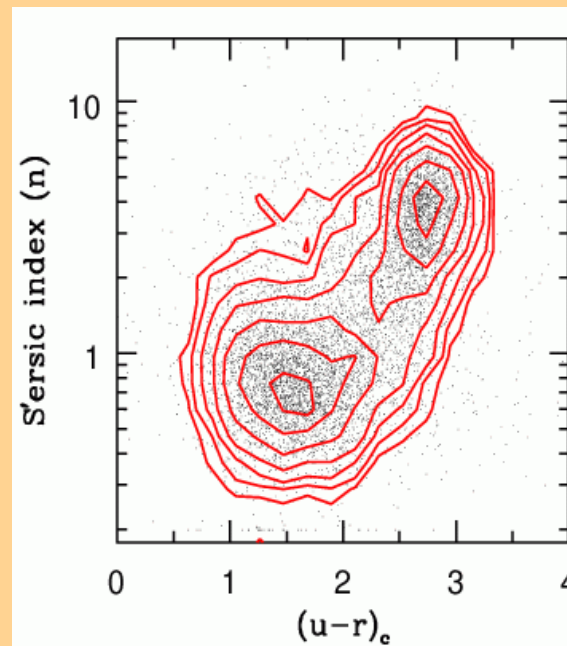


Bimodality of the galaxy population

Observed number

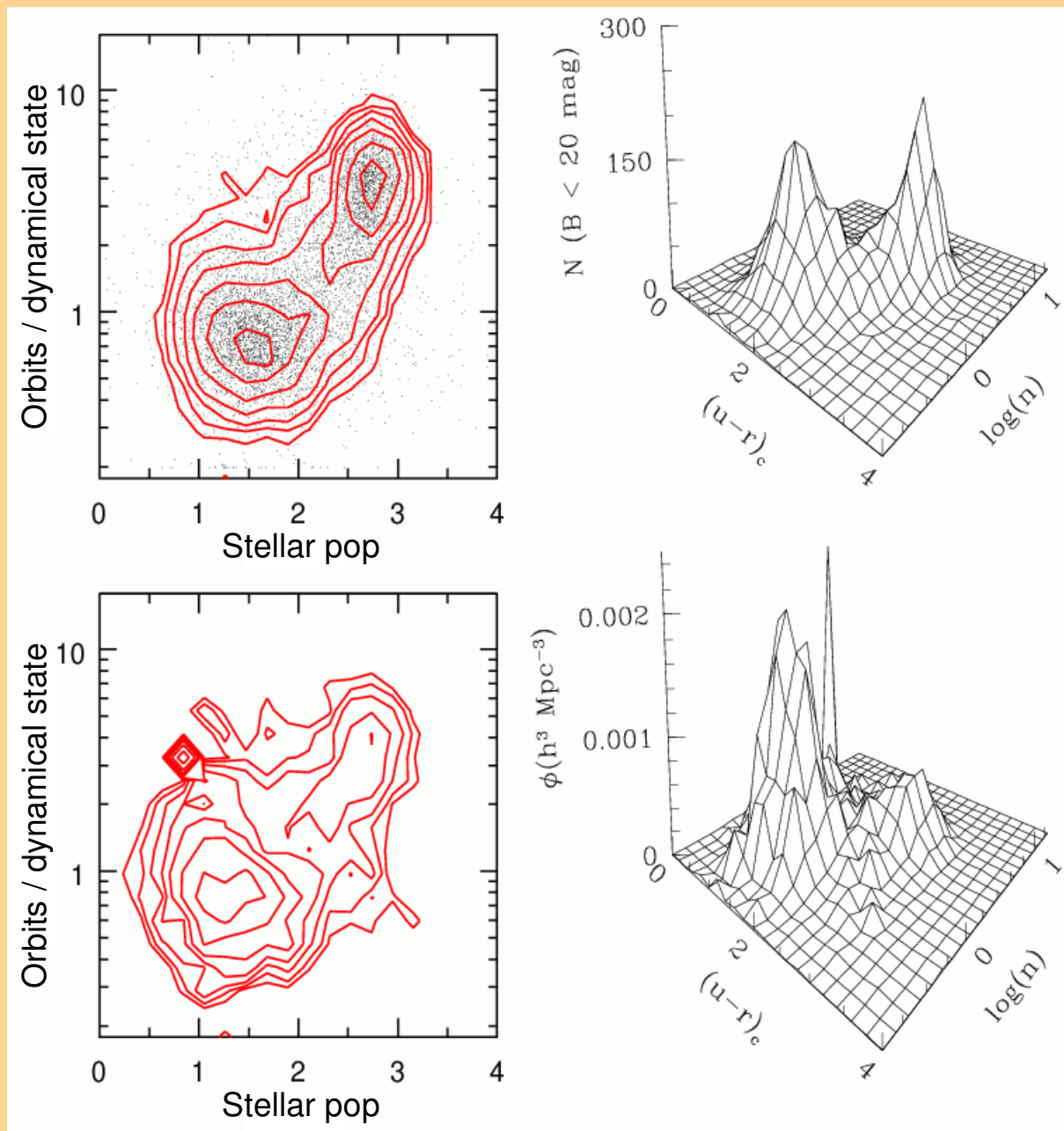
Bivariate Sersic index-
colour distribution

Volume corrected



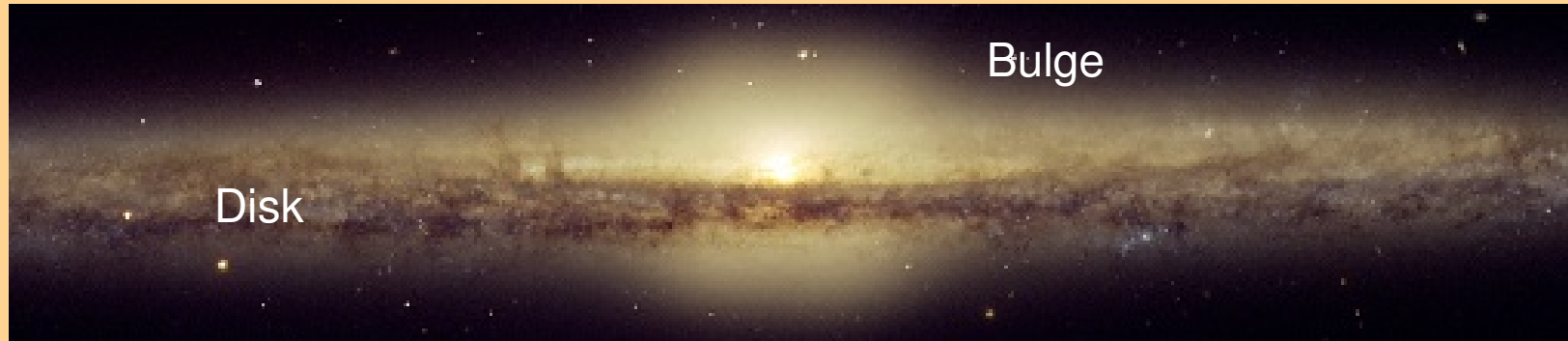
Bimodality of the galaxy population

- 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.



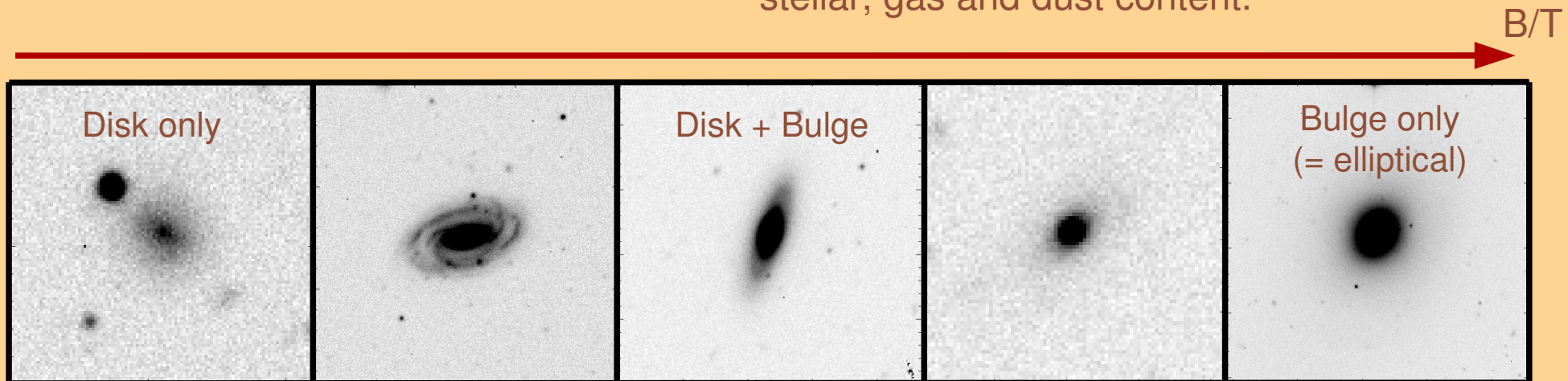
The two-component nature of galaxies

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



Bulges and disks differ in terms of:

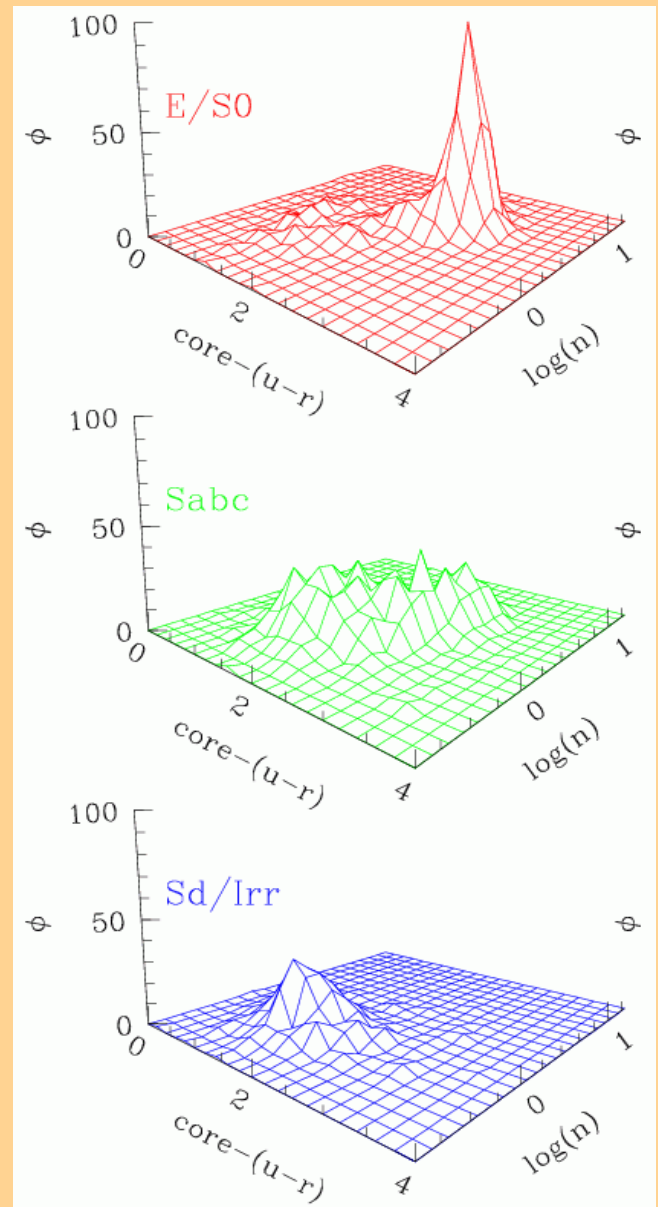
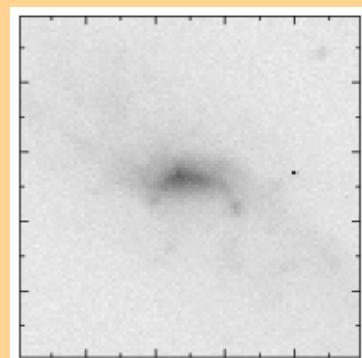
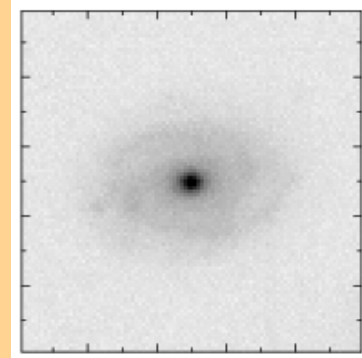
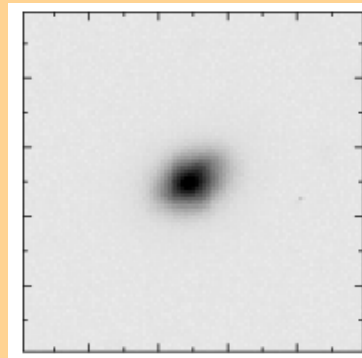
- photometric structure
- dynamics
- stellar, gas and dust content.



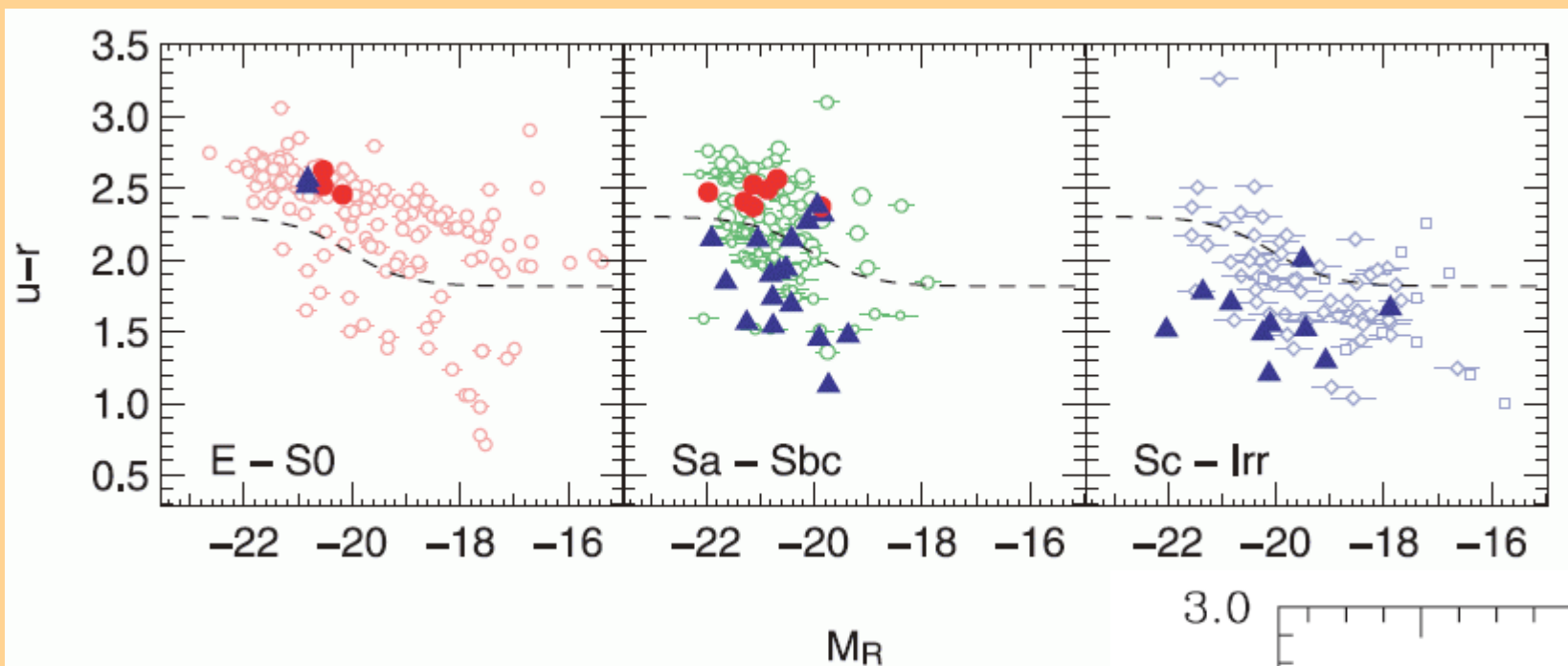
Bimodality \leftrightarrow 2-component nature?

$B/T \uparrow$
 Hubble type
 \downarrow
 location in colour $\log(n)$ plot

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



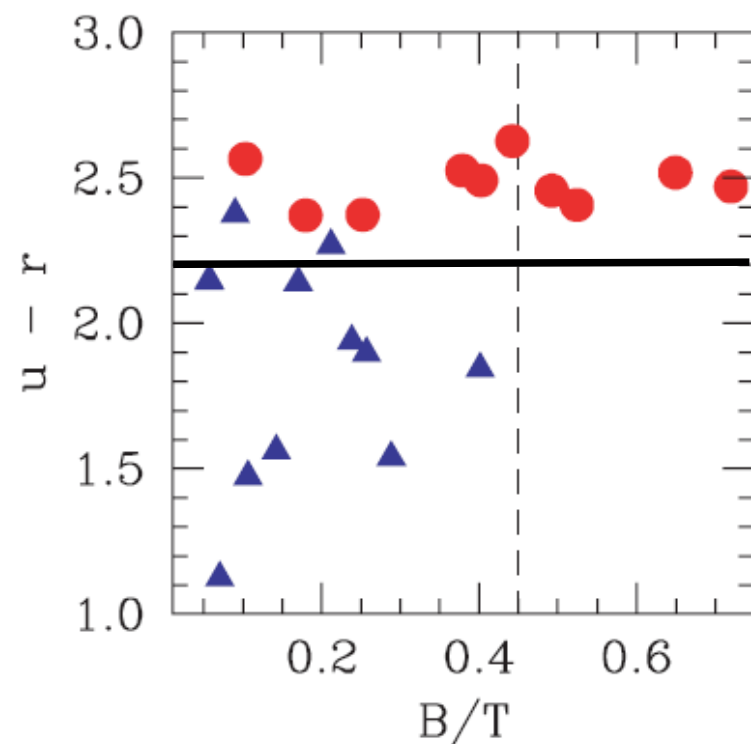
Bimodality \leftrightarrow 2-component nature?



Drozy & Fisher (2007)

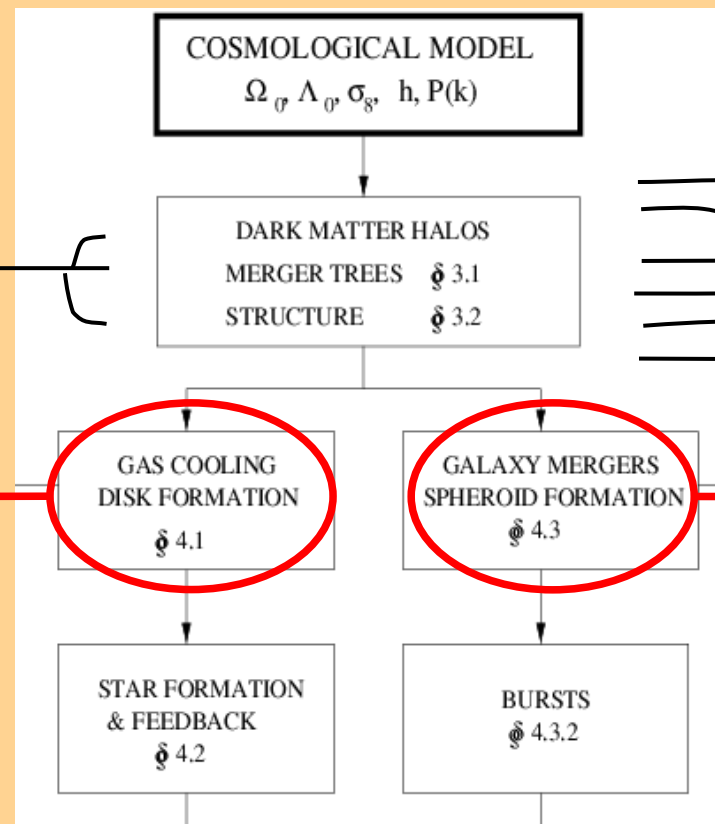
It's not that simple:

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 \neq 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.”



“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.”

Cole et al. (2000)

Implications

- There are clear observational and theoretical motivations to consider:
Galaxy types or classes

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~~Galaxy types or classes~~ → Galaxy components

- i.e., we should decompose galaxies into their major constituents and investigate *their* properties, as opposed to 'global' ones.

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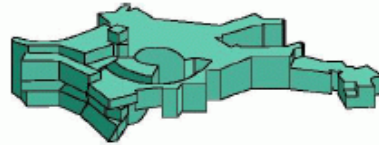
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Galaxy components

- i.e., we should decompose galaxies into their major constituents and investigate *their* properties
- The disk-bulge view of galaxies confront models of galaxy formation



Venice, October 2003

**The Formation of Galaxies:
connecting theory to data**

*Simon D.M. White
Max Planck Institute for Astrophysics*

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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

Interpretation of large multiwavelength datasets will require careful quantitative analysis using detailed physical models in the context of a standard structure formation paradigm

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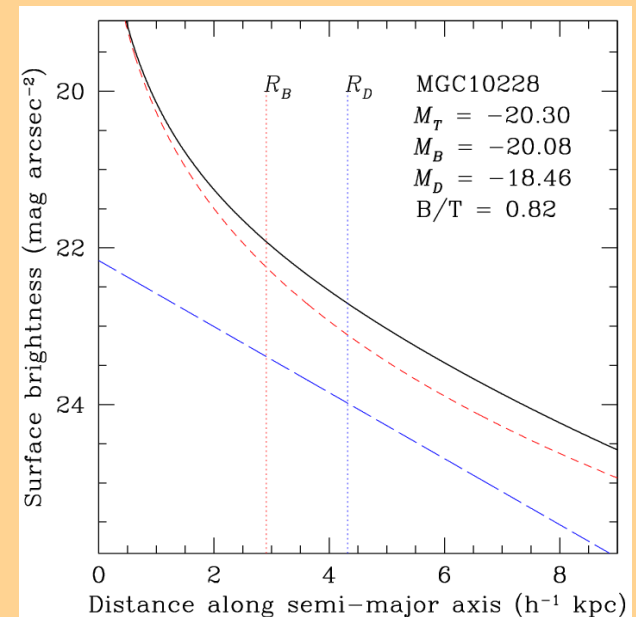
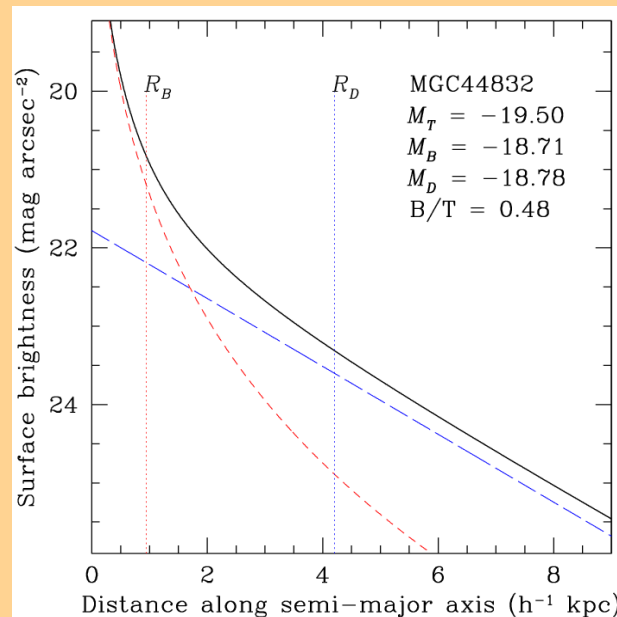
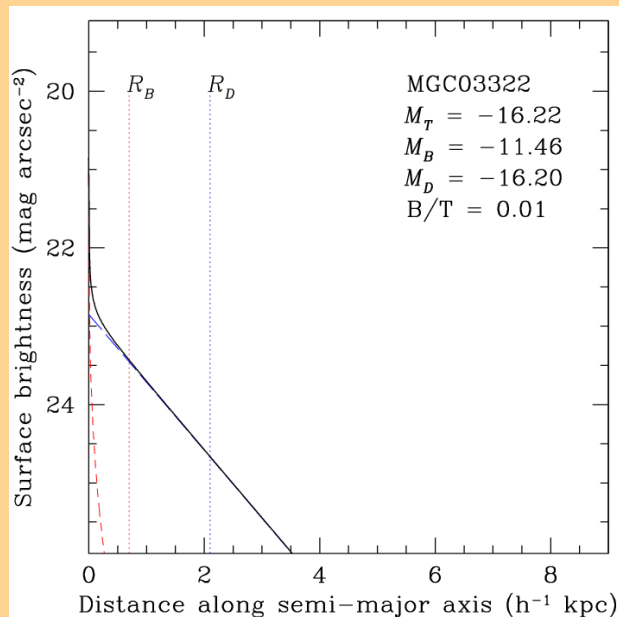
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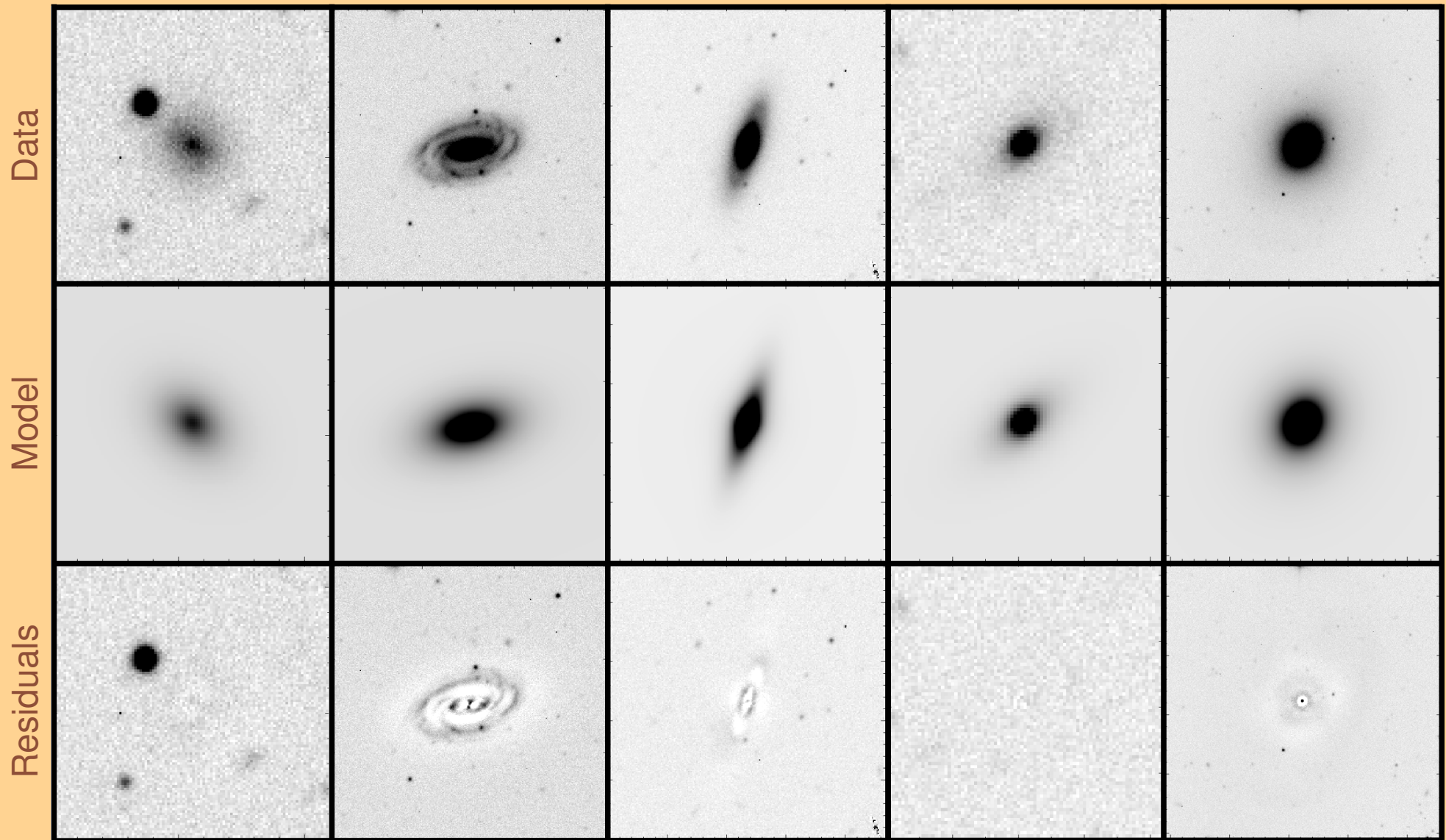
- i.e., we should decompose galaxies into their major constituents and investigate *their* properties, as opposed to 'global' ones.
- The disk-bulge view of galaxies is the most 'natural' language in which to confront models of galaxy formation and evolution with observations.
- To probe disk/bulge evolution 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

