Galaxy Bulge Formation: Observational Perspectives

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Collaborators:

Stephane Courteau (Queen's), Richard Ellis (Caltech), Tommaso Treu (UCSB), Sean Moran (JHU), Jesus Gonzalez (UNAM), Kevin Bundy (UC Berkley), etc...

RASC-Victoria Centre Seminar - Apr 14, 2010

Organisation of Talk

Part 0 -> Some Background Material

Part I -> Local Bulges

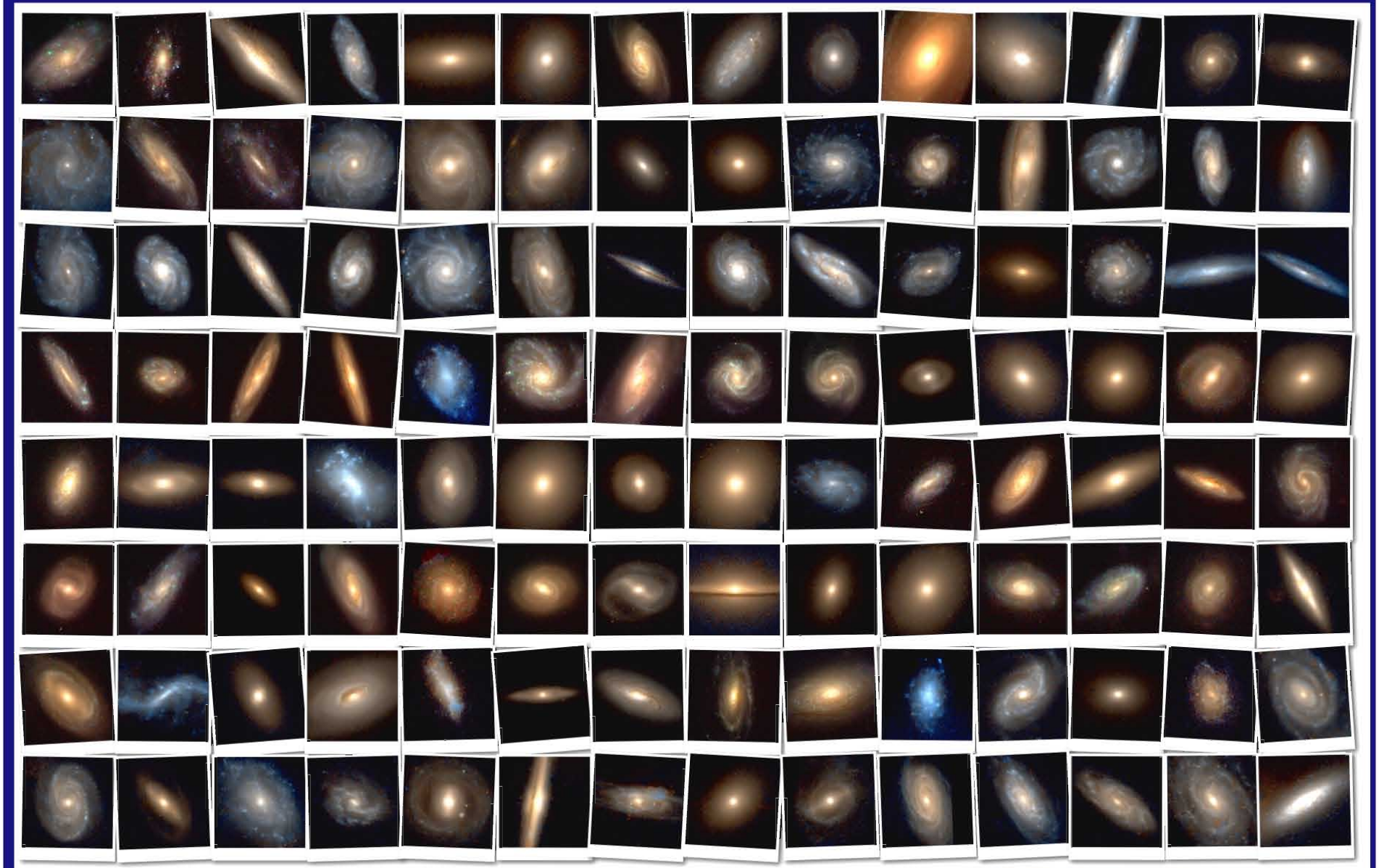
- Structural Analysis of Spirals Galaxies:
  - Imaging: Bulge/Disk Decompositions: shape of bulge profile
- Stellar Populations of Spiral Galaxy Bulges:
  - Spectroscopy: Full spectral fitting using stellar population models

Part II -> Distant Bulges

- Bulges at intermediate redshift ($z<1$):
  - Bulges vs. ellipticals on the Fundamental Plane

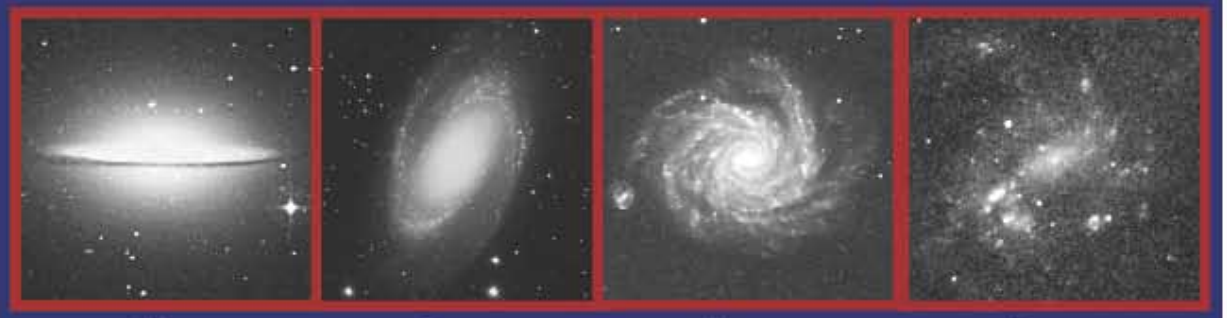
If Time Permits...

- Introduction to The Next Generation Virgo Cluster Survey (NGVS: PI Dr. Laura Ferrarese)



Created by Zsolt Frei and James E. Gunn

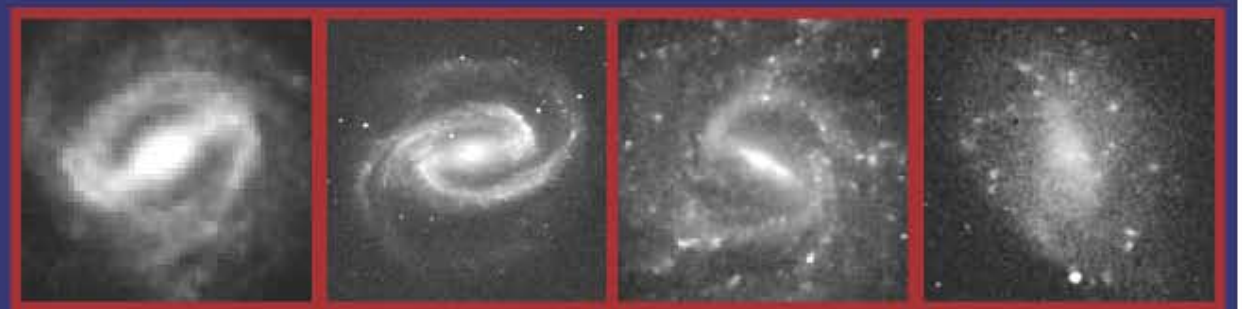
The Hubble Sequence (1926)



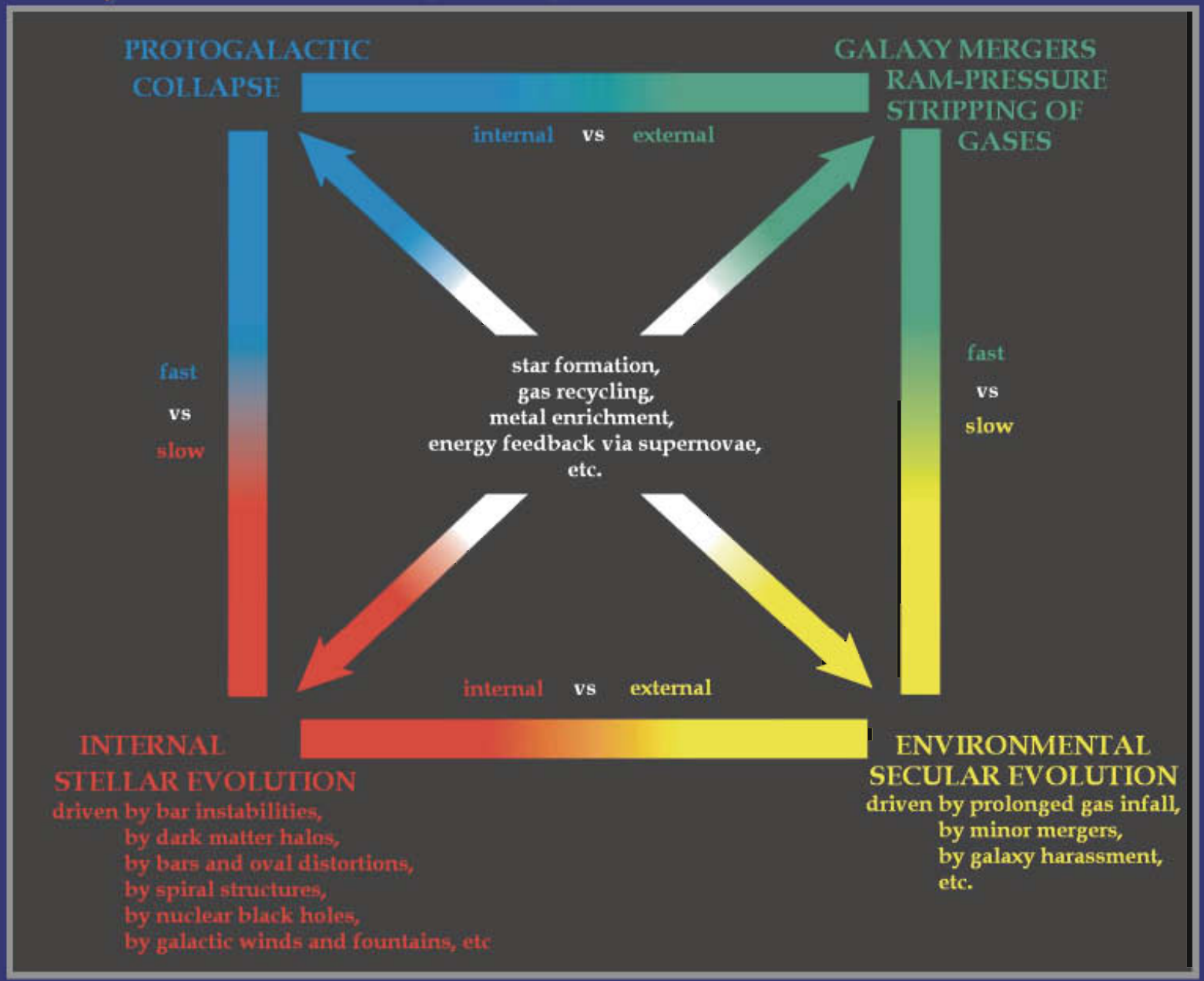
Sa Sb Sc Sd

E0 E6 S0

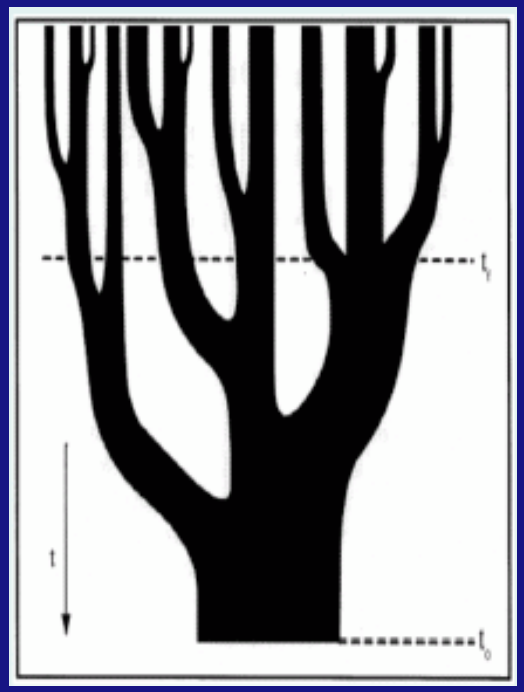
SBa SBb SBc SBd



Kormendy & Kennicutt (2004) Review on Secular Evolutiton:



Galaxy Formation Models

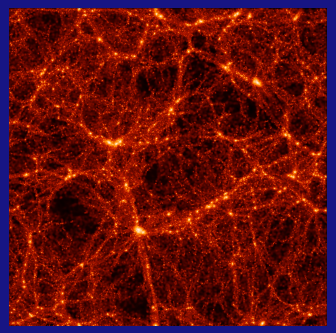


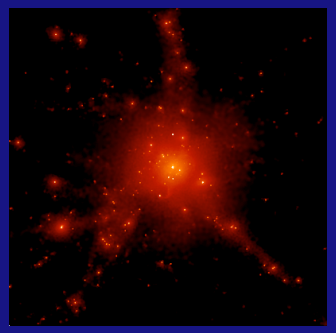
N-body merger trees

$z = 3$

$z = 1$

$z = 0$





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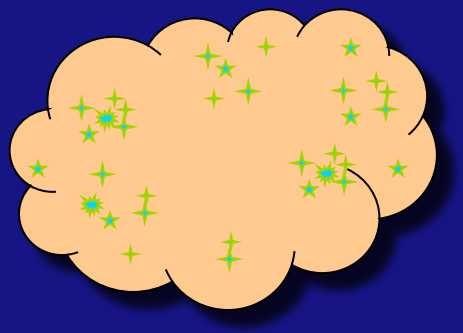
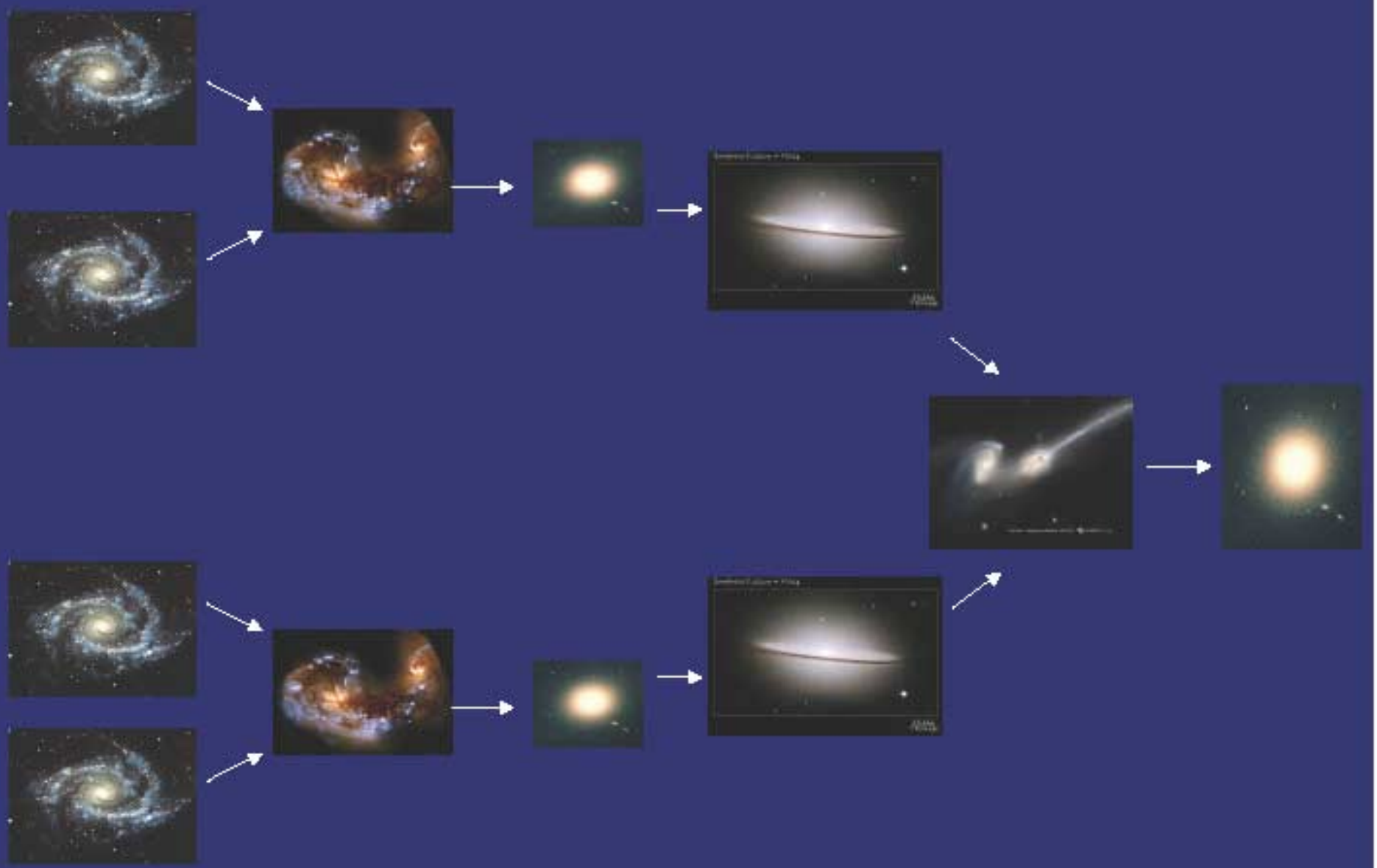


Messy physics
(gas cooling, star-formation,
dust, SN feedback
etc…)

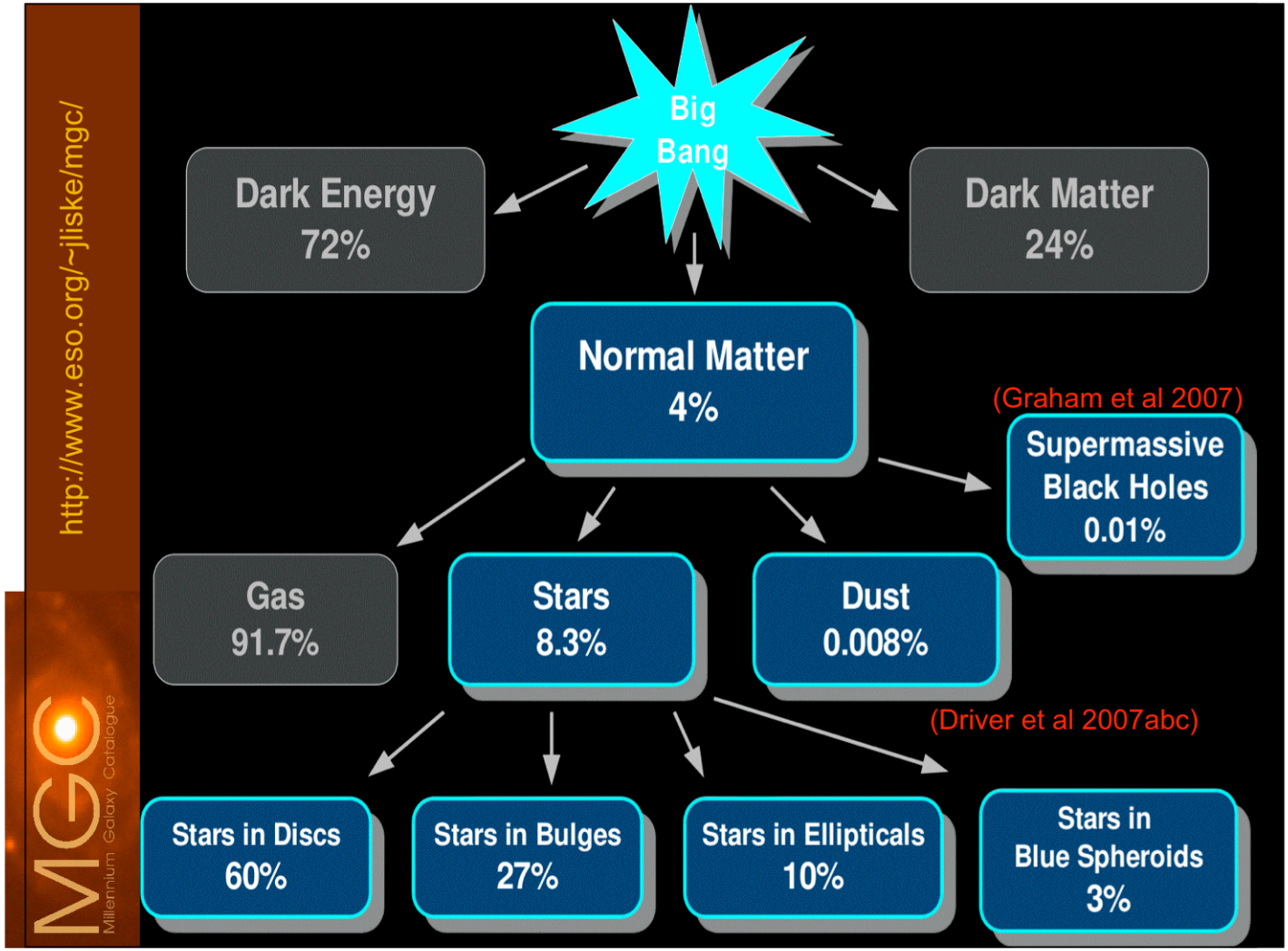
=

Hierarchical Galaxy Formation



Galaxy "Bulges"/Spheroids

Why Study Bulges?



