Toward 3D Spectra of Galaxies

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• *Extinction in star-forming disk galaxies from inclination-dependent composite spectra* (Yip et al. ApJ 2010)

• *Generating on-the-fly large samples of theoretical spectra through N-dimensional grid* (Yip AJ 2010)

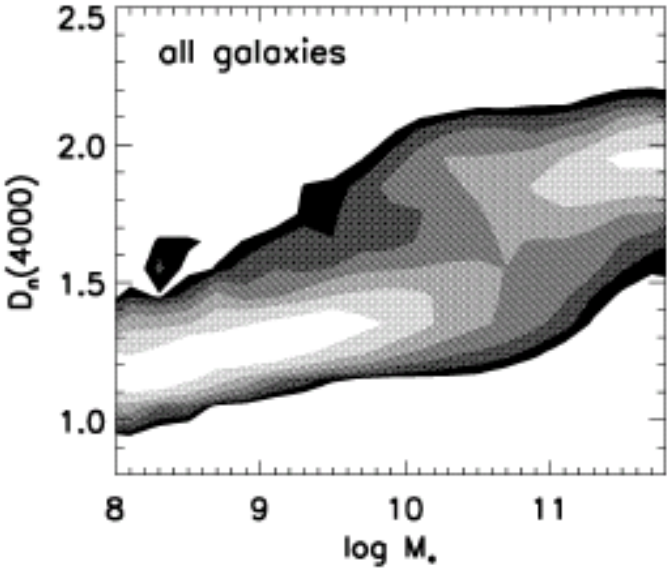
Outline

- Reconstructing galaxy spectra in 3D by stitching together SDSS fiber spectra
- Composite spectra of star-forming disk galaxies as a function of galaxy inclination
- What gave we learnt about star-forming disk galaxies
- Applications

Galaxies in 2009

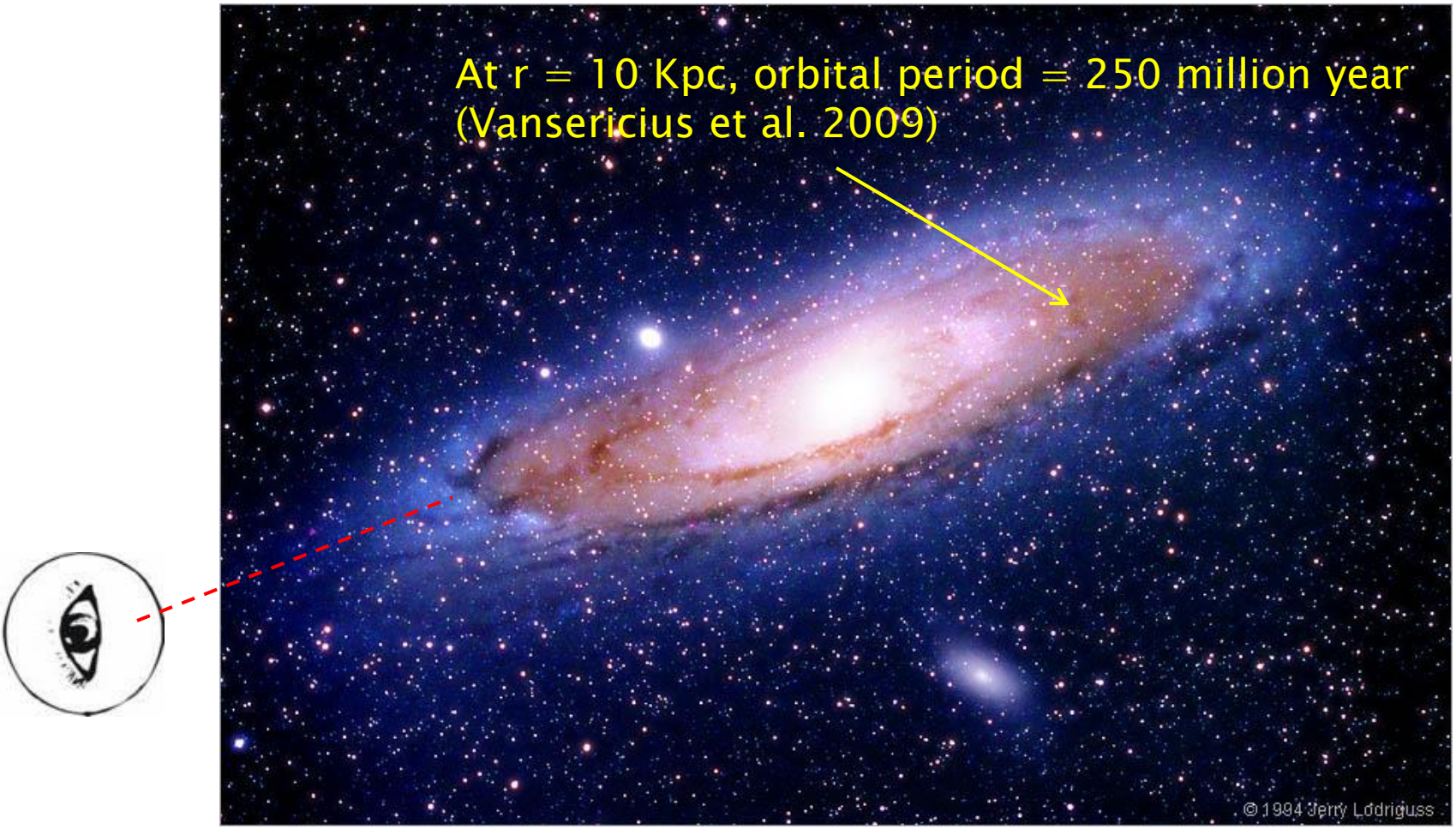
- Composition: 10^{11}–10^{12} stars + gas + dust
- Two main types
  - Blue cloud: blue, disk-dominated
  - Red sequence (Martin et al.): red, bulge-dominated
- Bimodality seen in many properties
  (e.g., Baldry et al. 2003, Kauffmann et al. 2003)
- A wealth of factors could affect galaxy evolution
  (e.g., central black holes, environmental effect)

(HST archive)



(Kauffmann et al. 2003)

Question: how does a galaxy look like from various viewing angles?

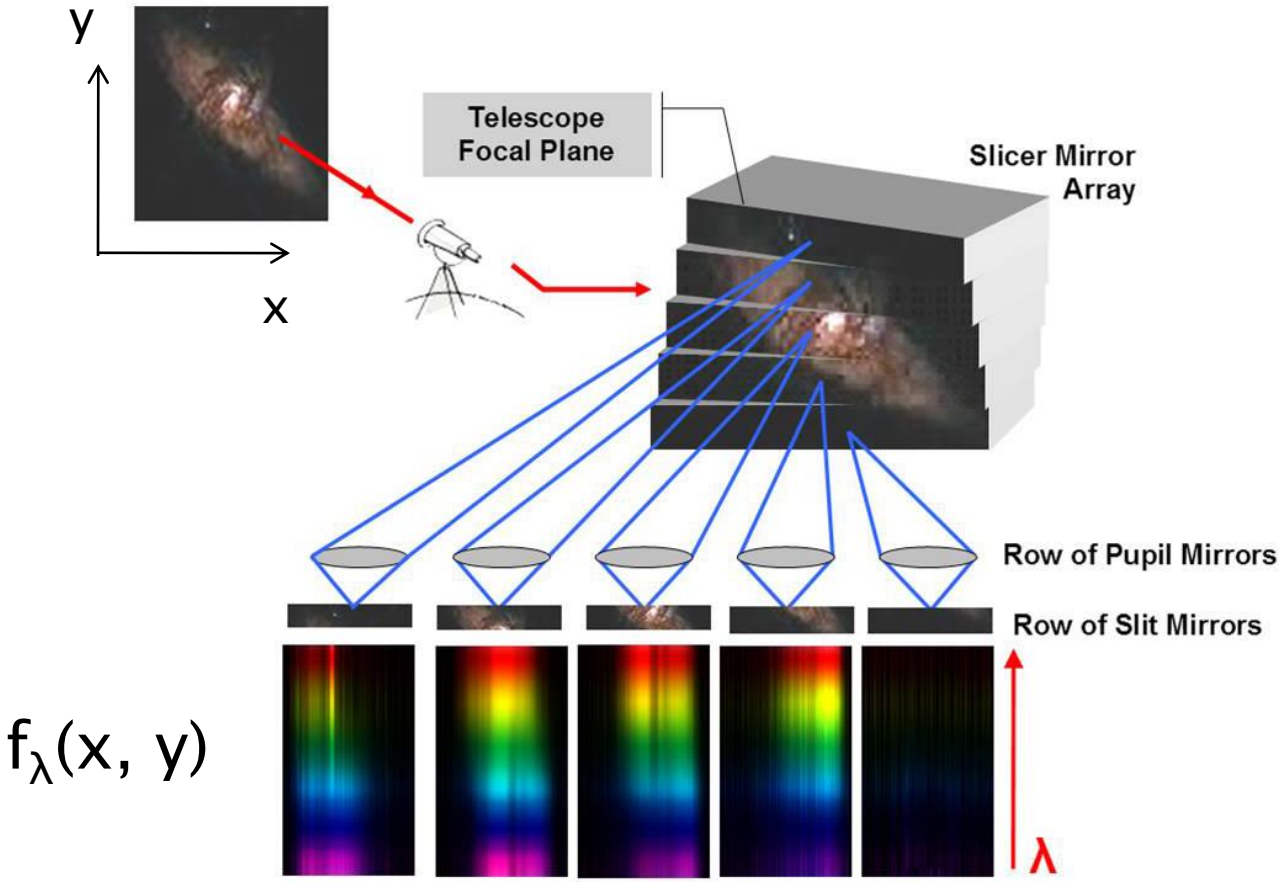


(M31 galaxy)

Galaxies are located at various inclinations & distances

(from SDSS JPEG Image Cutout tool)

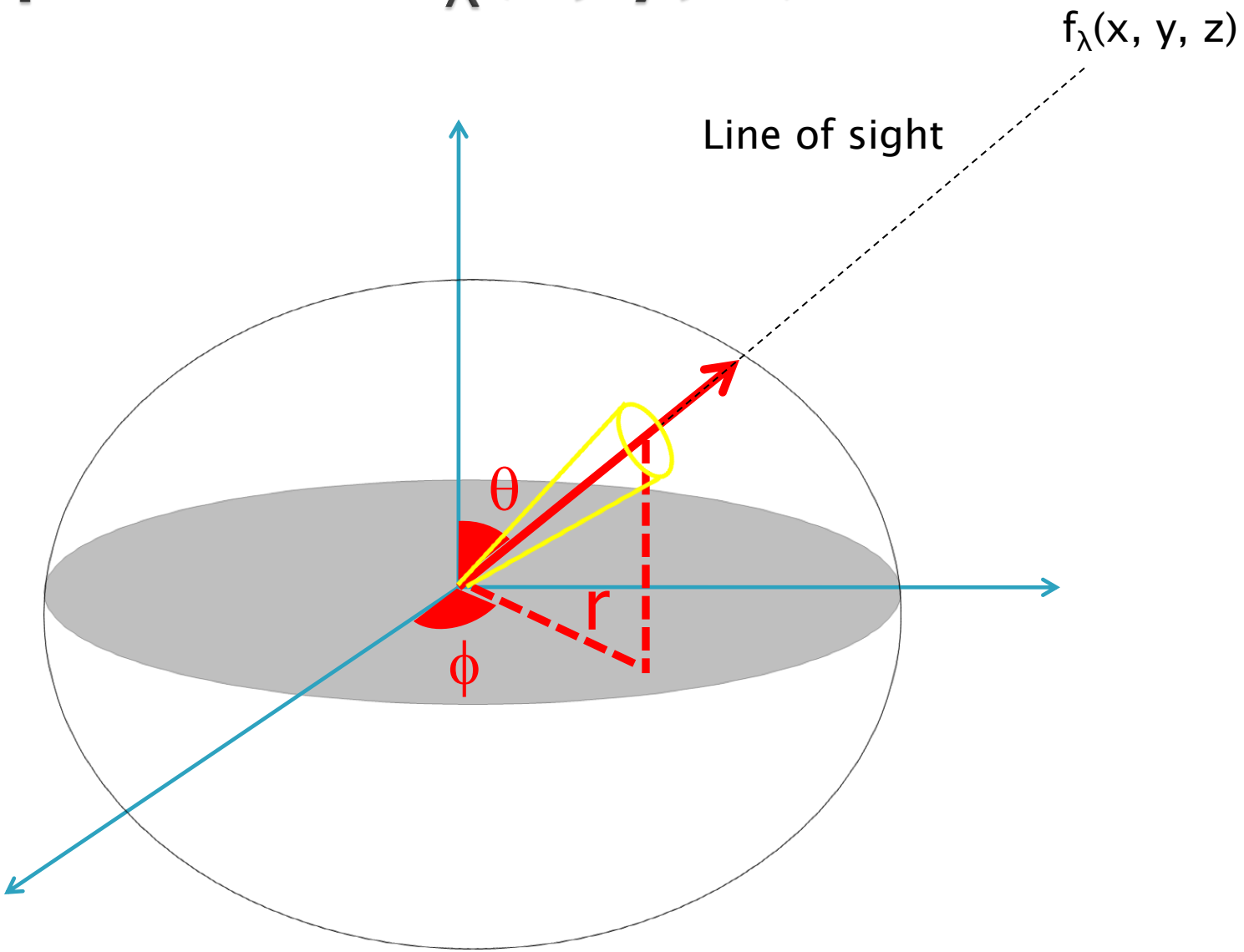
Comparison with Integral Field Spectroscopy (or "3D" Spectroscopy)