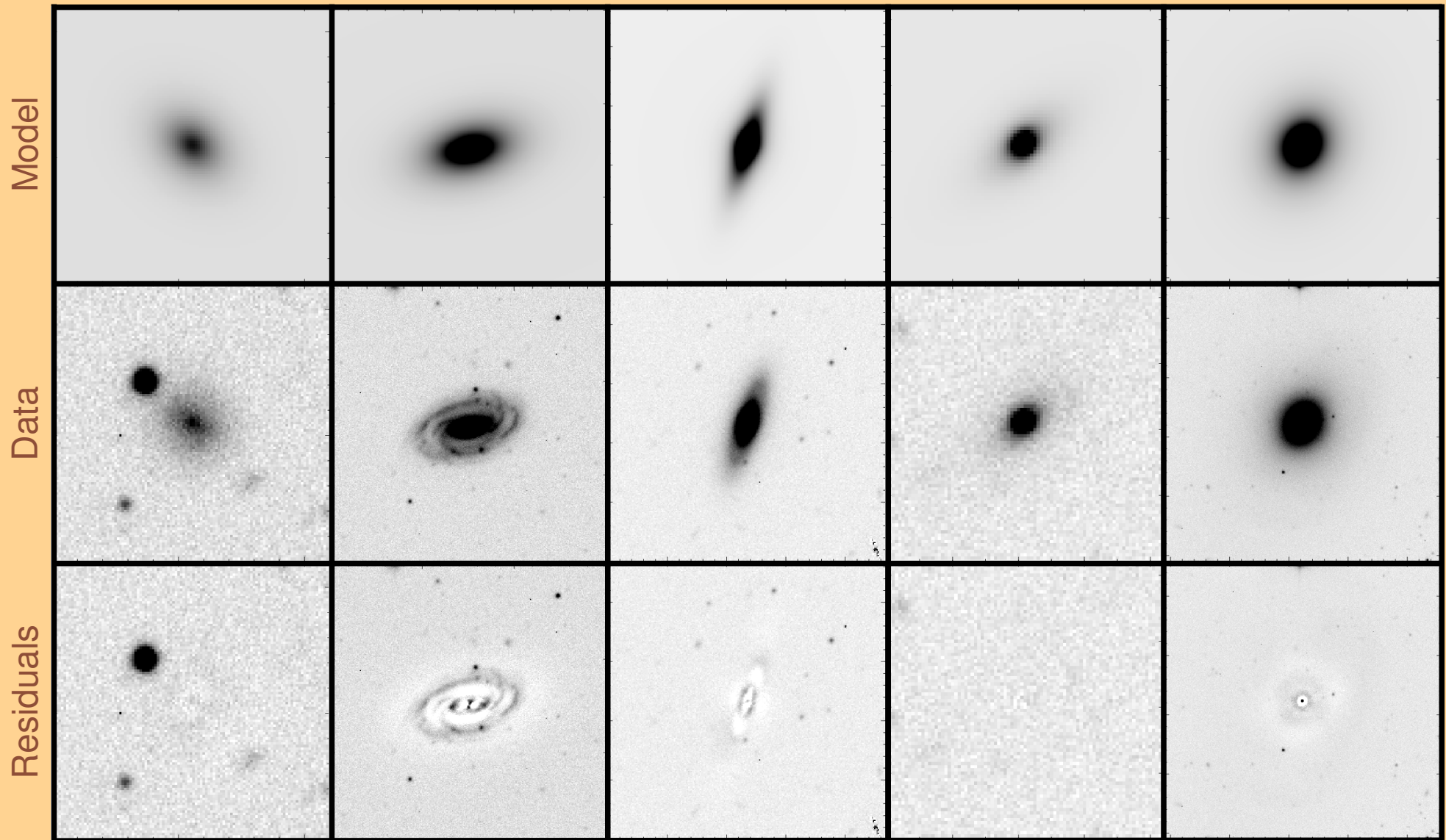
- Model: Sersic bulge + exponential disk \rightarrow 12 parameters
- Careful PSF modelling \rightarrow convolve model profile with seeing
- Used GIM2D (Simard et al. 2002)
- Applied to all 10,095 MGC galaxies with $B < 20$ mag \leftarrow largest available sample



MGC bulge-disk decomposition

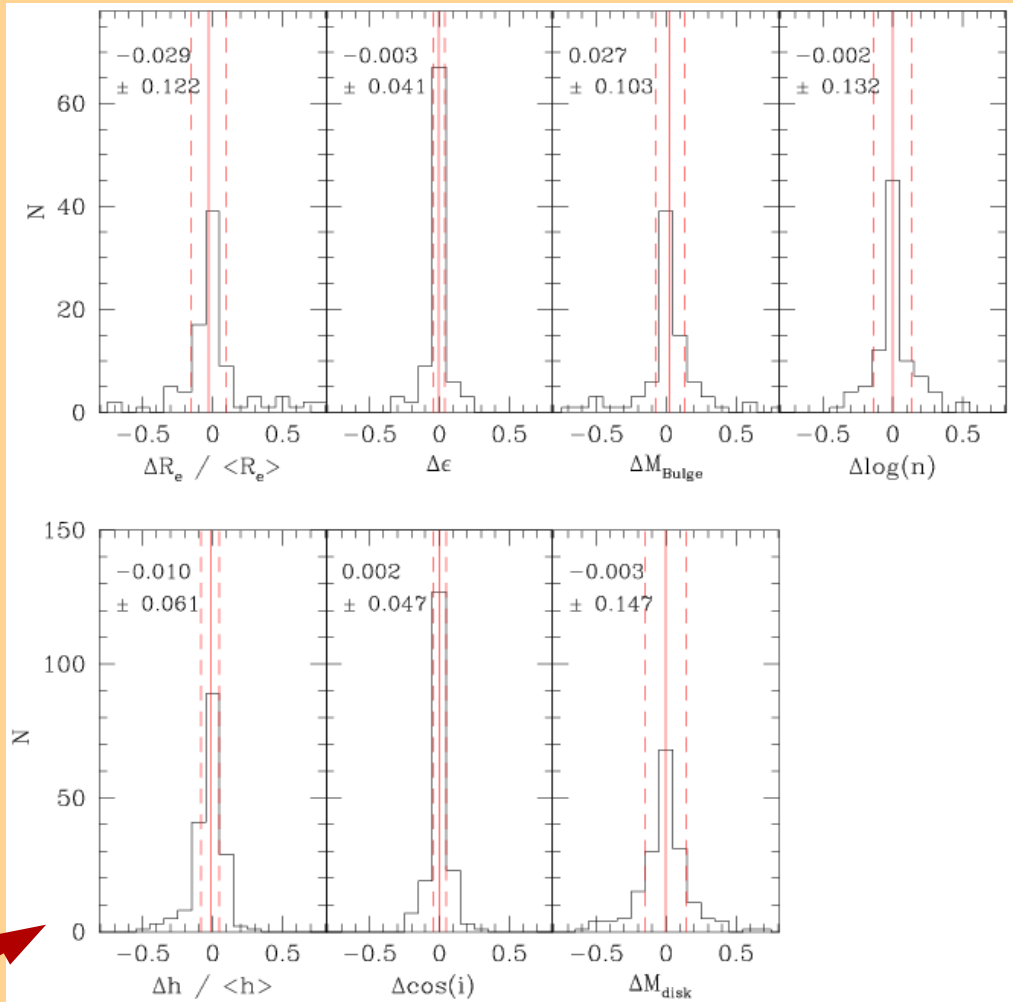
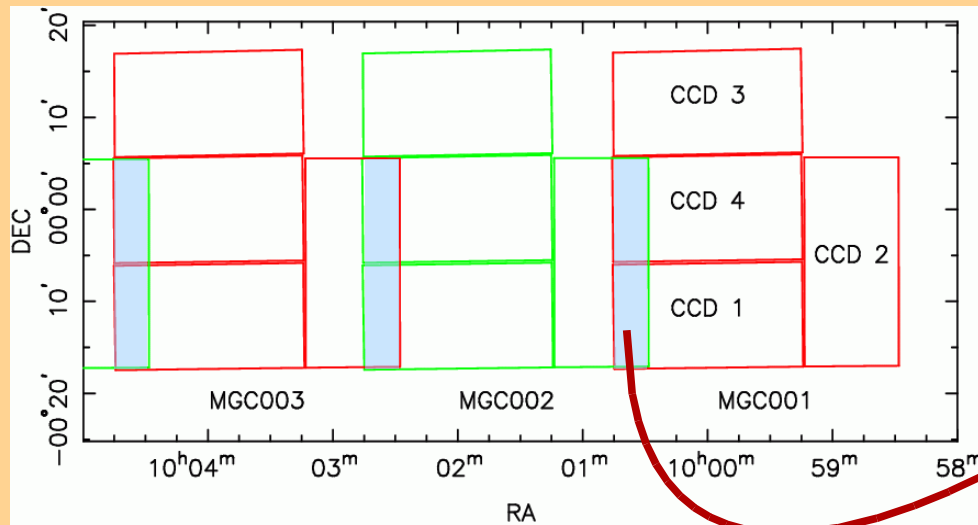


MGC bulge-disk decomposition

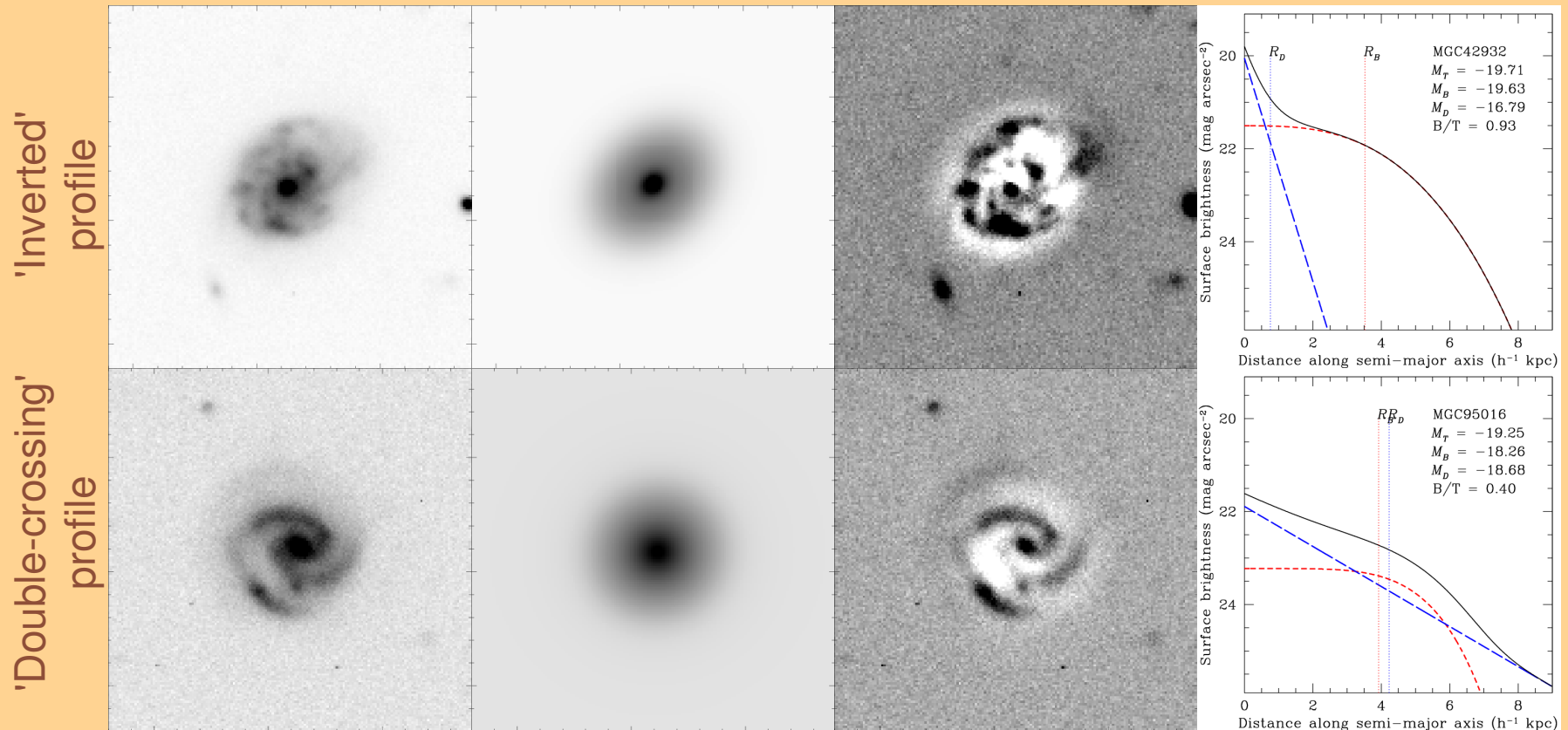


MGC bulge-disk decomposition

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



MGC B-D decomposition: problems



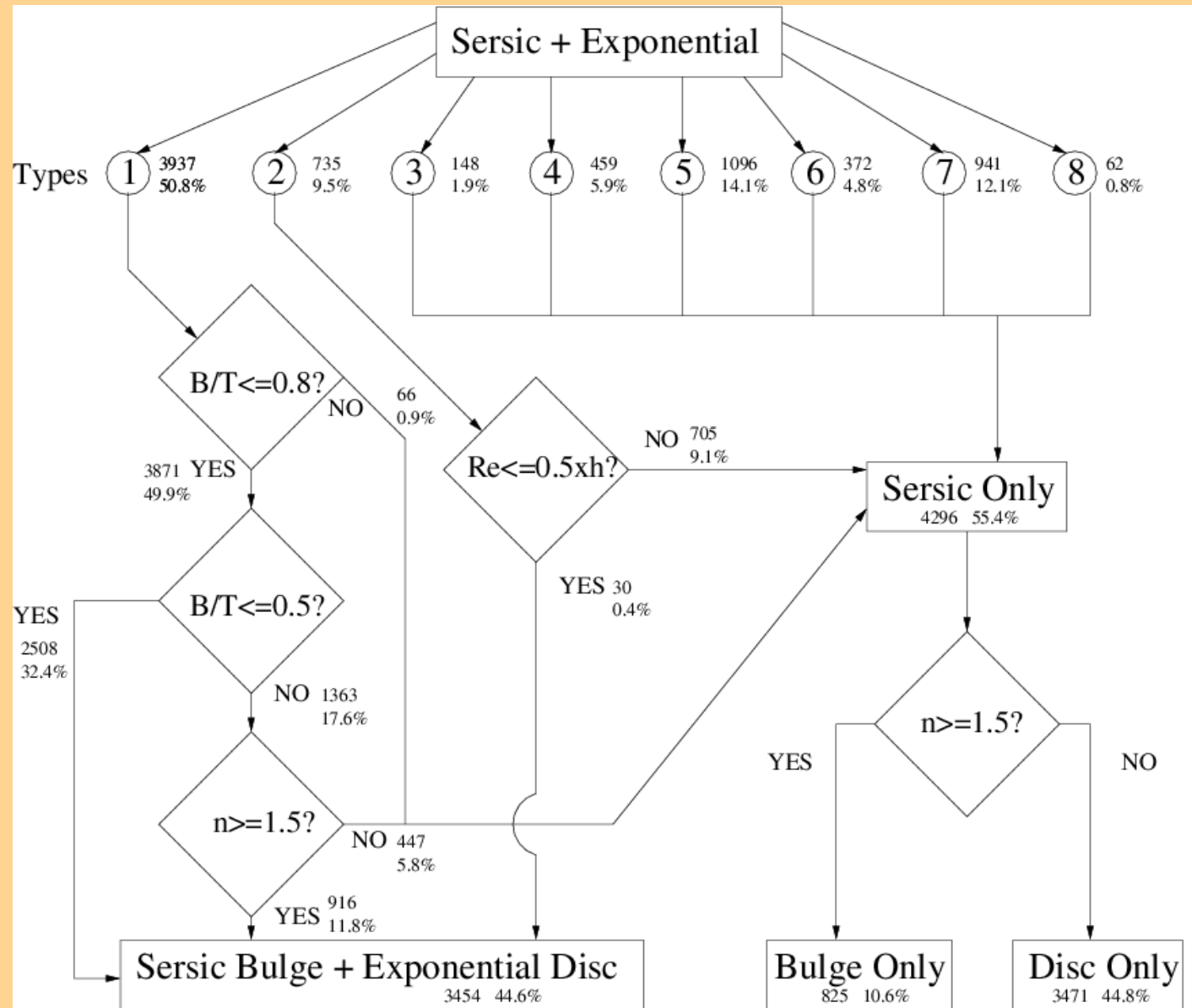
The presence of 'second order' features can result in (apparently?) unphysical models: Spiral arms, irregular morphology, dust, SF regions, truncated disks, bars, rings, inner disks, unresolved central components (AGN, nuclear starburst), twisted isophotes, perturbed background, ...

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 \longleftrightarrow Robustness

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

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



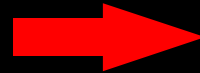
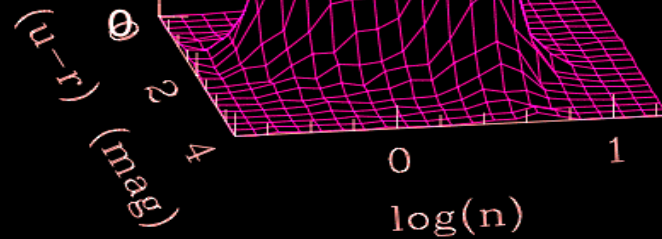
With respect to the model the compression is lossless.

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

Component bimodality

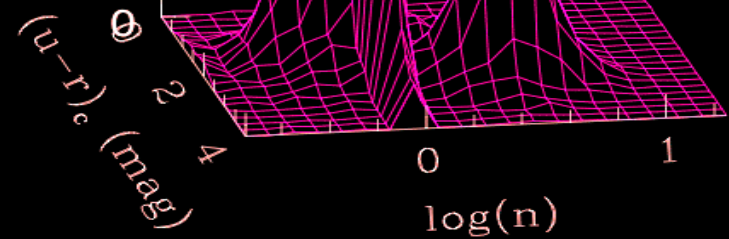
Composite galaxies
(1-component Sersic fits)

$N \approx 250$



Galaxy
components

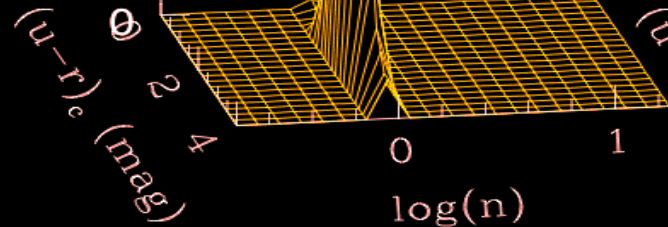
$N \approx 250$



Type I disks

500

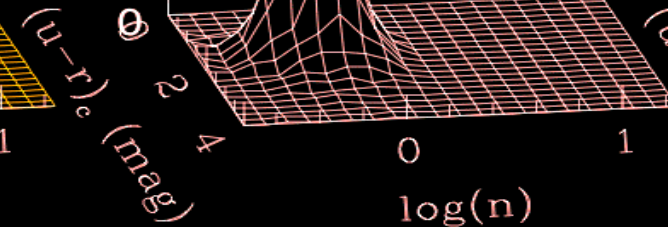
$N \approx 250$



Type II/III disks

500

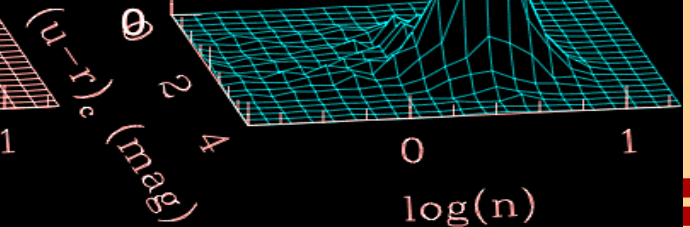
$N \approx 250$



Sersic Bulges

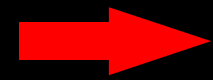
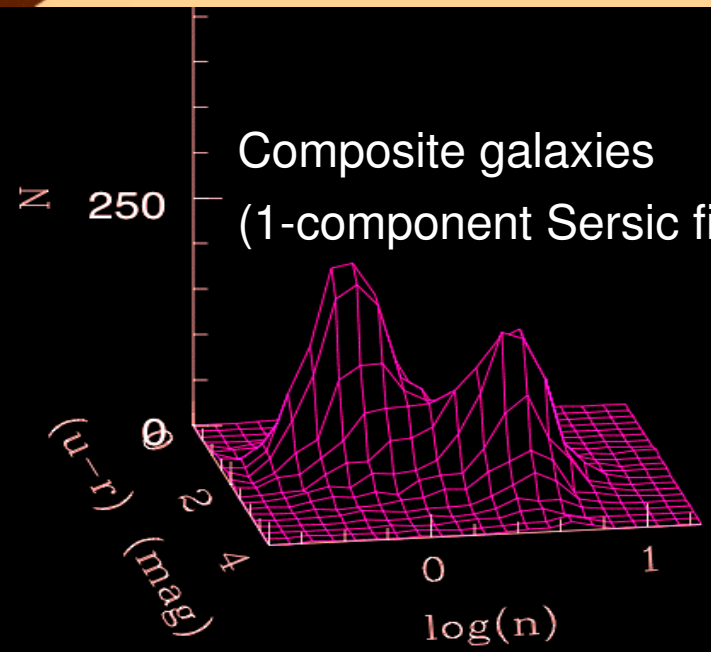
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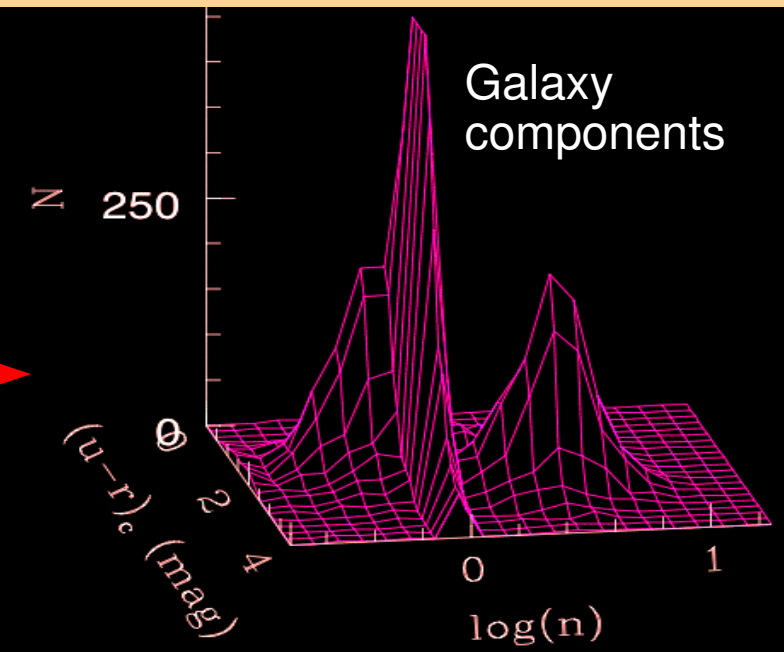


Component bimodality

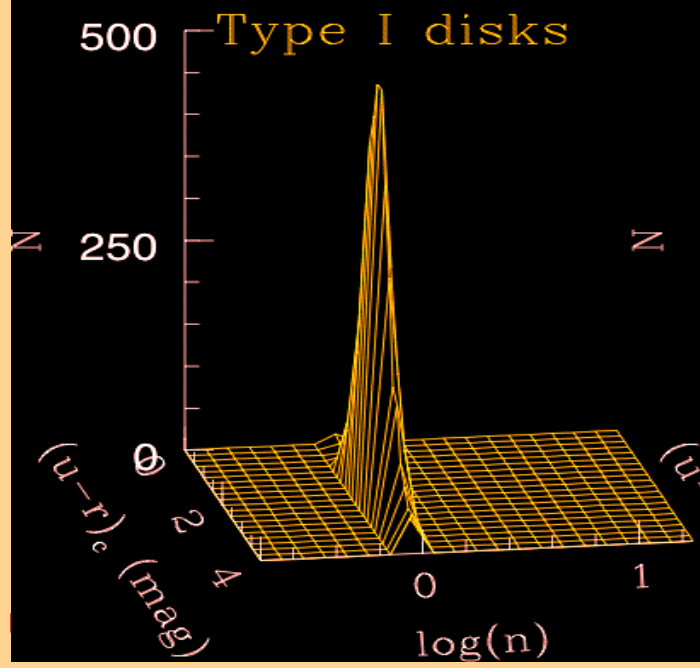
Composite galaxies
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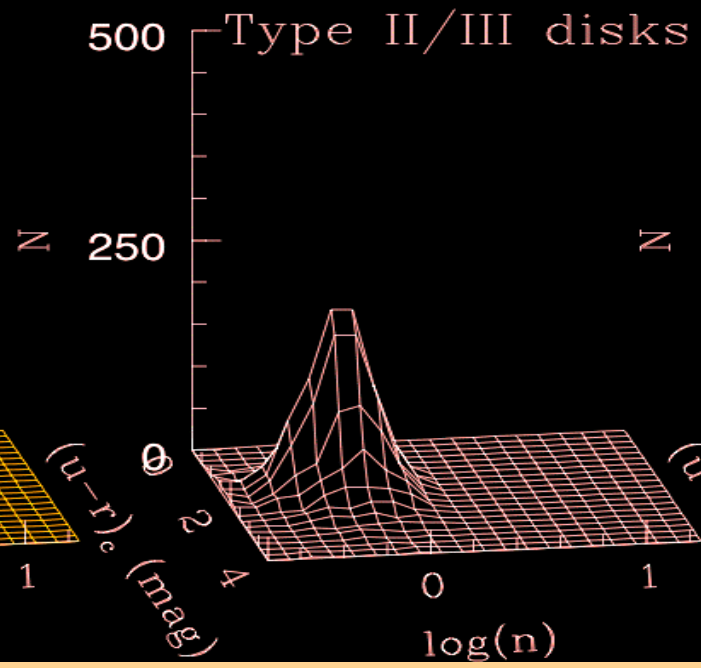
Galaxy components



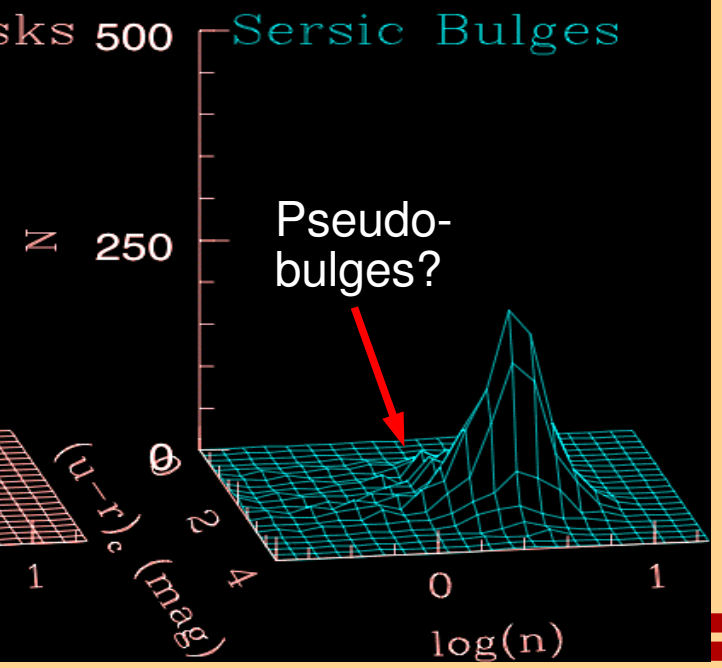
Type I disks



Type II/III disks

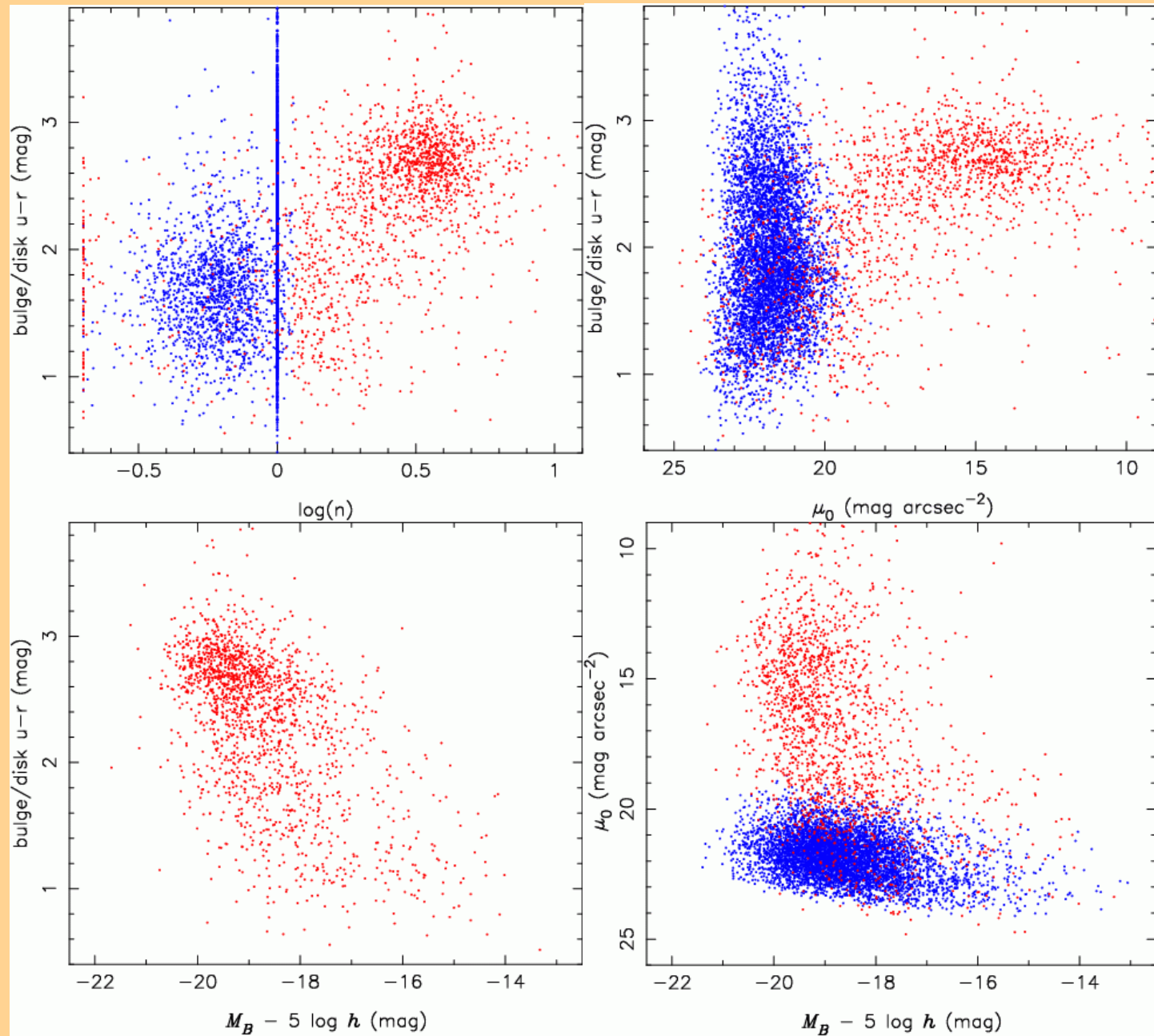


Sersic Bulges



Two types of bulges?