Driver et al. 2007abc

Definitions/Nomenclature

classical bulge:

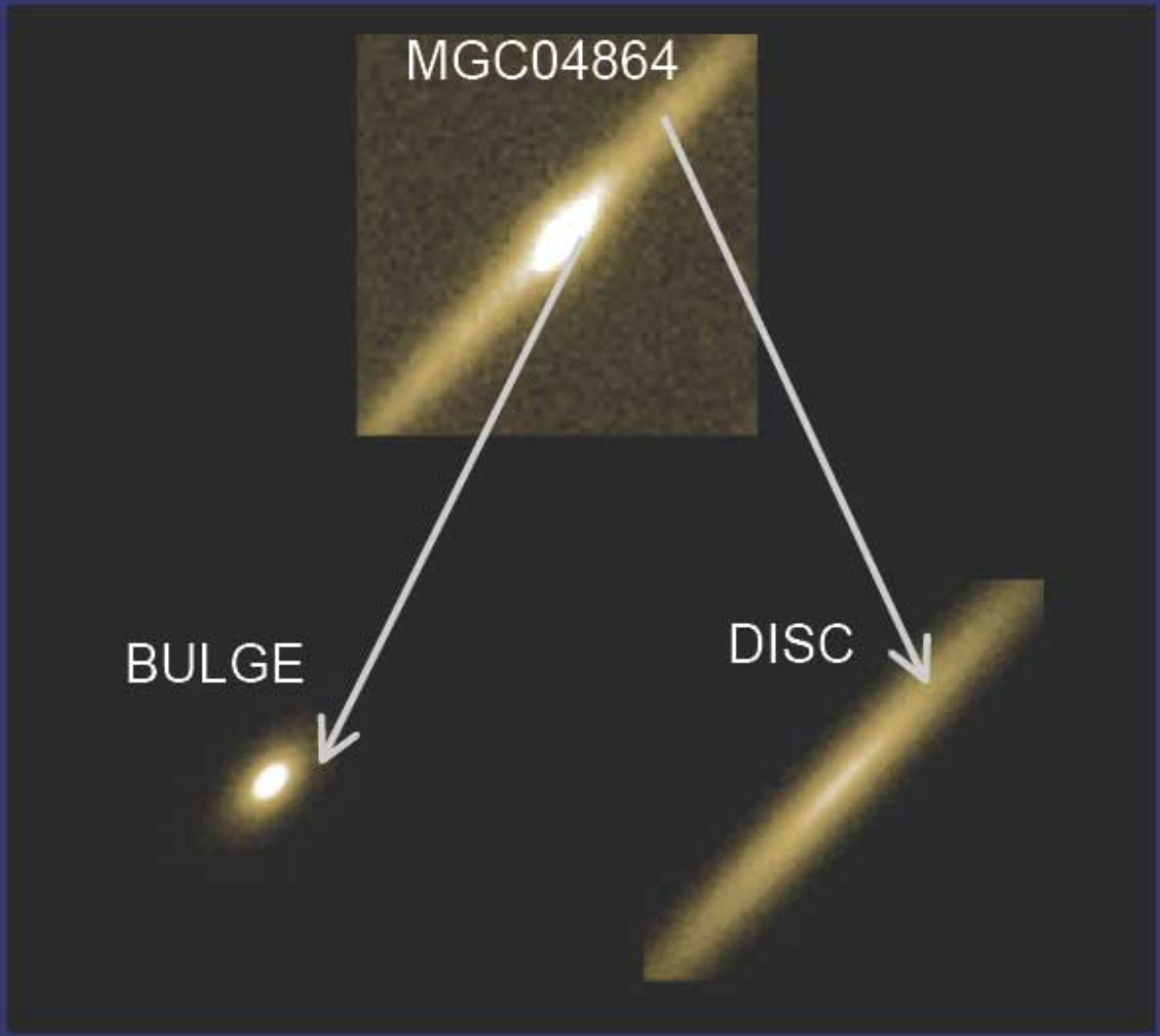
- ellipticals are formed via mergers &/or rapid collapse
- "classical" bulges are ellipticals that happen to have formed a prominent disk around them (after last major merger event)
- HOWEVER not every central component that is in excess of the inward extrapolation of an exponential fit to the disk SB profile is a "bulge"

pseudobulge:

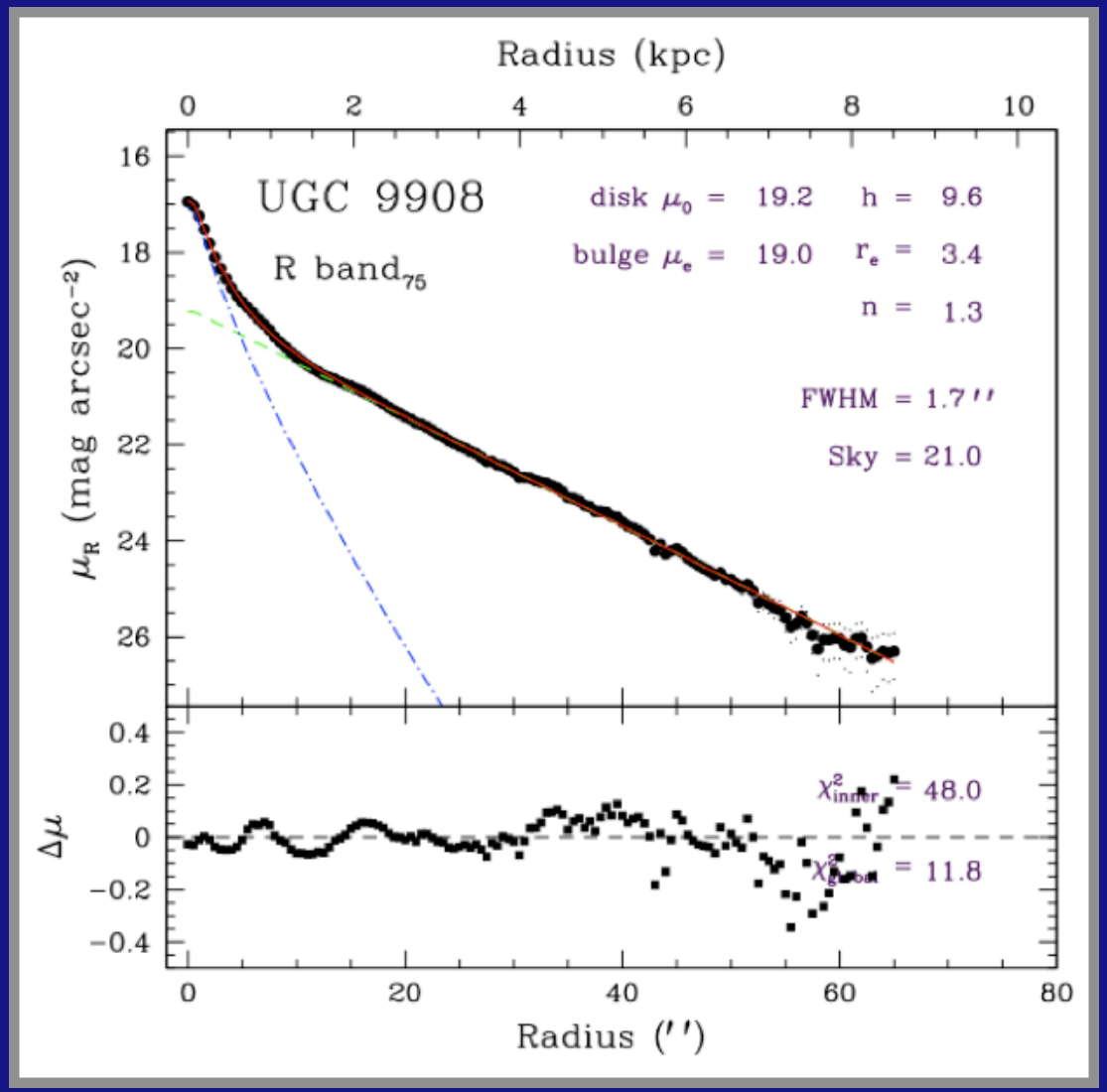
Formed by secular redistribution of disk material. Retain memory of "disky" origin:

1) apparent flattening is similar to that of the outer disk
2) contains a nuclear bar (will only see in face-on galaxies)
3) boxed shaped (only seen in edge-on galaxies)
4) has SB profile Sérsic index n ~ 1 – 2 (nearly-exponential light profile)
5) more rotation-dominated than classical bulge (in V_{max}/σ vs. ε diagram)
6) a low-σ outlier in the Faber-Jackson (1976) relation ($M_{B,bulge}$ vs. σ)
7) dominated by Pop^n I material (young stars, gas, dust) but no sign of merger

Structural Analyses: isolate disk and bulge components



Bulge-Disk Decompositions



Exponential disk:

$$I_{\text{disk}}(r) = I_0 \exp\left\{-\frac{r}{h}\right\}$$

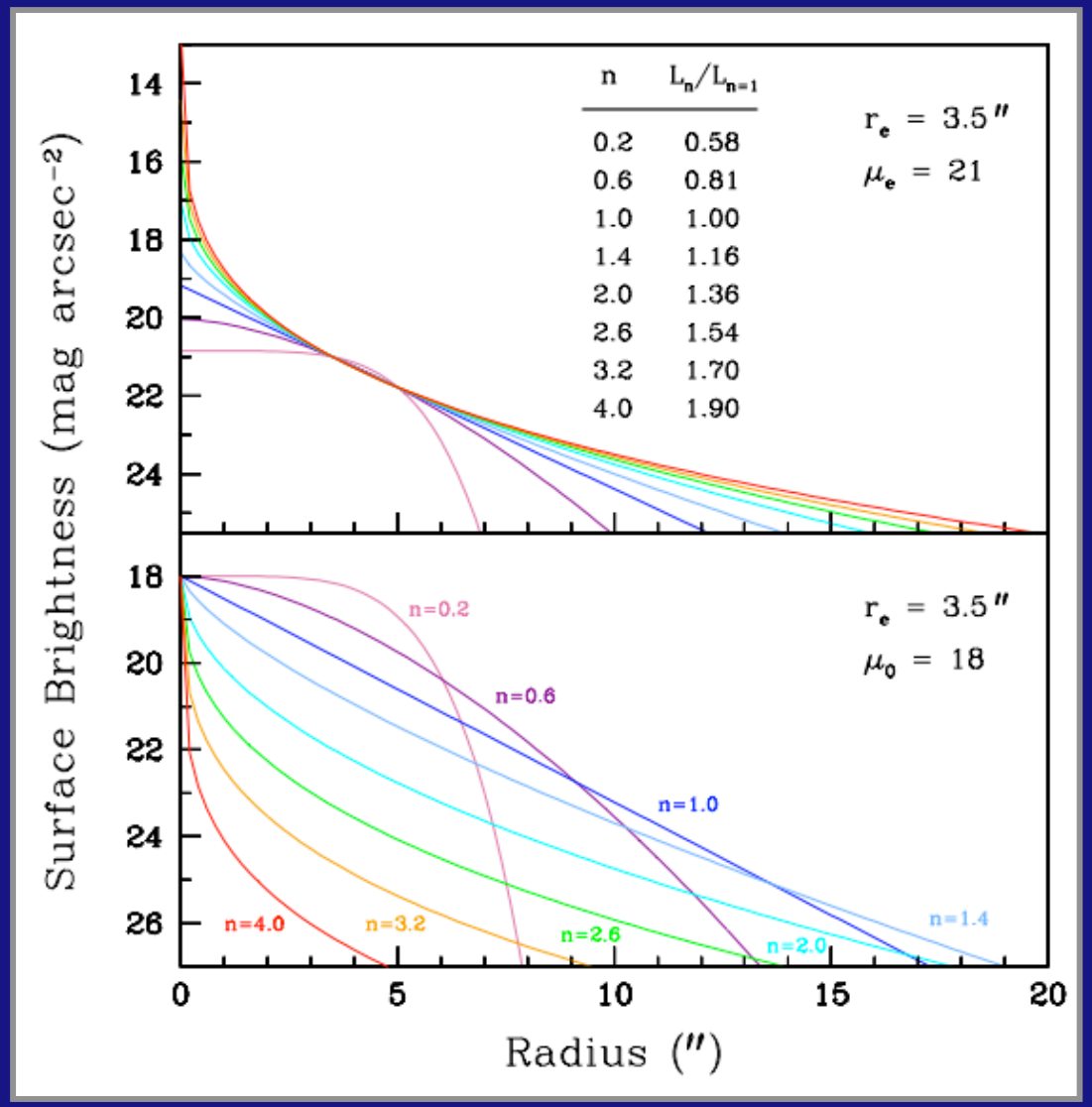
+

Sérsic bulge
(Generalized Gaussian):

$$I_{\text{bulge}}(r) = I_0 \exp\left\{\left(-\frac{r}{r_0}\right)^{1/n}\right\}$$

MacArthur, Courteau,
& Holtzman (2003)

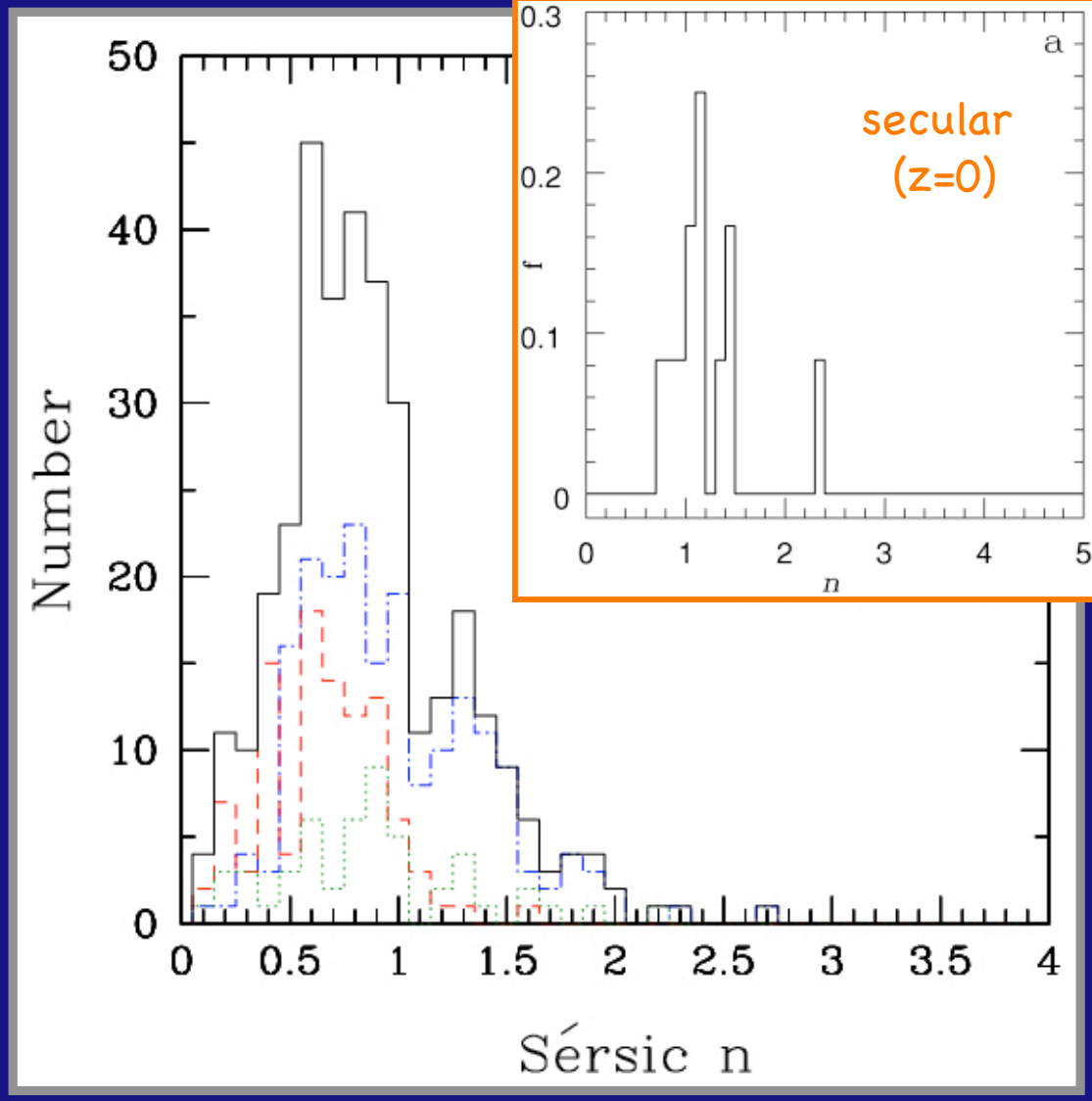
Sérsic Profiles

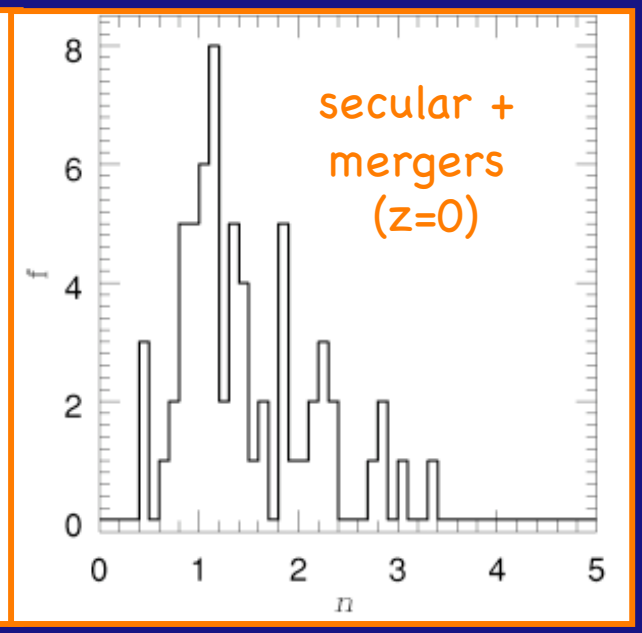


$$I(r) = I_o \exp\{-(\tfrac{r}{h})^{1/n}\}$$

MacArthur, Courteau, & Holtzman (2003)