$f_\lambda(x, y)$

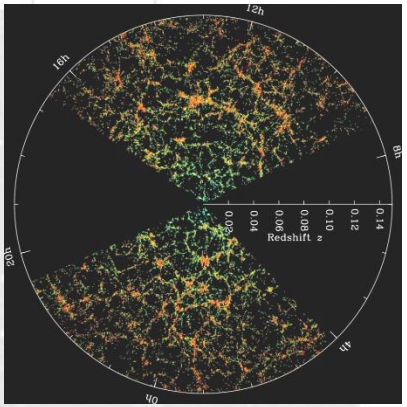
(Ealet et al. 2008)

3D Spectrum $f_\lambda(x, y, z)$



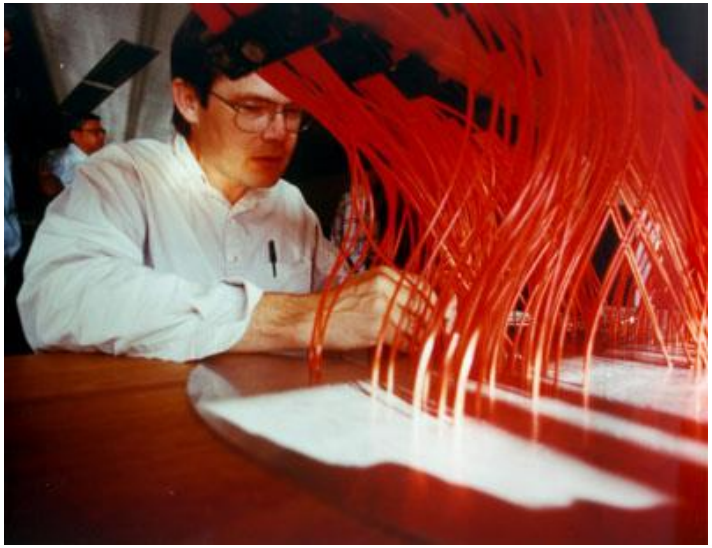
Sloan Digital Sky Survey

- Photometric + Spectroscopic Surveys
  - 11,000 square degree footprint (DR7)
  - 5.9 $\times 10^8$ u, g, r, i, z photometry
  - 1.6 $\times 10^6$ fiber spectra
- Phases
  - SDSS I (2000–05)
  - SDSS II (2005–08)
  - SDSS III (2008–14)
- Data are public
- Web interfaces for data download and exploration (e.g., SkyServer)

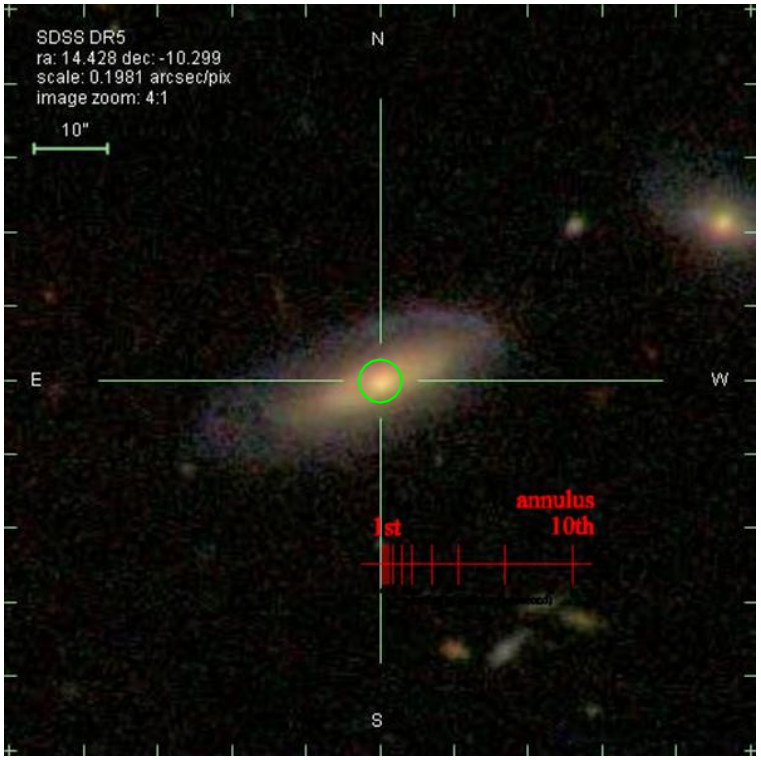


Galaxy light sampled by the SDSS spectroscopy

- SDSS offers fiber spectra at 3800-9200 Å, 69 km/s resolution.
- A fiber projects 3 arcsec-diameter area on the sky.

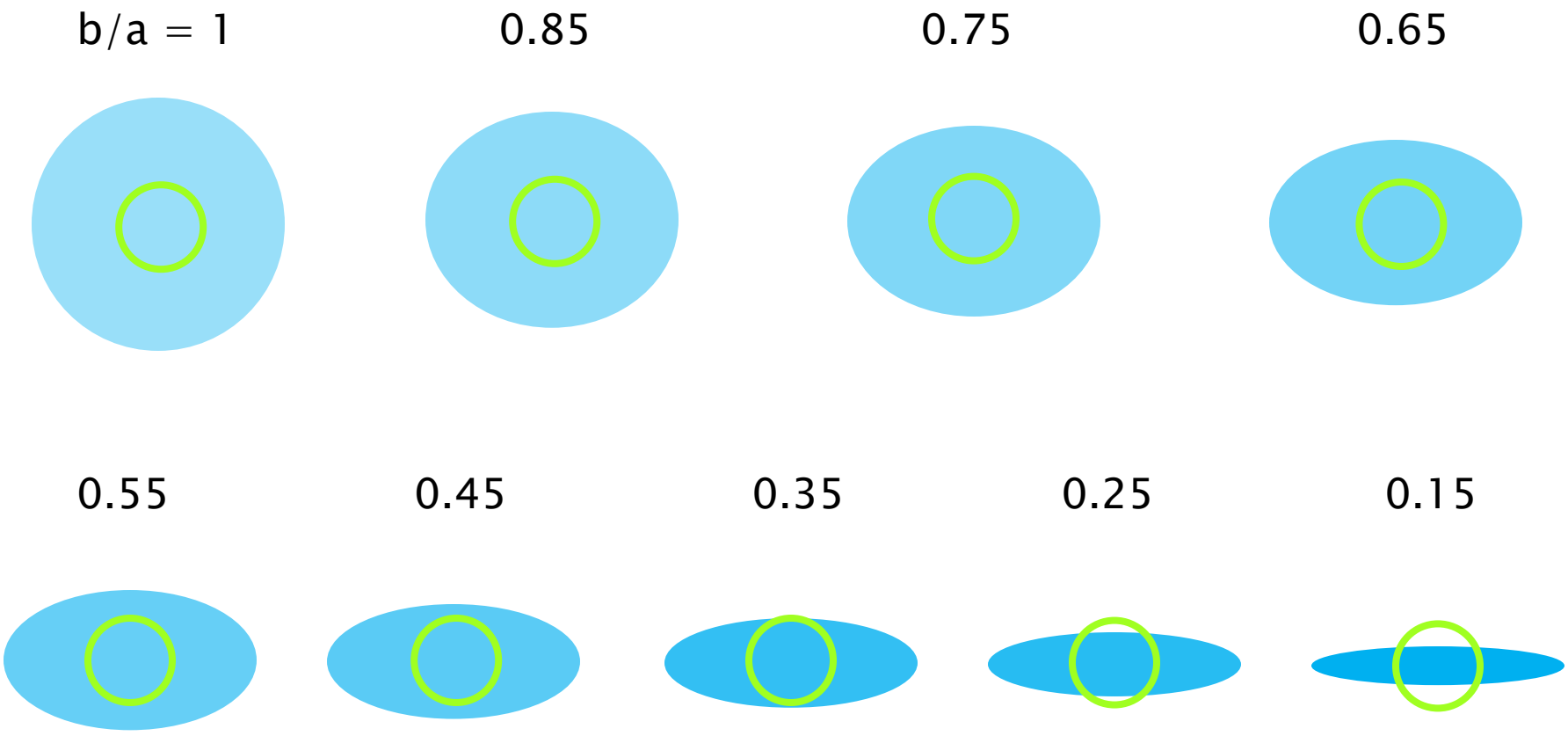


(SDSS fiber plug plate)



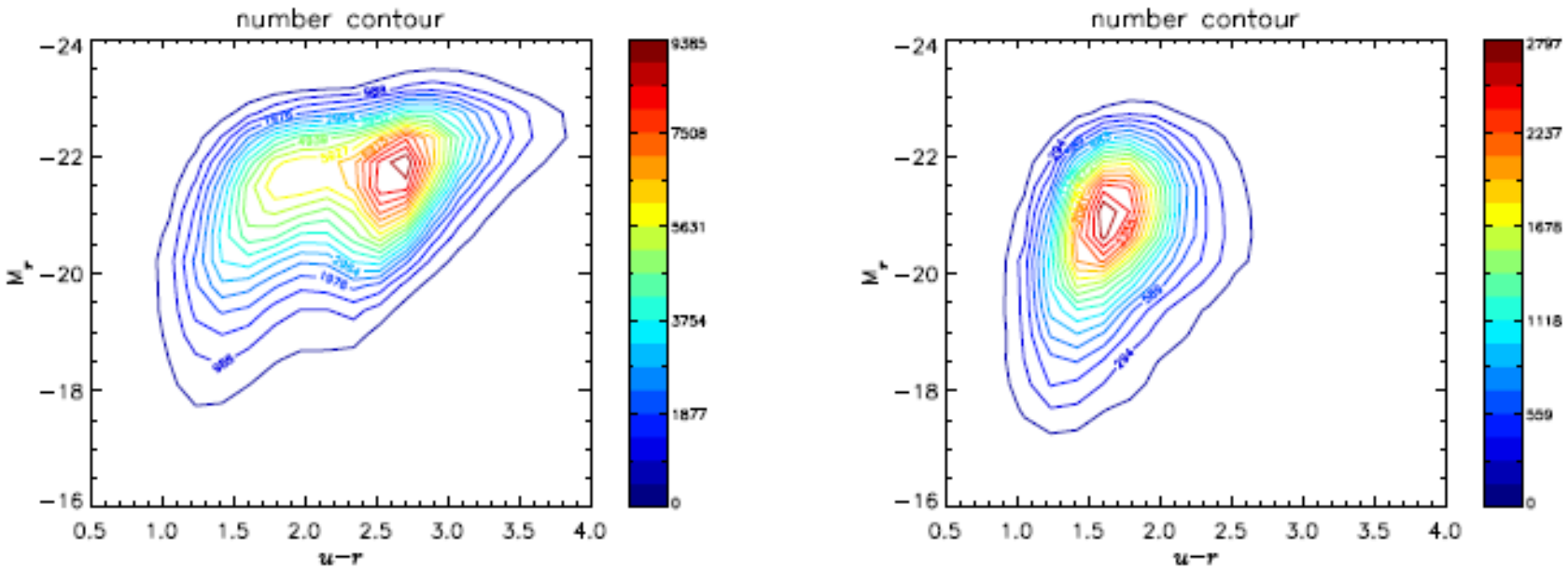
The central 3 arcsec of a galaxy (green circle).

$f_\lambda(\theta; \phi = 0 - 2\pi; r \leq r')$ through stitching fiber spectra at various galaxy inclination



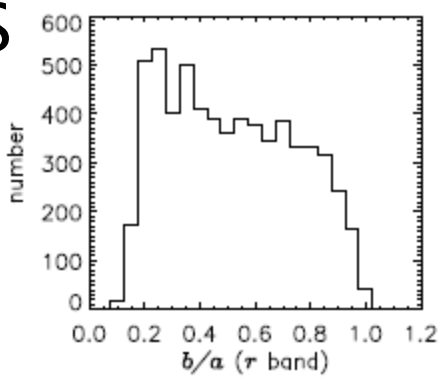
Sample

- Galaxies in SDSS DR5
  - disk dominated
    - bulge fraction < 0.1; u−r < 2.4 (Ryden 04)
  - star forming
    - BPT diagram (Kewley et al. 09)
  - *r* −band <17.77 mag.
  - redshift range 0.065 — 0.075

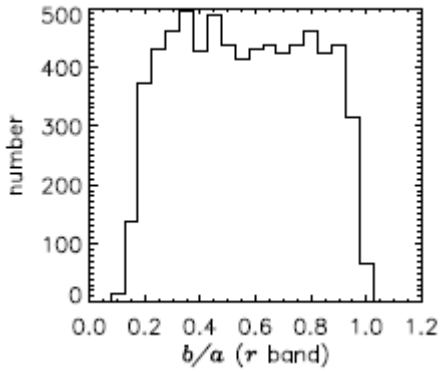


Unbiased sample of galaxy inclination

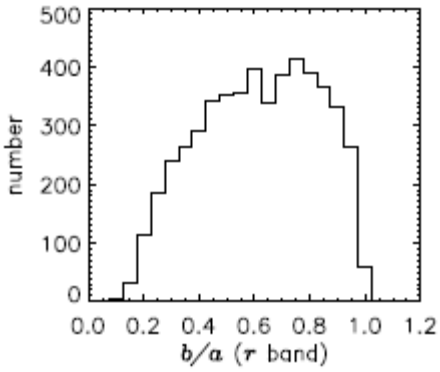
- Flux-limited nature of the SDSS spectroscopic sample may induce bias in the inclination distribution.