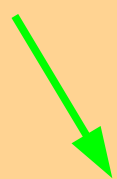
Disks
Bulges



Two types of bulges?

Disks

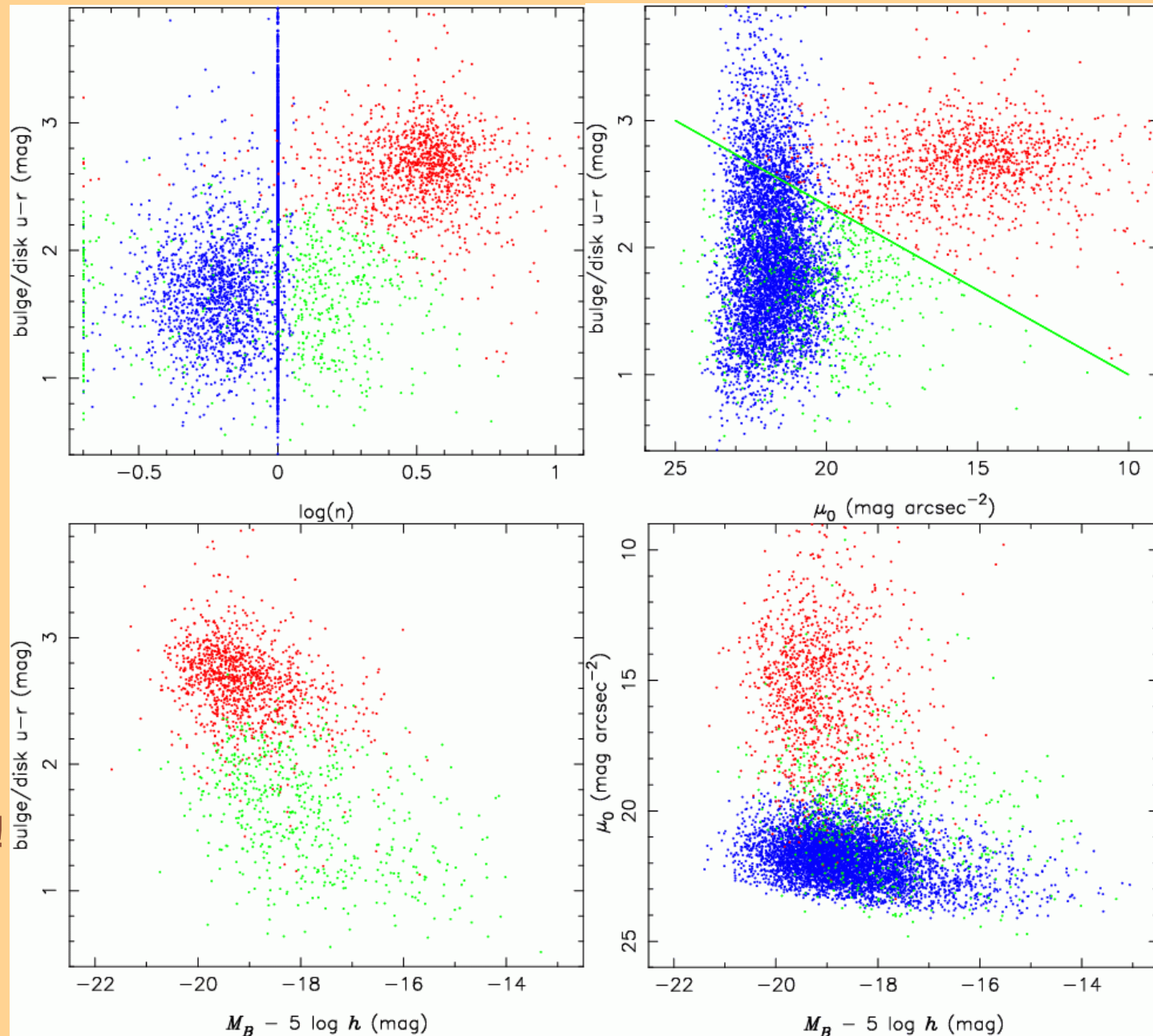
Bulges



'classical'
bulges

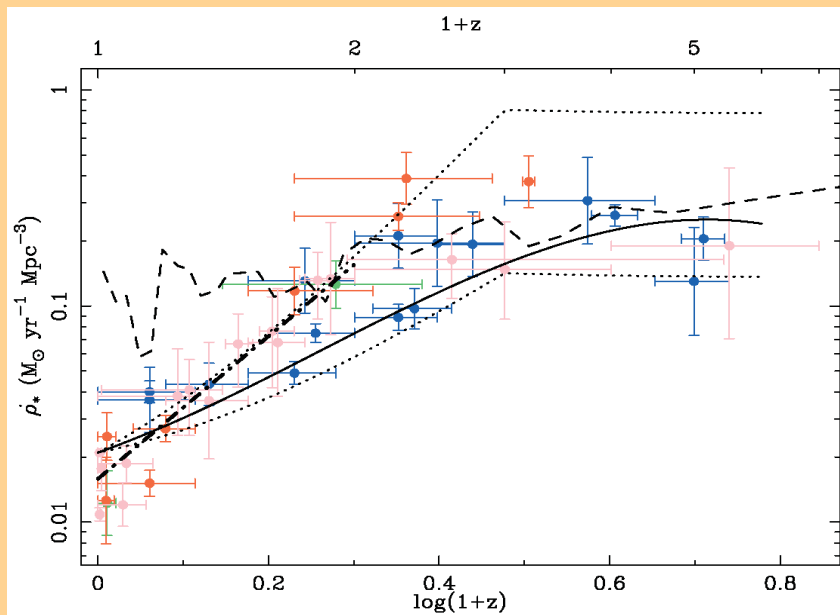
'pseudo'
bulges

Probably a
catch-all class!



Component luminosity functions

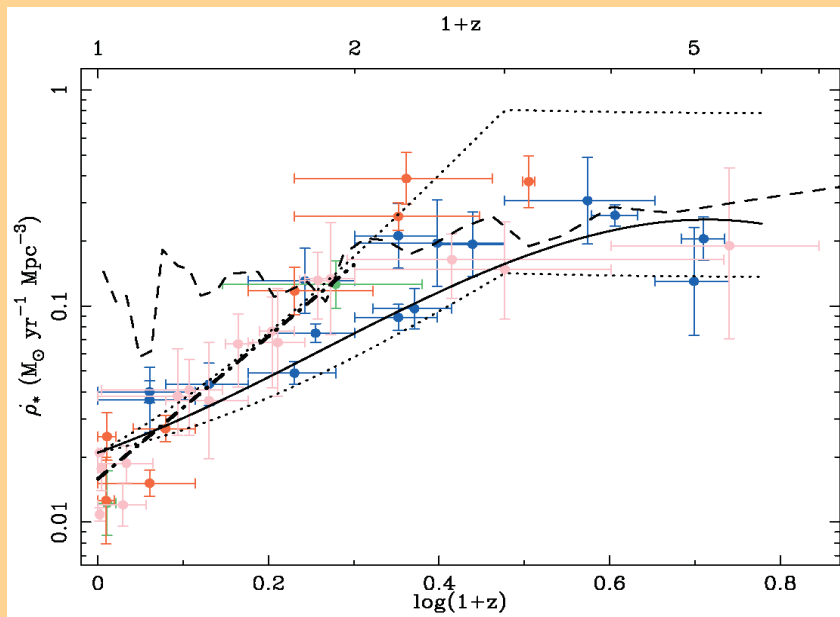
Global SFH tells us WHEN the bulk of present-day stars were formed. What structures did they assemble into? What is the relative importance of the formation mechanisms associated with these structures?



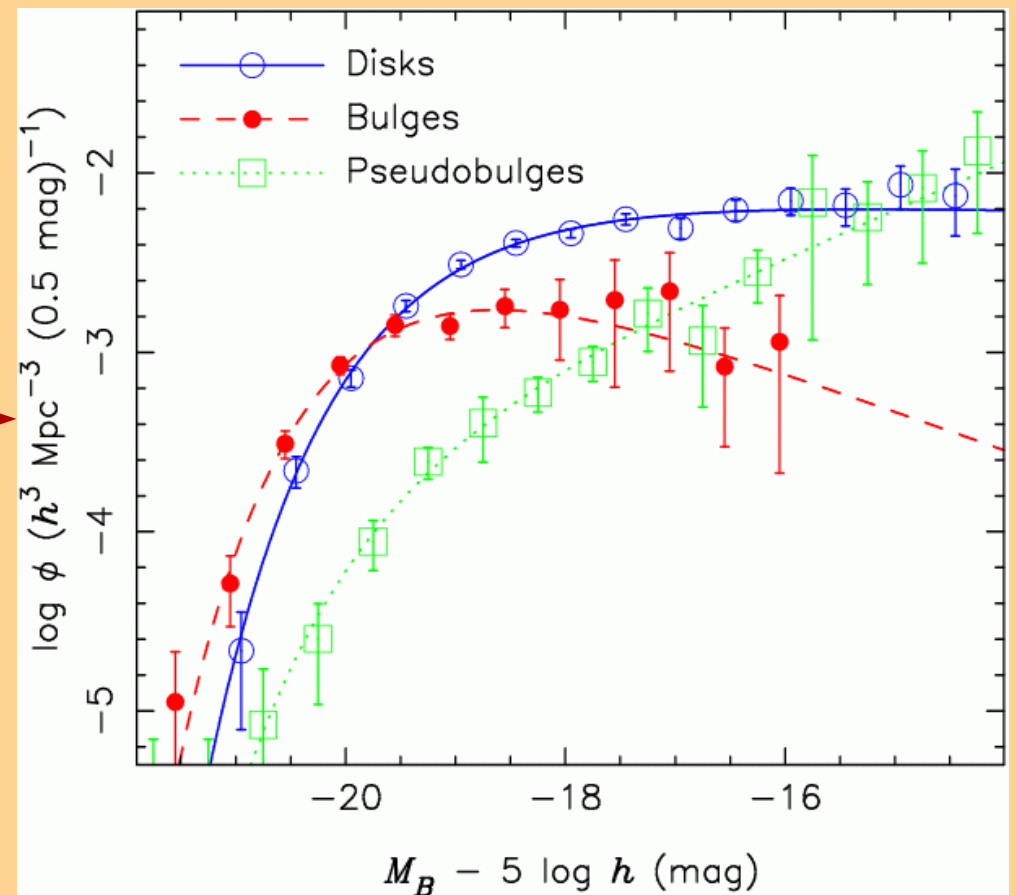
Hopkins (2004)

Component luminosity functions

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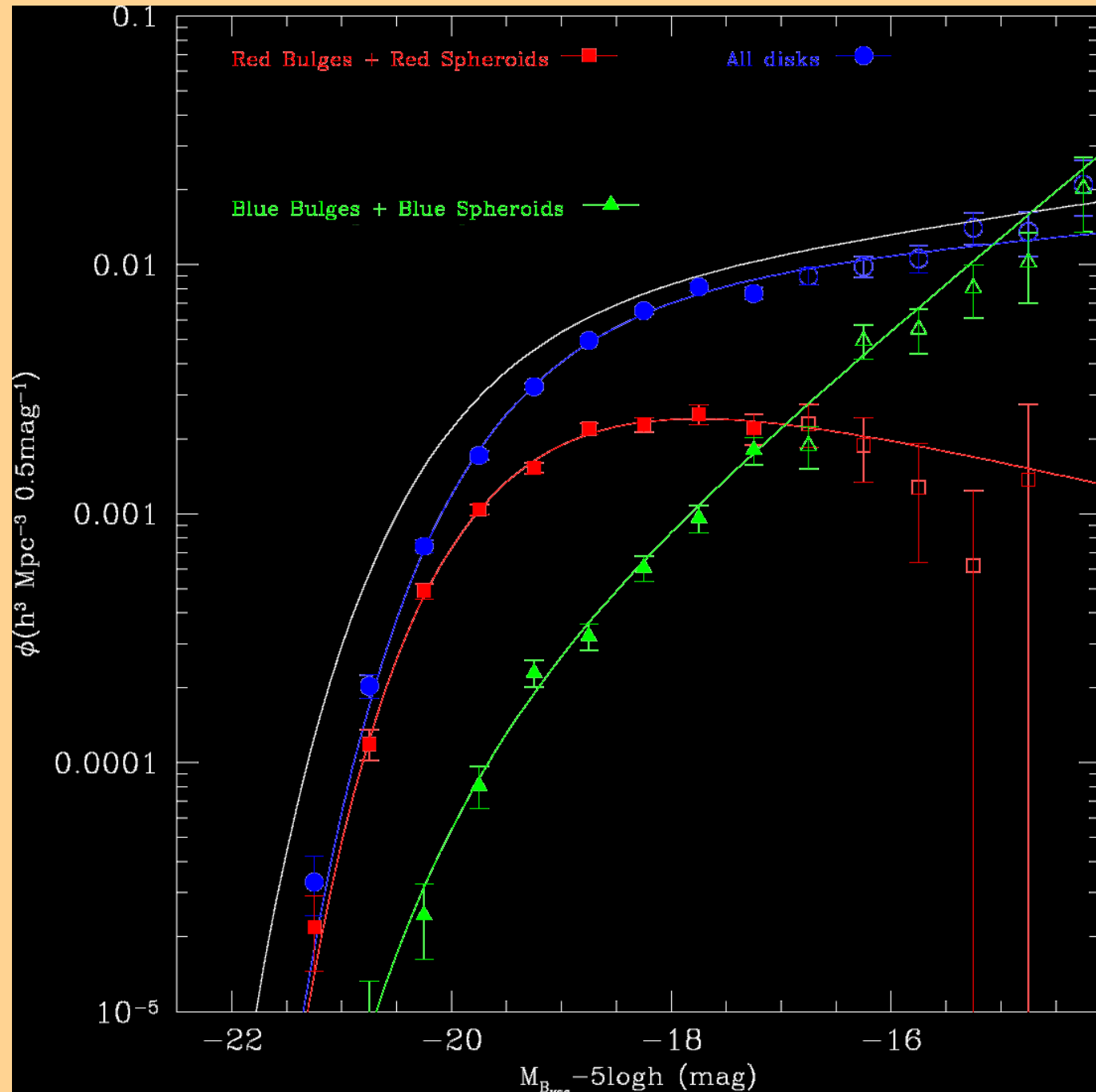
Hopkins (2004)



Component luminosity functions

Luminosity density:

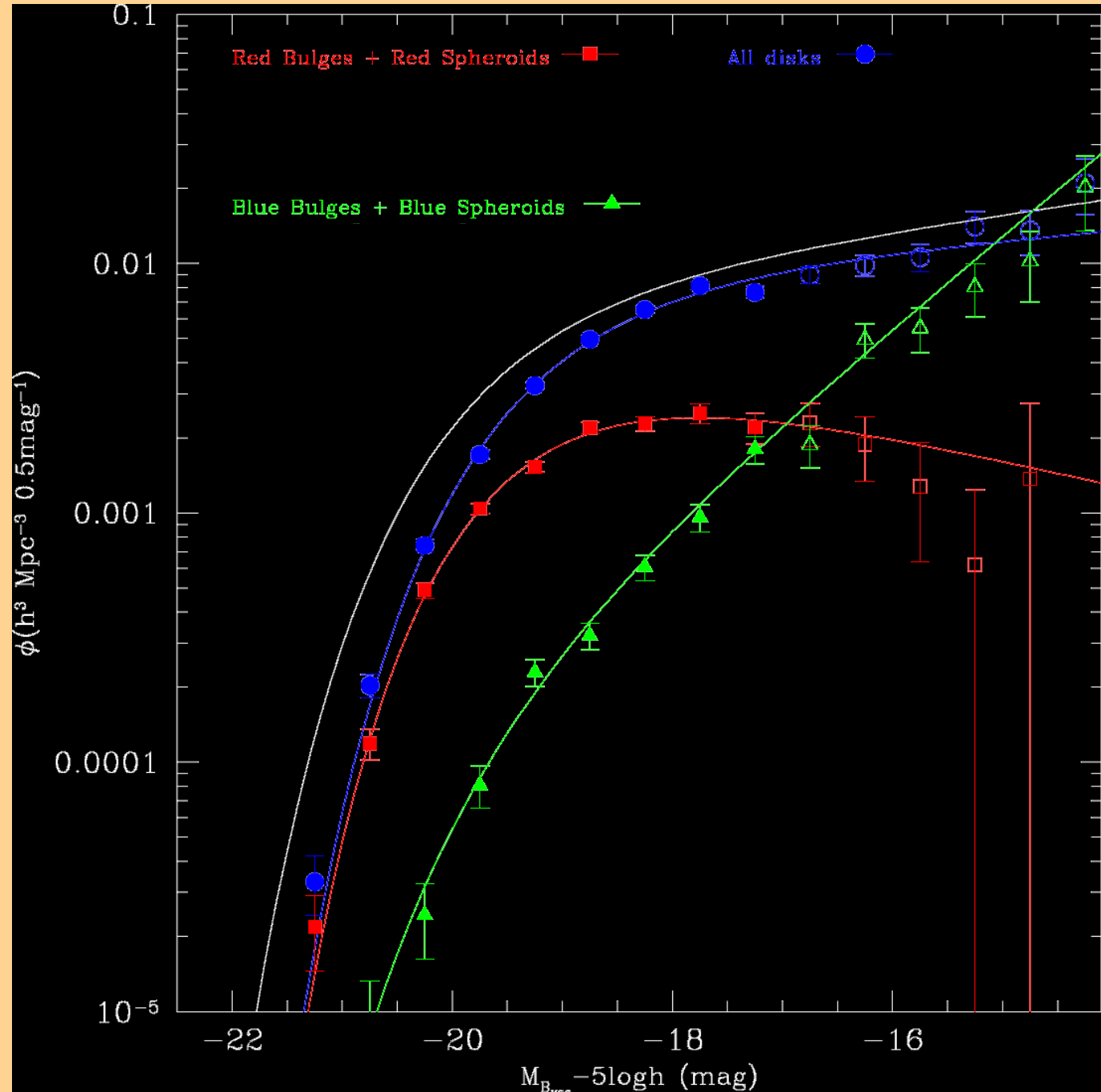
Disks	68%
Spheroids	32%
Bulges	19%
Ellipticals	13%
Red bulges	16%
Blue bulges	3%
Red ellipticals	10%
Blue ellipticals	3%
Red spheroids	26%
Blue spheroids	6%



Component luminosity functions

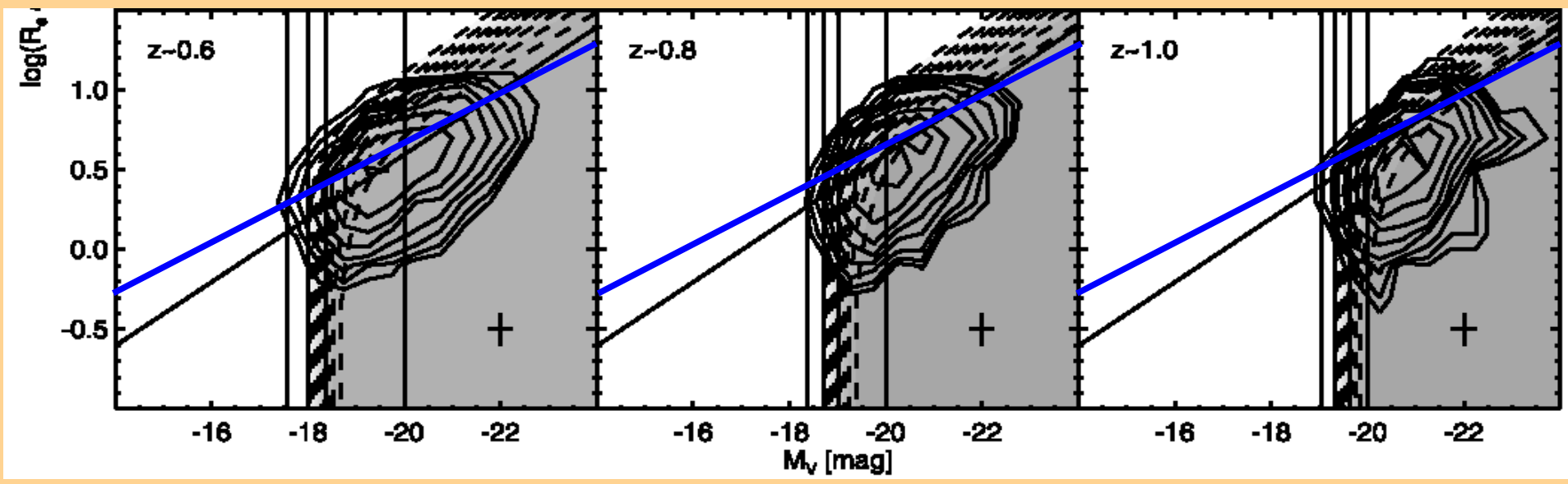
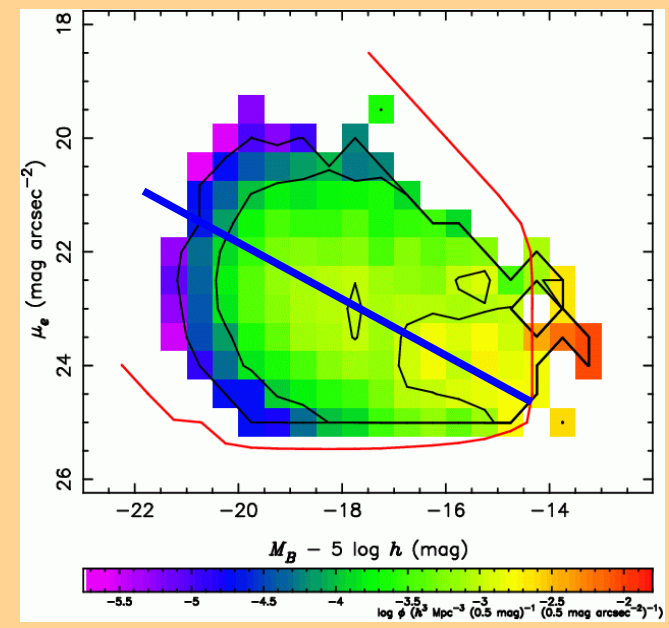
Stellar mass density:

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%



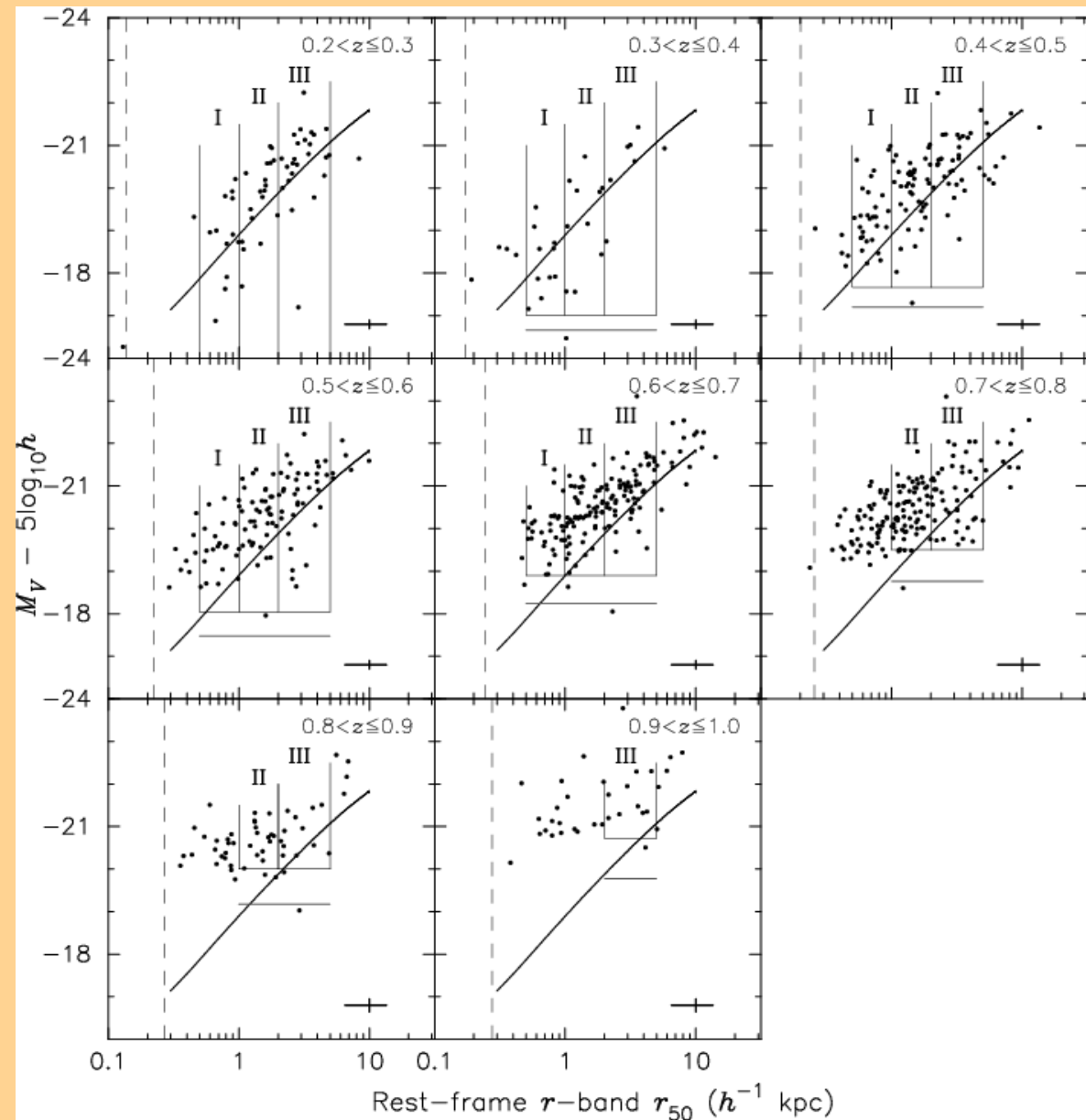
The luminosity-size relation of disks

- 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 produced disks that are far too small.)
- Barden et al. (2005) measure the L-R relation from GEMS/COMBO-17 data out $z \sim 1$.
- Comparing the local MGC relation with GEMS reveals an evolution $\sim 1 \text{ mag arcsec}^{-2}$ out to $z \sim 1$.
- This appears to be consistent with hierarchical models. BUT: need to convert to stellar mass.



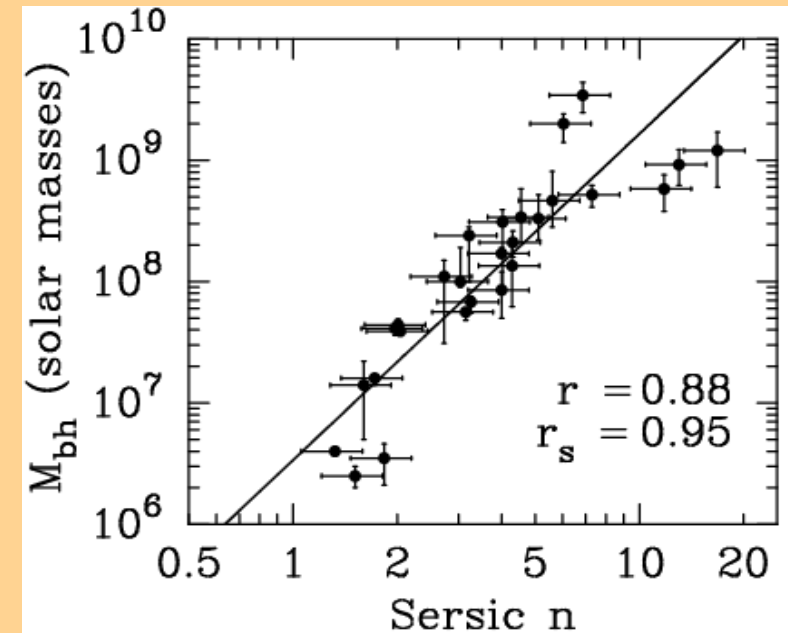
The luminosity-size relation of spheroids

- 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.