Bulge Shape for Late-Type Spirals



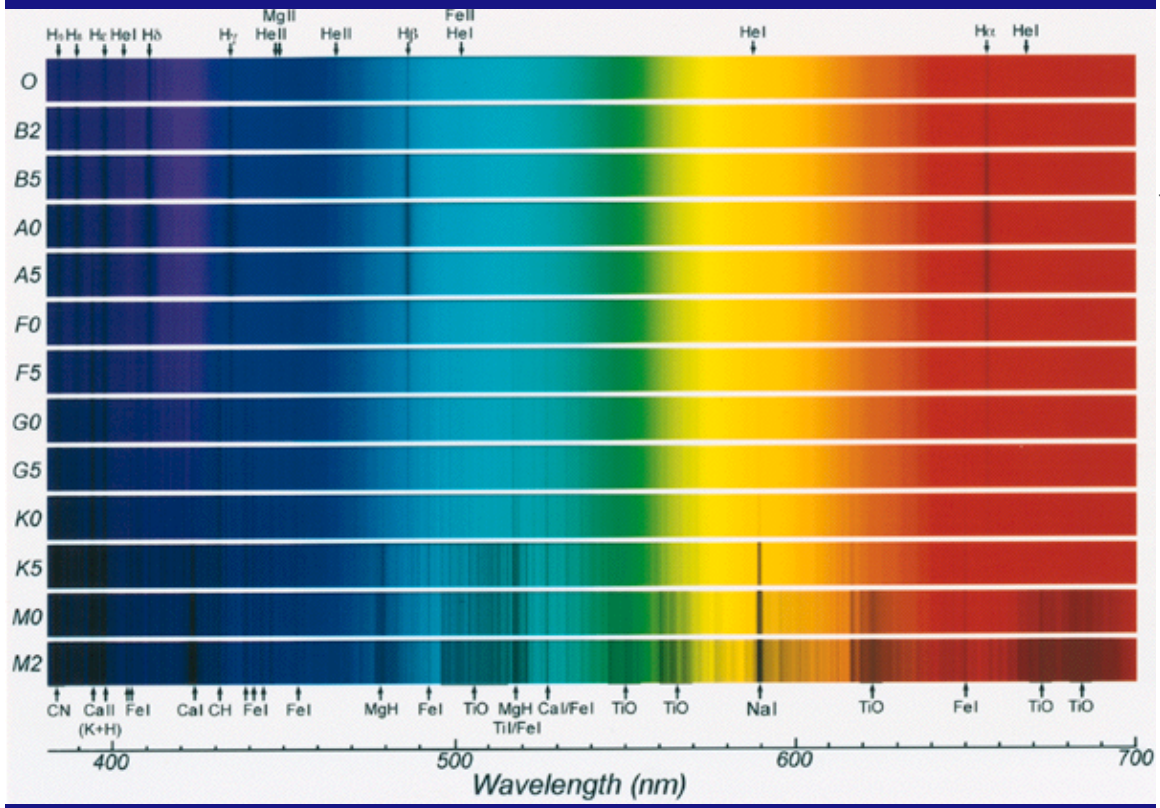


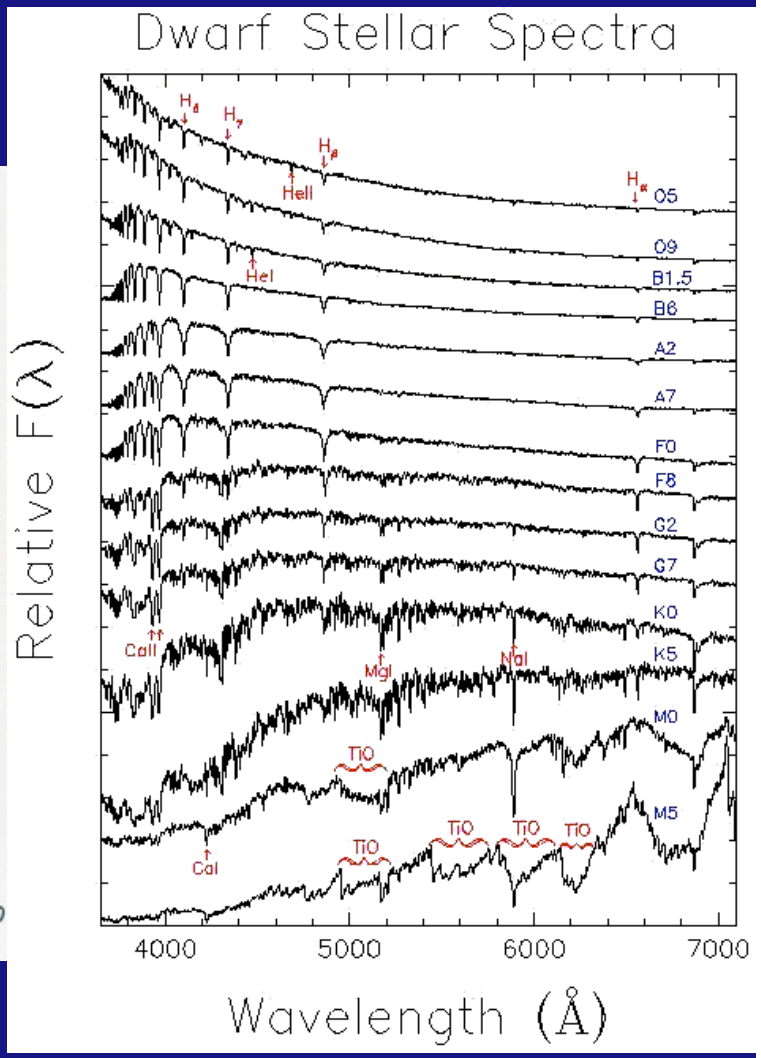
- Also consistent with N-body models of secular evolution (e.g. Scannapieco & Tissera 2003)

MacArthur, Courteau, & Holtzman (2003)

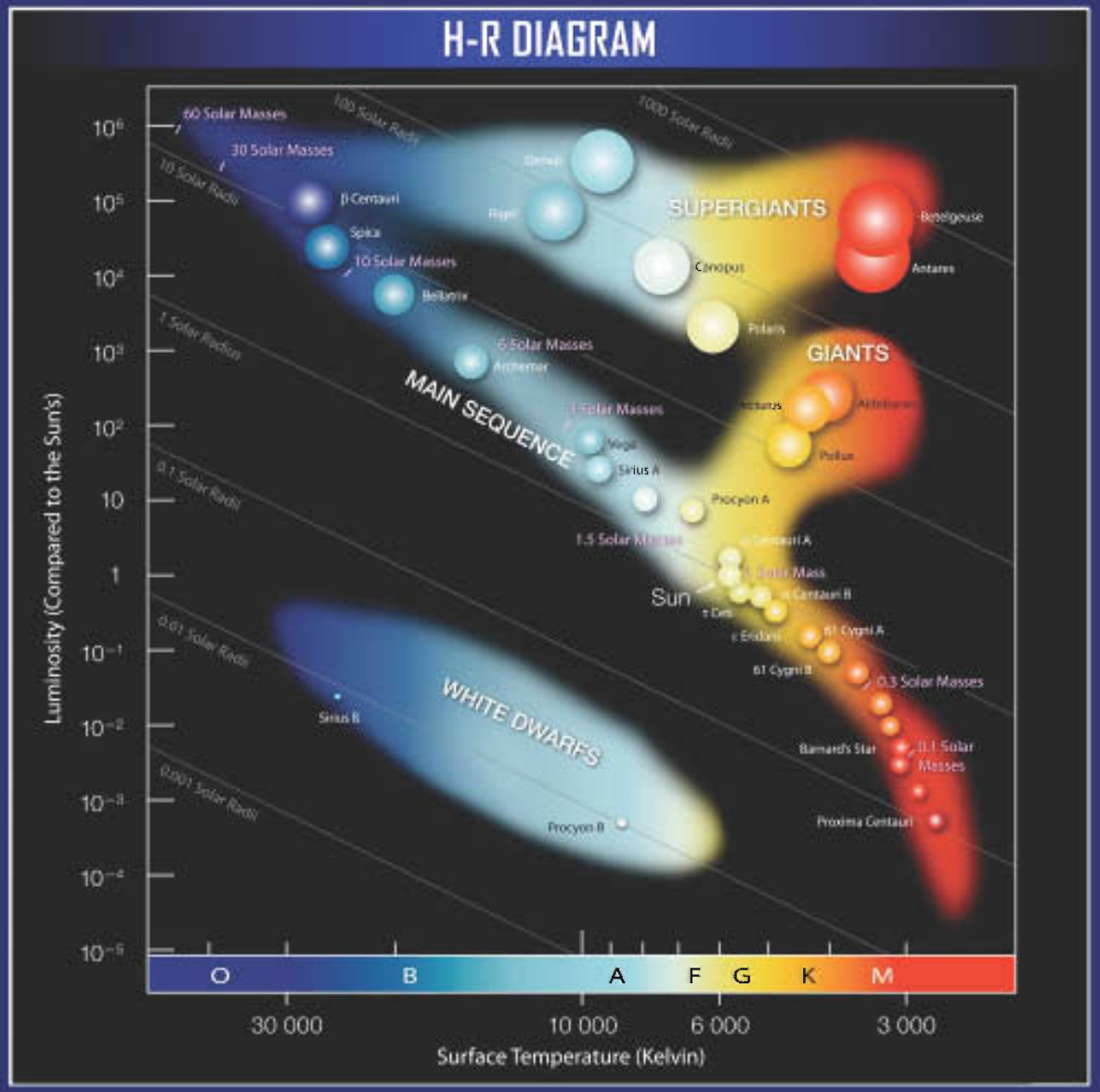
Overview of Stars: Spectra

Stars have spectra that depend on temperature, pressure, and chemical abundance





Overview of Stars: Hertzprung-Russel Diagram



Some Definitions/Nomenclature

metal: Any element other than Hydrogen or Helium

metallicity (Z): $(X,Y,Z) \equiv$ fractional abundance by WEIGHT of (H, He, Everything else) ⇨ $X + Y + Z = 1$

$[Fe/H] \equiv \log(n(Fe)/n(H)) - \log(n(Fe)/n(H))_{sun}$

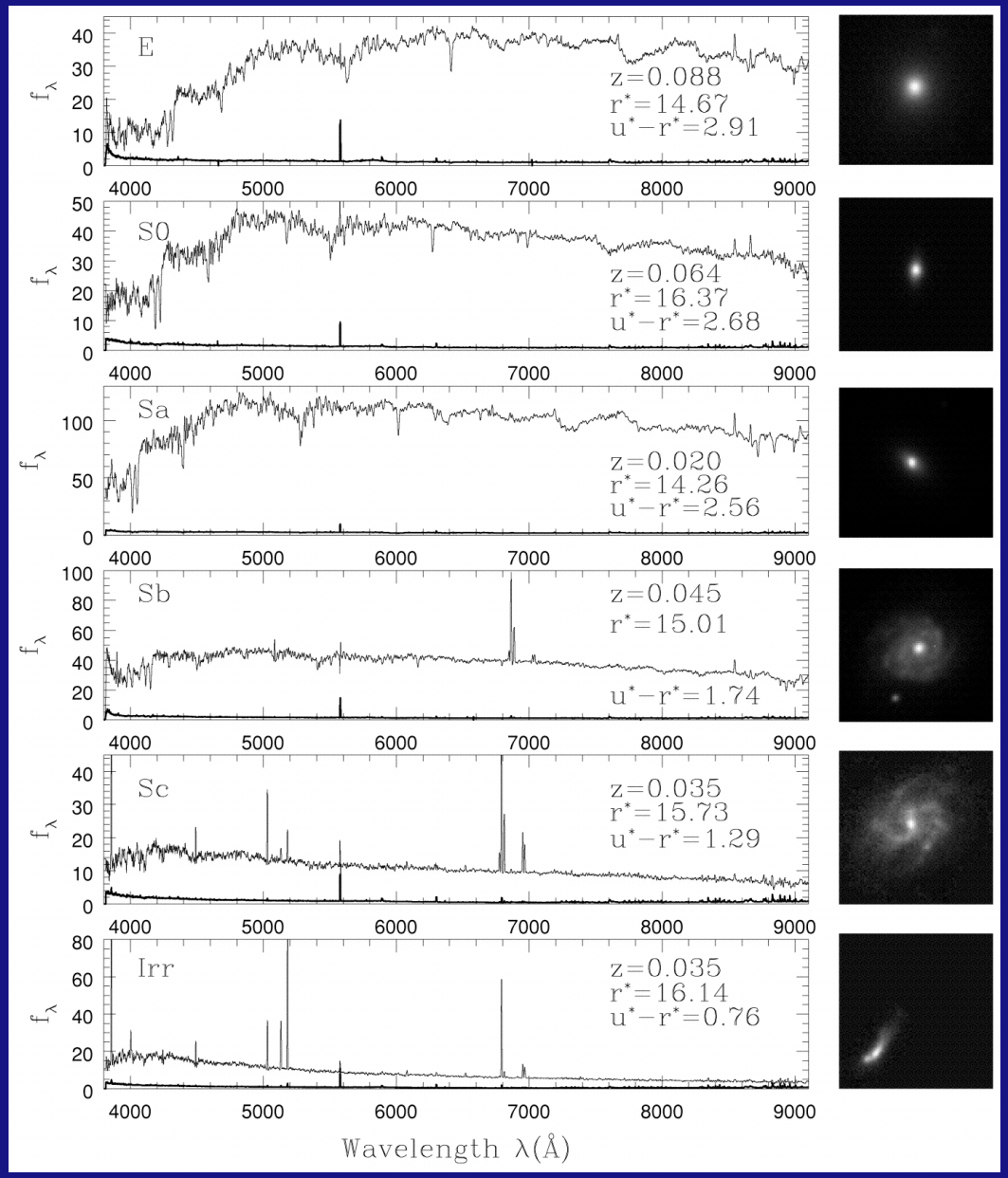
simple stellar population (SSP):

Single age, single metallicity stellar population (single burst of star formation)

composite stellar populations:

Luminosity-weighted sums of their SSP components

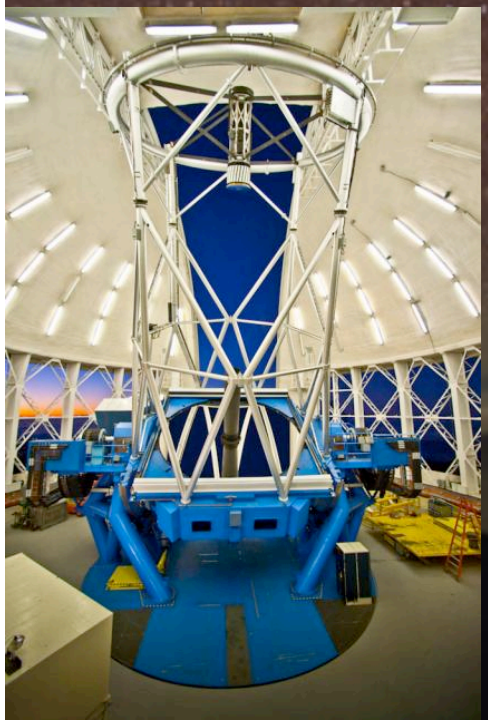
Different Types of Galaxies: Integrated Spectra



Strateva et al. (2001)