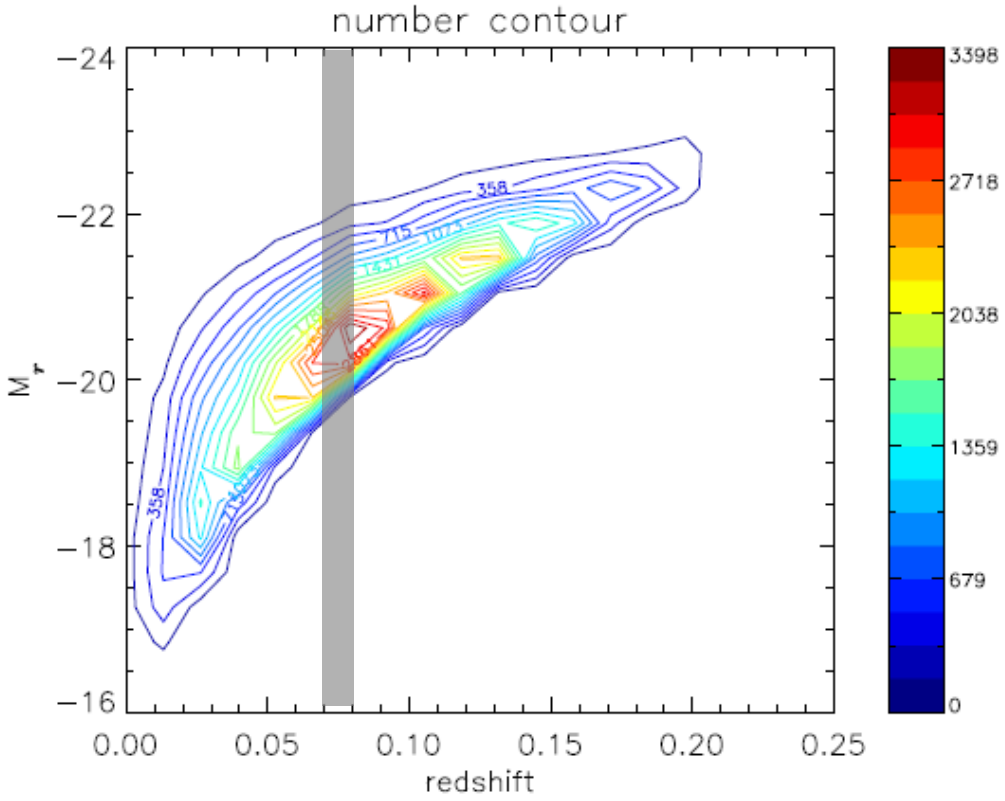
lower redshift



inter-mediate redshift



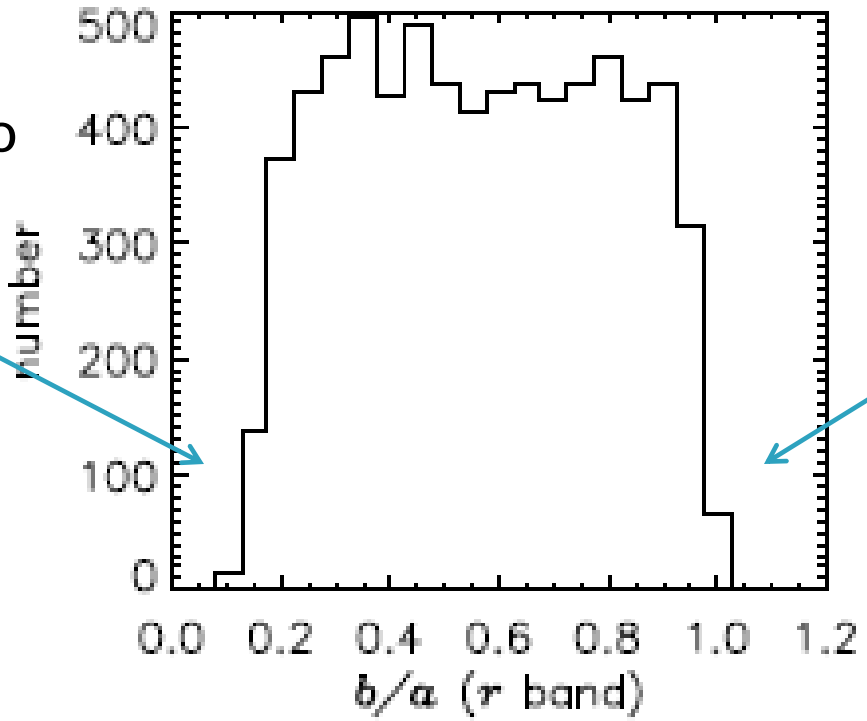
higher redshift



Unbiased sample of galaxy inclination

- Why are we missing galaxies at extreme inclination angles? (Shao et al. 07, Unterborn & Ryden 08)

Due to non-zero disk thickness



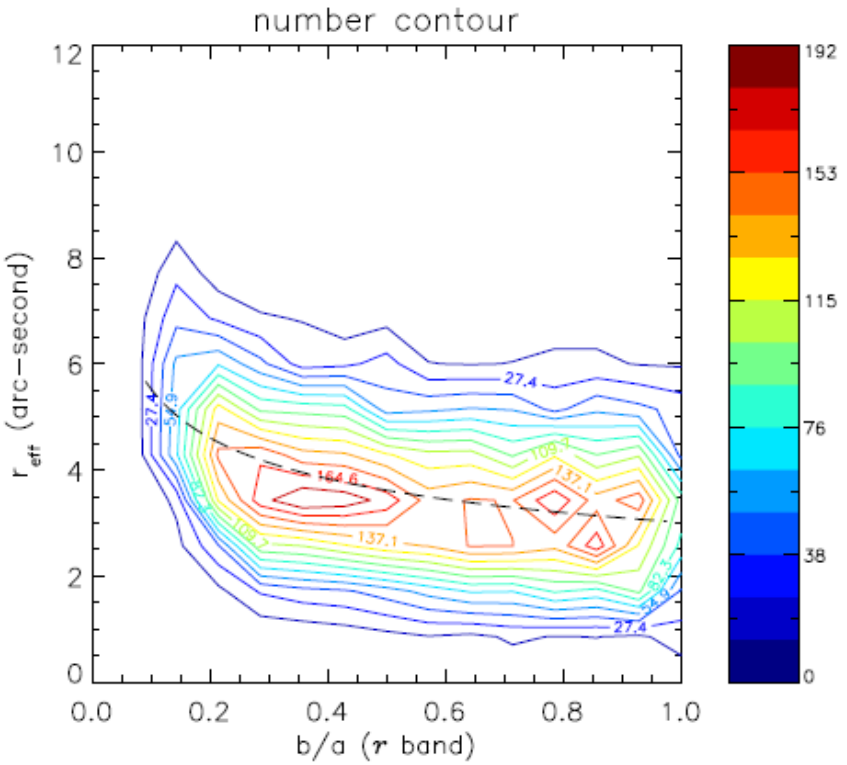
Due to non-zero disk ellipticity

Galaxy light through the SDSS spectroscopic fiber

- Disk galaxies appear larger when inclined

$$\log_{10}\left({r_{\rm eff}}^{b/a}\right) = \log_{10}\left({r_{\rm eff}}^{1}\right) - \beta_r \log_{10}\left(b/a\right)$$

- Found also in previous studies (Huizinga & van Albada 92, Mollenhoff et al. 2006, Maller et al. 09)



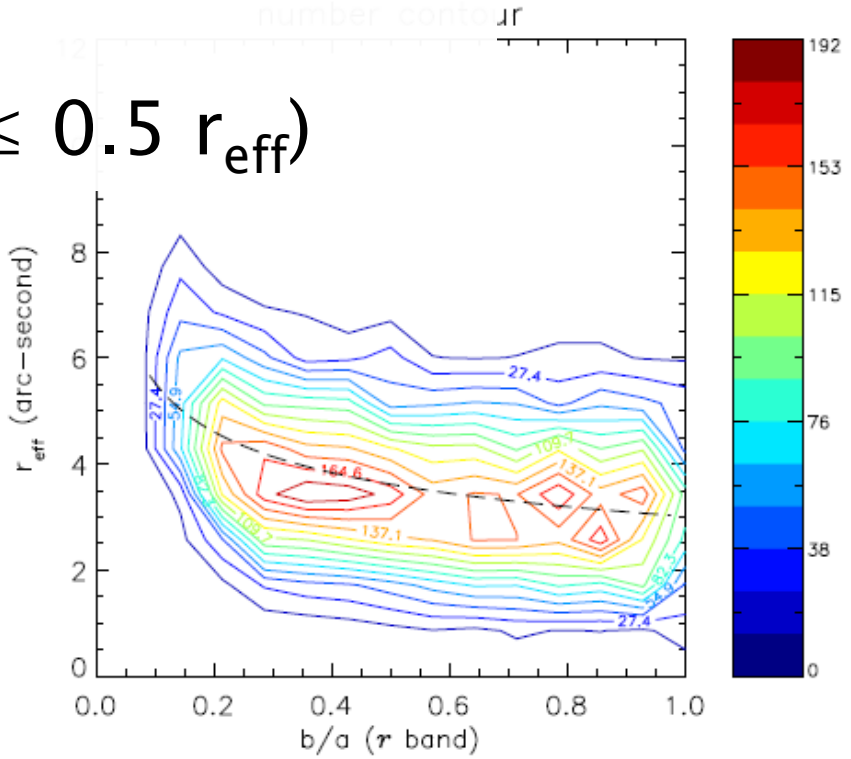
Galaxy light through the SDSS spectroscopic fiber

SDSS fiber radius (1.5″) is:

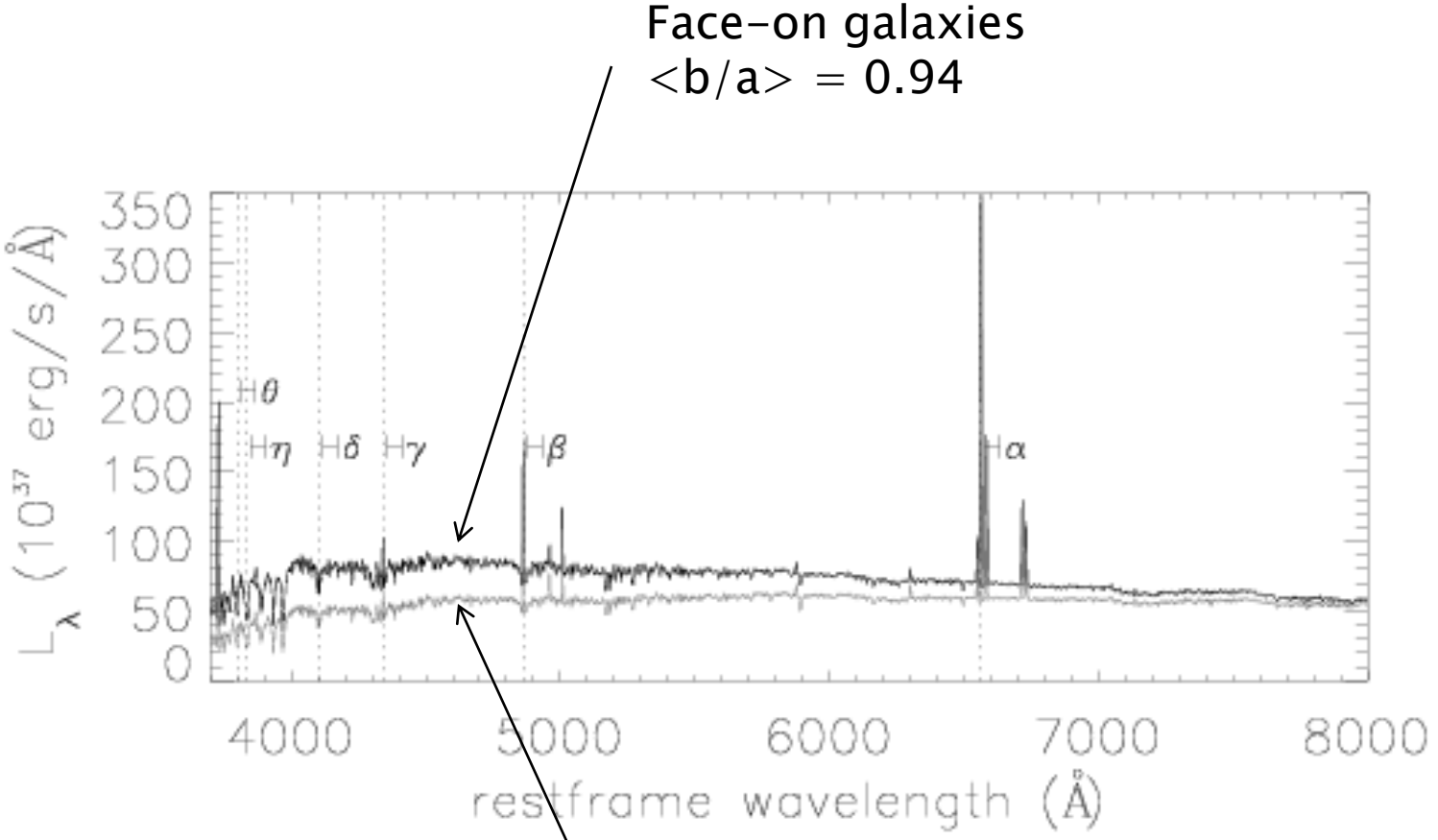
$$r_{fiber} = 0.5\ r_{eff}$$

The 3D spectra are:

$$f_\lambda(\theta;\ \phi = 0 - 2\pi;\ r \leq 0.5\ r_{eff})$$



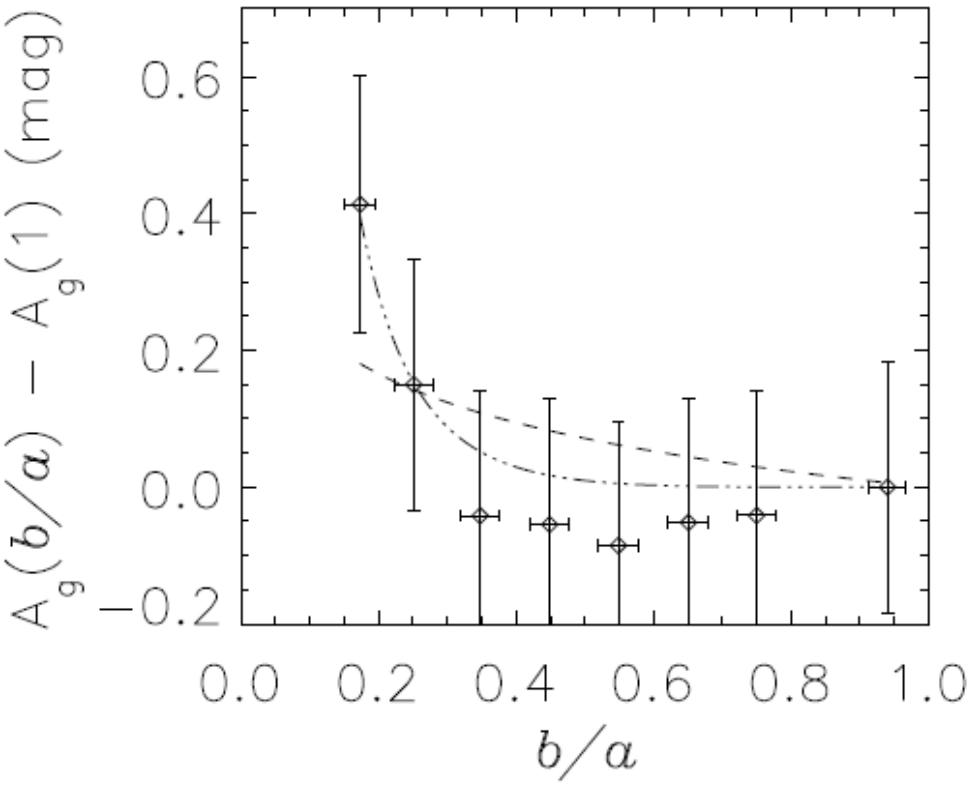
Inclination Dependency of Average Disk Galaxy Spectrum



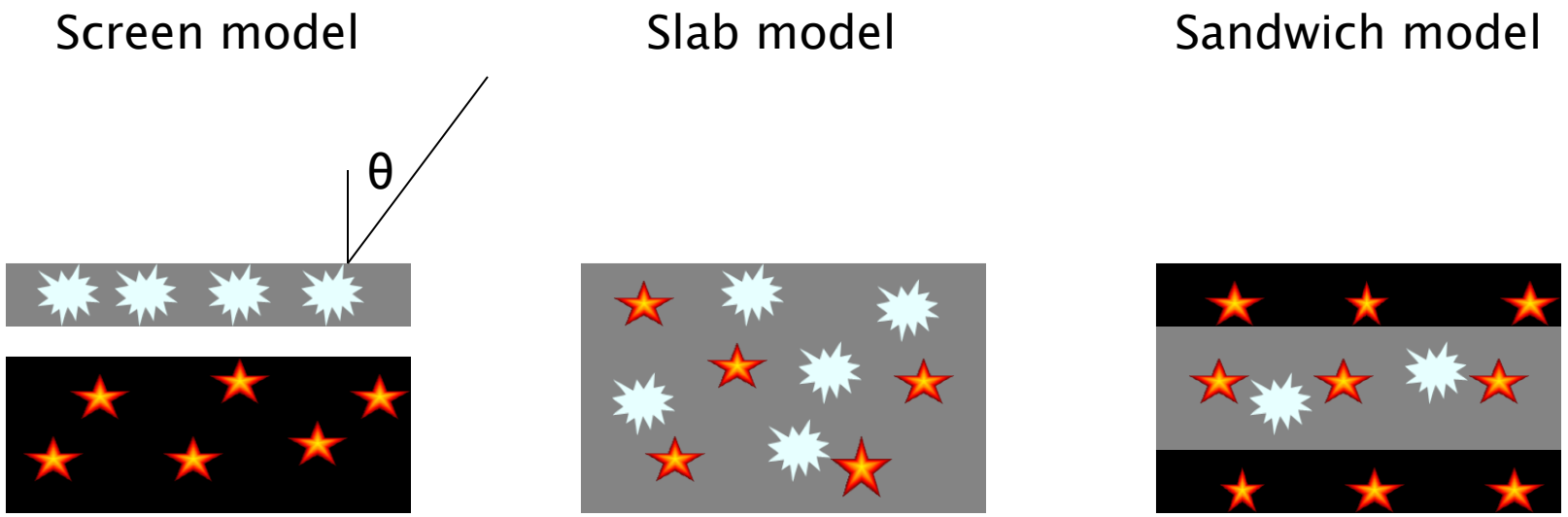
Inclination Dependency of Extinction in Stellar Continuum

- Edge-on galaxies show higher extinction than face-on galaxies.
- The best-fit empirical extinction law is

$$A_x(b/a) - A_x(1) = \eta_x \log_{10}^4 (b/a)$$



Optical Thickness of Stellar Continuum of Galaxies



- Best-fit theoretical model is the slab model.
- Best-fit face-on extinction is 0.2 mag (SDSS g band).

Theoretical model for distribution of dust and stars in galaxies

- Prediction of extinction vs. inclination (e.g., Disney 89):

Screen Model

$$A_x(b/a) = A_x(1)/(b/a)$$

Slab Model

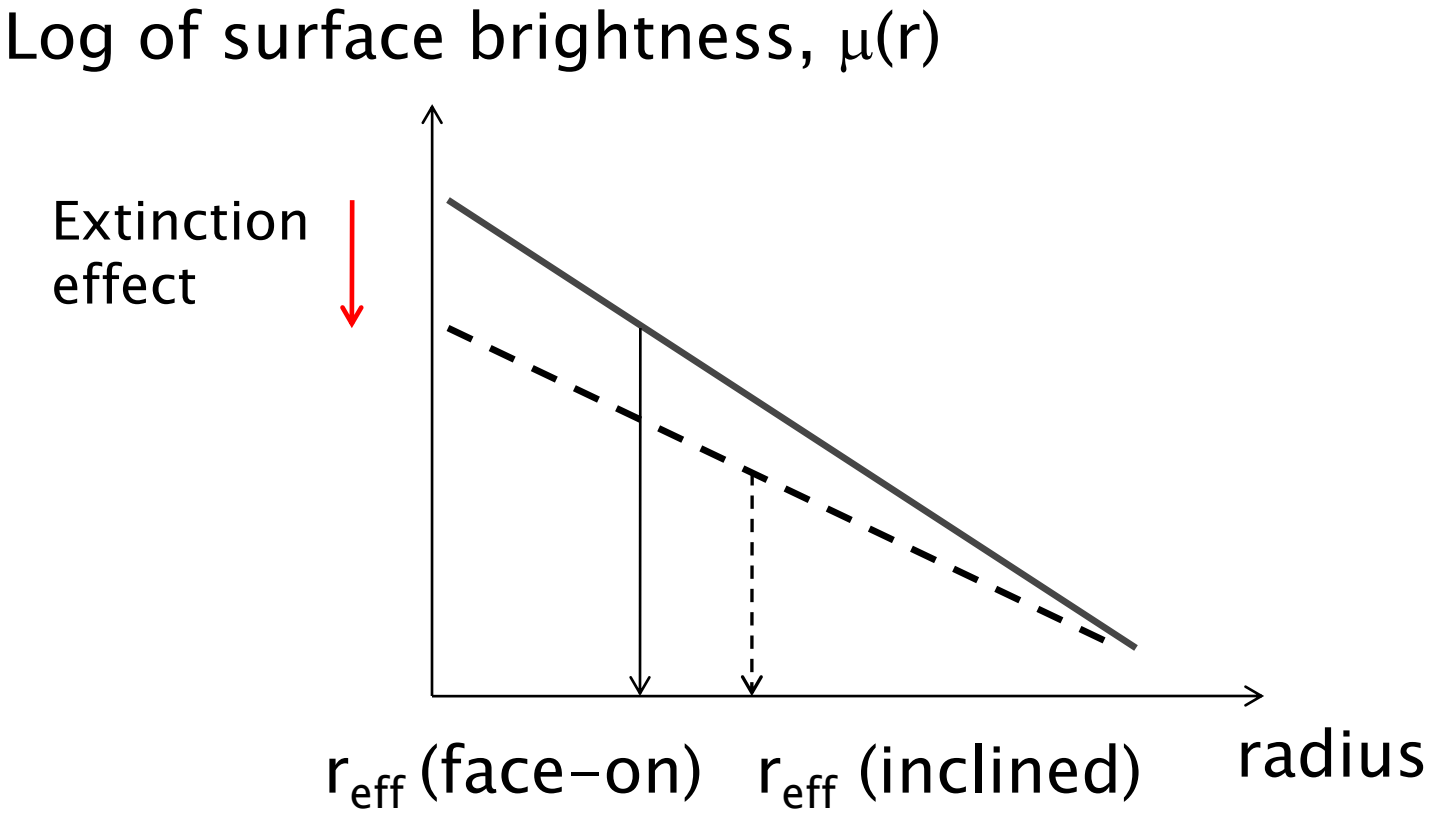
$$A_x(b/a) = -2.5\log_{10}\left[\frac{b/a}{\tau_x(1)}\left(1 - e^{-\tau_x(1)/(b/a)}\right)\right]$$

Sandwich Model

$$A_x(b/a) = -2.5\log_{10}\left[\frac{1-\zeta}{2}\left(1 + e^{-\tau_x(1)/(b/a)}\right) + \frac{\zeta * (b/a)}{\tau_x(1)}\left(1 - e^{-\tau_x(1)/(b/a)}\right)\right]$$

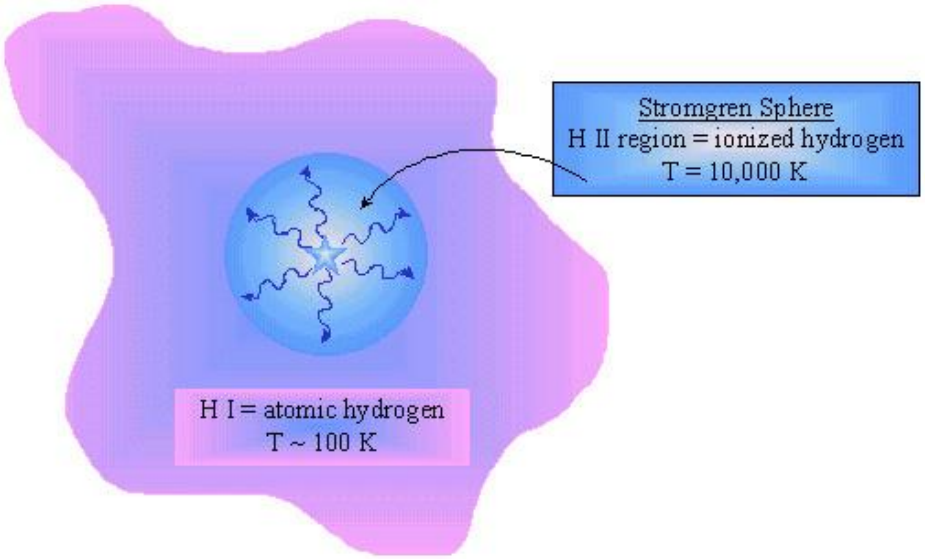
Why disk galaxies appear larger when inclined

- Because of the presence of dust extinction radial gradient on the galaxies.