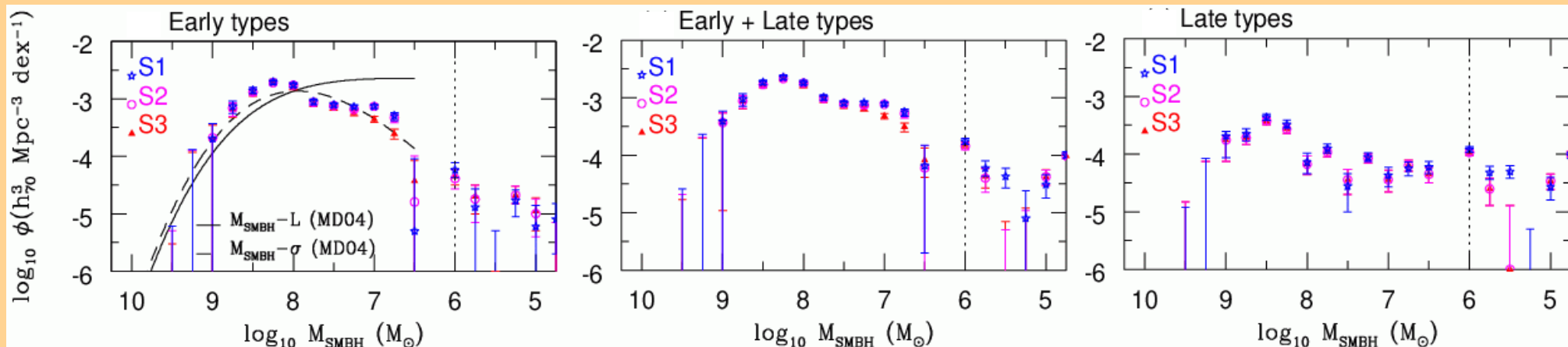


The mass function of SMBH

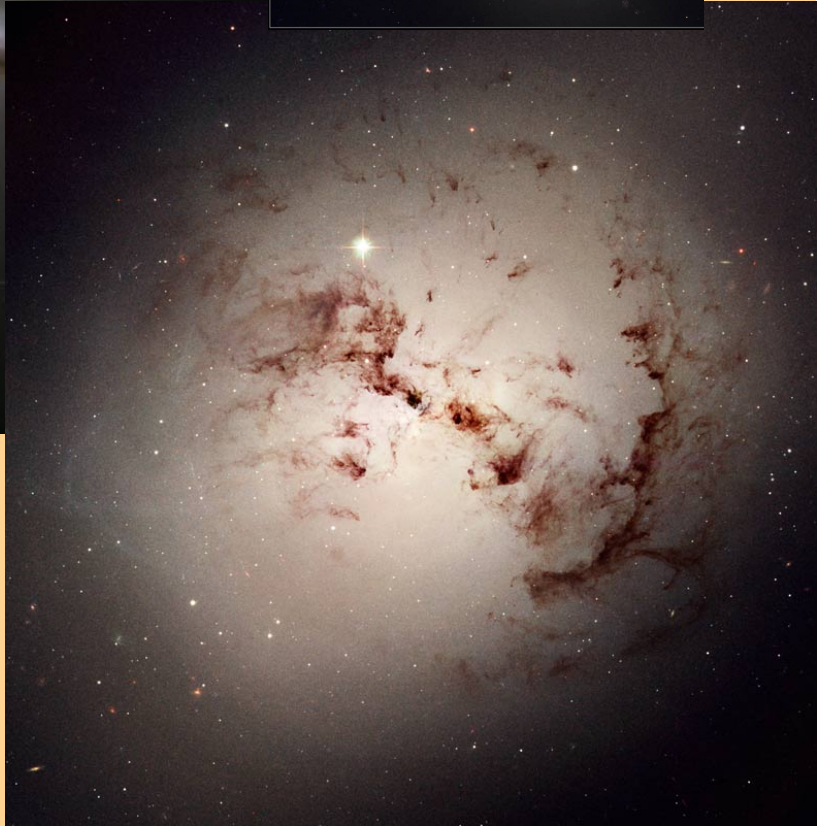
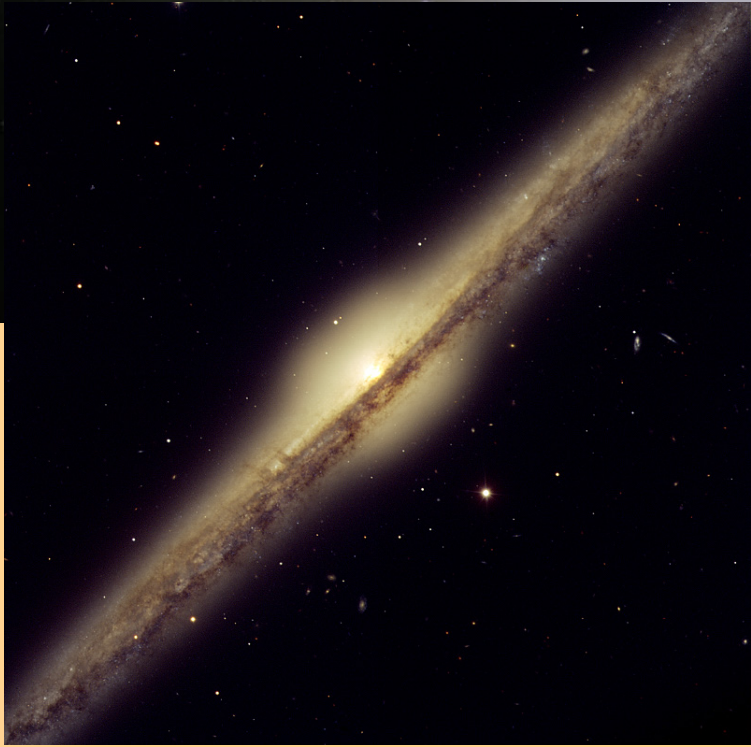
- Feedback from SMBH is currently the favoured process to curtail SF in massive galaxies.
 - The present-day mass function of SMBH tells how much material has been accreted in the past.
 - Combined with the luminosity function of QSOs one can estimate their average efficiency.
 - M_{SMBH} not only correlates with σ and L_{bulge} but also with Sersic index.
 - Use n-distribution to obtain mass function of SMBHs.
- $\Omega_{\text{SMBH}} = (3.8 \pm 1.3) \times 10^{-6} h$



Graham et al. (2006)



What about dust?



What about dust?

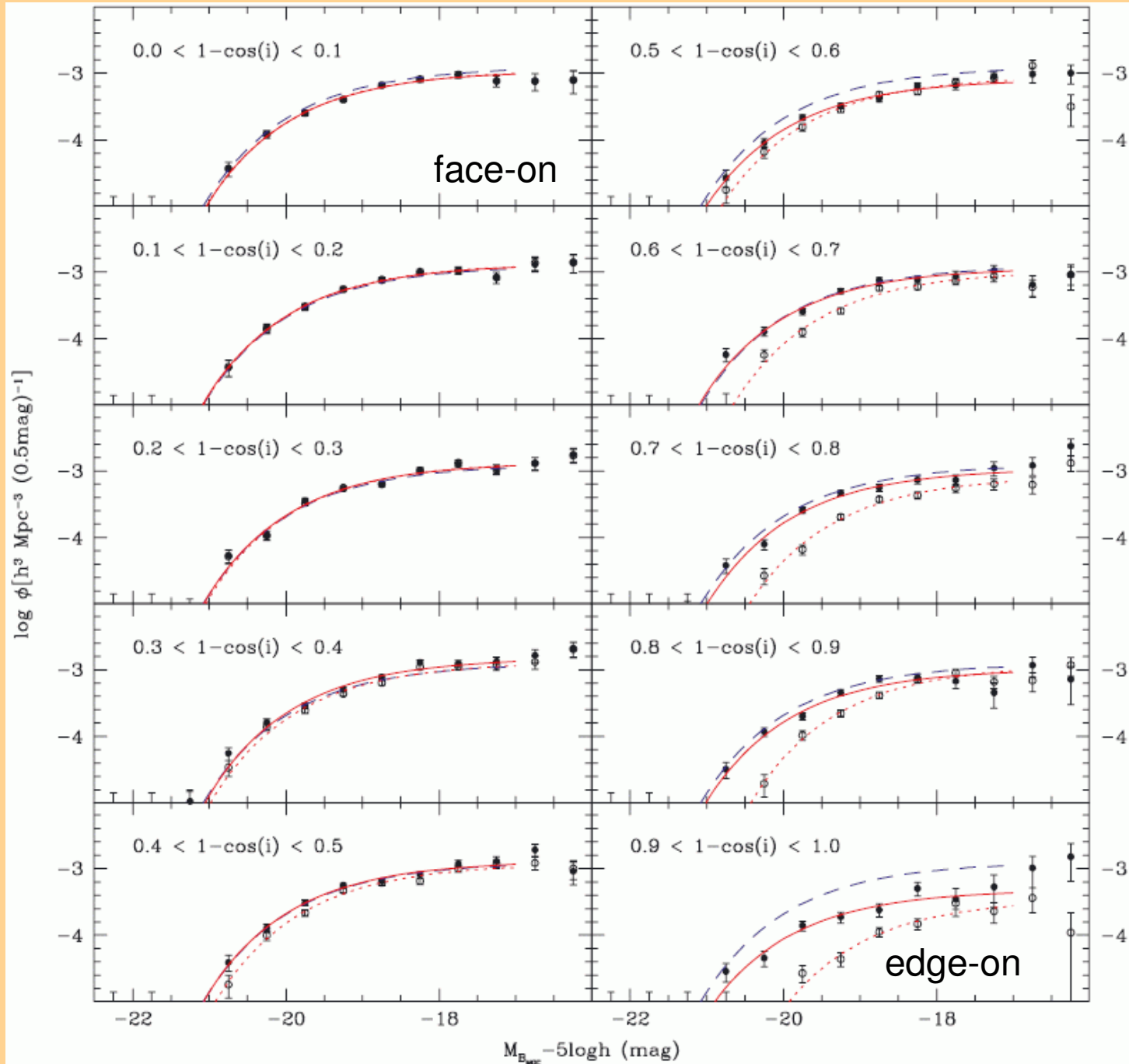
- Dust in the disks of galaxies may severely affect all photometric measurements (mags, colours), stellar mass, size, morphology, SB profile...
- (Spheroids are assumed to be dust-free.)
- **To what extent does dust distort our view of galaxies?**
- The Holmberg test: disk galaxy properties as a function 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

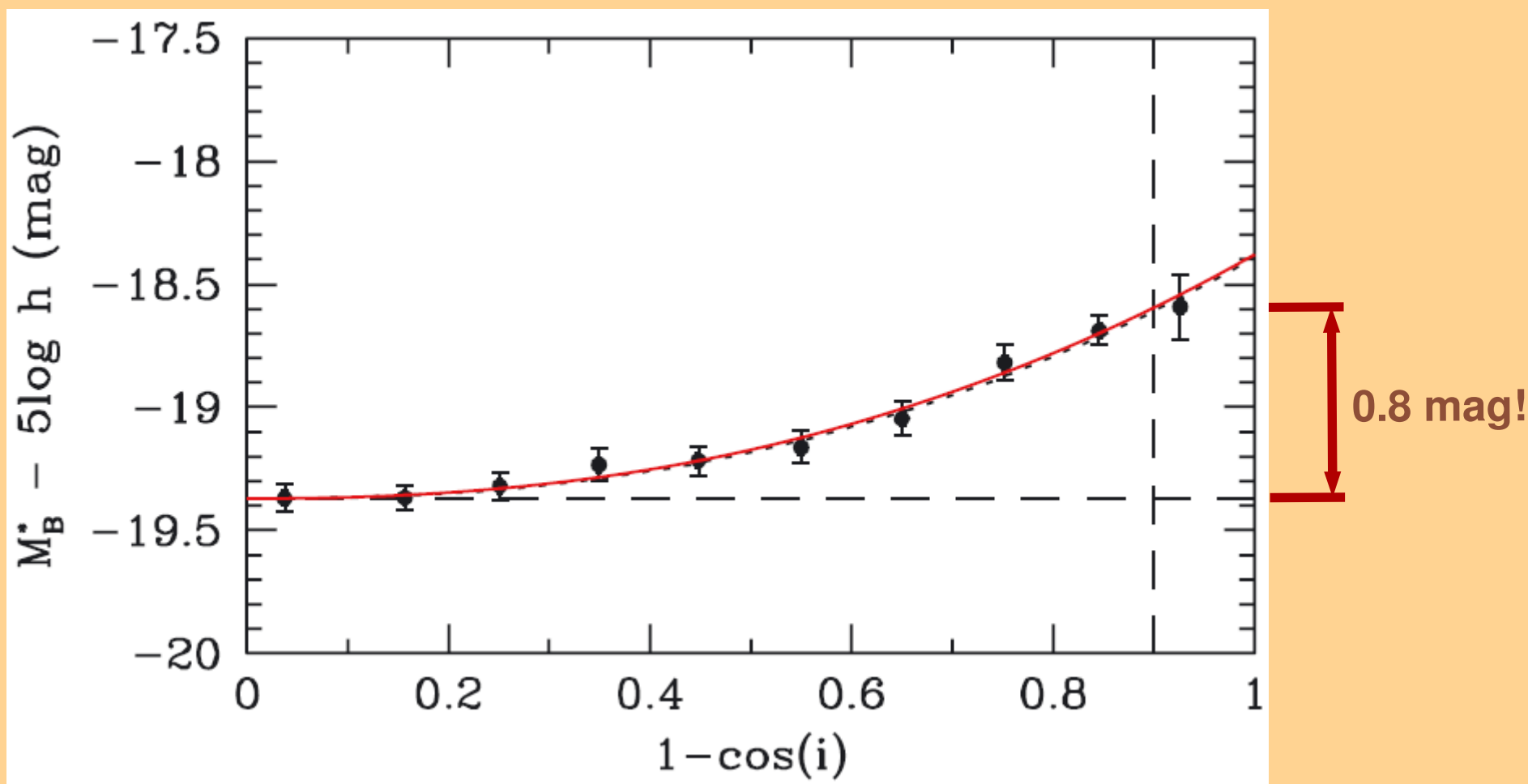
Red dotted line:
measured LF

Red solid line:
corrected LF

Blue dashed line:
face-on sample

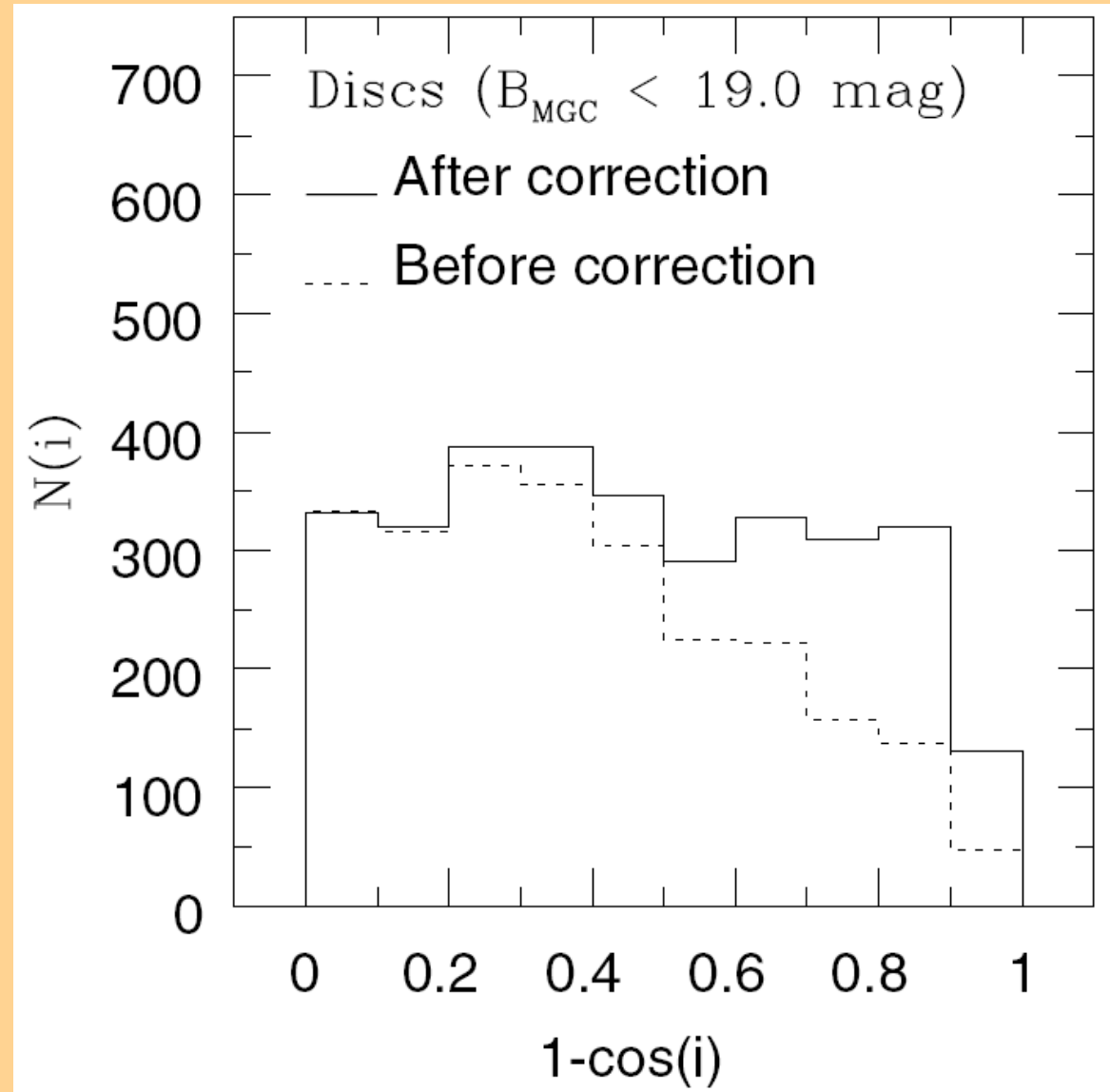


Disk attenuation-inclination relation



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:

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

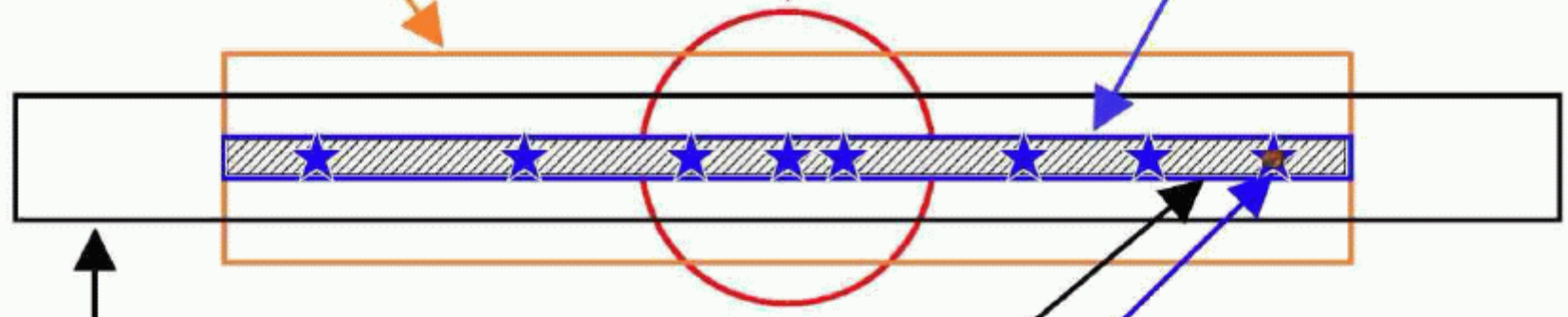
$$B = \frac{\sqrt{R^2 + z^2 (a/b)^2}}{R_e}$$

Old stellar disk:

$$\eta(\lambda, R, z) = \eta^{\text{disk}}(\lambda, 0, 0) \exp\left(-\frac{R}{h_s^{\text{disk}}} - \frac{|z|}{z_s^{\text{disk}}}\right)$$

Young stellar disk:

$$\eta^{\text{tdisk}}(\lambda, R, z) = \eta^{\text{tdisk}}(\lambda, 0, 0) \exp\left(-\frac{R}{h_s^{\text{tdisk}}} - \frac{|z|}{z_s^{\text{tdisk}}}\right)$$



Dust disk associated with the old stellar disk:

$$\kappa_{\text{ext}}^{\text{disk}}(\lambda, R, z) = \kappa_{\text{ext}}^{\text{disk}}(\lambda, 0, 0) \exp\left(-\frac{R}{h_d^{\text{disk}}} - \frac{|z|}{z_d^{\text{disk}}}\right)$$

Clumpy component



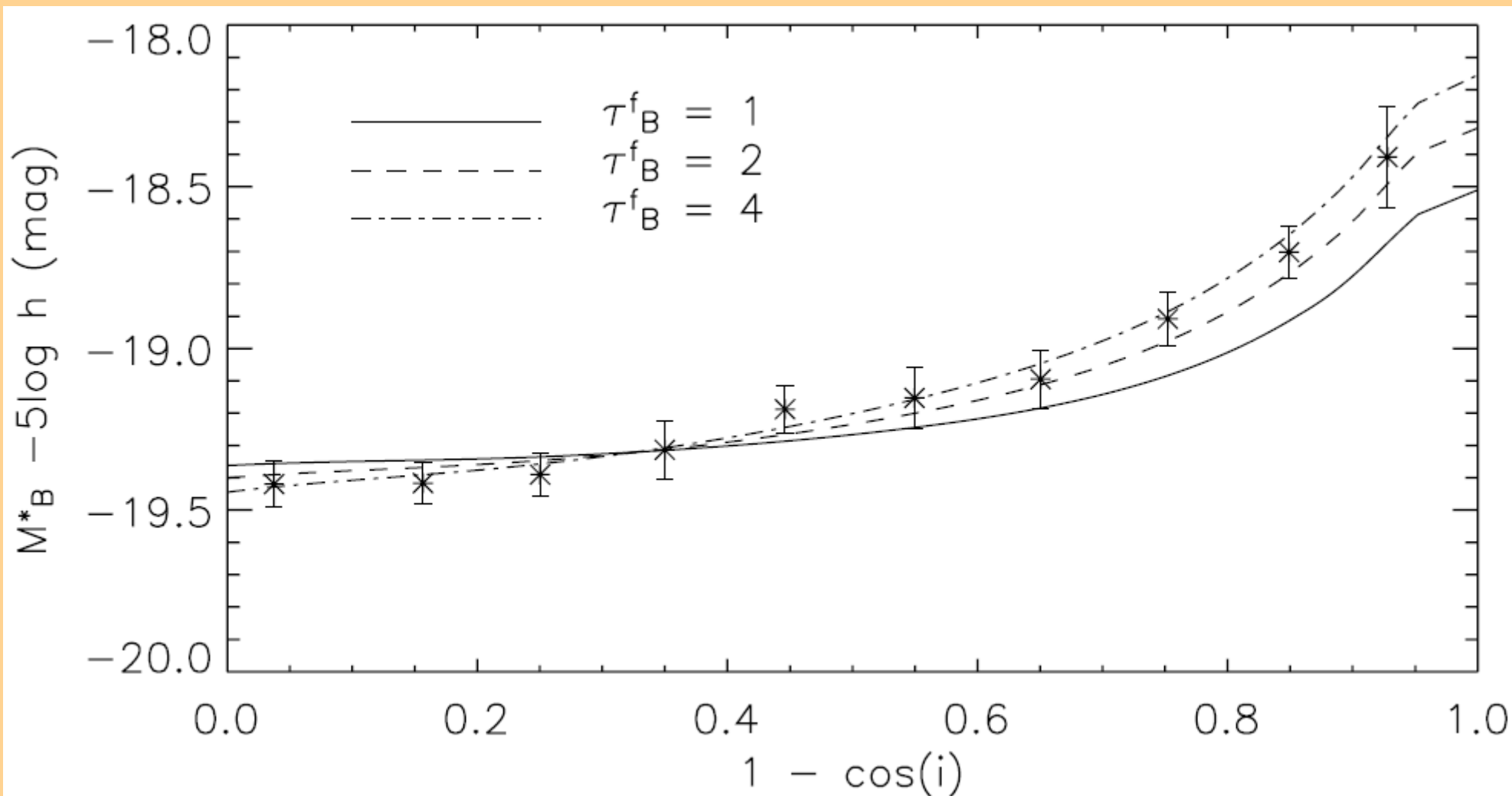
Based on UV+optical+NIR
+Spitzer data of 6 very nearby
galaxies.

Dust disk associated with the young stellar disk:

$$\kappa_{\text{ext}}^{\text{tdisk}}(\lambda, R, z) = \kappa_{\text{ext}}^{\text{tdisk}}(\lambda, 0, 0) \exp\left(-\frac{R}{h_d^{\text{tdisk}}} - \frac{|z|}{z_d^{\text{tdisk}}}\right)$$

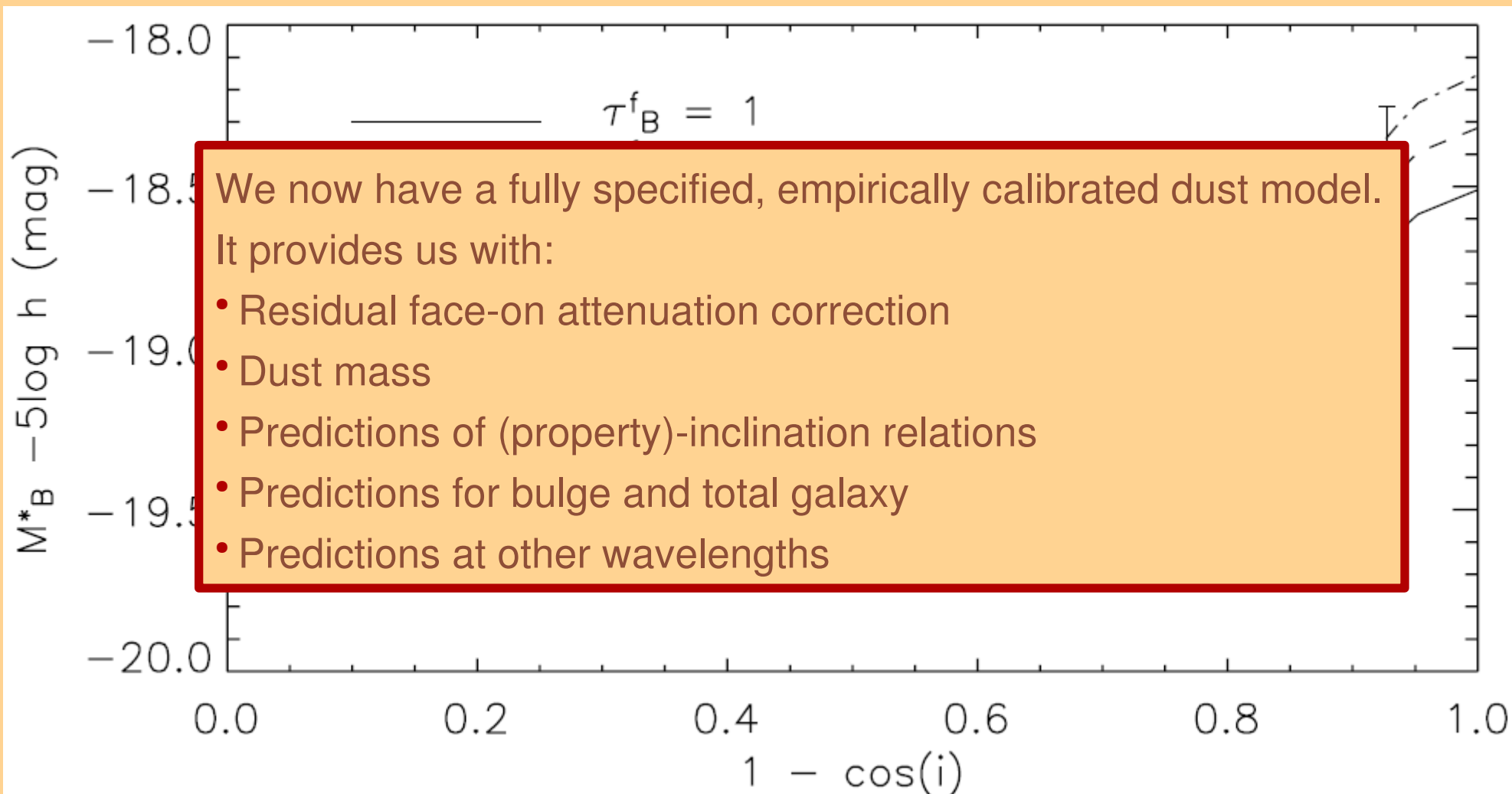
Modeling the dust

- The Popescu & Tuffs model has only one free parameter: the central face-on B-band optical depth.
- Best-fit $\tau_B^f = 3.8 \pm 0.7$
- Note: popular $\tau = 1$, one dust-disk models fail miserably!