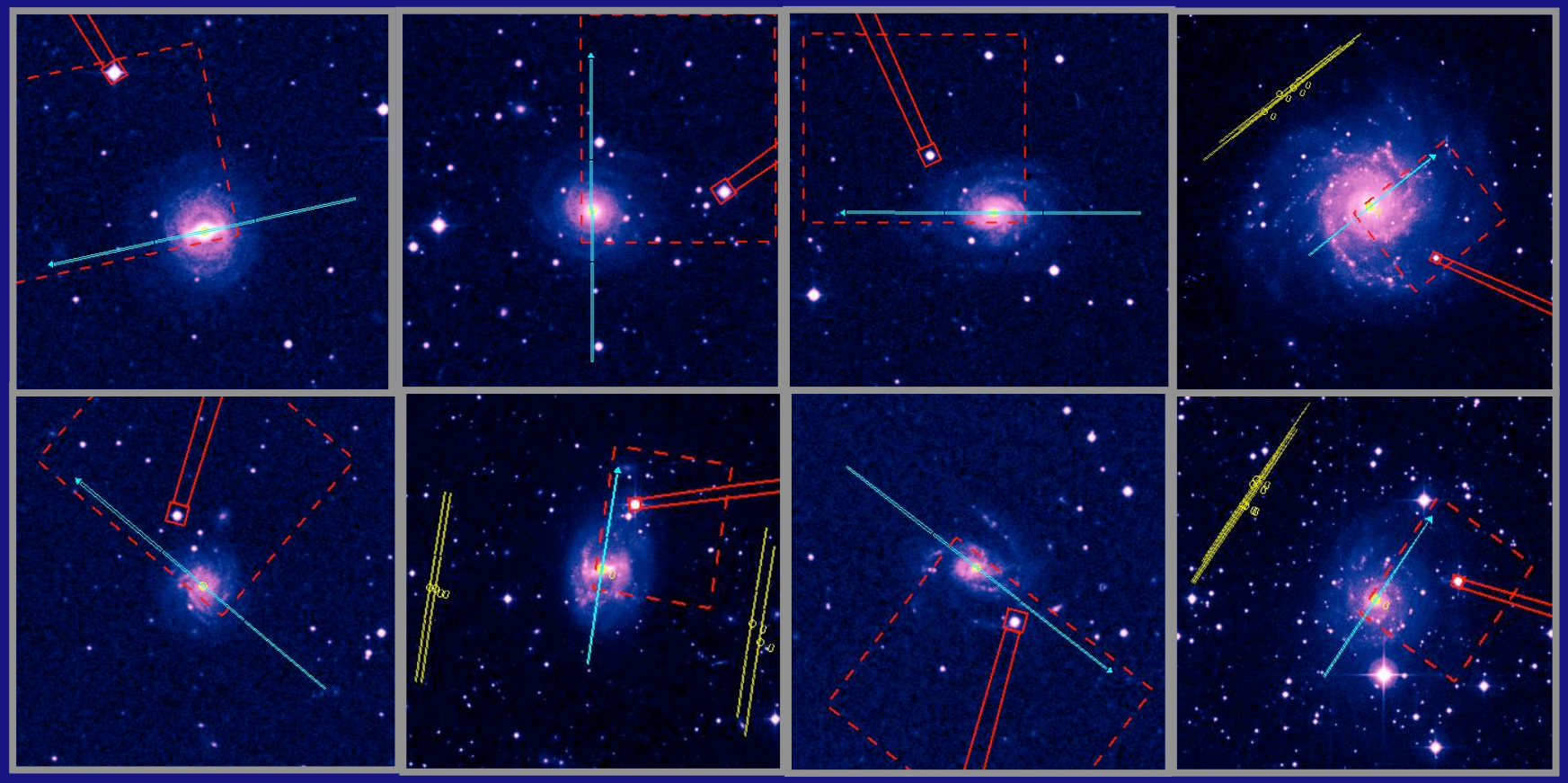
Gemini North

- Collected long-slit spectroscopy of 8 nearby face-on late-type barred/unbarred galaxies using the Gemini-Multi-Object Spectograph
- Spectral coverage in the optical(~4000-6700Å) Exposure times of ~1.5 hours per galaxy



GMOS/N Data

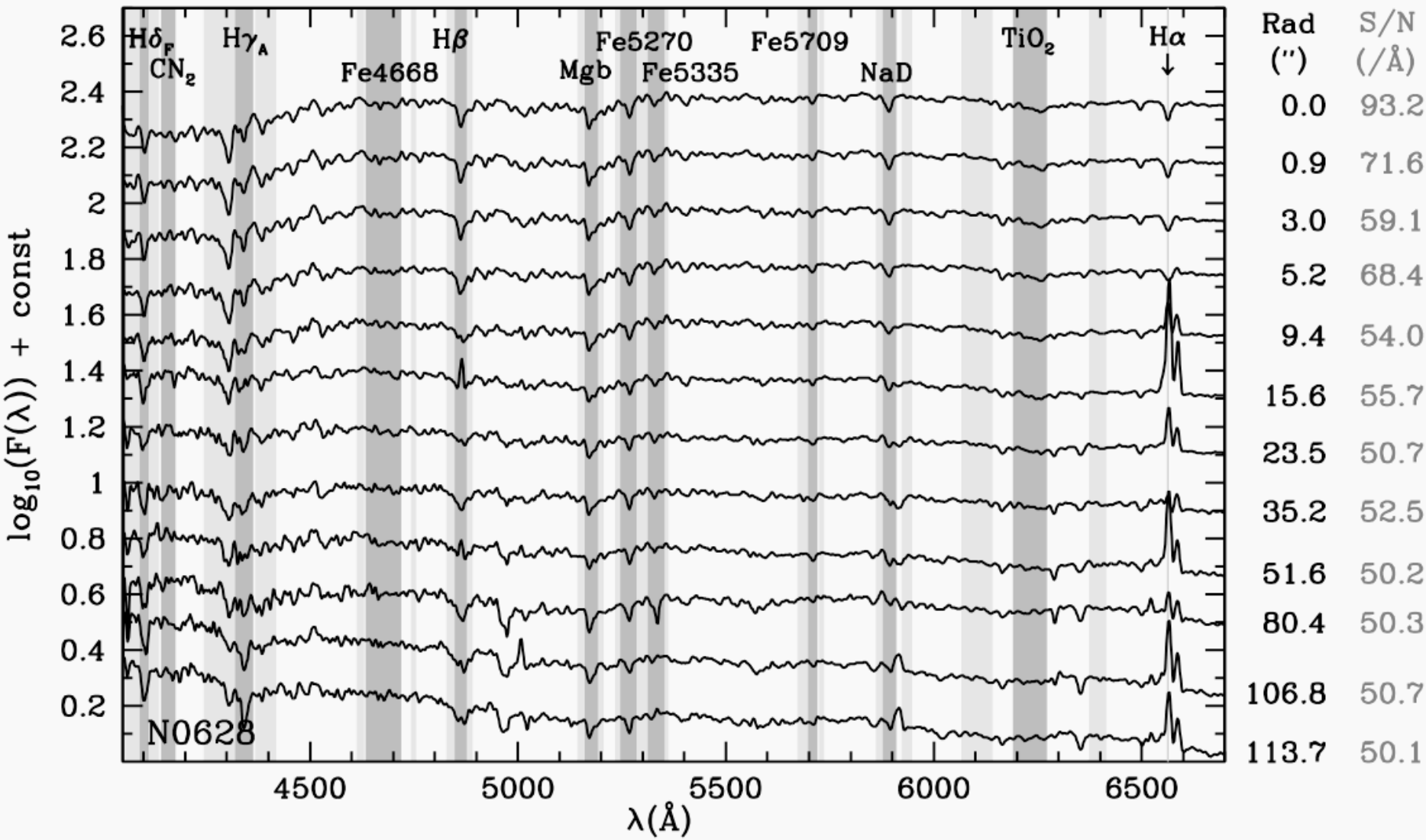
UGC 2124 (SBa) NGC 7490 (Sbc) NGC 173 (Sc) NGC 628 (Sc)



NGC 7495 (SABc) NGC 7741 (SBcd) NGC 7610 (Scd) IC 239 (SABcd)

M74 - "The Perfect Spiral"

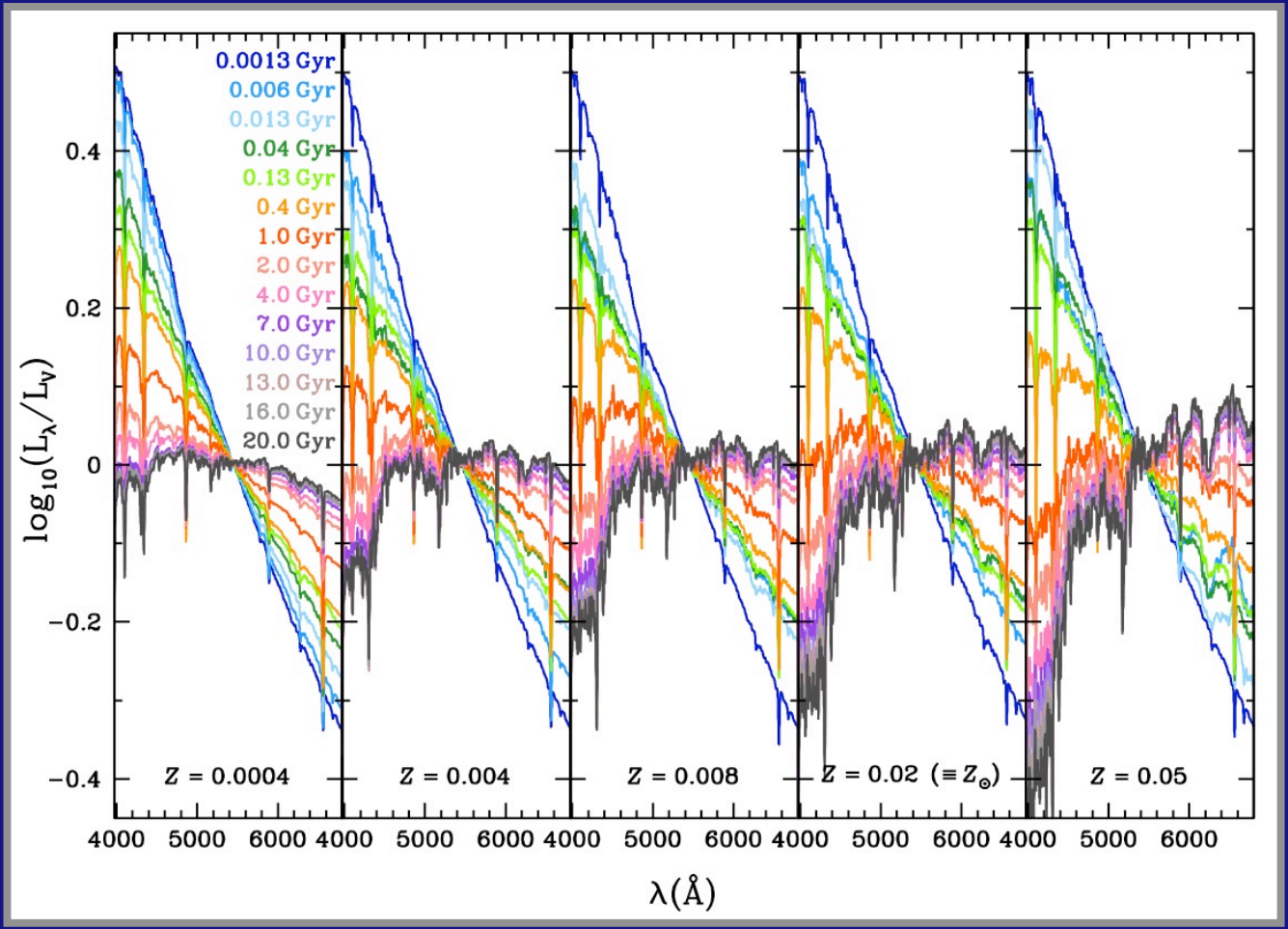
Radial Spectra: M74



MacArthur, González, & Courteau, 2009, MNRAS, 395, 28 $r_e = 11.3''$ $r_d = 70.6''$

Full Spectral Synthesis using model SSPs

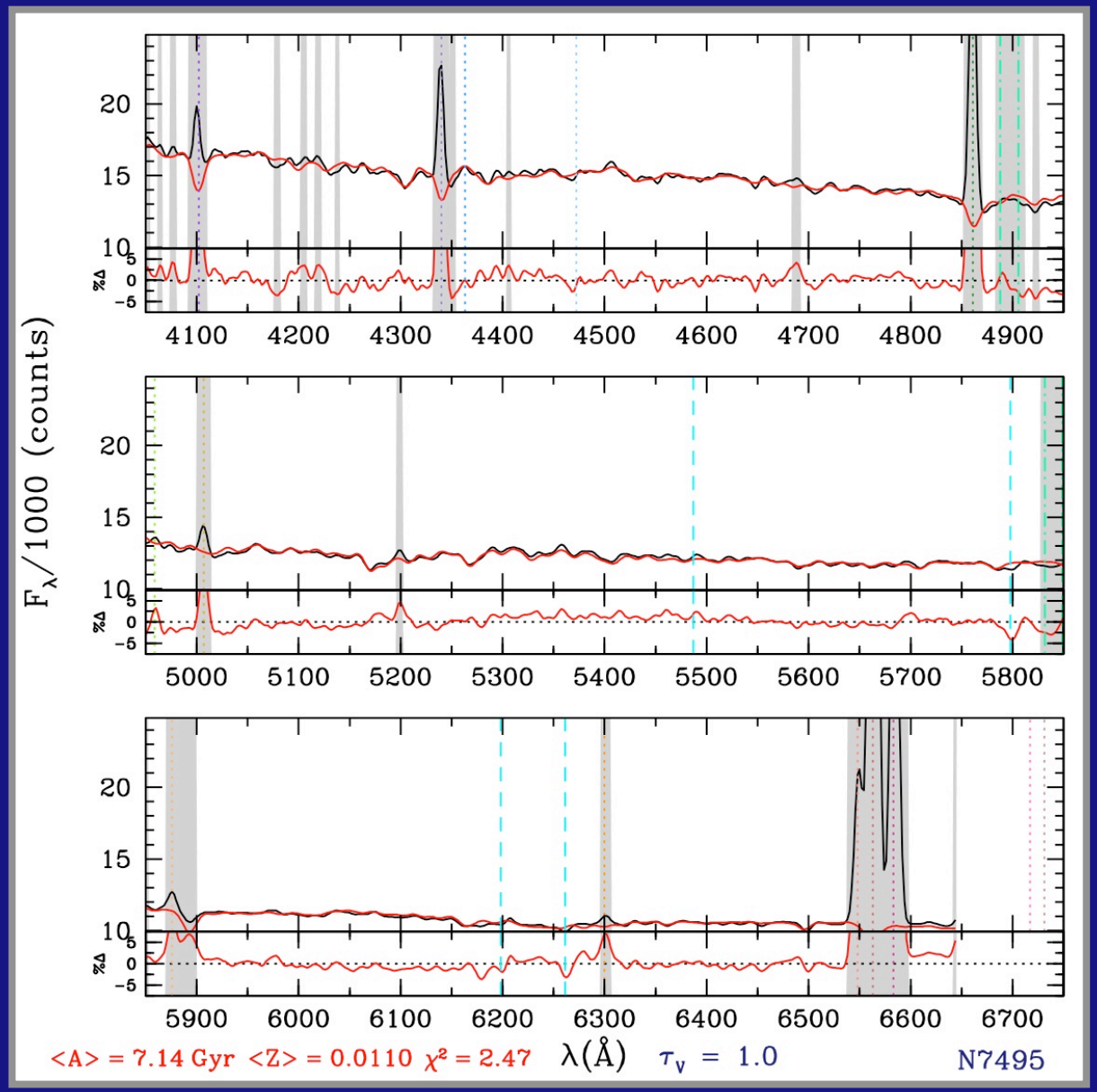
- bound-constrained optimization: best-fit linear non-zero combination of spectral templates



-> here using 70 templates from Bruzual & Charlot 2003 models with full range of age and metallicity

MacArthur, González, & Courteau, 2009, MNRAS, 395, 28

Stellar Populatitons in Galaxy Bulges



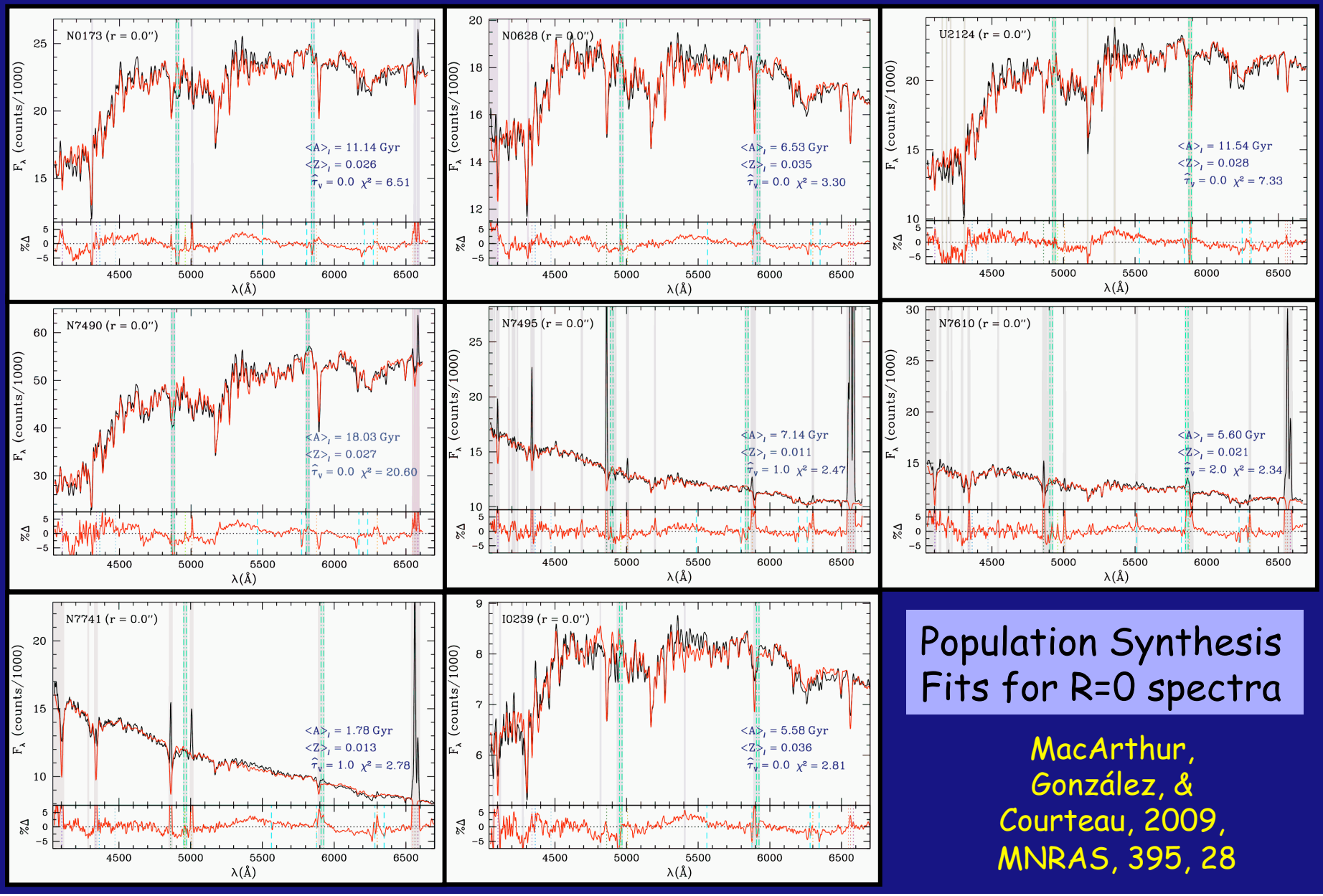
Data

Fit based on bound constrained optimization of a non-zero linear combination of SSP model spectra

