The baryon budget ($z=0$) & The Cosmic Energy Spectrum

- Dark Energy: 72%
- Dark Matter: 24%
- Normal Matter: 4%
- Gas: 91.7%
- Stars: 8.3%
- Dust: 0.008%
- Supermassive Black Holes: 0.01%
- Stars in Discs: 60%
- Stars in Bulges: 27%
- Stars in Ellipticals: 10%
- Stars in Blue Spheroids: 3%

---

**WAVELENGTH**

**ENERGY**

Pre-attenuated starlight (data)  
Pre-attenuated starlight (fit)  
Attenuated starlight (fit)  
Dust emission (fit)  

- ZCAT/2MASS Kochanek et al (2001)
- SDSS Bell et al
- Spitzer Babbedge et al (2005)
- Spitzer Huang et al (2007)
Physicist: baryon evolution
Astronomer: galaxy formation
Layperson: mass assembly

DAWN OF TIME

tiny fraction of a second

inflation

380,000 years

13.7 billion years
Tracing the Luminous Matter and Luminous Energy

• Objectives:
  – Build an empirical description of the *baryon concentrations* at all epochs
  – Understand the *luminous energy* output within the Universe at all epochs

• Progress/Science:
  – The Millennium Galaxy Catalogue (Medium Scale Galaxy Survey)
    • A local census of 10k galaxies over 37 sq deg of sky
  – The significance of galaxy structure (the modes of evolution)
  – The problem of dust attenuation
  – The \( z=0 \) baryon breakdown and the energy budget (according to the MGC)
  – A blueprint of galaxy formation ?

• Future directions:
  – Galaxy And Mass Assembly (Legacy Scale Galaxy/Group Survey)
    • Going massively multi-wavelength
  – Galaxy And Mass Assembly Deep (Legacy Galaxy/Group Survey)
    • Pushing back to very early epochs
Cosmological Context

\[ G_{\mu\nu} = -\kappa T_{\mu\nu} \]

Geometry (Dynamics) = Contents (Mass-Energy)

Equation does not balance with normal luminous matter and energy.

Needs extra stuff (DM, DE) or extra effects (Modified Gravity).

Independent Observations (CMB, SnIa etc) \~ No of free parameters.

Solving galaxy formation via numerics requires “knowing” the above.

The empirical approach bypasses this issue and allows one to build a galaxy blueprint while the Dark debate goes on.

Almost all recent advances have come from empirical breakthroughs.

There is no robust (predictive) model of baryon evolution.

Technological (multi-wavelength) explosion underway = big opportunity

[(s)he who builds the best database will lead the gal. form debate]
The Millennium Galaxy Catalogue

- UKIRT/LAS: 8 nights
- SDSS
- INT/WFC: 14 nights
- AAT/AAΩ: 15 nights + 2dFGRS
- GEMINI/GMOS: 3 nights
- TNG: 4 nights
- NTT: 3 nights
- 2.3m ANU: 12 nights

Near-IR (JHK) 

ugriz+z's

B, morph 
B/D decomp

Z, spectra

Z, LSBGs

Z, LSBG
HSBGS

SCIENCE
The Millennium Galaxy Catalogue

The MGC Core Team
Simon Driver (St Andrews)
Jochen Liske (ESO)
Alister Graham (Swinburne)
Ewan Cameron (ANU/St Andrews)
David Hill (St Andrews)

MGC Collaborators
Chris Conselice (Nott.)
Nicholas Cross (ROE)
Roberto De Propris (CTIO)
Simon Ellis (AAO)
Richard Tuffs (MPIK)
Cristina Popescu (UCLAN)
The Mass-Age plot

- LOCAL SPHERE
- 2dFGGRS
- MGC
- JWST
- NEW SDSS DWARFS
- UDF DATA
Driver et al. (2005)

The MGC probes to fainter abs. mag because the survey has a fainter app mag limit.

\[-19.60 \pm 0.05\]
\[-1.17 \pm 0.03\]
\[0.0184 \pm 0.05\]
BUT…still a long way to go at z=0

Space density of galaxies -->

MANY

NEW SDSS DWARFS

FEW

BRIGHT

Absolute magnitude --->

FAINT

???

???