Modeling the dust

- The Popescu & Tuffs model has only one free parameter: the central face-on B-band optical depth.
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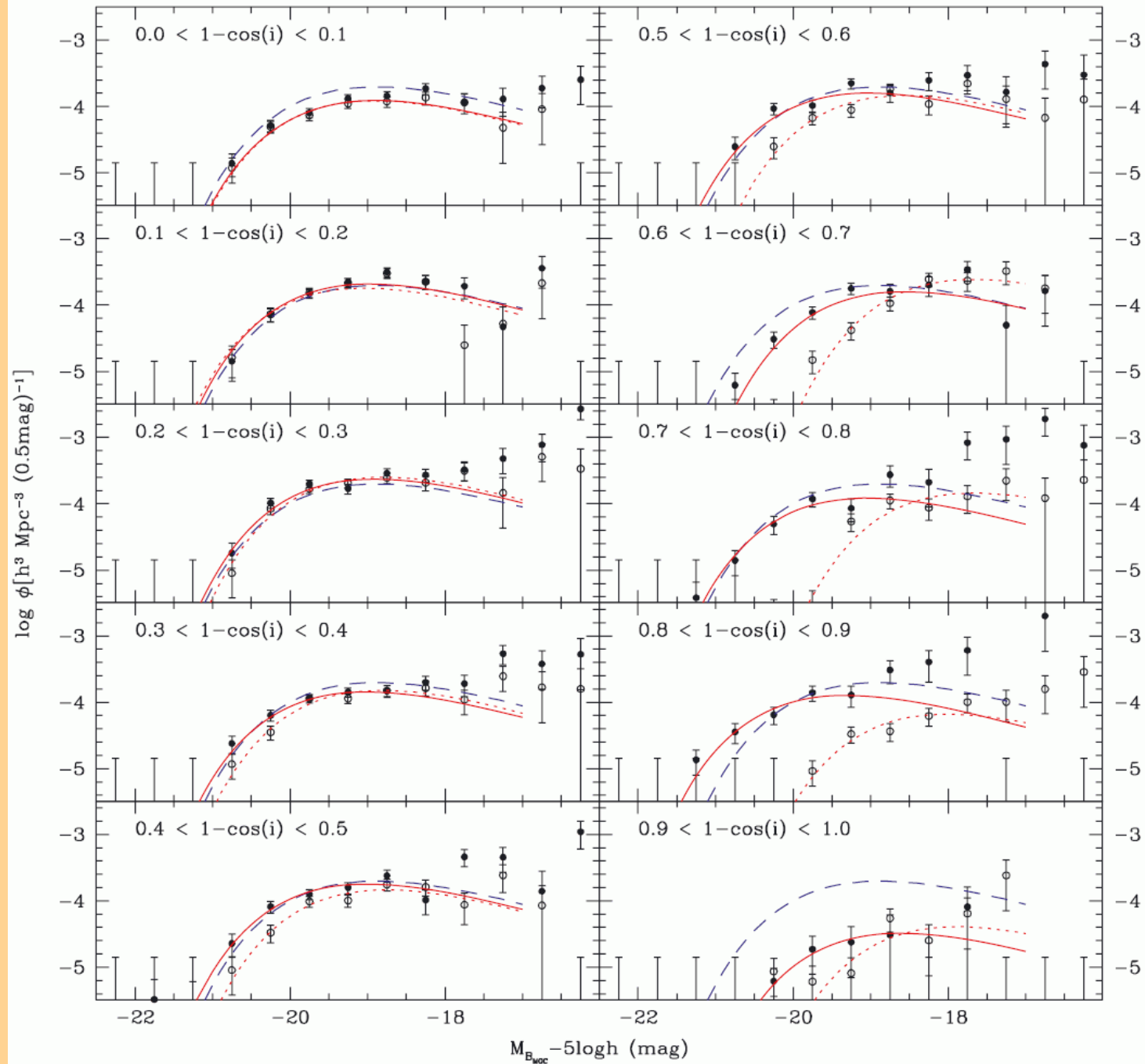


Bulge LF versus inclination

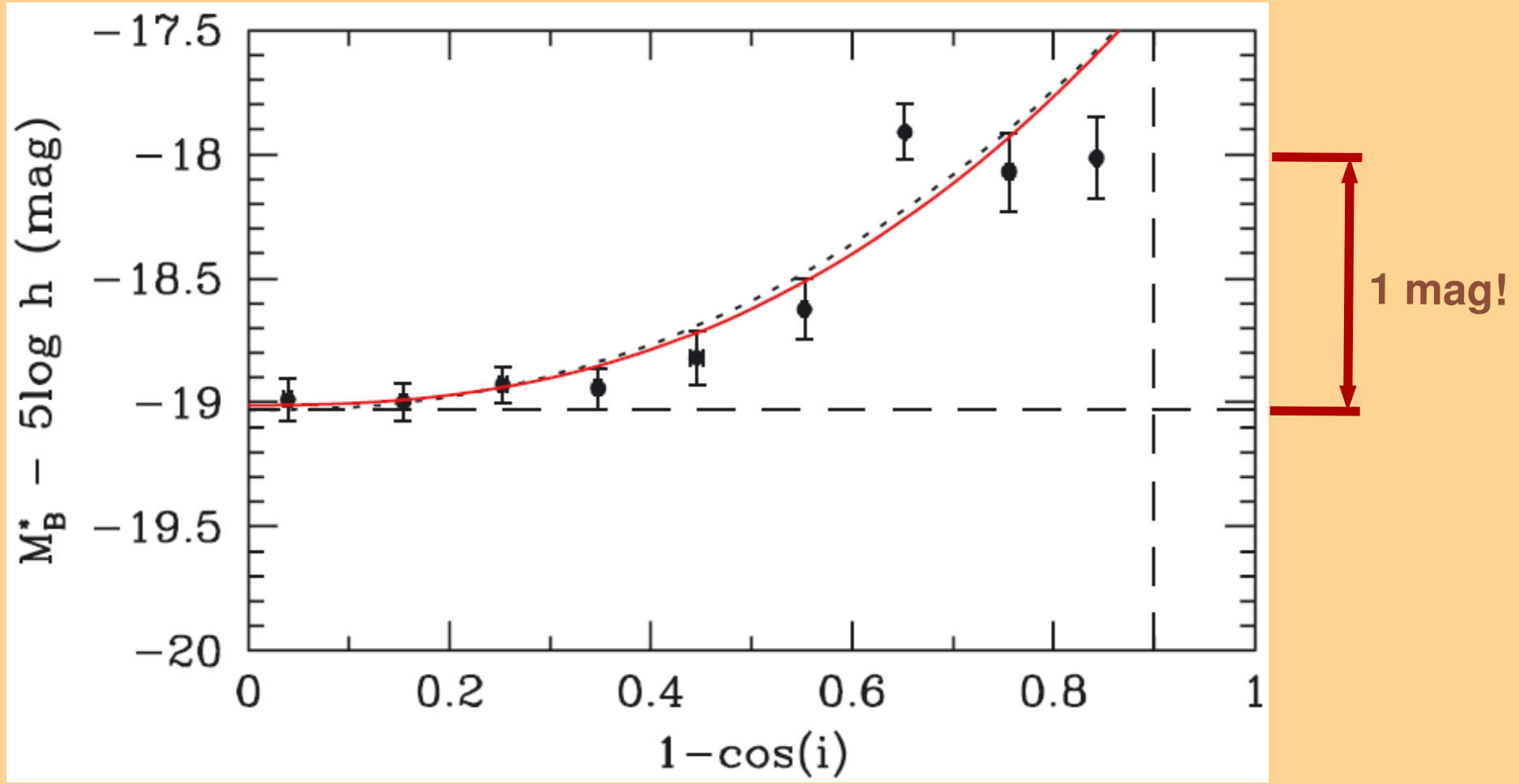
Red dotted line:
measured LF

Red solid line:
corrected LF

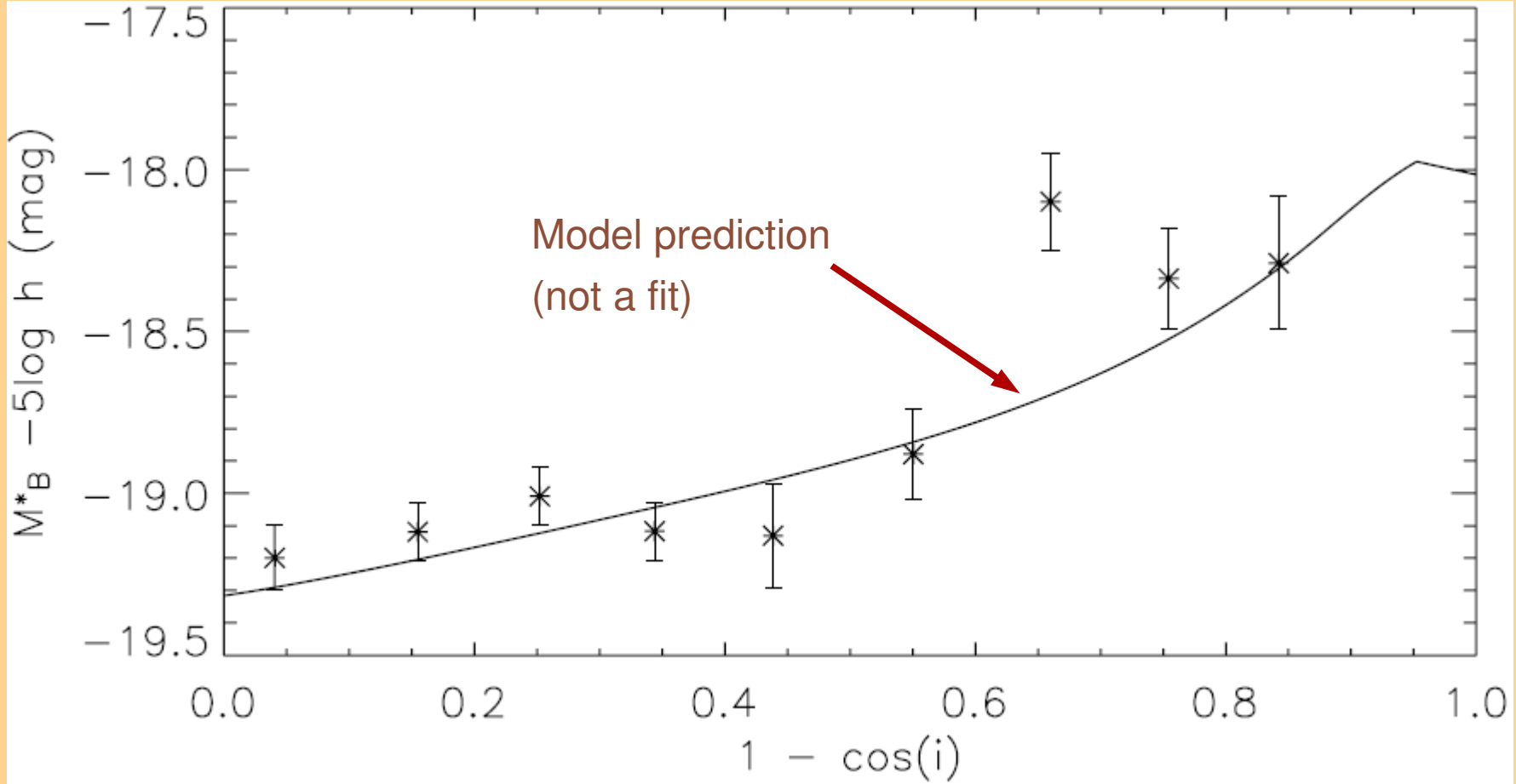
Blue dashed line:
face-on sample



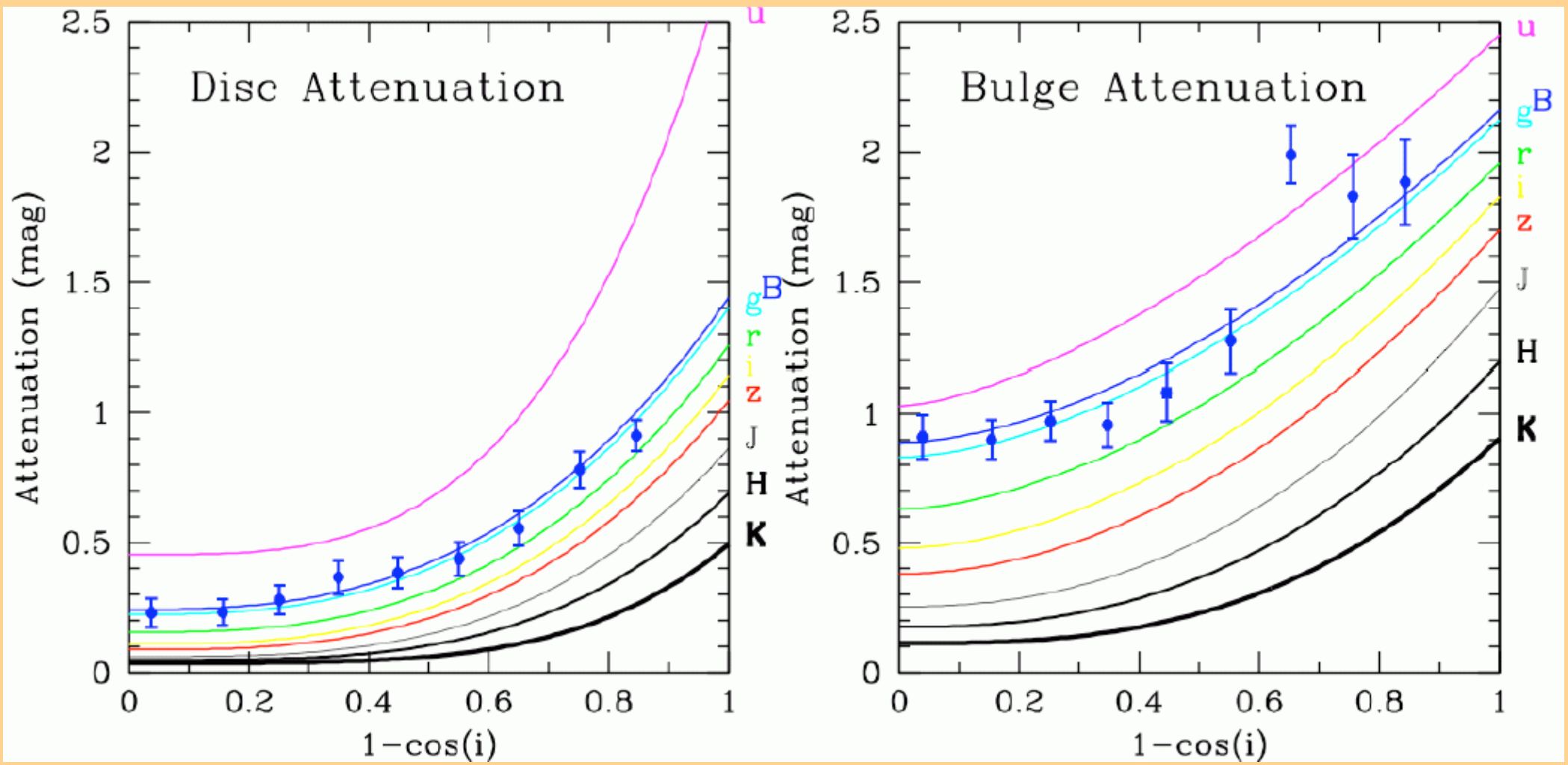
Bulge attenuation-inclination relation



Bulge attenuation-inclination relation



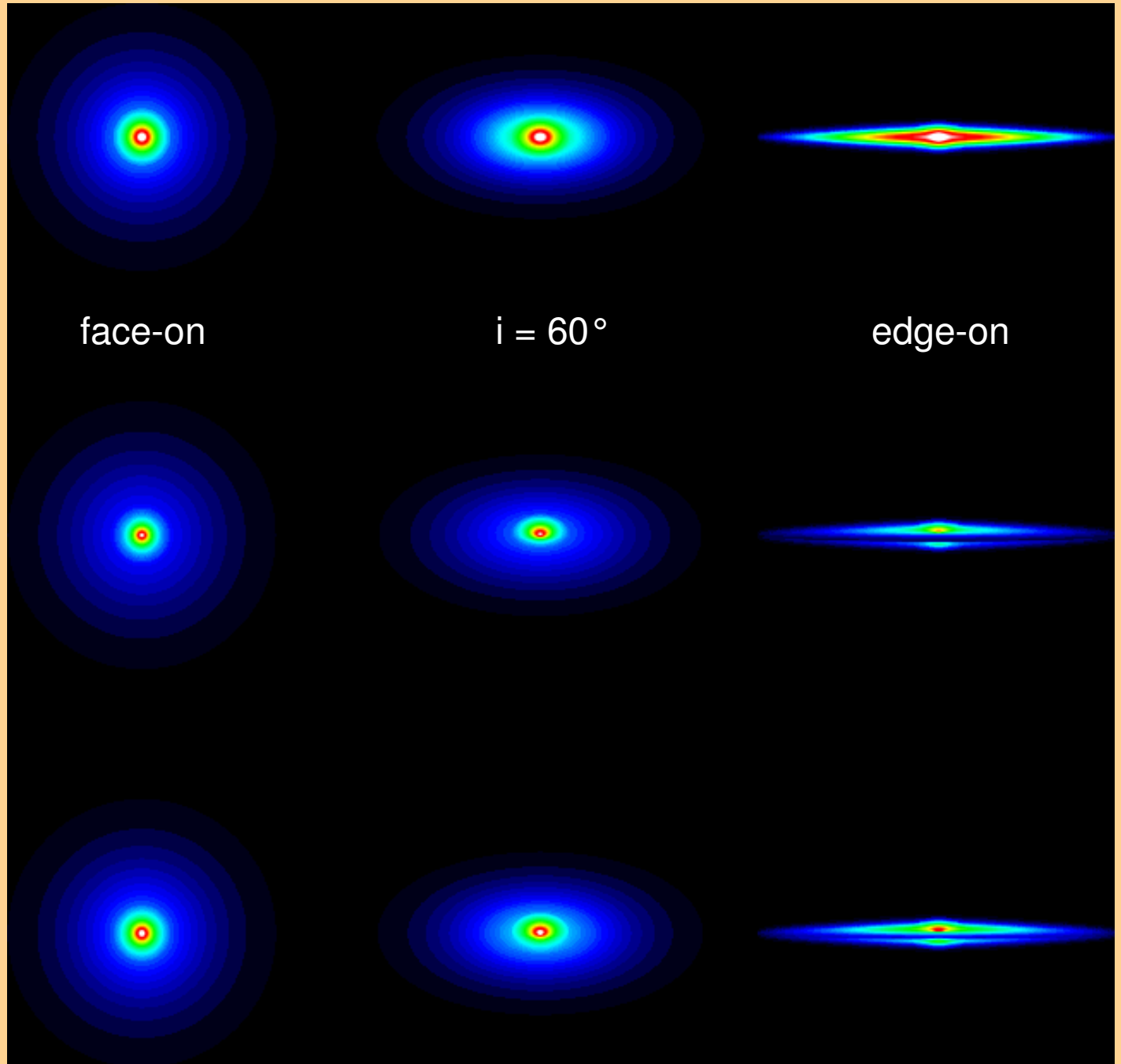
Total attenuation



Face-on B-band disk attenuation = 0.2 mag
 Face-on B-band bulge attenuation = 0.88 mag (!)

A model galaxy

No dust



face-on

$i = 60^\circ$

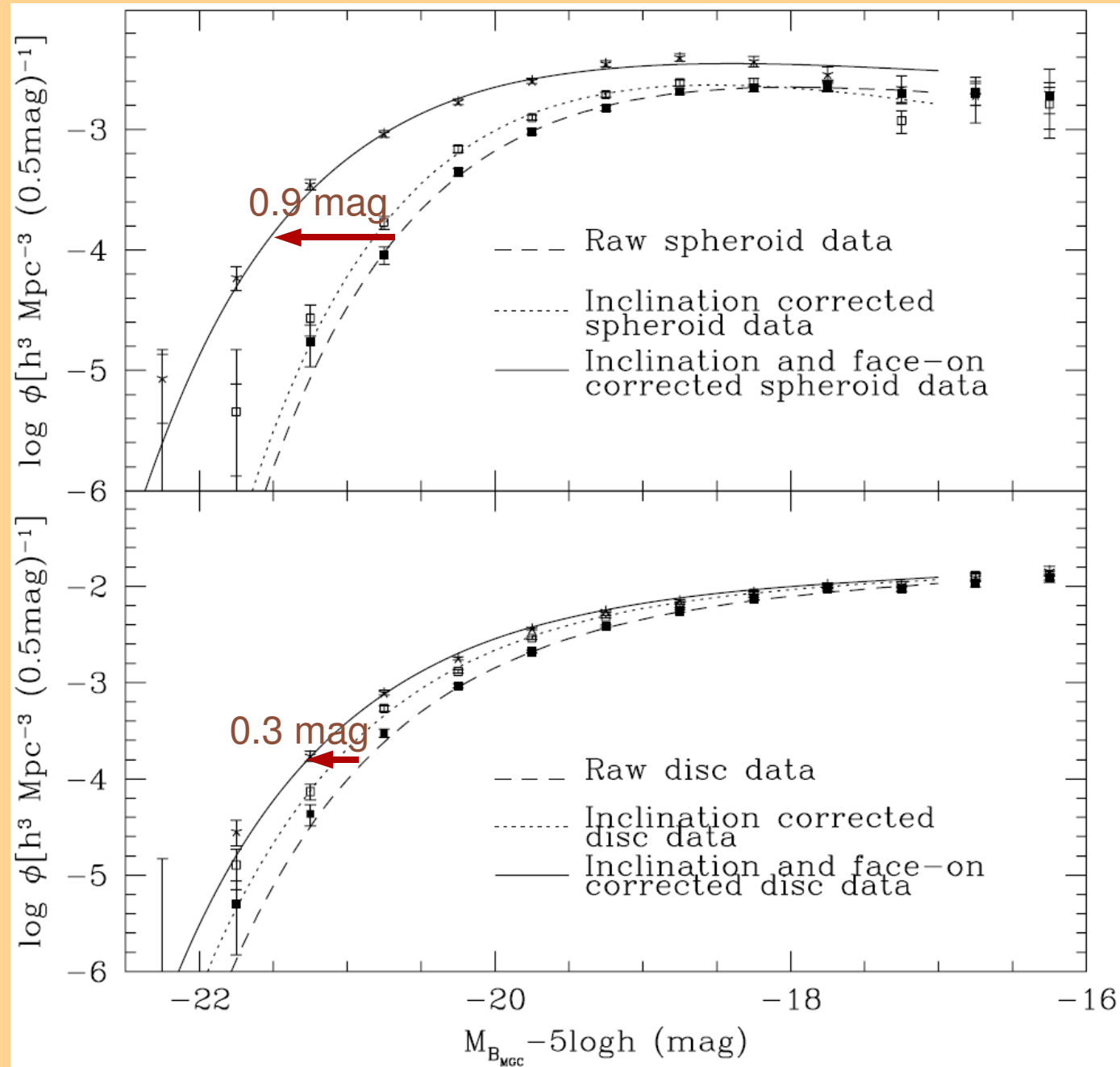
edge-on

B-band

K-band

Corrected component LFs

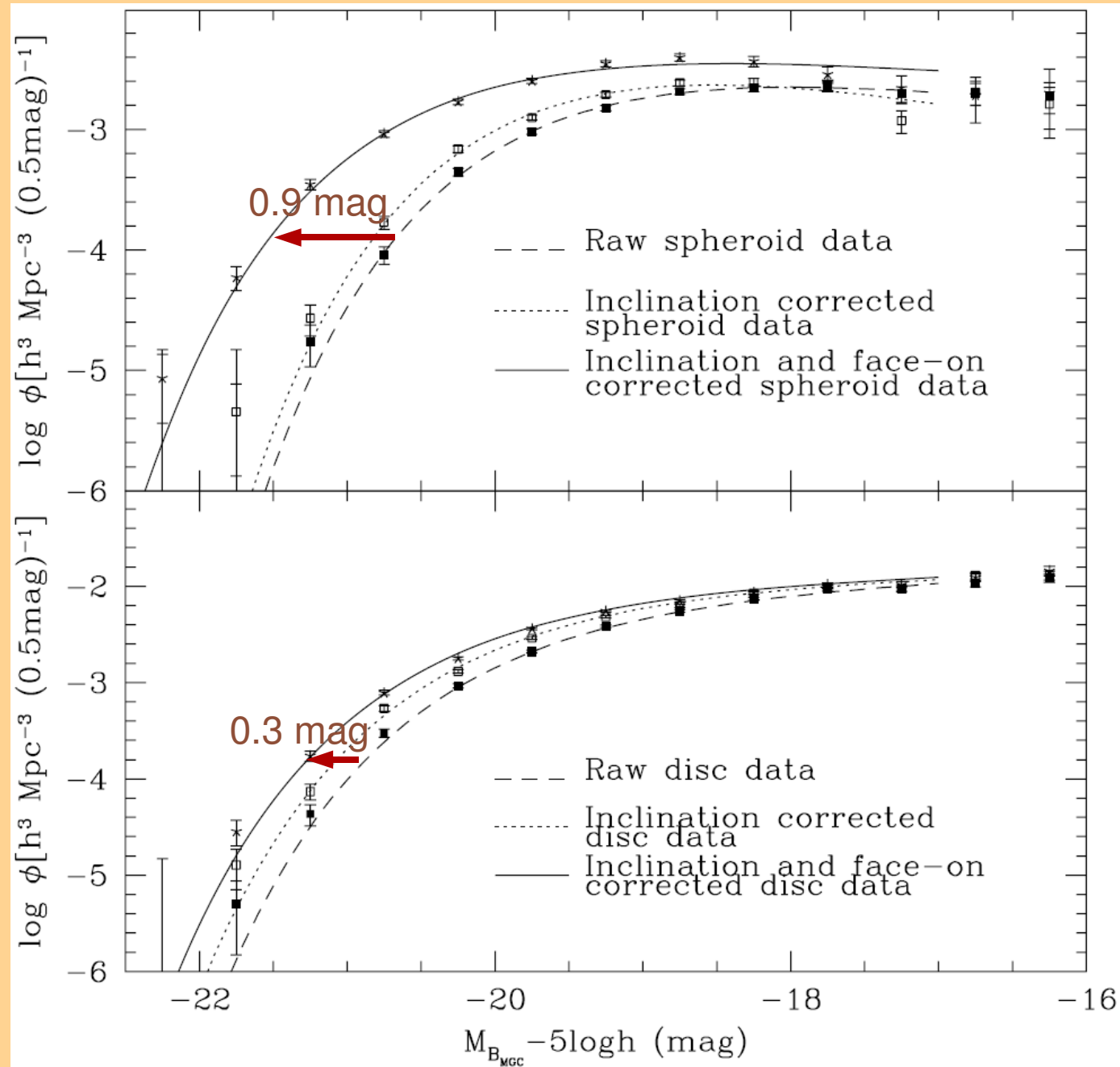
Luminosity density:
 Disks: up by 59%
 Bulges: up by 230%!
 Ellipticals: no change



Corrected component LFs

Stellar mass density:
 Disks: up by 16%
 Bulges: up by 38%
 Ellipticals: no change