Regions masked from fit

MacArthur, González, & Courteau, 2009, MNRAS, 395, 28

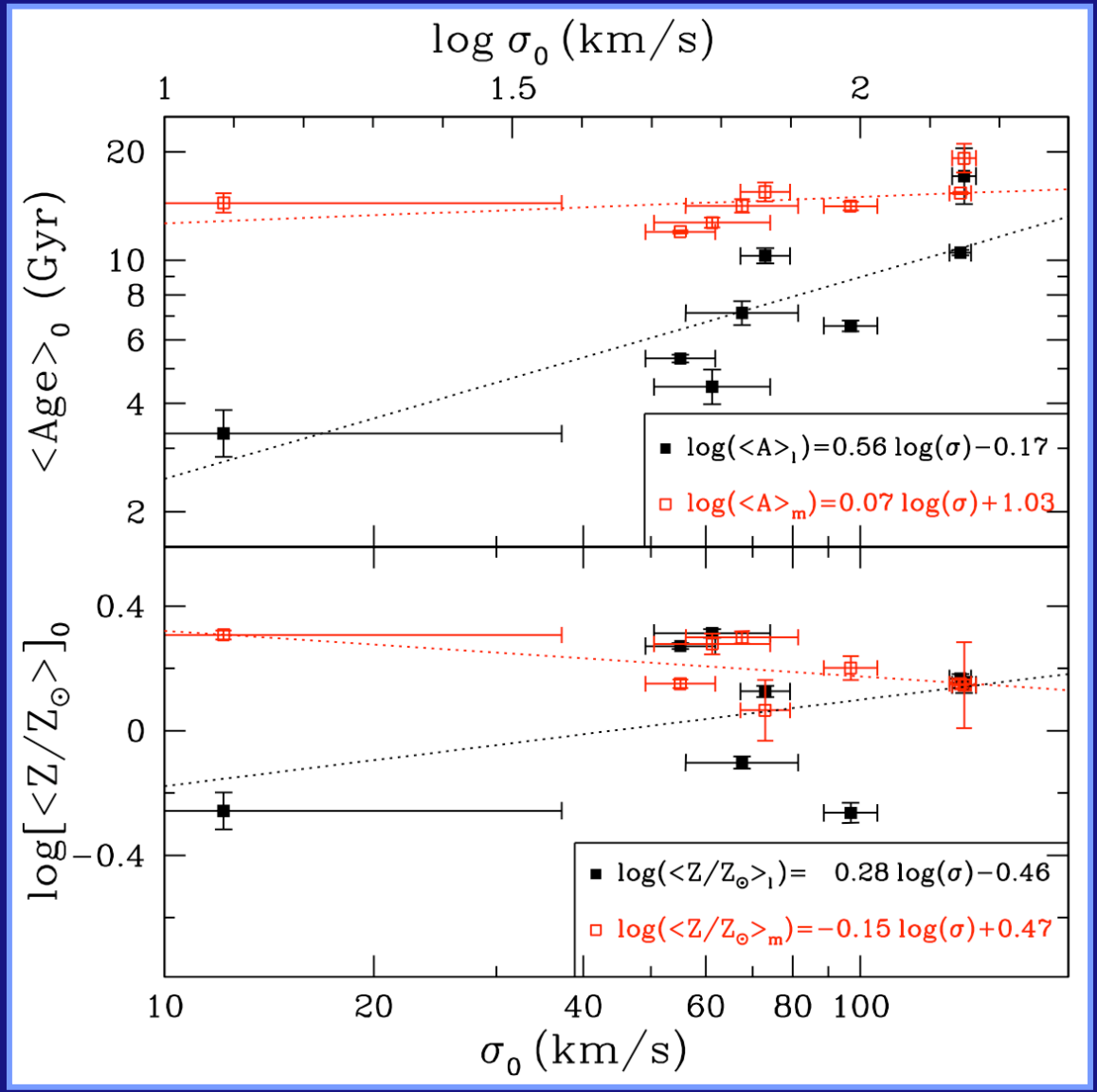
Stellar Populatitons in Galaxy Bulges



Population Synthesis Fits for R=0 spectra

MacArthur, González, & Courteau, 2009, MNRAS, 395, 28

Age/Z vs. "mass" for Bulges

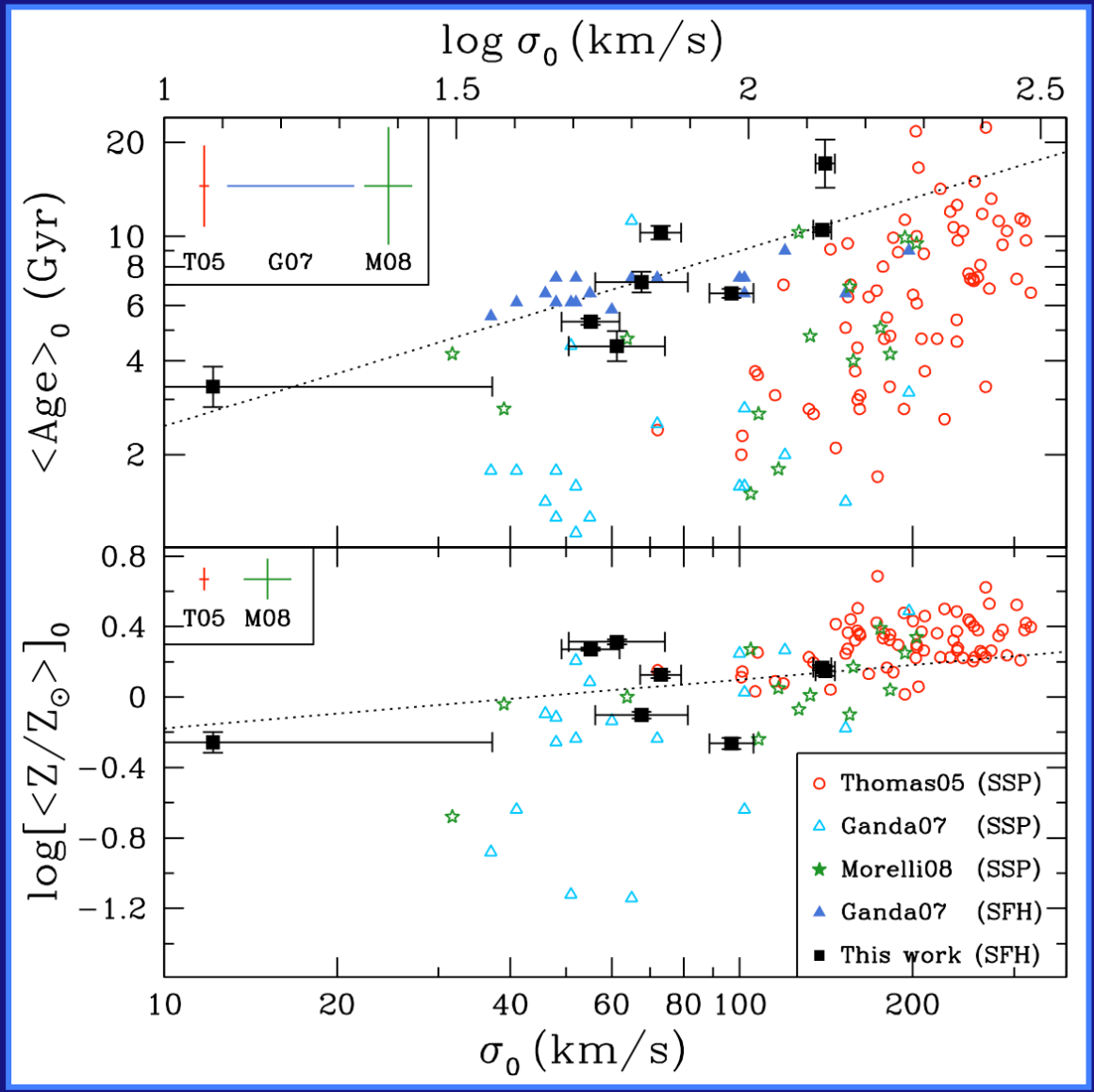


Light-Weighted values

Mass-Weighted values

MacArthur etal. 2009, MNRAS, 395, 28

Age/Z vs. "mass" for Spheroids



Ellipticals from Thomas et al. 2005: SSP

Bulges from Morelli et al. 2008: SSP

Bulges from Ganda et al. 2008: SFH

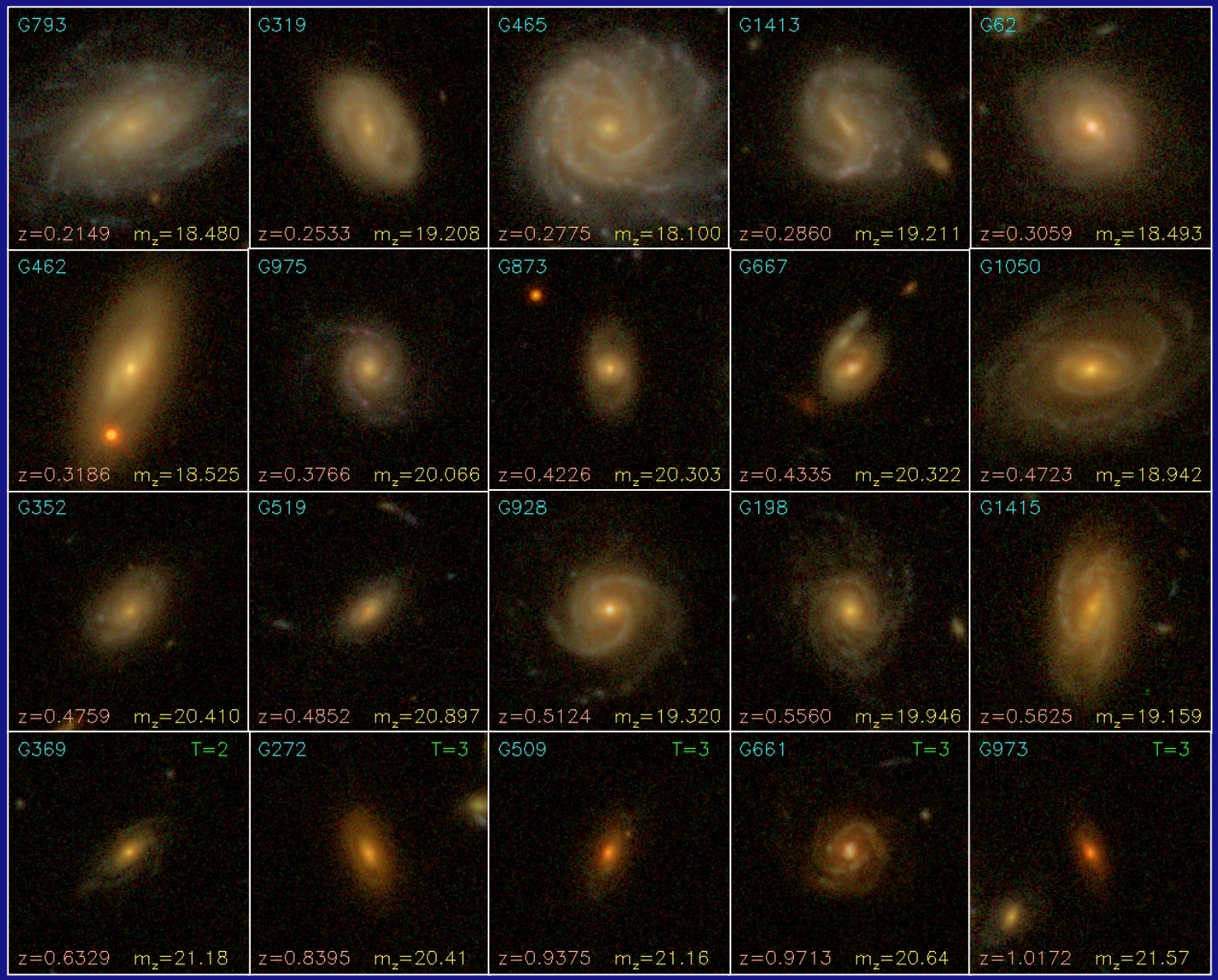
Bulges from Ganda et al. 2008: SFH

Bulges from MacArthur et al.

Part II: Bulge Formation at Intermediate-z

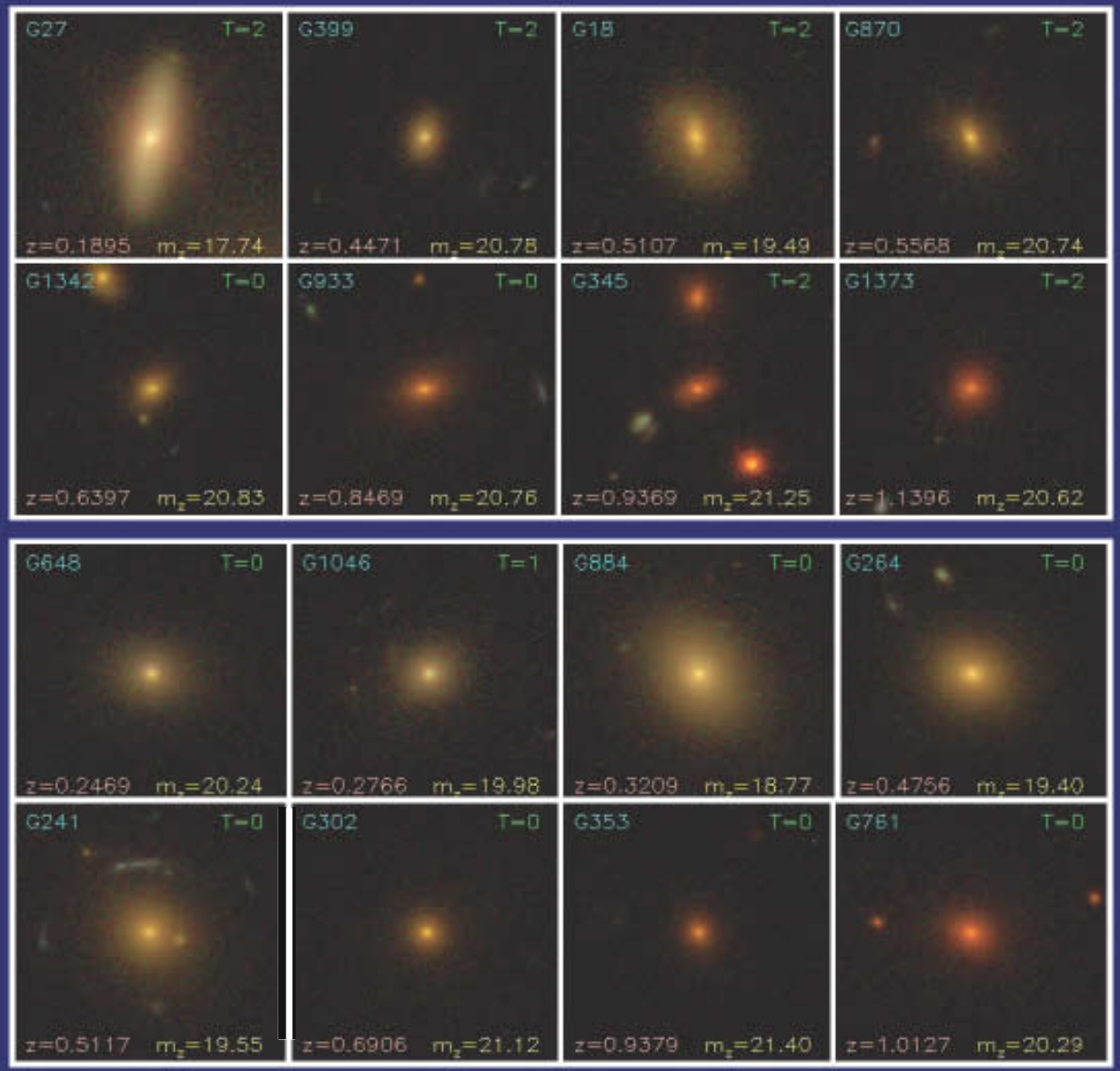
- observing distant galaxies requires a combination of high spatial resolution imaging from the Hubble Space Telescope and deep spectroscopy from Keck

Bulges at 0.2<z<1.1 (GOODS HST-ACS)