???
Exploring galaxy structure

GALAXY SAMPLES ($H_0 = 68$ km/s/Mpc)

KNOWN REGION

Structural Limit

AD HOC

NEW SDSS DWARFS

GCs

Effective surface brightness

Absolute B Magnitude
MGC bulge/disc decomposition

- Driver et al (2005)

96% redshift completeness (AAT/GEMINI) to B=20.0 mag,

YJHK(UKIRT) imaging now 50% complete

All data available online: http://www.eso.org/~jliske/mgc/
Example 1: MGC27301
Example 2: MGC61361
Galaxy bimodality in $(u-r)-\log(n)$

- Blue Diffuse
- Bridging Pop'n?
- Red Compact

Number density
Stellar mass density

<- Number density
Stellar mass density ->
Two populations or two components?

- E/S0
- Sa
- Sd/Irr
- Sc

- El (Old)
- Sabc (Intermediate)
- Sc (Young)

- Disk systems
- Bulge + Disks
Galaxy bimodality in (u-r)-log(n)


Blue Diffuse

Red Compact

Bridging Pop'n?

<- Number density
Stellar mass density ->
Two populations or two components?


Exponential discs
Truncated discs
Spheroids

Sersic only fits
Bulge+disc fits

Blue (pBulges?)
Red
Structure more fundamental than colour.

2 DISTINCT FORMATION MODES AND ERAs?

Infall/splashback?

Collapse or rapid mergers?

**SPHEROID**

**DISC**

$z > 2$

**SMBHs AGN?**

Fan et al

$z = 1-2.5$

SFR

$z = >2$

AGN

Structure more fundamental than colour.

2 DISTINCT FORMATION MODES AND ERAs?

Infall/splashback?

Collapse or rapid mergers?
The Component Luminosity Functions


RED SPHEROIDS (Classical)
BLUE SPHEROIDS (pBulges+BEs ?)
DISCS (Exp. + Trunc)

Decomps unreliable

DUST?

By mass:
E = 13% => Collapse
rB = 26% => or mergers
D = 58% => Infall
pB+BS = 3% => Secular+
Component LFs v $\cos(i)$

Nearly face-on galaxies only

Bulges $0.1 < 1 - \cos(i) < 0.2$

Discs

REFERENCE LINE

$0.1 < 1 - \cos(i) < 0.2$
Component LFs v cos(i)

Bulges \(0.2 < 1 - \cos(i) < 0.3\)  
Discs

\[\log \phi[h^3 \, \text{Mpc}^{-3} (0.5 \text{mag})^{-1}]\]

![Graph showing the distribution of galaxies with different inclinations.](image)
Component LFs v cos(i)

Bulges \(0.3 < 1 - \cos(i) < 0.4\)

Discs

![Graphs showing luminosity functions for bulges and discs with respect to the cosine of the inclination angle.](image)
Component LFs vs $\cos(i)$

- **Bulges**: $0.4 < 1 - \cos(i) < 0.5$
- **Discs**: $0.4 < 1 - \cos(i) < 0.5$
Component LFs $\nu \cos(i)$

Bulges $0.5 < 1 - \cos(i) < 0.6$

Discs
Component LFs vs \( \cos(i) \)

- **Bulges**: \( 0.6 < 1 - \cos(i) < 0.6 \)
- **Discs**

![Graphs showing the logarithmic relationship between \( \phi [h^3 \text{Mpc}^{-3} (0.5 \text{mag})^{-1}] \) and \( M_g - 5 \log h \) for both Bulges and Discs. The graphs are labeled with the respective ranges of \( \cos(i) \).](image)
Component LFs vs $\cos(i)$

Bulges  $0.7 < 1 - \cos(i) < 0.8$  Discs
Component LFs $\nu \cos(i)$

Bulges $0.8 < 1-\cos(i) < 0.9$

Discs

![Graphs showing the distribution of galaxy luminosities for different inclination angles.](image)
Component LFs v cos(i)

Bulges  \[ 0.9 < 1 - \cos(i) < 1.0 \]  Discs
Purely empirical result

Bulges severely attenuated in inclined systems up to 2 mag ex. face-on correction!

Dust in Lenticulars
Sanity check I: \( \cos(i) \) distributions

- In the absence of dust the \( \cos(i) \) density distribution should be flat. Initially they’re not.
- After implementing the dust correction they are!
Sanity II: Face-on v corrected LFs

Can construct component LFs using just face-on data and compare to LFs from corrected data.