Total: up by 19%



Corrected component LFs

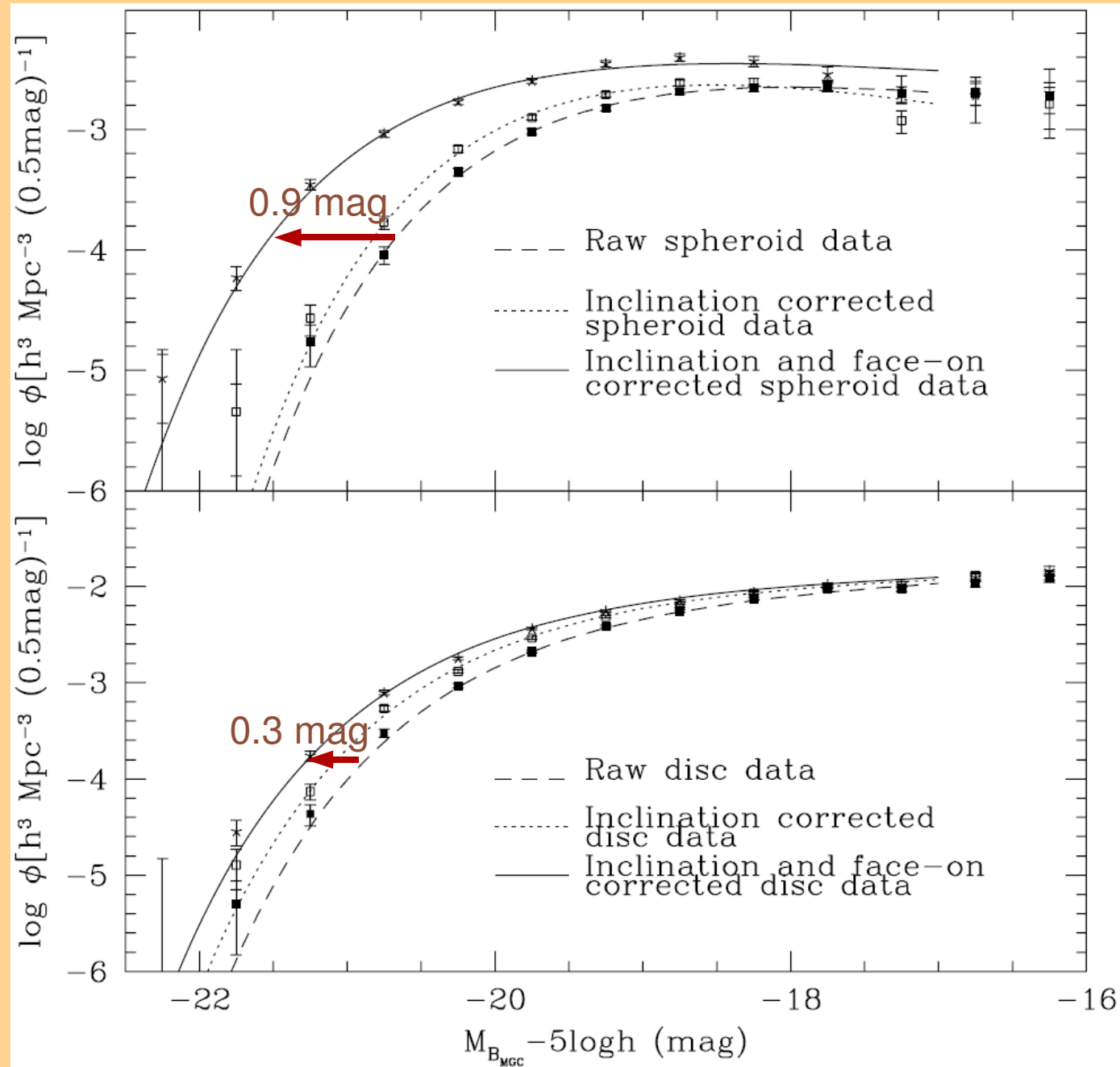
Stellar mass density split:

Disks: 58 → 58%

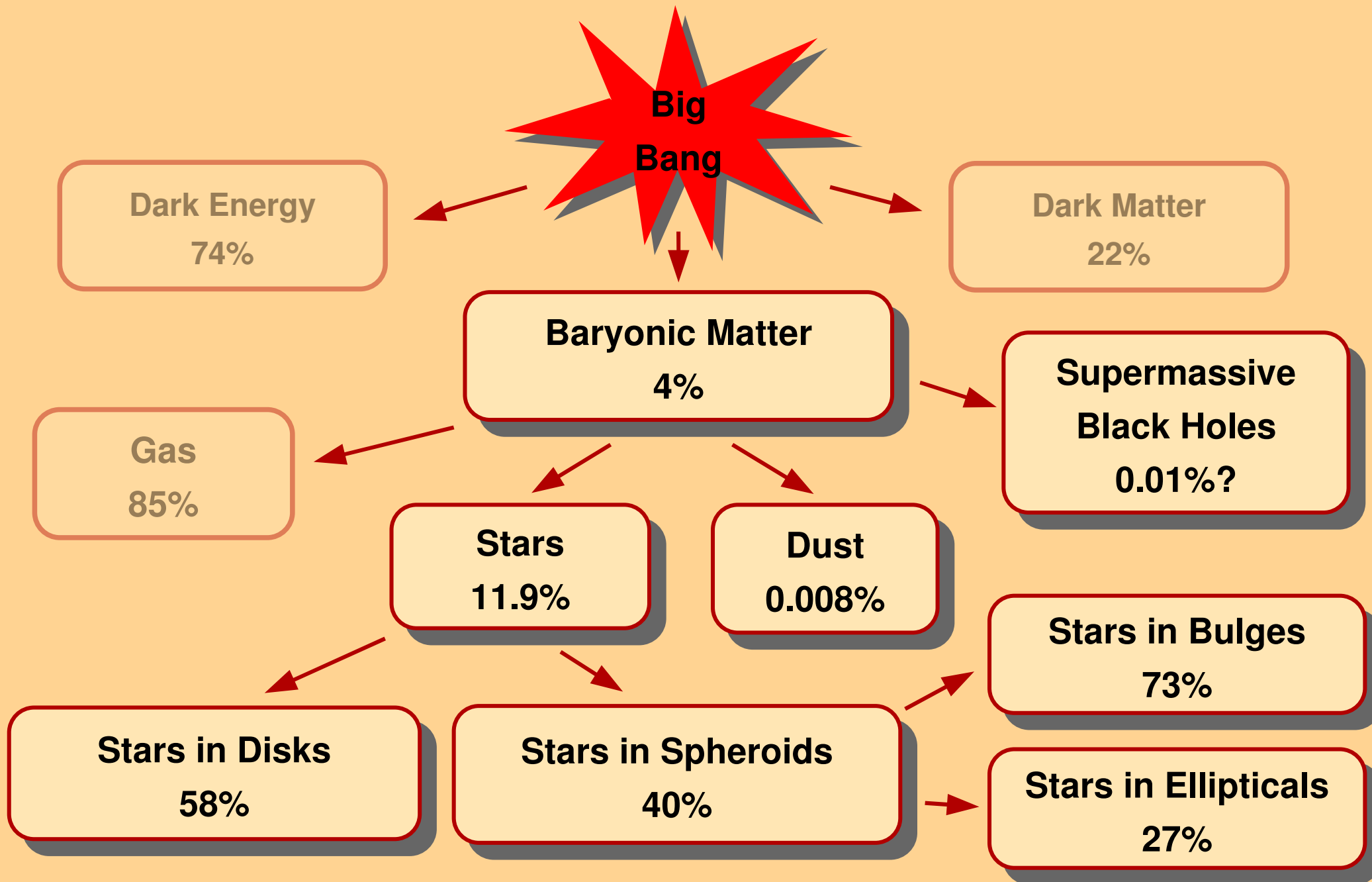
Bulges: 26 → 29%

Ellipticals: 13 → 10.5%

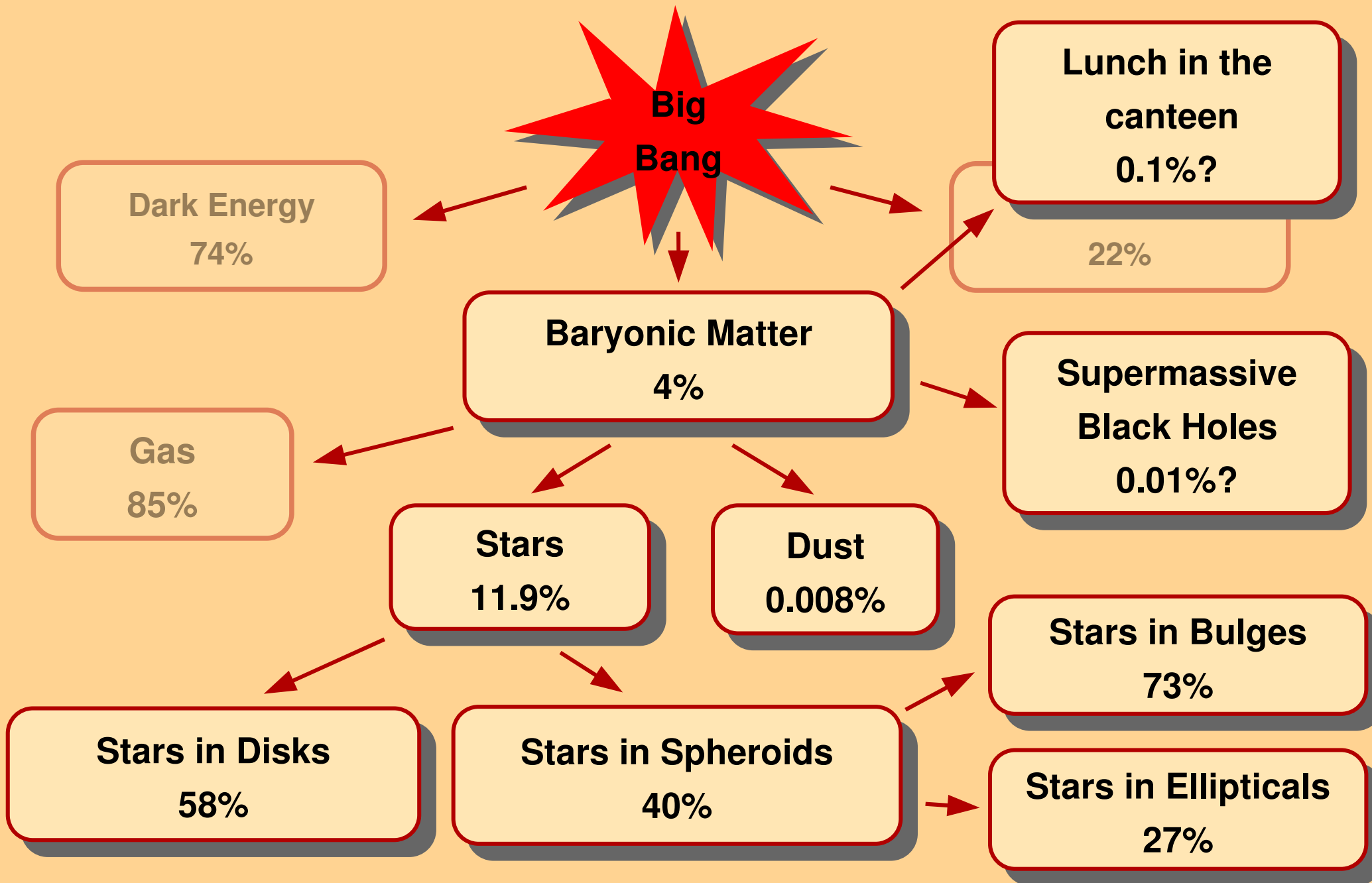
Blue spheroids: 3 → 2.5%



The cosmic mass budget



The cosmic mass budget



Corrected total galaxy LF

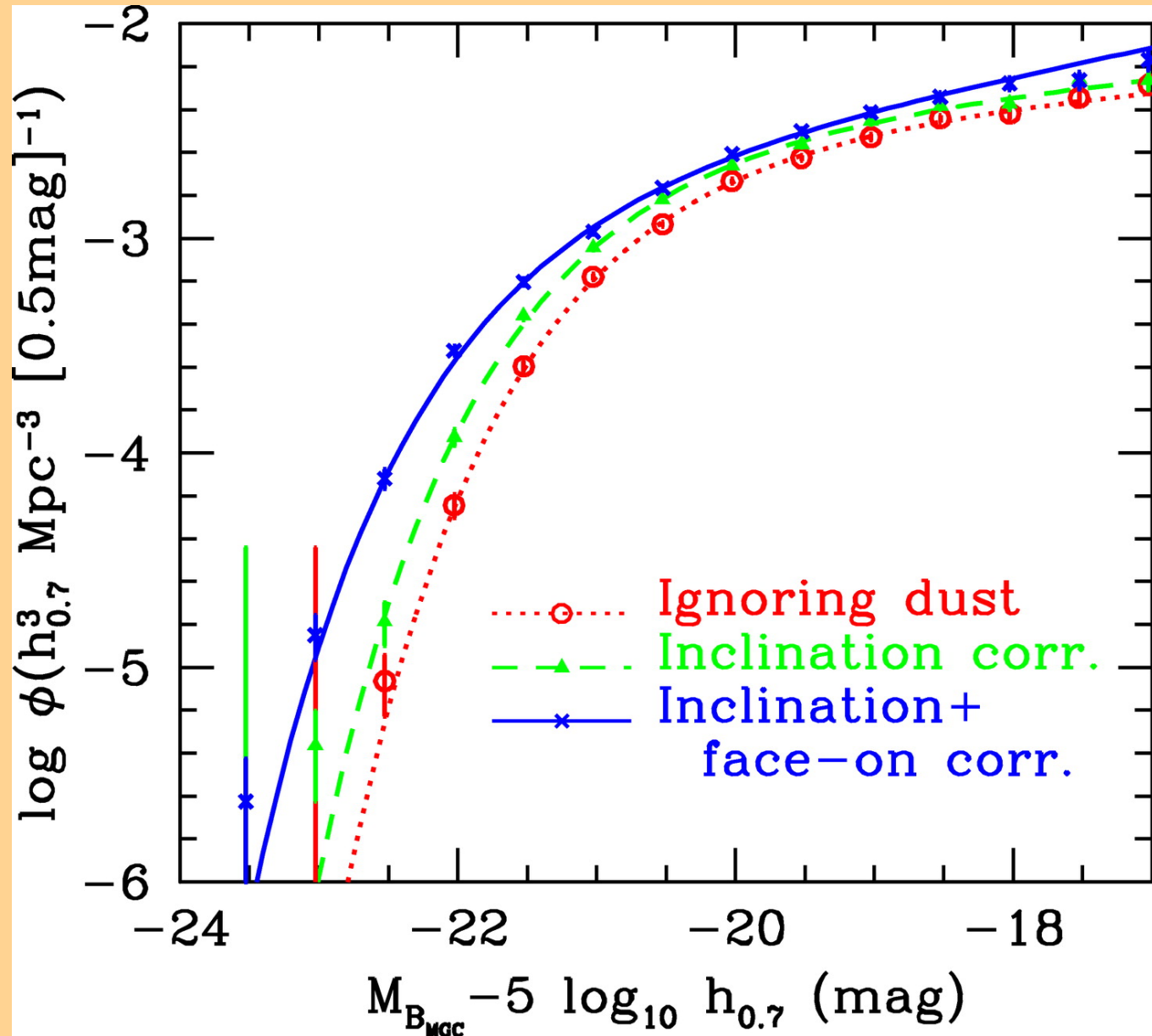
Full dust correction increases the total luminosity density increases by 63%.

In other words:

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

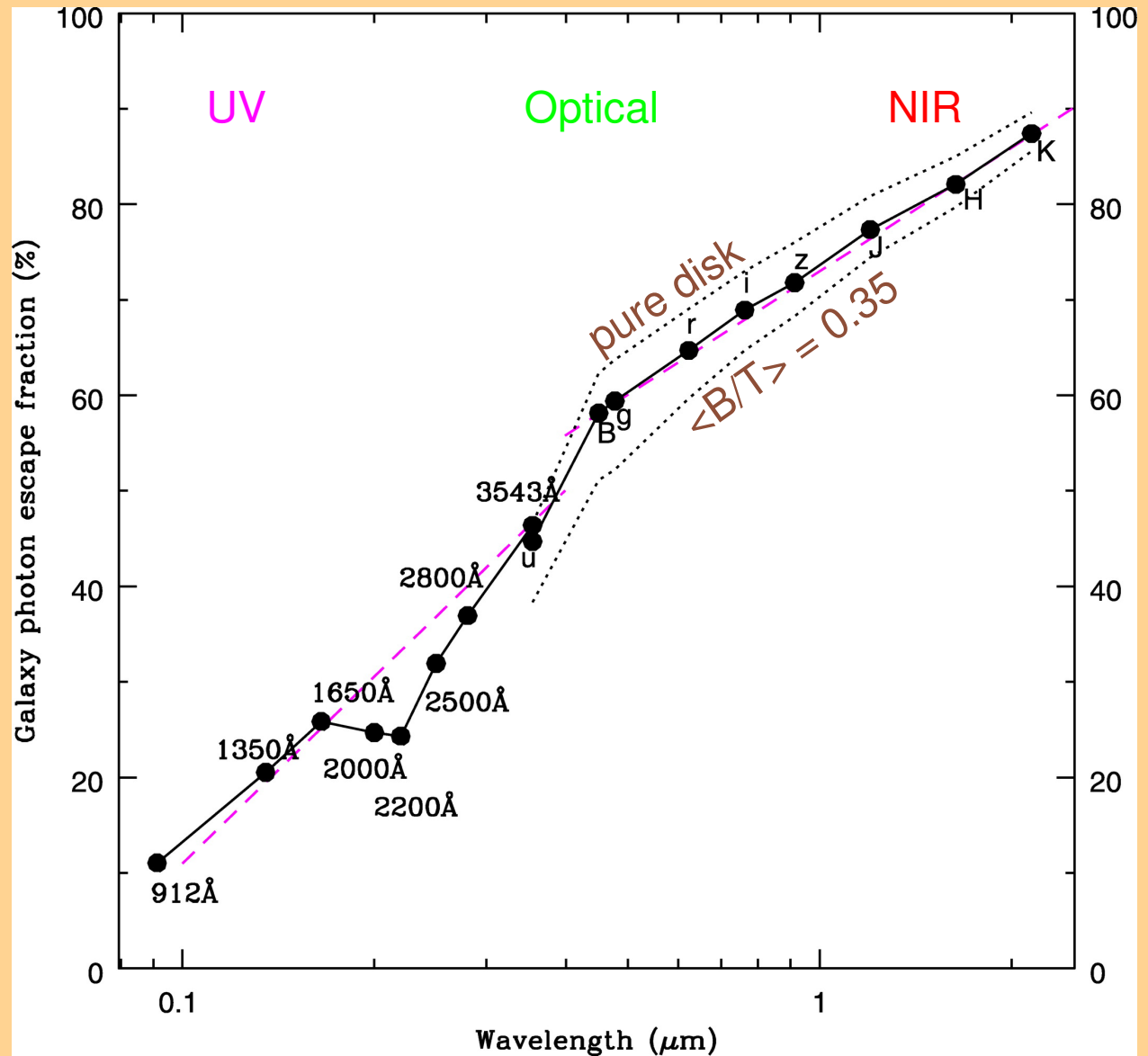
What about other wavelengths?

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

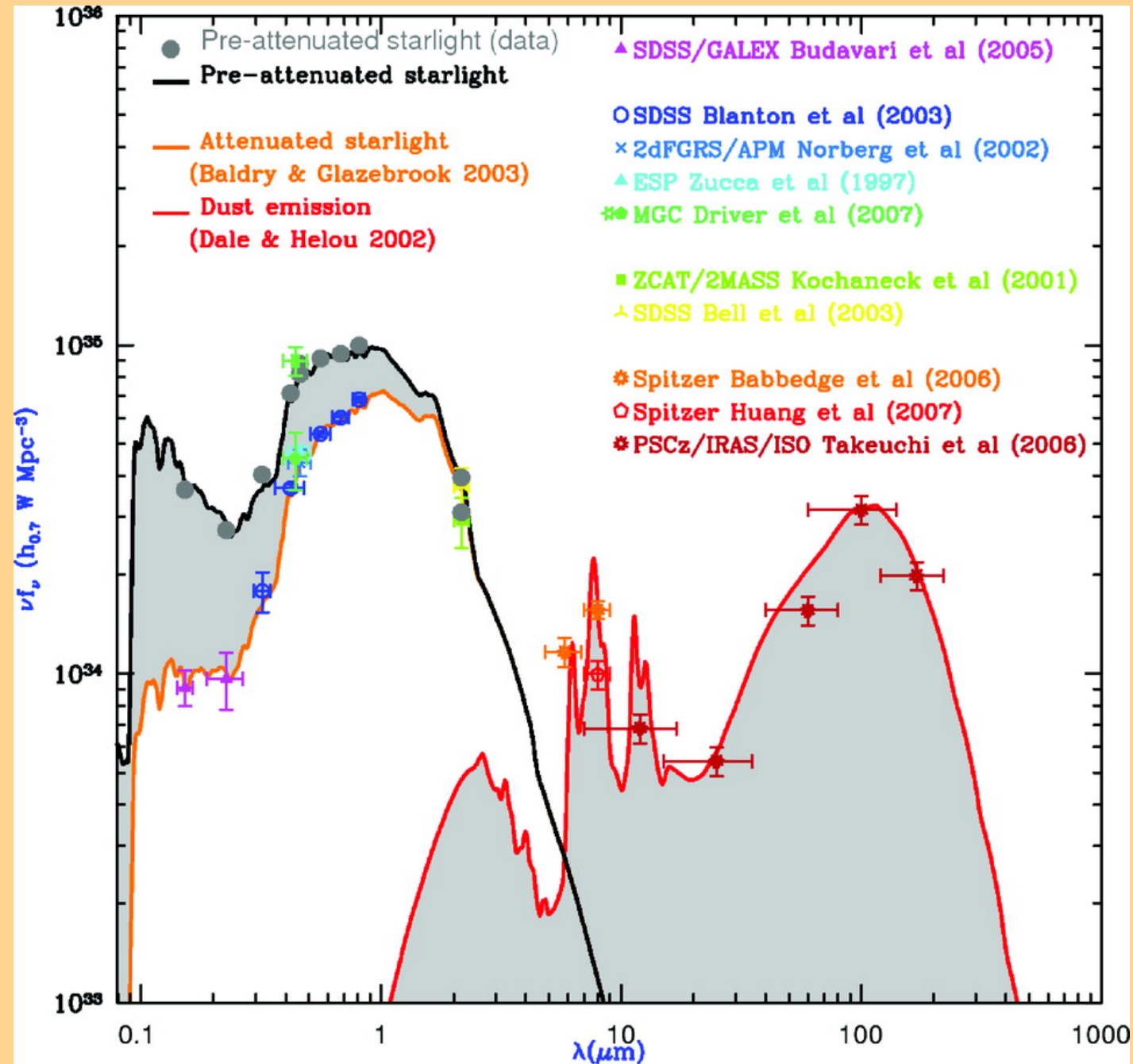


Photon escape fractions

- 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.



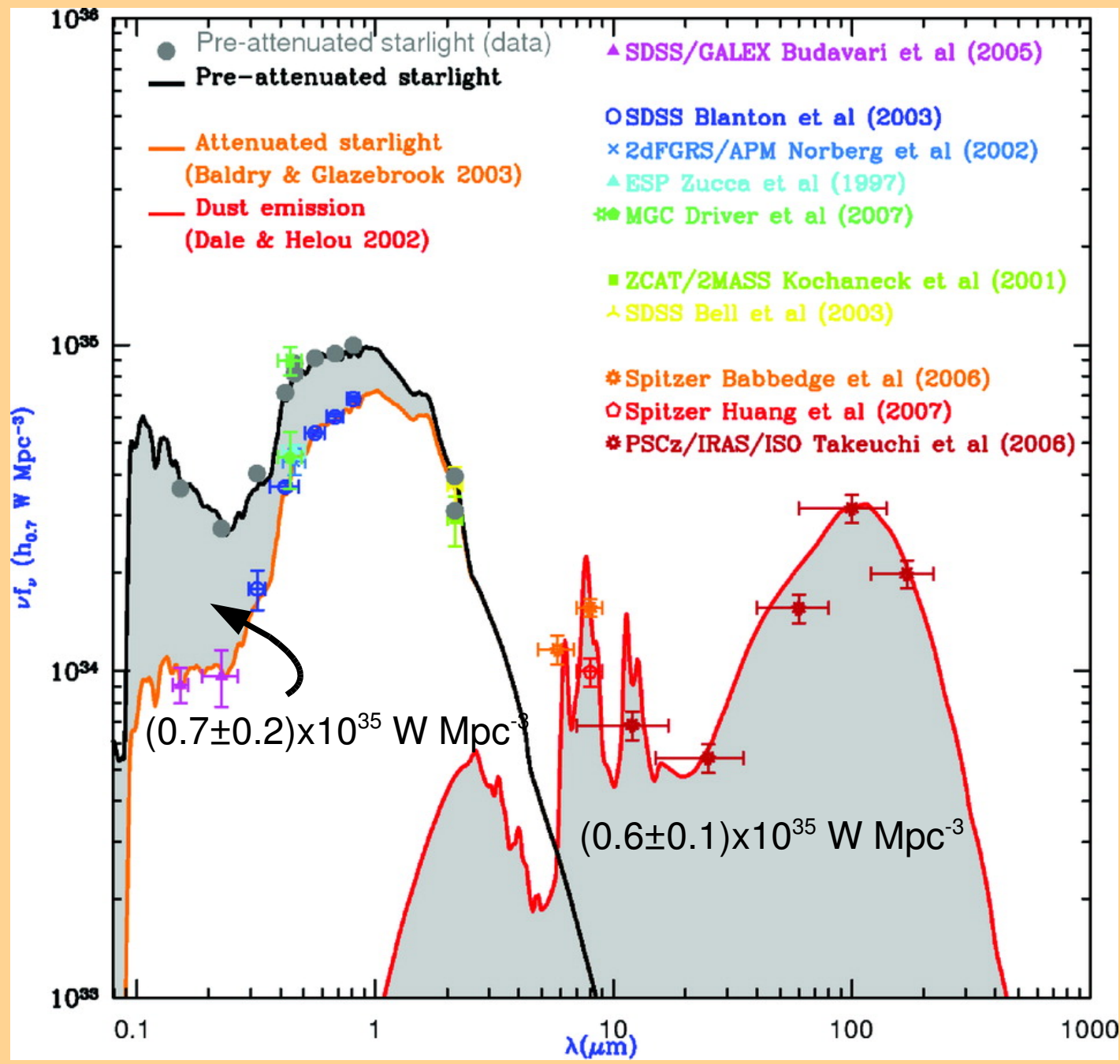
The cosmic SED



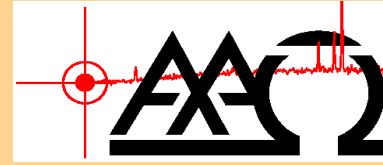
The cosmic SED

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 ugr_i imaging survey over $\sim 1000 \text{ deg}^2$ (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 $\sim 250 \text{ deg}^2$ (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 $\sim 2 \times 10^5$ 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, $\sim 250 \text{ deg}^2$, $\sim 250\text{K}$ galaxies to $r < 19.8 \text{ mag}$ + 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