H II regions in galaxies

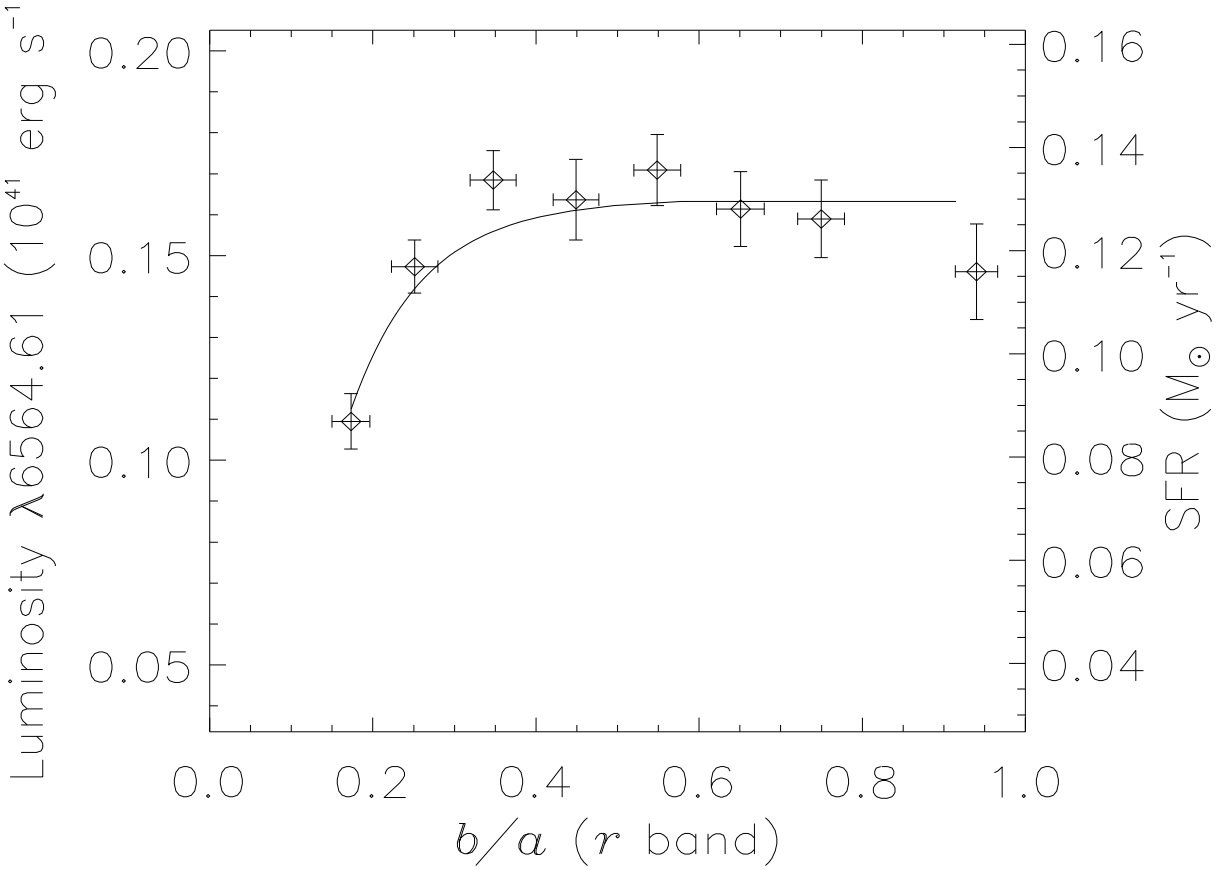
- UV photons from (young and massive) O/B stars ionize surrounding hydrogen atoms
- 10,000 K, 100 atoms/cm^3 (case B recombination)
- The region of influence is also called the Stromgren sphere



(Whirlpool galaxy, HST)

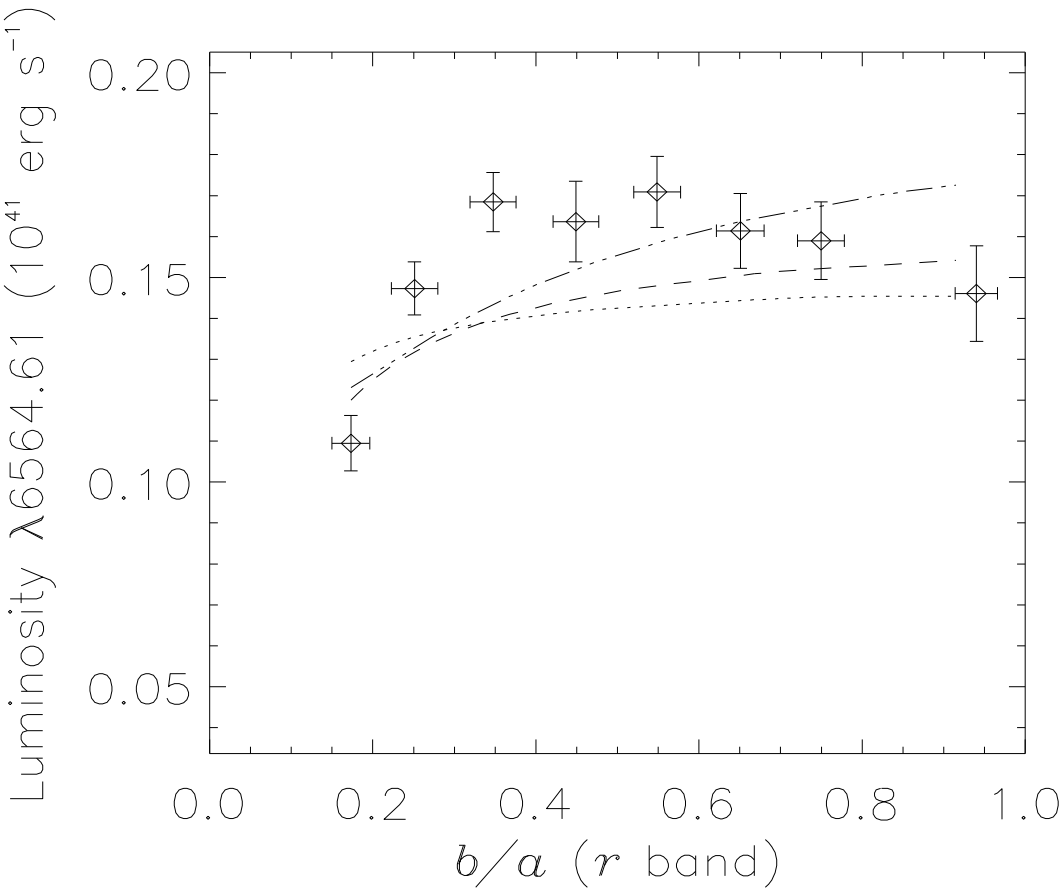
Inclination Dependency of H II Region Emission

- Hα luminosity decreases with higher galaxy inclination, indicating extinction in the galaxies.



Spatial Distribution of H II regions

- Screen/Slab/Sandwich models do not fit well to the Hα luminosity vs. inclination.
- cf. Slab model for stellar continuum → spatially non-uniform interstellar extinction.



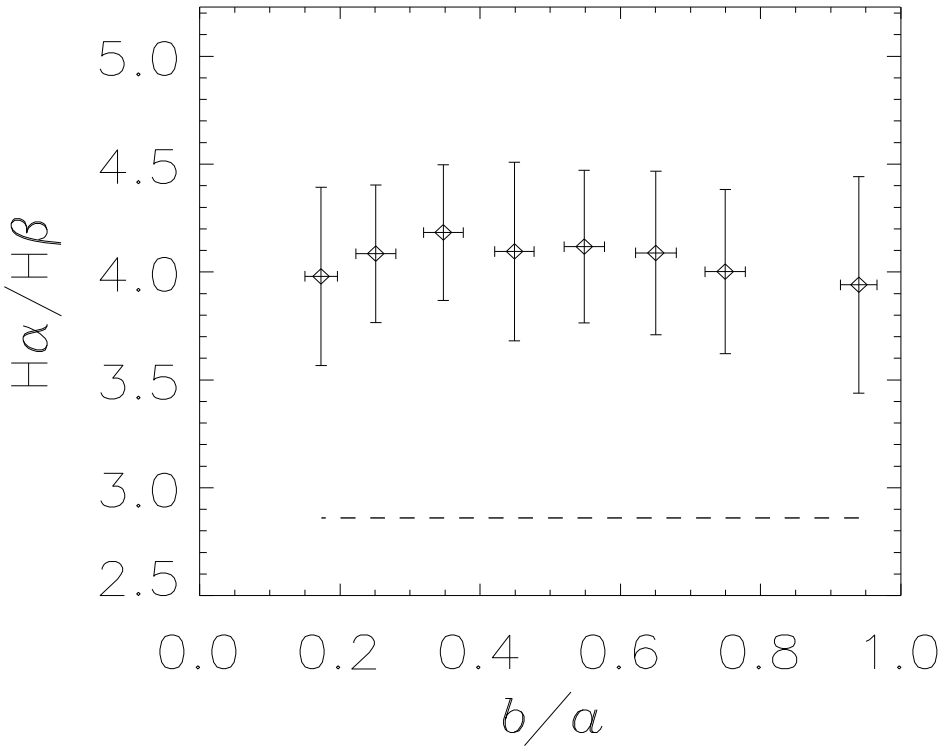
Spatial Distribution of H II regions

(Courtesy: Jim Heasley)

(Whirlpool galaxy & H II regions, HST)

Extinction properties in H II Region

- The Balmer decrement (= EW(Hα)/EW(Hβ)) is larger than the no-dust value, implying dust exists in the H II regions.
- The Balmer decrement remains constant with galaxy inclination.

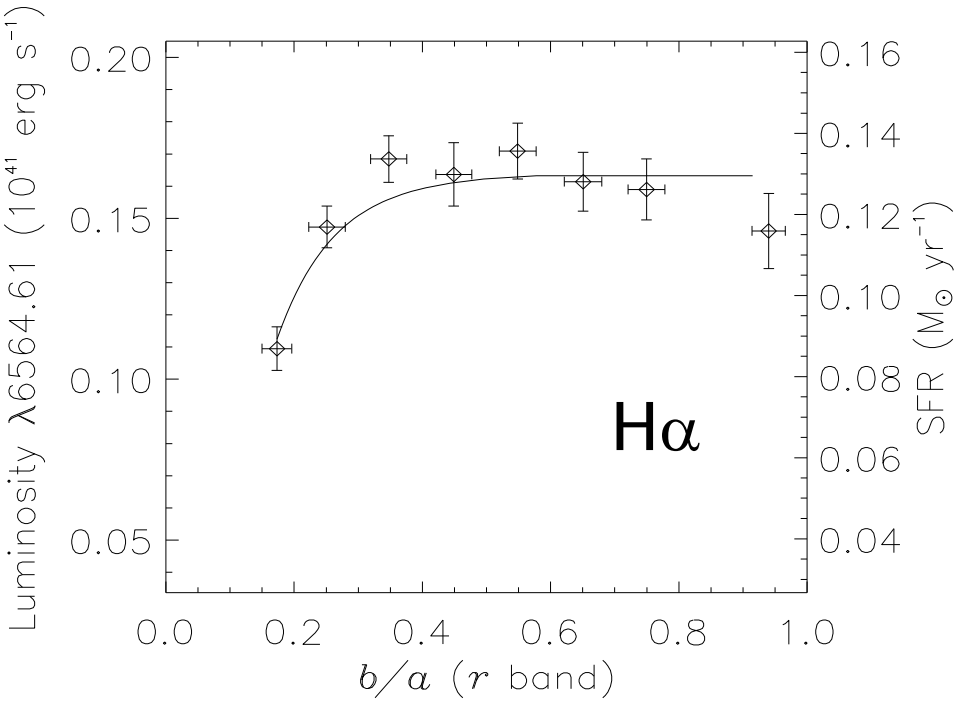


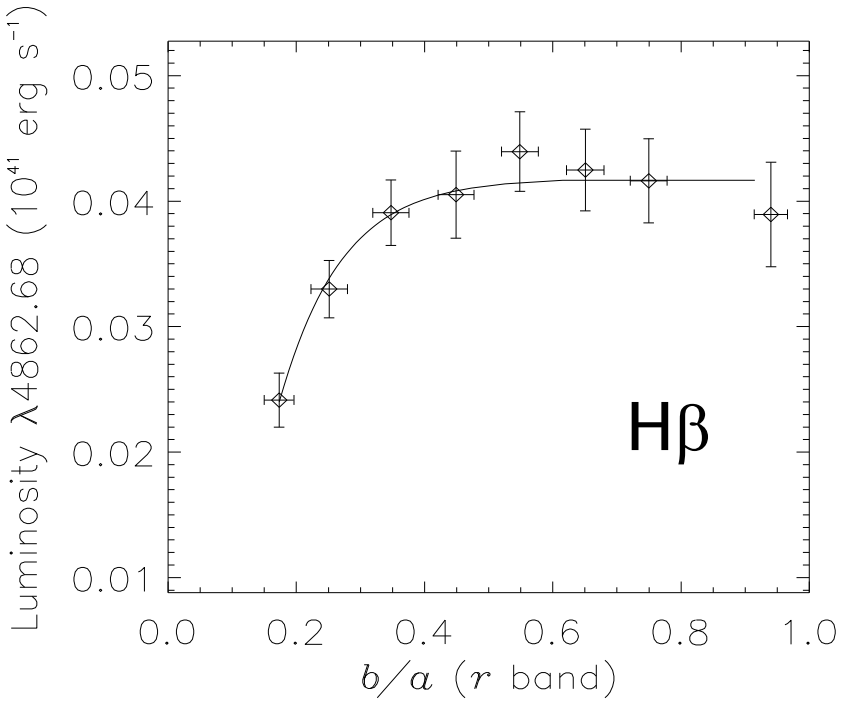
theoretical, no-dust value

Constant Balmer decrement

- Inclination modulation to the Hα and Hβ luminosity are found to be similar in the disk galaxies.