Results fully consistent

Still need face-on correction
Sanity Check III

Similar results being reported from SDSS (although without bulge disc decomposition or a detailed dust model), e.g.,

- Padilla & Strauss (2008), astro-ph/0802.0877

All reporting severe impact of dust!
Popular $\tau=1$ dust models fail

Tau=1 model
(I.e., conventional wisdom)
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:
\[ \eta(\lambda, R, z) = \eta^{\text{disk}}(\lambda, 0, 0) \exp\left(-\frac{R}{h_s^{\text{disk}}} - \frac{|z|}{\zeta_s^{\text{disk}}} \right) \]

Young stellar disk:
\[ \eta^{t\text{disk}}(\lambda, R, z) = \eta^{t\text{disk}}(\lambda, 0, 0) \exp\left(-\frac{R}{h_s^{t\text{disk}}} - \frac{|z|}{\zeta_s^{t\text{disk}}} \right) \]

Dust disk associated with the old stellar disk:
\[ \kappa_{\text{ext}}^{\text{disk}}(\lambda, R, z) = \kappa_{\text{ext}}^{\text{disk}}(\lambda, 0, 0) \exp\left(-\frac{R}{h_d^{\text{disk}}} - \frac{|z|}{\zeta_d^{\text{disk}}} \right) \]

Dust disk associated with the young stellar disk:
\[ \kappa_{\text{ext}}^{t\text{disk}}(\lambda, R, z) = \kappa_{\text{ext}}^{t\text{disk}}(\lambda, 0, 0) \exp\left(-\frac{R}{h_d^{t\text{disk}}} - \frac{|z|}{\zeta_d^{t\text{disk}}} \right) \]
We adopt the **Tuffs and Popescu dust model** and derive: $\tau_B = 3.8 \pm 0.7$


- Model based on UV+ugrizJHK+Spitzer data of 6 nearby galaxies
- One free parameter = face-on central B band disc opacity
Models imply that discs are optically thick in the centre, Hence $\sim$half of bulge flux is attenuated in face-on systems $=0.75$ mag, (as dust has thickness our value is 0.84).
Implications of the MGC dust results

1. The galaxy luminosity function
2. The cosmic energy density estimates
3. Stellar mass function estimates
4. Morphological transformation via dust removal
5. All faint galaxy photometry and size measurements require revision!
The MGC probes to fainter abs. mag because the survey has a fainter app mag limit.
Impact on global B band LF

i.e., only 48% of B-band photons escape into the IGM

The Galaxy LF

-2.4
-2
-1.6
-1.2
-0.8
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4

$\log \phi (h^3 \ Mpc^{-3} \ [0.5 \text{mag}^{-1}])$

$M_{B_{\text{corr}}} - 5 \log_{10} h \ (\text{mag})$

-24
-22
-20
-18

-21
-20

-1.4
-1.2
-1

-4
-5
-6
-7

Ignore dust

Incl-only dust corr.

Full dust corr.
Dust attenuation versus $\lambda$

Using calibrated Tuffs & Popescu model can derive inclination-attenuation relation for any wavelength. Attenuation still an issue in K for highly inclined systems.
Photon escape fraction averaged over entire nearby galaxy population

- Pure disc
- Pure bulge (+dust disc)

Define a canonical galaxy in B, modify its B/T according to colours, integrate over \( \cos(i) \).

<table>
<thead>
<tr>
<th>Wavelength (( \mu \text{m} ))</th>
<th>UV</th>
<th>OPTICAL</th>
<th>NEAR-IR</th>
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<tbody>
<tr>
<td>912Å</td>
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<td>3543Å</td>
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</tbody>
</table>

PHOTON ESCAPE FRACTION (%)
The Cosmic Energy Budget

Missing starlight = Far-IR dust emission = $0.7 \times 10^{35}$ W Mpc$^{-3}$

Therefore AGN heating of dust negligible at $z=0$
The stellar mass function

• More fundamental and more useful for comparisons to theory.

• \((g-r)\) an OK predictor of M/L (Bell & de Jong 2001)
A little higher because of the bulge corrections? i.e., we find a 20% impact in K which is ignored by most other surveys.
Hubble type transformation ?!