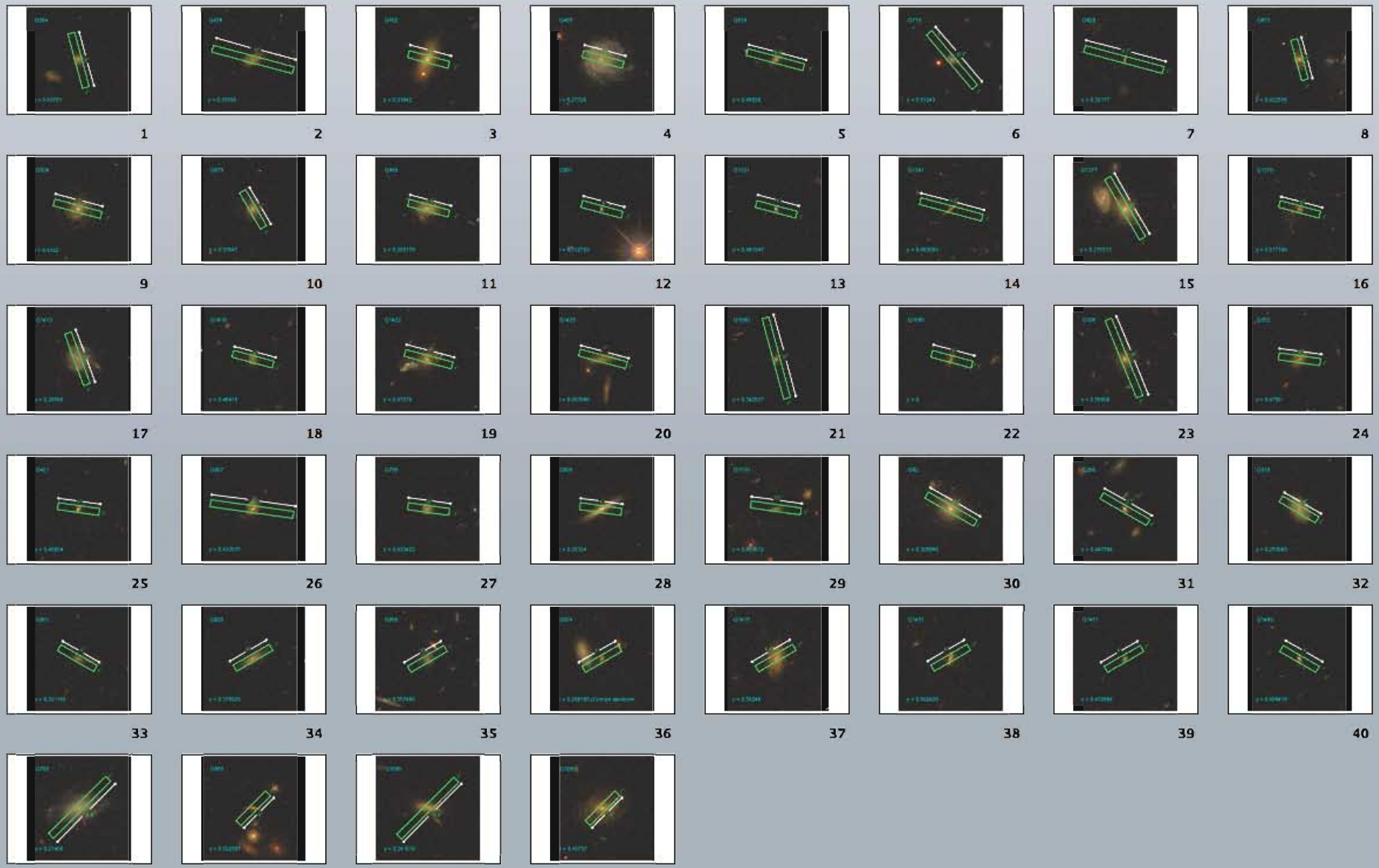


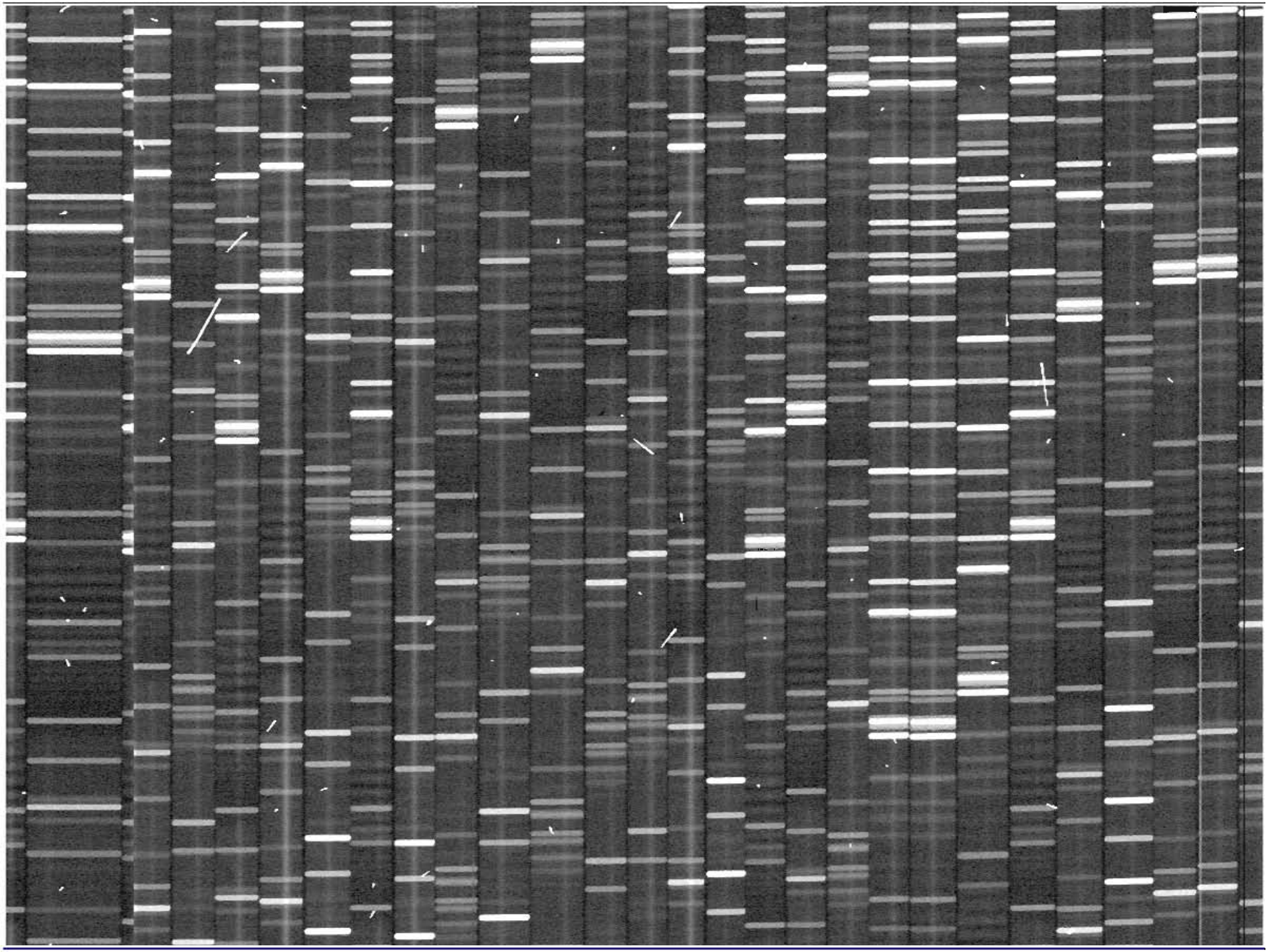
MacArthur et al. 2008, ApJ, 680, 70

S0/E 0.1<z<1.1 (GOODS HST-ACS)

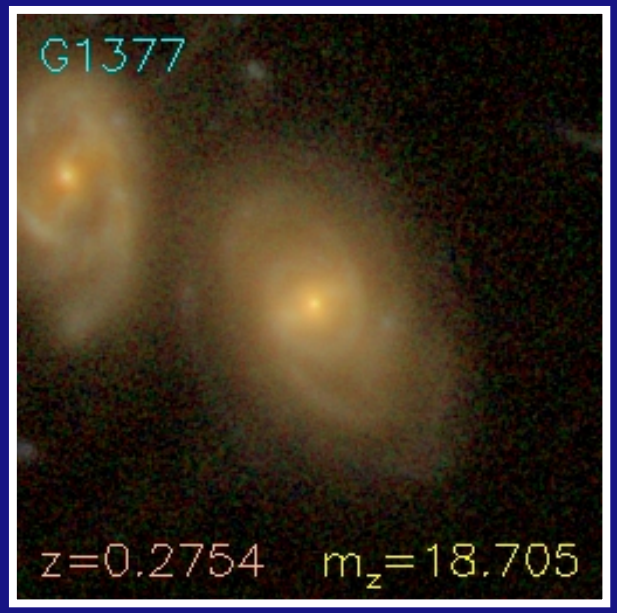


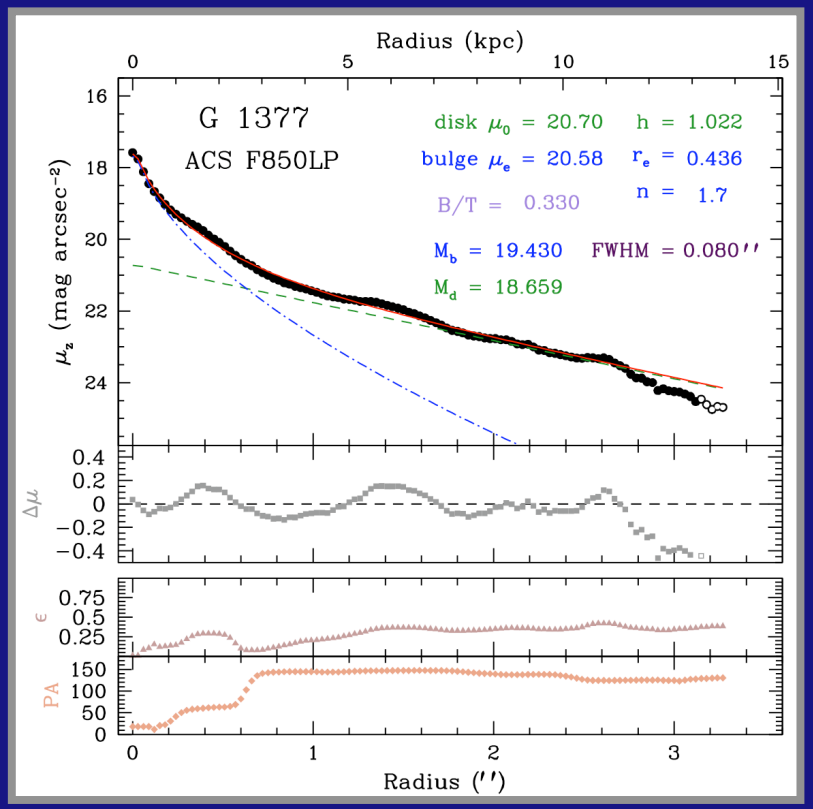
Multi-object Spectroscopy: Slit Mask





Bulge FP Parameters: Photometric





Exponential disk:

$$I_{\text{disk}}(r) = I_0 \exp\left\{-\frac{r}{h}\right\}$$

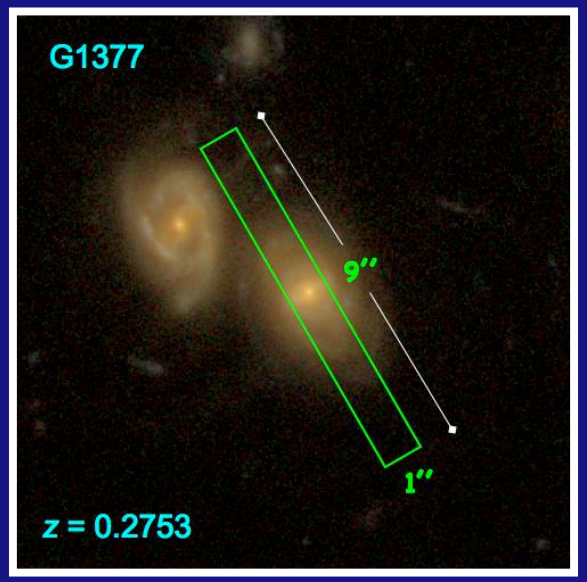
+

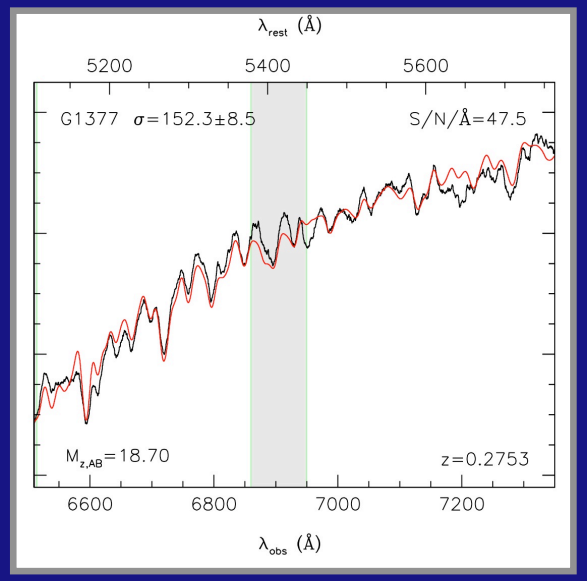
Sérsic bulge (Generalized Gaussian):

$$I_{\text{bulge}}(r) = I_0 \exp\left\{\left(-\frac{r}{r_0}\right)^{1/n}\right\}$$

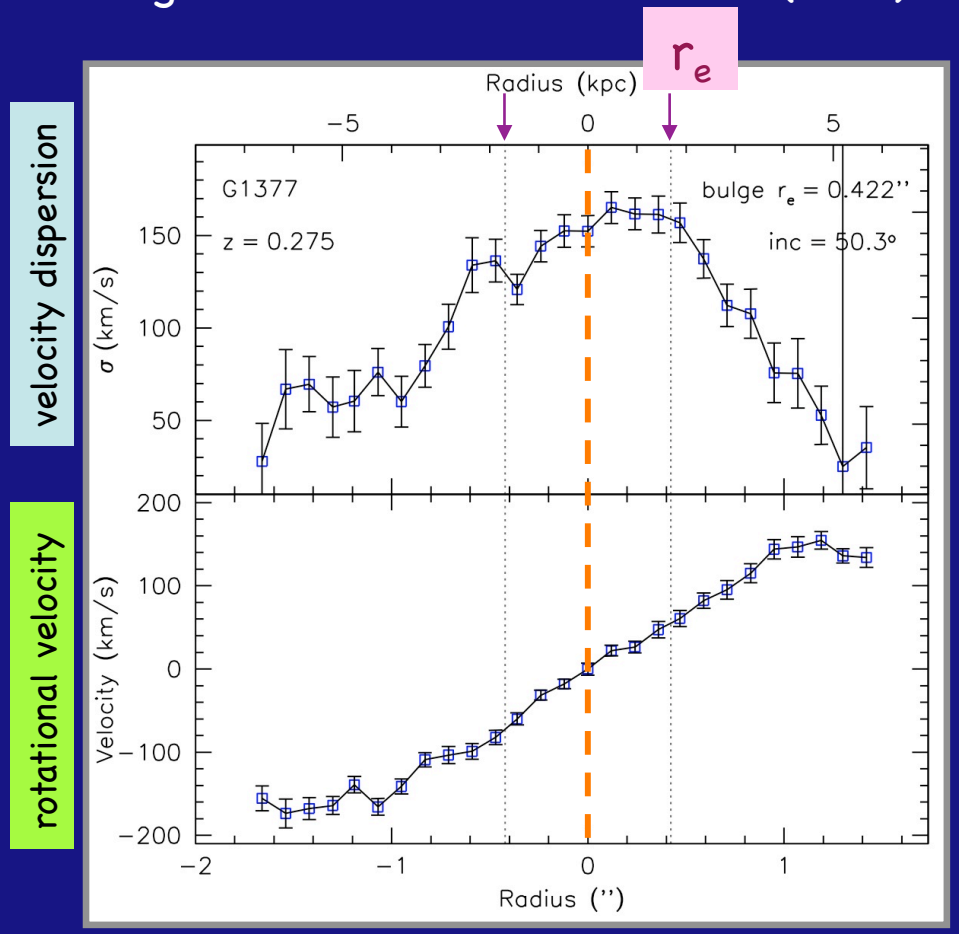
MacArthur, Courteau, & Holtzman (2003)

Bulge FP Parameters: Kinematic



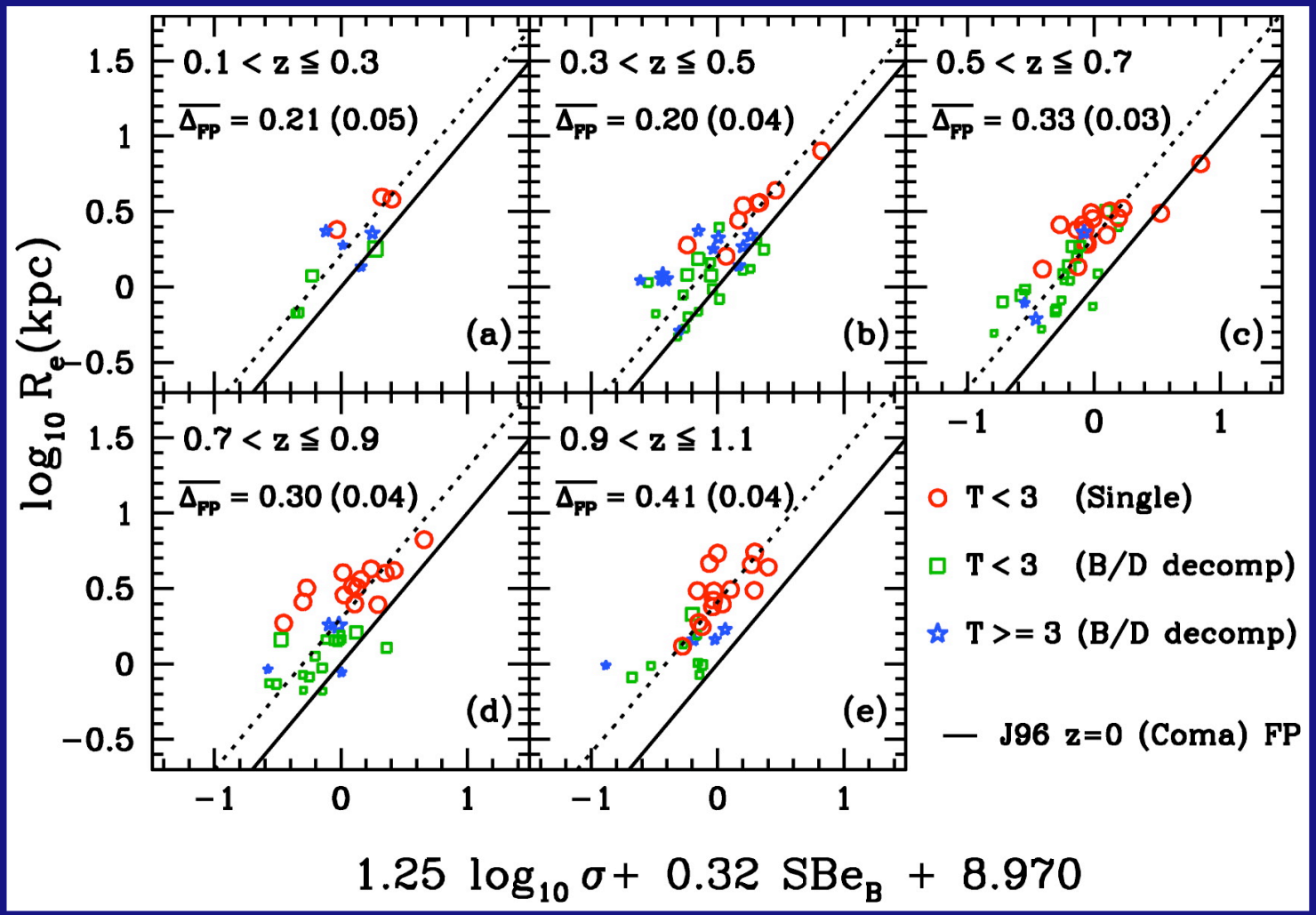


Kinematic profiles derived using pixel fitting software of van der Marel (1994)



MacArthur etal., 2008, ApJ, 680, 70

Evolution of FP for E/S0s & Bulges



MacArthur etal., 2008, ApJ, 680, 70

Summary

- Emerging picture for galaxy bulge formation from local galaxy studies plus higher redshift studies :
  bulge formation is dominated by processes that are common to all spheroids, whether or not they currently reside in a disk
- The formation process occurs on shorter timescales for spheroids with higher masses
- The contribution to the bulge mass via secular processes, or "rejuvenated" star formation is small, but generally increases in weight with smaller mass
- These observations provide fundamental constraints for galaxy formation models

Looking Ahead:

The Next Generation Virgo Cluster Survey

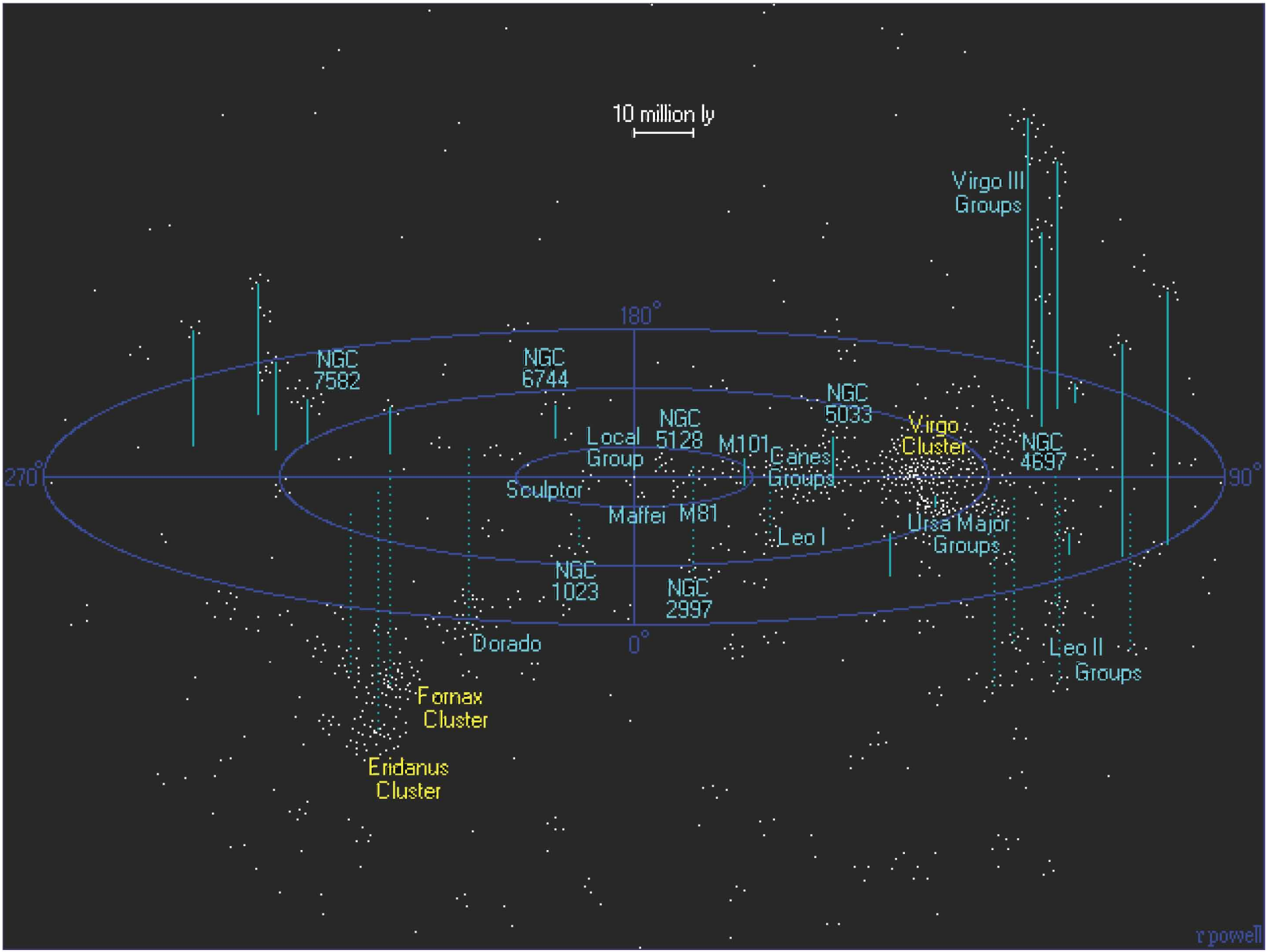
(PI Dr. Laura Ferrarese/ NRC-HIA)

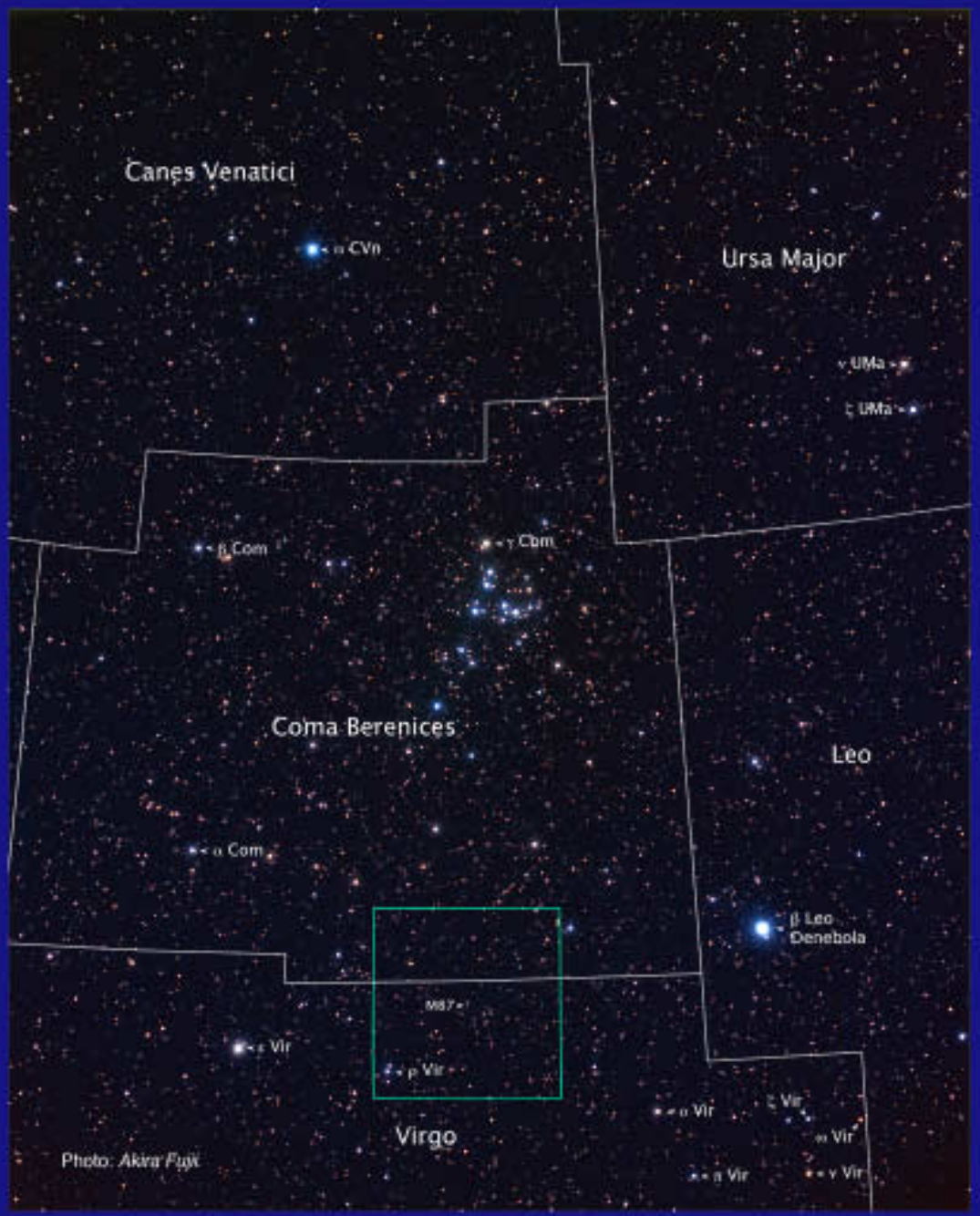
The NGVS Team

Chantal Balkowski
Nick Ball
Michael Balogh
John Blakeslee
Samuel Boissier
Alessandro Boselli
Frederic Bournaud
Claude Carignan
Ray Carlberg
Scott Chapman
Patrick Côté
Stephane Courteau
Tim Davidge
Serge Demers
Pierre-Alain Duc
Pat Durrell
Eric Emsellem
Laura Ferrarese (PI)
Giuseppe Gavazzi
Raphael Gavazzi
Stephen Gwyn

Henk Hoekstra
Andrés Jordán
Ariane Lancon
Lauren MacArthur
Alan McConnachie
Dean McLaughlin
Simona Mei
Yannick Mellier
Chris Mihos
Chien Peng
Eric Peng
Thomas Puzia
Marcin Sawicki
Luc Simard
James Taylor
John Tonry
R. Brent Tully
Wim van Driel
Ludo van Waerbeke
Bernd Vollmer
Christine Wilson

[green = NRC-HIA red=Canadian institution]

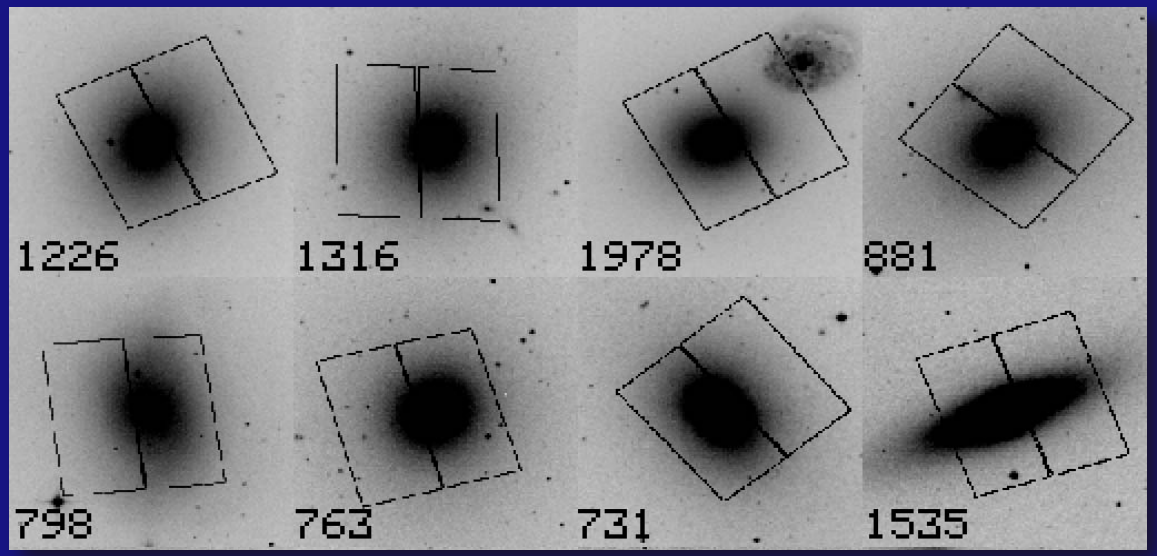

10 million ly
180°
270°
90°
0°
NGC 7582
NGC 6744
NGC 5128
M101
NGC 5033
Local Group
Canes Groups
Virgo Cluster
NGC 4697
Virgo III Groups
Sculptor
Maffei
M81
Leo I
Ursa Major Groups
NGC 1023
NGC 2997
Dorado
Leo II Groups
Fornax Cluster
Eridanus Cluster
r powell

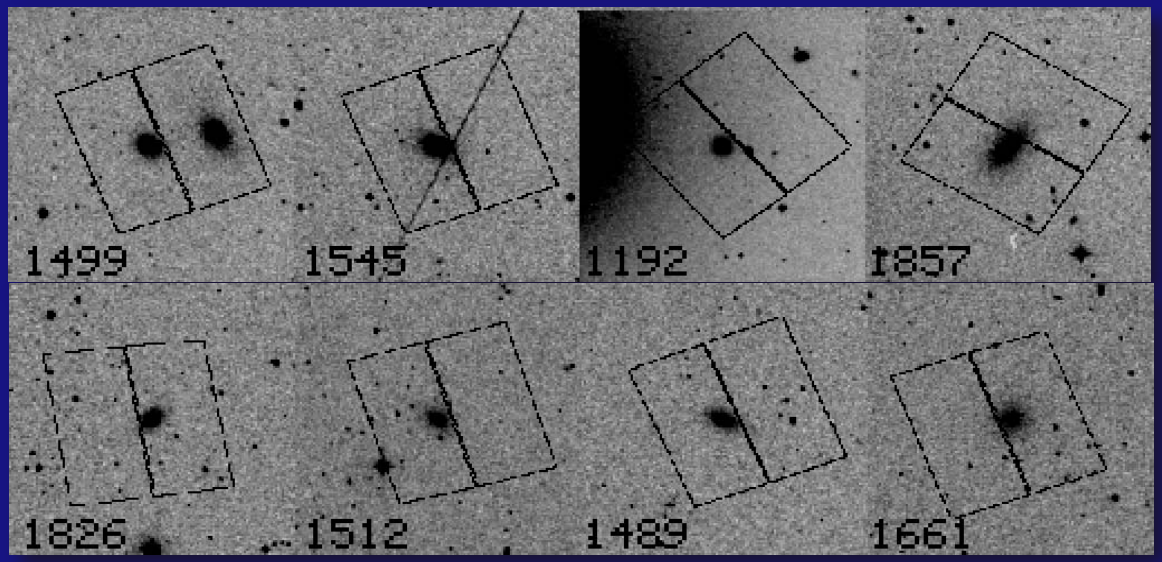

Canes Venatici
α CVn
Ursa Major
ν UMa
ζ UMa
β Com
γ Com
Coma Berenices
Leo
α Com
β Leo
Denebola
M87
ε Vir
ρ Vir
α Vir
ζ Vir
ω Vir
η Vir
γ Vir
Virgo
Photo: Akira Fuji

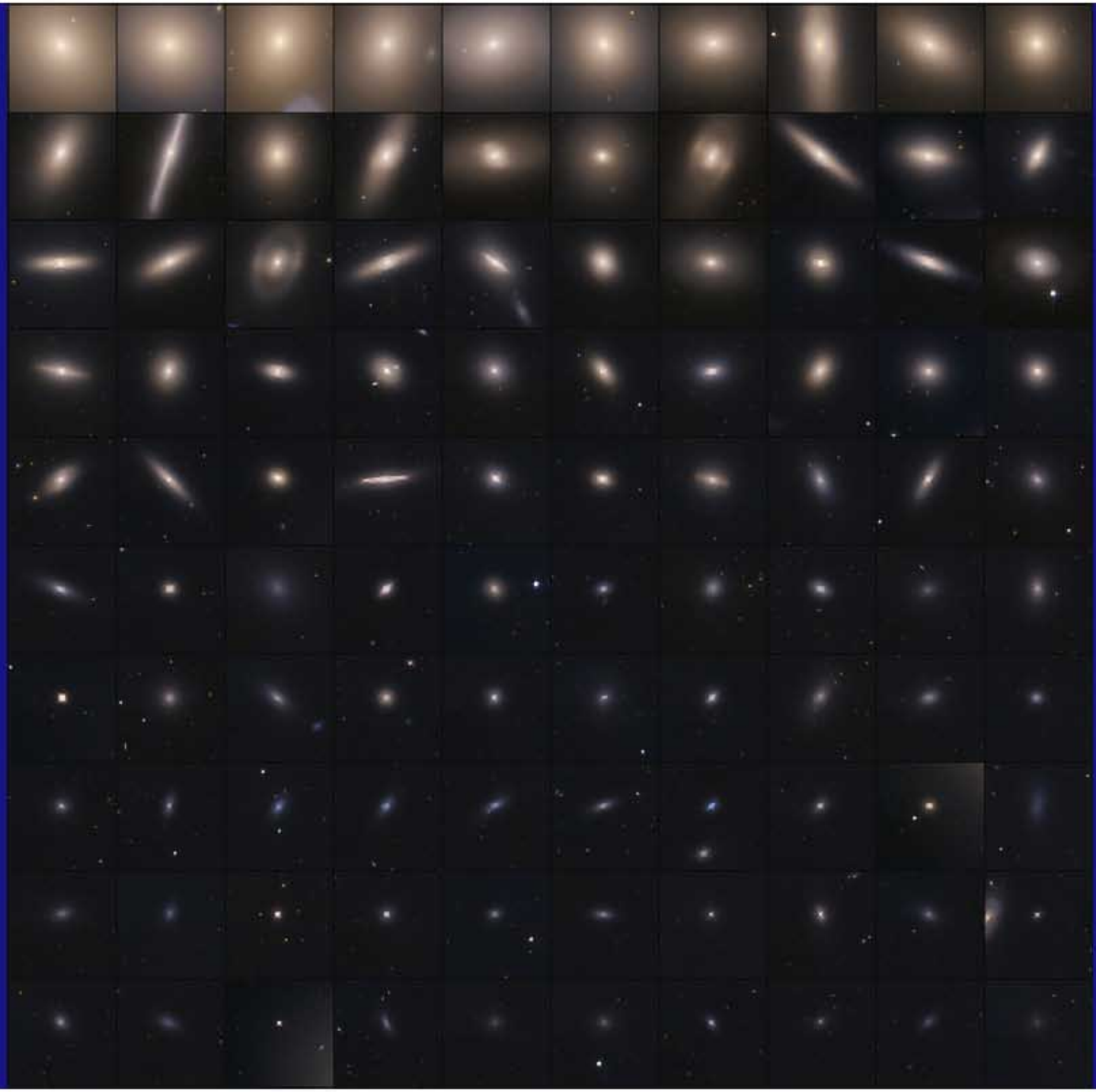
HST/ACS Virgo Cluster Survey
(PI Patrick Côté/NRC-HIA)

Each galaxy observed for a single orbit with the Advanced Camera for Surveys on HST: 0.05 arcsec/pixel, ~3.4 × 3.4 arcmin FOV)

Two Filters:
F475W (≈SDSS g)
F850LP (≈ SDSS z)