$$\frac{\mathrm{H}\alpha(b/a)}{\mathrm{H}\beta(b/a)} = \frac{\mathrm{H}\alpha(1) f_\alpha(b/a)}{\mathrm{H}\beta(1) f_\beta(b/a)} \Rightarrow \frac{\mathrm{H}\alpha(1)}{\mathrm{H}\beta(1)}$$

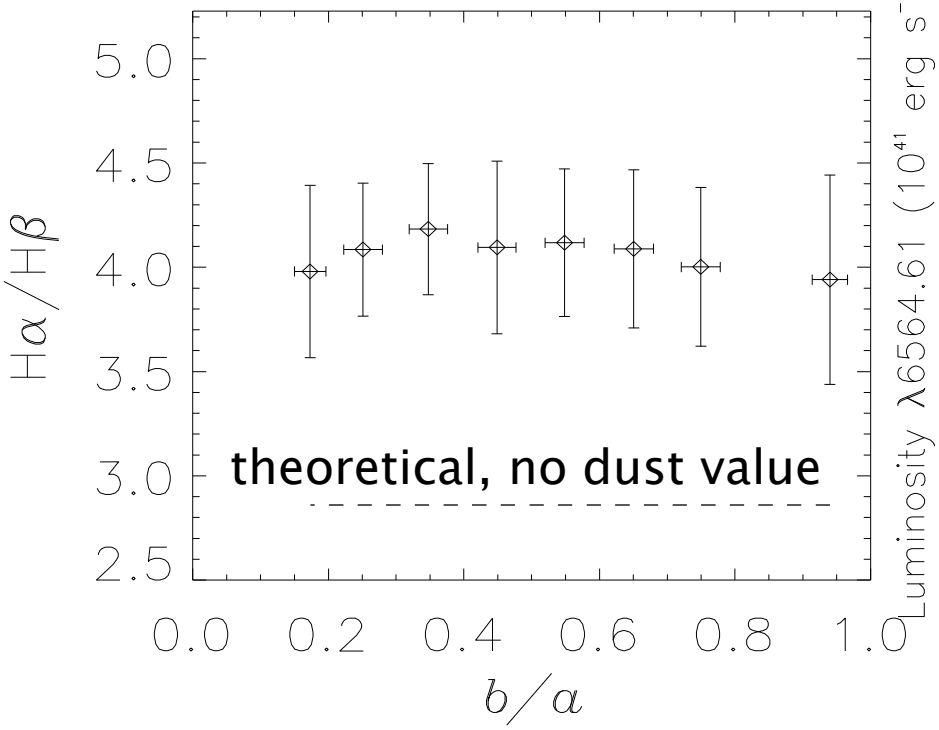




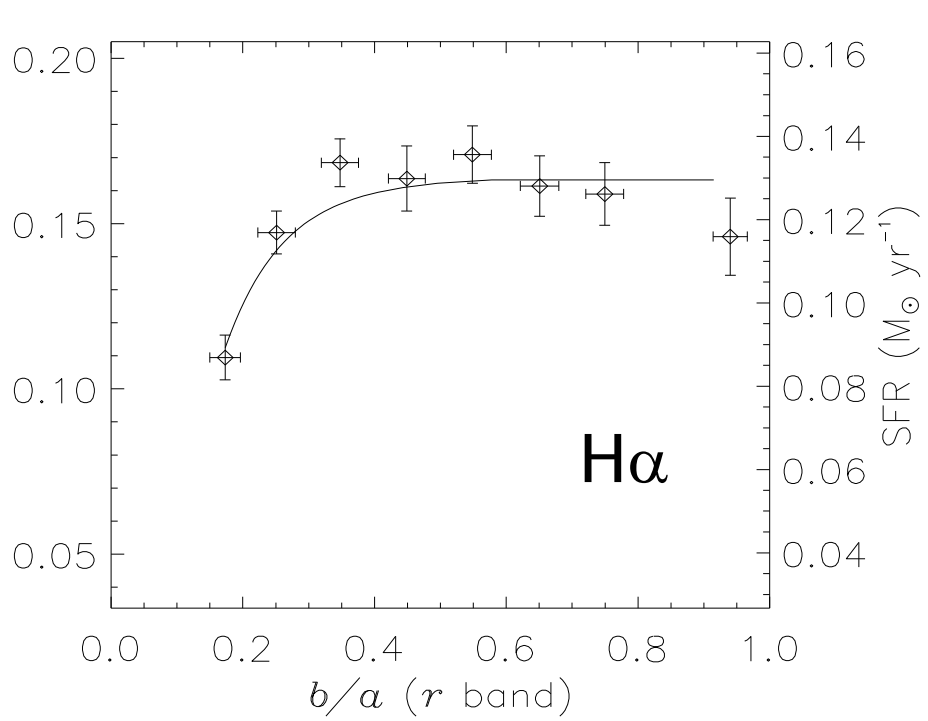
Dust in H II Region: which measure to use?

- Both: reddening vs. extinction.
- Balmer decrement is not affected by galaxy inclination.
- Line luminosity is affected by galaxy inclination.

Balmer decrement

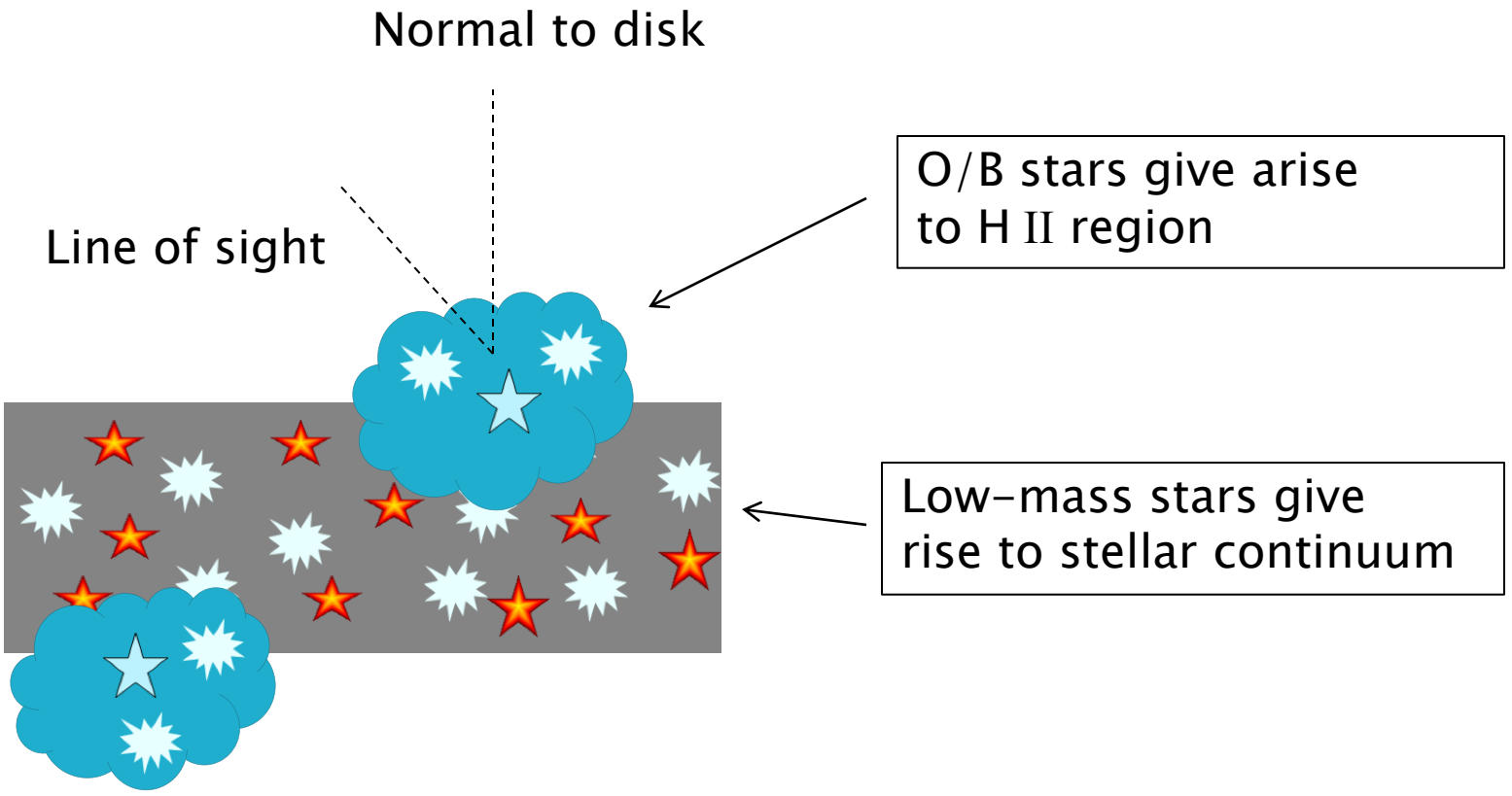


Individual line luminosity



Overall Configuration

- Uniform mix of dust/stars in the disk of the galaxies; with H II regions as pockets in the mix



(not to scale)

Applications: Inclination effect on photometric redshift

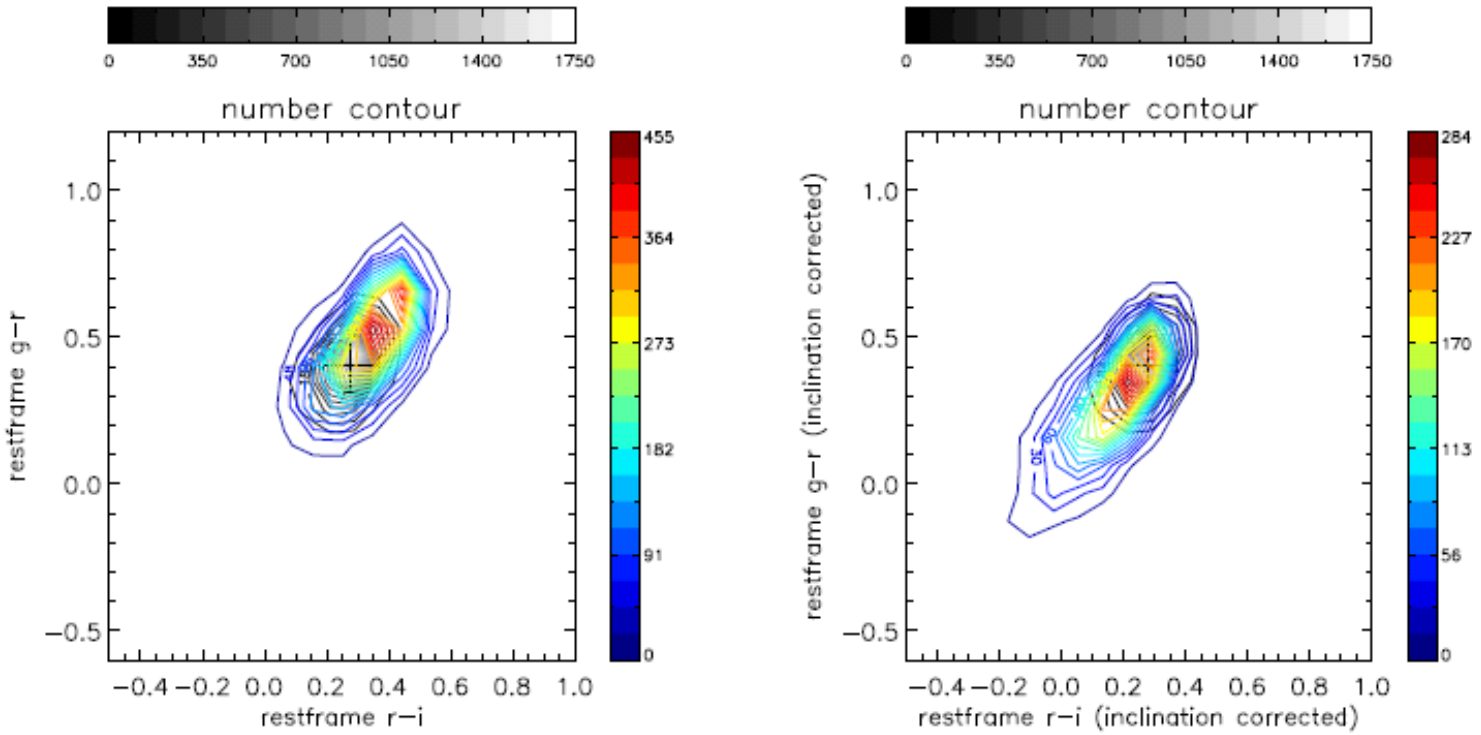
- Color-color diagram of galaxies before and after inclination correction (g-r vs. r-i):