1. Mid-type spiral falling into cluster (\(\cos i = 0.5\)):
   \(B=0.2, D=0.8, B/T=0.2, L=1.0, \text{Blue Sc}\) (NB: \(\cos(i)=0.0=\text{Sa}\), \(\cos(i)=1=\text{Sd}\))

2. *destroy dust* (heating):
   \(B=0.6, D=1.2, B/T=0.3, L=1.8 \text{ Green Sab}\)

3. Truncate star-formation in disc (stripping):
   \(B=0.6, D=0.8, B/T=0.4, L=1.4, \text{Red Sa/S0}\)

4. Further fading and harassment etc:
   \(B=0.6, D=0.6, B/T=0.5, L=1.2, \text{Red S0a}\)

5. Transformation from Sc-S0 purely by removing dust and switching off SF! it gets *redder* and *brighter* without dry mergers!
Component Stellar Mass Functions

The Stellar Mass Function (Components)

Log(Space density) vs Log(Stellar Mass)

DISCS
SPHEROIDS
pBULGES/BS
Spheroid formation

- Old population = early formation of stars
- \([\alpha/Fe]\)-enhanced = rapid formation (AGN feedback)
- SMBH-Bulge relation = formation coeval with peak of AGN activity, \(z>2.5\)
- No mini bulge-disc systems = mass regulation or downsizing with time

- Rapid merging or monolithic collapse ?
  - Merging: Elliptical SMF more massive than Bulge SMF
  - Collapse: Elliptical SMF = Bulge MF
Component Stellar Mass Functions

The Stellar Mass Function (Components)

Log(Space density)

Log(Stellar Mass)

DISCS

SPHEROIDS

pBULGES/BS
Component Stellar Mass Functions

The Stellar Mass Function (Components)

Log(Space density) vs Log(Stellar Mass)

- DISCS
- BULGES
- ELLIPTICALS
- pBULGES/BS
A blueprint for galaxy formation?

8+ Gyrs
- DM assembly via rapid merging
- major mergers destroy discs so must end before 8Gyrs (coincident with second inflation?)

10-13 Gyrs
- Spheroid formation via (predominantly) rapid collapse
- 37% of stellar mass (secondary mode)
- Mean age of spheroids 10-13Gyrs = AGN peak
- alpha-enhancement = short burst (AGN moderated)
- collapse inhibited during DM assembly => downsizing

5-8 Gyrs
- Disc growth via infall/splashback
- 60% of stellar mass (dominant mode)
- coupled with falling SFR
- mean age of discs 5-8Gyrs

0-5 Gyrs
- Pseudo-bulge growth & morphological transformations
- ages unchanged (material just shuffled)

But what is the variance, environmental & halo mass dependencies, and what about the neutral gas and plasma?
Optical image (Stars)

21cm image (Gas)
Galaxy And Matter Assembly

- Comprehensive
  - 250 sq degrees (5x50 sq deg. chunks), 250k galaxies (25x MGC)
- General science:
  - A study of structure on 1kpc-1Mpc scales, where baryon physics crucial
- Specific goals:
  - the CDM Halo mass function from group velocity dispersions
  - the stellar mass function into the intermediate mass regime
  - building total SEDs for galaxies and their components at z < 0.5
- Going massively multi-wavelength:
  - X-ray (XMM), UV (GALEX)
  - Optical: ugr (VST, SDSS), spectra (AAT)
  - Near-IR: ZYJHK (VISTA, UKIRT)
  - Far-IR (Herschel), sub-mm SCUBA-II
  - Radio: 21cm (ASKAP or meerKAT)
- Overcome secondary structural issues:
  - Nuclei-Bulge-Bar-Disc-Disc Truncation decompositions
- Disentangle environmental dependencies
GAMA: Contributing Facilities

- **UKIRT/LAS**: 14 nights
- **VISTA/VIKING**: 30 nights
- **VST/KIDS**: 48 nights
- **AAT/AAΩ**: 66 nights
- **HERSCHEL**: 150 hrs
- **XMM**: X-ray
- **GEMINI**: Near-IR, Optical, HI
- **ASKAP**: Far-IR, z, LSBGs, z, spectra