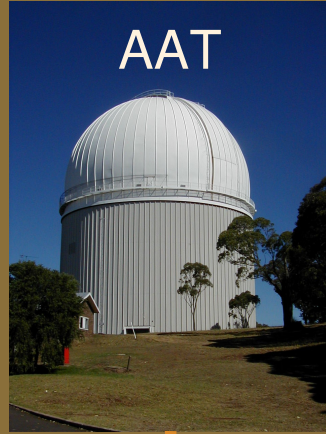


GAMA facilities

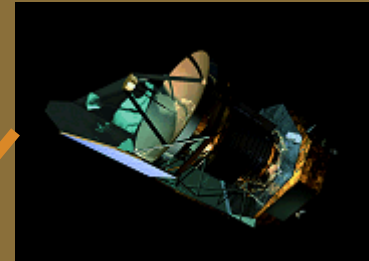
UKIRT



AAT



HERSCHEL



VISTA



VST



GAMA

ASKAP



Science

NIR

Spec

FIR

HI

NIR

Optical



GAMA team and structure

WORKING GROUPS AND HEADS

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

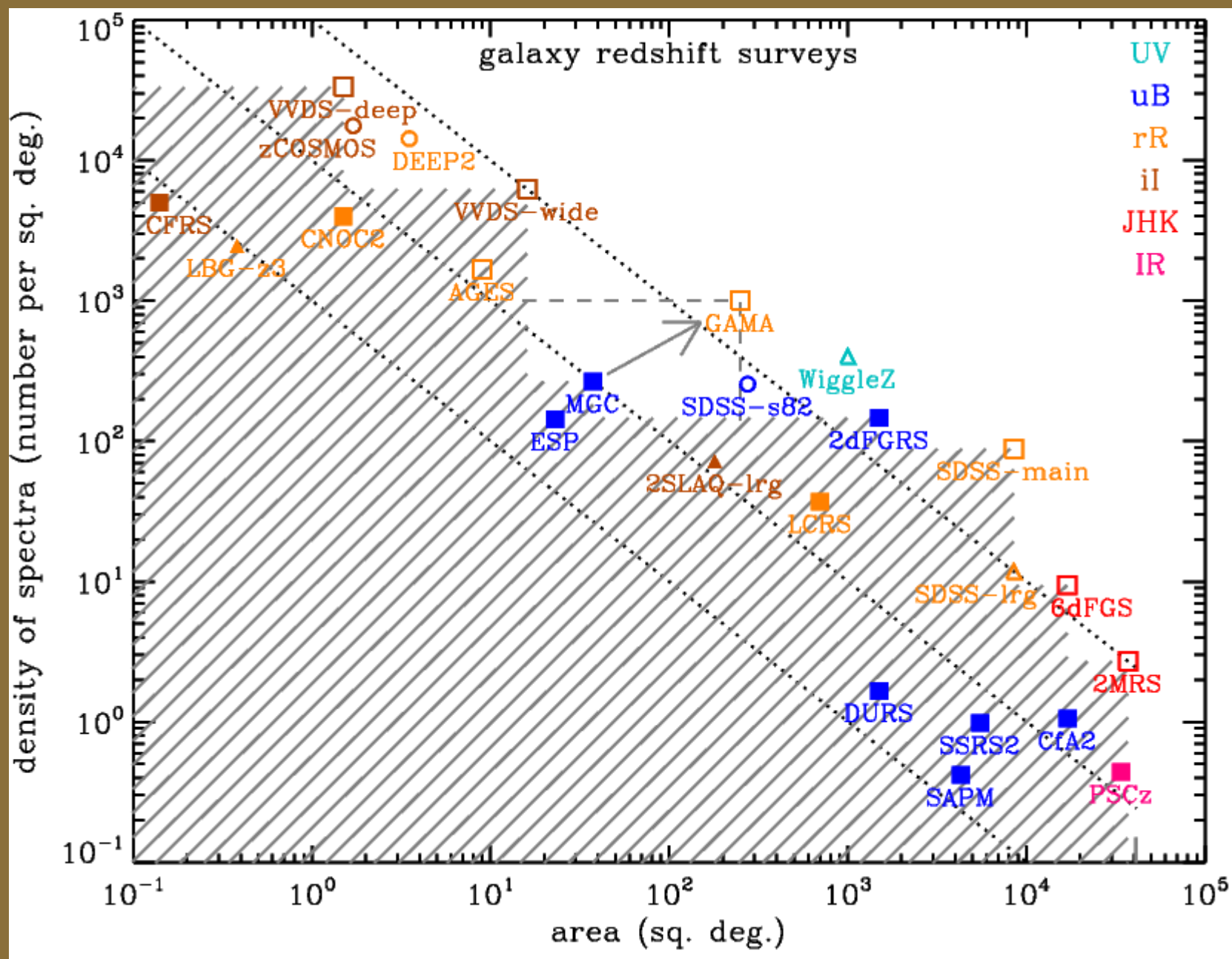
TEAM MEMBERS

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

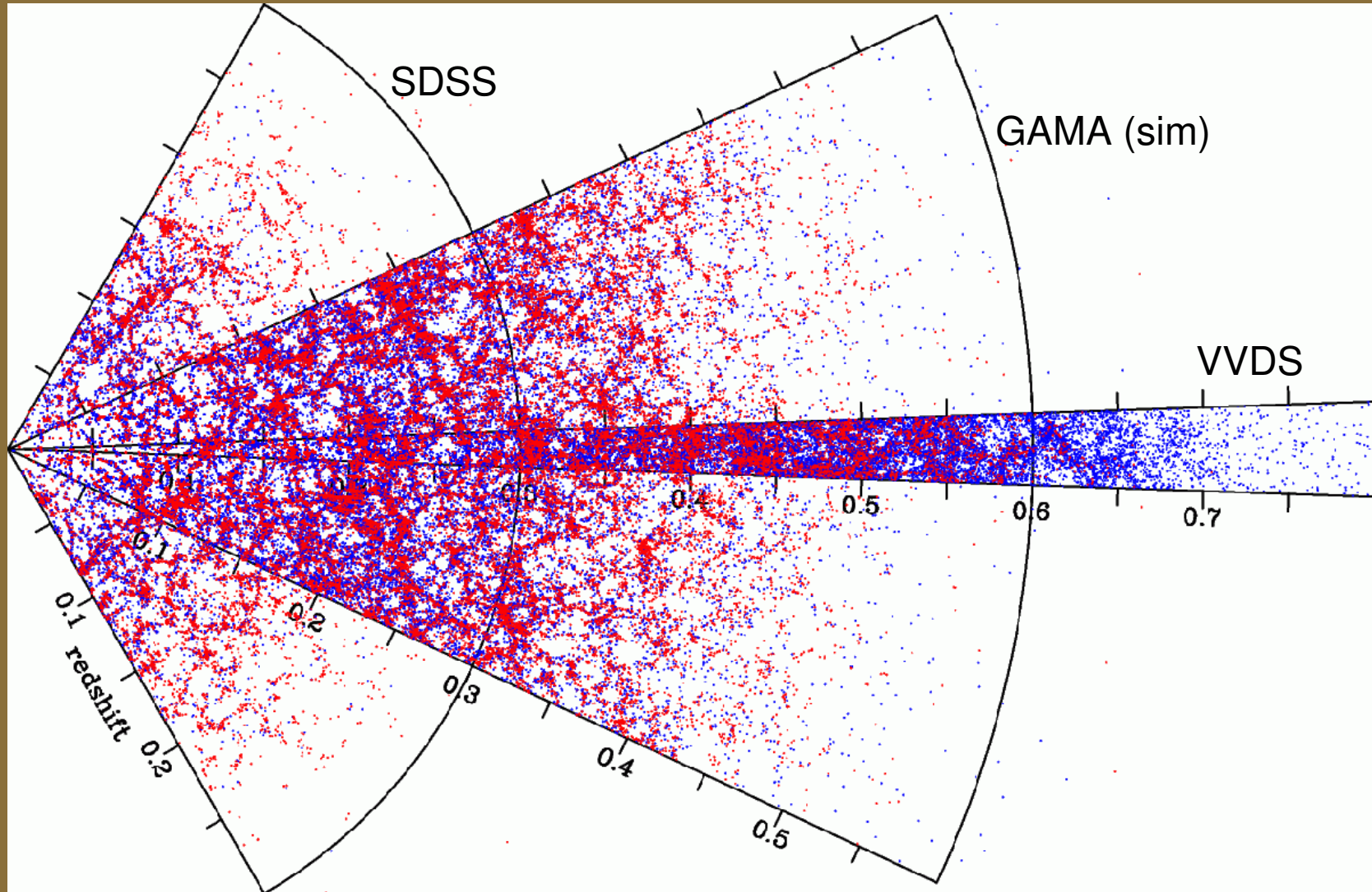


GAMA in comparison



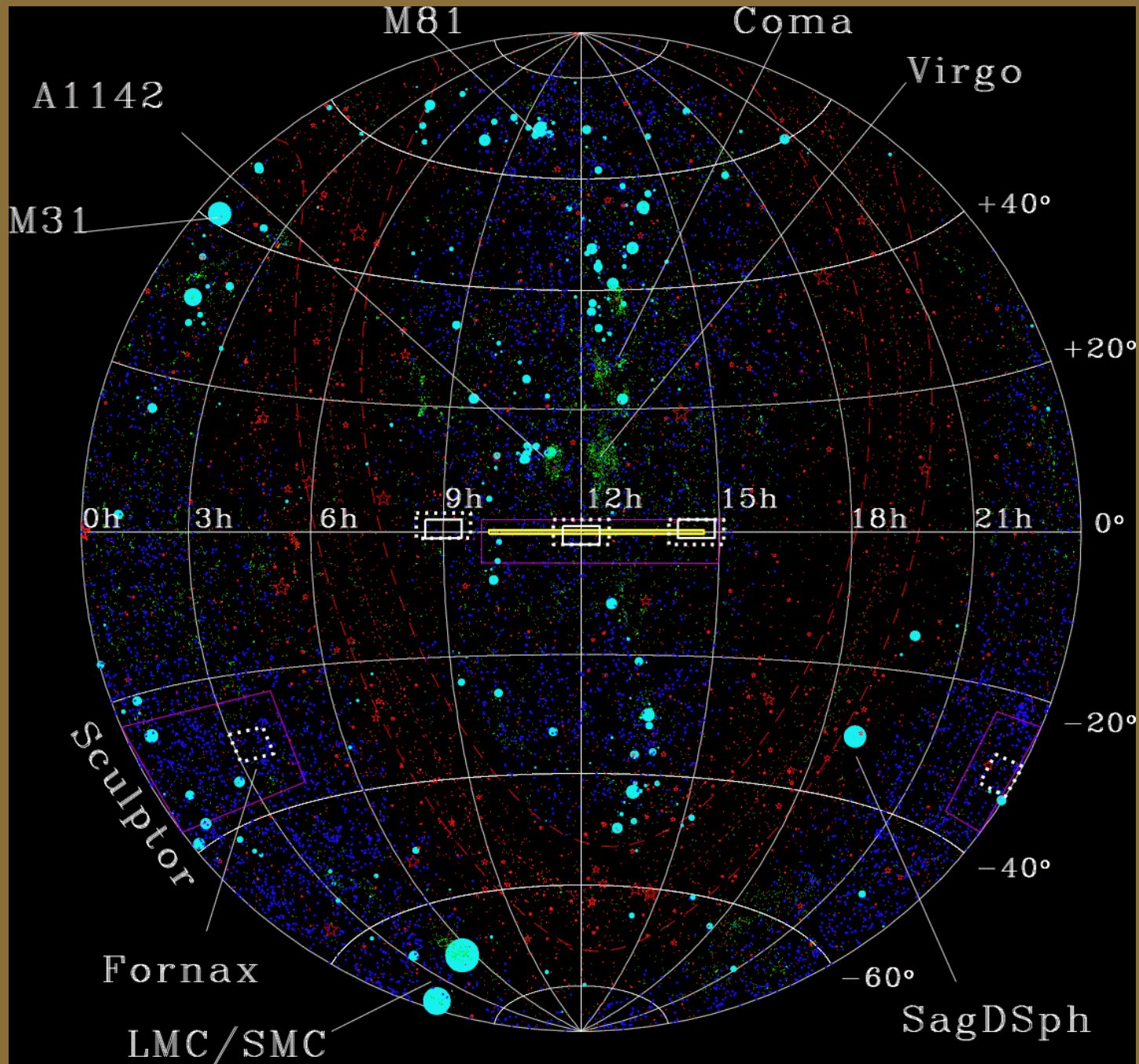


GAMA in comparison



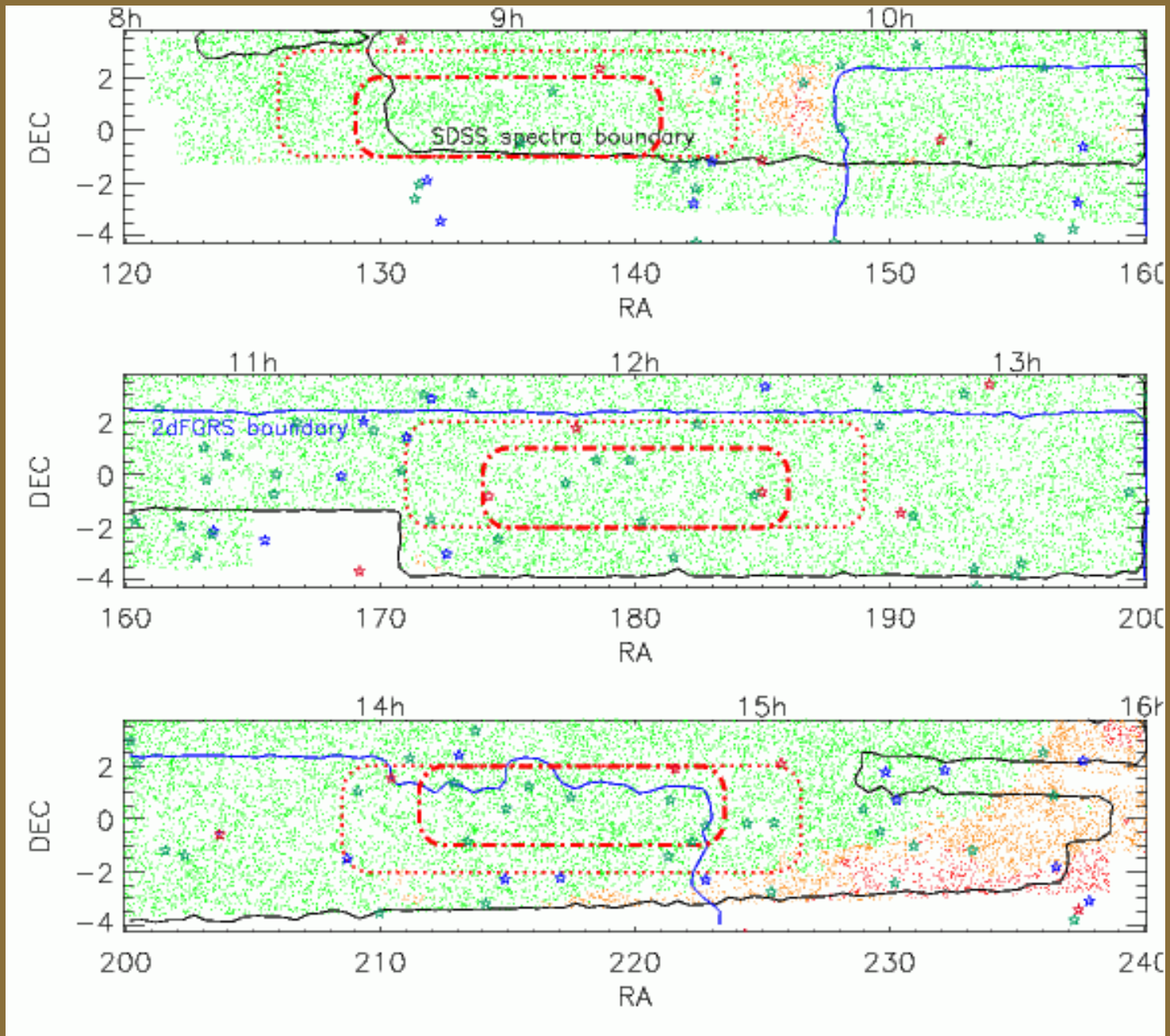


GAMA survey regions





GAMA survey regions





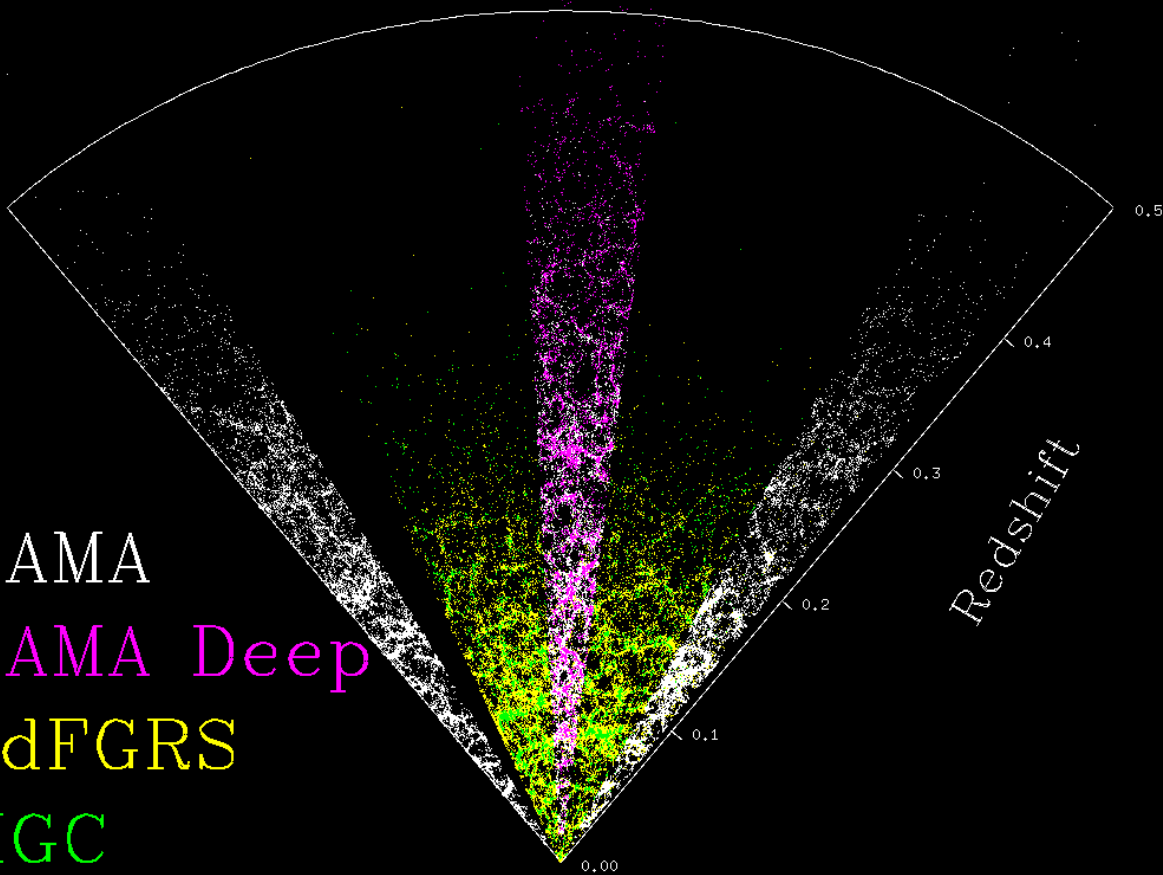
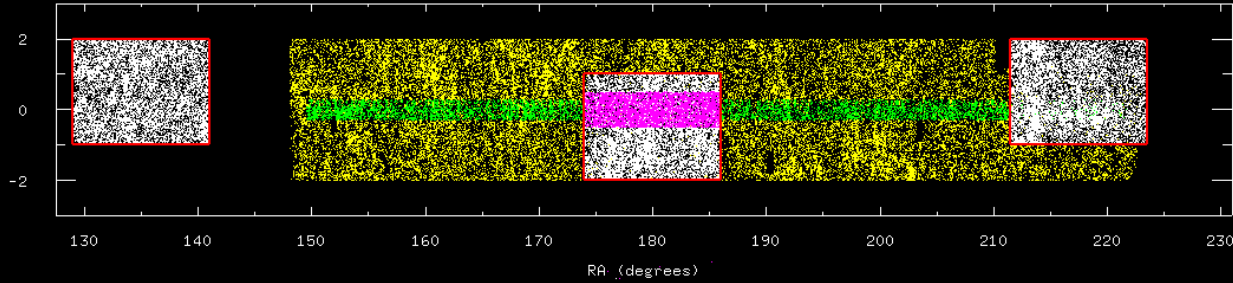
Survey progress

- 66 nights allocated over 3 years ($\sim 1/2$ of the nights required)
- 21/22 clear nights in March-April 2008
- 50-75 min exposures in dark/grey time
- 159 fields observed \rightarrow 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



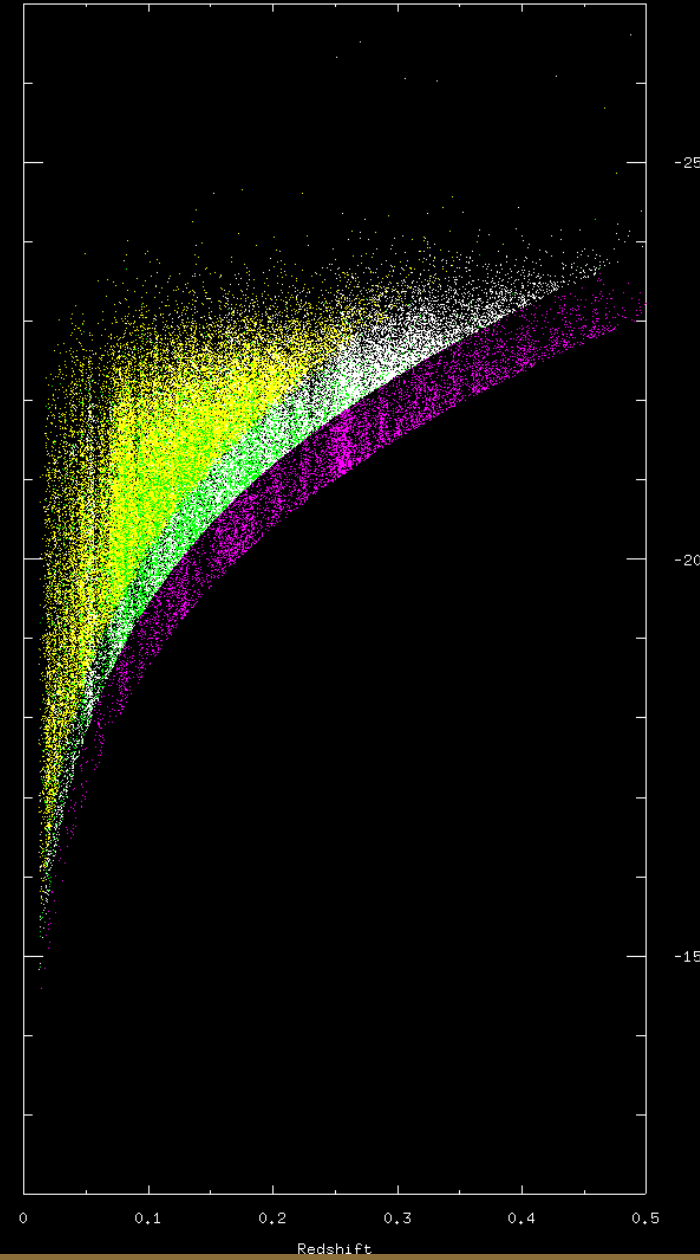
GAMA redshift cone

Dec (degrees)



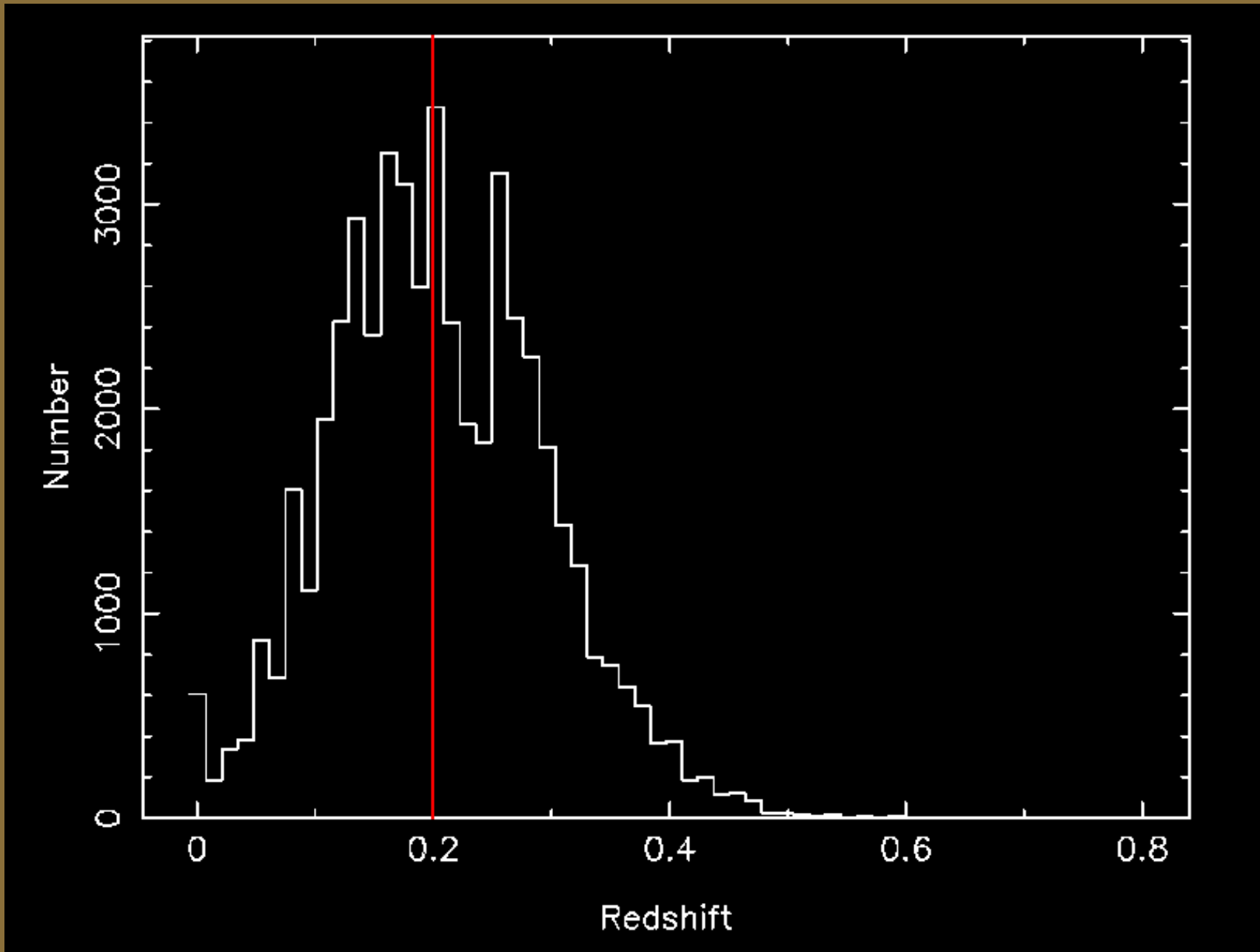
GAMA
GAMA Deep
2dFGRS
MGC

Abs. mag (r or B-1 mag)