Before

After

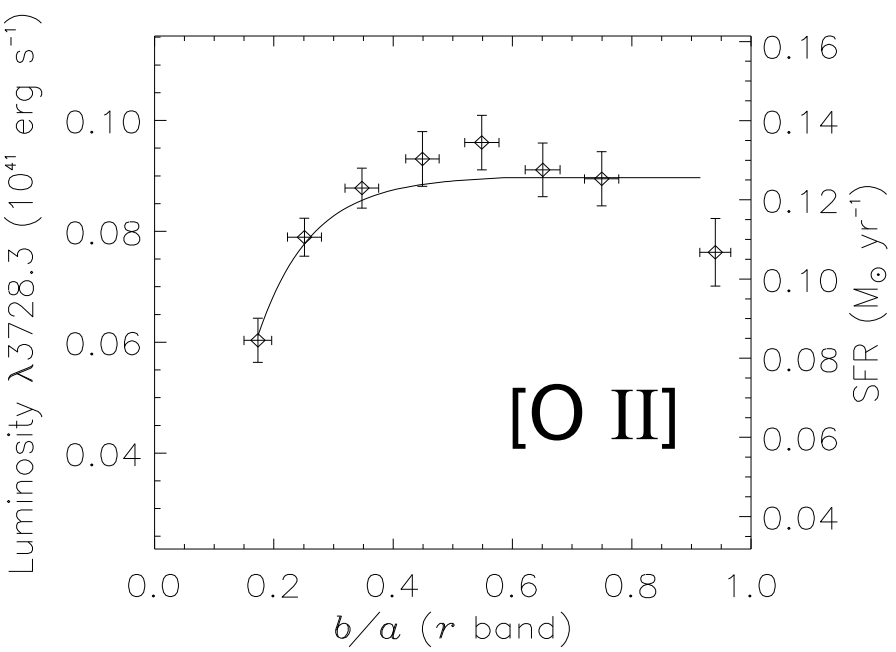
Gray: face-on galaxies

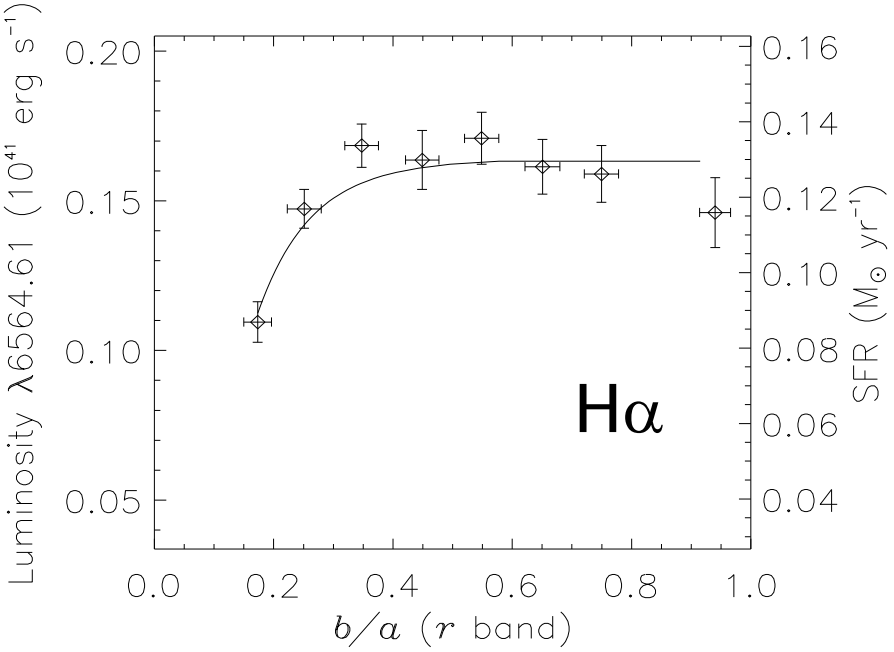
Color: edge-on galaxies



Applications: Inclination correction to star formation rate

- The Hα- and [O II]-derived present SFRs (using Kennicutt 98 calibration) agree to inclination-by-inclination.



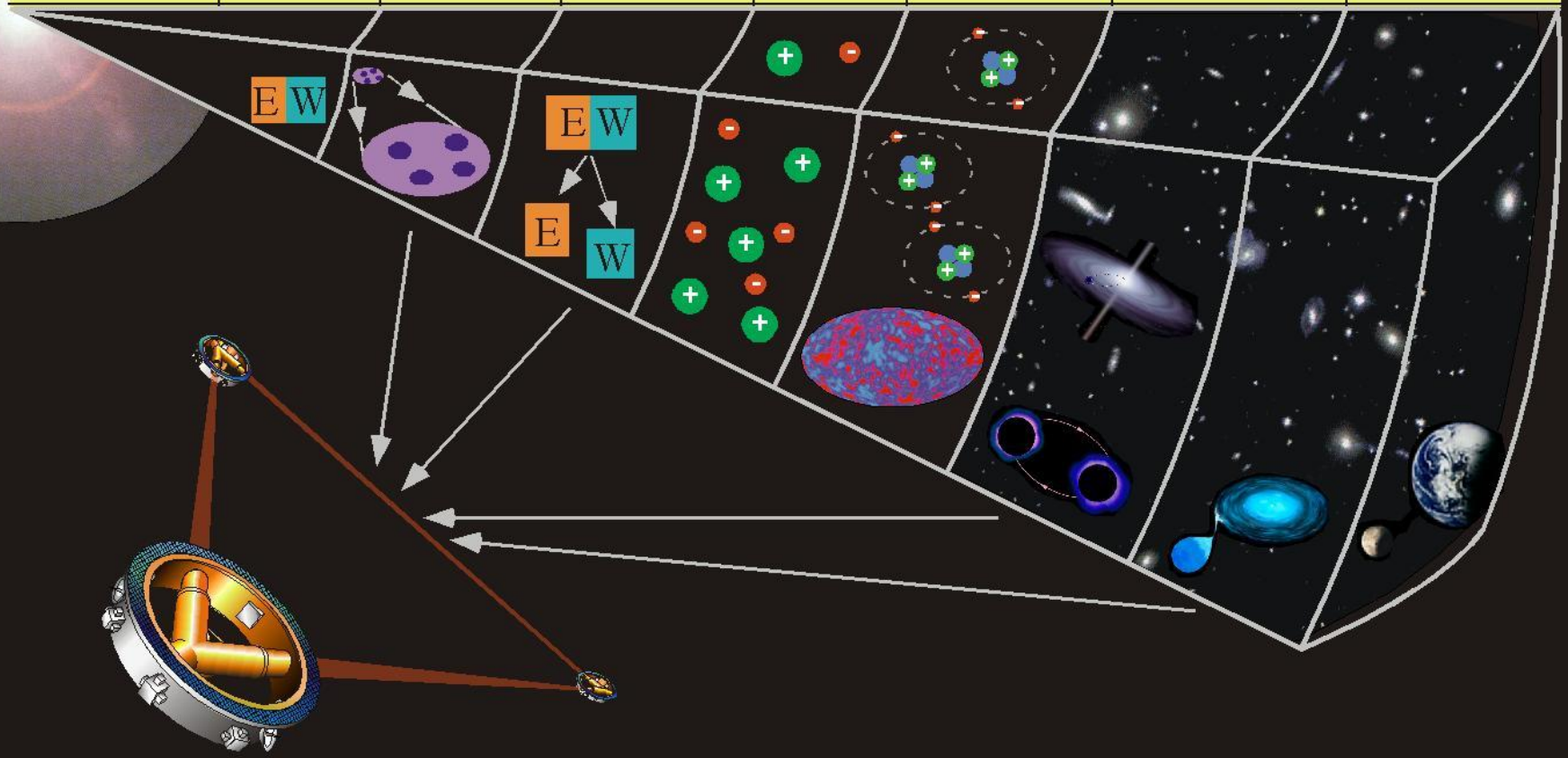


Big Bang

• Galaxies form & evolve

Time →

10^{-44} s	10^{-35} s	10^{-32} s	10^{-10} s	300 s	3×10^{5} yr	1×10^{9} yr	15×10^{9} yr
Superstring (?) Era	GUT Era	Inflation Era	Electro-weak Era	Particle Era	Recombination Era	Galaxy and Star Formation	Present Era



http://www.imperial.ac.uk/

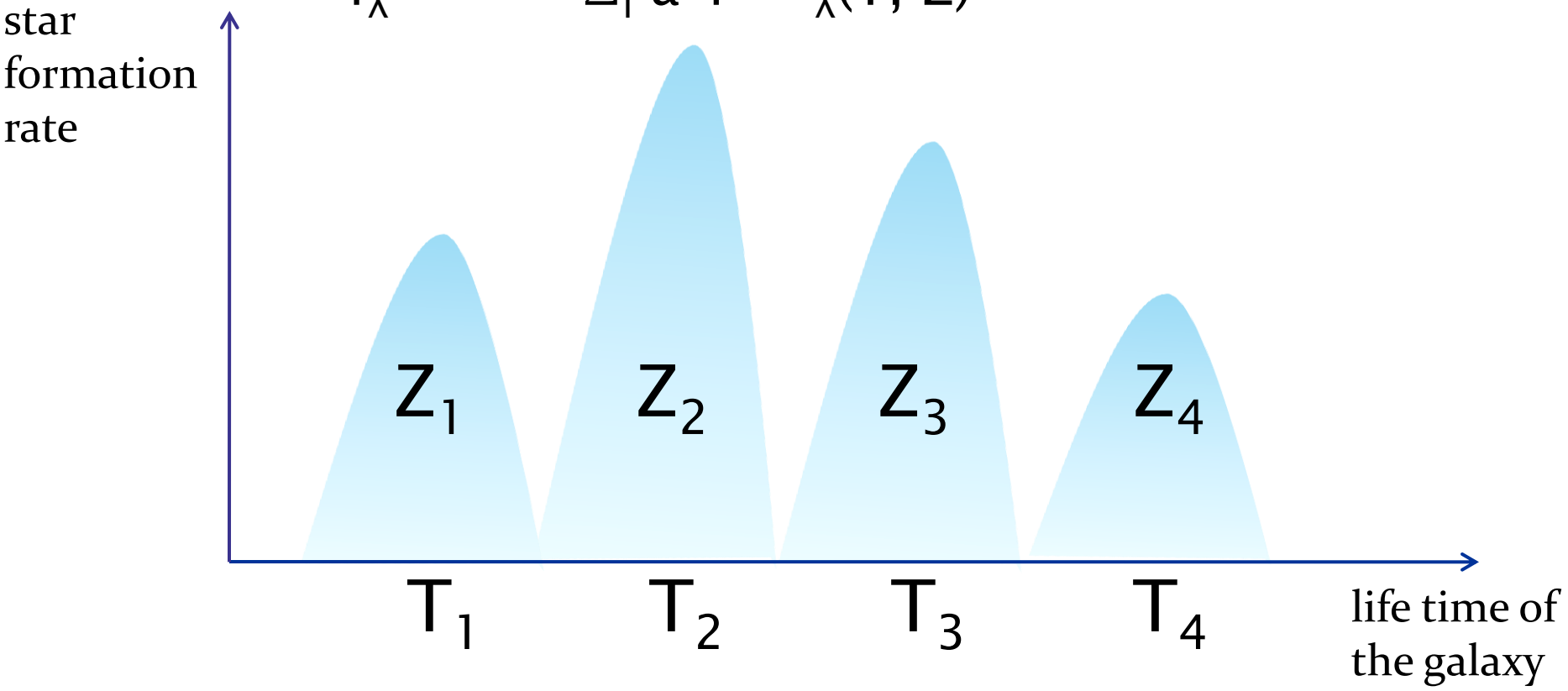
Galaxy Composition through Stellar Population Synthesis

- To model a galaxy is basically to model its star formation history.
- Recipes
  - theoretical stellar spectral library (e.g., Bruzual & Charlot 2003; Maraston et al. 2005):
    - Initial mass function + stellar evolution spectral library $\rightarrow$ single stellar population
    - Star formation history of a galaxy $\rightarrow$ combination of single stellar populations
    - Combine spectra of all single stellar populations $\rightarrow$ theoretical galaxy spectrum
  - Dust
    - extinction model (e.g., Calzetti et al. 2001)

To Model Integrated Stellar Light of Galaxy Spectra

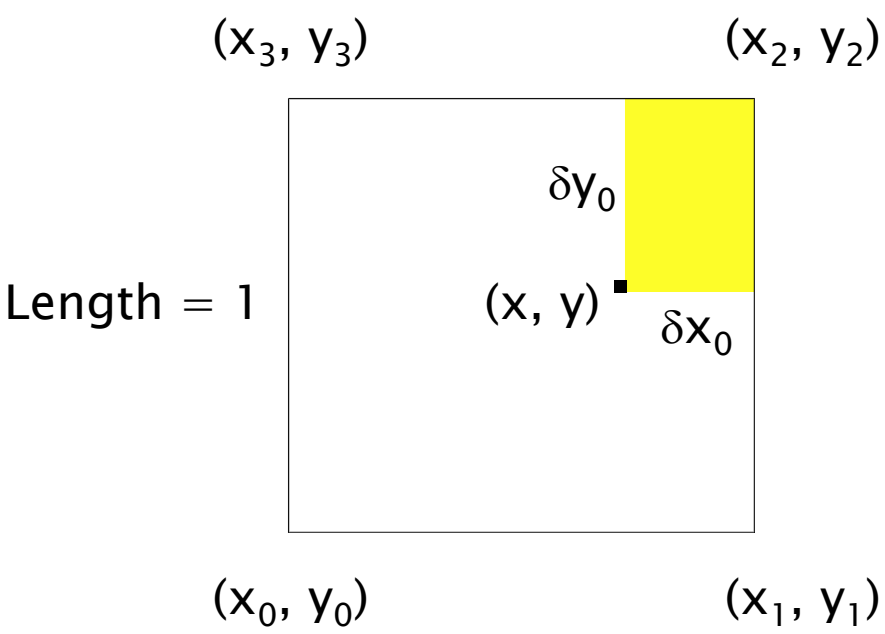
- We model each galaxy spectrum by a linear combination of single stellar populations (Tinsley 70'):

$$f_\lambda^{galaxy} = \sum_i a^i f^{star,i}_\lambda(T, Z)$$



Galaxy Composition through N-D Parameter Estimation

- N-D hypercube
- Multi-linear interpolation to achieve arbitrary computational resolution in parameters