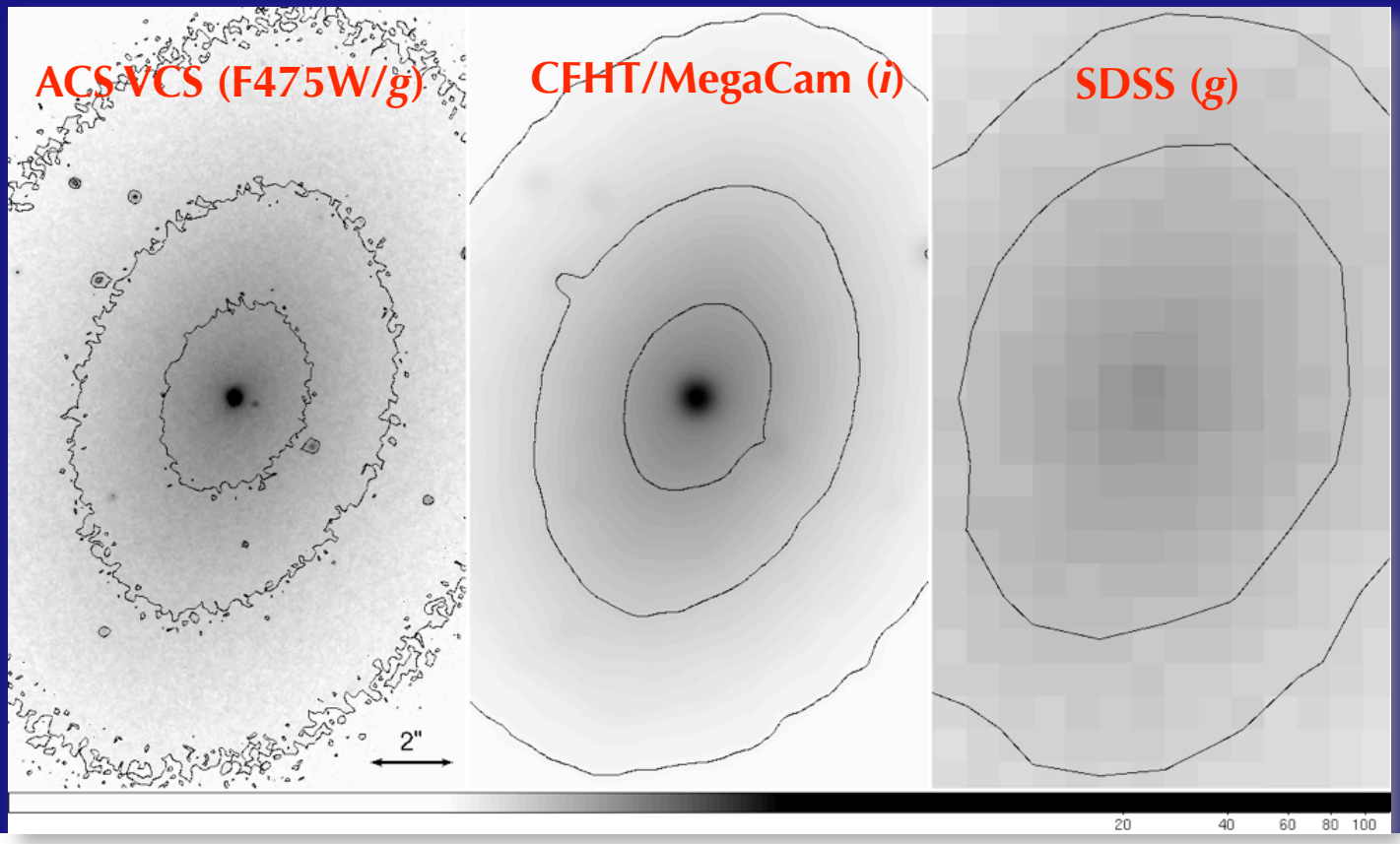




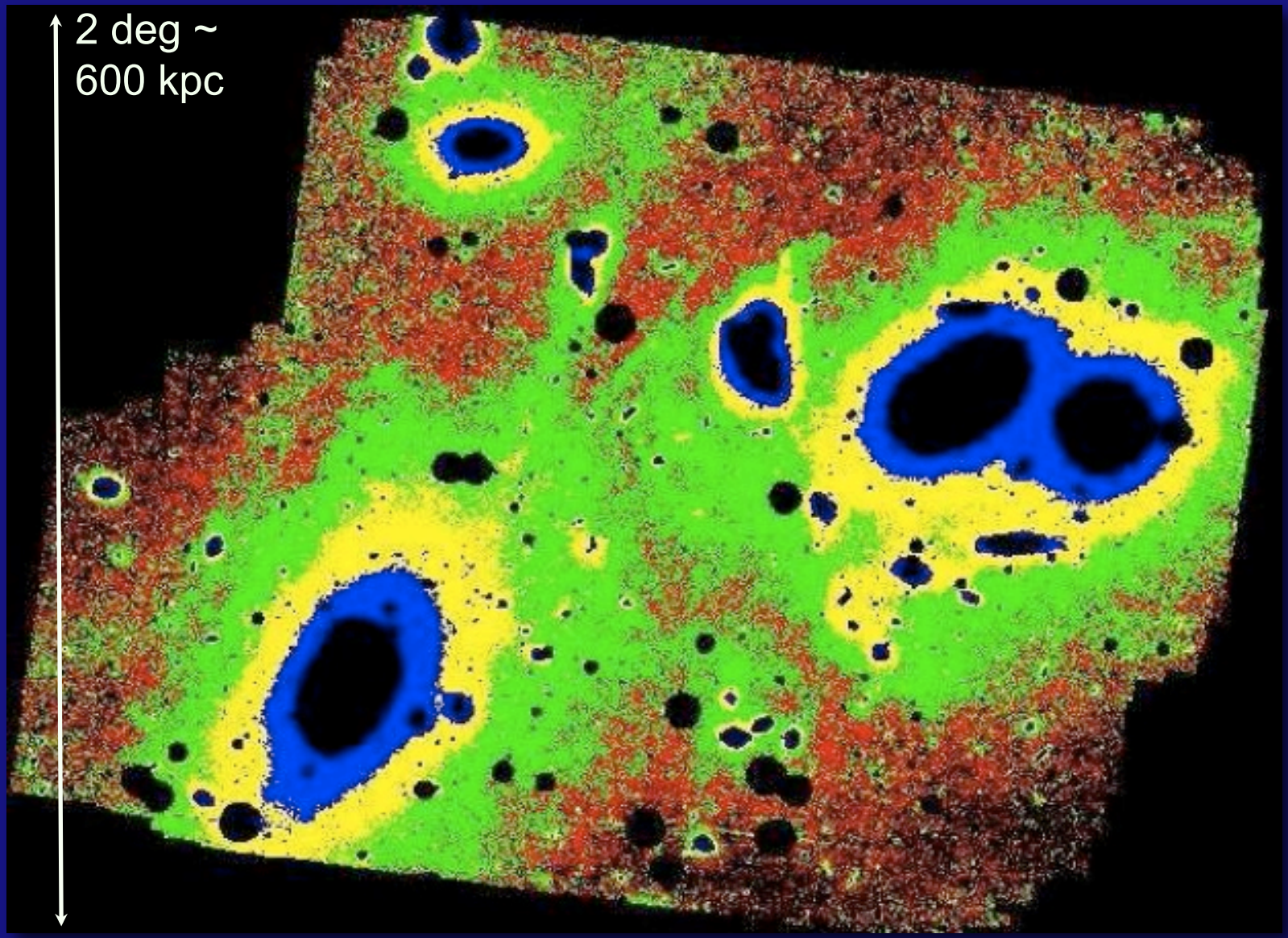


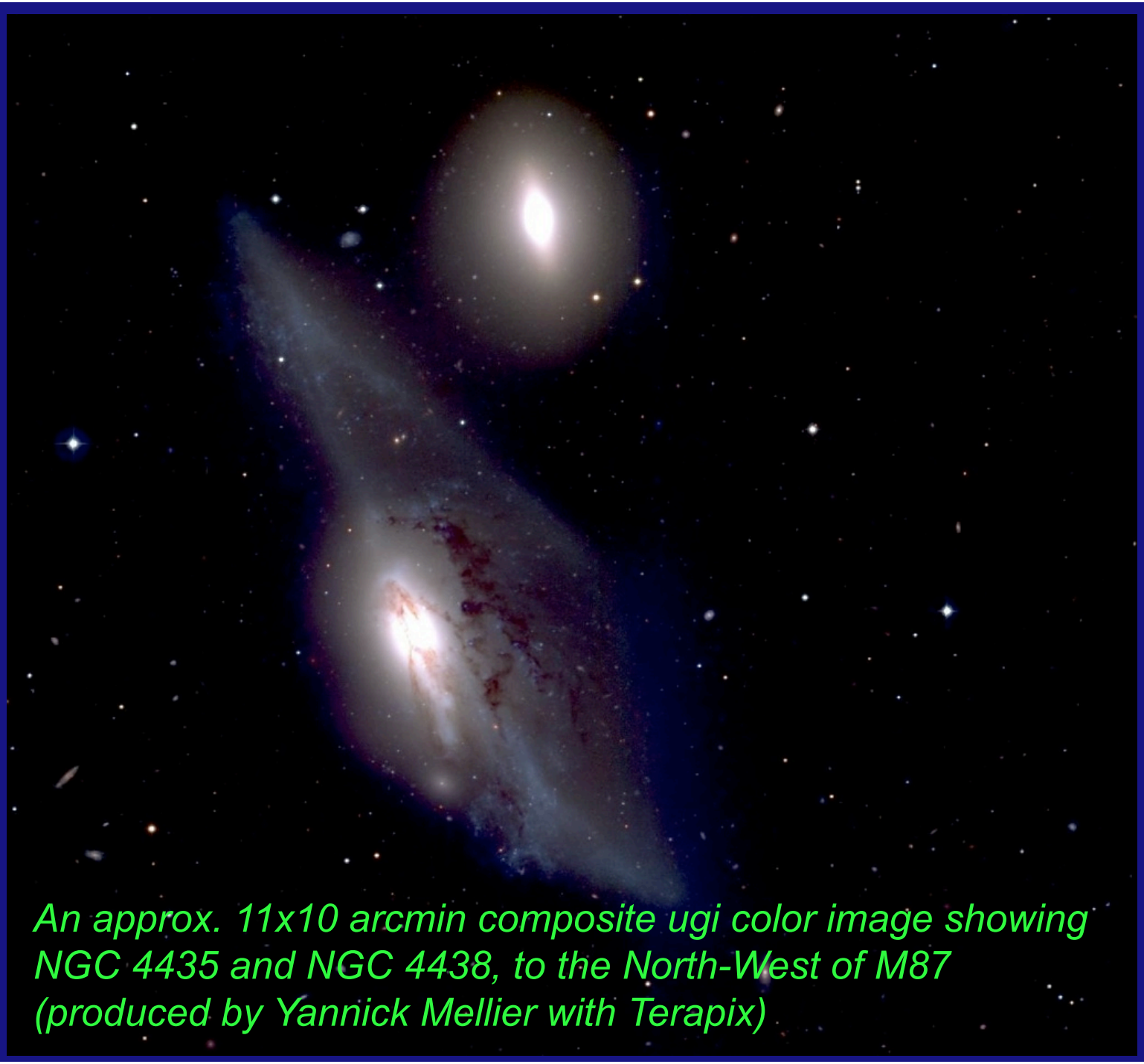
The NGVS: A CFHT Legacy

- The NGVS has been granted approx. 140 nights as a CFHT/MegaPrime Large Program. Data will be acquired in the four spring semester from 2009 to 2012.
- The NGVS will survey the Virgo Cluster out to its virial radii, in u*g′r′i′z′, to g′ ≈ 25.7 (10σ) and $\mu_{g'} \approx 27.7$ (2σ)
- Compared to the VCC: 100× improvement in depth, 40× in surface brightness, 6× in encircled energy, 5× in SED coverage. Plus, many synergistic opportunities with surveys at non-optical wavelengths.



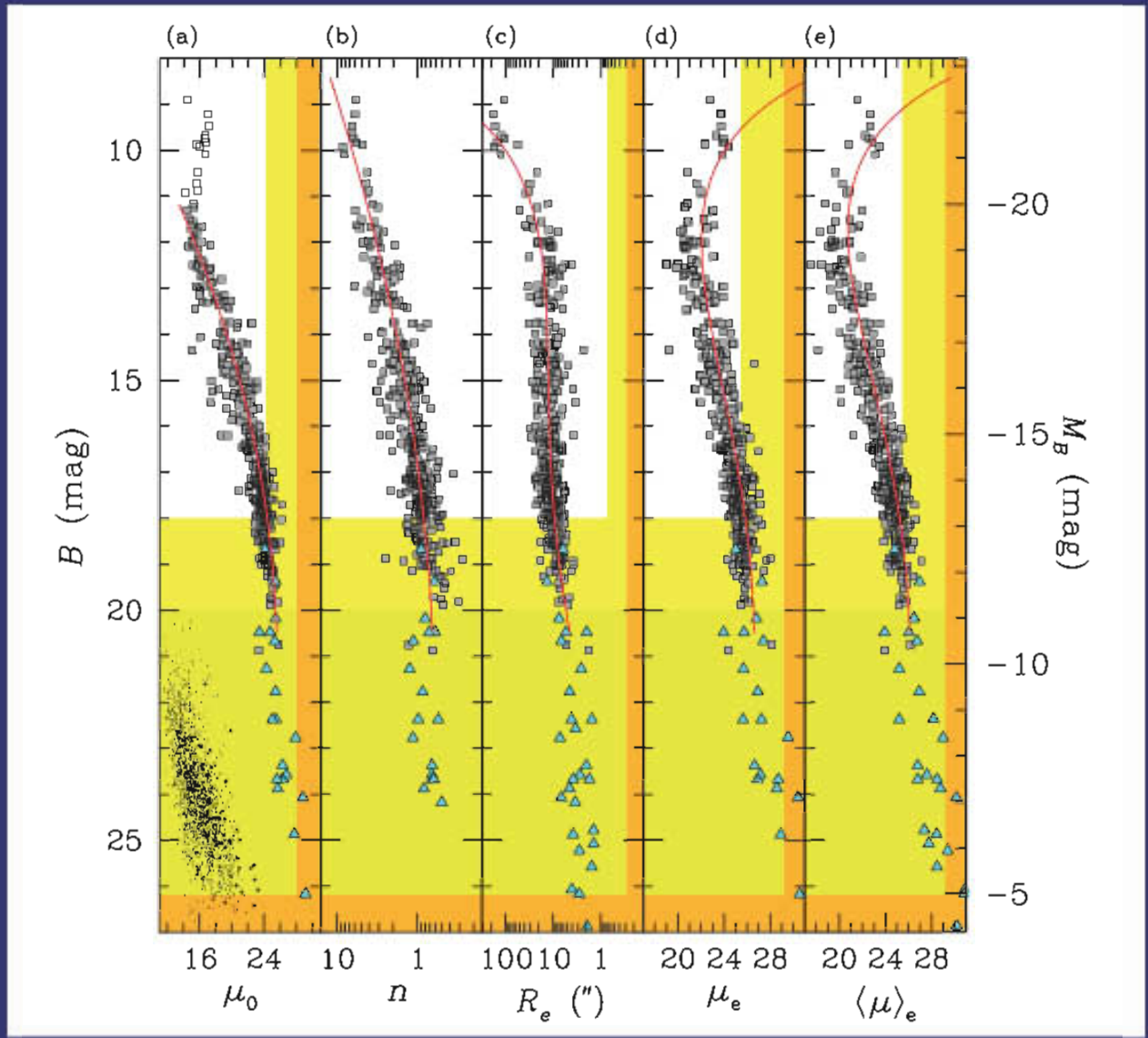
Diffuse Intra-cluster Light



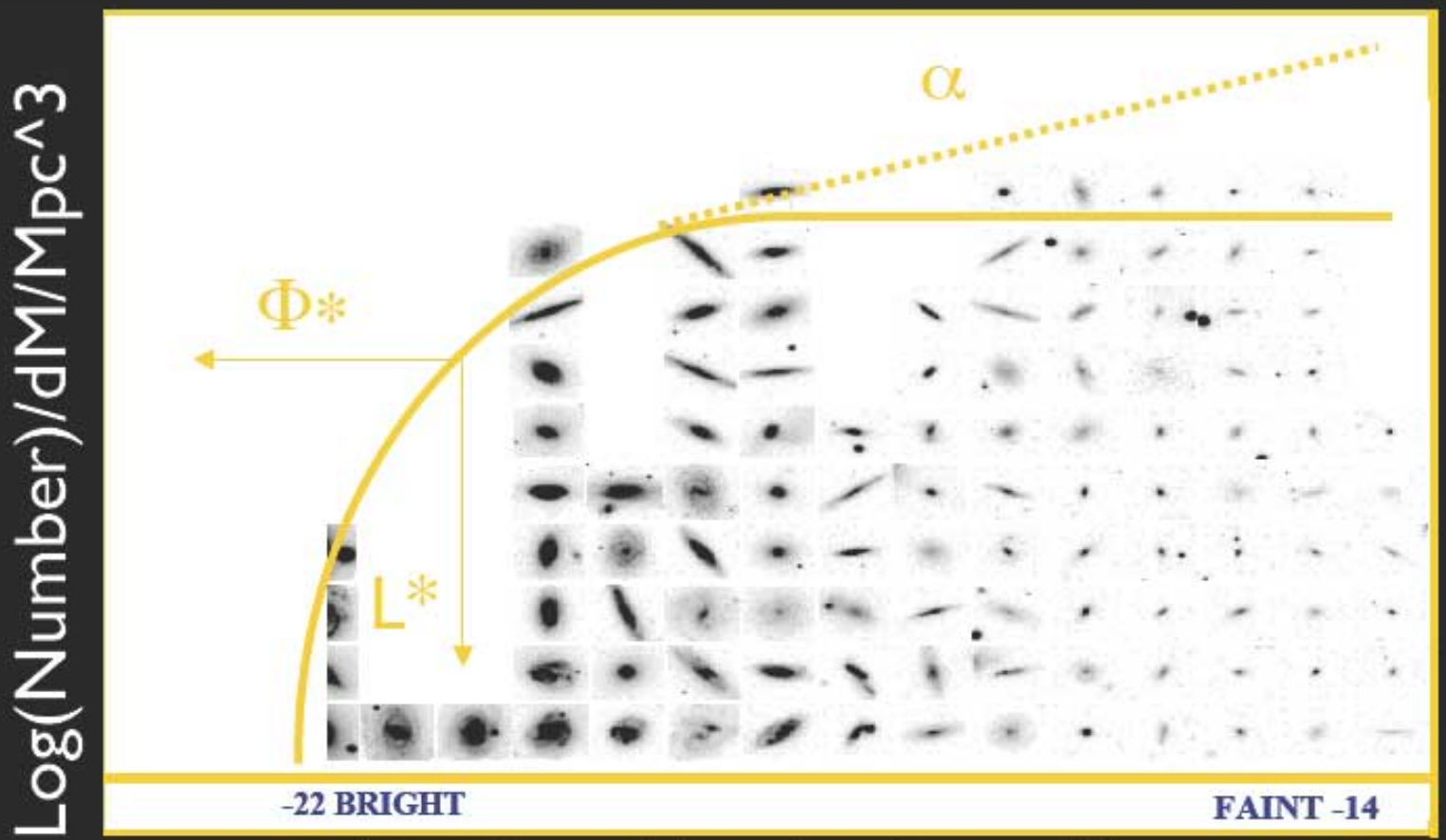


An approx. 11x10 arcmin composite ugi color image showing NGC 4435 and NGC 4438, to the North-West of M87 (produced by Yannick Mellier with Terapix)

Galaxy Scaling Relations: brightness, size, shape



Faint end of the Luminosity Function



Log(Number)/dM/Mpc^3

Absolute Magnitude or Mass

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THE NEXT GENERATION VIRGO CLUSTER SURVEY

THE NGVS: A CFHT LEGACY

The *Next Generation Virgo Cluster Survey* (NGVS) is a proposed Large Programme for the Canada French Hawaii Telescope (CFHT). The NGVS will use 119 nights of CFHT time, spread equally over the 2009A-2012A semesters, to image the Virgo Cluster – the dominant mass concentration in the local universe and the largest collection of galaxies within ≈35 Mpc – from its core to virial radius, in five filters (*u,g,r,i,z*), to unprecedented depths.

The NGVS will be the state-of-the-art optical survey of a low-redshift cluster environment for years to come. It will also offer a wealth of synergistic opportunities with the many on-going and planned surveys of the Virgo Cluster at longer and shorter wavelengths. The purpose of this web-page is to initiate such opportunities by providing some basic information about the NGVS. If the survey is approved, this webpage will be expanded to include real time information about the data acquisition and processing.

Left: A north-western portion of the Virgo Cluster, showing two of its brightest early-type galaxies, M84 and M86. At ≈1.1°×0.6°, the image is 1/160th the area proposed to be mapped by the NGVS (credit: NOAO/AURA/NSF). Top Right: A Hubble Space Telescope/ACS image of NGC 4526 (credit: ACSVCS team). Bottom Left: M87, the galaxy at Virgo's dynamical center, and its famous optical synchrotron jet, powered by a 3 billion solar masses black hole (credit: ACSVCS team). Bottom Right: the 3.6 metre Canada French Hawaii Telescope (CFHT) on Mauna Kea, Hawaii.

https://www.astrosci.ca/NGVS/Home.html

https://www.astrosci.ca/NGVS/NGVS_Movie/Movie.html