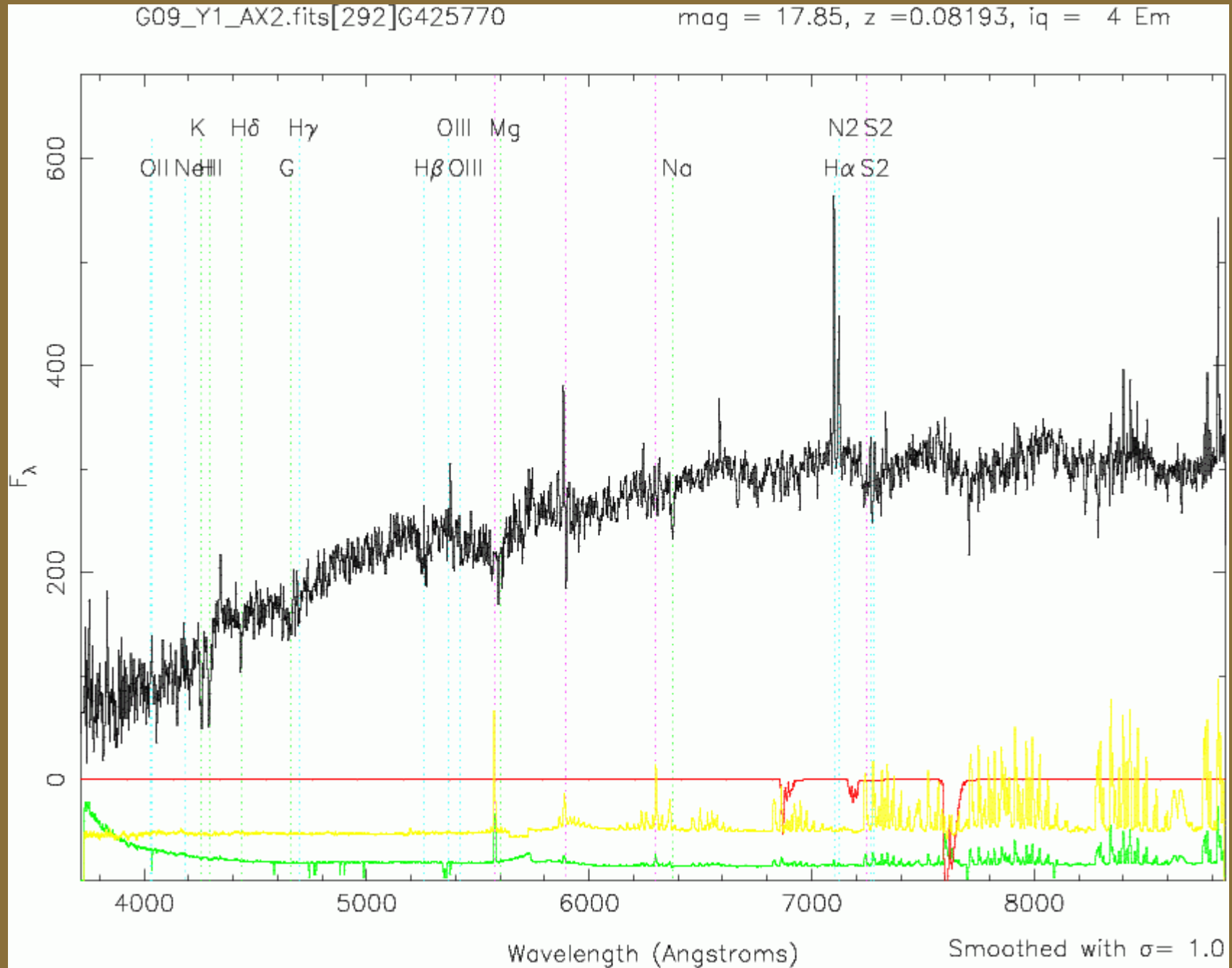


GAMA redshift distribution





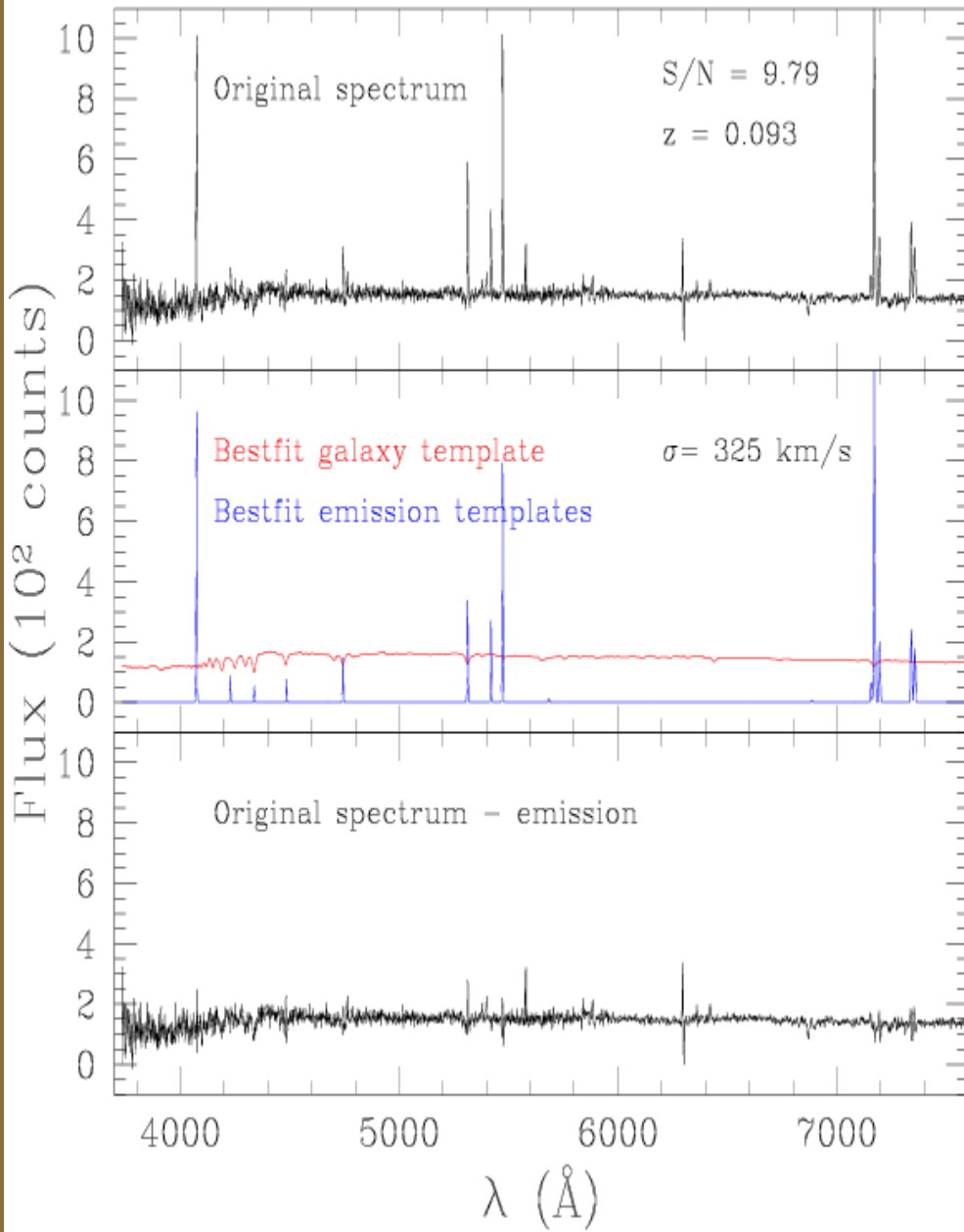
GAMA example spectra



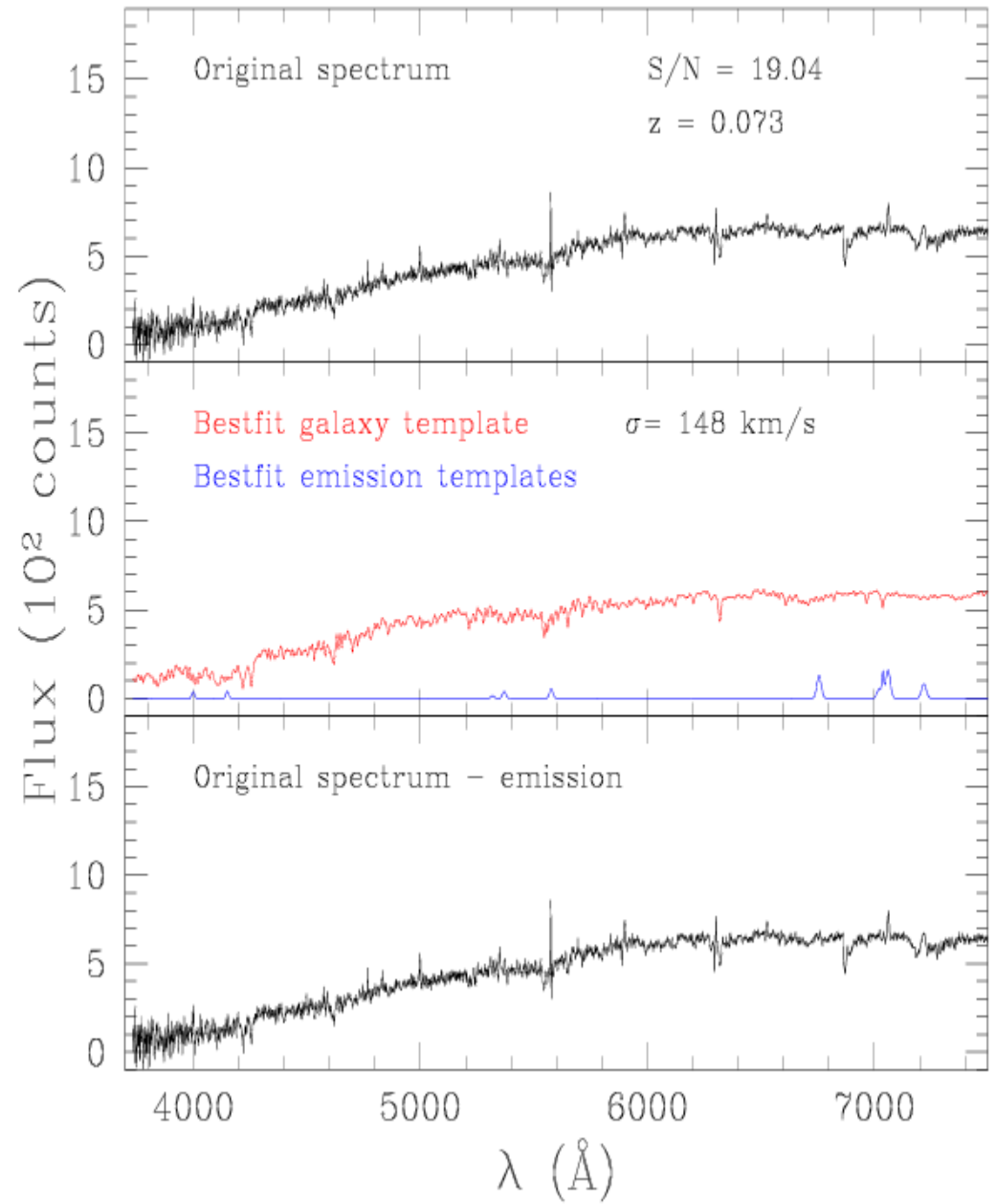


GAMA example spectra

Galaxy G00300337



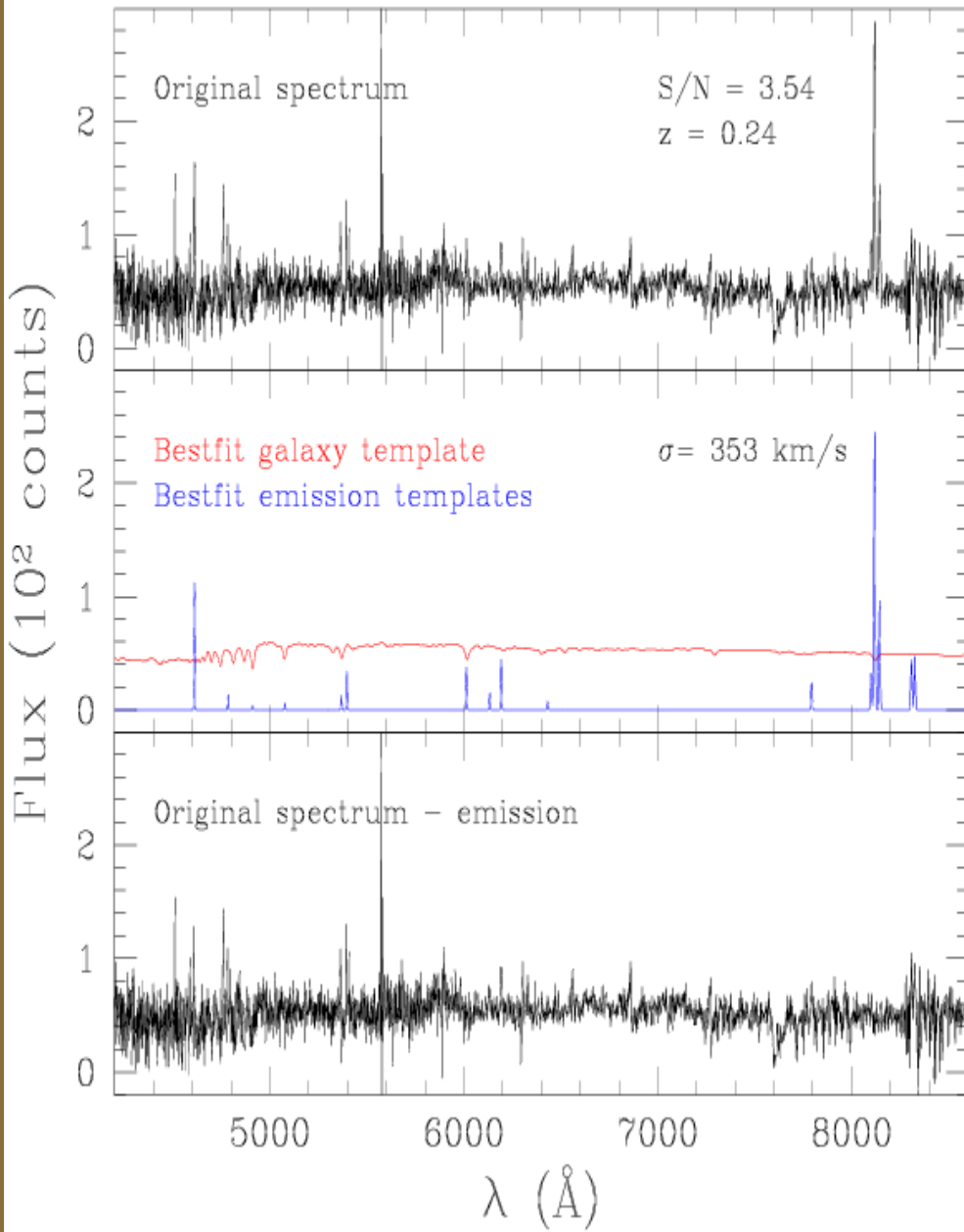
Galaxy G00380740



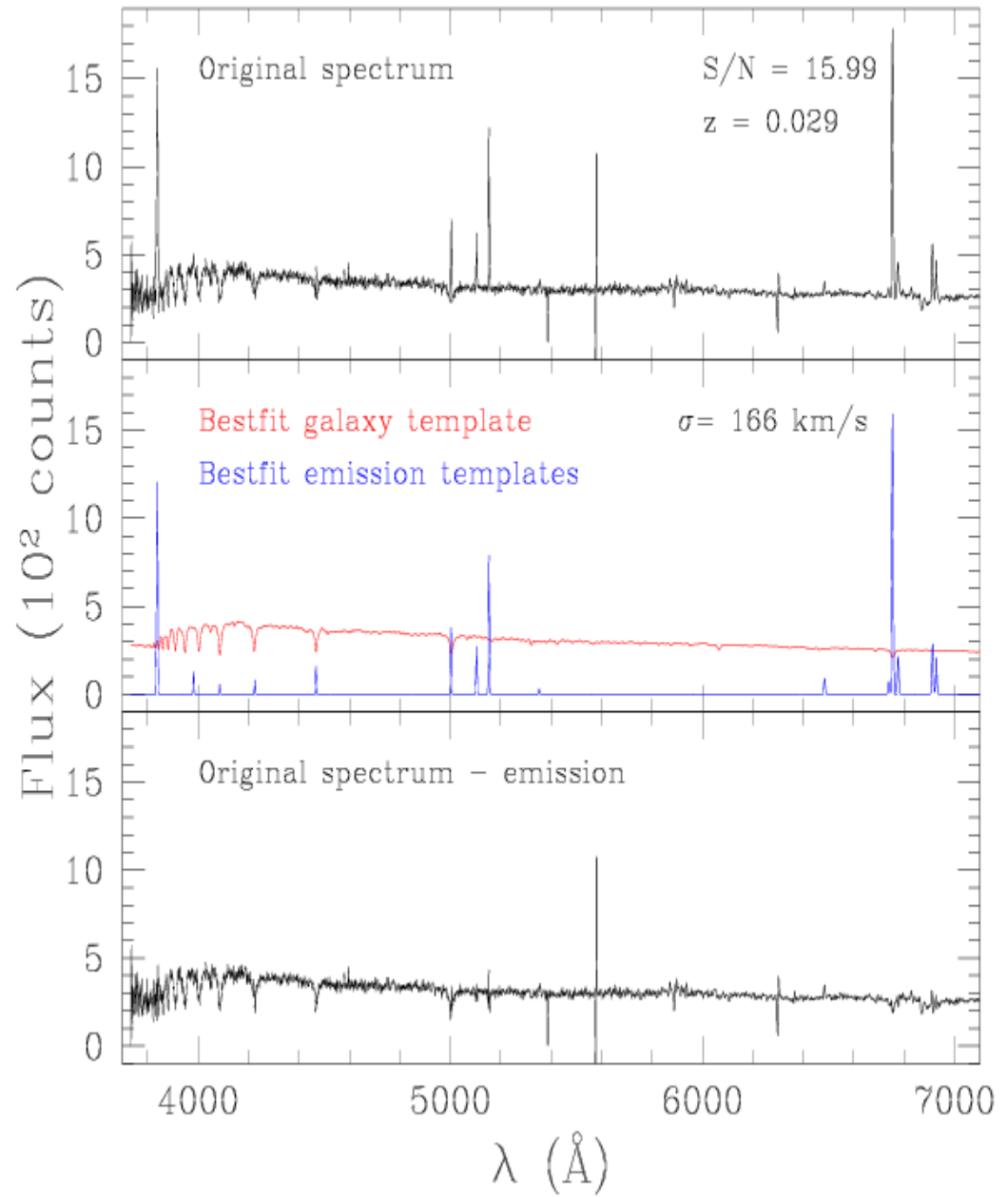


GAMA example spectra

Galaxy G00214312

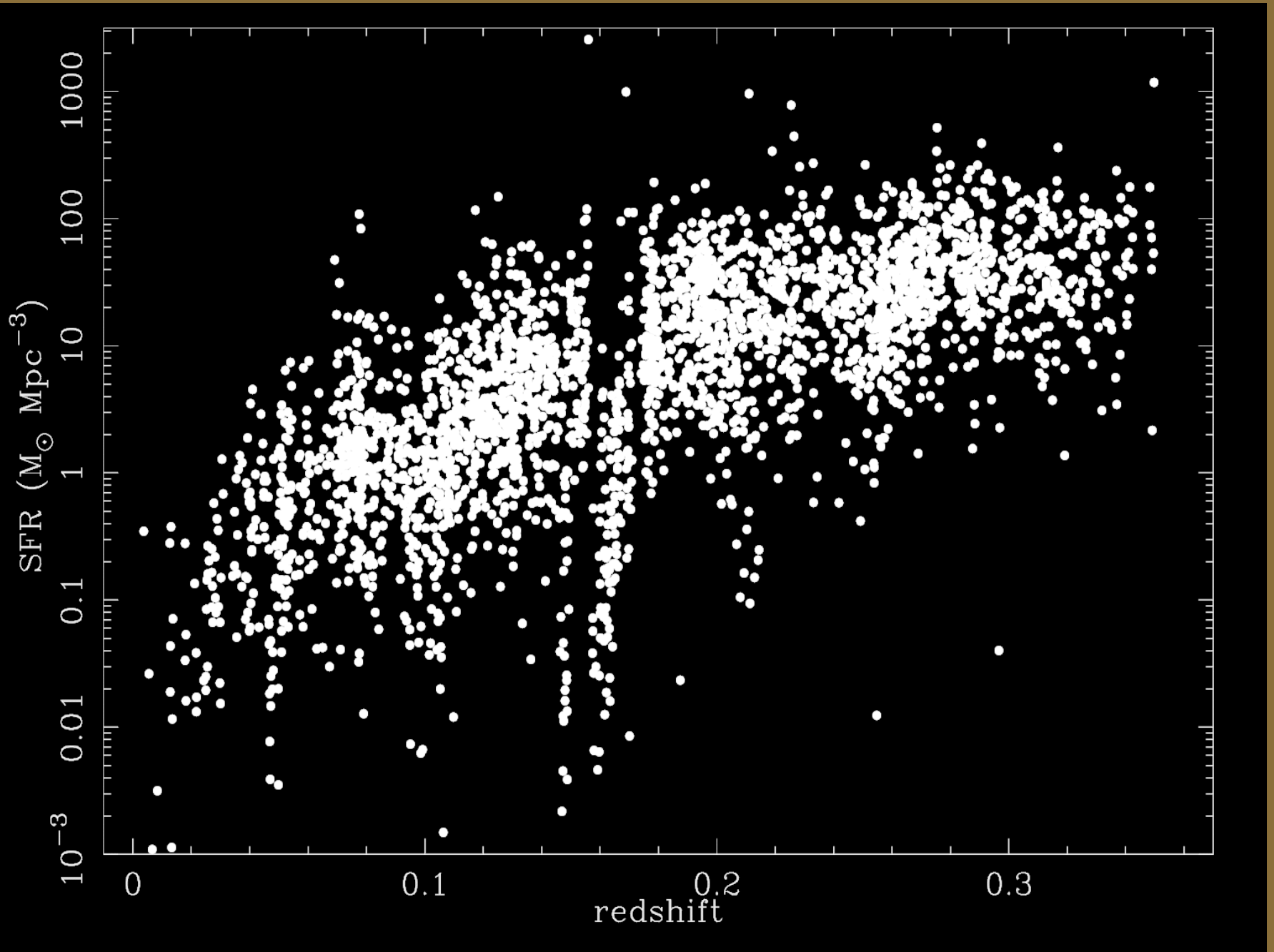


Galaxy G00375532



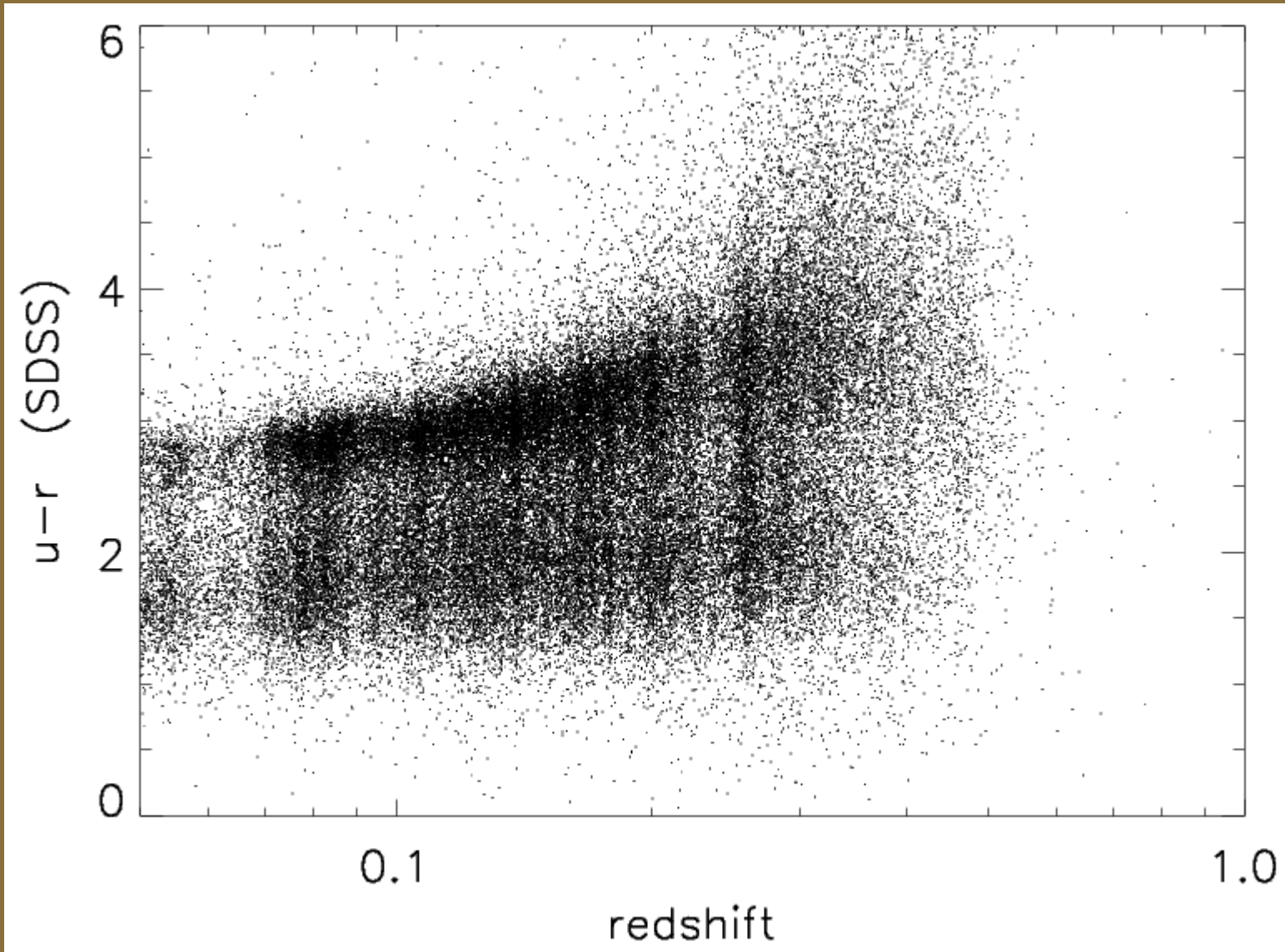


Quick-look science: SFR vs z



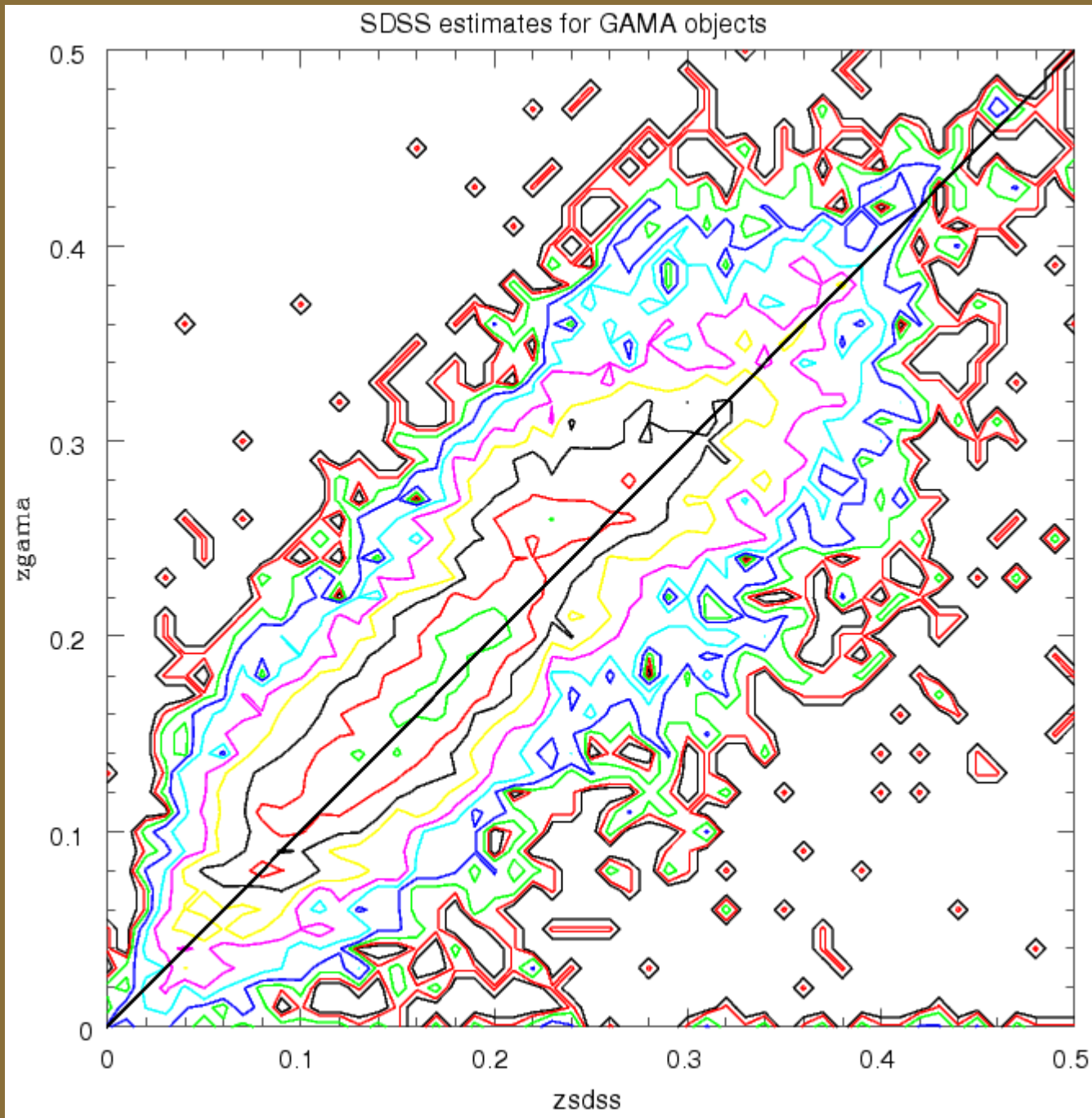


Quick-look science: colour bimodality vs z



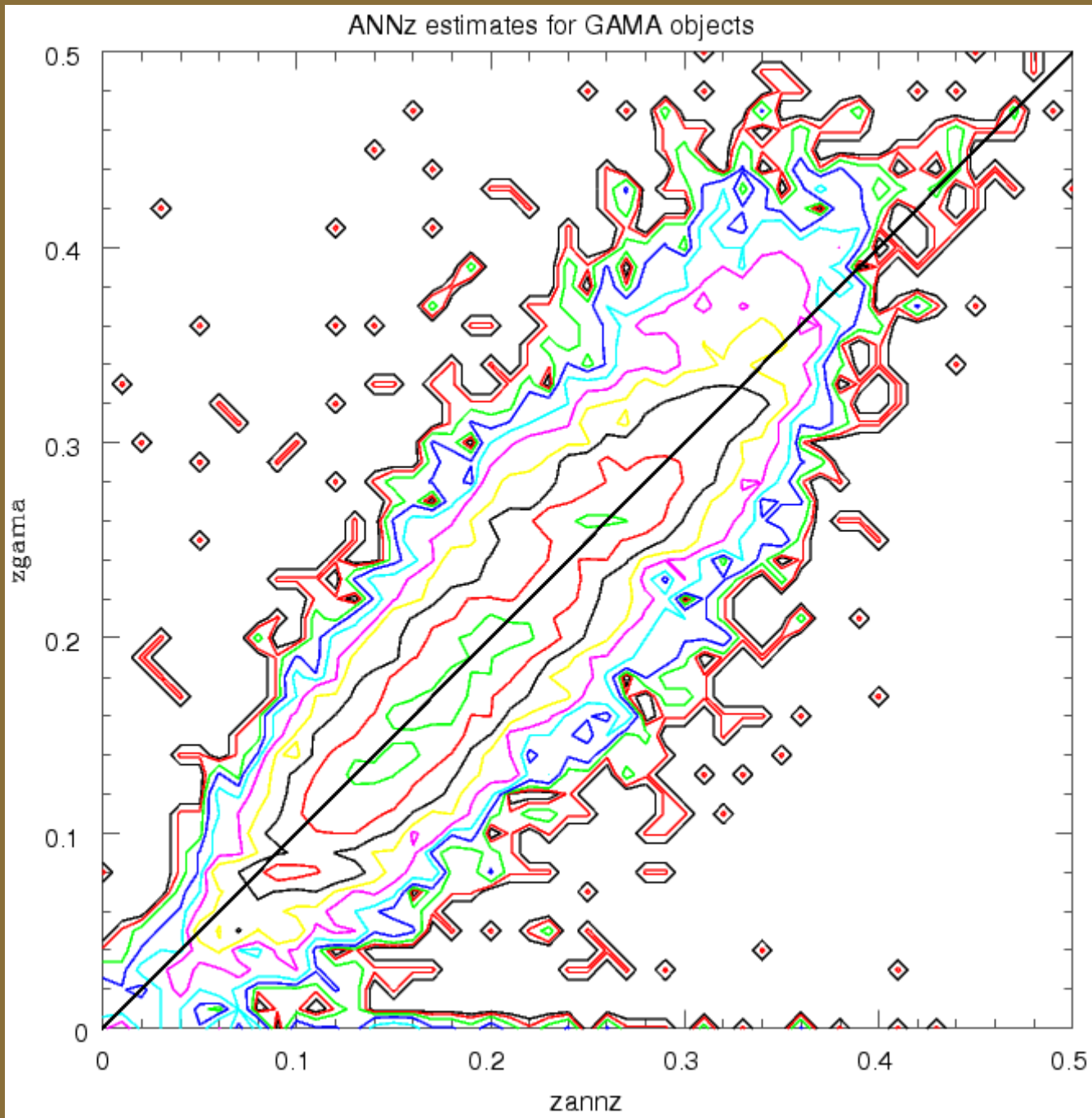


Quick-look science: photo-z improvement





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.