2-D:

$$f(x, y) = f(x_0, y_0) * (\delta x_0 * \delta y_0) + f(x_1, y_1) * (\delta x_1 * \delta y_1) + f(x_2, y_2) * (\delta x_2 * \delta y_2) + f(x_3, y_3) * (\delta x_3 * \delta y_3)$$

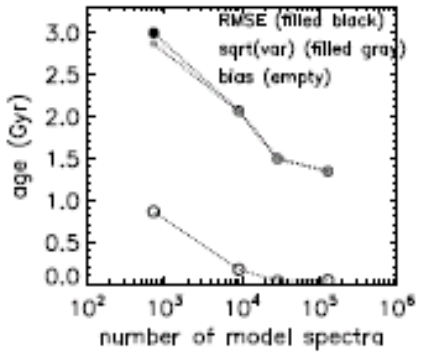
N-D:

$$f(x) = \Sigma\, f(zi)\, \Pi\, (1 - |xj - zij|)$$

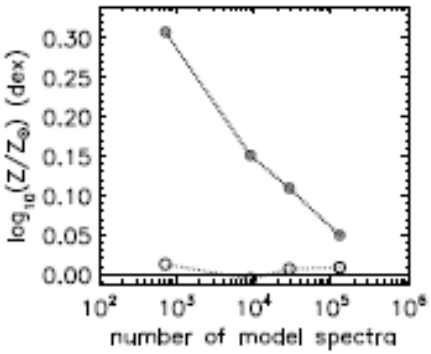
where zi are the neighboring parameter points

Mean square error vs. parameter grid resolution

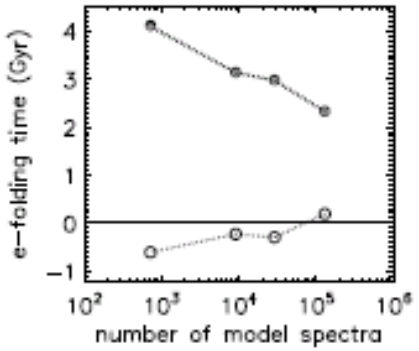
- Mean square error of the parameter estimates decreases with grid resolution.
- Improvement is simultaneous for all parameters.



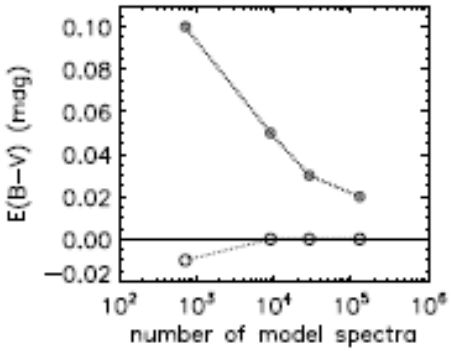
Age of oldest stars



Stellar Metallicity



e-folding time of tar formation

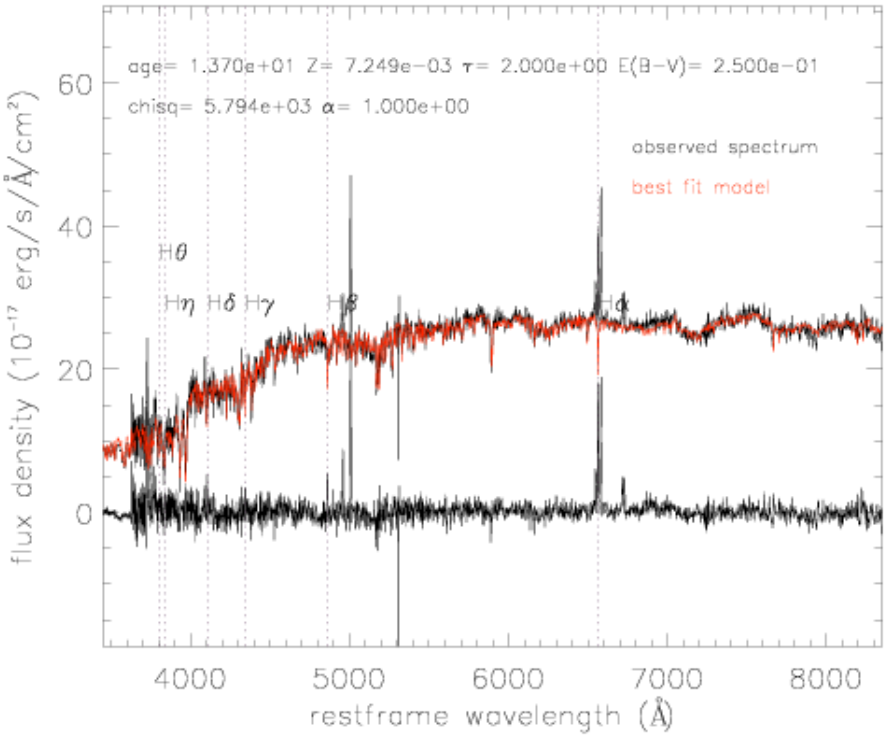


Dust reddening

N-D Parameter Estimation on Spectra

For 4D stellar population model (age, metallicity, star-forming time scale, extinction)

- 300,000 model spectra are generated on the fly
- 30 minutes (high resolution 70km/s in model and SDSS spectra)
- Parameter uncertainties are estimated on object-to-object basis



Age of the oldest stars = 13 Gyr

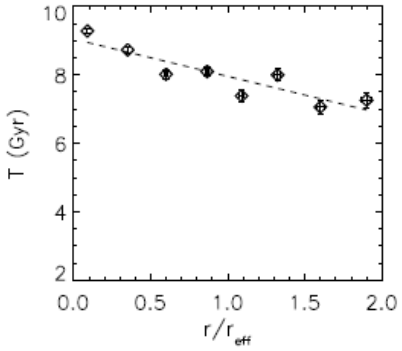
Metallicity = 0.35 solar

e-folding time of star formation = 2 Gyr

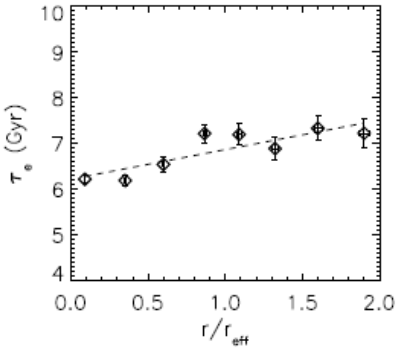
E(B-V) = 0.25 mag

N-D Parameter Estimation on Photometry

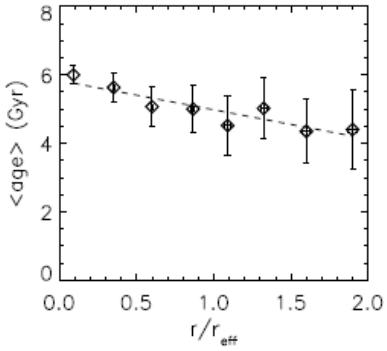
- Stellar population and dust properties as a function of galaxy radius
- Results support inside-out growth (Yip & Wyse 2010 in prep.)
- Similar to tree-ring studies



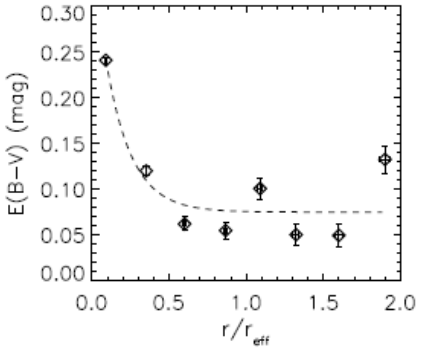
Age of oldest stars vs. radius



e-folding time vs. radius



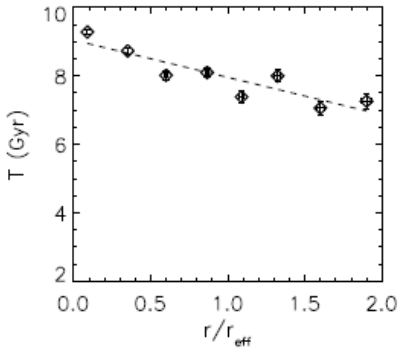
Mean stellar age vs. radius



E(B-V) vs. radius

N-D Parameter Estimation on Photometry

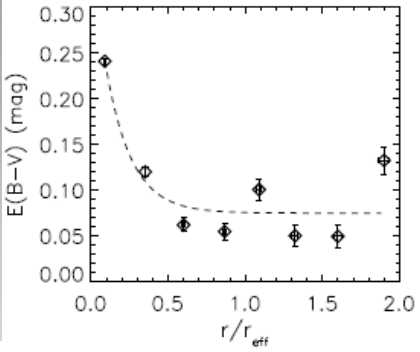
- Stellar p…es as a function…
- Results s… (Yip & W…
- Similar t…



Age of oldest stars vs. radius

e-folding time vs. radius

Mean stellar age vs. radius



E(B-V) vs. radius

Data Analysis through Database

- Automated data analysis:

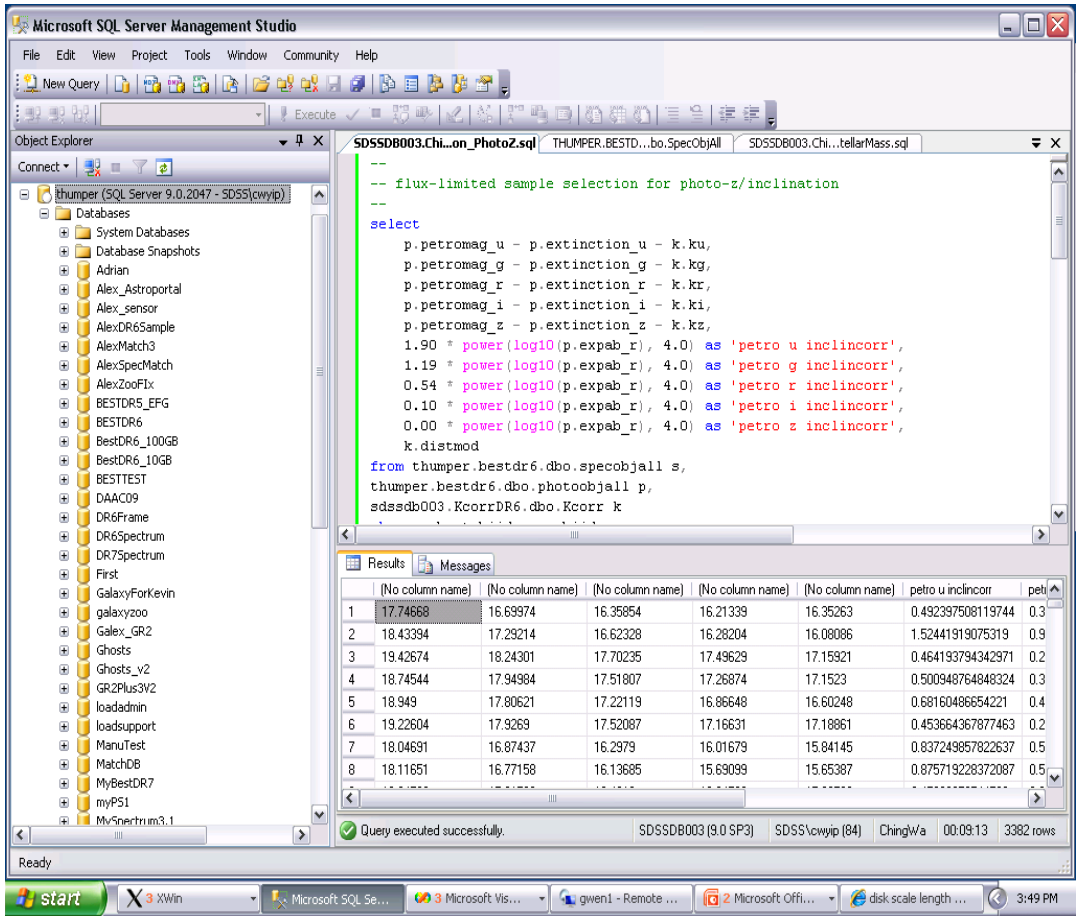
Select data from DB using C# routines with SQL scripts embedded

↓

Perform computations

↓

Output results to DB, if necessary



(MS SQL Server; source: Alex Szalay)

Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST)

- 4 meter segmented telescope, 5 degree FOV (cf. the Moon spans 0.5 degree)
- 4,000 fiber spectra into 16 spectrographs
- 10^7 fiber spectra, 10x more than the SDSS
- Spectral resolution:
  - medium-low
    R = 1,000 – 2,000
  - medium
    R = 5,000 – 10,000

Xinglong Station,
180 km north of Beijing

Summary

- 3D spectra of galaxies
  - We have derived empirically average spectrum of star-forming disk galaxies:

$$f_\lambda(\theta;\ \phi = 0 - 2\pi;\ r \leq 0.5\ r_{eff})$$

- Applications
  - Mapping distribution of stars, gas and dust, statistically.

- Next steps
  - Improving photo-z, present star formation rate, and galaxy classification.
  - Possibility of single-line extinction?
  - Spitzer for processed emissions (courtesy: J. Dalcanton)