**Contributing Facilities**

14 nights
30 nights
48 nights
66 nights
150hrs
XMM
GEMINI
ASKAP
GAMA Deep

SUBARU/WFMOS

ALMA

JWST

SKA

MGC

GAMA

GAMA DEEP

SCIENCE

220 hours
## GAMA: Team Affiliations and Structure

**PI:** Driver (St Andrews)

<table>
<thead>
<tr>
<th>SCIENCE</th>
<th>CATS</th>
<th>DATABASE</th>
<th>OBS</th>
<th>MOCKS</th>
<th>RADIO</th>
<th>SPEC. PIPE.</th>
<th>IMAGE. PIPE.</th>
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<tbody>
<tr>
<td>Peacock (ROE)</td>
<td>Baldry (LJMU)</td>
<td>Liske (ESO)</td>
<td>Driver (St And)</td>
<td>Norberg (ROE)</td>
<td>Hopkins (USyd)</td>
<td>Loveday (Sussex)</td>
<td>Bamford (Ports.)</td>
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### TEAM MEMBERS

<table>
<thead>
<tr>
<th>Bland-Haw’n (U.Syd)</th>
<th>Lahav (UCL)</th>
<th>Oliver (Sussex)</th>
<th>Phillipps (Bristol)</th>
<th>Popescu (UCLan)</th>
<th>Proctor (Swin.)</th>
<th>Sharp (AAO)</th>
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<td>Cameron (StA)</td>
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### TEAM AFFILIATIONS:
- UKIRT/LAS, VST/KIDS, VISTA/VIKING, HERSCHEL-ATLAS, DURHAM ICC
Galaxy redshift surveys:
optical-to-near-IR magnitude limited except for
(C) = colour selection used for photo-z limits
GAMA = Five
5x10 deg chunks
Started 01/08/08
G09=20% done
G12=20% done
G15=10% done
20k GAMA Redshifts obtained last week!
Observing ongoing…
GAMA12h proposed for Deep ASKAP followup

- GAMA depth and area well matched to the proposed ASKAP deep stare.

GAMA 12h
50 sq deg (5 x 10)
20% completed

Predicted ASKAP redshift dist (x0.1)
(Johnston et al., 2008)
Red Sequence
Colour Bimodality
Versus redshift (van Kampen)

Blue Sequence

Colour Bimodality Versus redshift (van Kampen)
Star-formation rate versus redshift. Hopkins et al. (2008)
The GAMA Stellar Mass function graph shows the number density of galaxies as a function of stellar mass. The y-axis represents the number density in units of $\text{dex}^{-1} \text{ Mpc}^{-3}$, while the x-axis represents the stellar mass in units of $\log (M/M_\odot)$. The graph includes data from various sources:

- **Bell et al. 2003 table 5**
- **Baldry et al. 2006 fig. 8**
- **New analysis using NYU–VAGC**
- **Cole et al. 2001 fig. 18**
- **Jones et al. 2006 table 4**

The data points and lines represent different studies and analyses, with the shaded area indicating the range of uncertainty. The GAMA (simulated) data points are clearly marked.
The CDM halo mass fn
SUMMARY

Bimodality due to two component nature of galaxies:

Structure more fundamental than colour: structure=1st order tracer of formation mechanism?

Fast/Hot mode (collapse/rapid merger) > Spheroids/AGN/SMBHs/high-\([\alpha/Fe]\), \(z > 2\)

Slow/Cold mode (accretion[lumpy]) > discs built slowly in field environment, \(z < 2-3\)

Stellar mass in each component: (D07 ApJL)

Discs = 60% Infall mode (half exponential, half truncated?, truncated are bluer)
Spheroids = 37% Collapse/Merger mode (ellipticals 10%, bulges 27%)
pBulges < 2% Secular mode (also see low luminosity blue spheroids at similar level)

Mean disc dust opacity high, bulges obscured by 0.8-2.5 mags ! (D07 MNRAS)

HTF an environmental effect of IGM & ICM ?

IGM allows disc construction via infall and dust production obscuring the bulges

ICM shuts down SF and destroys dust diminishing disc and unveiling bulge

Removing dust makes a galaxy redder and brighter (dry mergers may not be needed)

Cosmic energy budget balances: lost starlight=far-IR dust emission (D08 submitted)
Luminous Matter and Luminous Energy
Simon Driver (+MGC+GAMA teams)
University of St Andrews

The baryon budget (z=0) & The Cosmic Energy Spectrum